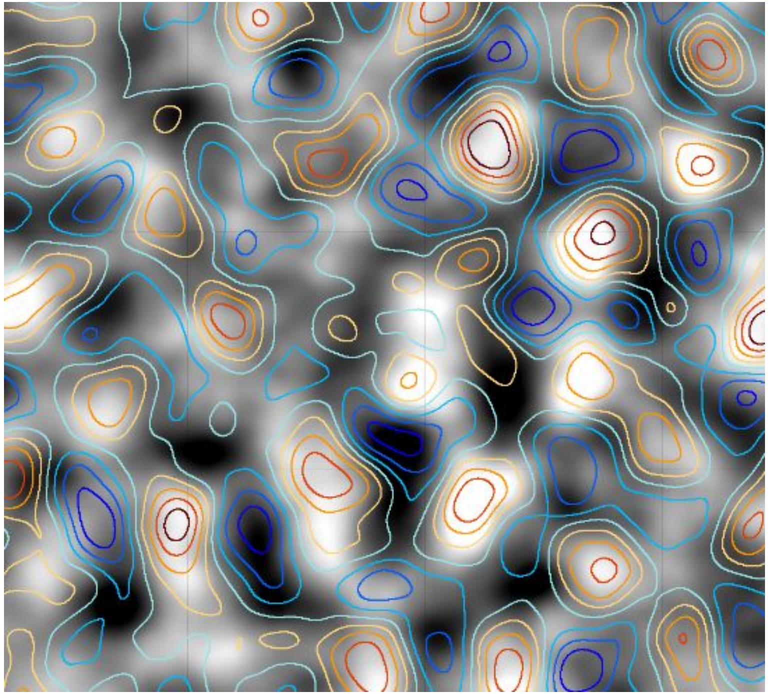
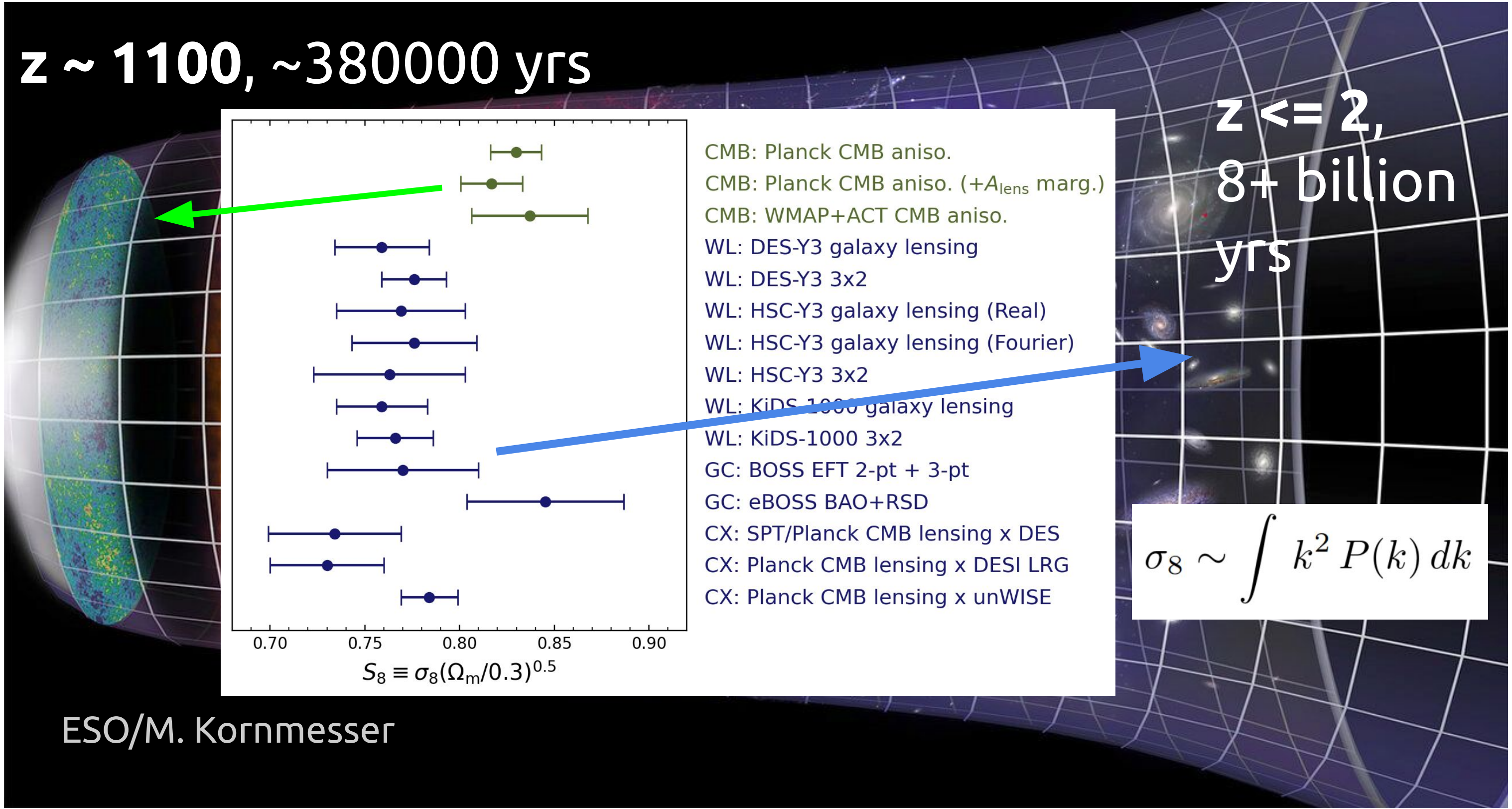


Constraining structure formation over cosmic time with CMB lensing

mm Universe conference | June 27, 2025

Joshua Kim (University of Pennsylvania)

Why do predictions of structure formation from early-time probes differ from late-time observations?



CMB lensing as a probe

Weak gravitational lensing of CMB photons traces the *unbiased* matter distribution from z ~ 1100.

$$T^{\text{lensed}}(\hat{\mathbf{n}}) = T^0(\hat{\mathbf{n}} + \boldsymbol{\alpha}), \;\; \boldsymbol{\alpha} = \nabla\phi$$

Breaks isotropy of the CMB:

$$\cancel{\langle T^{\text{lens}}(\ell) T^{\text{lens}}(\ell' \neq \ell)\rangle_{\text{CMB}} = 0}$$

$$\langle T^{\text{lens}}(\ell) T^{\text{lens}}(\ell' \neq \ell)\rangle_{\text{CMB}} \propto \phi(\mathbf{L} = \ell + \ell')$$

Motivates the **quadratic estimator**:

$$\underbrace{\hat{\phi}(\mathbf{L})}_{\textit{potential}} \sim \int \underbrace{\mathrm{d}^2\mathbf{l}\, T(\mathbf{l})\, T^*(\mathbf{l} - \mathbf{L})}_{\text{approx. quadratic in CMB fields!}}$$

