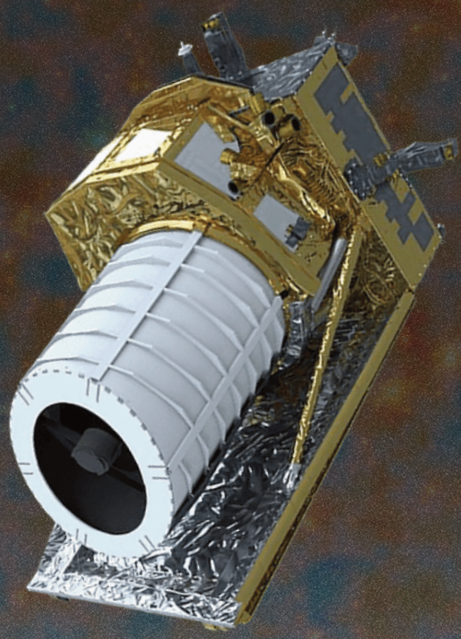
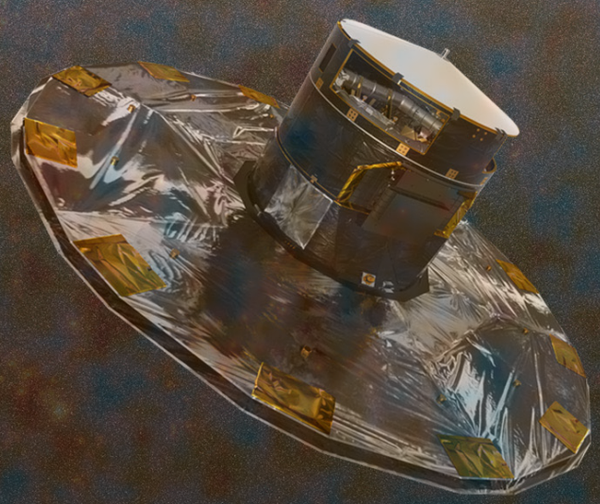
Cosmology with CMB and galaxy surveys from space



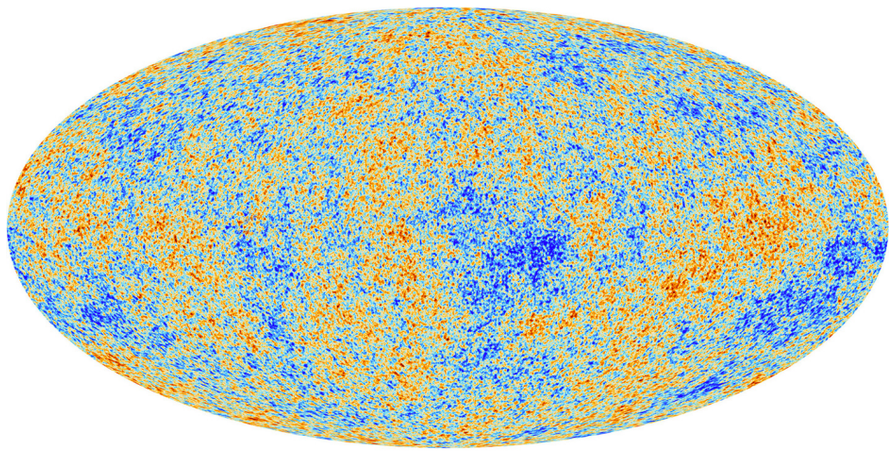


Giulio Fabbian

Institute d'Astrohysique Spatiale

Cosmological probes: CMB, large-scale structures

Cosmic Microwave Background (CMB)



Planck collaboration (2018)

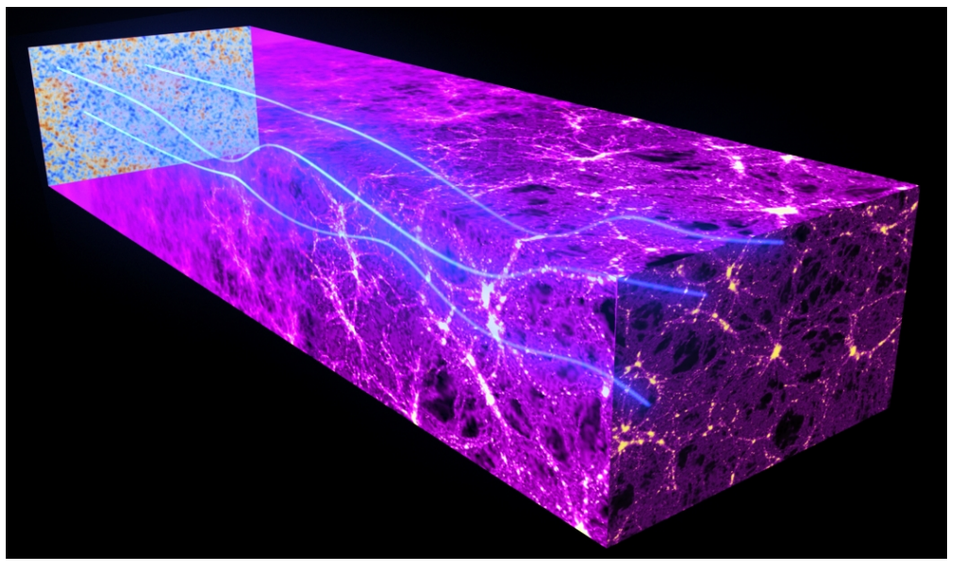
Intensity and polarization

- Constituents and composition of the Universe from early times.

Galaxy surveys

Galaxy position, distances, shapes

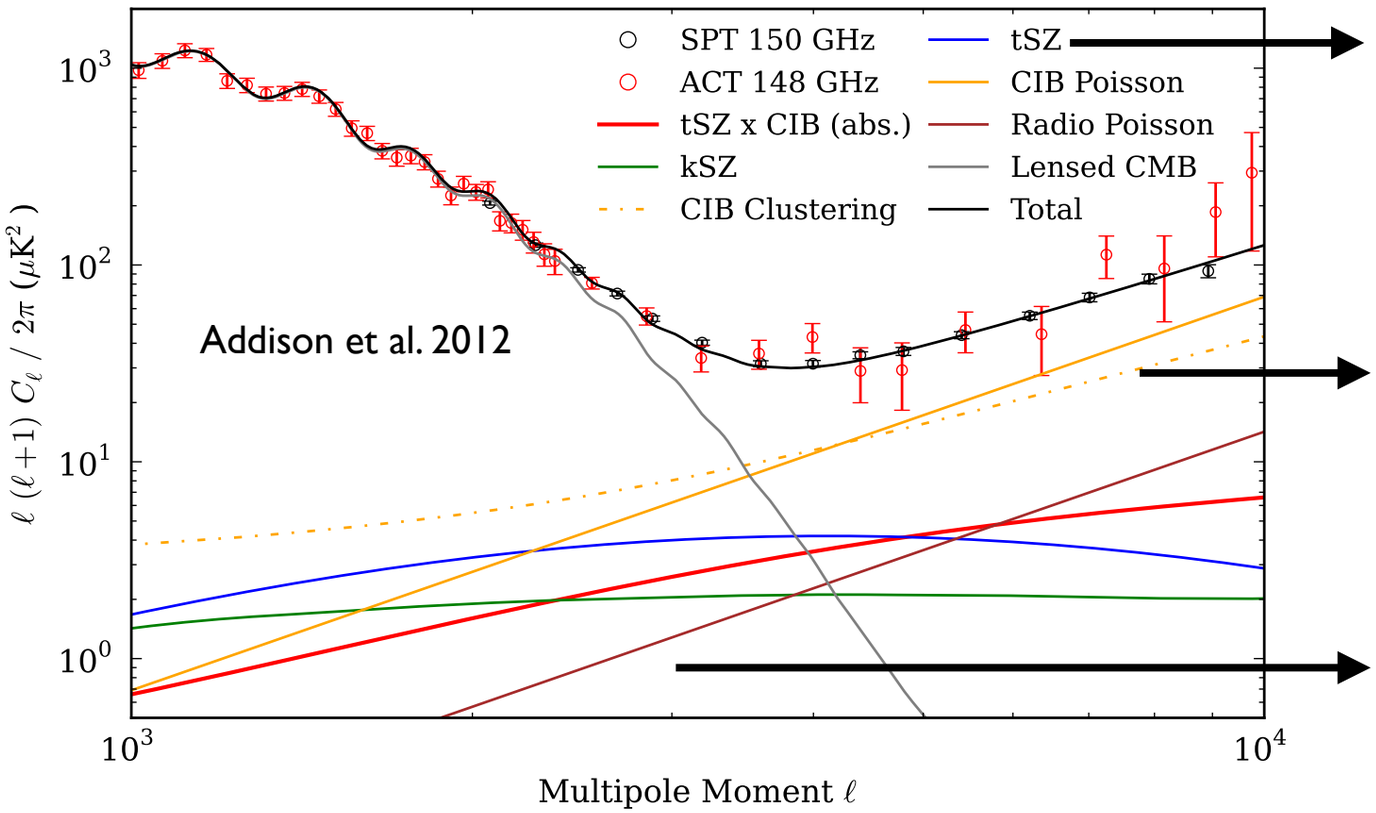
- Perturbations growth across-time and spatial distribution.
- More information on dark energy/neutrinos.

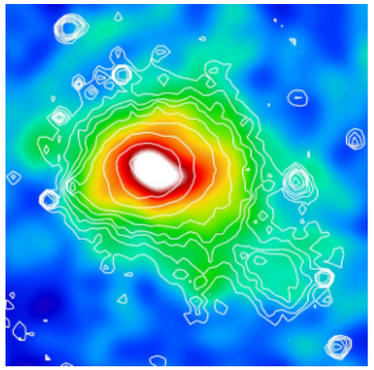


- Imprint of structures at different times

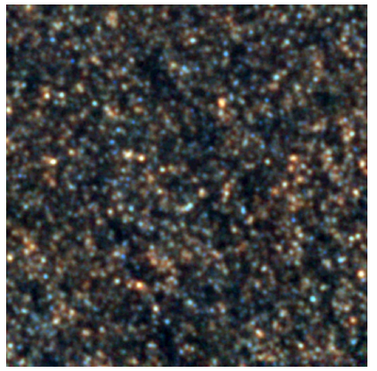
Is CMB "the" CMB?

- 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.

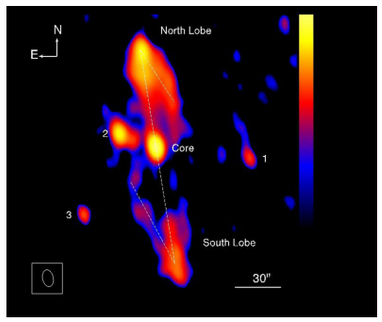




- ICM (g)astrophysics, cosmology (SZ)



- 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.

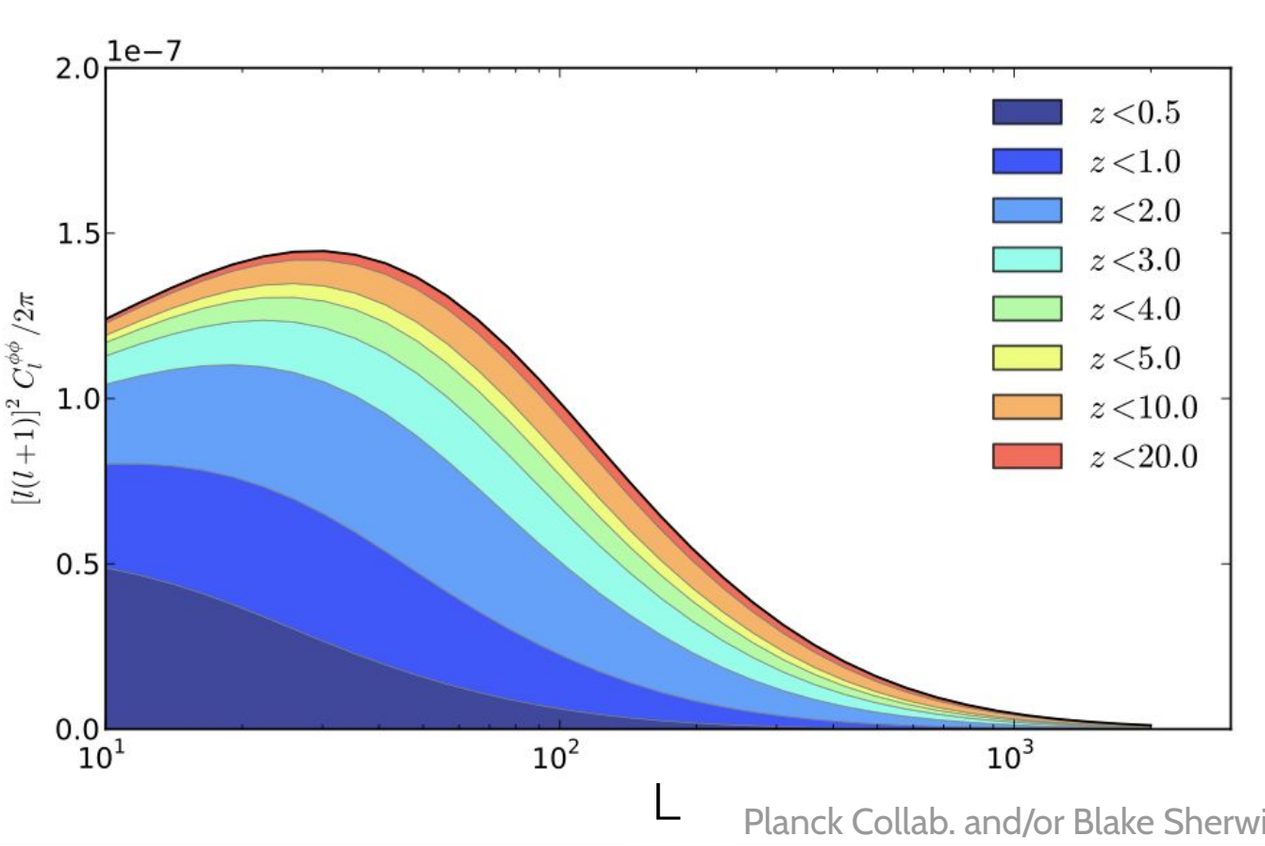
$$\phi(\boldsymbol{\theta}) = -2\int_0^{\chi_s} \frac{D_A(\chi_s - \chi')}{D_A(\chi_s)D_A(\chi')}\Psi\left(\boldsymbol{\theta}, \chi'\right)\mathrm{d}\chi'$$

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

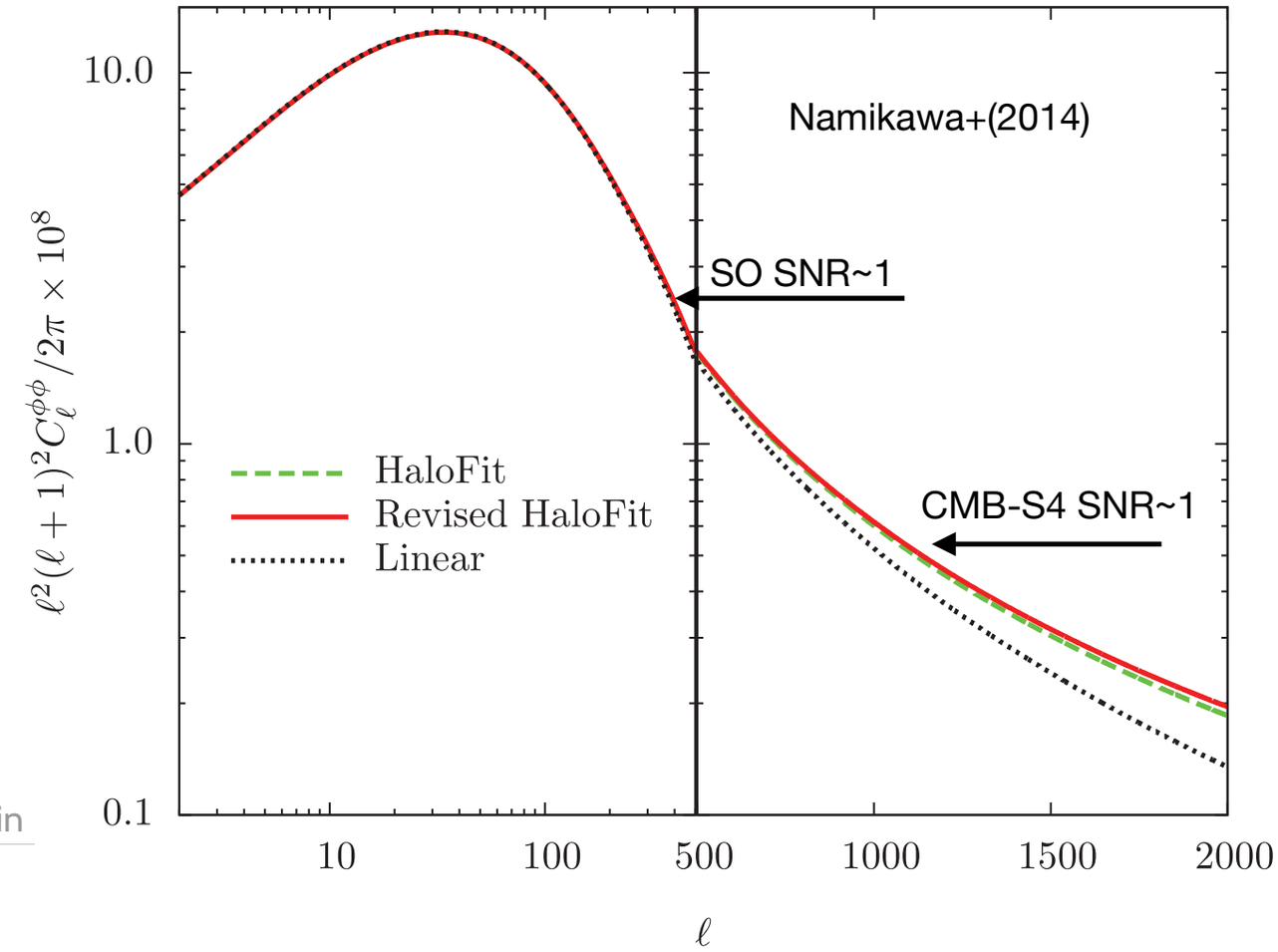
$$\kappa \propto -\nabla^2\phi \rightarrow \delta$$

Notation Warning!

