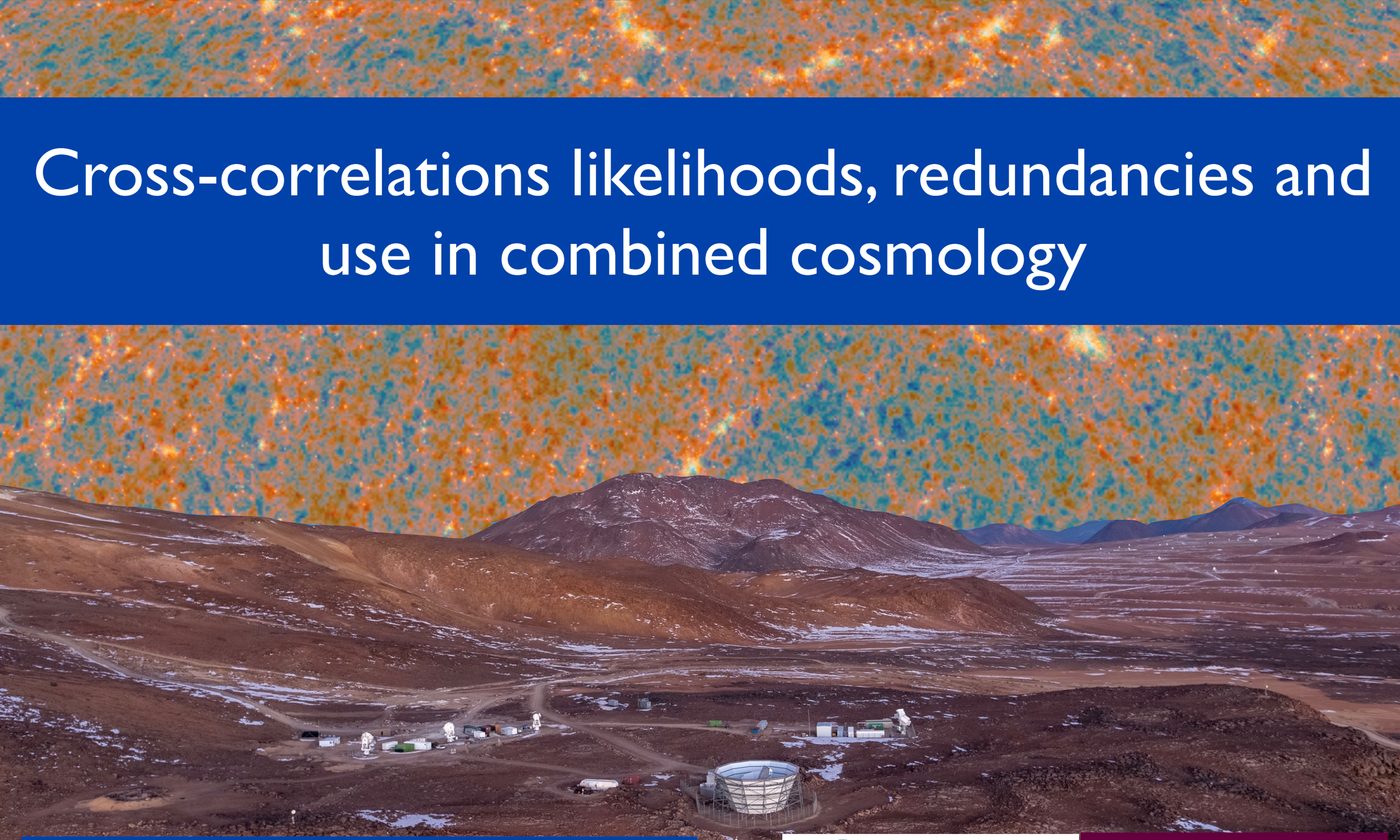
Cross-correlations likelihoods, redundancies and use in combined cosmology

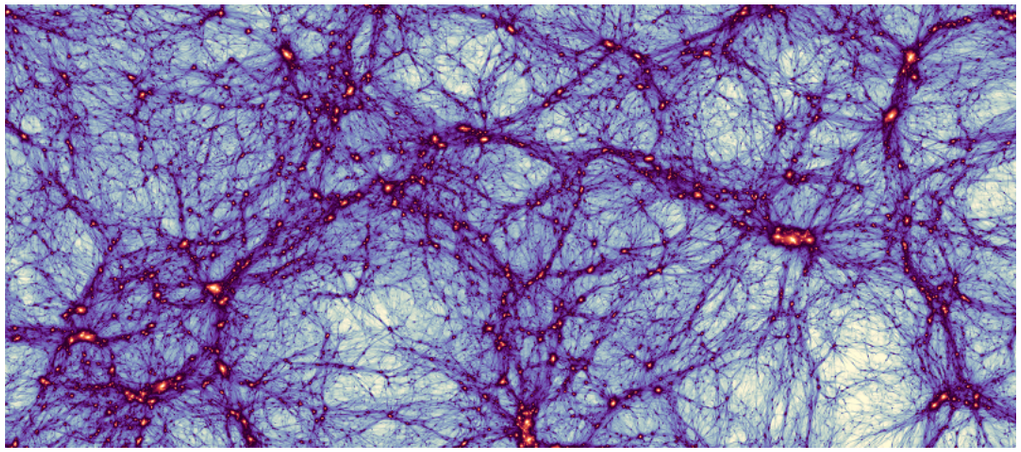


Giulio Fabbian

Institut d'Astrophysique Spatiale

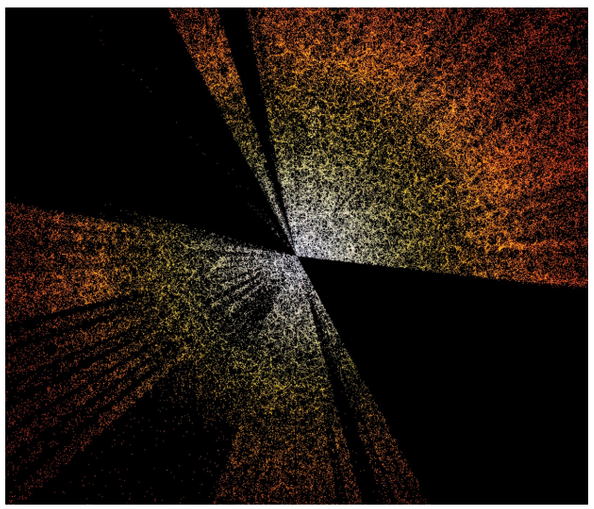
Beyond CMB observations

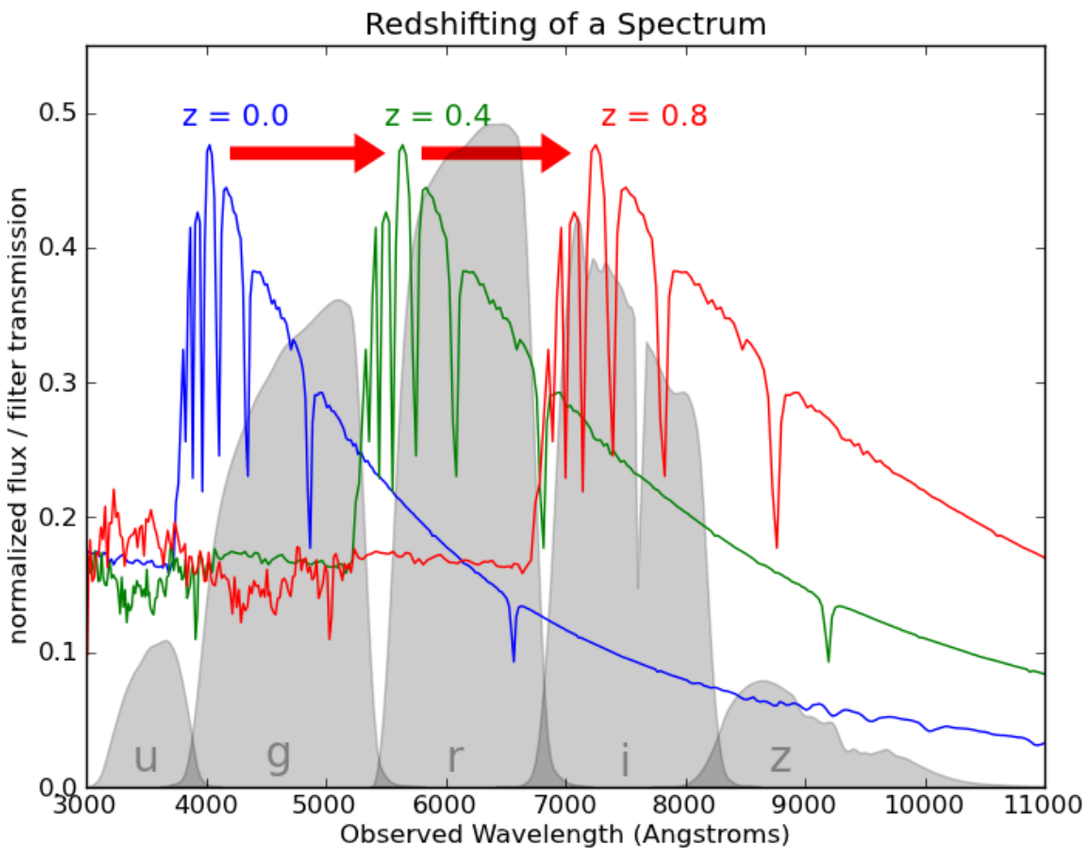
- Observing matter distributions as it grows: we need proxies



$$f[\delta_m]$$

- Spectroscopic surveys (e.g. DESI)

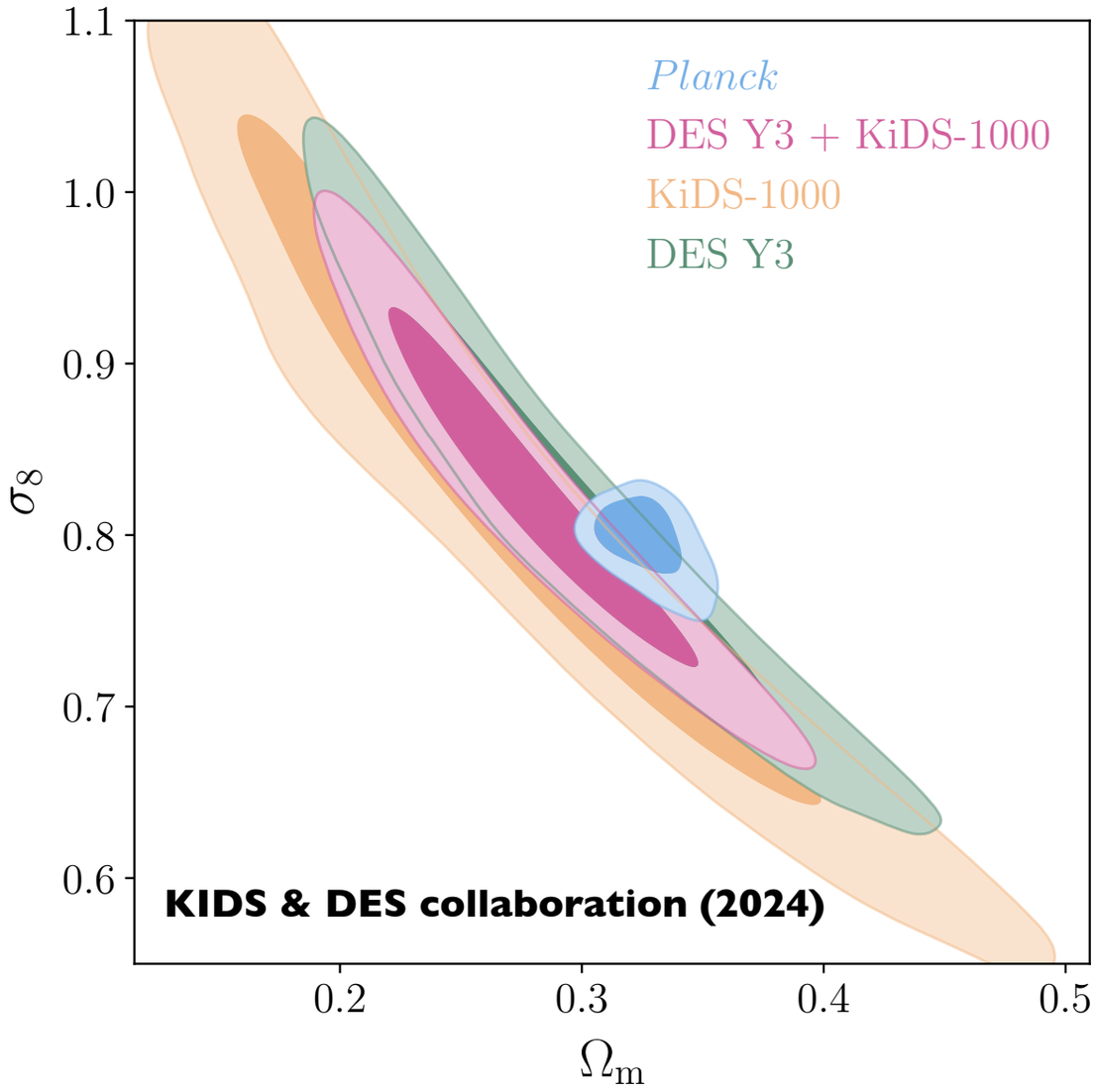


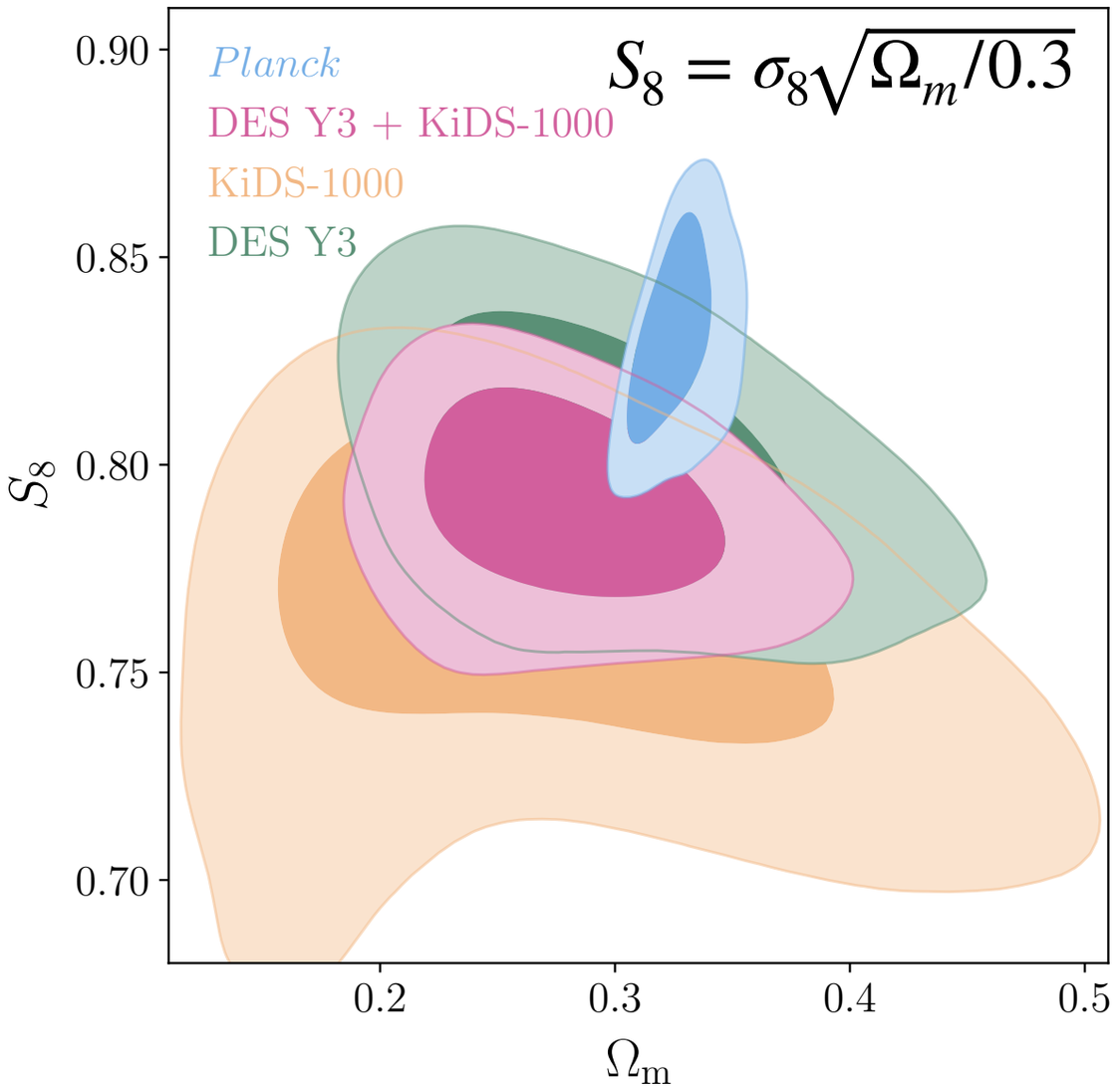


- Photometric surveys (e.g. Rubin)

Photometric 3x2pt

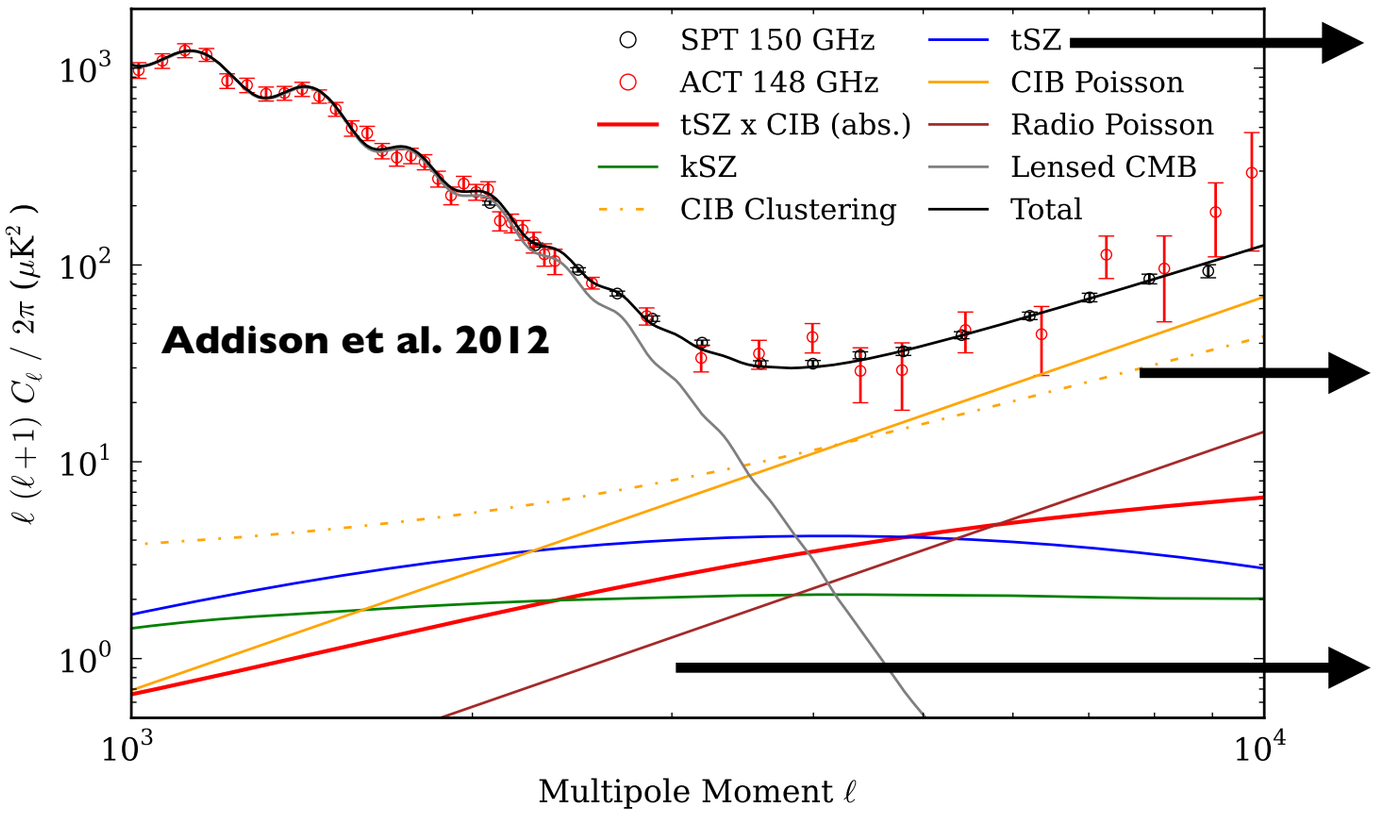
- Galaxy clustering: local, growth rate $C_\ell^{gg} \propto b_g^2 \sigma_8^2$
- Weak lensing /shear: LOS integrated, sensitive to amplitude
- Shear + galaxy-shear: sensitive to $\partial C_\ell / \partial P(k), C_\ell^{g\gamma} \propto b_g \sigma_8^2$

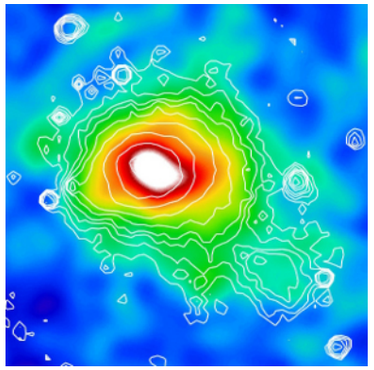




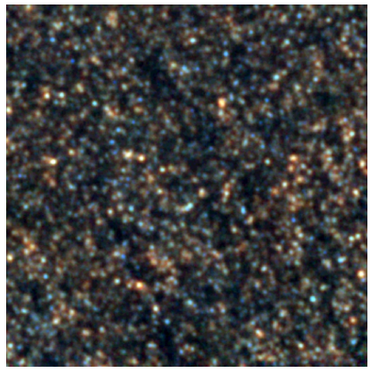
Is CMB "the" CMB?

