Weak gravitational lensing

The Stage III to Stage IV transition

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New physics from galaxy clustering, GGI

October 3, 2025

LSST DESC Dark Energy Science Collaboration · KiDS · Universiteit Leiden The Netherlands · Utrecht University · NWO

Gravitational lensing cosmology

Gravitational lensing → Weak / Strong → Accelerated expansion: *a(t)* / Dark matter nature

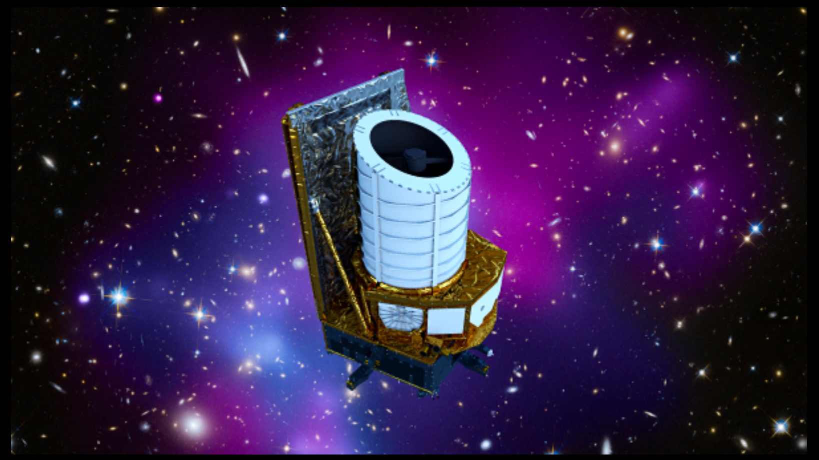
Past ——————————— Future →

KiDS

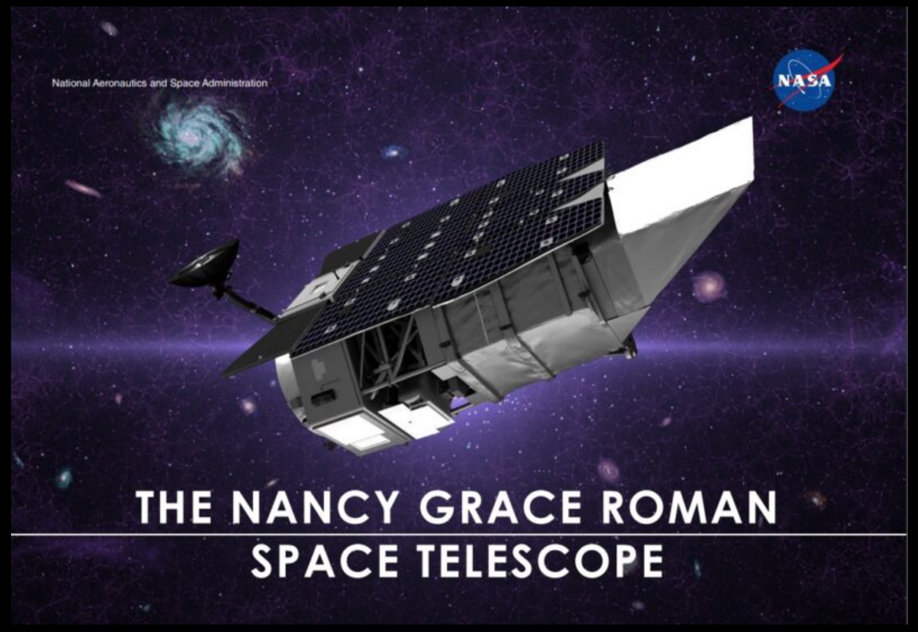
DARK ENERGY SURVEY

HSC

Rubin Observatory

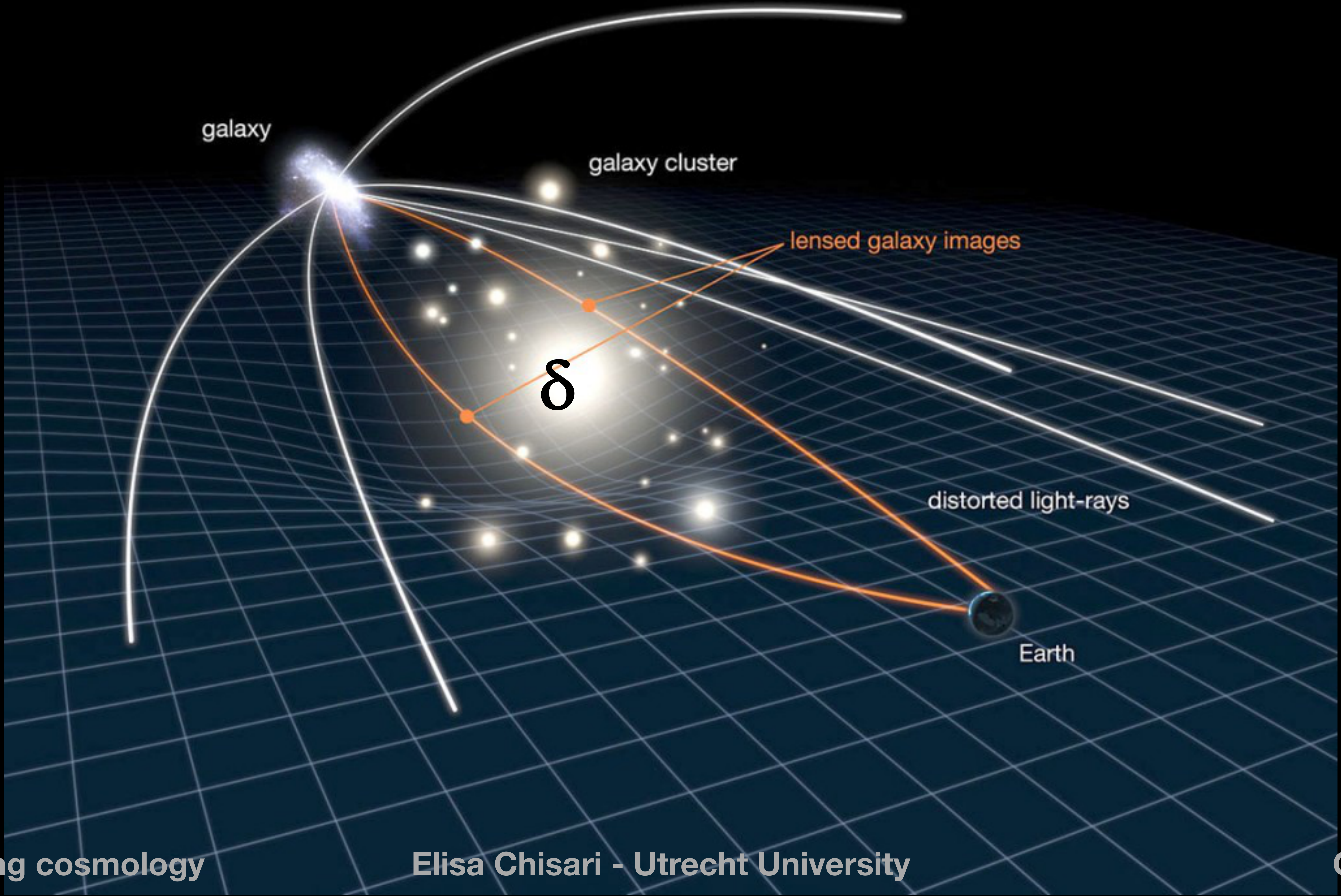


ESA's Euclid



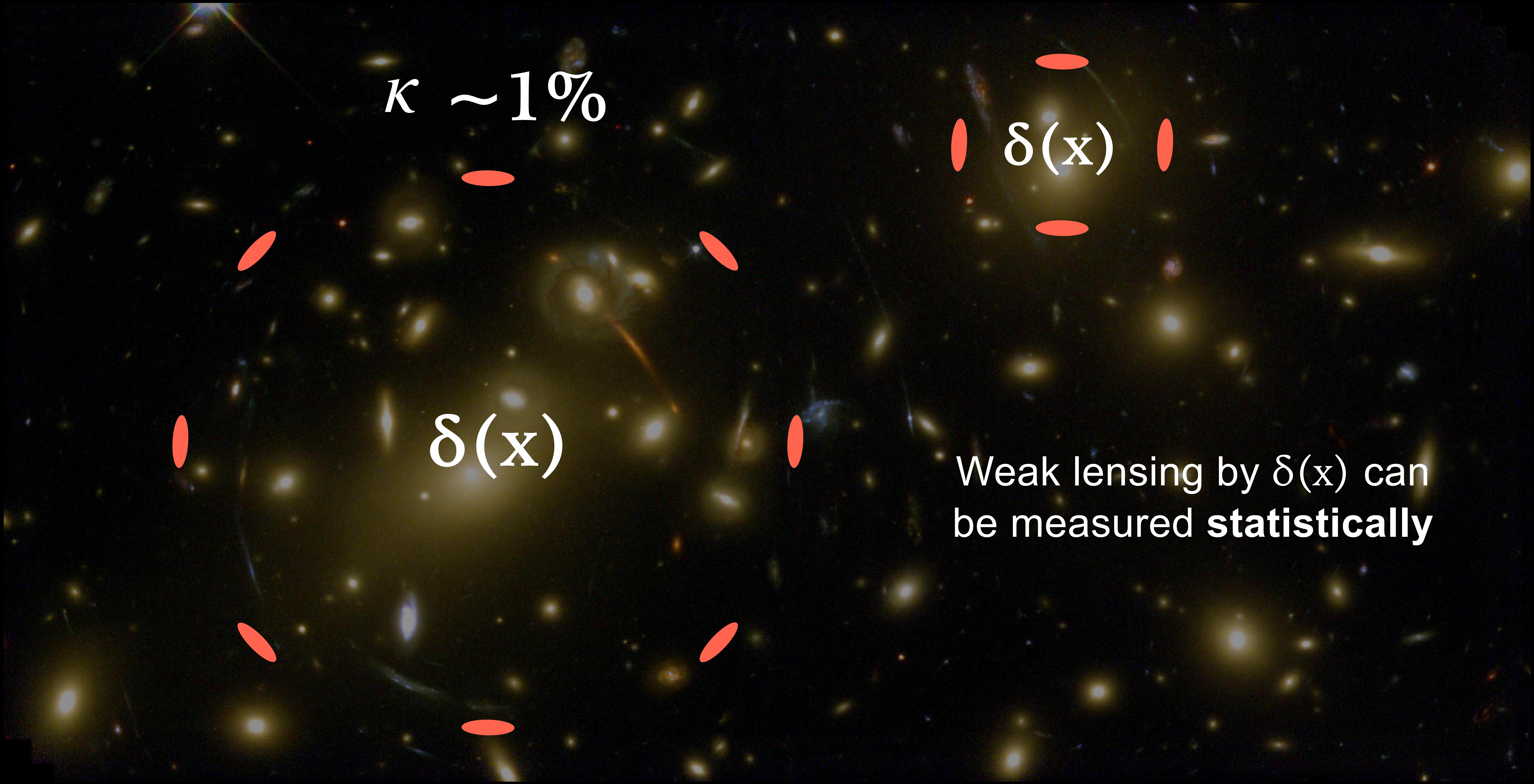
Gravitational lensing

Image: NASA/ESA

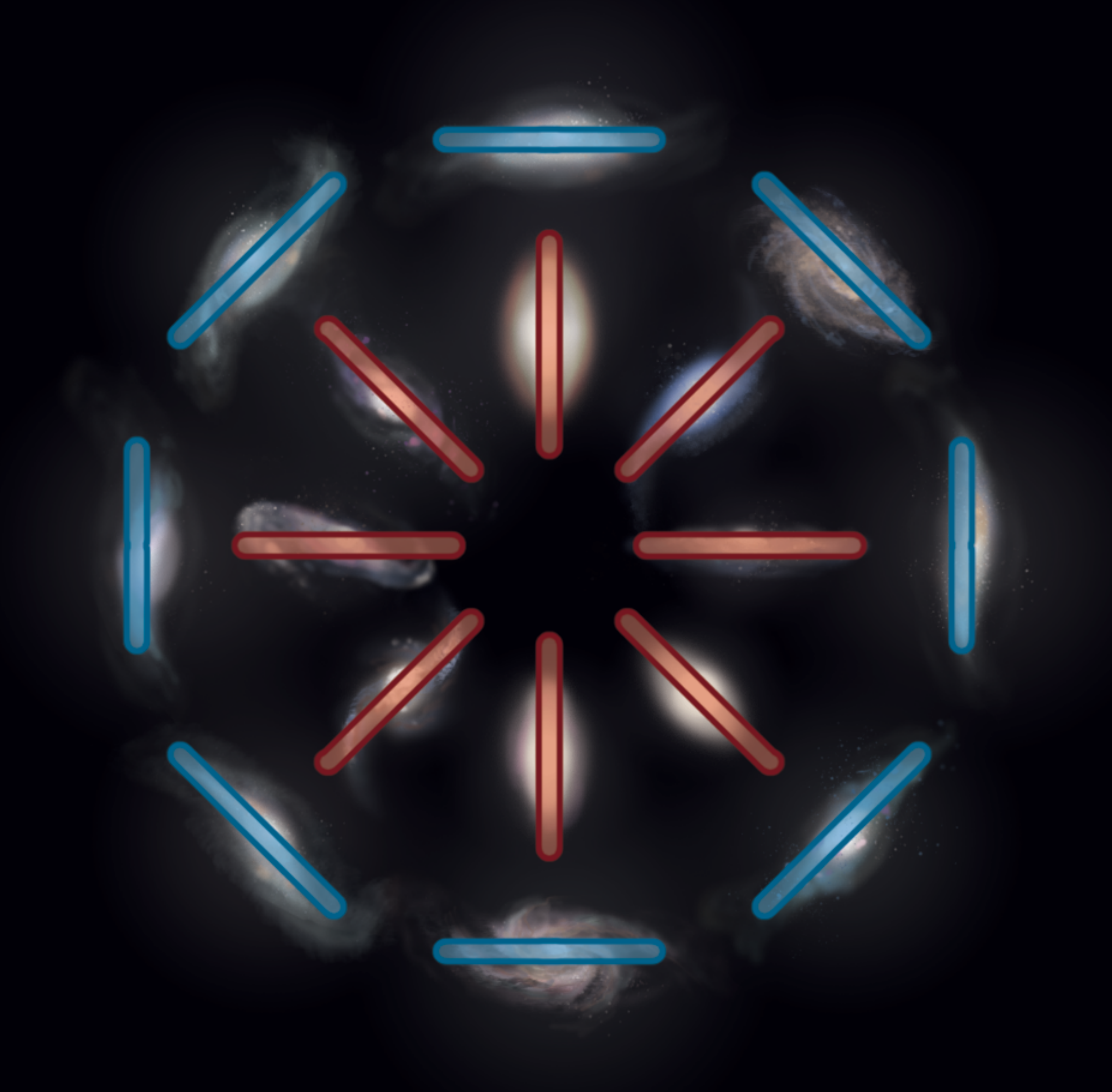


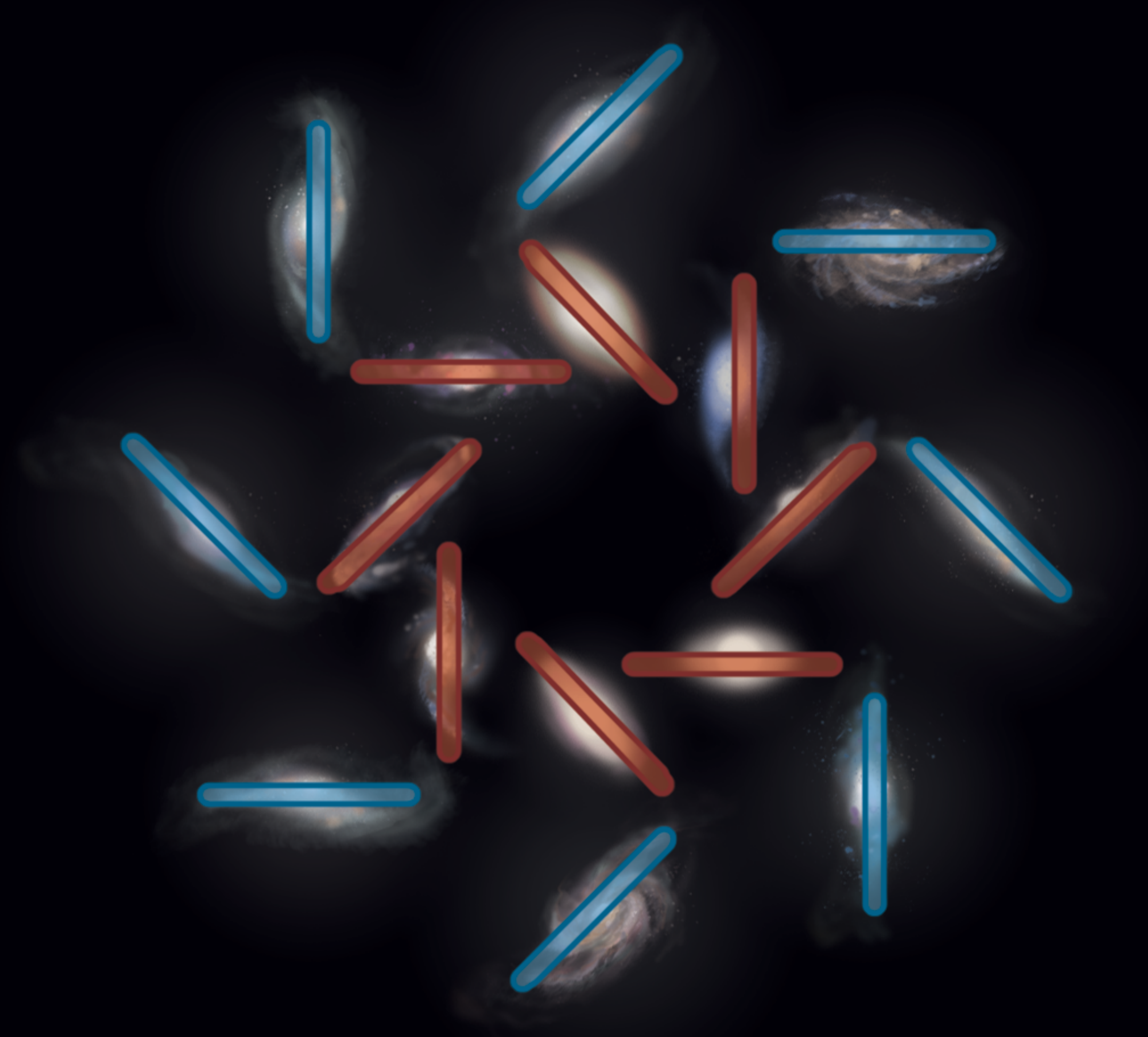
Weak lensing

Image: Abell 2218, NASA/ESA



Weak lensing





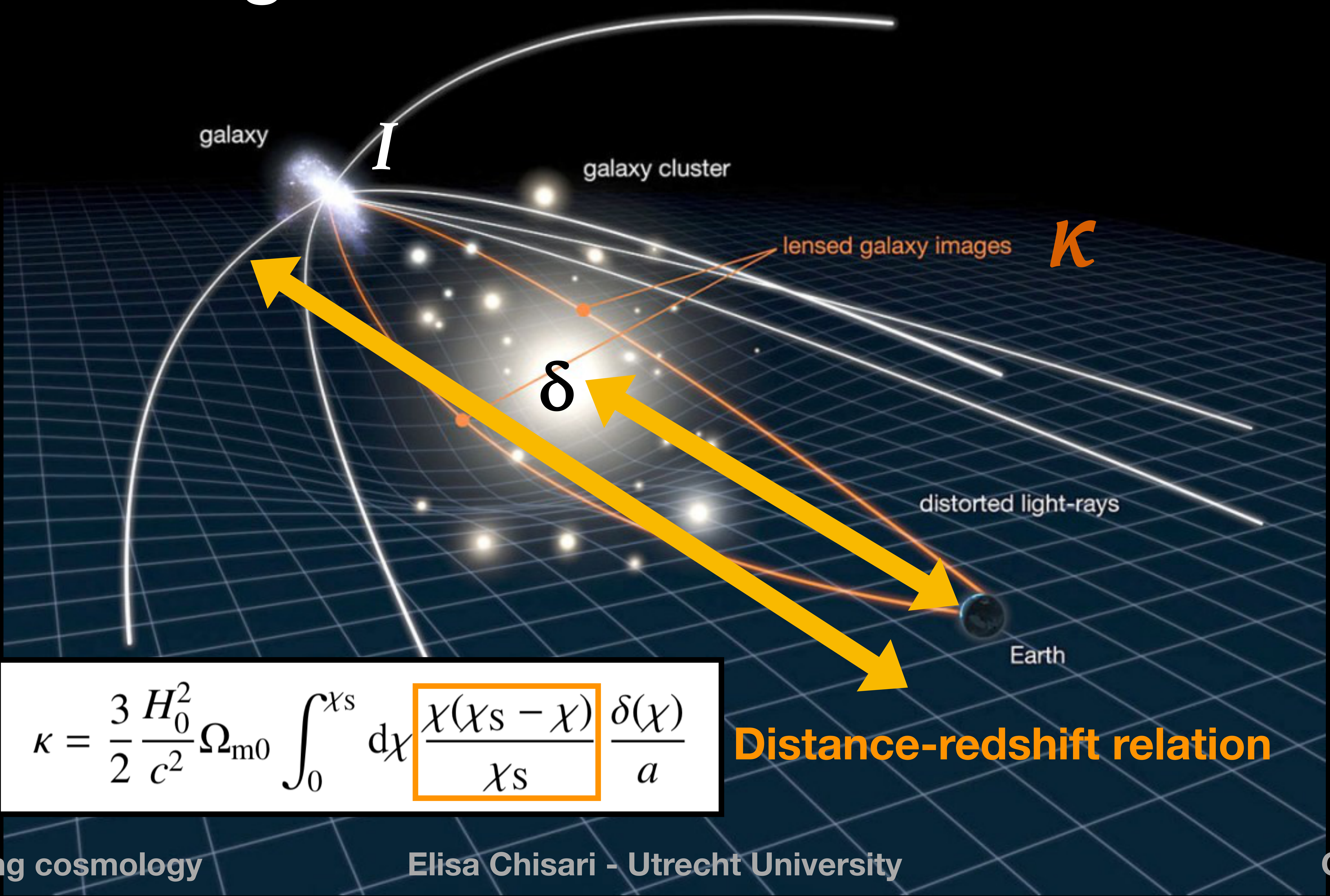
E-modes (cosmology)

B-modes (systematics)

Fortuna & EC (2022)

Weak lensing

Image: NASA/ESA

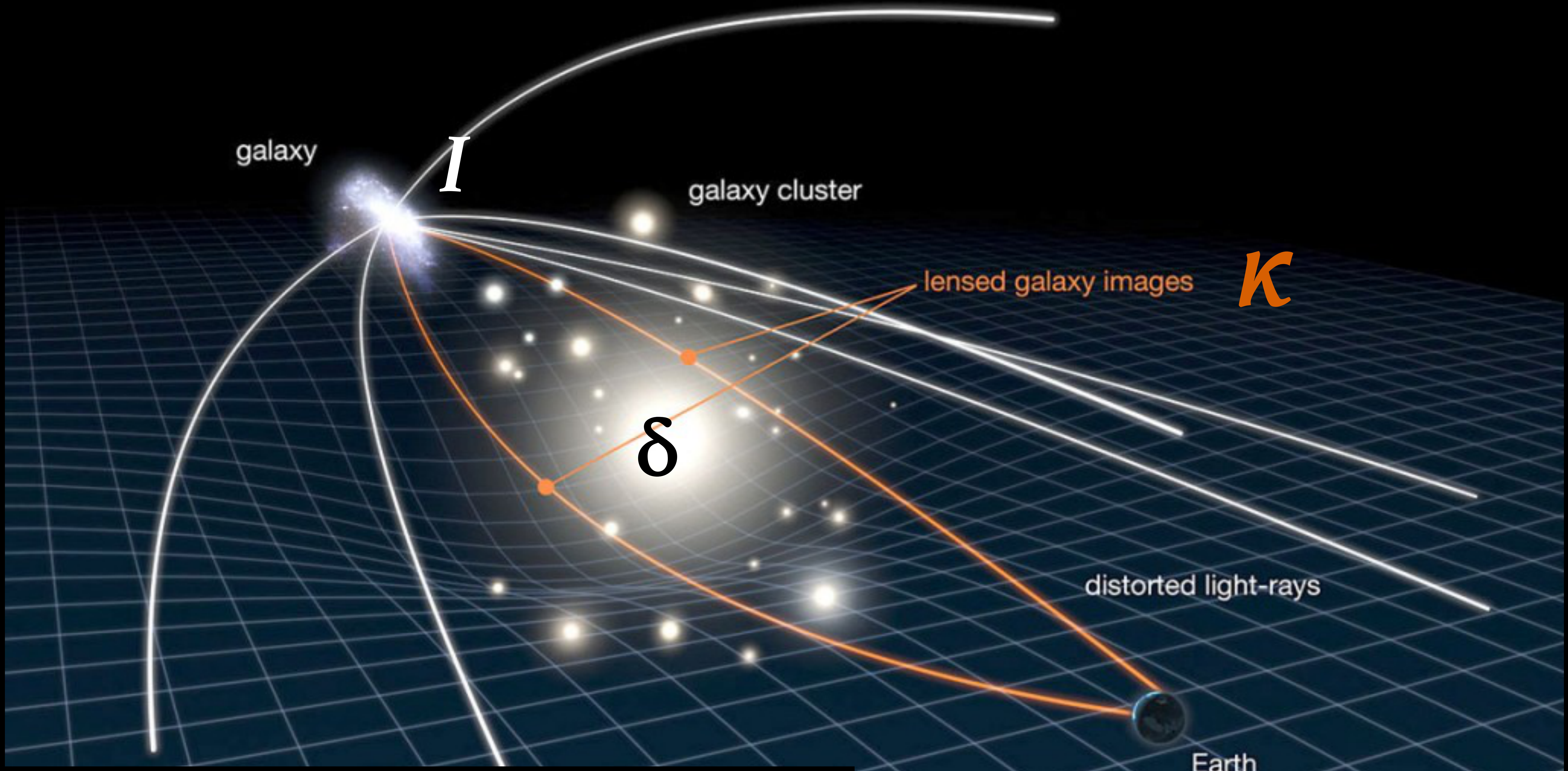


$$\kappa = \frac{3}{2}\frac{H_0^2}{c^2}\Omega_{\rm m0}\int_0^{\chi_{\rm s}} {\rm d}\chi \, \frac{\chi(\chi_{\rm s}-\chi)}{\chi_{\rm s}}\, \frac{\delta(\chi)}{a}$$

