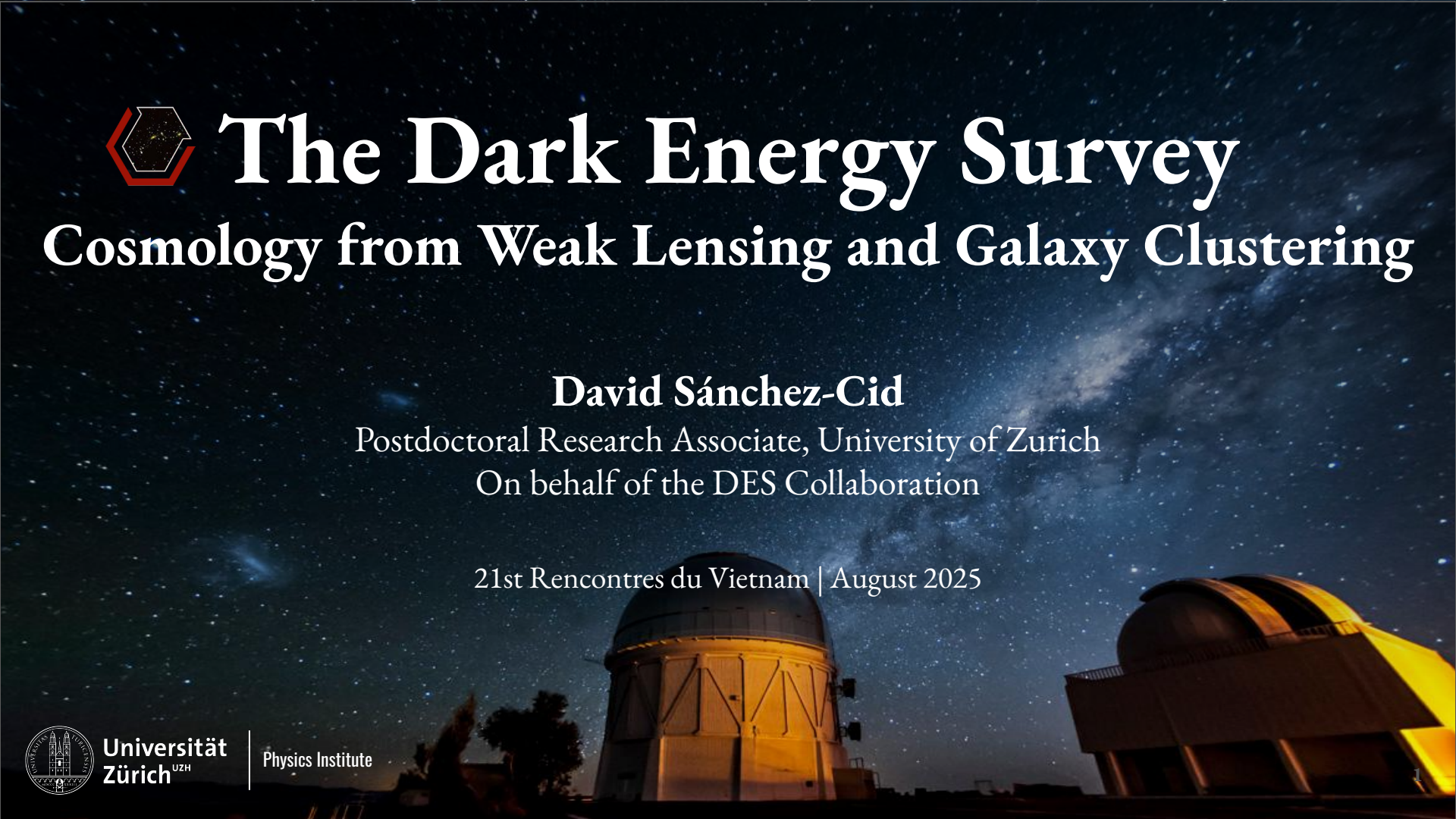


The Dark Energy Survey

Cosmology from Weak Lensing and Galaxy Clustering

David Sánchez-Cid
Postdoctoral Research Associate, University of Zurich
On behalf of the DES Collaboration

21st Rencontres du Vietnam | August 2025

Universität Zürich[UZH] | Physics Institute

The LCDM Model

Our current Standard of Cosmology

A flat Universe with Dark Energy (as a cosmological constant, Λ) + Cold Dark Matter.

Based on General Relativity.

Became the standard model after observations of Type Ia supernovae and the Cosmic Microwave Background.

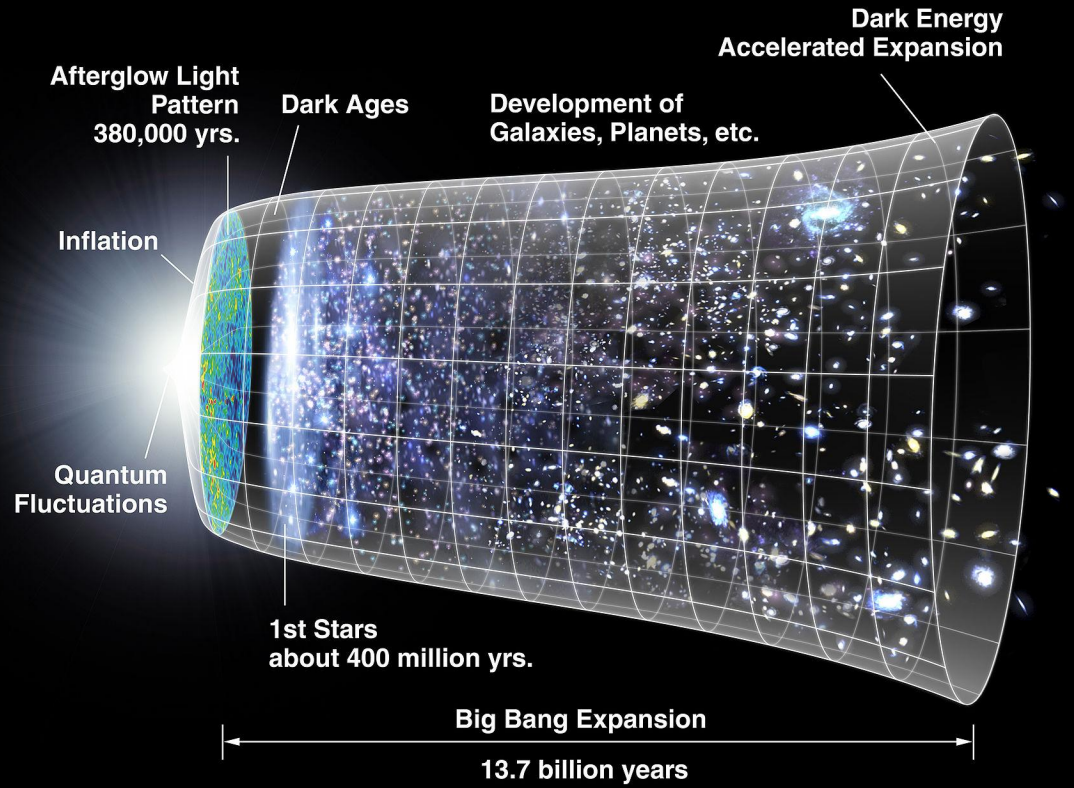
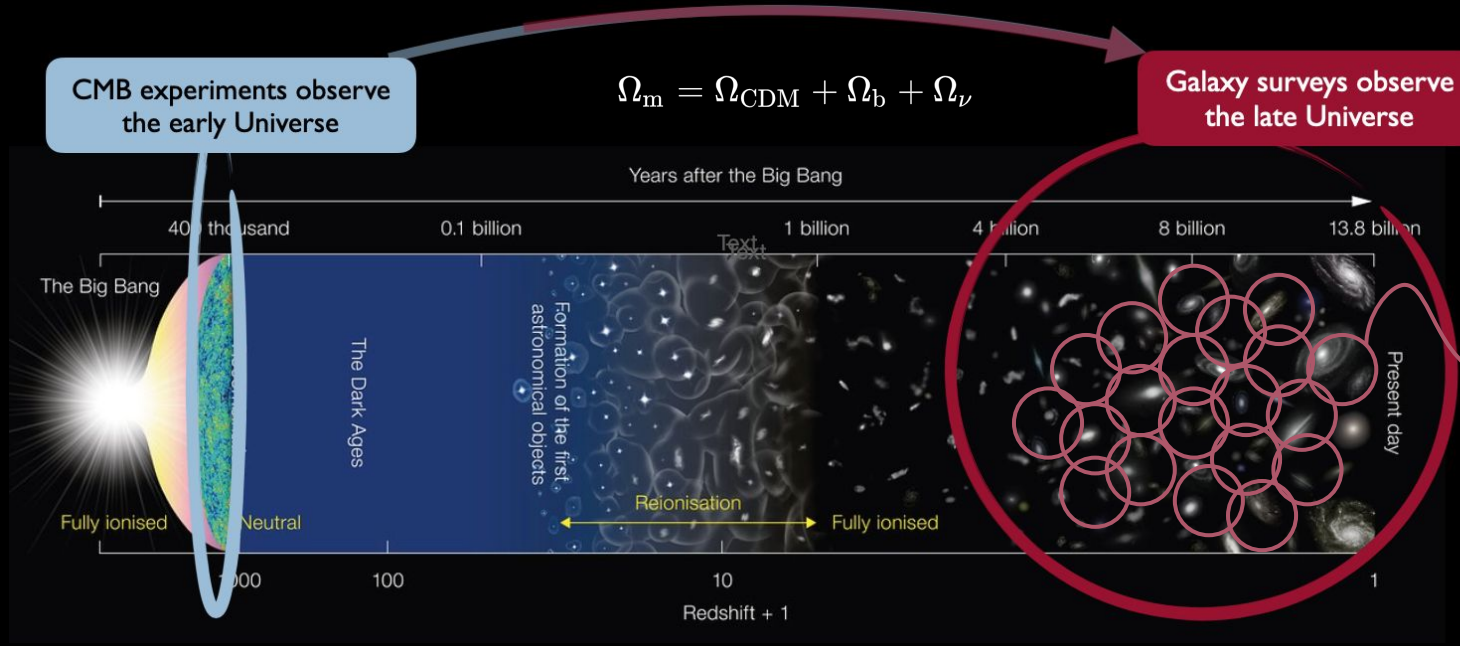


