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 (primarily) 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

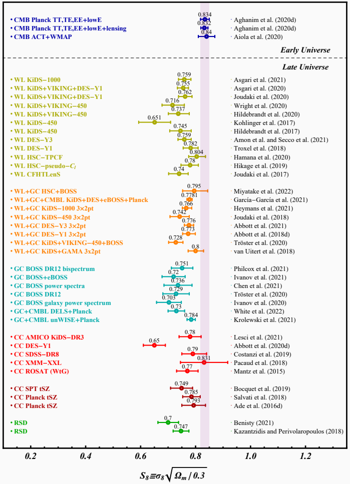
Why this is interesting

- 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

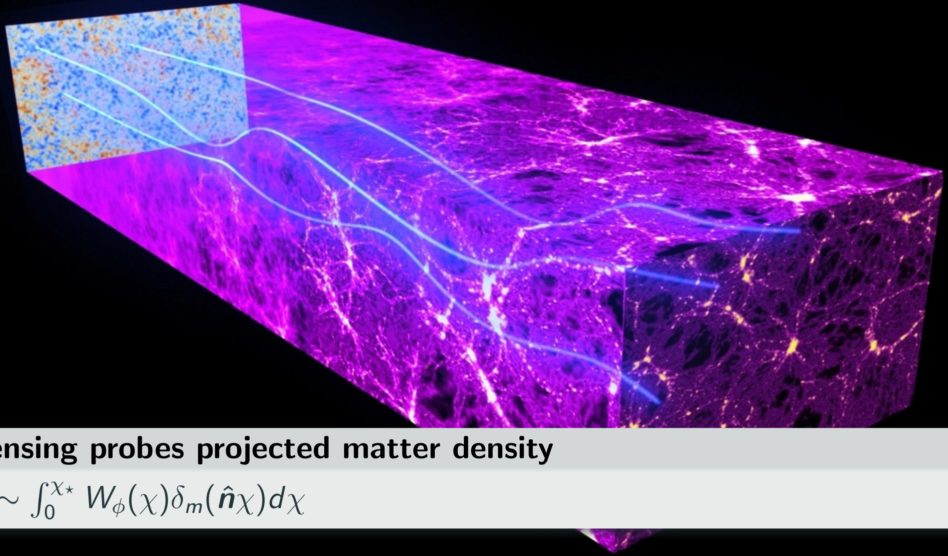


Two possible resolutions?

- 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)

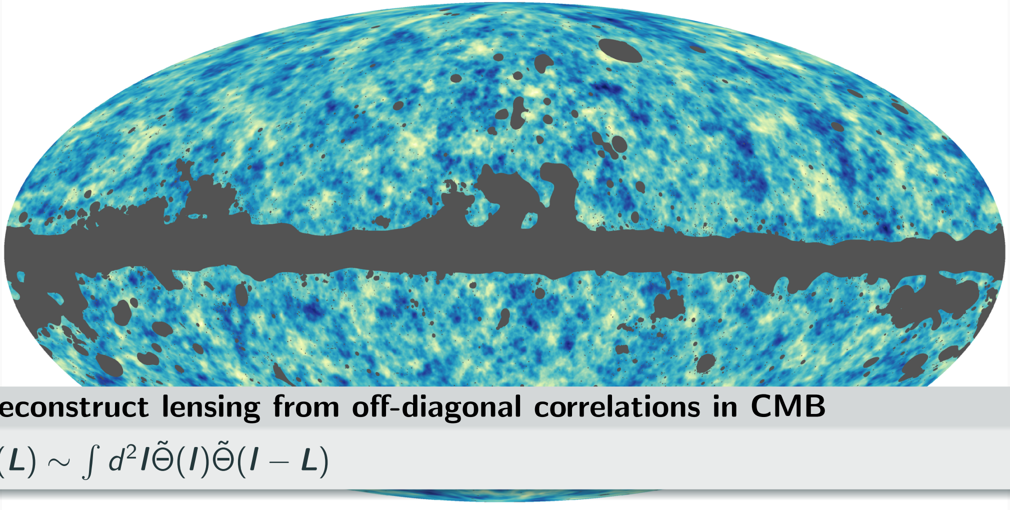
Introduction to CMB lensing



Lensing probes projected matter density

$\phi \sim \int_0^{\chi_\star} W_\phi(\chi)\delta_m(\hat{\boldsymbol{n}}\chi)d\chi$

Lensing reconstruction



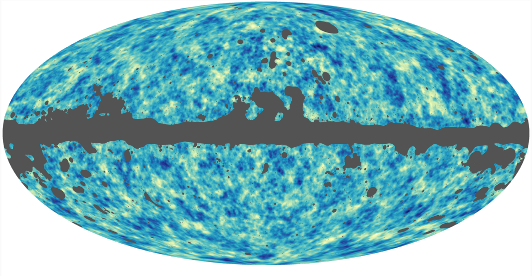
Reconstruct lensing from off-diagonal correlations in CMB

