U.S. DEPARTMENT OF ENERGY

Office of Science

BERKELEY LAB

Bringing Science Solutions to the World

The Atacama Cosmology Telescope:

Multi-probe cosmology with unWISE galaxies and CMB lensing

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based on work with Alex Krolewski, Frank Qu, Niall MacCrann, Boris Bolliet, Simone Ferraro, Blake Sherwin and the ACT Collaboration

arXiv:2309.05659, arXiv:2311.04213, and arXiv:2409.02109

TMEX, 21st Recontres du Vietnam, Jan 7 2025, Quy Nohn, Vietnam

The large scale structure of the universe

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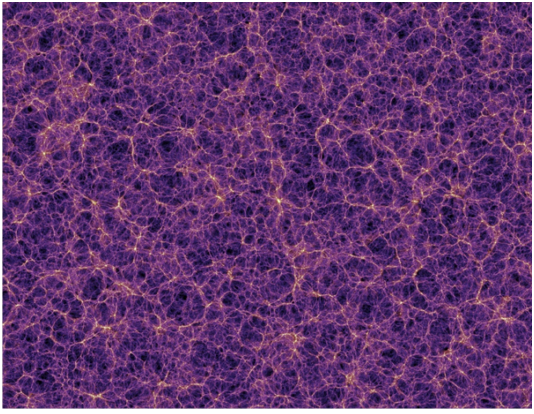
Learning from the distribution of matter in the universe:



- What is the nature of *dark matter* and *dark energy*?
- Is GR is the correct theory of gravity on all scales?
- What is the mass of the neutrinos?
- ...

Fundamental physics in the large scale structure

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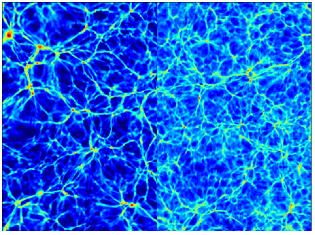
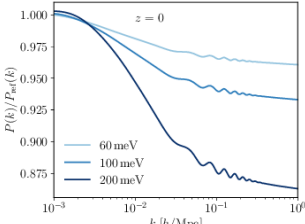
neutrinos

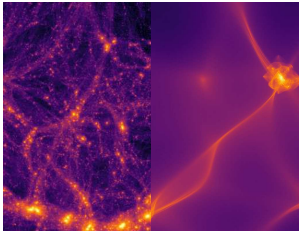
massless massive

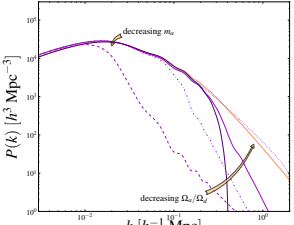




nature of dark matter

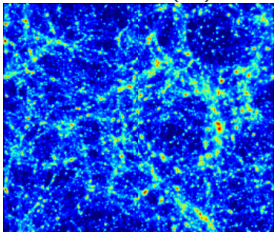
CDM FDM

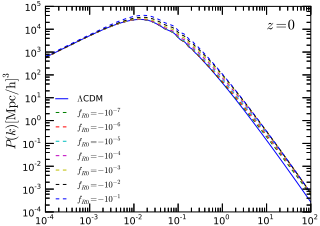




modified gravity

GR $f(R)$





G.S. Farren: CMB $\phi \times$ unWISE δ_g

Image Credit: (*nu*): Agarwal & Feldman, Gerbino et al.; (ULAs): Mocz et al., Marsh et al.; ($f(R)$): He et al.

Fundamental physics in the large scale structure

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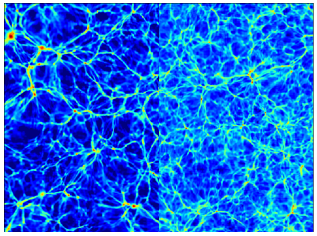

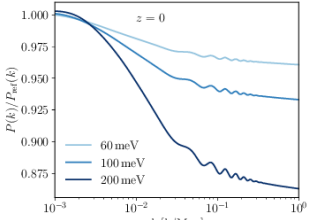

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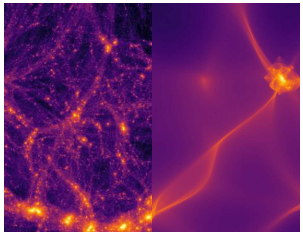

