The Dark Energy Survey Legacy
&
A decade of cosmological tensions and systematics in galaxy surveys

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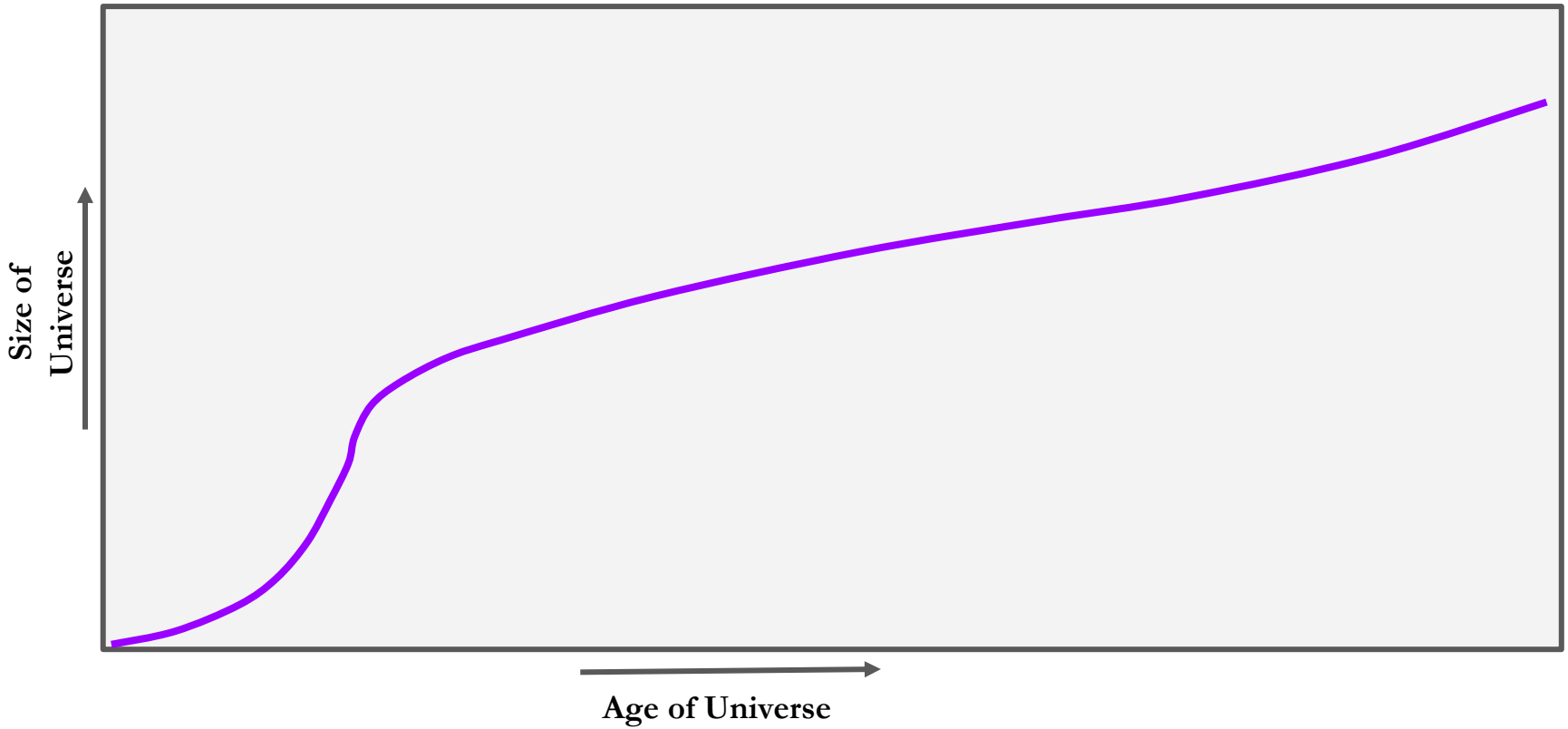
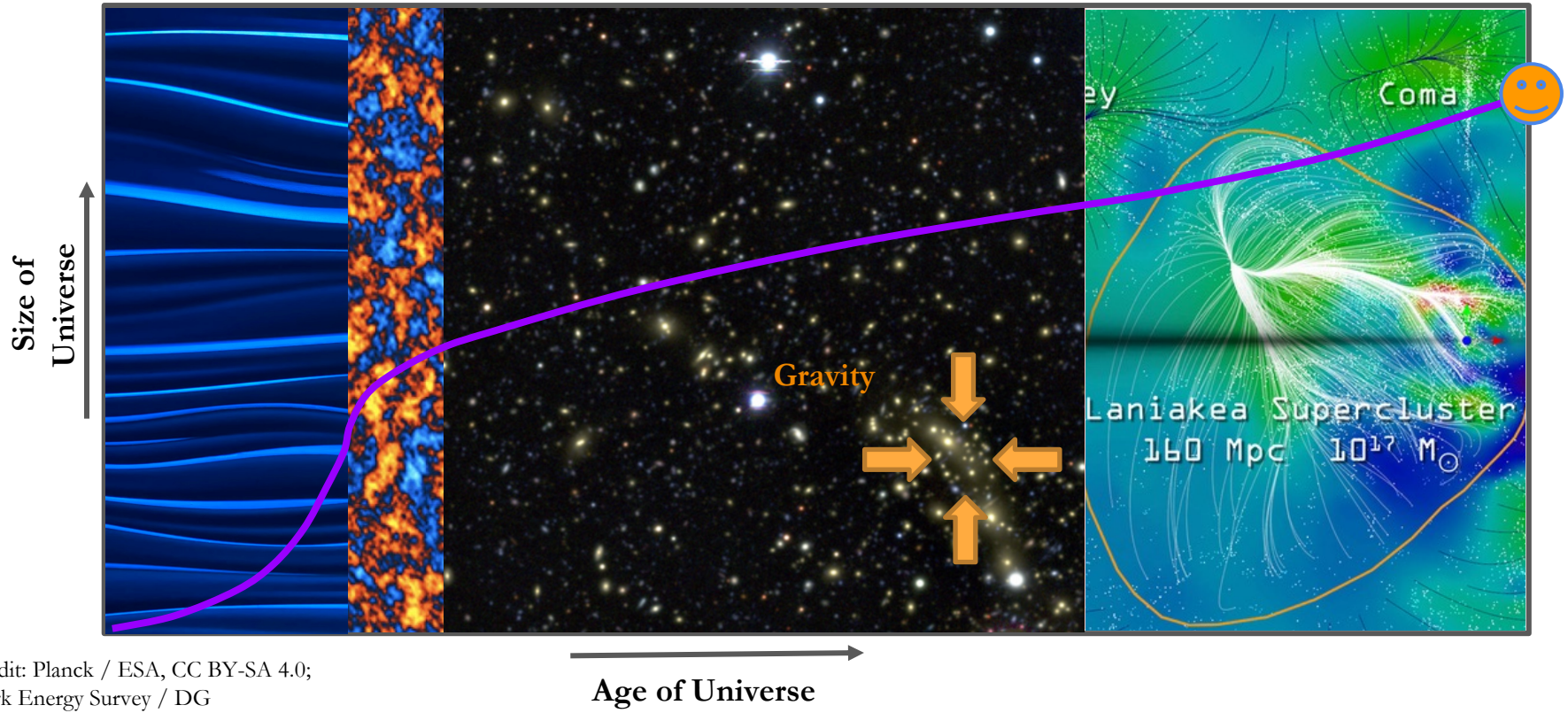
The story of the Universe as told by its expansion history



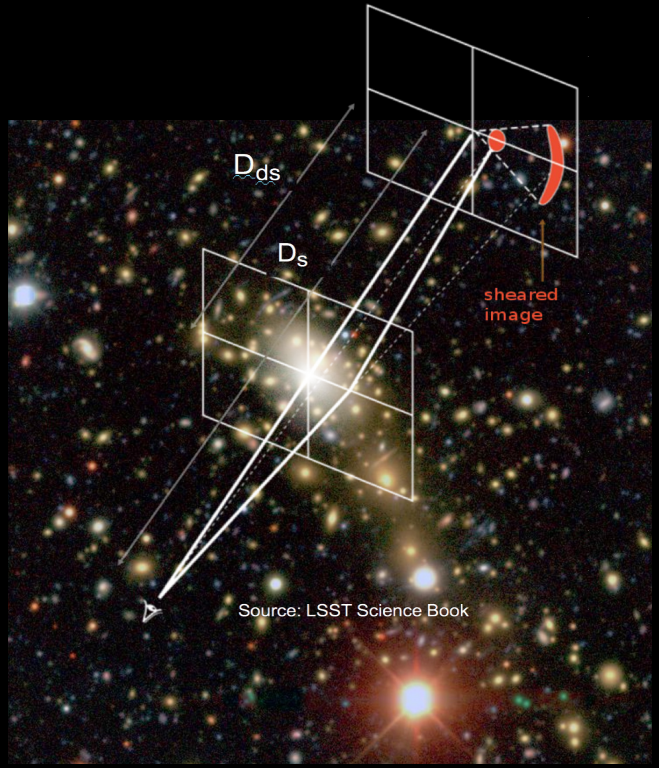
The story of the Universe as told by the growth of structure



Credit: Planck / ESA, CC BY-SA 4.0;
Dark Energy Survey / DG

How do we know? Weak gravitational lensing!

(of course also: galaxy clustering, cluster counts)



Source: LSST Science Book / LSST Corporation;
Dark Energy Survey Deep Field MACS0416 / DG

Weak gravitational lensing is the direct connection from observed images to underlying (dark) matter overdensity

Tangential alignment of galaxy shapes ~ overdensity

$$\gamma_t(\theta) = \langle\kappa(\theta')\rangle_{\theta'<\theta} - \kappa(\theta)$$

$$\kappa = \Sigma / \left[\frac{c^2}{4\pi G}\frac{D_s}{D_d D_{ds}}\right]$$

- Need shapes + distances of O(100 million) galaxies
- Need to predict statistics of those shapes (e.g. correlation functions) for hypotheses on cosmological physics, including baryons and intrinsic alignments

There has been talk of three tensions (maybe?) in Stage-III

- **H_0 tension**: The measured local expansion rate of the Universe does not fit observations based on the 'standard ruler' distance of baryonic acoustic oscillations
- **S_8 tension**: The measured amplitude of weak lensing due to structure in the recent Universe appears smaller than expected from CMB observations
- **Ω_m tension / w(z)**: Recent measurements of the latest stages of cosmic expansion, together with the CMB, prefer dark energy to have a time-varying equation of state

- No attractive model explains any or all of these tensions.

Which is real?
Poll now!