- CMB is a snapshot of the universe at z ~1100.... plus lots of other things!
  - Galactic foreground emissions (dust, synchrotron, free-free, AME)
  - Imprint of astrophysical objects / late time physics (**lensing**, ISW, SZs…)

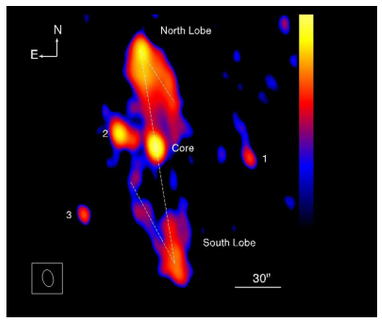




- ICM (g)astrophysics, cosmology (SZ)



- Star formation, cosmology (CIB)



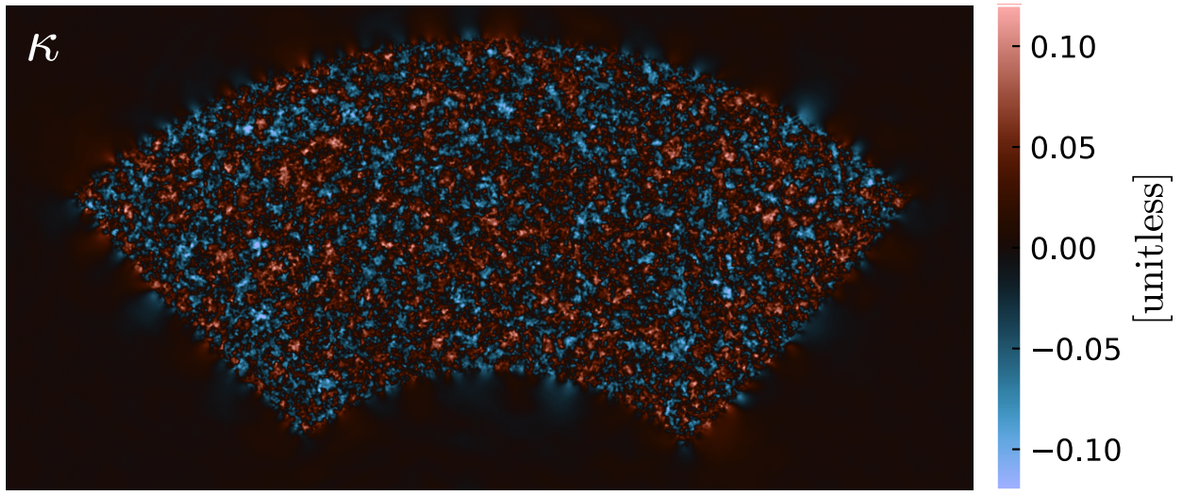
- Extragalactic astronomy, Galaxy evolution

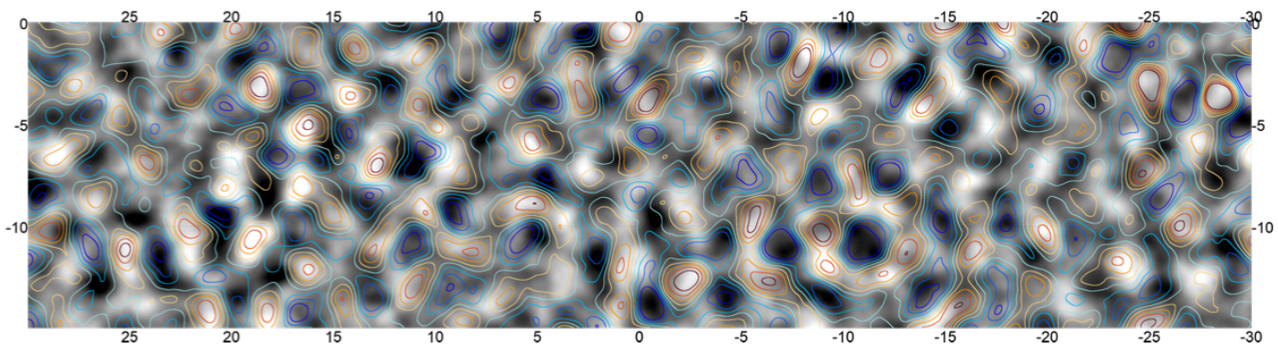
The CMB lensing potential

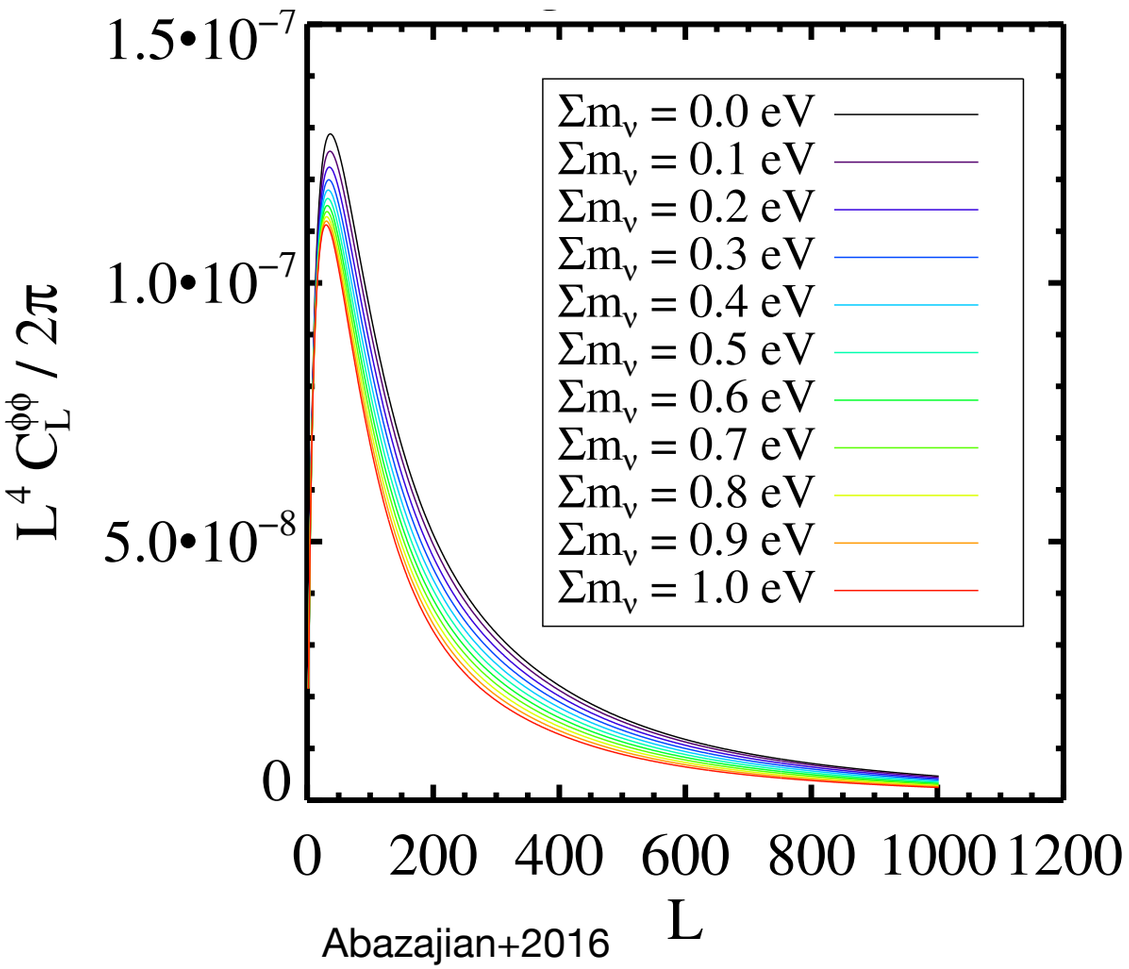
- Unbiased tracers of the whole integrated matter distribution along the line of sight.

$$\phi(\boldsymbol{\theta}) = -2 \int_0^{\chi_s} \frac{D_A(\chi_s - \chi')}{D_A(\chi_s) D_A(\chi')} \Psi\left(\boldsymbol{\theta}, \chi'\right) \mathrm{d}\chi'$$

- Sensitive to matter z~0.6-5, mildly non-linear scales, good for neutrino mass!

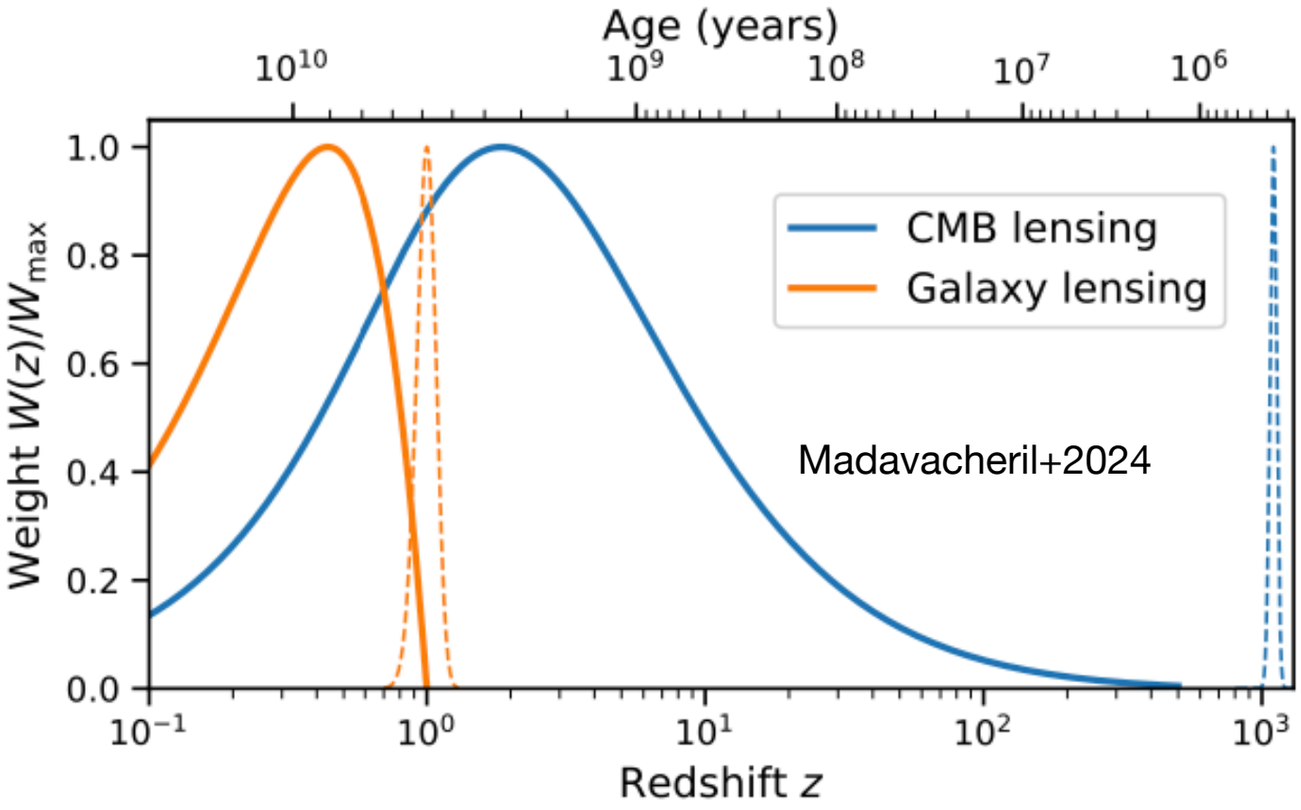






CMB matter probes and cross-correlation

- Overlaps with all the matter in the universe (integrated probes)
  - Synergies with any other probe of matter (e.g. LSS surveys).
- Reduces systematics $\langle \kappa_{CMB,obs} \kappa_{gal,obs} \rangle = \langle \kappa_{CMB} \kappa_{gal} \rangle + \cancel{\langle s_{CMB} s_{gal} \rangle} + \cancel{\langle \kappa_{CMB} s_{gal} \rangle} + \cancel{\langle \kappa_{gal} s_{CMB} \rangle}$



Cross-correlation primer and examples

$$C_L^{AB} \approx \int \frac{d\chi}{\chi^2} W_A(\chi) W_B(\chi) P_\delta \left(k = \frac{L+1/2}{\chi}, z(\chi) \right)$$

CMB lensing

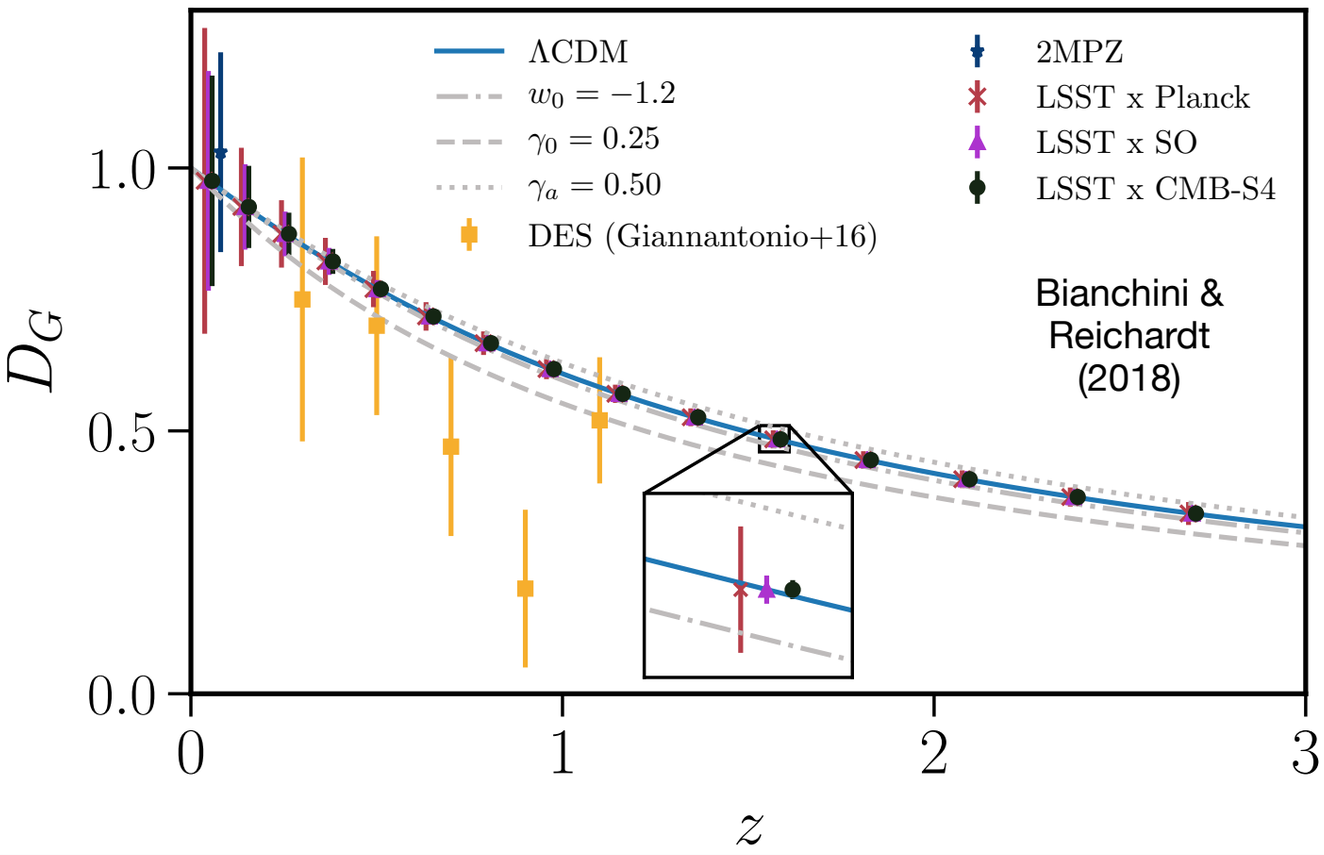
Photometric Galaxy clustering

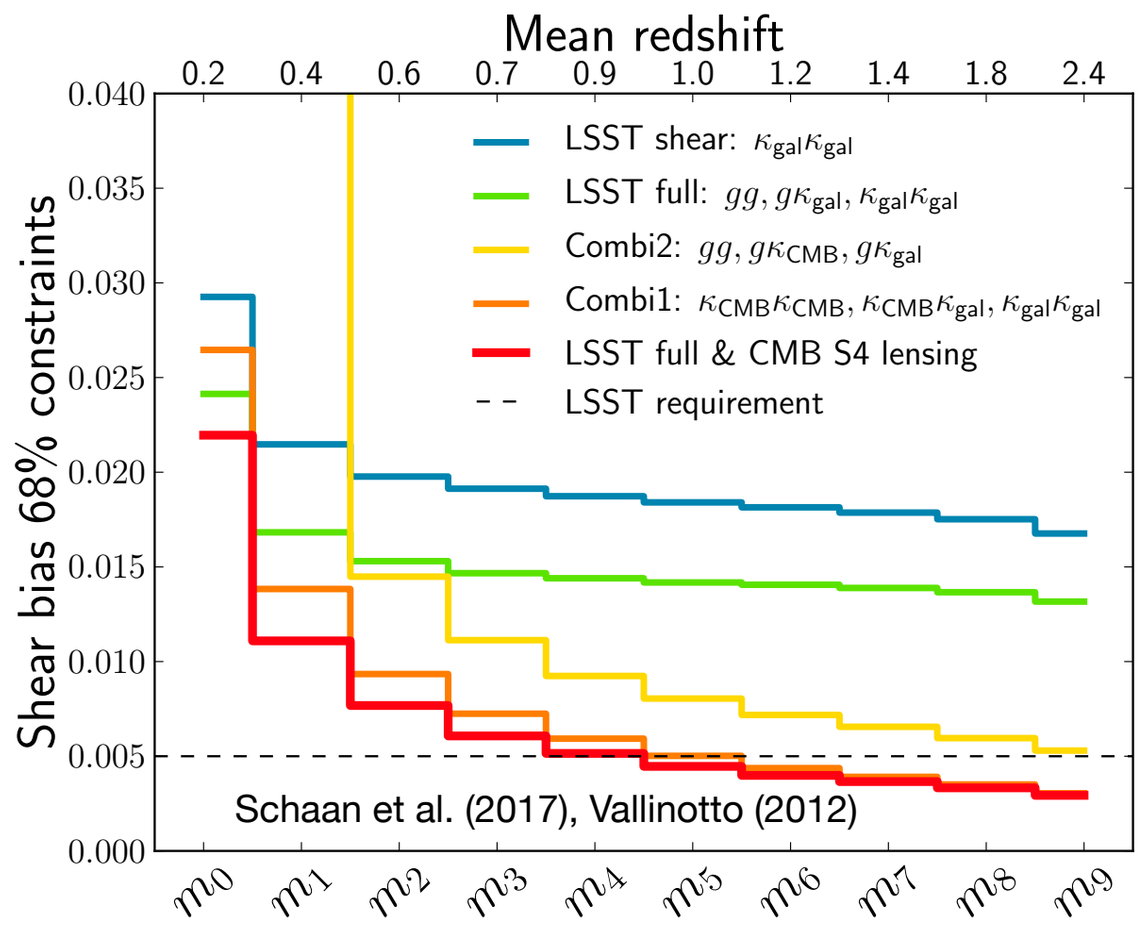
Galaxy lensing

$$W_g(\chi) = b_g(z) \frac{1}{n} \frac{dn}{dz} \frac{dz}{d\chi}$$

$$W_\kappa(\chi, \chi_s) = \gamma(\chi) \chi^2 \left(\frac{1}{\chi} - \frac{1}{\chi_s} \right) \Theta(\chi_s - \chi)$$

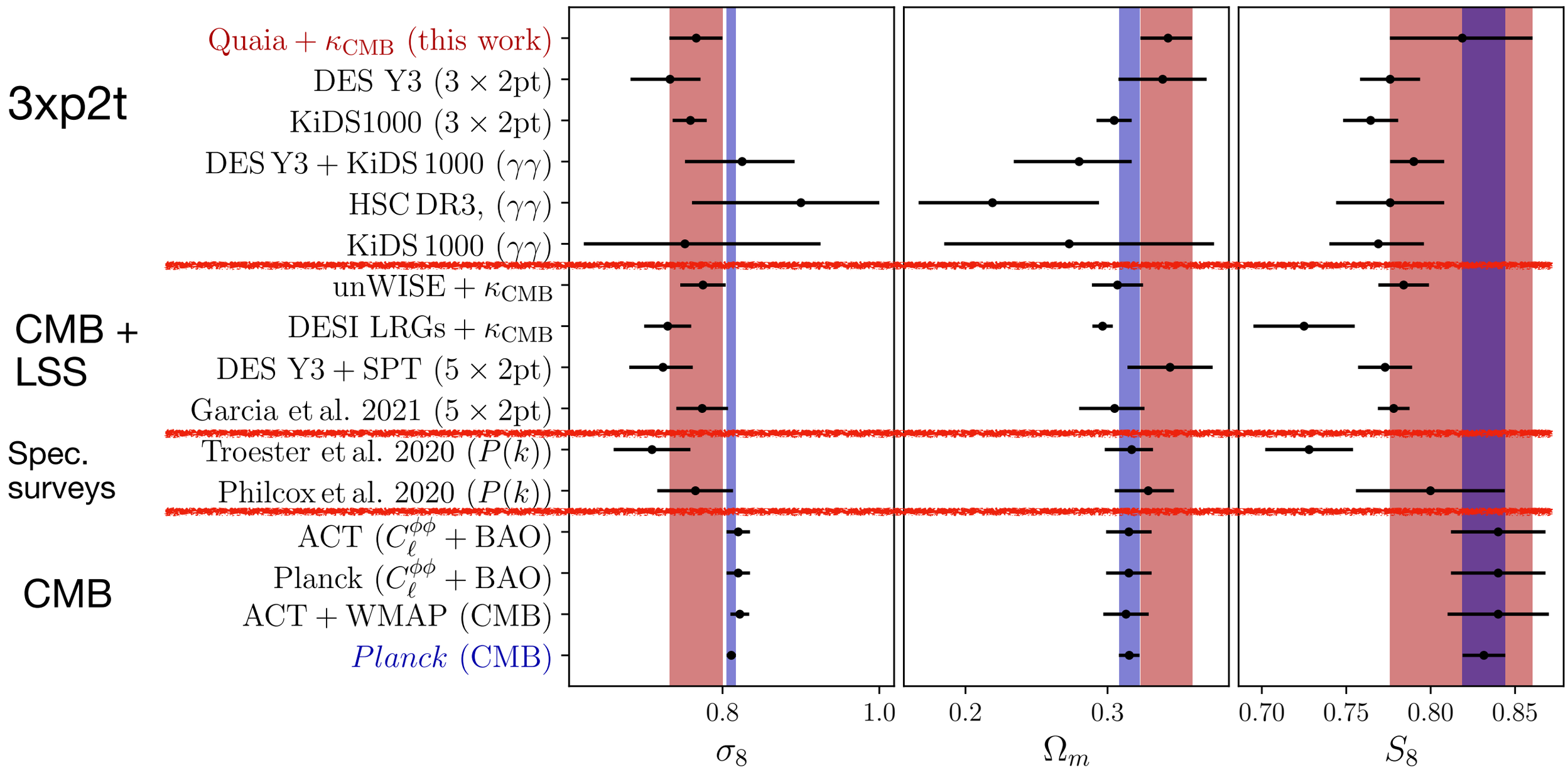
$$D_G \approx (C_\ell^{\kappa g})^2 / C_\ell^{gg} \approx \hat{\boldsymbol{\theta}} \in \{C_\ell^{\kappa g}, C_\ell^{gg}\}$$





State of the art on tensions (outdated)

- Lots of inconsistencies and agreement across data sets
- Is inconsistency between probes a consequence of new physics?

