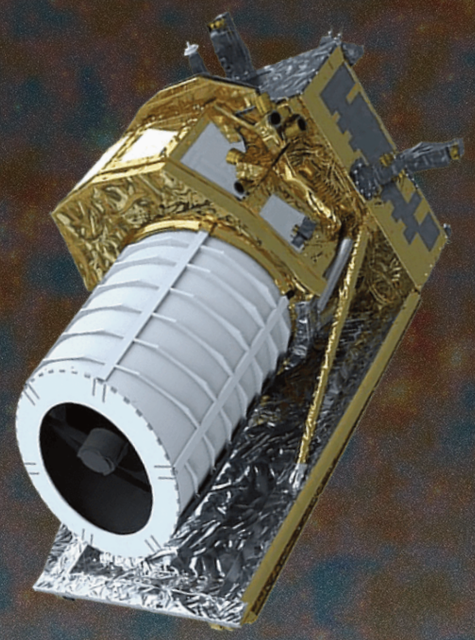
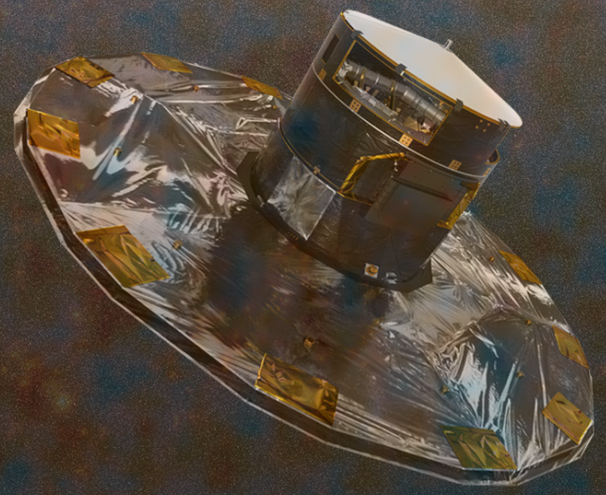
Cosmology with CMB and galaxy surveys from space

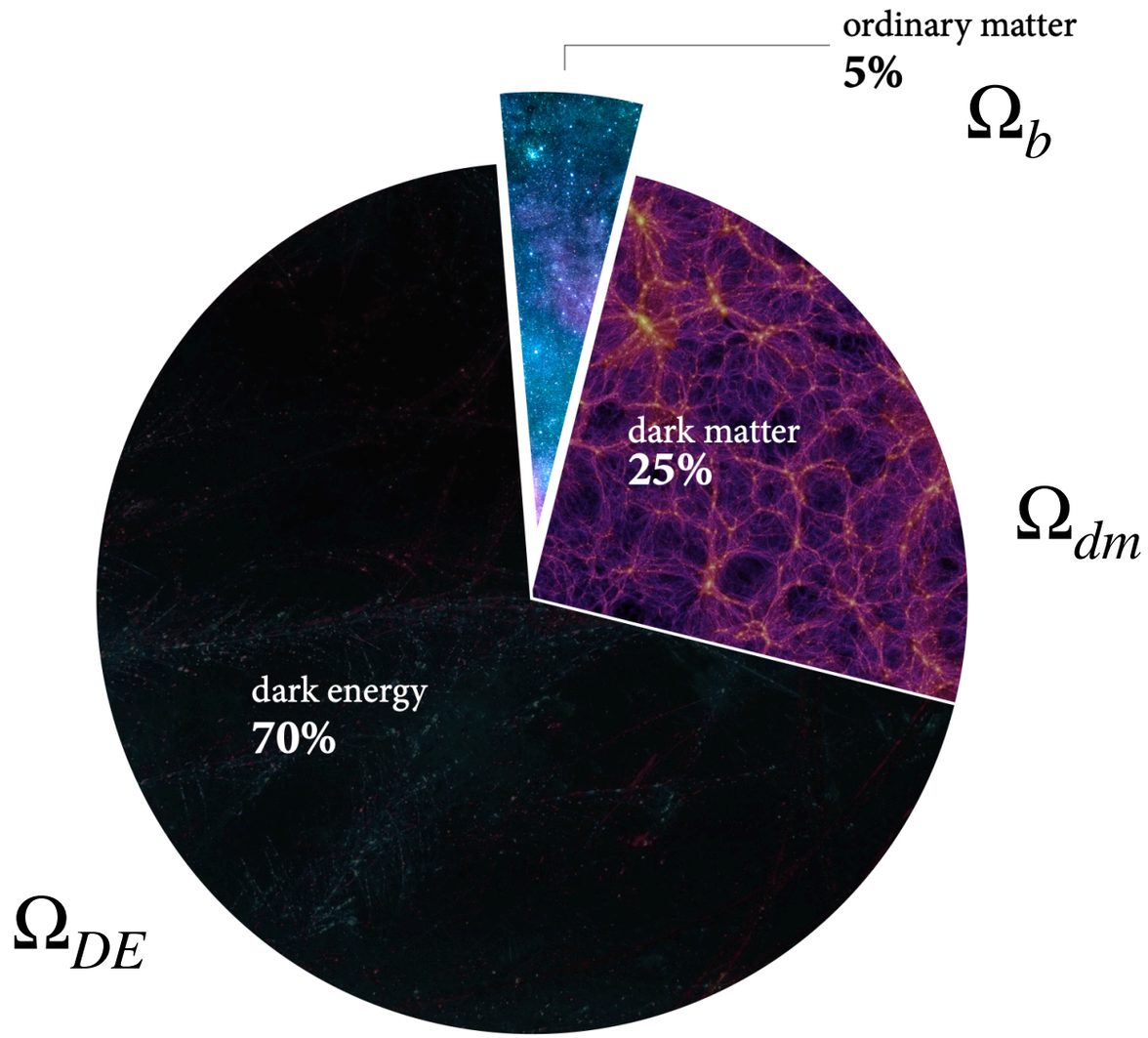




Giulio Fabbian

Institute d'Astrohysique Spatiale

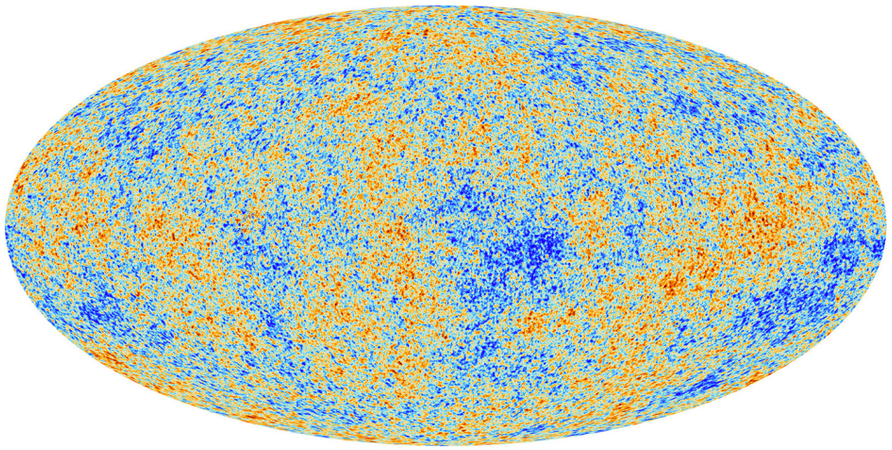
Open questions in cosmology as of 2025



- What is dark matter? Do **massive neutrinos** contribute?
- What is the nature of **dark energy**?
- Which mechanism driving primordial **inflation**?

Cosmological probes: CMB, large-scale structures

Cosmic Microwave Background (CMB)



Planck collaboration (2018)

Galaxy surveys

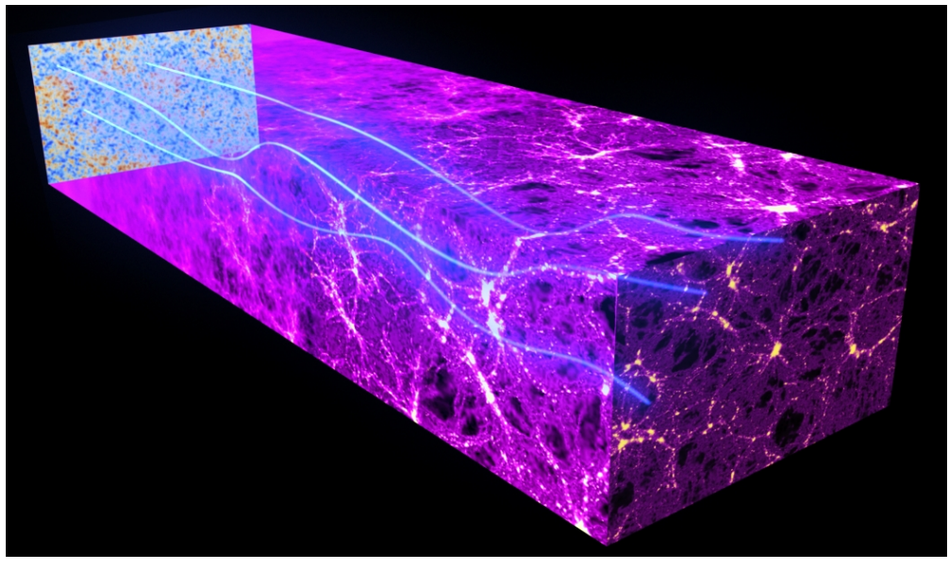
Intensity and polarization

- Constituents and composition of the Universe from early times.

Galaxy position, distances, shapes

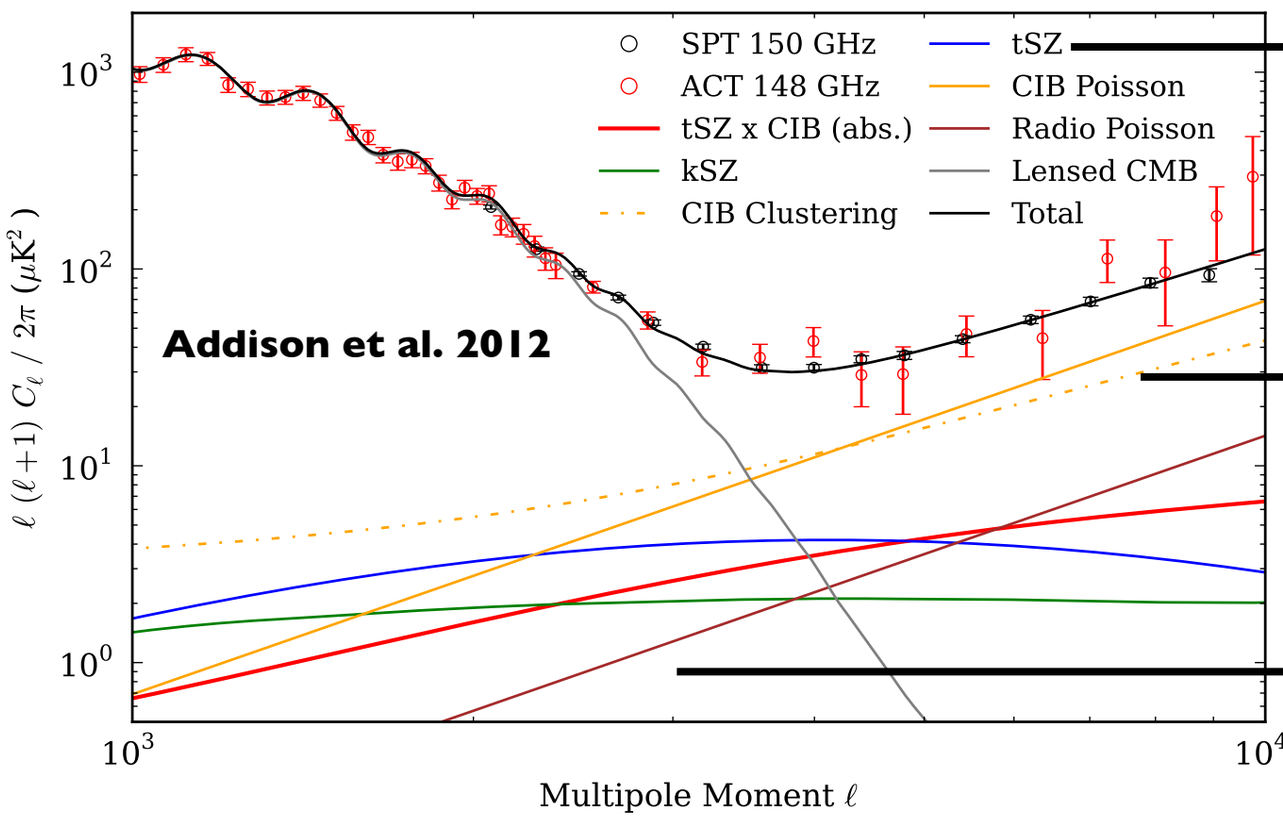
- Perturbations growth across-time and spatial distribution.
- More information on dark energy/neutrinos.

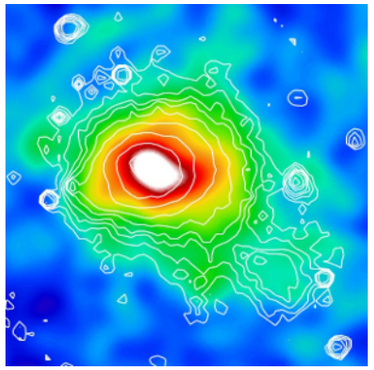
- Imprint of structures at different times



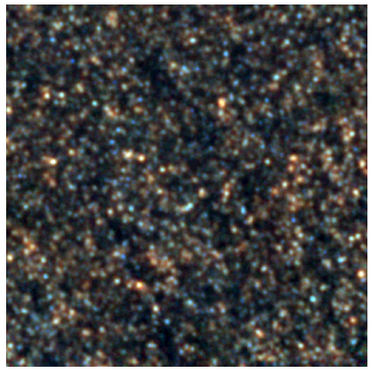
Is CMB "the" CMB?

- CMB is a snapshot of the universe at z ~1100.... plus lots of other things!
  - Imprint of astrophysical objects / late time physics (CIB, ISW, SZ).
  - Gravitational lensing.

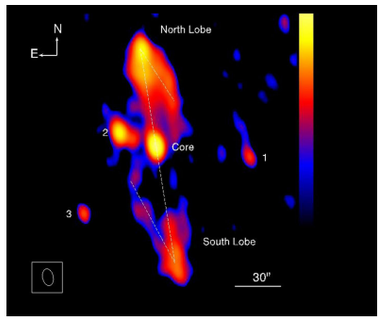




- ICM (g)astrophysics, cosmology (SZ)



- 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.

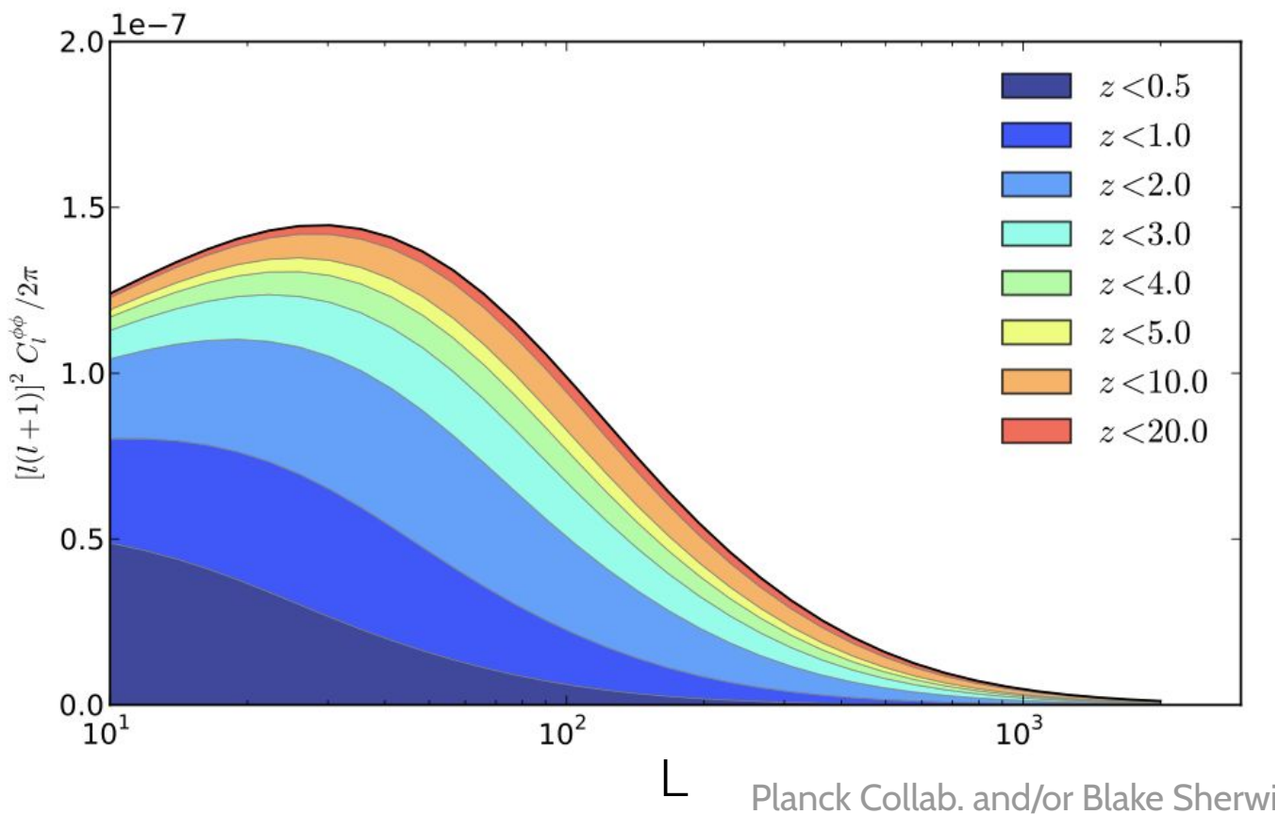
$$\phi(\boldsymbol{\theta}) = -2\int_0^{\chi_s} \frac{D_A(\chi_s - \chi')}{D_A(\chi_s)D_A(\chi')}\Psi\left(\boldsymbol{\theta}, \chi'\right) \mathrm{d}\chi'$$

$$\mathbf{d} = \nabla\phi$$

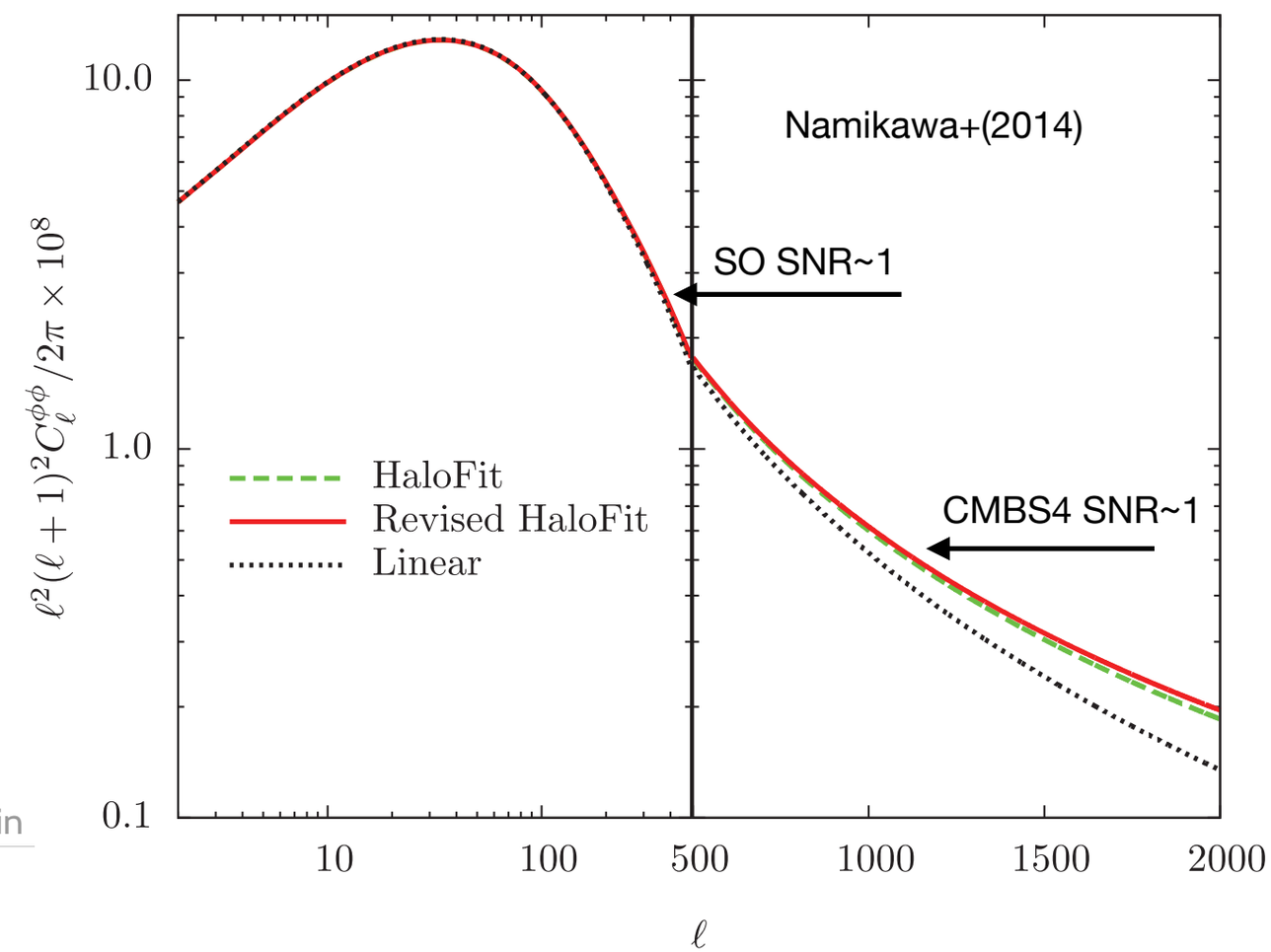
$$\kappa \propto -\nabla^2\phi \rightarrow \delta$$

Notation Warning!

- Sensitive to total matter distribution $\sigma_8\Omega_m^{0.25}$ at z~0.6-5 on mildly non-linear scales.

