Probing the Late-Time Universe with CMB Secondary Anisotropies

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4th (& final) year PhD student at the University of Cambridge

UC Berkeley
Cosmology Seminar
15th September



UNIVERSITY OF CAMBRIDGE





"la Caixa" Foundation





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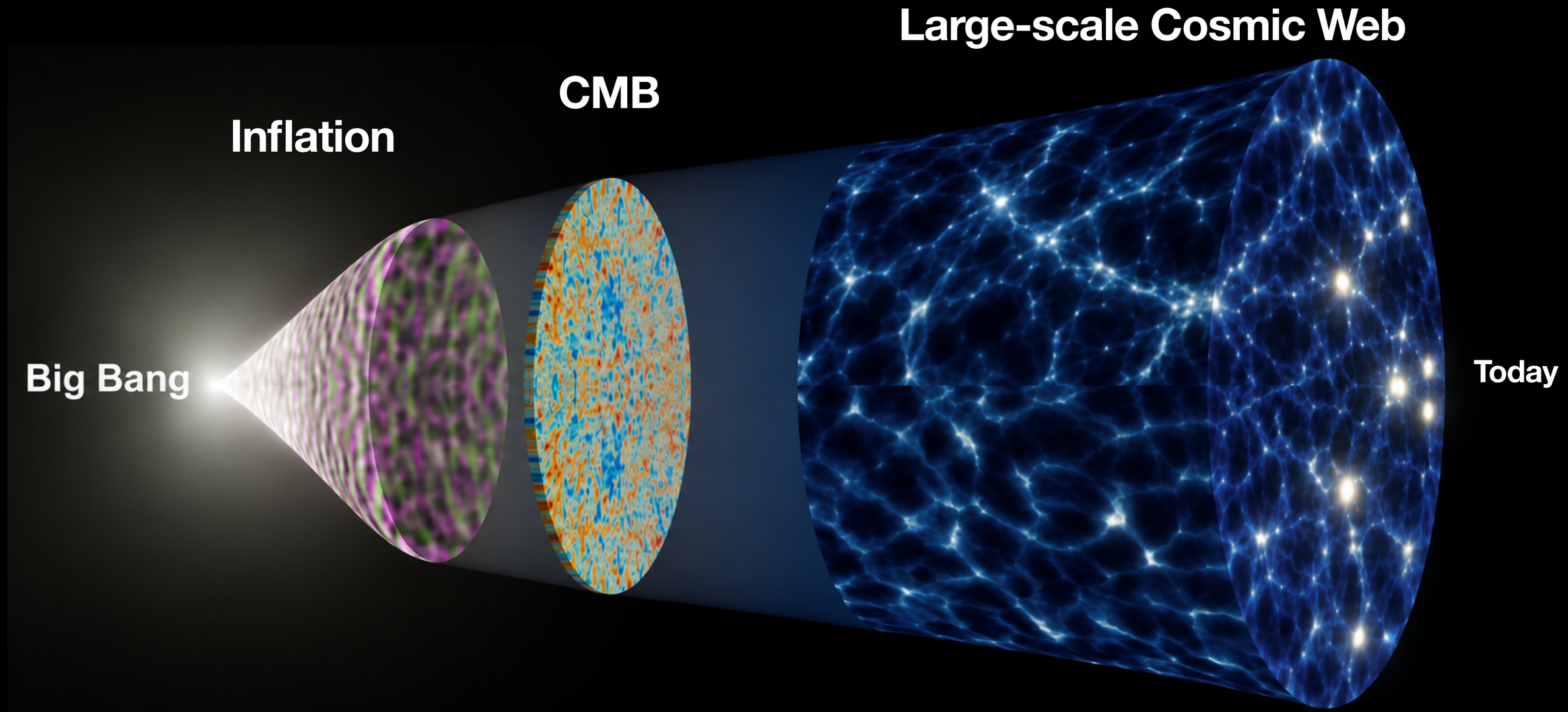
The Cosmic Microwave Background (CMB)



(Figure Edited from SphereX collaboration)

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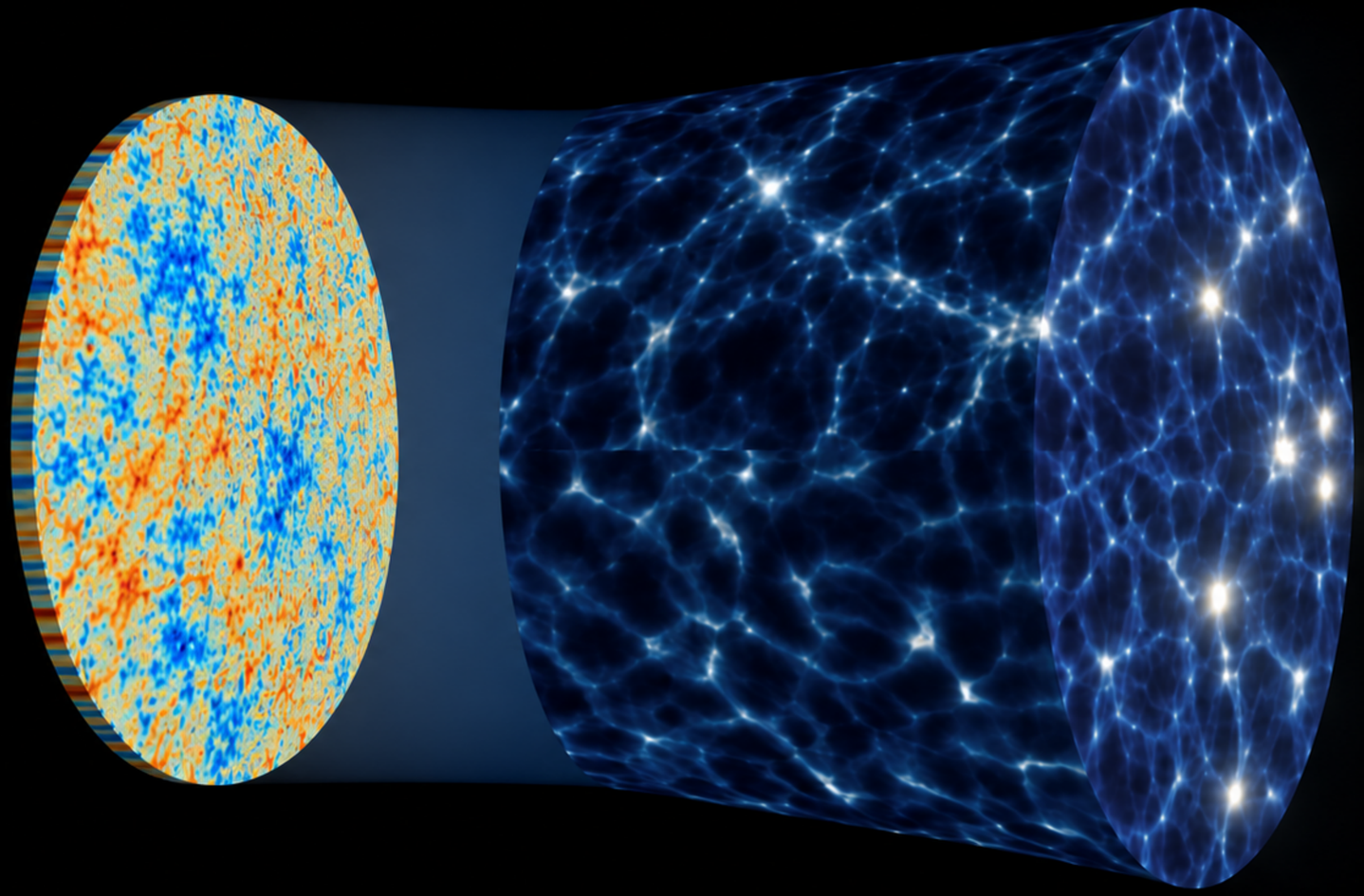
CMB as a Backlight: Secondary Anisotropies



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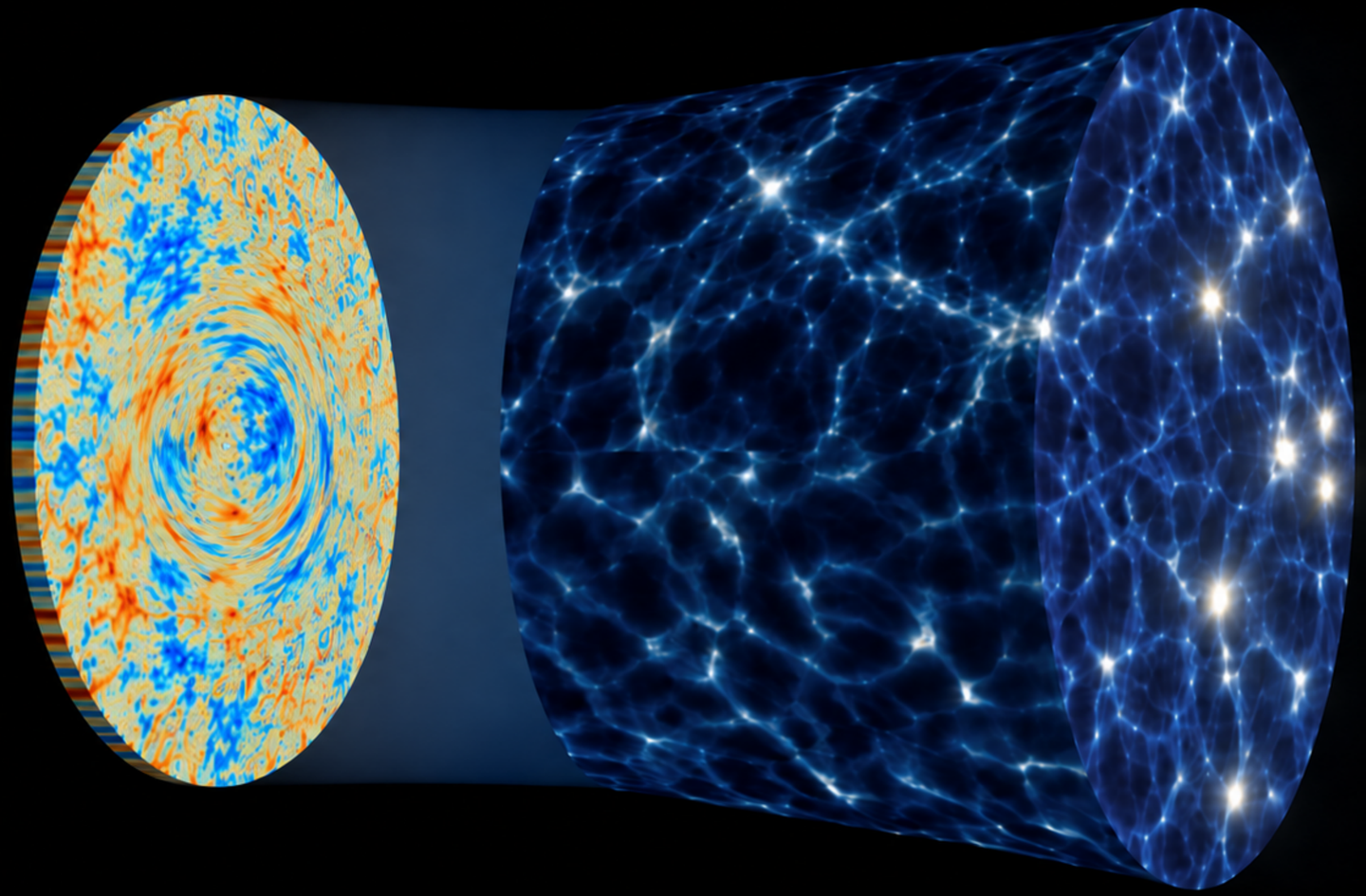
CMB as a Backlight

- CMB lensing

CMB photons get deflected on their way to our telescopes



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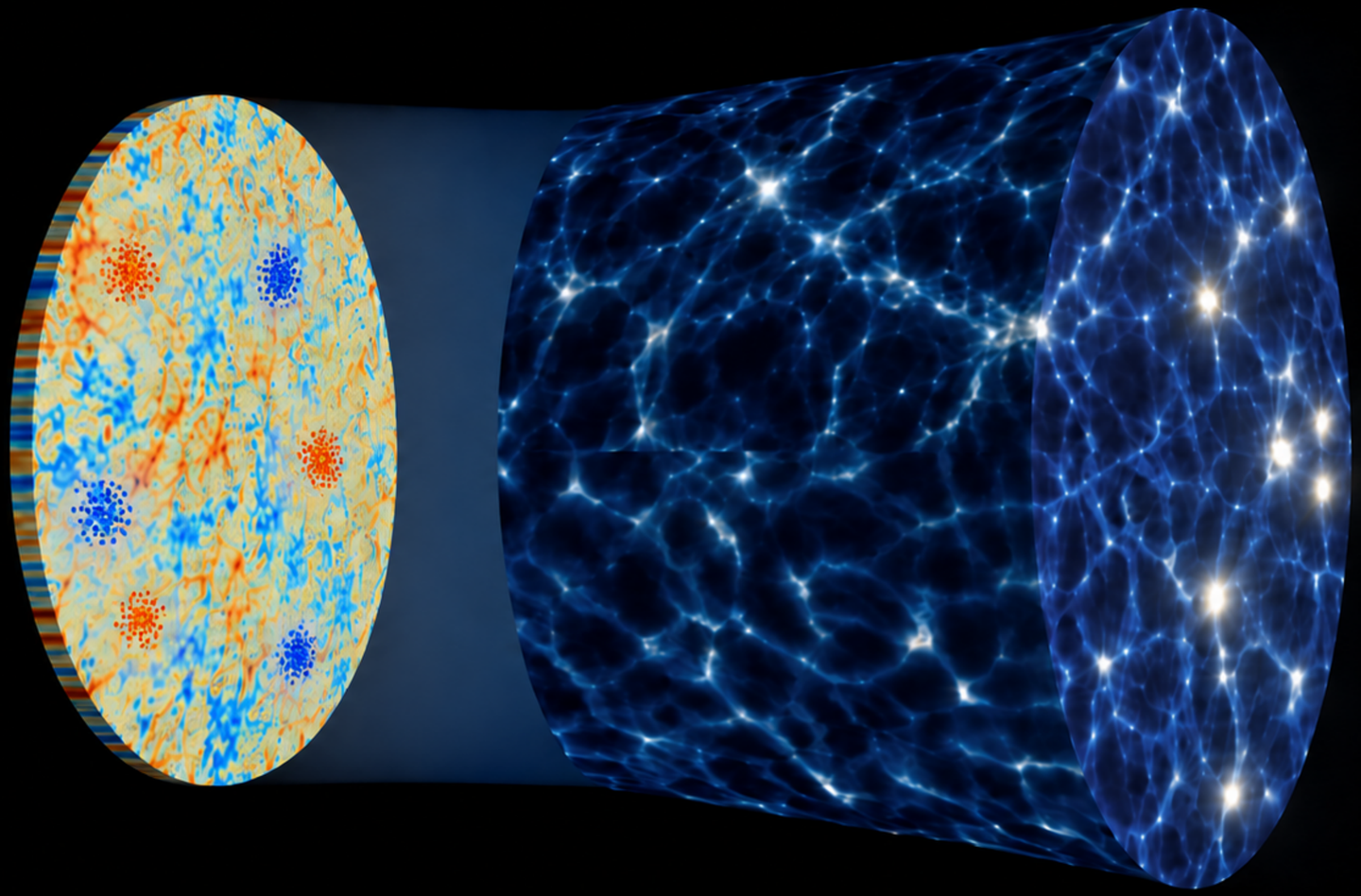
CMB as a Backlight

- Kinetic Sunyaev Zeldovich

CMB photons scatter off free moving electrons



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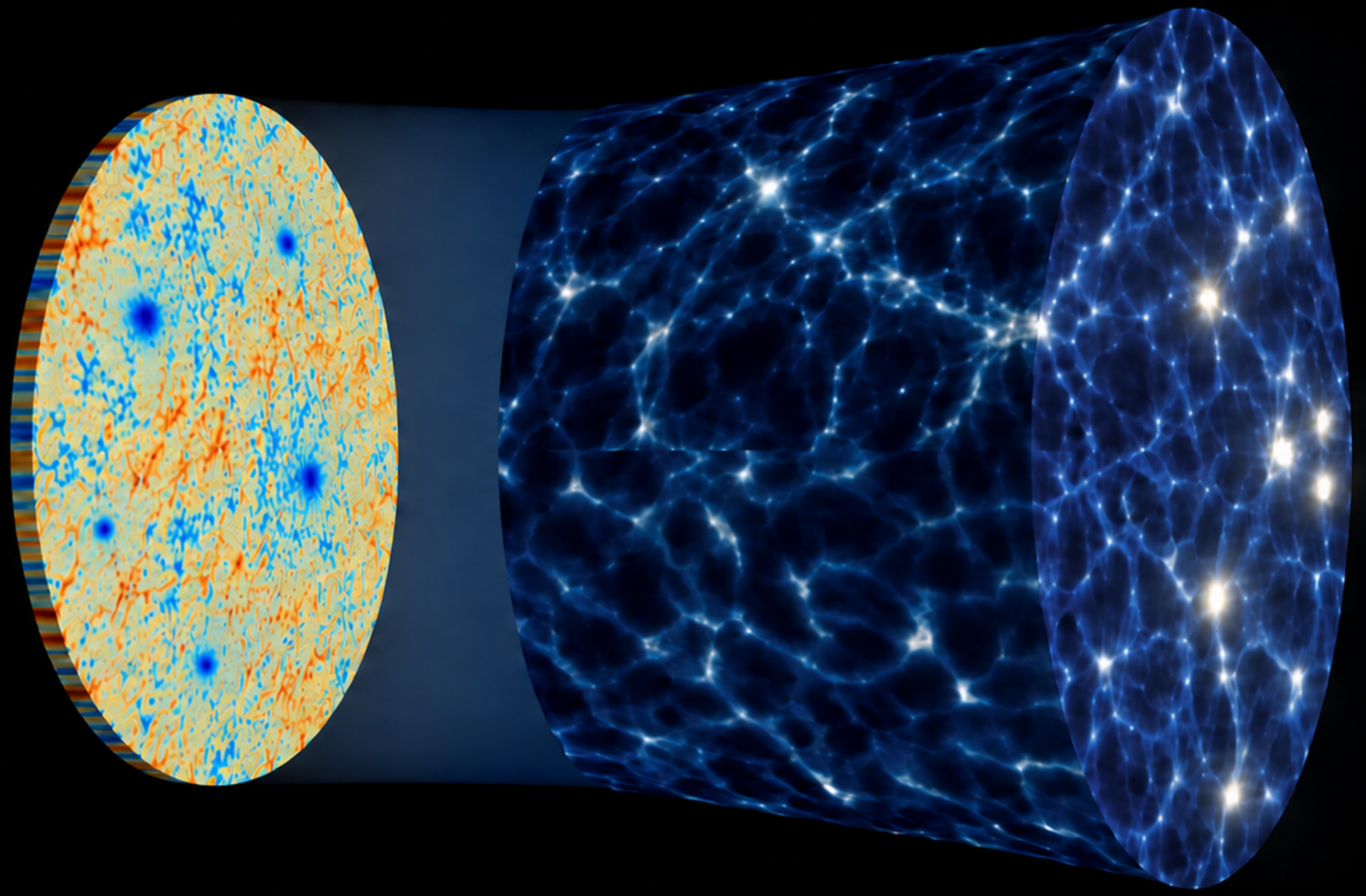
CMB as a Backlight



- Thermal Sunyaev Zeldovich

CMB photons inverse Compton scatter off free electrons

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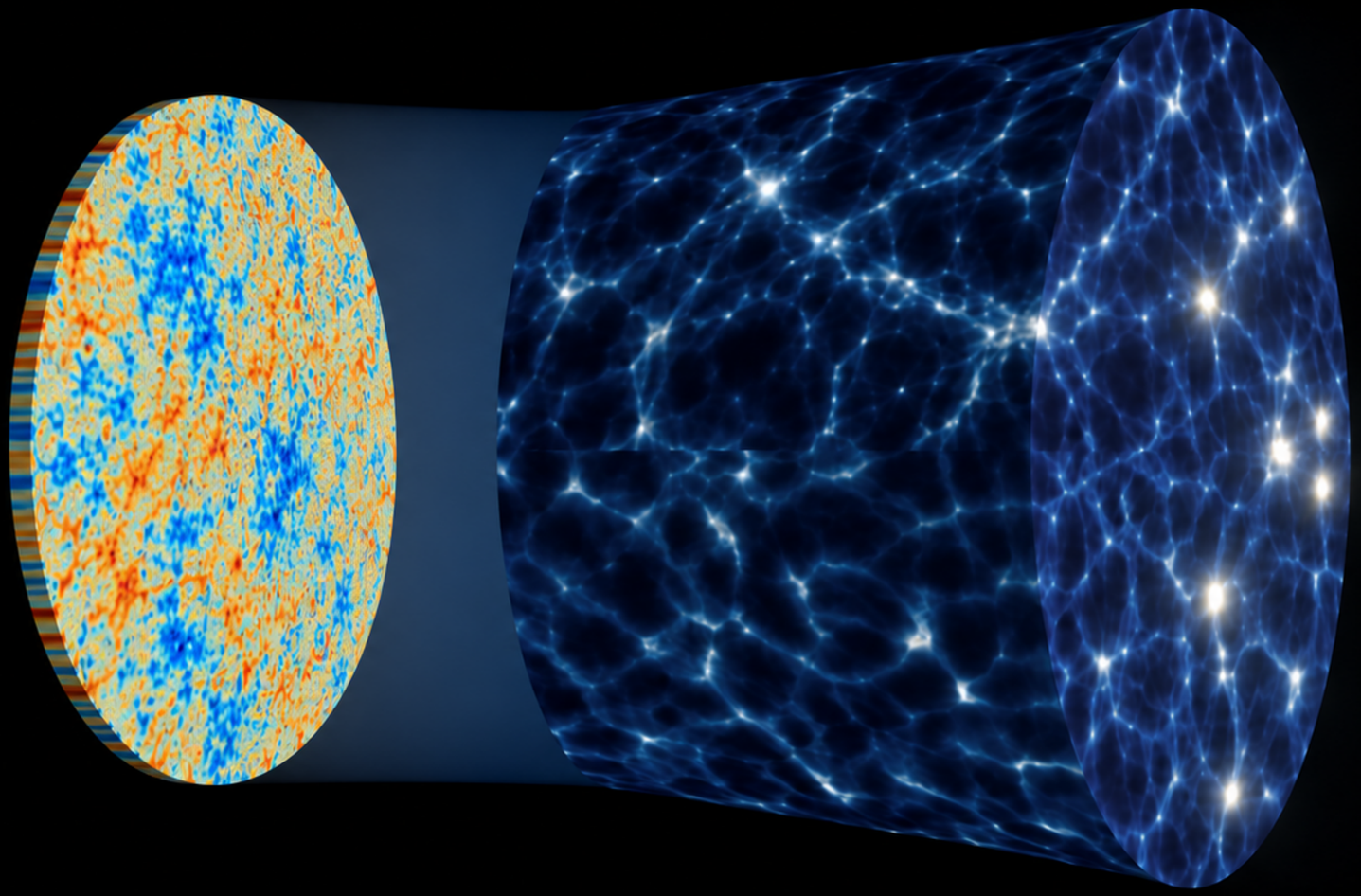
CMB as a Backlight

