

MEMOIRS

of the
American Mathematical Society

ISSN 0065-9266 (print)
ISSN 1947-6221 (online)

Number 1491

Multi-scale Sparse Domination

David Beltran
Joris Roos
Andreas Seeger

June 2024 • Volume 298 • Number 1491 (fifth of 7 numbers)

MEMOIRS

ISSN 0065-9266 (print)
ISSN 1947-6221 (online)

of the
American Mathematical Society

Number 1491

Multi-scale Sparse Domination

David Beltran
Joris Roos
Andreas Seeger

June 2024 • Volume 298 • Number 1491 (fifth of 7 numbers)

Library of Congress Cataloging-in-Publication Data

Cataloging-in-Publication Data has been applied for by the AMS.

See <http://www.loc.gov/publish/cip/>.

DOI: <https://doi.org/10.1090/memo/1491>

Memoirs of the American Mathematical Society

This journal is devoted entirely to research in pure and applied mathematics.

Subscription information. Beginning in 2024, *Memoirs* will be published monthly through 2026. *Memoirs* is also accessible from www.ams.org/journals. The 2024 subscription begins with volume 293 and consists of twelve mailings, each containing one or more numbers. Individual subscription prices for 2024 are as follows. For electronic only: US\$1013. For paper delivery: US\$1,163. Add US\$22 for delivery within the United States; US\$150 for surface delivery outside the United States. Upon request, subscribers to paper delivery of this journal are also entitled to receive electronic delivery. For information on institutional pricing, please visit <https://www.ams.org/publications/journals/subscriberinfo>. Subscription renewals are subject to late fees. See www.ams.org/journal-faq for more journal subscription information. Each number may be ordered separately; please specify number when ordering an individual number.

Back number information. For back issues see www.ams.org/backvols.

Subscriptions and orders should be addressed to the American Mathematical Society, P. O. Box 845904, Boston, MA 02284-5904 USA. *All orders must be accompanied by payment.* Other correspondence should be addressed to 201 Charles Street, Providence, RI 02904-2213 USA.

Copying and reprinting. Individual readers of this publication, and nonprofit libraries acting for them, are permitted to make fair use of the material, such as to copy select pages for use in teaching or research. Permission is granted to quote brief passages from this publication in reviews, provided the customary acknowledgment of the source is given.

Republication, systematic copying, or multiple reproduction of any material in this publication is permitted only under license from the American Mathematical Society. Requests for permission to reuse portions of AMS publication content are handled by the Copyright Clearance Center. For more information, please visit www.ams.org/publications/pubpermissions.

Send requests for translation rights and licensed reprints to reprint-permission@ams.org.

Excluded from these provisions is material for which the author holds copyright. In such cases, requests for permission to reuse or reprint material should be addressed directly to the author(s). Copyright ownership is indicated on the copyright page, or on the lower right-hand corner of the first page of each article within proceedings volumes.

Memoirs of the American Mathematical Society (ISSN 0065-9266 (print); 1947-6221 (online)) is published bimonthly (each volume consisting usually of more than one number) by the American Mathematical Society at 201 Charles Street, Providence, RI 02904-2213 USA. Periodicals postage paid at Providence, RI. Postmaster: Send address changes to *Memoirs*, American Mathematical Society, 201 Charles Street, Providence, RI 02904-2213 USA.

© 2024 by the American Mathematical Society. All rights reserved.

This publication is indexed in *Mathematical Reviews*[®], *Zentralblatt MATH*, *Science Citation Index*[®], *Science Citation IndexTM-Expanded*, *ISI Alerting ServicesSM*, *SciSearch*[®], *Research Alert*[®], *CompuMath Citation Index*[®], *Current Contents*[®]/*Physical, Chemical & Earth Sciences*.

This publication is archived in *Portico* and *CLOCKSS*.

Printed in the United States of America.

∞ The paper used in this book is acid-free and falls within the guidelines established to ensure permanence and durability.

Visit the AMS home page at <https://www.ams.org/>

10 9 8 7 6 5 4 3 2 1 29 28 27 26 25 24

Contents

Chapter 1. Introduction	1
1.1. The main result	4
1.2. Necessary conditions	6
1.3. An application to maximal functions	7
1.4. Fourier multipliers	9
1.5. Application to weighted norm inequalities	11
1.6. Organization and notation	11
Acknowledgments	13
Chapter 2. Necessary Conditions	15
2.1. The local integrability hypothesis	16
2.2. The reflexivity hypothesis	19
Chapter 3. Single scale sparse domination	23
3.1. A single scale estimate	23
3.2. A resolution of the identity	24
3.3. Single scale regularity	24
Chapter 4. Proof of the main result	29
4.1. A modified version of sparse forms	29
4.2. Proof of the main theorem given the inductive claim	30
4.3. Proof of the corollary of the main theorem	31
4.4. The inductive step	32
Chapter 5. Maximal operators, square functions and long variations	43
5.1. Maximal functions and ℓ^r -variants	43
5.2. Variation norms	45
5.3. Truncations of sums	46
5.4. Some simplifications for maximal operators	48
Chapter 6. Fourier multipliers	51
6.1. The main multiplier theorem	51
6.2. A result involving localizations of Fourier multipliers	53
6.3. Proof of the main multiplier theorem	54
Chapter 7. Sample applications	59
7.1. Operators generated by compactly supported distributions	59
7.1.1. Maximal functions	59
7.1.2. Variational operators	61

7.1.3. Lacunary maximal functions for convolutions associated with the wave equation	63
7.2. General classes of multipliers	64
7.2.1. Miyachi classes and subdyadic Hörmander conditions	66
7.2.2. Multiscale variants of oscillatory multipliers	68
7.3. Prototypical versions of singular Radon transforms	71
7.3.1. An approach via Fourier multipliers	72
7.4. Densities on spheres: Maximal singular integrals	73
7.5. On radial Fourier multipliers	76
7.6. Stein's square function	78
7.6.1. The case $1 < p \leq 2$	78
7.6.2. The case $2 < p < \infty$	80
Appendix A. Facts about sparse domination	81
A.1. Replacing simple functions	81
A.2. The Hardy–Littlewood maximal function	82
A.3. Operators associated with dilates of Schwartz functions	83
Appendix B. Sparse domination: Cases where $p = 1$ or $q = \infty$	85
B.1. The case $p = 1, q < \infty$	85
B.2. The case $p > 1, q = \infty$	87
B.3. The case $p = 1$ and $q = \infty$	92
Appendix C. Facts about fourier multipliers	95
C.1. Multiplication by smooth symbols	96
C.2. Independence of ϕ, Ψ in the finiteness of $\mathcal{B}[m]$	96
Bibliography	99

Abstract

We prove a bilinear form sparse domination theorem that applies to many multi-scale operators beyond Calderón–Zygmund theory, and also establish necessary conditions. Among the applications, we cover large classes of Fourier multipliers, maximal functions, square functions and variation norm operators.

Received by the editor September 4, 2020, and, in revised form, December 30, 2021.

Article electronically published on June 13, 2024.

DOI: <https://doi.org/10.1090/memo/1491>

2020 *Mathematics Subject Classification*. Primary 42B15, 42B20, 42B25.

Key words and phrases. Sparse domination, Fourier multipliers, maximal functions, square functions, variation norm.

D.B. was partially supported by NSF grant DMS-1954479. J.R. and A.S. were partially supported by NSF grant DMS-1764295, and A.S. was partially supported by a Simons fellowship.

©2024 American Mathematical Society

Introduction

Sparse domination results have received considerable interest in recent years since the fundamental work of Lerner on Calderón–Zygmund operators [75, 76], which provided an alternative proof of the A_2 -theorem [57]. The original Banach space domination result was refined and streamlined to a pointwise result [31, 65, 77, 79], but it is the concept of sparse domination in terms of bilinear (or multilinear) forms [18, 33] that has allowed to extend the subject to many operators in harmonic analysis beyond the scope of Calderón–Zygmund theory. Among other examples, one may find the bilinear Hilbert transform [33], singular integrals with limited regularity assumptions [15, 29, 78], Bochner–Riesz operators [16, 68], spherical maximal functions [66], singular Radon transforms [28, 54, 89], pseudo-differential operators [11], maximally modulated singular integrals [8, 38], non-integral square functions [6], and variational operators [17, 35, 36], as well as results in a discrete setting (see for instance [2, 34, 64]).

Many operators in analysis have a multiscale structure, either on the space or frequency side. We consider sums

$$T = \sum_{j \in \mathbb{Z}} T_j,$$

where the Schwartz kernel of T_j is supported in a 2^j neighborhood of the diagonal and where suitable rescalings of the individual operators T_j and their adjoints satisfy uniform $L^p \rightarrow L^q$ bounds. Moreover we assume that all partial sums $\sum_{j=N_1}^{N_2} T_j$ satisfy uniform $L^p \rightarrow L^{p,\infty}$ and $L^{q,1} \rightarrow L^q$ bounds. The goal of this memoir is to show bilinear form (p, q') -sparse domination results (with $q' = q/(q-1)$ the dual exponent) and investigate to which extent our assumptions are necessary. We prove such results under a very mild additional regularity assumption on the rescaled pieces; for a precise statement see Theorem 1.1. To increase applicability, we cover vector-valued situations, thus consider functions with values in a Banach space B_1 and operators that map simple B_1 -valued functions to functions with values in a Banach space B_2 . Our results apply to many classes of operators beyond Calderón–Zygmund theory, and cover general classes of convolution operators with weak assumptions on the dyadic frequency localizations, together with associated maximal functions, square functions, variation norm operators, and more. See Theorem 1.4 for a particularly clean result on translation invariant maximal functions. We shall formulate the results with respect to cubes in the standard Euclidean geometry but there are no fundamental obstructions to extend them to other geometries involving nonisotropic dilations (see *e.g.* [28]). Our approach to sparse domination extends ideas in the papers by Lacey [66] on spherical maximal functions and by R. Oberlin [89] on singular Radon transforms to more general situations.

We now describe the framework for our main theorem and first review basic definitions. For a Banach space B let S_B be the space of all B -valued simple functions on \mathbb{R}^d with compact support, i.e. all functions of the form $f = \sum_{i=1}^N a_i \mathbf{1}_{E_i}$ where $a_i \in B$ and E_i are Lebesgue measurable subsets of \mathbb{R}^d contained in a compact set. For Banach spaces B_1, B_2 we consider the space Op_{B_1, B_2} of linear operators T mapping functions in S_{B_1} to weakly measurable B_2 -valued functions (see *e.g.* [56] for an exposition of Banach-space integration theory) with the property that $x \mapsto \langle Tf(x), \lambda \rangle$ is locally integrable for any bounded linear functional $\lambda \in B_2^*$. If $T \in \text{Op}_{B_1, B_2}$, then the integral

$$\langle Tf_1, f_2 \rangle = \int_{\mathbb{R}^d} \langle Tf_1(x), f_2(x) \rangle_{(B_2, B_2^*)} dx$$

is well-defined for all $f_1 \in S_{B_1}$ and $f_2 \in S_{B_2^*}$. For a Banach space B and $p, r \in [1, \infty]$ we define the Lorentz space $L_B^{p,r}$ as the space of strongly measurable functions $f: \mathbb{R}^d \rightarrow B$ so that the function $x \mapsto |f(x)|_B$ is in the scalar Lorentz space $L^{p,r}$ (and we endow $L_B^{p,r}$ with the topology inherited from $L^{p,r}$). In particular, $L_B^p = L_B^{p,p}$ coincides with the standard Banach space valued L^p space as defined in [56], up to equivalence of norms. If $p \in (1, \infty)$ and $r \in [1, \infty]$, then $L_B^{p,r}$ is normable and we write $\|\cdot\|_{L_B^{p,r}}$ to denote the norm induced by the norm on scalar $L^{p,r}$ defined via the maximal function of the nonincreasing rearrangement [55].

In the definition of sparse forms it is convenient to work with a dyadic lattice $\mathfrak{Q} = \cup_{k \in \mathbb{Z}} \mathfrak{Q}_k$ of cubes, in the sense of Lerner and Nazarov [79, §2]. A prototypical example is when the cubes in the k -th generation \mathfrak{Q}_k are given by

$$\mathfrak{Q}_k = \begin{cases} \{2^{-k} \mathfrak{z} + [-\frac{1}{3}2^{-k}, \frac{1}{3}2^{-k+1}]^d : \mathfrak{z} \in \mathbb{Z}^d\} & \text{if } k \text{ is odd,} \\ \{2^{-k} \mathfrak{z} + [-\frac{1}{3}2^{-k+1}, \frac{1}{3}2^{-k}]^d : \mathfrak{z} \in \mathbb{Z}^d\} & \text{if } k \text{ is even,} \end{cases}$$

but many other choices are possible. Notice in this example the cubes in \mathfrak{Q}_k have side length 2^{-k} . This family satisfies the three axioms of a *dyadic lattice* in [79]. We briefly review the definition. \mathfrak{Q} is a dyadic lattice if

- (i) every child of a cube $Q \in \mathfrak{Q}$ is in \mathfrak{Q} ,
- (ii) every two cubes Q, Q' have a common ancestor in \mathfrak{Q} , and
- (iii) every compact set in \mathbb{R}^d is contained in a cube in \mathfrak{Q} .

For each dyadic lattice there is an $\alpha \in [1, 2)$ such that all cubes $Q \in \mathfrak{Q}$ are of side length $\alpha 2^{-k}$ for some $k \in \mathbb{Z}$. Fixing k we then call the cubes of side length $\alpha 2^{-k}$ the k -th generation cubes in \mathfrak{Q} . If $Q \in \mathfrak{Q}$ we can, for every $l \geq 0$, tile Q into disjoint subcubes Q' of side length equal to 2^{-l} times the side length of Q . We denote this family by $\mathcal{D}_l(Q)$ and let $\mathcal{D}(Q) = \cup_{l \geq 0} \mathcal{D}_l(Q)$, the family of all dyadic subcubes of Q . Then for every $Q \in \mathfrak{Q}$ we have $\mathcal{D}(Q) \subset \mathfrak{Q}$. Note that because of condition (iii) the standard dyadic lattice is not a dyadic lattice in the above sense.

DEFINITION. Let $0 < \gamma < 1$. A collection $\mathfrak{S} \subset \mathfrak{Q}$ is γ -sparse if for every $Q \in \mathfrak{S}$ there is a measurable subset $E_Q \subset Q$ such that $|E_Q| \geq \gamma|Q|$ and such that the sets on the family $\{E_Q : Q \in \mathfrak{S}\}$ are pairwise disjoint.

We next review the concept of sparse domination. Given a cube Q , $1 \leq p < \infty$ and a B -valued strongly measurable locally integrable function f we use the notations

$$\text{av}_Q f = |Q|^{-1} \int_Q f(x) dx, \quad \langle f \rangle_{Q,p,B} = \left(|Q|^{-1} \int_Q |f(x)|_B^p dx \right)^{1/p}$$

for the average of f over Q and the L^p norm on Q with normalized measure, thus $\langle f \rangle_{Q,p,B} = (\text{av}_Q |f|_B^p)^{1/p}$. For an operator $T \in \text{Op}_{B_1, B_2}$ we say that pointwise sparse domination [31, 79] by L^p -averages holds if for every $f \in \mathcal{S}_{B_1}$ there are at most 3^d sparse families $\mathfrak{S}_i(f)$ such that

$$(1.1) \quad |Tf(x)|_{B_2} \leq C \sum_{i=1}^{3^d} \sum_{Q \in \mathfrak{S}_i(f)} \langle f \rangle_{Q,p,B_1} \mathbf{1}_Q(x) \quad \text{for a.e. } x$$

and we denote by $\|T\|_{\text{Sp}_\gamma(p, B_1, B_2)}$ the infimum over all C such that (1.1) holds for some collection of 3^d γ -sparse families depending on f .

For many operators it is not possible to obtain pointwise sparse domination and the concept of sparse domination of bilinear forms, which goes back to [18] and [33], is an appropriate substitute. Given a γ -sparse collection of cubes \mathfrak{S} and $1 \leq p_1, p_2 < \infty$, one defines an associated sparse (p_1, p_2) -form acting on pairs (f_1, f_2) where f_1 is a simple B_1 -valued function and f_2 is a simple B_2^* -valued function. It is given by

$$(1.2) \quad \Lambda_{p_1, B_1, p_2, B_2^*}^{\mathfrak{S}}(f_1, f_2) = \sum_{Q \in \mathfrak{S}} |Q| \langle f_1 \rangle_{Q, p_1, B_1} \langle f_2 \rangle_{Q, p_2, B_2^*},$$

and will be abbreviated by $\Lambda_{p_1, p_2}^{\mathfrak{S}}(f_1, f_2)$ if the choice of B_1, B_2^* is clear from context. The form (1.2) acts a bi-sublinear form on $(|f_1|_{B_1}, |f_2|_{B_2^*})$. All sparse forms are dominated by a maximal form

$$(1.3) \quad \Lambda_{p_1, B_1, p_2, B_2^*}^*(f_1, f_2) = \sup_{\mathfrak{S}: \gamma\text{-sparse}} \Lambda_{p_1, B_1, p_2, B_2^*}^{\mathfrak{S}}(f_1, f_2),$$

again also abbreviated by $\Lambda_{p_1, p_2}^*(f_1, f_2)$ if the choice of B_1, B_2^* is clear from the context. The maximal form may not be a sparse form itself but, obviously, for every f_1, f_2 there exists a sparse family $\mathfrak{S}(f_1, f_2)$ such that $\Lambda_{p_1, B_1, p_2, B_2^*}^{\mathfrak{S}(f_1, f_2)}(f_1, f_2) \geq \frac{1}{2} \Lambda_{p_1, B_1, p_2, B_2^*}^*(f_1, f_2)$ (cf. [67], [32] for more explicit constructions). Note from (1.2) that for each pair of simple functions (f_1, f_2) ,

$$\Lambda_{p_1, B_1, p_2, B_2^*}^*(f_1, f_2) \leq \gamma^{-1} \|f_1\|_\infty \|f_2\|_\infty \text{meas}(\text{supp } f_1 \cup \text{supp } f_2) < \infty.$$

We say that $T \in \text{Op}_{B_1, B_2}$ satisfies a sparse (p_1, p_2) bound if there is a constant C so that for all $f_1 \in \mathcal{S}_{B_1}$ and $f_2 \in \mathcal{S}_{B_2^*}$ the inequality

$$(1.4) \quad |\langle Tf_1, f_2 \rangle| \leq C \Lambda_{p_1, B_1, p_2, B_2^*}^*(f_1, f_2)$$

is satisfied. The best constant in (1.4) defines a norm $\|\cdot\|_{\text{Sp}_\gamma(p_1, B_1, p_2, B_2^*)}$ on a subspace of Op_{B_1, B_2} . Thus $\|T\|_{\text{Sp}_\gamma(p_1, B_1; p_2, B_2^*)}$ is given by

$$(1.5) \quad \sup \left\{ \frac{|\langle Tf_1, f_2 \rangle|}{\Lambda_{p_1, B_1, p_2, B_2^*}^*(f_1, f_2)} : f_1 \in \mathcal{S}_{B_1}, f_2 \in \mathcal{S}_{B_2^*}, f_i \neq 0, i = 1, 2 \right\},$$

where $f_i \neq 0$ means that $f_i(x) \neq 0$ on a set of positive measure. It is then immediate that $\|T\|_{\text{Sp}_\gamma(p_1, B_1, p_2, B_2^*)} \leq \|T\|_{\text{Sp}_\gamma(p_1, B_1, B_2)}$ for $p_2 \geq 1$. It can be shown that the space of operators in Op_{B_1, B_2} for which (1.4) holds for all f_1, f_2 with a finite C does not depend on γ . We denote this space by $\text{Sp}(p_1, B_1, p_2, B_2^*)$ or simply $\text{Sp}(p_1, p_2)$ if the choices of B_1, B_2^* are clear from context. The norms $\|\cdot\|_{\text{Sp}_\gamma(p_1, B_1, p_2, B_2^*)}$, $0 < \gamma < 1$, are equivalent norms on $\text{Sp}(p_1, B_1, p_2, B_2^*)$. Moreover, if B_1, B_2 are separable Banach spaces and $p_1 < p < p_2'$, then all operators in $\text{Sp}(p_1, B_1, p_2, B_2^*)$ extend to bounded operators from $L_{B_1}^p$ to $L_{B_2}^{p'}$.

1.1. The main result

For a function f define $\text{Dil}_t f(x) = f(tx)$. For an operator T define the dilated operator $\text{Dil}_t T$ by

$$\text{Dil}_t T = \text{Dil}_t \circ T \circ \text{Dil}_{t^{-1}}.$$

Note that if T is given by a Schwartz kernel $(x, y) \mapsto K(x, y)$, then the Schwartz kernel of $\text{Dil}_t T$ is given by $(x, y) \mapsto t^d K(tx, ty)$.

Basic assumptions. Let $\{T_j\}_{j \in \mathbb{Z}}$ be a family of operators in Op_{B_1, B_2} . We shall make the following assumptions.

Support condition. For all $f \in \mathcal{S}_{B_1}$,

$$(1.6) \quad \text{supp}(\text{Dil}_{2^j} T_j) f \subset \{x \in \mathbb{R}^d : \text{dist}(x, \text{supp} f) \leq 1\}.$$

This means that if T_j is given by integration against a Schwartz kernel K_j , then K_j lives on a 2^j -neighborhood of the diagonal.

Weak type (p, p) condition. For all integers $N_1 \leq N_2$, the sums $\sum_{j=N_1}^{N_2} T_j$ are of weak type (p, p) , with uniform bounds,

$$(1.7a) \quad \sup_{N_1 \leq N_2} \left\| \sum_{j=N_1}^{N_2} T_j \right\|_{L_{B_1}^p \rightarrow L_{B_2}^{p, \infty}} \leq A(p).$$

Restricted strong type (q, q) condition. For all integers $N_1 \leq N_2$, the sums $\sum_{j=N_1}^{N_2} T_j$ are of restricted strong type (q, q) , with uniform bounds,

$$(1.7b) \quad \sup_{N_1 \leq N_2} \left\| \sum_{j=N_1}^{N_2} T_j \right\|_{L_{B_1}^{q, 1} \rightarrow L_{B_2}^q} \leq A(q).$$

Single scale (p, q) condition. The operators T_j satisfy the uniform improving bounds

$$(1.8) \quad \sup_{j \in \mathbb{Z}} \|\text{Dil}_{2^j} T_j\|_{L_{B_1}^p \rightarrow L_{B_2}^q} \leq A_0(p, q).$$

Single scale ε -regularity conditions. For some $\varepsilon > 0$ the operators T_j and the adjoints T_j^* satisfy

$$(1.9a) \quad \sup_{|h| \leq 1} |h|^{-\varepsilon} \sup_{j \in \mathbb{Z}} \|(\text{Dil}_{2^j} T_j) \circ \Delta_h\|_{L_{B_1}^p \rightarrow L_{B_2}^q} \leq B,$$

$$(1.9b) \quad \sup_{|h| \leq 1} |h|^{-\varepsilon} \sup_{j \in \mathbb{Z}} \|(\text{Dil}_{2^j} T_j^*) \circ \Delta_h\|_{L_{B_2^*}^{q'} \rightarrow L_{B_1^*}^{p'}} \leq B,$$

where

$$(1.10) \quad \Delta_h f(x) := f(x + h) - f(x).$$

The above hypotheses assume certain boundedness assumptions in Lebesgue or Lorentz spaces of vector-valued functions; it is then implied that all operators T_j map simple B_1 -valued functions to B_2 -valued functions which are strongly measurable with respect to Lebesgue measure. We formulate our main result for $1 < p \leq q < \infty$ and refer to Appendix B for variants with $p = 1$ or $q = \infty$.

THEOREM 1.1. *Let $1 < p \leq q < \infty$. Let $\{T_j\}_{j \in \mathbb{Z}}$ be a family of operators in Op_{B_1, B_2} such that*

- *the support condition (1.6) holds,*
- *the weak type (p, p) condition (1.7a) holds,*
- *the restricted strong type (q, q) condition (1.7b) holds,*

- the single scale (p, q) condition (1.8) holds,
- the single scale ε -regularity conditions (1.9a), (1.9b) hold.

Define

$$(1.11) \quad \mathcal{C} = A(p) + A(q) + A_\circ(p, q) \log \left(2 + \frac{B}{A_\circ(p, q)} \right).$$

Then, for all integers N_1, N_2 with $N_1 \leq N_2$,

$$(1.12) \quad \left\| \sum_{j=N_1}^{N_2} T_j \right\|_{\mathbb{S}_{p_\gamma(p, B_1, q', B_2^*)}} \lesssim_{p, q, \varepsilon, \gamma, d} \mathcal{C}.$$

The estimate (1.12) implies, via a linearization technique (*cf.* Lemma 4.4) the following variant which leads to a sparse domination result for maximal functions, square functions and variational operators, see Ch. 5. Instead of $T_j \in \text{Op}_{B_1, B_2}$ we use the more restrictive assumption that the T_j map functions in \mathbb{S}_{B_1} to locally integrable B_2 -valued functions. We let $L^1_{B_2, \text{loc}}$ be the space of all strongly measurable B_2 -valued functions which are Bochner integrable over compact sets.

COROLLARY 1.2. *Let $1 < p \leq q < \infty$. Let $\{T_j\}_{j \in \mathbb{Z}}$ be a family of operators, with $T_j : \mathbb{S}_{B_1} \rightarrow L^1_{B_2, \text{loc}}$, and satisfying the assumptions of Theorem 1.1. Let \mathcal{C} be as in (1.11). Then for all $f \in \mathbb{S}_{B_1}$, all \mathbb{R} -valued nonnegative measurable functions ω , and all integers N_1, N_2 with $N_1 \leq N_2$,*

$$(1.13) \quad \int_{\mathbb{R}^d} \left| \sum_{j=N_1}^{N_2} T_j f(x) \right|_{B_2} \omega(x) dx \lesssim_{p, q, \varepsilon, \gamma, d} \mathcal{C} \Lambda_{p, B_1, q', \mathbb{R}}^*(f, \omega).$$

REMARKS.

- (i) We emphasize that the implicit constants in (1.12) and (1.13) are dependent on the input constants in (1.7a), (1.7b), (1.8), (1.9a), (1.9b) but otherwise not dependent on the specific choices of the Banach spaces B_1, B_2 . In some applications this enables us to perform certain approximation arguments, where for example the Banach spaces are replaced by finite-dimensional subspaces of large dimension.
- (ii) We note that for operators T_j which commute with translations Condition (1.9b) is implied by Condition (1.9a).
- (iii) The Hölder-type regularity assumption (1.9) for the operator norm can be further weakened. In applications this will often be used for the situation that an operator T is split into a sum $\sum_{\ell \geq 0} T^\ell$ where each $T^\ell = \sum_j T_j^\ell$ satisfies the assumptions with $A(p), A(q), A_\circ(p, q) = O(2^{-\ell \varepsilon'})$ for some $\varepsilon' > 0$ and $B = 2^{\ell M}$, for a possibly very large M . The conclusion will then say that $\|T^\ell\|_{\mathbb{S}_{p_\gamma(p, q')}} = O(\ell 2^{-\ell \varepsilon'})$, which can be summed in ℓ , leading to a sparse bound for T .
- (iv) In this memoir we are mainly interested in applications beyond the Calderón–Zygmund theory and focus on the case $p > 1$ and $q < \infty$. There are some elements in our proof such as the property of $L^{p, \infty}$ being the dual space of $L^{p', 1}$ for which there is no analog for $p = 1$ and similarly the failure of a suitable notion of restricted strong type for $q = \infty$; hence Theorem 1.1 does not immediately apply to the situations where $p = 1$ or $q = \infty$. Nevertheless one can formulate variants of the theorem which cover these missing cases. We treat them in Appendix B; indeed they are close to results already covered in other works, in particular [29].

- (v) The role of the simple functions is not essential in Theorem 1.1, and the sparse bound can be extended to other classes of functions under appropriate hypotheses; see Lemma A.1.
- (vi) We use the Banach space valued formulation only to increase applicability. We emphasize that we make no specific assumptions on the Banach spaces in our formulation of Theorem 1.1 (such as UMD in the theory of Banach space valued singular integrals). In applications to Banach space valued singular integrals, such assumptions are made only because they may be needed to verify L^p -boundedness hypotheses but they are not needed to establish the implication in Theorem 1.1.

1.2. Necessary conditions

Under the additional assumption that $T_j : S_{B_1} \rightarrow L^1_{B_2, \text{loc}}$, together with $p < q$, one has that the weak type (p, p) condition (1.7a) and the restricted strong type condition (1.7b) are necessary for the conclusion of Theorem 1.1 to hold. Moreover, if we strengthen the support condition (1.6) assuming that the Schwartz kernels of T_j are not only supported in $\{|x - y| \lesssim 2^j\}$ but actually in $\{|x - y| \approx 2^j\}$, then we can also show that the single scale (p, q) condition (1.8) is necessary.

We also have an analogous statement for Corollary 1.2. Indeed, as the corollary is proved via the implication

$$(1.12) \implies (1.13),$$

see Lemma 4.4, we will simply formulate the necessary conditions for the conclusion in Corollary 1.2, which will also imply those in Theorem 1.1.

To be precise in the general setting, let us formulate the following assumption on a family of operators $\{T_j\}_{j \in \mathbb{Z}}$.

Strengthened support condition. There are $\delta_1 > \delta_2 > 0$ such that for all $j \in \mathbb{Z}$ and all $f \in S_{B_1}$

$$(1.14) \quad \text{supp}(\text{Dil}_{2^j} T_j f) \subset \{x : \delta_1 \leq \text{dist}(x, \text{supp} f) \leq 1\},$$

whenever $\text{diam}(\text{supp} f) \leq \delta_2$.

If the T_j are given by a Schwartz kernel K_j , then the condition is satisfied provided that

$$\text{supp}(K_j) \subset \{(x, y) : (\delta_1 - \delta_2)2^j \leq |x - y| \leq 2^j\}.$$

THEOREM 1.3. *Suppose that $1 < p < q < \infty$. Let $\{T_j\}_{j \in \mathbb{Z}}$ be a family of operators, with $T_j : S_{B_1} \rightarrow L^1_{B_2, \text{loc}}$, and satisfying the support condition (1.6). Assume the conclusion of Corollary 1.2, that is, there exists $\mathcal{C} > 0$ such that for all N_1, N_2 with $N_1 \leq N_2$, all $f_1 \in S_{B_1}$, and all nonnegative simple functions ω*

$$\int_{\mathbb{R}^d} \left| \sum_{j=N_1}^{N_2} T_j f_1(x) \right| \omega(x) dx \leq \mathcal{C} \Lambda_{p, B_1, q', \mathbb{R}}^*(f, \omega).$$

Then

- (i) *Conditions (1.7a) and (1.7b) hold, i.e., there is a constant $c > 0$ only depending on d, p, q, γ such that for all N_1, N_2 with $N_1 \leq N_2$,*

$$\left\| \sum_{j=N_1}^{N_2} T_j \right\|_{L^p_{B_1} \rightarrow L^{p, \infty}_{B_2}} \leq c \mathcal{C}, \quad \left\| \sum_{j=N_1}^{N_2} T_j \right\|_{L^{q, 1}_{B_1} \rightarrow L^q_{B_2}} \leq c \mathcal{C}.$$

- (ii) If, in addition, the T_j satisfy the strengthened support condition (1.14) then condition (1.8) holds, i.e., there is a constant $c > 0$ only depending on d, p, q, γ such that

$$\sup_{j \in \mathbb{Z}} \|\text{Dil}_{2^j} T_j\|_{L_{B_1}^p \rightarrow L_{B_2}^q} \leq c \mathcal{C}.$$

REMARKS.

- (i) Note that in Theorem 1.3 there are no additional assumptions on the Banach spaces. The a priori assumption $T_j : S_{B_1} \rightarrow L_{B_2, \text{loc}}^1$ enters in the proof of necessary conditions for both Theorem 1.1 and Corollary 1.2.
- (ii) There is an alternative version for necessary conditions for Theorem 1.1 where one a priori assumes merely that the T_j belong to Op_{B_1, B_2} (i.e. $T_j f$ is only a priori weakly integrable for $f \in S_{B_1}$), but where one imposes the assumption that B_2 is reflexive. See Theorem 2.5.
- (iii) We have no necessity statement regarding the regularity conditions (1.9) in Theorem 1.1, or Corollary 1.2. However, these conditions enter in the conclusion of both Theorem 1.1 and Corollary 1.2 only in a logarithmic way (see (1.11)), hence the gap between necessity and sufficiency appears to be small. Note that the necessary and sufficient conditions are formulated for a uniform statement on a family of operators $\{\sum_{j=N_1}^{N_2} T_j\}_{N_1, N_2}$ but, with the generality of our current formulation, we are unable to prove a necessary condition for sparse domination for a specific operator in this family. Nevertheless, the formulation allows us to show necessary conditions for several specific maximal operators, variation norm operators and other vector-valued variants, in particular those considered in Sections 5.1, 5.2, 5.3 and Section 7.1.
- (iv) The constant c in the conclusion of Theorem 1.3 is independent of the particular pair of Banach spaces B_1, B_2 . This is significant for applying the theorem to families of maximal and variational operators where for the necessity conditions one can replace the spaces $\ell^\infty, L^\infty, V^r$ by finite-dimensional subspaces of large dimension.
- (v) Since $\|T\|_{\text{Sp}_\gamma(p_1, B_1, p_2, B_2^*)} \leq \|T\|_{\text{Sp}_\gamma(p_1, B_1, B_2)}$ for $p_2 \geq 1$, the necessary conditions in Theorem 1.3 can also be used to prove the impossibility of pointwise sparse domination for many of the operators considered in this memoir.

1.3. An application to maximal functions

We illustrate Remark (iii) above with a brief discussion about maximal operators associated to a distribution σ compactly supported in $\mathbb{R}^d \setminus \{0\}$ (for example a measure), for which we have necessary conditions for sparse bounds. Denote by $\sigma_t = t^{-d} \sigma(t^{-1} \cdot)$ the t -dilate in the sense of distributions. For a dilation set $E \subset (0, \infty)$ we consider the maximal operator

$$(1.15) \quad M_E^\sigma f(x) = \sup_{t \in E} |f * \sigma_t(x)|.$$

The maximal function is a priori well defined as measurable function if f is in the Schwartz class; alternatively we may just restrict to countable E (Section 7.1.1 for comments why this is not a significant restriction).

For the formulation of our theorem we also need the rescaled local operators $M_{E_j}^\sigma$ with

$$(1.16) \quad E_j = (2^{-j}E) \cap [1, 2].$$

A model case is given when E consists of all dyadic dilates of a set in $[1, 2]$, *i.e.*

$$E = \bigcup_{j \in \mathbb{Z}} 2^j E^\circ \quad \text{with } E^\circ \subset [1, 2].$$

In this case

$$M_{E_j}^\sigma = M_{(2^{-j}E) \cap [1, 2]}^\sigma = M_{E^\circ}^\sigma \quad \text{for all } j \in \mathbb{Z}.$$

DEFINITION. The *Lebesgue exponent set* of the pair (σ, E) , denoted by $\mathcal{L}(\sigma, E)$, consists of all $(1/p, 1/q)$ for which

$$(1.17) \quad \|M_E^\sigma\|_{L^p \rightarrow L^{p, \infty}} + \|M_E^\sigma\|_{L^{q, 1} \rightarrow L^q} + \sup_{j \in \mathbb{Z}} \|M_{E_j}^\sigma\|_{L^p \rightarrow L^q} < \infty.$$

The *sparse exponent set* of M_E , denoted by $\text{Sp}[M_E^\sigma]$ consists of all pairs

$$(1/p_1, 1/p_2)$$

with $1/p_2 \geq 1/p_1$ for which there is $0 < \gamma < 1$ and a constant C such that

$$\int_{\mathbb{R}^d} M_E^\sigma f(x) \omega(x) dx \leq C \Lambda_{p_1, p_2}^*(f, \omega)$$

for all simple f and simple nonnegative ω .

Let $\varepsilon > 0$. We let $\mathcal{E}_{\text{ann}}(\lambda)$ be the space of tempered distributions whose Fourier transform is supported in $\{\xi : \lambda/2 < |\xi| < 2\lambda\}$. We say that the pair (σ, E) satisfies an ε -*regularity condition* if there exists $C \geq 0$, and an exponent $p_0 \geq 1$ such that for all $\lambda > 2$, $j \in \mathbb{Z}$, we have

$$(1.18) \quad \|M_{E_j}^\sigma f\|_{p_0} \leq C \lambda^{-\varepsilon} \|f\|_{p_0} \quad \text{for all } f \in \mathcal{S} \cap \mathcal{E}_{\text{ann}}(\lambda).$$

REMARK. The usual lacunary maximal operator correspond to the case where $E_\circ = \{1\}$ (so $E_j = \{2^j\}$). Under this assumption, M_E^σ satisfies an ε -regularity condition for some $\varepsilon > 0$ if and only if there is an $\varepsilon' > 0$ such that

$$\widehat{\sigma}(\xi) = O(|\xi|^{-\varepsilon'}).$$

Moreover the condition $\sup_{j \in \mathbb{Z}} \|M_{E_j}^\sigma\|_{L^p \rightarrow L^q} < \infty$ is, in this particular case, equivalent with the L^p improving inequality

$$\|\sigma * f\|_q \lesssim \|f\|_p$$

for all $f \in L^p$.

Denote by $\text{Int}(\Omega)$ the interior of a planar set Ω . Define $\Phi : \mathbb{R}^2 \rightarrow \mathbb{R}^2$ by

$$\Phi(x, y) = (x, 1 - y).$$

We will show that, under the assumption of an ε -regularity condition for some $\varepsilon > 0$, the interiors of $\mathcal{L}(\sigma, E)$ and $\text{Sp}[M_E^\sigma]$ are in unique correspondence under Φ (see Figure 1). That is,

$$(1.19) \quad \text{Int}(\text{Sp}[M_E^\sigma]) = \Phi(\text{Int}(\mathcal{L}(\sigma, E)));$$

this can be deduced as a consequence of Corollary 1.2 and Theorem 1.3. The next theorem contains a slightly more precise statement.

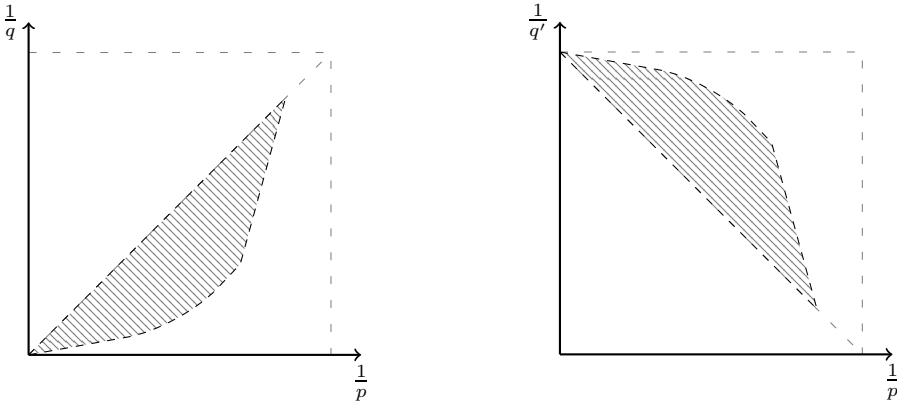


FIGURE 1.1. Example for $\mathcal{L}(\sigma, E)$ (left) and $\text{Sp}[M_E^\sigma]$ (right). It may occur that the closure of $\mathcal{L}(\sigma, E)$ is not a polygonal region, see for example [93].

THEOREM 1.4. *Suppose that σ is a compactly supported distribution supported in $\mathbb{R}^d \setminus \{0\}$, and suppose that (σ, E) satisfies the ε -regularity condition (1.18) for some $\varepsilon > 0$. Let $1 < p < q < \infty$. Then the following implications hold:*

$$(1.20) \quad \left(\frac{1}{p}, \frac{1}{q}\right) \in \text{Int}(\mathcal{L}(\sigma, E)) \implies \left(\frac{1}{p}, \frac{1}{q}\right) \in \text{Sp}[M_E^\sigma],$$

$$(1.21) \quad \left(\frac{1}{p}, \frac{1}{q}\right) \in \mathcal{L}(\sigma, E) \longleftarrow \left(\frac{1}{p}, \frac{1}{q}\right) \in \text{Sp}[M_E^\sigma].$$

REMARKS.

- (i) The correspondence (1.19) is an immediate consequence of Theorem 1.4.
- (ii) If σ is as in Theorem 1.4 then similar statements characterizing the sparse exponent set hold for variation norm operators. See the statement of Propositions 7.2.
- (iii) In the case of σ being the surface measure on the unit sphere one recovers as a special case the results by Lacey [66] on the lacunary and full spherical maximal functions.

1.4. Fourier multipliers

Given a bounded function m we consider the convolution operator \mathcal{T} given on Schwartz functions $f : \mathbb{R}^d \rightarrow \mathbb{C}$ by

$$(1.22) \quad \widehat{\mathcal{T}f}(\xi) = m(\xi)\widehat{f}(\xi), \quad \xi \in \widehat{\mathbb{R}^d},$$

i.e. $\mathcal{T}f = \mathcal{F}^{-1}[m] * f$ where $\mathcal{F}^{-1}[m]$ is the Fourier inverse of m in the sense of tempered distributions. If $1 \leq p < \infty$, we say that $m \in M^p$ if \mathcal{T} extends to a bounded operator on L^p and we define $\|m\|_{M^p}$ to be the $L^p \rightarrow L^p$ operator norm of \mathcal{T} . A similar definition applies to $p = \infty$; however one replaces L^∞ by the space C_0 of continuous functions that vanish at ∞ (i.e. the closure of the Schwartz functions in the L^∞ norm). By duality we have $M^p = M^{p'}$ for $1/p' = 1 - 1/p$. Moreover, $M^2 = L^\infty$, $M^p \subset L^\infty$ and M^1 is the space of Fourier transforms of finite Borel measures. Similarly, if $1 \leq p, q < \infty$, we say that $m \in M^{p,q}$ if \mathcal{T} is bounded from L^p to L^q and we define by $\|m\|_{M^{p,q}}$ to be the $L^p \rightarrow L^q$ operator norm of \mathcal{T} . For these and other simple facts on Fourier multipliers see [53] or [106].

Let ϕ be a nontrivial radial C_c^∞ function compactly supported in $\widehat{\mathbb{R}^d} \setminus \{0\}$. A natural single scale assumption would be to assume a uniform M^{p_0} bound for the pieces $\phi(t^{-1}\cdot)m$ which is equivalent by dilation-invariance to the condition

$$(1.23) \quad \sup_{t>0} \|\phi m(t\cdot)\|_{M^{p_0}} < \infty.$$

Inequality (1.23) is a necessary and sufficient condition for \mathcal{T} to be bounded on the homogeneous Besov spaces $\dot{B}_{p_0,q}^s$, for any $s \in \mathbb{R}, 0 < q \leq \infty$; see [107], [110, §2.6]. However, it does *not* imply boundedness on the Lebesgue spaces, except on L^2 . Indeed, Littman, McCarthy and Rivière [84] and Stein and Zygmund [107] give examples of m satisfying (1.23) for a $p_0 \neq 2$ for which $m \notin M^p$ for all $p \neq 2$.

The papers by Carbery [24] and by one of the authors [98] provide positive results under an additional dilation invariant regularity condition,

$$(1.24) \quad \sup_{t>0} \|\phi m(t\cdot)\|_{C^\varepsilon} < \infty,$$

where C^ε is the standard Hölder space. Indeed, it is shown in [24, 98] that for $1 < p_0 < 2, 0 < \varepsilon < 1$,

$$\|m\|_{M^p} \leq C(p, \varepsilon) \sup_{t>0} (\|\phi m(t\cdot)\|_{M^{p_0}} + \|\phi m(t\cdot)\|_{C^\varepsilon}), \quad p_0 < p < p'_0.$$

If the standard Hölder condition $\|\phi m(t\cdot)\|_{C^\varepsilon} = O(1)$ is replaced by its M^{p_0} variant, $\sup_{t>0} \|\Delta_h[\phi m(t\cdot)]\|_{M^{p_0}} = O(|h|^\varepsilon)$, one obtains a conclusion for $p = p_0$. We will show that for fixed $p \in (p_0, p'_0)$, the L^p -boundedness self-improves to a sparse domination inequality.

THEOREM 1.5. *Let $1 < p_0 < 2, 0 < \varepsilon < 1$, and assume that (1.23) and (1.24) hold. Then for every $p \in (p_0, 2]$ there is a $\delta = \delta(p) > 0$ such that $\mathcal{T} \in \text{Sp}(p-\delta, p'-\delta)$.*

We note that, in view of the compact support, for $p \leq q$ the quantity

$$\|\phi m(t\cdot)\|_{M^{p,q}}$$

can be bounded by $C\|\phi m(t\cdot)\|_{M^p}$ via Young's inequality. In Theorem 1.5 the self-improvement to a sparse bound is due to a tiny bit of regularity as hypothesized in (1.24). This together with (1.23) implies a mild regularity condition for $\phi m(t\cdot)$ measured in the $M^{p,q}$ norm. If one seeks better results on the sparse bound in terms of q a further specification of this regularity is needed. For this we use the iterated difference operators

$$\Delta_h^M = \Delta_h \Delta_h^{M-1} \quad \text{for } M \geq 2,$$

where Δ_h is as in (1.10). With ϕ as above we get the following.

THEOREM 1.6. *Let $m \in L^\infty(\mathbb{R}^d)$ and \mathcal{T} as in (1.22). Let $1 < p \leq q < \infty$. Assume that there exists $s > d(1/p - 1/q)$ and an $M \in \mathbb{N}$ such that*

$$(1.25) \quad \sup_{t>0} \sup_{|h|\leq 1} |h|^{-s} \|\Delta_h^M[\phi m(t\cdot)]\|_{M^{p,q}} < \infty.$$

Then $\mathcal{T} \in \text{Sp}(p, q)$.

One should always take $M > s$. Indeed, note that if $M < s$, then (1.25) implies $m \equiv 0$. We note that the $L^p \rightarrow L^q$ conditions (1.8), (1.9) in Theorem 1.1 correspond in the instance of convolution operators to an $M^{p,q}$ condition of derivatives of order $s > d(1/p - 1/q)$ on the localizations of the Fourier multiplier. Also, for fixed $s > d(1/p - 1/q)$, if (1.25) holds with some $M \geq s$, then it holds

for all integers $M > s$. For an illustration of this and the broad scope of Theorem 1.6, see the discussion on singular Radon transforms in Section 7.3.1 and on various classes of Fourier multipliers related to oscillatory multipliers in Section 7.2 and to radial multipliers in Section 7.5.

Theorems 1.5 and 1.6 will be deduced in Section 6.1 from the more precise, but also more technical Theorem 6.1 which expresses the regularity via dyadic decompositions of $\mathcal{F}^{-1}[\phi m(\cdot)]$. Moreover, there we will cover a version involving Hilbert space valued functions which is useful for sparse domination results for objects such as Stein's square function associated with Bochner–Riesz means.

1.5. Application to weighted norm inequalities

It is well known that sparse domination implies a number of weighted inequalities in the context of Muckenhoupt and reverse Hölder classes of weights, and indeed this serves as a first motivation for the subject; see the lecture notes by Pereyra [91] for more information. Here we just cite a general result about this connection which can be directly applied to all of our results on sparse domination and is due to Bernicot, Frey and Petermichl [18]. Recall the definition of the Muckenhoupt class A_t consisting of weights for which

$$[w]_{A_t} = \sup_Q \langle w \rangle_{Q,1} \langle w^{-1} \rangle_{Q,t^{t-1}} < \infty,$$

and the definition of the reverse Hölder class RH_s consisting of weights for which

$$[w]_{\text{RH}_s} = \sup_Q \frac{\langle w \rangle_{Q,s}}{\langle w \rangle_{Q,1}} < \infty.$$

In both cases the supremum is taken over all cubes Q in \mathbb{R}^d .

PROPOSITION 1.7 ([18]). *If $T \in \text{Sp}(L^p_{B_1}, L^q_{B_2^*})$, then one has the weighted norm inequality*

$$\left(\int_{\mathbb{R}^d} |Tf(x)|_{B_2}^r w(x) dx \right)^{\frac{1}{r}} \lesssim \|T\|_{\text{Sp}_\gamma(p_1, B_1; p_2, B_2^*)} \times \\ ([w]_{A_{r/p}} [w]_{\text{RH}_{(q/r)'}})^\alpha \left(\int_{\mathbb{R}^d} |f(x)|_{B_1}^r w(x) dx \right)^{\frac{1}{r}}$$

for all $w \in A_{r/p} \cap \text{RH}_{(q/r)'}$ and $p < r < q$, where $\alpha := \max(\frac{1}{r-p}, \frac{q-1}{q-r})$.

We refer to [18, §6] for more information and a detailed exposition. See also [44] for other weighted norm inequalities.

1.6. Organization and notation

Structure of the memoir. We begin addressing necessary conditions, and prove Theorem 1.3. In Chapter 3 we review useful preliminary facts needed in the proof of Theorem 1.1 regarding the single scale regularity conditions; in particular, an alternative form for the regularity conditions in (1.9). The proof of Theorem 1.1 is presented in Chapter 4. The main part of the argument consists of an induction step, which is contained in Section 4.4. The implication that yields Corollary 1.2 from Theorem 1.1 is given in Section 4.3. In Chapter 5 we apply Corollary 1.2 to deduce sparse domination results for maximal functions, square functions and variation norm operators, as well as Cotlar-type operators associated to truncations

of operators. In the case of maximal functions, the assumptions of Theorem 1.1 can be slightly weakened, and we present this in Section 5.4. Theorems 1.5 and 1.6 are proved in Chapter 6. Finally, in Chapter 7 we apply our main theorems to several specific examples, including the proof of Theorem 1.4 in Section 7.1.1. Moreover, we give several applications of Theorem 1.6 to specific classes of multipliers. For completeness, we include several appendices. Appendix A covers some basic facts on sparse domination. Appendix B covers versions of the main Theorem 1.1 for $p = 1$ and/or $q = \infty$. Some basic facts on Fourier multipliers needed in Chapter 6 are covered in Appendix C. Theorems, Propositions and Lemmata are numbered as N.Y where N is the chapter number, likewise displayed formulas may be labelled (N.Y) when this occurs in chapter N. In cross references we refer to §X as a section in the same chapter, unless the chapter is explicitly specified.

NOTATION. The notation $A \lesssim B$ will be used to denote that $A \leq C \cdot B$, where the constant C may change from line to line. Dependence of C on various parameters may be denoted by a subscript or will be clear from the context. We use $A \approx B$ to denote that $A \lesssim B$ and $B \lesssim A$.

We shall use the definition $\widehat{f}(\xi) = \mathcal{F}f(\xi) = \int_{\mathbb{R}^d} e^{-i\langle y, \xi \rangle} f(y) dy$ for the Fourier transform on \mathbb{R}^d . We let \mathcal{F}^{-1} be the inverse Fourier transform and use the notation $m(D)f = \mathcal{F}^{-1}[m\widehat{f}]$. We denote by $\mathcal{S} \equiv \mathcal{S}(\mathbb{R}^d)$ the space of Schwartz functions on \mathbb{R}^d , by \mathcal{S}' the space of tempered distributions on \mathbb{R}^d , and by $\mathcal{E}_{\text{ann}}(\lambda)$ the space of all $f \in \mathcal{S}'$ such that the Fourier transform \widehat{f} is supported in the open annulus $\{\xi \in \mathbb{R}^d : \lambda/2 < |\xi| < 2\lambda\}$.