Distance-redshift relation

Weak lensing

Image: NASA/ESA

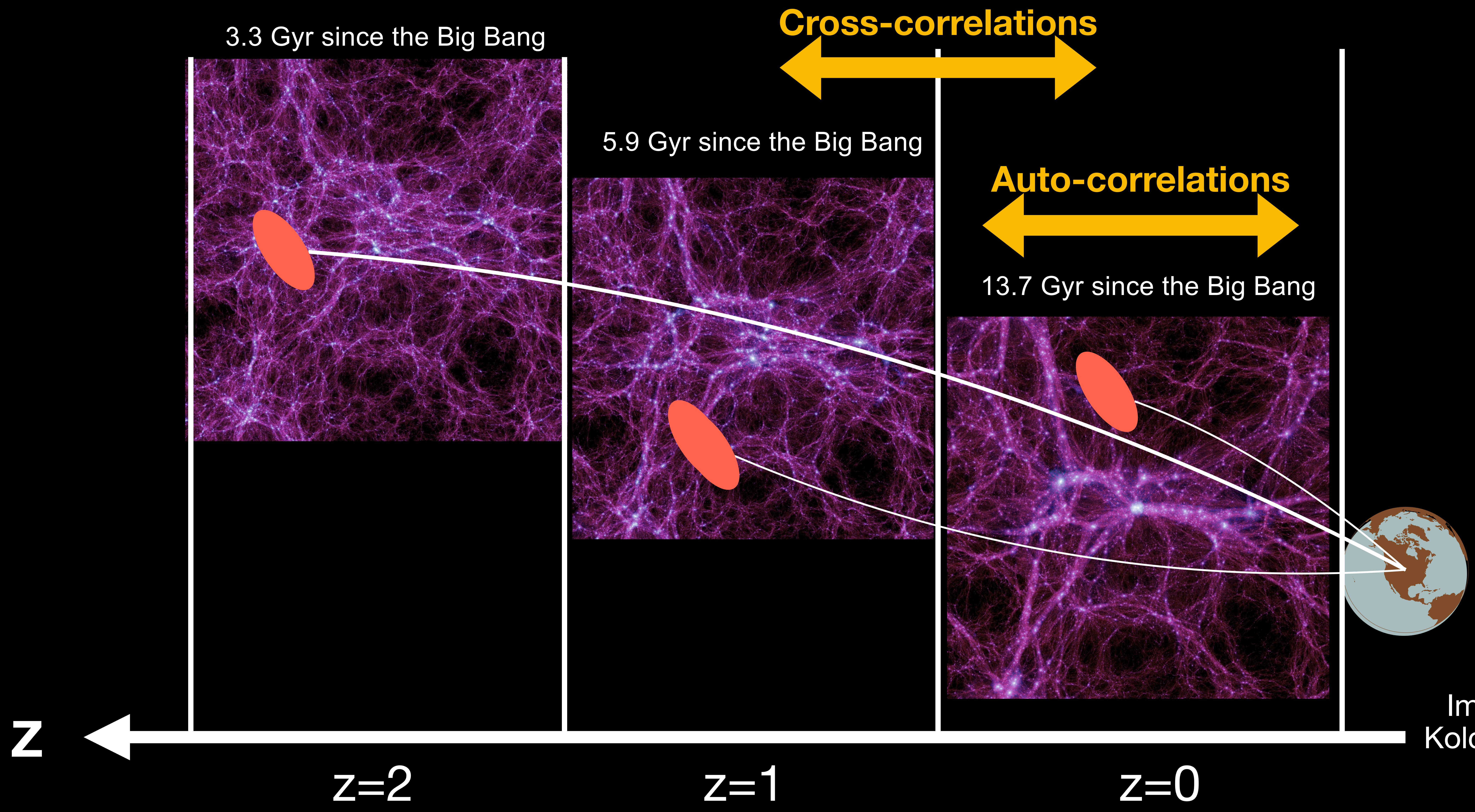


$$\kappa = \frac{3}{2}\frac{H_0^2}{c^2}\Omega_{\mathrm{m0}}\int_0^{\chi_{\mathrm{s}}} \mathrm{d}\chi\, \frac{\chi(\chi_{\mathrm{s}}-\chi)}{\chi_{\mathrm{s}}} \boxed{\frac{\delta(\chi)}{a}}$$

Growth history

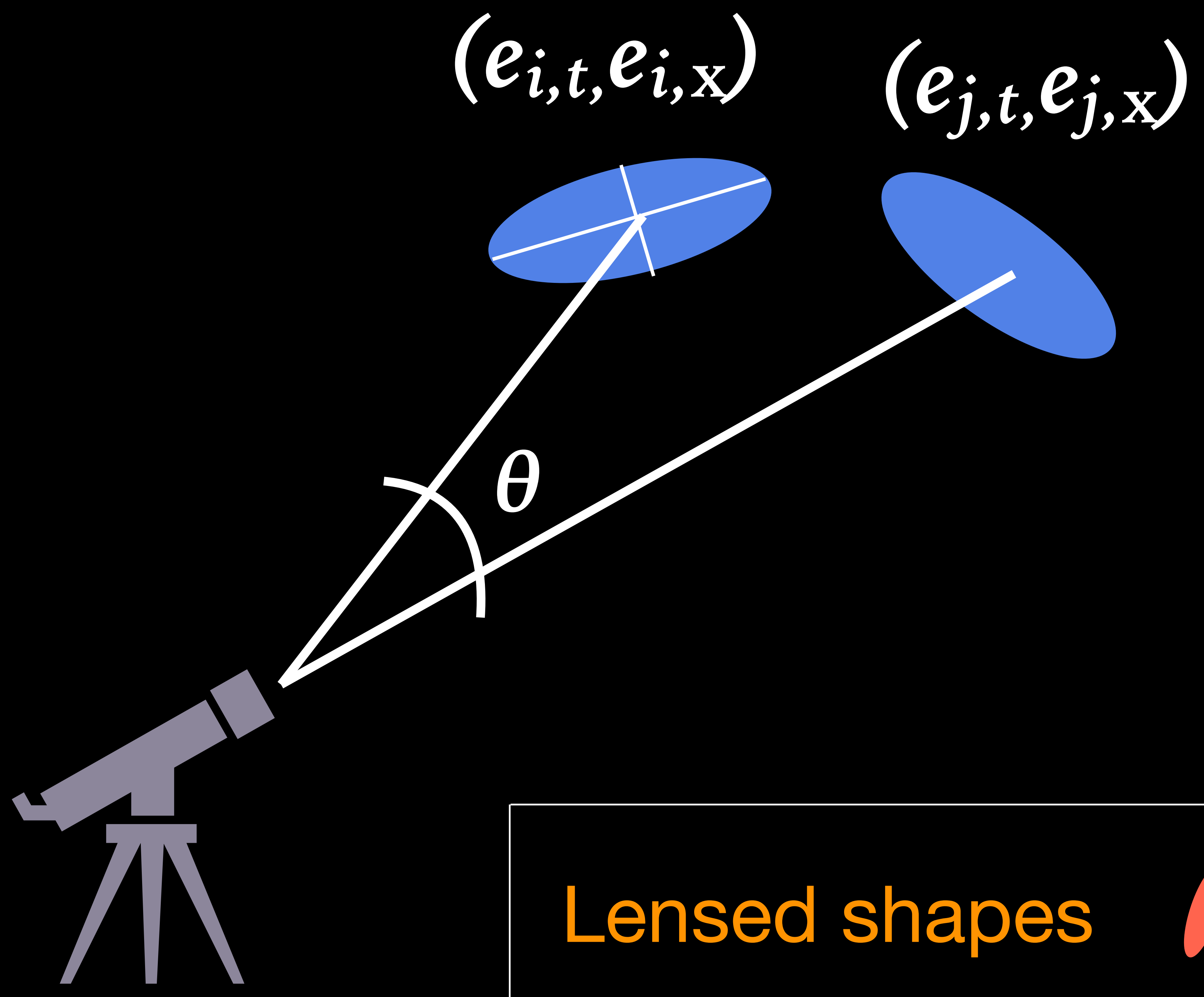
Matter distribution

Observables: “cosmic shear”



Images: M. Boylan-Kolchin et al. (2009) - Millennium-II

Observables: up to “3x2pt”



Auto- and cross- correlations between galaxy shapes and galaxy positions: same underlying matter field

	Lensed shapes	Galaxy positions
Lensed shapes	**“Cosmic shear”**	“Galaxy-galaxy lensing”
Galaxy positions	-	“Galaxy clustering”

Probing wCDM cosmology and beyond

Accelerated expansion: *a(t)*

Distance-redshift relation: $\rho = w(z)\,P$, **equation of state of dark energy**

w(z) maps to different physical behaviours

e.g. Caldwell & Linder (2005)

+ Growth history: modifications of gravity

parametrised (e.g. μ, Σ)

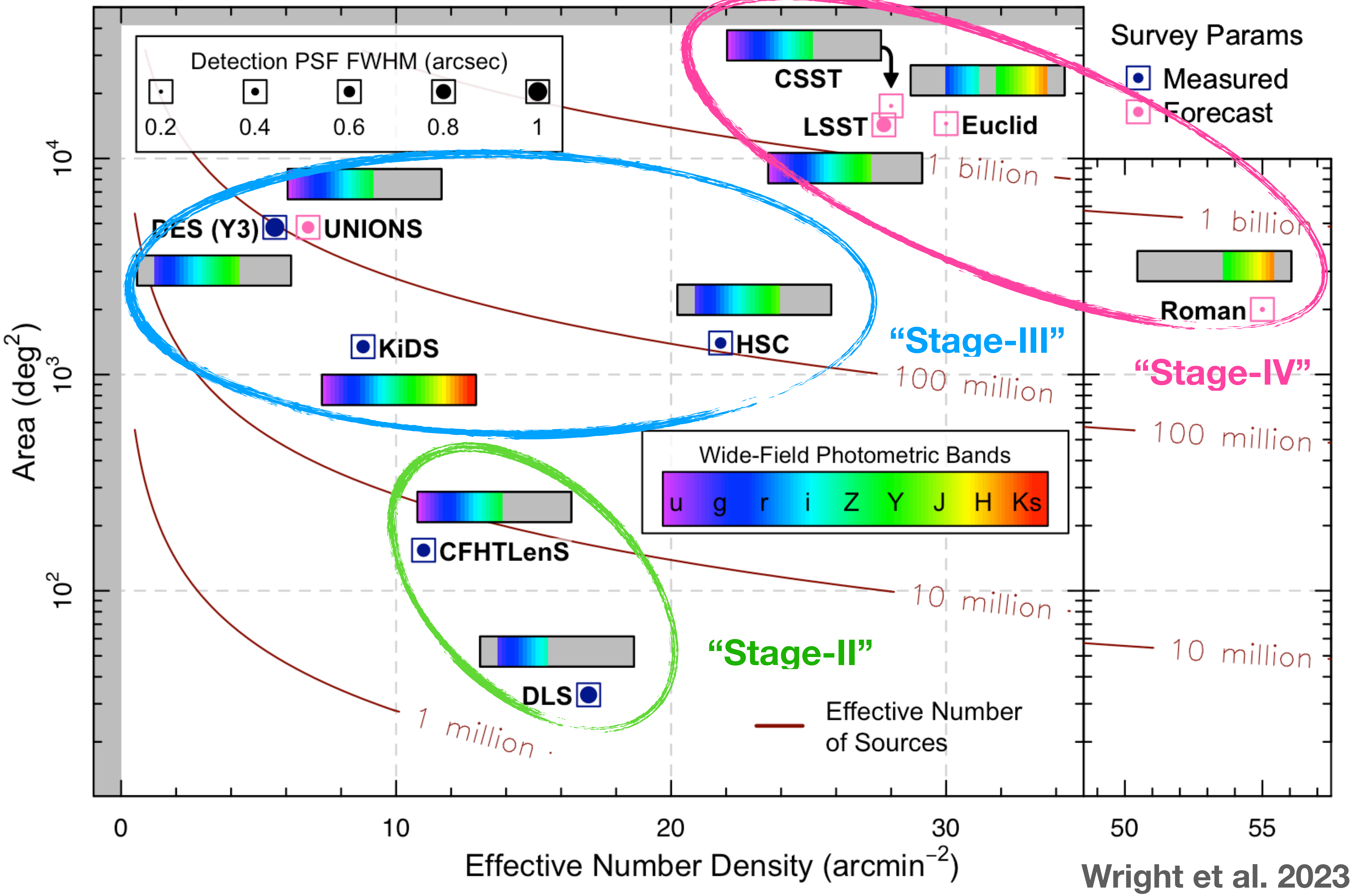
or specific (e.g. Horndeski, bigravity, non-local gravity)

Ishak et al., LSST DESC (2019)

Current constraints focus on $S_8 \equiv \sigma_8\sqrt{\Omega_\mathrm{m}/0.3}$ (assess *tension* with Planck)

Jain & Seljak (1997)

Surveys



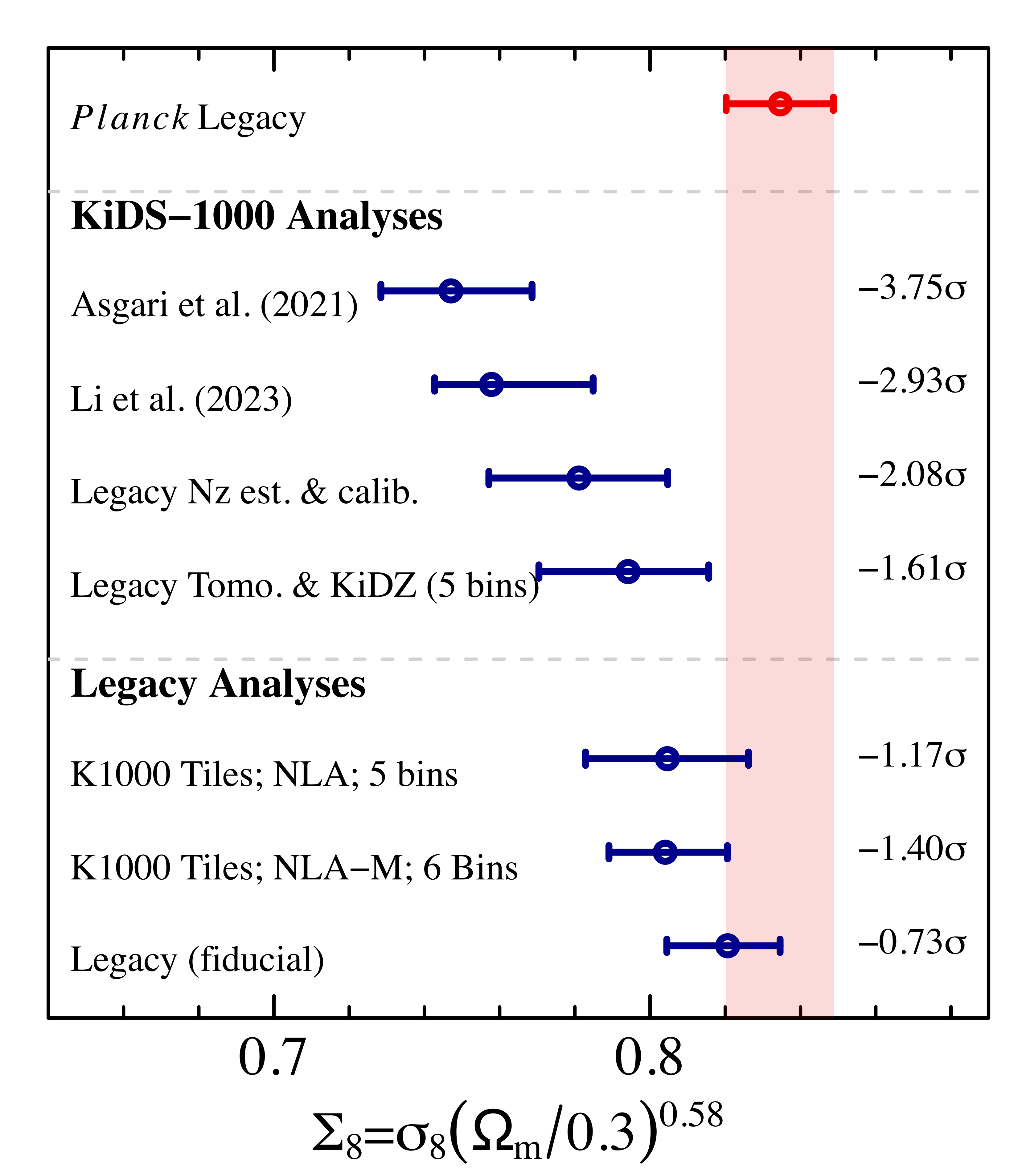
Wright et al. 2023

Stage III results

Current constraints (ΛCDM)

KiDS-Legacy cosmic shear: no tension with Planck

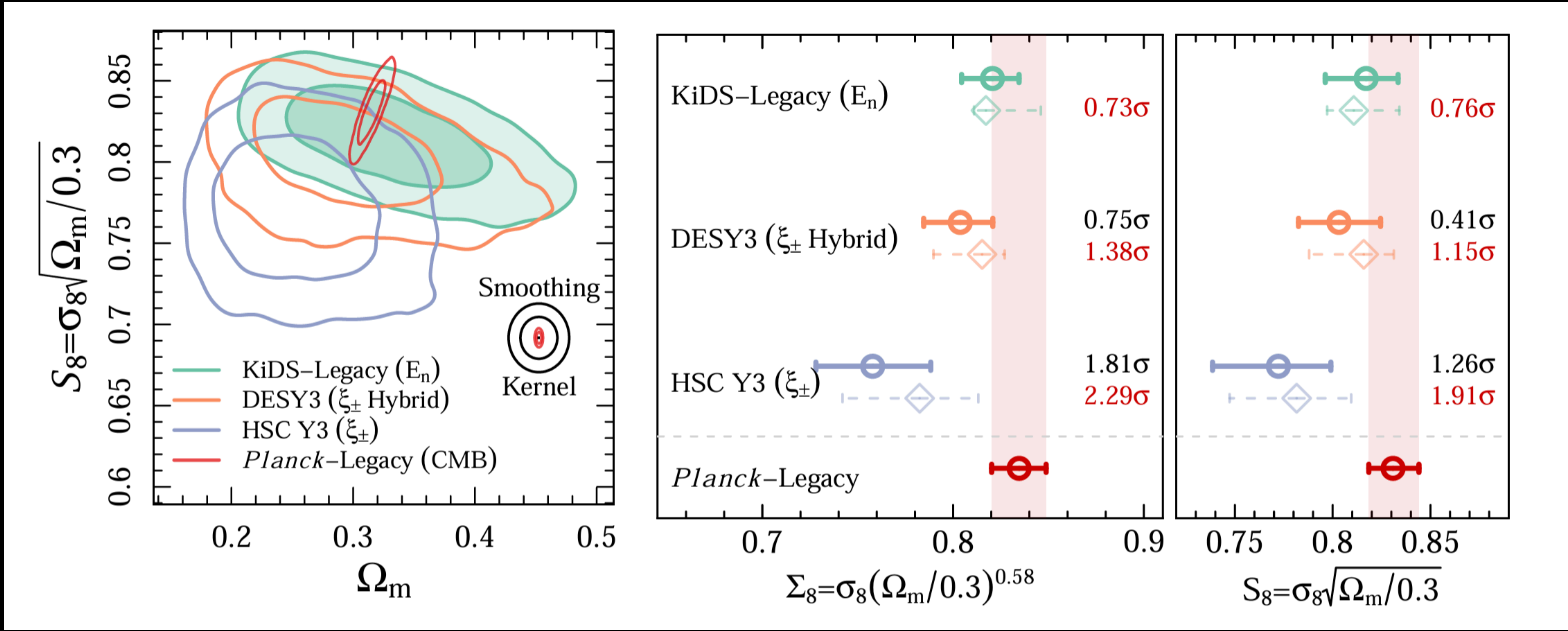
- Better statistics from1350 sq. deg. and sixth tomographic bin.
- Better image simulations.
- New spectroscopic sample for $n(z)$ estimation (from taking KiDS+VIKING new observations in available spec-z fields).
- Updated $n(z)$ calibration and estimation methods.



Wright+ (2025)

Current constraints (ΛCDM)

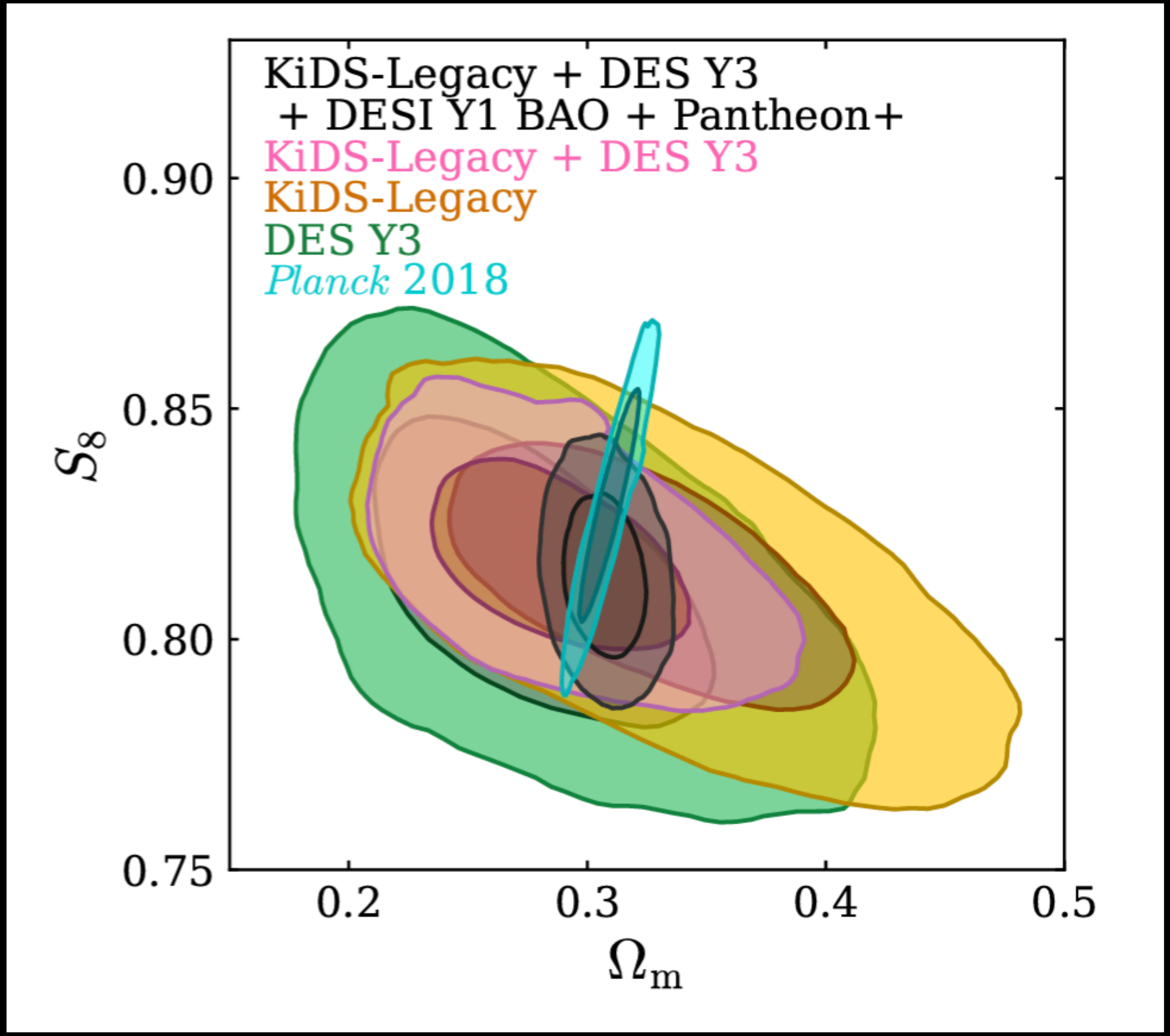
Comparison of KiDS, DES Y3, HSC Y3



Wright+ (2025)

Current constraints (ΛCDM)

Combining KiDS, DES Y3 and external probes



Stolzner+ (2025)

Current constraints (wCDM from 3x2pt)