CMB Secondaries

Predominantly appear on small angular scales. Next generation of CMB experiments (already taking data!) are turning these signals into precision cosmological probes



LSS surveys enhance — and in some cases enable — the cosmological power of CMB secondaries

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No time like the present

Unprecedented era for CMB × LSS surveys

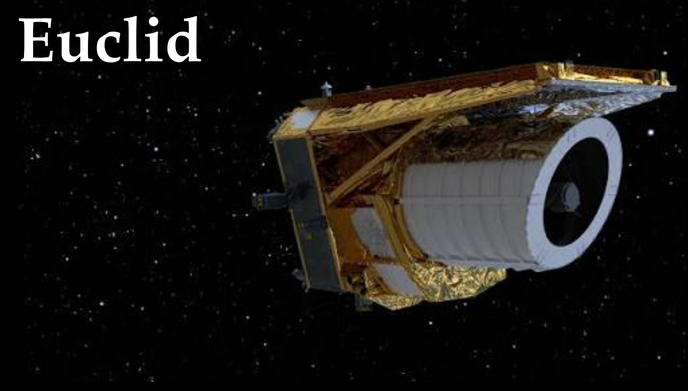
Simons Observatory

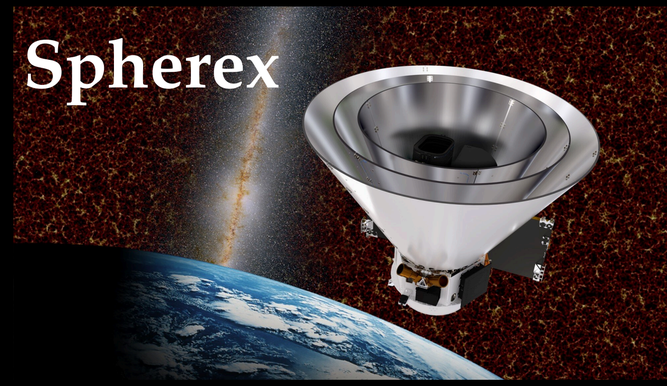


×









And many more…

Contents

Part I: **kSZ velocity reconstruction**

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Part II: **CI**

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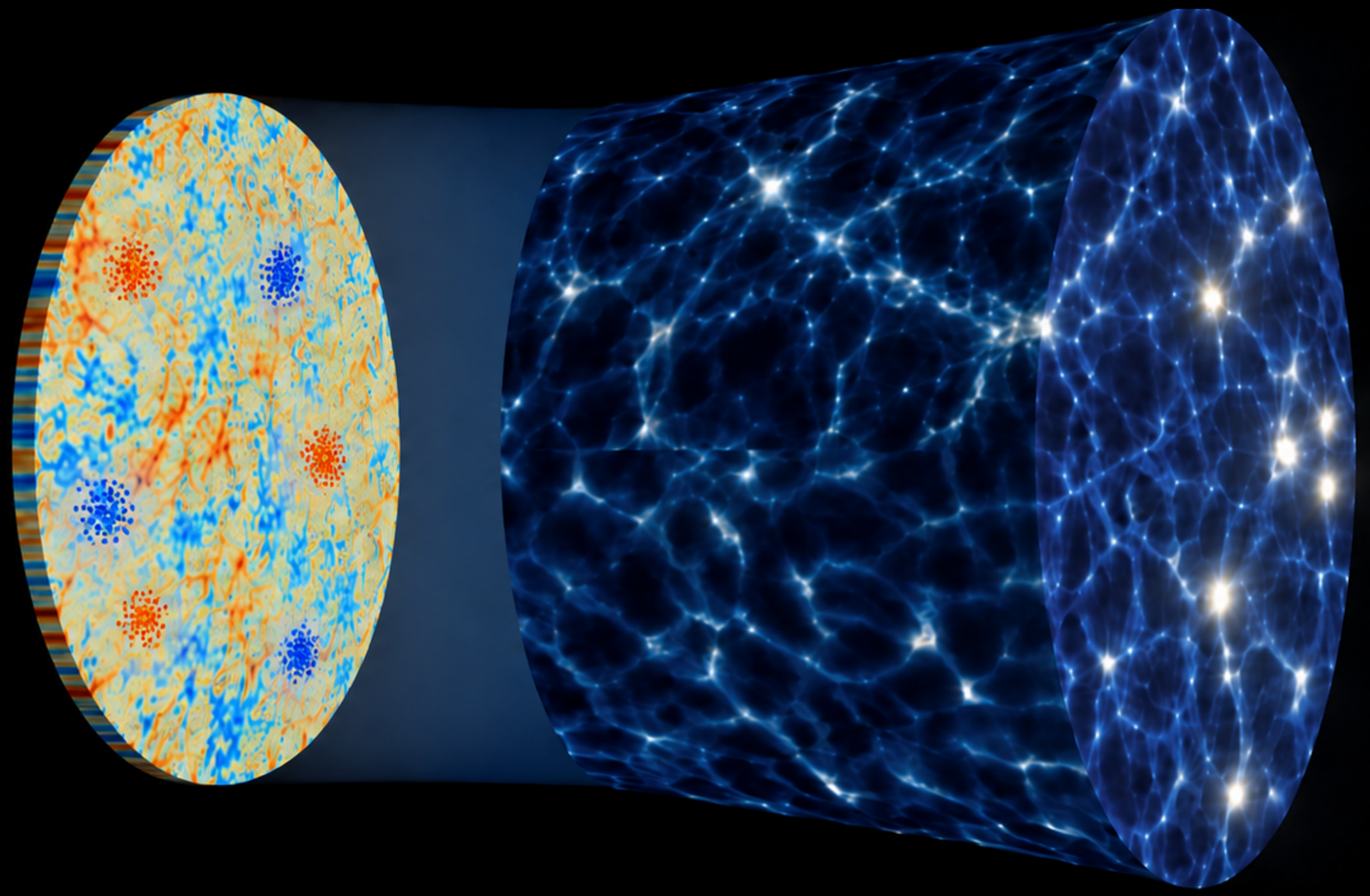
2026 (arxiv:



Part III: **Fie**

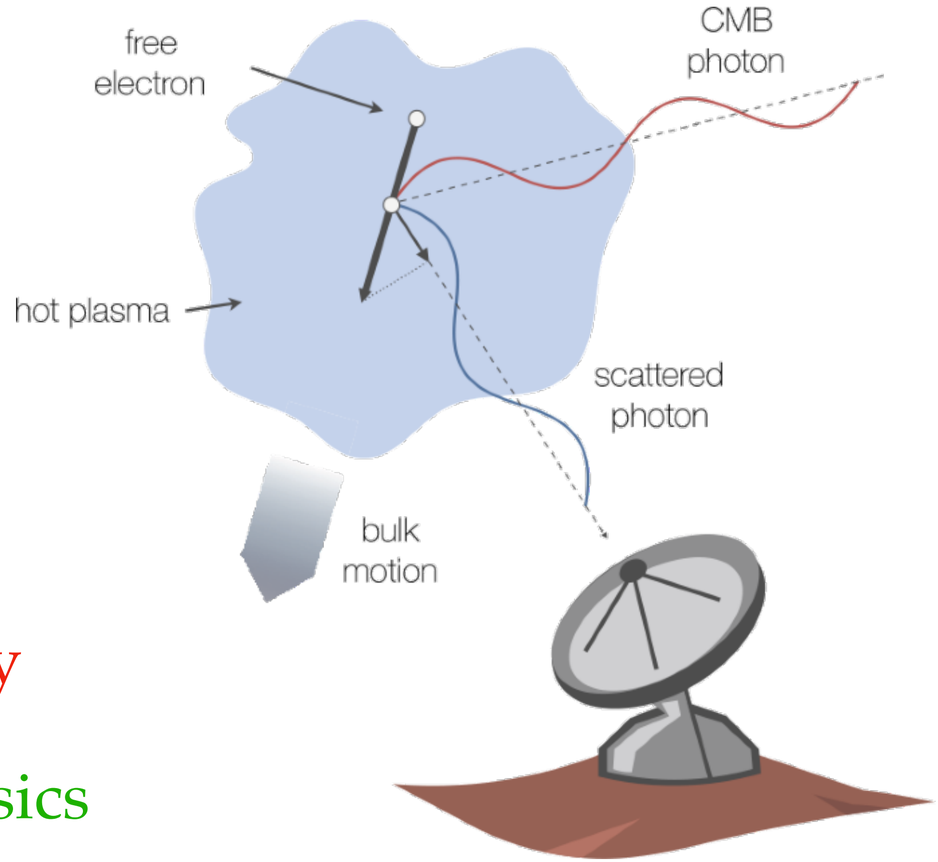
Rec

)

Kinetic Sunyaev-Zel'dovich effect

The kSZ anisotropy:

$$\frac{\Delta T^{\rm kSZ}}{T_{\rm CMB}}(\hat{\boldsymbol{n}}) = -\sigma_T \int d\chi a(\chi) v_r(\chi, \hat{\boldsymbol{n}}) n_e(\chi, \hat{\boldsymbol{n}})$$

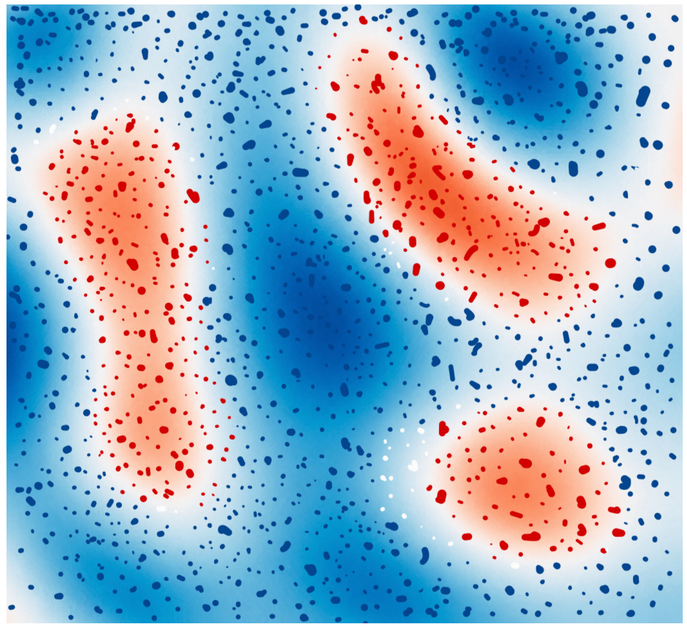


Signal depends on:

- Bulk velocity $v_r(\chi, \hat{\boldsymbol{n}})$ → probes Cosmology
- Electron density $n_e(\chi, \hat{\boldsymbol{n}})$ → probes Astrophysics

Radial velocity from the kSZ effect

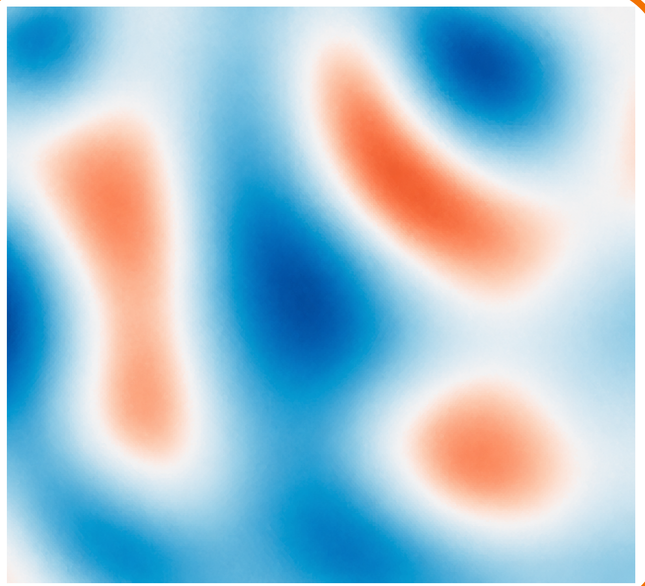
$T^{\rm kSZ}$



(Edited from McCarthy et al. 2024 measurement)

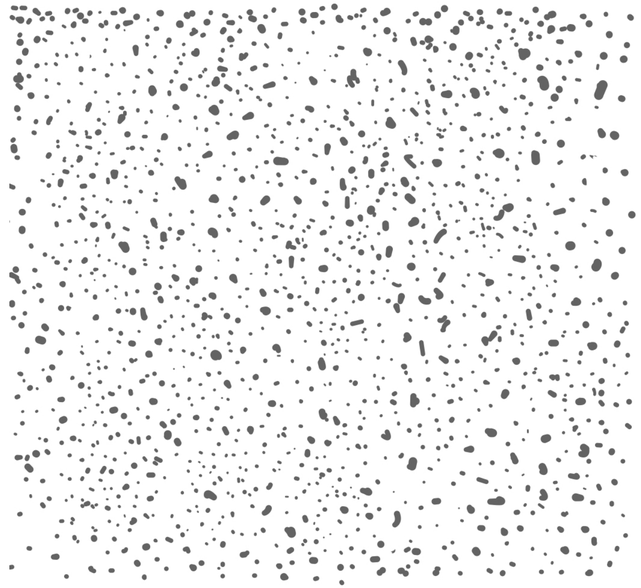
$\sim$

$v_r(\chi, \hat{\boldsymbol{n}})$



$\times$

$n_e(\chi, \hat{\boldsymbol{n}})$

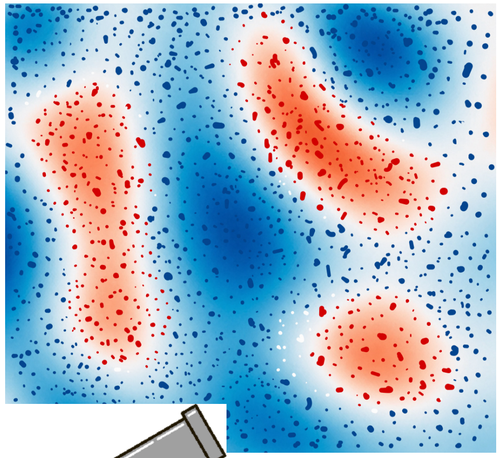


The large-scale velocity field modulates the large scale changes to the kSZ signal

$$\Rightarrow v_r(\chi, \hat{\boldsymbol{n}}) \sim \frac{T^{\rm kSZ}}{n_e(\chi, \hat{\boldsymbol{n}})}$$

Radial velocity field estimator

$T^{\rm kSZ}$



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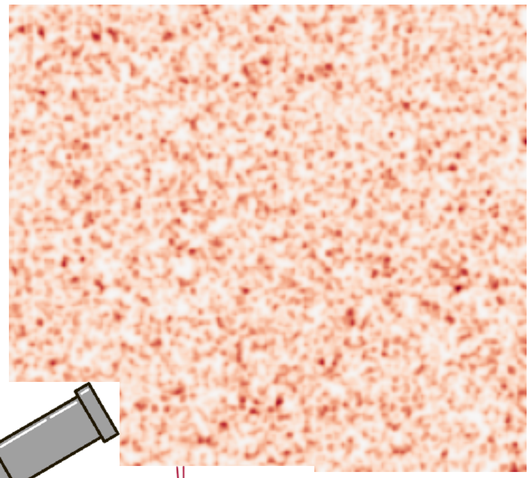
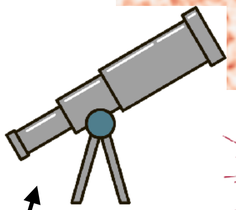
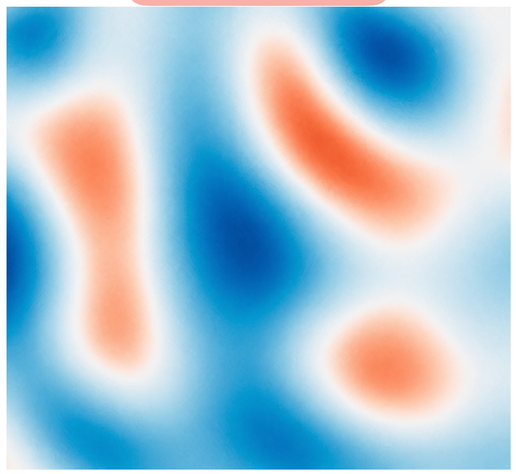








$v_r(\chi, \hat{\boldsymbol{n}})$



$\hat{v}_r \sim \dfrac{T^{\rm obs} \times g}{\langle g\ n_e \rangle}$

Galaxies as proxies for e^-

Modelled or measured on simulations

Cosmology from the radial velocity field

- The radial velocity is an **unbiased** tracer of the density field

$$\text{Continuity equation (linear order):} \quad v_r(k) = \frac{i f a H \mu}{k} \delta_m(k)$$

- The kSZ can be used to probe cosmological modes on the largest scales

Application to primordial non-Gaussianity:

- In cross-correlation with large-scale galaxies, we are sensitive to scale dependent bias induced by non-zero primordial non-Gaussianity f_{NL}

$$\frac{g_L}{v_r} \sim k \left(b_1 + \frac{b_\Phi}{T_{\Phi \to \delta}(k)} f_{\rm NL}^{\rm loc} \right)$$

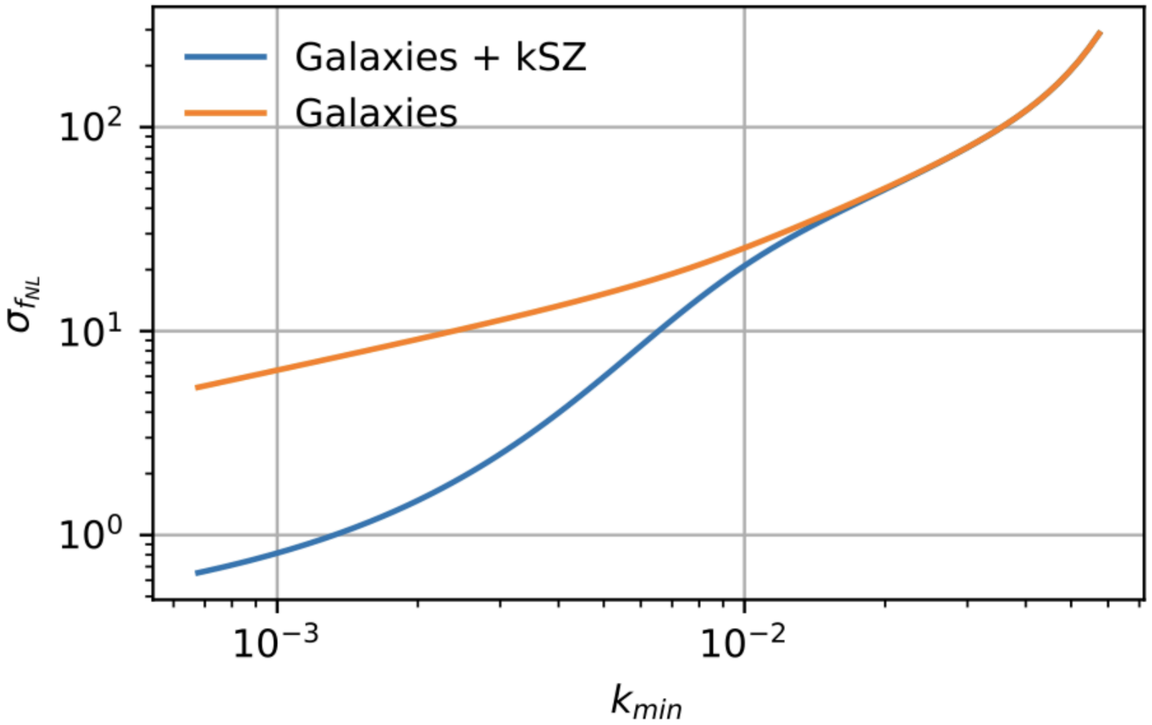
see Munchmeyer et al 2019

Correlator of interest: $\langle \hat{v}_r \, g_L \rangle \sim \langle T_S \; g_S \; g_L \rangle \sim f_{\rm NL}^{\rm local}$

A very exciting prospect

Forecasts on $f_{\rm NL}$

- For LSST:



Münchmeyer et al. 2018

- kSZ can constrain f_{NL} to O(1). Key threshold for ruling out single field inflation.

