The S_8 tension (with KiDS, Euclid)

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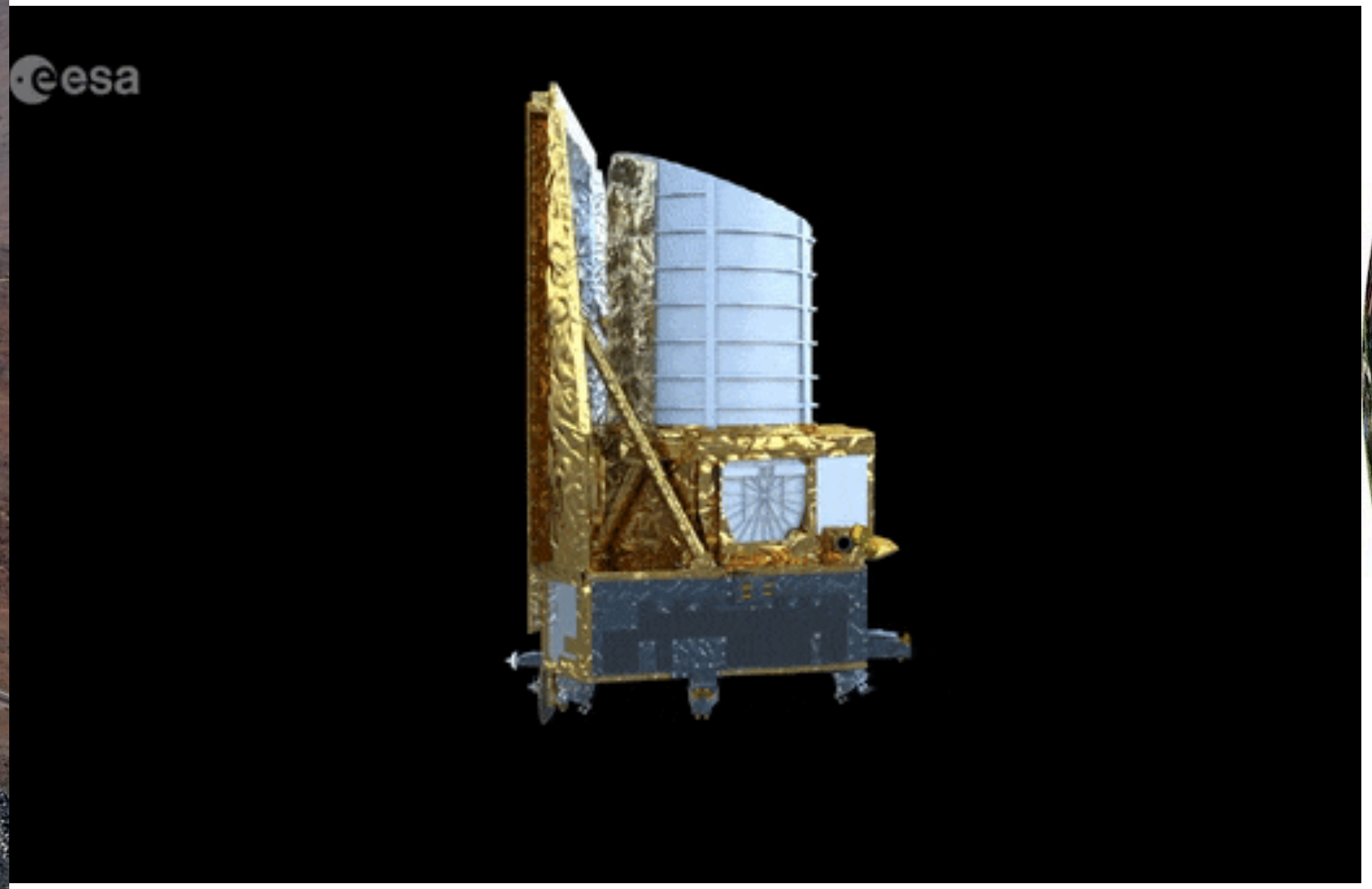
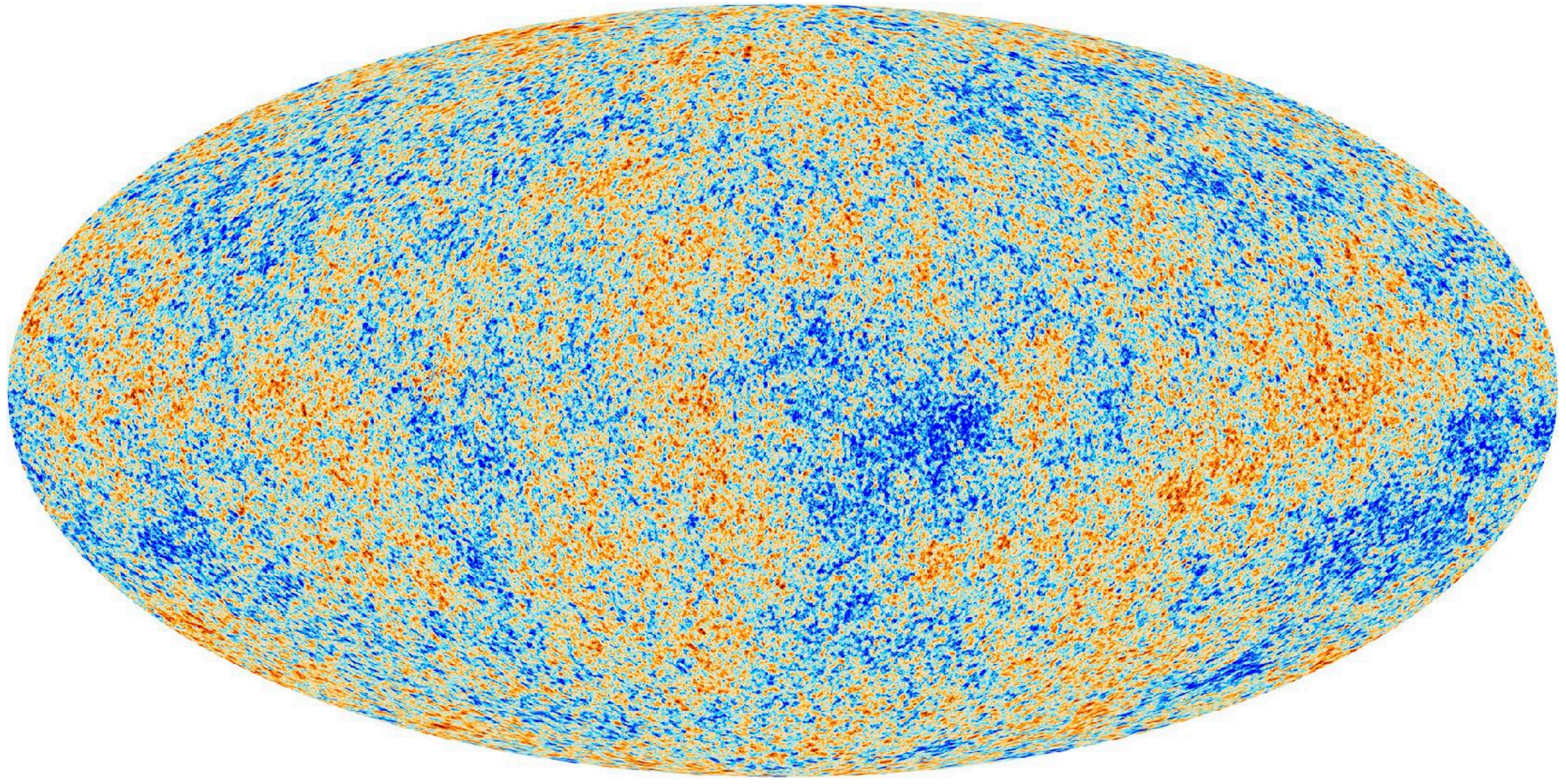
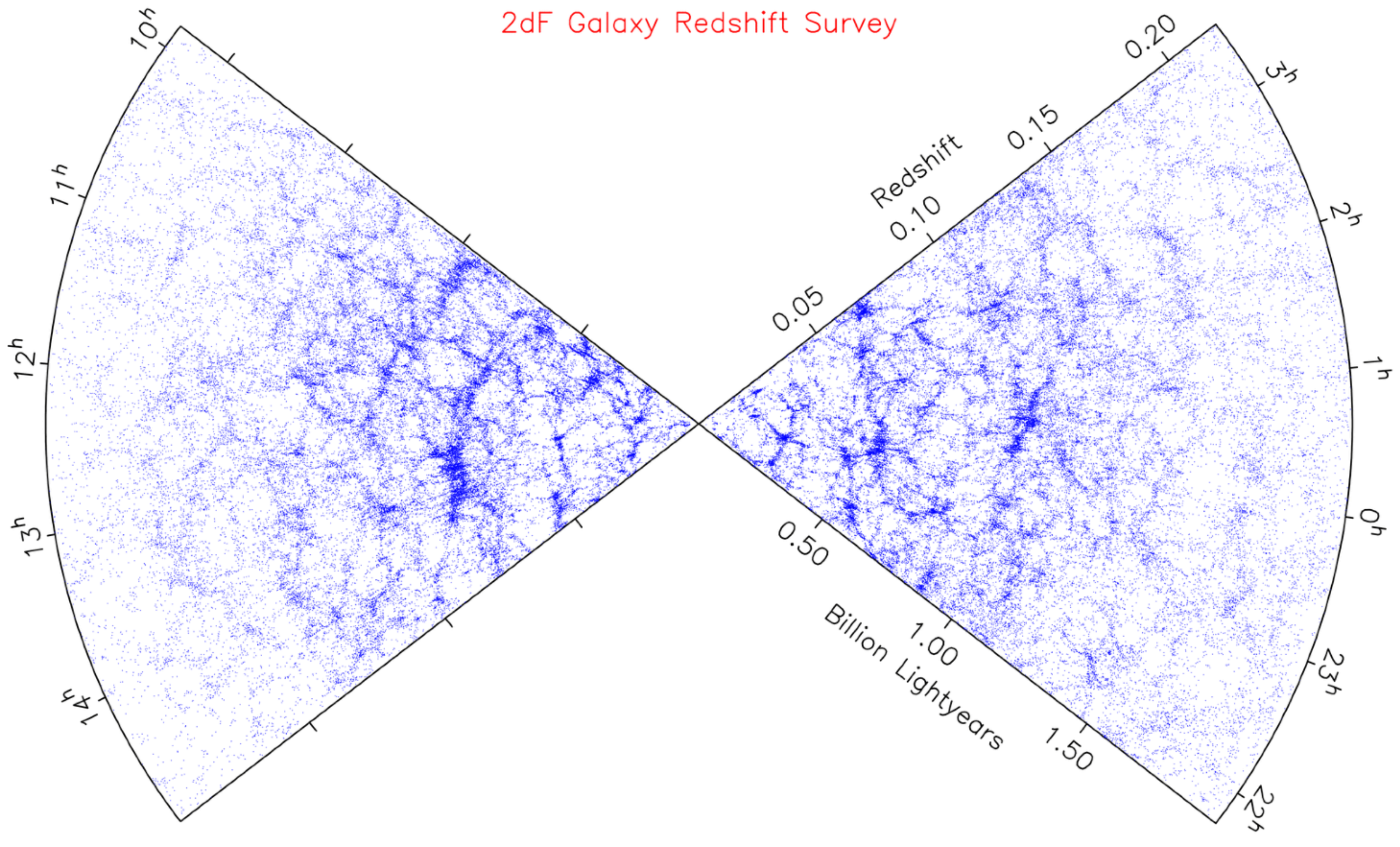


Large-scale structure

- **Early-time** large-scale structure well measured from CMB anisotropies
  - z ~ 1000, t ~ 300.000y
- **Late-time** large-scale structure is reflected in x,v distribution of galaxies (*biased*)
- and in the weak lensing of distant galaxy images



ΛCDM



- Model comparison of amplitudes in context of structure formation in ΛCDM

Gravitational lensing/cosmic shear

- Gravitational fields deflect light rays ($\propto$ mass), which distorts the sky -- ***shear***
- Shear can be measured by stacking galaxy ellipticities
- Shear can be converted to mass map of large-scale structure

