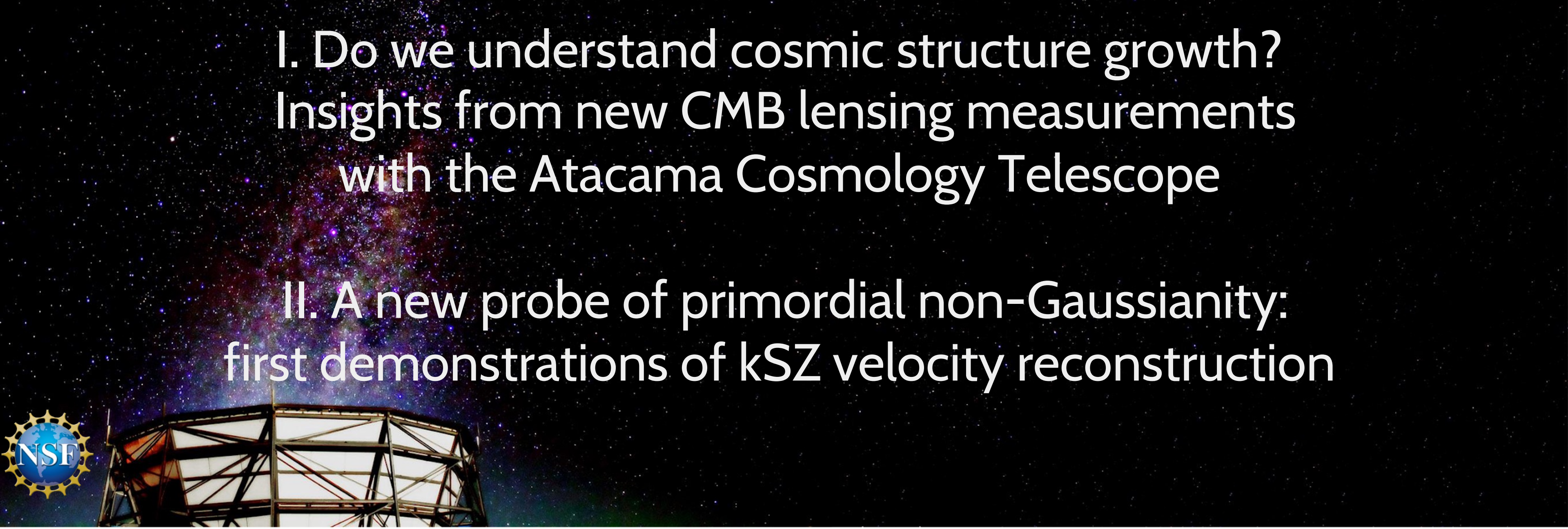
Insights into structure growth and the early universe from CMB lensing and kSZ

Blake Sherwin
DAMTP & Kavli Institute for Cosmology, University of Cambridge
ACT Collaboration

European Research Council
Established by the European Commission



I. Do we understand cosmic structure growth? Insights from new CMB lensing measurements with the Atacama Cosmology Telescope

II. A new probe of primordial non-Gaussianity: first demonstrations of kSZ velocity reconstruction

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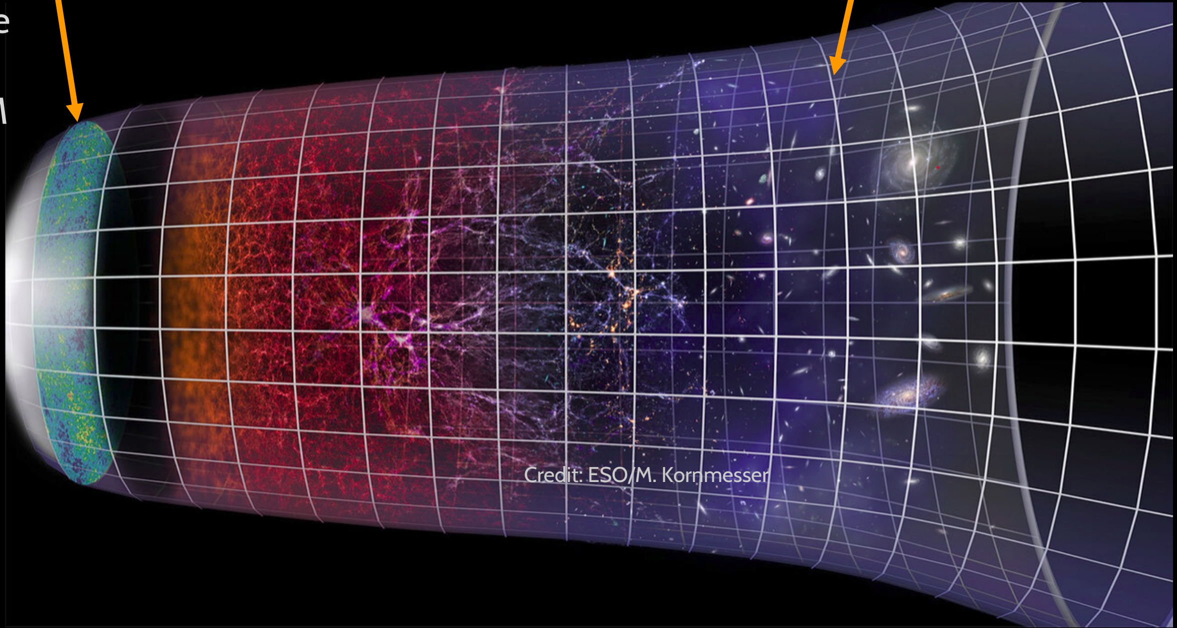
Does large-scale structure grow as standard cosmology predicts?

"Predicted, indirect σ_8 "

1. Fit LCDM model (standard cosmological model) to CMB at z~1100
2. Predict structure growth to z~0, assuming LCDM

"Direct σ_8"

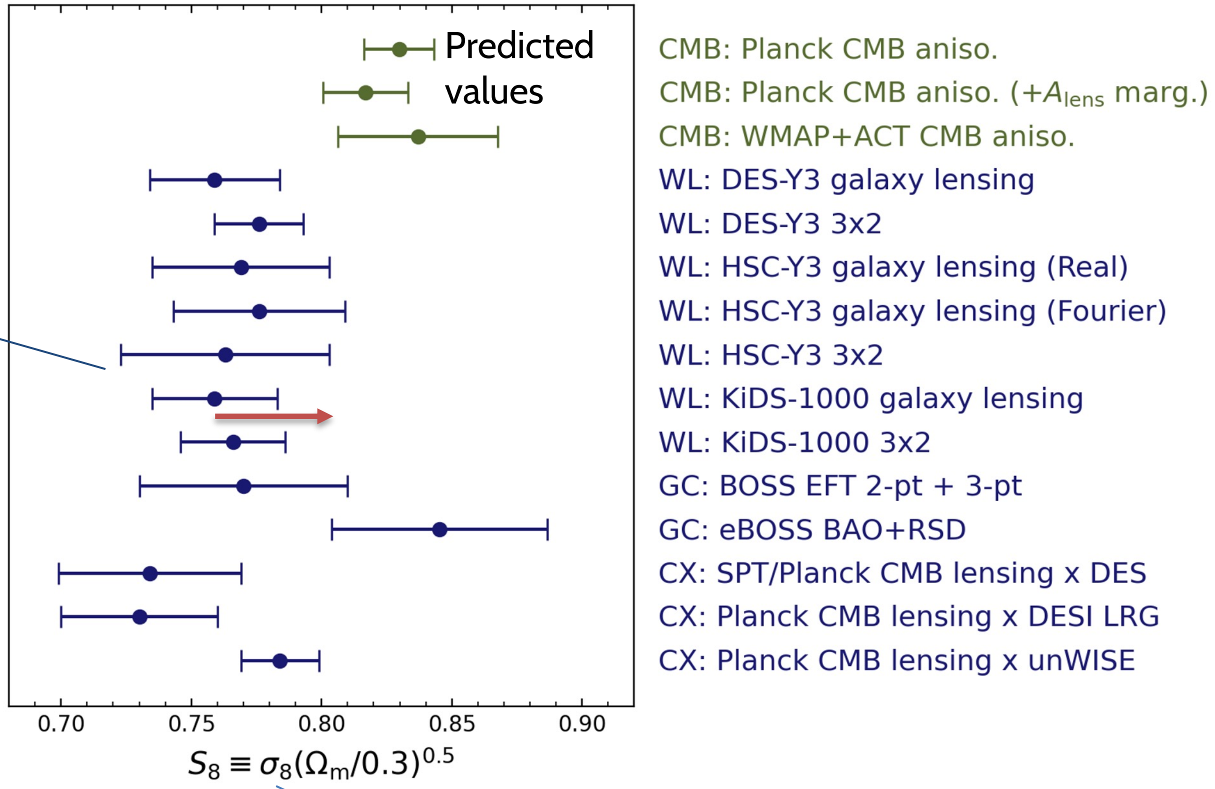
1. Measure matter "clumpyness" σ_8 [=RMS fluctuation on 8Mpc/h scales] directly at low-z with lensing++
2. Can compare with prediction



Credit: ESO/M. Kornmesser

Is something wrong with large-scale structure growth?
σ_8 or S_8 tension

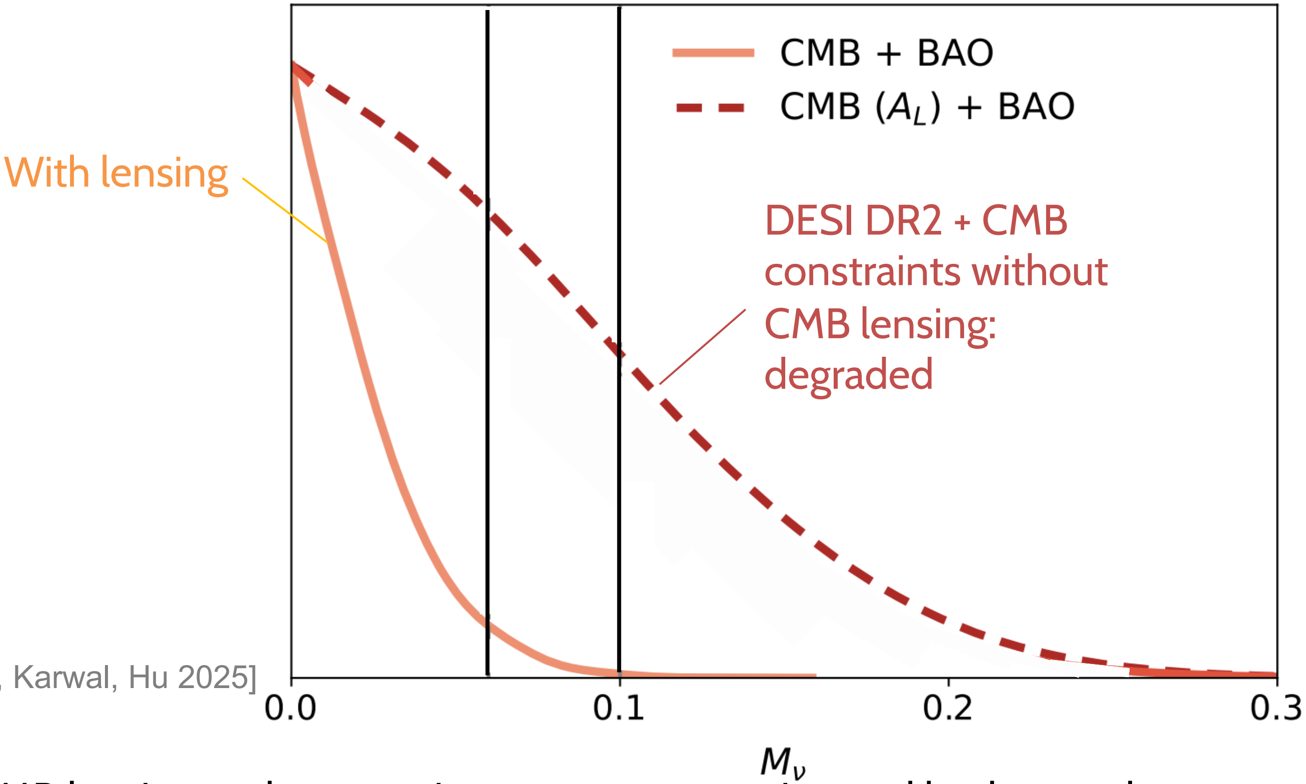
Direct low-z
measurements from galaxy surveys: 2-3 sigma low in several channels



matter clumpyness σ_8
[=RMS mass fluctuation on 8Mpc/h scales]

Fluctuations, systematics, new physics?
New insights from CMB lensing power spectrum, which probes $S_8^{\mathrm{CMBL}} \equiv \sigma_8 \left(\frac{\Omega_m}{0.3}\right)^{0.25}$

Lensing is important for measuring neutrino mass (recently particularly interesting and perhaps relevant to DESI)

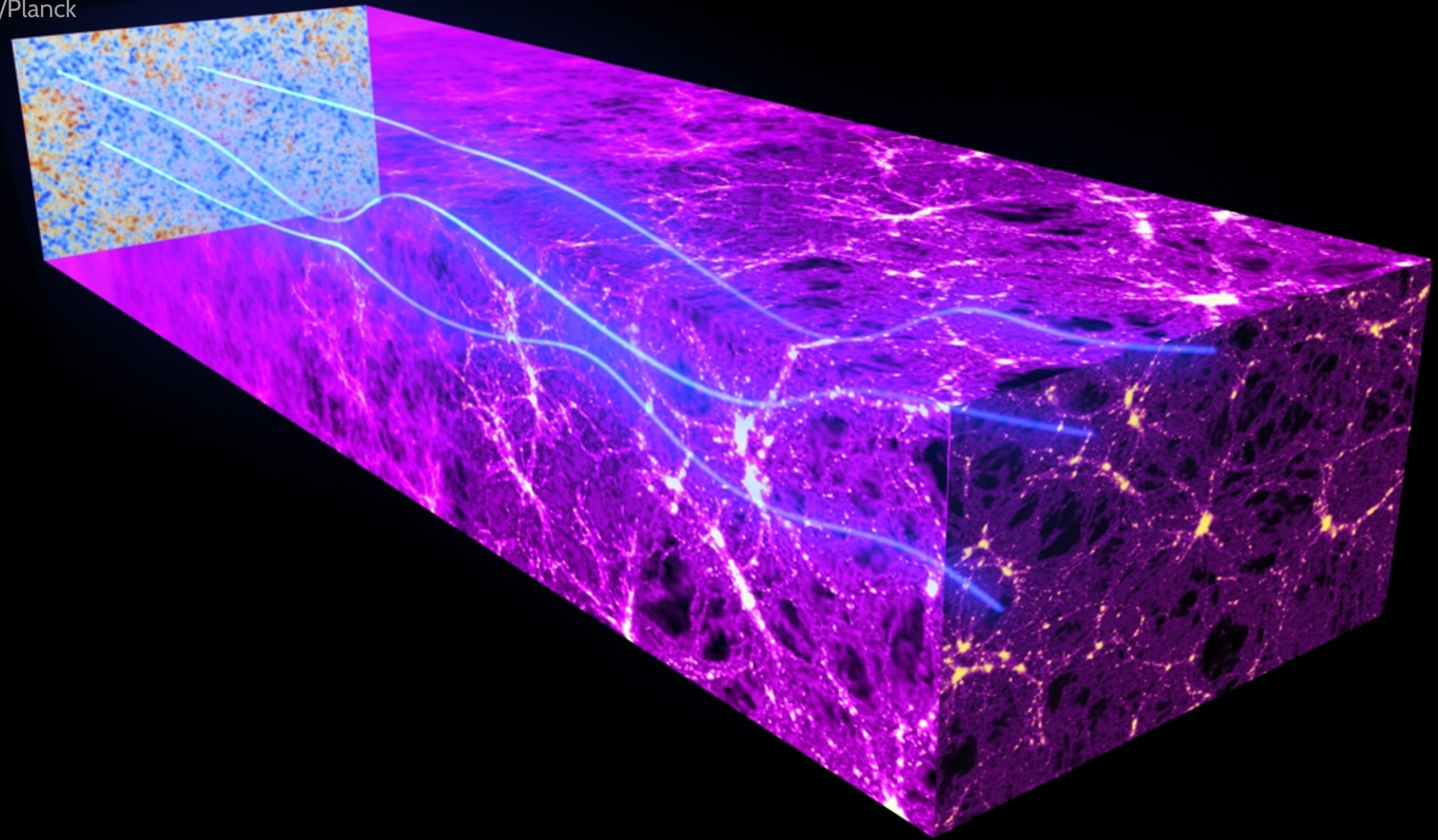


[Jhaveri, Karwal, Hu 2025]

- CMB lensing probes neutrino power suppression and background matter

CMB Gravitational Lensing

Image: ESA/Planck



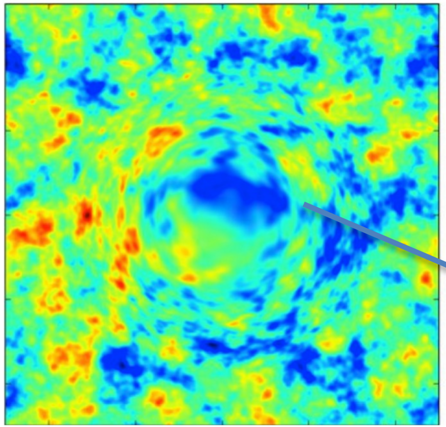
Distribution of mass deflects CMB light that passes through by angle $\nabla \phi$

CMB Lensing Measurement

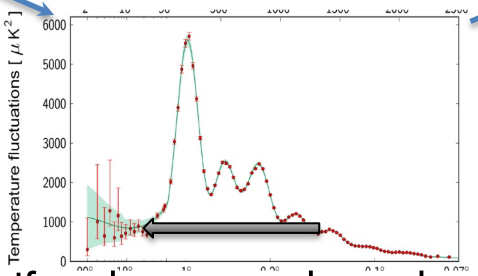
- Algorithm (quadratic estimator): [+similar in polarization]

$$\hat{\phi}(\mathbf{L}) \sim \int \mathrm{d}^2\mathbf{l}\; T(\mathbf{l}) T^*(\mathbf{l} - \mathbf{L})$$

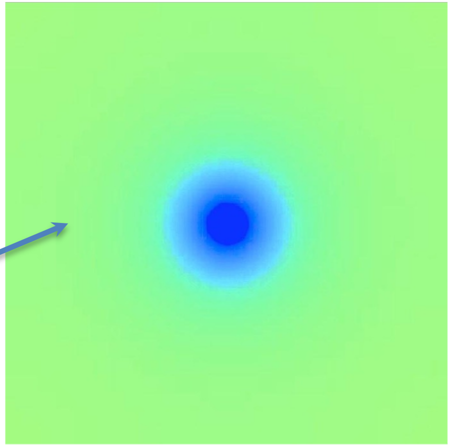
- Approximate explanation:



CMB Temp. + Pol.



