Measurement of large-scale velocity field of DESI LRG + DESI extended LRG galaxies with ACT DR6 kSZ

Fiona McCarthy

arXiv:2410.06229 (JCAP05(2025)057)

+ Simone Ferraro, Boryana Hadzhiyska, Matthew Johnson, Blake Sherwin, ACT++

FLATIRON INSTITUTE

UNIVERSITY OF CAMBRIDGE

mm Universe conference, University of Chicago, 25 June 2025

Intro: summary

- Demonstration of large-scale kSZ velocity reconstruction with ACT DR6 data
- We reconstruct the velocity field of the DESI LRGs using kSZ quadratic estimator
- We cross correlate with BOSS galaxy velocities (estimated with **continuity equation**)
- We detect a non-zero cross-correlation and prefer ΛCDM(+kSZ) to no-kSZ at 3.8σ
- Ongoing analysis of higher significance dataset

See also this afternoon!

- This is a fast-moving field!!

- If you are interested, please attend the afternoon parallel session and see talks from **Selim Hotinli** and **Anderson Lai, Moritz Münchmeyer**, **Avery Tishue**

Overview

Measuring velocity with the kSZ

$T_S^{kSZ} - \delta_S^e - v_L$ bispectrum

Sensitivity to galaxy bias

Scale dependent galaxy bias and primordial non-Gaussianity f_{NL}

Quadratic estimator

Extraction of v_L from small-scale T^{kSZ} and δ^g

Application on ACT data

JCAP 05(2025)057 + detection with ACT DR6 + DESILRGs

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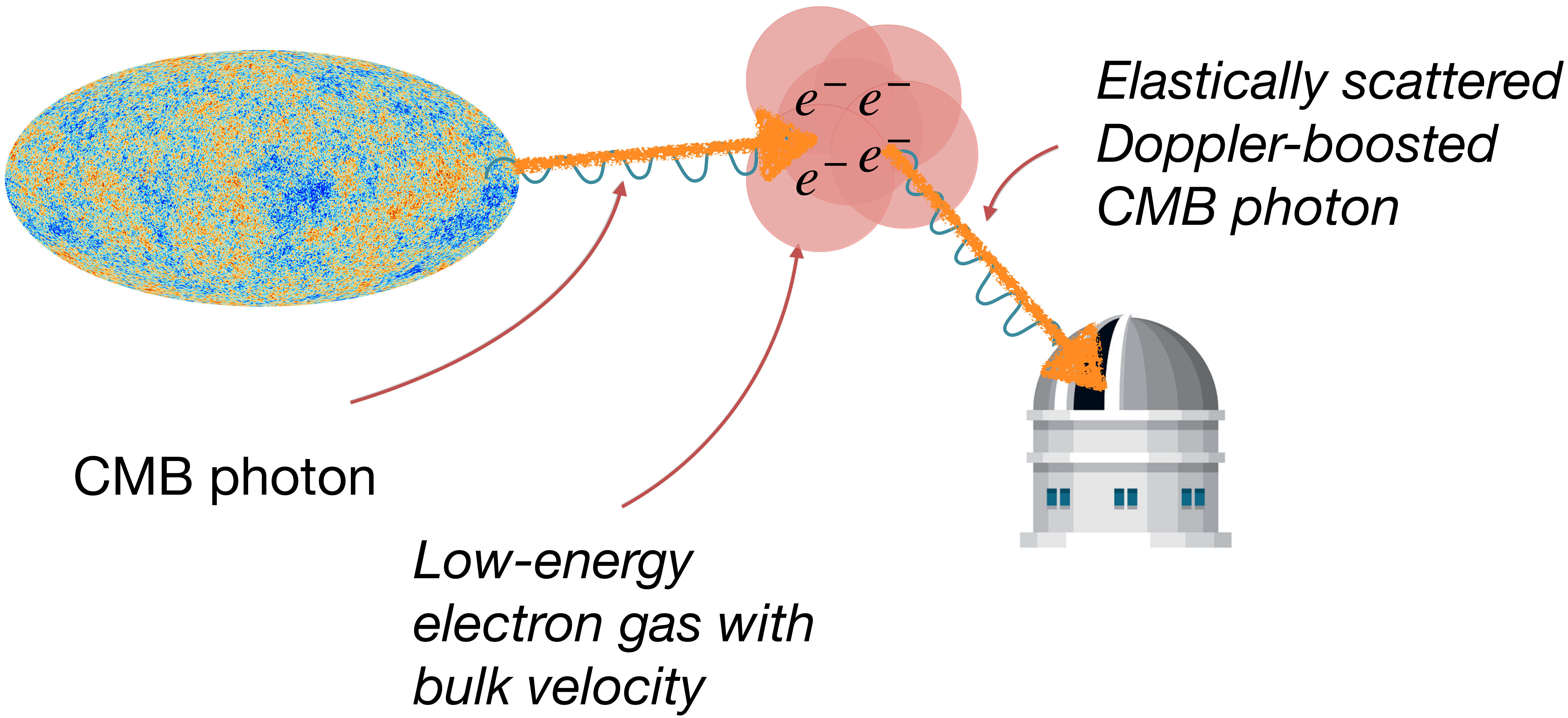
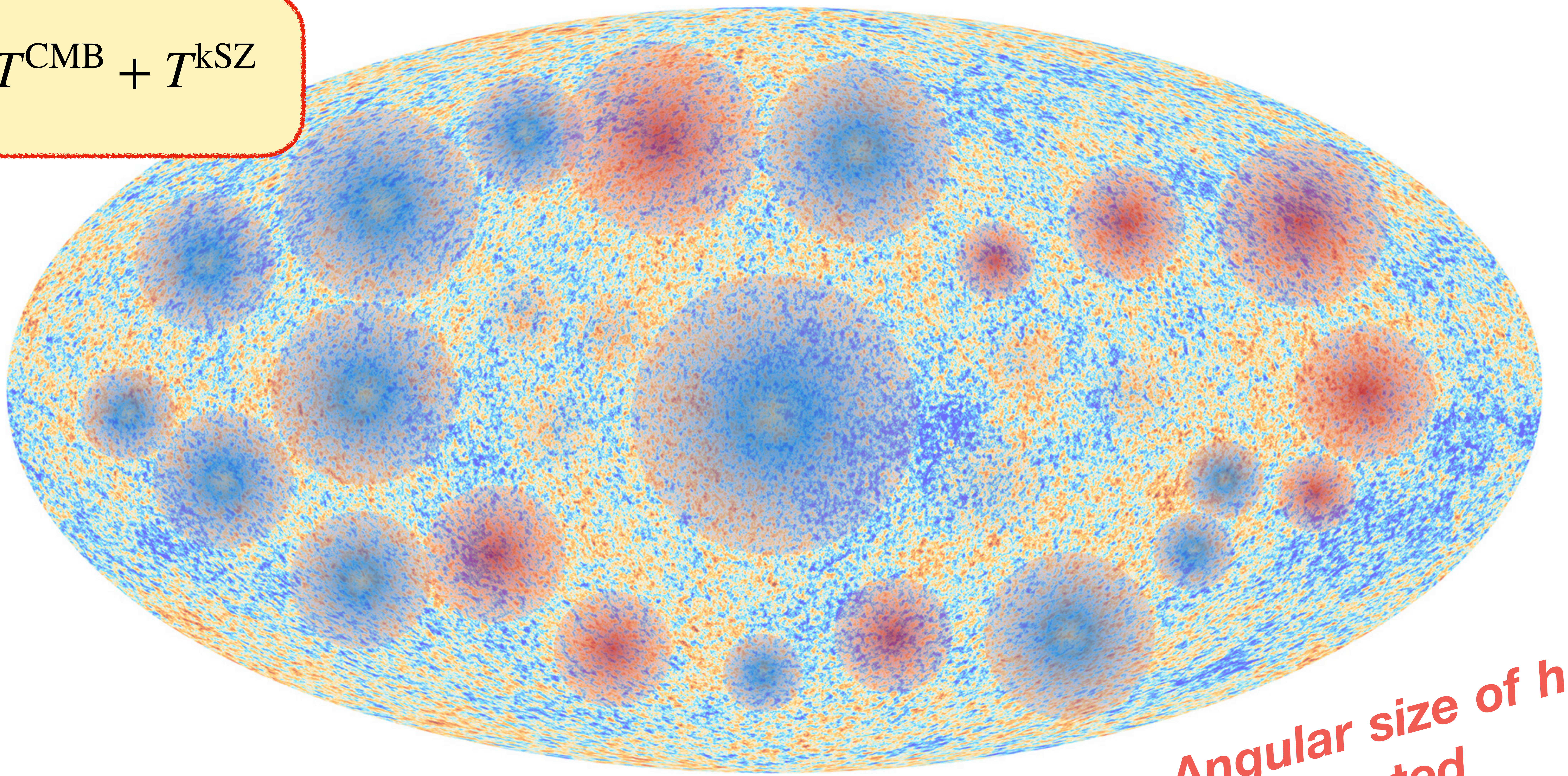
What does the kSZ look like?



What does the kSZ look like?

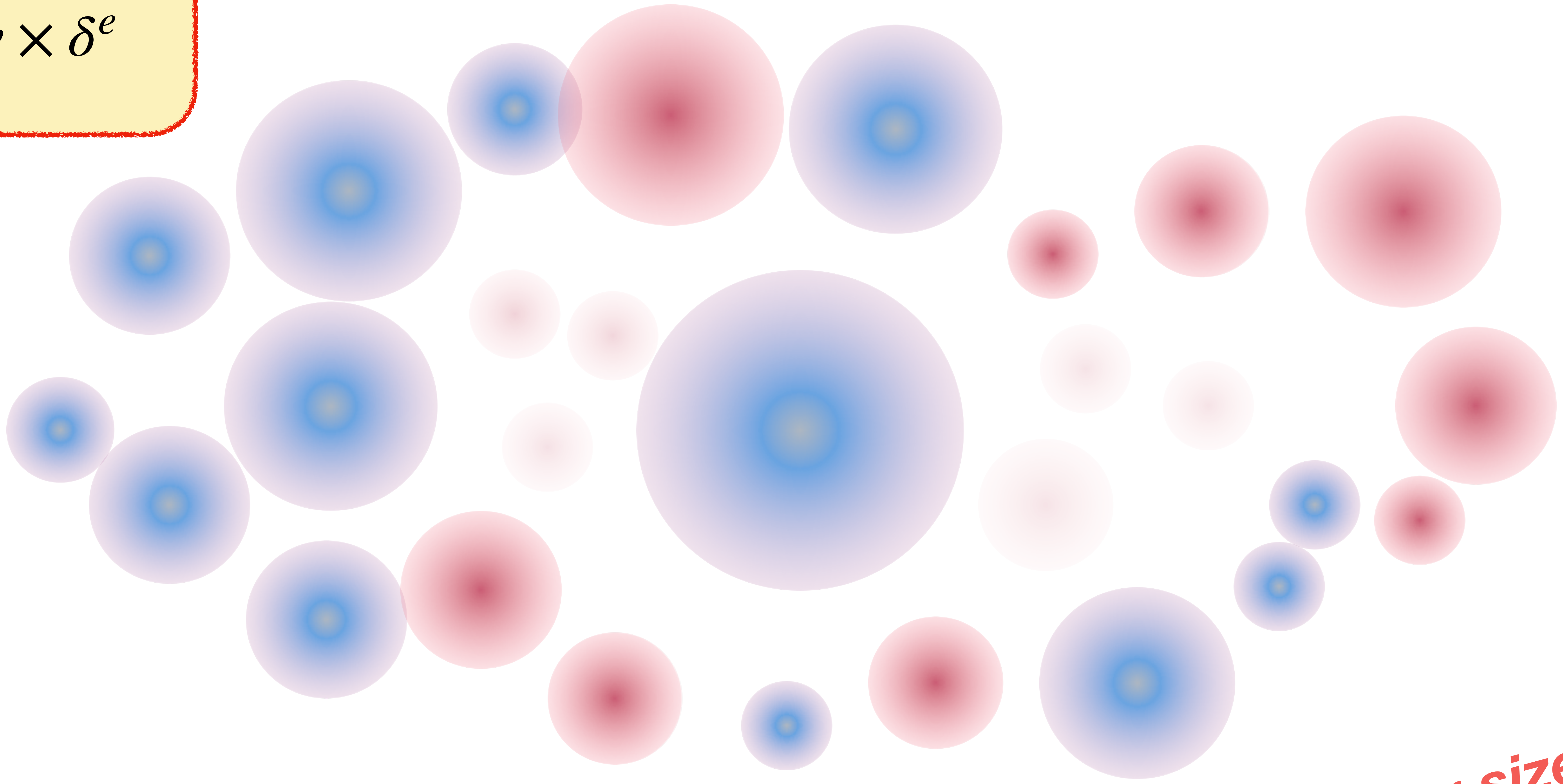
$$T = T^{\mathrm{CMB}} + T^{\mathrm{kSZ}}$$



Angular size of halos is exagerrated

What does the kSZ look like?

$$T^{\mathrm{kSZ}} \sim v \times \delta^e$$



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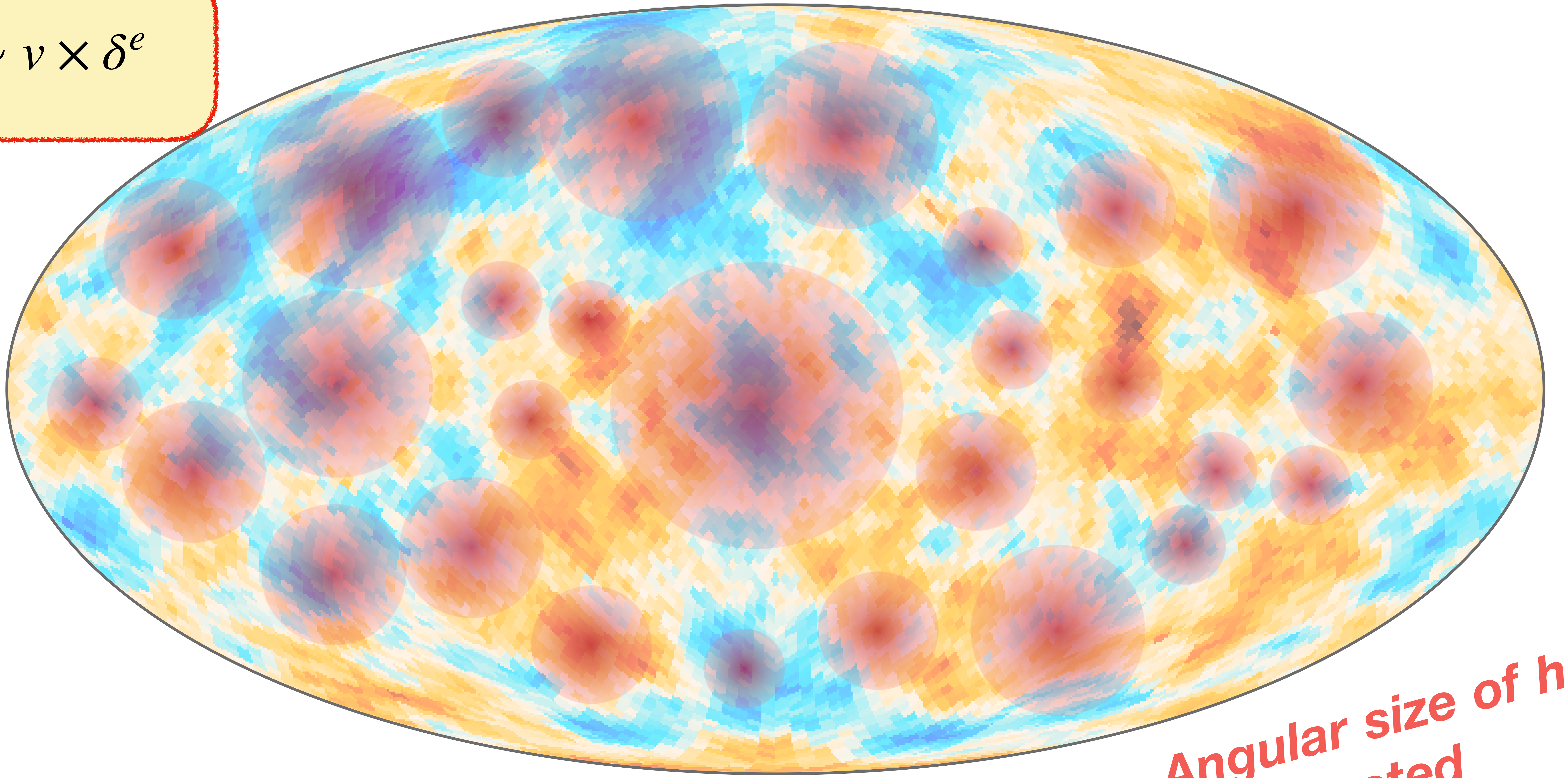

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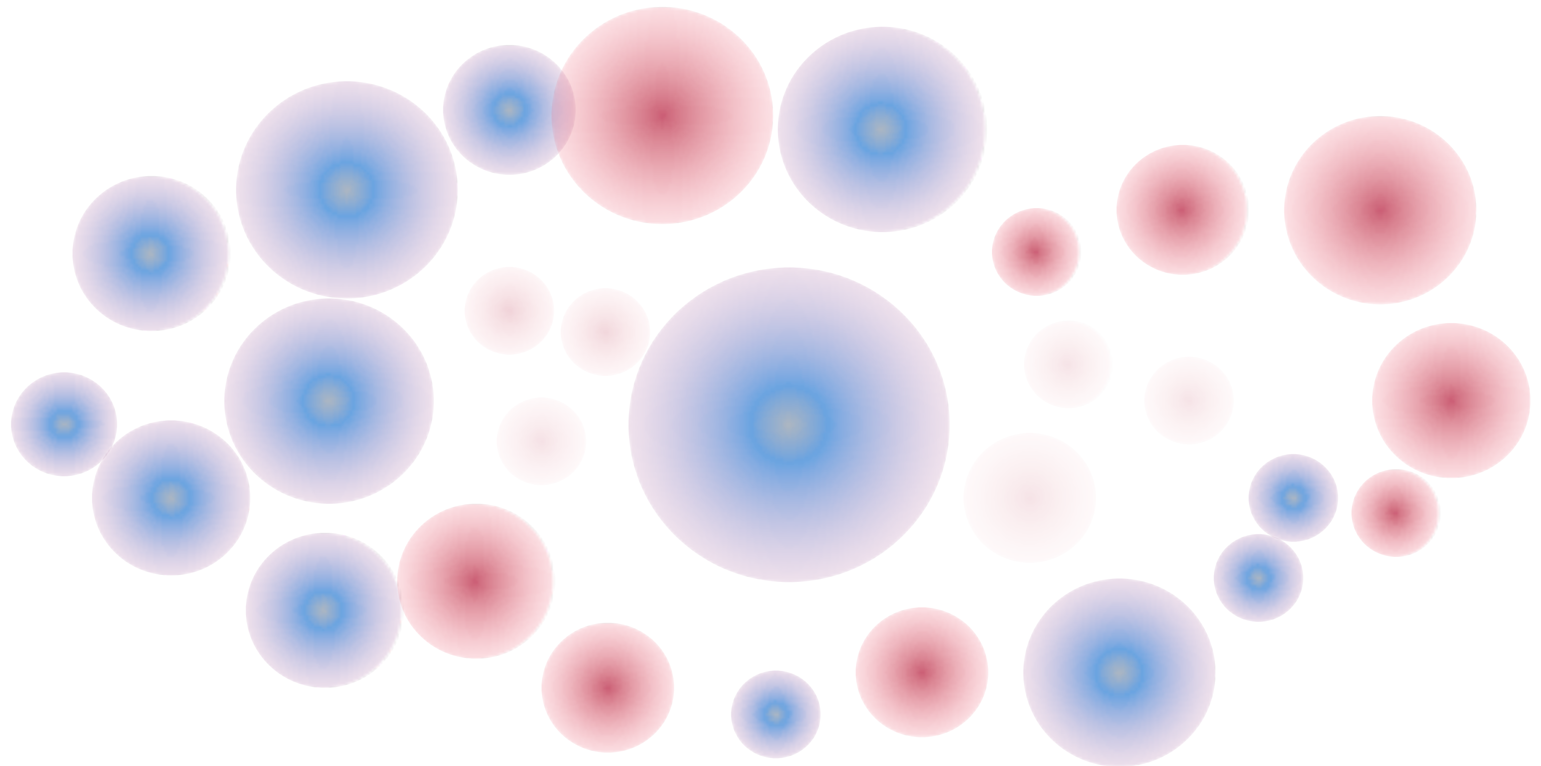

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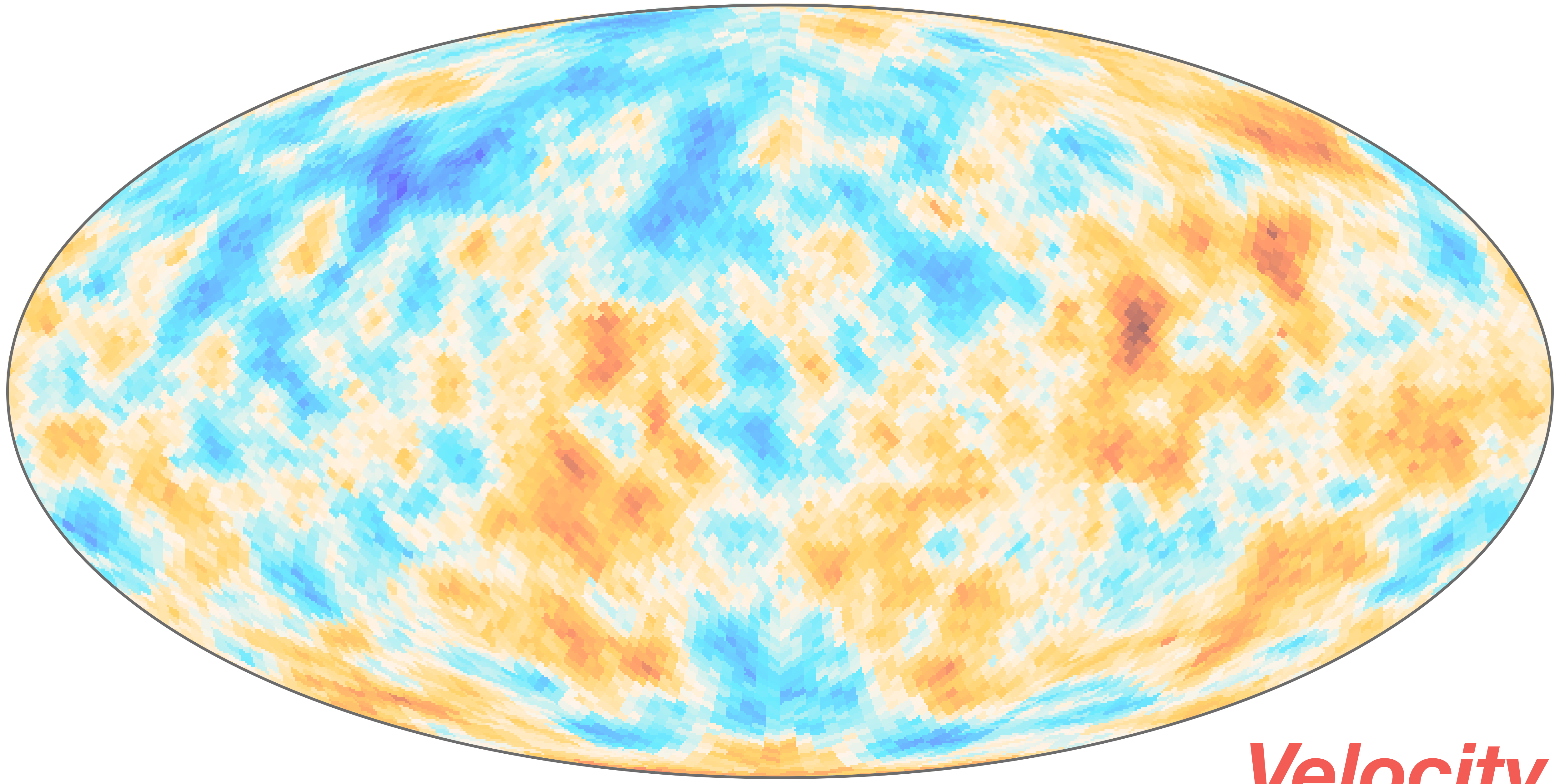