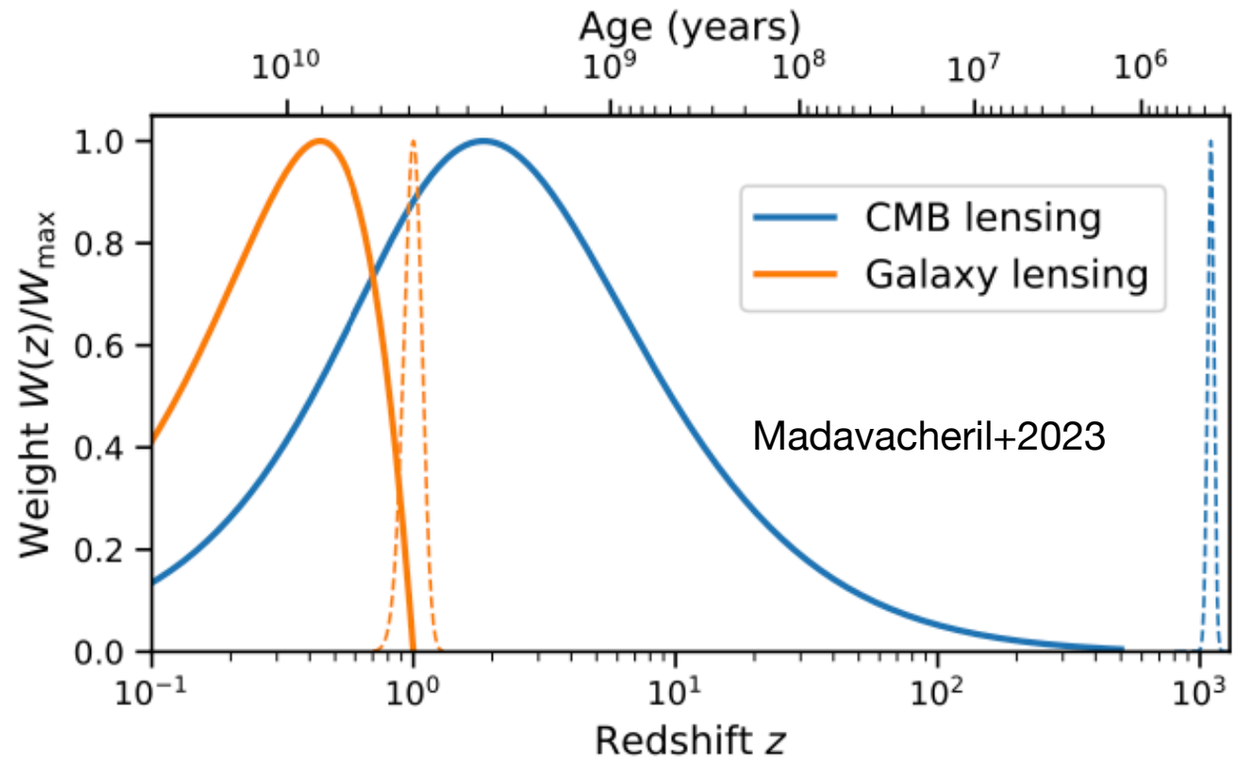


Planck Collab. and/or Blake Sherwin



CMB probes and cross-correlation

- CMB lensing: integrated, 2D projected, unbiased probe of matter.
- Integrated = overlaps with all the matter in the universe.
- Synergies with any other probe of matter e.g. LSS surveys.
- Reduces systematics



$$\kappa_{gal,obs} = \kappa_{gal} + s_{gal} \qquad \kappa_{CMB,obs} = \kappa_{CMB} + s_{CMB}$$

$$\langle \kappa_{gal,obs}\kappa_{gal,obs} \rangle = \langle \kappa_{gal}\kappa_{gal} \rangle + \langle s_{gal}s_{gal} \rangle + \langle \kappa_{gal}s_{gal} \rangle$$

$$\langle \kappa_{CMB,obs}\kappa_{CMB,obs} \rangle = \langle \kappa_{CMB}\kappa_{CMB} \rangle + \langle s_{CMB}s_{CMB} \rangle + \langle \kappa_{CMB}s_{CMB} \rangle$$

$$\langle \kappa_{CMB,obs}\kappa_{gal,obs} \rangle = \langle \kappa_{CMB}\kappa_{gal} \rangle + \cancel{\langle s_{CMB}s_{gal} \rangle} + \cancel{\langle \kappa_{CMB}s_{gal} \rangle} + \cancel{\langle \kappa_{gal}s_{CMB} \rangle}$$

Cross-correlation basis and examples

CMB lensing

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

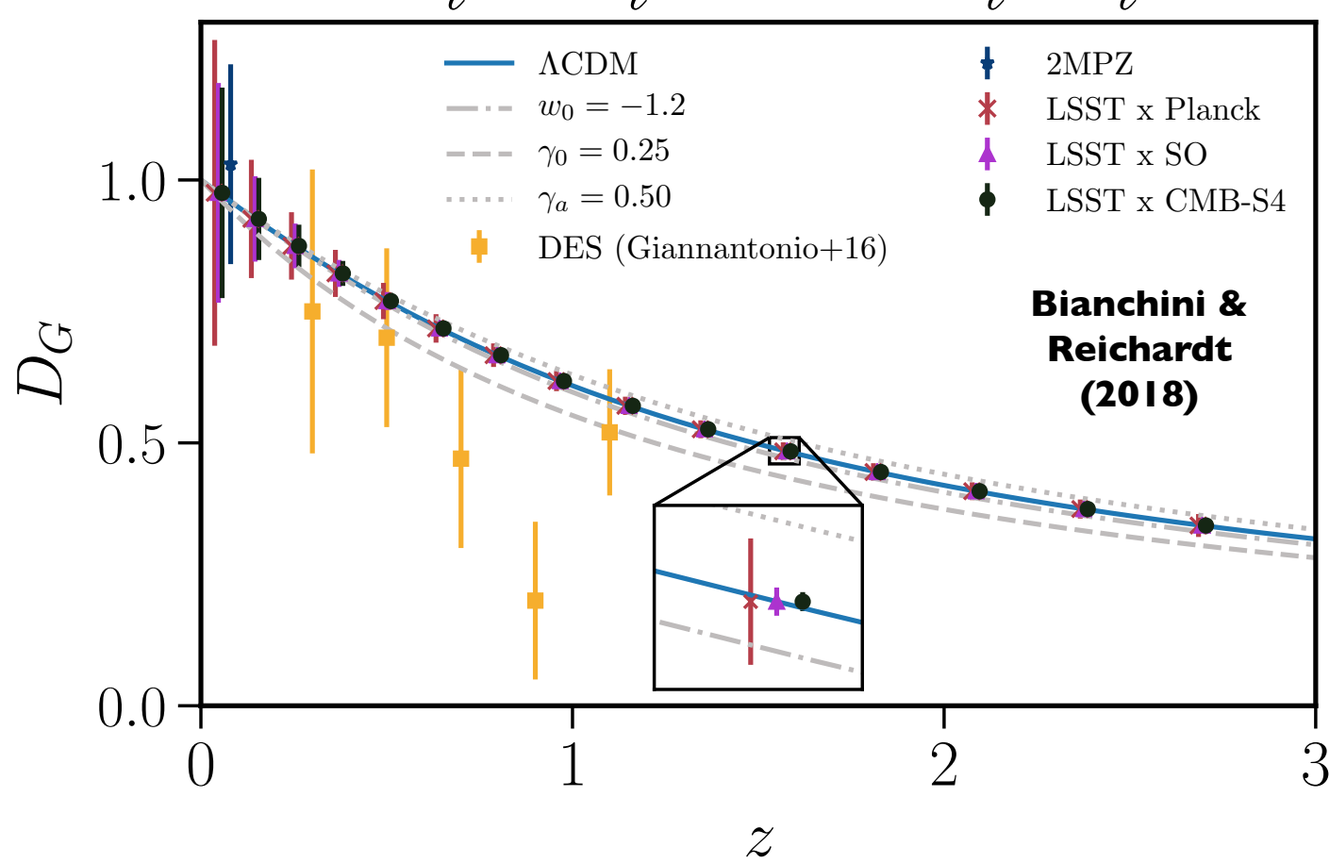
Photometric Galaxy clustering

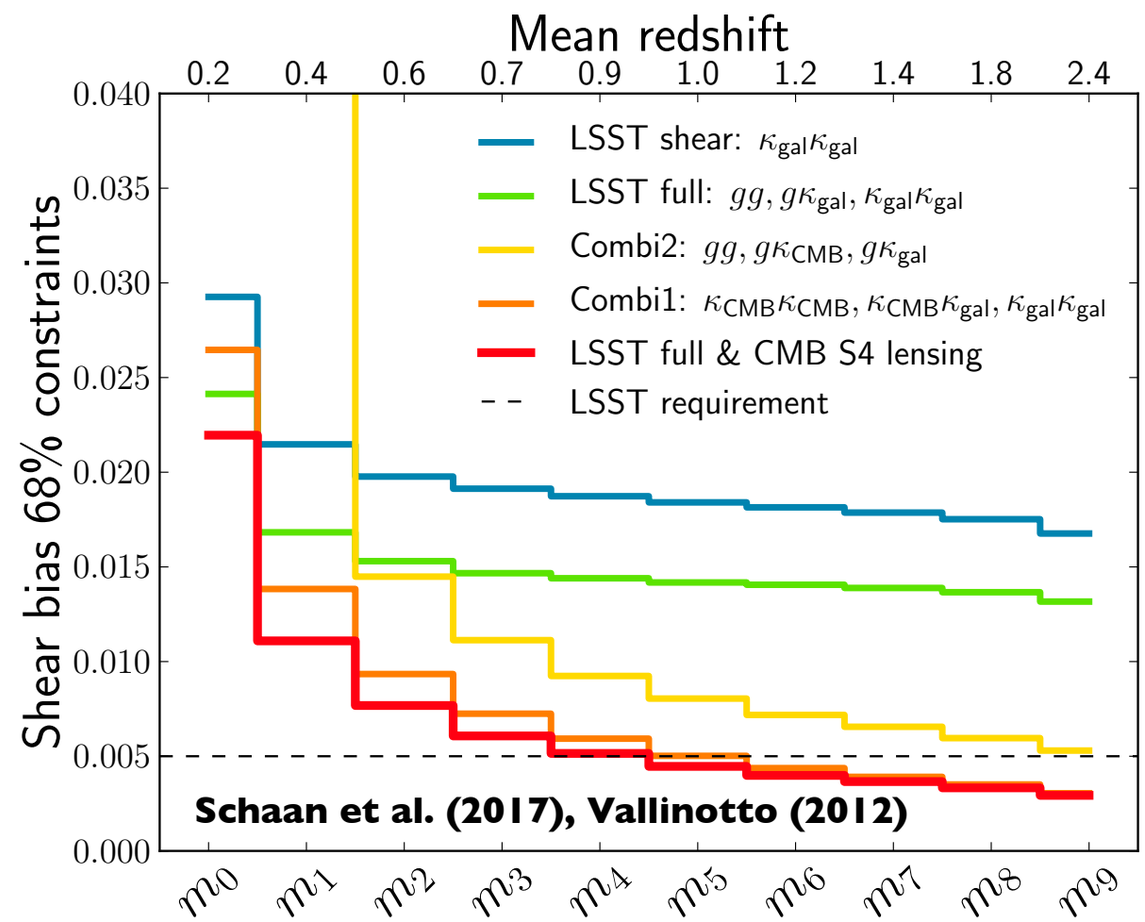
$$W_g(\chi) = b_g(z) \frac{1}{n} \frac{dn}{dz} \frac{dz}{d\chi}$$

Galaxy lensing

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

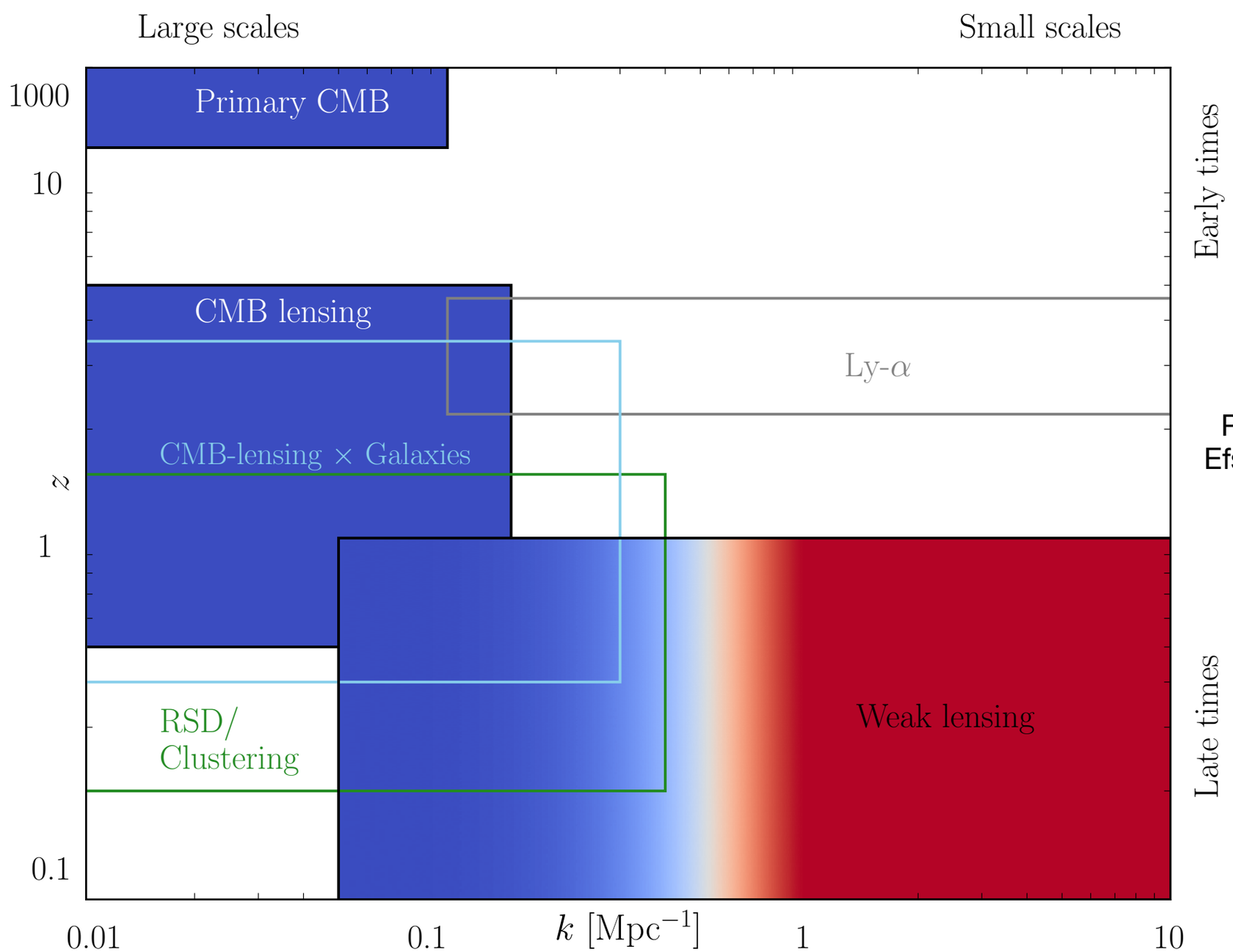
$$D_G \approx (C_\ell^{\kappa g})^2 / C_\ell^{gg} \approx \hat{\boldsymbol{\theta}} \in \{C_\ell^{\kappa g}, C_\ell^{gg}\}$$





Cosmological probes and cross-correlations

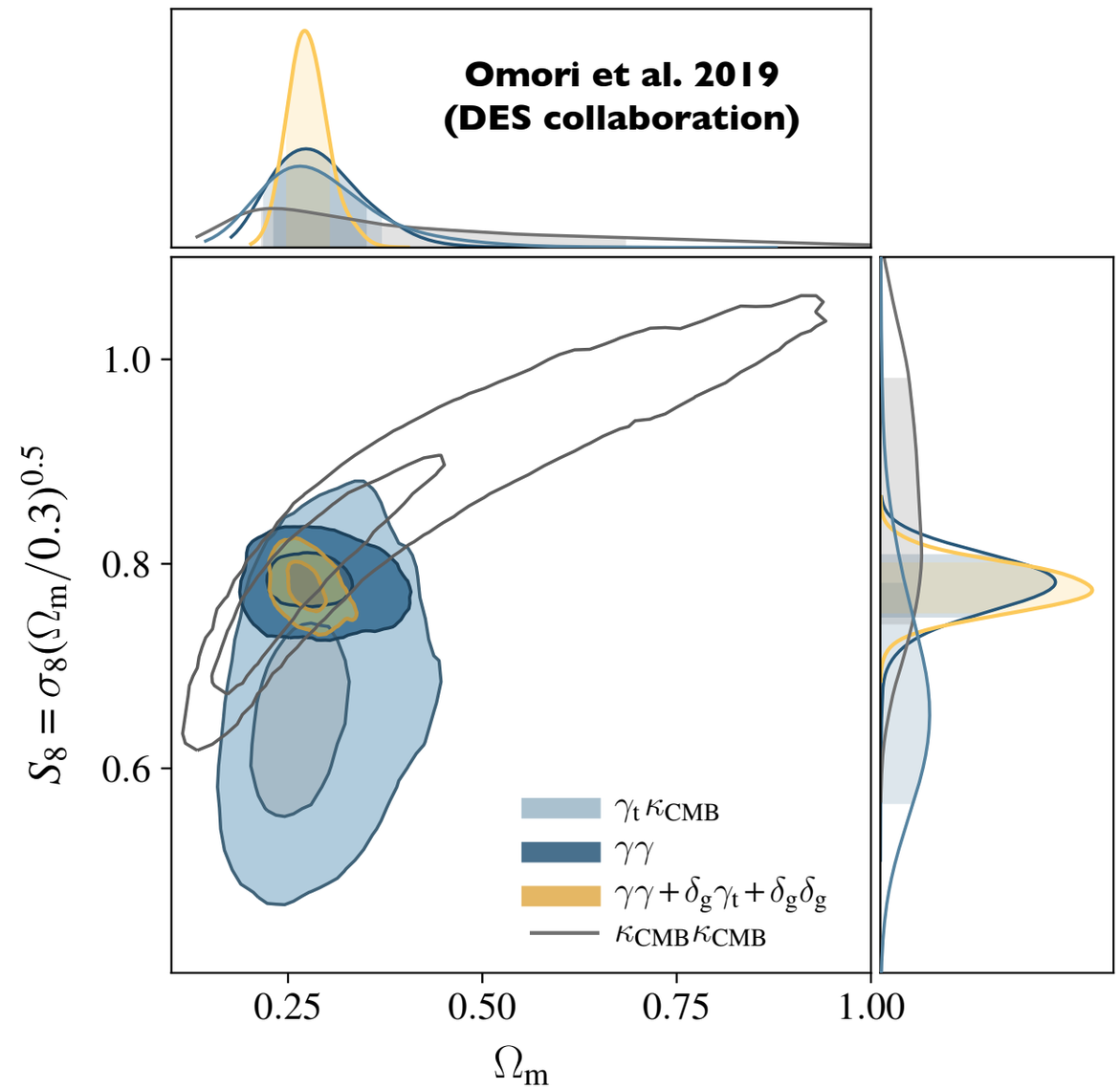
- Different probes test different scales and redshift (and different systematics).
- Need to assess if growth tension is real or effect of non-linear physics.



Preston, Amon, Efsthathiou (2023)

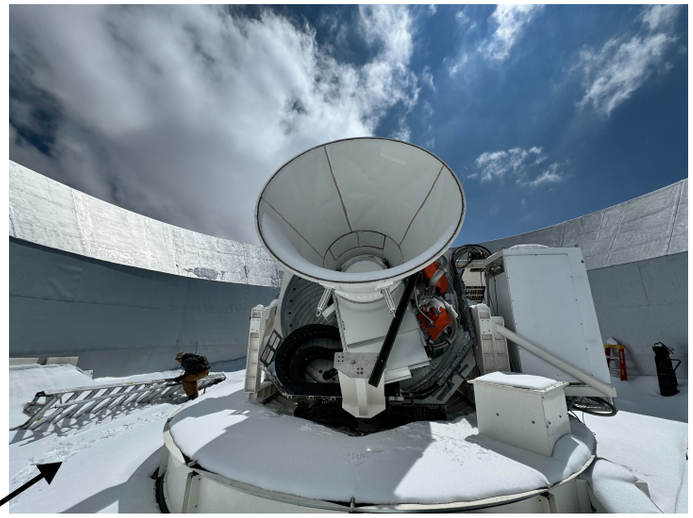
CMB cross-correlations for cosmology

- Current data:
  - marginalizing over systematics at limited cost
  - limited additional power!
- Situation bound to change very soon:
  - New CMB data on sky!
  - New galaxy surveys on sky!



AOB: Simons Observatory first light achieved!

Small Aperture Telescopes (SATs), on sky!



- B-modes r~0.003
- 3 there, more soon!
- Commissioning data!

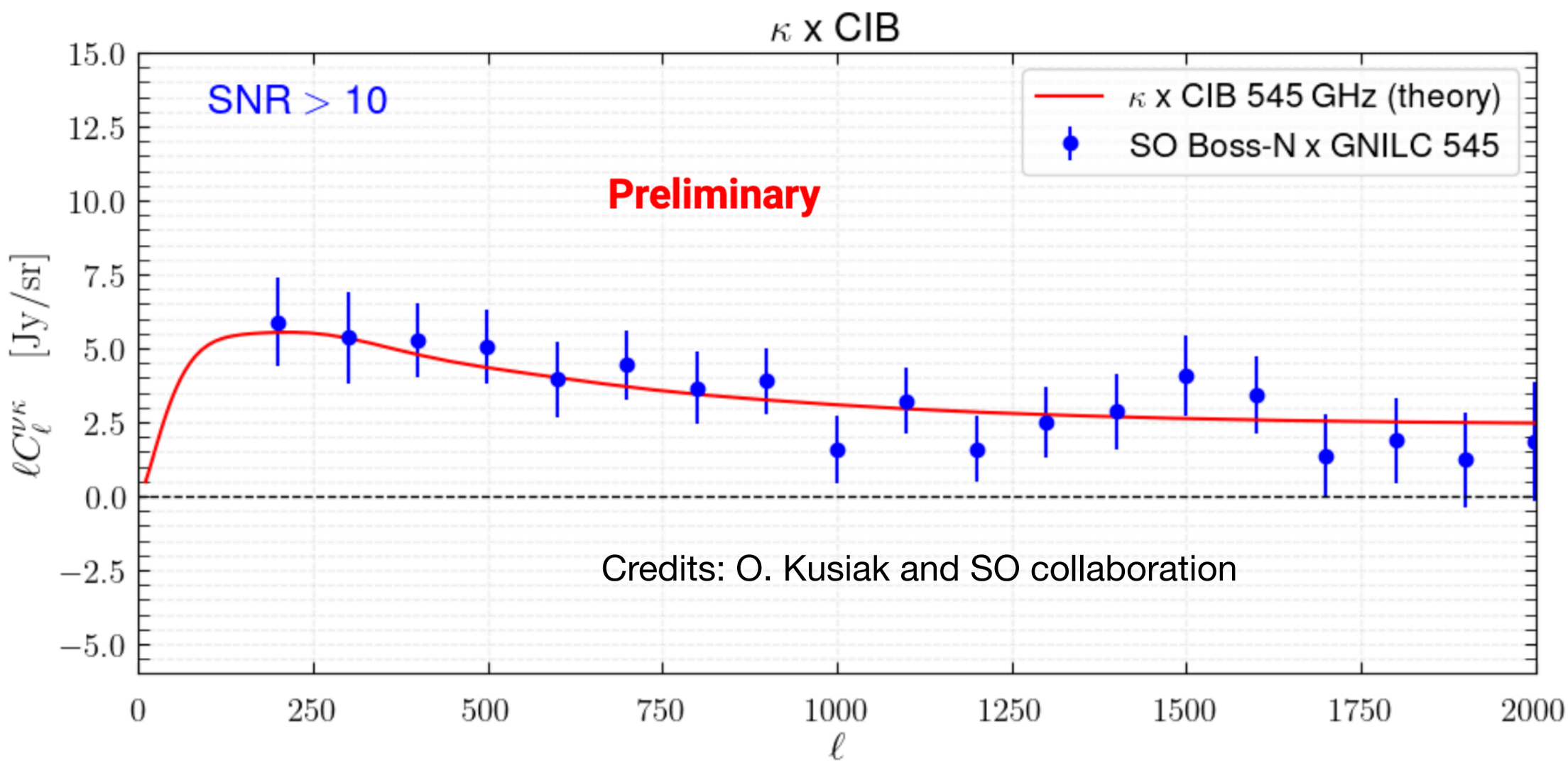
Simons Observatory collaboration: science goals and forecasts (2019)

Large Aperture Telescope (LAT) in Feb 2025!