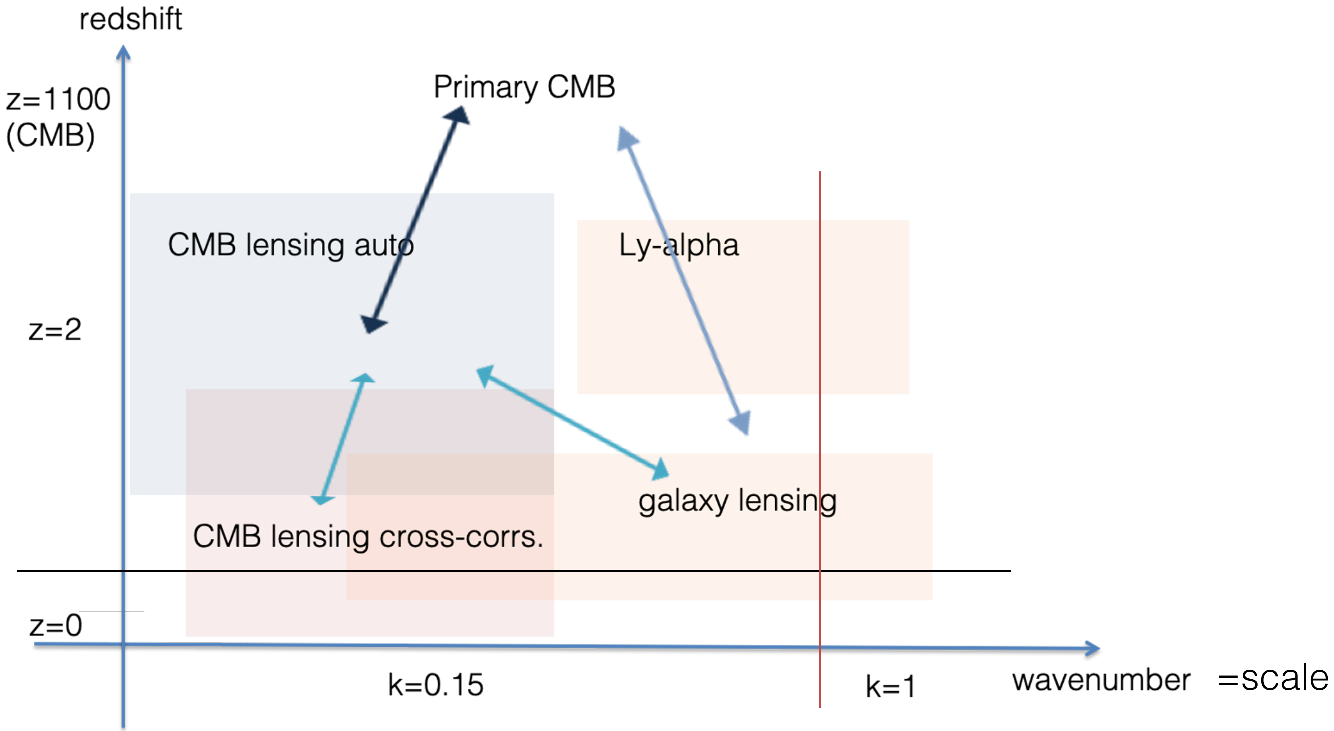
shift to larger angular scales



Lensing; inferred from stretching/shearing of the local CMB two-point function

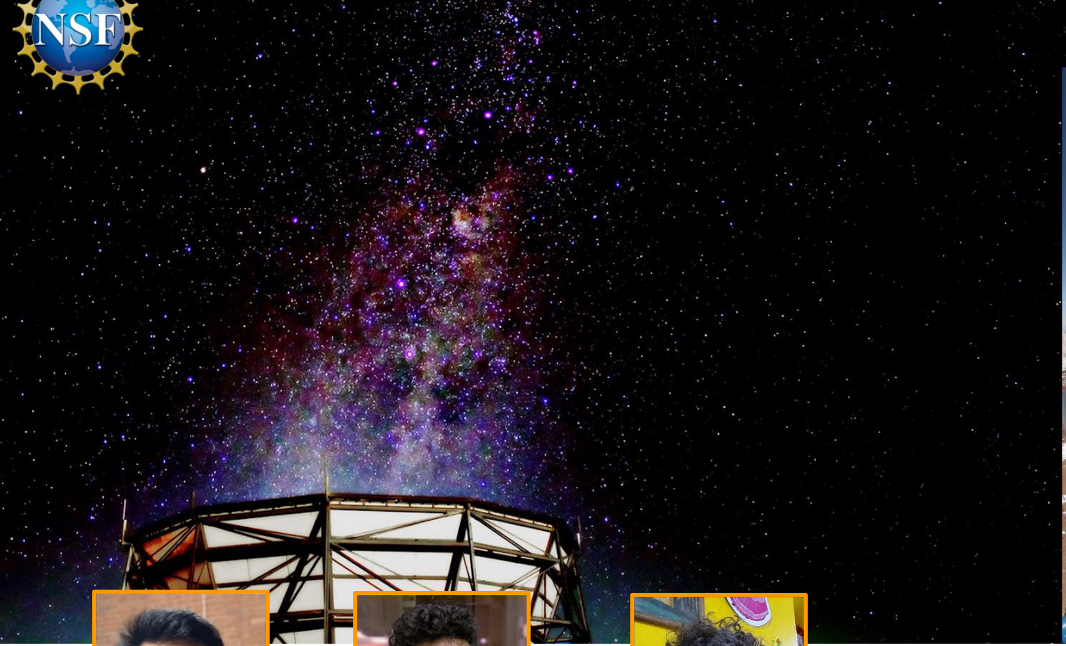
How can CMB lensing look for new physics / clarify tensions?

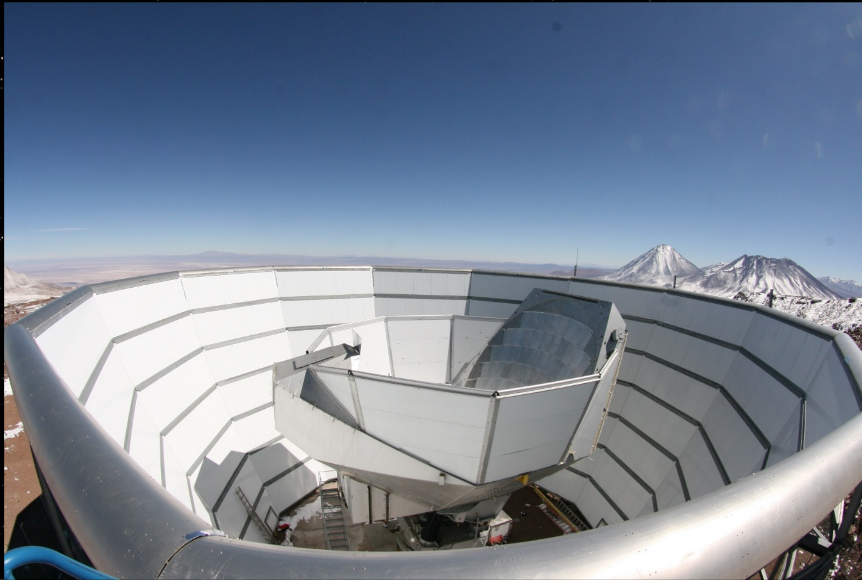
- CMB lensing power spectrum $C_L^{\phi\phi}$ probes matter power spectrum + hence $S_8^{\rm CMBL} \equiv \sigma_8 \left(\frac{\Omega_m}{0.3}\right)^{0.25}$
- Can test z/scale dependence of any new physics



(Some) new dark energy physics (low-z)

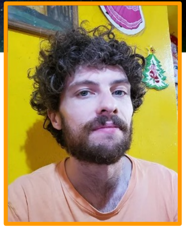
New dark matter physics (small scales)





Frank Qu
(Cambridge
→Stanford)

Mat Madhavacheril
(U. Penn)



Niall MacCrann
(Cambridge)

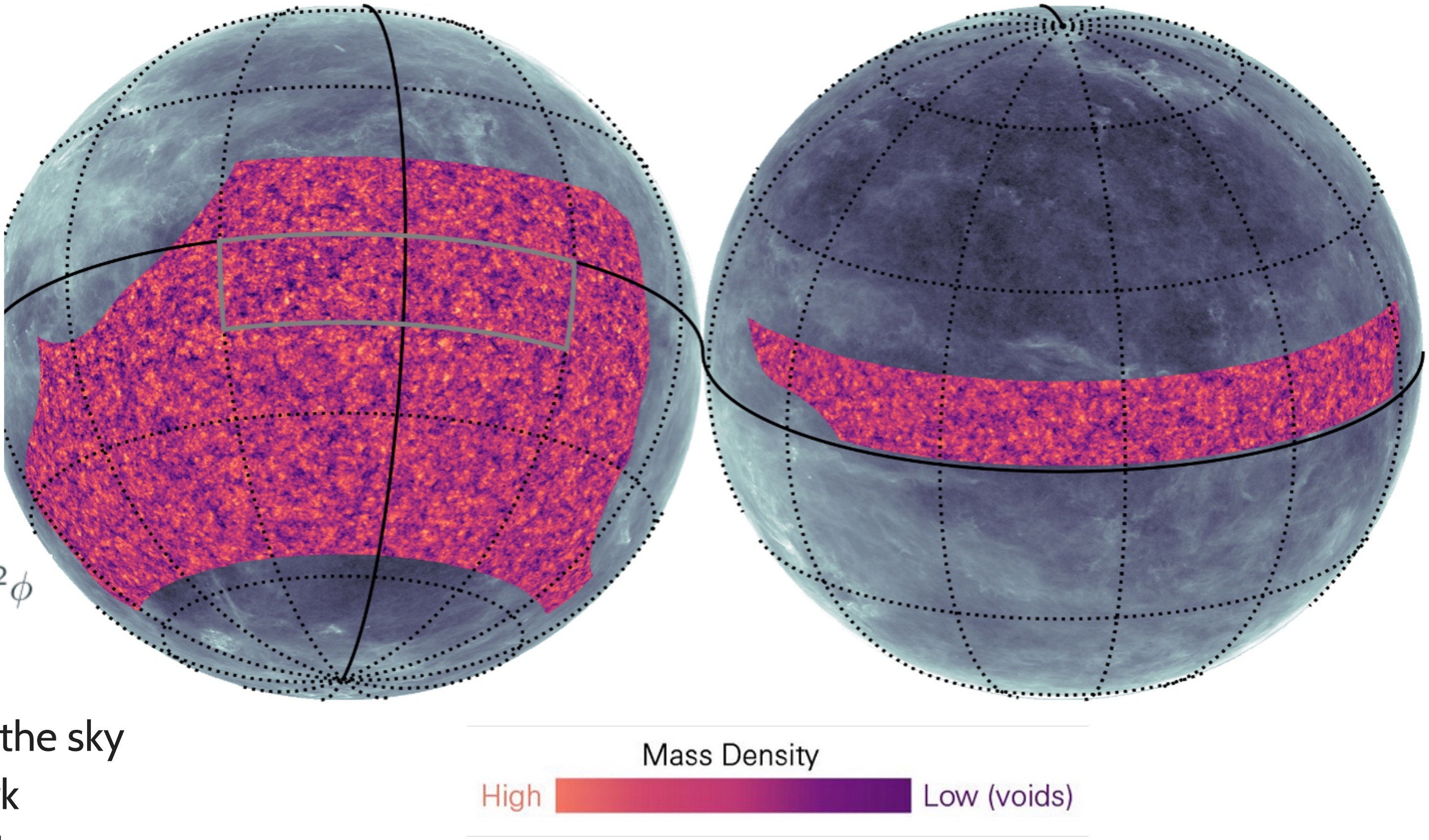
+Dongwon Han
(Cambridge)

The Atacama Cosmology Telescope (ACT)
2007 - 2022

Recent DR6 ACT lensing maps, spectra, implications for growth

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

ACT DR6 CMB lensing mass map



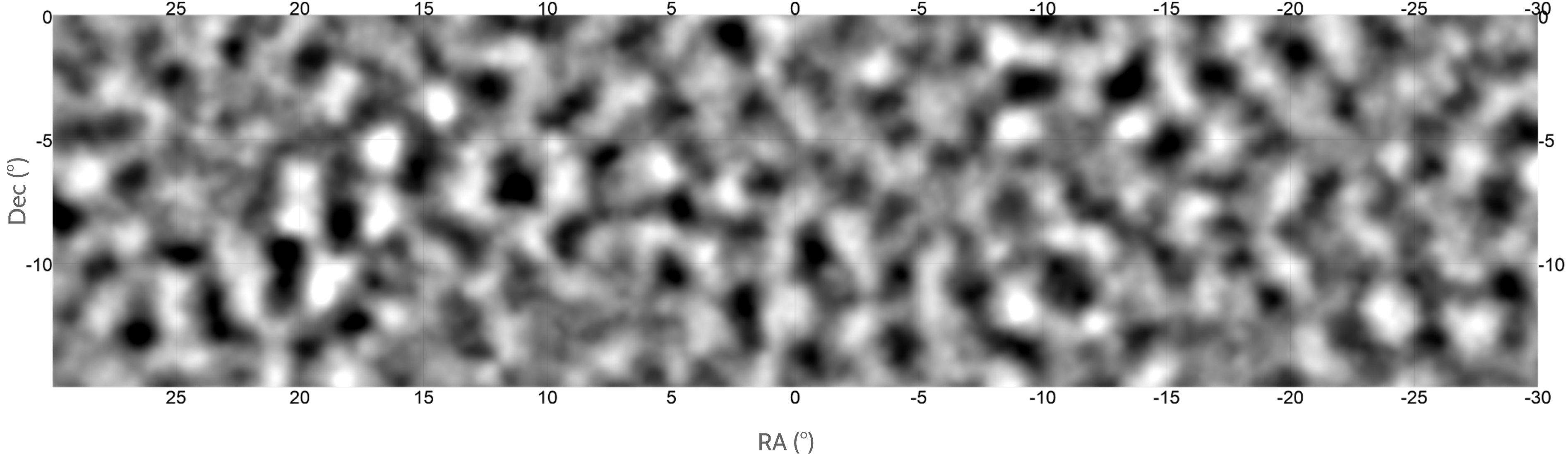
[Madhavacheril, Qu, Sherwin, et al. 2023, Qu, Sherwin et al. 2023; MacCrann, Sherwin et al. 2023]

Gravitational Lensing
Convergence $\kappa = -\frac{1}{2}\nabla^2\phi$
$\boldsymbol{\kappa} \propto$ mass density

- Covers a quarter of the sky
- You can see the dark matter distribution by eye
- 2x SNR/mode c.f. Planck

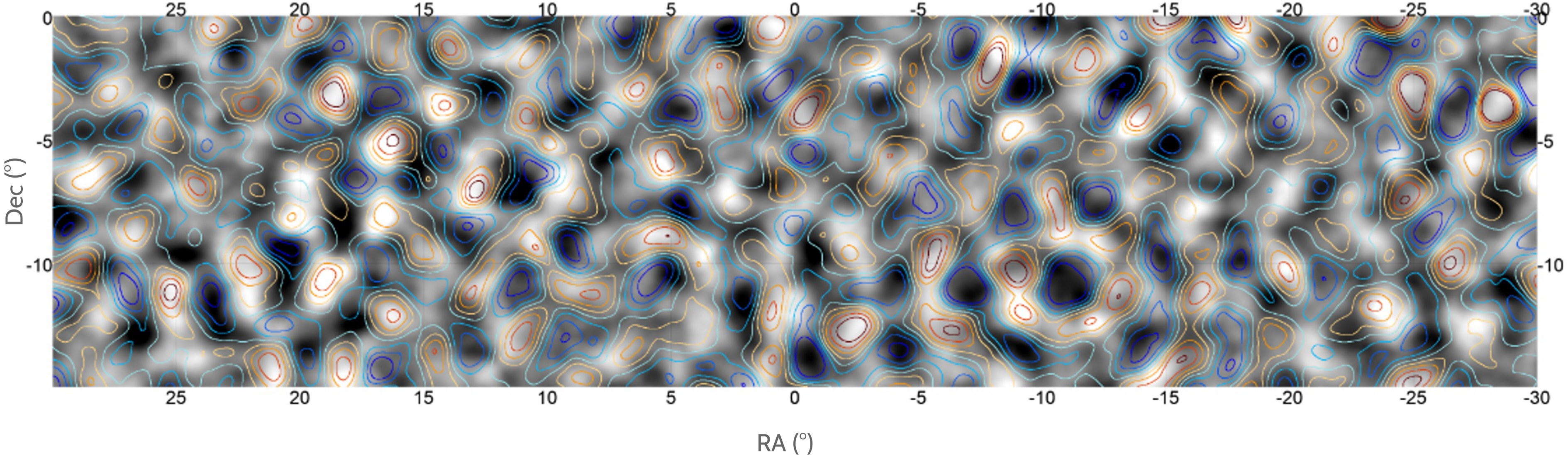
Zoom-in of 900 sq. deg. of 9400. sq. deg. mass map

Lensing map of mass (lensing potential)



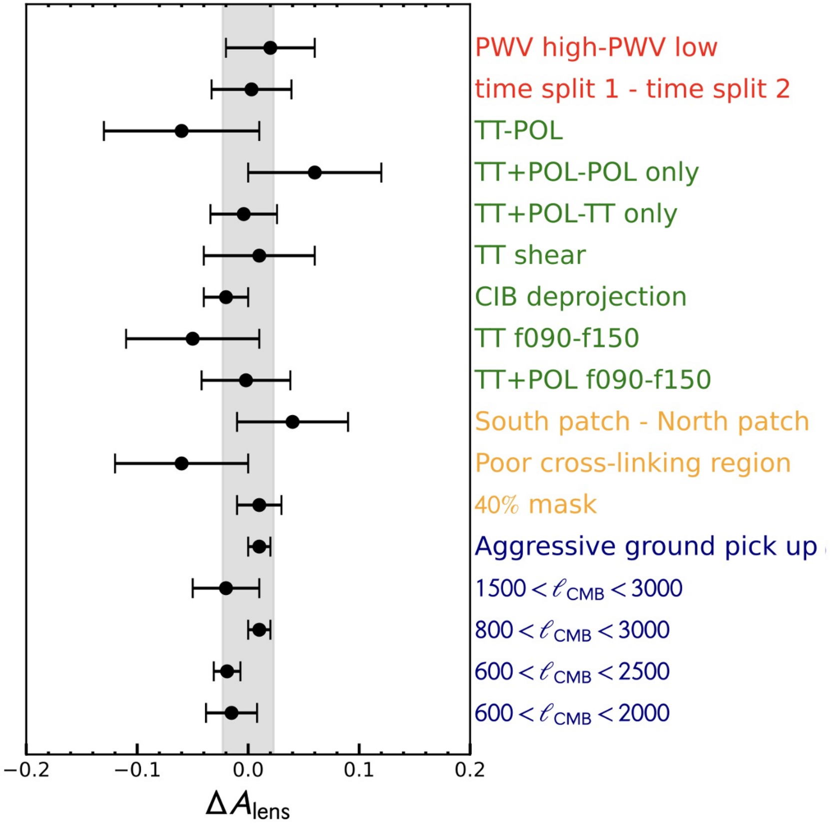
Zoom-in of 900 sq. deg. of 9400. sq. deg. mass map: Correlation with dusty galaxies seen by eye

Lensing map (potential) + Cosmic Infrared Background (contours)



Null test suite testing stability of lensing spectrum:

Consistent amplitude of lensing spectrum A_{lens} ....



