Cosmology and astrophysics from the combination of CMB and galaxy lensing

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BCCP Seminar 11/10/2025

Outline

1. Motivation and Background
2. SPT-3G CMB Lensing Maps
3. Cross-correlation with DES Y3 cosmic shear
4. Future Prospects

Motivation

Weak gravitational lensing directly traces the integrated LoS density perturbations

Can be measured using:

- The CMB: through lensing-induced anisotropies
- Galaxies: through correlated shape distortions

Cross-correlation of CMB lensing and galaxy lensing provides useful tests of:

- **Consistency of ΛCDM** due to different redshift and scale dependence
- **Survey systematics** due to very different measurements of same physical effect

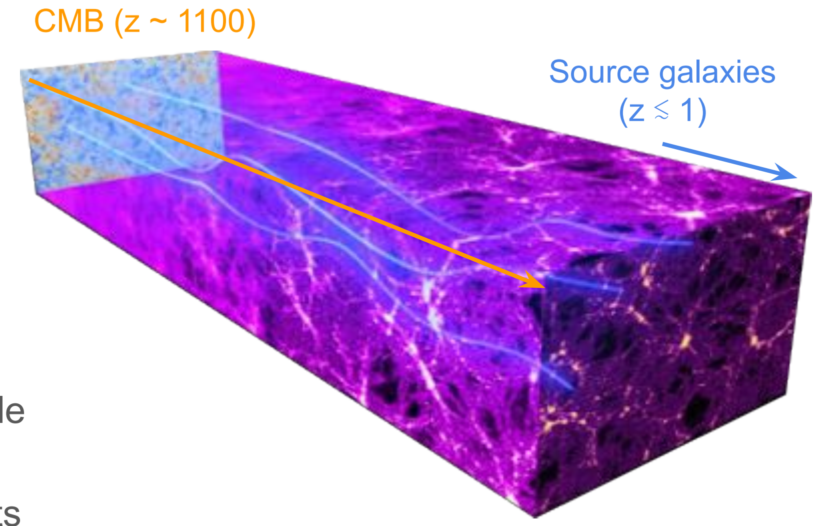


Image: ESA and the Planck Collaboration

CMB lensing

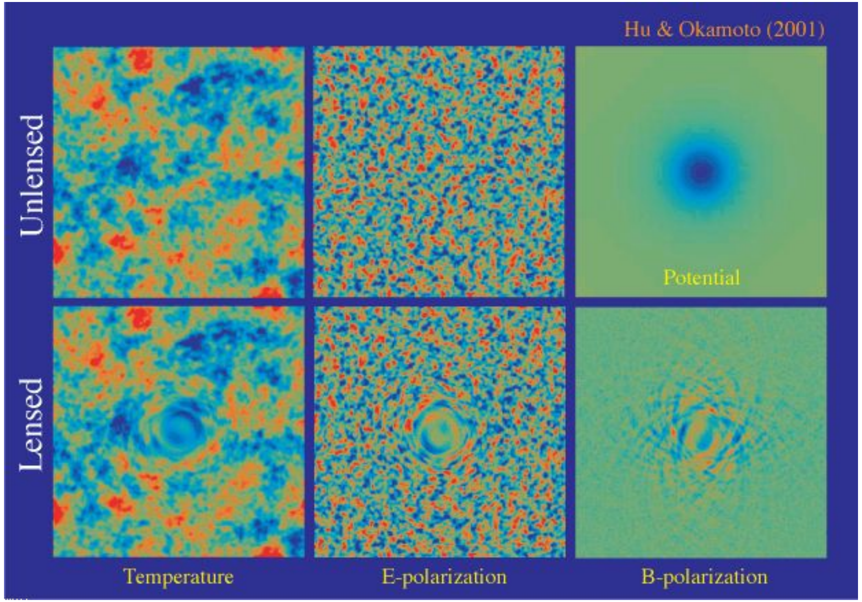
Lensing induces off-diagonal correlations between CMB modes and turns *E*-modes into *B*-modes

Standard method: quadratic estimator (QE) combines 2 CMB maps to reconstruct the lensing potential ϕ

Schematically (in harmonic space):

$$\text{off diagonal } \langle TT \rangle \sim \phi \qquad \langle TTTT \rangle \sim C_\ell^{\phi\phi}$$

In real space, can also write $\nabla\phi \sim T\nabla T$



Estimator can be constructed with any pairs of *T, E, B* fields, combine to get minimum variance

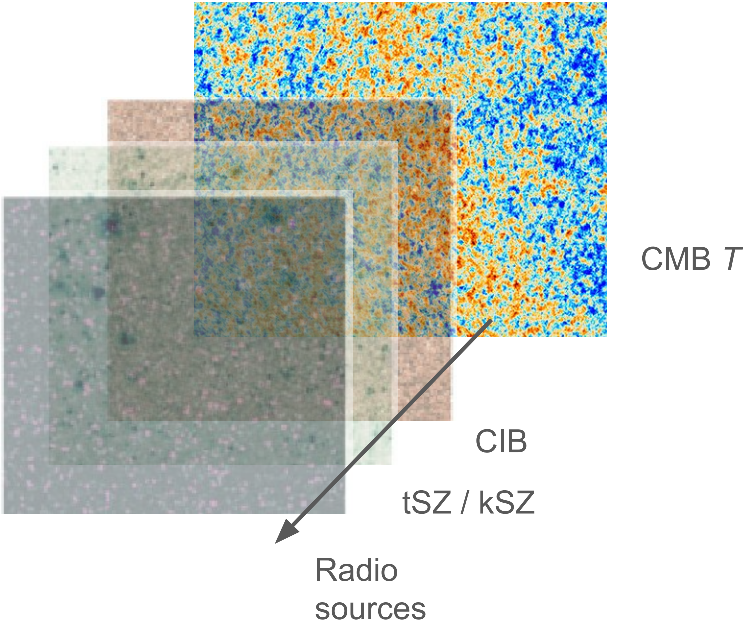
In absence of noise, *EB* estimator is the most powerful (no sample variance)

CMB Lensing: foregrounds

Non-Gaussian foregrounds induce a bias in the CMB lensing reconstruction due to extra contribution to 4-pt function $\langle TTTT \rangle$

Foregrounds are highly correlated with low-z structure – bias becomes more significant for cross-correlations due to nonzero bispectrum $\langle TT\delta \rangle$

Need some mitigation techniques if CMB temperature is included in reconstruction



Agora sims, Omori 2024

[van Engelen+ 2014; Osborne 2014; Schaan 2019; Baleato Lizancos+ 2022,2025; Sailer+ 2023; …]

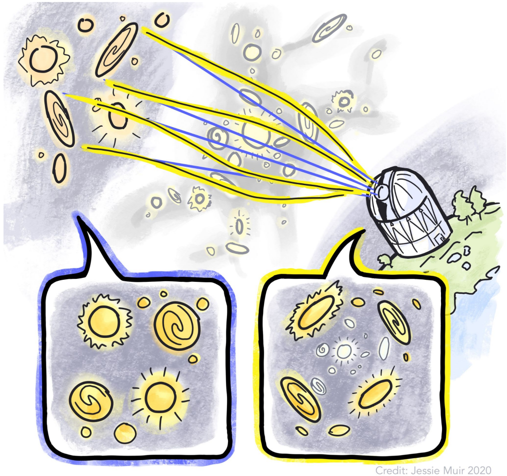
Cosmic shear

Galaxy shape distortions are correlated across the sky – directly sensitive to the leaning potential

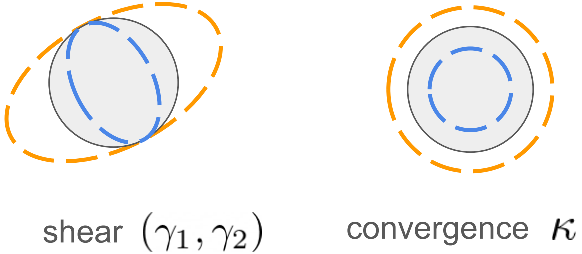
Need to account for *intrinsic alignments*: galaxies tend to align with the large-scale tidal field

Potential for lots of systematics in measurement (PSF, photo-z's, calibration, …)

CMB lensing has long been proposed as a way of calibrating cosmic shear measurements [ex: Vallinotto 2012, Schaan+ 2017], but need deep surveys



Jessie Muir

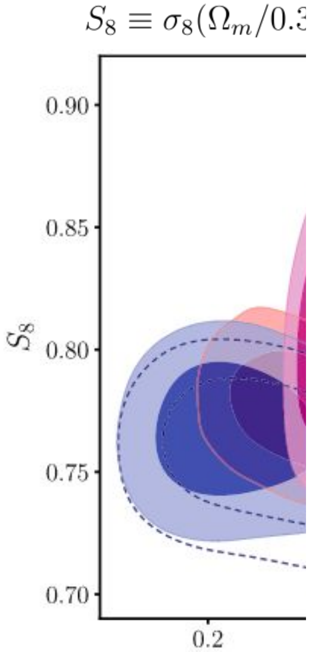


S_8 Tension? Or just baryons?

