Dark Energy Survey Year 6 Cosmological Results and Lensing Ratios

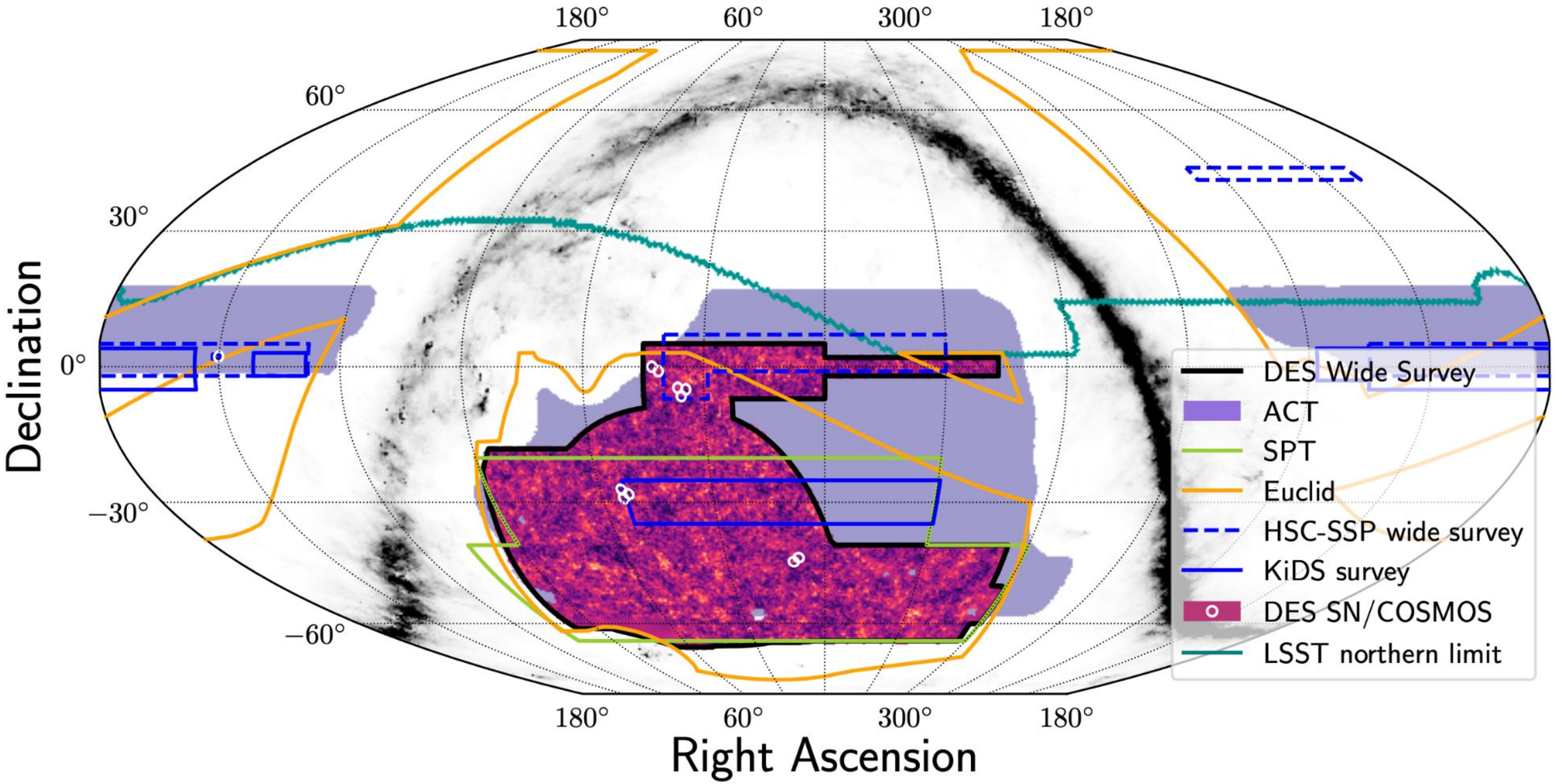
Gisela C. Camacho-Ciurana

Institute of Space Science (ICE-CSIC), Barcelona (Spain)

Institute of Space Sciences
CSIC
Consejo Superior de Investigaciones Científicas
IEEC
"la Caixa" Foundation

