UNIVERSITY OF CAMBRIDGE

unWISE galaxies x CMB Lensing

new results from unWISE x Planck Lensing and towards unWISE x ACT DR6 Lensing

Gerrit S. Farren

Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge, UK

work with Alex Krolewski, Blake Sherwin, Simone Ferraro, Niall MacCrann, Frank Qu and others

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Intro

What we plan to do

- Measure S_8 using galaxy - CMB lensing cross-correlations

What data we are using

- using unWISE catalog
- CMB lensing reconstructions from Planck and (soon) from ACT

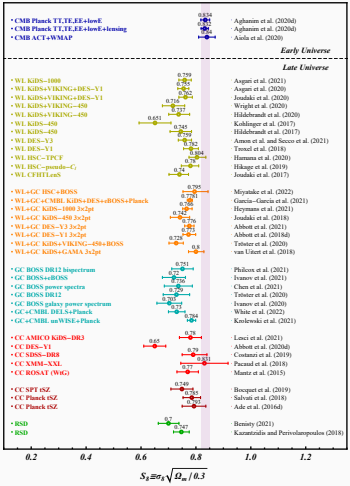
Why this is interesting

- long standing S_8 tension
- previously unWISE$\times$Planck lensing found low S_8 (Krolewski *et al.*, 2021)

How we are doing it

- model C_ℓ^{gg} and $C_\ell^{\kappa g}$ to break b_g-σ_8 degeneracy

S_8 tension

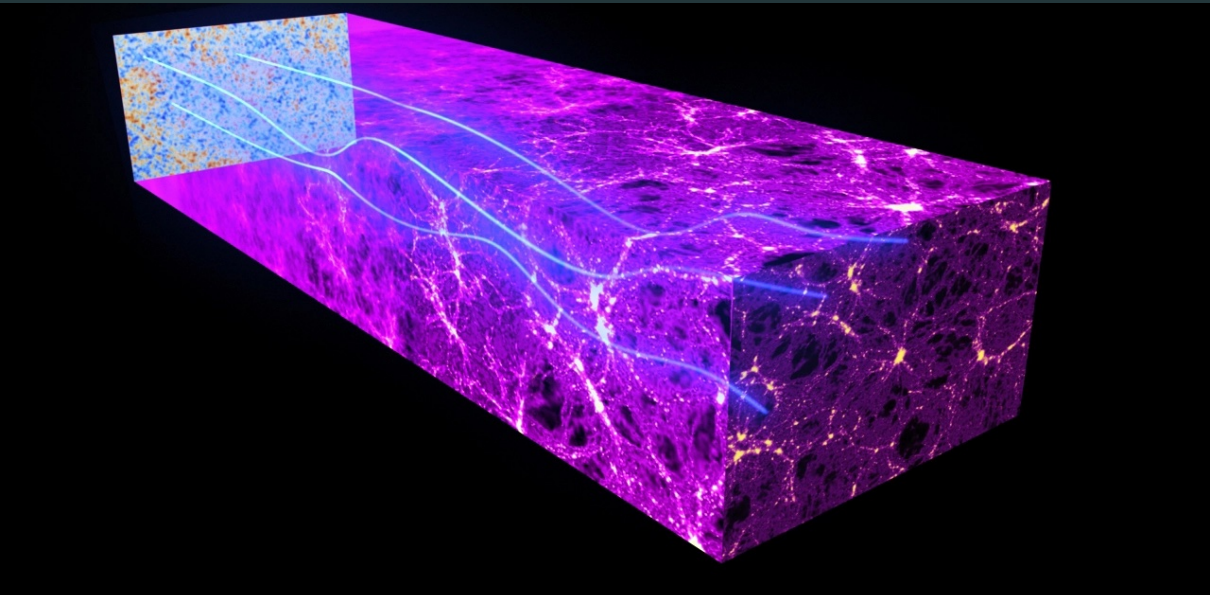


Two possible resolutions?

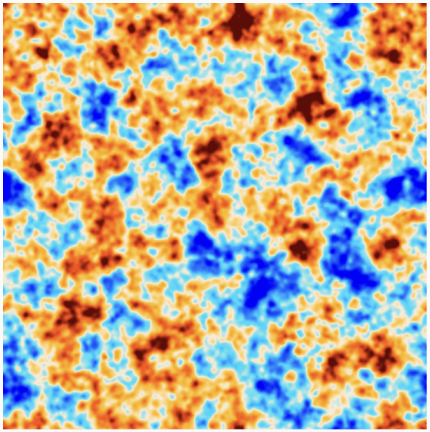
- scale dependent suppression of power
  - non-linear structure growth
  - (stronger than expected) baryon feedback
  - ...
- redshift dependent suppression of power
  - dark energy evolution
  - ....

Image Credit: Abdalla *et al.* (2022)

Introduction to CMB lensing



The effect of CMB lensing

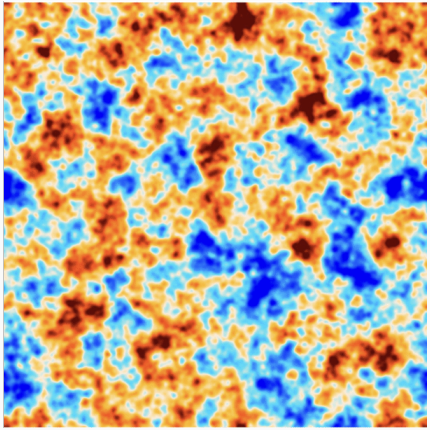


- observed field = unlensed field evaluated at a different position

$$\tilde{\Theta}(\boldsymbol{x}) = \Theta_0(\hat{\boldsymbol{n}} + \boldsymbol{\nabla}\phi)$$

- small-scale ($\mathcal{O}$(arc-minute)) deflections described by a deflection potential ϕ
- coherent over larger, $\mathcal{O}(\mathrm{degree})$, scales
- lensing convergence $\kappa = -\frac{1}{2}\boldsymbol{\nabla}^2\phi$
- $\phi \sim \int_0^{\chi_\star} W_\phi(\chi)\delta_m(\hat{\boldsymbol{n}}\chi)d\chi$

The effect of CMB lensing



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CMB lensing reconstruction

- the unlensed CMB is statistically isotropic

$$\langle \Theta_0(\boldsymbol{l})\Theta_0(\boldsymbol{l}-\boldsymbol{L})\rangle = \delta(\boldsymbol{L})C_L$$

- lensing breaks isotropy and couples different modes

$$\langle \tilde{\Theta}(\boldsymbol{l})\tilde{\Theta}(\boldsymbol{l}-\boldsymbol{L})\rangle - \delta(\boldsymbol{L})C_L \sim \phi(\boldsymbol{L})$$

- estimate lensing signal from off-diagonal correlations

$$\hat{\phi}(\boldsymbol{L}) \sim \int d^2\boldsymbol{l}\tilde{\Theta}(\boldsymbol{l})\tilde{\Theta}(\boldsymbol{l}-\boldsymbol{L})$$