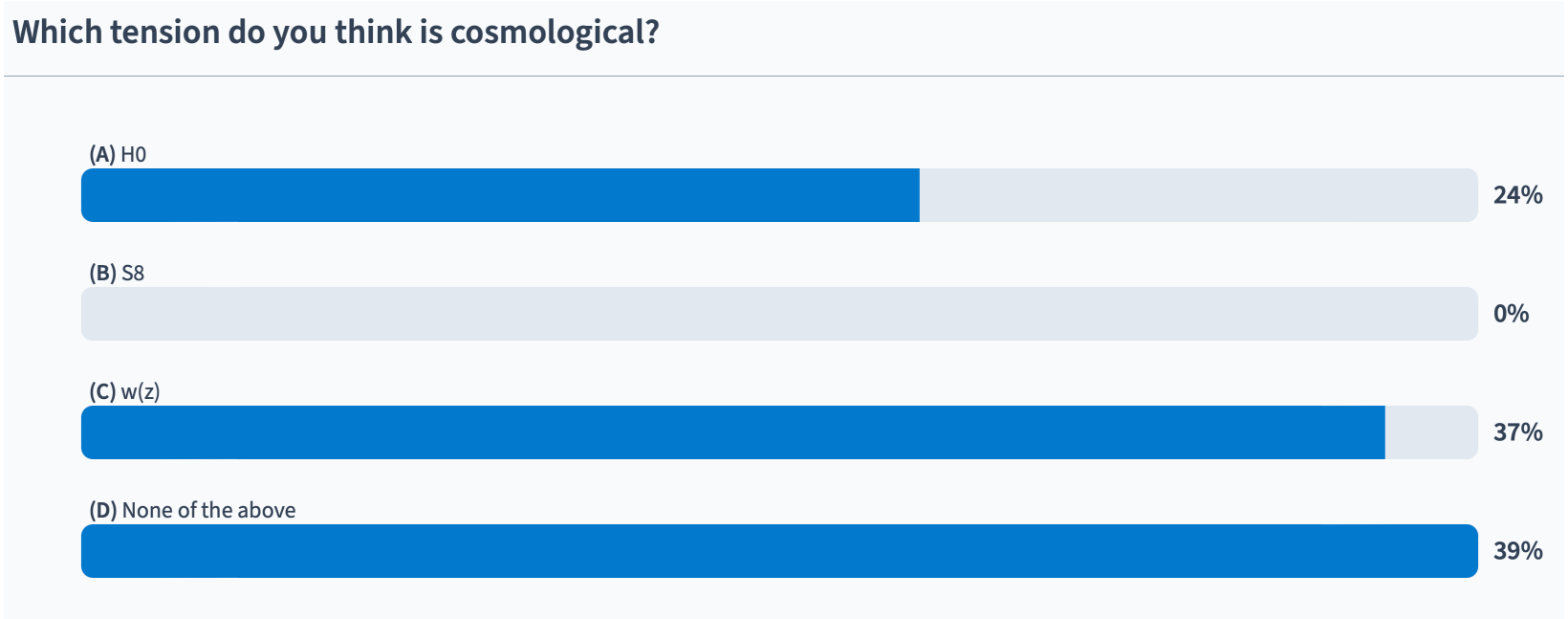
Which tension do you think is cosmological?

H0 0%

S8 0%

w(z) 0%

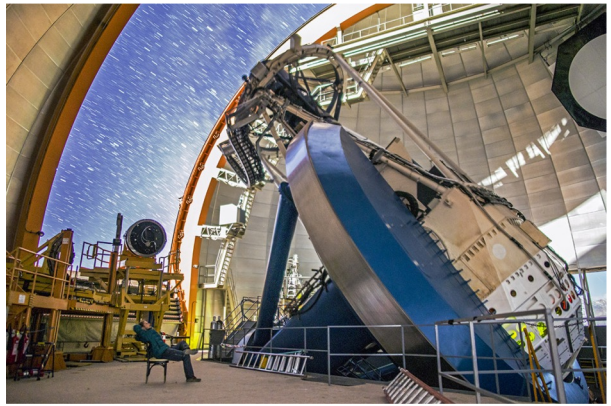
None of the above 0%

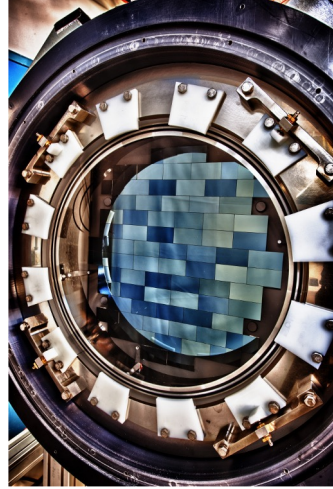


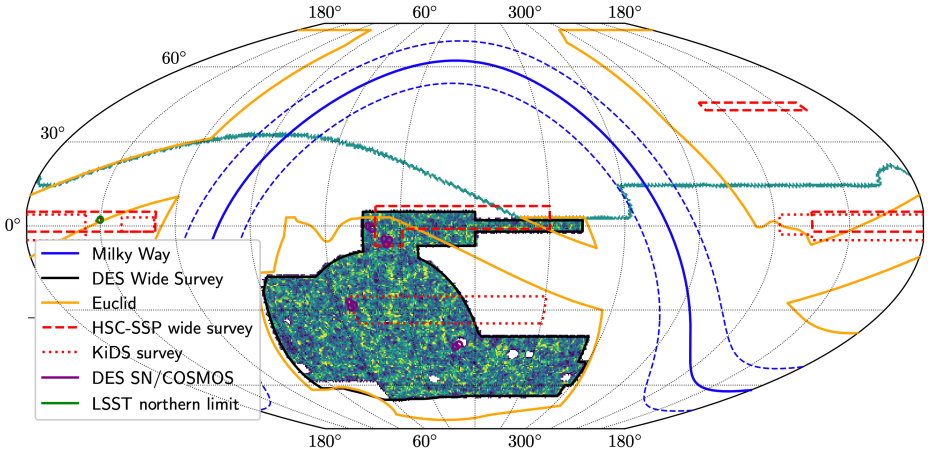
Responses at MIAPbP workshop last month:
'Big Data, Big Questions: The Future of Cosmological Surveys'

The Dark Energy Survey

- 5.5-year survey with dedicated Dark Energy Camera on Blanco/CTIO
- griz(y) bands, 5000 deg^2, 10 visits
- DOE / Fermilab-led global collaboration of ~900 scientists
- Cosmological probes: Photometric BAO, Supernovae, Galaxy Clusters, Gravitational Lensing
- Survey finished 2019, data public
- Final cosmology analyses in progress, final lensing data to become public soon







DES Y6: Bechtol et al. 2025

The Department of Energy review was lukewarm at times!

- Comments

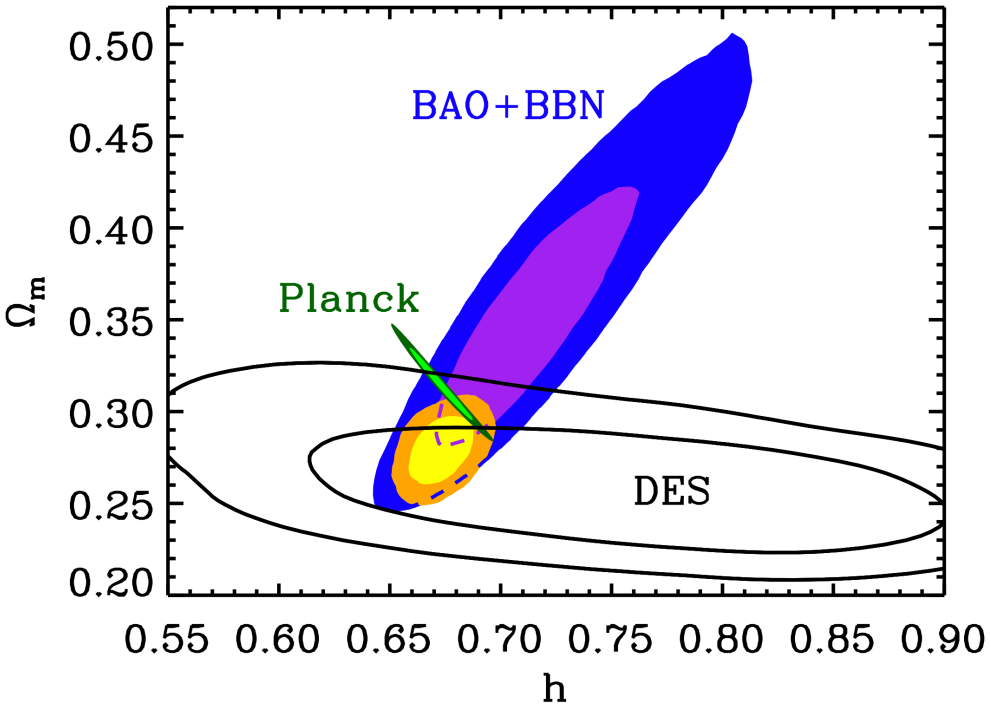
DES Lesson: Getting things right is more important than external pressure

Courtesy: Brenna Flaugher

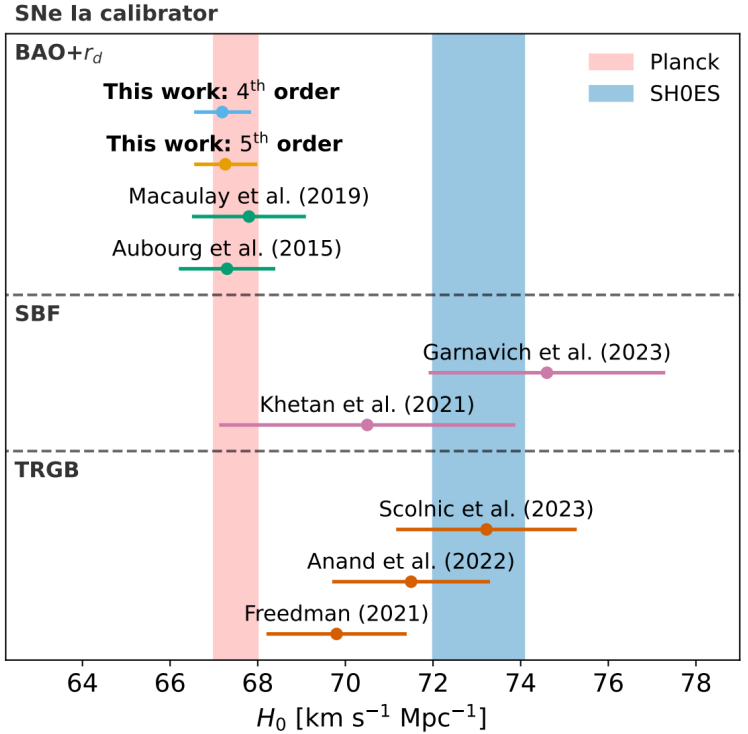
Science

- DES is not the ultimate experiment of its kind. PanSTARRS, LSST, and SNAP offer superior capability for similar measurements.
- The timing of DES is therefore crucial to its scientific impact. It will see first light in 9/2008. As presently planned, LSST will come on line in 1/2012. If DES is significantly delayed (> 2 years) and LSST holds schedule, DES will be eclipsed by LSST before it can complete its scientific program.
- PanSTARRS will be on-line in a similar time-frame to DES. However, PanSTARRS will be sited in Hawaii, and will not be able to followup the SPT clusters. *In terms of the complemenatarity to SPT, DES is unique in the 2008-2012 timeframe.*