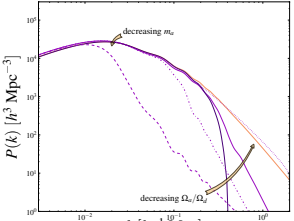

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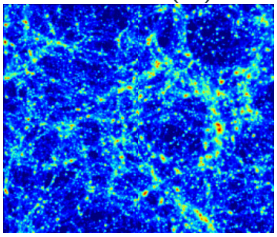

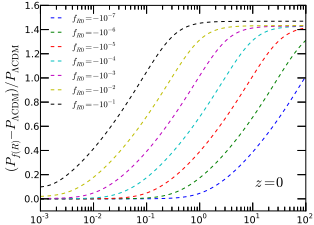

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Introduction to CMB lensing

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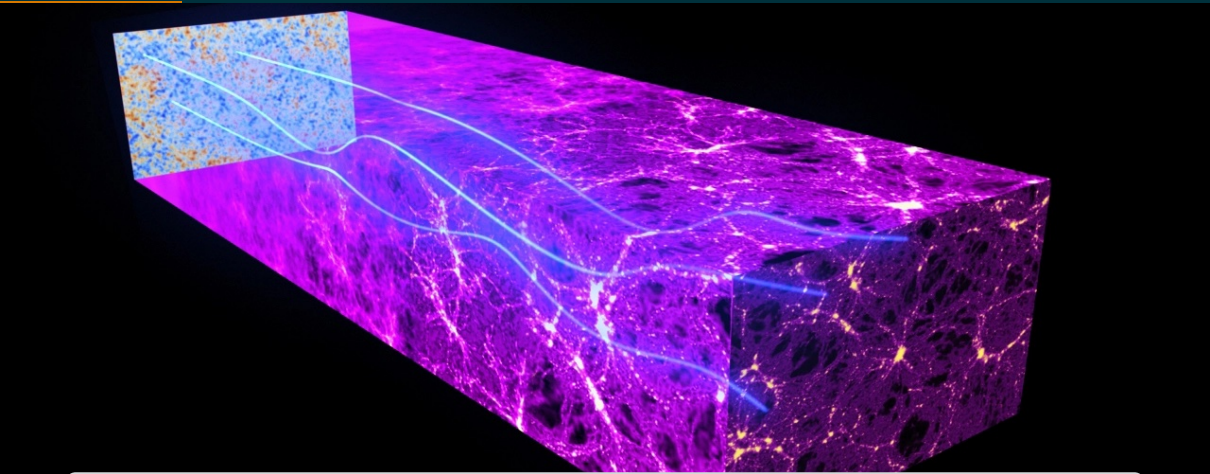

Lensing probes projected matter density

$$\phi \sim \int_0^{\chi_\star} W_\phi(\chi)\delta_m(\hat{\boldsymbol{n}}\chi)d\chi \qquad \kappa = \boldsymbol{\nabla}^2\phi$$

Introduction to CMB lensing

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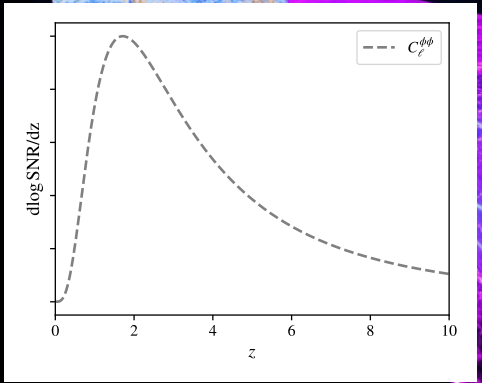

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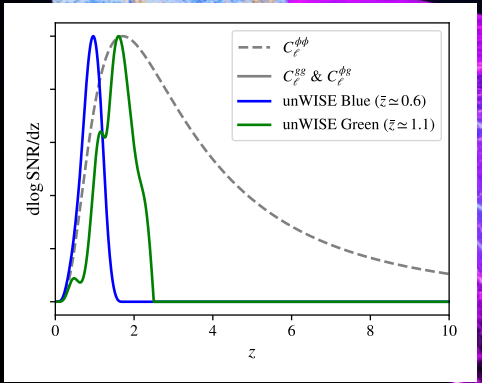

