Comunidad de Madrid

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Multi-survey cosmology
from galaxy clustering and weak lensing

Anna Porredon
César Nombela Talent Attraction Fellow

CIEMAT, March 19, 2026

Image credit: DES collaboration

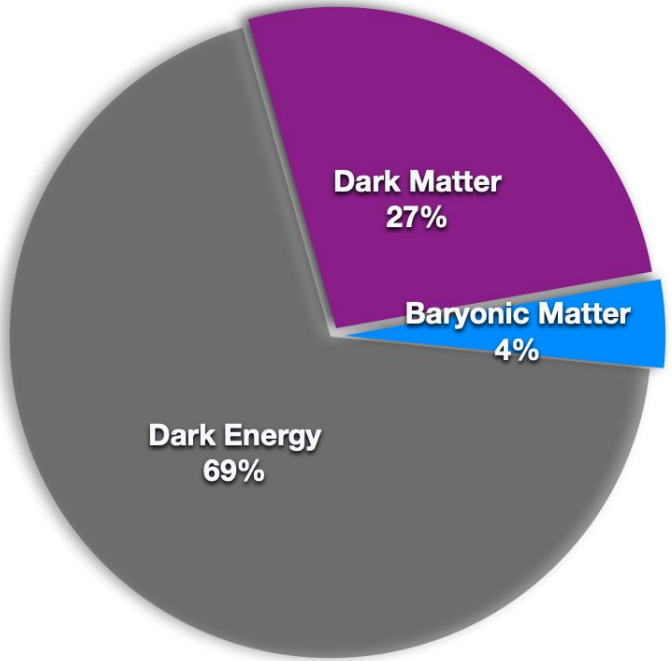
Outline

Introduction

Cosmology from galaxy clustering and weak lensing in DES

Cross-survey cosmology from galaxy clustering and weak lensing

Standard Cosmological Model: ΛCDM

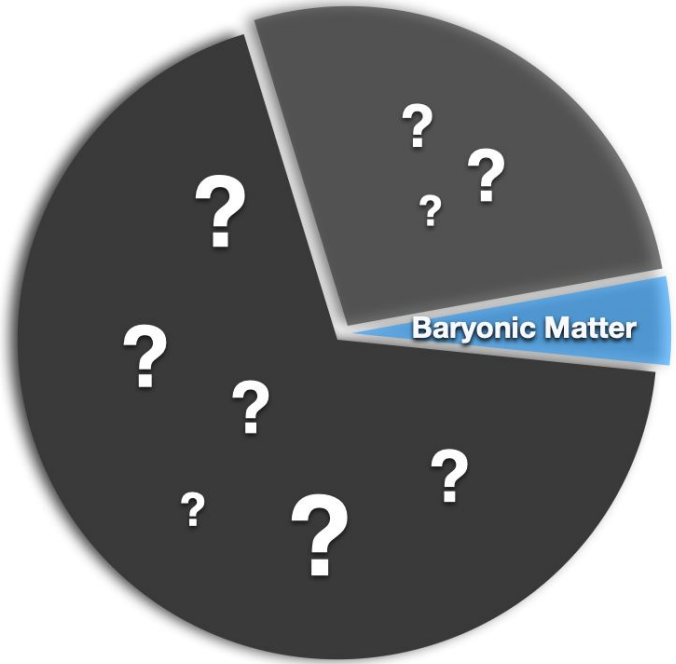


$$\Omega_m = 0.31$$

matter energy density

responsible for the accelerating expansion of the Universe

Standard Cosmological Model: ΛCDM



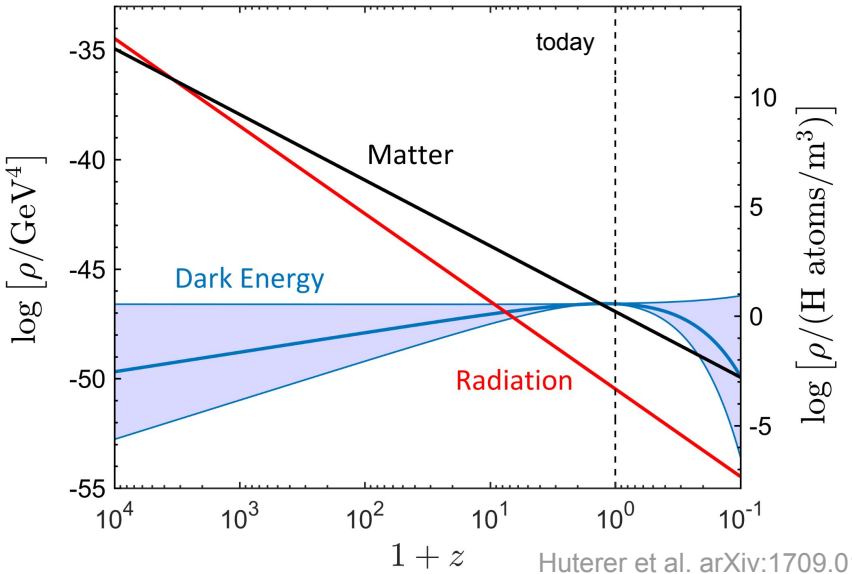
Standard Cosmological Model: ΛCDM

Dark Energy acts like a fluid with energy density constant with time and negative pressure

$$w = -1$$

dark energy equation of state

Need more precise measurements to test General Relativity and the nature of dark energy, e.g. to check if its energy density is actually constant or it evolves slowly with time



Huterer et al. arXiv:1709.01091

Testing ΛCDM: Are the late time observations compatible with those from the early universe?

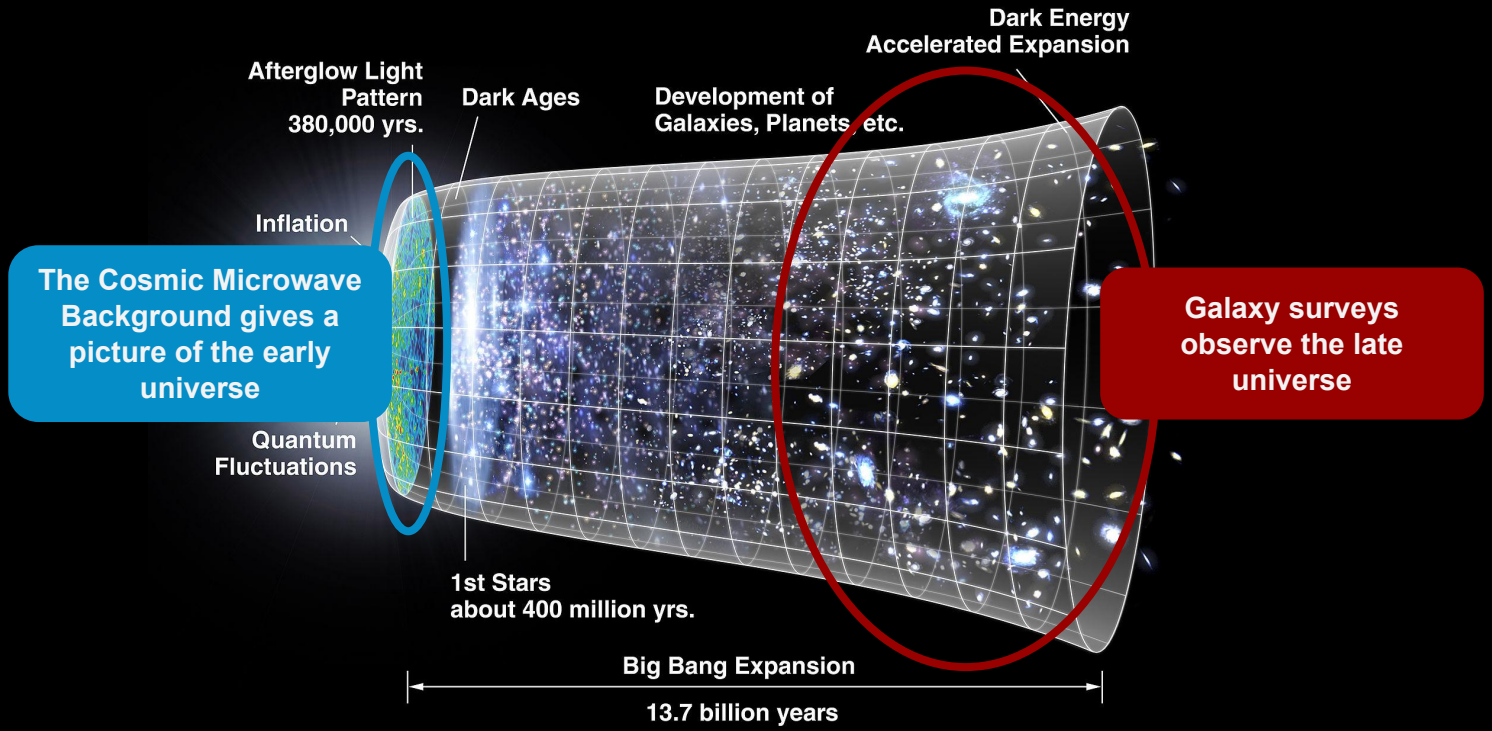
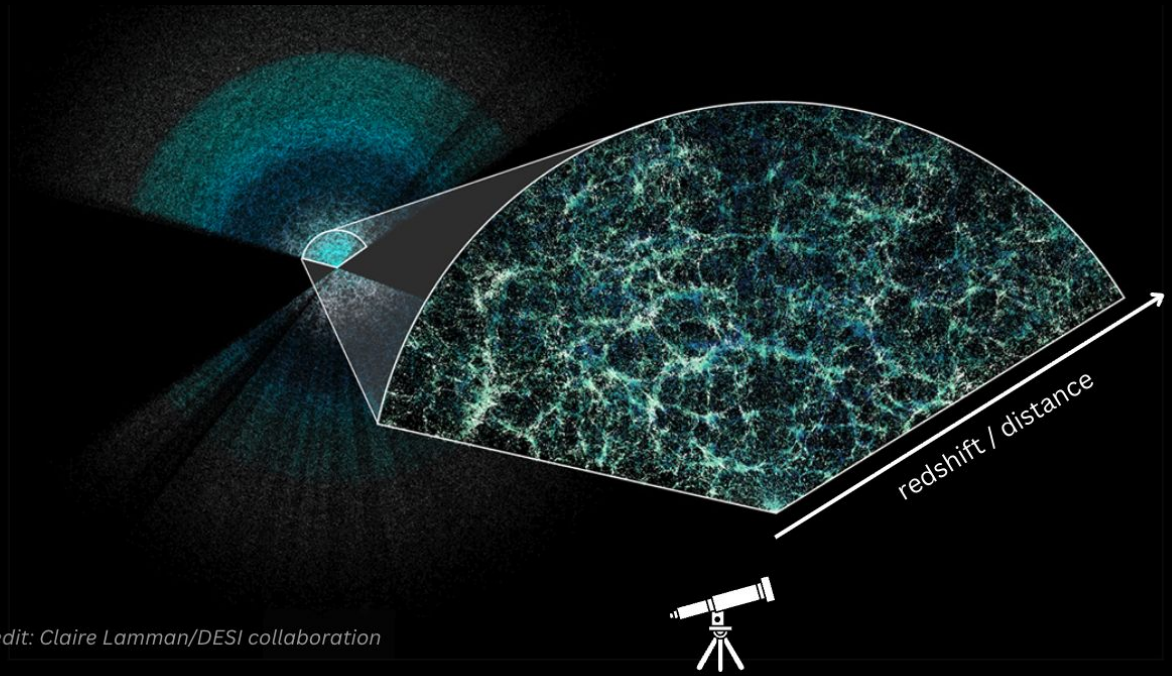


Image Credit: NASA / LAMBDA Archive / WMAP Science Team

Large scale structure and galaxy clustering

We can learn more about dark matter and dark energy by **mapping the distribution of the large scale structure (tracer of the matter distribution in the Universe)**



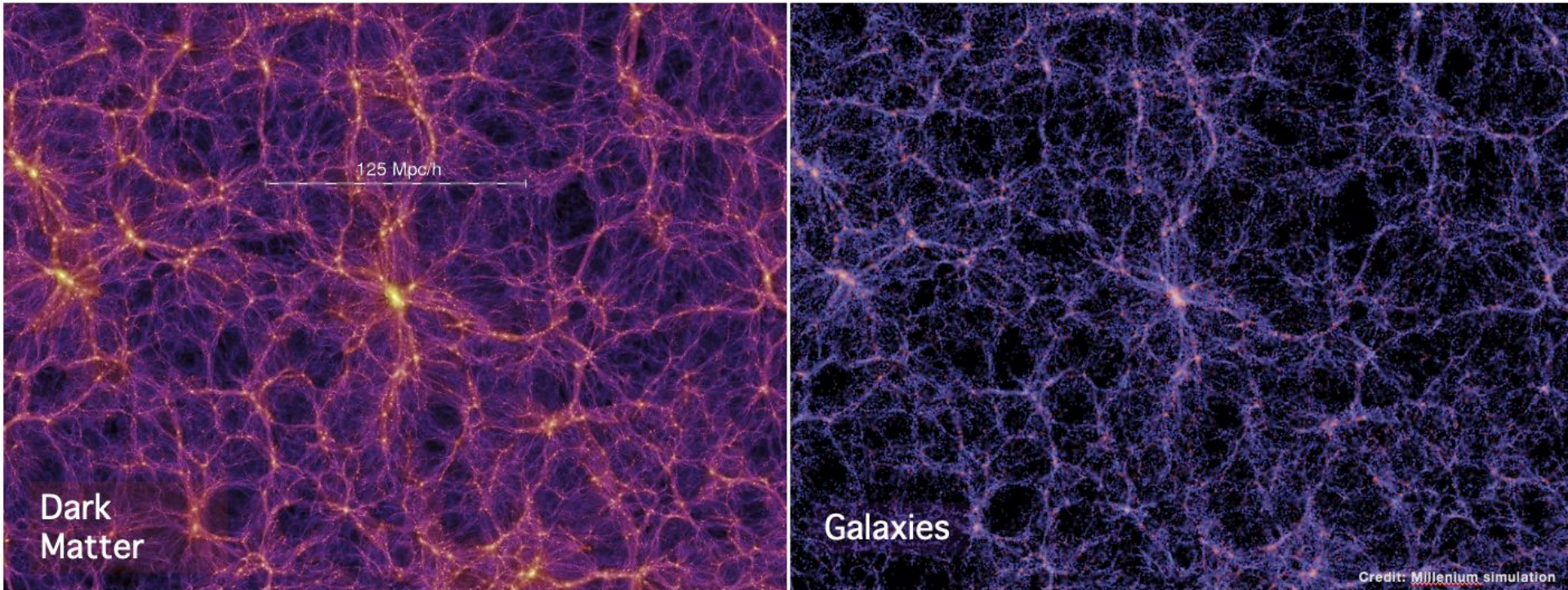
Credit: Claire Lamman/DESI collaboration

- The positions of galaxies are tracers of the underlying matter distribution
- We use two-point statistics to characterize the distribution of the positions of galaxies (**galaxy clustering**)