The Dark Energy Survey: BAO-based low H_0



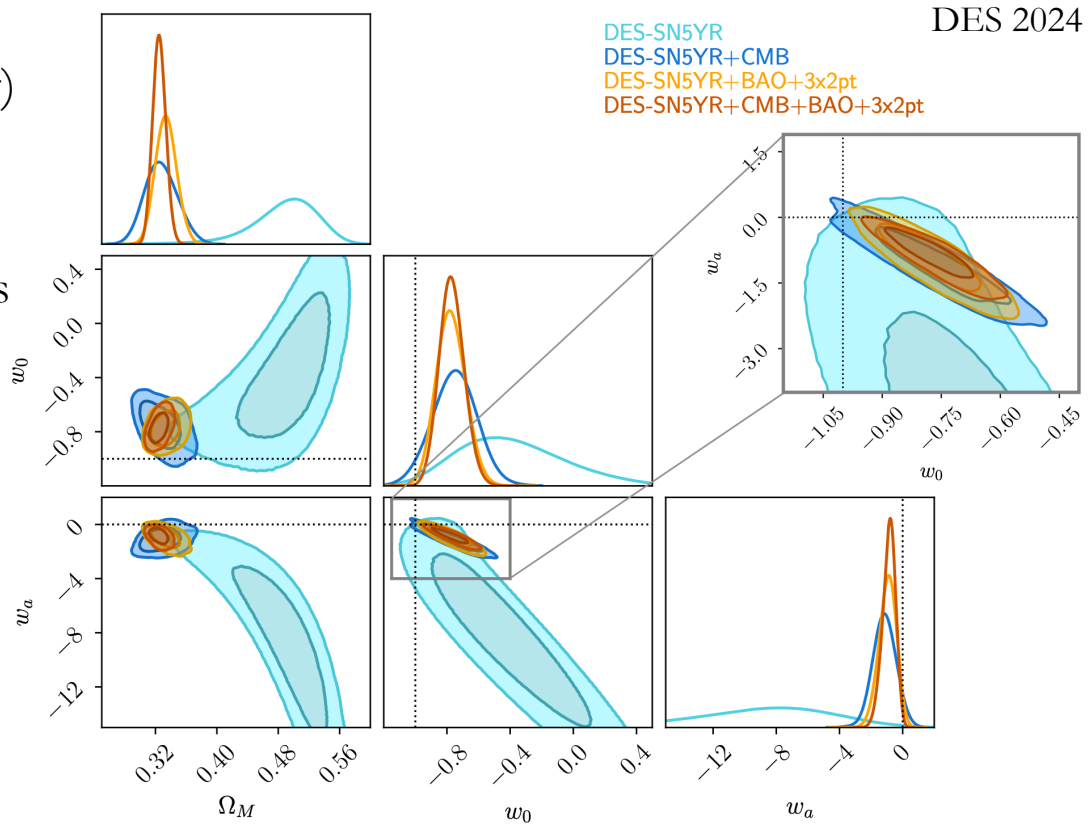
BAO, BBN, and DES 3x2pt: DES 2018



DES Supernova Inverse Distance Ladder: Camillieri+2024

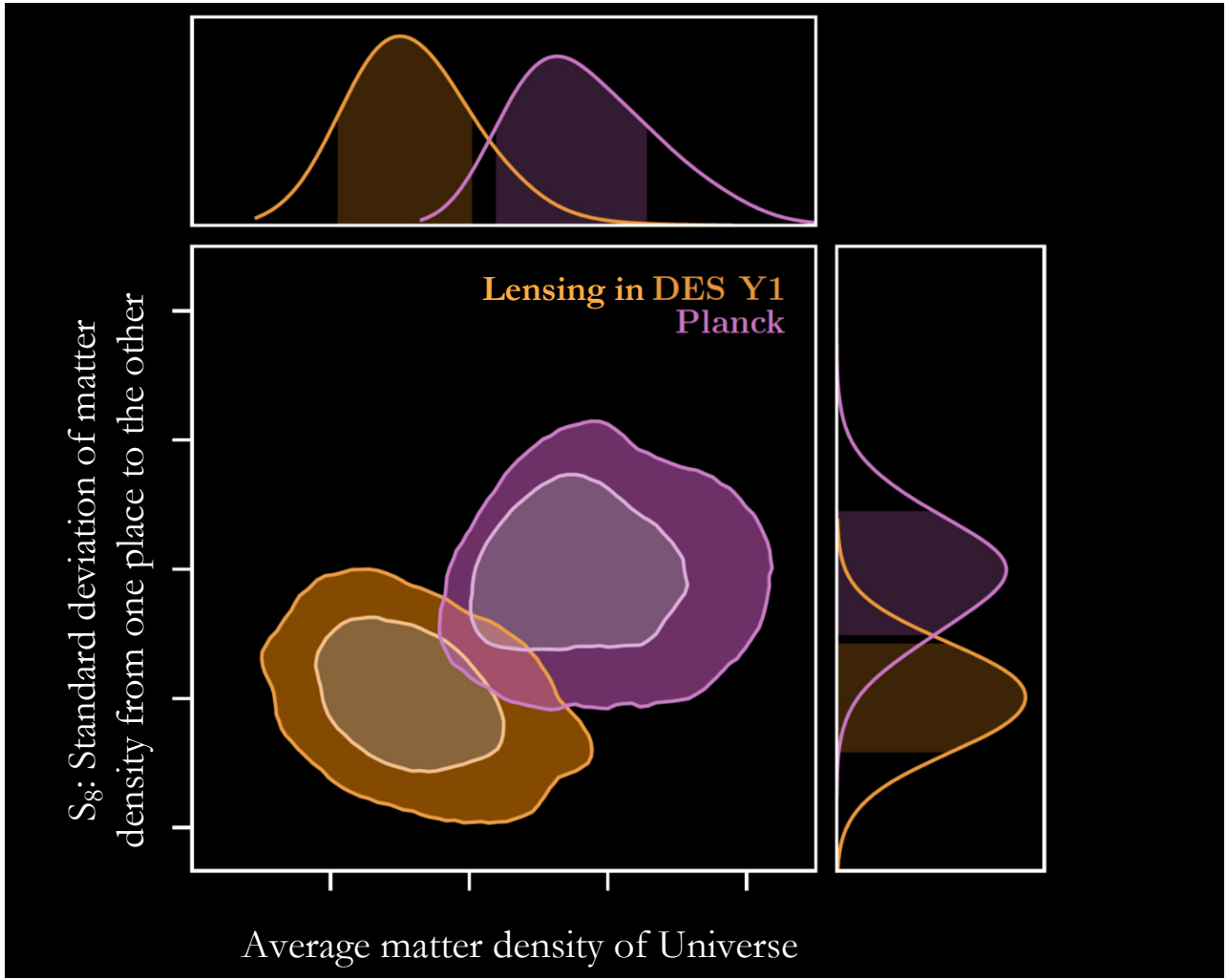
The Dark Energy Survey and Ω_m / w(z)

- DES supernovae have mild (2σ) preference for time-varying w
- Joint with CMB, pre-DESI-BAO, and 3x2pt, tension grows
- Together with latest DESI BAO: 4σ
- Forecast with final DES 3x2pt: 5σ if best fit stays as is



Flashback to 2017:
Dark Energy Survey
Year 1 results on S_8

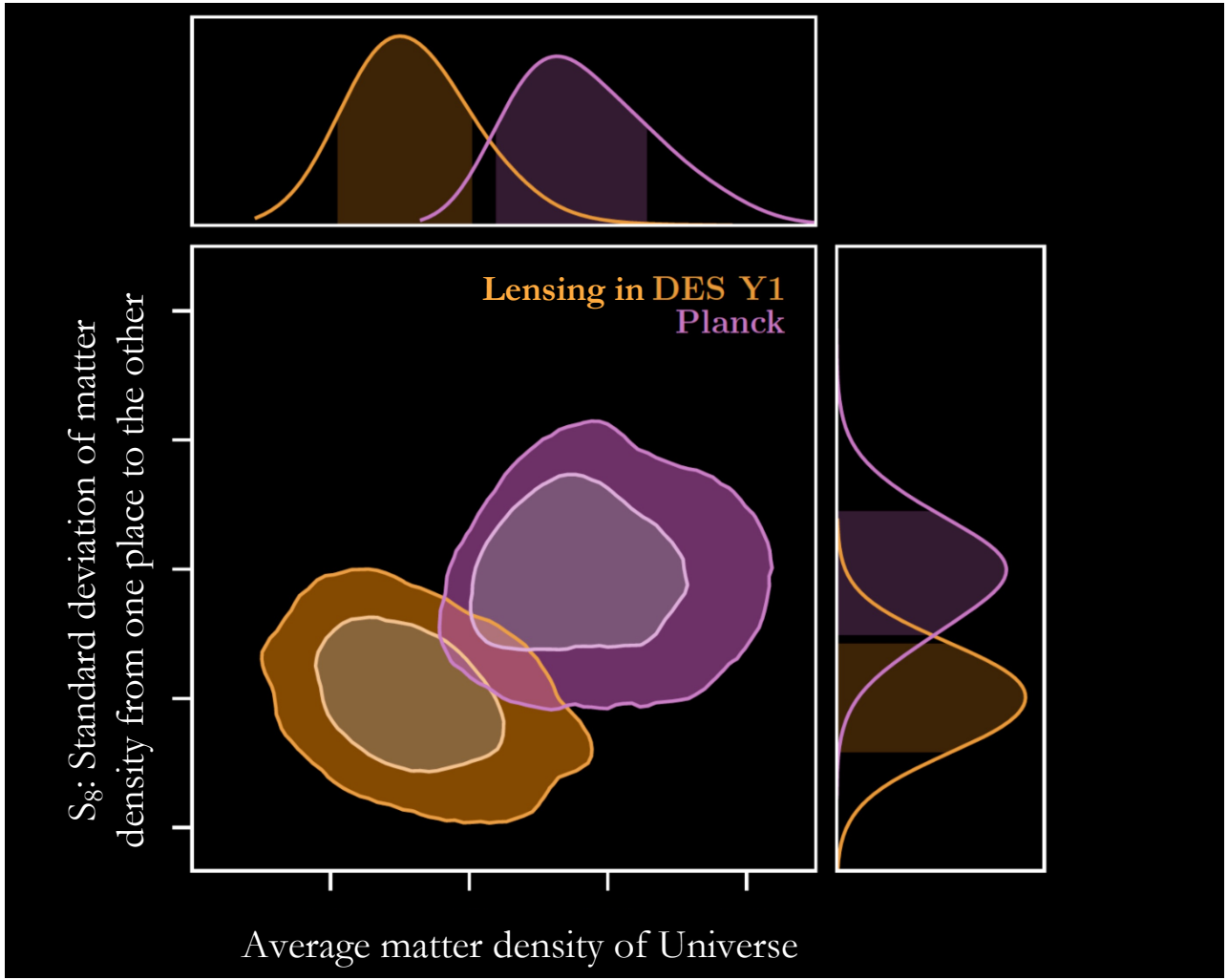
???



Flashback to 2017:
Dark Energy Survey
Year 1 results on S_8

???

DES Legacy:
being cautious with
interpresting hints



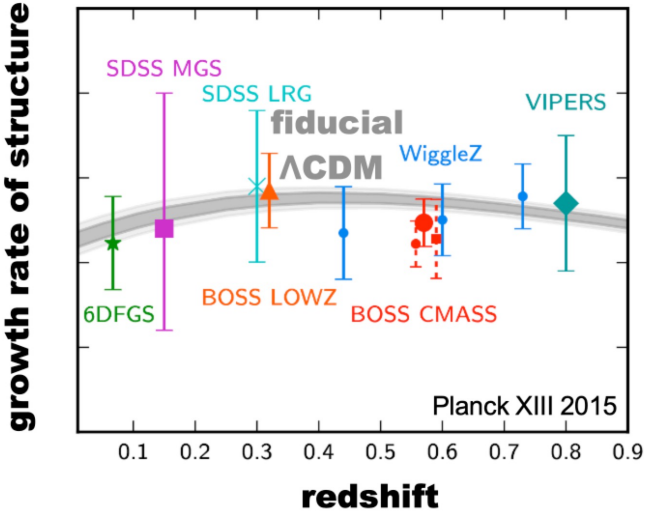
Measurements of evolved structure

Flashback to 2017

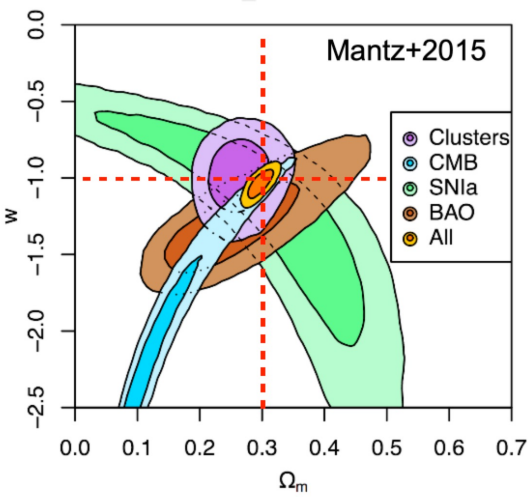
Clusters and redshift space distortions were fine

(they still are – just better)

Redshift space distortions: growth in action



Galaxy cluster counts: final stage of growth



✔ Growth rate and count of massive, virialized haloes are consistent with geometric probes and fiducial ΛCDM model

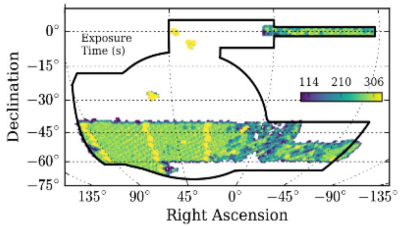
Flashback to 2017

DES Legacy: a spirit of taking great care

see also talk by Elisa Legnani on also Y6 methodology updates

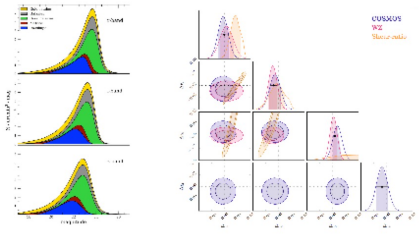
With great statistical power comes great systematic responsibility

Unprecedented size and depth of photometric data



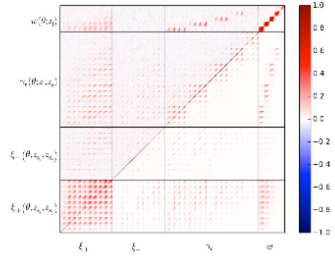
Drlica-Wagner, Rykoff, Sevilla+ released today

Two independent shape & photo-z catalogs and calibrations

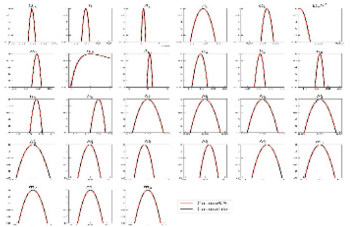


Zuntz, Sheldon+; Samuroff+; Hoyle, Gruen+ released today; Davis+, Gatti, Vielzeuf+, Cawthon+ in prep.