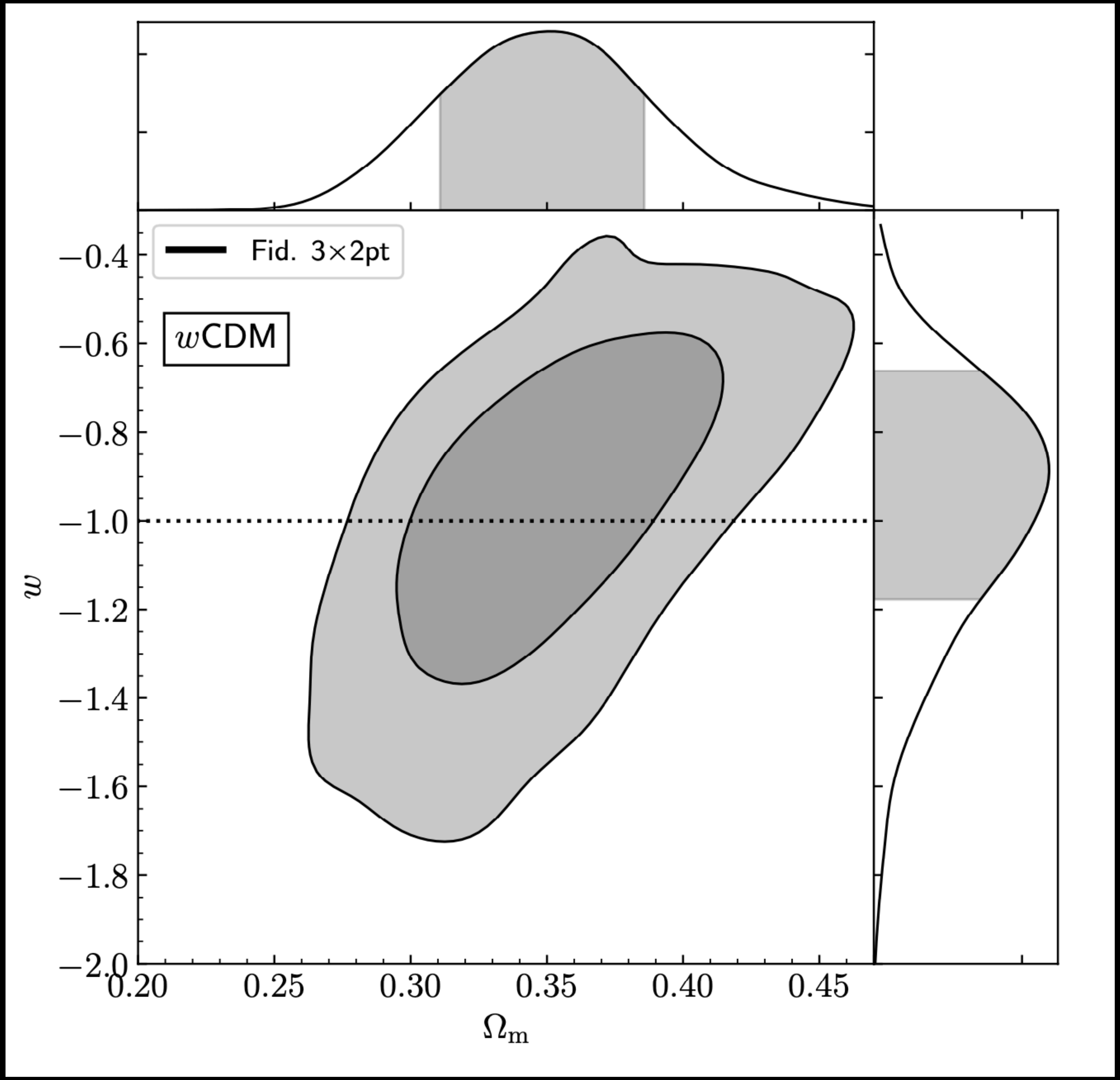
Y3: 100 million shapes over 4000 sq. deg.; MagLim z<0.85 lenses.

$$w = -0.98^{+0.32}_{-0.20}$$

The model is not preferred:

$$R = \frac{P(\hat{\mathbf{D}}\,|\,\Lambda\mathrm{CDM})}{P(\hat{\mathbf{D}}\,|\,w\mathrm{CDM})} = 4.3 > 1$$

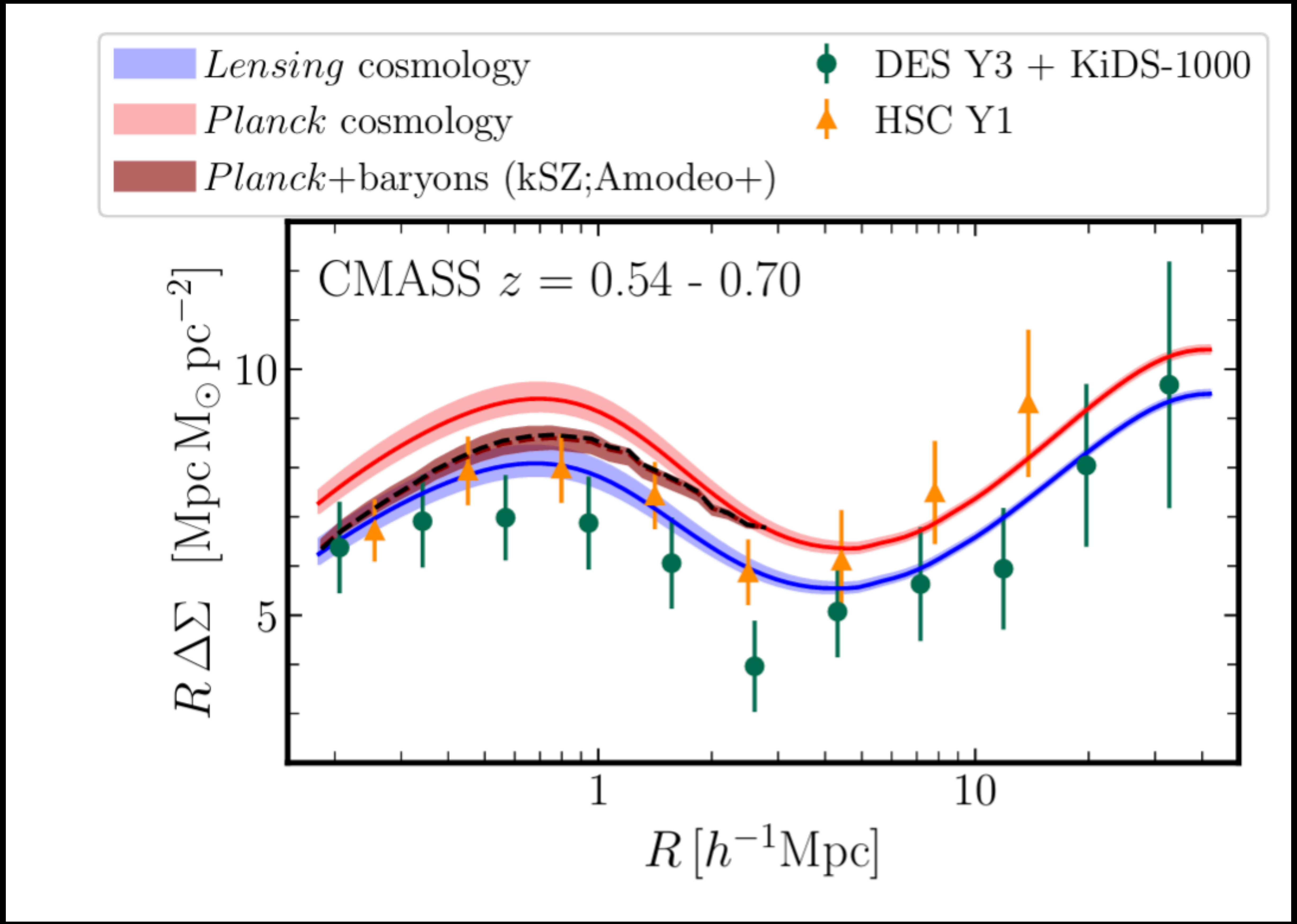
For KiDS1000, Troster+: $w = -0.99^{+0.11}_{-0.13}$



DES Y3

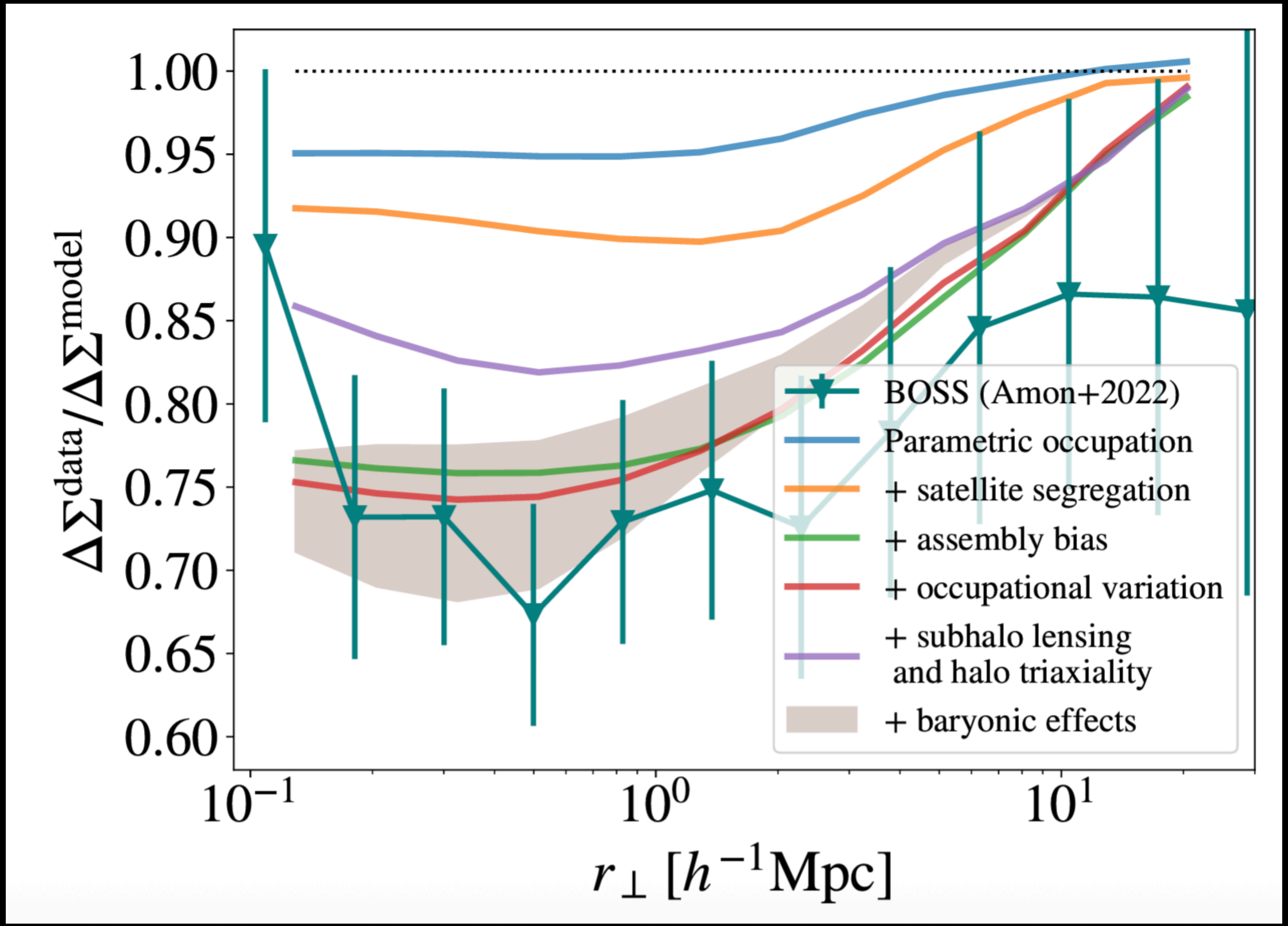
Are there still tensions?

"Lensing is low": galaxy-galaxy lensing



Amon+ (2022)

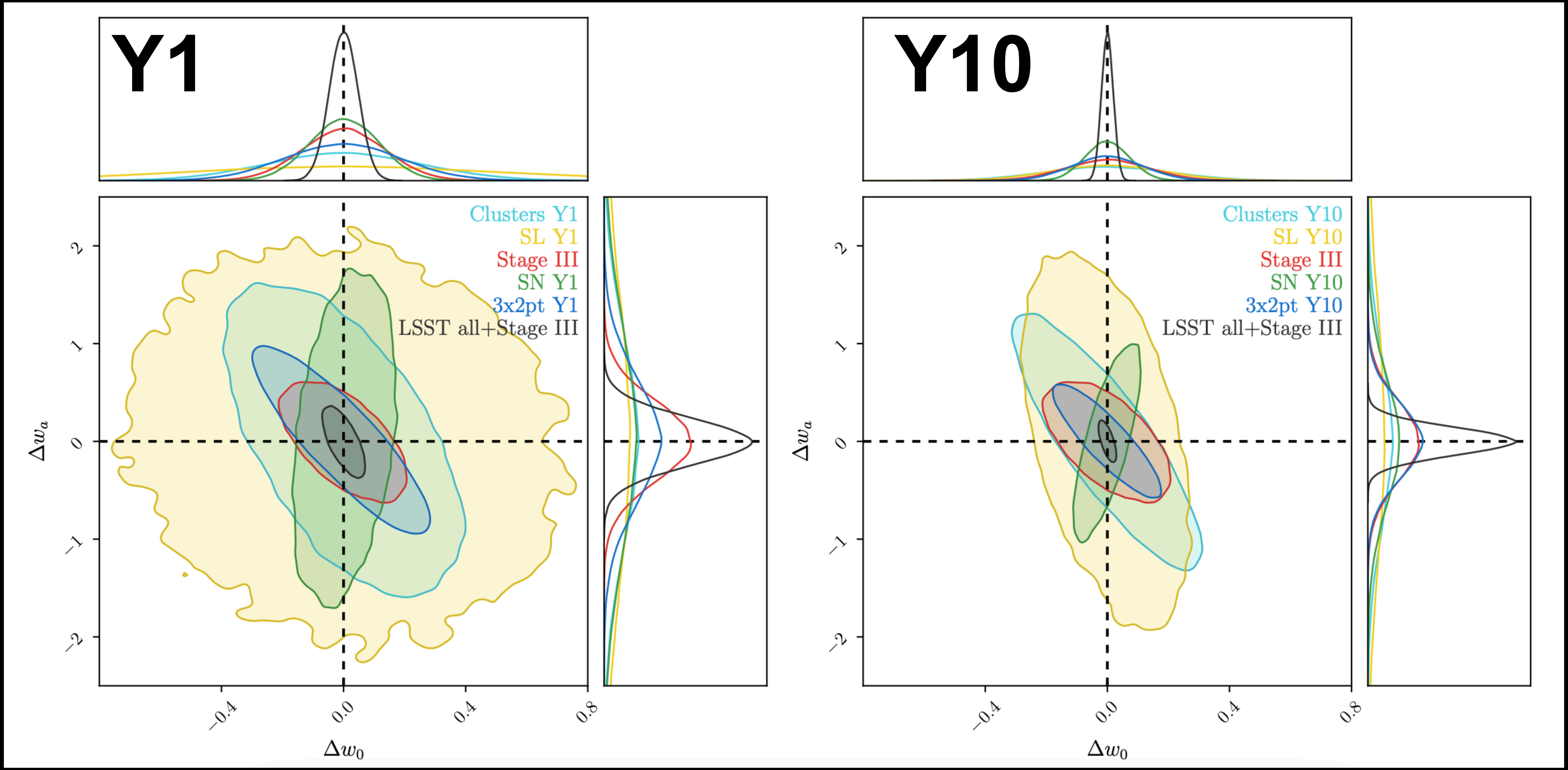
Possible solutions



Chaves-Montero+ (2022)

Constraining power for Stage IV

~10% on (w_0, w_a)

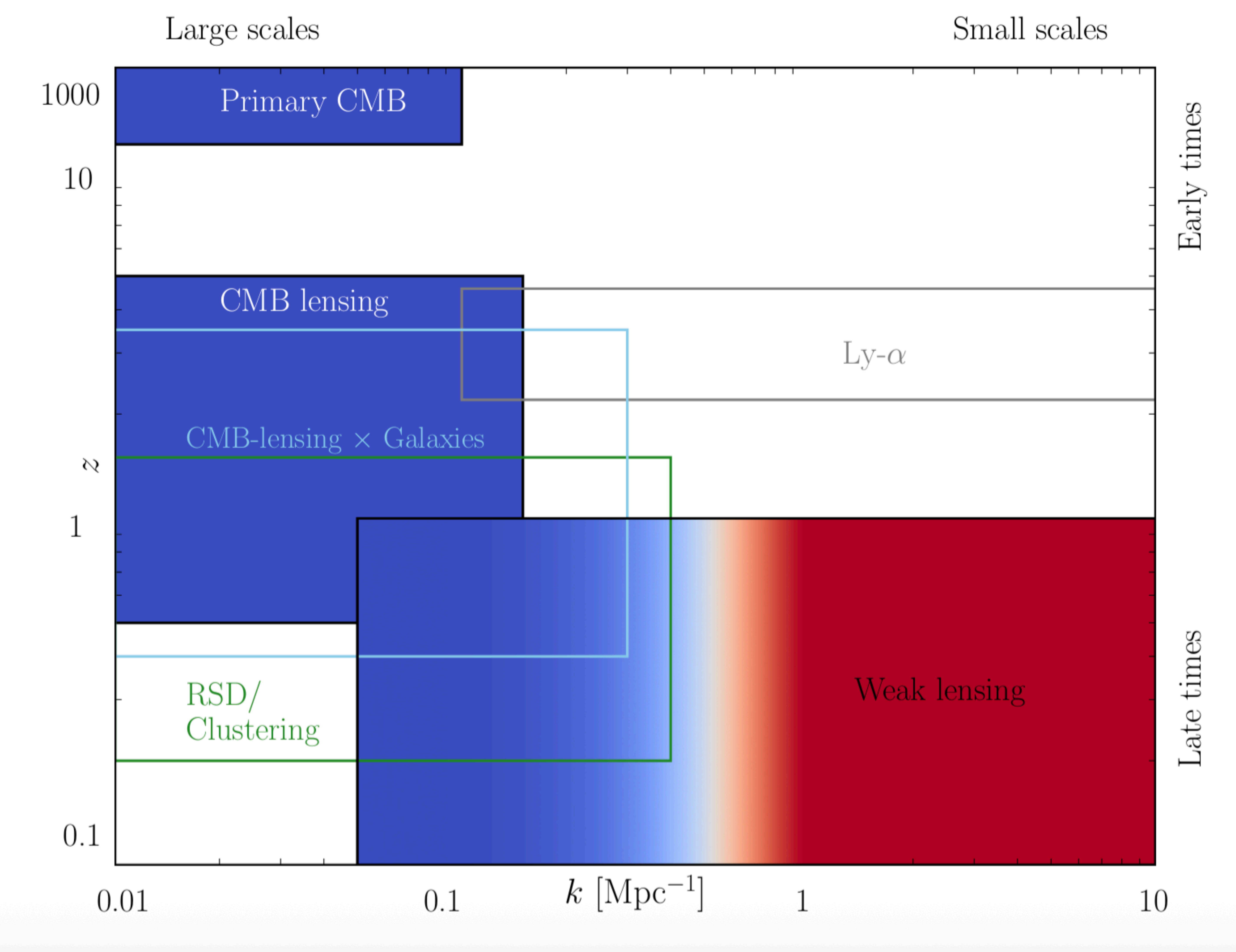


Mandelbaum+, incl. EC, **LSST DESC** Science Requirements Document (2018)

Stage IV transition

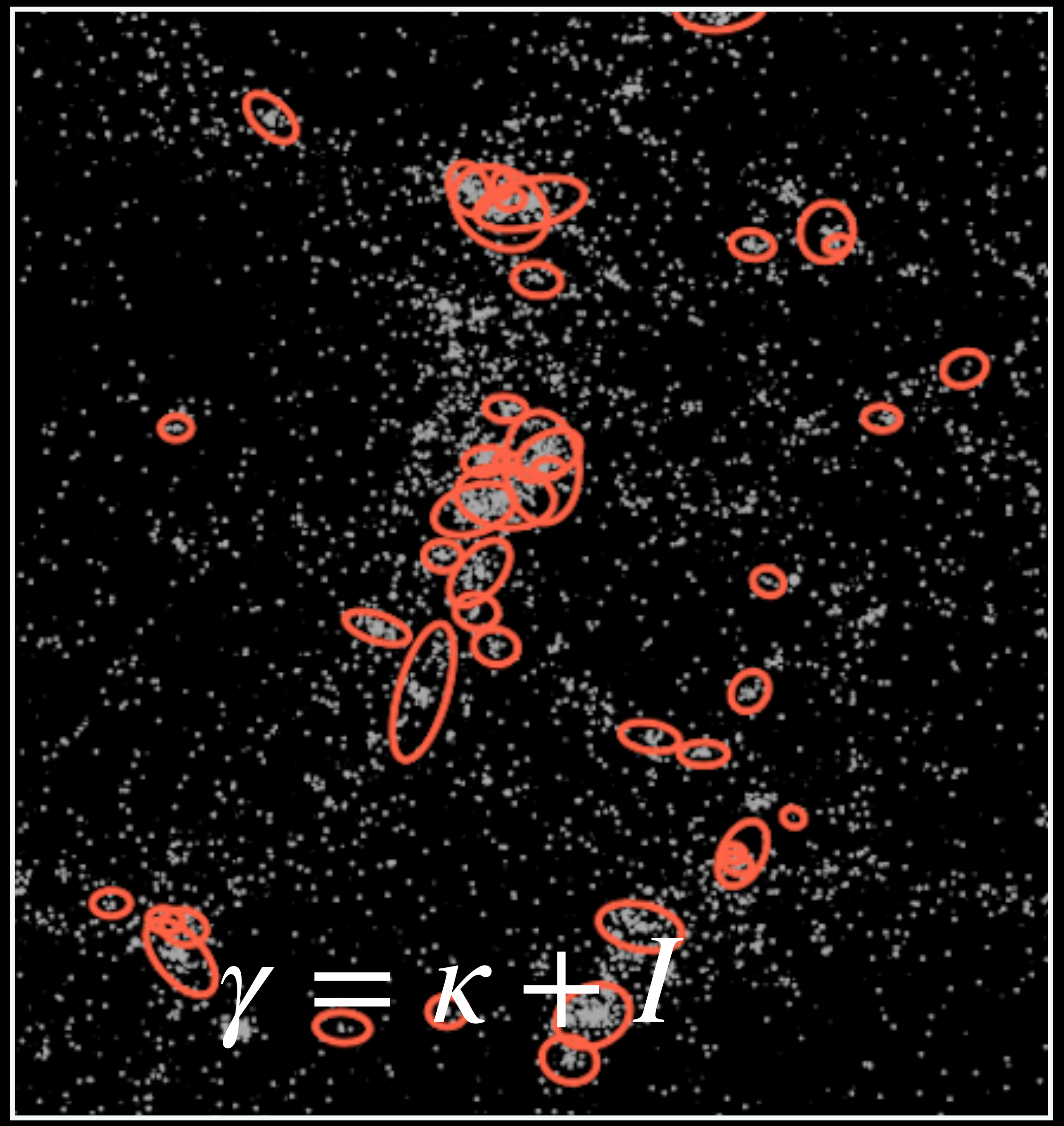
(some of the challenges)