- Small-scale E/B-modes
- Lensing and SZ
- Neff ~ 0.07
- $\sum m_\nu$~50meV

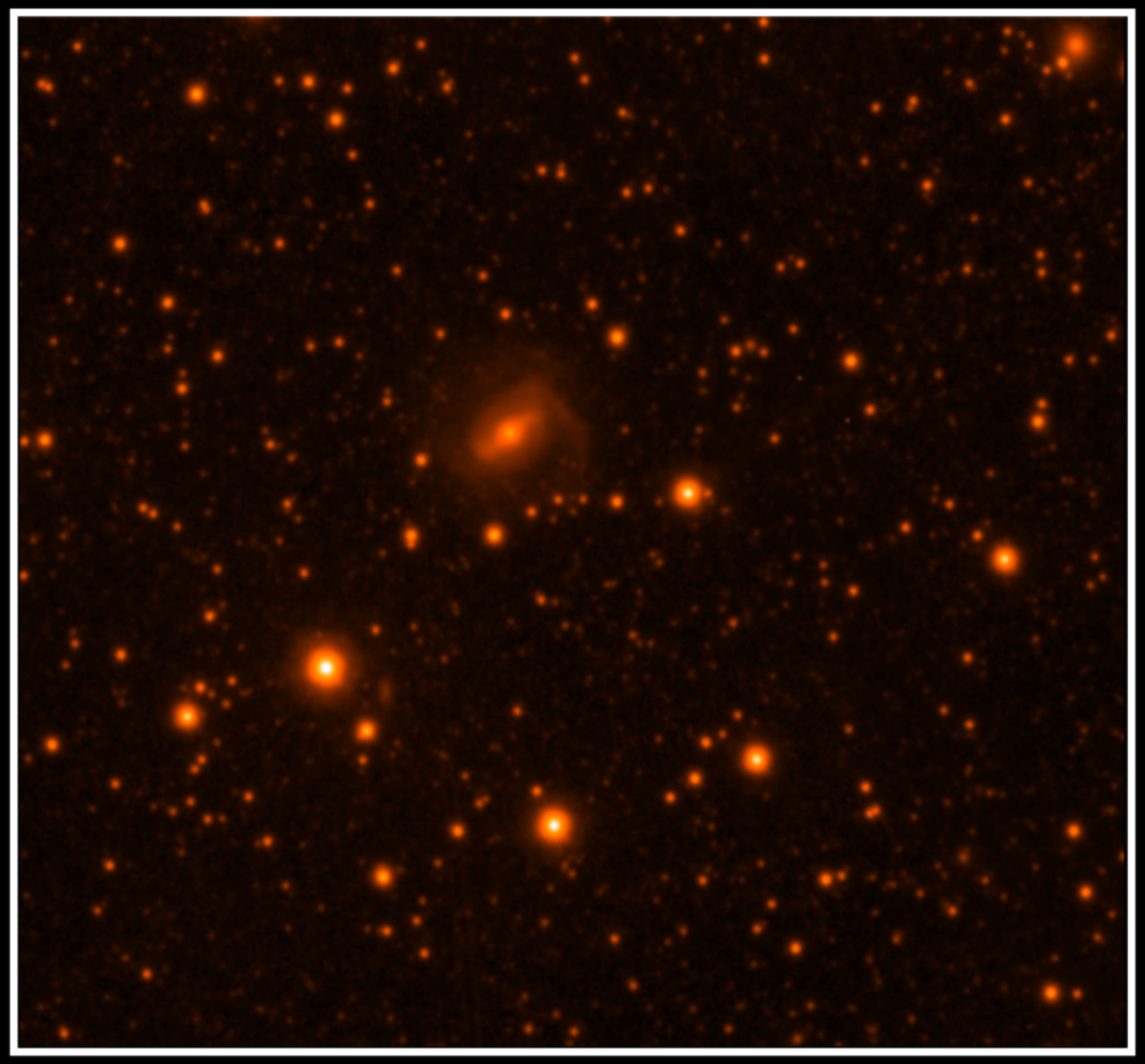
Sneak preview

- Just ~2 weeks of science commissioning data….
- Includes foreground hardening

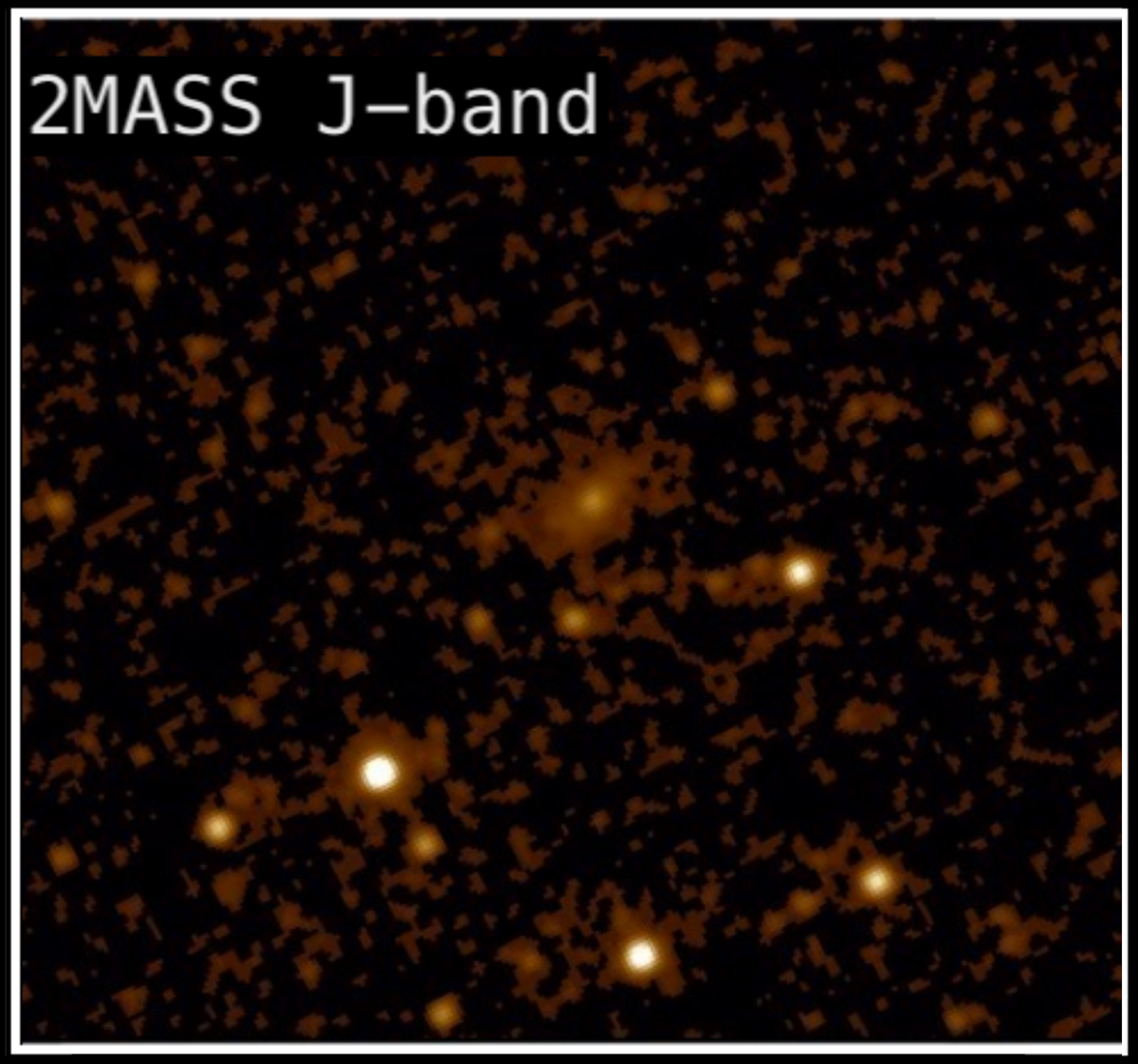


EUCLID

RESULTS SO FAR



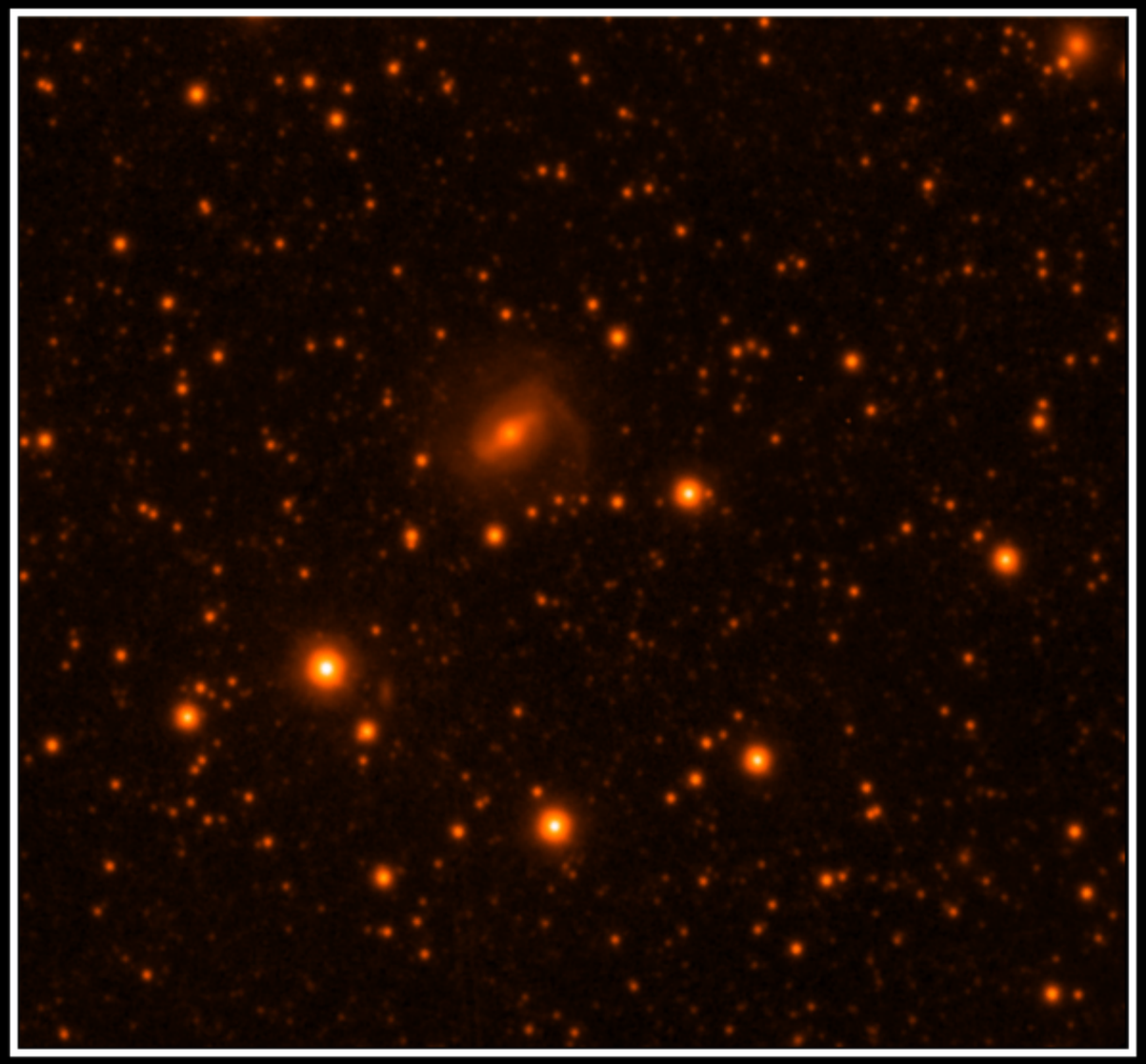
VISTA VMC J-band



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

EUCLID

RESULTS SO FAR



VISTA VMC J-band

Euclid NISP Test Image

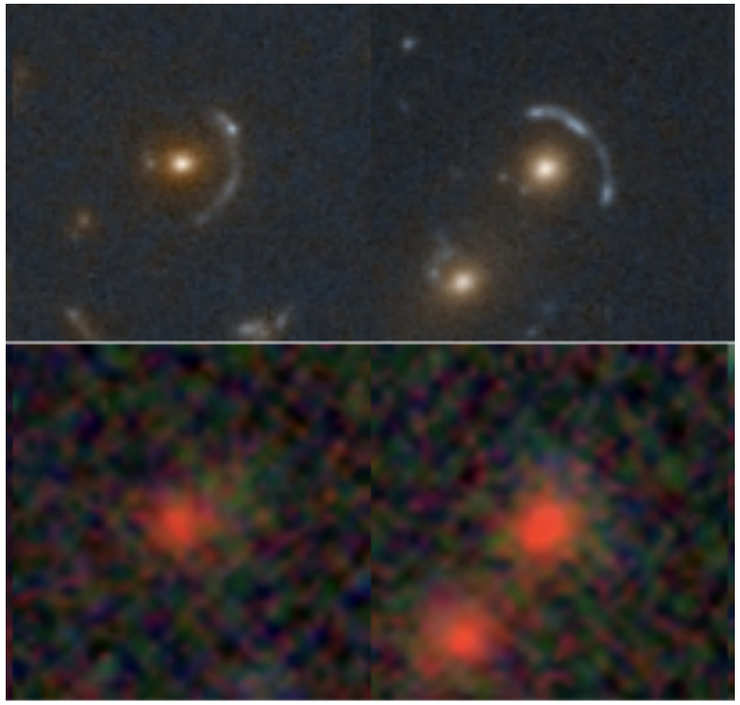
Credit: Ralf Bender & Ross Collins using public data from Euclid and VISTA

What to expect: synergies between surveys.

Euclid Early Release Observation image

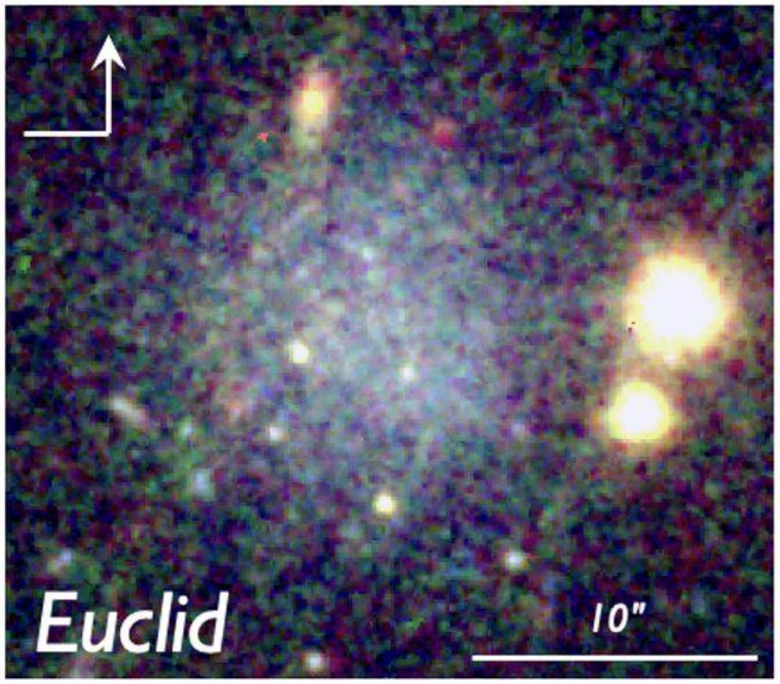
Rubin 1st wide image

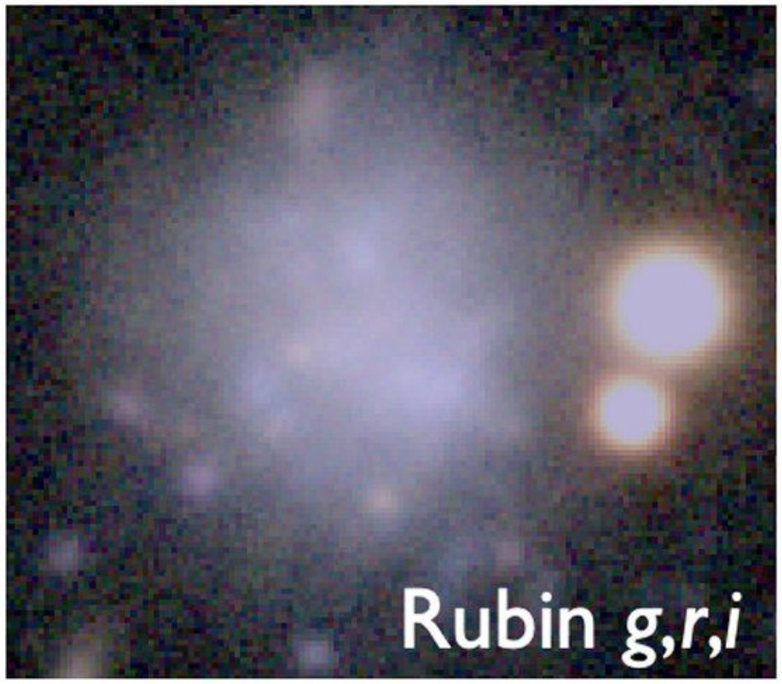
Euclid Q1 release



DESI Legacy Imaging Survey

Romanowsky+(2025)

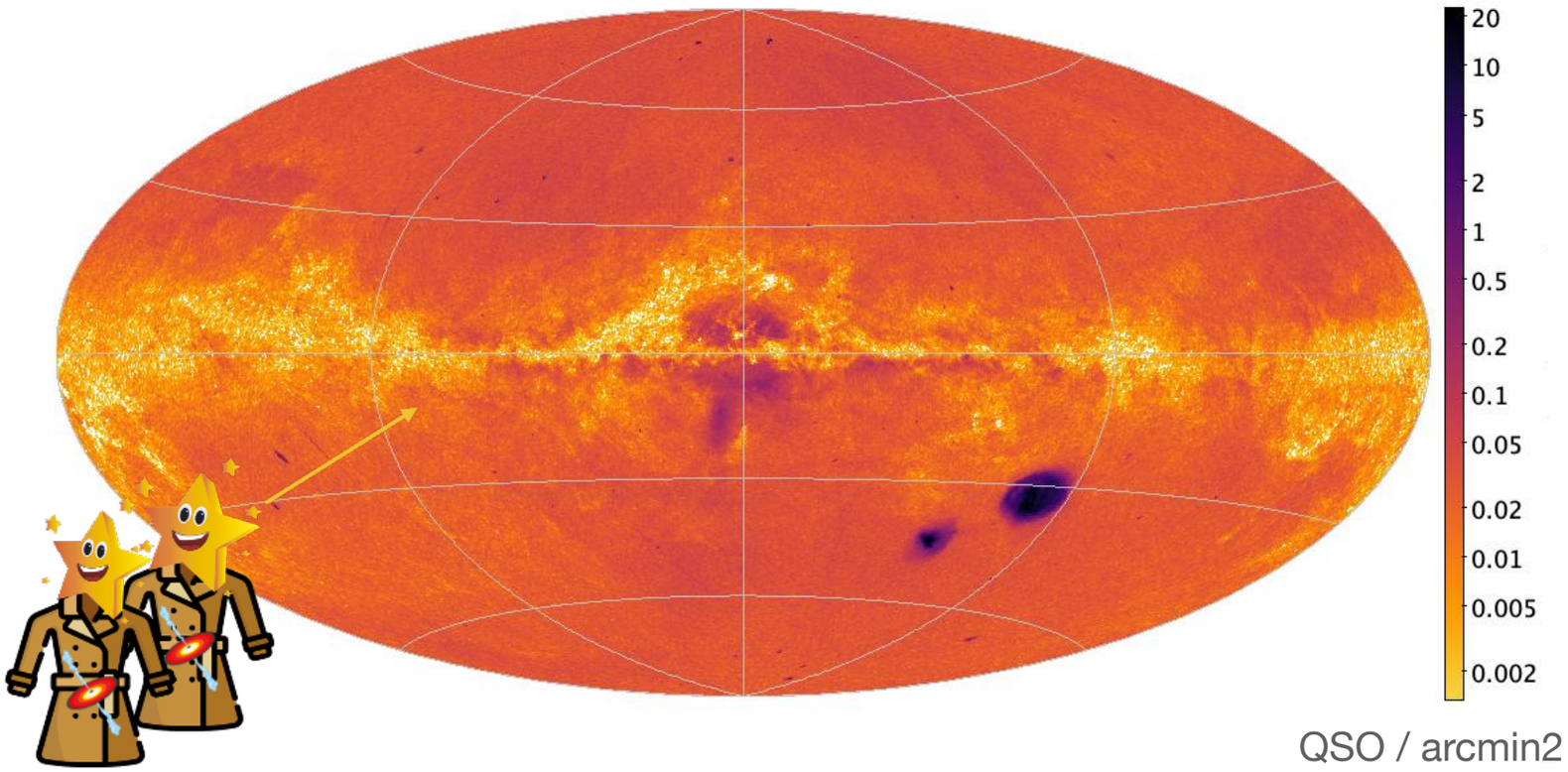




In the meantime… Gaia!

- Photometry, astrometry, slitless spectroscopy with $30 \leq \lambda/\Delta\lambda \leq 100$ resolution

- DR3 released 6.6 million quasar candidates!

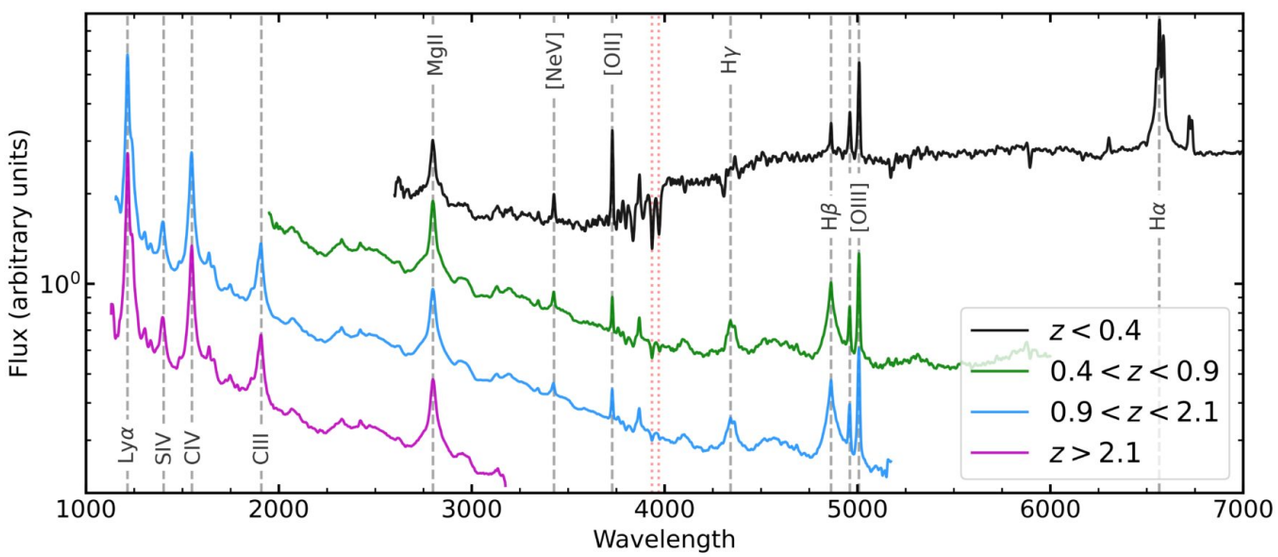


Bailer-Jones+2022

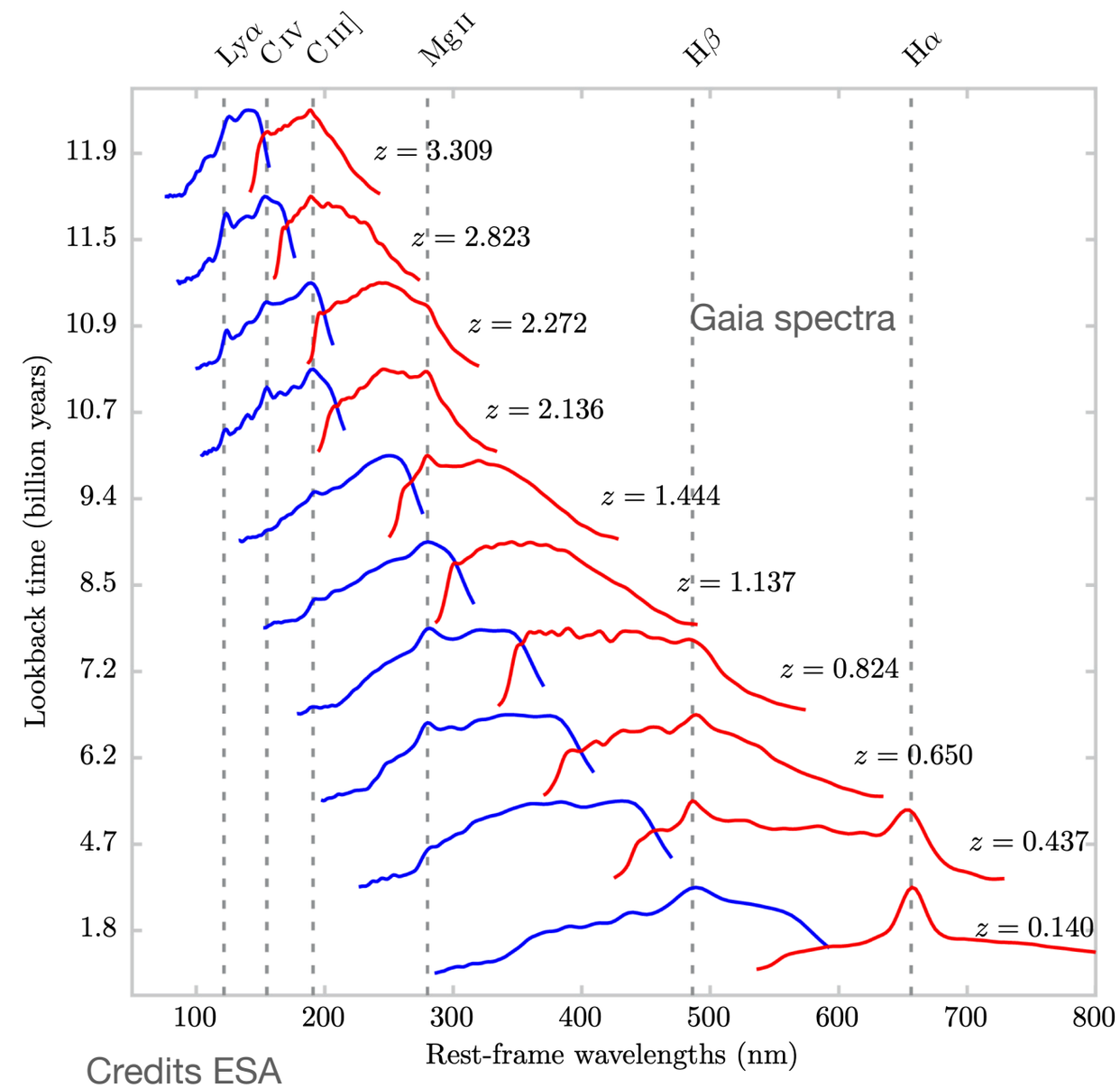
- Complete, low purity, as many are stars masquerading as QSO :/ but… we can improve it