Full, validated treatment of covariance and nuisance parameters (including v)

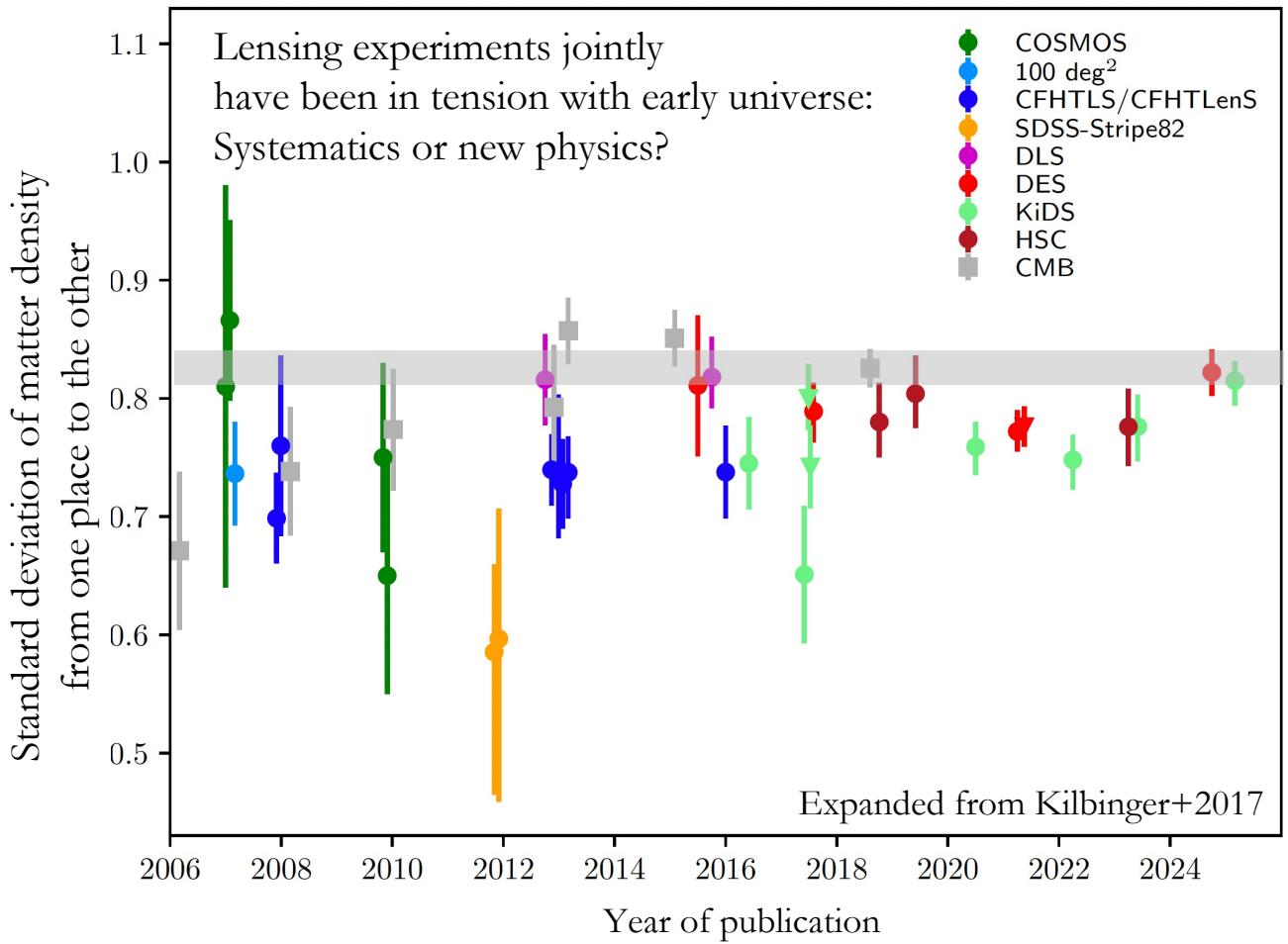


Theory and simulation tested, blind, analysis with two independent codes, CosmoLike and CosmoSIS

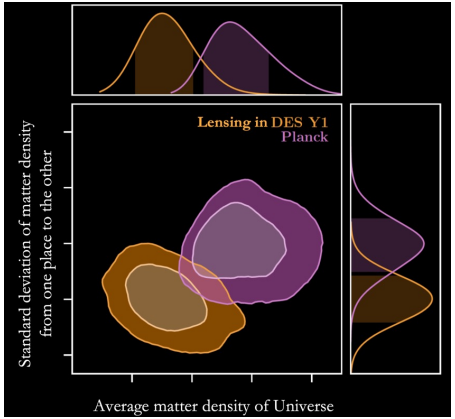


Krause, Eifler+2017; MacCrann, DeRose+ in prep

Lensing was low



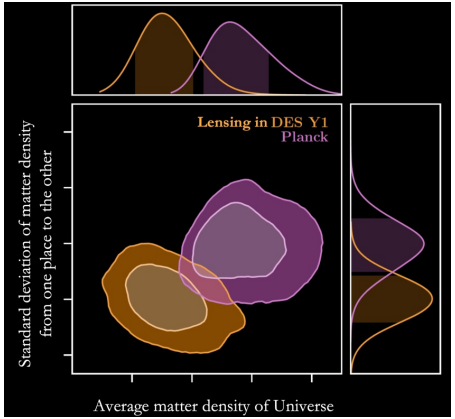
What could possibly go wrong with S_8?



A comprehensive list:

- It could be just noise
- It could be some very strange fundamental physics nobody is expecting
- Maybe *Planck* is wrong

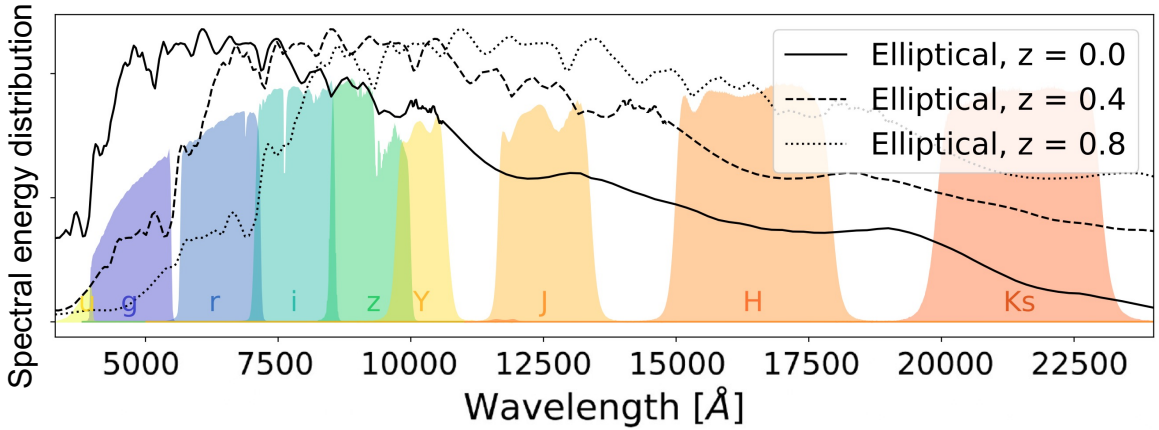
What could possibly go wrong with S_8?



A comprehensive list:

- It could be just noise
- It could be some very strange fundamental physics nobody is expecting
- It could be systematic error, in particular:

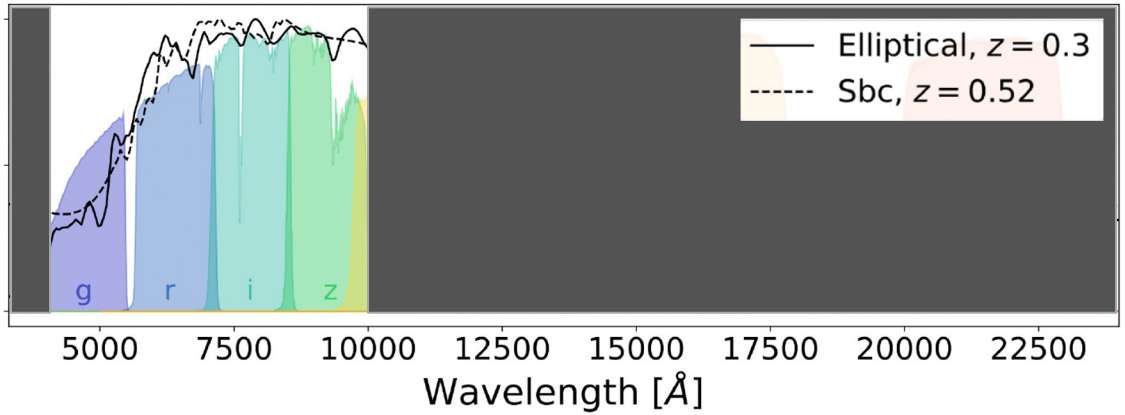
1. Maybe we overestimated galaxy distance or underestimated their shear
2. Maybe we underestimated how much explosive events redistribute matter
3. Maybe we falsely modelled some of the signal as intrinsic alignment of galaxies



