Growth of structure using cross-correlation of CMB lensing and cosmic shear

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ACT & DES Collaborations

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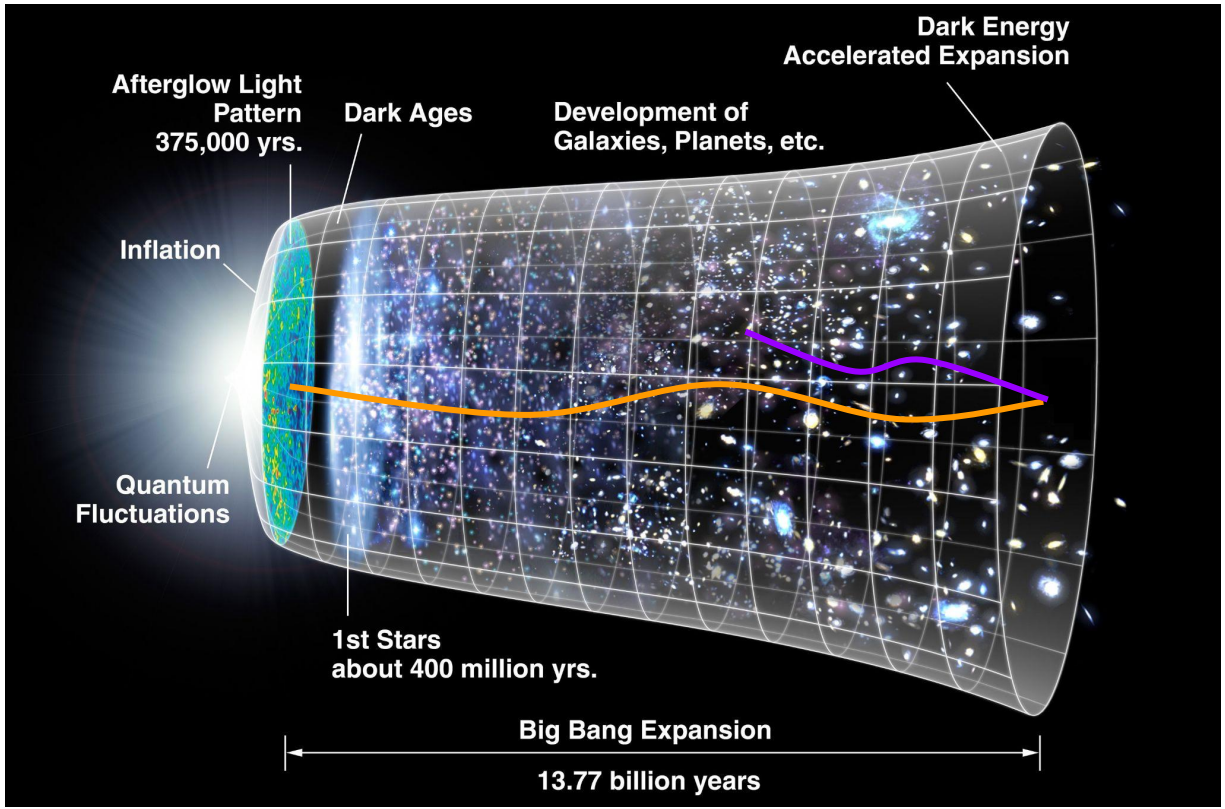
Outline

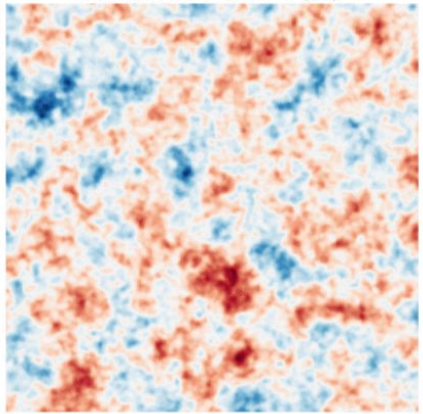
- Weak gravitational lensing of CMB and galaxies
- Cross-correlation of
  - lensing of CMB (Atacama Cosmology Telescope)
  - lensing of galaxies - “Cosmic Shear” (Dark Energy Survey)
- Inference of amplitude of matter fluctuations
- Discussion of systematics
  - Intrinsic Alignment of galaxies (Cosmic Shear)
  - Extragalactic foregrounds (CMB lensing)
- Summary