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

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

Cross-correlation with galaxies

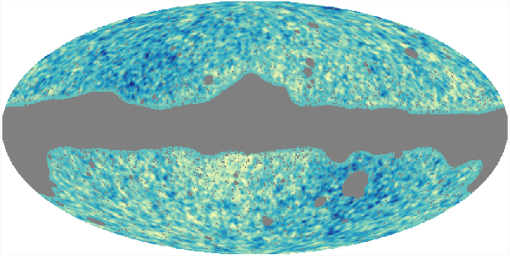
CMB Lensing reconstruction



Planck or ACT

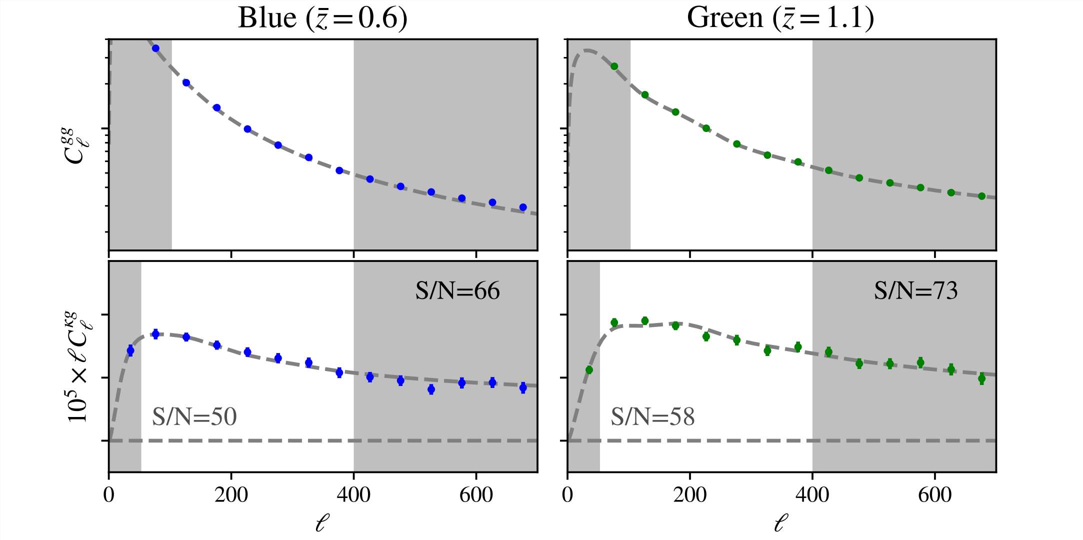
$\times$

Galaxy number density

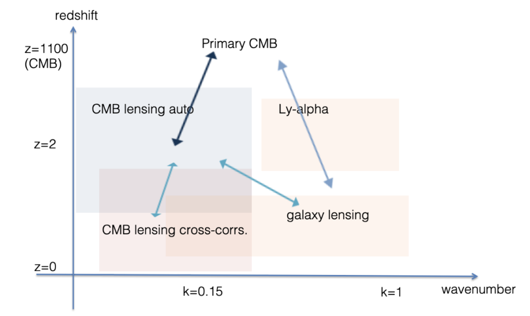


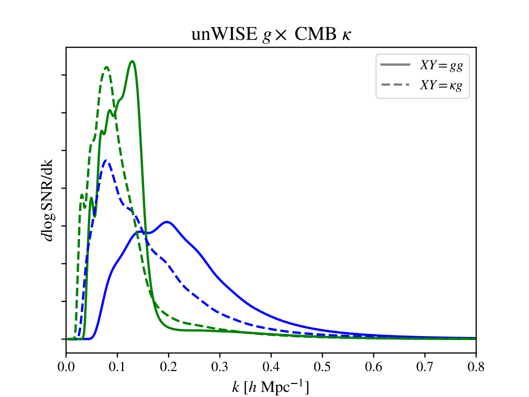
here **unWISE**

The cross-correlation



Complementary probes of large scale structure

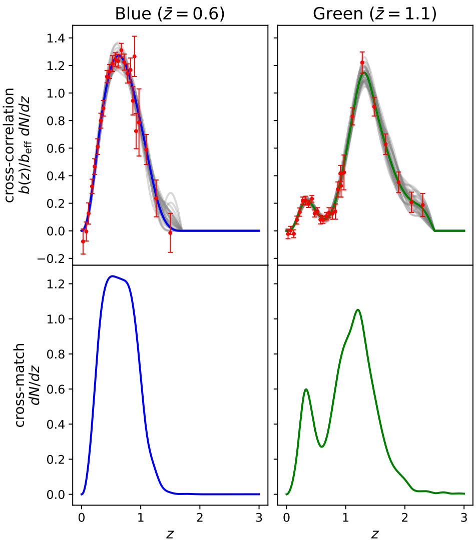




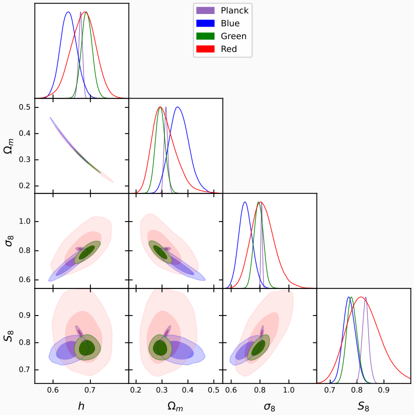
The unWISE samples

- 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

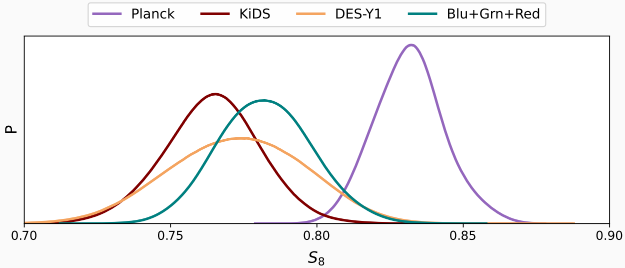


Previous work on Planck lensing x unWISE