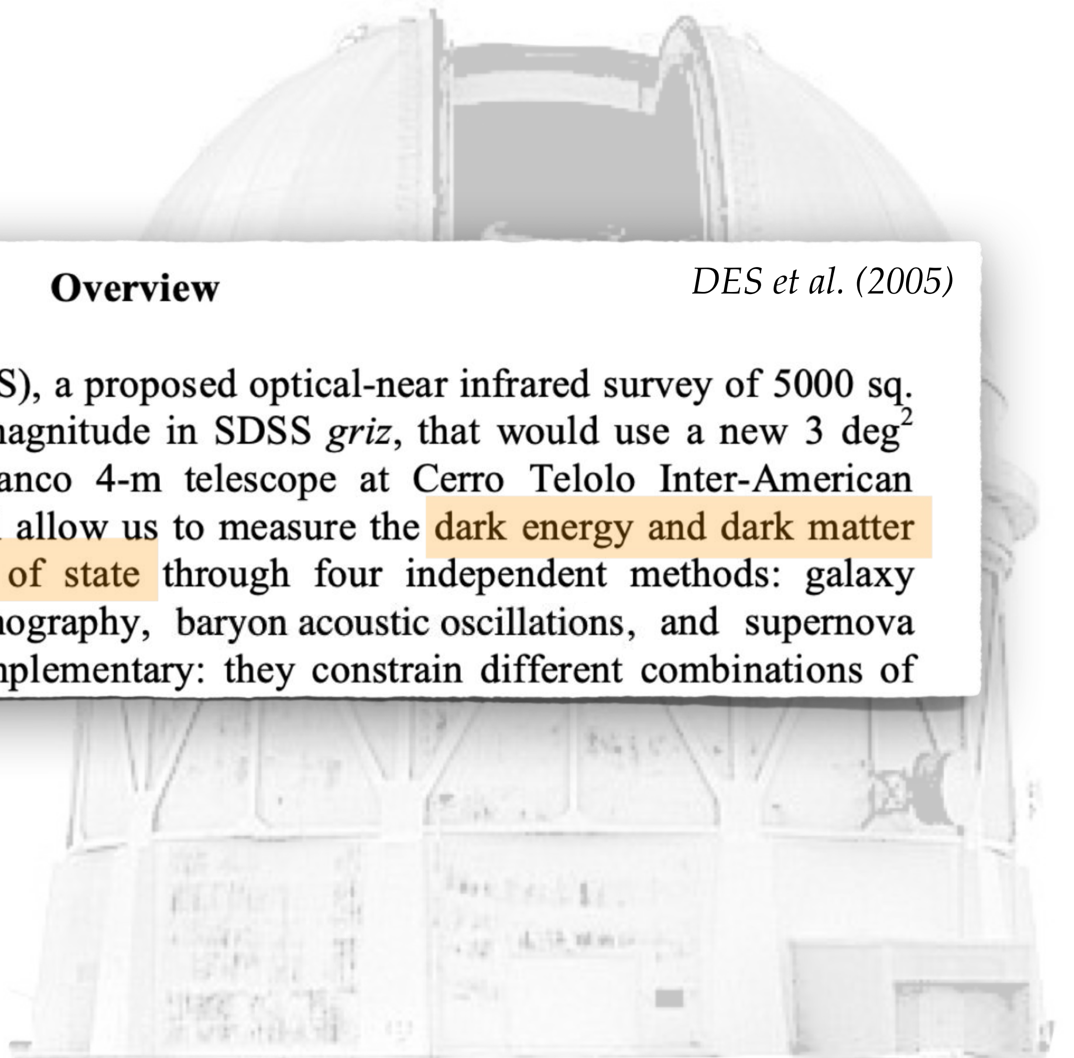
The Dark Energy Survey Legacy Data

<u>6 years</u> of data: 2013 - 2019



DES et al. (2026)

The Core Mission of DES



DES et al. (2005)

Overview

We describe the Dark Energy Survey (DES), a proposed optical-near infrared survey of 5000 sq. deg of the South Galactic Cap to ~24^{th} magnitude in SDSS *griz*, that would use a new 3 deg^2 CCD camera to be mounted on the Blanco 4-m telescope at Cerro Telolo Inter-American Observatory (CTIO). The survey data will allow us to measure the dark energy and dark matter densities and the dark energy equation of state through four independent methods: galaxy clusters, weak gravitational lensing tomography, baryon acoustic oscillations, and supernova distances. These methods are doubly complementary: they constrain different combinations of

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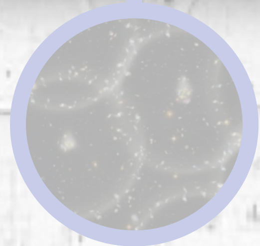