For a d -dimensional rectangle $R = [a_1, b_1] \times \cdots \times [a_d, b_d]$ we denote by x_R the center of R , i.e. the points with coordinates $x_{R,i} = (a_i + b_i)/2$, $i = 1, \dots, d$. If $\tau > 0$, we denote by τR to be the τ -dilate of R with respect to its center, i.e.

$$\tau R = \left\{ x \in \mathbb{R}^d : x_R + \frac{x - x_R}{\tau} \in R \right\}.$$

We shall use many spatial or frequency decomposition throughout this work:

- $\{\lambda_k\}_{k \geq 0}$, $\{\widetilde{\lambda}_k\}_{k \geq 0}$ are specific families of Littlewood–Paley type operators that can be used for a reproducing formula (3.1); they are compactly supported and have vanishing moments (*cf.* Section 3.2);
- $\{\Psi_\ell\}_{\ell \geq 0}$ is an inhomogeneous dyadic decomposition in x -space, compactly supported where $|x| \approx 2^\ell$ if $\ell > 0$ (*cf.* Section 6.1);
- $\{\eta_\ell\}_{\ell \geq 0}$ is an inhomogeneous dyadic frequency decomposition so that $\widehat{\eta}_\ell$ is supported where $|\xi| \approx 2^\ell$ if $\ell > 0$ (*cf.* Sections 3.3 and 7.4).

Similarly, we shall use the following bump functions:

- ϕ is a radial $C^\infty(\widehat{\mathbb{R}}^d)$ function supported in $|\xi| \approx 1$ and not identically zero (*cf.* Section 6.1);
- θ is a radial $C^\infty(\mathbb{R}^d)$ function supported in $|x| \lesssim 1$ with vanishing moments and such that $\widehat{\theta}(\xi) > 0$ in $|\xi| \approx 1$ (*cf.* Section 6.1)
- β is any nontrivial $C_c^\infty(\widehat{\mathbb{R}})$ function with compact support in $(0, \infty)$ (*cf.* Section 7.5).

REMARK. After we circulated the first version of the manuscript, José M. Conde-Alonso, Francesco Di Plinio, Ioannis Parissis and Manasa N. Vempati kindly shared their preprint [30], in which they develop a metric theory of sparse domination on spaces of homogeneous type. There is a small overlap with our work, as [30]

covers classes of singular Radon transforms, in particular non-isotropic versions of results in Section 7.3.

Acknowledgments

We would like to thank Richard Oberlin and Luz Roncal for informative conversations regarding sparse domination. We thank the referee for various valuable suggestions and in particular for recommending to formulate versions of our results for the cases $p = 1$ and $q = \infty$. We thank Tuomas Hytönen for pointing out an inaccuracy in the original formula (4.24).

Necessary Conditions

In this chapter we prove Theorem 1.3 and another partial converse for Theorem 1.1, namely Theorem 2.5.

We begin with an immediate and well known, but significant estimate for the maximal sparse forms which will lead to simple necessary conditions. In what follows, let \mathcal{M} denote the Hardy–Littlewood maximal operator.

LEMMA 2.1. *The following hold for the maximal forms defined in (1.3).*

(i) For $f_1 \in \mathcal{S}_{B_1}$, $f_2 \in \mathcal{S}_{B_2^*}$,

$$(2.1) \quad \Lambda_{p_1, B_1, p_2, B_2^*}^*(f_1, f_2) \leq \gamma^{-1} \int_{\mathbb{R}^d} (\mathcal{M}[|f_1|_{B_1}^{p_1}](x))^{1/p_1} (\mathcal{M}[|f_2|_{B_2^*}^{p_2}](x))^{1/p_2} dx.$$

(ii) If $1 \leq p_1 < p$, and $f_1 \in L_{B_1}^{p, 1}$, $f_2 \in L_{B_2^*}^{p'}$, then

$$(2.2) \quad \Lambda_{p_1, B_1, p', B_2^*}^*(f_1, f_2) \lesssim_{p, p_1} \gamma^{-1} \|f_1\|_{L_{B_1}^{p, 1}} \|f_2\|_{L_{B_2^*}^{p'}}.$$

(iii) If $1 < p < p'_2$, and $f_1 \in L_{B_1}^p$, $f_2 \in L_{B_2^*}^{p'_2, 1}$, then

$$(2.3) \quad \Lambda_{p, B_1, p_2, B_2^*}^*(f_1, f_2) \lesssim_{p, p_2} \gamma^{-1} \|f_1\|_{L_{B_1}^p} \|f_2\|_{L_{B_2^*}^{p'_2, 1}}.$$

PROOF. For a γ -sparse family of cubes we have

$$\Lambda_{p_1, B_1, p_2, B_2^*}^{\mathfrak{S}}(f_1, f_2) \leq \sum_{Q \in \mathfrak{S}} \frac{1}{\gamma} \int_{E_Q} (\mathcal{M}[|f_1|_{B_1}^{p_1}](x))^{1/p_1} (\mathcal{M}[|f_2|_{B_2^*}^{p_2}](x))^{1/p_2} dx$$

and (2.1) follows by the disjointness of the sets E_Q and taking supremum over all sparse families.

Now let $f_1 \in \mathcal{S}_{B_1}$, $f_2 \in \mathcal{S}_{B_2^*}$. For (2.2) we use (2.1), with $p_2 = p'$, together with the fact that for $p_1 < p$ the operator $g \mapsto (\mathcal{M}[g|_{B_1}^{p_1}])^{1/p_1}$ maps $L_{B_1}^{p, 1}$ to itself; this follows by real interpolation from the fact that it maps L^p to itself, for all $p > p_1$. We can now estimate

$$\begin{aligned} \Lambda_{p_1, B_1, p', B_2^*}^*(f_1, f_2) &\lesssim \gamma^{-1} \|(\mathcal{M}[|f_1|_{B_1}^{p_1}])^{1/p_1}\|_{L^{p, 1}} \|(\mathcal{M}[|f_2|_{B_2^*}^{p'}])^{1/p'}\|_{L^{p', \infty}} \\ &\lesssim_{p, p_1} \gamma^{-1} \|f_1\|_{L_{B_1}^{p, 1}} \|f_2\|_{L_{B_2^*}^{p'}}. \end{aligned}$$

Since simple B_1 -valued functions are dense in $L_{B_1}^{p, 1}$ and simple B_2^* -valued functions are dense in $L_{B_2^*}^{p'}$ we get (2.7) for all $f_1 \in L_{B_1}^{p, 1}$ and $f_2 \in L_{B_2^*}^{p'}$, by a straightforward limiting argument.

For (2.3) we argue similarly. We use (2.1) with $p_1 = p$, together with the fact that for $p_2 < p'$ the operator $g \mapsto (\mathcal{M}|g|_{B_2^*}^{p_2})^{1/p_2}$ maps $L_{B_2^*}^{p',1}$ to itself, and hence

$$\begin{aligned} \Lambda_{p,B_1,p_2,B_2^*}^*(f_1, f_2) &\lesssim \gamma^{-1} \|(\mathcal{M}[|f_1|_{B_1}^p])^{1/p}\|_{L^{p,\infty}} \|(\mathcal{M}[|f_2|_{B_2^*}^{p_2}])^{1/p_2}\|_{L^{p',1}} \\ &\lesssim_{p,p_2} \gamma^{-1} \|f_1\|_{L_{B_1}^p} \|f_2\|_{L_{B_2^*}^{p',1}}. \end{aligned} \quad \square$$

The estimates in Lemma 2.1 immediate yield estimates for the forms $\langle Tf_1, f_2 \rangle$, since by the definition (1.5)

$$|\langle Tf_1, f_2 \rangle| \leq \|T\|_{S_{p,\gamma}(p_1, B_1; p_2, B_2^*)} \Lambda_{p_1, B_1, p_2, B_2^*}^{\gamma, *}(f_1, f_2).$$

We shall now prove Theorem 1.3 in Section 2.1, and a variant under reflexivity of B_2 in Section 2.2.

2.1. The local integrability hypothesis

If $Tf_1 \in L_{B_2, \text{loc}}^1$, Lemma 2.1 further yields bounds for the $L_{B_2}^p$ or $L_{B_2}^{p,\infty}$ norms of Tf_1 via a duality result for scalar functions.

LEMMA 2.2. *Suppose $T : S_{B_1} \rightarrow L_{B_2, \text{loc}}^1$. Then the following hold.*

- (i) *If $1 \leq p_1 < p < \infty$ and if for all $f \in S_{B_1}$ and all \mathbb{R} -valued nonnegative simple functions ω*

$$\int_{\mathbb{R}^d} |Tf(x)|_{B_2} \omega(x) dx \leq A_1 \Lambda_{p_1, B_1, p', \mathbb{R}}^*(f, \omega),$$

then T extends to a bounded operator from $L_{B_1}^{p_1,1}$ to $L_{B_2}^p$ so that

$$(2.4) \quad \|T\|_{L_{B_1}^{p_1,1} \rightarrow L_{B_2}^p} \lesssim_{p_1,p} \gamma^{-1} A_1.$$

- (ii) *If $1 < p < p'_2$ and if for all $f \in S_{B_1}$ and all \mathbb{R} -valued nonnegative simple functions ω*

$$\int_{\mathbb{R}^d} |Tf(x)|_{B_2} \omega(x) dx \leq A_2 \Lambda_{p, B_1, p_2, \mathbb{R}}^*(f, \omega),$$

then T extends to a bounded operator from $L_{B_1}^p$ to $L_{B_2}^{p,\infty}$ so that

$$(2.5) \quad \|T\|_{L_{B_1}^p \rightarrow L_{B_2}^{p,\infty}} \lesssim_{p_2,p} \gamma^{-1} A_2.$$

PROOF. We rely on Lemma 2.1. For part (i) we use (2.2) to estimate, for $f_2 \in S_{B_2}$,

$$\int_{\mathbb{R}^d} |Tf(x)|_{B_2} \omega(x) dx \lesssim \gamma^{-1} A_1 \|f\|_{L_{B_1}^{p_1,1}} \|\omega\|_{L^{p',1}}.$$

By L^p duality this implies an L^p bound for the locally integrable scalar function $x \mapsto |Tf(x)|_{B_2}$ and consequently $Tf \in L_{B_2}^p$ with

$$\|Tf\|_{L_{B_2}^p} \lesssim \gamma^{-1} A_1 \|f\|_{L_{B_1}^{p_1,1}}$$

and (2.4) follows.

For part (ii) we argue similarly. We use (2.3) to estimate

$$\int_{\mathbb{R}^d} |Tf(x)|_{B_2} \omega(x) dx \lesssim \gamma^{-1} A_2 \|f\|_{L_{B_1}^p} \|\omega\|_{L^{p',1}}.$$

By the duality $(L^{p',1})^* = L^{p,\infty}$ for scalar functions for $1 < p < \infty$ [55] we get

$$\|Tf\|_{L_{B_2}^{p,\infty}} \lesssim \gamma^{-1} A_2 \|f_1\|_{L_{B_1}^p}$$

and (2.5) follows. \square

COROLLARY 2.3. *Assume that $T : S_{B_1} \rightarrow L_{B_2, \text{loc}}^1$ and let $1 \leq p_1 < p < p'_2$. If for all $f \in S_{B_1}$ and all \mathbb{R} -valued nonnegative simple functions ω*

$$\int_{\mathbb{R}^d} |Tf(x)|_{B_2} \omega(x) dx \leq A \Lambda_{p_1, B, p_2, \mathbb{R}}^*(f, \omega),$$

then T extends to a bounded operator from $L_{B_1}^p$ to $L_{B_2}^p$ so that

$$(2.6) \quad \|T\|_{L_{B_1}^p \rightarrow L_{B_2}^p} \lesssim_{p, p_1, p_2} \gamma^{-1} A.$$

PROOF. Lemma 2.2 implies T maps boundedly $L_{B_1}^{\tilde{p}_1} \rightarrow L_{B_2}^{\tilde{p}_1, \infty}$ and $L_{B_1}^{\tilde{p}'_2, 1} \rightarrow L_{B_2}^{\tilde{p}'_2}$ for any $p_1 < \tilde{p}_1 < p$ and $p < \tilde{p}'_2 < p'_2$; the desired $L_{B_1}^p \rightarrow L_{B_2}^p$ boundedness for $p_1 < p < p'_2$ then follows by interpolation.

Alternatively, one could deduce this result directly from (2.1). Arguing as in the proofs of (ii) or (iii) in Lemma 2.1, by the Hardy–Littlewood theorem and (2.1) one has

$$(2.7) \quad \Lambda_{p_1, B_1, p_2, B_2}^*(f_1, f_2) \lesssim_{p, p_1, p_2} \gamma^{-1} \|f_1\|_{L_{B_1}^p} \|f_2\|_{L_{B_2}^{p'}}$$

for $1 \leq p_1 < p < p'_2$. Then one can argue as in the proof of Lemma 2.2, to deduce (2.6) from (2.7). \square

We next turn to the necessity of the condition (1.8) in Corollary 1.2 and Theorem 1.1. In this generality, this type of implication appears to be new in the sparse domination literature. It is inspired by the philosophy of adapting the counterexamples for $L^p \rightarrow L^q$ estimates to sparse bounds (see *i.e.* the examples for spherical maximal operators in [66]).

LEMMA 2.4. *Let $\{T_j\}_{j \in \mathbb{Z}}$ be a family of operators, with $T_j : S_{B_1} \rightarrow L_{B_2, \text{loc}}^1$, and satisfying the strengthened support condition (1.14). Let $1 \leq p < q \leq \infty$ and suppose that for all $f \in S_{B_1}$ and all \mathbb{R} -valued nonnegative simple function ω , the estimate*

$$\int_{\mathbb{R}^d} |T_j f(x)|_{B_2} \omega(x) dx \leq \mathcal{C} \Lambda_{p, B_1, q', \mathbb{R}}^*(f, \omega)$$

holds uniformly in $j \in \mathbb{Z}$. Then

$$\sup_{j \in \mathbb{Z}} \|\text{Dil}_{2^j} T_j\|_{L_{B_1}^p \rightarrow L_{B_2}^q} \lesssim_{\gamma, d, \delta_1, \delta_2, p, q} \mathcal{C}.$$

PROOF. Fix $j \in \mathbb{Z}$ and let $S = \text{Dil}_{2^j} T_j$. We first apply a scaling argument. Note that by assumption

$$\begin{aligned} \int |Sf(x)|_{B_2} \omega(x) dx &= 2^{-jd} \int |T_j[f(2^{-j}\cdot)](x)|_{B_2} \omega(2^{-j}x) dx \\ &\leq \mathcal{C} 2^{-jd} \Lambda_{p, B_1, q', \mathbb{R}}^*(f(2^{-j}\cdot), \omega(2^{-j}\cdot)) \end{aligned}$$

If $\Lambda_{p, B_1, q, \mathbb{R}}^{\mathfrak{S}}$ is a sparse form with a γ -sparse collection of cubes we form the collection \mathfrak{S}_j of dilated cubes $\{2^{-j}y : y \in Q\}$ where $Q \in \mathfrak{S}$. Then

$$2^{-jd} \Lambda_{p, B_1, q', \mathbb{R}}^{\mathfrak{S}}(f(2^{-j}\cdot), \omega(2^{-j}\cdot)) = \Lambda_{p, B_1, q', \mathbb{R}}^{\mathfrak{S}_j}(f, \omega)$$

and therefore we get the estimate

$$(2.8) \quad \int |Sf(x)|_{B_2} \omega(x) dx \leq \mathcal{C} \Lambda_{p, B_1, q', \mathbb{R}}^*(f, \omega).$$

Suppose that b is the smallest positive integer such that

$$2^{-b} \leq d^{-1/2} \min\{\delta_1/2, \delta_2\}.$$

For $\mathfrak{z} \in \mathbb{Z}^d$ let

$$Q_{\mathfrak{z}} = \{x : 2^{-b} \mathfrak{z}_i \leq x_i < 2^{-b}(\mathfrak{z}_i + 1), i = 1, \dots, d\}$$

and let $f_{\mathfrak{z}} = f \mathbf{1}_{Q_{\mathfrak{z}}}$. Let $R_{\mathfrak{z}}$ the cube of side length 3 centered at $2^{-b} \mathfrak{z}$. Then $Sf_{\mathfrak{z}}$ is supported in $R_{\mathfrak{z}}$. We decompose $R_{\mathfrak{z}}$ into $3^{d} 2^{bd}$ cubes $R_{\mathfrak{z}, \nu}$ of side length 2^{-b} , here $\nu \in \mathcal{I}_{\mathfrak{z}}$ with $\#\mathcal{I}_{\mathfrak{z}} = 3^{d} 2^{bd}$.

Fix \mathfrak{z}, ν and a simple nonnegative function ω with $\|\omega\|_{L^{q'}} \leq 1$. We first prove that for $\nu \in \mathcal{I}_{\mathfrak{z}}$

$$(2.9) \quad \int |Sf_{\mathfrak{z}}(x)|_{B_2} \omega(x) \mathbf{1}_{R_{\mathfrak{z}, \nu}}(x) dx \lesssim \mathcal{C} \|f_{\mathfrak{z}}\|_{L_{B_1}^p} \|\omega\|_{L^{q'}}.$$

In this argument we shall not use strong measurability of $Sf_{\mathfrak{z}}$. By (2.8) we have

$$\int |Sf_{\mathfrak{z}}(x)|_{B_2} \omega(x) \mathbf{1}_{R_{\mathfrak{z}, \nu}}(x) dx \leq \mathcal{C} \Lambda_{p, B_1, q', \mathbb{R}}^*(f_{\mathfrak{z}}, \omega \mathbf{1}_{R_{\mathfrak{z}, \nu}})$$

and therefore we find a sparse family $\mathfrak{S}_{\mathfrak{z}, \nu}$ such that

$$(2.10) \quad \int |Sf_{\mathfrak{z}}(x)|_{B_2} \omega(x) \mathbf{1}_{R_{\mathfrak{z}, \nu}}(x) dx \leq 2\mathcal{C} \sum_{Q \in \mathfrak{S}_{\mathfrak{z}, \nu}} |Q| \langle f_{\mathfrak{z}} \rangle_{Q, p} \langle \omega \mathbf{1}_{R_{\mathfrak{z}, \nu}} \rangle_{Q, q'}.$$

By the strengthened support condition, (1.14),

$$(2.11) \quad Sf_{\mathfrak{z}} \mathbf{1}_{R_{\mathfrak{z}, \nu}} \neq 0 \implies \text{dist}(Q_{\mathfrak{z}}, R_{\mathfrak{z}, \nu}) \geq \delta_1 - 2^{-b} \sqrt{d}.$$

Assuming that the left-hand side is not 0 in (2.10), and in view of (2.11), we see that for a cube $Q \in \mathfrak{S}_{\mathfrak{z}, \nu}$ we have, recalling that $\delta_1 \geq \sqrt{d} 2^{-b+1}$,

$$\left. \begin{array}{l} Q_{\mathfrak{z}} \cap Q \neq \emptyset \\ R_{\mathfrak{z}, \nu} \cap Q \neq \emptyset \end{array} \right\} \implies \text{diam}(Q) \geq \delta_1 - 2^{-b} \sqrt{d} \geq 2^{-b} \sqrt{d}.$$

Hence all cubes that contribute to the sum in (2.10) have side length $\geq 2^{-b}$. Denote the cubes in $\mathfrak{S}_{\mathfrak{z}, \nu}$ with side length in $[2^{\ell}, 2^{\ell+1})$ by $\mathfrak{S}_{\mathfrak{z}, \nu}(\ell)$ and note that for every $\ell \geq -b$ there are at most $C(d)$ many cubes that contribute. Hence we may estimate

$$\begin{aligned} & \sum_{Q \in \mathfrak{S}_{\mathfrak{z}, \nu}} |Q| \langle f_{\mathfrak{z}} \rangle_{Q, p} \langle \omega \mathbf{1}_{R_{\mathfrak{z}, \nu}} \rangle_{Q, q'} \\ & \leq \sum_{\ell \geq -b} \sum_{Q \in \mathfrak{S}_{\mathfrak{z}, \nu}(\ell)} |Q|^{\frac{1}{q'} - \frac{1}{p}} \left(\int_Q |f_{\mathfrak{z}}(y)|_{B_1}^p dy \right)^{\frac{1}{p}} \left(\int_Q |\omega(x) \mathbf{1}_{R_{\mathfrak{z}, \nu}}(x)|^{q'} dx \right)^{\frac{1}{q'}} \\ & \lesssim d \sum_{\ell \geq -b} 2^{\ell d (\frac{1}{q'} - \frac{1}{p})} \|f_{\mathfrak{z}}\|_{L_{B_1}^p} \|\omega\|_{L^{q'}} \lesssim_{b, d, p, q} \|f_{\mathfrak{z}}\|_{L_{B_1}^p} \end{aligned}$$

where we used the assumption $q > p$ to sum in ℓ . This establishes (2.9).

By duality combined with (2.9) we have

$$(2.12) \quad \|Sf_3\|_{L_{B_2}^q(R_{3,\nu})} \lesssim \sup_{\substack{\omega \in S_{\mathbb{R}} \\ \|\omega\|_{L^{q'}} \leq 1}} \int |Sf_3(x)|_{B_2} |\omega(x)| \mathbb{1}_{R_{3,\nu}}(x) dx \lesssim \mathcal{C} \|f_3\|_{L_{B_1}^p}.$$

Considering this for various $\nu \in \mathcal{I}_3$ we get

$$\|Sf_3\|_{L_{B_2}^q} \lesssim \sum_{\nu \in \mathcal{I}_3} \|Sf_3\|_{L_{B_2}^q(R_{3,\nu})} \lesssim \sum_{\nu \in \mathcal{I}_3} \mathcal{C} \|f_3\|_{L_{B_1}^p} \lesssim_{d,\delta_1,\delta_2} \mathcal{C} \|f_3\|_{L_{B_1}^p}.$$

Then

$$(2.13) \quad \|Sf\|_{L_{B_2}^q} = \left\| \sum_{3 \in \mathbb{Z}^d} Sf_3 \right\|_{L_{B_2}^q} \lesssim C_d 2^{bd} \left(\sum_{3 \in \mathbb{Z}^d} \|Sf_3\|_{L_{B_2}^q}^q \right)^{1/q} \\ \lesssim_{d,\delta_1,\delta_2} \mathcal{C} \left(\sum_{3 \in \mathbb{Z}^d} \|f_3\|_{L_{B_1}^p}^q \right)^{1/q} \lesssim \mathcal{C} \left(\sum_{3 \in \mathbb{Z}^d} \|f_3\|_{L_{B_1}^p}^p \right)^{1/p} \lesssim \mathcal{C} \|f\|_{L_{B_1}^p}. \quad \square$$

Theorem 1.3 now follows from Lemmata 2.2 and 2.4.

2.2. The reflexivity hypothesis

In this section we prove a version of Theorem 1.3 where we drop the a priori assumption on T_j sending S_{B_1} to $L_{B_2,\text{loc}}^1$ and thus we can no longer assume the strong B_2 measurability of Tf . We still get a partial converse to Theorem 1.1 if we assume that the Banach space B_2 is reflexive.

THEOREM 2.5. *Let B_2 be reflexive and let $1 < p < q < \infty$. Let $\{T_j\}_{j \in \mathbb{Z}}$ be a family of operators in Op_{B_1, B_2} satisfying the support condition (1.6). Assume the conclusion of Theorem 1.1, that is, there exists $\mathcal{C} > 0$ such that for all N_1, N_2 with $N_1 \leq N_2$ and every $f_1 \in S_{B_1}, f_2 \in S_{B_2}^*$,*

$$\left| \left\langle \sum_{j=N_1}^{N_2} T_j f_1, f_2 \right\rangle \right| \leq \mathcal{C} \Lambda_{p, B_1, q', B_2}^*(f_1, f_2).$$

Then

- (i) *Conditions (1.7a) and (1.7b) hold, i.e., there is a constant $c > 0$ only depending on d, p, q, γ such that for all N_1, N_2 with $N_1 \leq N_2$,*

$$\left\| \sum_{j=N_1}^{N_2} T_j \right\|_{L_{B_1}^p \rightarrow L_{B_2}^{p,\infty}} \leq c \mathcal{C}, \quad \left\| \sum_{j=N_1}^{N_2} T_j \right\|_{L_{B_1}^{q,1} \rightarrow L_{B_2}^q} \leq c \mathcal{C}.$$

- (ii) *If, in addition, the T_j satisfy the strengthened support condition (1.14) then condition (1.8) holds, i.e., there is a constant $c > 0$ only depending on d, p, q, γ such that*

$$\sup_{j \in \mathbb{Z}} \|\text{Dil}_{2^j} T_j\|_{L_{B_1}^p \rightarrow L_{B_2}^q} \leq c \mathcal{C}.$$

In the vector valued setting of Theorem 2.5 we need to use a more abstract duality argument which requires some care because of a potential lack of strong local integrability. We briefly discuss the issue of duality.

Let B be a Banach space. Recall that for $1 \leq p \leq \infty$, $1/p + 1/p' = 1$, the space $L_{B^*}^{p'}$ is embedded in $(L_B^p)^*$ via the canonical isometric homomorphism. In the scalar case this isometry is also surjective when $1 \leq p < \infty$, and the proof of this fact

relies on the Radon–Nikodym theorem. In the vector-valued case the surjectivity is equivalent with the dual space B^* having the *Radon–Nikodym property* (RNP) with respect to Lebesgue measure (see [56, Chapter 1.3.b] for the formal definition). Thus under this assumption we have an identification of the dual of L_B^p with $L_{B^*}^{p'}$. To summarize,

$$(2.14) \quad B^* \in \text{RNP} \iff (L_B^p)^* = L_{B^*}^{p'}, \quad 1 \leq p < \infty.$$

Similarly, the Radon–Nikodym property for B^* also implies

$$(L_B^{p,r})^* = L_{B^*}^{p',r'}, \quad 1 < p < \infty, \quad 1 \leq r < \infty;$$

this is not stated in [56] but follows by a similar argument as in the scalar case [55, (2.7)], essentially with the exception of the application of the Radon–Nikodym property in place of the scalar Radon–Nikodym theorem. For a detailed discussion of the Radon–Nikodym properties and its applications we refer to [56, Chapter 1.3.c]. The class of spaces which have the Radon–Nikodym property with respect to all σ -finite measure spaces includes all *reflexive* spaces and also all spaces that have a *separable dual* (cf. [56, Theorem 1.3.21]). If B is reflexive, so is B^* , and therefore (2.14) holds for reflexive spaces B .

Under the assumption that the double dual B_2^{**} satisfies the Radon–Nikodym property, we can show that the sparse bound implies that Tf can be identified with a B_2^{**} strongly measurable function. This leads to a satisfactory conclusion under the stronger assumption that B_2 is reflexive.

LEMMA 2.6. *Assume that $T \in \text{Op}_{B_1, B_2}$ and that B_2^{**} satisfies the Radon–Nikodym property. Then the following hold.*

(i) *If $1 \leq p_1 < p < \infty$ and $T \in \text{Sp}_\gamma(p_1, B_1, p', B_2^*)$ then T extends to a bounded operator from $L_{B_1}^{p_1}$ to $L_{B_2^{**}}^{p'}$ so that*

$$(2.15) \quad \|T\|_{L_{B_1}^{p_1} \rightarrow L_{B_2^{**}}^{p'}} \lesssim_{p_1} \gamma^{-1} \|T\|_{\text{Sp}_\gamma(p_1, B_1, p', B_2^*)}.$$

(ii) *If $1 < p < p'_2$ and $T \in \text{Sp}_\gamma(p, B_1, p_2, B_2^*)$ then T extends to a bounded operator from $L_{B_1}^p$ to $L_{B_2^{**}}^{p_2}$ so that*

$$(2.16) \quad \|T\|_{L_{B_1}^p \rightarrow L_{B_2^{**}}^{p_2}} \lesssim_{p_2} \gamma^{-1} \|T\|_{\text{Sp}_\gamma(p, B_1, p_2, B_2^*)}.$$

PROOF. We rely, as in the proof of Lemma 2.2, on Lemma 2.1.

For part (i), we use (2.2) to obtain

$$|\langle Tf_1, f_2 \rangle| \lesssim \gamma^{-1} \|T\|_{\text{Sp}_\gamma(p, B_1, p_2, B_2^*)} \|f_1\|_{L_{B_1}^{p_1}} \|f_2\|_{L_{B_2^*}^{p'}}.$$

This inequality establishes the form $f_2 \mapsto \langle Tf_1, f_2 \rangle$ as a linear functional on $L_{B_2^*}^{p'}$. Since B_2^{**} has the Radon–Nikodym property and thus $(L_{B_2^*}^{p'})^* = L_{B_2^{**}}^p$, we can identify Tf_1 as a member of $L_{B_2^{**}}^p$. Since

$$\|T\|_{L_{B_1}^{p_1} \rightarrow L_{B_2^{**}}^p} = \sup_{\|f_1\|_{L_{B_1}^{p_1}} \leq 1} \sup_{\|f_2\|_{L_{B_2^*}^{p'}} \leq 1} |\langle Tf_1, f_2 \rangle|,$$

we have established (2.15).

Similarly, for part (ii) we use (2.3) to obtain

$$|\langle Tf_1, f_2 \rangle| \lesssim \gamma^{-1} \|T\|_{\text{Sp}_\gamma(p, B_1, p_2, B_2^*)} \|f\|_{L_{B_1}^p} \|g\|_{L_{B_2^*}^{p'_2}}.$$

Since $L_{B_2^{**}}^{p,\infty}$ can be identified with $(L_{B_2^*}^{p',1})^*$ we then get

$$\|T\|_{L_{B_1}^p \rightarrow L_{B_2^{**}}^{p,\infty}} = \sup_{\|f_1\|_{L_{B_1}^p} \leq 1} \sup_{\|f_2\|_{L_{B_2^*}^{p',1}} \leq 1} |\langle Tf_1, f_2 \rangle|$$

and obtain (2.16). \square

LEMMA 2.7. *Assume that B_2^{**} satisfies the Radon–Nikodym property. Let $\{T_j\}_{j \in \mathbb{Z}}$ be a family of operators in Op_{B_1, B_2} , satisfying the strengthened support condition (1.14). Suppose that $1 \leq p < q \leq \infty$ and*

$$\sup_{j \in \mathbb{Z}} \|T_j\|_{\text{Sp}_{\gamma}(p, B_1, q', B_2^*)} \leq \mathcal{C}.$$

Then

$$\sup_{j \in \mathbb{Z}} \|\text{Dil}_{2^j} T_j\|_{L_{B_1}^p \rightarrow L_{B_2^{**}}^q} \lesssim_{\gamma, d, \delta_1, \delta_2, p, q} \mathcal{C}.$$

PROOF. We let $S = \text{Dil}_{2^j} T_j$, R_3 , $R_{3,\nu}$, $\nu \in \mathcal{I}_3$ as in the proof of Lemma 2.4. The proof of (2.9) can be modified just with appropriate notational changes, such as replacing expressions as one the left-hand side of (2.9) with

$$\lambda_{f,3,\nu}(g) := \langle Sf_3, g \mathbf{1}_{R_{3,\nu}} \rangle.$$

This leads to the inequality

$$(2.17) \quad |\langle Sf_3, g \mathbf{1}_{R_{3,\nu}} \rangle| \lesssim \mathcal{C} \|f_3\|_{L_{B_1}^p} \|g\|_{L_{B_2^*}^q}$$

in the place of (2.9). Inequality (2.17) shows that $\lambda_{f,3,\nu}$ is a continuous linear functional on the space $L_{B_2^*}^{q'}(R_{3,\nu})$; recall that by assumption $1 \leq q' < \infty$. By the Radon–Nikodym property of B_2^{**} , the linear functional $\lambda_{f,3,\nu}$ is identified with a function Sf_3 restricted to $R_{3,\nu}$, in the space $L_{B_2^{**}}^q(R_{3,\nu})$. Hence we now get a variant of inequality (2.12), namely

$$\begin{aligned} \|Sf_3\|_{L_{B_2^{**}}^q} &\lesssim \sum_{\nu \in \mathcal{I}_3} \|Sf_3\|_{L_{B_2^{**}}^q(R_{3,\nu})} \\ &\lesssim \sum_{\nu \in \mathcal{I}_3} \sup_{\|g\|_{L_{B_2^*}^{q'}} \leq 1} |\langle Sf_3, g \mathbf{1}_{R_{3,\nu}} \rangle| \lesssim_{d, \delta_1, \delta_2} \mathcal{C} \|f_3\|_{L_{B_1}^p}. \end{aligned}$$

We finish as in (2.13) to bound $\|Sf\|_{L_{B_2^{**}}^q} \lesssim \mathcal{C} \|f\|_{L_{B_1}^p}$. \square

CONCLUSION OF THE PROOF OF THEOREM 2.5. Since we are assuming that B_2 is reflexive we have that $B_2 = B_2^{**}$ satisfies the Radon–Nikodym property. Hence now the necessity of the $L_{B_1}^{q,1} \rightarrow L_{B_2}^q$ and $L_{B_1}^p \rightarrow L_{B_2^{**}}^{p,\infty}$ conditions follow from Lemma 2.6, and the necessity of the single scale $L^p \rightarrow L^q$ conditions follows from using the assumption with $N_1 = N_2$ and applying Lemma 2.7. \square

Single scale sparse domination

We collect some preliminary results which are needed in the proof of Theorem 1.1.

3.1. A single scale estimate

We state an elementary lemma which is used to establish the base case in the induction proof of Theorem 1.1. Recall that for a cube Q , we let $3Q$ denote the cube centered at the center of Q with three times the side length of Q , which is also the union of Q and its neighbors of the same side length.

LEMMA 3.1. *Let $T_j \in \text{Op}_{B_1, B_2}$ satisfy (1.6) and (1.8) for some exponents $p, q \in [1, \infty]$. Let Q be a cube of side length 2^j . Then for $f_1 \in \mathcal{S}_{B_1}$, $f_2 \in \mathcal{S}_{B_2^*}$,*

$$|\langle T_j[f_1 \mathbf{1}_Q], f_2 \rangle| \leq 3^{d/q'} A_o(p, q) |Q| \langle f_1 \rangle_{Q, p} \langle f_2 \rangle_{3Q, q'}.$$

PROOF. By the support property (1.6), $T_j[f_1 \mathbf{1}_Q]$ is supported in $3Q$. By re-scaling we get from (1.8) that

$$\|T_j\|_{L^p \rightarrow L^q} \leq 2^{-jd(1/p-1/q)} A_o(p, q)$$

and thus

$$\begin{aligned} |\langle T_j[f_1 \mathbf{1}_Q], f_2 \rangle| &= |\langle T_j[f_1 \mathbf{1}_Q], f_2 \mathbf{1}_{3Q} \rangle| \\ &\leq A_o(p, q) 2^{-jd(1/p-1/q)} \|f_1 \mathbf{1}_Q\|_p \|f_2 \mathbf{1}_{3Q}\|_{q'} \\ &= A_o(p, q) 3^{d/q'} |Q| \langle f_1 \rangle_{Q, p} \langle f_2 \rangle_{3Q, q'}, \end{aligned}$$

as claimed. \square

This implies a sparse bound for the single scale operators T_j ; indeed the sparse collection is a disjoint collection of cubes.

COROLLARY 3.2. *For $0 < \gamma \leq 1$ and $1 \leq p, q \leq \infty$,*

$$\|T_j\|_{\text{Sp}_\gamma(p, q')} \leq 3^{d(1/p+1/q')} A_o(p, q).$$

PROOF. We tile \mathbb{R}^d by a family Ω_j of dyadic cubes of side length 2^j and estimate

$$\begin{aligned} |\langle T_j f_1, f_2 \rangle| &\leq \sum_{Q \in \Omega_j} |\langle T_j[f_1 \mathbf{1}_Q], f_2 \rangle| \\ &\leq A_o(p, q) 3^{d/q'} \sum_{Q \in \Omega_j} |Q| \langle f_1 \rangle_{Q, p} \langle f_2 \rangle_{3Q, q'} \\ &\leq A_o(p, q) 3^{d(1/q'-1/p')} \sum_{Q \in \Omega_j} |3Q| \langle f_1 \rangle_{3Q, p} \langle f_2 \rangle_{3Q, q'}. \end{aligned}$$

The family $\{3Q : Q \in \mathfrak{Q}_j\}$ can be split into 3^d subfamilies consisting each of *disjoint* cubes of side length $3 \cdot 2^j$. This implies the assertion (for every $0 < \gamma \leq 1$) since for every $3Q$ involved in each subfamily we can choose $E_{3Q} = 3Q$. \square

3.2. A resolution of the identity

It will be quite convenient to work with a resolution of the identity using Littlewood–Paley decompositions which are localized in space. We have

$$(3.1) \quad \mathbb{I} = \sum_{k=0}^{\infty} \Lambda_k \tilde{\Lambda}_k$$

which converges in the strong operator topology on $L_{B_1}^p(\mathbb{R}^d)$, $1 \leq p < \infty$. Here $\Lambda_k, \tilde{\Lambda}_k$ are convolution operators with convolution kernels $\lambda_k, \tilde{\lambda}_k$ such that $\lambda_0 \in C_c^\infty$ has support in $\{x : |x| < 1/2\}$, $\int \lambda_0 = 1$, $\lambda_1 = 2\lambda_0(2\cdot) - \lambda_0$ and $\tilde{\lambda}_0, \tilde{\lambda}_1 \in \mathcal{S}$ with $\int \tilde{\lambda}_0 = 1$, and $\int \tilde{\lambda}_1 = 0$. Moreover, for $k \geq 1$, $\lambda_k = 2^{(k-1)d}\lambda_1(2^{k-1}\cdot)$, $\tilde{\lambda}_k = 2^{(k-1)d}\tilde{\lambda}_1(2^{k-1}\cdot)$. For later applicability we may choose λ_1 , so that

$$\int \lambda_1(x) \prod_{i=1}^d x_i^{\alpha_i} dx = 0, \quad \text{for } \sum_{i=1}^d \alpha_i \leq 100d$$

and the same for $\tilde{\lambda}_1$.

A proof of (3.1) with these specifications can be found in [100, Lemma 2.1] (the calculation there shows that $\tilde{\lambda}_0, \tilde{\lambda}_1$ can be chosen with compact support as well). For later use we let P_k be the operator given by convolution with $2^{kd}\lambda_0(2^k\cdot)$ for $k \geq 0$, and also set $P_{-1} = 0$, and observe that by our construction

$$(3.2) \quad \Lambda_k = P_k - P_{k-1}, \quad \text{for } k \geq 1.$$

3.3. Single scale regularity

In our proof of Theorem 1.1 it will be useful to work with other versions of the regularity conditions (1.9) which are adapted to the dyadic setting. To formulate these, we fix a dyadic lattice of cubes \mathfrak{Q} . Let $\{\mathbb{E}_n\}_{n \in \mathbb{Z}}$ be the conditional expectation operators associated to the σ -algebra generated by the subfamily \mathfrak{Q}_n of cubes in \mathfrak{Q} of side length in $[2^{-n}, 2^{1-n})$, that is, $\mathbb{E}_n f(x) = \text{av}_Q f$ for every $x \in Q$ with $Q \in \mathfrak{Q}_n$. Define the martingale difference operator \mathbb{D}_n by

$$\mathbb{D}_n = \mathbb{E}_n - \mathbb{E}_{n-1} \quad \text{for } n \geq 1.$$

We also use the operators $\Lambda_k, \tilde{\Lambda}_k$ in the decomposition (3.1).

LEMMA 3.3. *Let $T \in \text{Op}_{B_1, B_2}$.*

(i) *Let $1 \leq p \leq q < \infty$, $0 < \vartheta < 1/p$. Then*

$$(3.3) \quad \|T\mathbb{E}_0\|_{L_{B_1}^p \rightarrow L_{B_2}^q} + \sup_{n>0} 2^{n\vartheta} \|T\mathbb{D}_n\|_{L_{B_1}^p \rightarrow L_{B_2}^q} \lesssim_{\vartheta} \sup_{k \geq 0} 2^{k\vartheta} \|T\Lambda_k\|_{L_{B_1}^p \rightarrow L_{B_2}^q}.$$

(ii) *Let $1 \leq p \leq q \leq \infty$, $0 < \vartheta < 1$. Then*

$$(3.4) \quad \sup_{k \geq 0} 2^{k\vartheta} \|T\Lambda_k\|_{L_{B_1}^p \rightarrow L_{B_2}^q} \approx_{\vartheta} \|T\|_{L_{B_1}^p \rightarrow L_{B_2}^q} + \sup_{0 < |h| < 1} |h|^{-\vartheta} \|T\Delta_h\|_{L_{B_1}^p \rightarrow L_{B_2}^q}.$$

(iii) *Let $1 < p \leq q \leq \infty$, $0 < \vartheta < 1 - 1/p$. Then*

$$(3.5) \quad \sup_{k \geq 0} 2^{k\vartheta} \|T\Lambda_k\|_{L_{B_1}^p \rightarrow L_{B_2}^q} \lesssim_{\vartheta} \|T\mathbb{E}_0\|_{L_{B_1}^p \rightarrow L_{B_2}^q} + \sup_{n>0} 2^{n\vartheta} \|T\mathbb{D}_n\|_{L_{B_1}^p \rightarrow L_{B_2}^q}.$$

An immediate consequence is the following.

COROLLARY 3.4. *For $1 < p \leq q < \infty$ and $0 < \vartheta < \min\{1/p, 1 - 1/p\}$,*

$$\|T\mathbb{E}_0\|_{L_{B_1}^p \rightarrow L_{B_2}^q} + \sup_{n>0} 2^{n\vartheta} \|T\mathbb{D}_n\|_{L_{B_1}^p \rightarrow L_{B_2}^q} \approx \vartheta$$

$$\|T\|_{L_{B_1}^p \rightarrow L_{B_2}^q} + \sup_{0<|h|<1} |h|^{-\vartheta} \|T\Delta_h\|_{L_{B_1}^p \rightarrow L_{B_2}^q}.$$

PROOF OF LEMMA 3.3. We rely on arguments used before in considerations of variational estimates [58], [59], of basis properties of the Haar system in spaces measuring smoothness [47] and elsewhere. We use

$$\|\Lambda_k\|_{L_{B_1}^p \rightarrow L_{B_1}^p} = O(1), \quad \|\tilde{\Lambda}_k\|_{L_{B_1}^p \rightarrow L_{B_1}^p} = O(1), \quad \|\mathbb{E}_n\|_{L_{B_1}^p \rightarrow L_{B_1}^p} = O(1)$$

throughout the proof. Since $\vartheta > 0$ we get from (3.1)

$$\|T\mathbb{E}_0\|_{L_{B_1}^p \rightarrow L_{B_2}^q} \lesssim \sum_{k \geq 0} \|T\Lambda_k\|_{L_{B_1}^p \rightarrow L_{B_2}^q} \lesssim \vartheta \sup_{k \geq 0} 2^{k\vartheta} \|T\Lambda_k\|_{L_{B_1}^p \rightarrow L_{B_2}^q}.$$

To estimate $T\mathbb{D}_n$ we will need

$$(3.6) \quad \|\tilde{\Lambda}_k \mathbb{D}_n\|_{L_{B_1}^p \rightarrow L_{B_1}^p} \lesssim \min\{1, 2^{(k-n)/p}\},$$

and only the case $k \leq n$ needs a proof. A standard calculation using cancellation of \mathbb{D}_n yields (3.6) for $p = 1$ and the rest follows by interpolation. Consequently we can estimate

$$\begin{aligned} 2^{n\vartheta} \|T\mathbb{D}_n\|_{L_{B_1}^p \rightarrow L_{B_2}^q} &\leq 2^{n\vartheta} \sum_{k \geq 0} \|T\Lambda_k \tilde{\Lambda}_k \mathbb{D}_n\|_{L_{B_1}^p \rightarrow L_{B_2}^q} \\ &\leq 2^{n\vartheta} \sum_{k \geq 0} \|T\Lambda_k\|_{L_{B_1}^p \rightarrow L_{B_2}^q} \|\tilde{\Lambda}_k \mathbb{D}_n\|_{L_{B_1}^p \rightarrow L_{B_1}^p} \\ &\lesssim \sum_{0 \leq k \leq n} 2^{k\vartheta} \|T\Lambda_k\|_{L_{B_1}^p \rightarrow L_{B_2}^q} 2^{-(n-k)(\frac{1}{p}-\vartheta)} \\ &\quad + \sum_{k > n} 2^{k\vartheta} \|T\Lambda_k\|_{L_{B_1}^p \rightarrow L_{B_2}^q} 2^{-(k-n)\vartheta} \\ &\lesssim \sup_{k \geq 0} 2^{k\vartheta} \|T\Lambda_k\|_{L_{B_1}^p \rightarrow L_{B_2}^q}, \end{aligned}$$

where we used $\vartheta < 1/p$ for the first sum. This proves (3.3).

We now turn to (3.4) and estimate the left-hand side. By (3.2) we can write

$$\|T\Lambda_k\|_{L_{B_1}^p \rightarrow L_{B_2}^q} \leq \|T(\mathbb{I} - P_k)\|_{L_{B_1}^p \rightarrow L_{B_2}^q} + \|T(\mathbb{I} - P_{k-1})\|_{L_{B_1}^p \rightarrow L_{B_2}^q}.$$

Note that, as $\int \lambda_0 = 1$,

$$(\mathbb{I} - P_{k-1})f(x) = \int 2^{(k-1)d} \lambda_0(2^{k-1}h) \Delta_{-h} f(x) dh,$$

so

$$\begin{aligned} \|T(\mathbb{I} - P_{k-1})f\|_{L_{B_1}^p \rightarrow L_{B_2}^q} &= \int 2^{(k-1)d} |\lambda_0(2^{k-1}h)| \|T\Delta_{-h}\|_{L_{B_1}^p \rightarrow L_{B_2}^q} dh \\ &\lesssim \sup_{|h| \leq 2^{-k}} \|T\Delta_h\|_{L_{B_1}^p \rightarrow L_{B_2}^q} \end{aligned}$$

and the same bound for $\|T(\mathbb{I} - P_k)f\|_{L_{B_1}^p \rightarrow L_{B_2}^q}$. This establishes that the left-hand side is smaller than the right-hand side in (3.4).

We argue similarly for the converse inequality. We estimate

$$\|T\|_{L_{B_1}^p \rightarrow L_{B_2}^q} \leq \sum_{k \geq 0} \|T\Lambda_k\|_{L_{B_1}^p \rightarrow L_{B_2}^q} \lesssim \sup_{k \geq 0} 2^{k\vartheta} \|T\Lambda_k\|_{L_{B_1}^p \rightarrow L_{B_2}^q}.$$

For the main terms

$$\|T\Delta_h\|_{L_{B_1}^p \rightarrow L_{B_2}^q} \leq \sum_{k \geq 0} \|T\Lambda_k\|_{L_{B_1}^p \rightarrow L_{B_2}^q} \|\tilde{\Lambda}_k \Delta_h\|_{L_{B_1}^p \rightarrow L_{B_1}^p}.$$

Now

$$(3.7) \quad \|\tilde{\Lambda}_k \Delta_h\|_{L_{B_1}^p \rightarrow L_{B_1}^p} \lesssim \|\lambda_k(\cdot + h) - \lambda_k(\cdot)\|_1 \lesssim \min\{1, 2^k|h|\}$$

and therefore

$$\begin{aligned} |h|^{-\vartheta} \|T\Delta_h\|_{L_{B_1}^p \rightarrow L_{B_2}^q} &\leq \sum_{k \geq 0} \|T\Lambda_k\|_{L_{B_1}^p \rightarrow L_{B_2}^q} 2^{k\vartheta} (2^k|h|)^{-\vartheta} \min\{1, 2^k|h|\} \\ &\lesssim \sup_{k \geq 0} 2^{k\vartheta} \|T\Lambda_k\|_{L_{B_1}^p \rightarrow L_{B_2}^q} \end{aligned}$$

since $\sum_{k \geq 0} (2^k|h|)^{-\vartheta} \min\{1, 2^k|h|\} \lesssim_{\vartheta} 1$ if $0 < \vartheta < 1$. This completes the proof of (3.4).

It remains to prove (3.5). Setting $\mathbb{D}_0 := \mathbb{E}_0$ we observe that $\mathbb{I} = \sum_{n \geq 0} \mathbb{D}_n$ and $\mathbb{D}_n = \mathbb{D}_n \mathbb{D}_n$, and thus

$$\|T\Lambda_k\|_{L_{B_1}^p \rightarrow L_{B_2}^q} \leq \sum_{n \geq 0} \|T\mathbb{D}_n\|_{L_{B_1}^p \rightarrow L_{B_2}^q} \|\mathbb{D}_n \Lambda_k\|_{L_{B_1}^p \rightarrow L_{B_1}^p}.$$

We use $\|\mathbb{D}_n \Lambda_k\|_{L_{B_1}^p \rightarrow L_{B_1}^p} \lesssim 1$ for $n \geq k$ and

$$(3.8) \quad \|\mathbb{D}_n \Lambda_k\|_{L_{B_1}^p \rightarrow L_{B_1}^p} \lesssim 2^{(n-k)(1-\frac{1}{p})} \text{ for } n < k.$$

This is clear for $p = 1$ and by interpolation it suffices to show it for $p = \infty$. Let Q be a dyadic cube of side length 2^{-n+1} . Let $\text{Ch}(Q)$ be the set of 2^d dyadic children of Q (i.e. the dyadic sub-cubes of side length 2^{-n}). Let

$$F_{Q,k} = \{x : \text{dist}(x, \partial\tilde{Q}) \leq 2^{-k} \text{ for some } \tilde{Q} \in \text{Ch}(Q)\}.$$

Then $|F_{Q,k-1}| \lesssim 2^{-n(d-1)} 2^{-k}$. Let $g_{Q,k} = f \mathbb{1}_{Q \setminus F_{Q,k}}$ and observe that by Fubini's theorem and the cancellation and support properties of λ_k

$$\mathbb{E}_n \Lambda_k g_{Q,k}(x) = 0 \quad \text{and} \quad \mathbb{E}_{n-1} \Lambda_k g_{Q,k}(x) = 0 \quad \text{for } x \in Q.$$

Hence for $x \in Q$,

$$\begin{aligned} |\mathbb{D}_n \Lambda_k f(x)| &= |\mathbb{D}_n \Lambda_k (f \mathbb{1}_{F_{Q,k}})(x)| \\ &\lesssim 2^{nd} \int \int |\lambda_k(w-y)| |f(y)| dw \mathbb{1}_{F_{Q,k}}(y) dy \\ &\lesssim 2^{nd} |F_{Q,k-1}| \|f\|_{\infty} \lesssim 2^{n-k} \|f\|_{\infty}. \end{aligned}$$

This implies (3.8) for $p = \infty$.

To finish we write

$$\begin{aligned} 2^{k\vartheta} \|T\Lambda_k\|_{L_{B_1}^p \rightarrow L_{B_2}^q} &\leq \sum_{n \geq 0} \|T\mathbb{D}_n\|_{L_{B_1}^p \rightarrow L_{B_2}^q} 2^{k\vartheta} \min\{1, 2^{(n-k)(1-1/p)}\} \\ &\lesssim \sup_{n \geq 0} 2^{n\vartheta} \|T\mathbb{D}_n\|_{L_{B_1}^p \rightarrow L_{B_2}^q} \end{aligned}$$

where we used $\sum_{n \geq 0} 2^{(k-n)\vartheta} \min\{1, 2^{(n-k)(1-1/p)}\} \lesssim 1$ provided that $0 < \vartheta < 1 - 1/p$. This proves (3.5). \square

In the proof of Theorem 1.1 we use the following Corollary.