Difference in Amplitude of lensing

at different times

in polarization

w. different foreground cleaning

at different frequencies

in different parts of sky

on different scales

+... many more tests!

Lensing spectrum challenge 1: Noise bias subtraction

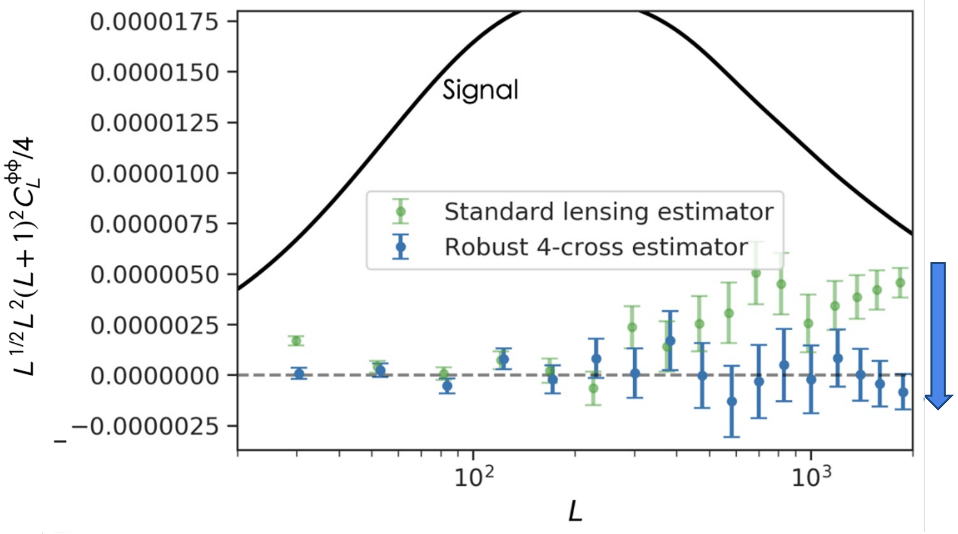
- Challenge: noise complexity causes bias subtraction problem

- Solution: Use 4 CMB maps with independent noise. Noise bias zeroed so immune!

Madhavacheril, Smith, Sherwin, Naess et al 2020, JCAP

$$C_L^{\phi\phi,\mathrm{cross}} \sim \langle T_1 T_2 T_3 T_4 \rangle$$

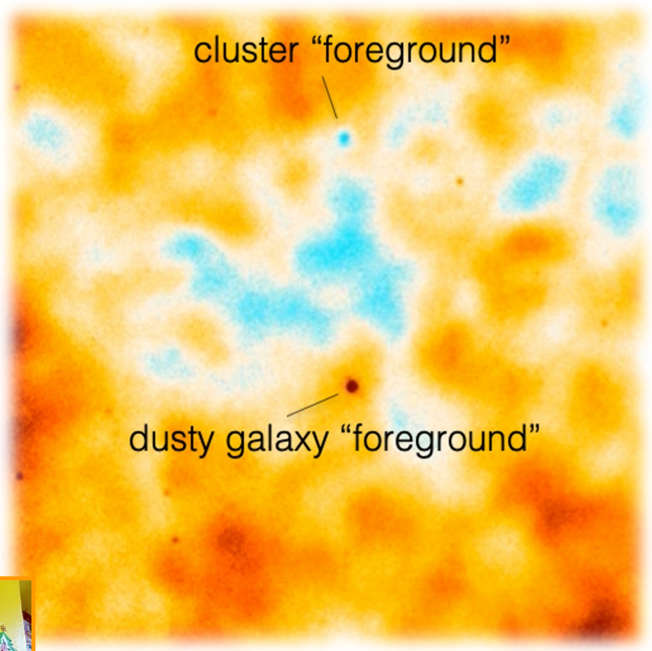
maps with independent noise

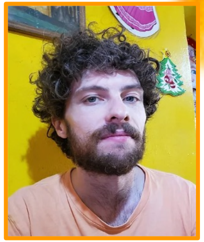


now pass the null test with robust, new cross estimator

Lensing spectrum challenge 2: Extragalactic foregrounds

CMB map cutout (3°x3°)





Niall MacCrann (Cambridge)

How to mitigate SZ, CIB... foreground biases?

- Note: typically, foregrounds would lower lensing power

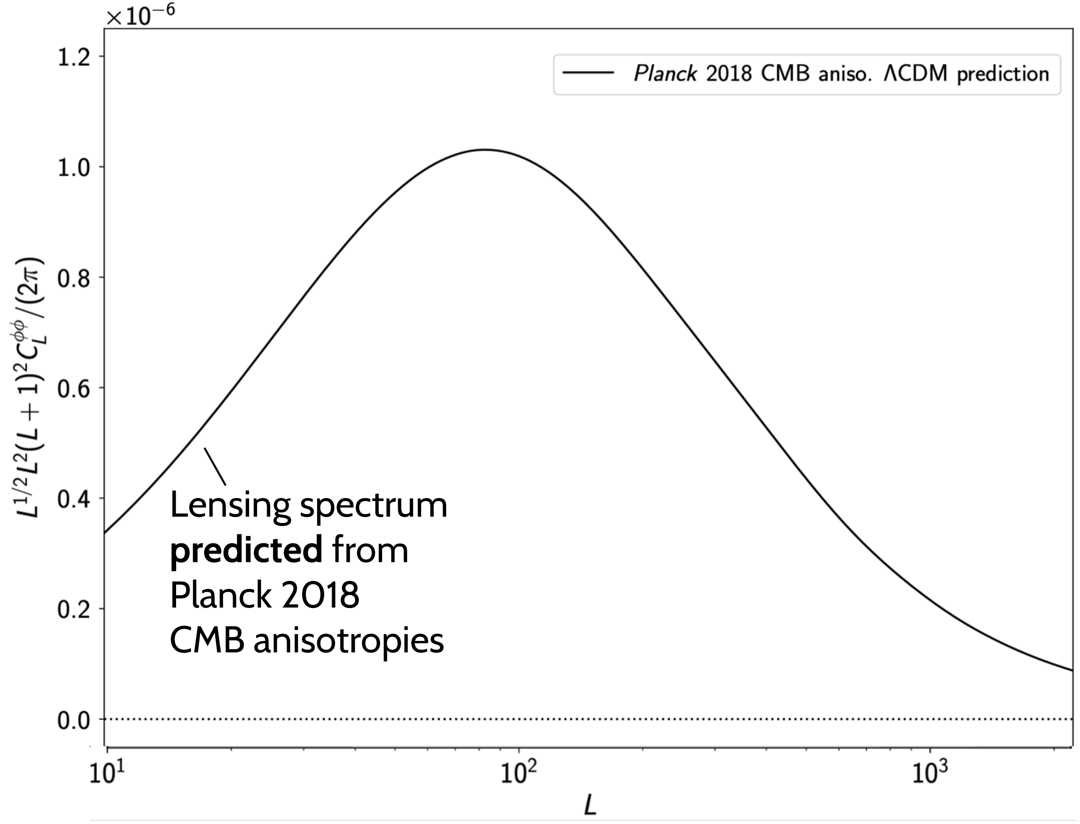
Sailer++2020

- **Geometric** – modify estimator to be insensitive to Poisson distributed sources
  OR

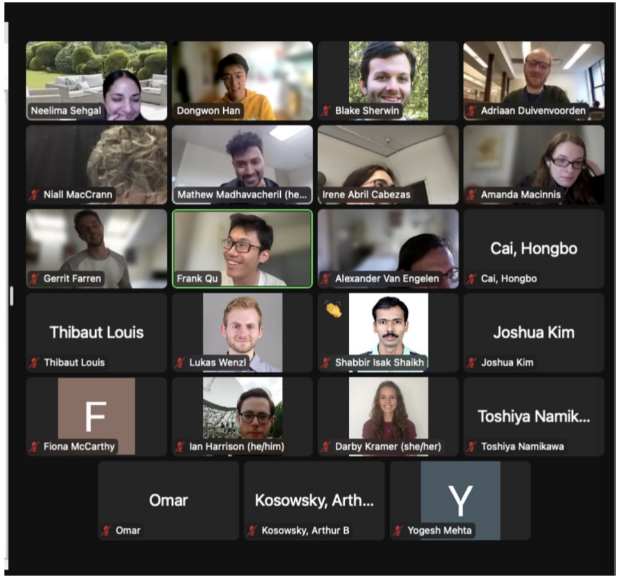
- **Frequency-based** – use data at different frequencies to remove foregrounds (e.g. “ILC”)

Both give negligible foreground bias in sims and data tests; both consistent

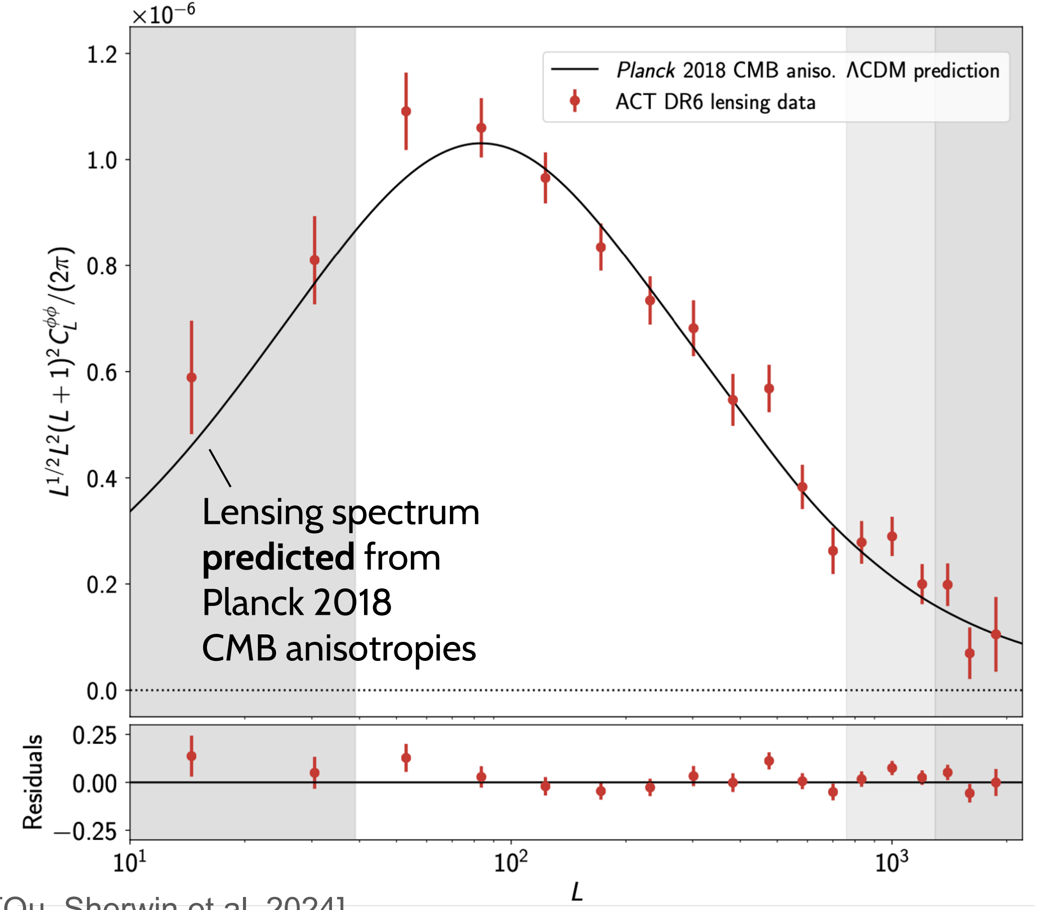
Planck CMB anisotropy prediction



- Unblinded after passing 200+ null tests



Unblinded results: ACT DR6 lensing power spectrum

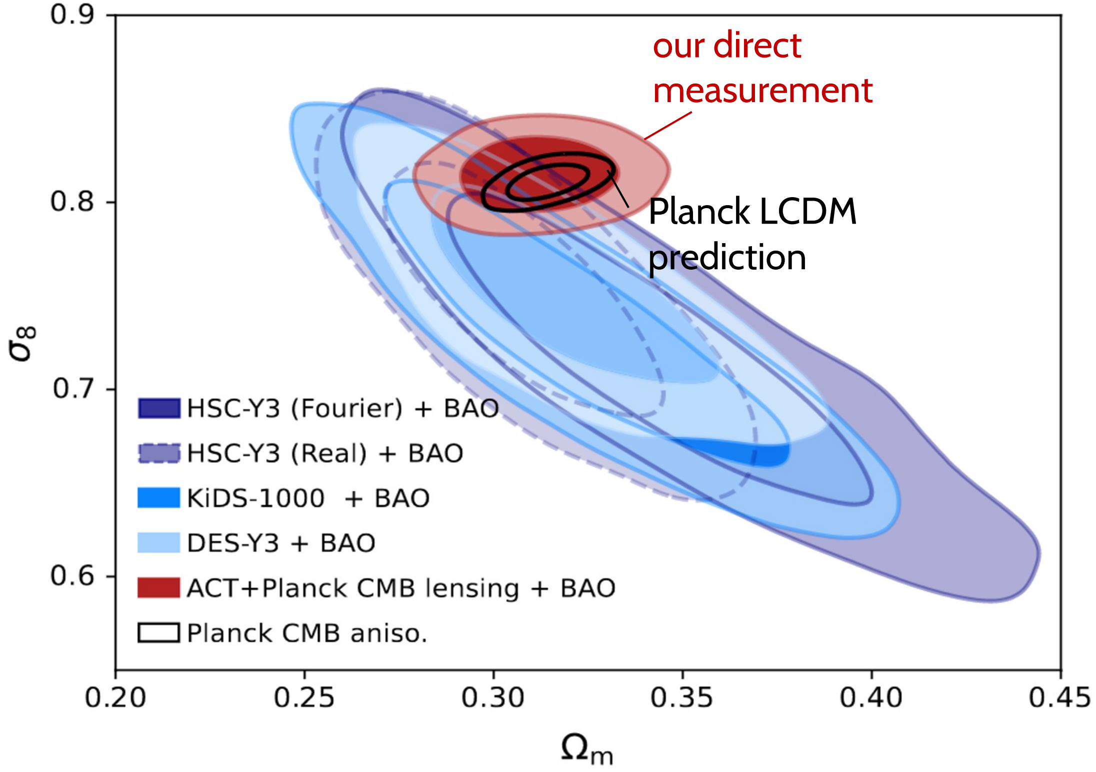


[Qu, Sherwin et al. 2024]

- Unblinded after passing 200+ null tests
- Agrees with the LCDM theory predictions based on *Planck* 2018 CMB power spectra (PTE of 0.17). Success for LCDM!!
- SNR ~43, amplitude of lensing (relative to theory amplitude) determined to 2.3%

$$A_{\mathrm{lens}} = 1.013 \pm 0.023$$

Comparison with cosmic shear: shear lower but consistent (1.7-2.1σ)

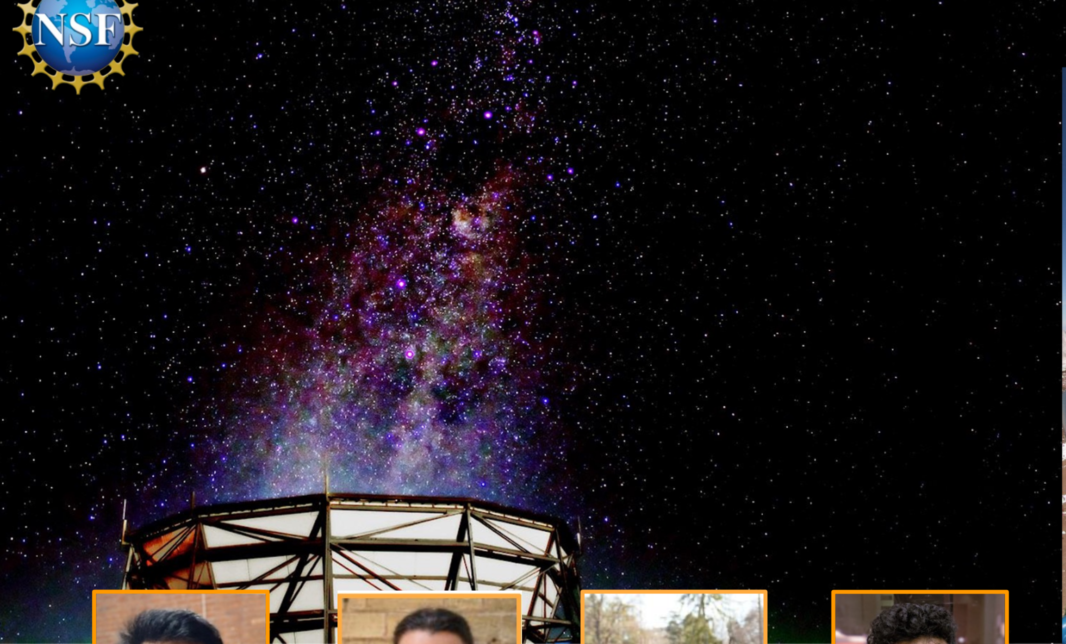


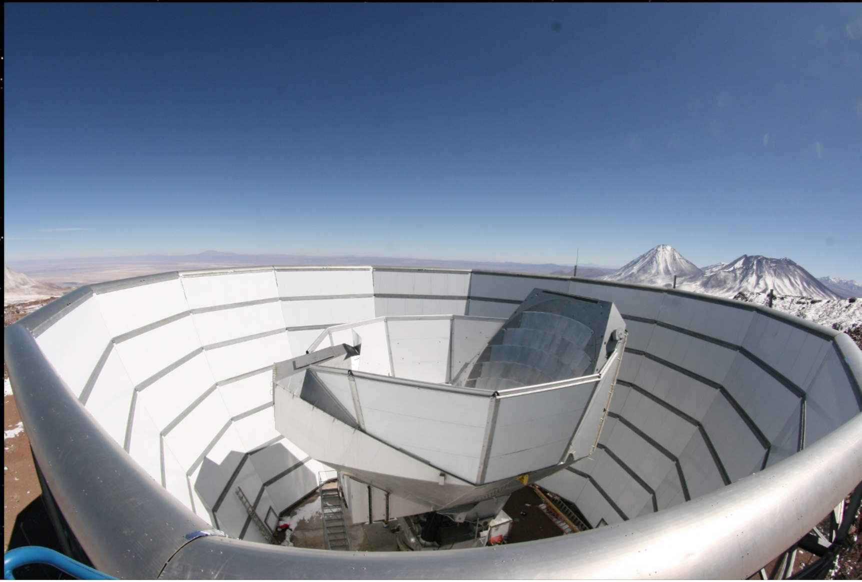
ACT/Planck lensing + BAO:

$$\boxed{\sigma_8 = 0.812 \pm 0.013}$$

1.6% measurement for ACT+Planck lensing combination

- Disfavors new physics that affects structure growth at high z>1 and large scales k<0.2





ACT
2007 - 2022

Frank Qu
(Cambridge
→Stanford)

Irene Abril-Cabezas
(Cambridge)

Joshua Kim
(U. Penn)