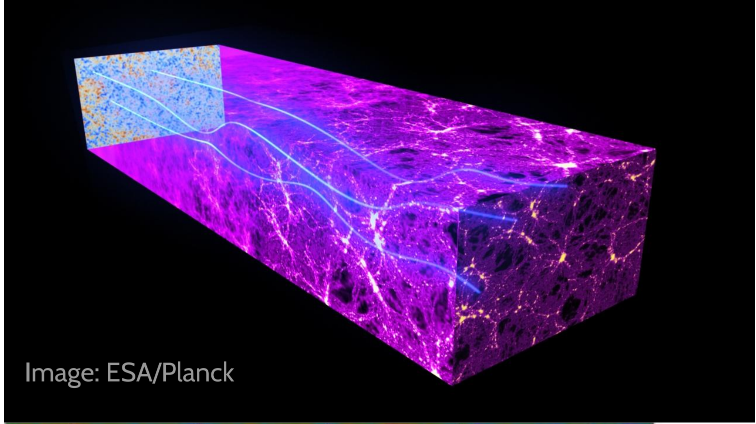
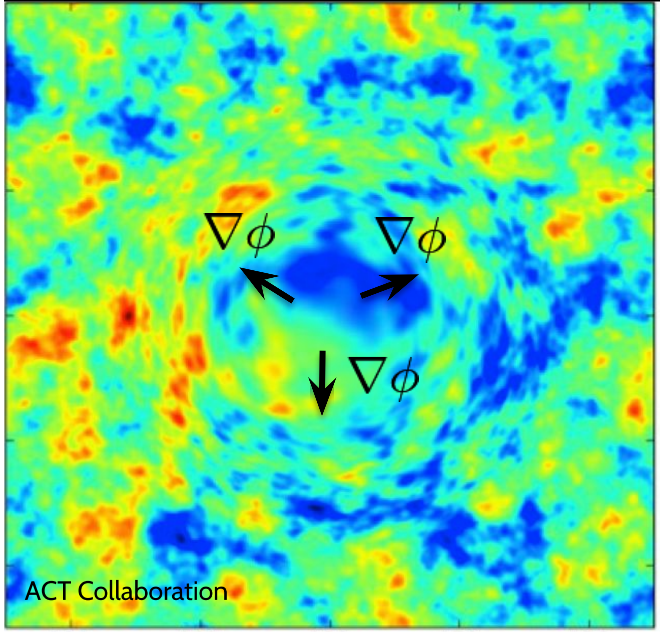
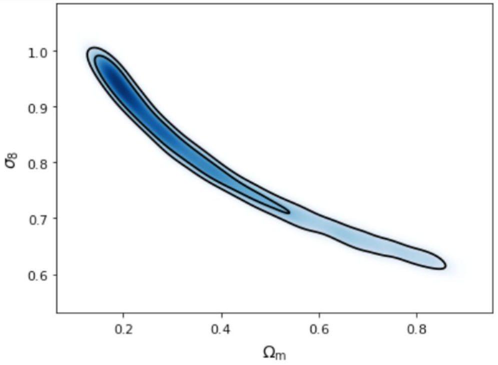


Image: ESA/Planck



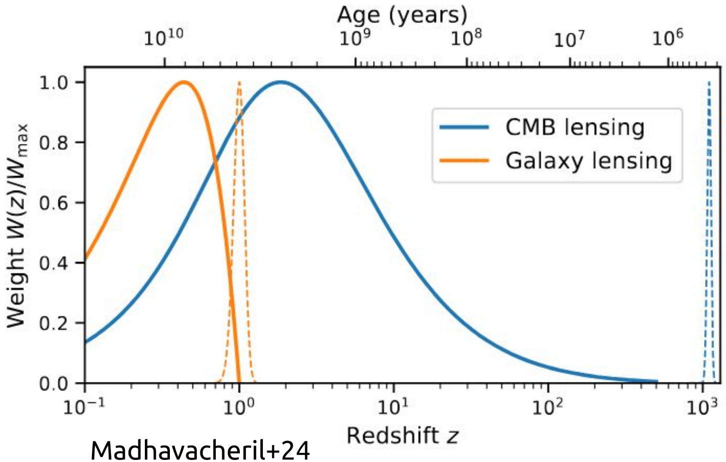
ACT Collaboration

Using CMB lensing *power spectra* to constrain structure growth



1. CMB lensing **cross-correlation** with galaxies

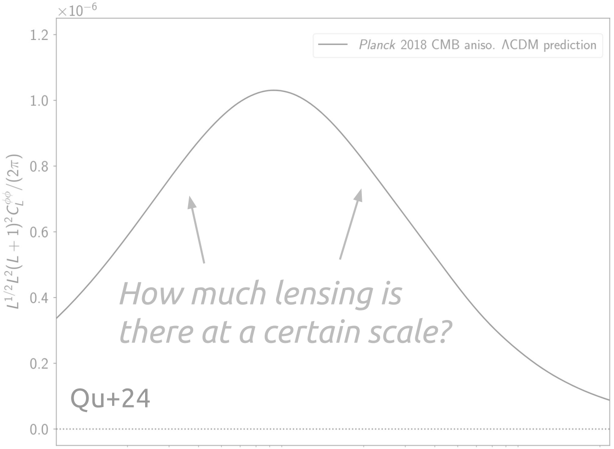
$$\frac{(C_L^{\kappa g})^2}{C_L^{gg}} \sim \frac{b^2\sigma_8^4}{b^2\sigma_8^2} \sim \boxed{\sigma_8^2}$$



Madhavacheril+24

2. CMB lensing **auto-correlation** (lensing power spectrum)

$$L^4\, C_L^{\phi\phi} \sim \int_0^{1100} dz\, [W_\kappa(z)]^2\, P(k \approx L/\chi, z)$$



Kim+24: [2407.04606]
Sailer+24: [2407.04607]

CMB lensing x DESI LRGs

CMB lensing mass maps from ACT DR6 and Planck PR4

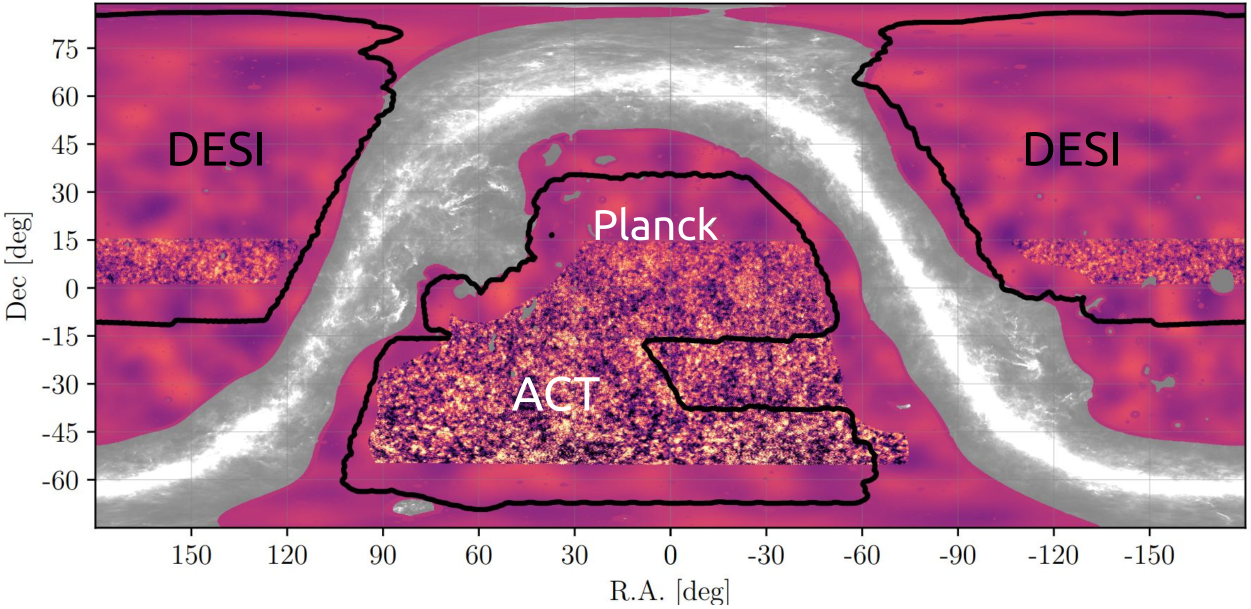
Qu+23
Madhavacheril+23
MacCrann+23

Carron+22

State-of-the-art data!