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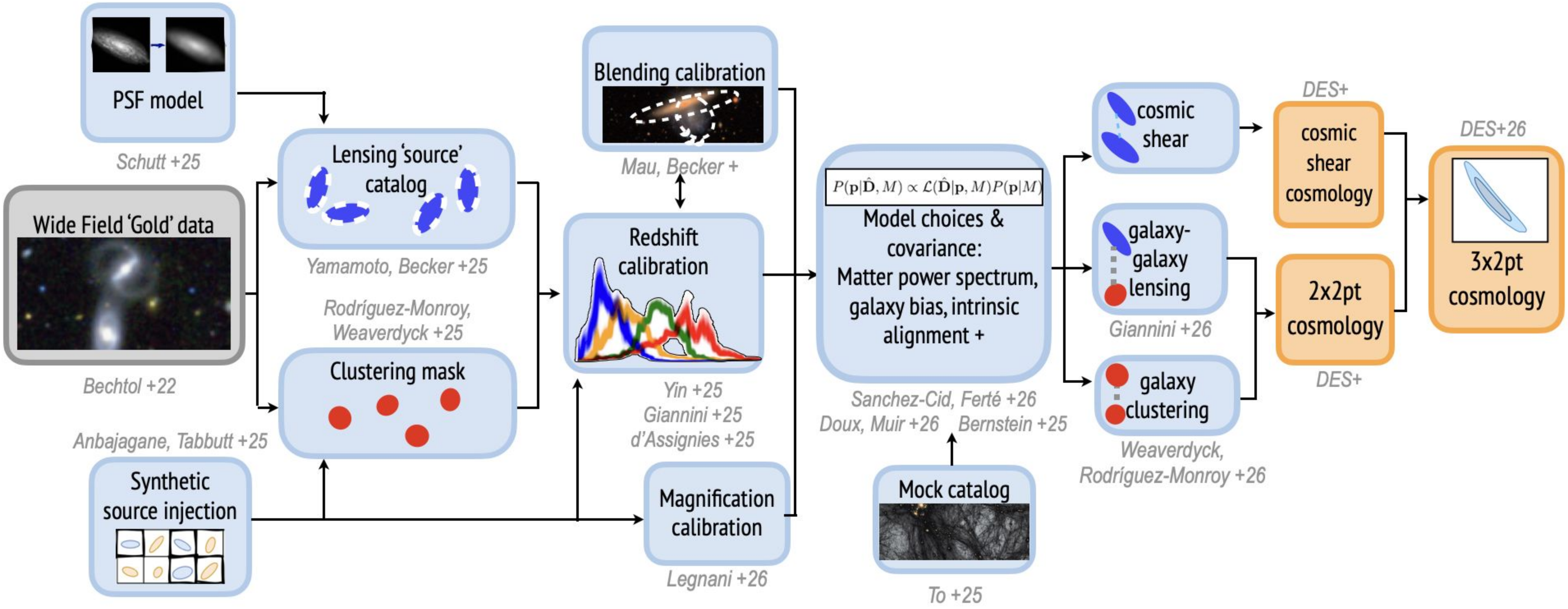
Authors of this Analysis

T. M. C. Abbott, M. Adamow, M. Aguena, A. Alarcon, S. S. Allam, **O. Alves**, A. Amon, **D. Anbajagane**, F. Andrade-Oliveira, S. Avila, D. Bacon, E. J. Baxter, **J. Beas-Gonzalez**, K. Bechtol, M. R. Becker, G. M. Bernstein, E. Bertin, J. Blazek, S. Bocquet, D. Brooks, D. Brout, **H. Camacho**, **G. Camacho-Ciurana**, **R. Camilleri**, **G. Campailla**, **A. Campos**, A. Carnero Rosell, M. Carrasco Kind, J. Carretero, P. Carrilho, F. J. Castander, R. Cawthon, C. Chang, A. Choi, **J. M. Coloma-Nadal**, M. Costanzi, M. Crocce, **W. d'Assignies**, L. N. da Costa, M. E. da Silva Pereira, T. M. Davis, **J. De Vicente**, J. DeRose, H. T. Diehl, S. Dodelson, C. Doux, A. Drlica-Wagner, T. F. Eifler, J. Elvin-Poole, J. Estrada, **S. Everett**, A. E. Evrard, J. Fang, A. Farahi, A. Ferte, B. Flaugher, P. Fosalba, J. Frieman, J. Garcia-Bellido, M. Gatti, E. Gaztanaga, **G. Giannini**, P. Giles, K. Glazebrook, **M. Gorsuch**, D. Gruen, R. A. Gruendl, J. Gschwend, G. Gutierrez, I. Harrison, W. G. Hartley, E. Henning, K. Herner, S. R. Hinton, D. L. Hollowood, K. Honscheid, E. M. Huff, D. Huterer, B. Jain, D. J. James, M. Jarvis, N. Jeffrey, T. Jeltema, T. Kacprzak, S. Kent, A. Kovacs, E. Krause, R. Kron, K. Kuehn, O. Lahav, **S. Lee**, **E. Legnani**, C. Lidman, H. Lin, **N. MacCrann**, M. Manera, T. Manning, R. Marco, J. L. Marshall, **S. Mau**, **J. McCullough**, **J. Mena-Fernandez**, F. Menanteau, R. Miquel, J. J. Mohr, J. Muir, **J. Myles**, R. C. Nichol, B. Nord, **J. H. O'Donnell**, R. L. C. Ogando, A. Palmese, M. Paterno, J. Peoples, W. J. Percival, D. Petravick, A. Pieres, A. A. Plazas Malagon, A. Porredon, A. Pourtsidou, J. Prat, **C. Preston**, M. Raveri, **W. Riquelme**, **M. Rodriguez-Monroy**, **P. Rogozenski**, A. K. Romer, A. Roodman, R. Rosenfeld, A. J. Ross, E. Rozo, E. S. Rykoff, **S. Samuroff**, C. Sanchez, E. Sanchez, **D. Sanchez Cid**, **T. Schutt**, I. Sevilla-Noarbe, E. Sheldon, **N. Sherman**, **T. Shin**, M. Smith, M. Soares-Santos, E. Suchyta, M. E. C. Swanson, **M. Tabbutt**, G. Tarle, D. Thomas, **C. To**, **A. Tong**, L. Toribio San Cipriano, M. A. Troxel, M. Tsedrik, D. L. Tucker, V. Vikram, A. R. Walker, **N. Weaverdyck**, R. H. Wechsler, D. H. Weinberg, J. Weller, **V. Wetzell**, **A. Whyley**, R.D. Wilkinson, P. Wiseman, H.-Y. Wu, **M. Yamamoto**, B. Yanny, **B. Yin**, **G. Zacharegkas**, Y. Zhang, J. Zuntz