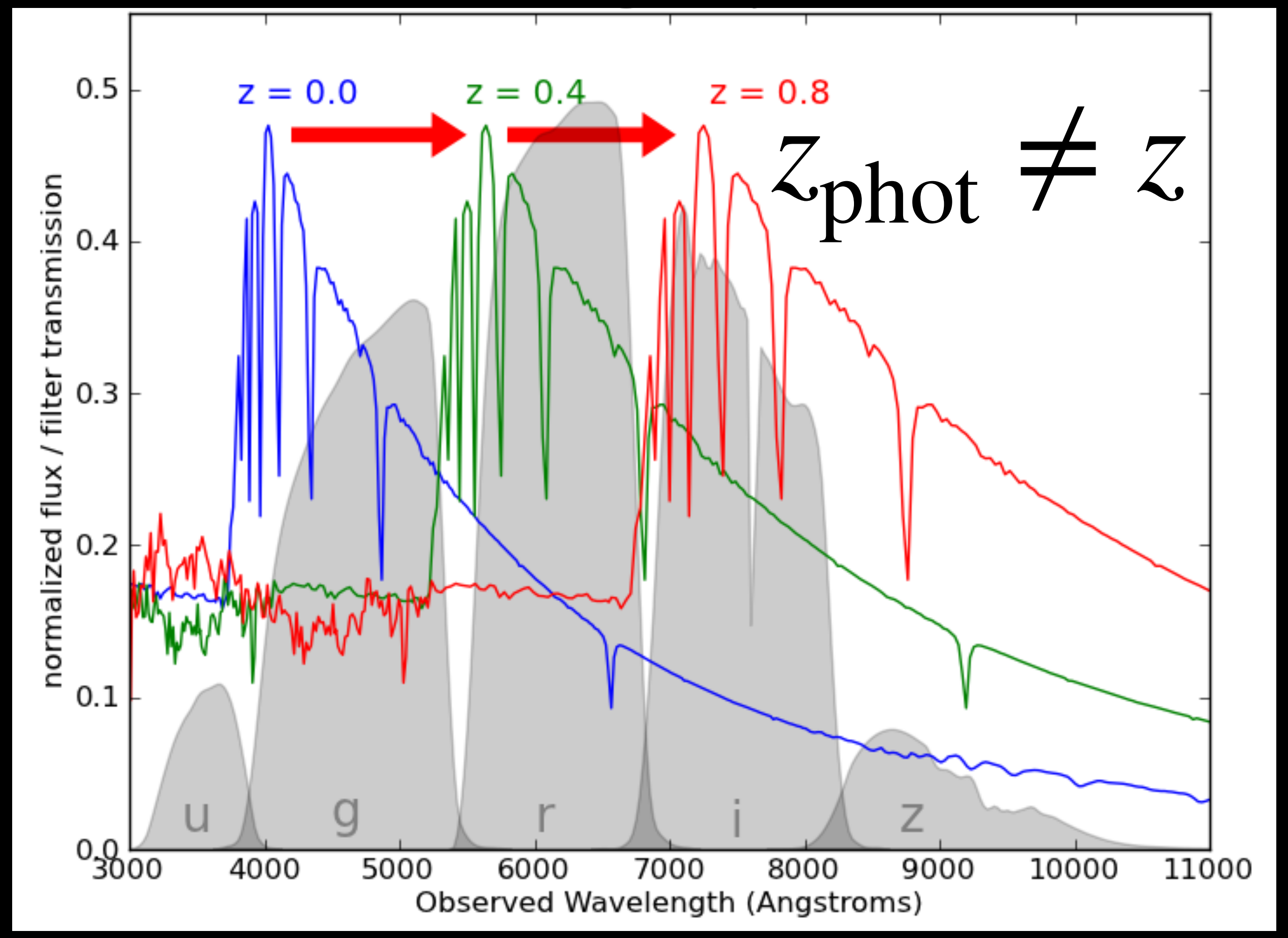
Weak lensing information is nonlinear

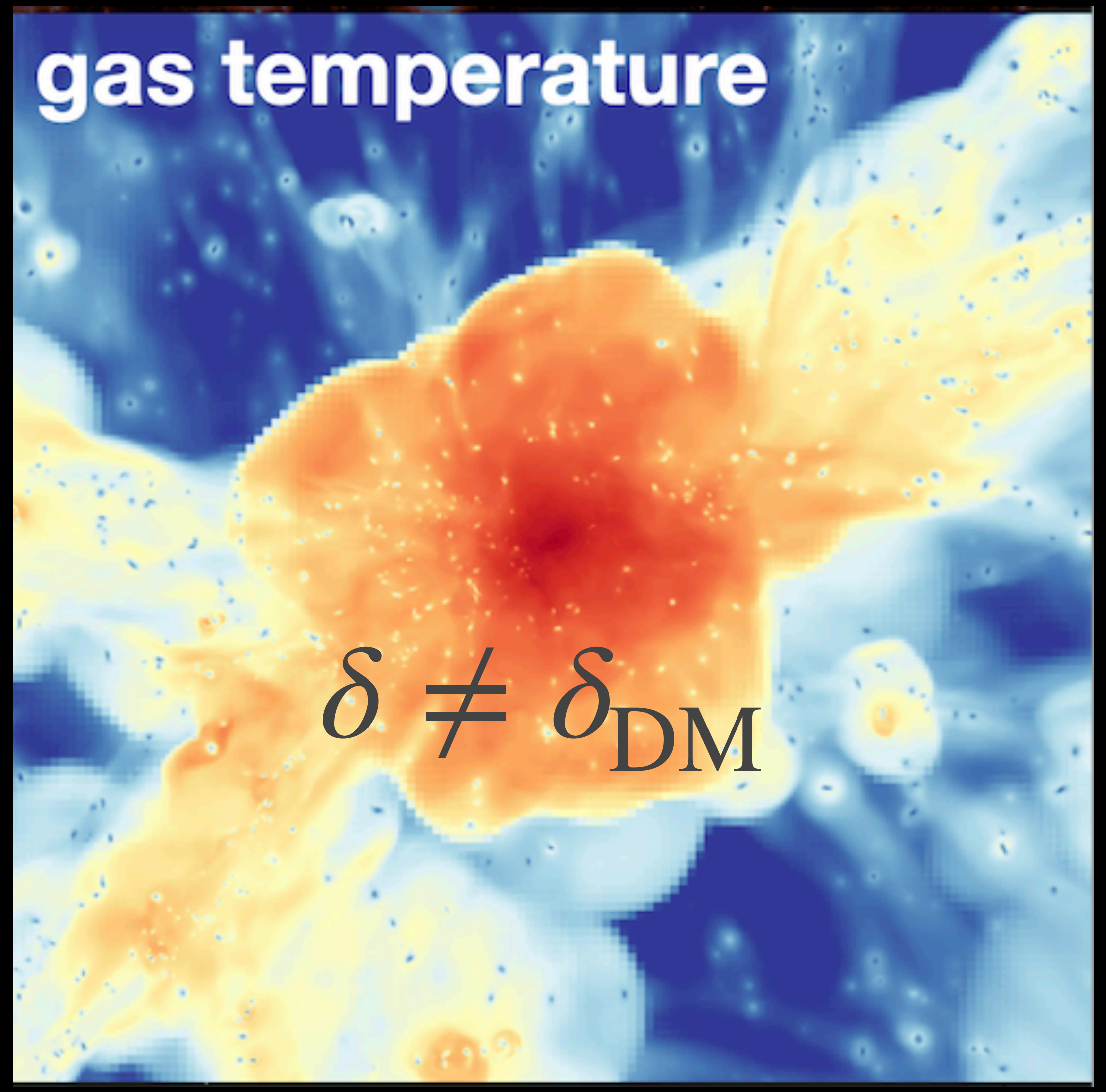


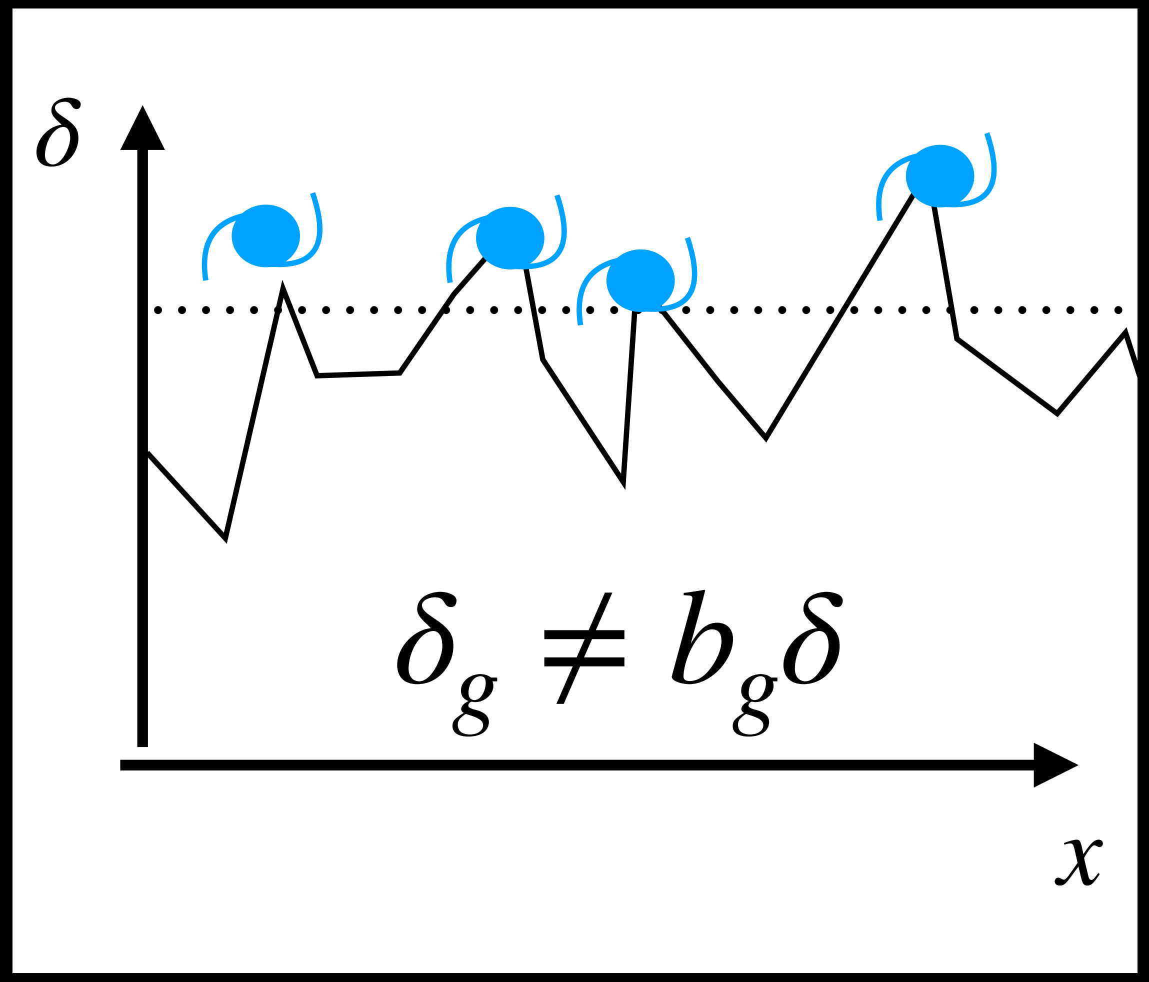
Preston+ (2023)

Systematics at all scales and in all observables









Intrinsic alignments mimic the lensing signal across all scales (opposite sign E-modes)

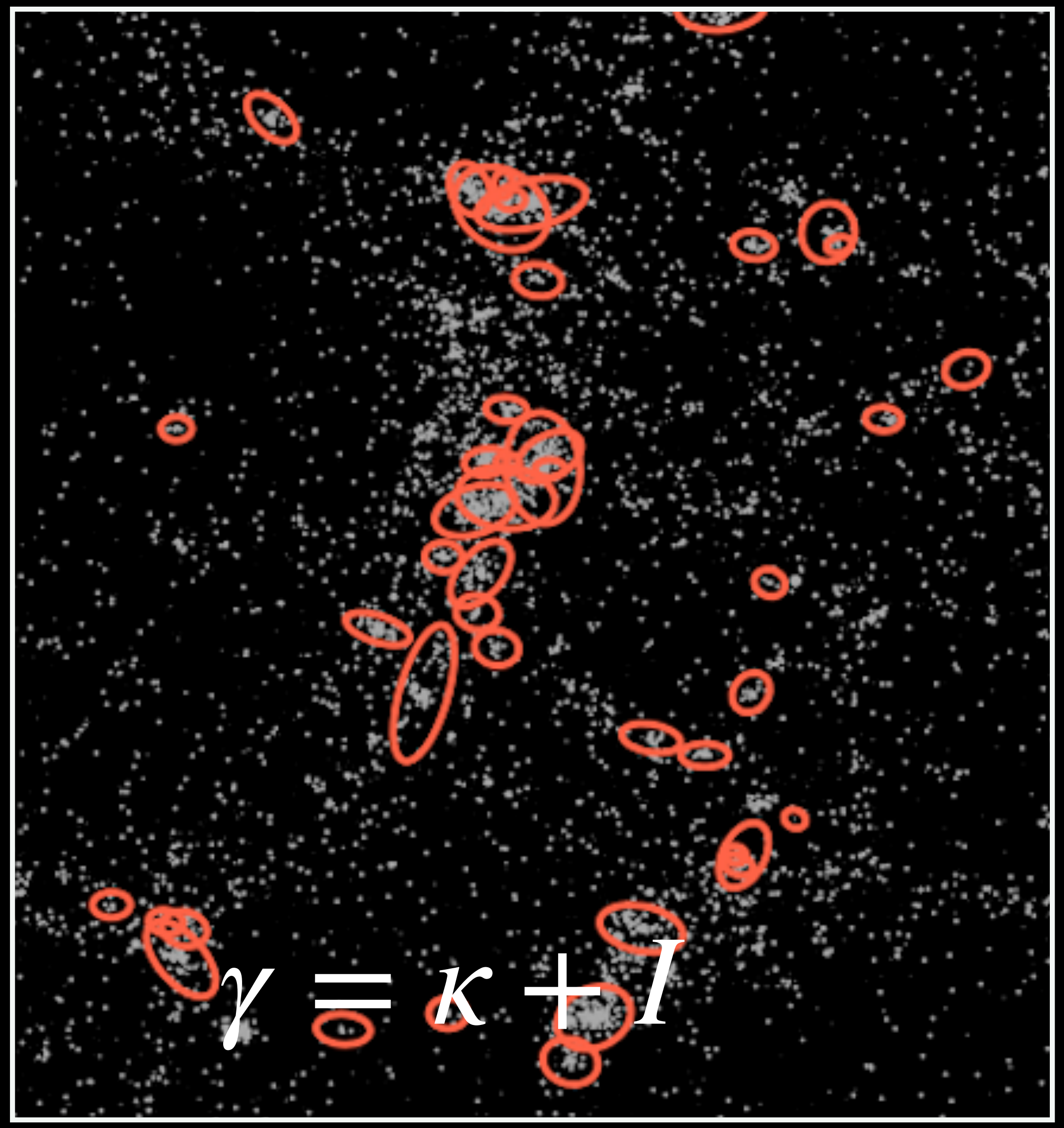
Photometric redshifts lead to confusion and bias in which matter field we are probing.

Gastrophysics affect the distribution of matter at small scales.

Nonlinear galaxy bias affects inference of cosmology from 2x2pt and 3x2pt.

+ magnification, shear calibration, blending, the time it takes to run a sampler…

Systematics at all scales and in all observables



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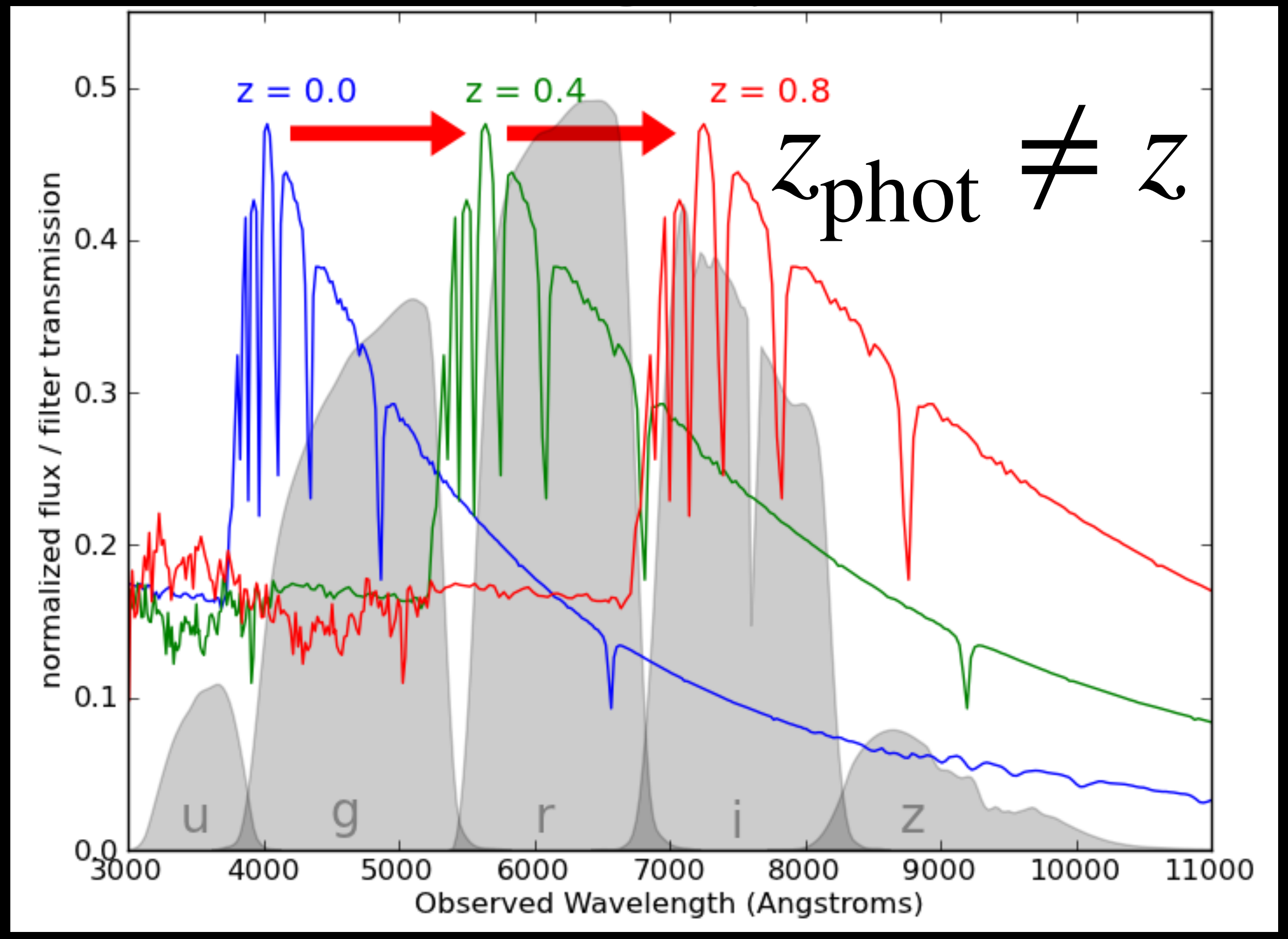

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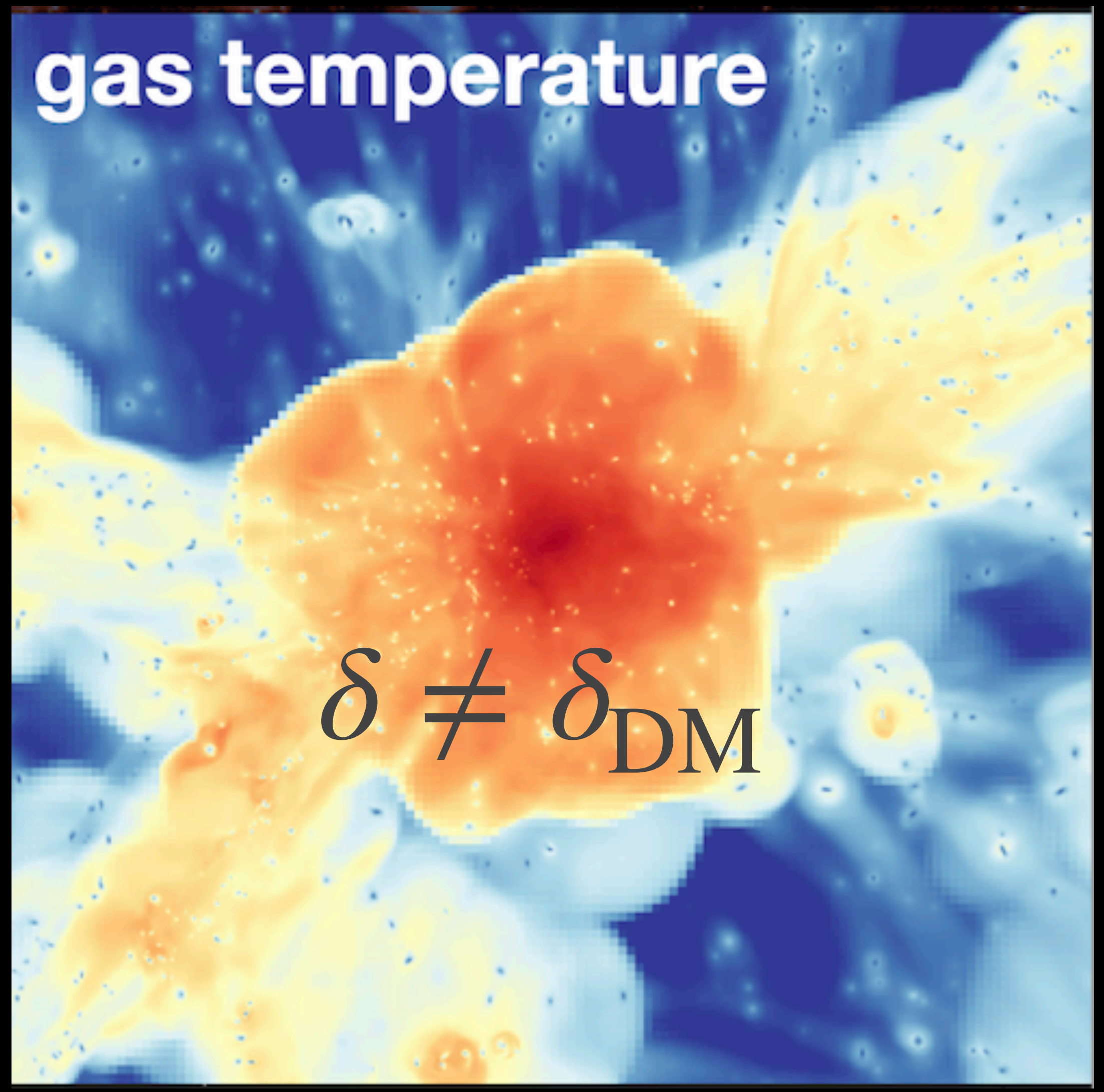
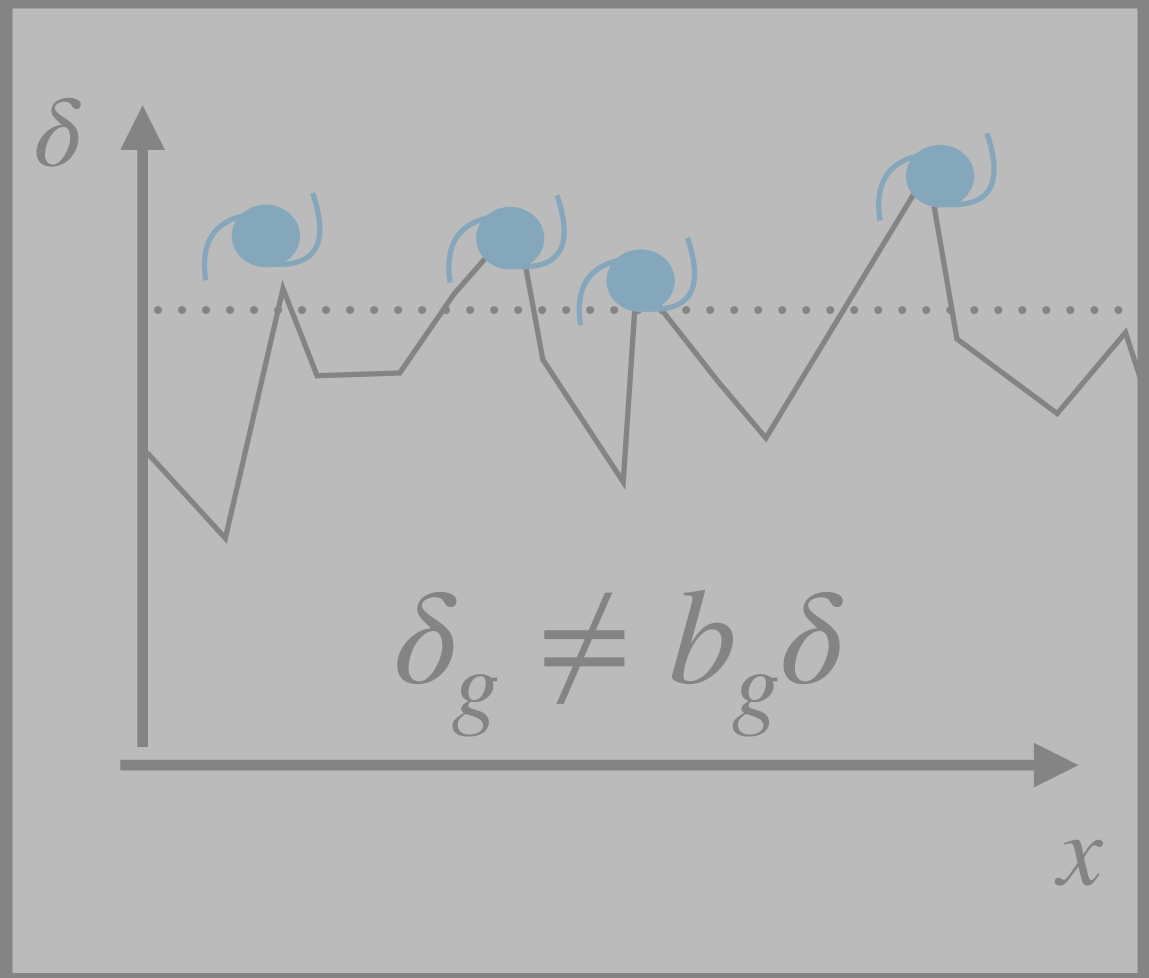


Gastrophysics affect the distribution of matter at small scales.