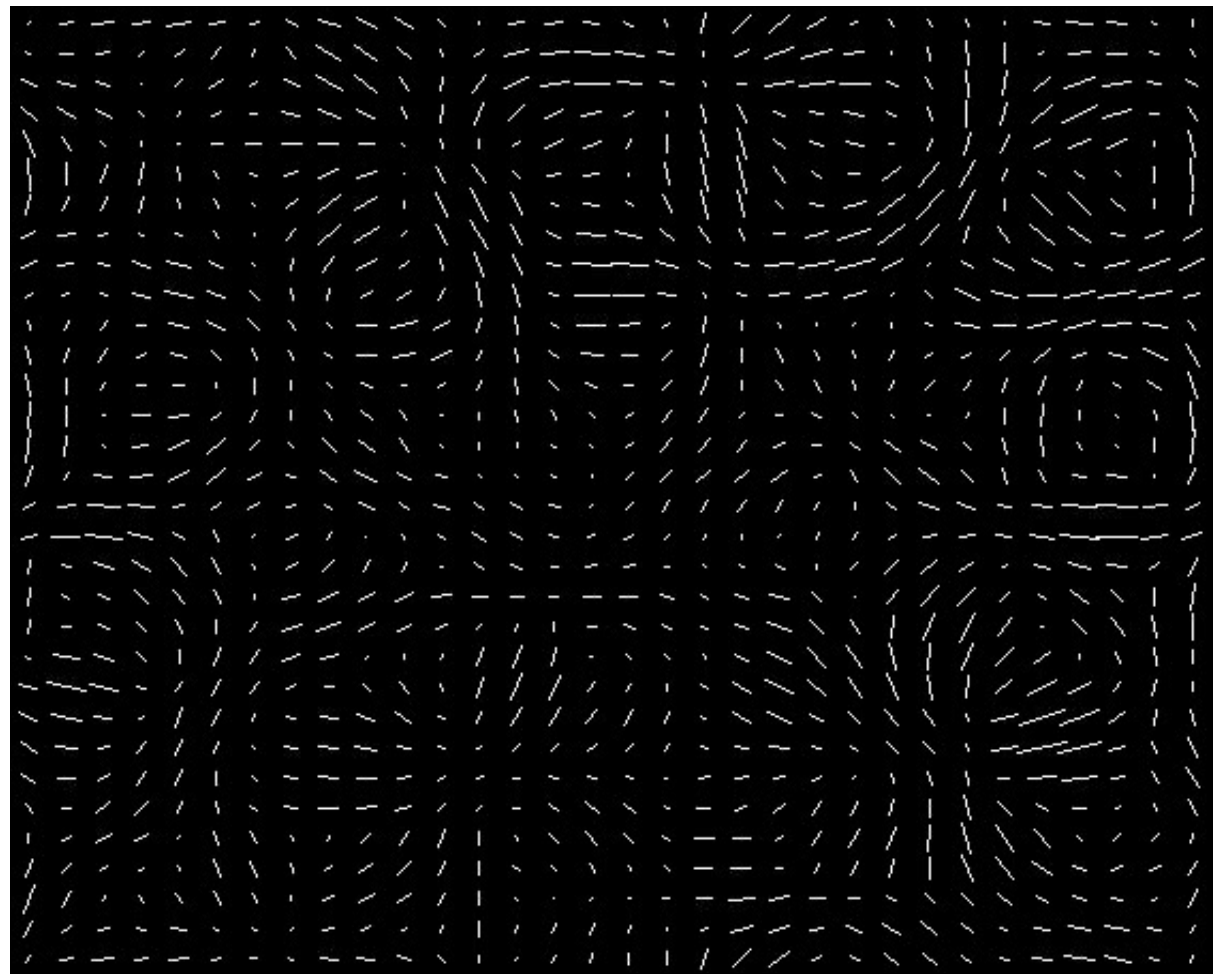
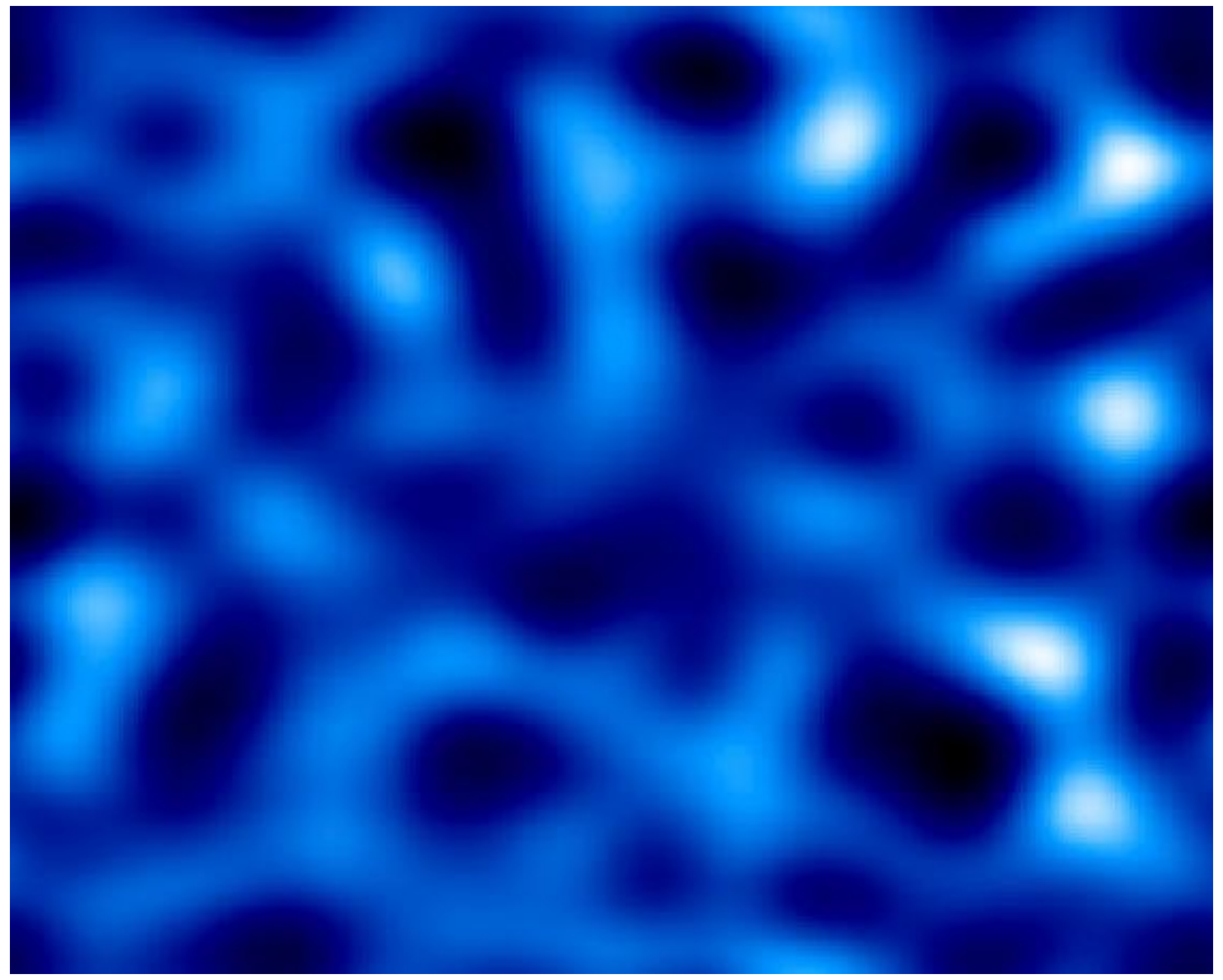
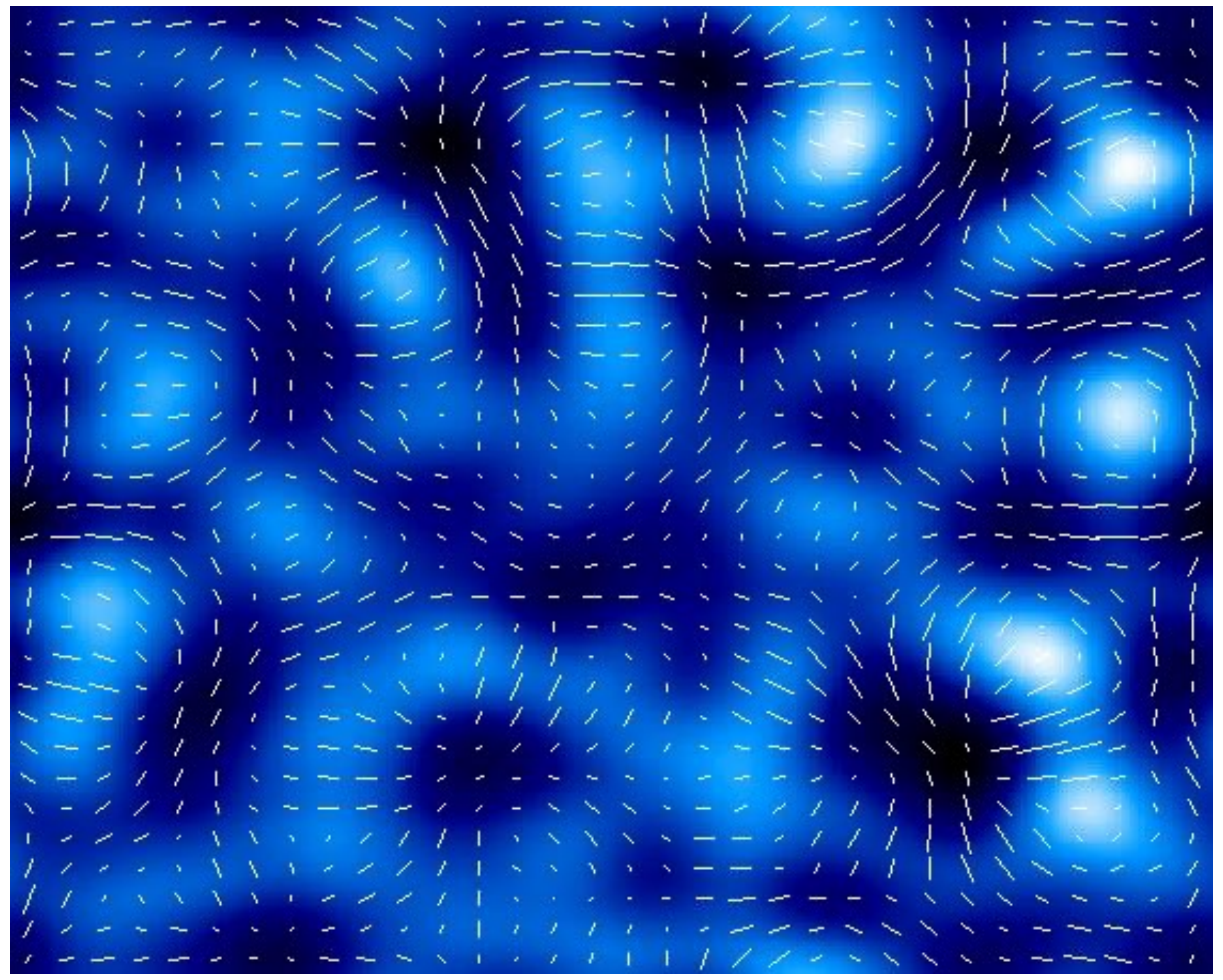




image credit: A.Amara

- Effect first detected in 2001; last decade has seen 3 dedicated surveys

KiDS **DES** **HSC**

Weak gravitational lensing

- Distortions of the sky that accompany displacements due to lensing
- Mapping the distortions → mapping the mass

Three weak lensing surveys

hundred(s) of nights of telescope time each!

	DES	KiDS	HSC
total area	5000	1350	1400
telescope	4m CTIO	2.6m VST (opt) 3.9m VISTA (IR)	8m SUBARU
image quality	0.9”	0.7”	0.6”
inverse shear var arcmin^{-2}	65-90	105	>200
bands	grizy	ugriZYJHK	grizy
mean redshift	0.7	0.77	~0.9
results so far	5000 deg^2 (yr 3)	1000 deg^2 (DR4)	300 deg^2 (DR2)

Bananas - why S_8 ?

KiDS

- Cosmic shear is mainly sensitive to large-scale **mass density excess**
  - high mass density with small relative overdensity
  - low mass density with high relative overdensity

  } **very similar lensing power spectrum**

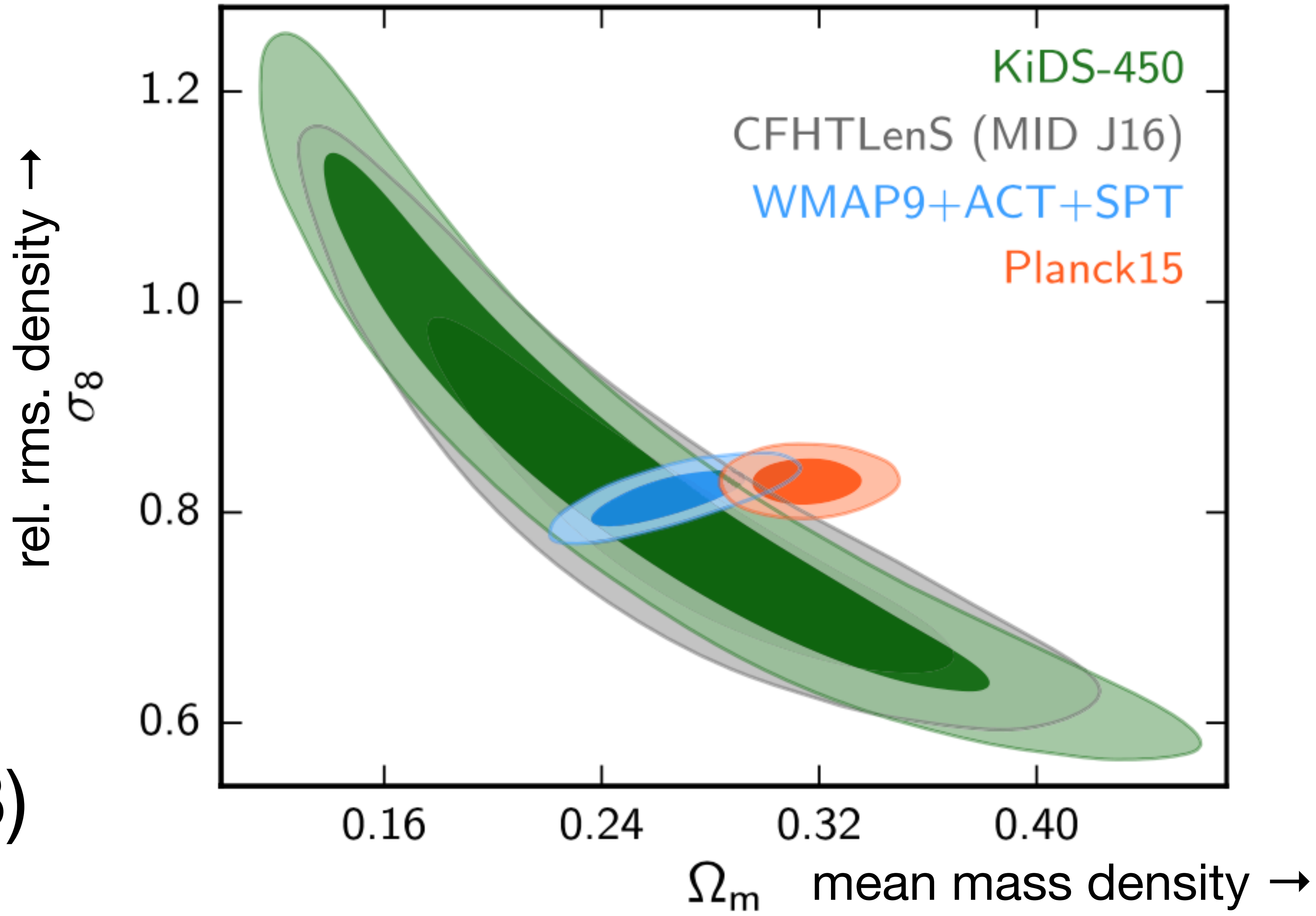
- Lensing bananas! $S_8 = \sigma_8\sqrt{\Omega_m/0.3}$

- Reason for degeneracy along banana:

  long line of sight integrations

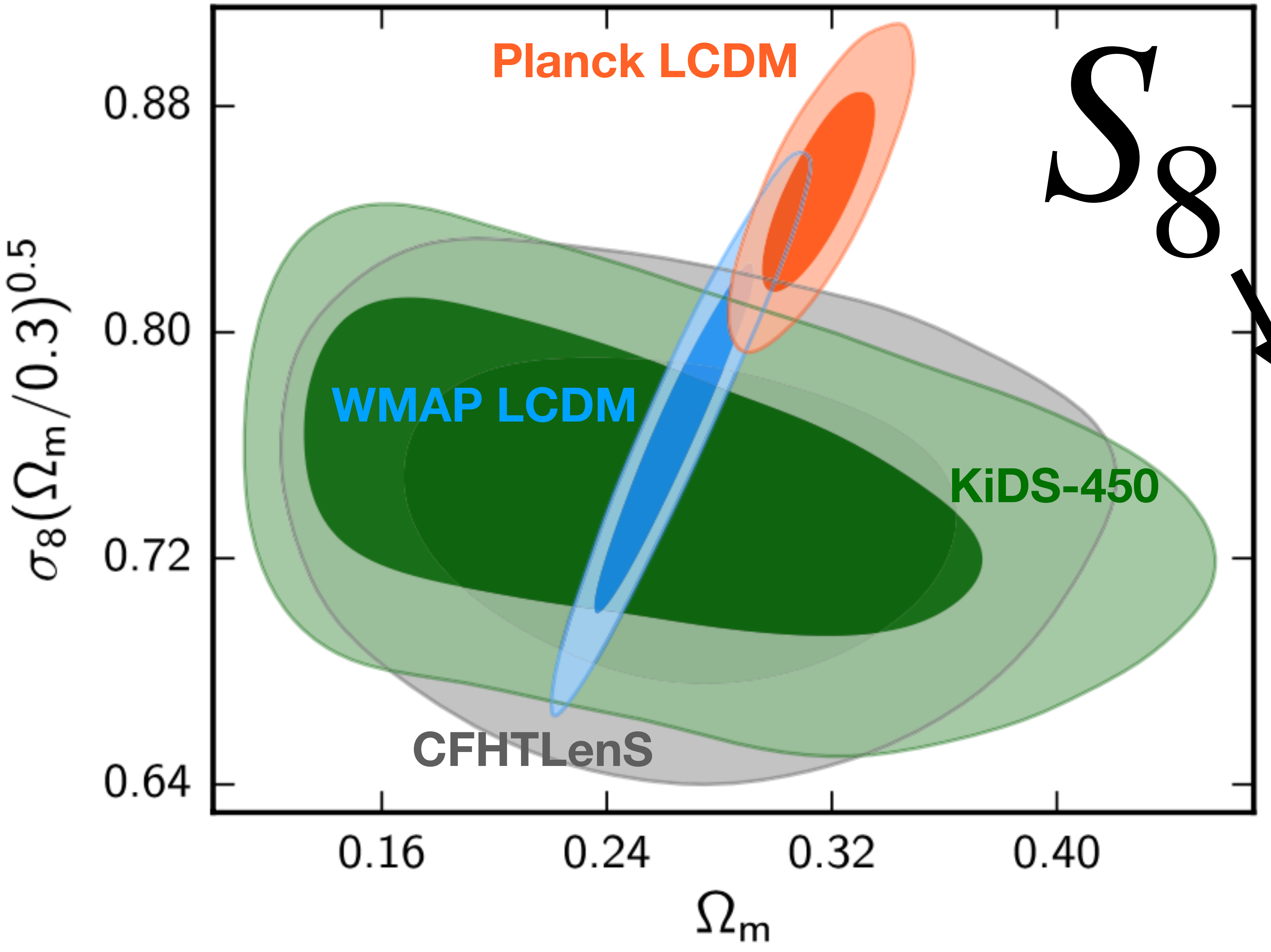
  mixes scales from different redshifts

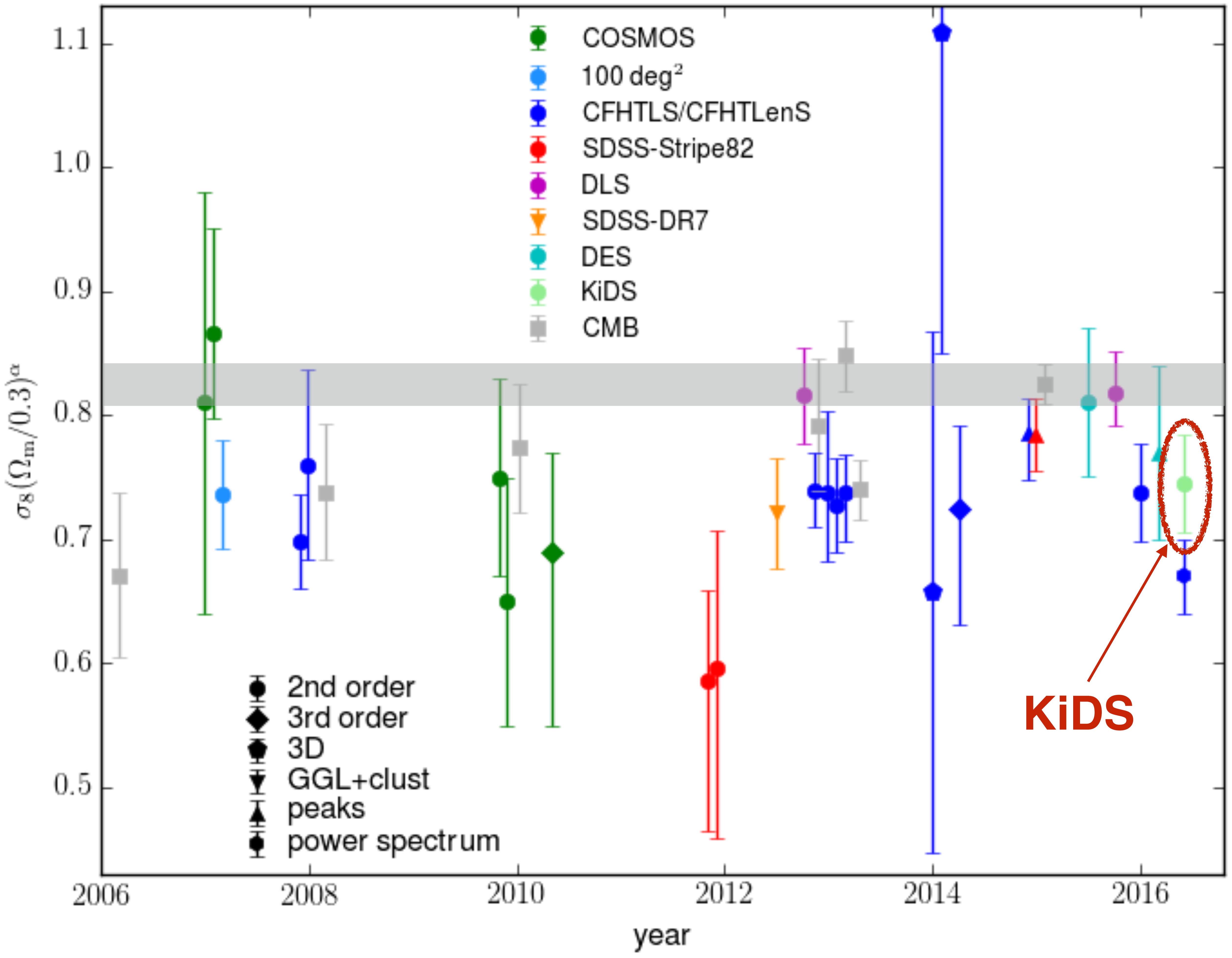
  (10' at z=0.7 = 4.3Mpc; =2.7Mpc at z=0.3)