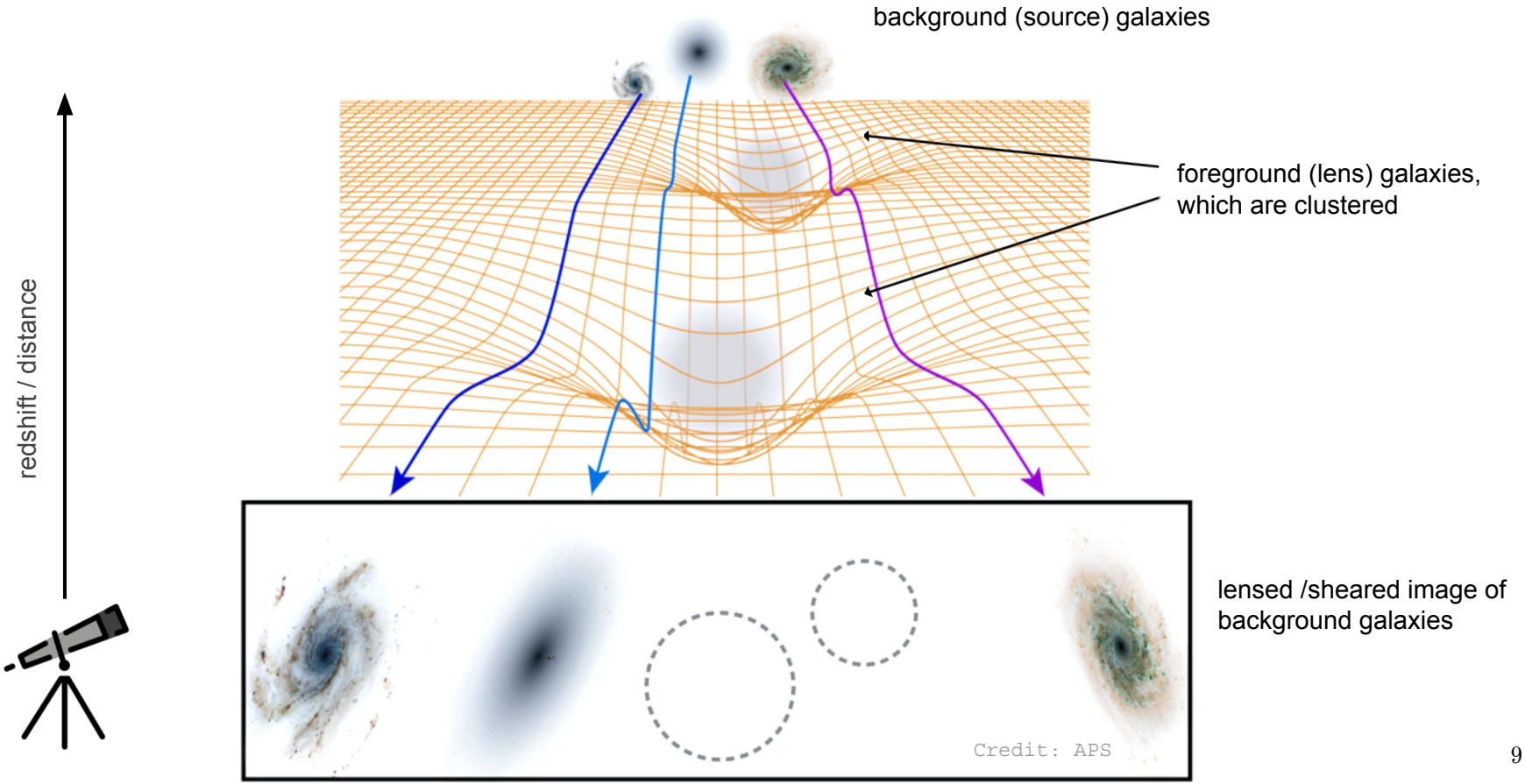
Galaxy bias

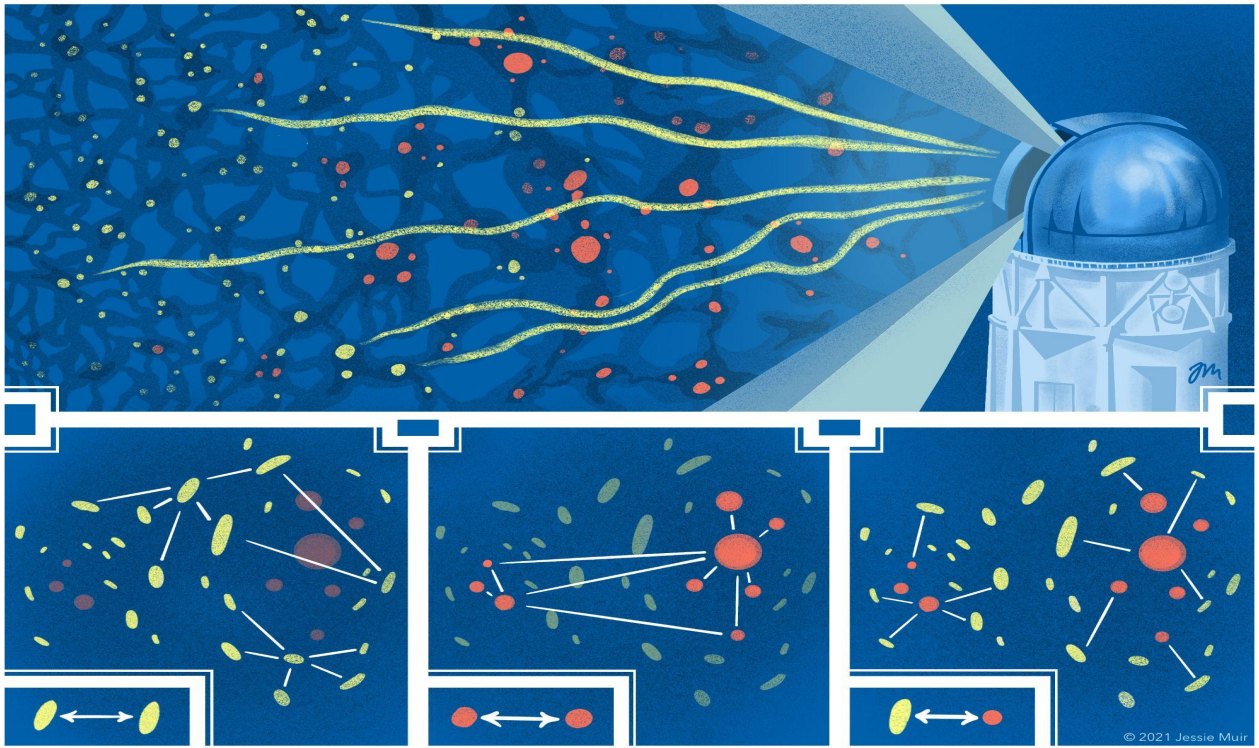
Galaxies are a biased tracer of the underlying matter density field

$$\delta_g = b\,\delta$$



Weak gravitational lensing





cosmic shear

correlation in the shapes of (source) galaxies

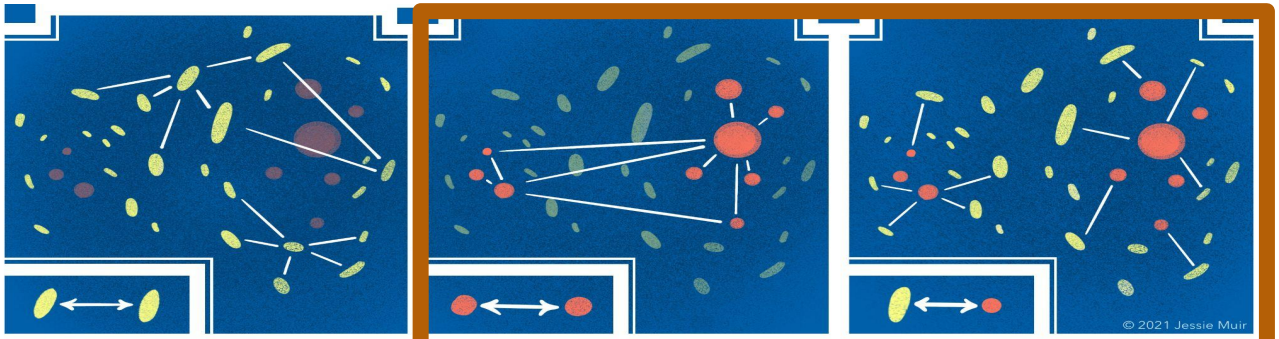
galaxy clustering

correlation in the positions of (lens) galaxies

galaxy-galaxy lensing

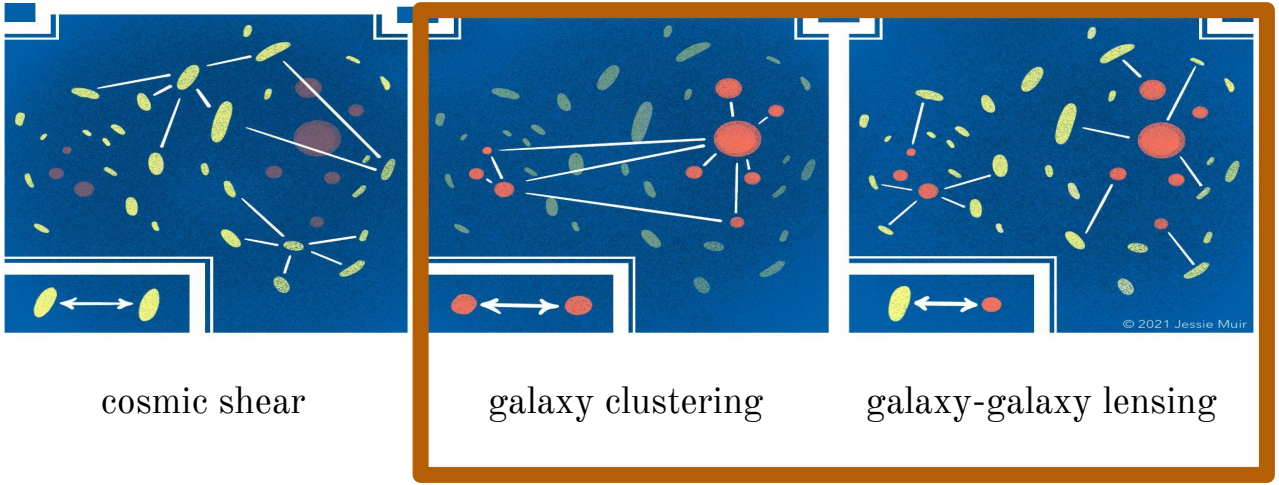
correlation between positions of the lenses and shapes of the sources

2x2pt

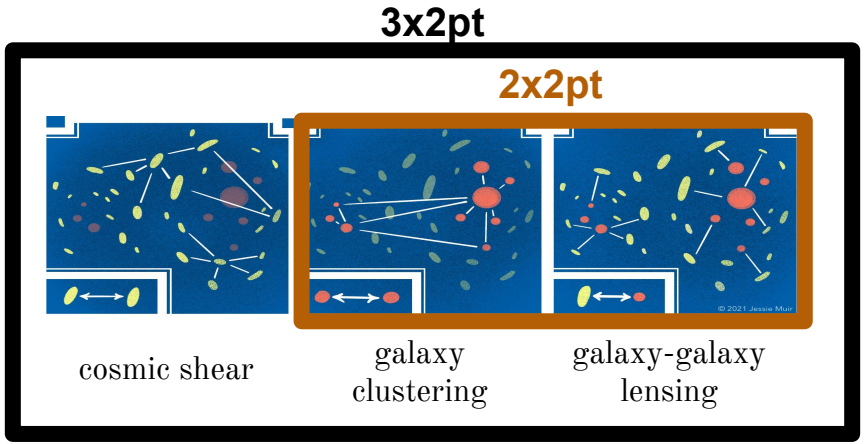


cosmic shear | galaxy clustering | galaxy-galaxy lensing

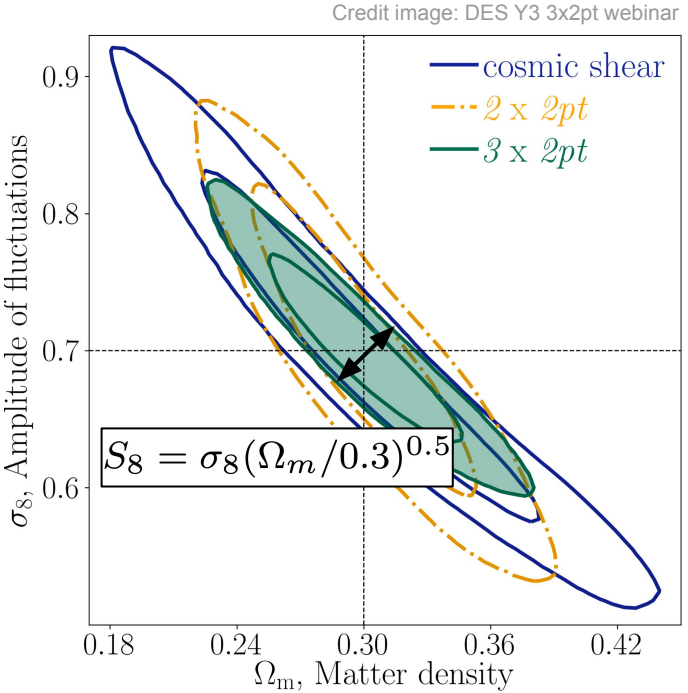
3x2pt


2x2pt
© 2021 Jessie Muir
cosmic shear
galaxy clustering
galaxy-galaxy lensing

3x2pt cosmology

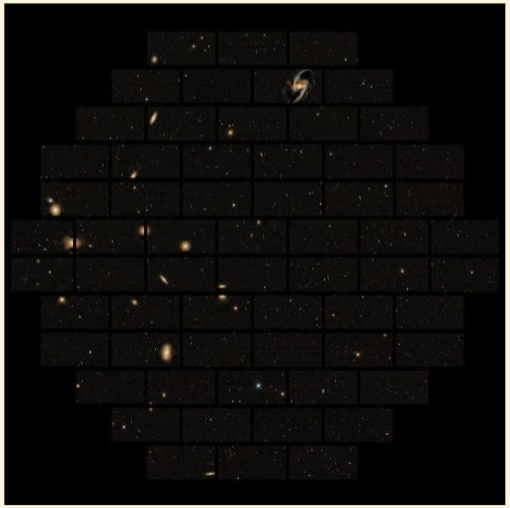


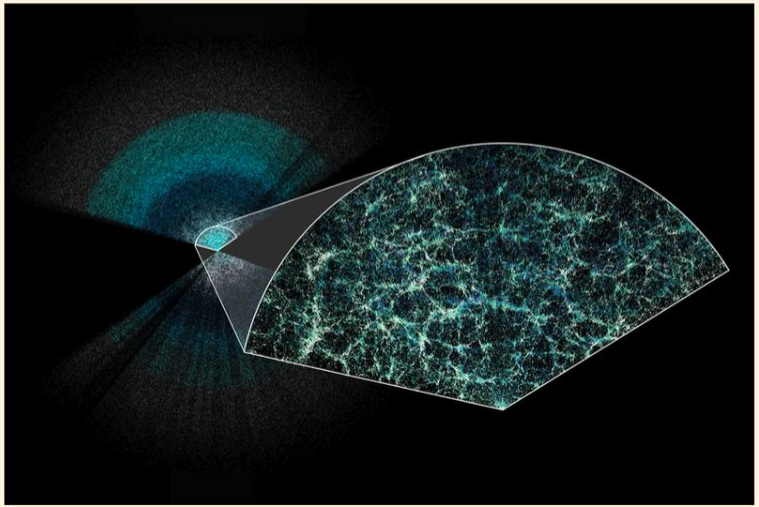
Credit image: DES Y3 3x2pt webinar



A joint analysis maximizes the cosmological information and robustly constrains astrophysical & observational systematics in the analysis!

SURVEYS
photometric vs spectroscopic

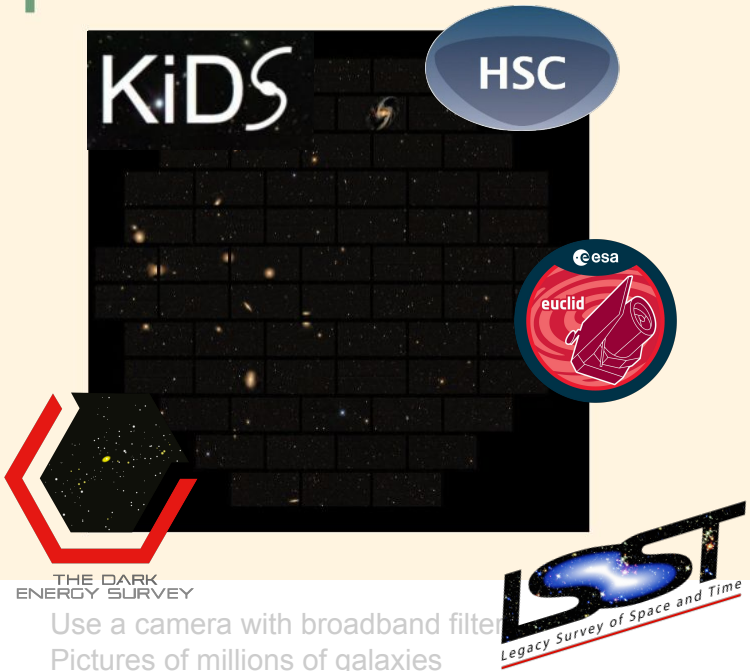




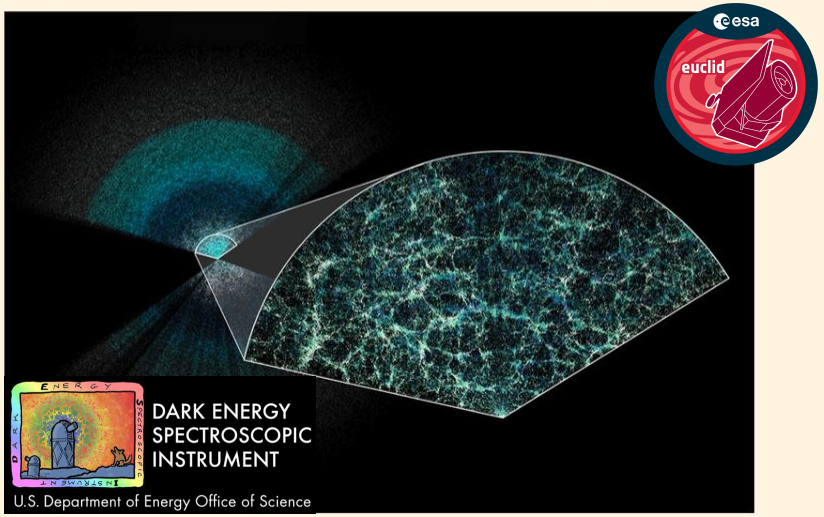
- Use a camera with broadband filters
- Pictures of millions of galaxies
- Allows to measure **weak gravitational lensing** of galaxies
- Needed to find the targets for spectroscopic surveys
- Worse precision for the redshift of galaxies

- Obtain the spectra from each object/galaxy
- Allows to measure the redshift of galaxies with high precision
- Allows to measure **galaxy clustering with high precision**