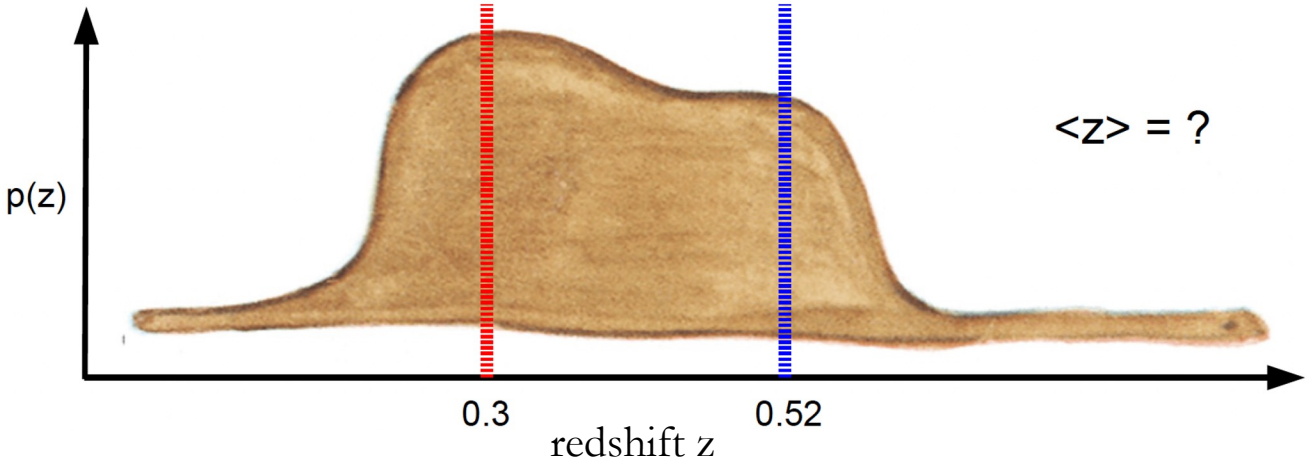
Buchs, Davis, DG+2019

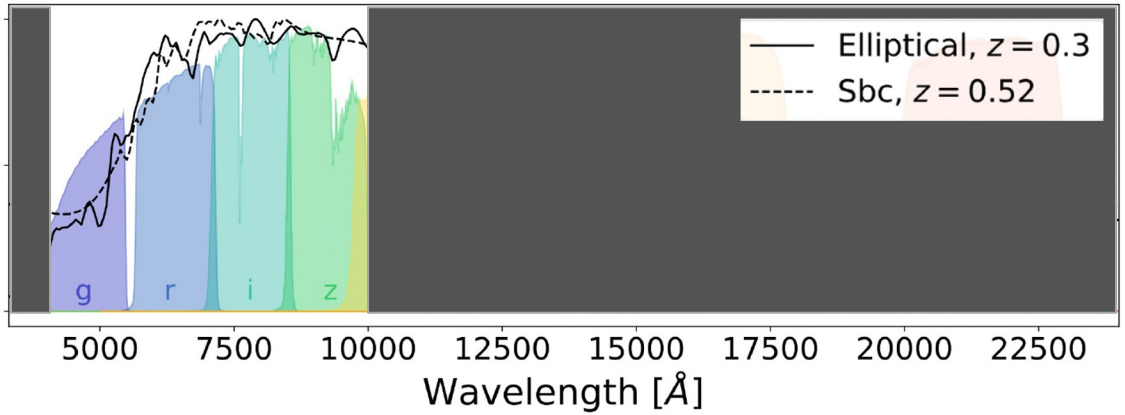
It is ~2010 and photo-z seems manageable:

Just fit galaxy SED templates to observed colors,
varying their redshift until they match

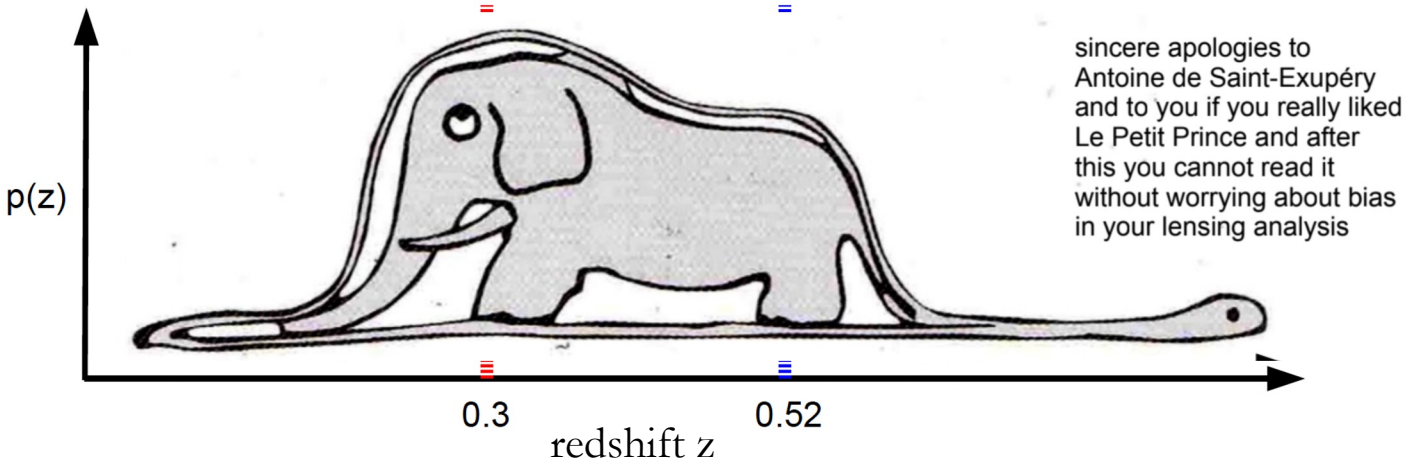


Buchs, Davis, DG+2019





DG & Brimioulle 2017
Buchs, Davis, DG+2019



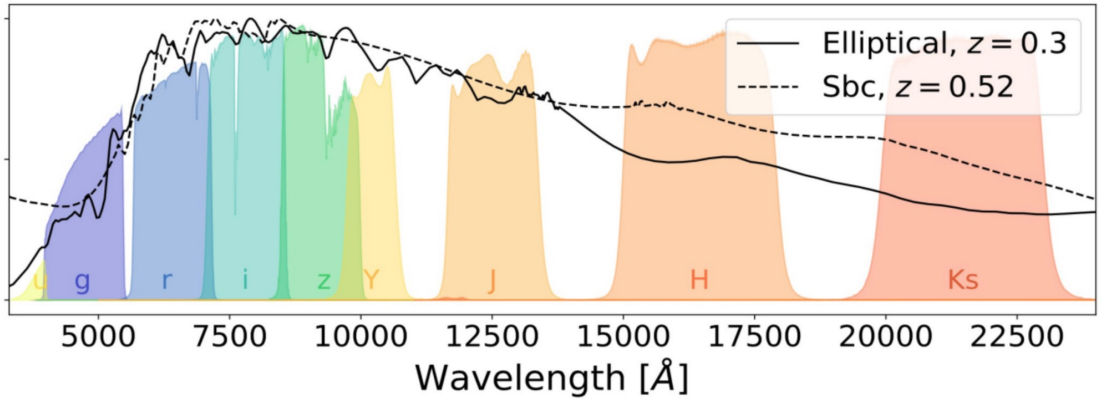
Elephant in the room: Few-band COLOURS of galaxies are ambiguous, with a degeneracy between intrinsic type and redshift.

Choose your field wisely

- Type/redshift degeneracy in wide-field data causes irreducible issues in photometric redshift calibration
- We cannot hope to get wide-field data that is good enough at distinguishing type/redshift

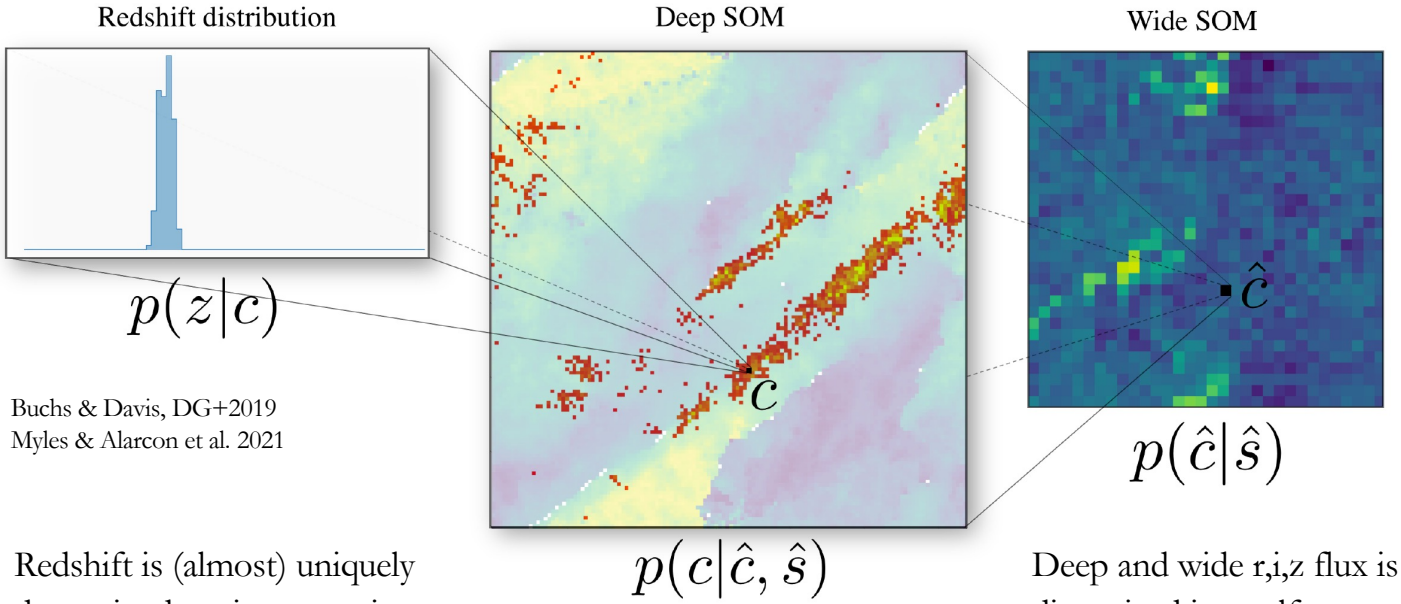
Choose your deep fields wisely to break type/redshift degeneracy

- Type/redshift degeneracy in wide-field data causes irreducible issues in photometric redshift calibration
- We cannot hope to get wide-field data that is good enough at distinguishing type/redshift
- But we could collect additional deep-multi-band photometry and spectroscopy over a large enough calibration area to know well enough what's the mix of types/redshifts at given wide-field photometry



DG & Brimioulle 2017
Buchs, Davis, DG+2019

DES Legacy: Combining wide, deep, and spec-z fields for photometric redshift calibration



Buchs & Davis, DG+2019
Myles & Alarcon et al. 2021

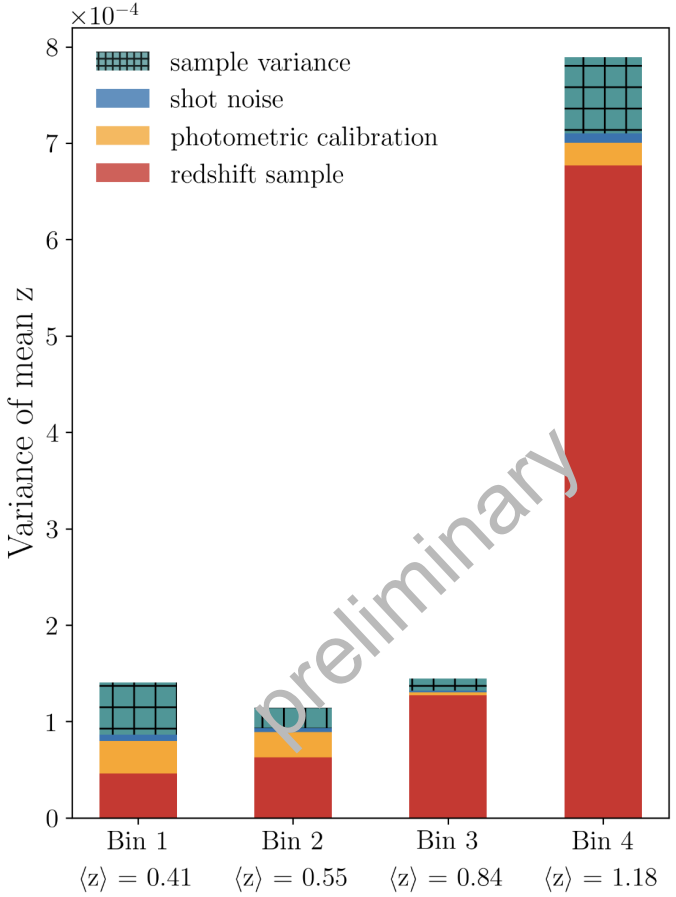
Redshift is (almost) uniquely determined at given u,g,r,i,z, Y,J,H,K, reducing selection bias and cosmic variance from spec-z sample

Large deep sample constrains mix of u,g,Y,J,H,K at given r,i,z to reduce cosmic variance

Deep and wide r,i,z flux is discretized in a self-organizing map to handle survey transfer and selection function.

DES Y6 redshift limitations

- DES Y6: similar redshift methodology
- Highly uncertain for fainter sources due to limited spectroscopic samples
- Not good news for ~~future~~ present surveys!