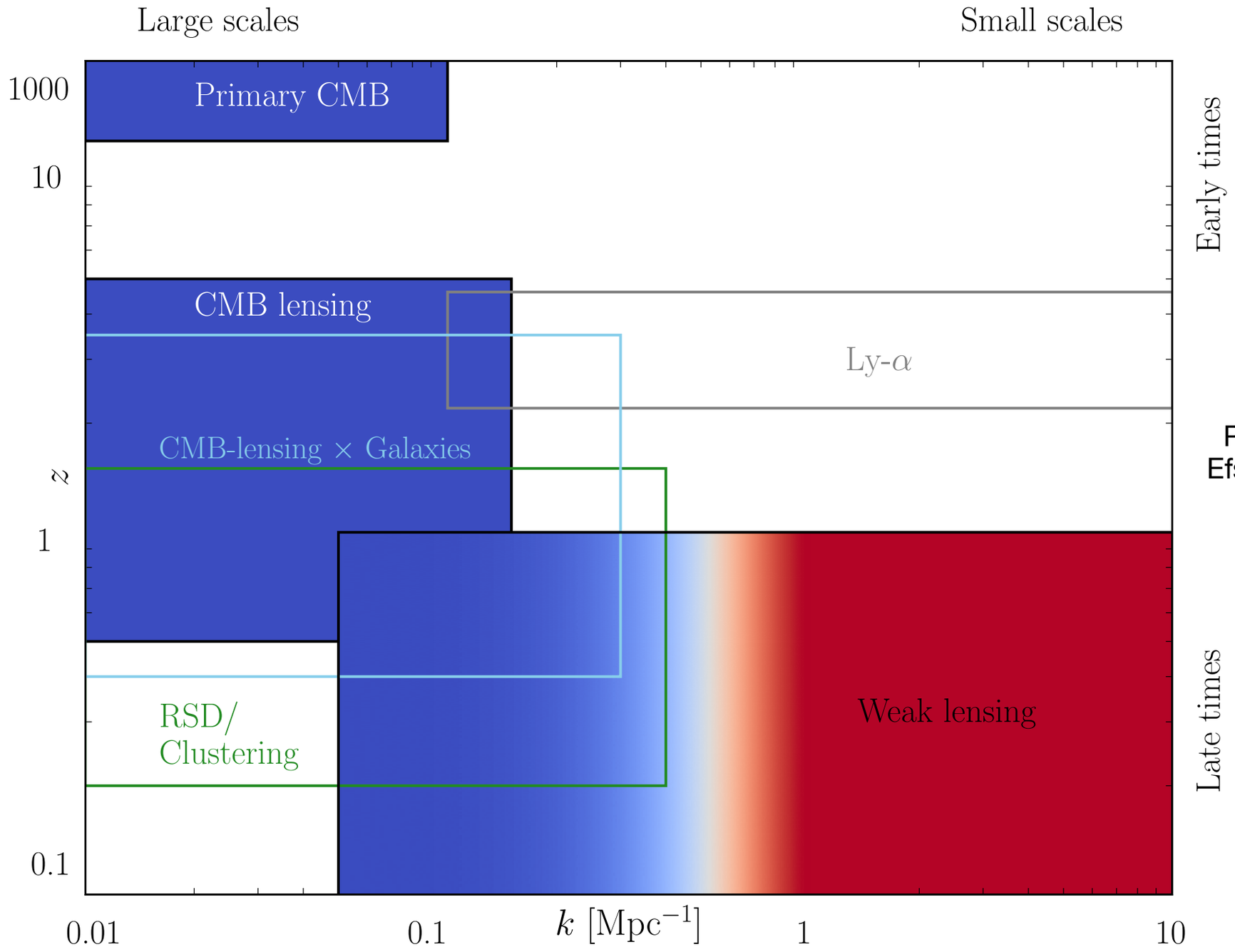


Alonso, Fabbian, Storey-Fisher+(2023)

Cosmological probes and cross-correlations

- Different probes test different scales and redshift (and different systematics).

- Tackling DE: to assess if growth tension is real or effect of non-linear physics.

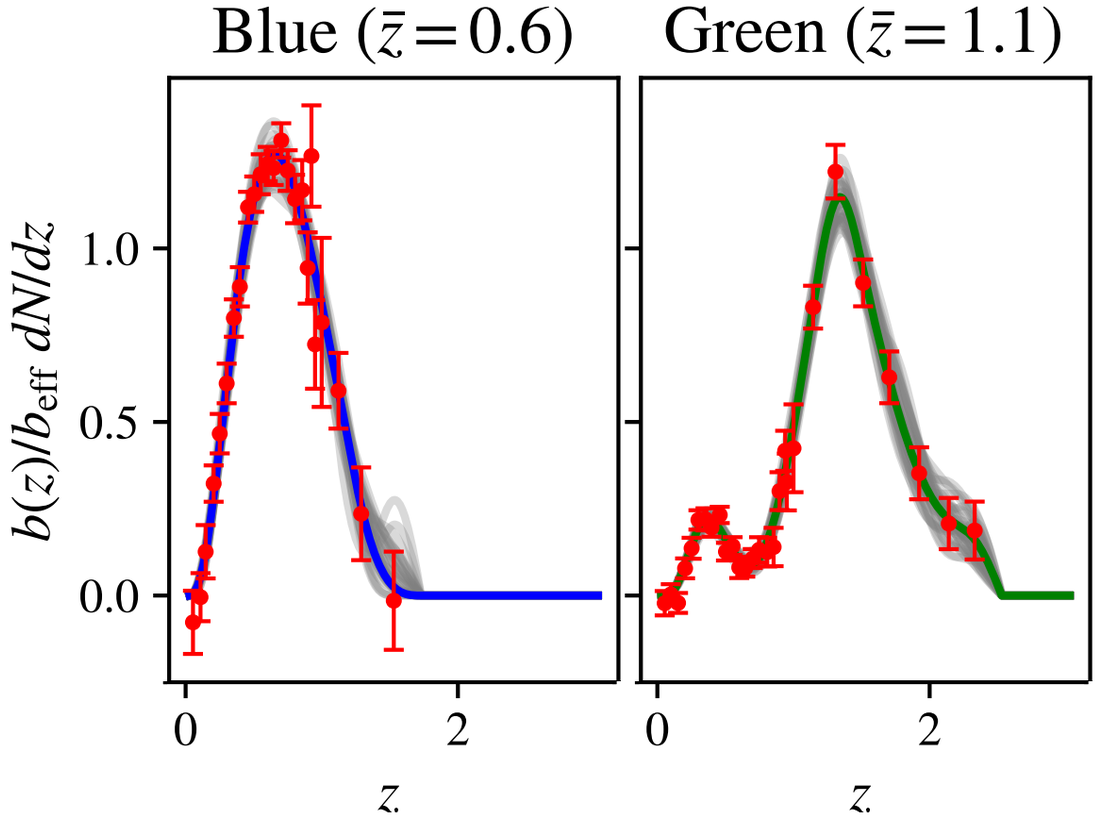


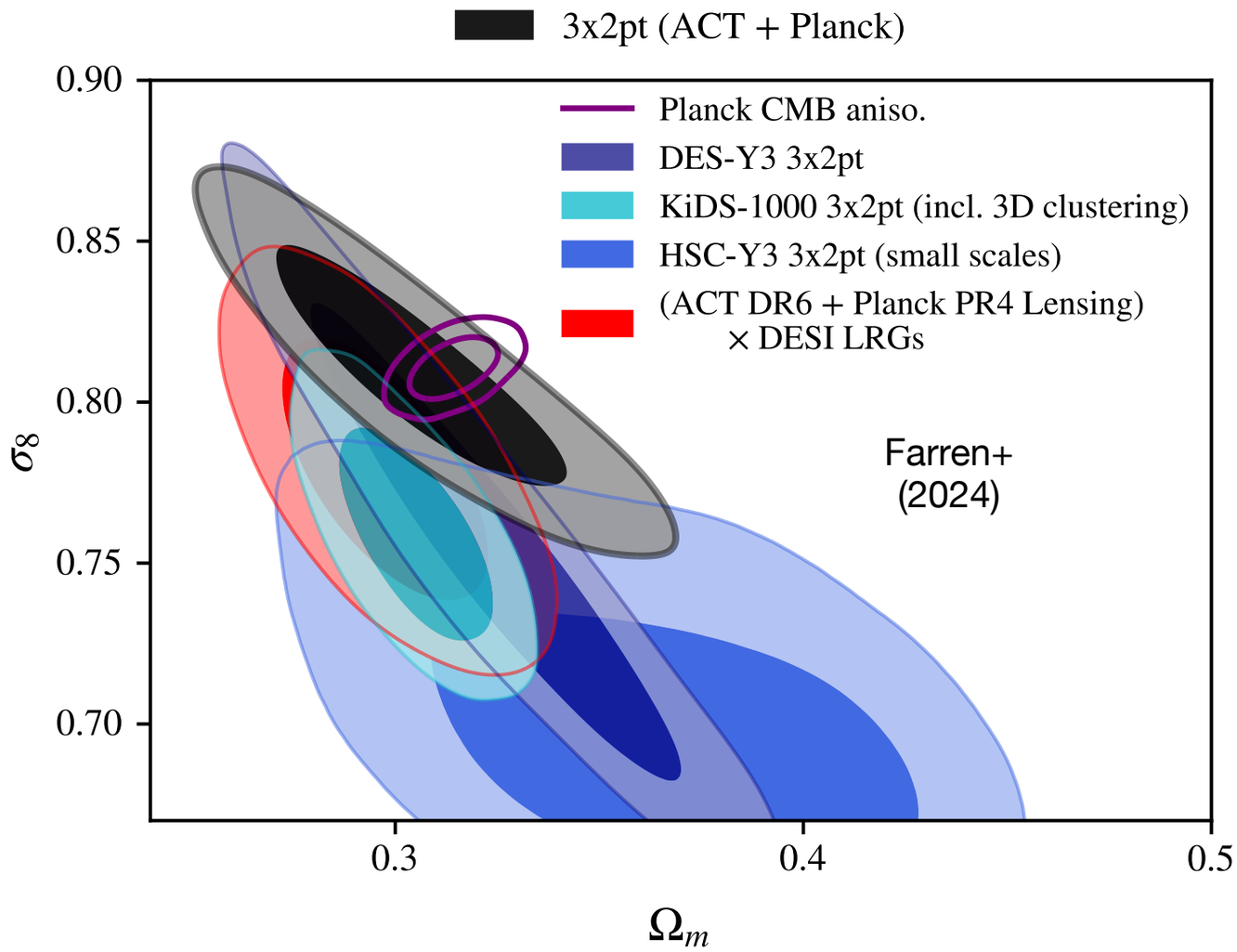
Preston, Amon, Efsthathiou (2023)

CMB lensing x galaxies: state of the art I

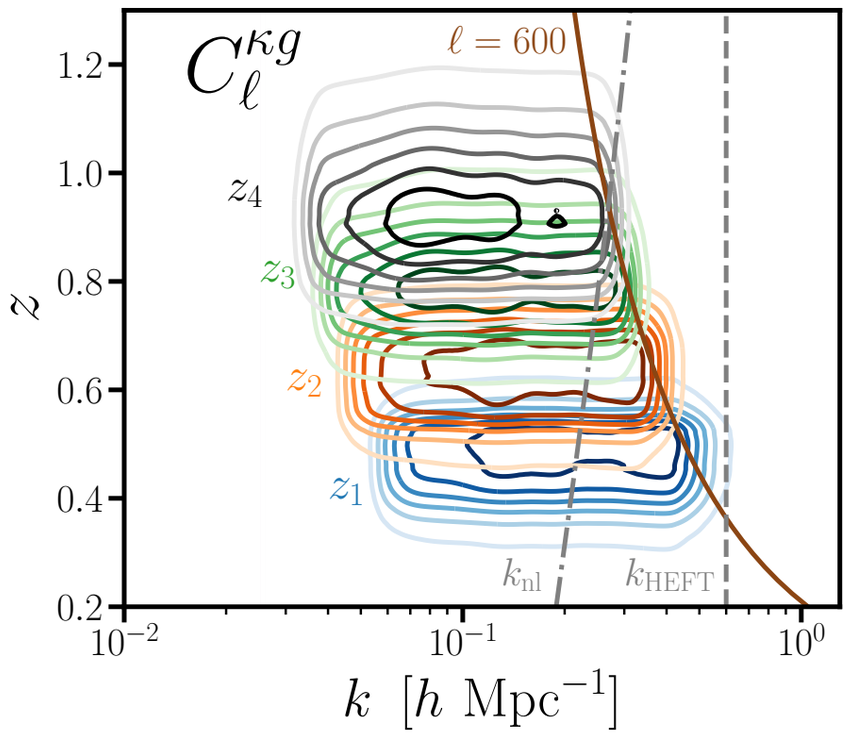
- 6xp2t w/ UNWISE x ACT DR6 & Planck PR4: in agreement with CMB primary
- UNWISe Green / blue galaxies at z~0.6 / 1.1
- Tensions limited to $k \gtrsim 0.3\ h/\mathrm{Mpc}$ in $0.2 \leq z \leq 1.6$ (from 2x2pt)

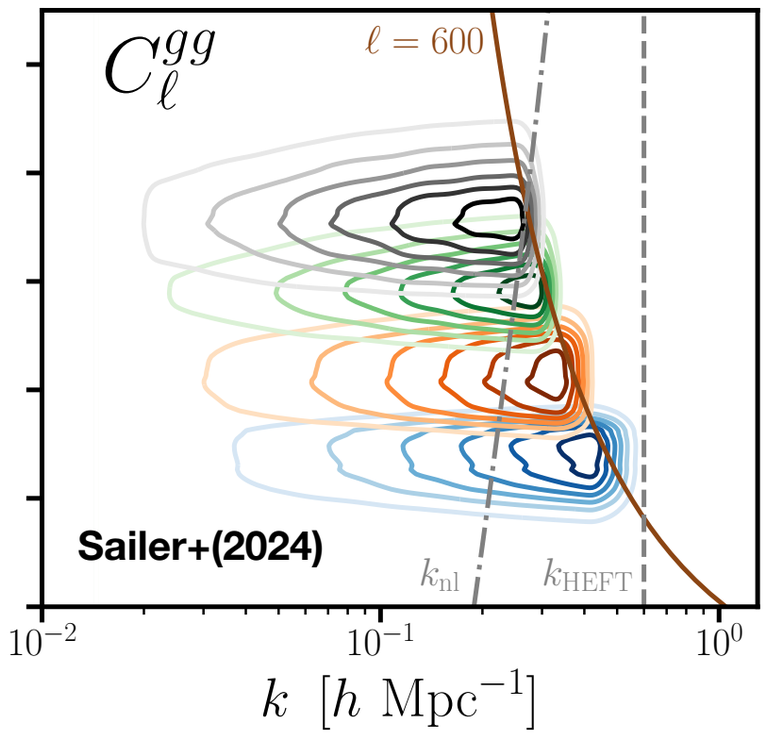
$$S_8 = 0.816 \pm 0.015 \qquad \sigma_8 = 0.815 \pm 0.012$$



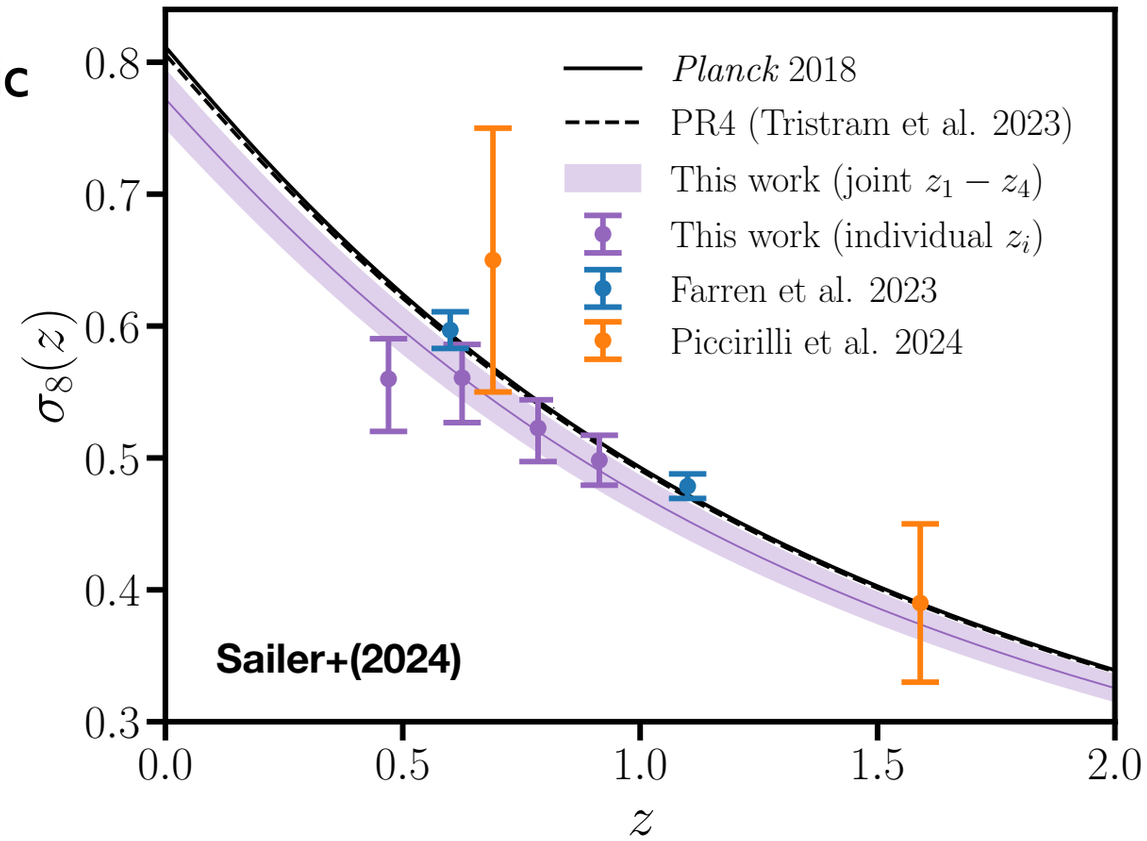


CMB lensing x galaxies: state of the art 2



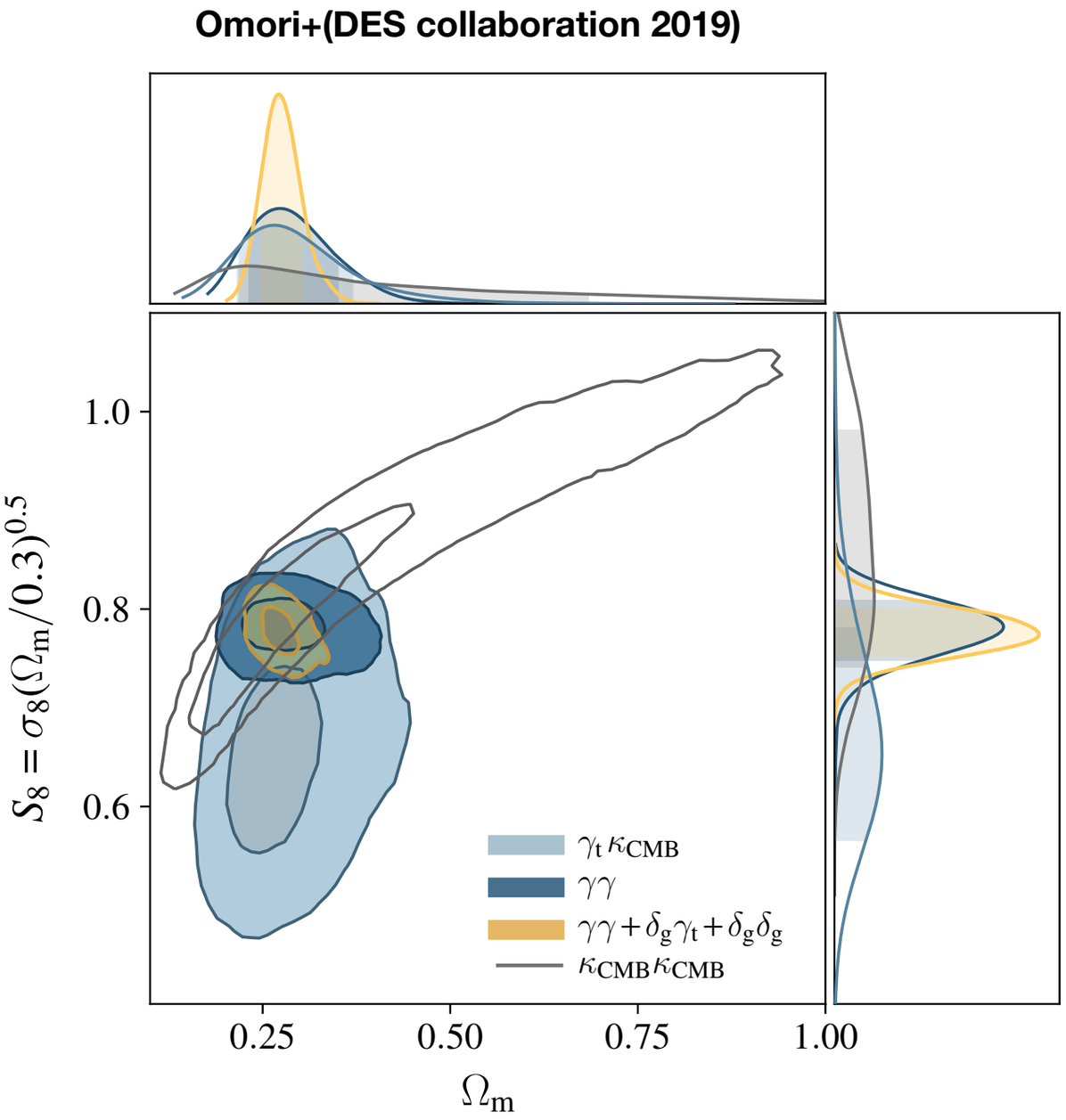


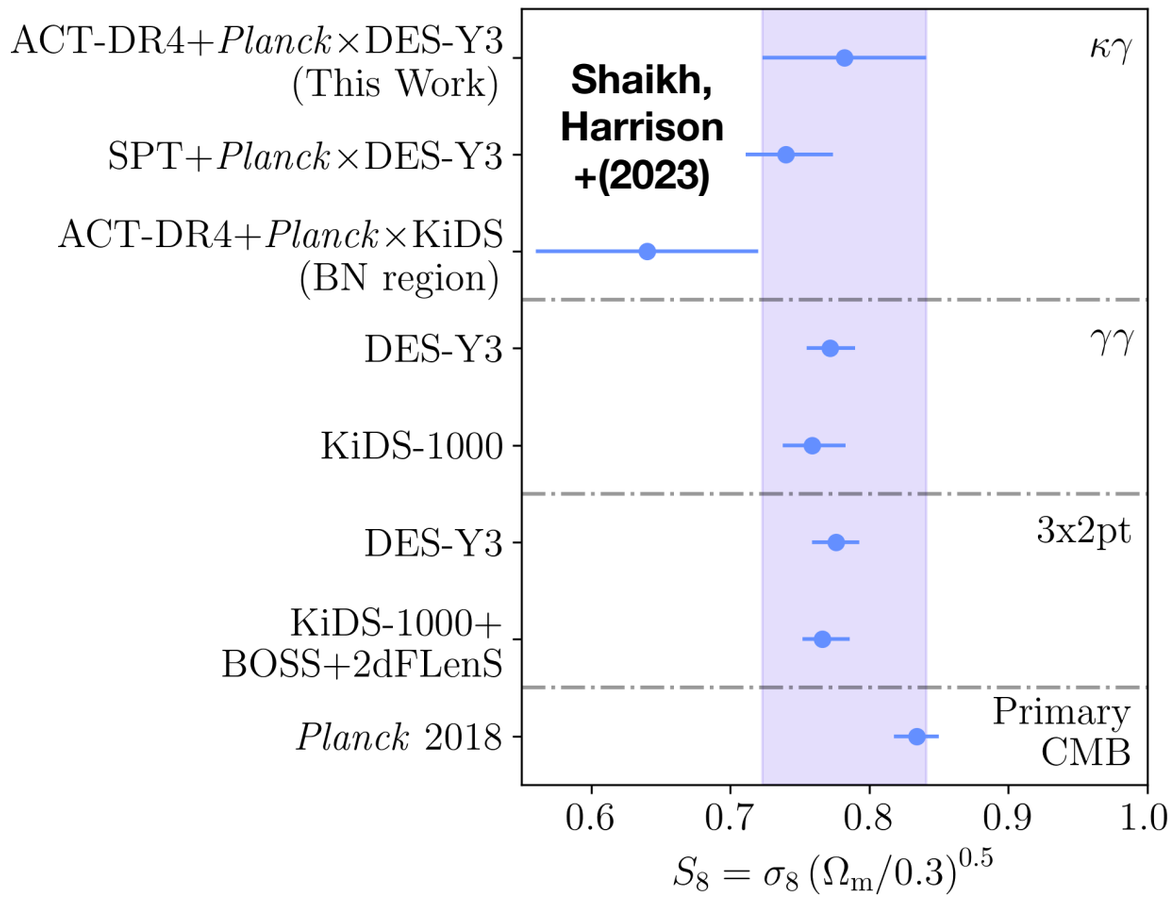
- DESI Legacy LRGs calibrated with spectroscopic data x ACT DR6
- Complementary scales wrt UNWISE.
- Highly tested for bias expansion
- Consistent results with CMB, now also with BGS…