- using quadratic estimators

Planck lensing reconstruction

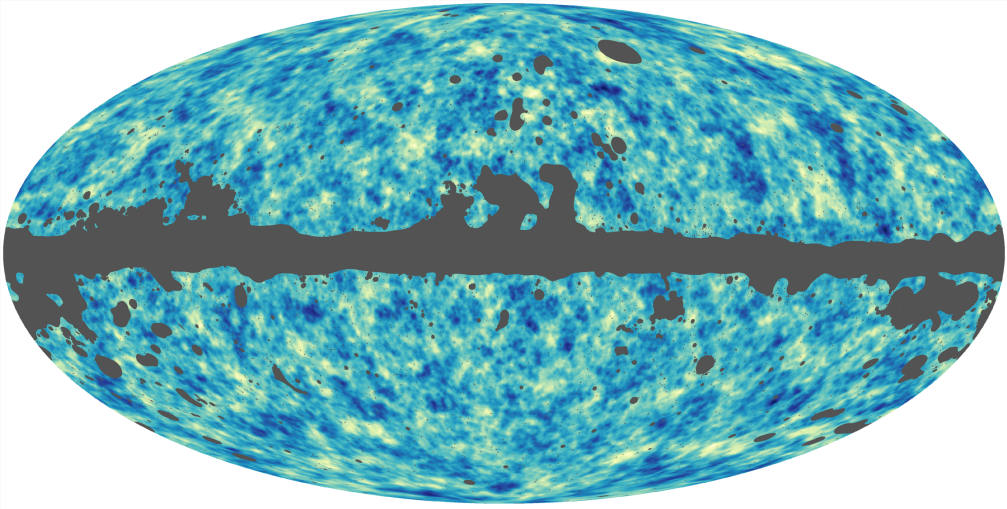


Image Credit: Planck Collaboration *et al.* (2020)

Planck lensing power

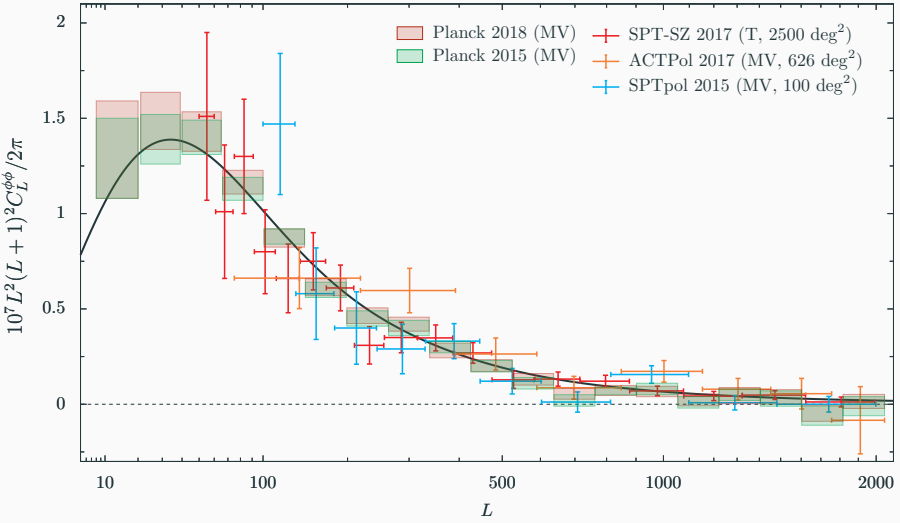
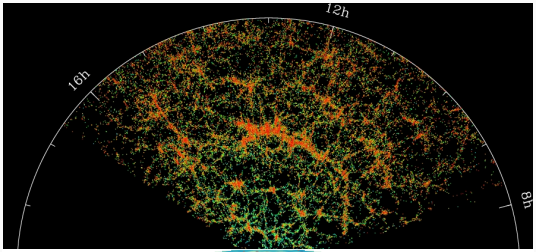
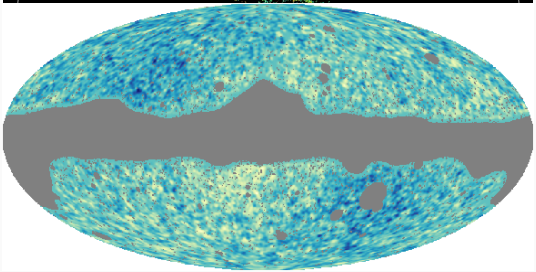
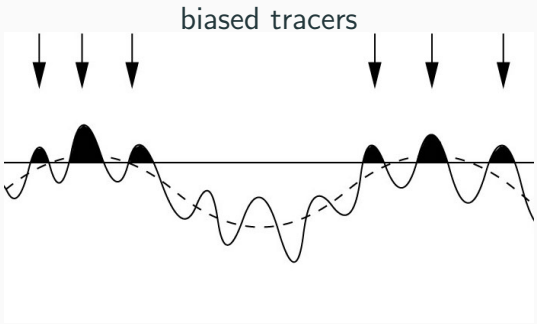


Image Credit: Planck Collaboration *et al.* (2020)

Galaxy clustering



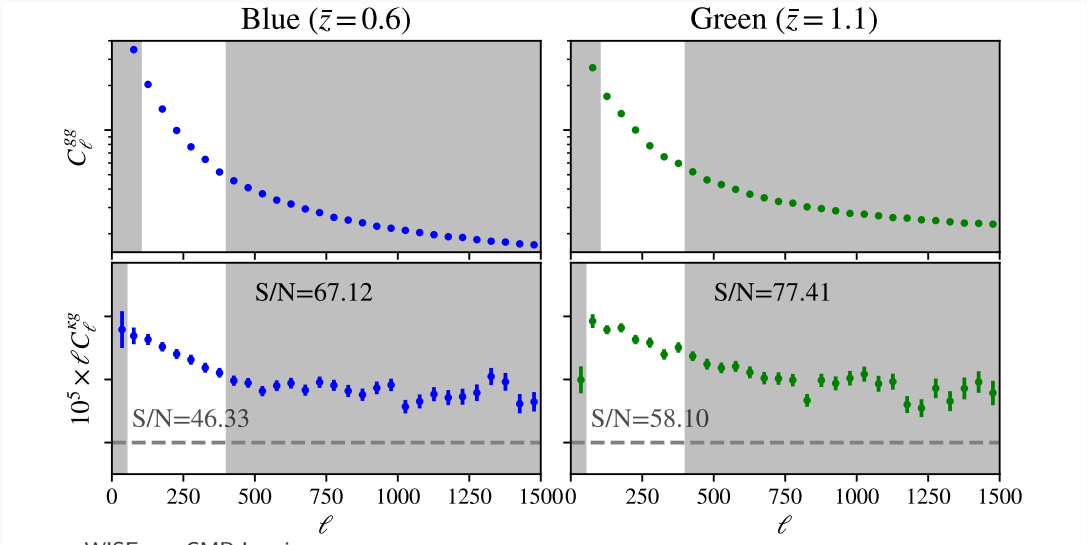




$$\delta_g \sim b_g \delta_m$$

Image Credit: SDSS Survey + Peacock (2003)