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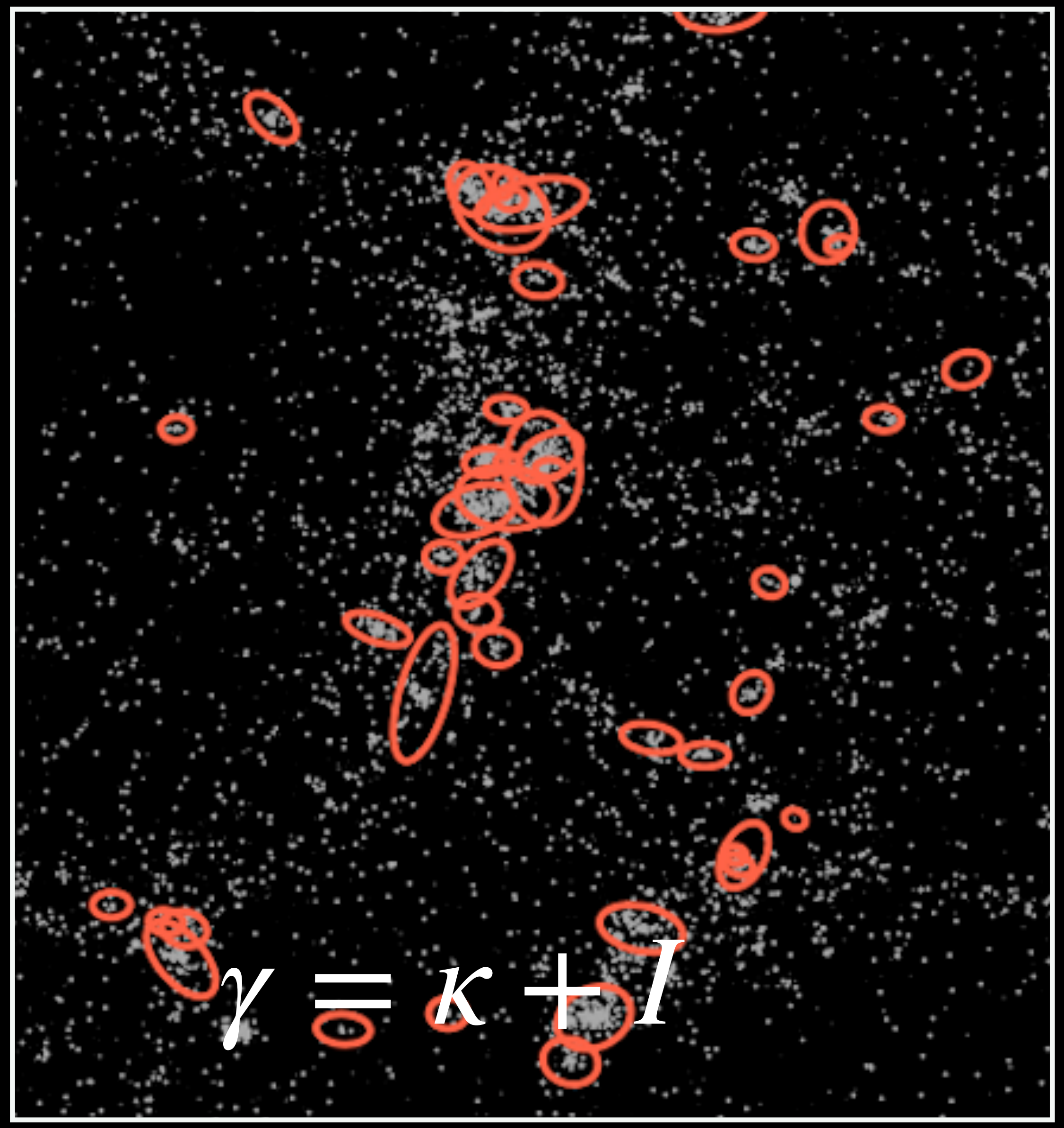
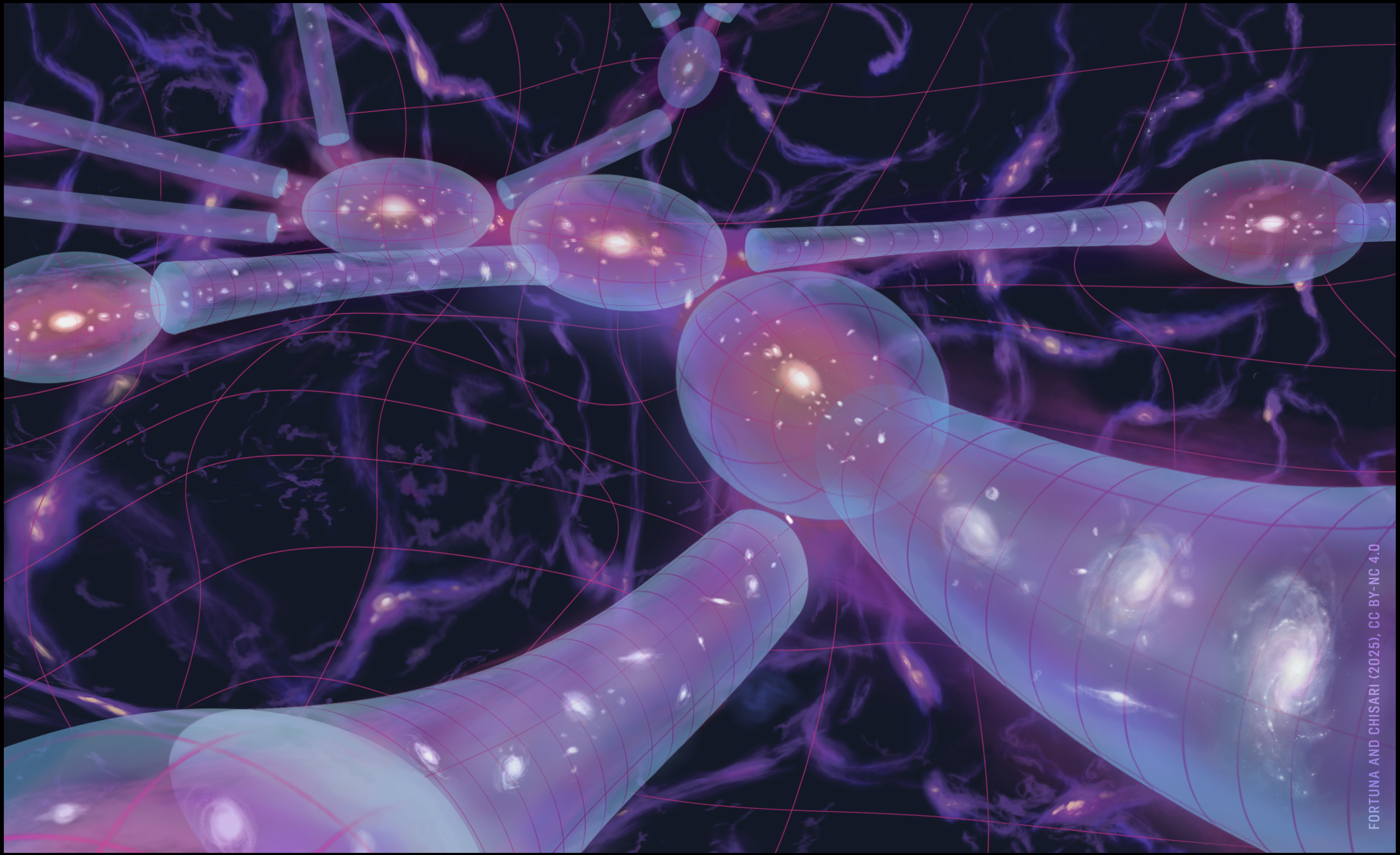


Intrinsic alignments
mimic the lensing signal across all scales (opposite sign E-modes)

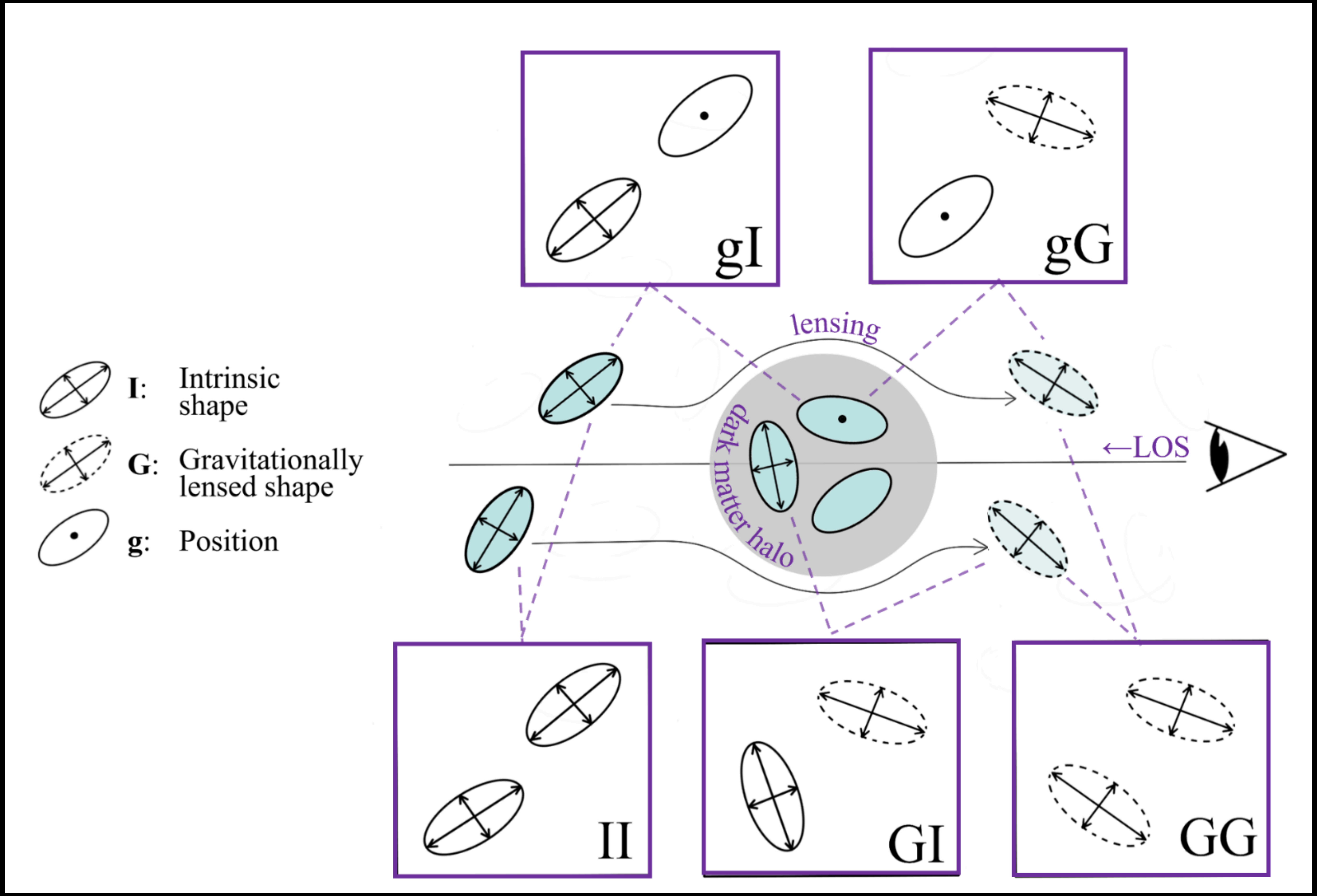
Intrinsic alignments



Fortuna & EC (2025)

Intrinsic alignment contamination

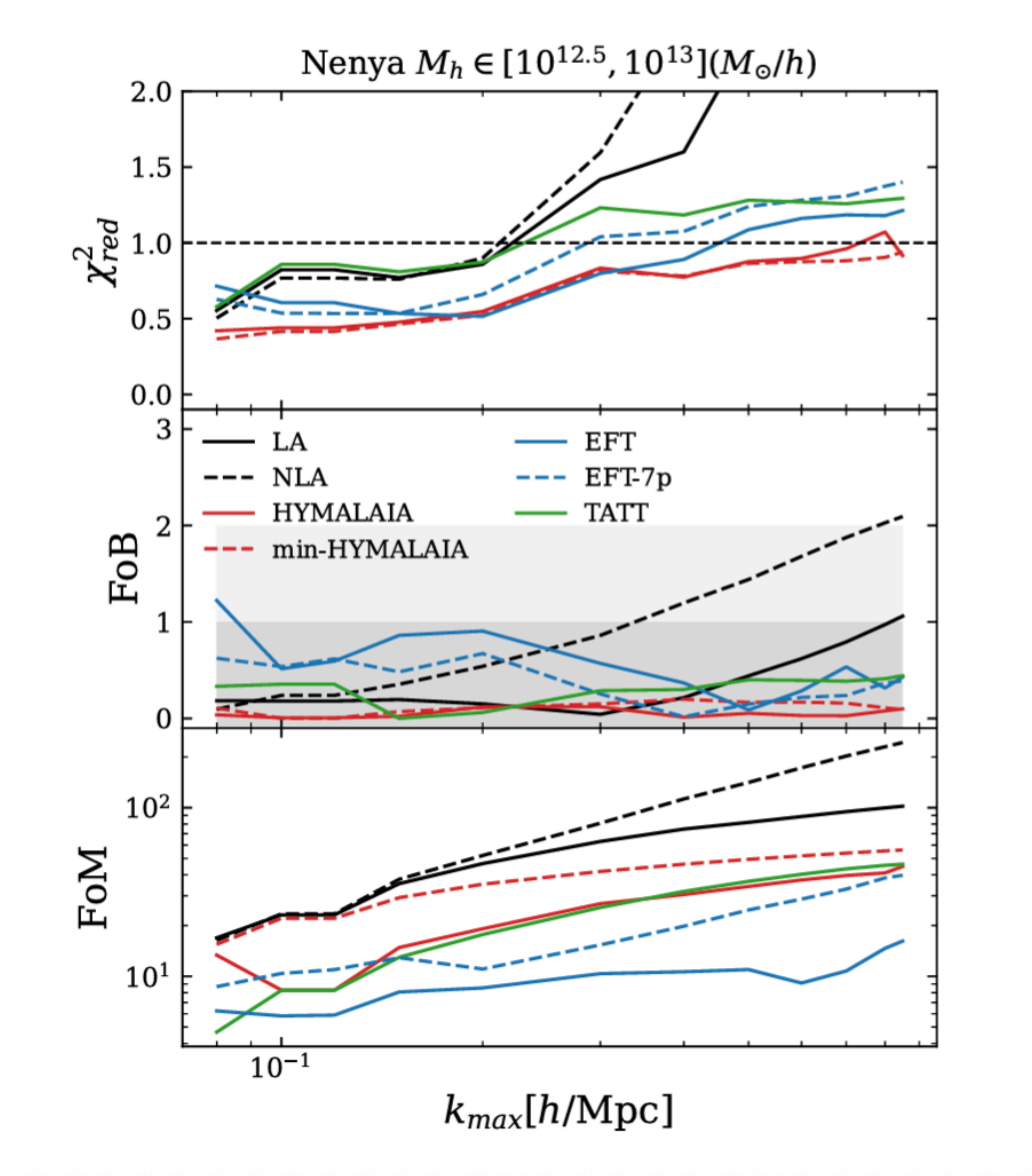
$$C_{\gamma\gamma}(l) = C_{\kappa}(l) + C_{\kappa I}(l) + C_{I\kappa}(l) + C_{I}(l)$$



Lamman+ (2023)
The IA Guide

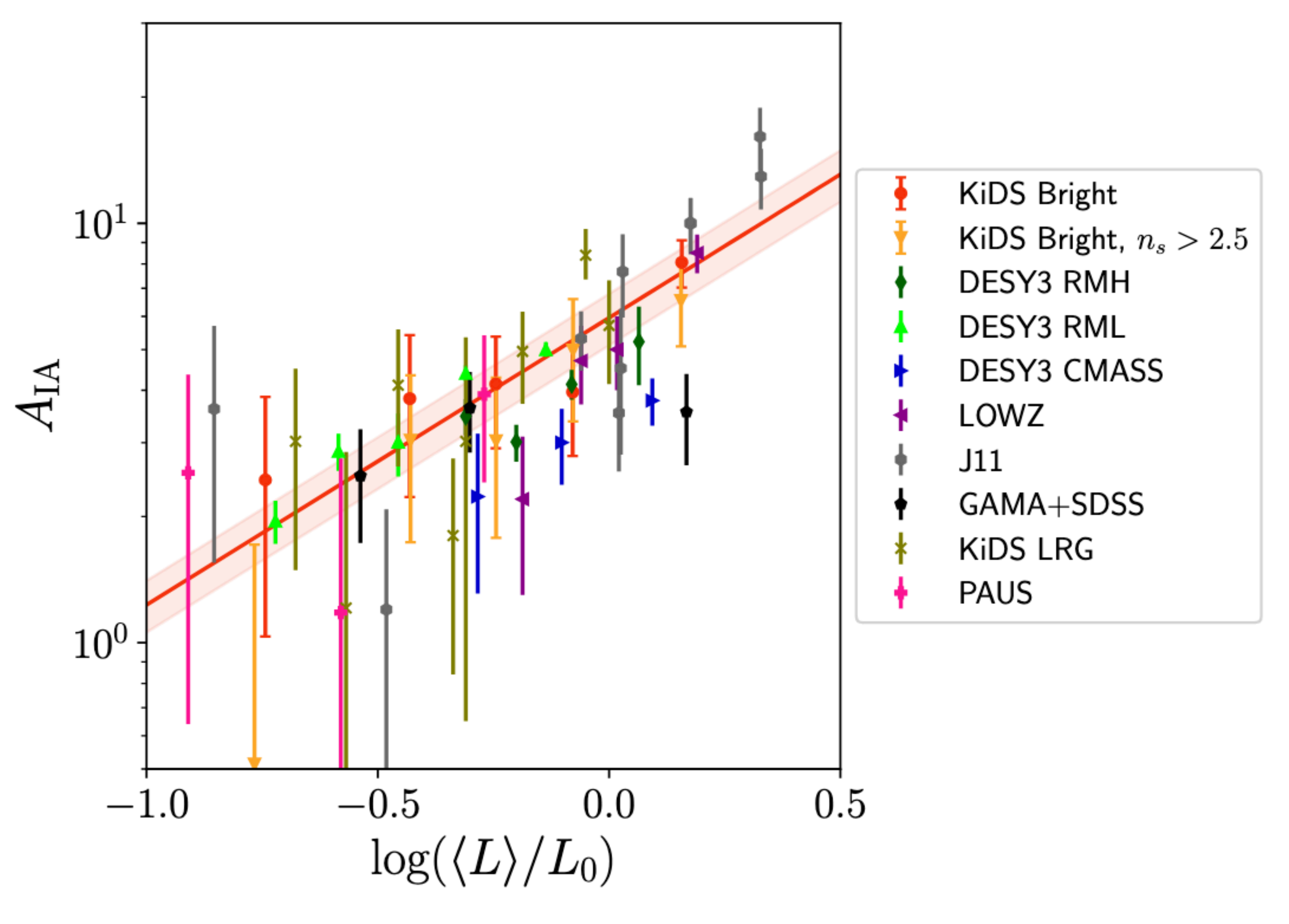
Modelling tools for IA

- **LA/NLA model (Catelan+,Hirata&Seljak)**
  - Single amplitude $A_{\rm IA}$: bias parameter for shapes
- **TATT (Blazek+)**
  - 2-3 free parameters that capture higher order terms
- **EFT of shapes (Vlah+,Bakx+,Chen+)**
  - 6-8 free parameters up to third order
- **Hybrid approach (Maion+)**
  - Uses N-body simulations for displacements (2 free params)
- **Halo model (Schneider & Bridle, Fortuna+)**
  - Fully non-linear
- **No emulators for now but fast mocks (van Alfen+)**



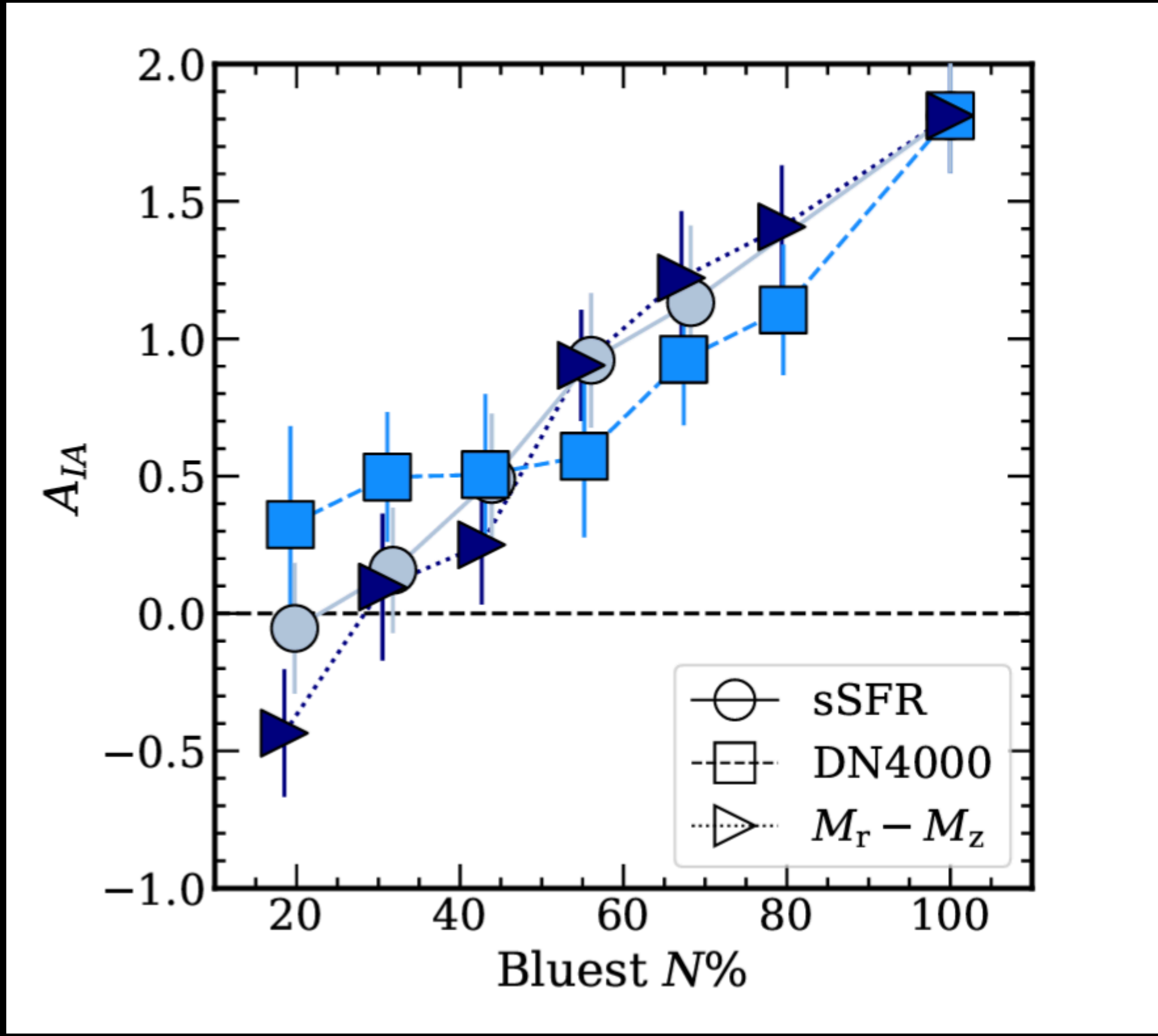
Maion+, incl Bakx, EC, 23

Direct observational priors



Red galaxy alignment is strong and depends on mass/luminosity

Georgiou,EC+, KiDS (2025)



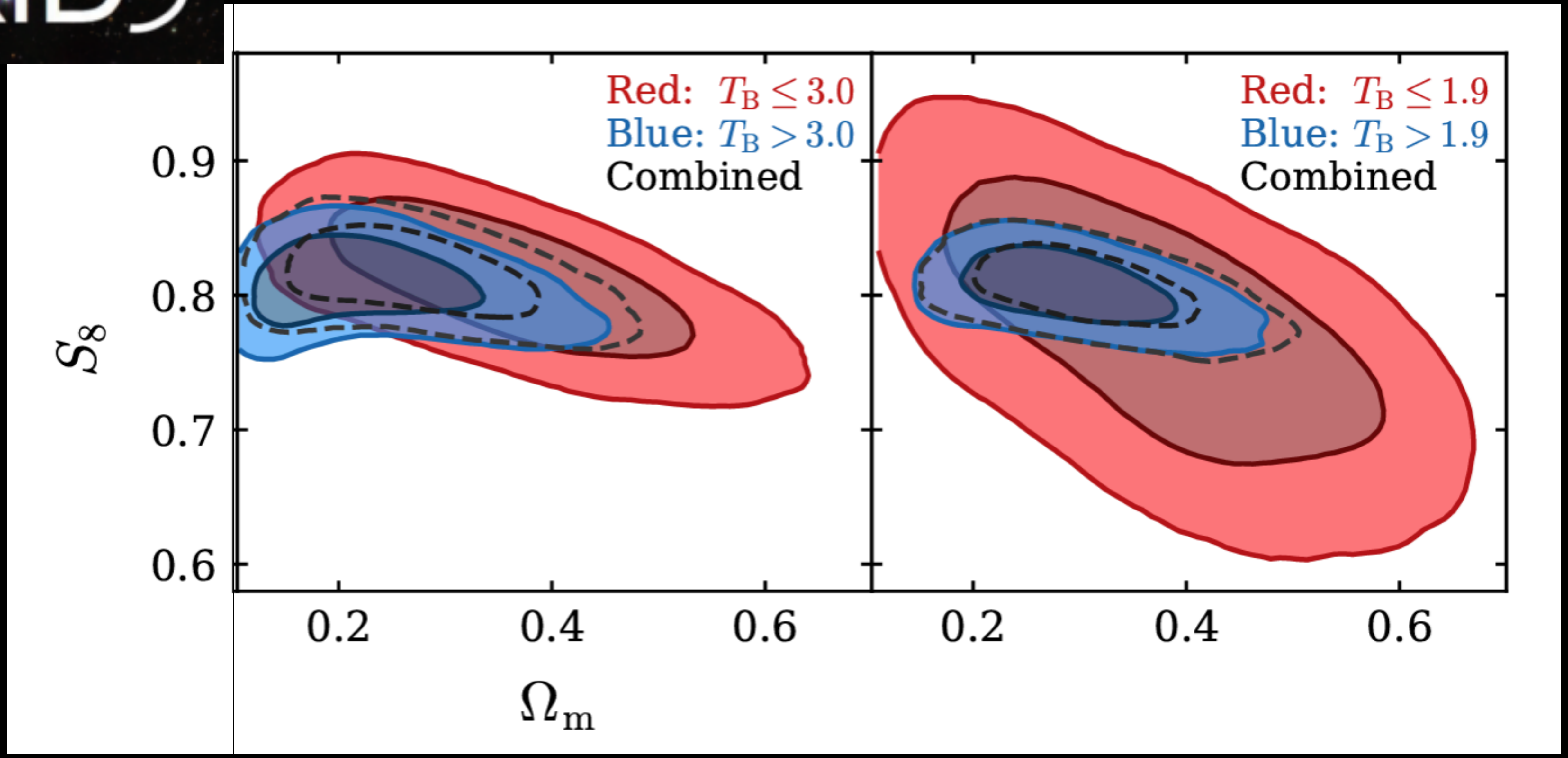
Blue galaxy alignment consistent with null.

