

# Carleson Measures for Besov-Sobolev Spaces and Non-Homogeneous Harmonic Analysis

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# Talk Outline

- Motivation of the Problem
  - Besov-Sobolev Spaces of analytic functions on  $\mathbb{B}_n$
  - Carleson Measures for Besov-Sobolev Spaces
  - Connections to Non-Homogeneous Harmonic Analysis
- Statement of Main Results
  - $T(1)$ -Theorem for Bergman-type operators
  - Characterization of Carleson measures for Besov-Sobolev Spaces
- Further Results

# Besov-Sobolev Spaces

- The space  $B_2^\sigma(\mathbb{B}_n)$  is the collection of holomorphic functions  $f$  on the unit ball  $\mathbb{B}_n := \{z \in \mathbb{C}^n : |z| < 1\}$  such that

$$\left\{ \sum_{k=0}^{m-1} |f^{(k)}(0)|^2 + \int_{\mathbb{B}_n} \left| (1 - |z|^2)^{m+\sigma} f^{(m)}(z) \right|^2 d\lambda_n(z) \right\}^{\frac{1}{2}} < \infty,$$

where  $d\lambda_n(z) = (1 - |z|^2)^{-n-1} dV(z)$  is the invariant measure on  $\mathbb{B}_n$  and  $m + \sigma > \frac{n}{2}$ .

- Various choices of  $\sigma$  give important examples of classical function spaces:
  - $\sigma = 0$ : Corresponds to the Dirichlet Space;
  - $\sigma = \frac{1}{2}$ : Drury-Arveson Hardy Space;
  - $\sigma = \frac{n}{2}$ : Classical Hardy Space;
  - $\sigma > \frac{n}{2}$ : Bergman Spaces.

# Besov-Sobolev Spaces

- The spaces  $B_2^\sigma(\mathbb{B}_n)$  are examples of reproducing kernel Hilbert spaces.
- Namely, for each point  $\lambda \in \mathbb{B}_n$  there exists a function  $k_\lambda^\sigma \in B_2^\sigma(\mathbb{B}_n)$  such that

$$f(\lambda) = \langle f, k_\lambda^\sigma \rangle_{B_2^\sigma(\mathbb{B}_n)}$$

- A computation shows that the kernel function  $k_\lambda^\sigma(z)$  is given by:

$$k_\lambda^\sigma(z) = \frac{1}{(1 - \bar{\lambda}z)^{2\sigma}}$$

- $\sigma = \frac{1}{2}$ : Drury-Arveson Hardy Space;  $k_\lambda^{\frac{1}{2}}(z) = \frac{1}{1 - \bar{\lambda}z}$
- $\sigma = \frac{n}{2}$ : Classical Hardy Space;  $k_\lambda^{\frac{n}{2}}(z) = \frac{1}{(1 - \bar{\lambda}z)^n}$
- $\sigma = \frac{n+1}{2}$ : Bergman Space;  $k_\lambda^{\frac{n+1}{2}}(z) = \frac{1}{(1 - \bar{\lambda}z)^{n+1}}$

# Carleson Measures for Besov-Sobolev Spaces

## Definition (Carleson Measure for Besov-Sobolev Spaces)

A non-negative Borel measure  $\mu$  is a  $B_2^\sigma(\mathbb{B}_n)$ -Carleson measure if

$$\int_{\mathbb{B}_n} |f(z)|^2 d\mu(z) \leq C(\mu)^2 \|f\|_{B_2^\sigma(\mathbb{B}_n)}^2 \quad \forall f \in B_2^\sigma(\mathbb{B}_n).$$

As is well-known Carleson measures play an important role in both the function theory of the space (e.g., characterization of the multipliers for the space and the interpolating sequences) and more generally play a predominant role in harmonic analysis.

The definition is in terms of function theoretic information, and it would be more useful to have a “testable” condition to check.

# Carleson Measures for Besov-Sobolev Spaces

## Question

Give a 'geometric' characterization of these measures.

Testing on the reproducing kernel  $k_\lambda^\sigma$  we always have a necessary geometric condition for the measure  $\mu$  to be Carleson:

$$\mu(T(B_r(\xi))) \lesssim r^{2\sigma} \quad \forall \xi \in \partial\mathbb{B}_n, r > 0$$

Here  $T(B_r(\xi))$  is the tent over the ball of radius  $r > 0$  in the boundary  $\partial\mathbb{B}_n$

When  $\sigma \geq \frac{n}{2}$  then this necessary condition is also sufficient.