Gaia: more than astrometry

- Space-quality data means e.g. no seeing, airmass, stable observing conditions…
  - larger volume, cleaner selection function than any existing sample (full sky).
  - Synergies with external data allowed to clean this sample further: Quaia



DESI spectra

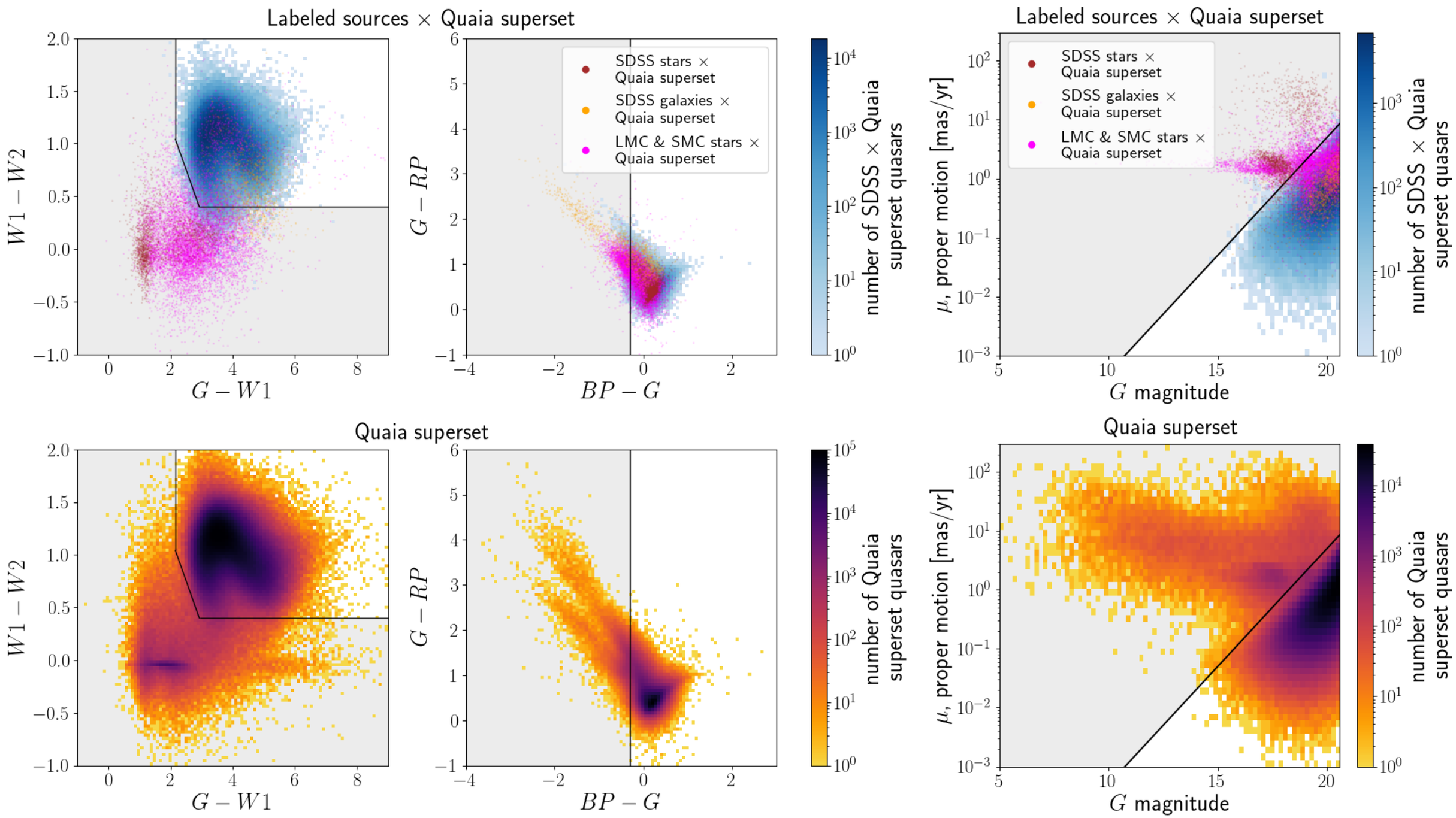


Credits ESA

Quaia: the cosmological QSO sample of Gaia

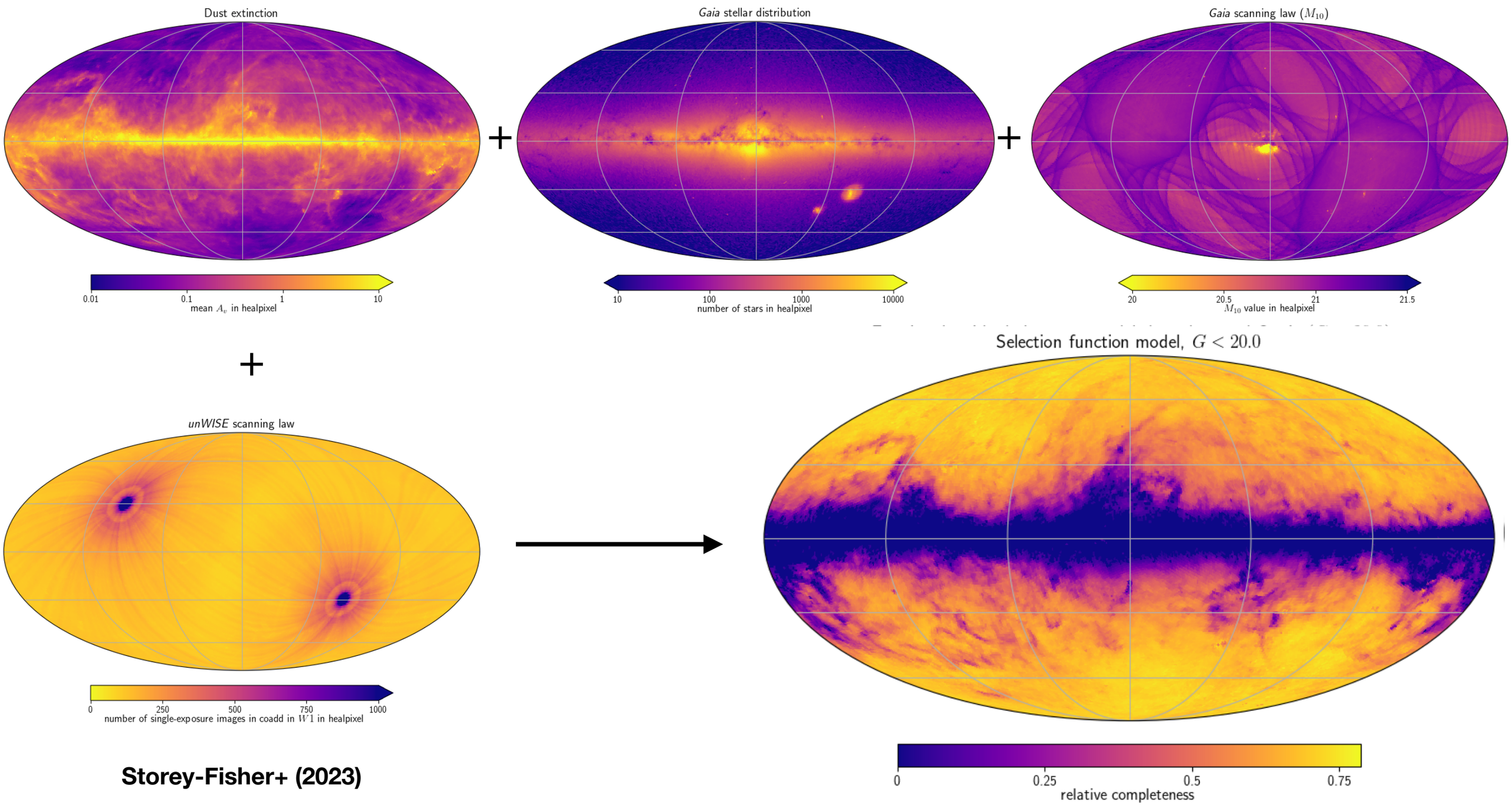
- unWISE + SDSS DR18 + color and proper motion cuts = better purity, low systematics

Storey-Fisher+ (2023)



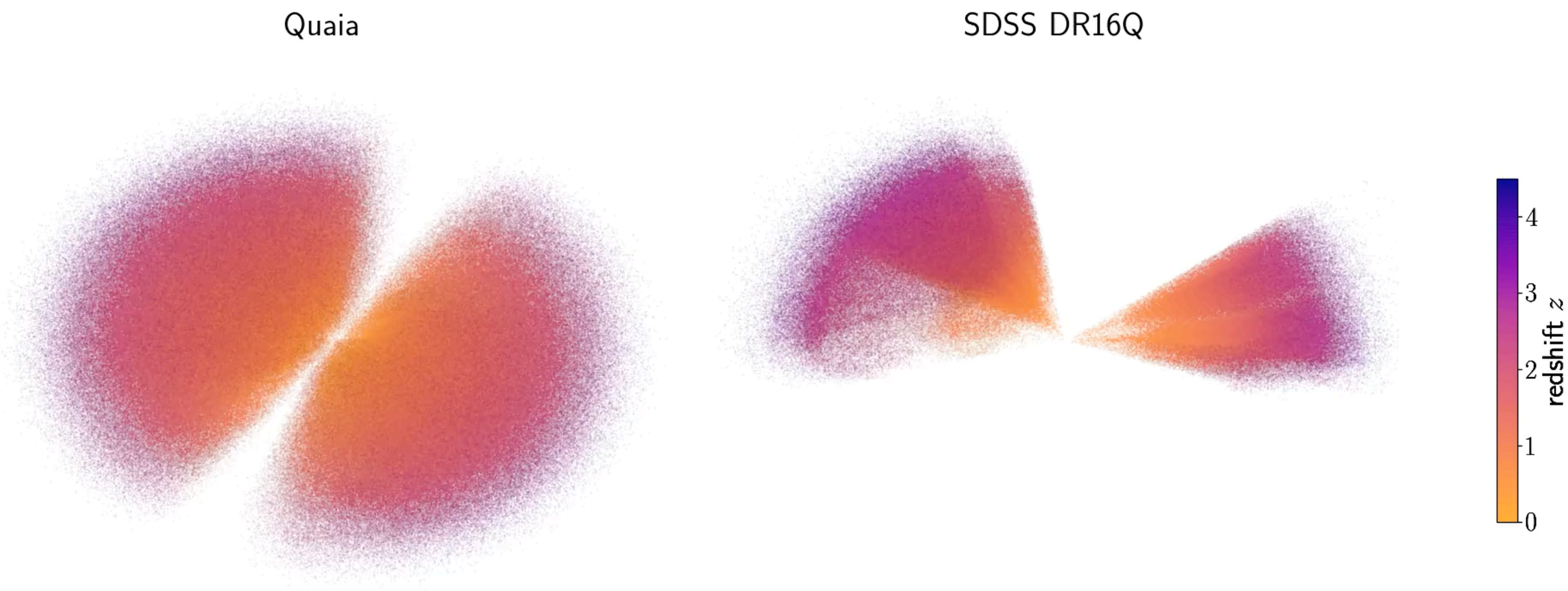
The selection function

- A handful of templates + Gaussian processes corrects for scanning pattern, stars, extinction…
- Some further updates ongoing, new Gaia DR also soon… (Williams, Storey-Fisher+ in prep.)



Storey-Fisher+ (2023)

How it compares?

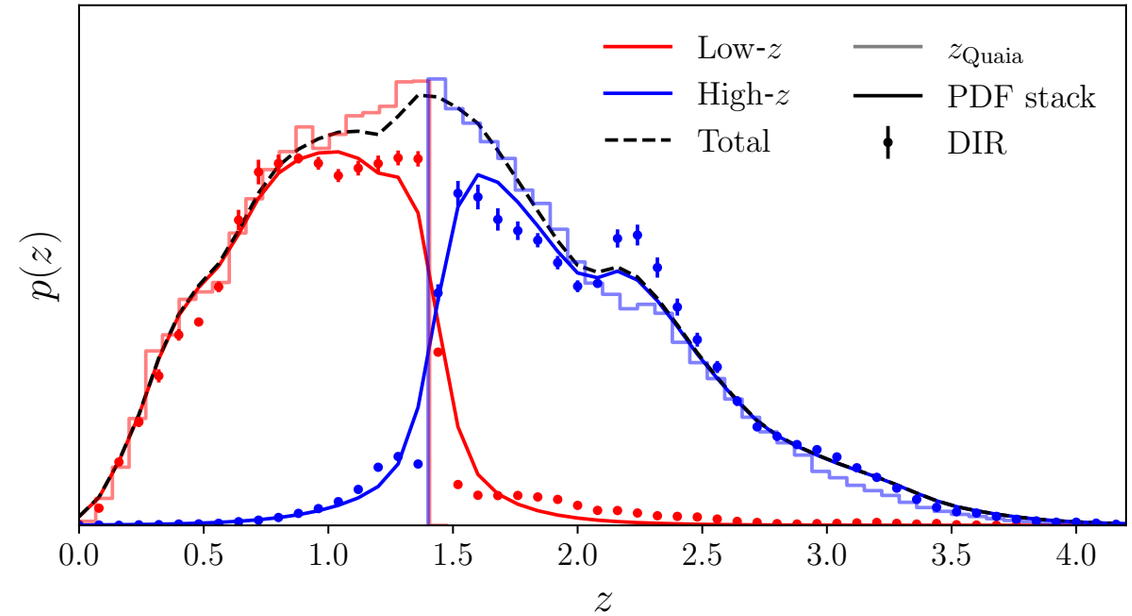


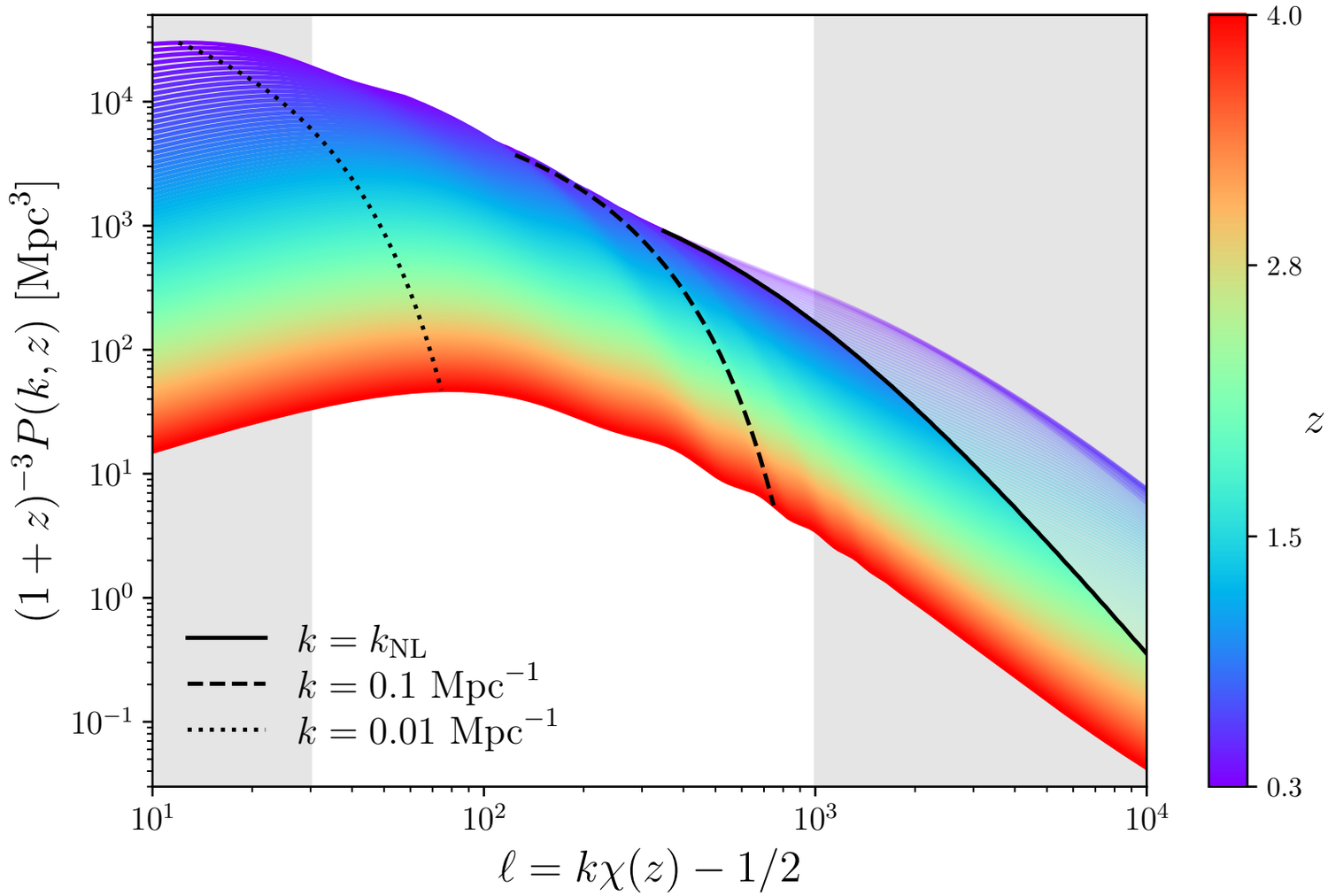
Credits Kate Storey-Fisher

	N	$f_{\rm sky}$	$\bar{n}$, deg^{-2}	$V_{\rm span}$, $(h^{-1}\,{\rm Gpc})^3$	$V_{\rm eff}$, $(h^{-1}\,{\rm Gpc})^3$	$z_{\rm med}$	$f(\lvert\delta z\rvert < 0.01)$	$f(\lvert\delta z\rvert < 0.1)$
Quaia	**1,209,833**	**0.71**	**41.50**	**138.46**	**7.01**	**1.47**	**0.61**	**0.83**
Gaia Purer	1,261,884	0.71	43.29	138.44	6.43	1.61	0.62	0.70
WISE-PS1	1,106,010	0.54	49.81	105.45	7.21	1.43	0.12	0.76
eBOSS	190,194	0.14	34.03	26.55	1.01	1.49		

What Quaia can do for cosmology?

- High redshift
- Linear or quasi-linear scales.



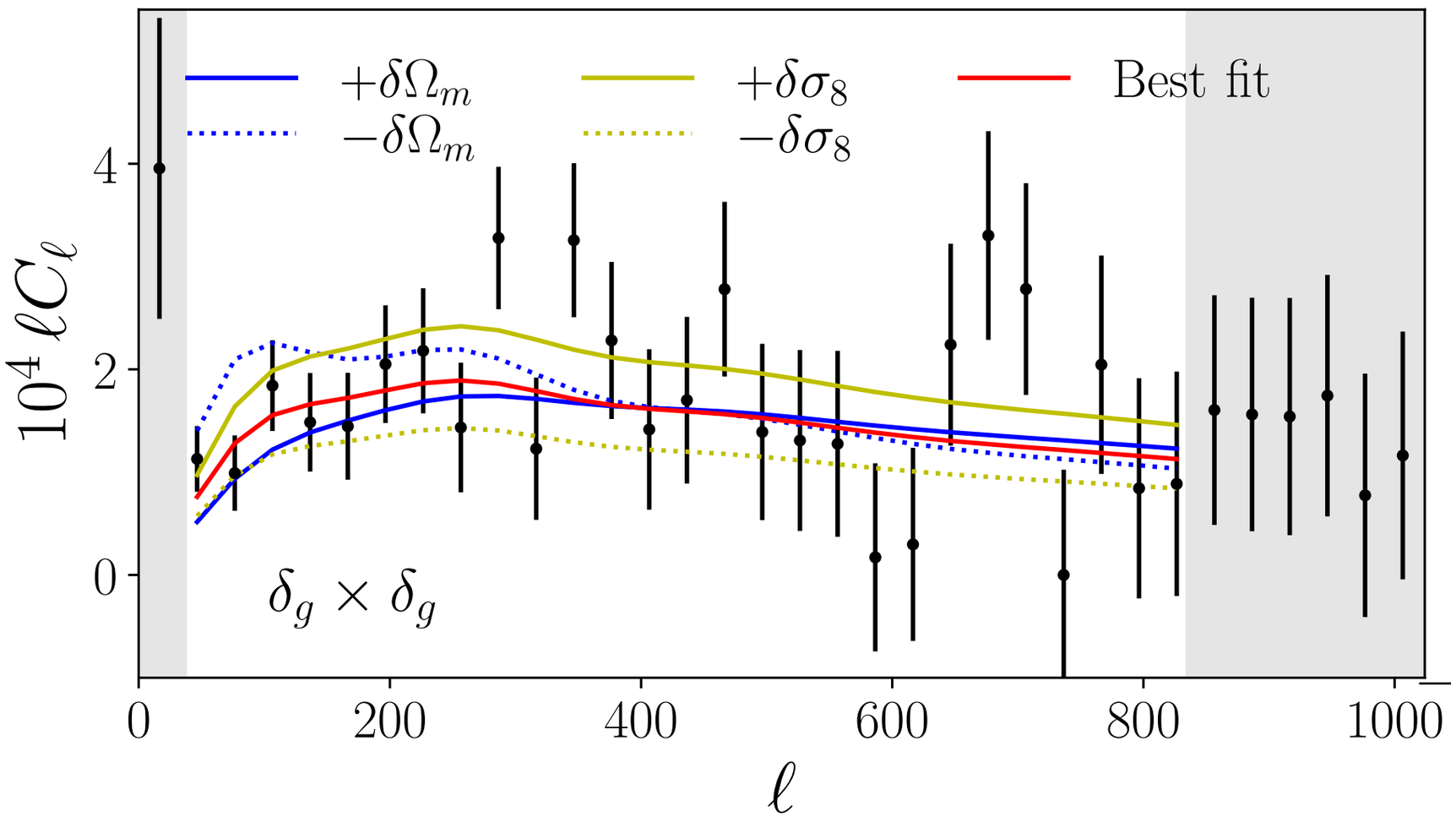


Storey-Fisher+ (w/ GF, 2023)

Alonso, GF, Storey-Fisher+(2023)

What Quaia can do for cosmology?