- Simons Observatory's tightest constraints on f_{NL} forecasted to come from kSZ measurements

Parameter	SO-Baseline[b] (no syst)	**SO-Baseline**[c]	SO-Goal[d]	Current[e]	Method	Sec.
r	0.0024	**0.003**	0.002	0.03	BB + ext delens	3.4
$e^{-2\tau}\mathcal{P}(k = 0.2/\mathrm{Mpc})$	0.4%	**0.5%**	0.4%	3%	$TT/TE/EE$	4.2
$f_{\rm NL}^{\rm local}$	1.8	**3**	1	5	$\kappa\kappa$ × LSST-LSS + 3-pt	5.3
	1	**2**	1		kSZ + LSST-LSS	7.5

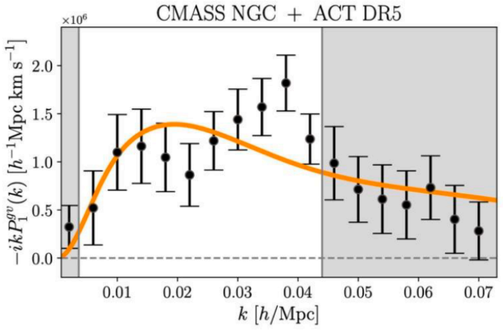
SO collaboration 2019

And a very busy present

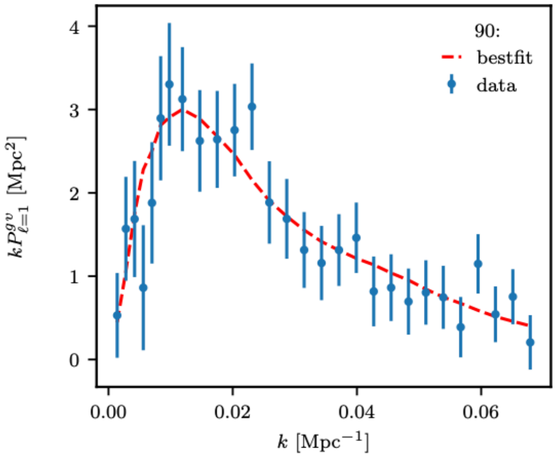
Measurements of kSZ velocity cross-correlations in the past ~year

- **3D velocity reconstruction**

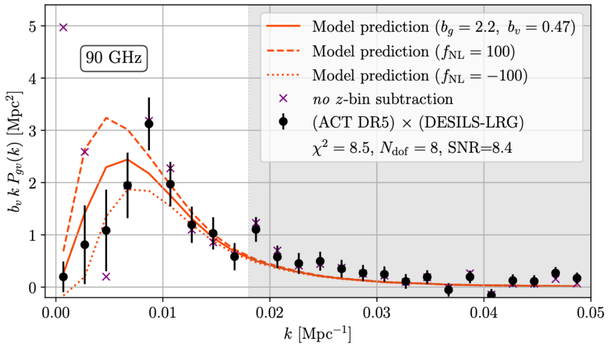
Laguë et al. 2025



Chaussidon et al. 2026



Hotinli et al. 2026

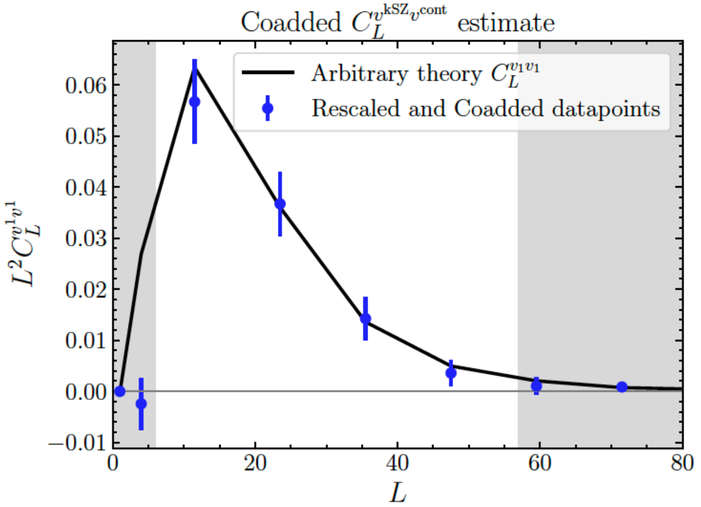


- **Projected velocity reconstruction**

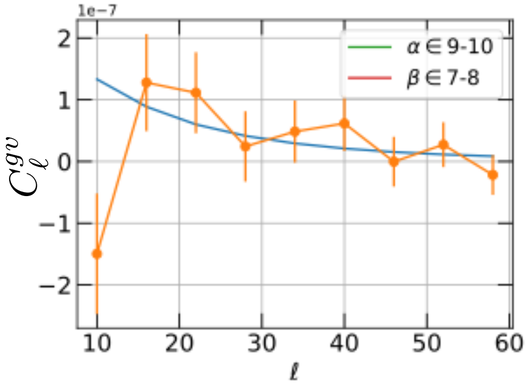
McCarthy et al. 2025

$\sim 10\sigma$ detection

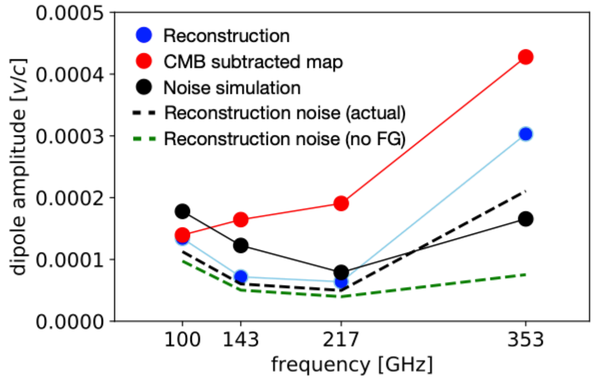
$\sigma(f_{\rm NL}) \sim 60 - 85$



Lai et al. 2025



Bloch & Johnson 2024, Krywonos et al. 2024

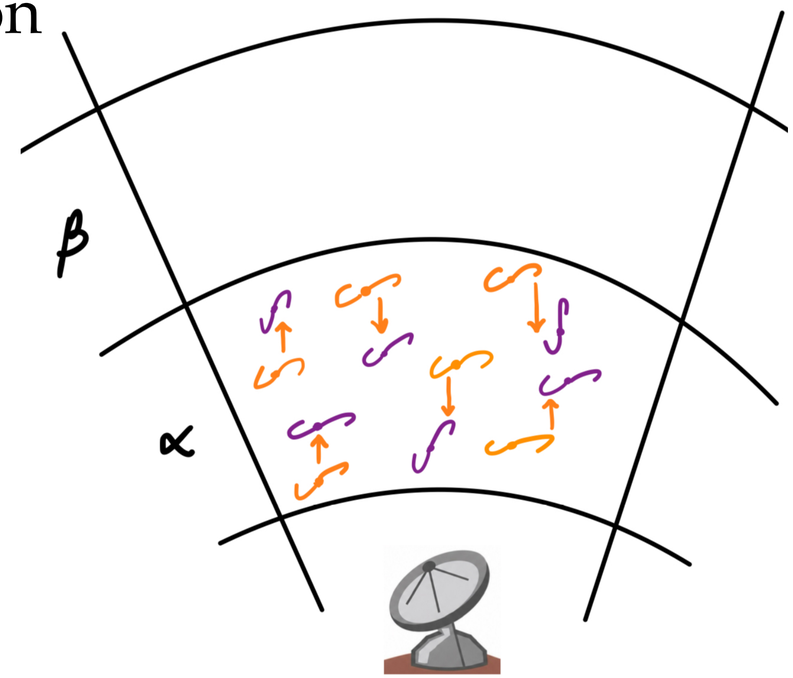


Projected kSZ velocity reconstruction

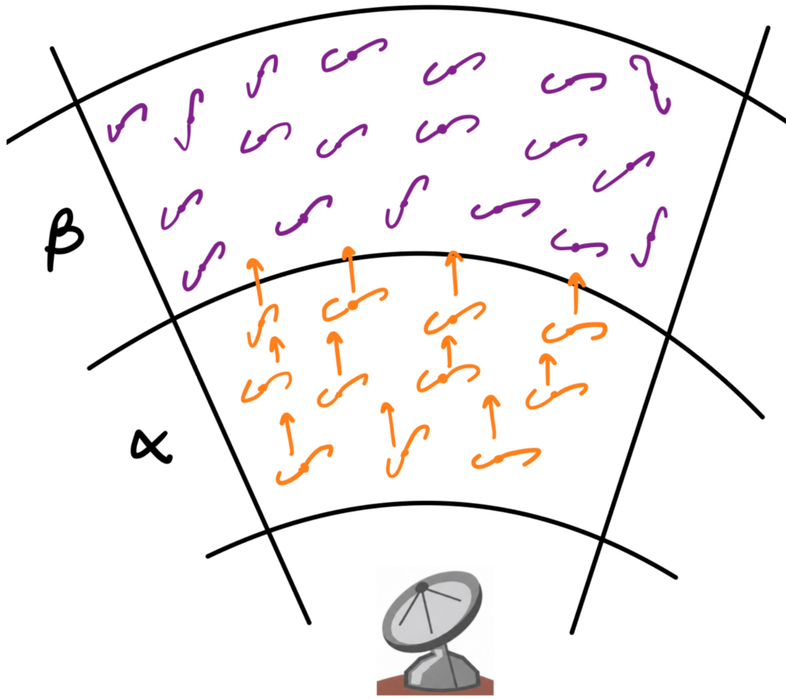
- Both small-scale galaxies g_S used in $\hat{v}_r$ reconstruction and large scale-galaxies g_L are projected

$$\langle \hat{v}_r^{\alpha}\, g_L^{\beta} \rangle \sim \langle T_S\, g_S^{\alpha}\, g_L^{\beta} \rangle$$

- Same-bin correlation $\langle \hat{v}_r^{\alpha}\, g^{\alpha} \rangle \sim 0$



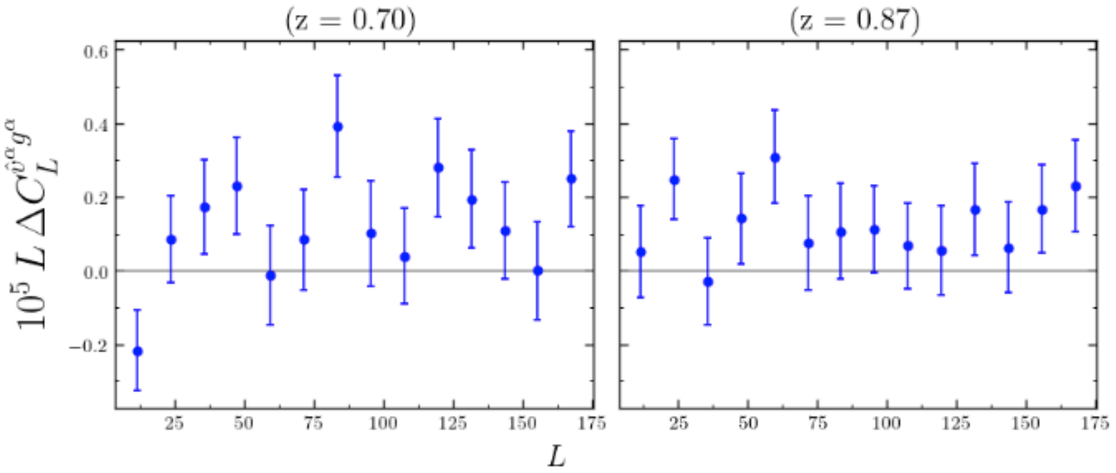
- Neighbouring-bin correlation $\langle \hat{v}_r^{\alpha}\, g^{\beta} \rangle \propto 0$



Presence of foregrounds

Based on **CEV** et al. 2026 (arxiv: 2603.28746). Work with Fiona McCarthy, Anton Baleato Lizancos, Blake Sherwin and Anthony Challinor

- Already seen in current analyses
- $\langle \hat{v}_r^\alpha g_L^\beta \rangle$ measured in the same bin $\alpha = \beta$ **should be close to zero**! however…
- Had to constrain cosmology from a velocity template instead: $\langle \hat{v}^\alpha v^{\rm cont} \rangle$



[Single frequency measurement using McCarthy et al. 2025 pipeline]

Aim: characterise and mitigate these foreground contributions

Studied in depth for the 3D case in Chaussidon et al. 2026

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The projected velocity estimator

See Deutsch et al 2017
Kvasiuk et al. 2023

Fourier space: $$\hat{v}_r^{\alpha}(\boldsymbol{L}) = \lambda(L) \int d^2\boldsymbol{\ell}\, h^{\alpha}(\boldsymbol{\ell}, \boldsymbol{L}-\boldsymbol{\ell})\, T^{\rm obs}(\boldsymbol{\ell})\, g^{\alpha}(\boldsymbol{L}-\boldsymbol{\ell})$$

optimal filters

Foregrounds (tSZ, CIB, …)

However, $T^{\rm obs}$ contains more than our signal: $$T^{\rm obs} = T^{\rm kSZ} + f + n$$

$$\langle \hat{v}_r^{\alpha}(\mathbf{L}) \rangle = \langle \hat{v}_r^{\alpha}(\mathbf{L}) \rangle_{\rm signal} + \langle \hat{v}_r^{\alpha}(\mathbf{L}) \rangle_{f} + \text{uncorrelated noise}$$

True velocity signal

Foreground contribution

Response formalism intuition

- From the foreground contribution to the velocity estimator

$$\langle \hat{v}^{\alpha}_{r,f}(\mathbf{L}) \rangle = \lambda(L) \int d^2\ell \; h^{\alpha}(\boldsymbol{\ell}, \mathbf{L} - \boldsymbol{\ell}) \langle f(\boldsymbol{\ell}) \; g^{\alpha}(\mathbf{L} - \boldsymbol{\ell}) \rangle$$

- From the response formalism: large-scale modulations averaged over small scale modes are directly proportional to the matter density field

$$\langle f_{\rm 3D}(\boldsymbol{k}) \, \delta_g(\boldsymbol{K} - \boldsymbol{k}) \rangle_S \approx \mathcal{R}(k, \mu_{\boldsymbol{k},\boldsymbol{K}}) P^{fg}(k) \delta_m(\boldsymbol{K})$$

Barreira & Schmidt 2017

- Foreground contribution to the reconstructed velocity is directly proportional to the density field (in projection)

$$\langle \hat{v}^{\alpha}_{r,f}(\hat{\mathbf{n}}) \rangle_S \approx \int d\chi \; \frac{W_f(\chi) W^{\alpha}_g(\chi)}{\chi^2} \, b^{\alpha}_{fg}(\chi) \; \delta_m(\chi \hat{\mathbf{n}}, \chi)$$

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The foreground bispectrum

The velocity-galaxy cross-correlation:

$$\left\langle \hat{v}_r^{\alpha}(\mathbf{L})\, g_L^{\beta}(\mathbf{L}') \right\rangle = \lambda(L) \int d^2\ell\, h^{\alpha}(\boldsymbol{\ell}, \mathbf{L}-\boldsymbol{\ell}) \left\langle T^{\rm obs}(\boldsymbol{\ell})\, g_S^{\alpha}(\mathbf{L}-\boldsymbol{\ell})\, g_L^{\beta}(\mathbf{L}') \right\rangle$$

$$T^{\rm obs} = T^{\rm kSZ} + f + n$$

Foreground contribution:

$$\left\langle \hat{v}_r^{\alpha}(\mathbf{L})\, g_L^{\beta}(\mathbf{L}') \right\rangle_f = \lambda(L) \int d^2\ell\, h^{\alpha}(\boldsymbol{\ell}, \mathbf{L}-\boldsymbol{\ell}) \left\langle f(\boldsymbol{\ell})\, g_S^{\alpha}(\mathbf{L}-\boldsymbol{\ell})\, g_L^{\beta}(\mathbf{L}') \right\rangle$$

Baleato Lizancos et al. 2025

abaleato / CosmoBLENDER

mode coupling integral

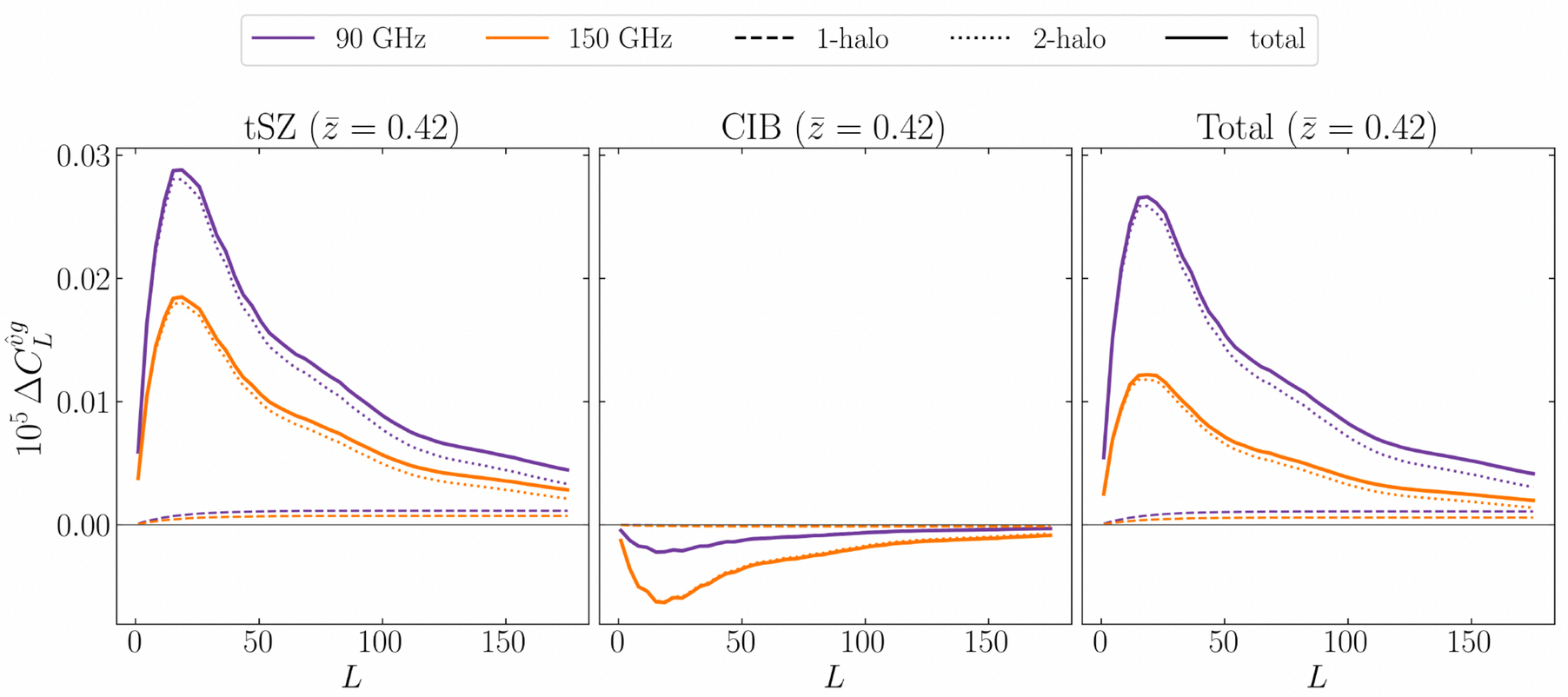
Halo model

simonsobs / hmvec

$$f = \{\rm tSZ, CIB\}$$

Foreground estimation

- Computed for $\hat{v}$ and g in same redshift bin (kSZ signal is zero)

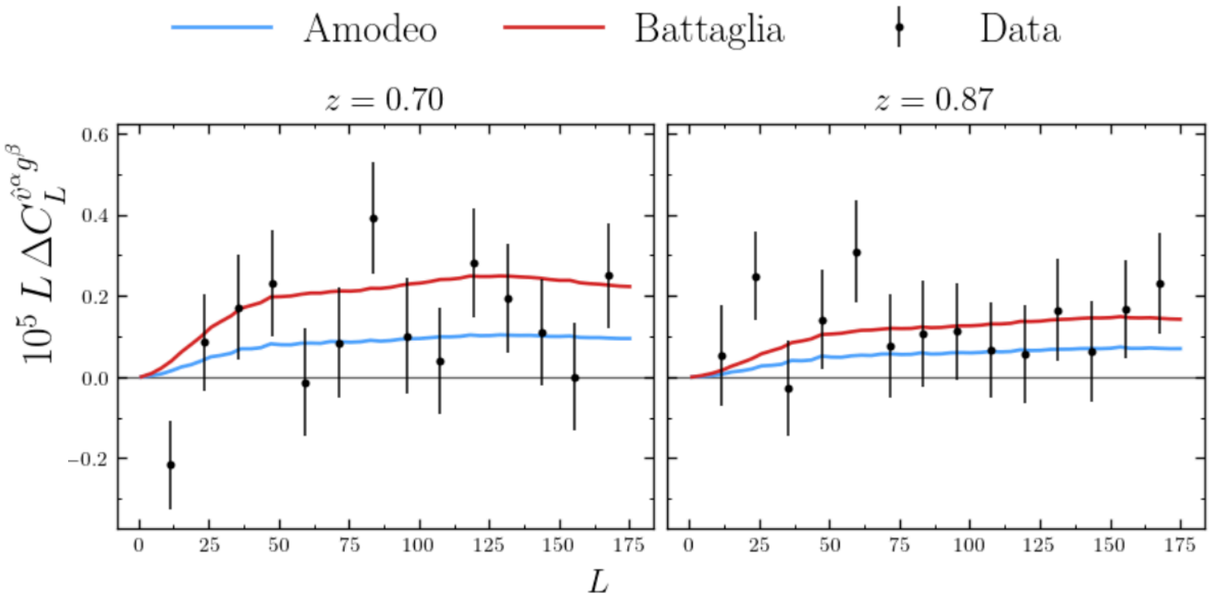


- 2-halo term dominates
- tSZ and CIB contributions partially cancel out

Comparison to data

- Compare our predictions to single-frequency data points using McCarthy et al. 2025 pipeline: DESI LRGs and ACT DR6 CMB temperature.