Spectra: Krolewski *et al.* (2020)

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



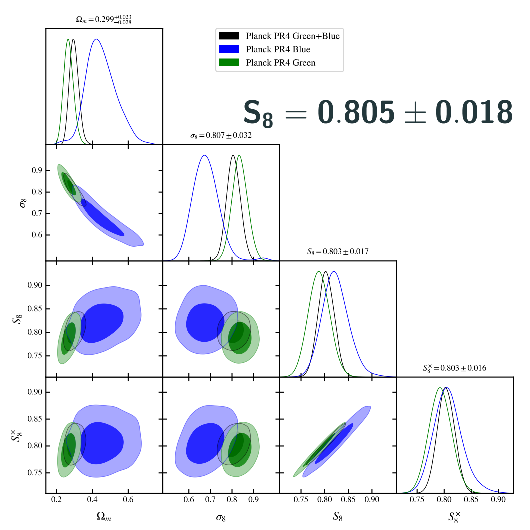
$$S_8 = 0.782 \pm 0.015$$

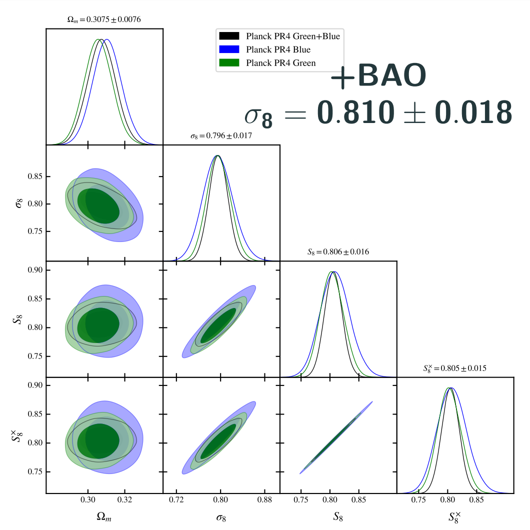
$\implies$ $\sim$2.4σ tension with Planck 2pt

What's new?

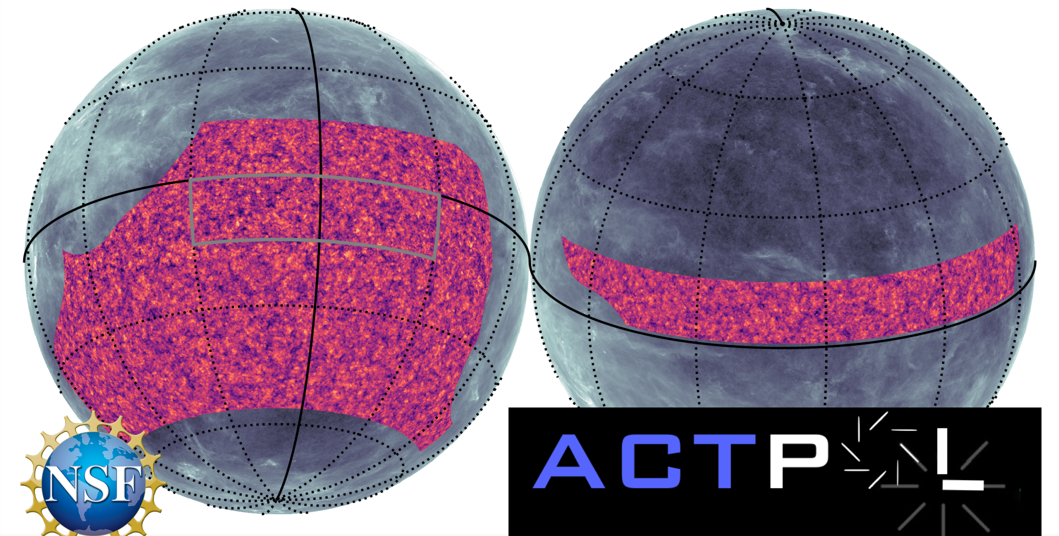
	Impact on S_8
Monte Carlo lensing norm correction	$+0.6\sigma$
modelling improvements	-0.5σ
Systematics weighting	$+0.4\sigma$
Additional spectroscopic data	$+0.8\sigma$
use of *Planck* PR4 lensing reconstruction	$+0.2\sigma$
PCA based dN/dz marginalisation	-0.2σ + $\sim$15% wider posteriors
fid. cosmo. correction	change in degeneracy directions
Total	$+\mathbf{1.3}\sigma$ + $\sim$**15% wider posteriors**