- Large sky coverage means capability to measure large angular scales.
- Towards non-degenerate σ_8, Ω_m measurements

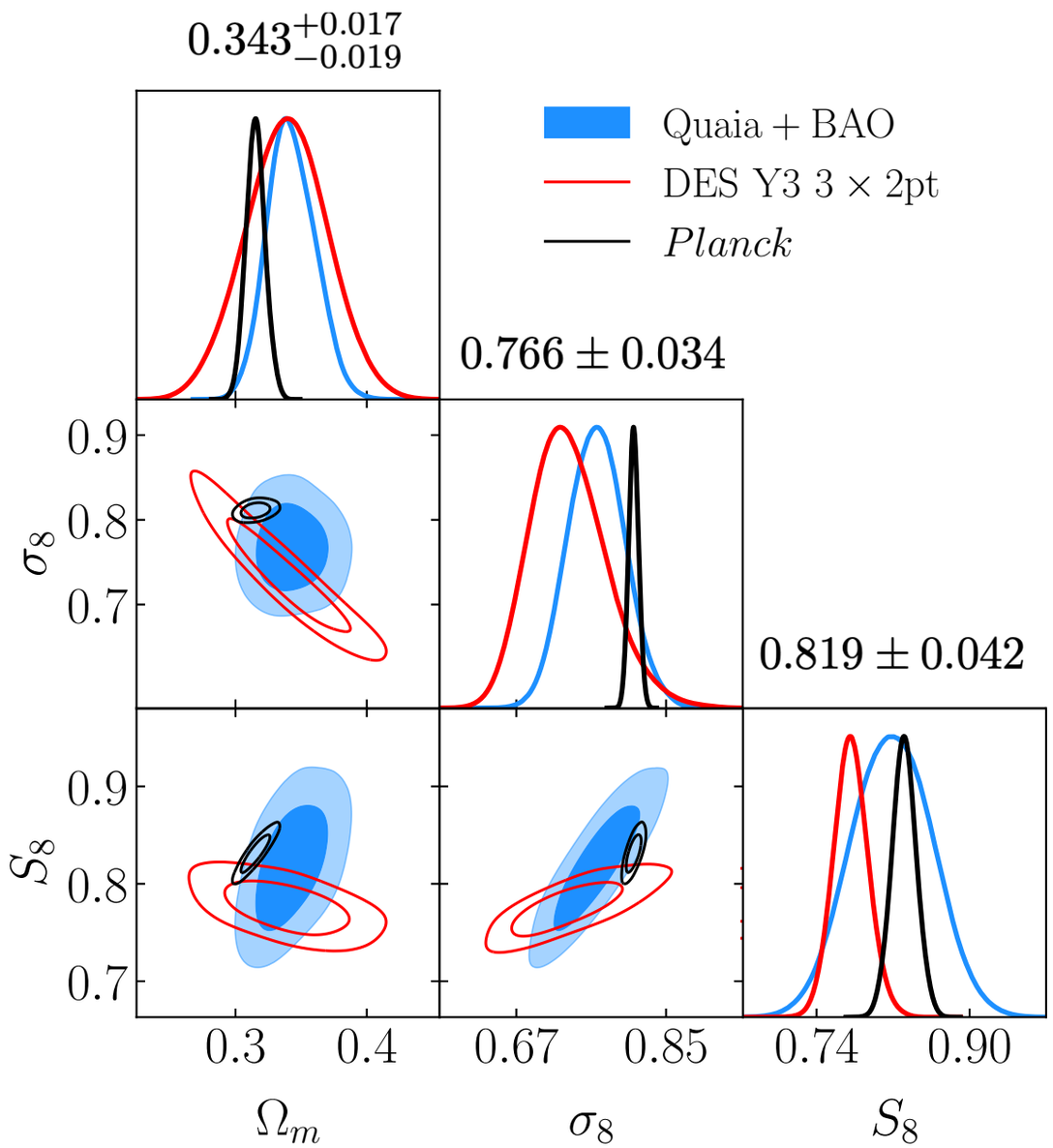


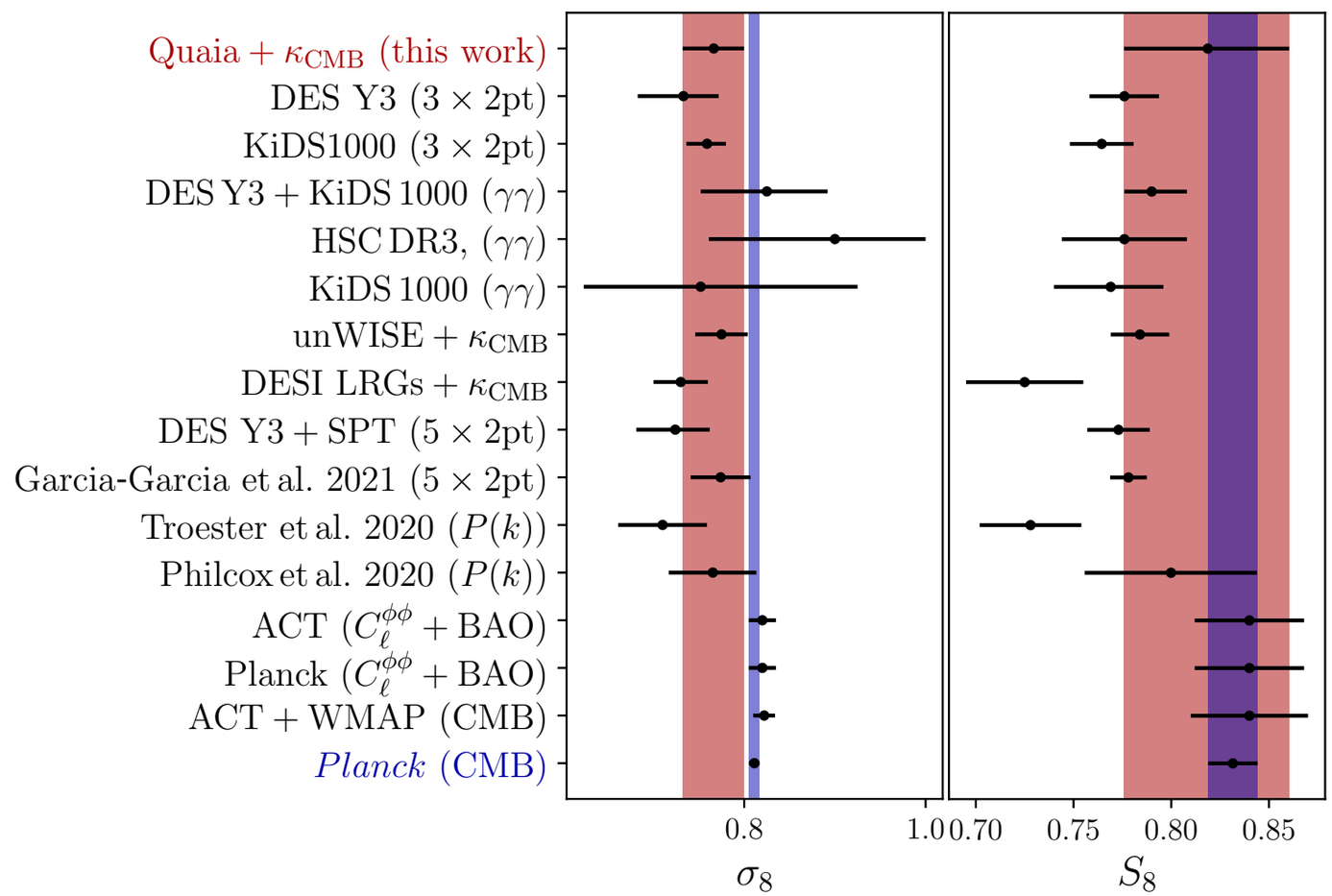
Alonso, GF, Storey-Fisher+(2023)

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.



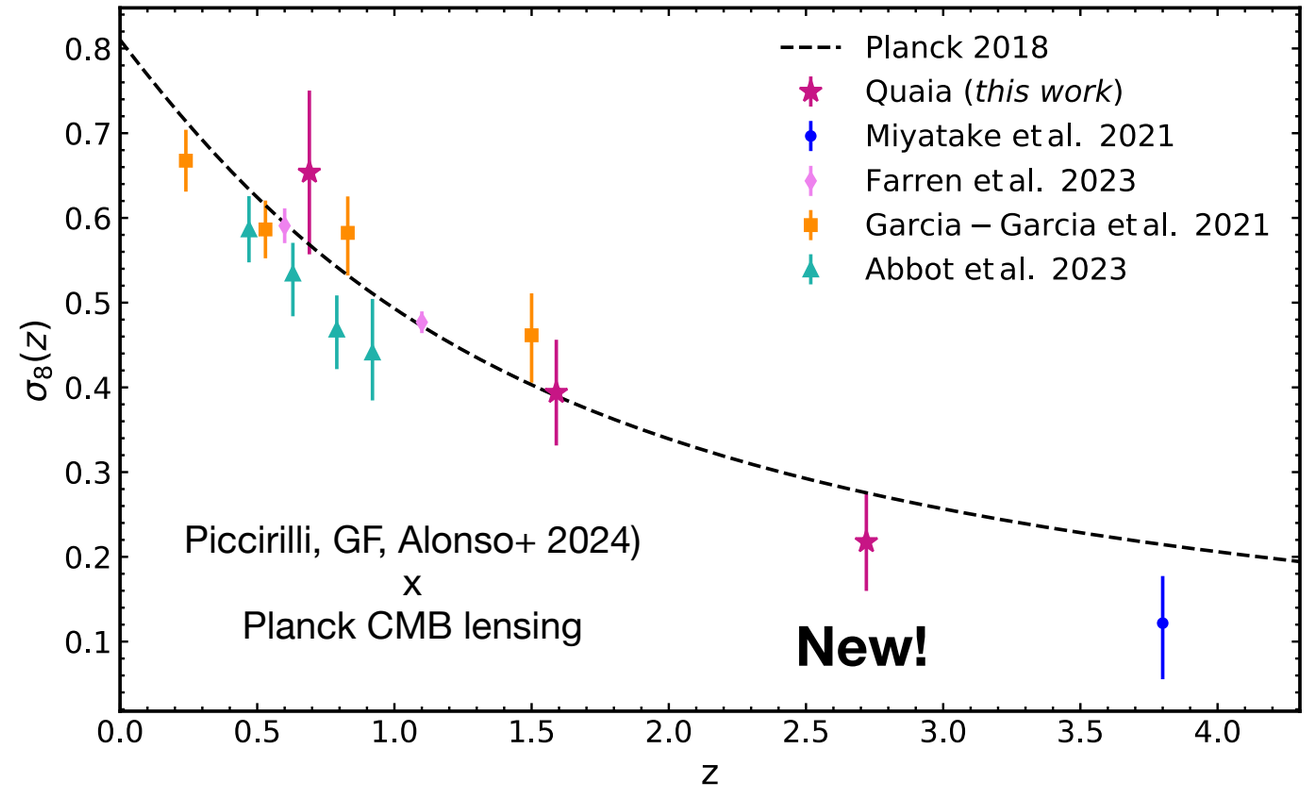


Alonso, GF, Storey-Fisher+(2023)

No tension with Planck!

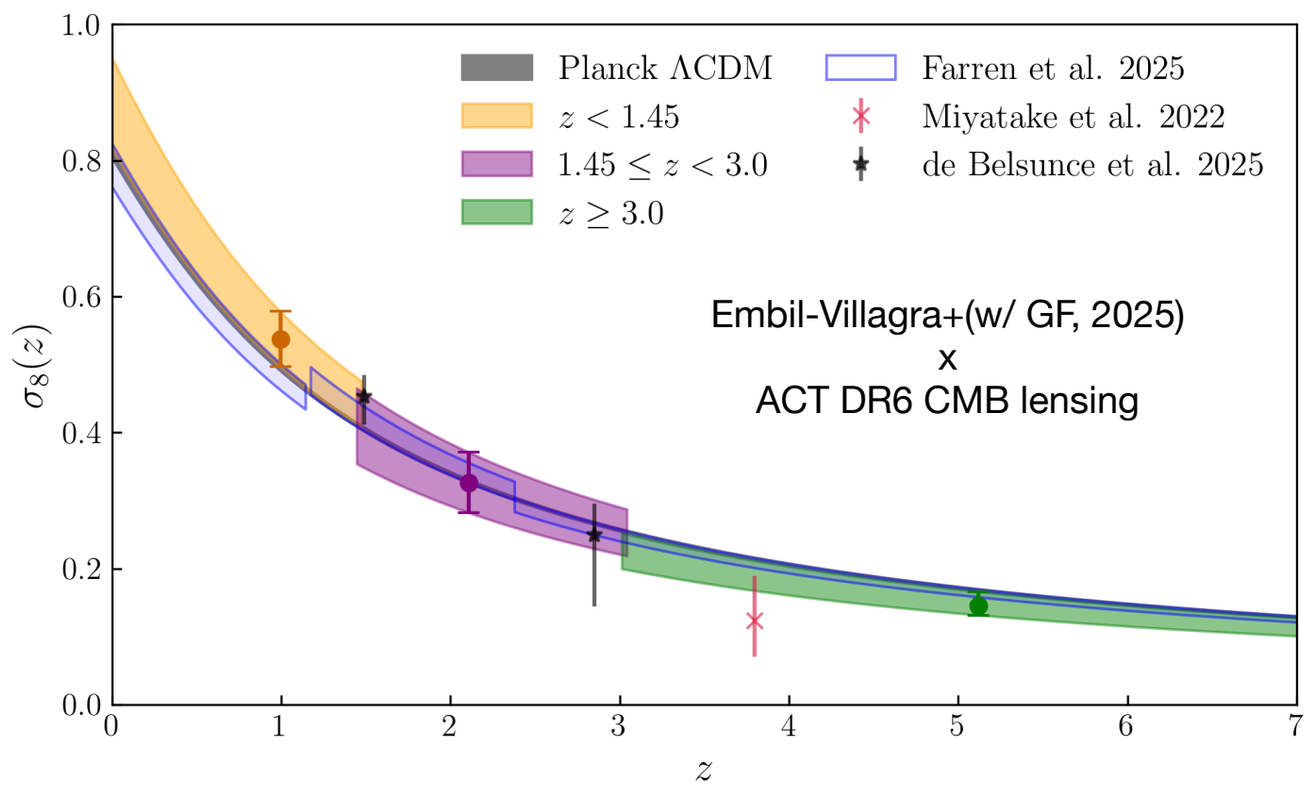
Cosmology from Quaia x CMB lensing

- Tomographic $C_\ell^{gg}, C_\ell^{\kappa g}$ with Planck lensing
  - New high-z σ_8 constraints
  - Results competitive with current LSS surveys with fewer objects and/or worse redshifts.



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

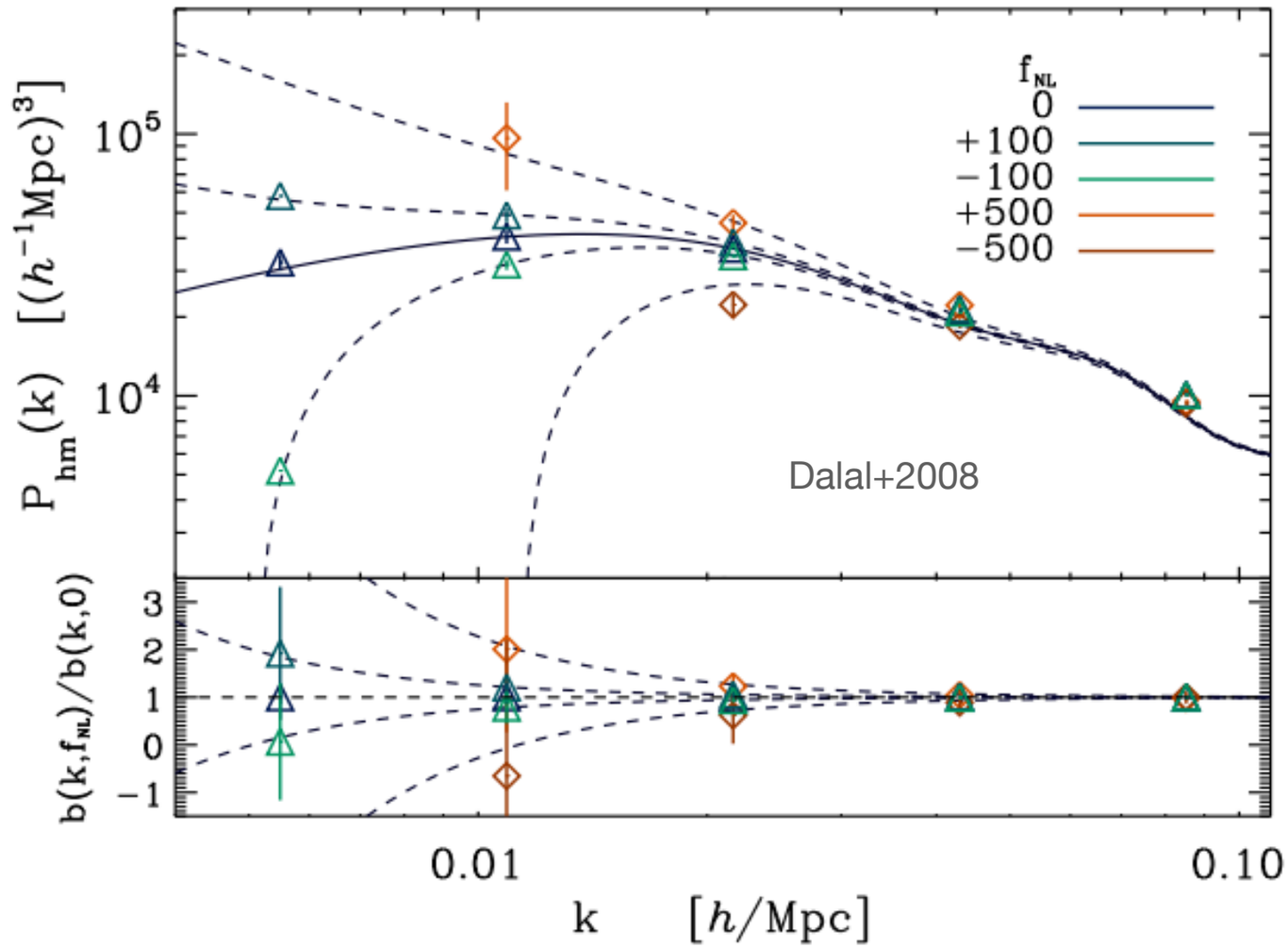
$$P_{\rm lin}^{\rm new}(k,z) = P_{\rm lin}^{\rm input}(k,z)A(z)$$
$$= P_{\rm lin}^{\rm input}(k,z)\begin{cases} A_0 & 0 \le z < z_1 \\ A_1 & z_1 \le z < z_2 \\ A_2 & z_2 \le z \end{cases}.$$



Non-Gaussianities and scale dependent bias

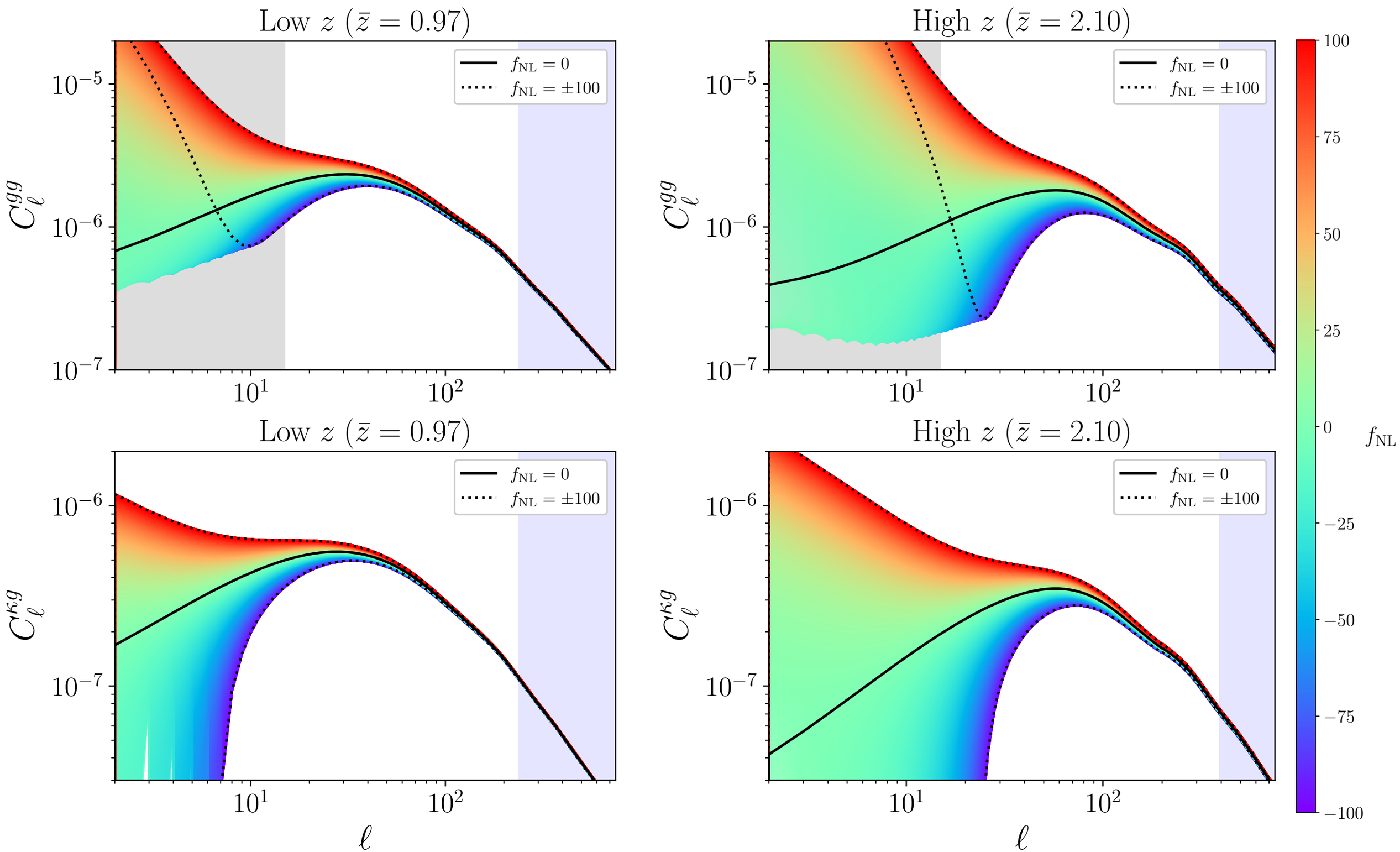
$$\Phi(\mathbf{x})_{\rm NG} = \Phi(\mathbf{x}) + f_{\rm NL}\left(\Phi^2(\mathbf{x}) - \langle\Phi^2\rangle\right)$$

$$\Delta b_1 \propto \frac{f_{\rm NL} b_1 b_\phi}{k^2 T(k)}$$



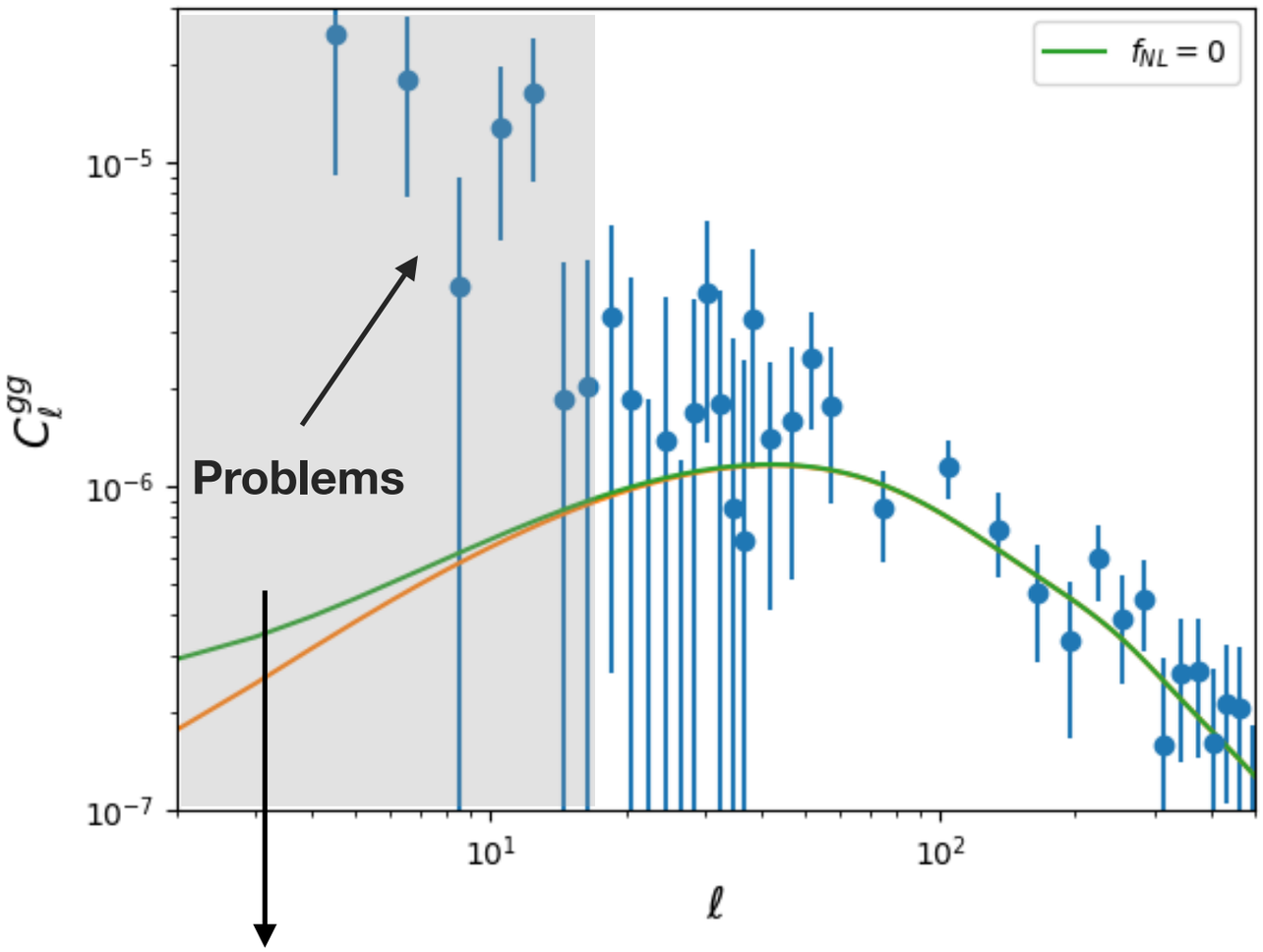
- Huge volume and high bias tracers is required to enhance detection.
- Quasars: detectable at high z thanks to bright AGNs, ~linear scales, ideal for f_{NL} studies.
- Galactic extinction, stellar contamination, seeing, survey depth inhomogeneity cause large scale variations / power excess in clustering measurements…