DESI luminous red galaxies (~1e7) with 4 redshift bins from 0.4 < z < 1.0

Zhou+22
Zhou+23



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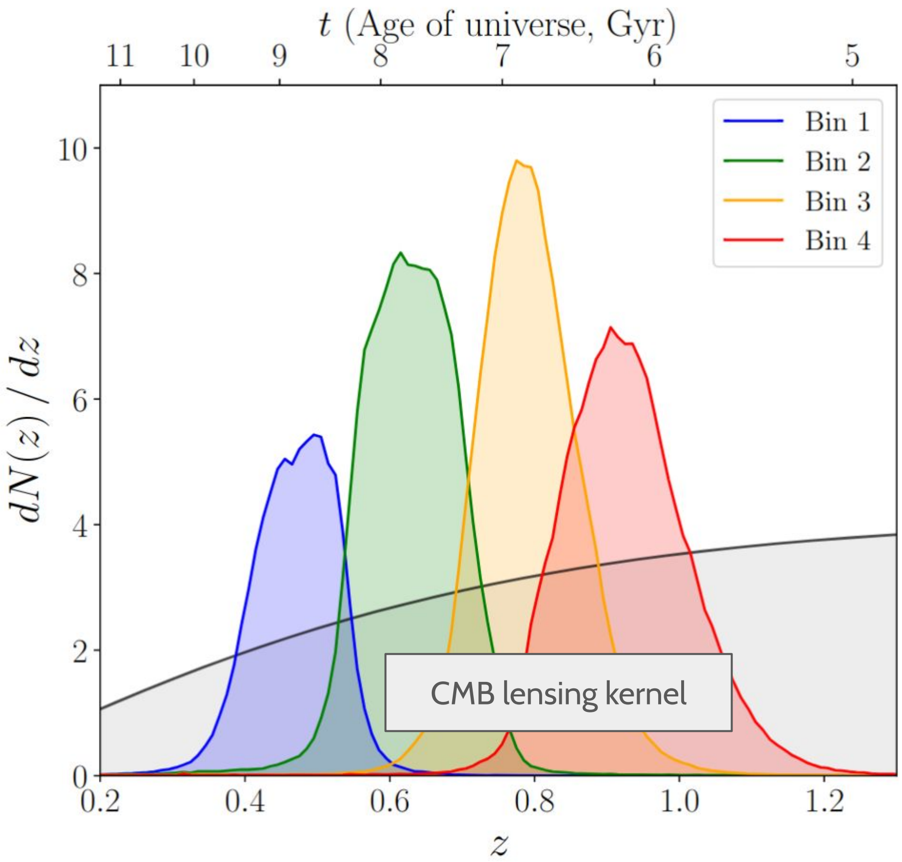

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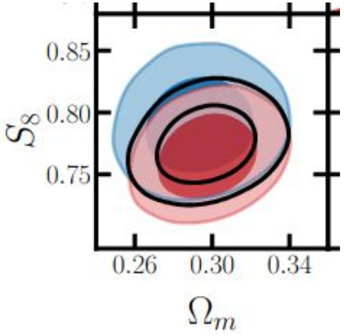

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Zhou+22
Zhou+23

Cross-correlation PS pipeline feat. mode-coupling

Hivon+02
Alonso+19

Robustness / consistency tests (foregrounds, systematics, etc.)