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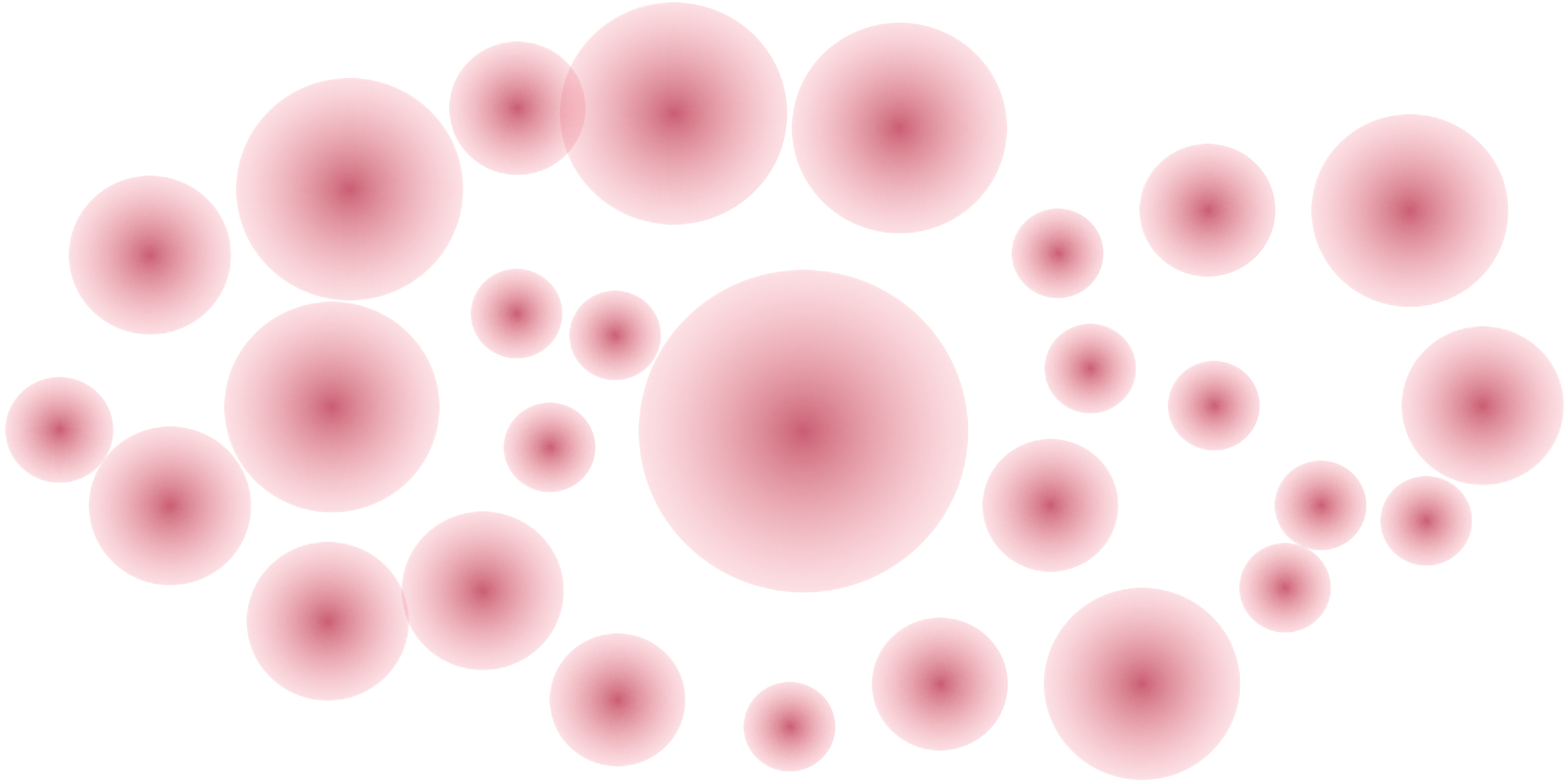
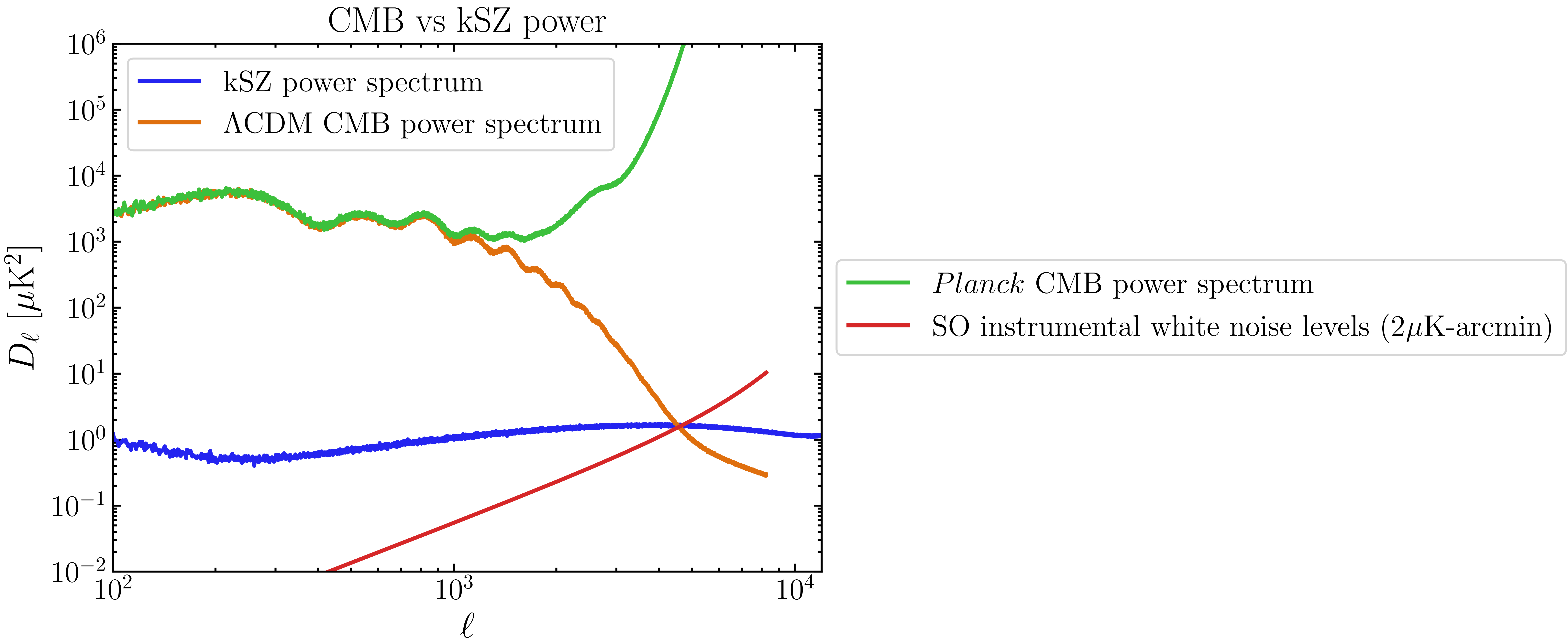


Velocity

Electron density

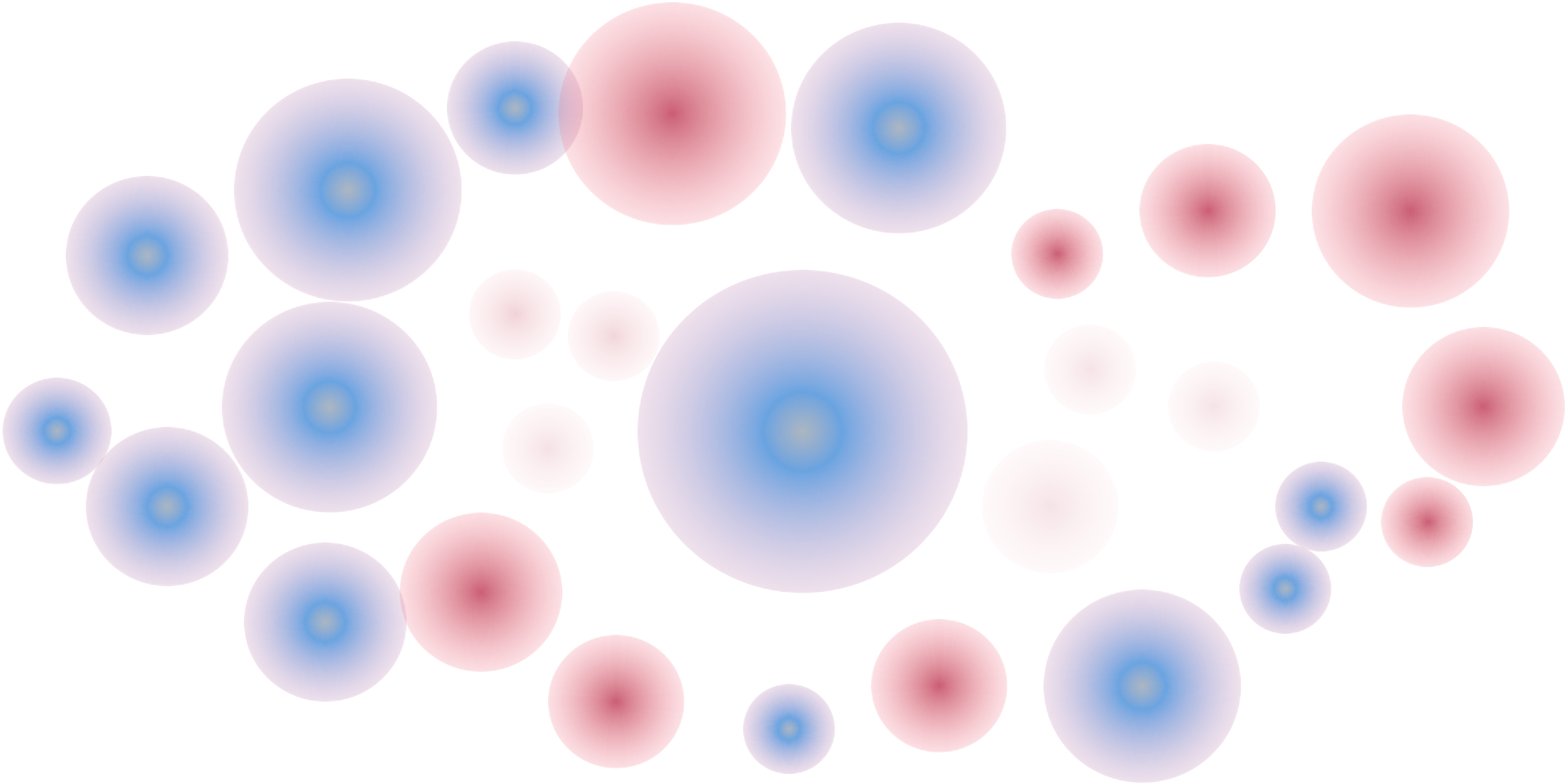
Measuring the kSZ: small scales

- kSZ dominates over primary CMB at $\ell \gtrsim 6000$



- We are measuring the CMB on small scales with ACT and SO!! kSZ measurements are getting really good

Measuring the kSZ: cross-correlations



- kSZ signal changes on large scales due to **large-scale velocity field**
- Naïvely, all large-scale information would be buried beneath the primary CMB. But this is a **non-Gaussian effect**
- Can extract the velocity field from the induced $T_S - \delta_S - v_L$ **bispectrum**

Measurement: $\langle T^{\mathrm{kSZ}} \delta v \rangle$

- Can extract the velocity field from the induced $T_S - \delta_S - v_L$ **bispectrum**

$$T^{\mathrm{kSZ}} \sim v \times \delta^e$$

$$\langle T_S^{\mathrm{kSZ}} \delta_S v_L \rangle \sim \langle (v\delta^e) \delta_S v_L \rangle \sim \langle v_L v_L \rangle \langle \delta_S^e \delta_S \rangle$$

- We can measure the left hand side, and model $\langle \delta_S^e \delta_S \rangle$ to estimate $\langle v_L v_L \rangle$

$$\langle v_L v_L \rangle \sim \frac{\langle T_S^{\mathrm{kSZ}} \delta_S v_L \rangle}{\langle \delta_S^e \delta_S \rangle}$$

Measure

Model

What is the measurement?

$$\langle v_L v_L \rangle \sim \frac{\langle T_S^{\mathrm{kSZ}} \delta_S v_L \rangle}{\langle \delta_S^e \delta_S \rangle}$$

Measure

Model

- $\langle T_S^{\mathrm{kSZ}} \delta_S v_L \rangle$ needs:
  - Small-scale CMB temperature measurement $\hat{T}_S$ (this is noisy due to primary CMB, foregrounds, and instrumental noise)
  - Small-scale overdensity measurement δ_S (eg a **galaxy overdensity** δ_S^g)
  - Large-scale velocity measurement v_L: eg from a **3-d galaxy survey**
- So $\langle T_S^{\mathrm{kSZ}} \delta_S v_L \rangle \sim \langle T_S^{\mathrm{kSZ}} \delta_S \delta_L \rangle$

$v_L \sim \delta_L$

Quadratic estimator of $\hat{v}$

- $\left\langle T_S^{\mathrm{kSZ}} \delta_S v_L \right\rangle$ under the hood:
    - Use a quadratic estimator of $(T_S^{\mathrm{kSZ}}, \delta_S)$ to estimate $\hat{v}_L$
    - Cross-correlate the result directly with the large-scale velocity measurement (or galaxy measurement)
- $v_L \leftrightarrow \delta_L$ conversion uses the continuity equation

$$\nabla v = -aHf\delta \text{ (or } -i\vec{k}\cdot\vec{v} = -aHf\delta\text{)}$$

- From galaxy surveys we get a **biased measurement of delta** $\delta^g = b^g\delta$

$$\text{So } -i\vec{k}\cdot\vec{v}b^g = -aHf\delta^g$$

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A galaxy bias measurement

$$\left\langle v_L v_L \right\rangle \sim \frac{\left\langle T_S^{\mathrm{kSZ}} \delta_S v_L \right\rangle}{\left\langle \delta_S^e \delta_S \right\rangle} \sim \frac{b^g \left\langle \hat{v}_L v_L \right\rangle}{\left\langle \delta_S^e \delta_S \right\rangle}$$

- From cross-correlating with large-scale galaxies (or velocity) we are sensitive to large-scale galaxy bias
- Scale-independent galaxy bias is **degenerate with mismodelling of** $\langle \delta^e \delta \rangle$
- But we can isolate scale-dependence $\rightarrow f_{NL}^{\mathrm{loc}}$

Constraining inflation

- (Local) Primordial non-Gaussianity is quantified by f_{NL}

$$\Phi = \phi + f_{NL}\phi^2$$

Initial conditions

- In the presence of **primordial non-Gaussianity**

$$b^g \to \left(b^g + A\frac{f_{NL}}{k^2}(b^g - 1)\right)$$

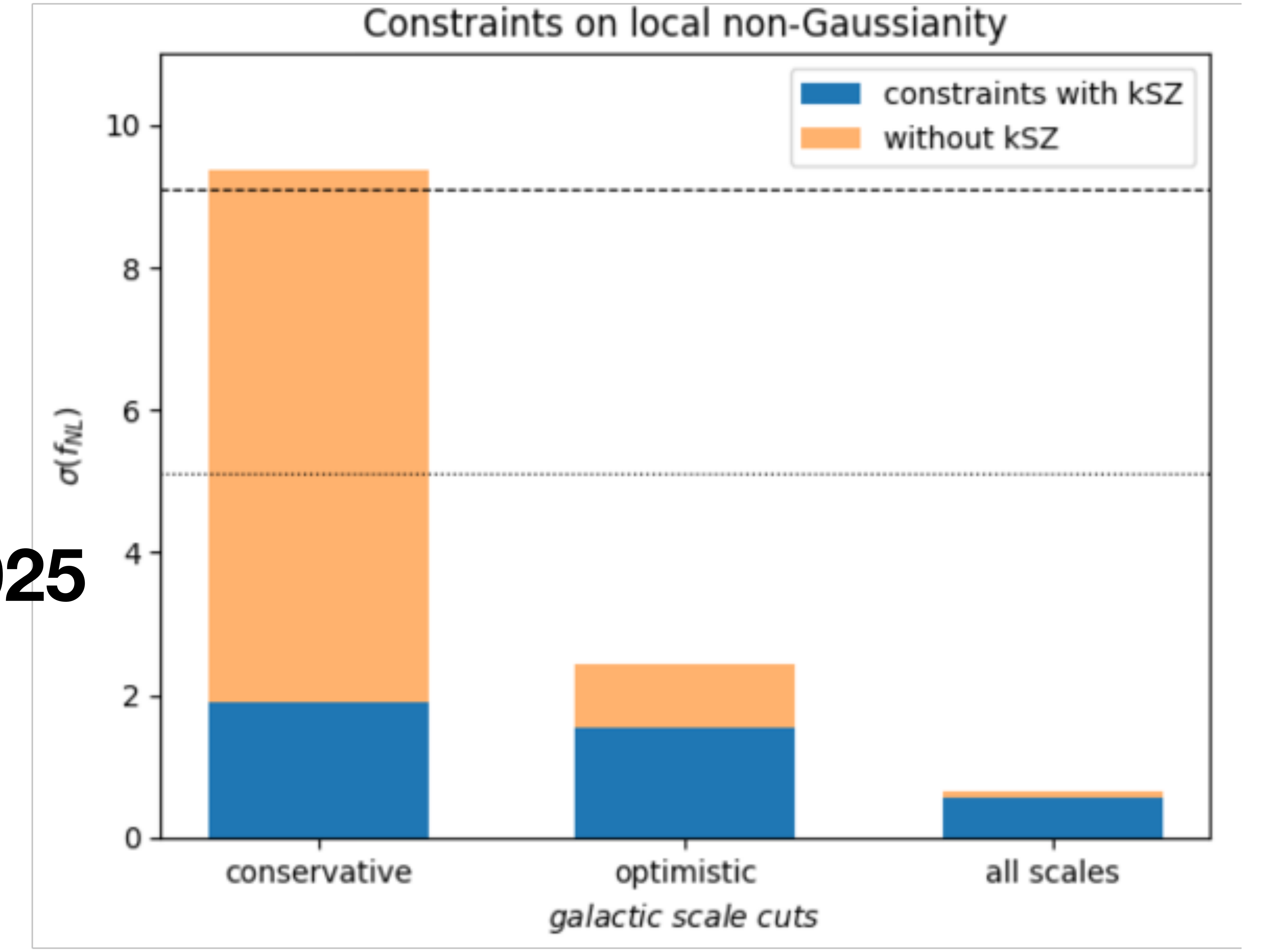
- A **generic prediction of multi-field inflation** is $f_{NL} \sim 1$
- CMB constraints: $f_{NL}^{\mathrm{local}} = -0.9 \pm 5.1$ from *Planck*
- Galaxy surveys will measure better than the CMB soon. **Why include kSZ?**

Constraining f_{NL} with kSZ measurements

- Improved constraints on f_{NL} come from **sample variance cancellation** *(see Münchmeyer et al 2018) and* **robustness** (through cross-correlation)

- Forecast for SO-LSST:

  conservative: auto only at $\ell > 100$
  optimistic: auto only at $\ell > 30$



- See **Krywonos et al 2024** and **Laguë et al 2025** as well as **Selim's talk** for constraints with *Planck*/ACT data!

