

Title: The Atacama Cosmology Telescope: Probing the large scale structure with ACT DR6 CMB lensing and cross-correlation with unWISE

Speakers: Gerrit Farren

Series: Cosmology & Gravitation

Date: October 31, 2023 - 11:00 AM

URL: <https://pirsa.org/23100120>

Abstract: I will present work on probing the large scale structure of the universe using CMB lensing from the upcoming Data Release 6 of the Atacama Cosmology Telescope (ACT) and cross-correlations with galaxies from the unWISE galaxy catalog. My talk will focus on how our highly competitive constraints from CMB lensing and CMB lensing cross-correlations can provide insight into the widely discussed " $S_8/\sigma_8$  tension". For this purpose I will briefly introduce the high fidelity CMB lensing reconstruction obtained by the ACT Collaboration and results from the analysis of the lensing auto-correlation. I will discuss new results from the cross-correlation between ACT CMB lensing and unWISE galaxies, highlighting improvements to the analysis pipeline compared to previous work on the cross-correlation between Planck CMB lensing and unWISE by some of my collaborators (Krolewski et al. 2021). I will also show a reanalysis of Planck CMB lensing x unWISE and a joined analysis of the ACT and Planck CMB lensing cross-correlations with unWISE.

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Zoom link <https://pitp.zoom.us/j/99192611116?pwd=TU9iMjhrejVESjNRdi92M0ZXN2ZEQT09>



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# The Atacama Cosmology Telescope:

cosmology from DR6 CMB lensing and cross-correlations with unWISE

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## Gerrit S. Farren

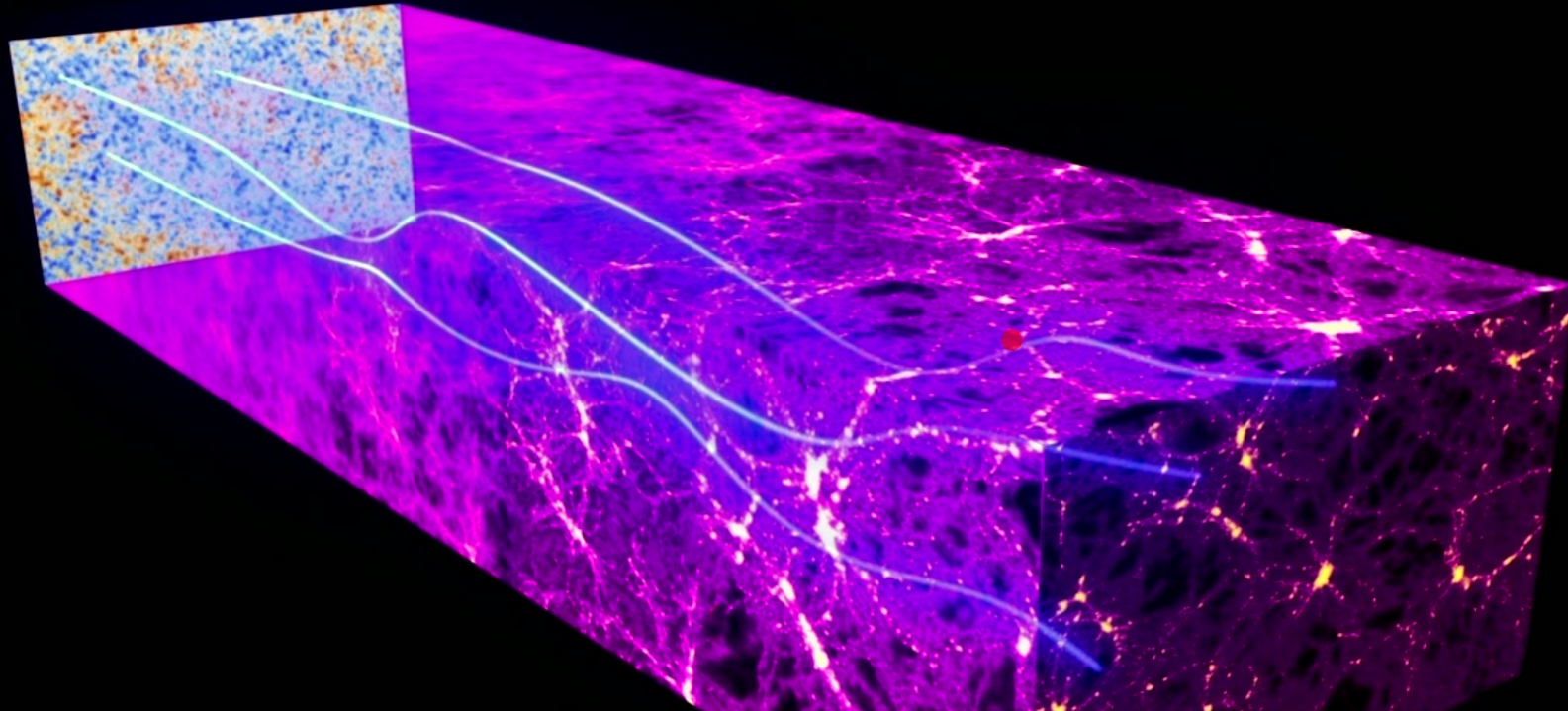
Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge, UK  
Kavli Institute for Cosmology Cambridge, Cambridge, UK

work with the ACT Collaboration and external collaborators

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Perimeter Institute, Cosmology Seminar, Oct 31 2023

# Introduction to CMB lensing

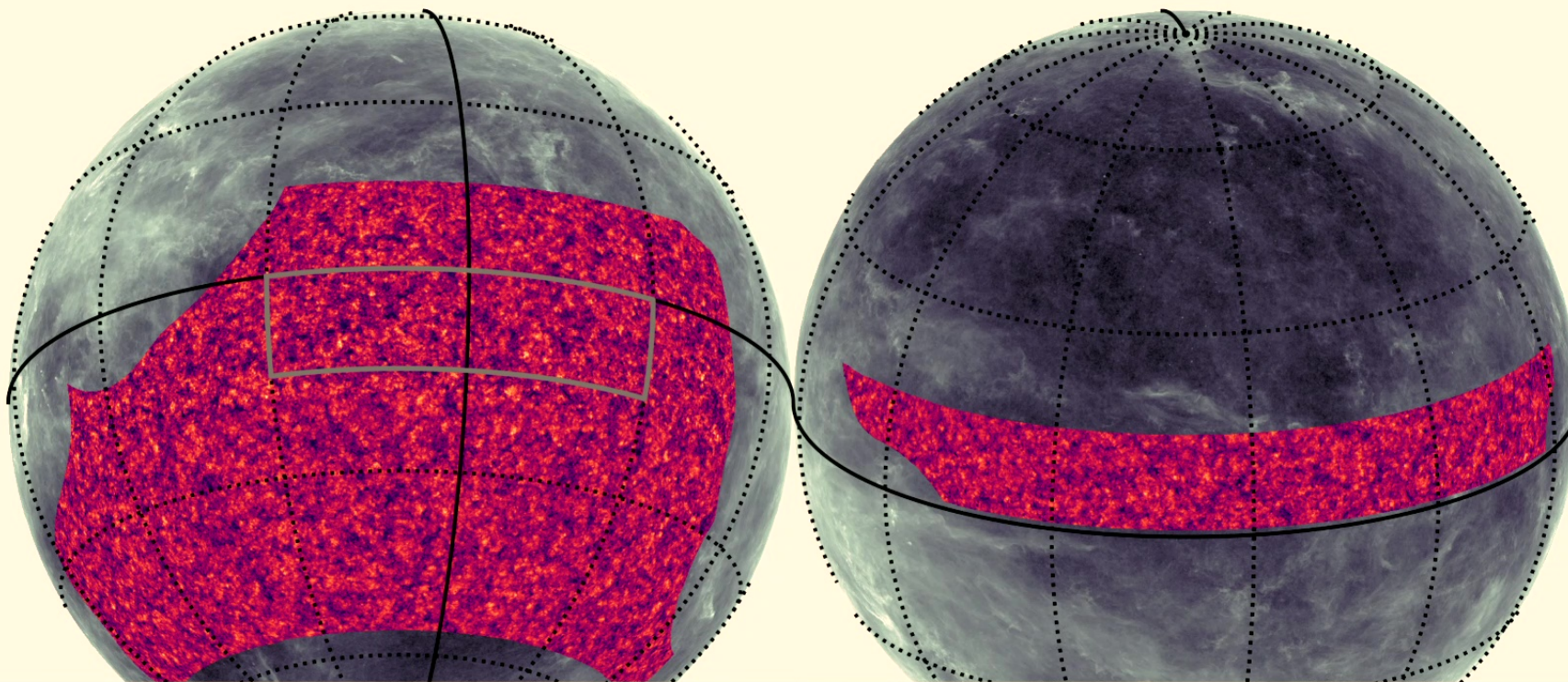


Lensing probes projected matter density

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



# Lensing reconstruction

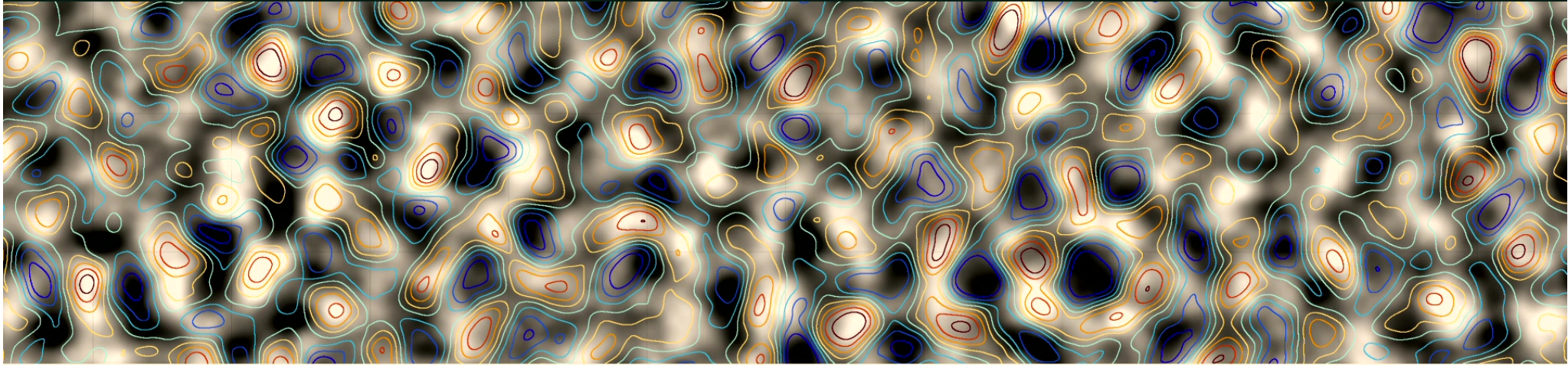


Reconstruct lensing from off-diagonal correlations in CMB

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



# Lensing reconstruction



Frank Qu  
(Cambridge)



Mat Madhavacheril  
(UPenn)



Niall MacCrann  
(Cambridge)



Dongwon Han  
(Cambridge)

# Lensing reconstruction

## Presented in ...

- **Qu et al.:** lensing power spectrum + lensing-only parameters
- **Madhavacheril et al.:** lensing map + comb. w/ external data + extended models
- **Mac Crann et al.:** lensing systematics investigation



Frank Qu  
(Cambridge)



Mat Madhavacheril  
(UPenn)



