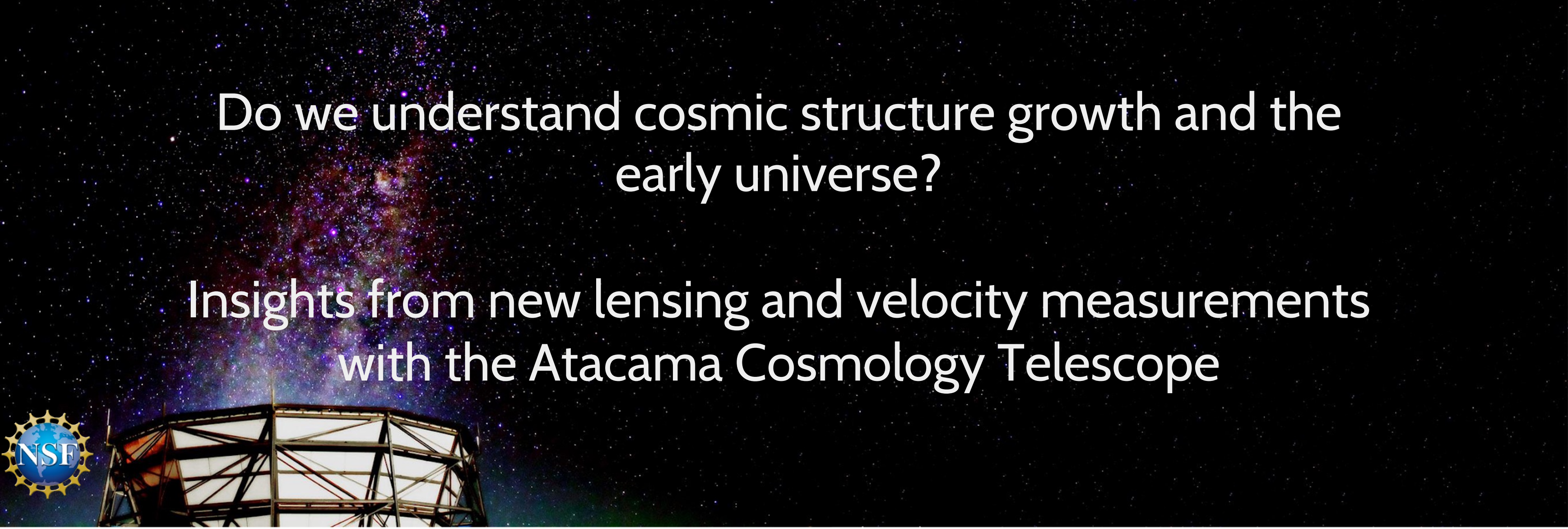


Do we understand cosmic structure growth and the early universe?

Insights from new lensing and velocity measurements with the Atacama Cosmology Telescope

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

Outline

- Part I: New CMB lensing measurements and their implications for structure growth

  a) Introduction and recent lensing results with ACT; b) New results and next steps

Qu, Sherwin et al. 2024
Madhavacheril, Qu, Sherwin et al. 2024
MacCrann, Sherwin et al. 2024

Frank Qu
(Cambridge)

Mat Madhavacheril
(U. Penn)

Irene Abril Cabezas
(Cambridge)

Niall MacCrann
(Cambridge)

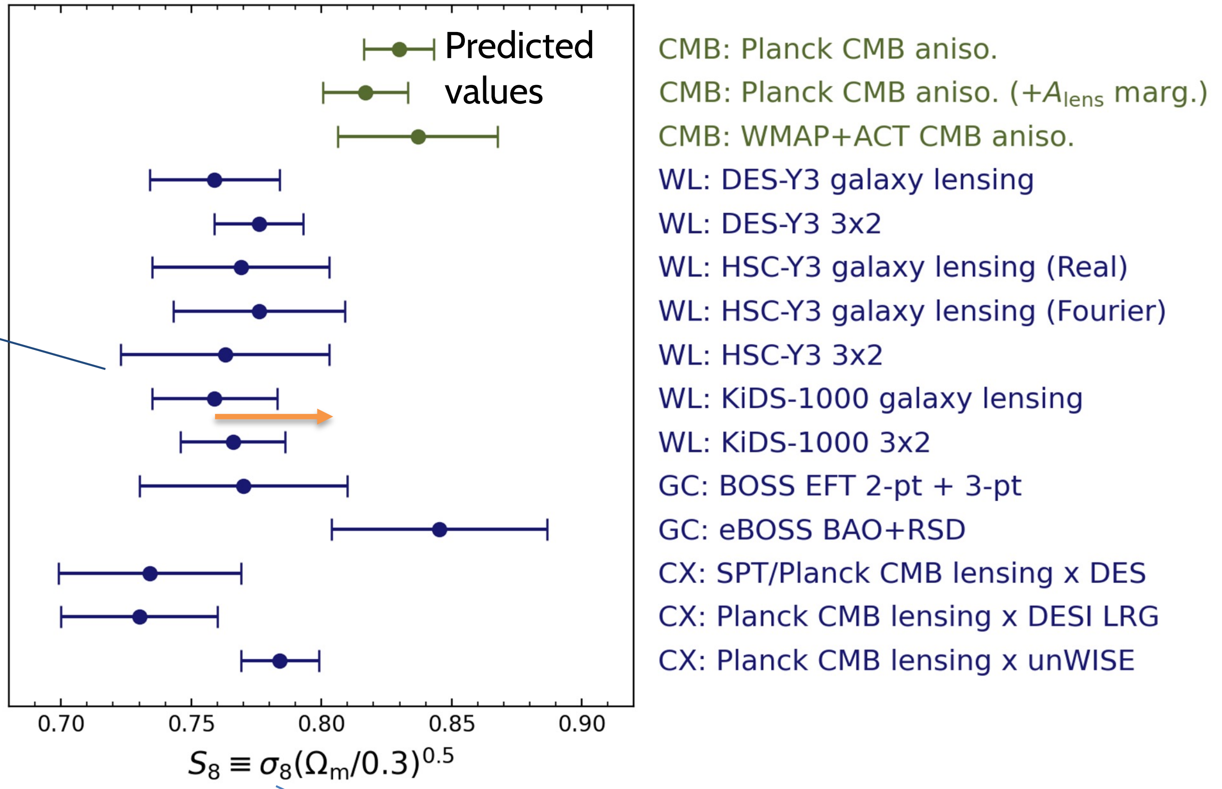
- Part II: A new probe of the early universe – first demonstrations of kSZ velocity reconstruction

McCarthy et al. 2025

Fiona McCarthy
(Cambridge)

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

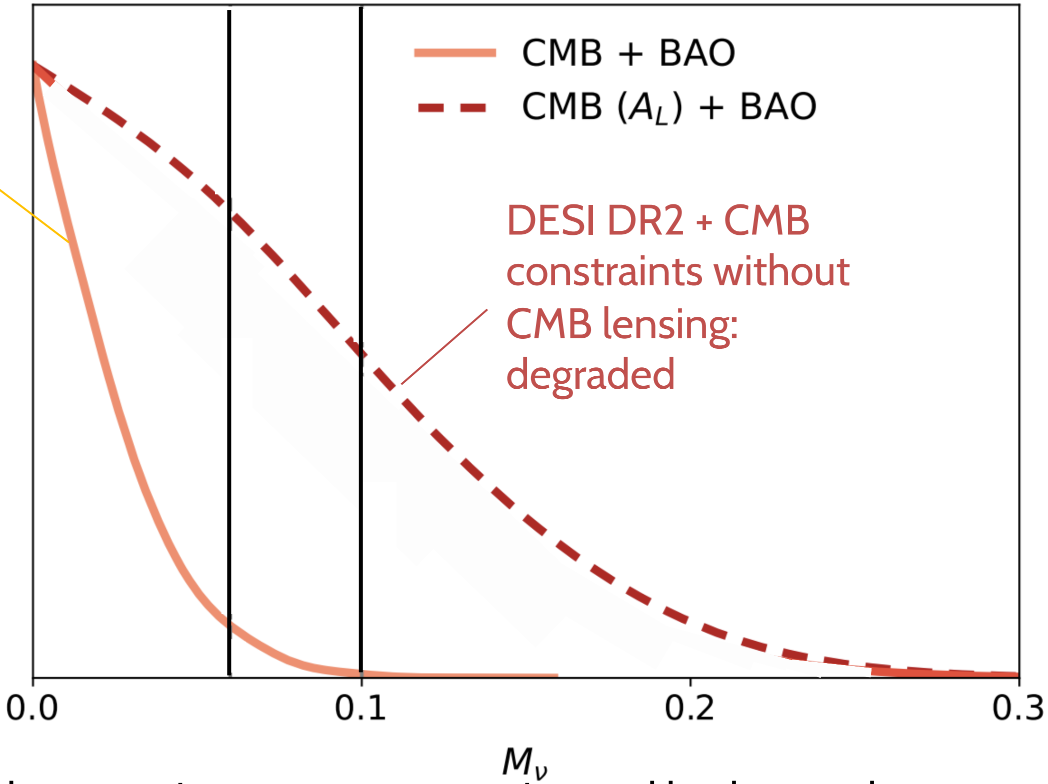


matter clumpyness σ_8
[=RMS mass fluctuation on 8Mpc/h scales]

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

Lensing is important for measuring neutrino mass (recently particularly interesting!)

With lensing



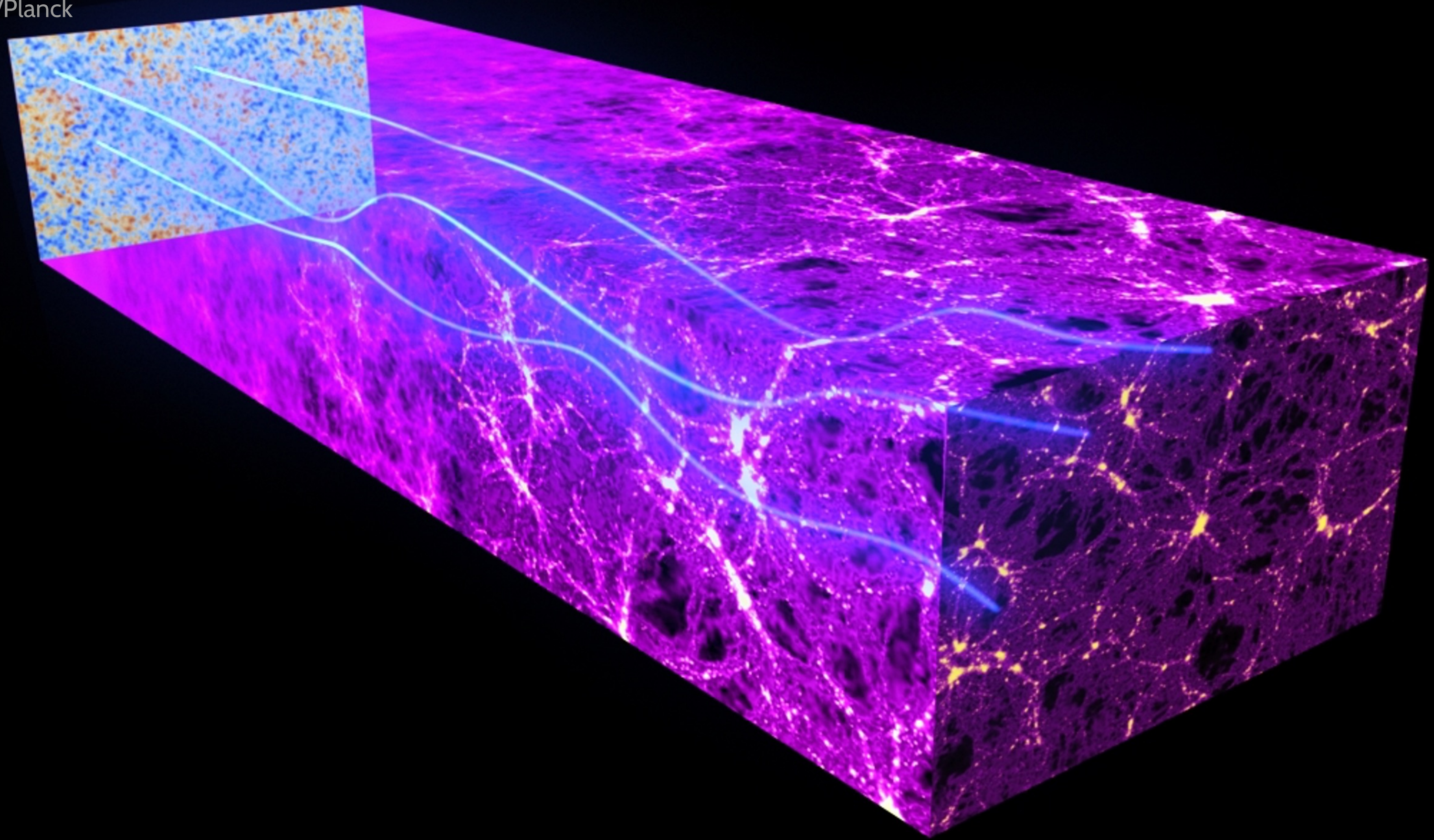
DESI DR2 + CMB constraints without CMB lensing: degraded

[Jhaveri, Karwal, Hu 2025]

- CMB lensing probes neutrino power suppression and background matter

CMB Gravitational Lensing

Image: ESA/Planck

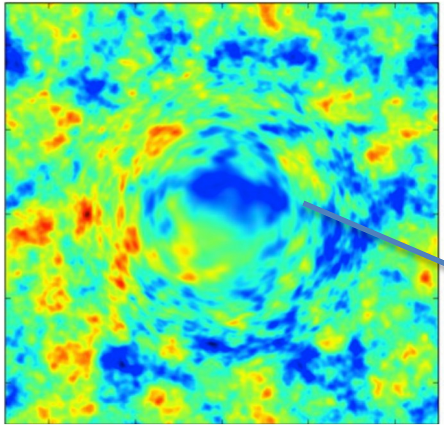


Distribution of mass deflects CMB light that passes through by angle $\nabla\phi$

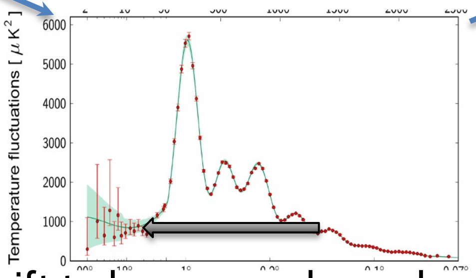
CMB Lensing Measurement

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

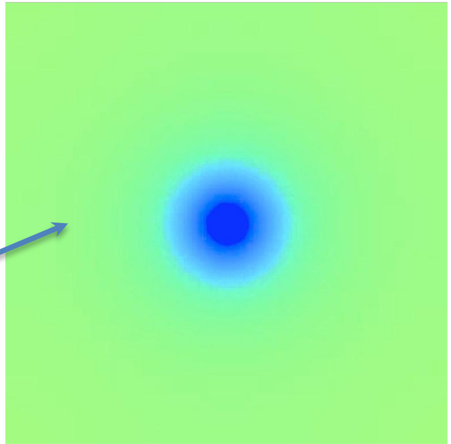
- Approximate explanation:



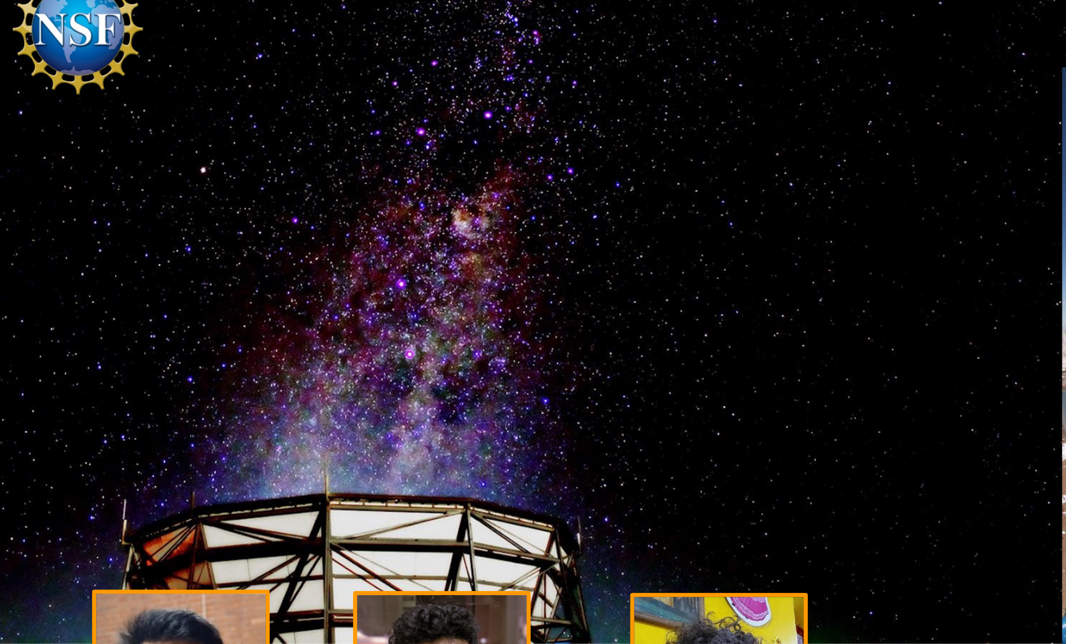
CMB Temp. + Pol.

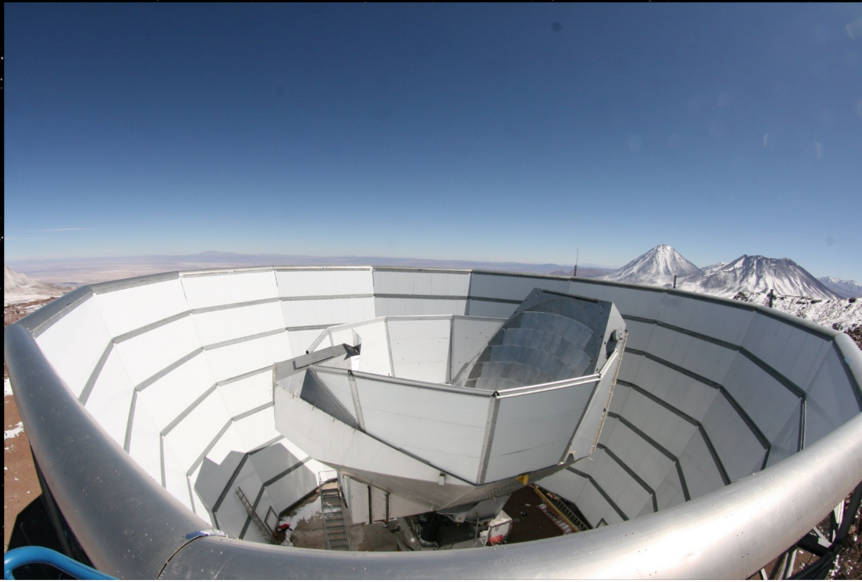


shift to larger angular scales



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





Frank Qu
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Mat Madhavacheril
(U. Penn)

Niall MacCrann
(Cambridge)

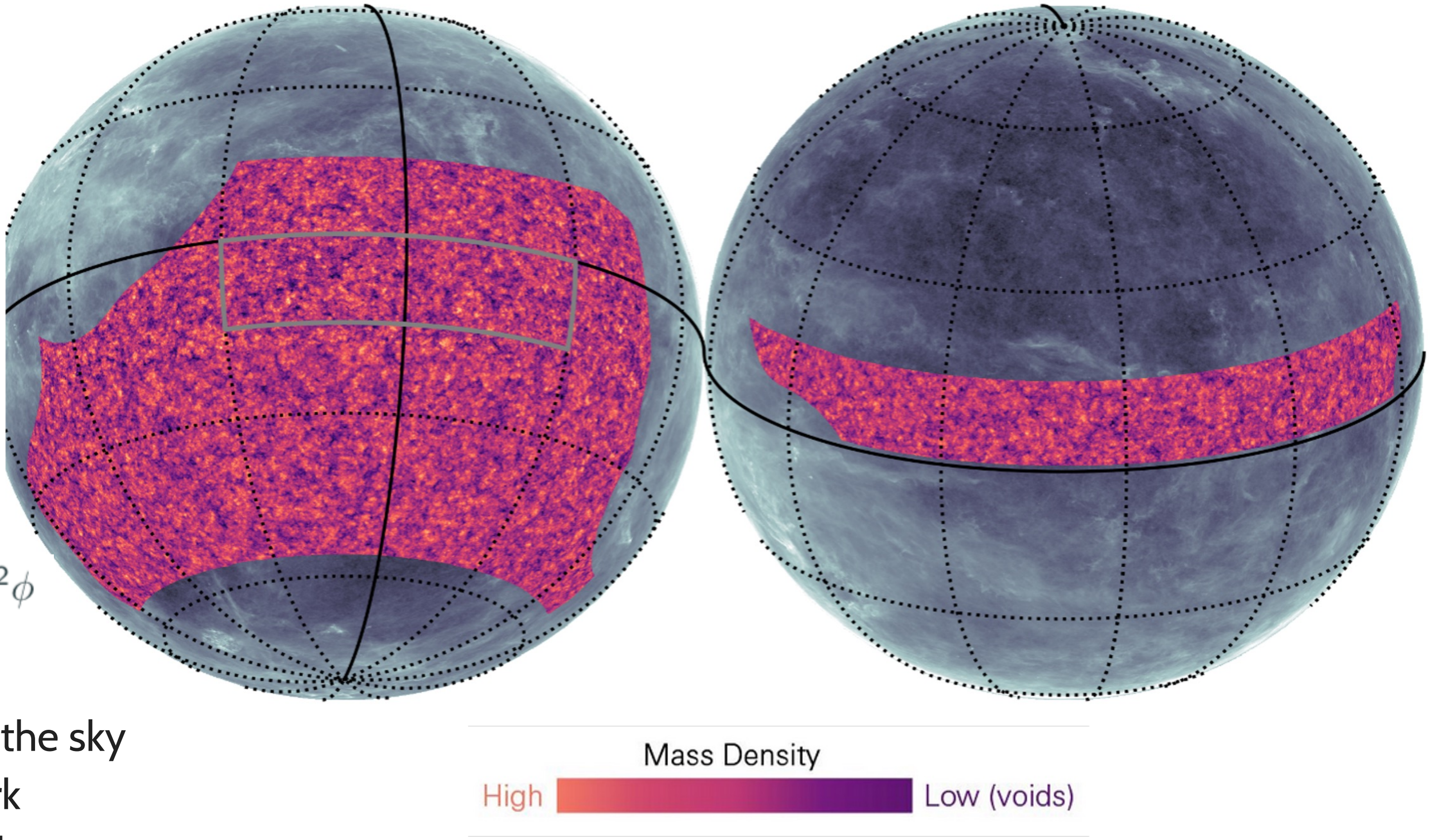
+Dongwon Han
(Cambridge)