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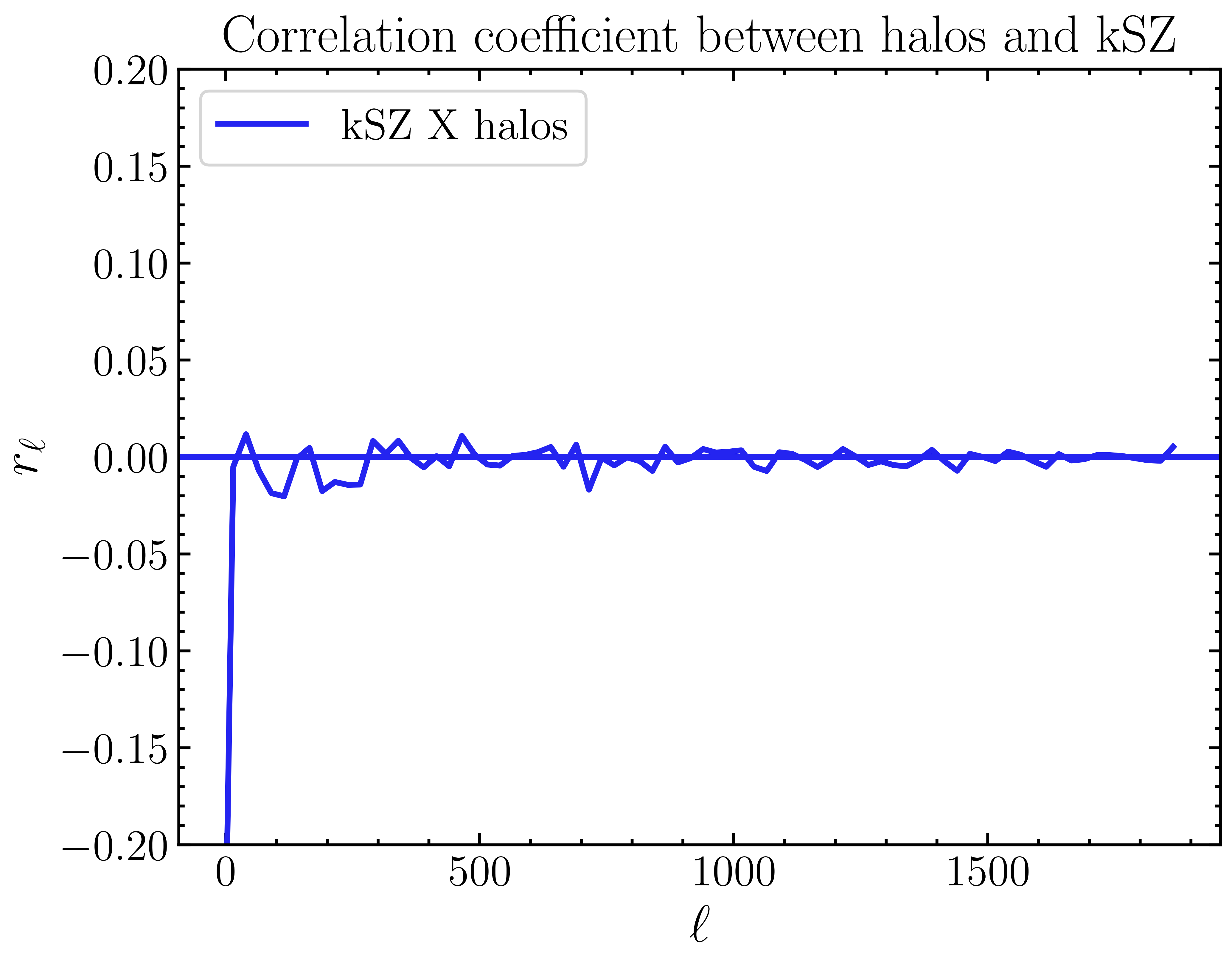
$\left\langle T^{\mathrm{kSZ}} \delta^{g} \right\rangle = 0?$

- Correlation coefficient of kSZ and over density almost vanishes

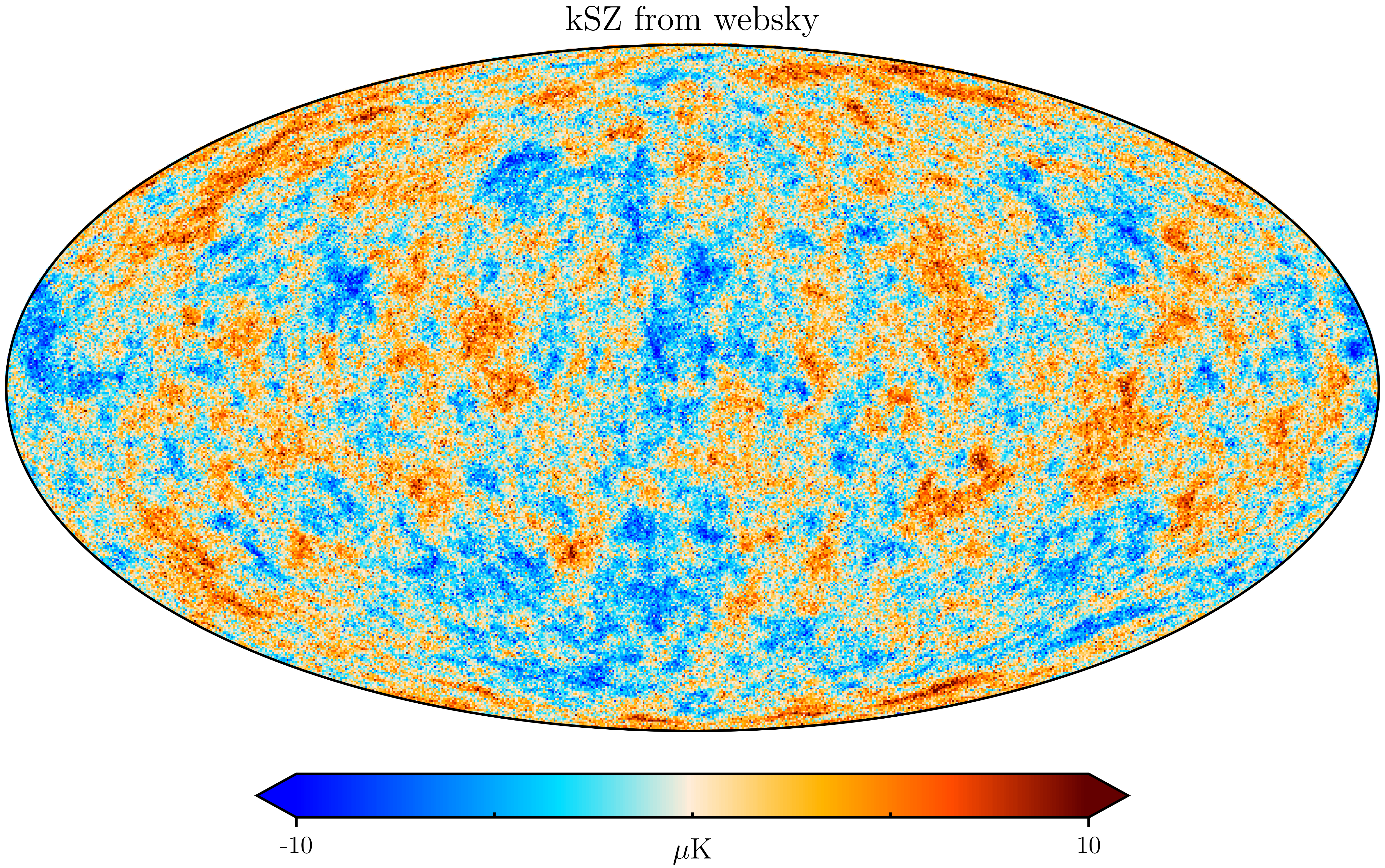
$$T^{\mathrm{kSZ}} \sim v \times n_e$$

$$\left\langle v n_e \delta_g \right\rangle = 0$$

- Objects are as likely to be moving away as towards us



Is $\langle T^{\mathrm{kSZ}}\delta^g \rangle$ really zero?



- No, it's just position dependent. Focus on where the velocity is positive…

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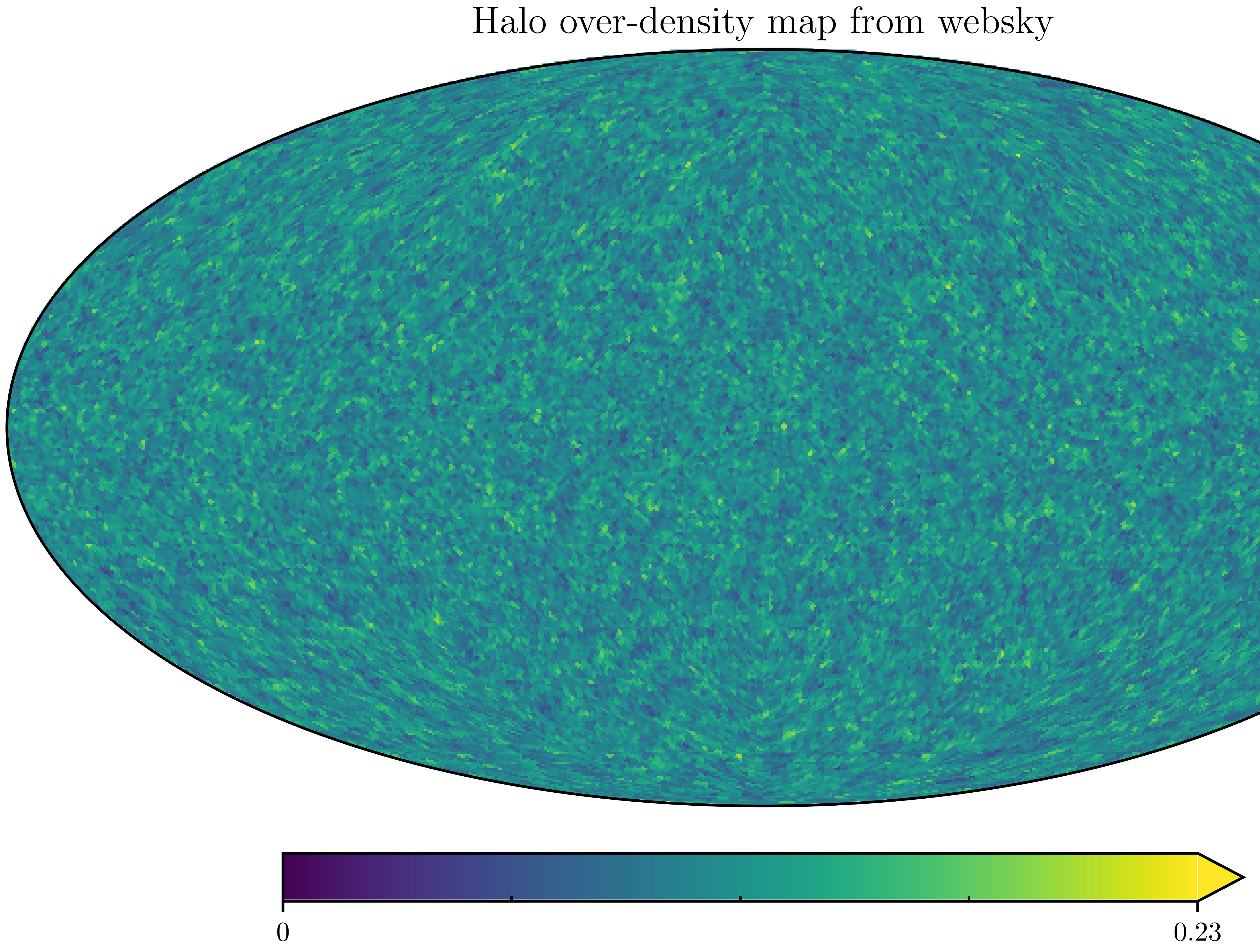

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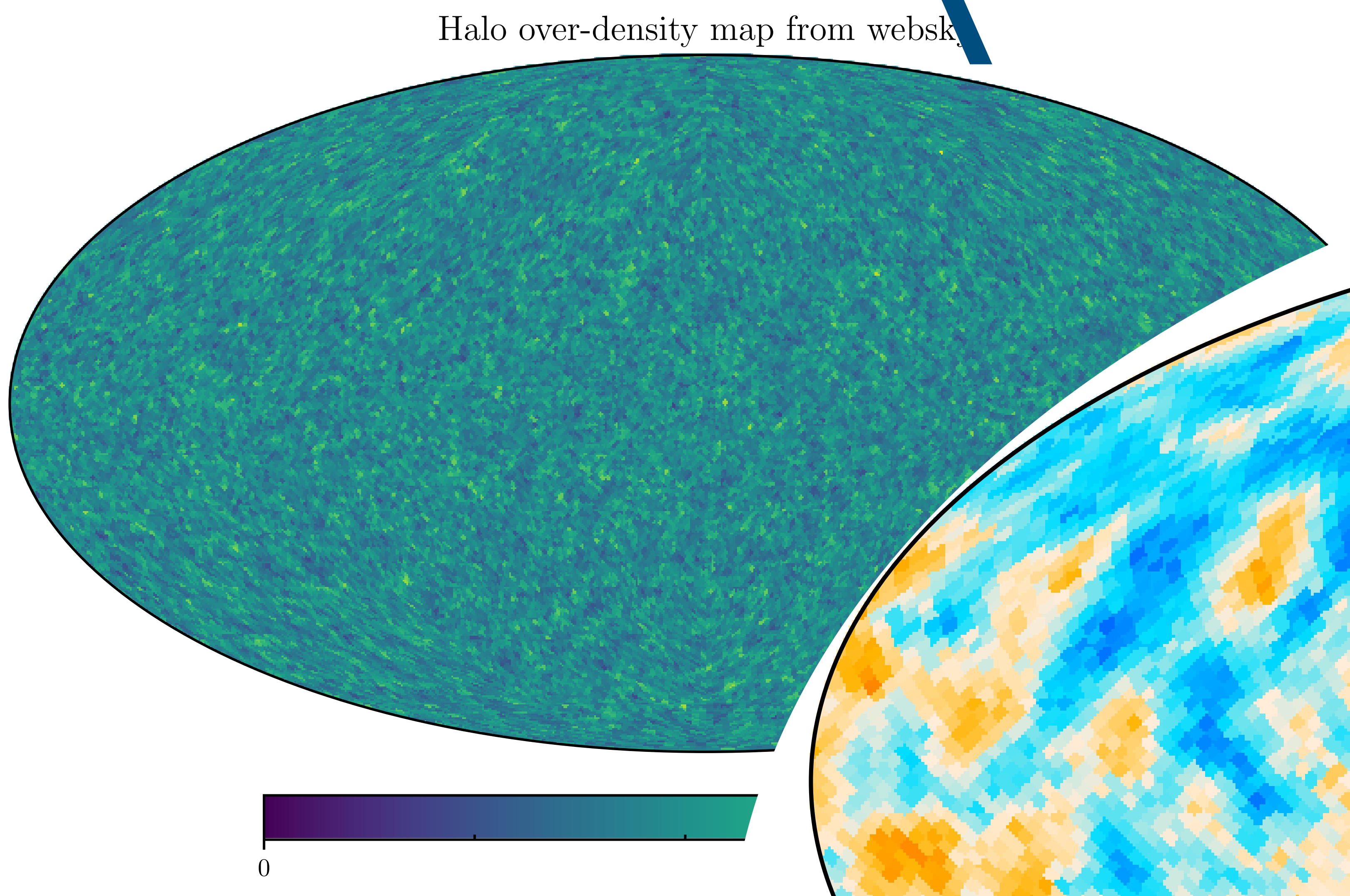

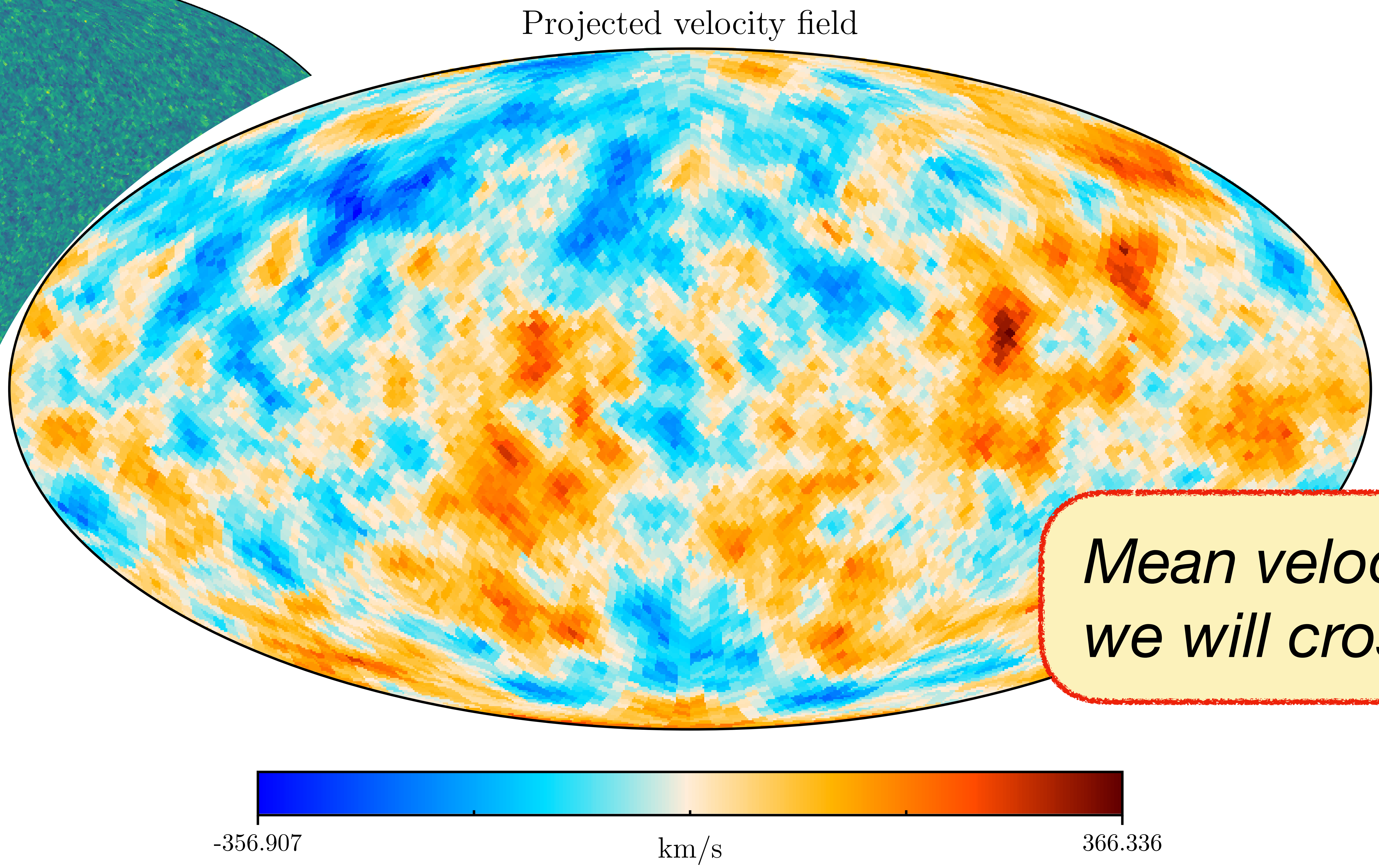

Mean velocity of the halos we will cross-correlate with

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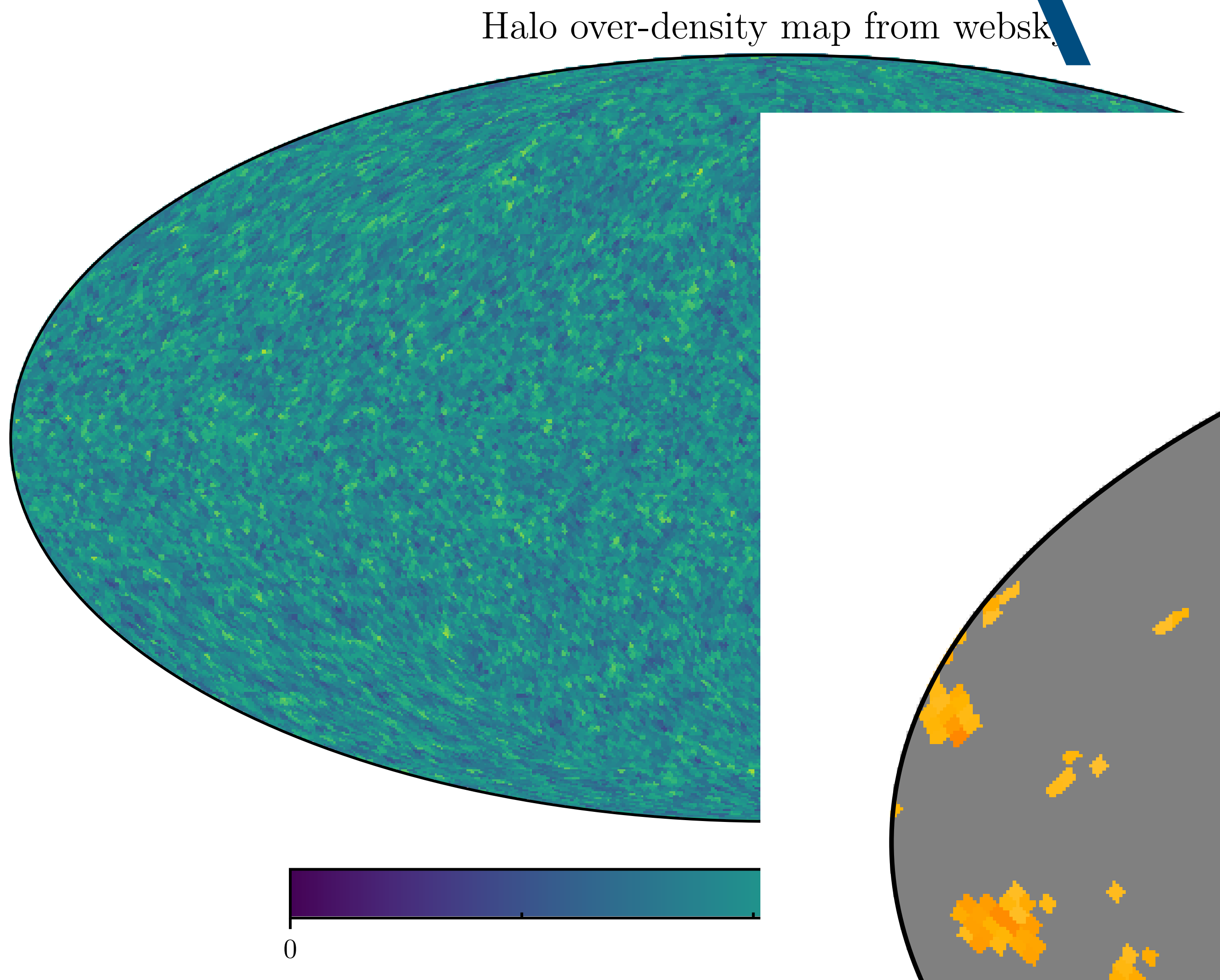