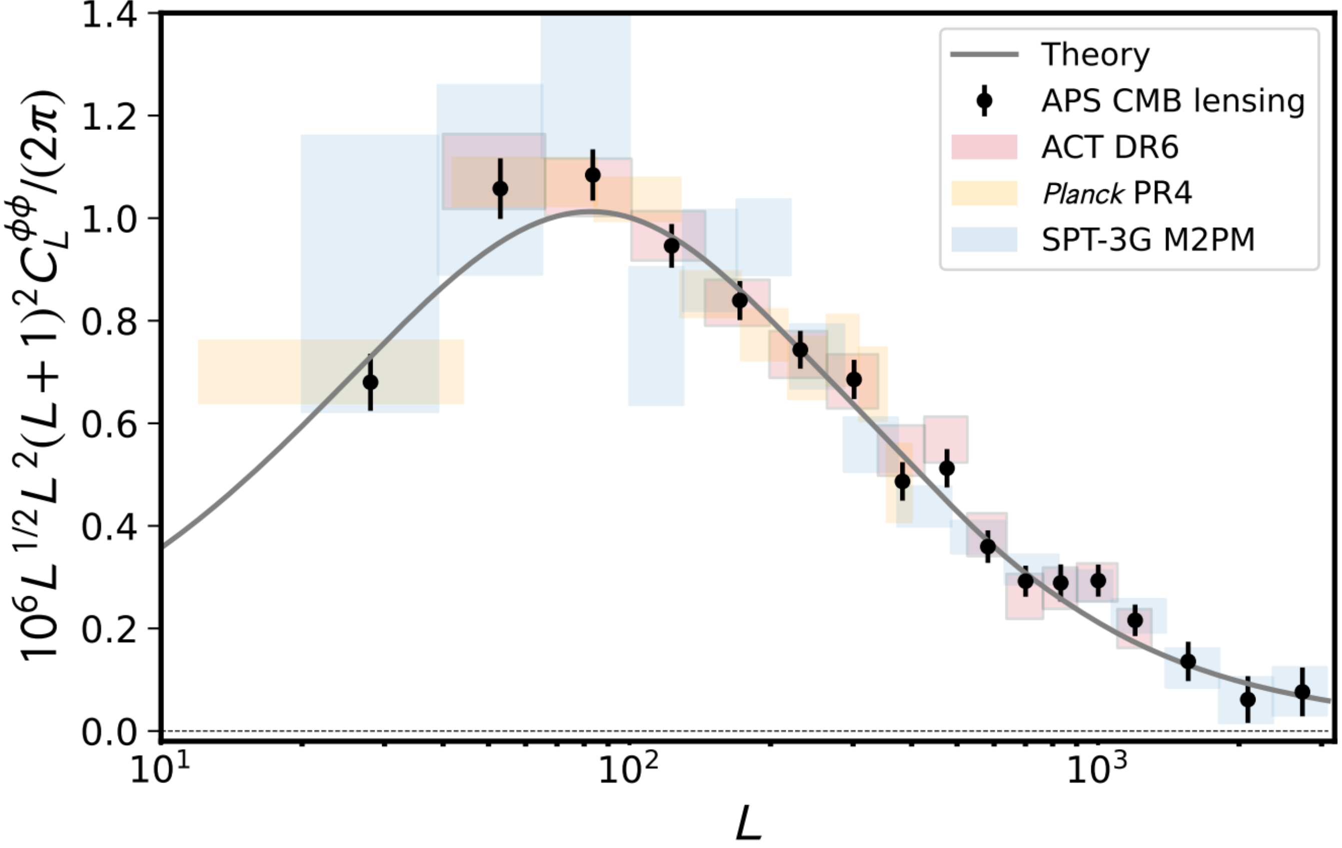
Mat Madhavacheril
(U. Penn)

+Niall MacCrann, Karen Perez-Sarmiento, Toshiya Namikawa,...

New and upcoming results: ACT+SPT / daytime / DR6+ / SO

[Qu et al. 2025, Abril-Cabezas et al. in prep a/b, Kim et al. in prep, Qu et al. in prep]

ACT+Planck+SPT lensing: combined spectrum (SNR~61)

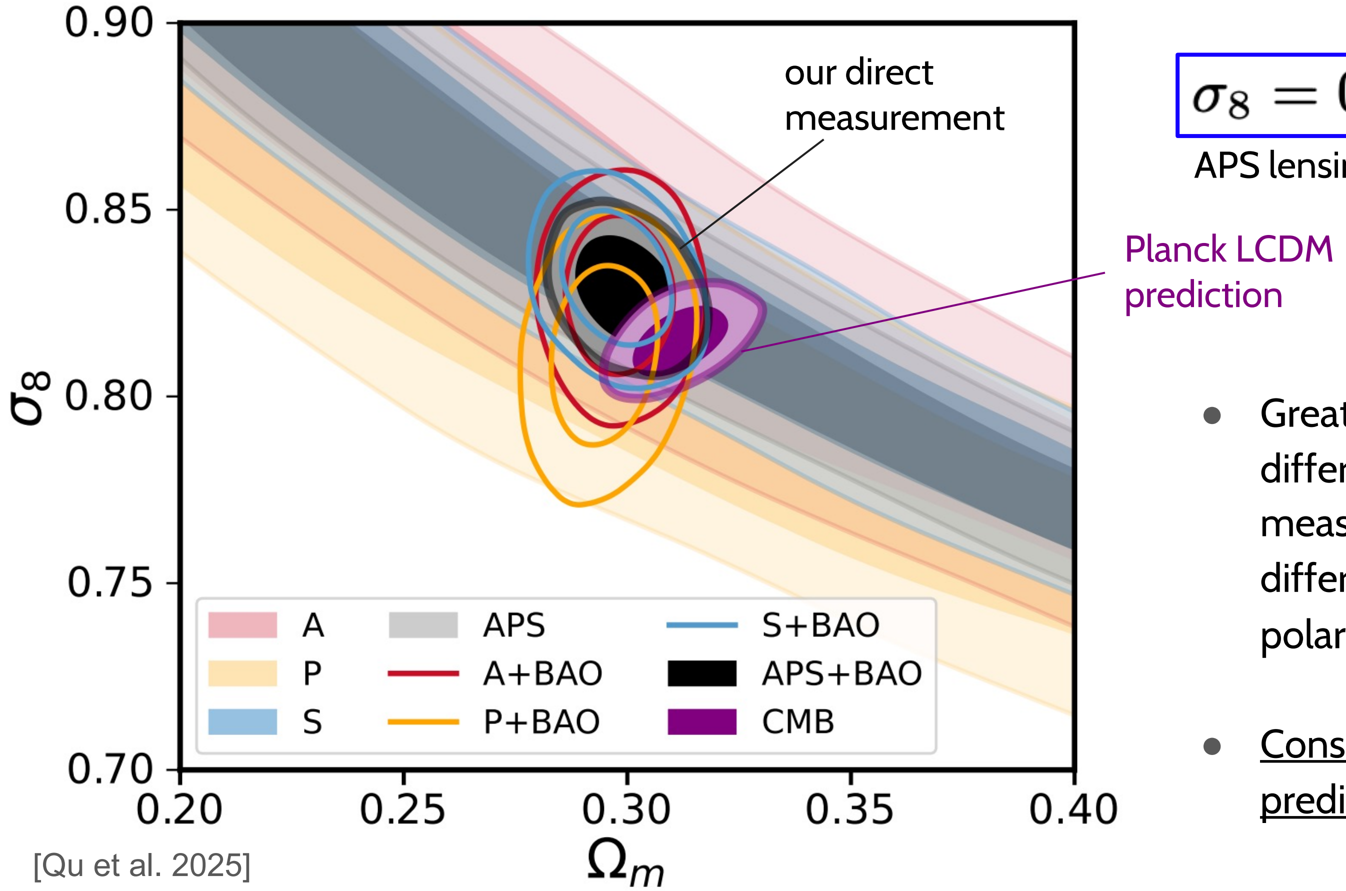


Frank Qu (Cambridge →Stanford)

Fei Ge (Stanford)

[Qu, Ge, Wu, et al. 2025]

ACT+Planck+SPT lensing: constraints on structure growth



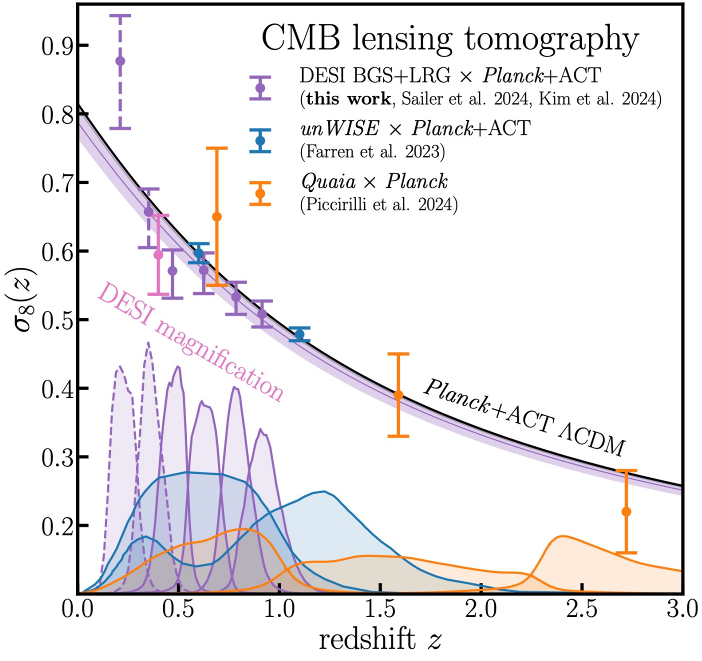
[Qu et al. 2025]

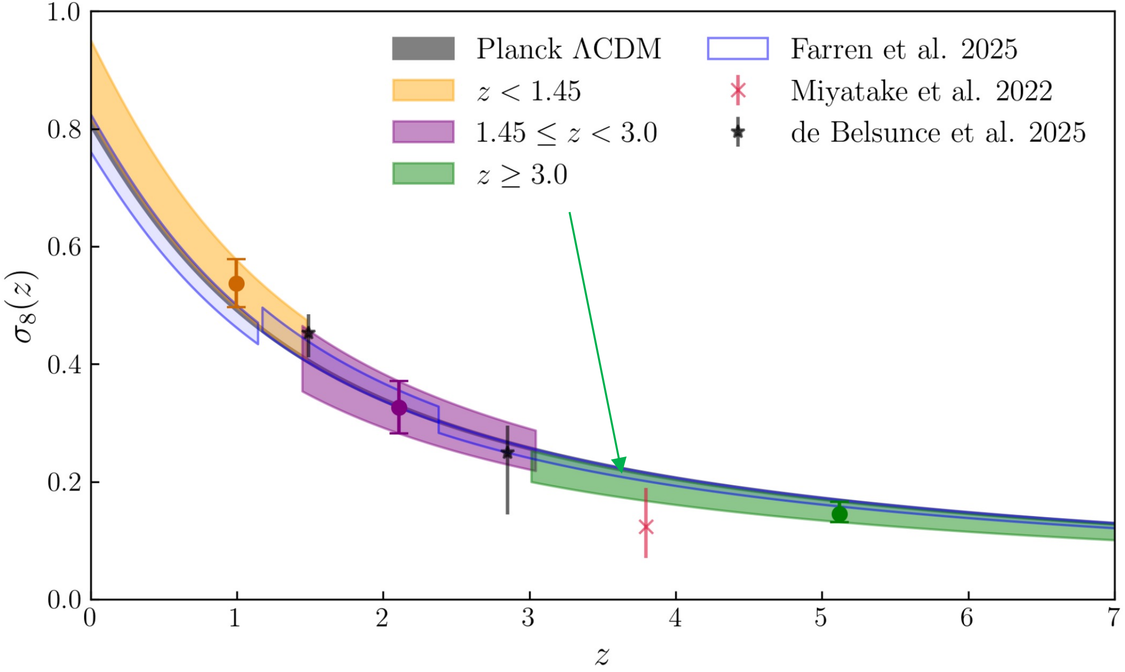
$$\boxed{\sigma_8 = 0.829 \pm 0.009}$$

APS lensing + DESI BAO!

- Great consistency of three different CMB lensing measurements - notable as from different scales / amounts of polarization
- <u>Consistency with LCDM prediction at high precision</u>

ACT lensing results: redshift-dependent growth from cross-correlations

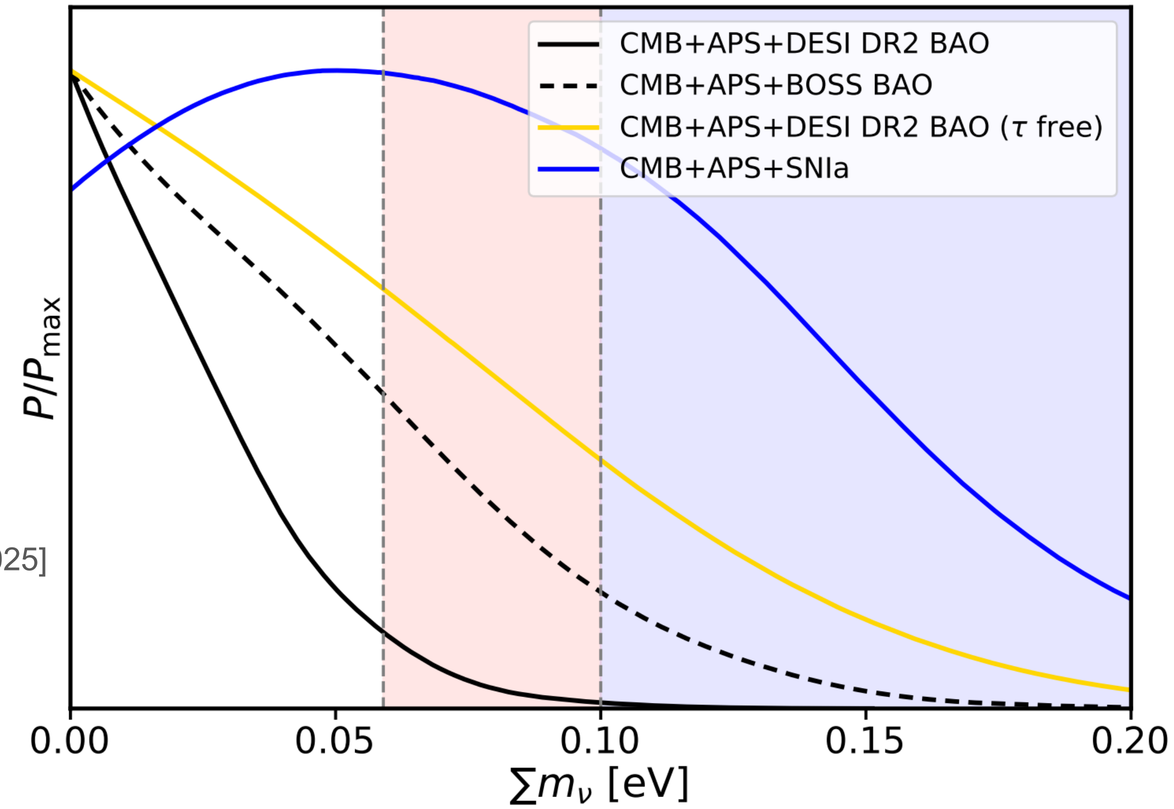




[**Gerrit Farren** et al. 2023 / 2024, **Noah Sailer/Joshua Kim** et al. 2024, **Carmen Embil-Villagra** et al. 2025]

- Combined auto/cross-analysis (3x2): structure growth generally (?) seems to follows LCDM prediction

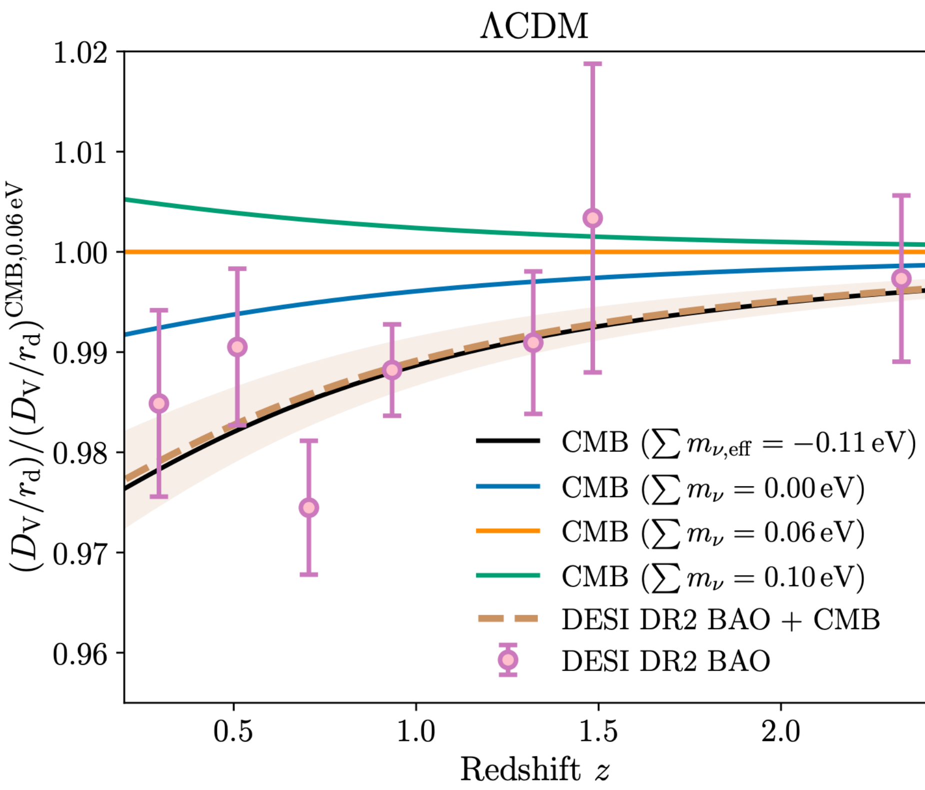
ACT+Planck+SPT lensing+DESI: constraints on neutrino mass



[Qu, Ge, Wu, et al. 2025]