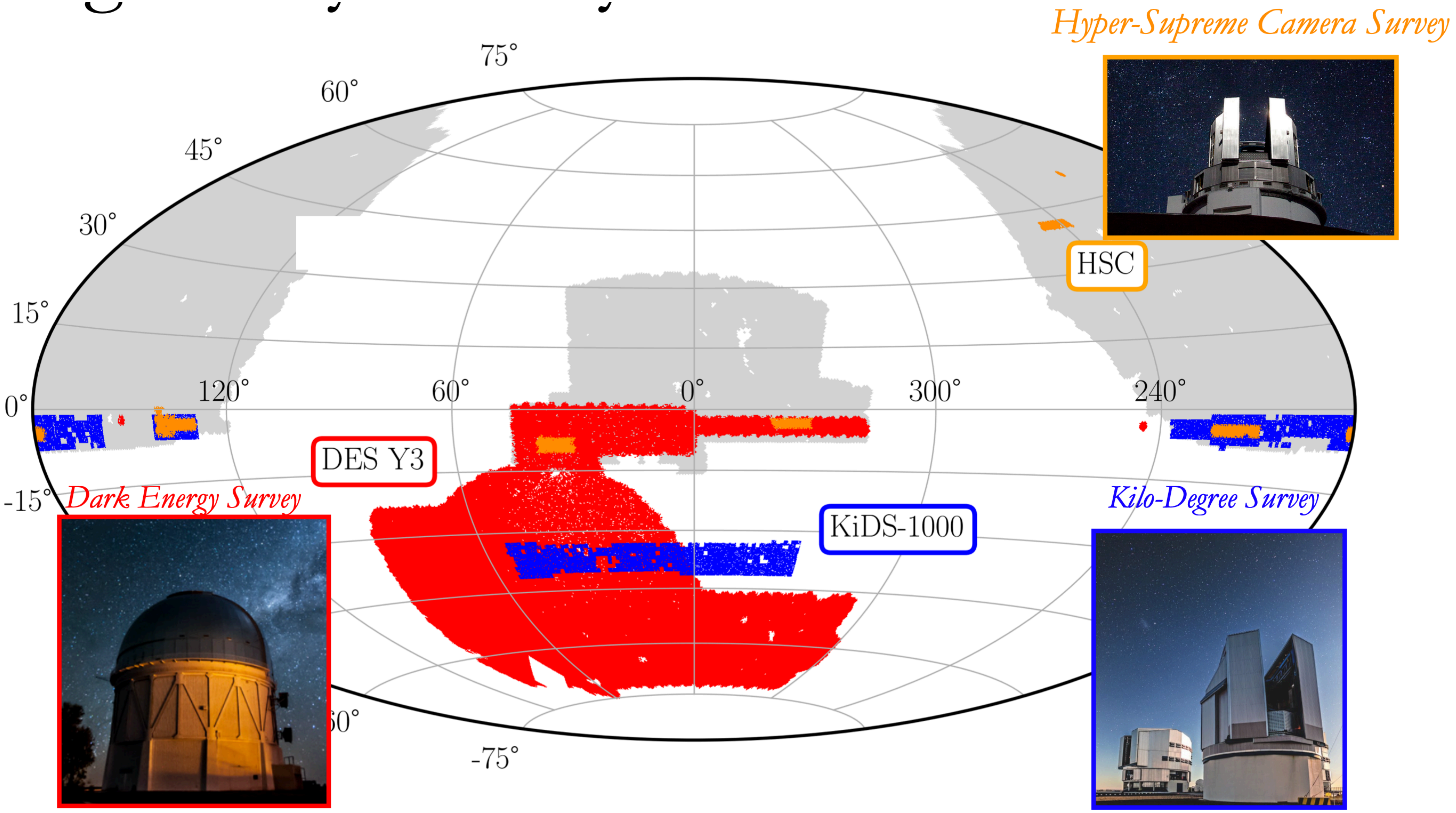


S_8 from KiDS-450, CFHTLS

- 'Kilbinger plot' (2015++)



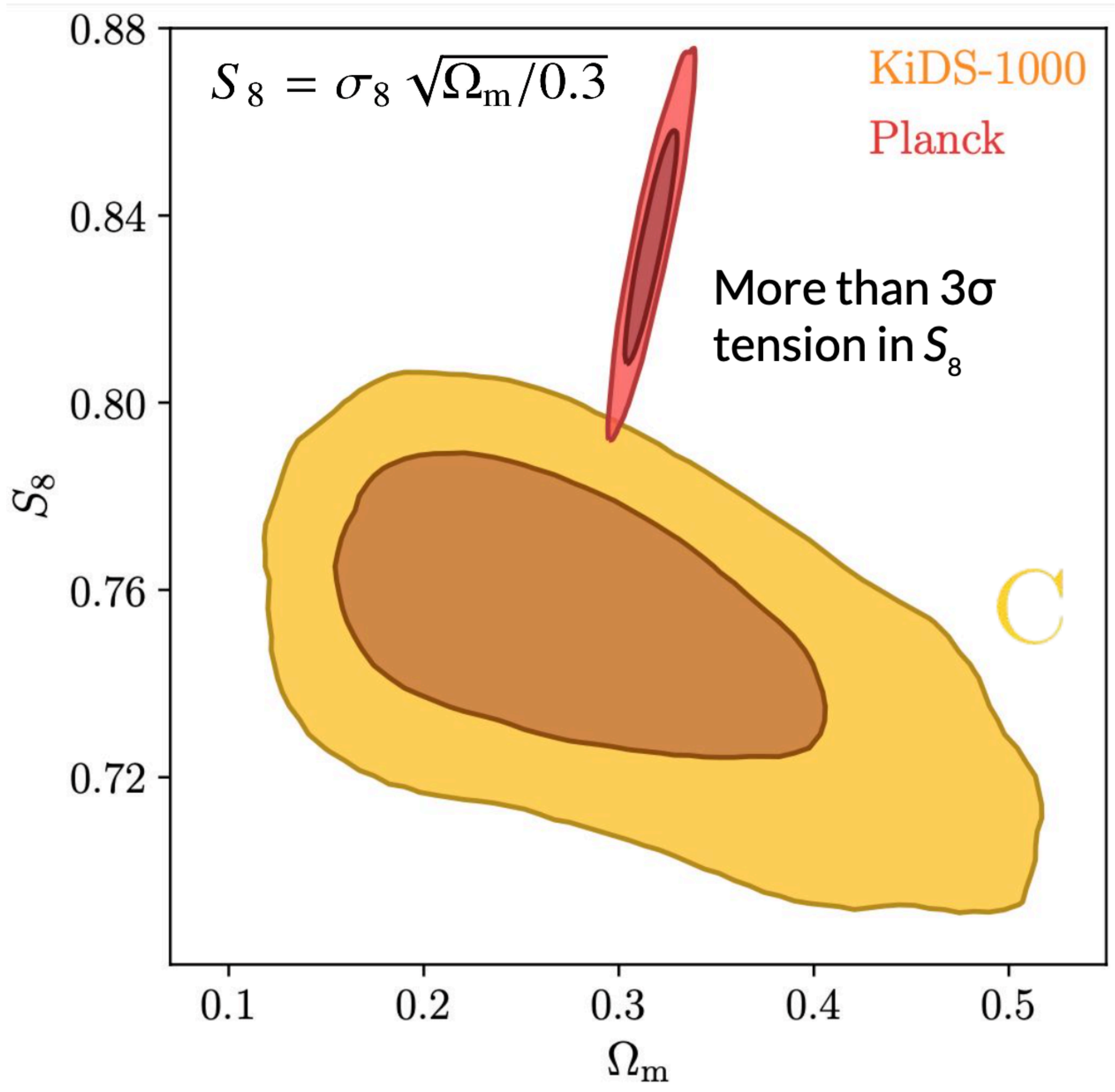


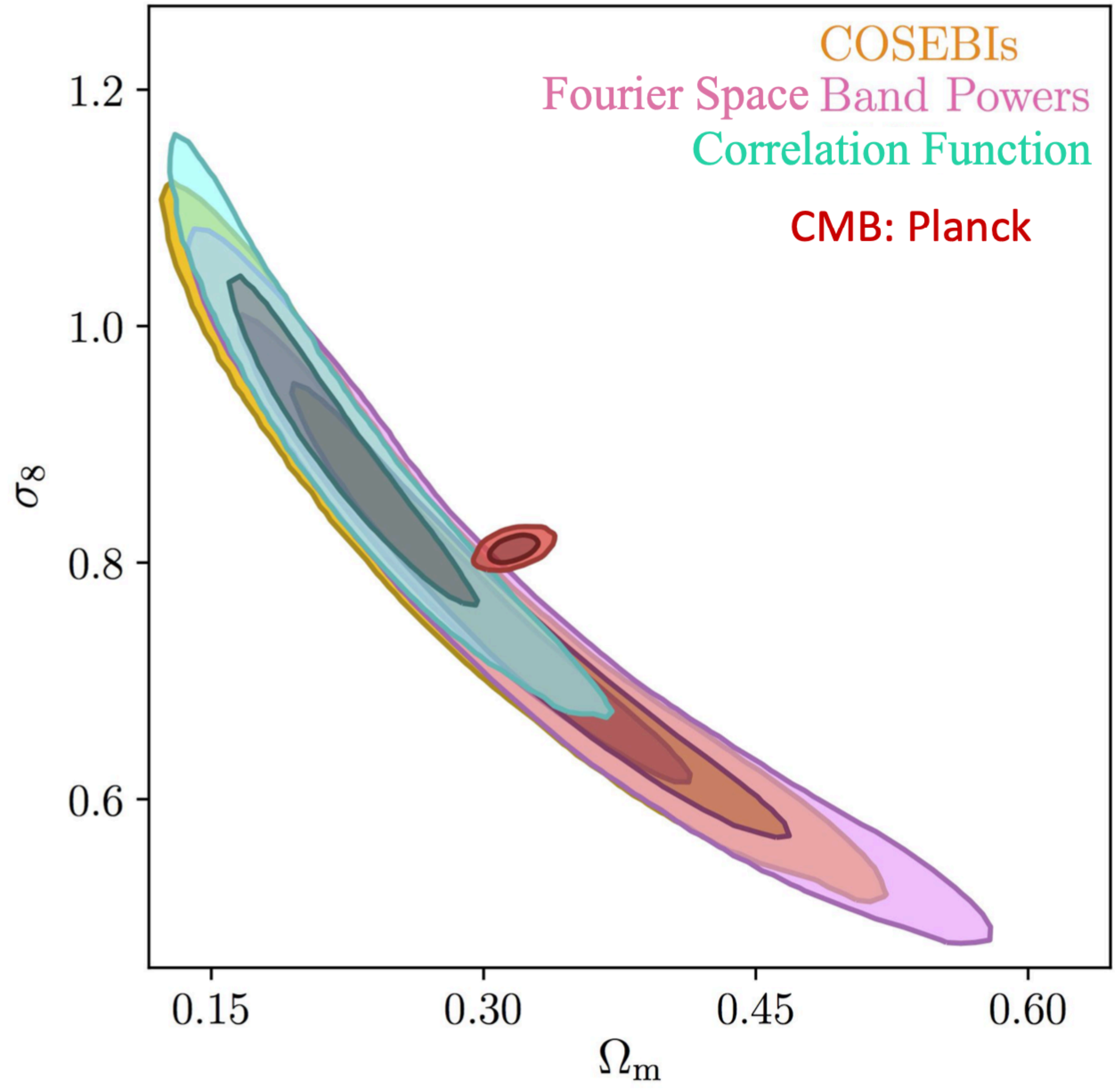


[*Amon & Robertson+2022*]

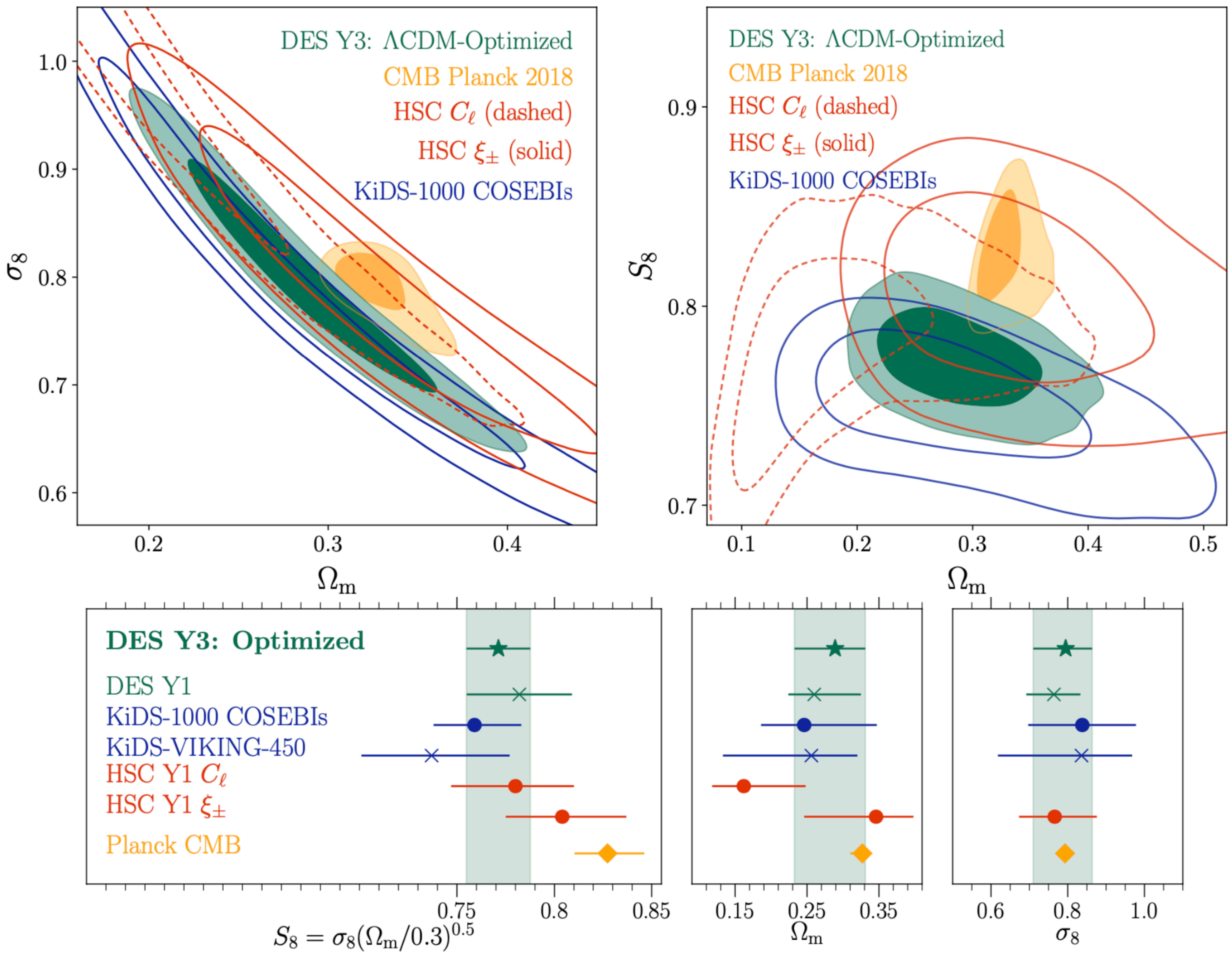
KiDS-1000 , DES-Y3, HSC-Y1

- KiDS-1000 (Asgari et al 2020): cosmic shear tension confirmed after doubling data