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

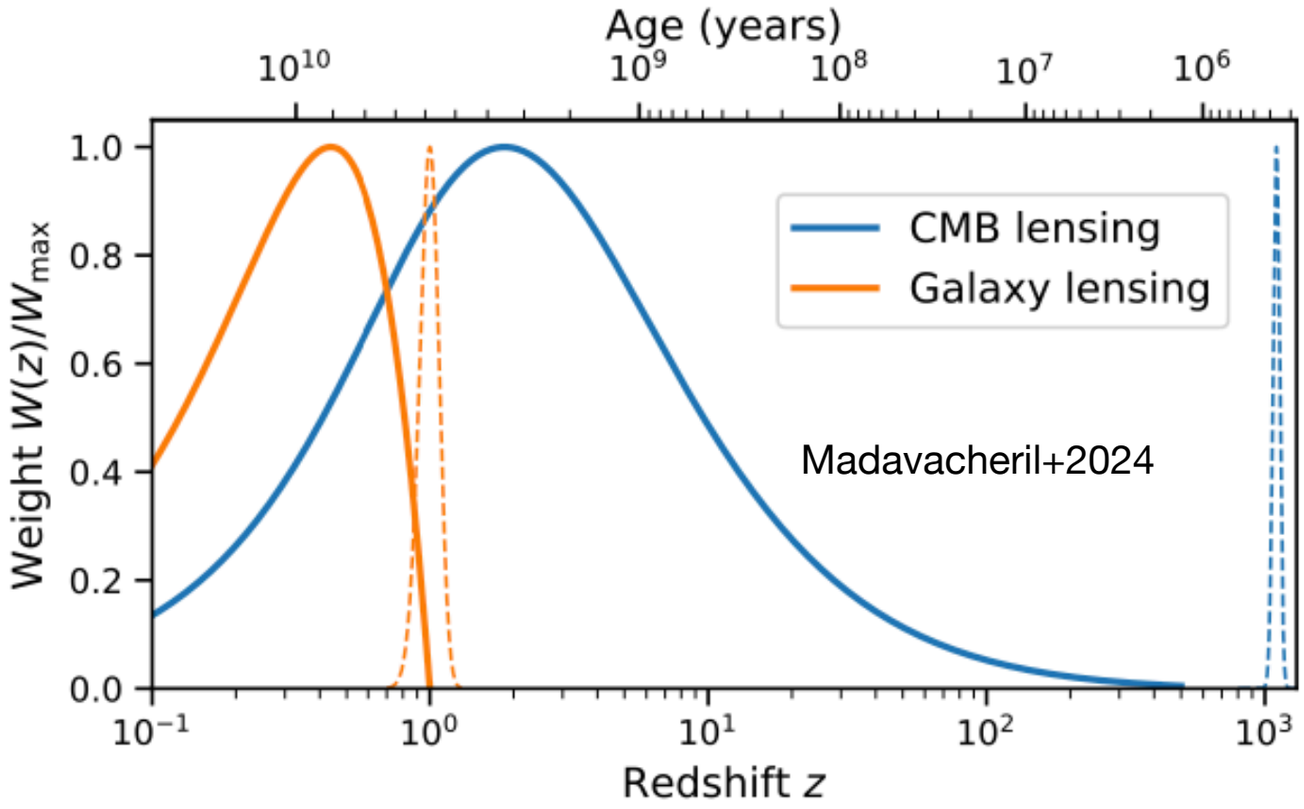


Planck Collab. and/or Blake Sherwin



CMB probes and cross-correlation

- 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 basis and examples

CMB lensing

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

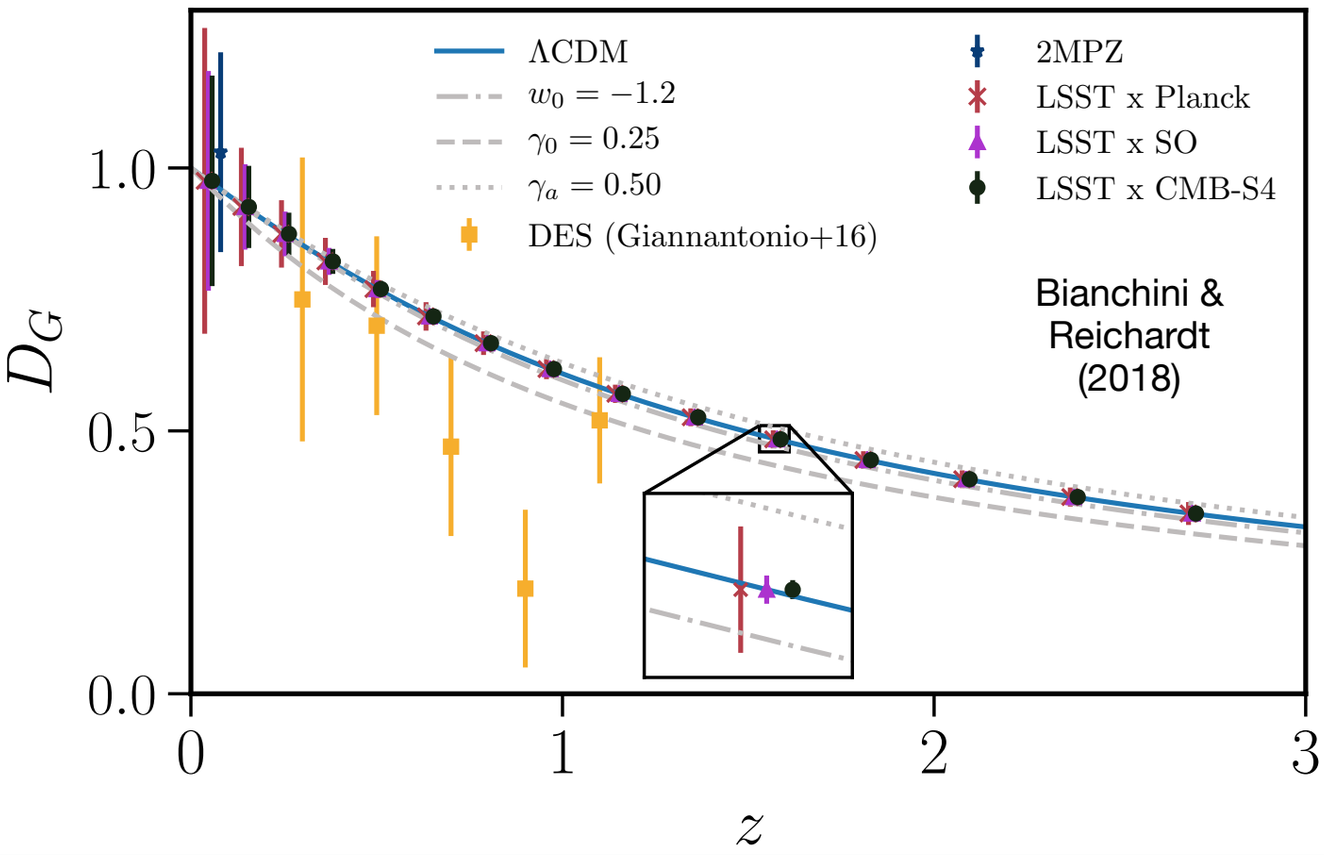
Photometric Galaxy clustering

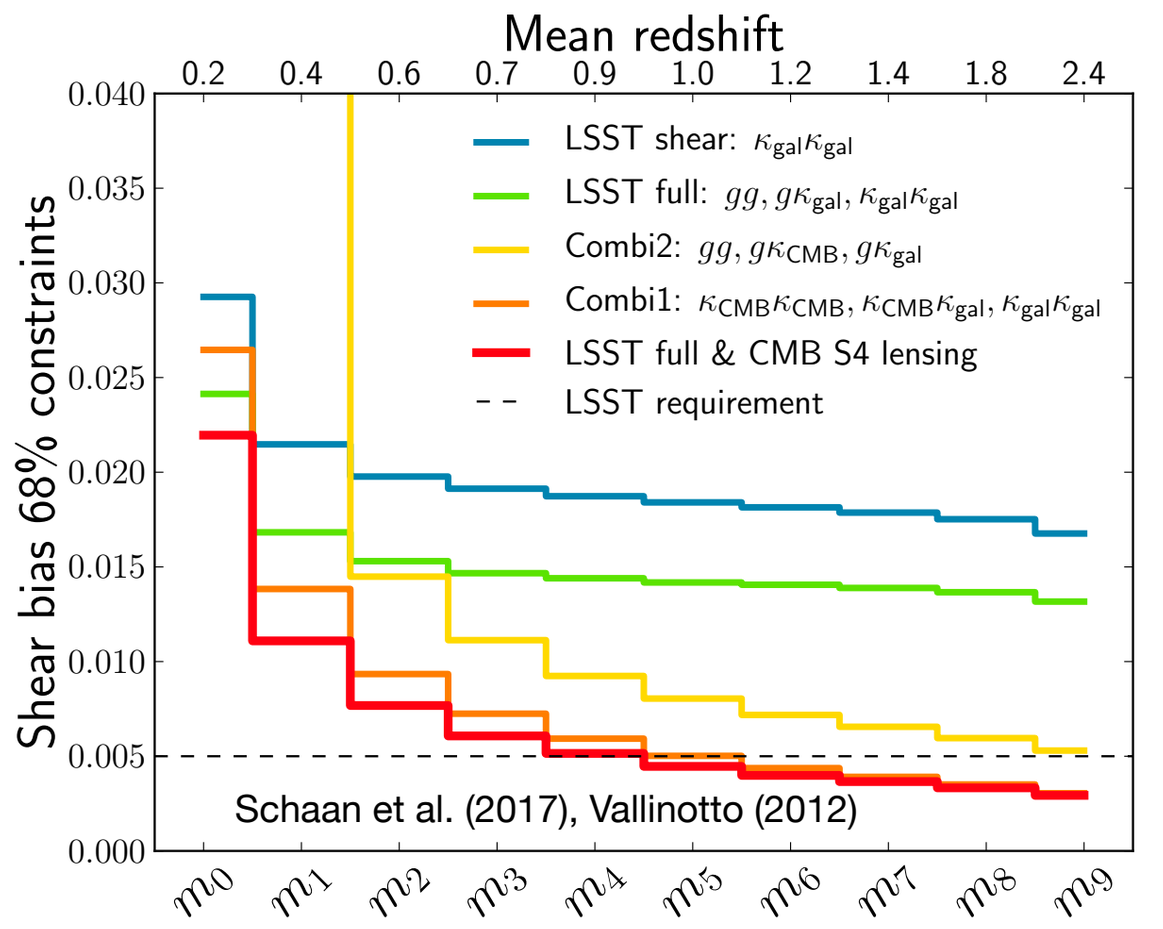
$$W_g(\chi) = b_g(z) \frac{1}{n} \frac{dn}{dz} \frac{dz}{d\chi}$$

Galaxy lensing

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

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

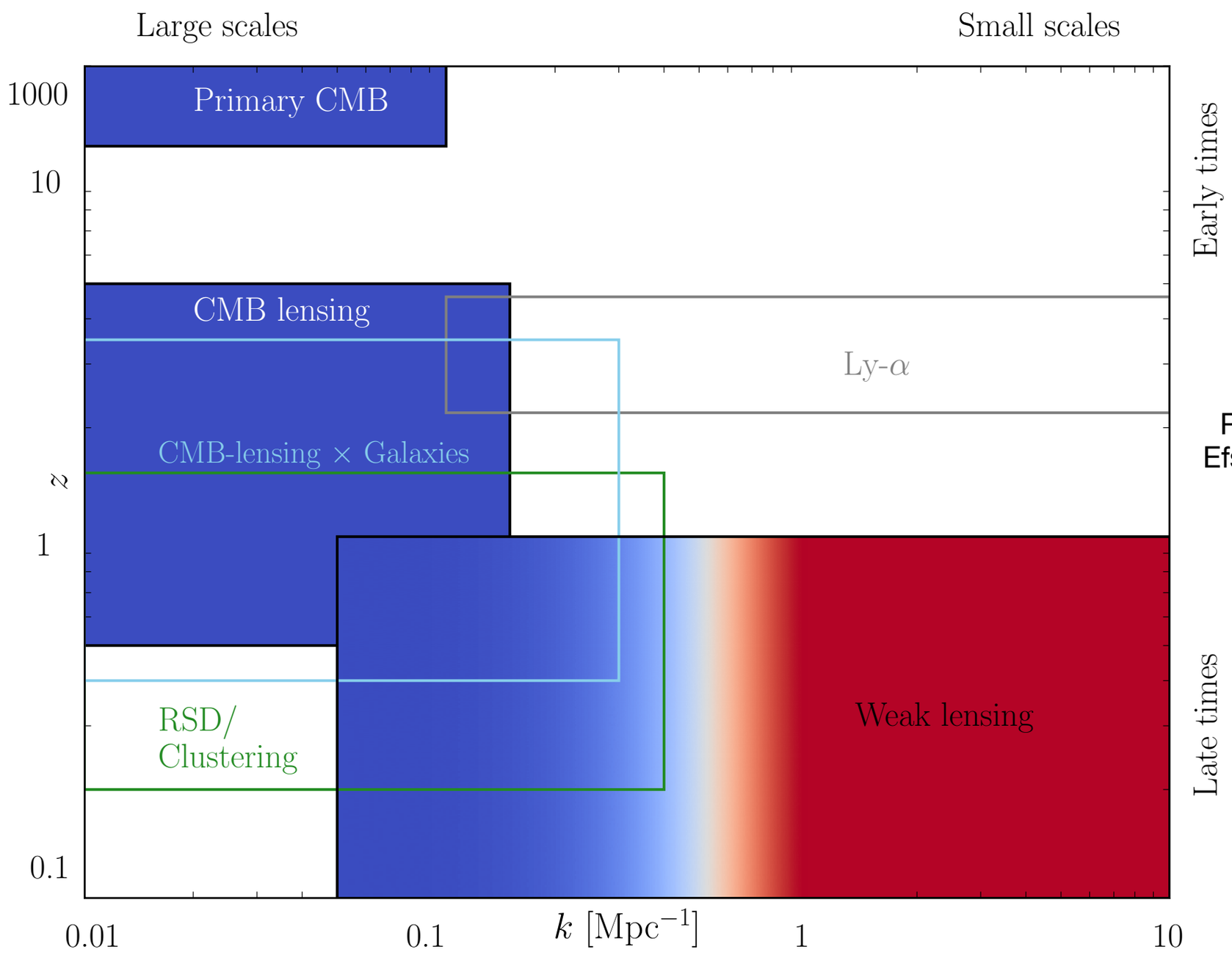




Cosmological probes and cross-correlations

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

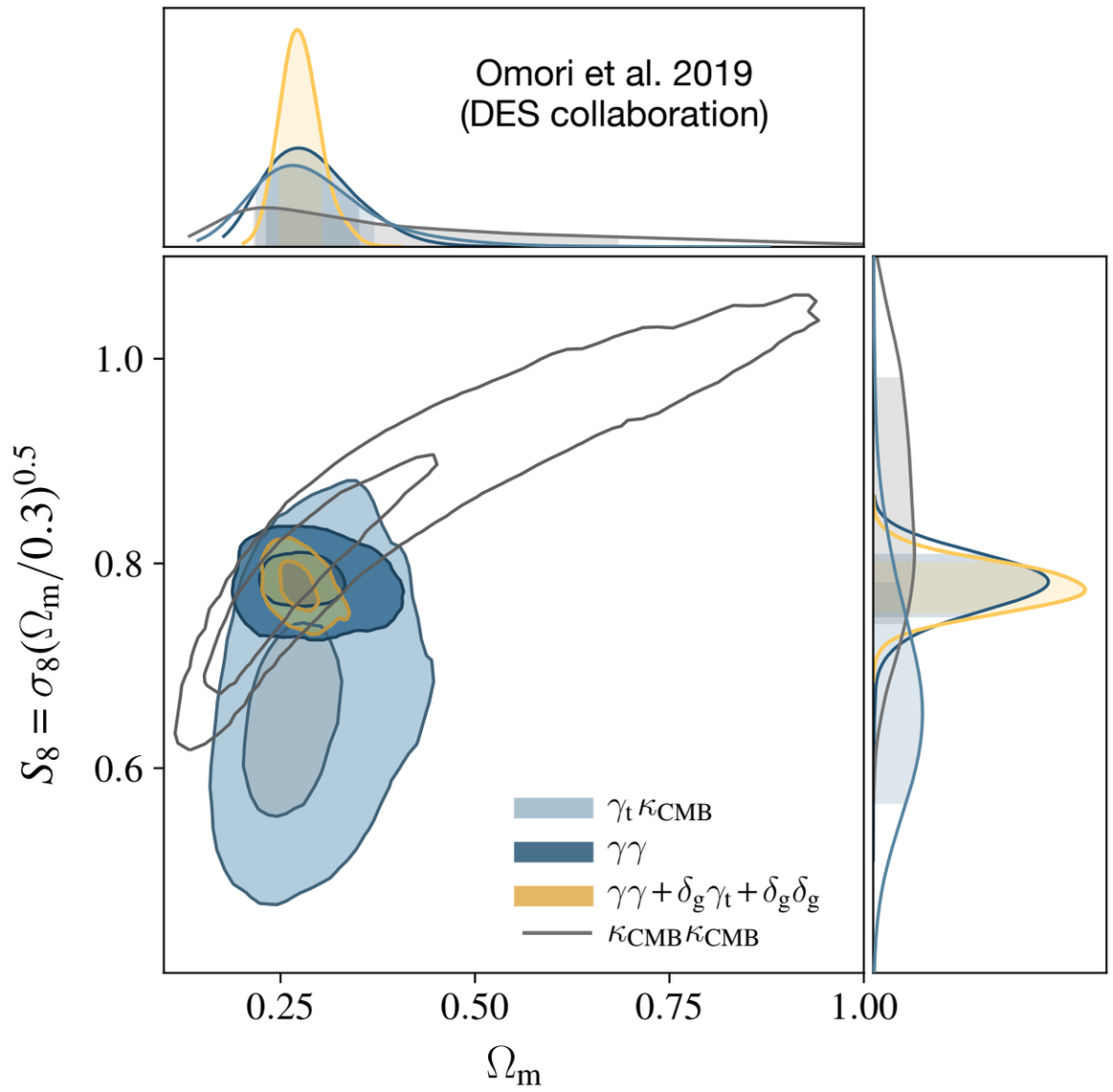
- Tackling DE: to assess if growth tension is real or effect of non-linear physics.



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! **SO: see Thibaut's talk!**
  - New galaxy surveys on sky!