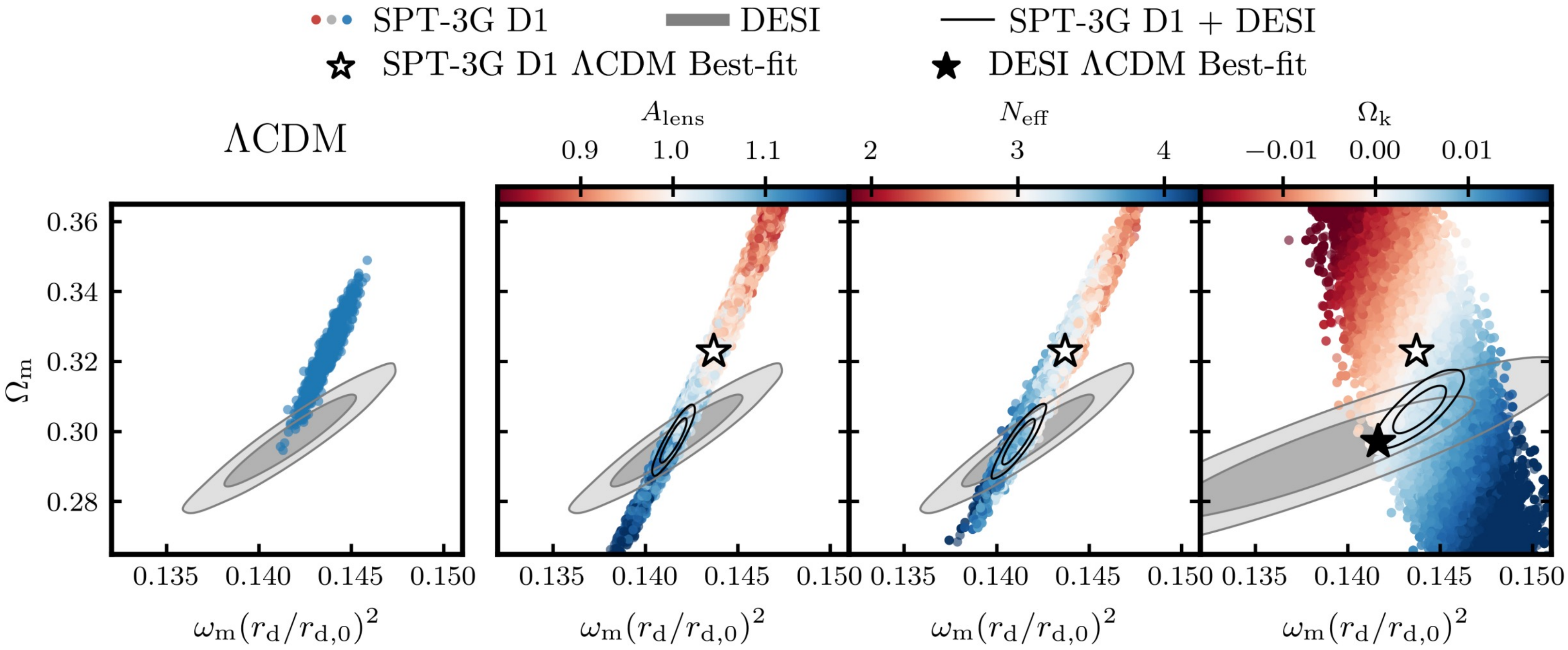
- Very tight constraints on neutrino mass $\Sigma m_\nu < 0.062\ \mathrm{eV}\ (95\%\ \mathrm{C.L.},\ \mathrm{CMB} + \mathrm{APS} + \mathrm{BAO}).$

DESI: constraints on neutrino mass



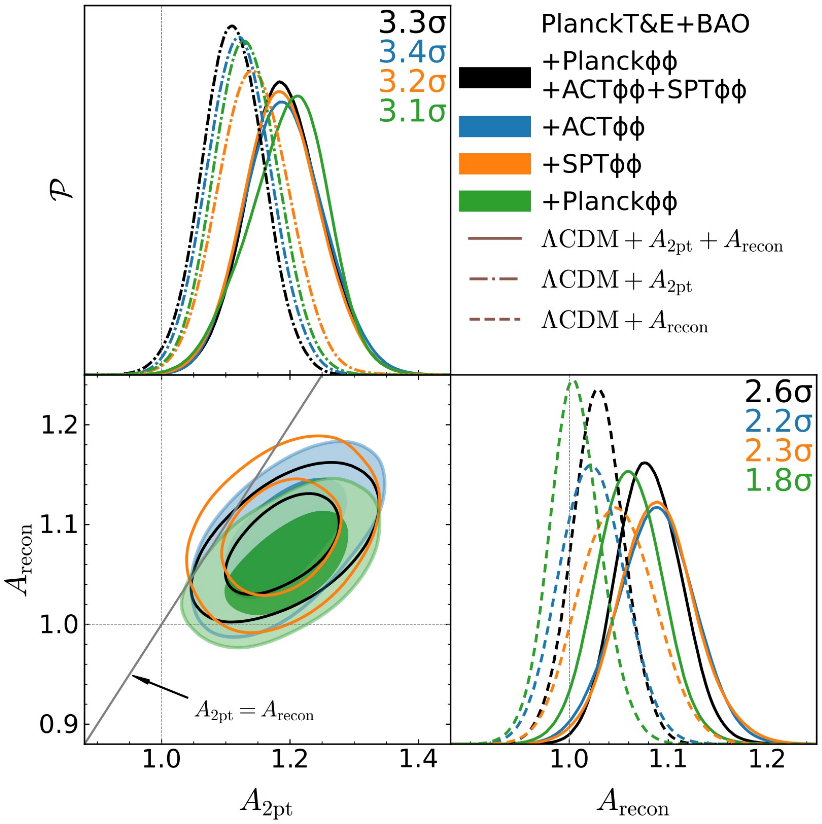
- Preference for unphysical negative neutrino mass – due to combination of background and growth

Can changing CMB lensing help?



- Changing lensing amplitude can help improve consistency, but hard to do…

Is CMB lensing actually a bit high?

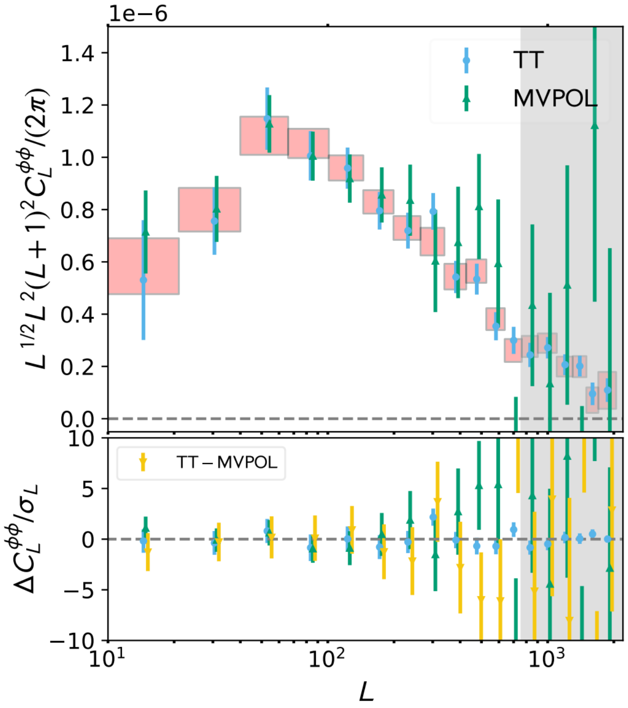


[Ge et al. 2024]

- Note: this is “worst case scenario”, uses Planck PR3 not PR4, and ACT+SPT Alens not high

CMB + DESI inconsistency:
Are lensing-related issues/new-physics likely?

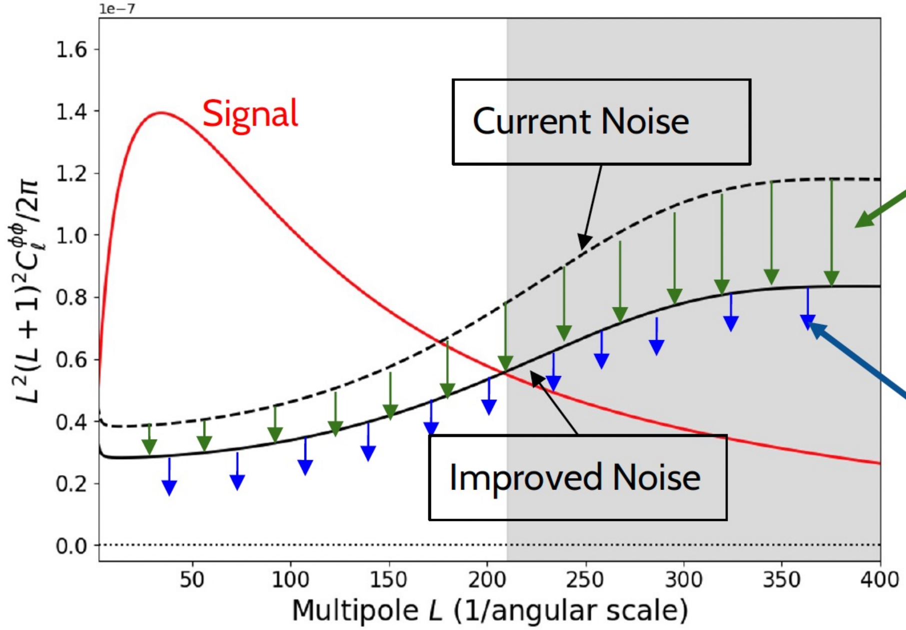
- Lensing generally quite clean. Foregrounds typically lower lensing.
- Consistency of three different experiments ACT, Planck, SPT – notable as from different scales, amounts of polarization (so e.g. foregrounds matter differently)
- Consistency of T and polarization – speaks against CMB modulation new physics explanations
- Consistency of 2pt and 4pt despite near-independence
- Maybe fluctuation that contributes to several issues?



Irene Abril-Cabezas

Coming soon: DR6+ lensing analysis

Irene Abril-Cabezas ++ / **Joshua Kim ++** / **Frank Qu ++** in prep.



- **Inclusion of the daytime data: ~ 1.7x amount of data**

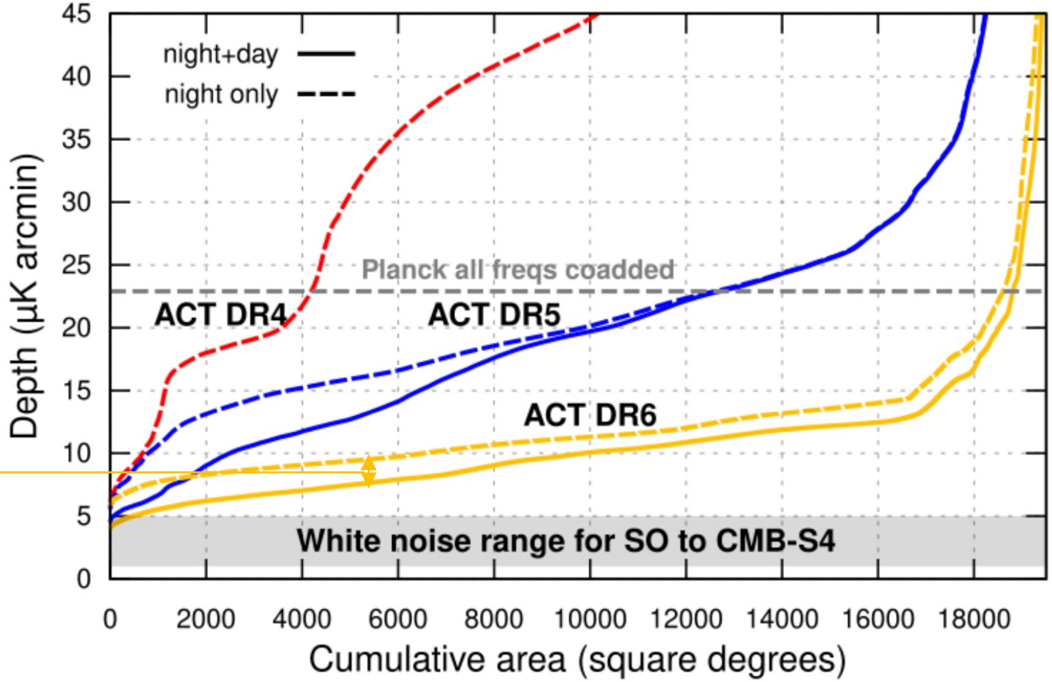
- **Optimal Filtering (10-15% improvement)**
- **Increase the number of splits used for the cross-estimator (~10% improvement)**
- **Improve sky-cuts (~10% improvement)**
- **Map-level combination with Planck**

Potential for SNR 60-70 instead of 43, in next year.

Daytime data: background

- Data taken during the day (11am-11pm); 6 observing seasons (2016-22)
- Challenging: Sun's heat distorts the telescope mirror, causing pointing offsets and beam deformations. Not used for CMB power spectra.
- However, nearly a factor 2 in data if we can use it!

Total intensity



Irene Abril-Cabezas

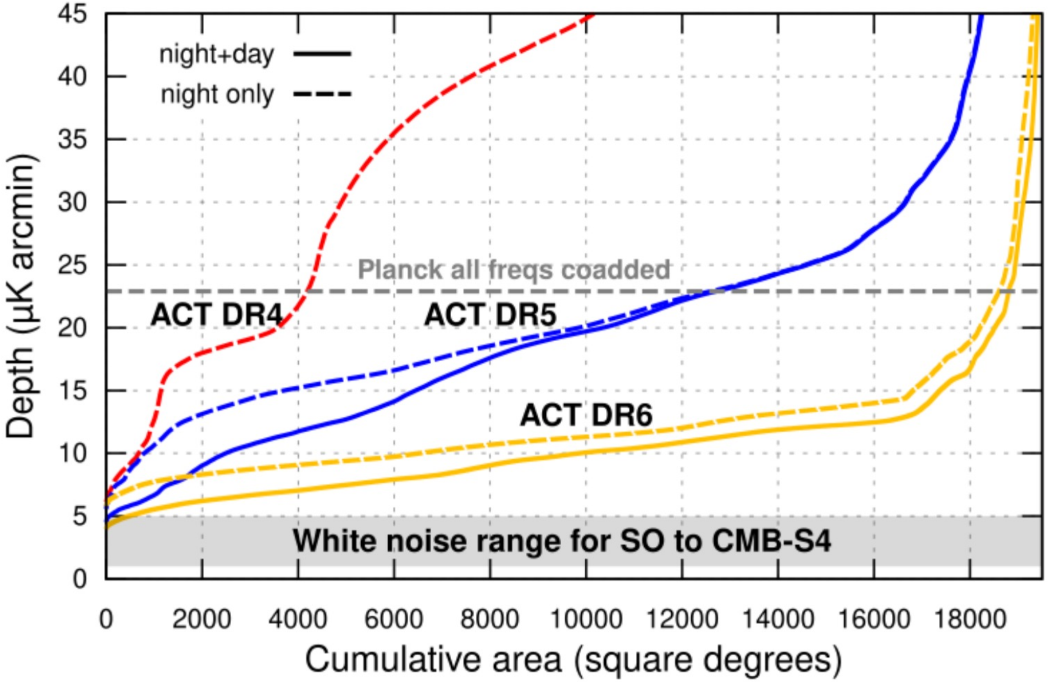
Daytime lensing: improving the maps

- Although likely only mimics lensing on largest scales, several steps to improve data quality:

- Fit pointing and effective beams based mostly on sources, comparing to night

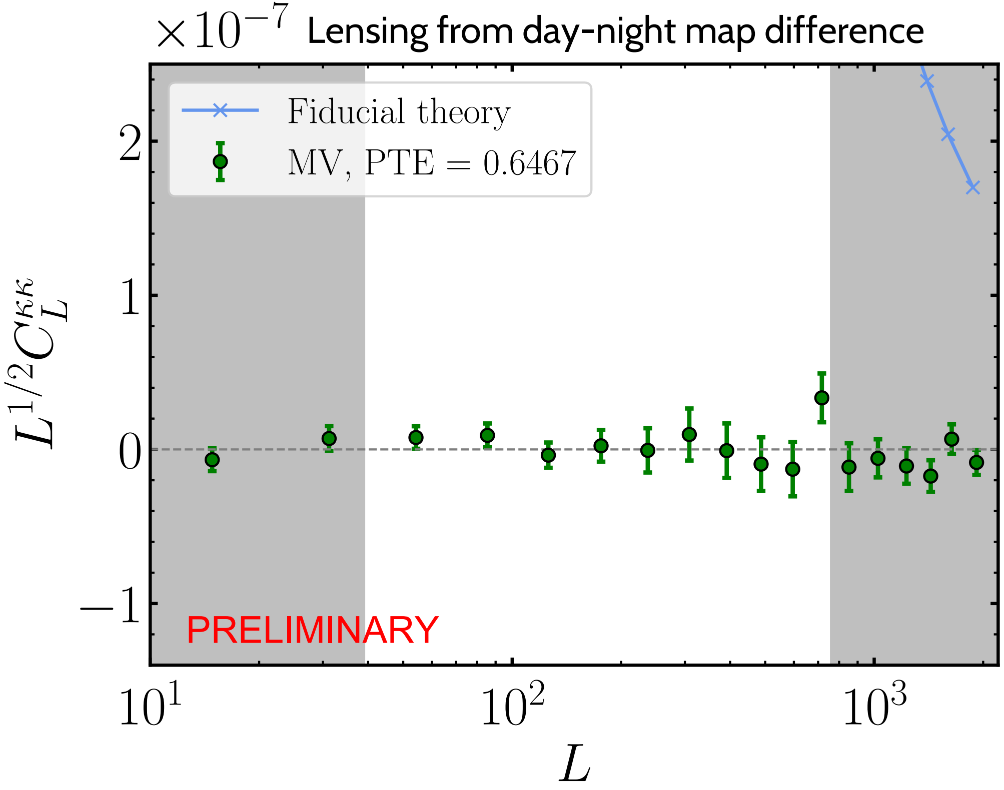
- Then additionally scale, so that day-spectra match night-spectra on the exact sky areas analyzed

Total intensity

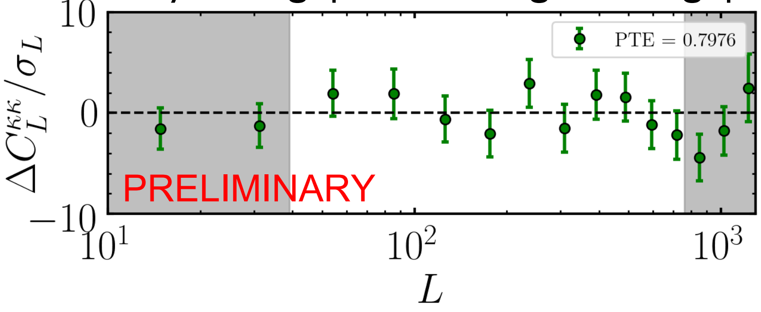


Daytime lensing: stringent null tests vs. night

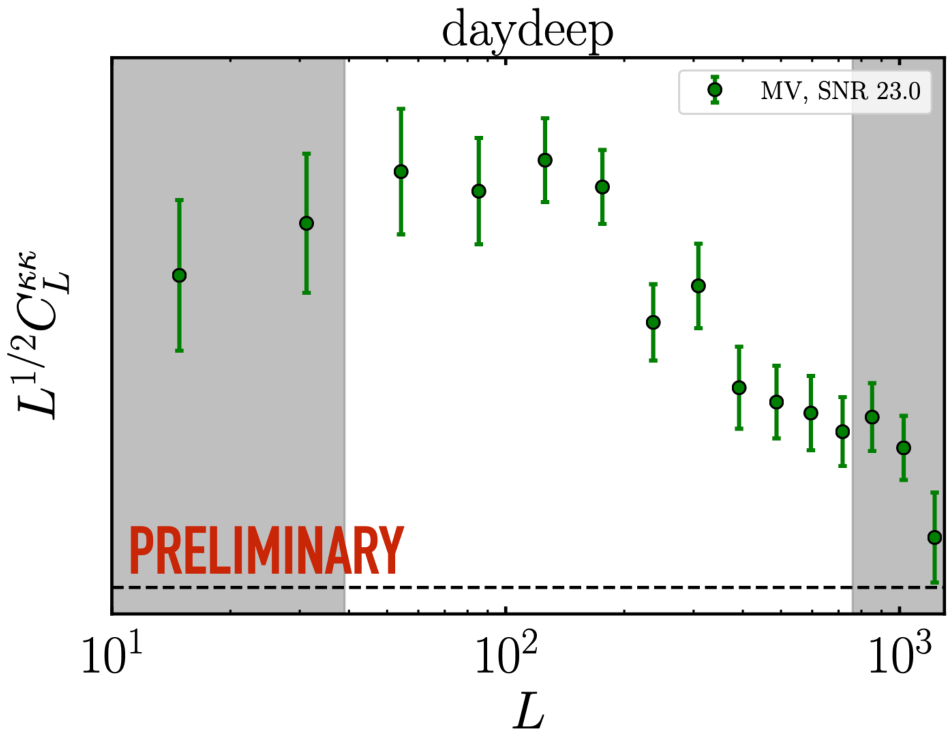
Irene Abril-Cabezas



- Suite of 60+ day vs. night nulls give confidence in results
- Powerful due to sample variance cancellation: some errors 100 x below signal