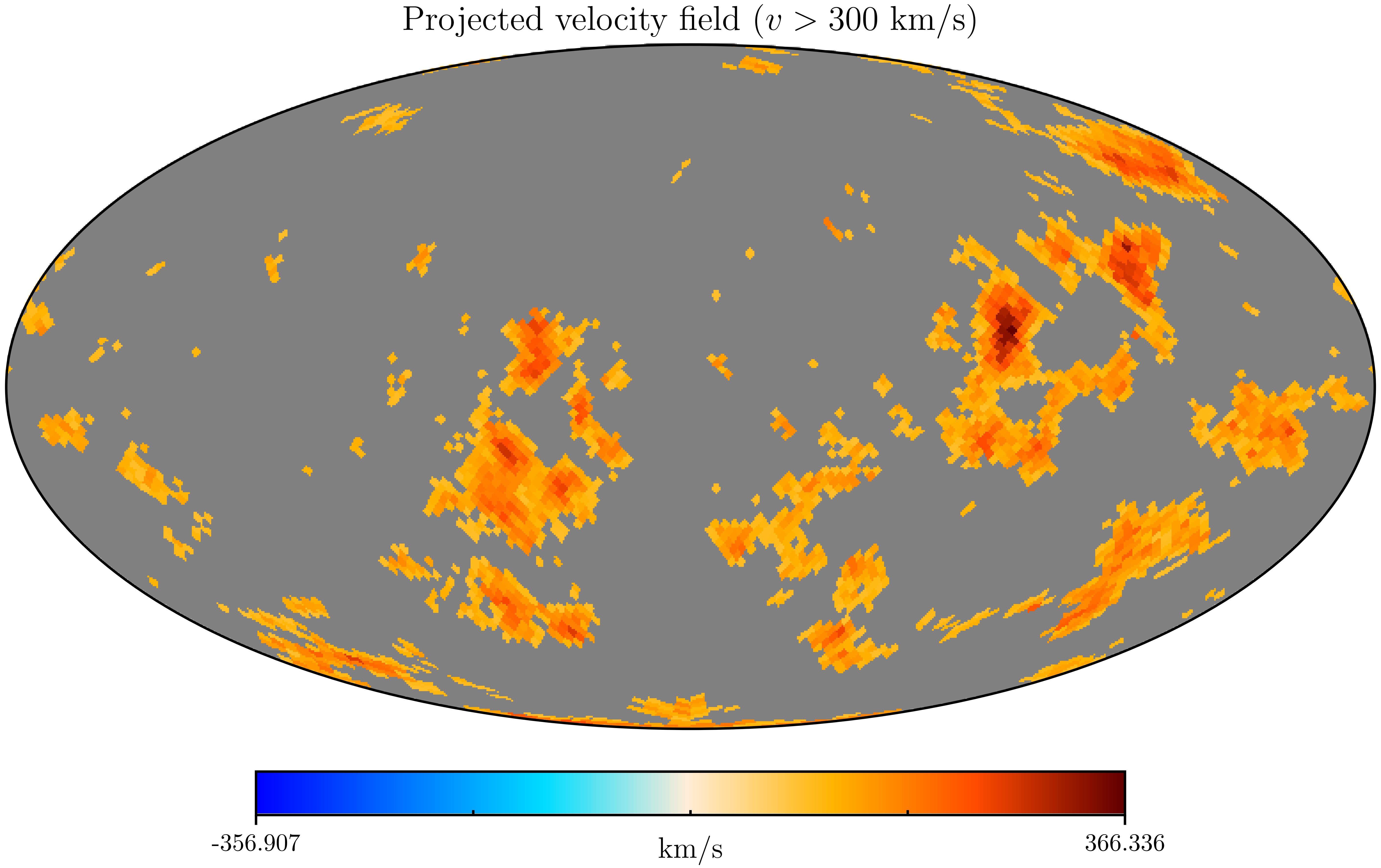

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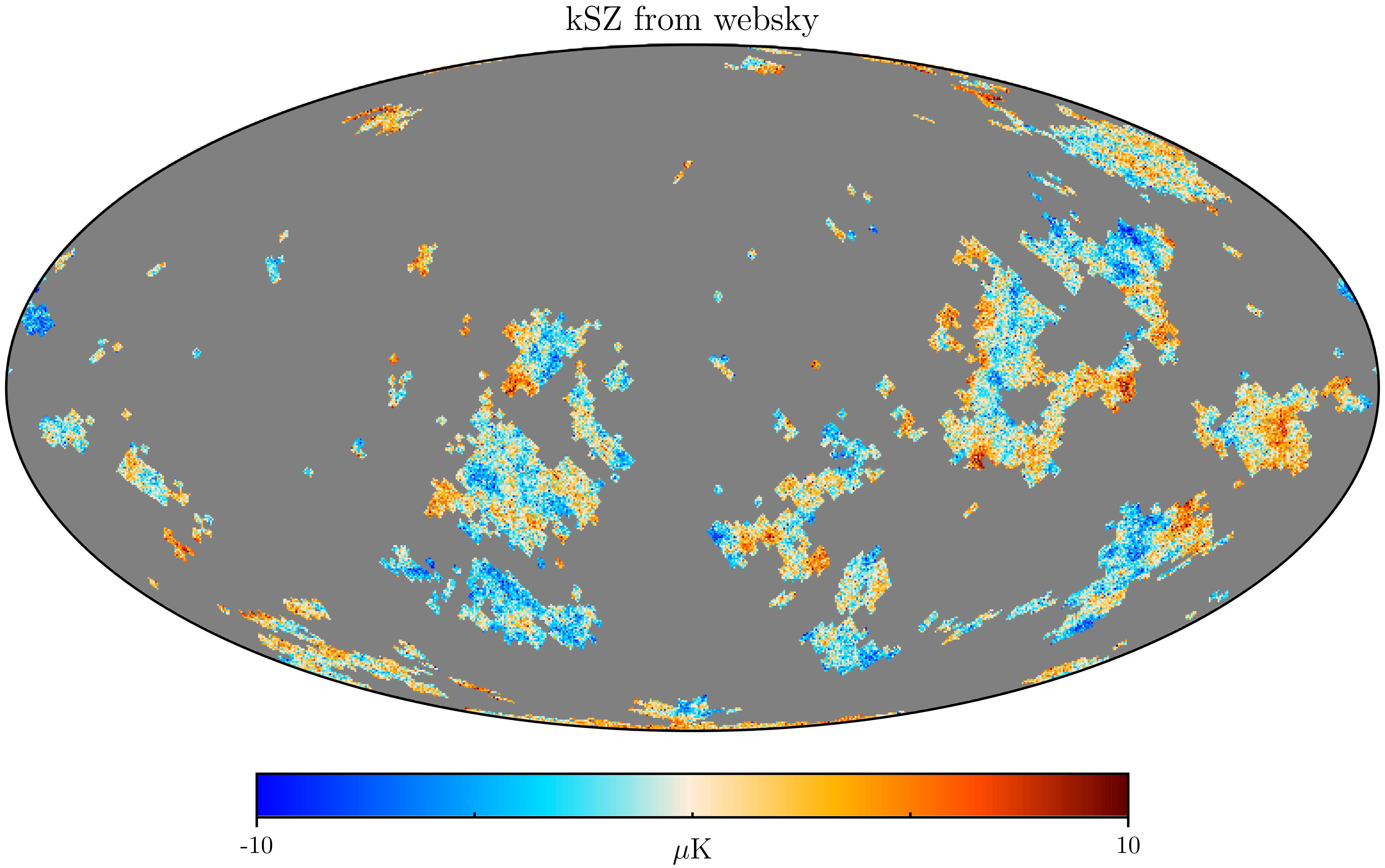

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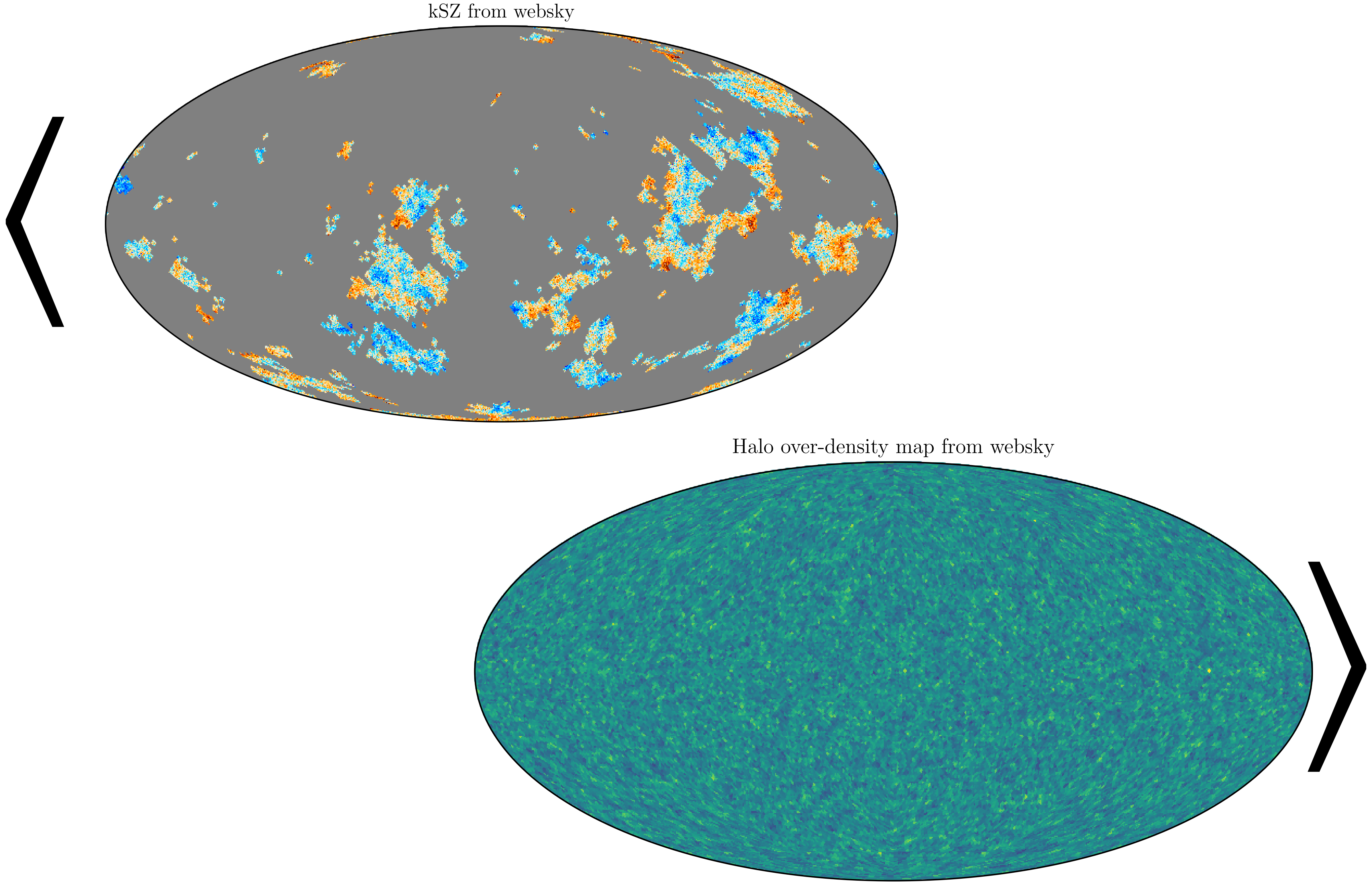
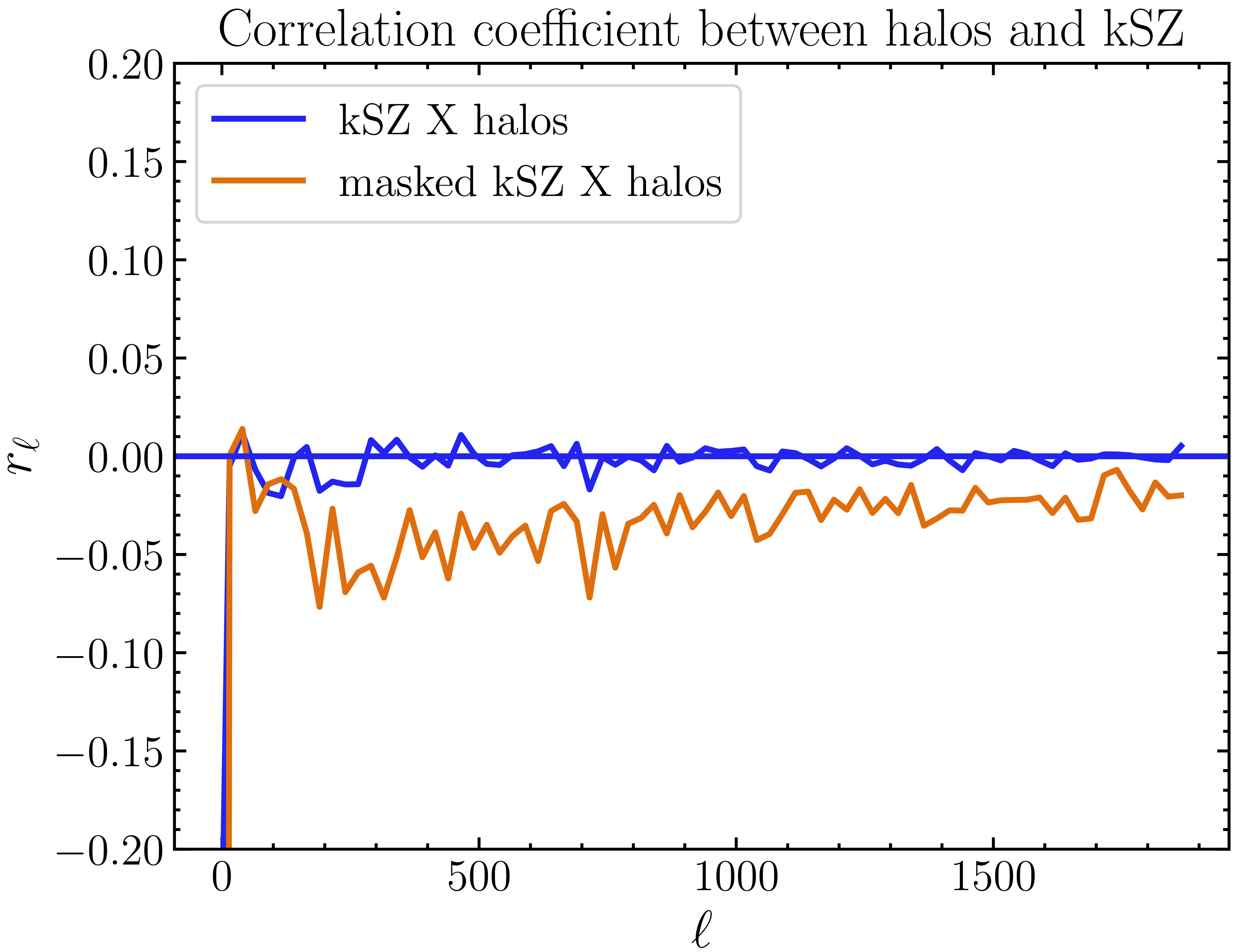
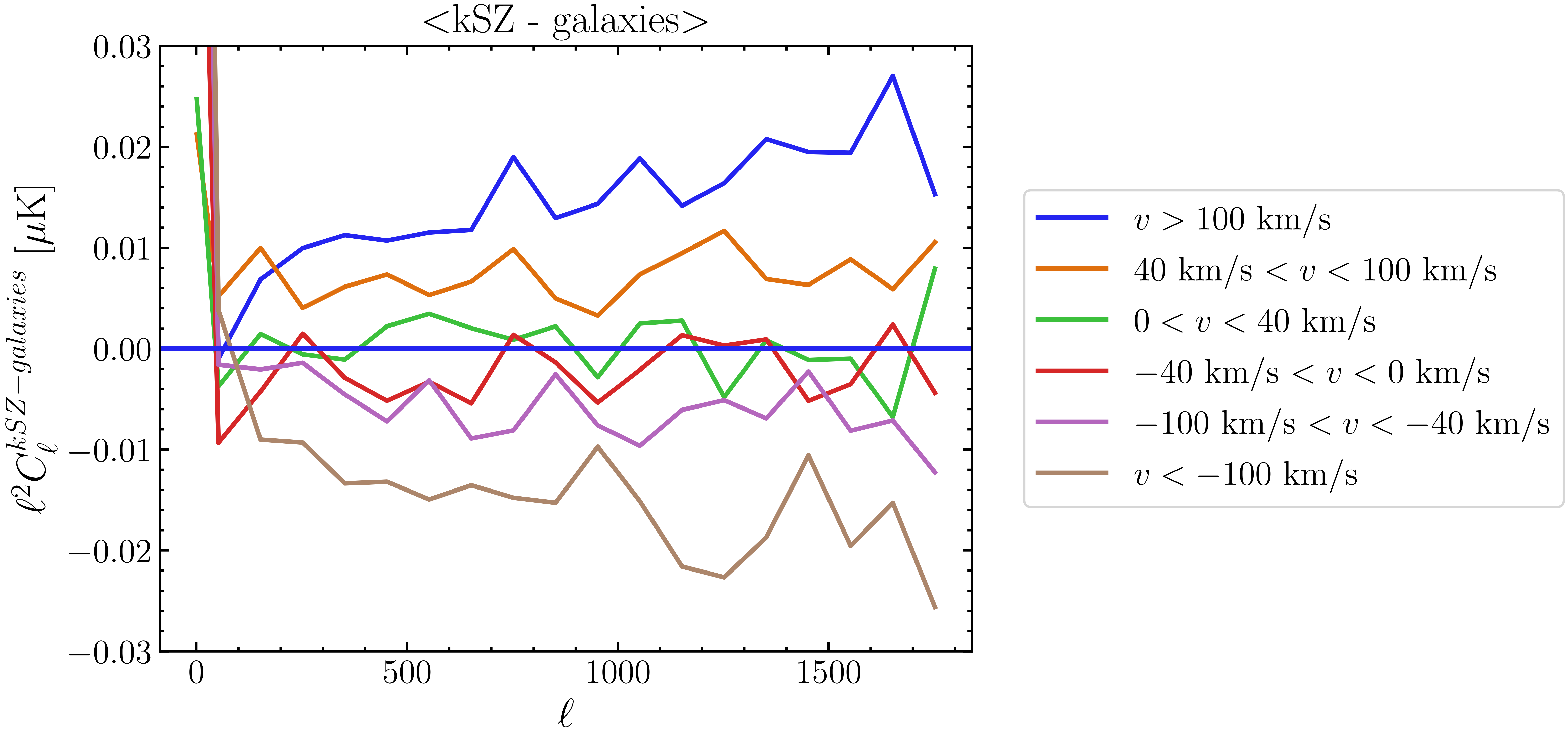




Is $\langle T^{\mathrm{kSZ}} \delta^g \rangle$ really zero?

- Measured value of C_ℓ^{kSZg} depends on the area of sky you measure on…



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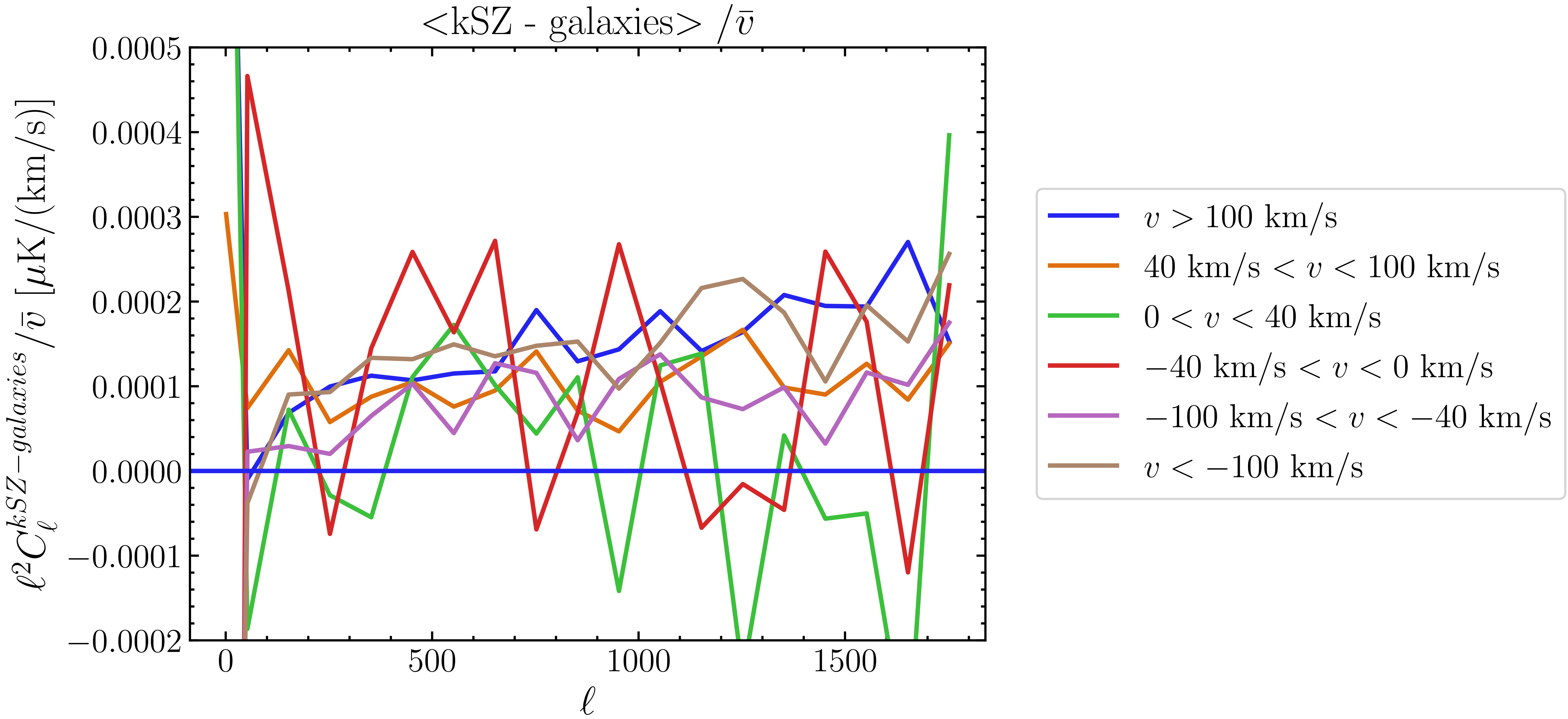

*Divide the signal by the mean local velocity → **isotropy***

- It only depends on the **local** value of the large-scale velocity!
- Analagous to CMB lensing → CMB power spectrum changes over large scales due to foreground ϕ

$\langle T^{\mathrm{kSZ}}\delta^g \rangle$: statistical anisotropy

- Math is very similar to CMB lensing. See **Deutsch et al 2017** for Hu&Okamoto-like estimator
- Large-scale modulation of small-scale isotropy:

$$\left\langle (Aa)_{\ell m} b_{\ell' m'} \right\rangle = \sum_{LM} W^{\ell\ell' L}_{mm' M} A_{LM} C^{ab}_{\ell}$$

$$\boxed{\left\langle (v_r\delta^e)_{\ell m} \delta^g_{\ell' m'} \right\rangle = \sum_{LM} W^{\ell\ell' L}_{mm' M} v_{LM} C^{eg}_{\ell}}$$

- With knowledge of C^{ab}_{ℓ}, this can be inverted!

$$A_{LM} = \sum_{\ell m;\ell' m'} W'^{\ell\ell' L}_{mm' M} (Aa)_{\ell m} b_{\ell' m'}$$

$$\boxed{v_{LM} = \sum_{\ell m;\ell' m'} W'^{\ell\ell' L}_{mm' M} \hat{T}^{\mathrm{kSZ}}_{\ell m} \hat{\delta}^g_{\ell' m'}}$$

- Optimal weights W' depend on C^{gg}_{ℓ},C^{TT}_{ℓ}, and C^{ge}_{ℓ}.