All cosmological radiation is lensed to some extent



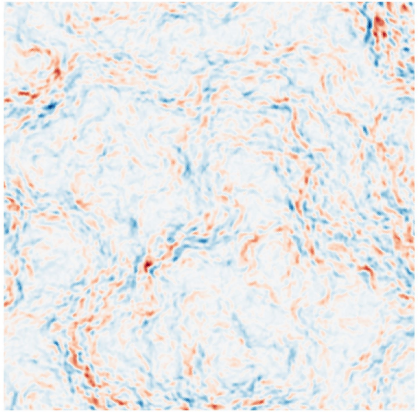
Gravitational lensing of the CMB

Lensed CMB $T(\hat{n})$



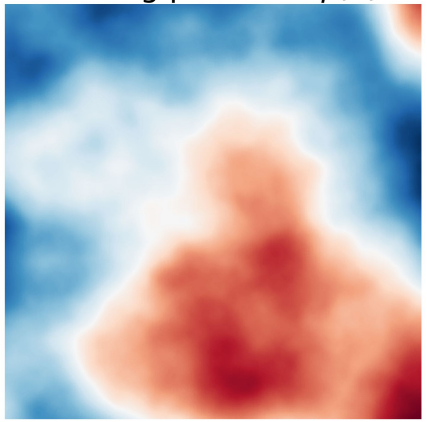
10°

lensed - unlensed



Difference
on arcmin scale

lensing potential $\phi(\hat{n})$

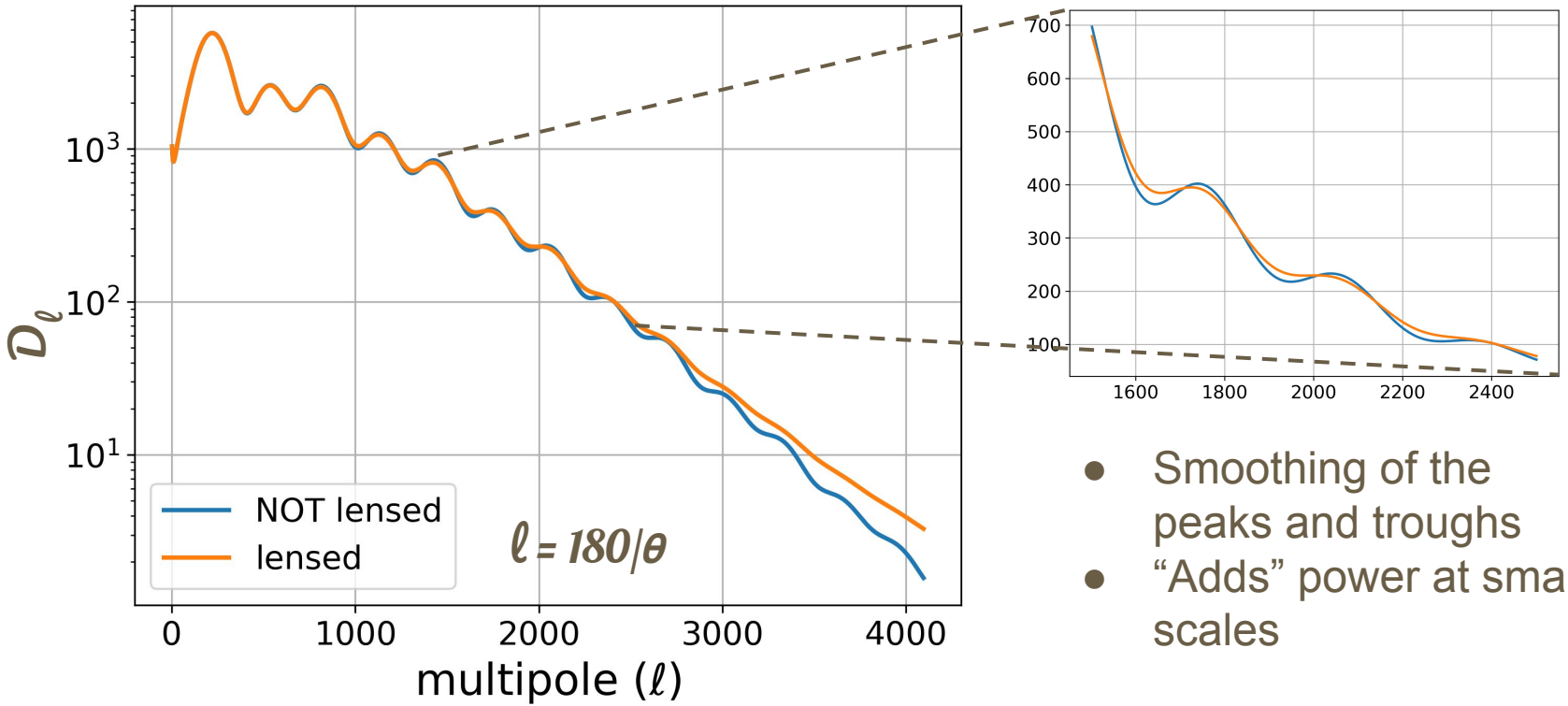


10°

Lensing Potential

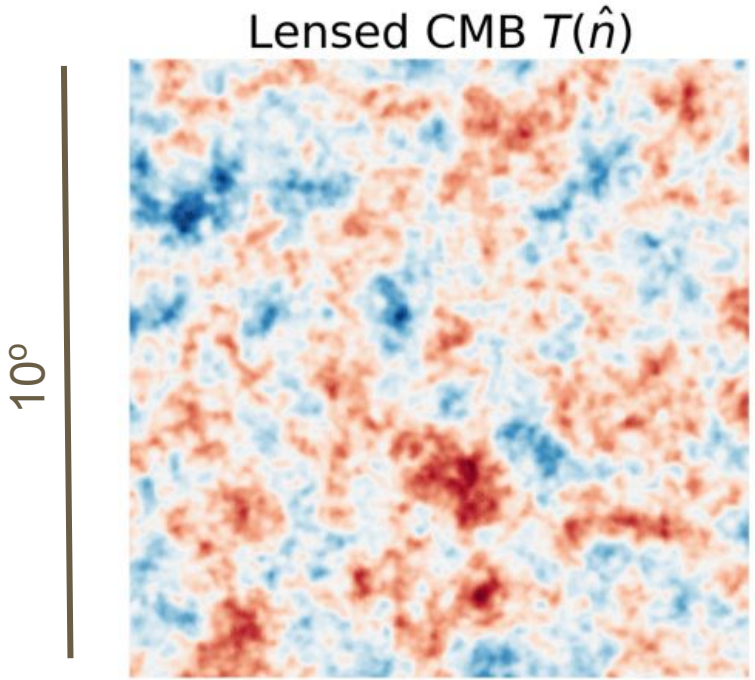
Lensing changes CMB on *small* scales

Effect of lensing on angular power spectrum



- Smoothing of the peaks and troughs
- “Adds” power at small scales

Reconstruction of gravitational lensing potential



Lensing deflects the CMB photons and correlates different harmonic modes of the anisotropies.

$$\Delta T(\hat{n}) \rightarrow \Delta T(\hat{n} + \bar{\nabla}\phi)$$

$$\langle \Delta T_l \; \Delta T_{L-l} \rangle \propto \phi_L$$

⇒ **“Quadratic Estimator” (QE)**

Lensing potential:

Gravitational potential

$$\phi(\hat{n}) = \int_0^{\chi_s} d\chi \, W^{\phi}(\chi) \Phi(\chi, \hat{n})$$

Lensing weight

Some of the CMB lensing measurements

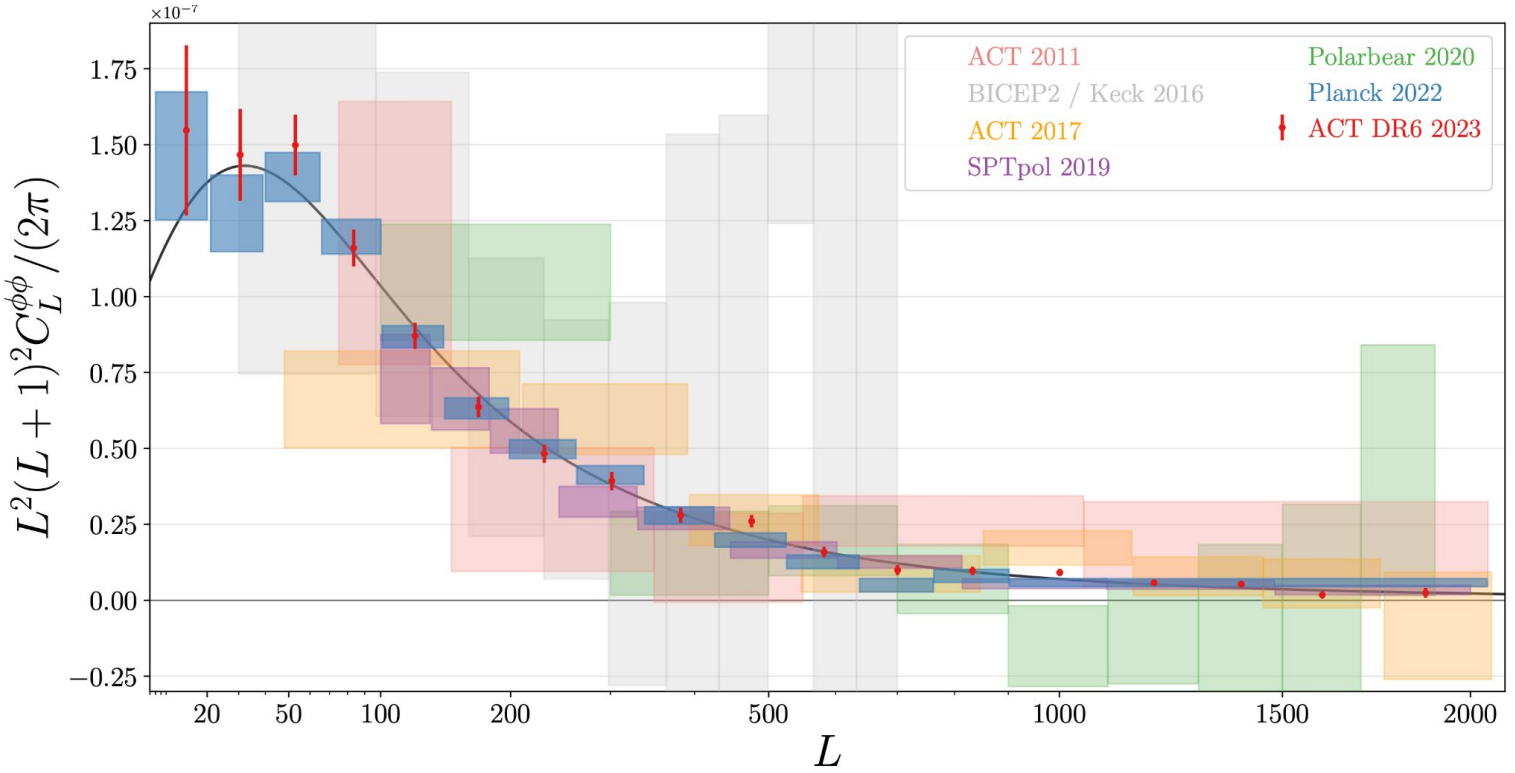
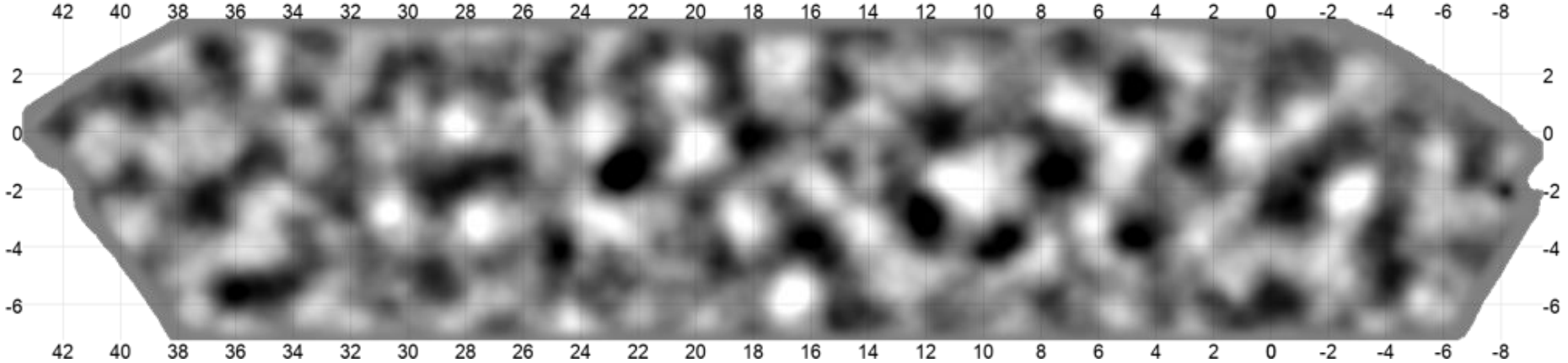