Re-analysis of unWISE x Planck lensing

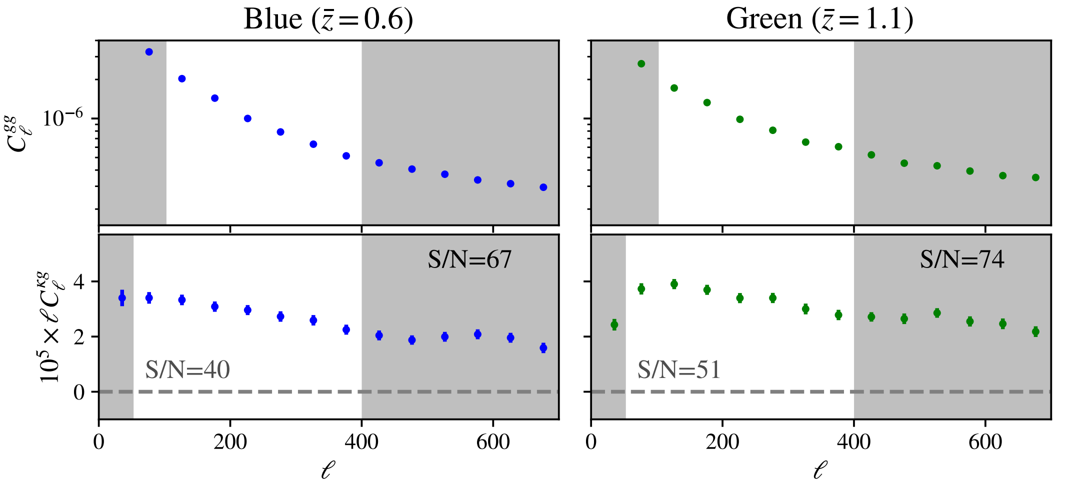




ACT lensing reconstruction



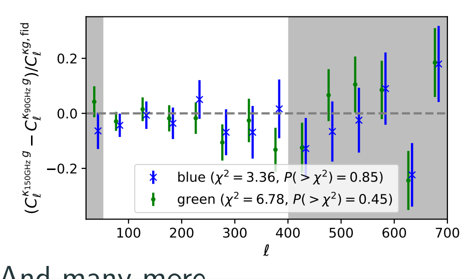
cross-spectra unWISE x ACT DR6 lensing



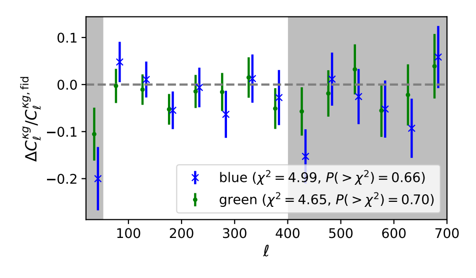
Testing for systematic contamination

Data Null-tests

frequency comparison



galactic mask comparison

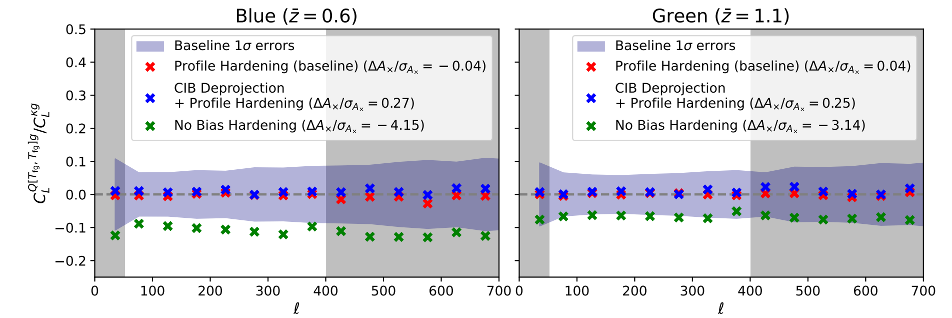


And many more ...

- 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, ...)