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A "quadratic estimator"

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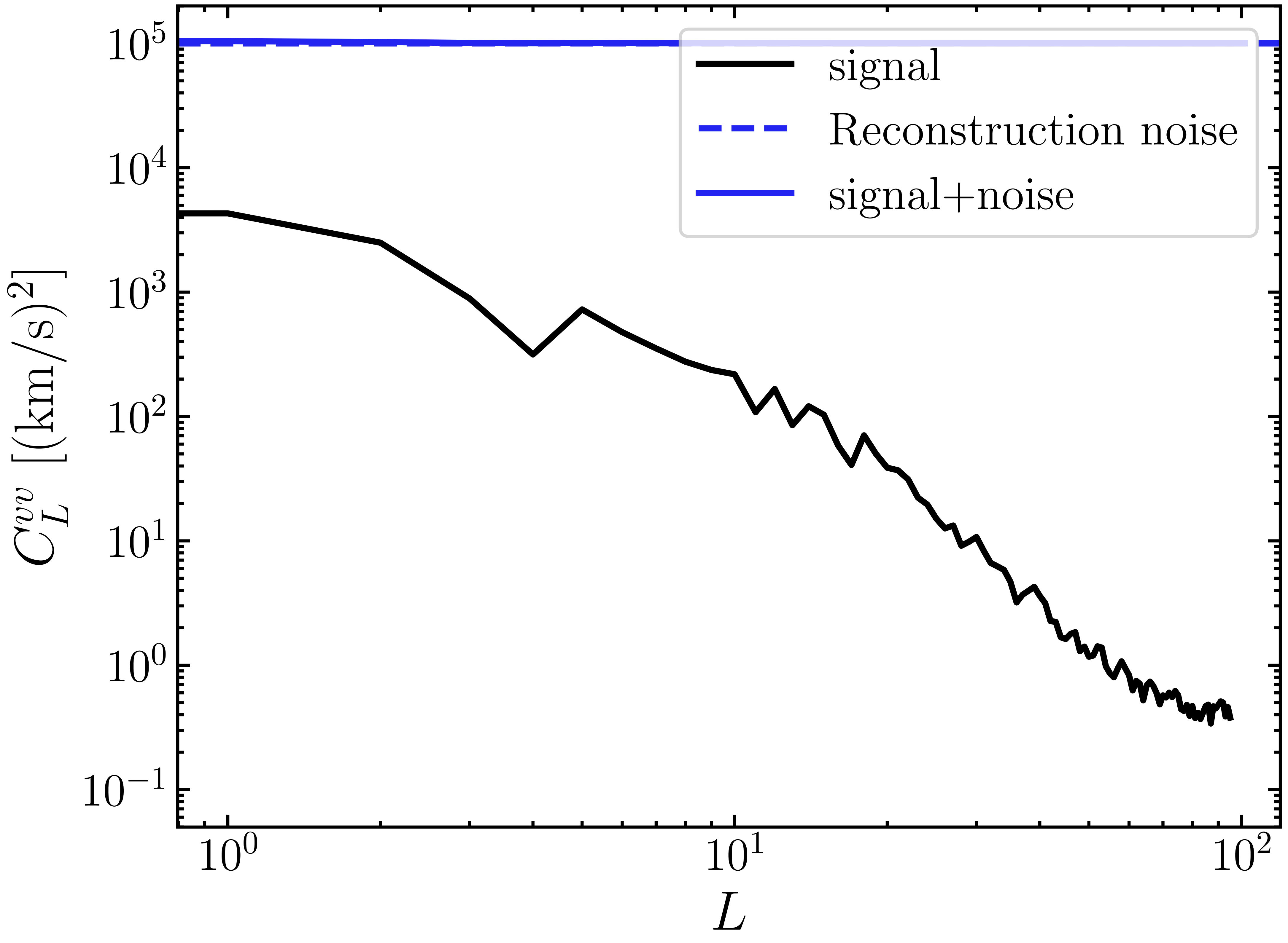
Model

Large-scale v from small-scale g, T

$$\boxed{\hat{T}, \hat{\delta}^g, C_\ell^{ge} \rightarrow \hat{v}}$$

- Large-scale statistical power comes from **better measurement of small scales**

Reconstruction noise from chance correlations in a Gaussian signal



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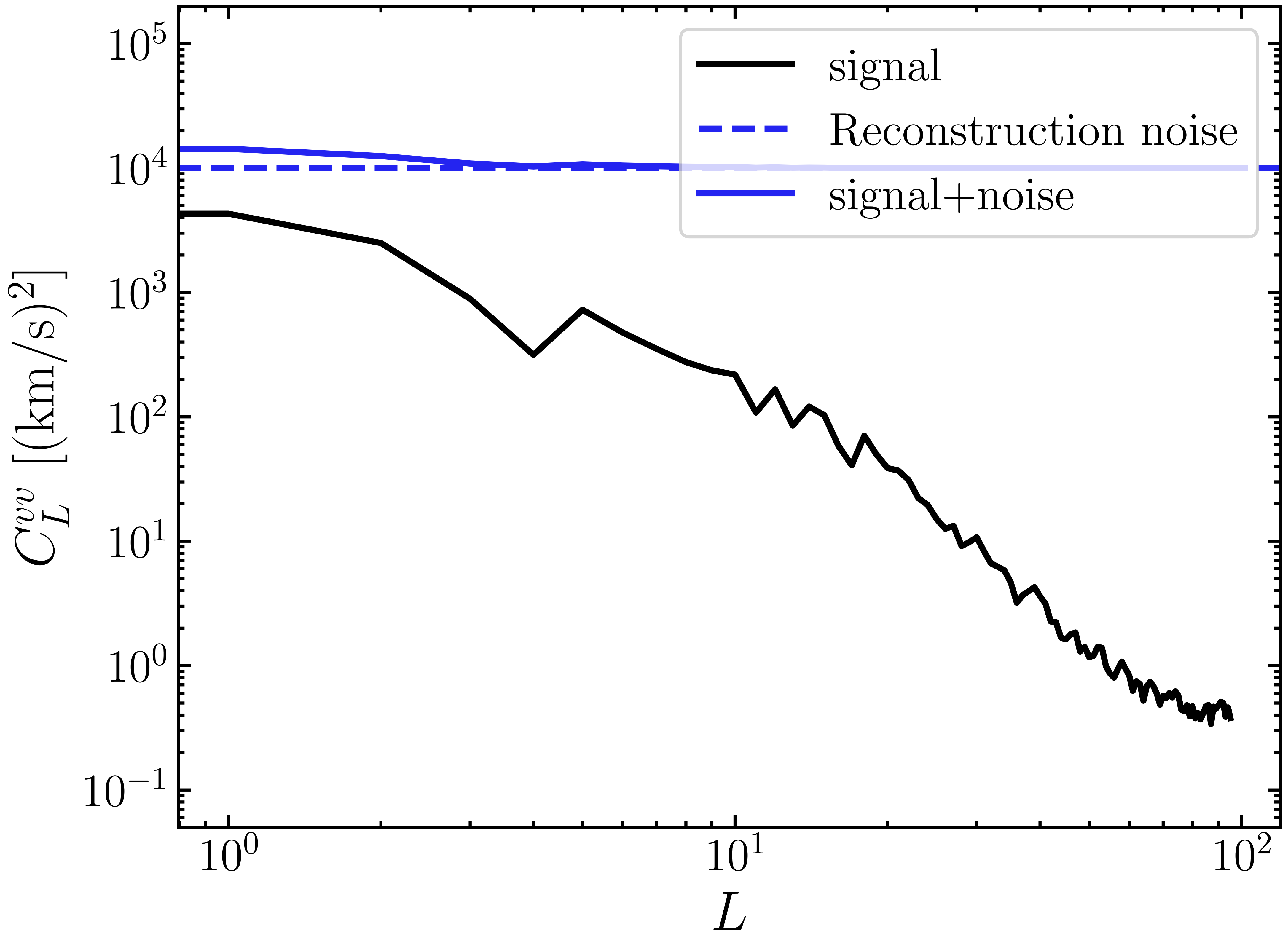

~Planck + unWISE

(See Bloch + Johnson arXiv:2405.00809)

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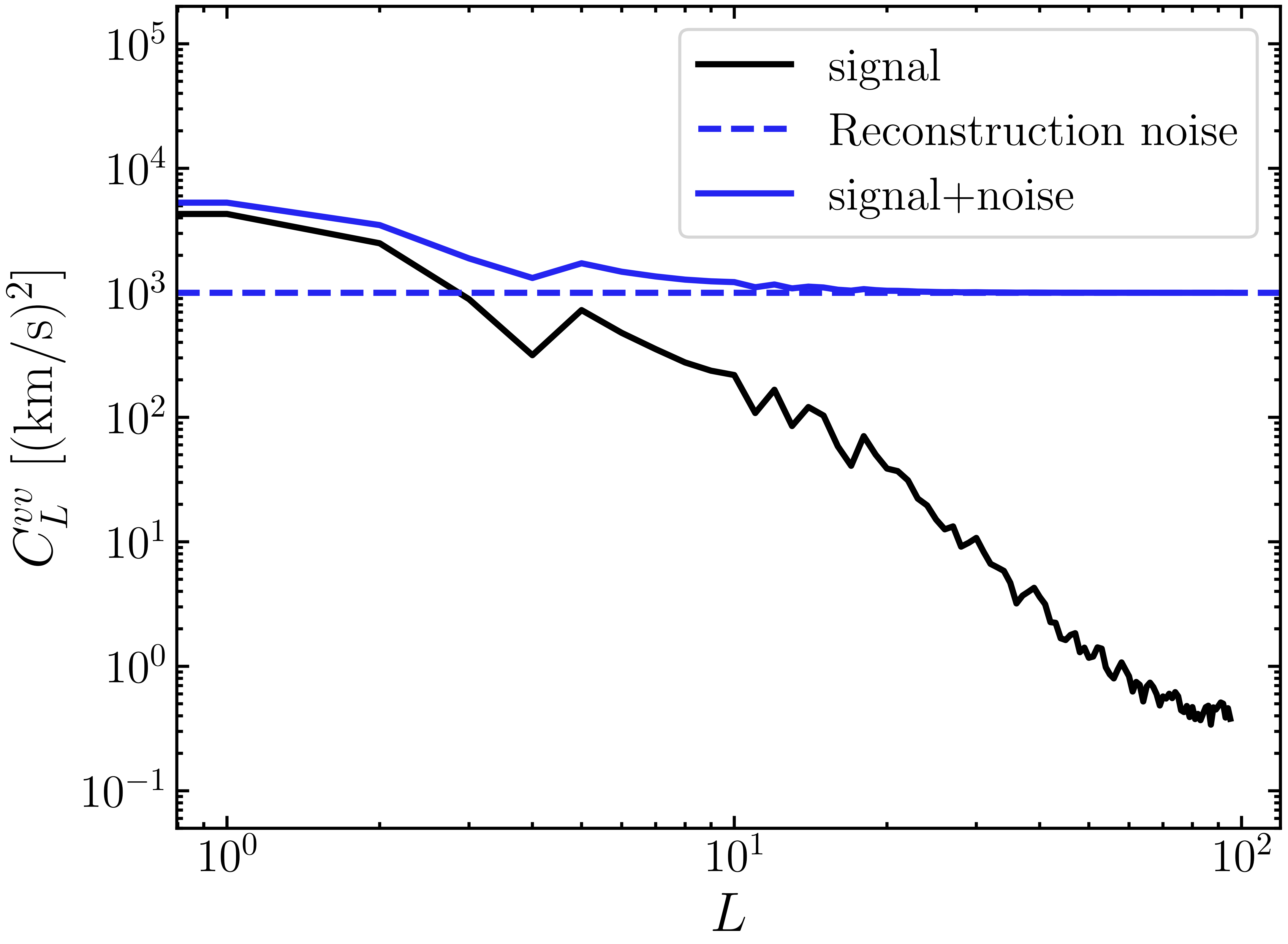

~ACT + DESI-LRGs

(See FMcC et al arXiv:2410.06229)

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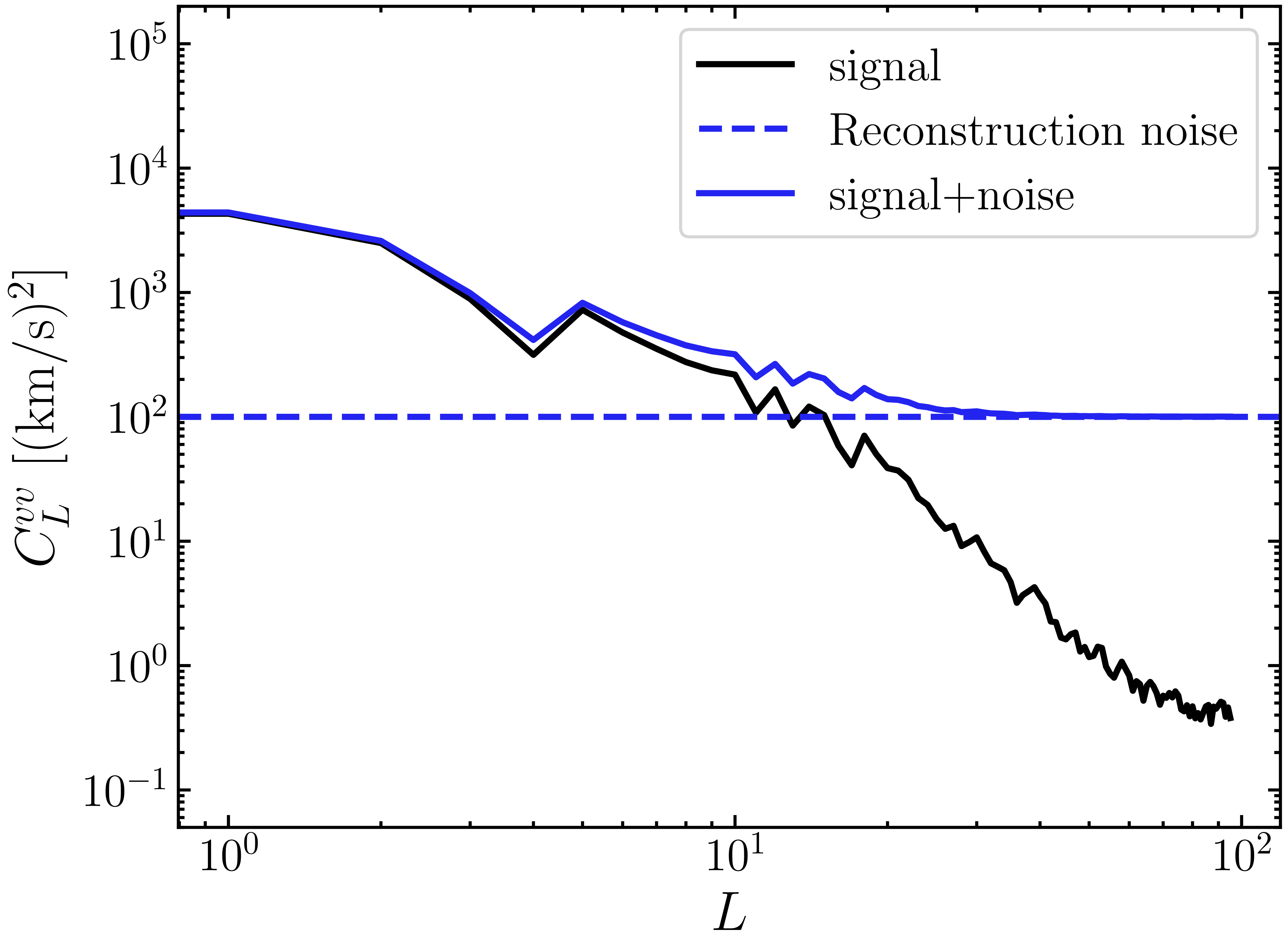

Future experiments!

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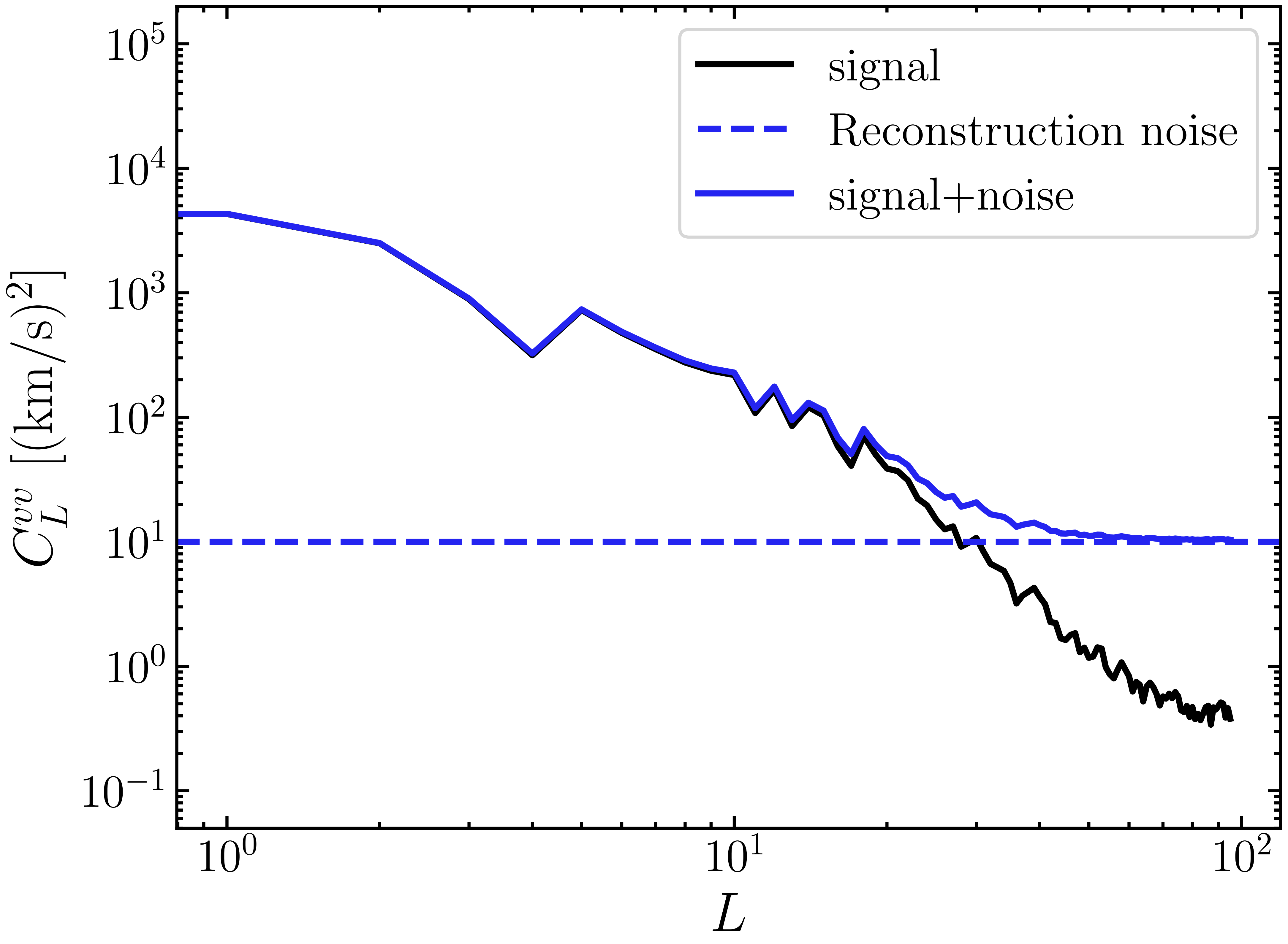