The cross-correlation

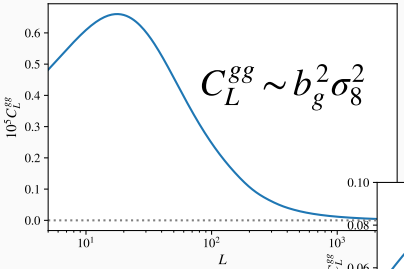


Measuring S_8 with galaxy - CMB lensing cross-correlations

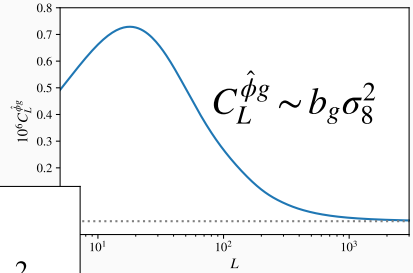
interested in

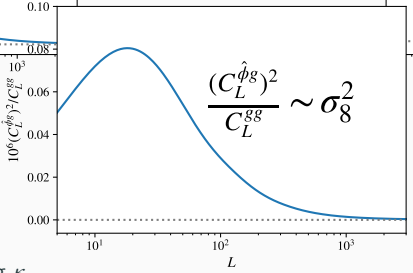
$\sigma_8^2 \sim \langle \delta_m^2 \rangle$

from galaxies

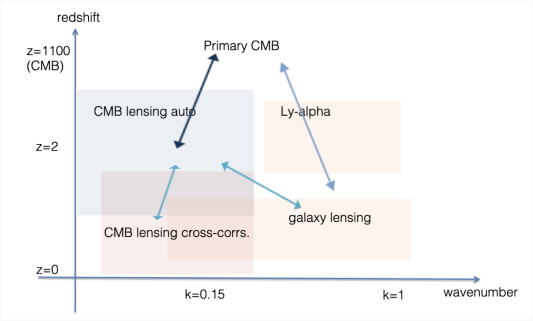


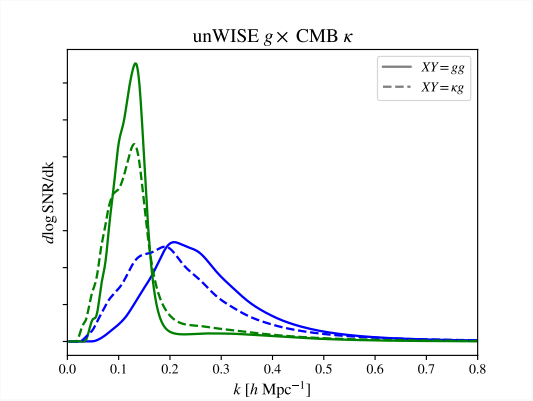
from galaxies × lensing





Complementary probes of large scale structure

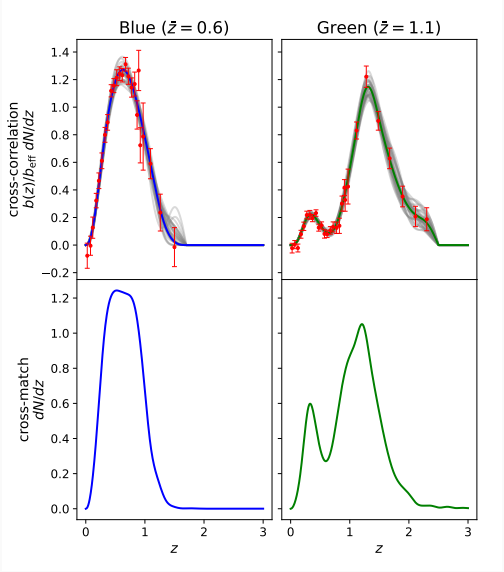




The unWISE samples

- galaxies from the WISE survey
- including 2 years of post-cryogenic observations (at 3.4 and 4.6 μm)
- $>$500 million galaxies
- $0 \lesssim z \lesssim 2$
- color selection for two samples

sample	$\bar{z}$	$\bar{n}$
Blue	0.6	$\sim$3400
Green	1.1	$\sim$1800



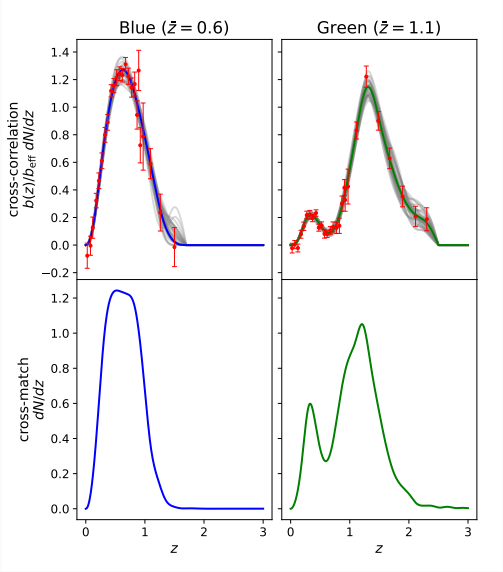
Redshifts for unWISE

dN/dz from ...

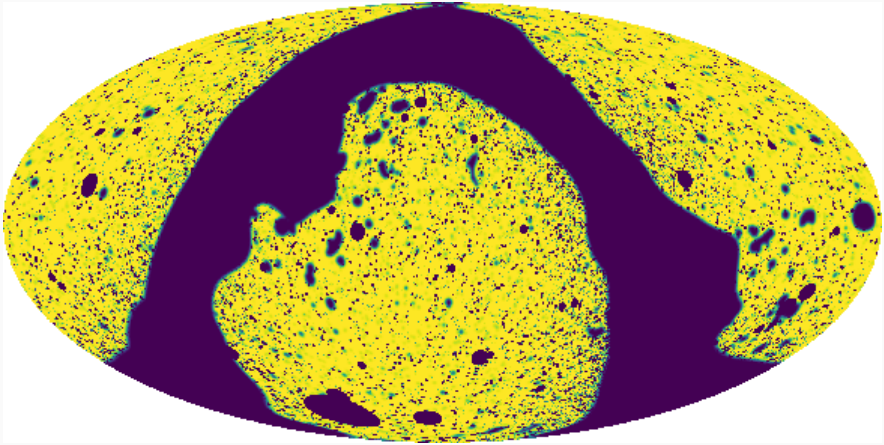
- cross-correlating with spectroscopic surveys (BOSS, eBOSS)

$$b_{\text{photo.}}\widehat{\frac{dN_{\text{photo.}}}{dz}} \propto \frac{w^{\text{spec.}\times\text{photo.}}(z)}{\sqrt{w^{\text{spec.}\times\text{spec.}}(z)}}$$