COROLLARY 3.5. *Let $1 \leq p \leq q < \infty$ and $0 < \vartheta < 1/p$. Then*

(i) *For any $n \geq 0$,*

$$\|T(\mathbb{I} - \mathbb{E}_n)\|_{L_{B_1}^p \rightarrow L_{B_2}^q} \lesssim_{\vartheta} 2^{-n\vartheta} \sup_{0 < |h| < 1} |h|^{-\vartheta} \|T\Delta_h\|_{L_{B_1}^p \rightarrow L_{B_2}^q}.$$

(ii) *If T_j is such that (1.9a) holds then*

$$\|T_j(\mathbb{I} - \mathbb{E}_{n-j})\|_{L_{B_1}^p \rightarrow L_{B_2}^q} \lesssim_{\vartheta} B 2^{-n\vartheta} 2^{-jd(\frac{1}{p} - \frac{1}{q})}.$$

PROOF. We write $\mathbb{I} = \mathbb{E}_n + \sum_{k=1}^{\infty} \mathbb{D}_{n+k}$, and thus

$$\begin{aligned} \|T(\mathbb{I} - \mathbb{E}_n)\|_{L_{B_1}^p \rightarrow L_{B_2}^q} &\leq \sum_{k=1}^{\infty} \|T\mathbb{D}_{n+k}\|_{L_{B_1}^p \rightarrow L_{B_2}^q} \\ &\lesssim_{\vartheta} \sum_{k=1}^{\infty} 2^{-(n+k)\vartheta} \sup_{0 < |h| < 1} |h|^{-\vartheta} \|T\Delta_h\|_{L_{B_1}^p \rightarrow L_{B_2}^q} \end{aligned}$$

by combining part (3.3), (3.4) in the statement of Lemma 3.3. We sum and get the assertion. Part (ii) follows by rescaling and the hypotheses. \square

We finally discuss a formulation of the regularity condition which involves the Fourier support of the function and is therefore limited to the case where B_1 is a separable Hilbert space, here denoted by \mathcal{H} . It is convenient to use a frequency decomposition

$$(3.9) \quad f = \sum_{\ell \geq 0} \eta_{\ell} * f,$$

with $\widehat{\eta}_0$ is supported in $\{\xi : |\xi| < 1\}$ such that $\widehat{\eta}_0(\xi) = 1$ for $|\xi| \leq \frac{3}{4}$, and with η_{ℓ} defined by $\widehat{\eta}_{\ell}(\xi) = \widehat{\eta}_0(2^{-\ell}\xi) - \widehat{\eta}_0(2^{1-\ell}\xi)$ for $\ell \geq 1$, *i.e.* we have

$$(3.10) \quad \text{supp}(\widehat{\eta}_{\ell}) \subset \{\xi : 2^{\ell-2} < |\xi| < 2^{\ell}\}, \quad \ell \geq 1.$$

Recall that $\mathcal{E}_{\text{ann}}(\lambda)$ denotes the space of tempered distributions whose Fourier transform is supported in $\{\xi : \lambda/2 < |\xi| < 2\lambda\}$.

LEMMA 3.6. *Let \mathcal{H} be a separable Hilbert space and $T \in \text{Op}_{\mathcal{H}, B_2}$. Suppose that $T : L_{\mathcal{H}}^p \rightarrow L_{B_2}^q$ satisfies*

$$(3.11) \quad \|T\|_{L_{\mathcal{H}}^p \rightarrow L_{B_2}^q} \leq A,$$

and for all $\lambda > 2$ and all \mathcal{H} -valued Schwartz functions $f \in \mathcal{E}_{\text{ann}}(\lambda)$,

$$(3.12) \quad \|Tf\|_{L_{B_2}^q} \leq A\lambda^{-\vartheta} \|f\|_{L_{\mathcal{H}}^p}.$$

Then

$$\sup_{0 < |h| < 1} |h|^{-\vartheta} \|T\Delta_h\|_{L_{\mathcal{H}}^p \rightarrow L_{B_2}^q} \lesssim_{\vartheta} A.$$

PROOF. By the assumptions (3.11) ($\ell = 0$) and (3.12) ($\ell \geq 1$) we have

$$\|T[\eta_\ell * \Delta_h f]\|_{L_{B_2}^q} \leq A2^{(1-\ell)\vartheta} \|\eta_\ell * \Delta_h f\|_{L_{\mathfrak{J}_c}^p}$$

Arguing as in (3.7) we get

$$\|\eta_\ell * \Delta_h f\|_{L_{\mathfrak{J}_c}^p} = \|\Delta_h \eta_\ell * f\|_{L_{\mathfrak{J}_c}^p} \lesssim \min\{1, 2^\ell |h|\} \|f\|_{L_{\mathfrak{J}_c}^p}.$$

Thus using (3.9) we obtain

$$\|T\Delta_h f\|_{L_{B_2}^q} \leq \sum_{\ell=0}^{\infty} \|T[\eta_\ell * \Delta_h f]\|_{L_{B_2}^q} \lesssim A \sum_{\ell=0}^{\infty} 2^{-\ell\vartheta} \min\{1, 2^\ell |h|\} \|f\|_{L_{\mathfrak{J}_c}^p}$$

and after summing in ℓ we arrive at $\|T\Delta_h f\|_{L_{B_2}^q} \lesssim_{\vartheta} |h|^{\vartheta} \|f\|_{L_{\mathfrak{J}_c}^p}$. □

Proof of the main result

4.1. A modified version of sparse forms

We fix a dyadic lattice \mathfrak{Q} in the sense of Lerner and Nazarov, where we assume that the side length of each cube in \mathfrak{Q} is dyadic, *i.e.* of the form 2^k with $k \in \mathbb{Z}$. Also fix $\gamma \in (0, 1)$ and $1 < p \leq q < \infty$. It will be convenient to use variants $\mathfrak{G}_{Q_0} \equiv \mathfrak{G}_{Q_0, \gamma}$ of the maximal form $\Lambda_{p, q'}^*$ defined in (1.3). The presence of the triple cubes in the new form allows one to exploit more effectively the support condition (1.6).

DEFINITION 4.1. Given a cube $Q_0 \in \mathfrak{Q}$ let

$$\mathfrak{G}_{Q_0}(f_1, f_2) = \sup_{Q \in \mathfrak{G}} \sum |Q| \langle f_1 \rangle_{Q, p, B_1} \langle f_2 \rangle_{3Q, q', B_2^*}$$

where the supremum is taken over all γ -sparse collections \mathfrak{G} consisting of cubes in $\mathcal{D}(Q_0)$.

Notational convention. From now on in this proof, the dependence on the Banach spaces B_1, B_2^* will not be explicitly indicated, *i.e.* $\langle f_1 \rangle_{Q, p}$ should be understood as $\langle f_1 \rangle_{Q, p, B_1}$ and $\langle f_2 \rangle_{Q, q'}$ should be understood as $\langle f_2 \rangle_{Q, q', B_2^*}$.

The key step towards proving Theorem 1.1 is to establish a variant in which $\Lambda_{p, q'}^*$ is replaced by \mathfrak{G}_{Q_0} , that is,

$$(4.1) \quad \left| \left\langle \sum_{j=N_1}^{N_2} T_j f_1, f_2 \right\rangle \right| \lesssim_{p, q, \varepsilon, d, \gamma} \mathcal{C} \mathfrak{G}_{Q_0}(f_1, f_2)$$

for $f_1 \in S_{B_1}, f_2 \in S_{B_2^*}$ and a sufficiently large cube $Q_0 \in \mathfrak{Q}$. The reader will notice that \mathfrak{G}_{Q_0} does not define a sparse form, and we will show in §4.2 how to finish the proof of Theorem 1.1 given (4.1). The proof of (4.1) will be done by induction, which leads us to the following definition.

DEFINITION 4.2. For $n = 0, 1, 2, \dots$ let $U(n)$ be the smallest constant U so that for all families of operators $\{T_j\}$ satisfying the assumptions of Theorem 1.1, for all pairs (N_1, N_2) with $0 \leq N_2 - N_1 \leq n$ and for all dyadic cubes $Q_0 \in \mathfrak{Q}$ of side length 2^{N_2} we have

$$\left| \left\langle \sum_{j=N_1}^{N_2} T_j f_1, f_2 \right\rangle \right| \leq U \mathfrak{G}_{Q_0}(f_1, f_2)$$

whenever $f_1 \in S_{B_1}$ with $\text{supp}(f_1) \subset Q_0$ and $f_2 \in S_{B_2^*}$.

Thus, in order to show (4.1), it suffices to show that

$$U(n) \lesssim_{p, q, \varepsilon, d, \gamma} \mathcal{C}$$

uniformly in $n \in \mathbb{N}_0$. This will be proven by induction on n . By Lemma 3.1 we have the base case

$$(4.2) \quad U(0) \leq 3^{d/q'} A_o(p, q)$$

and, more generally, $U(n) \leq (n+1)3^{d/q'} A_o(p, q)$, which shows the finiteness of the $U(n)$. The proof then reduces to the verification of the following inductive claim.

CLAIM 4.3. There is a constant $c = c_{p,q,\varepsilon,d,\gamma}$ such that for all $n > 0$,

$$U(n) \leq \max\{U(n-1), c\mathcal{C}\},$$

with \mathcal{C} defined as in (1.11).

Our proof of the claim is an extension of the proof for sparse bounds of the prototypical singular Radon transforms in [89], which itself builds on ideas in [66]. It is contained in §4.4.

4.2. Proof of the main theorem given the inductive claim

We prove Theorem 1.1 given Claim 4.3. Fix $N_1 \leq N_2$, $f_1 \in S_{B_1}$, $f_2 \in S_{B_2^*}$. We choose any dyadic lattice with cubes of dyadic side length as in the previous section. By (1.6) we may choose a cube $Q_0 \in \mathfrak{Q}$ of side length $2^{L(Q_0)}$ with $L(Q_0) \geq N_2$ such that f_1 is supported in Q_0 . Then $\sum_{j=N_1}^{N_2} T_j f_1$ is supported in $3Q_0$. Define the operators $S_j = T_j$ when $N_1 \leq j \leq N_2$ and $S_j = 0$ otherwise. Then the assumptions of Theorem 1.1 apply to the family $\{S_j\}$. By (4.2) and Claim 4.3 applied to $S = \sum_{j=N_1}^{L(Q_0)} S_j = \sum_{j=N_1}^{N_2} T_j$ we obtain

$$|\langle Sf_1, f_2 \rangle| \leq c_{p,q,\varepsilon,d,\gamma} \mathcal{C} \mathfrak{G}_{Q_0}(f_1, f_2).$$

In order to complete the proof of Theorem 1.1 it remains to replace \mathfrak{G}_{Q_0} by the maximal sparse form $\Lambda_{p,q}^*$. This argument relies on facts in dyadic analysis which we quote from the book by Lerner and Nazarov [79].

We first note that for $\varepsilon > 0$ there is a γ -sparse collection $\mathfrak{S}_\varepsilon \subset \mathcal{D}(Q_0)$ such that

$$(4.3) \quad \begin{aligned} |\langle Sf_1, f_2 \rangle| &\leq (c_{p,q,\varepsilon,d,\gamma} \mathcal{C} + \varepsilon) \sum_{Q \in \mathfrak{S}_\varepsilon} |Q| \langle f_1 \rangle_{Q,p} \langle f_2 \rangle_{3Q,q'} \\ &\leq 3^{d/p-d} (c_{p,q,\varepsilon,d,\gamma} \mathcal{C} + \varepsilon) \sum_{Q \in \mathfrak{S}_\varepsilon} |3Q| \langle f_1 \rangle_{3Q,p} \langle f_2 \rangle_{3Q,q'}. \end{aligned}$$

By the Three Lattice Theorem [79, Theorem 3.1] there are dyadic lattices $\mathcal{D}^{(\nu)}$, $\nu = 1, \dots, 3^d$, such that every cube in the collection $3\mathfrak{S}_\varepsilon := \{3Q : Q \in \mathfrak{S}_\varepsilon\}$ belongs to one of the dyadic lattices $\mathcal{D}^{(\nu)}$. Moreover, each collection

$$\mathfrak{S}_\varepsilon^{(\nu)} = 3\mathfrak{S}_\varepsilon \cap \mathcal{D}^{(\nu)}$$

is a $3^{-d}\gamma$ -sparse collection of cubes in $\mathcal{D}^{(\nu)}$. Each $\mathfrak{S}_\varepsilon^{(\nu)}$ is a $3^d\gamma^{-1}$ -Carleson family in the sense of [79, Definition 6.2]. By [79, Lemma 6.6] we can write, for each integer $M \geq 2$, the family $\mathfrak{S}_\varepsilon^{(\nu)}$ as a union of M sub-families $\mathfrak{S}_{\varepsilon,i}^{(\nu)}$, each of which is a \widetilde{M} -Carleson family, with $\widetilde{M} = 1 + M^{-1}(3^d\gamma^{-1} - 1)$. By [79, Lemma 6.3] the collections $\mathfrak{S}_{\varepsilon,i}^{(\nu)}$ are $\widetilde{\gamma}$ -sparse families where $\widetilde{\gamma} = \widetilde{M}^{-1} = (1 + M^{-1}(3^d\gamma^{-1} - 1))^{-1}$.

By choosing M large enough we can have $\tilde{\gamma} > \gamma$ and then, from (4.3), one has

$$\begin{aligned} |\langle Sf_1, f_2 \rangle| &\leq 3^{d/p-d} (c_{p,q,\varepsilon,d,\gamma} \mathcal{C} + \epsilon) \sum_{Q \in \mathfrak{S}_\epsilon} |3Q| \langle f_1 \rangle_{3Q,p} \langle f_2 \rangle_{3Q,q'} \\ &\leq M 3^{d/p} (c_{p,q,\varepsilon,d,\gamma} \mathcal{C} + \epsilon) \sup_{\substack{i=1,\dots,M \\ \nu=1,\dots,3^d}} \sum_{R \in \mathfrak{S}_{\epsilon,i}^{(\nu)}} |R| \langle f_1 \rangle_{R,p} \langle f_2 \rangle_{R,q'} \\ &\leq M 3^{d/p} (c_{p,q,\varepsilon,d,\gamma} \mathcal{C} + \epsilon) \Lambda_{p,q}^*(f_1, f_2) \end{aligned}$$

which gives the desired γ -sparse bound with $\|S\|_{\text{Sp}_\gamma(p,q')} \leq M 3^{d/p} c_{p,q,\varepsilon,d,\gamma} \mathcal{C}$.

4.3. Proof of the corollary of the main theorem

We prove Corollary 1.2. It is a consequence of Theorem 1.1 and the following lemma, applied to $T = \sum_{j=N_1}^{N_2} T_j$.

LEMMA 4.4. *Let $T : S_{B_1} \rightarrow L_{B_2,\text{loc}}^1$ and assume that*

$$\|T\|_{\text{Sp}_\gamma(p,B_1;q',B_2^*)} \leq \mathcal{C}.$$

Then we have for all $f \in S_{B_1}$ and all nonnegative simple ω

$$(4.4) \quad \int_{\mathbb{R}^d} |Tf(x)|_{B_2} \omega(x) dx \leq \mathcal{C} \Lambda_{p,B_1,q',\mathbb{R}}^*(f, \omega).$$

PROOF. By the monotone convergence theorem we may assume that ω is a compactly supported simple function. Moreover, since $T : S_{B_1} \rightarrow L_{B_2,\text{loc}}^1$ we can approximate, in the $L_{B_2}^1(K)$ norm for every compact set K , the function Tf (for $f \in S_{B_1}$) by simple B_2 -valued functions. Thus given $\epsilon > 0$ there is $h \in S_{B_2}$ such that

$$\int_{\mathbb{R}^d} |Tf(x) - h(x)|_{B_2} \omega(x) dx \leq \epsilon.$$

Moreover, there is a compactly supported $\lambda \in S_{B_2^*}$ with $\max_{x \in \mathbb{R}^d} |\lambda(x)|_{B_2^*} \leq 1$ (depending on h, ω) such that

$$\int_{\mathbb{R}^d} |h(x)|_{B_2} \omega(x) dx \leq \epsilon + \int_{\mathbb{R}^d} \langle h(x), \lambda(x) \rangle \omega(x) dx,$$

and we also have

$$\left| \int_{\mathbb{R}^d} \langle h(x) - Tf(x), \lambda(x) \rangle \omega(x) dx \right| \leq \int_{\mathbb{R}^d} |h(x) - Tf(x)|_{B_2} \omega(x) dx \leq \epsilon.$$

Consequently

$$\int_{\mathbb{R}^d} |Tf(x)|_{B_2} \omega(x) dx \leq 3\epsilon + \int_{\mathbb{R}^d} \langle Tf(x), \lambda(x) \rangle \omega(x) dx.$$

Thus in order to show (4.4) it suffices to show

$$(4.5) \quad \int_{\mathbb{R}^d} \langle Tf(x), \lambda(x) \rangle \omega(x) dx \leq \mathcal{C} \Lambda_{p_1,B_1,p_2,\mathbb{R}}^*(f, \omega)$$

for any choice of compactly supported $\lambda \in S_{B_2^*}$ such that $\|\lambda\|_{L_{B_2^*}^\infty} \leq 1$. Let $f_2(x) = \omega(x)\lambda(x)$. Then $f_2 \in S_{B_2^*}$ with $|f_2(x)|_{B_2^*} \leq \omega(x)$ for all $x \in \mathbb{R}^d$. By the hypothesis, applied to f and $f_2 = \omega\lambda$,

$$\int_{\mathbb{R}^d} \langle Tf(x), \omega(x)\lambda(x) \rangle dx \leq \mathcal{C} \Lambda_{p_1,B_1,p_2,B_2^*}^*(f, \omega\lambda).$$

Since $\langle \omega \lambda \rangle_{Q, p_2, B_2^*} \leq \langle \omega \rangle_{Q, p_2, \mathbb{R}}$, we have established (4.5), and the proof is finished by letting $\epsilon \rightarrow 0$. \square

4.4. The inductive step

In this section we prove Claim 4.3, the key ingredient in the proof of Theorem 1.1. Let Q_0 be a dyadic cube of side length 2^{N_2} . Recall that f_1 is supported in Q_0 and thus

$$\left\langle \sum_{j=N_1}^{N_2} T_j f_1, f_2 \right\rangle = \left\langle \sum_{j=N_1}^{N_2} T_j f_1, f_2 \mathbf{1}_{3Q_0} \right\rangle.$$

Hence without loss of generality we may assume that f_2 is supported in $3Q_0$.

Let \mathcal{M} denote the Hardy–Littlewood maximal operator and let

$$\mathcal{M}_p f = (\mathcal{M}|f|^p)^{1/p}.$$

By the well known weak type (1, 1) inequality for \mathcal{M} ,

$$\text{meas}(\{x \in \mathbb{R}^d : \mathcal{M}_p f > \lambda\}) \leq 5^d \lambda^{-p} \|f\|_p^p.$$

Define $\Omega = \Omega_1 \cup \Omega_2$ where

$$(4.6) \quad \begin{aligned} \Omega_1 &= \{x \in 3Q_0 : \mathcal{M}_p f_1(x) > \left(\frac{100^d}{1-\gamma}\right)^{1/p} \langle f_1 \rangle_{Q_0, p}\}, \\ \Omega_2 &= \{x \in 3Q_0 : \mathcal{M}_{q'} f_2(x) > \left(\frac{100^d}{1-\gamma}\right)^{1/q'} \langle f_2 \rangle_{3Q_0, q'}\}. \end{aligned}$$

We then have $|\Omega| \leq |\Omega_1| + |\Omega_2| < (1-\gamma)|Q_0|$ and if we set

$$E_{Q_0} = Q_0 \setminus \Omega,$$

then $|E_{Q_0}| > \gamma|Q_0|$.

We perform a Whitney decomposition of Ω . It is shown in [103, VI.1.2] that given any $\beta > \sqrt{d}$, one can write Ω as a union of disjoint dyadic Whitney cubes $W \in \mathcal{W}^\beta \subset \Omega$, with side length $2^{L(W)}$ and $L(W) \in \mathbb{Z}$, so that

$$(\beta - \sqrt{d})2^{L(W)} \leq \text{dist}(W, \Omega^c) \leq \beta 2^{L(W)+1}$$

for $W \in \mathcal{W}^\beta$. In [103, VI.1.1] the choice of $\beta = 2\sqrt{d}$ is made; here we need to choose β sufficiently large and $\beta = 6\sqrt{d}$ will work for us. We fix this choice and label as \mathcal{W} the corresponding family of Whitney cubes. We then have

$$(4.7) \quad 5 \text{diam}(W) \leq \text{dist}(W, \Omega^c) \leq 12 \text{diam}(W) \quad \text{for all } W \in \mathcal{W}.$$

We set for $i = 1, 2$,

$$\begin{aligned} f_{i,W} &= f_i \mathbf{1}_W, \\ b_{i,W} &= (f_i - \text{av}_W f_i) \mathbf{1}_W \\ &= (\mathbf{I} - \mathbb{E}_{-L(W)}) f_{i,W}, \end{aligned}$$

and

$$\begin{aligned} b_i &= \sum_{W \in \mathcal{W}} b_{i,W}, \\ g_i &= f_i \mathbf{1}_{\Omega^c} + \sum_{W \in \mathcal{W}} \text{av}_W f_i \mathbf{1}_W. \end{aligned}$$

Then we have the Calderón–Zygmund decompositions $f_i = g_i + b_i$ (using the same above family of Whitney cubes for f_1 and f_2). For $i = 1$ we add an observation, namely that

$$b_1 = \sum_{\substack{W \in \mathcal{W} \\ W \subset Q_0}} b_{1,W}.$$

Since f_1 is supported in Q_0 , this follows from the fact that

$$(4.8) \quad W \cap Q_0 \neq \emptyset \implies W \subsetneq Q_0.$$

Indeed, if (4.8) fails, we must have $Q_0 \subseteq W$ as W and Q_0 are dyadic. But then $|Q_0| \leq |W| \leq |\Omega| < (1 - \gamma)|Q_0|$, which is a contradiction.

We note from (4.7) and the definition of Ω that

$$(4.9a) \quad \langle f_1 \rangle_{W,p} \lesssim_{d,\gamma} \langle f_1 \rangle_{Q_0,p}, \quad \langle f_2 \rangle_{W,q'} \lesssim_{d,\gamma} \langle f_2 \rangle_{3Q_0,q'}$$

for every $W \in \mathcal{W}$, as a fixed dilate of W intersects Ω^c . Indeed,

$$(4.9b) \quad \langle f_1 \rangle_{Q,p} \lesssim_{d,\gamma} \langle f_1 \rangle_{Q_0,p}, \quad \langle f_2 \rangle_{Q,q'} \lesssim_{d,\gamma} \langle f_2 \rangle_{3Q_0,q'}$$

for every cube Q which contains a $W \in \mathcal{W}$. Moreover, by the definition of g_i and Ω ,

$$(4.10) \quad \|g_1\|_{L_{B_1}^\infty} \lesssim_{d,\gamma} \langle f_1 \rangle_{Q_0,p}, \quad \|g_2\|_{L_{B_2^*}^\infty} \lesssim_{d,\gamma} \langle f_2 \rangle_{3Q_0,q'}.$$

Since $\text{supp}(f_1) \subset Q_0$ and $\text{supp}(f_2) \subset 3Q_0$ we also get $\text{supp}(g_1) \subset Q_0$ and $\text{supp}(g_2) \subset 3Q_0$; here we use (4.8). Since $\|\mathbb{1}_Q\|_{L^{r,1}} \lesssim_r |Q|^{1/r}$ for $r < \infty$, we obtain from (4.10) that for $r_1, r_2 < \infty$,

$$(4.11) \quad \|g_1\|_{L_{B_1}^{r_1,1}} \lesssim_{d,r_1,\gamma} |Q_0|^{1/r_1} \langle f_1 \rangle_{Q_0,p}, \quad \|g_2\|_{L_{B_2^*}^{r_2,1}} \lesssim_{d,r_2,\gamma} |Q_0|^{1/r_2} \langle f_2 \rangle_{3Q_0,q'}.$$

For every dyadic cube $Q \in \Omega$ we have by disjointness of the W

$$\left\| \sum_{W \subset Q} b_{1,W} \right\|_{L_{B_1}^r} \lesssim \left(\sum_{W \subset Q} \|f_{1,W}\|_{L_{B_1}^r}^r \right)^{1/r}$$

and thus

$$(4.12) \quad \left\| \sum_{W \subset Q} b_{1,W} \right\|_{L_{B_1}^r} \lesssim \left(\int_Q |f_1(x)|_{B_1}^r dx \right)^{1/r}.$$

Likewise we get for f_2 ,

$$\left\| \sum_{W \subset Q} b_{2,W} \right\|_{L_{B_2^*}^r} \lesssim \left(\int_Q |f_2(x)|_{B_2^*}^r dx \right)^{1/r}.$$

We now begin the proof of the induction step in Claim 4.3. Let

$$S \equiv S_{N_1, N_2} = \sum_{j=N_1}^{N_2} T_j.$$

By the Calderón–Zygmund decomposition for f_1 we have

$$(4.13) \quad |\langle S f_1, f_2 \rangle| \leq |\langle S g_1, f_2 \rangle| + |\langle S b_1, f_2 \rangle|.$$

Using the $L_{B_1}^{q,1} \rightarrow L_{B_2}^q$ boundedness of S (from the restricted strong type (q, q) condition (1.7b)) and (4.11) with $r_1 = q < \infty$ we get

$$\begin{aligned}
(4.14) \quad |\langle Sg_1, f_2 \rangle| &\leq \|Sg_1\|_{L_{B_2}^q} \|f_2 \mathbf{1}_{3Q_0}\|_{L_{B_2^*}^{q'}} \\
&\leq A(q) \|g_1\|_{L_{B_1}^{q,1}} \|f_2 \mathbf{1}_{3Q_0}\|_{L_{B_2^*}^{q'}} \\
&\lesssim_{d,q,\gamma} A(q) |Q_0| \langle f_1 \rangle_{Q_0,p} \langle f_2 \rangle_{3Q_0,q'}.
\end{aligned}$$

Define, for each $W \in \mathcal{W}$ (recalling that the side length of W is $2^{L(W)}$),

$$S_W f = S_{N_1, L(W)} [f \mathbf{1}_W] \equiv \sum_{N_1 \leq j \leq L(W)} T_j [f \mathbf{1}_W].$$

We decompose the second term in (4.13) as in [89] and write

$$\langle S b_1, f_2 \rangle = I + II + III,$$

where

$$(4.15a) \quad I = \left\langle \sum_{W \in \mathcal{W}} S_W f_1, f_2 \right\rangle,$$

$$(4.15b) \quad II = - \left\langle \sum_{W \in \mathcal{W}} S_W (\text{av}_W [f_1] \mathbf{1}_W), f_2 \right\rangle,$$

$$(4.15c) \quad III = \left\langle \sum_{W \in \mathcal{W}} (S - S_W) b_{1,W}, f_2 \right\rangle.$$

The first term (4.15a) is handled by the induction hypothesis. In view of (4.8), each W that contributes a non-zero summand in (4.15a) is a proper subcube of Q_0 . Therefore we have $L(W) - N_1 \leq n - 1$ and thus by the induction hypothesis,

$$|\langle S_W f_1, f_2 \rangle| \leq U(n-1) \mathfrak{G}_W(f_1 \mathbf{1}_W, f_2).$$

That is, given any $\epsilon > 0$ there is a γ -sparse collection $\mathfrak{S}_{W,\epsilon}$ of subcubes of W such that

$$(4.16) \quad |\langle S_W f_1, f_2 \rangle| \leq (U(n-1) + \epsilon) \sum_{Q \in \mathfrak{S}_{W,\epsilon}} |Q| \langle f_1 \rangle_{Q,p} \langle f_2 \rangle_{3Q,q'}.$$

Because of the γ -sparsity there are measurable subsets E_Q of Q with $|E_Q| \geq \gamma|Q|$ so that the E_Q with $Q \in \mathfrak{S}_{W,\epsilon}$ are disjoint. We combine the various collections $\mathfrak{S}_{W,\epsilon}$ and form the collection \mathfrak{S}_ϵ of cubes

$$\mathfrak{S}_\epsilon := \{Q_0\} \cup \bigcup_{\substack{W \in \mathcal{W} \\ W \subset Q_0}} \mathfrak{S}_{W,\epsilon}.$$

Observe that the collection \mathfrak{S}_ϵ is indeed γ -sparse: as defined above, $E_{Q_0} = Q_0 \setminus \Omega$, and therefore $|E_{Q_0}| > \gamma|Q_0|$. By disjointness of the $W \subset Q_0$ the sets E_Q , for $Q \in \mathfrak{S}_\epsilon$ are disjoint; moreover they satisfy $|E_Q| \geq \gamma|Q|$.

We consider the term II in (4.15b). Here we will use that the restricted strong type (q, q) condition (1.7b) implies $\|S_W\|_{L_{B_1}^{q,1} \rightarrow L_{B_2}^q} \leq A(q)$, and

$$\|\text{av}_W [f_1] \mathbf{1}_W\|_{L_{B_1}^{q,1}} \lesssim |\text{av}_W [f_1]|_{B_1} |W|^{1/q} \lesssim_q \langle f_1 \rangle_{W,p} |W|^{1/q}$$

for $q < \infty$. Together with the disjointness of the cubes W and (4.9a), we get

$$\begin{aligned}
(4.17) \quad |II| &\leq \sum_{W \in \mathcal{W}} \|S_W(\text{av}_W[f_1] \mathbb{1}_W)\|_{L_{B_2}^q} \|f_2 \mathbb{1}_{3W}\|_{L_{B_2^*}^{q'}} \\
&\lesssim_q \sum_{W \in \mathcal{W}} \langle f_1 \rangle_{W,p} A(q) |W|^{1/q} (3^d |W|)^{1/q'} \langle f_2 \rangle_{3W,q'} \\
&\lesssim_{d,q,\gamma} A(q) \sum_{W \in \mathcal{W}} |W| \langle f_1 \rangle_{Q_0,p} \langle f_2 \rangle_{3Q_0,q'} \\
&\lesssim_{d,q,\gamma} A(q) |Q_0| \langle f_1 \rangle_{Q_0,p} \langle f_2 \rangle_{3Q_0,q'}.
\end{aligned}$$

Regarding the third term in (4.15c) we claim that

$$(4.18) \quad |III| \lesssim_{p,q,\varepsilon,d,\gamma} (A(p) + A_\circ(p,q) \log(2 + \frac{B}{A_\circ(p,q)})) |Q_0| \langle f_1 \rangle_{Q_0,p} \langle f_2 \rangle_{3Q_0,q'}.$$

Taking (4.18) for granted we obtain from (4.14), (4.17), (4.18) and (4.16) that there exist constants $C_1(d, q, \gamma)$ and $C_2(p, q, \varepsilon, d, \gamma)$ such that

$$\begin{aligned}
|\langle Sf_1, f_2 \rangle| &\leq C_1(d, q, \gamma) A(q) |Q_0| \langle f_1 \rangle_{Q_0,p} \langle f_2 \rangle_{3Q_0,q'} \\
&\quad + C_2(p, q, \varepsilon, d, \gamma) (A(p) + A_\circ(p,q) \log(2 + \frac{B}{A_\circ(p,q)})) |Q_0| \langle f_1 \rangle_{Q_0,p} \langle f_2 \rangle_{3Q_0,q'} \\
&\quad + \sum_{\substack{W \in \mathcal{W} \\ W \subset Q_0}} \sum_{Q \in \mathfrak{S}_{W,\varepsilon}} (U(n-1) + \varepsilon) |Q| \langle f_1 \rangle_{Q,p} \langle f_2 \rangle_{3Q,q'}.
\end{aligned}$$

This implies

$$\begin{aligned}
|\langle Sf_1, f_2 \rangle| &\leq \max\{U(n-1) + \varepsilon, c_{p,q,\varepsilon,d,\gamma} \mathcal{C}\} \sum_{Q \in \mathfrak{S}_\varepsilon} |Q| \langle f_1 \rangle_{Q,p} \langle f_2 \rangle_{3Q,q'} \\
&\leq \max\{U(n-1) + \varepsilon, c_{p,q,\varepsilon,d,\gamma} \mathcal{C}\} \mathfrak{G}_{Q_0}(f_1, f_2)
\end{aligned}$$

for all $\varepsilon > 0$. Letting $\varepsilon \rightarrow 0$ implies Claim 4.3. We are now coming to the most technical part of the proof, the estimation of the error term III in (4.15c) for which we have to establish the claim (4.18).

PROOF OF (4.18). We now use the Calderón–Zygmund decomposition for $f_2 = g_2 + \sum_{W \in \mathcal{W}} b_{2,W}$ as described above. We split $III = \sum_{i=1}^4 III_i$ where

$$(4.19a) \quad III_1 = \left\langle \sum_{W \in \mathcal{W}} S b_{1,W}, g_2 \right\rangle,$$

$$(4.19b) \quad III_2 = - \sum_{W \in \mathcal{W}} \langle S_W b_{1,W}, g_2 \rangle,$$

$$(4.19c) \quad III_3 = \sum_{N_1 \leq j \leq N_2} \sum_{\substack{W \in \mathcal{W}: \\ L(W) < j}} \sum_{\substack{W' \in \mathcal{W}: \\ L(W') \geq j}} \langle T_j b_{1,W}, b_{2,W'} \rangle,$$

$$(4.19d) \quad III_4 = \sum_{N_1 \leq j \leq N_2} \sum_{\substack{W \in \mathcal{W}: \\ L(W) < j}} \sum_{\substack{W' \in \mathcal{W}: \\ L(W') < j}} \langle T_j b_{1,W}, b_{2,W'} \rangle.$$

We use the weak type (p, p) condition (1.7a) that S maps $L_{B_1}^p$ to $L_{B_2}^{p,\infty}$, which is isometrically embedded in $L_{B_2^{**}}^{p,\infty}$. As $p > 1$, we obtain using (4.11) for $r_2 = p' < \infty$

$$\begin{aligned}
|III_1| &\leq \left\| S \left[\sum_{W \in \mathcal{W}} b_{1,W} \right] \right\|_{L_{B_2^{**}}^{p,\infty}} \|g_2\|_{L_{B_2^*}^{p',1}} \\
&\lesssim_{d,p,\gamma} \|S\|_{L_{B_1}^p \rightarrow L_{B_2}^{p,\infty}} \left\| \sum_{W \in \mathcal{W}} b_{1,W} \right\|_{L_{B_1}^p} |Q_0|^{1/p'} \langle f_2 \rangle_{3Q_0, q'}.
\end{aligned}$$

By (4.12) for $r = p$ we obtain

$$|III_1| \lesssim_{d,p,\gamma} A(p) |Q_0| \langle f_1 \rangle_{Q_0, p} \langle f_2 \rangle_{3Q_0, q'}.$$

Likewise, the weak type (p, p) condition (1.7a) implies $L_{B_1}^p \rightarrow L_{B_2}^{p,\infty}$ boundedness of S_W . Using this and $\text{supp}(S_W b_{1,W}) \subset 3W$, (4.9a), (4.10), and $p > 1$ we estimate,

$$\begin{aligned}
|III_2| &\leq \sum_{W \in \mathcal{W}} \|S_W b_{1,W}\|_{L_{B_2^{**}}^{p,\infty}} \|g_2 \mathbf{1}_{3W}\|_{L_{B_2^*}^{p',1}} \\
&\leq A(p) \sum_{W \in \mathcal{W}} \|b_{1,W}\|_{L_{B_1}^p} \|g_2\|_{L_{B_2^*}^\infty} \|\mathbf{1}_{3W}\|_{L_{B_2^*}^{p',1}} \\
&\lesssim_{d,p,\gamma} A(p) \sum_{W \in \mathcal{W}} |W|^{1/p} \langle f_1 \rangle_{W,p} \|g_2\|_{L_{B_2^*}^\infty} |W|^{1/p'} \\
&\lesssim_{d,\gamma} A(p) \sum_{W \in \mathcal{W}} |W| \langle f_1 \rangle_{Q_0, p} \langle f_2 \rangle_{3Q_0, q'}.
\end{aligned}$$

and hence, by the disjointness of the cubes W ,

$$|III_2| \lesssim_{d,p,\gamma} A(p) |Q_0| \langle f_1 \rangle_{Q_0, p} \langle f_2 \rangle_{3Q_0, q'}.$$

Next we estimate III_3 and first show that

$$(4.20) \quad \left. \begin{array}{l} \langle T_j b_{1,W}, b_{2,W'} \rangle \neq 0 \\ L(W) < j \leq L(W') \end{array} \right\} \implies j \leq L(W') \leq L(W) + 2 \leq j + 2.$$

To see (4.20) first observe that $T_j b_{1,W}$ is supported on a cube R_W centered at x_W with side length $2^{j+1} + 2^{L(W)}$. Hence, if $\langle T_j b_{1,W}, b_{2,W'} \rangle \neq 0$, then we get from (4.7) and the triangle inequality

$$\begin{aligned}
5 \text{diam}(W') &\leq \text{dist}(W', \Omega^{\mathfrak{b}}) \leq \text{diam}(W') + \text{diam}(R_W) + \text{dist}(W, \Omega^{\mathfrak{b}}) \\
&\leq \text{diam}(W') + (2^{j+1} + 2^{L(W)})\sqrt{d} + 12\sqrt{d}2^{L(W)}.
\end{aligned}$$

Hence since $L(W) < j \leq L(W')$ we get $2^{L(W')+1} \leq 13 \cdot 2^{L(W)}$ which gives (4.20). Also, with these specifications $W \subset 3W'$ if $\langle T_j b_{1,W}, b_{2,W'} \rangle \neq 0$. By the single scale (p, q) condition (1.8),

$$(4.21) \quad \|T_j\|_{L^p \rightarrow L^q} \leq 2^{-jd(1/p-1/q)} A_o(p, q).$$

Hence using Hölder's inequality, (4.21) and (4.9a) we get

$$\begin{aligned}
|III_3| &\leq \sum_{N_1 \leq j \leq N_2} \sum_{\substack{W' \in \mathcal{W}: \\ j \leq L(W') \leq j+2}} \sum_{\substack{W \in \mathcal{W}: \\ L(W')-2 \leq L(W) \leq j \\ W \subset 3W'}} |\langle T_j b_{1,W}, b_{2,W'} \rangle| \\
&\leq A_o(p, q) \sum_{N_1 \leq j \leq N_2} 2^{-jd(1/p-1/q)} \sum_{\substack{W, W' \in \mathcal{W}: W \subset 3W' \\ j \leq L(W') \leq j+2 \\ L(W')-2 \leq L(W) \leq j}} \|b_{1,W}\|_{L_{B_1}^p} \|b_{2,W'}\|_{L_{B_2^*}^{q'}} \\
&\lesssim_{d,\gamma} A_o(p, q) \langle f_1 \rangle_{Q_{0,p}} \langle f_2 \rangle_{3Q_{0,q'}} \\
&\quad \times \sum_{N_1 \leq j \leq N_2} \sum_{\substack{W, W' \in \mathcal{W}: W \subset 3W' \\ j \leq L(W') \leq j+2 \\ L(W')-2 \leq L(W) \leq j}} 2^{-jd(1/p-1/q)} |W|^{1/p} |W'|^{1-1/q} \\
&\lesssim_{d,\gamma} A_o(p, q) \langle f_1 \rangle_{Q_{0,p}} \langle f_2 \rangle_{3Q_{0,q'}} \sum_{W' \in \mathcal{W}} |W'|
\end{aligned}$$

and thus, by disjointness of the W' ,

$$|III_3| \lesssim_{d,\gamma} A_o(p, q) \langle f_1 \rangle_{Q_{0,p}} \langle f_2 \rangle_{3Q_{0,q'}} |Q_0|.$$

Finally, consider the term

$$(4.22) \quad III_4 = \sum_{N_1 \leq j \leq N_2} \sum_{\substack{(W, W') \in \mathcal{W} \times \mathcal{W} \\ L(W) < j \\ L(W') < j}} \langle T_j b_{1,W}, b_{2,W'} \rangle.$$

Let $\varepsilon' > 0$ such that

$$(4.23) \quad \varepsilon' < \min\{1/p, 1/q', \varepsilon\}$$

and let ℓ be a positive integer so that

$$(4.24) \quad \ell < \frac{100}{\varepsilon'} \log_2 \left(2 + \frac{B}{A_o(p, q)} \right) \leq \ell + 1.$$

We split

$$\mathcal{V}_j = (-\infty, j)^2 \cap \mathbb{Z}^2 = \mathcal{V}_{j,1} \cup \mathcal{V}_{j,2} \cup \mathcal{V}_{j,3}$$

into three regions putting

$$\mathcal{V}_{j,1} = \{(L_1, L_2) \in \mathcal{V}_j : j - \ell \leq L_1 < j, j - \ell \leq L_2 < j\},$$

$$\mathcal{V}_{j,2} = \{(L_1, L_2) \in \mathcal{V}_j \setminus \mathcal{V}_{j,1} : L_1 \leq L_2\},$$

$$\mathcal{V}_{j,3} = \{(L_1, L_2) \in \mathcal{V}_j \setminus \mathcal{V}_{j,1} : L_1 > L_2\}.$$

Then $III_4 = \sum_{i=1}^3 IV_i$ where for $i = 1, 2, 3$,

$$(4.25) \quad IV_i = \sum_{N_1 \leq j \leq N_2} \sum_{\substack{W, W' \in \mathcal{W} \\ (L(W), L(W')) \in \mathcal{V}_{j,i}}} \langle T_j b_{1,W}, b_{2,W'} \rangle.$$

Let \mathfrak{R}_j be the collection of dyadic subcubes of Q_0 of side length 2^j . To estimate IV_1 we tile Q_0 into such cubes and write

$$(4.26) \quad IV_1 = \sum_{N_1 \leq j \leq N_2} \sum_{R \in \mathfrak{R}_j} \left\langle \sum_{\substack{W \subset R \\ j-\ell \leq L(W) < j}} T_j b_{1,W}, \sum_{j-\ell \leq L(W') < j} b_{2,W'} \mathbb{1}_{3R} \right\rangle.$$

By Hölder's inequality and the single scale (p, q) condition (1.8) (in the form of (4.21)) we get

$$\begin{aligned}
|IV_1| &\leq A_o(p, q) \sum_{N_1 \leq j \leq N_2} 2^{-jd(1/p-1/q)} \\
&\quad \times \sum_{R \in \mathfrak{R}_j} \left\| \sum_{\substack{W \subset R \\ j-\ell \leq L(W) < j}} b_{1,W} \right\|_{L^p_{B_1}} \left\| \sum_{j-\ell \leq L(W') < j} b_{2,W'} \mathbb{1}_{3R} \right\|_{L^{q'}_{B_2^*}} \\
&\leq A_o(p, q) \sum_{N_1 \leq j \leq N_2} \sum_{R \in \mathfrak{R}_j} |R|^{-(1/p-1/q)} \\
&\quad \times \left(\sum_{\substack{W \subset R \\ j-\ell \leq L(W) < j}} \|b_{1,W}\|_{L^p_{B_1}} \right)^{1/p} \left(\sum_{\substack{W' \subset 3R \\ j-\ell \leq L(W') < j}} \|b_{2,W'}\|_{L^{q'}_{B_2^*}} \right)^{1/q'}
\end{aligned}$$

and using (4.9a) this expression is bounded by $C_{d,\gamma} A_o(p, q)$ times

$$\begin{aligned}
&\sum_{N_1 \leq j \leq N_2} \langle f_1 \rangle_{Q_0,p} \langle f_2 \rangle_{3Q_0,q'} \sum_{R \in \mathfrak{R}_j} |R|^{-(1/p-1/q)} \\
&\quad \times \left(\sum_{\substack{W \subset R \\ j-\ell \leq L(W) < j}} |W| \right)^{1/p} \left(\sum_{\substack{W' \subset 3R \\ j-\ell \leq L(W') < j}} |W'| \right)^{1/q'} \\
&\lesssim_{d,\gamma} \sum_{N_1 \leq j \leq N_2} \langle f_1 \rangle_{Q_0,p} \langle f_2 \rangle_{3Q_0,q'} \\
&\quad \times \sum_{R \in \mathfrak{R}_j} |R|^{-(1/p-1/q)} \left(\sum_{\substack{W \subset 3R \\ j-\ell \leq L(W) < j}} |W| \right)^{1/p+1-1/q}.
\end{aligned}$$

Using $p \leq q$ and the disjointness of the W we see that the last expression is dominated by a constant $\tilde{C}_{d,\gamma,p,q}$ times

$$\begin{aligned}
&\langle f_1 \rangle_{Q_0,p} \langle f_2 \rangle_{3Q_0,q'} \sum_{N_1 \leq j \leq N_2} \sum_{R \in \mathfrak{R}_j} \sum_{\substack{W \subset 3R \\ j-\ell \leq L(W) < j}} |W| \\
&\leq 3^d \langle f_1 \rangle_{Q_0,p} \langle f_2 \rangle_{3Q_0,q'} \sum_{N_1 \leq j \leq N_2} \sum_{R \in \mathfrak{R}_j} \sum_{\substack{W \subset R \\ j-\ell \leq L(W) < j}} |W| \\
&\lesssim_d \langle f_1 \rangle_{Q_0,p} \langle f_2 \rangle_{3Q_0,q'} \sum_{W \in \mathcal{W}} |W| \sum_{\substack{j: N_1 \leq j \leq N_2 \\ L(W) < j \leq L(W) + \ell}} 1 \\
&\lesssim_d \ell |Q_0| \langle f_1 \rangle_{Q_0,p} \langle f_2 \rangle_{3Q_0,q'}.
\end{aligned}$$

Thus, using the definition of ℓ in (4.24) we get

$$(4.27) \quad |IV_1| \lesssim_{d,\gamma,\varepsilon,p,q} A_o(p, q) \log \left(2 + \frac{B}{A_o(p, q)} \right) |Q_0| \langle f_1 \rangle_{Q_0,p} \langle f_2 \rangle_{3Q_0,q'}.$$

We now turn to the terms IV_2 , IV_3 and claim that

$$(4.28) \quad |IV_2| + |IV_3| \lesssim_{d,\gamma,p,q,\varepsilon} A_o(p, q) |Q_0| \langle f_1 \rangle_{Q_0,p} \langle f_2 \rangle_{3Q_0,q'}.$$

We first note that by the single scale ε -regularity conditions (1.9a), (1.9b), and Corollary 3.5,

$$(4.29a) \quad \|T_j(I - \mathbb{E}_{s_1-j})\|_{L_{B_1}^p \rightarrow L_{B_2}^q} \lesssim_\varepsilon B 2^{-jd(\frac{1}{p}-\frac{1}{q})} 2^{-\varepsilon' s_1},$$

$$(4.29b) \quad \|T_j^*(I - \mathbb{E}_{s_2-j})\|_{L_{B_2^*}^{q'} \rightarrow L_{B_1^*}^{p'}} \lesssim_\varepsilon B 2^{-jd(\frac{1}{p}-\frac{1}{q})} 2^{-\varepsilon' s_2}.$$

where ε' is as in (4.23).

Write, with \mathfrak{R}_j as in (4.26),

$$(4.30) \quad IV_2 = \sum_{N_1 \leq j \leq N_2} \sum_{R \in \mathfrak{R}_j} \sum_{s_2=1}^{\infty} \sum_{s_1=\max\{s_2, \ell+1\}}^{\infty} \left\langle \sum_{\substack{W \subset R \\ L(W)=j-s_1}} T_j b_{1,W}, \sum_{\substack{W' \subset 3R \\ L(W')=j-s_2}} b_{2,W'} \mathbf{1}_{3R} \right\rangle.$$

Note that for $L(W) = j - s_1$, we have $b_{1,W} = (I - \mathbb{E}_{s_1-j})f_{1,W}$. By Hölder's inequality and (4.29a) we get for $R \in \mathfrak{R}_j$,

$$\begin{aligned} & \left| \left\langle \sum_{\substack{W \subset R \\ L(W)=j-s_1}} T_j b_{1,W}, \sum_{\substack{W' \subset 3R \\ L(W')=j-s_2}} b_{2,W'} \mathbf{1}_{3R} \right\rangle \right| \\ & \leq \left\| T_j(I - \mathbb{E}_{s_1-j}) \sum_{\substack{W \subset R \\ L(W)=j-s_1}} f_{1,W} \right\|_{L_{B_2}^q} \left\| \sum_{\substack{W' \subset 3R \\ L(W')=j-s_2}} b_{2,W'} \right\|_{L_{B_2^*}^{q'}} \\ & \lesssim_\varepsilon B 2^{-\varepsilon' s_1} |R|^{-\left(\frac{1}{p}-\frac{1}{q}\right)} \left(\sum_{\substack{W \subset R \\ L(W)=j-s_1}} \|f_{1,W}\|_{L_{B_1}^p}^p \right)^{1/p} \left(\sum_{\substack{W' \subset 3R \\ L(W')=j-s_2}} \|b_{2,W'}\|_{L_{B_2^*}^{q'}}^{q'} \right)^{1/q'}. \end{aligned}$$

In the above formula for IV_2 we interchange the j -sum and the (s_1, s_2) -sums, write $j = s_1 n + i$ with $i = 1, \dots, s_1$ and estimate (invoking (4.9a) again)

$$\begin{aligned} |IV_2| & \lesssim_\varepsilon \sum_{s_2=1}^{\infty} \sum_{s_1=\max\{s_2, \ell+1\}}^{\infty} B 2^{-\varepsilon' s_1} \sum_{i=1}^{s_1} \sum_{\substack{n \in \mathbb{Z} \\ s_1 n + i \in [N_1, N_2]}} \sum_{R \in \mathfrak{R}_{s_1 n + i}} |R|^{-\left(\frac{1}{p}-\frac{1}{q}\right)} \\ & \quad \times \left(\sum_{\substack{W \subset R \\ L(W)=s_1 n + i - s_1}} \|f_{1,W}\|_{L_{B_1}^p}^p \right)^{\frac{1}{p}} \left(\sum_{\substack{W' \subset 3R \\ L(W')=s_1 n + i - s_2}} \|b_{2,W'}\|_{L_{B_2^*}^{q'}}^{q'} \right)^{\frac{1}{q'}} \\ & \lesssim_{d, \gamma} \sum_{s_2=1}^{\infty} \sum_{s_1=\max\{s_2, \ell+1\}}^{\infty} B 2^{-\varepsilon' s_1} \\ & \quad \times \sum_{i=1}^{s_1} \sum_{\substack{n \in \mathbb{Z} \\ s_1 n + i \in [N_1, N_2]}} \sum_{R \in \mathfrak{R}_{s_1 n + i}} \langle f_1 \rangle_{Q_{0,p}} \langle f_2 \rangle_{3Q_{0,q'}} \Gamma(R, n, i), \end{aligned}$$

where

$$\Gamma(R, n, i) = |R|^{-\left(\frac{1}{p}-\frac{1}{q}\right)} \left(\sum_{\substack{W \subset R \\ L(W)=s_1 n + i - s_1}} |W| \right)^{\frac{1}{p}} \left(\sum_{\substack{W' \subset 3R \\ L(W')=s_1 n + i - s_2}} |W'| \right)^{1-\frac{1}{q}}.$$

We crudely estimate, using $p \leq q$,

$$\begin{aligned} \Gamma(R, n, i) &\leq |R|^{-(1/p-1/q)} \left(\sum_{\nu=s_1n+i-s_1}^{s_1n+i-s_2} \sum_{\substack{W \subset 3R \\ L(W)=\nu}} |W| \right)^{1/p+1-1/q} \\ &\leq 3^{d(1/p-1/q)} \sum_{\nu=s_1n+i-s_1}^{s_1n+i-s_2} \sum_{\substack{W \subset 3R \\ L(W)=\nu}} |W|. \end{aligned}$$

For fixed $W \in \mathcal{W}$ consider the set of all triples (R, n, i) such that $s_1n + i - s_1 \leq L(W) \leq s_1n + i - s_2$, $R \in \mathfrak{R}_{s_1n+i}$ and $W \subset 3R$, and observe that the cardinality of this set is bounded above by $3^d(s_1 - s_2 + 1)$. Combining this with the above estimates and summing over $W \in \mathcal{W}$ we obtain the bound

$$|IV_2| \lesssim_{d,\gamma,\varepsilon} \langle f_1 \rangle_{Q_0,p} \langle f_2 \rangle_{3Q_0,q'} |Q_0| \sum_{s_2=1}^{\infty} \sum_{s_1=\max\{s_2,\ell+1\}}^{\infty} B2^{-\varepsilon' s_1} (s_1 - s_2 + 1)$$

and the double sum is bounded by

$$\begin{aligned} C_{\varepsilon,p,q} \left(\sum_{s_2=1}^{\ell+1} B2^{-\varepsilon' \ell} (\ell + 1) + \sum_{s_2=\ell+1}^{\infty} B2^{-\varepsilon' s_2} \right) \\ \lesssim_{\varepsilon,p,q} B2^{-\varepsilon' \ell} (\ell + 1)^2 \lesssim_{\varepsilon,p,q} B2^{-\varepsilon' \ell/2} \lesssim_{\varepsilon,p,q} A_o(p, q) \end{aligned}$$

by the definition of ℓ in (4.24). This establishes (4.28) for the term $|IV_2|$.