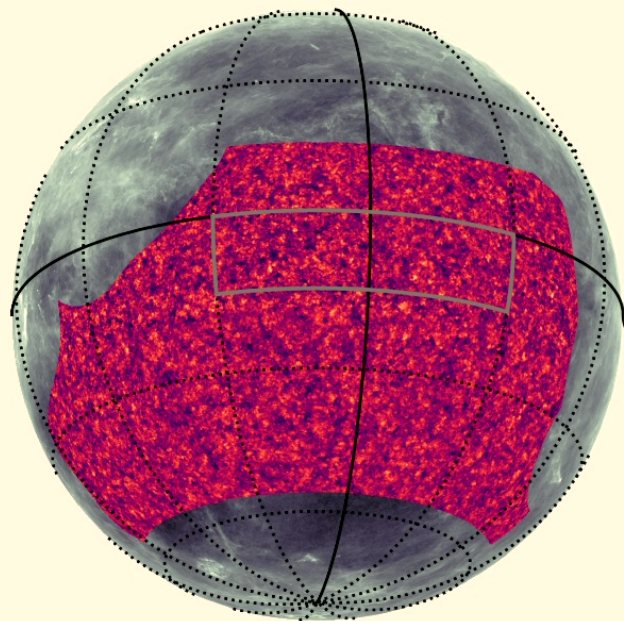
Niall MacCrann  
(Cambridge)



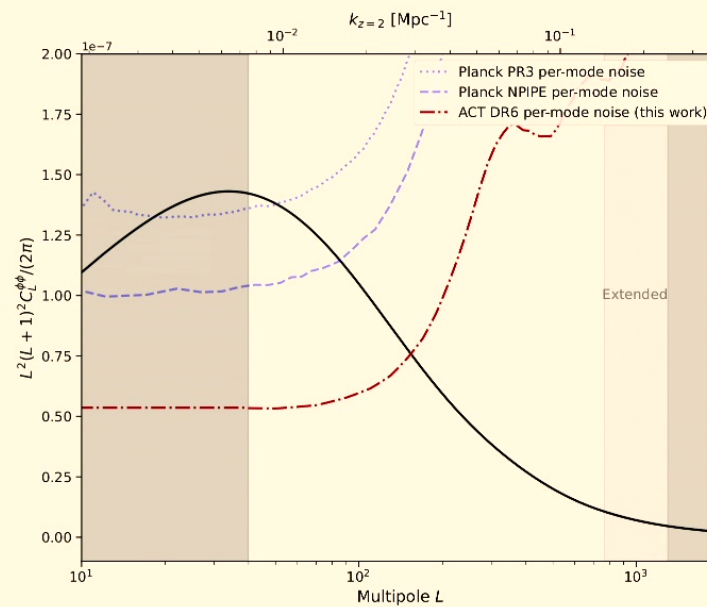
Dongwon Han  
(Cambridge)



# The lensing power spectrum



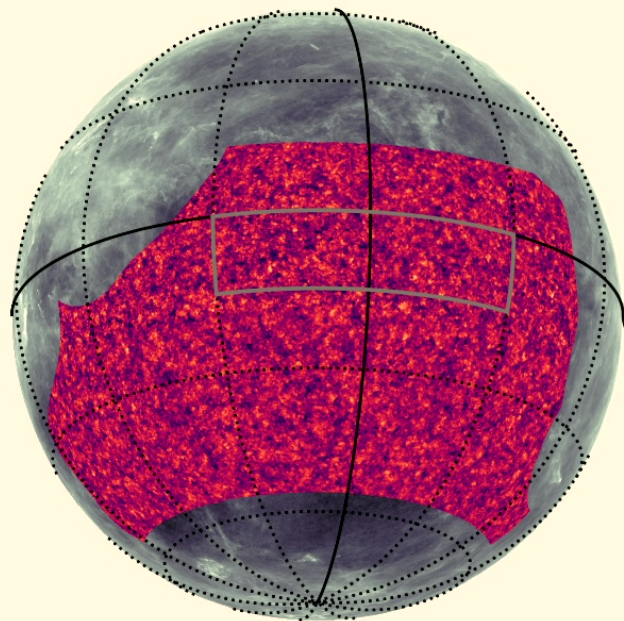
$$\hat{C}_\ell^{\phi\phi} \sim \langle \hat{\phi}_{\ell m} \hat{\phi}_{\ell m}^* \rangle$$



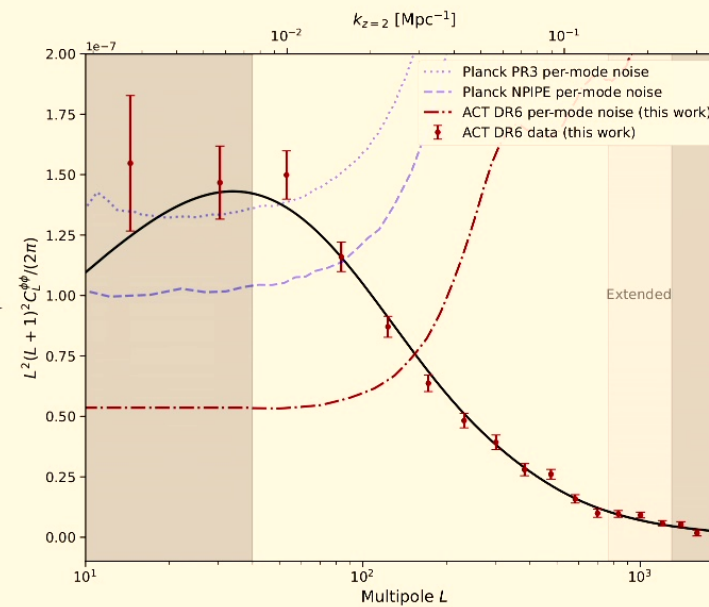
G. Farren: ACT DR6 lensing and cross-correlations



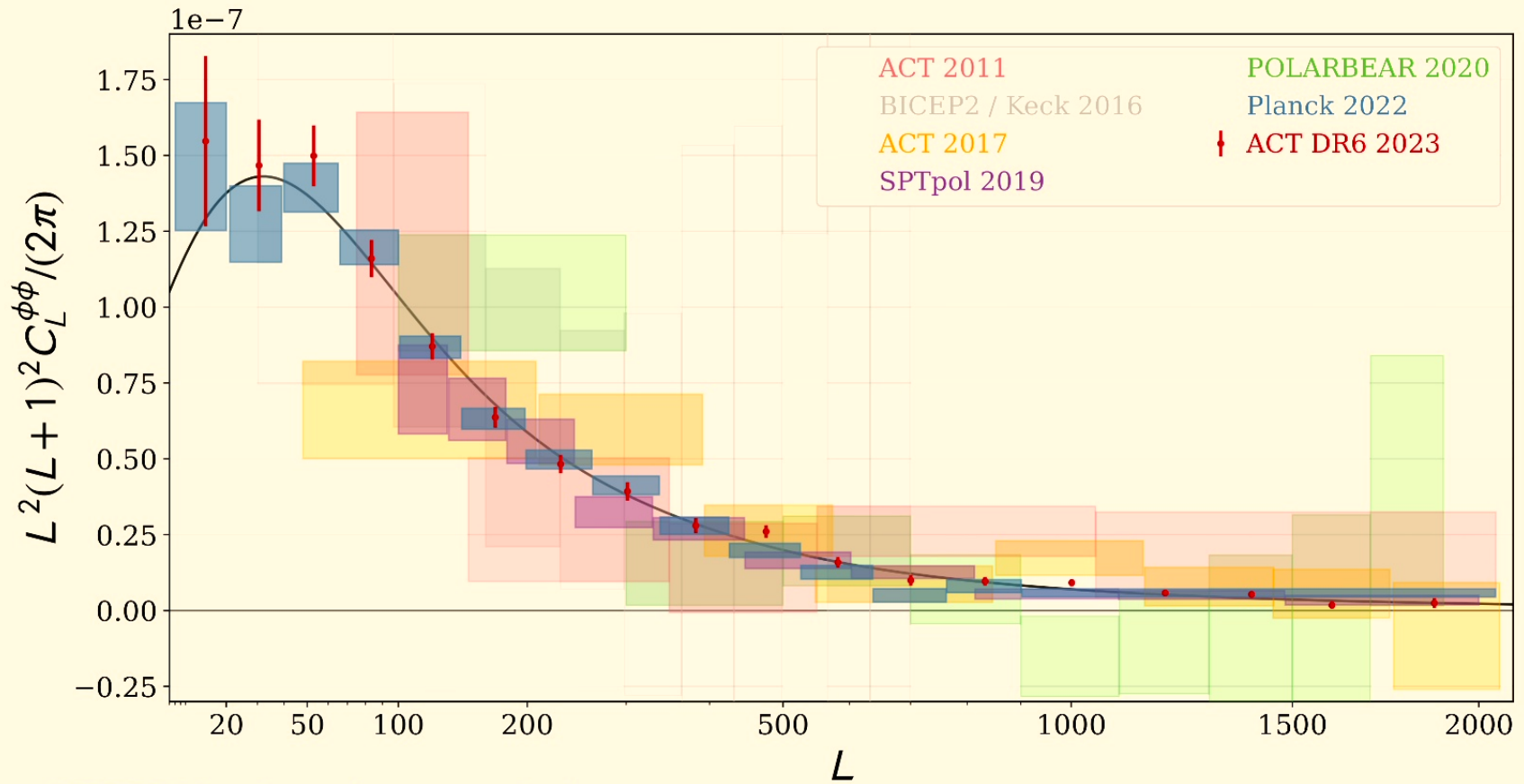
# The lensing power spectrum



$$\hat{C}_\ell^{\phi\phi} \sim \langle \hat{\phi}_{\ell m} \hat{\phi}_{\ell m}^* \rangle$$



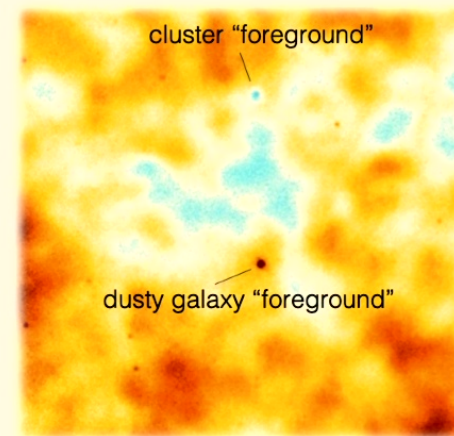
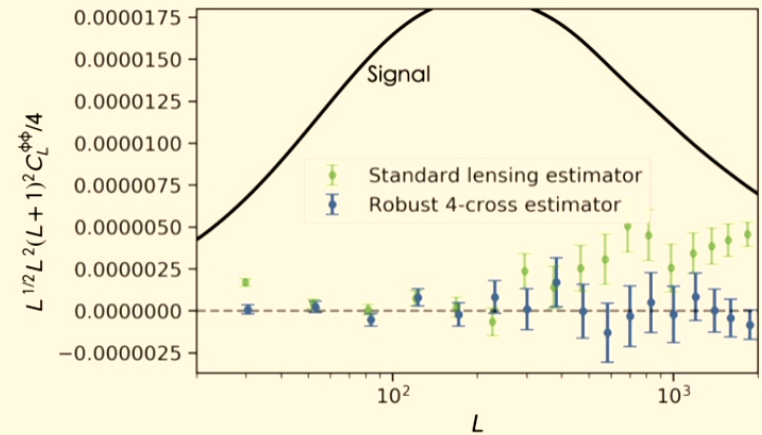
# The lensing power spectrum