Image Credit: NASA / LAMBDA Archive / WMAP Science Team

From the Early Universe to today

Growth of structure

Gravitational collapse sourced by Ω_m vs. expansion due to the dark energy



Spheres with radius 8 Mpc/h

A_s: Amplitude of primordial scalar density fluctuations.

σ_8: Amplitude of mass fluctuations today.

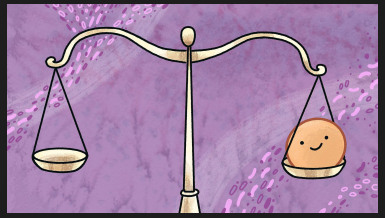
Image credit: NAOJ

Beyond Dark Energy

Key Open Questions in Cosmology

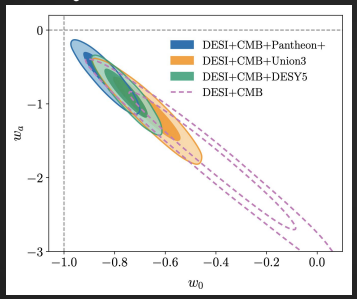
What is **Dark Matter**?

What is the **mass of the neutrinos**?



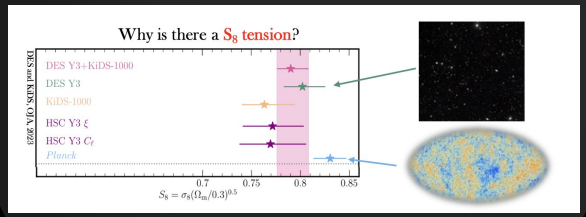
Hints of **dynamical Dark Energy**?

DESI DR2



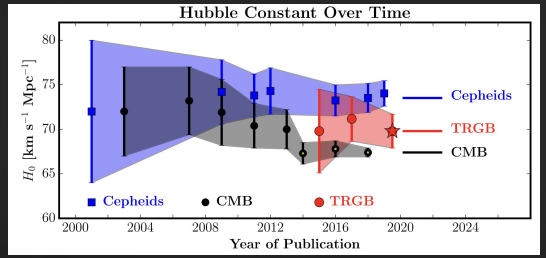
Why is there an S_8 **tension**?

KiDS+DES cosmic shear



Why is there and H_0 **tension**?

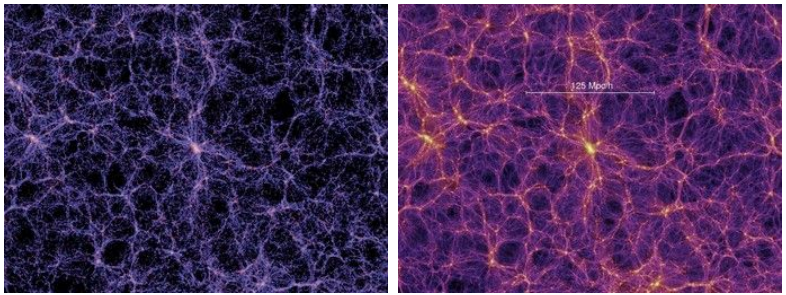
Riess et al.

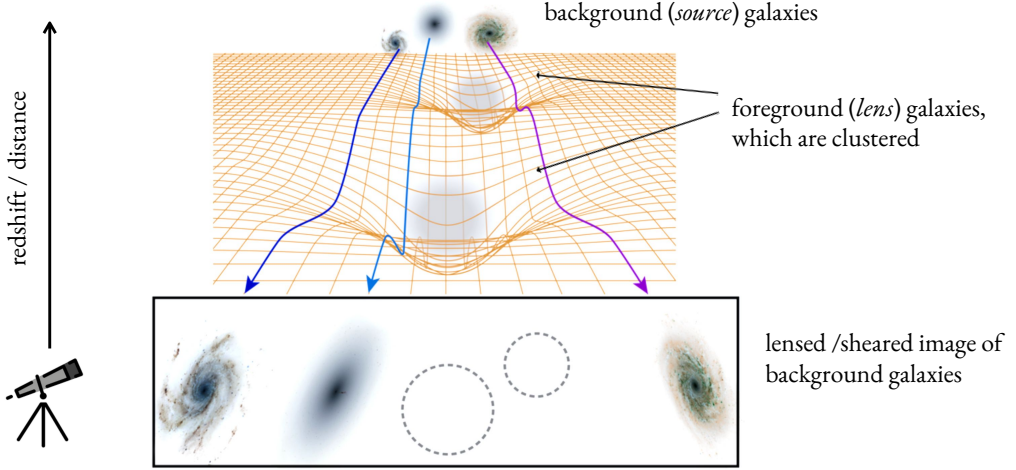


Into the era of precision cosmology with galaxy surveys

Observed galaxies used as:

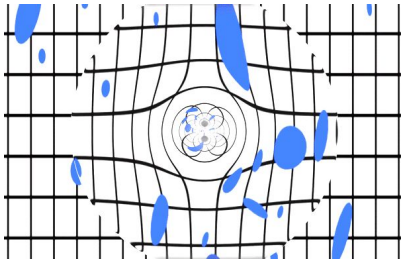
- (*biased*) **tracer** of the dark matter large-scale structure,
- **background light**, to statistically probe the matter distribution.