SURVEYS
photometric vs spectroscopic



- Use a camera with broadband filters
- Pictures of millions of galaxies
- Allows to measure **weak gravitational lensing** of galaxies
- Needed to find the targets for spectroscopic surveys
- Worse precision for the redshift of galaxies

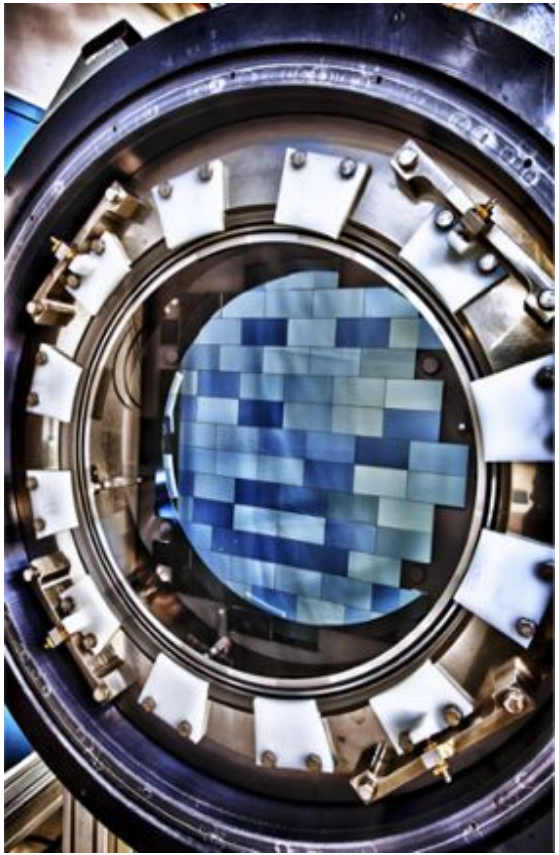


- Obtain the spectra from each object/galaxy
- Allows to measure the redshift of galaxies with high precision
- Allows to measure **galaxy clustering with high precision**

Cosmology from galaxy clustering and weak lensing in DES

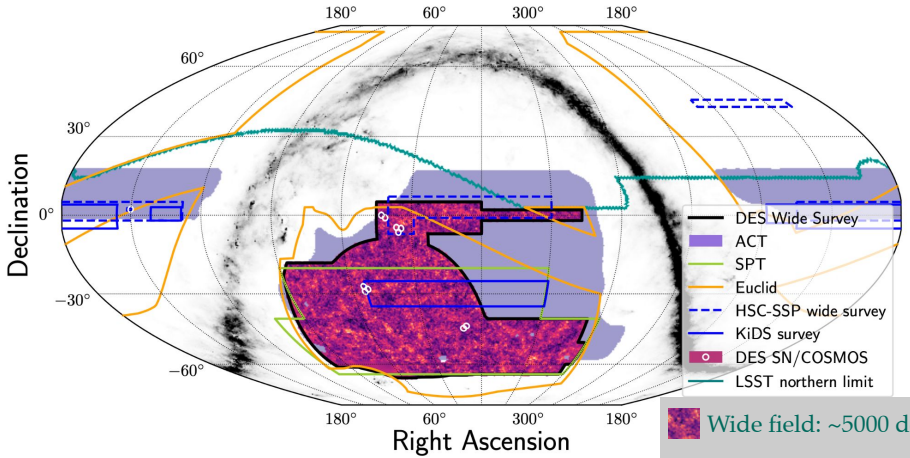
Credit image: DES

The Dark Energy Survey



Credit image: DES

- 570 Megapixel camera for the Blanco 4m telescope in Chile.
- Full survey 2013-2019 (Y3 2013-16).
- **Wide field:** 5000 sq. deg. in 5 optical bands (grizY)
- Compared to Y3, Y6 reaches higher redshift, with 50% higher source density (used for weak lensing)

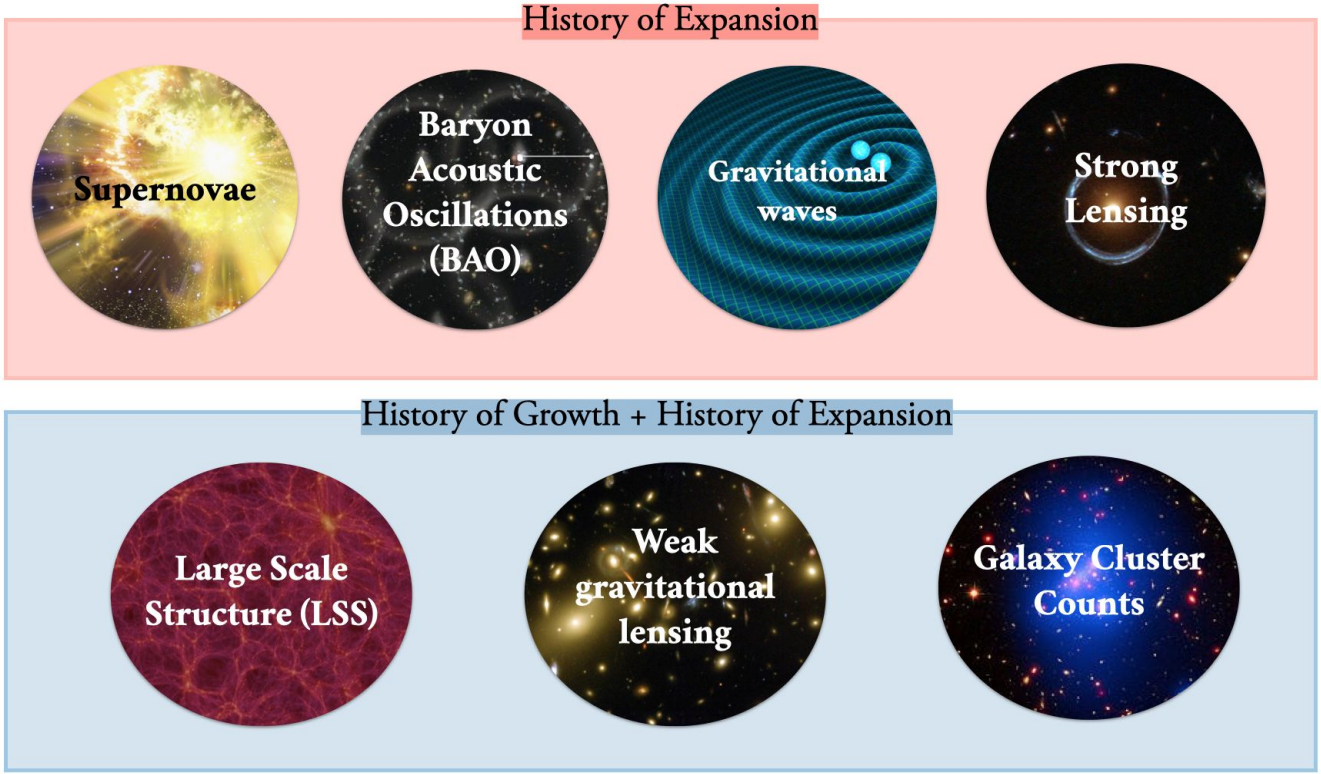


DES Collaboration 2026
arXiv:2601.14559

Wide field: ~5000 deg^2, i~24

Deep field: ~27 deg^2, ~7 day cadence

Probes used within DES

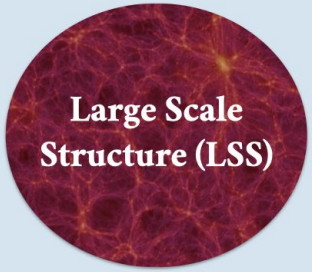


Probes used within DES

Y5 cosmology ✅
arXiv:2401.02929

History of Expansion

History of Growth + History of Expansion



Probes used within DES

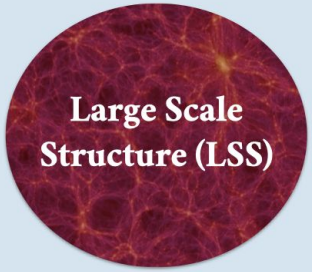
Y5 cosmology ✅
arXiv:2401.02929

History of Expansion

Y6 measurement ✅
arXiv:2402.10696

Combination with SN ✅
arXiv:2503.06712

History of Growth + History of Expansion



Probes used within DES

Y5 cosmology ✅
arXiv:2401.02929

History of Expansion

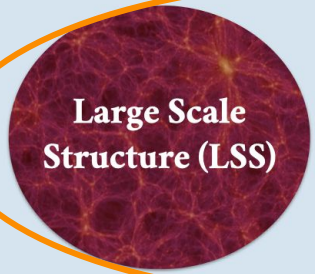
Y6 measurement ✅
arXiv:2402.10696

Combination with SN ✅
arXiv:2503.06712

History of Growth + History of Expansion

Y6 3x2pt ✅
arXiv:2601.14559

Focus of this talk!



Probes used within DES

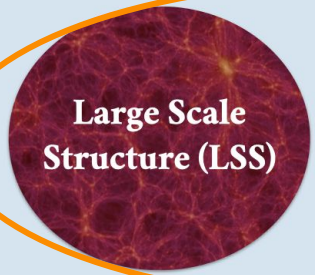
Y5 cosmology ✅
arXiv:2401.02929

History of Expansion

Y6 measurement ✅
arXiv:2402.10696

Combination with SN ✅
arXiv:2503.06712

History of Growth + History of Expansion



Expected in 2026

Y6 3x2pt ✅
arXiv:2601.14559

Focus of this talk!

DES Y6 Cosmology Papers

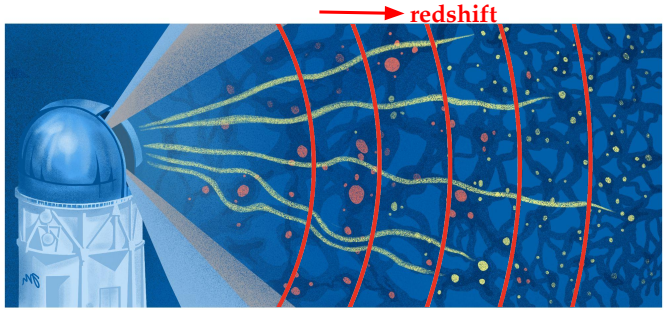
Webinar from Jan 22, 2026: DES Y6 3x2pt results webinar – January 22, 2026

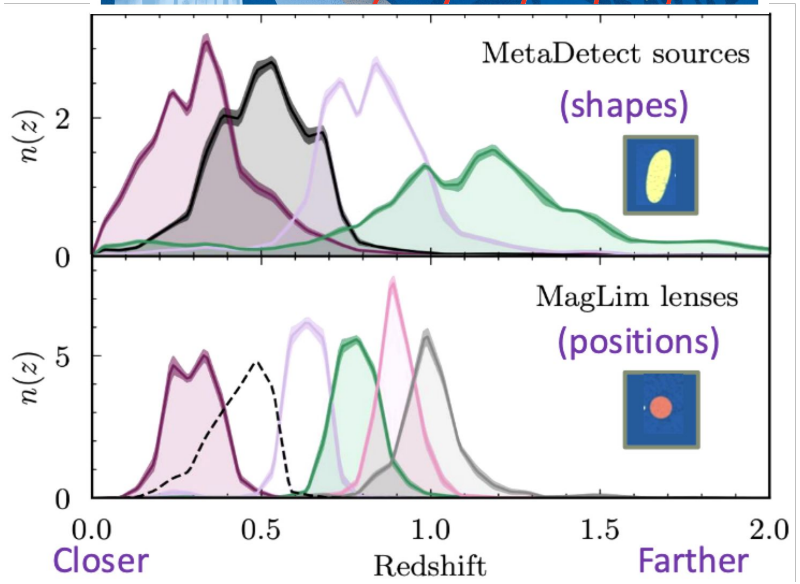
Our Year 6 cosmology analysis of galaxy clustering and gravitational lensing is a massive effort from more than one hundred scientists. There will be more than 20 interconnected papers in all, with the main cosmology analysis, and an ‘extended models’ analysis, at the bottom of the page. We provide links to papers that are public.

Key paper: 3×2 cosmology result arXiv: arXiv:2601.14559

https://www.darkenergysurvey.org/des-y6-cosmology-results-papers/

Galaxy samples





We split the galaxy samples in several redshift bins

Weak lensing sources: MetaDetect

- Used for the cosmic shear measurements
- 140M galaxy shapes
- 4 tomographic redshift bins

Lens sample: MagLim

- Used for the galaxy clustering measurements
- 11M galaxy positions
- 6 tomographic redshift bins
- Selection optimised in Porredon et al. 2021

Slide adapted from J. Muir & M. Becker

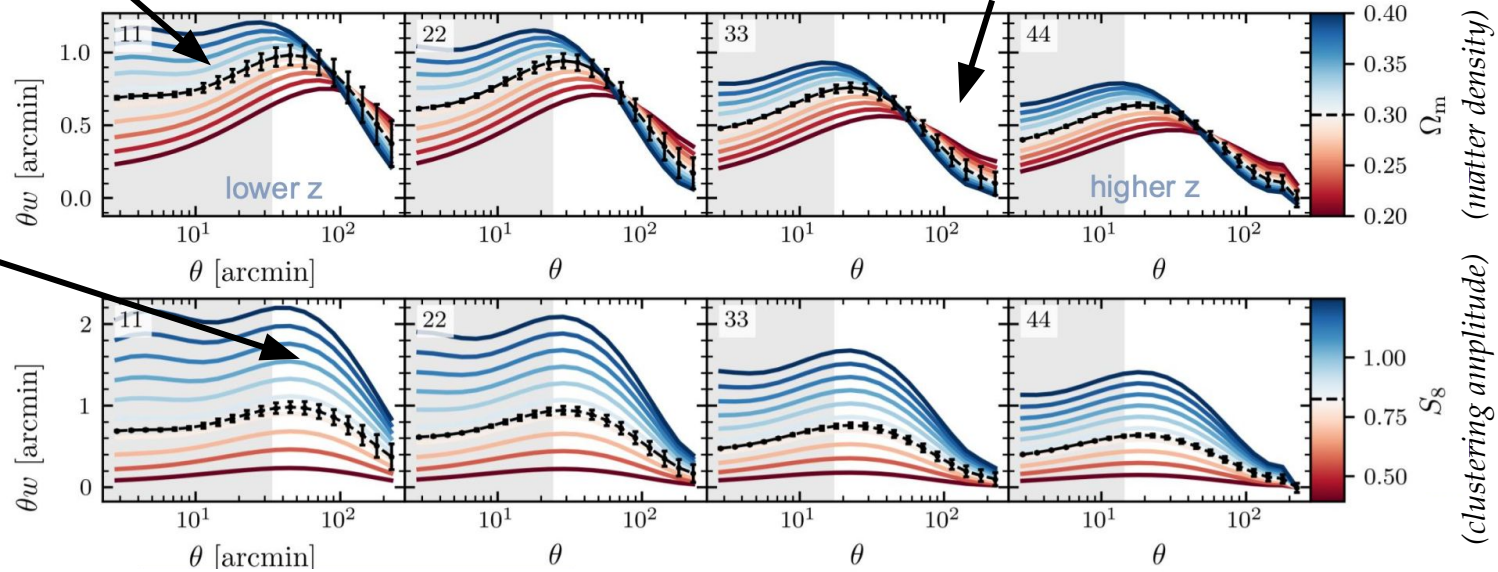
Example: Galaxy Clustering Signals

Our full model for the 3x2pt data has over 50 parameters, only 6 of which are cosmological.

We ignore small-scale measurements in the gray regions because we cannot make accurate predictions for them.

The effects of Ωm are approximately orthogonal to S_8 (i.e., tilting the signal vs. changing the amplitude).

The parameter combination $S_8=\sigma_8(\Omega m/0.3)^{0.5}$ approximately sets the overall amplitude of the signal, and so is the best constrained parameter.