Signature of f_{NL} for projected statistics

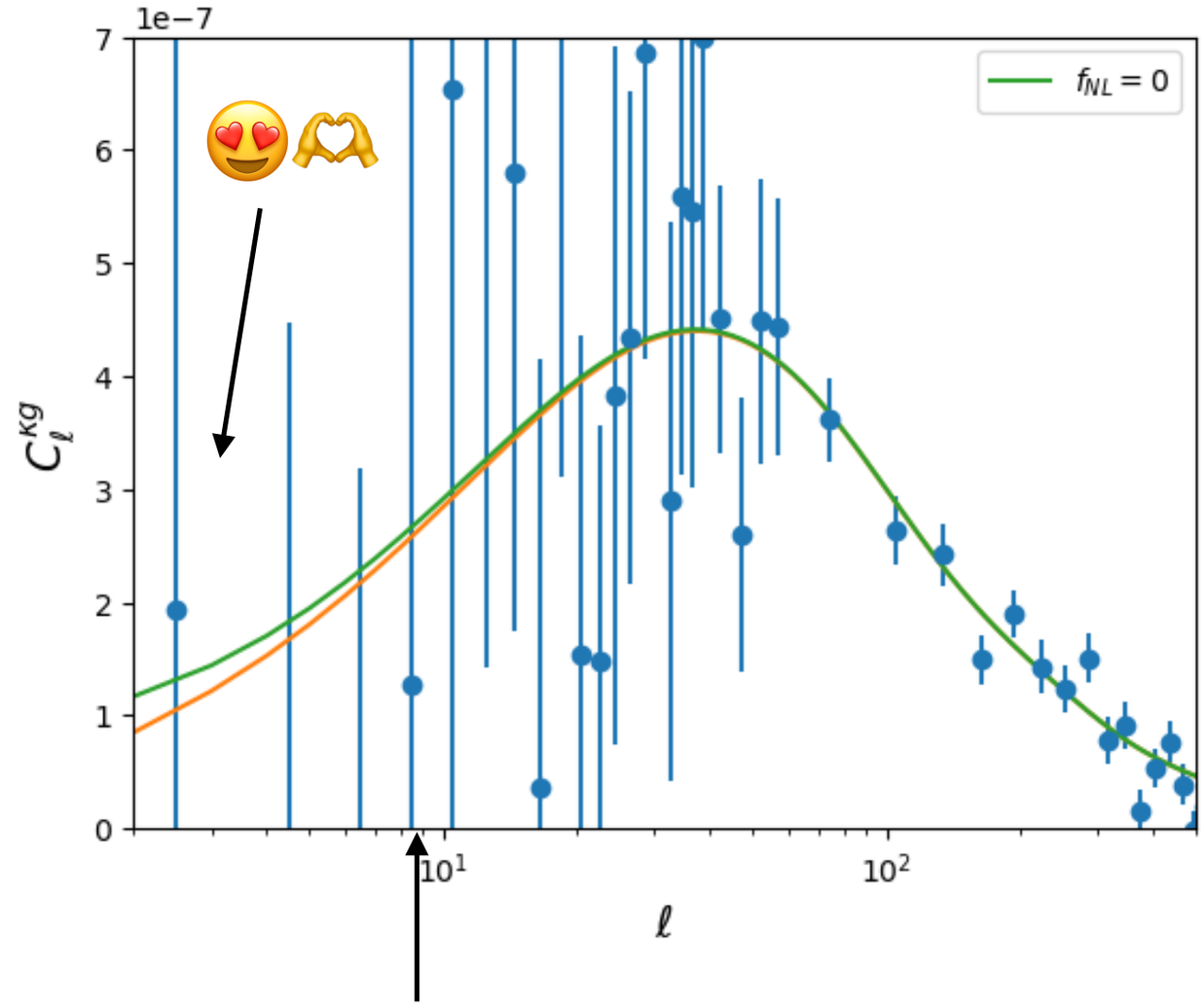


Fabbian, Alonso, Storey-Fisher (2025)

Constraints on f_{NL}



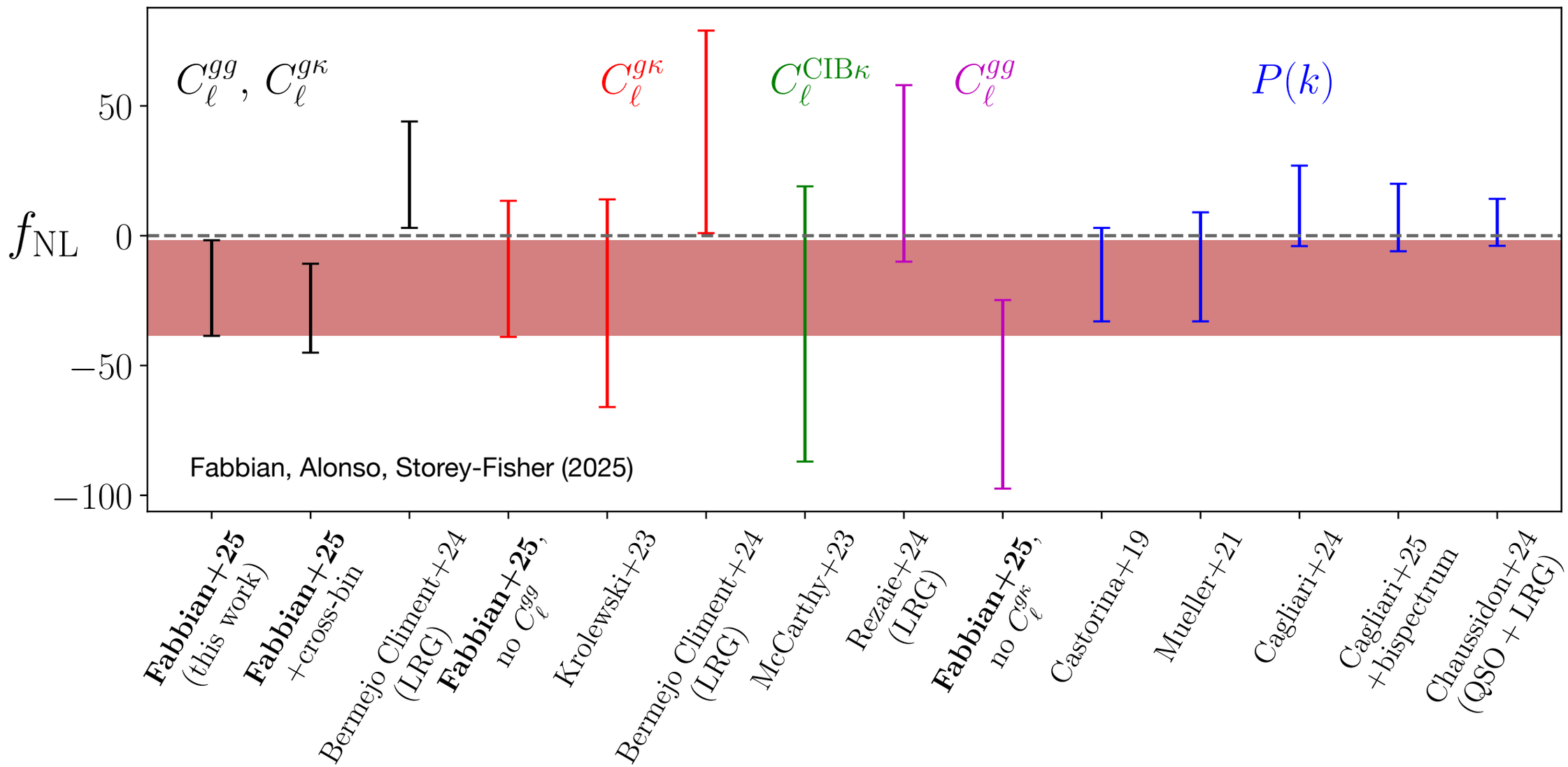
Aggressive systematics subtraction needs: ~3x degradation of results (Rezeie+2025)



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

- Cross-correlation can reach the largest scales!
- $\sigma(f_{\rm NL})$: worse than expectations due to residual systematics $\Delta C_\ell^{\kappa g} \propto \sqrt{C_\ell^{\kappa\kappa} C_\ell^{gg}}$

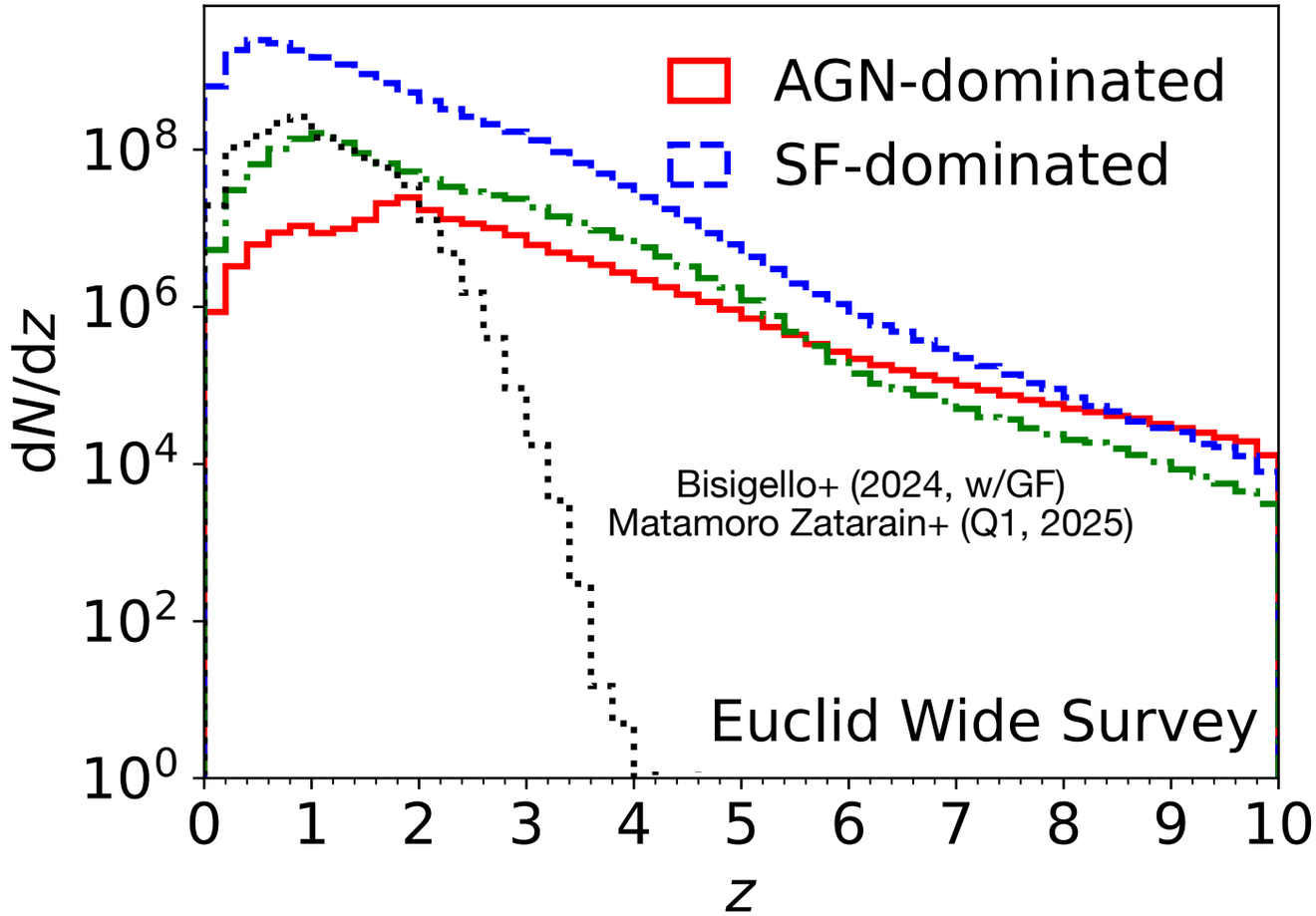
Robustness tests and perspectives

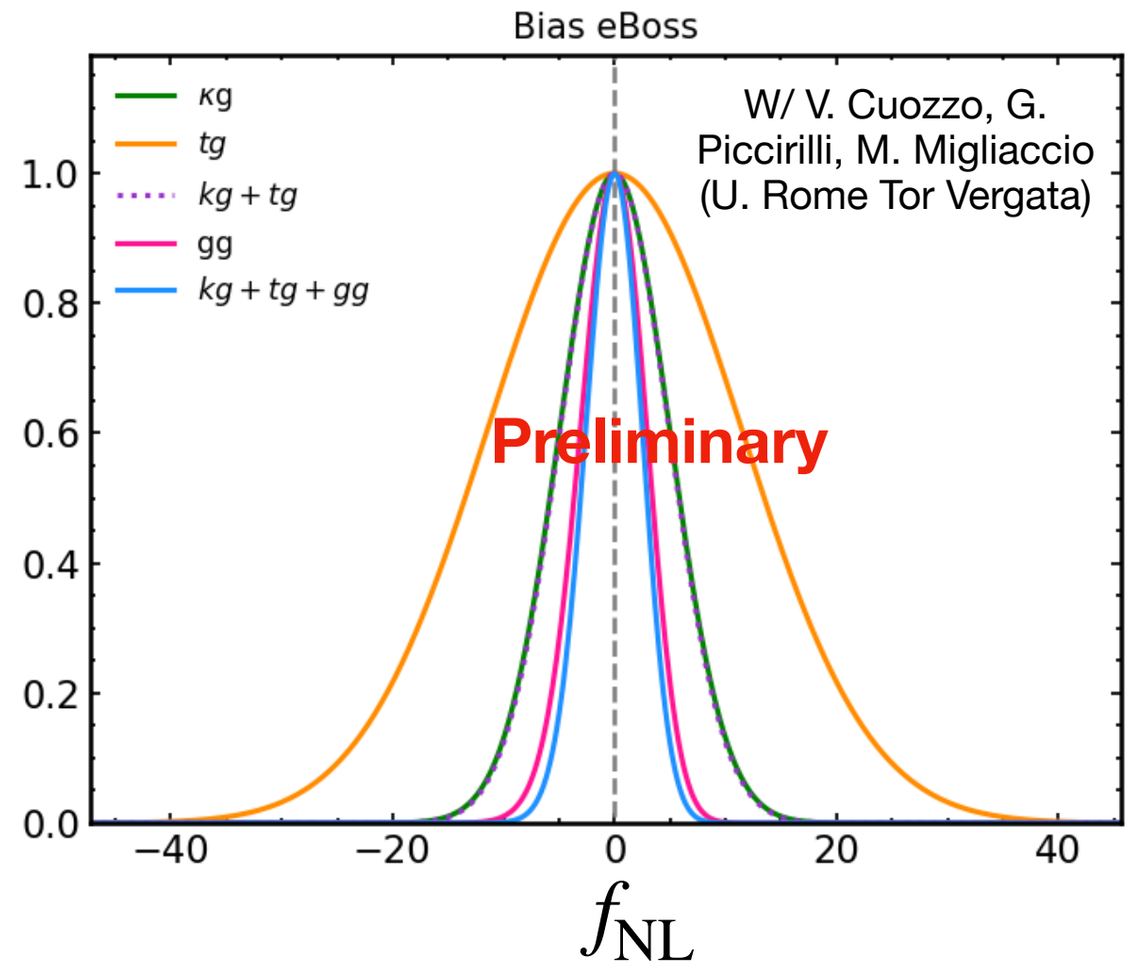


- Sensitivity comparable to spectroscopic galaxy surveys in 3D
- Limited by systematics on auto correlation on large scales but highly robust to systematics.
- Newer data releases from Gaia could improve this results $\sigma(f_{NL}) \sim 9$ (more sources, different source separation, new data…)

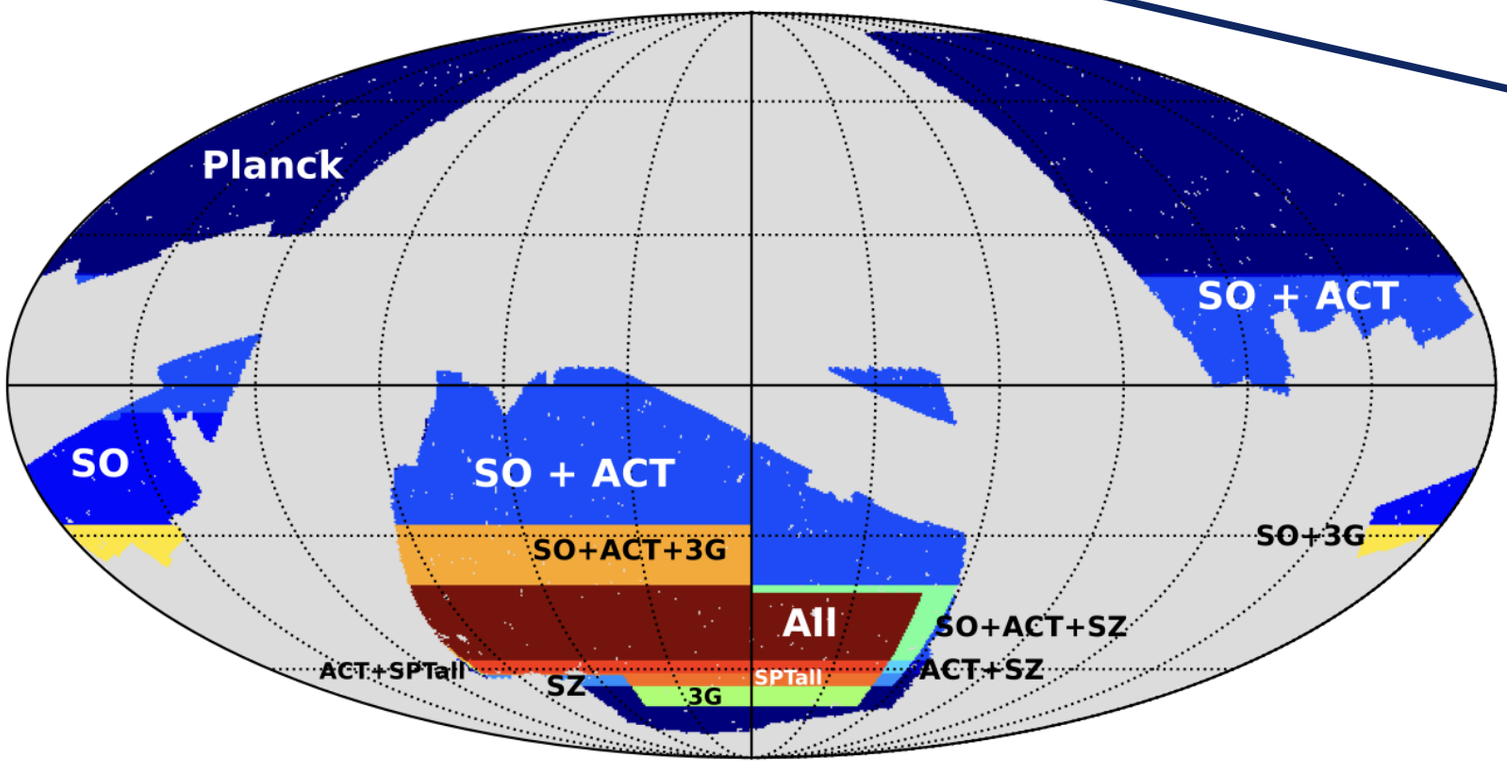
An example of Euclid synergies

- Large number of objects detected as dropouts in Euclid bands…
- AGN/QSO cosmological sample can be constructed, work in progress…
  - Build from Quaia work to construct / improve samples.
- Robust constraints can be achieved for non-Gaussianities $\sigma(f_{NL}) \sim 2$





Towards Euclid DR3

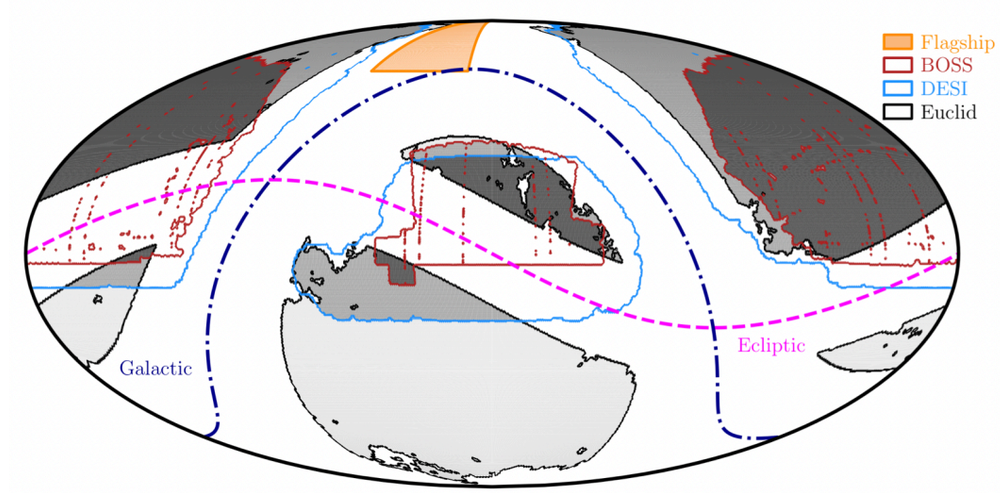


expected in Oct 2031
covering 15 k deg^2

Overlap with **other LSS survey:**

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

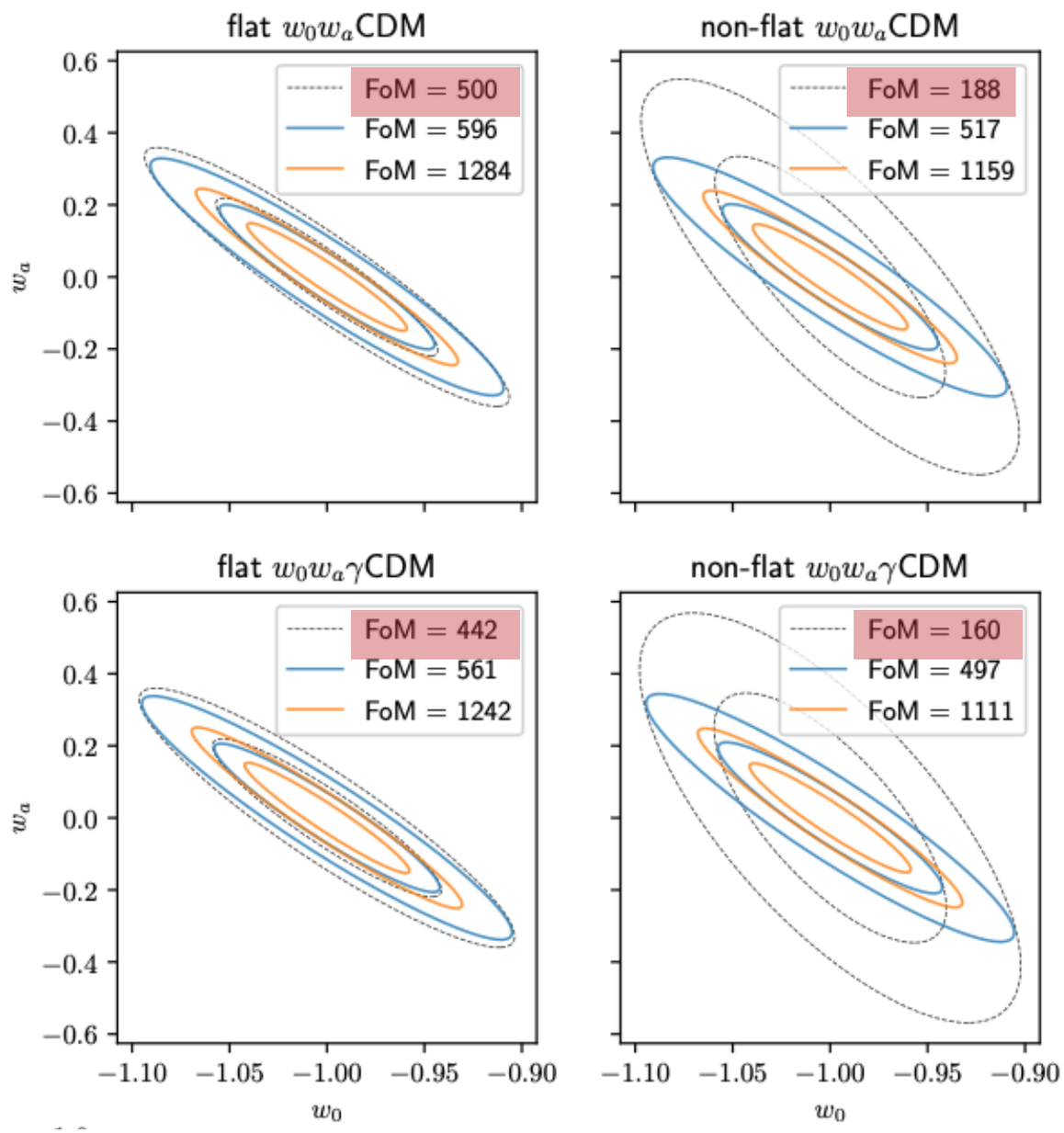
- **SO has the largest overlap with Euclid** (65% overlap)
- SPT3G-WIDE is the second best (45%)
- ACT: similar SO overlap but with lower sensitivity