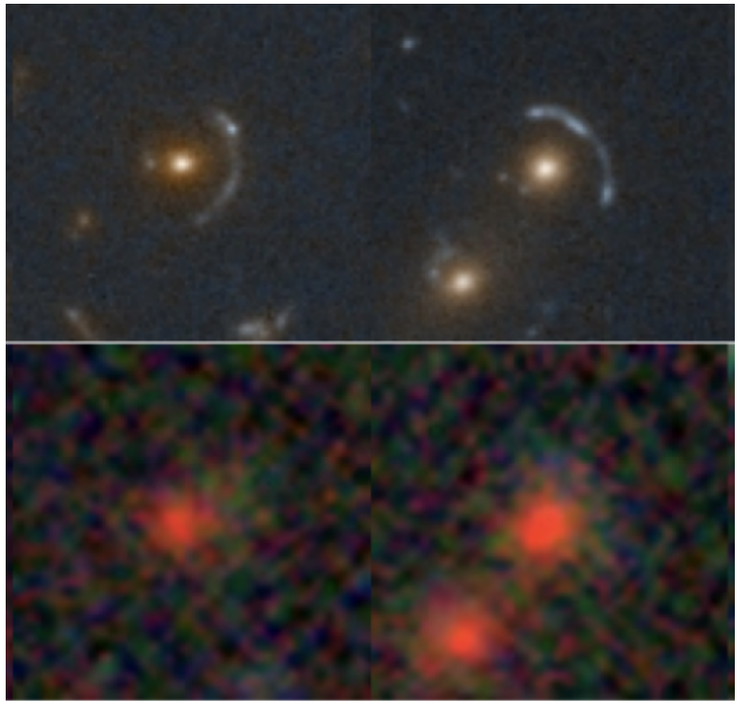


What to expect from next generation surveys

Euclid Early Release Observation image

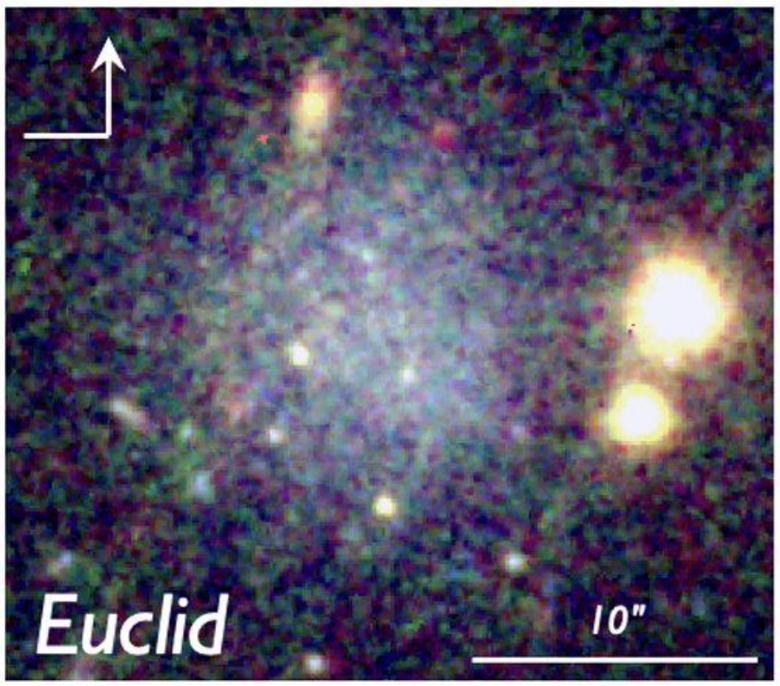
Rubin 1st wide image

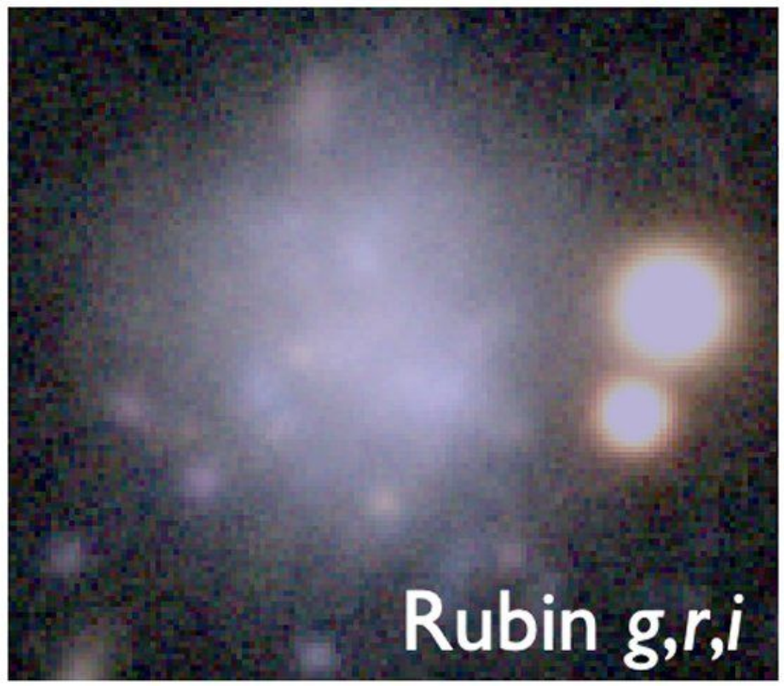
Euclid Q1 release



DESI Legacy Imaging Survey

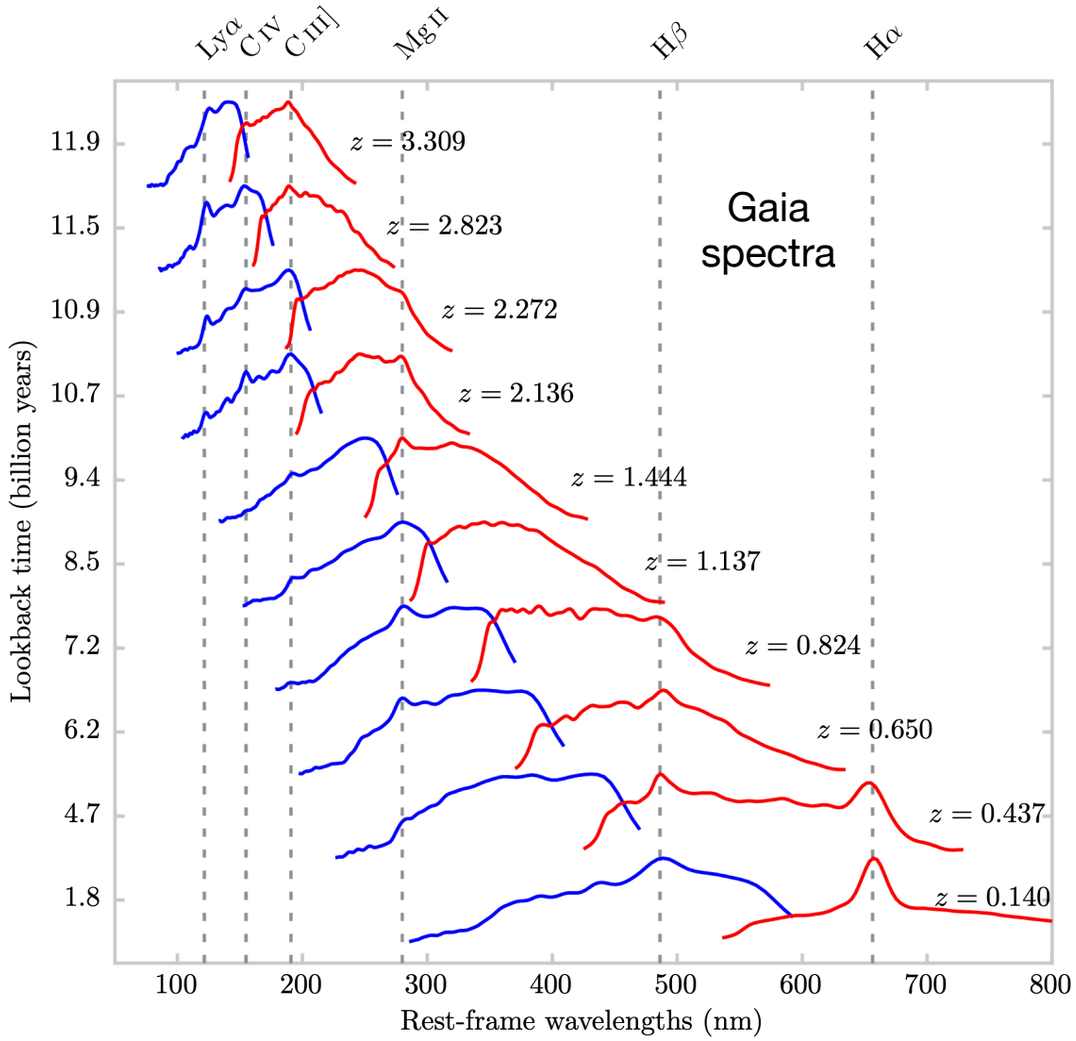
Romanowsky+(2025)

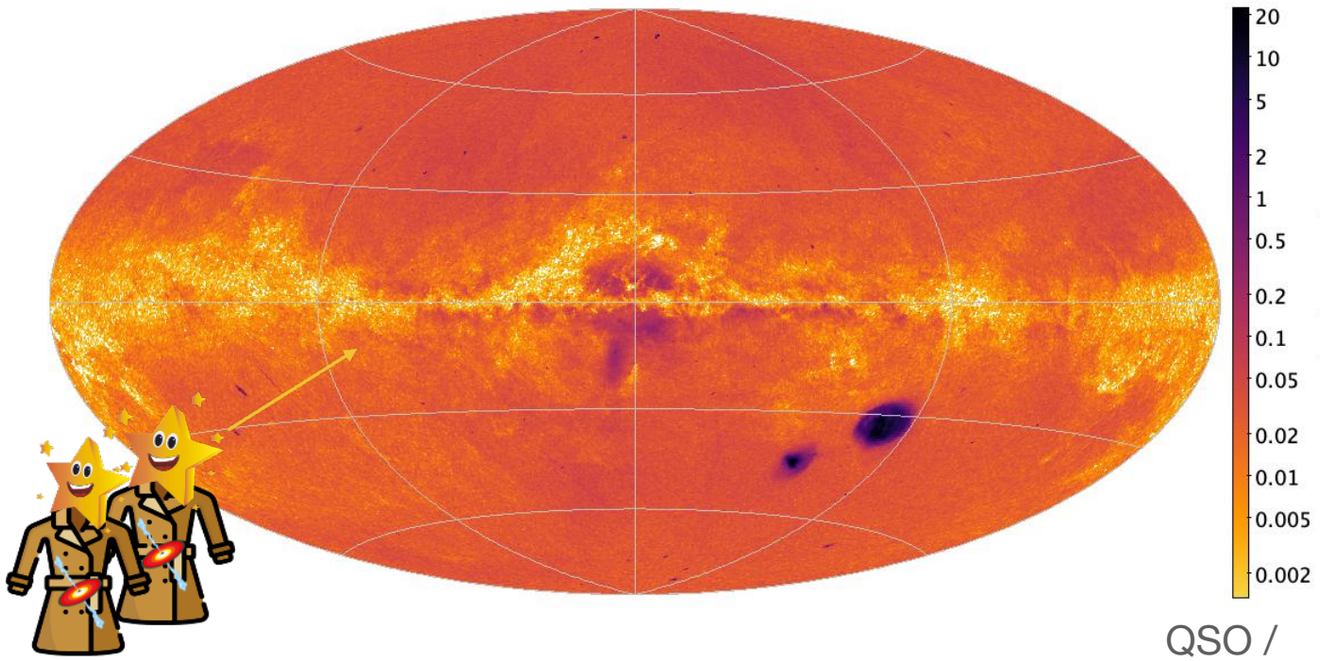




In the meantime… Gaia!

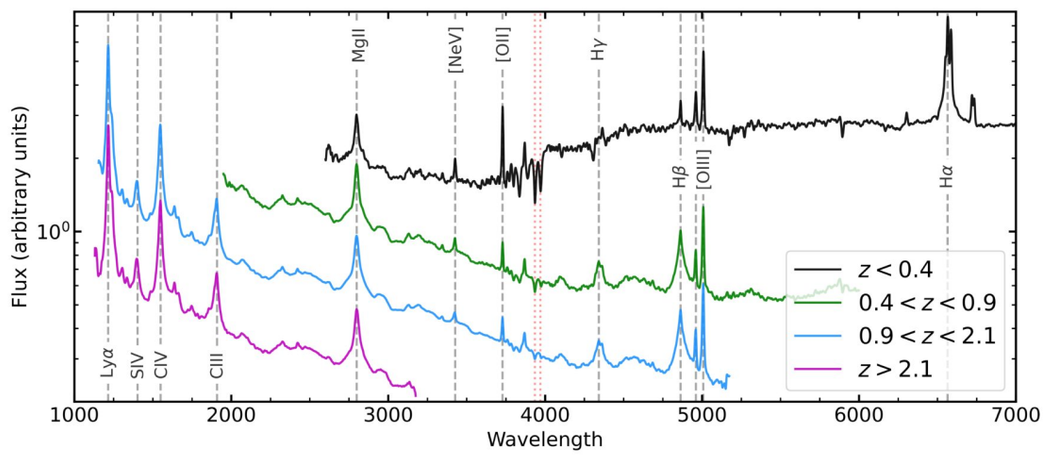
- Gaia: photometry, astrometry, slitless spectroscopy with $30 \leq \lambda/\Delta\lambda \leq 100$
- DR3 released 6.6 million quasar candidates.
  - Stable conditions, cleaner selection.
  - Complete but low purity: many stars masquerading as QSO :/





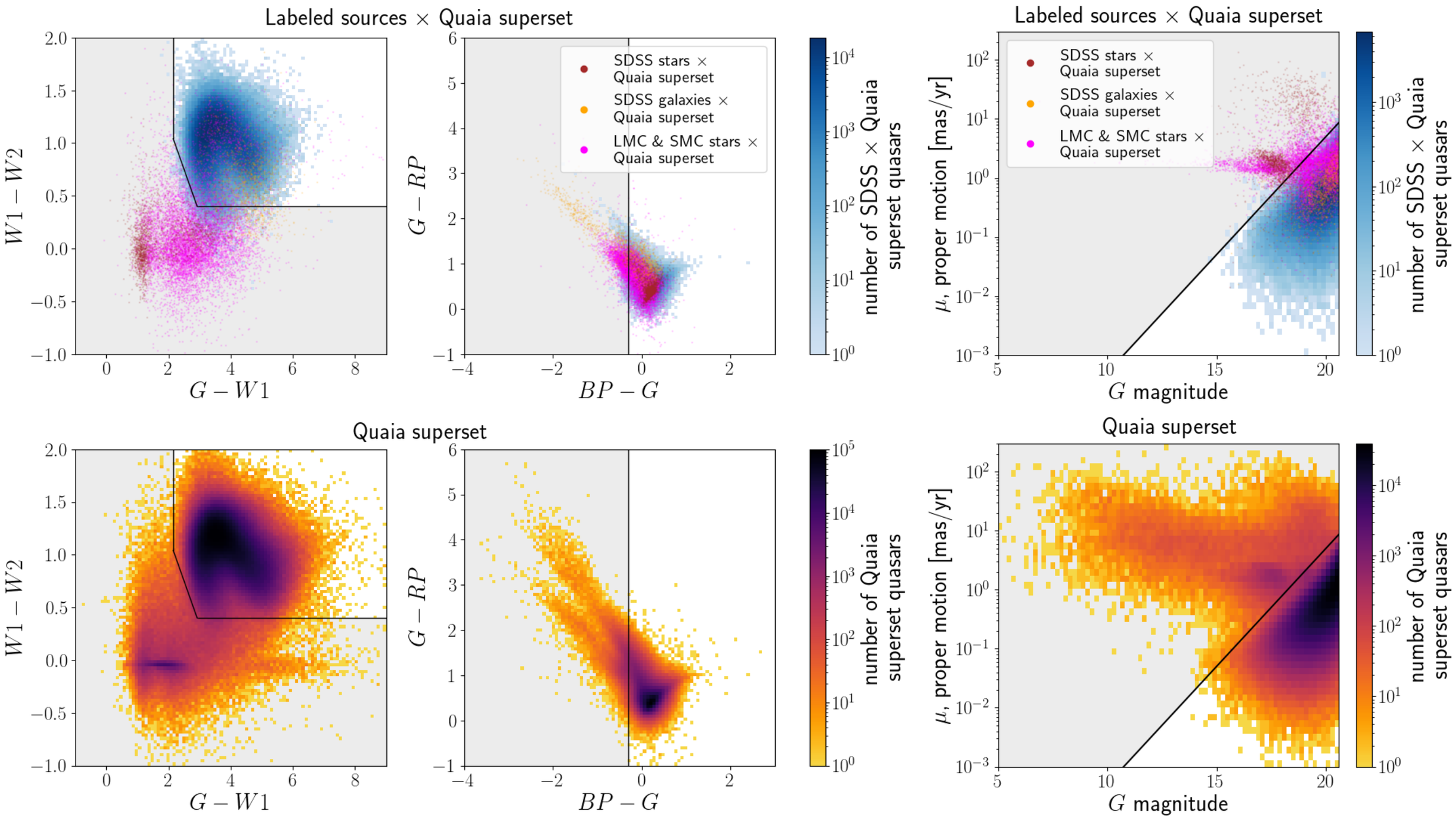
Bailer-Jones+2022

DESI spectra (DESI coll.)



Quaia: the cosmological QSO sample of Gaia

- Better purity and low systematics thanks to synergies with external data.
  - unWISE + SDSS DR18 + color and proper motion cuts



Storey-Fisher+ (w/ GF, 2024)

How it compares?

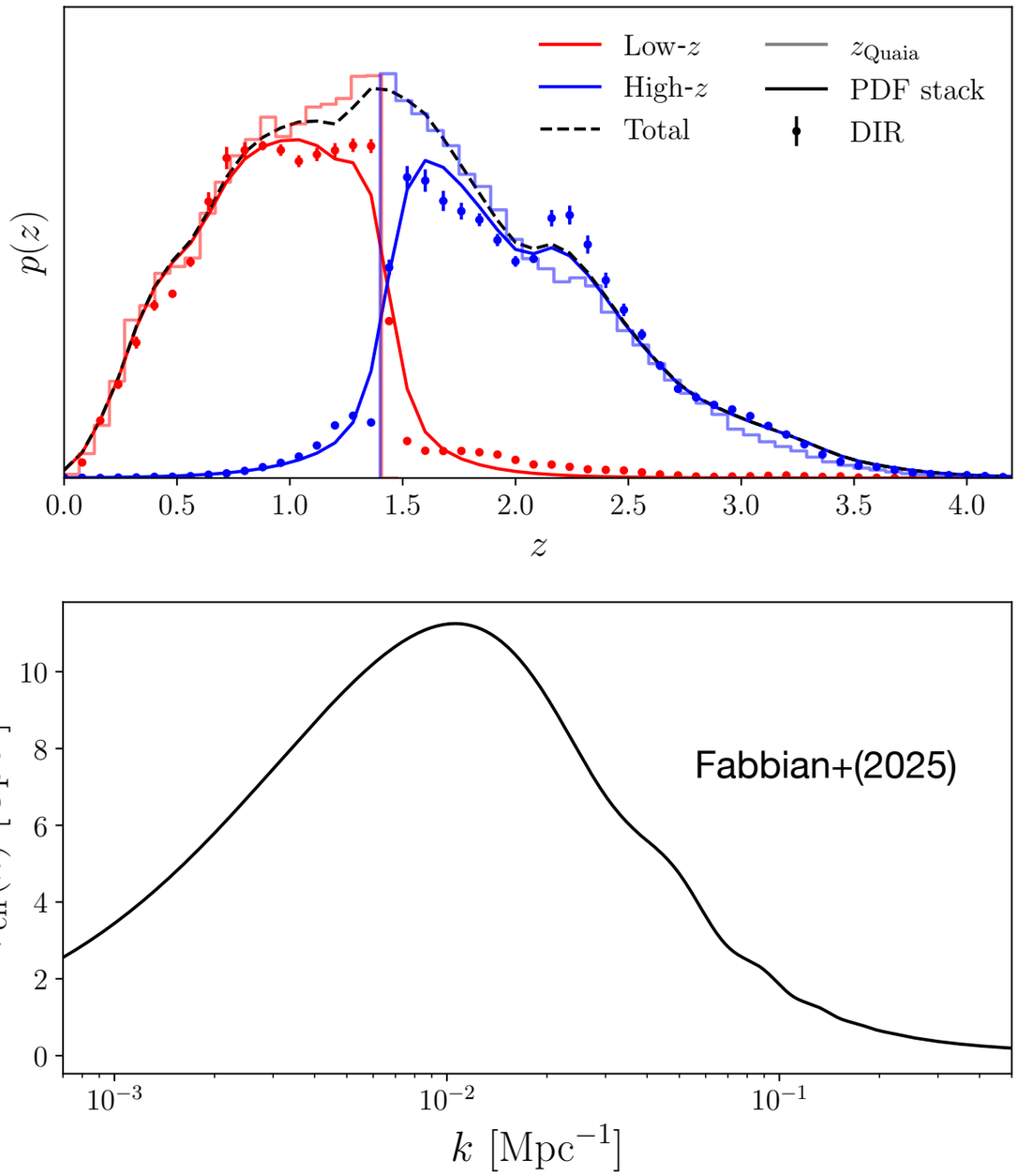
Credits Kate Storey-Fisher

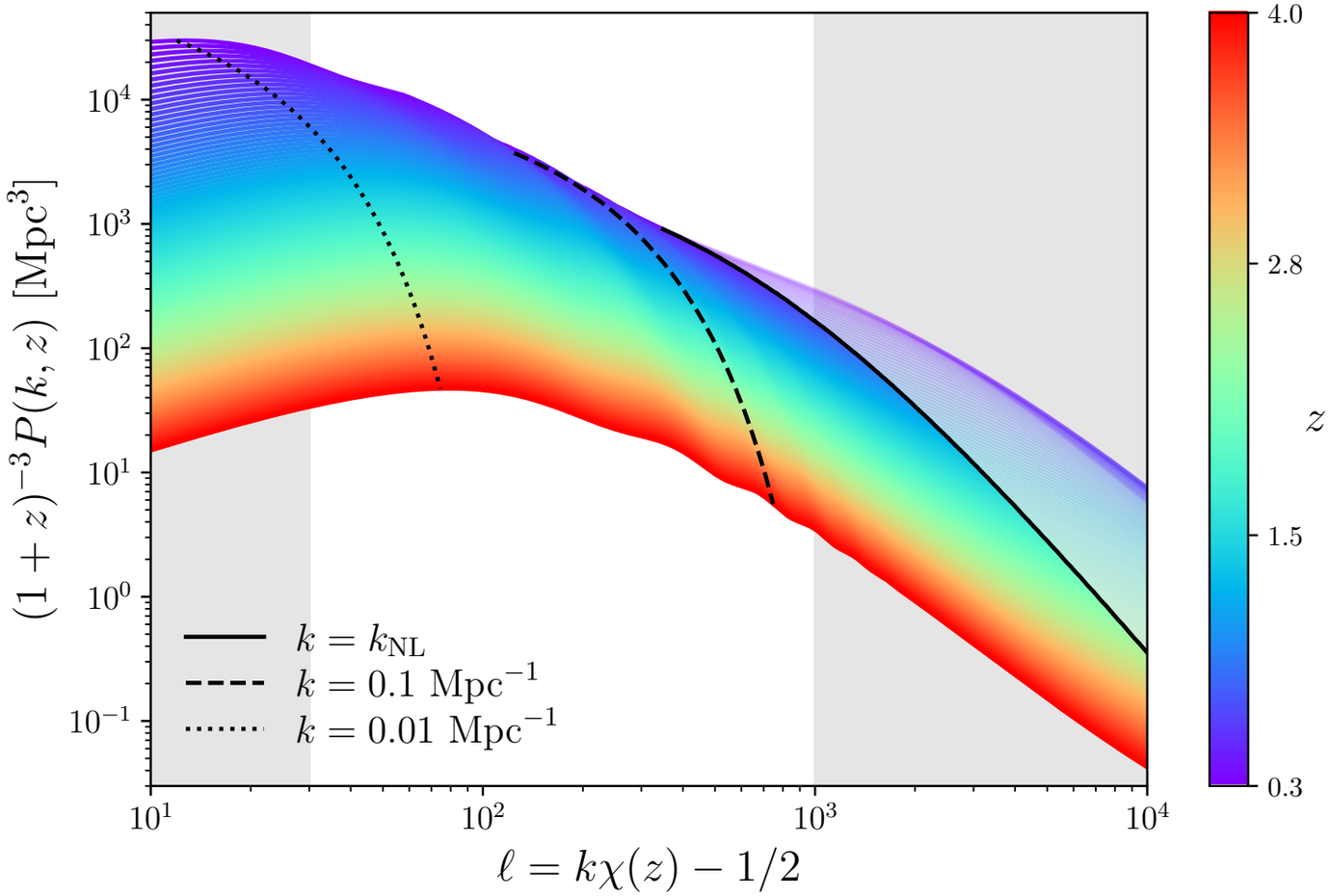
	N	$f_{\rm sky}$	$\bar{n}$, $\rm deg^{-2}$	$V_{\rm span}$, $(h^{-1}\,\rm Gpc)^3$	$V_{\rm eff}$, $(h^{-1}\,\rm Gpc)^3$	$z_{\rm med}$	$f(\lvert\delta z\rvert < 0.01)$	$f(\lvert\delta z\rvert < 0.1)$
Quaia	**1,234,715**	**0.73**	**40.78**	**143.78**	**7.08**	**1.48**	**0.63**	**0.84**
Gaia Purer	1,647,311	0.73	54.42	143.76	9.24	1.63	0.53	0.62
WISE-PS1	2,386,121	0.56	103.89	109.08	20.88	1.38	0.11	0.71
SDSS DR16Q	637,371	0.26	60.18	50.30	4.16	1.77	∼1	∼1
eBOSS Clustering	409,286	0.14	72.52	26.80	3.21	1.60	∼1	∼1

NB: after DESI, still largest QSO sample (slightly) and ~2.5x spanning volume

What Quaia can do for cosmology?