DES Y6: Boyan Yin et al. in prep

McCoullough et al. 2024

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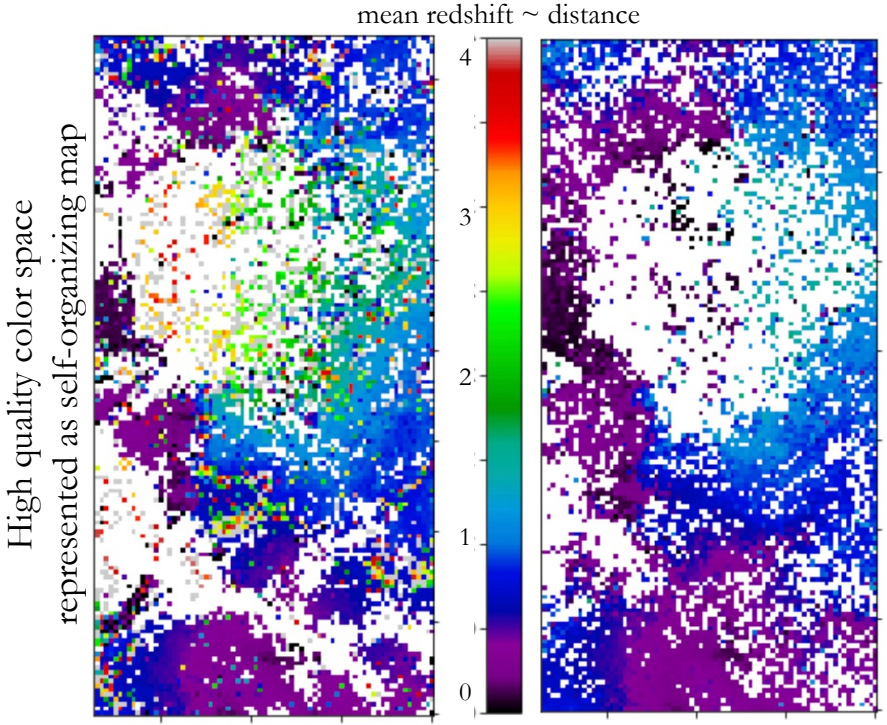
- DES Lesson: new spec-z need to be collected. Work underway with DESI, 4MOST, and 8m-class telescopes



McCoullough et al. 2024

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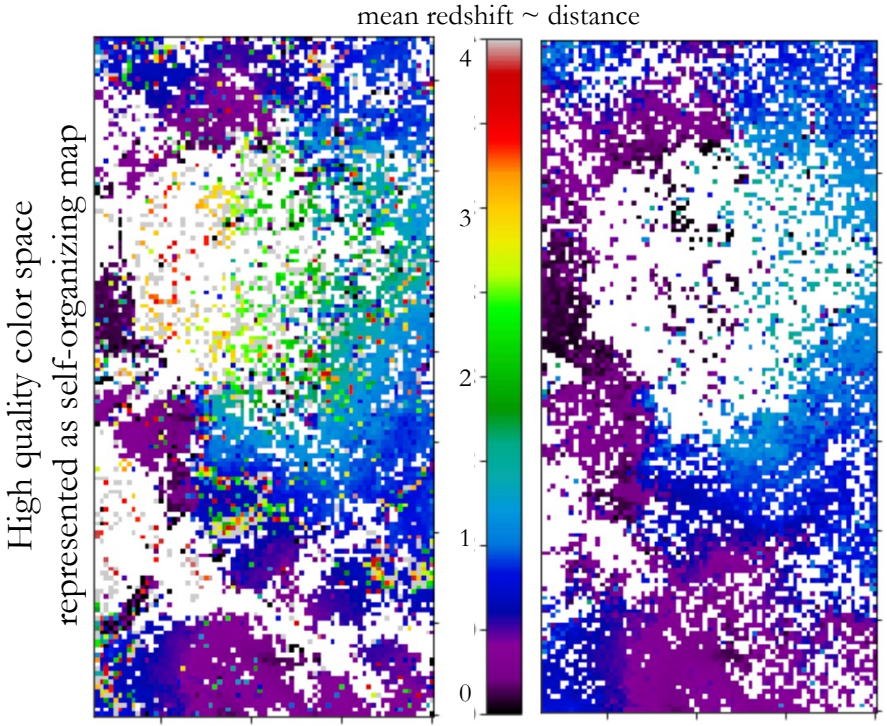
- DES Lesson: spec-z samples need to be collected. Work underway with DESI, 4MOST, and 8m-class telescopes
- DES Lesson: We have to reinvent photo-z once again. See talk by Luca Tortorelli.

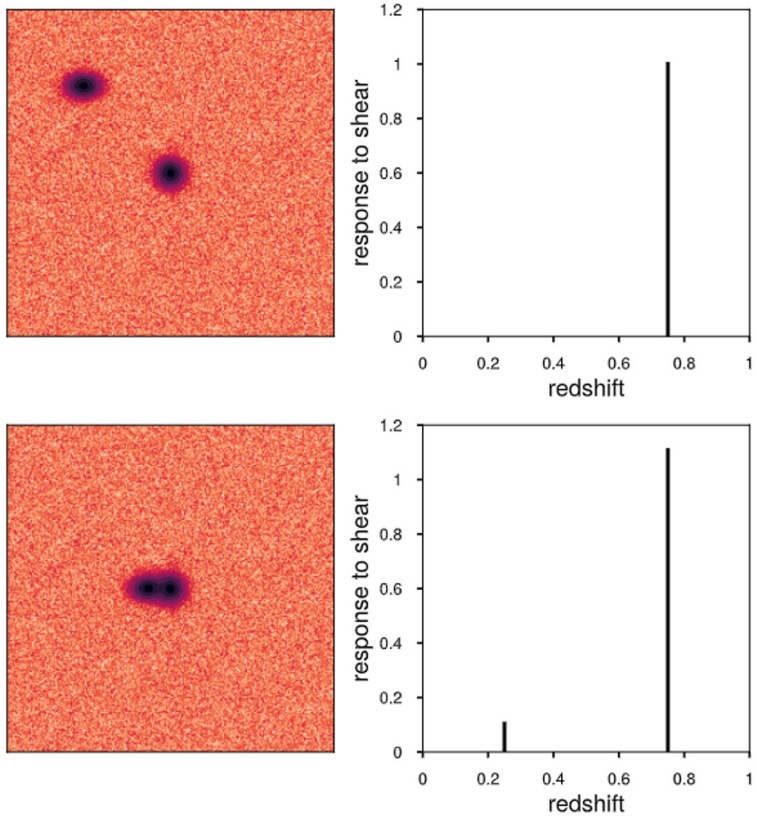


30,000 spectra using Keck, VLT, LBT: C3R2 [Masters et al., Guglielmo & Saglia et al., ++]

300,000 spectra using half a year of **DESI**, and soon 4MOST: DC3R2 and 4C3R2 [McCullough, Tortorelli, DG]

Blending and redshift

- ‘Detections’ in catalog are commonly from a superposition of light from different redshifts
- ‘Shape’ of detection responds to shear applied to any of its components
- ‘Redshift distribution’ for lensing purposes must be corrected for this effect



MacCrann, Becker, McCullough, Amon, DG+2021; Li+2023

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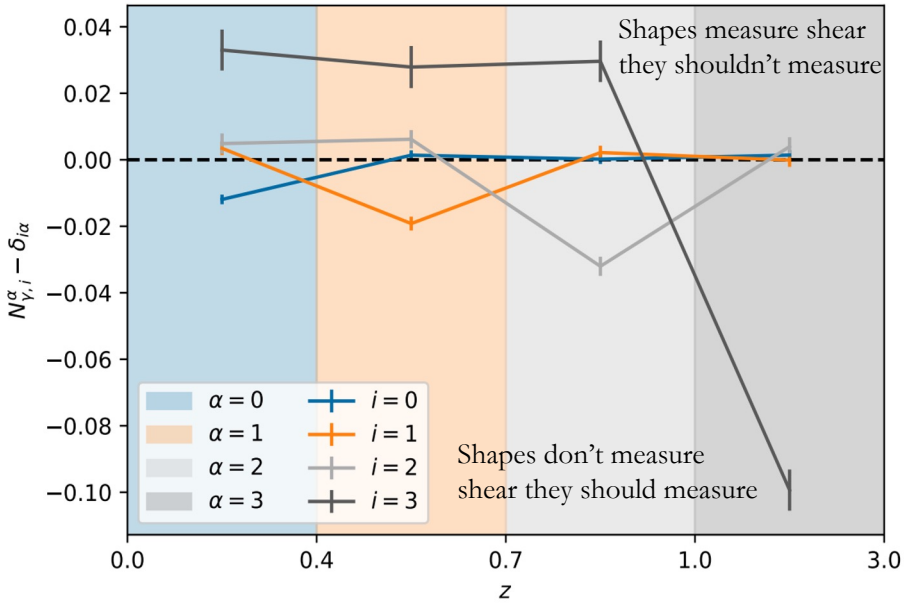
- This is a few-per-cent effect for faint sources
- Limited by coarse simulations feasible to date



MacCrann, Becker, McCullough, Amon, DG+2021; Li+2023

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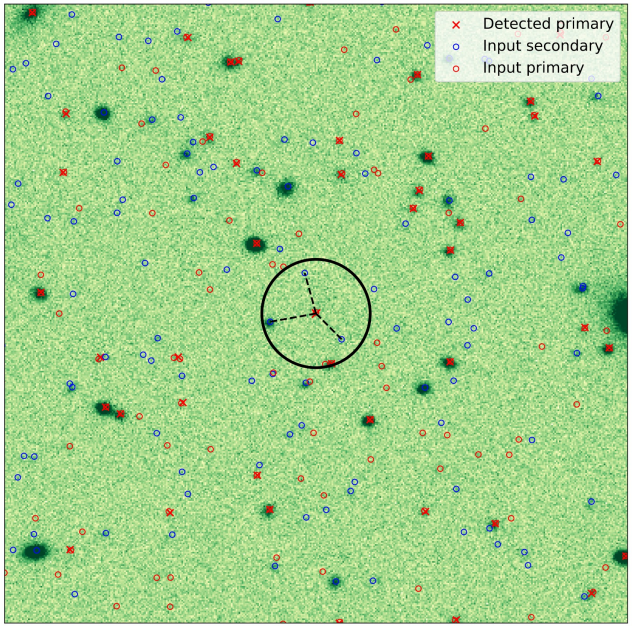
- Limited by coarse simulations feasible to date
- But can simulate a ‘half-sheared’ sky and emulate effect