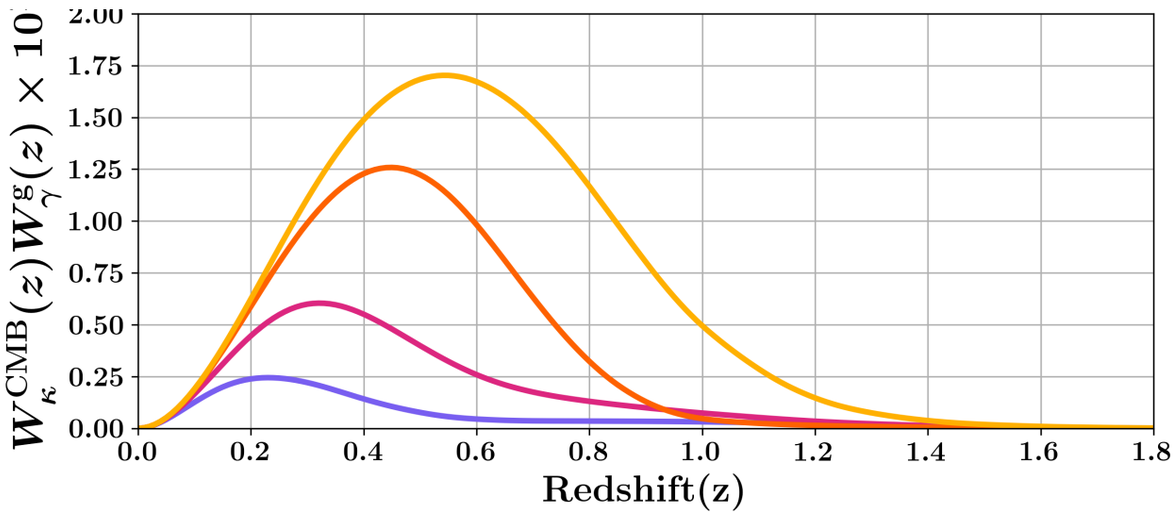


ACT DR4 & SPT X DES cosmic shear

- Tightens systematics but large uncertainties new analyses on the way.



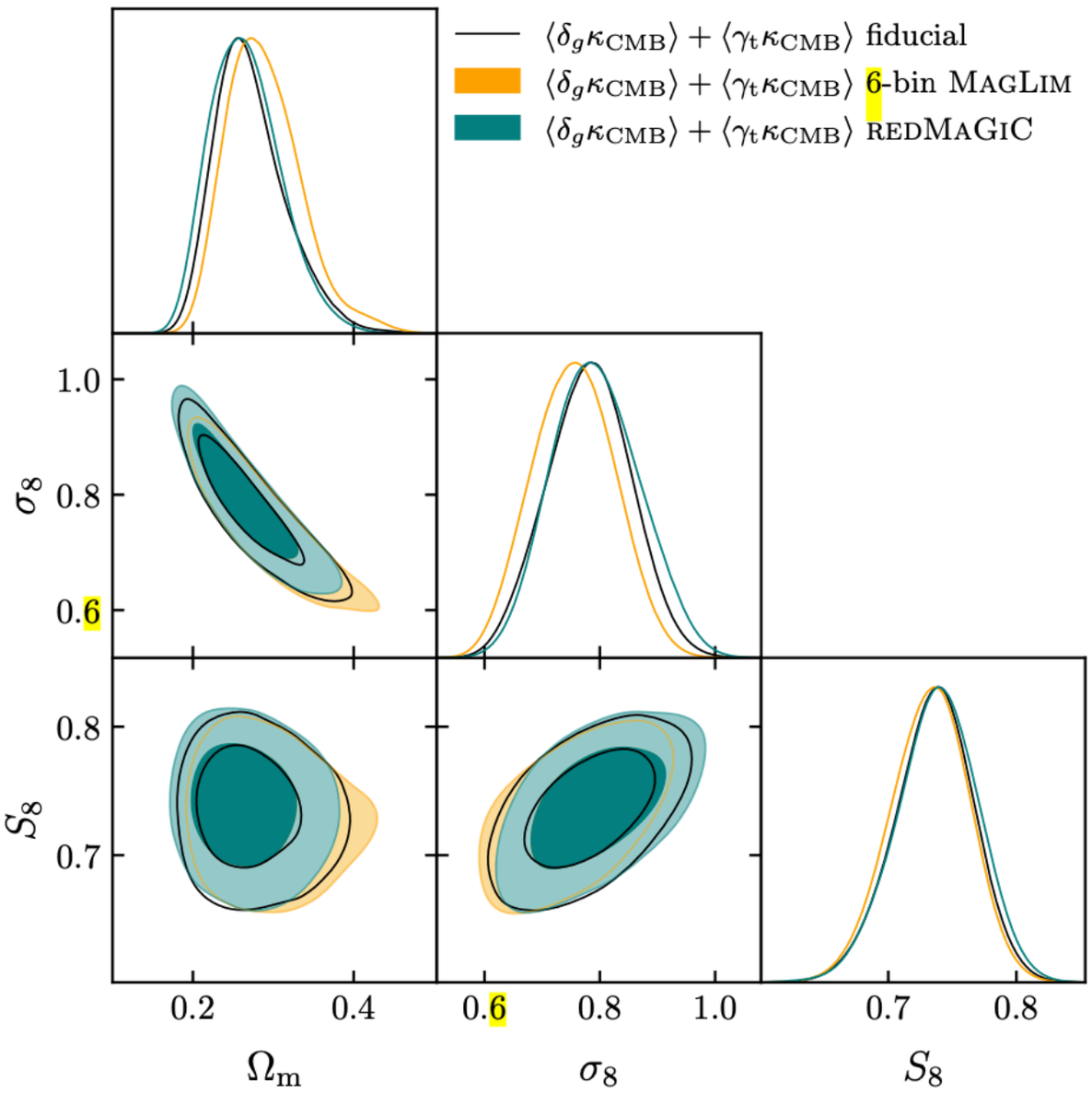




SPT X DES Year 3 towards 6x2pt

- Joint cosmological inference from cross-correlation not yet including CMB lensing auto spectrum…

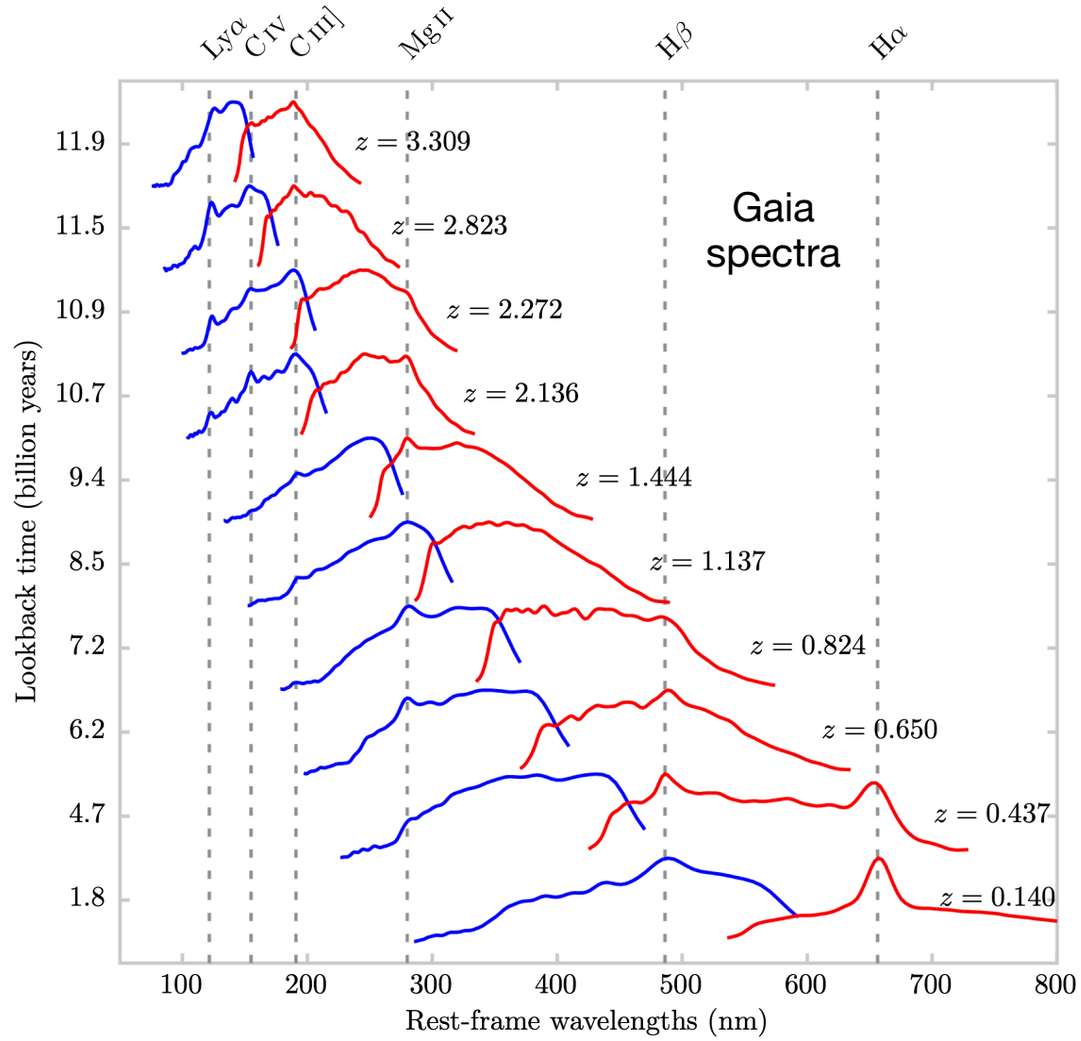
  - Need to interface for covariances and external likelihood consistently to go from 2x2pt to 6x2pt

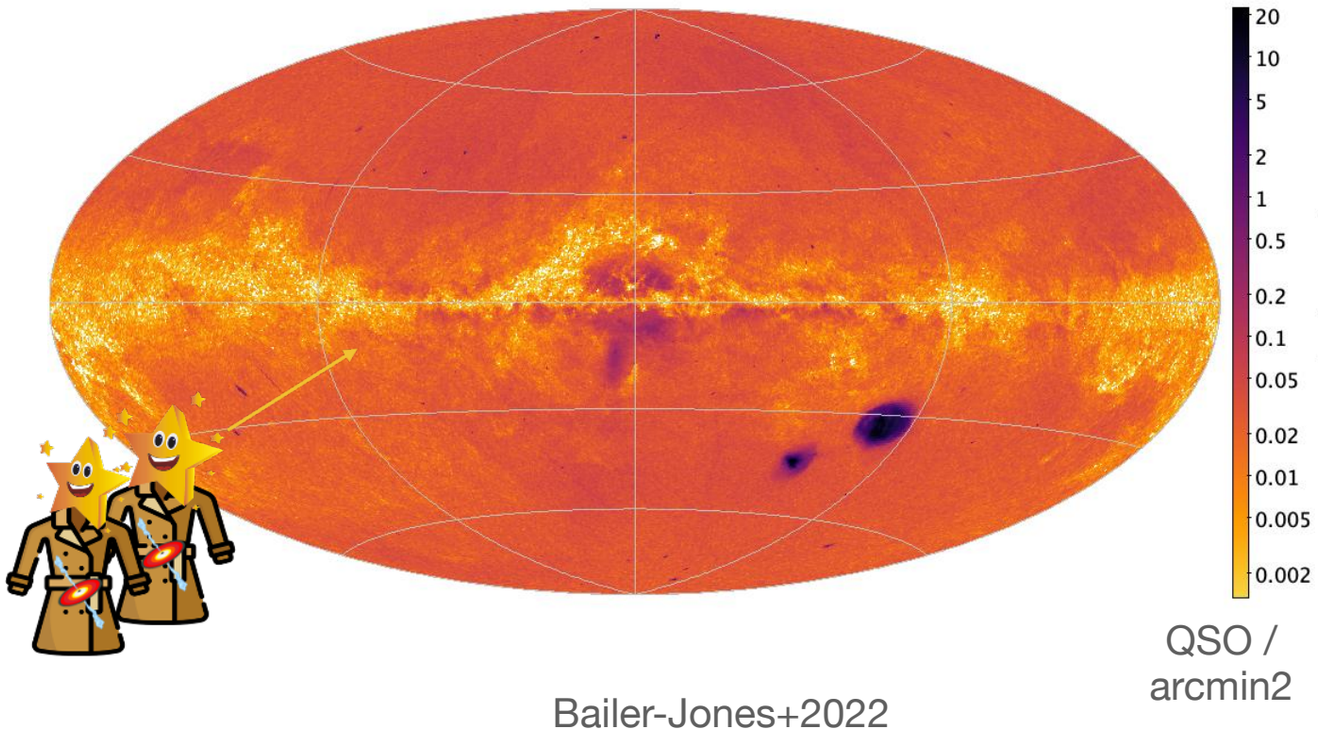


Chang+(2022)

In the meantime… Gaia!

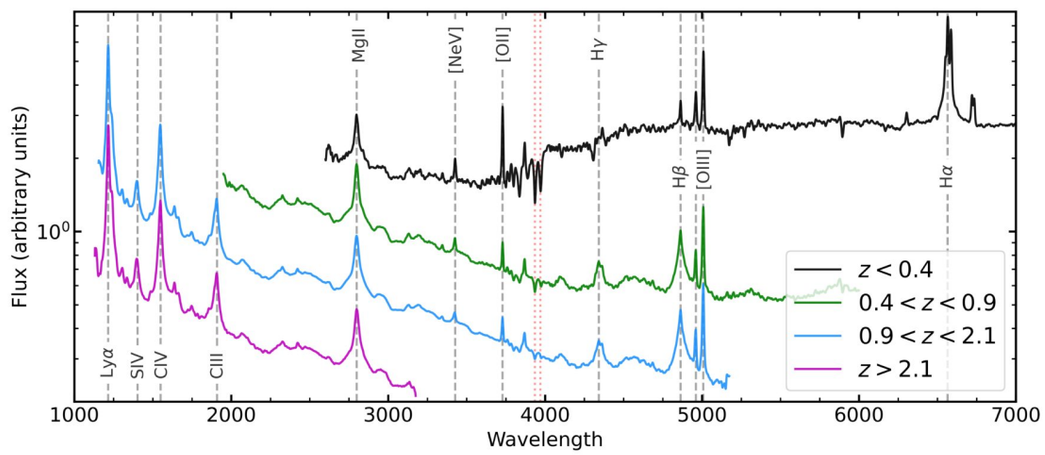
- Gaia: photometry, astrometry, slitless spectroscopy with $30 \leq \lambda/\Delta\lambda \leq 100$
- DR3 released 6.6 million quasar candidates.
  - Stable conditions, cleanest selection.
  - Complete but low purity: many stars masquerading as QSO :/





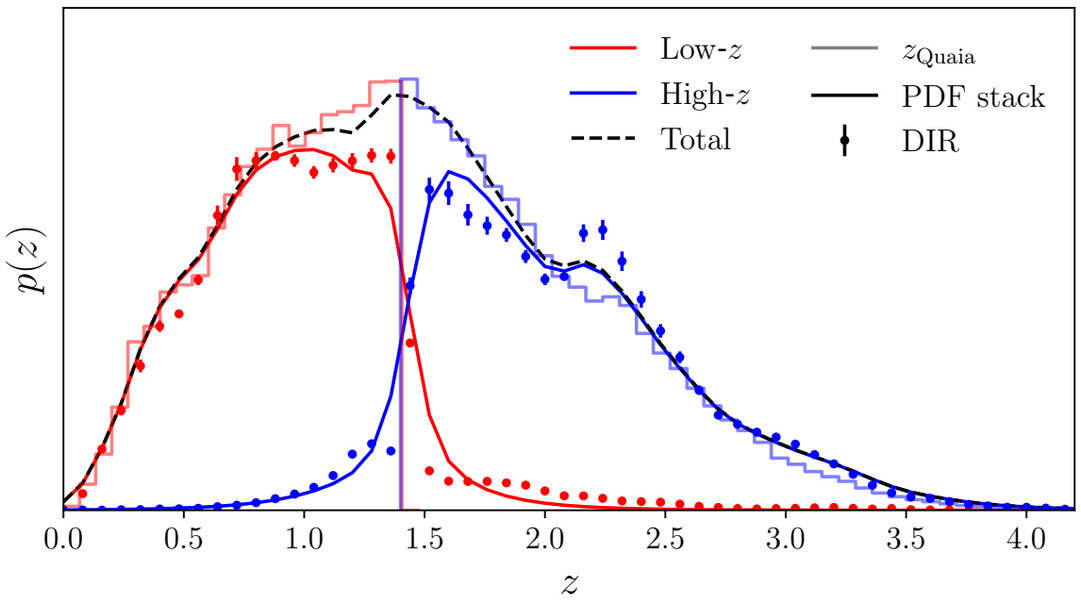
Bailer-Jones+2022

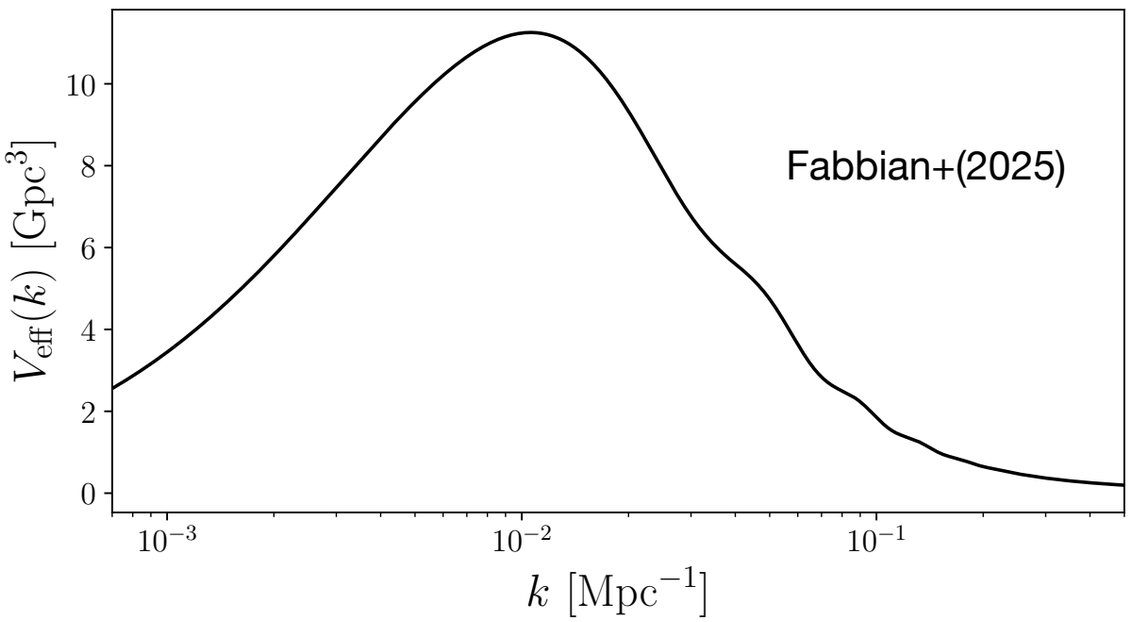
DESI spectra (DESI coll.)