G. Farren: ACT DR6 lensing and cross-correlations

# Highlights of the new ACT DR6 CMB lensing analysis

- noise-bias immune cross-correlation based estimator:  $\hat{C}_\ell^{\phi\phi} \sim \langle \Theta_A \Theta_B \Theta_C \Theta_D \rangle$
- foreground bias hardened estimator
- simulation based foreground bias investigation
- extensive null-tests
- fully blind analysis



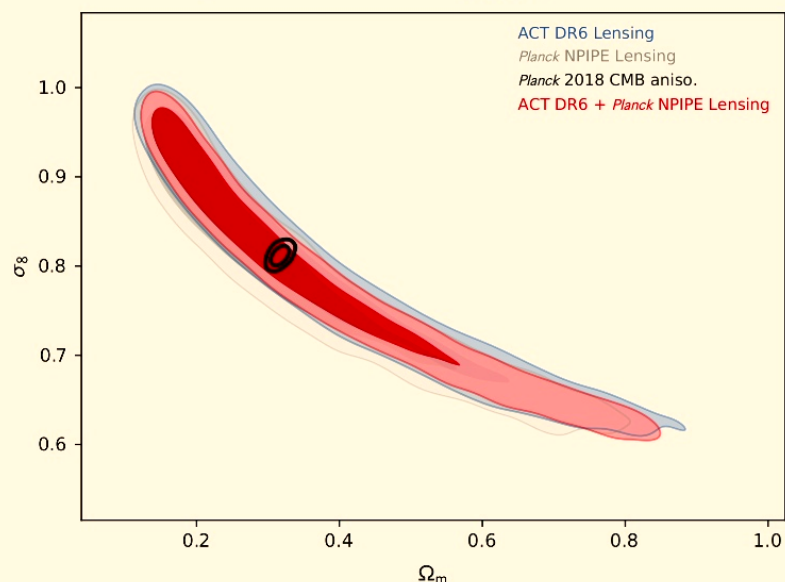
G. Farren: ACT DR6 lensing and cross-correlations



# Constraints on structure growth

Best constrained parameter

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



**ACT DR6 Lensing**

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

**ACT DR6 + Planck PR4 Lensing**

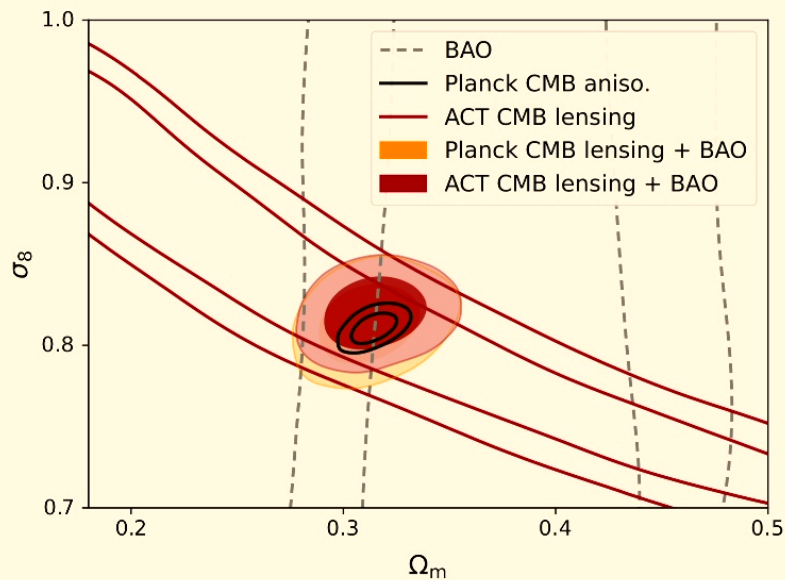
$$S_8^{\text{CMBL}} = 0.813 \pm 0.018$$

**cf. primary CMB aniso.**

$$S_8^{\text{CMBL}} = 0.823 \pm 0.011 \text{ (Planck 2018)}$$

$$S_8^{\text{CMBL}} = 0.828 \pm 0.022 \text{ (ACT+WMAP)}$$

# Constraints on structure growth



## ACT DR6 Lensing + BAO

$$\sigma_8 = 0.819 \pm 0.015$$

## ACT DR6 + Planck PR4 Lensing

$$\sigma_8 = 0.812 \pm 0.013$$

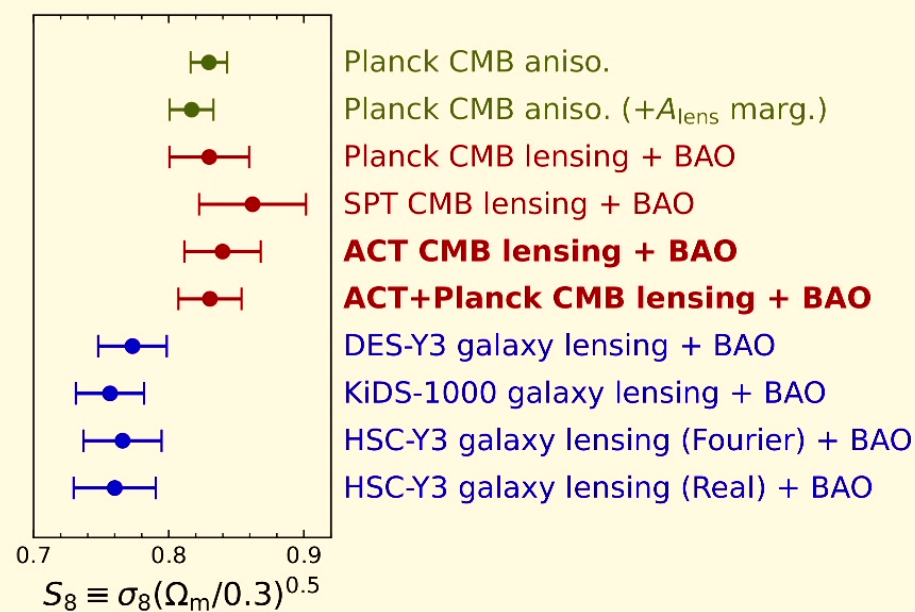
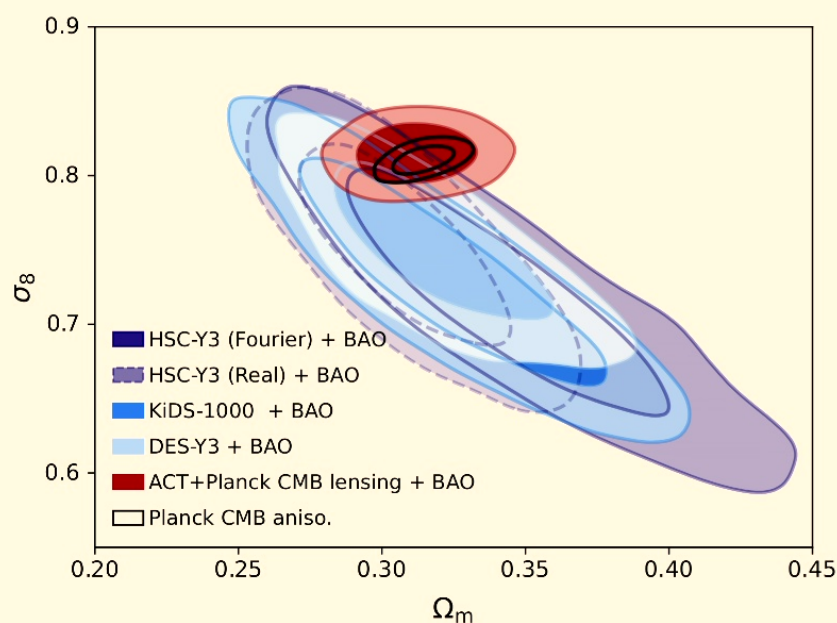
## cf. primary CMB aniso.

$$\sigma_8 = 0.811 \pm 0.006 \text{ (Planck 2018)}$$

$$\sigma_8 = 0.822 \pm 0.012 \text{ (ACT+WMAP)}$$

# Constraints on structure growth - comp. to galaxy weak lensing

ACT CMB lensing is **consistent** with (at  $1.7 - 2.1\sigma$ ) but **consistently higher** than galaxy weak lensing shear

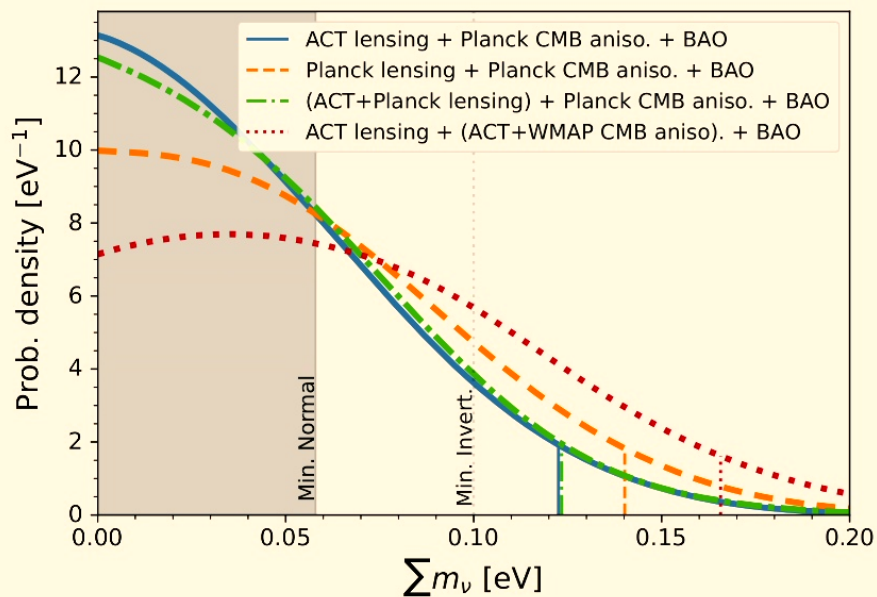


G. Farren: ACT DR6 lensing and cross-correlations

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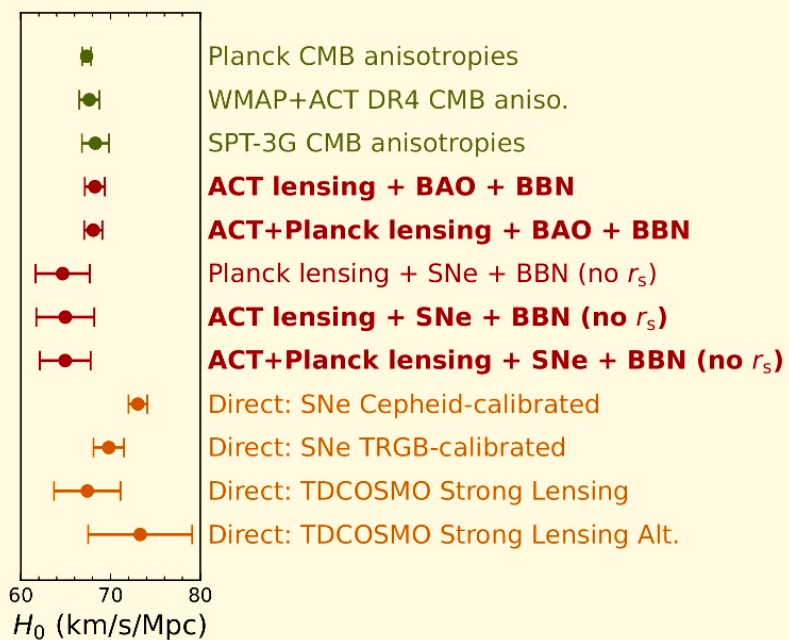
# Constraints on Neutrinos