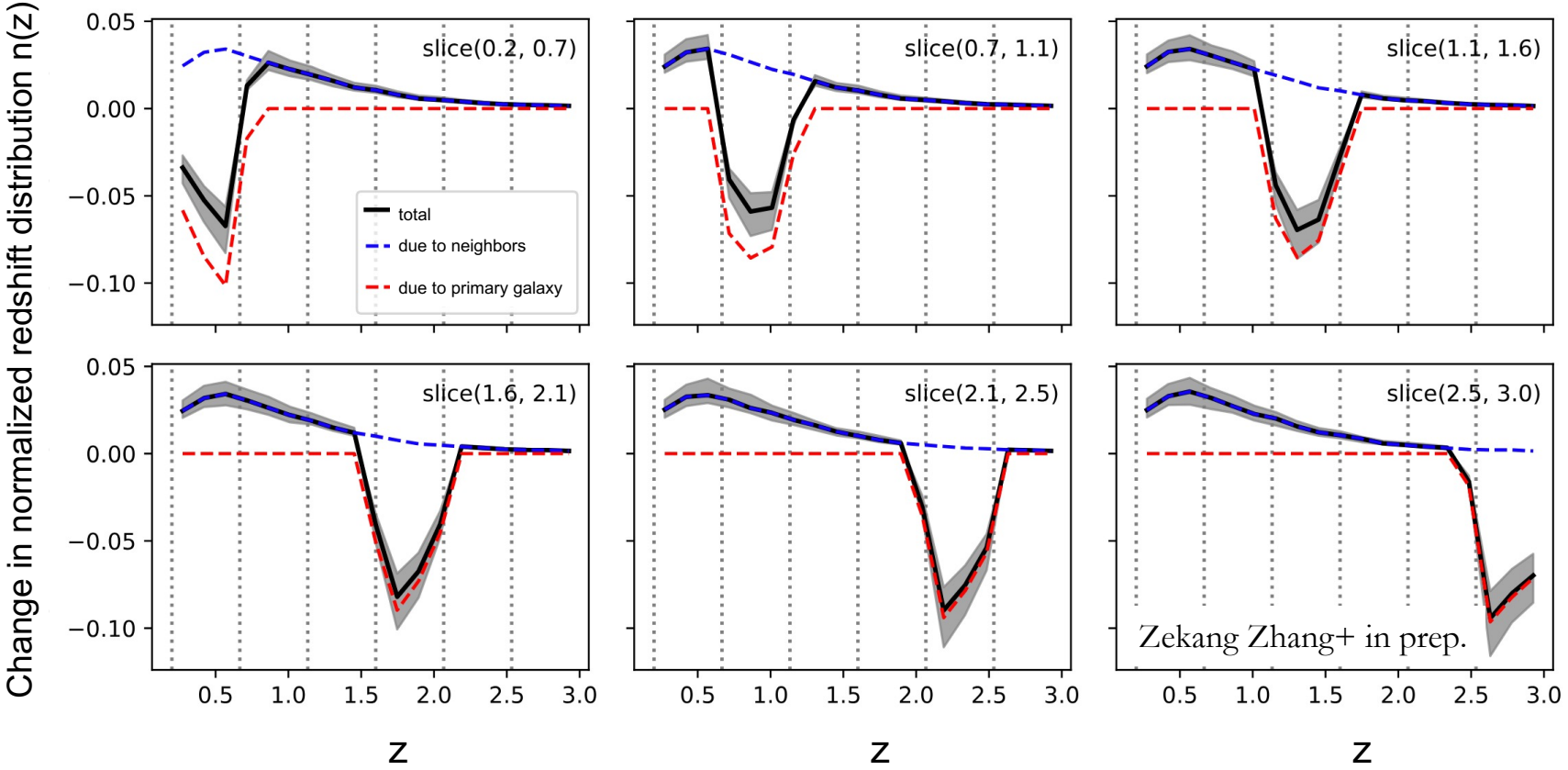


Zekang Zhang+ in prep.

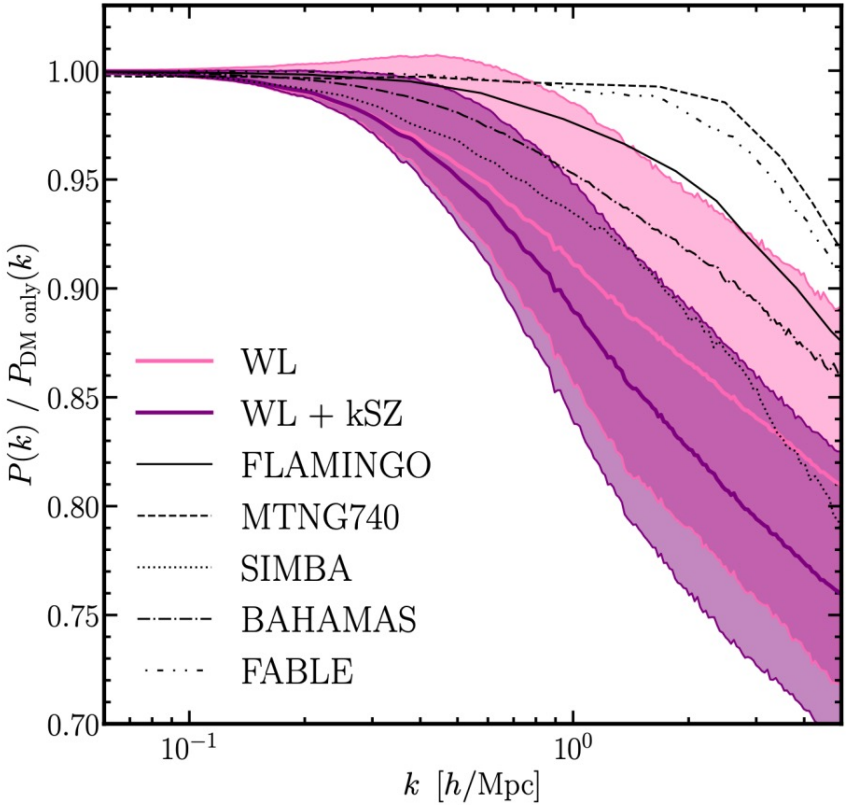
Blending and redshift

DES Lesson:

Blending related effects likely to be the leading Stage-IV lensing systematic



What could possibly go wrong II: Baryons



kSZ pushes us to a more 'extreme' feedback scenario than the hydrodynamical simulations predict

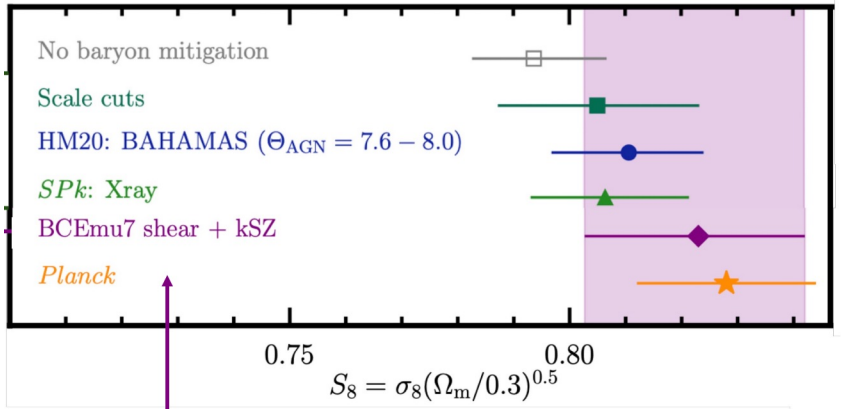
DES Lesson: Don't ignore baryons

[*Bigwood, Amon+2024*]

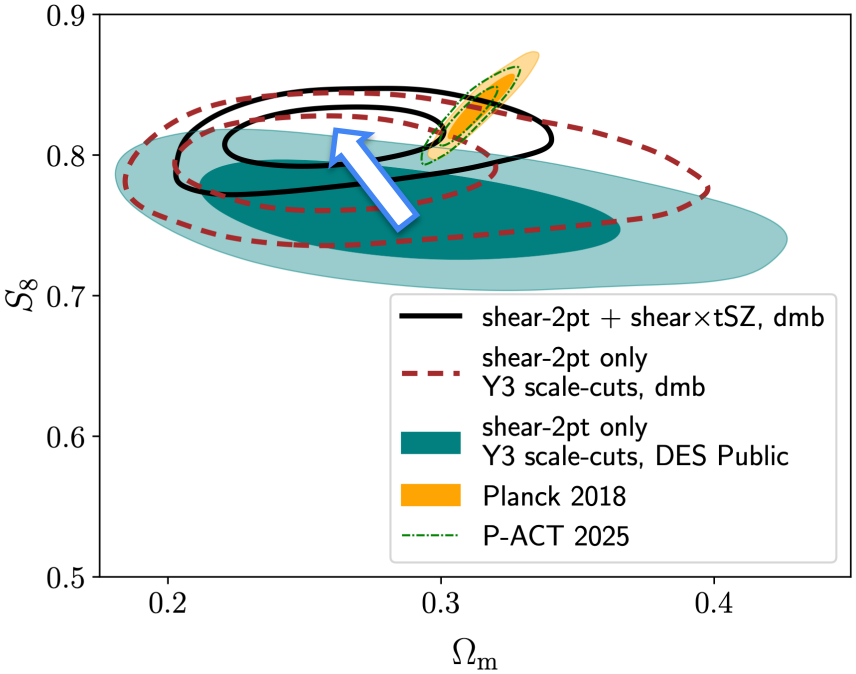
What could possibly go wrong II: Baryons

DES Legacy: Probes of baryons + lensing tell us feedback may be extreme

[Bigwood, Amon+2024]



Highly flexible model + kSZ effect:
Baryonification (analytic model based on N-body simulations)

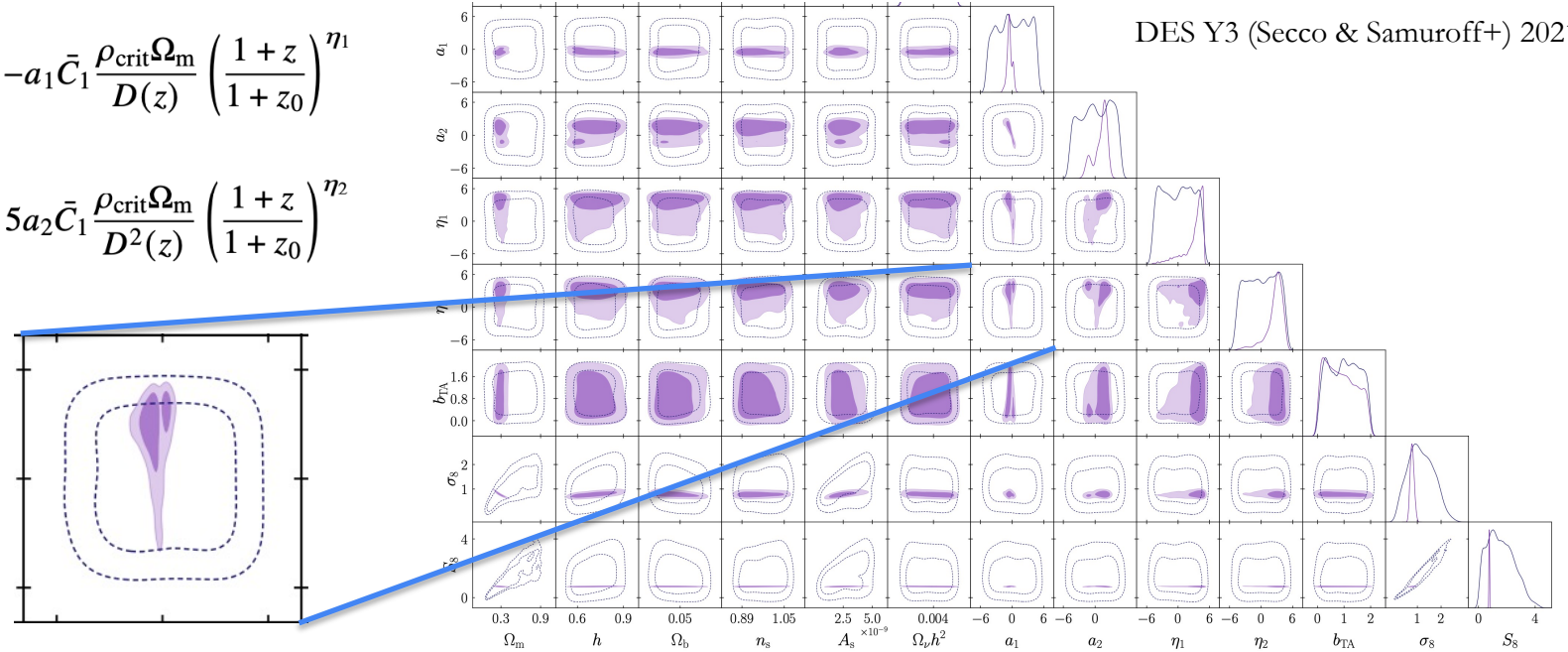


Pandey et al. 2025, DES Y3 cosmic shear + ACT tSZ in halo model

What could possibly go wrong III: Intrinsic Alignments

$$A_1(z) = -a_1 \bar{C}_1 \frac{\rho_{\rm crit}\Omega_{\rm m}}{D(z)} \left(\frac{1+z}{1+z_0}\right)^{\eta_1}$$