- High redshift, linear or quasi-linear scales.
- Large scales (in angles and k)

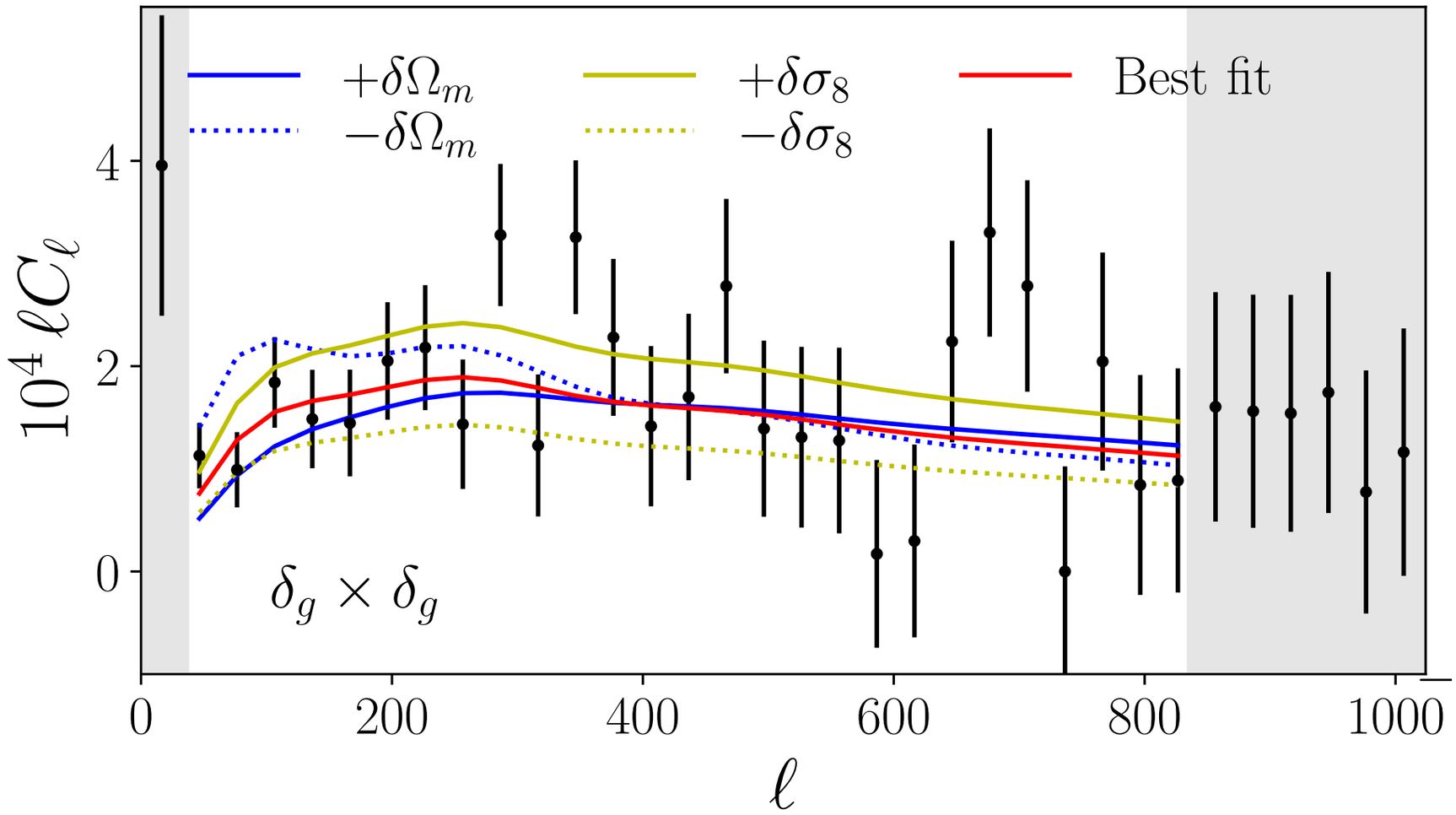


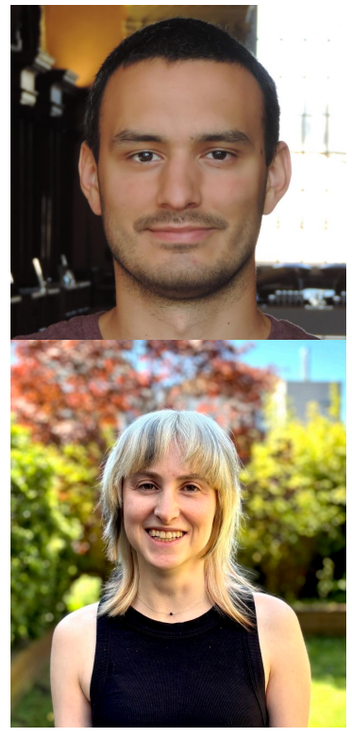


Alonso, Fabbian, Storey-Fisher+ (2023)

What Quaia can do for cosmology?

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



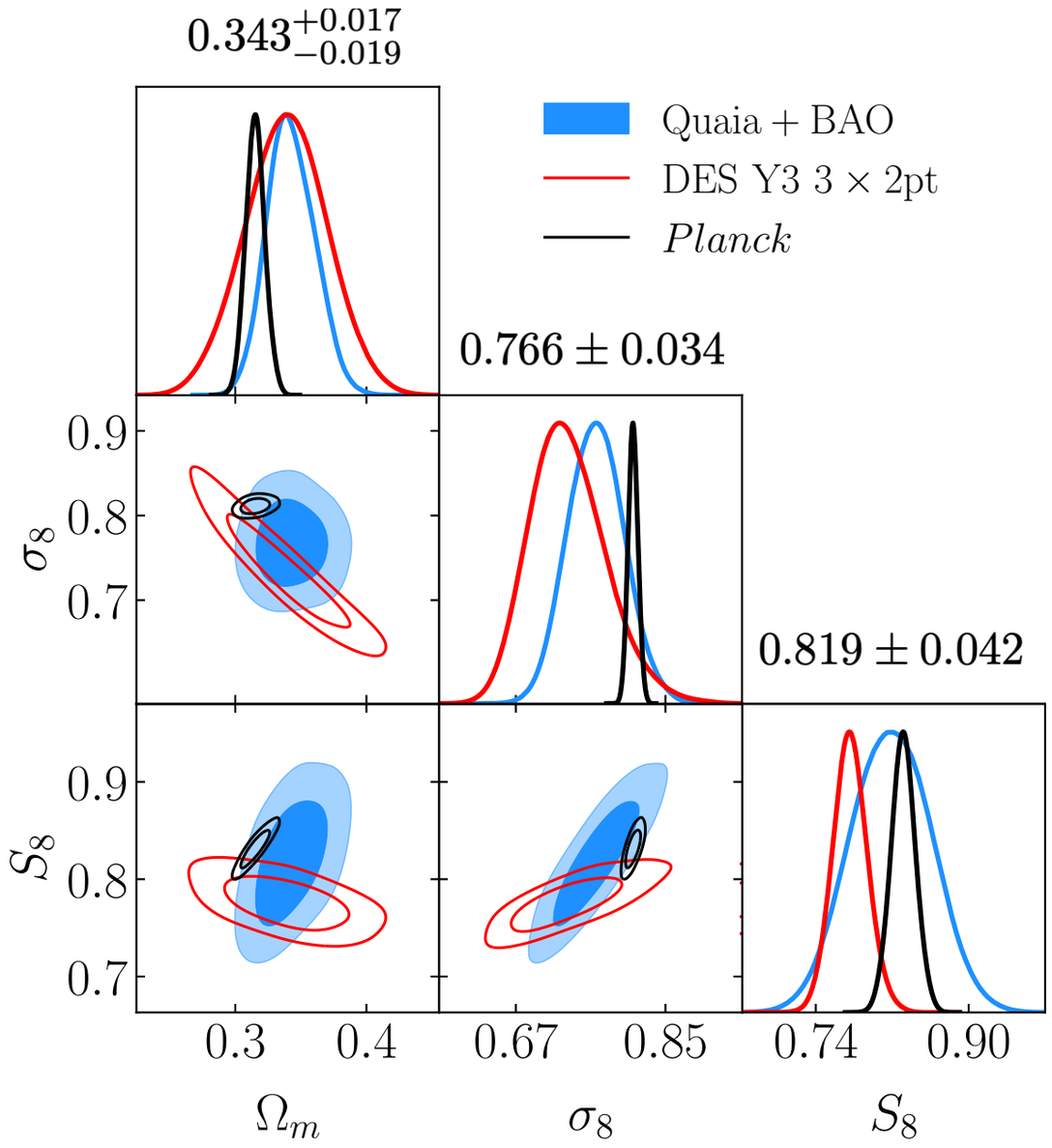


Alonso, Fabbian, Storey-Fisher+(2023)

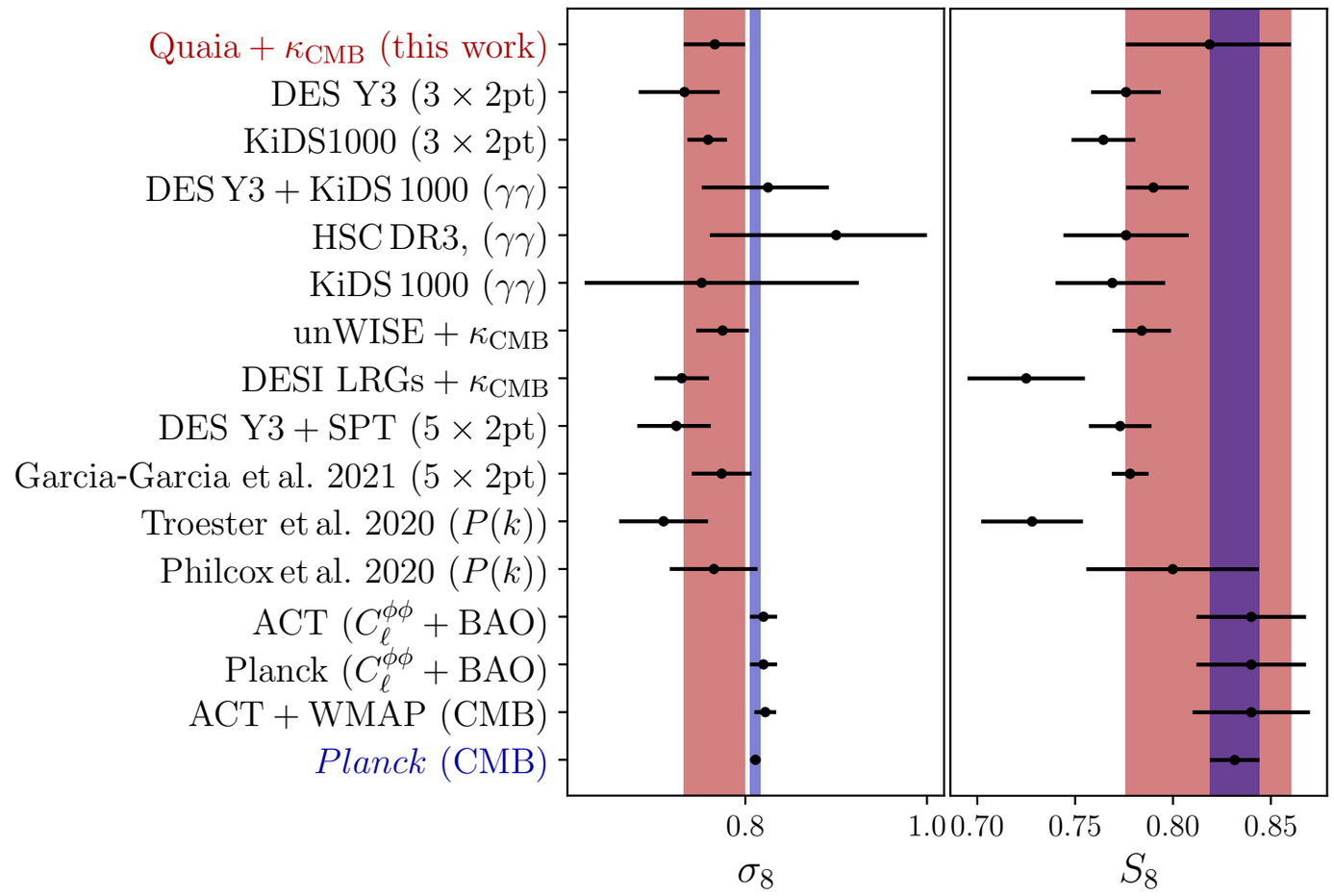
Cosmology from Quaia x Planck CMB lensing

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

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



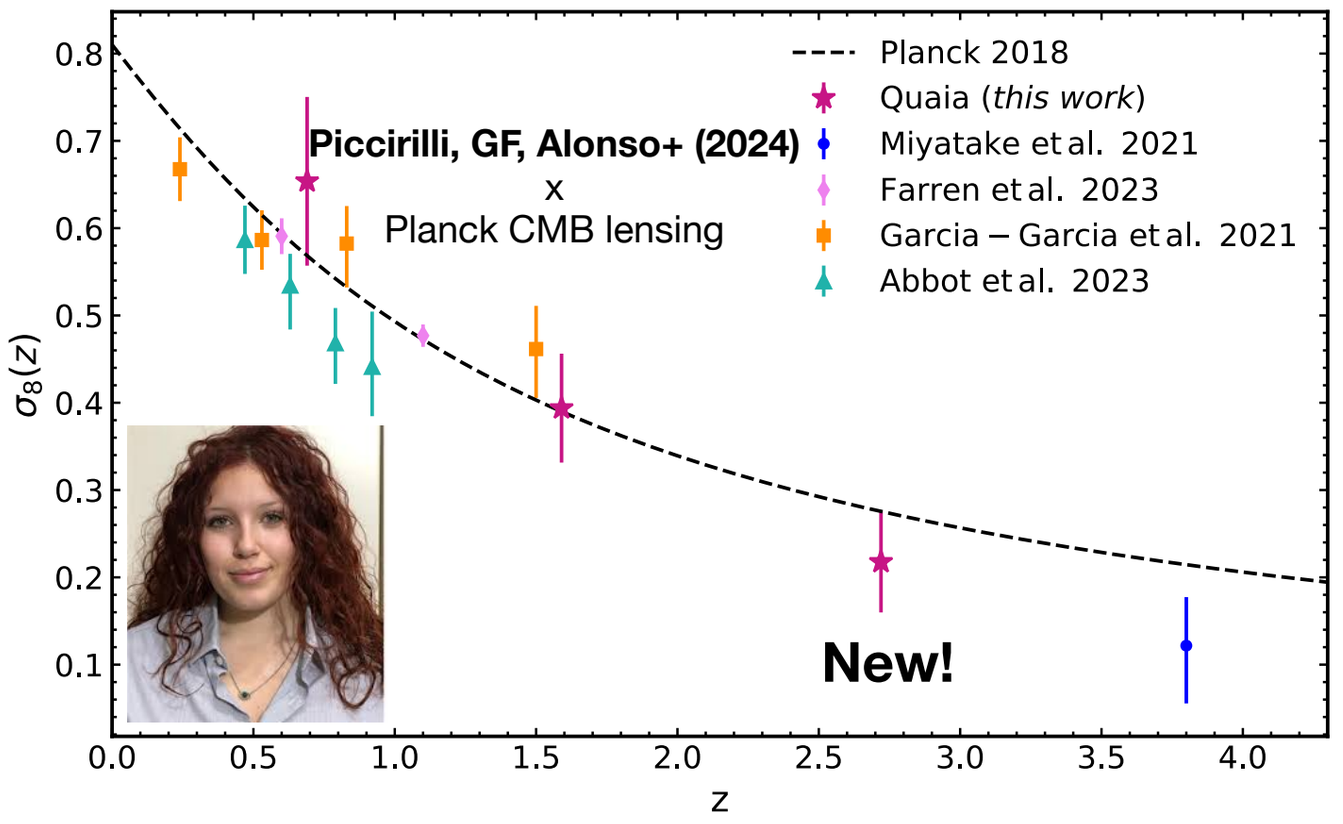
No tension with Planck!