**ACT DR6 Lensing + Planck + BAO**

$$\sum m_\nu < 0.12 \text{ eV}; 95\% \text{ c.l.}$$

# Constraints on $H_0$



## ACT DR6 Lensing + BAO + BBN

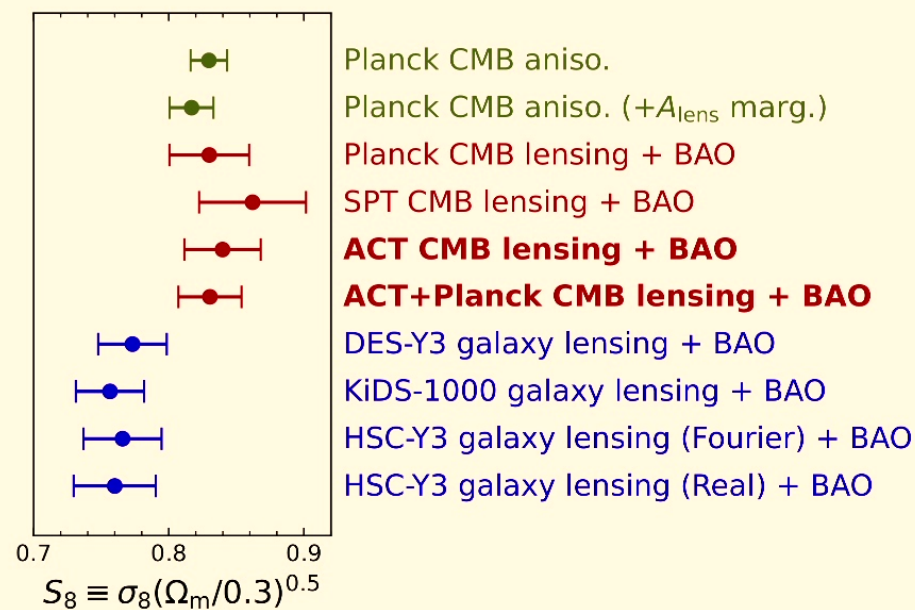
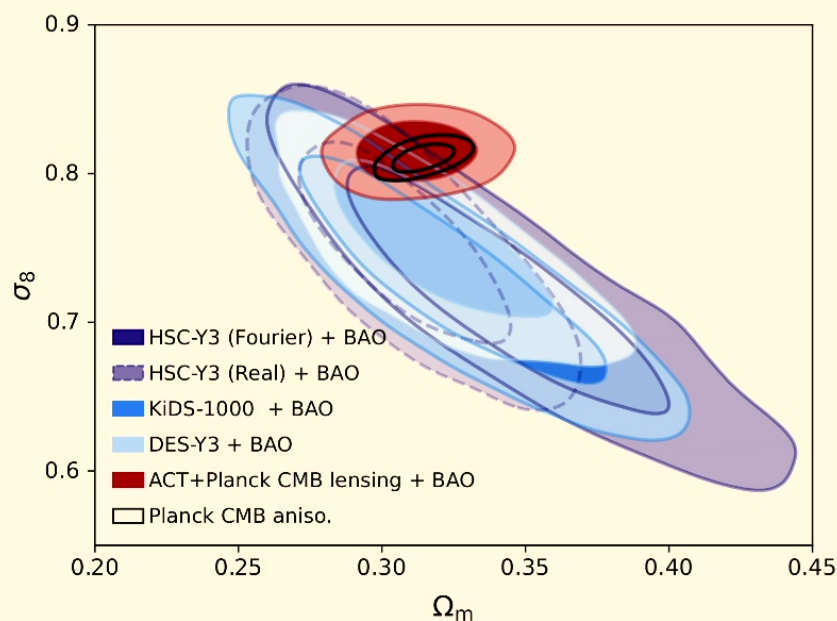
$$H_0 = 68.3 \pm 1.1 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

## ACT DR6 Lensing + Pantheon (w/o $r_s$ )

$$H_0 = 65 \pm 3.2 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

# Constraints on structure growth - comp. to galaxy weak lensing

ACT CMB lensing is **consistent** with (at  $1.7 - 2.1\sigma$ ) but **consistently higher** than galaxy weak lensing shear

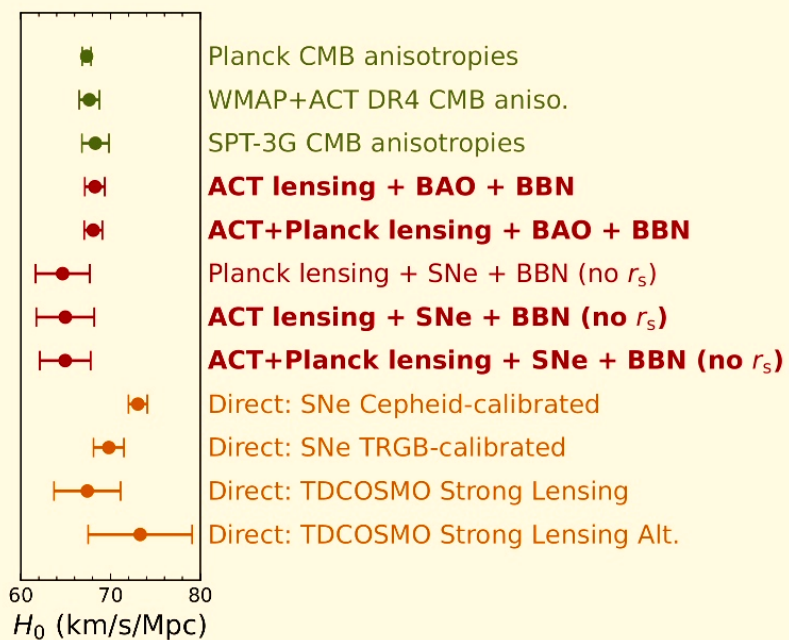


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# Constraints on $H_0$



## ACT DR6 Lensing + BAO + BBN

$$H_0 = 68.3 \pm 1.1 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

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**Cosmology from the ACT DR6  
CMB lensing  $\times$  unWISE galaxies  
structure growth at low redshift**

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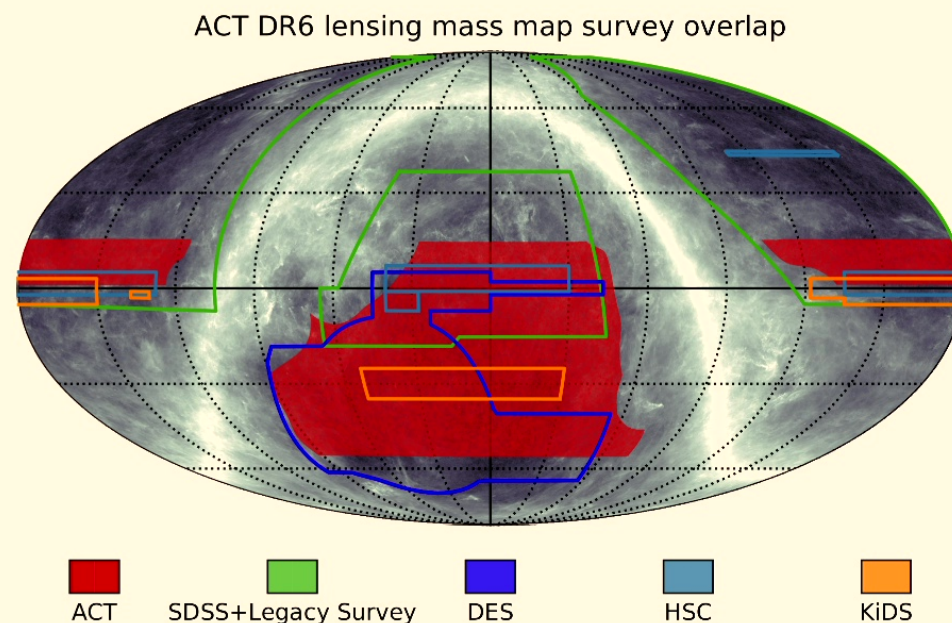
# Cross-correlation science with ACT DR6 lensing

Large sky overlap with:

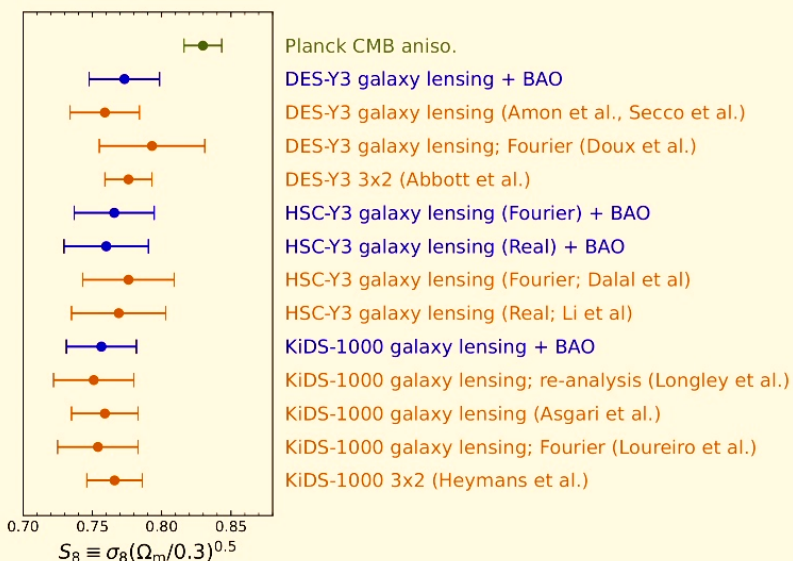
- DESI
- DES
- HSC
- KiDS

Science cases:

- tomographic structure formation:  $\sigma_8(z)$
- primordial non-Gaussianity:  $f_{\text{NL}}$



# Narrowing in on the $S_8$ tension



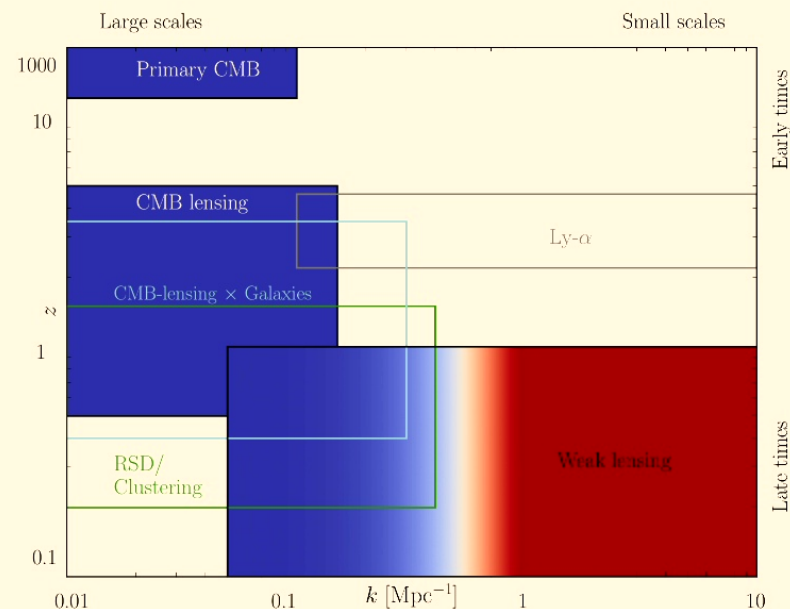
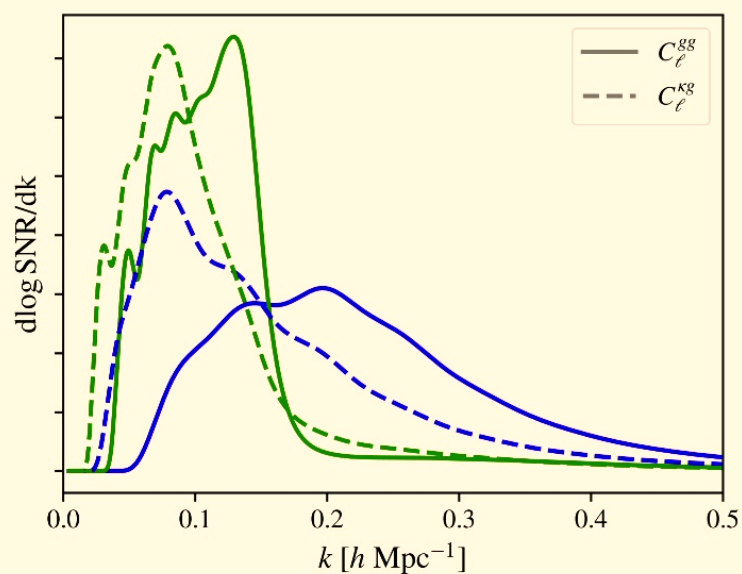
## Two possible resolutions?