Slide credit: J. Muir & M. Becker

Pixels to cosmology

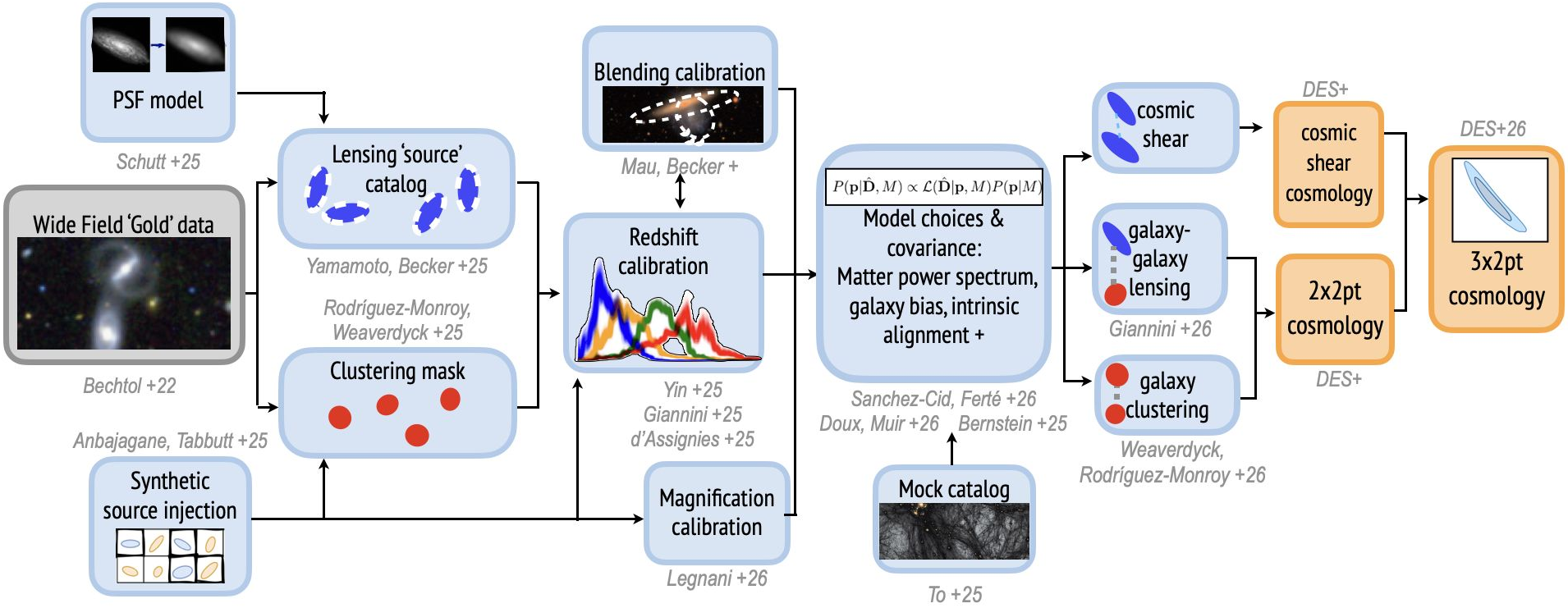
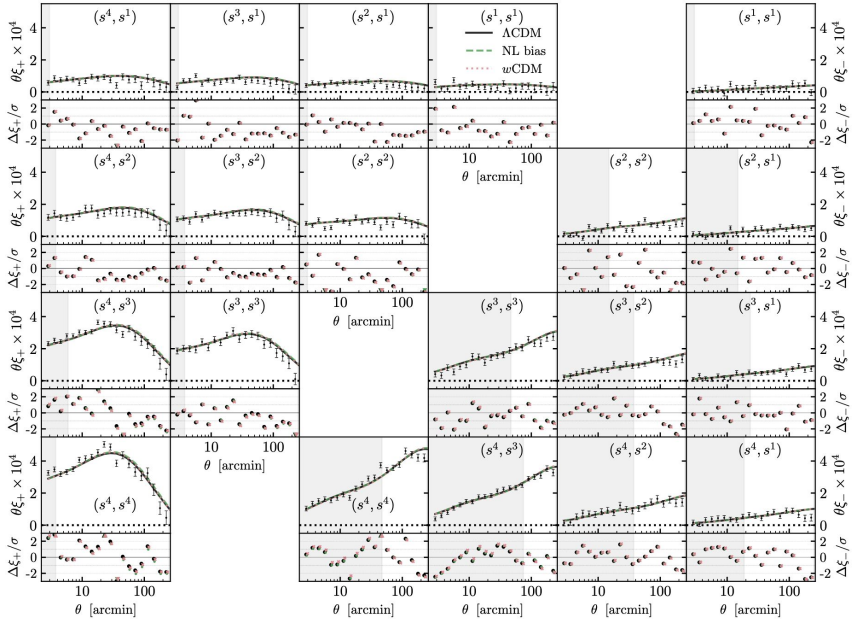
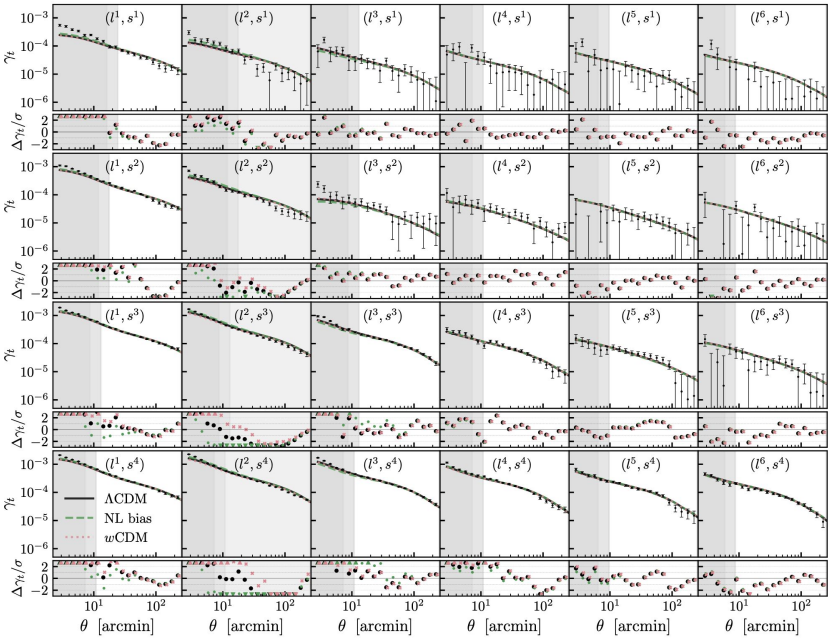


Image credit: A. Amon

Cosmic Shear: S/N = 83 (Y3 ~ 40)

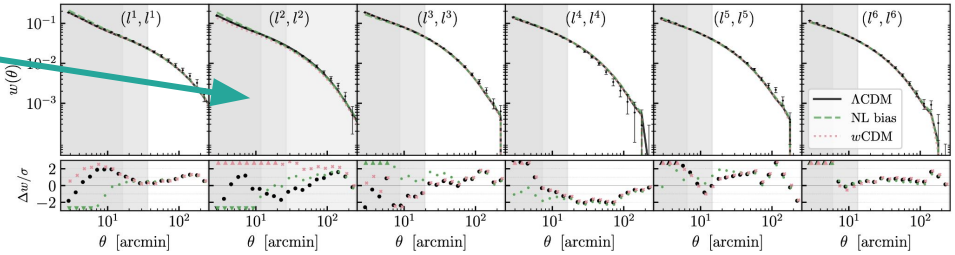


Galaxy-galaxy Lensing: S/N = 39 (Y3 ~ 28)



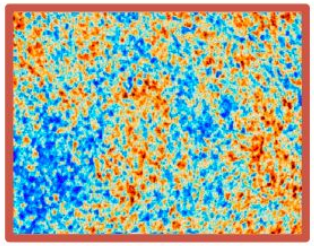
We removed lens bin 2 from the analysis due to a systematic effect we can detect, but don't understand.

Galaxy Clustering: S/N = 90 (Y3 ~ 63)

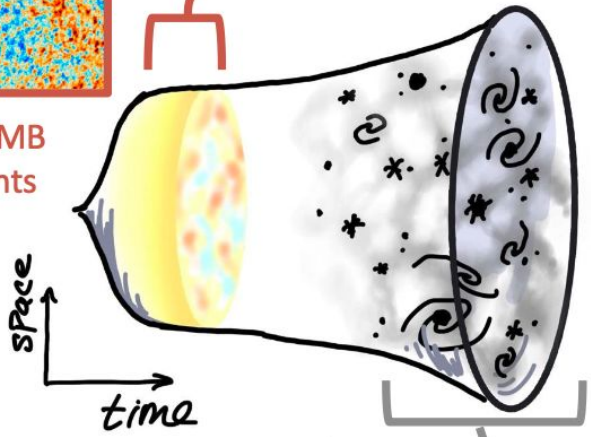


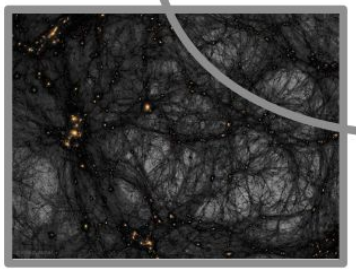
Slide credit: D. Sanchez-Cid

Testing ΛCDM



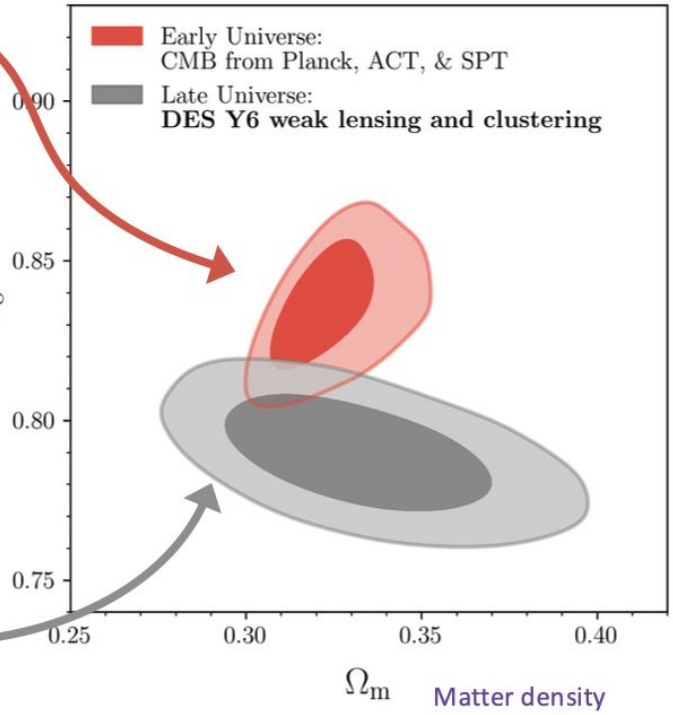
Early-time CMB measurements





Late-time structure measurements from DES

Inner contours: 68% confidence region
Outer contours: 95% confidence region



DES Collaboration 2026, arXiv:2601.14559

Slide credit: J. Muir

DES 3x2pt vs CMB: evolution across releases

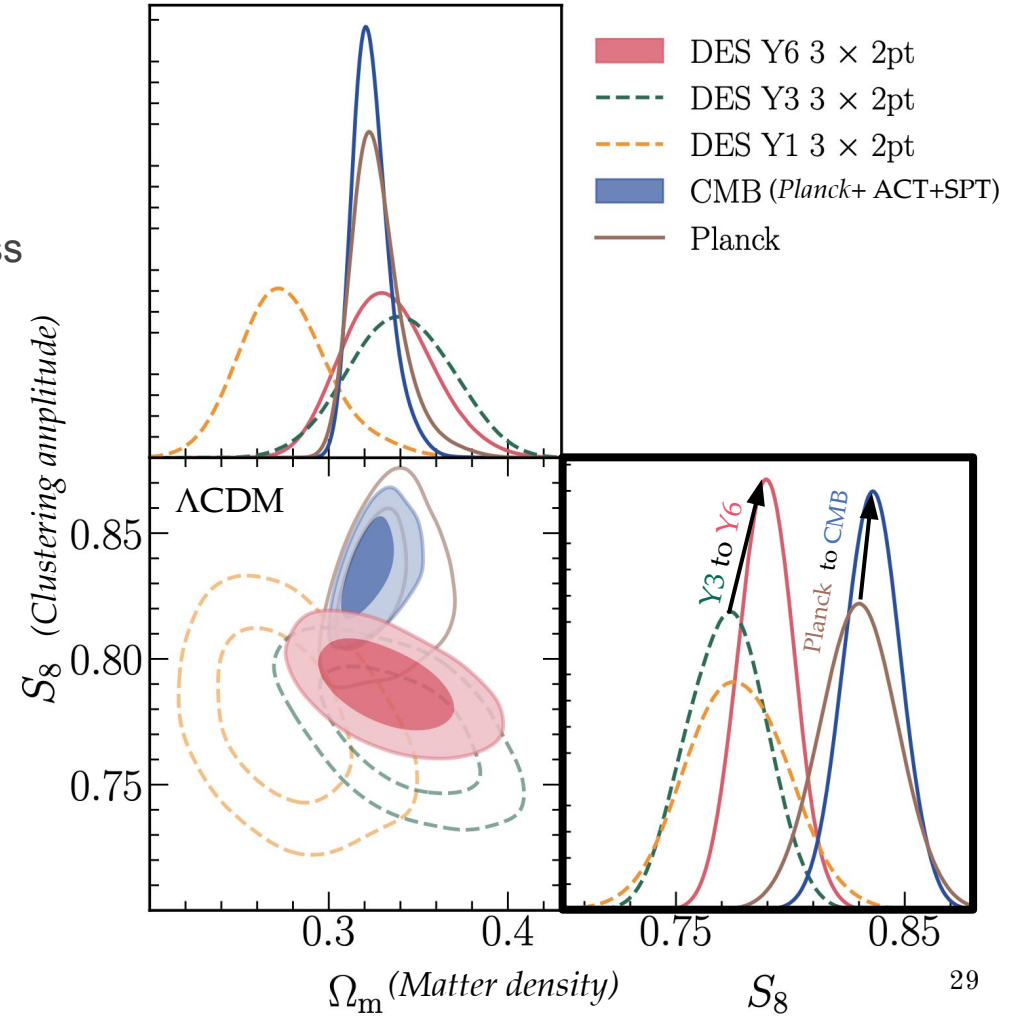
DES 3x2pt S_8 constraints are consistent across releases.

CMB (*Planck* + SPT+ ACT) constraints and 3x2pt both have increased precision.

Full-parameter differences are:

- Y6 vs CMB: 1.8σ
- Y6 vs *Planck*: 1.0σ
- Y3 vs *Planck*: 1.5σ

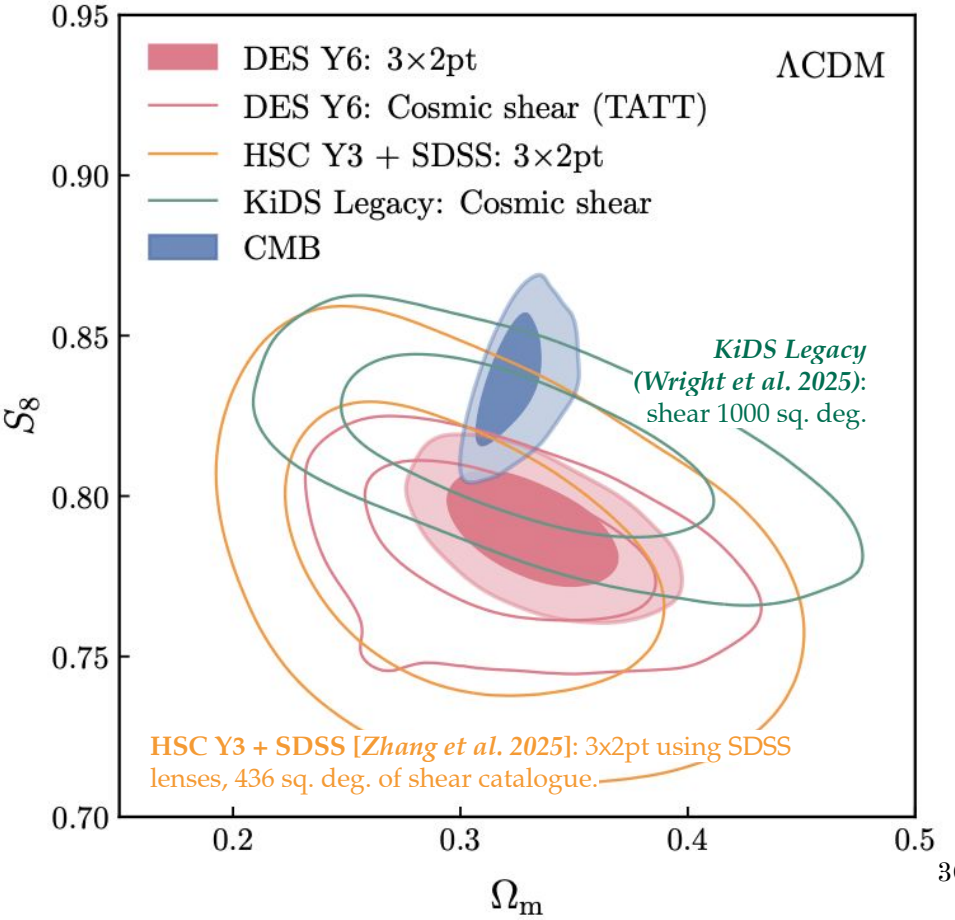
With respect to *Planck* the difference has decreased, even with tighter constraints**.**



Comparison of lensing probes

The final DES 3×2pt and cosmic shear analyses are consistent with the latest results from the other Stage-III weak-lensing surveys and with the CMB.