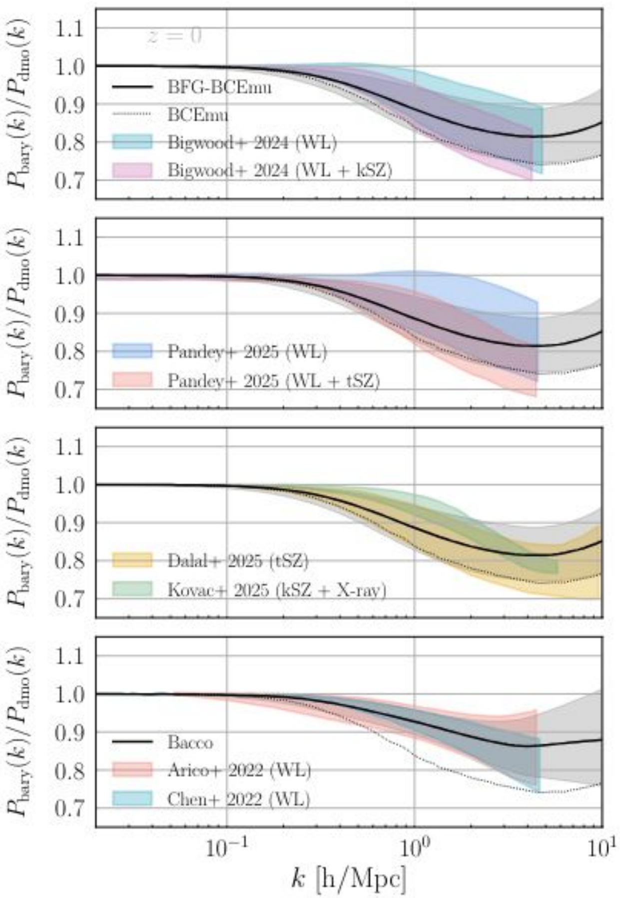
Mild tension(?) between amplitude of clustering measured by cosmic shear and that inferred from primary CMB (assuming ΛCDM)

new physics? baryons? systematics?

Cosmic shear + CMB lensing probes S_8 across a wider range of scales and redshifts and potentially disentangles astrophysical uncertainties



Amon & Efstathiou, 2022



Abajagane et al, 2025

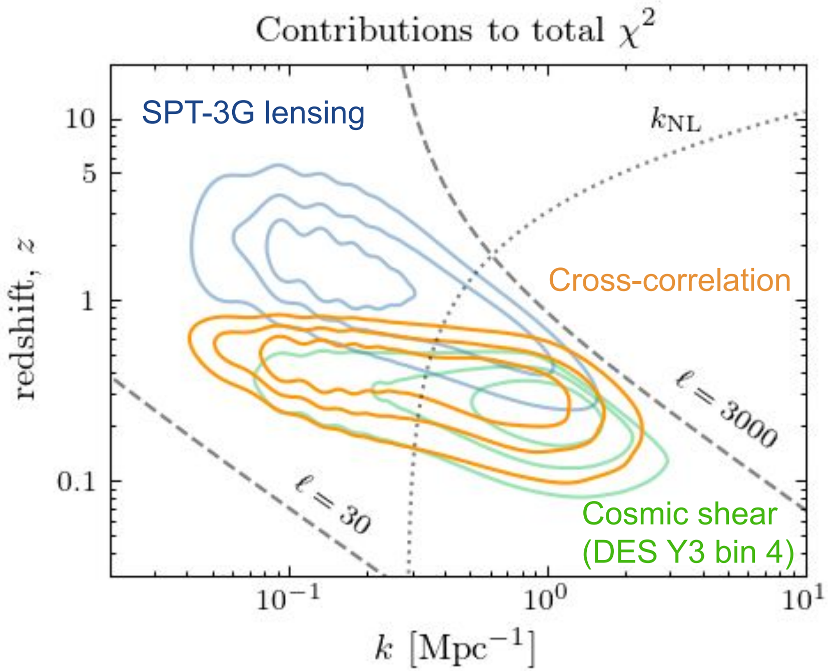
Probes are sensitive to different scale / redshift ranges

Differential contribution: $$\frac{d\chi^2}{d\ln z \; d\ln k}$$

$$\chi^2 = \sum_\ell [C_\ell/\sigma(C_\ell)]^2$$

(Calculated using theory vectors and empirical covariance)

See also: Ge et al, 2025; Doux et al, 2022; Doux & Karwal et al, 2025



SPT-3G Lensing Maps

Omori et al., in prep
(CMB lensing maps and analysis, paper coming soon)

South Pole Telescope

10 meter mm-wave telescope at the South Pole

3 frequency bands (95, 150, 220 GHz) with ~arcmin resolution

SPT-3G:
3rd generation camera (since 2017), ~16,000 detectors measuring temperature and polarization

SPT-3G+
2029? ~50% increase in number of detectors

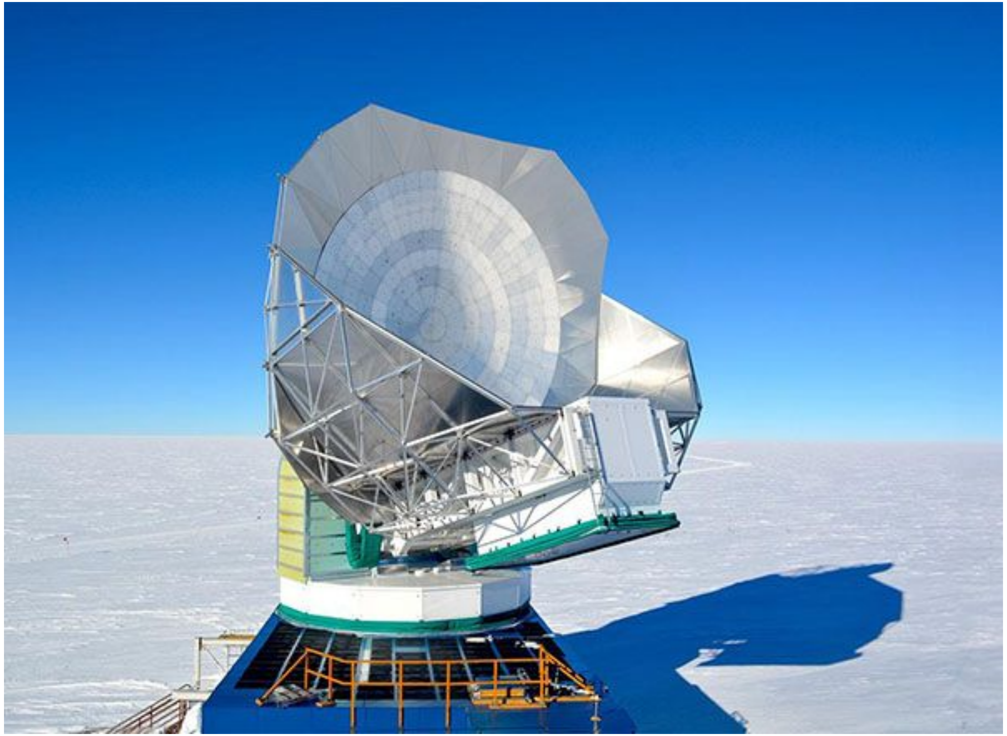
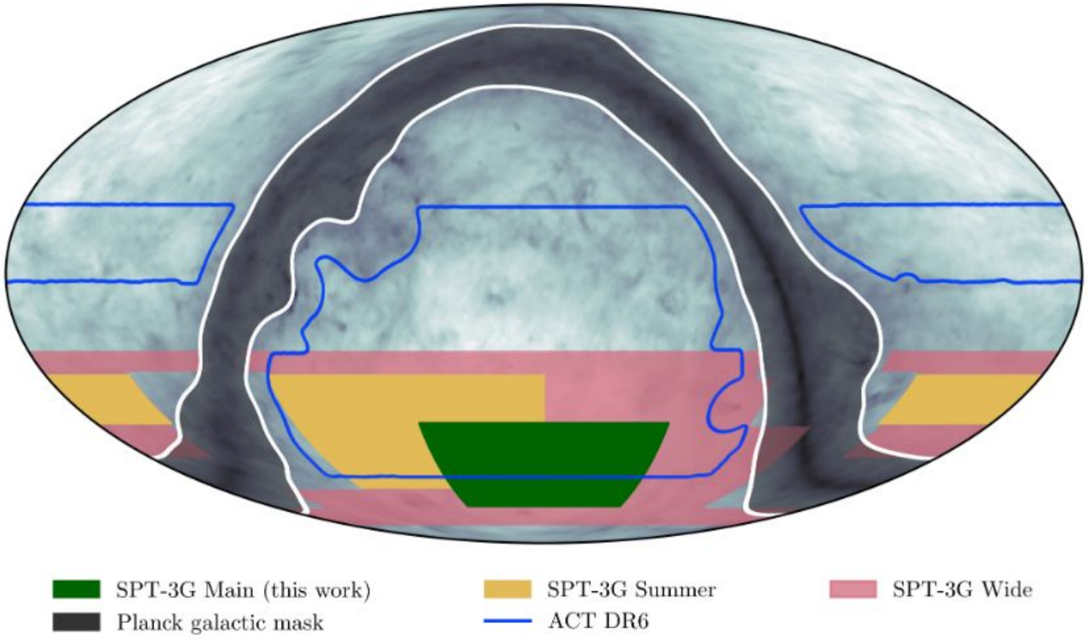