(150GHz)



- We are able to explain the excess found on same redshift bin signal.
- Compare predictions with two different pressure profiles for tSZ modelling, due to astrophysical uncertainty.
- When computing there for neighbouring redshift bins we find foreground contribution could be of the order of the signal

Mitigation strategy

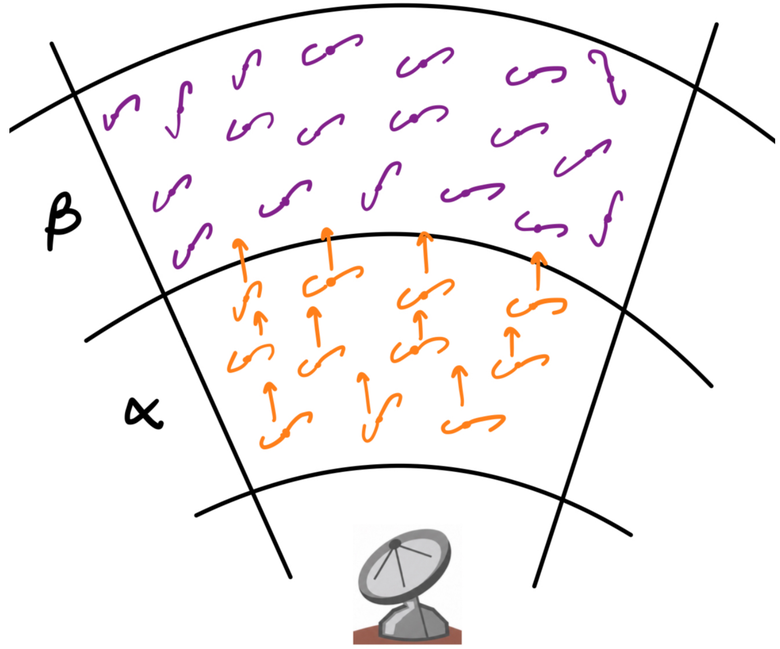
Parity odd estimator

$$C_L^{\hat{v}g,\mathrm{ODD}^{\alpha,\beta}} \equiv C_L^{\hat{v}^\alpha g^\beta} - C_L^{\hat{v}^\beta g^\alpha}$$

- Signal is preserved:

$$C_L^{\hat{v}g,\mathrm{ODD}^{\alpha,\beta}} \approx 2\, C_L^{\hat{v}^\alpha g^\beta,\mathrm{true}}$$

$C_L^{\hat{v}^\alpha g^\beta}$



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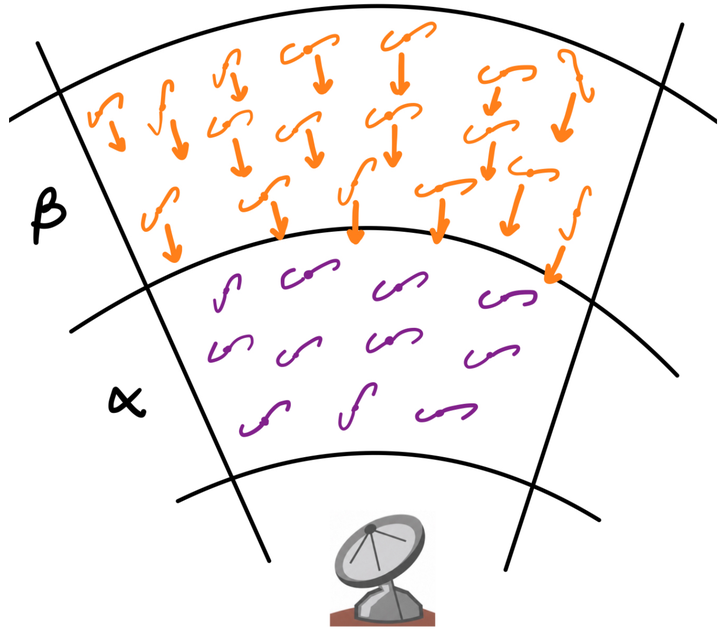
$C_L^{\hat{v}^\beta g^\alpha}$



Mitigation strategy

Parity odd estimator

$$C_L^{\hat{v}g,\mathrm{ODD}^{\alpha,\beta}} \equiv C_L^{\hat{v}^\alpha g^\beta} - C_L^{\hat{v}^\beta g^\alpha}$$

- Signal is preserved:

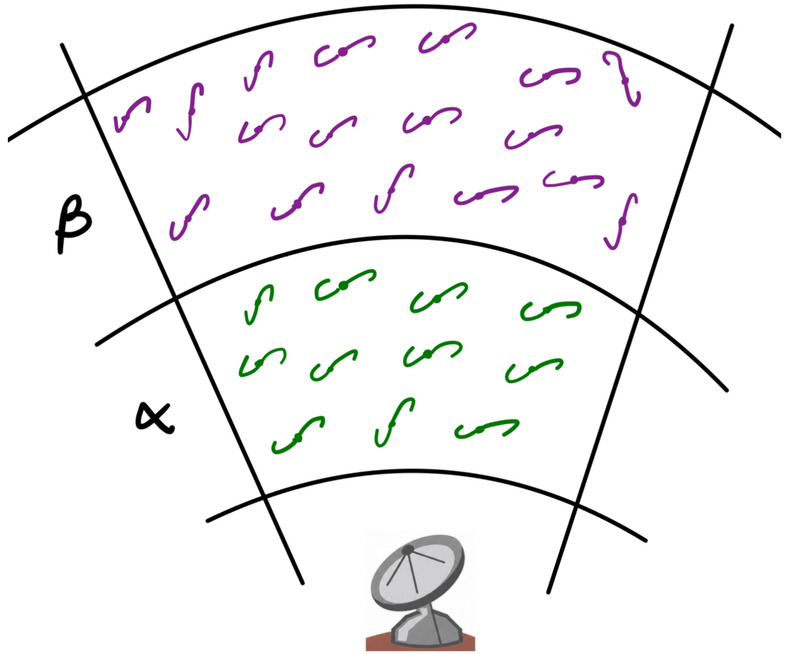
$$C_L^{\hat{v}g,\mathrm{ODD}^{\alpha,\beta}} \approx 2\, C_L^{\hat{v}^\alpha g^\beta,\mathrm{true}}$$

- Foreground contribution cancels

$$\Delta C_L^{\hat{v}^\alpha g^\beta} = C_L^{f^\alpha g^\beta} - C_L^{f^\beta g^\alpha} \approx 0$$

Without any loss of signal-to-noise!

$C_L^{f^\alpha g^\beta}$



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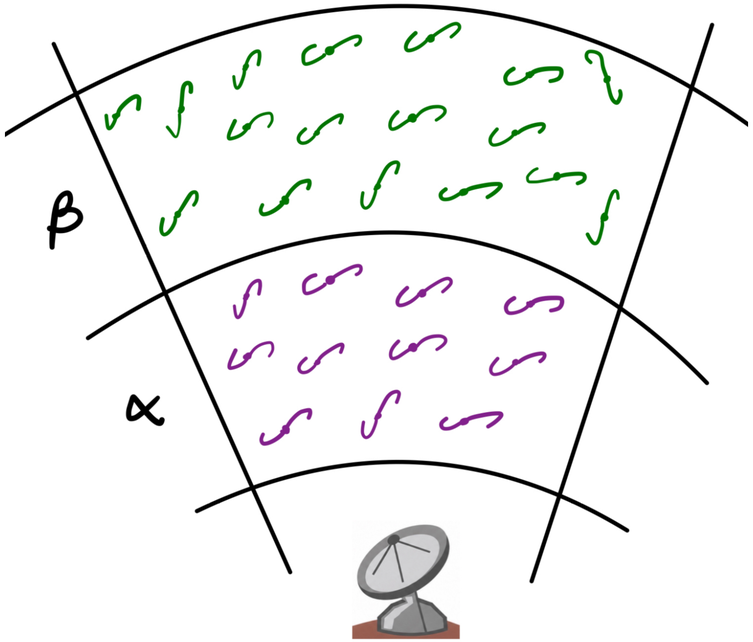
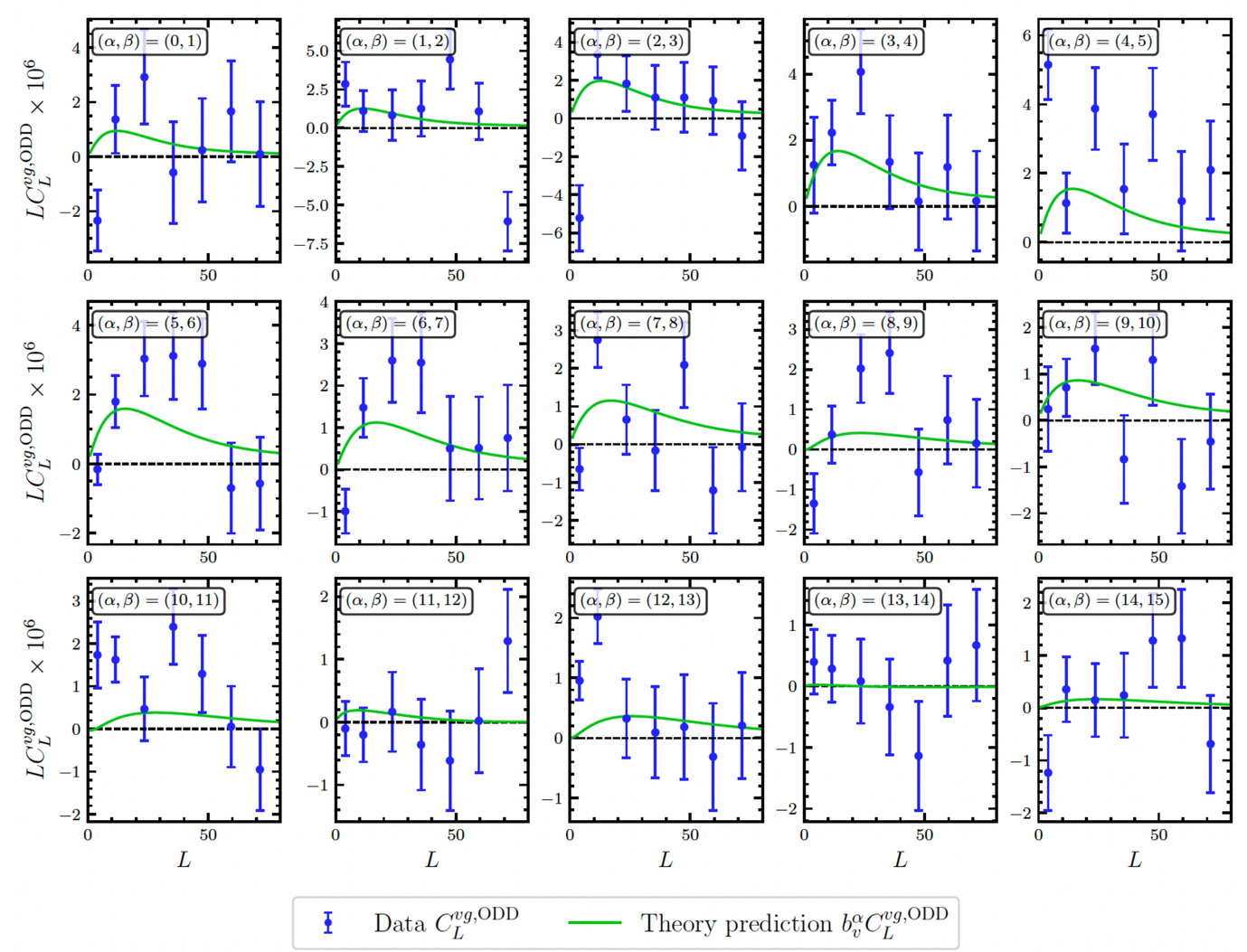
$C_L^{f^\beta g^\alpha}$



We applied it to data

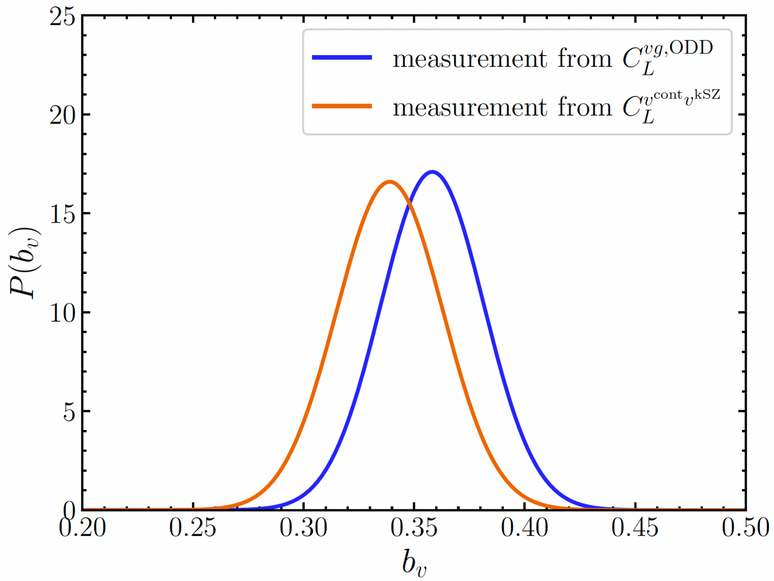
And found a dramatic improvement in goodness-of-fit!



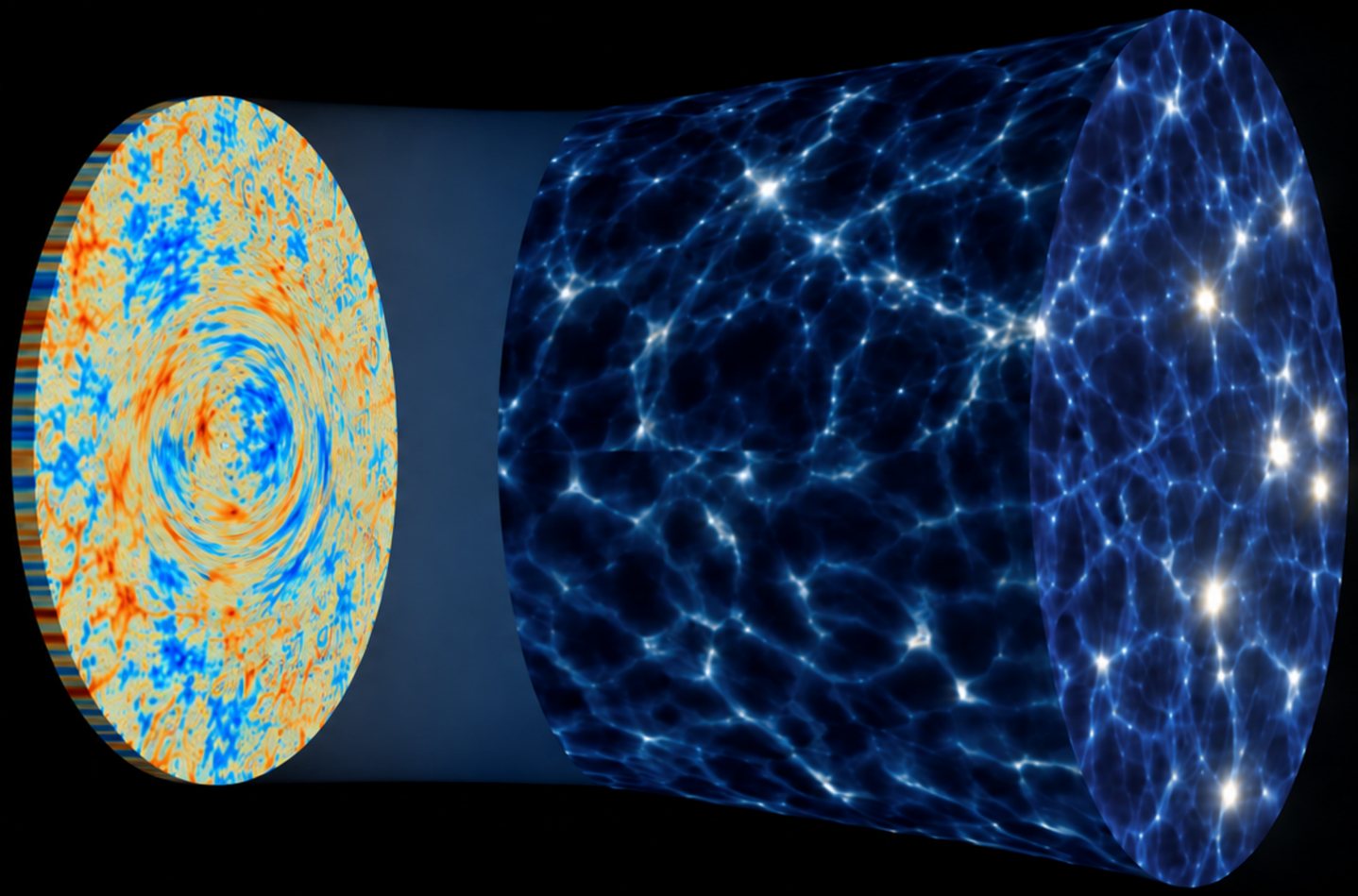
dataset	$\chi^2_{\rm min}(b_v^\alpha)$	DOF	PTE
$C_L^{v^\alpha g^\beta}$	207	$120-16$	8×10^{-7}
$C_L^{vg,\mathrm{ODD}}$	54	$60-16$	0.46

Finally a good fit to $C_L^{\hat{v}g}$

Without any loss of SNR



Part II: CMB lensing cross-correlations



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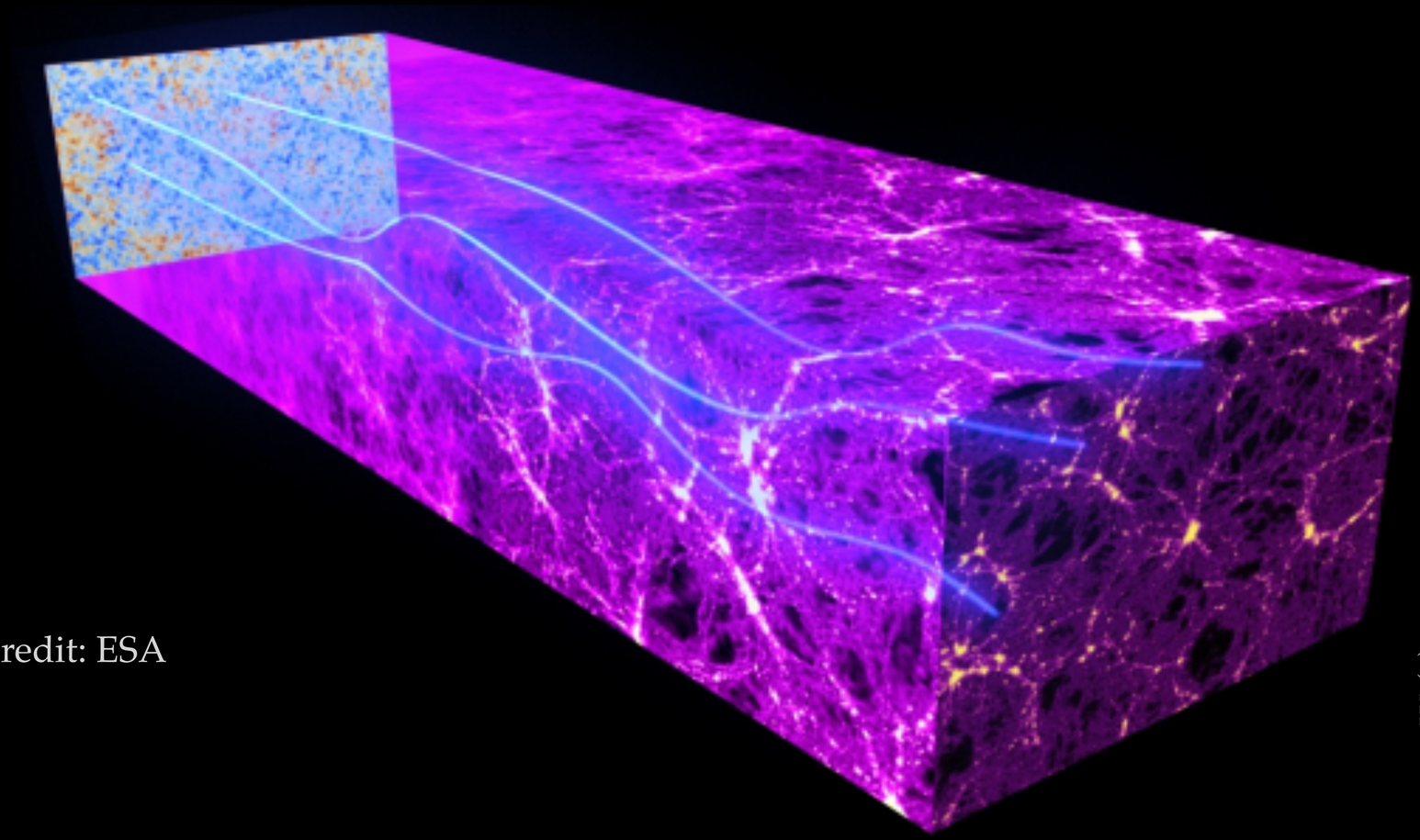
CMB lensing