# Carleson Measures for Besov-Sobolev Spaces

When  $0 \leq \sigma \leq \frac{1}{2}$  then a geometric characterization of Carleson measures is known.

- If  $n = 1$ , then the results can be expressed in terms of capacity conditions. More precisely,

$$\mu(T(\Omega)) \lesssim \text{Cap}_\sigma(\Omega) \quad \forall \text{open } \Omega \subset \mathbb{T}.$$

See for example Stegenga, Maz'ya, Verbitsky, Carleson.

- If  $n > 1$  then there are two different characterizations of Carleson measures for  $B_2^\sigma(\mathbb{B}_n)$  when  $0 \leq \sigma \leq \frac{1}{2}$ :
  - One method via integration operators on trees (dyadic structures on the ball  $\mathbb{B}_n$ ) by Arcozzi, Rochberg and Sawyer.
  - One method via “T(1)” conditions by E. Tchoundja.

**Question (Main Problem: Characterization in the Difficult Range)**

*Characterize the Carleson measures when  $\frac{1}{2} < \sigma < \frac{n}{2}$ .*



# Operator Theoretic Characterization of Carleson Measures

The following observations hold in an arbitrary Hilbert space with a reproducing kernel.

- Let  $\mathcal{J}$  be a Hilbert space of functions on a domain  $X$  with reproducing kernel function  $j_x$ , i.e.,

$$f(x) = \langle f, j_x \rangle_{\mathcal{J}} \quad \forall f \in \mathcal{J}.$$

- A measure  $\mu$  is Carleson exactly if the inclusion map  $\iota$  from  $\mathcal{J}$  to  $L^2(X; \mu)$  is bounded, or

$$\int_X |f(x)|^2 d\mu(z) \leq C(\mu) \|f\|_{\mathcal{J}}^2.$$

We can give a characterization of Carleson measures for the space  $\mathcal{J}$  in terms of information about the boundedness of a certain linear operator related to the reproducing kernel  $j_x$ .

# Operator Theoretic Characterization of Carleson Measures

## Statement and Proof

### Proposition

A measure  $\mu$  is a  $\mathcal{J}$ -Carleson measure if and only if the linear map

$$f(z) \rightarrow T(f)(z) = \int_X \operatorname{Re} j_x(z) f(x) d\mu(x)$$

is bounded on  $L^2(X; \mu)$ .

When we apply this proposition to the spaces  $B_2^\sigma(\mathbb{B}_n)$  this suggests that we study the operator

$$T_{\mu, 2\sigma}(f)(z) = \int_{\mathbb{B}_n} \operatorname{Re} \left( \frac{1}{(1 - \bar{w}z)^{2\sigma}} \right) f(w) d\mu(w) : L^2(\mathbb{B}_n; \mu) \rightarrow L^2(\mathbb{B}_n; \mu)$$

and find some conditions that will let us determine when it is bounded.

# Calderón–Zygmund Estimates for $T_{\mu,2\sigma}$

If we define

$$\Delta(z, w) := \begin{cases} ||z| - |w|| + \left| 1 - \frac{z\bar{w}}{|z||w|} \right| & : z, w \in \mathbb{B}_n \setminus \{0\} \\ |z| + |w| & : \text{otherwise.} \end{cases}$$

Then  $\Delta$  is a pseudo-metric and makes the ball into a space of homogeneous type.

A computation demonstrates that the kernel of  $T_{\mu,2\sigma}$  satisfies the following estimates:

$$|K_{2\sigma}(z, w)| \lesssim \frac{1}{\Delta(z, w)^{2\sigma}} \quad \forall z, w \in \mathbb{B}_n;$$

If  $\Delta(\zeta, w) < \frac{1}{2}\Delta(z, w)$  then

$$|K_{2\sigma}(\zeta, w) - K_{2\sigma}(z, w)| \lesssim \frac{\Delta(\zeta, w)^{1/2}}{\Delta(z, w)^{2\sigma+1/2}}.$$

# Calderón-Zygmund Estimates for $T_{\mu, 2\sigma}$

- These estimates on  $K_{2\sigma}(z, w)$  say that it is a Calderón-Zygmund kernel of order  $2\sigma$  with respect to the metric  $\Delta$ .
  - Unfortunately, we can't apply the standard  $T(1)$  technology (adapted to a space of homogeneous type) to study the operators  $T_{\mu, 2\sigma}$ . We would need the estimates of order  $n$  instead of  $2\sigma$ .
- However, the measures we want to study (the Carleson measures for the space) satisfy the growth estimate

$$\mu(T(B_r)) \lesssim r^{2\sigma}$$

and this is exactly the issue that will save us!