MacCrann+23
Farren+23

Hybrid effective field theory modeling, using LPT basis and *N*-body sims

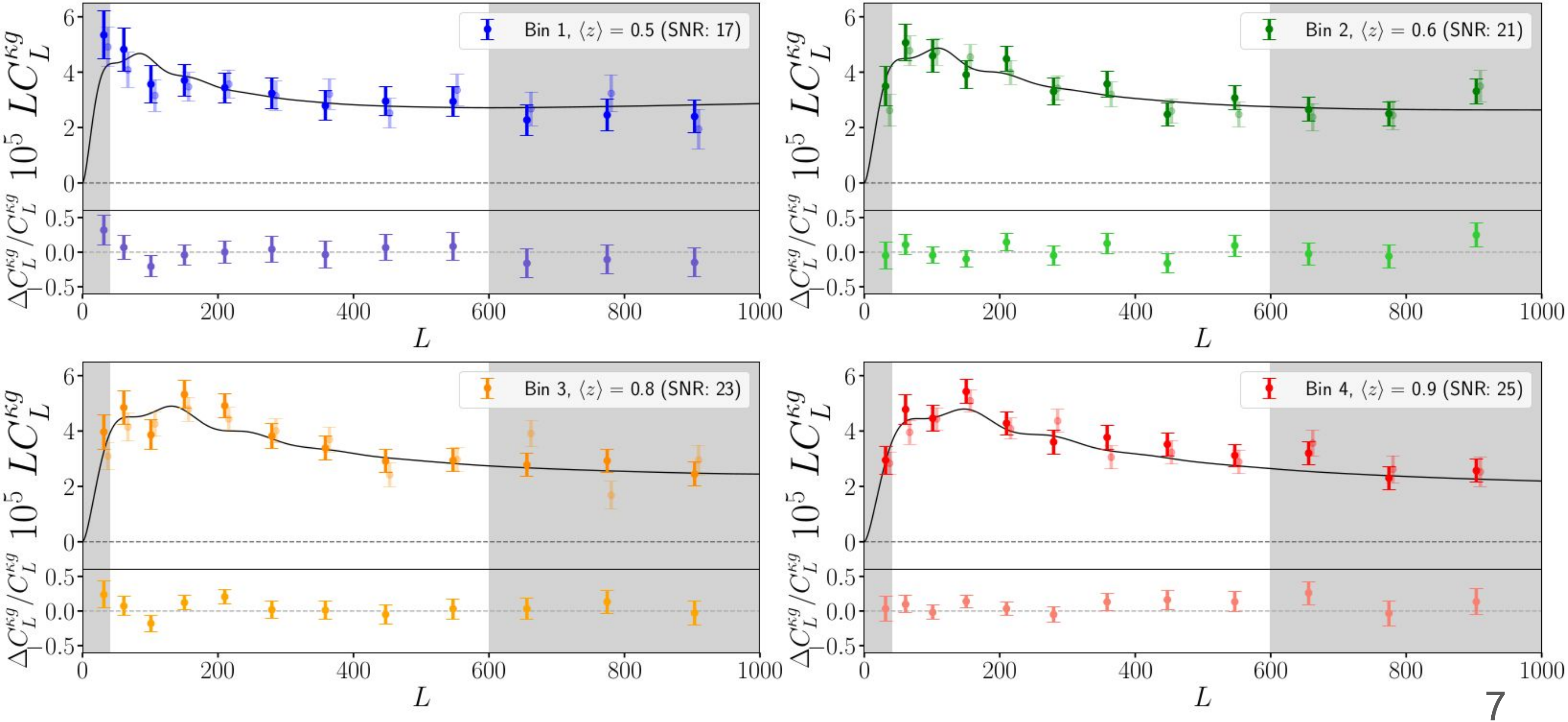
Kokron+21
DeRose+23

Simulation-informed covariance

MCMC to infer cosmological parameters of structure formation

CMB lensing x DESI LRGs

*~**50σ** measurement!*

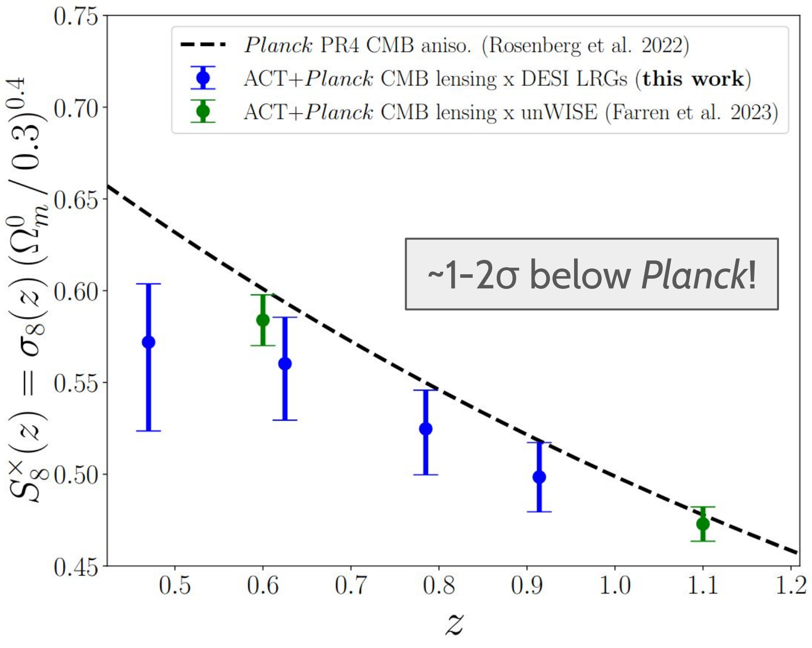


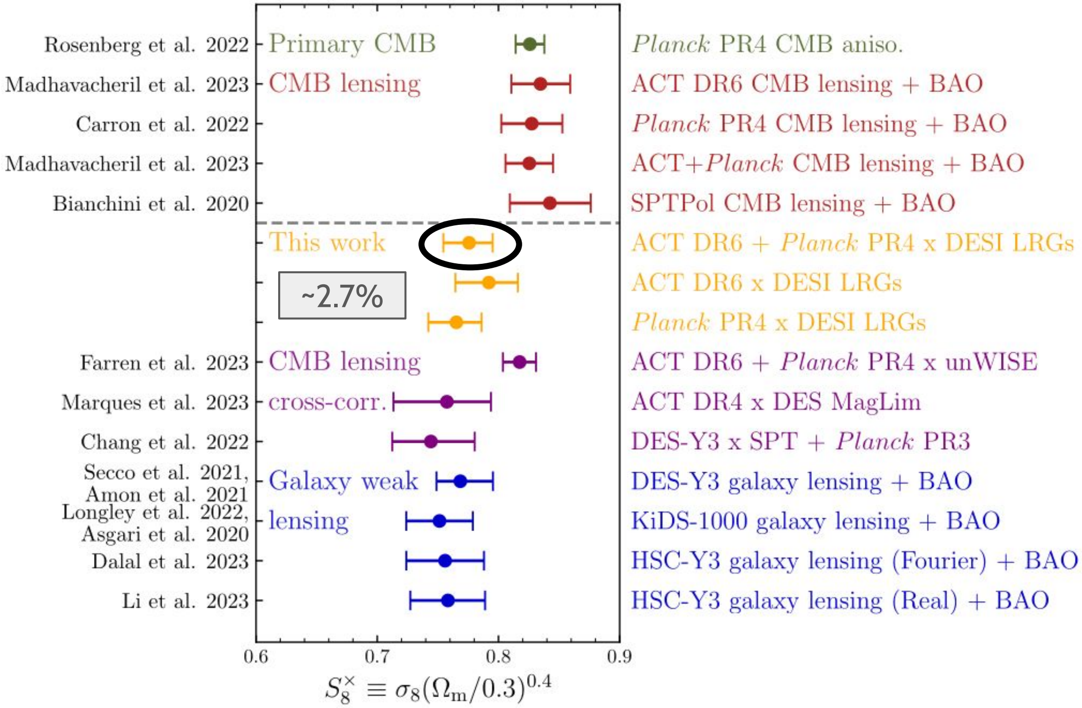
Kim+24: 2407.04606
Sailer+24: 2407.04607

CMB lensing x DESI LRGs

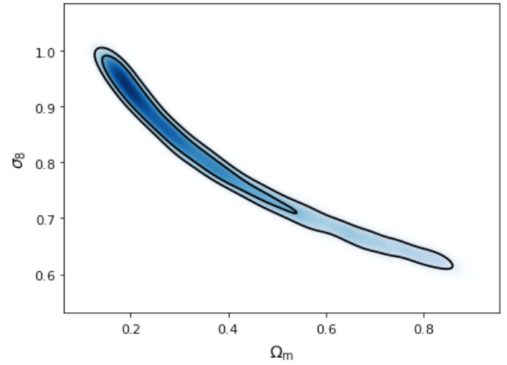
Also see Sailer+25 (2503.24385), combining this analysis with DESI BGS (z < 0.4) cross-correlation!

Using **tomography** to probe structure growth over time:





Using CMB lensing *power spectra* to constrain structure growth



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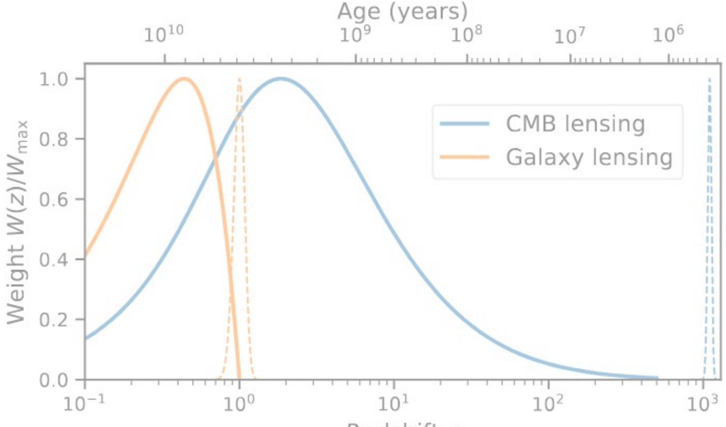

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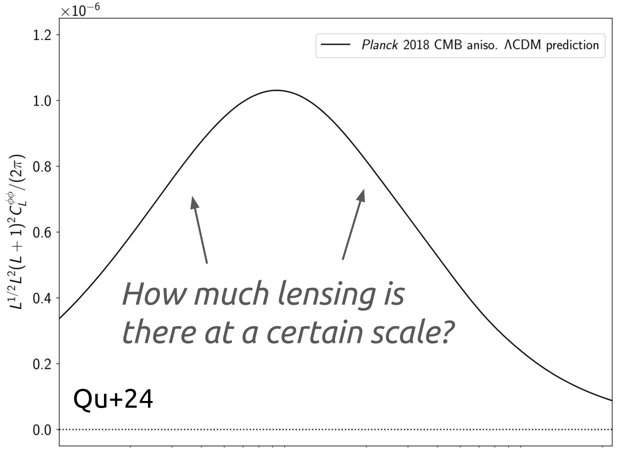
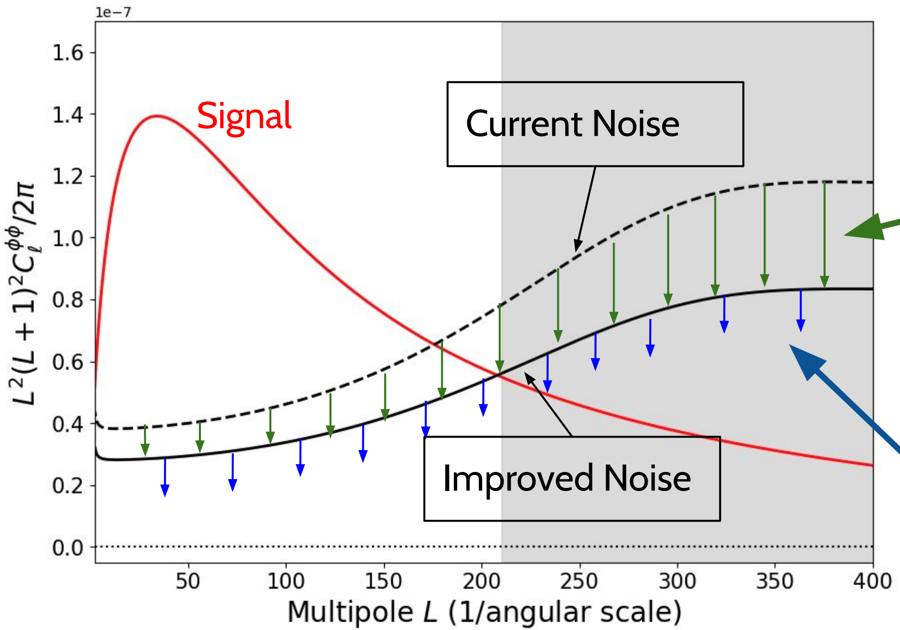