- cross matching with photometric redshifts on smaller field (COSMOS)

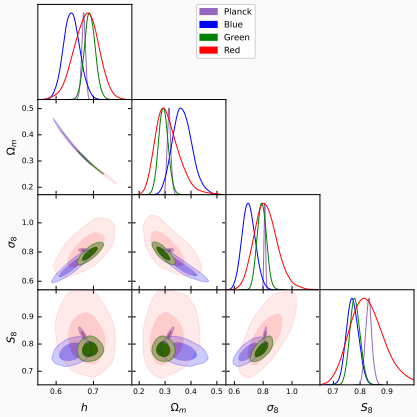


Sky-coverage - unWISE



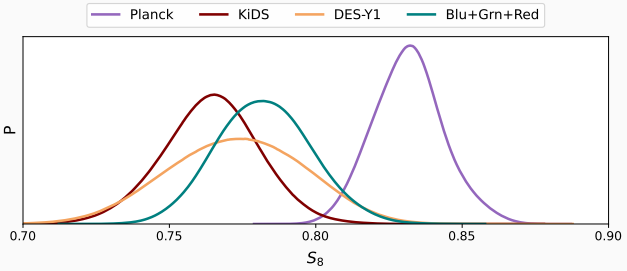
$f_{\rm sky} \simeq 0.59$

Previous work on Planck lensing x unWISE



Spectra: Krolewski *et al.* (2020)

Cosmology analysis: Krolewski *et al.* (2021)



$$S_8 = 0.782 \pm 0.015$$

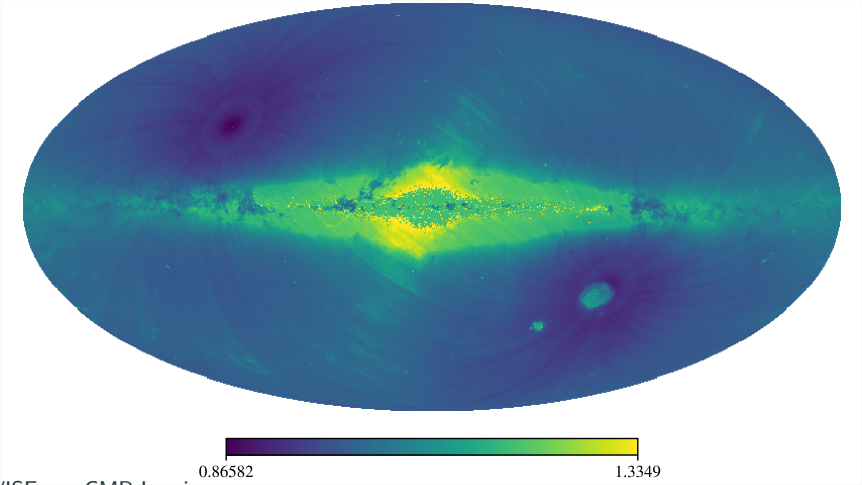
$$\implies \sim 2.4\sigma \text{ tension with Planck 2pt}$$

What's new?

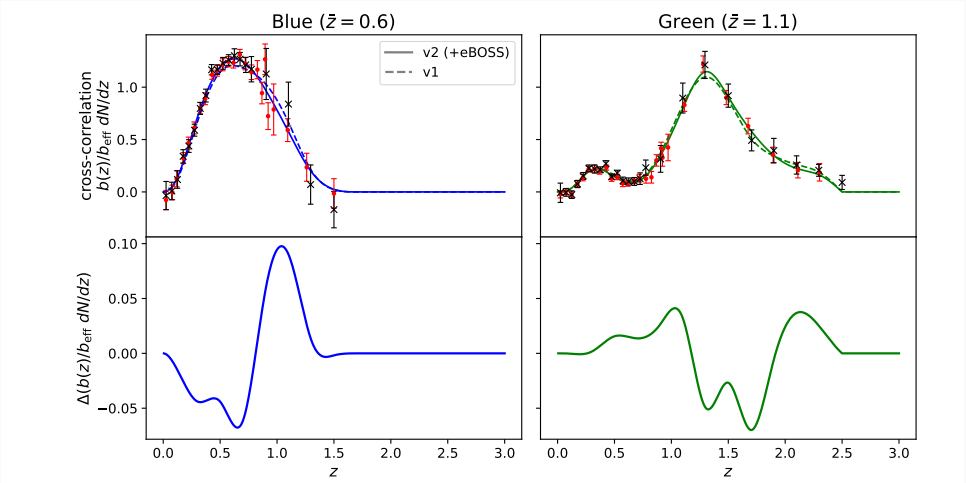
- Systematics weighting for galaxy samples
- Additional spectroscopic data from eBOSS for cross-correlation redshifts
- PCA based marginalisation over dN/dz uncertainties
- Correction for fiducial cosmology assumed in cross-correlation redshifts
- Modelling improvements: marginalisation over higher order biases and consistent treatment of massive neutrinos
- Inclusion of monte-carlo norm correction for Planck lensing reconstruction
- Use of improved Planck PR4 (NPIPE) lensing reconstruction

Systematics weighting

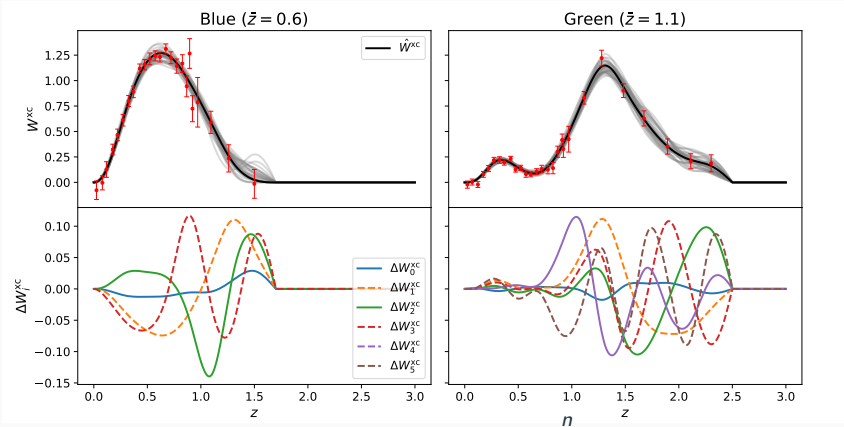
piecewise linear trends for **survey depth** and **stellar density**