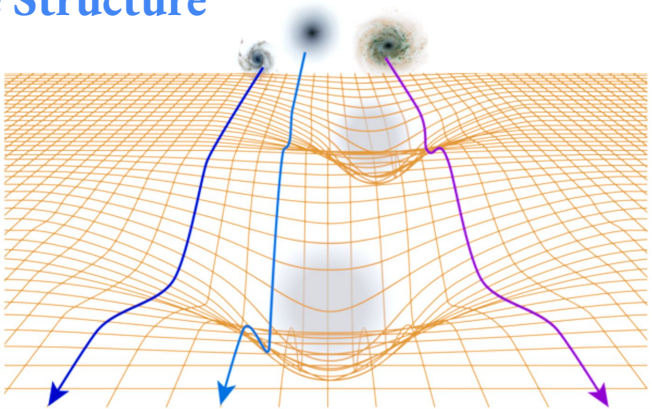


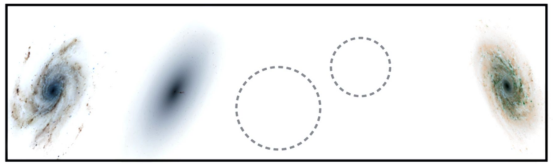
Weak gravitational lensing

Tracing the Large-Scale Structure



Credits to Jamie McCullough





Light from distant galaxies is weakly distorted by mass along the line-of-sight

Distortion changes galaxy shapes in a coherent way (WL signal < **1%** vs intrinsic alignment ~30%)

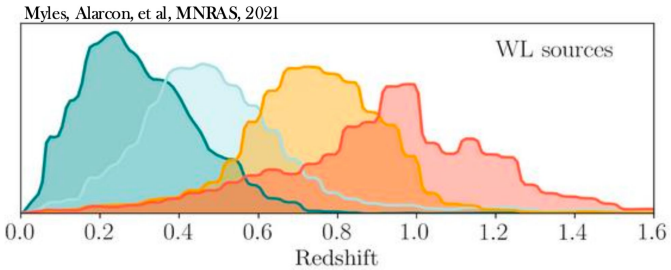
Shear signal decomposed into gravitational lensing, intrinsic alignments, and noise:

$$\gamma = \gamma_G + \gamma_{IA} + \epsilon_0$$

Requires statistical measurement over millions of galaxies → wide galaxy surveys

Summarising field-level information

2-point Statistics

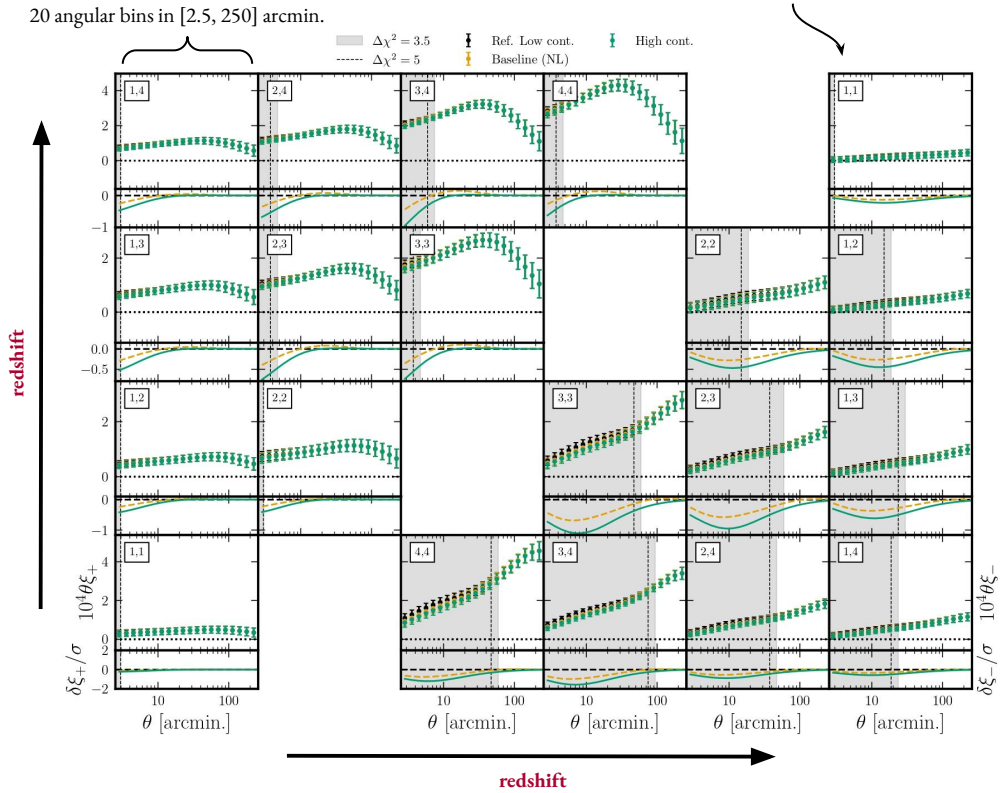


Slicing in redshift bins

Matter distribution is mostly Gaussian -> encode field information in **2-point correlation functions**

In tomographic redshift bins to learn about the **evolution and growth of structure with time.**

Summarising information from the **matter density** and **shear fields**.

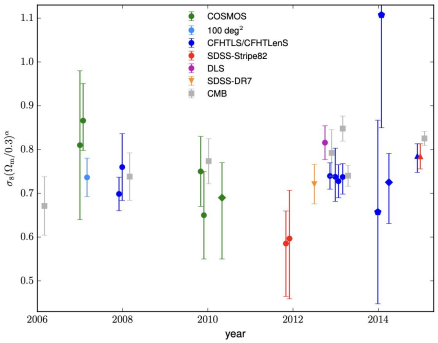


Tomographic 2-point angular correlation function

A timeline of Weak Lensing cosmology

2000s — 2010s — 2020s

First cosmic shear measurements



Kilbinger, 2015

Stage-III

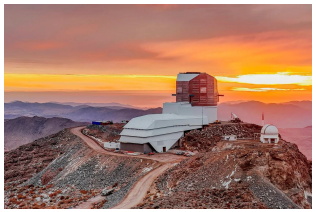
KiDS — FALL, 2011

THE DARK ENERGY SURVEY — SPRING, 2013

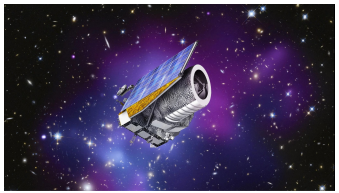
HSC — SPRING, 2014

Stage-IV

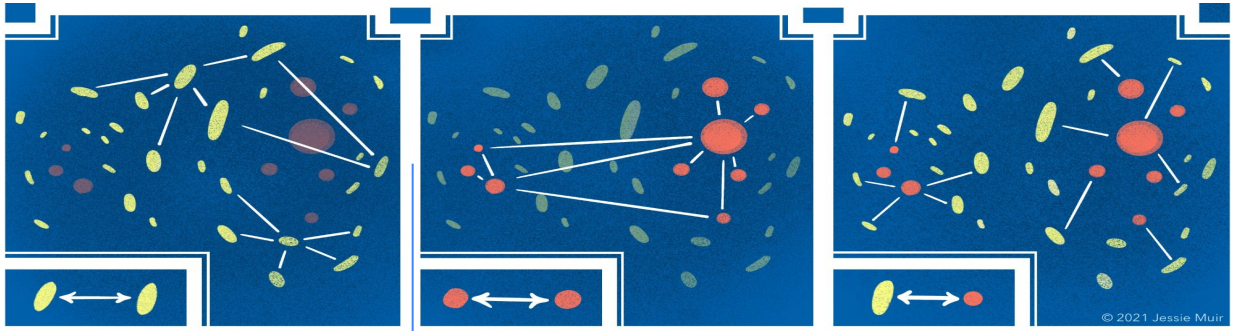
Vera C. Rubin Observatory



Euclid



Roman space telescope



cosmic shear

correlation of source galaxy shapes

$$\xi_{+/-} = \langle e_t(\theta')e_t(\theta'+\theta)\rangle - \langle e_\times(\theta')e_\times(\theta'+\theta)\rangle$$

$$\propto \sigma_8^2$$

galaxy clustering

correlation of lens galaxy positions

$$w(\theta) = \langle \delta(\theta')\delta(\theta'+\theta)\rangle$$

$$\propto b^2\sigma_8^2$$

galaxy-galaxy lensing

correlation between position of lenses and the shape of sources

$$\gamma_t = \langle \delta(\theta')e_t(\theta'+\theta)\rangle$$

$$\propto b\sigma_8^2$$

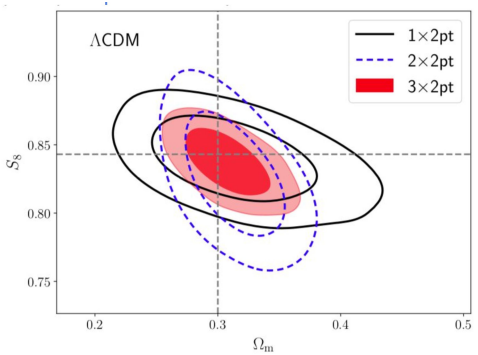
$1 \times 2pt$

$2 \times 2pt$

3x2pt is sensitive to S_8, and is a powerful probe of dark energy, gravity:

$$S_8 \equiv \sigma_8(\Omega_m/0.3)^{1/2}$$

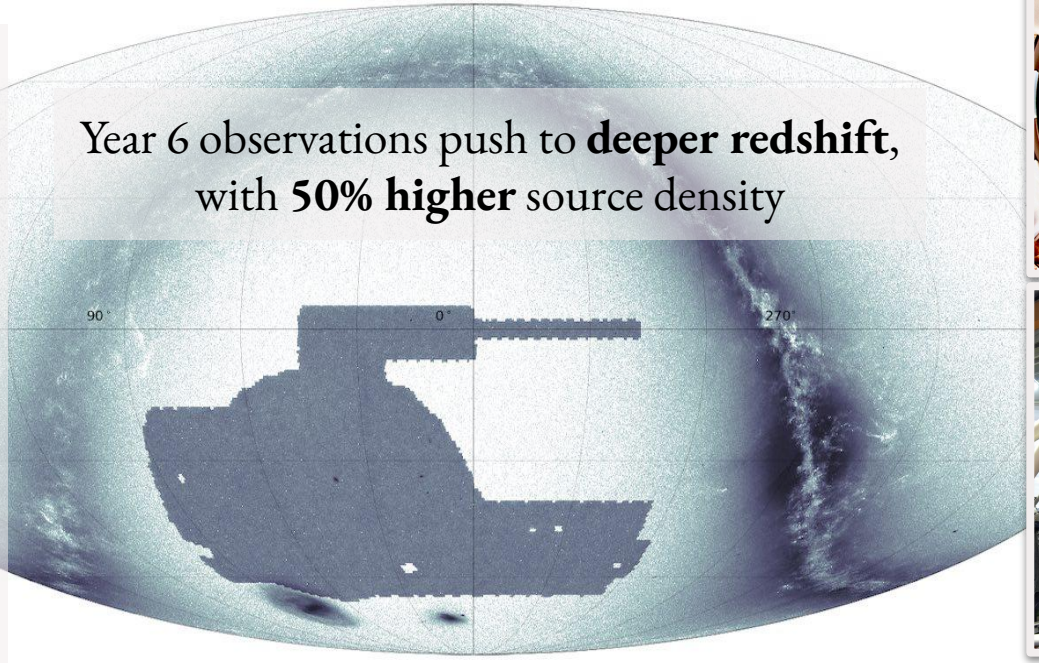
$3 \times 2pt$



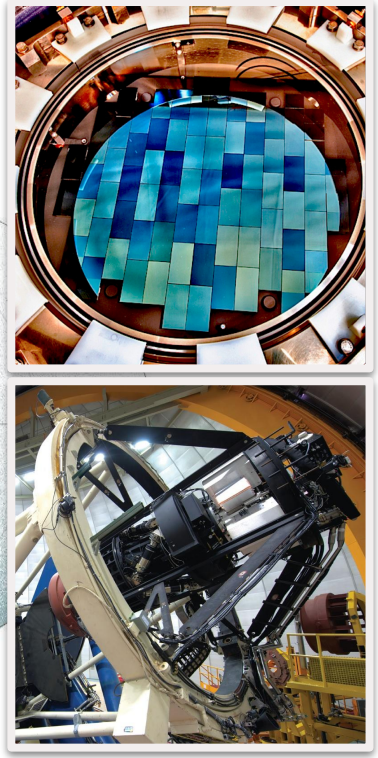
The Dark Energy Survey

A Flagship Photometric Galaxy Survey

- 570 Megapixel camera for the Blanco 4m telescope in Chile.
- Full survey 2013-2019
- **Wide field:** 5000 sq. deg. in 5 bands. i~24 magnitude.
- **Growth of structure** and **geometry** probes
- **DES Year 6 results analysing**: positions and shapes of > 140M galaxies.



Year 6 observations push to **deeper redshift**, with **50% higher** source density



DES Year 6 3x2pt

The Final Analysis

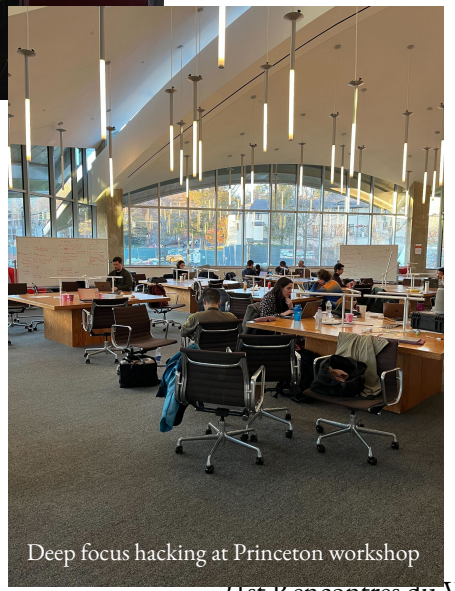
Huge collaborative effort coordinated by Martin Crocce and Matthew Becker, with several analysis teams building blocks of the analysis.

Year 6 analysis is built on top of previous DES efforts with major advancements:

- Color dependent PSF modeling, T. Schutt et al. OJA, 8, 2025,
- Modeling on small scales, DSC, A. Ferte et al. (*in prep.*)
- Photometric redshift uncertainty calibration [B. Yin et al., G. Giannini et al., D'Assignies et al. (*in prep*)], among other improvements.


UChicago workshop

> 50 active contributors *spanning many different time zones!*


Deep focus hacking at Princeton workshop

DES Year 6 3x2pt

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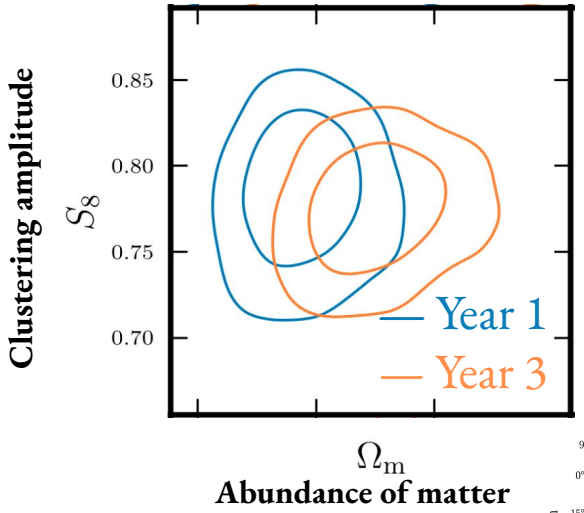
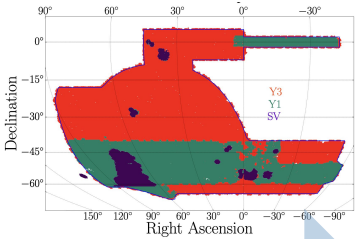
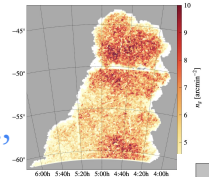
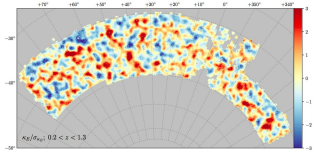
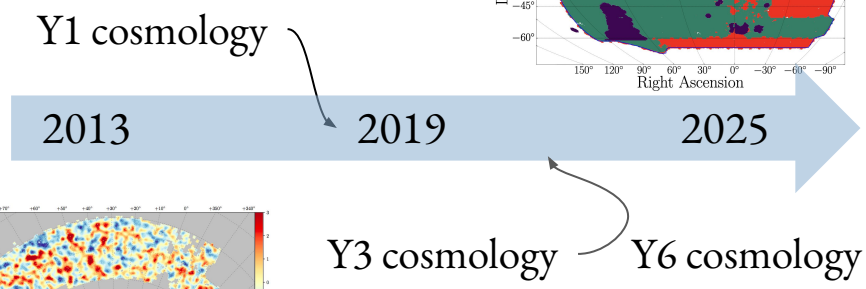