Lensing power spectrum analysis beyond ACT DR6



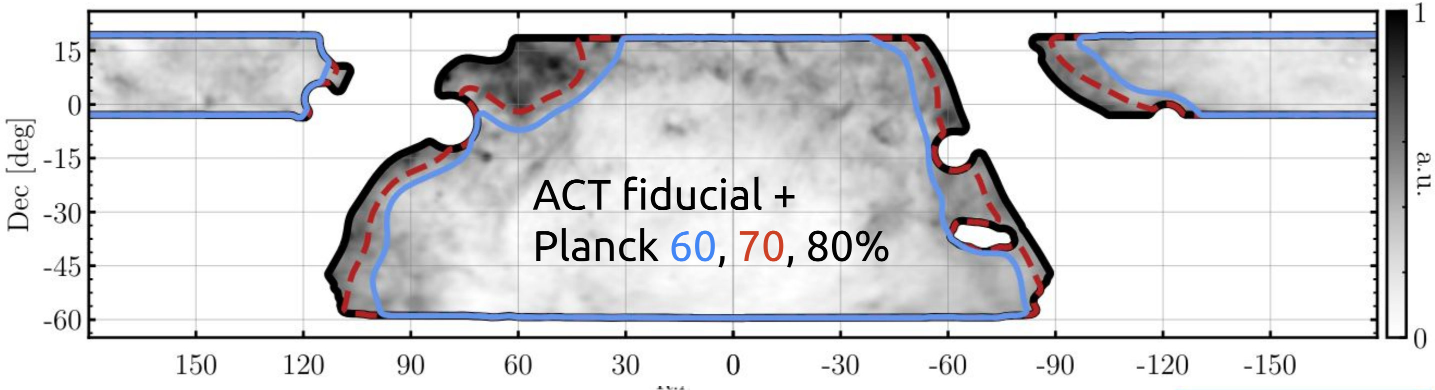
Expected improvements (to SNR ~ **60+**):

- Inclusion of *daytime* data: ~1.7x amount of the data
- Additional seasons (2022 night, 220 GHz data)

See Frank's talk!

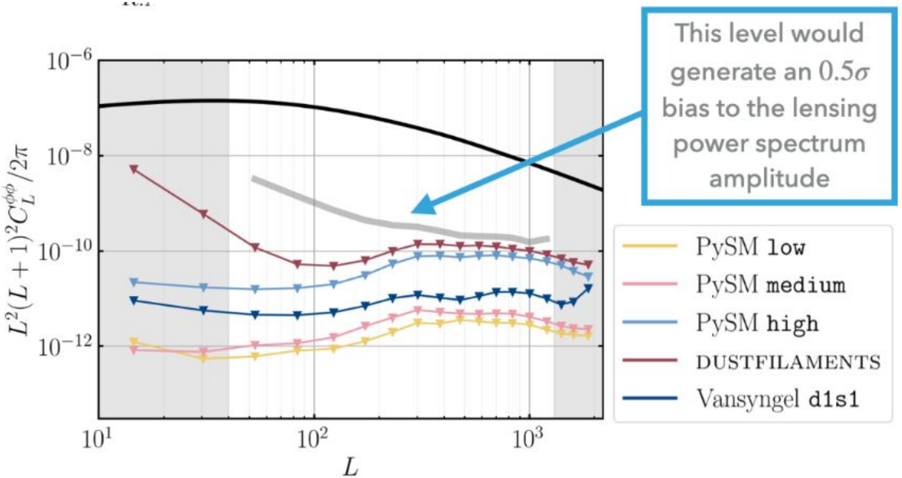
- **Improved sky-cuts** (~10% improvement)
- **Map-level combination with Planck**
- **Optimal filtering** (10-15% improvement)

Improved sky cuts (Abril-Cabezas+25, 2505.03737)



Irene Abril-Cabezas
PhD student @ Cambridge

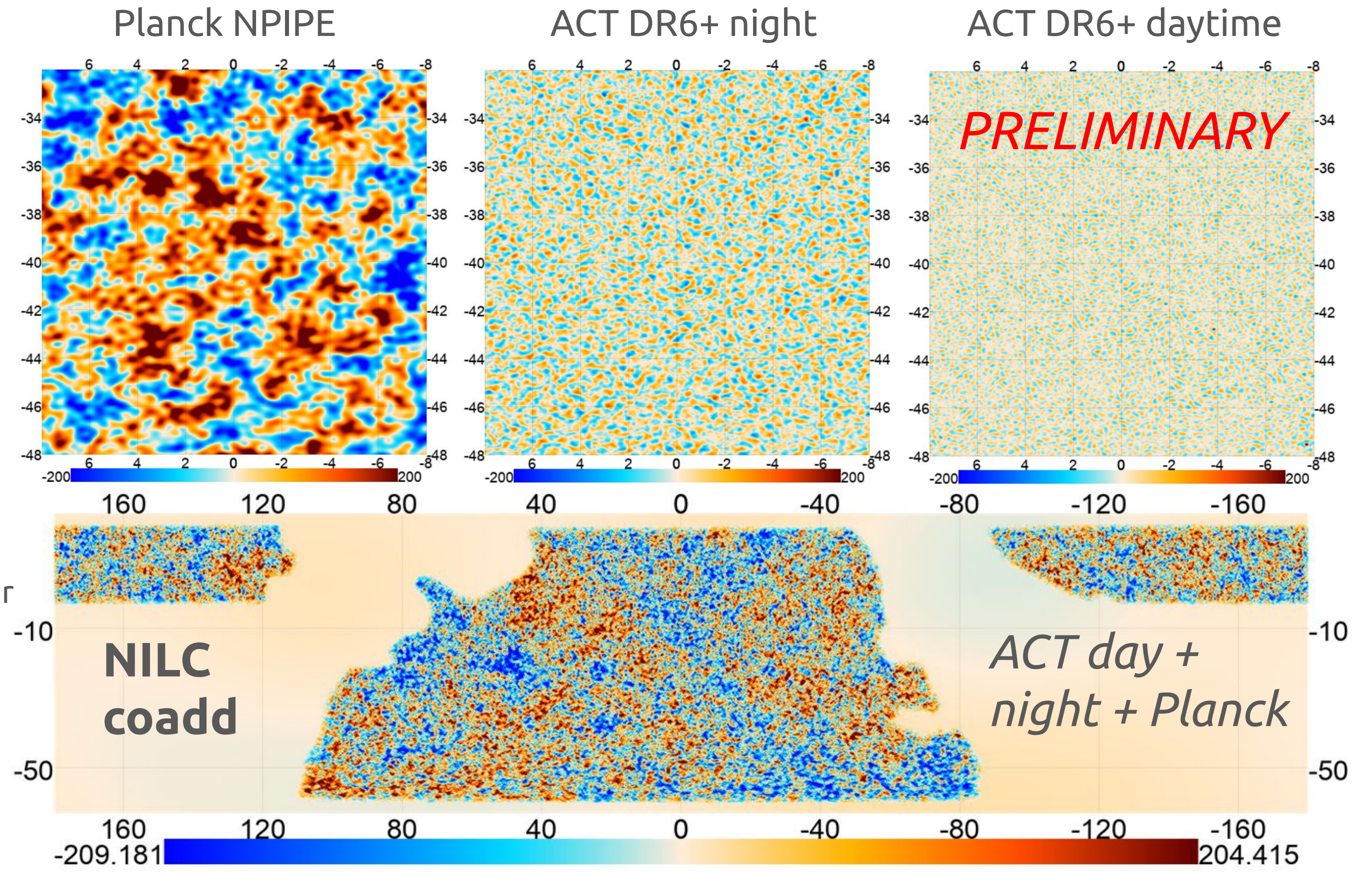
Will our lensing power spectrum be biased if we increase our analysis sky fraction?