Image Credit: Frank J. Qu

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

ACT Data Release 4 (DR4) lensing potential map

Filtered map showing signal dominated modes

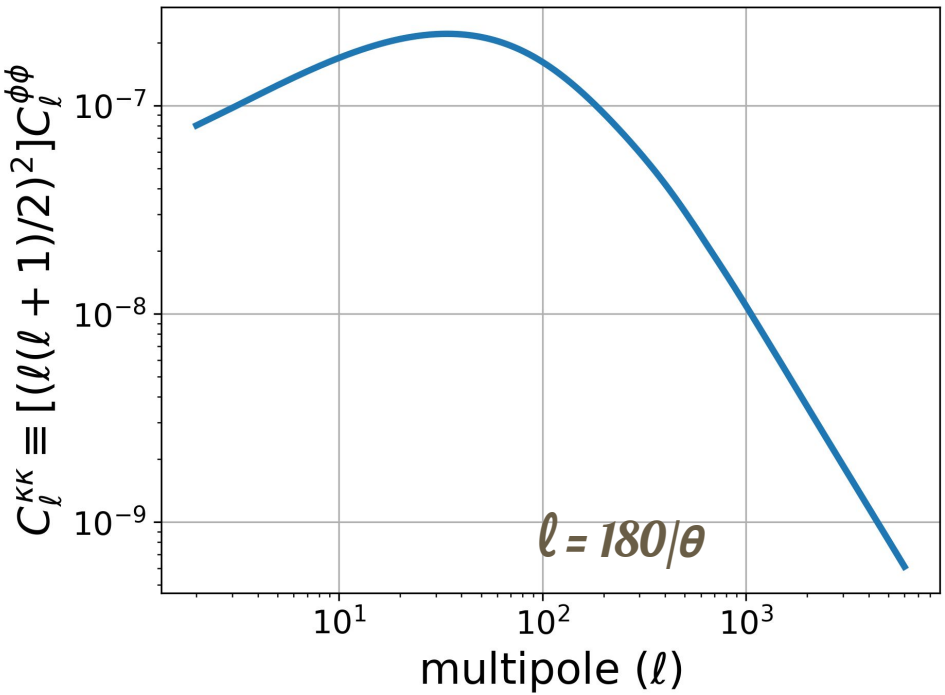


Darwish et al., 2020

white →more dense

Obtained using “quadratic estimator”. Recall: $\langle \Delta T_l \ \Delta T_{L-l} \rangle \propto \phi_L$

Power spectrum of gravitational lensing potential



$$\Delta T(\hat{n}) \rightarrow \Delta T(\hat{n} + \bar{\nabla}\phi)$$

Lensing potential:

Gravitational potential

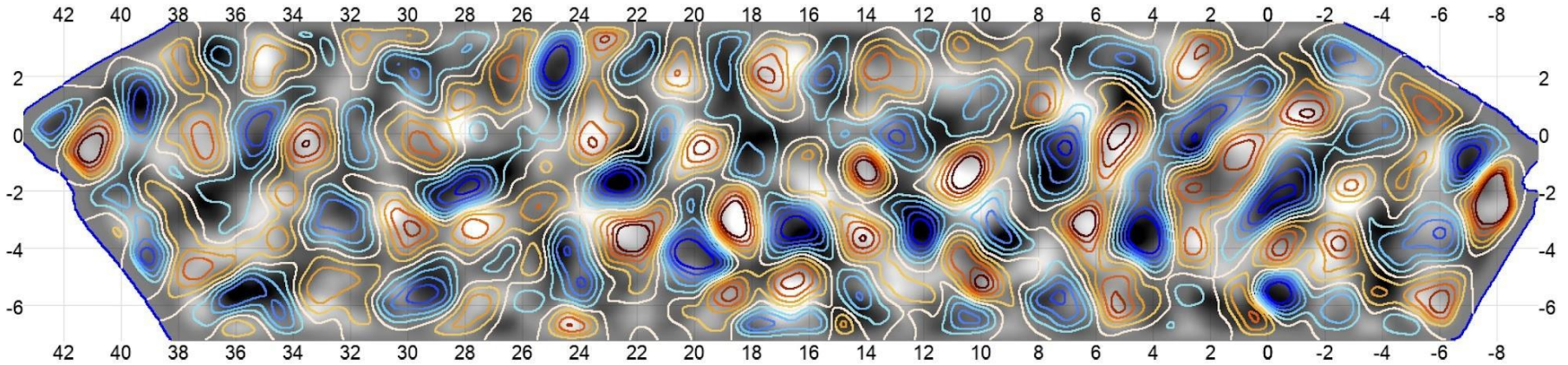
$$\phi(\hat{n}) = \int_0^{\chi_s} d\chi \; W^{\phi}(\chi) \Phi(\chi, \hat{n})$$

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

$$\kappa(\chi_s, \hat{n}) = \int_0^{\chi_s} W(\chi, \chi_s)\delta(\chi, \hat{n})d\chi$$

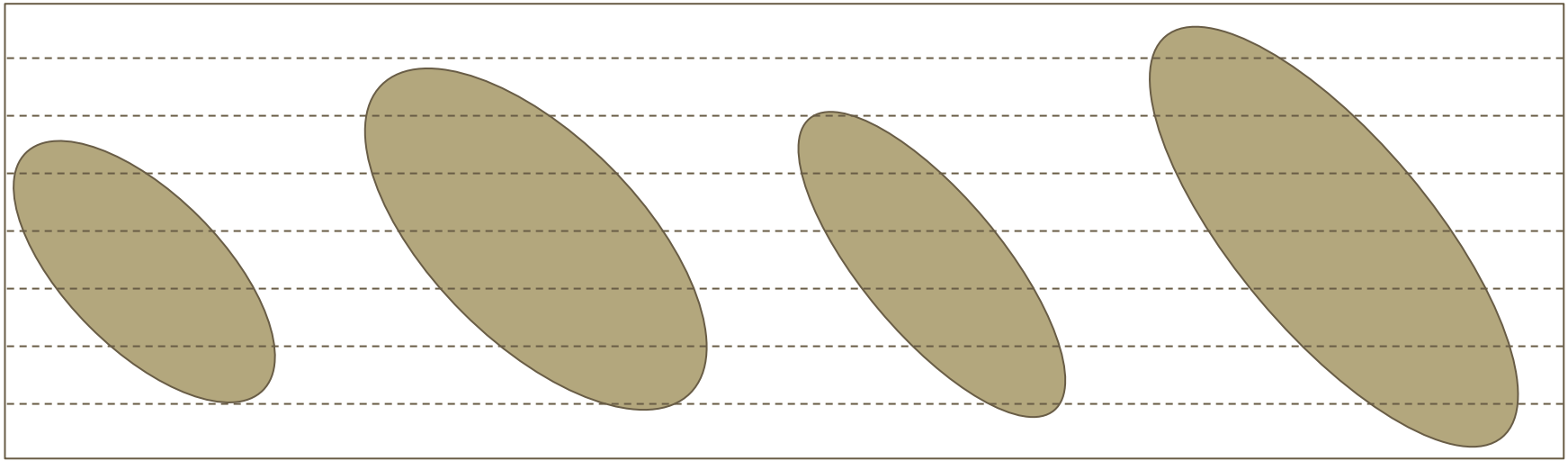
ACT Data Release 4 (DR4) lensing potential map

Filtered map showing signal dominated modes
Now with *Planck* Cosmic Infrared Background (545 GHz) map as contour levels



Darwish et al., 2020

Weak gravitational lensing of galaxies



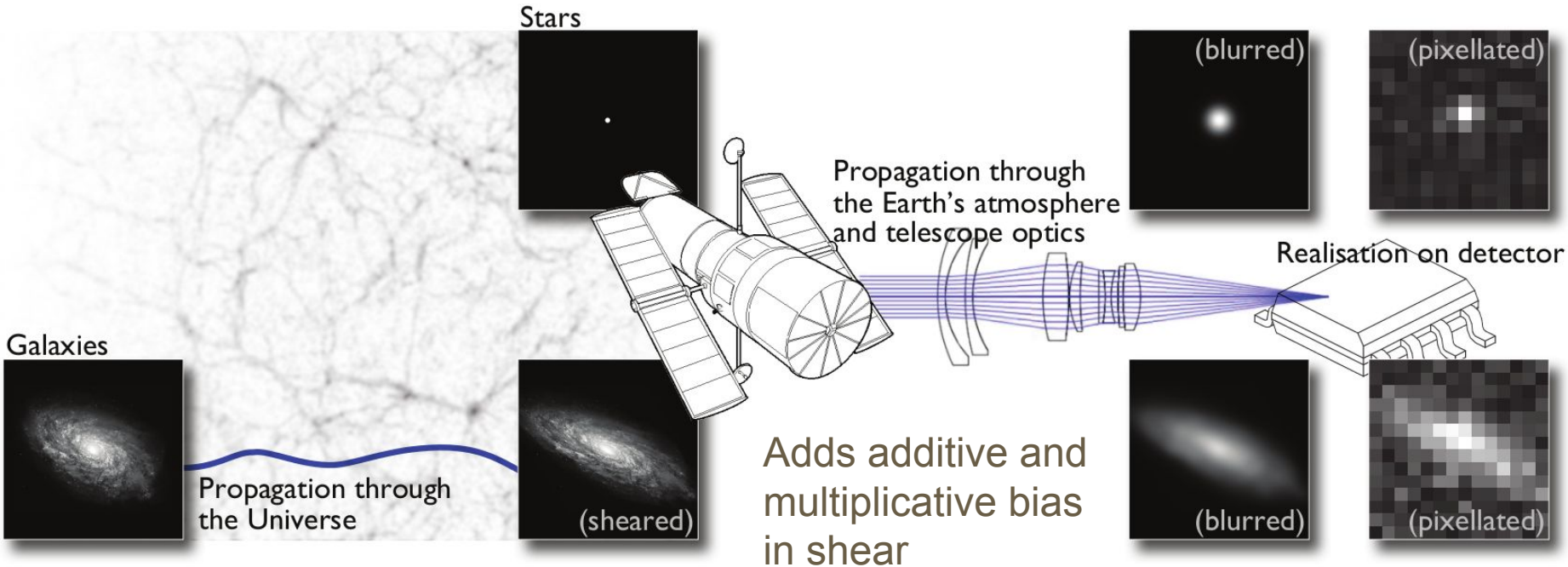
Original

Convergence

Shear

Convergence + Shear

Weak gravitational lensing of galaxies
In practice



Adds additive and multiplicative bias in shear measurement

Image Credit: Mandelbaum 2017

Cosmic Shear

Shape of lensed galaxies is a statistical measure of lensing induced "cosmic" shear (γ)