KiDS-1000 , DES-Y3, HSC-Y1



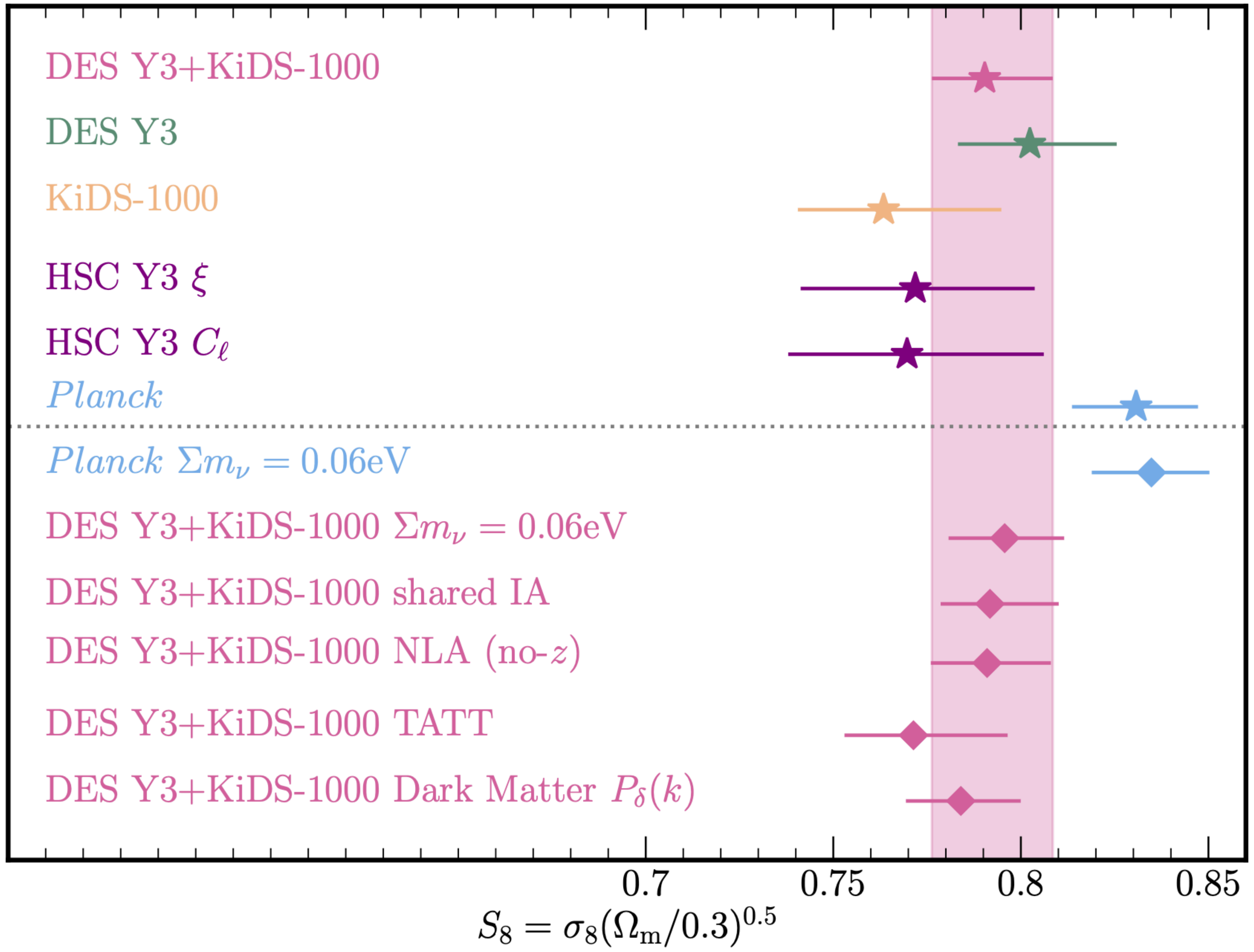
Hikage et al. 2019
Hamana et al. 2020

NB different Planck posterior - due to free neutrino mass

[*Amon+2021*]

Latest: KiDS+DES, HSC-Y3

- Combined constraints from KiDS-1000 and DES-Y3 (DES & KiDS collab's 2023)
  - Not simply multiplying the posteriors!
  - Requires harmonising analysis choices
    - cuts vs baryon modelling, IA, 2-pt statistic, MCMC sampler, cosmology code...
    - S_8 remains low cf. CMB



- HSC-Y3 (Dalal++2023, Li++2023)
  - very deep data, photo-z uncertain

KiDS

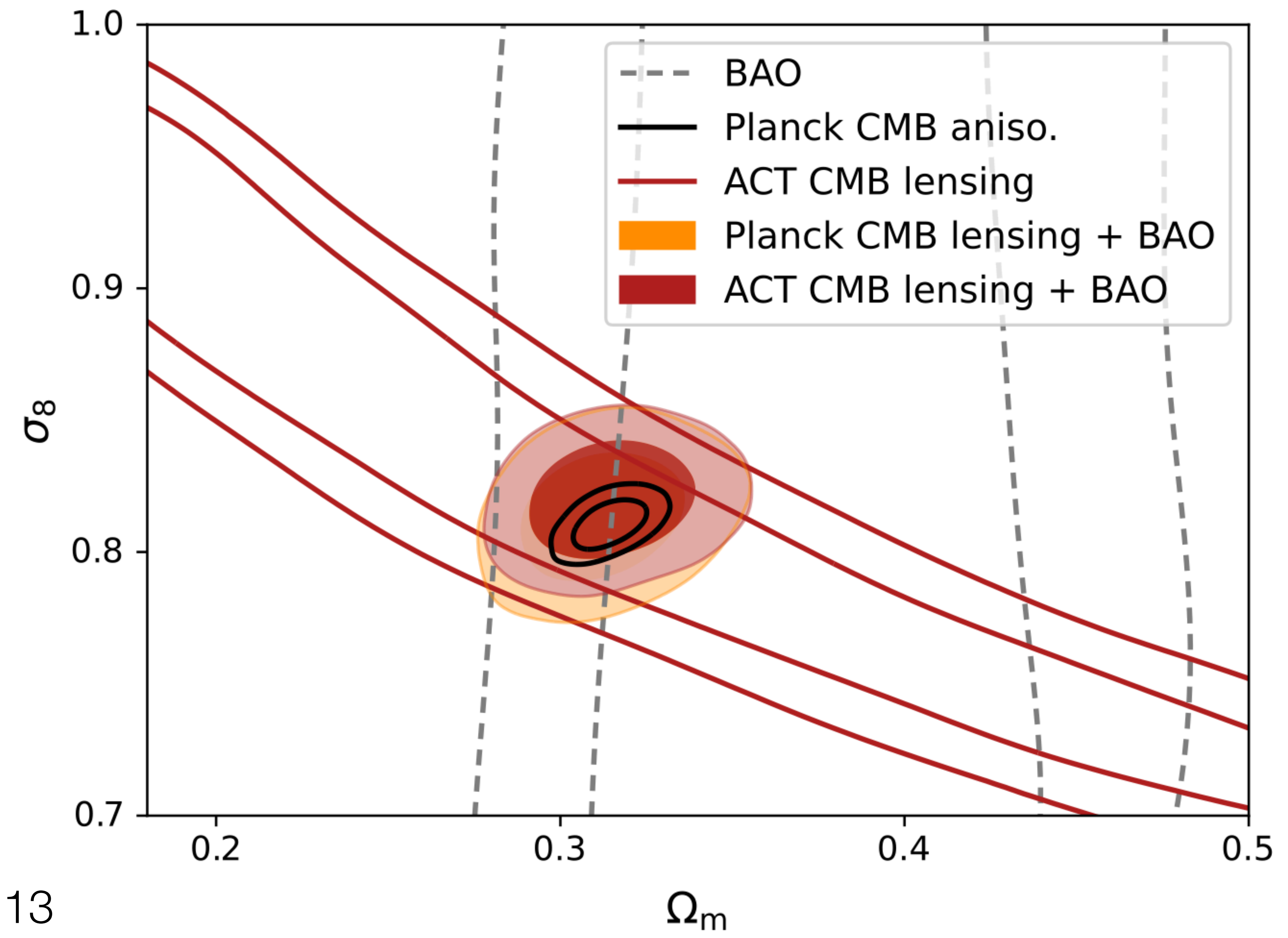
Galaxy weak-lensing measurement of S_8

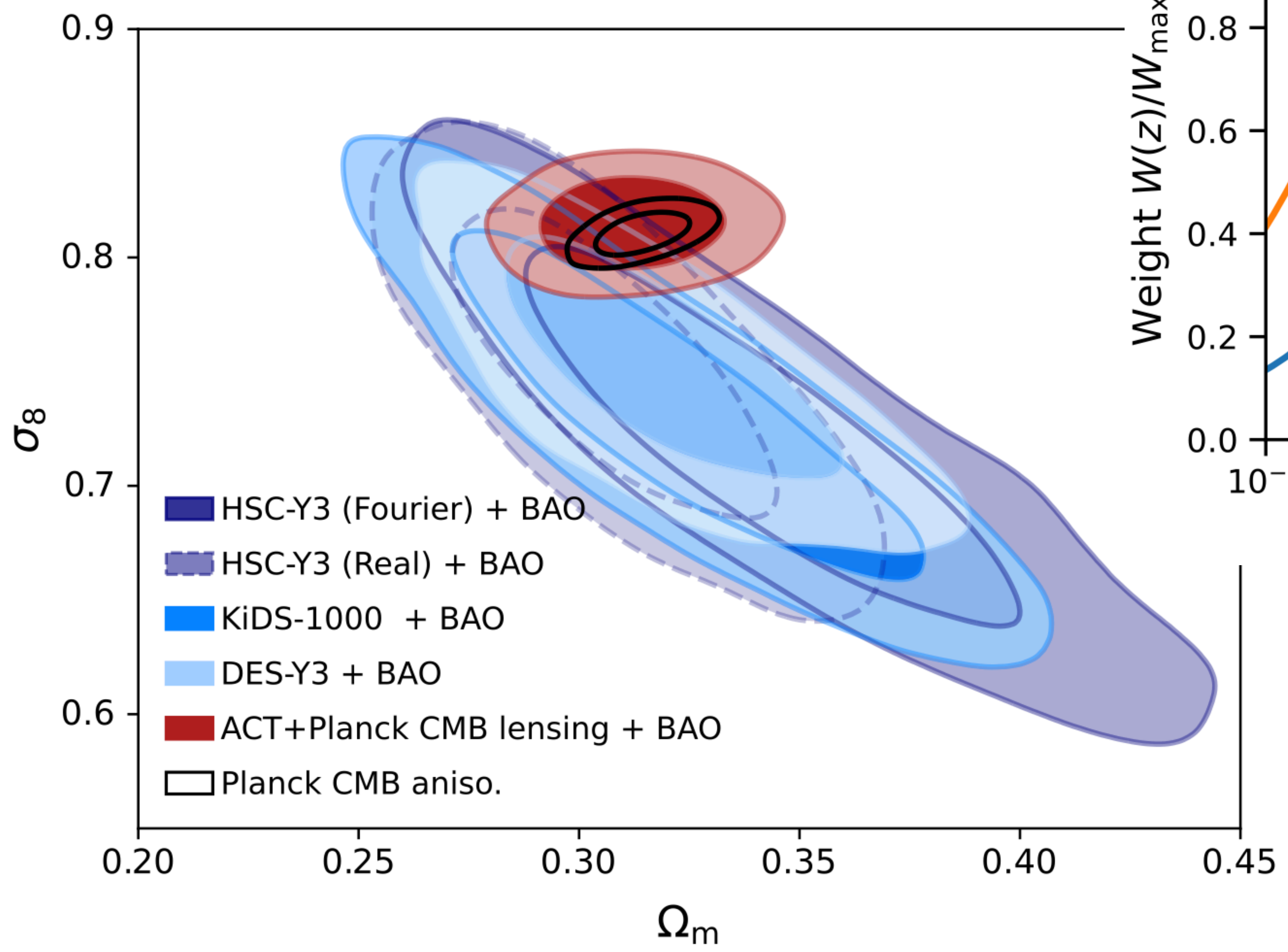
~ 10±4% lower than predicted

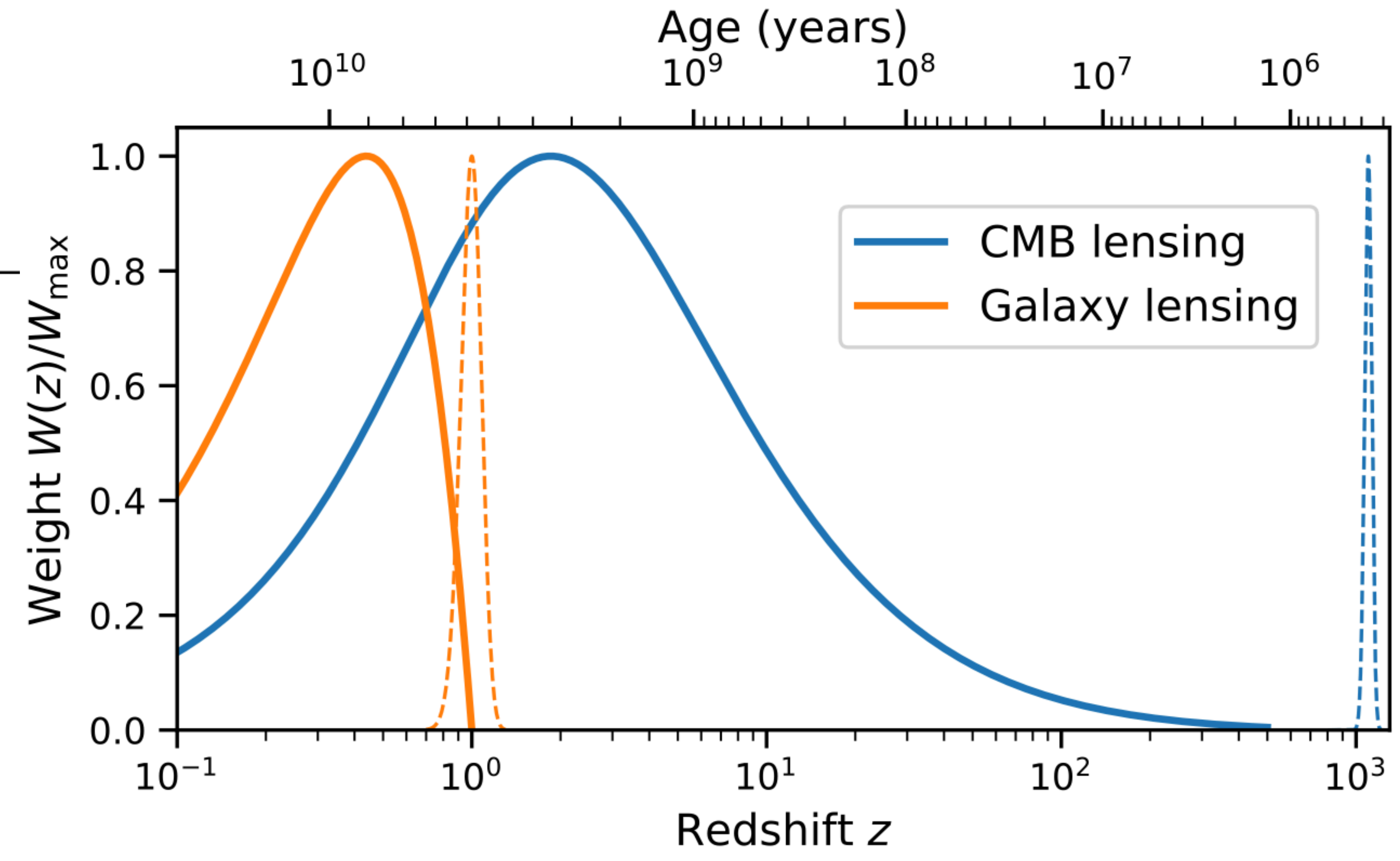
by best-fit $\Lambda\mathrm{CDM}$ model from Planck

CMB lensing: no S_8 tension!