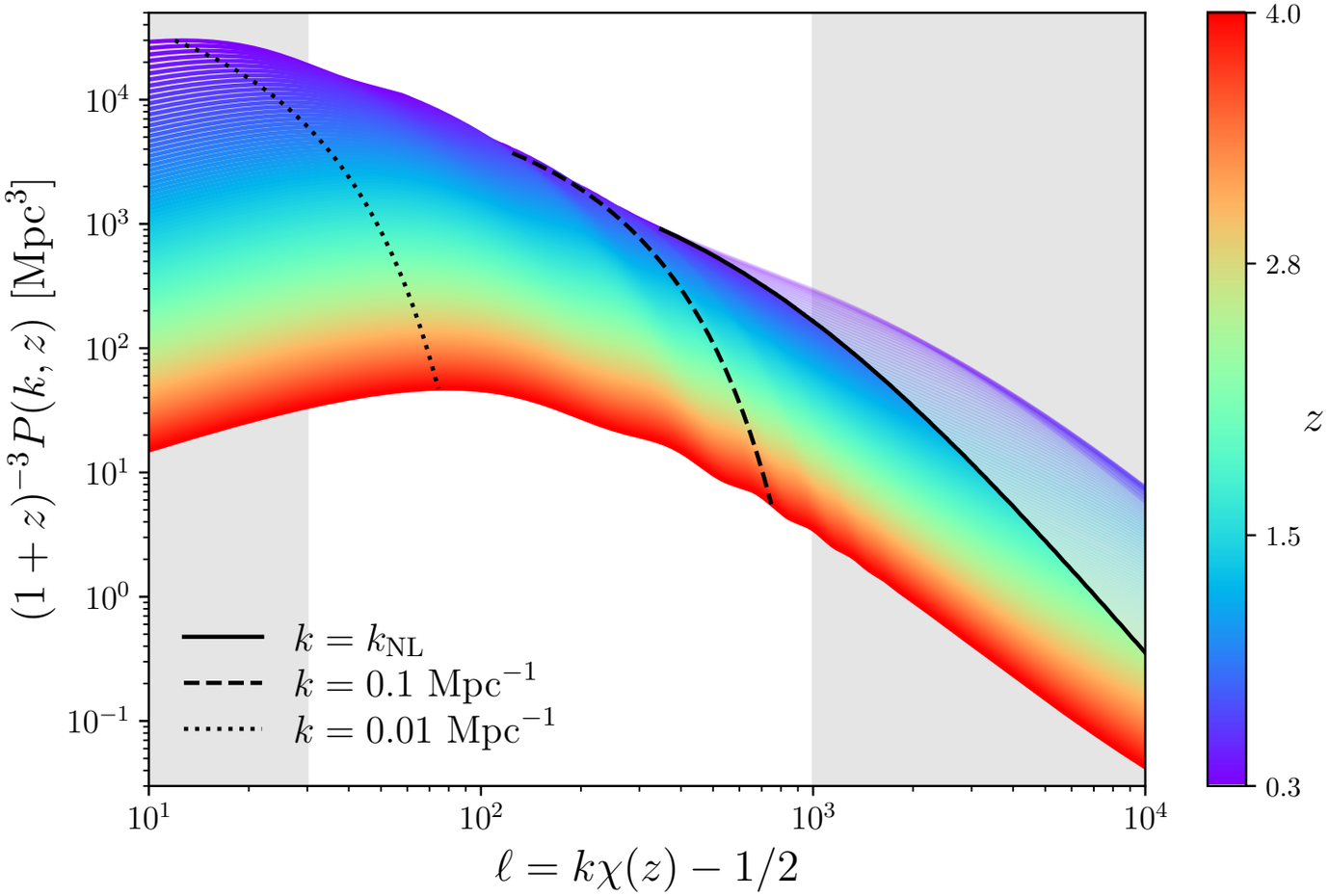


What Quaia can do for cosmology?

- High z, linear or quasi-linear scales, arge scales (in angles and k)
  - NB: after DESI, still largest QSO sample (slightly) and ~2.5x spanning volume





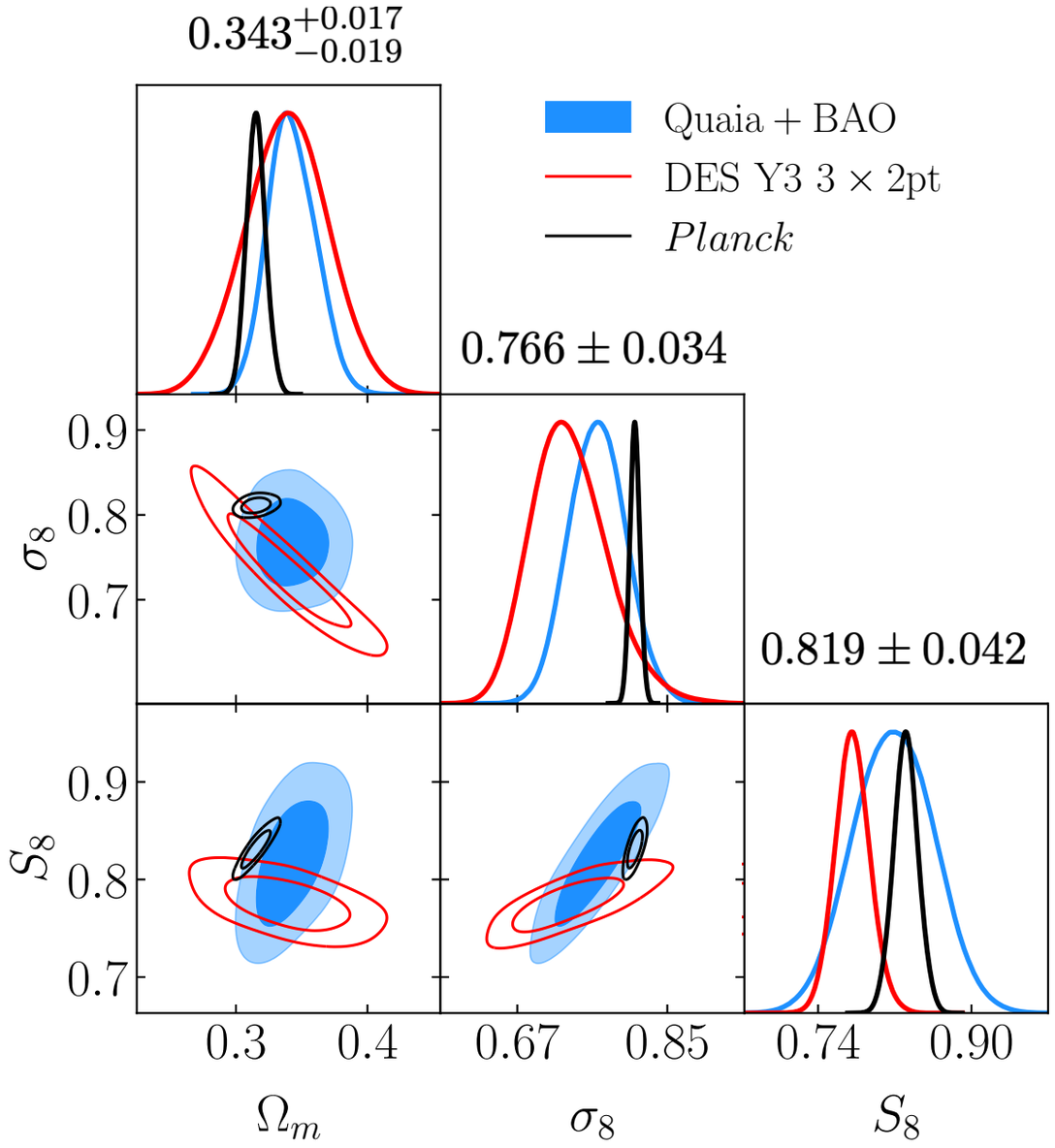


Alonso, Fabbian, Storey-Fisher+ (2023)

Cosmology from Quaia x Planck CMB lensing

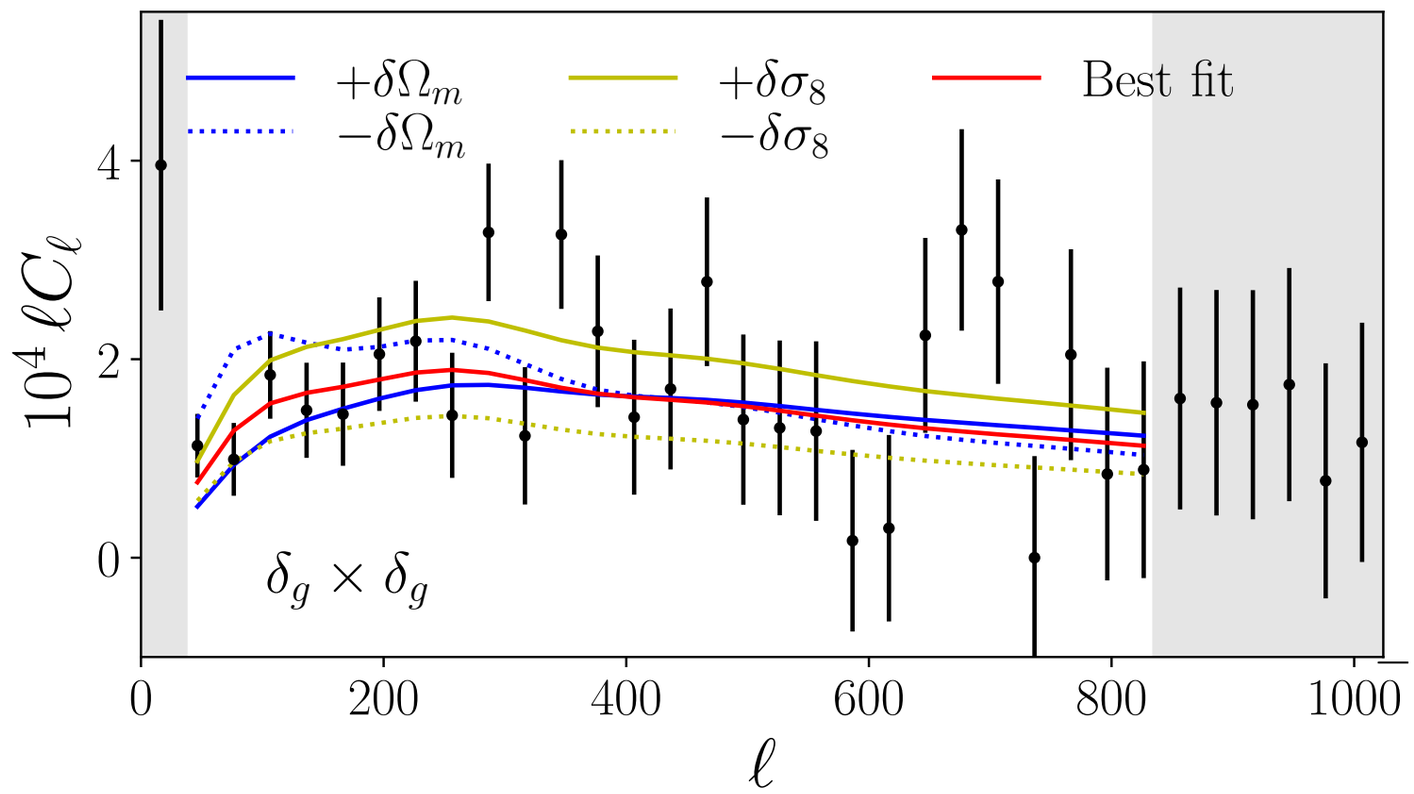
- $C_\ell^{gg}, C_\ell^{\kappa g}$ with Planck PR4 CMB lensing in 2 redshift bins.

- Results competitive with current LSS surveys with fewer objects and/or worse redshifts.



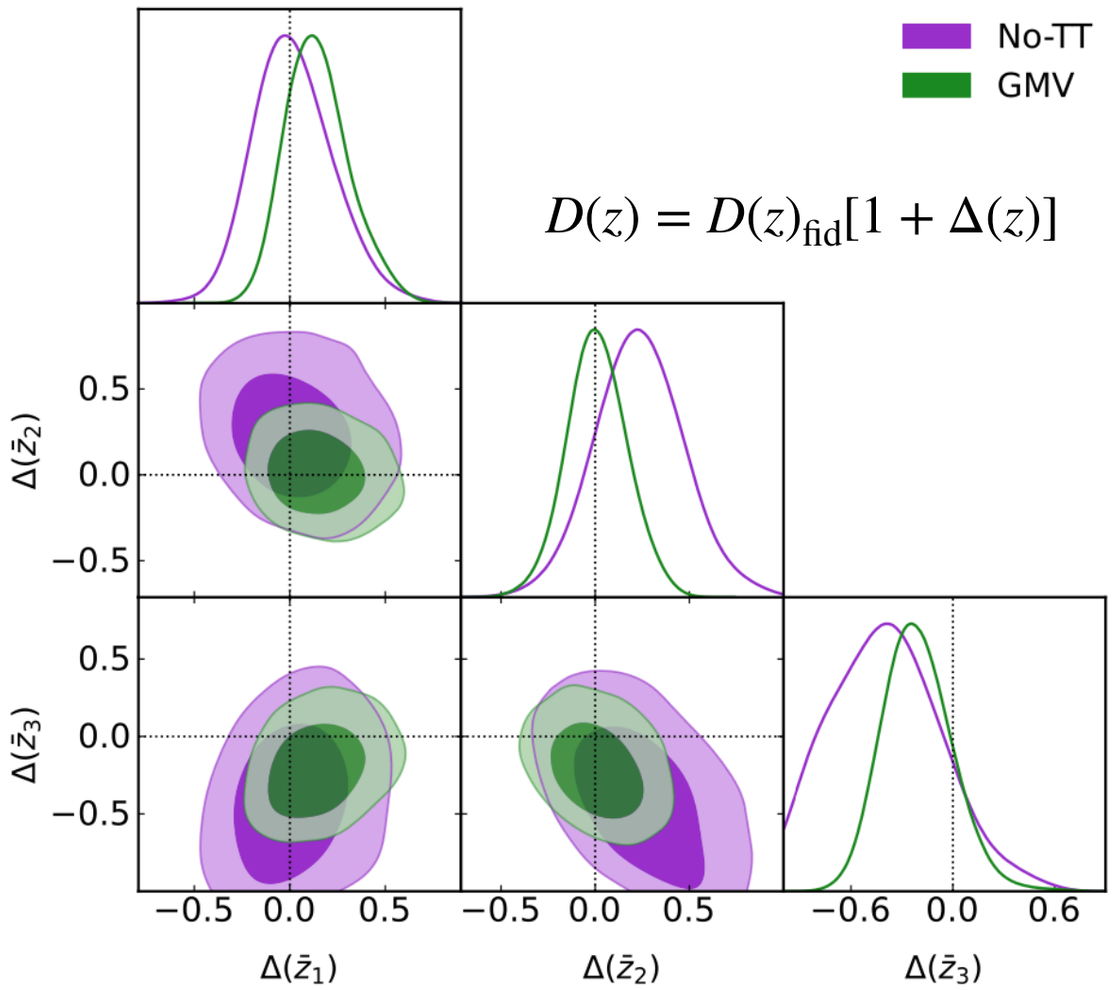
No tension with Planck!

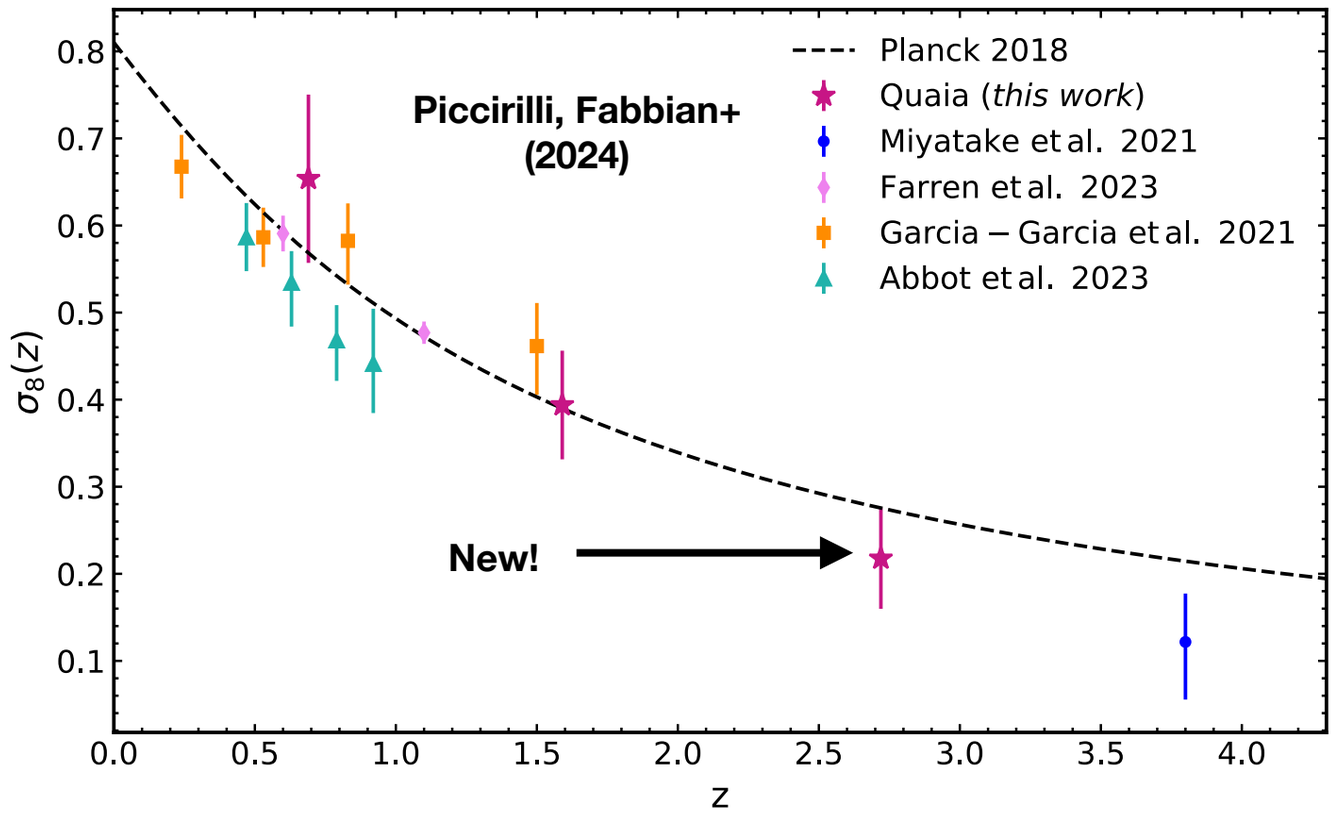
Alonso, Fabbian, Storey-Fisher+(2023)



Perturbation evolution at high-z Quaia

- Model independent assessment of structure growth consistent with LCDM
- New high-redshift direct measurement at z~2.5 robust to systematics !
  - Careful foreground assessments (CIB…)

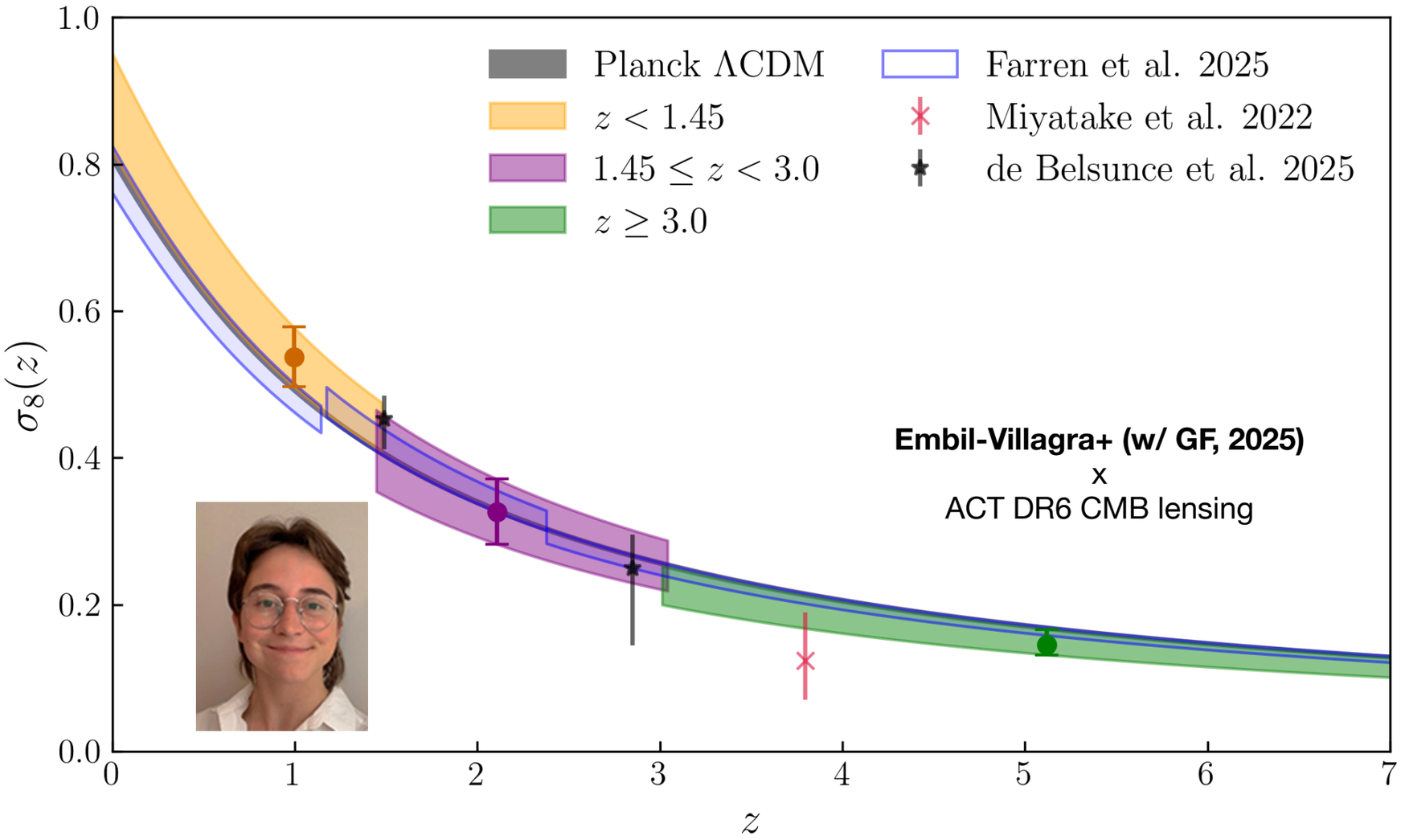




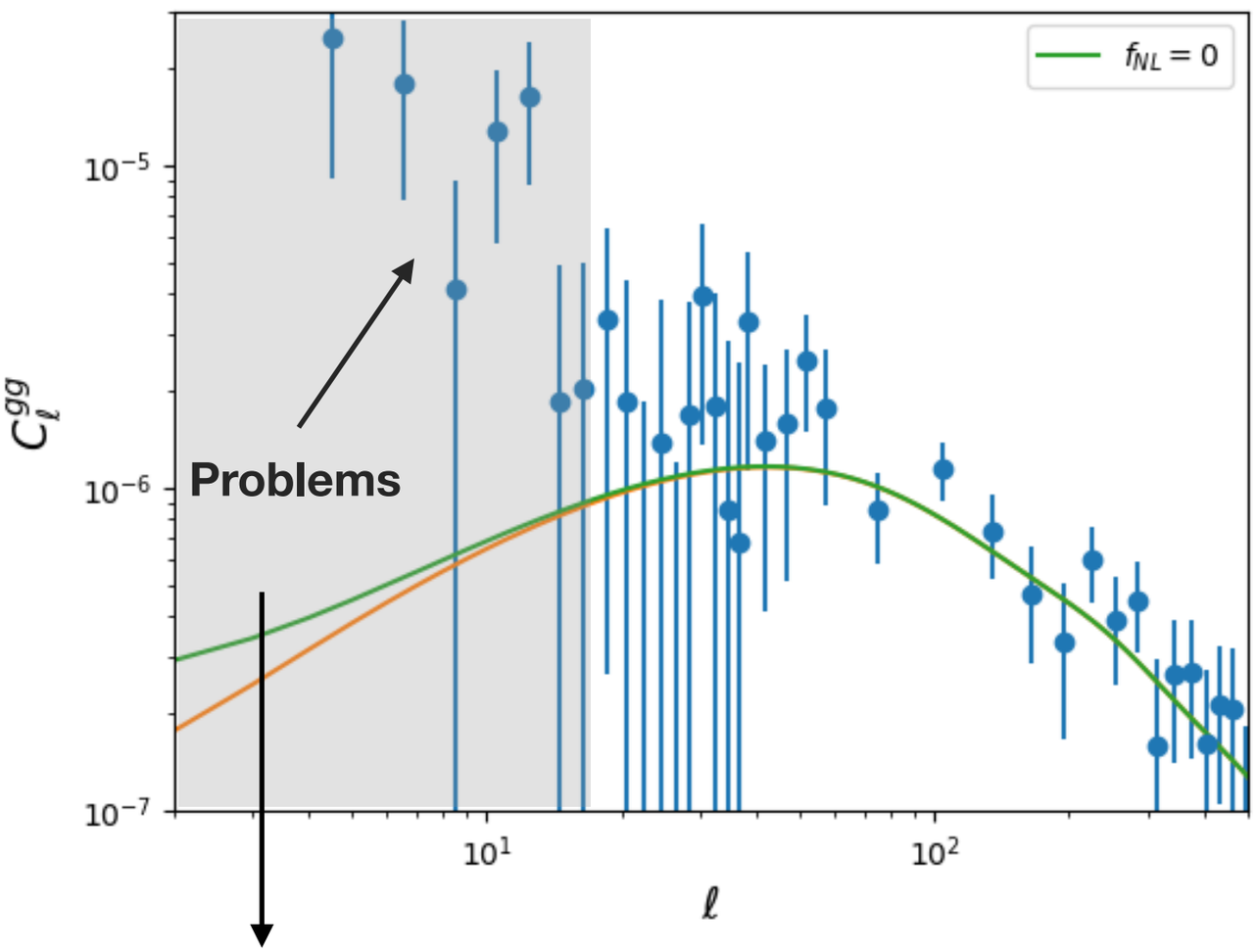
Cosmology from Quaia x CMB lensing

- Tomographic 3x2pt $C_\ell^{gg}, C_\ell^{\kappa g}, C_\ell^{\kappa\kappa}$ with ACT CMB lensing allows constraints on $\sigma_8(z = 5.1)$