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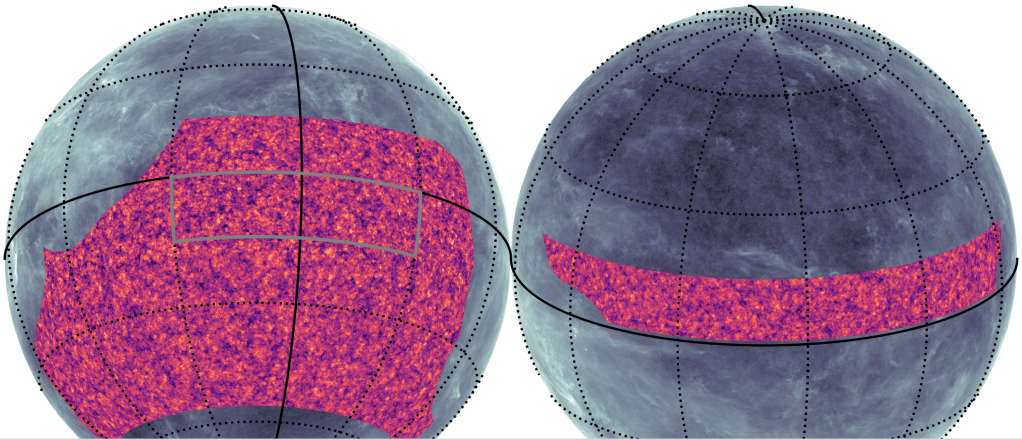
Lensing reconstruction



Reconstruct lensing from off-diagonal correlations in CMB

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

Lensing reconstruction

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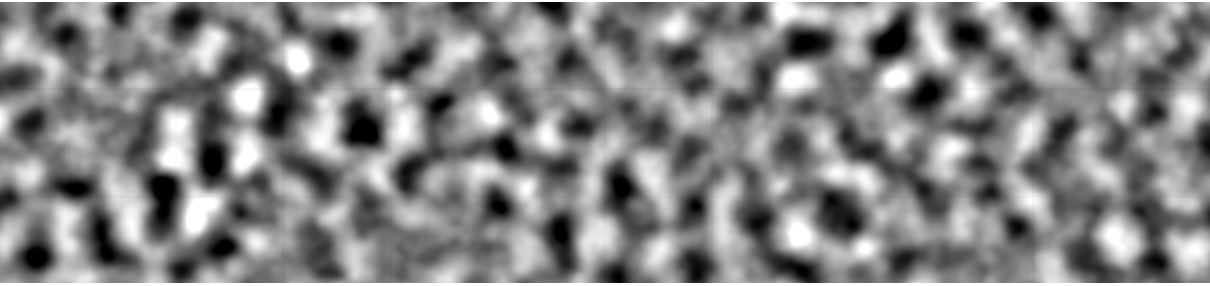

Lensing reconstruction

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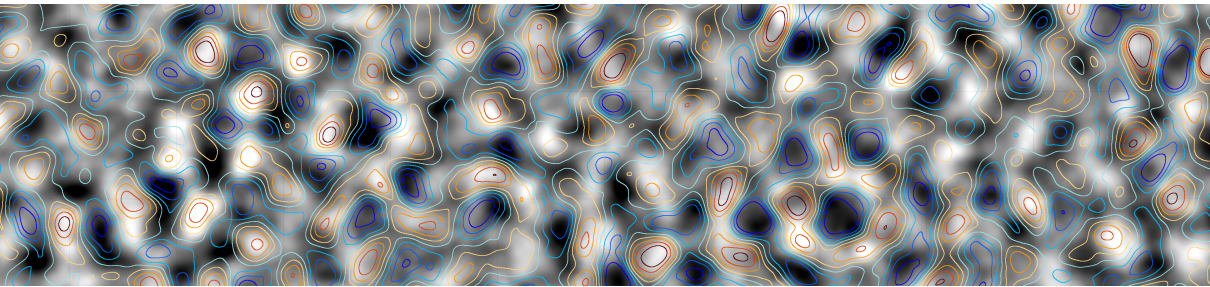

