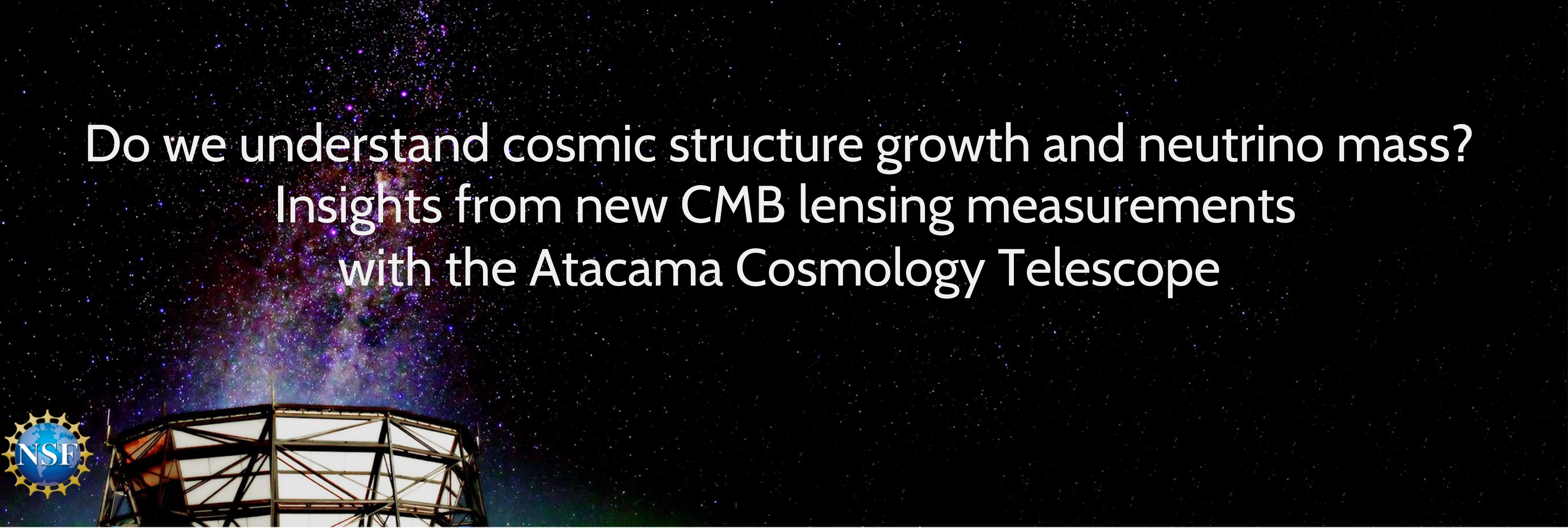
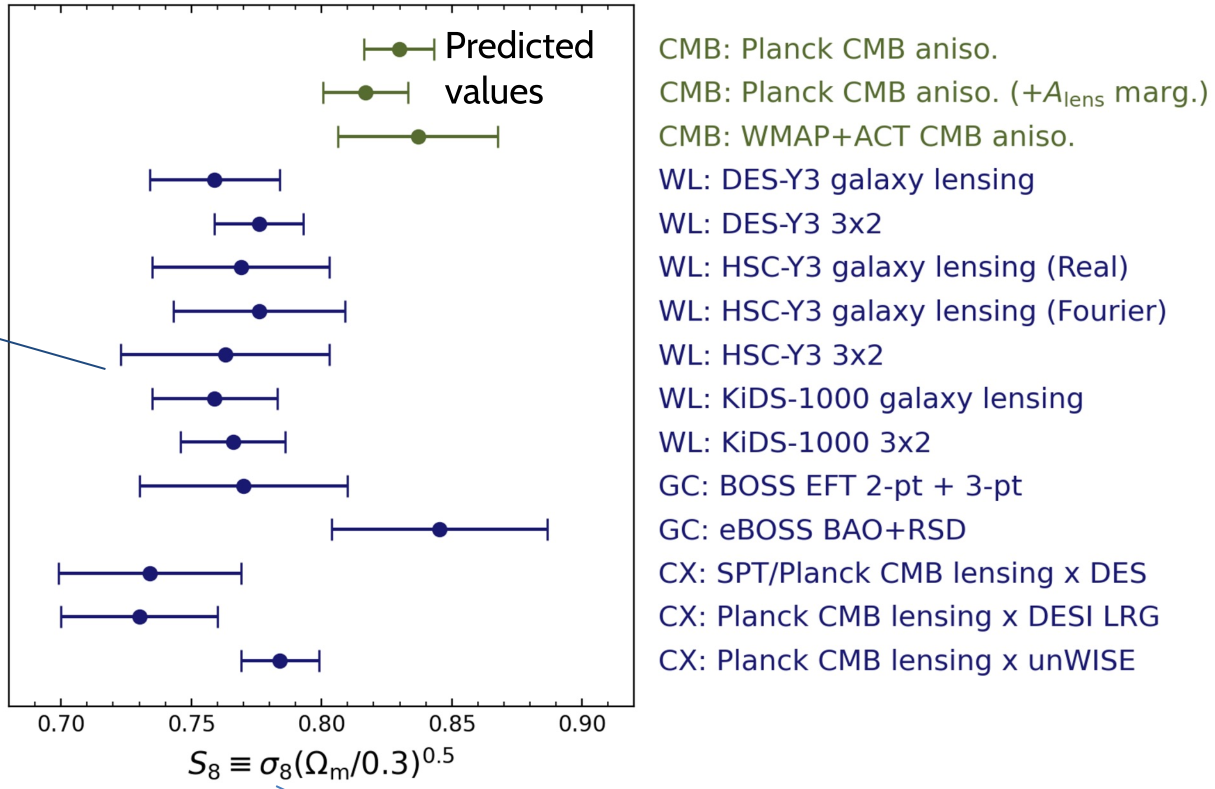


Do we understand cosmic structure growth and neutrino mass? Insights from new CMB lensing measurements with the Atacama Cosmology Telescope

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

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

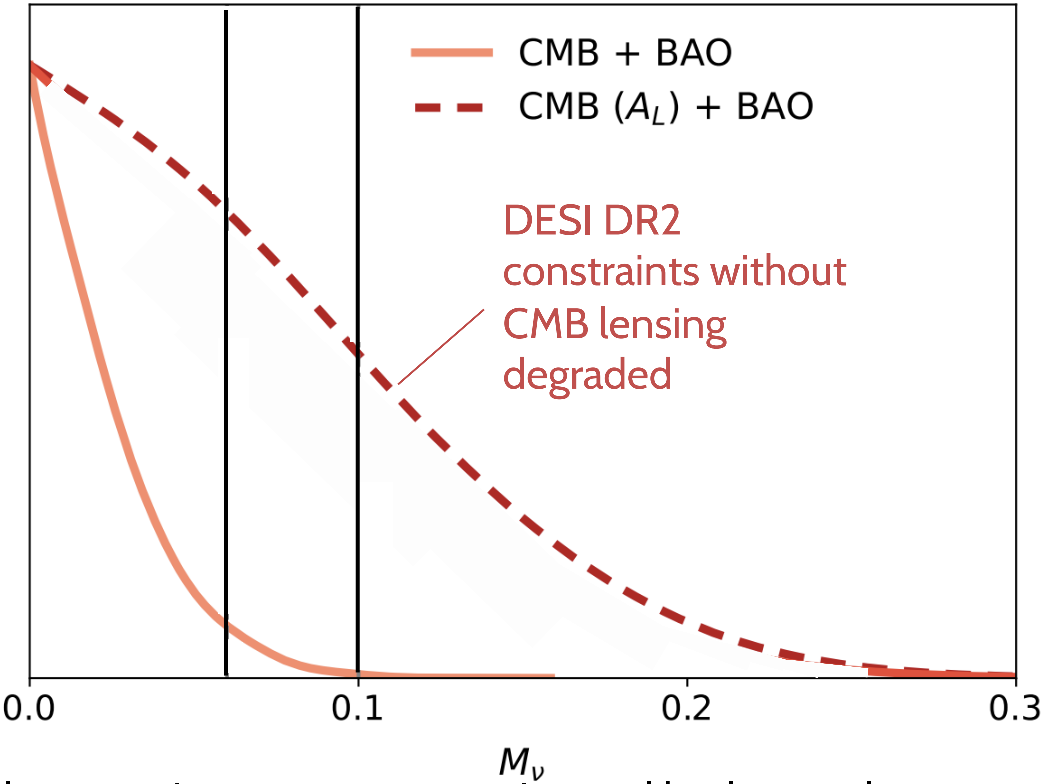
Direct low-z measurements from galaxy surveys: 2-3 sigma low in several channels



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!)

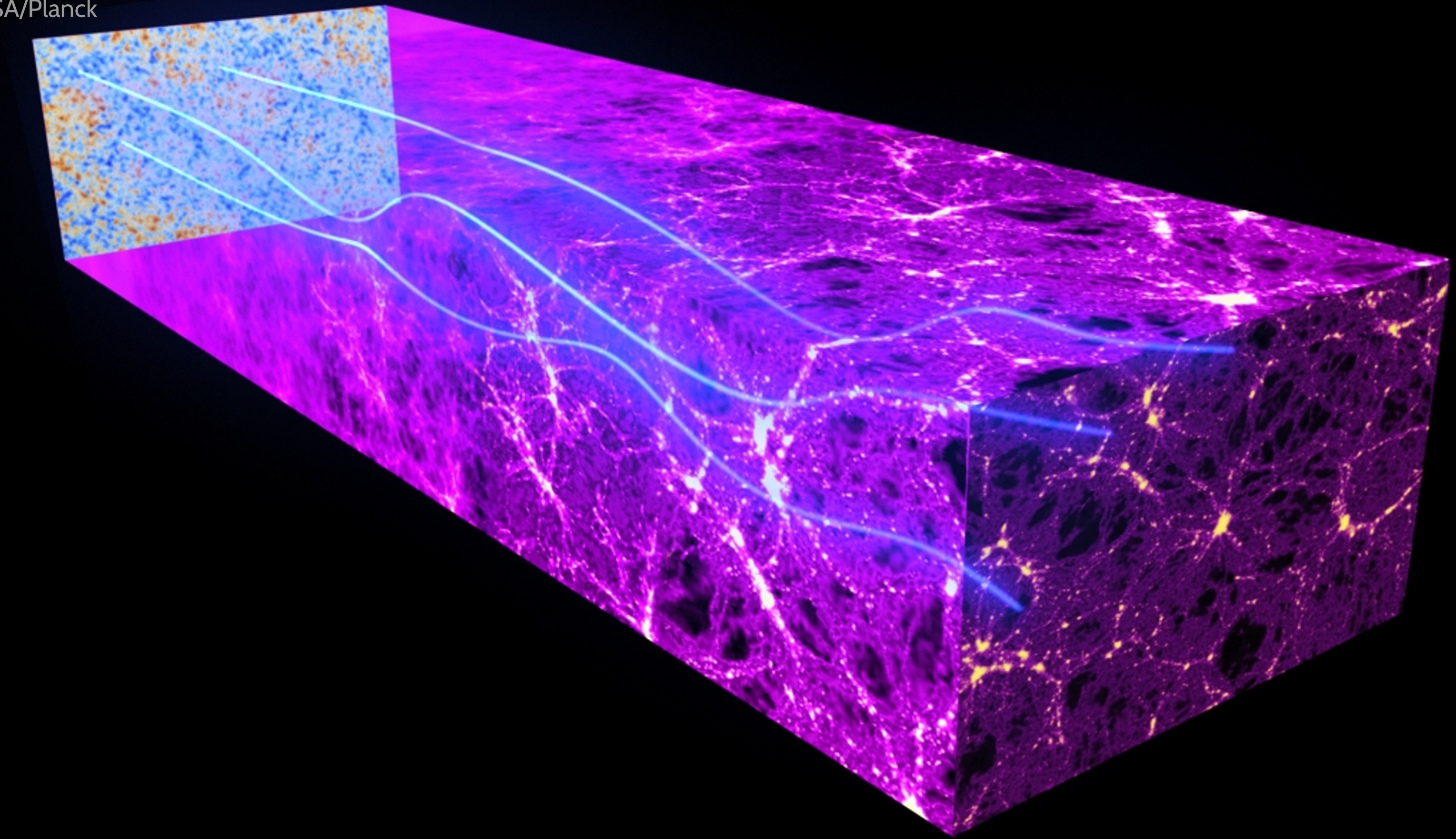


[Jhaveri, Karwal, Hu 2025]

- CMB lensing probes neutrino power suppression and background matter

CMB Gravitational Lensing

Image: ESA/Planck

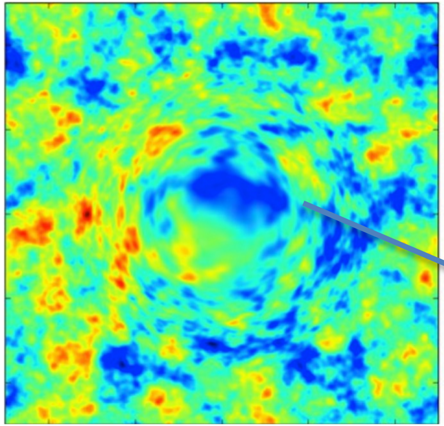


Distribution of mass deflects CMB light that passes through by angle $\nabla \phi$

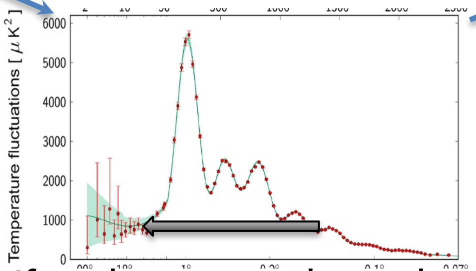
CMB Lensing Measurement

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

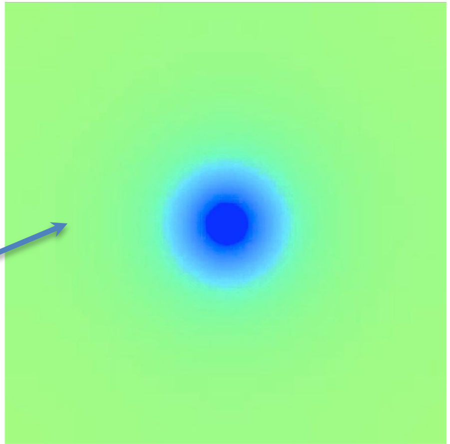
- Approximate explanation:



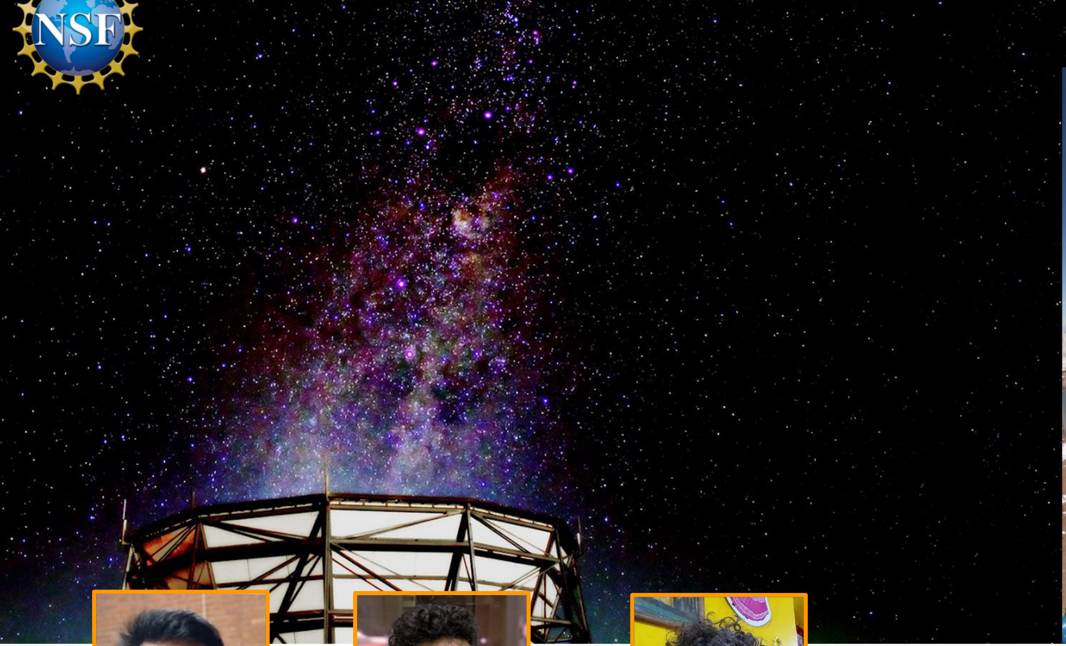
CMB Temp. + Pol.