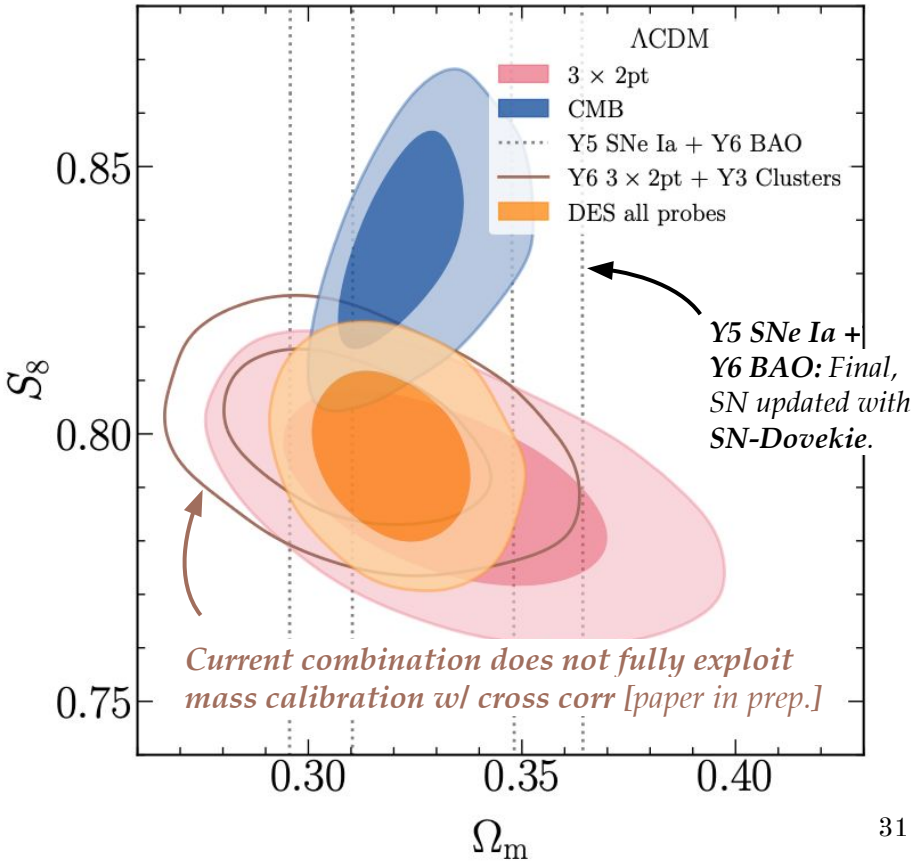
Tension metrics across weak lensing experiments with the CMB still range from ~ 1σ to ≲ 3σ.



DES dark-energy probes combined: 3x2pt, BAO, SN, Clusters

- All four probes are fully consistent 🎉
- For the first time we combined all four dark energy probes as originally designed for DES.
- First time this is done within a single survey.
- DES all-probes has similar constraining power as CMB in both S_8 and Ω_m.

Full-parameter difference of 2.8σ with the CMB, with fully consistent Ω_m

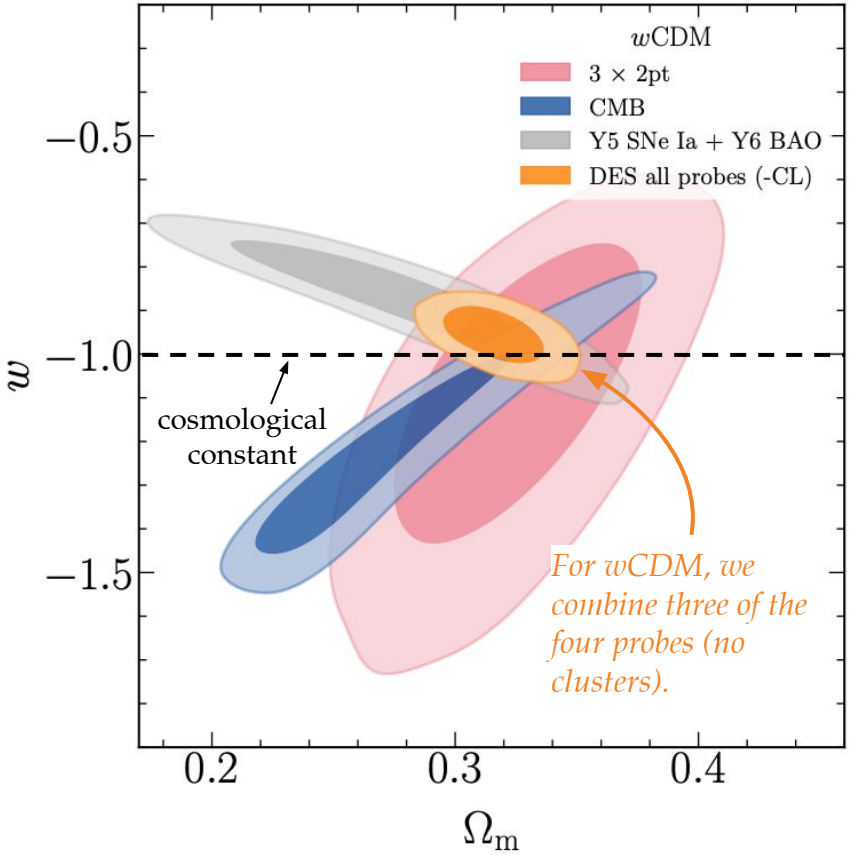


DES dark-energy probes in wCDM: 3x2pt, BAO, SN

We constrain the equation of state parameter to 4%, and find no evidence for departure from a cosmological constant of $w = -1$

We find no significant preference of *w*CDM over ΛCDM when doing model comparison via $\Delta\chi^2$

The full parameter difference with the CMB is 2.5 σ (similar to the ΛCDM case)



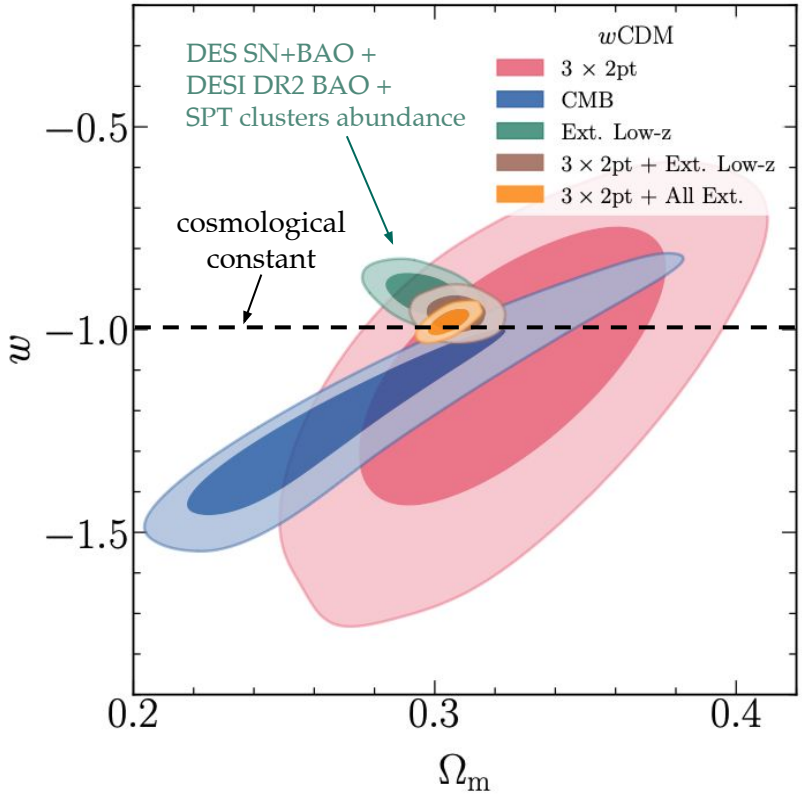
Joint cosmological constraints in wCDM

From the best-available data sets to date:

$$S_8 = 0.807^{+0.007}_{-0.007}$$
$$\Omega_{\rm m} = 0.305^{+0.004}_{-0.005}$$
$$w = -0.981^{+0.021}_{-0.022}$$

We find no significant preference of wCDM over ΛCDM.

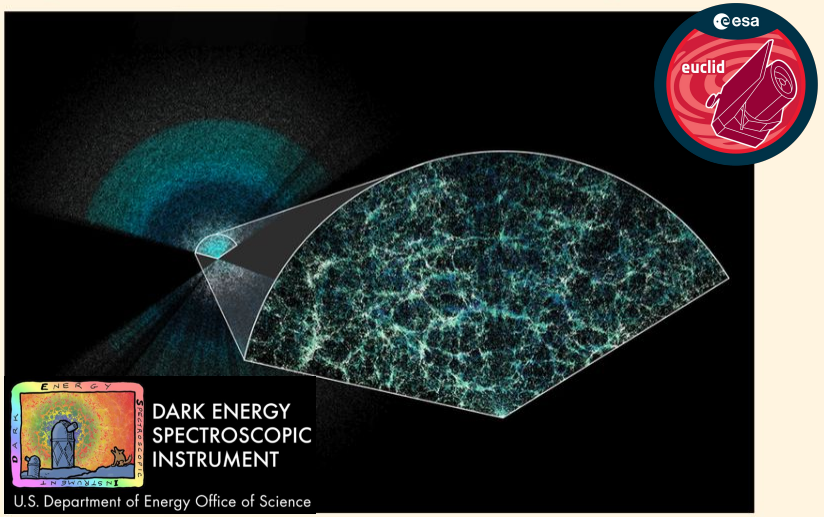
Stay tuned for more complex evolving dark energy models and modified gravity later this year!



Cross-survey cosmology from galaxy clustering and weak lensing

SURVEYS
photometric vs spectroscopic

- Use a camera with broadband filters
- Pictures of millions of galaxies
- Allows to measure **weak gravitational lensing** of galaxies
- Needed to find the targets for spectroscopic surveys
- Worse precision for the redshift of galaxies



- Obtain the spectra from each object/galaxy
- Allows to measure the redshift of galaxies with high precision
- Allows to measure **galaxy clustering with high precision**

Dark Energy Spectroscopic Instrument

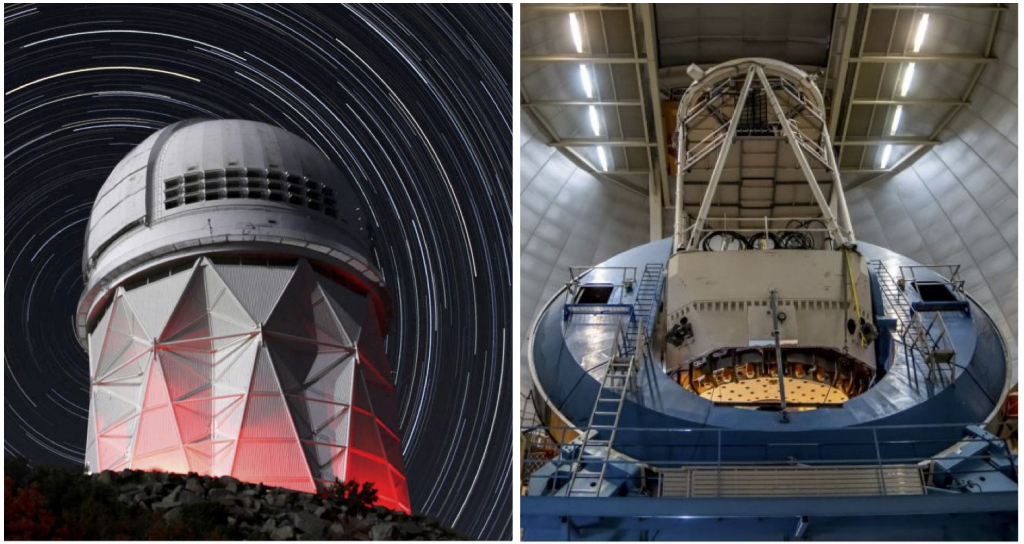
DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

Stage IV 5-year spectroscopic survey using the Mayall 4-meter telescope at Kitt Peak National Observatory

Image credit: DESI

The DESI survey started in May 2021 and is finishing the first 5 years of observations

The instrument has **5000 robotically-controlled optical fibres**. In total, it's expected to catalogue redshifts from over **60 million galaxies** in 8 years, covering 17,000 sq. deg.



4m Mayall at Kitt Peak, Arizona. Twin to the Blanco, CTIO

DESI and weak lensing surveys

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

Focus on combined-probe analyses of DESI spectroscopic samples with public weak lensing data

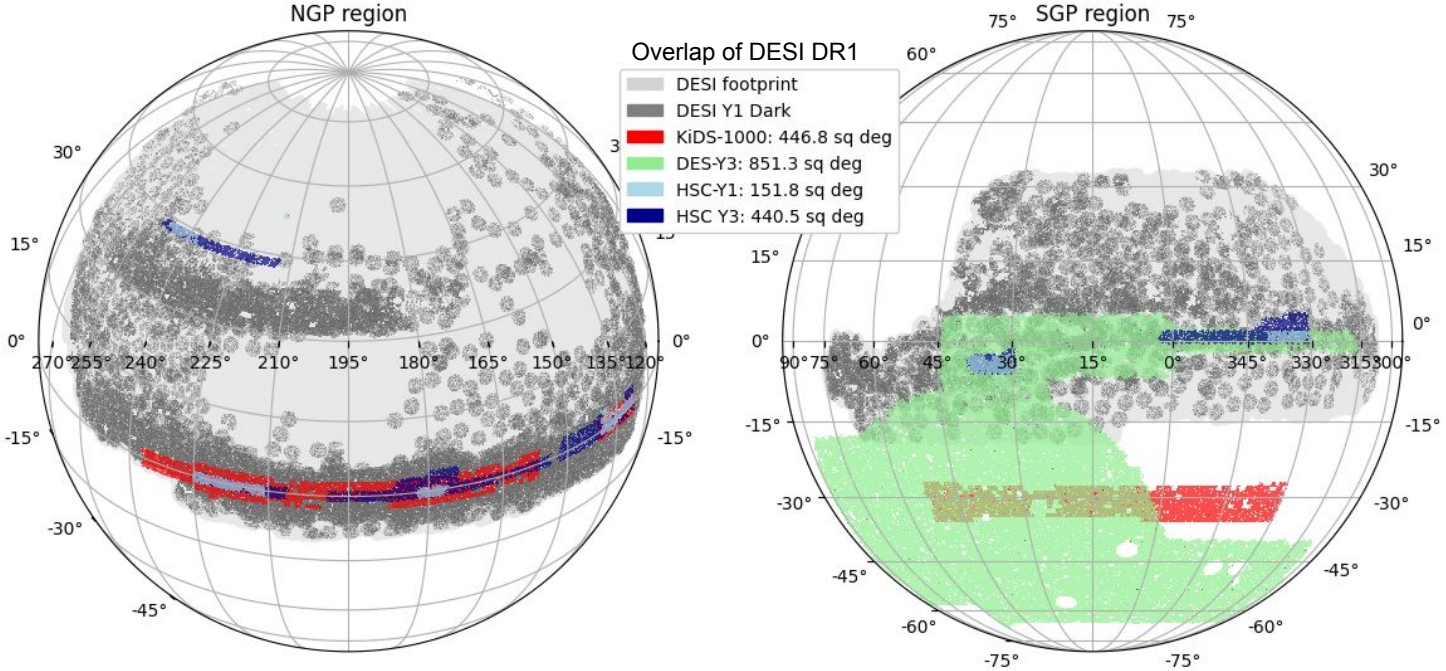
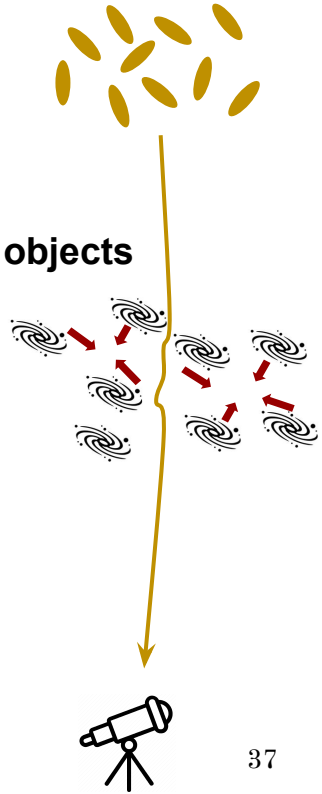


Figure credit: Chris Blake

Other surveys
(DES, HSC, KIDS)