The lensing power spectrum - $\hat{C}_\ell^{\phi\phi}$

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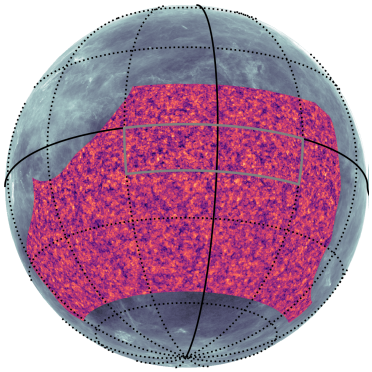
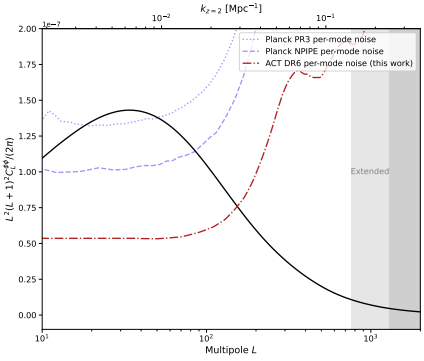


$$\hat{C}_\ell^{\phi\phi} \sim \langle \hat{\phi}_{\ell m} \hat{\phi}^*_{\ell m} \rangle$$



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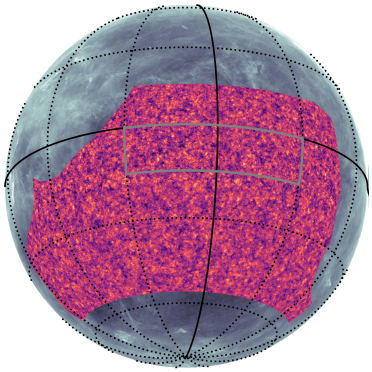

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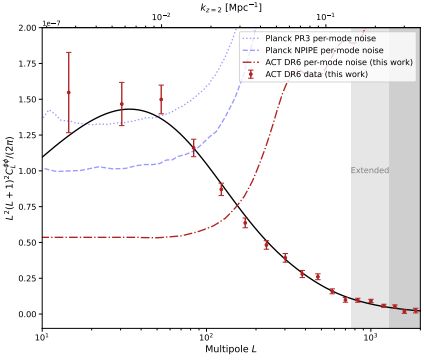

Constraints on cosmic structure form $\hat{C}_\ell^{\phi\phi}$

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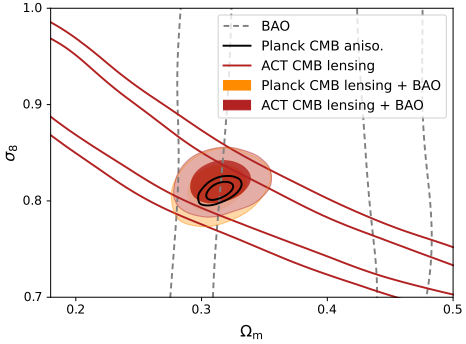
Best constrained parameter

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



ACT DR6 + Planck PR4 Lensing

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

ACT DR6 + Planck PR4 Lensing + BAO

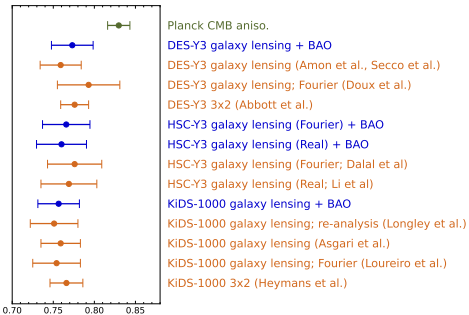
$\sigma_8 = 0.812 \pm 0.013$

cf. primary CMB aniso. (Planck 2018)

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

$\sigma_8 = 0.811 \pm 0.006$

Narrowing in on the S_8 tension



$$S_8 = \sigma_8 \left(\frac{\Omega_m}{0.3}\right)^{0.5}$$

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
  - ....