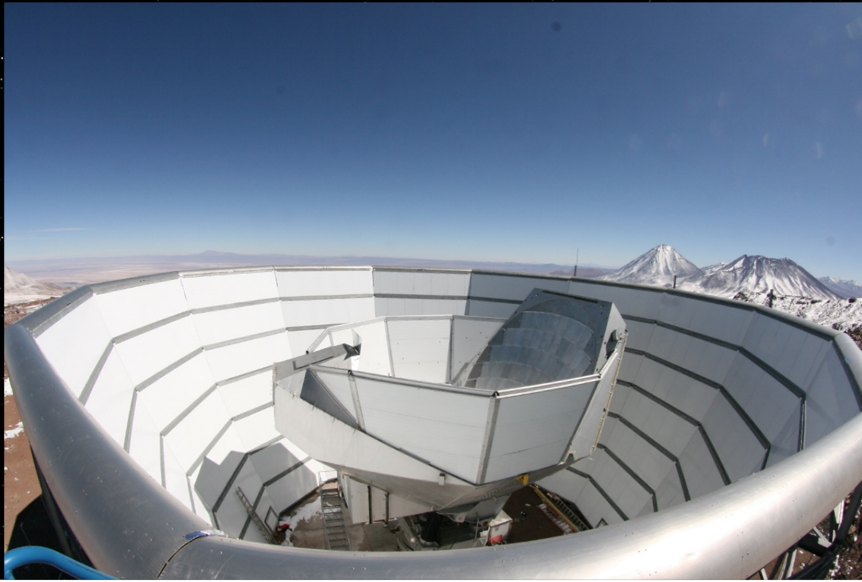


shift to larger angular scales



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





Frank Qu
(Cambridge
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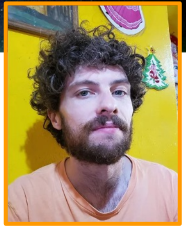
Mat Madhavacheril
(U. Penn)



Niall MacCrann
(Cambridge)

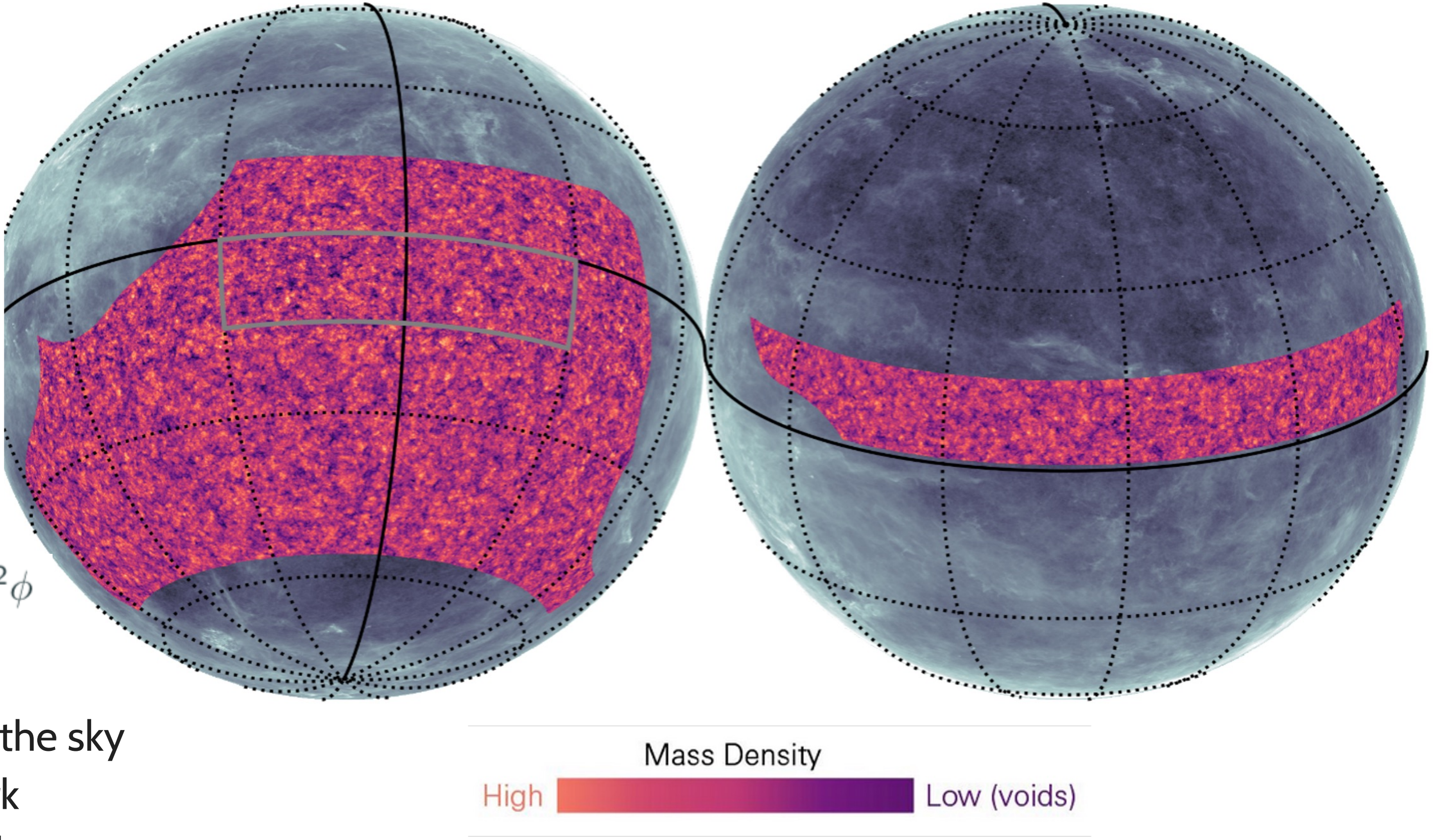
+Dongwon Han
(Cambridge)

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

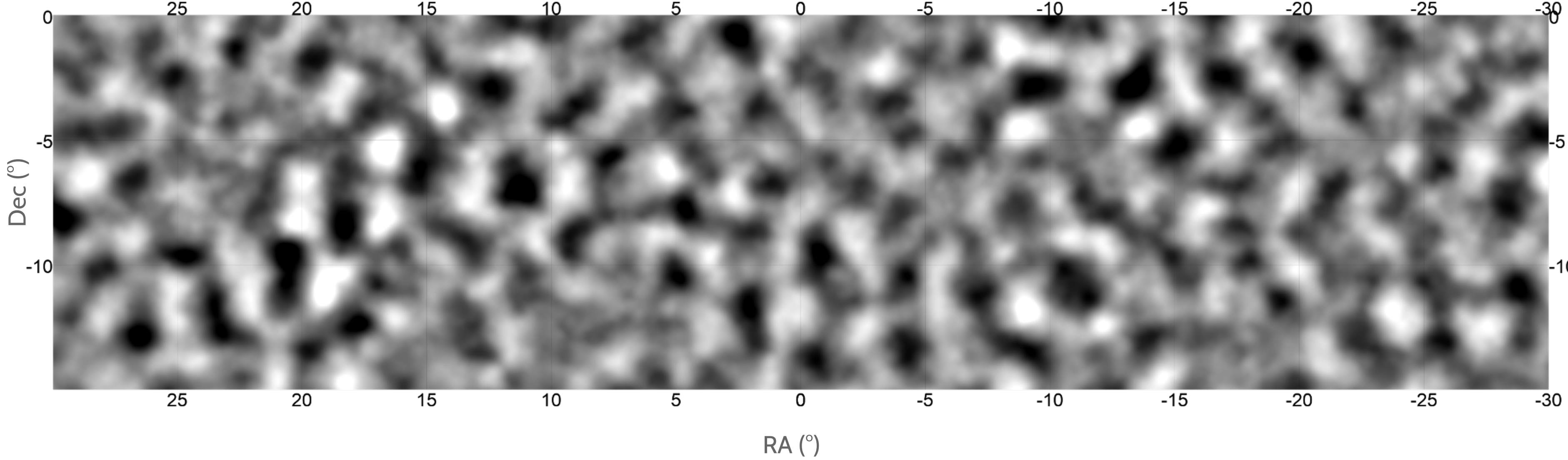
κ ∝ mass density

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

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

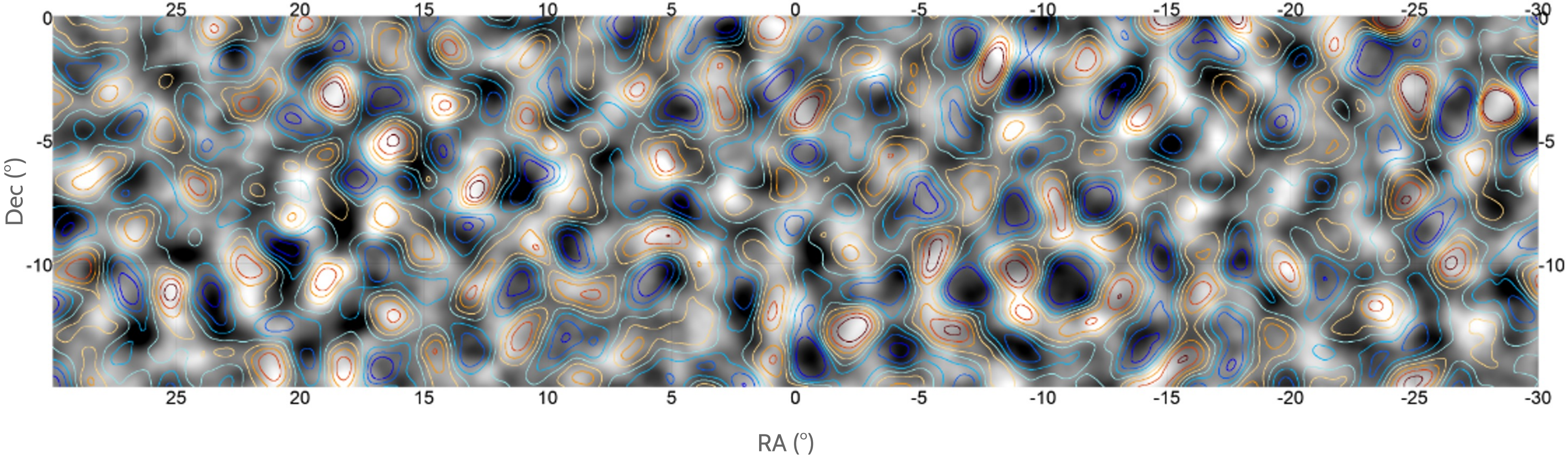
Zoom-in of 900 sq. deg. of 9400. sq. deg. mass map

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 challenge 1: Noise bias subtraction

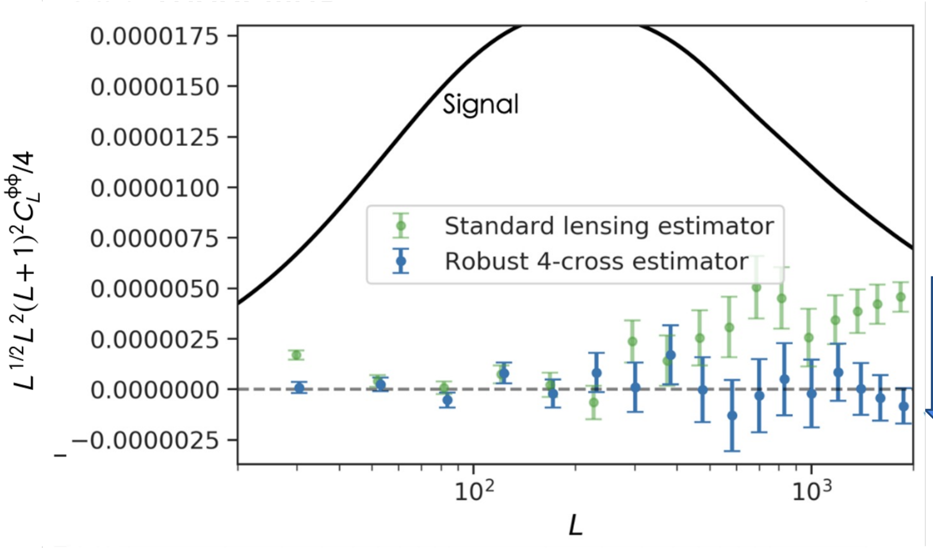
- Challenge: noise complexity causes bias subtraction problem

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

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

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

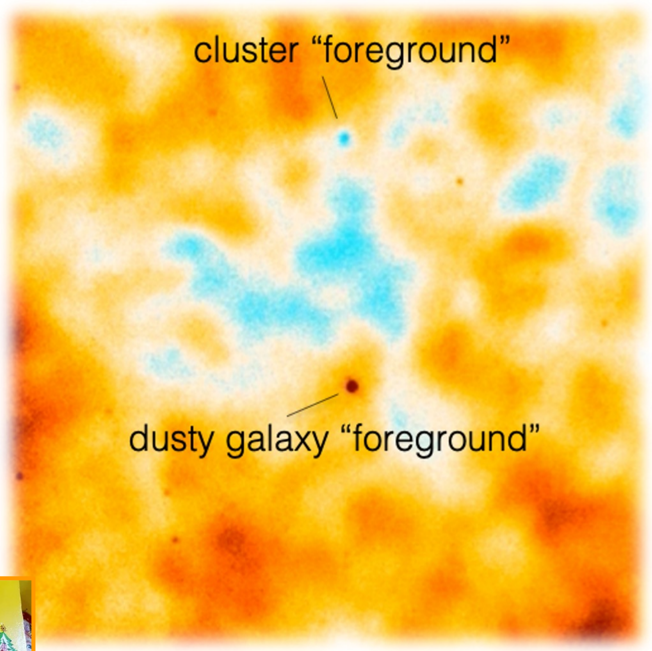
maps with independent noise

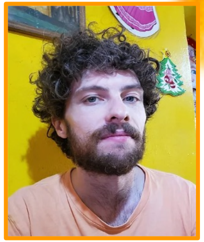


now pass the null test with robust, new cross estimator

Lensing spectrum challenge 2: Extragalactic foregrounds

CMB map cutout (3°x3°)





Niall MacCrann (Cambridge)

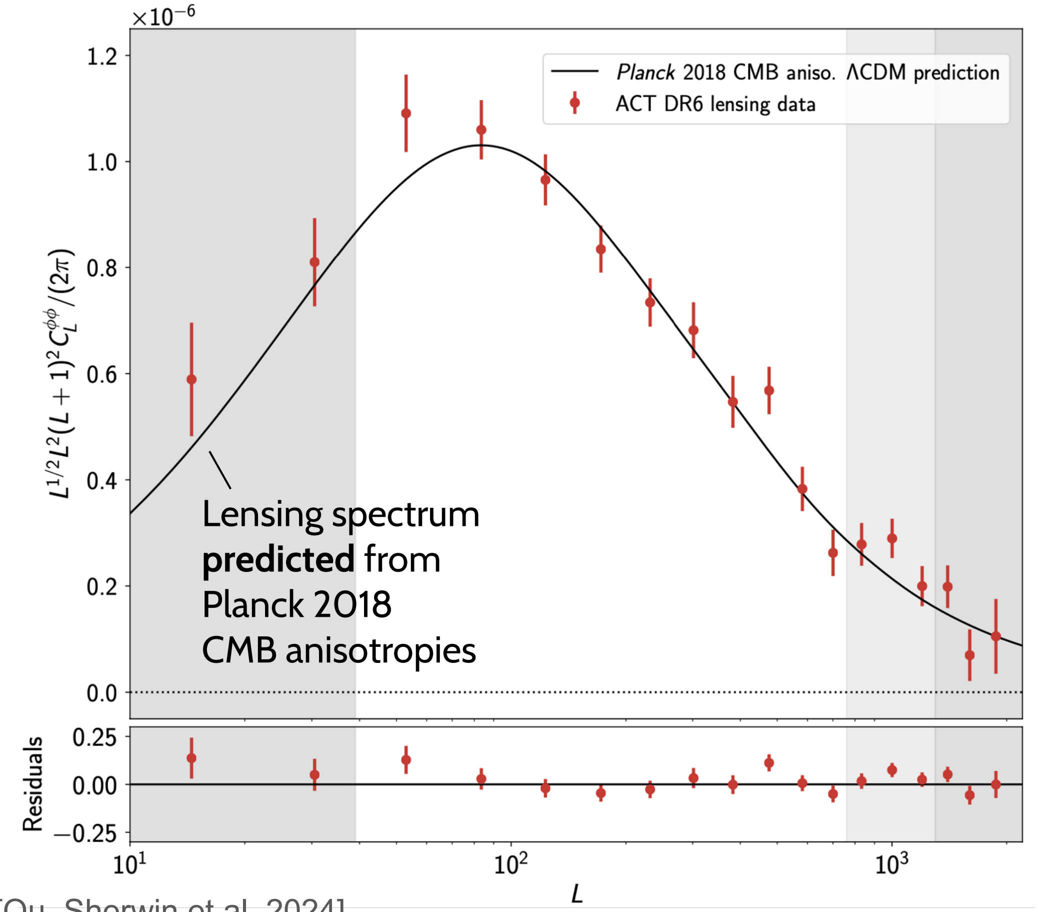
How to mitigate SZ, CIB... foreground biases?