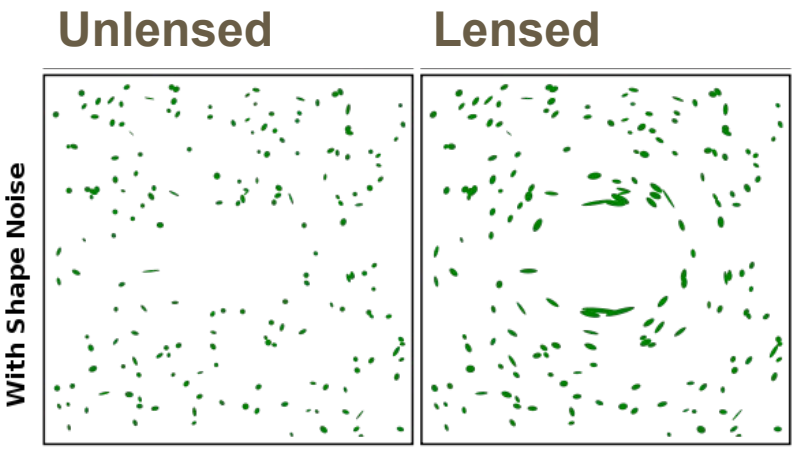


Image Credit: Wikipedia

$$e = e_{\text{intrinsic}} + \gamma \Rightarrow \langle e \rangle = \langle \gamma \rangle$$

RMS: ~ 0.25 ~ 0.01 ⇒ SNR per galaxy low

Weak lensing surveys measure shapes of many galaxies

For example,

DES Y3: n_{eff} = 5.59 gal/arcmin^2, 4143 deg^2

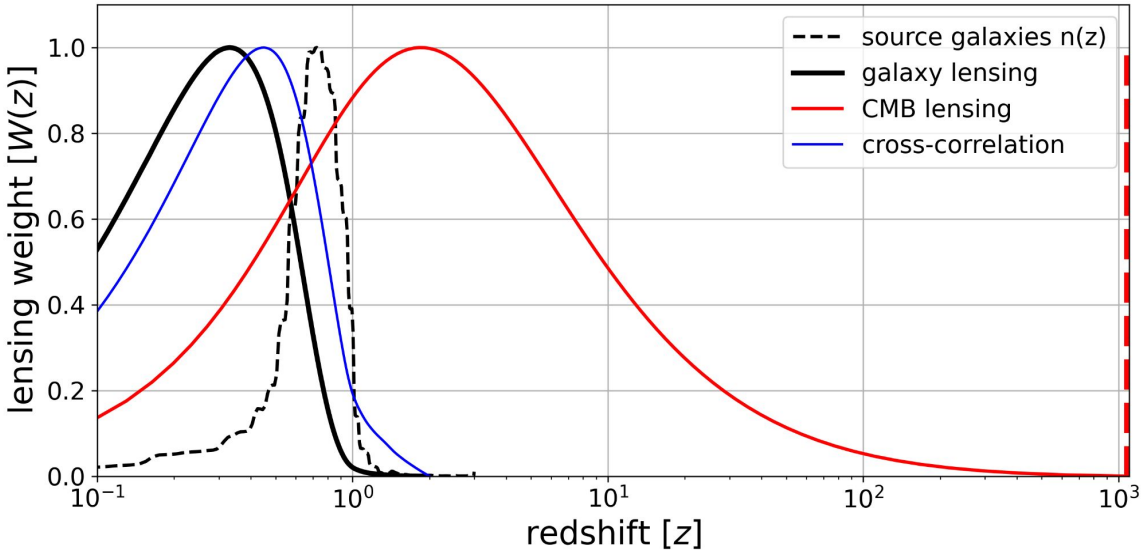
Shear and convergence are related: $\gamma_L^E \longleftarrow \kappa_L$ $\quad \kappa(z_s, \hat{n}) = \int_0^{z_s} W(z, z_s)\delta(z, \hat{n})dz.$

Some reasons for cross-correlations

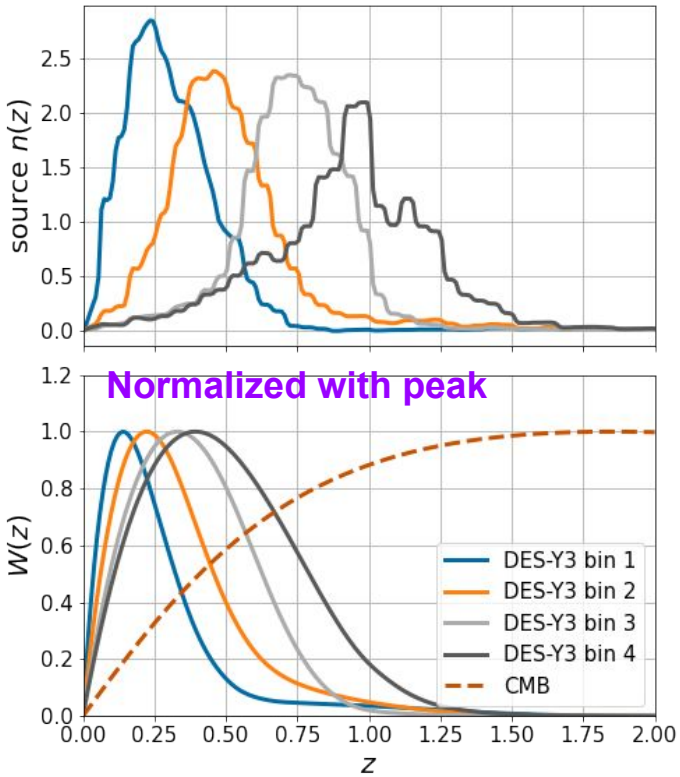
1) Cancellation of uncorrelated additive systematics:

$$\langle(\delta_1 + s_1)(\delta_2 + s_2)\rangle = \langle\delta_1\delta_2\rangle + \langle\delta_1 s_2\rangle + \langle\delta_2 s_1\rangle + \langle s_1 s_2\rangle$$

2) Cross-correlation probes slightly different redshift range than that probed by individual observable.



DES source galaxies redshift distribution and lensing kernel

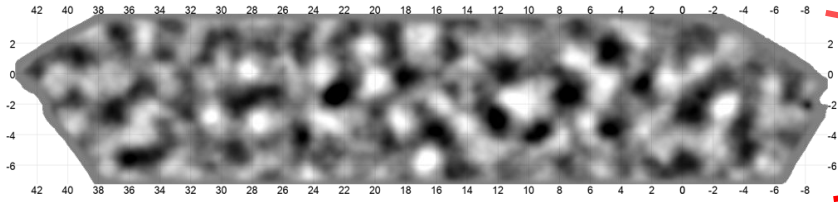


Redshift distribution of source galaxies

Lensing weight of source galaxies, along with the CMB lensing weight.

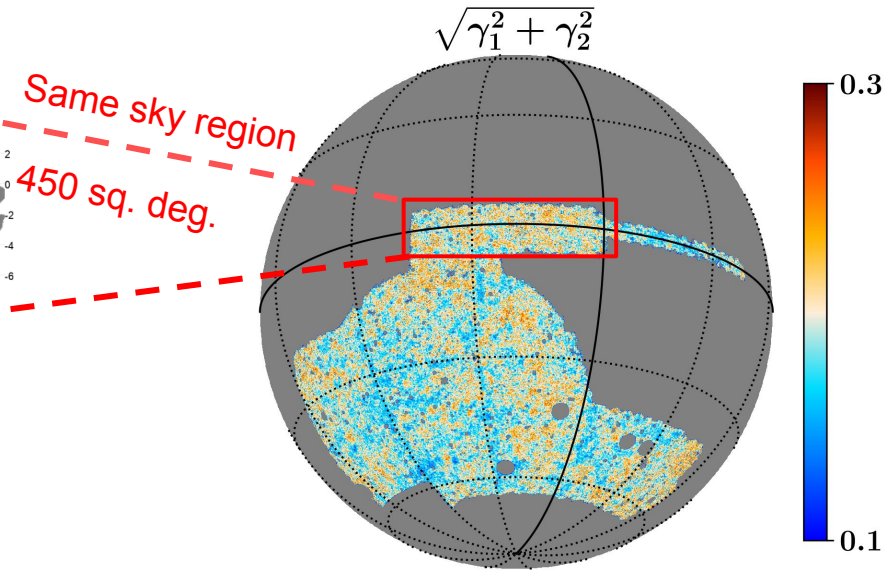
Weak gravitational lensing of CMB and galaxies
ACT DR4 and DES-Y3