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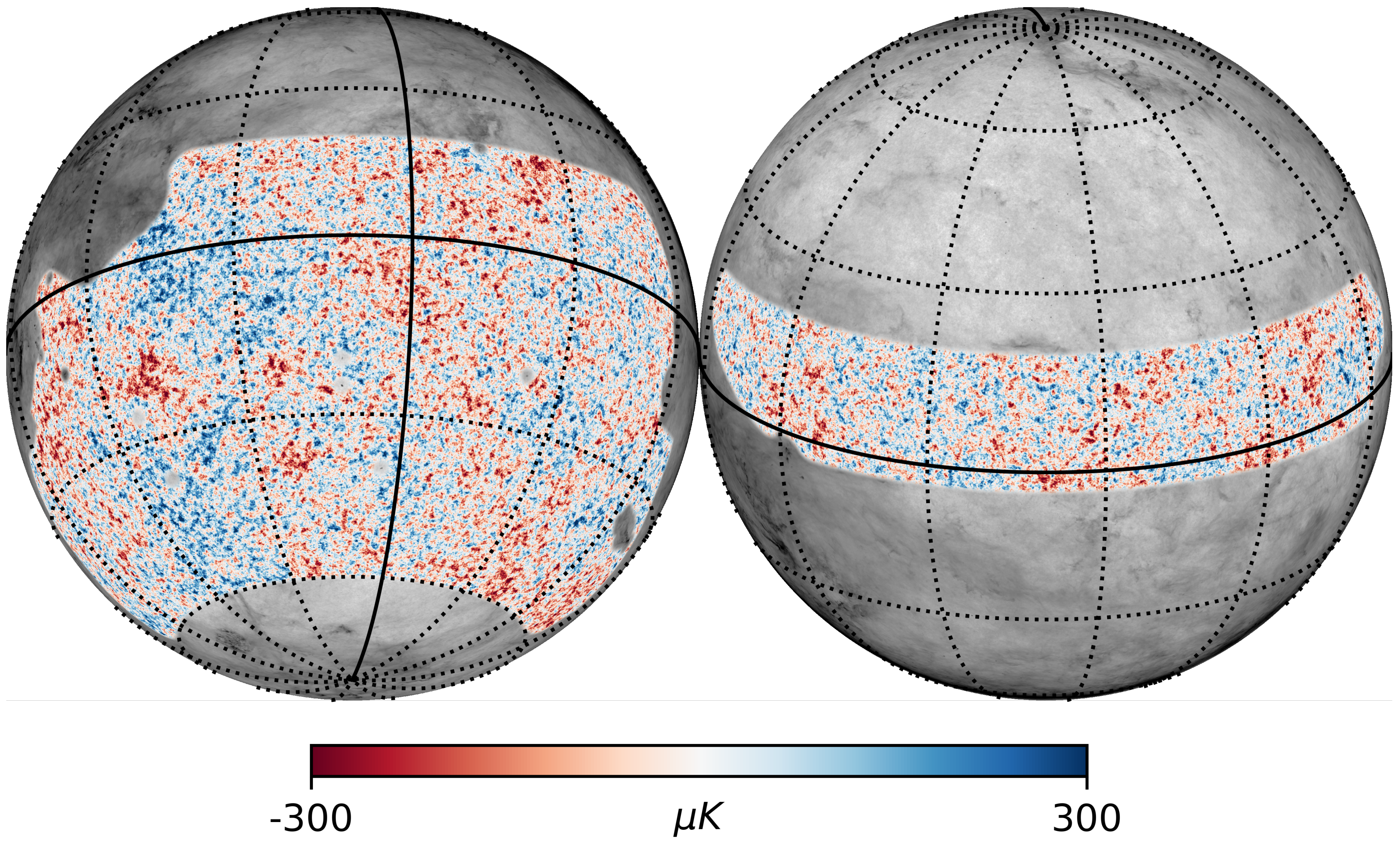
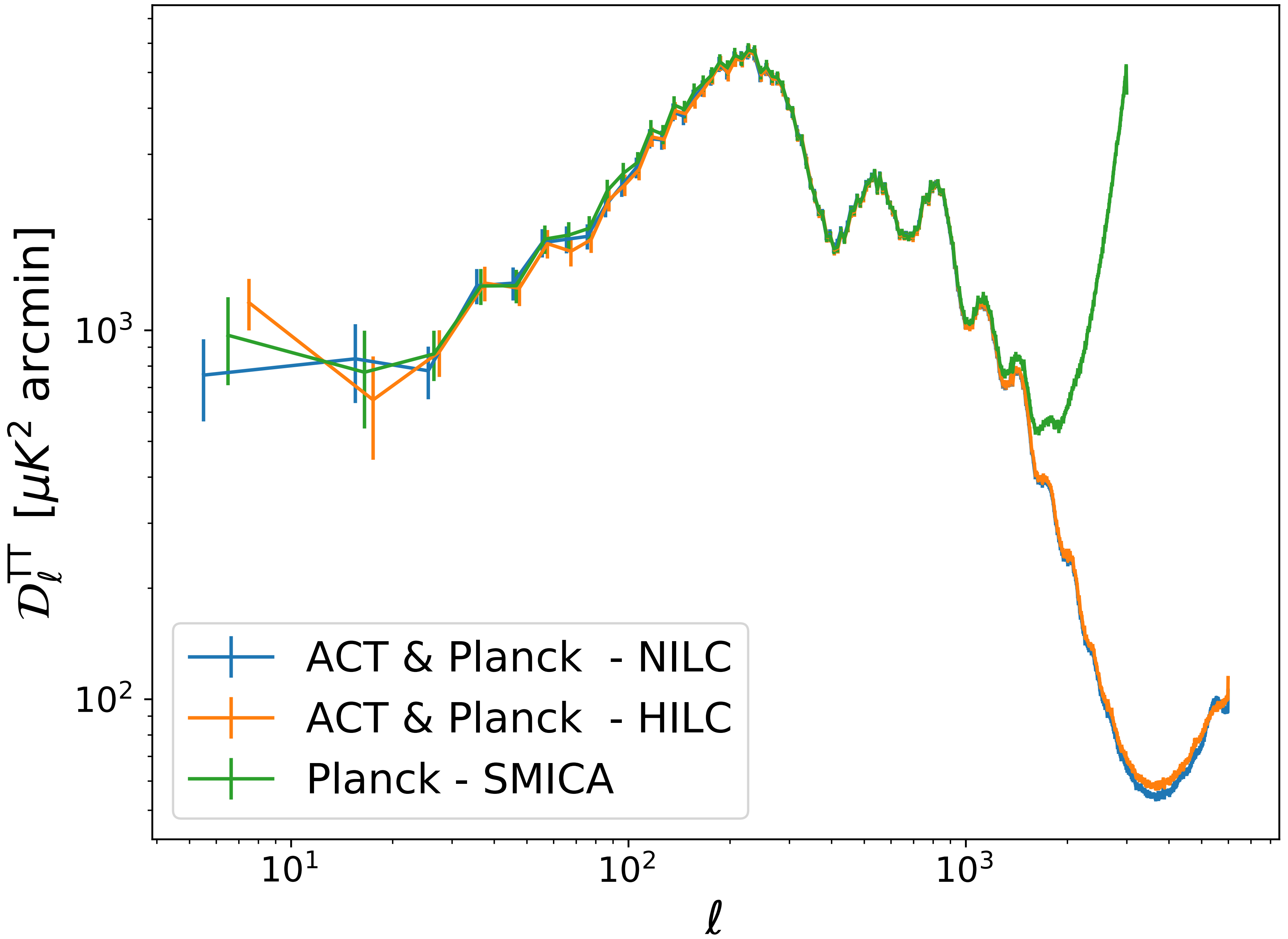
JCAP 05(2025)057 + detection with ACT DR6 + DESILRGs

Temperature data: ACT DR6

- We use the ACT DR6 temperature map from **Coulton et al 2023**



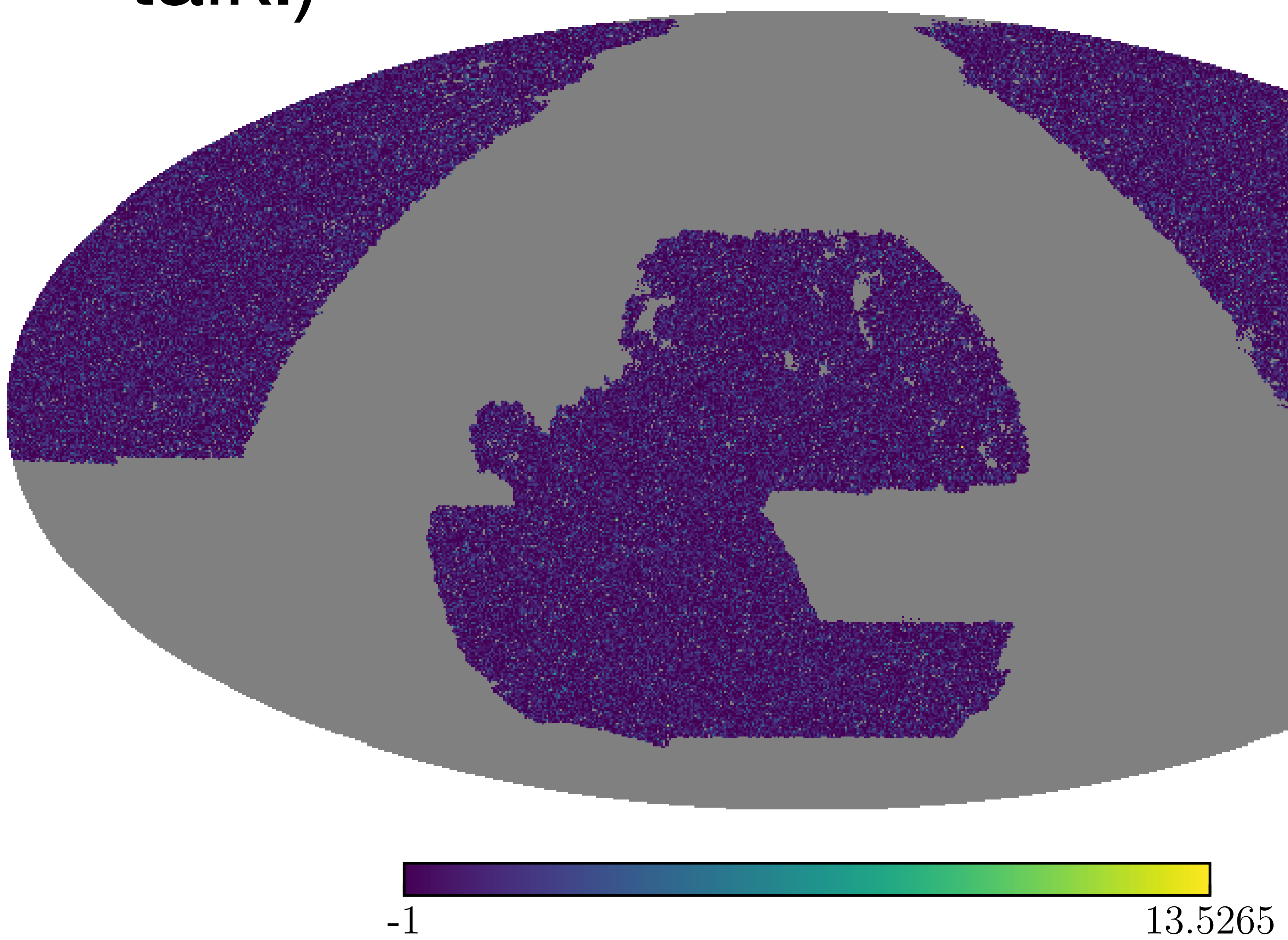


Figures from Coulton et al 2023

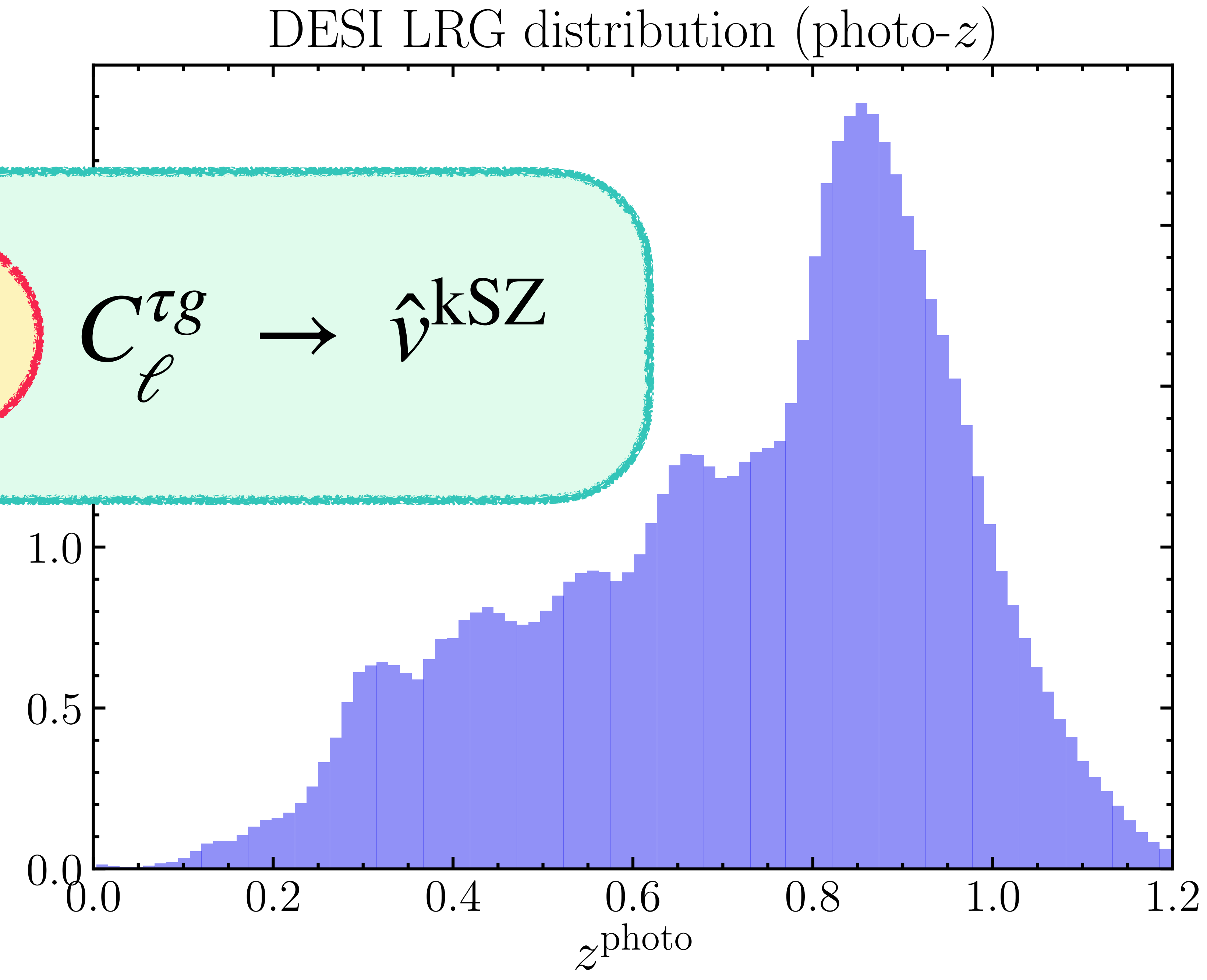
$$\hat{T},\ \hat{\delta}^g,\quad C_\ell^{\tau g} \rightarrow \hat{v}^{\mathrm{kSZ}}$$

Galaxy data: DESI-LRGs

- We use the DESI LRG extended sample from **Zhou et al 2023** (see Simone's talk!)



$$\hat{T}, \hat{\delta}^g, C_\ell^{\tau g} \rightarrow \hat{v}^{\mathrm{kSZ}}$$



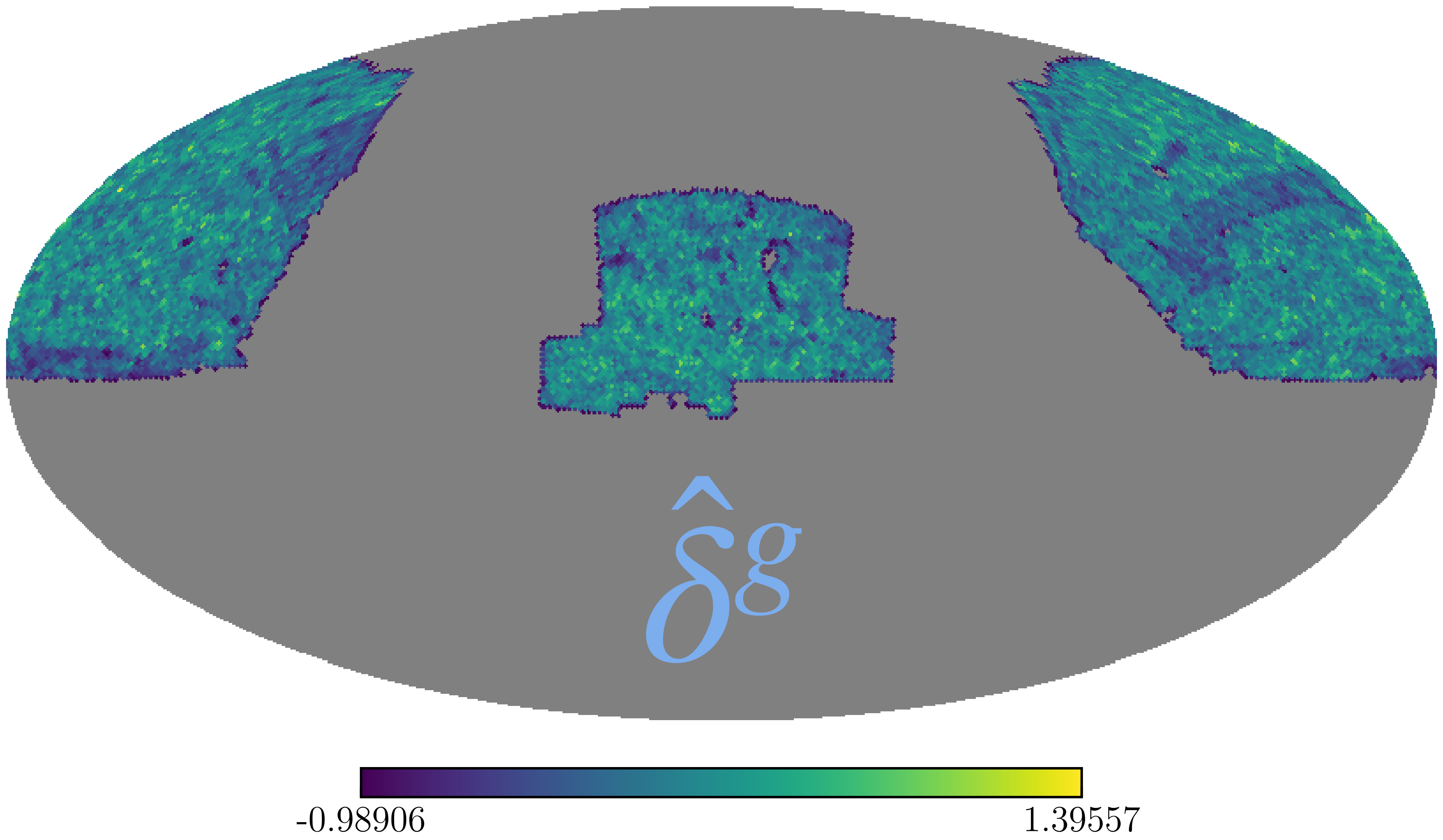
- These are at redshift ~ $0.4 < z < 1$
- Photometric redshift error $\dfrac{\sigma(z)}{1+z} \sim 0.02$

27,253,833 objects
18,000 square degrees

Fiona McCarthy, mm Universe, 25 June 2025

External velocity data: BOSS

- Use BOSS galaxies to make velocity template for cross-correlation
- Galaxies move in a gravitational field -> **infer the velocity from density** (using GR)



$$\left\langle v^{\mathrm{k}SZ} v^{\mathrm{external}} \right\rangle ?$$

Continuity equation:

$$-i\vec{k}\cdot\vec{v} - i\vec{k}\cdot\left(v_{||}\hat{n}\right) = -aHf\frac{\delta_g}{b}$$

Reconstruction from Kendrick Smith

External velocity data: BOSS

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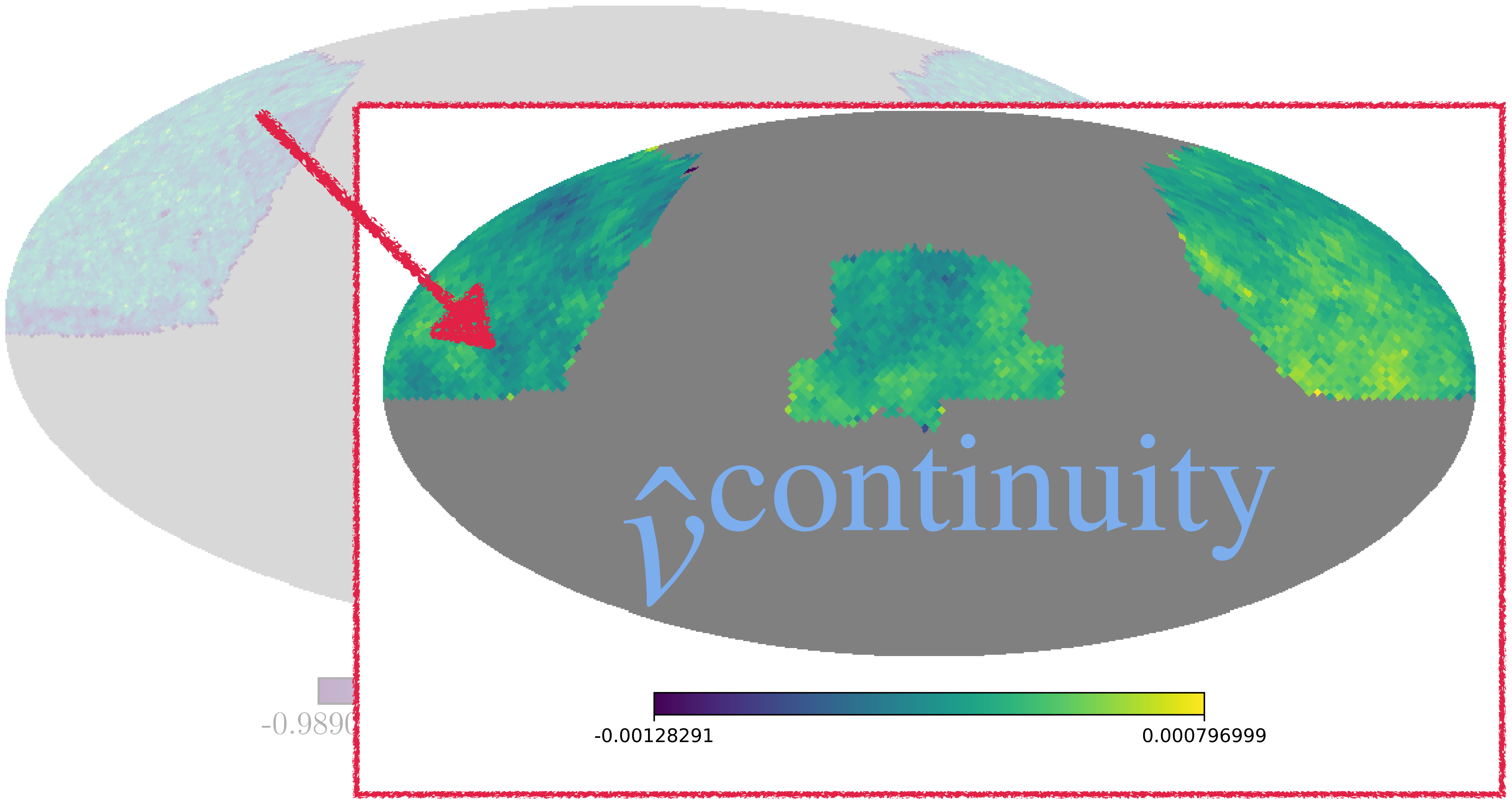