Daytime-only lensing spectrum and DR6+ outlook

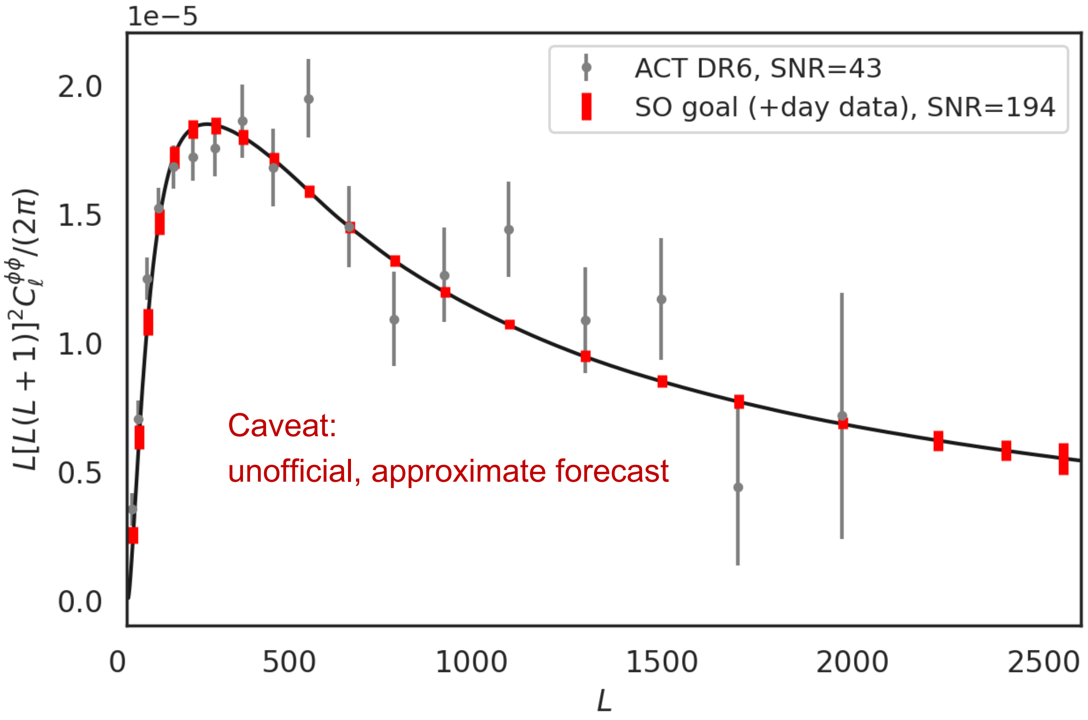


[Abril-Cabezas et al. in prep.]

- Expect SNR of 20-30 from daytime alone (c.f. 43 for last DR6 lensing)
- Contributes to significant boost in precision along with more area, better filtering etc. Methods will carry forward to SO.
- <u>Stay tuned for upcoming DR6+ analysis out soon – SNR 60—70!</u>

Irene Abril-Cabezas

SO lensing: Daytime and other improvements may give further boost

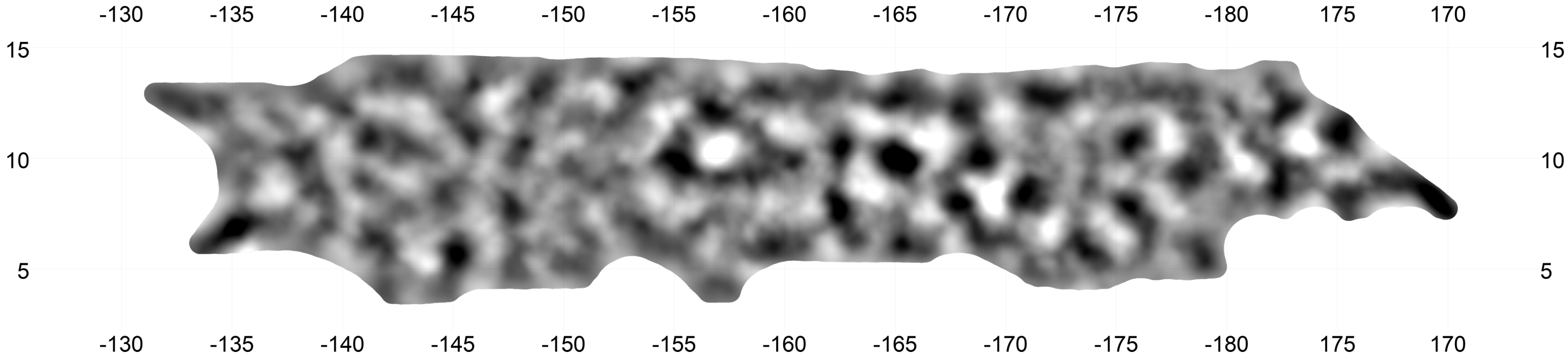


- Basic SO lensing forecasts: already impressive, SNR~130
- But daytime lensing and other new methods may allow further improvements with further SNR boosts
- Also, Advanced SO detectors now to be deployed early...


Simons Observatory

Preview: first look at Simons Observatory lensing

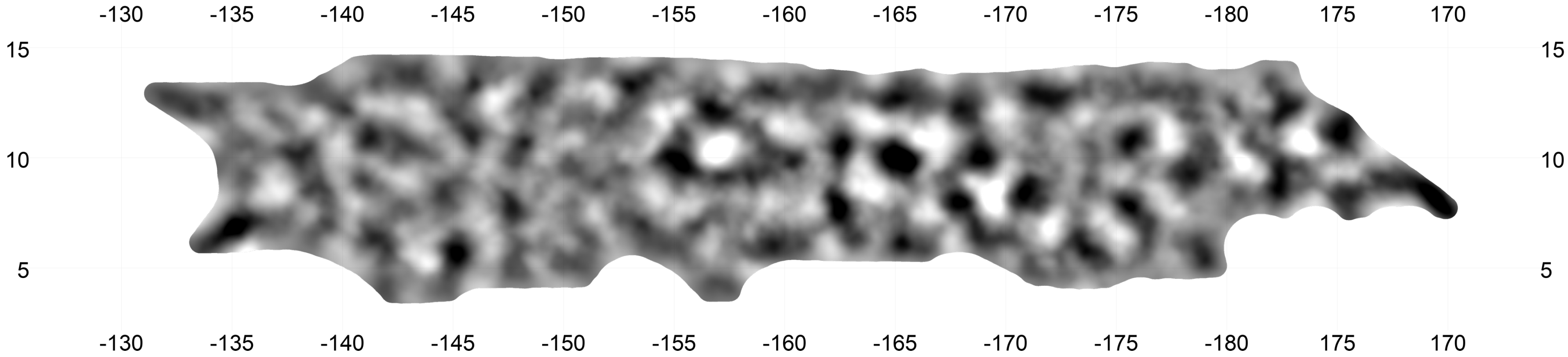
Lensing map from just 144 hours of observations [A. Kusiak (Cambridge), K. Perez-Sarmiento++]

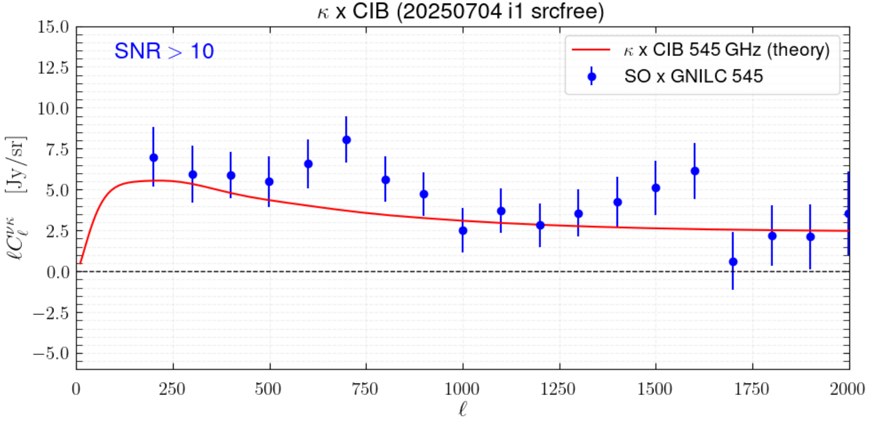


Ola Kusiak (Cambridge)

Preview: first look at Simons Observatory lensing

Lensing map from just 144 hours of observations [A. Kusiak (Cambridge), K. Perez-Sarmiento++]





Lensing-CIB cross-correlation at SNR >10, already more powerful than 1 year of recent experiment (ACTPol)!

And now, for something ~~completely~~ slightly different

II. A new probe of primordial non-Gaussianity: first demonstrations of kSZ velocity reconstruction

[McCarthy et al. 2025]

Fiona McCarthy (Cambridge/CCA)

European Research Council
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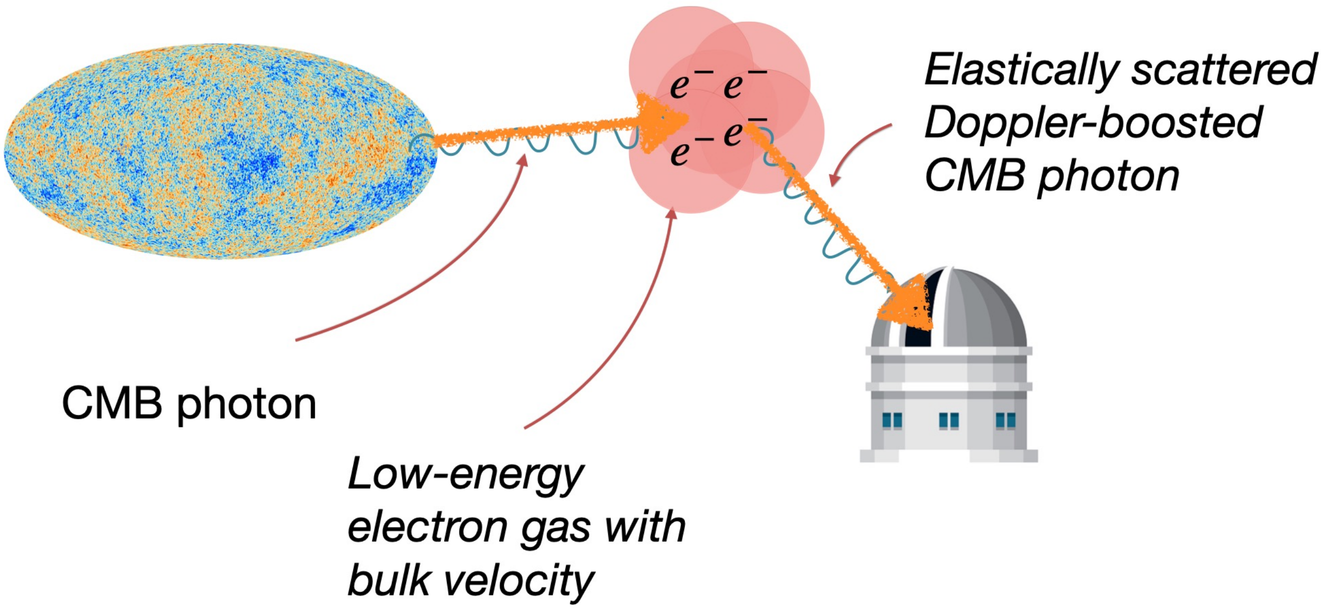
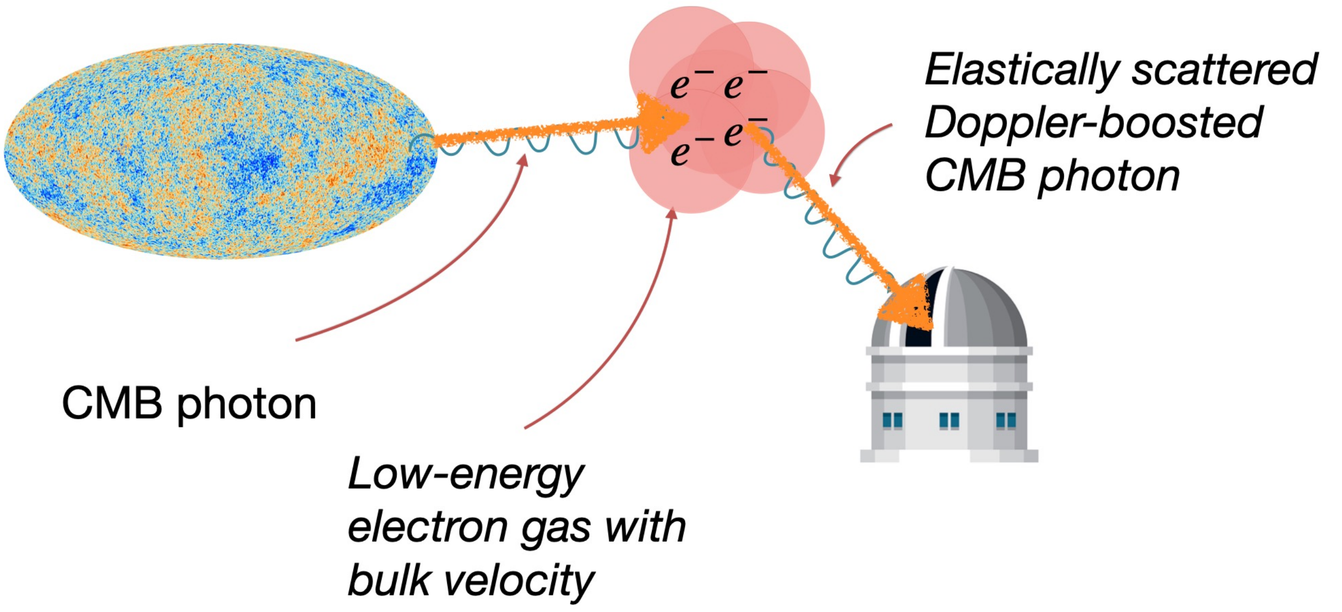
The kinetic Sunyaev-Zel’dovich (kSZ) effect



The kinetic Sunyaev-Zel'dovich (kSZ) effect



- Due to scattering, CMB temperature probes the momentum of electrons

$$\frac{\delta T}{T} = \int \overbrace{\mathrm{d}l\, \underbrace{n_e}_{\text{electron density}} \sigma_T}^{\tau} \overbrace{\frac{v}{c}}^{\text{velocity}}$$

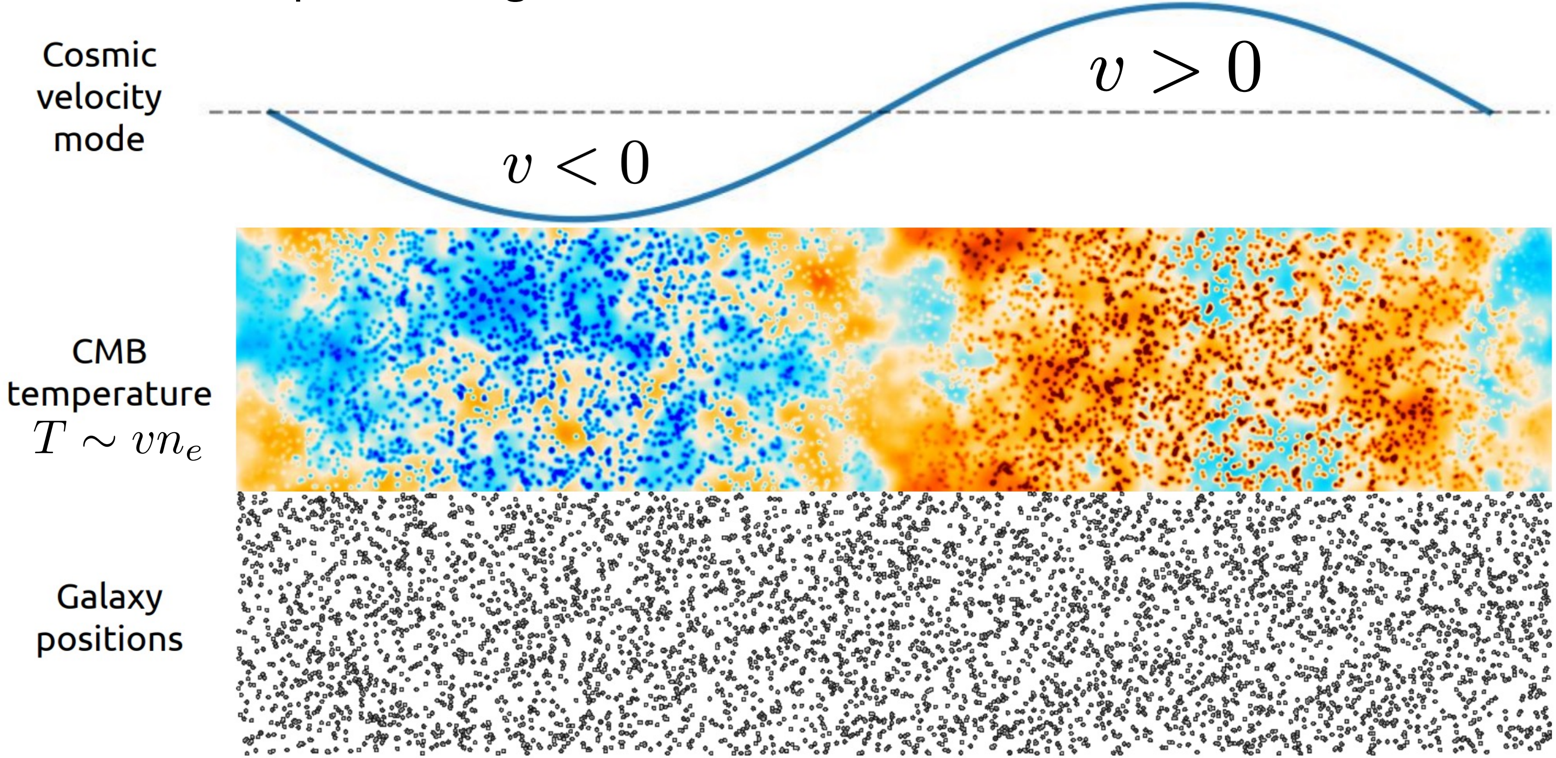
kSZ velocity reconstruction using CMB and galaxy density