Lensing potential (ϕ) map from
CMB observations in ACT-D56 region



ACT collaboration, Darwish et al. 2020

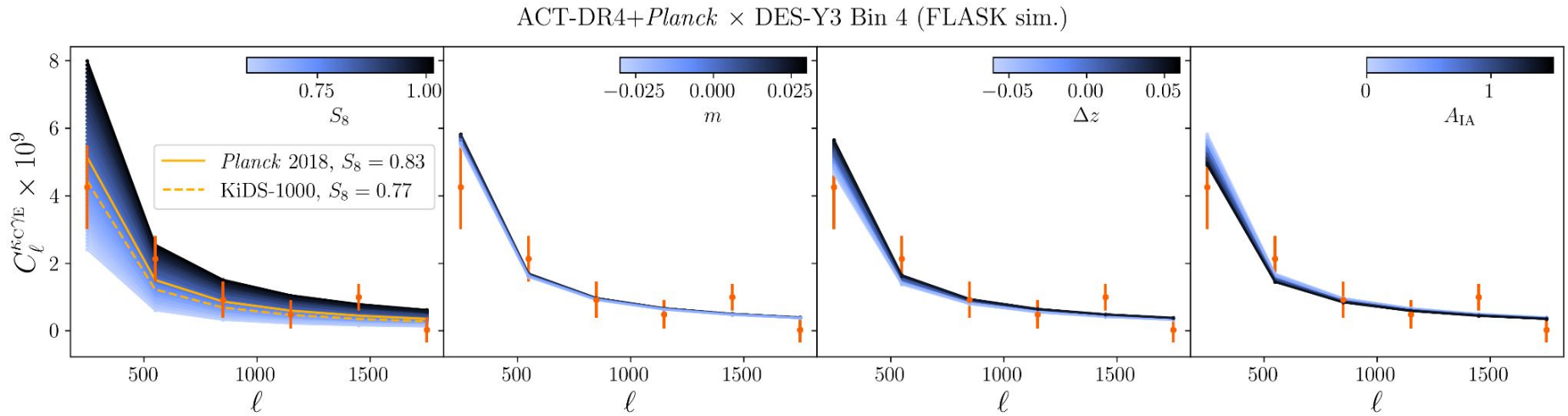
Noisy |shear| map from DES-Y3 shape catalog



Shaikh, Harrison et al., 2023

CMB and cosmic shear cross angular power spectrum

Effect of various parameters



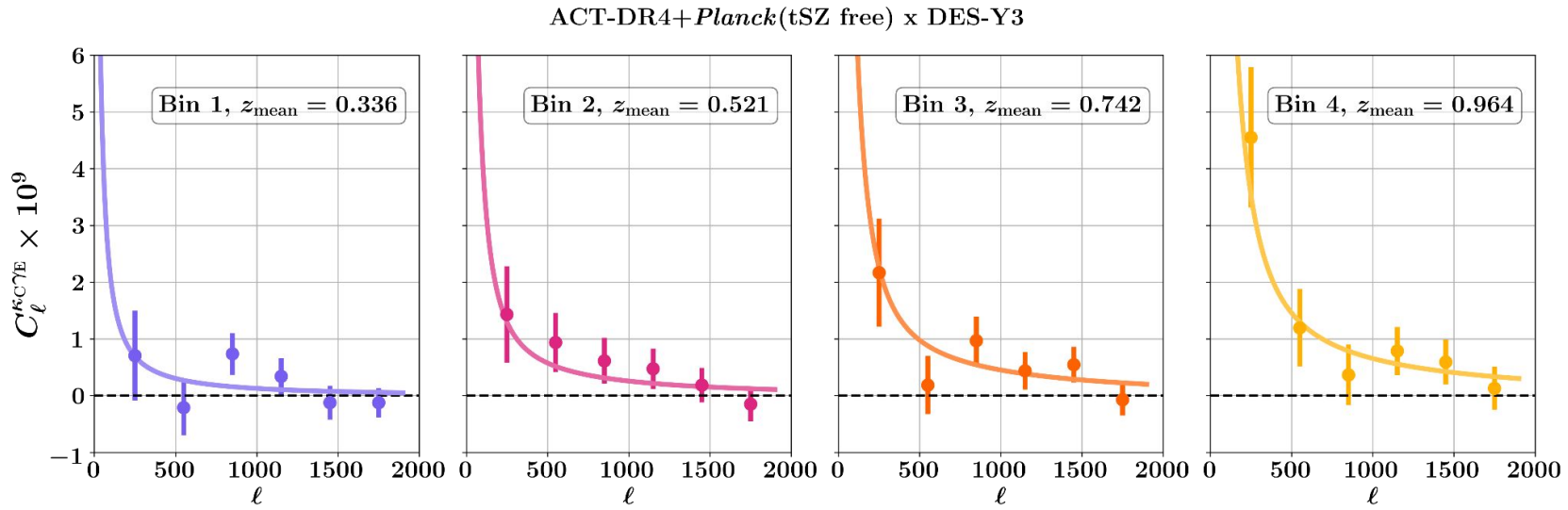
S_8

Shear multiplicative bias

Photo-z uncertainty

Intrinsic alignment

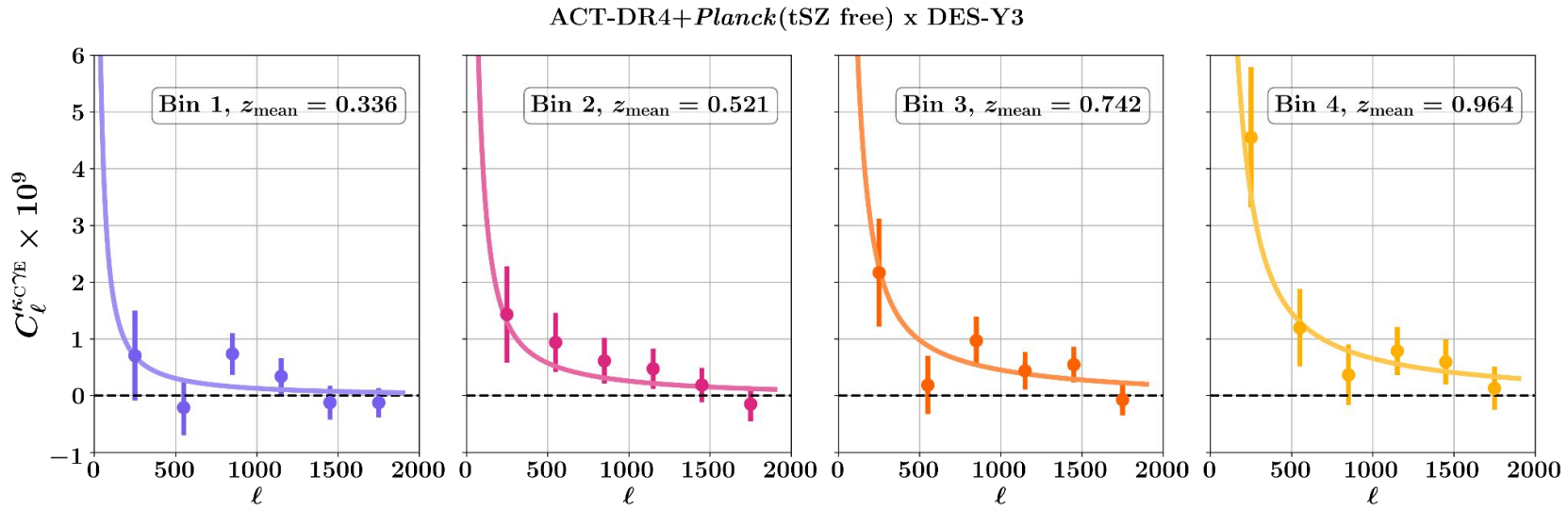
Measurement of cross-angular power spectrum



Bandpowers obtained using NaMaster (Alonso et al., 2019).

Error bars using FLASK lognormal simulations (Xavier et al., 2016) and ACT lensing reconstruction simulations.

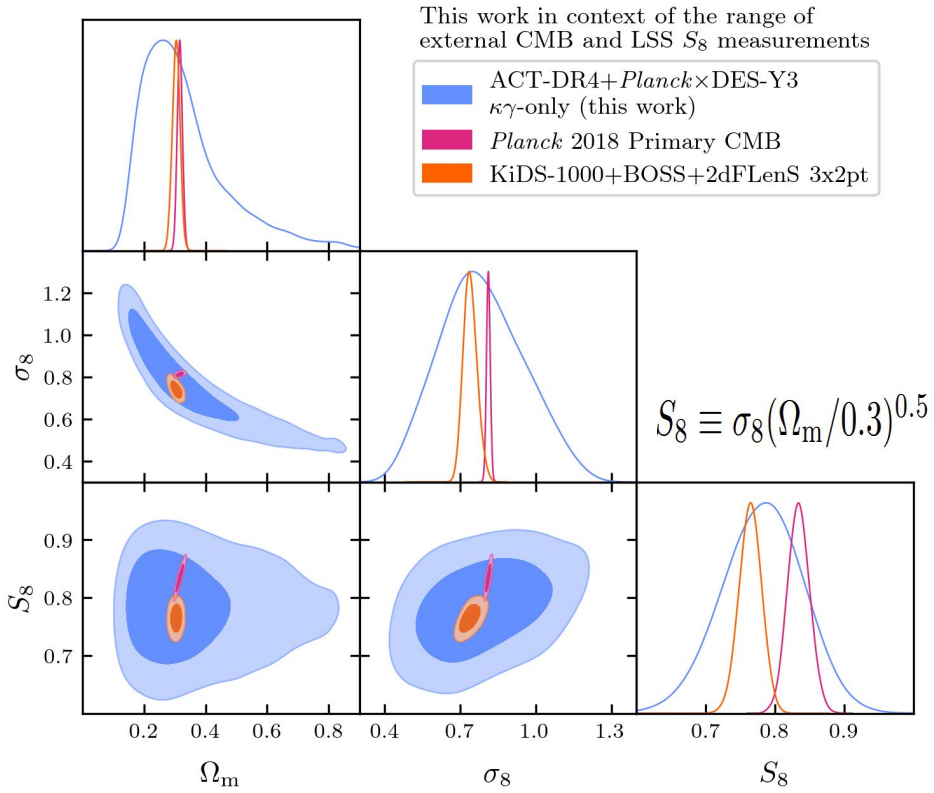
Measurement of cross-angular power spectrum