Additional spectroscopic data from eBOSS

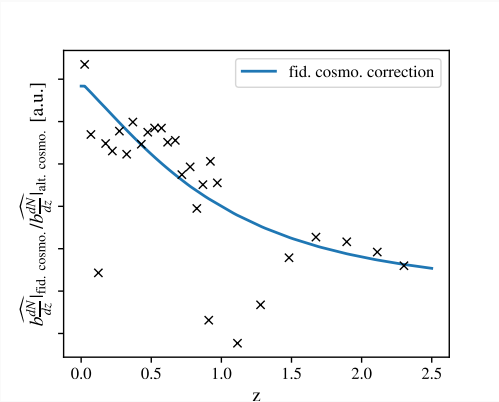


PCA based dN/dz marginalisation



$$W^{\rm xc}(z) = \hat{W}^{\rm xc}(z) + \Delta W_0^{\rm xc}(z) + \sum_{i=1}^{n} c_i \Delta W_i^{\rm xc}(z)$$

Correcting fid. cosmo. dependence of cross-correlation redshifts



- assume fid. cosmo. to measure cross-correlation redshifts
- marginalise over amplitude of $\widehat{b\frac{dN}{dz}}$
- need to correct z-dependent fid. cosmo. dependence

$$\widehat{b\frac{dN}{dz}} = \widehat{b\frac{dN}{dz}}\bigg|_{\text{fid. cosmo.}} \frac{\mathcal{C}(z)}{\mathcal{C}(z)|_{\text{fid. cosmo.}}}$$

$$\mathcal{C}(z) = \left[\Delta z H(z) \int k dk P_{gg}(k,z) W(k,z)\right]^{-1/2}$$

Model

- Limber approximation for C_ℓ^{gg} and $C_\ell^{\kappa g}$
- including lensing magnification
- Power spectrum model: Hybrid Halofit + LPT (like Krolewski *et al.*, 2021)

$$\begin{aligned} P_{gg}(k,z) &= b_{1,E}^2(z)P_{mm,\mathrm{HF}} + b_{2,L}(z)P_{b_2}(k,z) + b_{s,L}(z)P_{b_s}(k,z) \\ &\quad + b_{1,L}(z)b_{2,L}(z)P_{b_1 b_2}(k,z) + \cdots + P_{\text{shot noise}} \\ P_{gm}(k,z) &= b_{1,E}(z)P_{mm,\mathrm{HF}} + \frac{b_{2,L}(z)}{2}P_{b_2}(k,z) + \frac{b_{s,L}(z)}{2}P_{b_s}(k,z) \\ P_{mm}(k,z) &= P_{mm,\mathrm{HF}}(k,z). \end{aligned}$$

- higher order biases set by co-evolution relations + free offset (co-evolution and priors from simulations)

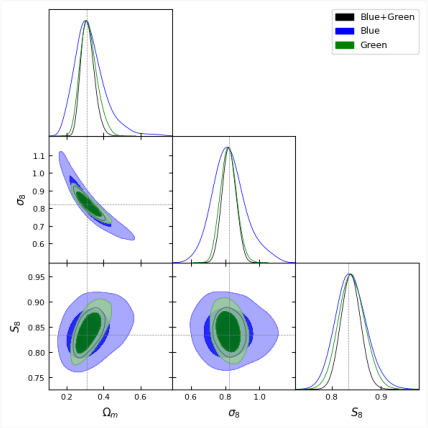
$$b_{X,L} = b_{X,L}^{\mathrm{co-evol.}}(b_{1,E}^{\mathrm{fid}}(z)) + c_{b_{X,L}}^{\mathrm{offset}}$$

Model (massive neutrinos)

account for non-clustering neutrinos by using (following Chen *et al.*, 2022)

- P_{gg}: ν-free power spectrum, $\langle \delta_{cb} \delta_{cb} \rangle$
- P_{mm}: power spectrum including neutrinos, $\langle \delta_m \delta_m \rangle$
- P_{mg}: cross power spectrum between total matter (including neutrinos) and non-relativistic matter (baryons and dark matter only), $\langle \delta_m \delta_{cb} \rangle$

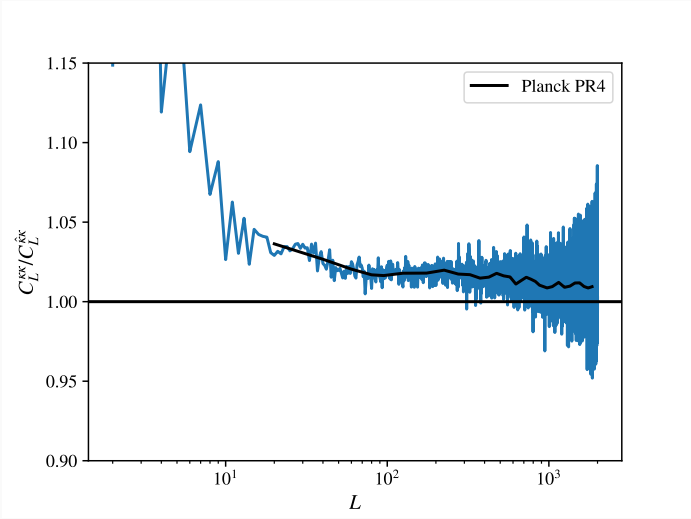
Model verification



- N-body sims populated with HOD tuned to reproduce unWISE samples (from Krolewski *et al.*, 2021)
- allow offset in $b_{2,L}$ and $b_{s,L}$ with priors $\mathcal{N}(\mu_c^{\text{fixed cosmo}}, \left|\mu_c^{\text{fixed cosmo}}\right|)$

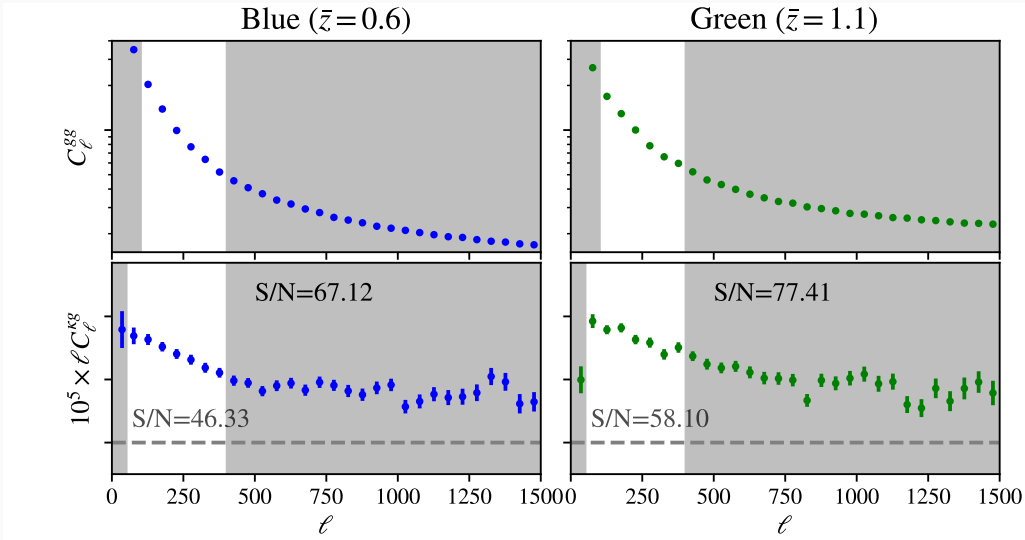
	$\Delta\Omega_m/\sigma_{\Omega_m}$	$\Delta\sigma_8/\sigma_{\sigma_8}$	$\Delta S_8/\sigma_{S_8}$
Blue	0.21	0.02	0.17
Green	0.24	-0.06	0.25
Joined	0.15	0.02	0.22