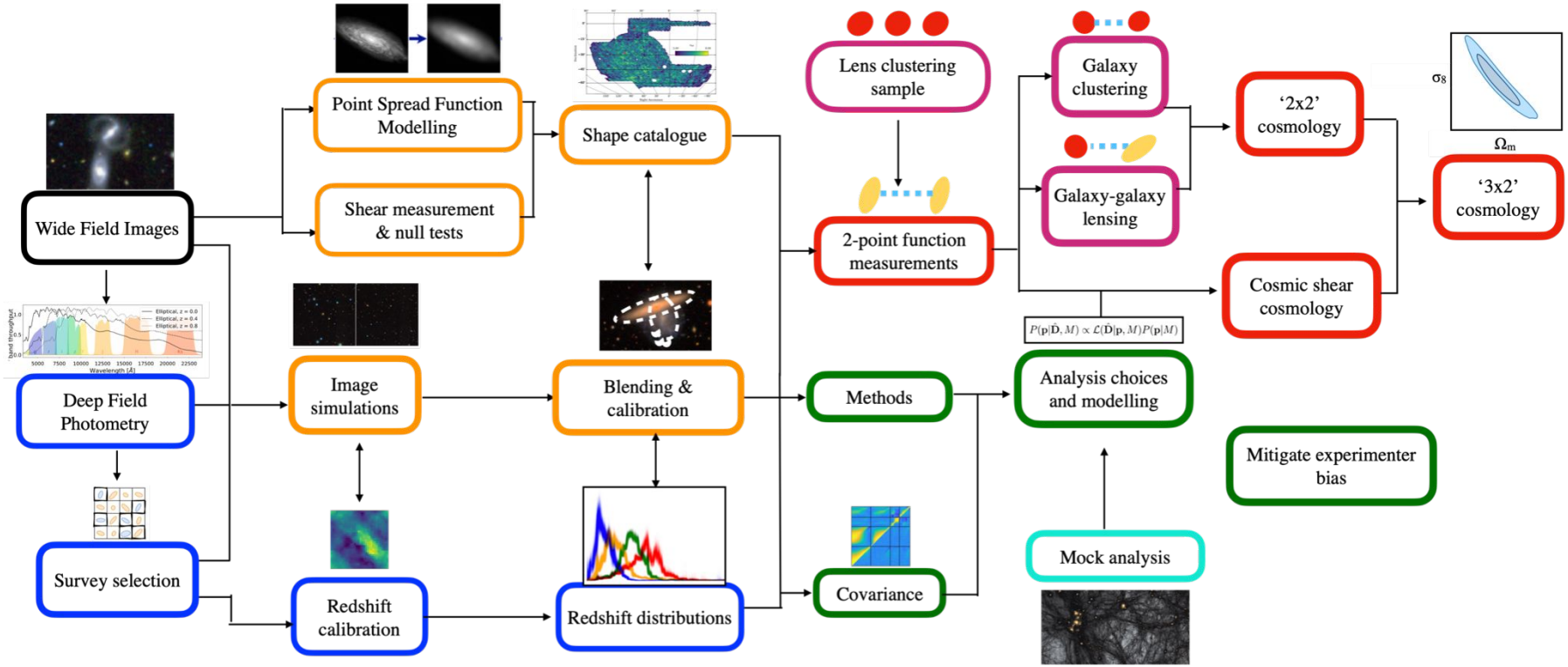






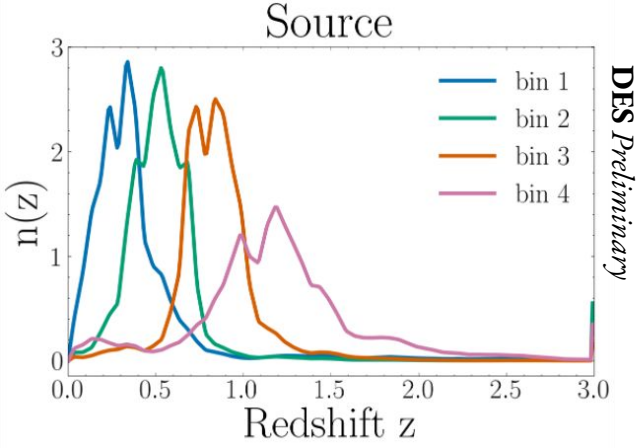


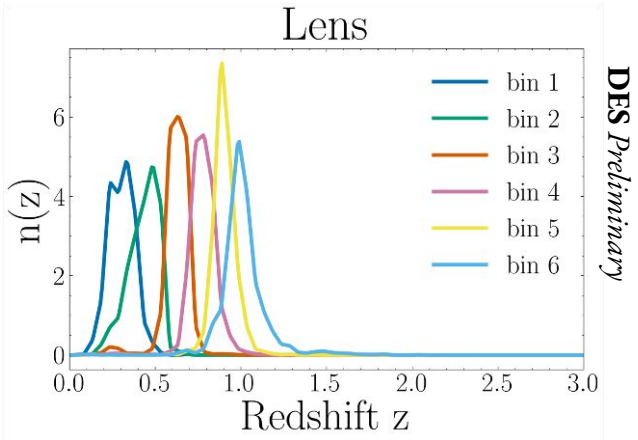
Dark Energy Survey – from pixels to cosmology



LCDM —— WL+LSS —— Redshifts —— Shapes —— Clustering —— Simulations —— Theory —— Results

Source and lens galaxy samples





Source sample = Metadetection [M. Yamamoto, M. R. Becker et al.]

~ 150 million galaxies

n_{eff} = 8 gals / arcmin2 and σ_e = 0.272

Reduced shear bias (e.g. in blended objects).

50% more sources than Y3.

Lens sample = MagLim [A. Porredon, M. Crocce et al.]

11 million galaxies with mag cut : $i < 4\,z\text{phot} + 18$

Better star-galaxy cleaning and mitigation of observing conditions,

Redshift estimates with SOMPZ + WZ

Redundancy is relevant!

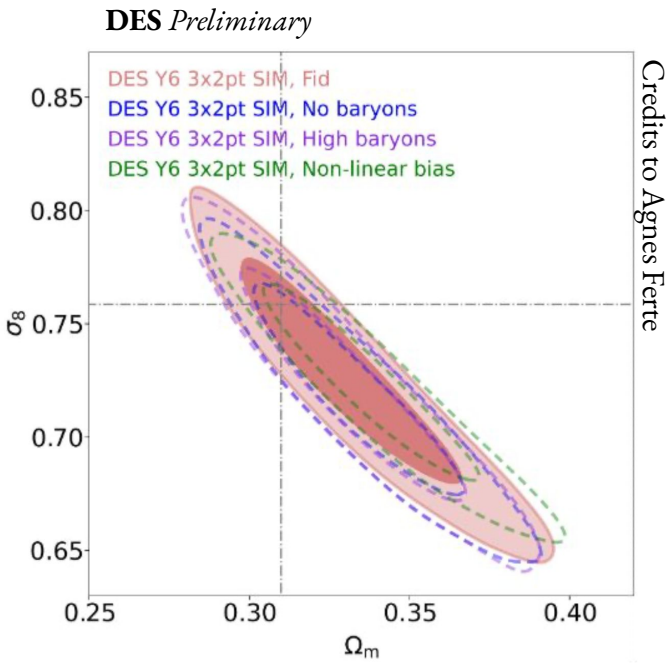
- **Alternative lens sample** = broad $\square^2$ Redmagic
  Twice more galaxies, slightly worse photo-z than Year 3
- **Alternative source sample** = BFD [bayesian fourier domain, Bernstein and Armstrong 2014]
  200 million shapes a bit worse shape noise than Metadetect.