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



# Probing different scales and redshifts

- $C_\ell^{\phi\phi}$ :  $z \gtrsim 1.0$  &  $k \lesssim 0.2 h \text{Mpc}^{-1}$

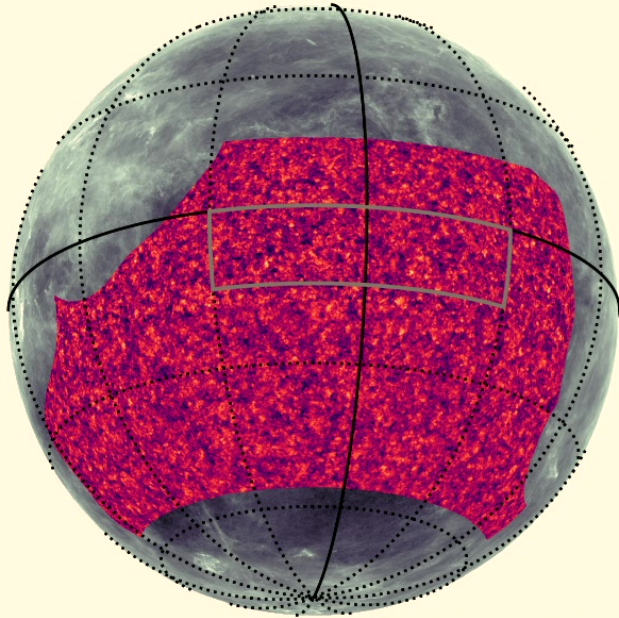


from Preston *et al.* (2023)

- $C_\ell^{\phi g}$ :  $z \simeq 0.2 - 1.6$  &  $k \lesssim 0.3 h \text{Mpc}^{-1}$

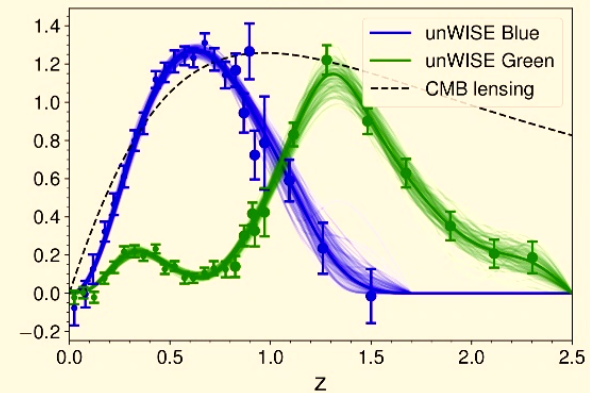
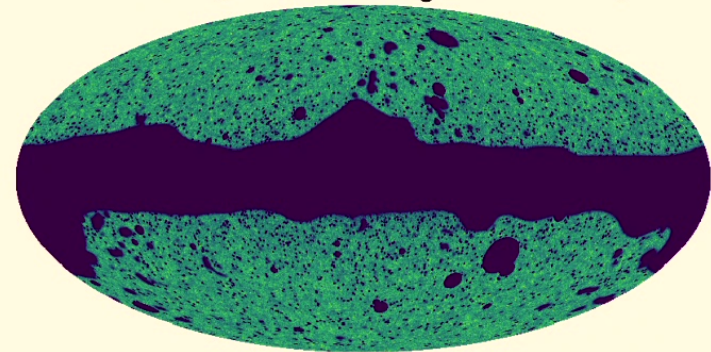
# Cross-correlation between ACT DR6 lensing and unWISE

## CMB Lensing reconstruction



×

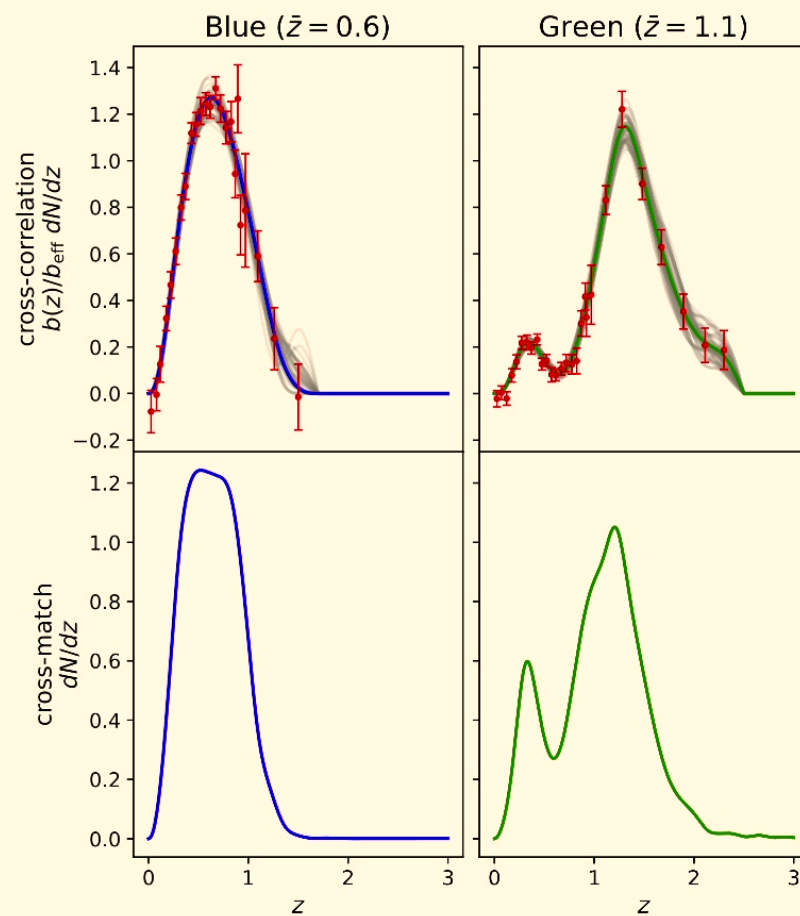
## Galaxy number density



# The unWISE samples

- galaxies from the WISE survey
- including 2 years of post-cryogenic observations (at 3.4 and 4.6  $\mu\text{m}$ )
- >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	$\sim 1800$



G. Farren: ACT DR6 lensing and cross-correlations

# Redshifts for unWISE

$dN/dz$  from ...

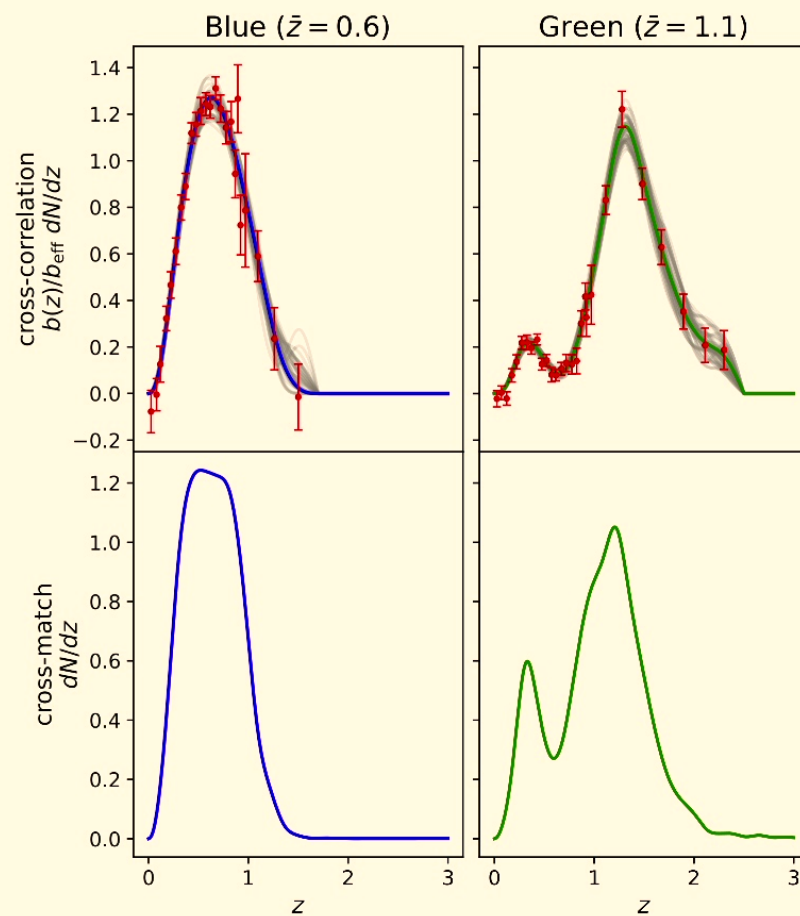
- cross-correlating with spectroscopic surveys (BOSS, eBOSS)

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

(Ménard *et al.*, 2013)