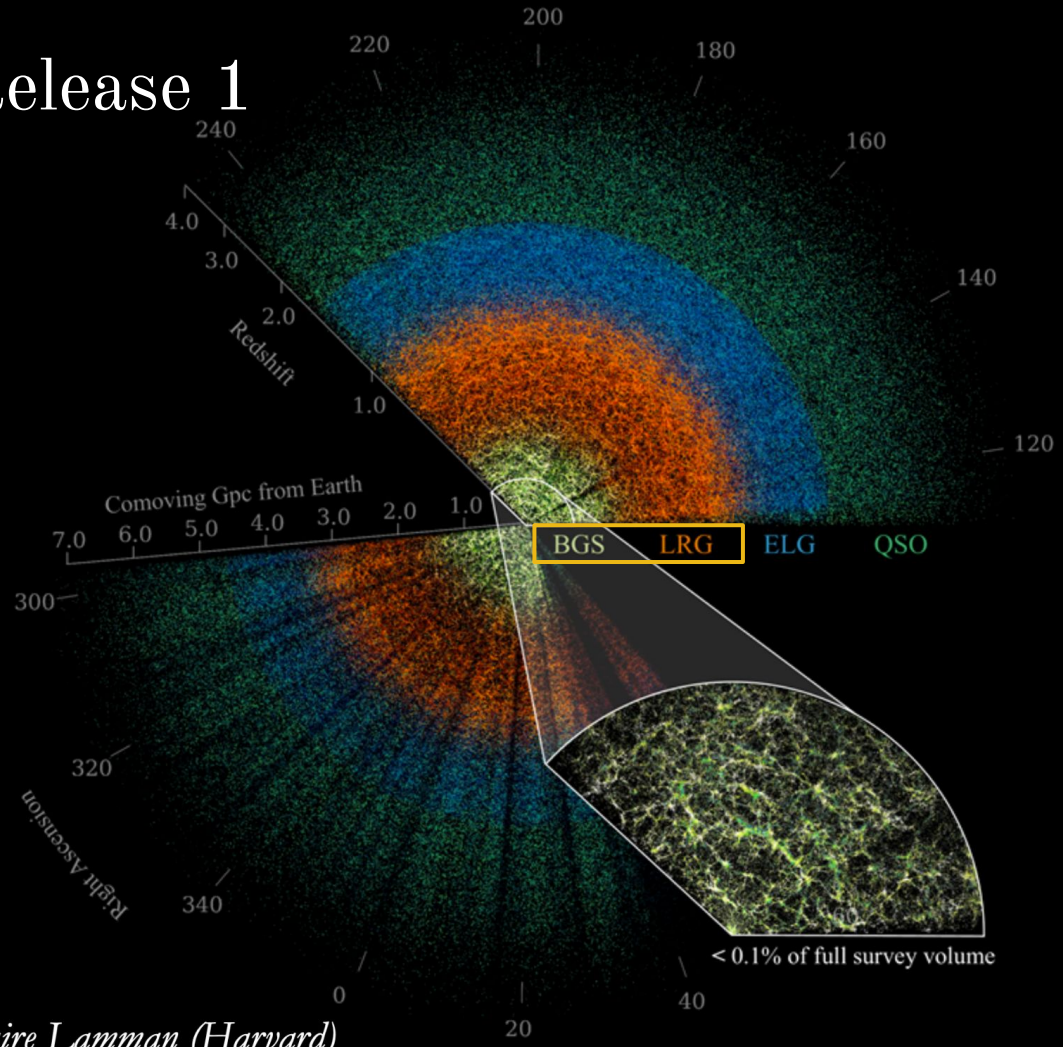
DESI objects



DESI Data Release 1

DESI collaboration 2025
https://arxiv.org/abs/2503.14745

DR1: 13.1M galaxy redshifts released in March 2025



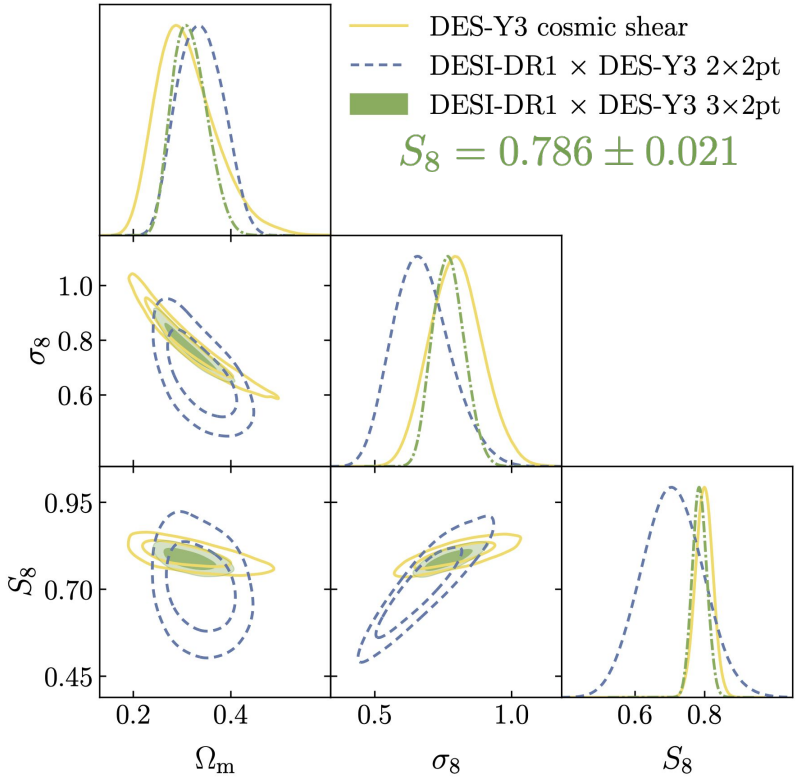
Credit: Claire Lamman (Harvard)

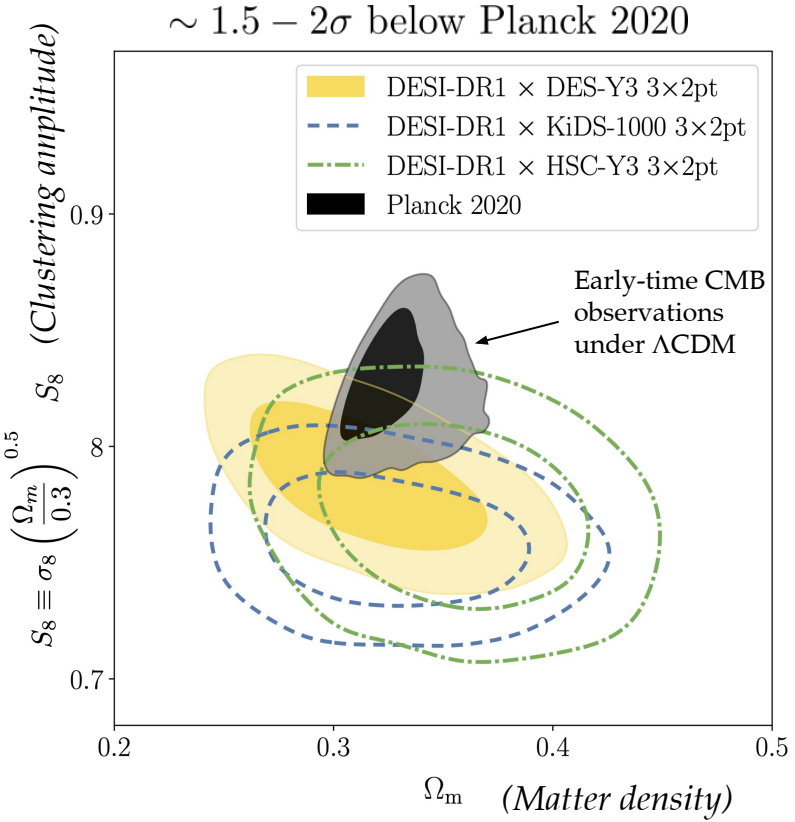
DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

DESI DR1 3x2pt analysis

Porredon et al. 2025
https://arxiv.org/abs/2512.15960

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science





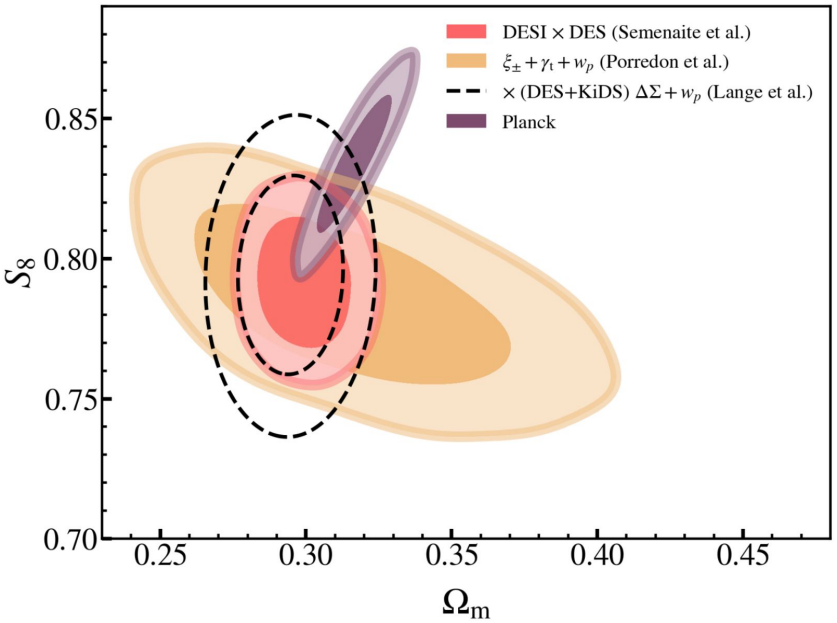
DESI DR1 x weak lensing cosmology papers

DARK ENERGY SPECTROSCOPIC INSTRUMENT

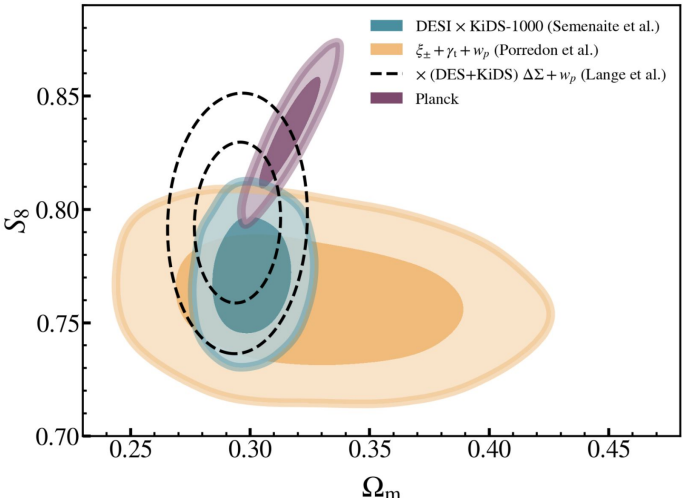
U.S. Department of Energy Office of Science

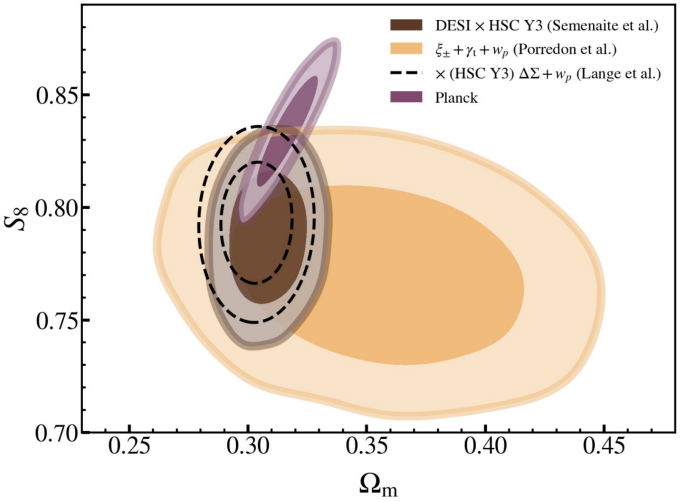
- **Porredon** et al., 2025 - 3x2pt with projected two-point functions (2D), most similar to DES 3x2pt.
- **Semenaite**, Blake, Porredon et al., 2025 - using full 3D information for the galaxy clustering part
- **Lange** et al., 2025 - simulation-based analysis with a frequentist approach. 2D, but not including cosmic shear.

DESI-DR1 results comparison



Very different scales, priors, and assumptions, but highly consistent results!





Comparison with other analyses

Cosmic shear

https://arxiv.org/abs/2512.15960

DES-Y3 $\xi_\pm$ (this work)

DES-Y3 $\xi_\pm$ hybrid

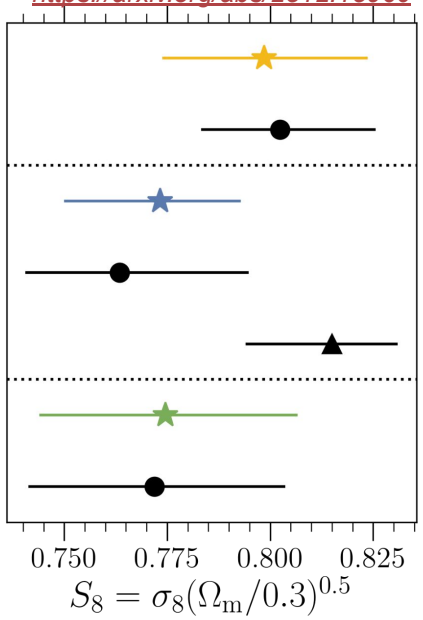
KiDS-1000 $\xi_\pm$ (this work)

KiDS-1000 COSEBIs hybrid

KiDS-Legacy COSEBIs fiducial

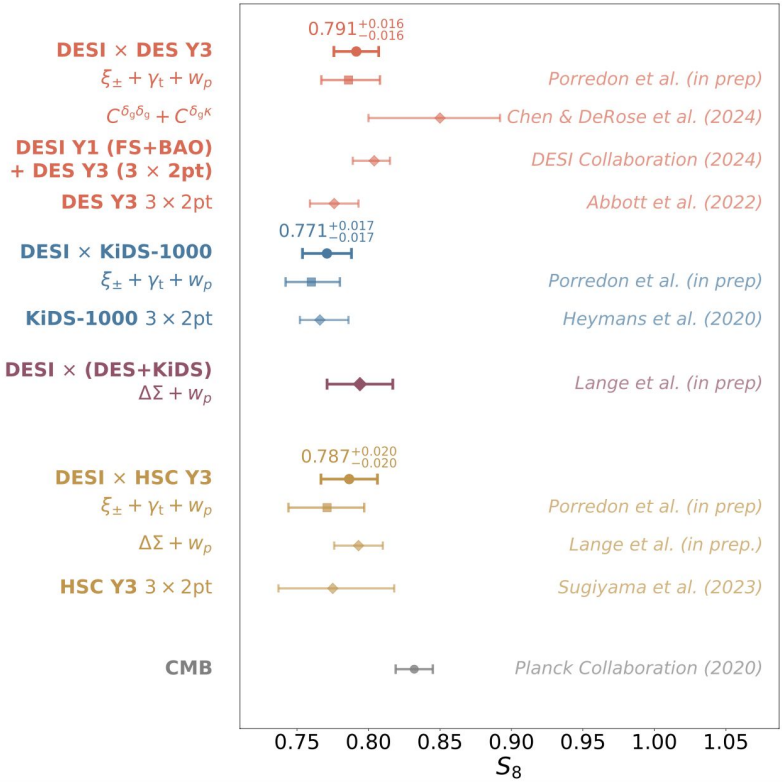
HSC-Y3 $\xi_\pm$ (this work)

HSC-Y3 $\xi_\pm$ hybrid



Clustering and WL combinations

https://arxiv.org/abs/2512.15961



DR2 cross-weak lensing key project

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

Constraining power will improve significantly with DESI-DR2 data (first 3 years)

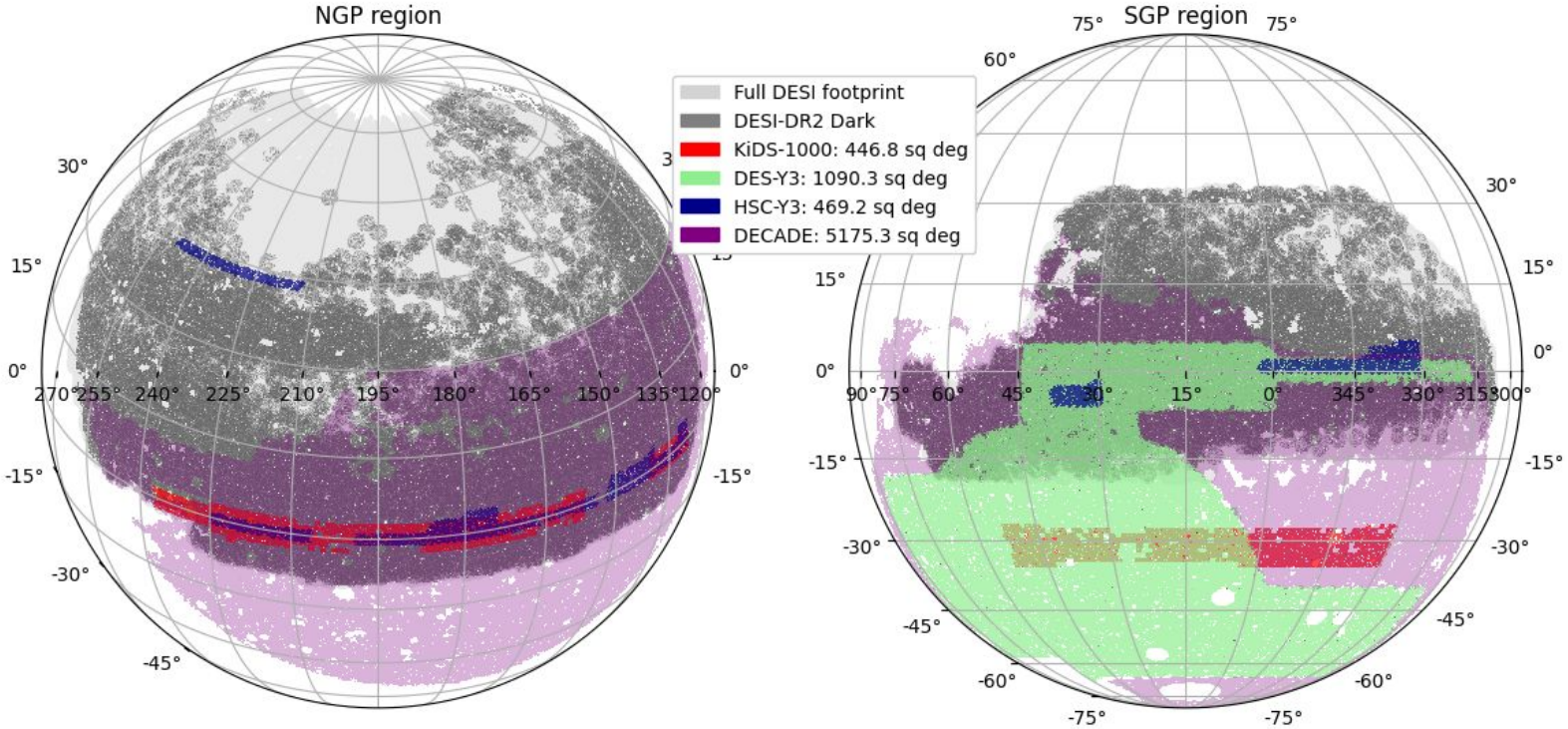


Figure credit: Chris Blake

Looking ahead: Euclid x DESI

About ~200 sq. deg. of overlap with DR1, which will increase significantly with further Euclid and DESI data releases