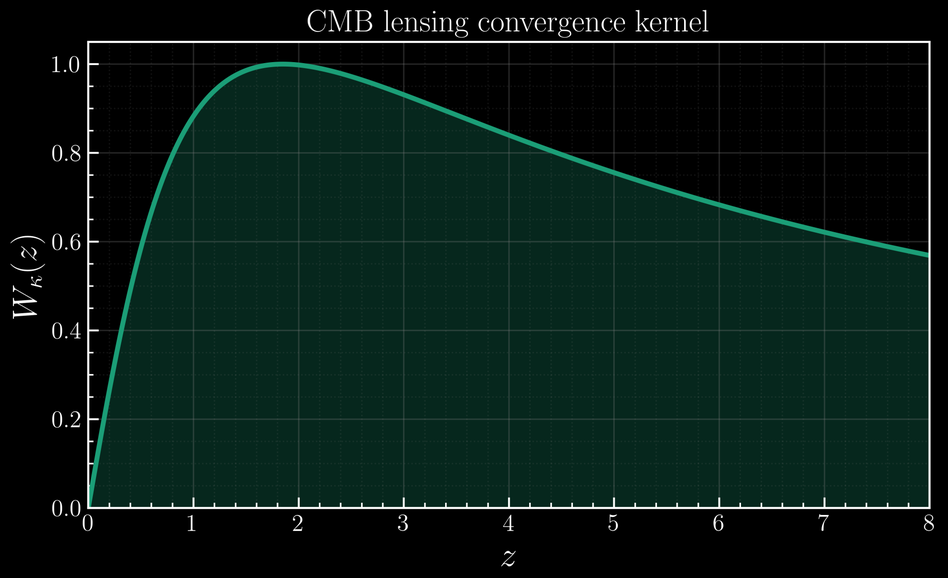
CMB gets deflected by an angle

$$T = T^0(\hat{\boldsymbol{n}} + \nabla\phi)$$

Observable: Lensing potential



Credit: ESA



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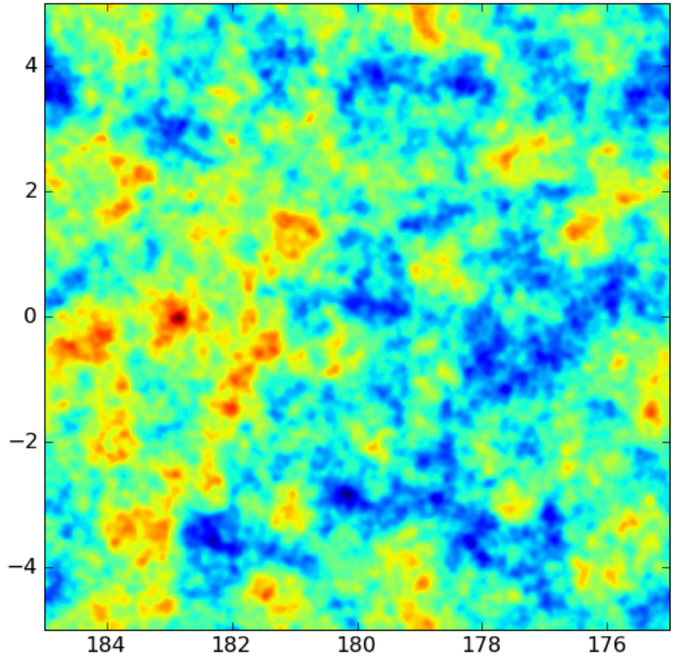
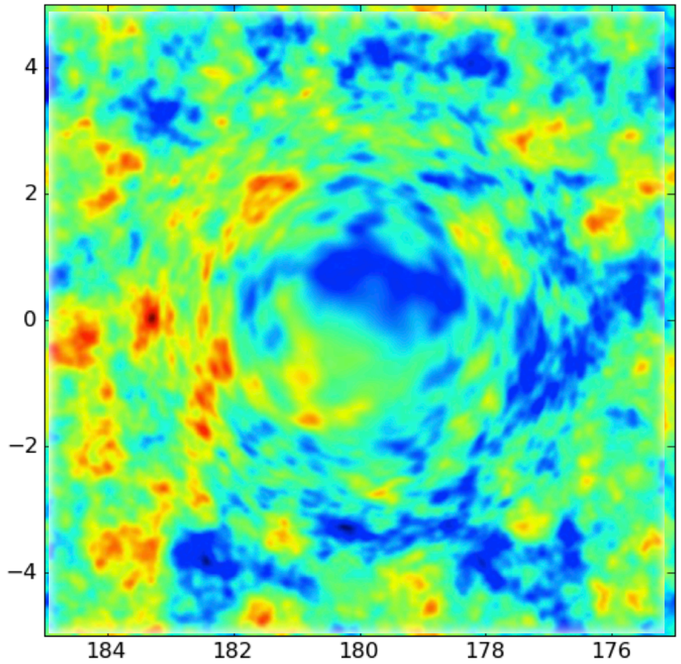
Lensing reconstruction in a nutshell

Unlensed



Lensed

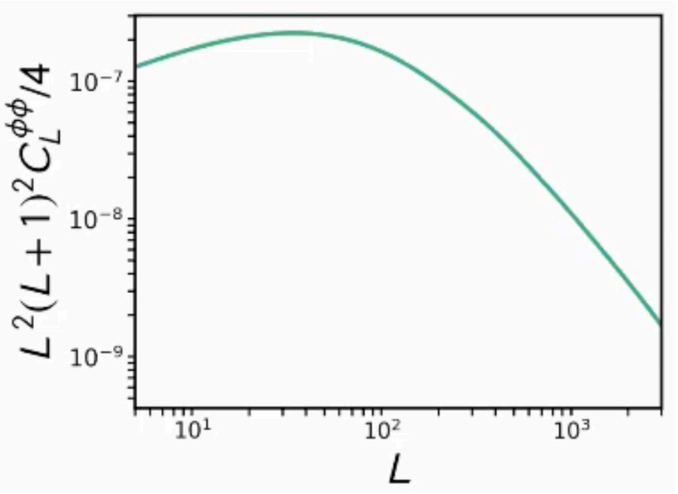


Quadratic estimator:

Lensing potential is reconstructed mode by mode

$$\hat{\phi}(\boldsymbol{L}) \propto \int d^2\boldsymbol{\ell} T(\boldsymbol{\ell}) T^*(\boldsymbol{\ell} - \boldsymbol{L})$$

$$L^4 C_L^{\phi\phi}/4 = \int_0^{z^*} dz \left(W_\kappa(z)\right)^2 P_{mm}(k = L/\chi, z)$$



Unlensed: $\langle T(\boldsymbol{\ell}) T^*(\boldsymbol{\ell} - \boldsymbol{L}) \rangle_{\rm CMB} = 0$

Lensed: $\langle T(\boldsymbol{\ell}) T^*(\boldsymbol{\ell} - \boldsymbol{L}) \rangle_{\rm CMB} \propto \phi(\boldsymbol{L})$

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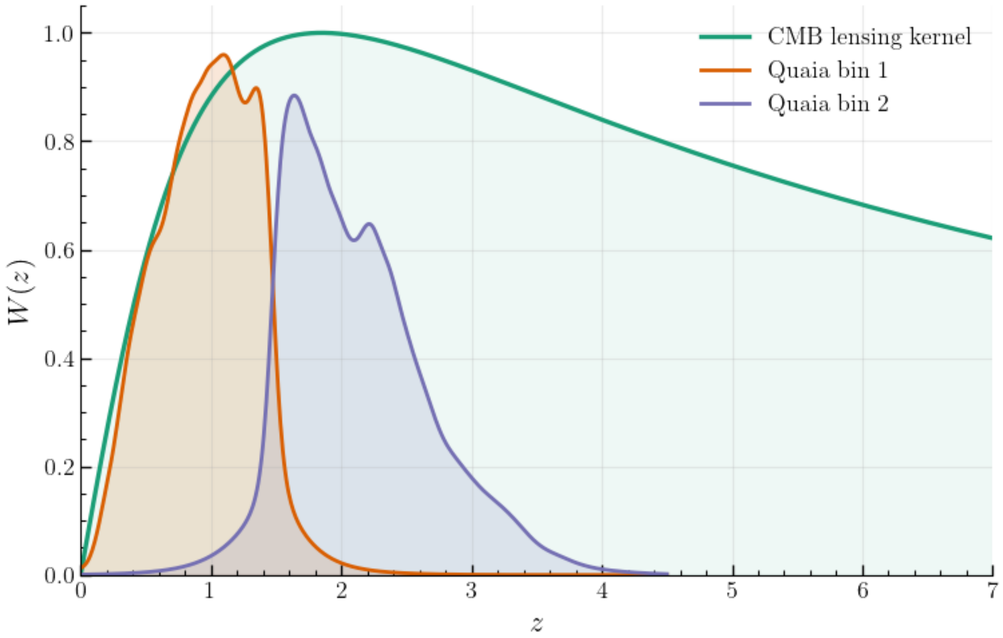
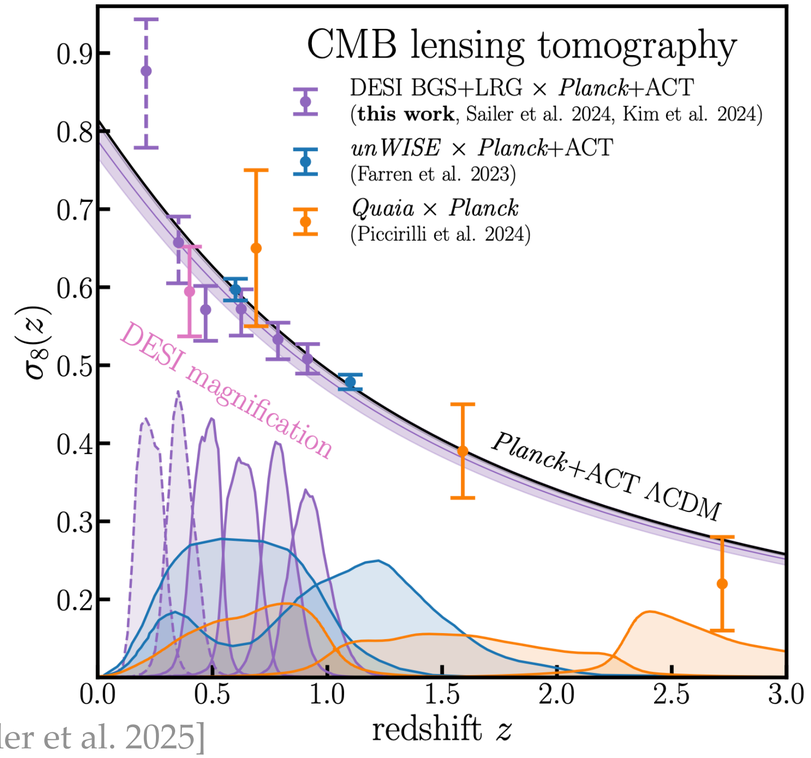
Science case I: structure growth
CMB lensing tomography

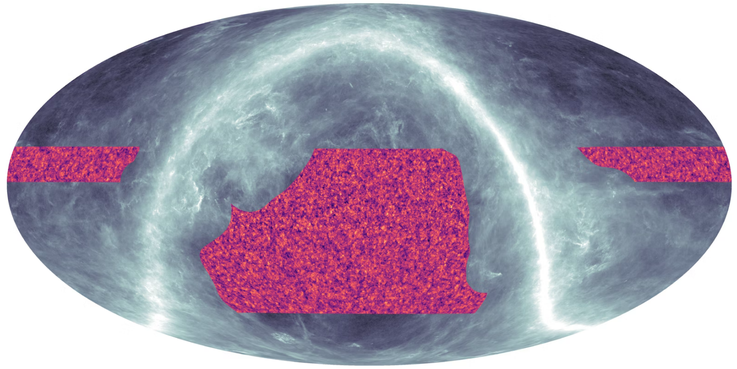
Based on **CEV** et al. 2026 (arxiv: 2603.28746)

$$(\kappa \propto \nabla^2\phi) \quad \left.\begin{aligned} C_\ell^{\kappa g} &\propto b\sigma_8^2 \\ C_\ell^{gg} &\propto b^2\sigma_8^2 \end{aligned}\right\} \quad \frac{C_\ell^{\kappa g}}{\sqrt{C_\ell^{gg}}} \propto \frac{b\sigma_8^2}{\sqrt{b^2\sigma_8^2}} = \sigma_8$$

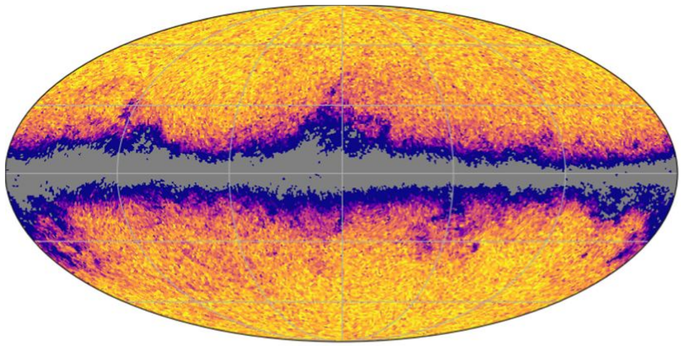




[Sailer et al. 2025]



X



Past cross-correlations with ACT

[Farren et al 2023; Kim et al. 2024; Sailer et al. 2024; Sailer et al. 2025]

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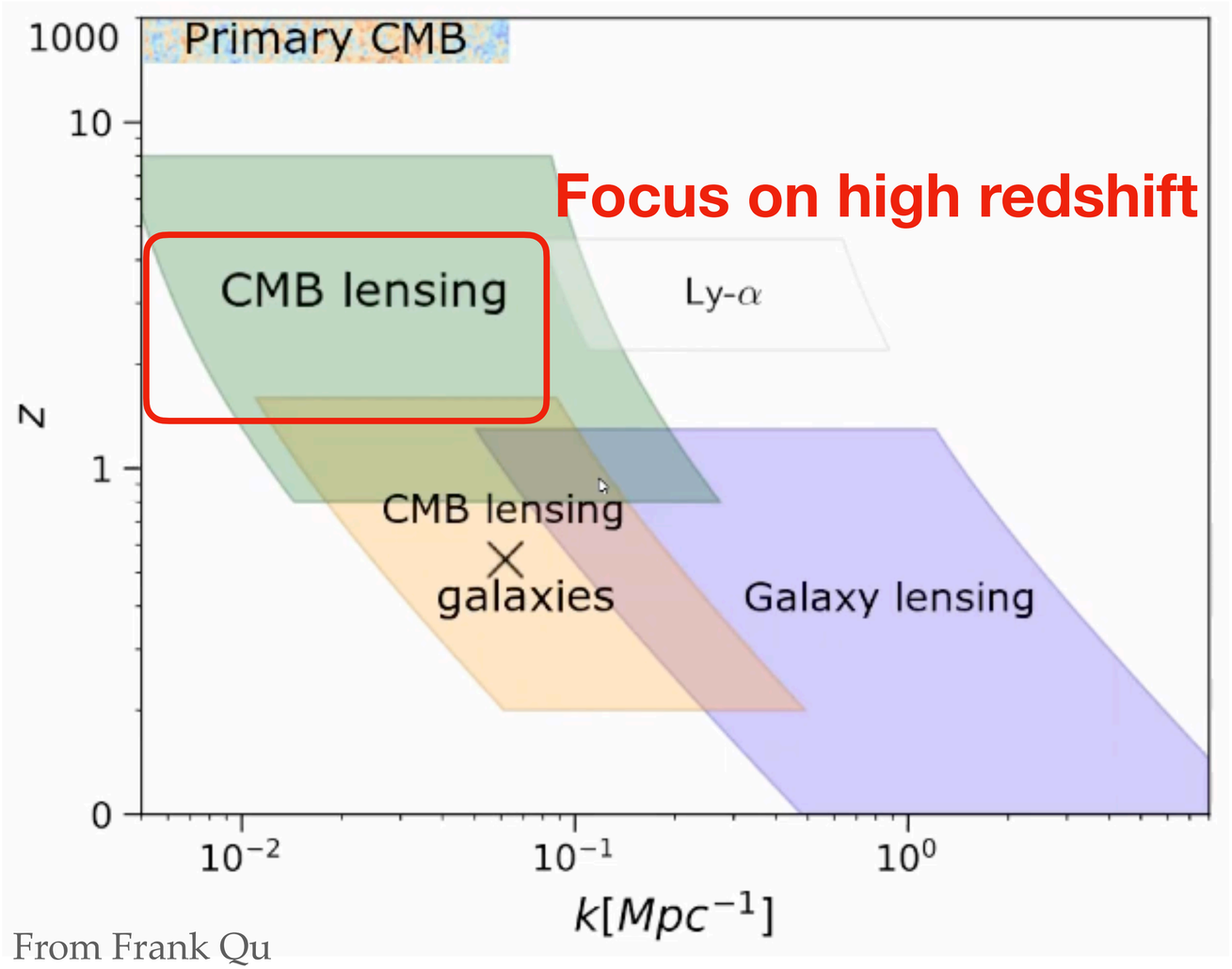
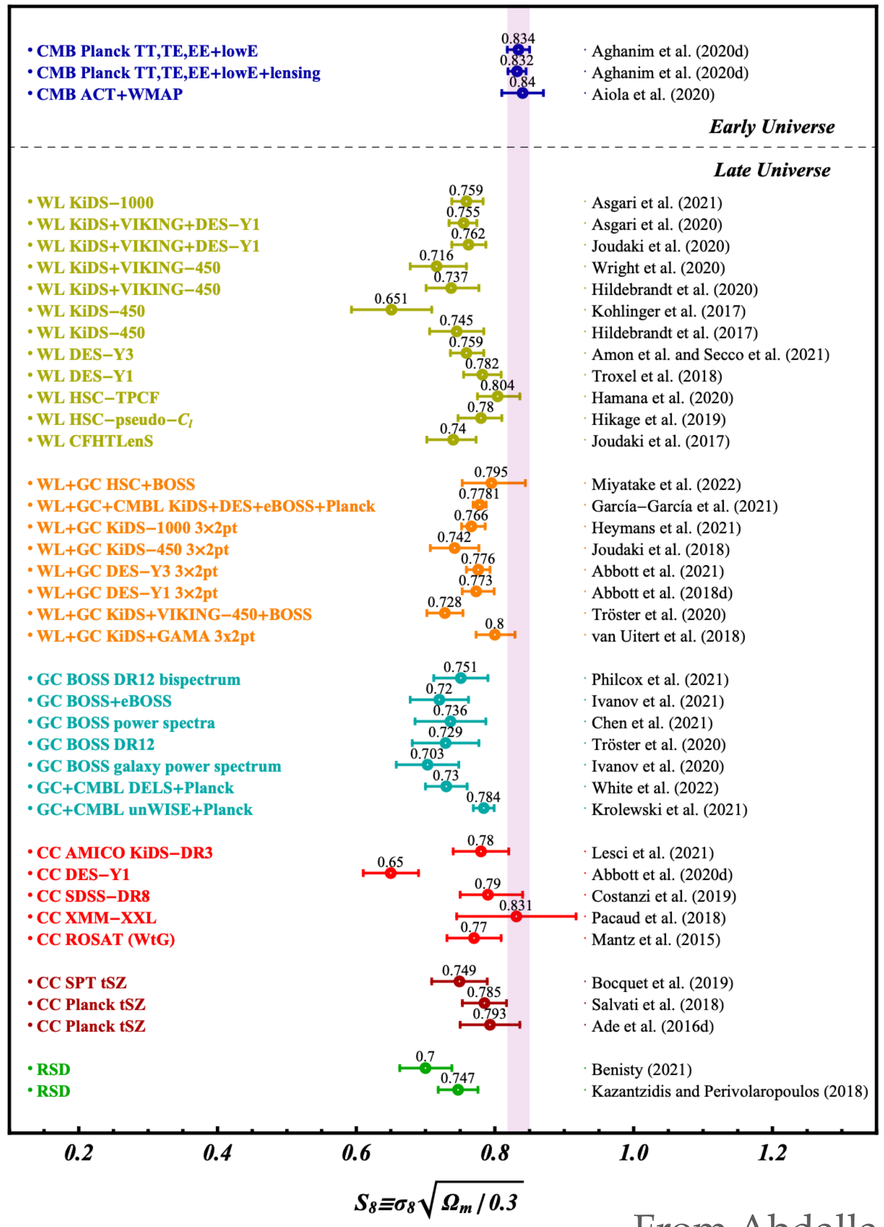
The S8 “tension”

Highlights need to test out theories across scales and redshifts



From Frank Qu



From Abdalla et al. 2022

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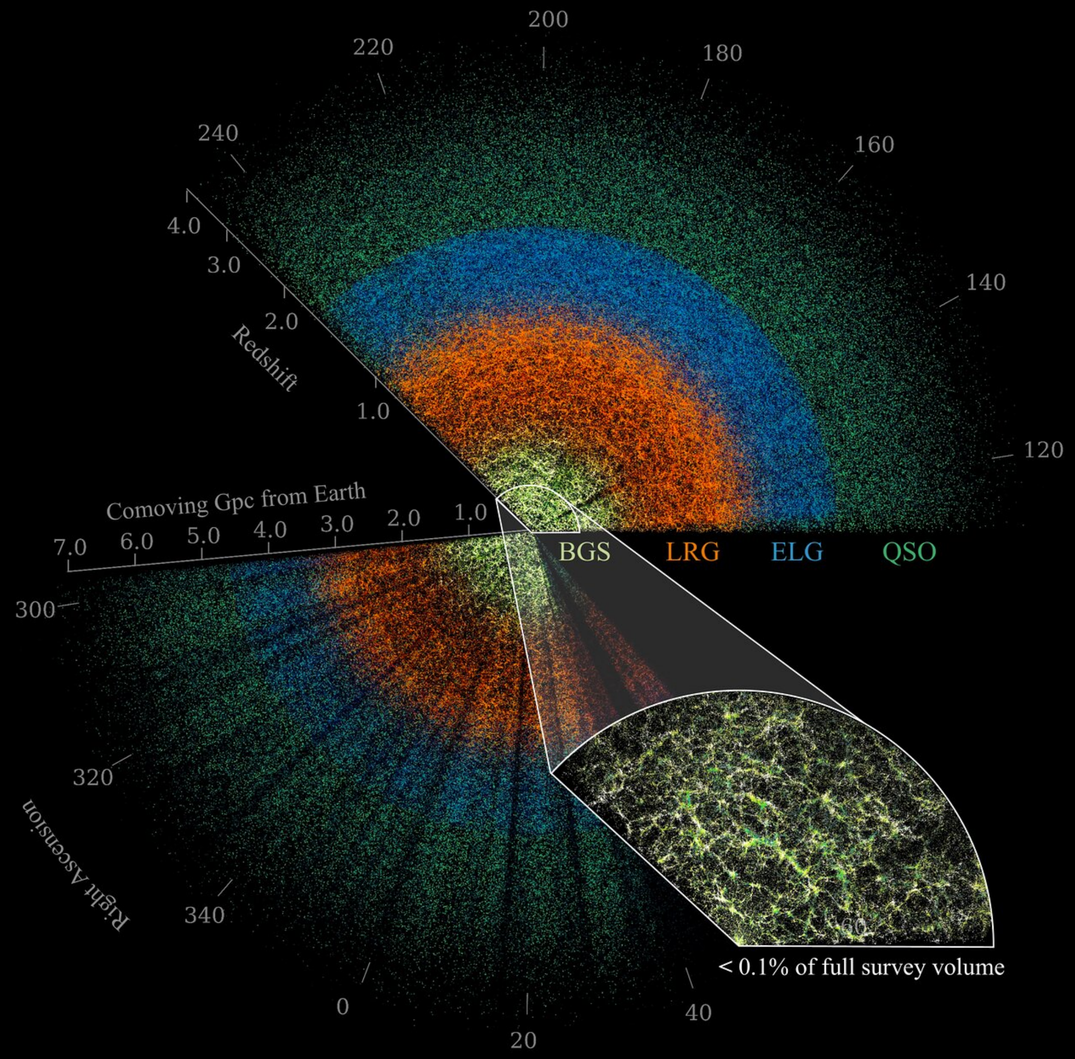
Why go to high redshifts?



Most of the large-scale matter distribution beyond $z \gtrsim 3$ remains only sparsely mapped.

There's 3x more volume at redshifts $2 < z < 6$ than $z < 2$. => more modes

Current/upcoming surveys targeting high redshifts:

- DESI - II : focus at z>2
- PUMA (21cm intensity mapping)

Turns out… we can already access some of this information!