Alonso, Fabbian, Storey-Fisher+(2023)

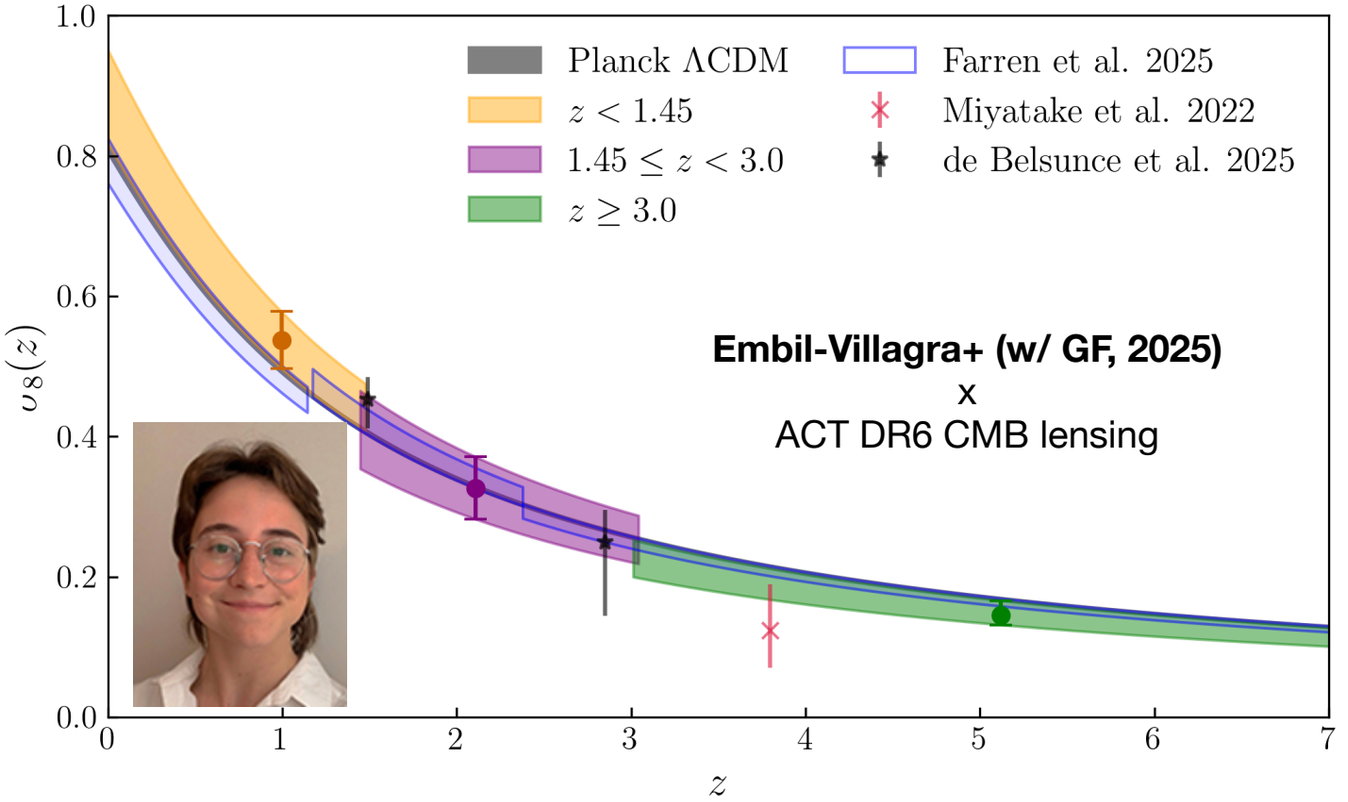
Cosmology from Quaia x CMB lensing

- Tomographic $C_\ell^{gg}, C_\ell^{\kappa g}$ with Planck lensing
  - New high-z σ_8 constraints
  - Model independent approach
  - Careful foreground assessments (CIB…)



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

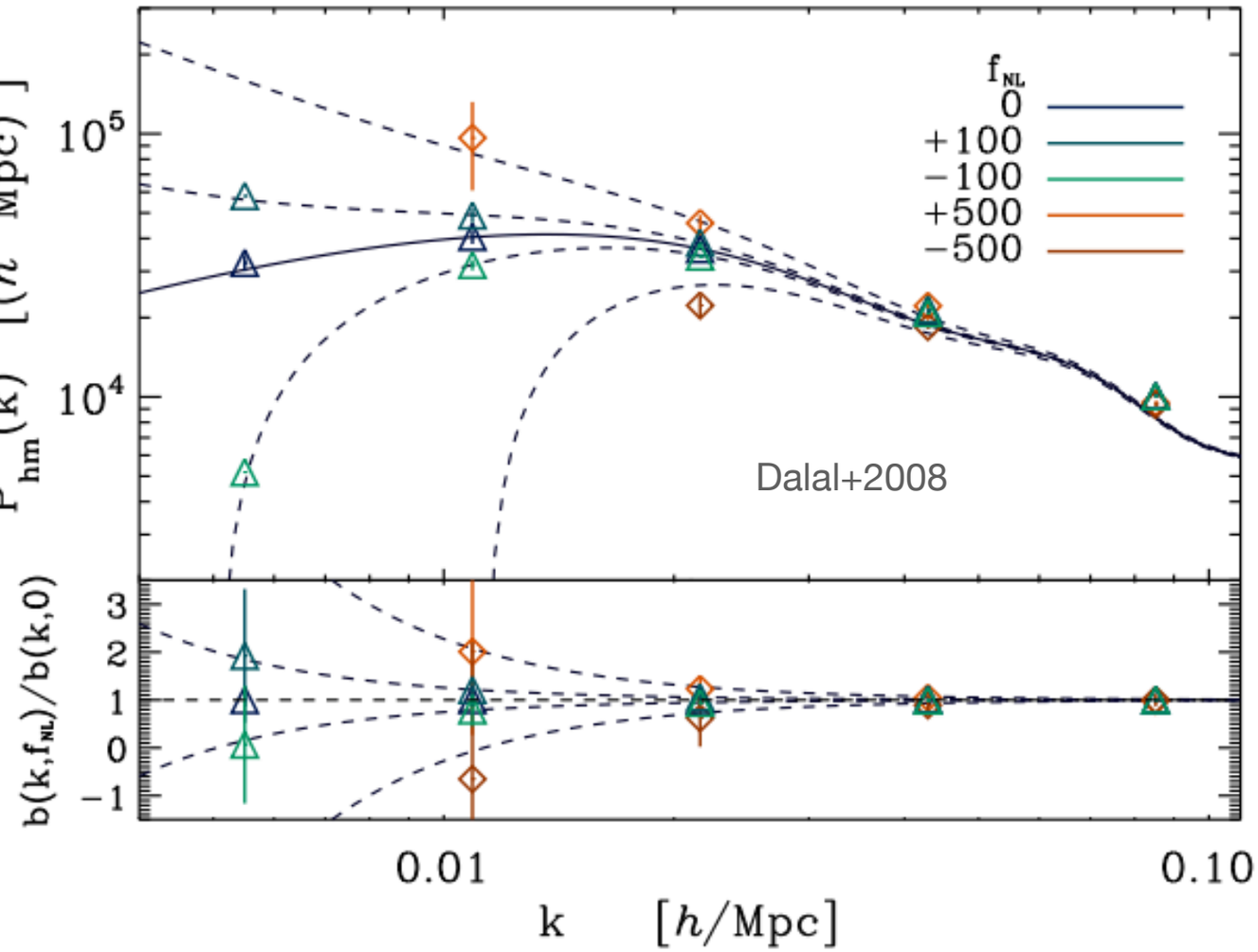
$$P_{\rm lin}^{\rm new}(k,z) = P_{\rm lin}^{\rm input}(k,z)A(z)$$
$$= P_{\rm lin}^{\rm input}(k,z) \begin{cases} A_0 & 0 \le z < z_1 \\ A_1 & z_1 \le z < z_2 \\ A_2 & z_2 \le z \end{cases} .$$



Non-Gaussianities and scale dependent bias

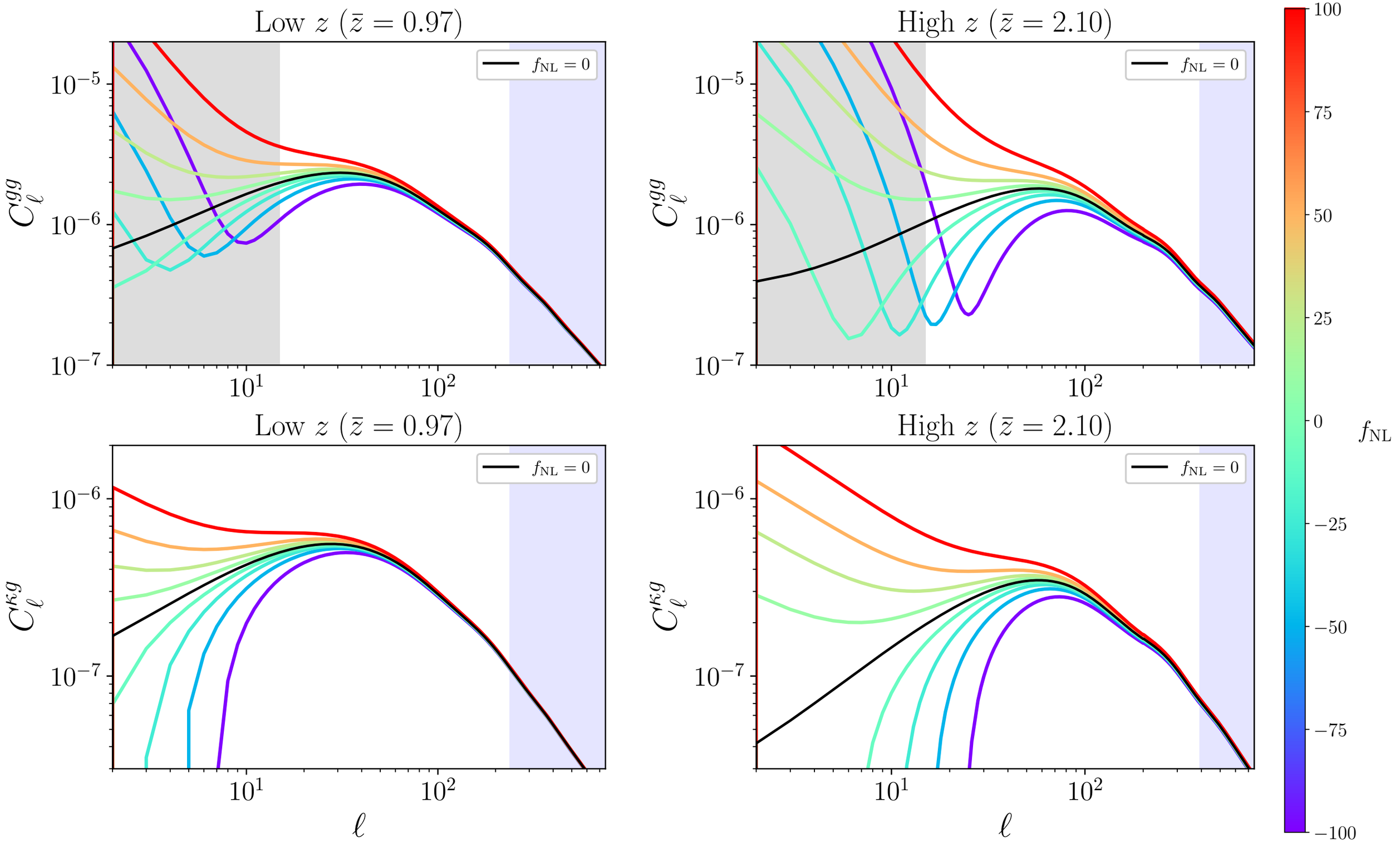
$$\Phi(\mathbf{x})_{\rm NG} = \Phi(\mathbf{x}) + f_{\rm NL}\left(\Phi^2(\mathbf{x}) - \langle\Phi^2\rangle\right)$$

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



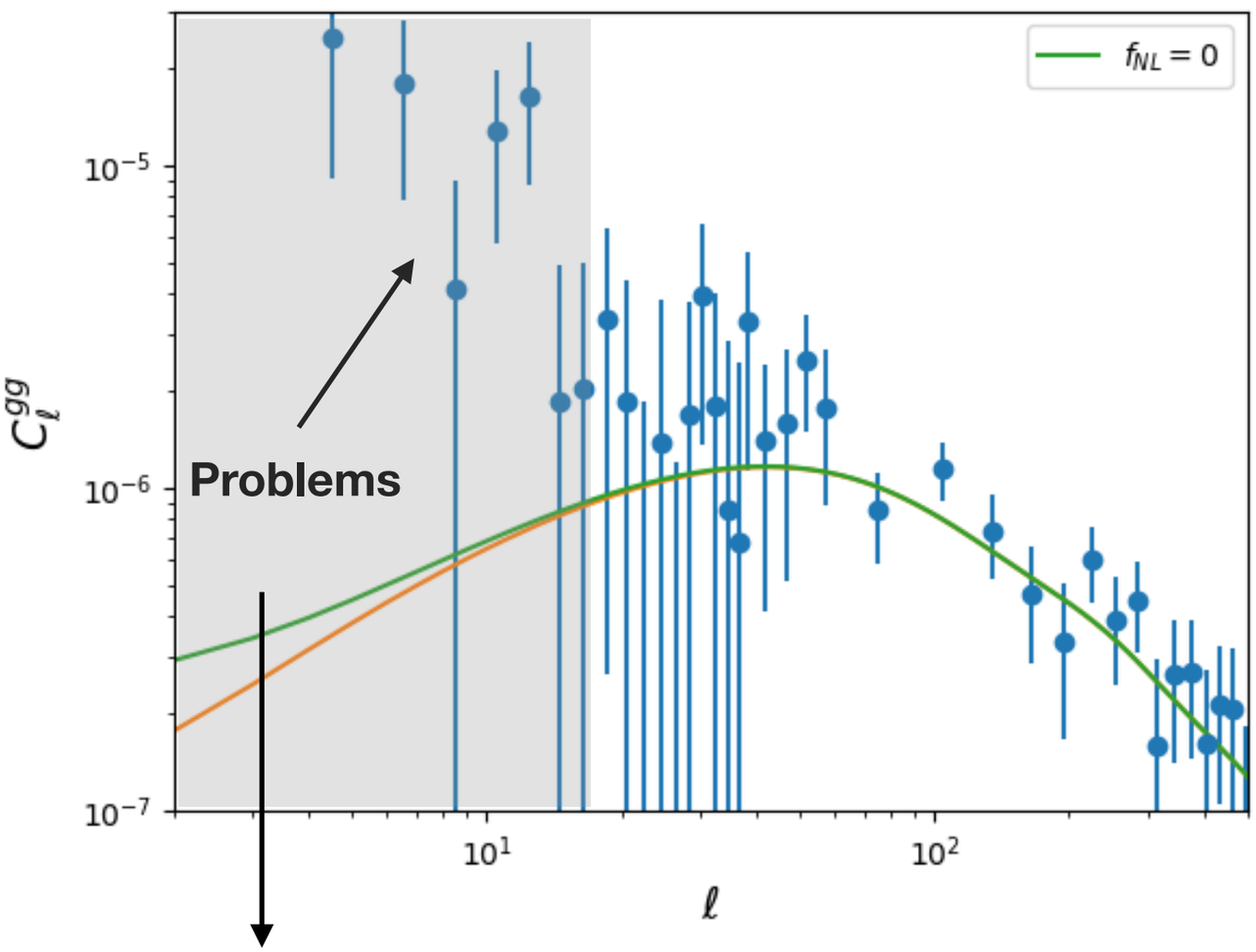
- Huge volume and high bias tracers is required to enhance detection.
- Quasars: detectable at high z thanks to bright AGNs, ~linear scales, ideal for f_{NL} studies.
- Galactic extinction, stellar contamination, seeing, survey depth inhomogeneity cause large scale variations / power excess in clustering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

Signature of f_{NL} for projected statistics

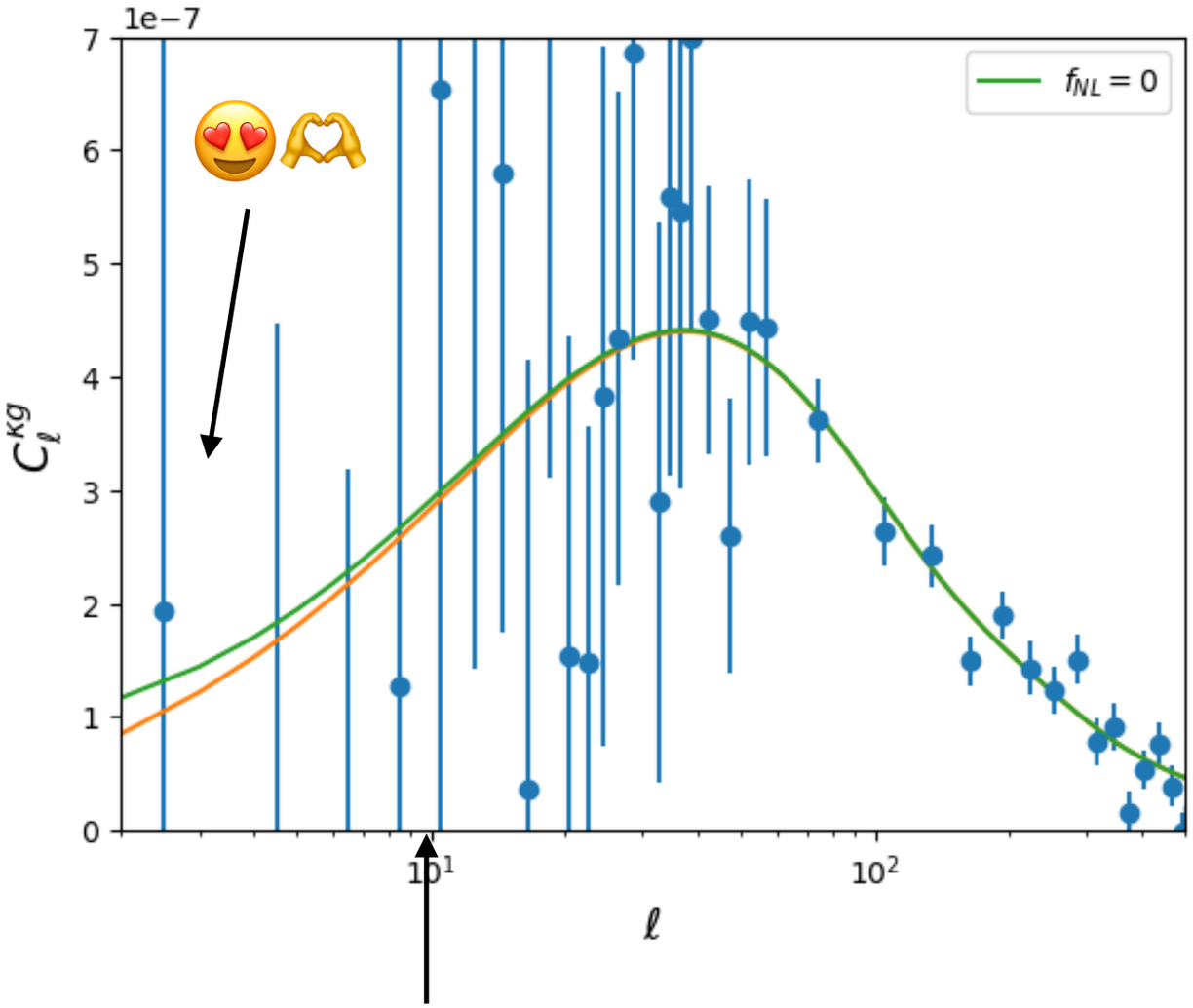


Fabbian, Alonso, Storey-Fisher+(2025)

Constraints on f_{NL}



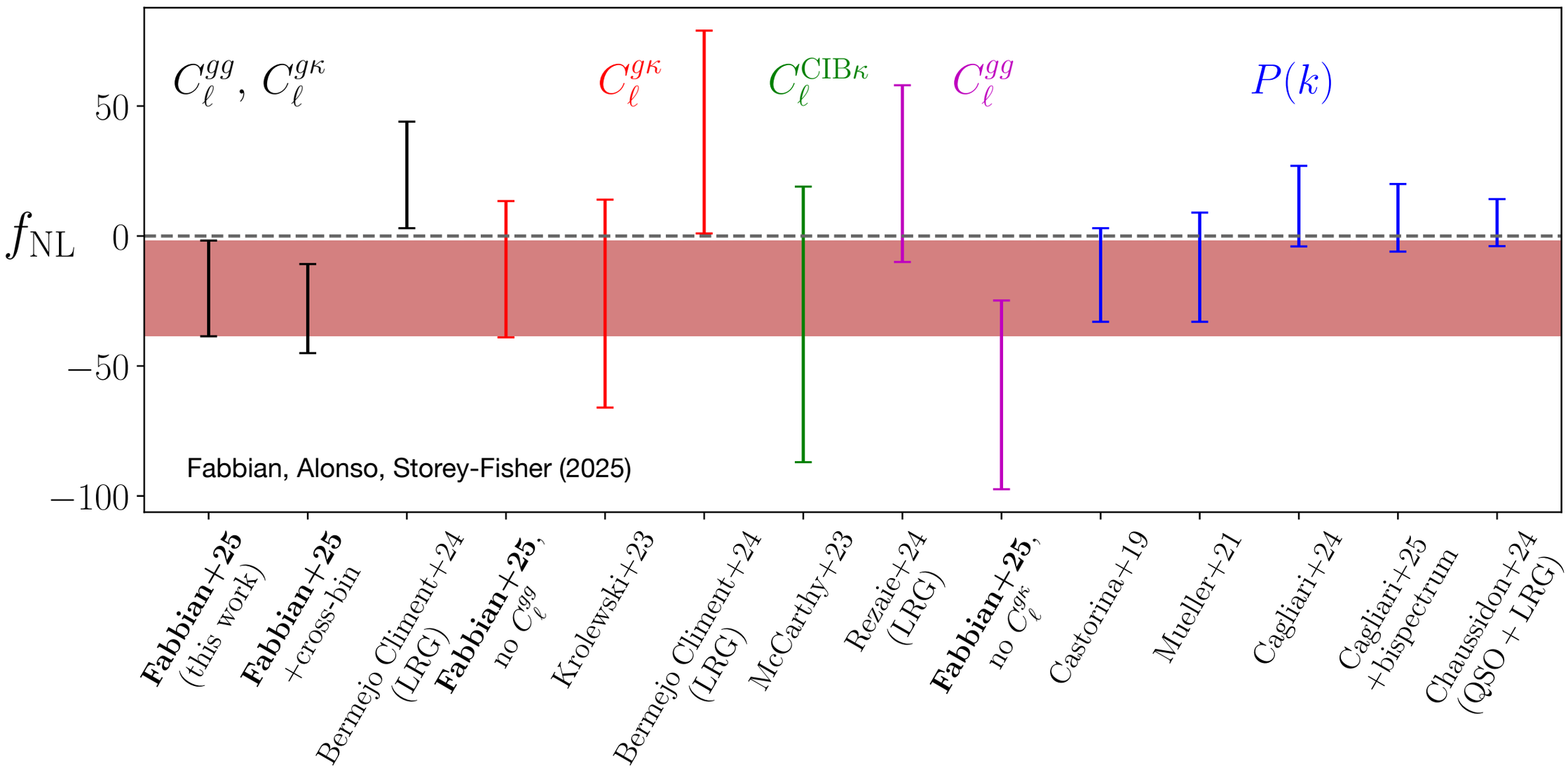
Aggressive systematics subtraction:
~3x degradation of results
(Rezeie+2025)