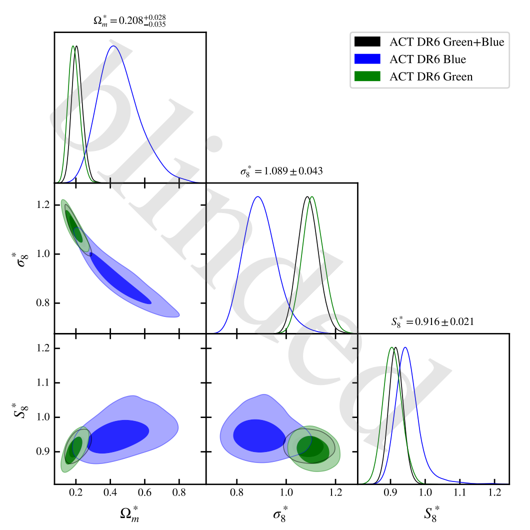
Testing for systematic contamination (continued)

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



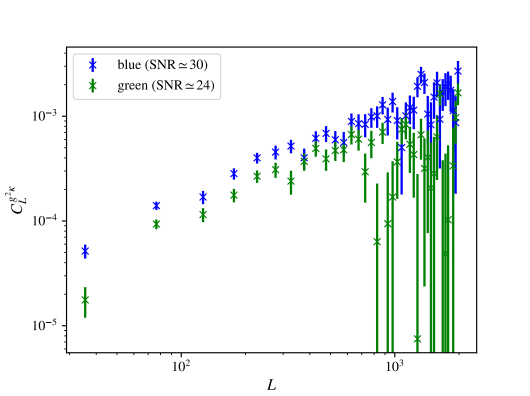
- comparable precision to Planck
- have recently unblinded
- results are forthcoming

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)
- (eventually) Simons Observatory Lensing $\times$ e.g. LSST

Thank you!

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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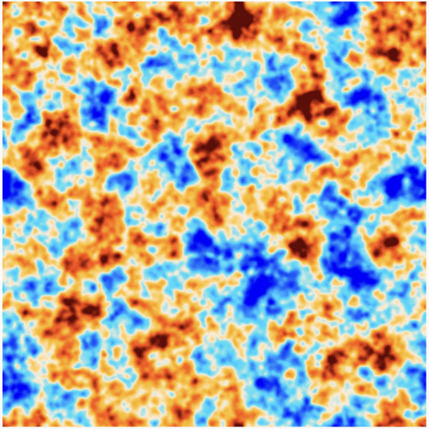
The effect of CMB lensing

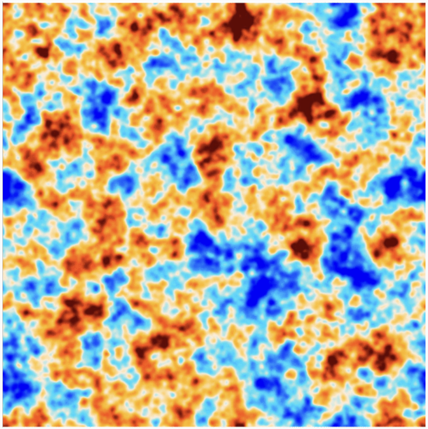


- observed field = unlensed field evaluated at a different position

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

- 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

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

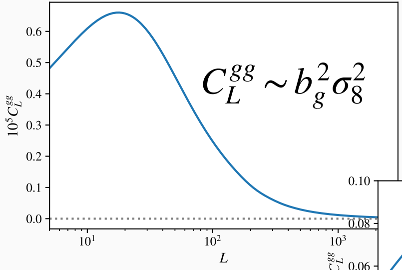
- estimate lensing signal from off-diagonal correlations

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

- using quadratic estimators

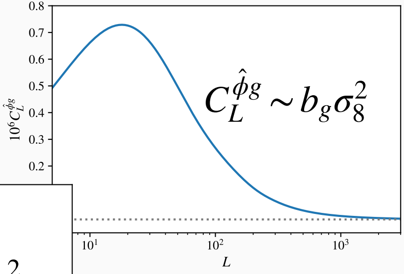
Measuring S_8 with galaxy - CMB lensing cross-correlations