Credit: DESI

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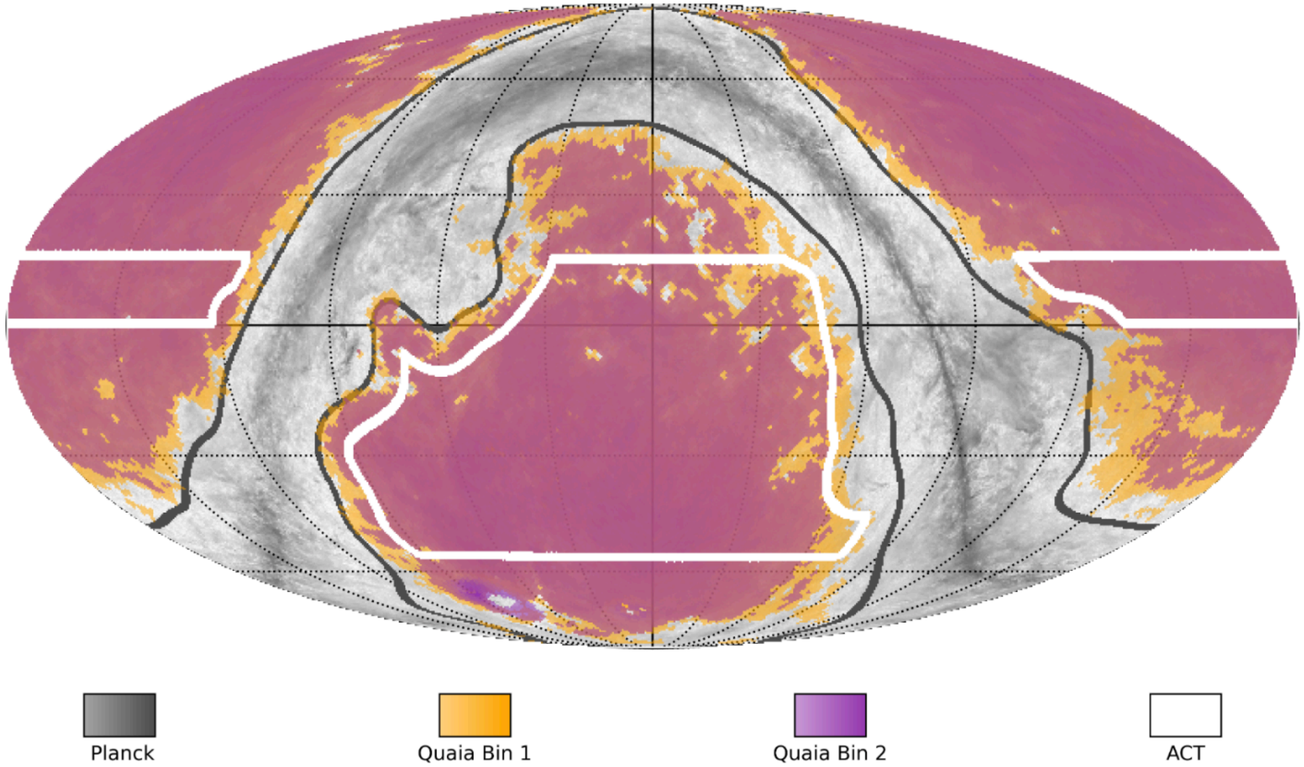
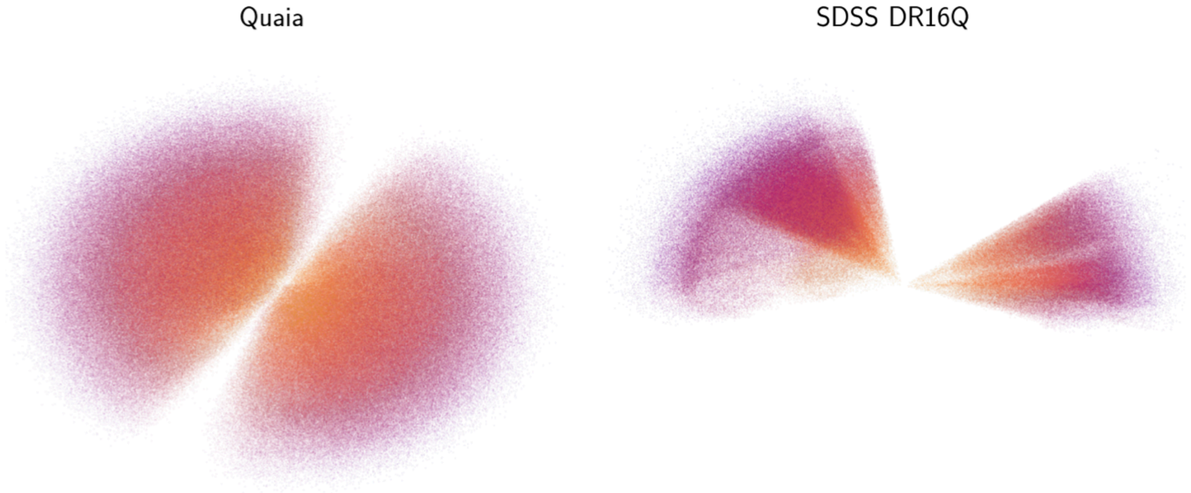
Quaia - the Gaia and unWISE quasar cataogue

All-sky quasar catalog obtained with the combination of Gaia and unWISE [Storey-Fisher et al. 2023]

Spectroscopically calibrated redshifts cross-matched with SDSS DR16Q





Two redshift bins:

Sample	$\bar{z}$	10^5 SN	$\bar{n}[\mathrm{deg}^{-2}]$	ℓ_{max}	b_g^i
z_1	1.0	1.38	34.2	316	$1.16^{+0.22}_{-0.25}$
z_2	2.1	1.29	37.7	526	$1.02^{+0.20}_{-0.23}$

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ACT DR6 lensing



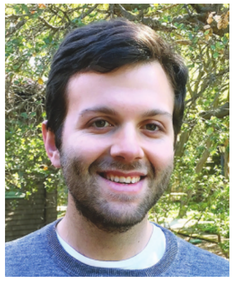
Frank J. Qu
(Cambridge
->Stanford)



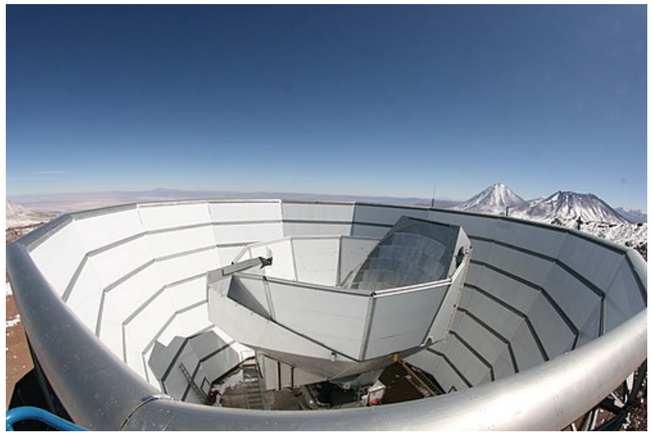
Mat Madhavacheril
(UPenn)



Niall MacCrann
(Cambridge)



Blake Sherwin
(Cambridge)

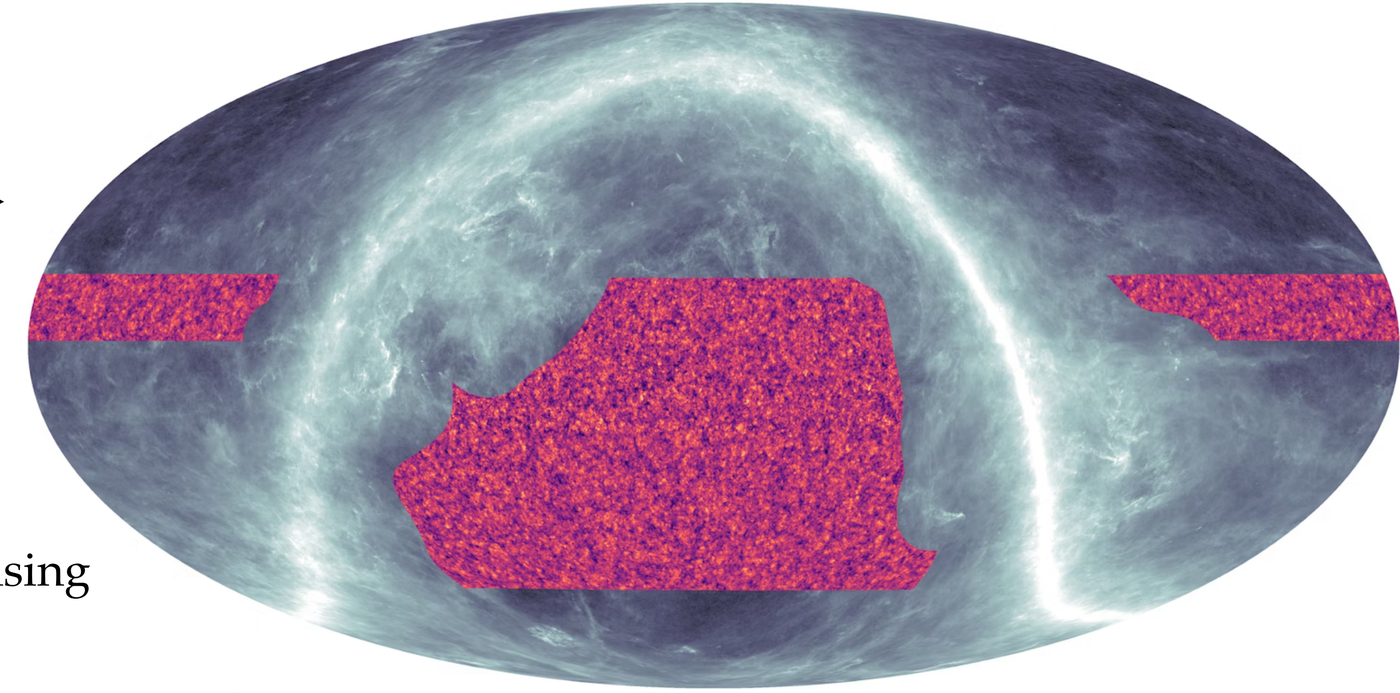




The Atacama Cosmology Telescope (ACT) : 2007 - 2022

Gravitational lensing convergence map ⟶

$$\kappa = -\frac{1}{2}\nabla^2\phi \propto \text{ mass density}$$



- Covers 9400 deg^2 (about 1/4 of the sky)
- About 2x the SNR/mode compared to Planck lensing

New and improved DR6+ release coming on 2026, stay tuned!

[Qu et al. 2024; Madhavacheril et al. 2024; MacCrann et al. 2024]

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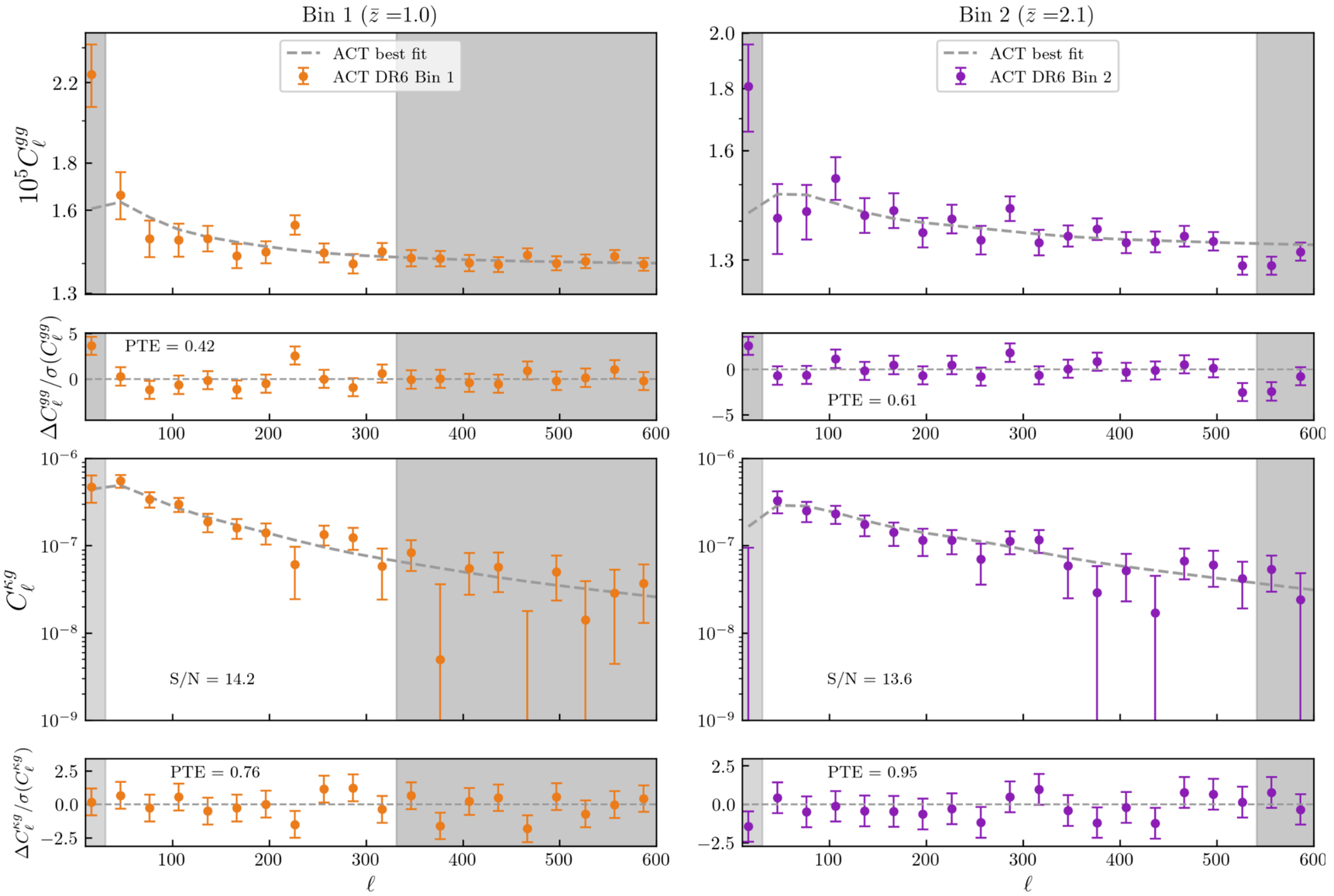
Measurement and challenges

- Shot noise marginalisation
- Conservative scale cuts consistent with a linear bias model:

$$k_{\max} = 0.15h/\mathrm{Mpc}$$

- Built Gaussian simulations:
  - Covariance
  - Normalisation correction
- **Foreground contamination and systematics tests**

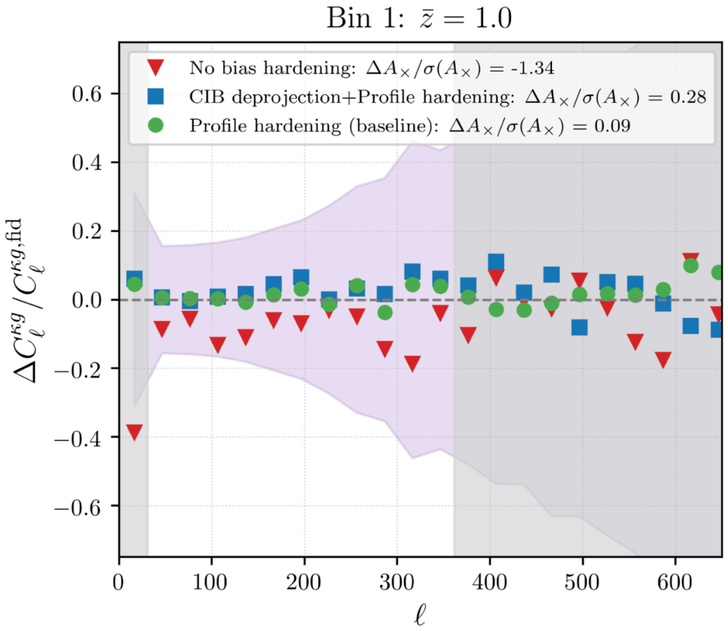


Foreground contamination tests

Context: previous cross-correlations with Quaia found possible hints of extragalactic foreground contamination in the Planck lensing maps

- **Test on simulations**

Populate `WebSky` haloes using a Quaia HOD and cross correlate with foreground-only map

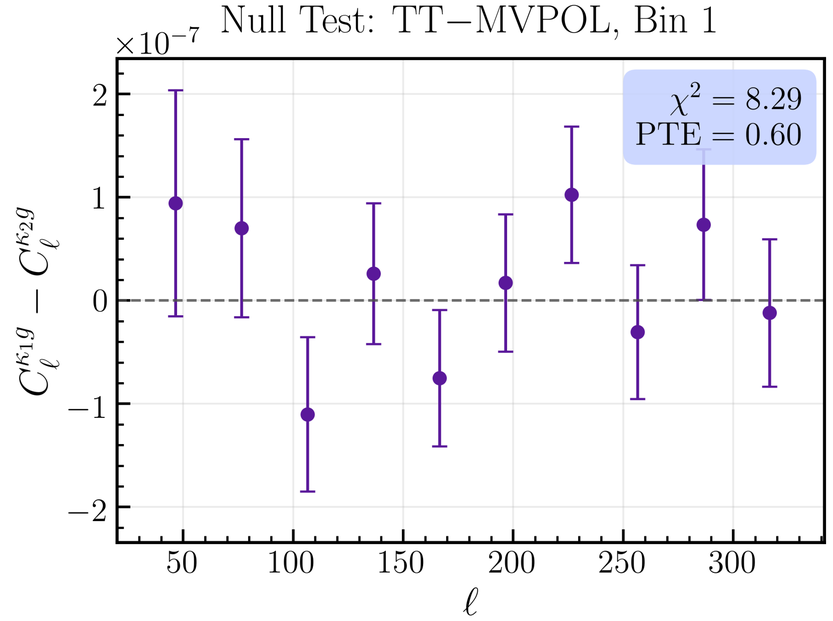


We find no significant foreground contamination in our lensing maps

- **Bandpower null tests**

Compare cross-correlations doing lensing reconstruction on different CMB lensing maps $C_\ell^{\kappa_1 g} - C_\ell^{\kappa_2 g}$

(Temperature × g - Polarization × g)



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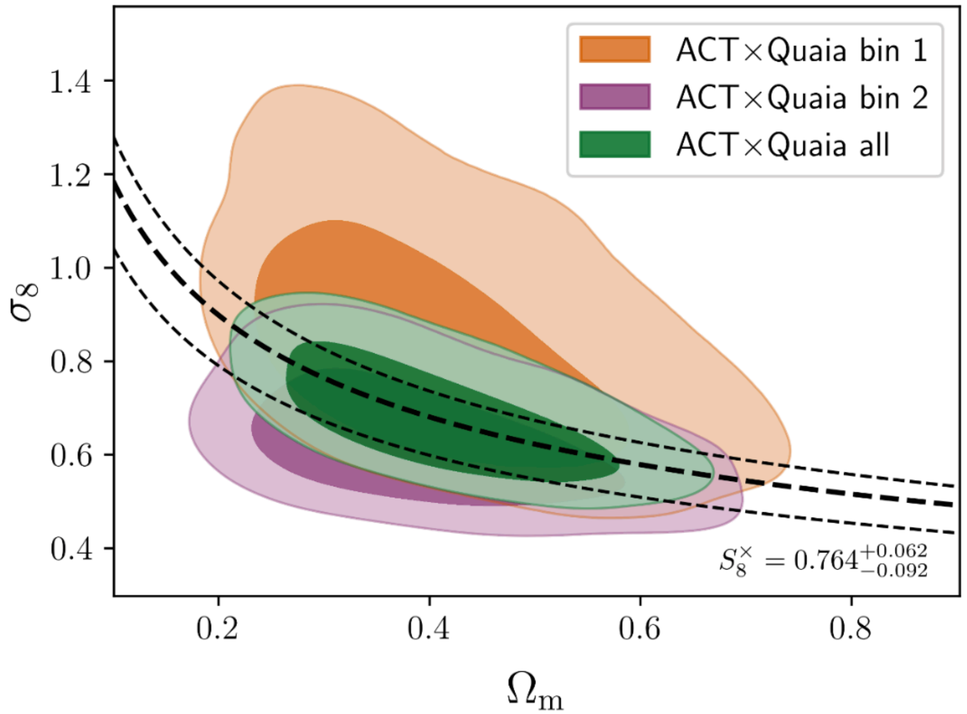
Results: ACT x Quaia & combination with Planck lensing

ACT only

Best constrained parameter:

$$S_8^{\times} = \sigma_8 \left(\frac{\Omega_m}{0.3}\right)^{0.4} = 0.764^{+0.062}_{-0.092}$$

Consistent with prediction from primary CMB

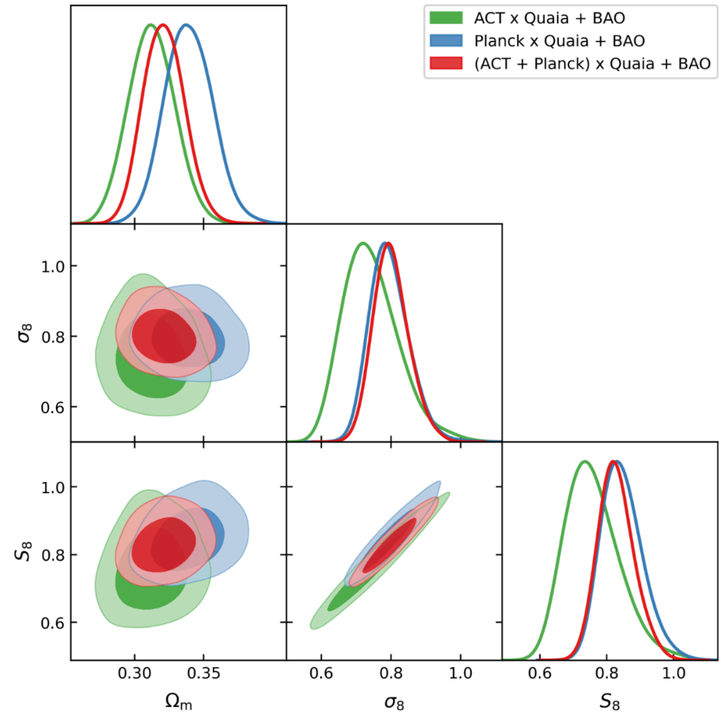


(ACT + Planck) x Quaia + BAO

- Used simulations to compute correlations between ACT and Planck
- Consistent with LCDM predicted by Planck

$$\sigma_8 = 0.802^{+0.045}_{-0.057}$$

Very competitive compared to other measurements at this redshifts!