Monte-carlo lensing norm correction



$$A^{\kappa}_{\rm MC} = \frac{\langle \kappa_{\rm input} \times \kappa_{\rm input} \rangle}{\langle \hat{\kappa}_{\rm recon.} \times \kappa_{\rm input} \rangle}$$

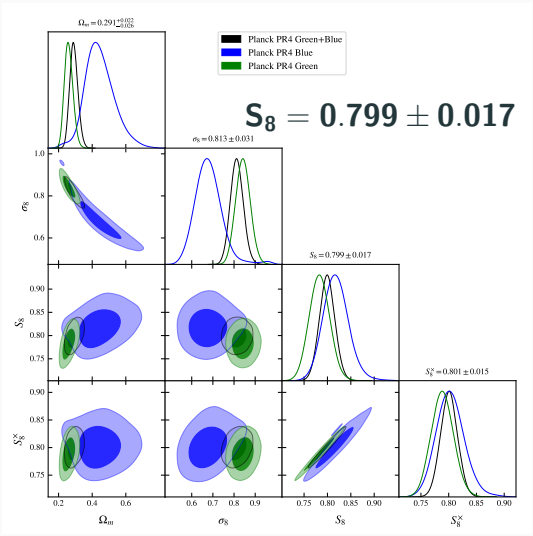
Improved Planck PR4 (NPIPE) lensing reconstruction

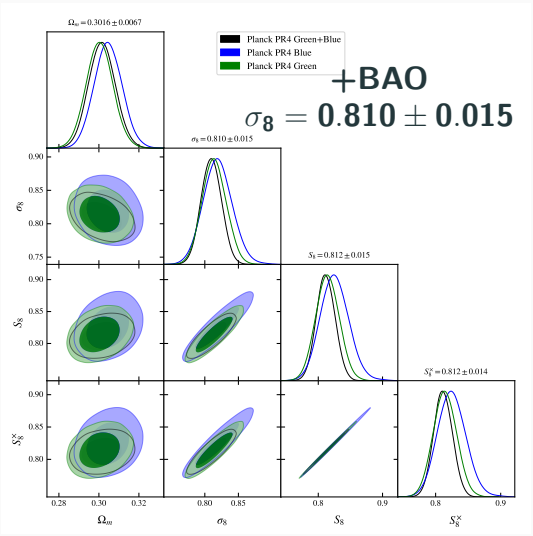


Summary of changes and their impact

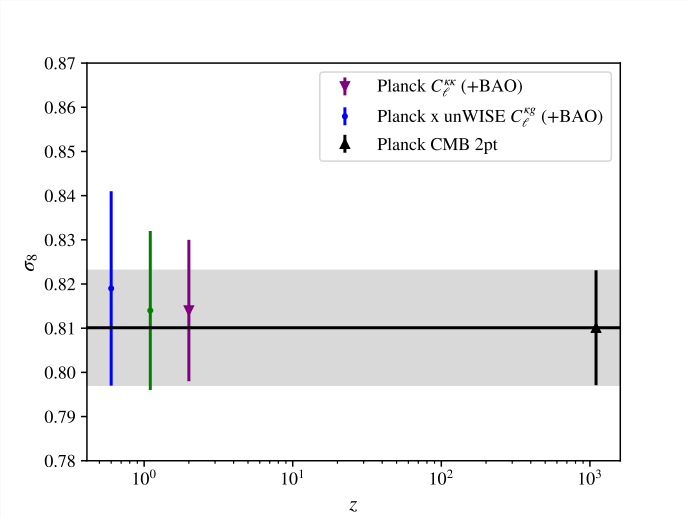
	Impact on S_8
Systematics weighting	$\uparrow \sim 0.5\sigma$
Additional spectroscopic data	$\uparrow \sim 0.6\sigma$
PCA based dN/dz marginalisation	$\sim$10-15% wider posteriors
fid. cosmo. correction	$\sim$5% wider posteriors + change in degeneracy directions
modelling improvements	$\downarrow \sim 0.9\sigma$
monte-carlo lensing norm correction	$\uparrow \sim 0.9\sigma$
use of Planck PR4 lensing reconstruction	$\downarrow \sim 0.1\sigma$
Total	$\uparrow \sim \mathbf{1.0\sigma} + \sim$**15% wider posteriors**

Re-analysis of unWISE x Planck lensing

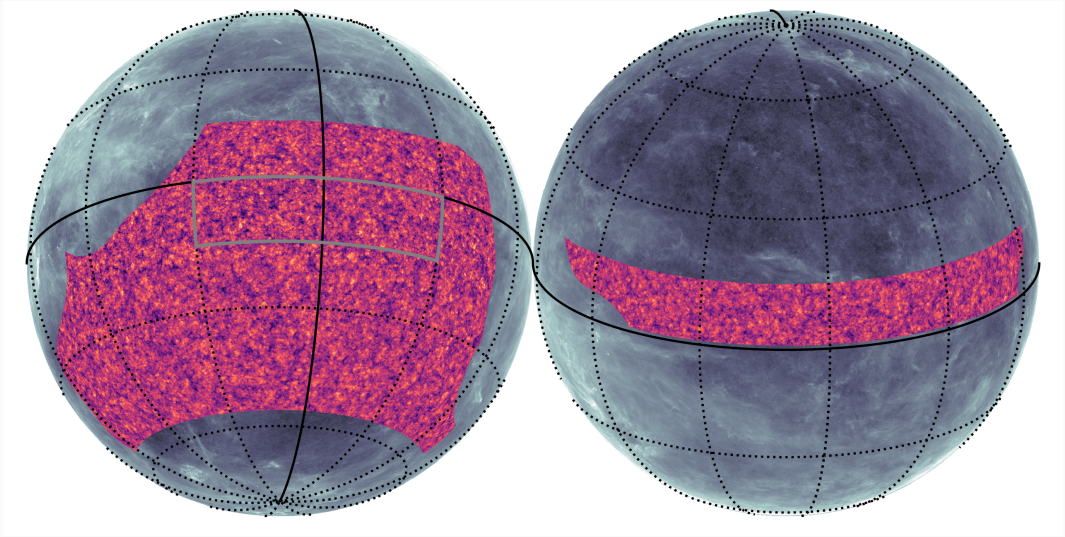




$\sigma_8(z)$ from unWISE x Planck lensing (+BAO)