Photo: Brad Benson

SPT-3G surveys: 25% of the sky



Camphuis et al, 2025; Vitrier et al, 2025

Main: 1500 deg^2 8 mo/yr, 2018, 2019-23, 2025-26+

Summer: 2600 deg^2 4 mo/yr, 2019-23

Wide: 6000 deg^2 1yr, 2024

Target noise levels:
(coadded temperature)

< 1.6 / 6 / 9 μK-arcmin

Current data: Main 2yrs, 3.3 / 5.1 μK-arcmin in Temp / Pol

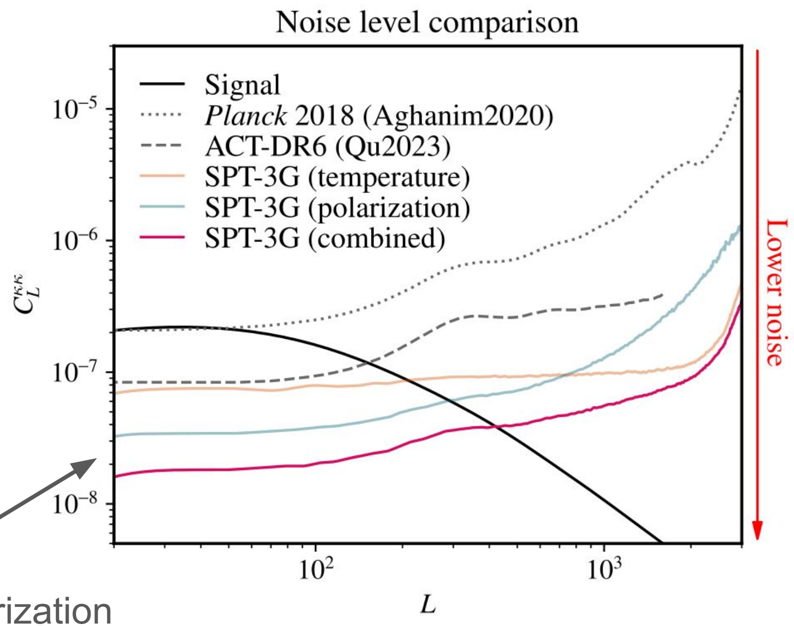
SPT-3G CMB lensing maps

Lensing maps reconstructed over the main field from 2 yrs of observations (curved-sky QE)

Deepest lensing maps made to date!

- *Good synergy with low-z tracers*

(Compare to SPT-3G MUSE lensing [Ge, Millea, et al, 2025]: Bayesian reconstruction of EE+$\phi\phi$ power spectra using polarization data)



Dominated by polarization on large scales!

Plot: Yuuki Omori

SPT-3G CMB lensing maps

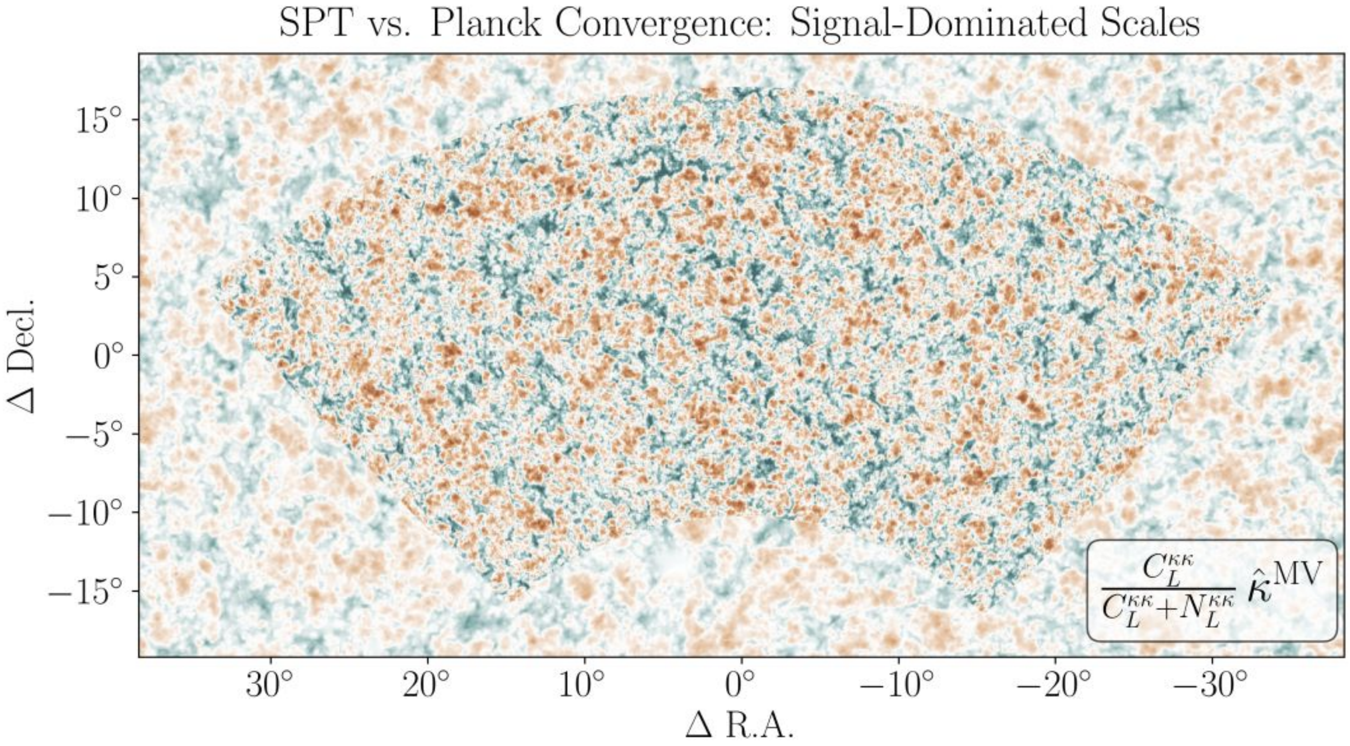
5 lensing reconstruction variants (contamination / noise tradeoffs):

- Global minimum variance (**GMV**) - optimal combination of T and P data, but contaminated
- Profile-hardened (**Prof**) - de-project trispectra of assumed source profiles from QE
- Gradient-cleaned (**MH**) and cross-ILC (**xILC**) - use component separation to clean foregrounds from one or both of the QE legs
- Polarization-only (**Pol**) - only uses P data

Significant advantage for x-corr studies:
polarization maps are largely immune to foregrounds (tSZ, CIB), don't lose much S/N on large scales

[Maniyar et al, 2021; Namikawa et al, 2013; Osborne et al, 2013; Madhavacheril & Hill, 2018; Raghunathan & Omori 2023]