Amplitude of power spectrum with respect to *Planck* 2018 primary CMB prediction:

$$C_\ell^{\kappa C\gamma E}{}_{\rm obs} = A_{\rm cross} C_\ell^{\kappa C\gamma E}{}_{\rm Planck} \qquad A_{\rm cross} = 0.84^{+0.16}_{-0.13}$$

Inferred cosmological parameters



Marginalised over

- intrinsic alignment
- multiplicative shear bias
- photo-z uncertainty

Summary of marginalised 1D posterior distributions

$$\Omega_m = 0.338^{+0.05}_{-0.17};$$
$$\sigma_8 = 0.79^{+0.16}_{-0.19};$$
$$S_8 = 0.782 \pm 0.059.$$

S_8 measurement in context

Different set of measurements are bridging the redshift and length scales.

In this case between cosmic shear and CMB lensing

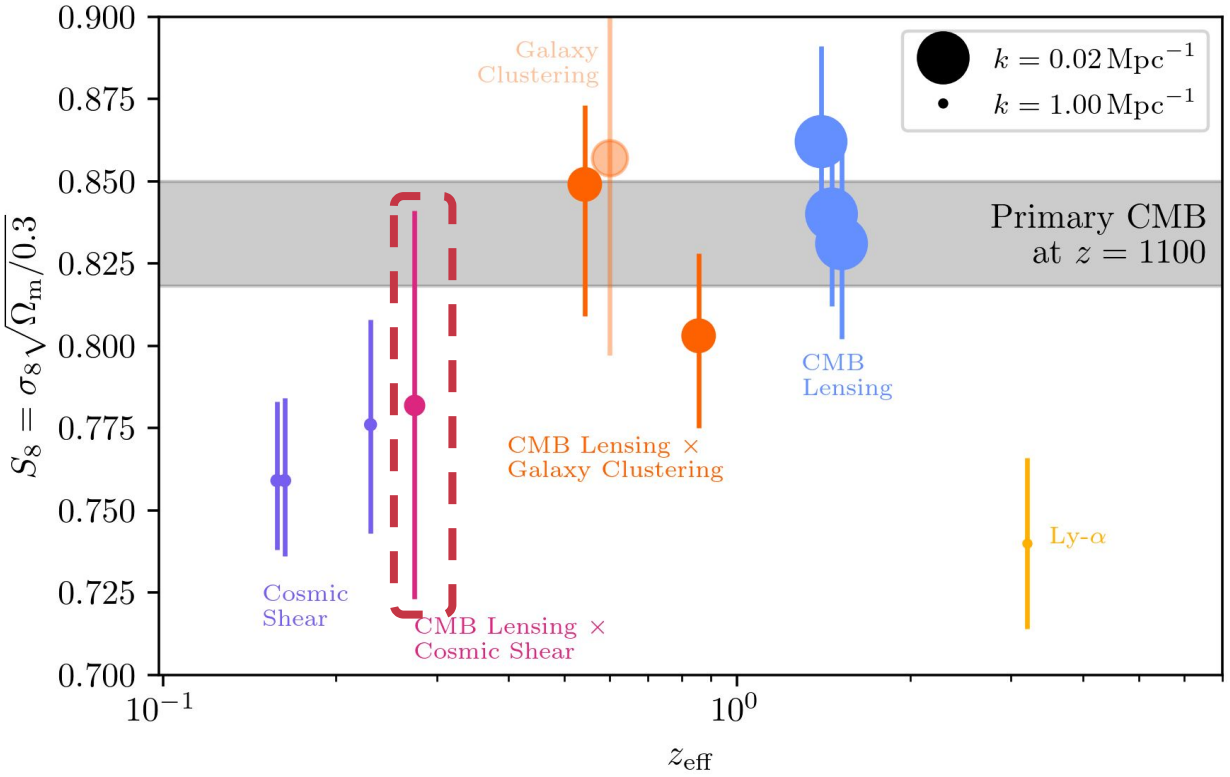
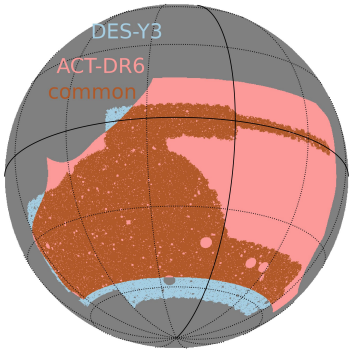
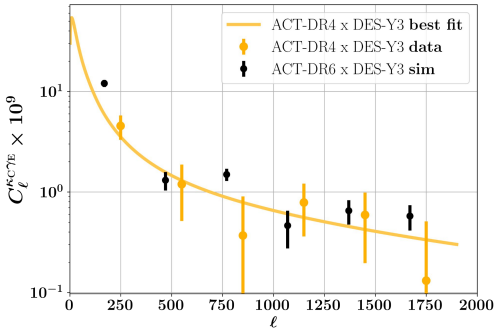


Image Credit: Ian Harrison

ACT DR6 lensing x DES Y3 lensing: forecast

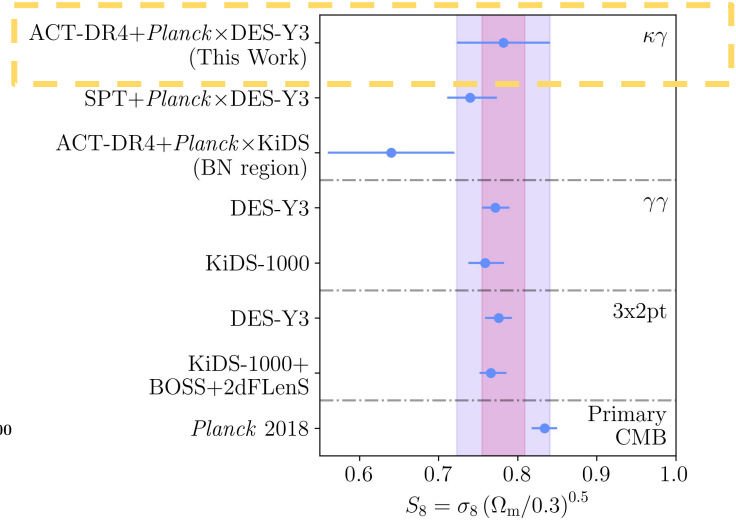
ACT DR6 lensing overlaps with ~ 95% of DES-Y3





Parameter constraints

Error forecast for DR6 ACT lensing map

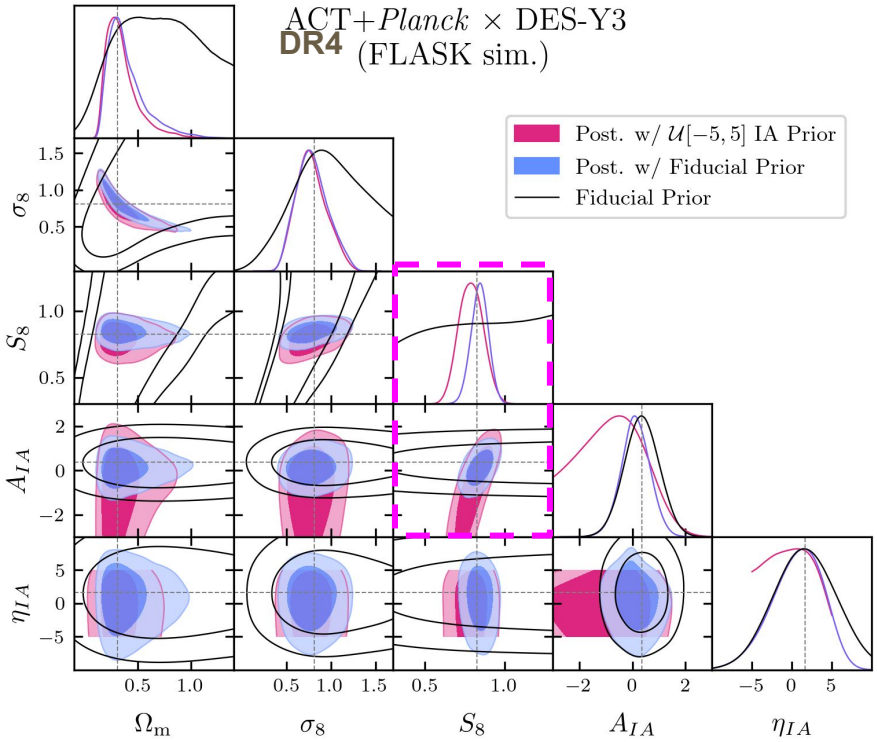


$$S_8 \equiv \sigma_8(\Omega_{\rm m}/0.3)^{0.5} = 0.782 \pm 0.059$$ ⟶ ~ 0.03 with ACT DR6 (**preliminary**)

Shaikh, Harrison et al., 2023

Model and prior choices: Intrinsic Alignment

- S_8 is degenerate with the amplitude of intrinsic alignment (A_{IA})
- Galaxy Intrinsic Alignment parameters:
  - Baseline analysis: NLA (A_{IA}, η_{IA}) model, with priors ~ to DES Y1 posterior.
  - But, widening IA prior significantly degrades S_8 constraints.
- Galaxy lensing nuisance parameters:
  - $m_{1\text{-}4}$, $\Delta z_{1\text{-}4}$ with DES priors
- With broader IA priors, we see information gain in A_{IA} .