The estimation of IV_3 is very similar. We may write

$$(4.31) \quad IV_3 = \sum_{N_1 \leq j \leq N_2} \sum_{R \in \mathfrak{R}_j} \sum_{s_1=1}^{\infty} \sum_{s_2=\max\{s_1+1,\ell+1\}}^{\infty} \left\langle \sum_{\substack{W \in \mathcal{W}: \\ W \subset R \\ L(W)=j-s_1}} b_{1,W} \mathbf{1}_R, \sum_{\substack{W' \in \mathcal{W}: \\ L(W')=j-s_2}} T_j^*[b_{2,W'} \mathbf{1}_{3R}] \right\rangle$$

By Hölder's inequality and (4.29b) we get for $R \in \mathfrak{R}_j$

$$\begin{aligned} \left| \left\langle \sum_{\substack{W \subset R \\ L(W)=j-s_1}} b_{1,W}, \sum_{L(W')=j-s_2} T_j^*[b_{2,W'} \mathbf{1}_{3R}] \right\rangle \right| \\ \lesssim_{\varepsilon} B2^{-\varepsilon' s_2} |R|^{-(\frac{1}{p}-\frac{1}{q})} \left(\sum_{\substack{W \subset R \\ L(W)=j-s_1}} \|b_{1,W}\|_{L^p_{B_1}} \right)^{1/p} \left(\sum_{\substack{W' \subset 3R \\ L(W')=j-s_2}} \|f_{2,W'}\|_{L^{q'}_{B_2^*}} \right)^{1/q'} \end{aligned}$$

and from here on the argument is analogous to the treatment of the term IV_2 . \square

REMARK. It is instructive to observe that the term III_4 can be treated more crudely if one does not aim to obtain the constant $A_o(p, q) \log(2 + \frac{B}{A_o(p, q)})$ in (1.11). More precisely, one simply splits $(-\infty, j)^2 \cap \mathbb{Z}^2$ into two regions $\tilde{\mathcal{V}}_{j,2}$ and $\tilde{\mathcal{V}}_{j,3}$, where

$$\tilde{\mathcal{V}}_{j,2} = \{(L_1, L_2) : L_1 \leq L_2 < j\} \quad \text{and} \quad \tilde{\mathcal{V}}_{j,3} = \{(L_1, L_2) : j > L_1 > L_2\}.$$

Then split $III_4 = \sum_{i=2}^3 IV_i$, where IV_i are as in (4.25) but with $\mathcal{V}_{j,i}$ replaced by $\tilde{\mathcal{V}}_{j,i}$. One then considers the sum in s_1 in (4.30) to start directly from s_2 , and the

sum in s_2 in (4.31) to start directly from $s_1 + 1$. Using the same arguments, one obtains

$$|IV_2| + |IV_3| \lesssim_{d,\gamma,p,q,\varepsilon} B |Q_0| \langle f_1 \rangle_{Q_{0,p}} \langle f_2 \rangle_{3Q_{0,q'}}$$

instead of (4.28). Note that, as the term IV_1 does not appear in this case (see the bound (4.27)), this yields sparse domination with the constant \mathcal{C} in (1.11) replaced by $A(p) + A(q) + A_\circ(p, q) + B$.

Maximal operators, square functions and long variations

In this section we show that Corollary 1.2 yields sparse domination results for maximal functions, ℓ^r -valued variants, r -variation norm operators and maximal and variational truncations of sums of operators. An application of Theorem 1.3 also yields necessary conditions for our sparse domination inequalities. We will formally state necessary conditions only for maximal functions and ℓ^r -valued functions (Theorem 5.1) and leave to the reader the analogous formulations of those conditions for r -variation norm operators (Theorem 5.2), maximal truncations (Theorem 5.3) and variational truncations (Theorem 5.4).

5.1. Maximal functions and ℓ^r -variants

Given a family of operators $\{T_j\}_{j \in \mathbb{Z}}$ in Op_{B_1, B_2} , consider the operators

$$(5.1) \quad S_r T f(x) = \left(\sum_{j \in \mathbb{Z}} |T_j f(x)|_{B_2}^r \right)^{1/r}$$

when $1 \leq r < \infty$ and also the maximal operator

$$(5.2) \quad S_\infty T f(x) = \sup_{j \in \mathbb{Z}} |T_j f(x)|_{B_2}.$$

THEOREM 5.1. *Let $1 < p \leq q < \infty$ and $1 \leq r \leq \infty$. Let $\{T_j\}_{j \in \mathbb{Z}}$ be a family of operators in Op_{B_1, B_2} satisfying (1.6).*

(i) *Suppose that the inequalities*

$$(5.3) \quad \|S_r T f\|_{L^{p, \infty}} \leq A(p) \|f\|_{L_{B_1}^p} \quad \text{and} \quad \|S_r T f\|_{L^q} \leq A(q) \|f\|_{L_{B_1}^{q, 1}}$$

hold for all $f \in \mathbb{S}_{B_1}$. Moreover, assume that the rescaled operators $\text{Dil}_{2^j} T_j$ satisfy the single scale (p, q) condition (1.8) and single scale ε -regularity conditions (1.9a) and (1.9b). Let \mathcal{C} be as in (1.11). Then for all $f \in \mathbb{S}_{B_1}$ and all \mathbb{R} -valued nonnegative measurable functions ω ,

$$(5.4) \quad \langle S_r T f, \omega \rangle \lesssim \mathcal{C} \Lambda_{p, q}^*(f, \omega).$$

(ii) *In addition, assume $1 < p < q < \infty$. If the family of operators $\{T_j\}_{j \in \mathbb{Z}}$ satisfies $T_j : \mathbb{S}_{B_1} \rightarrow L_{B_2, \text{loc}}^1$ and the strengthened support condition (1.14), then the condition*

$$\|S_r T\|_{L_{B_1}^p \rightarrow L^{p, \infty}} + \|S_r T\|_{L_{B_1}^{q, 1} \rightarrow L^q} + \sup_{j \in \mathbb{Z}} \|\text{Dil}_{2^j} T_j\|_{L_{B_1}^p \rightarrow L_{B_2}^q} < \infty$$

is necessary for the conclusion (5.4) to hold.

PROOF OF THEOREM 5.1. We begin with the proof for $1 \leq r < \infty$.

Let $\delta_{kk} = 1$ and $\delta_{jk} = 0$ if $j \neq k$. Let $N_1 \leq N_2$ be integers, and for each integer $j \in [N_1, N_2]$, we define the operator H_j sending $L^p_{B_1}$ functions to $\ell^r_{B_2}$ -valued functions by

$$(5.5) \quad H_j f(x, k) = \begin{cases} \delta_{jk} T_j f(x) & \text{if } N_1 \leq k \leq N_2, \\ 0 & \text{if } k \notin [N_1, N_2]. \end{cases}$$

We note that

$$(5.6) \quad \left(\sum_{j=N_1}^{N_2} |T_j f(x)|_{B_2}^r \right)^{1/r} = \left(\sum_{k=-\infty}^{\infty} \left| \sum_{j=N_1}^{N_2} H_j f(x, k) \right|_{B_2}^r \right)^{1/r}.$$

By (5.3) we have

$$\left\| \sum_{j=N_1}^{N_2} H_j \right\|_{L^p_{B_1} \rightarrow L^{p, \infty}(\ell^r_{B_2})} \leq A(p), \quad \left\| \sum_{j=N_1}^{N_2} H_j \right\|_{L^{q, 1}_{B_1} \rightarrow L^q(\ell^r_{B_2})} \leq A(q),$$

where we write $L^{p, \infty}(\ell^r_{B_2})$ to denote $L^{p, \infty}_{\ell^r_{B_2}}$. The adjoint of H_j , acting on $\ell^{r'}_{B_2^*}$ -valued functions g , is given by

$$H_j^* g(x) = \sum_{k=N_1}^{N_2} \delta_{jk} T_j^* g_k(x).$$

The assumptions on $\text{Dil}_{2^j} T_j$ can be rewritten as

$$\sup_{j \in \mathbb{Z}} \|\text{Dil}_{2^j} H_j\|_{L^p_{B_1} \rightarrow L^q(\ell^r_{B_2})} \leq A_0(p, q)$$

and

$$\begin{aligned} \sup_{|h| \leq 1} |h|^{-\varepsilon} \sup_{j \in \mathbb{Z}} \|(\text{Dil}_{2^j} H_j) \circ \Delta_h\|_{L^p_{B_1} \rightarrow L^q(\ell^r_{B_2})} &\leq B \\ \sup_{|h| \leq 1} |h|^{-\varepsilon} \sup_{j \in \mathbb{Z}} \|(\text{Dil}_{2^j} H_j^*) \circ \Delta_h\|_{L^{q'}(\ell^{r'}_{B_2^*}) \rightarrow L^{p'}_{B_1^*}} &\leq B. \end{aligned}$$

By Corollary 1.2 applied to the sequence $\{H_j\}_{j \in \mathbb{Z}}$ in $\text{Op}_{B_1, \ell^r_{B_2}}$, we get the conclusion

$$\int_{\mathbb{R}^d} \left(\sum_{k=-\infty}^{\infty} \left| \sum_{j=N_1}^{N_2} H_j f(x, k) \right|_{B_2}^r \right)^{1/r} \omega(x) dx \lesssim C \Lambda_{p, q'}^*(f, \omega),$$

which by (5.6) implies

$$\int_{\mathbb{R}^d} \left(\sum_{j=N_1}^{N_2} |T_j f(x)|_{B_2}^r \right)^{1/r} \omega(x) dx \lesssim C \Lambda_{p, q'}^*(f, \omega).$$

We apply the monotone convergence theorem to let $N_1 \rightarrow -\infty$ and $N_2 \rightarrow \infty$ and obtain the desired conclusion. This is possible since the implicit constant in the conclusion of Corollary 1.2 does not depend on B_1, B_2 .

The proof for $r = \infty$ is essentially the same, with notional changes. Since $H_j f(\cdot, k) = 0$ when $k \notin [N_1, N_2]$, we can work with $\ell^\infty_{B_2}$ over the finite set $\mathbb{Z} \cap [N_1, N_2]$. Then there are no complications with the dual space, which is $\ell^1_{B_2^*}$ over $\mathbb{Z} \cap [N_1, N_2]$.

For part (ii) one uses Theorem 1.3 in conjunction with (5.6) and immediately arrives at the desired conclusion, via the monotone convergence theorem. \square

5.2. Variation norms

We now turn to the variation norms $V_{B_2}^r \equiv V_{B_2}^r(\mathbb{Z})$ defined on B_2 -valued functions of the integers $n \mapsto a(n)$. Let $|a|_{V_{B_2}^\infty} = |a|_{L_{B_2}^\infty}$ and, for $1 \leq r < \infty$,

$$(5.7) \quad |a|_{V_{B_2}^r} = \sup_{n_1 < \dots < n_M} |a(n_1)|_{B_2} + \left(\sum_{\nu=1}^{M-1} |a(n_{\nu+1}) - a(n_\nu)|_{B_2}^r \right)^{1/r}$$

where the supremum is taken over all positive integers M and all finite increasing sequences of integers $n_1 < \dots < n_M$. Similarly, if $I_{N_1, N_2} = [N_1, N_2] \cap \mathbb{Z}$ we define the $V_{B_2}^r(I_{N_1, N_2})$ norm on functions on I_{N_1, N_2} in the same way, restricting n_1, \dots, n_M to I_{N_1, N_2} .

Given a sequence $T = \{T_j\}_{j \in \mathbb{Z}}$ in Op_{B_1, B_2} we define $\mathcal{V}^r T f(x)$ to be the $V_{B_2}^r$ norm of the sequence $j \mapsto T_j f(x)$. The L^p norm of $\mathcal{V}^r T f$ is just the $L^p(V_{B_2}^r)$ norm of the sequence $\{T_j f\}_{j \in \mathbb{Z}}$. We define $\mathcal{V}_{N_1, N_2}^r T f(x)$ to be the $V_{B_2}^r$ norm of the sequence $j \mapsto \mathbf{1}_{I_{N_1, N_2}}(j) T_j f(x)$.

The proof of the following theorem is almost identical to that of Theorem 5.1.

THEOREM 5.2. *Let $1 < p \leq q < \infty$ and $1 \leq r \leq \infty$. Let $\{T_j\}_{j \in \mathbb{Z}}$ be a family of operators in Op_{B_1, B_2} satisfying (1.6). Suppose that the inequalities*

$$(5.8) \quad \|\mathcal{V}^r T f\|_{L^{p, \infty}} \leq A(p) \|f\|_{L_{B_1}^p} \quad \text{and} \quad \|\mathcal{V}^r T f\|_{L^q} \leq A(q) \|f\|_{L_{B_1}^{q, 1}}$$

hold for all $f \in S_{B_1}$. Moreover, assume that the rescaled operators $\text{Dil}_{2^j} T_j$ satisfy the single scale (p, q) condition (1.8) and single scale ε -regularity conditions (1.9a) and (1.9b). Let \mathcal{C} be as in (1.11). Then for all $f \in S_{B_1}$ and all \mathbb{R} -valued nonnegative measurable functions ω ,

$$(5.9) \quad \langle \mathcal{V}^r T f, \omega \rangle \lesssim \mathcal{C} \Lambda_{p, q'}^*(f, \omega).$$

PROOF. In view of Theorem 5.1, it suffices to consider the case $r < \infty$. Given $N_1 \leq N_2$ we define $H_j f(x, k)$ as in (5.5), for $N_1 \leq k \leq N_2$. Note that for fixed x , $N_1 \leq n_1 < \dots < n_M \leq N_2$,

$$(5.10) \quad |T_{n_1} f(x)|_{B_2} + \left(\sum_{\nu=1}^{M-1} |T_{n_{\nu+1}} f(x) - T_{n_\nu} f(x)|_{B_2}^r \right)^{1/r} \\ = \left| \sum_{j=N_1}^{N_2} H_j f(x, n_1) \right|_{B_2} + \left(\sum_{\nu=1}^{M-1} \left| \sum_{j=1}^N H_j f(x, n_{\nu+1}) - \sum_{j=1}^N H_j f(x, n_\nu) \right|_{B_2}^r \right)^{1/r}.$$

By (5.8) we have

$$\left\| \sum_{j=N_1}^{N_2} H_j \right\|_{L_{B_1}^p \rightarrow L^{p, \infty}(V_{B_2}^r)} \leq A(p), \quad \left\| \sum_{j=N_1}^{N_2} H_j \right\|_{L_{B_1}^{q, 1} \rightarrow L^q(V_{B_2}^r)} \leq A(q),$$

where $V_{B_2}^r$ is interpreted to be the space $V_{B_2}^r(I_{N_1, N_2})$ and all the constants in what follows will be independent of N_1 and N_2 . The pairing between $V_{B_2}^r(I_{N_1, N_2})$ and its dual is the standard one,

$$\langle a, b \rangle = \sum_{n=N_1}^{N_2} \langle a(n), b(n) \rangle_{(B_2, B_2^*)}$$

and we have,

$$|b|_{(V_{B_2}^r(I_{N_1, N_2}))^*} = \sup_{|a|_{V_{B_2}^r(I_{N_1, N_2})} \leq 1} \left| \sum_{n=N_1}^{N_2} \langle a(n), b(n) \rangle_{(B_2, B_2^*)} \right|.$$

For $\delta^{(j)} = (\delta_{j, N_1}, \dots, \delta_{j, N_2})$ we have, for $j = N_1, \dots, N_2$,

$$|\delta^{(j)}|_{V_{B_2}^r(I_{N_1, N_2})} = 2^{1/r} \quad \text{and} \quad |\delta^{(j)}|_{(V_{B_2}^r(I_{N_1, N_2}))^*} = 2^{1/r'}.$$

The adjoint of H_j , acting on $(V_{B_2}^r(I_{N_1, N_2}))^*$ -valued functions $g = \{g_k\}_{k=N_1}^{N_2}$, is given by

$$H_j^* g(x) = \sum_{k=N_1}^{N_2} \delta_{jk} T_j^* g_k(x).$$

These observations imply

$$\begin{aligned} \|\text{Dil}_{2^j} H_j\|_{L_{B_1}^p \rightarrow L^q(V_{B_2}^r)} &= 2^{1/r} \|\text{Dil}_{2^j} T_j\|_{L_{B_1}^p \rightarrow L_{B_2}^q}, \\ \|(\text{Dil}_{2^j} H_j) \circ \Delta_h\|_{L_{B_1}^p \rightarrow L^q(V_{B_2}^r)} &= 2^{1/r} \|(\text{Dil}_{2^j} T_j) \circ \Delta_h\|_{L_{B_1}^p \rightarrow L_{B_2}^q}, \\ \|(\text{Dil}_{2^j} H_j^*) \circ \Delta_h\|_{L^{q'}((V_{B_2}^r)^*) \rightarrow L_{B_1}^{p'}} &= 2^{1/r'} \|(\text{Dil}_{2^j} T_j^*) \circ \Delta_h\|_{L_{B_2}^{q'} \rightarrow L_{B_1}^{p'}}. \end{aligned}$$

The hypothesis of Theorem 1.1 are then satisfied for the sequence $\{H_j\}_{j \in \mathbb{Z}}$ in $\text{Op}_{B_1, V_{B_2}^r}$. Thus, by Corollary 1.2 we obtain

$$\int_{\mathbb{R}^d} \left| \sum_{j=N_1}^{N_2} H_j f(x, \cdot) \right|_{V_{B_2}^r} \omega(x) dx \lesssim \mathcal{C} \Lambda_{p, q'}^*(f, \omega),$$

which by (5.10) implies

$$\int_{\mathbb{R}^d} \mathcal{V}_{N_1, N_2}^r T f(x) \omega(x) dx \lesssim \mathcal{C} \Lambda_{p, q'}^*(f, \omega).$$

As the implicit constant in Corollary 1.2 does not depend on the Banach spaces B_1, B_2 we may apply the monotone convergence theorem and let $N_1 \rightarrow -\infty$ and $N_2 \rightarrow \infty$ to obtain the desired conclusion (5.9). \square

5.3. Truncations of sums

We will give a variant of Corollary 1.2 in the spirit of Cotlar's inequality on maximal operators for truncations of singular integrals.

THEOREM 5.3. *Let $1 < p \leq q < \infty$. Let $\{T_j\}_{j \in \mathbb{Z}}$ be a family of operators in Op_{B_1, B_2} satisfying (1.6), (1.8), (1.9a), and (1.9b). Moreover, assume that the estimates*

$$(5.11a) \quad \left\| \sup_{\substack{(n_1, n_2): \\ N_1 \leq n_1 \leq n_2 \leq N_2}} \left| \sum_{j=n_1}^{n_2} T_j f \right|_{B_2} \right\|_{L^{p, \infty}} \leq A(p) \|f\|_{L_{B_1}^p},$$

$$(5.11b) \quad \left\| \sup_{\substack{(n_1, n_2): \\ N_1 \leq n_1 \leq n_2 \leq N_2}} \left| \sum_{j=n_1}^{n_2} T_j f \right|_{B_2} \right\|_{L^q} \leq A(q) \|f\|_{L_{B_1}^{q, 1}}$$

hold uniformly for all (N_1, N_2) with $N_1 \leq N_2$. Let \mathcal{C} be as in (1.11). Then for all $f \in \mathbb{S}_{B_1}$, all \mathbb{R} -valued nonnegative measurable functions ω , and all integers N_1, N_2 with $N_1 \leq N_2$,

$$\int_{\mathbb{R}^d} \sup_{\substack{(n_1, n_2): \\ N_1 \leq n_1 \leq n_2 \leq N_2}} \left| \sum_{j=n_1}^{n_2} T_j f(x) \right|_{B_2} \omega(x) dx \lesssim \mathcal{C} \Lambda_{p, q'}^*(f, \omega).$$

PROOF. Define $U(N_1, N_2) = \{(n_1, n_2) : N_1 \leq n_1 \leq n_2 \leq N_2\}$ and $\ell_{B_2}^\infty$ as the space of all bounded B_2 -valued functions on $U(N_1, N_2)$. Define operators H_j in $\text{Op}_{B_1, \ell_{B_2}^\infty}$ by

$$H_j f(x, n_1, n_2) = \begin{cases} T_j f(x) & \text{if } N_1 \leq n_1 \leq j \leq n_2 \leq N_2, \\ 0 & \text{otherwise.} \end{cases}$$

Then apply Corollary 1.2 to the operators $\sum_{j=N_1}^{N_2} H_j$ as in the proof of Theorems 5.1. \square

We also have a variational analogue.

THEOREM 5.4. *Let $1 < p \leq q < \infty$. Let $\{T_j\}_{j \in \mathbb{Z}}$ be a family of operators in Op_{B_1, B_2} satisfying (1.6), (1.7a), (1.7b), (1.8), (1.9a), and (1.9b). Moreover, assume that the estimates*

$$(5.12a) \quad \left\| \sup_{M \in \mathbb{N}} \sup_{N_1 \leq n_1 < \dots < n_M \leq N_2} \left(\sum_{\nu=1}^{M-1} \left| \sum_{j=n_\nu+1}^{n_{\nu+1}} T_j f \right|_{B_2}^r \right)^{1/r} \right\|_{L^{p, \infty}} \leq A(p) \|f\|_{L_{B_1}^p}$$

$$(5.12b) \quad \left\| \sup_{M \in \mathbb{N}} \sup_{N_1 \leq n_1 < \dots < n_M \leq N_2} \left(\sum_{\nu=1}^{M-1} \left| \sum_{j=n_\nu+1}^{n_{\nu+1}} T_j f \right|_{B_2}^r \right)^{1/r} \right\|_{L^q} \leq A(p) \|f\|_{L_{B_1}^{q, 1}}$$

hold uniformly for all (N_1, N_2) with $N_1 \leq N_2$. Let \mathcal{C} be as in (1.11). Then for all $f \in \mathbb{S}_{B_1}$, all \mathbb{R} -valued nonnegative measurable functions ω , and all integers N_1, N_2 with $N_1 \leq N_2$,

$$(5.13) \quad \int_{\mathbb{R}^d} \sup_{M \in \mathbb{N}} \sup_{N_1 \leq n_1 < \dots < n_M \leq N_2} \left(\sum_{\nu=1}^{M-1} \left| \sum_{j=n_\nu+1}^{n_{\nu+1}} T_j f(x) \right|_{B_2}^r \right)^{1/r} \omega(x) dx \lesssim \mathcal{C} \Lambda_{p, q'}^*(f, \omega).$$

PROOF. Let $V_{B_2}^r \equiv V_{B_2}^r(I_{N_1, N_2})$ denote the r -variation space of B_2 -valued functions over the integers in $[N_1, N_2]$ and for $N_1 \leq j \leq N_2$, $N_1 \leq n \leq N_2$, define the operators $H_j \in \text{Op}_{B_1, V_{B_2}^r}$ by

$$H_j f(x, n) = \begin{cases} T_j f(x) & \text{if } N_1 \leq j \leq n \leq N_2, \\ 0 & \text{if } j > n. \end{cases}$$

Note that, by definition of H_j , $|\sum_{j=N_1}^{N_2} H_j f(x, \cdot)|_{V_{B_2}^r}$ equals to

$$(5.14) \quad \sup_{\substack{M \in \mathbb{N} \\ N_1 \leq n_1 < \dots < n_M \leq N_2}} \left| \sum_{j=N_1}^{n_1} T_j f(x) \right|_{B_2} + \left(\sum_{\nu=1}^{M-1} \left| \sum_{j=N_1}^{n_\nu+1} T_j f(x) - \sum_{j=N_1}^{n_\nu} T_j f(x) \right|_{B_2}^r \right)^{1/r}$$

and $|H_j f(x, \cdot)|_{V_{B_2}^r} = |T_j f(x)|_{B_2}$. Arguing as in Theorem 5.2, one may apply Corollary 1.2 to the operators $\sum_{j=N_1}^{N_2} H_j$ in $\text{Op}_{B_1, V_{B_2}^r}$. Note, in particular, that in view of (5.14) the conditions (1.7a) and (1.7b) for $\sum_{j=N_1}^{N_2} H_j$ follow from (5.12a) and (5.12b) together with the fact that $\{T_j\}_{j \in \mathbb{Z}}$ in Op_{B_1, B_2} satisfy (1.7a) and (1.7b). This automatically yields (5.13). \square

5.4. Some simplifications for maximal operators

The goal of this section is to remark that the proof of Theorem 5.1 can be simplified in the case $q \leq r \leq \infty$. Rather than deducing it from Corollary 1.2, we shall apply the proof method of Theorem 1.1 to the operators S_r and observe that a Calderón–Zygmund decomposition on f_2 is not required for the proof to work. In particular, this allows us to remove the regularity hypothesis (1.9b) on the adjoints T_j^* . The precise statement reads as follows.

THEOREM 5.5. *Let $1 < p \leq q < \infty$ and $q \leq r \leq \infty$. Let $\{T_j\}_{j \in \mathbb{Z}}$ be a family of operators in Op_{B_1, B_2} satisfying (1.6). Suppose that the inequalities*

$$(5.15) \quad \|S_r T f\|_{L^{p, \infty}} \leq A(p) \|f\|_{L_{B_1}^p} \quad \text{and} \quad \|S_r T f\|_{L^q} \leq A(q) \|f\|_{L_{B_1}^{q, 1}}$$

hold for all $f \in S_{B_1}$. Moreover, assume that the rescaled operators $\text{Dil}_{2^j} T_j$ satisfy the single scale (p, q) condition (1.8) and single scale ε -regularity condition (1.9a). Let \mathcal{C} be as in (1.11). Then for all $f \in S_{B_1}$ and all \mathbb{R} -valued nonnegative measurable functions ω ,

$$\langle S_r T f, \omega \rangle \lesssim \mathcal{C} \Lambda_{p, q'}^*(f, \omega).$$

PROOF. We sketch the main changes with respect to the proof of Theorem 1.1. As in Theorem 1.1, it suffices to show

$$\int_{\mathbb{R}^d} S_{r, N_1, N_2} f_1(x) f_2(x) dx \lesssim \mathcal{C} \Lambda_{p, q'}^*(f_1, f_2)$$

uniformly in $N_1 \leq N_2$ for all $f_1 \in S_{B_1}$ and $f_2 \in S_{\mathbb{R}}$, where

$$S_{r, N_1, N_2} f(x) := \left(\sum_{j=N_1}^{N_2} |T_j f(x)|_{B_2}^r \right)^{1/r}$$

for $q \leq r < \infty$ and

$$S_{\infty, N_1, N_2} f(x) := \sup_{N_1 \leq j \leq N_2} |T_j f(x)|_{B_2}.$$

This will in turn follow from verifying the inductive step in Claim 4.3 for the operators S_{r, N_1, N_2} .

If $r = \infty$, let $\lambda_j(x) \in B_2^*$ with $|\lambda_j(x)|_{B_2^*} \leq 1$ such that

$$|T_j f_1(x)|_{B_2} = \langle T_j f_1, \lambda_j \rangle_{(B_2, B_2^*)}$$

and let $x \mapsto j(x)$ be a measurable function such that

$$S_{\infty, N_1, N_2} f_1(x) \leq 2 |T_{j(x)} f_1(x)|_{B_2}.$$

Setting $X_j := \{x : j(x) = j\}$, note that

$$S f_1(x) \equiv |T_{j(x)} f_1(x)|_{B_2} = \sum_{j=N_1}^{N_2} \langle T_j f_1(x), \lambda_j(x) \mathbf{1}_{X_j}(x) \rangle_{(B_2, B_2^*)}$$

and that the X_j are disjoint measurable sets such that $\sum_j \mathbb{1}_{X_j} \leq \mathbb{1}_{3Q_0}$. If $q \leq r < \infty$, we linearize the $\ell^r(B_2)$ -norm for each x . That is, there exists $\{a_j(x)\}_{j \in \mathbb{Z}} \in \ell^{r'}(B_2^*)$, with $\|a_j(x)\|_{\ell^{r'}(B_2^*)} \leq 1$, such that

$$Sf_1(x) \equiv S_{r, N_1, N_2} f_1(x) = \sum_{j=N_1}^{N_2} \langle T_j f_1(x), a_j(x) \rangle_{(B_2, B_2^*)}.$$

Note that we can treat the cases $r = \infty$ and $q \leq r < \infty$ together by setting $a_j(x) = \lambda_j(x) \mathbb{1}_{X_j}(x)$ for all $x \in 3Q_0$ and all $N_1 \leq j \leq N_2$, and $a_j(x) = 0$ otherwise; then $\{a_j(x)\}_{j \in \mathbb{Z}} \in \ell^1(B_2^*)$. Clearly, the operator S satisfies the bounds (1.7a), (1.7b) in view of (5.15).

We then perform a Calderón–Zygmund decomposition of f_1 as in (4.13). The first term in (4.13), corresponding to g_1 , can be treated analogously. The second term in (4.13), corresponding to $\sum_{W \in \mathcal{W}} b_{1,W}$ can be further split as in (4.15), and I and II can be treated analogously. One is then left with proving (4.18) for III . Rather than performing a Calderón–Zygmund decomposition on f_2 , we estimate the term directly.

Indeed, the analysis for III amounts to a simplified version of the analysis of the term III_4 in (4.22). One can define ℓ as in (4.24) and split

$$(-\infty, j) \cap \mathbb{Z} = \mathcal{V}_{j,1} \cup \mathcal{V}_{j,2},$$

where $\mathcal{V}_{j,1} := \{L : j - \ell \leq L < j\}$ and $\mathcal{V}_{j,2} = \{L : L < j - \ell\}$. Note that here there is no further need to split $\mathcal{V}_{j,2}$, since we do not make use of a Calderón–Zygmund decomposition of f_2 . Write $III = IV_1^b + IV_2^b$, where for $i = 1, 2$,

$$IV_i^b = \left\langle \sum_{N_1 \leq j \leq N_2} \sum_{\substack{W \in \mathcal{W}, \\ L(W) \in \mathcal{V}_{j,i}}} T_j b_{1,W}, f_2 \right\rangle.$$

We first focus on IV_1^b . By Hölder's inequality with respect to x and j

$$(5.16) \quad IV_1^b \leq IV_{1,1}^b IV_{1,2}^b,$$

where

$$IV_{1,1}^b = \left(\sum_{j=N_1}^{N_2} \int \left| \sum_{j-\ell \leq L(W) < j} T_j b_{1,W}(x) \right|_{B_2}^q dx \right)^{1/q},$$

$$IV_{1,2}^b = \left(\sum_{j=N_1}^{N_2} \int |a_j(x)|_{B_2}^{q'} |f_2(x)|^{q'} dx \right)^{1/q'}.$$

Using that $\|a_j(x)\|_{\ell^{q'}(B_2^*)} \leq \|a_j(x)\|_{\ell^{r'}(B_2^*)} = 1$ if $1 \leq r' \leq q'$, we get

$$(5.17) \quad IV_{1,2}^b \lesssim \left(\int_{3Q_0} |f_2(x)|^{q'} dx \right)^{1/q'} \lesssim |Q_0|^{1-1/q} \langle f_2 \rangle_{3Q_0, q'}.$$

For the term $IV_{1,1}^b$, introduce as in (4.26) the family \mathfrak{R}_j of subcubes of Q_0 of side length 2^j and use the bounded overlap of $3R$ to write

$$IV_{1,1}^b \lesssim \left(\sum_{j=N_1}^{N_2} \sum_{R \in \mathfrak{R}_j} \left\| \sum_{\substack{W \subset R \\ j-\ell \leq L(W) < j}} T_j b_{1,W} \right\|_{L_{B_2}^q}^q \right)^{1/q}.$$

The right-hand side above can then be handled essentially as IV_1 in (4.26) after using the single scale (p, q) condition (1.8) for each T_j (in the form (4.21)); the only difference is the presence of an ℓ^q -sum. More precisely,

$$\begin{aligned}
IV_{1,1}^b &\lesssim A_o(p, q) \left(\sum_{j=N_1}^{N_2} \sum_{R \in \mathfrak{R}_j} |R|^{-\left(\frac{1}{p}-\frac{1}{q}\right)q} \left(\sum_{\substack{W \subset R \\ j-\ell \leq L(W) < j}} \|b_{1,W}\|_{L_{B_1}^p}^p \right)^{q/p} \right)^{1/q} \\
&\lesssim_d A_o(p, q) \langle f_1 \rangle_{Q_0, p, B_1} \left(\sum_{j=N_1}^{N_2} \sum_{R \in \mathfrak{R}_j} |R|^{-\left(\frac{1}{p}-\frac{1}{q}\right)q} \left(\sum_{\substack{W \subset R \\ j-\ell \leq L(W) < j}} |W| \right)^{q/p} \right)^{1/q} \\
&\lesssim_d A_o(p, q) \langle f_1 \rangle_{Q_0, p, B_1} \left(\sum_{j=N_1}^{N_2} \sum_{R \in \mathfrak{R}_j} \sum_{\substack{W \subset R \\ j-\ell \leq L(W) < j}} |W| \right)^{1/q} \\
&\lesssim \ell^{1/q} \langle f_1 \rangle_{Q_0, p, B_1} |Q_0|^{1/q},
\end{aligned}$$

and combining this with (5.17), the bound for IV_1^b immediately follows.

Regarding IV_2^b , write $IV_2^b = \sum_{s=\ell+1}^{\infty} IV_2^b(s)$, where $IV_2^b(s)$ has the sum in $L(W) < j - \ell$ further restricted to $L(W) = j - s$. For each fixed s , one can apply Hölder's inequality with respect to x and j as in (5.16),

$$IV_2^b(s) \leq IV_{2,1}^b(s) IV_{2,2}^b,$$

where the term $IV_{2,2}^b$ (which is independent of s) can be treated as $IV_{1,2}^b$ in (5.17). For each $IV_{2,1}^b(s)$ we write again

$$IV_{2,1}^b(s) \lesssim \left(\sum_{j=N_1}^{N_2} \sum_{R \in \mathfrak{R}_j} \left\| \sum_{\substack{W \subset R \\ L(W)=j-s}} T_j b_{1,W} \right\|_{L_{B_2}^q}^q \right)^{1/q}.$$

This term can now be treated as the term IV_2 in (4.30) using the ε -regularity condition (1.9a) to get a decay of $2^{-s\varepsilon'}$ (as in (4.29a)). The only difference with respect to (4.30) is the presence of the ℓ^q -sum, which introduces no difficulty, as shown above for $IV_{1,1}^b$. This completes the proof. \square

Fourier multipliers

In this chapter we deduce Theorems 1.5 and 1.6 from a more general result which will lead to more precise sparse domination results and also cover Hilbert space valued versions. We are given two separable Hilbert spaces $\mathcal{H}_1, \mathcal{H}_2$ and denote by $\mathcal{L}(\mathcal{H}_1, \mathcal{H}_2)$ the space of bounded linear operators from \mathcal{H}_1 to \mathcal{H}_2 (in our applications one of the Hilbert spaces will be usually \mathbb{C}). Consider the translation invariant operator $\mathcal{T} = \mathcal{T}_m$ mapping \mathcal{H}_1 -valued functions to \mathcal{H}_2 -valued functions given via a multiplier

$$\widehat{\mathcal{T}f}(\xi) = m(\xi)\widehat{f}(\xi),$$

where $m(\xi) \in \mathcal{L}(\mathcal{H}_1, \mathcal{H}_2)$ for almost every ξ . For $1 \leq p \leq q \leq \infty$ we write $m \in M_{\mathcal{H}_1, \mathcal{H}_2}^{p,q}$ if the inequality

$$\|\mathcal{T}f\|_{L^q(\mathcal{H}_2)} \leq C\|f\|_{L^p(\mathcal{H}_1)}$$

holds for all \mathcal{H}_1 -valued Schwartz functions, and the best constant defines the norm in $M_{\mathcal{H}_1, \mathcal{H}_2}^{p,q}$. We may occasionally drop the Hilbert spaces if it is understood from the context and also write M^p for $M^{p,p}$. Note that $m \in M_{\mathcal{H}_1, \mathcal{H}_2}^{p,q}$ implies by a duality argument that $m \in M_{\mathcal{H}_2^*, \mathcal{H}_1^*}^{q', p'}$. The $M_{\mathcal{H}_1, \mathcal{H}_2}^{2,2}$ norm is bounded by $\|m\|_{L_{\mathcal{H}_1, \mathcal{H}_2}^\infty}$ where we write $L_{\mathcal{H}_1, \mathcal{H}_2}^\infty$ for $L_{\mathcal{L}(\mathcal{H}_1, \mathcal{H}_2)}^\infty$. Also note that by the Marcinkiewicz–Zygmund theorem [56, §2.1b] any scalar multiplier in $M^{p,q}$ extends naturally, for any separable Hilbert space \mathcal{H} , to a multiplier

$$m \otimes I_{\mathcal{H}} \in M_{\mathcal{H}, \mathcal{H}}^{p,q}, \text{ with } m \otimes I_{\mathcal{H}} : \begin{cases} \mathbb{R}^d \rightarrow \mathcal{L}(\mathcal{H}, \mathcal{H}), \\ \xi \mapsto (v \mapsto m(\xi)v) \end{cases}$$

and we have $\|m \otimes I_{\mathcal{H}}\|_{M_{\mathcal{H}, \mathcal{H}}^{p,q}} \leq C\|m\|_{M^{p,q}}$ where C does not depend on the Hilbert space.

6.1. The main multiplier theorem

In what follows let ϕ be a radial C^∞ function supported in $\{\xi \in \widehat{\mathbb{R}}^d : 1/2 < |\xi| < 2\}$ (not identically zero). Let $\Psi_0 \in C^\infty(\mathbb{R}^d)$ be supported in $\{x \in \mathbb{R}^d : |x| < 1/2\}$ such that $\Psi_0(x) = 1$ for $|x| \leq 1/4$. For $\ell > 0$ define

$$(6.1) \quad \Psi_\ell(x) = \Psi_0(2^{-\ell}x) - \Psi_0(2^{-\ell+1}x)$$

which is supported in $\{x : 2^{\ell-3} \leq |x| \leq 2^{\ell-1}\}$. Define

$$(6.2a) \quad \mathcal{B}[m] := \sum_{\ell \geq 0} \sup_{t > 0} \|[\phi m(t \cdot)] * \widehat{\Psi}_\ell\|_{M_{\mathcal{H}_1, \mathcal{H}_2}^{p,q}} 2^{\ell d(1/p-1/q)}(1 + \ell),$$

$$(6.2b) \quad \mathcal{B}_\circ[m] := \sum_{\ell \geq 0} \sup_{t > 0} \|[\phi m(t \cdot)] * \widehat{\Psi}_\ell\|_{L_{\mathcal{H}_1, \mathcal{H}_2}^\infty}.$$

THEOREM 6.1. *Let $1 < p \leq q < \infty$, $1/q' = 1 - 1/q$, and assume that $m \in L^\infty_{\mathcal{H}_1, \mathcal{H}_2}$ is such that $\mathcal{B}_o[m]$ and $\mathcal{B}[m]$ are finite. Then $\mathcal{T}_m \in \text{Sp}(p, \mathcal{H}_1, q', \mathcal{H}_2^*)$ with*

$$\|\mathcal{T}_m\|_{\text{Sp}_\gamma(p, \mathcal{H}_1, q', \mathcal{H}_2^*)} \lesssim_{d, \gamma, p, q} \mathcal{B}[m] + \mathcal{B}_o[m].$$

The implicit constant does not depend on $m, \mathcal{H}_1, \mathcal{H}_2$.

We note that the finiteness of $\mathcal{B}_o[m]$ is implied by the finiteness of $\mathcal{B}[m]$ in the case $\mathcal{H}_1 = \mathcal{H}_2 = \mathbb{C}$.

REMARK 6.2. The function space of all m with $\mathcal{B}_o[m] + \mathcal{B}[m] < \infty$ exhibits familiar properties of similarly defined function spaces in multiplier theory. For example:

- (1) The space is invariant under multiplication by a standard smooth symbol of order 0. This fact will be used in the proof of Theorem 6.1 and for the convenience of the reader, the precise statement and proof are contained in Appendix C, §C.1 below.
- (2) The finiteness of $\mathcal{B}[m]$ and $\mathcal{B}_o[m]$ is independent of the choice of the specific functions ϕ and Ψ . This observation will be convenient in the proof of Theorem 6.1. It can be verified by standard arguments but, for completeness, the proof is provided in Appendix C, §C.2 below.

We begin by showing how Theorem 6.1 implies Theorems 1.5 and 1.6. Then we review some known facts and estimates for Fourier multipliers and deduce the proof of Theorem 6.1 from our main Theorem 1.1.

PROOF OF THEOREM 1.5 USING THEOREM 6.1. We have to check the assumptions of Theorem 6.1. Assumption (1.24) is equivalent with

$$\|[\phi m(t \cdot)] * \widehat{\Psi}_\ell\|_{M^2} \leq 2^{-\ell\varepsilon}.$$

Thus interpolating (1.24) and (1.23) we get for $p \in (p_0, 2)$,

$$\|[\phi m(t \cdot)] * \widehat{\Psi}_\ell\|_{M^p} \leq 2^{-\ell\varepsilon(p)} \text{ where } \varepsilon(p) = \varepsilon\left(\frac{1}{p_0} - \frac{1}{p}\right) / \left(\frac{1}{p_0} - \frac{1}{2}\right).$$

Let $\chi \in C_c^\infty(\mathbb{R}^d \setminus \{0\})$ so that $\chi(\xi) = 1$ in a neighborhood of $\text{supp}(\phi)$. Then by Young's convolution inequality for all $p \in (p_0, 2)$, $q \in [p, \infty]$, $t > 0$,

$$\|\chi([\phi m(t \cdot)] * \widehat{\Psi}_\ell)\|_{M^{p,q}} \lesssim \|[\phi m(t \cdot)] * \widehat{\Psi}_\ell\|_{M^p} \lesssim 2^{-\ell\varepsilon(p)}.$$

On the other hand we claim that

$$(6.3) \quad \|(1 - \chi)([\phi m(t \cdot)] * \widehat{\Psi}_\ell)\|_{M^{p,q}} \lesssim_N \|\varphi m(t \cdot)\|_1 2^{-\ell N}.$$

Indeed, integration by parts in ξ in the integral

$$\int \int e^{ix \cdot \xi} (1 - \chi)(\xi) [\phi m(t \cdot)](\zeta) 2^{\ell d} \widehat{\Psi}(2^\ell(\xi - \zeta)) d\xi d\zeta$$

implies the pointwise estimate

$$|\mathcal{F}^{-1}((1 - \chi)([\phi m(t \cdot)] * \widehat{\Psi}_\ell))(x)| \lesssim_N 2^{-\ell N} (1 + |x|)^{-N} \|\phi m(t \cdot)\|_1,$$

and now (6.3) follows from Young's convolution inequality.

Fix $p \in (p_0, 2)$. Combining the two estimates we see that condition (6.2a) holds for a pair of exponents (p_1, q_1) if $p_1 \in (p_0, p)$, $q_1 > p_1$ and

$$d(1/p_1 - 1/q_1) < \varepsilon(p_1).$$

Then Theorem 6.1 gives $\mathcal{T} \in \text{Sp}(p_1, q_1')$. One can then choose $\delta = \delta(p) > 0$ small enough so that $p_1 = p - \delta$ and $q_1' = p' - \delta$ satisfy the above conditions. This concludes the proof. \square

PROOF OF THEOREM 1.6 USING THEOREM 6.1. We need to check that $\mathcal{B}[m]$ is finite, which will follow from showing that

$$(6.4) \quad \sup_{t>0} \|[\phi m(t \cdot)] * \widehat{\Psi}_\ell\|_{M^{p,q}} \lesssim 2^{-\ell s}$$

for some $s > d(1/p - 1/q)$. Here we are in the case $\mathcal{H}_1 = \mathcal{H}_2 = \mathbb{C}$, so this also implies $\mathcal{B}_o[m] < \infty$.

We decompose Ψ_ℓ into slightly smaller pieces. Recall that Ψ_1 is supported in $\{x : 1/4 \leq |x| \leq 1\}$ and $\Psi_\ell(x) = \Psi_1(2^{1-\ell}x)$. We form a partition of unity $\{\varsigma_\nu : \nu \in \mathcal{I}\}$ such that $\sum_{\nu \in \mathcal{I}} \varsigma_\nu(x) = 1$ for $|x| \in [1/8, 2]$, and ς is a C^∞ function supported in a ball $B(x_\nu, r_\nu)$ centered at x_ν , with $|x_\nu| \in [1/4, 1]$ and radius $r_\nu \leq 10^{-2}$. Let

$$u_\nu = \frac{\pi}{2} \frac{x_\nu}{|x_\nu|^2}$$

so that $|u_\nu| \in [1, 8]$ and $\langle x_\nu, u_\nu \rangle = \pi/2$. This implies that $|\text{Im}(e^{i\langle x, u_\nu \rangle}) - 1| > 1/2$ for $x \in \text{supp}(\varsigma_\nu)$. Define, for M as in (1.25),

$$\Psi_{1,\nu}(x) = \frac{\Psi_1(x)\varsigma_\nu(x)}{(e^{i\langle x, u_\nu \rangle} - 1)^M}, \quad \Psi_{\ell,\nu}(x) = \Psi_{1,\nu}(2^{1-\ell}x)$$

and note that $\Psi_{1,\nu}$ is smooth and $\Psi_\ell(x) = \sum_\nu \Psi_{\ell,\nu}(x)(e^{i\langle x, 2^{1-\ell}u_\nu \rangle} - 1)^M$. Hence

$$\phi m(t \cdot) * \widehat{\Psi}_\ell = \sum_\nu \Delta_{-2^{1-\ell}u_\nu}^M [\phi m(t \cdot)] * \widehat{\Psi}_{\ell,\nu}$$

and by assumption we have for some $s > d(1/p - 1/q)$,

$$\|\phi m(t \cdot) * \widehat{\Psi}_\ell\|_{M^{p,q}} \lesssim \sum_\nu \|\Delta_{-2^{1-\ell}u_\nu}^M [\phi m(t \cdot)]\|_{M^{p,q}} \lesssim 2^{-\ell s}.$$

This implies (6.4) and now Theorem 1.6 follows from Theorem 6.1. \square

6.2. A result involving localizations of Fourier multipliers

We recall a theorem from [98] (see also [24] for a similar result) which we will formulate in the vector-valued version (see also [51]).

Let ϕ be as before, and fix $1 < p < \infty$. Assume

$$(6.5a) \quad \sup_{t>0} \|\phi m(t \cdot)\|_{M_{\mathcal{H}_1, \mathcal{H}_2}^p} \leq \mathbf{a}$$

$$(6.5b) \quad \sup_{t>0} \|\phi m(t \cdot)\|_{L_{\mathcal{H}_1, \mathcal{H}_2}^\infty} \leq \mathbf{a}_o,$$

and

$$(6.5c) \quad \sum_{|\alpha| \leq d+1} \sup_{t>0} \sup_{\xi \in \mathbb{R}^d} |\partial_\xi^\alpha (\phi m(t \cdot))(\xi)|_{\mathcal{L}(\mathcal{H}_1, \mathcal{H}_2)} \leq \mathbf{b},$$

where $\alpha \in \mathbb{N}_0^d$. Then

$$(6.6) \quad \|m\|_{M_{\mathcal{H}_1, \mathcal{H}_2}^p} \lesssim \mathbf{a}_o + \mathbf{a} \log(2 + \mathbf{b}/\mathbf{a})^{|\frac{1}{p} - \frac{1}{2}|}.$$

Of course, in the special case $\mathcal{H}_1 = \mathcal{H}_2 = \mathbb{C}$ the L^2 -boundedness condition (6.5b) with $\mathbf{a}_o \leq \mathbf{a}$ is implied by (6.5a) (cf. an analogous remark following Theorem 6.1).

6.3. Proof of the main multiplier theorem

We give the proof of Theorem 6.1. First assume that m is compactly supported in $\widehat{\mathbb{R}}^d \setminus \{0\}$ without making any quantitative assumption on the support.

Note that by Remark 6.2 we have some freedom to make a convenient choice of the localizing function ϕ , and we will denote this choice by φ . In what follows, let $\theta \in C_c^\infty(\mathbb{R}^d)$ be radial such that θ is supported in $\{x \in \mathbb{R}^d : |x| < 1/2\}$, such that $\int \theta(x)\pi(x)dx = 0$ for all polynomials π of degree at most $10d$, and such that $\widehat{\theta}(\xi) > 0$ for $1/4 \leq |\xi| \leq 4$. We then choose φ to be a radial C^∞ function supported in $\{\xi \in \widehat{\mathbb{R}}^d : 1/2 < |\xi| < 2\}$ such that

$$\sum_{k \in \mathbb{Z}} \varphi(2^{-k}\xi) \widehat{\theta}(2^{-k}\xi) = 1$$

for all $\xi \neq 0$.