*ACT 60% -> 70% leads to **<0.3σ**.*

Map-level coaddition of data

- **Needlet ILC** to coadd:
  - 30 ~ 353 GHz CMB from Planck NPIPE
  - 90, 150, 220 GHz CMB from ACT DR6+ night
  - 90, 150 GHz CMB from ACT DR6+ day
- Expanding on work done in Coulton+24:
  - Run on O(100) signal + noise simulations to infer lensing biases
  - Using independent pipeline, **coberus**
- Negligible effect from "ILC bias"



Using optimal filtering for CMB lensing reconstruction

- ~10-15% improvement over *isotropic filtering*

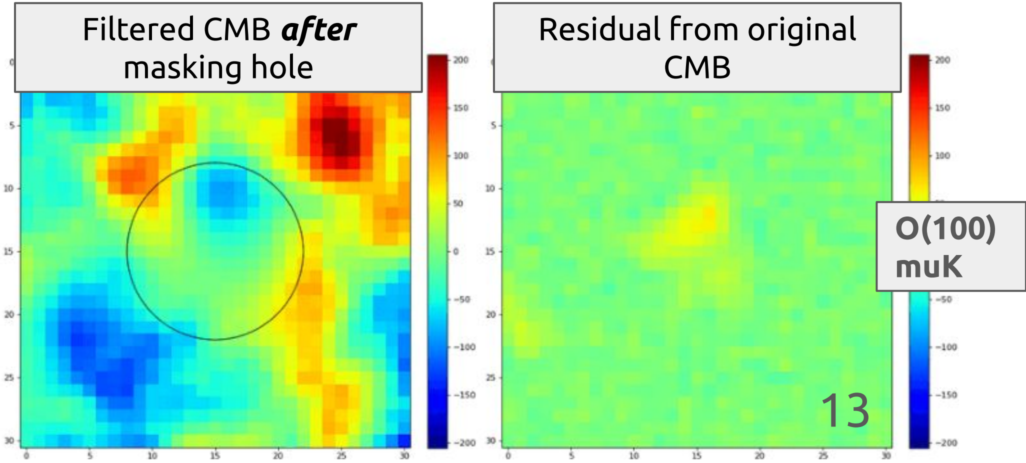
- Approaching Wiener filtering of the CMB optimally using:
  - Inhomogeneous noise maps (Mirmelstein+19, Carron+22)
  - Preconditioned conjugate gradient solver (optweight by Adri)
  - Joint temperature + polarization filtering
  - Unbiased realizations to fill masked holes for point sources, tSZ clusters, etc. (Lembo+19)

- Done in Planck analyses, but not for ACT DR6!

$$X_{WF}^{\rm isofilt}(\ell) = \left(\frac{C_\ell^{fid}}{C_\ell^{fid} + N_\ell^{fid}}\right)^2 \times \mathbf{d}(\ell)$$

$$\left(\mathbf{B}C^{fid}\mathbf{B}^T + \mathbf{N}\right) X_{WF}^{\rm optfilt} = \left(\mathbf{B}C^{fid}\mathbf{B}^T\right)\mathbf{d}$$

Given noise covariance and fiducial theory spectra, how can we *invert the LHS* to solve for X?



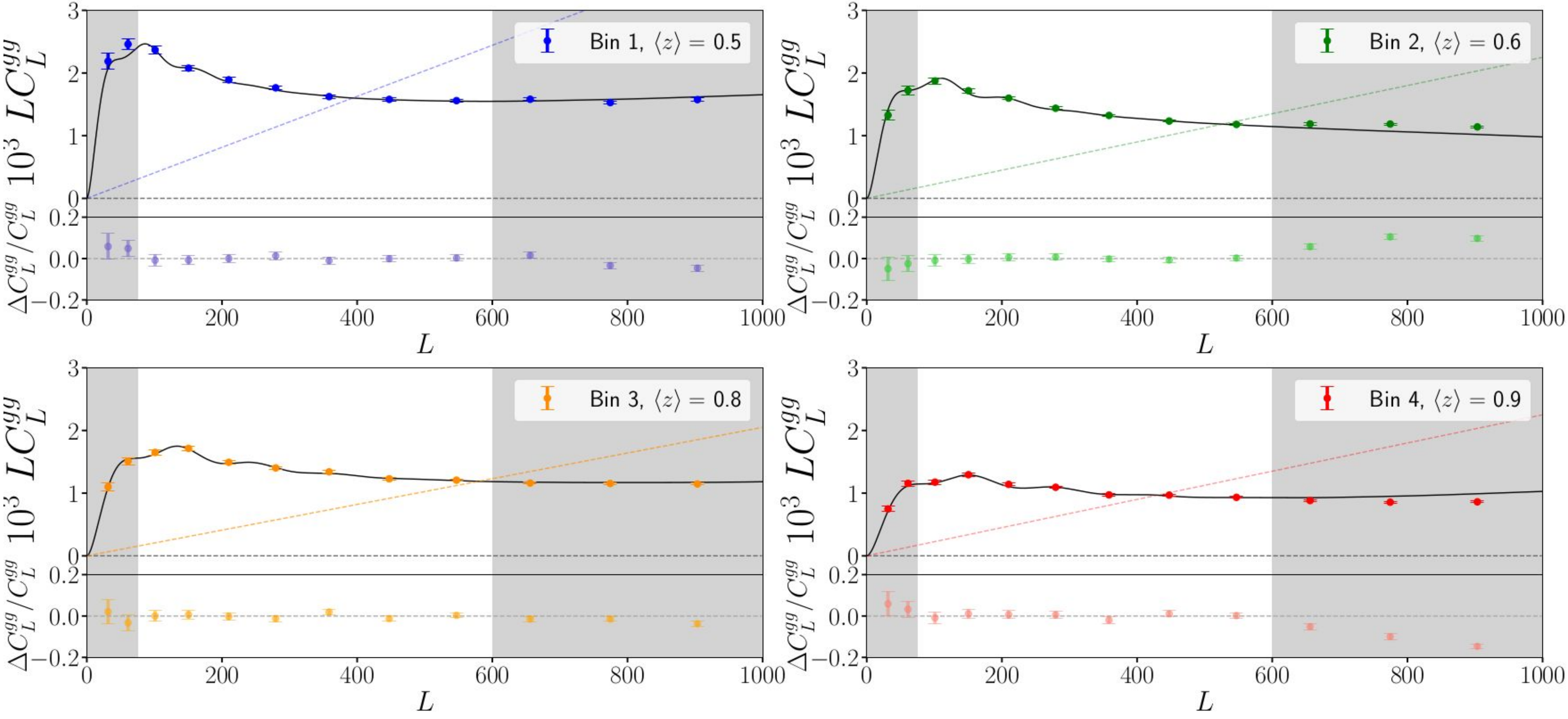
Conclusion and outlooks

CMB lensing cross-correlations and its auto-spectrum can be used to probe the matter distribution and constrain structure growth.

- ACT DR6 (+ PR4) x DESI LRGs offers <3% constraints on structure growth parameters.
- Featuring notable improvements from DR6, the ACT DR6+ lensing power spectrum analysis aims for SNR ~ 60+
- Lensing pipelines are developed with SO LAT compatibility in mind!
- **Stay tuned for our papers!**
    - Kim *et al.* in prep
    - Abril-Cabezas *et al.* in prep a/b
    - Qu *et al.* in prep

Backup slides

DESI galaxy auto-spectra



Theory model

P_{gg}, P_{gm}, and P_{mm} modeled with "**Hybrid Effective Field Theory**" (HEFT) Modi, Chen, White 2019

Galaxies form a biased tracer of initial gravitational potential (q = Lagrangian, or initial position) moving with the DM.

$$1 + \delta_g(\boldsymbol{x}) = \int d^3\boldsymbol{q}\, F(\boldsymbol{q})\, \delta^D(\boldsymbol{x} - \boldsymbol{q} - \boldsymbol{\Psi}_{cb})$$

Computed from Aemulus-nu simulations (DeRose+23)

$$F(\boldsymbol{q}) = 1 + b_1^L \delta_{cb}(\boldsymbol{q}) + \frac{b_2^L}{2}\left(\delta_{cb}^2(\boldsymbol{q}) - \langle \delta_{cb}^2 \rangle\right) + b_s^L\left(s_{cb}^2(\boldsymbol{q}) - \langle s_{cb}^2 \rangle\right) + \frac{b_{\nabla^2}^L}{4}\left(\nabla^2 \delta_{cb}(\boldsymbol{q}) - \langle \nabla^2 \delta_{cb} \rangle\right) + \mathcal{E}(\boldsymbol{q})$$

Computing the power spectra from these densities:

$$P_{gg}(k) = \left(1 - \frac{\alpha_a k^2}{2}\right) P_{cb}(k) + 2\sum_X b_X^L P_{cb,X}(k) + \sum_{XY} b_X^L b_Y^L P_{XY}(k) + \mathrm{SN}^{3\mathrm{D}}$$

$X, Y \in [1, 2, s]$

$$P_{gm}(k) = \left(1 - \frac{\alpha_x k^2}{2}\right) P_{cb,m}(k) + \sum_X b_X^L P_{m,X}(k)$$

In 3D this HEFT model has shown to be robust up to **k ~ 0.5-0.6 h / Mpc.**

Do galaxies correlate with systematics in data?