- **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

Unblinded results: ACT DR6 lensing power spectrum

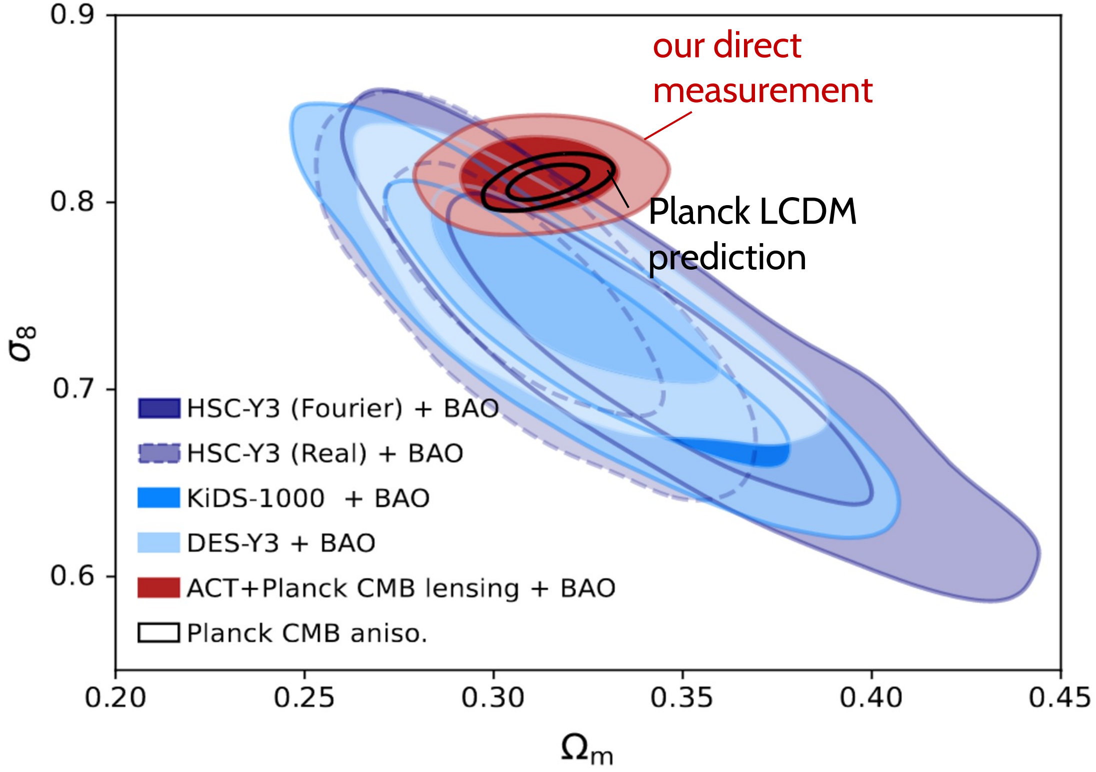


[Qu, Sherwin et al. 2024]

- 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)

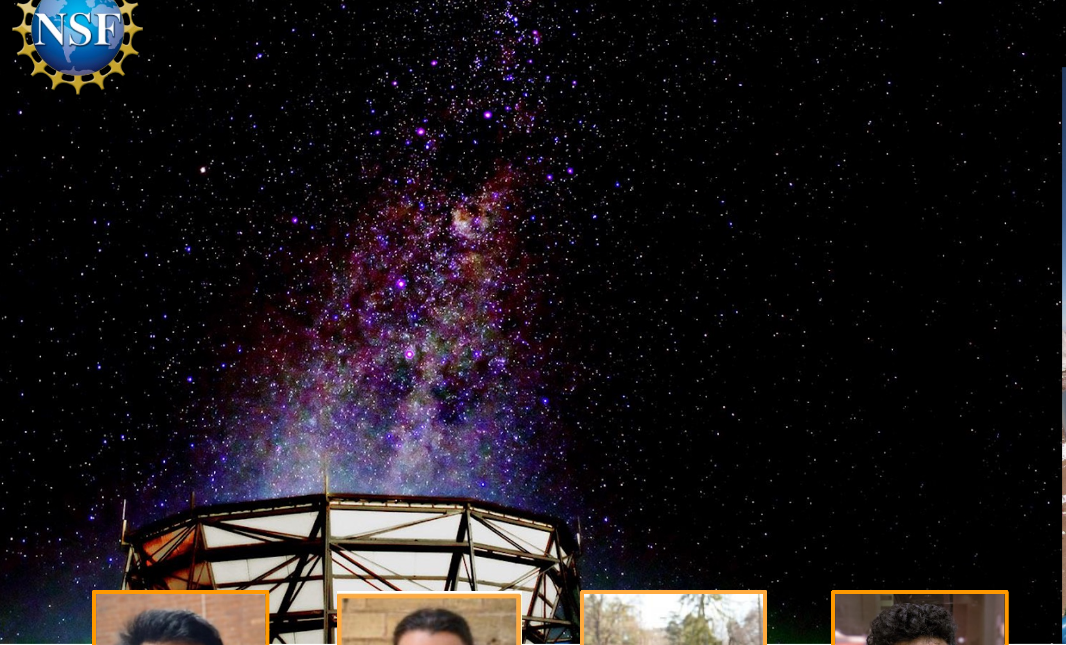


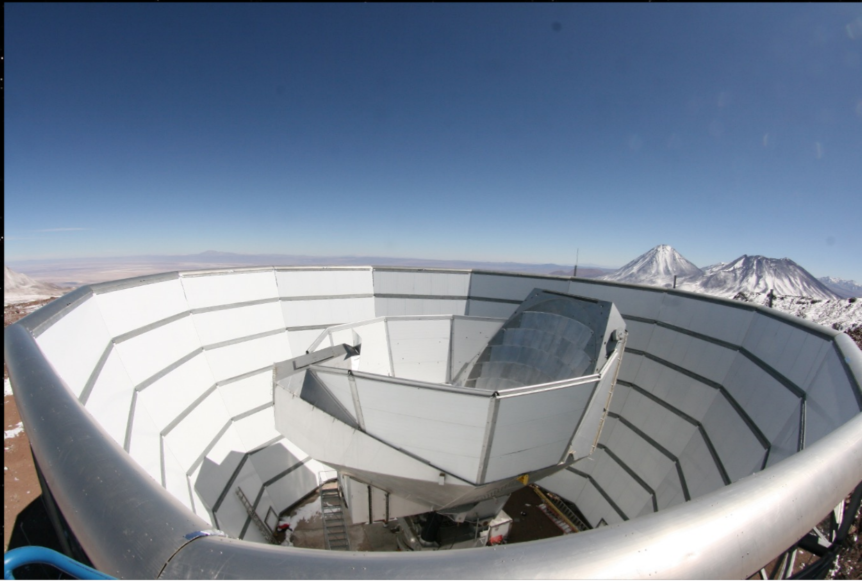
ACT/Planck lensing + BAO:

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

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
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Irene Abril-Cabezas
(Cambridge)

Joshua Kim
(U. Penn)

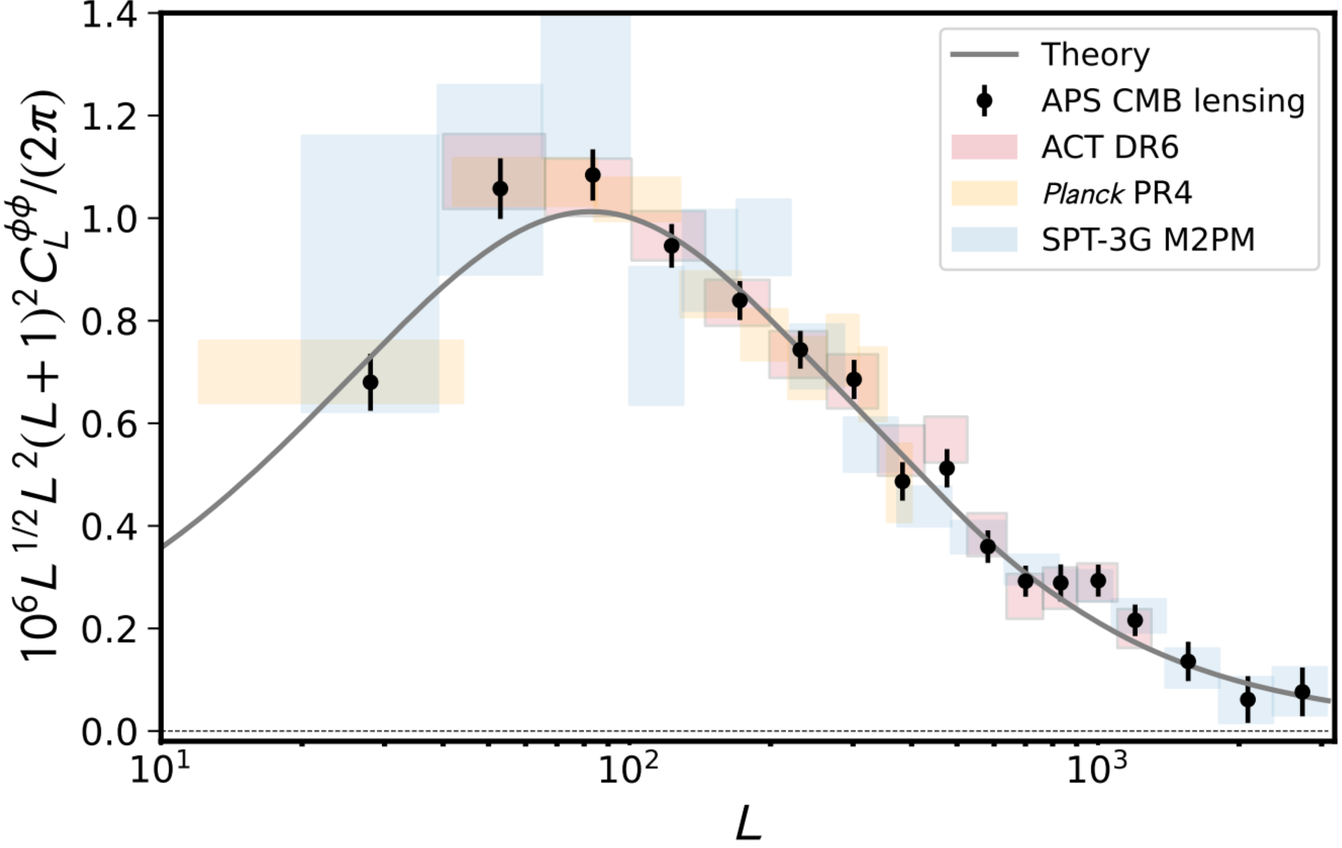
Mat Madhavacheril
(U. Penn)

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

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

[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
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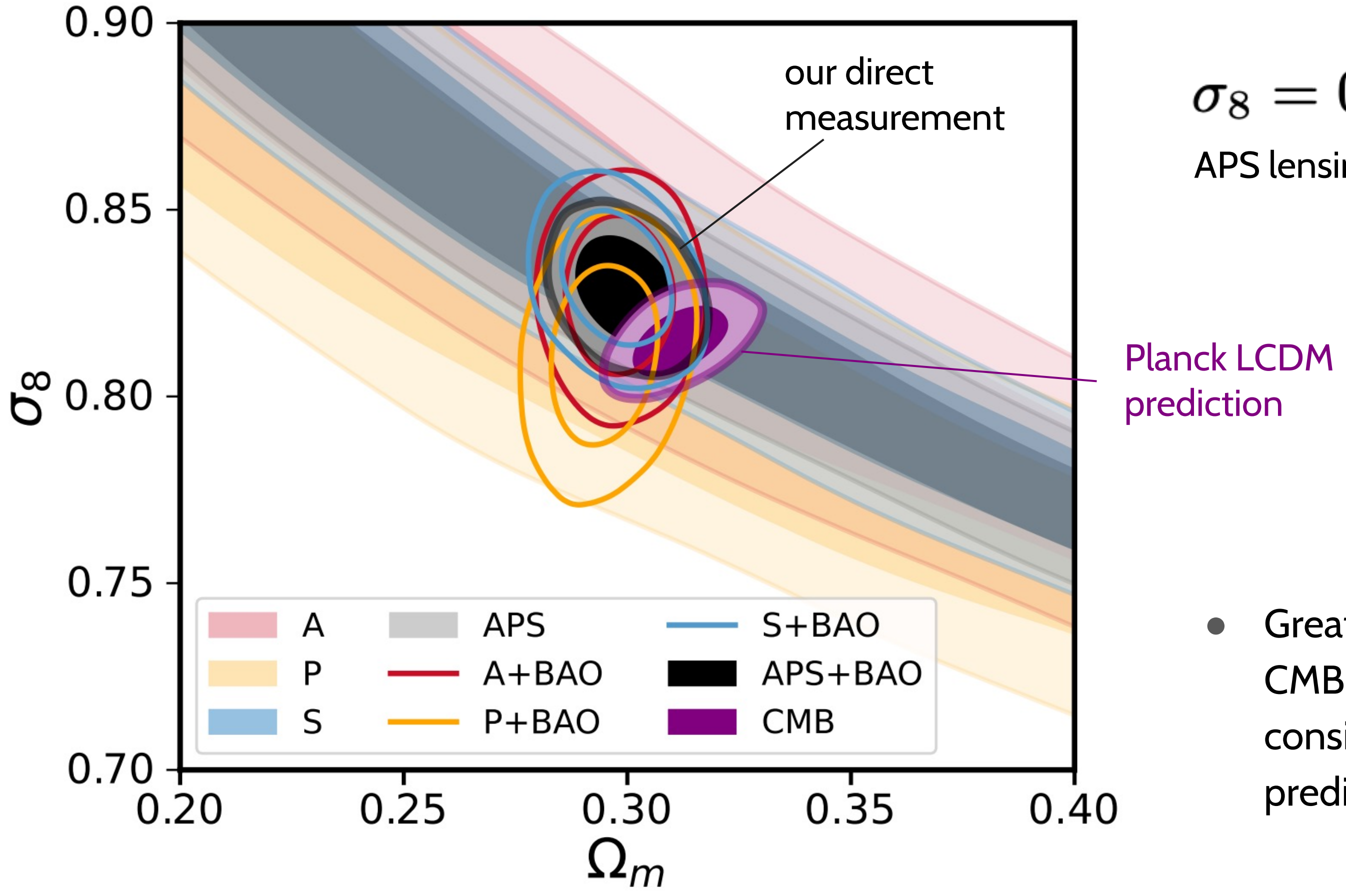
Fei Ge
(Stanford)