We then decompose \mathcal{T} by writing

$$m(\xi) = \sum_{k=n_1}^{n_2} \widehat{\theta}(2^{-k}\xi) \varphi(2^{-k}\xi) m(\xi)$$

where $n_1, n_2 \in \mathbb{Z}$. We then decompose

$$\mathcal{F}^{-1}[\varphi m(2^k \cdot)](x) = \sum_{\ell \geq 0} \mathcal{F}^{-1}[\varphi m(2^k \cdot)](x) \Psi_\ell(x)$$

which yields

$$\mathcal{F}^{-1}[m \widehat{f}](x) = \sum_{\ell \geq 0} \mathcal{T}^\ell f(x) = \sum_{\ell \geq 0} \sum_{k=n_1}^{n_2} \mathcal{T}^{\ell, k} f(x)$$

where

$$\widehat{\mathcal{T}^{\ell, k} f}(\xi) = \widehat{\theta}(2^{-k}\xi) [\varphi m(2^k \cdot)] * \widehat{\Psi}_\ell(2^{-k}\xi).$$

We can write $\mathcal{T}^{\ell, k} f = K_k^\ell * f$ with

$$K_k^\ell(x) = \int \mathcal{F}^{-1}[\varphi(2^{-k} \cdot) m](x-y) \Psi_\ell(2^k(x-y)) 2^{kd} \theta(2^k y) dy.$$

Observe that $K_k^\ell(x)$ is supported in $\{x \in \mathbb{R}^d : |x| \leq 2^{\ell+1-k}\}$. We wish to apply Theorem 1.1 to the operators \mathcal{T}^ℓ defined by

$$\mathcal{T}^\ell f = \sum_{k=n_1}^{n_2} K_k^\ell * f = \sum_{j=\ell+1-n_2}^{\ell+1-n_1} T_j^\ell f \quad \text{with } T_j^\ell f = K_{\ell+1-j}^\ell * f.$$

The operators T_j^ℓ satisfy the support condition (1.6). To check the conditions (1.7a), (1.7b) we apply the above mentioned theorem from [98] (see (6.6)). We first claim that

$$(6.7) \quad \|\varphi \sum_{k=n_1}^{n_2} \widehat{K}_k^\ell(s) \|_{M_{\mathfrak{J}\mathfrak{c}_1, \mathfrak{J}\mathfrak{c}_2}^p} \lesssim \mathfrak{a}_\ell := \sup_{t>0} \|[\varphi m(t \cdot)] * \widehat{\Psi}_\ell \|_{M_{\mathfrak{J}\mathfrak{c}_1, \mathfrak{J}\mathfrak{c}_2}^{p, q}} 2^{\ell d(1/p-1/q)}$$

and

$$(6.8) \quad \|\varphi \sum_{k=n_1}^{n_2} \widehat{K}_k^\ell(s) \|_{L_{\mathfrak{J}\mathfrak{c}_1, \mathfrak{J}\mathfrak{c}_2}^\infty} \lesssim \mathfrak{a}_{\circ, \ell} := \sup_{t>0} \|[\varphi m(t \cdot)] * \widehat{\Psi}_\ell \|_{L_{\mathfrak{J}\mathfrak{c}_1, \mathfrak{J}\mathfrak{c}_2}^\infty},$$

uniformly in n_1, n_2 . We only give the proof of (6.7) as the the proof of (6.8) is similar but more straightforward. To see this we estimate, using dilation invariance,

$$\|\varphi \sum_{k=n_1}^{n_2} \widehat{K}_k^\ell(s \cdot)\|_{M_{\mathcal{H}_1, \mathcal{H}_2}^p} \leq \sum_{k=n_1}^{n_2} \|\varphi \widehat{\theta}(2^{-k}s \cdot)\|_{M^p} \|[\varphi m(2^k \cdot)] * \widehat{\Psi}_\ell\|_{M_{\mathcal{H}_1, \mathcal{H}_2}^p}.$$

Since $\theta \in \mathcal{S}(\mathbb{R}^d)$ and since all moments of η up to order $10d$ vanish we get

$$(6.9) \quad \|\varphi \widehat{\theta}(2^{-k}s \cdot)\|_{M^p} \lesssim \min\{(2^{-k}s)^{10d}, (2^{-k}s)^{-10d}\}.$$

Moreover,

$$(6.10) \quad \|[\varphi m(2^k \cdot)] * \widehat{\Psi}_\ell\|_{M_{\mathcal{H}_1, \mathcal{H}_2}^p} \lesssim 2^{\ell d(1/p-1/q)} \|[\varphi m(2^k \cdot)] * \widehat{\Psi}_\ell\|_{M_{\mathcal{H}_1, \mathcal{H}_2}^{p,q}}$$

and (6.7) follows combining the above. To verify (6.10) we decompose

$$f = \sum_{\nu} f_{\nu},$$

where $f_{\nu} = f \mathbf{1}_{R_{\ell, \nu}}$ and the $R_{\ell, \nu}$ form a grid of cubes of side length 2^ℓ . Note that the convolution kernel $\mathcal{K}_\ell := \mathcal{F}^{-1}[\varphi m(2^k \cdot)] * \widehat{\Psi}_\ell$ is supported in the ball of radius 2^ℓ centered at the origin. Hence, by Hölder's inequality

$$\begin{aligned} \|\mathcal{K}_\ell * f\|_{L_{\mathcal{H}_2}^p} &= \left\| \sum_{\nu} \mathcal{K}_\ell * f_{\nu} \right\|_{L_{\mathcal{H}_2}^p} \lesssim \left(\sum_{\nu} \|\mathcal{K}_\ell * f_{\nu}\|_{L_{\mathcal{H}_2}^p}^p \right)^{1/p} \\ &\lesssim 2^{\ell d(1/p-1/q)} \left(\sum_{\nu} \|\mathcal{K}_\ell * f_{\nu}\|_{L_{\mathcal{H}_2}^q}^p \right)^{1/p} \\ &\lesssim 2^{\ell d(1/p-1/q)} \|\widehat{\mathcal{K}}_\ell\|_{M_{\mathcal{H}_1, \mathcal{H}_2}^{p,q}} \left(\sum_{\nu} \|f_{\nu}\|_{L_{\mathcal{H}_1}^p}^p \right)^{1/p} \end{aligned}$$

and since $(\sum_{\nu} \|f_{\nu}\|_{L_{\mathcal{H}_1}^p}^p)^{1/p} = \|f\|_{L_{\mathcal{H}_1}^p}$ we get (6.10).

Straightforward calculation using (6.9) yields

$$(6.11) \quad \sum_{|\alpha| \leq d+1} \sum_{k=n_1}^{n_2} \sup_{t>0} \sup_{\xi \in \mathbb{R}^d} |\partial_\xi^\alpha (\varphi \widehat{K}_k^\ell(t\xi))|_{\mathcal{L}(\mathcal{H}_1, \mathcal{H}_2)} \leq \mathbf{b}_\ell := \|m\|_{L_{\mathcal{H}_1, \mathcal{H}_2}^\infty} 2^{\ell(d+1)}$$

uniformly in n_1, n_2 . We combine the two estimates (6.7), (6.8) and (6.11) and using (6.6) we get

$$\|\mathcal{T}^\ell\|_{L_{\mathcal{H}_1}^p \rightarrow L_{\mathcal{H}_2}^p} \lesssim (1+\ell)^{|\frac{1}{p}-\frac{1}{2}|} \mathbf{a}_\ell + \mathbf{a}_{\circ, \ell}.$$

The L^q estimates are similar. For $m(\xi) \in \mathcal{L}(\mathcal{H}_1, \mathcal{H}_2)$ denote by $m^*(\xi) \in \mathcal{L}(\mathcal{H}_2^*, \mathcal{H}_1^*)$ its adjoint. Note that

$$\|[\varphi m^*(t \cdot)] * \widehat{\Psi}_\ell\|_{L_{\mathcal{H}_2^*, \mathcal{H}_1^*}^\infty} = \|[\varphi m(t \cdot)] * \widehat{\Psi}_\ell\|_{L_{\mathcal{H}_1, \mathcal{H}_2}^\infty} \leq \mathbf{a}_{\circ, \ell}.$$

Since $q' \leq p'$ the previous calculation gives

$$\begin{aligned} \|\mathcal{T}^\ell\|_{L_{\mathcal{H}_1}^q \rightarrow L_{\mathcal{H}_2}^q} &= \|(\mathcal{T}^\ell)^*\|_{L_{\mathcal{H}_2^*}^{q'} \rightarrow L_{\mathcal{H}_1^*}^{q'}} \\ &\lesssim (1+\ell)^{|\frac{1}{q'}-\frac{1}{2}|} 2^{\ell d(1/q'-1/p')} \sup_{t>0} \|[\varphi m^*(t \cdot)] * \widehat{\Psi}_\ell\|_{M_{\mathcal{H}_2^*, \mathcal{H}_1^*}^{q', p'}} + \mathbf{a}_{\circ, \ell} \\ &\lesssim (1+\ell)^{|\frac{1}{q}-\frac{1}{2}|} 2^{\ell d(1/p-1/q)} \sup_{t>0} \|[\varphi m(t \cdot)] * \widehat{\Psi}_\ell\|_{M_{\mathcal{H}_1, \mathcal{H}_2}^{p, q}} + \mathbf{a}_{\circ, \ell} \\ &= (1+\ell)^{|\frac{1}{q}-\frac{1}{2}|} \mathbf{a}_\ell + \mathbf{a}_{\circ, \ell}. \end{aligned}$$

To summarize,

$$(6.12) \quad \left\| \sum_j T_j^\ell \right\|_{L^p \rightarrow L^p} + \left\| \sum_j T_j^\ell \right\|_{L^q \rightarrow L^q} \leq \mathbf{a}_{\circ, \ell} + \mathbf{a}_\ell \left((1 + \ell)^{|\frac{1}{p} - \frac{1}{2}|} + (1 + \ell)^{|\frac{1}{q} - \frac{1}{2}|} \right).$$

To verify the single scale (p, q) condition (1.8) we next examine the $L_{\mathfrak{J}c_1}^p \rightarrow L_{\mathfrak{J}c_2}^q$ -norms of the convolution operators $\text{Dil}_{2^j} T_j^\ell$ with convolution kernels $2^{jd} K_{\ell+1-j}^\ell(2^j \cdot)$. We have

$$\|\text{Dil}_{2^j} T_j^\ell\|_{L_{\mathfrak{J}c_1}^p \rightarrow L_{\mathfrak{J}c_2}^q} = \|\widehat{K_{\ell+1-j}^\ell}(2^{-j} \cdot)\|_{M_{\mathfrak{J}c_1, \mathfrak{J}c_2}^{p, q}}$$

and

$$\widehat{K_{\ell+1-j}^\ell}(2^{-j} \xi) = \widehat{\theta}(2^{-\ell-1} \xi) [\varphi m(2^{\ell+1-j} \cdot)] * \widehat{\Psi}_\ell(2^{-\ell-1} \xi),$$

and we get

$$\|\widehat{K_{\ell+1-j}^\ell}(2^{-j} \cdot)\|_{M_{\mathfrak{J}c_1, \mathfrak{J}c_2}^{p, q}} \leq \|\theta\|_1 2^{(\ell+1)d(1/p-1/q)} \|[\varphi m(2^{\ell+1-j} \cdot)] * \widehat{\Psi}_\ell\|_{M_{\mathfrak{J}c_1, \mathfrak{J}c_2}^{p, q}}.$$

Hence

$$(6.13) \quad \sup_j \|\text{Dil}_{2^j} T_j^\ell\|_{L^p \rightarrow L^q} \lesssim \mathbf{a}_\ell$$

Next we turn to the ε -regularity conditions (1.9a) and (1.9b). By translation invariance of the operators T_j^ℓ it suffices to verify (1.9a). Using the above formulas for the Fourier transform of $2^{jd} K_{\ell+1-j}^\ell(2^j \cdot)$ we get

$$\begin{aligned} & \|(\text{Dil}_{2^j} T_j^\ell) \circ \Delta_h\|_{L_{\mathfrak{J}c_1}^p \rightarrow L_{\mathfrak{J}c_2}^q} \\ &= \|\widehat{\theta}(2^{-\ell-1} \cdot) [(\varphi m(2^{\ell+1-j} \cdot)) * \widehat{\Psi}_\ell](2^{-\ell-1} \cdot) (e^{i\langle \cdot, h \rangle} - 1)\|_{M_{\mathfrak{J}c_1, \mathfrak{J}c_2}^{p, q}} \\ &\leq 2^{(\ell+1)d(1/p-1/q)} \|\widehat{\theta}[e^{i\langle 2^\ell \cdot, h \rangle} - 1]\|_{M^p} \|[\varphi m(2^{\ell+1-j} \cdot)] * \widehat{\Psi}_\ell\|_{M_{\mathfrak{J}c_1, \mathfrak{J}c_2}^{p, q}}. \end{aligned}$$

Observe that for $0 < \varepsilon < 1$,

$$|h|^{-\varepsilon} \|\widehat{\theta}[e^{i\langle 2^\ell \cdot, h \rangle} - 1]\|_{M^p} \lesssim 2^{\ell\varepsilon}$$

and hence we get

$$(6.14) \quad \sup_{|h| \leq 1} |h|^{-\varepsilon} \sup_j \|(\text{Dil}_{2^j} T_j^\ell) \circ \Delta_h\|_{L_{\mathfrak{J}c_1}^p \rightarrow L_{\mathfrak{J}c_2}^q} \lesssim 2^{\ell\varepsilon} \mathbf{a}_\ell$$

In view of (6.12), (6.13) and (6.14) we can now apply Theorem 1.1 and obtain

$$\begin{aligned} \|\mathcal{T}^\ell\|_{\text{Sp}(p, q)} &\lesssim \sup_{t > 0} \|[\varphi m(t \cdot)] * \widehat{\Psi}_\ell\|_{L_{\mathfrak{J}c_1, \mathfrak{J}c_2}^\infty} \\ &+ \left((1 + \ell)^{|\frac{1}{p} - \frac{1}{2}|} + (1 + \ell)^{|\frac{1}{q} - \frac{1}{2}|} + (1 + \ell) \right) 2^{\ell d(\frac{1}{p} - \frac{1}{q})} \sup_{t > 0} \|[\varphi m(t \cdot)] * \widehat{\Psi}_\ell\|_{M_{\mathfrak{J}c_1, \mathfrak{J}c_2}^{p, q}}. \end{aligned}$$

The desired conclusion then follows from summing in $\ell \geq 0$.

Finally, to remove the assumption of m being compactly supported we observe that by Lemma A.1 it suffices to prove the sparse bound

$$(6.15) \quad \int_{\mathbb{R}^d} \mathcal{F}^{-1}[m \widehat{f}_1](x) f_2(x) dx \leq C(\mathcal{B}_\circ[m] + \mathcal{B}[m]) \Lambda_{p_1, p_2}^*(f_1, f_2)$$

for f_i in the dense class $\mathcal{S}_0(\mathbb{R}^d, \mathcal{H}_i)$ of functions whose Fourier transform is compactly supported in $\widehat{\mathbb{R}}^d \setminus \{0\}$. But for those functions we have

$$\mathcal{F}^{-1}[m \widehat{f}_1] = \mathcal{F}^{-1}[m_{n_1, n_2} \widehat{f}_1],$$

where

$$m_{n_1, n_2} = \sum_{k=n_1}^{n_2} \widehat{\theta}(2^{-k}\xi) \varphi(2^{-k}\xi) m(\xi)$$

with suitable $n_1, n_2 \in \mathbb{Z}$ (depending on f_1). By invariance under multiplication by smooth symbols (see Lemma C.3) we have

$$\sup_{n_1, n_2} \mathcal{B}[m_{n_1, n_2}] \lesssim \mathcal{B}[m]$$

and an analogous inequality involving $\mathcal{B}_o[m]$. We then get (6.15) for $f_i \in \mathcal{S}_0(\mathbb{R}^d, \mathcal{H}_i)$, $i = 1, 2$. A second application of Lemma A.1 yields (6.15) for all $f \in L^p_{\mathcal{H}_1}$ and all $f_2 \in L^{p'}_{\mathcal{H}_2^*}$. \square

Sample applications

In this section we give a number of specific examples of operators to which Theorem 1.1 and its consequences can be applied. Some of the resulting sparse bounds are well-known and others appear to be new.

7.1. Operators generated by compactly supported distributions

In what follows let σ be a distribution which is compactly supported and let $\sigma_t \equiv \text{Dil}_{1/t}\sigma$ denote the t -dilate $t^{-d}\sigma(t^{-1}\cdot)$ given by

$$\langle \sigma_t, f \rangle = \langle \sigma, f(t\cdot) \rangle.$$

Without loss of generality we may assume that the support of σ is contained in $\{x : |x| \leq 1\}$, otherwise argue with a rescaling.

Let

$$(7.1) \quad A_t f(x) = f * \sigma_t(x)$$

which is well defined on Schwartz functions as a continuous function of (x, t) . Many interesting operators in harmonic analysis are generated by dilations of such a single compactly supported distribution (often a measure) and we shall be interested in the corresponding maximal and variational operators. The domain of the dilation parameter t will be either $(0, \infty)$ or $[1, 2]$ or a more general subset E of $(0, \infty)$.

7.1.1. Maximal functions. We are interested in sparse domination results for the maximal functions, as defined in (1.15),

$$M_E^\sigma f(x) = \sup_{t \in E} |A_t f(x)|$$

where $E \subset (0, \infty)$.

If we assume that f is a Schwartz function then M_E^σ is well defined as a measurable function, but for general L^p functions the measurability of M_E^σ is a priori not clear unless we assume that E is countable. In our statements we will restrict ourselves to a priori estimates, but note that in many applications the proof of L^p bounds shows also a priori estimates for the function $t \mapsto \sigma_t * f(x)$ in suitable subspaces of $C(\mathbb{R})$, for almost all $x \in \mathbb{R}^d$. This observation then ensures the measurability of the maximal functions for f in the relevant L^p classes. In the general case, let $I_{k,n} = [k2^{-n}, (k+1)2^{-n})$ and pick, for each (k, n) such that $E \cap I_{k,n} \neq \emptyset$, a representative $t_{k,n} \in E \cap I_{k,n}$ and let \tilde{E} consist of these picked $t_{k,n}$. Then \tilde{E} is countable and we have $M_E^\sigma f(x) = M_{\tilde{E}}^\sigma f(x)$ for all $x \in \mathbb{R}^d$ and all Schwartz functions f . Thus one can assume that E is countable without loss of generality.

We shall now discuss sparse domination inequalities for the operator M_E^σ . Recall the local variants $M_{E_j}^\sigma$, with the rescaled sets $E_j \subset [1, 2]$ as in (1.16). In what

follows recall that

$$\Lambda_{p,q'}^{\mathfrak{S}}(f, \omega) = \sum_{Q \in \mathfrak{S}} |Q| \langle f \rangle_{Q,p} \langle \omega \rangle_{Q,q'},$$

with $\Lambda_{p,q'}^*(f, \omega)$ the supremum of all $\Lambda_{p,q'}^{\mathfrak{S}}(f, \omega)$ over all γ -sparse families \mathfrak{S} .

PROPOSITION 7.1.

(i) *Let $1 < p \leq q < \infty$. Let σ be a compactly supported distribution such that*

$$(7.2) \quad \|M_E^\sigma\|_{L^p \rightarrow L^{p,\infty}} + \|M_E^\sigma\|_{L^{q,1} \rightarrow L^q} < \infty,$$

$$(7.3) \quad \sup_{j \in \mathbb{Z}} \|M_{E_j}^\sigma\|_{L^p \rightarrow L^q} < \infty,$$

and assume that there is an $\epsilon > 0$ so that for all $\lambda \geq 2$,

$$(7.4) \quad \|M_{E_j}^\sigma f\|_q \leq C \lambda^{-\epsilon} \|f\|_p, \quad f \in \mathcal{E}_{\text{ann}}(\lambda).$$

Then for all $f \in L^p$ and all simple non-negative functions ω , we have the sparse domination inequality

$$(7.5) \quad \langle M_E^\sigma f, \omega \rangle \lesssim \Lambda_{p,q'}^*(f, \omega).$$

(ii) *Conversely, if σ has compact support in $\mathbb{R}^d \setminus \{0\}$ then the sparse bound (7.5) for $p < q$ implies that conditions (7.2) and (7.3) hold.*

PROOF. We will apply Theorem 5.1 with $r = \infty$, $B_2 = \ell^\infty(E')$, where E' is a finite subset of E , and

$$(7.6) \quad T_j f(x, t) = \begin{cases} \sigma_t * f(x) & \text{if } t \in E' \cap [2^j, 2^{j+1}) \\ 0 & \text{otherwise.} \end{cases}$$

Note that

$$(7.7a) \quad S_\infty T f(x) \equiv \sup_{j \in \mathbb{Z}} |T_j f(x)|_{B_2} = M_{E'}^\sigma f(x),$$

and, with $E'_j = 2^{-j} E' \cap [1, 2]$,

$$(7.7b) \quad |\text{Dil}_{2^j} T_j f(x)|_{B_2} = M_{E'_j}^\sigma f(x), \quad j \in \mathbb{Z}.$$

As σ is supported in $\{x : |x| \leq 1\}$, the operators T_j satisfy the support condition (1.6). Moreover, (7.2) and (7.7a) guarantee (5.3) with $r = \infty$, and similarly (7.3) and (7.7b) guarantee the single scale (p, q) condition (1.8). It remains to verify the single scale ε -regularity conditions (1.9) for the operators T_j . But this follows from (7.4) and (7.3) via Lemma 3.6 and the fact that for translation-invariant operators T_j , the conditions (1.9a) and (1.9b) are equivalent (alternatively, one can apply Theorem 5.5 for maximal functions). All hypotheses in the first part of Theorem 5.1 are then satisfied and we thus obtain a sparse bound for the maximal operator $M_{E'}^\sigma$. An application of the monotone convergence theorem then yields the desired sparse bound for M_E^σ and concludes the proof of part (i).

For part (ii) note that the assumption that σ is supported away from the origin corresponds to the strengthened support condition (1.14). Thus we can deduce part (ii) directly from part (ii) of Theorem 5.1. \square

PROOF OF THEOREM 1.4. Because of the $L^p \rightarrow L^q$ condition on the operators $M_{E_j}^\sigma$ in (1.17) and the ε -regularity assumption (1.18), it follows by interpolation that the condition (7.4) is satisfied for all $(1/p, 1/q)$ in the interior of $\mathcal{L}(\sigma, E)$. Thus Proposition 7.1 establishes the sufficiency of the conditions, that is, (1.20). The converse follows immediately from part (ii) of Proposition 7.1. \square

Prototypical examples for Proposition 7.1 are the spherical maximal functions where σ is the surface measure on the sphere (for L^p bounds see the classical results by Stein [105] and Bourgain [19], and for $L^p \rightarrow L^q$ bounds see [95, 96]). The proposition covers the results by Lacey [66] for the lacunary and full spherical maximal functions and also the extension to spherical maximal operators with suitable assumptions about various fractal dimensions of E , see [3, 93, 101]. In this context we note that in [5, 45], Lacey’s approach was used to establish sparse domination results for two versions of lacunary spherical maximal functions on the Heisenberg group, defined via the automorphic dilations, and essentially optimal results for the problem considered in [5] can be obtained by combining the sparse technique developed in that paper with recent $L^p \rightarrow L^q$ bounds in [94].

One can also cover more singular measures with Fourier conditions (as in [39], [40]) and this leads to questions about the precise range of L^p improving estimates for the local variants of the maximal functions. As an example consider a curve $s \mapsto \gamma(s)$ in \mathbb{R}^3 with nonvanishing curvature and torsion, and the measures μ_t given by

$$\langle f, \mu_t \rangle = \int f(t\gamma(s))\chi(s)ds$$

with compactly supported χ . A result in [92], applied in combination with decoupling results in [20, 111] yields that the maximal operators M_E are bounded on $L^p(\mathbb{R}^3)$ for $p > 4$. The optimal result for $p > 3$ was recently obtained in [12] and, independently, in [62]. Moreover, the analysis in these papers yield, for the local analogues of these maximal functions (i.e. $E = [1, 2]$), certain $L^p \rightarrow L^q$ bounds for some $q > p$. It would be very interesting to find precise ranges of $L^p \rightarrow L^q$ boundedness of M_E depending on E , and corresponding sparse bounds for related global maximal functions. Similar questions can be considered in higher dimensions but the optimal bounds are currently unknown (for partial results see [13], [63]).

7.1.2. Variational operators. Given $1 \leq r \leq \infty$ and a set $E \subset (0, \infty)$ we define the r -variation seminorm $|\cdot|_{v^r(E)}$ and the r -variation norm $|\cdot|_{V^r(E)}$ of a function $a : E \rightarrow \mathbb{C}$ by

$$|a|_{v^r(E)} = \sup_{M \in \mathbb{N}} \sup_{\substack{t_1 < \dots < t_M \\ t_i \in E}} \left(\sum_{i=1}^{M-1} |a(t_{i+1}) - a(t_i)|^r \right)^{1/r}$$

$$|a|_{V^r(E)} = \sup_{M \in \mathbb{N}} \sup_{\substack{t_1 < \dots < t_M \\ t_i \in E}} \left\{ |a(t_1)| + \left(\sum_{i=1}^{M-1} |a(t_{i+1}) - a(t_i)|^r \right)^{1/r} \right\}.$$

Define the r -variation operators $v_E^r A, \mathcal{V}_E^r A$ for the family of operators of convolution with σ_t by taking the r -variation norm in t ,

$$(7.8) \quad v_E^r A f(x) := |\{\sigma_t * f(x)\}|_{v^r(E)}, \quad \mathcal{V}_E^r A f(x) := |\{\sigma_t * f(x)\}|_{V^r(E)}.$$

This that the above definition of variation is analogous to the definition in (5.7) where we considered the r -variation for functions integers. The results in Chapter 5

mostly apply to the situation where the current E is a subset of $\{2^j : j \in \mathbb{Z}\}$. For general sets $E \subset (0, \infty)$, we will deduce results directly from Corollary 1.2 and Theorem 1.3.

As before we may assume that E is countable (as this does not affect priori estimates). Let $E_j \subset [1, 2]$ be the rescaled sets as in (1.16).

PROPOSITION 7.2.

(i) Let $1 < p \leq q < \infty$. Let σ be a compactly supported distribution such that

$$(7.9) \quad \|\mathcal{V}_E^r A\|_{L^p \rightarrow L^{p,\infty}} + \|\mathcal{V}_E^r A\|_{L^{q,1} \rightarrow L^q} < \infty,$$

$$(7.10) \quad \sup_{j \in \mathbb{Z}} \|\mathcal{V}_{E_j}^r A\|_{L^p \rightarrow L^q} < \infty$$

and assume that there is an $\epsilon > 0$ so that for all $\lambda \geq 2$,

$$(7.11) \quad \|\mathcal{V}_{E_j}^r f\|_q \leq C\lambda^{-\epsilon} \|f\|_p, \quad f \in \mathcal{E}_{\text{ann}}(\lambda).$$

Then for all $f \in L^p$ and all simple nonnegative functions ω , we have the sparse domination inequality

$$(7.12) \quad \langle \mathcal{V}_E^r f, \omega \rangle \lesssim \Lambda_{p,q'}^*(f, \omega).$$

(ii) Conversely, if σ has compact support in $\mathbb{R}^d \setminus \{0\}$ then the sparse bound (7.12) for $p < q$ implies that conditions (7.9) and (7.10) hold.

PROOF. We are aiming to apply Corollary 1.2 with $B_2 = V^r(E')$ for any finite $E' \subset E$. With $T_j f(x, t)$ as in (7.6) and $E'(N_1, N_2) = E' \cap [2^{N_1}, 2^{N_2+1}]$, we get

$$(7.13a) \quad \left| \sum_{j=N_1}^{N_2} T_j f(x) \right|_{V_{E'}^r} = \mathcal{V}_{E'(N_1, N_2)}^r A f(x)$$

and

$$(7.13b) \quad |\text{Dil}_{2^j} T_j f(x)|_{V_{E'}^r} = \mathcal{V}_{2^{-j} E' \cap [1, 2]}^r A f(x).$$

We need to check the assumptions of Corollary 1.2 (i.e. the assumptions of Theorem 1.1). Conditions (1.7a), (1.7b) hold by (7.9) and (7.13a), condition (1.8) holds by (7.10) and (7.13b) and condition (1.9a) follows from (7.10), (7.11), and Lemma 3.6. Condition (1.9a) is equivalent with (1.9b) in the current translation invariant setting.

For the necessity, observe that the assumption that σ is supported away from the origin which corresponds to the strengthened support condition in Theorem 1.3. A sparse bound for $\mathcal{V}_E^r A$ implies via (7.13a) a sparse bound for $\sum_{j=N_1}^{N_2} T_j$ for any pair of integers $N_1 \leq N_2$. We apply Theorem 1.3 and obtain via (7.13a) and (7.13b) that

$$\begin{aligned} & \|\mathcal{V}_{E'(N_1, N_2)}^r A\|_{L^p \rightarrow L^{p,\infty}} + \|\mathcal{V}_{E'(N_1, N_2)}^r A\|_{L^{q,1} \rightarrow L^q} \leq C, \\ & \sup_{N_1 \leq j \leq N_2} \|\mathcal{V}_{2^{-j} E' \cap [1, 2]}^r A\|_{L^p \rightarrow L^q} \leq C, \end{aligned}$$

with the constant C independent of N_1, N_2 and the particular finite subset E' of E . Applications of the monotone convergence theorem then yield the asserted necessary conditions for $\mathcal{V}_E^r A$, that is, (7.9) and (7.10). \square

Proposition 7.2 can be applied to obtain a sparse domination inequality for the r -variation operator associated with the spherical means in \mathbb{R}^d . For the necessary global $L^p \rightarrow L^p$ bounds see [59] and for $L^p \rightarrow L^q$ bounds for the local variation operators we refer to the recent paper [14]. This addresses a question posed in [66] and [1].

REMARK 7.3. In verifying $L^p \rightarrow L^{p,\infty}$ and $L^{q,1} \rightarrow L^q$ assumptions for the variation operators it is (as shown in [58, 59]) often advantageous to write $V_E^r Af(x) \leq V_{\text{dyad}}^r Af(x) + V_{E,\text{sh}}^r Af(x)$ where

$$V_{\text{dyad}}^r Af(x) := \mathcal{V}_{2^{\mathbb{Z}}}^r Af(x)$$

is the standard variation norm over $2^{\mathbb{Z}} := \{2^j : j \in \mathbb{Z}\}$, labeled the *dyadic* or *long variation operator* and where

$$V_{E,\text{sh}}^r Af(x) := \left(\sum_{j \in \mathbb{Z}} |v_{E \cap [2^j, 2^{j+1}]}^r Af(x)|^r \right)^{1/r},$$

is the so-called *short variation operator* which uses only variation seminorms over E within dyadic intervals. The L^p -boundedness of the long variation operators is usually reduced to Lepingle’s theorem [73] (which requires $r > 2$) while the short variation operator is often estimated using a Sobolev embedding inequality (see [58], [59]). We note that it is possible to prove results analogous to Proposition 7.2 for the long variation operator and the short variation operators individually as direct consequences of Theorems 5.2 and 5.1 respectively; the details are left to the reader.

7.1.3. Lacunary maximal functions for convolutions associated with the wave equation. In this section we consider a maximal function generated by convolutions with dilates of a tempered distribution, which is not compactly supported (but still concentrated on a compact set). This class is associated with L^p regularity results for solutions of the wave equation. For both simplicity and definiteness of results we shall only consider a lacunary version, but the argument to deduce the sparse bound extends to other sets of dilations and also to variational variants (for which Lemma A.3 would be useful to treat nonlocal error terms).

For $\beta > 0$ define

$$m_\beta(\xi) = \frac{\cos |\xi|}{(1 + |\xi|^2)^{\beta/2}}$$

and let

$$\mathcal{M}_{\text{lac}}^\beta f(x) = \sup_{k \in \mathbb{Z}} |m_\beta(2^k D)f(x)|.$$

It was shown by Peral in [90] and Miyachi in [87] that $m_\beta(D)$ is bounded on L^p for $\beta \geq (d-1)|1/p - 1/2|$, $1 < p < \infty$. $L^p \rightarrow L^q$ results for m_β go back to [21, 83, 108]; it is known that $m_\beta(D) : L^p \rightarrow L^q$ is bounded if either

- (W) $1 < p \leq 2$, $p \leq q \leq p'$, $\beta \geq (d-1)(\frac{1}{p} - \frac{1}{2}) + \frac{1}{p} - \frac{1}{q}$, or
- (W') $1 < p < \infty$, $\max\{p, p'\} \leq q < \infty$, $\beta \geq (d-1)(\frac{1}{2} - \frac{1}{q}) + \frac{1}{p} - \frac{1}{q}$.

Note that (W') follows from (W) by duality. Moreover it can be shown that $\mathcal{M}_{\text{lac}}^\beta$ is bounded on L^p for $\beta > (d-1)|1/p - 1/2|$ via a single scale analysis, and either Littlewood–Paley theory for $p \geq 2$ or the result stated in Section 6.2 for $1 < p < 2$.

We have the following sparse bound for $\mathcal{M}_{\text{lac}}^\beta$ in the non-endpoint case.

PROPOSITION 7.4. *Suppose $1 < p \leq q < \infty$ and that one of the following two conditions holds.*

$$\begin{aligned} (\text{W}_*) \quad & 1 < p \leq 2, p \leq q \leq p', \beta > (d-1)\left(\frac{1}{p} - \frac{1}{2}\right) + \frac{1}{p} - \frac{1}{q}. \\ (\text{W}'_*) \quad & 1 < p < \infty, \max\{p, p'\} \leq q < \infty, \beta > (d-1)\left(\frac{1}{2} - \frac{1}{q}\right) + \frac{1}{p} - \frac{1}{q}. \end{aligned}$$

Then $\mathcal{M}_{\text{lac}}^\beta \in \text{Sp}(p, q')$.

PROOF. Let $K = \mathcal{F}^{-1}[m_\beta(2\cdot)]$ so that the singular support of K is $\{x : |x| = 1/2\}$. Let $K_{\ell,0} = K * \eta_\ell = \mathcal{F}^{-1}[m_\beta \hat{\eta}_\ell]$, with η_ℓ defined as in (3.9), and split $K_{\ell,0} * f = \mathcal{A}_\ell f + \mathcal{R}_\ell f$ where the convolution kernel R_ℓ of \mathcal{R}_ℓ is supported in $\{x : |x| \geq 1\}$. The maximal function associated to R_ℓ is dominated by $2^{-\ell N}$ times the Hardy–Littlewood maximal function of f , similarly the maximal functions associated to A_ℓ are controlled by the Hardy–Littlewood maximal function for small ℓ and therefore satisfy a (p, q') sparse bound by Section A.2. We use the notation $A_{\ell,0}, R_{\ell,0}$ for the convolution kernels of \mathcal{A}_ℓ and \mathcal{R}_ℓ . Set $K_{\ell,k} = 2^{-kd} K_{\ell,0}(2^{-k}\cdot)$, and similarly define the kernels $A_{\ell,k}$ and $R_{\ell,k}$.

By the $L^p \rightarrow L^p$ result for $m_\beta(D)$ together with the multiplier result mentioned in §6.2 one can easily derive for $\ell > 0$ and any $\varepsilon > 0$

$$\left\| \left(\sum_{k \in \mathbb{Z}} |K_{\ell,k} * f|^2 \right)^{1/2} \right\|_p \lesssim 2^{\ell((d-1)|\frac{1}{p} - \frac{1}{2}| + \varepsilon - \beta)} \|f\|_p$$

for all $1 < p < \infty$ which of course implies

$$\left\| \sup_{k \in \mathbb{Z}} |K_{\ell,k} * f| \right\|_p \lesssim 2^{\ell((d-1)|\frac{1}{p} - \frac{1}{2}| + \varepsilon - \beta)} \|f\|_p.$$

We also have the single scale results

$$(7.14) \quad 2^{\ell\beta} \|K_{\ell,0} * f\|_q \lesssim 2^{\ell((d-1)(\frac{1}{p} - \frac{1}{2}) + \frac{1}{p} - \frac{1}{q})} \|f\|_p$$

if $1 < p \leq 2, p \leq q \leq p'$, and

$$(7.15) \quad 2^{\ell\beta} \|K_{\ell,0} * f\|_q \lesssim 2^{\ell((d-1)(\frac{1}{2} - \frac{1}{q}) + \frac{1}{p} - \frac{1}{q})} \|f\|_p$$

if $1 < p \leq 2, p' < q < \infty$ or $2 \leq p < \infty, p \leq q < \infty$.

By the above mentioned bounds for the operator \mathcal{R}_ℓ and the lacunary maximal operator generated by it we can replace $K_{\ell,k}$ and $K_{\ell,0}$ by $A_{\ell,k}$ and $A_{\ell,0}$, respectively.

Note that the exponents for L^p -boundedness and for L^q boundedness, i.e. $(d-1)|1/p - 1/2|$, $(d-1)|1/q - 1/2|$ are not larger than the exponents in the displayed inequalities (7.14) and (7.15) in their respective ranges. An application of Proposition 7.1 gives the desired sparse results for the maximal function generated by the $A_{\ell,k}$ and then also for the maximal function generated by convolution with $K_{\ell,k}$. Summing in ℓ we can complete the proof of the proposition. \square

REMARK. The multiplier m_β can be replaced by other variants such as

$$m_{\beta,1}(\xi) = \frac{\sin |\xi|}{|\xi|} \frac{1}{(1 + |\xi|^2)^{(\beta-1)/2}}, \quad m_{\beta,2}(\xi) = \frac{J_{\beta-1/2}(|\xi|)}{|\xi|^{\beta-1/2}}.$$

7.2. General classes of multipliers

It is well known that the classical Mihklin–Hörmander multiplier theorem [53, 103] can be interpolated with the L^2 -estimate for multiplier transformations $m(D)$

with bounded multipliers [81, 82]. In particular one gets for $1 < p \leq 2$,

$$(7.16) \quad \|m\|_{M^p} \lesssim \sup_{t>0} \|\phi m(t \cdot)\|_{L_\alpha^r}, \quad 1/r = 1/p - 1/2, \quad \alpha > d/r,$$

where $\|g\|_{L_\alpha^r} = \|(1 + |D|^2)^{\alpha/2} g\|_r$ and ϕ is a nontrivial radial function supported with compact support away from the origin.

We give a sparse bound for this class of multipliers.

PROPOSITION 7.5. *Let $1 < p \leq 2$, $1/r = 1/p - 1/2$ and let m satisfy*

$$(7.17) \quad \sup_{t>0} \|\phi m(t \cdot)\|_{L_\alpha^r} \leq A.$$

Suppose one of the following holds:

- (i) $1 < p \leq q \leq 2$, and $\alpha > d(1/p - 1/2)$.
- (ii) $2 \leq q < \infty$ and $\alpha > d(1/p - 1/q)$.

Then

$$\|m(D)\|_{\text{Sp}_\gamma(p,q')} \lesssim_{p,r,q,\alpha,\gamma} A.$$

PROOF. We deduce this result from Theorem 1.6. Observe the inequality

$$\|g\|_{M^{p,2}} \leq \|g\|_{L^r}, \quad 1/r = 1/p - 1/2,$$

valid for $1 \leq p \leq 2$ which follows by interpolation from the standard cases $p = 1$ and $p = 2$. In view of the embedding $B_{r,1}^0 \hookrightarrow L^r$ (see [110] for the definition and properties of Besov spaces) we get, for $1 \leq p \leq 2$,

$$(7.18) \quad \|g\|_{M^{p,2}} \lesssim \|g\|_{B_{r,1}^0}, \quad 1/r = 1/p - 1/2.$$

Interpolating Bernstein's theorem $B_{2,1}^{d/2} \hookrightarrow \widehat{L^1}$ (which follows from the Cauchy-Schwarz inequality and Plancherel's theorem) with the embedding $B_{\infty,1}^0 \hookrightarrow L^\infty$, we also have for $1 \leq p \leq 2$,

$$(7.19) \quad \|g\|_{M^{p,p}} \lesssim \|g\|_{B_{r,1}^{d/r}}, \quad 1/r = 1/p - 1/2.$$

A further interpolation of (7.18) and (7.19) yields for $1 \leq p \leq q \leq 2$

$$\|g\|_{M^{p,q}} \lesssim \|g\|_{B_{r,1}^{d(\frac{1}{q} - \frac{1}{2})}}, \quad 1/r = 1/p - 1/2.$$

Finally, we have for $M \geq s$, the well-known inequality

$$\|\Delta_h^M g\|_{B_{r,1}^\beta} \lesssim |h|^s \|g\|_{B_{r,1}^{s+\beta}}$$

which we shall use for $\beta = d(1/q - 1/2)$ and which can be deduced from standard L^1 -convolution inequalities.

Now let $r = 2p/(2 - p)$, i.e. $1/r = 1/p - 1/2$. Applying the above inequalities to $g = \phi m(t \cdot)$ we get for $M \geq s$,

$$\sup_{|h| \leq 1} |h|^{-s} \|\Delta_h^M [\phi m(t \cdot)]\|_{M^{p,q}} \lesssim \|\phi m(t \cdot)\|_{B_{r,1}^{d(\frac{1}{q} - \frac{1}{2}) + s}}.$$

Now since $\alpha > d(1/p - 1/2)$ we can find $s > d(1/p - 1/q)$ such that

$$\alpha > d(1/q - 1/2) + s > d(1/p - 1/2).$$

Thus if α is as in the display, then $L_\alpha^r \hookrightarrow B_{r,1}^{d(1/q - 1/2) + s}$ and an application of Theorem 1.6 yields the sparse bound stated in part (i).

For part (ii) let $2 \leq q < \infty$ and observe that

$$(7.20) \quad \|g\|_{M^{p,q}} \lesssim_K \|g\|_{M^{p,2}} \quad \text{if } \text{supp}(g) \subset K, \quad K \text{ compact.}$$

To see this take a Schwartz function v whose Fourier transform equals 1 on K and observe that by Young's inequality convolution with v maps L^2 into L^q . We see from (7.20) and (7.18) that for such compactly supported g and $M > s$,

$$|h|^{-s} \|\Delta_h^M g\|_{M^{p,q}} \lesssim |h|^{-s} \|\Delta_h^M g\|_{B_{r,1}^s} \lesssim \|g\|_{B_{r,1}^s}.$$

This we use for $g = \phi m(\cdot)$ and $\alpha > s > d(1/p - 1/q)$. Then part (ii) follows by the embedding $L_\alpha^r \hookrightarrow B_{r,1}^s$ and an application of Theorem 1.6. \square

REMARK 7.6. The assumption $p \leq 2$ is not a significant restriction. Indeed observe that by definition of the sparse operator classes we have $T \in \text{Sp}(p_1, p_2)$ if and only if $T^* \in \text{Sp}(p_2, p_1)$. For multiplier transformations we have $m(D)^* = m(-D)$ and $m(-D)f(-x) = m(D)[f(\cdot)](x)$ which implies that $m(D) \in \text{Sp}(p_1, p_2)$ if and only if $m(D) \in \text{Sp}(p_2, p_1)$.

We can draw two conclusions from this duality argument. First, the range $1 \leq p \leq 2$, $q \geq p'$ in Proposition 7.5 could be deduced from the result in the range $1 \leq p \leq 2$, $2 \leq q \leq p'$. Second, the result in Proposition 7.5 also implies a result in the range $2 \leq p \leq q < \infty$. Namely, in this case, if $1/r = 1/2 - 1/q$ and $\alpha > d(1/2 - 1/q)$ then one gets $m(D) \in \text{Sp}(p, q')$ under the assumption (7.17).

7.2.1. Miyachi classes and subdyadic Hörmander conditions. We now discuss some consequences for multiplier classes considered by Miyachi [88] and their corresponding versions under a subdyadic Hörmander-type formulation [10]. Given $a > 0, b \in \mathbb{R}$, let $\text{Miy}(a, b)$ denote the class of smooth functions $m : \mathbb{R}^d \rightarrow \mathbb{C}$ supported on $\{\xi : |\xi| \geq 1\}$ and satisfying the differential inequalities

$$(7.21) \quad |\partial^\nu m(\xi)| \lesssim_\nu |\xi|^{-b+|\nu|(a-1)}$$

for all $|\xi| \geq 1$ and all multiindices $\nu \in \mathbb{N}_0^d$ satisfying $|\nu| \leq \lfloor d/2 \rfloor + 1$. The oscillatory multipliers $m_{a,b}$ defined below in (7.26) are considered model cases, at least in regards to the $L^p \rightarrow L^p$ boundedness properties. It is known that multipliers in $\text{Miy}(a, b)$ belong to M^p whenever $b \geq ad|1/p - 1/2|$ and $1 < p < \infty$, see [43, 88]. It has also been observed that these endpoint results are special cases of Hörmander-type multiplier theorems involving certain endpoint Besov spaces, see [4, 99]. Sparse bounds for multipliers in $\text{Miy}(a, b)$ in the non-endpoint range $b > ad|1/p - 1/2|$ were obtained by Cladek and the first author in [11] via a single scale analysis, under the additional assumption that (7.21) hold for all multiindices $\nu \in \mathbb{N}_0^d$. We note that in the range $0 < a < 1$ they also extended these results to larger closely related classes of pseudo-differential operators, cf. [11, 41].

The subdyadic Hörmander-type classes, also extending the class $\text{Miy}(a, b)$ are obtained by replacing the pointwise condition (7.21) by

$$(7.22) \quad \sup_B \text{dist}(B, 0)^{b+(1-a)|\nu|} \left(\frac{1}{|B|} \int_B |D^\nu m(\xi)|^2 d\xi \right)^{1/2} < \infty$$

for all $\nu \in \mathbb{N}_0^d$ with $|\nu| \leq \lfloor d/2 \rfloor + 1$. Here the supremum is taken over all euclidean balls B in \mathbb{R}^d with $\text{dist}(B, 0) \geq 1$ such that $r(B) \sim \text{dist}(B, 0)^{1-a}$, where $r(B)$ denotes the radius of B . This class was considered in [10] which contains sharp weighted inequalities of Fefferman–Stein type that can be used to recover the sharp L^p estimates. In [11, §3] the question was raised whether the results on sparse bounds for multiplier transformations in the Miyachi class can be extended to multipliers satisfying a subdyadic condition above, in the sense that it is sufficient to assume that (7.21) or (7.22) hold for all $|\nu| \leq \lfloor d/2 \rfloor + 1$ rather than for all $\nu \in \mathbb{N}_0^d$.

We shall see that this is the case, and that such and more general multi-scale results can be obtained from Proposition 7.5. The following simple observation will be helpful; note that condition (7.22) (and therefore (7.21)) implies (7.23).

LEMMA 7.7. *Let $a > 0$, $2 \leq r < \infty$, $b > ad/r$. Suppose m_k are supported in $\{\xi : |\xi| \geq 1\}$ and suppose that there is a constant C such that*

$$(7.23) \quad \sup_{t>1} t^{b-a|\iota|} \left(t^{-d} \int_{t/2 \leq |\xi| \leq 2t} [|\xi|^{|\iota|} \partial^\iota m_k(\xi)]^r d\xi \right)^{1/r} \leq C$$

for all multiindices ι with $|\iota| \leq \lfloor d/r \rfloor + 1$ and for all $k \in \mathbb{Z}$. Then the family $\{m_k\}$ satisfies condition

$$(7.24) \quad \sup_{k \in \mathbb{Z}} \sup_{t>0} t^{b-a\alpha} \|\phi m_k(t \cdot)\|_{L_\alpha^r} < \infty$$

for some $\alpha > d/r$.

PROOF. A change of variable shows that the condition (7.23) is equivalent to

$$\|\partial^\iota [\phi m_k(s \cdot)]\|_r \lesssim s^{a|\iota| - b}$$

for all multiindices ι with $|\iota| \leq \lfloor d/r \rfloor + 1$. Pick $\alpha \in (d/r, \lfloor d/r \rfloor + 1)$ such that $\alpha a < b$. Then the condition implies

$$\sup_s \|\phi m_k(s \cdot)\|_{L_\alpha^r} s^{b-a\alpha} < \infty,$$

which implies (7.24) in view of the assumption on the supports since $\alpha > d/r$. \square

We shall now formulate a result for families of multipliers satisfying condition (7.24). For simplicity of our statements, we consider only the case $p \leq 2$ and argue by duality for $p > 2$ (see Remark 7.6).

PROPOSITION 7.8. *Let $1 < p \leq 2$, $r = \frac{2p}{2-p}$ (i.e. $\frac{1}{r} = \frac{1}{p} - \frac{1}{2}$), and let, for $k \in \mathbb{Z}$, m_k be supported in $\{\xi : |\xi| \geq 1\}$. Let $a, b \geq 0$ such that $b > ad(\frac{1}{p} - \frac{1}{2})$ and suppose that either*

- (i) $1 < p \leq q \leq 2$ and $b > ad(\frac{1}{p} - \frac{1}{2})$, or
- (ii) $2 \leq q < \infty$ and $b > ad(\frac{1}{p} - \frac{1}{q})$.

Let $\alpha > d(\frac{1}{p} - \frac{1}{2})$ and assume $\sup_{k \in \mathbb{Z}} \sup_{t>0} t^{b-a\alpha} \|\phi m_k(t \cdot)\|_{L_\alpha^r} < \infty$.

Then $m := \sum_{k \in \mathbb{Z}} m_k(2^k \cdot) \in M_p$ and $m(D) \in \text{Sp}(p, q')$

PROOF. We split, by a dyadic decomposition $m_k(\xi) = \sum_{n=1}^{\infty} m_{k,n}(\xi)$ where $m_{k,n}$ is supported in an annulus $\{\xi : |\xi| \approx 2^n\}$, for all $k \in \mathbb{Z}$; in fact we can set $m_{k,n}(\xi) = m_k(\xi) \hat{\eta}_n(\xi)$ with $\hat{\eta}_n$ as in (3.10). Observe that $m_k \hat{\eta}_0 = 0$ by the support properties of m_k and $\hat{\eta}_0$. Now form $m^n(\xi) = \sum_{k \in \mathbb{Z}} m_{k,n}(2^k \xi)$. We wish to apply Proposition 7.5 to m^n , for every $n \geq 0$.

Fix any $t > 0$ and use the assumption to compute

$$\|\phi m^n(t \cdot)\|_{L_\alpha^r} \lesssim \sum_{\substack{k \in \mathbb{Z}: \\ c_1 2^n \leq 2^k t \leq C_1 2^n}} \|\phi m_{k,n}(2^k t \cdot)\|_{L_\alpha^r} \lesssim 2^{-n(b-a\alpha)}.$$

By (7.16) we obtain $\|m^n\|_{M_p} \lesssim 2^{-n(b-a\alpha)}$ and similarly, by Proposition 7.5 we obtain $\|m^n(D)\|_{\text{Sp}(p, q')} \lesssim 2^{-n(b-a\alpha)}$. The desired bounds follow by summing in n as $\alpha < b/a$. \square

As a consequence we can obtain a sparse bound for the lacunary maximal function $\sup_k |m(2^k D)f|$ and indeed a square function that dominates it.

COROLLARY 7.9. *Let p, r, q, a, b as in Proposition 7.8. Let m be supported in $\{\xi : |\xi| \geq 1\}$ satisfying $\sup_{t>0} t^{b-a\alpha} \|\phi m(t \cdot)\|_{L_\alpha^r} < \infty$. Then we have the (p, q') -sparse bound*

$$\int_{\mathbb{R}^d} \left(\sum_{k \in \mathbb{Z}} |m(2^k D)f(x)|^2 \right)^{1/2} \omega(x) dx \lesssim \Lambda_{p, q'}^*(f, \omega).$$

PROOF. Consider the multiplier $m_v(\xi) = \sum_{k \in \mathbb{Z}} r_k(v) m(2^k \xi)$ where $(r_k)_{k \in \mathbb{N}}$ denotes the sequence of Rademacher functions defined on the unit interval. Then by Proposition 7.8 applied to $m_k(\xi) = r_k(v) m(\xi)$ we obtain

$$(7.25) \quad \left| \int_{\mathbb{R}^d} m_v(D) f_1(x) f_2(x) dx \right| \lesssim \Lambda_{p, q'}^*(f_1, f_2),$$

with the implicit constant independent of v . Let $u_v(x) = \frac{m_v(D)f(x)}{|m_v(D)f(x)|}$ so that u_v is unimodular, and we also get by (7.25) with $f_2 = \omega u_v$

$$\begin{aligned} \int_{\mathbb{R}^d} |m_v(D)f| \omega(x) dx &= \int_{\mathbb{R}^d} m_v(D)f(x) \omega(x) u_v(x) dx \\ &\lesssim \Lambda_{p, q'}^*(f, u_v \omega) \\ &= \Lambda_{p, q'}^*(f, \omega). \end{aligned}$$

Integrating in v and using Fubini's theorem and Khinchine's inequality, one obtains

$$\begin{aligned} \int_{\mathbb{R}^d} \left(\sum_{k \in \mathbb{Z}} |m_k(2^k D)f|^2 \right)^{1/2} \omega(x) dx &\lesssim \int_{\mathbb{R}^d} \int_0^1 |m_v(D)f(x)| dv \omega(x) dx \\ &= \int_0^1 \int_{\mathbb{R}^d} |m_v(D)f(x)| \omega(x) dx dv \\ &\lesssim \Lambda_{p, q'}^*(f, \omega) \end{aligned}$$

and the proof is complete. \square

REMARK. Similar results can be obtained for versions of the previous multiplier classes if $a < 0$ and m is supported in $\{\xi : |\xi| \leq 1\}$. We omit the statements.