Siegel+, DESI+DES+KiDS+SDSS(2025)

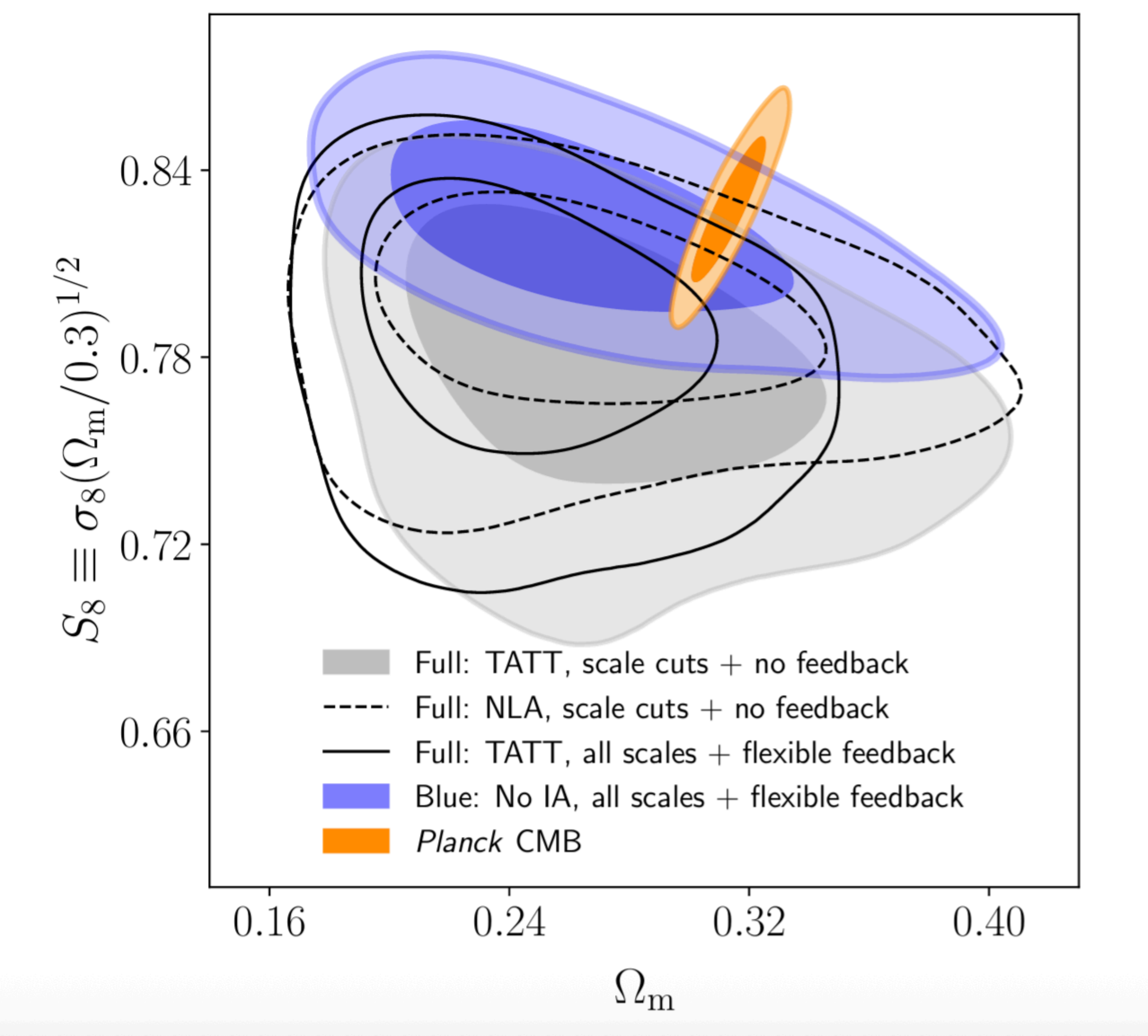
Impact on cosmic shear analysis

Internal consistency of cosmic shear analyses to color splits

KiDS

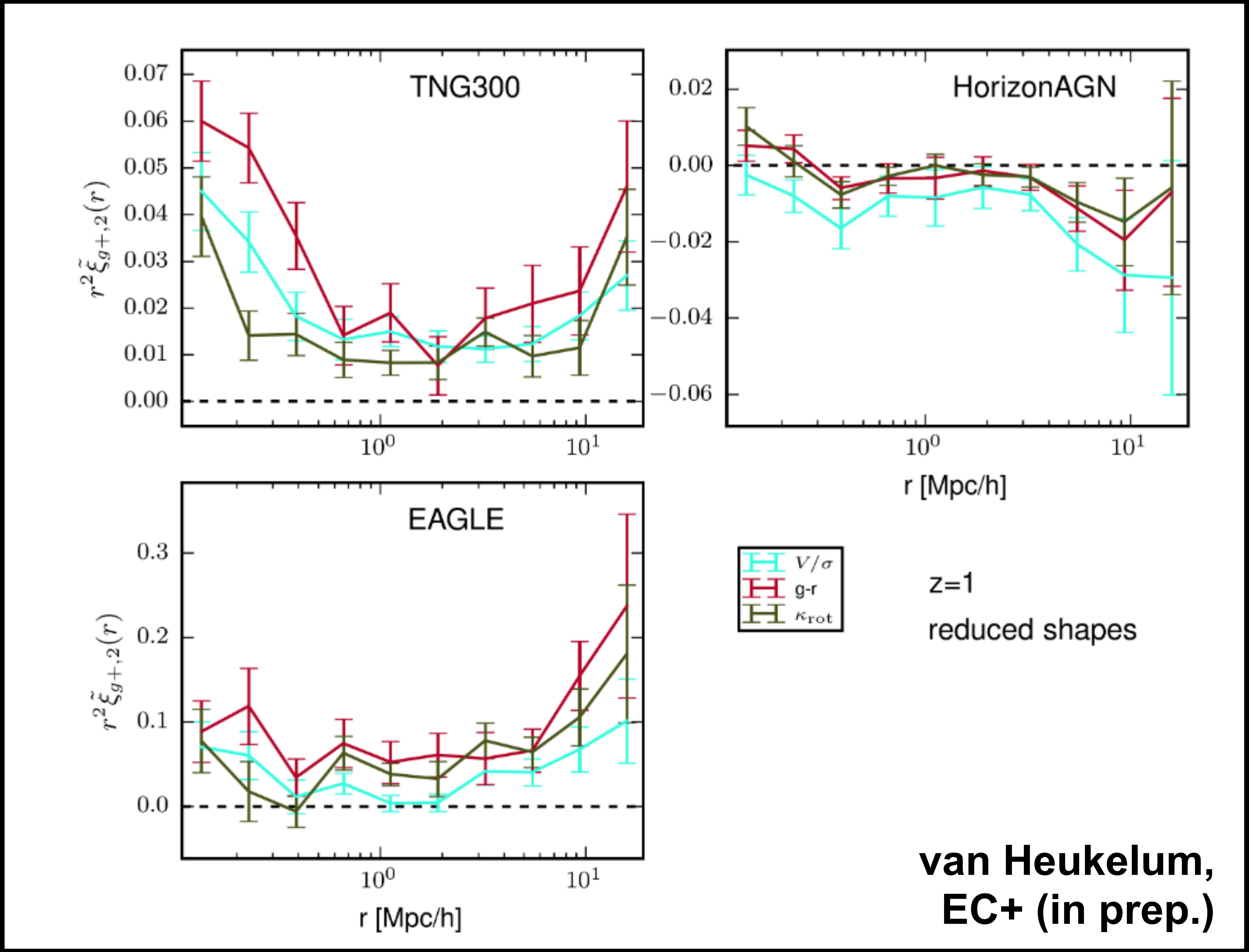


Stolzner+ (2025)



McCullough+ (2024)

Blue galaxies: no alignments? We are not sure



- Blue/disk galaxy alignment is small but **significant** at $z = 1$.
- **Conflicting signs** from hydro sims cannot be resolved easily.
- Amplitude range suggests it cannot be easily ignored without **potentially incurring on a bias** in Stage IV.
- **Larger hydro boxes** coming up should allow better understanding of prior ranges.

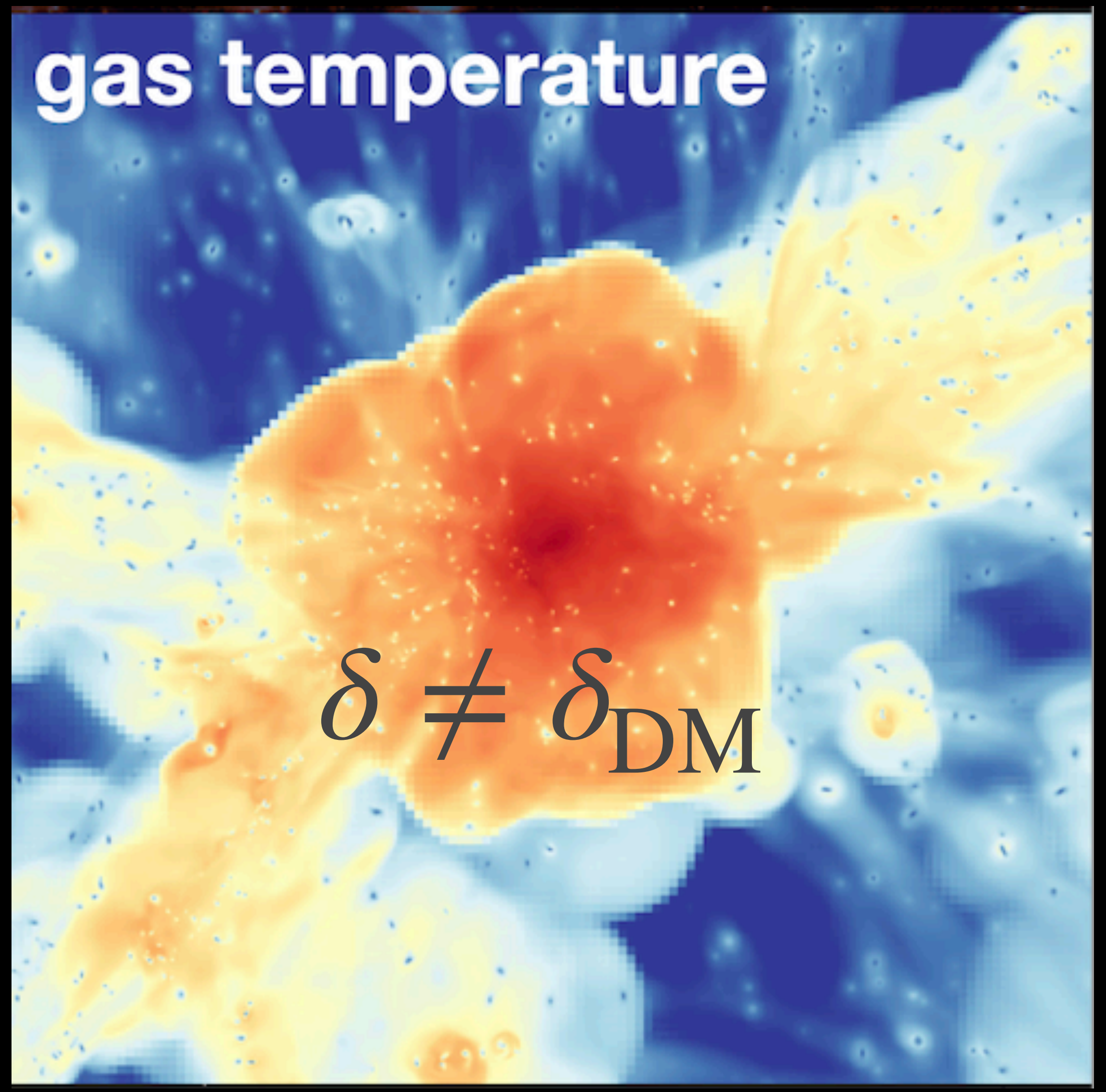
Intrinsic alignments - new physics

Table 3 Cosmological applications of intrinsic alignments and the corresponding references for theoretical modelling, validation in simulations and application to observations, when available. In addition, Philcox et al (2024) provides a general treatment of tensor and vector perturbation signatures in intrinsic alignments.

Application	Theory	Simulations	Observations
Growth of structure	Taruya and Okumura (2020); Zwetsloot and Chisari (2022); van Gemeren and Chisari (2020); Okumura and Taruya (2023)	-	Okumura and Taruya (2022)
Baryon acoustic oscillations	Chisari and Dvorkin (2013); van Dompseler et al (2023)	Xia et al (2017); Okumura et al (2019, 2020); Kurita et al (2021)	Xu et al (2023)
Primordial non-Gaussianity	Schmidt et al (2015); Kogai et al (2018, 2021)	Akitsu et al (2021)	Kurita and Takada (2023)
Massive $s \neq 0$ fields	”	-	-
Primordial magnetic fields	Schmidt et al (2015); Saga et al (2024)	-	-
Gravitational wave background	Schmidt and Jeong (2012b); Schmidt et al (2014); Chisari et al (2014a); Biagetti and Orlando (2020)	Akitsu et al (2023a)	-
Parity violation	Vlah et al (2021); Biagetti and Orlando (2020); Yin et al (2025)	-	-
Isotropy	Shiraishi et al (2023)	-	-
Modified gravity	Reischke et al (2022)	L'Huillier et al (2017); Chuang et al (2022)	-
Relativistic effects	Saga et al (2023)	-	-
Nature of dark matter	-	Harvey et al (2021); Dome et al (2023)	-

EC, A&A review, to appear

Systematics at all scales and in all observables



Gastrophysics affect the distribution of matter at small scales.

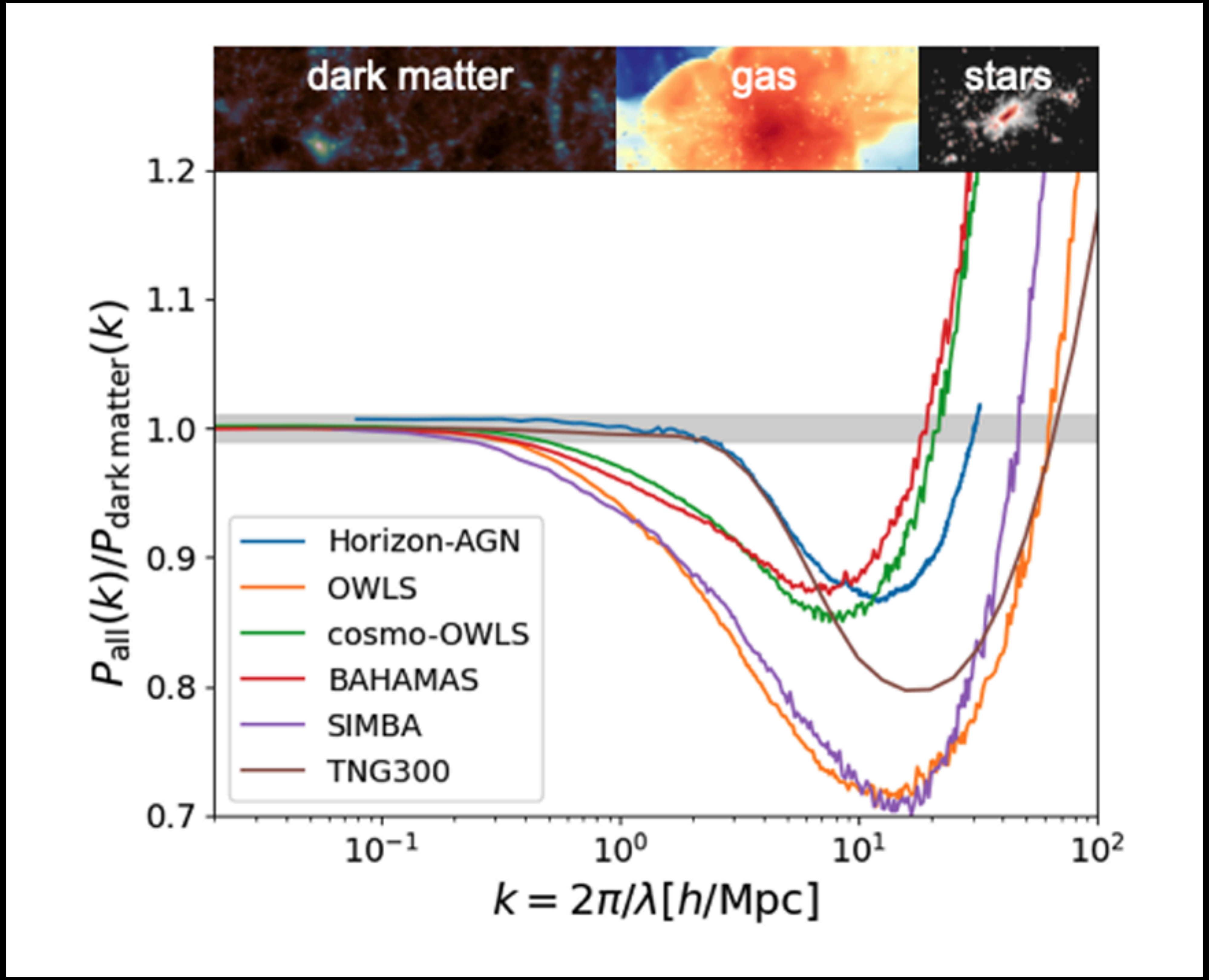
Emmanuel Schaan's talk for tSZ and kSZ

Baryonic effects

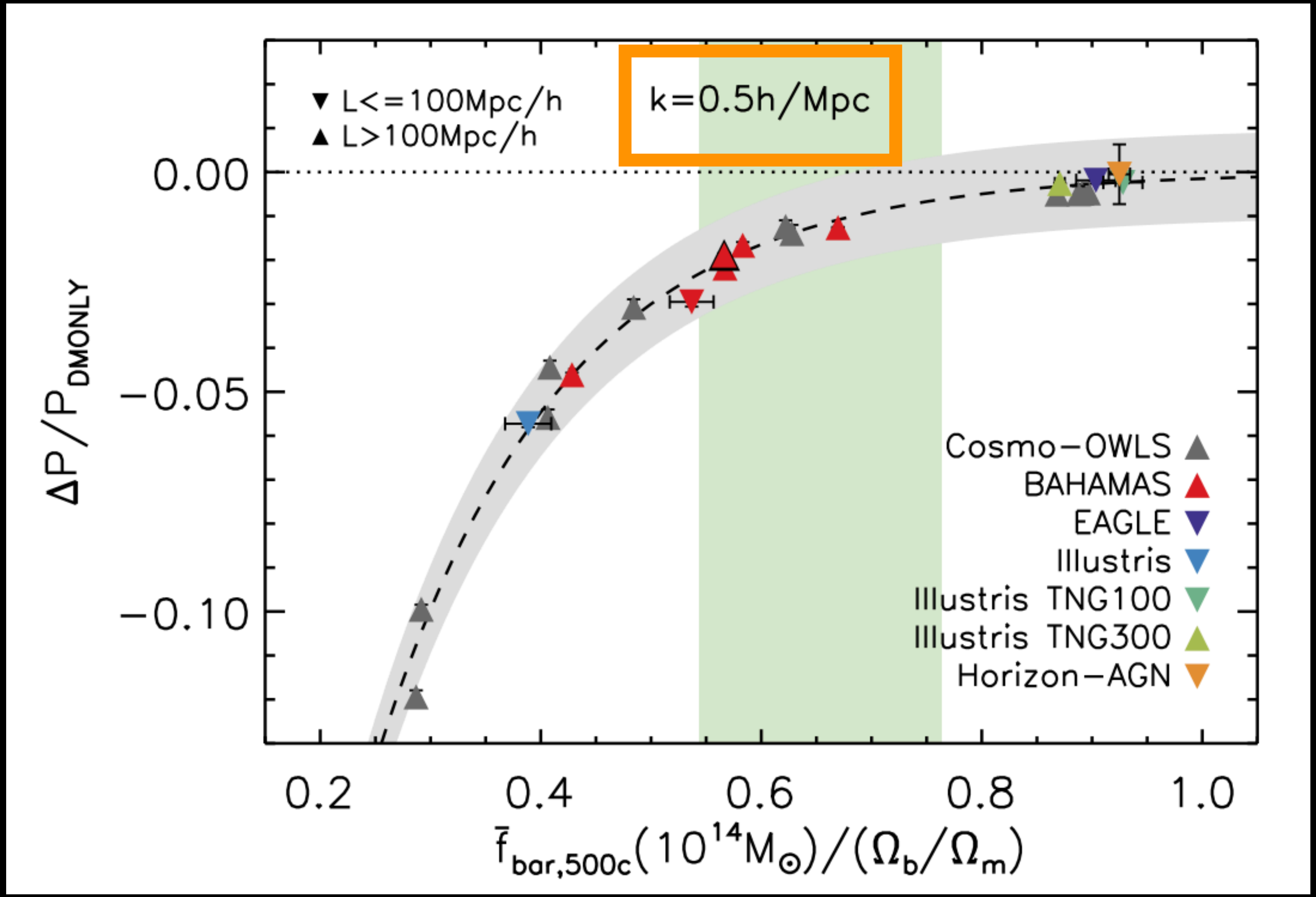
$$C_\kappa(l) = \int_0^{\chi_{\rm H}} d\chi \frac{q_a(\chi)q_b(\chi)}{\chi^2} P_\delta(l/\chi, \chi)$$

van Daalen+ (2011)

EC (2025)



van Daalen+ (2020)

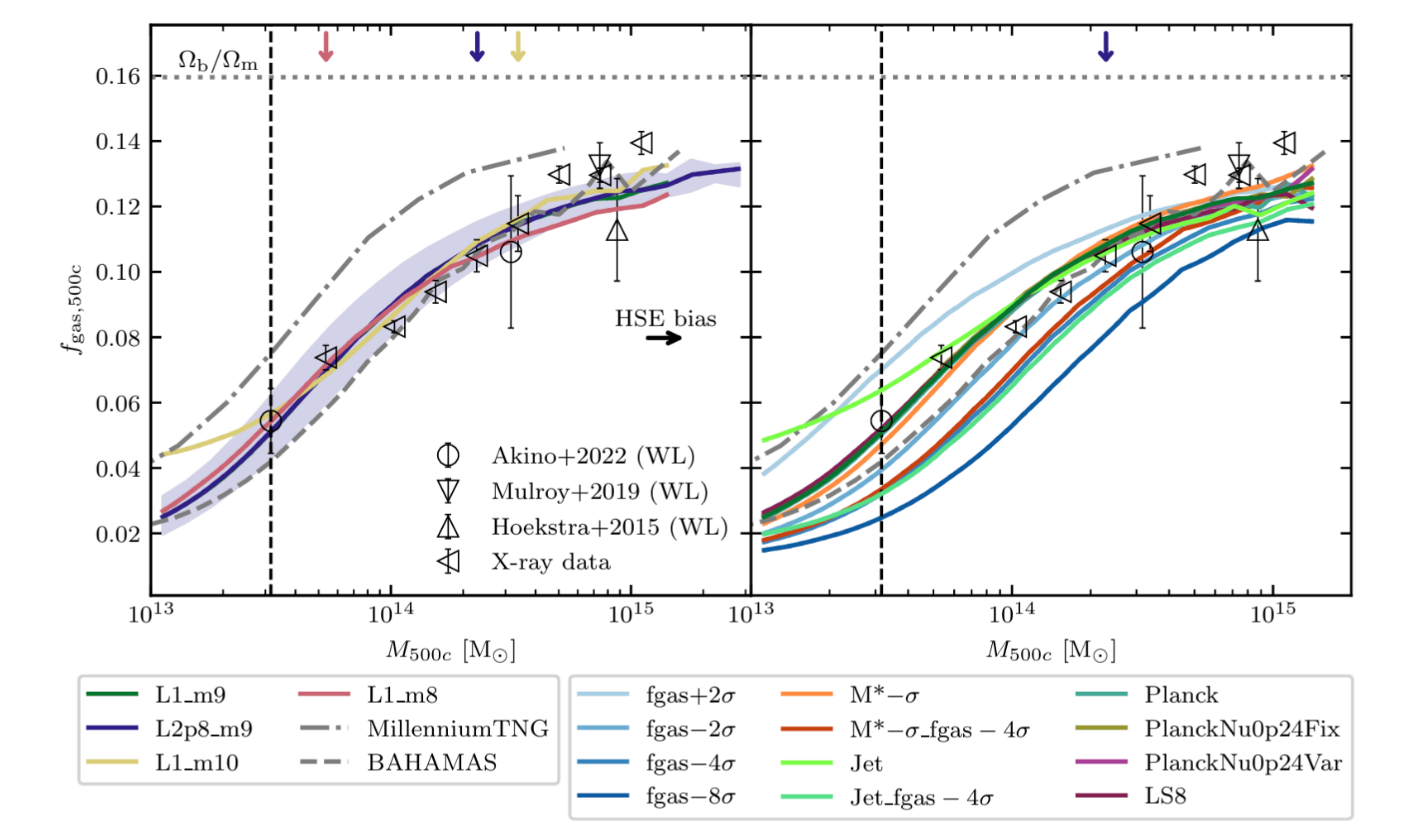


Baryonic effects

Modelling tools

- **EFT** of LSS with baryons (Lewandowski+)
- **Hybrid** PT (Kokron+)
- **Halo model** with baryons (Fedeli)
- **Baryonic correction model** (Schneider+)
- **Emulators** from hydro sims (Arico+, Schaller+)
- Effective **parameterisations** (van Daalen+, Arico+, Mead+, van Loon & van Daalen)