bold: early career scientists

blue: mid-career scientists (at least partially) trained in DES

Pixels to cosmology



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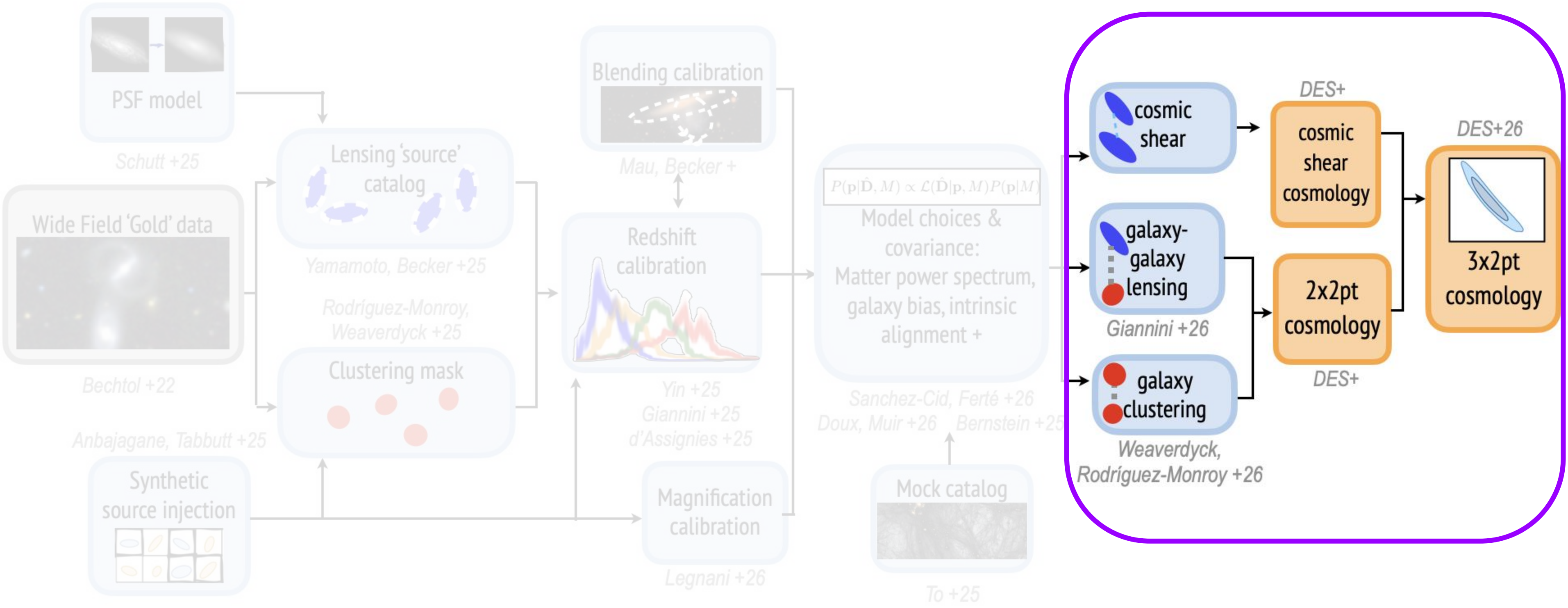
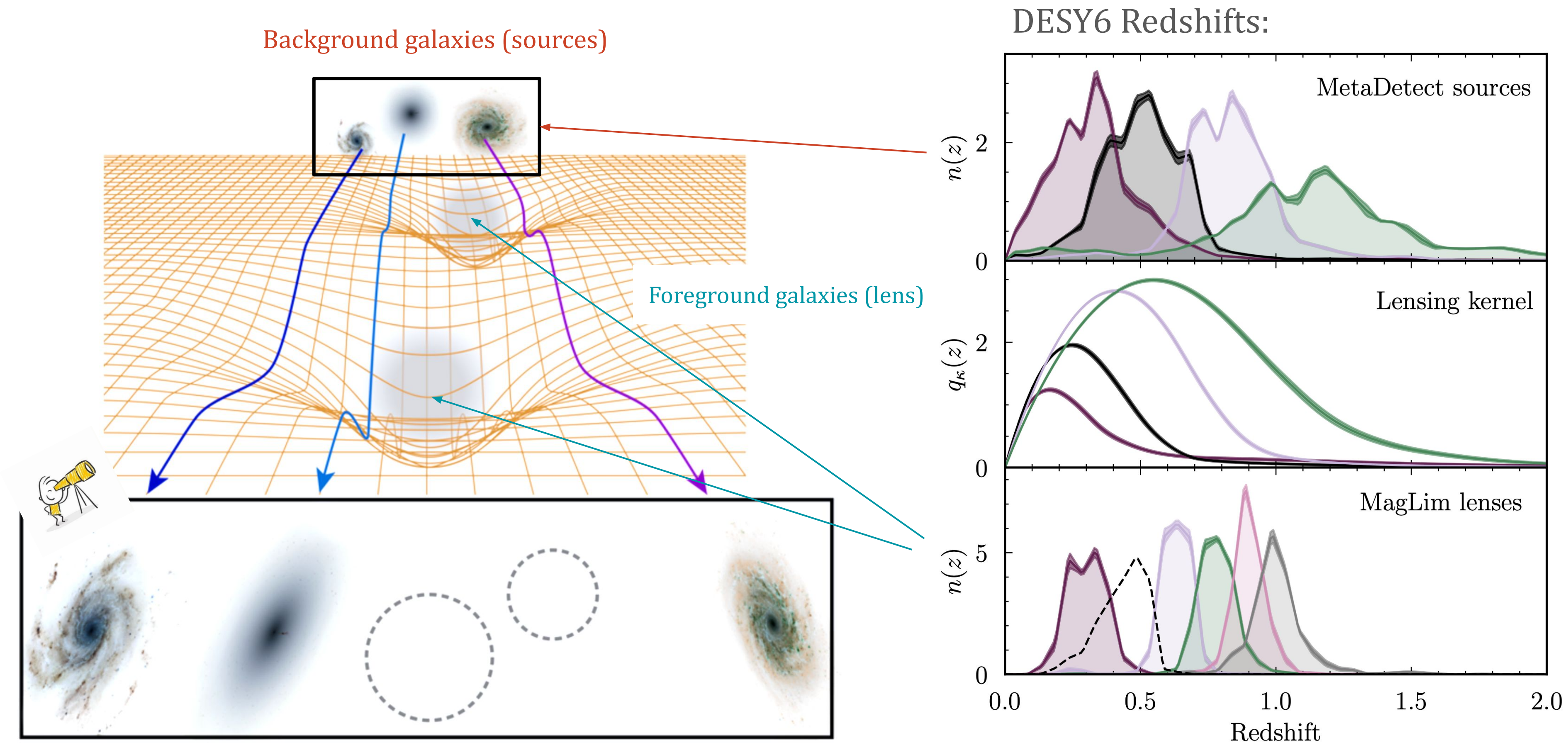
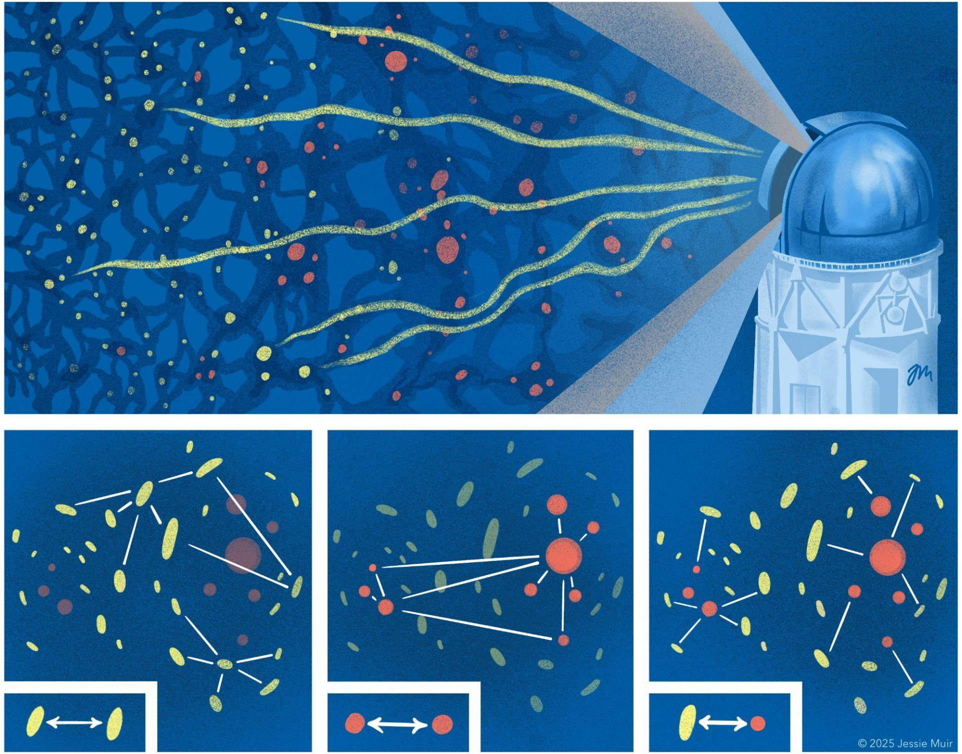