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



Gravitational Lensing

Convergence $\kappa = -\frac{1}{2}\nabla^2\phi$

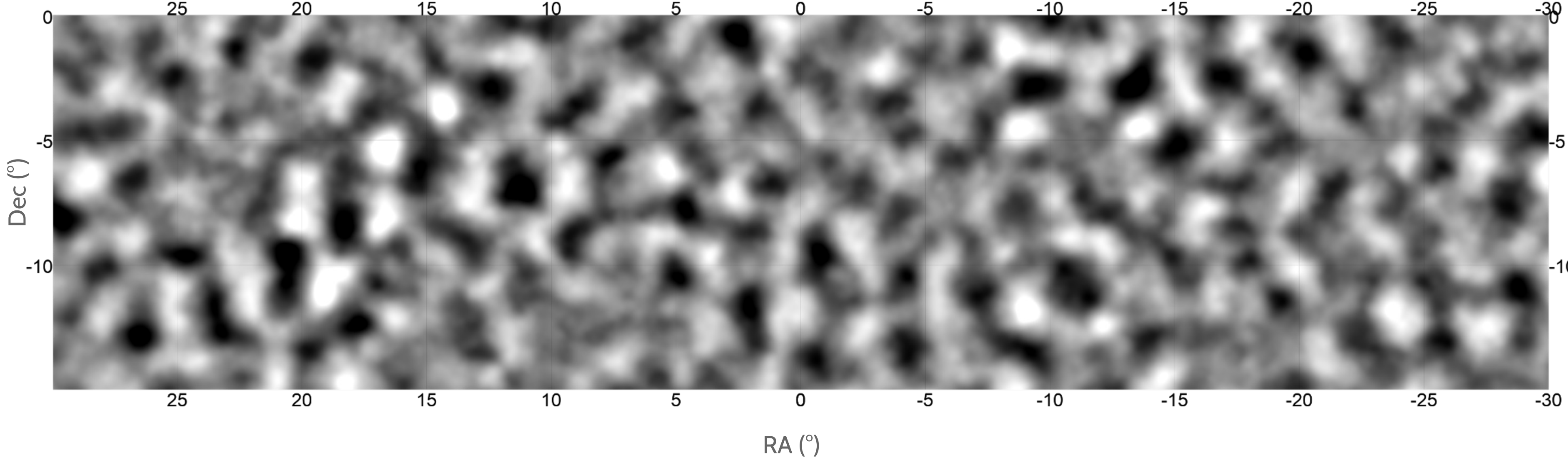
κ ∝ mass density

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

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

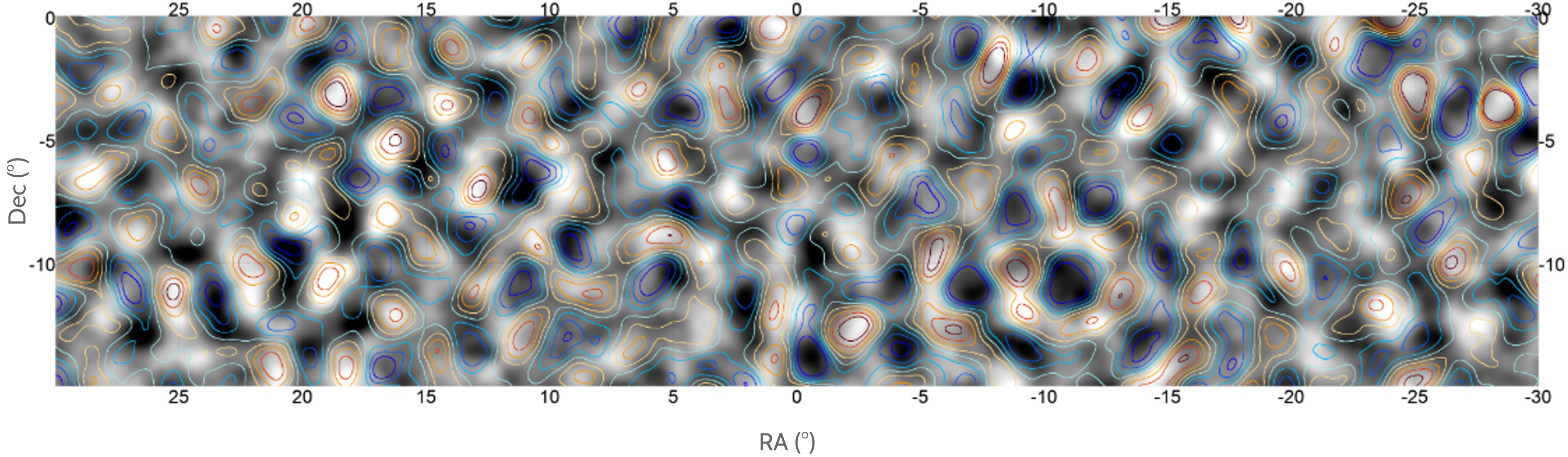
Zoom-in of 900 sq. deg. of 9400. sq. deg. mass map

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)

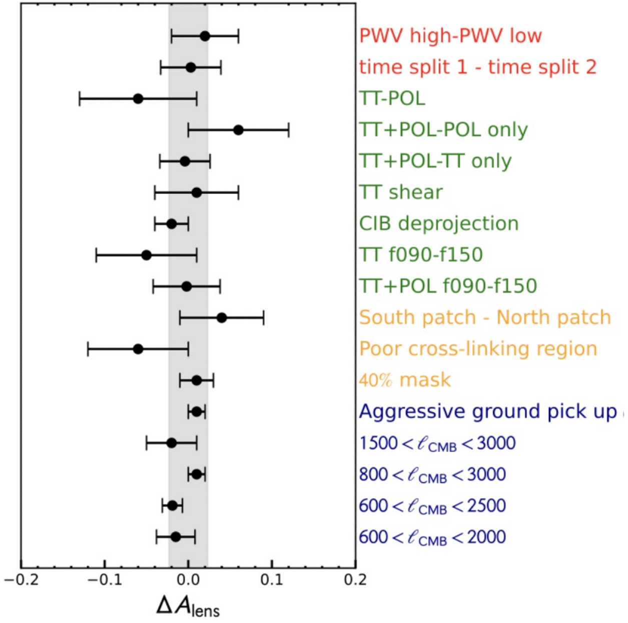


Lensing spectrum: tested with broad null test suite

$$C_L^{\phi\phi} \sim \langle \phi(\mathbf{L})\phi^*(\mathbf{L})\rangle - \text{Gaussian bias}$$

- Redundancy allows 200 null tests (!) in various categories, in blind analysis method

Frank Qu



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!

13

Two challenges: 1) noise complexity 2) foregrounds

Lensing spectrum challenge 1: Noise bias subtraction

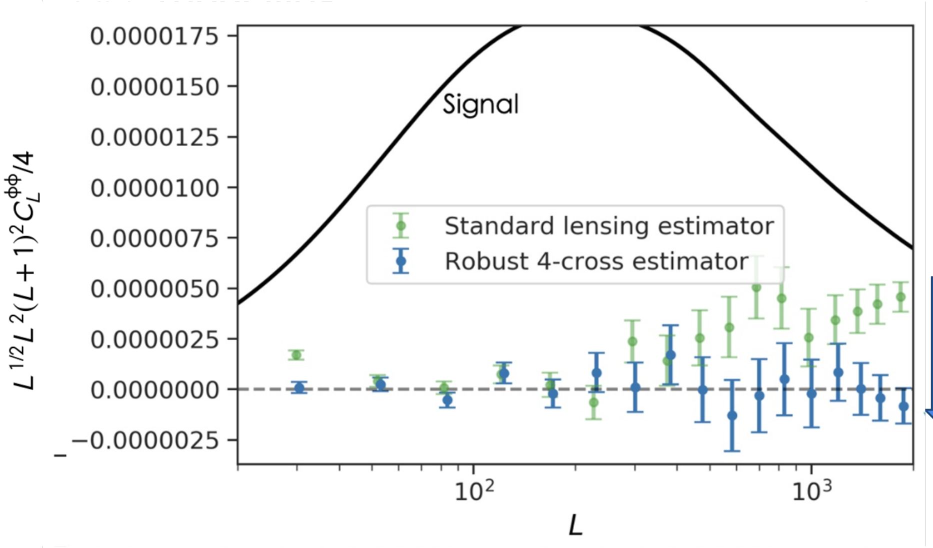
- Challenge: noise complexity causes bias subtraction problem

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

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

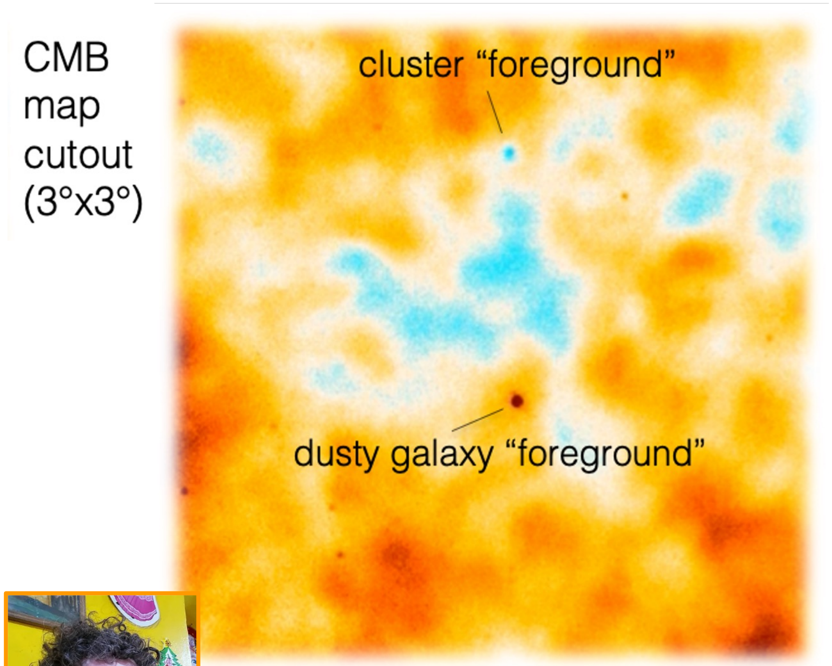
$$C_L^{\phi\phi,\mathrm{cross}} \sim \langle T_1 T_2 T_3 T_4 \rangle$$

maps with independent noise



now pass the null test with robust, new cross estimator

Lensing spectrum challenge 2: Extragalactic foregrounds

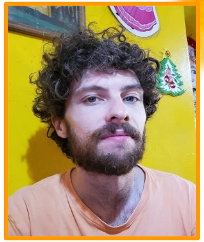


How to mitigate SZ, CIB... foreground biases?

- **Geometric** – modify estimator to be insensitive to Poisson distributed sources
  OR Sailor++2020

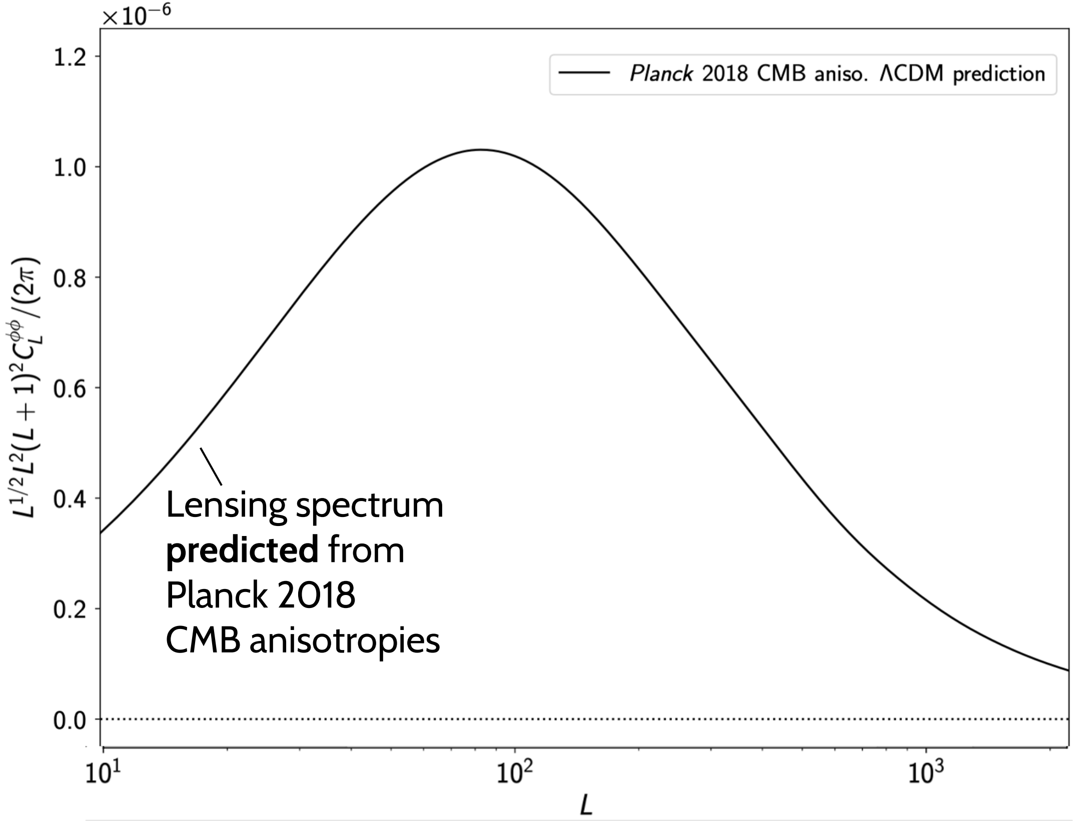
- **Frequency-based** – use data at different frequencies to remove foregrounds (e.g. "ILC")

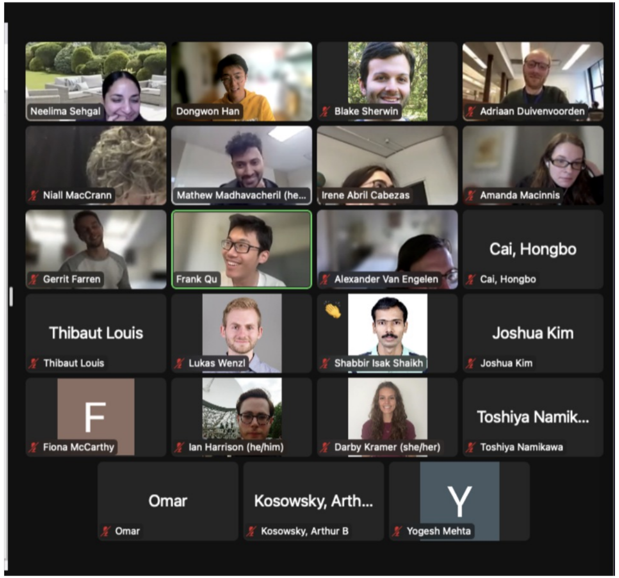
Both give negligible foreground bias in sims and data tests; both consistent



Niall MacCrann
(Cambridge)

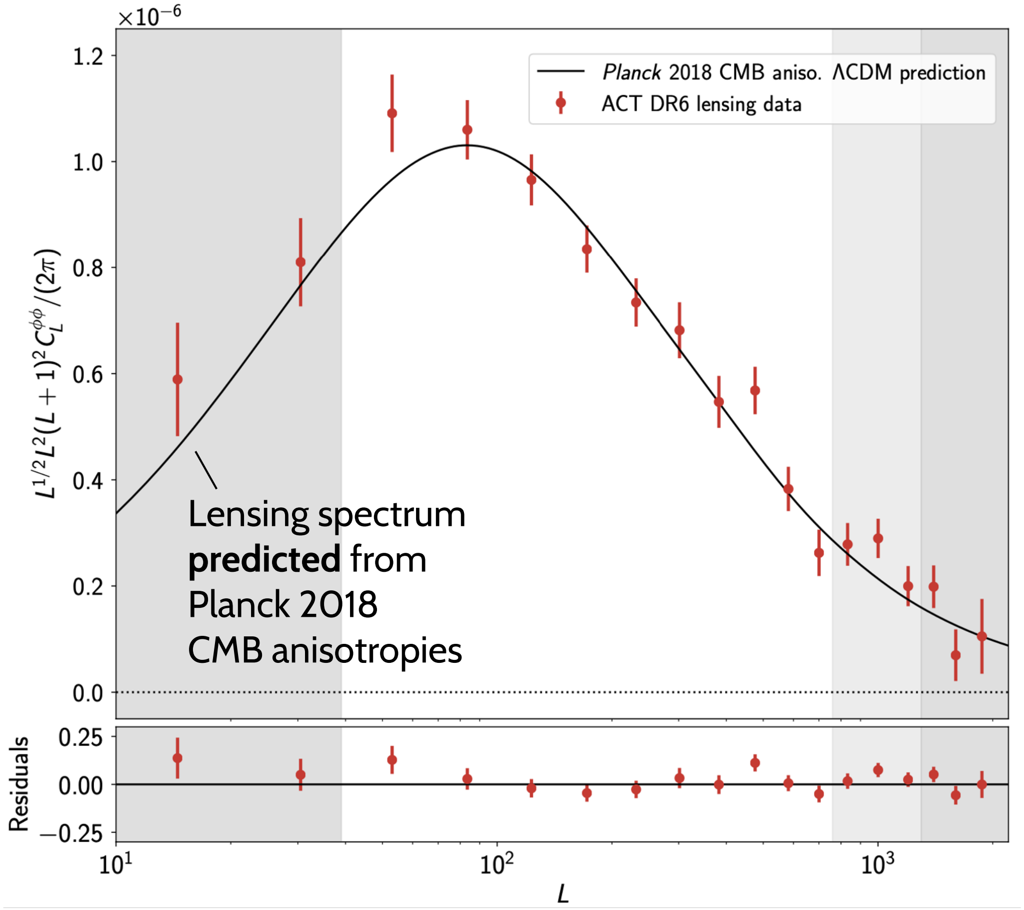
Planck CMB anisotropy prediction





Frank Qu
(Cambridge
→ Stanford)

Unblinded results: ACT DR6 lensing power spectrum

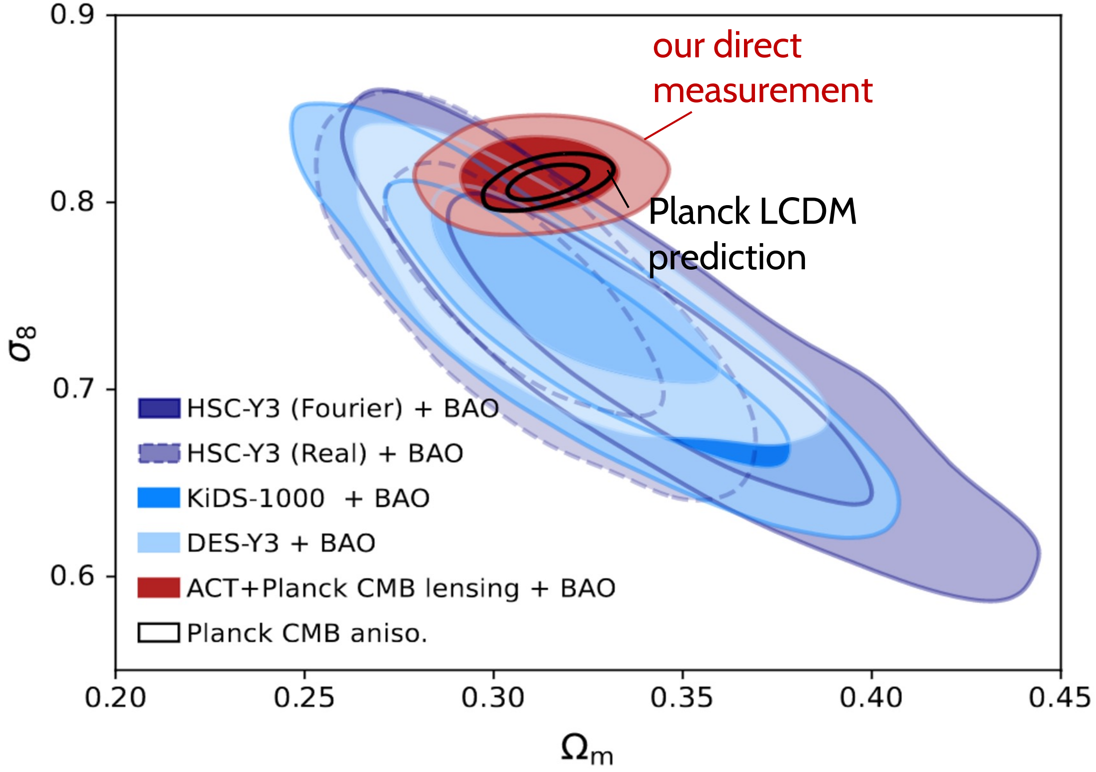


- Unblinded after passing 200+ null tests
- Agrees with the LCDM theory predictions based on CMB power spectra (PTE of 0.17). Success for LCDM!!
- SNR ~43, amplitude of lensing (relative to theory amplitude) determined to 2.3%

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

Frank Qu (Cambridge)

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

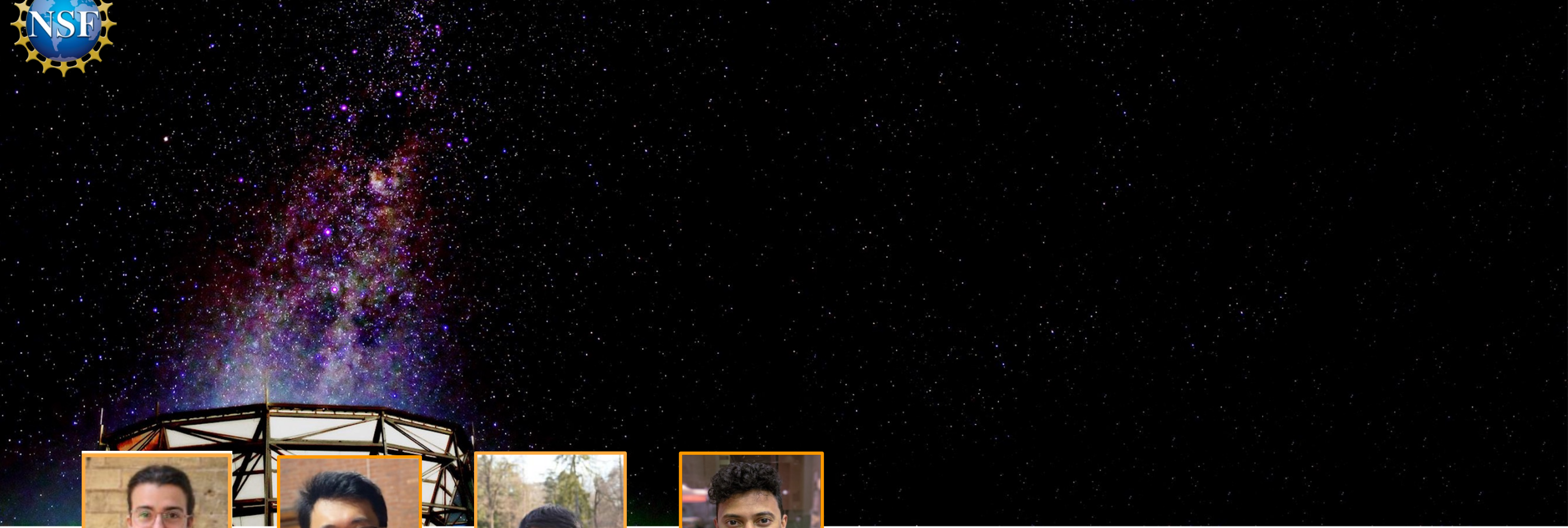


ACT/Planck lensing + BAO:

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

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



Irene Abril-Cabezas
(Cambridge)

Frank Qu
(Cambridge
→Stanford)

Joshua Kim
(U. Penn)

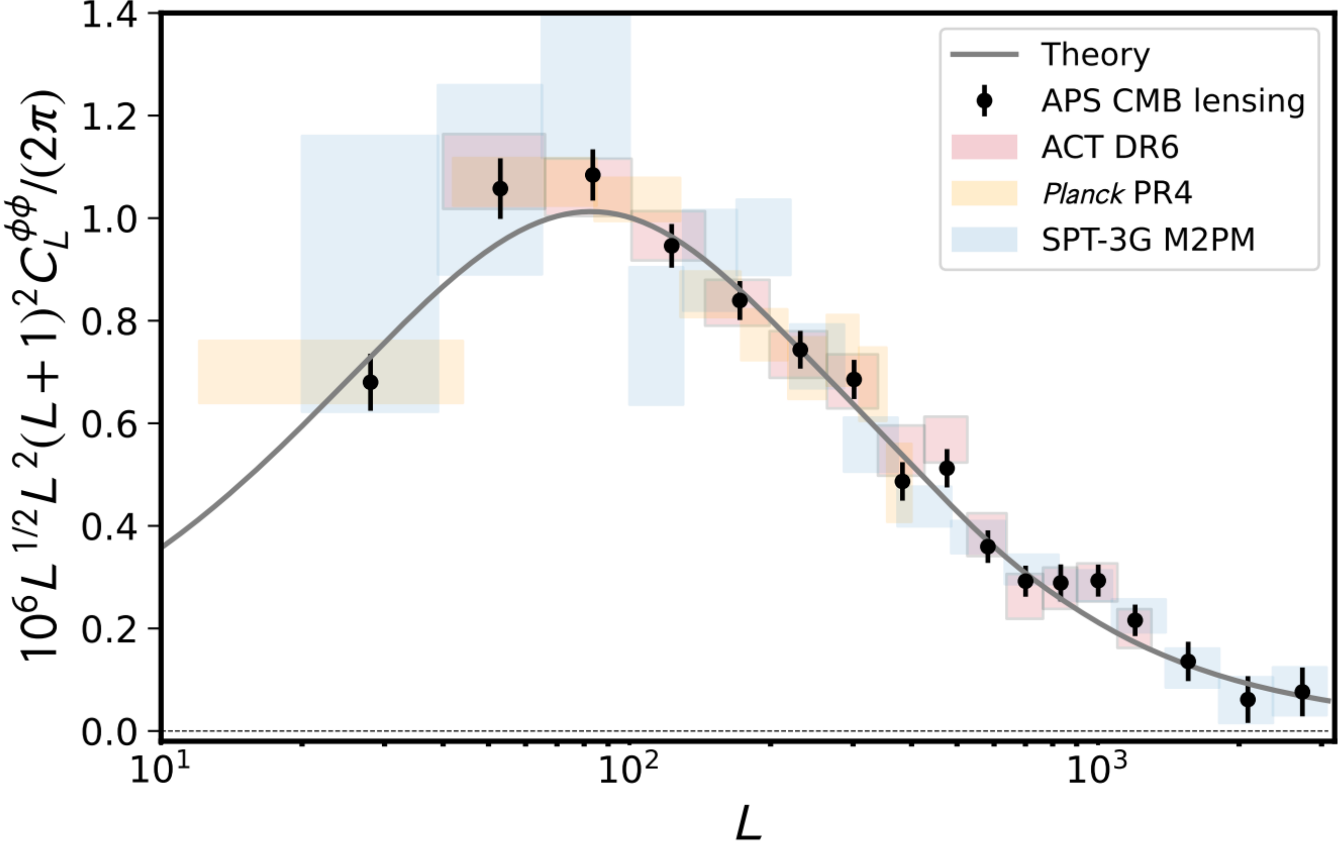
Mat Madhavacheril
(U. Penn)

+Ola Kusiak, Karen Perez-Sarmiento, Toshiya Namikawa,...