- Cross-correlating galaxy maps with combinations of lensing products where *null* signals are expected

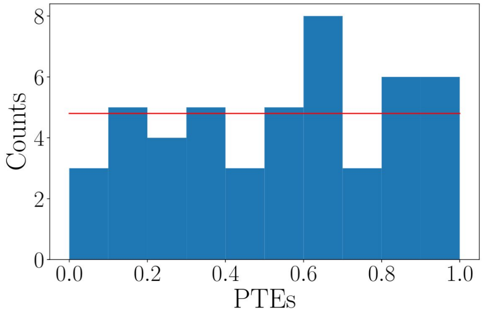
- 5/48 failures ~ **10.4%** failure rate (expecting 10% *uncorrelated* failures on avg)

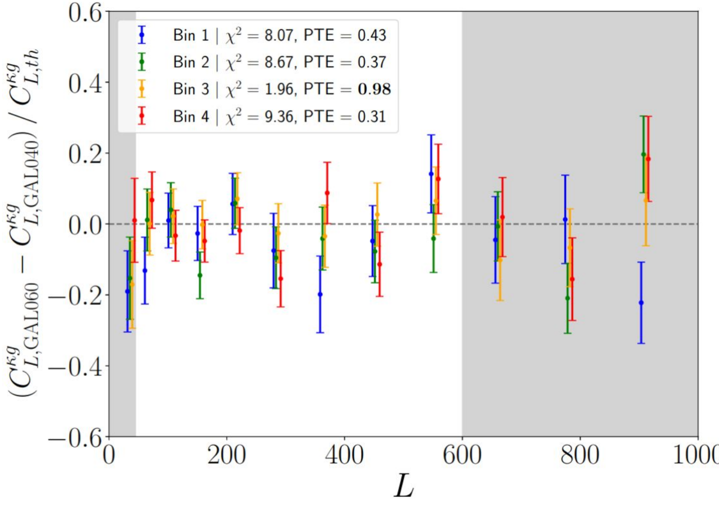
Current null test PTEs				
Null test	Bin 1	Bin 2	Bin 3	Bin 4
$QE(f150 - f090\ \mathrm{MV}) \times g$	0.490	0.852	0.538	0.864
$QE(f150 - f090\ \mathrm{TT}) \times g$	**0.971**	0.135	0.296	0.130
$QE(\mathrm{curl}) \times g$	0.086	0.586	0.093	0.244
$QE(f150\ \mathrm{MV}) \times g - QE(f090\ \mathrm{MV}) \times g$	0.631	0.862	0.891	0.671
$QE(f150\ \mathrm{TT}) \times g - QE(f090\ \mathrm{TT}) \times g$	**0.995**	0.719	0.945	0.662
$QE(f090\ \mathrm{MV}) \times g - QE(f090\ \mathrm{TT}) \times g$	0.325	0.408	0.583	0.330
$QE(f150\ \mathrm{MV}) \times g - QE(f150\ \mathrm{TT}) \times g$	**0.971**	0.161	0.263	0.535
$QE(\text{baseline MV}) \times g - QE(\text{baseline MVPOL}) \times g$	**0.985**	0.690	0.778	0.648
$QE(\text{baseline MV}) \times g - QE(\text{CIB deproj.}) \times g$	0.103	0.553	0.820	0.655
$QE(\text{baseline } 60\%) \times g - QE(\text{baseline } 40\%) \times g$	0.427	0.371	**0.982**	0.313
$QE(\text{baseline MV}) \times g - QE(\text{baseline MV}) \times g_{\text{DES area}}$	0.169	0.876	0.252	0.759
$QE(\text{baseline, NGC}) \times g - QE(\text{baseline, SGC}) \times g$	0.056	0.639	0.644	0.374

Hypothesis: $\mathbf{d} = 0$.

$$\chi^2 = \mathbf{d}^T \mathbb{C}^{-1} \mathbf{d}$$
$$\mathrm{PTE} = 1 - \mathrm{CDF}_{\chi^2}(\chi^2/\ \mathrm{d.o.f})$$

Null test failure: $\boxed{\mathrm{PTE} \leq 0.05 \text{ or } \mathrm{PTE} \geq 0.95}$





Do galaxies correlate with systematics in data?

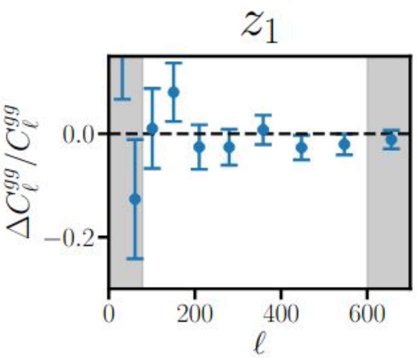
Now checking for LRG auto-spectrum variations:

- Across different imaging footprints
- North vs South (DECaLs, DES vs non-DES)
- Stricter extinction / stellar density cut
    - Testing for Galactic contamination

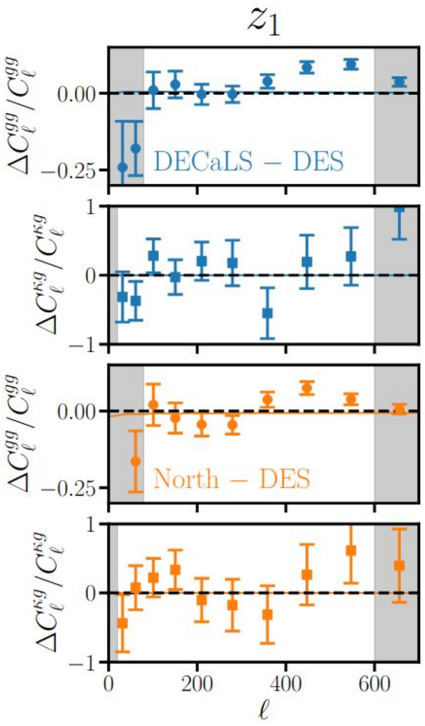
Checking for spurious correlations between:

- SFD's dust extinction map
- Systematic weights used in Zhou+23 to prepare LRG density map

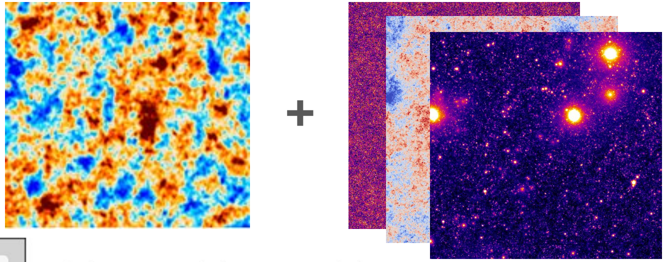
These tests are highlighted in Sailer+24.