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

ACT+Planck+SPT lensing: constraints on structure growth

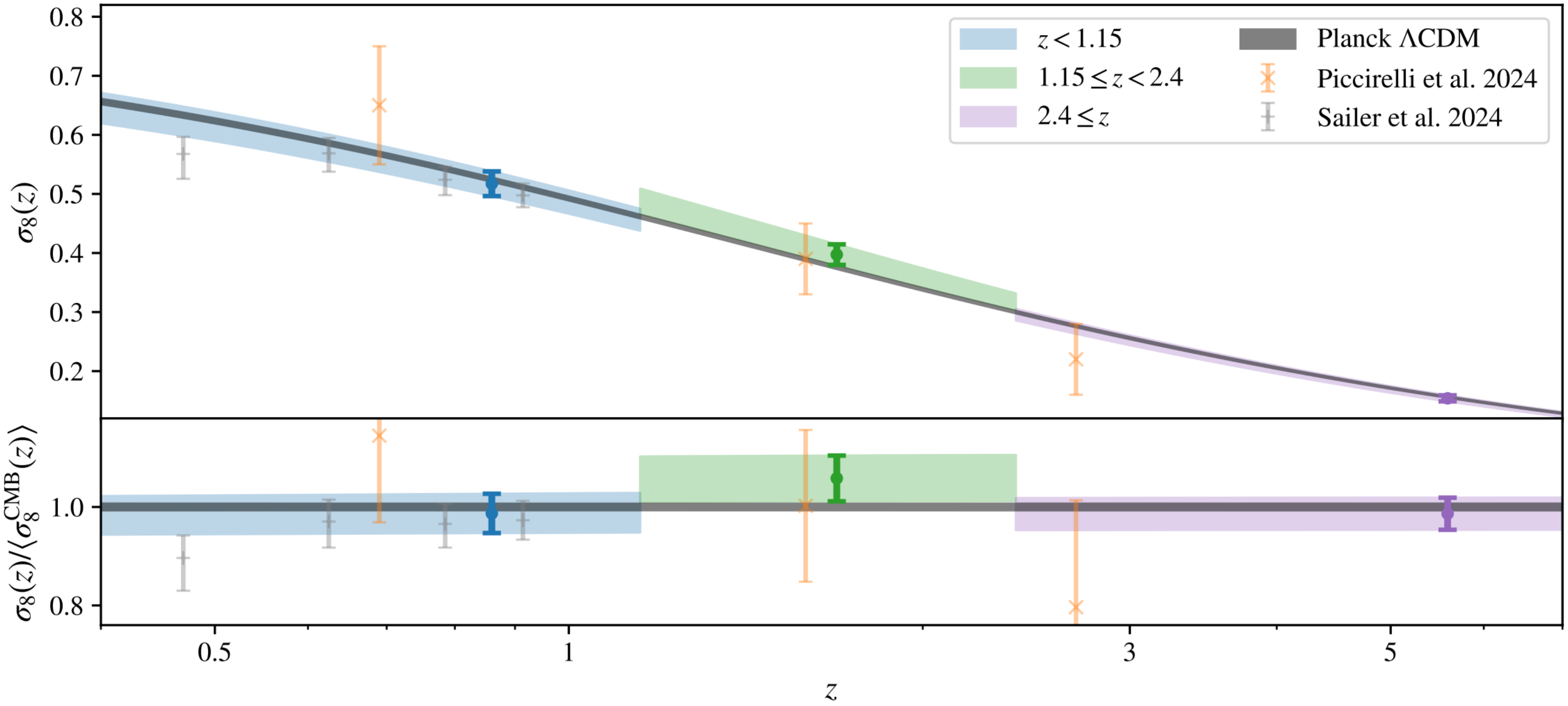


$$\sigma_8 = 0.829 \pm 0.009$$

APS lensing + DESI BAO!

- Great consistency of different CMB lensing measurements + consistency with LCDM prediction at high precision

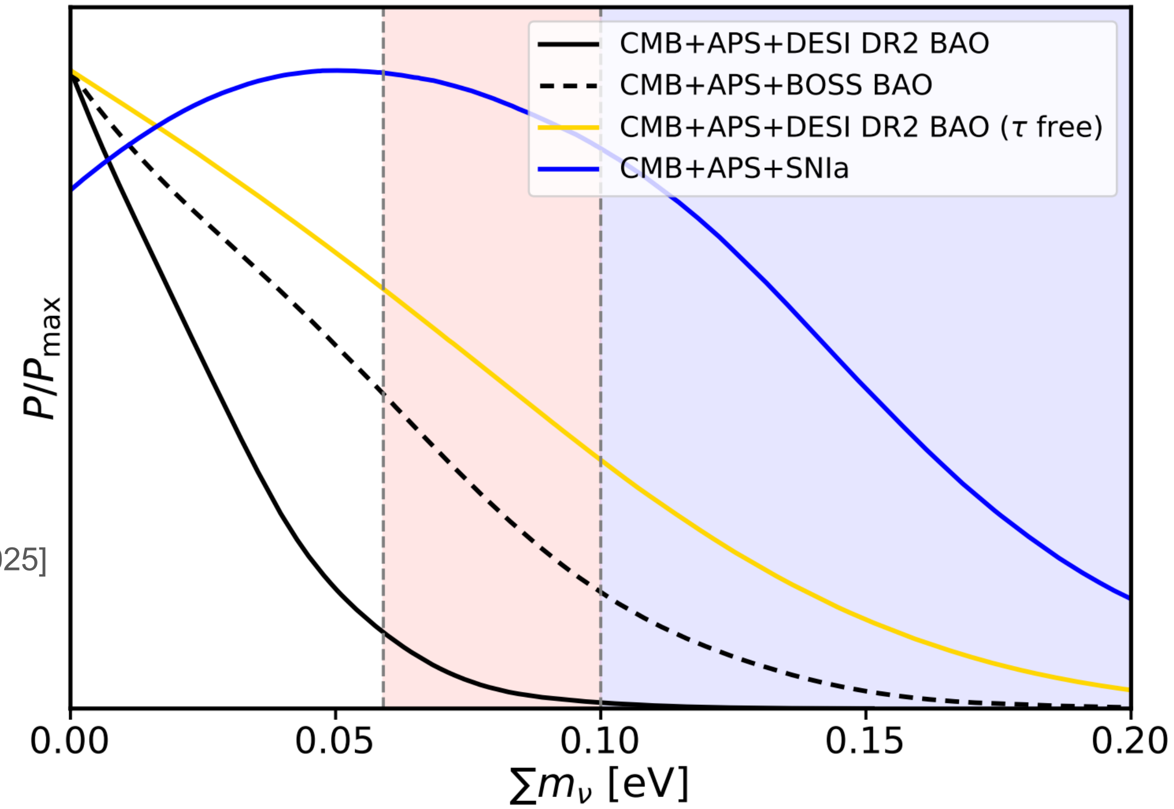
ACT lensing results: redshift dependent growth from cross-correlations



[**Gerrit Farren** et al. 2023 / 2024, **Joshua Kim** et al. 2024, **Noah Sailer** et al. 2024, …]

- Combined auto/cross-analysis (3x2): structure growth seems to follows LCDM prediction, even at high z~5!

ACT+Planck+SPT lensing: constraints on neutrino mass

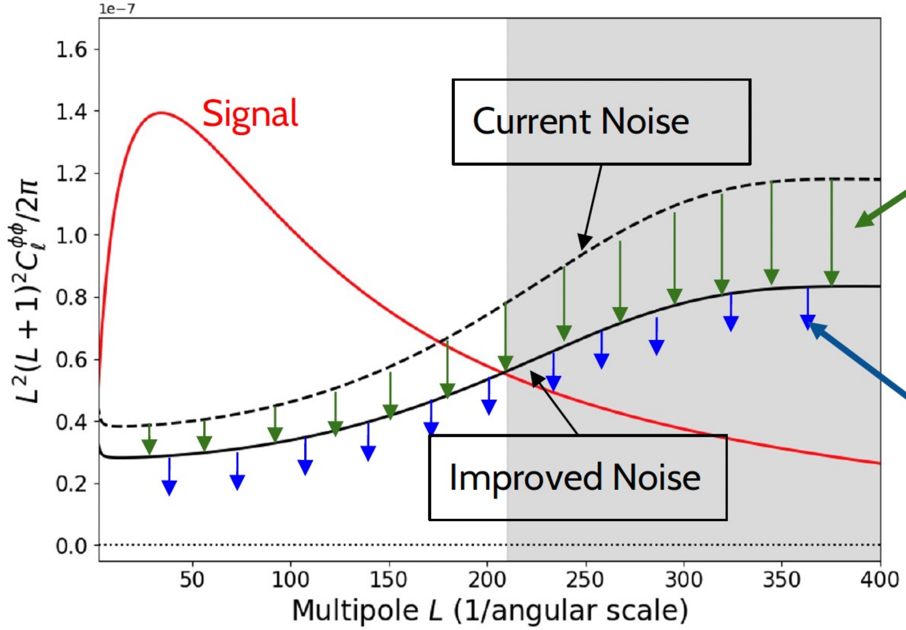


[Qu, Ge, Wu, et al. 2025]

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

Coming soon: DR6+ lensing analysis

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



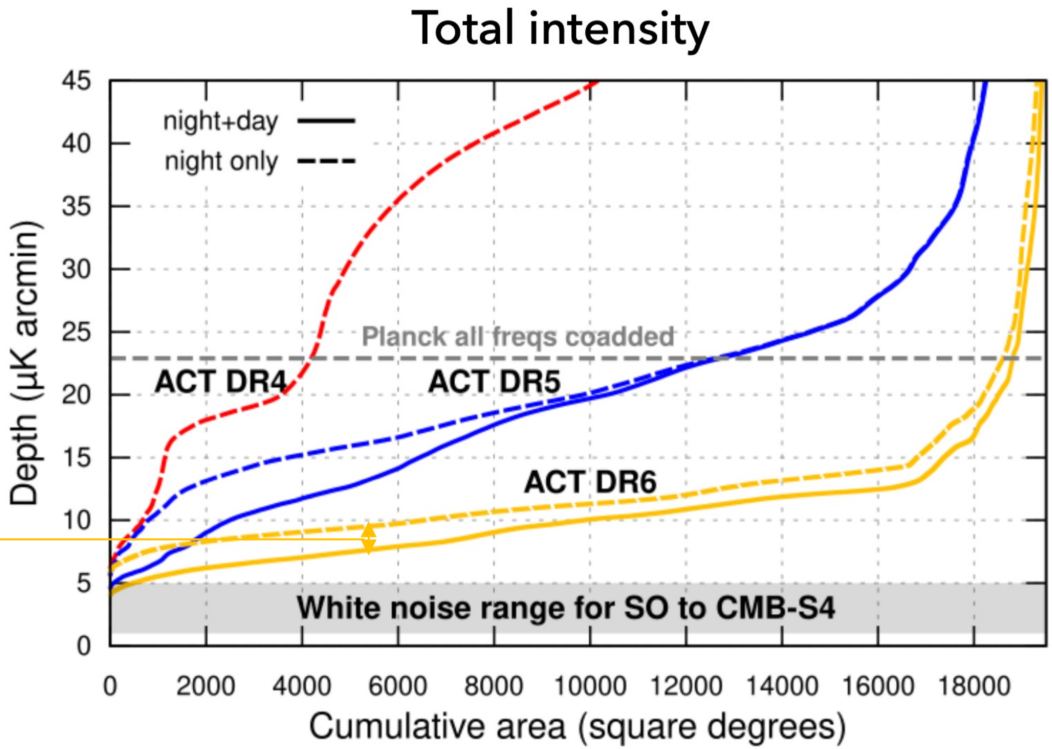
- **Inclusion of the daytime data: ~ 1.7x amount of data**

- **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

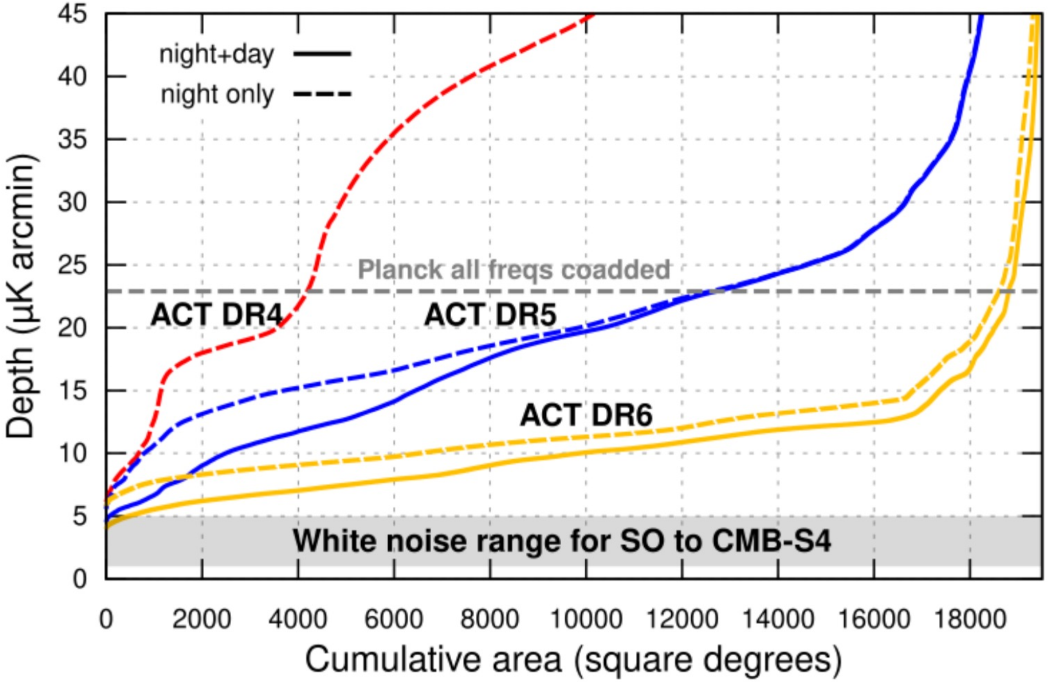
- Data taken during the day (11am-11pm); 6 observing seasons (2016-22)
- Challenging: Sun's heat distorts the telescope mirror, causing pointing offsets and beam deformations. Not used for CMB power spectra.
- However, nearly a factor 2 in data if we can use it!