- Reconstruct by measuring v-induced T-g mode coupling $\hat{v}(\mathbf{L}) \sim \int dl \ T(\mathbf{l})g^*(\mathbf{l}-\mathbf{L})$

[Muenchmeyer et al. 2019]

kSZ velocity reconstruction using CMB and galaxy density

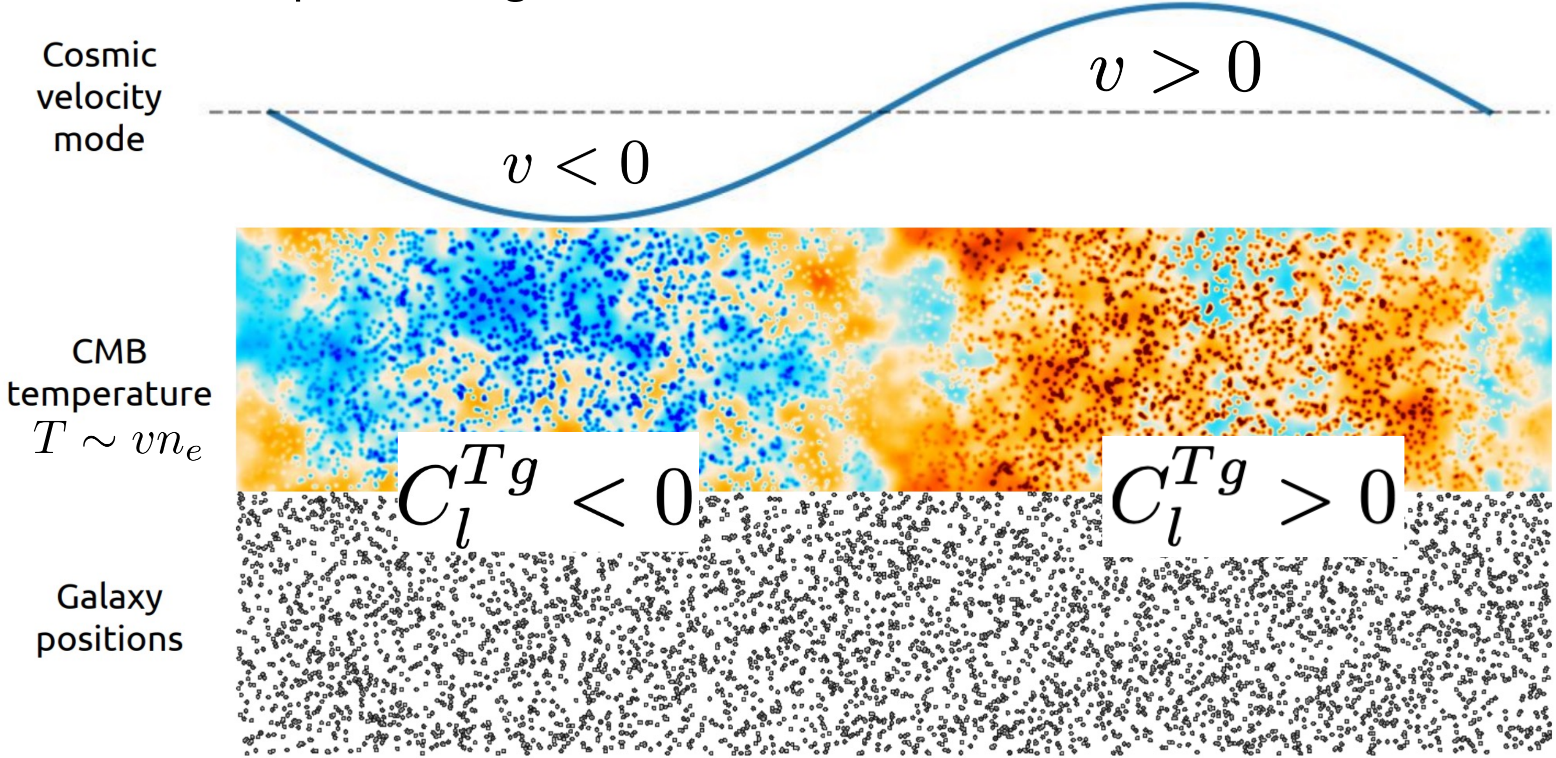
- Reconstruct by measuring v-induced T-g mode coupling $\hat{v}(\mathbf{L}) \sim \int dl\ T(\mathbf{l}) g^*(\mathbf{l} - \mathbf{L})$
- Intuition: v-dependent T-g correlation



[Image. M. Madhavacheril]

kSZ velocity reconstruction using CMB and galaxy density

- Reconstruct by measuring v-induced T-g mode coupling $\hat{v}(\mathbf{L}) \sim \int dl \; T(\mathbf{l}) g^*(\mathbf{l} - \mathbf{L})$
- Intuition: v-dependent T-g correlation



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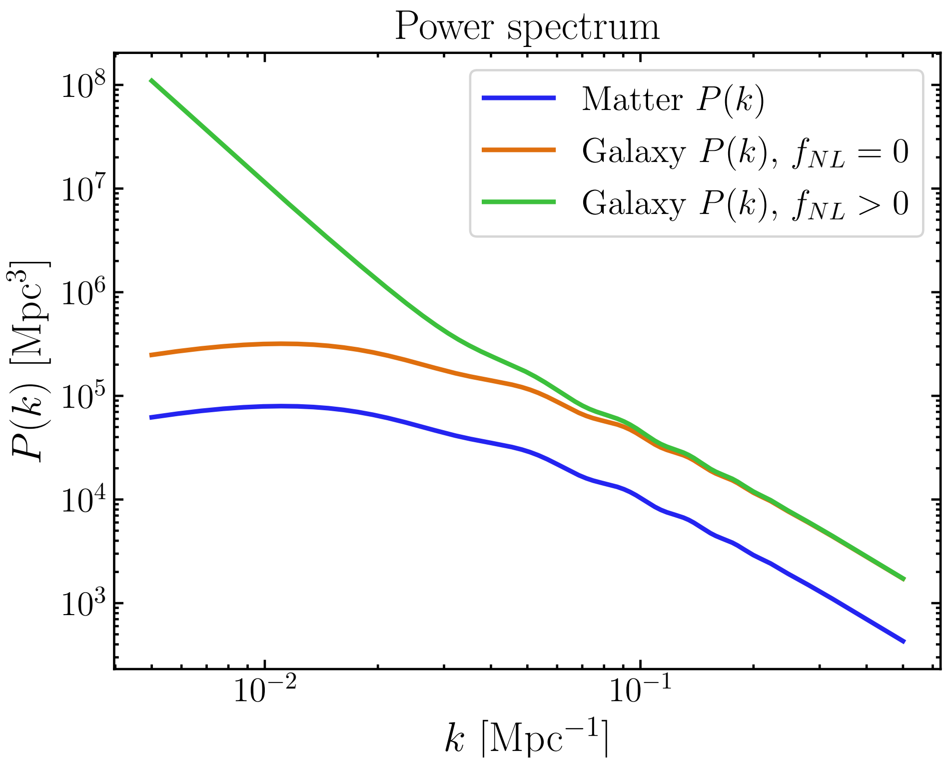
- Key point: all astrophysical complications (relating electrons to g) absorbed in overall constant bias factor

- Easily convert to density $v \leftrightarrow \dfrac{-i\mathbf{k} f a H}{k^2} \delta_m$ – great probe of largest-scale modes

Primordial non-Gaussianity: Challenges in measuring scale dependent bias

$$b(k) \propto b_1 + c\frac{f_{NL}}{k^2}$$

- Scale dependent galaxy bias is a key signature for local non-Gaussianity, but two challenges:



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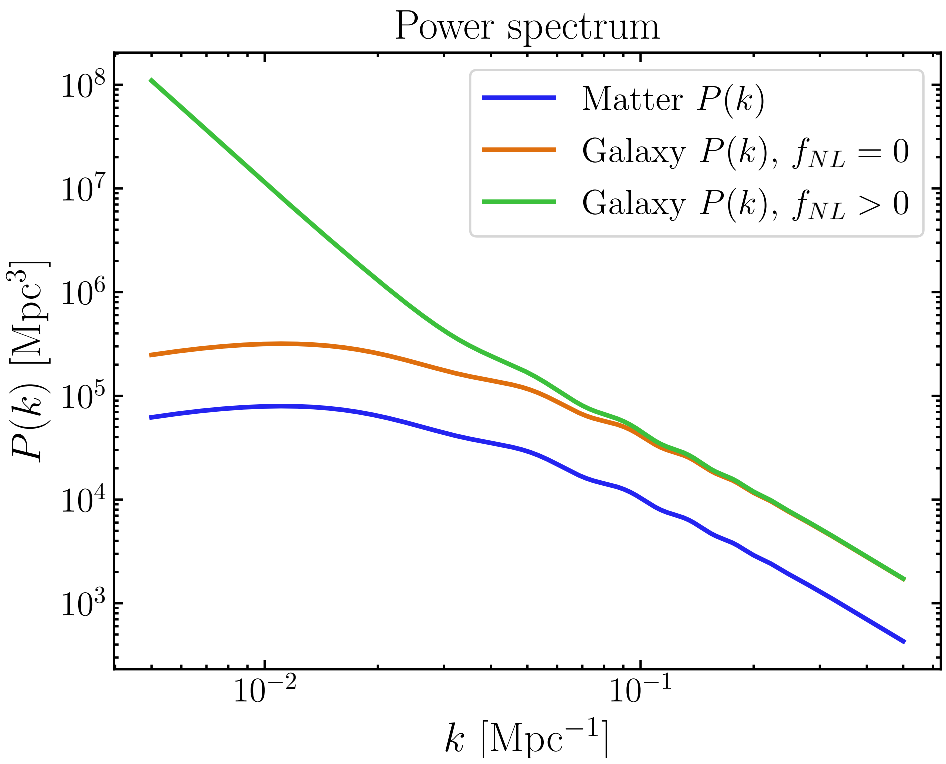
- Large-scale systematics

$$\hat{P}_{gg}(k) = P_{gg}(k) + P_{NN}(k)$$

- Large-scale sample variance

$$\sigma(P_{gg}(k)) \propto \frac{P_{gg}(k)}{k} + \frac{1}{k\bar{n}}$$



Primordial non-Gaussianity:
Solution: add a new, clean tracer of density field

- Large-scale systematics:

$$\cancel{\hat{P}_{gg}(k) = P_{gg}(k) + \boxed{P_{NN}(k)}}$$

$$\hat{P}_{gX}(k) = P_{gX}(k)$$

overcome via cross-correlation!

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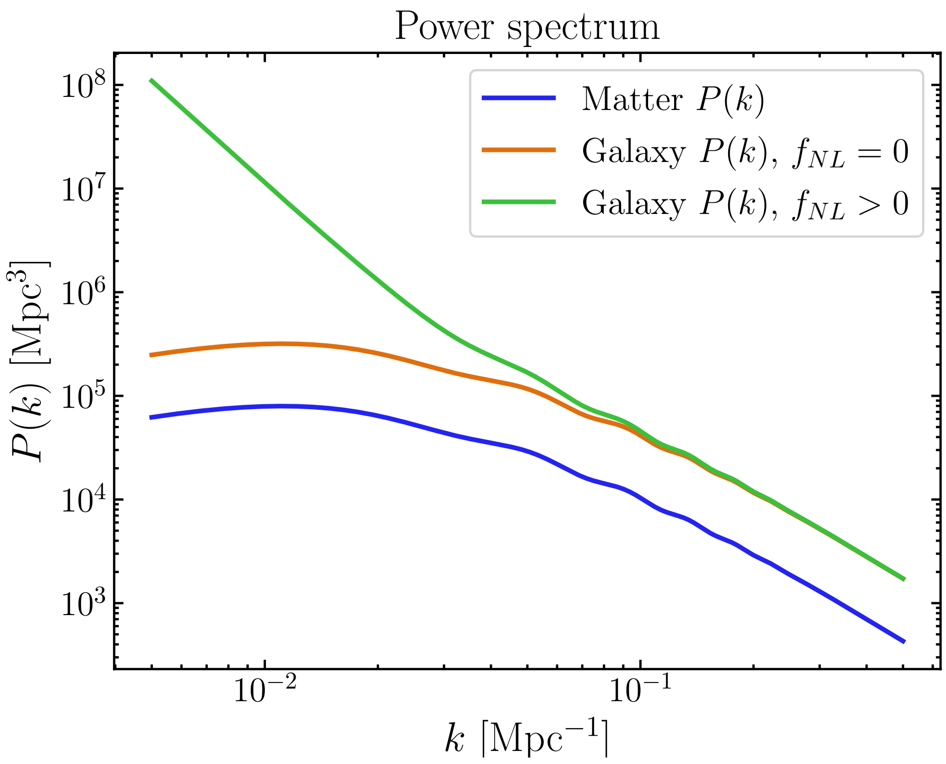
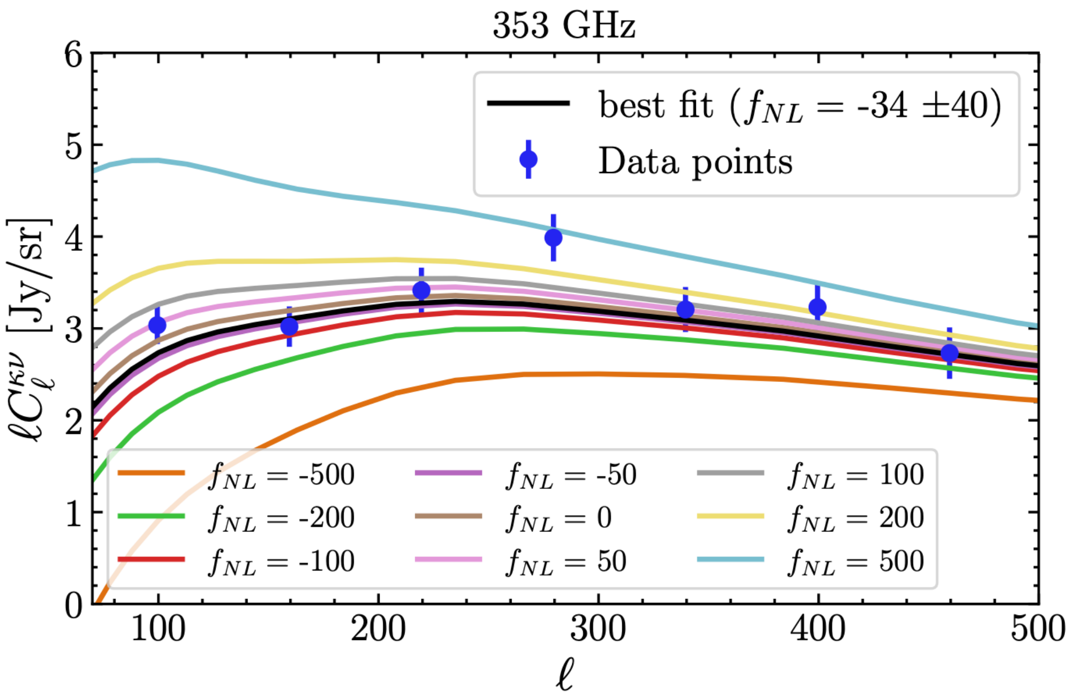
reduce via sample variance cancellation!



CMB lensing cross-correlations work to some extent



- Cleans up even very contaminated tracer, CIB! At least x2 improvements possible, see Thornton++ in prep.
- Although limited by redshift overlap for cross-correlation-only information – hard to reach errors ~1?

Primordial non-Gaussianity:
Solution: add large scale velocity from kSZ

- Say we have a clean velocity tracer of large-scale modes, insensitive to fNL
- Large-scale systematics:

$$\cancel{\hat{P}_{gg}(k) = P_{gg}(k) + P_{NN}(k)}$$

$$\hat{P}_{gX}(k) = P_{gX}(k)$$

overcome via cross-correlation!