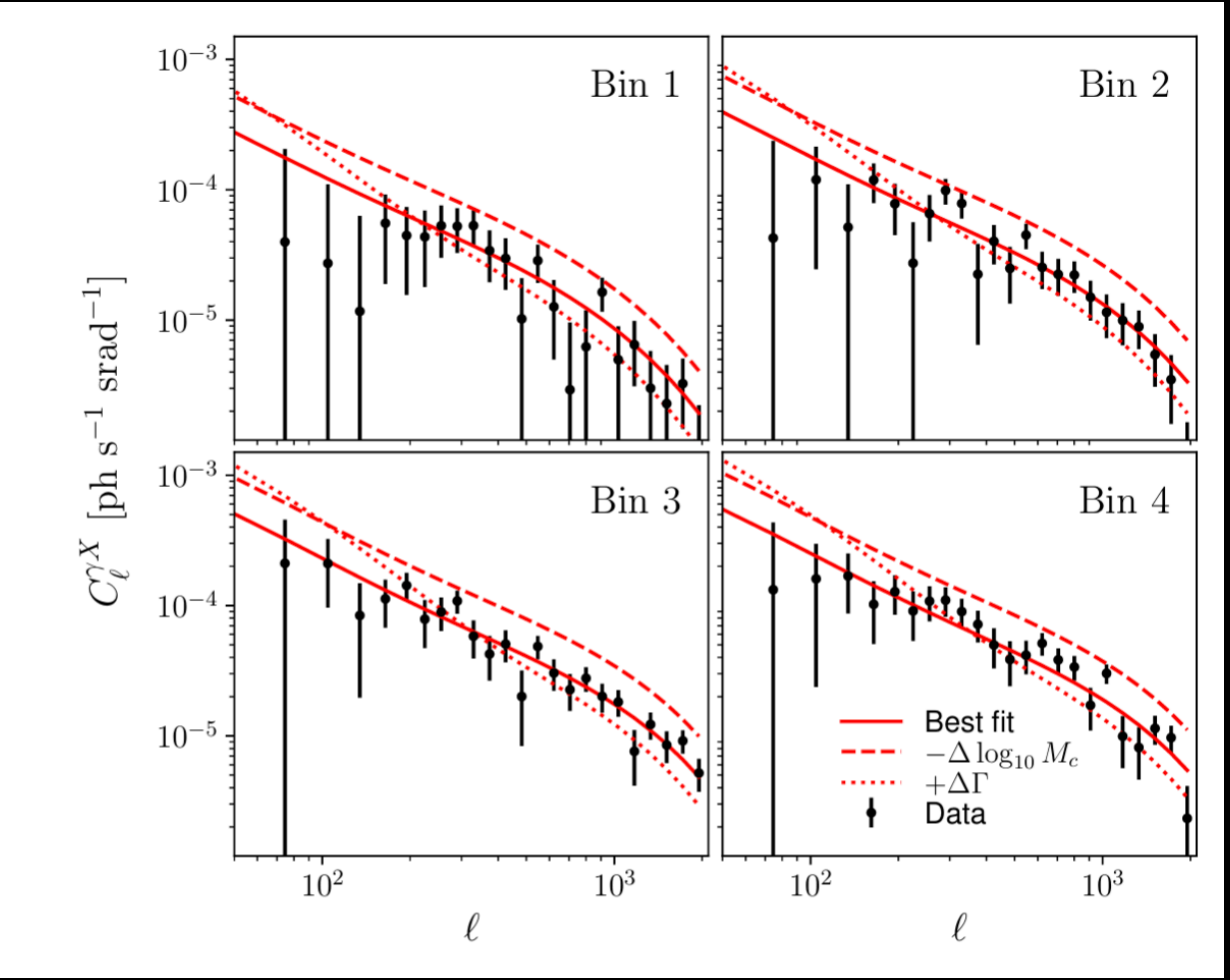
Observational priors



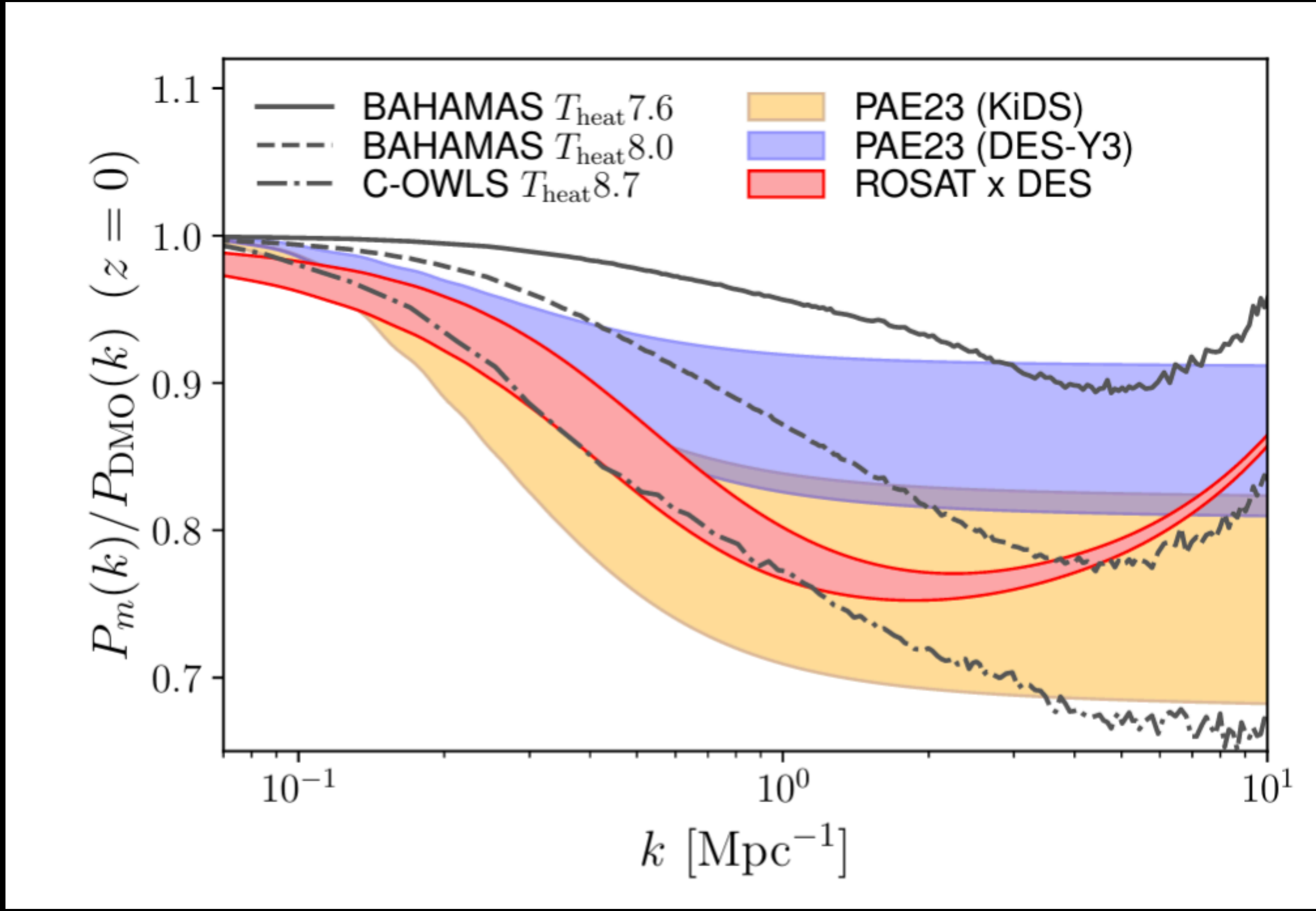
Schaye+23 - FLAMINGO

Baryonic effects

Observational priors: cross-correlation diffuse X-ray



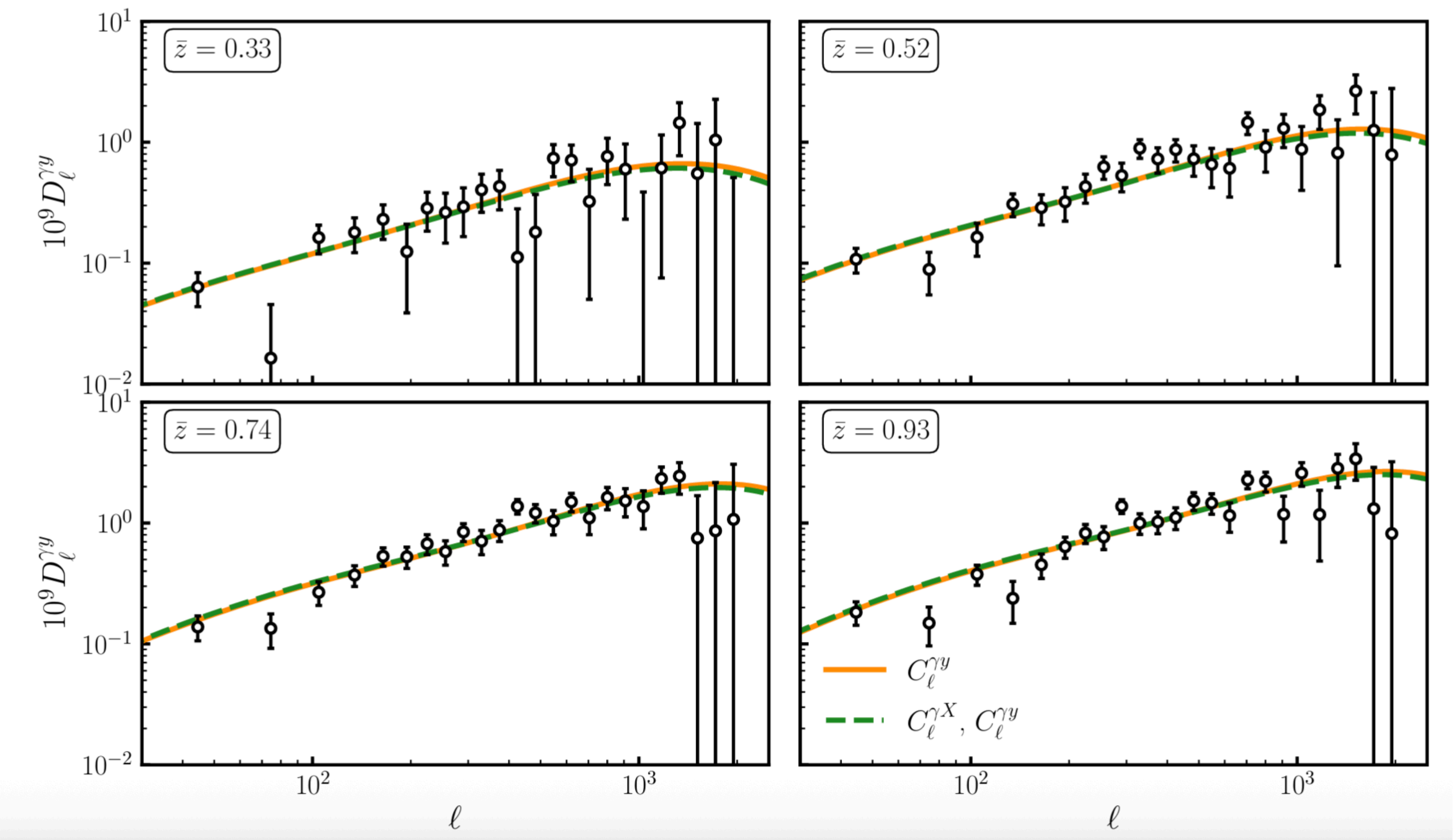
DES Y3 x ROSAT

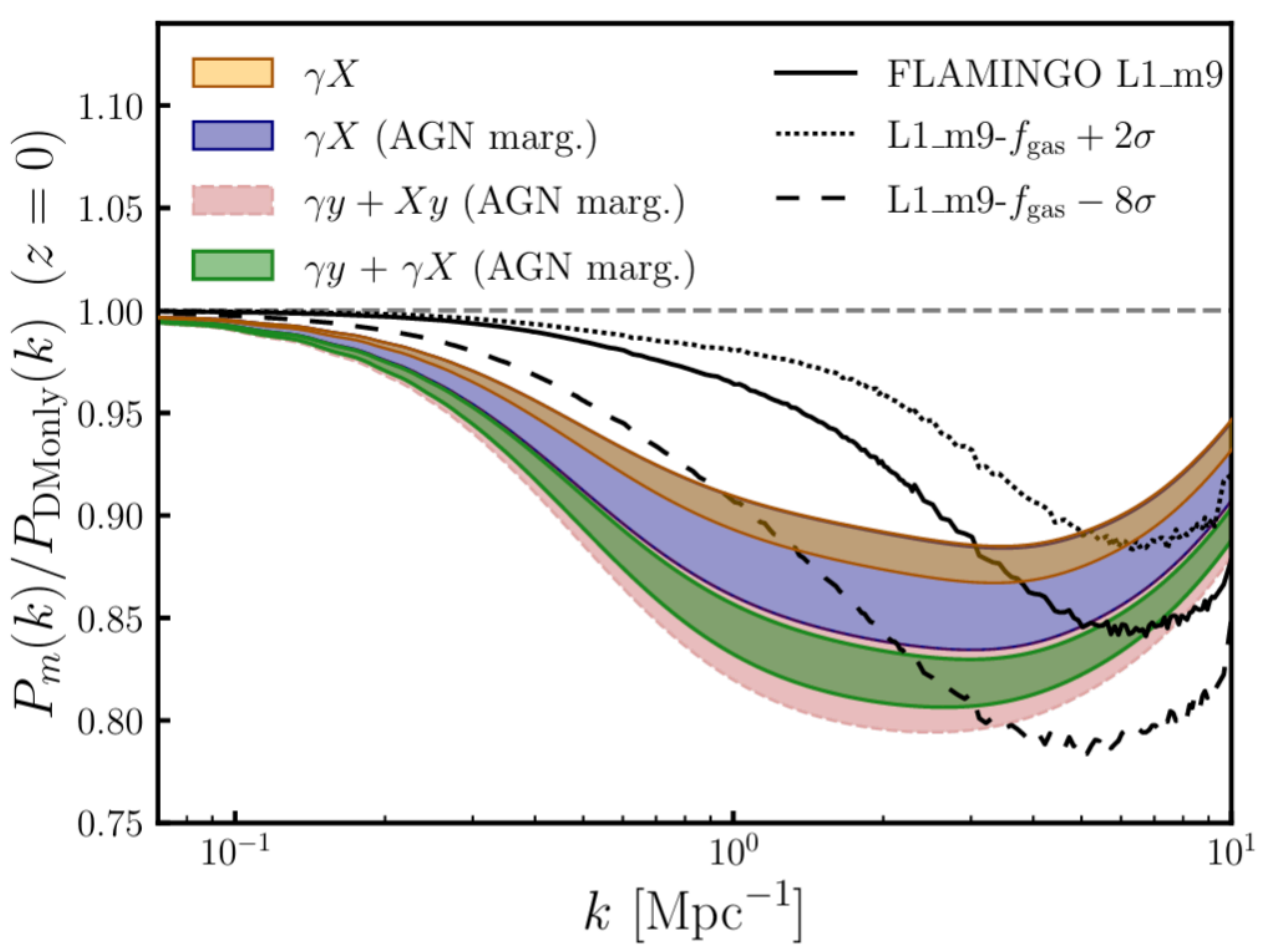


Ferreira+, incl EC (2023)

Baryonic effects

Observational priors: cross-correlation diffuse X-ray+SZ





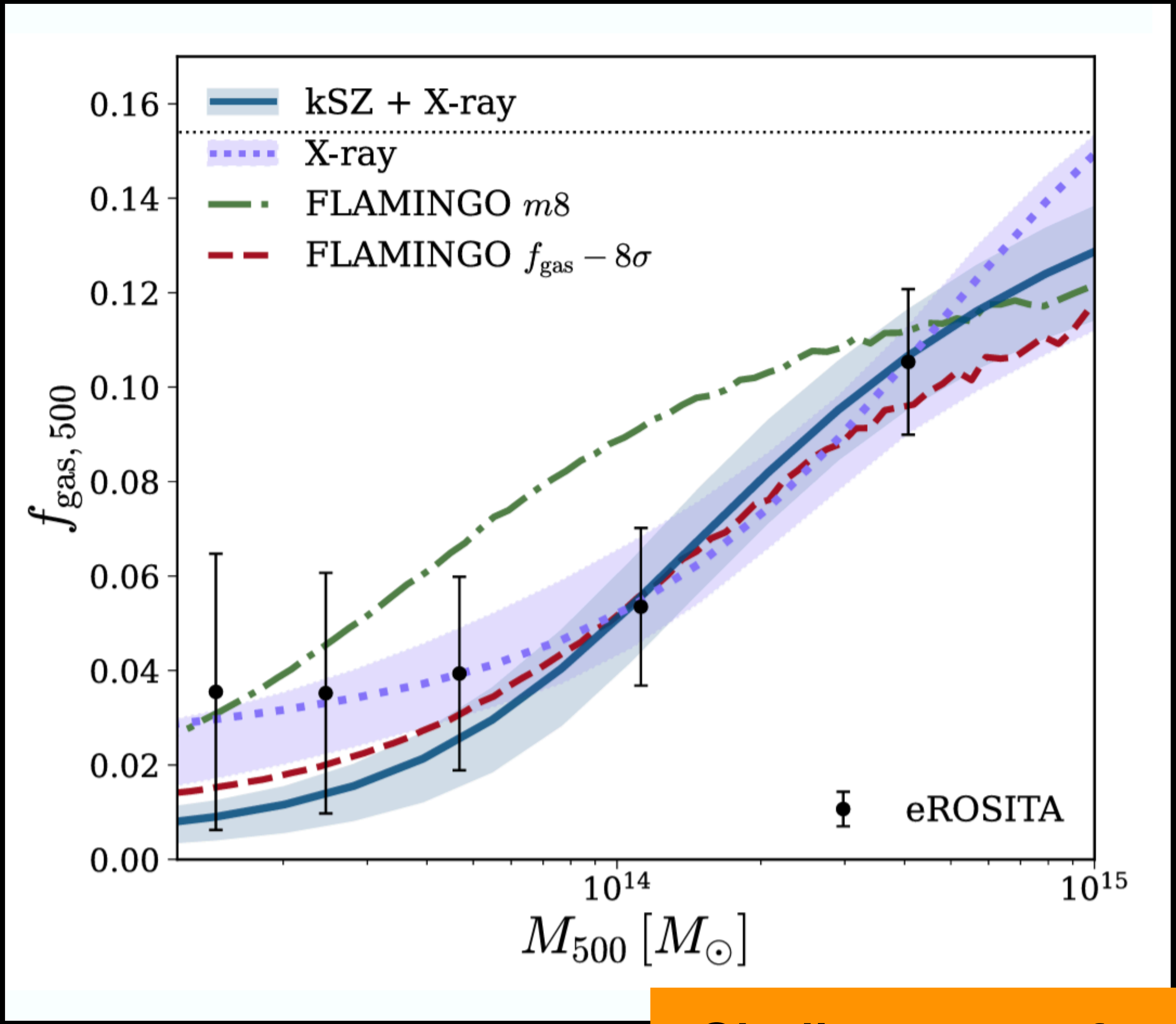
DES Y3 x ROSAT

La Posta+, incl EC (2024)

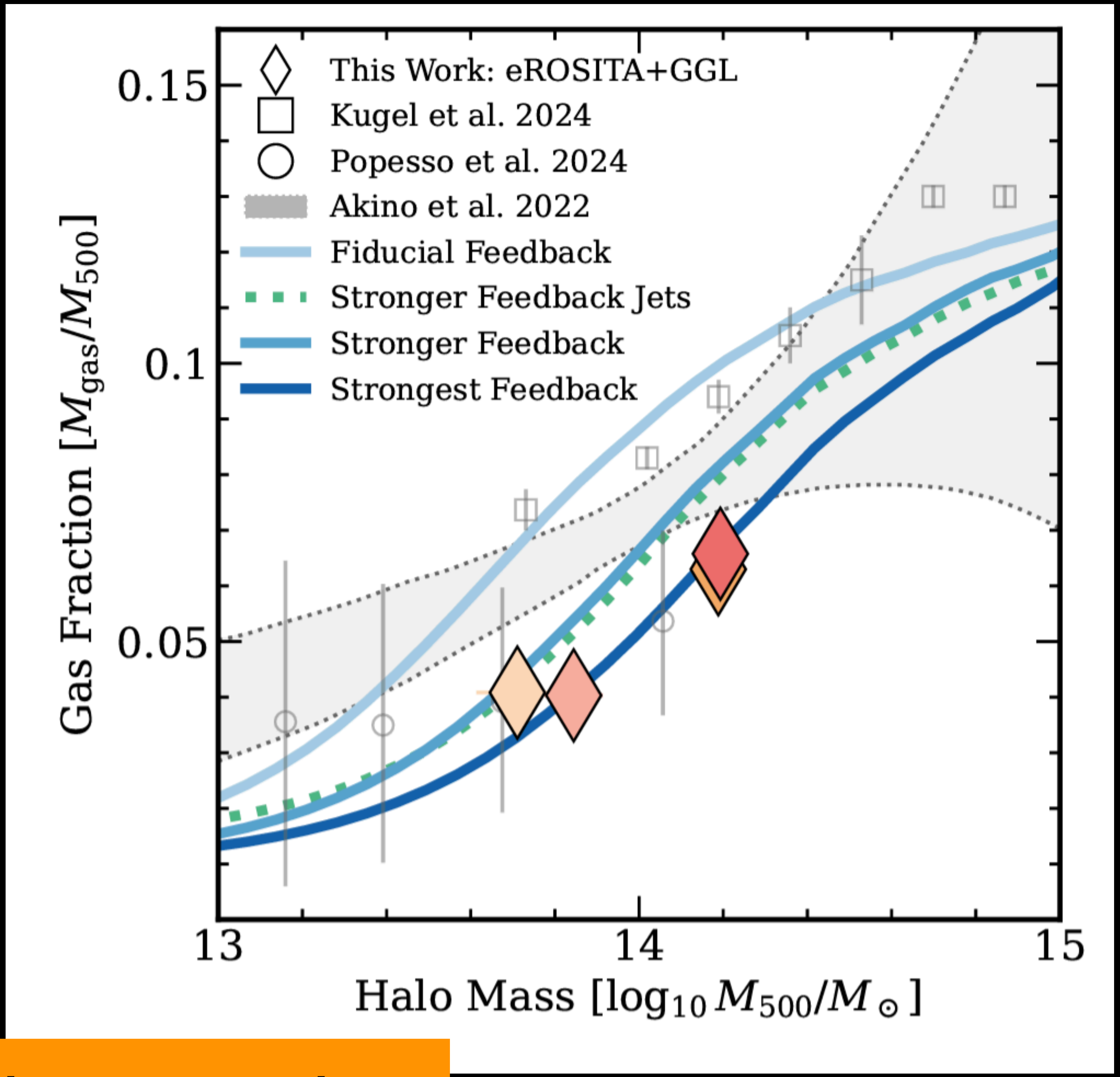
High feedback scenario also **evidenced in kSZ** (Ried Guachalla+)

Baryonic effects

Observational priors: gas fractions eROSITA



Kovac+25

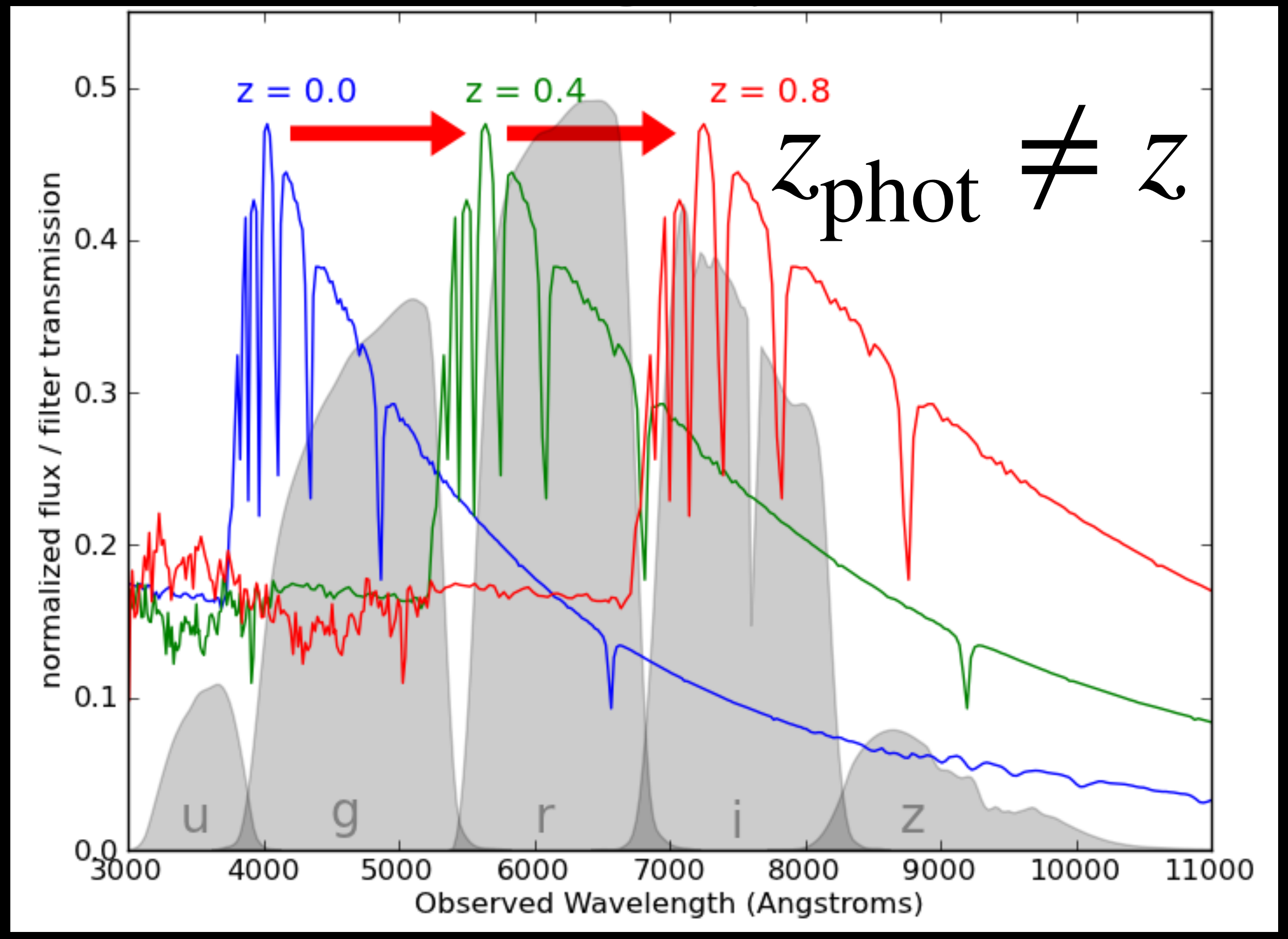


Siegel+25

Similar strong feedback suppression

Are we sensitive to the same state of the gas? Are we modeling this correctly?