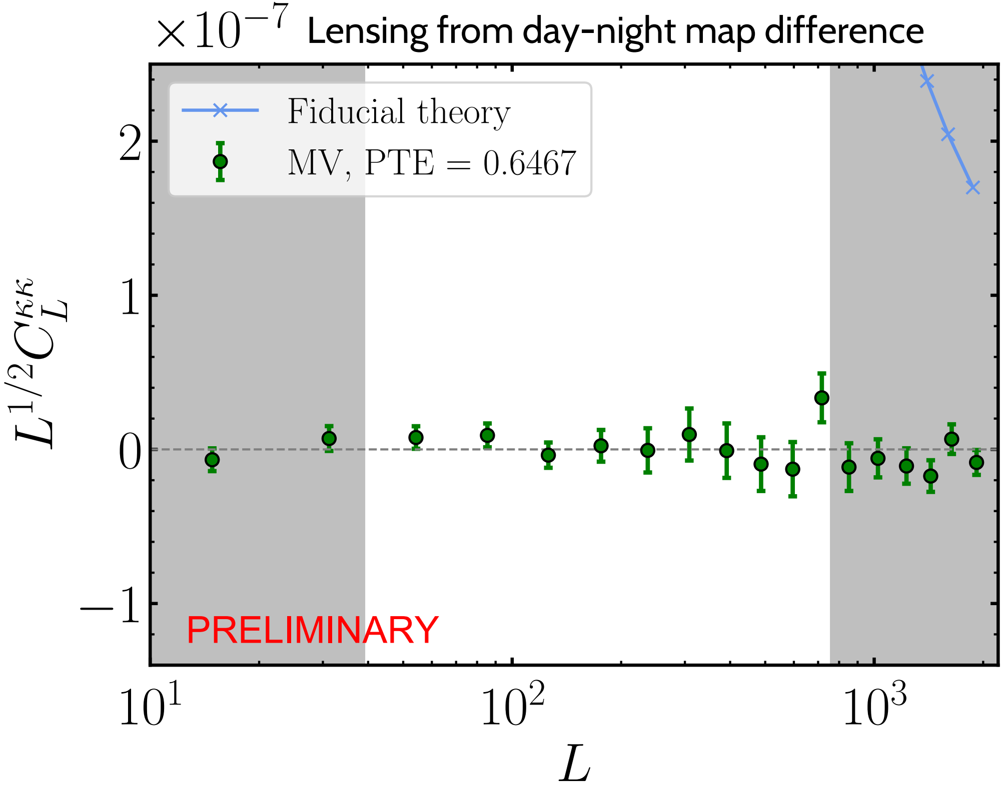
Daytime lensing: improving the maps

- 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

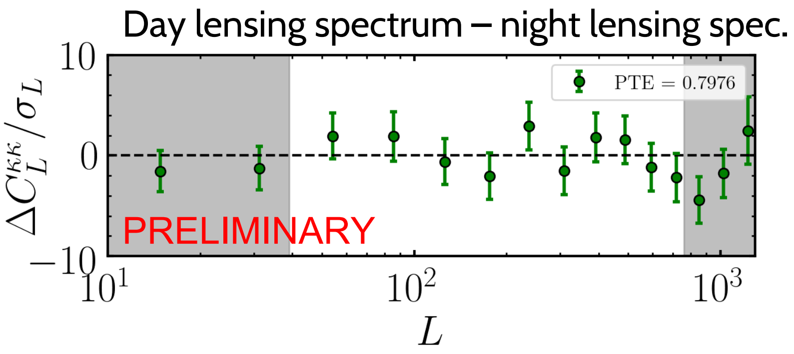
Total intensity



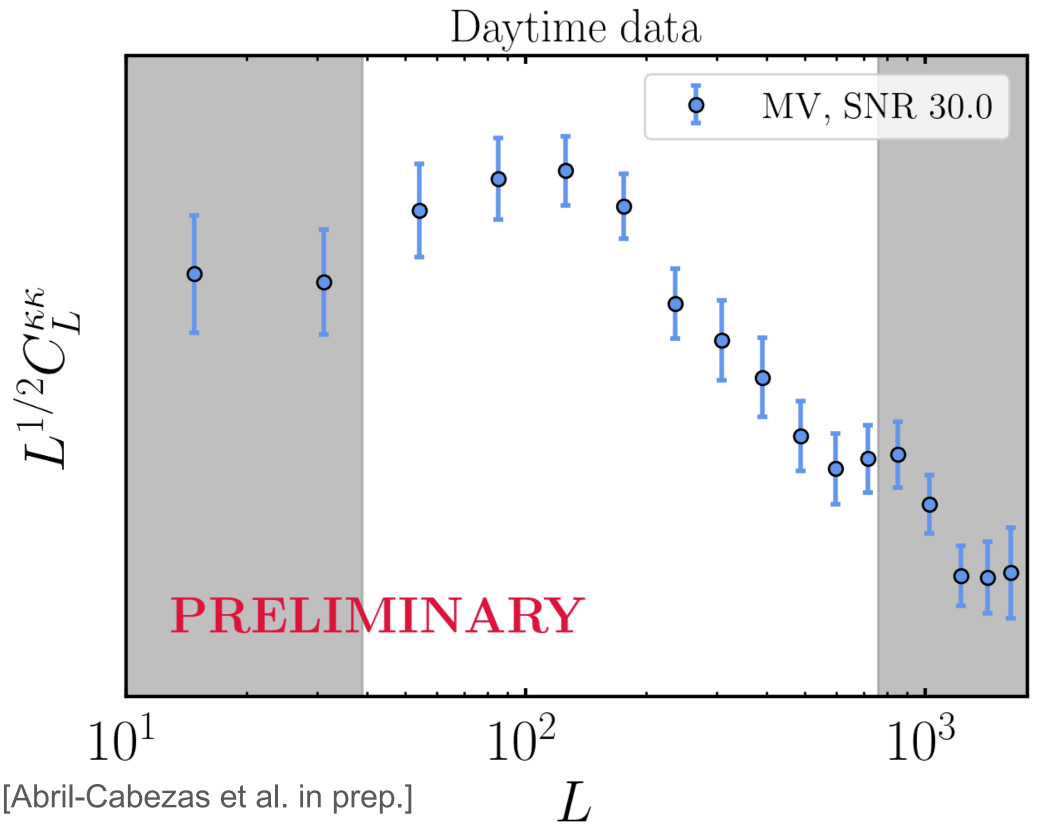
Daytime lensing: stringent null tests vs. night



- 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 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.
- Stay tuned for upcoming DR6+ analysis out soon – SNR 60—70!

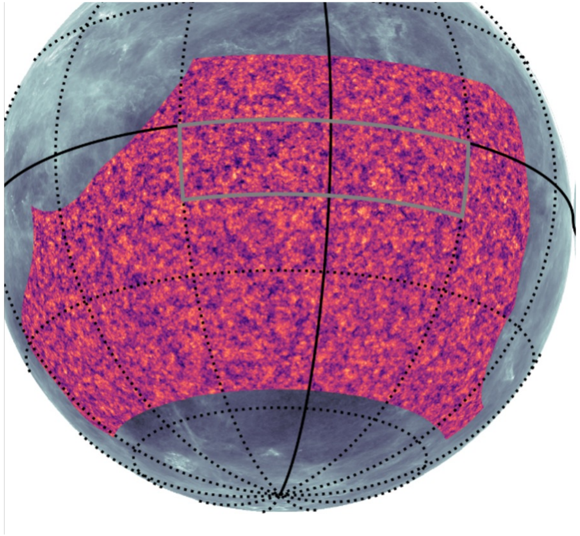
Summary

- 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 scales/redshifts probed, $\sigma_8 = 0.829 \pm 0.009$ neutrino mass bounds remain tight, $\Sigma m_\nu < 0.062\ \mathrm{eV}$

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

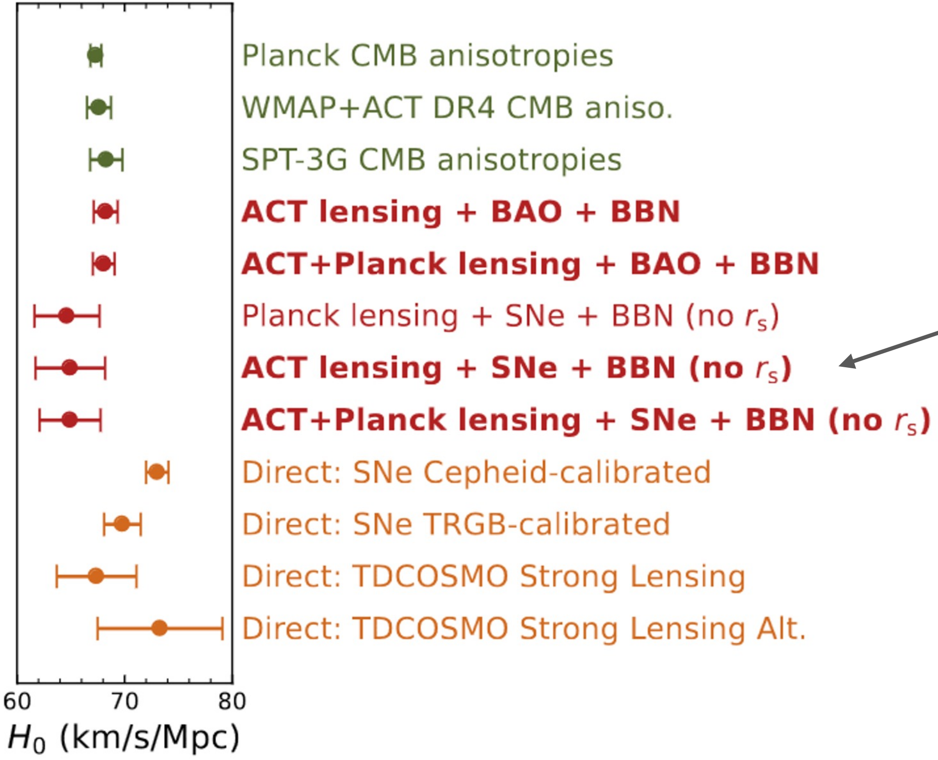
mass



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

Backup slides

H_0 from lensing



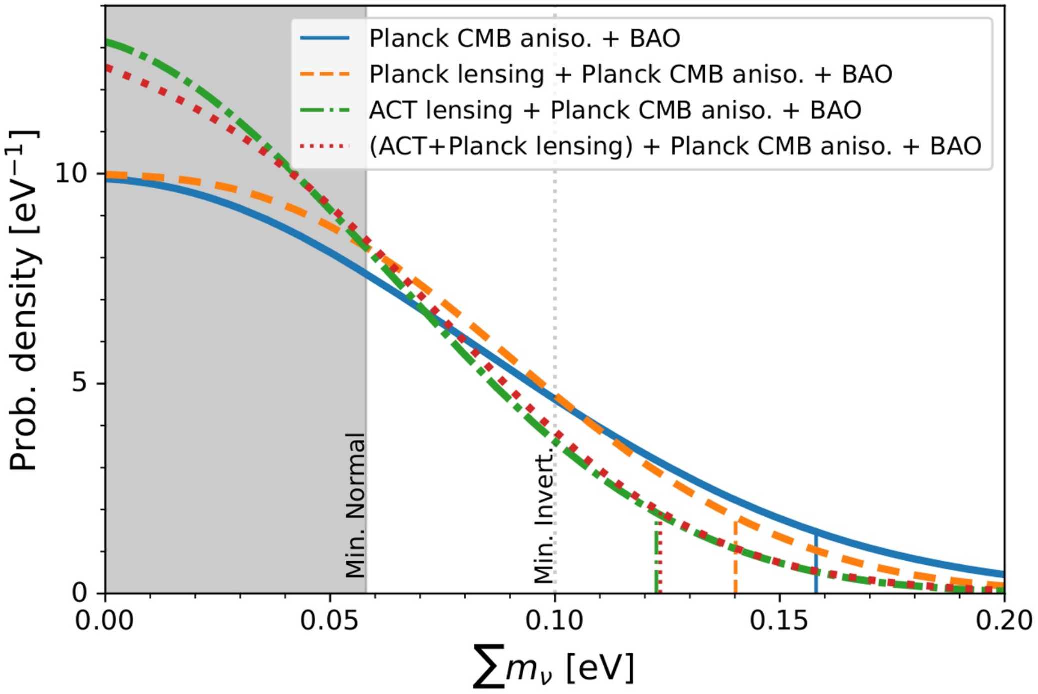
- Hubble constraint from ACT lensing without sound horizon info

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

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

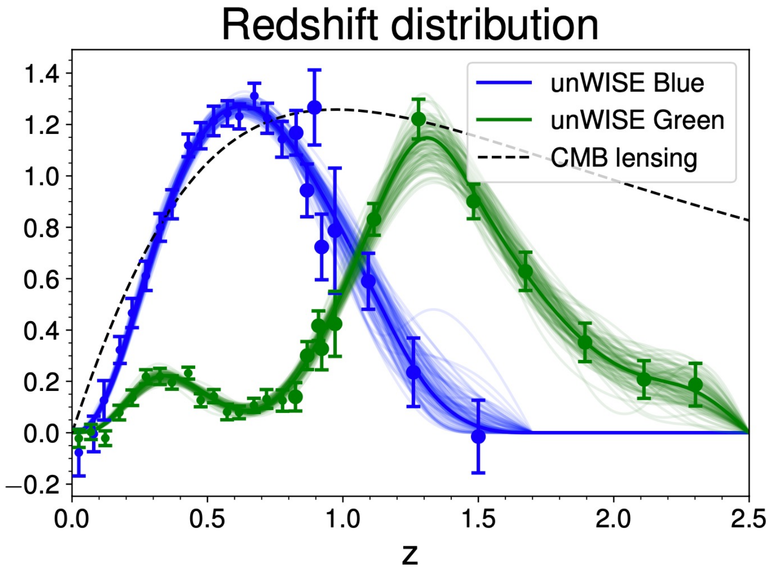
Analysis improvements highlights: better redshifts and modeling

- 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

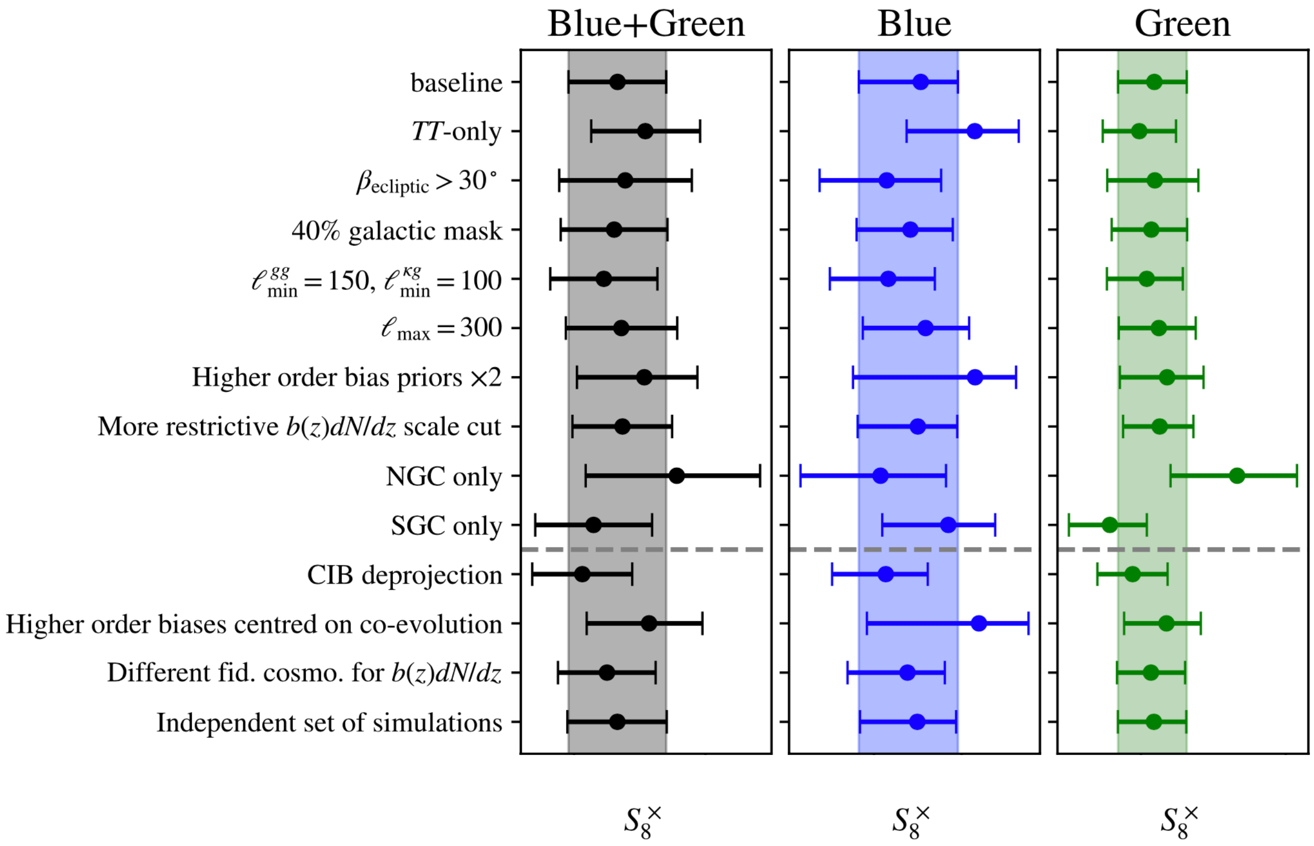
$$P_{gg}(k,z) = b_{1,E}^2(z)P_{mm,\mathrm{HF}} + \underbrace{b_{2,L}(z)P_{b_2}(k,z) + \ldots}_{\mathrm{LPT\ terms}} + P_{\mathrm{shot\ noise}}$$

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



Null and systematics tests: parameter stability

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

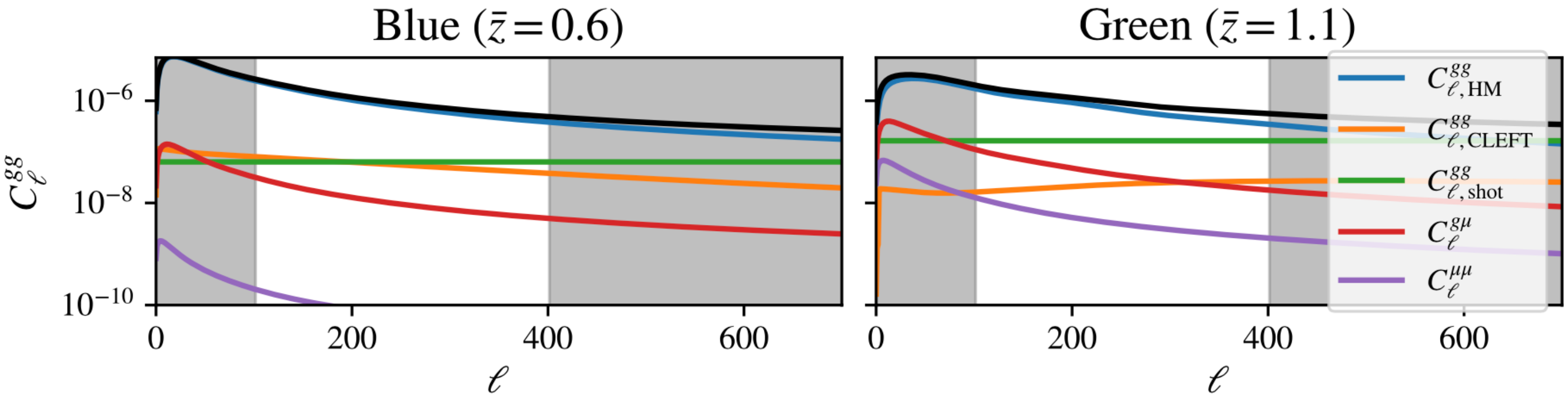


Analysis improvements II: better theory modeling

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

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

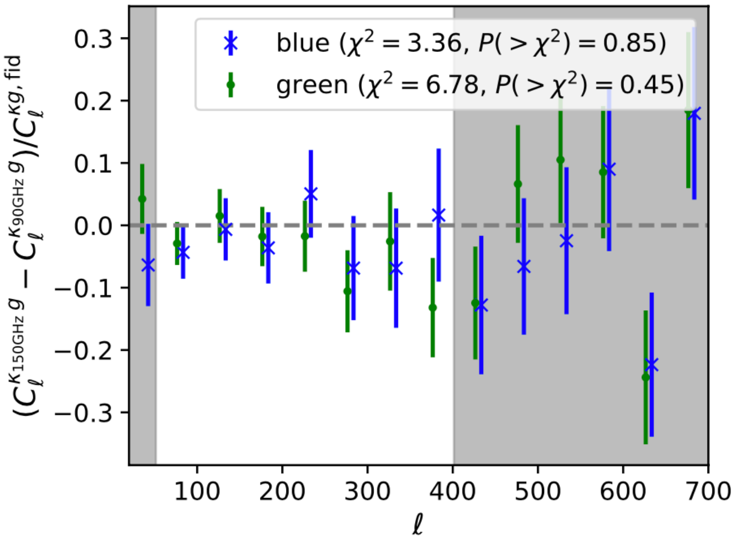
$$P_{gm}(k,z) = b_{1,E}(z)P_{mm,\mathrm{HF}} + \overbrace{\frac{b_{2,L}(z)}{2}P_{b_2}(k,z) + \ldots}$$