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

- Cross-correlation can reach the largest scales with no systematics contamination!
- $\sigma(f_{\rm NL})$: worse than expectations due to residual systematics $\Delta C_\ell^{\kappa g} \propto \sqrt{C_\ell^{\kappa\kappa} C_\ell^{gg}}$

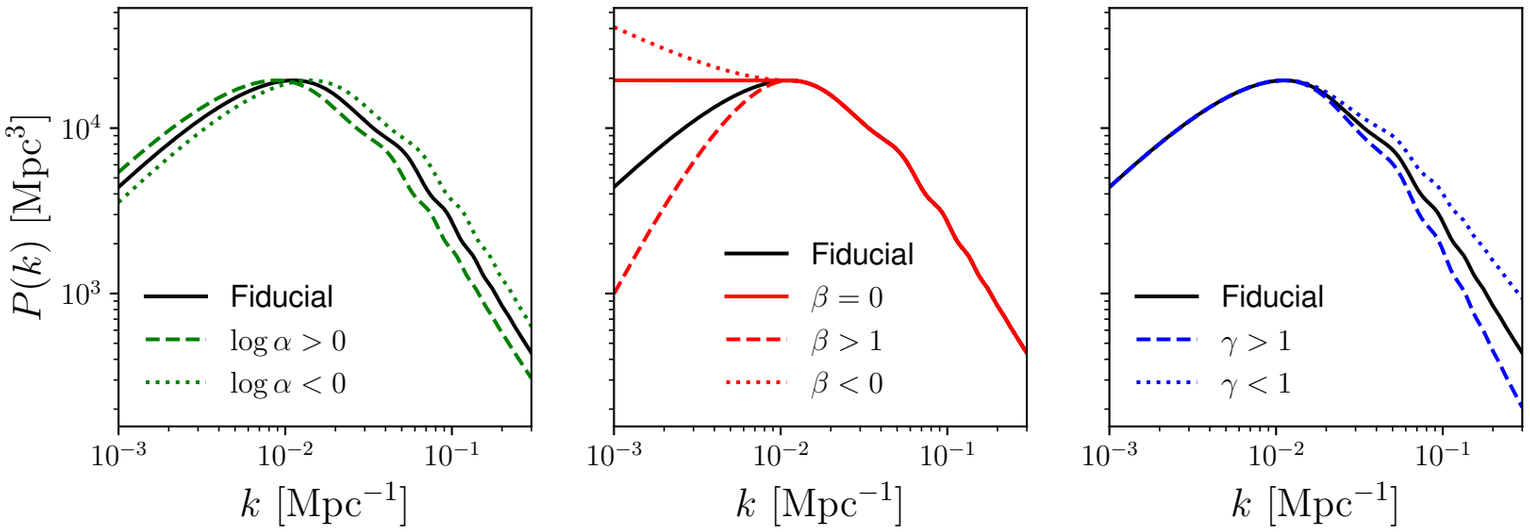
Robustness tests and perspectives

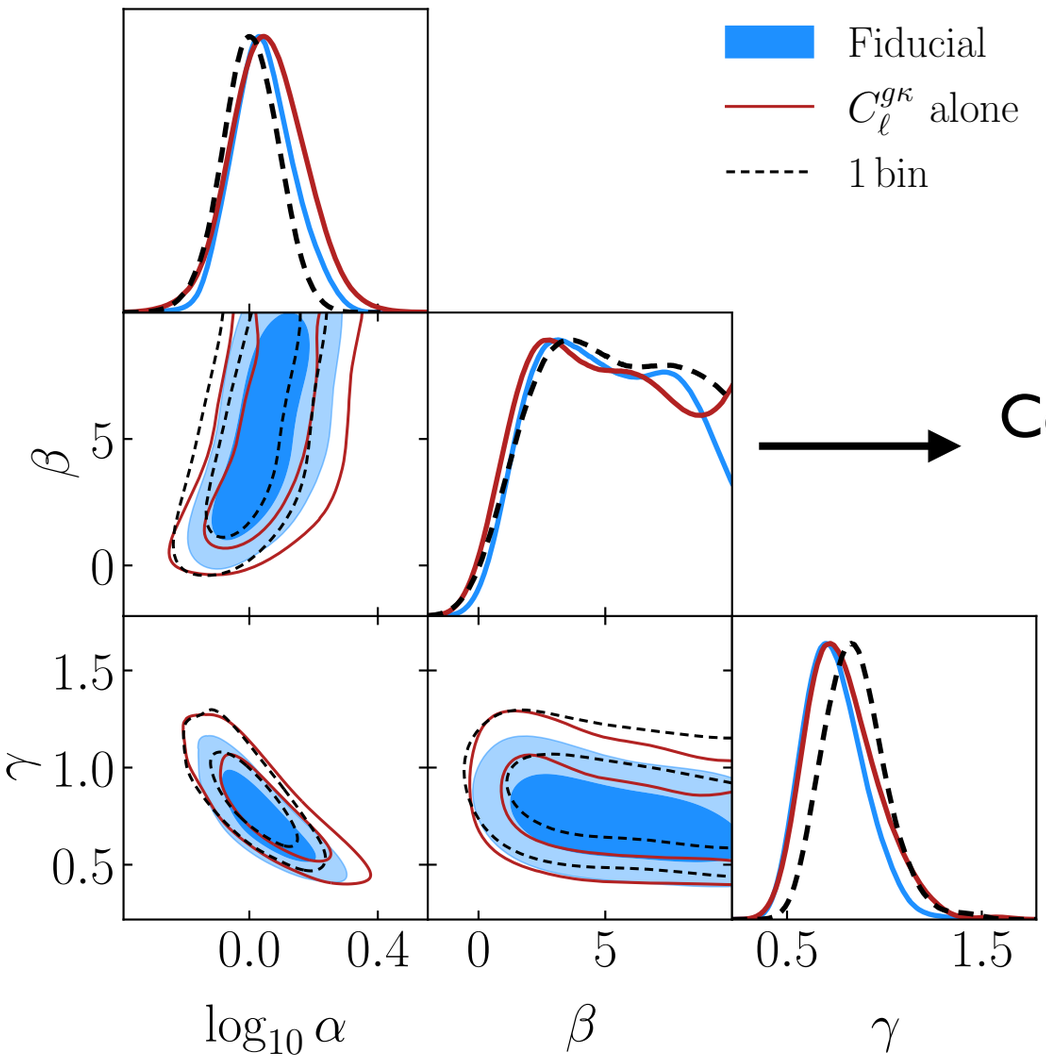


- Sensitivity comparable to spectroscopic galaxy surveys in 3D $\sigma(f_{NL}) \sim 17$ $(p_\phi = 1)$
- Limited by systematics on auto correlation on large scales but highly robust to systematics.
- With newer Gaia DR $\sigma(f_{NL}) \lesssim 9$ (more sources, different source separation, new data…)

1st k_{eq} measurement from cross-correlation

$$P_{mm}(k) = A\,P_{\rm fid}(\alpha k)\left(\frac{P^{\rm LS}_{\rm flat}(\alpha k)}{P_{\rm fid}(\alpha k)}\right)^{1-\beta}\left(\frac{P^{\rm SS}_{\rm flat}(\alpha k)}{P_{\rm fid}(\alpha k)}\right)^{1-\gamma}$$





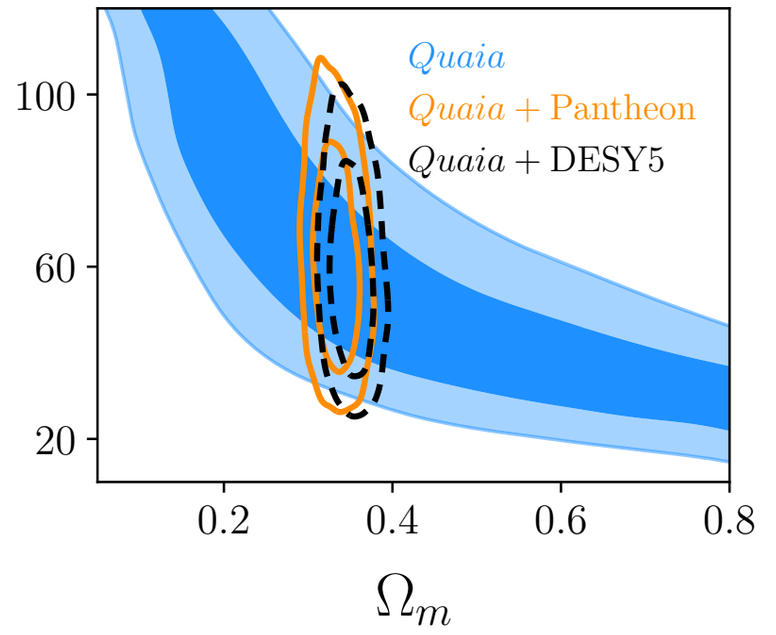
Detection of turnaround!

Cosmology from α

k_{eq} consistent with Planck within 0.5σ

See Bahr-Kalus+(2025) for 3D DESI QSO+LRGs

Sound-horizon independent



$H_0 \sim 63 \pm 16$km/s/Mpc

Alonso, Hetmansev, Fabbian+ (2025)

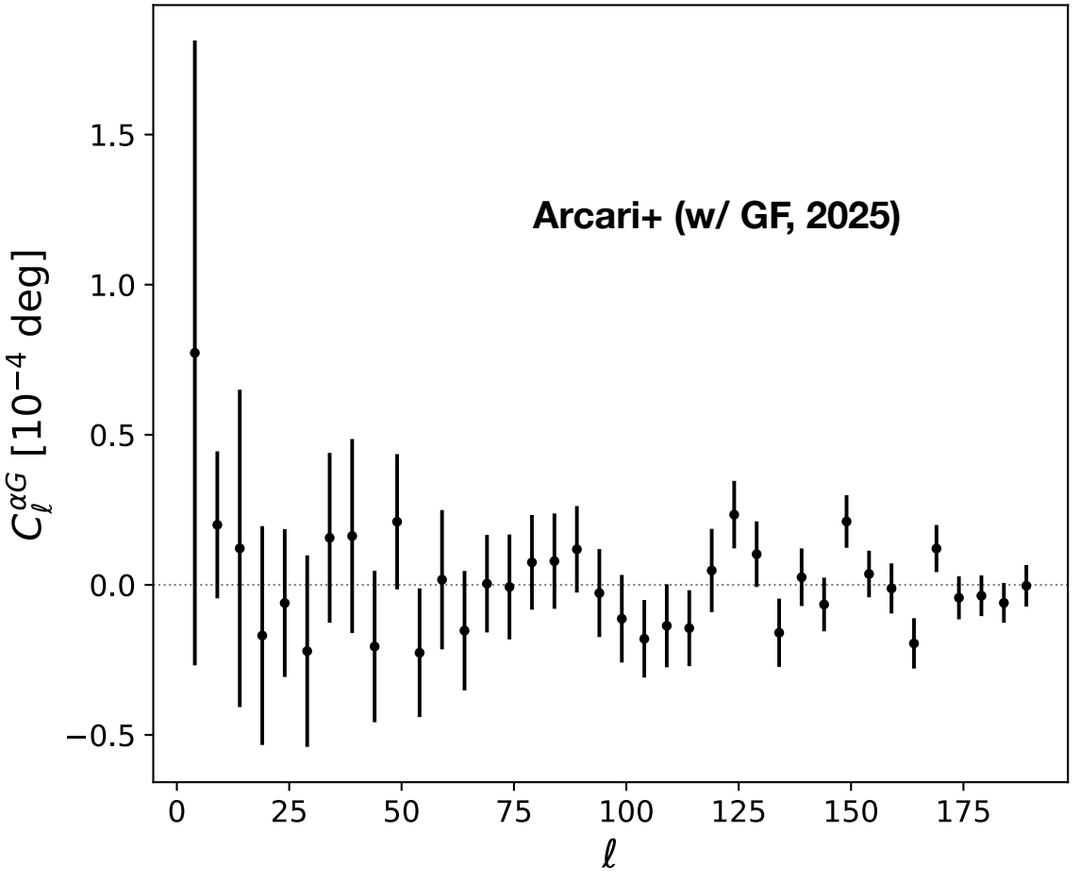
Cross-correlation with cosmic birefringence

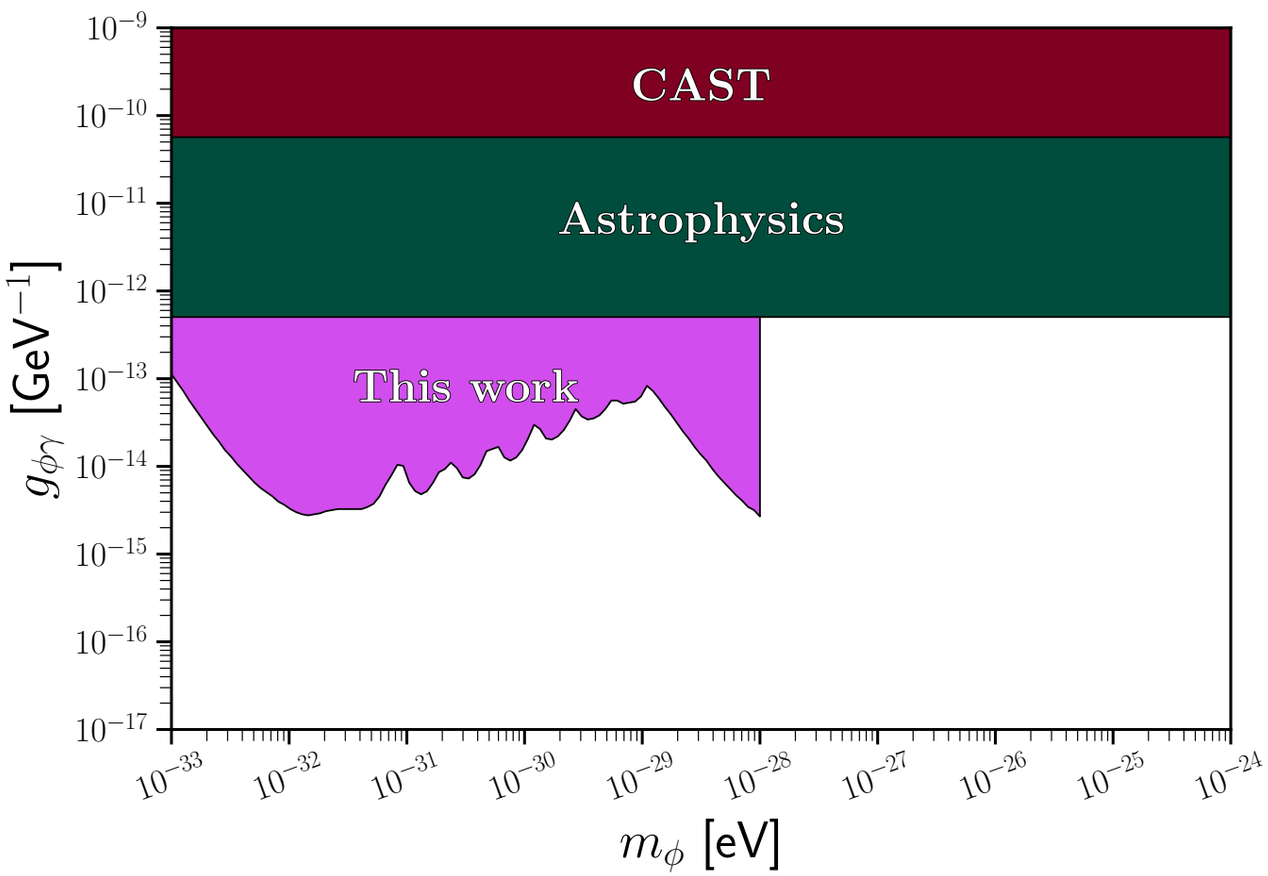
- Presence of axion like coupling can generate cosmic birefringence

$$\mathscr{L} \supset -\frac{1}{2} g^{\mu\nu} \partial_\mu \phi \, \partial_\nu \phi - V(\phi) - \frac{1}{4} g_{\phi\gamma} \, \phi \, F_{\mu\nu} \tilde{F}^{\mu\nu} \quad \longrightarrow \quad Q \pm iU \to e^{\mp 2i\alpha(\hat{\mathbf{n}})} (Q \pm iU)$$

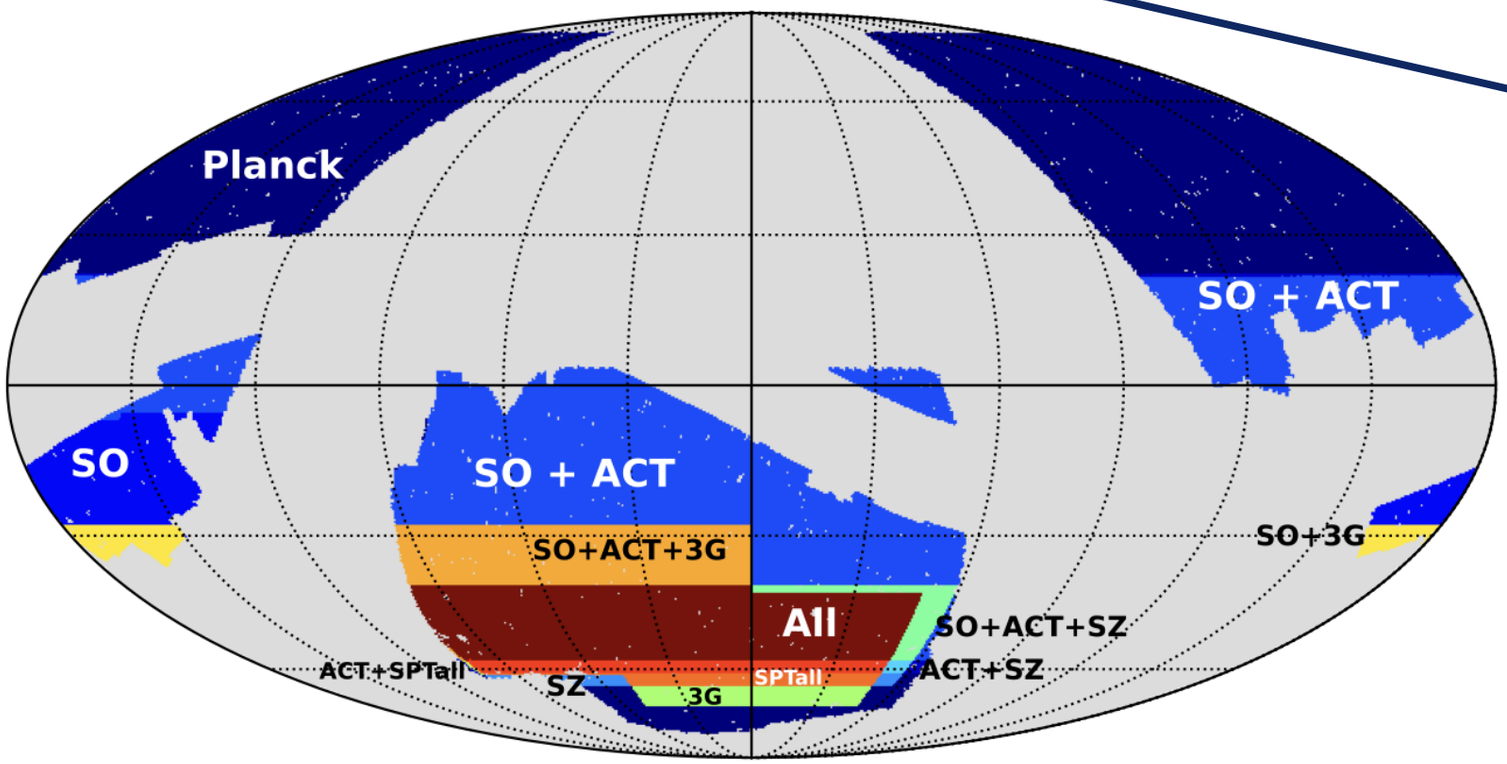
- $\alpha(\hat{\mathbf{n}})$ can be reconstructed with quadratic estimators and correlated with matter tracers.