7.2.2. Multiscale variants of oscillatory multipliers. Given $a > 0$, $a \neq 1$, $b \in \mathbb{R}$, consider the oscillatory Fourier multipliers

$$(7.26) \quad m_{a,b}(\xi) = \chi_\infty(\xi) |\xi|^{-b} e^{i|\xi|^a},$$

where $\chi_\infty \in C^\infty(\mathbb{R}^d)$ is such that $\chi(\xi) = 0$ for $|\xi| \leq 1$ and $\chi_\infty(\xi) = 1$ for $|\xi| \geq 2$. As already mentioned the operators $m_{a,b}(D)$ are sometimes considered model cases of the class $\text{Miy}(a, b)$, known to be bounded on L^p if and only if $b \geq ad|1/p - 1/2|$ and $1 < p < \infty$; see [104], [43], [88]. This result is sharp when $a \neq 1$; the case $a = 1$ forms an exceptional case corresponding to the wave multipliers considered previously in this chapter, in §7.1.3; we exclude it in this section.

Given a sequence $(c_k)_{k \in \mathbb{Z}}$ with $|c_k| \leq 1$ we form the multiscale variant

$$(7.27) \quad m(\xi) = \sum_{k \in \mathbb{Z}} c_k m_{a,b}(2^k \xi)$$

which is bounded on L^p for $b > ad|1/p - 1/2|$. Proposition 7.8 shows that for $1 < p \leq 2$ we have $m(D) \in \text{Sp}(p, 2)$ for $q \leq 2$, but in order to get a $\text{Sp}(p, q')$ bound

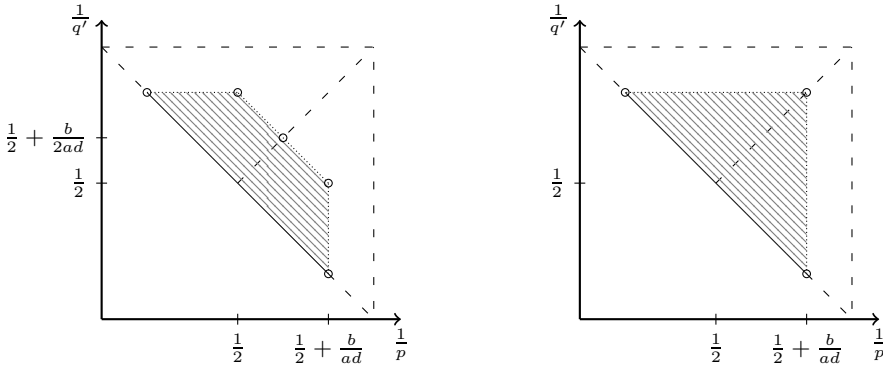


FIGURE 7.1. Sparse bounds for a general multiplier in $\text{Miy}(a, b)$ (left) and for the oscillatory multipliers $m_{a,b}$ (right) for given $a, b > 0$. The condition (ii) in Proposition 7.8 can be relaxed for the specific $m_{a,b}$ (Proposition 7.10).

for $q > 2$ we had to impose the more restrictive condition $b > ad(1/p - 1/q)$. We show that this estimate can be improved, in particular an additional restriction is not necessary for $q \leq p'$ and in this range we can upgrade the $\text{Sp}(p, 2)$ bound to an $\text{Sp}(p, p)$ bound for the multipliers in (7.27) (see Figure 7.1).

This improvement relies on special features of the multipliers $m_{a,b}$ which are not shared by a general multiplier in the class $\text{Miy}(a, b)$. Unlike in the proof of Proposition 7.8 we can no longer rely on analyzing the problem on the multiplier side. Instead we have to analyze Schwartz kernels and employ stationary phase estimates, taking advantage of the fact that the Hessian of the phase function $\xi \mapsto |\xi|^a$ is nondegenerate when $a \neq 1$, $a > 0$. Incidentally, this also reveals that the $m_{a,b}$ satisfy better $L^p \rightarrow L^q$ mapping properties than a general multiplier in $\text{Miy}(a, b)$ when $1 < p \leq 2$, $2 < q \leq p'$. It is therefore more natural to base the proof directly on Theorem 6.1 rather than on the formulation in Theorem 1.6.

PROPOSITION 7.10. *Let $1 < p \leq 2$, $a \in (0, \infty) \setminus \{1\}$, and m as in (7.27), with $\sup_k |c_k| \leq 1$. Let $b > ad(1/p - 1/2)$. Then $m(D) \in \text{Sp}(p, p)$.*

PROOF. We decompose as in the proof of Proposition 7.8. Recall that $\widehat{\eta}_0$ is supported in $\{|\xi| < 1\}$ and $m_{a,b}$ in $\{|\xi| > 1\}$, hence $\widehat{\eta}_0 m_{a,b} = 0$, and we can write $m = \sum_{n=1}^{\infty} m^n$ where

$$m^n(\xi) = \sum_{k \in \mathbb{Z}} c_k m_{a,b}(2^k \xi) \widehat{\eta}_n(2^k \xi).$$

We shall show that

$$(7.28) \quad \|m^n(D)\|_{\text{Sp}_\gamma(p,p)} \lesssim 2^{-n\varepsilon(p)}$$

with $\varepsilon(p) > 0$ and then sum in n .

To verify the claim (7.28) we use Theorem 6.1. For this we have to analyze, for radial $\phi \in C_c^\infty$ supported in $\{|\xi| : 1/2 < |\xi| < 2\}$, the expression

$$\|[\phi m^n(t \cdot)] * \widehat{\Psi}_\ell\|_{M^{p,p'}} \leq \sum_{\substack{k \in \mathbb{Z} \\ 2^{n-3} \leq 2^k t \leq 2^{n+1}}} \|[\phi m_{a,b}(2^k t \cdot) \widehat{\eta}_n(2^k t \cdot)] * \widehat{\Psi}_\ell\|_{M^{p,p'}}$$

and show that for some $\varepsilon > 0$

$$(7.29) \quad \sum_{\ell \geq 0} \sup_{t > 0} \|[\phi m^n(t)] * \widehat{\Psi}_\ell\|_{M^{p,p'}} 2^{\ell(d(1/p-1/p')+\varepsilon)} \lesssim 2^{-n\varepsilon(p)}.$$

To this end, fix k, t with $2^{n-3} \leq 2^k t \leq 2^{n+1}$ and analyze the Fourier inverse of $\phi m_{a,b}(2^k t \cdot) \widehat{\eta}_n(2^k t \cdot)$, i.e.

$$K_n(x) = (2\pi)^{-d} \int \phi(\xi) \widehat{\eta}_n(2^k t \xi) \chi_\infty(2^k t \xi) (2^k t |\xi|)^{-b} e^{i\langle x, \xi \rangle + i(2^k t)^a |\xi|^a} d\xi.$$

The phase function $\langle x, \xi \rangle + (2^k t)^a |\xi|^a$ becomes stationary on the support of ϕ only when $|x| \approx (2^k t)^a \approx 2^{na}$ and the Hessian of $|\xi|^a$ is nondegenerate there. Thus by integration by parts we see that there are constants $c_1 < 1, C_1 > 1$ such that

$$|K_n(x)| \leq \begin{cases} C_N 2^{-n(b+N)} & \text{for } |x| \leq c_1 2^{na} \\ C_N 2^{-nb} |x|^{-N} & \text{for } |x| \geq C_1 2^{na} \end{cases}$$

and by the method of stationary phase

$$|K_n(x)| \lesssim 2^{-n(b+ad/2)}, \quad \text{for } c_1 2^{na} \leq |x| \leq C_1 2^{na}.$$

This implies for $2^{n-3} \leq 2^k t \leq 2^{n+1}$ and suitable C , independently of k, t ,

$$(7.30) \quad \begin{aligned} \|[\phi m^n(2^k t \cdot)] * \widehat{\Psi}_\ell\|_{M^{1,\infty}} & \\ & \lesssim \begin{cases} 2^{-n(b+ad/2)} & \text{for } |\ell - na| \leq C \\ \min\{C_N 2^{-n(b+N)}, C_N 2^{-nb} 2^{-\ell N}\} & \text{for } |\ell - na| > C. \end{cases} \end{aligned}$$

We also have the $M^{2,2}$ bound

$$(7.31) \quad \begin{aligned} \|[\phi m^n(2^k t \cdot)] * \widehat{\Psi}_\ell\|_\infty & \\ & \lesssim \begin{cases} 2^{-nb} & \text{for } |\ell - na| \leq C \\ \min\{C_N 2^{-n(b+N-d)}, C_N 2^{-nb} 2^{-\ell(N-d)}\} & \text{for } |\ell - na| > C. \end{cases} \end{aligned}$$

Interpolating (7.30) and (7.31) we get

$$\|[\phi m^n(2^k t \cdot)] * \widehat{\Psi}_\ell\|_{M^{p,p'}} \lesssim \begin{cases} 2^{-n(b+ad(1/p-1/2))} & \text{for } |\ell - na| \leq C \\ 2^{-nb} C_N \min\{2^{-nN}, 2^{-\ell N}\} & \text{for } |\ell - na| > C. \end{cases}$$

Only the five terms with $2^{n-3} \leq 2^k t \leq 2^{n+1}$ make a contribution. We sum those terms, then take a supremum in t (observing that the displayed bound above is independent of t) and then sum in $\ell \geq 0$. We obtain

$$\begin{aligned} \sum_{\ell \geq 0} \sup_{t > 0} \|[\phi m^n(t \cdot)] * \widehat{\Psi}_\ell\|_{M^{p,p'}} 2^{\ell(d(\frac{1}{p}-\frac{1}{p'})+\varepsilon)} & \\ & \lesssim_\varepsilon 2^{-n(b+ad(\frac{1}{p}-\frac{1}{2}))} 2^{na(d(\frac{1}{p}-\frac{1}{p'})+\varepsilon)} \lesssim 2^{-n(b-ad(\frac{1}{p}-\frac{1}{2}-\varepsilon))}. \end{aligned}$$

Since we assume $b > ad(1/p-1/2)$ this leads to (7.29) and then to the claim (7.28) via Theorem 6.1. \square

Given Proposition 7.10, we can now derive an improved sparse bound for a lacunary maximal function and a corresponding square function associated with the multipliers $m_{a,b}$; thus for these examples we improve on Corollary 7.9.

COROLLARY 7.11. *Let $1 < p \leq 2$, $a > 0$, $b > ad(1/p - 1/2)$. Then*

$$\int_{\mathbb{R}^d} \left(\sum_{k \in \mathbb{Z}} |m_{a,b}(2^k D)f(x)|^2 \right)^{1/2} \omega(x) dx \lesssim \Lambda_{p,p}^*(f, \omega).$$

PROOF. Choose $c_k = \pm 1$ in (7.26). Then Proposition 7.10 together with a randomization argument exactly as in the proof of Corollary 7.9 yields the assertion. \square

7.3. Prototypical versions of singular Radon transforms

Let σ be a bounded Borel measure supported in $\{x : |x| \leq 1\}$ and satisfying

$$(7.32) \quad \int d\sigma = 0 \quad \text{and} \quad \sup_{\xi \in \mathbb{R}^d} (1 + |\xi|)^b |\widehat{\sigma}(\xi)| < \infty \quad \text{for some } b > 0.$$

Let $\{a_j\}_{j \in \mathbb{Z}}$ satisfy

$$(7.33) \quad |a_j| \leq 1$$

and define

$$\mathcal{S}^{N_1, N_2} f(x) = \sum_{j=N_1}^{N_2} a_j 2^{-jd} \sigma(2^{-j} \cdot) * f(x)$$

and

$$(7.34) \quad \mathcal{S}f(x) = \lim_{\substack{N_2 \rightarrow \infty \\ N_1 \rightarrow -\infty}} \mathcal{S}^{N_1, N_2} f(x).$$

This is the ‘‘prototypical’’ singular Radon transform considered by R. Oberlin [89], see also Duoandikoetxea and Rubio de Francia [39]. It is easy to see using the cancellation of the kernel that the limit exists pointwise for C_c^∞ functions.

In addition, we assume that σ is L^{p_0} improving, i.e.

$$(7.35) \quad \|\sigma * f\|_q \leq A \|f\|_{p_0}$$

for some q with $p_0 < q < \infty$. The following result is due to R. Oberlin.

PROPOSITION 7.12 ([89]). *Let σ be as in (7.32), and $\{a_j\}_{j \in \mathbb{Z}}$, \mathcal{S} be as in (7.33), (7.34). Let $1 < p_0 < p < q < \infty$ and assume that (7.35) holds. Then \mathcal{S} satisfies the (p, q') -sparse bound*

$$|\langle \mathcal{S}f, \omega \rangle| \lesssim \Lambda_{p, q'}^*(f, \omega).$$

The same sparse bound holds for the operators \mathcal{S}_{N_1, N_2} , uniformly in N_1, N_2 .

We emphasize that Oberlin also proved certain endpoint estimates for $p = p_0$, working with local Orlicz norms in the definition of sparse forms.

One can extend Proposition 7.12 to cover associated maximal truncation and variational truncation operators defined by

$$\mathcal{S}_* f(x) = \sup_{N_1 < N_2} \left| \sum_{j=N_1}^{N_2} a_j 2^{-jd} \sigma(2^{-j} \cdot) * f(x) \right|,$$

$$\mathcal{V}_*^r \mathcal{S}f(x) = \sup_{M \in \mathbb{N}} \sup_{n_1 < \dots < n_M} \left(\sum_{i=1}^{M-1} \left| \sum_{j=n_i+1}^{n_{i+1}} a_j 2^{-jd} \sigma(2^{-j} \cdot) * f(x) \right|^r \right)^{1/r}.$$

PROPOSITION 7.13. *Let $1 < p_0 < p < q < \infty$, $r > 2$ and σ , $\{a_j\}$ be as in (7.32), (7.33), (7.35). Then \mathcal{S}_* and $\mathcal{V}_*^r \mathcal{S}$ satisfy the sparse bounds*

$$|\langle \mathcal{S}_* f, \omega \rangle| + |\langle \mathcal{V}_*^r \mathcal{S} f, \omega \rangle| \lesssim \Lambda_{p,q'}^*(f, \omega).$$

PROOF. We apply Theorems 5.3 and 5.4. To verify the assumptions (5.11a), (5.11b) see [39, Theorem E]. To verify assumptions (5.12a), (5.12b) see [59, Theorem 1.2]. Interpolation arguments using the Fourier decay assumption in (7.32), and Lemma 3.6 can be used to establish the additional Hölder condition in (1.9). \square

The setup above is also similar in spirit to the theorems on truncations of rough singular integrals with bounded kernels [37]. We have been deliberately short in our presentation as the results in this section are essentially known. For a more detailed exposition the reader may consult §7.4 below in this chapter, in which a singular Radon transform built on spherical integrals is considered, and also other versions of maximal functions associated to singular Radon transforms.

7.3.1. An approach via Fourier multipliers. In order to understand the scope of our multiplier theorems, it is instructive to deduce the sparse bounds for the prototypical singular Radon transform \mathcal{S} in Proposition 7.12 from Theorem 6.1 (or Theorem 1.6). Since σ is a finite Borel measure we have $\|\phi\widehat{\sigma}(2^j t \cdot)\|_{M^{q,q}} = O(1)$ for $1 \leq q \leq \infty$. By (7.32) and interpolation with $L^2 \rightarrow L^2$ bounds we have for some $\varepsilon_0(q) > 0$

$$(7.36) \quad \|\phi\widehat{\sigma}(2^j t \cdot)\|_{M^{q,q}} \lesssim C_q \min\{(2^j t)^{\varepsilon_0(q)}, (2^j t)^{-\varepsilon_0(q)}\}, \quad 1 < q < \infty,$$

using either cancellation or decay, and by Young's inequality we get the same bound for $\|\phi\widehat{\sigma}(2^j t \cdot)\|_{M^{p,q}}$ when $1 \leq p \leq q$, $1 < q < \infty$. This takes care of the term $\ell = 0$ in the condition (6.2a). To verify the remaining hypothesis of Theorem 6.1 it suffices to check that for $\ell > 0$ the condition

$$(7.37) \quad \sup_{t>0} \sum_{j \in \mathbb{Z}} \|[\phi\widehat{\sigma}(2^j t \cdot)] * \widehat{\Psi}_\ell\|_{M^{p,q}} \lesssim 2^{-\ell(d(1/p-1/q)+\varepsilon)}$$

is satisfied, as the condition (6.2b) trivially follows by the assumption (7.32).

Since $\widehat{\sigma}$ is smooth we have for $2^j t \leq 1$

$$\|[\phi\widehat{\sigma}(2^j t \cdot)] * \widehat{\Psi}_\ell\|_{M^{r,s}} \lesssim C_N 2^{-\ell N}, \quad 2^j t \leq 1,$$

for $1 \leq r \leq s \leq \infty$ and therefore by interpolation with (7.36) and taking geometric means we see that there is an $\varepsilon_1(r, s)$ such that $\varepsilon_1(r, s) > 0$ if $1 < r \leq s < \infty$ and

$$(7.38) \quad \|[\phi\widehat{\sigma}(2^j t \cdot)] * \widehat{\Psi}_\ell\|_{M^{r,s}} \lesssim C_N 2^{-\ell d} (2^j t)^{\varepsilon_1(r,s)}, \quad 2^j t \leq 1.$$

The contributions for $2^j t \geq 1$ are more interesting. Since σ is supported in $\{x : |x| \leq 1\}$ we have the kernel estimate

$$|\mathcal{F}^{-1}[\phi\widehat{\sigma}(2^j t \cdot)](x)| \lesssim_N |x|^{-N} \quad \text{for } |x| \geq 2^{j+1}t$$

and hence

$$(7.39) \quad \|[\phi\widehat{\sigma}(2^j t \cdot)] * \widehat{\Psi}_\ell\|_{M^{p,q}} \lesssim 2^{-\ell N} \quad \text{for } 2^\ell \geq 2^{j+4}t \geq 1.$$

For $2^\ell \leq 2^{j+4}t$ we do a rescaling argument to estimate

$$\|[\phi\widehat{\sigma}(2^j t \cdot)] * \widehat{\Psi}_\ell\|_{M^{p_0,q}} \lesssim \|\widehat{\sigma}(2^j t \cdot)\|_{M^{p_0,q}} = (2^j t)^{-d(1/p_0-1/q)} \|\widehat{\sigma}\|_{M^{p_0,q}}$$

and by assumption $\widehat{\sigma} \in M^{p_0, q}$. Interpolating with the $M^{q, q}$ estimate in (7.36) we get for $p_0 < p \leq q$

$$(7.40) \quad \|[\phi\widehat{\sigma}(2^j t \cdot)] * \widehat{\Psi}_\ell\|_{M^{p, q}} \lesssim (2^j t)^{-d(1/p-1/q)-\epsilon(p, q)} \quad \text{for } 2^{j+4}t \geq 2^\ell.$$

Combining (7.38), (7.39) and (7.40) and summing in j we get (7.37) for a suitable $\epsilon = \epsilon(p, q) > 0$.

7.4. Densities on spheres: Maximal singular integrals

As discussed in §7.3 the Corollary 1.2 covers classes of singular Radon transforms and also associated maximal operators for truncations. Here we will consider a natural singular integral variant of the spherical maximal function, and obtain a sparse domination inequality analogous to the one for spherical maximal functions with specific dilation sets in [3, 93]. Let σ be the surface measure on the unit sphere $\{x : |x| = 1\}$ in \mathbb{R}^d for $d \geq 2$ and $\mu = \chi\sigma$ with a choice of smooth χ such that

$$\int d\mu = 0.$$

For every $t \in [1, 2]$ we consider, for fixed $t \in [1, 2]$, the prototypical singular Radon transform as in the previous section

$$(7.41) \quad \mathcal{S}_t^{N_1, N_2} f = \sum_{j=N_1}^{N_2} \mu_{2^j t} * f, \quad \mathcal{S}_t f = \lim_{\substack{N_2 \rightarrow \infty, \\ N_1 \rightarrow -\infty}} \mathcal{S}_t^{N_1, N_2} f$$

and then form, for $E \subset [1, 2]$, the maximal function

$$(7.42) \quad \mathcal{S}_E f(x) = \sup_{t \in E} |\mathcal{S}_t f(x)|.$$

For $0 \leq \beta \leq \alpha \leq 1$ define $\mathcal{R}(\beta, \alpha) \subset [0, 1]^2$ as the union of the interior of the convex hull of the points

$$Q_1 = (0, 0), \quad Q_{2, \beta} = \left(\frac{d-1}{d-1+\beta}, \frac{d-1}{d-1+\beta}\right), \\ Q_{3, \beta} = \left(\frac{d-\beta}{d-\beta+1}, \frac{1}{d-\beta+1}\right), \quad Q_{4, \alpha} = \left(\frac{d(d-1)}{d^2+2\alpha-1}, \frac{d-1}{d^2+2\alpha-1}\right)$$

with the open segment connecting Q_1 and $Q_{2, \beta}$.

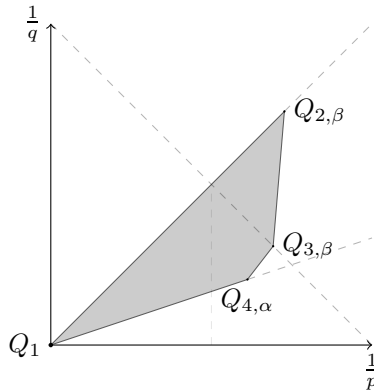


FIGURE 7.2. The region $\mathcal{R}(\beta, \alpha)$ with $\beta = 0.75$, $\alpha = 0.9$, $d = 3$.

For $E \subset [1, 2]$ denote by $\dim_M E$ the upper Minkowski dimension of E and by $\dim_{qA} E$ the quasi-Assouad dimension of E (see [93] for definitions and background, and for a discussion of classes of sets E for which the single-scaled $L^p \rightarrow L^q$ results described above are sharp).

PROPOSITION 7.14. *Let $d \geq 2$, $E \subset [1, 2]$ and $(1/p, 1/q) \in \mathcal{R}(\beta, \alpha)$ with $\beta = \dim_M E$, $\alpha = \dim_{qA} E$. Then there is the (p, q') -sparse domination inequality*

$$|\langle \mathcal{S}_E f, \omega \rangle| \leq C \Lambda_{p, q'}^*(f, \omega).$$

The two-dimensional version of our operator models a maximal operator associated to a family of Hilbert transforms on curves considered in [49, 50] where nonisotropic dilations are used (see also the previous papers [48, 86] for related problems). In this nonisotropic case one could also consider more general situations, i.e. when E is not a subset of $[1, 2]$ (see also the prior work [86] on maximal functions) but this involves multi-parameter structures for which sparse domination result are difficult and in some cases are proved to not hold [7].

PROOF OF PROPOSITION 7.14. Using the density Lemma A.1 we may assume that $f \in C_c^\infty$. It is then easy to see that for any bounded set $U \in \mathbb{R}^n$ we have $\mu_{2^j t} * f(x) = 0$ for all $x \in U$, $t \in [1, 2]$ and sufficiently large j . Moreover using the cancellation of μ and the smoothness of f we see that $\mu_{2^j t} * f(x) = O(2^j)$ as $j \rightarrow -\infty$. Thus we see that for $f \in C_c^\infty$ the function $\mathcal{S}_t f$ is well defined and

$$\lim_{\substack{N_2 \rightarrow \infty \\ N_1 \rightarrow -\infty}} \sup_{t \in [1, 2]} |\mathcal{S}_t f - \mathcal{S}_t^{N_1, N_2} f| = 0,$$

where the limit is uniform on compact sets. It is therefore sufficient to prove a sparse bound for the maximal function $\sup_{t \in E} |\mathcal{S}_t^{N_1, N_2} f|$ which is uniform in N_1, N_2 . In what follows we will drop the superscript in $\mathcal{S}_t^{N_1, N_2}$ but assume that we still working with a truncated sum depending on N_1, N_2 .

To verify conditions (1.8), (1.9) in Corollary 1.2 we first note that for $(\frac{1}{p}, \frac{1}{q}) \in \mathcal{R}(\beta, \alpha)$ there is $\varepsilon(p, q) > 0$ such that for $\lambda > 2$

$$(7.43) \quad \left\| \sup_{t \in E} |\mu_t * f| \right\|_q \lesssim_{p, q} \lambda^{-\varepsilon(p, q)} \|f\|_p, \quad f \in \mathcal{E}_{\text{ann}}(\lambda).$$

This is coupled with an elementary $L^p \rightarrow L^q$ estimate with constant $O(1)$ estimate for functions with frequency support near the origin to yield (1.9a) via Lemma 3.6; this also settles (1.9a) by translation invariance. For inequality (7.43) we may refer to [93, Cor. 2.2].

It remains to verify (1.7a) and (1.7b) which follow by verifying the L^p boundedness of \mathcal{S}_E for $(\frac{1}{p}, \frac{1}{p})$ on the open interval $(Q_1 Q_{2, \beta})$. To accomplish this we make a further decomposition on the frequency side. Let η_ℓ be as in (3.9), (3.10), and set $\eta_{\ell, j} = 2^{-jd} \eta_\ell(2^{-j} \cdot)$, so that $\widehat{\eta_{0, j}}$ is supported where $|\xi| \lesssim 2^{-j}$ and $\widehat{\eta_{\ell, j}}$ is supported where $|\xi| \approx 2^{\ell-j}$. Setting

$$\mathcal{S}_E^\ell f(x) = \sup_{t \in E} \left| \sum_{j=N_1}^{N_2} \mu_{2^j t} * \eta_{\ell, j} * f(x) \right|,$$

it then suffices to show

$$(7.44) \quad \|\mathcal{S}_E^\ell f\|_p \lesssim_p 2^{-\ell \delta(p)} \|f\|_p$$

with $\delta(p) > 0$ for $(\frac{1}{p}, \frac{1}{p}) \in (Q_1 Q_{2,\beta})$. The estimate for $\ell = 0$ reduces to standard singular integral theory; this uses the cancellation of μ . Thus from now on we assume $\ell > 0$.

We shall first discuss the case when either $d \geq 3$ or $d = 2, \beta < 1$ where we use arguments as in [101]. Because of $|\widehat{\mu}(\xi)| \lesssim \min\{|\xi|, |\xi|^{-(d-1)/2}\}$ we get

$$\sup_{\xi \in \mathbb{R}^d} \left| \sum_{j=N_1}^{N_2} \widehat{\mu_{2^j t}}(\xi) \widehat{\eta_{\ell,j}}(\xi) \right| \lesssim 2^{-\ell(d-1)/2},$$

which implies an L^2 boundedness result for the operators \mathcal{S}_t^ℓ with constant

$$O(2^{-\ell(d-1)/2}),$$

uniformly in $t \in [1, 2]$.

We also have the L^p boundedness result

$$\left\| \sum_{j=N_1}^{N_2} \mu_{2^j t} * \eta_{\ell,j} * f \right\|_p \lesssim C_p \|f\|_p, \quad 1 < p < \infty$$

which is a consequence of results on isotropic singular Radon transforms as, say, in [39]. By interpolation we get for all $\varepsilon > 0$

$$\left\| \sum_{j=N_1}^{N_2} \mu_{2^j t} * \eta_{\ell,j} * f \right\|_p \lesssim C_{\varepsilon,p} 2^{\ell\varepsilon(1-1/p)} \min(2^{-\ell\frac{d-1}{p}}, 2^{-\ell\frac{d-1}{p'}}) \|f\|_p, \quad 1 < p < \infty.$$

The same estimate with $\mu_{2^j t} * \eta_{\ell,j}$ replaced by $2^{-\ell} 2^{-jd} [\frac{d}{dt} \mu_t * \eta_\ell](2^{-j}\cdot)$ also holds. We cover the set E with $O(2^{\ell(\beta+\varepsilon)})$ intervals of length $2^{-\ell}$ and argue as in [101, p.119] to obtain

$$\|\mathcal{S}_E^\ell f\|_p \lesssim_\varepsilon 2^{\ell(\frac{\beta}{p}+\varepsilon)} \min(2^{-\ell\frac{d-1}{p}}, 2^{-\ell\frac{d-1}{p'}}) \|f\|_p.$$

This gives (7.44), provided that $d \geq 3$ or $d = 2, \beta < 1$.

For the case $d = 2, \beta = 1$, we need to show L^p boundedness for $p > 2$. By a Sobolev embedding argument this follows from the inequality

$$(7.45) \quad \left(\int_1^2 \left\| \sum_{j=N_1}^{N_2} \mu_{2^j t} * \eta_{\ell,j} * f \right\|_p^p dt \right)^{1/p} + 2^{-\ell} \left(\int_1^2 \left\| \frac{\partial}{\partial t} \sum_{j=N_1}^{N_2} \mu_{2^j t} * \eta_{\ell,j} * f \right\|_p^p dt \right)^{1/p} \lesssim 2^{-\ell/p - \ell a(p)} \|f\|_p$$

where $a(p) > 0$ for $2 < p < \infty$. By Littlewood–Paley theory we see that the bound for the first term in (7.45) reduces to

$$(7.46) \quad \left(\int_1^2 \left\| \left(\sum_{j=N_1}^{N_2} |\mu_{2^j t} * \eta_{\ell,j} * f_j|^2 \right)^{1/2} \right\|_p^p dt \right)^{1/p} \lesssim 2^{-\ell/p - \ell a(p)} \left\| \left(\sum_j |f_j|^2 \right)^{1/2} \right\|_p$$

for $2 < p < \infty$. (7.46) is established by a local smoothing argument as in [49] (see in particular an isotropic version of Corollary 3.6 of that paper). We thus have established the bound for the first term in (7.45), and the argument for the second term is analogous. Finally from (7.45) we obtain (7.44) by another application of Littlewood–Paley theory (applying the inequality to functions f_j with $\widehat{f_j}$ supported where $|\xi| \approx 2^{\ell-j}$). \square

7.5. On radial Fourier multipliers

We consider radial Fourier multipliers on $\widehat{\mathbb{R}}^d$ with $d \geq 2$, of the form $m(\xi) = h(|\xi|)$ where h satisfies the condition $\sup_{t>0} \|\beta h(t \cdot)\|_{L_\alpha^2} < \infty$ for suitable α ; here L_α^2 is the usual Sobolev space on the real line and β is any nontrivial C_c^∞ function with compact support in $(0, \infty)$. By duality we only need to consider the range $p \leq 2$.

The inequality

$$(7.47) \quad \|h(|\cdot|)\|_{M^{p,q}} \lesssim \sup_{t>0} t^{d(\frac{1}{p}-\frac{1}{q})} \|\beta h(t \cdot)\|_{L_\alpha^2}, \quad \alpha > d(1/q - 1/2)$$

is known to hold for $1 < p < \frac{2(d+1)}{d+3}$, $p \leq q \leq 2$ and one may conjecture that it holds for $\frac{2(d+1)}{d+3} < p \leq \frac{2d}{d+1}$ and $p \leq q < \frac{d-1}{d+1}p'$. Indeed, as a straightforward consequence of the Stein–Tomas restriction theorem and Littlewood–Paley theory one gets for the endpoint $p = \frac{2(d+1)}{d+3}$, $q = 2$, $\alpha = 0$, a complete characterization of radial Fourier multipliers in $M^{p,2}$; namely

$$\|h(|\cdot|)\|_{M^{p,2}} \approx \sup_{t>0} t^{d(\frac{1}{p}-\frac{1}{2})} \left(\int_t^{2t} |h(s)|^2 \frac{ds}{s} \right)^{1/2},$$

see *e.g.* [46]. The case $p = q = \frac{2d}{d-1}$ has been settled only in two dimensions in [22, 25], but remains open in three and higher dimensions. Note that as a special case one has the Bochner–Riesz conjecture when $h(s) = (1 - s^2)_+^\lambda$. For partial $L^p \rightarrow L^p$ results in higher dimensions (via the connection [25] with Stein’s square function) we refer to [27, 69, 70, 97], *cf.* §7.6.2.

We formulate sparse bounds for the multipliers satisfying (7.47); in fact our hypotheses will involve the single scale variant

$$(7.48) \quad \|g(|\cdot|)\|_{M^{p,q}} \leq C(\alpha) \|g\|_{L_\alpha^2}, \quad \alpha > d(1/q - 1/2), \quad \text{supp}(g) \subset [1/2, 2].$$

Typically, the assumption (7.48) will be applied to g of the form $\beta h(t \cdot)$.

Theorem 6.1 leads to the following result.

PROPOSITION 7.15. *Let $1 < p \leq q \leq 2$ and let T_h be the convolution operator with multiplier $h(|\cdot|)$. Then*

- (i) *Assume (7.48) holds for a specific exponent pair (p, q) with $1 < p \leq \frac{2d}{d+1}$, $p \leq q \leq \min\{\frac{d-1}{d+1}p', 2\}$, and all $\alpha > d(1/q - 1/2)$. Then*

$$(7.49) \quad \|T_h\|_{\text{Sp}_\gamma(p,q')} \leq C_b \sup_{t>0} \|\beta h(t \cdot)\|_{L_b^2}, \quad b > d(1/p - 1/2).$$

- (ii) *In particular, (7.49) holds true for $1 < p \leq \frac{2(d+1)}{d+3}$, $p \leq q \leq 2$.*

PROOF. We need to verify the assumptions of Theorem 6.1. This amounts to verifying the finiteness of the condition (6.2a). Setting $g = \beta h(t \cdot)$ and fixing $b > d(1/p - 1/2)$ this follows from proving that for $\ell \geq 1$ we have

$$(7.50) \quad \|g(|\cdot|) * \widehat{\Psi}_\ell\|_{M^{p,q}} \lesssim 2^{-\ell(\frac{d}{p} - \frac{d}{q} + \varepsilon(b))} \|g\|_{L_b^2}$$

for some $\varepsilon(b) > 0$.

Let v_0 be supported in $\{s \in \mathbb{R} : |s| < 1/2\}$ such that $\int v_0(s) ds = 1$. For $n \geq 1$ let $v_n(s) = v_0(2^n s) - v_0(2^{n-1} s)$, and define $g_n(s) = g * v_n(s)$. By assumption (7.48), we have $\|g_n(|\cdot|)\|_{M^{p,q}} \lesssim \|g_n\|_{L_\alpha^2}$ for any $\alpha > d(1/q - 1/2)$ and hence also

$$(7.51) \quad \|g_n(|\cdot|) * \widehat{\Psi}_\ell\|_{M^{p,q}} \lesssim \|g_n(|\cdot|)\|_{M^{p,q}} \lesssim \|g_n\|_{L_\alpha^2} \lesssim 2^{-n(b-\alpha)} \|g\|_{L_b^2}.$$

For our fixed choice of $b > d(1/p - 1/2)$, we choose $b_1 < b$ such that $d(1/p - 1/2) < b_1 < b$, so that (7.51) holds for the choice $\alpha = b_1 - d(1/p - 1/q) > d(1/q - 1/2)$.

We let $\epsilon = (b - b_1)(2d)^{-1}$ and use (7.51) for $n \geq \ell(1 + \epsilon)^{-1}$. Since

$$\frac{d(\frac{1}{p} - \frac{1}{q}) + b - b_1}{1 + \epsilon} - d(\frac{1}{p} - \frac{1}{q}) = \frac{b - b_1 - \epsilon d(\frac{1}{p} - \frac{1}{q})}{1 + \epsilon} \leq \frac{b - b_1}{1 + \epsilon} := \varepsilon(b) > 0$$

we get

$$\sum_{n \geq \frac{\ell}{1+\epsilon}} \|g_n(|\cdot|) * \widehat{\Psi}_\ell\|_{M^{p,q}} \lesssim 2^{-\frac{\ell}{1+\epsilon}(\frac{d}{p} - \frac{d}{q} + b - b_1)} \|g\|_{L_b^2} \lesssim 2^{-\ell(\frac{d}{p} - \frac{d}{q} + \varepsilon(b))} \|g\|_{L_b^2}.$$

For $n \leq \ell/(1 + \epsilon)$ we observe that any derivative of order k of $g_n(|\cdot|)$ is $O(2^{kn}\|g\|_1)$ and an N -fold integration by parts gives $|\mathcal{F}^{-1}[g_n(|\cdot|)](x)| \leq C_N 2^{(n-\ell)N}$ for $|x| \approx 2^\ell$, for all $N \in \mathbb{N}$. We use this with $N := 10d\frac{1+\epsilon}{\epsilon}$. By Young's inequality

$$\sum_{n \leq \frac{\ell}{1+\epsilon_1}} \|\mathcal{F}^{-1}[g_n(|\cdot|) * \widehat{\Psi}_\ell]\|_{M^{p,q}} \lesssim C_N \ell 2^{\ell(d - d(\frac{1}{p} - \frac{1}{q}))} 2^{-\ell(\frac{\epsilon}{1+\epsilon}N)} \lesssim C(\epsilon) 2^{-8d\ell}$$

and (7.50) is verified. \square

As an example in the above class of multiplier transformations we consider a multi-scale version of Bochner–Riesz operators. The Bochner–Riesz means of the Fourier integral are defined by

$$(7.52) \quad \widehat{S_t^\lambda f}(\xi) = (1 - |\xi|^2/t^2)_+^\lambda \widehat{f}(\xi)$$

and are conjectured to be bounded from $L^p \rightarrow L^q$ if $\lambda > d(1/q - 1/2) - 1/2$ and $1 \leq p \leq q \leq \min\{\frac{d-1}{d+1}p', 2\}$, with operator norm $O(t^{d(1/p-1/q)})$. One may reduce to $t = 1$ by scaling, and if $h_\lambda(s) = (1 - s^2)_+^\lambda$ then $h_\lambda \in L_\nu^2$ for $\lambda > \nu + 1/2$. Therefore, Proposition 7.15 immediate leads to sparse bounds for operators such as $\sum_{k=-\infty}^{\infty} \pm (S_{2^k}^\lambda - S_{2^{k+1}}^\lambda)$, with uniform bounds in the choice of the sequence of signs. After a standard averaging argument using Rademacher functions this implies sparse bounds for lacunary square functions; indeed the vector-valued version of Theorem 6.1 leads to sparse domination for the lacunary square-function

$$\left(\sum_{k \in \mathbb{Z}} |S_{2^k}^\lambda f - S_{2^{k+1}}^\lambda f|^2 \right)^{1/2}$$

and consequently to sparse bounds for lacunary Bochner–Riesz maximal functions $M_\lambda f = \sup_{k \in \mathbb{Z}} |S_{2^k}^\lambda f|$. These results can be viewed as a natural multi-scale generalization of the sparse domination results for Bochner–Riesz means in [16, 68]. In this context, we remark that there are sharper endpoint sparse domination result for Bochner–Riesz means [61] which yield back some of the known weak type (p, p) endpoint bounds for

$$\lambda = d(1/p - 1/2) - 1/2.$$

However, currently there are no satisfactory sparse bound for analogous endpoint situations which involve multiple frequency scales. We hope to return to this question in the future.

7.6. Stein's square function

In [102] Stein introduced the square function defined via Bochner–Riesz means by,

$$\begin{aligned} G^\alpha f(x) &= \left(\int_0^\infty \left| \frac{\partial S_t^\alpha f(x)}{\partial t} \right|^2 t dt \right)^{1/2} \\ &= c_\alpha \left(\int_0^\infty |S_t^{\alpha-1} f(x) - S_t^\alpha f(x)|^2 \frac{dt}{t} \right)^{1/2} \end{aligned}$$

in order to establish pointwise convergence and strong summability results. Another important connection was established in [25], namely that an L^p -boundedness result for G^α implies that the condition $\sup_{t>0} \|\beta h(t \cdot)\|_{L_\alpha^2} < \infty$ is sufficient for $h(|\cdot|) \in M_p$. Moreover, G^α also controls maximal operators associated to radial Fourier multipliers [23].

The expression $G^\alpha f(x)$ is almost everywhere equivalent to many alternative square functions, which can be obtained via versions of Plancherel's theorem with respect to the t -variable; see the paper by Kaneko and Sunouchi [60]. We distinguish the cases $1 < p \leq 2$, in which by a result of Sunouchi [109] we have L^p boundedness for $\alpha > d(1/p - 1/2) + 1/2$, and the more subtle case $2 \leq p < \infty$, where $L^p(\mathbb{R}^d)$ boundedness for $d \geq 2$ is conjectured for $p > \frac{2d}{d-1}$ and $\alpha > d(1/2 - 1/p)$, and known if $d = 2$ [22]. L^p boundedness in the latter problem is closely related to the multiplier problem discussed in §7.5; see [27, 69, 70, 97] for partial results and [71, 72] for certain endpoint and weighted bounds.

We recall some basic decompositions of the Bochner–Riesz means. One splits

$$(1 - |\xi|^2)_+^{\alpha-1} - (1 - |\xi|^2)_+^\alpha = \sum_{n \geq 0} 2^{-n(\alpha-1)} u_n(|\xi|),$$

where $u_0(0) = 0$, the u_n are smooth, and for $n \geq 1$ we have

$$\text{supp}(u_n) \subset (1 - 2^{-n+1}, 1 - 2^{-n-1})$$

and $|\frac{d^j}{ds^j} u_n(s)| \leq C_j 2^{nj}$ for $j \in \mathbb{N}_0$. Let $K_n = \mathcal{F}^{-1}[u_n(|\cdot|)]$, $K_{n,s} = s^d K_n(s \cdot)$ and

$$G_n f(x) = \left(\int_0^\infty |K_{n,s} * f(x)|^2 \frac{ds}{s} \right)^{1/2},$$

so that

$$G^\alpha f(x) \lesssim \sum_{n=0}^\infty 2^{-n(\alpha-1)} G_n f(x).$$

We shall rely on the standard pointwise estimates obtained by stationary phase calculations,

$$(7.53) \quad |K_n(x)| \lesssim_N (1 + |x|)^{-\frac{d+1}{2}} (1 + 2^{-n}|x|)^{-N}.$$

7.6.1. The case $1 < p \leq 2$. A pointwise sparse domination result for $\alpha > (d+1)/2$ was proved by Carro and Domingo-Salazar [26]. For $1/2 < \alpha \leq (d+1)/2$ we have L^p boundedness ($p \leq 2$) only in the restricted range $\frac{2d}{2\alpha+2d-1} < p \leq 2$, by Sunouchi's result, which is sharp. Thus in this range we are seeking sparse domination results for the forms $\langle G^\alpha f_1, f_2 \rangle$. Theorem 6.1 yields the following.

PROPOSITION 7.16. *Let $d \geq 2$, $\frac{1}{2} < \alpha \leq \frac{d+1}{2}$. Then for $\frac{2d}{2\alpha+2d-1} < p \leq 2$ we have the (p, p) -sparse domination inequality*

$$|\langle G^\alpha f, \omega \rangle| \leq C \Lambda_{p,p}^*(f, \omega).$$

PROOF. The operators G_n are defined through smooth kernels and therefore the result in [26] yields pointwise sparse bounds, with norms depending on n . This settles the case of small values of n . For large values of n , given $\varepsilon > 0$ we have to show

$$(7.54) \quad |\langle G_n f, \omega \rangle| \lesssim_\varepsilon 2^{n(\frac{d}{p} - \frac{d}{2} - \frac{1}{2} + \varepsilon)} \Lambda_{p,p}^{\gamma,*}(f, \omega)$$

since in the assumed range of p we have $\alpha - 1 > d/p - d/2 - 1/2$ and therefore we can sum in n to obtain the result for G^α . Let \mathcal{H} be the Hilbert space $L^2(\mathbb{R}^+, \frac{ds}{s})$. By the linearization argument in Section 4.3, the inequality (7.54) follows, for a scalar function f_1 and an \mathcal{H} -valued function $f_2 = \{f_{2,s}\}$, from

$$\left| \iint K_{n,s} * f_1(x) f_{2,s}(x) \frac{ds}{s} dx \right| \lesssim_\varepsilon 2^{n(\frac{d}{p} - \frac{d}{2} - \frac{1}{2} + \varepsilon)} \Lambda_{p,\mathbb{C},p,\mathcal{H}^*}^{\gamma,*}(f_1, f_2).$$

By Theorem 6.1 this follows from

$$(7.55) \quad \sup_{t>0} \left\| [\beta(|\cdot|) u_n(t|\cdot|)] * \widehat{\Psi}_\ell \right\|_{M_{\mathbb{C},\mathcal{H}^*}^{p,p'}} 2^{\ell(\frac{d}{p} - \frac{d}{p'} + \varepsilon_1)} \lesssim_\varepsilon 2^{n(\frac{d}{p} - \frac{d}{2} - \frac{1}{2} + \varepsilon)}$$

for some $\varepsilon_1 > 0$. To verify (7.55) we argue by interpolation and reduce to the cases $p = 2$ and $p = 1$. It will be helpful to observe that for $1/8 \leq t/s \leq 8$ we can replace the kernel K_n on the left hand side of the inequality in (7.53) by $\mathcal{F}^{-1}[\beta(|\cdot|) u_n(\frac{t}{s}|\cdot|)]$. Thus

$$(7.56) \quad \left(\int |\mathcal{F}^{-1}[\beta(|\cdot|) u_n(\frac{t}{s}|\cdot|)](x)|^2 \frac{ds}{s} \right)^{1/2} \lesssim_N (1 + |x|)^{-\frac{d+1}{2}} (1 + 2^{-n}|x|)^{-N}.$$

Here we used that given t the integrand is zero unless $s \in [t/2, 2t]$. Hence for any $\varepsilon_2 > 0$ (which we choose $\ll \min\{\varepsilon, \varepsilon_1\}$) we get

$$(7.57) \quad \sup_{t>0} \left\| [\beta(|\cdot|) u_n(t|\cdot|)] * \widehat{\Psi}_\ell \right\|_{M_{\mathbb{C},\mathcal{H}^*}^{p,q}} \lesssim_{\varepsilon_2, N} 2^{-\ell N} \quad \text{if } \ell > n(1 + \varepsilon_2).$$

If $p = 2$ we have also have, for $\ell \leq n(1 + \varepsilon_2)$,

$$(7.58) \quad \begin{aligned} \left\| [\beta(|\cdot|) u_n(t|\cdot|)] * \widehat{\Psi}_\ell \right\|_{M_{\mathbb{C},\mathcal{H}^*}^{2,2}} 2^{\ell \varepsilon_1} &\lesssim 2^{\ell \varepsilon_1} \sup_\xi \left(\int |\beta(|\xi|) u_n(\frac{t}{s}|\xi|)|^2 \frac{ds}{s} \right)^{1/2} \\ &\lesssim 2^{\ell \varepsilon_1} 2^{-n/2} \lesssim 2^{n \varepsilon_1 (1 + \varepsilon_2)} 2^{-n/2}. \end{aligned}$$

Furthermore, for $p = 1$ and $\ell \leq n(1 + \varepsilon_2)$ we use (7.56) to see that

$$(7.59) \quad \begin{aligned} \left\| [\beta(|\cdot|) u_n(t|\cdot|)] * \widehat{\Psi}_\ell \right\|_{M_{\mathbb{C},\mathcal{H}^*}^{1,\infty}} 2^{\ell(d+\varepsilon_1)} \\ \lesssim 2^{\ell(d+\varepsilon_1)} 2^{-n(d+1)/2} \lesssim 2^{n(1+\varepsilon_2)(d+\varepsilon_1) - n(d+1)/2} \lesssim 2^{n(d-1)/2 + \varepsilon}. \end{aligned}$$

Combining (7.58), (7.59) with (7.57) we obtain the cases of (7.55) for $p = 1$ and $p = 2$ and (7.55) in the full range $1 \leq p \leq 2$ follows by interpolation. \square

7.6.2. The case $2 < p < \infty$. The reduction to sparse bounds will be similar as in the case $p \leq 2$, but the input information is more subtle. Instead of the pointwise bounds (7.53) we now use that

$$(7.60) \quad \left\| \left(\int_{1/8}^8 |K_{n,s} * f|^2 \frac{ds}{s} \right)^{1/2} \right\|_p \lesssim 2^{n(\frac{d}{2} - \frac{d}{r} - 1)} \|f\|_r,$$

for $2 \leq r \leq p$, $p \geq \frac{2(d+1)}{d-1}$, which was proved using the Stein–Tomas restriction theorem [27, 71, 97]. We then obtain a satisfactory result for $\alpha \geq \frac{d}{d+1}$.

PROPOSITION 7.17. *Let $d \geq 2$, $\frac{d}{d+1} \leq \alpha \leq \frac{d}{2}$. Then for $\frac{2d}{d-2\alpha} < p < \infty$ we have the $(2, p)$ -sparse domination inequality*

$$|\langle G^\alpha f, \omega \rangle| \leq C \Lambda_{2,p}^*(f, \omega).$$

PROOF. Note that in the given p -range, $p > \frac{2(d+1)}{d-1}$ when $\alpha \geq \frac{d}{d+1}$. We use the notation in the proof of the preceding proposition. By linearization (see the argument in Section 4.3) it suffices to prove

$$\left| \iint K_{n,s} * f_1(x) f_{2,s}(x) \frac{ds}{s} dx \right| \lesssim_\varepsilon 2^{n(\frac{d}{2} - \frac{d}{p} - 1 + \varepsilon)} \Lambda_{2,\mathbb{C},p,\mathcal{H}^*}^{\gamma,*}(f_1, f_2)$$

and by Theorem 6.1 this follows, given $\varepsilon > 0$, from

$$(7.61) \quad \left\| [\beta(|\cdot|) u_n(t|\cdot|)] * \widehat{\Psi}_\ell \right\|_{M_{\mathbb{C},\mathcal{H}^*}^{2,p}} 2^{\ell(\frac{d}{2} - \frac{d}{p} + \varepsilon_1)} \lesssim_\varepsilon 2^{n(\frac{d}{2} - \frac{d}{p} - 1 + \varepsilon)}$$

for some $\varepsilon_1 > 0$, uniformly in $t > 0$. For $\ell < n(1 + \varepsilon_2)$ the left hand side is bounded by a constant times

$$(7.62) \quad 2^{n(1+\varepsilon_2)(\frac{d}{2} - \frac{d}{p} + \varepsilon_1)} \left\| \beta(|\cdot|) u_n(t|\cdot|) \right\|_{M_{\mathbb{C},\mathcal{H}^*}^{2,p}}.$$

Using (7.60) for $r = 2$ we get

$$\left\| \left(\int_{t/8}^{8t} |\mathcal{F}^{-1}[\beta(|\cdot|) u_n(\frac{t}{s}|\cdot|) \widehat{f}]|^2 \frac{ds}{s} \right)^{1/2} \right\|_p \lesssim 2^{-n} \|f\|_2$$

and thus the expression in (7.62) is $O(2^{n(1+\varepsilon_2)(\frac{d}{2} - \frac{d}{p} + \varepsilon_1) - n})$. Finally, we choose $\varepsilon_1, \varepsilon_2 \ll \varepsilon$ and combine this with the error estimates (7.57). This completes the verification of (7.61). \square

APPENDIX A

Facts about sparse domination

For completeness, we collect a number of auxiliary results, some of them well-known, about sparse domination.

A.1. Replacing simple functions

It is often convenient to replace the spaces S_{B_1} and $S_{B_2^*}$ in the definition of the $\text{Sp}_\gamma(p_1, B_1, p_2, B_2^*)$ norms by other suitable test function classes such as the spaces of compactly supported C^∞ functions or Schwartz functions. This is justified by the following Lemma.