ACT and Simons Observatory: New lensing results and next steps

[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)

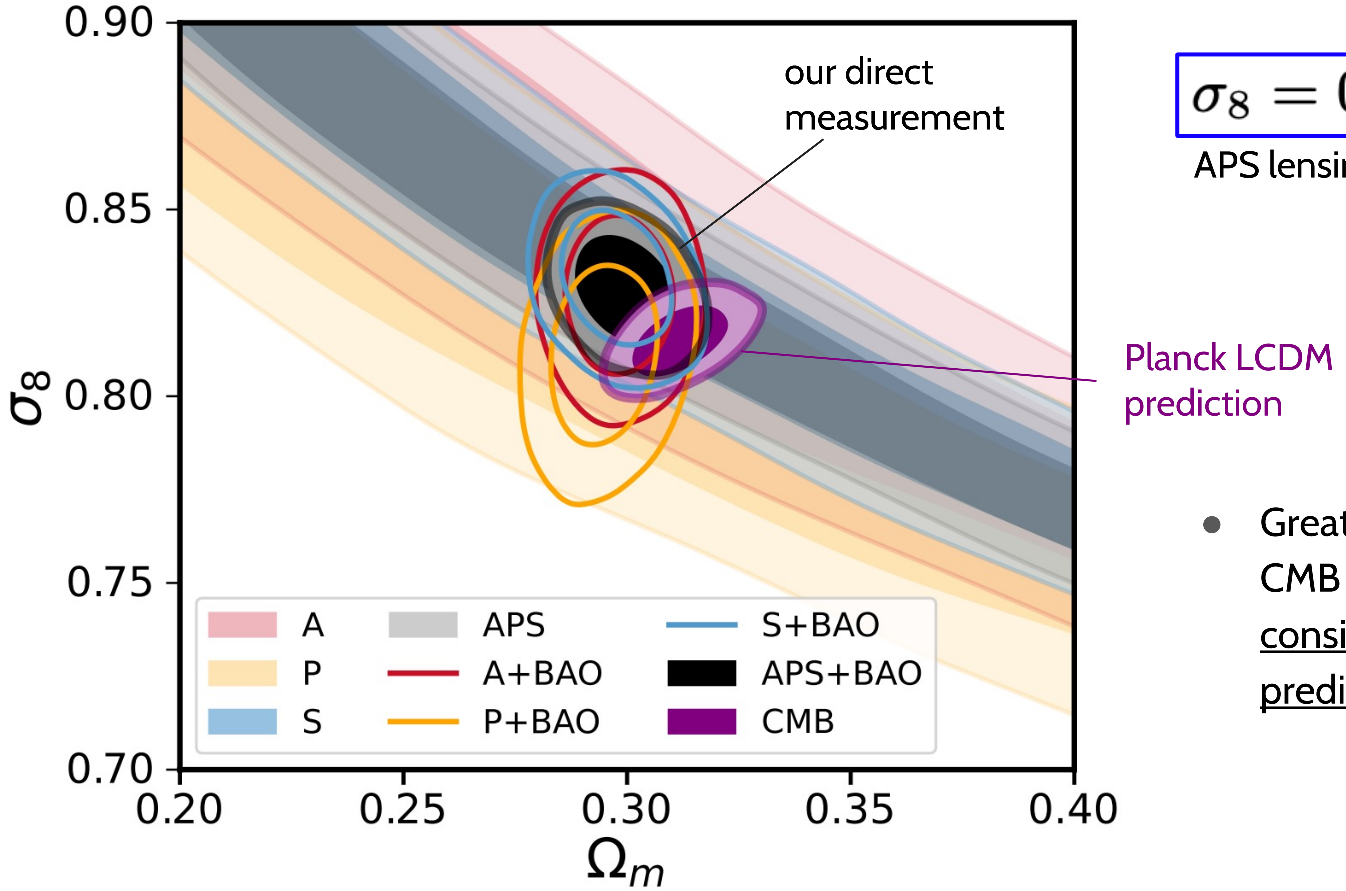


Frank Qu (Cambridge →Stanford)

Fei Ge (Stanford)

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

ACT+Planck+SPT lensing: constraints on structure growth

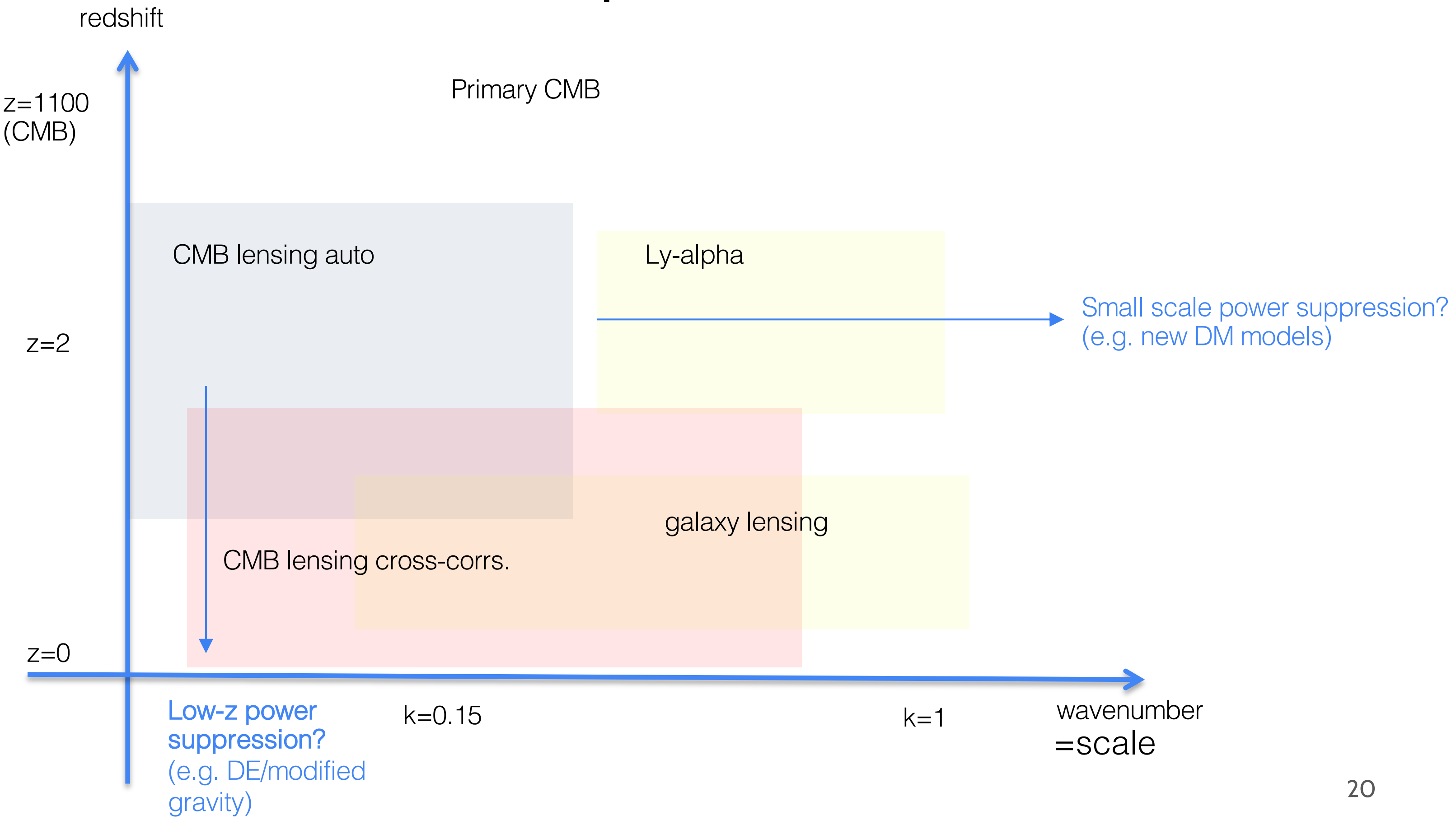


$$\boxed{\sigma_8 = 0.829 \pm 0.009}$$

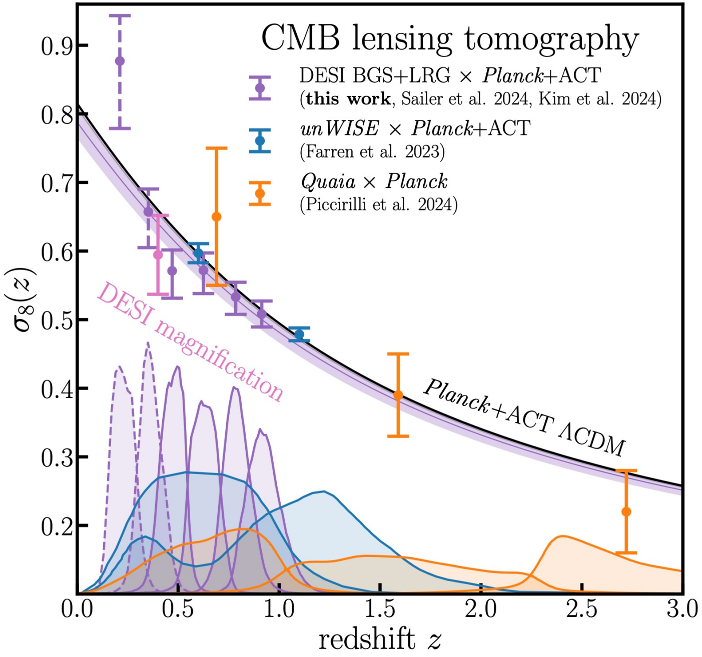
APS lensing + DESI BAO!

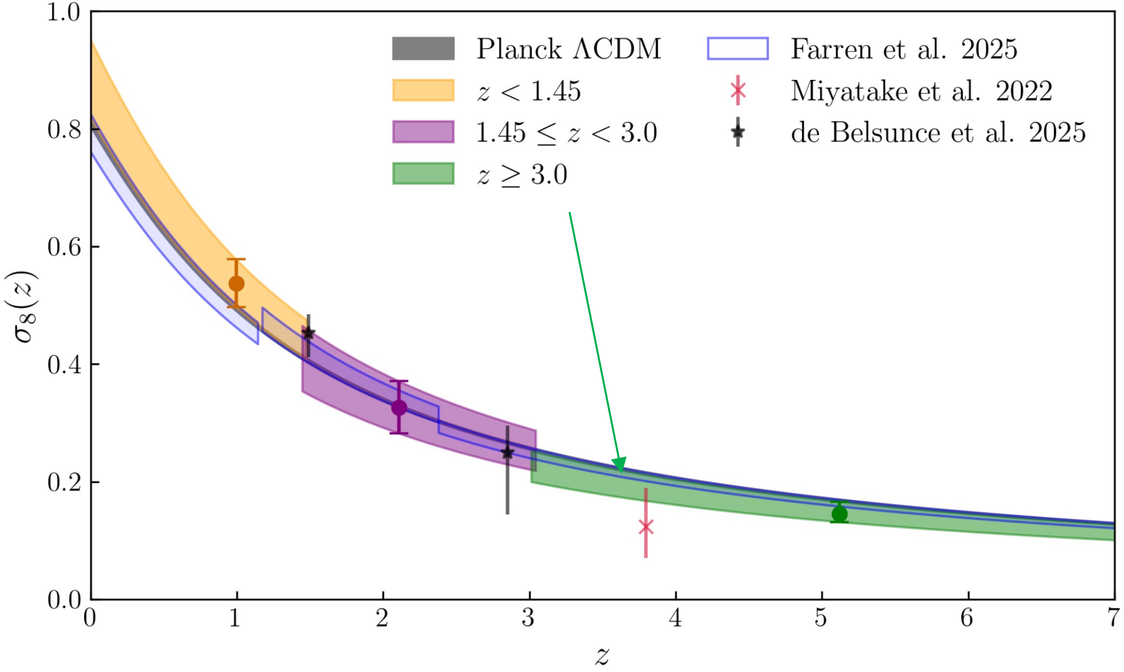
- Great consistency of different CMB lensing measurements + <u>consistency with LCDM prediction at high precision</u>

Testing structure growth in different regimes: could tensions be z-dependent (low-z) effect?



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



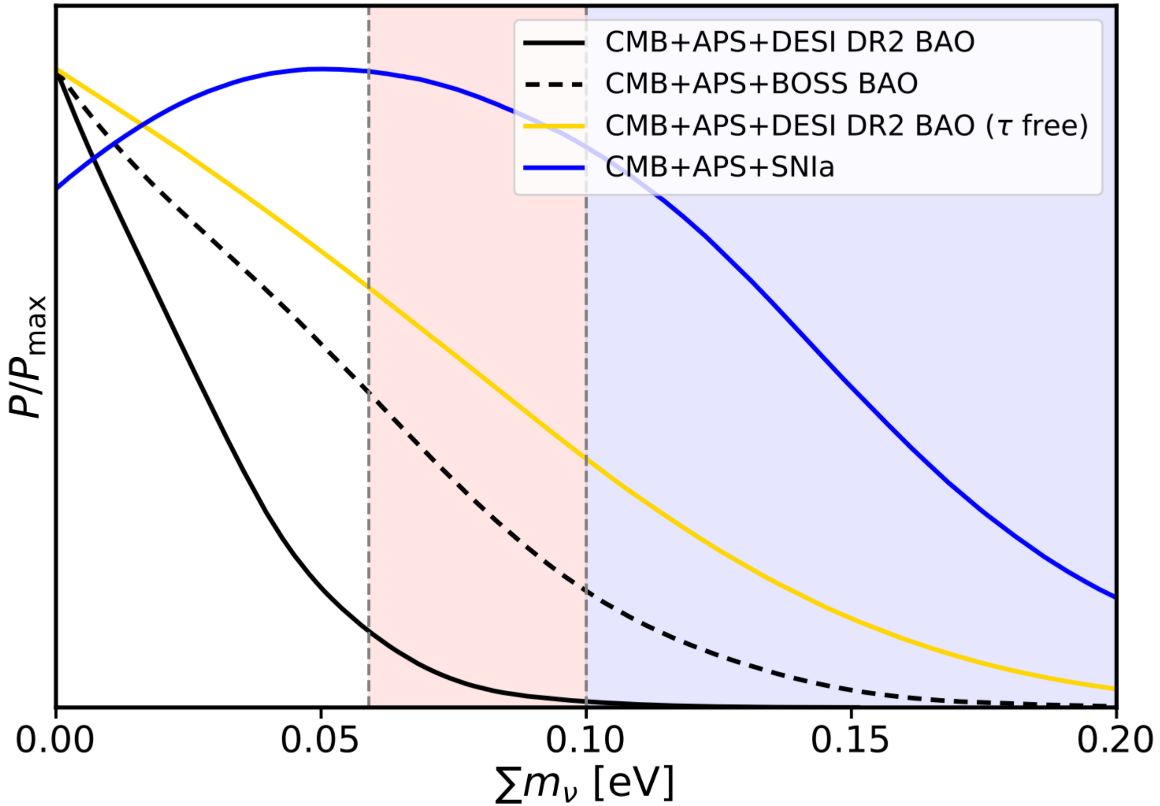


[**Gerrit Farren** et al. 2023 / 2024, **Noah Sailer/Joshua Kim** et al. 2024, **Carmen Embil-Villagra** et al. 2025]

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

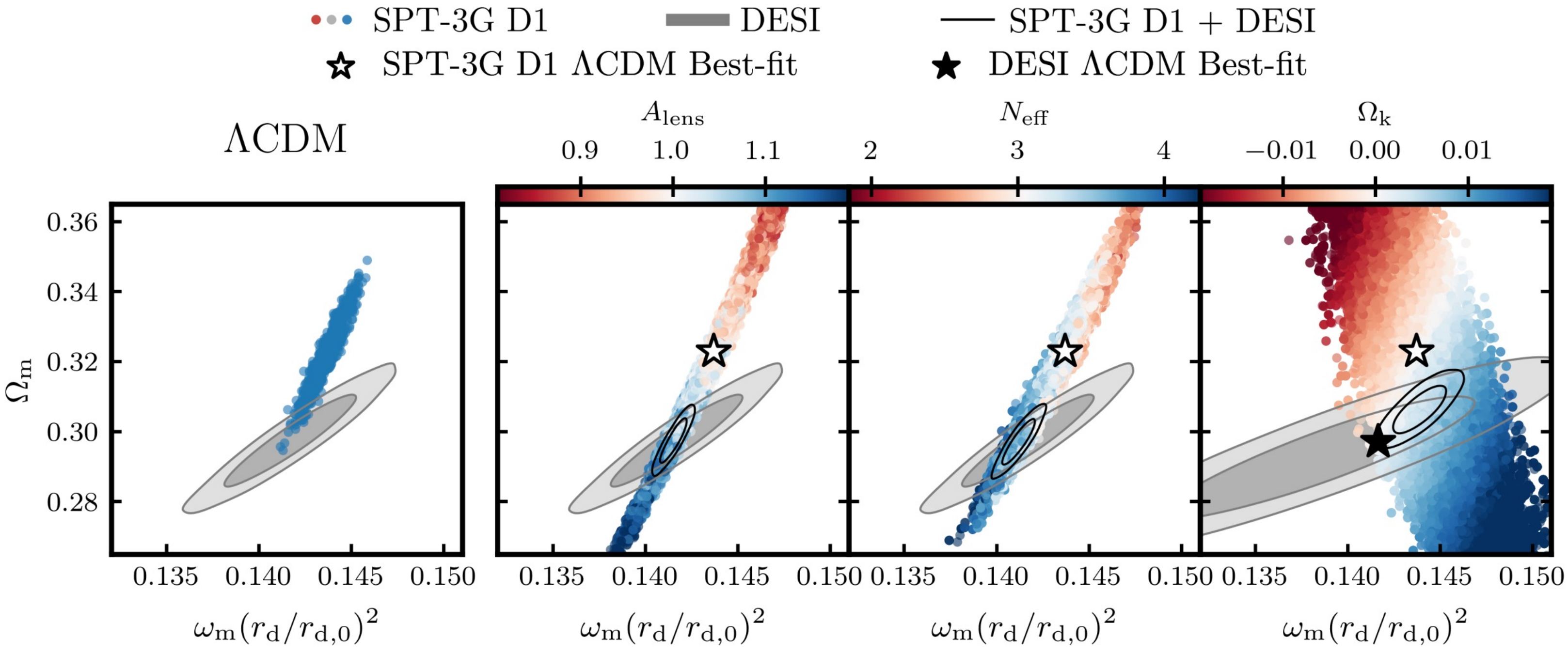
ACT+Planck+SPT lensing: constraints on neutrino mass

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



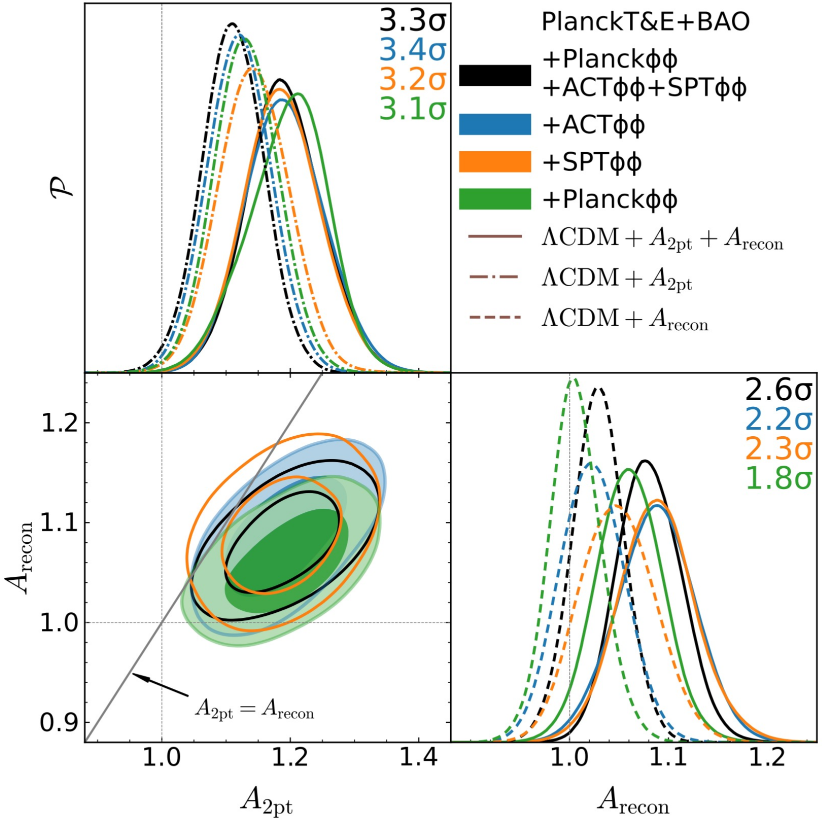
- Very tight constraints on neutrino mass $\Sigma m_\nu < 0.062$ eV (95% C.L., CMB + APS + BAO).
- Preference for unphysical "negative neutrino mass" – driven by DESI/CMB tensions

Can changing CMB lensing help?



- Changing lensing amplitude can help improve DESI-CMB consistency (but not well motivated?)