- This places us in the setting of non-homogeneous harmonic analysis as developed by Nazarov, Treil and Volberg. We have an operator with a Calderón-Zygmund kernel satisfying estimates of order  $2\sigma$ , a measure  $\mu$  of order  $2\sigma$ , and are interested in  $L^2(\mathbb{B}_n; \mu) \rightarrow L^2(\mathbb{B}_n; \mu)$  bounds.

# Euclidean Variant of the Question

There is a natural extension of these questions/ideas to the Euclidean setting  $\mathbb{R}^d$ .

More precisely, for  $m \leq d$  we are interested in Calderón-Zygmund kernels that satisfy the following estimates:

$$|k(x, y)| \leq \frac{C_{CZ}}{|x - y|^m},$$

and

$$|k(y, x) - k(y, x')| + |k(x, y) - k(x', y)| \leq C_{CZ} \frac{|x - x'|^\tau}{|x - y|^{m+\tau}}$$

provided that  $|x - x'| \leq \frac{1}{2}|x - y|$ , with some (fixed)  $0 < \tau \leq 1$  and  $0 < C_{CZ} < \infty$ .

# Euclidean Variant of the Question

Additionally the kernels will have the following property

$$|k(x, y)| \leq \frac{1}{\max(d(x)^m, d(y)^m)},$$

where  $d(x) := \text{dist}(x, \mathbb{R}^d \setminus H)$  and  $H$  being an open set in  $\mathbb{R}^d$ .

Key examples: Let  $H = \mathbb{B}_d$ , the unit ball in  $\mathbb{R}^d$  and

$$k(x, y) = \frac{1}{(1 - x \cdot y)^m}.$$

We will say that  $k$  is a Calderón-Zygmund kernel on a closed subset  $X$  of  $\mathbb{R}^d$  if  $k(x, y)$  is defined only on  $X \times X$  and the previous properties of  $k$  are satisfied whenever  $x, x', y \in X$ .

Once the kernel has been defined, then we say that a  $L^2(\mathbb{R}^d; \mu)$  bounded operator is a Calderón-Zygmund operator with kernel  $k$  if,

$$T_{\mu, m} f(x) = \int_{\mathbb{R}^d} k(x, y) f(y) d\mu(y) \quad \forall x \notin \text{supp} f.$$

# Main Results

## T(1)-Theorem for Bergman-Type Operators

### Theorem (T(1)-Theorem for Bergman-Type Operators, Volberg and Wick (2009))

Let  $k(x, y)$  be a Calderón-Zygmund kernel of order  $m$  on  $X \subset \mathbb{R}^d$ ,  $m \leq d$  with Calderón-Zygmund constants  $C_{CZ}$  and  $\tau$ . Let  $\mu$  be a probability measure with compact support in  $X$  and all balls such that  $\mu(B_r(x)) > r^m$  lie in an open set  $H$ . Let also

$$|k(x, y)| \leq \frac{1}{\max(d(x)^m, d(y)^m)},$$

where  $d(x) := \text{dist}(x, \mathbb{R}^d \setminus H)$ . Finally, suppose also that:

$$\|T_{\mu, m} \chi_Q\|_{L^2(\mathbb{R}^d; \mu)}^2 \leq A \mu(Q), \quad \|T_{\mu, m}^* \chi_Q\|_{L^2(\mathbb{R}^d; \mu)}^2 \leq A \mu(Q).$$

Then  $\|T_{\mu, m}\|_{L^2(\mathbb{R}^d; \mu) \rightarrow L^2(\mathbb{R}^d; \mu)} \leq C(A, m, d, \tau)$ .