CMB lensing ϕ × unWISE δ_g

The unWISE galaxy catalogue

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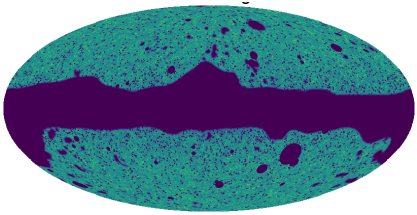
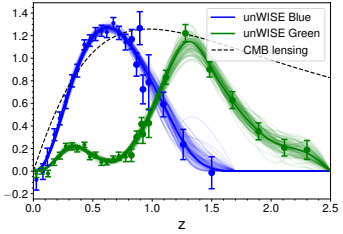
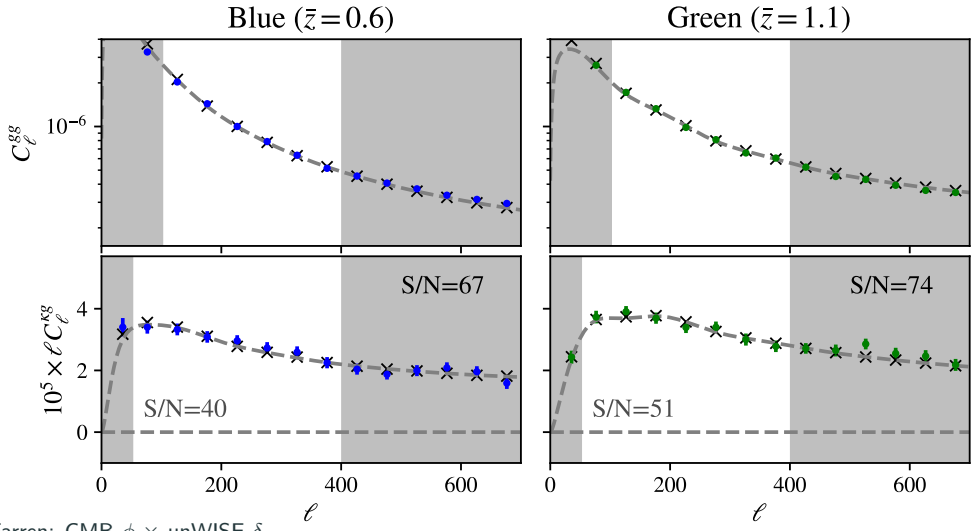
- galaxies from the WISE survey
- >500 million galaxies
- $0 \lesssim z \lesssim 2.5$
- color selection for two samples

sample	$\bar{z}$	$\bar{n}$ [deg^{-2}]
Blue	0.6	∼3400
Green	1.1	∼1800



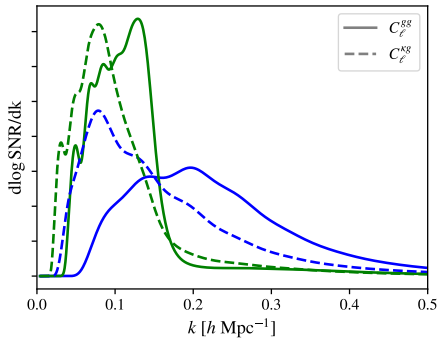


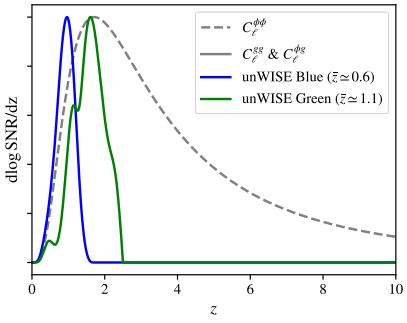
ACT DR6 lensing × unWISE - spectra



Probing different scales and redshifts

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





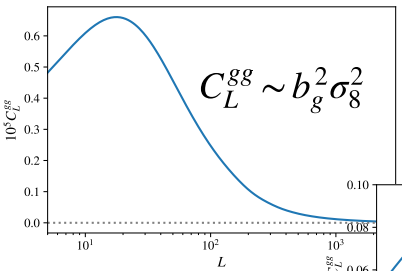
- $C_\ell^{\phi g}$: $z \simeq 0.2 - 1.6$ & $k \lesssim 0.3h\,\mathrm{Mpc}^{-1}$