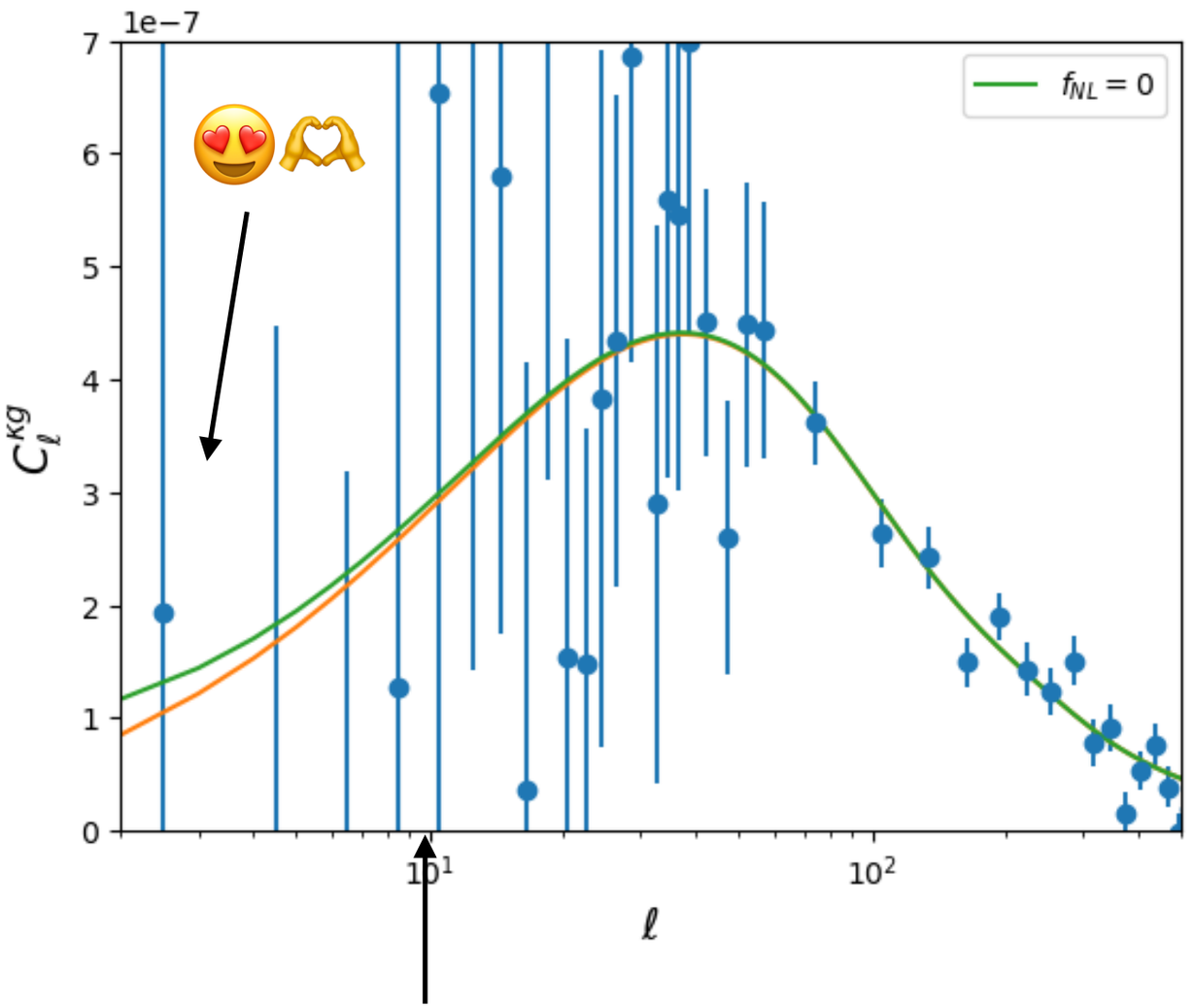
$$P_{\rm lin}^{\rm new}(k,z) = P_{\rm lin}^{\rm input}(k,z)A(z)$$
$$= P_{\rm lin}^{\rm input}(k,z)\begin{cases} A_0 & 0 \le z < z_1 \\ A_1 & z_1 \le z < z_2 \\ A_2 & z_2 \le z \end{cases}.$$



Large scale cosmology from space e.g. f_{NL}



Aggressive systematics subtraction:
~3x degradation of results
(Rezeie+2025)



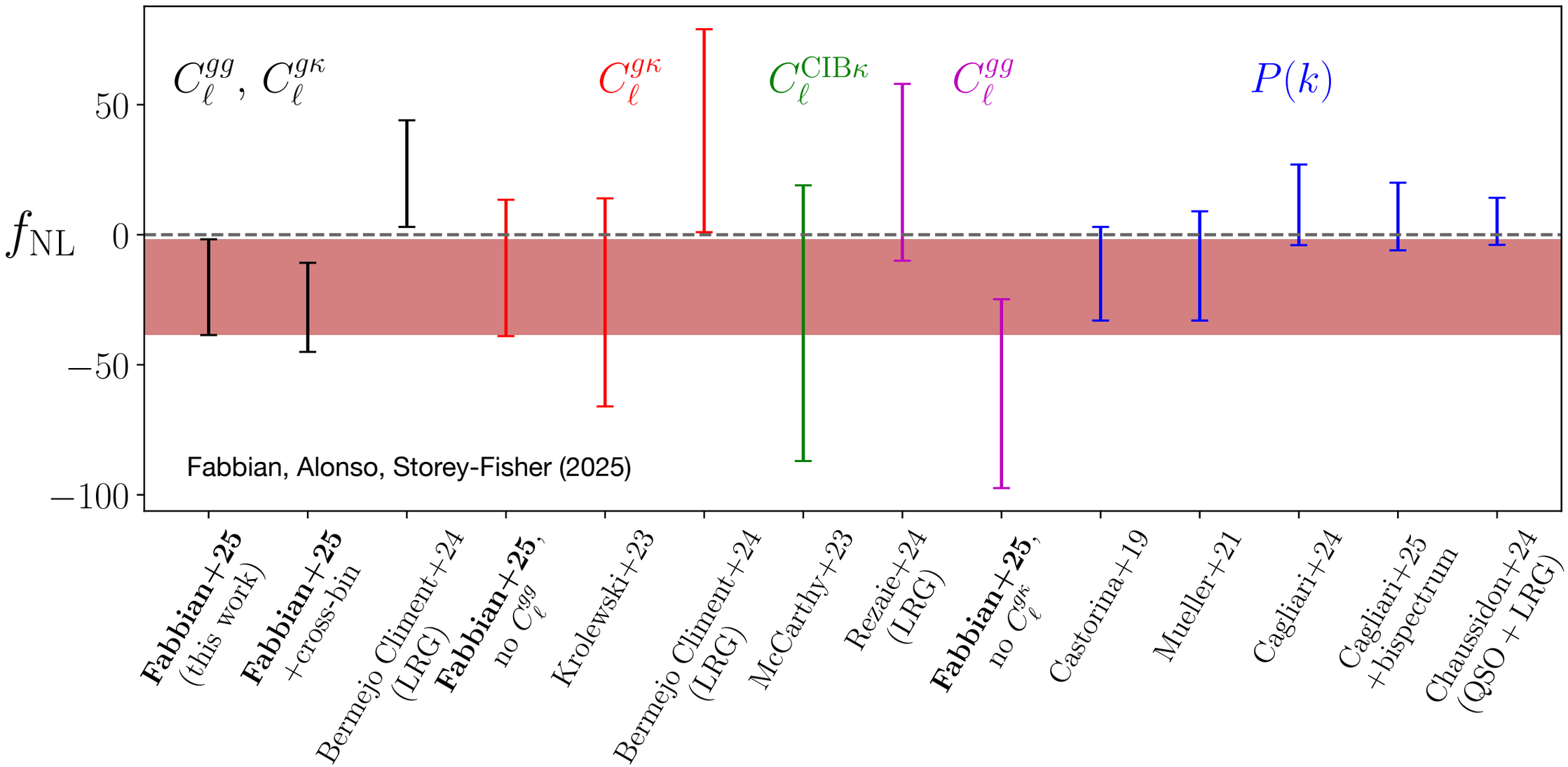
Scale cuts from ground-based surveys
(Krolewski+2023)

- Cross-correlation can reach the largest scales with no systematics contamination (though $\Delta C_\ell^{\kappa g} \propto \sqrt{C_\ell^{\kappa\kappa} C_\ell^{gg}} \ldots$)

- Also first sound-horizon free H0 determination from cross-correlation!

Alonso, Hetmansev, Fabbian+ (2024)

Robustness tests and perspectives

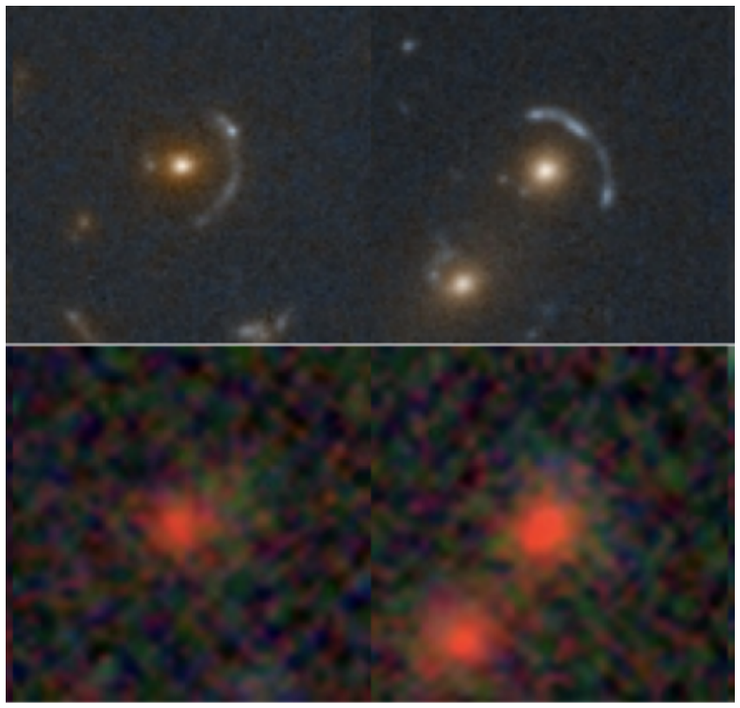


- Sensitivity comparable to spectroscopic galaxy surveys in 3D $\sigma(f_{NL}) \sim 17$ $(p_\phi = 1)$, highly robust to systematics.
- With newer Gaia DR $\sigma(f_{NL}) \lesssim 9$ (more sources, different source separation, new data…)
- $\sigma(f_{NL}) \lesssim 2$ achievable with similar techniques for Euclid!

What to expect from next generation surveys

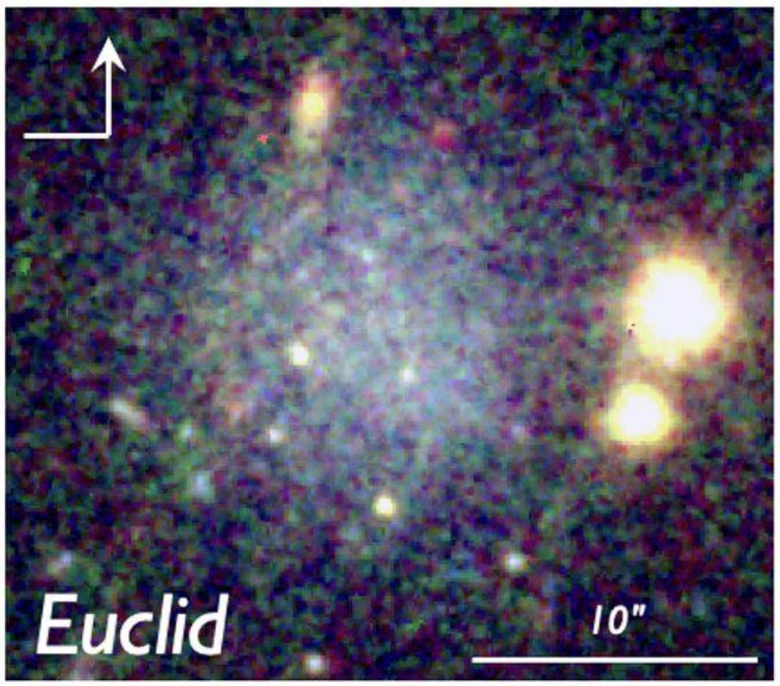
Euclid Early Release Observation image

Euclid Q1 release

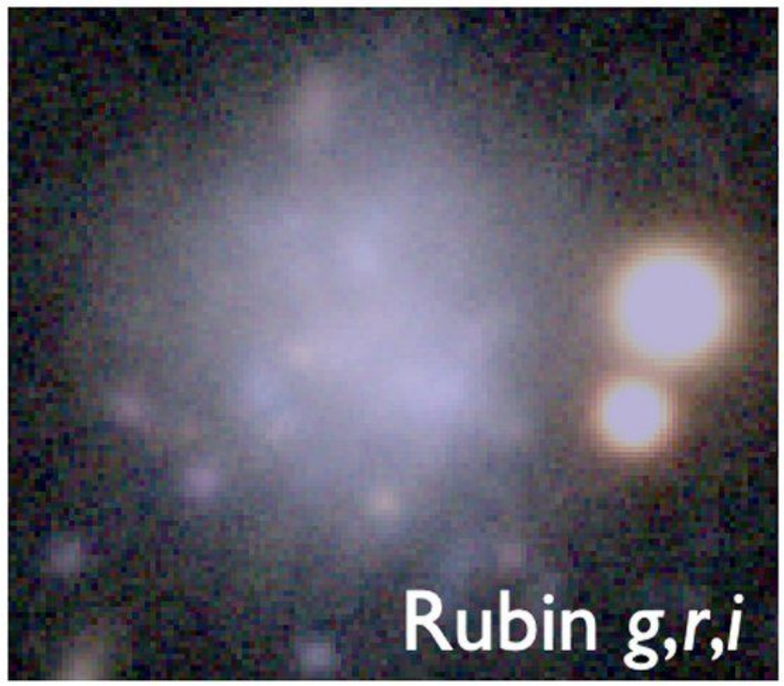


DESI Legacy Imaging Survey

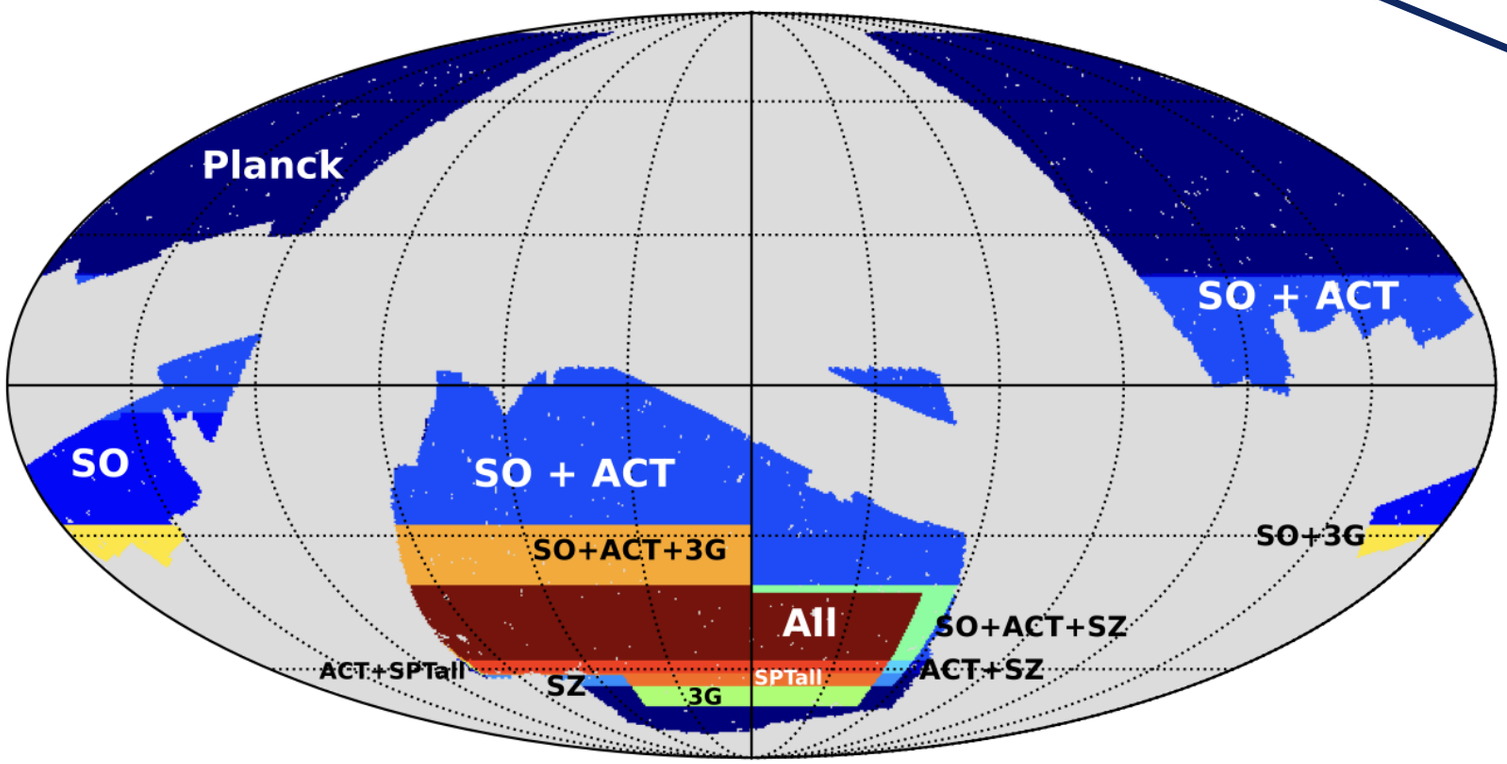
Romanowsky+(2025)



Rubin 1st wide image



Cross-correlation with Euclid DR3



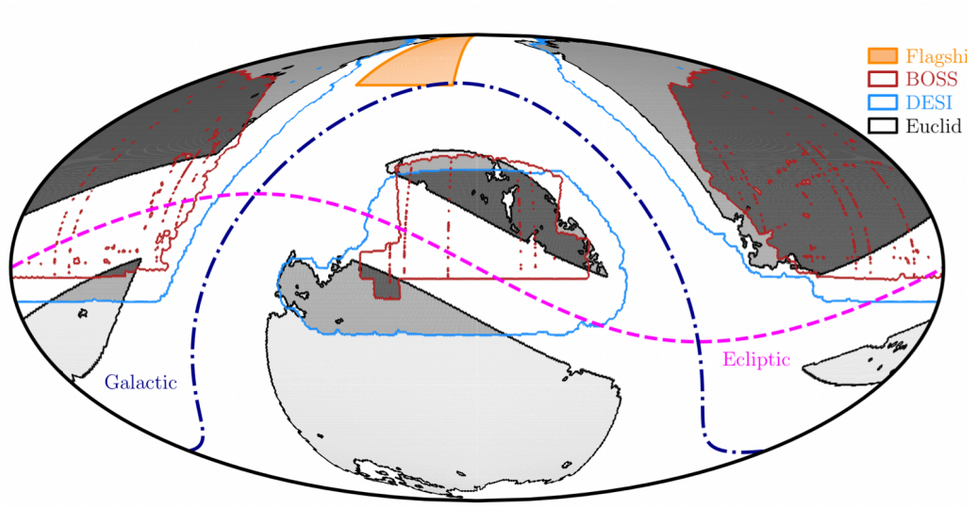
expected in Oct 2031
covering 15 k deg^2