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3x2pt measurement: going even higher in redshift!

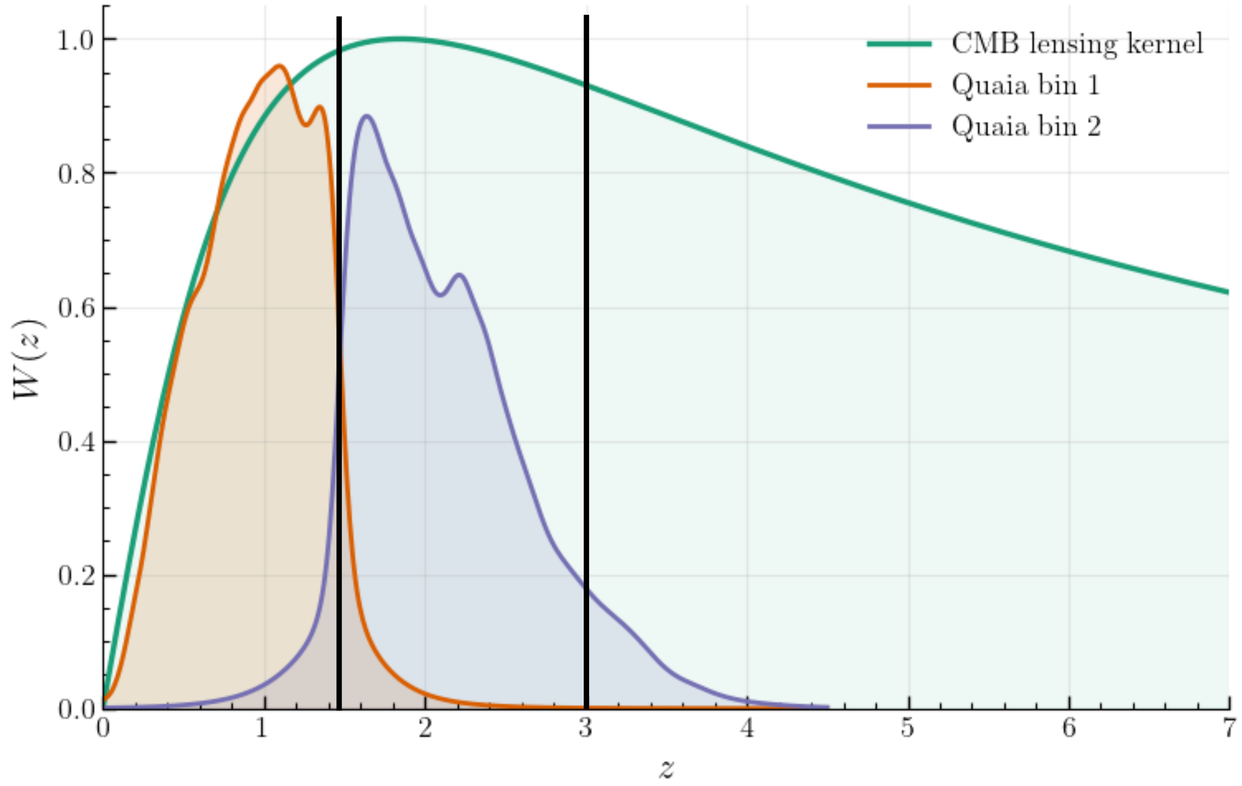
- Combine the 2x2pt ($C_\ell^{\kappa g}$, C_ℓ^{gg}) measurement with the lensing auto-correlation: $C_\ell^{\kappa\kappa}$

- Leverage redshift overlap to extract information beyond the Quaia sample:

Reparametrisation:

$$P_{\rm lin}^{\rm new}(k,z) = P_{\rm lin}(k,z)A(z)$$

$$A(z) = \begin{cases} A_1 & 0 \leq z < 1.45\ , \\ A_2 & 1.45 \leq z < 3.0\ , \\ A_3 & 3.0 \leq z\ , \end{cases}$$



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Results & comparison to other high redshift measurements

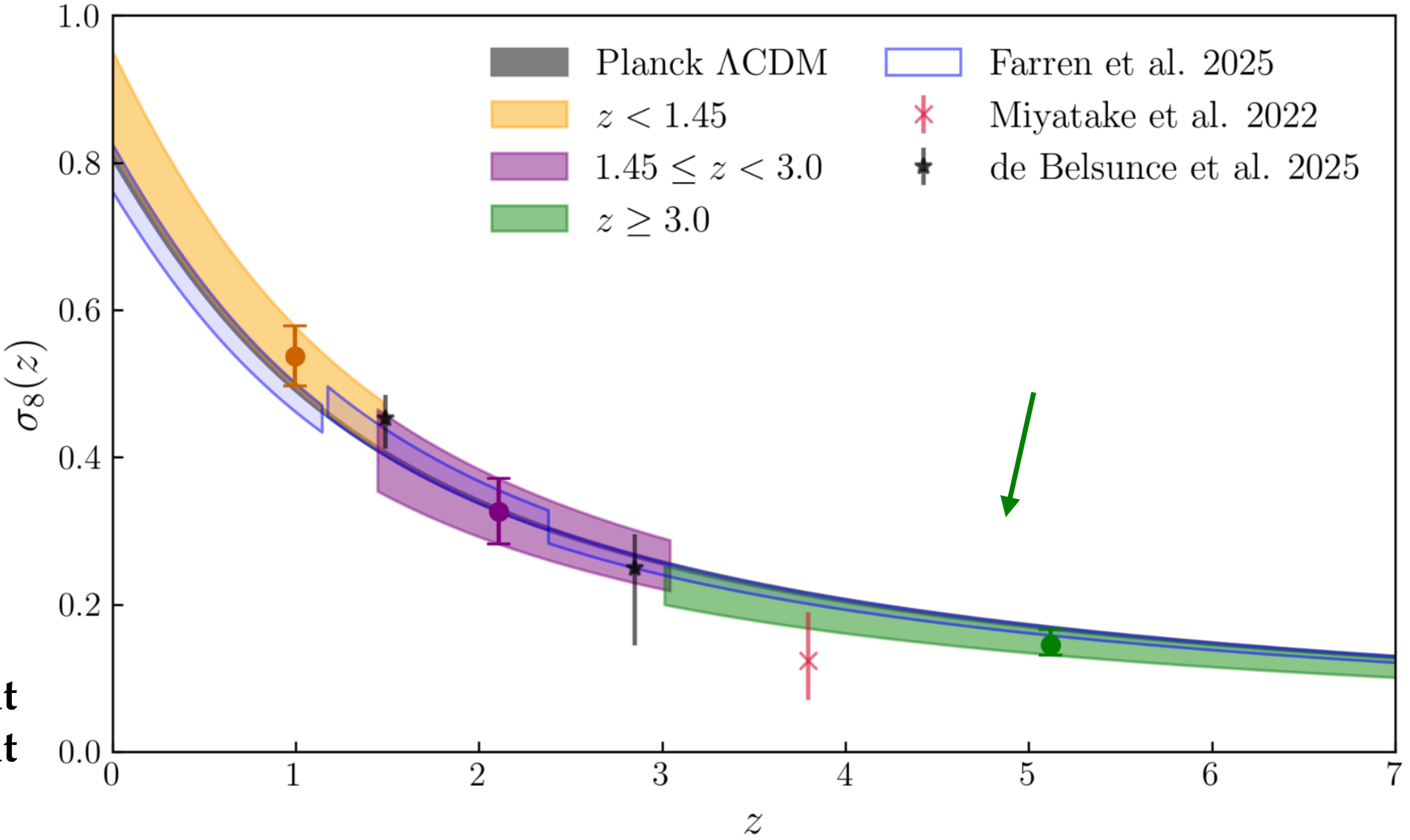
New parameters of interest:

$\sigma_8\sqrt{A_0}$

$\sigma_8\sqrt{A_1}$

$\sigma_8\sqrt{A_2}$

Unique measurement of structure growth at high z



Science case II: primordial non-Gaussianity

CMB lensing × Cosmic Infrared Background (CIB)

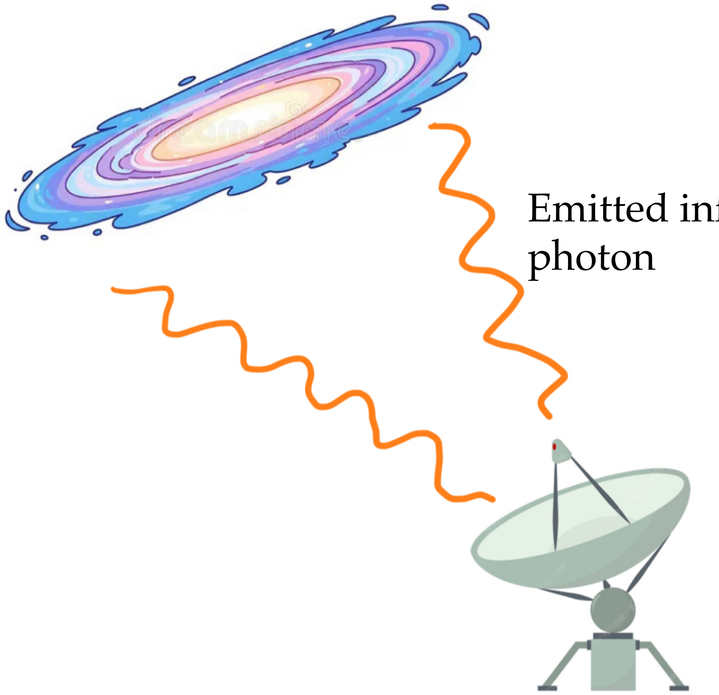


Joseph Thornton

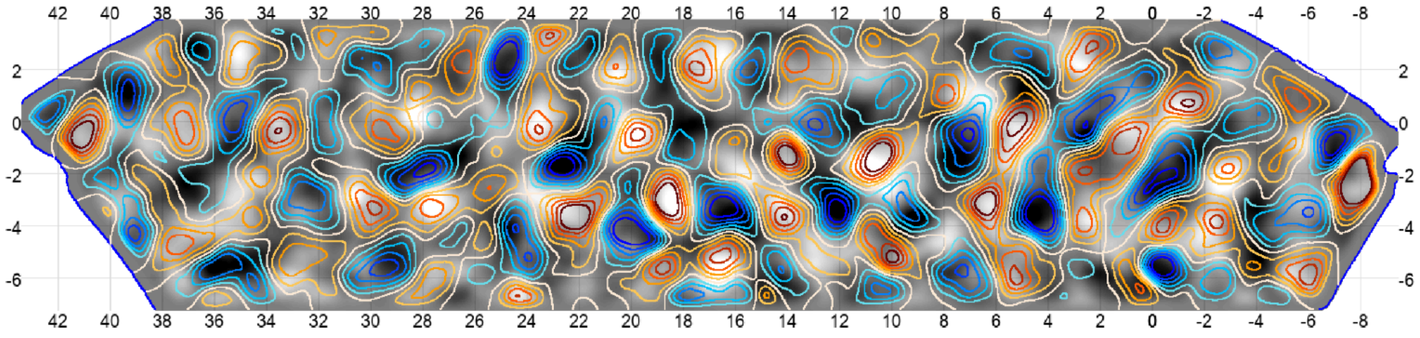
CIB:

Tracer for star-forming, dusty galaxies

$$\left.\begin{aligned} C_\ell^{\kappa g} &\propto b\sigma_8^2 \\ C_\ell^{gg} &\propto b^2\sigma_8^2 \end{aligned}\right\} \quad \frac{C_\ell^{gg}}{C_\ell^{\kappa g}} \propto b \propto f_{NL}$$



Highly correlated with CMB lensing



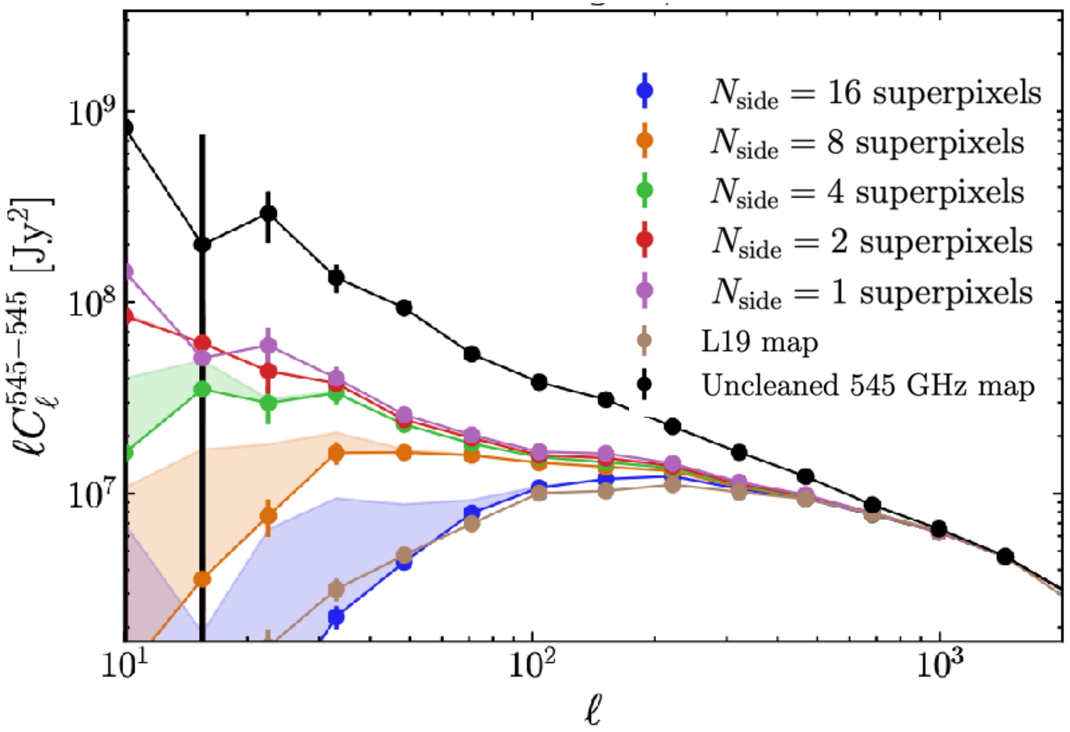
from Darwish et al 2020

CMB lensing × CIB robustness

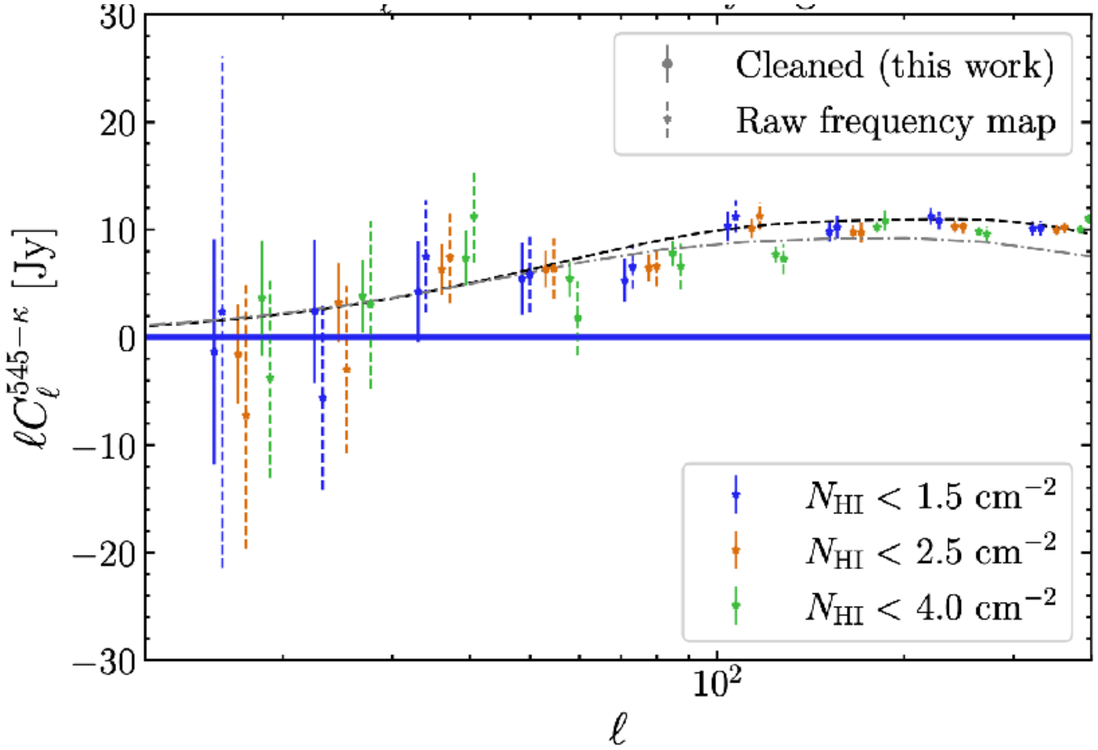
Main contaminant for CIB on large scales are galactic foregrounds

(different cleaning techniques)

CIB auto

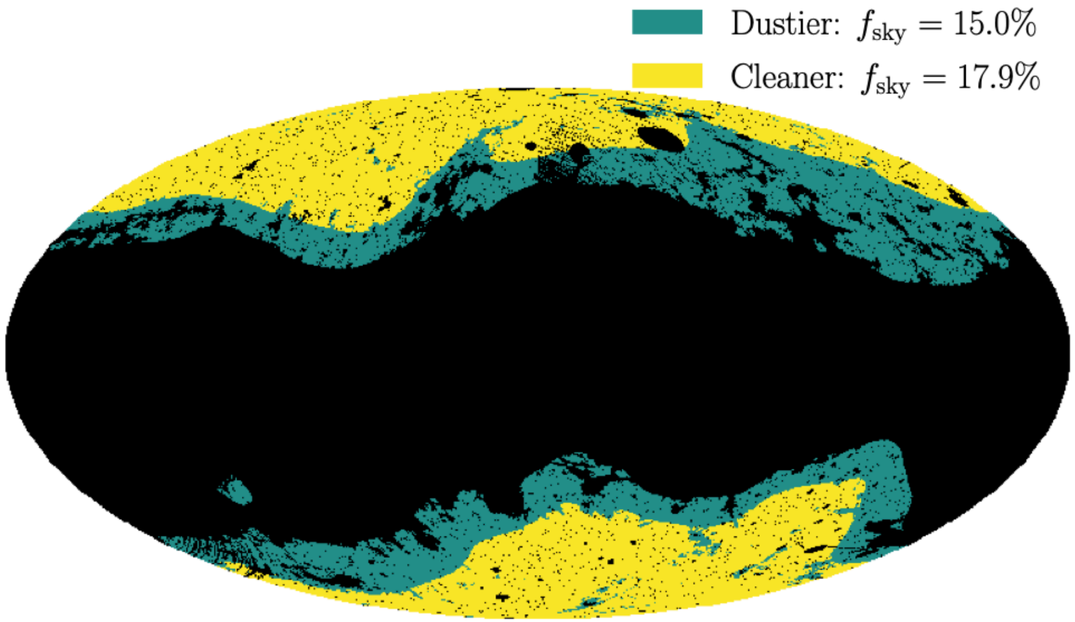


CIB × CMB lensing



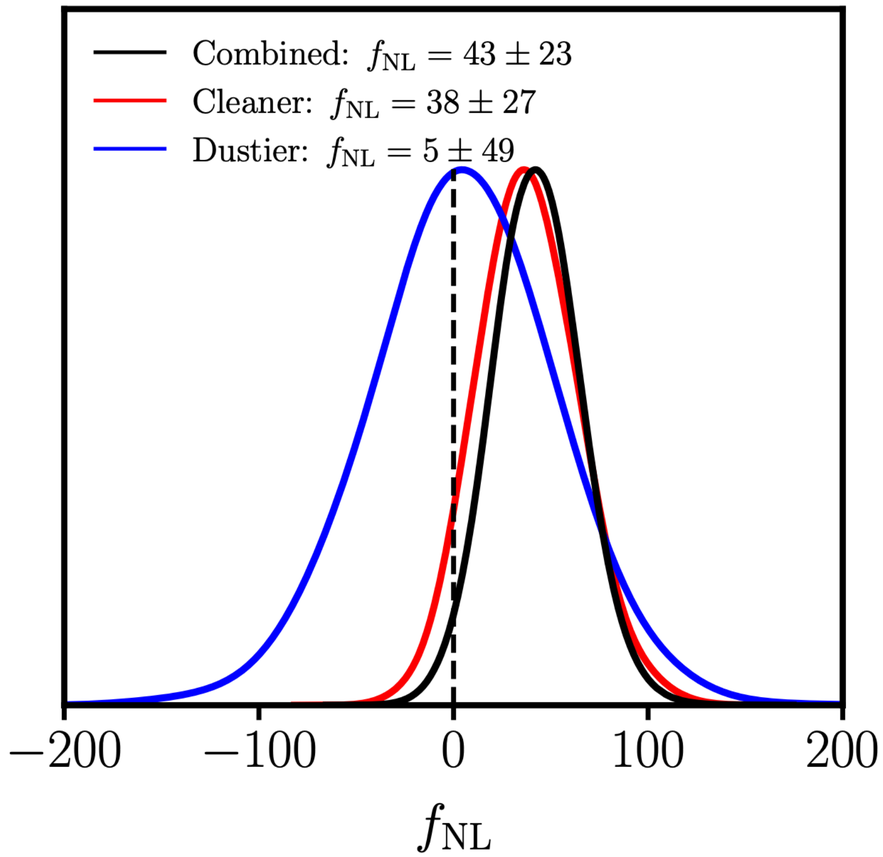
Results from new CIB maps

- CIB maps specifically built to use on large scales
- Access to larger areas
- Combined with Planck CMB lensing