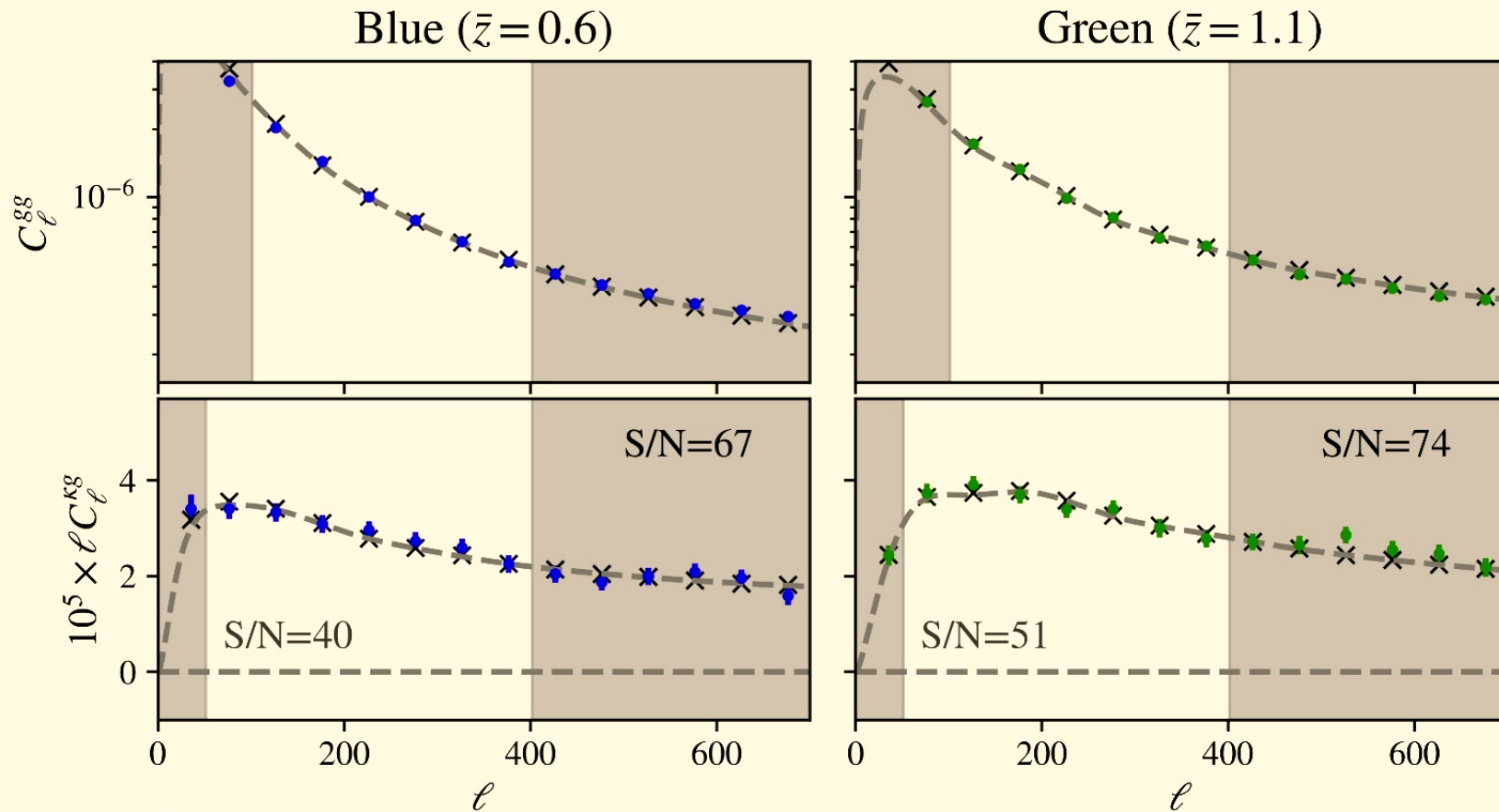
- cross matching with photometric redshifts on smaller field (COSMOS)

G. Farren: ACT DR6 lensing and cross-correlations



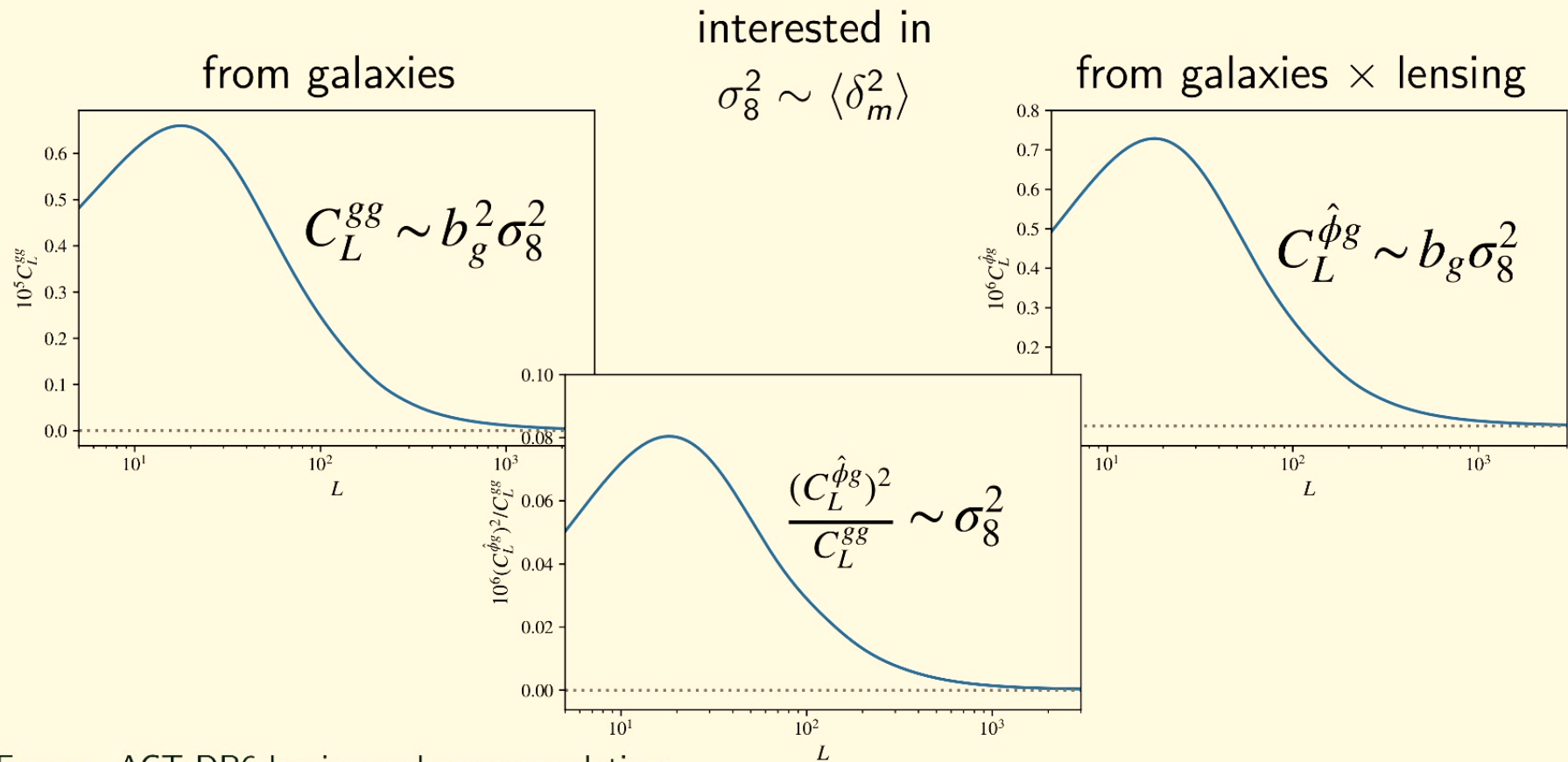


# ACT DR6 lensing $\times$ unWISE - spectra



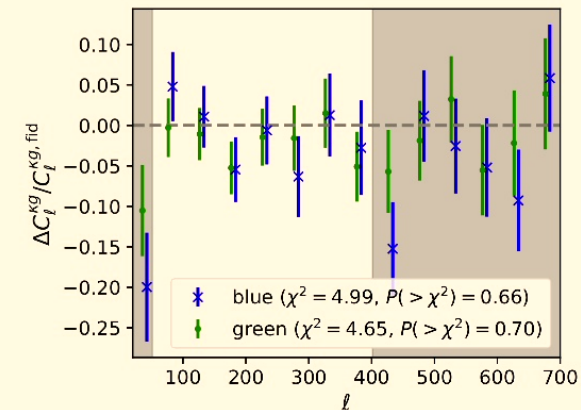
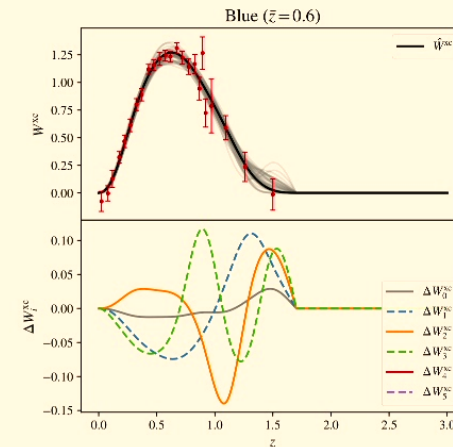
G. Farren: ACT DR6 lensing and cross-correlations

# Measuring $S_8$ with galaxy - CMB lensing cross-correlations



# Highlights of ACT DR6 CMB lensing × unWISE analysis

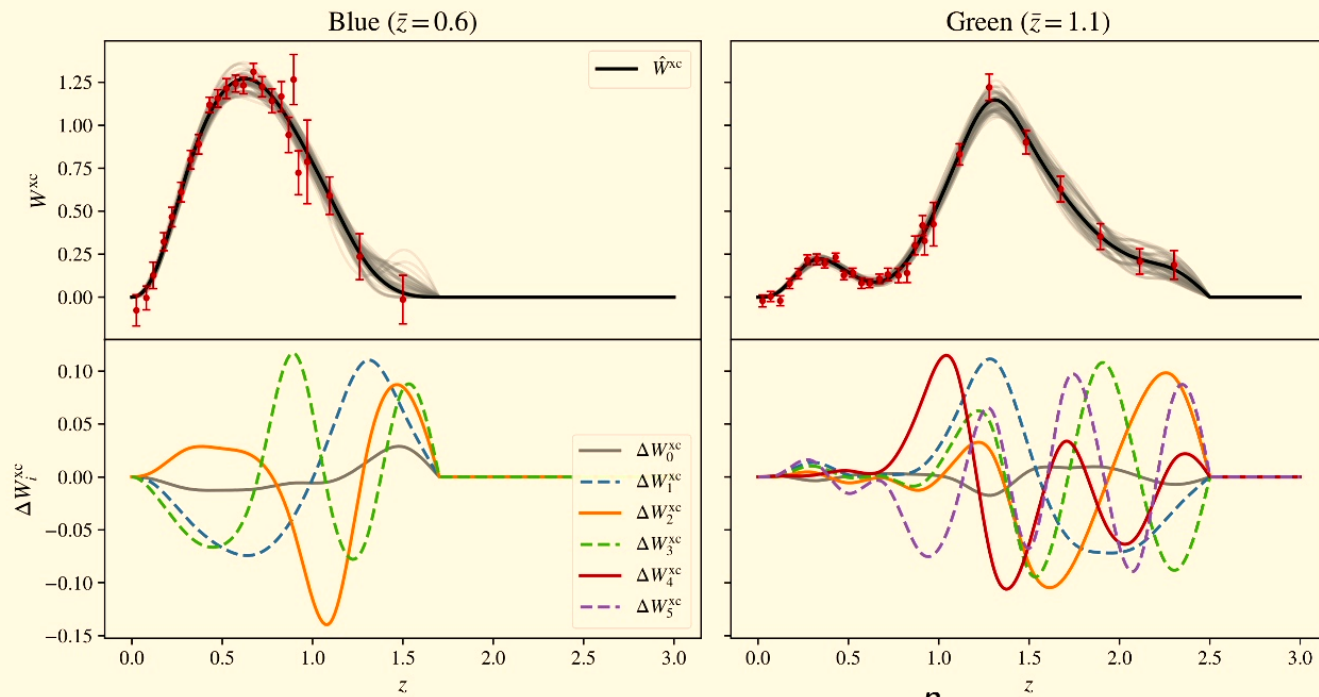
- Improved clustering redshifts for unWISE galaxies
- **PCA based marginalisation over redshift uncertainties**
- imaging systematics mitigation
- **Hybrid HMCode + LPT model**
- **simulation based foreground tests**
- **extensive null- and consistency tests**
- fully blind analysis