Measuring S_8 with galaxy - CMB lensing cross-correlations

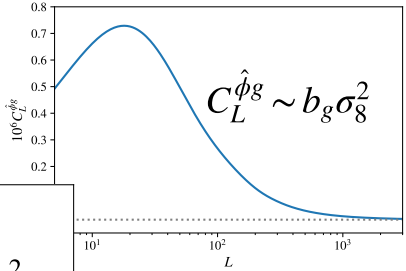
interested in

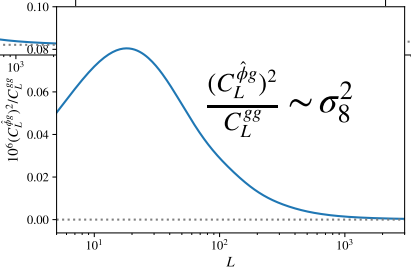
$\sigma_8^2 \sim \langle \delta_m^2 \rangle$

from galaxies



from galaxies × lensing





Highlights of CMB lensing $\times$ unWISE analysis

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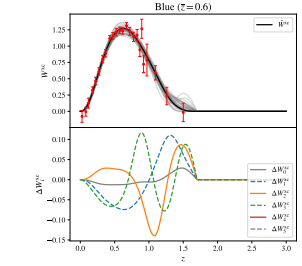
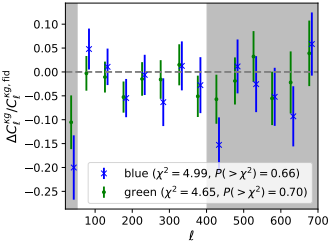
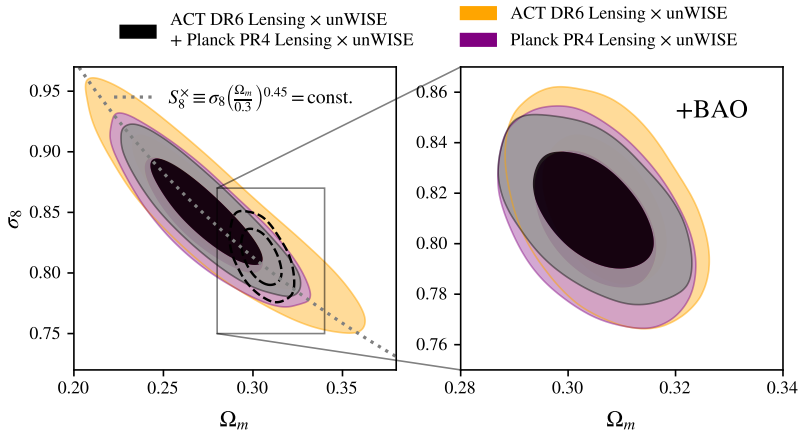
- clustering redshifts for unWISE galaxies
- PCA based marginalisation over redshift uncertainties
- Hybrid `HMCode` + LPT model
- imaging systematics mitigation
- simulation based foreground tests
- extensive null- and consistency tests
- fully blind analysis





Cross-correlation constraints ($C_\ell^{gg} + C_\ell^{\phi g}$)

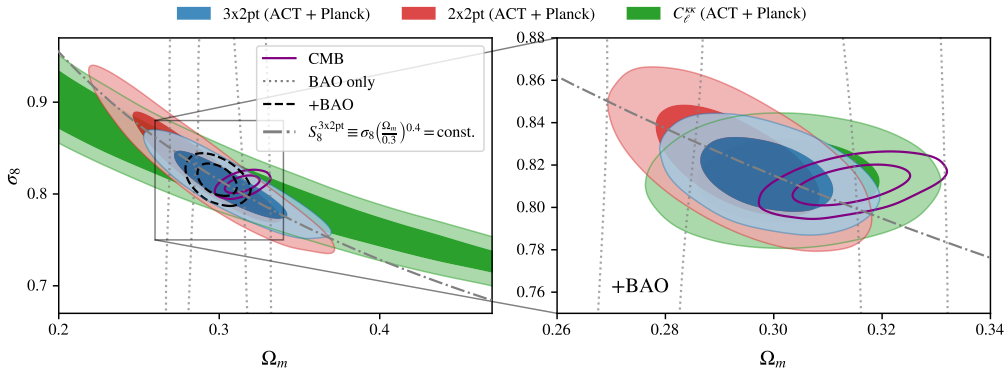


ACT + *Planck* × unWISE:

$$\mathbf{S_8 = 0.810 \pm 0.015} \qquad \sigma_8 = \mathbf{0.813 \pm 0.015}$$

Joint analysis of C_ℓ^{gg}, $C_\ell^{\phi g}$, and $C_\ell^{\phi\phi}$ - 3x2pt

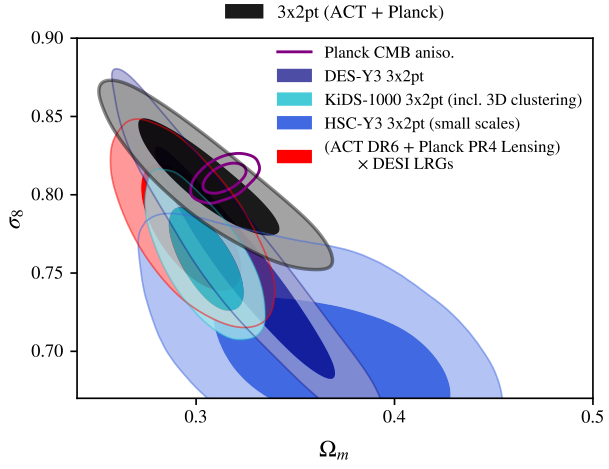
3x2pt vs 2x2pt vs $C_\ell^{\phi\phi}$



ACT + *Planck* & unWISE (3x2pt):

$$\mathbf{S_8 = 0.816 \pm 0.015} \qquad \sigma_8 = \mathbf{0.815 \pm 0.012}$$

Comparing to other probes



What can we do apart from S_8/σ_8?

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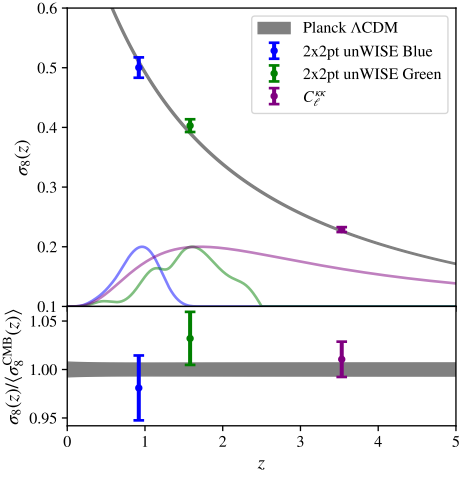
Reconstruct growth of structure



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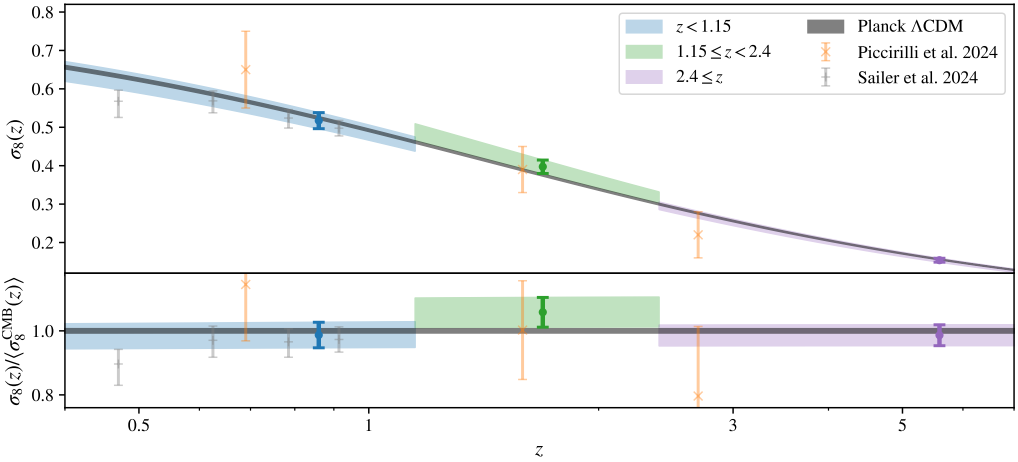

What can we do apart from S_8/σ_8?