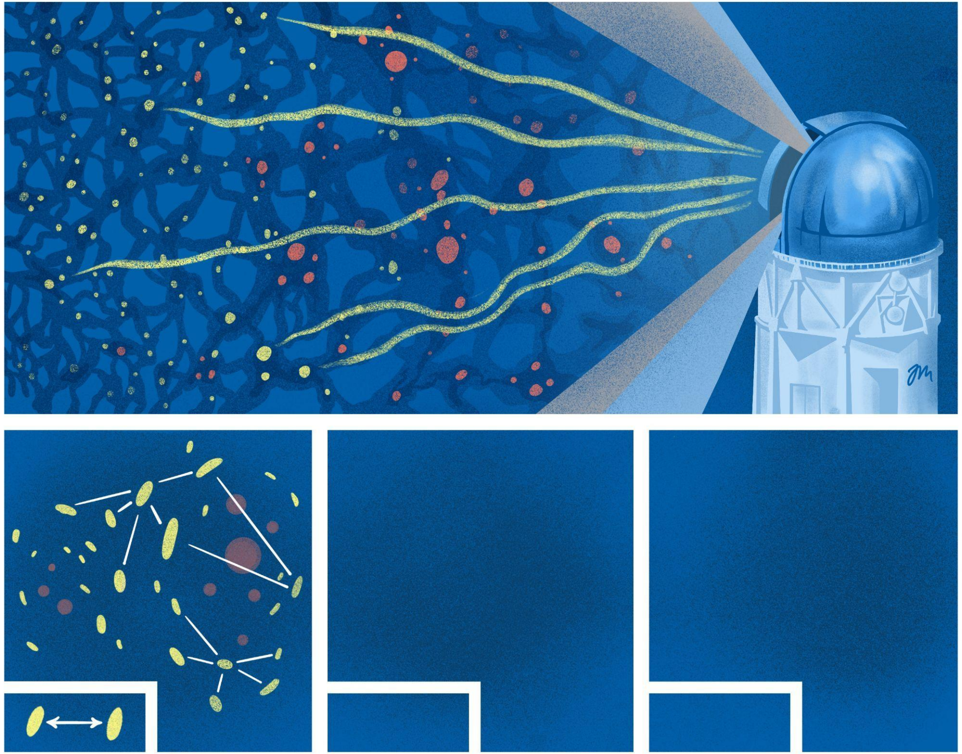
Background galaxies (sources)
Foreground galaxies (lens)
DESY6 Redshifts:
MetaDetect sources
Lensing kernel
MagLim lenses
$n(z)$
$q_\kappa(z)$
0
2
5
0.0
0.5
1.0
1.5
2.0
Redshift