Comparison with Planck

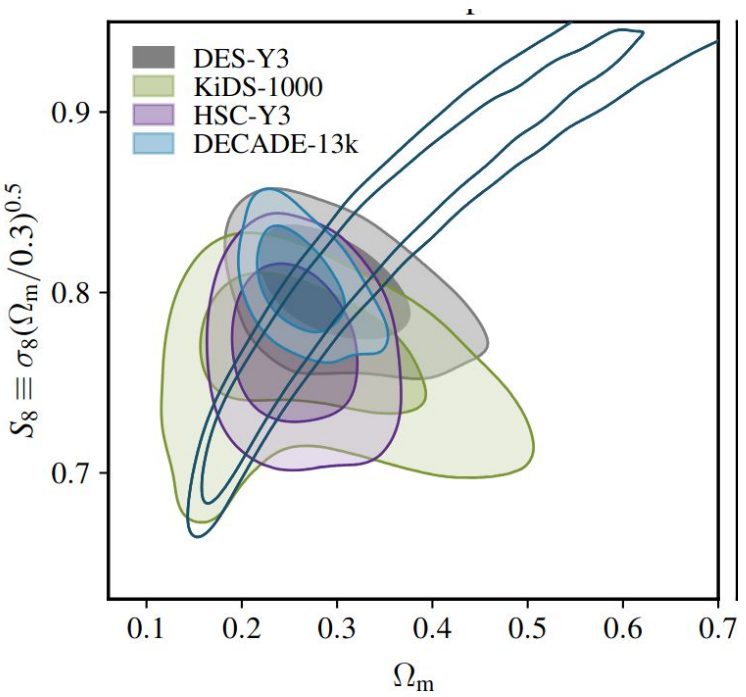


Yuuki Omori

Forecasted constraints from CMB lensing auto-spectrum

Combination most tightly constrained by CMB lensing: $S_8^{\rm CMB} = \sigma_8(\Omega_m/0.3)^{0.25}$

SPT-3G GMV (marg. over foregrounds): +/- 0.011 (1.8% constraint)



Yuuki Omori

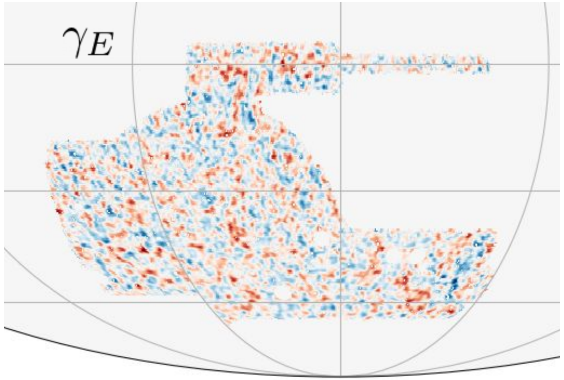
Cross-correlation with cosmic shear

Ouellette et al., in prep.

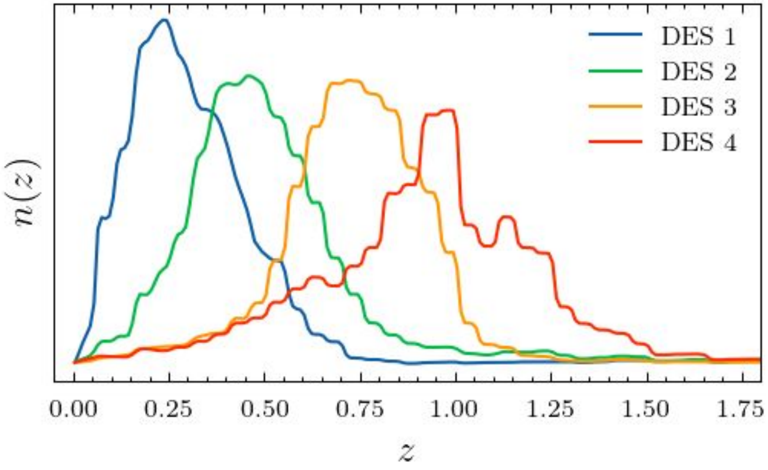
DES Y3 shear catalogs

We use the public DES Y3 shear catalogs (Gatti+, 2022)

- Consists of ~100 million galaxies over 5,000 deg^2, divided into four tomographic bins
- Galaxy shapes – spin-2 field, calibrate to get shear field γ



Shear E-mode, smoothed for visualization

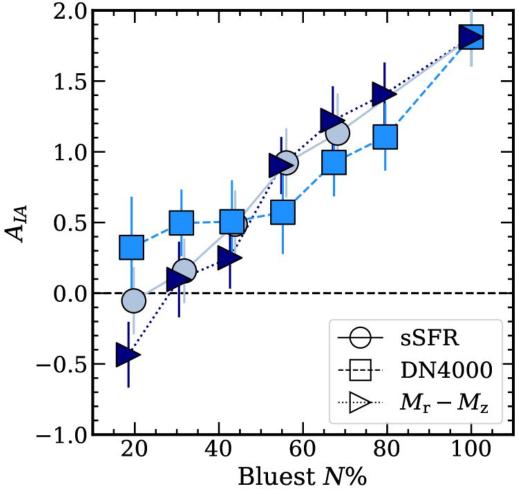


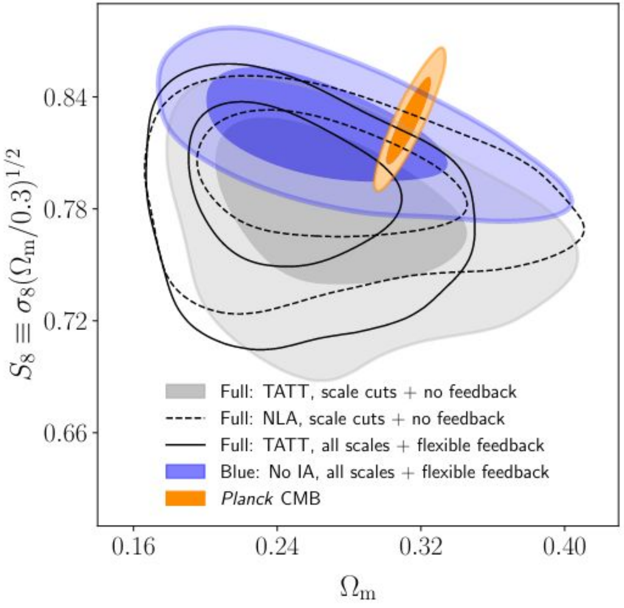
DES Y3 shear catalogs

Additionally, use the blue subsample (McCullough+, 2024)

- ~ 65% of the full DES Y3 catalog
- Designed as a pure blue galaxy sample to reduce impact of intrinsic alignments

Latest IA result from DESI (Siegel et al, 2025)





Plot from McCullough et al, 2024

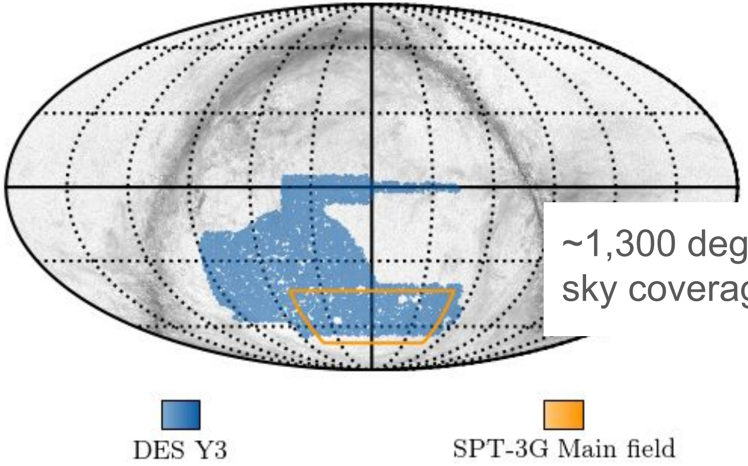
Lensing-shear cross-correlation

Cross-correlation: $$C_\ell^{\kappa\gamma} = \frac{1}{2\ell+1}\sum_m \kappa_{\ell m}\gamma_{\ell m}^E$$

(shear *B*-modes expected to be consistent with zero, but could be useful in the future [ex: James+25, Georgiu+25])

CMB lensing convergence (scalar field)

Cosmic shear (*E*-mode of spin-2 field)



~1,300 deg^2 of overlapping sky coverage

Data overview:

- **Shear:** Full, Blue
- **Lensing:** GMV, Pol, Prof, MH, xILC

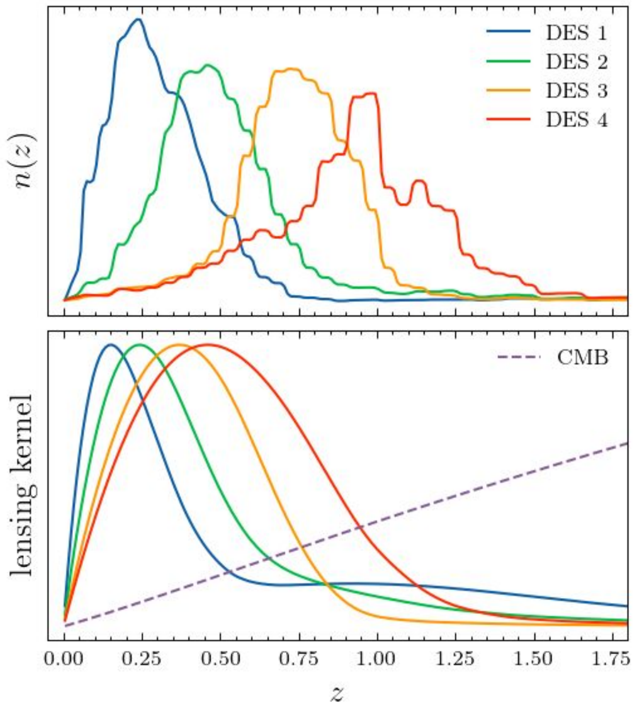
Enables data-driven consistency tests

Modelling

Limber approximation:

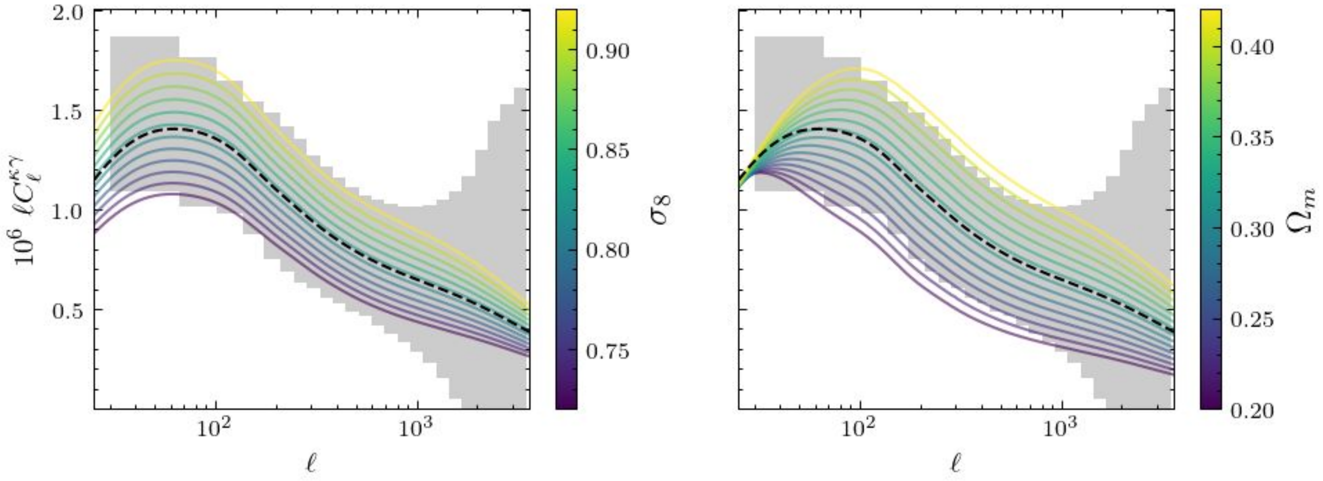
$$C_\ell^{\kappa\gamma} = \int \frac{d\chi}{\chi^2} W_\kappa(\chi) W_\gamma(\chi) P_m \left(k = \frac{\ell + 1/2}{\chi}, z(\chi) \right)$$

- *Intrinsic alignments:* galaxies tend to align with background tidal field
  - Full sample: NLA model, Blue sample: fixed to zero
- *Baryonic feedback*: modelled using HMCode (calibrated against BAHAMAS hydro sims)
- Marginalize over *DES nuisance parameters* (photo-z's, calibration)



Impact of cosmology

Weak lensing is mostly sensitive to the amount of matter clustering

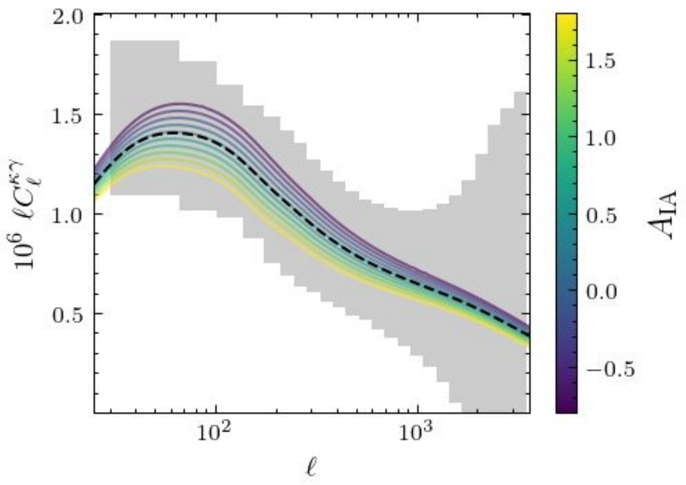


(Theory curves based on DES bin 4)

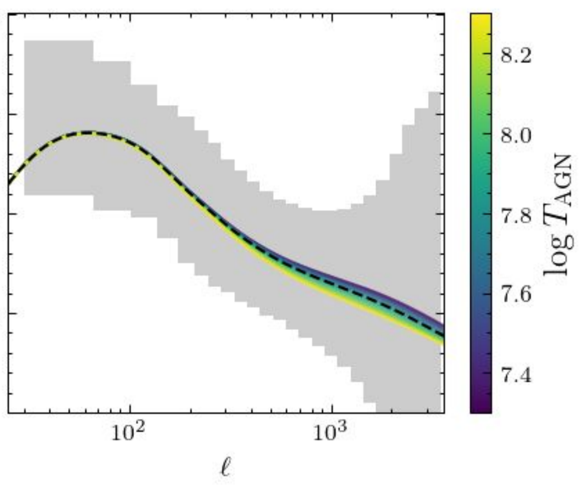
Lensing data is most sensitive to the parameter combination $S_8 = \sigma_8\sqrt{\Omega_m/0.3}$

Impact of astrophysics

Intrinsic alignment



Baryonic feedback



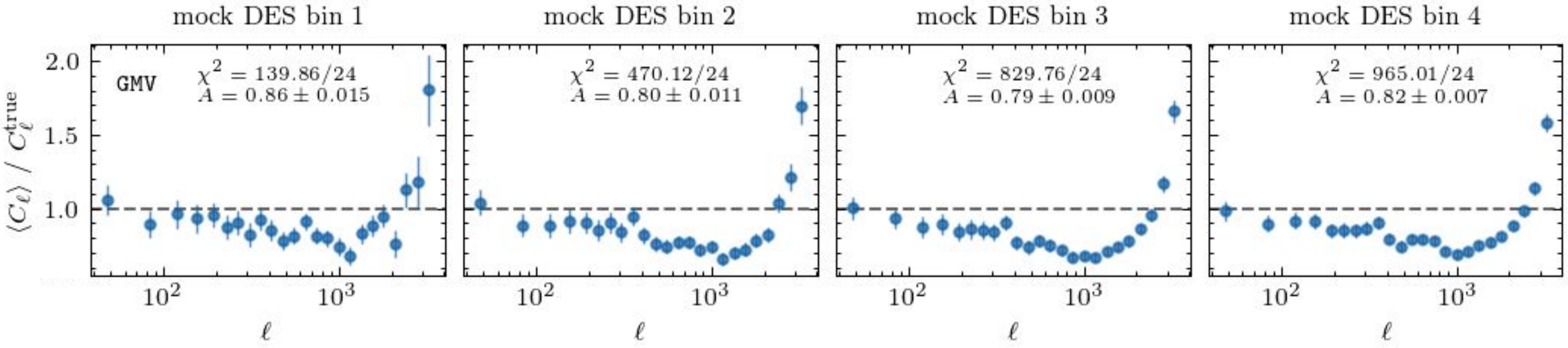
IA is anti-correlated with S_8, introduces significant theoretical uncertainty