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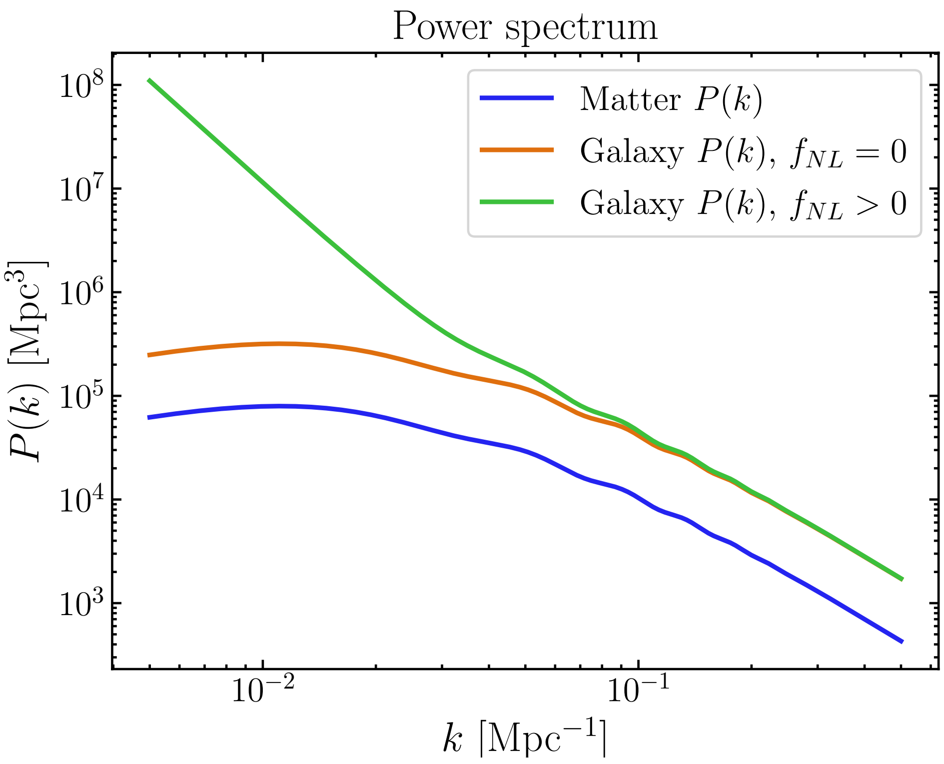
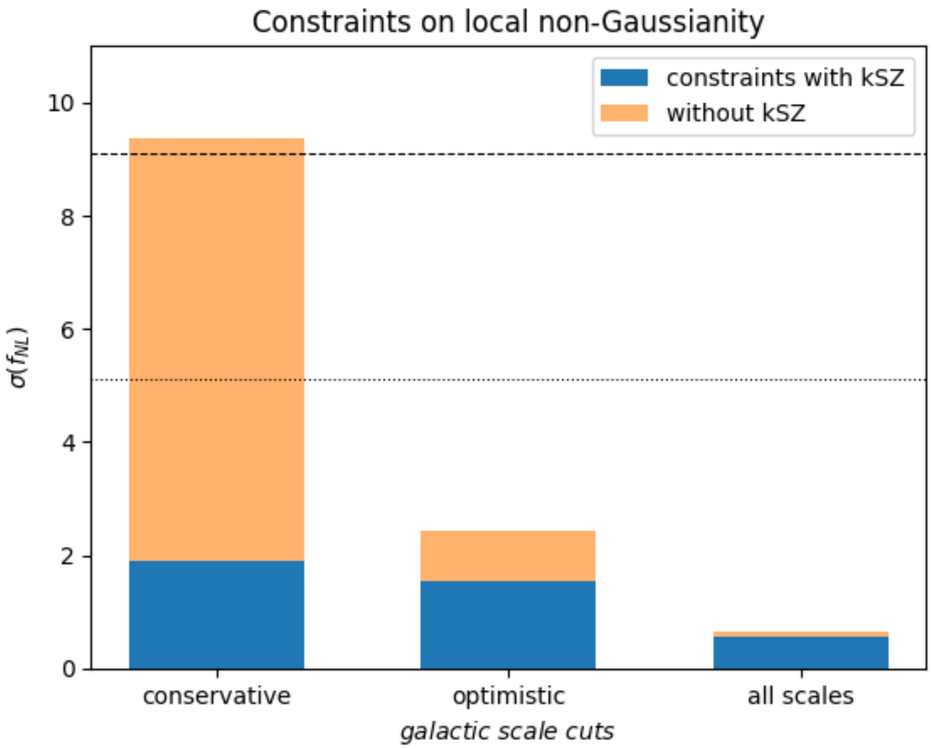
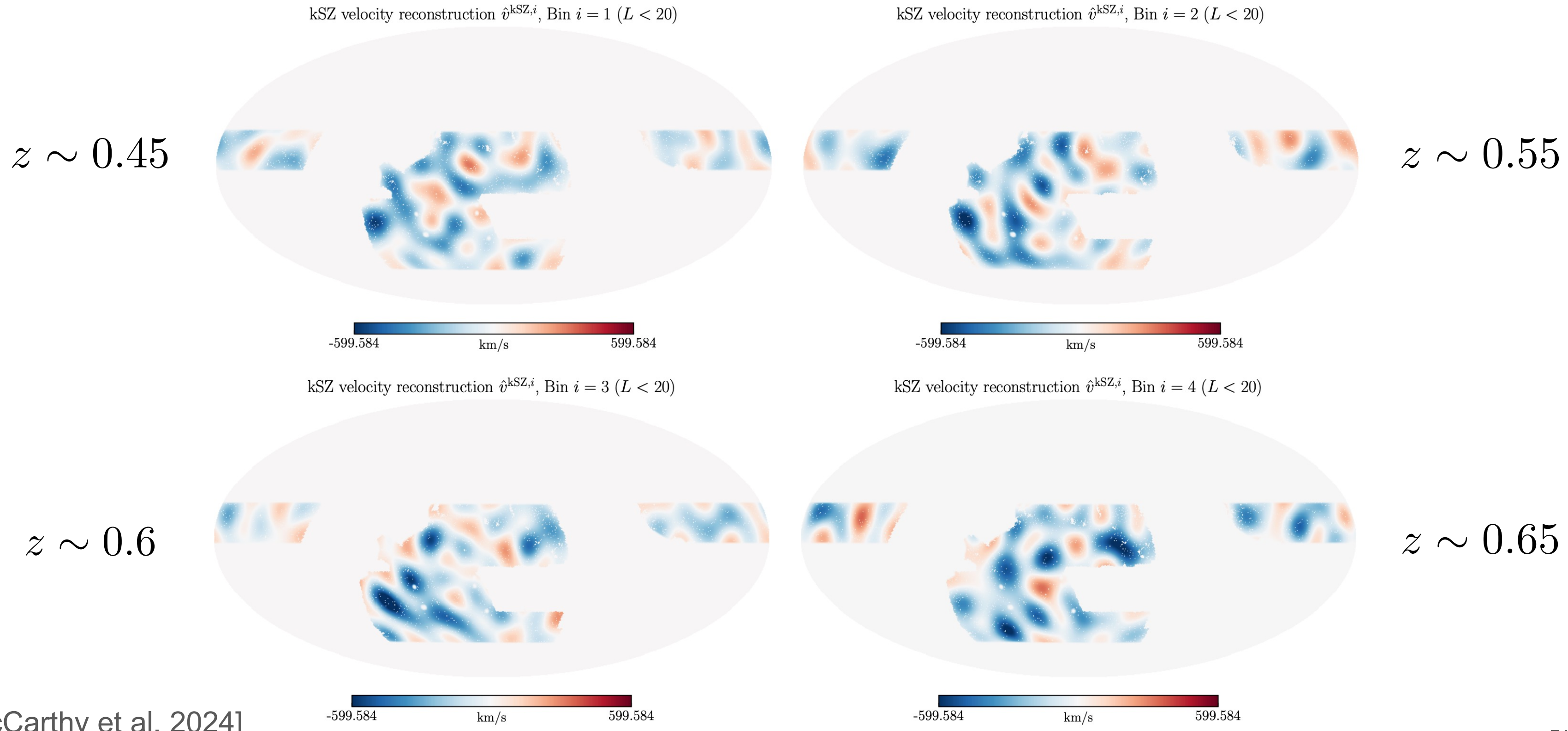


kSZ velocity reconstruction: More reliable f_{NL} from cross-correlations alone (SO x LSST forecast)



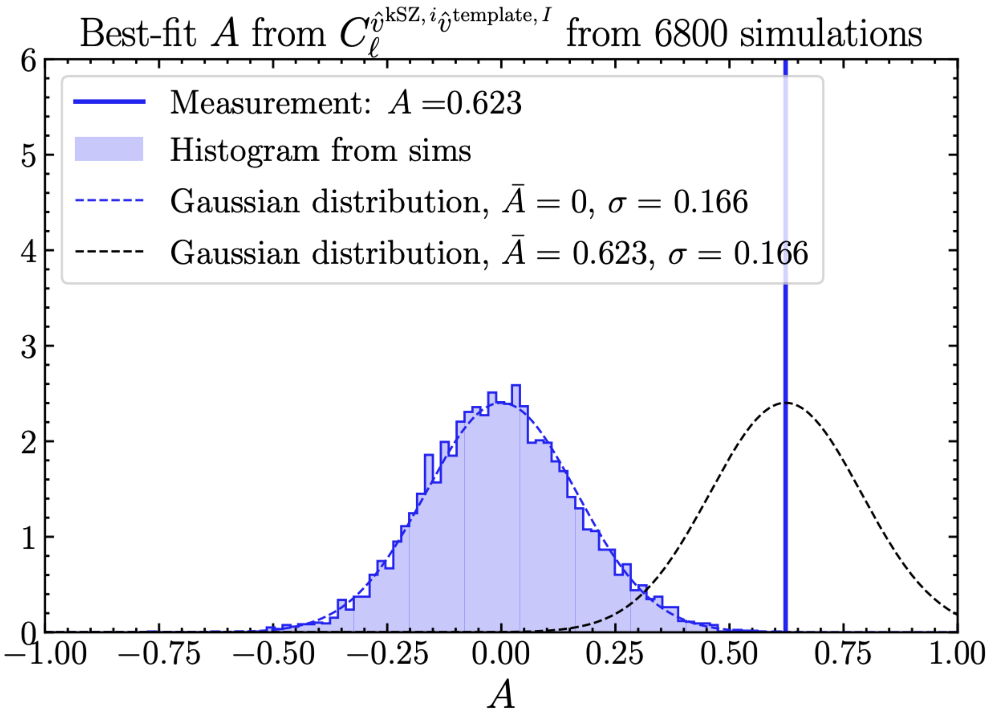
- Great potential to reach f_{NL}~1-2 from cross-correlations alone! But, until recently, no significant measurement of velocity with kSZ

New: kSZ velocity reconstruction –
first demonstration with ACT CMB + DESI LRG galaxies



[McCarthy et al. 2024]

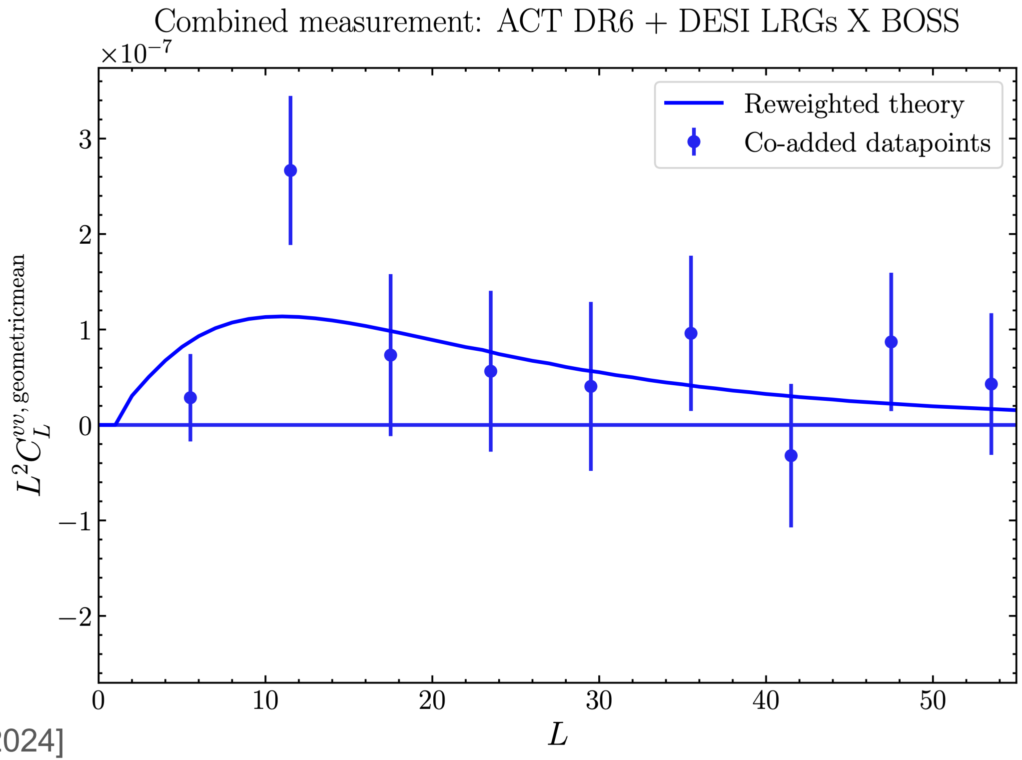
kSZ velocity reconstruction x galaxies: first demonstration with ACT + DESI LRGs



[McCarthy et al. 2024]

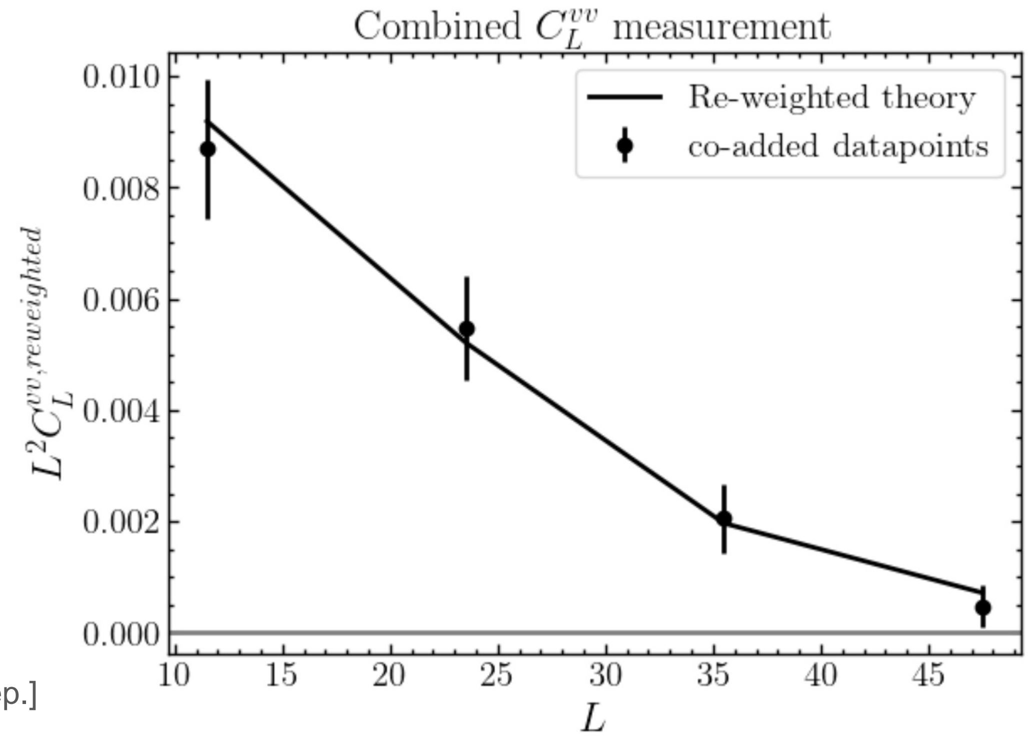
- Correlate with BOSS galaxies (velocity template), measure amplitude – seen at 3.8 sigma

kSZ velocity reconstruction x galaxies: first demonstration with ACT + DESI LRGs (3.8 sigma)



[McCarthy et al. 2024;
See also Lague et al. 2024]

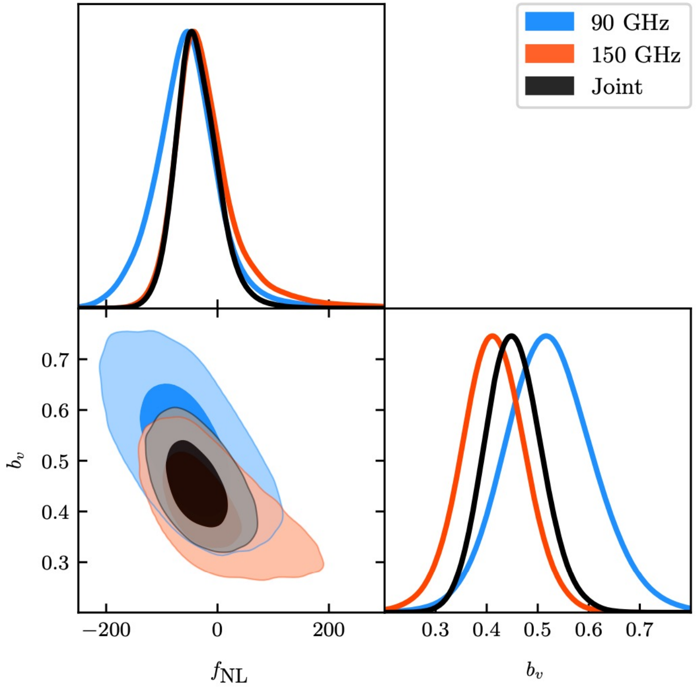
kSZ velocity reconstruction x galaxies: rapid progress



[McCarthy et al. in prep.]

- With larger galaxy sample already have SNR~10 [preliminary]

kSZ velocity reconstruction x galaxies: rapid progress



[Hotinli et al. 2025;
See also Lai et al. 2025]

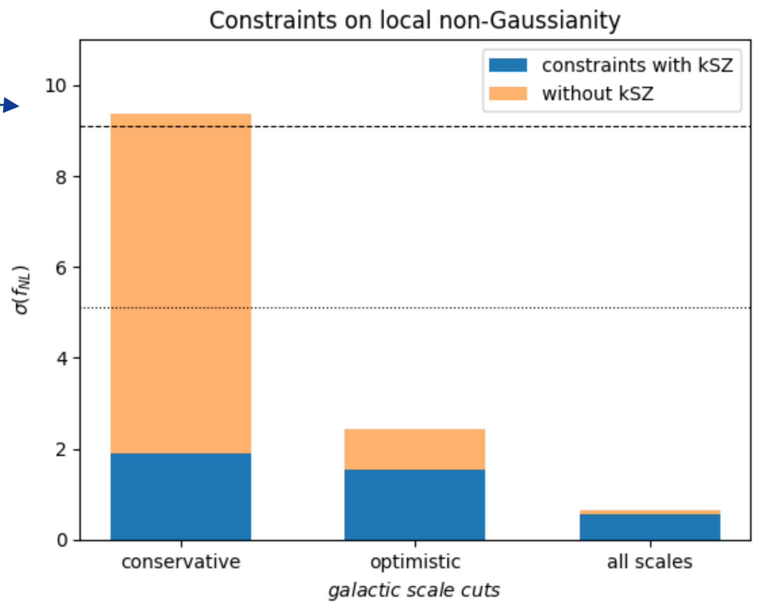
- With kSZ velocity reconstruction, un-measured until last year, f_{NL} constraint has already reached +/-40 – rapid progress

Challenges and Open Questions

To reach such constraints:

- What is the impact of foreground systematics?
- What higher-order effects are important?
- What is the impact of galaxy systematics?

Ongoing research!



Summary

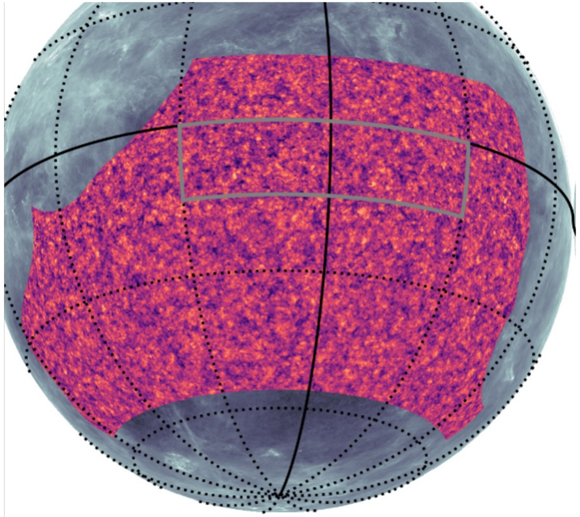
- To test cosmic structure growth and neutrino masses: high-fidelity lensing mass maps over ¼ sky, CMB lensing power spectra from ACT with state-of-art precision.

- Most recent constraints from ACT+SPT CMB lensing spectrum (+BAO): structure growth seems to agree with LCDM on large scales, $\sigma_8 = 0.829 \pm 0.009$
neutrino mass bounds remain (strangely?) tight $\Sigma m_\nu < 0.062$ eV

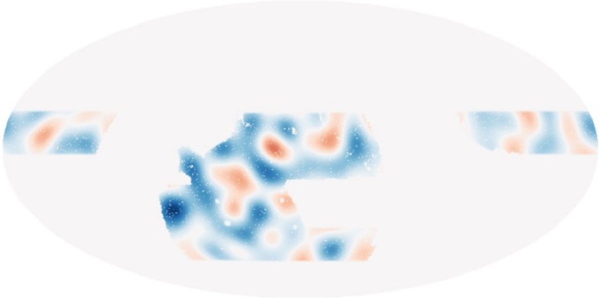
- Coming soon: DR6+ lensing analysis with improved SNR of 60-70; one key source of improvement: first analysis of ACT daytime observations, as shown here. Then SO!

- Also: first demonstration of kSZ velocity reconstruction – promising technique for robustly constraining primordial non-Gaussianity with cross-correlations

mass



velocity



Qu, Sherwin, Madhavacheril, Han, Crowley et al. 2023
Madhavacheril, Qu, Sherwin, MacCrann, Li et al. 2023
MacCrann, Sherwin, Qu, Namikawa, Madhavacheril et al. 2023
Farren et al. 2023
Qu et al. 2025
McCarthy et al. 2024