3x2pt cosmology

Framework that combines **three two-point correlation functions**, measured tomographically in **redshift** bins



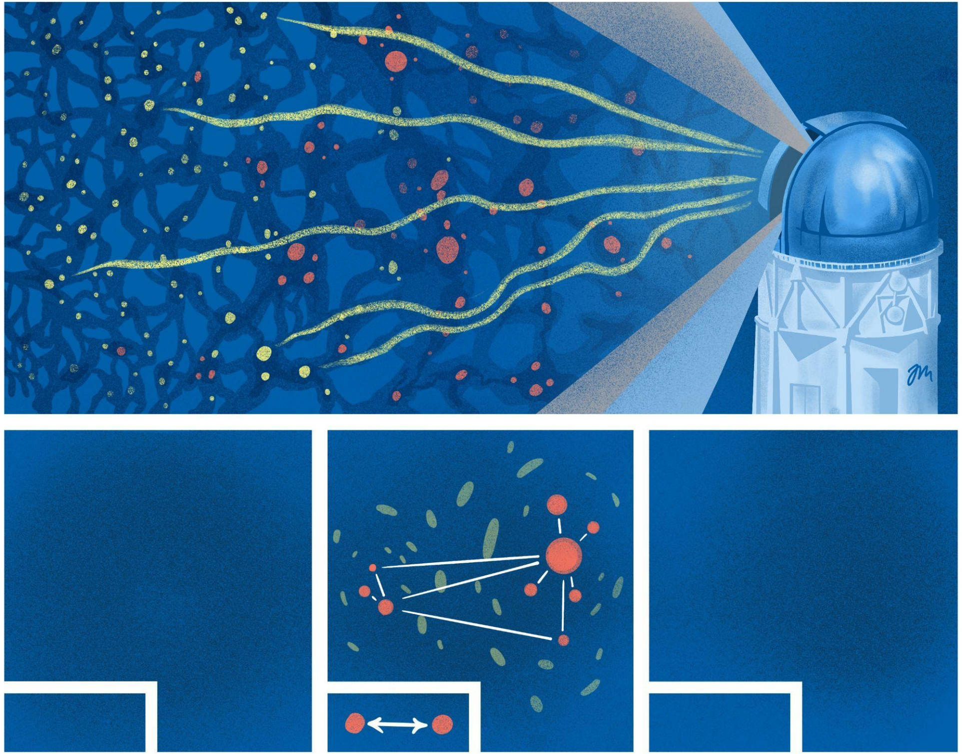
3x2pt cosmology



Cosmic shear

We measure the correlation of the **shapes** of background **source** galaxy pairs