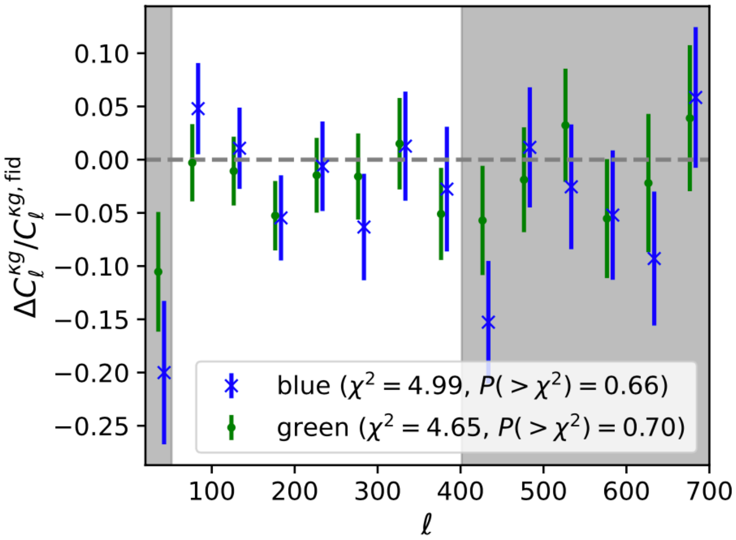
Systematics tests: nulls

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

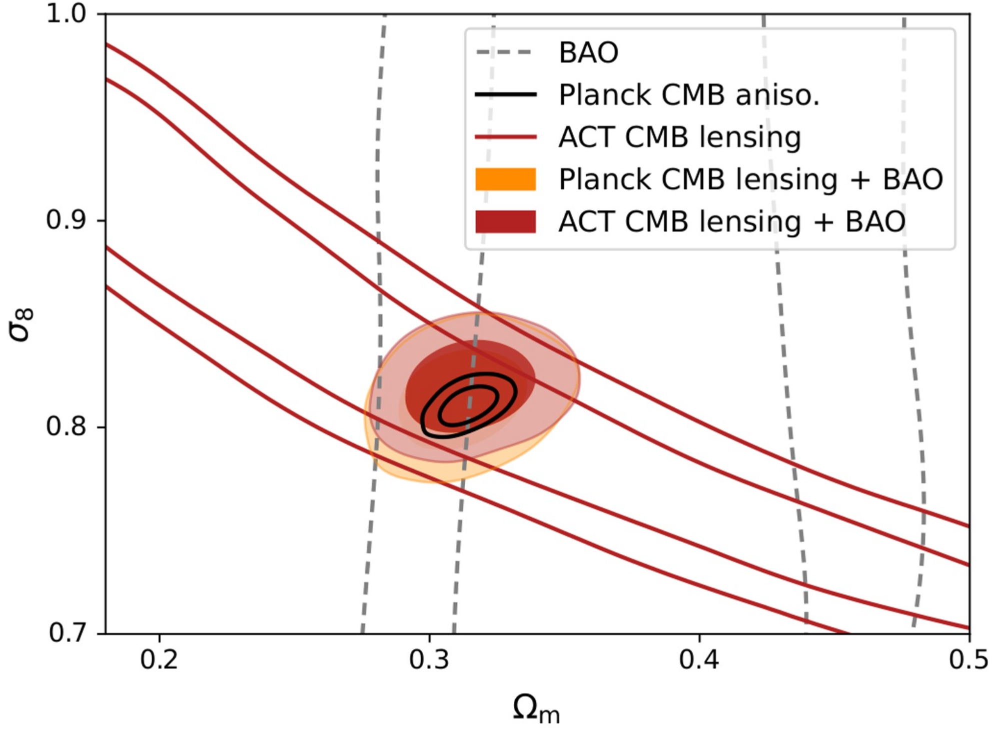
frequency comparison



galactic mask comparison



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



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

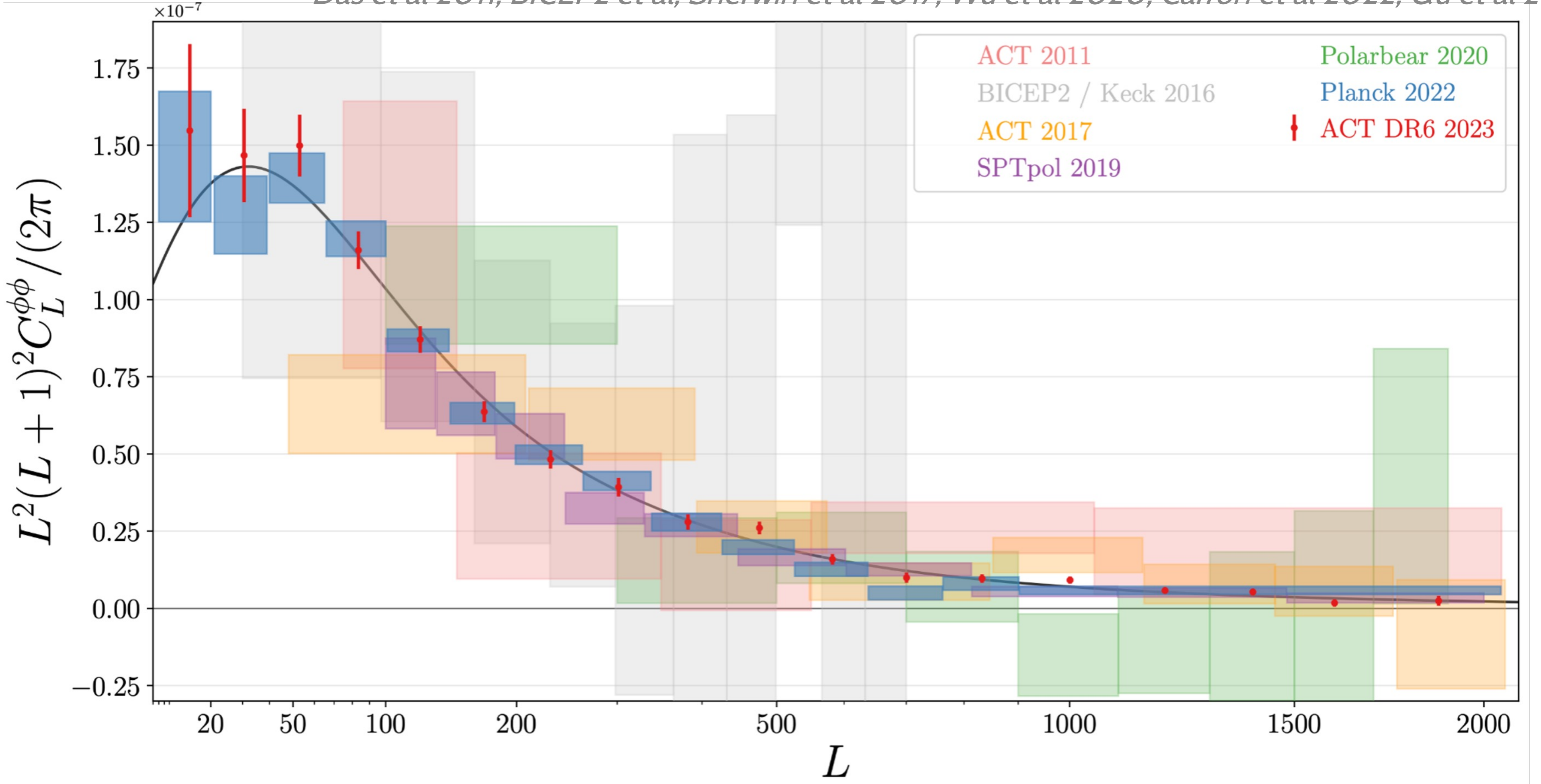
Combination with BAO isolates σ_8

$$\sigma_8 = 0.819 \pm 0.015$$

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



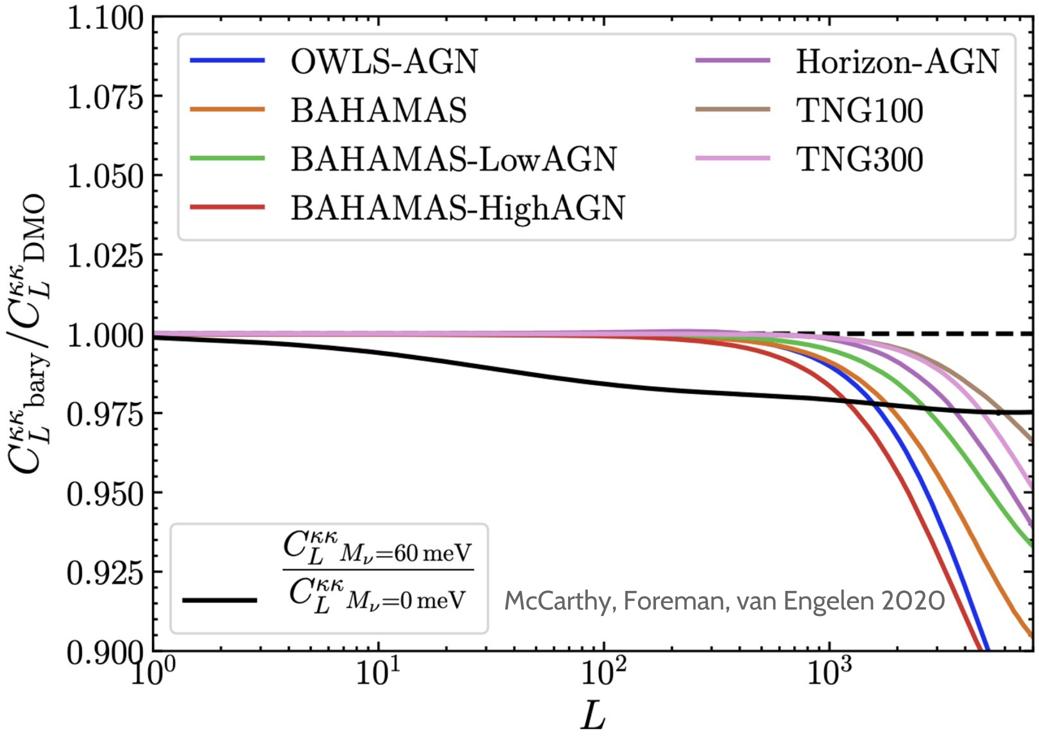
Analysis Improvements to unWISE x Planck lensing: shift in results!

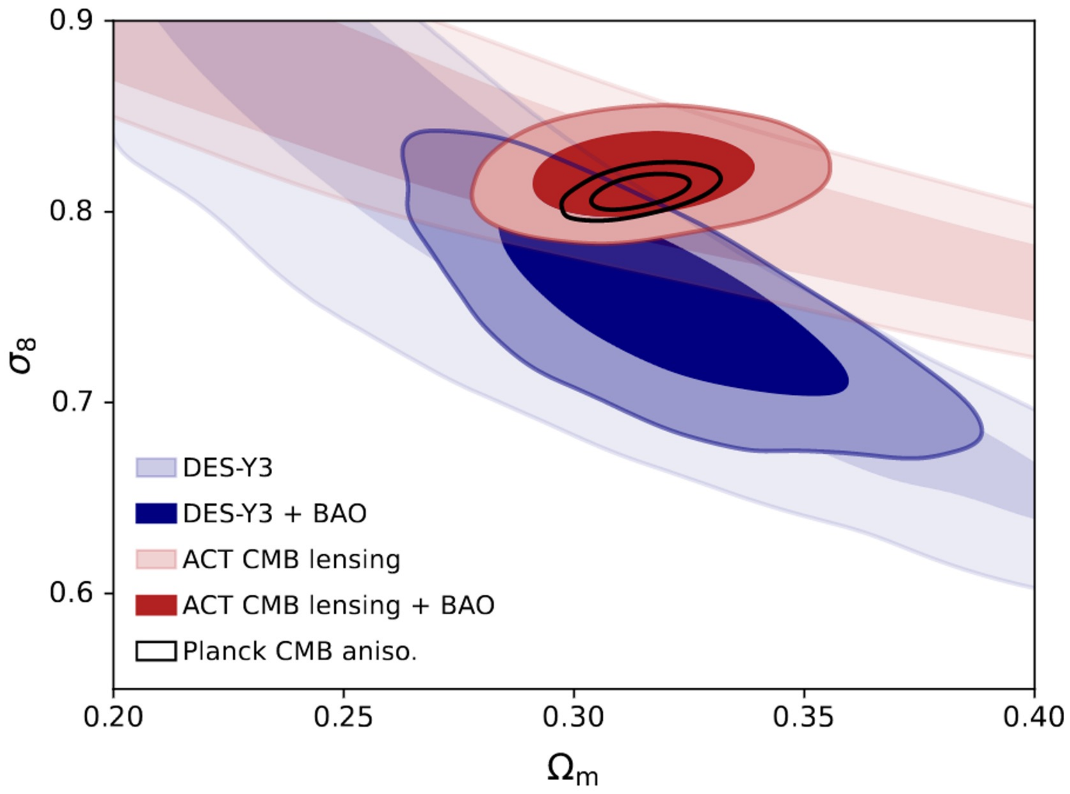
- Lots of analysis improvements in lensing x unWISE correlation

	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**

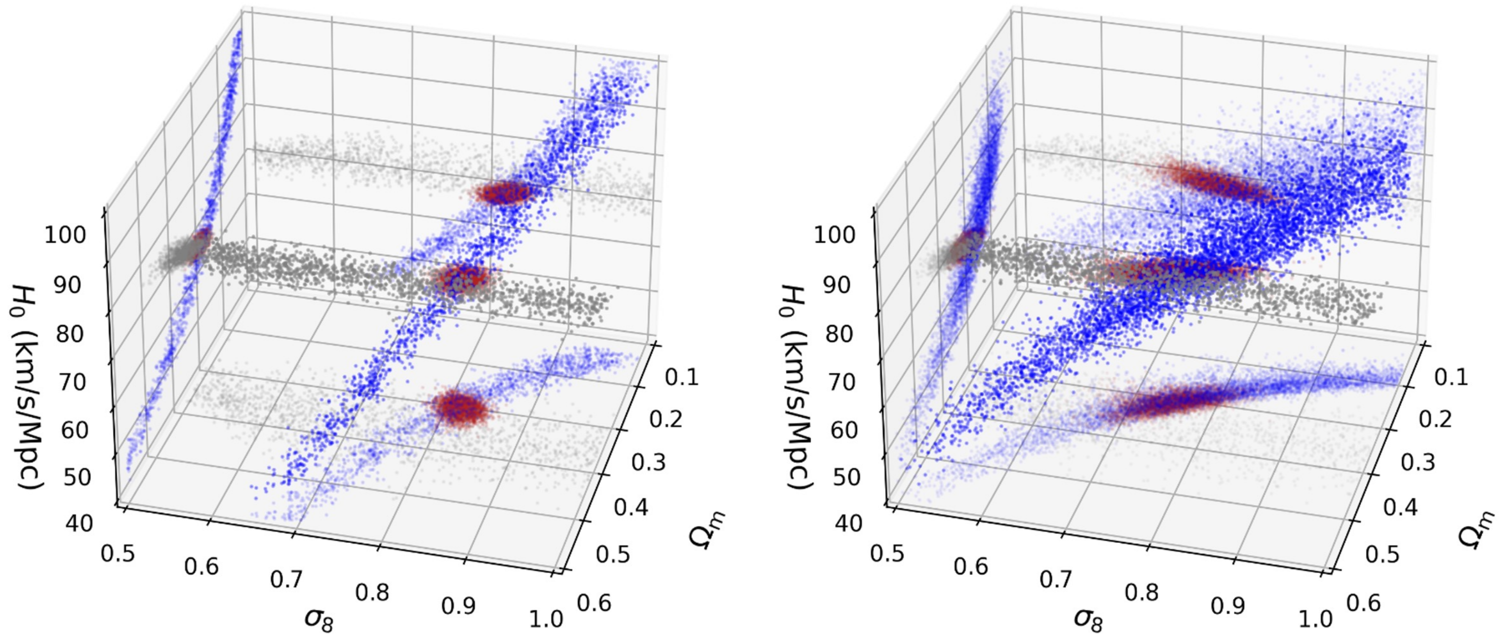
- Constraints (from z~0.6-1) change to $S_8 = 0.803 \pm 0.017$ (c.f. old $S_8 = 0.782 \pm 0.015$)
- Stay tuned for ACT results!