G. Farren: ACT DR6 lensing and cross-correlations

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# PCA based $dN/dz$ marginalisation



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



# Model

- Limber approximation for  $C_\ell^{gg}$  and  $C_\ell^{\kappa g}$
- Power spectrum model: Hybrid HMCode + LPT

$$P_{gg}(k, z) = b_{1,E}^2(z)P_{mm,HM} + b_{2,L}(z)P_{b_2}(k, z) + b_{s,L}(z)P_{b_s}(k, z) \\ + b_{1,L}(z)b_{2,L}(z)P_{b_1 b_2}(k, z) + \dots + P_{\text{shot noise}}$$

$$P_{gm}(k, z) = b_{1,E}(z)P_{mm,HM} + \frac{b_{2,L}(z)}{2}P_{b_2}(k, z) + \frac{b_{s,L}(z)}{2}P_{b_s}(k, z)$$

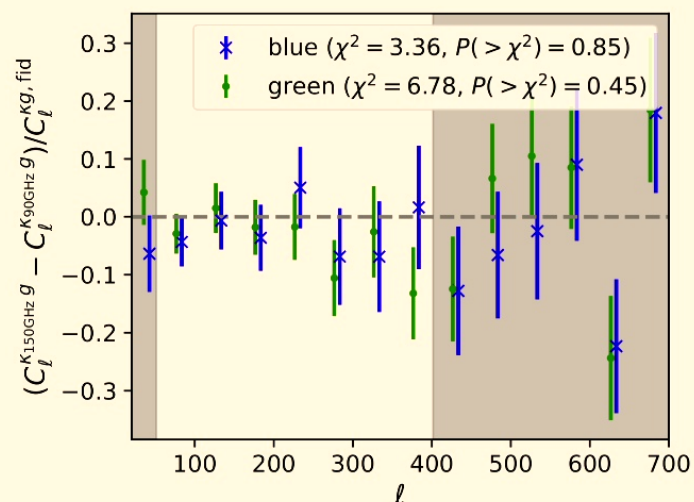
$$P_{mm}(k, z) = P_{mm,HM}(k, z).$$

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

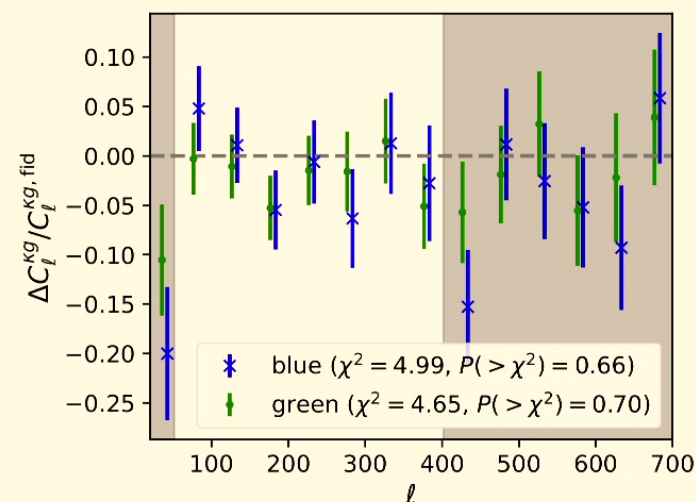
$$b_{X,L} = b_{X,L}^{\text{co-evol.}}(b_{1,E}^{\text{fid}}(z)) + c_{b_{X,L}}^{\text{offset}}$$

# Series of systematics tests: Data null-tests

frequency comparison



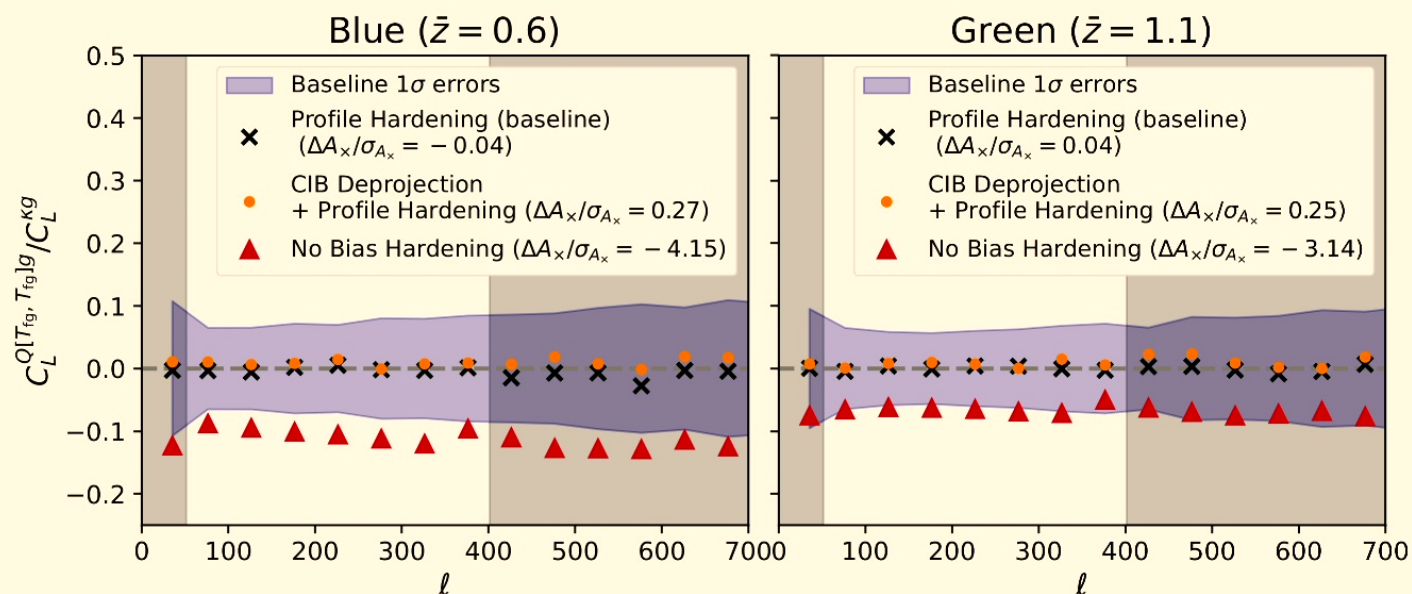
galactic mask comparison



And many more ...

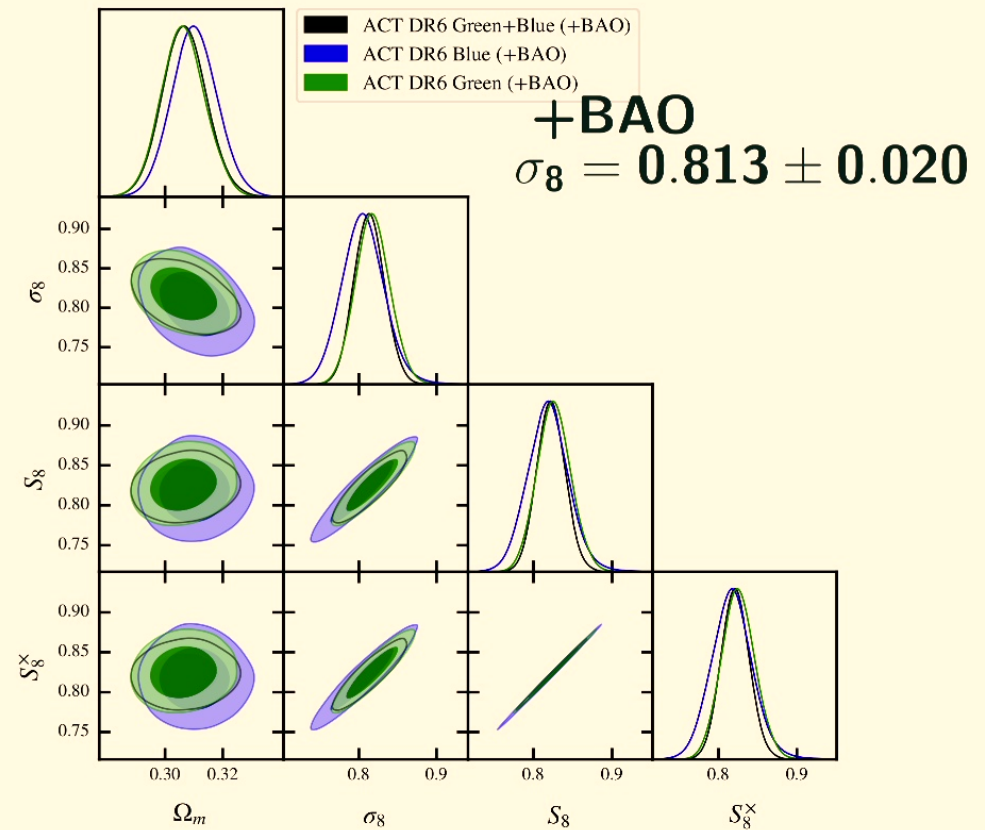
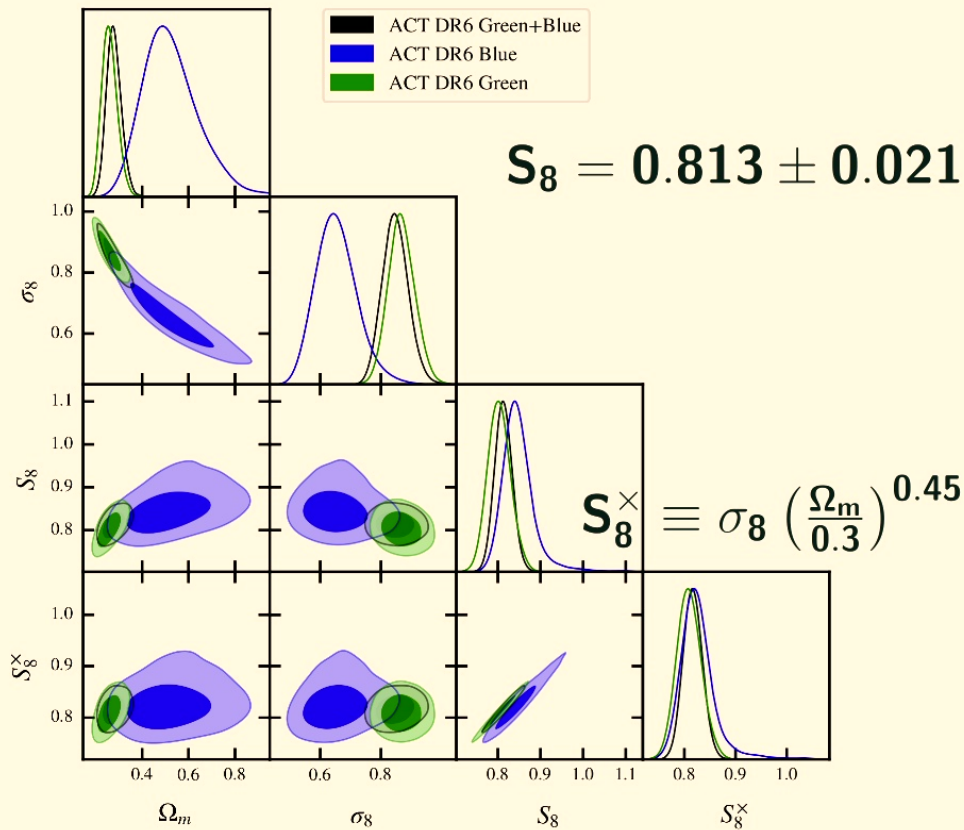
- different reconstruction and bias mitigation strategies
- various different masks