Overlap with **other LSS survey:**

- with with DESI over ~9000 deg^2
- with both BOSS and DESI over ~6000 deg^2

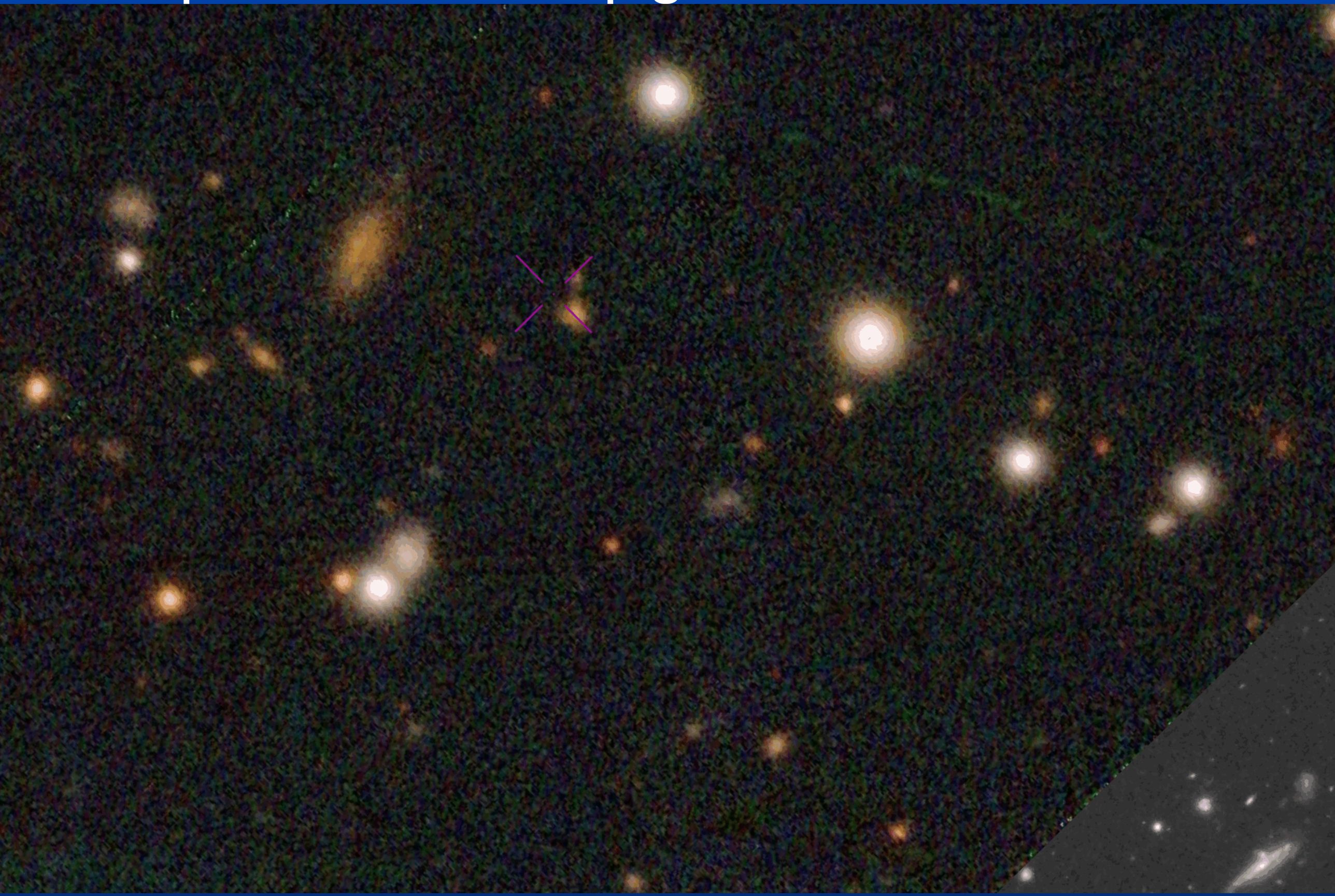
- **SO has the largest overlap with Euclid** (65% overlap)
- SPT3G-WIDE is the second best (45%)
- ACT: similar SO overlap but with lower sensitivity

Courtesy M. Lembo



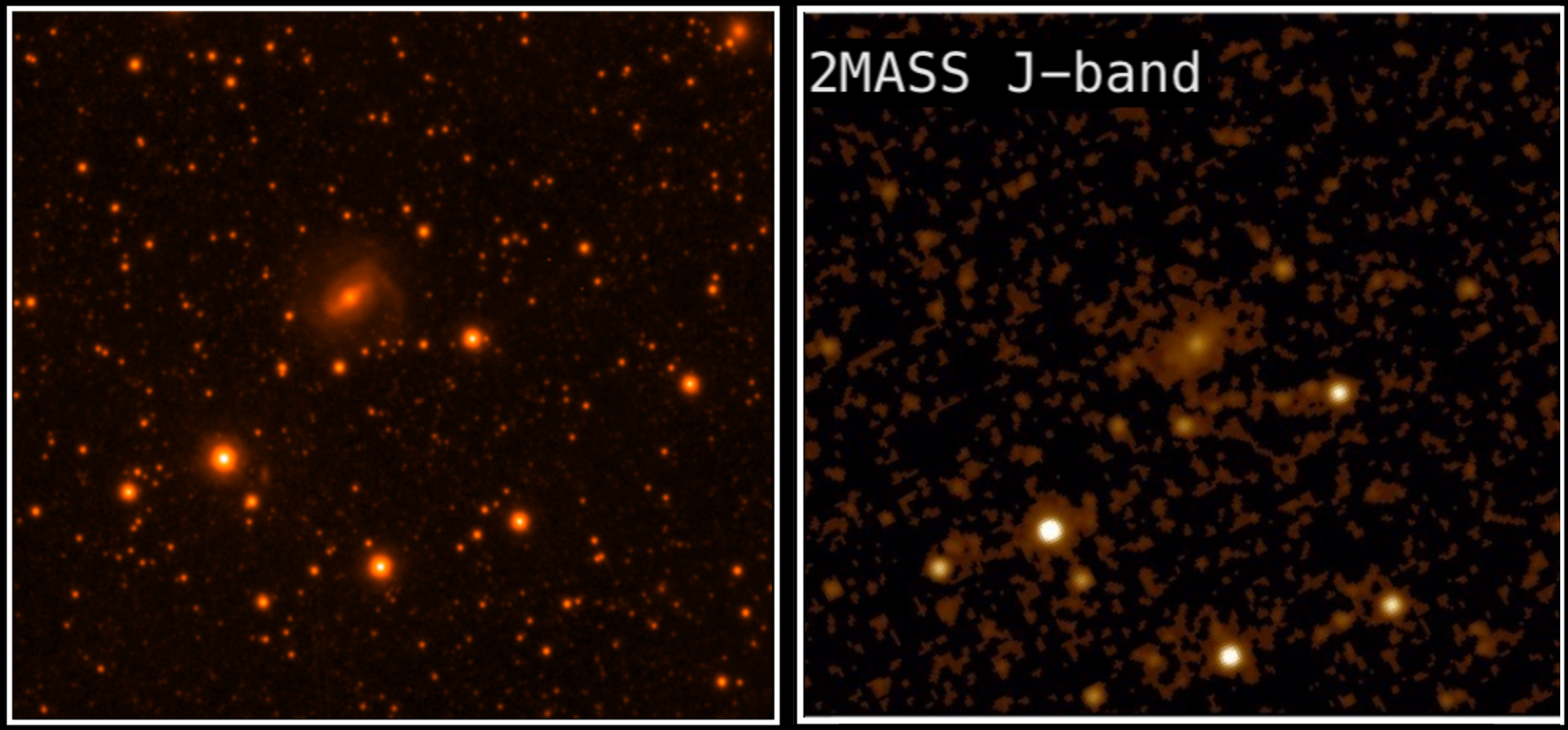
Naidoo et al, 2023 (Euclid collab paper)

A comparison with deep ground-based data…



EUCLID

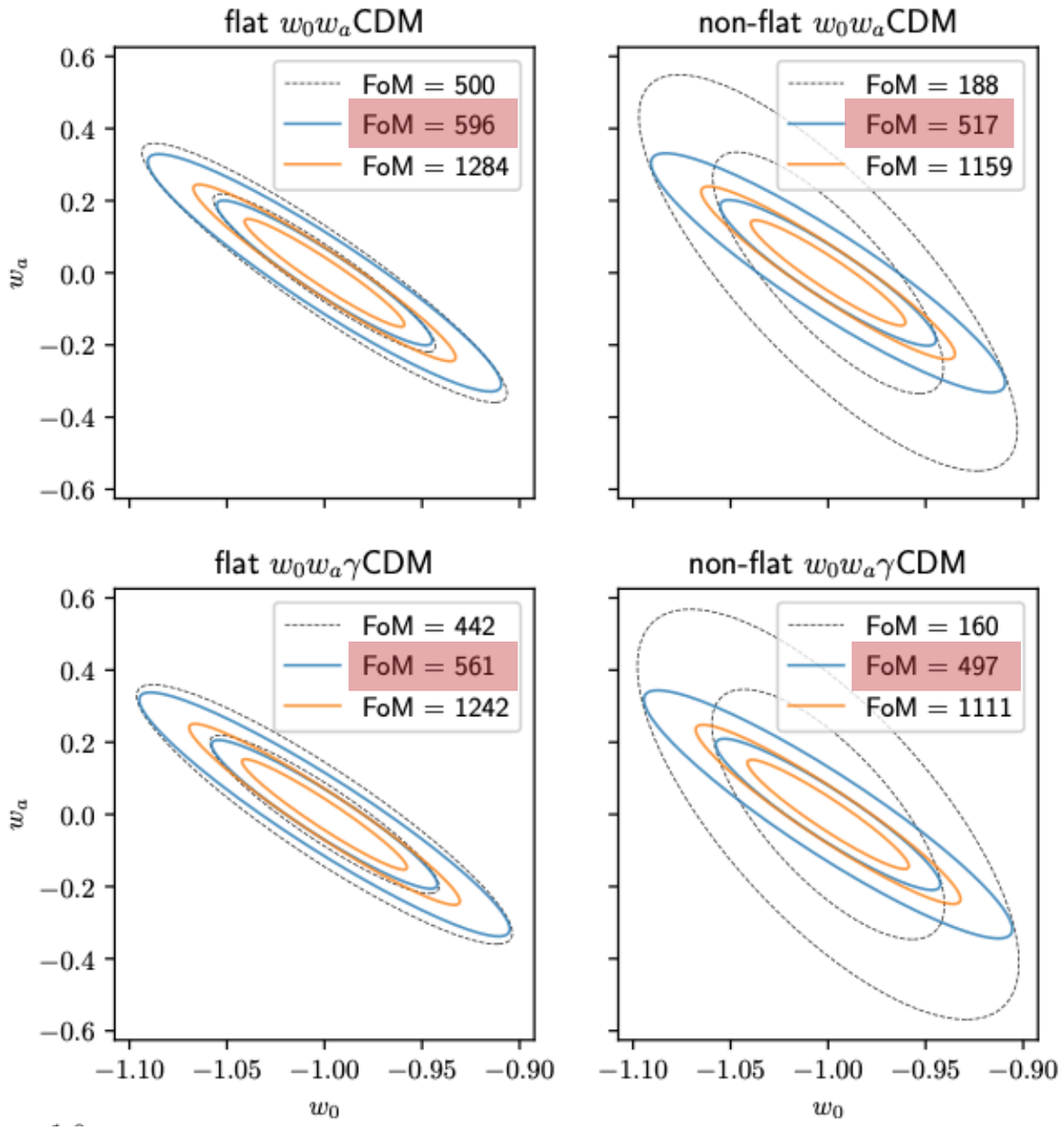
RESULTS SO FAR

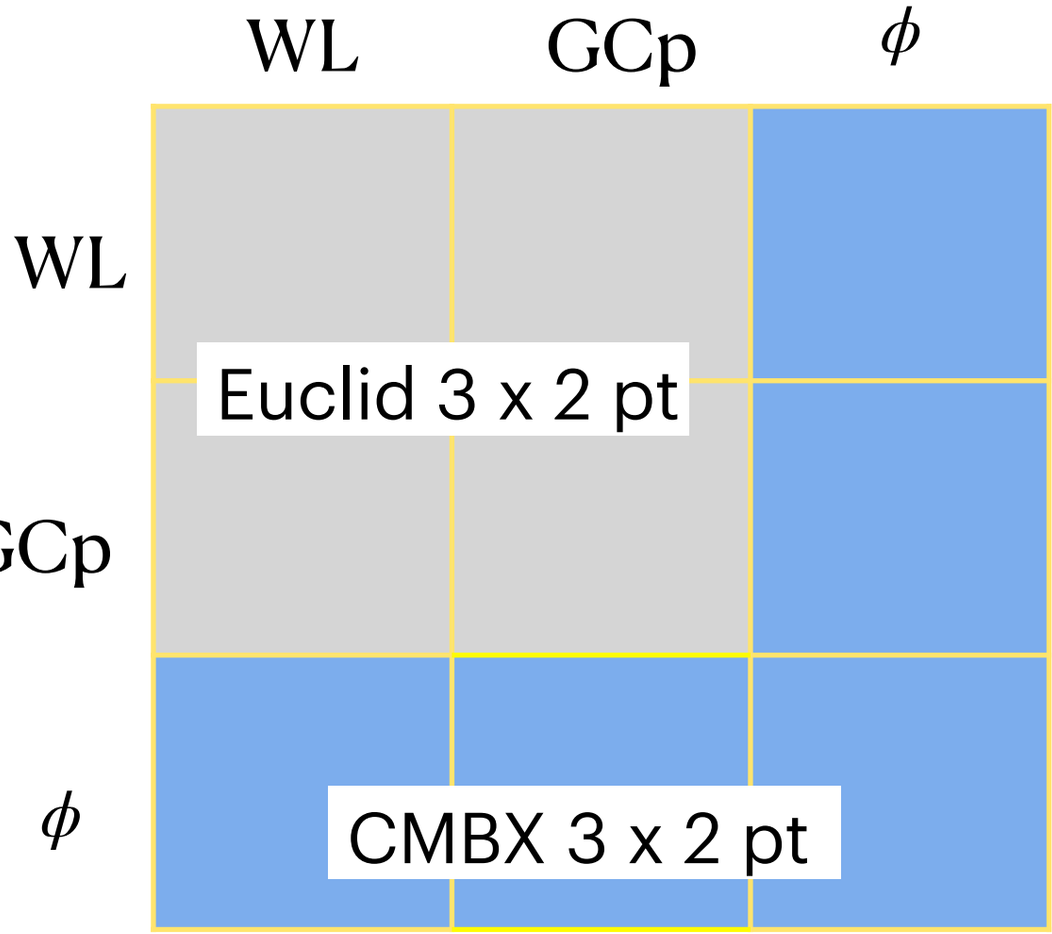


Credit: Ralf Bender & Ross Collins using public data from Euclid and VISTA

Forecast for 6x2pt analysis

- Pessimistic Euclid survey in ~5 tomographic redshift bins and WL, zmax=1 and SO-like baseline sensitivity (conservative)
  - 4-10x improvements in dark energy / modified gravity parameters!

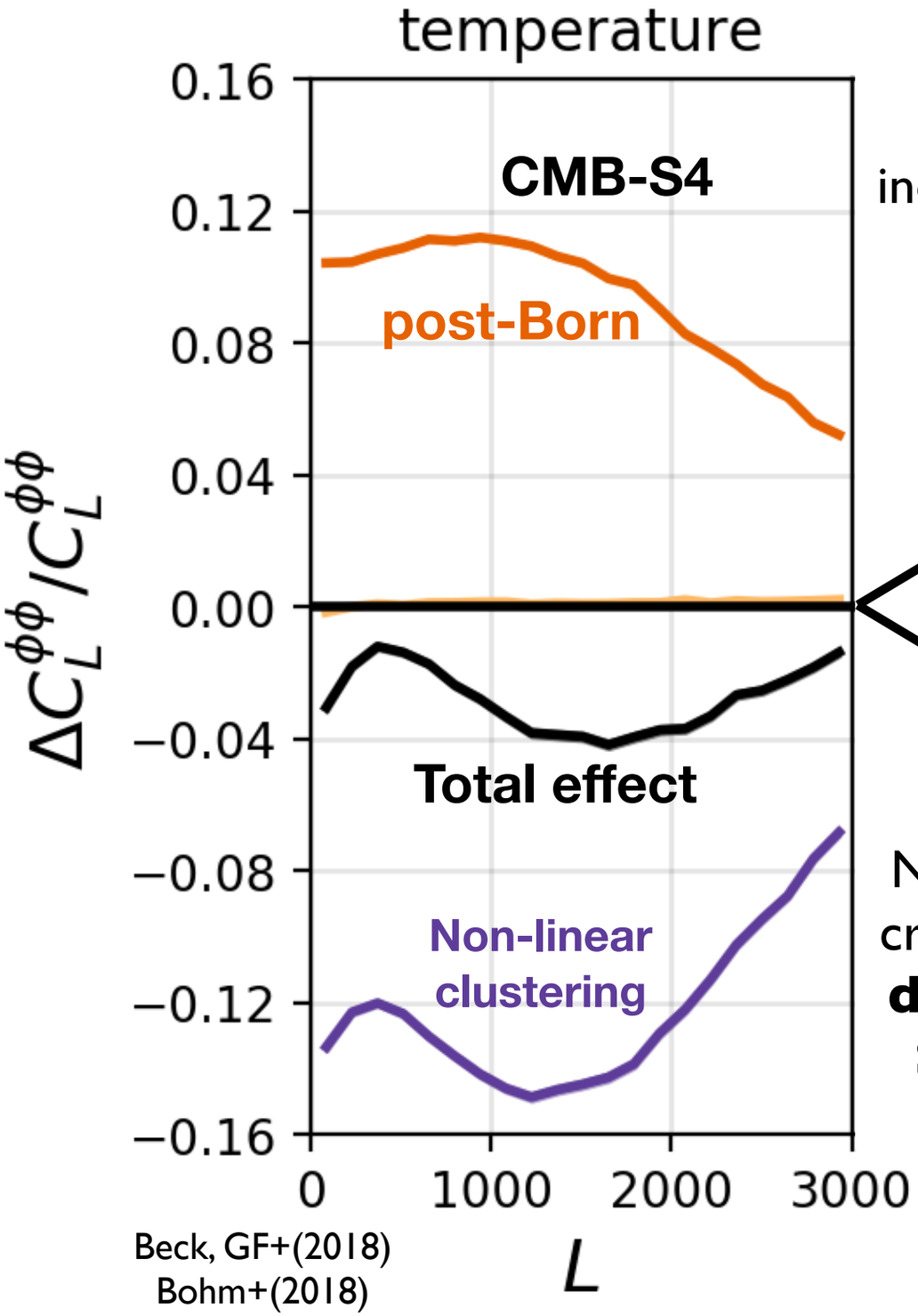




Euclid collab. (Blanchard+19)

Euclid collab. w/ CMBX SWG (Ilic+21)

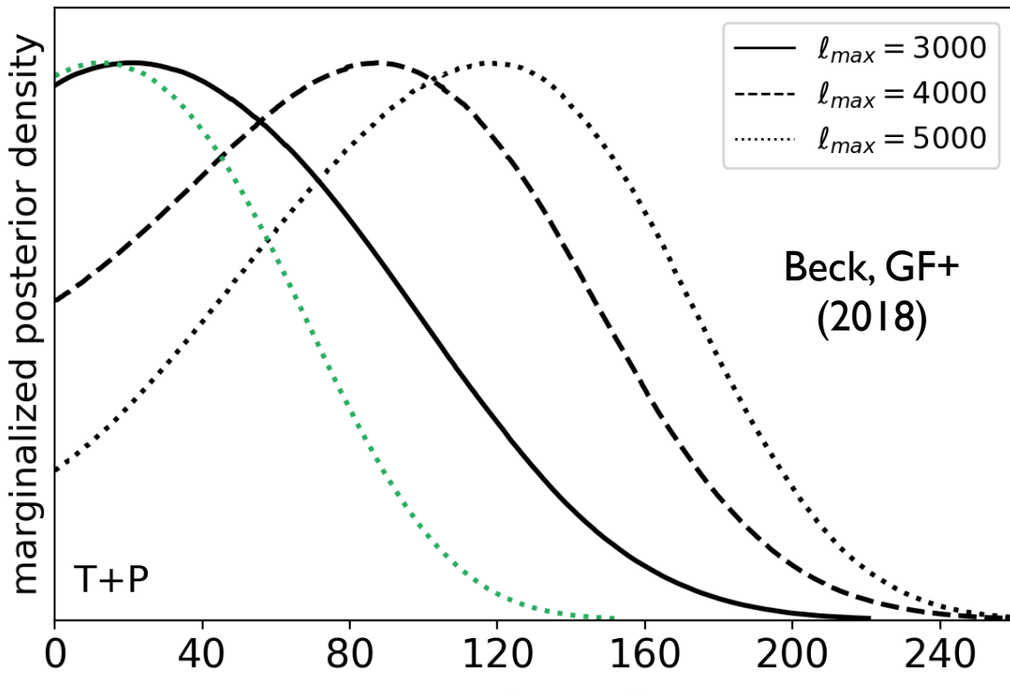
Non-Gaussian effects in reconstructed ϕ ($N^{3/2}$)

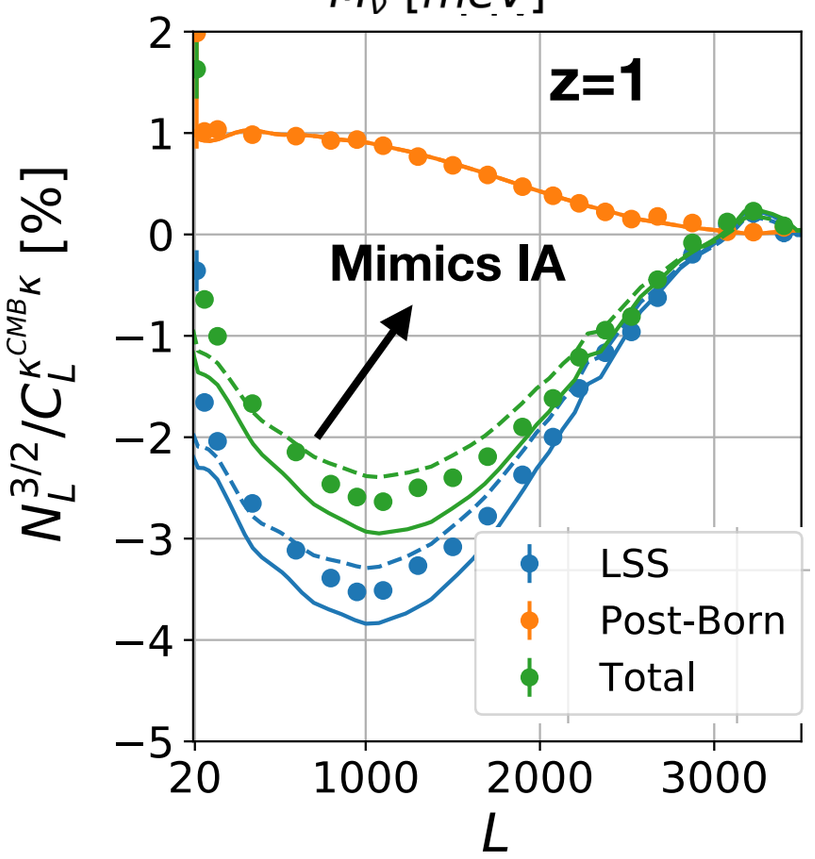


Beck, GF+(2018)
Bohm+(2018)

Biases or inconsistencies in cosmological parameters

Nasty effects in cross-correlation **detectable in SO+Rubin/ Euclid!**





Fabbian+ (2019)

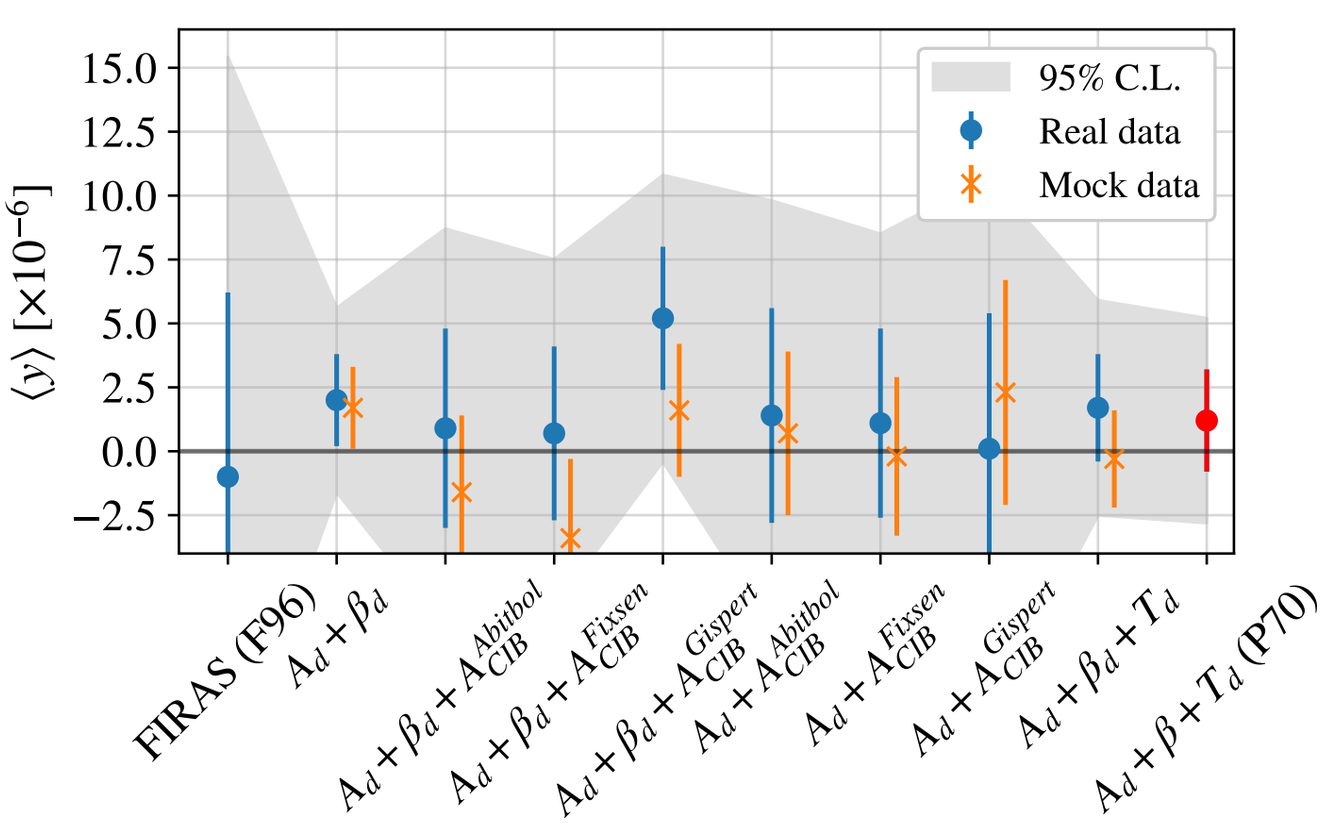
The importance of global views…

- y distortions are dominated by late time gas physics: unique probe of feedback.