- Lensing causes non-gaussianities in the CMB
  - powerspectrum distorted on the sky → 4-point correlation
  - measured in Planck and recently in ACT (Madhavacheril++ 2023)
  - sensitive to lenses at redshifts 1-5



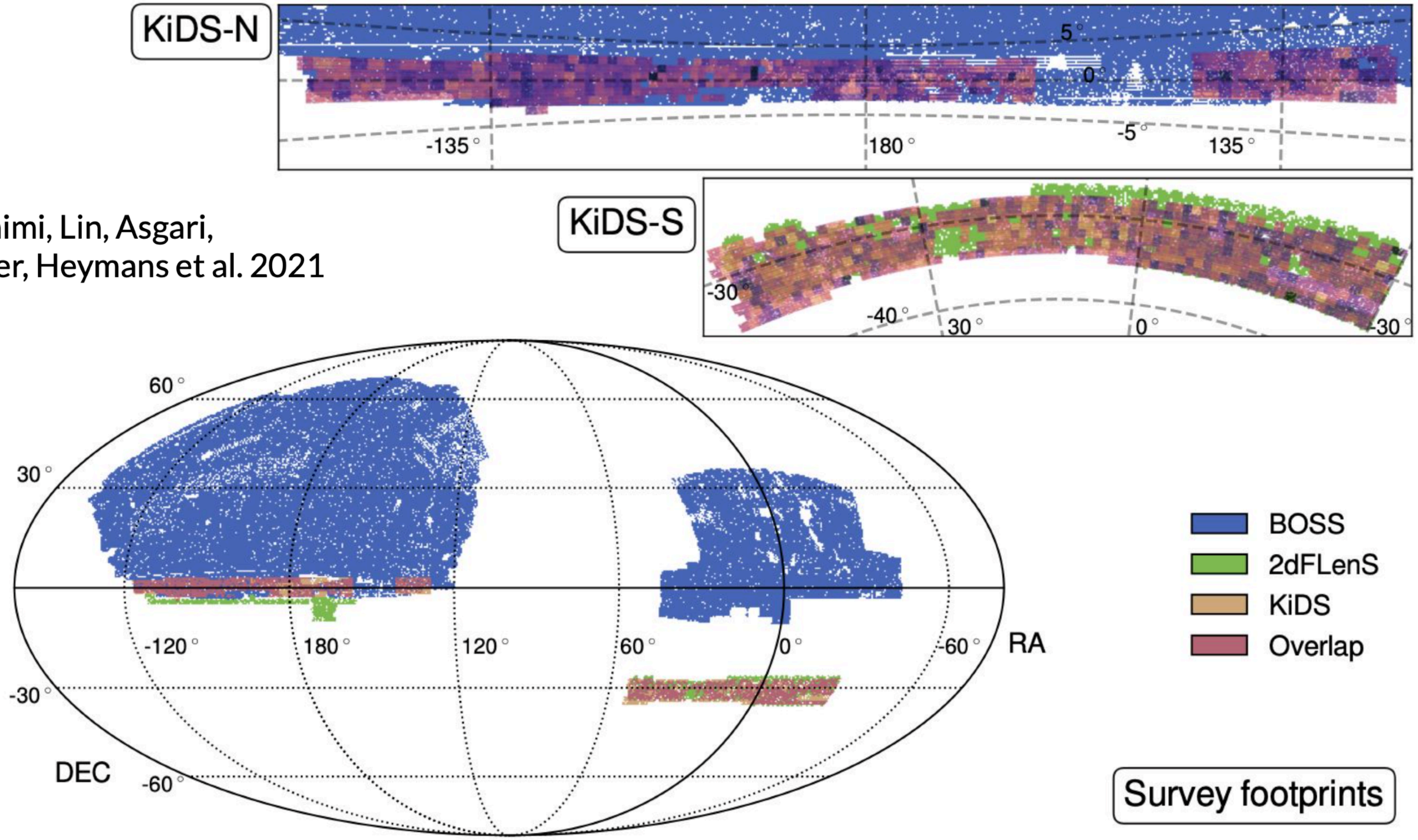




Adding more information: 3x2pt

- Include galaxy clustering (bias!) and galaxy-galaxy lensing
  - bias constrained via redshift space distortion of spectroscopic survey

Joachimi, Lin, Asgari,
Tröster, Heymans et al. 2021

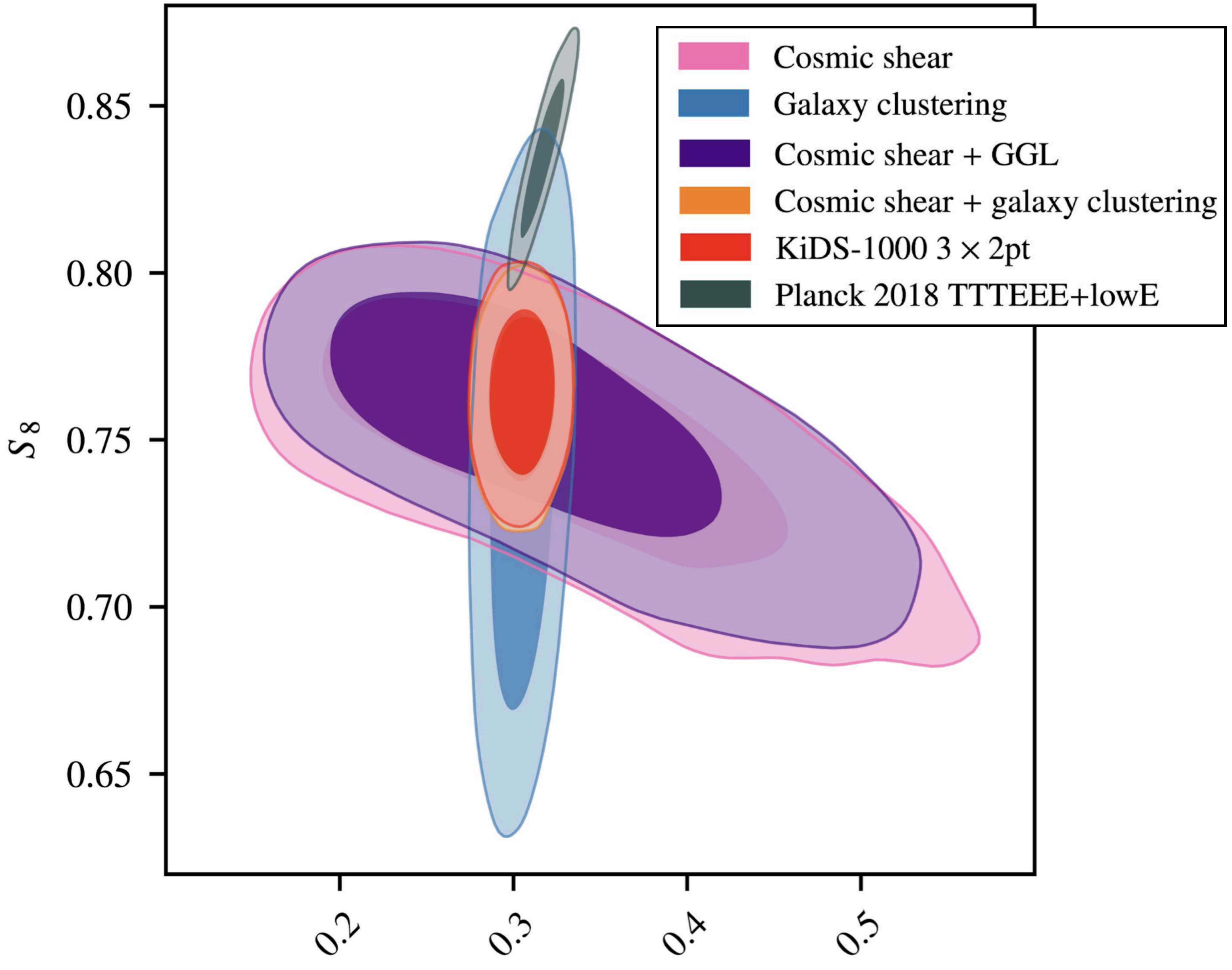


Joachimi et al 2021

KiDS-1000, BOSS, 2dFlens

- Clustering from (somewhat) overlapping **spectroscopic** survey

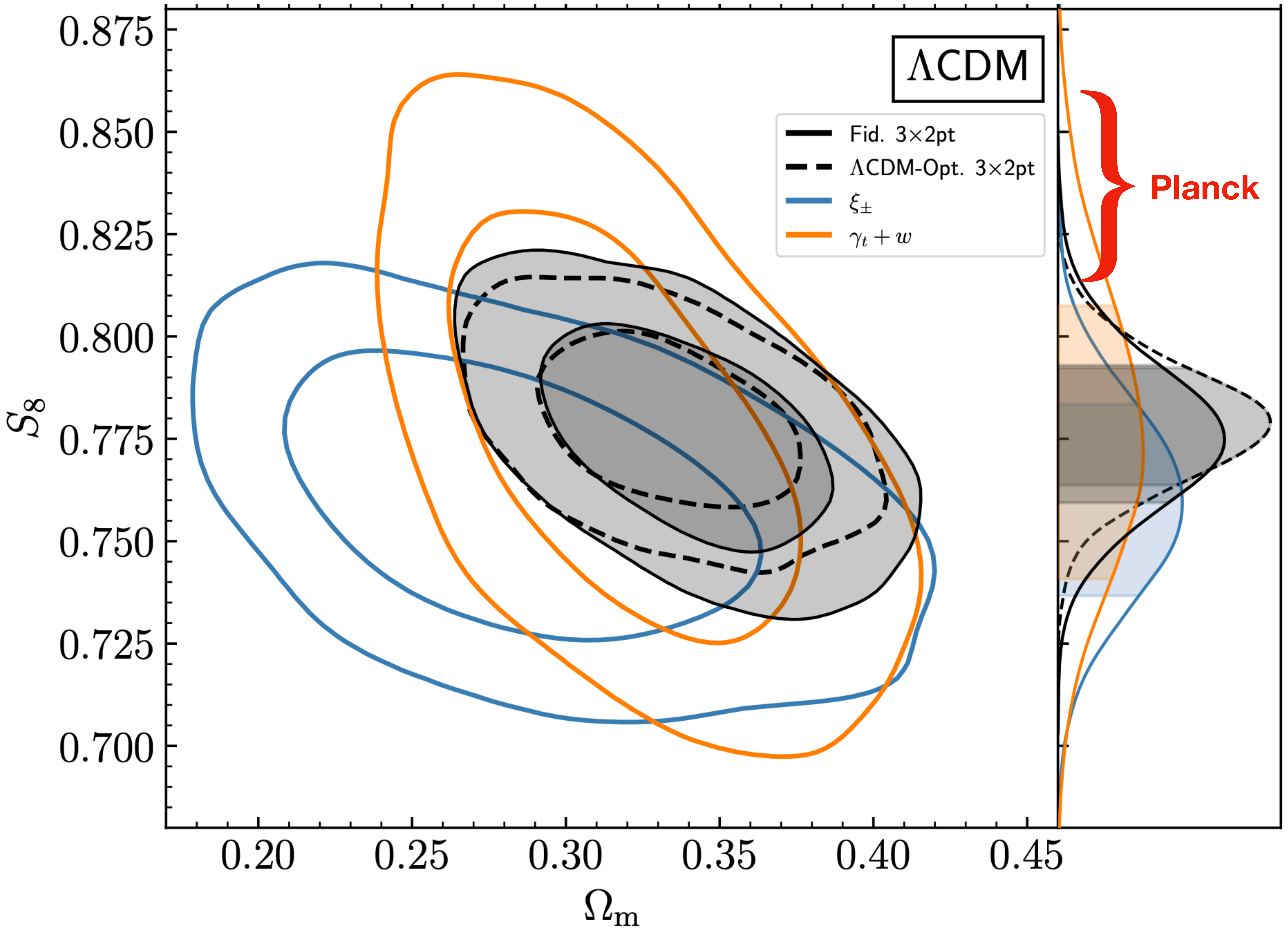
- Galaxy clustering constrains the power spectrum shape → Ω_m. Not (yet) more constraining in σ_8.



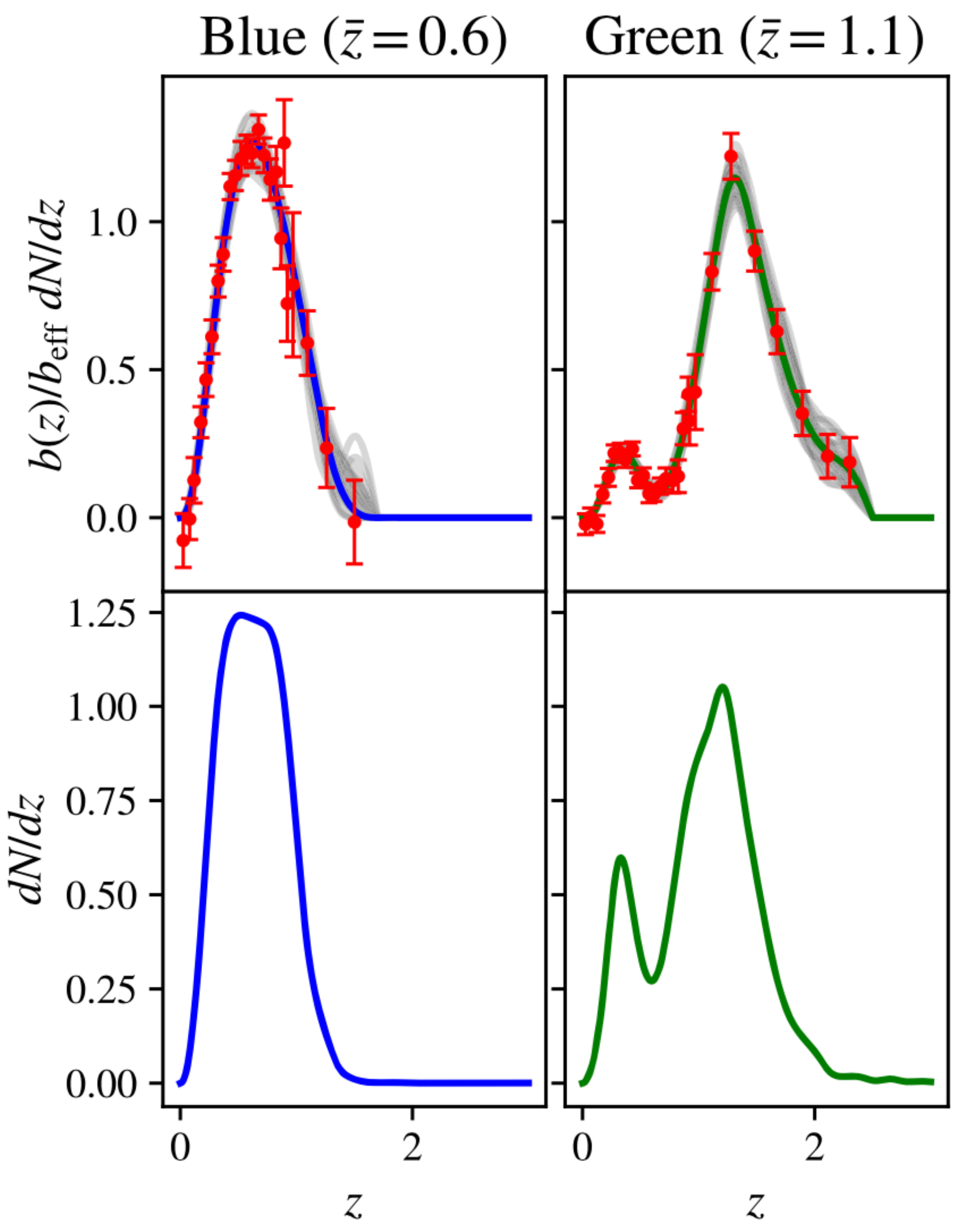
DES 3x2pt (photometric clustering)

- Use **photometric** sample for **clustering**
    - get bias from gg-lensing
- Survey-internal!
- But challenging to control redshift uncertainties

- Some differences between 'MagLim' and 'RedMAGIC' samples
- But S_8 consistently <0.8.



CMB lensing: no S_8 tension!



The Astrophysical Journal, 966:157 (57pp), 2024 May 10 Farren et al.