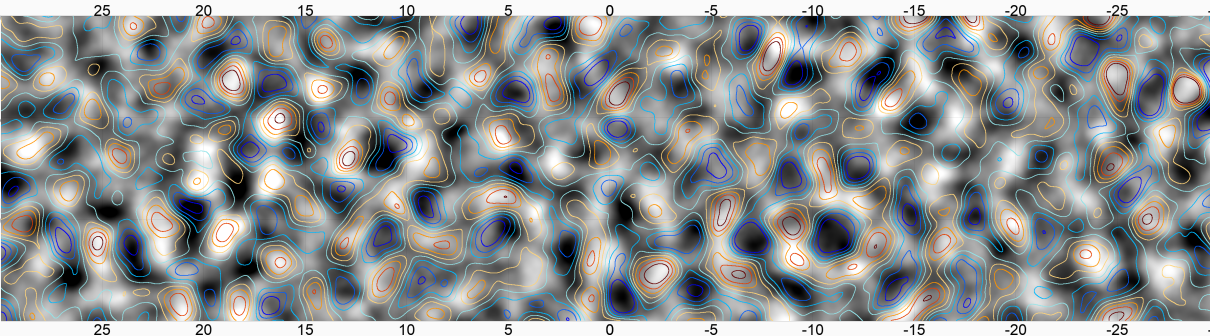


ACT lensing reconstruction



ACT lensing reconstruction

work by Frank Qu, Niall MacCrann, Dongwon 'DW' Han (Cambridge), Mat Madhavacheril (UPenn) and others



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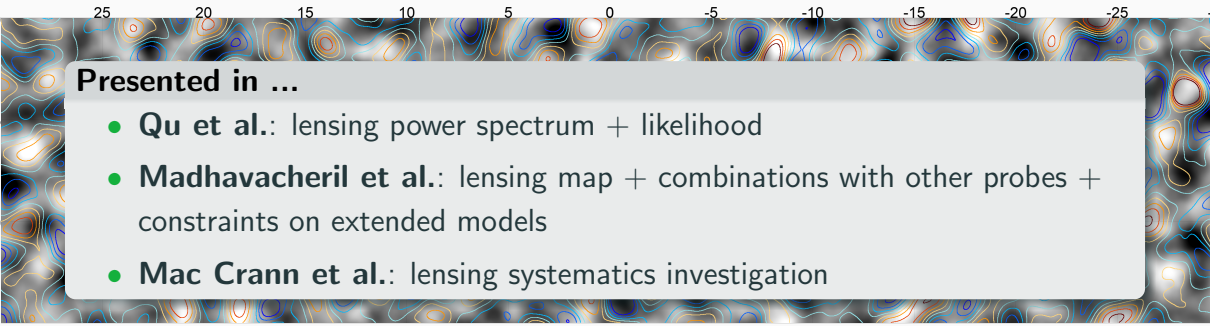
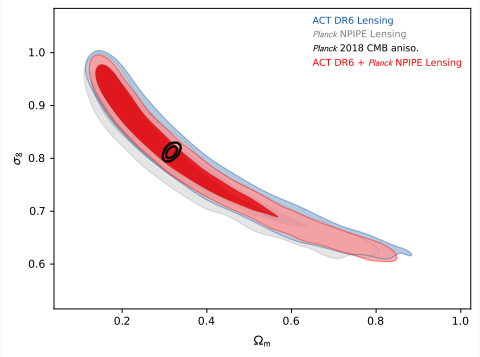


Presented in ...

- **Qu et al.**: lensing power spectrum + likelihood
- **Madhavacheril et al.**: lensing map + combinations with other probes + constraints on extended models
- **Mac Crann et al.**: lensing systematics investigation

ACT DR6 lensing auto-spectrum results



Best constrained parameter

$$S_8^{\mathrm{CMBL}} = \sigma_8 \left(\frac{\Omega_m}{0.3}\right)^{0.25}$$

ACT DR6 Lensing

$$\mathbf{S_8^{CMBL} = 0.818 \pm 0.022}$$

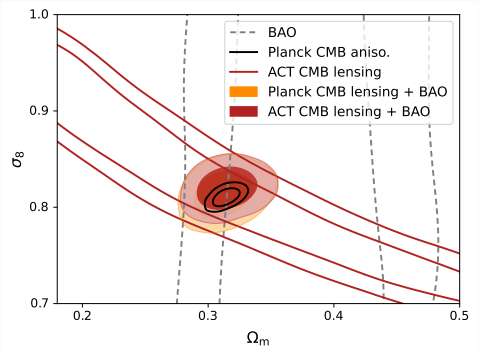
ACT DR6 + Planck PR4 Lensing

$$S_8^{\mathrm{CMBL}} = 0.813 \pm 0.018$$

Planck 2018 CMB aniso.

$$S_8^{\mathrm{CMBL}} = 0.823 \pm 0.011$$

ACT DR6 lensing auto-spectrum results



ACT DR6 Lensing + BAO

$\sigma_8 = 0.819 \pm 0.015$

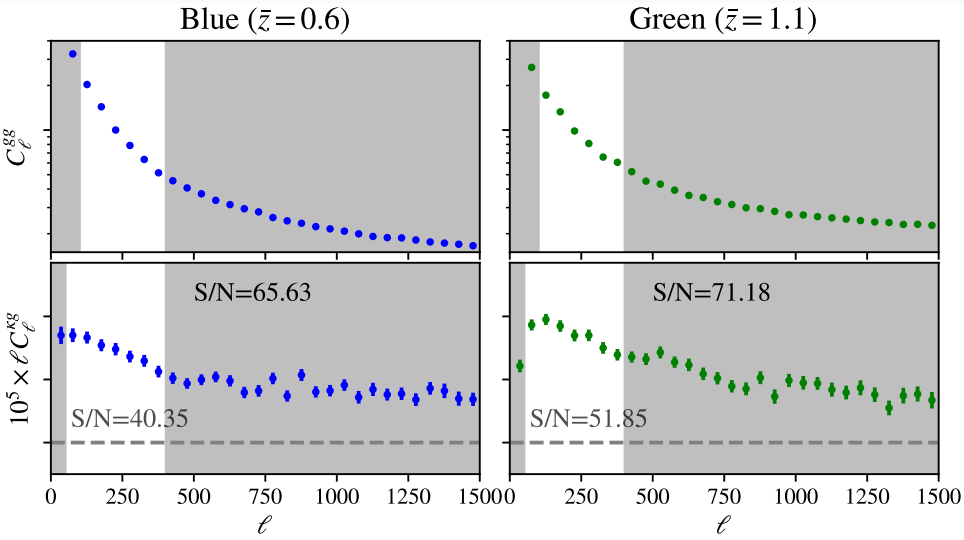
ACT DR6 + Planck PR4 Lensing

$\sigma_8 = 0.812 \pm 0.013$

Planck 2018 CMB aniso.