LEMMA A.1. *Suppose $1 \leq p_1 < p'_2$ and $p_1 < p < p'_2$ and let $T \in \text{Sp}_\gamma(p_1, p_2)$. Let \mathcal{V}_1 be a dense subspace of $L^p_{B_1}$ and \mathcal{V}_2 be a dense subspace of $L^{p'_2}_{B_2^*}$. Then*

$$(A.1) \quad \|T\|_{\text{Sp}_\gamma(p_1, B_1, p_2, B_2^*)} = \sup \left\{ \frac{|\langle Tf_1, f_2 \rangle|}{\Lambda_{p_1, B_1, p_2, B_2^*}^*(f_1, f_2)} : f_i \in \mathcal{V}_i, f_i \neq 0, i = 1, 2 \right\}.$$

PROOF. We first assume that $\mathcal{V}_1 = L^p_{B_1}$ and $\mathcal{V}_2 = L^{p'_2}_{B_2^*}$. In what follows we omit the reference to B_1, B_2^* . The right-hand side of (A.1) dominates $\|T\|_{\text{Sp}_\gamma(p_1, p_2)}$, defined in (1.5). In order to verify the reverse inequality we have to show that given $\epsilon > 0$ and given $f_1 \in L^p, f_2 \in L^{p'}$ we have the inequality

$$(A.2) \quad |\langle Tf_1, f_2 \rangle| \leq (\|T\|_{\text{Sp}_\gamma(p_1, p_2)} + \epsilon) \Lambda_{p_1, p_2}^*(f_1, f_2).$$

This is clear if one of the f_i is zero almost everywhere. We may thus assume that $\|f_1\|_p > 0, \|f_2\|_{p'} > 0$. For any $\epsilon_1 > 0$ choose $g_1 \in S_{B_1}, g_2 \in S_{B_2^*}$ so that $\|f_1 - g_1\|_p \leq \epsilon_1, \|f_2 - g_2\|_{p'} \leq \epsilon_1$, and also $\|g_1\|_p \leq 2\|f_1\|_p, \|g_2\|_{p'} \leq 2\|f_2\|_{p'}$ and estimate, using the definition of $\|T\|_{\text{Sp}_\gamma(p_1, p_2)}$,

$$\begin{aligned} |\langle Tf_1, f_2 \rangle| &\leq |\langle T[f_1 - g_1], f_2 \rangle| + |\langle Tf_1, f_2 - g_2 \rangle| + |\langle Tg_1, g_2 \rangle| \\ &\leq \|T\|_{p-p} (\|f_1 - g_1\|_p \|f_2\|_{p'} + \|f_1\|_p \|f_2 - g_2\|_{p'}) \\ &\quad + \|T\|_{\text{Sp}_\gamma(p_1, p_2)} \Lambda_{p_1, p_2}^*(g_1, g_2) \\ &\leq \|T\|_{p-p} (\epsilon_1 \|f_2\|_{p'} + \|f_1\|_p \epsilon_1) + \|T\|_{\text{Sp}_\gamma(p_1, p_2)} \Lambda_{p_1, p_2}^*(g_1, g_2). \end{aligned}$$

Moreover, for $p_1 < p < p'_2$, one has using (ii) in Lemma A.2. that

$$\begin{aligned} \Lambda_{p_1, p_2}^*(g_1, g_2) &\leq \Lambda_{p_1, p_2}^*(g_1 - f_1, g_2) + \Lambda_{p_1, p_2}^*(f_1, g_2 - f_2) + \Lambda_{p_1, p_2}^*(f_1, f_2) \\ &\leq C_1(p, p_1, p_2) (\|g_1 - f_1\|_p \|g_2\|_{p'} + \|f_1\|_p \|g_2 - f_2\|_{p'}) \\ &\quad + \Lambda_{p_1, p_2}^*(f_1, f_2) \\ &\leq C_1(p, p_1, p_2) (2\|f_2\|_{p'} \epsilon_1 + \|f_1\|_p \epsilon_1) + \Lambda_{p_1, p_2}^*(f_1, f_2) \end{aligned}$$

and thus

$$|\langle Tf_1, f_2 \rangle| \leq \|T\|_{\text{Sp}_\gamma(p_1, p_2)} \Lambda_{p_1, p_2}^*(f_1, f_2) + \mathcal{E},$$

with $\mathcal{E} \leq C(f_1, f_2, p, p_1, p_2, T)\epsilon_1$. Choosing a suitable ϵ_1 depending on ϵ we obtain the assertion (A.2), for the case $\mathcal{V}_1 = L^p$, $\mathcal{V}_2 = L^{p'}$.

In the general case we replace the couple of pairs $(S_{B_1}, S_{B_2^*})$ and $(L^p, L^{p'})$ by the couple of pairs $(\mathcal{V}_1, \mathcal{V}_2)$ and $(L^p, L^{p'})$ and see that a repetition of the above arguments settles this case as well. \square

A.2. The Hardy–Littlewood maximal function

It is a well-known fact that the Hardy–Littlewood maximal operator, denoted by \mathcal{M} , satisfies a sparse domination inequality. We have not been able to identify the original reference for this fact and refer to Lerner’s expository lecture [74] instead. This constitutes a first nontrivial example for sparse domination and we include a standard proof for completeness.

LEMMA A.2. *Let $f \in L^1_{loc}(\mathbb{R}^d)$. Then there exist γ -sparse families $\mathfrak{S}_i(f)$, $i = 1, \dots, 3^d$, such that*

$$\mathcal{M}f(x) \leq 2^d(1 - \gamma)^{-1} \sum_{i=1}^{3^d} \sum_{Q \in \mathfrak{S}_i(f)} \langle f \rangle_{Q,1} \mathbf{1}_Q(x).$$

PROOF. Let \mathfrak{D} be a dyadic lattice and let $\mathcal{M}^{\mathfrak{D}}$ denote the dyadic maximal function associated to \mathfrak{D} , that is, $\mathcal{M}^{\mathfrak{D}}f(x) := \sup_{\substack{Q \ni x \\ Q \in \mathfrak{D}}} \langle f \rangle_Q$. Let

$$(A.3) \quad a = 2^d(1 - \gamma)^{-1}.$$

For each $k \in \mathbb{Z}$, define the sets

$$\Omega_k := \{x \in \mathbb{R}^d : \mathcal{M}^{\mathfrak{D}}f(x) > a^k\}.$$

Let $\mathfrak{Q}(k) = \{Q_k^j\}_j$ be the collection of maximal dyadic cubes with the property $\langle f \rangle_Q > a^k$. If $\text{par}(Q)$ denotes the parent cube of Q then $\langle f \rangle_{\text{par}(Q_k^j)} \leq a^k$ and hence we have

$$(A.4) \quad a^k < \langle f \rangle_{Q_k^j} \leq a^k 2^d$$

for all j . Observe that $Q_k^j \subset \Omega_k$ and $\Omega_k \subseteq \cup_j Q_k^j$. Moreover, the cubes in $\mathfrak{Q}(k)$ are disjoint, and hence Ω_k is the disjoint union of the cubes in $\mathfrak{Q}(k)$.

Define the sets $E_k^j := Q_k^j \setminus \Omega_{k+1}$, and note that the family of sets $\{E_k^j\}_{k,j}$ is pairwise disjoint and $|E_k^j| > (1 - \frac{2^d}{a})|Q_k^j|$; for the last claim, note that

$$\begin{aligned} |Q_k^j \cap \Omega_{k+1}| &= \sum_i |Q_k^j \cap Q_{k+1,i}| \\ &= \sum_{i: Q_{k+1,i}^i \subset Q_k^j} |Q_{k+1,i}^i| \\ &< \sum_{i: Q_{k+1,i}^i \subset Q_k^j} \frac{1}{a^{k+1}} \int_{Q_{k+1,i}^i} |f| \\ &\leq \frac{1}{a^{k+1}} \int_{Q_k^j} |f| \\ &\leq \frac{2^d}{a} |Q_k^j|, \end{aligned}$$

using the disjointness of the cubes Q_{k+1}^i and (A.4) for Q_{k+1}^i and Q_k^j . By our choice (A.3) we see that $|E_k^j| > \gamma|Q_k^j|$ and thus $\mathfrak{S}(f) := \{Q_{k,j}^j\}_{k,j}$ is a γ -sparse family. Moreover,

$$\begin{aligned} \mathcal{M}^{\mathfrak{D}} f(x) &= \sum_{k \in \mathbb{Z}} \mathcal{M}^{\mathfrak{D}} f(x) \mathbf{1}_{\Omega_k \setminus \Omega_{k+1}}(x) \\ &\leq \sum_{k \in \mathbb{Z}} \sum_{Q_k^j} a^{k+1} \mathbf{1}_{E_k^j}(x) \\ &\leq a \sum_{k,j} \langle f \rangle_{Q_k^j} \mathbf{1}_{Q_k^j}(x) \\ &= a \sum_{Q \in \mathfrak{S}(f)} \langle f \rangle_Q \mathbf{1}_Q(x), \end{aligned}$$

by (A.4). Finally, the result for the maximal function \mathcal{M} follows from the 3^d -trick (see [79, Remark 3.2]), which ensures that there exist 3^d dyadic lattices \mathfrak{D}_i , $i = 1, \dots, 3^d$ such that

$$\mathcal{M}f(x) \leq \sum_{i=1}^{3^d} \mathcal{M}^{\mathfrak{D}_i} f(x). \quad \square$$

REMARK. If f has values in a Banach space B , the same argument applies to $f \mapsto \mathcal{M}(|f|_B)$. However, there are more interesting vector-valued extensions such as in the Fefferman–Stein theorem [42], and corresponding general sparse domination results with additional hypotheses on the Banach space are discussed in a paper by Hänninen and Lorist [52].

A.3. Operators associated with dilates of Schwartz functions

It is convenient in many applications to observe that maximal functions and variation operators generated by convolution operators with Schwarz functions satisfy sparse bounds. We choose to deduce the variational statements as a consequence of our Theorems in Chapter 5, but it could also be based *e.g.* on [37]. For the definition of the dyadic and short variation operators we refer to Remark 7.3; here V_{sh}^r is understood with $E = (0, \infty)$.

LEMMA A.3. *Let $K \in C^2(\mathbb{R}^d)$ be a convolution kernel satisfying, for all multi-indices $\alpha \in \mathbb{N}_0^d$ with $\sum_i |\alpha_i| \leq 2$,*

$$|\partial^\alpha K(x)| \leq (1 + |x|)^{-d-2}.$$

*Let $K_t(x) = t^{-d}K(t^{-1}x)$ and let $\mathcal{K}_t f = K_t * f(x)$. Then for $1 < p \leq q < \infty$*

$$\begin{aligned} |\langle \sup_{t>0} |\mathcal{K}_t f|, \omega \rangle| &\lesssim \Lambda_{p,q}^*(f, \omega) \\ |\langle V_{\text{dyad}}^r \mathcal{K} f, \omega \rangle| &\lesssim \Lambda_{p,q}^*(f, \omega), \quad 2 < r < \infty, \\ |\langle V_{\text{sh}}^r \mathcal{K} f, \omega \rangle| &\lesssim \Lambda_{p,q}^*(f, \omega), \quad 2 \leq r < \infty. \end{aligned}$$

PROOF. Since $\sup_{t>0} |\mathcal{K}_t * f|$ is pointwise dominated by the Hardy–Littlewood maximal function the sparse bound for $\langle \sup_{t>0} |\mathcal{K}_t f|, \omega \rangle$ can be directly deduced from the sparse bound for the Hardy–Littlewood maximal function \mathcal{M} in §A.2.

For the variation norm inequalities we decompose $\mathcal{K} = \sum_{n=0}^\infty \mathcal{K}^n$ where \mathcal{K}^n denotes convolution with $K^n := K\Psi_n$ (here Ψ_n is supported where $|x| \approx 2^n$ when

$n > 0$, see (6.1)). We can form the long and short variation operators with respect to the family of operators $\{\mathcal{K}_t^n\}_{t>0}$ where \mathcal{K}_t^n denotes convolution with $K_t^n := t^{-d}K^n(t^{-1}\cdot)$. Using the pointwise bound on ∇K and results in [58] or [59] we have

$$\begin{aligned}\|V_{\text{dyad}}^r \mathcal{K}^n f\|_p &\lesssim_p 2^{-n} \|f\|_p, \quad 1 < p \leq \infty, \quad r > 2, \\ \|V_{\text{sh}}^r \mathcal{K}^n f\|_p &\lesssim_p 2^{-n} \|f\|_p, \quad 1 < p \leq \infty, \quad r \geq 2.\end{aligned}$$

The kernel K_t^n is supported in $\{x : |x| \leq 2^{n-1}t\}$ and from our assumptions it is easy to see that the rescaled estimate

$$\|V_{[1,2]}^r \{2^{nd} K_t^n(2^n \cdot) * f\}\|_q \lesssim 2^{-n} \|f\|_p, \quad 1 \leq p \leq q \leq \infty, \quad 1 \leq r \leq \infty,$$

holds. Moreover, using the bound for ∇K and $\nabla^2 K$ we also get

$$\|V_{[1,2]}^r \{2^{nd} K_t^n(2^n \cdot) * \Delta_h f\}\|_q \lesssim 2^{n(1/r-1)} |h|^{1/r} \|f\|_p$$

for $1 \leq p \leq q \leq \infty$, $1 < r \leq \infty$. Applications of Theorem 5.2 and Theorem 5.1 (for ℓ^r -sums and with the choice of B_2 a subspace of $V_{[1,2]}^r$ of large finite dimension) together with the monotone convergence theorem yield

$$\begin{aligned}|\langle V_{\text{dyad}}^r \mathcal{K}^n f, \omega \rangle| &\lesssim 2^{-n} \Lambda_{p,q'}^*(f, \omega), \quad r > 2, \\ |\langle V_{\text{sh}}^r \mathcal{K}^n f, \omega \rangle| &\lesssim 2^{-n(1-1/r)} \Lambda_{p,q'}^*(f, \omega), \quad r \geq 2.\end{aligned}$$

The proof is completed by summation in n . □

APPENDIX B

Sparse domination: Cases where $p = 1$ or $q = \infty$

Here we describe analogues of our main result Theorem 1.1 which cover cases where $p = 1$ or $q = \infty$; we refer to Remark (iv) following the statement of Theorem 1.1 for an explanation of why these cases need to be treated separately. We formulate three different results, one for $p = 1$, $q < \infty$, one for $q = \infty$, $p > 1$, and one for $p = 1$, $q = \infty$. This allows us to recover the classical case of Calderón–Zygmund operators, although we do not claim universality of sparse-domination results here: for example, we do not recover the sparse domination for Carleson-type operators from [8, 9, 38], neither the works for $p = 1$ by Conde-Alonso, Culiuc, Di Plinio and Ou [29] and by Lerner [78] which also treat results on rough singular integrals, nor the works for $q = \infty$ which can often be upgraded to stronger pointwise sparse domination results of the type (1.1) (see in particular [77], [80], [85]).

We will sketch the proofs of our results, indicating only what modifications need to be made compared to the proof of Theorem 1.1. Theorems B.1, B.2 and B.3 below have applications to maximal operators, square functions and long variation operators (as formulated in Chapter 5) similar to those of Theorem 1.1. We leave the details to the interested reader.

B.1. The case $p = 1, q < \infty$

If $p = 1$, one can drop the condition of weak type (1, 1). Our variant of Theorem 1.1 is then as follows.

THEOREM B.1. *Let $1 \leq q < \infty$. Let $\{T_j\}_{j \in \mathbb{Z}}$ be a family of operators in Op_{B_1, B_2} such that*

- *the support condition (1.6) holds,*
- *the restricted strong type (q, q) condition (1.7b) holds,*
- *the single scale $(1, q)$ condition (1.8) holds,*
- *the single scale ε -regularity conditions (1.9a), (1.9b) hold with $p = 1$.*

Define

$$\mathcal{C} = A(q) + A_\circ(1, q) \log \left(2 + \frac{B}{A_\circ(1, q)} \right).$$

Then, for all integers N_1, N_2 with $N_1 \leq N_2$,

$$\left\| \sum_{j=N_1}^{N_2} T_j \right\|_{\text{Sp}_\gamma(1, B_1, q', B_2^*)} \lesssim_{q, \varepsilon, \gamma, d} \mathcal{C}.$$

PROOF. We argue as in the proof of Theorem 1.1, with the decomposition (4.13) and the bound (4.14). The terms (4.15a), (4.15b) are handled exactly as in the proof of Theorem 1.1. Consider the splitting of *III* as in (4.19). The terms (4.19c) and (4.19d) are estimated as in the proof of Theorem 1.1. We are thus only

left with estimating the term

$$III_1 + III_2 = \sum_{N_1 \leq j \leq N_2} \sum_{\substack{W \in \mathcal{W} \\ L(W) < j}} \langle T_j b_{1,W}, g_2 \rangle.$$

The argument in the proof of Theorem 1.1 does no longer work; recall that for $p > 1$ these terms were bounded immediately via the weak type (p, p) condition (1.7a) and the duality of $L_{B_2^{**}}^{p, \infty}$ and $L_{B_2^*}^{p', 1}$. Instead, here we will bound $III_1 + III_2$ using (1.8) and the regularity condition (1.9a), close in spirit to the bounds of the terms IV_1 and IV_2 (defined in (4.25)) in the proof of Theorem 1.1.

We let $0 < \varepsilon' < \min\{1/q', \varepsilon\}$ and $\ell > 0$ be as in (4.24), that is,

$$2^\ell < \frac{100}{\varepsilon'} \left(2 + \frac{B}{A_o(1, q)} \right) \leq 2^{\ell+1}.$$

Let \mathfrak{R}_j be the collection of dyadic subcubes of Q_0 of side length 2^j . We tile Q_0 into such cubes and write

$$III_1 + III_2 = \sum_s \widetilde{III}_s,$$

where

$$(B.1) \quad \widetilde{III}_s = \sum_{N_1 \leq j \leq N_2} \sum_{R \in \mathfrak{R}_j} \left\langle \sum_{\substack{W \subset R \\ L(W) = j-s}} T_j b_{1,W}, g_2 \mathbb{1}_{3R} \right\rangle.$$

We first note

$$(B.2a) \quad \|T_j\|_{L_{B_1}^1 \rightarrow L_{B_2}^q} \lesssim A_o(1, q) 2^{-jd(1-\frac{1}{q})},$$

$$(B.2b) \quad \|T_j(I - \mathbb{E}_{s-j})\|_{L_{B_1}^1 \rightarrow L_{B_2}^q} \lesssim_\varepsilon B 2^{-jd(1-\frac{1}{q})} 2^{-\varepsilon' s},$$

where (B.2a) follows from the single scale $(1, q)$ condition (1.8) and (B.2b) follows from the single scale ε -regularity condition (1.9a) and Corollary 3.5.

For $L(W) = j - s$, we have $b_{1,W} = (I - \mathbb{E}_{s-j})f_{1,W}$. Let $R \in \mathfrak{R}_j$. By (B.2a) we get

$$(B.3a) \quad \begin{aligned} & \left| \left\langle \sum_{\substack{W \subset R \\ L(W) = j-s}} T_j b_{1,W}, g_2 \mathbb{1}_{3R} \right\rangle \right| \\ & \leq \left\| T_j \sum_{\substack{W \subset R \\ L(W) = j-s}} b_{1,W} \right\|_{L_{B_2}^q} \left\| g_2 \mathbb{1}_{3R} \right\|_{L_{B_2^*}^{q'}} \\ & \lesssim A_o(1, q) |R|^{-(1-\frac{1}{q})} \sum_{\substack{W \subset R \\ L(W) = j-s}} \|b_{1,W}\|_{L_{B_1}^1} |R|^{1/q'} \langle f_2 \rangle_{3Q_0, q'} \\ & \lesssim A_o(1, q) \sum_{\substack{W \subset R \\ L(W) = j-s}} |W| \langle f_1 \rangle_{Q_0, 1} \langle f_2 \rangle_{3Q_0, q'}, \end{aligned}$$

and by (B.2b),

$$\begin{aligned}
& \left| \left\langle \sum_{\substack{W \subset R \\ L(W)=j-s}} T_j b_{1,W}, g_2 \mathbb{1}_{3R} \right\rangle \right| \\
& \leq \left\| T_j (I - \mathbb{E}_{s-j}) \sum_{\substack{W \subset R \\ L(W)=j-s}} f_{1,W} \right\|_{L^q_{B_2}} \left\| g_2 \mathbb{1}_{3R} \right\|_{L^{q'}_{B_2^*}} \\
& \lesssim_\varepsilon B 2^{-\varepsilon' s} |R|^{-(1-\frac{1}{q})} \sum_{\substack{W \subset R \\ L(W)=j-s}} \|f_{1,W}\|_{L^1_{B_1}} |R|^{1/q'} \langle f_2 \rangle_{3Q_{0,q'}} \\
\text{(B.3b)} \quad & \lesssim B 2^{-\varepsilon' s} \sum_{\substack{W \subset R \\ L(W)=j-s}} |W| \langle f_1 \rangle_{Q_{0,1}} \langle f_2 \rangle_{3Q_{0,q'}}.
\end{aligned}$$

Note that in obtaining the above bounds we have used (4.9a) and (4.10).

In the above definition (B.1) for \widetilde{III}_s we write $j = sn + i$ with $i = 1, \dots, s$ so that

$$\begin{aligned}
|\widetilde{III}_s| & \lesssim_\varepsilon \min\{A_o(1, q), B 2^{-\varepsilon' s}\} \\
& \sum_{i=1}^s \sum_{\substack{n \in \mathbb{Z} \\ sn+i \in [N_1, N_2]}} \sum_{R \in \mathfrak{R}_{sn+i}} \sum_{\substack{W \subset R \\ L(W)=sn+i-s}} |W| \langle f_1 \rangle_{Q_{0,p}} \langle f_2 \rangle_{3Q_{0,q'}}.
\end{aligned}$$

Now interchange the order of summation; here consider for fixed $W \in \mathcal{W}$ the set of all triples (R, n, i) such that $L(W) = s(n-1) + i$, $R \in \mathfrak{R}_{sn+i}$ and $W \subset 3R$, and observe that the cardinality of this set is 1. Combining this with the above estimates and summing over the disjoint cubes $W \in \mathcal{W}$ we obtain the bound

$$\begin{aligned}
|III_1 + III_2| & \lesssim_{d,\gamma,\varepsilon} \langle f_1 \rangle_{Q_{0,1}} \langle f_2 \rangle_{3Q_{0,q'}} \sum_{W \in \mathcal{W}} |W| \sum_{s=1}^{\infty} \min\{A_o(1, q), B 2^{-\varepsilon' s}\} \\
& \lesssim A_o(1, q) \log\left(2 + \frac{B}{A_o(1, q)}\right) |Q_0| \langle f_1 \rangle_{Q_{0,1}} \langle f_2 \rangle_{3Q_{0,q'}}
\end{aligned}$$

as desired. \square

In the spirit of Chapter 2, it is possible to deduce that the sparse bound in Theorem B.1 implies that the multi-scale sums $\sum_{j=N_1}^{N_2} T_j$ are of weak-type $(1, 1)$. The proof of this fact is slightly different than the one given in Chapter 2 for $p > 1$, as it cannot rely on the duality between $L^{p,\infty}$ and $L^{p,1}$. We refer to the reader to [29, Appendix B] for details.

B.2. The case $p > 1, q = \infty$

If $q = \infty$ one can drop the restricted strong type (q, q) condition (1.7b). Our variant of Theorem 1.1 is then as follows.

THEOREM B.2. *Let $1 < p \leq \infty$. Let $\{T_j\}_{j \in \mathbb{Z}}$ be a family of operators in Op_{B_1, B_2} such that*

- the support condition (1.6) holds,*
- the weak type (p, p) condition (1.7a) holds,*
- the single scale (p, ∞) condition (1.8) holds,*

◦ the single scale ε -regularity conditions (1.9a), (1.9b) hold with $q = \infty$.

Define

$$\mathcal{C} = A(p) + A_\circ(p, \infty) \log \left(2 + \frac{B}{A_\circ(p, \infty)} \right).$$

Then, for all integers N_1, N_2 with $N_1 \leq N_2$,

$$\left\| \sum_{j=N_1}^{N_2} T_j \right\|_{\text{Sp}_\gamma(p, B_1, 1, B_2^*)} \lesssim_{p, \varepsilon, \gamma, d} \mathcal{C}.$$

PROOF. Again we argue as in the proof of Theorem 1.1 and describe the main induction step. Using the previous notations we now decompose

$$(B.4) \quad \langle S f_1, f_2 \rangle = \text{I} + \text{II} + \text{III} + \text{IV}$$

where

$$\begin{aligned} \text{I} &= \sum_{W \in \mathcal{W}} \langle S_W f_1, f_2 \rangle \\ \text{II} &= \langle (S - \sum_{W \in \mathcal{W}} S_W) f_1, g_2 \rangle \\ \text{III} &= \langle (S - \sum_{W \in \mathcal{W}} S_W) g_1, b_2 \rangle \\ \text{IV} &= \langle (S - \sum_{W \in \mathcal{W}} S_W) b_1, b_2 \rangle. \end{aligned}$$

Note that the numbering here is slightly different from the one in the proof of Theorem 1.1. We deal with the term I using the induction hypothesis as in the proof of Theorem 1.1 and, using the argument therein, it suffices to show that the terms II, III and IV are bounded by $c\mathcal{C}|Q_0|\langle f_1 \rangle_{Q_0, p} \langle f_2 \rangle_{3Q_0, 1}$.

We first consider $\text{II} = \text{II}_1 - \text{II}_2$ where

$$\text{II}_1 = \langle S f_1, g_2 \rangle, \quad \text{II}_2 = \sum_W \langle S_W f_1, g_2 \rangle.$$

Here we use the weak type (p, p) assumption (1.7a) for $p > 1$ and (4.11) for $r_2 = p' < \infty$ to get

$$\begin{aligned} \langle S f_1, g_2 \rangle &\leq \|S f_1\|_{L_{B_2^*}^{p, \infty}} \|g_2 \mathbf{1}_{3Q_0}\|_{L_{B_2^*}^{p', 1}} \\ &\lesssim A(p) \|f_1\|_p \langle f_2 \rangle_{3Q_0, 1} |Q_0|^{1-1/p} \\ &\lesssim A(p) |Q_0| \langle f_1 \rangle_{p, Q_0} \langle f_2 \rangle_{3Q_0, 1} \end{aligned}$$

and

$$\begin{aligned} \sum_{W \in \mathcal{W}} \langle S_W f_1, g_2 \rangle &\leq \sum_W \|S_W [f_1 \mathbf{1}_W]\|_{L_{B_2^*}^{p, \infty}} \|g_2\|_{L_{B_2^*}^\infty} \|\mathbf{1}_{3W}\|_{L_{B_2^*}^{p', 1}} \\ &\lesssim A(p) \sum_{W \in \mathcal{W}} \|f_1 \mathbf{1}_W\|_p \langle f_2 \rangle_{3Q_0, 1} |W|^{1-1/p} \\ &\lesssim A(p) \sum_{W \in \mathcal{W}} |W| \langle f_1 \rangle_{Q_0, p} \langle f_2 \rangle_{3Q_0, 1} \end{aligned}$$

and hence, by the disjointness of the cubes $W \in \mathcal{W}$,

$$(B.5) \quad |\text{II}| \leq |\text{II}_1| + |\text{II}_2| \lesssim A(p) |Q_0| \langle f_1 \rangle_{p, Q_0} \langle f_2 \rangle_{3Q_0, 1}.$$

The last term IV corresponds exactly to the sum $III_3 + III_4$ in the proof of Theorem 1.1, defined in (4.19c), (4.19d), and it is therefore treated in the same way; here the weak type and restricted strong type assumptions are not used. In particular, we obtain

$$(B.6) \quad |IV| \lesssim A_o(p, \infty) \log \left(2 + \frac{B}{A_o(p, \infty)} \right) |Q_0| \langle f_1 \rangle_{p, Q_0} \langle f_2 \rangle_{3Q_0, 1}.$$

It remains to bound the term III. By the definition of g_1 and S_W we have

$$\sum_{W \in \mathcal{W}} S_W g_1 = \sum_{W \in \mathcal{W}} \sum_{j=N_1}^{L(W)} T_j [\text{av}_W [f_1] \mathbf{1}_W] = \sum_{j=N_1}^{N_2} \sum_{\substack{W \in \mathcal{W} \\ j \leq L(W)}} T_j [\text{av}_W [f_1] \mathbf{1}_W]$$

and thus we may split $III = III_1 + III_2$ where

$$\begin{aligned} III_1 &= \langle S[g_1 \mathbf{1}_{\Omega^c}], b_2 \rangle, \\ III_2 &= \sum_{j=N_1}^{N_2} \sum_{\substack{W \in \mathcal{W} \\ L(W) < j}} \langle T_j [\text{av}_W [f_1] \mathbf{1}_W], b_2 \rangle. \end{aligned}$$

Let \mathfrak{R}_j be the collection of dyadic subcubes of Q_0 of side length 2^j . We tile Q_0 into such cubes and write

$$III_1 = \sum_{j=N_1}^{N_2} \sum_{R \in \mathfrak{R}_j} \langle T_j [g_1 \mathbf{1}_{\Omega^c \cap R}], b_2 \rangle = \sum_{j=N_1}^{N_2} \sum_{R \in \mathfrak{R}_j} \langle T_j [g_1 \mathbf{1}_{\Omega^c \cap R}], \sum_{W' \in \mathcal{W}} b_{2, W'} \mathbf{1}_{3R} \rangle.$$

Next, note that in order to have $\langle T_j [g_1 \mathbf{1}_{\Omega^c \cap R}], \sum_{W' \in \mathcal{W}} b_{2, W'} \mathbf{1}_{3R} \rangle \neq 0$ we must have that $\Omega^c \cap R \neq \emptyset$ and $W' \cap 3R \neq \emptyset$. As $W' \in \mathcal{W}$, the above implies

$$5 \text{diam}(W') \leq \text{dist}(W', \Omega^c) \leq 3 \text{diam}(R)$$

and therefore $L(W') < j$. Thus,

$$(B.7) \quad III_1 = \sum_{j=N_1}^{N_2} \sum_{R \in \mathfrak{R}_j} \langle T_j [g_1 \mathbf{1}_{\Omega^c \cap R}], \sum_{\substack{W' \in \mathcal{W} \\ L(W') < j}} b_{2, W'} \mathbf{1}_{3R} \rangle.$$

We next decompose $III_2 = III_{2,1} + III_{2,2}$, where

$$(B.8a) \quad III_{2,1} := \sum_{j=N_1}^{N_2} \langle T_j \left[\sum_{\substack{W \in \mathcal{W} \\ L(W) < j}} \text{av}_W [f_1] \mathbf{1}_W \right], \sum_{\substack{W' \in \mathcal{W} \\ L(W') \geq j}} b_{2, W'} \rangle,$$

$$(B.8b) \quad III_{2,2} := \sum_{j=N_1}^{N_2} \sum_{\substack{W \in \mathcal{W} \\ L(W) < j}} \langle T_j [\text{av}_W [f_1] \mathbf{1}_W], \sum_{\substack{W' \in \mathcal{W} \\ L(W') < j}} b_{2, W'} \rangle.$$

The term $III_{2,1}$ can be treated as in the estimation of the term III_3 in the proof of Theorem 1.1, defined in (4.19c), as cancellation does not play a role in this argument. The geometry expressed in (4.20) is crucial, i.e. we have likewise

$$(B.9) \quad \left. \begin{aligned} \langle T_j [\text{av}_W f_1 \mathbf{1}_W], b_{2, W'} \rangle \neq 0 \\ L(W) < j \leq L(W') \end{aligned} \right\} \implies j \leq L(W') \leq L(W) + 2 \leq j + 2.$$

This implies

$$\begin{aligned}
|\text{III}_{2,1}| &\leq \sum_{N_1 \leq j \leq N_2} \sum_{\substack{W' \in \mathcal{W}: \\ j \leq L(W') \leq j+2}} \sum_{\substack{W \in \mathcal{W}: \\ L(W')-2 \leq L(W) \leq j \\ W \subset 3W'}} |\langle T_j[\text{av}_W[f_1]\mathbb{1}_W], b_{2,W'} \rangle| \\
&\leq A_o(p, \infty) \sum_{N_1 \leq j \leq N_2} 2^{-jd/p} \sum_{\substack{W, W' \in \mathcal{W}: W \subset 3W' \\ j \leq L(W') \leq j+2 \\ L(W')-2 \leq L(W) \leq j}} \|\text{av}_W[f_1]\mathbb{1}_W\|_{L_{B_1}^p} \|b_{2,W'}\|_{L_{B_2}^1} \\
&\lesssim A_o(p, \infty) \langle f_1 \rangle_{Q_0, p} \langle f_2 \rangle_{3Q_0, 1} \\
&\quad \times \sum_{N_1 \leq j \leq N_2} \sum_{\substack{W, W': W \subset 3W' \\ j \leq L(W') \leq j+2 \\ L(W')-2 \leq L(W) \leq j}} 2^{-jd/p} |W|^{1/p} |W'| \\
&\lesssim A_o(p, \infty) \langle f_1 \rangle_{Q_0, p} \langle f_2 \rangle_{3Q_0, 1} \sum_{W' \in \mathcal{W}} |W'| \lesssim A_o(p, \infty) |Q_0| \langle f_1 \rangle_{Q_0, p} \langle f_2 \rangle_{3Q_0, 1}.
\end{aligned}$$

The terms III_1 and $\text{III}_{2,2}$ can be treated in a similar way as in the estimation of the terms IV_1, IV_3 (defined in (4.25)) in the proof of Theorem 1.1. Let $0 < \varepsilon' < \min\{1/p, \varepsilon\}$ and $\ell > 0$ be as in (4.24). Then we split

$$\text{III}_1 = \text{III}_1^{\text{lg}} + \text{III}_1^{\text{sm}}, \quad \text{III}_{2,2} = \text{III}_{2,2}^{\text{lg}} + \text{III}_{2,2}^{\text{sm}}$$

where

$$\begin{aligned}
\text{III}_1^{\text{lg}} &= \sum_{j=N_1}^{N_2} \sum_{R \in \mathfrak{R}_j} \sum_{s=1}^{\ell} \langle T_j[g_1 \mathbb{1}_{\Omega^c \cap R}], \sum_{\substack{W' \in \mathcal{W} \\ L(W')=j-s}} b_{2,W'} \mathbb{1}_{3R} \rangle \\
\text{III}_1^{\text{sm}} &= \sum_{j=N_1}^{N_2} \sum_{R \in \mathfrak{R}_j} \sum_{s=\ell+1}^{\infty} \langle g_1 \mathbb{1}_{\Omega^c \cap R}, T_j^* \left[\sum_{\substack{W' \in \mathcal{W} \\ L(W')=j-s}} b_{2,W'} \mathbb{1}_{3R} \right] \rangle
\end{aligned}$$

and

$$\begin{aligned}
\text{III}_{2,2}^{\text{lg}} &= \sum_{j=N_1}^{N_2} \sum_{R \in \mathfrak{R}_j} \sum_{s=1}^{\ell} \left\langle \sum_{\substack{W \subset R \\ L(W) < j}} T_j[\text{av}_W[f_1]\mathbb{1}_W], \sum_{\substack{W' \in \mathcal{W} \\ L(W')=j-s}} b_{2,W'} \mathbb{1}_{3R} \right\rangle, \\
\text{III}_{2,2}^{\text{sm}} &= \sum_{j=N_1}^{N_2} \sum_{R \in \mathfrak{R}_j} \sum_{s=\ell+1}^{\infty} \left\langle \sum_{\substack{W \subset R \\ L(W) < j}} \text{av}_W[f_1]\mathbb{1}_W, T_j^* \left[\sum_{\substack{W' \in \mathcal{W} \\ L(W')=j-s}} b_{2,W'} \mathbb{1}_{3R} \right] \right\rangle.
\end{aligned}$$

Observe that the terms $\text{III}_1^{\text{sm}}, \text{III}_{2,2}^{\text{sm}}$ involve very small cubes W' for which the cancellation of $b_{2,W'}$ can be most effectively used. The terms $\text{III}_1^{\text{lg}}, \text{III}_{2,2}^{\text{lg}}$ involve larger cubes; for these terms it is more effective to use the single scale (p, q) conditions (1.8).

We note that the terms III_1^{lg} and $\text{III}_{2,2}^{\text{lg}}$ behave very similarly, and also the terms III_1^{sm} and $\text{III}_{2,2}^{\text{sm}}$.

Indeed, if h_R, \tilde{h}_R denote either of the first functions on the bilinear form,

$$h_R(x) = g_1(x)\mathbb{1}_{\Omega^c \cap R}, \quad \tilde{h}_R(x) = \sum_{\substack{W \subset R \\ L(W) < j}} \text{av}_W[f_1]\mathbb{1}_W(x),$$

then it follows from the definition of $\Omega^{\mathfrak{G}}$ and the disjointness of the $W \in \mathcal{W}$ that h_R, \tilde{h}_R share the relevant property

$$\|h_R\|_{L_{B_1}^r}, \|\tilde{h}_R\|_{L_{B_1}^r} \leq |R|^{1/r} \langle f_1 \rangle_{Q_0, p}, \quad 1 \leq r \leq \infty,$$

which we will use with $r = p$.

By the above considerations, the hypothesis (1.8) and (4.9a) we have

$$\begin{aligned} \text{III}_1^{\text{lg}} &= \sum_{j=N_1}^{N_2} \sum_{R \in \mathfrak{R}_j} \sum_{s=1}^{\ell} \langle T_j h_R, \sum_{\substack{W' \in \mathcal{W} \\ L(W')=j-s}} b_{2, W'} \mathbb{1}_{3R} \rangle \\ &\lesssim \sum_{s=1}^{\ell} \sum_{j=N_1}^{N_2} \sum_{R \in \mathfrak{R}_j} A_o(p, \infty) 2^{-jd/p} \|h_R\|_{L_{B_1}^p} \left\| \sum_{\substack{W' \in \mathcal{W} \\ L(W')=j-s}} b_{2, W'} \mathbb{1}_{3R} \right\|_{L_{B_2^*}^1} \\ &\lesssim \sum_{s=1}^{\ell} A_o(p, \infty) \langle f_1 \rangle_{Q_0, p} \sum_{j=N_1}^{N_2} \sum_{R \in \mathfrak{R}_j} \sum_{\substack{W' \subset 3R \\ L(W')=j-s}} \|b_{2, W'}\|_{L_{B_2^*}^1} \\ &\lesssim A_o(p, \infty) \langle f_1 \rangle_{Q_0, p} \langle f_2 \rangle_{3Q_0, 1} \sum_{s=1}^{\ell} \sum_{j=N_1}^{N_2} \sum_{\substack{W' \in \mathcal{W} \\ L(W')=j-s}} |W'| \\ &\lesssim \ell A_o(p, \infty) |Q_0| \langle f_1 \rangle_{Q_0, p} \langle f_2 \rangle_{3Q_0, 1} \end{aligned}$$

and hence, by the definition of ℓ ,

$$\text{III}_1^{\text{lg}} \lesssim A_o(p, \infty) \log\left(2 + \frac{B}{A_o(p, \infty)}\right) |Q_0| \langle f_1 \rangle_{Q_0, p} \langle f_2 \rangle_{3Q_0, 1}.$$

Similarly we show (after replacing h_R with \tilde{h}_R in the above calculation)

$$\text{III}_{2,2}^{\text{lg}} \lesssim A_o(p, \infty) \log\left(2 + \frac{B}{A_o(p, \infty)}\right) |Q_0| \langle f_1 \rangle_{Q_0, p} \langle f_2 \rangle_{3Q_0, 1}.$$

For the estimation of $\text{III}_1^{\text{sm}}, \text{III}_{2,2}^{\text{sm}}$ we use the ε -regularity property (1.9b) and Corollary 3.5 to get

$$(B.10) \quad \|T_j^*(\mathbf{I} - \mathbb{E}_{s-j})\|_{L_{B_1}^1 \rightarrow L_{B_2}^{p'}} \lesssim_{\varepsilon} B 2^{-jd/p} 2^{-\varepsilon s}.$$

Moreover we use the formula $b_{2,W'} = (I - \mathbb{E}_{s-j})f_{2,W'}$, valid for $L(W') = j - s$. Thus, via Hölder's inequality

$$\begin{aligned}
& \sum_{j=N_1}^{N_2} \sum_{R \in \mathfrak{R}_j} \sum_{s=\ell+1}^{\infty} \langle h_R, T_j^* \left[\sum_{\substack{W' \in \mathcal{W} \\ L(W')=j-s}} b_{2,W'} \mathbb{1}_{3R} \right] \rangle \\
& \lesssim \sum_{j=N_1}^{N_2} \sum_{s=\ell+1}^{\infty} \|h_R\|_{L_{B_1}^p} \|T_j^*(I - \mathbb{E}_{s-j})\|_{L_{B_2^*}^1 \rightarrow L_{B_1}^{p'}} \left\| \sum_{\substack{W' \in \mathcal{W} \\ L(W')=j-s}} f_{2,W'} \mathbb{1}_{3R} \right\|_{L_{B_2^*}^1} \\
& \lesssim \sum_{j=N_1}^{N_2} \sum_{R \in \mathfrak{R}_j} \sum_{s=\ell+1}^{\infty} |R|^{1/p} \langle f_1 \rangle_{Q_{0,p}} B 2^{-\varepsilon' s} 2^{-jd/p} \left\| \sum_{\substack{W' \in \mathcal{W} \\ L(W')=j-s_2}} f_{2,W'} \mathbb{1}_{3R} \right\|_{L_{B_2^*}^1} \\
& \lesssim \sum_{j=N_1}^{N_2} \sum_{s=\ell+1}^{\infty} B 2^{-\varepsilon' s} \langle f_1 \rangle_{Q_{0,p}} \sum_{R \in \mathfrak{R}_j} \sum_{\substack{W' \subseteq 3R \\ L(W')=j-s}} \|f_{2,W'}\|_{L_{B_2^*}^1} \\
& \lesssim \sum_{j=N_1}^{N_2} \sum_{s=\ell+1}^{\infty} B 2^{-\varepsilon' s} \langle f_1 \rangle_{Q_{0,p}} \langle f_2 \rangle_{3Q_{0,1}} \sum_{R \in \mathfrak{R}_j} \sum_{\substack{W' \subseteq 3R \\ L(W')=j-s}} |W'|.
\end{aligned}$$

We sum in W' and then use $\sum_{s=\ell+1}^{\infty} B 2^{-\varepsilon' s} \lesssim A_o(p, \infty)$ to obtain

$$|\text{III}_1^{\text{sm}}| \lesssim A_o(p, \infty) |Q_0| \langle f_1 \rangle_{Q_{0,p}} \langle f_2 \rangle_{3Q_{0,1}}.$$

In exactly the same way (replacing h_R by \tilde{h}_R) we obtain

$$|\text{III}_{2,2}^{\text{sm}}| \lesssim A_o(p, \infty) |Q_0| \langle f_1 \rangle_{Q_{0,p}} \langle f_2 \rangle_{3Q_{0,1}}.$$

This concludes the proof. \square

B.3. The case $p = 1$ and $q = \infty$

In this case we can get rid of both the weak (p, p) and restricted strong type (q, q) hypotheses, but we shall still assume either a weak-type estimate (r, r) or restricted strong type (r, r) for some $1 < r < \infty$.

THEOREM B.3. *Let $\{T_j\}_{j \in \mathbb{Z}}$ be a family of operators in Op_{B_1, B_2} such that*

- *the support condition (1.6) holds,*
- *there exists $r \in (1, \infty)$ so that either the weak type (r, r) condition (1.7a) holds or the restricted strong type (r, r) condition (1.7b) holds,*
- *the single scale $(1, \infty)$ condition (1.8) holds,*
- *the single scale ε -regularity conditions (1.9a), (1.9b) hold with $p = 1$ and $q = \infty$.*

Define

$$\mathcal{C} = A(r) + A_o(1, \infty) \log \left(2 + \frac{B}{A_o(1, \infty)} \right).$$

Then, for all integers N_1, N_2 with $N_1 \leq N_2$,

$$\left\| \sum_{j=N_1}^{N_2} T_j \right\|_{\text{Sp}_{\gamma}(1, B_{1,1}, B_2^*)} \lesssim_{r, \varepsilon, \gamma, d} \mathcal{C}.$$

SKETCH OF PROOF. We use the terminology in the proofs of Theorems B.1 and B.2. An examination of the proofs reveals that it only remains to establish the inequality

$$(B.11) \quad |\langle (S - \sum_{W \in \mathcal{W}} S_W)g_1, g_2 \rangle| \lesssim A(r)|Q_0|\langle f_1 \rangle_{Q_{0,1}}\langle f_2 \rangle_{3Q_{0,1}},$$

either under the restricted strong type (r, r) assumption (1.7b), or under the weak type (r, r) assumption (1.7a). Here we will strongly use (4.10) for both g_1 and g_2 .

We first verify (B.11) assuming (1.7b). By Hölder's inequality,

$$\begin{aligned} |\langle Sg_1, g_2 \rangle| &\lesssim \|Sg_1\|_{L_{B_1}^r} \|g_2\|_{L_{B_2^*}^{r'}} \\ &\lesssim A(r)\|g_1\|_{L_{B_1}^{r,1}} |Q_0|^{1/r'} \|g_2\|_{L_{B_2^*}^\infty} \\ &\lesssim A(r)|Q_0|\langle f_1 \rangle_{Q_{0,p}}\langle f_2 \rangle_{3Q_{0,1}}. \end{aligned}$$

Moreover for each $W \in \mathcal{W}$

$$\begin{aligned} |\langle S_W g_1, g_2 \rangle| &= |\langle S_W [g_1 \mathbf{1}_W], g_2 \mathbf{1}_{3W} \rangle| \\ &\leq \|S_W [g_1 \mathbf{1}_W]\|_{L_{B_1}^r} \|g_2 \mathbf{1}_{3W}\|_{L_{B_2^*}^{r'}} \\ &\lesssim A(r)\|g_1 \mathbf{1}_W\|_{L_{B_1}^{r,1}} |W|^{1/r'} \|g_2 \mathbf{1}_{3W}\|_{L_{B_2^*}^\infty} \\ &\lesssim A(r)|W|\langle f_1 \rangle_{Q_{0,p}}\langle f_2 \rangle_{3Q_{0,1}}, \end{aligned}$$

and by summing over the disjoint cubes $W \in \mathcal{W}$ we obtain

$$\sum_{W \in \mathcal{W}} |\langle S_W g_1, g_2 \rangle| \lesssim A(r)|Q_0|\langle f_1 \rangle_{Q_{0,p}}\langle f_2 \rangle_{3Q_{0,1}}.$$

Combining the two bounds yields (B.11) (under the assumption (1.7b)).

We now verify (B.11) assuming (1.7a). First, by Hölder's inequality for Lorentz spaces,

$$\begin{aligned} |\langle Sg_1, g_2 \rangle| &\lesssim \|Sg_1\|_{L_{B_1}^{r,\infty}} \|g_2\|_{L_{B_2^*}^{r',1}} \\ &\lesssim A(r)\|g_1\|_{L_{B_1}^r} |Q_0|^{1/r'} \|g_2\|_{L_{B_2^*}^\infty} \\ &\lesssim |Q_0|\langle f_1 \rangle_{Q_{0,p}}\langle f_2 \rangle_{3Q_{0,1}}. \end{aligned}$$

Similarly, for all $W \in \mathcal{W}$,

$$|\langle S_W g_1, g_2 \rangle| \lesssim |W|\langle f_1 \rangle_{Q_{0,p}}\langle f_2 \rangle_{3Q_{0,1}}$$

and then after summation

$$\sum_{W \in \mathcal{W}} |\langle S_W g_1, g_2 \rangle| \lesssim |Q_0|\langle f_1 \rangle_{Q_{0,p}}\langle f_2 \rangle_{3Q_{0,1}}.$$

This yields (B.11) (under the assumption (1.7a)). \square

APPENDIX C

Facts about fourier multipliers

For completeness, we provide proofs of the facts stated in the remark after the definition of the $\mathcal{B}[m]$. The proofs will be given for scalar multipliers but they carry over to the setting with $\mathcal{L}(\mathcal{H}_1, \mathcal{H}_2)$ -valued multipliers. We start with the following simple observations.

LEMMA C.1. *Let $\Psi \in C_c^\infty(\mathbb{R}^d)$ be supported in $\{x \in \mathbb{R}^d : 1/2 < |x| < 2\}$. Let $\Phi \in C_c^\infty(\mathbb{R}^d)$ be supported in $\{x \in \mathbb{R}^d : |x| < 2\}$. Let $N > d$ and κ be such that*

$$\sup_{x \in \mathbb{R}^d} (1 + |x|)^N |\kappa(x)| \leq 1.$$

Then the following hold.

(i) *Let $1 \leq \rho \leq R/8$. Then*

$$\|[\widehat{\kappa}(m * R^d \widehat{\Psi}(R \cdot))] * \rho^d \widehat{\Phi}(\rho \cdot)\|_{M^{p,q}} \lesssim R^{d-N} \|m * R^d \widehat{\Psi}(R \cdot)\|_{M^{p,q}}.$$

(ii) *Let $1 \leq \rho \leq R/8$. Then*

$$\|[\widehat{\kappa}(m * \rho^d \widehat{\Phi}(\rho \cdot))] * R^d \widehat{\Psi}(R \cdot)\|_{M^{p,q}} \lesssim R^{d-N} \|m * \rho^d \widehat{\Phi}(\rho \cdot)\|_{M^{p,q}}.$$

PROOF. Let $K = \mathcal{F}^{-1}[m]$ and set $\|K\|_{cv(p,q)} := \|\widehat{K}\|_{M^{p,q}}$. The expression in (i) is equal to

$$\left\| \Phi(\rho^{-1} \cdot) \int \kappa(y) K(\cdot - y) \Psi(R^{-1}(\cdot - y)) dy \right\|_{cv(p,q)}.$$

Observe that by the support properties of Φ, Ψ the integral in y is extended over $R/2 - 2\rho \leq |y| \leq 2R + 2\rho$, hence $|y| \in (R/4, 4R)$. Thus the displayed quantity is bounded by

$$\begin{aligned} & \int_{R/4 \leq |y| \leq 4R} |\kappa(y)| \|K(\cdot - y) \Psi(R^{-1}(\cdot - y))\|_{cv(p,q)} dy \\ & \leq \int_{R/4 \leq |y| \leq 4R} |\kappa(y)| dy \|m * R^d \widehat{\Psi}(R \cdot)\|_{M^{p,q}} \end{aligned}$$

and the desired bound follows from the hypothesis on κ . Part (ii) is proved in the same way. \square

LEMMA C.2. *Let $\Psi_n, n \geq 0$, be as in Ch. 6, §6.1. Let $N > d$ and let χ be such that $\|\partial_\xi^\alpha \chi\|_1 \leq A$ for all $\alpha \in \mathbb{N}_0$ such that $|\alpha| \leq N$. Let $h \in L^1(\widehat{\mathbb{R}}^d)$ be supported in $\{\xi \in \widehat{\mathbb{R}}^d : 1/2 \leq |\xi| \leq 2\}$. Then*

$$\|(h\chi) * \widehat{\Psi}_\ell\|_{M^{p,q}} \lesssim A \sum_{n=0}^{\infty} C_{N-d}(n, \ell) \|h * \widehat{\Psi}_n\|_{M^{p,q}}$$

for any $\ell \geq 0$, where

$$(C.1) \quad C_{N_1}(n, \ell) := \begin{cases} 1 & \text{if } \ell - 5 \leq n \leq \ell + 5, \\ 2^{-\ell N_1} & \text{if } 0 \leq n < \ell - 5, \\ 2^{-n N_1} & \text{if } \ell + 5 < n. \end{cases}$$

PROOF. We write $(h\chi) * \widehat{\Psi}_\ell = \sum_{n=0}^{\infty} [(h * \widehat{\Psi}_n)\chi] * \widehat{\Psi}_\ell$. The result then follows by noting that $|\mathcal{F}^{-1}[\chi](x)| \lesssim (1 + |x|)^{-N}$ and an application of Lemma C.1. \square

C.1. Multiplication by smooth symbols

The above observations can be applied to show that the space defined by the finiteness of $\mathcal{B}[m]$ in (6.2a) is invariant under multiplication with multipliers satisfying a standard symbol of order 0 assumption. There is of course also a corresponding similar and immediate statement for $\mathcal{B}_\circ[m]$.