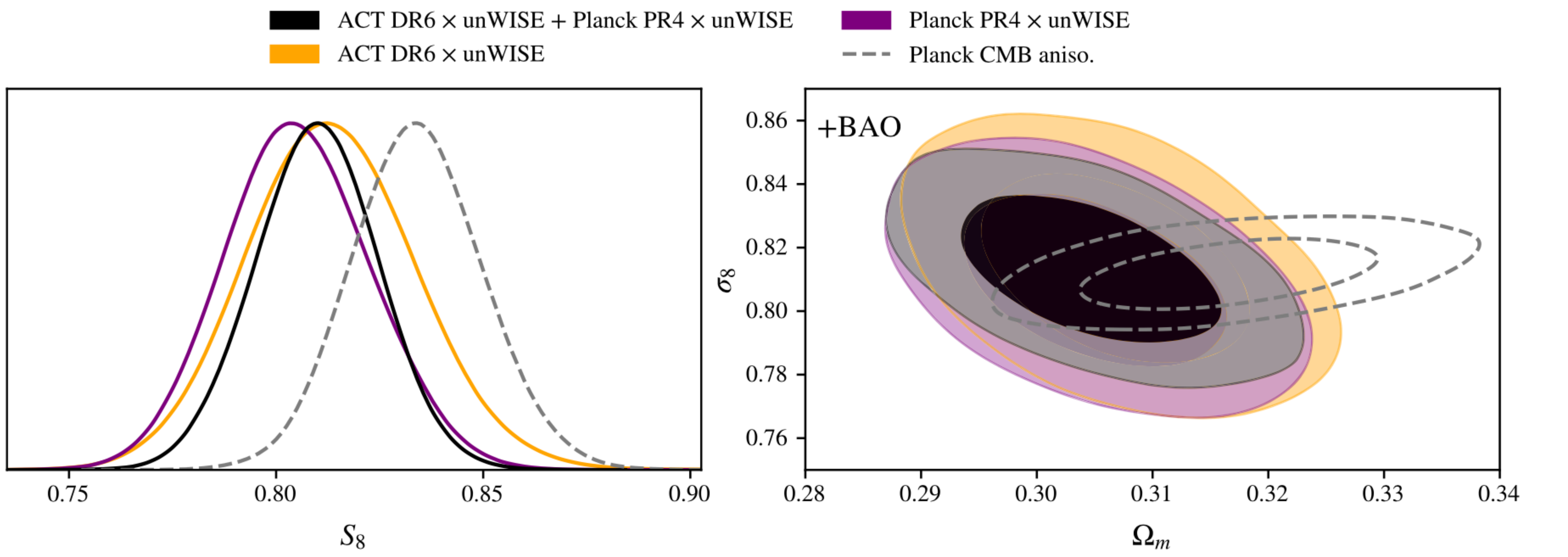


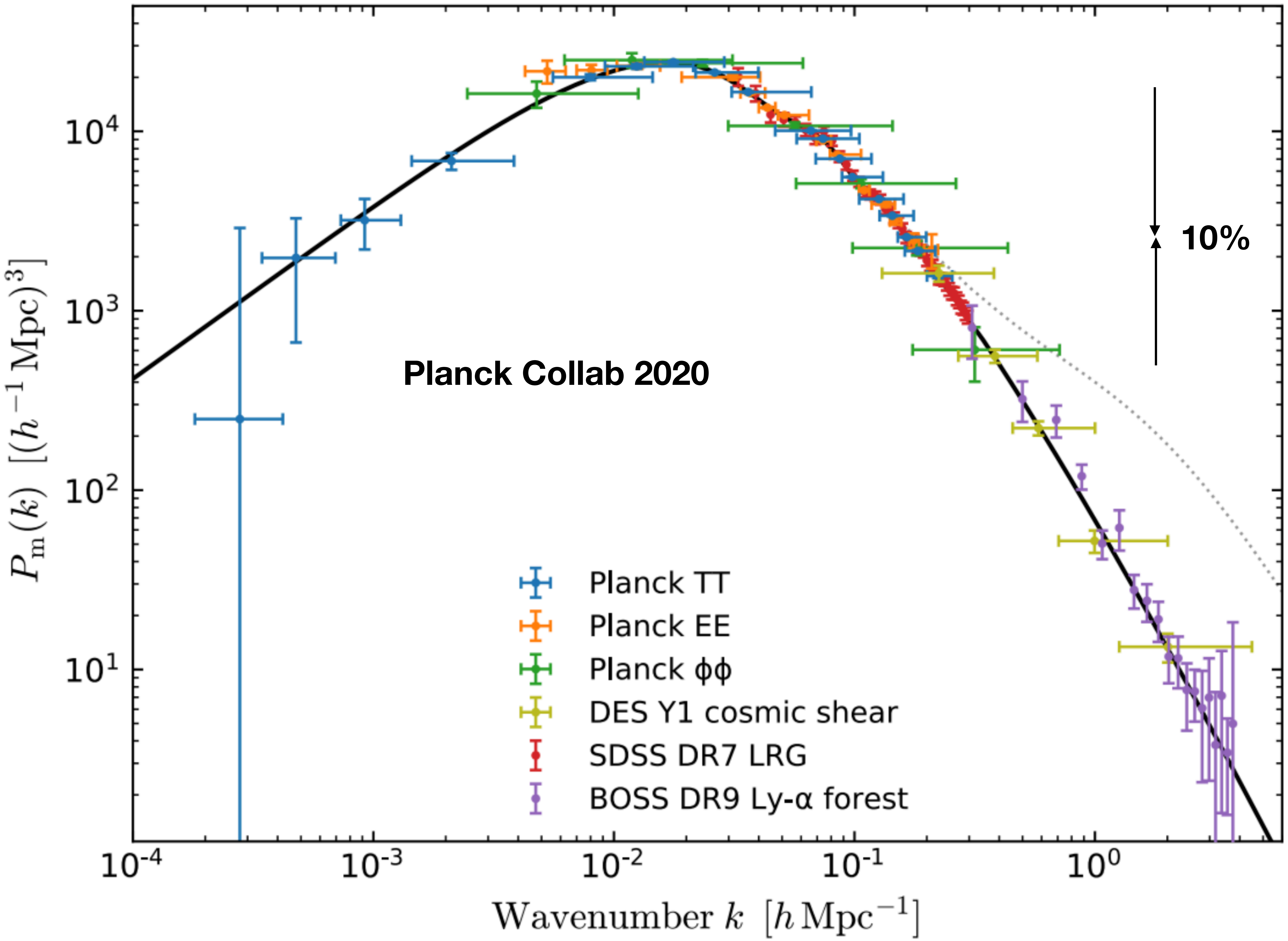
Figure 1. The main result from this work is a constraint on the amplitude of low-redshift structure captured by the parameter $S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$ (left). We obtain $S_8 = 0.810 \pm 0.015$ using the combination of cross-correlation measurements of the unWISE galaxies with ACT DR6 and Planck PR4 lensing reconstructions. Combined with BAO, which constrains Ω_m, we obtain constraints on σ_8 of $\sigma_8 = 0.813 \pm 0.015$ (right). Our results show no significant tension with values inferred from the primary CMB from Planck.

- CMB lensing (ACT and Planck) x unWISE galaxies (z~0.6,1) (3x2pt)

What might cause the tension?

- Systematic effects in the measurements
  - always a possibility - photo-z or shape measurements - but techniques have advanced greatly
- Non-lensing ellipticity correlations ('intrinsic' tidal alignments)
  - are present, constrained by the data, and marginalised over
- Mis-prediction of the power spectrum for given $(\Omega_{\rm m}, \sigma_8, H_0, \ldots)$
  - baryonic effects are important on small scales - scales are cut or effects are marginalised over
- Statistical fluke?
  - get more data! (though primary CMB uncertainty will soon be limiting factor)
- New physics?

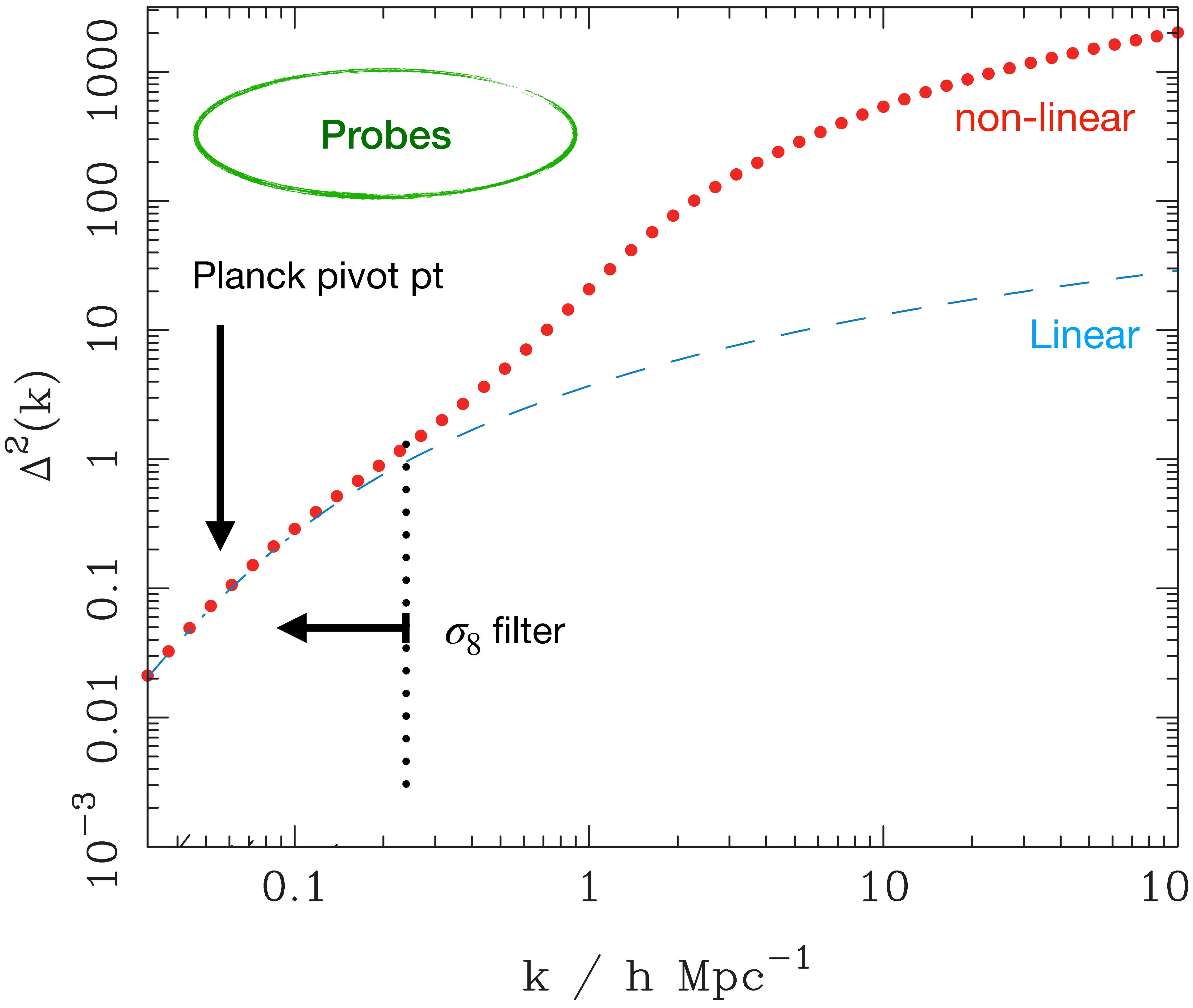
Being able to talk about tension is a luxury!!



Interpreting the S_8 tension: what are we looking at?

- Nobody 'measures' σ_8 or S_8 !
- An amplitude parameter for ΛCDM fits to different data sets...
  - ...that also undoes nonlinear growth, baryons, ...
- Makes it hard to compare probes directly

Peacock (2003)

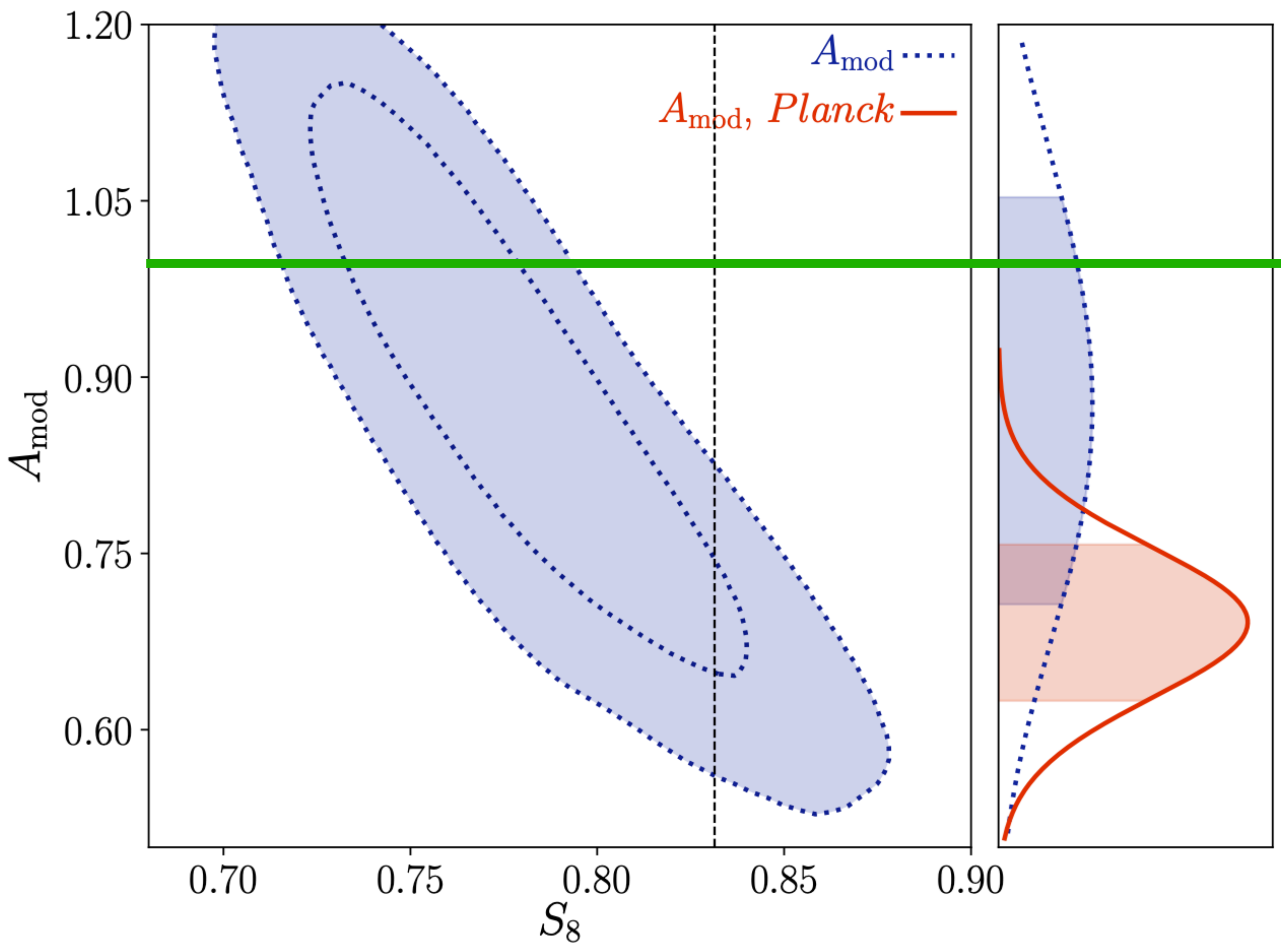


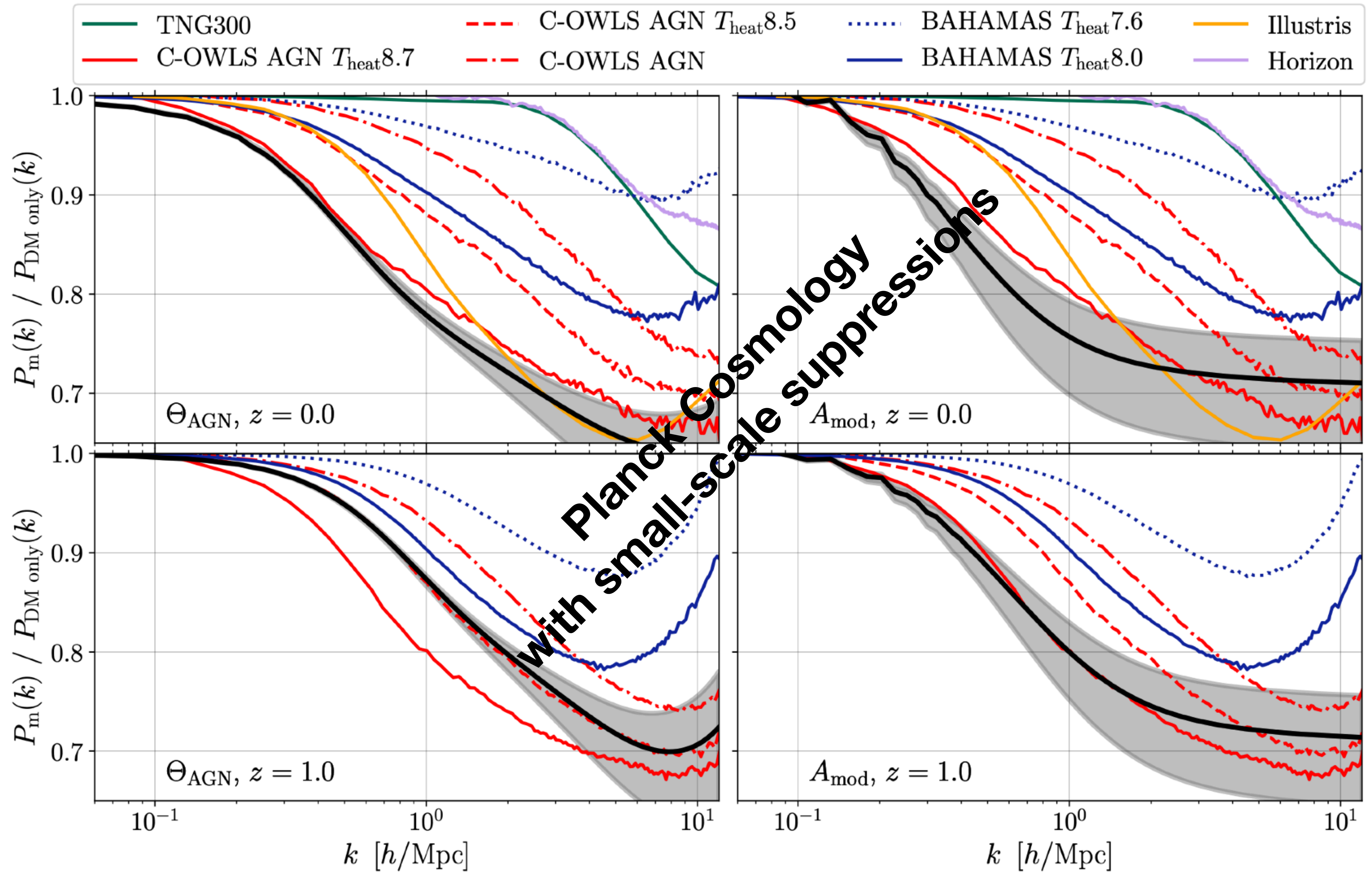
Amon & Efstathiou (2022)