Not very sensitive to strength of feedback due to large noise on small scales

Validation: bandpowers

Agora simulations (Omori, 2024) – full-sky realizations of CMB lensing, galaxy lensing, non-Gaussian foregrounds (CIB, tSZ, kSZ, radio), …

Check cross-correlations using mock lensing maps and noiseless shear catalogs (average over 10 x 1,500 deg^2 patches)



GMV: large bias across all scales, mainly due to tSZ bispectrum when x-correlating with low-z tracer

Validation: bandpowers

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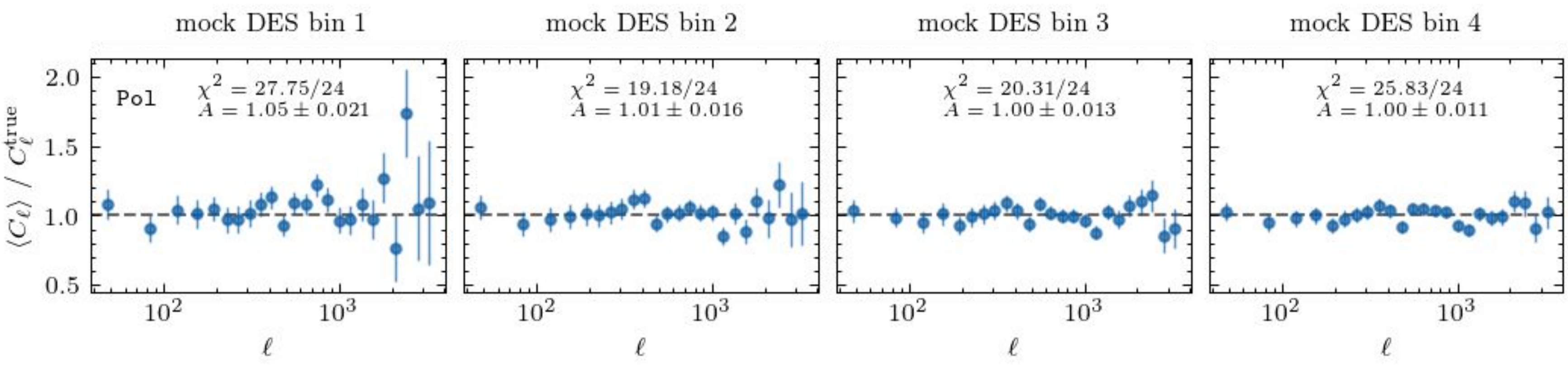


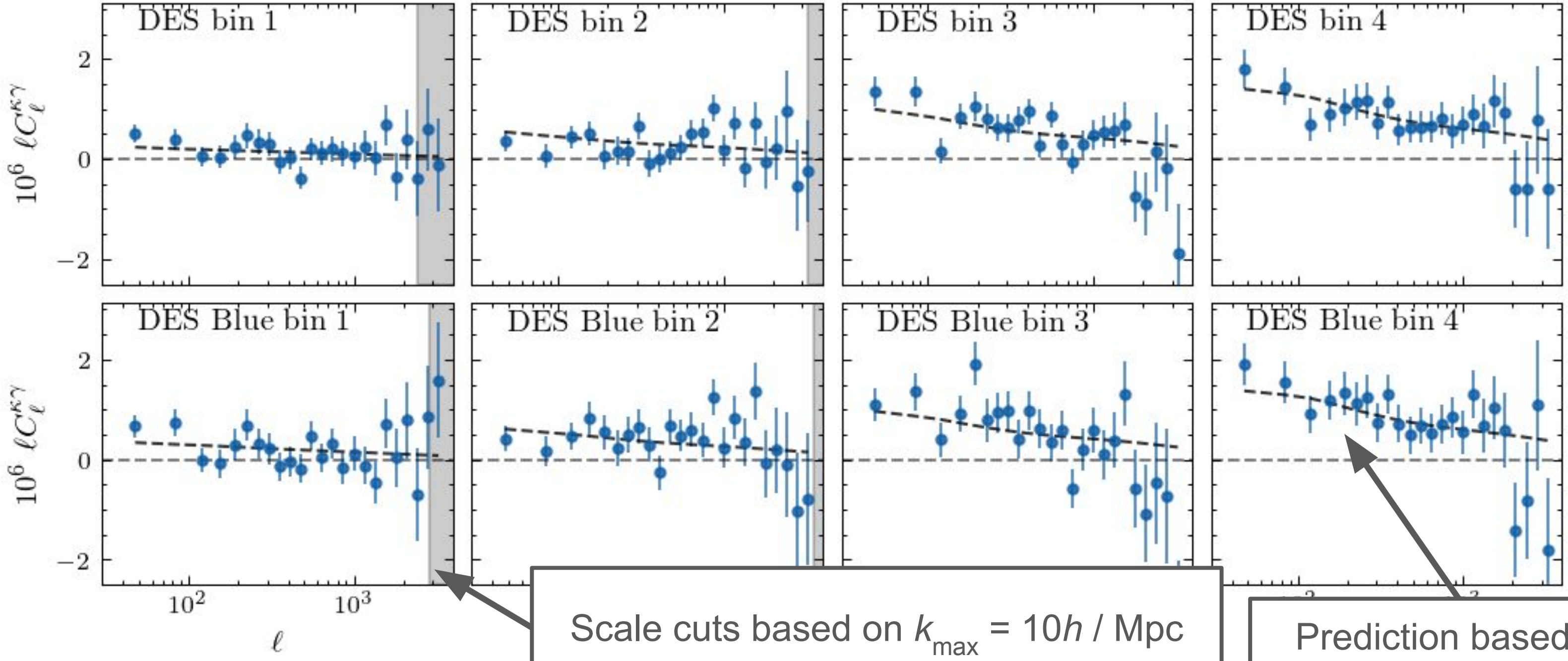
Pol: unbiased!

Similar results for **Prof**, **MH**, **xILC** (at most ~4% bias)

Preliminary Results

Measured cross-correlation

SPT-3G Pol-only lensing X DES Y3 cosmic shear:



Scale cuts based on k_{max} = 10h / Mpc

Prediction based on Planck 2018

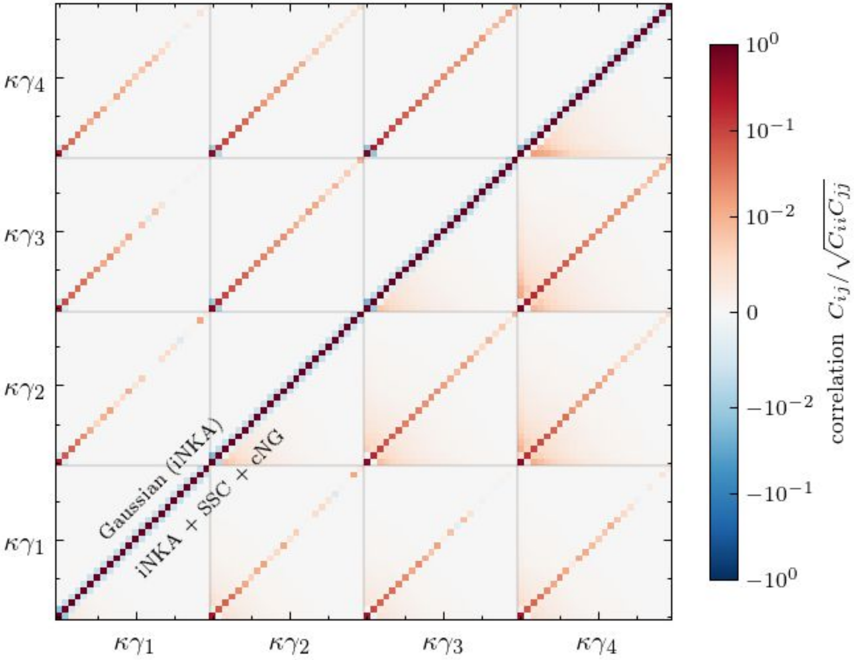
Data covariance

3 terms: $\mathrm{C} = \mathrm{C_G} + \mathrm{C_{SSC}} + \mathrm{C_{cNG}}$

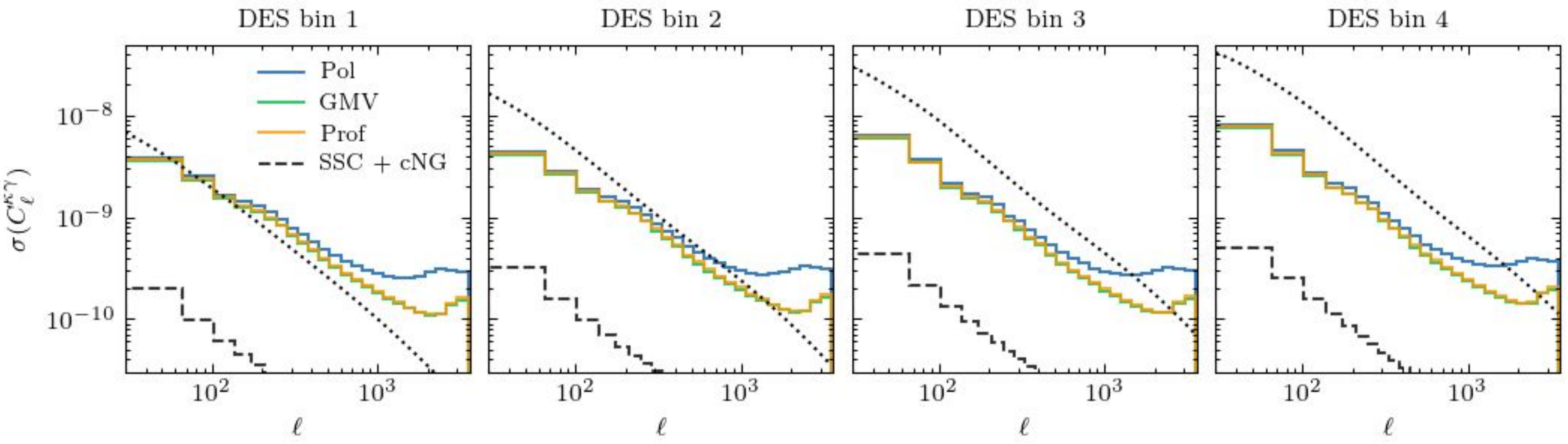
- **Gaussian:** assuming Gaussian fields, includes mode coupling from mask
- **Super-sample covariance:** non-Gaussian contribution from modes larger than mask
- **Connected non-Gaussian:** contribution from non-Gaussianity of LSS (matter trispectrum)

SSC and cNG terms calculated using a halo model approximation

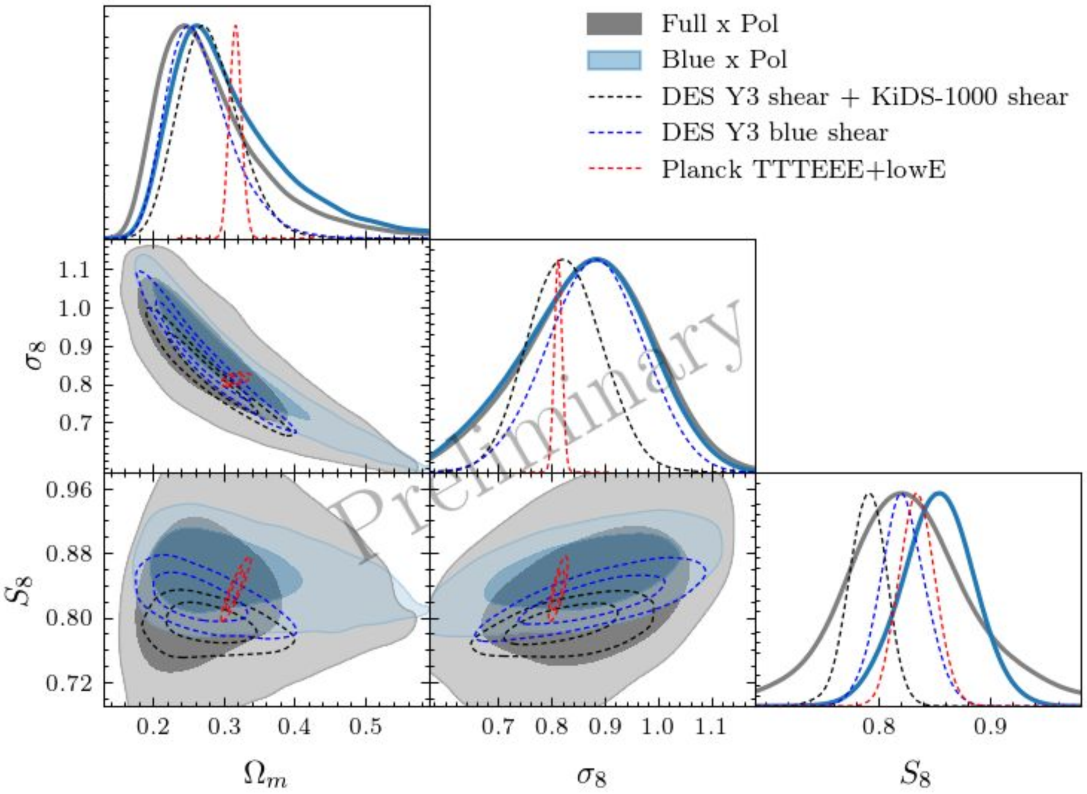
[Garcia-Garcia+ 2019, Takada & Hu 2013, Takada & Jain 2014]



S/N comparison



Preliminary results: cosmology



See: DES + KiDS collaborations, 2023 and McCullough et al., 2024

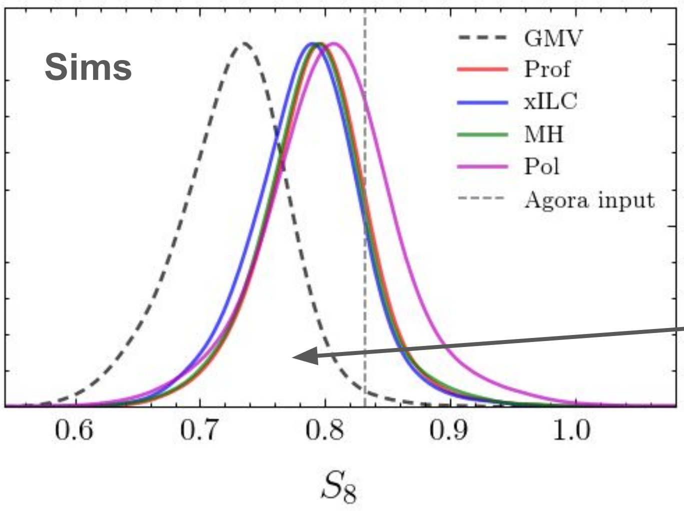
Results are consistent with both shear auto-correlations and the primary CMB

Constraint on S_8 can be significantly improved (**2x tighter)** by reducing IA uncertainty

Blue x Pol: ~4% constraint on S_8

Comparison of foreground mitigation techniques

Adding CMB temperature information increases S/N on small scales, but need to worry about foregrounds



Ideally, model this bias with priors from measurements of the Sunyaev-Zeldovich effects

[ex: Baleato Lizancos+ 2025]