Analysis choices for DES Year 6

Pushing to Smaller Scales

Modeling effort lead by DSC, A. Ferte, and J. Blazek, to build the likelihood pipeline, compute the analytical covariance and validate modeling choices (blinded!):

- HMCode 2020 for **nonlinear DM P(k)**
- **Linear** and **non-linear (EPT) galaxy bias** analyses
- Inclusion of fixed **baryon feedback** signal with log(Tagn) = 7.7 and flat prior on **neutrino mass**.
- **Intrinsic alignment**
  - TATT 4 parameters for 3x2 and 2x2 (bta=1)
  - NLA and TATT for 1x2
- Mitigate poorly described data points with **scale cuts:** i) linear scales down to 6 Mpc/*h*, and ii- non-linear down to 4 Mpc/*h*.

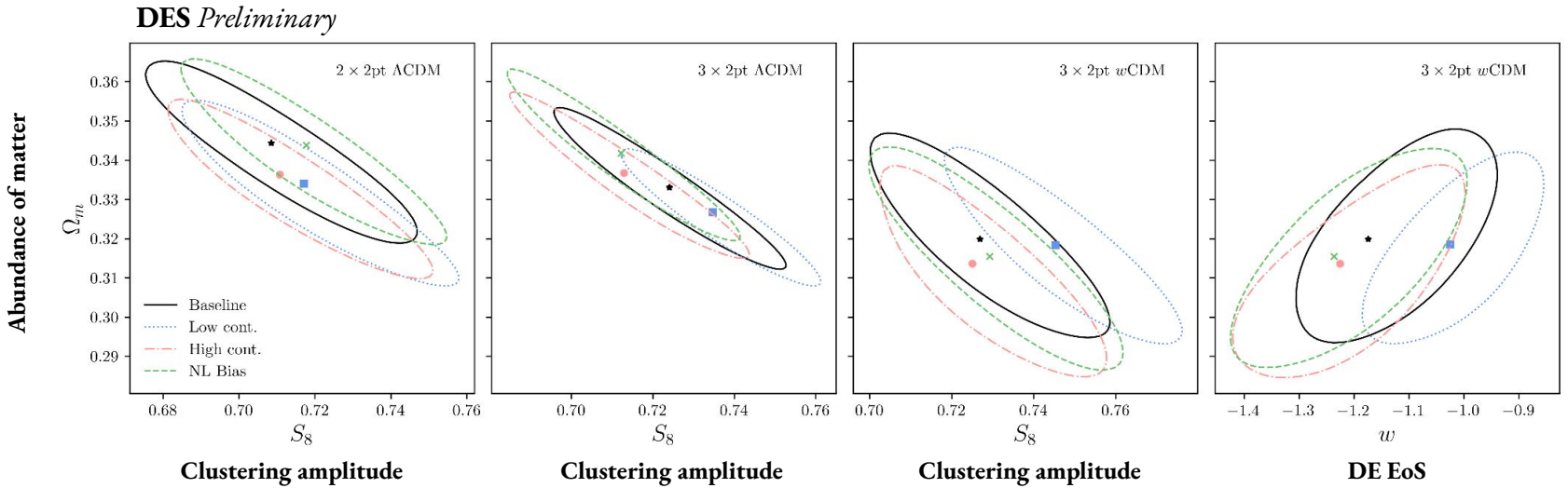


Unaccounted baryonic feedback can bias cosmology substantially

Ensuring robust and unbiased cosmology constraints

Scale cuts definition and validation with synthetic data

Scale cuts for the linear galaxy bias analysis efficiently **mitigate unmodeled systematics**...



... keeping potential biases on the best-constrained parameters **below the 0.5σ** threshold.

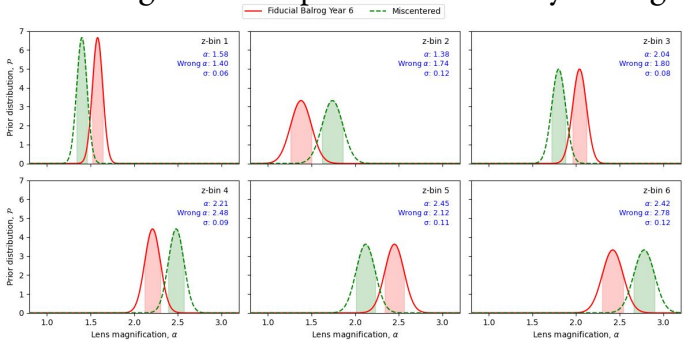
Modeling Calibration Uncertainty

Shedding Light with Simulations

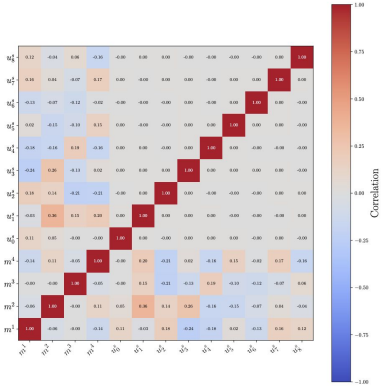
Balrog simulated images (D. Anbajagane et al.) tailored to DES conditions to derive priors for:

- **Lens Magnification** marginalised with a Gaussian prior centered on Balrog measurements [E. Legnani et al.]
- **Redshift distributions** marginalised over their shapes using PCA-like modes [G. Bernstein et al.] and correlating source redshift and shear bias.

Lens magnification priors informed by Balrog



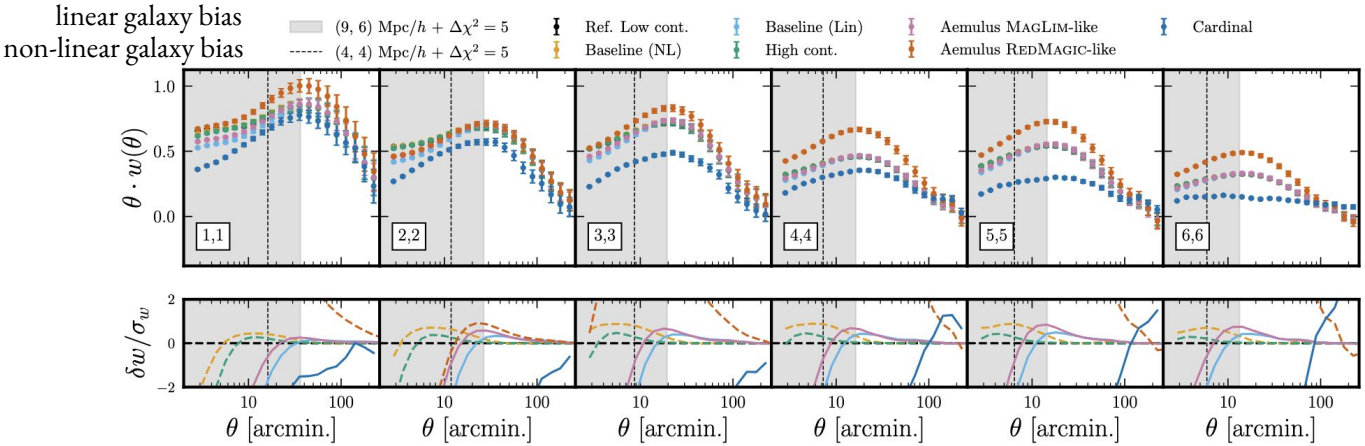
Correlation matrix for source priors



What to expect from DES Year 6?

Mock signal!
Real data signal **passed** all **unblinding** tests! ✅

Galaxy clustering



Measured scales in [0, 1000] arcmin but **not all are usable**!