$$\delta\phi'' + 2\mathscr{H}\,\delta\phi' + \left(k^2 + a^2 \frac{d^2V}{d\bar{\phi}^2}\right)\delta\phi = -\frac{1}{2} h' \bar{\phi}' \qquad \Delta^{\alpha}_{\ell}(k) = g_{\phi\gamma} \int_0^{\tau_0} \mathrm{d}\tau \; g(\tau) T_{\delta\phi}(\tau, k) j_\ell \left[k(\tau_0 - \tau)\right]$$





Towards Euclid DR3



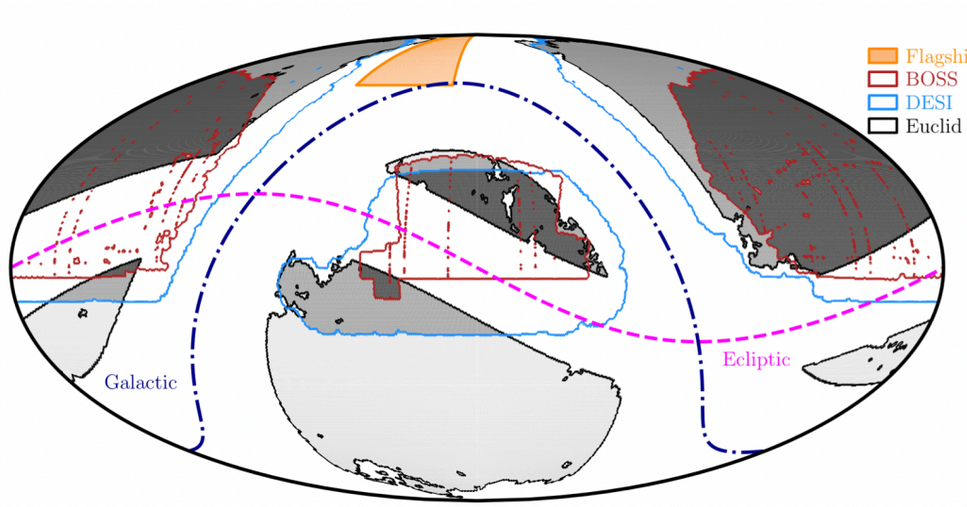
expected in Oct 2031
covering 15 k deg^2

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

Courtesy M. Lembo

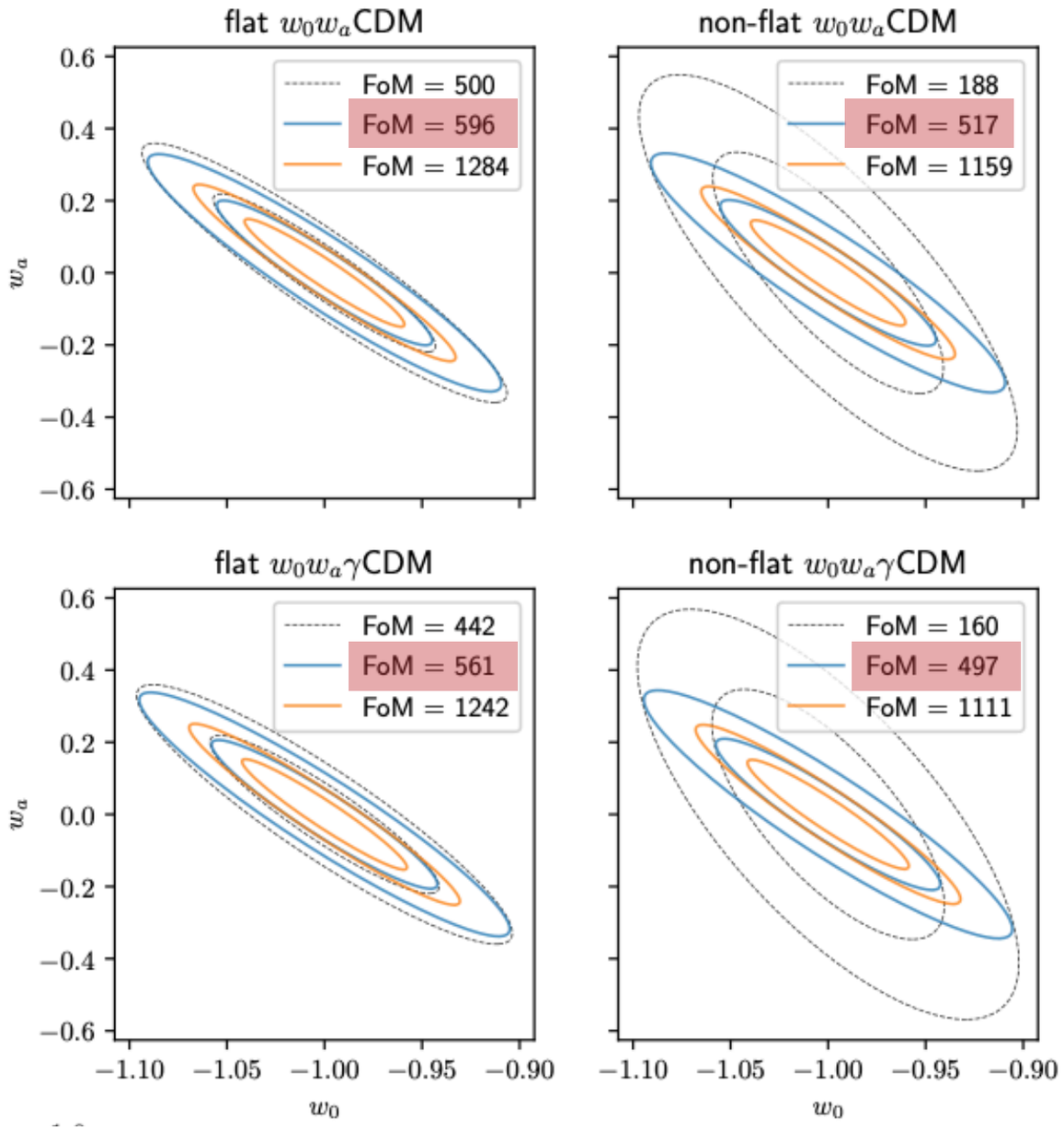


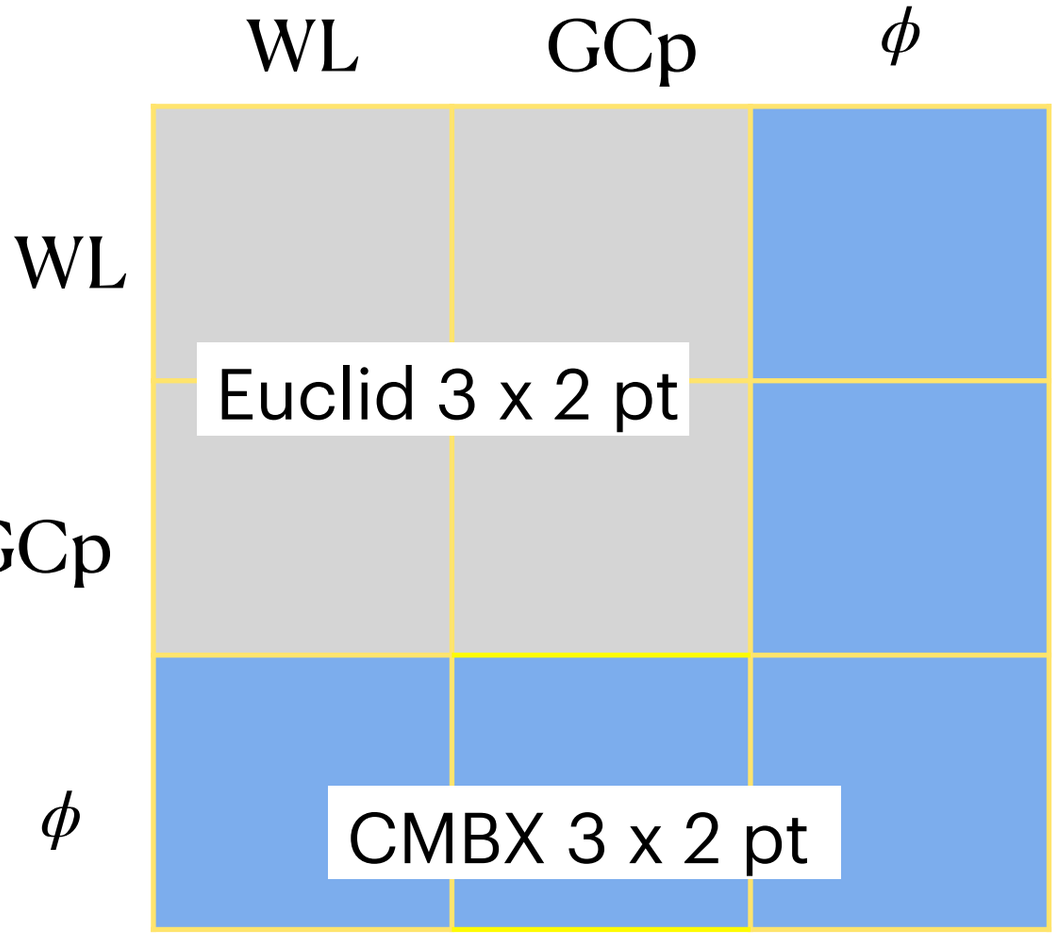
Naidoo et al, 2023 (Euclid collab paper)

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!



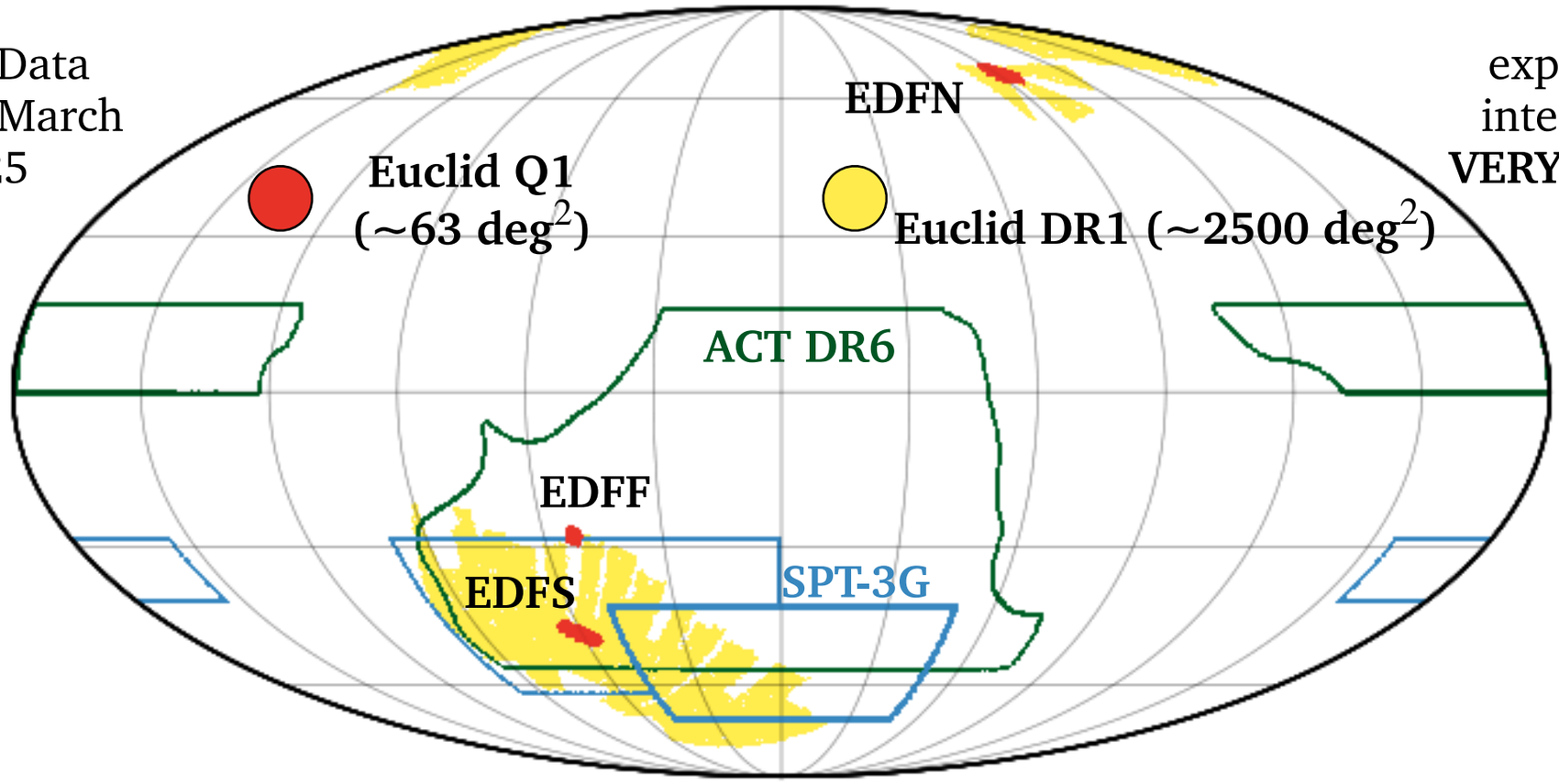


Euclid collab. (Blanchard+19)

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

Towards DR1: the Q1 data release

Quick Data Release March 2025



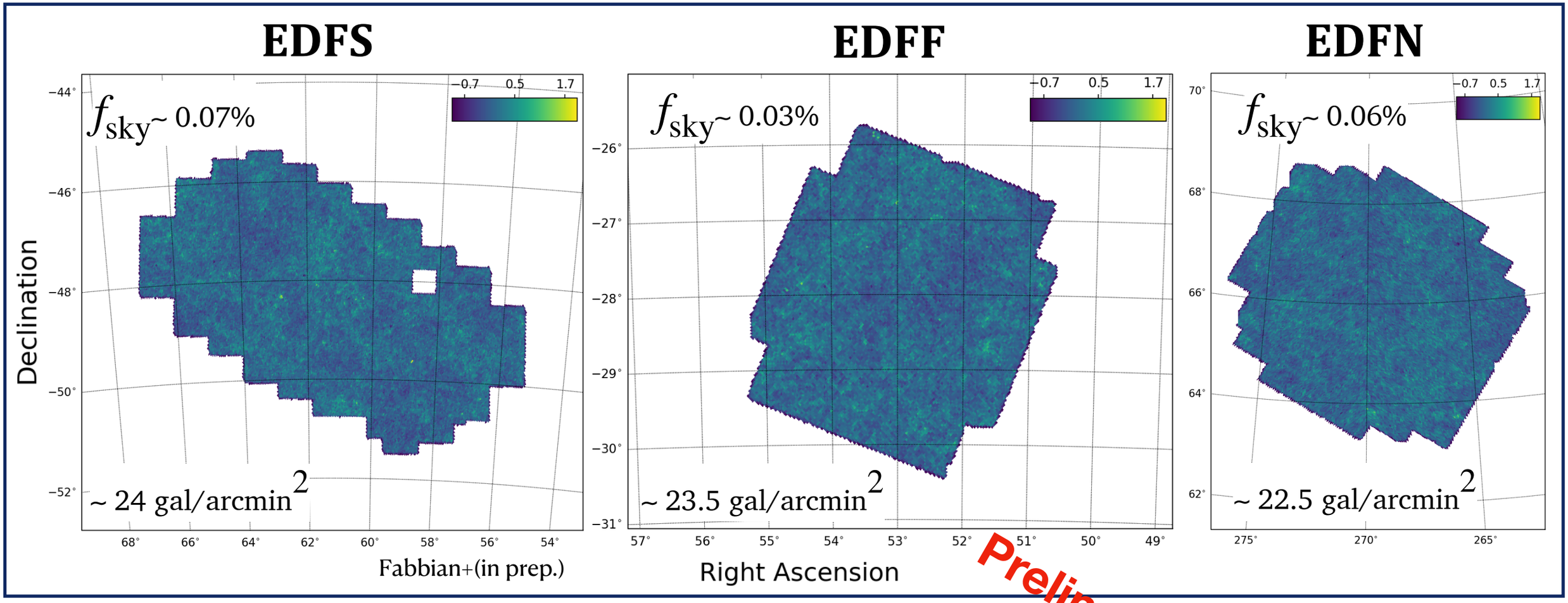
expected internally **VERY SOON**

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

Fabbian, Legrand, Pagano, Lembo, Piccirilli, Kou, Hartley, Tessore+(in prep.)

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

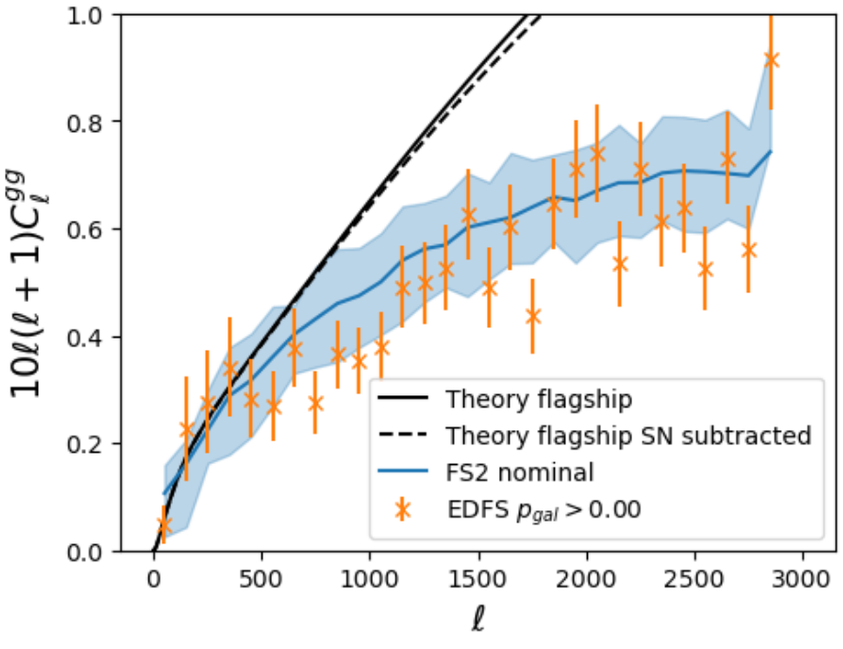
Towards DR1: the Q1 data release



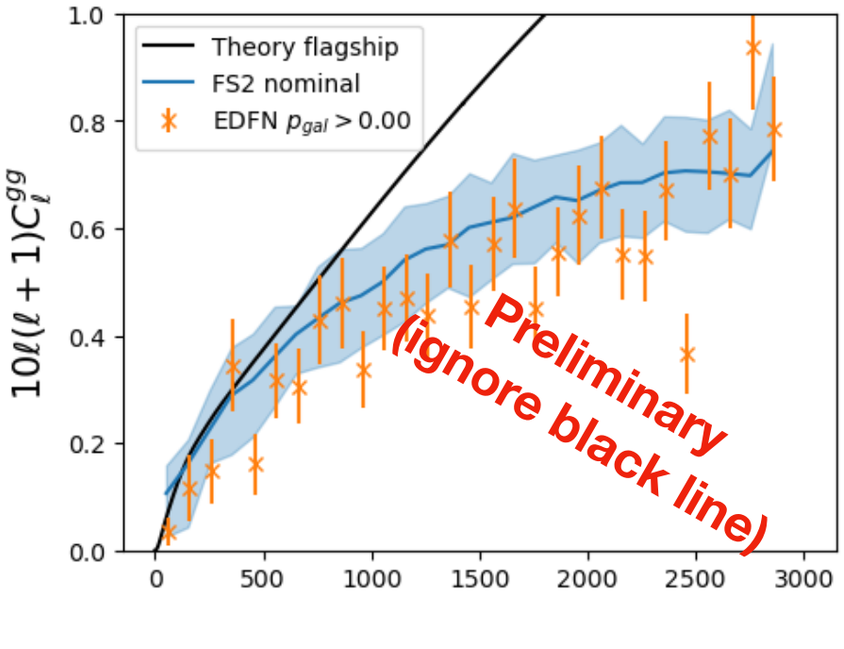
- Magnitude cut in VIS<24.5
- Properties consistent across fields
- Agreement with Flagship simulation predictions "uncalibrated"!!!!!