NGC vs SGC in DECaLS region



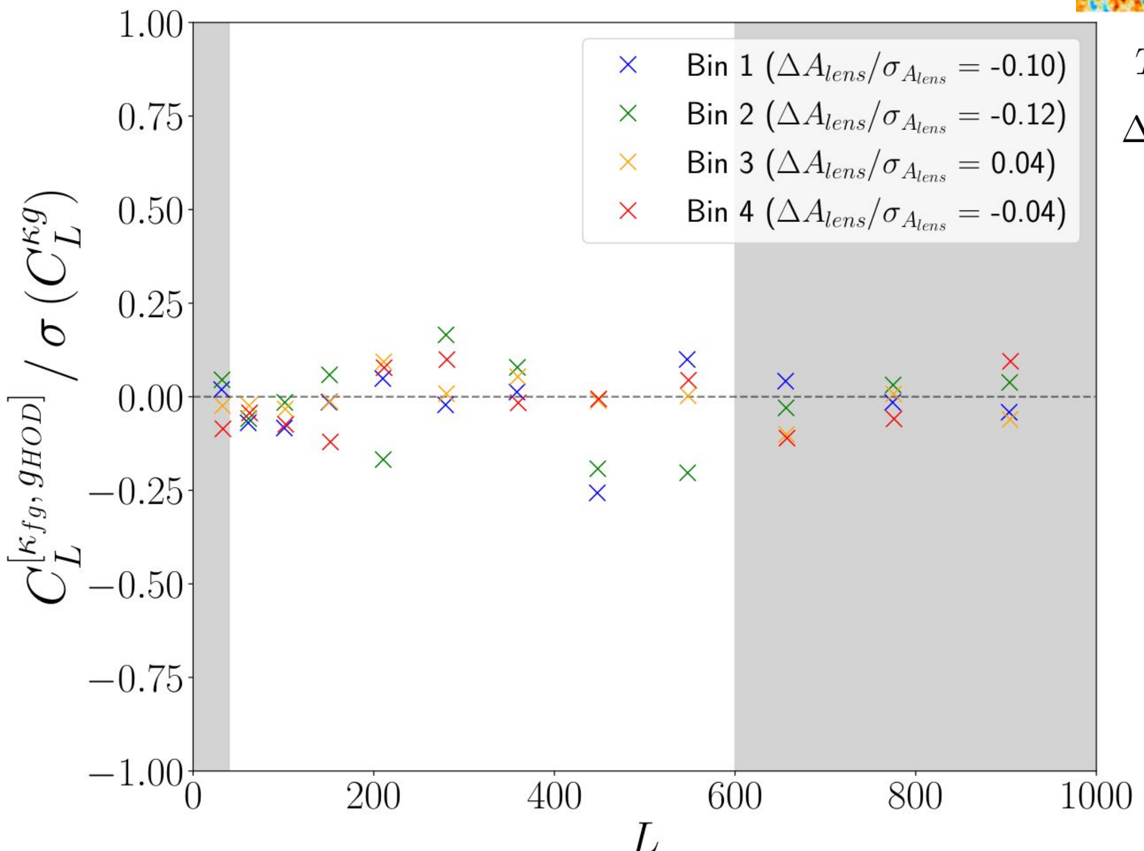
Do galaxies correlate with foregrounds in simulations?



From Websky simulations, Stein+20

$$T_{true} = T_{\rm CMB} + T_{fg}$$

$$\Delta C_L^{\kappa g} \equiv C_L^{\langle QE(T_{true}, T_{true}) g \rangle} - C_L^{\langle QE(T_{\rm CMB}, T_{\rm CMB}) g \rangle}$$
$$\approx 2 \cancel{\langle QE(T_{\rm CMB}, T_{fg}) g \rangle} + \langle QE(T_{fg}, T_{fg}) g \rangle$$



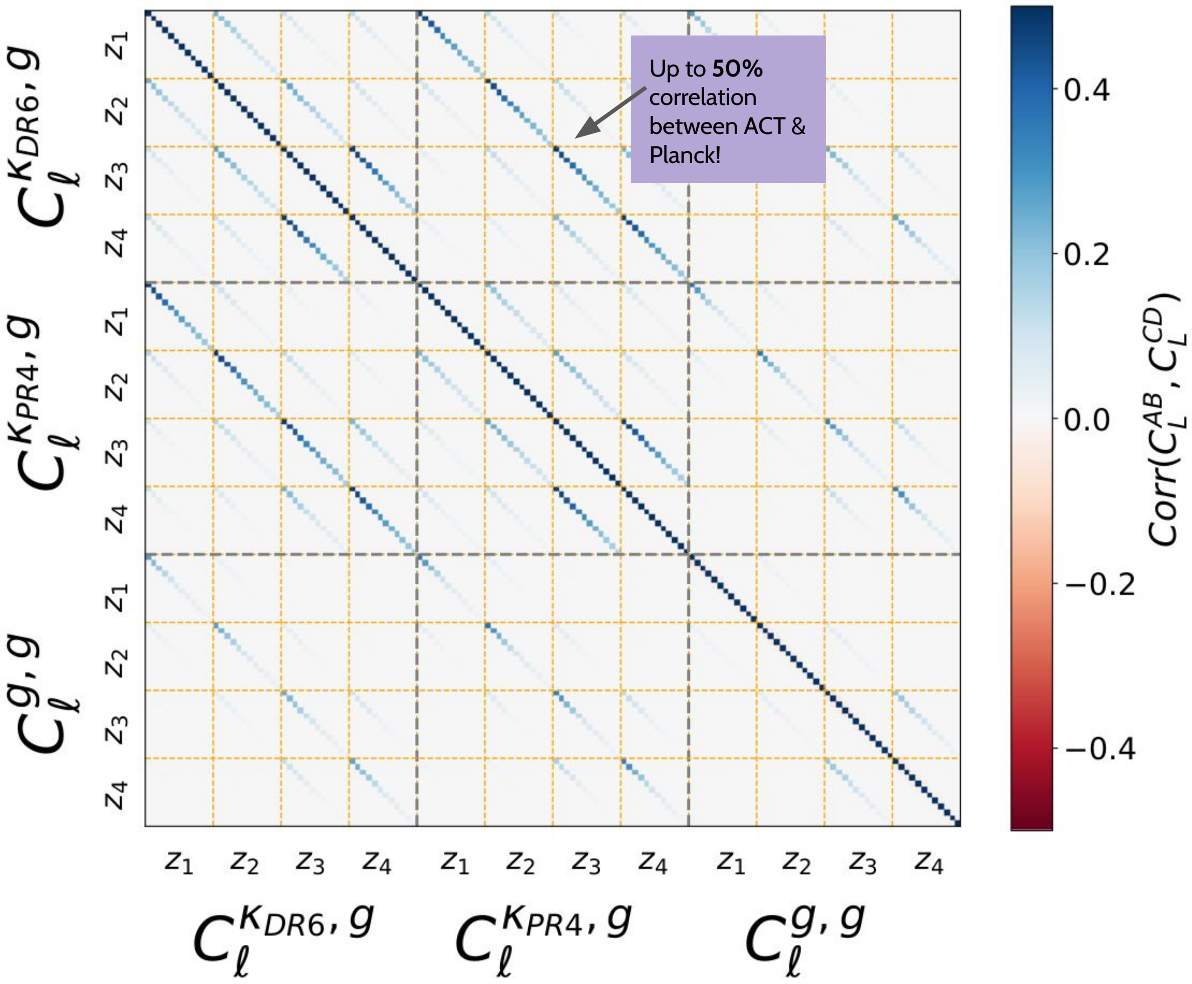
- Built LRG-like HOD into the **Websky simulations**, cross-correlated with foregrounds-only lensing reconstruction (MacCrann+23)
- Shift in power spectrum amplitude due to foregrounds cross-corr. is ~0.1 sigma, **not significant!**

Covariance matrix

- Computed correlations between **ACT Clkg**, **Planck Clkg**, and **Clgg** using a theory-based Gaussian covariance

- Used Gaussian simulations to inform the main diagonal of this **“hybrid” covariance matrix**:

$$C_{ij}^{\text{hybrid}} = C_{ij}^{\text{theory}} \times \sqrt{\frac{C_{ii}^{\text{sim}} C_{jj}^{\text{sim}}}{C_{ii}^{\text{theory}} C_{jj}^{\text{theory}}}}$$



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Given noise covariance and fiducial theory spectra, how can we quickly *invert the LHS* to solve for a Wiener filtered field?

Works well on simulations…