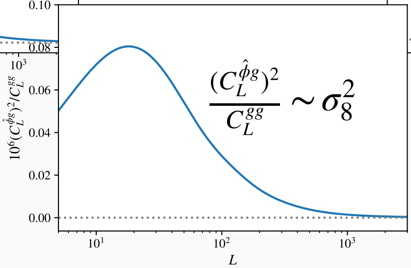
from galaxies



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

from galaxies × lensing





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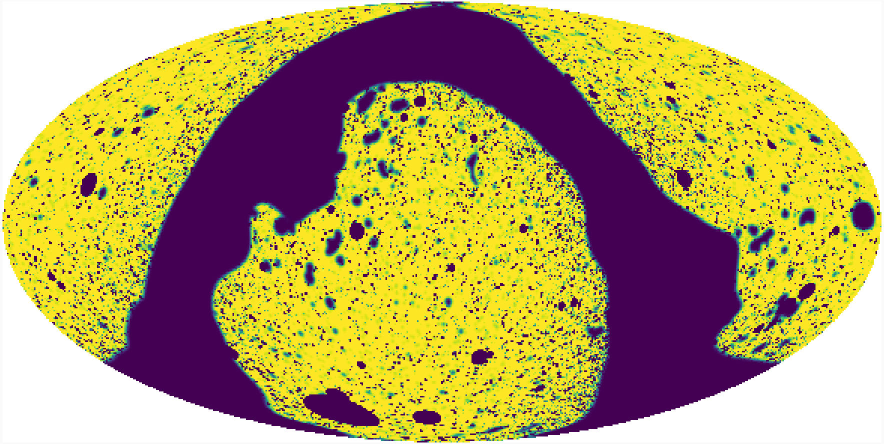
Sky-coverage - unWISE



$f_{\rm sky} \simeq 0.59$

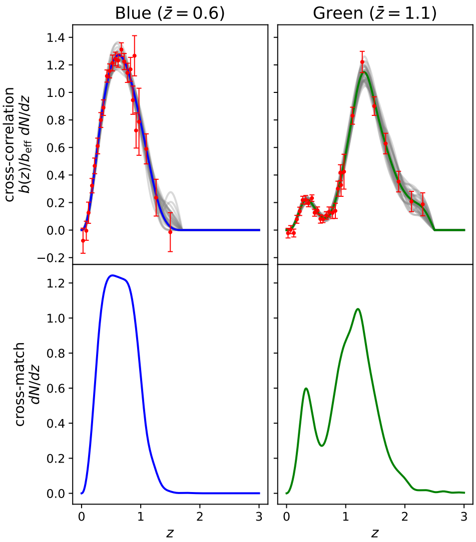
Redshifts for unWISE

dN/dz from ...

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

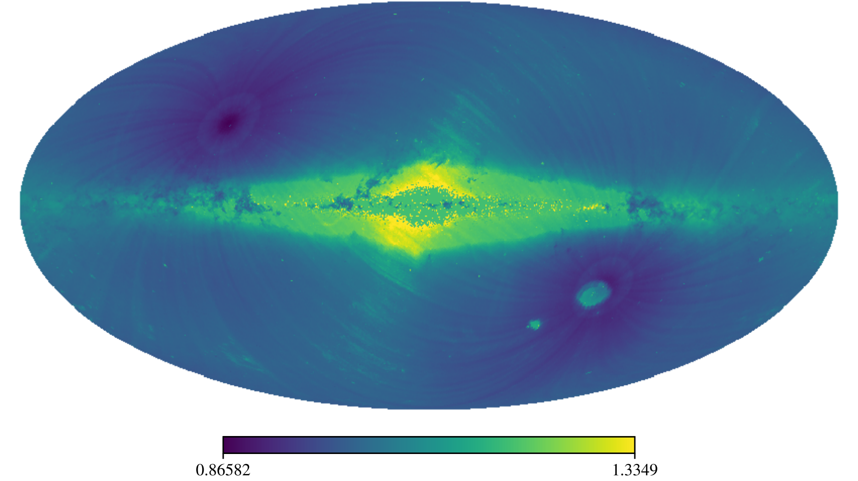
$$b_{\text{photo.}} \widehat{\frac{dN_{\text{photo.}}}{dz}} \propto \frac{w^{\text{spec.}\times\text{photo.}}(z)}{\sqrt{w^{\text{spec.}\times\text{spec.}}(z)}}$$