Extragalactic foreground biases

Extragalactic foregrounds in the observed map

$$T(l) = T^{\mathrm{CMB}}(l) + T^{\mathrm{fg}}(l)$$

If not mitigated, can pass through QE and result in lensing map having spurious correlations with LSS tracers.

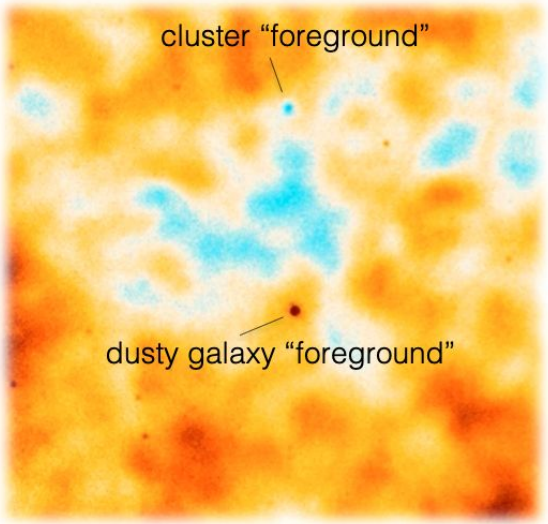


Image Credit: Niall MacCrann

Foreground bias in CMB lensing X cosmic shear

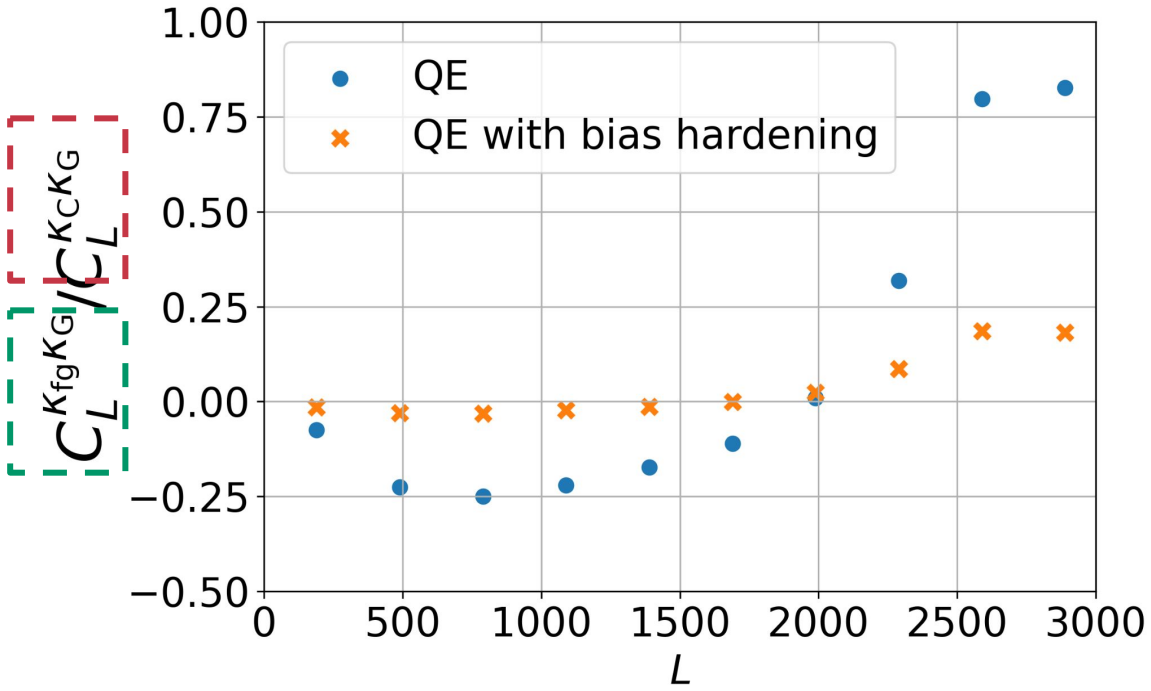
Estimate using Agora simulations

Bias due to extragalactic foreground in xcorr

Fiducial signal amplitude

Preliminary exploration based on **approximate ACT DR6 and DES Y3** analysis settings.

Agora Simulations
Omori 2022



Summary

- CMB Lensing x Cosmic Shear measures S_8 **at higher redshifts, larger scales than cosmic shear alone**, robust to certain systematics.
- ACT-DR6 x DES-Y3 will be factor of two improvement in S_8 constraint over ACT-DR4 x DES-Y3
- However, as we push the measurement towards high SNR and higher multipoles, the effect of systematics will be non-negligible for cross-correlations.
- S_8 is degenerate with the amplitude of intrinsic alignment and will require better prior and/or joint analysis with cosmic shear autocorrelation

Thank you.

Extra slides

Model and prior choices

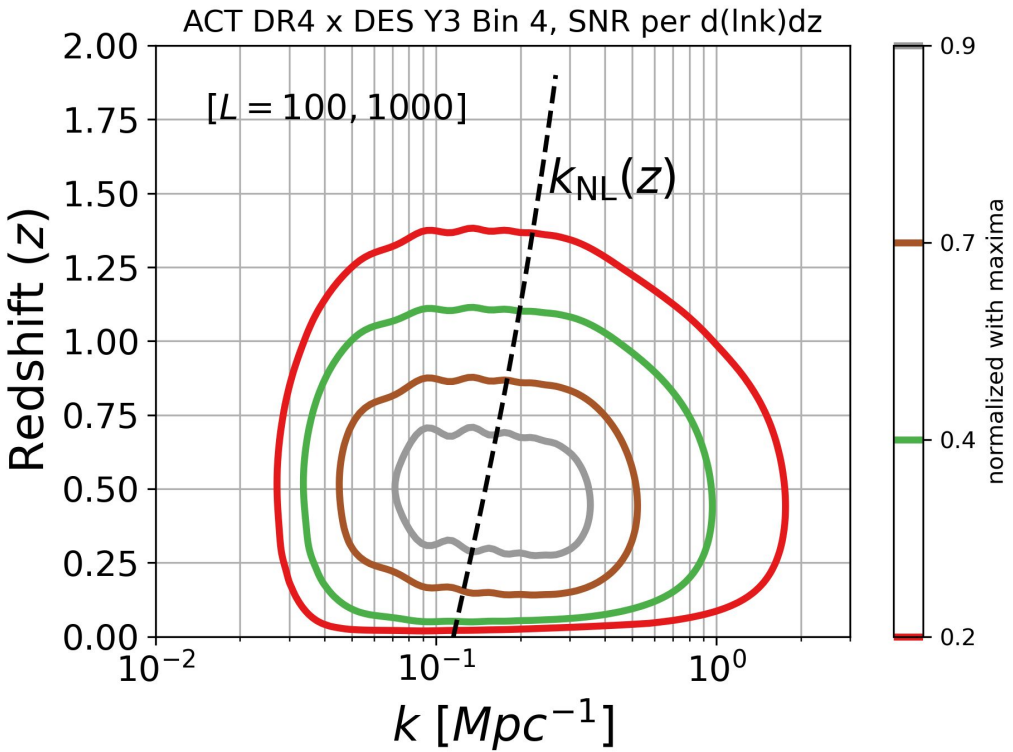
- Theory from Limber calculation of power spectrum
  - Halofit matter power

$$C_\ell^{\kappa_{\rm C}\gamma_{\rm E}} = \int_0^{z_H} dz \frac{H(z)}{\chi^2(z)c} W_\kappa^{\rm CMB}(z) W_\gamma^{\rm g}(z) P_{\delta\delta}\left(k = \frac{\ell + 0.5}{\chi(z)}, z\right)$$

- Cosmology parameters:
  - S_8, Ω_m with broad priors
- Galaxy Intrinsic Alignment parameters:
  - Two parameter NLA (A_{IA}, η_{IA}) with priors comparable to Y1 posterior (on independent sky region)
- Galaxy lensing nuisance parameters:
  - $m_{1\text{-}4}$, $\Delta z_{1\text{-}4}$ with DES priors