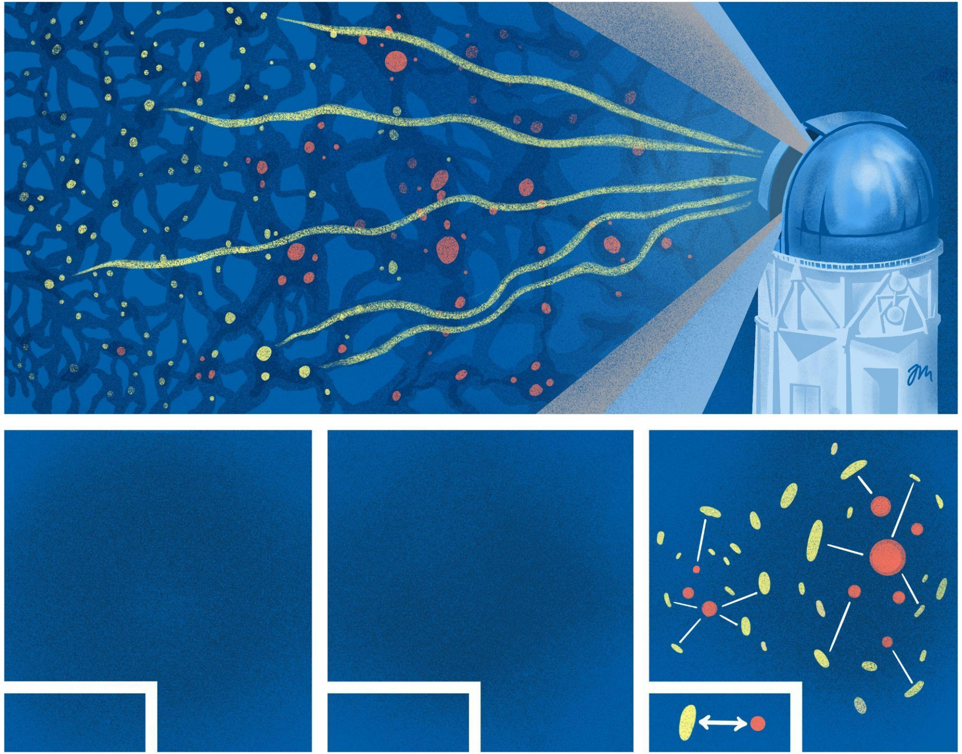
3x2pt cosmology



Galaxy clustering

We measure the correlation of the **positions** of foreground **lens** galaxies pairs

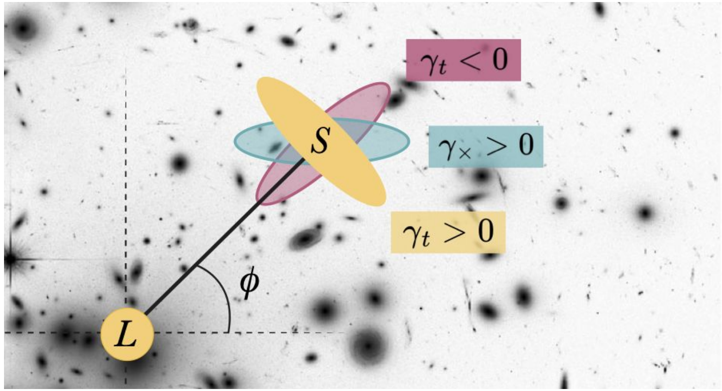
3x2pt cosmology

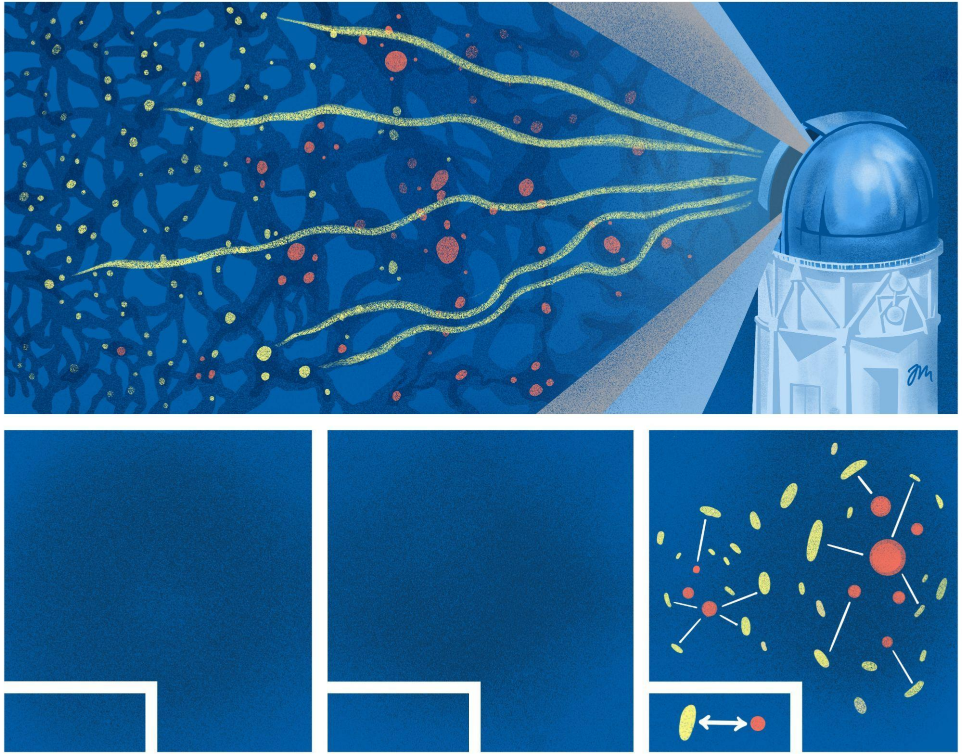


Galaxy-galaxy lensing

We measure the **tangential shear** of the background source galaxies around the foreground lens galaxies