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

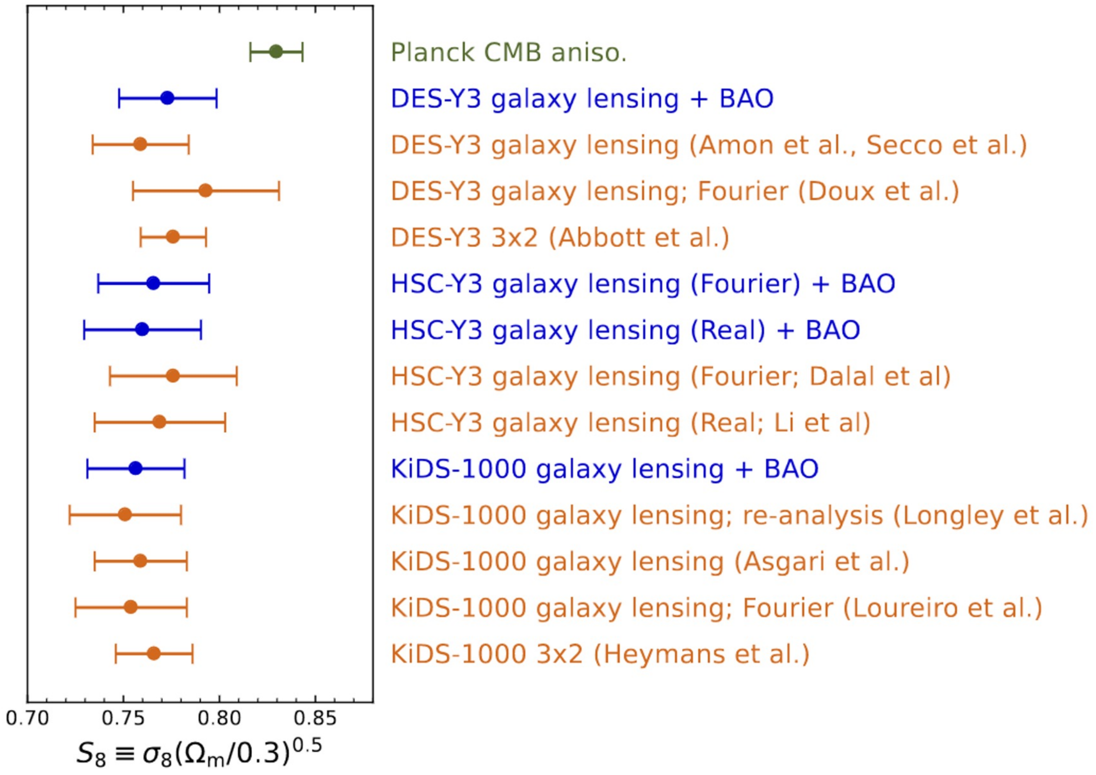




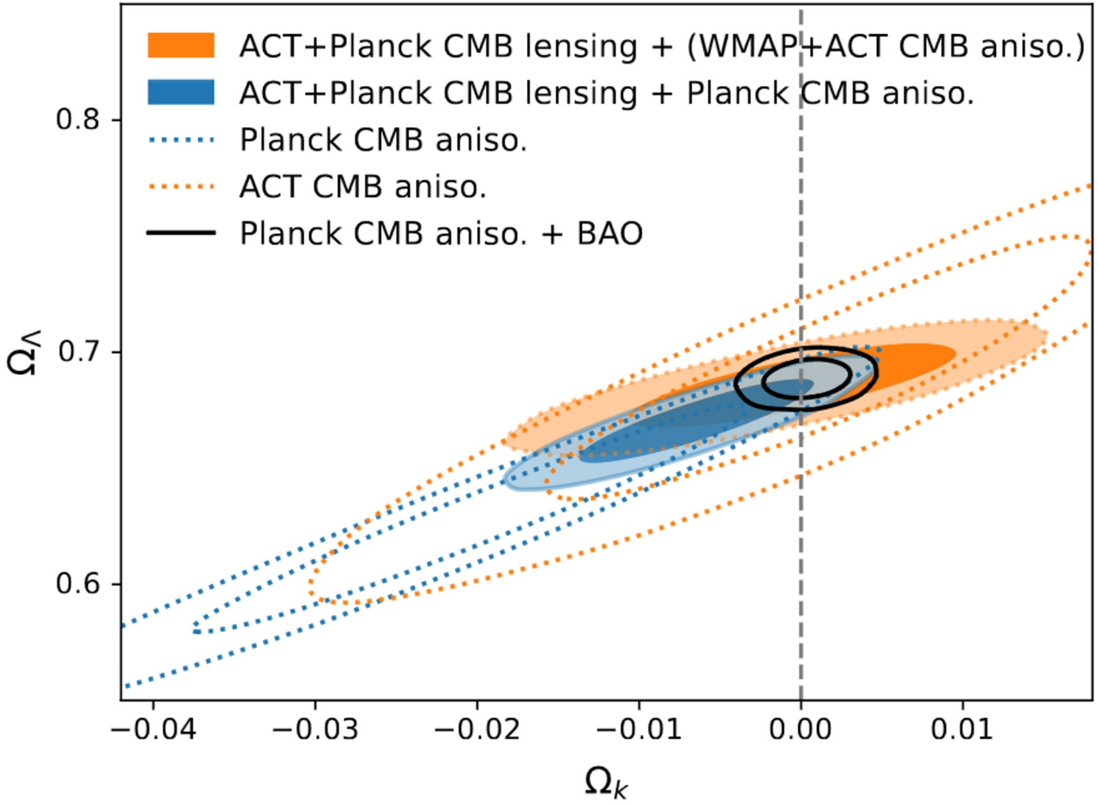
0.9
0.8
0.7
0.6
σ_8
0.20
0.25
0.30
0.35
0.40
Ω_m
DES-Y3
DES-Y3 + BAO
ACT CMB lensing
ACT CMB lensing + BAO
Planck CMB aniso.

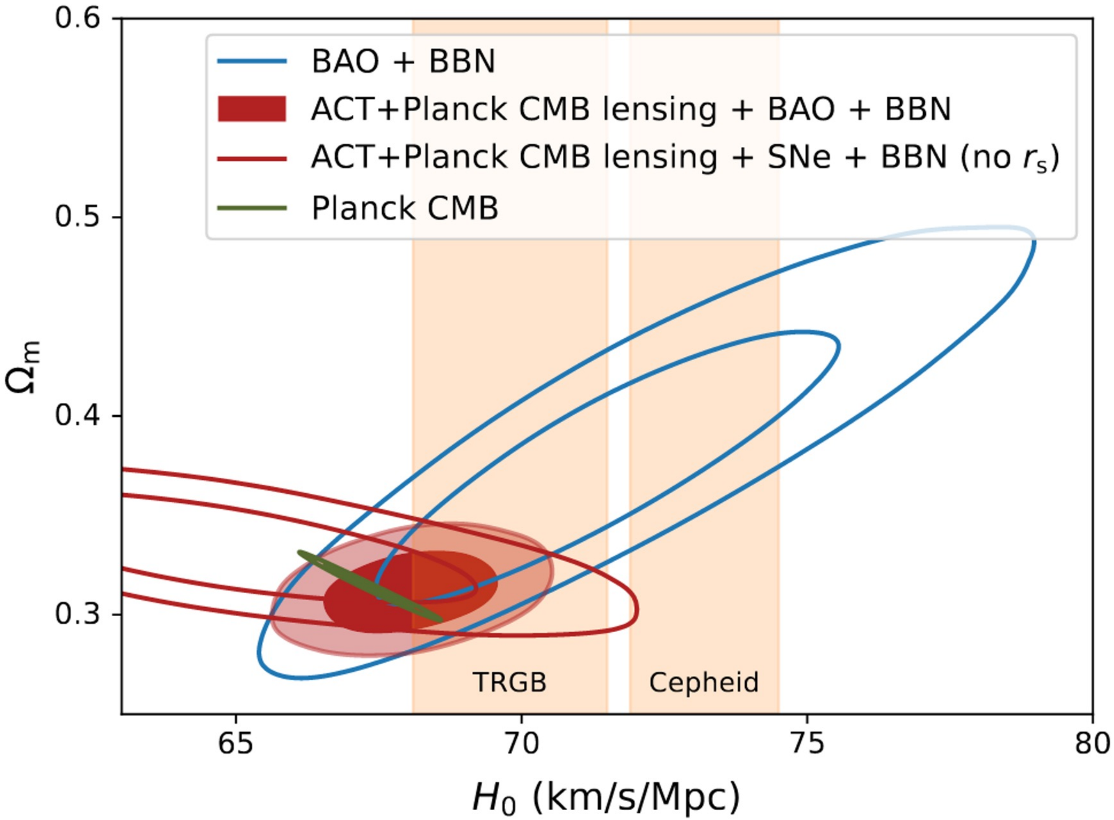


H_0 (km/s/Mpc)
100
90
80
70
60
50
40
σ_8
0.5
0.6
0.7
0.8
0.9
1.0
Ω_m
0.1
0.2
0.3
0.4
0.5
0.6

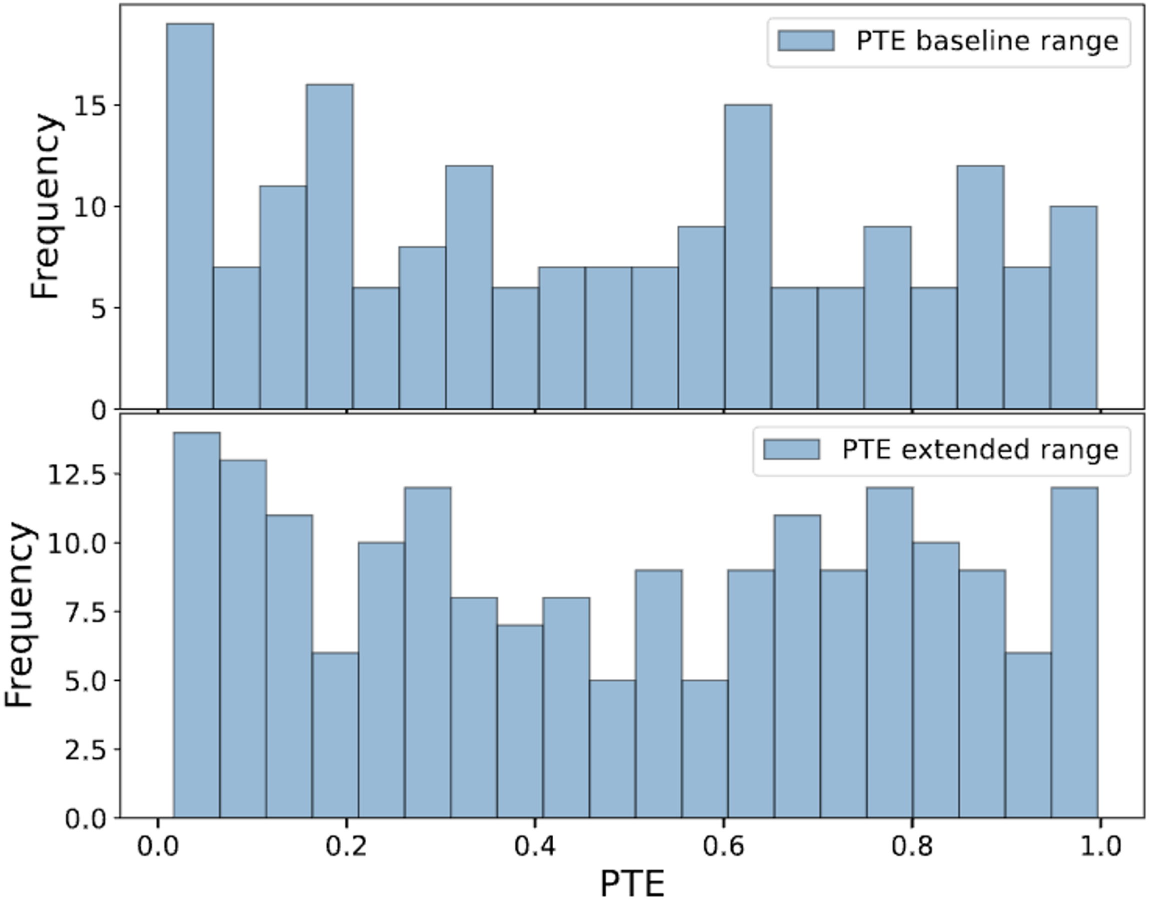


Planck CMB aniso.
DES-Y3 galaxy lensing + BAO
DES-Y3 galaxy lensing (Amon et al., Secco et al.)
DES-Y3 galaxy lensing; Fourier (Doux et al.)
DES-Y3 3x2 (Abbott et al.)
HSC-Y3 galaxy lensing (Fourier) + BAO
HSC-Y3 galaxy lensing (Real) + BAO
HSC-Y3 galaxy lensing (Fourier; Dalal et al)
HSC-Y3 galaxy lensing (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
H_0 (km/s/Mpc)
0.6
0.5
0.4
0.3
65
70
75
80

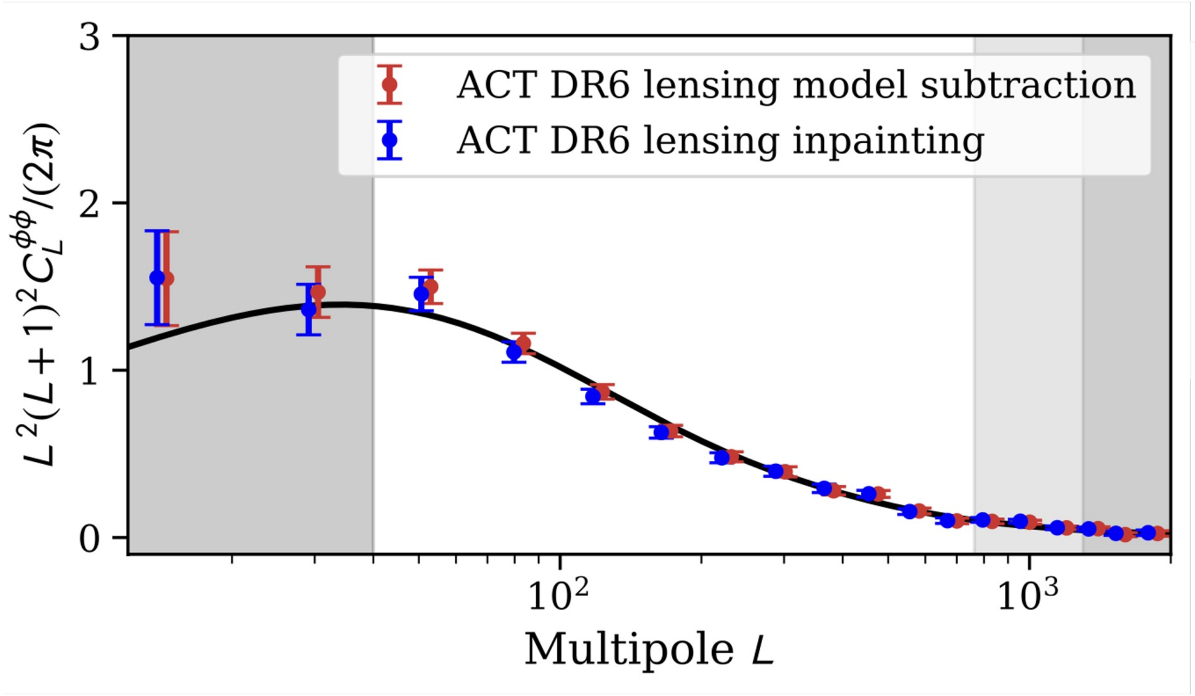

PTE baseline range
Frequency
15
10
5
0
PTE extended range
Frequency
12.5
10.0
7.5
5.0
2.5
0.0
0.0
0.2
0.4
0.6
0.8
1.0
PTE