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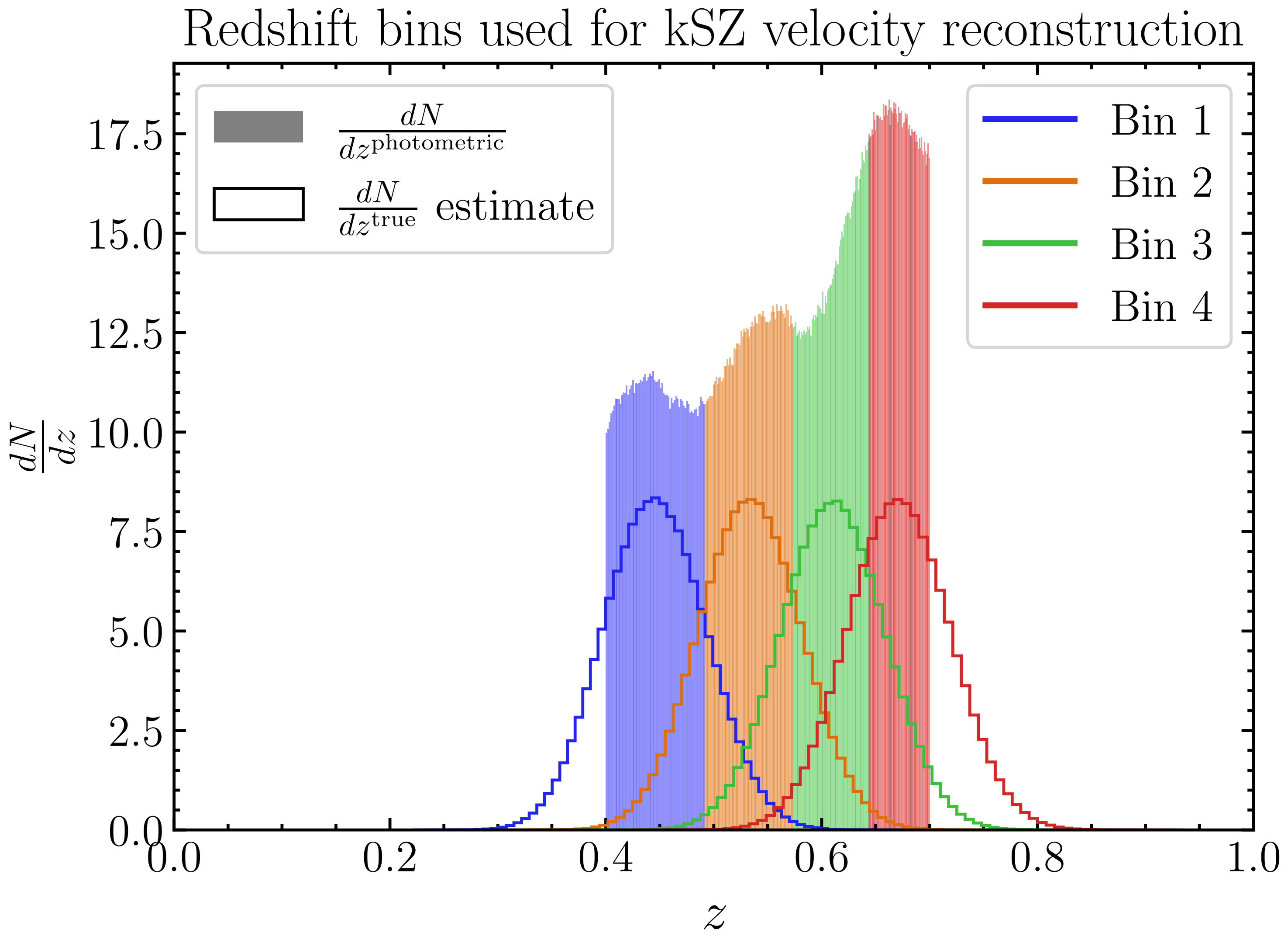
Reconstruction from Kendrick Smith

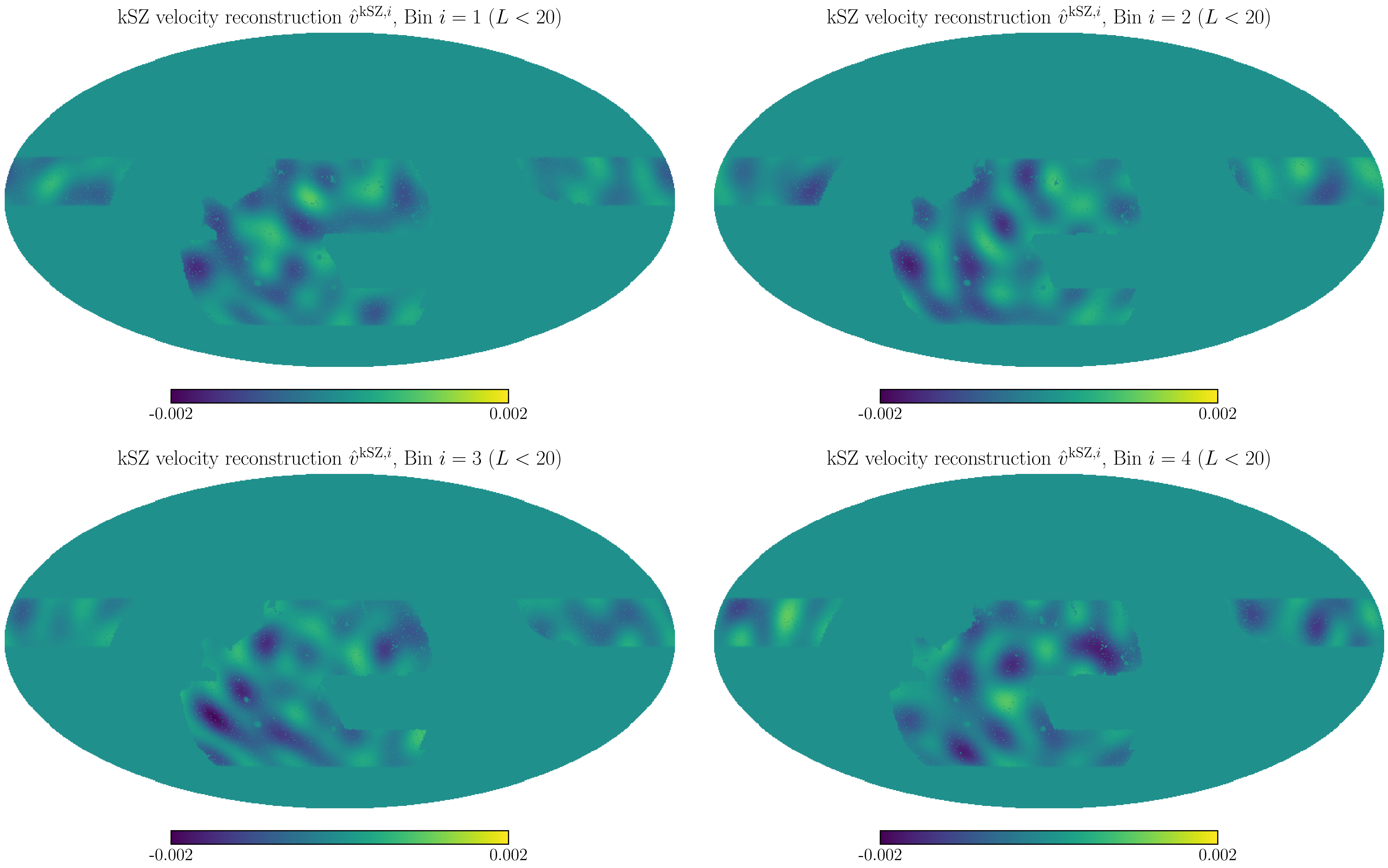
$$\hat{T}, \hat{\delta}^g, C_\ell^{\tau g} \rightarrow \hat{v}$$

Reconstruction: $\hat{v}^{\mathrm{kSZ}}$

jcayuso / ReCCO

- $\hat{v}^{kSZ}$ from QE pipeline
- Gain signal-to-noise by redshift binning





Pipeline modified from arXiv:2111.11526 (Cayuso et al)

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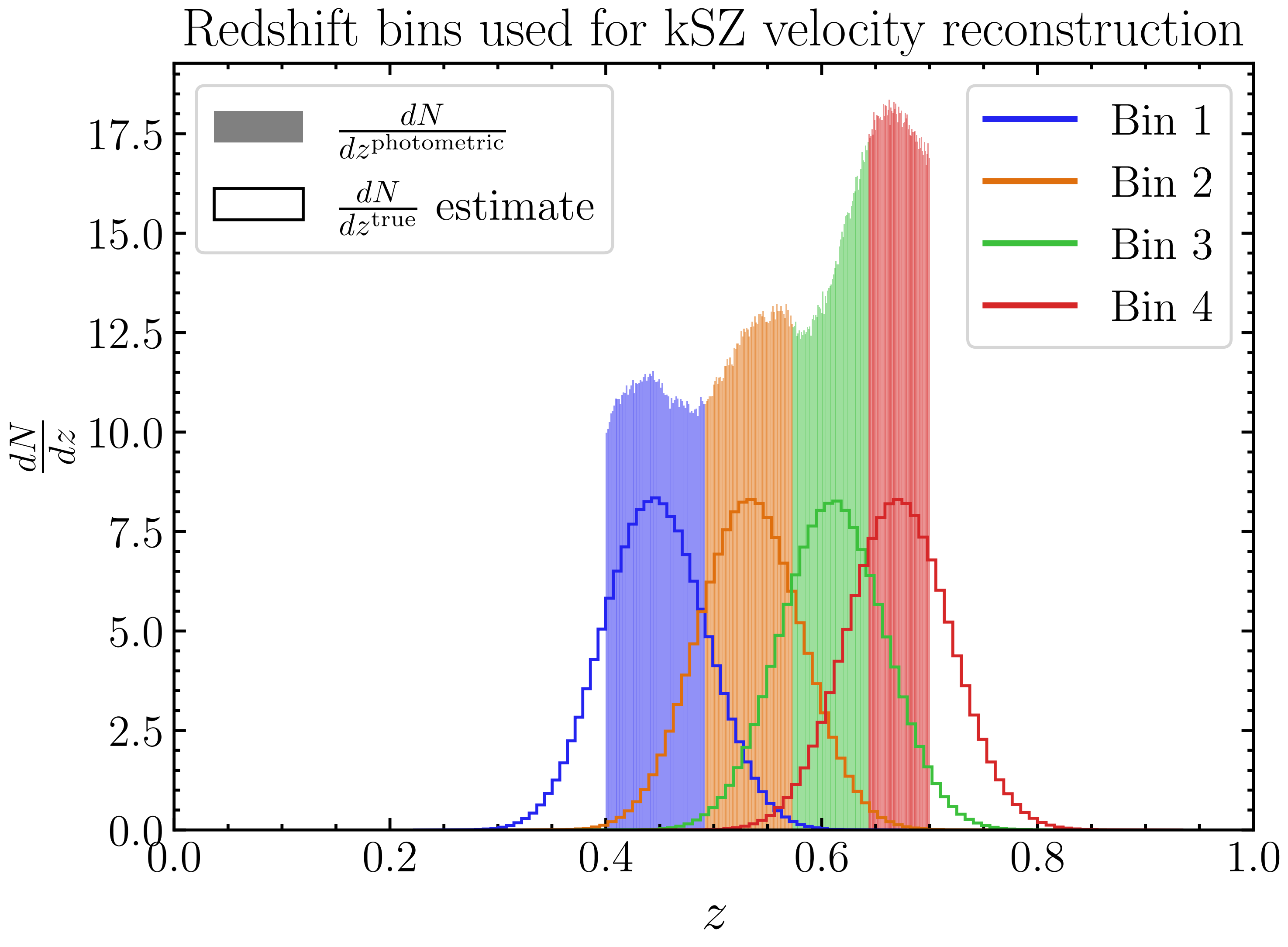

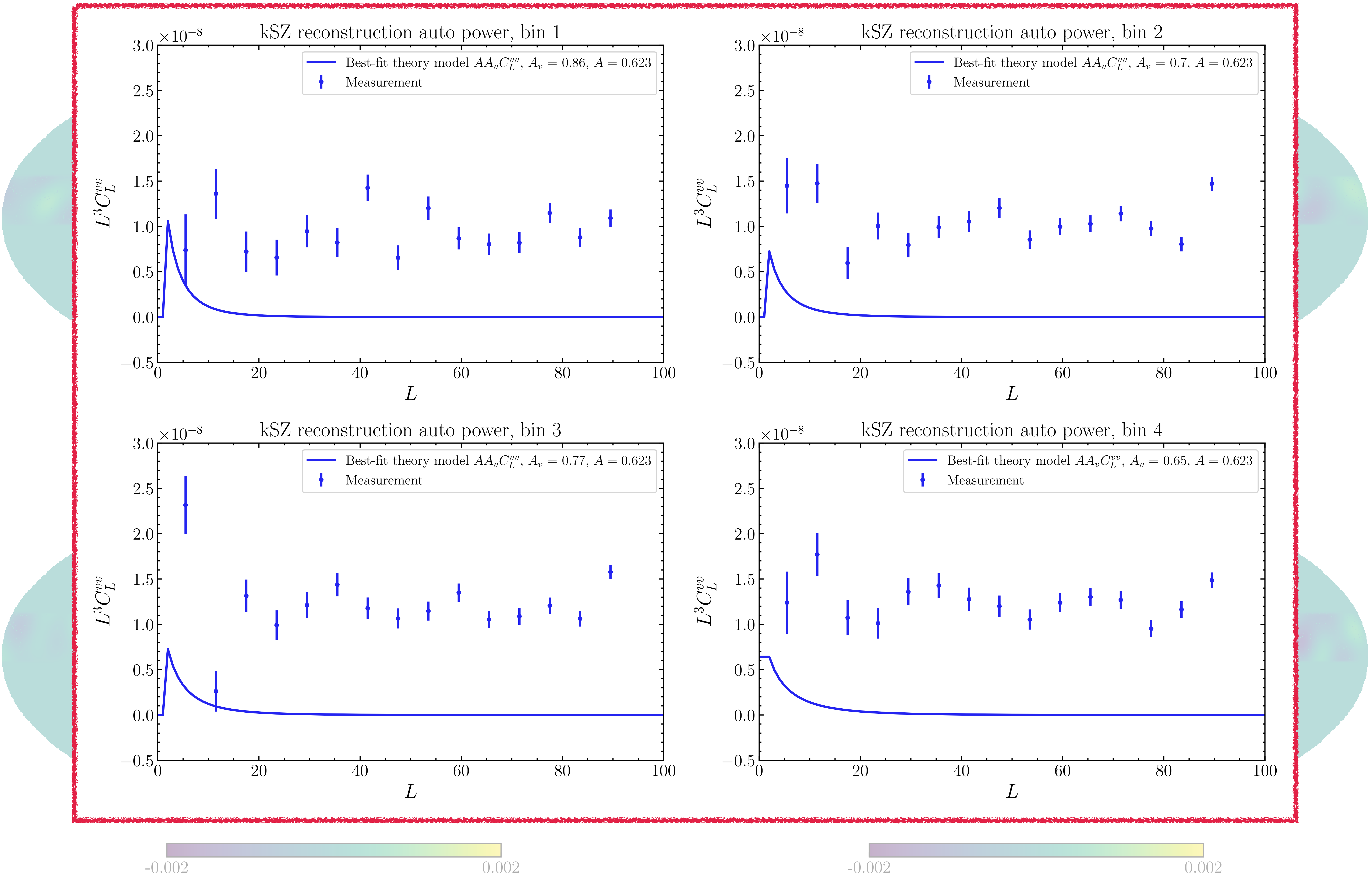

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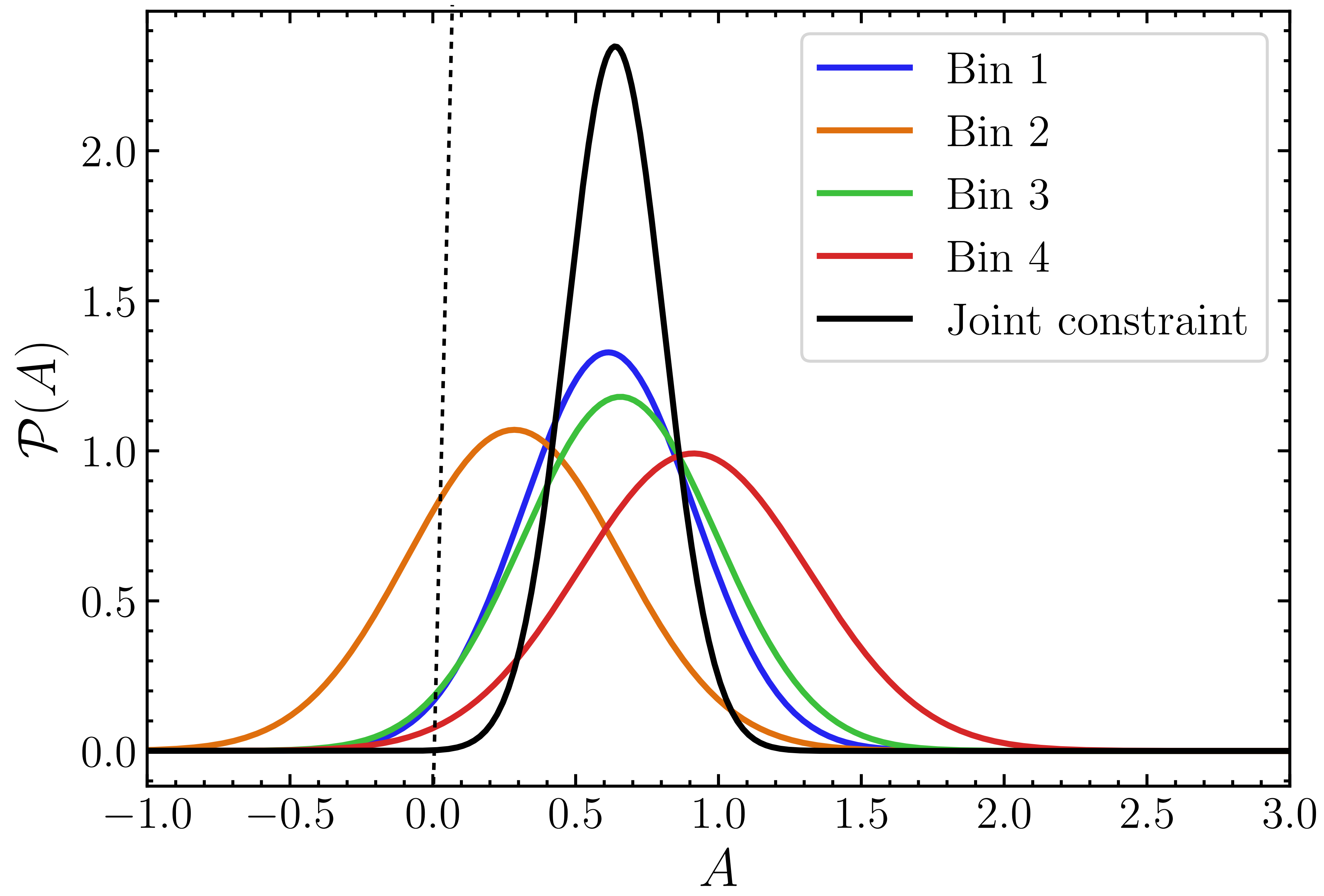
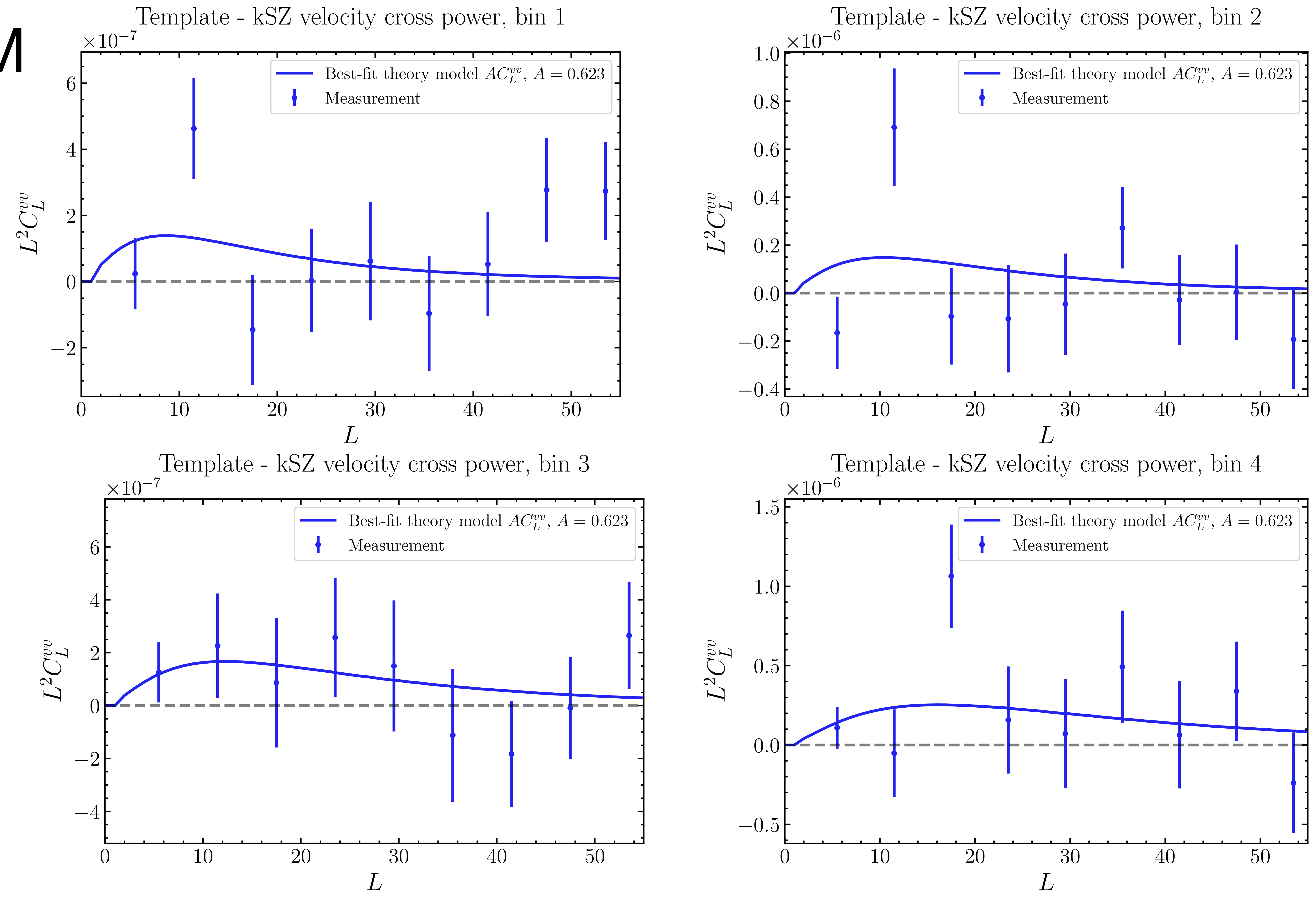
Cross-correlation measurement

- Compute velocity signal with ΛCDM
- Compare theory and measurement
- Best-fit A is 0.623 ± 0.166 (3.8σ rejection of 0)