Is CMB lensing actually a bit high? Yes, relative to no-lensing cosmology



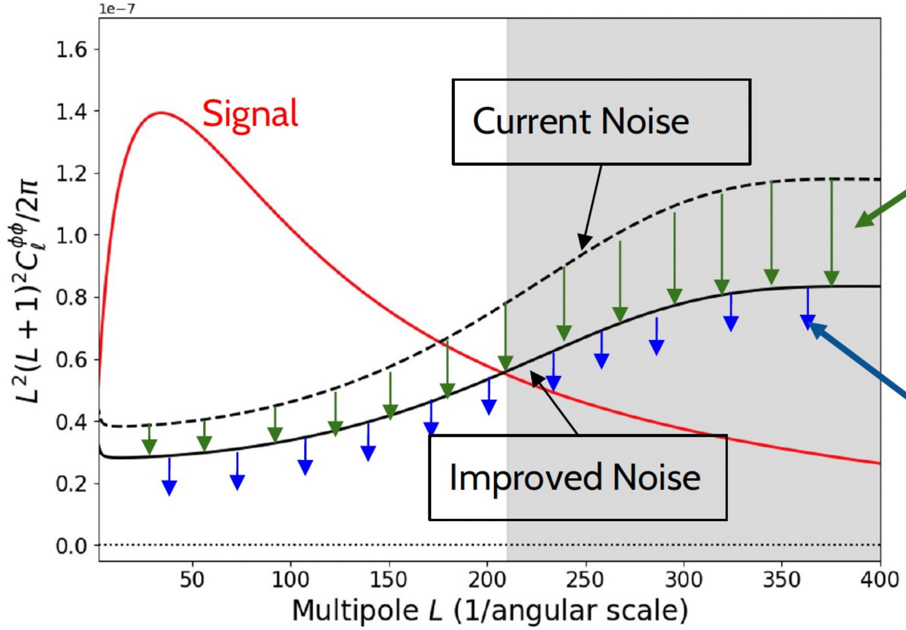
[Ge et al. 2024]

- Note: this is "worst case scenario", uses Planck PR3 not PR4, and ACT+SPT Alens not high
- My opinion – likely fluctuation rather than systematic, as T/pol and ACT/SPT/Planck consistent

Irene Abril-Cabezas

Coming soon: DR6+ lensing analysis

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



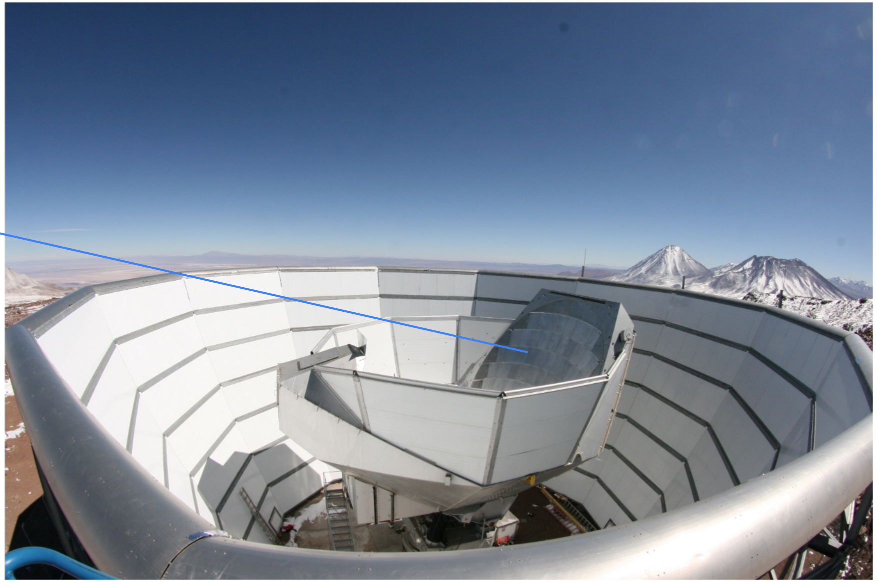
- **Inclusion of the daytime data: ~ 1.7x amount of data**

- **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 lensing: introduction

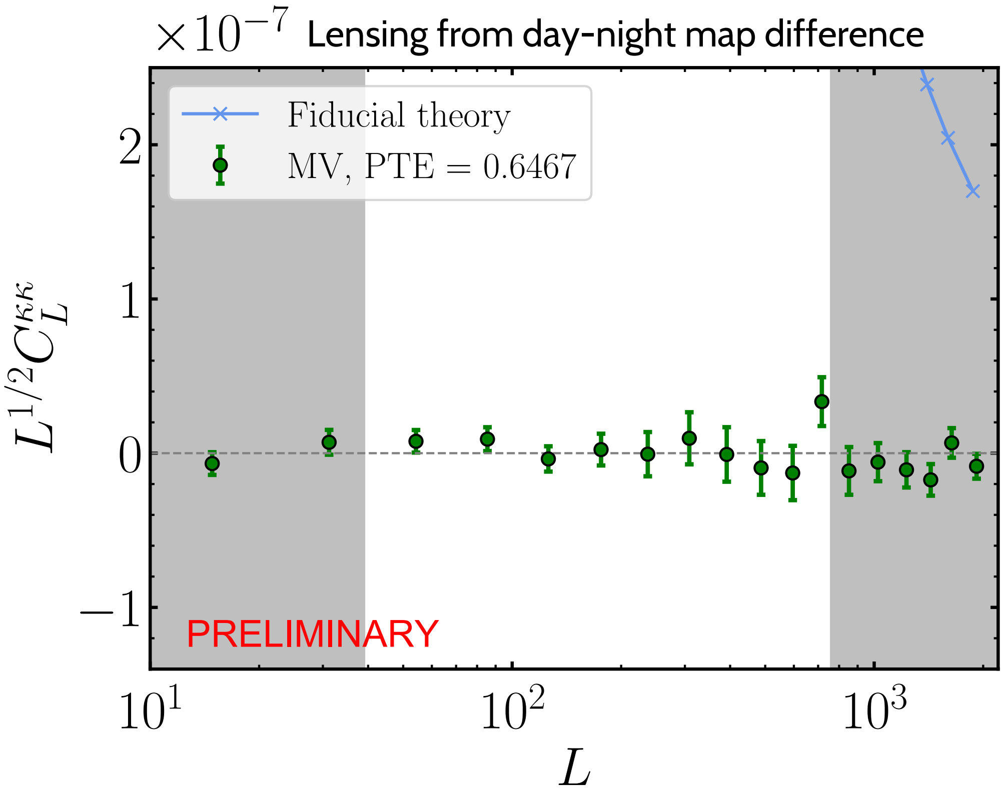
- Data taken during the day (11am-11pm)
- Challenging: Sun's heat distorts the telescope mirror, causing pointing offsets and beam deformations.
- However, nearly a factor 2 in data if we can use it!



The Atacama Cosmology Telescope (ACT)

Irene Abril-Cabezas

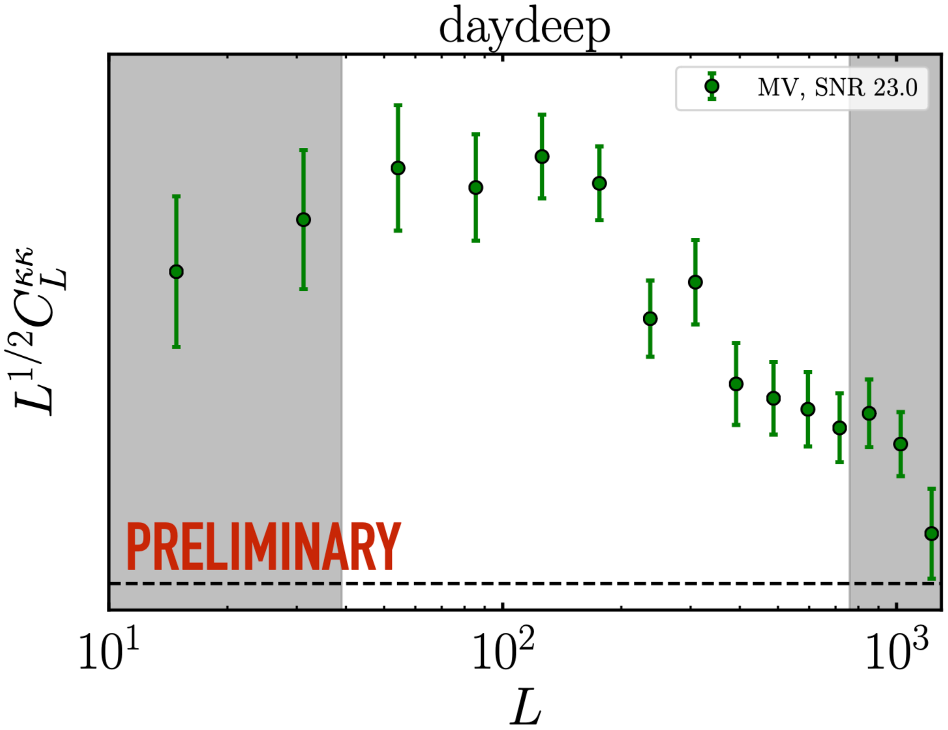
Daytime lensing: stringent null tests vs. night



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

Irene Abril-Cabezas

Daytime-only lensing spectrum and next paper outlook



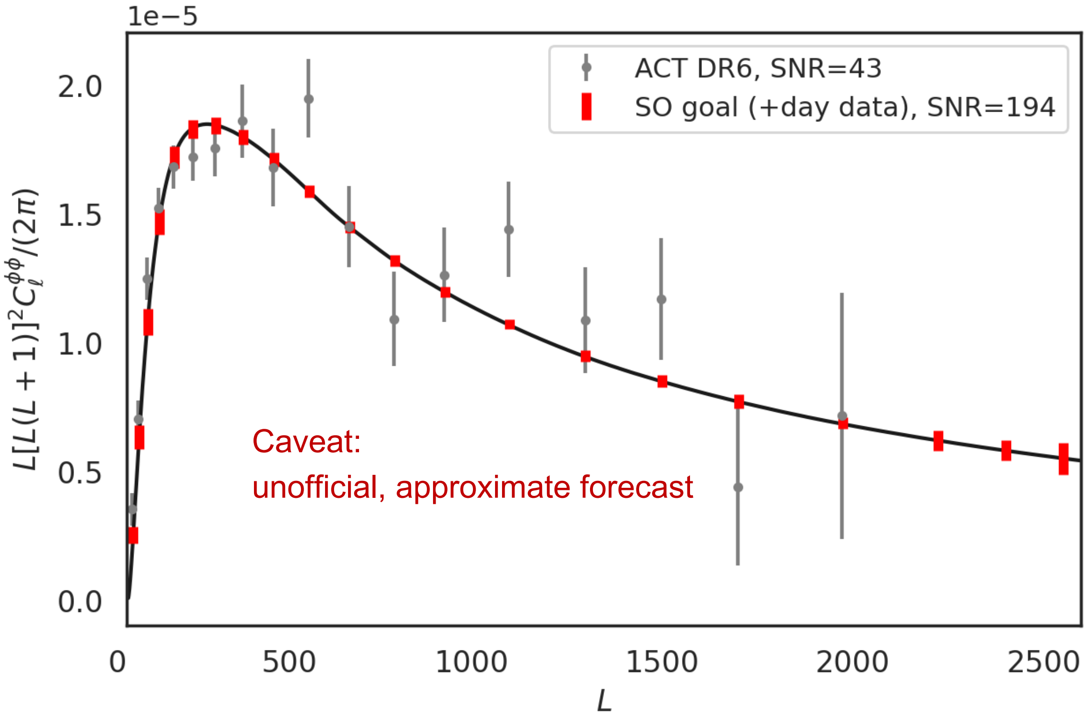
[Abril-Cabezas et al. in prep.]

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

Irene Abril-Cabezas

Simons Observatory (SO)

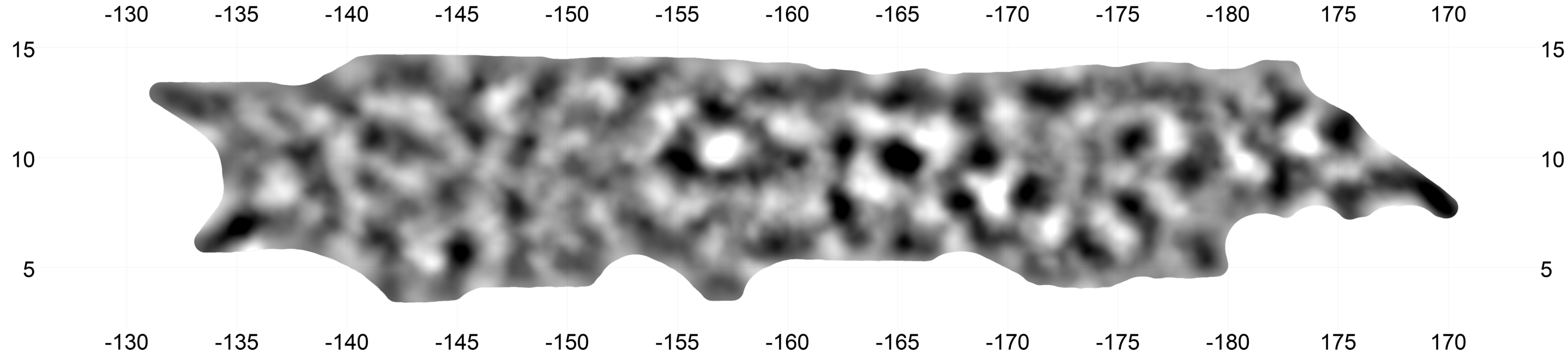
Simons Observatory: Remarkable potential for CMB lensing



- Basic SO lensing forecasts: already impressive, SNR~130
- But daytime lensing and other new methods may allow further improvements

Preview: first look at Simons Observatory lensing

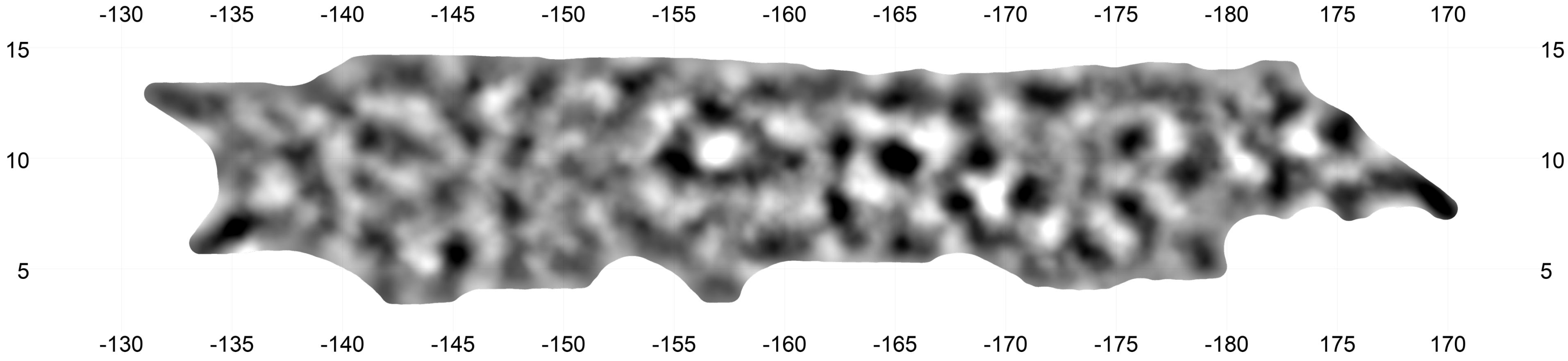
Lensing map from just 144 hours of observations [A. Kusiak, K. Perez-Sarmiento++]

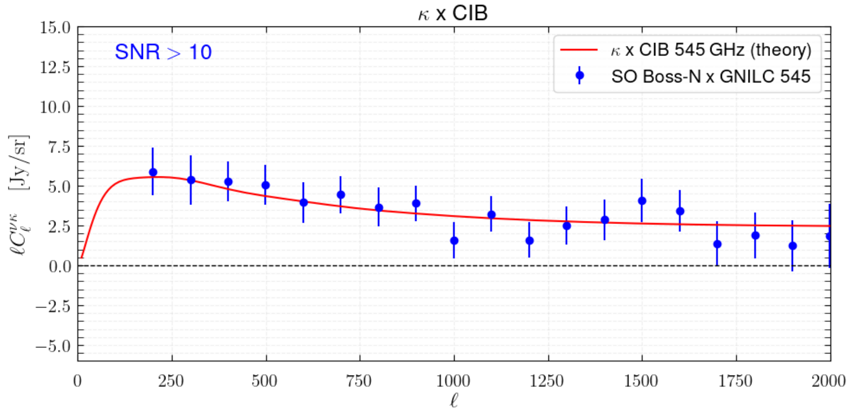


Ola
Kusiak
(Cambridge)

Preview: first look at Simons Observatory lensing

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





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

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

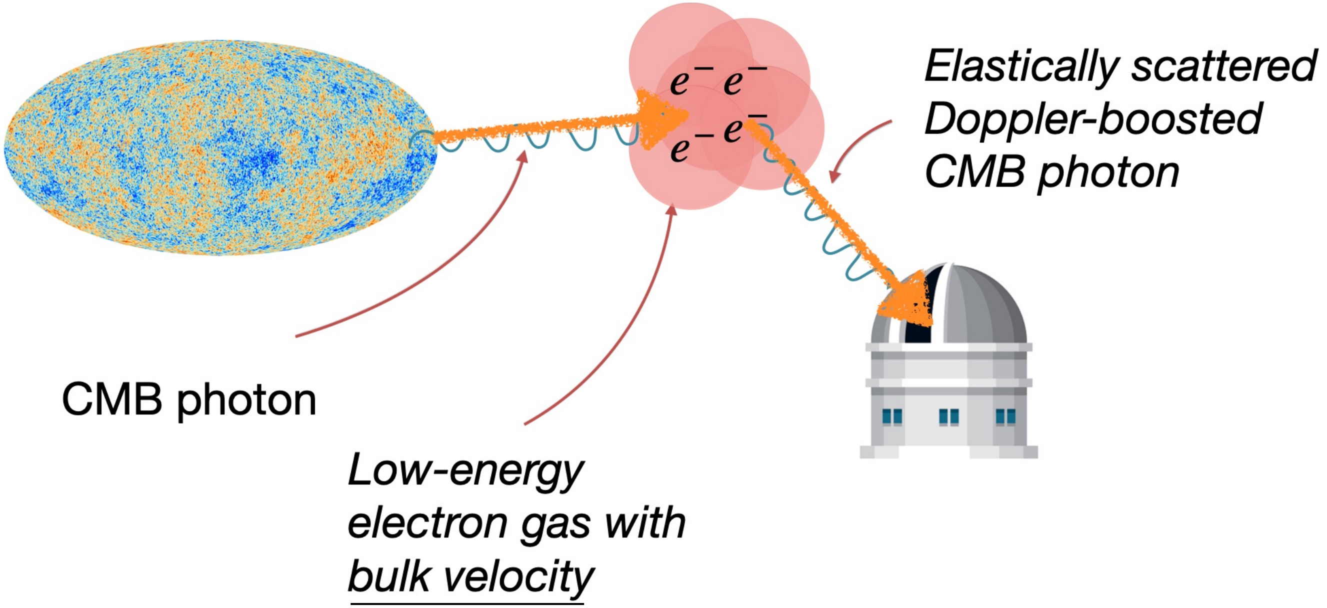
II. A new probe of primordial non-Gaussianity: first demonstrations of kSZ velocity reconstruction

[McCarthy et al. 2024]

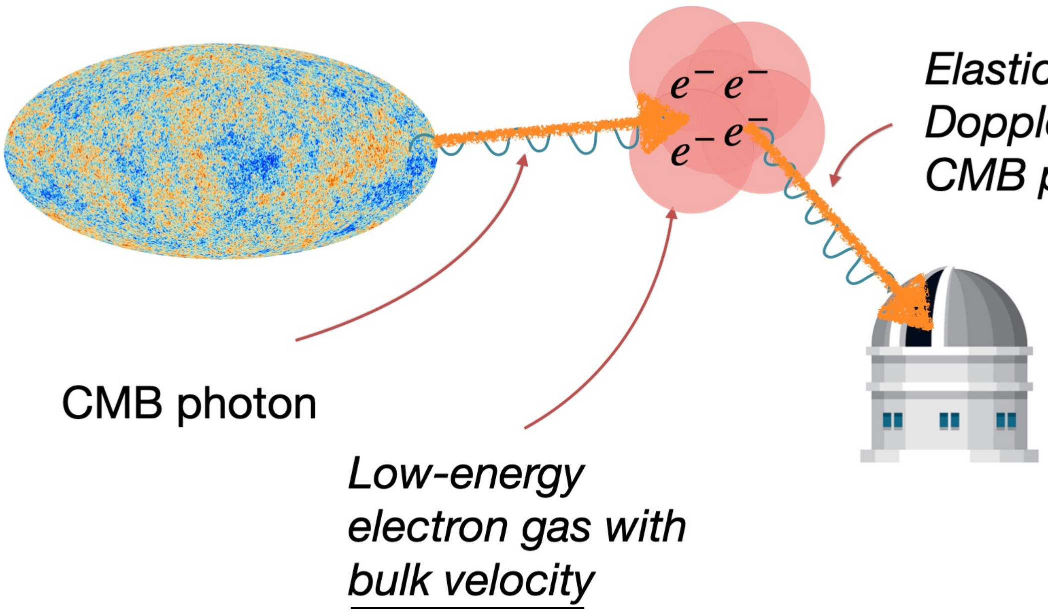
Fiona McCarthy (Cambridge)

European Research Council
Established by the European Commission

The kinetic Sunyaev-Zel'dovich (kSZ) effect



The kinetic Sunyaev-Zel'dovich (kSZ) effect



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

Electron density

$$\frac{\delta T}{T} = \int d\chi n_e \sigma_T v$$

Velocity

kSZ velocity reconstruction using CMB and galaxy density

- Reconstruct v with quadratic estimator (CMB, galaxies)

$$\hat{v}(\mathbf{L}) \sim \int dl \; T(\mathbf{l}) g^*(\mathbf{l} - \mathbf{L})$$

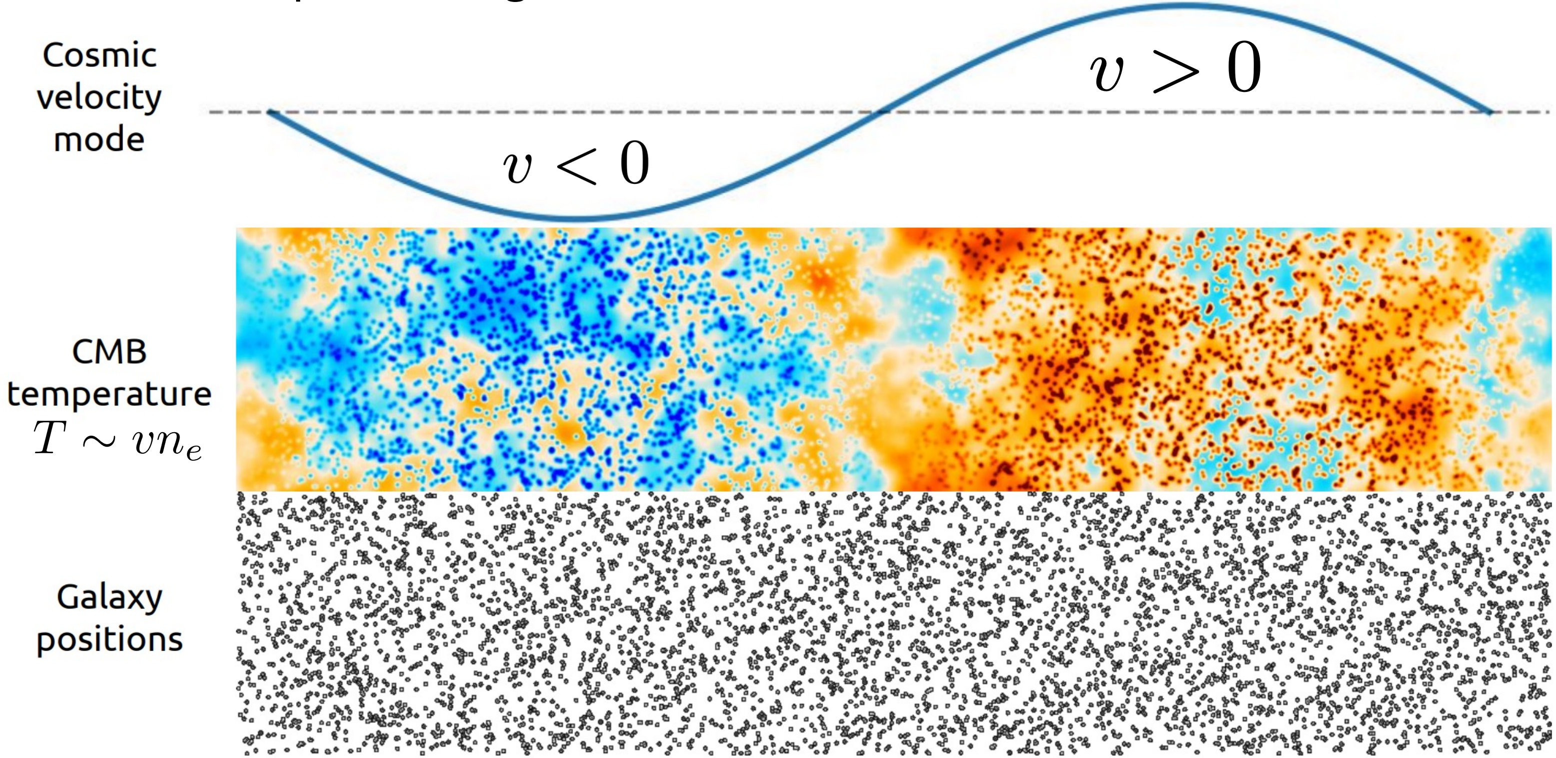
[Muenchmeyer et al. 2019]

[Note: I will discuss 2D reconstruction with projected tracers in redshift bins – arguably a natural formalism for photometric samples (LSST etc.)]