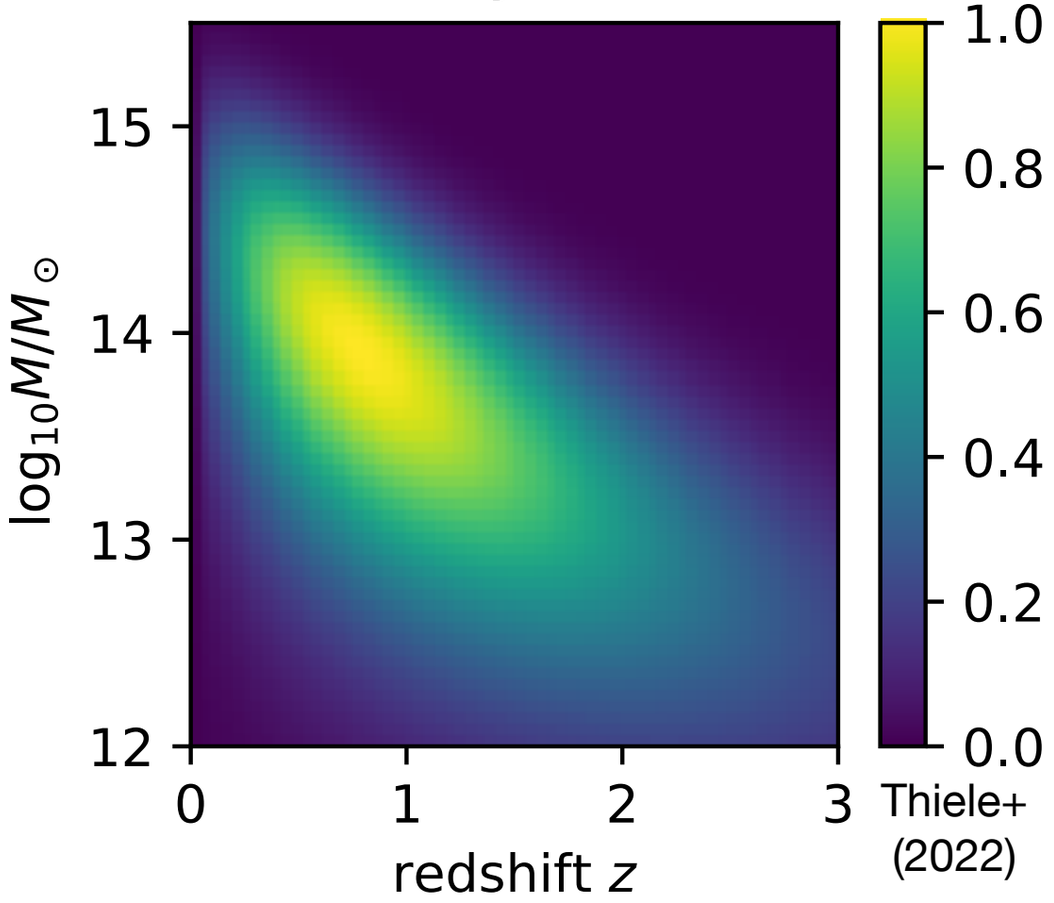
$$\langle y \rangle \equiv \langle y(\hat{\mathbf{n}}) \rangle_{\hat{\mathbf{n}}} = \int \frac{d\hat{n}}{4\pi} \frac{\sigma_T}{m_e} \int P_e(\hat{\mathbf{n}}, l) dl$$

- New upper, 3x better measurement from FIRAS $\langle y \rangle \times 10^6 = -1 \pm 2.1$

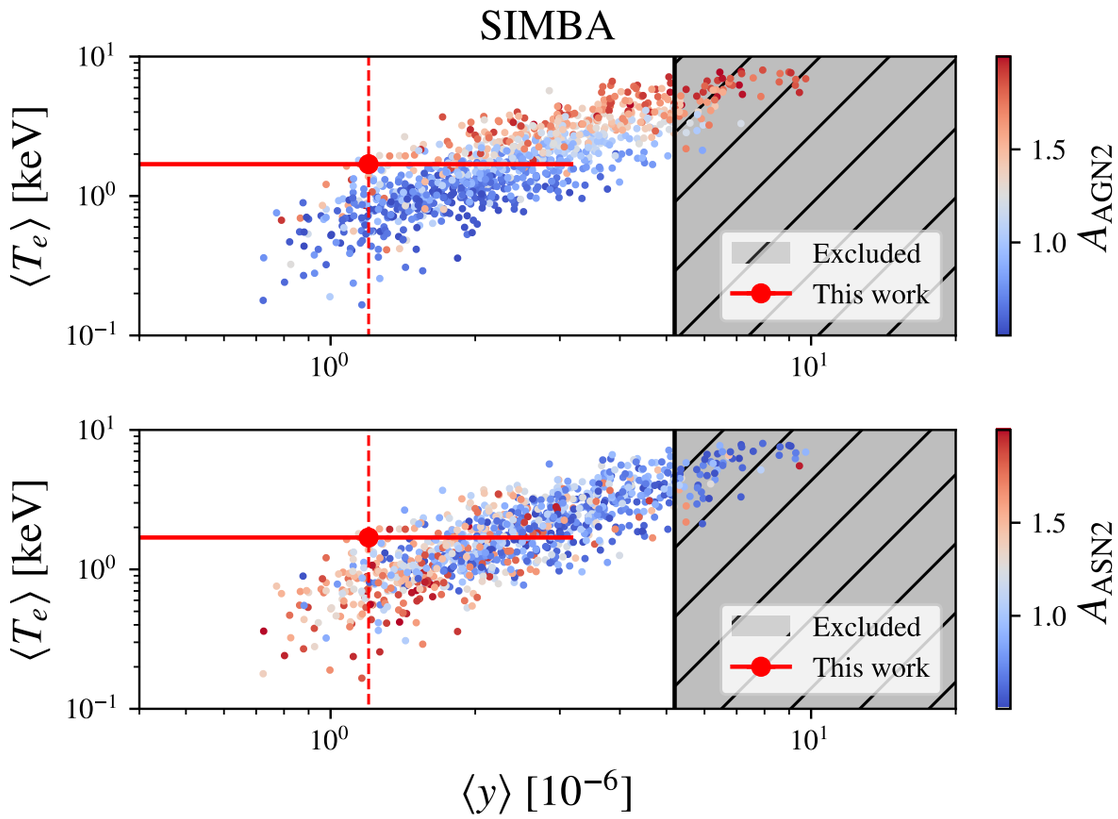
- Complementary integrated observable w.r.t. tSZ power spectrum and kSZ…

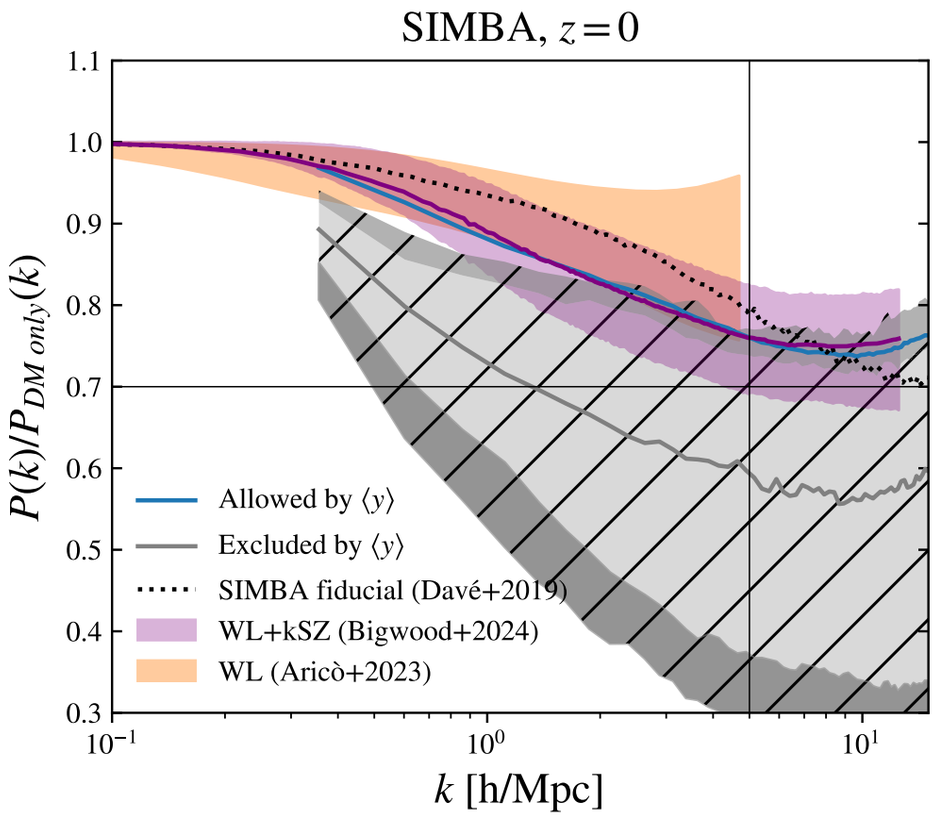


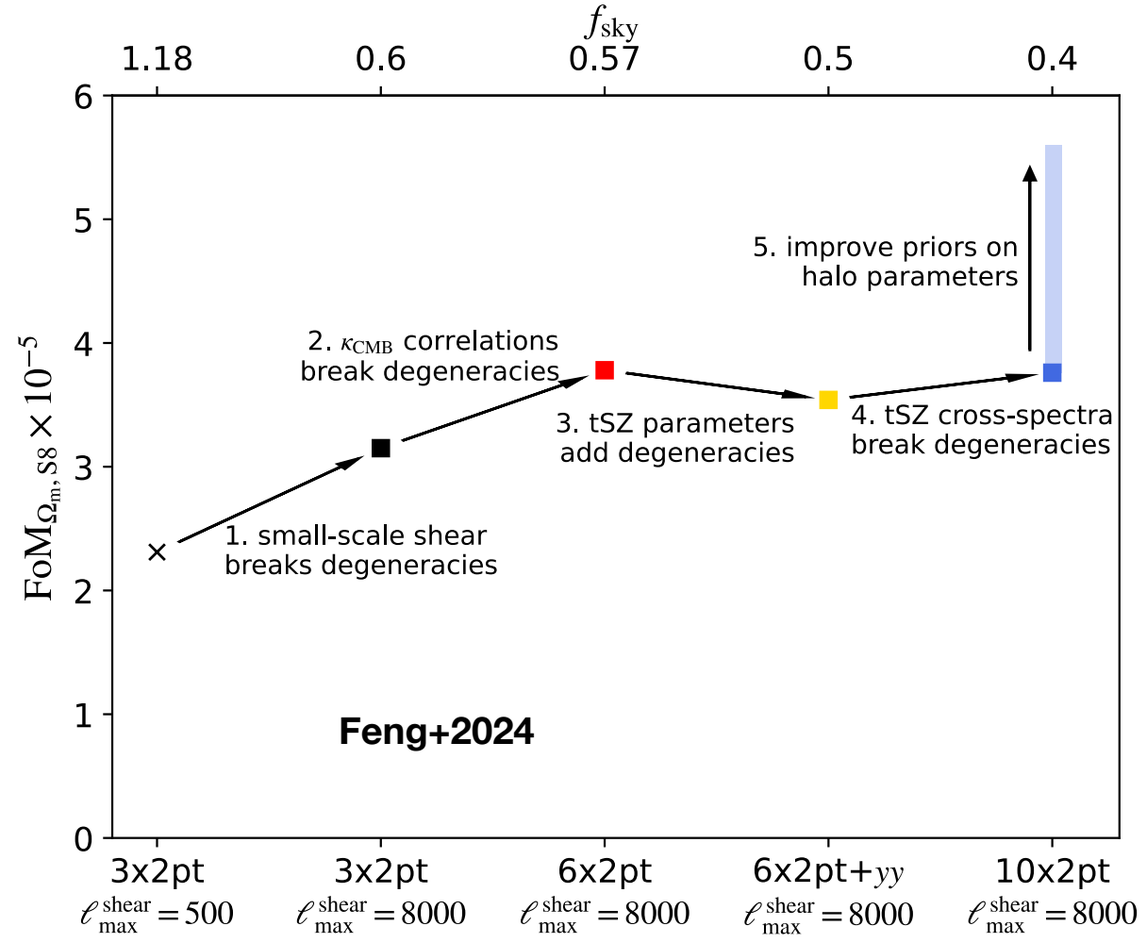
$\langle y \rangle$



The importance of global views…



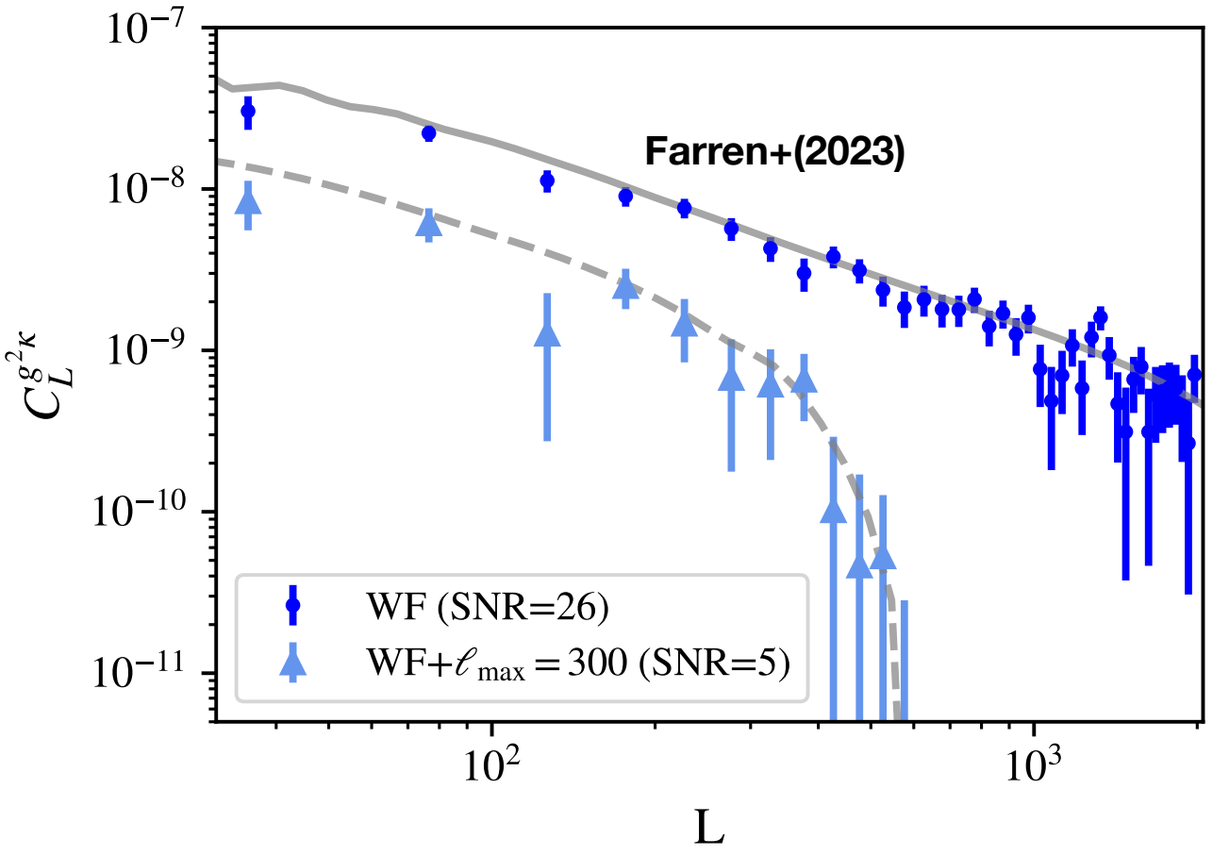


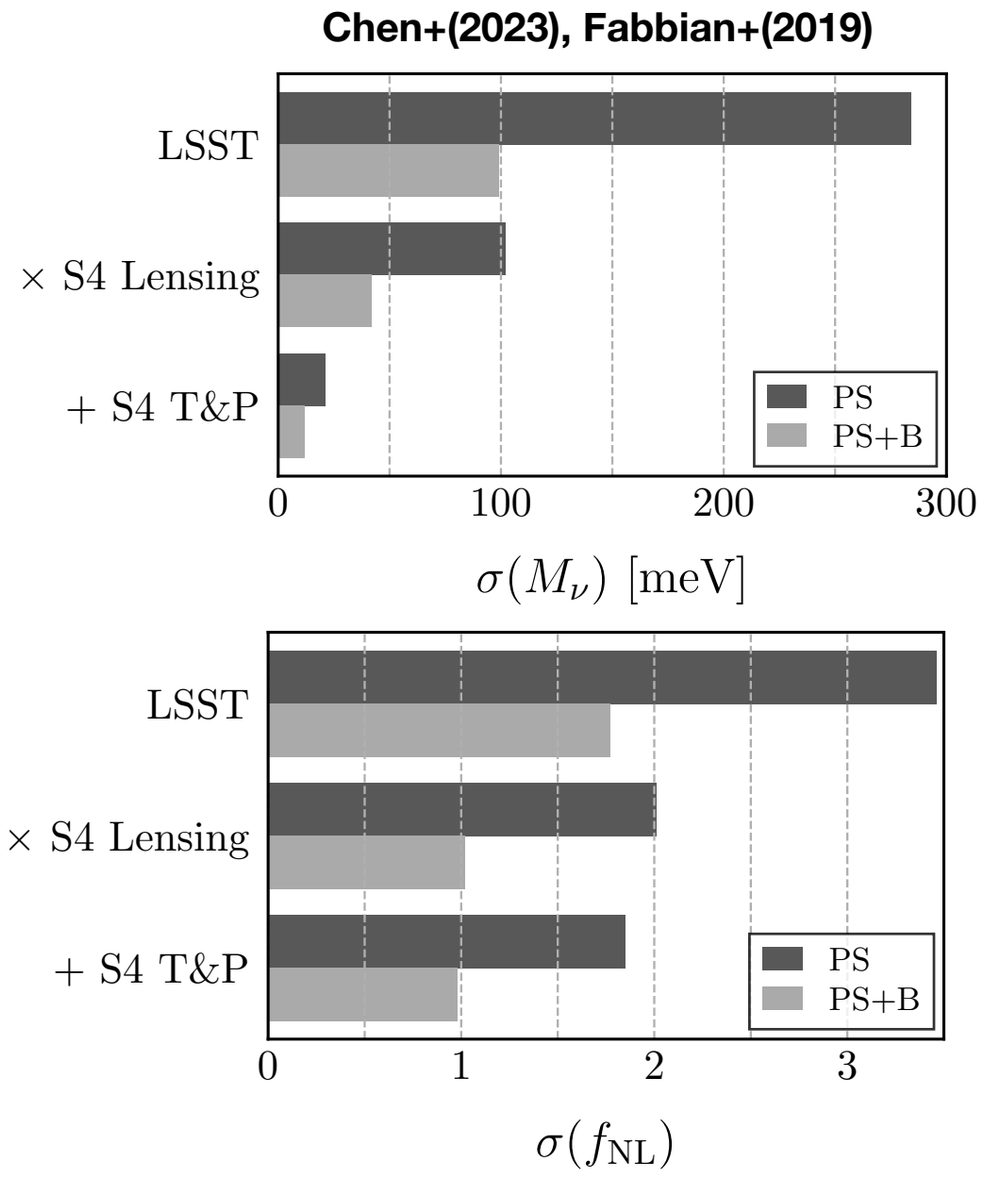


GF, F. Bianchini, A. Sabyr, C. Hill, C. Lovell, L. Thiele, D. Spergel

Higher-order cross-correlation

- Why limit to 2-point correlation functions….
- kkg, kgg: great tools to reduce errors due to galaxy bias uncertainties.
- Modeling TBD…





Conclusions

- **Exciting prospects from new CMB X galaxy surveys data…**
  - Quaia+Euclid Q1: interesting preview of what is achievable from space…
  - Shear validation ongoing but looking very promising both w/ ACT and SPT!

- **What we need to do**
  - Compliant likelihoods for CMB matter probes to be imported in survey pipelines
  - Joint covariances
  - Bias /theory modeling flexible enough also on the emulation level
  - We need to be able to add self-consistently other gas probes for robustness both on CMB and LSS side.