Analysis	Scale cuts	ξ_+	ξ_-	γ_t	$w(\theta)$	Total	SNR
Cosmic shear NLA	$\Delta\chi^2 = 3.5$	178	89	-	-	267	37.52
Cosmic shear TATT-4	$\Delta\chi^2 = 5$	183	99	-	-	282	39.76
2 × 2pt ΛCDM Linear	(9, 6) Mpc/h	-	-	312	66	378	114.71
3 × 2pt w/ΛCDM Linear	(9, 6) Mpc/h + $\Delta\chi^2 = 5$	183	99	312	66	660	115.85
2 × 2pt ΛCDM Non-linear	(4, 4) Mpc/h	-	-	348	87	435	171.58
3 × 2pt w/ΛCDM Non-linear	(4, 4) Mpc/h + $\Delta\chi^2 = 5$	183	99	348	87	717	172.2
3x2pt LCDM Year linear							87

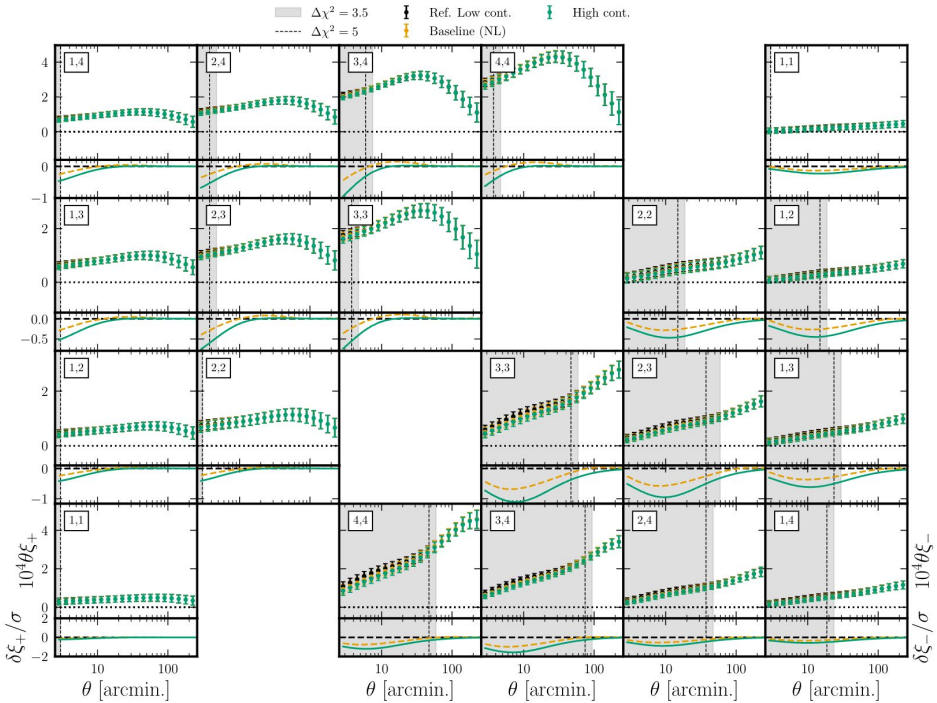
32% higher SNR

97% higher SNR

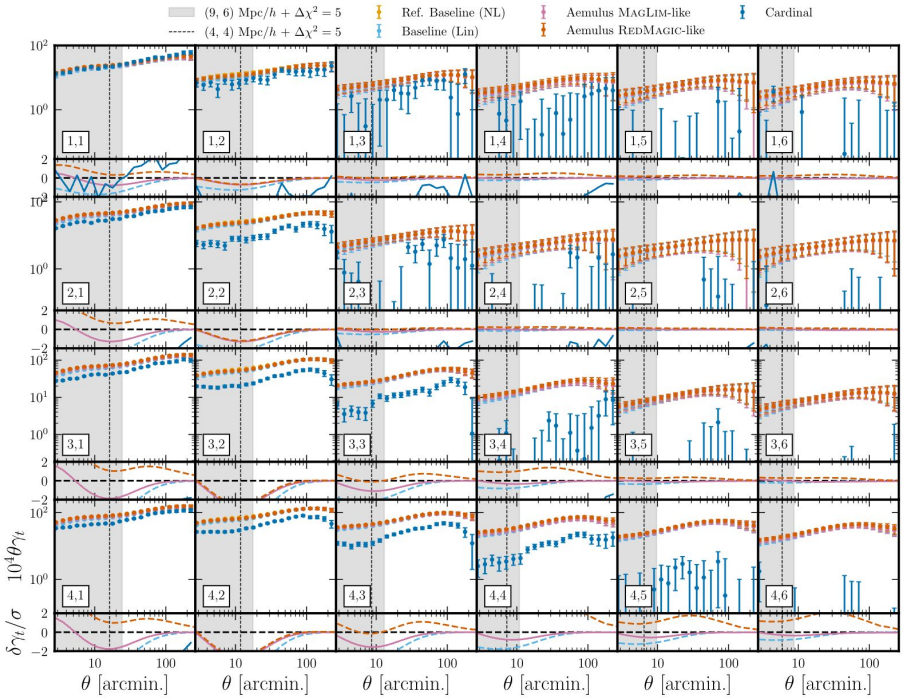
What to expect from DES Year 6?

Total of 50 correlation functions!

Cosmic shear

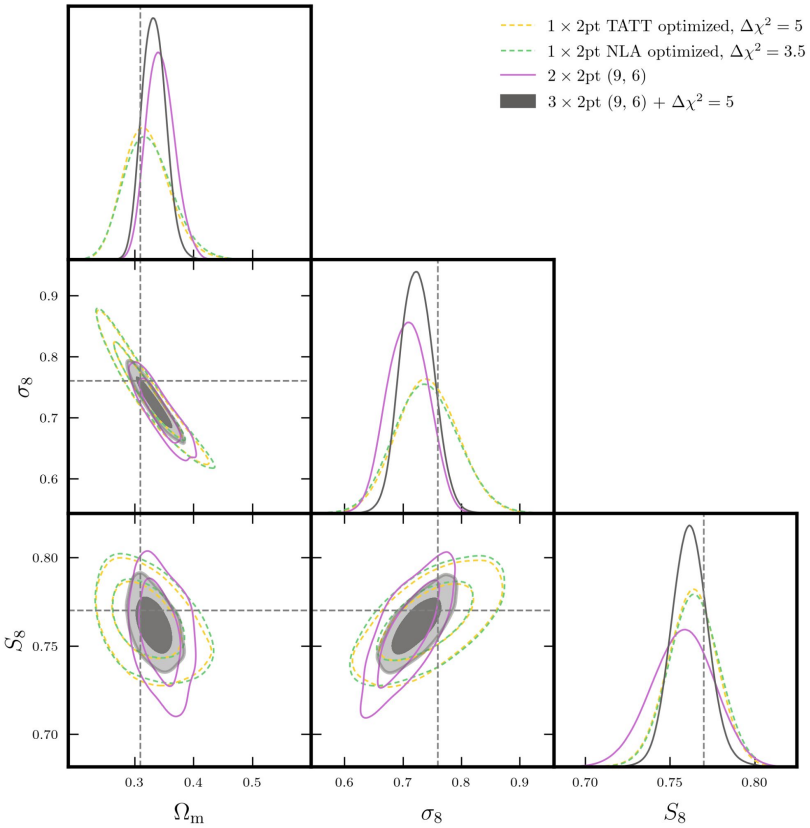


Galaxy-galaxy lensing



The sustained gain of 1x2pt + 2x2pt

Linear galaxy bias analysis



More than a factor of 2 increase in FoM in LCDM in 3x2pt wrt shear alone.

3x2pt is very **robust** to systematics in general + IA and galaxy bias

$$\mathrm{FoM}_{\Omega_m,\sigma_8} = 1/\det\left(\mathrm{Cov}^{-1}_{\Omega_m,\sigma_8}\right)$$

Case	$\mathrm{FoM}_{\Omega_m,\sigma_8}$	Relative Difference (%)
DES Y6 - 1 × 2pt	1812.45	-
DES Y6 - 2 × 2pt	2019.41	11.42%
DES Y6 - 3 × 2pt	4942.84	172.72%
DES Y3 - 3x2pt	2068	

What to expect from DES Year 6?