kSZ velocity reconstruction using CMB and galaxy density

- Reconstruct v with quadratic estimator (CMB, galaxies)
- Intuition: v-dependent T-g correlation

$$\hat{v}(\mathbf{L}) \sim \int dl\ T(\mathbf{l})g^*(\mathbf{l}-\mathbf{L})$$

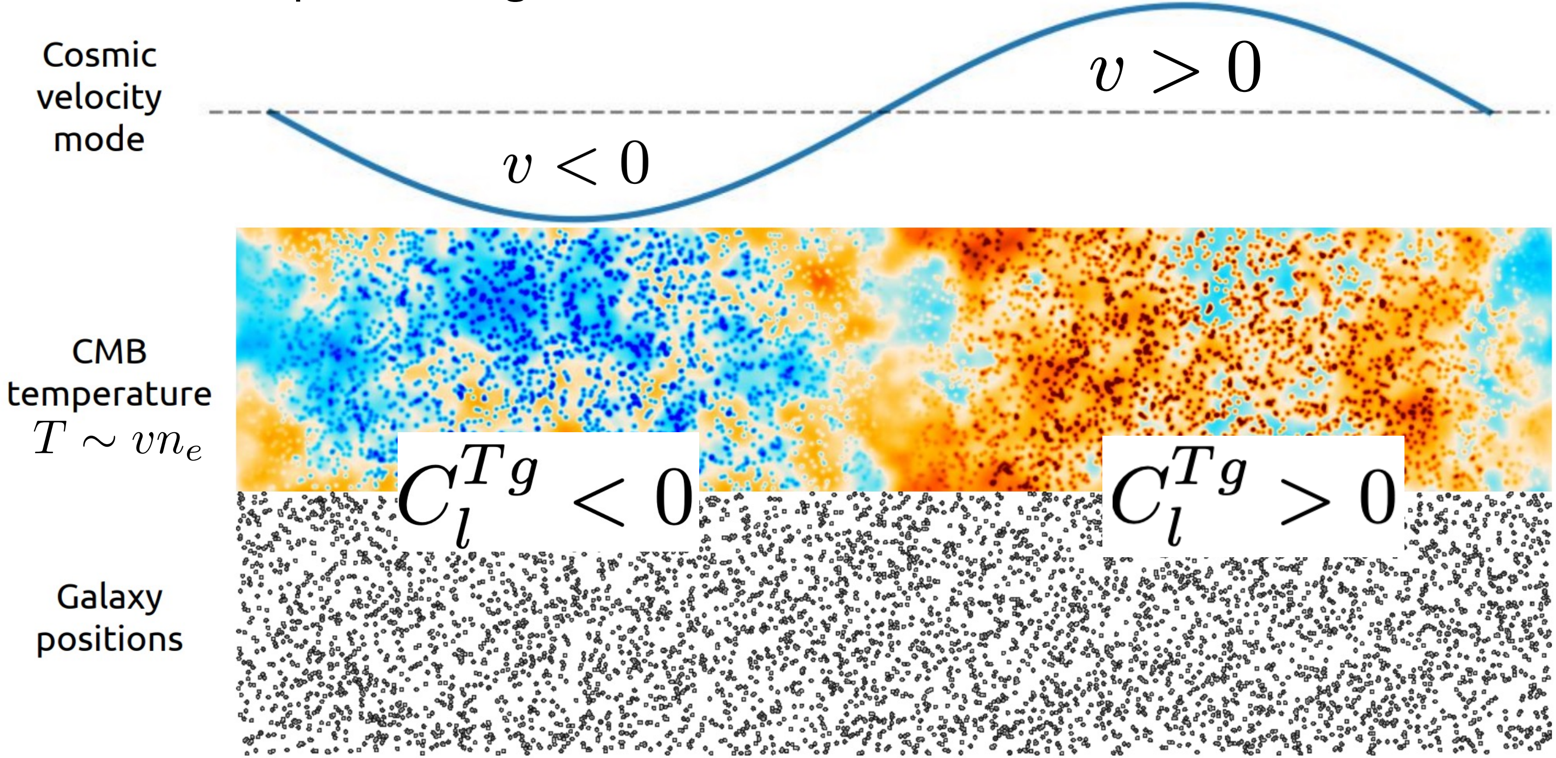


[Image. M. Madhavacheril]

kSZ velocity reconstruction using CMB and galaxy density

- Reconstruct v with quadratic estimator (CMB, galaxies)
- Intuition: v-dependent T-g correlation

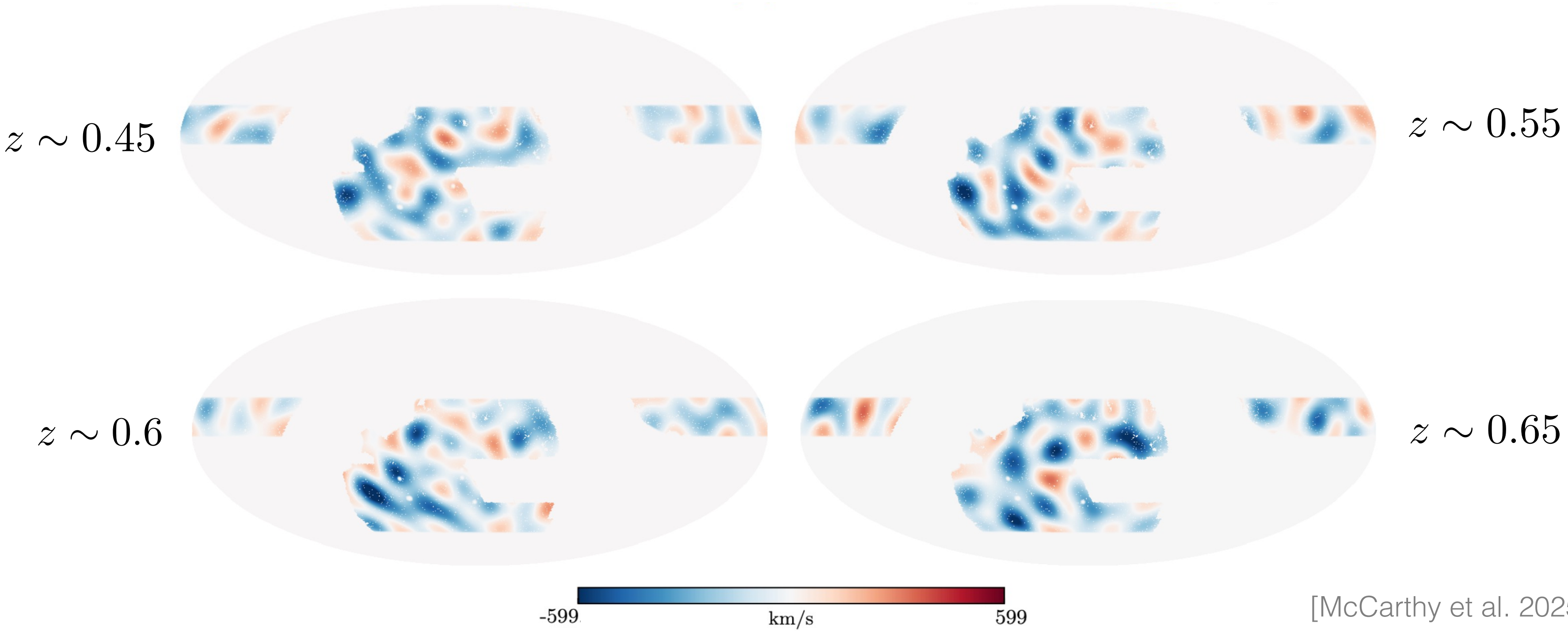
$$\hat{v}(\mathbf{L}) \sim \int dl \; T(\mathbf{l}) g^*(\mathbf{l}-\mathbf{L})$$



[Note: all astrophysical complications (relating electrons to galaxies) absorbed in overall constant bias factor]

Cosmic velocity maps, a new probe of the early universe

first radial velocity maps (at still low SNR of 3.8) from the kinetic Sunyaev-Zel'dovich effect
[made by Fiona McCarthy]



[McCarthy et al. 2025]

- With new methods and new Simons Obs. data, potential to improve velocity precision by 10x
- Easily convert to density $v \leftrightarrow \frac{-i\mathbf{k}faH}{k^2}\delta_m$ – great probe of largest-scale modes

Primordial non-Gaussianity: Challenges in measuring scale dependent bias

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

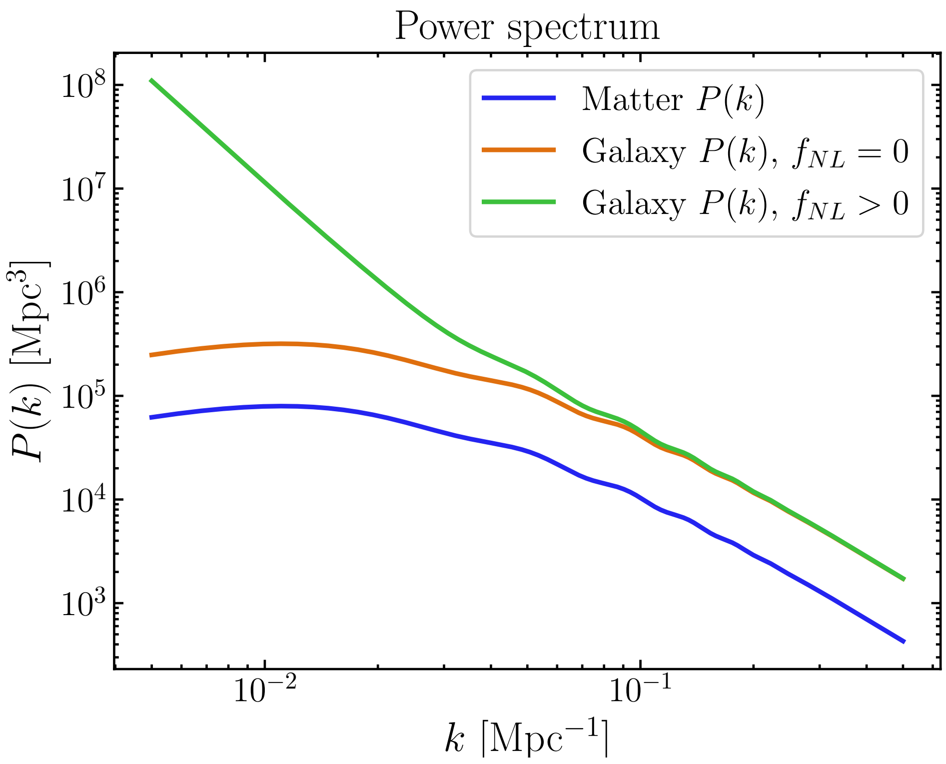
- Scale dependent galaxy bias is a key signature for local non-Gaussianity, but two challenges:

- 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 large scale velocity from kSZ

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

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

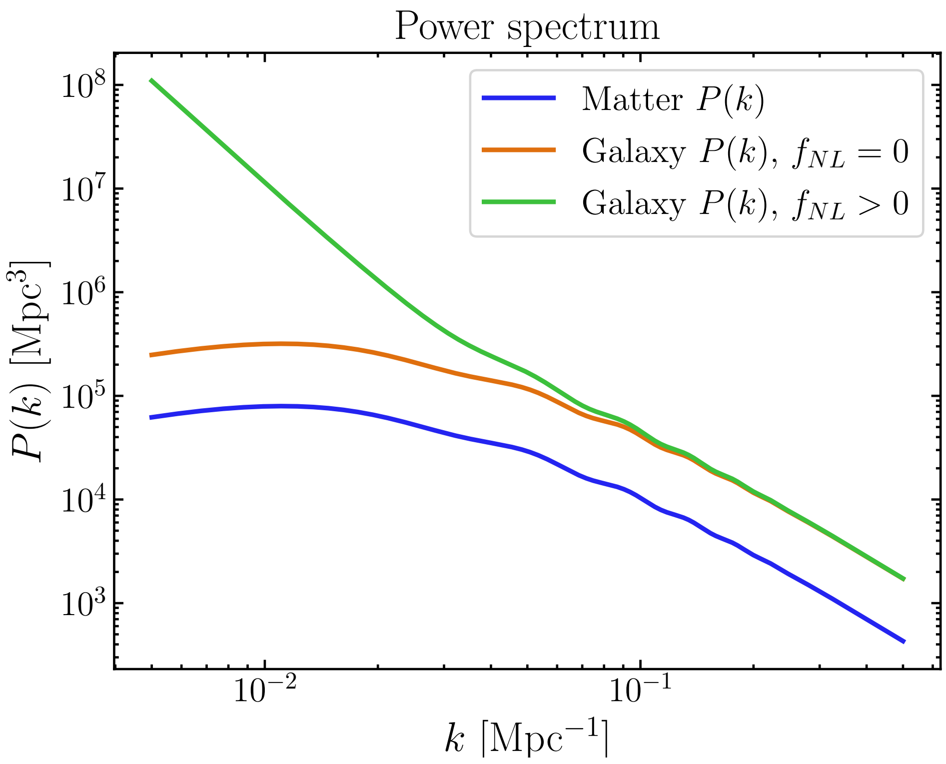
$$\hat{P}_{gX}(k) = P_{gX}(k)$$

overcome via cross-correlation!

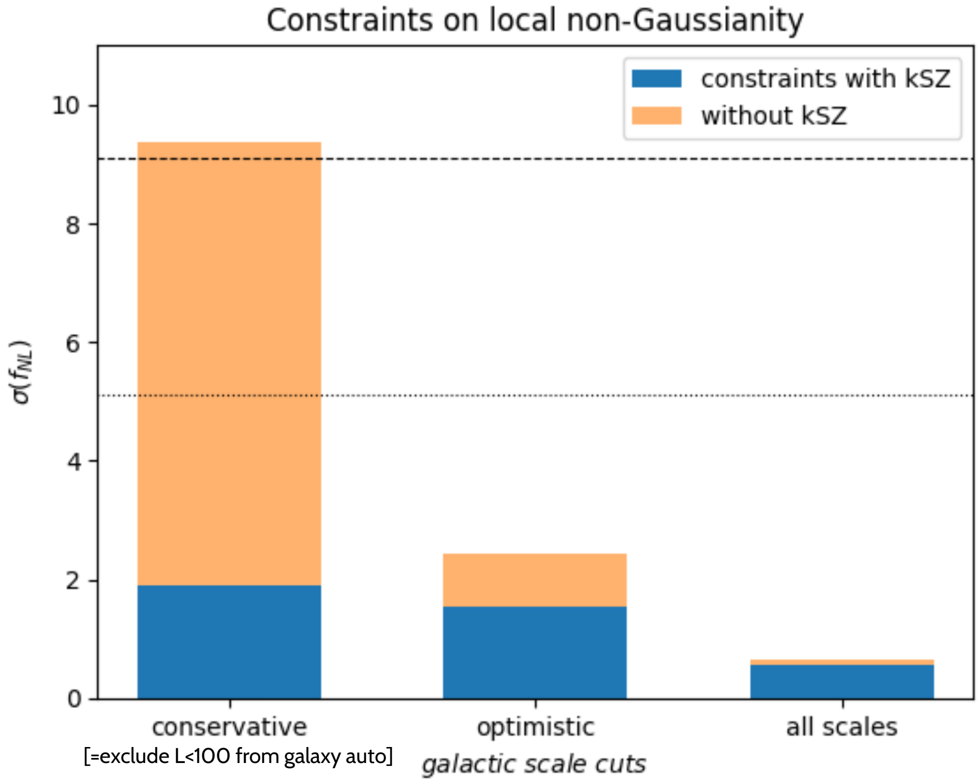
- Large-scale sample variance

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

reduce via sample variance cancellation



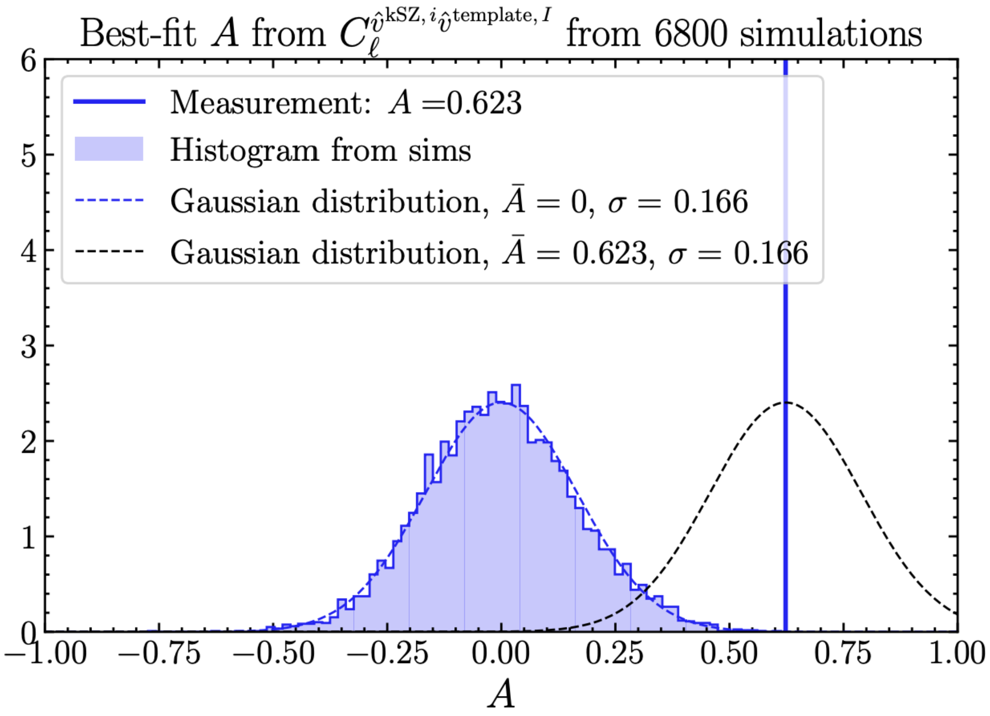
kSZ velocity reconstruction:
More reliable f_{NL} from cross-correlations alone (SO x LSST forecast)



[=exclude L<100 from galaxy auto]

- Great potential! But, until recently, no significant measurement of velocity with kSZ

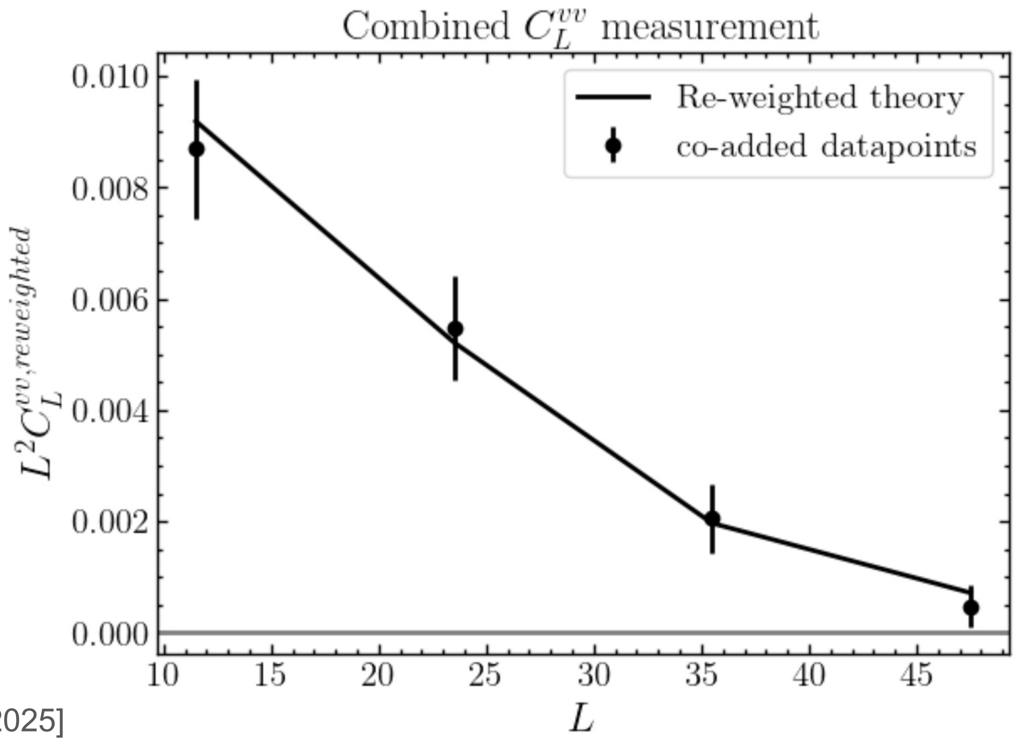
kSZ velocity reconstruction in data: rapid progress



[McCarthy et al. 2024]

- First demonstration: correlate with BOSS galaxies, measure amplitude A – seen at 3.8 sigma

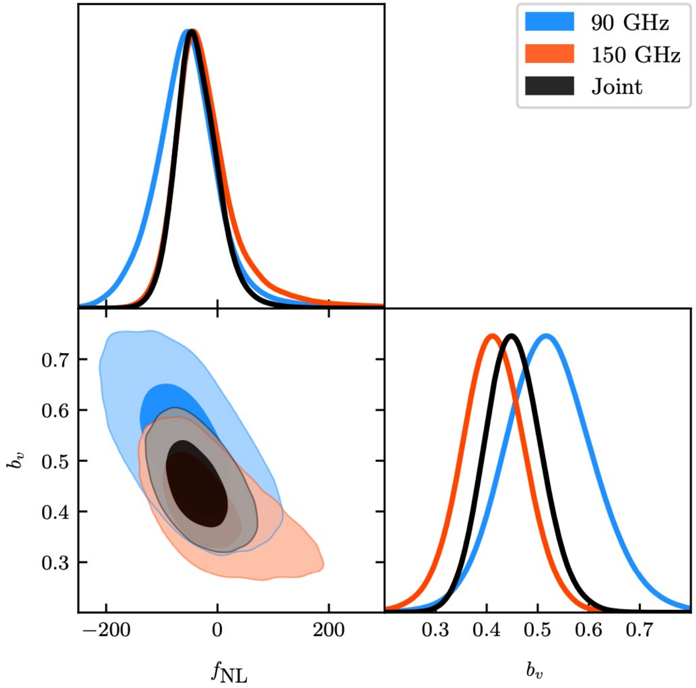
kSZ velocity reconstruction in data: rapid progress



[McCarthy et al. in prep. 2025]

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

kSZ velocity reconstruction in data: rapid progress (see Edmond's talk!)



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

- With kSZ velocity reconstruction, un-measured until last year, f_{NL} constraint has already reached +/-40 [only a few times worse than best galaxy constraints] – rapid progress

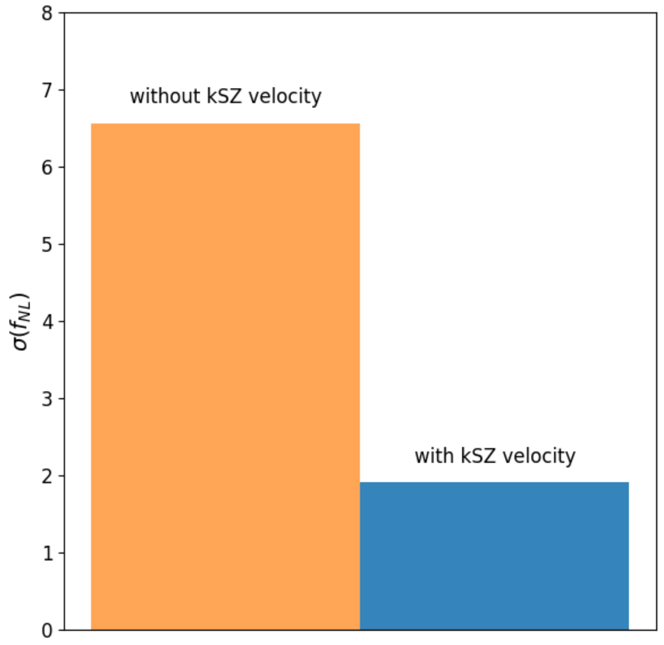
Challenges and Open Questions

To reach powerful early universe constraints with SO + LSST:

- More work on impact of foreground systematics in 2D reconstruction [Understand separation better in 2D, test approximations]
- What is the impact of galaxy systematics – fully nulled?
- How to jointly constrain velocities and baryons with kSZ?

...

Ongoing research!



Summary

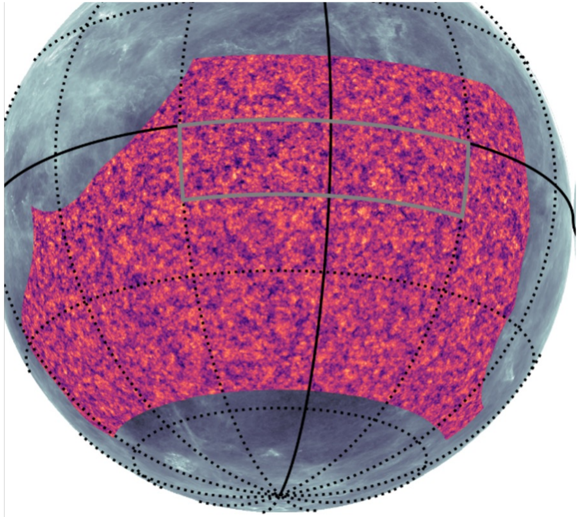
- To test cosmic structure growth and neutrino masses: high-fidelity lensing mass maps, CMB lensing power spectra from ACT with state-of-art precision.

- 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

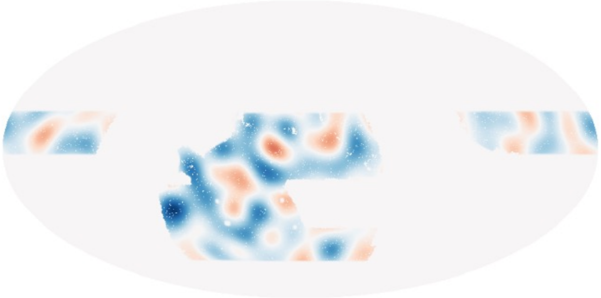
- Coming soon: DR6+ lensing analysis with improved SNR of 60-70; key source of improvement: first analysis of ACT daytime observations. Then SO!