Parameter	Fiducial	Prior
Cosmology Sampled		
$\Omega_c h^2$	0.120	$\mathcal{U}[0.05, 0.99]$
$\log(A_s 10^{10})$	3.042	$\mathcal{U}[1.6, 4.0]$
H_0	67.36	$\mathcal{U}[40, 100]$
Cosmology Fixed		
$\Omega_b h^2$	0.0224	-
n_s	0.9649	-
$\sum m_\nu$ [eV]	0.06	-
Galaxy Intrinsic Alignment		
$A_{\rm AIA}$	0.35	$\mathcal{N}(0.35, 0.65)$
$\eta_{\rm AIA}$	1.66	$\mathcal{N}(1.66, 4)$
Galaxy redshift calibration		
Δz_1	0.0	$\mathcal{N}(0.0, 0.018)$
Δz_2	0.0	$\mathcal{N}(0.0, 0.015)$
Δz_3	0.0	$\mathcal{N}(0.0, 0.011)$
Δz_4	0.0	$\mathcal{N}(0.0, 0.017)$
Galaxy shear calibration		
m_1	-0.006	$\mathcal{N}(-0.006, 0.009)$
m_2	-0.020	$\mathcal{N}(-0.020, 0.008)$
m_3	-0.024	$\mathcal{N}(-0.024, 0.008)$
m_4	-0.037	$\mathcal{N}(-0.037, 0.008)$

SNR per d(lnk) and dz: ACT DR4 x DES Y3



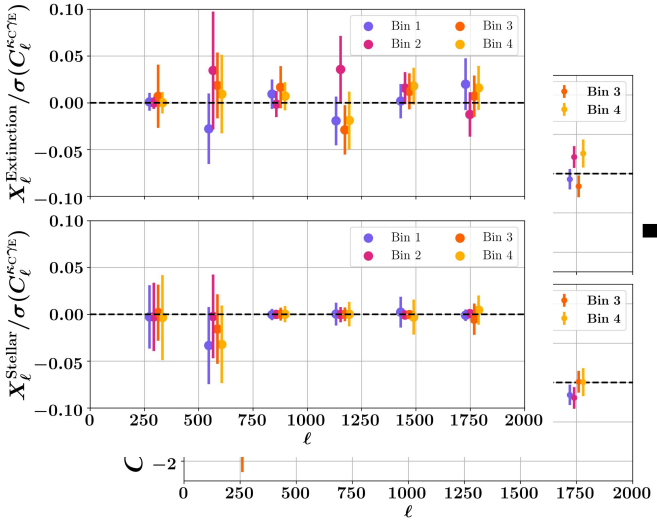
$$k_{\rm NL}^{-2} = \frac{1}{6\pi^2} \int dk\ P_{\rm lin}(k)$$

$$\vec{x}(\vec{q}, t) = \vec{q} + \vec{\Psi}(\vec{q}, t)$$

$$P_{\delta\delta}(k) = k^2 P_{\Psi\Psi}(k)$$

Blind analysis

- Passing null tests +
  successful model recovery +
  stability of measurement to data cuts = unblind the data vector!



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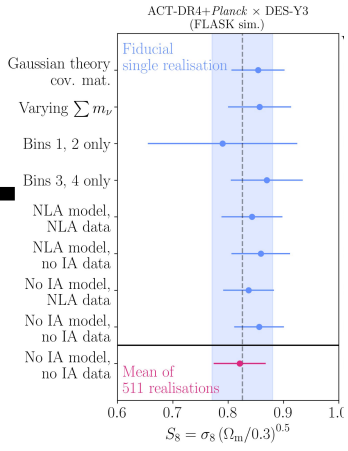

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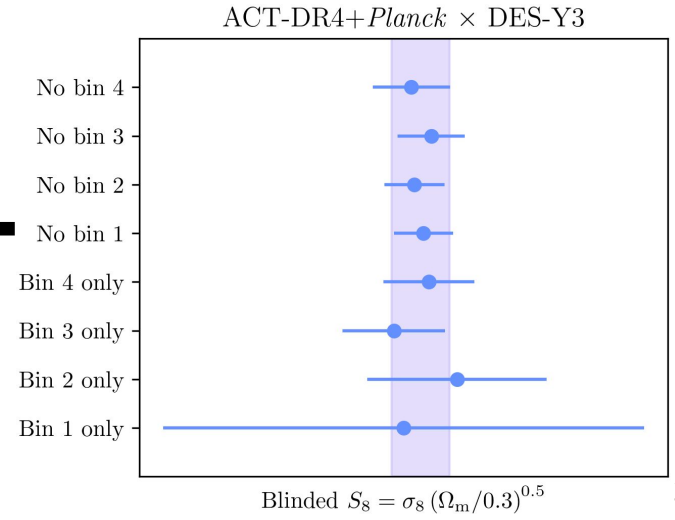
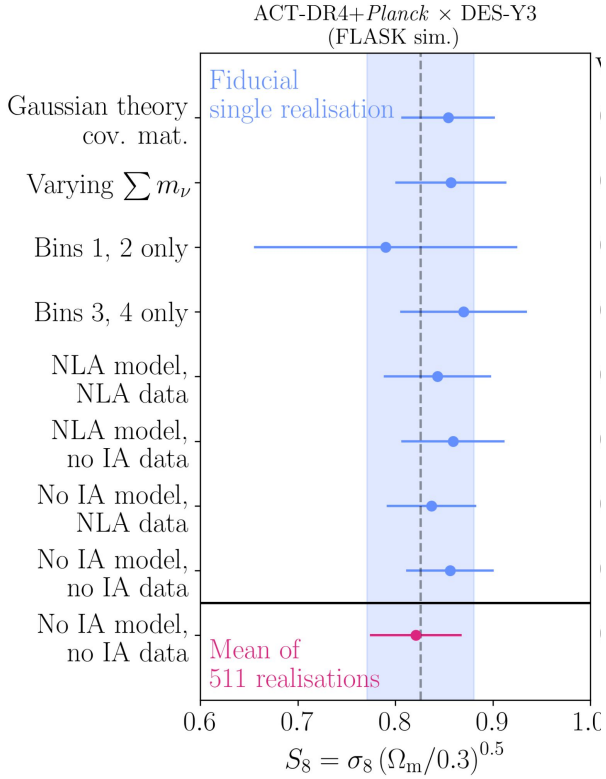


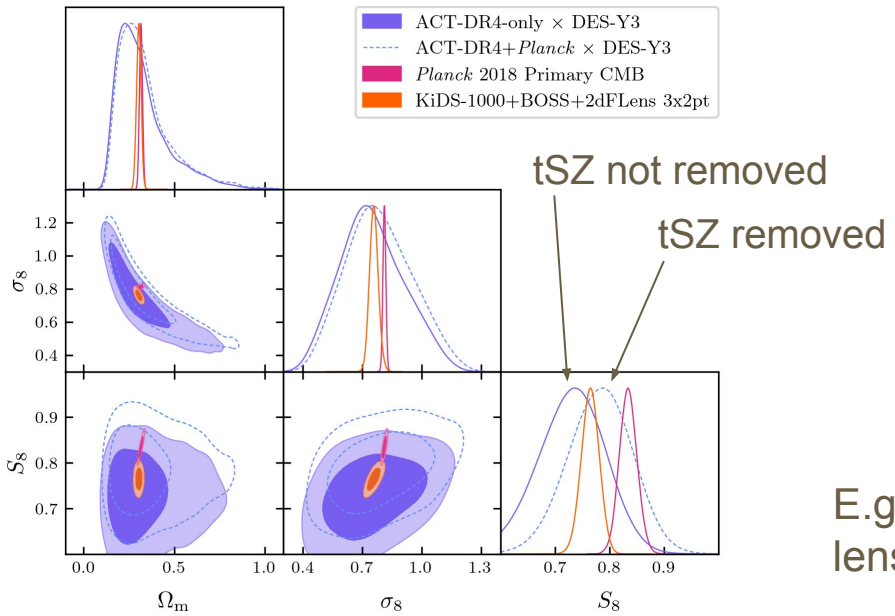
Analysis steps and cross-checks

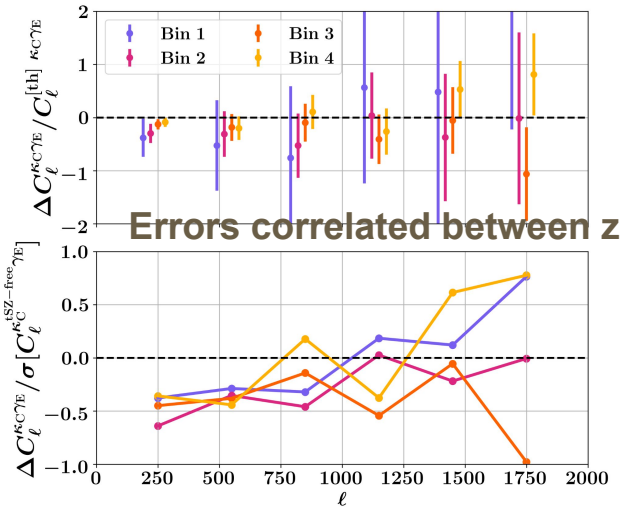
- **Pseudo-Cl method** to estimate power spectra of masked input fields
- **Covariance matrix** from log-normal Signal + Noise simulations
- **Scale cuts**:
  - L_{min} **= 100** (avoid *mean field bias* in CMB lensing reconstruction)
  - L_{max} **= 1900** (baryonic effects less than 1% of errorbar at L < 1900)
- **Inference** with Cobaya and SOLikeT
- **Test** cosmology recovery from a single simulation realisation



Foreground mitigation in CMB lensing map: implications

Using κ obtained from ACT DR4 frequency maps without tSZ mitigation leads to shift in inferred S_8, (though statistically less significant).





E.g. MacCrann et al., 2023 for ACT DR6 CMB lensing foreground mitigations

Binned theory Cl vector with HMCode: log TAGN = 8.0