Towards DR1: the Q1 data release

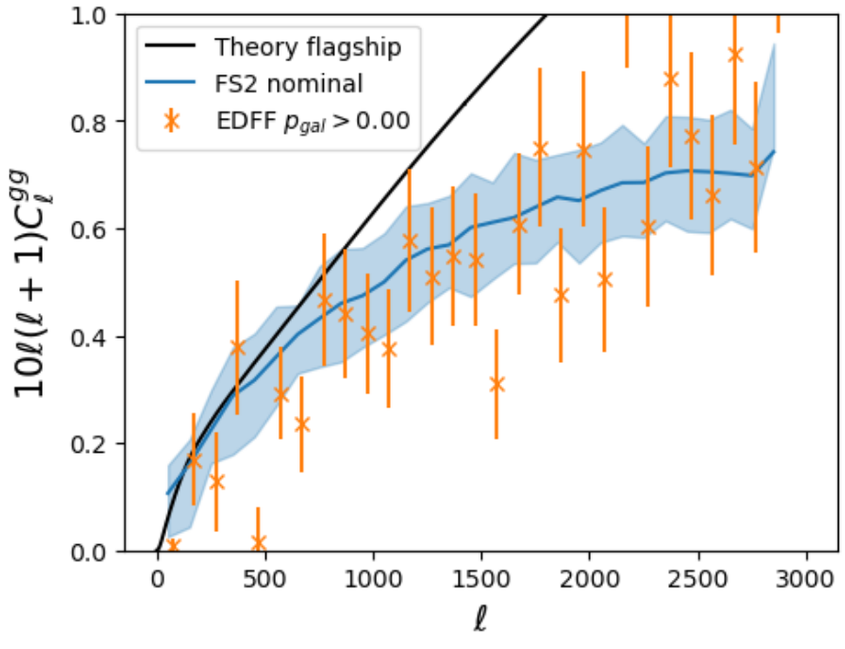
EDFS



EDFN



EDFF



Fabbian+(in prep.)

Preliminary

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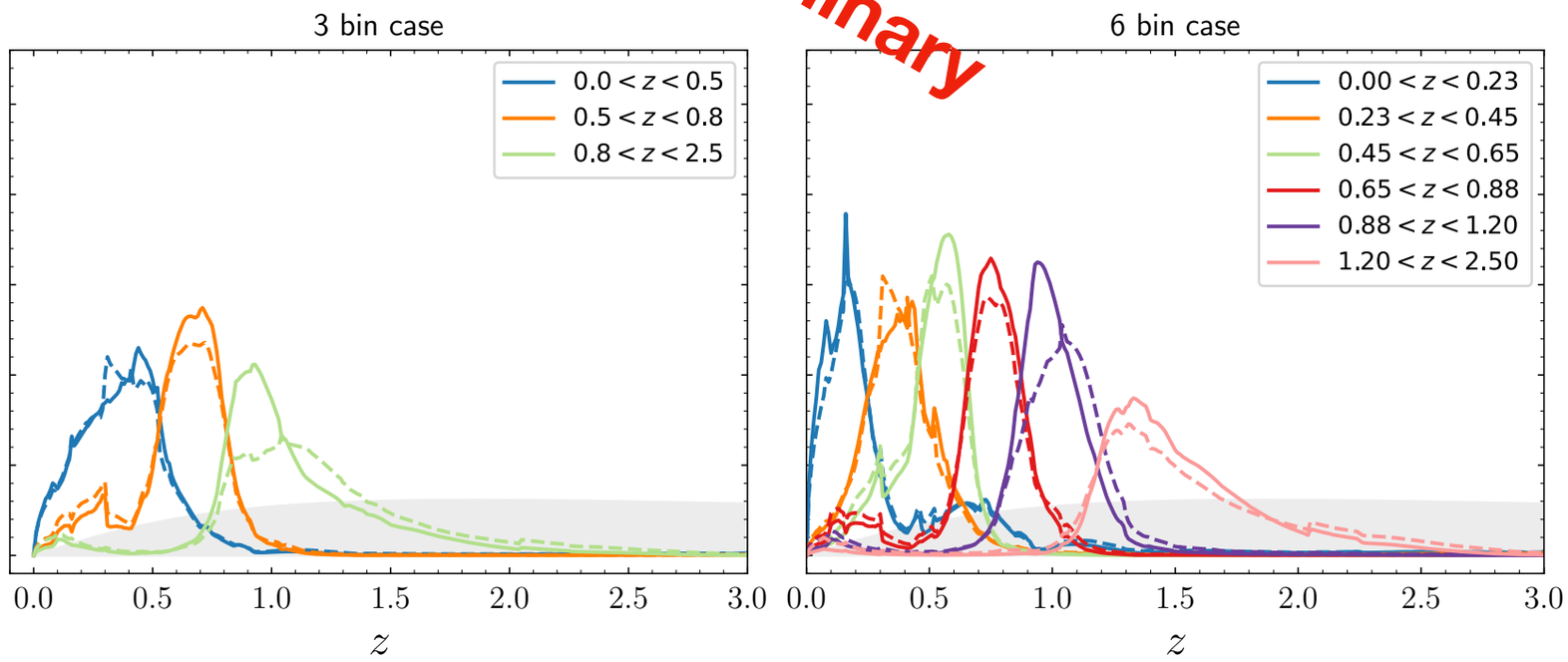
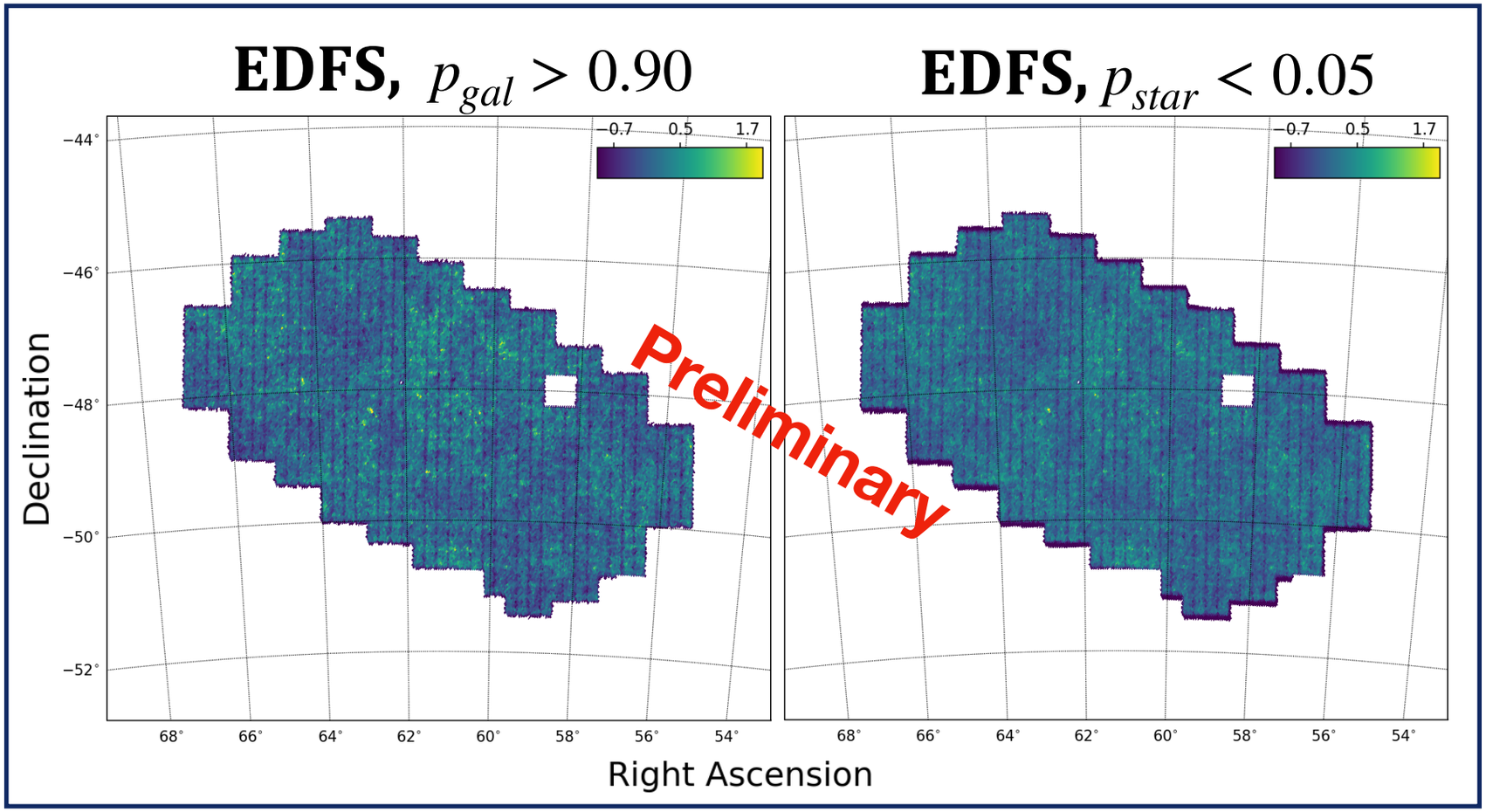


Towards DR1: the Q1 data release



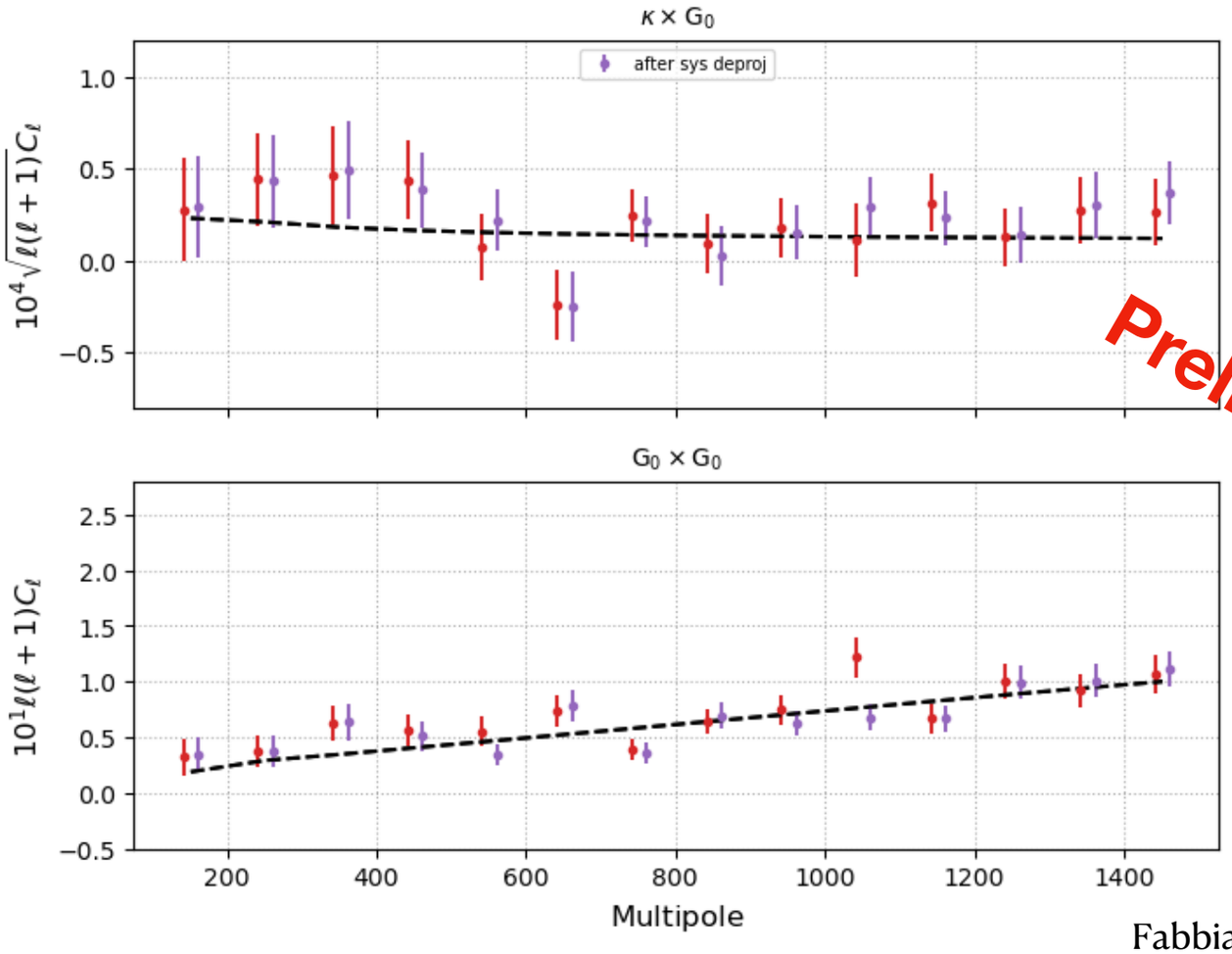
- Two different sample selection based on purity of galaxy classification or star classification rejection respectively.

- The two cuts deliver samples with: ~11 gal/arcmin, ~ 21 gal/arcmin, with different redshift limits (z_{max}~1.2, z_{max}~2.5)

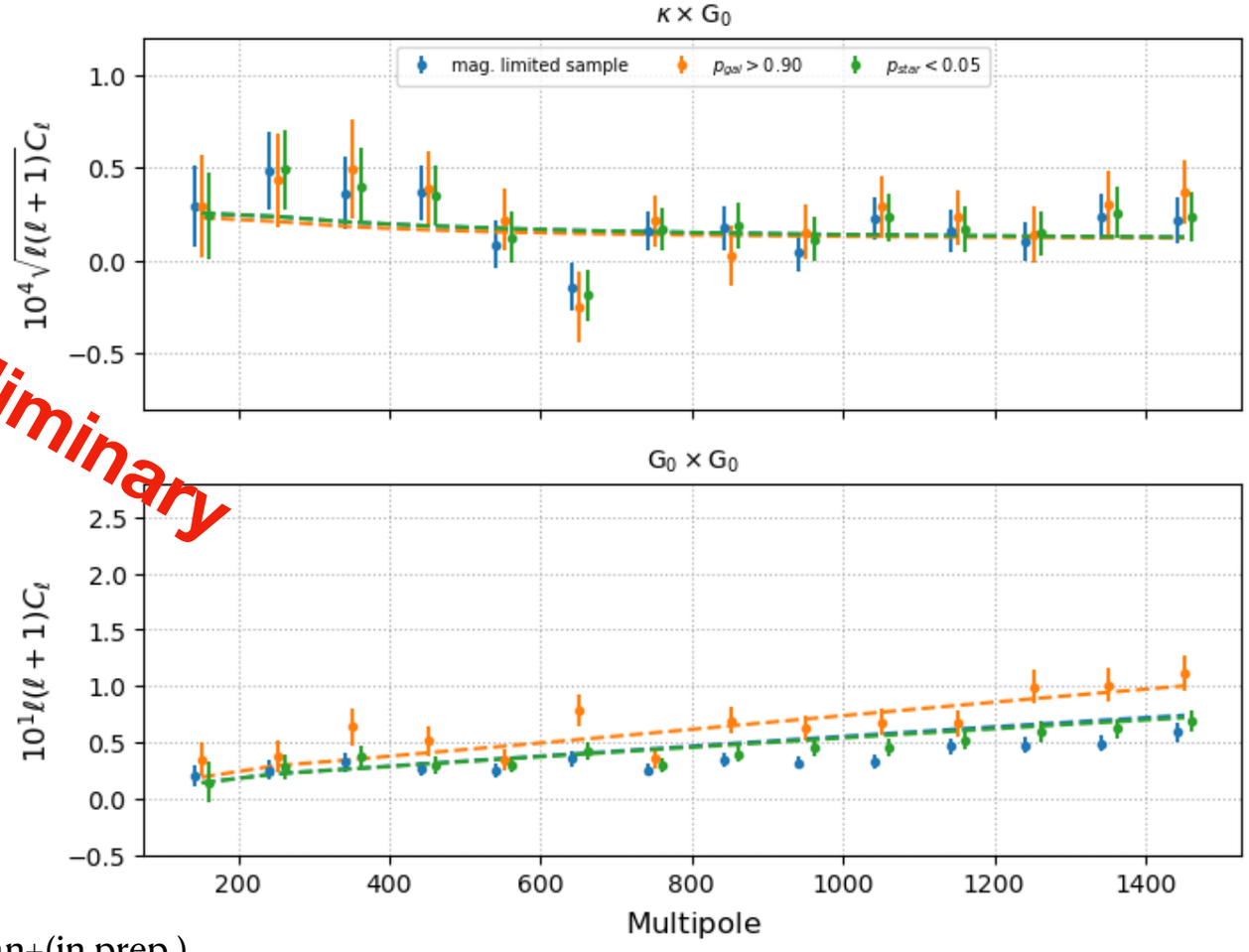
- Systematics deprojection needed due to lack of deep external data and no full visibility processing (minimal effects)

Preliminary results: single bin

w vs /wo systematics deproj



Different sample selections



Preliminary

Fabbian+(in prep.)

- WARNING: theory lines are not fits!
  - Planck 2018 + estimated N(z) + fiducial Flagship calibrated galaxy bias model.
  - **TLDR**: great $\tilde{\chi}^2$ (w/ RSD, magnification bias matching expectations)
- Cross-correlation extremely stable and robust to any systematics deprojection!

Some preliminary findings

			$p_{gal}>0.90$		$p_{star}<0.05$	
Field	**Spectra**	z **bins**	**PTE**	**S/N**	**PTE**	**S/N**
South	κg	1	0.281	4.5	0.159	4.9
	gg		0.028	13	0.321	13
	$\kappa g + gg$		0.1	13	0.228	13
	κg	3	0.937	5.4	0.726	6.3
	gg		0.702	23	0.008	24
	$\kappa g + gg$		0.947	24	0.011	24
	κg	6	0.815	7.4	0.406	8.2
	gg		0.092	27	0.0	33
	$\kappa g + gg$		0.130	28	0.0	33
Fornax	κg	1	0.639	2.4	0.303	2.7
	gg		0.423	8.1	0.177	7.6
	$\kappa g + gg$		0.619	8.3	0.135	8.0
	κg	3	0.973	3.6	0.949	3.6
	gg		0.641	15	0.336	15
	$\kappa g + gg$		0.936	15	0.676	15
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North	κg	1	0.103	2.7	0.166	3.5
	gg		0.098	12	0.275	12
	$\kappa g + gg$		0.036	11	0.237	11
	κg	3	0.197	4.7	0.322	5.3
	gg		0.002	20	0.0	22
	$\kappa g + gg$		0.1	20	0.0	21
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	gg		0.0	23	0.0	30
	$\kappa g + gg$		0.0	25	0.0	28

- CMB lensing cross-correlation is ready for fine bin tomography.
  - Well modeled across different fields and fine redshift binning
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Conclusions

- **Exciting prospects from new CMB X space-based galaxy surveys data…**
- **Quaia: a powerful public legacy QSO data set**
  - Quaia x CMB lensing : robust and competitive results $\sigma_8,\ \Omega_m,\ S_8, f_{\rm NL}^{loc}, H_0, k_{eq}, m_\gamma, g_{\gamma\phi}$
  - More to come (matter dipole, CIB, tSZ/kSZ, DESI combination, new Gaia DR)
- **Euclid is working beautifully!**
  - Promising benchmark from Q1 data ….
  - but not without challenges: **A TON OF SALT** needed
- **Results coming soon, stay tuned!**