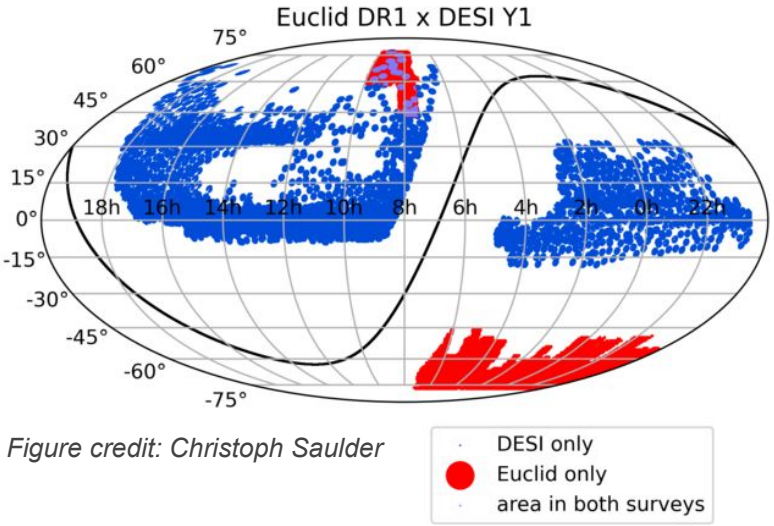
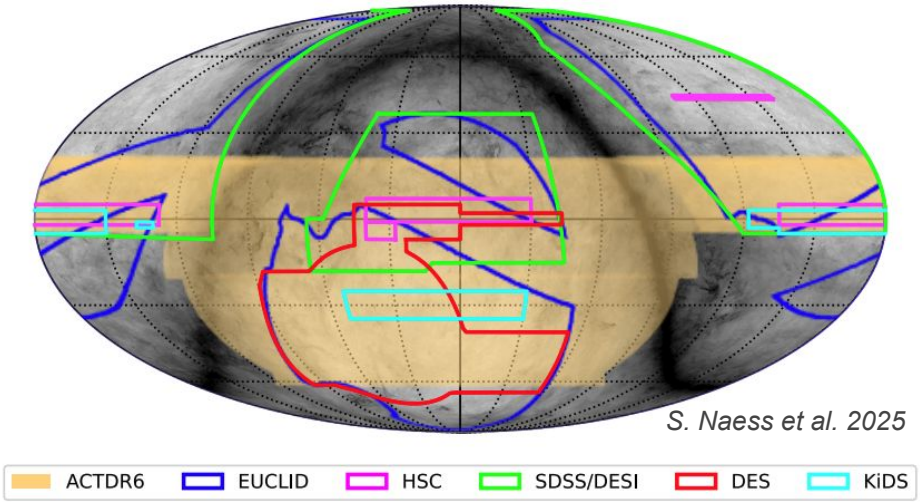


Figure credit: Christoph Saulder



S. Naess et al. 2025

Conclusions

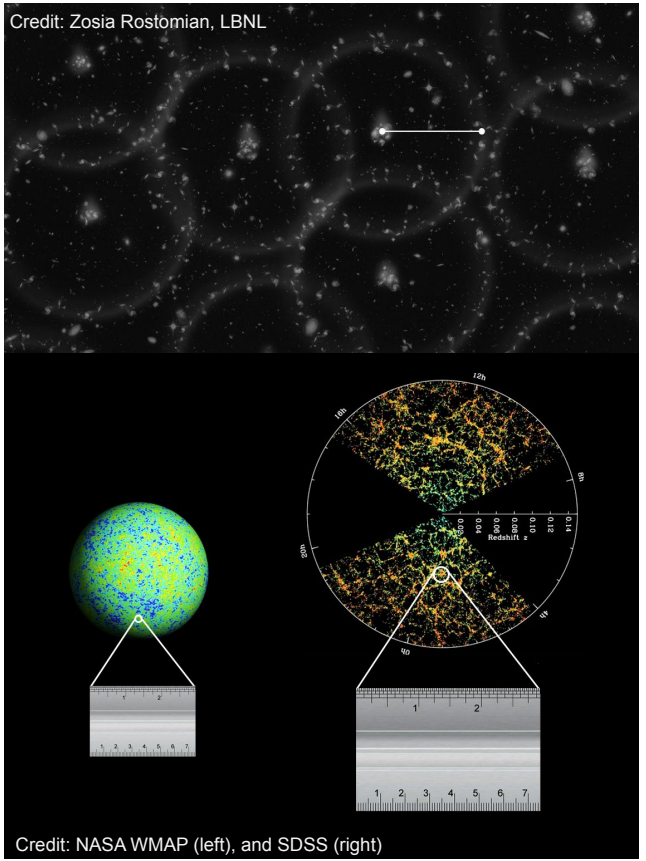
- Presented legacy results from DES 6 years of observations from the combination of weak lensing and galaxy clustering
  - We find **~2-3σ lower values of S_8** (clustering amplitude) **compared to the CMB**
  - First time we combine all four dark-energy probes proposed at the DES inception: 3×2pt, BAO, SN and Clusters. Similar constraining power as CMB in the main constrained parameters.
  - In wCDM: **DES constraints dark energy equation of state to 4%** (consistent with ΛCDM). Full joint constraints find a 2% result on w, no preference for wCDM over ΛCDM.
- Obtained cosmological constraints from the **combination of KiDS, DES, and HSC weak lensing data with DESI-DR1 galaxy clustering**
  - Reanalysed state-of-the-art public weak lensing data with a unified pipeline, finding consistency between surveys and with each survey's fiducial results.
  - We find lower values of S_8 compared to the CMB from Planck (consistent with other analyses)


Thank
You!

Extra slides

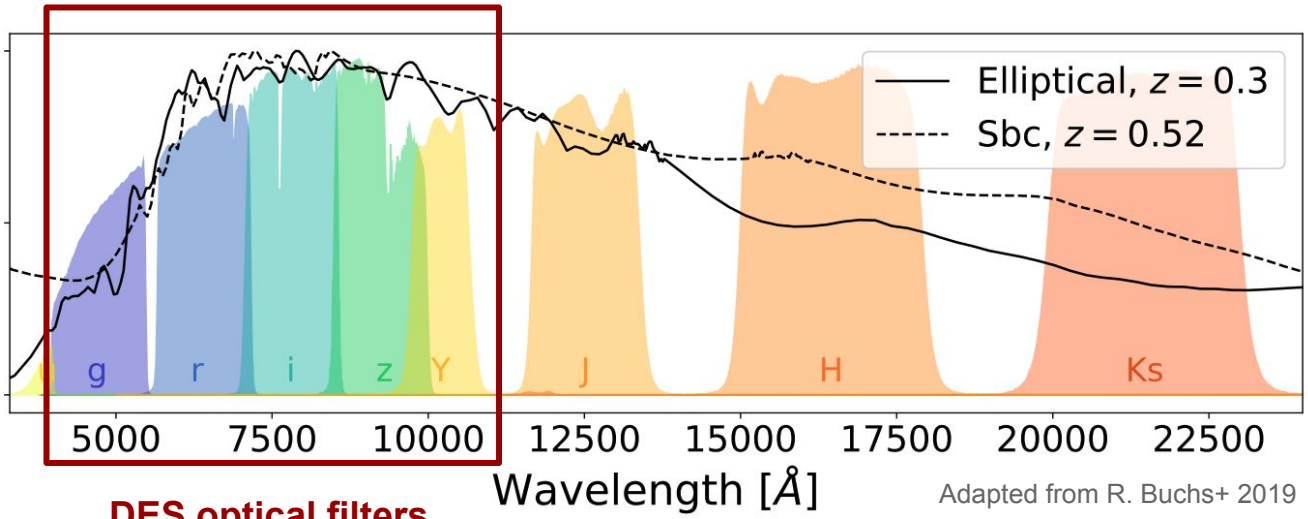
Baryon Acoustic Oscillations (BAO)

- The interplay between gravity and pressure in the early-Universe hot plasma generated sound waves that propagated through it
- At the time of decoupling, the waves froze, leaving an imprint on the spatial distribution of matter
- This particular scale can still be observed today in the distribution of matter and serves as a standard ruler



DES is an imaging galaxy survey

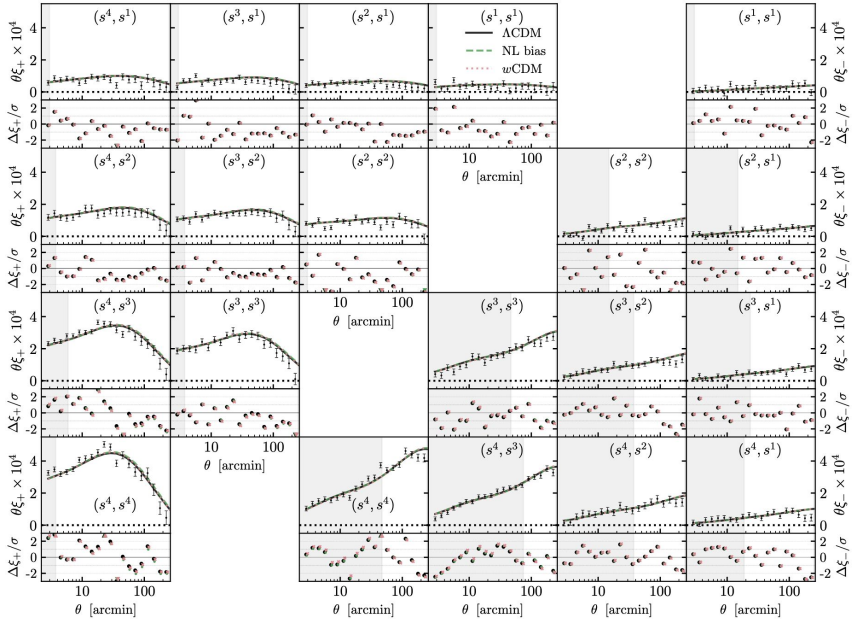
Estimating the redshift (z) of each galaxy is challenging



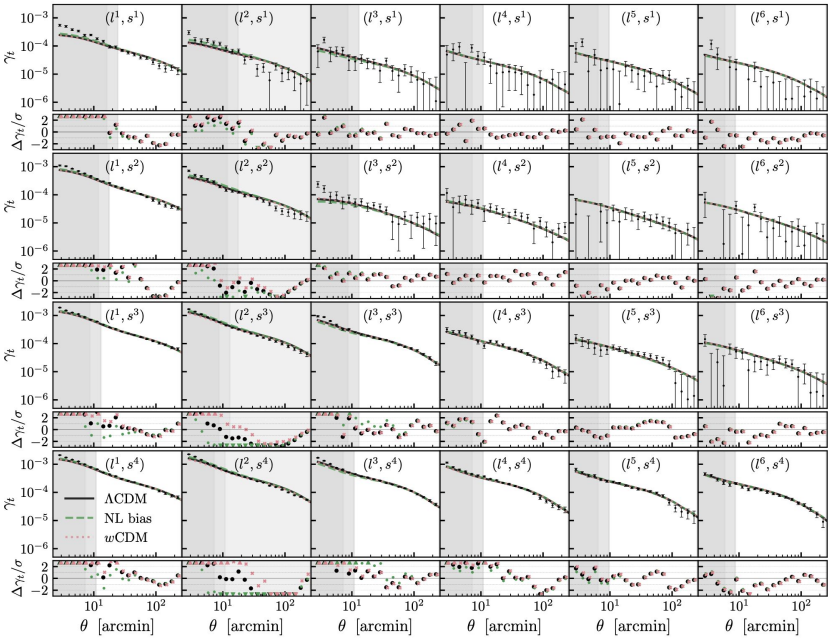
DES optical filters

Adapted from R. Buchs+ 2019

Cosmic Shear: S/N = 83 (Y3 ~ 40)

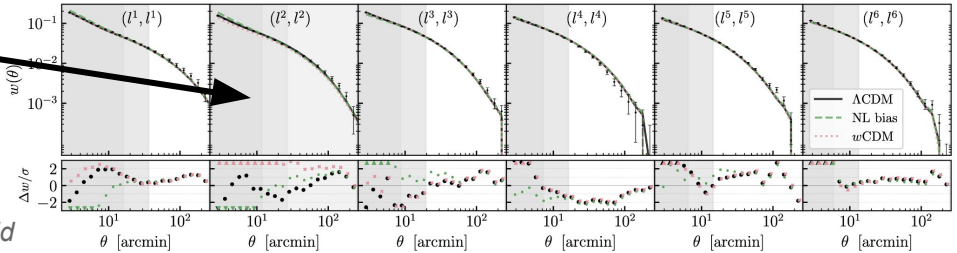


Galaxy-galaxy Lensing: S/N = 39 (Y3 ~ 28)



We removed lens bin 2 from the analysis due to a systematic effect we can detect, but don't understand.

Galaxy Clustering: S/N = 90 (Y3 ~ 63)



Linear cuts (light grey band)

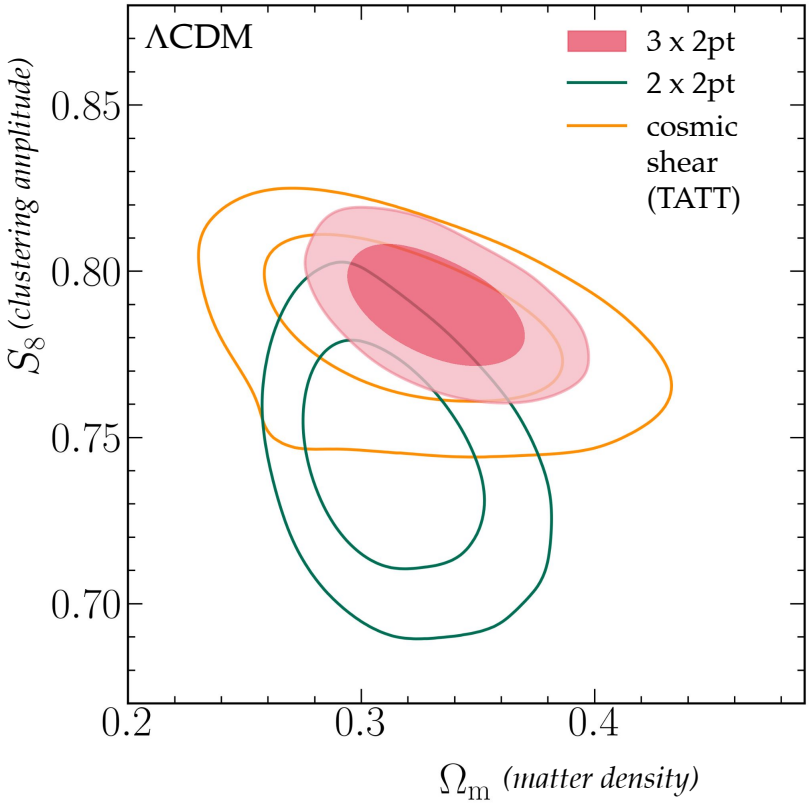
$(R_{\mathrm{min},\,w(\theta)},\ R_{\mathrm{min},\,\gamma_t}) = (9, 6)\ \mathrm{Mpc}/h$

Non-linear cuts (dark grey band)

$(R_{\mathrm{min},\,w(\theta)},\ R_{\mathrm{min},\,\gamma_t}) = (4, 4)\ \mathrm{Mpc}/h$

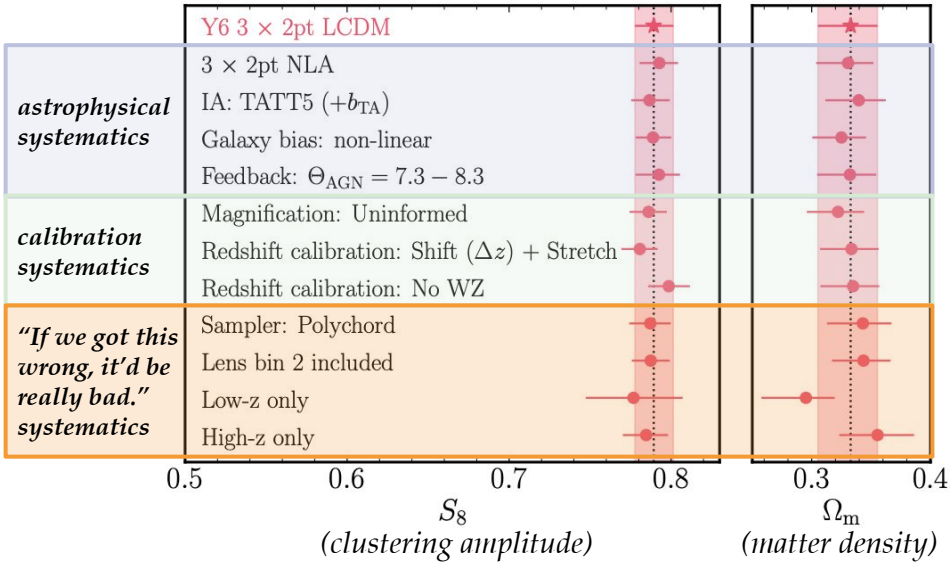
Slide credit: D. Sanchez-Cid

What about systematic effects?