Systematics at all scales and in all observables



Photometric redshifts lead to confusion and bias in which matter field we are probing.

Photo-z calibration

Table 2. Spectroscopic redshift samples used for the KiDS-Legacy redshift calibration.

Survey/Field	$N_{\rm spec}$	Area [deg^2]	Density [arcmin^{-2}]	Usage
KiDZ compilation	126 085	19.3	3.77	SOM
2dFLenS	22 675	382.4	0.02	CC
BOSS DR12	60 482	422.6	0.04	CC
DESI EDR	109 381	44.2	0.69	CC
GAMA DR4	161 839	136.1	0.33	CC
VIPERS	26 408	9.3	0.79	CC

Wright+24

Direct calibration from spectroscopic samples in deep fields

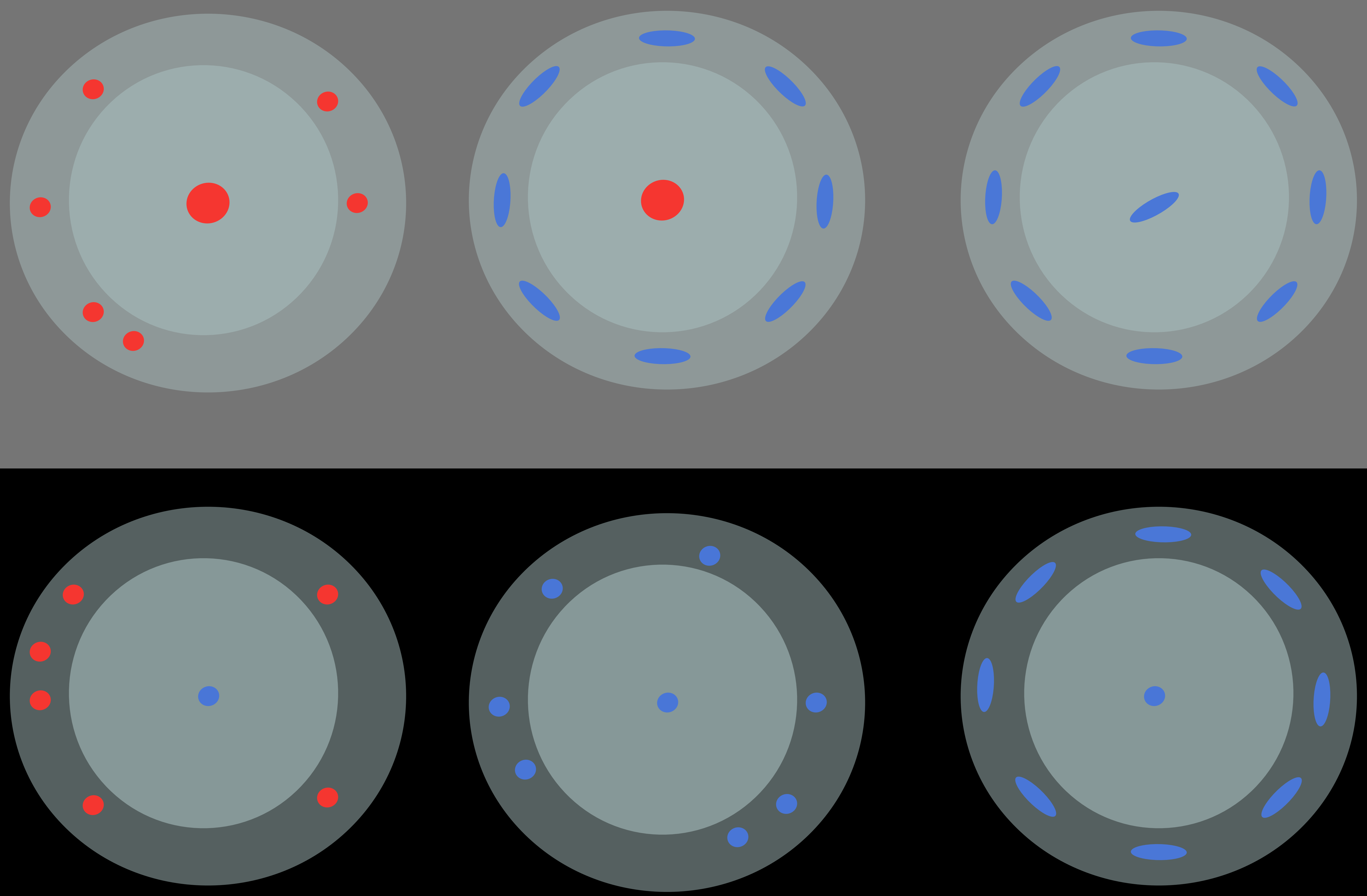
+

Cross-correlation "clustering" redshifts at higher redshift

Mitigating photo-z with 6x2pt

Original 3x2pt

Add new correlations



Spectroscopic-photometric cross-clustering.

Photometric clustering.

Lensing around photometric lenses.

Why extend this?

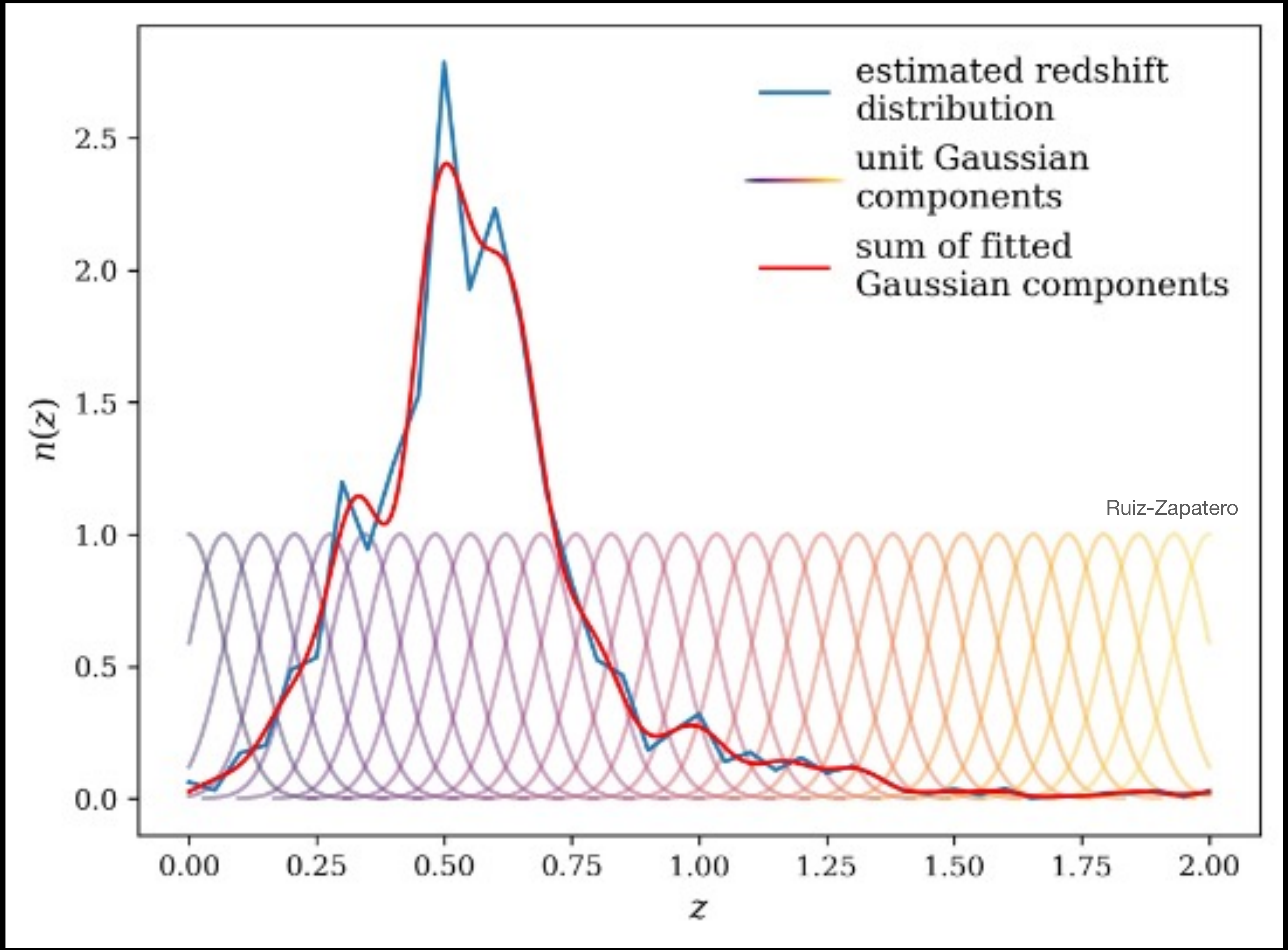
- Higher number density.
- Requirements on n(z) uncertainty more stringent.
- Shared redshift distribution.

✓ Tighter constraints (~40%).

✓ Better redshift self-calibration

Johnston, EC+24

Flexible n(z) parametrization



Initial comb fit: Concatenated vector of α tomographic redshift distributions is $n_{\rm comb}(z)$ is fit to any arbitrary $N(z)$, with associated covariance $\Sigma_{n(z)}$.

$\mathcal{N}_{\rm comb}$: allow data to **calibrate the comb at fixed cosmology.**

More flexibility? Allow for **shifts** when opening up the cosmology ($\mathcal{N}_{\rm comb} + \delta z_i$)

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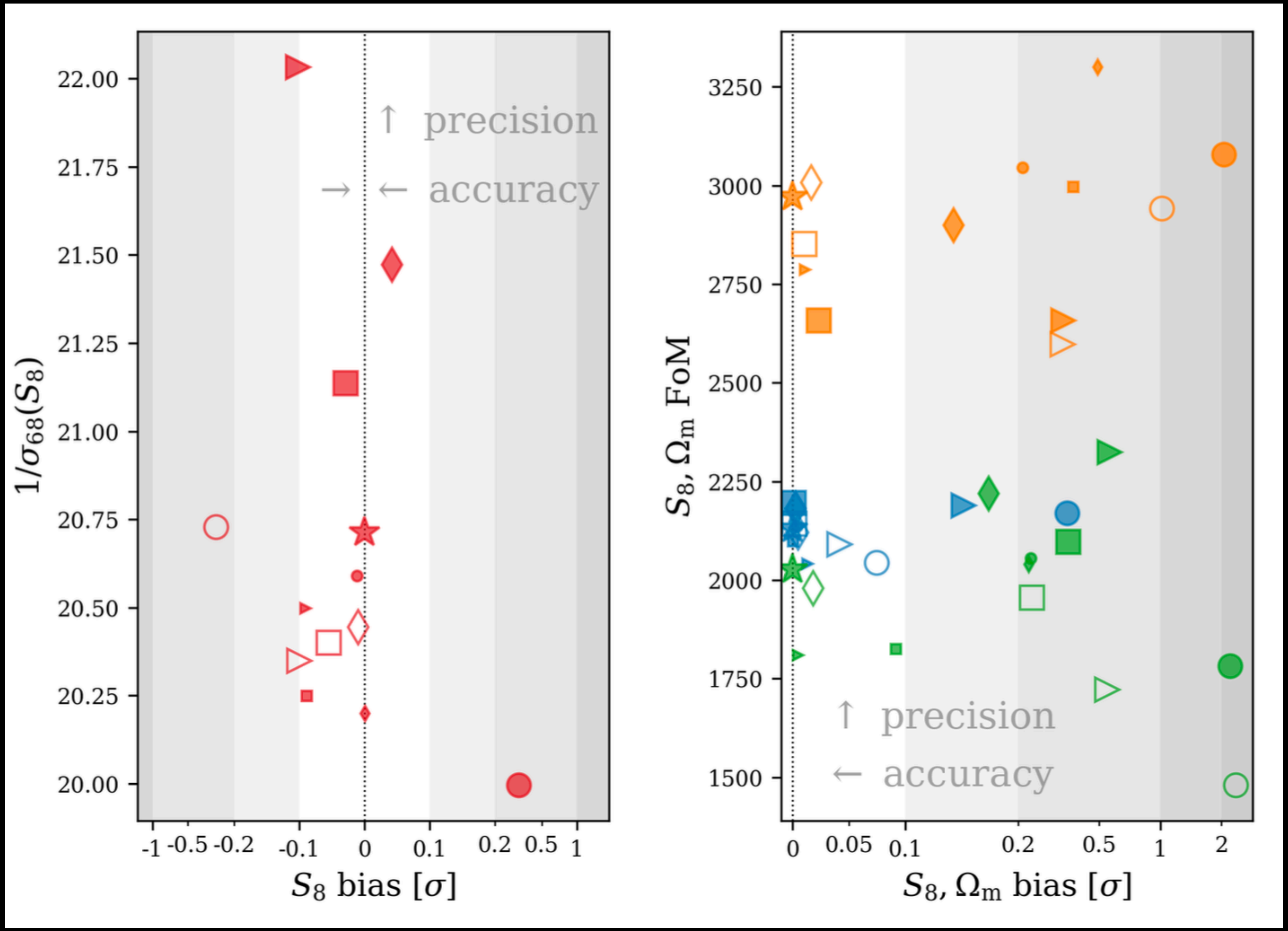
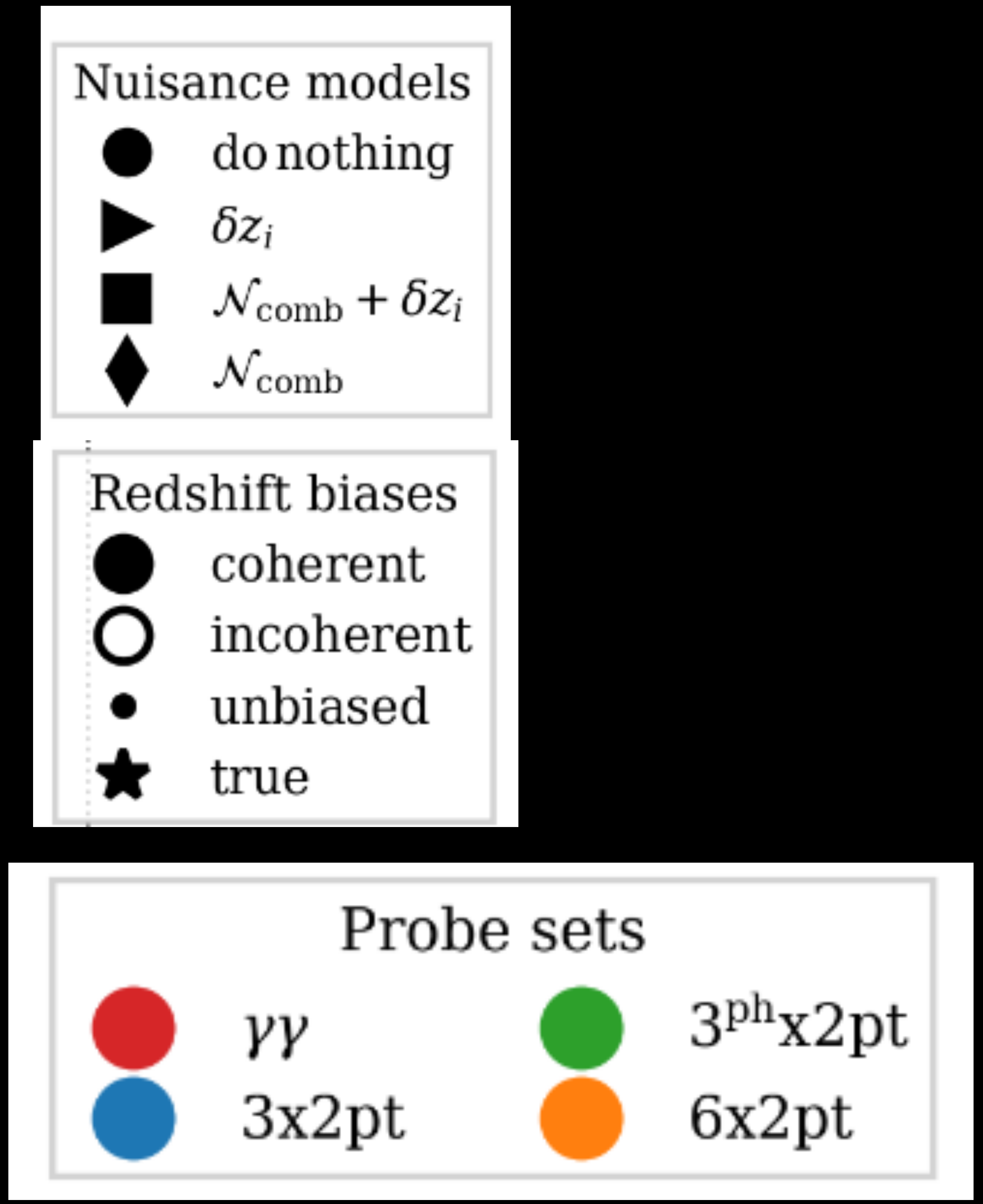
Kuijken+ (proposed)
Stolzner+ (applied to cosmic shear)
Other options: Ruiz-Zapatero+

Mitigating photo-z with 6x2pt: Stage III





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Mitigating photo-z with 6x2pt: Stage IV

Unmitigated shifts result in $> 6\sigma$ biases.

Idealised 6x2pt FoM retained at >90% because shifts are self-calibrated (much less for other probe combinations)

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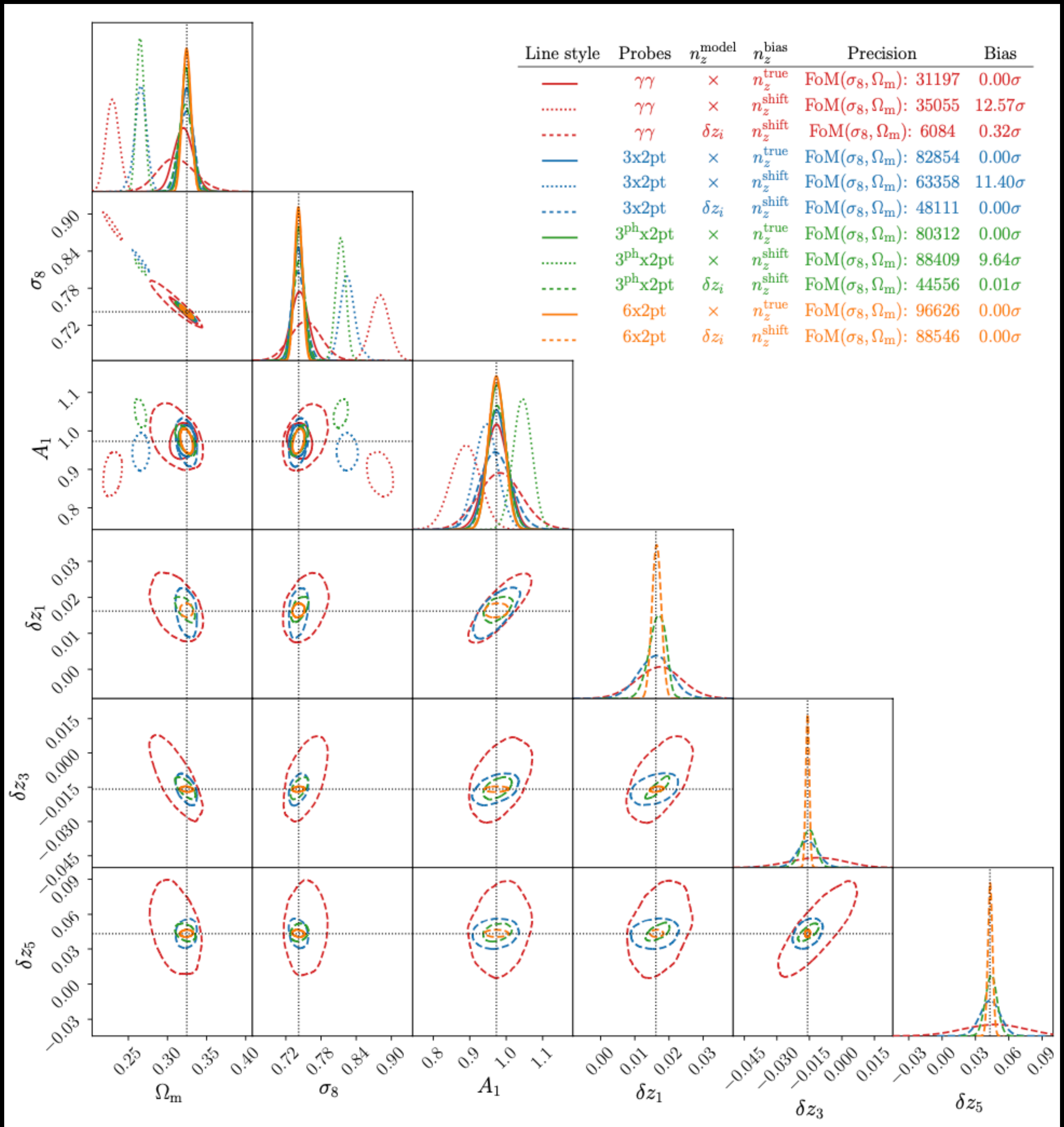


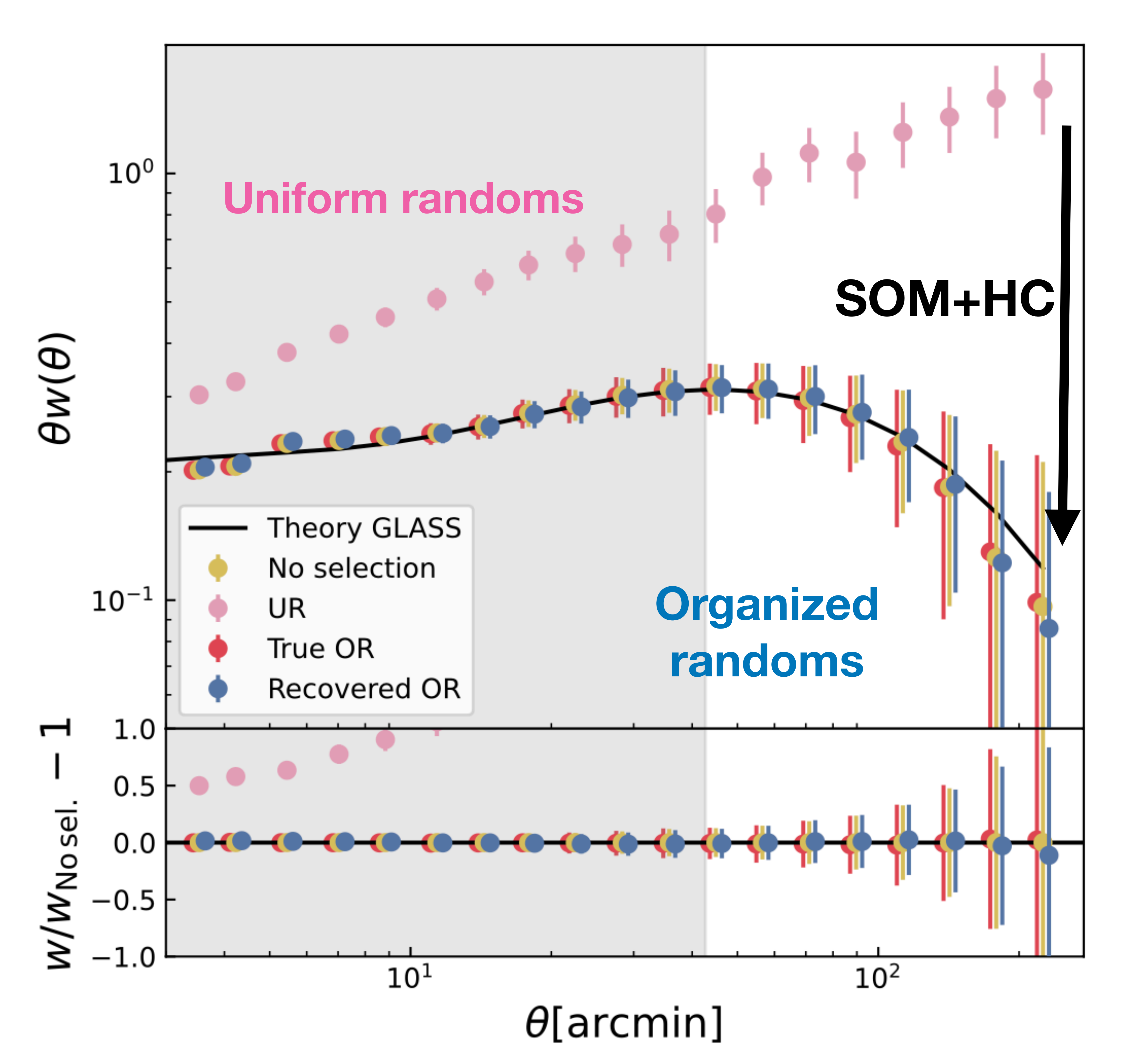
How hard is photometric clustering at full depth?

Particularly sensitive to **survey systematics** like: depth, PSF size, etc.

Corrected with **organized random** weights derived from Self-Organising Maps (SOM) + hierarchical clustering at **full depth.**

We tested the method on **lognormal mocks,** applied to the **blinded KiDS-Legacy data** with similar results.

Yan+24, see Johnston+21 for our bright sample (-5 dex).



Cosmology with (weak) gravitational lensing

Summary

- Weak lensing probes dark energy through **distances and growth.**
- **Cosmic shear and 3x2pt** analyses are ongoing and face several **modelling challenges:** e.g. bias, baryons, alignments, photo-z.
- Most recent weak lensing constraints from KiDS Legacy **consistent with Planck**. (Improved photo-z calibration + increased statistics main drivers.) **Other surveys consistent** as well.
- Euclid and LSST will deliver **<10% constraints** on the equation of state of dark energy. We need to be **well-prepared.**
- **Cross-correlations** will help towards mitigating some of the systematics (photo-z, baryons). For IA, modeling and marginalization, with conservative priors.