# Series of systematics tests: Simulation driven tests



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

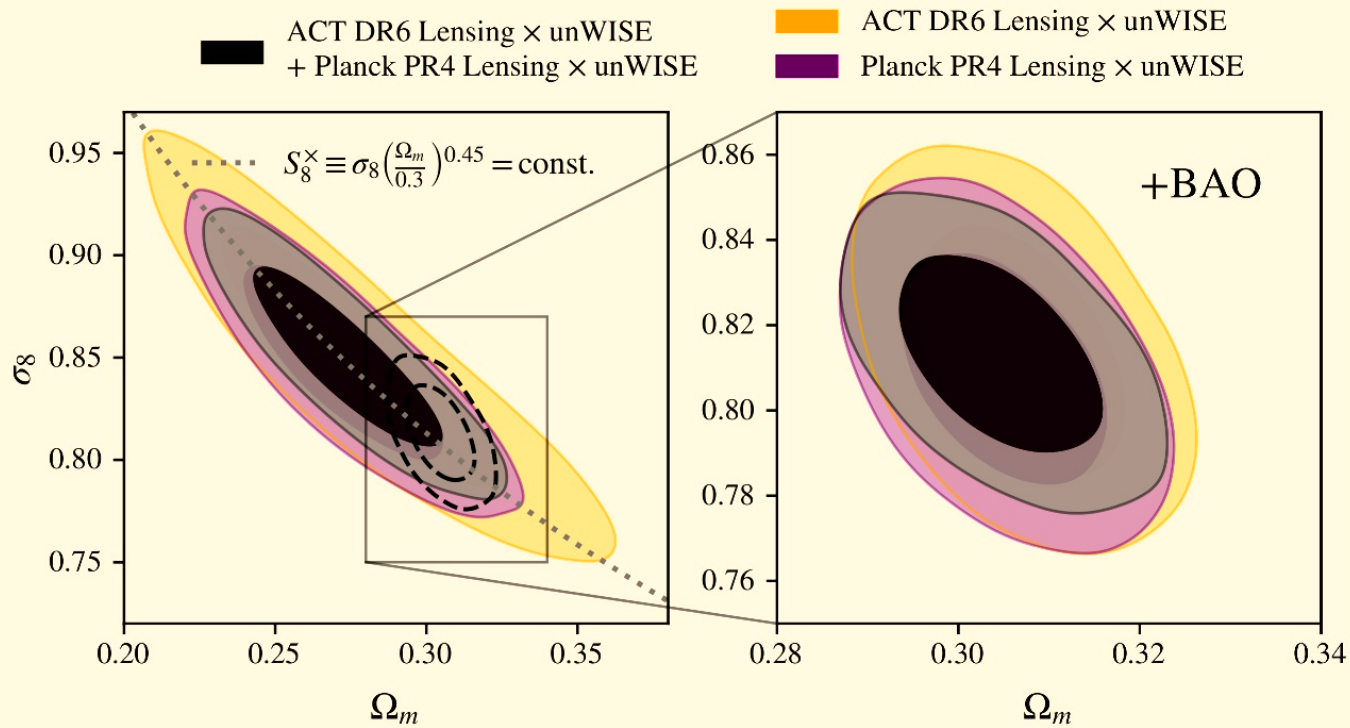
# Cosmology from ACT DR6 Lensing $\times$ unWISE



G. Farren: ACT DR6 lensing and cross-correlations



# Combining with Planck PR4 $\times$ unWISE

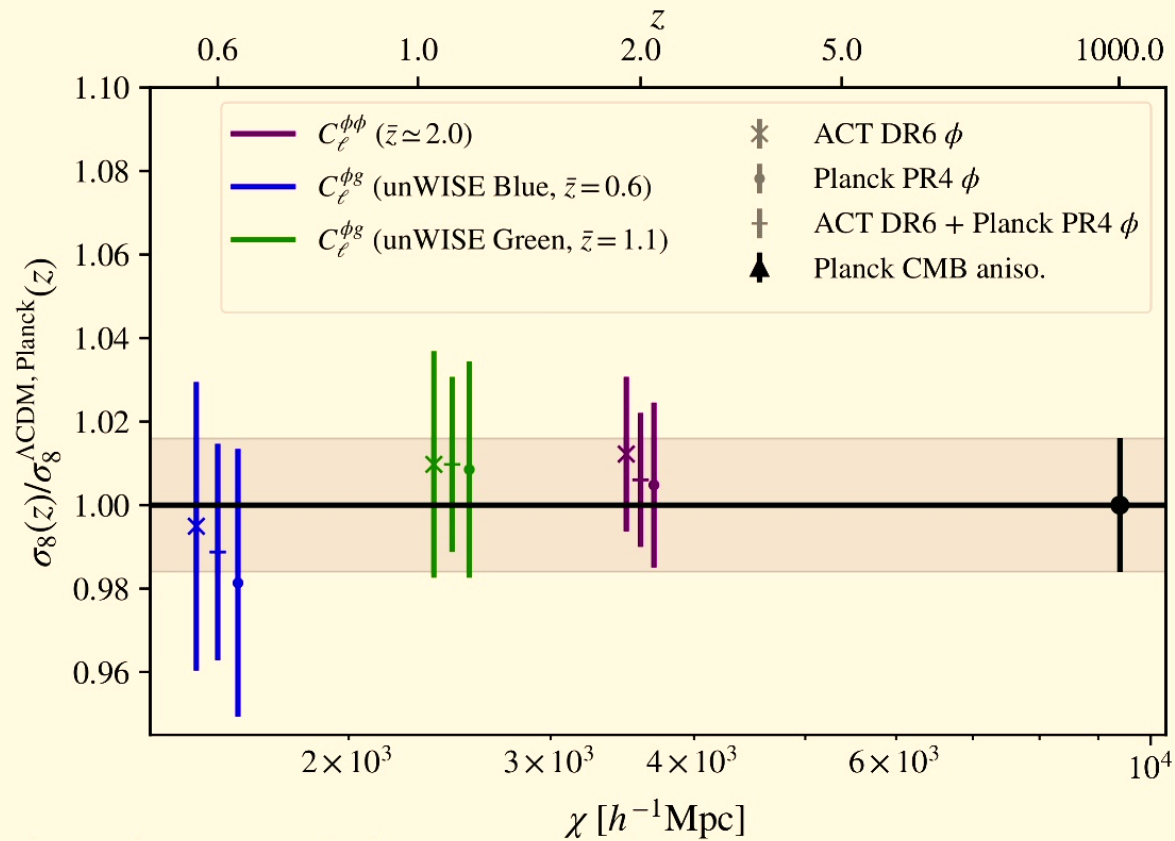


ACT + *Planck*  $\times$  unWISE:

$$S_8 = \mathbf{0.810 \pm 0.015}$$

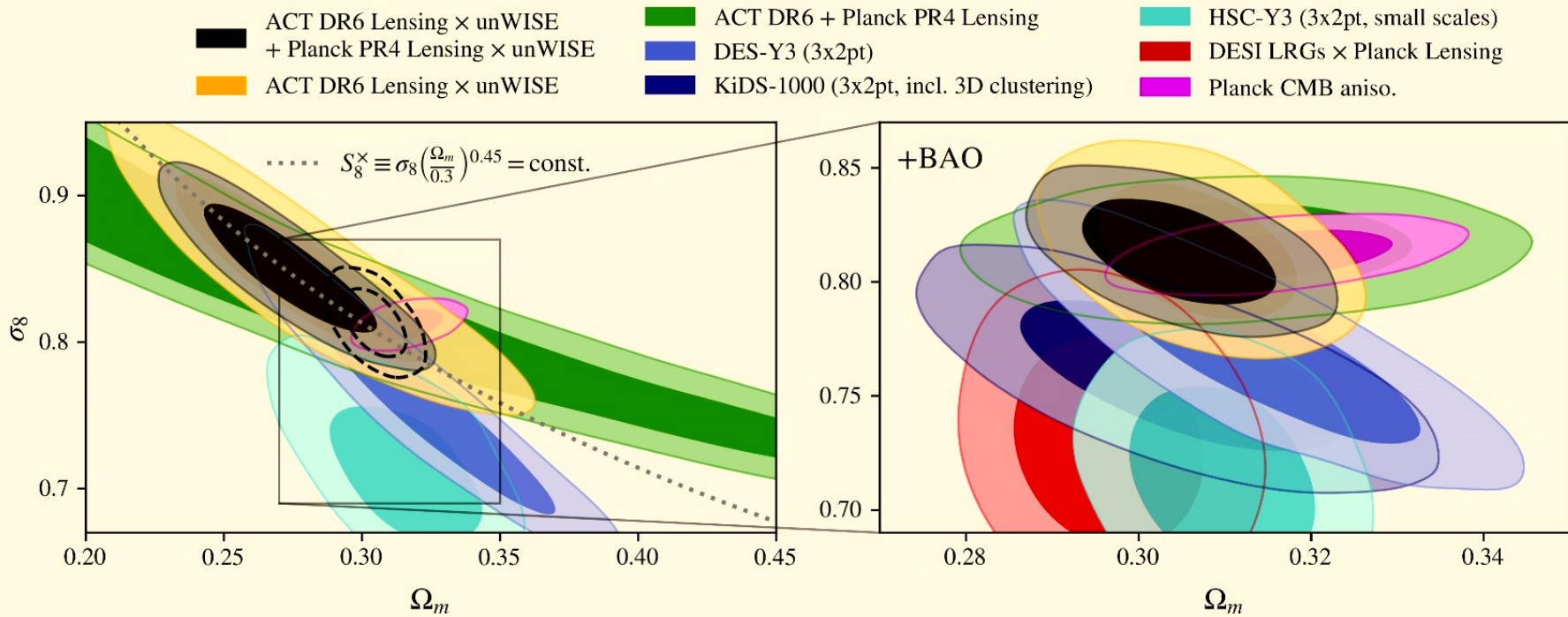
$$\sigma_8 = \mathbf{0.813 \pm 0.015}$$

# Tomographic structure growth - $\sigma_8(z)$



G. Farren: ACT DR6 lensing and cross-correlations

# Comparing to other analyses



# Summary and looking ahead

ACT DR6  $C_\ell^{\phi\phi}$  and  $C_\ell^{\phi g}$  with unWISE are **consistent with primary CMB**:  
no evidence for suppression of structure growth for  $z \gtrsim 0.2$  &  $k \lesssim 0.3h \text{ Mpc}^{-1}$

## Looking ahead

- 3x2pt analysis:  $C_\ell^{\phi\phi} + C_\ell^{g\phi}$  &  $C_\ell^{gg}$
- 3x2pt + primary CMB:  $\sum m_\nu$
- DR6+: additional data (incl. day time), optimal filtering



# Other cross-correlations

## in preparation:

**DESI LRGs:** Kim & Sailer *et al.*  
Hang & Qu *et al.*

**SDSS BOSS:** Wenzl *et al.*

**DES-Y3:** Darwish *et al.*  
Shaikh & Harrison *et al.*  
Pitocco *et al.*  
Kim *et al.*

**Planck CIB:** Mheta *et al.*

**Planck/ACT tSZ :** Bolliet *et al.*

...

ACT DR6 lensing mass map survey overlap