Linear galaxy bias analysis

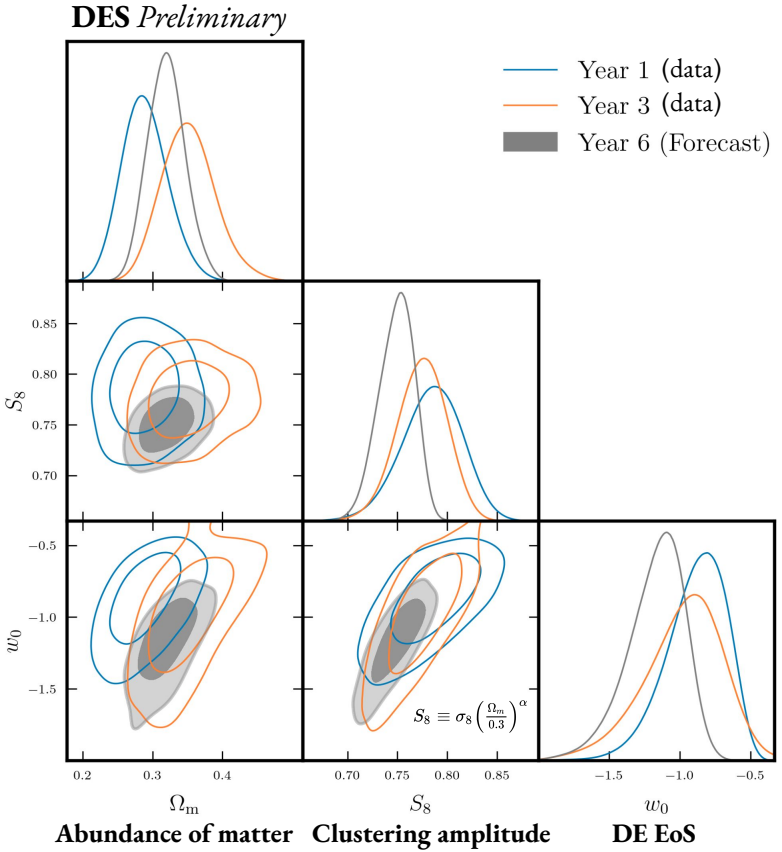
High-dimensional/complex parameter space

with > 50 parameters

Case	$\text{FoM}_{\Omega_m,\sigma_8}$	Relative Difference (%)
DES Y3 - 3 × 2pt	2011.20	-
DES Y6 - 3 × 2pt	4942.84	145.77%

Also, more than a factor of 2 gain in compared to Year 3 linear (with 4 lens bins and no SR)

Case	$\Delta_\sigma\ (\Omega_m)$	$\Delta_\sigma\ (\sigma_8)$	$\Delta_\sigma\ (S_8)$
Ref.-DES Y3 - 3 × 2pt	–	–	–
DES Y6 - 1 × 2pt	15.21	−6.14	−19.48
DES Y6 - 2 × 2pt	1.78	−8.55	−3.59
DES Y6 - 3 × 2pt	−22.39	−27.2	−34.59



DES Year 6 constraints to beyond LCDM models

Dynamical dark energy and more

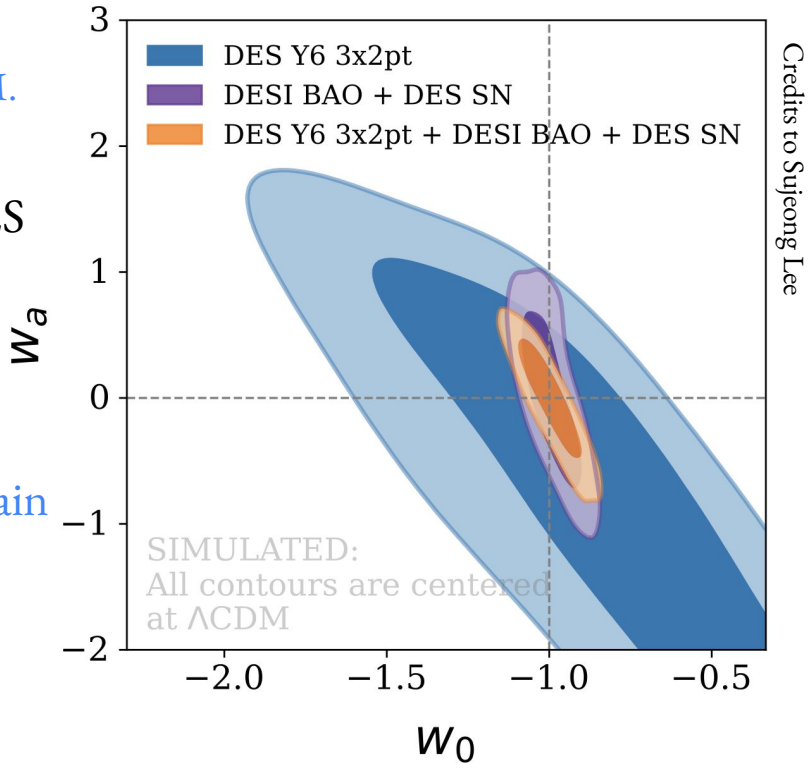
Studies beyond LCDM lead by O. Alves, S. Lee, and M. Raveri.

In the light of DESI BAO + SN + CMB *w*0*w*a, DES can contribute to the discussion with:

- geometry DES SN + BAO (previous talk,)
- growth of structure

Adding 3x2pt to DESI BAO + DES SN -> ~46% gain in σ(wa)

+ modified gravity, curvature, massive neutrinos, binned σ_8, ...



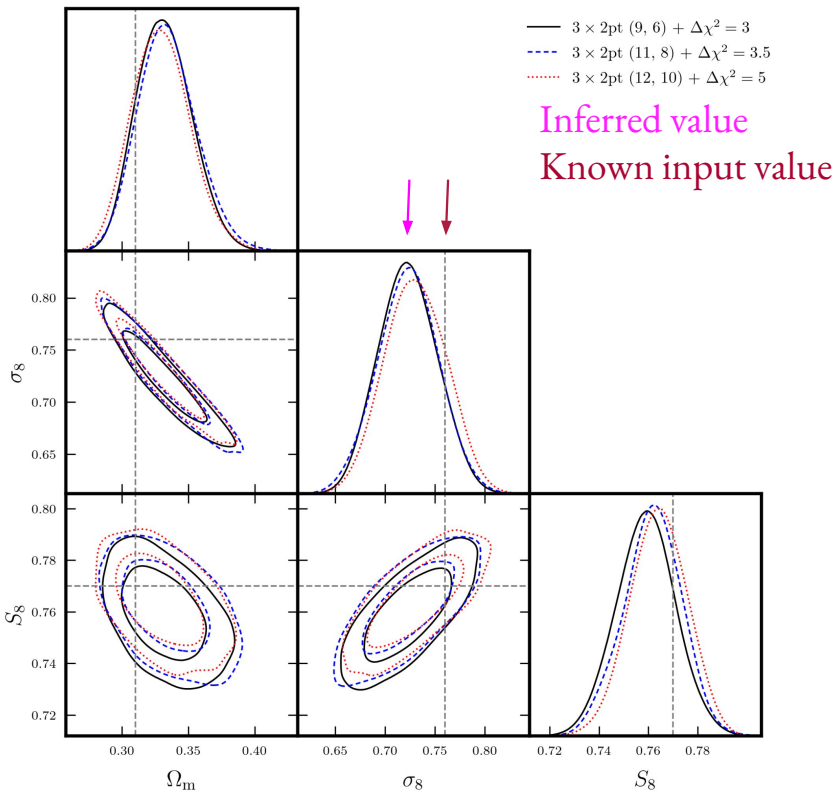
Challenges of a Growing Parameter Space

Projection effects and computational cost

i) High-dimensional parameter space → projection / volume effects shift inferred values (e.g., neutrino mass, galaxy bias).

ii) Large-scale MCMC campaigns are computationally expensive → require P(k) emulators and optimized sampling. Other ideas?

1.3M CPU-hours total to get our first version of scale cuts for shear, 2x2pt and 3x2pt Λ/wCDM and in linear and non-linear galaxy bias model (estimate by Agnes Ferte)



Cosmology with DES Year 6 3x2pt

Key Takeaways

- DES sets the benchmark for 3×2pt cosmology, with forecasted Y6 surpassing Y3 constraining power.
- Analysis improvements: deeper imaging, larger catalogs, improved 2PCF and redshift calibration, refined small-scale modeling.
- Constraints on w/LCDM and beyond, informing w_0w_a dark energy models via growth of structure.
- Methodology provides a foundation for Euclid, Roman, and Rubin analyses.
- Tackling theoretical and computational challenges will ensure success for next-generation surveys.

Contact: david.sanchezcid@physik.uzh.ch

Universität Zürich[UZH]