- Also: first demonstration of kSZ velocity reconstruction – promising technique for reliably constraining early universe physics

mass



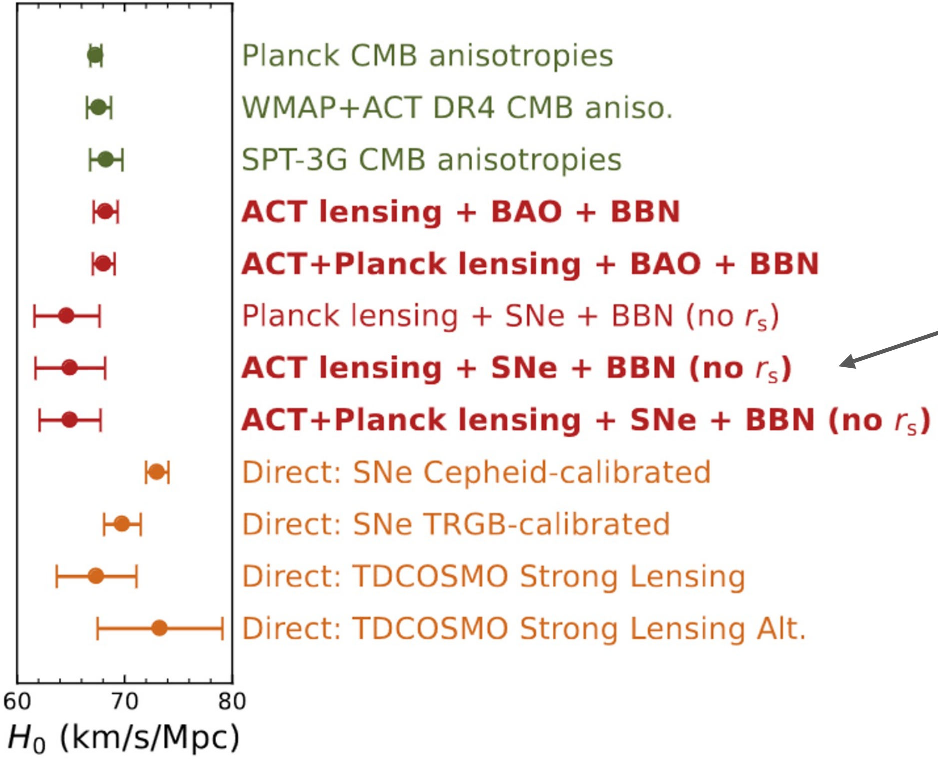
velocity



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

Backup slides

H_0 from lensing



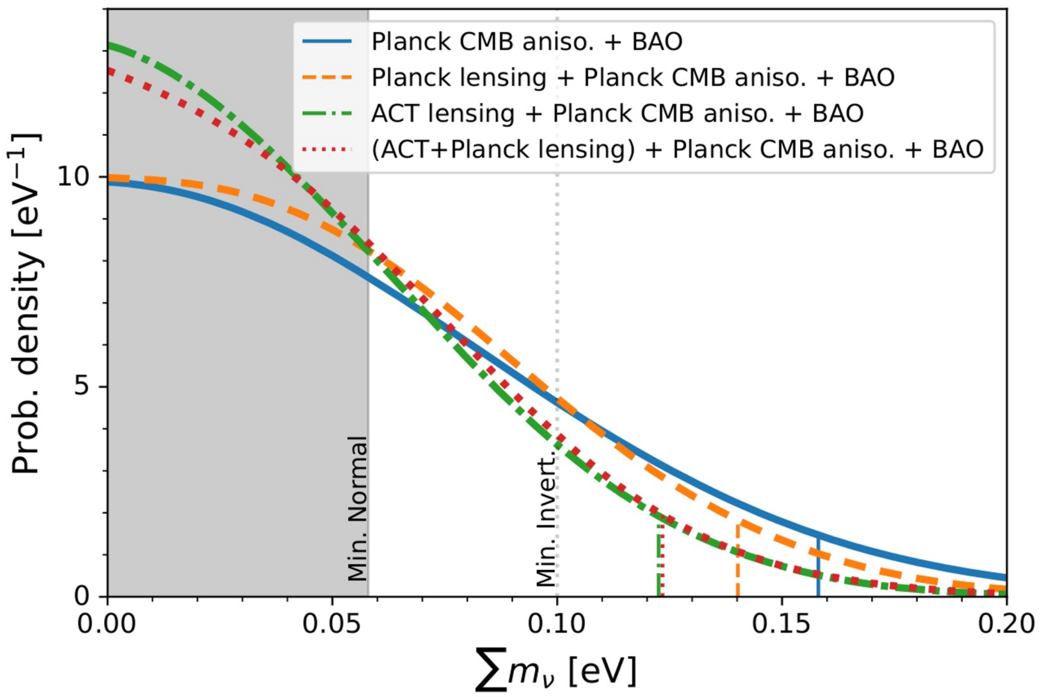
- Hubble constraint from ACT lensing without sound horizon info

$$\boxed{H_0 = 65.0 \pm 3.2\,\mathrm{km\,s^{-1}\,Mpc^{-1}}}$$

Constraints on neutrino masses

- Neutrino mass constraint from power spectrum suppression:
  m<0.12 eV 95% c.l.
  Compare to:
  (m<0.14 eV; Planck lensing)

- Even better with DESI BAO:
  currently **m<0.07 eV 95% c.l.** –
  stay tuned for further DESI releases



Many unWISE x CMB lensing analysis improvements

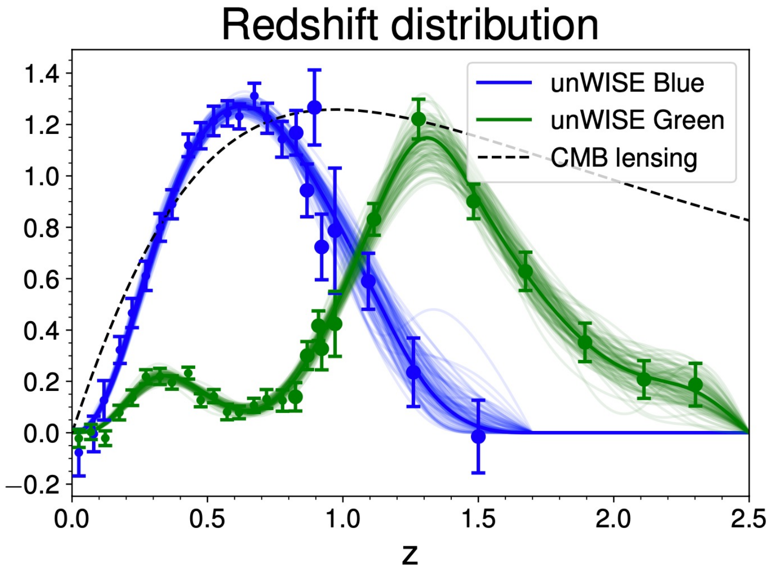
- Note: old unWISE x Planck lensing gives low S_8 = 0.782 +/- 0.015, 2.4 sigma below Planck
- But: many improvements made for new ACT analysis

Systematics weighting for galaxy samples
Extra spectroscopic data from eBOSS
PCA-based marginalization over redshift uncertainties
Correction for fiducial cosmology assumed in cross-corr. redshifts
Modeling improvements: marginalization over higher order biases
Inclusion of simulated normalization correction for Planck lensing
Use of better (PR4) Planck lensing reconstruction...

- Similarly updated unWISE x Planck results change by 1.3 sigma

Analysis improvements highlights: better redshifts and modeling

- Redshifts from cross-correlations with spectroscopic data. Now better data (eBOSS) and errors better accounted for with new PCA method



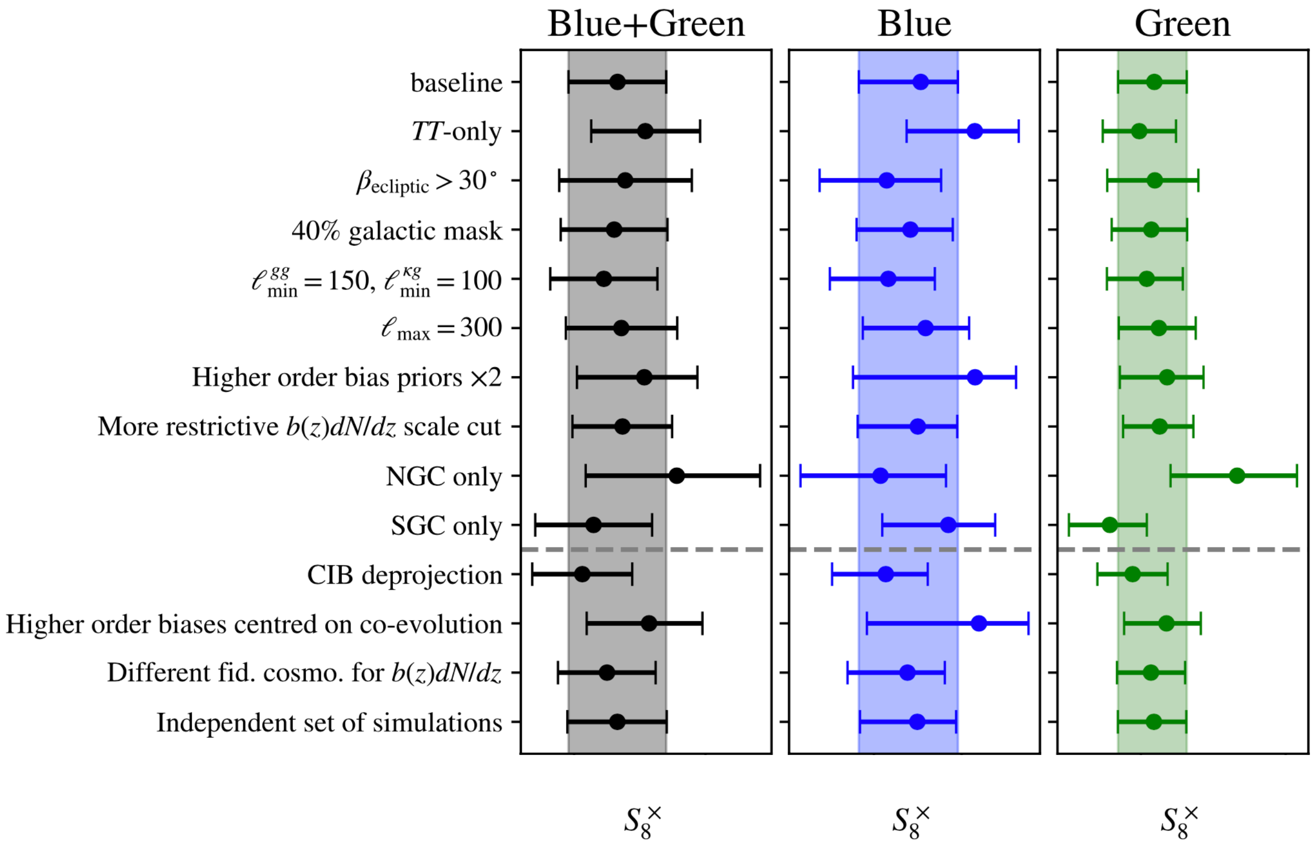
- Modeling (with Hybrid HMCode + LPT) now includes full marginalization over higher order galaxy biases

$$P_{gg}(k,z) = b_{1,E}^2(z)P_{mm,\mathrm{HF}} + \underbrace{b_{2,L}(z)P_{b_2}(k,z) + \ldots}_{\mathrm{LPT\ terms}} + P_{\mathrm{shot\ noise}}$$

$$P_{gm}(k,z) = b_{1,E}(z)P_{mm,\mathrm{HF}} + \overbrace{\frac{b_{2,L}(z)}{2}P_{b_2}(k,z) + \ldots}$$

Null and systematics tests: parameter stability

- Blind analysis with O(100) null tests
- Stable against different analysis variants, e.g. probing angular systematics

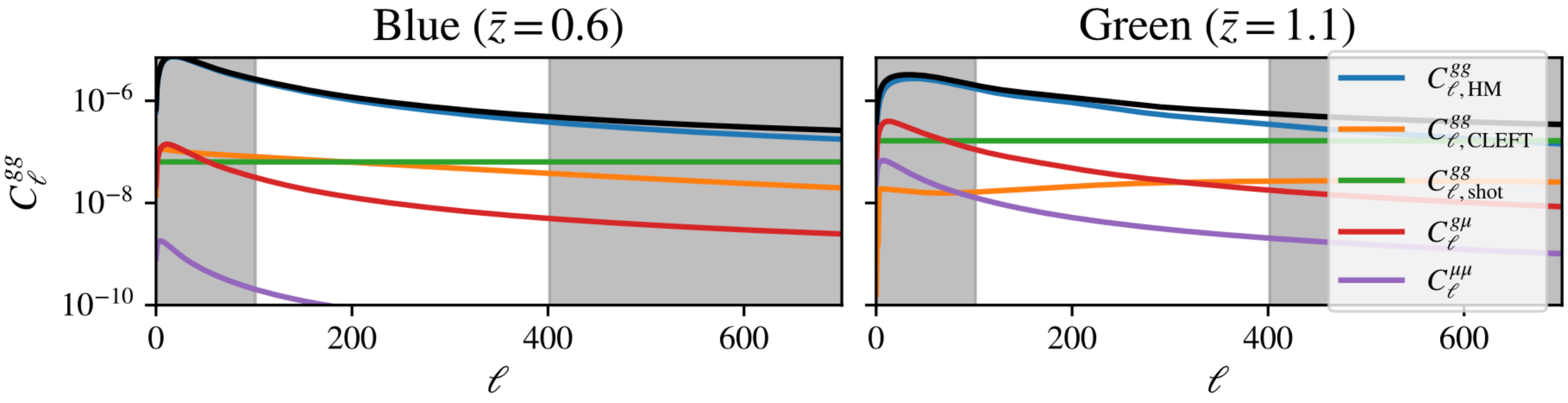


Analysis improvements II: better theory modeling

- Modeling with Hybrid HMCode + LPT now includes free marginalization over higher order biases:

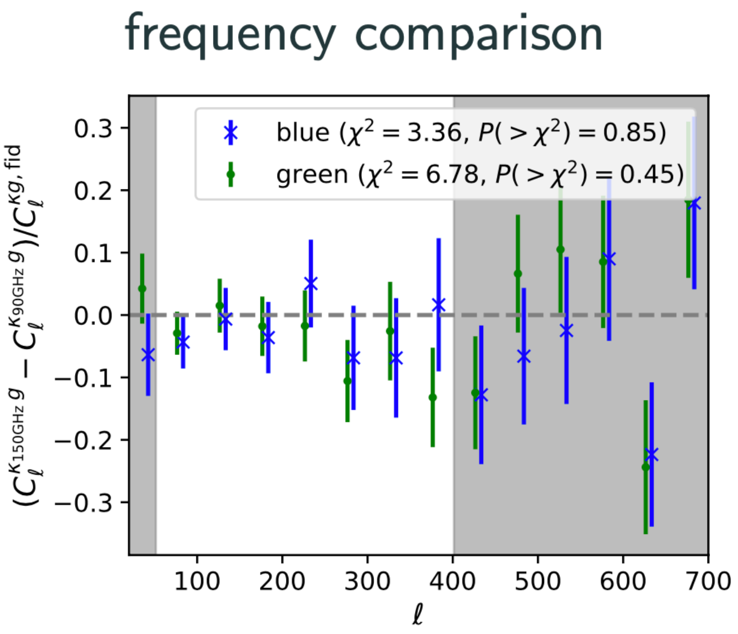
$$P_{gg}(k,z) = b_{1,E}^2(z)P_{mm,\mathrm{HF}} + \underbrace{b_{2,L}(z)P_{b_2}(k,z)+\dots}_{\text{LPT terms}} + P_{\text{shot noise}}$$

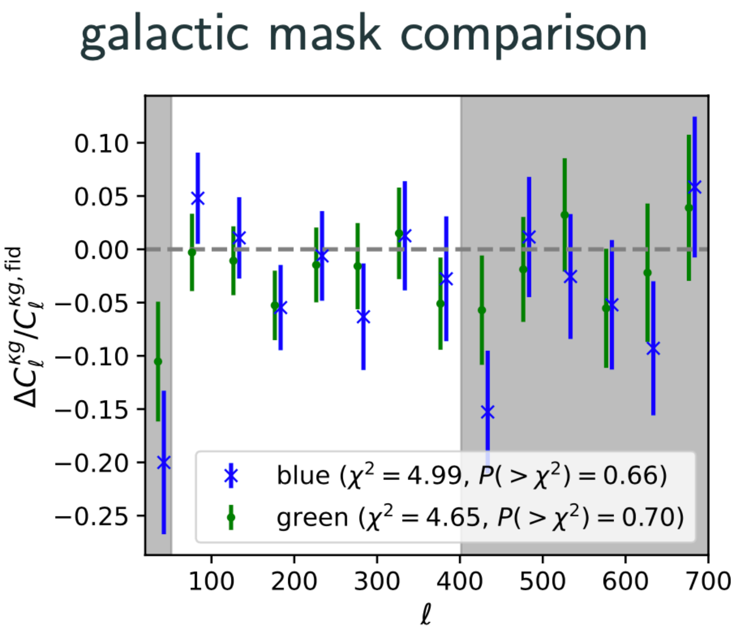
$$P_{gm}(k,z) = b_{1,E}(z)P_{mm,\mathrm{HF}} + \overbrace{\frac{b_{2,L}(z)}{2}P_{b_2}(k,z)+\dots}$$



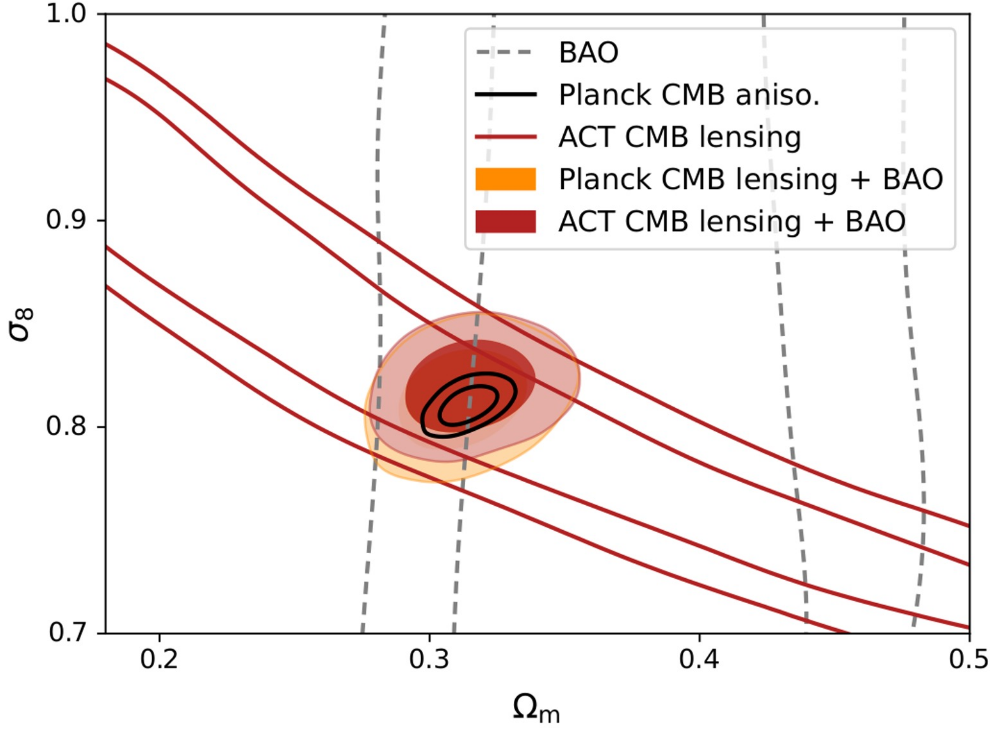
Systematics tests: nulls

- Again, blinded analysis framework relying O(100) null tests e.g.





Adding BAO: CMB lensing measured at z=0.5-5 and linear scales is not low



CMB lensing alone measures $\sigma_8\,\Omega_m^{0.25}$

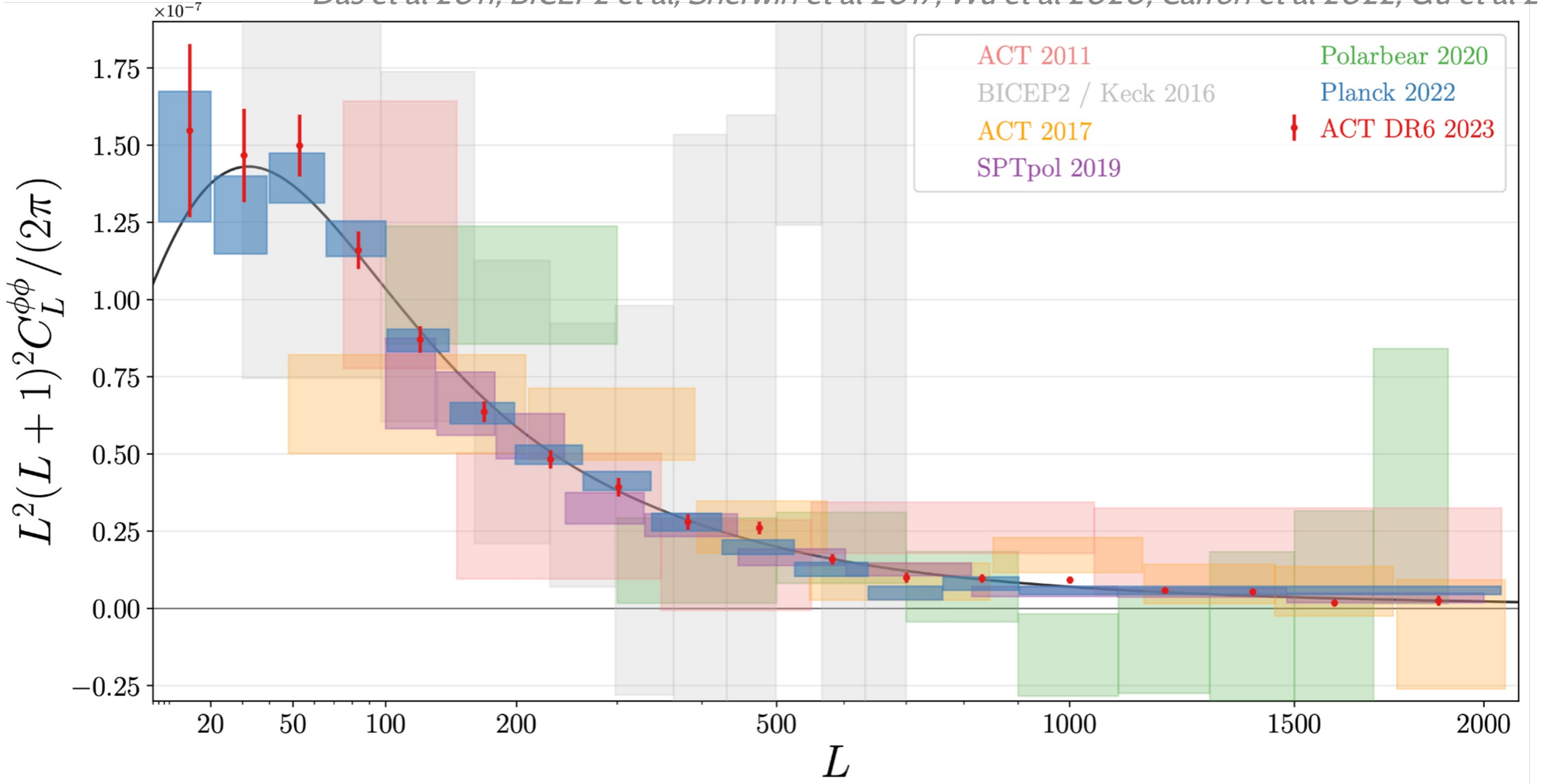
Combination with BAO isolates σ_8

$$\sigma_8 = 0.819 \pm 0.015$$

1.8% measurement

Summary of current CMB lensing spectra: good consistency

Das et al 2011, BICEP2 et al, Sherwin et al 2017, Wu et al 2020, Carron et al 2022, Qu et al 2023



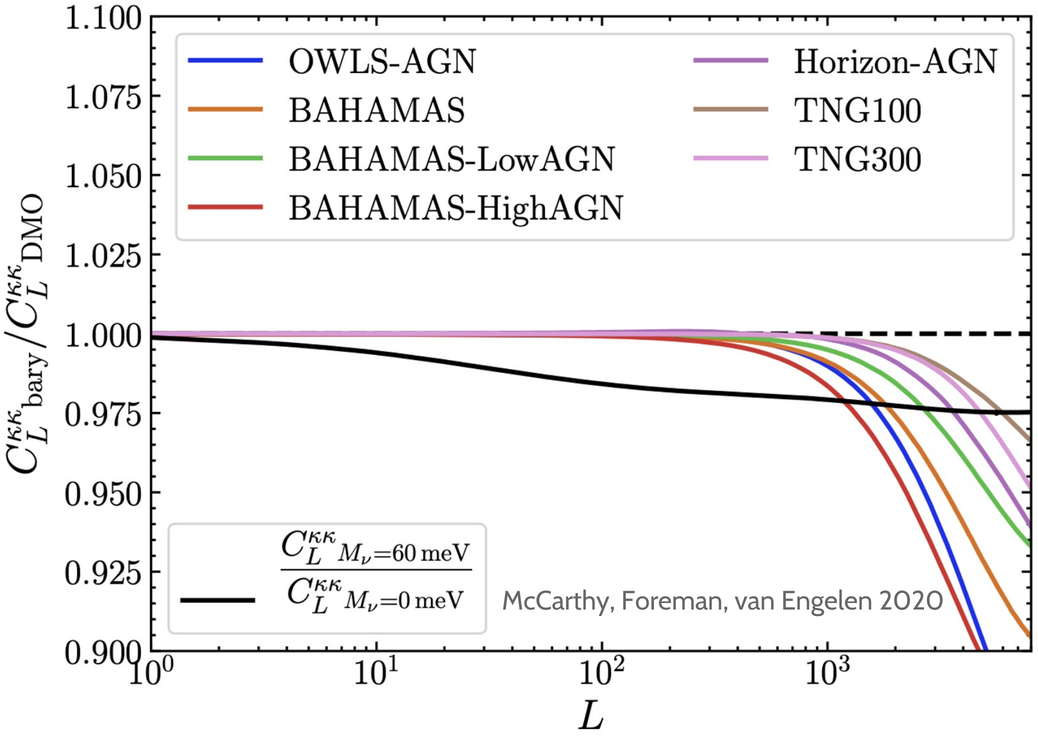
Analysis Improvements to unWISE x Planck lensing: shift in results!