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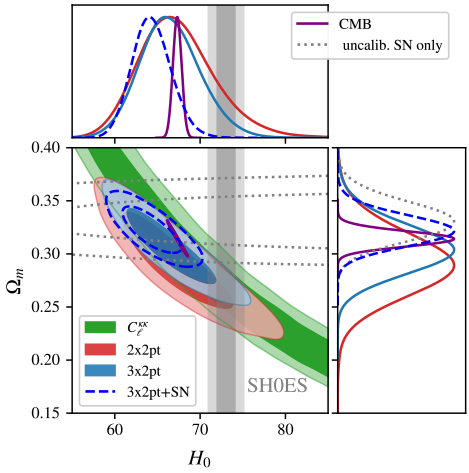
H_0 from the equality scale



- can constrain H_0 without r_s (independent of BAO and CMB)
- without external data:
  $\mathbf{H_0 = 66.5^{+3.2}_{-3.7}\,\mathrm{km\,s^{-1}Mpc^{-1}}}$
- with Ω_M from uncalib. SN:
  $\mathbf{H_0 = 64.3^{+2.1}_{-2.4}\,\mathrm{km\,s^{-1}Mpc^{-1}}}$

Bonus: We have 3x2pt, what about Nx3pt?

measuring $\langle \delta_g \delta_g \phi \rangle$-bispectrum

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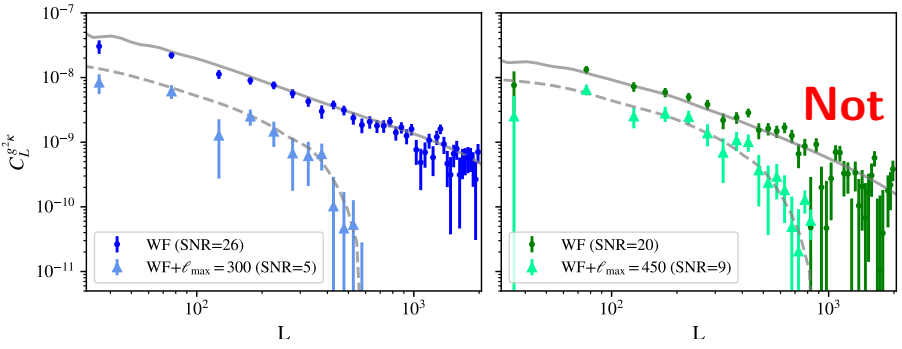

Not a fit!

$$\langle (\tilde{\delta}_g^2)_{LM} \tilde{\phi}^*_{L'M'} \rangle = \delta_{LL'} \delta_{MM'} \underbrace{\sum_{\ell,\ell'} \gamma_{\ell\ell'} B^{gg\phi}_{\ell\ell' L} \overbrace{w^g_\ell w^g_{\ell'} w^\phi_L}^{\text{filters}}}_{C_L^{g^2\phi}}$$

What to take away/look forward to?

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- Powerful constraints on structure formation (including as a function of z)
- and on H_0 independent from other probes
- everything consistent with *Planck* CMB (sorry!)

- data and likelihood available upon publication of 3x2pt paper ($\mathcal{O}(\mathrm{month})$)
- working on...
  a) ACT DR6+ CMB lensing: $\sim 30\%$ larger SNR
  b) unWISE+: deeper, multiband photometry for higher redshift samples, better systematics control
  c) improved x-corr. redshifts with DESI data

The road ahead

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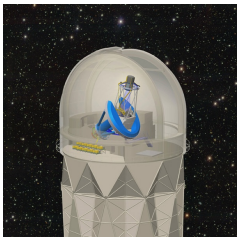
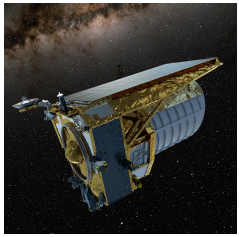
What's next?

- **New data**: SO†, DESI†, LSST, Euclid
- **Improved modelling**: Hybrid EFT, joined photo. and spec. x-corr.
- **Bispectra**: fold in non-Gaussian/non-linear info.

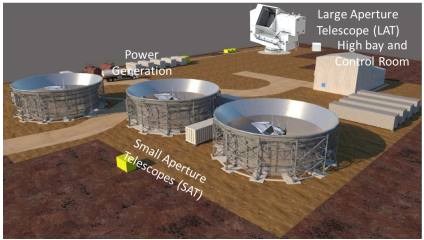
†active member



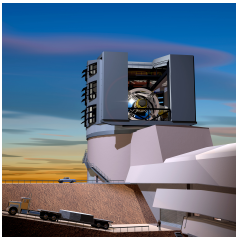
DESI
(2021-2026+)



Euclid
(2023-2029+)



Simons Observatory (2024-2029+)



VRO/LSST
(2026-2036)

Thank you!