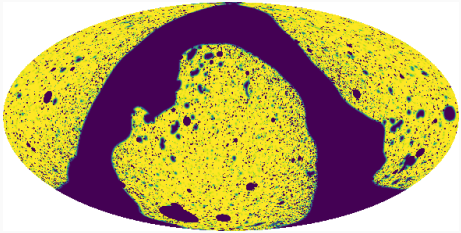
$\sigma_8 = 0.811 \pm 0.006$

cross-spectra unWISE x ACT DR6 lensing



Sky-coverage - unWISE x ACT

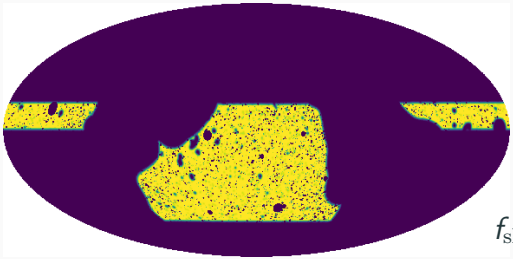
unWISE



$f_{\rm sky} \simeq 0.59$

ACT lensing

$f_{\rm sky} \simeq 0.23$



$f_{\rm sky} \simeq 0.20$

Blinding

We perform our analysis fully blinded!

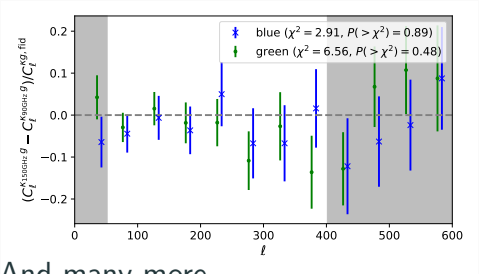
Before unblinding our cosmological constraints we...

- perform $\mathcal{O}(100)$ bandpower and map level null-tests for $C_\ell^{\kappa g}$ and C_ℓ^{gg}
- estimate (extragalactic) foreground biases from realistic simulations
- verify our model on N-body simulations
- perform a series of blind parameter consistency test examining different data cuts and analysis choices
- freeze all baseline priors and scale cuts

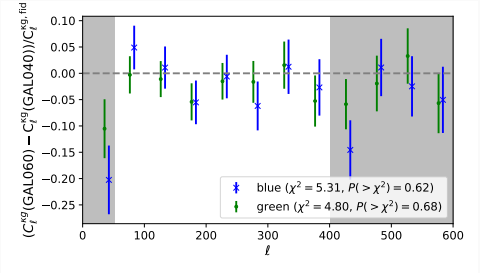
Testing for systematic contamination

Data Null-tests

frequency comparison



galactic mask comparison

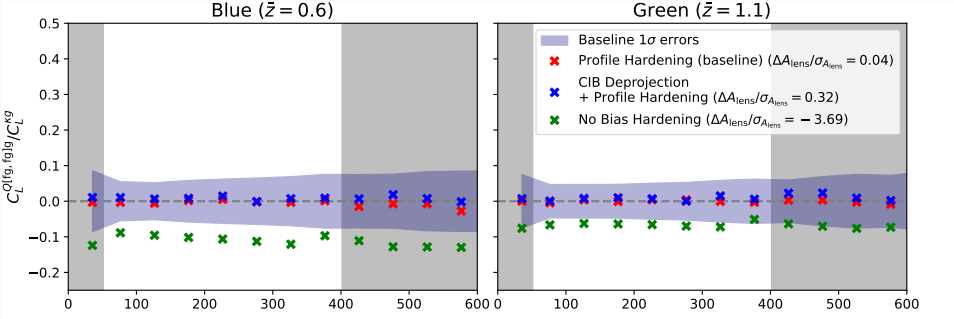


And many more ...

- different reconstruction and bias mitigation strategies (using CMB temperature/polarisation only, deprojecting CIB contamination, ...)
- various different masks (northern vs southern galactic cap, low vs higher ecliptic latitude, ...)

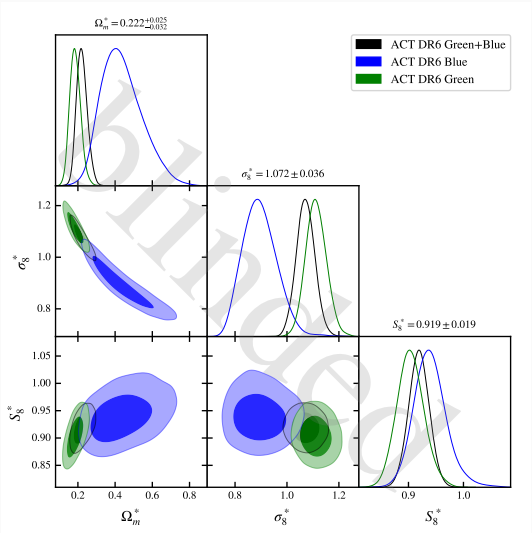
Testing for systematic contamination (continued)

Tests on simulations



- extragalactic foreground maps from WEBSKY simulations
- galaxy sample generated using unWISE HOD on WEBSKY halo catalog
- measure lensing signal induced by foregrounds

Stay tuned for unWISE x ACT DR6 lensing cosmology

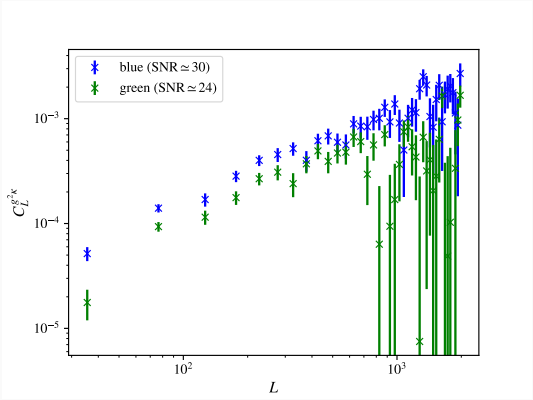


- comparable precision to Planck
- have recently unblinded
- results are forthcoming

Looking further ahead

- will combined with other probes (including $C_\ell^{\kappa\kappa}$ and $C_\ell^{TT}+C_\ell^{TE}$, etc)
- probe extended models beyond vanilla ΛCDM (e.g. $\sum m_\nu$)
- will get further improved redshifts with DESI
- improved modelling using simulation derived emulators (e.g. Hybrid EFT; see DeRose *et al.* (2023))
- pushing to smaller scales
- (eventually) Simons Observatory Lensing $\times$ e.g. LSST

Aside: Detected $gg\kappa$-bispectrum



Very preliminary!

- use small scales and halo model to constrain HOD parameter
- use large scales and LPT model to constrain higher order biases

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