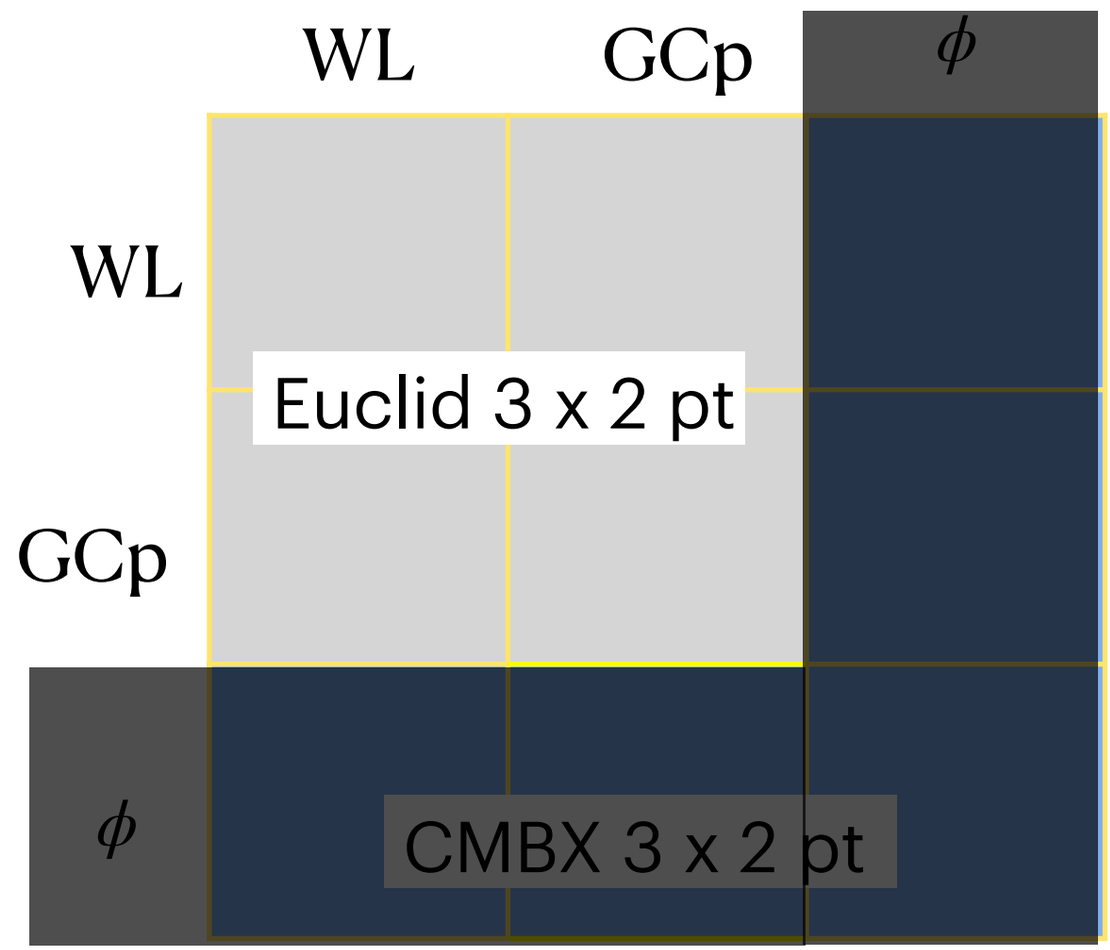


Naidoo et al, 2023 (Euclid collab paper)

Forecast for 3x2pt analysis

- Assumes the pessimistic Euclid survey in ~5 tomographic redshift bins for GC-phtometric and WL, zmax=1



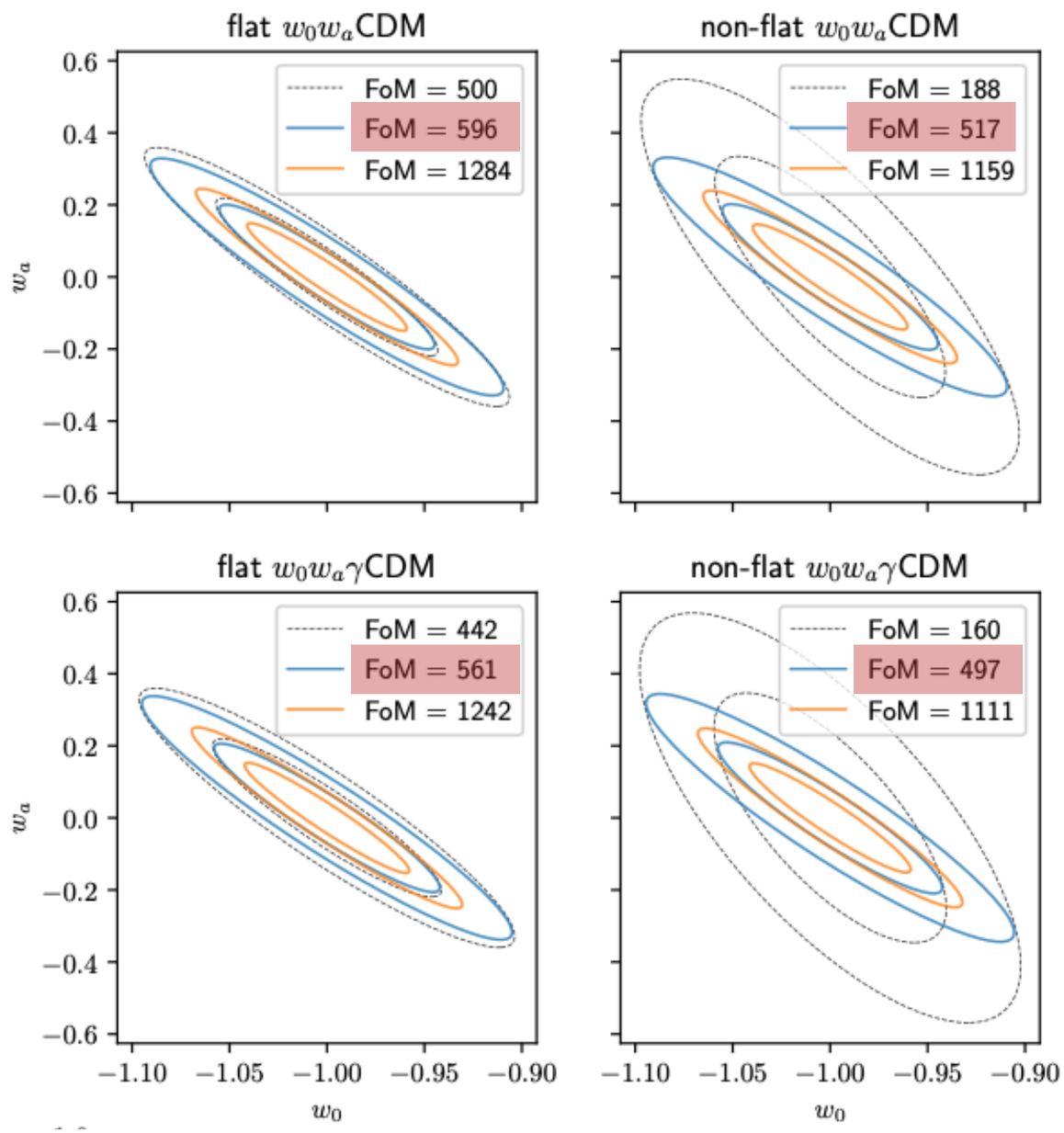


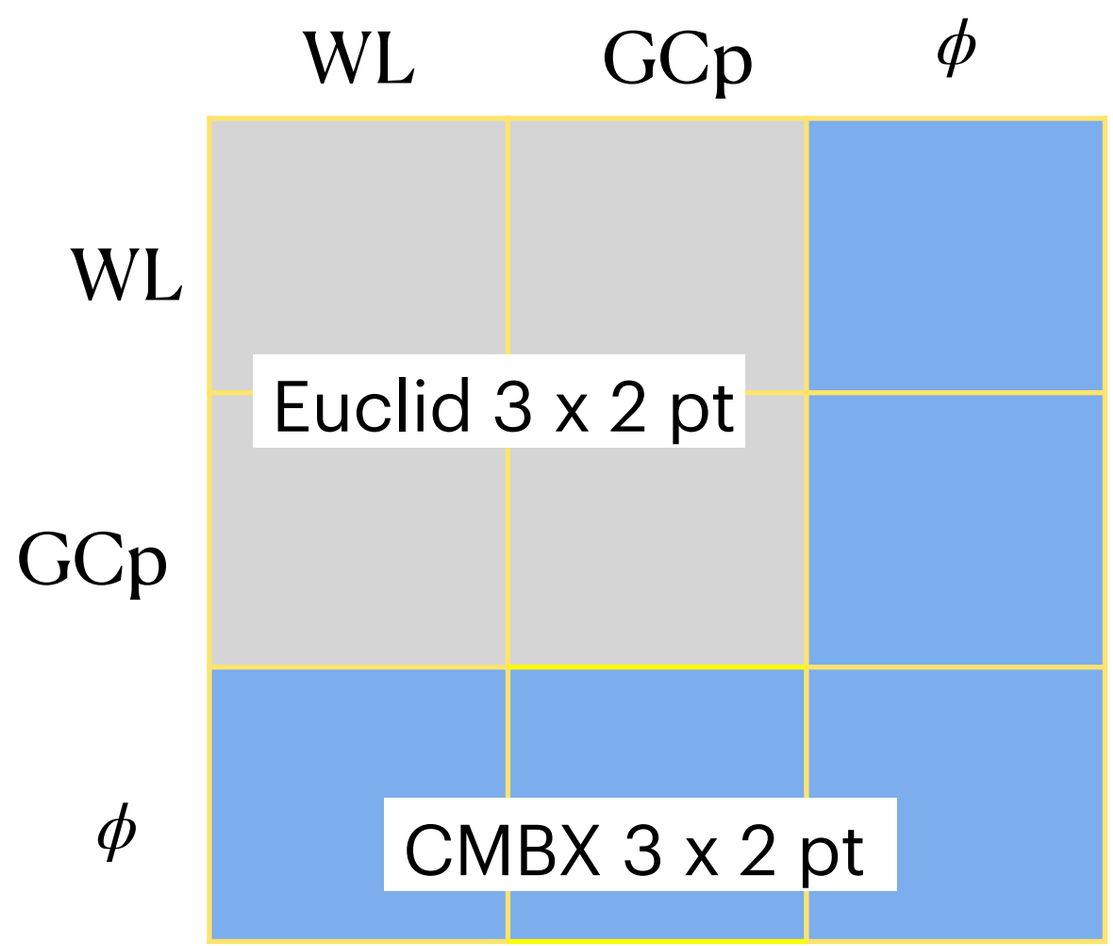
Euclid collab. (Blanchard+19)

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

Forecast for 6x2pt analysis

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



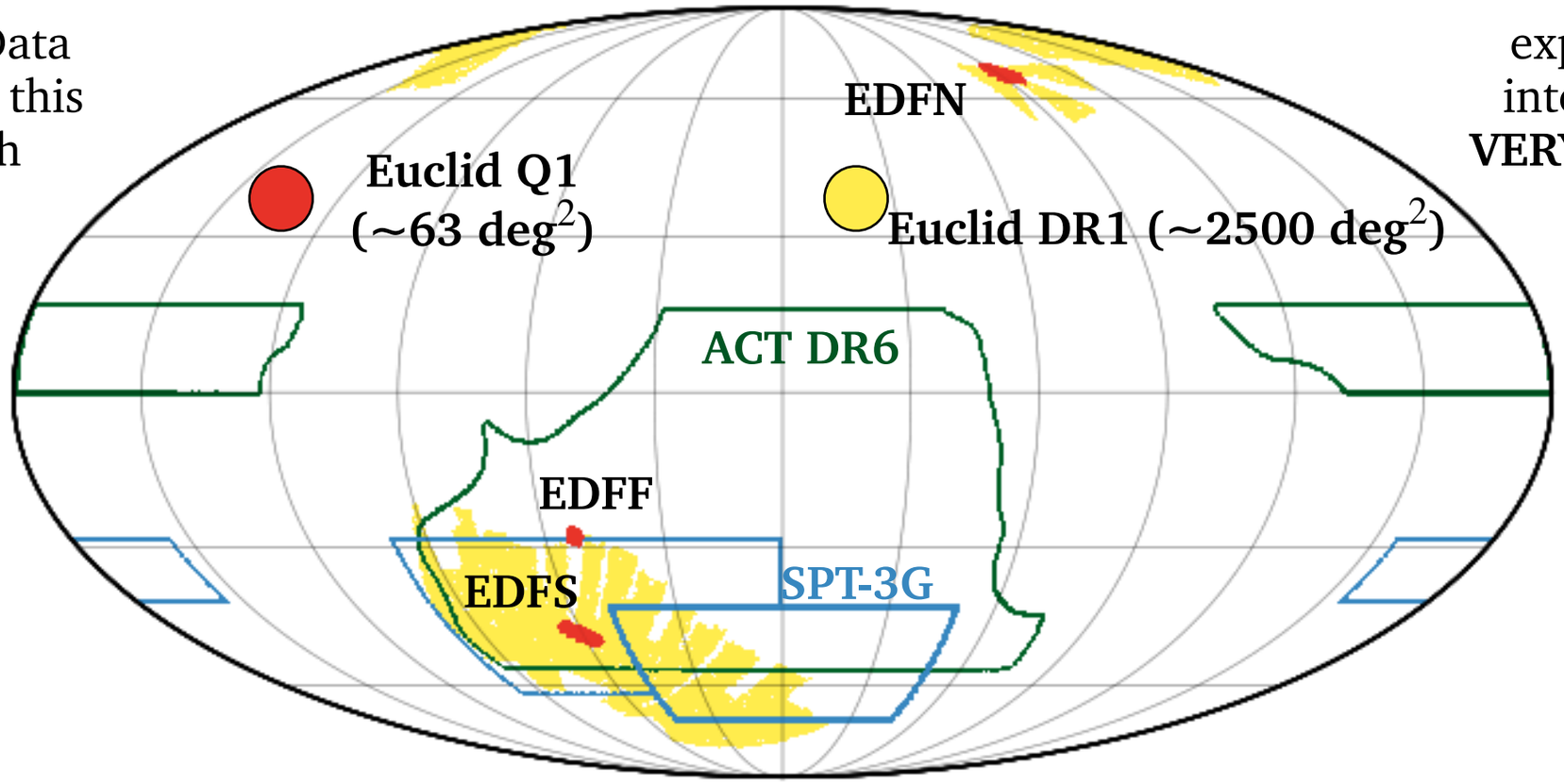


Euclid collab. (Blanchard+19)

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

Towards DR1: the Q1 data release

Quick Data Release this March



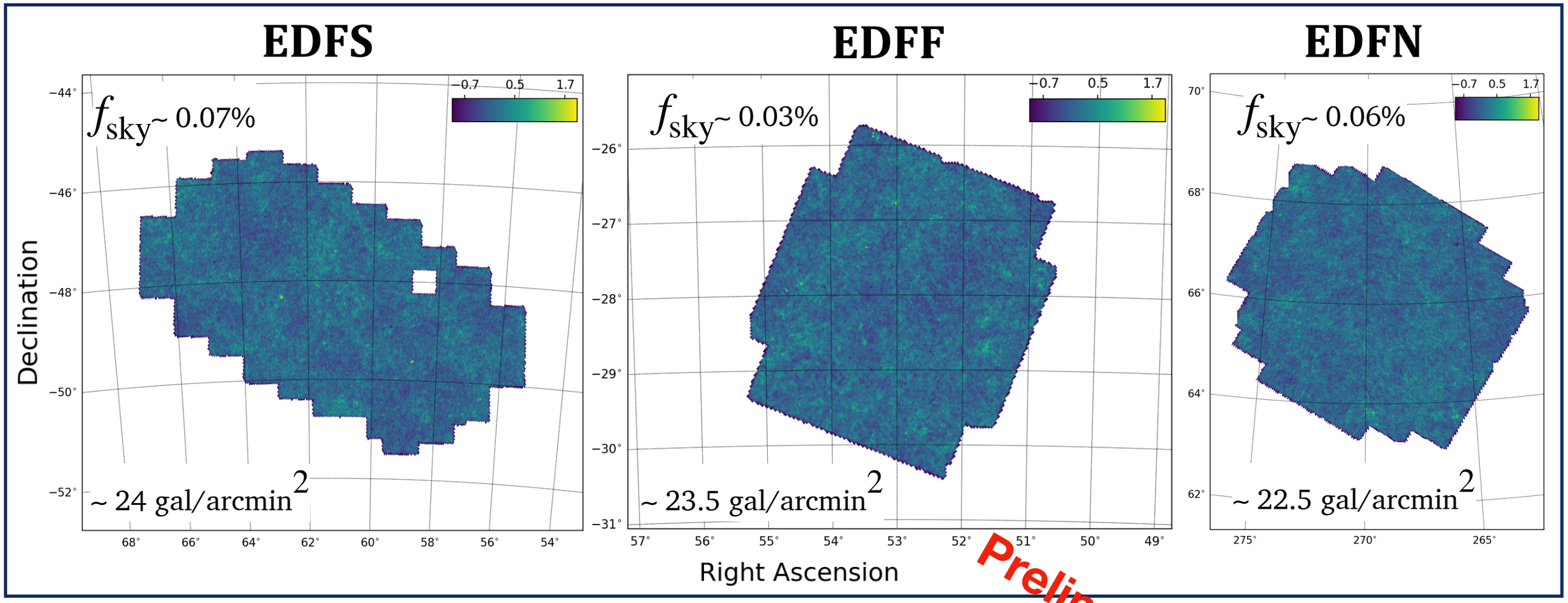
expected internally **VERY SOON**

- Preliminary realease with 1st quarter of data (Q1) included ~60 deg2 with "pre-launch" pipeline.
  - Ideal for cross-correlation!

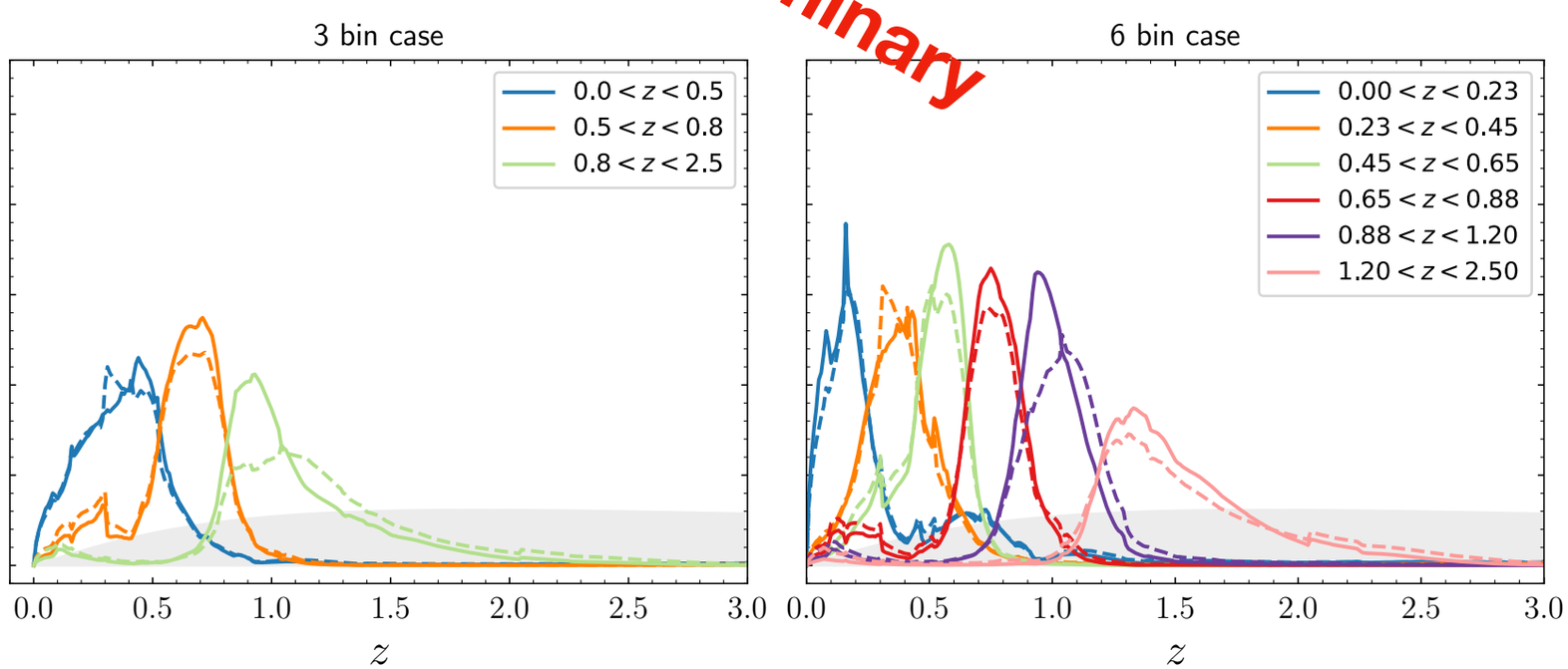
Fabbian, Legrand, Pagano, Lembo, Piccirilli, Kou+CMBX SWG (in prep.)

- DR1 analysis: Planck for the north, both ACT and SPT in the south patch
- Q1 analysis: Planck for the north, ACT for the EDFF and EDFS patches

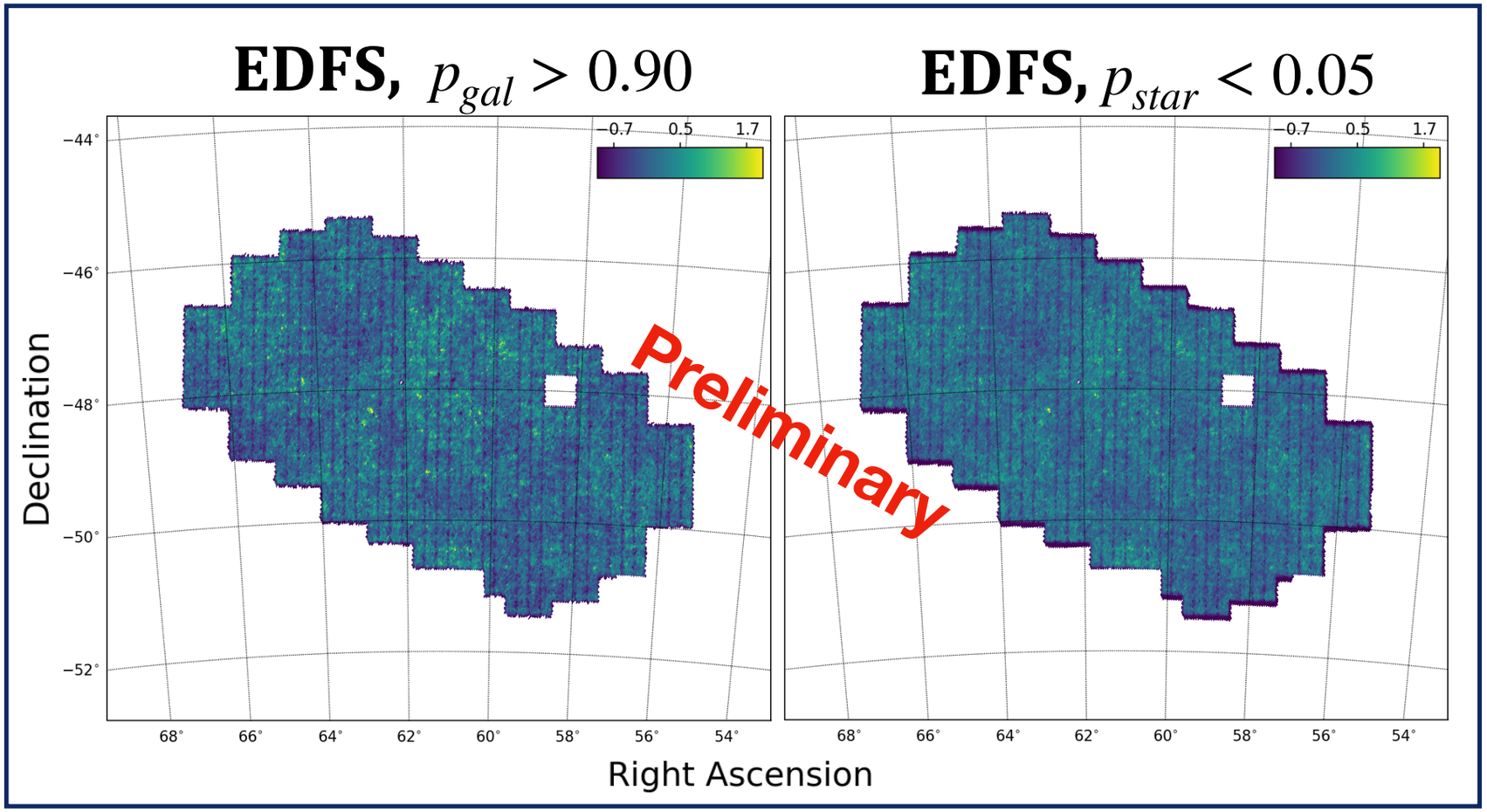
Towards DR1: the Q1 data release



- Magnitude cut in VIS<24.5
- Properties consistent across fields
- Agreement with Flagship simulation predictions "uncalibrated"!!!!!