$A = 0.623 \pm 0.166$

PTE = 21.33%

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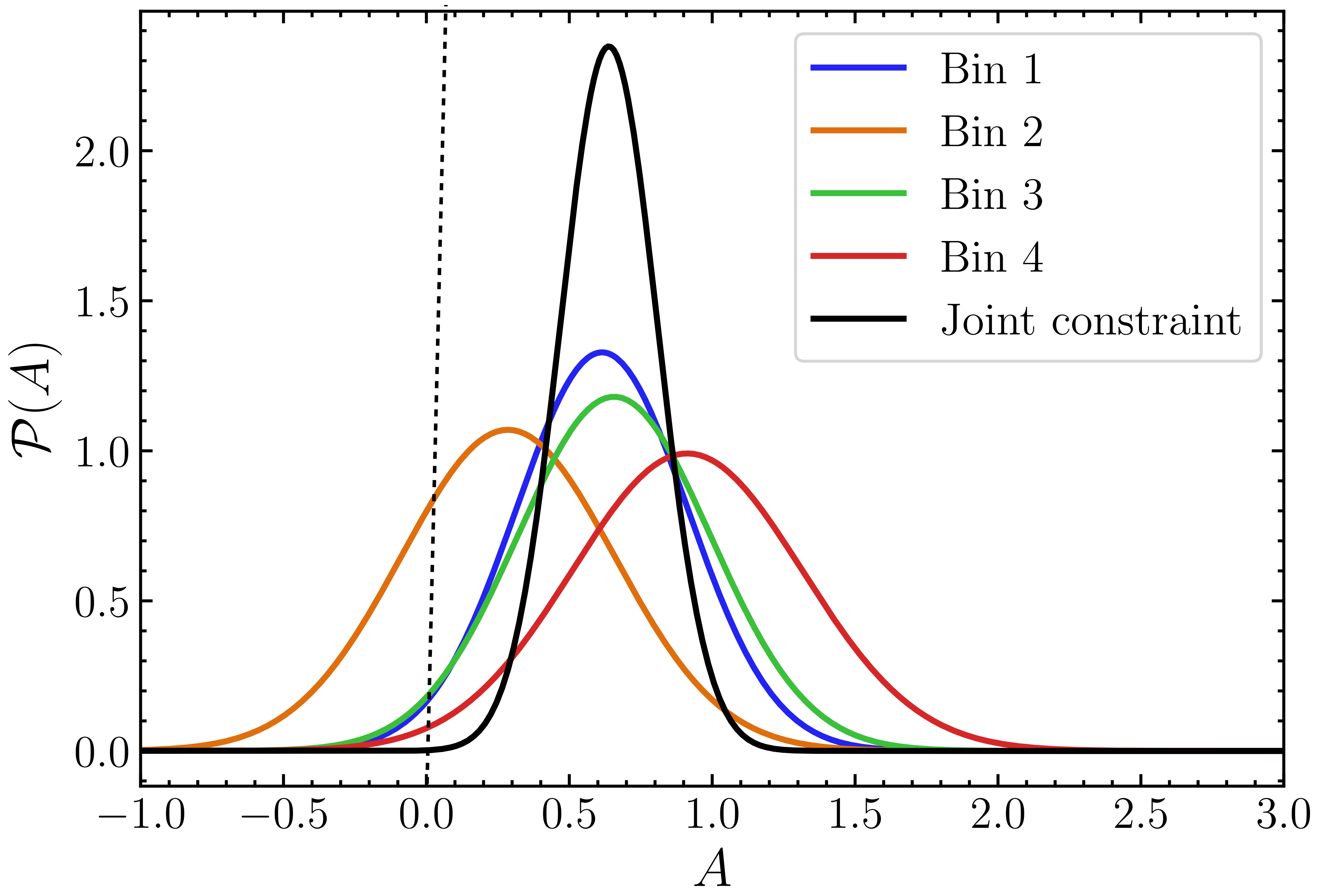

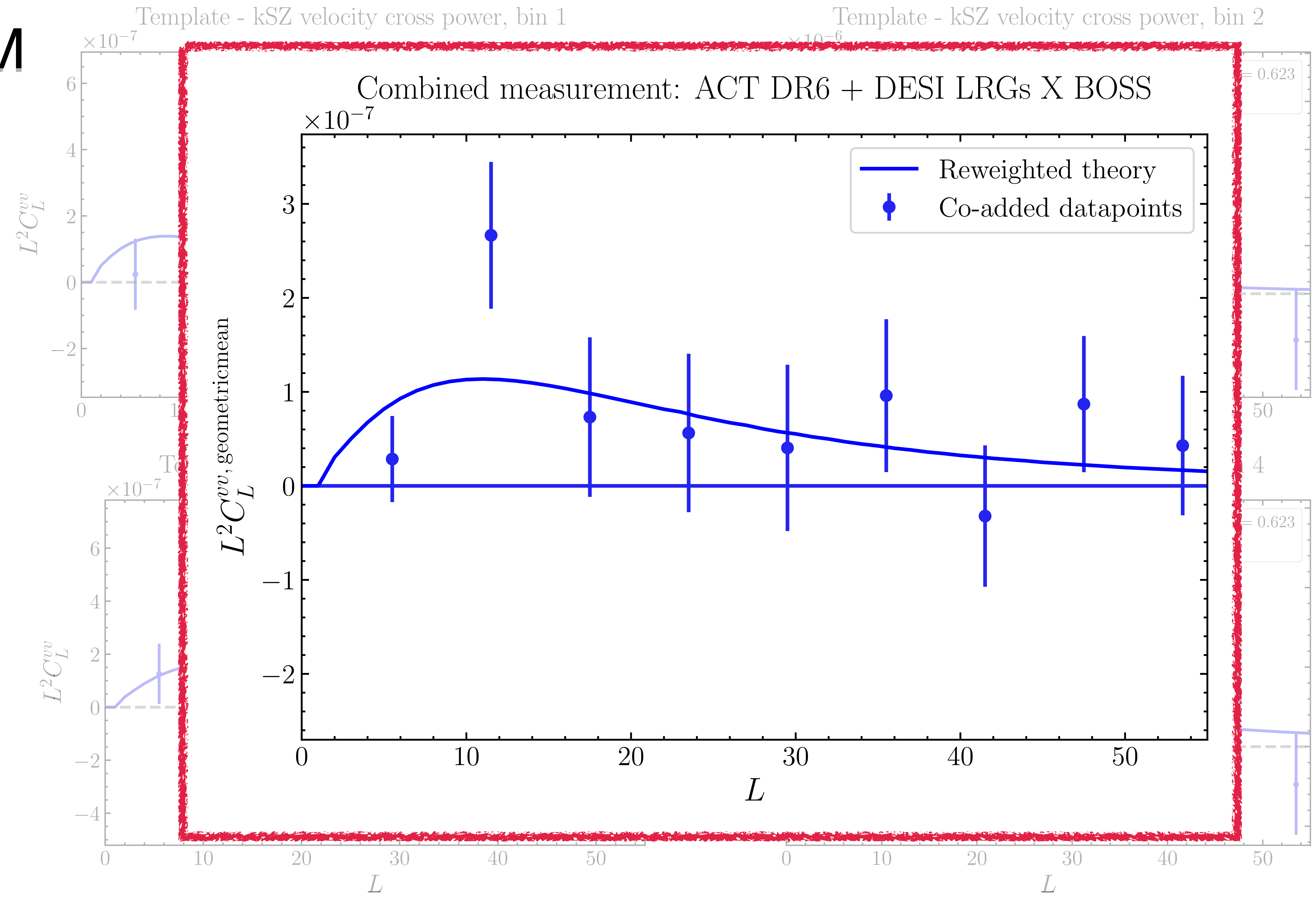

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Ongoing analysis

- Compute velocity s
- Compare theory an
- Best-fit A is 0.623 ±
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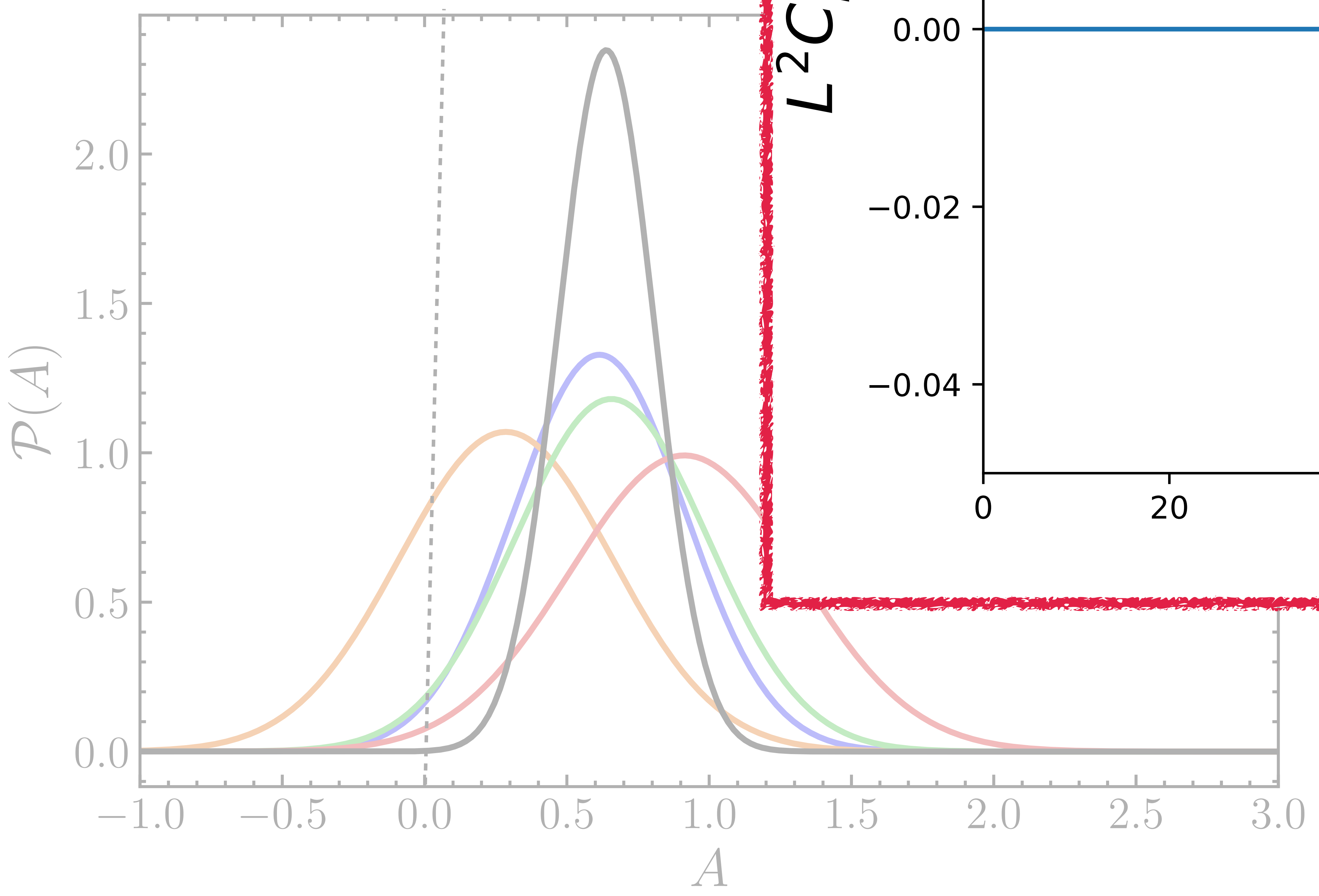

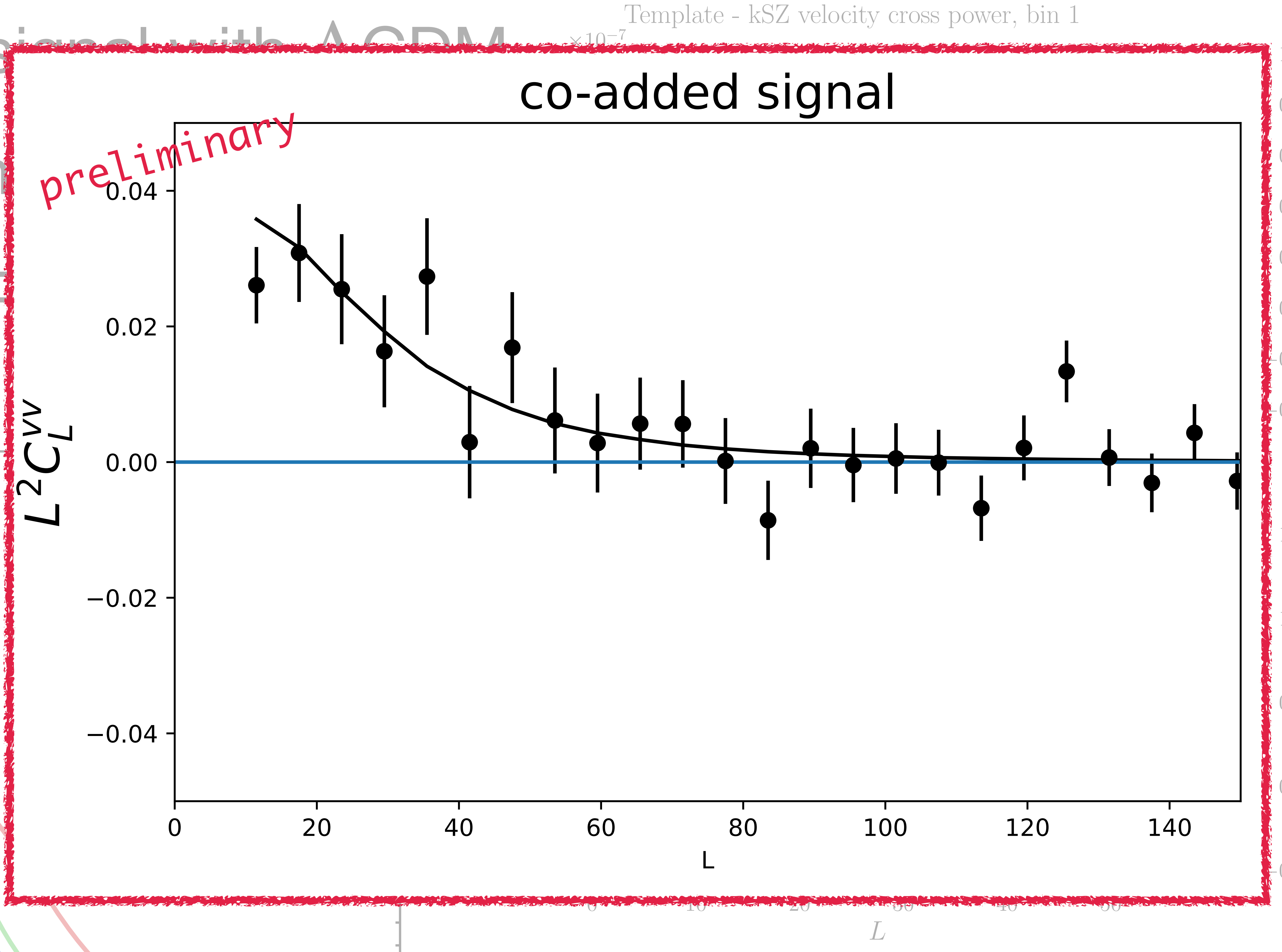

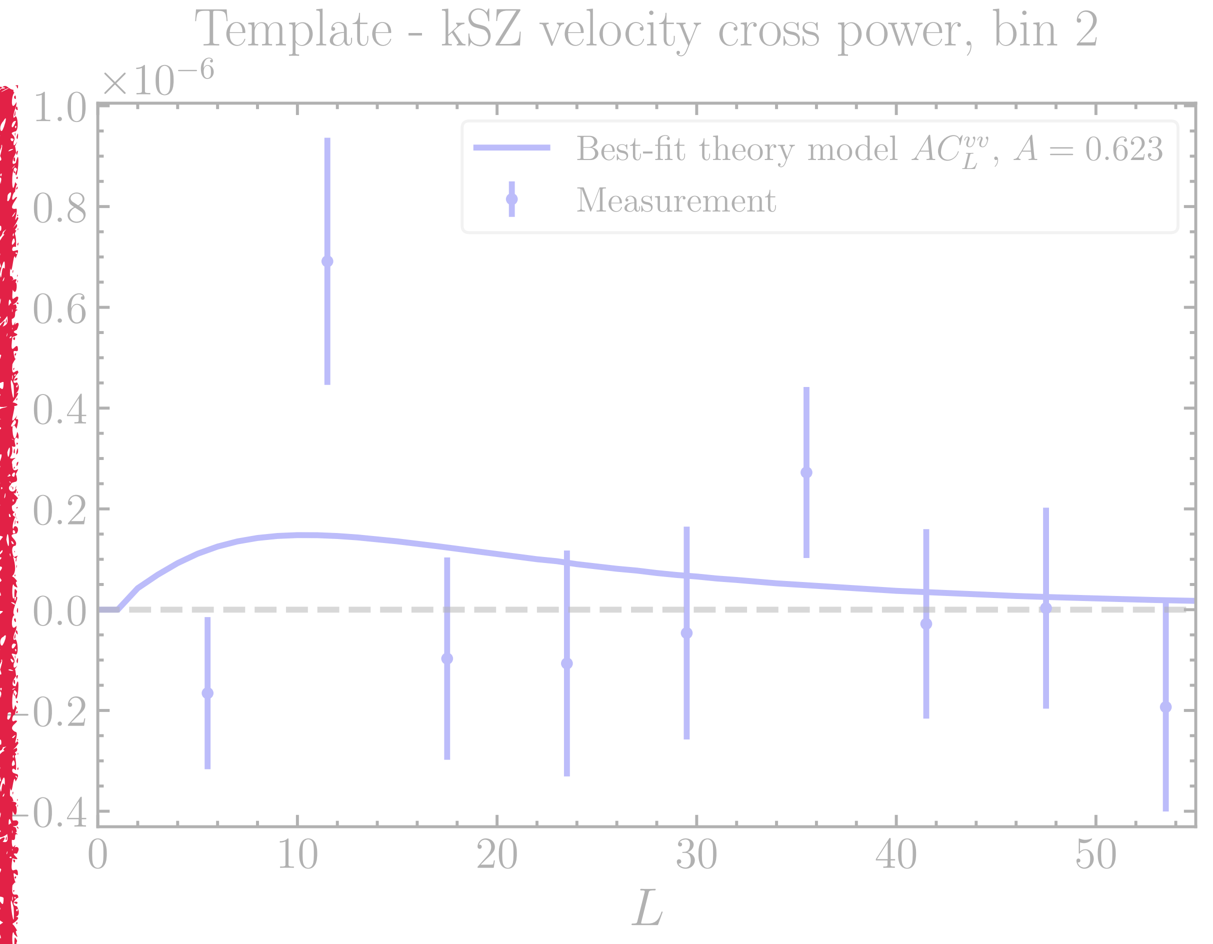

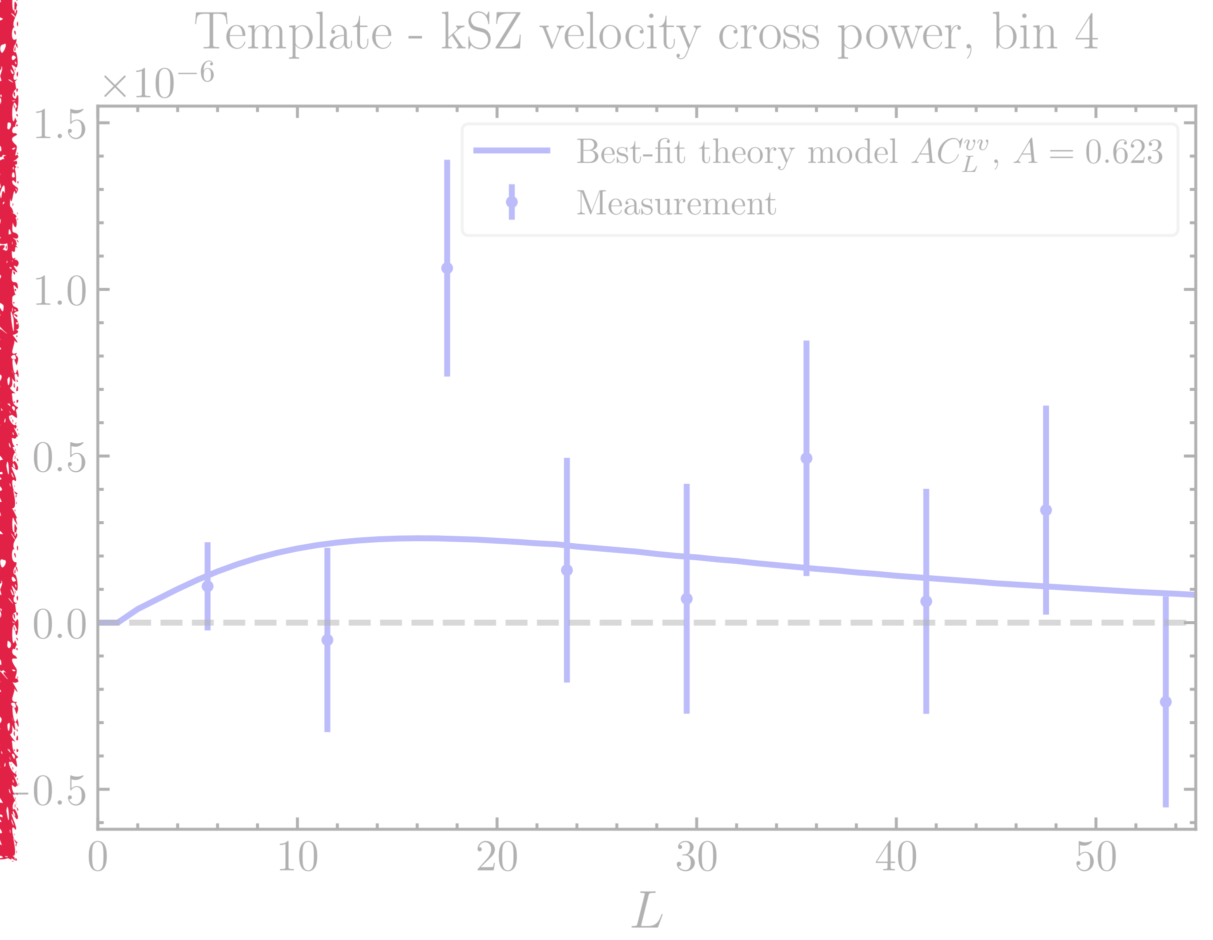

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Summary

- Demonstration of large-scale kSZ velocity reconstruction with ACT DR6 data
- We reconstruct the velocity field of the DESI LRGs using kSZ quadratic estimator
- We cross correlate with BOSS galaxy velocities (estimated with **continuity equation**)
- We detect a non-zero cross-correlation and prefer ΛCDM(+kSZ) to no-kSZ at 3.8σ
- Ongoing analysis of higher significance dataset
- See talks from **Selim Hotinli** and **Anderson Lai** later for exciting results!