LEMMA C.3. *Let $a \in C^\infty(\widehat{\mathbb{R}}^d)$. Then*

$$\mathcal{B}[am] \lesssim \mathcal{B}[m] \sum_{|\alpha| \leq 2d+1} \sup_{\xi \in \widehat{\mathbb{R}}^d} |\xi|^{|\alpha|} |\partial^\alpha a(\xi)|,$$

where $\alpha \in \mathbb{N}_0$. Consequently, if $|\partial^\alpha a(\xi)| \lesssim_\alpha (1 + |\xi|)^{-|\alpha|}$ for all $\xi \in \widehat{\mathbb{R}}^d$ and all $\alpha \in \mathbb{N}_0^d$, we have $\mathcal{B}[am] \lesssim \mathcal{B}[m]$.

PROOF. Let $\tilde{\phi} \in C_c^\infty(\widehat{\mathbb{R}}^d)$ be supported in $\{\xi \in \widehat{\mathbb{R}}^d : 1/4 \leq |\xi| \leq 4\}$ and such that $\tilde{\phi}(\xi) = 1$ for $1/2 \leq |\xi| \leq 2$. Let $a^t(\xi) = \tilde{\phi}(\xi)a(t\xi)$. We may write

$$[\varphi a(t \cdot)m(t \cdot)] * \widehat{\Psi}_\ell = \sum_{n=0}^{\infty} [([\varphi m(t \cdot)] * \widehat{\Psi}_n) a^t] * \widehat{\Psi}_\ell.$$

Observe $\sum_{|\alpha| \leq 2d+1} |\partial^\alpha a^t(\xi)| \lesssim 1$, uniformly in t . By Lemma C.2 with $N_1 = 2d + 1$,

$$\begin{aligned} & \sum_{\ell=0}^{\infty} (1 + \ell) 2^{\ell d(1/p-1/q)} \|[\phi a(t \cdot)m(t \cdot)] * \widehat{\Psi}_\ell\|_{M^{p,q}} \\ & \lesssim \sum_{\ell=0}^{\infty} \sum_{n=0}^{\infty} C_{d+1}(n, \ell) (1 + \ell) 2^{\ell d(1/p-1/q)} \|[\phi m(t \cdot)] * \widehat{\Psi}_n\|_{M^{p,q}} \\ & \lesssim \sum_{n=0}^{\infty} (1 + n) 2^{n d(1/p-1/q)} \|[\varphi m(t \cdot)] * \widehat{\Psi}_n\|_{M^{p,q}} \end{aligned}$$

where in the last line we used that

$$\sup_{n \geq 0} \sum_{\ell=0}^{\infty} \frac{1 + \ell}{1 + n} 2^{(\ell-n)d(\frac{1}{p}-\frac{1}{q})} C_{d+1}(n, \ell) < \infty. \quad \square$$

C.2. Independence of ϕ, Ψ in the finiteness of $\mathcal{B}[m]$

The previous argument in Lemma C.3 can also be used to show that the space defined by the finiteness of $\mathcal{B}[m]$, $\mathcal{B}_\circ[m]$ is independent of the specific choices of ϕ, Ψ in Section 6.1. We only give the argument for $\mathcal{B}[m]$ and a similar reasoning applies to $\mathcal{B}_\circ[m]$.

LEMMA C.4. Denote the left hand side of (6.2a) by $\mathcal{B}[m, \phi, \Psi]$. Given two choices of (ϕ, Ψ) and $(\tilde{\phi}, \tilde{\Psi})$ with the specifications in the first paragraph of Section 6.1, there is a constant $C = C(\phi, \Psi) > 1$ such that

$$C^{-1}\mathcal{B}[m, \phi, \Psi] \leq \mathcal{B}[m, \tilde{\phi}, \tilde{\Psi}] \leq C\mathcal{B}[m, \phi, \Psi].$$

PROOF. We show the second inequality. Note that $\int_0^\infty |\phi(s\xi)|^2 \frac{ds}{s} \geq c > 0$ for $\xi \neq 0$. Let β^s be defined by

$$\widehat{\beta}^s(\xi) = \frac{\tilde{\phi}(s^{-1}\xi)\phi(\xi)}{\int_0^\infty |\phi(\sigma s^{-1}\xi)|^2 \frac{d\sigma}{\sigma}}.$$

We then have, in view of the support conditions on ϕ and $\tilde{\phi}$,

$$\tilde{\phi}(\xi) = \int_{1/4}^4 \widehat{\beta}^s(s\xi)\phi(s\xi) \frac{ds}{s}$$

and hence

$$\begin{aligned} \|\tilde{\phi}m(t) * \widehat{\Psi}_\ell\|_{M^{p,q}} &\leq \int_{1/4}^4 \|[\widehat{\beta}^s(s) \phi(s \cdot) m(t \cdot)] * \widehat{\Psi}_\ell\|_{M^{p,q}} \frac{ds}{s} \\ &= \int_{1/4}^4 s^{d(\frac{1}{p} - \frac{1}{q})} \|[\widehat{\beta}^s \phi(\cdot) m(ts^{-1} \cdot)] * s^{-d} \widehat{\Psi}_\ell(s^{-1} \cdot)\|_{M^{p,q}} \frac{ds}{s} \\ &\lesssim \sum_{n=0}^\infty \int_{1/4}^4 \|(\widehat{\beta}^s([\phi(\cdot) m(ts^{-1} \cdot)] * \widehat{\Psi}_n)) * s^{-d} \widehat{\Psi}_\ell(s^{-1} \cdot)\|_{M^{p,q}} \frac{ds}{s}. \end{aligned}$$

By Lemma C.2 this is dominated by

$$C_{N-d}(n, \ell) \int_{1/4}^4 \|[\phi(\cdot) m(ts^{-1} \cdot)] * \widehat{\Psi}_n\|_{M^{p,q}} \frac{ds}{s},$$

where $C_{N-d}(n, \ell)$ is as in (C.1). It is now easy to see that for $N \geq 2d + 1$

$$\begin{aligned} &\sum_{\ell \geq 0} 2^{\ell d(\frac{1}{p} - \frac{1}{q})} (1 + \ell) \|\tilde{\phi}m(t) * \widehat{\Psi}_\ell\|_{M^{p,q}} \\ &\lesssim \int_{1/4}^4 \sum_{\ell \geq 0} \sum_{n \geq 0} C_{N-d}(n, \ell) 2^{\ell d(\frac{1}{p} - \frac{1}{q})} (1 + \ell) \|[\phi(\cdot) m(ts^{-1} \cdot)] * \widehat{\Psi}_n\|_{M^{p,q}} \frac{ds}{s} \\ &\lesssim \sup_\tau \sum_{n=0}^\infty 2^{nd(\frac{1}{p} - \frac{1}{q})} \|[\phi(\cdot) m(\tau \cdot)] * \widehat{\Psi}_n\|_{M^{p,q}}. \end{aligned}$$

This establishes the inequality $\mathcal{B}[m, \tilde{\phi}, \tilde{\Psi}] \leq C\mathcal{B}[m, \phi, \Psi]$ and the converse follows by interchanging the roles of (ϕ, Ψ) and $(\tilde{\phi}, \tilde{\Psi})$. \square

Bibliography

- [1] AimPL, *Sparse domination of singular integral operators*, American Institute of Mathematics Problem List, edited by Dario Mena, available at <http://aimpl.org/sparsedomop>.
- [2] Theresa C. Anderson, Bingyang Hu, and Joris Roos, *Sparse bounds for discrete singular Radon transforms*, Colloq. Math. **165** (2021), no. 2, 199–217, DOI 10.4064/cm8296-8-2020. MR4262892
- [3] T. Anderson, K. Hughes, J. Roos, and A. Seeger, $L^p \rightarrow L^q$ bounds for spherical maximal operators, Math. Z. **297** (2021), no. 3-4, 1057–1074, DOI 10.1007/s00209-020-02546-0. MR4229592
- [4] A. Baernstein II and E. T. Sawyer, *Embedding and multiplier theorems for $H^p(\mathbf{R}^n)$* , Mem. Amer. Math. Soc. **53** (1985), no. 318, iv+82, DOI 10.1090/memo/0318. MR776176
- [5] Sayan Bagchi, Sourav Hait, Luz Roncal, and Sundaram Thangavelu, *On the maximal function associated to the spherical means on the Heisenberg group*, New York J. Math. **27** (2021), 631–675. MR4250270
- [6] Julian Bailey, Gianmarco Brocchi, and Maria Carmen Reguera, *Quadratic sparse domination and weighted estimates for non-integral square functions*, J. Geom. Anal. **33** (2023), no. 1, Paper No. 20, 49, DOI 10.1007/s12220-022-01031-w. MR4509112
- [7] Alex Barron, José M. Conde-Alonso, Yumeng Ou, and Guillermo Rey, *Sparse domination and the strong maximal function*, Adv. Math. **345** (2019), 1–26, DOI 10.1016/j.aim.2019.01.007. MR3897437
- [8] David Beltran, *Geometric control of oscillatory integrals*, Ph.D. thesis, University of Birmingham, 2017.
- [9] Victor Lie, *On the boundedness of the bilinear Hilbert transform along “non-flat” smooth curves. The Banach triangle case (L^r , $1 \leq r < \infty$)*, Rev. Mat. Iberoam. **34** (2018), no. 1, 331–353, DOI 10.4171/RMI/987. MR3763348
- [10] David Beltran and Jonathan Bennett, *Subdyadic square functions and applications to weighted harmonic analysis*, Adv. Math. **307** (2017), 72–99, DOI 10.1016/j.aim.2016.11.018. MR3590514
- [11] David Beltran and Laura Cladek, *Sparse bounds for pseudodifferential operators*, J. Anal. Math. **140** (2020), no. 1, 89–116, DOI 10.1007/s11854-020-0083-x. MR4094458
- [12] David Beltran, Shaoming Guo, Jonathan Hickman and Andreas Seeger, *Sharp L^p bounds for the helical maximal function*, Preprint, [arXiv:2102.08272](https://arxiv.org/abs/2102.08272), February 2021.
- [13] David Beltran, Shaoming Guo, Jonathan Hickman, and Andreas Seeger, *Sobolev improving for averages over curves in \mathbb{R}^4* , Adv. Math. **393** (2021), Paper No. 108089, 85, DOI 10.1016/j.aim.2021.108089. MR4340226
- [14] David Beltran, Richard Oberlin, Luz Roncal, Andreas Seeger, and Betsy Stovall, *Variation bounds for spherical averages*, Math. Ann. **382** (2022), no. 1-2, 459–512, DOI 10.1007/s00208-021-02218-2. MR4377310
- [15] Cristina Benea and Frédéric Bernicot, *Conservation de certaines propriétés à travers un contrôle épars d’un opérateur et applications au projecteur de Leray-Hopf* (French, with English and French summaries), Ann. Inst. Fourier (Grenoble) **68** (2018), no. 6, 2329–2379. MR3897969
- [16] Cristina Benea, Frédéric Bernicot, and Teresa Luque, *Sparse bilinear forms for Bochner Riesz multipliers and applications*, Trans. London Math. Soc. **4** (2017), no. 1, 110–128, DOI 10.1112/tlm3.12005. MR3653057
- [17] Cristina Benea and Camil Muscalu, *Sparse domination via the helicoidal method*, Rev. Mat. Iberoam. **37** (2021), no. 6, 2037–2118, DOI 10.4171/rmi/1266. MR4310287

- [18] Frédéric Bernicot, Dorothee Frey, and Stefanie Petermichl, *Sharp weighted norm estimates beyond Calderón-Zygmund theory*, Anal. PDE **9** (2016), no. 5, 1079–1113, DOI 10.2140/apde.2016.9.1079. MR3531367
- [19] J. Bourgain, *Averages in the plane over convex curves and maximal operators*, J. Analyse Math. **47** (1986), 69–85, DOI 10.1007/BF02792533. MR874045
- [20] Jean Bourgain and Ciprian Demeter, *The proof of the l^2 decoupling conjecture*, Ann. of Math. (2) **182** (2015), no. 1, 351–389, DOI 10.4007/annals.2015.182.1.9. MR3374964
- [21] Philip Brenner, *On $L_p - L_{p'}$ estimates for the wave-equation*, Math. Z. **145** (1975), no. 3, 251–254, DOI 10.1007/BF01215290. MR387819
- [22] Anthony Carbery, *The boundedness of the maximal Bochner-Riesz operator on $L^4(\mathbf{R}^2)$* , Duke Math. J. **50** (1983), no. 2, 409–416. MR705033
- [23] José L. Rubio de Francia, *Some maximal inequalities*, Recent progress in Fourier analysis (El Escorial, 1983), North-Holland Math. Stud., vol. 111, North-Holland, Amsterdam, 1985, pp. 203–214. MR848147
- [24] Anthony Carbery, *Variants of the Calderón-Zygmund theory for L^p -spaces*, Rev. Mat. Iberoamericana **2** (1986), no. 4, 381–396, DOI 10.4171/RMI/40. MR913694
- [25] Anthony Carbery, George Gasper, and Walter Trebels, *Radial Fourier multipliers of $L^p(\mathbf{R}^2)$* , Proc. Nat. Acad. Sci. U.S.A. **81** (1984), no. 10, , Phys. Sci., 3254–3255, DOI 10.1073/pnas.81.10.3254. MR747595
- [26] María J. Carro and Carlos Domingo-Salazar, *Stein’s square function G_α and sparse operators*, J. Geom. Anal. **27** (2017), no. 2, 1624–1635, DOI 10.1007/s12220-016-9733-8. MR3625166
- [27] Michael Christ, *On almost everywhere convergence of Bochner-Riesz means in higher dimensions*, Proc. Amer. Math. Soc. **95** (1985), no. 1, 16–20, DOI 10.2307/2045566. MR796439
- [28] Laura Cladek and Yumeng Ou, *Sparse domination of Hilbert transforms along curves*, Math. Res. Lett. **25** (2018), no. 2, 415–436, DOI 10.4310/MRL.2018.v25.n2.a4. MR3826828
- [29] José M. Conde-Alonso, Amalia Culiuc, Francesco Di Plinio, and Yumeng Ou, *A sparse domination principle for rough singular integrals*, Anal. PDE **10** (2017), no. 5, 1255–1284, DOI 10.2140/apde.2017.10.1255. MR3668591
- [30] José M. Conde-Alonso, Francesco Di Plinio, Ioannis Parissis, and Manasa N. Vempati, *A metric approach to sparse domination*, Ann. Mat. Pura Appl. (4) **201** (2022), no. 4, 1639–1675, DOI 10.1007/s10231-021-01174-7. MR4454372
- [31] José M. Conde-Alonso and Guillermo Rey, *A pointwise estimate for positive dyadic shifts and some applications*, Math. Ann. **365** (2016), no. 3-4, 1111–1135, DOI 10.1007/s00208-015-1320-y. MR3521084
- [32] Amalia Culiuc, Francesco Di Plinio, and Yumeng Ou, *A sparse estimate for multilinear forms involving vector-valued maximal functions* (English, with English and Italian summaries), Bruno Pini Mathematical Analysis Seminar 2017, Bruno Pini Math. Anal. Semin., vol. 8, Univ. Bologna, Alma Mater Stud., Bologna, 2017, pp. 168–184. MR3893587
- [33] Amalia Culiuc, Francesco Di Plinio, and Yumeng Ou, *Domination of multilinear singular integrals by positive sparse forms*, J. Lond. Math. Soc. (2) **98** (2018), no. 2, 369–392, DOI 10.1112/jlms.12139. MR3873113
- [34] Amalia Culiuc, Robert Kesler, and Michael T. Lacey, *Sparse bounds for the discrete cubic Hilbert transform*, Anal. PDE **12** (2019), no. 5, 1259–1272, DOI 10.2140/apde.2019.12.1259. MR3892403
- [35] Fernanda Clara de França Silva and Pavel Zorin-Kranich, *Sparse domination of sharp variational truncations*, arXiv:1604.05506, 2016.
- [36] Francesco Di Plinio, Yen Q. Do, and Gennady N. Uraltsev, *Positive sparse domination of variational Carleson operators*, Ann. Sc. Norm. Super. Pisa Cl. Sci. (5) **18** (2018), no. 4, 1443–1458. MR3829751
- [37] Francesco Di Plinio, Tuomas P. Hytönen, and Kangwei Li, *Sparse bounds for maximal rough singular integrals via the Fourier transform* (English, with English and French summaries), Ann. Inst. Fourier (Grenoble) **70** (2020), no. 5, 1871–1902. MR4245601
- [38] Francesco Di Plinio and Andrei K. Lerner, *On weighted norm inequalities for the Carleson and Walsh-Carleson operator*, J. Lond. Math. Soc. (2) **90** (2014), no. 3, 654–674, DOI 10.1112/jlms/jdu049. MR3291794

- [39] Javier Duoandikoetxea and José L. Rubio de Francia, *Maximal and singular integral operators via Fourier transform estimates*, *Invent. Math.* **84** (1986), no. 3, 541–561, DOI 10.1007/BF01388746. MR837527
- [40] Javier Duoandikoetxea and Ana Vargas, *Maximal operators associated to Fourier multipliers with an arbitrary set of parameters*, *Proc. Roy. Soc. Edinburgh Sect. A* **128** (1998), no. 4, 683–696, DOI 10.1017/S0308210500021715. MR1635404
- [41] Charles Fefferman, *L^p bounds for pseudo-differential operators*, *Israel J. Math.* **14** (1973), 413–417, DOI 10.1007/BF02764718. MR336453
- [42] C. Fefferman and E. M. Stein, *Some maximal inequalities*, *Amer. J. Math.* **93** (1971), 107–115, DOI 10.2307/2373450. MR284802
- [43] C. Fefferman and E. M. Stein, *H^p spaces of several variables*, *Acta Math.* **129** (1972), no. 3-4, 137–193, DOI 10.1007/BF02392215. MR447953
- [44] Dorothee Frey and Zoe Nieraeth, *Weak and strong type $A_1 - A_\infty$ estimates for sparsely dominated operators*, *J. Geom. Anal.* **29** (2019), no. 1, 247–282, DOI 10.1007/s12220-018-9989-2. MR3897012
- [45] Pritam Ganguly and Sundaram Thangavelu, *On the lacunary spherical maximal function on the Heisenberg group*, *J. Funct. Anal.* **280** (2021), no. 3, Paper No. 108832, 32, DOI 10.1016/j.jfa.2020.108832. MR4170795
- [46] Gustavo Garrigós and Andreas Seeger, *Characterizations of Hankel multipliers*, *Math. Ann.* **342** (2008), no. 1, 31–68, DOI 10.1007/s00208-008-0221-8. MR2415314
- [47] Gustavo Garrigós, Andreas Seeger, and Tino Ullrich, *The Haar system as a Schauder basis in spaces of Hardy-Sobolev type*, *J. Fourier Anal. Appl.* **24** (2018), no. 5, 1319–1339, DOI 10.1007/s00041-017-9583-1. MR3856231
- [48] Shaoming Guo, Jonathan Hickman, Victor Lie, and Joris Roos, *Maximal operators and Hilbert transforms along variable non-flat homogeneous curves*, *Proc. Lond. Math. Soc. (3)* **115** (2017), no. 1, 177–219, DOI 10.1112/plms.12037. MR3669936
- [49] Shaoming Guo, Joris Roos, Andreas Seeger, and Po-Lam Yung, *A maximal function for families of Hilbert transforms along homogeneous curves*, *Math. Ann.* **377** (2020), no. 1-2, 69–114, DOI 10.1007/s00208-019-01915-3. MR4099627
- [50] Shaoming Guo, Joris Roos, Andreas Seeger, and Po-Lam Yung, *Maximal functions associated with families of homogeneous curves: L^p bounds for $P \leq 2$* , *Proc. Edinb. Math. Soc. (2)* **63** (2020), no. 2, 398–412, DOI 10.1017/s0013091519000439. MR4089381
- [51] Shaoming Guo, Joris Roos, and Po-Lam Yung, *Sharp variation-norm estimates for oscillatory integrals related to Carleson’s theorem*, *Anal. PDE* **13** (2020), no. 5, 1457–1500, DOI 10.2140/apde.2020.13.1457. MR4149067
- [52] Timo S. Hänninen and Emiel Lorist, *Sparse domination for the lattice Hardy-Littlewood maximal operator*, *Proc. Amer. Math. Soc.* **147** (2019), no. 1, 271–284, DOI 10.1090/proc/14236. MR3876748
- [53] Lars Hörmander, *Estimates for translation invariant operators in L^p spaces*, *Acta Math.* **104** (1960), 93–140, DOI 10.1007/BF02547187. MR121655
- [54] Bingyang Hu, *Sparse domination of singular Radon transform* (English, with English and French summaries), *J. Math. Pures Appl. (9)* **139** (2020), 235–316, DOI 10.1016/j.matpur.2020.03.012. MR4108413
- [55] Richard A. Hunt, *On $L(p, q)$ spaces*, *Enseign. Math. (2)* **12** (1966), 249–276. MR223874
- [56] Tuomas Hytönen, Jan van Neerven, Mark Veraar, and Lutz Weis, *Analysis in Banach spaces. Vol. I. Martingales and Littlewood-Paley theory*, *Ergebnisse der Mathematik und ihrer Grenzgebiete. 3. Folge. A Series of Modern Surveys in Mathematics [Results in Mathematics and Related Areas. 3rd Series. A Series of Modern Surveys in Mathematics]*, vol. 63, Springer, Cham, 2016. MR3617205
- [57] Tuomas P. Hytönen, *The sharp weighted bound for general Calderón-Zygmund operators*, *Ann. of Math. (2)* **175** (2012), no. 3, 1473–1506, DOI 10.4007/annals.2012.175.3.9. MR2912709
- [58] Roger L. Jones, Robert Kaufman, Joseph M. Rosenblatt, and Máté Wierdl, *Oscillation in ergodic theory*, *Ergodic Theory Dynam. Systems* **18** (1998), no. 4, 889–935, DOI 10.1017/S0143385798108349. MR1645330
- [59] Roger L. Jones, Andreas Seeger, and James Wright, *Strong variational and jump inequalities in harmonic analysis*, *Trans. Amer. Math. Soc.* **360** (2008), no. 12, 6711–6742, DOI 10.1090/S0002-9947-08-04538-8. MR2434308

- [60] Makoto Kaneko and Gen-ichirō Sunouchi, *On the Littlewood-Paley and Marcinkiewicz functions in higher dimensions*, Tohoku Math. J. (2) **37** (1985), no. 3, 343–365, DOI 10.2748/tmj/1178228647. MR799527
- [61] Robert Kesler and Michael T. Lacey, *Sparse endpoint estimates for Bochner-Riesz multipliers on the plane*, Collect. Math. **69** (2018), no. 3, 427–435, DOI 10.1007/s13348-018-0214-1. MR3842215
- [62] Hyerim Ko, Sanghyuk Lee, and Sewook Oh, *Maximal estimates for averages over space curves*, Invent. Math. **228** (2022), no. 2, 991–1035, DOI 10.1007/s00222-021-01094-6. MR4411734
- [63] Hyerim Ko, Sanghyuk Lee, and Sewook Oh, *Sharp smoothing properties of averages over curves*, Forum Math. Pi **11** (2023), Paper No. e4, 33, DOI 10.1017/fmp.2023.2. MR4549710
- [64] Ben Krause and Michael T. Lacey, *Sparse bounds for random discrete Carleson theorems, 50 years with Hardy spaces*, Oper. Theory Adv. Appl., vol. 261, Birkhäuser/Springer, Cham, 2018, pp. 317–332. MR3792103
- [65] Michael T. Lacey, *An elementary proof of the A_2 bound*, Israel J. Math. **217** (2017), no. 1, 181–195, DOI 10.1007/s11856-017-1442-x. MR3625108
- [66] Michael T. Lacey, *Sparse bounds for spherical maximal functions*, J. Anal. Math. **139** (2019), no. 2, 613–635, DOI 10.1007/s11854-019-0070-2. MR4041115
- [67] Michael T. Lacey and Darío Mena Arias, *The sparse $T1$ theorem*, Houston J. Math. **43** (2017), no. 1, 111–127. MR3647935
- [68] Michael T. Lacey, Darío Mena, and Maria Carmen Reguera, *Sparse bounds for Bochner-Riesz multipliers*, J. Fourier Anal. Appl. **25** (2019), no. 2, 523–537, DOI 10.1007/s00041-017-9590-2. MR3917956
- [69] Sanghyuk Lee, *Square function estimates for the Bochner-Riesz means*, Anal. PDE **11** (2018), no. 6, 1535–1586, DOI 10.2140/apde.2018.11.1535. MR3803718
- [70] Sanghyuk Lee, Keith M. Rogers, and Andreas Seeger, *Improved bounds for Stein’s square functions*, Proc. Lond. Math. Soc. (3) **104** (2012), no. 6, 1198–1234, DOI 10.1112/plms/pdr067. MR2946085
- [71] Sanghyuk Lee, Keith M. Rogers, and Andreas Seeger, *Square functions and maximal operators associated with radial Fourier multipliers*, Advances in analysis: the legacy of Elias M. Stein, Princeton Math. Ser., vol. 50, Princeton Univ. Press, Princeton, NJ, 2014, pp. 273–302. MR3329855
- [72] Sanghyuk Lee and Andreas Seeger, *On radial Fourier multipliers and almost everywhere convergence*, J. Lond. Math. Soc. (2) **91** (2015), no. 1, 105–126, DOI 10.1112/jlms/jdu066. MR3338611
- [73] D. Lépingle, *La variation d’ordre p des semi-martingales* (French), Z. Wahrscheinlichkeitstheorie und Verw. Gebiete **36** (1976), no. 4, 295–316, DOI 10.1007/BF00532696. MR420837
- [74] Andrei K. Lerner, *On pointwise estimates involving sparse operators*, New York J. Math. **22** (2016), 341–349. MR3484688
- [75] Andrei K. Lerner, *On an estimate of Calderón-Zygmund operators by dyadic positive operators*, J. Anal. Math. **121** (2013), 141–161, DOI 10.1007/s11854-013-0030-1. MR3127380
- [76] Andrei K. Lerner, *A simple proof of the A_2 conjecture*, Int. Math. Res. Not. IMRN (2013), no. 14, 3159–3170. MR3085756
- [77] Andrei K. Lerner, *On pointwise estimates involving sparse operators*, New York J. Math. **22** (2016), 341–349. MR3484688
- [78] Andrei K. Lerner, *A weak type estimate for rough singular integrals*, Rev. Mat. Iberoam. **35** (2019), no. 5, 1583–1602, DOI 10.4171/rmi/1094. MR4018107
- [79] Andrei K. Lerner and Fedor Nazarov, *Intuitive dyadic calculus: the basics*, Expo. Math. **37** (2019), no. 3, 225–265, DOI 10.1016/j.exmath.2018.01.001. MR4007575
- [80] Andrei K. Lerner and Sheldy Ombrosi, *Some remarks on the pointwise sparse domination*, J. Geom. Anal. **30** (2020), no. 1, 1011–1027, DOI 10.1007/s12220-019-00172-9. MR4058547
- [81] J.-L. Lions and J. Peetre, *Sur une classe d’espaces d’interpolation* (French), Inst. Hautes Études Sci. Publ. Math. **19** (1964), 5–68. MR165343
- [82] Walter Littman, *Multipliers in L^p and interpolation*, Bull. Amer. Math. Soc. **71** (1965), 764–766, DOI 10.1090/S0002-9904-1965-11382-9. MR179544

- [83] Walter Littman, *$L^p - L^q$ -estimates for singular integral operators arising from hyperbolic equations*, Partial differential equations (Proc. Sympos. Pure Math., Vol. XXIII, Univ. California, Berkeley, Calif., 1971), Amer. Math. Soc., Providence, R.I., 1973, pp. 479–481. MR0358443
- [84] W. Littman, C. McCarthy, and N. Rivière, *L^p -multiplier theorems*, Studia Math. **30** (1968), 193–217, DOI 10.4064/sm-30-2-193-217. MR231126
- [85] Emiel Lorist, *On pointwise ℓ^r -sparse domination in a space of homogeneous type*, J. Geom. Anal. **31** (2021), no. 9, 9366–9405, DOI 10.1007/s12220-020-00514-y. MR4302224
- [86] Gianfranco Marletta and Fulvio Ricci, *Two-parameter maximal functions associated with homogeneous surfaces in \mathbf{R}^n* , Studia Math. **130** (1998), no. 1, 53–65. MR1623004
- [87] Akihiko Miyachi, *On some estimates for the wave equation in L^p and H^p* , J. Fac. Sci. Univ. Tokyo Sect. IA Math. **27** (1980), no. 2, 331–354. MR586454
- [88] Kensaku Gomi, *Standard subgroups of type $\mathrm{Sp}_6(2)$. I, II*, J. Fac. Sci. Univ. Tokyo Sect. IA Math. **27** (1980), no. 1, 87–107, 109–156. MR573334
- [89] Richard Oberlin, *Sparse bounds for a prototypical singular Radon transform*, Canad. Math. Bull. **62** (2019), no. 2, 405–415, DOI 10.4153/cmb-2018-007-5. MR3952528
- [90] Juan C. Peral, *L^p estimates for the wave equation*, J. Functional Analysis **36** (1980), no. 1, 114–145, DOI 10.1016/0022-1236(80)90110-X. MR568979
- [91] María Cristina Pereyra, *Dyadic harmonic analysis and weighted inequalities: the sparse revolution*, New trends in applied harmonic analysis. Vol. 2—harmonic analysis, geometric measure theory, and applications, Appl. Numer. Harmon. Anal., Birkhäuser/Springer, Cham, [2019] ©2019, pp. 159–239, DOI 10.1007/978-3-030-32353-0_7. MR4311199
- [92] Malabika Pramanik and Andreas Seeger, *L^p regularity of averages over curves and bounds for associated maximal operators*, Amer. J. Math. **129** (2007), no. 1, 61–103, DOI 10.1353/ajm.2007.0003. MR2288738
- [93] Joris Roos and Andreas Seeger, *Spherical maximal functions and fractal dimensions of dilation sets*, Amer. J. Math. **145** (2023), no. 4, 1077–1110, DOI 10.1353/ajm.2023.a902955. MR4621382
- [94] Joris Roos, Andreas Seeger, and Rajula Srivastava, *Lebesgue space estimates for spherical maximal functions on Heisenberg groups*, Int. Math. Res. Not. IMRN **24** (2022), 19222–19257, DOI 10.1093/imrn/rnab246. MR4523247
- [95] W. Schlag, *A generalization of Bourgain’s circular maximal theorem*, J. Amer. Math. Soc. **10** (1997), no. 1, 103–122, DOI 10.1090/S0894-0347-97-00217-8. MR1388870
- [96] Wilhelm Schlag and Christopher D. Sogge, *Local smoothing estimates related to the circular maximal theorem*, Math. Res. Lett. **4** (1997), no. 1, 1–15, DOI 10.4310/MRL.1997.v4.n1.a1. MR1432805
- [97] Andreas Seeger, *On quasiradial Fourier multipliers and their maximal functions*, J. Reine Angew. Math. **370** (1986), 61–73, DOI 10.1515/crll.1986.370.61. MR852510
- [98] Andreas Seeger, *Some inequalities for singular convolution operators in L^p -spaces*, Trans. Amer. Math. Soc. **308** (1988), no. 1, 259–272, DOI 10.2307/2000962. MR955772
- [99] Peter emrl, *On algebraic generation of $B(X)$ by two subalgebras with square zero*, Studia Math. **97** (1990), no. 2, 139–142, DOI 10.4064/sm-97-2-139-142. MR1083343
- [100] Andreas Seeger and Terence Tao, *Sharp Lorentz space estimates for rough operators*, Math. Ann. **320** (2001), no. 2, 381–415, DOI 10.1007/PL00004479. MR1839769
- [101] Andreas Seeger, Stephen Wainger, and James Wright, *Pointwise convergence of spherical means*, Math. Proc. Cambridge Philos. Soc. **118** (1995), no. 1, 115–124, DOI 10.1017/S0305004100073503. MR1329463
- [102] Elias M. Stein, *Localization and summability of multiple Fourier series*, Acta Math. **100** (1958), 93–147, DOI 10.1007/BF02559603. MR105592
- [103] Elias M. Stein, *Singular integrals and differentiability properties of functions*, Princeton Mathematical Series, No. 30, Princeton University Press, Princeton, N.J., 1970. MR0290095
- [104] E. M. Stein, *L^p boundedness of certain convolution operators*, Bull. Amer. Math. Soc. **77** (1971), 404–405, DOI 10.1090/S0002-9904-1971-12716-7. MR276757
- [105] Elias M. Stein, *Maximal functions. I. Spherical means*, Proc. Nat. Acad. Sci. U.S.A. **73** (1976), no. 7, 2174–2175, DOI 10.1073/pnas.73.7.2174. MR420116
- [106] Elias M. Stein and Guido Weiss, *Introduction to Fourier analysis on Euclidean spaces*, Princeton Mathematical Series, No. 32, Princeton University Press, Princeton, N.J., 1971. MR0304972

- [107] E. M. Stein and A. Zygmund, *Boundedness of translation invariant operators on Hölder spaces and L^p -spaces*, Ann. of Math. (2) **85** (1967), 337–349, DOI 10.2307/1970445. MR215121
- [108] Robert S. Strichartz, *Convolutions with kernels having singularities on a sphere*, Trans. Amer. Math. Soc. **148** (1970), 461–471, DOI 10.2307/1995383. MR256219
- [109] Gen-ichirō Sunouchi, *On the Littlewood-Paley function g^* of multiple Fourier integrals and Hankel multiplier transformations*, Tohoku Math. J. (2) **19** (1967), 496–511, DOI 10.2748/tmj/1178243254. MR225097
- [110] Hans Triebel, *Theory of function spaces*, Monographs in Mathematics, vol. 78, Birkhäuser Verlag, Basel, 1983, DOI 10.1007/978-3-0346-0416-1. MR781540
- [111] T. Wolff, *Local smoothing type estimates on L^p for large p* , Geom. Funct. Anal. **10** (2000), no. 5, 1237–1288, DOI 10.1007/PL00001652. MR1800068

Editorial Information

To be published in the *Memoirs*, a paper must be correct, new, nontrivial, and significant. Further, it must be well written and of interest to a substantial number of mathematicians. Piecemeal results, such as an inconclusive step toward an unproved major theorem or a minor variation on a known result, are in general not acceptable for publication.

Papers appearing in *Memoirs* are generally at least 80 and not more than 200 published pages in length. Papers less than 80 or more than 200 published pages require the approval of the Managing Editor of the Transactions/Memoirs Editorial Board. Published pages are the same size as those generated in the style files provided for $\mathcal{A}\mathcal{M}\mathcal{S}$ - $\mathcal{L}\mathcal{T}\mathcal{E}\mathcal{X}$.

Information on the backlog for this journal can be found on the AMS website starting from <http://www.ams.org/memo>.

A Consent to Publish is required before we can begin processing your paper. After a paper is accepted for publication, the Providence office will send a Consent to Publish and Copyright Agreement to all authors of the paper. By submitting a paper to the *Memoirs*, authors certify that the results have not been submitted to nor are they under consideration for publication by another journal, conference proceedings, or similar publication.

Information for Authors

Memoirs is an author-prepared publication. Once formatted for print and on-line publication, articles will be published as is with the addition of AMS-prepared frontmatter and backmatter. Articles are not copyedited; however, confirmation copy will be sent to the authors.

Initial submission. The AMS uses Centralized Manuscript Processing for initial submissions. Authors should submit a PDF file using the Initial Manuscript Submission form found at www.ams.org/submission/memo, or send one copy of the manuscript to the following address: Centralized Manuscript Processing, MEMOIRS OF THE AMS, 201 Charles Street, Providence, RI 02904-2294 USA. If a paper copy is being forwarded to the AMS, indicate that it is for *Memoirs* and include the name of the corresponding author, contact information such as email address or mailing address, and the name of an appropriate Editor to review the paper (see the list of Editors below).

The paper must contain a *descriptive title* and an *abstract* that summarizes the article in language suitable for workers in the general field (algebra, analysis, etc.). The *descriptive title* should be short, but informative; useless or vague phrases such as “some remarks about” or “concerning” should be avoided. The *abstract* should be at least one complete sentence, and at most 300 words. Included with the footnotes to the paper should be the 2020 *Mathematics Subject Classification* representing the primary and secondary subjects of the article. The classifications are accessible from www.ams.org/msc/. The Mathematics Subject Classification footnote may be followed by a list of *key words and phrases* describing the subject matter of the article and taken from it. Journal abbreviations used in bibliographies are listed in the latest *Mathematical Reviews* annual index. The series abbreviations are also accessible from www.ams.org/msnhtml/serials.pdf. To help in preparing and verifying references, the AMS offers MR Lookup, a Reference Tool for Linking, at www.ams.org/mrlookup/.

Electronically prepared manuscripts. The AMS encourages electronically prepared manuscripts, with a strong preference for $\mathcal{A}\mathcal{M}\mathcal{S}$ - $\mathcal{L}\mathcal{T}\mathcal{E}\mathcal{X}$. To this end, the Society has prepared $\mathcal{A}\mathcal{M}\mathcal{S}$ - $\mathcal{L}\mathcal{T}\mathcal{E}\mathcal{X}$ author packages for each AMS publication. Author packages include instructions for preparing electronic manuscripts, samples, and a style file that generates the particular design specifications of that publication series.

Authors may retrieve an author package for *Memoirs of the AMS* from www.ams.org/journals/memo/memoauthorpac.html. The *AMS Author Handbook* is available in PDF format from the author package link. The author package can also be obtained free of charge by sending email to tech-support@ams.org or from the Publication Division,

American Mathematical Society, 201 Charles St., Providence, RI 02904-2294, USA. When requesting an author package, please specify the publication in which your paper will appear. Please be sure to include your complete mailing address.

After acceptance. The source files for the final version of the electronic manuscript should be sent to the Providence office immediately after the paper has been accepted for publication. The author should also submit a PDF of the final version of the paper to the editor, who will forward a copy to the Providence office.

Accepted electronically prepared files can be submitted via the web at www.ams.org/submit-book-journal/, sent via FTP, or sent on CD to the Electronic Prepress Department, American Mathematical Society, 201 Charles Street, Providence, RI 02904-2294 USA. T_EX source files and graphic files can be transferred over the Internet by FTP to the Internet node [ftp.ams.org](ftp://ftp.ams.org) (130.44.1.100). When sending a manuscript electronically via CD, please be sure to include a message indicating that the paper is for the *Memoirs*.

Electronic graphics. Comprehensive instructions on preparing graphics are available at www.ams.org/authors/journals.html. A few of the major requirements are given here.

Submit files for graphics as EPS (Encapsulated PostScript) files. This includes graphics originated via a graphics application as well as scanned photographs or other computer-generated images. If this is not possible, TIFF files are acceptable as long as they can be opened in Adobe Photoshop or Illustrator.

Authors using graphics packages for the creation of electronic art should also avoid the use of any lines thinner than 0.5 points in width. Many graphics packages allow the user to specify a “hairline” for a very thin line. Hairlines often look acceptable when proofed on a typical laser printer. However, when produced on a high-resolution laser imagesetter, hairlines become nearly invisible and will be lost entirely in the final printing process.

Screens should be set to values between 15% and 85%. Screens which fall outside of this range are too light or too dark to print correctly. Variations of screens within a graphic should be no less than 10%.

Any graphics created in color will be rendered in grayscale for the printed version unless color printing is authorized by the Managing Editor and the Publisher. In general, color graphics will appear in color in the online version.

Inquiries. Any inquiries concerning a paper that has been accepted for publication should be sent to memo-query@ams.org or directly to the Electronic Prepress Department, American Mathematical Society, 201 Charles St., Providence, RI 02904-2294 USA.

Editors

This journal is designed particularly for long research papers, normally at least 80 pages in length, and groups of cognate papers in pure and applied mathematics. Papers intended for publication in the *Memoirs* should be addressed to one of the following editors. The AMS uses Centralized Manuscript Processing for initial submissions to AMS journals. Authors should follow instructions listed on the Initial Submission page found at www.ams.org/memo/memosubmit.html.

Managing Editor: Dan Abramovich, Department of Mathematics, Brown University, Providence, RI 02912 USA; e-mail: Dan_Abramovich@TAMS@brown.edu

1. GEOMETRY, TOPOLOGY & LOGIC

Coordinating Editor: Mariya Ivanova Soskova, Department of Mathematics, University of Wisconsin–Madison, Madison, WI 53706 USA; e-mail: moskova@math.wisc.edu

Algebraic topology, Craig Westerland, School of Mathematics, University of Minnesota, 206 Church St. SE, Minneapolis, MN 55455 USA; e-mail: cwesterl@umn.edu

Geometric group theory and low-dimensional geometry and topology, Christopher Leininger, Department of Mathematics, Rice University, Houston, TX 77005 USA; e-mail: cjl2@rice.edu

Geometric topology, Jennifer Hom, School of Mathematics, Georgia Institute of Technology, 686 Cherry Street, Atlanta, GA 30332 USA; e-mail: jhom@gatech.edu

Homotopy theory, higher category theory, and geometric applications, Clark Barwick, School of Mathematics, University of Edinburgh, James Clerk Maxwell Building, Peter Guthrie Tait Road, Edinburgh, EH9 3FD, United Kingdom; e-mail: clarkbar@ams@pm.me

Logic, Mariya Ivanova Soskova

Symplectic geometry, Yael Karshon, Department of Mathematics, University of Toronto, Toronto, Ontario M5S 2E4, Canada; e-mail: karshon@math.toronto.edu

2. ALGEBRA AND NUMBER THEORY

Coordinating Editor: Radha Kessar, Department of Mathematics, The Alan Turing Building, The University of Manchester, Oxford Road, Manchester M13 9PL United Kingdom; e-mail: radha.kessar@manchester.ac.uk

Algebra, Algebraic and Arithmetic Geometry, Daniel Krashen, 3E6 David Rittenhouse Lab., University of Pennsylvania, Department of Mathematics, 209 South 33rd Street, Philadelphia, PA 19104 USA; e-mail: daniel.krashen@gmail.com

Algebraic geometry, Dan Abramovich, Department of Mathematics, Brown University, Providence, RI 02912 USA; e-mail: Dan_Abramovich@TAMS@brown.edu

Arithmetic algebraic geometry, Ehud de Shalit, Institute of Mathematics, Hebrew University, Giv'at-Ram, Jerusalem 91904 Israel; e-mail: deshalit@math.huji.ac.il

Arithmetic geometry and number theory, Elena Mantovan, Department of Mathematics, PMA, California Institute of Technology, M/C 253-37, 1200 E California Blvd, Pasadena, CA 91125 USA; e-mail: mantovan@caltech.edu

Associative rings and algebras, category theory, homological algebra, group theory and generalizations, Daniel Nakano, Department of Mathematics, University of Georgia, Athens, Georgia 30602 USA; e-mail: nakano@uga.edu

Commutative algebra, Irena Peeva, Department of Mathematics, Cornell University, Ithaca, NY 14853 USA; e-mail: irena@math.cornell.edu

Representation theory and group theory, Radha Kessar

3. GEOMETRIC ANALYSIS & PDE

Coordinating Editor: Joachim Krieger, Bâtiment de Mathématiques, École Polytechnique Fédérale de Lausanne, Station 8, 1015 Lausanne Vaud, Switzerland; e-mail: joachim.krieger@epfl.ch

Calculus of variations, geometric measure theory, elliptic PDEs, Francesco Maggi, Department of Mathematics, The University of Texas at Austin, 2515 Speedway, Stop C1200, Austin TX 78712-1202 USA; e-mail: maggi@math.utexas.edu

Elliptic and parabolic PDEs, geometric analysis, Ben Weinkove, Mathematics Department, Northwestern University, 2033 Sheridan Rd, Evanston, IL 60201 USA; e-mail: weinkove@math.northwestern.edu

Elliptic PDEs, geometric analysis, Eugenia Malinikova, Department of Mathematics, Stanford University, Stanford, CA 94305 USA; e-mail: eugeniam@stanford.edu

Harmonic analysis and partial differential equations, Monica Visan, Department of Mathematics, University of California Los Angeles, 520 Portola Plaza, Los Angeles, CA 90095 USA; e-mail: visan@math.ucla.edu

Nonlinear Fourier and harmonic analysis and partial differential equations, Andrea R. Nahmod, Department of Mathematics and Statistics, University of Massachusetts Amherst, 710 N. Pleasant St. Lederle GRT, Amherst, MA 01003 USA; e-mail: nahmod@umass.edu

Real analysis and partial differential equations, Joachim Krieger

Riemannian geometry, metric geometry, mathematical general relativity, and geometric measure theory, Christina Sormani, Lehman College and CUNY Graduate Center, 250 Bedford Park Boulevard West, Bronx, NY 10468 USA; e-mail: sormanic@gmail.com

4. ANALYSIS & DYNAMICS

Coordinating Editor: Krzysztof Frączek, Faculty of Math and Computer Science, Nicolaus Copernicus University, Ul. Chopina 12/18 87-100 Toruń, Poland; e-mail: fraczek@mat.umk.pl

Analysis, probability and ergodic theory, Tim Austin, Department of Mathematics, University of California, Los Angeles, Los Angeles, CA 90095 USA; e-mail: tim@math.ucla.edu

Ergodic theory and dynamical systems, Krzysztof Frączek

Ergodic theory, applications to combinatorics and number theory, Nikos Frantzikinakis, University of Crete, Rethymno, Crete, Greece; e-mail: frantzikinakis@gmail.com

Functional analysis, groups and operator algebras, analysis in quantum information theory, Magdalena Musat, Department of Mathematical Sciences, University of Copenhagen, Universitetsparken 5, 2100 Copenhagen, Denmark; e-mail: musat@math.ku.dk

Operator algebras and ergodic theory, David Kerr, Mathematisches Institut, University of Münster, Einsteinstrasse 62, 48149 Münster, Germany; e-mail: kerrd@uni-muenster.de

5. PROBABILITY & COMBINATORICS

Coordinating Editor: Davar Khoshnevisan, Department of Mathematics, The University of Utah, Salt Lake City, UT 84112 USA; e-mail: davar@math.utah.edu

Combinatorics, Jacob Fox, Department of Mathematics, 450 Jane Stanford Way, Building 380, Stanford, CA 94305 USA; e-mail: jacobfox@stanford.edu

Enumeration, algebraic combinatorics, integrable probability, symmetric functions, Sylvie Corteel, Department of Mathematics, University of California, Berkeley, Berkeley, CA 94720 USA; CNRS, IRIF et Université Paris Cité, Paris, France; e-mail: corteel@berkeley.edu

Probability theory and statistical physics, Jian Ding, School of Mathematical Sciences, Peking University, Beijing 100871, China; e-mail: dingjian@math.pku.edu.cn

Probability theory and stochastic analysis, Davar Khoshnevisan

Probability theory, probabilistic combinatorics, statistical physics, Eyal Lubetzky, Department of Mathematics, Courant Institute of Mathematical Sciences, New York University, New York, NY 10012 USA; e-mail: eyal@courant.nyu.edu

SELECTED PUBLISHED TITLES IN THIS SERIES

- 1486 **M. Gekhtman, M. Shapiro, and A. Vainshtein**, A Plethora of Cluster Structures on GL_n , 2024
- 1485 **David Ayala, Aaron Mazel-Gee, and Nick Rozenblyum**, Stratified Noncommutative Geometry, 2024
- 1484 **Brandon Doherty, Krzysztof Kapulkin, Zachery Lindsey, and Christian Sattler**, Cubical Models of $(\infty, 1)$ -Categories, 2024
- 1483 **Masao Oi**, Simple Supercuspidal L -Packets of Quasi-Split Classical Groups, 2024
- 1482 **David Burns and Daniel Macias Castillo**, On Refined Conjectures of Birch and Swinnerton-Dyer Type for Hasse–Weil–Artin L -Series, 2024
- 1481 **Sonja Cox, Martin Hutzenthaler, and Arnulf Jentzen**, Local Lipschitz Continuity in the Initial Value and Strong Completeness for Nonlinear Stochastic Differential Equations, 2024
- 1480 **Nicolas Burq and Laurent Thomann**, Almost Sure Scattering for the One Dimensional Nonlinear Schrödinger Equation, 2024
- 1479 **Eva Elduque, Christian Geske, Moisés Herradón Cueto, Laurențiu G. Maxim, and Botong Wang**, Mixed Hodge Structures on Alexander Modules, 2024
- 1478 **Qi Chen, Dongyi Wei, and Zhifei Zhang**, Transition Threshold for the 3D Couette Flow in a Finite Channel, 2024
- 1477 **Vincent Guirardel, Gilbert Levitt, and Rizos Sklinos**, Towers and the First-Order Theories of Hyperbolic Groups, 2024
- 1476 **Gaëtan Borot, Vincent Bouchard, Nitin K. Chidambaram, Thomas Creutzig, and Dmitry Noshchenko**, Higher Airy Structures, \mathcal{W} Algebras and Topological Recursion, 2024
- 1475 **Sam Chow and Niclas Technau**, Littlewood and Duffin–Schaeffer-Type Problems in Diophantine Approximation, 2024
- 1474 **Christian Blohmann and Alan Weinstein**, Hamiltonian Lie Algebroids, 2024
- 1473 **Dihua Jiang, Zhilin Luo, and Lei Zhang**, Harmonic Analysis and Gamma Functions on Symplectic Groups, 2024
- 1472 **Thomas Creutzig, Shashank Kanade, and Robert McRae**, Tensor Categories for Vertex Operator Superalgebra Extensions, 2024
- 1471 **Roberto Feola and Filippo Giuliani**, Quasi-Periodic Traveling Waves on an Infinitely Deep Perfect Fluid Under Gravity, 2024
- 1470 **Maxwell Stolarski**, Curvature Blow-up in Doubly-warped Product Metrics Evolving by Ricci Flow, 2024
- 1469 **Steve Boyer, Cameron McA. Gordon, and Xingru Zhang**, Dehn Fillings of Knot Manifolds Containing Essential Twice-Punctured Tori, 2024
- 1468 **Alice Hedenlund and John Rognes**, A Multiplicative Tate Spectral Sequence for Compact Lie Group Actions, 2024
- 1467 **Qi Lü and Xu Zhang**, Optimal Feedback for Stochastic Linear Quadratic Control and Backward Stochastic Riccati Equations in Infinite Dimensions, 2024
- 1466 **Martin W. Liebeck, Gary M. Seitz, and Donna M. Testerman**, Multiplicity-free Representations of Algebraic Groups, 2024
- 1465 **Tobias Rossmann and Christopher Voll**, Groups, Graphs, and Hypergraphs: Average Sizes of Kernels of Generic Matrices with Support Constraints, 2024
- 1464 **Jens Marklof and Andreas Strömbergsson**, Kinetic Theory for the Low-Density Lorentz Gas, 2024
- 1463 **You Qi and Joshua Sussan**, p -DG Cyclotomic nilHecke Algebras II, 2024

For a complete list of titles in this series, visit the
AMS Bookstore at www.ams.org/bookstore/memoseries/.

ISBN 978-1-4704-7042-5



9 781470 470425

MEMO/298/1491



www.ams.org