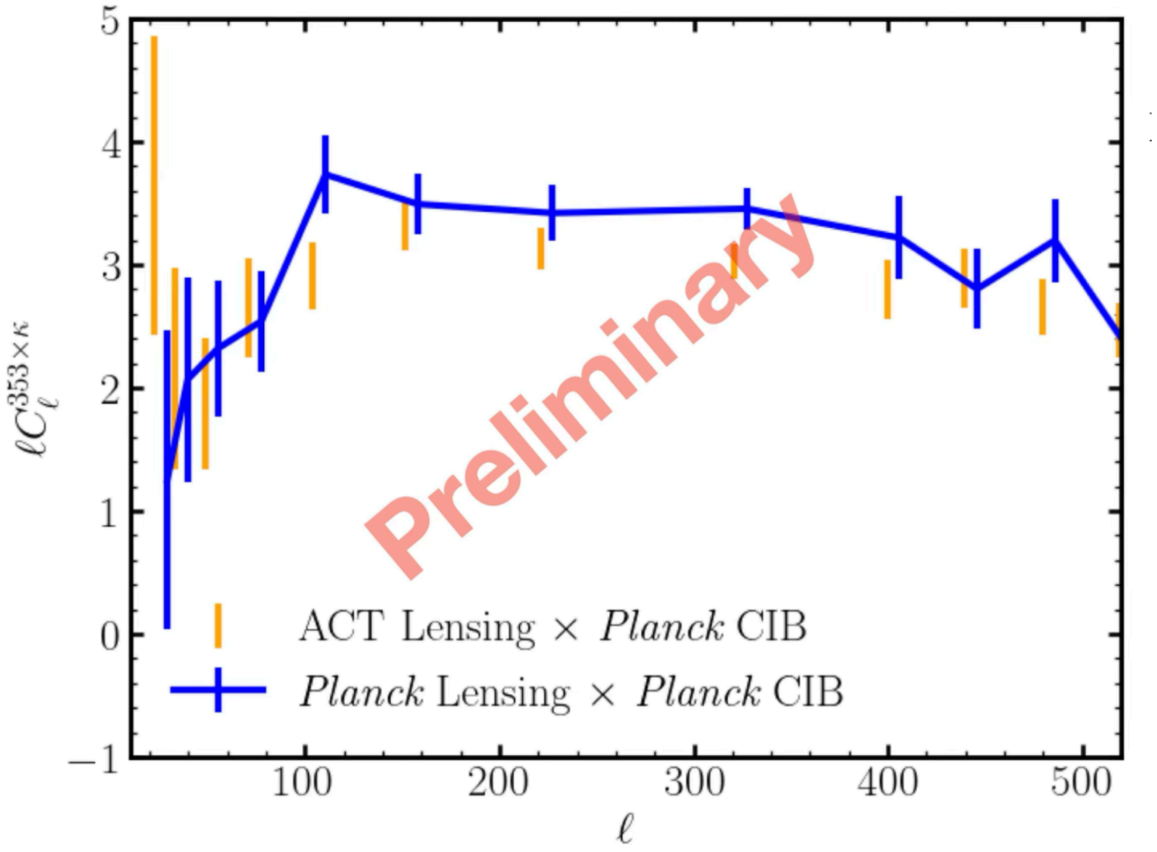


Competitive constraints on non-Gaussianity from cross-correlations alone

$$f_{NL} = 43 \pm 23$$



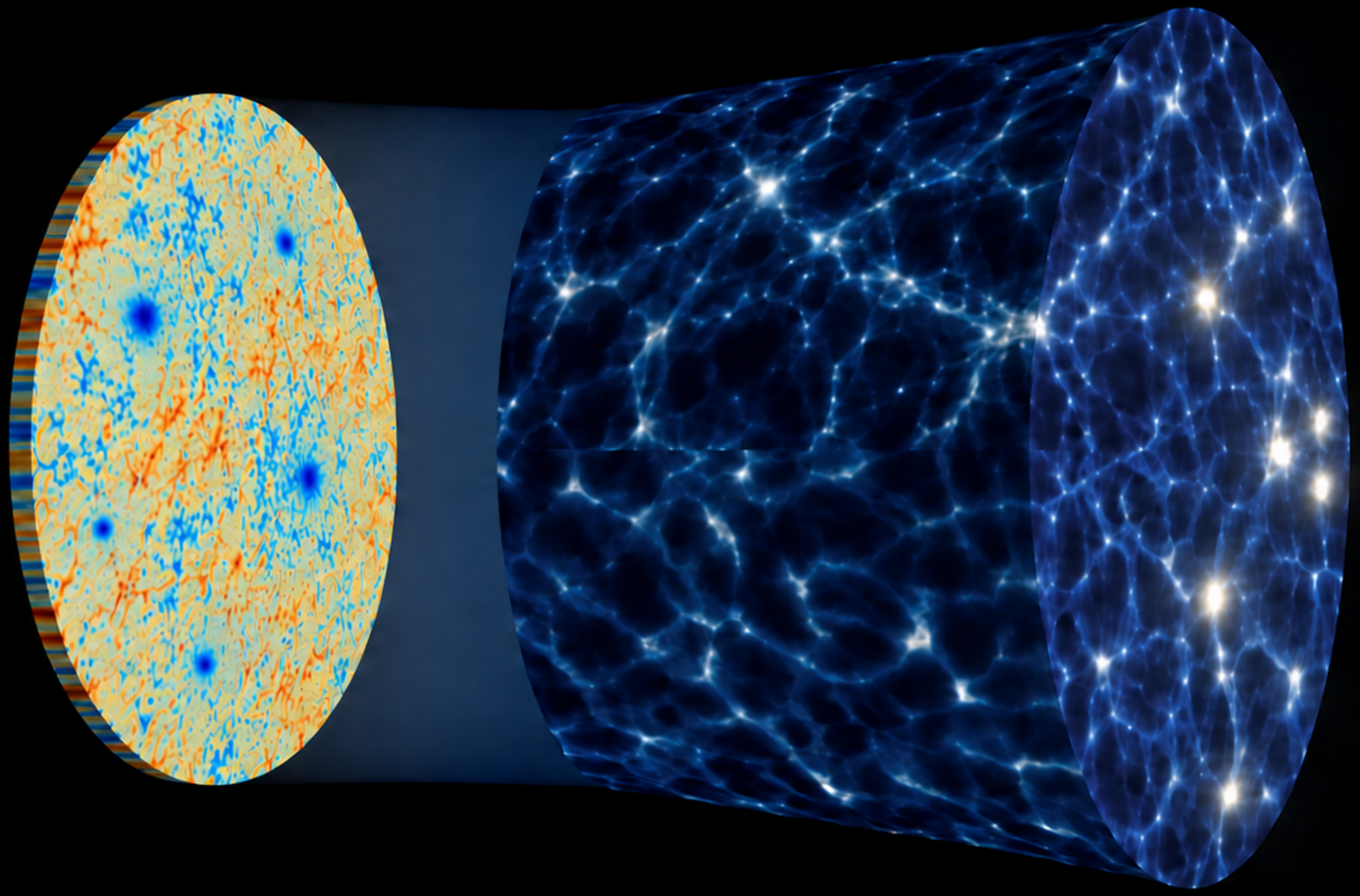
CIB × CMB lensing: what's next



- Ongoing: combining the new large-scale CIB maps with ACT lensing.

- Cross-correlations with LSS can reach O(1.5) constraints on f_{NL} with LSST.

Part III: Field-level inference on the tSZ field



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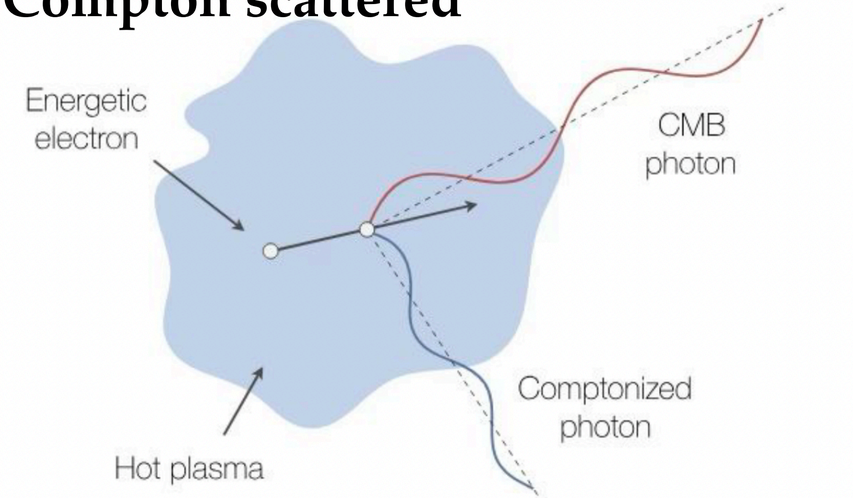
How much information is there in the tSZ field?

Perform field level inference and compare to a summary statistic

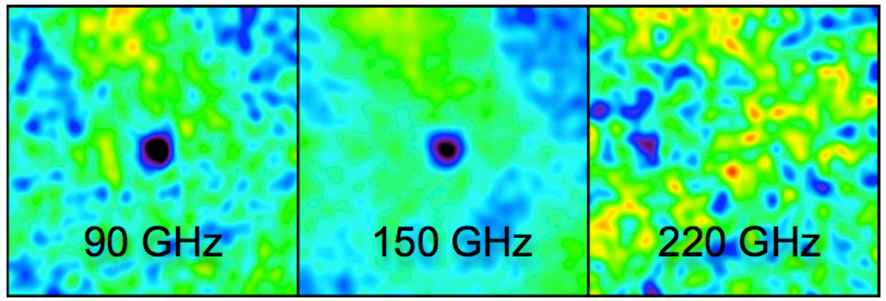
The thermal Sunyaev-Zel'dovich (tSZ) effect:

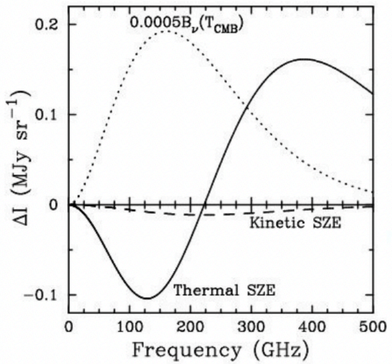
When CMB photons pass through hot, ionised gas they get **inverse Compton scattered**

Photons gain a small amount of energy -> shift from low to high frequencies. **Creating a distinct spectral signature**



What we use to separate this signal from primary CMB





Strength of tSZ effect depends on the electron pressure

Compton-y parameter: $$y = \int n_e \frac{k_B T_e}{m_e c^2} \sigma_T dl$$

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Some tSZ summary statistics

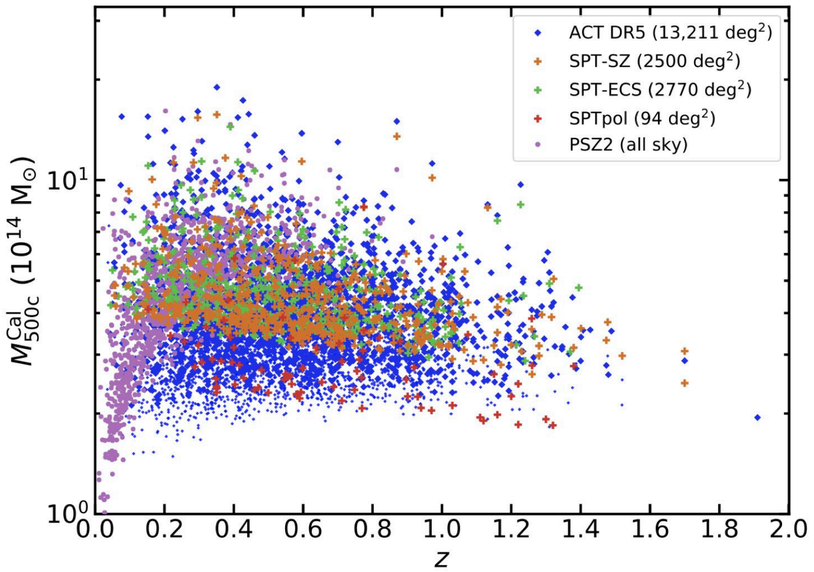
tSZ is a tracer for the most massive, hottest structures in the universe: galaxy clusters $M \gtrsim 10^{13} M_\odot$

Very non-Gaussian field. What is the best way of extracting information?

Mostly dominated by the 1 halo term

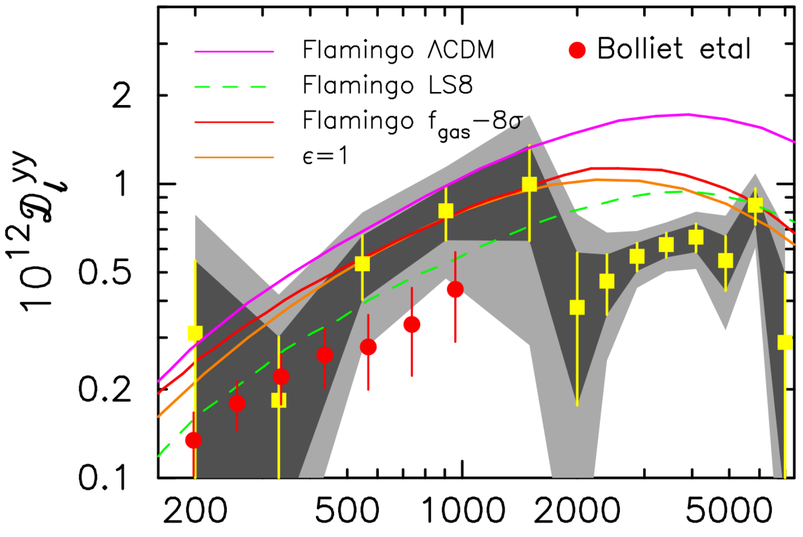
Most informative? Is there any more information?

Cluster number counts



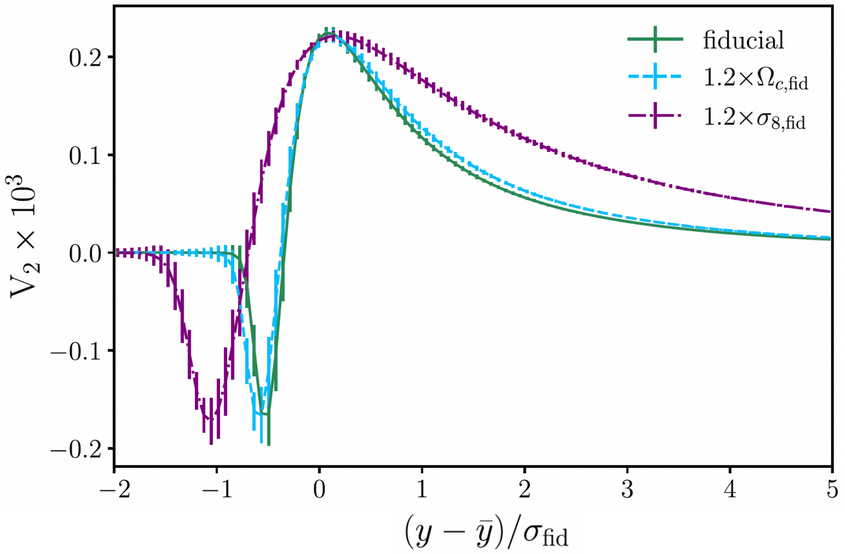
[Hilton et al. 2021]

Power Spectrum



[Efstathiou & McCarthy 2025]

Minkowski Functionals



[Sabyr et al. 2025]

Field-Level Inference

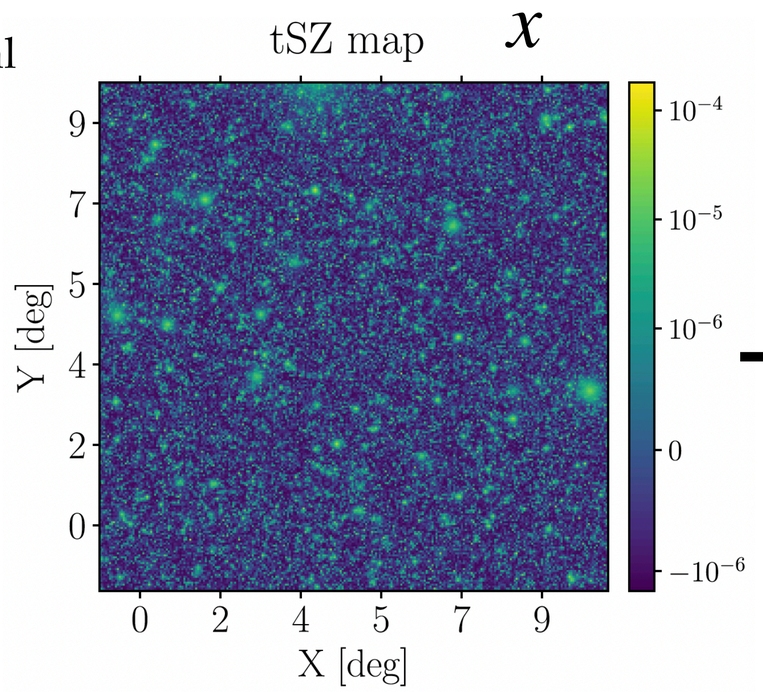
Work with Alina Sabyr, Adrian Bayer, Will Coulton, Paco Villaescusa Navarro, Blake Sherwin, and Anthony Challinor

Sample cosmological parameters

$\Omega_c \in \{0.21, 0.32\}$

$\sigma_8 \in \{0.6, 1.0\}$

[Simulator]



Learned summary of the map

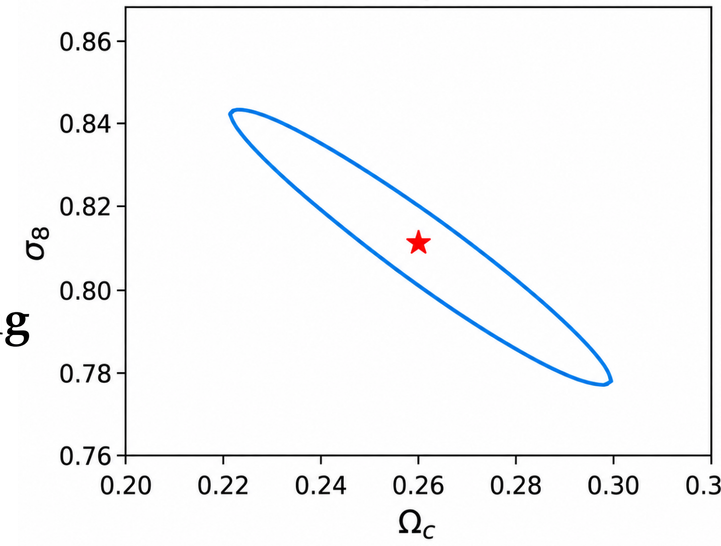
$s(x)$

[ResNet]

[Normalising flow]

(Trained jointly)

Loss: $-\log p(\theta \mid s(x))$



We learn a compression of the full field that is optimised to retain cosmological information

Results (On 10k simulations with realistic SO noise)

PRELIMINARY

- **V0:** one-point information (cdf)
- **V1 and V2:** boundary length and curvature of the field encode most of the non-Gaussian information
- **Combined Minkowsky Functionals ≈ field-level constraints**
- NEXT: which summary remains informative and robust to astrophysics?

CMB secondaries: the time is now!

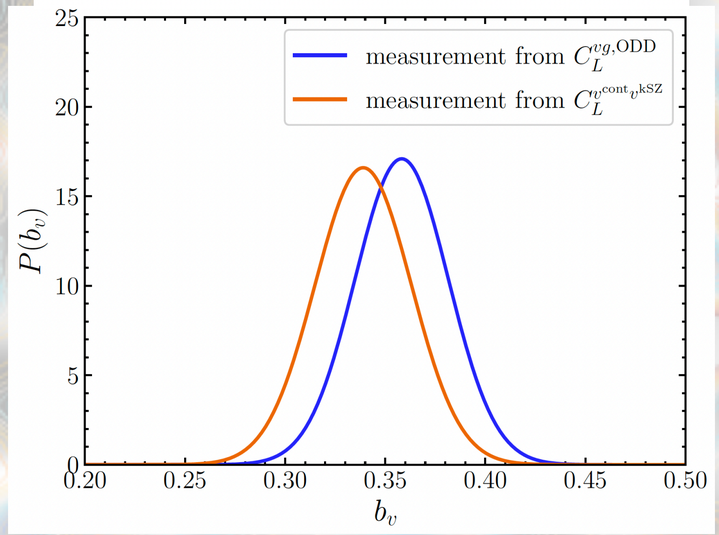
Summary:

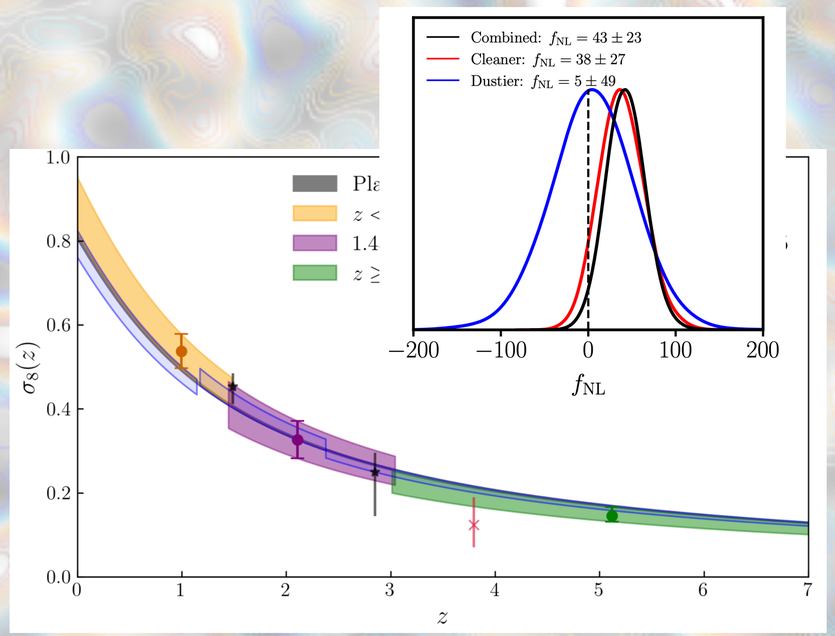
kSZ $\hat{v}_r$ reconstruction

CMB lensing × LSS

ML applied to tSZ

$$C_L^{\hat{v}g,\mathrm{ODD}^{\alpha,\beta}} \equiv C_L^{\hat{v}^\alpha g^\beta} - C_L^{\hat{v}^\beta g^\alpha}$$





PRELIMINARY