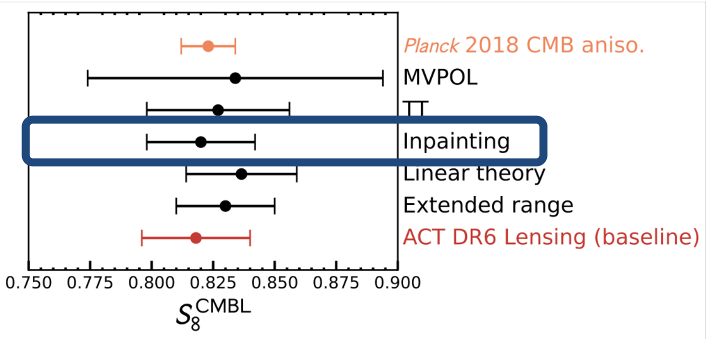
Instrumental Systematics

Systematic	Estimator	$\Delta A_{\rm lens}$
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

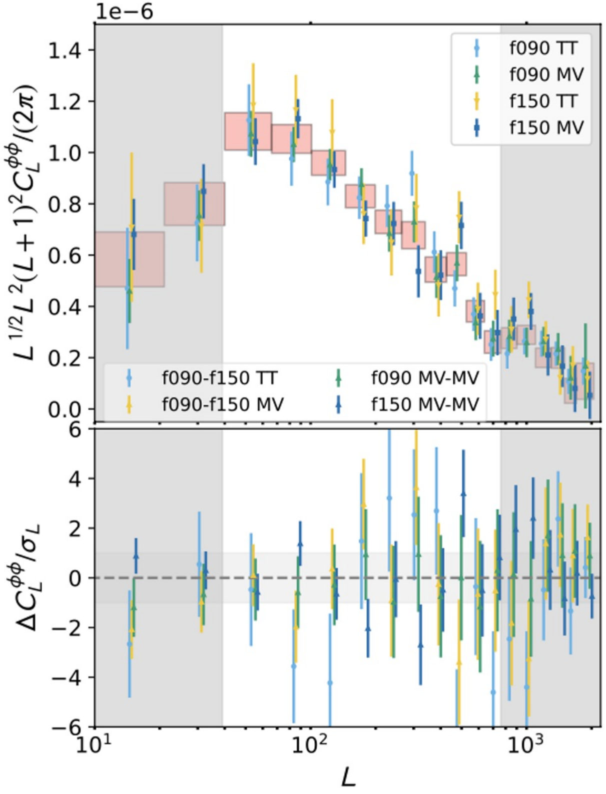
Post unblinding changes



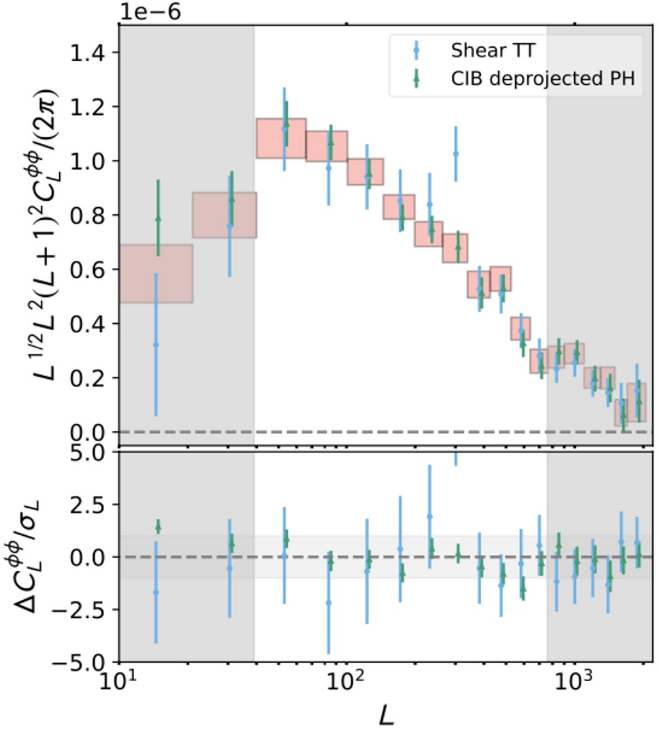


0.15sigma shift compared to baseline

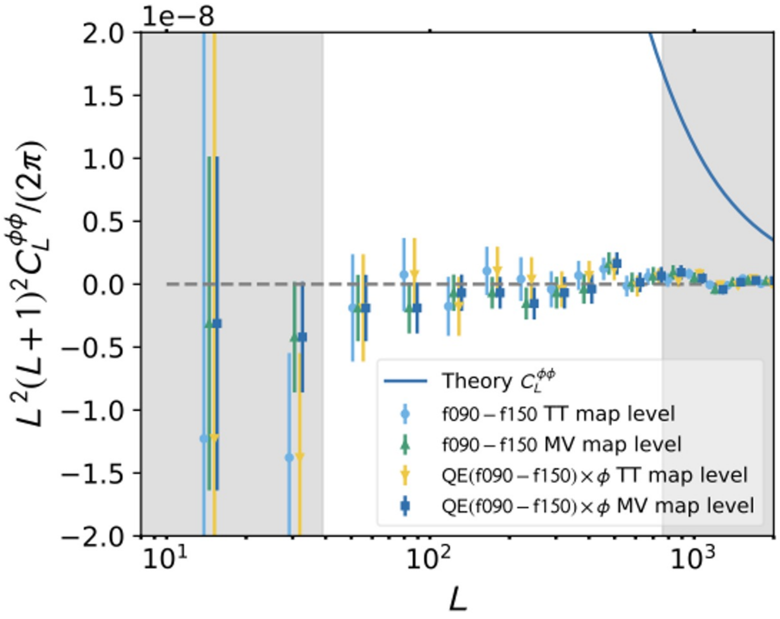
Null tests



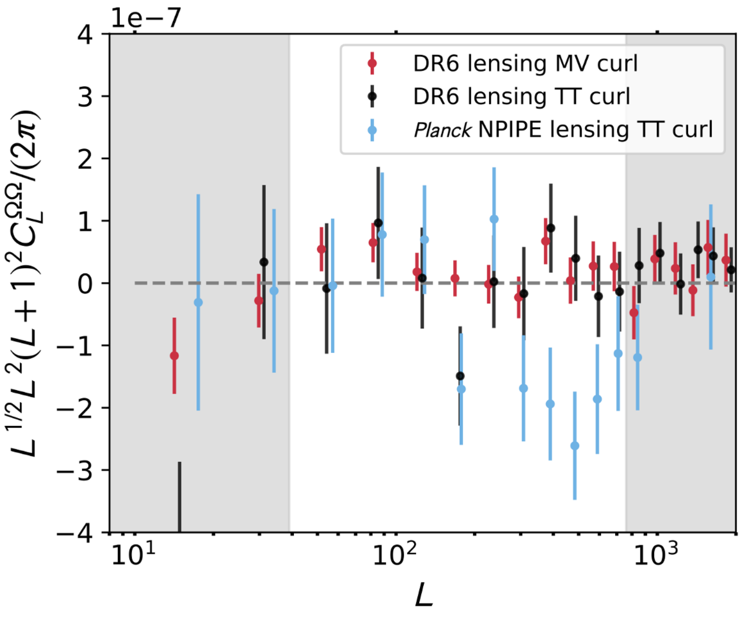
1e−6
f090 TT
f090 MV
f150 TT
f150 MV
f090-f150 TT
f090-f150 MV
f090 MV-MV
f150 MV-MV
$L^{1/2}L^2(L+1)^2C_L^{\phi\phi}/(2\pi)$
$\Delta C_L^{\phi\phi}/\sigma_L$
L



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



1e−8
$L^2(L+1)^2C_L^{\phi\phi}/(2\pi)$
L
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



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

Null test summary

Bandpower null test	χ^2	(PTE)	$\Delta A^{\rm lens}$
$600 < \ell_{\rm CMB} < 2000$	2.9	(0.98)	-0.015 ± 0.023
$600 < \ell_{\rm CMB} < 2500$	9.6	(0.48)	-0.019 ± 0.012
$800 < \ell_{\rm CMB} < 3000$	10.9	(0.37)	0.01 ± 0.01
$1500 < \ell_{\rm CMB} < 3000$	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! $\quad r = \frac{\hat{C}_L^{\psi x}}{C_L^{\phi x}}$

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!

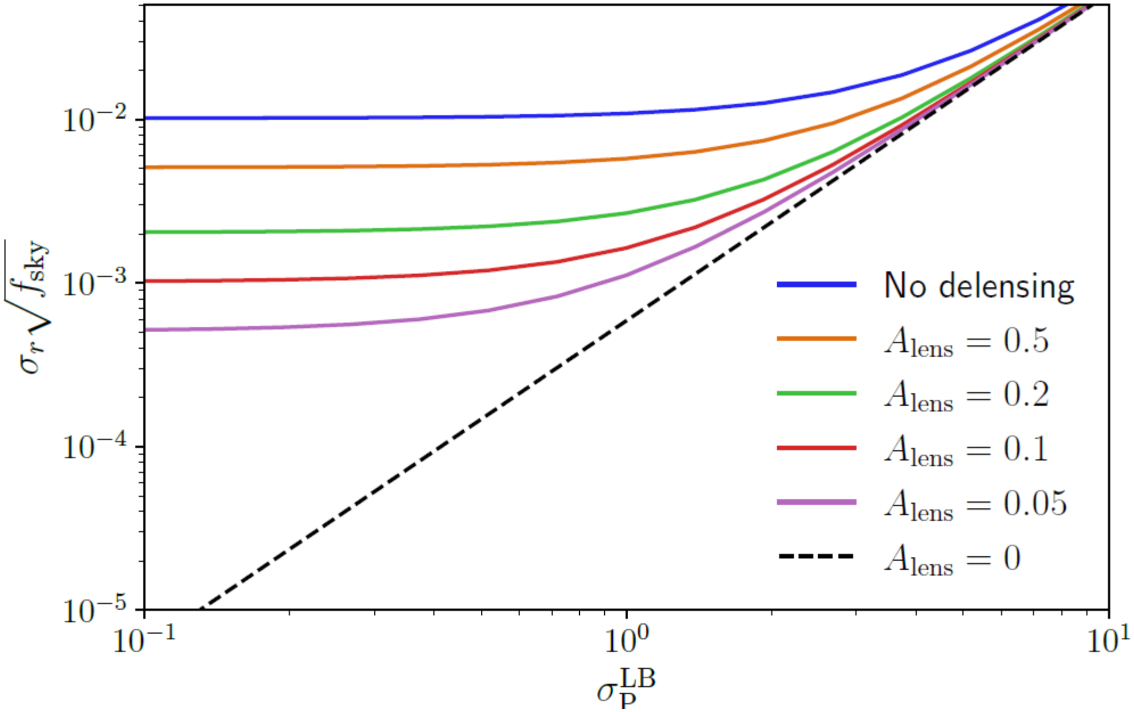
$$\sigma_r^{-2} = \sum_L \frac{(2L+1) f_{\rm sky} (\partial C^{\psi x}_L / \partial r)^2}{(r^2 C^{\phi\phi}_L + N^{\psi\psi}_L) \hat{C}^{xx}_L + (r C^{\phi x}_L)^2} ,$$

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

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.

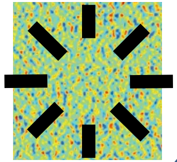


Post-component-separated noise level

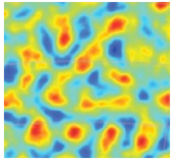
Important Step for Low Noise: Delensing

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

E mode map

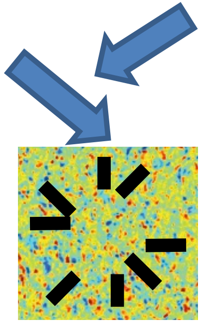


ϕ map



ϕ reconstructed from CMB

Distorted by lensing map



Lensing B-mode templ

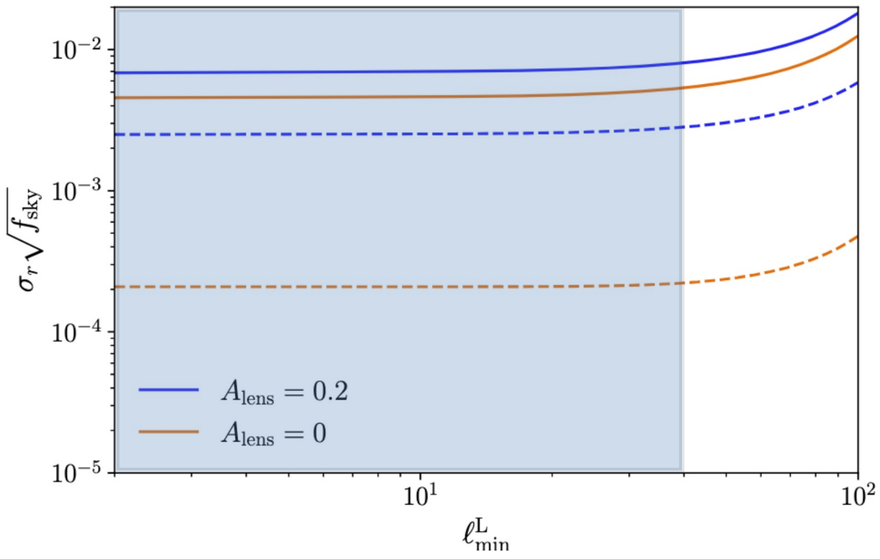
$$\hat{B}^{\rm del}_{\ell m} = \hat{B}_{\ell m} - \sum_{LM\ell' m'} (-1)^m \begin{pmatrix} \ell & L & \ell' \\ -m & M & m' \end{pmatrix} \times \left(\frac{C_L^{\phi\phi} \hat{\phi}_{LM}}{C_L^{\phi\phi} + N_L^{\phi\phi}} \right) \left(\frac{-{\rm i} C_{\ell'}^{EE} \hat{E}_{\ell' m'}}{C_{\ell'}^{EE} +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

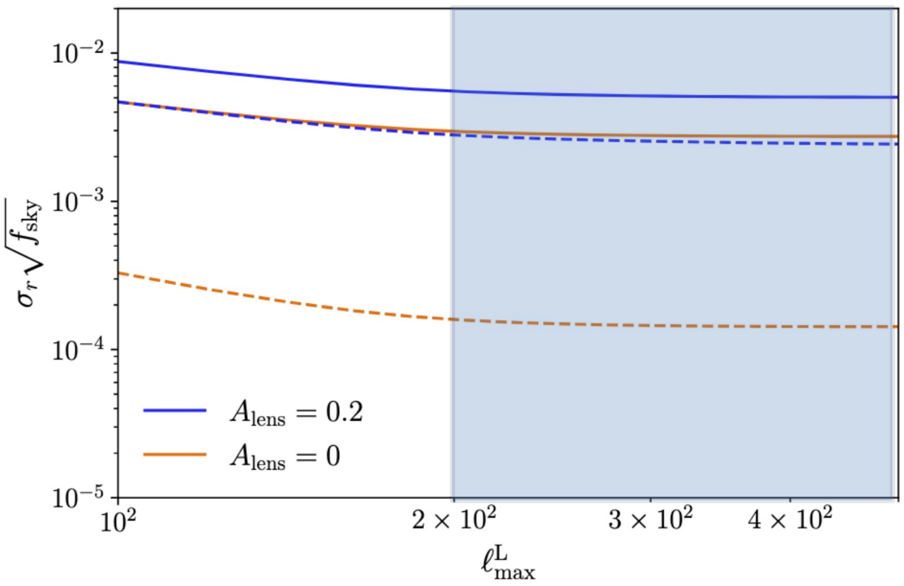
- Using this template, we can reduce scatter from lensing B-modes and improve constraint on IGWs

(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~1100?

- Also probes IGW B-modes on somewhat different scales.

- Could in principle combine with standard BB constraints as negligible correlation.