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

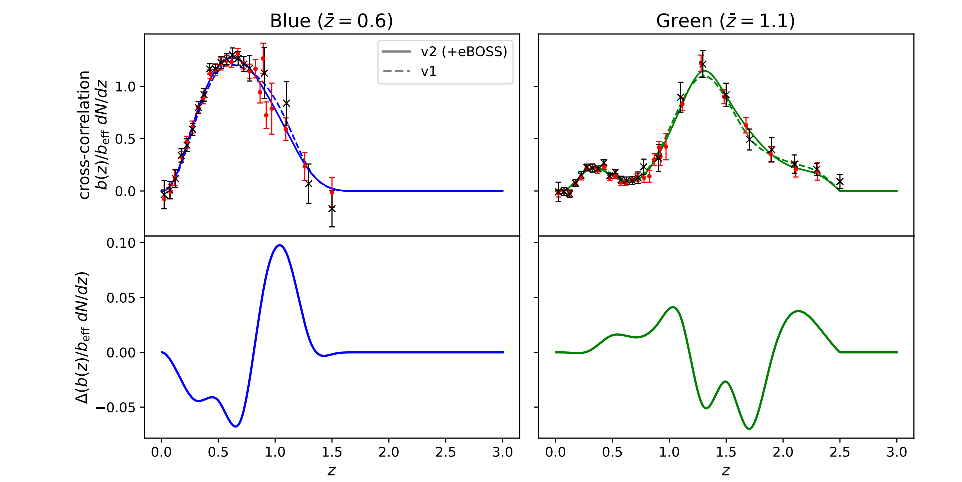


Systematics weighting

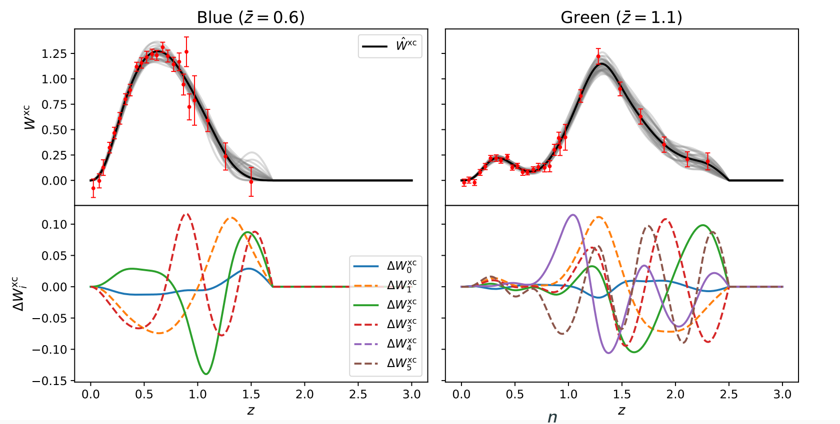
piecewise linear trends for **survey depth** and **stellar density**



Additional spectroscopic data from eBOSS



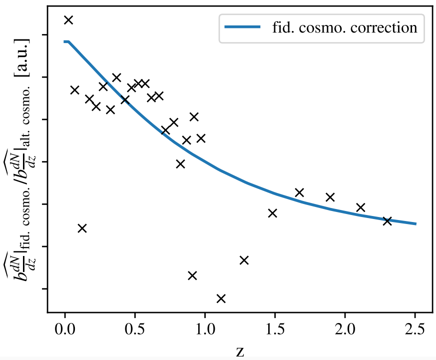
PCA based dN/dz marginalisation



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

G. Farren: unWISE g x CMB Lensing κ

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

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

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

Model

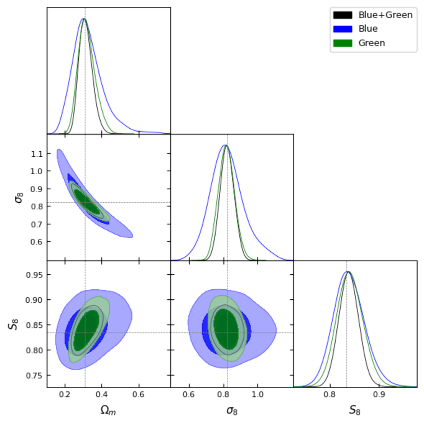
- Limber approximation for C_ℓ^{gg} and $C_\ell^{\kappa g}$
- including lensing magnification
- Power spectrum model: Hybrid Halofit + LPT (like Krolewski *et al.*, 2021)

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

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

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

Model verification



- N-body sims populated with HOD tuned to reproduce unWISE samples (from Krolewski *et al.*, 2021)

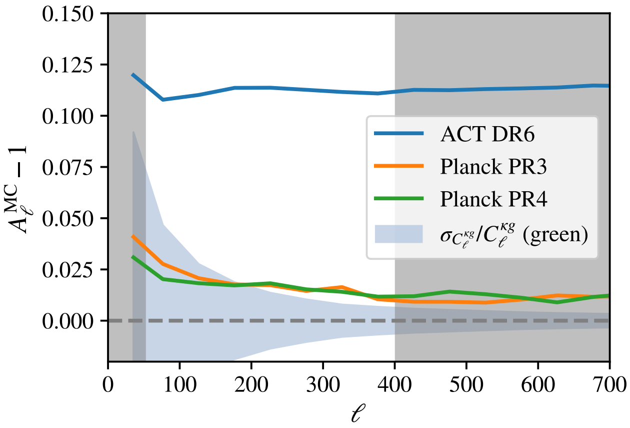
	$\Delta\Omega_m/\sigma_{\Omega_m}$	$\Delta\sigma_8/\sigma_{\sigma_8}$	$\Delta S_8/\sigma_{S_8}$
Blue	0.18	-0.07	0.28
Green	0.18	-0.14	0.07
Joint	0.19	-0.16	0.08

Model (massive neutrinos)