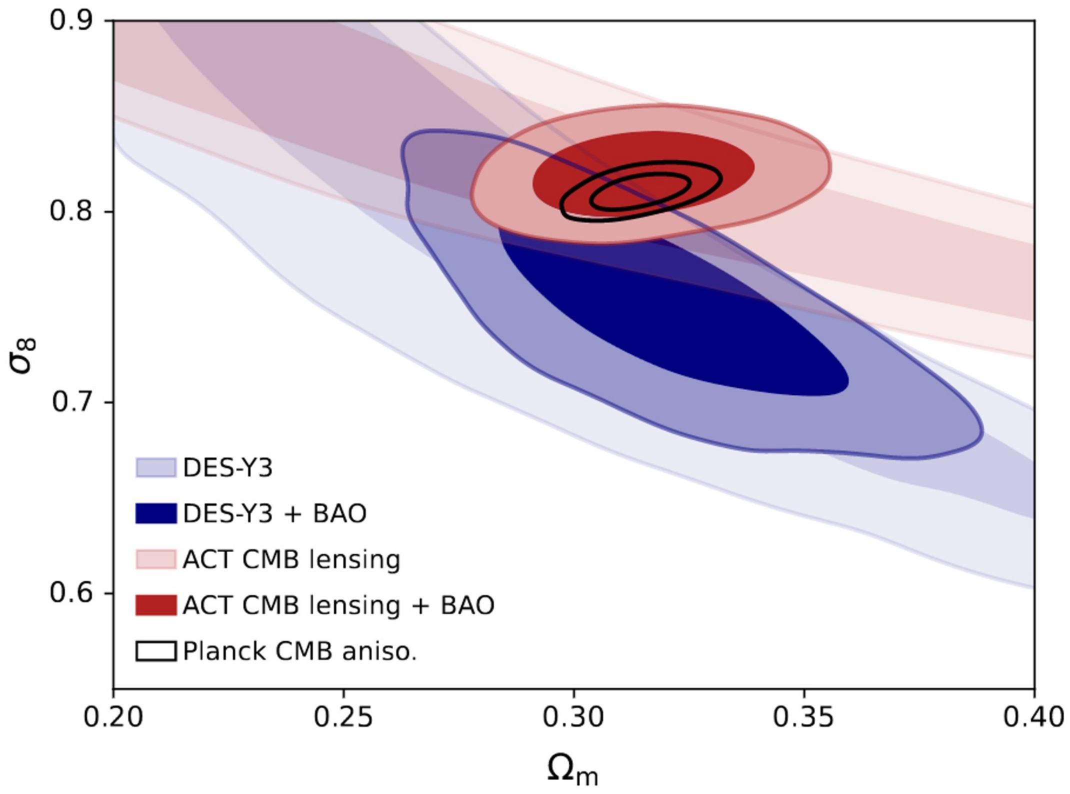
- Lots of analysis improvements in lensing x unWISE correlation

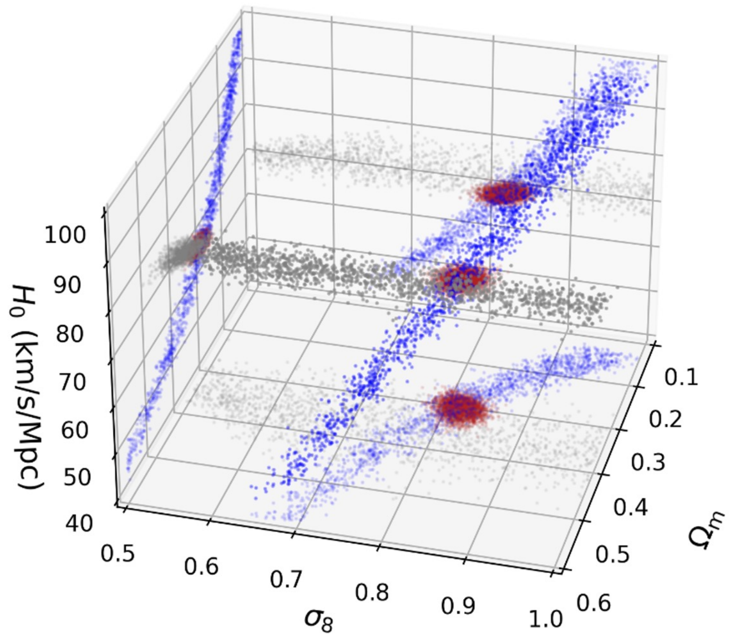
	Impact on S_8
monte-carlo lensing norm correction	$\uparrow \sim 1.1\sigma$
modelling improvements	$\downarrow \sim 0.9\sigma$
Systematics weighting	$\uparrow \sim 0.6\sigma$
Additional spectroscopic data	$\uparrow \sim 0.6\sigma$
use of Planck PR4 lensing reconstruction	$\uparrow \sim 0.1\sigma$
PCA based dN/dz marginalisation	$\downarrow \sim 0.2\sigma$ $+ \sim$10-15% wider posteriors
fid. cosmo. correction	$\sim$5% wider posteriors + change in degeneracy directions
Total	$\uparrow \sim \mathbf{1.3}\sigma + \sim$**15% wider posteriors**

- Constraints (from z~0.6-1) change to $S_8 = 0.803 \pm 0.017$ (c.f. old $S_8 = 0.782 \pm 0.015$)
- Stay tuned for ACT results!

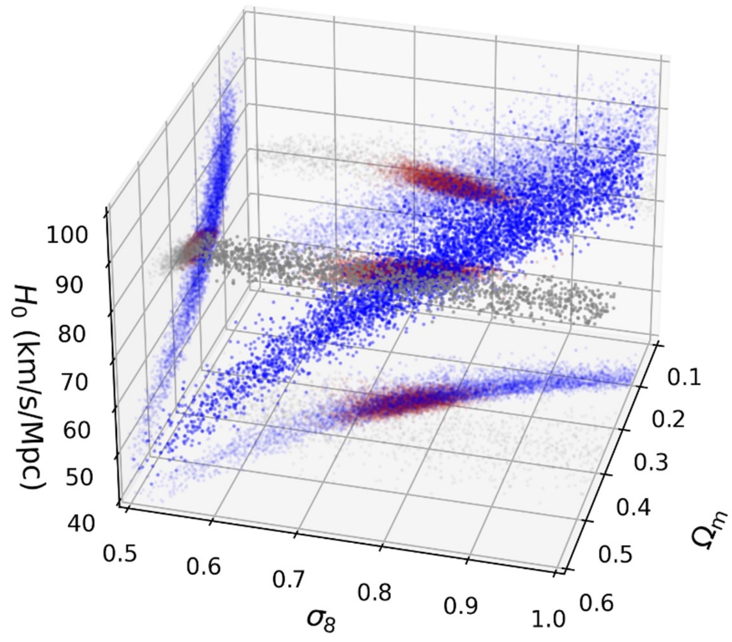
Baryonic effects - suppression negligible where our SNR arises (L<500)



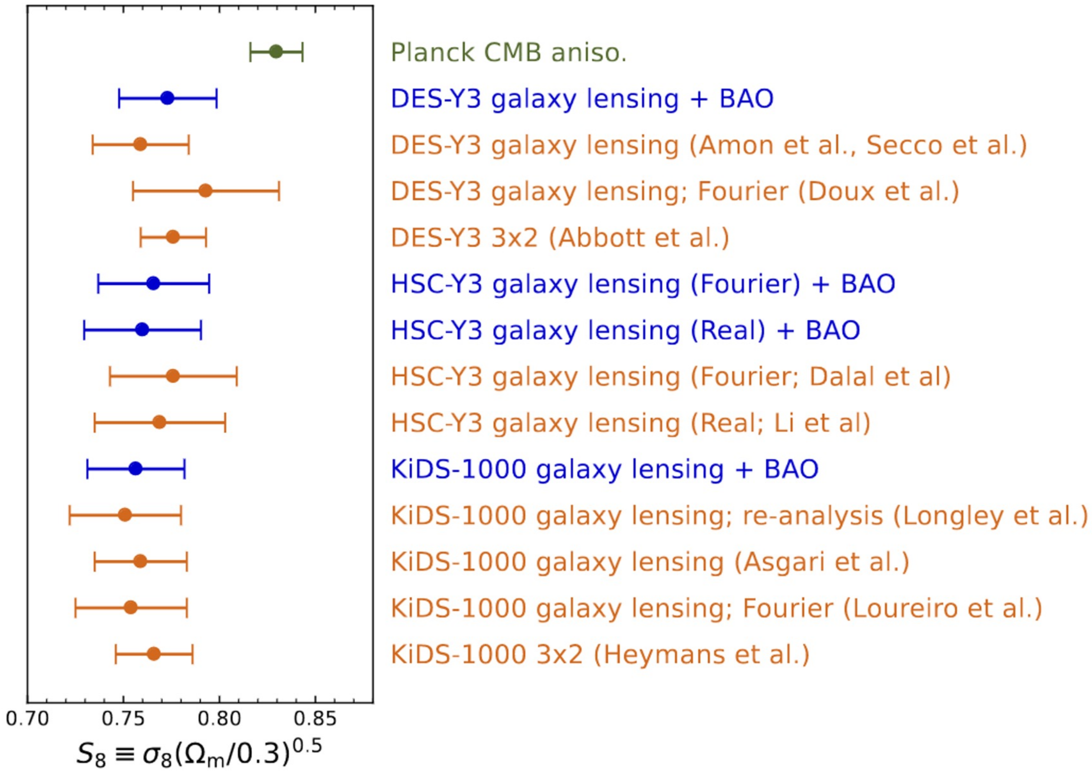

0.9
0.8
0.7
0.6
σ_8
0.20
0.25
0.30
0.35
0.40
Ω_m
DES-Y3
DES-Y3 + BAO
ACT CMB lensing
ACT CMB lensing + BAO
Planck CMB aniso.



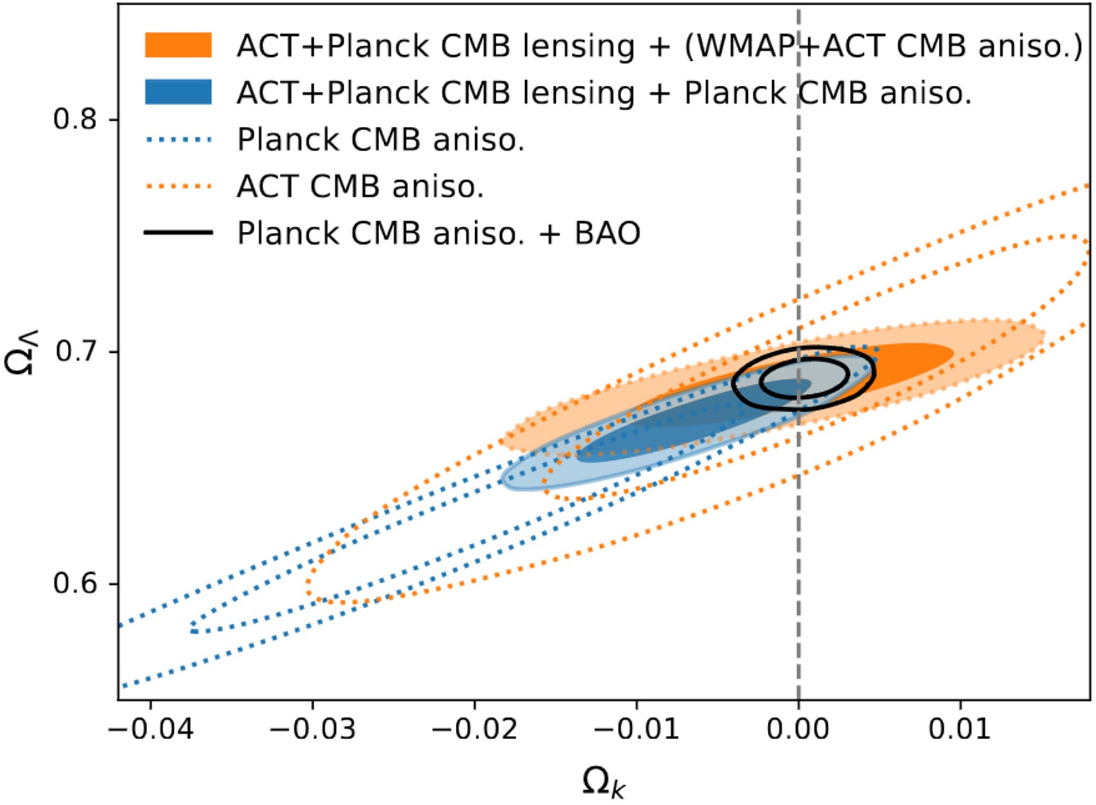
H_0 (km/s/Mpc)
40
50
60
70
80
90
100
σ_8
0.5
0.6
0.7
0.8
0.9
1.0
Ω_m
0.1
0.2
0.3
0.4
0.5
0.6

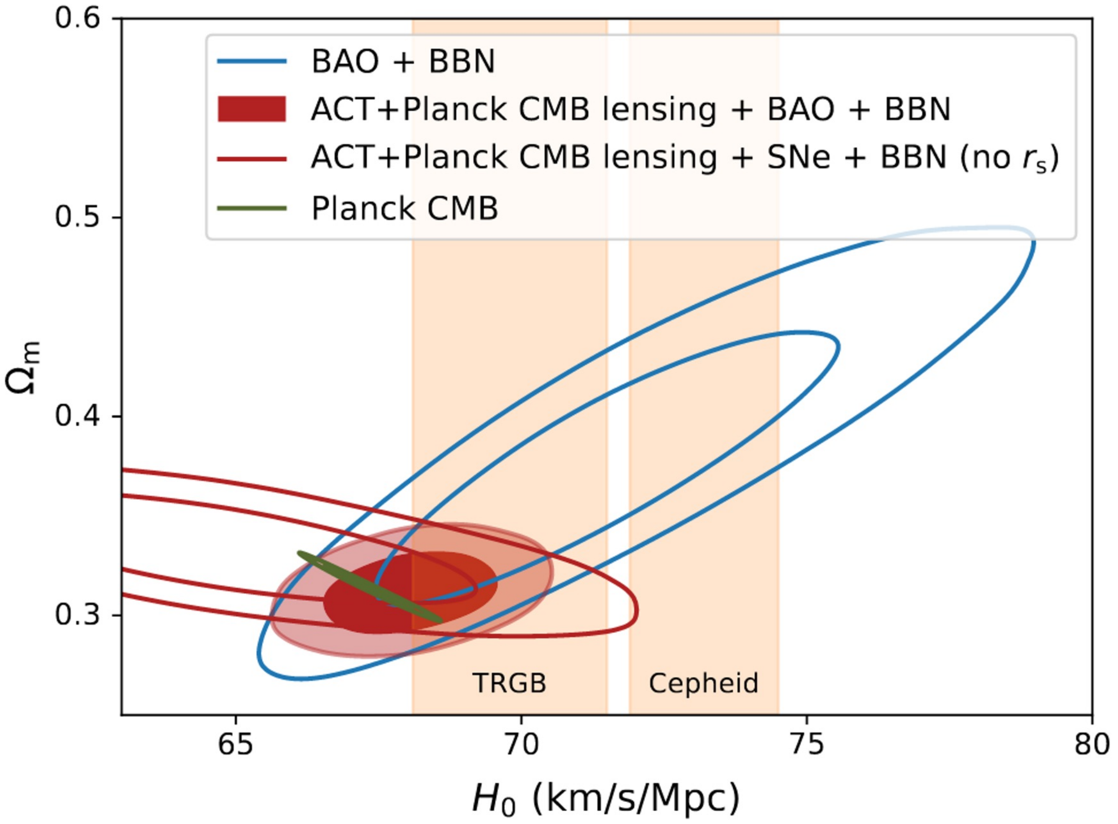


H_0 (km/s/Mpc)
40
50
60
70
80
90
100
σ_8
0.5
0.6
0.7
0.8
0.9
1.0
Ω_m
0.1
0.2
0.3
0.4
0.5
0.6

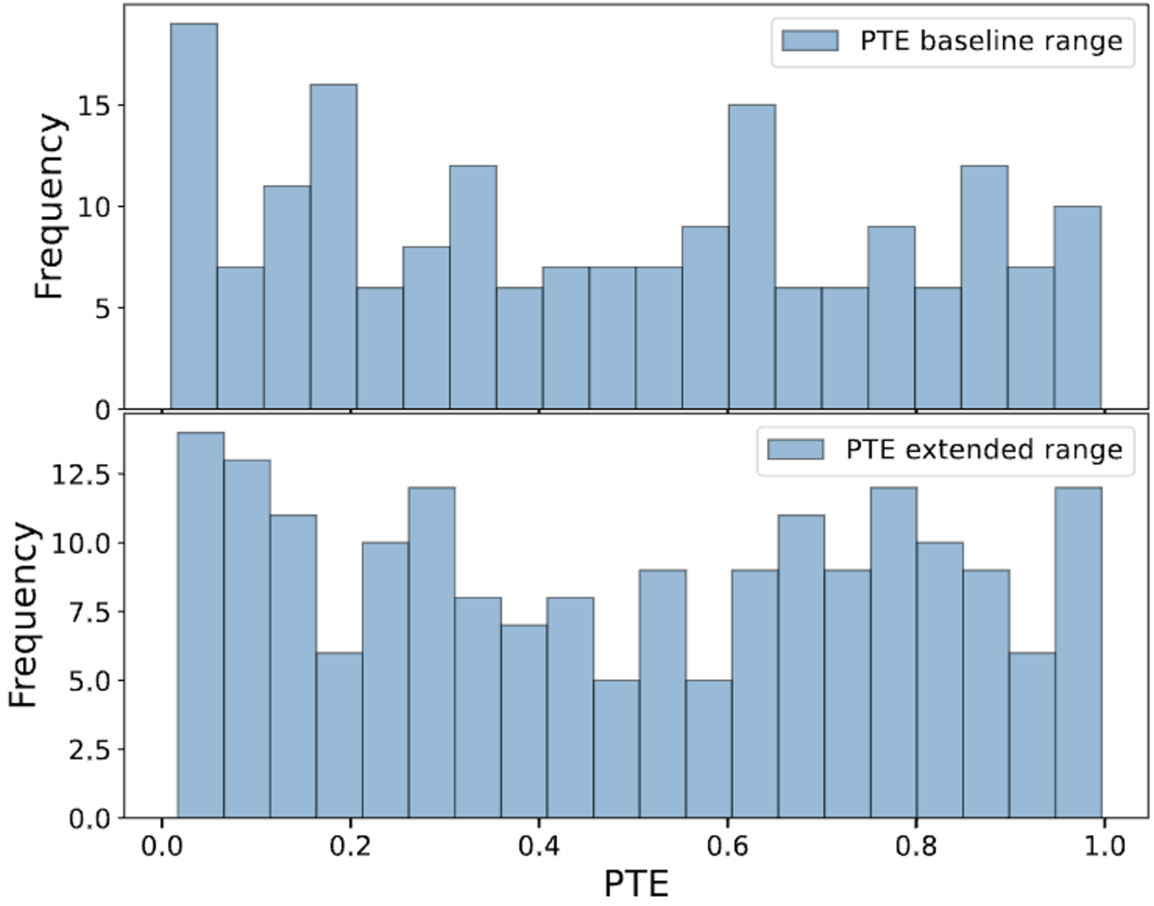


Planck CMB aniso.
DES-Y3 galaxy lensing + BAO
DES-Y3 galaxy lensing (Amon et al., Secco et al.)
DES-Y3 galaxy lensing; Fourier (Doux et al.)
DES-Y3 3x2 (Abbott et al.)
HSC-Y3 galaxy lensing (Fourier) + BAO
HSC-Y3 galaxy lensing (Real) + BAO
HSC-Y3 galaxy lensing (Fourier; Dalal et al)
HSC-Y3 galaxy lensing (Real; Li et al)
KiDS-1000 galaxy lensing + BAO
KiDS-1000 galaxy lensing; re-analysis (Longley et al.)
KiDS-1000 galaxy lensing (Asgari et al.)
KiDS-1000 galaxy lensing; Fourier (Loureiro et al.)
KiDS-1000 3x2 (Heymans et al.)
0.70
0.75
0.80
0.85
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$


ACT+Planck CMB lensing + (WMAP+ACT CMB aniso.)
ACT+Planck CMB lensing + Planck CMB aniso.
Planck CMB aniso.
ACT CMB aniso.
Planck CMB aniso. + BAO
0.8
0.7
0.6
Ω_Λ
−0.04
−0.03
−0.02
−0.01
0.00
0.01
Ω_k



BAO + BBN
ACT+Planck CMB lensing + BAO + BBN
ACT+Planck CMB lensing + SNe + BBN (no r_s)
Planck CMB
TRGB
Cepheid
Ω_m
0.6
0.5
0.4
0.3
65
70
75
80
H_0 (km/s/Mpc)

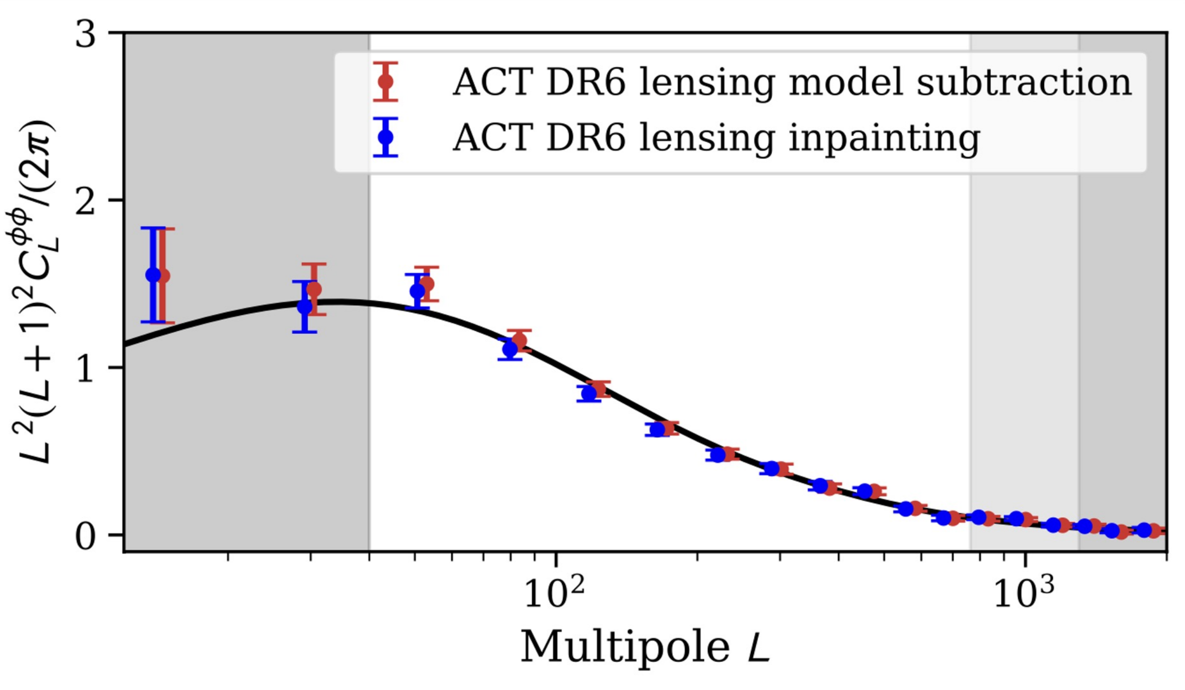

PTE baseline range
Frequency
0
5
10
15
PTE extended range
Frequency
0.0
2.5
5.0
7.5
10.0
12.5
0.0
0.2
0.4
0.6
0.8
1.0
PTE