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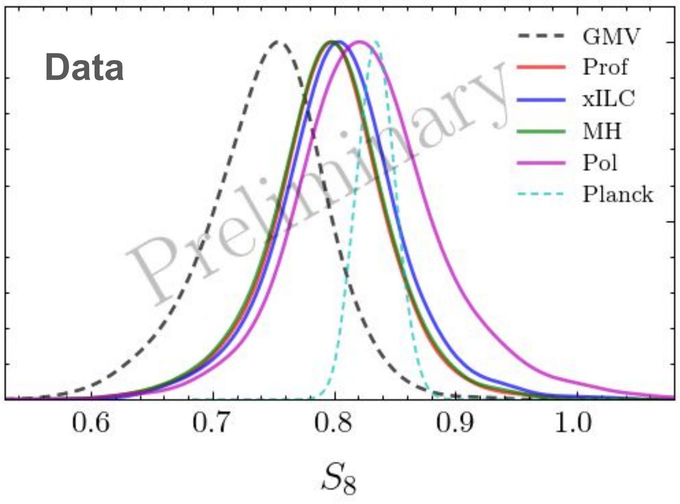
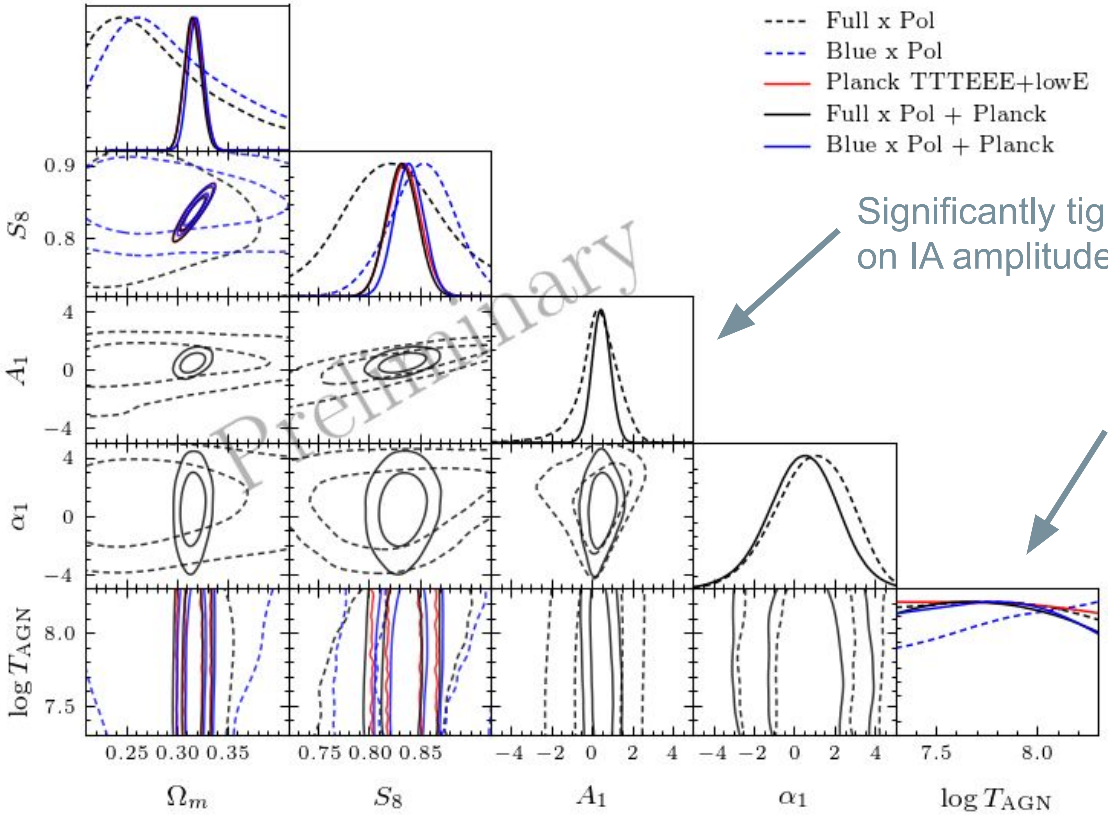


Consistency relative to *Planck*:

- **GMV: 1.7σ**
- Prof: 0.7σ
- MH: 0.5σ
- xILC: 0.7σ
- **Pol: 0.1σ**

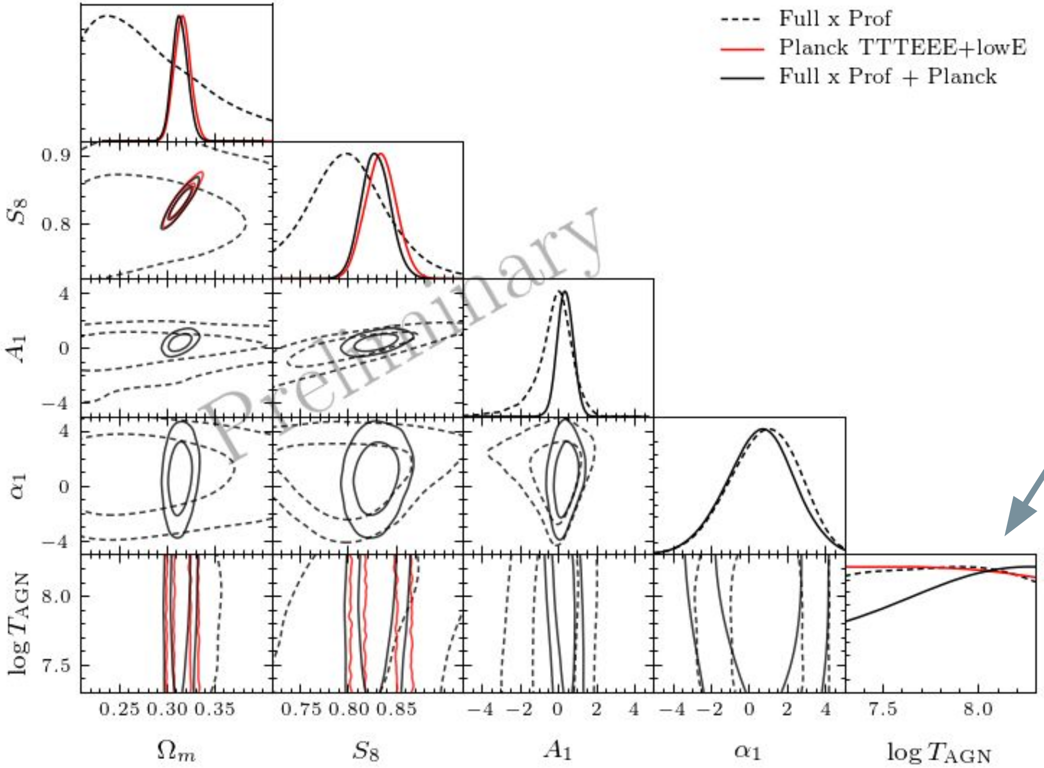
Combining with Planck: IA and feedback



Significantly tighter constraints on IA amplitude $A_{\rm IA} = 0.48 \pm 0.45$

Pol-only lensing map is too noisy on small scales to constrain baryonic feedback

Combining with Planck: IA and feedback



Including temperature information, but mitigating foregrounds with profile-hardening

Hints of a suppression of small-scale power

$$\log T_{\rm AGN} > 7.70 \quad \text{(at 68\% C.L.)}$$

Still in progress…

- Working on including shear auto-correlations (2x2-pt analysis: $\kappa\gamma$ + $\gamma\gamma$)
  - Using harmonic space ($C_\ell^{\gamma\gamma}$) rather than usual real space ($\xi_\pm(\theta)$)
  - Validating measurement on small-scales

- Galaxy clustering and cross-correlations
  - Provides more precise redshift slicing, but complicated by galaxy bias

6x2-pt analysis ($\kappa\gamma$ + $\gamma\gamma$ + κg + γg + gg + $\kappa\kappa$): test of structure growth across cosmic time, consistency tests, and astrophysical constraints

Main difficulty: accurate and consistent modeling

[Abbot+ 2023, Xu+ 2023, Xu+ 2025]

Future Prospects

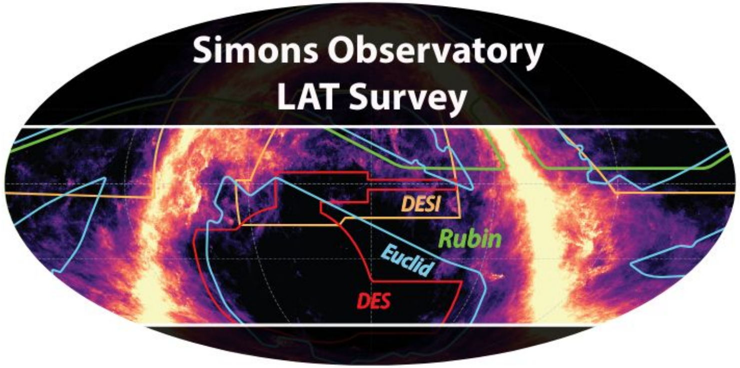
To improve measurement: deeper cosmic shear, lower noise CMB lensing, wider sky area

Immediate future: DES Y6 will provide ~50% more galaxies and better systematics

Expect significant improvement with next-gen shear surveys (LSST, *Euclid*, *Roman*) – great synergy with lensing from Simons Observatory

CMB lensing + cosmic shear will provide a powerful way to directly probe the matter power spectrum over cosmic time

If modeling can keep up with data!



Abitbol et al, 2025

Summary

- First high-significance measurement (~13σ) of lensing-shear cross-correlation using a polarization-only lensing map
    - Highlights the power of low-noise CMB polarization observations
    - Including CMB *T* information helps with S/N on small scales, but need to worry about foregrounds
    - Using a blue shear sample significantly reduces modeling uncertainty
    - **Paper coming soon!**
- Lots of future potential for cross-correlations between SO, LSST, *Euclid*, DESI, … !

Working towards testing **structure growth** and disentangling **astrophysical uncertainties**

Thank You!

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