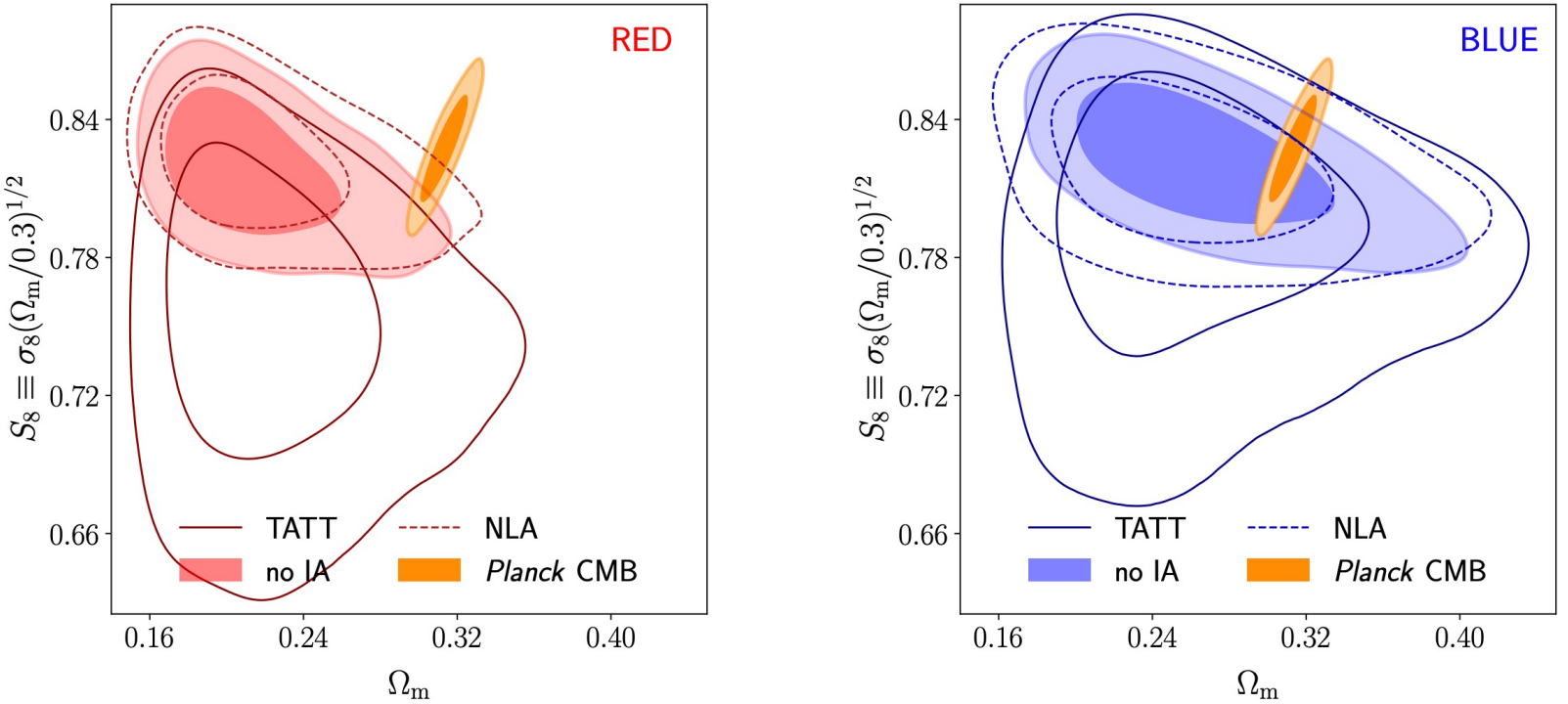
$$A_2(z) = 5a_2 \bar{C}_1 \frac{\rho_{\rm crit}\Omega_{\rm m}}{D^2(z)} \left(\frac{1+z}{1+z_0}\right)^{\eta_2}$$



DES Y3 used complex intrinsic alignment models, but preferred *none*

DES Lesson: Projection effects are an issue for marginalized posterior

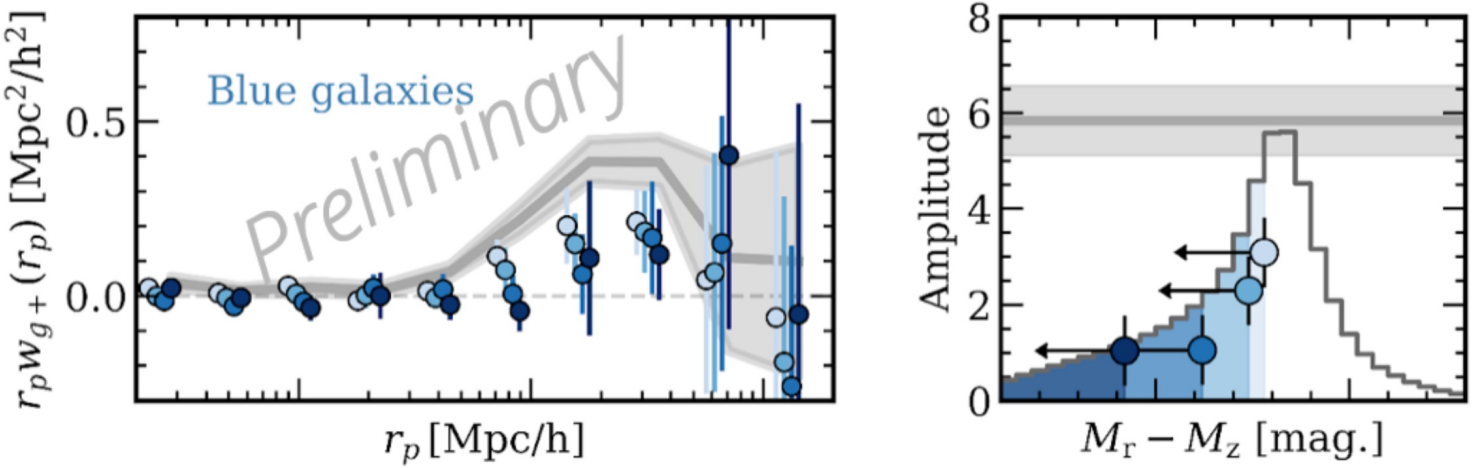
DES Legacy: how to not have to worry about intrinsic alignments



DES Y3 cosmic shear with a purely star-forming galaxy sample
McCullough, Amon, Legnani, DG et al. 2024

Direct measurements: how to know intrinsic alignments

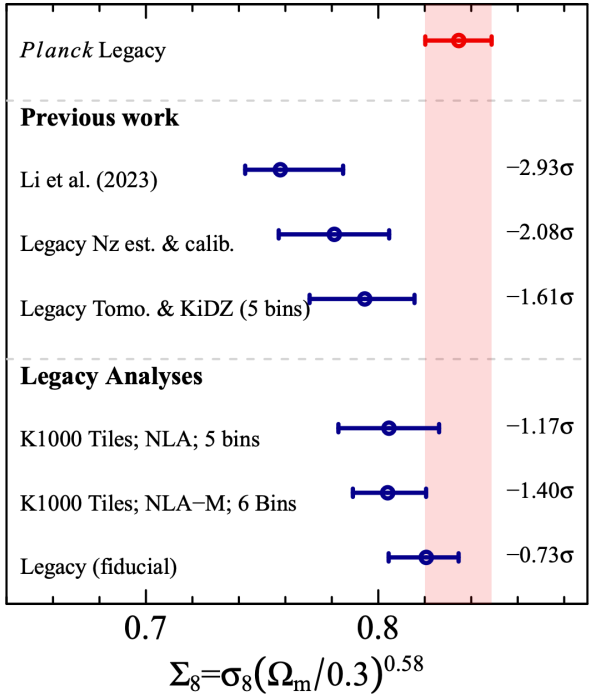
- DES Lesson:
  - Gains can be made by conscious, simulation/astrophysics informed analysis choices and priors
  - We will want to physically model the galaxy population in lensing



Siegel, McCullough, Amon in prep.: DESI direct measurements of IA

How KiDS have grown in S_8

- Updates to the redshift calibration in KiDS Legacy vs KiDS 1000 analysis remove tension (from 2.9 to 1.6σ)
- Choice of intrinsic alignment model and added area move S_8 up a bit further



KiDS-Legacy: Wright et al. 2025

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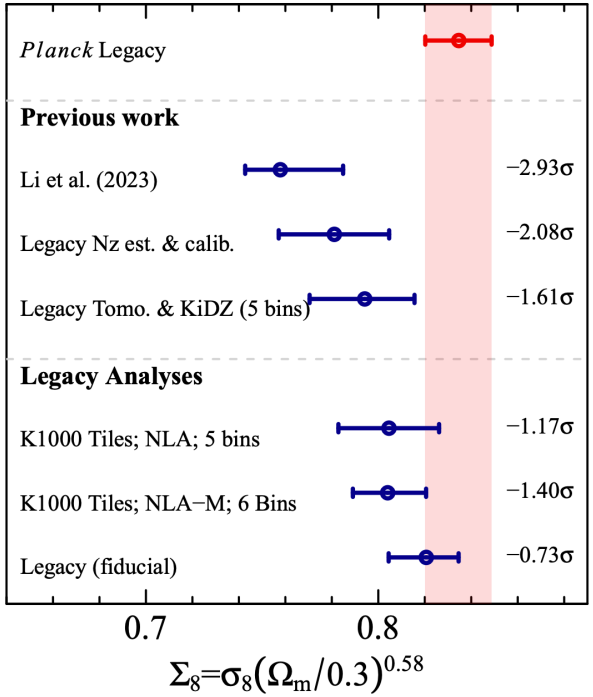
Does the KiDS-Legacy analysis resolve the S8 tension?

🧠 **Conclusion**

The comprehensive KiDS-Legacy analysis, with its methodological advancements and expanded dataset, has brought the S_8 measurements from weak lensing surveys into alignment with CMB observations. While this development significantly reduces the previously noted tension, ongoing and future surveys like Euclid and the Vera C. Rubin Observatory will continue to refine these measurements and further test the robustness of the ΛCDM model.



KiDS-Legacy: Wright et al. 2025

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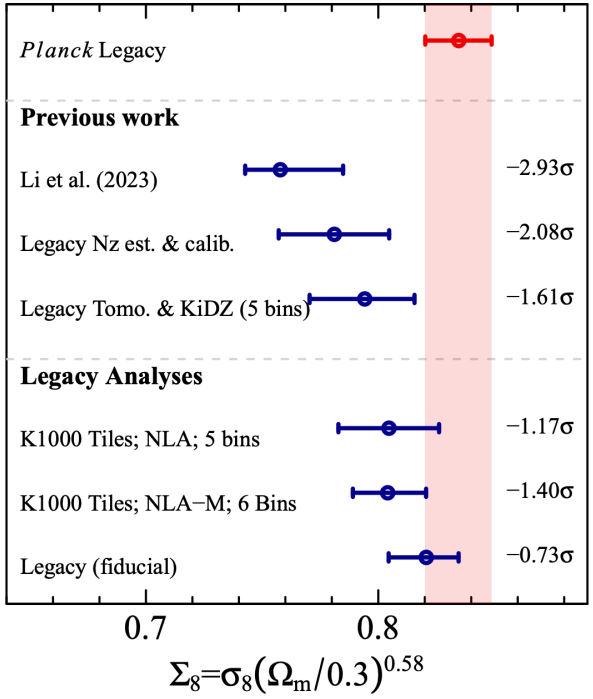
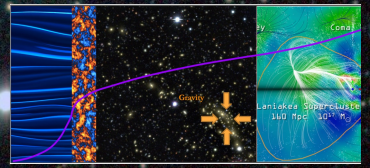
- IMO: If you were really excited about the S_8 tension then it's probably too soon to tell – clear improvements, but also room left in the redshift calibration choices



KiDS-Legacy: Wright et al. 2025

Galaxy surveys and cosmological tensions

- Small signals in galaxy images and spectra provide the key expansion and structure growth tests of Dark Energy



- Galaxy surveys have been questionably consistent with CMB
- For the amount of structure S_8, this tension recently decreased:
  - Shape and distance measurement of galaxy images improved
  - Explosive events == baryon feedback: strong
  - Intrinsic alignment modeling issues evaded
- There is >4σ evidence now in some data combinations for a time-evolving dark energy equation of state, and >5σ tension in H_0
- Whether real or not, tensions have prompted intensive progress