# Main Results

Characterization of Carleson Measures for  $B_2^\sigma(\mathbb{B}_n)$

## Theorem (Characterization of Carleson Measures for Besov-Sobolev Spaces, Volberg and Wick (2009))

Let  $\mu$  be a positive Borel measure in  $\mathbb{B}_n$ . Then the following conditions are equivalent:

- (a)  $\mu$  is a  $B_2^\sigma(\mathbb{B}_n)$ -Carleson measure;
- (b)  $T_{\mu,2\sigma} : L^2(\mathbb{B}_n; \mu) \rightarrow L^2(\mathbb{B}_n; \mu)$  is bounded;
- (c) There is a constant  $C$  such that
  - (i)  $\|T_{\mu,2\sigma}\chi_Q\|_{L^2(\mathbb{B}_n;\mu)}^2 \leq C\mu(Q)$  for all  $\Delta$ -cubes  $Q$ ;
  - (ii)  $\mu(B_\Delta(x,r)) \leq C r^{2\sigma}$  for all balls  $B_\Delta(x,r)$  that intersect  $\mathbb{C}^n \setminus \mathbb{B}_n$ .

Above, the sets  $B_\Delta$  are balls measured with respect to the metric  $\Delta$  and the set  $Q$  is a “cube” defined with respect to the metric  $\Delta$ .



# Remarks about Characterization of Carleson Measures

- We have already proved that  $(a) \Leftrightarrow (b)$ , and it is trivial  $(b) \Rightarrow (c)$ .
- It only remains to prove that  $(c) \Rightarrow (b)$ .
  - The proof of this Theorem follows from the  $T(1)$ -Theorem for Bergman-type operators.
  - In a neighborhood of the sphere  $\partial\mathbb{B}_n$  the metric  $\Delta$  looks a Euclidean-type quasi-metric. For example when  $n = 2$  we have that

$$\Delta(x, y) \approx |x_1 - y_1| + |x_2 - y_2| + |x_3 - y_3|^2 + |x_4 - y_4|^2$$

- The method of proof of the Euclidean Bergman-type  $T(1)$  theorem can then be modified to case of Calderón-Zygmund operators with respect to a quasi-metric (essentially verbatim).
- It is possible to show that the  $T(1)$  condition reduces to the simpler conditions in certain cases.
- An alternate proof of this Theorem was recently given by Hytönen and Martikainen. Their proof used a non-homogeneous  $T(b)$ -Theorem on metric spaces.

# Extension to “Nice” Metric Spaces

- It is possible to extend these results to Ahlfors regular metric spaces. Namely,  $(X, \rho, \nu)$  with  $(X, \rho)$  a complete metric space and  $\nu$  a Borel measure on  $X$  such that

$$\nu(B_r(x)) \approx r^n$$

- Suppose we have another measure  $\mu$  on the metric space  $X$  (which need not be doubling), but satisfies the following relationship, for some  $0 \leq m < n$

$$\mu(B(x, r)) \lesssim r^m \quad \forall x \in X, \quad \forall r. \quad (\text{H})$$

- A standard Calderón-Zygmund kernel of order  $0 < m \leq n$  is a function  $k : X \times X \setminus \{x = y\} \rightarrow \mathbb{C}$  such that there exist constants  $C_{CZ}, \tau, \delta > 0$

$$|k(x, y)| \leq \frac{C_{CZ}}{\rho(x, y)^m} \quad \forall x \neq y \in X;$$

# Extension to “Nice” Metric Spaces

and

$$|k(x, y) - k(x, y')| + |k(x, y) - k(x', y)| \leq C_{CZ} \frac{\rho(x, x')^\tau}{\rho(x, y)^{\tau+m}}$$

provided that  $\rho(x, x') \leq \delta\rho(x, y)$ . In this situation, we say that the kernel  $k$  satisfies the standard estimates.

- If we additionally suppose the kernels that have the additional property that

$$|k(x, y)| \leq \frac{1}{\max(d^m(x), d^m(y))},$$

where  $d(x) := \text{dist}(x, X \setminus \Omega) = \inf\{\rho(x, y) : y \in X \setminus \Omega\}$  and  $\Omega$  being an open set in  $X$ .

- Then the analogue of the Bergman-type T(1) Theorem holds with essentially the same proof.

Thank You!