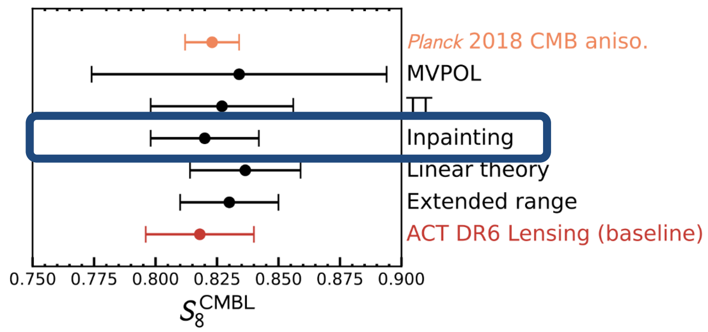
Instrumental Systematics

Systematic	Estimator	ΔA_{lens}
Miscalibration	MV	0.00432 (0.18σ)
Miscalibration	MVPol	0.00419 (0.09σ)
Beam uncertainty	MV	0.00113 (0.05σ)
Beam uncertainty	MVPol	0.00110 (0.02σ)
T$\rightarrow$P leakage (beam)	MV	-0.00021 (-0.01σ)
T$\rightarrow$P leakage (beam)	MVPol	-0.00052 (-0.01σ)
T$\rightarrow$P leakage (const.)	MV	-0.00461 (-0.19σ)
T$\rightarrow$P leakage (const.)	MVPol	-0.00887 (-0.18σ)
Polarization eff.	MV	-0.00896 (-0.37σ)
Polarization eff.	MVPol	-0.01884 (-0.38σ)
Polarization angle	MV	-0.00025 (-0.01σ)
Polarization angle	MVPol	0.00070 (0.01σ)

Conservative upper bounds from toy models

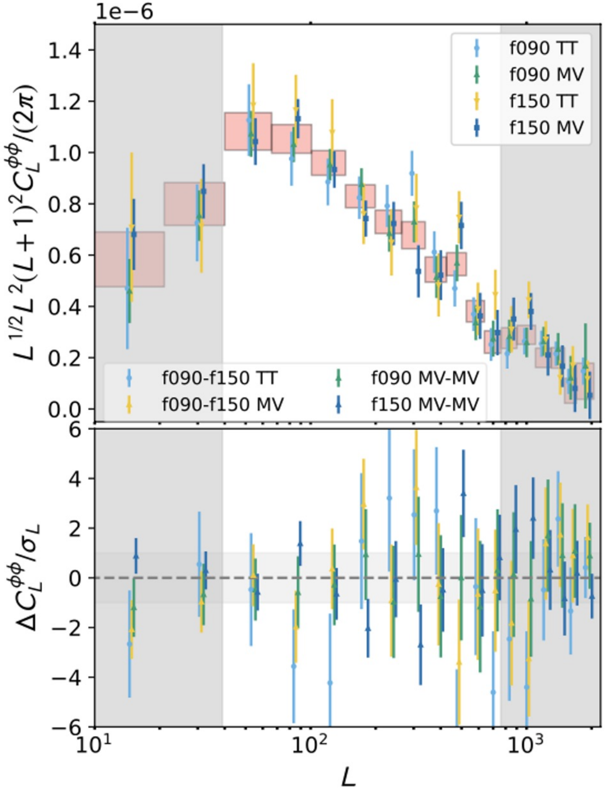
Post unblinding changes

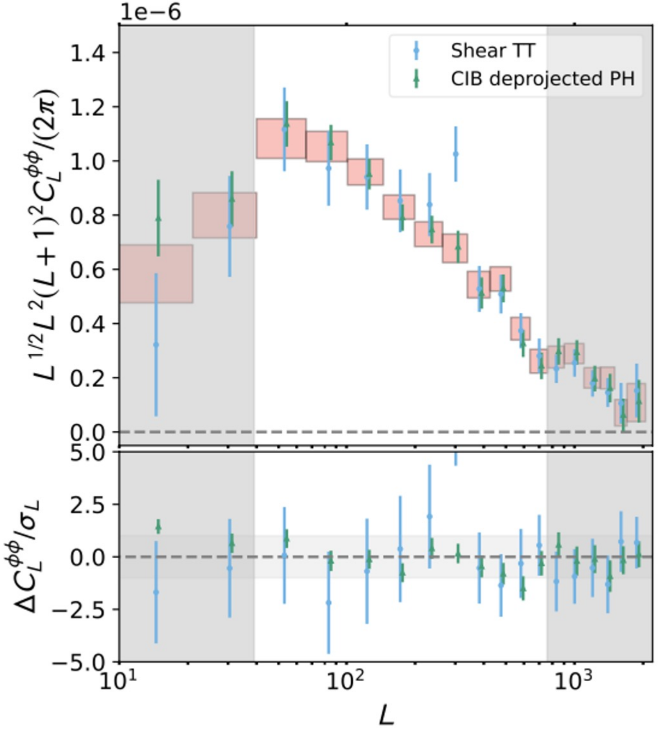


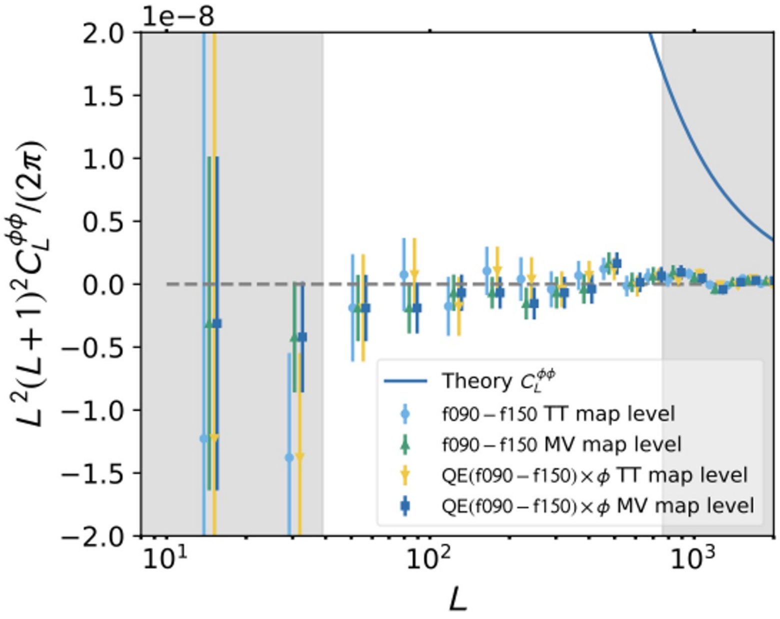


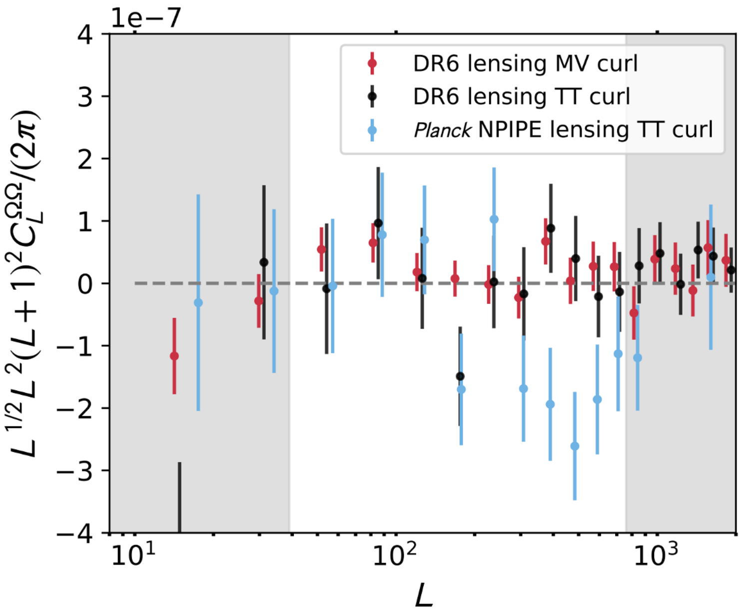
0.15sigma shift compared to baseline

Null tests


1e−6
f090 TT
f090 MV
f150 TT
f150 MV
f090-f150 TT
f090-f150 MV
f090 MV-MV
f150 MV-MV
$L^{1/2} L^2 (L+1)^2 C_L^{\phi\phi}/(2\pi)$
$\Delta C_L^{\phi\phi}/\sigma_L$
L


1e−6
Shear TT
CIB deprojected PH
$L^{1/2} L^2 (L+1)^2 C_L^{\phi\phi}/(2\pi)$
$\Delta C_L^{\phi\phi}/\sigma_L$
L


1e−8
Theory $C_L^{\phi\phi}$
f090 − f150 TT map level
f090 − f150 MV map level
QE(f090 − f150) × ϕ TT map level
QE(f090 − f150) × ϕ MV map level
$L^2(L+1)^2C_L^{\phi\phi}/(2\pi)$
L


1e−7
DR6 lensing MV curl
DR6 lensing TT curl
Planck NPIPE lensing TT curl
$L^{1/2}L^2(L+1)^2C_L^{\Omega\Omega}/(2\pi)$
L

Null test summary

Bandpower null test	χ^2	(PTE)	ΔA^{lens}
$600 < \ell_{\mathrm{CMB}} < 2000$	2.9	(0.98)	-0.015 ± 0.023
$600 < \ell_{\mathrm{CMB}} < 2500$	9.6	(0.48)	-0.019 ± 0.012
$800 < \ell_{\mathrm{CMB}} < 3000$	10.9	(0.37)	0.01 ± 0.01
$1500 < \ell_{\mathrm{CMB}} < 3000$	4.4	(0.93)	-0.02 ± 0.03
40% mask	7.2	(0.71)	0.01 ± 0.02
Aggr. ground pick up	14.8	(0.14)	0.01 ± 0.01
Poor cross-linking reg.	4.1	(0.94)	-0.06 ± 0.06
MV f090 – f150	9.1	(0.52)	-0.002 ± 0.04
TT f090 – f150	16.6	(0.08)	-0.05 ± 0.06
CIB deprojection	15.6	(0.11)	-0.02 ± 0.02
TT shear	13.5	(0.20)	0.01 ± 0.05
TT – MV	11.2	(0.34)	-0.004 ± 0.03
MVPOL – MV	6.9	(0.73)	0.06 ± 0.06
TT – MVPOL	7.4	(0.69)	-0.06 ± 0.07
South – North patch	4.77	(0.91)	0.04 ± 0.05
Time-split 1 – 2	11.4	(0.33)	0.003 ± 0.036
Time-split 1	8.1	(0.62)	-0.04 ± 0.04
Time-split 2	11.2	(0.33)	-0.04 ± 0.04
PA4 f150 – PA5 f090	9.1	(0.52)	0.0 ± 0.1
PA4 f150 – PA5 f150	7.0	(0.73)	0.1 ± 0.2
PA4 f150 – PA6 f090	9.1	(0.52)	0.0 ± 0.2
PA4 f150 – PA6 f150	20.1	(0.03)	0.11 ± 0.2
PA5 f090 – PA5 f150	5.8	(0.83)	0.13 ± 0.2
PA5 f090 – PA6 f090	9.5	(0.49)	0.02 ± 0.05
PA5 f090 – PA6 f150	19.6	(0.08)	0.02 ± 0.04
PA5 f150 – PA6 f090	10.4	(0.41)	-0.03 ± 0.07
PA5 f150 – PA6 f150	16.6	(0.08)	0.1 ± 0.2
PA6 f090 – PA6 f150	17.2	(0.07)	0.07 ± 0.2
PWV high – low	5.0	(0.89)	0.02 ± 0.04

Map level null test	χ^2	(PTE)
PA4 f150 noise-only	8.5	(0.58)
PA5 f090 noise-only	6.4	(0.77)
PA5 f150 noise-only	11	(0.35)
PA6 f090 noise-only	10	(0.49)
PA6 f150 noise-only	14	(0.17)
Coadded noise	21.2	(0.02)
PA4 f150 – PA5 f090	23	(0.01)
PA4 f150 – PA5 f150	19.5	(0.03)
PA4 f150 – PA6 f090	13.7	(0.19)
PA4 f150 – PA6 f150	19.0	(0.04)
PA5 f090 – PA5 f150	5.0	(0.89)
PA5 f090 – PA6 f090	7.5	(0.68)
PA5 f090 – PA6 f150	18.0	(0.06)
PA5 f150 – PA6 f090	12.3	(0.27)
PA5 f150 – PA6 f150	8.2	(0.61)
PA6 f090 – PA6 f150	9.7	(0.46)
$f090 - f150$ MV	7.6	(0.67)
$f090 - f150$ TT	8.1	(0.61)
$(f090 - f150) \times \phi$ MV	8.2	(0.61)
$(f090 - f150) \times \phi$ TT	4.3	(0.93)
Time-split difference	18.6	(0.05)

Detecting lensed IGW B-modes via LSS cross-correlations

- Lensing breaks statistical isotropy so different modes of lensed IGW B-modes are correlated

$$\langle \tilde{B}_{\ell m} \tilde{B}_{\ell' m'} \rangle = \sum_{LM} \begin{pmatrix} \ell & \ell' & L \\ m & m' & M \end{pmatrix} f^{\psi}_{\ell L \ell'} r \phi^*_{LM} \,,$$

$$f^{\psi}_{\ell L \ell'} = W^{+}_{\ell L \ell'} C^{BB,r=1}_{\ell'} + (-1)^{\ell+L+\ell'} W^{+}_{\ell' L \ell} C^{BB,r=1}_{\ell}$$

- We can reconstruct a quantity $\psi = r\phi$ using mode-coupling of B-modes

$$\hat{\psi}^*_{LM} = \frac{1}{2} A_L \sum_{\ell \ell' m m'} \begin{pmatrix} \ell & \ell' & L \\ m & m' & M \end{pmatrix} f^{\psi}_{\ell L \ell'} \frac{\hat{B}_{\ell m}}{\hat{C}^{BB}_{\ell}} \frac{\hat{B}_{\ell' m'}}{\hat{C}^{BB}_{\ell'}}$$

- The reconstructed ψ is then cross-correlated with an LSS tracer, x, which can galaxy density fluctuations g, CMB lensing ϕ, CIB, etc.

$$C_L^{\psi x} = r C_L^{\phi x}$$

Know $C_L^{\phi x}$ so can estimate r! $\quad r = \dfrac{\hat{C}_L^{\psi x}}{C_L^{\phi x}}$

Forecasting constraints on r: like lensing cross-correlations!

$$\hat{\psi}^*_{LM} = \frac{1}{2} A_L \sum_{\ell\ell' mm'} \begin{pmatrix} \ell & \ell' & L \\ m & m' & M \end{pmatrix} f^{\psi}_{\ell L \ell'} \frac{\hat{B}_{\ell m}}{\hat{C}^{BB}_{\ell}} \frac{\hat{B}_{\ell' m'}}{\hat{C}^{BB}_{\ell'}} \qquad f^{\psi}_{\ell L \ell'} = W^{+}_{\ell L \ell'} C^{BB,r=1}_{\ell'} + (-1)^{\ell+L+\ell'} W^{+}_{\ell' L \ell} C^{BB,r=1}_{\ell}$$

- Compute noise on $\psi = r\phi$ estimator just as for lensing

$$(N^{\psi\psi}_L)^{-1} = \frac{1}{2L+1} \sum_{\ell\ell'} \frac{(f^{\psi}_{\ell L \ell'})^2}{2\hat{C}^{BB}_{\ell}\hat{C}^{BB}_{\ell'}} \, .$$

- And forecast error on cross-correlation

Limited by B-mode power!

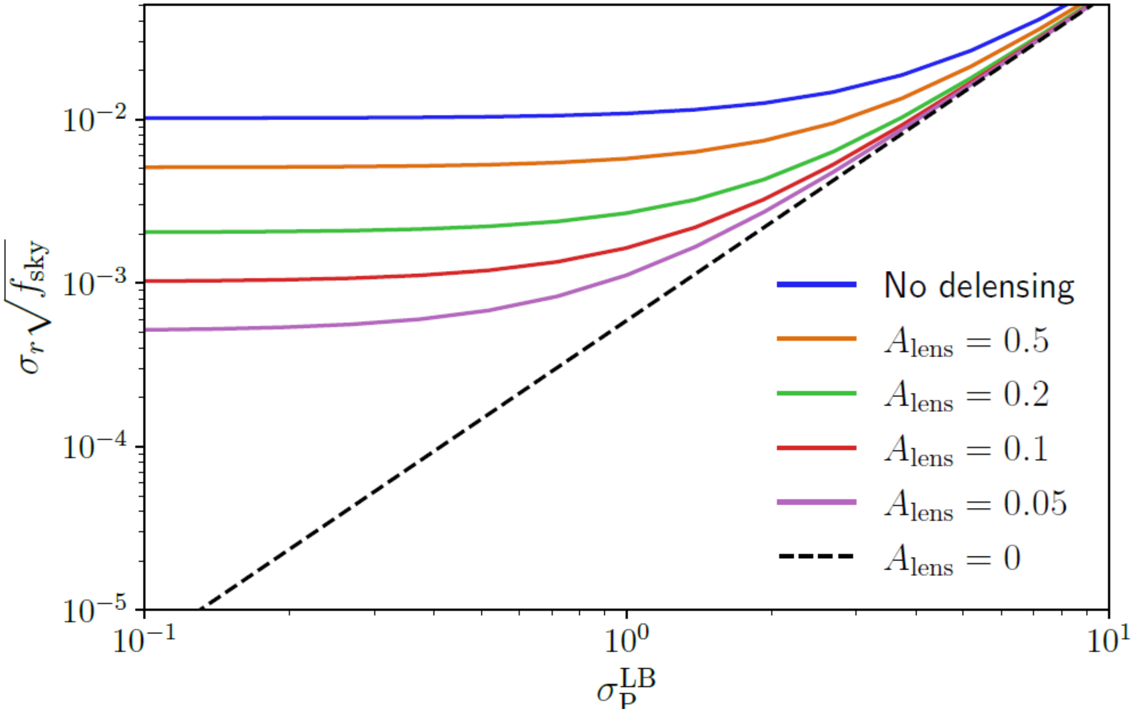
$$\sigma_r^{-2} = \sum_L \frac{(2L+1) f_{\rm sky} (\partial C^{\psi x}_L / \partial r)^2}{(r^2 C^{\phi\phi}_L + N^{\psi\psi}_L)\hat{C}^{xx}_L + (r C^{\phi x}_L)^2} \, ,$$

$$\sigma_r^{-2} \simeq \sum_L (2L+1) f_{\rm sky} \frac{\rho^2_L C^{\phi\phi}_L}{N^{\psi\psi}_L} \, ,$$

Note: Assuming delensed B in computing forecasts, will discuss.

Forecasts – Configuration Dependence

- Varying a LiteBIRD+CMB-S4-like configuration – depends on delensing and B-noise.



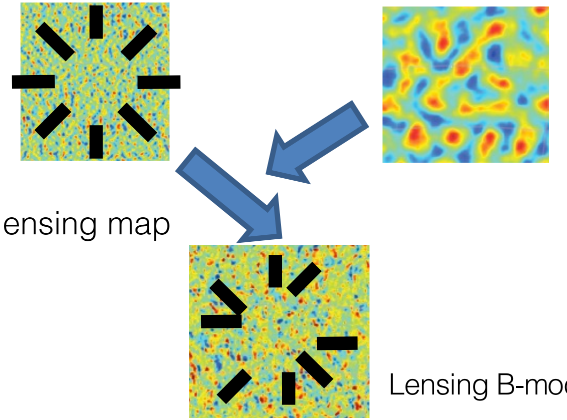
Post-component-separated noise level

Important Step for Low Noise: Delensing

- For given observed E-modes and lensing maps, we can estimate lensing B-modes by distorting E-modes by reconstructed ϕ

E mode map

ϕ map



ϕ reconstructed from CMB

Distorted by lensing map

Lensing B-mode templ

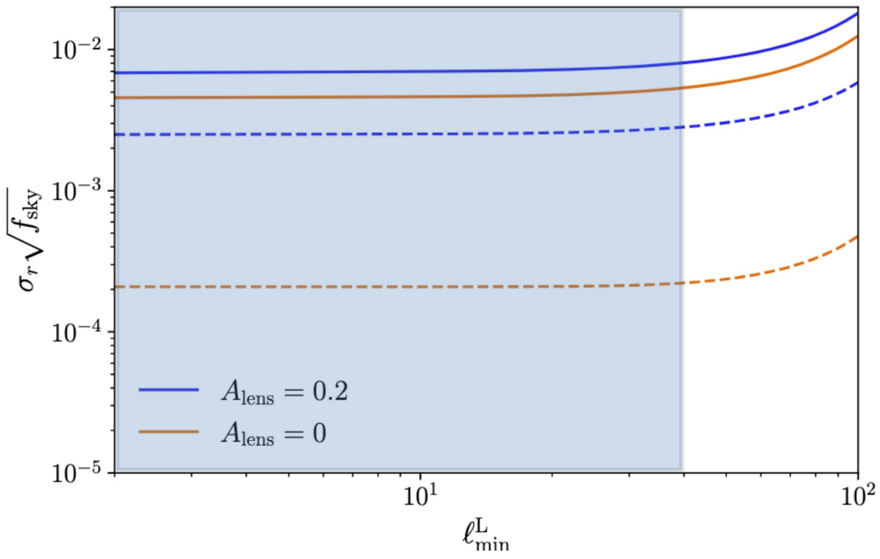
$$\hat{B}^{\mathrm{del}}_{\ell m} = \hat{B}_{\ell m} - \sum_{LM\ell'm'} (-1)^m \begin{pmatrix} \ell & L & \ell' \\ -m & M & m' \end{pmatrix} \times \left(\frac{C_L^{\phi\phi} \hat{\phi}_{LM}}{C_L^{\phi\phi} + N_L^{\phi\phi}} \right) \left(\frac{-\mathrm{i} C_{\ell'}^{EE} \hat{E}_{\ell' m'}}{C_{\ell'}^{EE} + N_{\ell'}^{EE}} \right) W^{-}_{\ell L \ell'} \, . \tag{8}$$

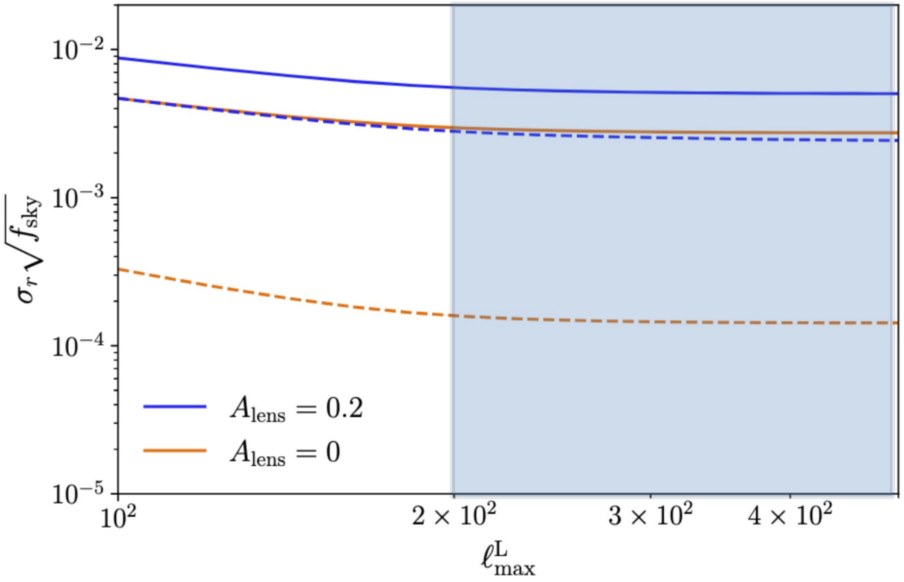
- Using this template, we can reduce scatter from lensing B-modes and improve constraint on IGWs

(But cannot delens using inverse-remapping!)

Advantage: Systematics Control and Ease of Measurement

- Cross-correlation with galaxies should cancel many instrument systematics.
- Insensitive to B-modes at ell<30-50 and B-modes at ell>200 – scales “easy” to measure





Other Notes

- Other work in progress: can we get factor of few better performance with improved component separation (just ILC) and or experiment setup (more delensing weight)
- Note that cross-correlation with different LSS tracers at different redshifts allows us to determine z origin of signal (tomography) – could confirm $z \sim 1100$?
- Also probes IGW B-modes on somewhat different scales.
- Could in principle combine with standard BB constraints as negligible correlation.