- Modify KiDS analysis HMCode+baryons power spectrum by rescaling nonlinear part of the density power spectrum, and switching off baryon feedback

$$P_{\rm m}(k,z) = P_{\rm m}^{\rm L}(k,z) + A_{\rm mod}[P_{\rm m}^{\rm NL}(k,z) - P_{\rm m}^{\rm L}(k,z)]\,,$$

- This mimics (extreme!) baryon effects





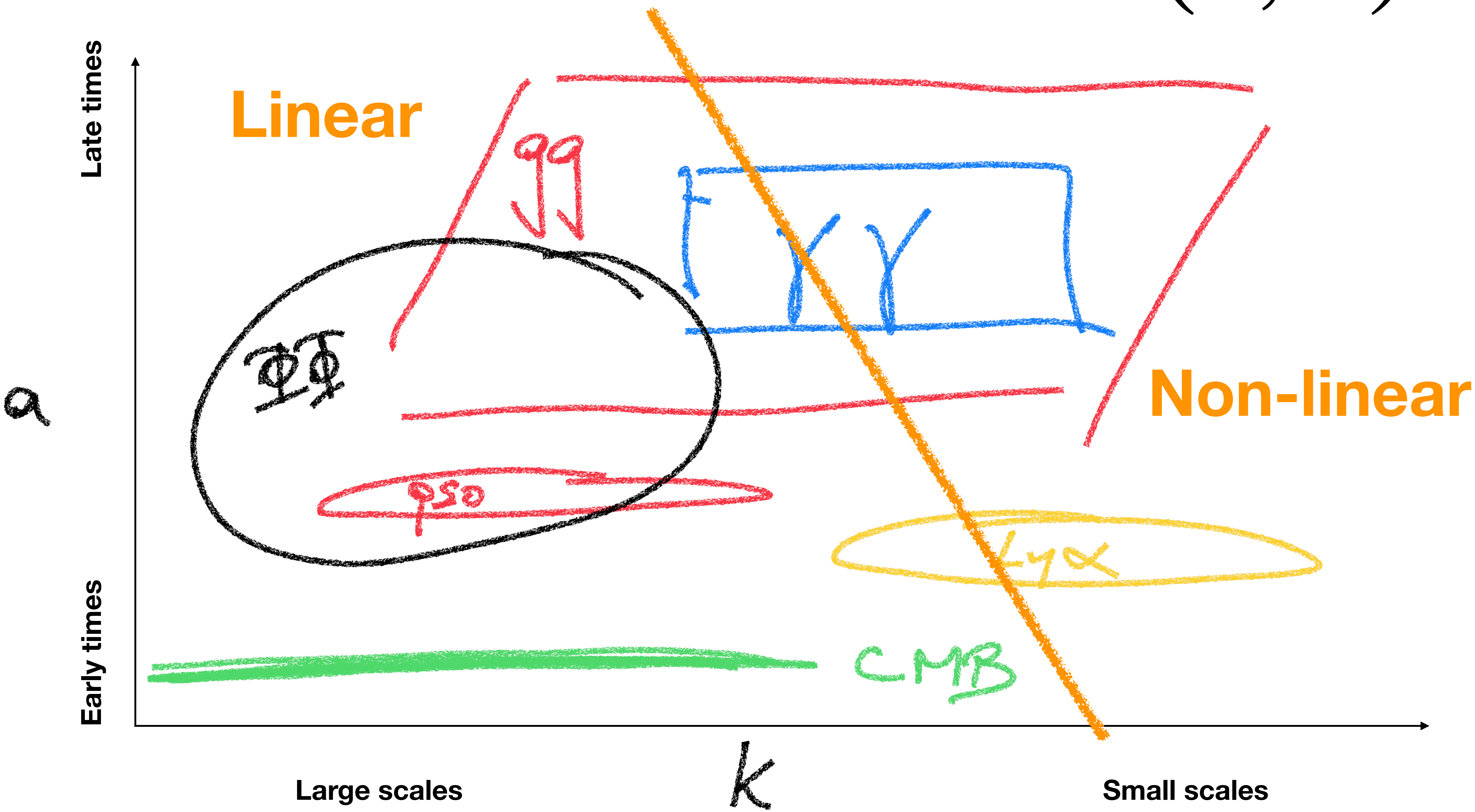
KiDS

Interpreting the S_8 tension

- S_8 (and σ_8) are *indirectly* related to the power spectrum of late time LSS
  - σ_8 = integral over *linear* overdensity power spectrum at scales >~ $8h^{-1}$Mpc
  - But many probes are sensitive to smaller scales
- Comparing best-fit S_8 values is OK if the model fits, but if it does not?
  - What are we actually measuring?
  - Unpacking the S_8 value from late-time, non-linear density fluctuations, is complex, and meaningless if you do not believe your model

- **Try to locate the discrepancy in scale k and cosmic expansion factor a.**

Locate the tension in (k, a) !

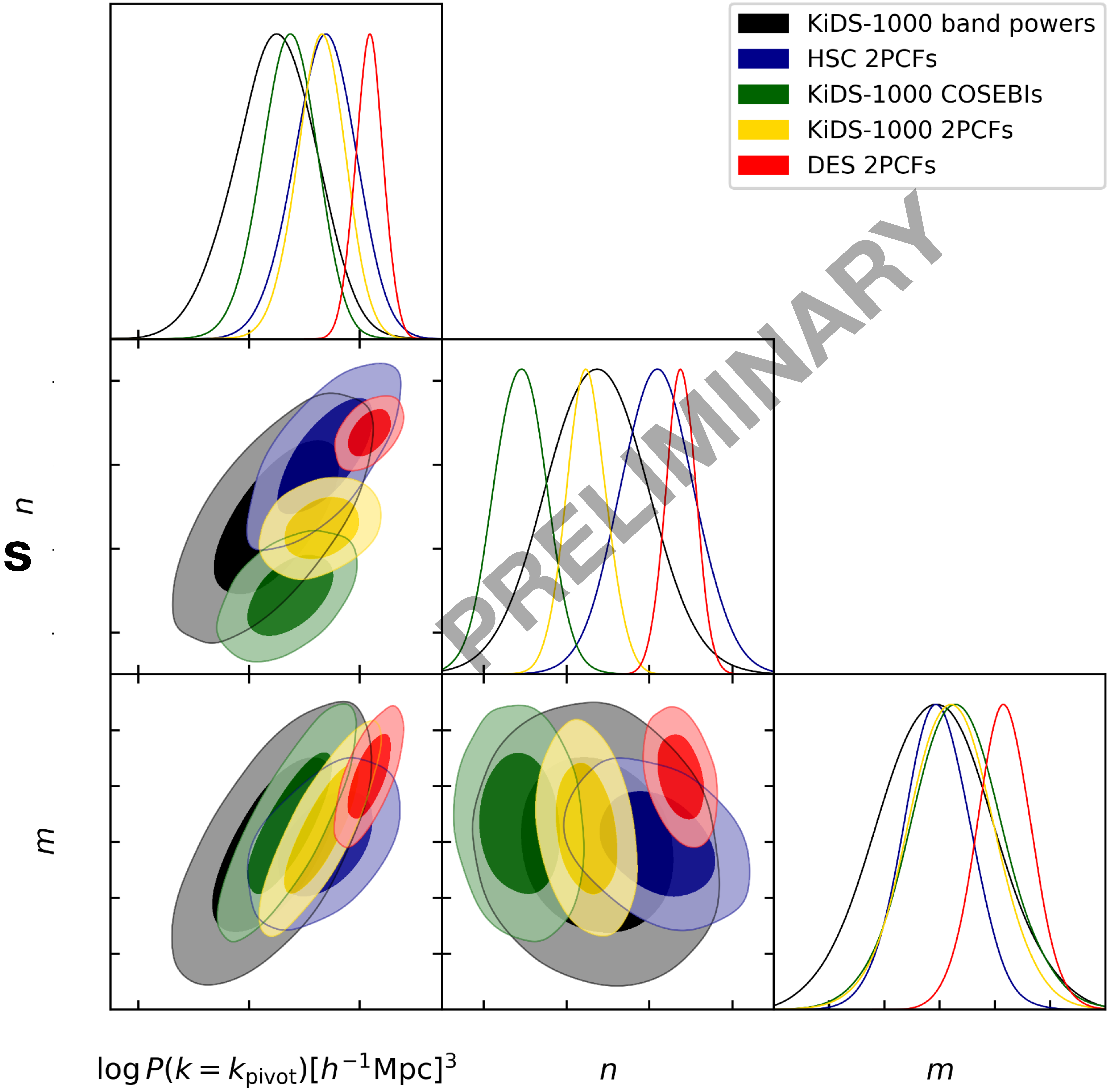


Powerlaw fit

- Report results in a way that is 'closer to the data'
- but remove some experiment signatures - eg n(z)
- e.g. **best-fit P(k) to cosmic shear 2pt fns**

$$P(k) = A \left(\frac{k}{k_{\rm piv}}\right)^n \left(\frac{a}{a_{\rm piv}}\right)^m$$

- while keeping background cosmology fixed (MSc thesis J. **Broxterman**)
    - and varying Intrinsic Alignment



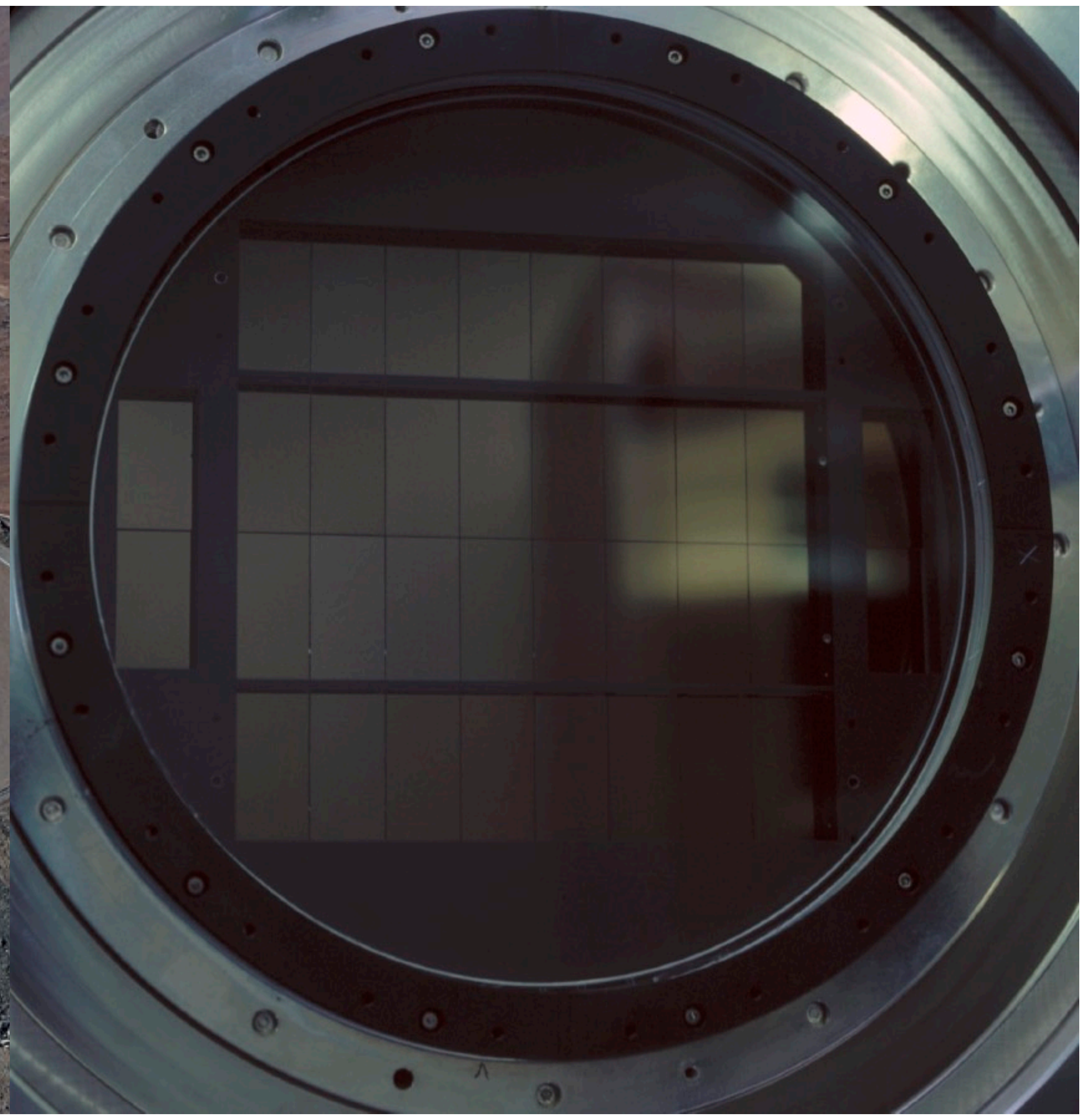
Expected improvements (from the ground)

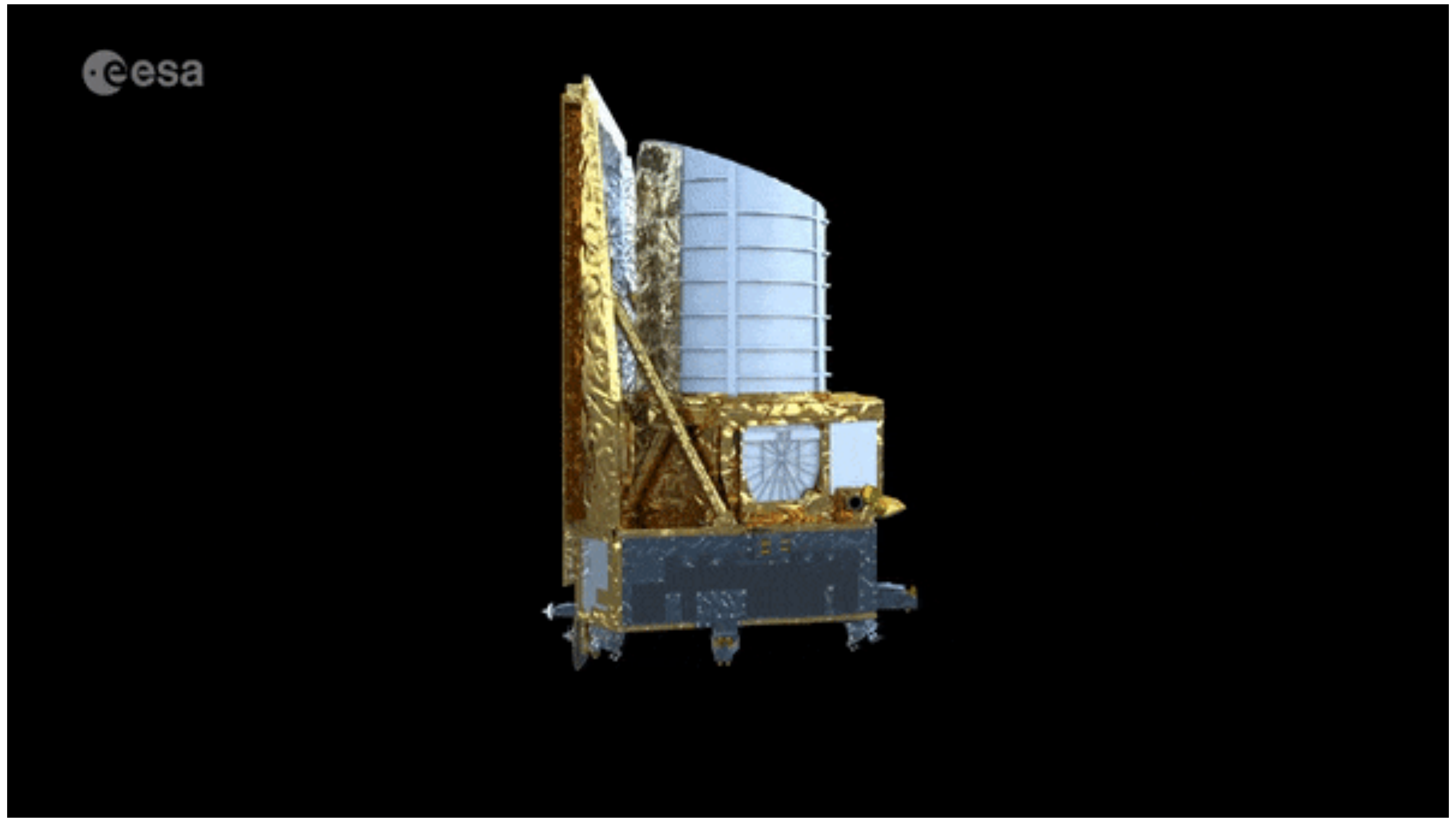
- Better redshift calibration
  - more spectra (eg 4C3R2), deeper photometry (DES Y3→Y6)
- Completion of the stage-III weak lensing surveys (more area/depth)
  - KiDS-1000 → 1350; HSC → ~1000; DES → deeper 6-year data
- Better constraints on baryon effects (new sims such as ***FLAMINGO***; SZ constraints)
- More detailed image simulations to calibrate blending of sources
- Higher redshifts (e.g., KiDS-Legacy pushing beyond z=1.2)
- Analyses combining photometric and spectroscopic clustering "5x2p, 6x2pt".
- New lensing data!!
  - → Rubin (2025), WFIRST (2027+?), CSST (2027+?), and Euclid (now!)