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

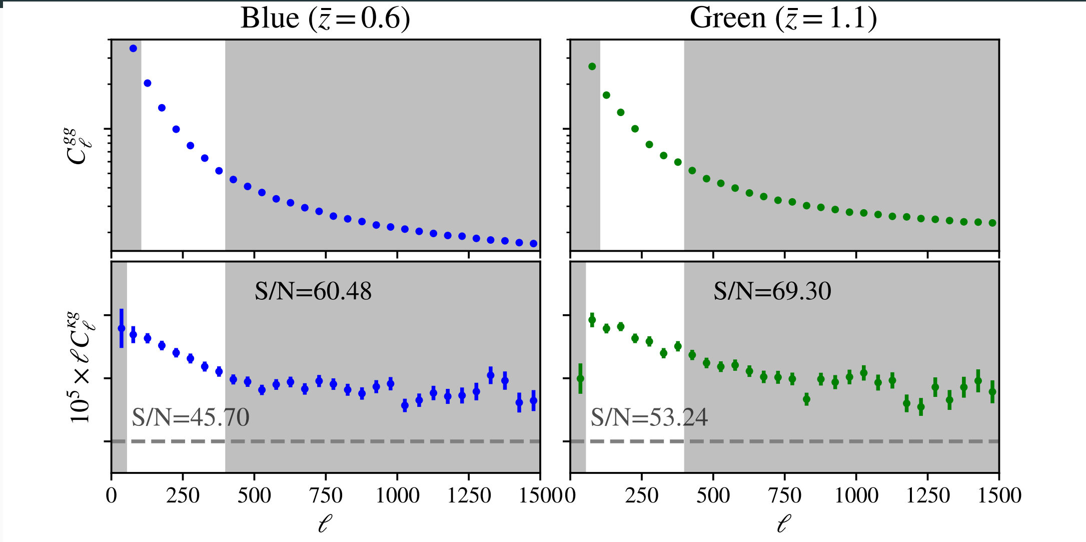
- P_{gg}: ν-free power spectrum, $\langle \delta_{cb} \delta_{cb} \rangle$
- P_{mm}: power spectrum including neutrinos, $\langle \delta_m \delta_m \rangle$
- P_{mg}: cross power spectrum between total matter (including neutrinos) and non-relativistic matter (baryons and dark matter only), $\langle \delta_m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

Monte-carlo lensing norm correction



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

Improved Planck PR4 (NPIPE) lensing reconstruction



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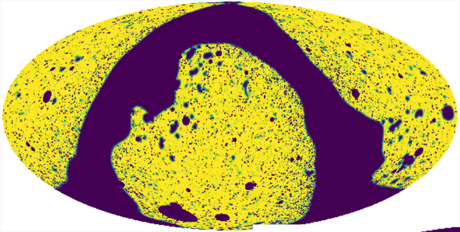
Sky-coverage - unWISE x ACT

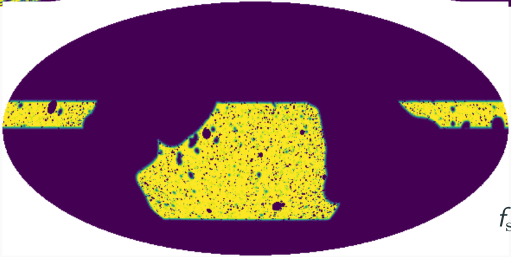
unWISE



$f_{\rm sky} \simeq 0.59$

ACT lensing

$f_{\rm sky} \simeq 0.23$



$f_{\rm sky} \simeq 0.20$

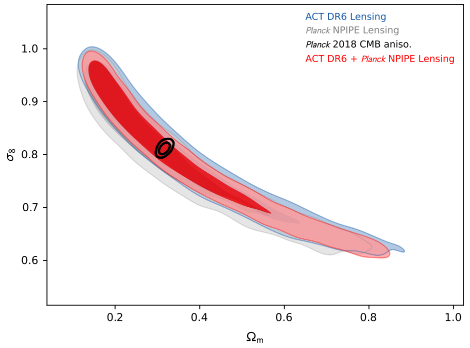
Blinding

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
- perform a series of blind parameter consistency test examining different data cuts and analysis choices
- freeze all baseline priors and scale cuts

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

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

ACT DR6 + Planck PR4 Lensing

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

Planck 2018 CMB aniso.

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

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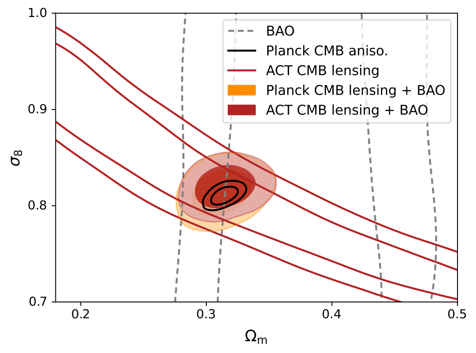
ACT DR6 lensing auto-spectrum results



ACT DR6 Lensing + BAO

$\boldsymbol{\sigma_8 = 0.819 \pm 0.015}$

ACT DR6 + Planck PR4 Lensing

$\sigma_8 = 0.812 \pm 0.013$

Planck 2018 CMB aniso.

$\sigma_8 = 0.811 \pm 0.006$

references i

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