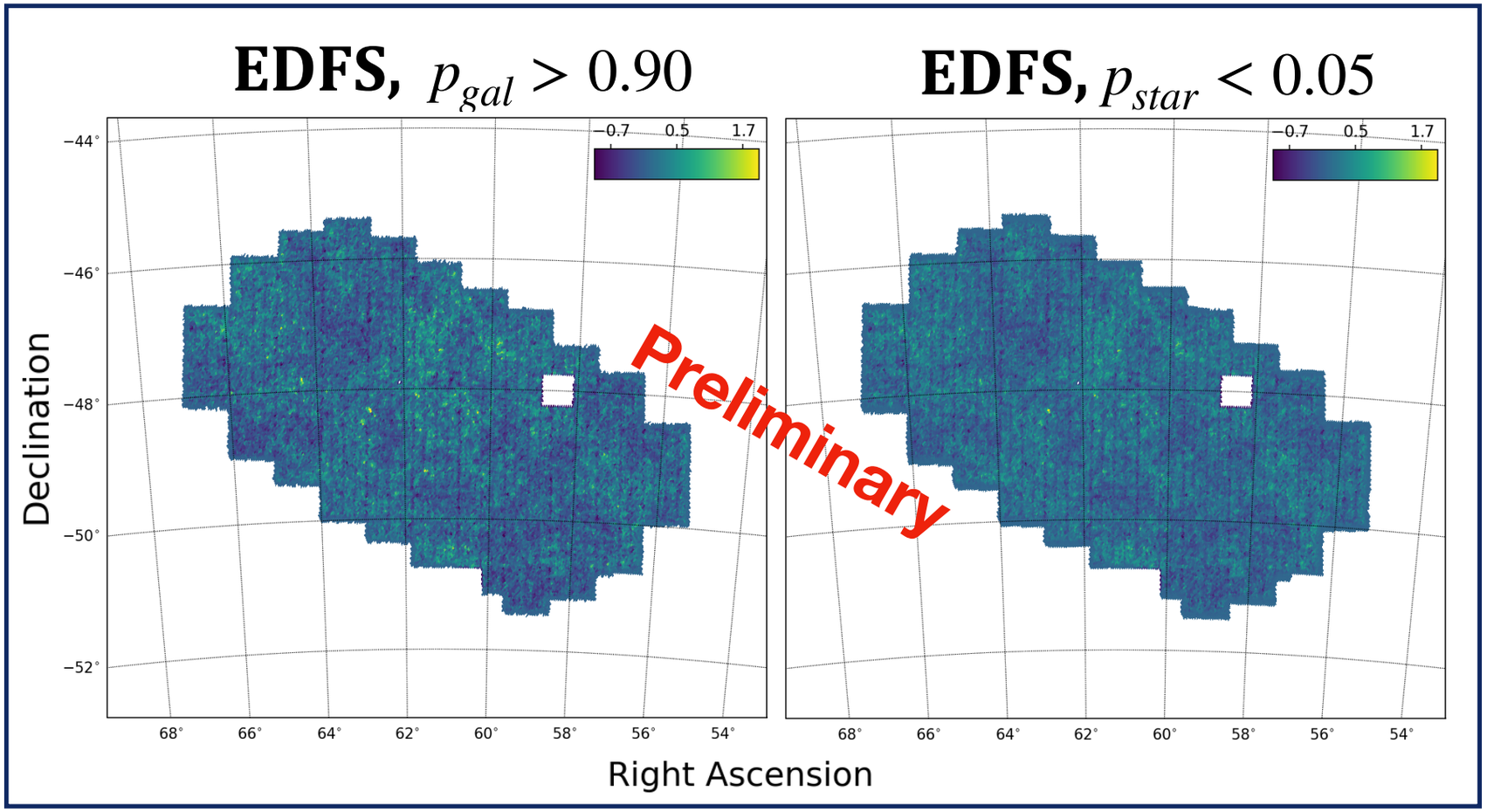


Towards DR1: the Q1 data release



- Two different sample selection based on purity of galaxy classification or star classification rejection respectively.
- The two cuts deliver samples with: ~11 gal/arcmin, ~ 21 gal/arcmin, with different redshift limits (~1.2, ~2.5)
- Systematics deprojection needed due to lack of deep external data and no full visibility processing (minimal effects)

Towards DR1: the Q1 data release

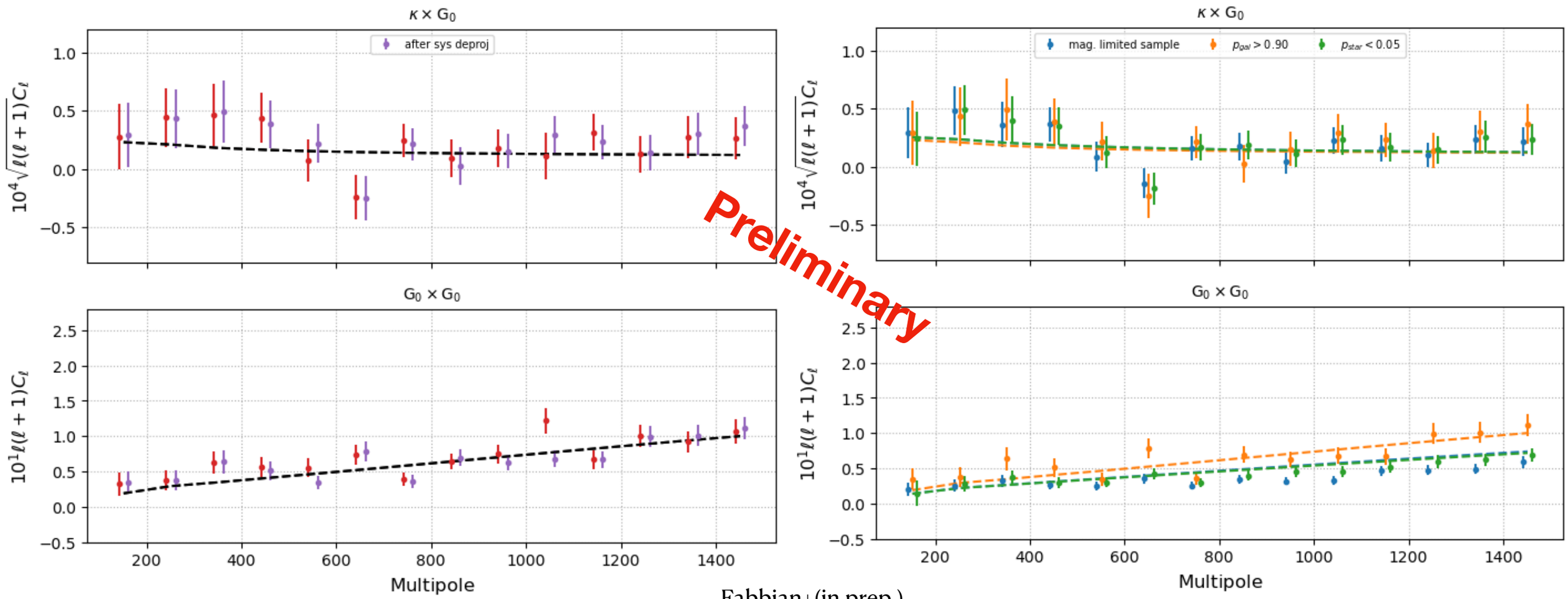


- Two different sample selection based on purity of galaxy classification or star classification rejection respectively.
- The two cuts deliver samples with: ~11 gal/arcmin, ~ 21 gal/arcmin, with different redshift limits (~1.2, ~2.5)
- Systematics deprojection needed due to lack of deep external data and no full visibility processing (minimal effects)

Preliminary results: single bin

w vs /wo systematics deproj

Different sample selections

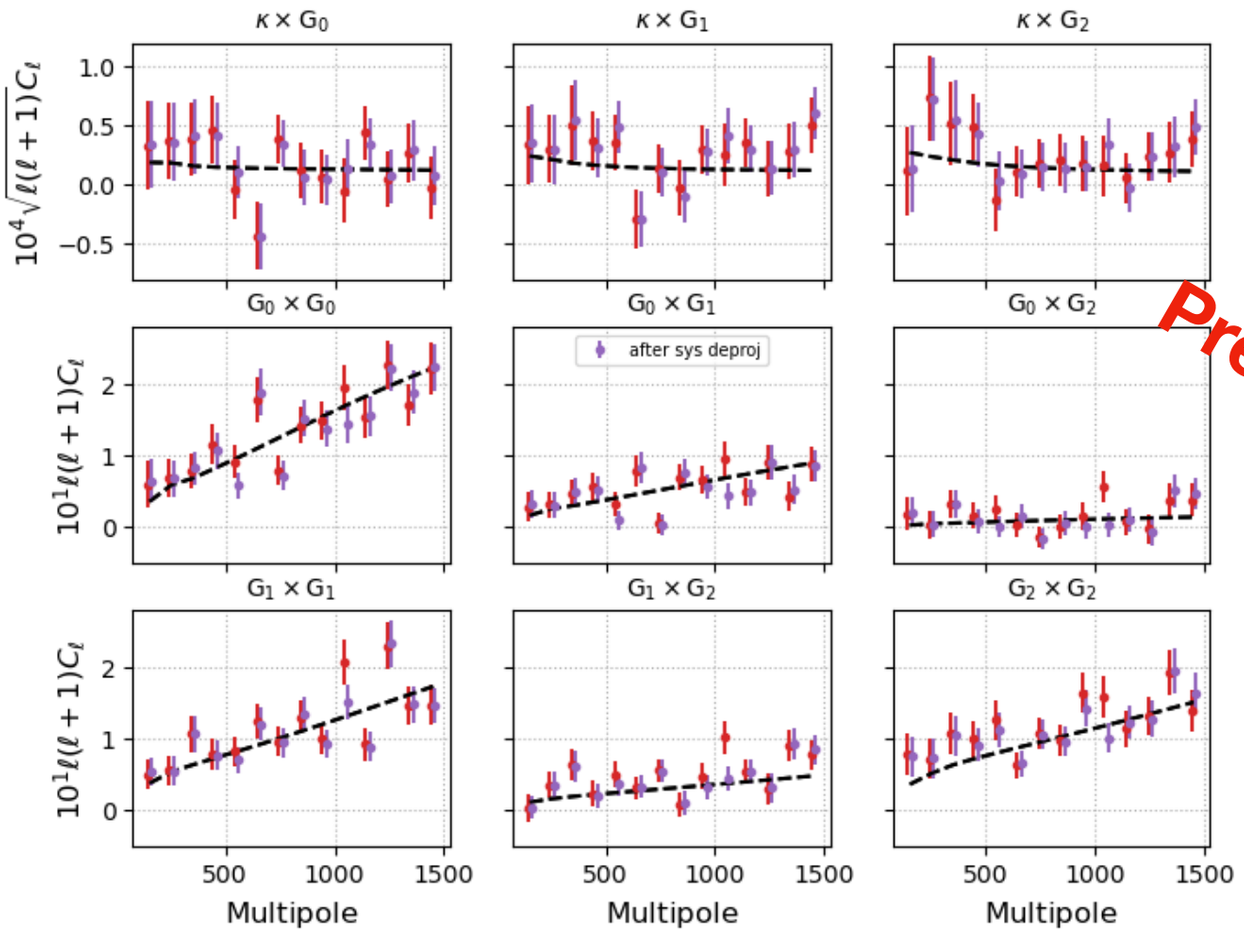


Fabbian+(in prep.)

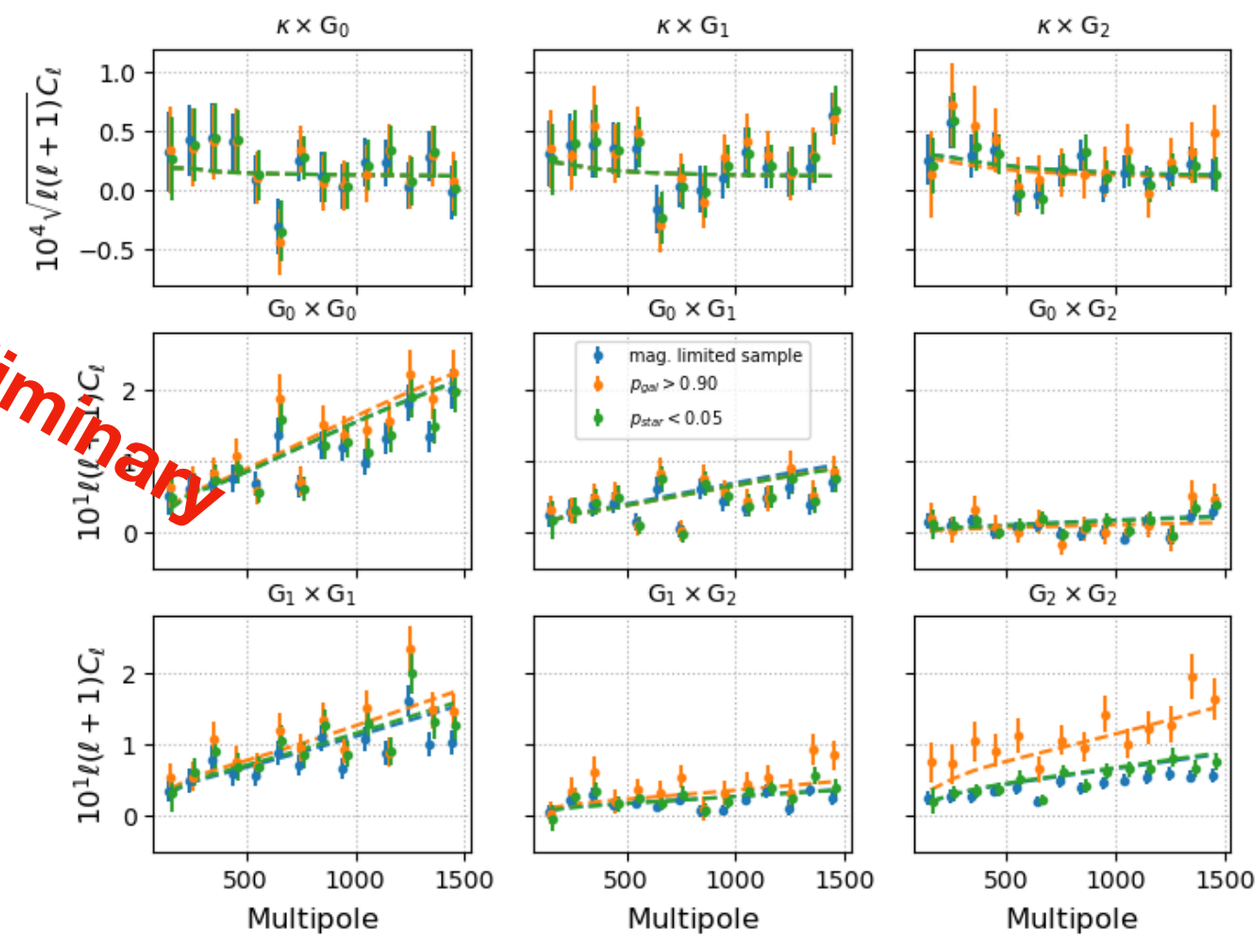
- WARNING: theory lines are not fits!
  - Planck 2018 + estimated N(z) + fiducial Flagship calibrated bias model.
  - TLDR: great PTEs (w/ RSD, magnification bias…)
- Cross-correlation extremely stable and robust to any systematics deprojection!

Preliminary results: 3 tomographic bins!

w vs /wo systematics deproj



Different sample selections



Preliminary

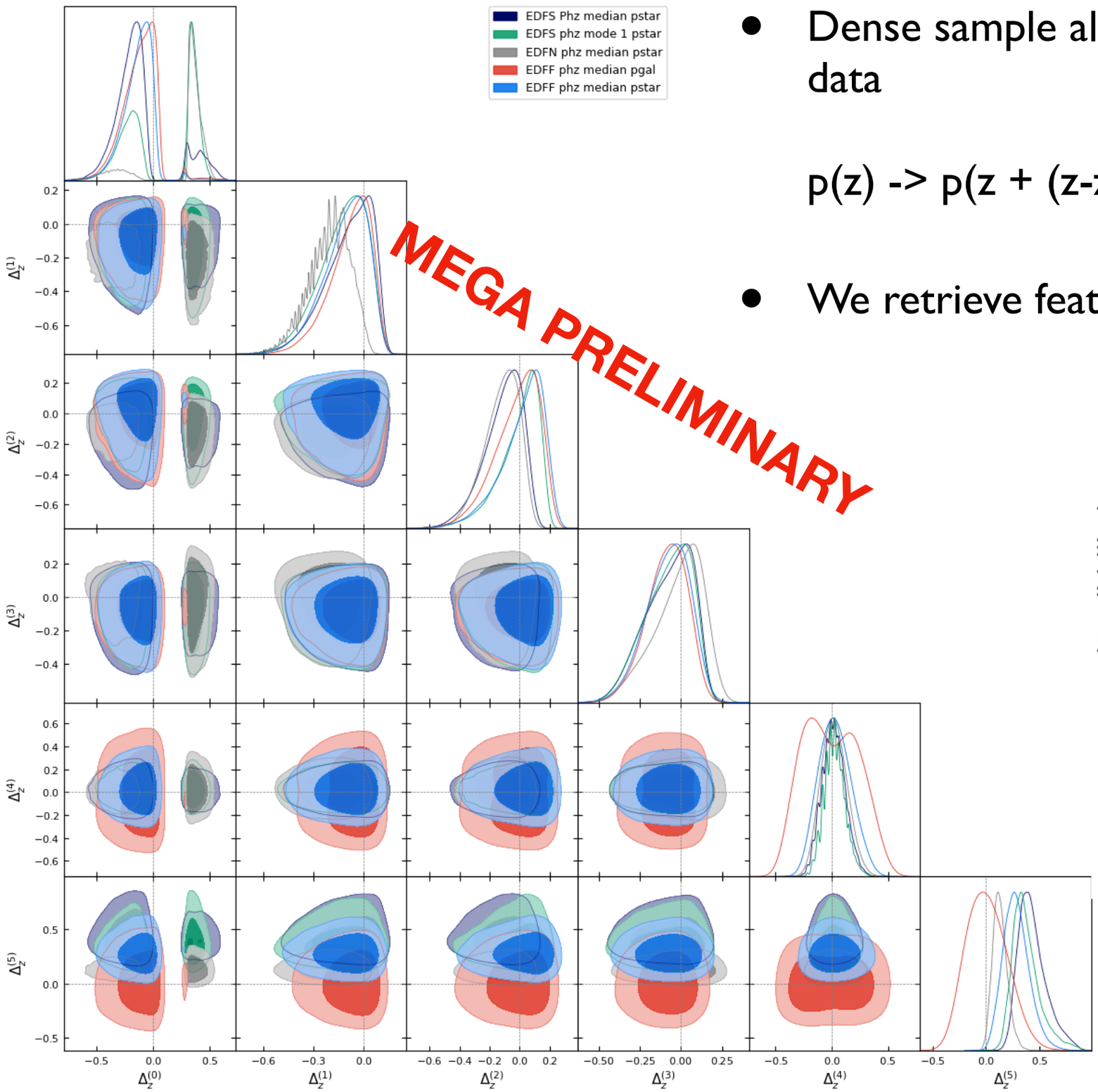
Fabbian+(in prep.)

- WARNING: theory lines are not fits!
  - Planck 2018 + estimated N(z) + fiducial Flagship calibrated PT bias model.
  - Great PTEs!
  - kmax ~0.5 h/Mpc (but good to smaller scales)

Some preliminary findings

- CMB lensing cross-correlation is ready for fine bin tomography.
    - Well modeled across different fields and fine redshift binning
- Auto-correlation: it depends….
    - We are seeing inhomogeneous redshift quality (as expected)
    - Limited tomographic capabilities.
    - Star galaxy separation…
- We can recover constraining power with cross-correlation.

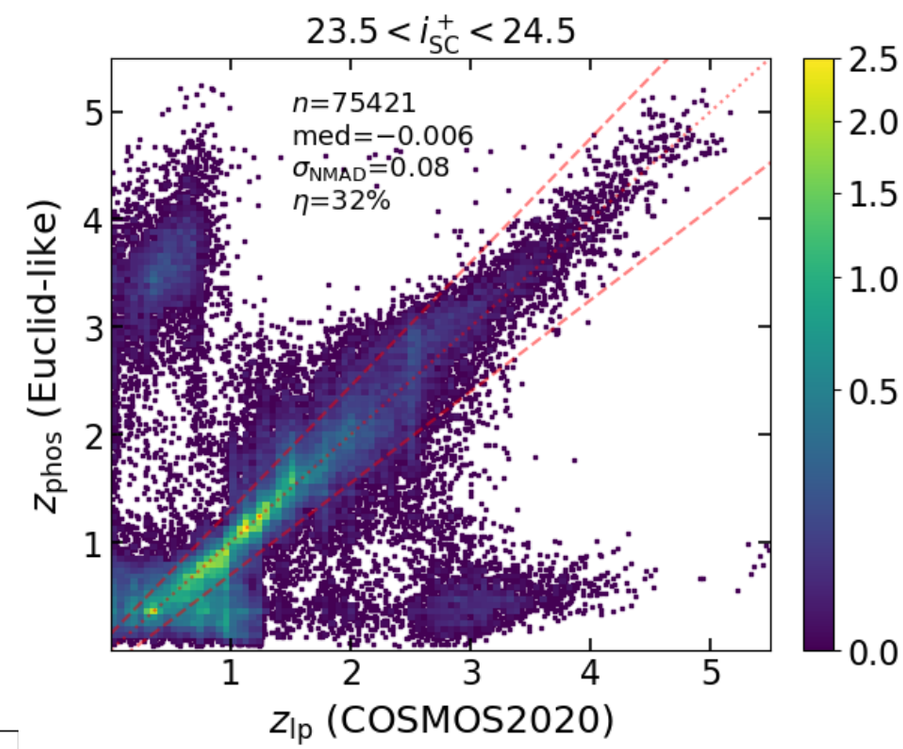
It's a long way to go



- Dense sample allows to fit redshift errors from data

  p(z) -> p(z + (z-z0)w + Delta)

- We retrieve feature of photo-z estimation.



Tucci+(2025, Euclid coll.)

Conclusions

- **Exciting prospects from new CMB and space-based galaxy surveys data…**
  - Quaia allowed for non-degenerate σ_8, Ω_m, S_8 consistent with Planck (and independent H0…)
  - Robust and competitive f_{NL} from cross-correlation with CMB lensing.
  - More is expected from SO and Euclid (e.g. delensing B-modes from inflation constraints).
- **Euclid is working beautifully!**
  - Q1 allowed us to benchmark the data for cosmology and all looks extremely promising so far.
  - But not without challenges: i.e. previous results with a pinch of salt…
  - We are catching up with the shear analysis…
- **Results coming soon, stay tuned!**