Instrumentation is key

- Mapping the dark matter with weak lensing requires
  - wide-field image of the sky
  - sharp images
  - redshift measurements

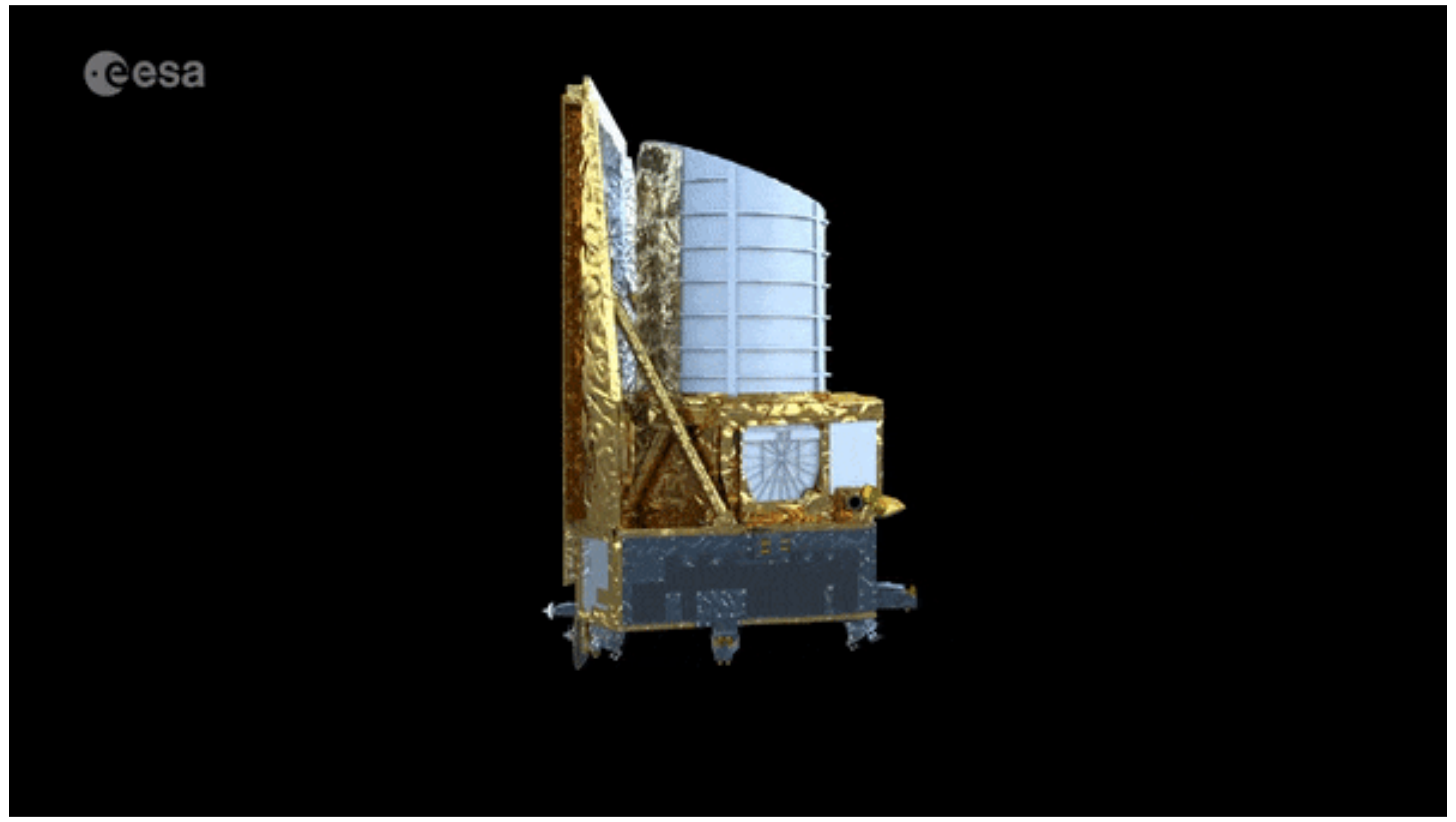
- Translation to requirements on instrumentation
  - gigapixel mosaic cameras
  - stable (or no) atmosphere
  - accurate colour measurements





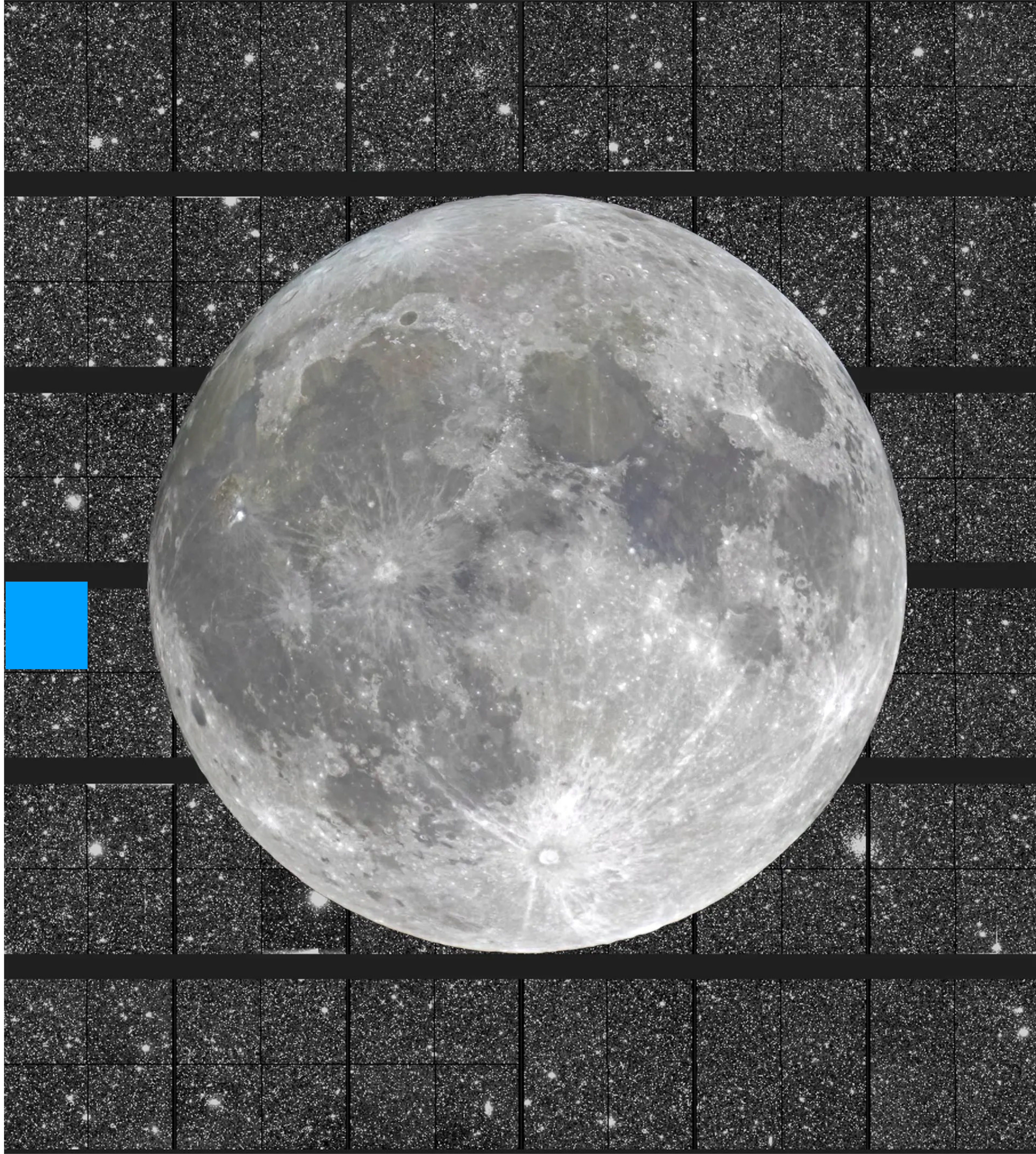
Now: *Euclid*

- Weak lensing + NIR images/spectra from space
- Thermally stable orbit around L2
- 14000 sq.deg., 36-CCD mosaic camera (600Mpix)
- survey started Feb 14 2024
- promising early science images!
- 6 year mission

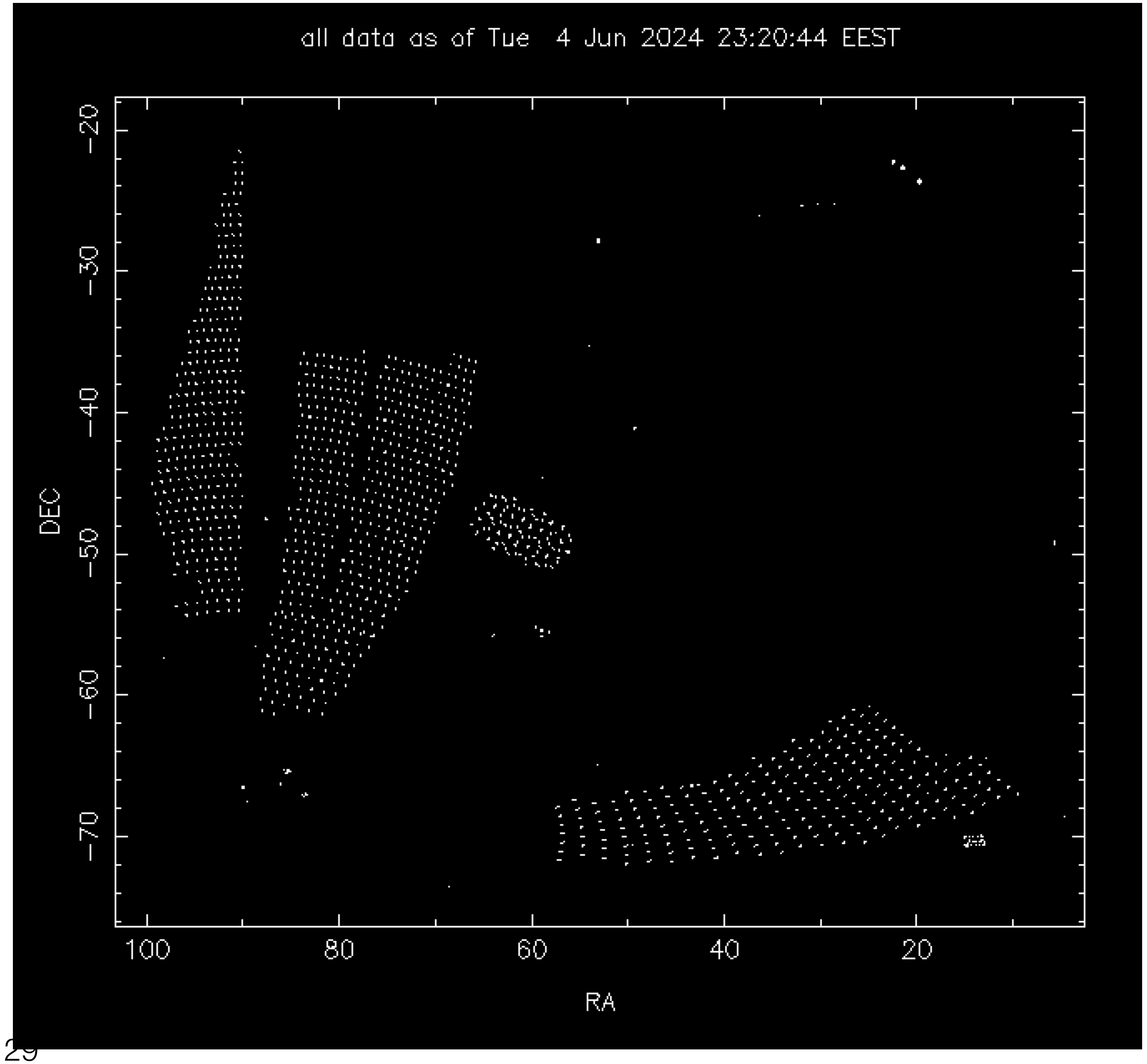


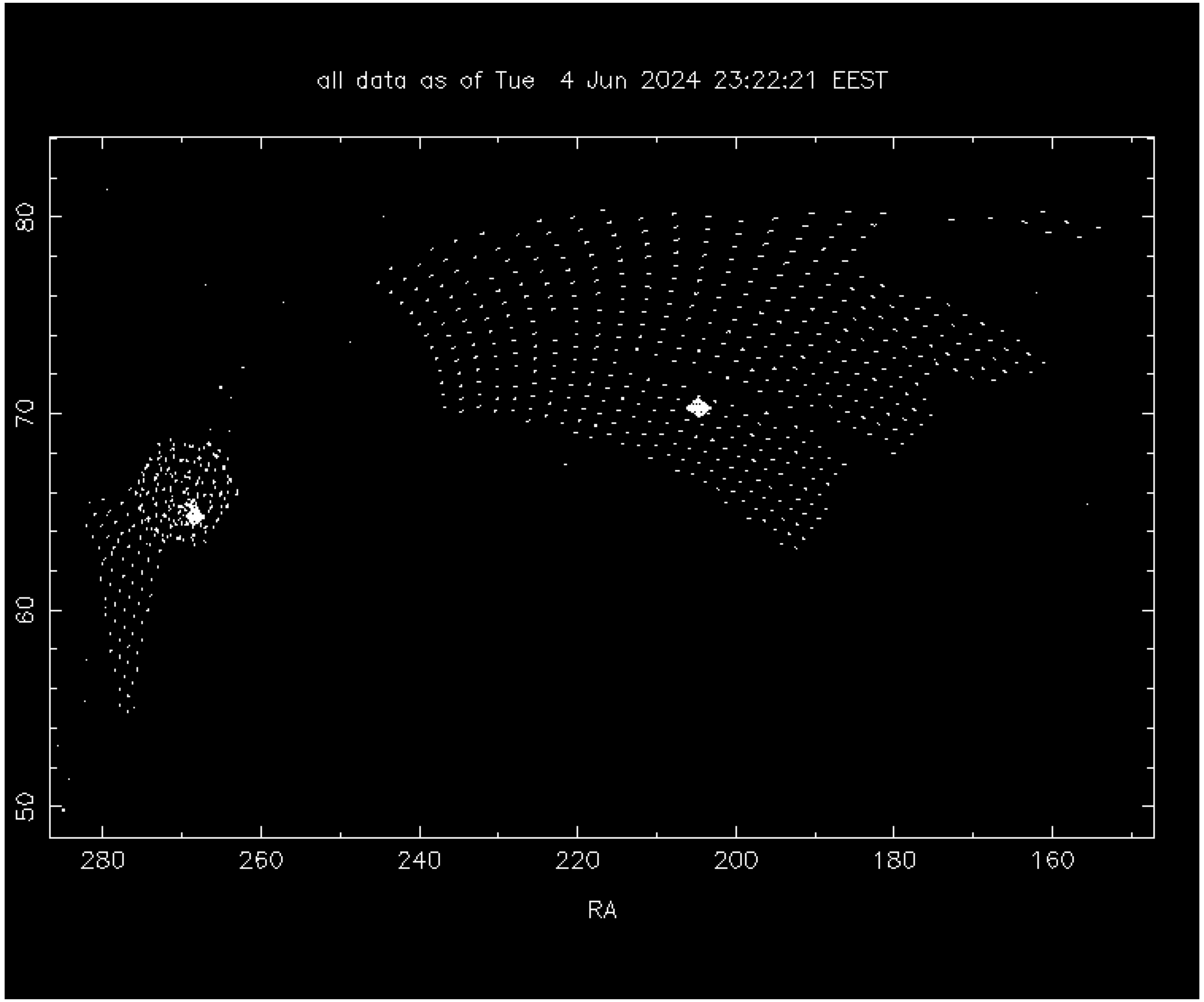
Euclid

- field of view 0.7 degrees
- 24000x24000 pixels (0.1 arcsec)
- >100x more efficient at surveying the sky than Hubble or JWST
- simultaneous optical and IR images
  - IR spectroscopy as well
- Survey: 14000 square degrees (wide) + 53 square degrees (deep)



It's happening! 10 sq.deg/24h





Spectacular early science data

Summary

- Weak gravitational lensing is a powerful probe of large scale structure and cosmology
- Current results suggest a (mild) S_8 tension (~10±4% low compared to Planck cosmology)
- Care interpreting what S_8 'measurement' actually represents
- New data coming, first and foremost Euclid (5x sharper, 10x larger than KiDS)