We test for systematic effects by examining:

- ***internal consistency***
- ***changes in analysis choices***



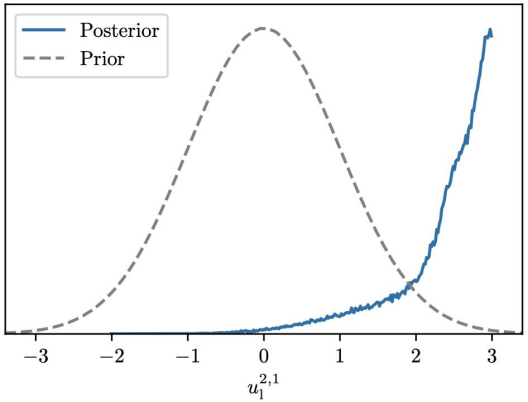
DES et al. (2026)

What's up with lens bin 2?

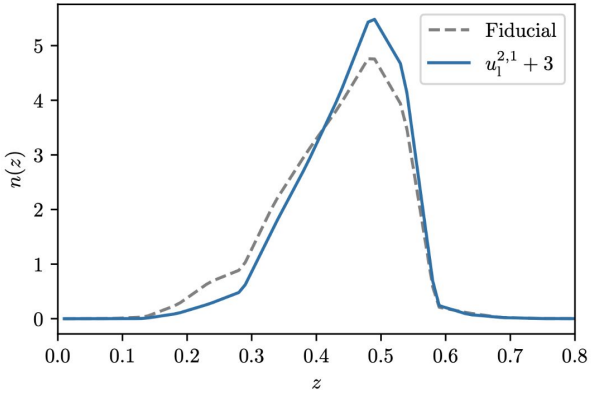
The symptom we see is that our best-fit models prefer a different redshift distribution for lens bin 2 than we would infer from the data.

This specific problem is difficult and weird for a few reasons:

- Both broader n(z) mode priors and an alternative shift + stretch parameterization don't help significantly.
- Lens bin 2 is at a redshift where we think *a priori* that we should be able to constrain the redshift distribution accurately.
- We see no signs of systematics in the clustering measurements themselves.



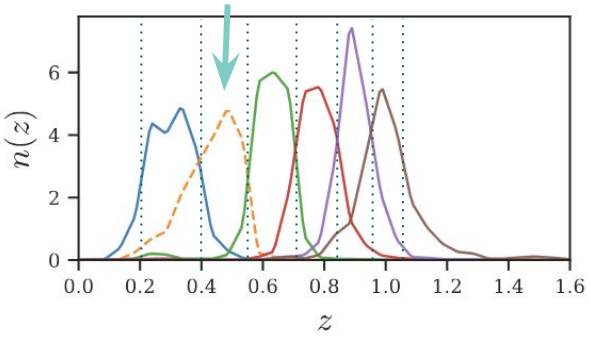
Redshift mode nuisance parameter



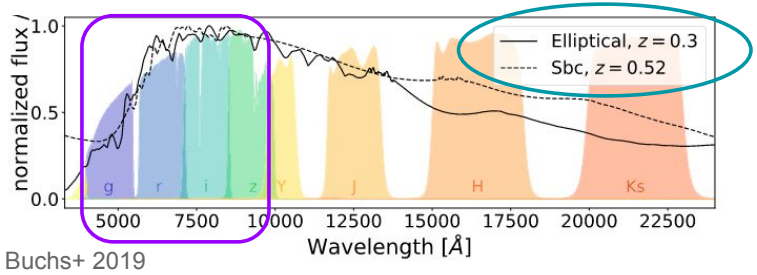
Preferred *n(z)*

What's up with lens bin 2?

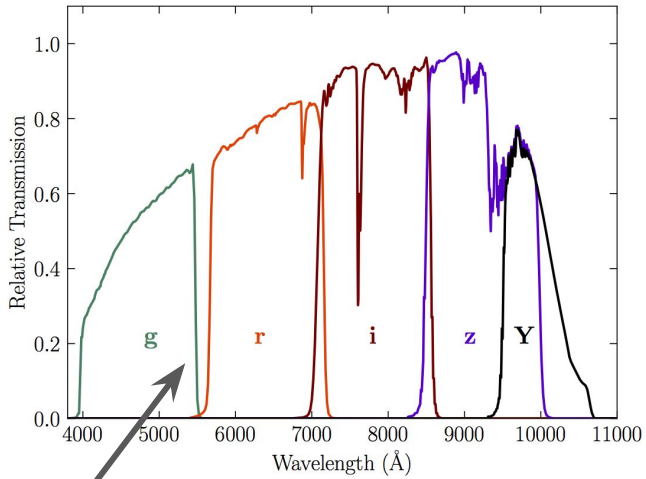
For the lens bin 2 redshift range, there are possible effects from



1. Color-redshift degeneracies



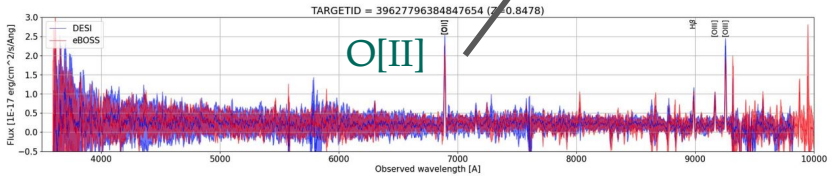
Buchs+ 2019



2. Gap between g, r filters

   Lose O[II] flux between z ~ [0.46, 0.52]

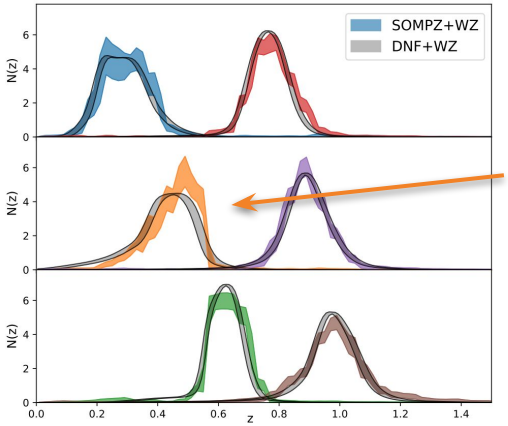
   4000A break crosses at z ~ [0.37, 0.42]



Challenges in lens bin 2

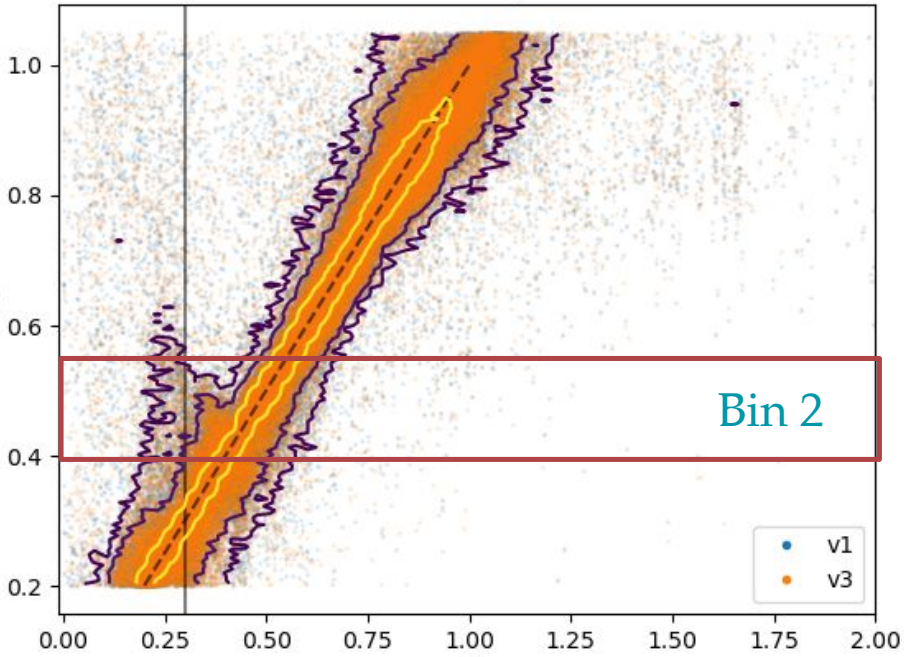
Bin 2 particularly susceptible to photo-z error, misbinning.

Giannini+ (DES Collaboration) 2022



Similar effect in Y3, but less statistical power

DNF Redshift



What's up with lens bin 2?

We see the effects of these difficulties on our magnification estimates.

Legnani+ 2026

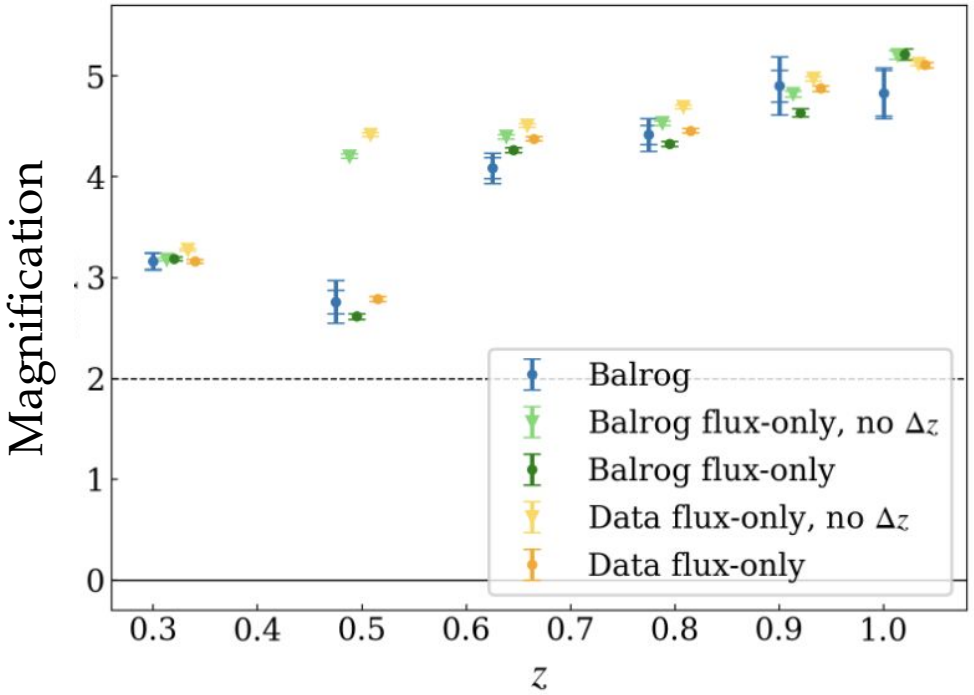
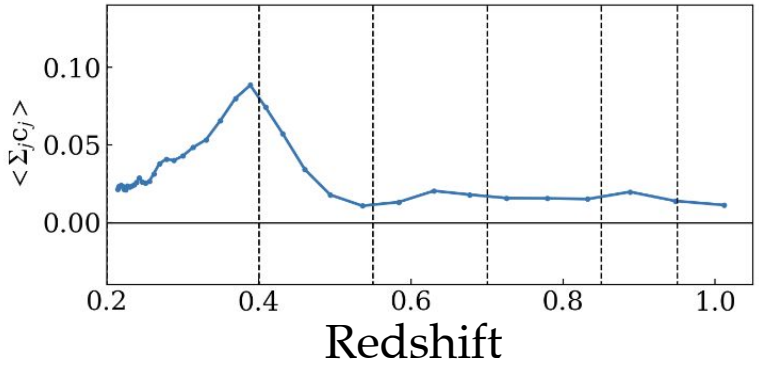
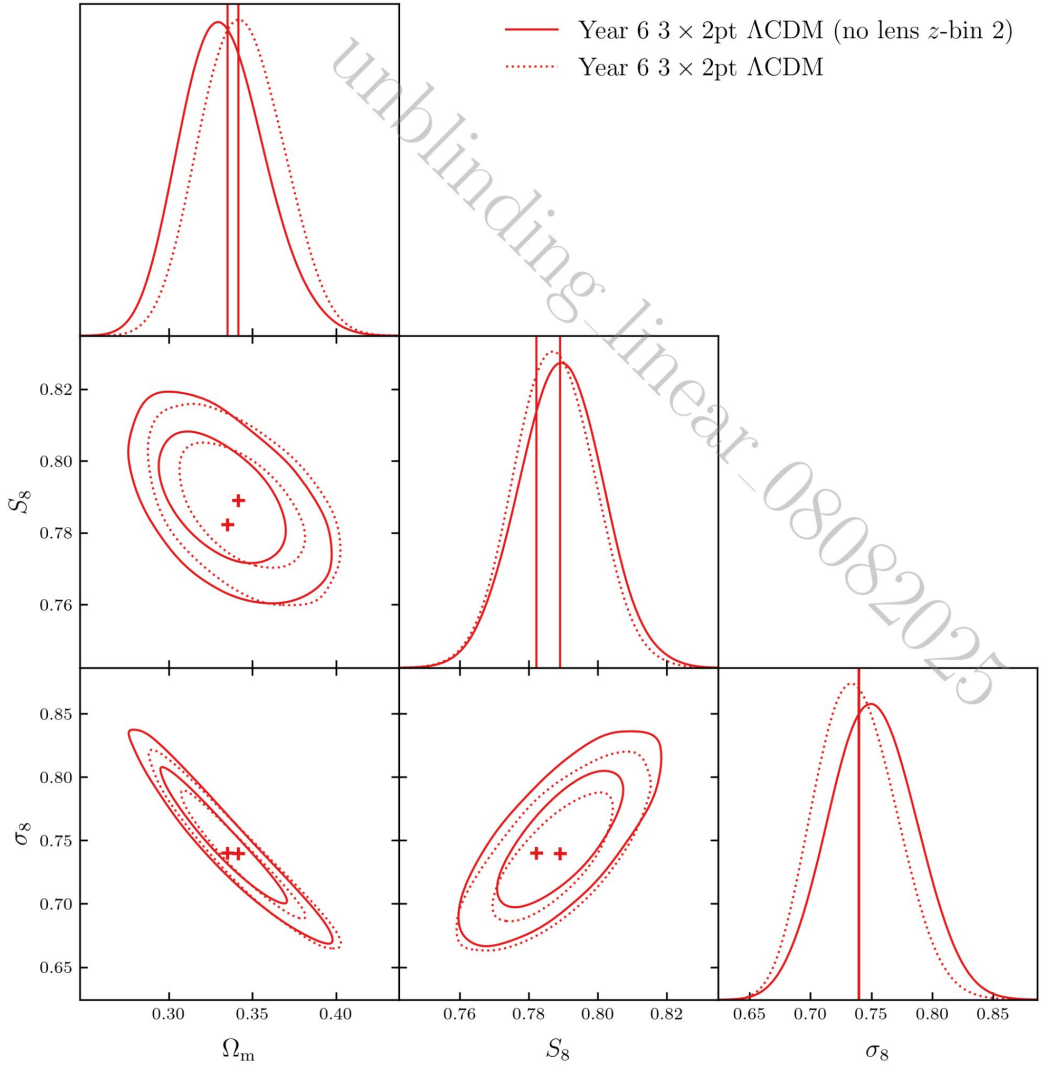


Photo-z sensitivity to flux errors



Lens bin 2 investigations



DESI DR1 x weak lensing cosmology papers

- **Semenaite** et al., Joint cosmological fits to DESI-DR1 full-shape clustering and weak gravitational lensing in **configuration space** -- https://arxiv.org/abs/2512.15961
- **Porredon** et al., DESI-DR1 3×2-pt analysis: consistent cosmology across weak lensing surveys -- https://arxiv.org/abs/2512.15960 (xi+/xi-, gamma_t, **w_p**)
- **Lange** et al., Cosmological Constraints from Full-Scale Clustering and Galaxy-Galaxy Lensing with DESI DR1 -- https://arxiv.org/abs/2512.15962 (2x2pt: Delta Sigma, w_p)
    - Simulation-based analysis based with a frequentist approach
- **DeRose** et al. (in preparation)
    - Unified HEFT+LPT pipeline to analyze DESI and different shear surveys in **harmonic space**