3x2pt cosmology





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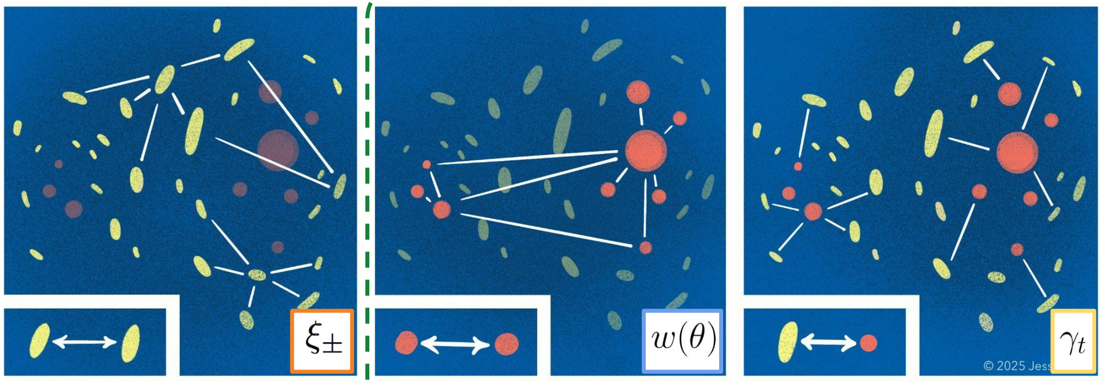
3x2pt cosmology

3x2pt



2x2pt

Cosmic Shear
shape-shape

Galaxy Clustering
position-position

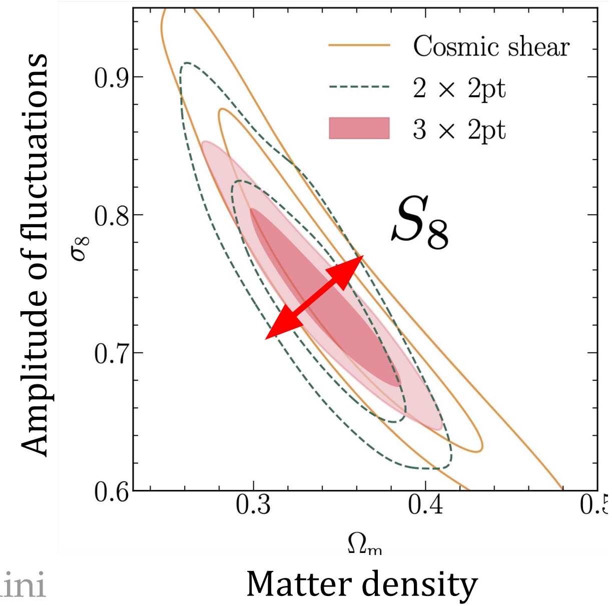
Galaxy-Galaxy Lensing
position-shape

A joint analysis **maximises the cosmological information** and robustly **constrains astrophysical & observational systematics!**

3x2pt cosmology

The 3x2pt analysis is most sensitive to:

- ❖ Matter density Ω_m
- ❖ σ_8 amplitude of density fluctuations



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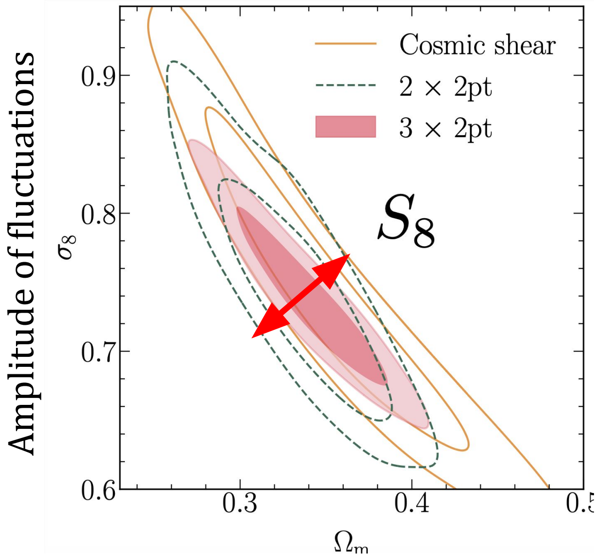
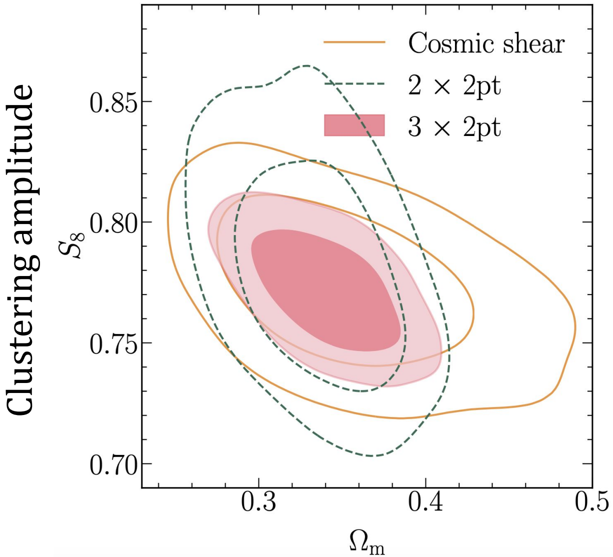
3x2pt cosmology

The 3x2pt analysis is most sensitive to:

- ❖ Matter density Ω_m
- ❖ σ_8 amplitude of density fluctuations → parameterized as $\boxed{S_8 = \sigma_8(\Omega_m/0.3)^{0.5}}$



Matter density



Matter density

$\Omega_m - S_8$: *best-constrained parameter combination!*

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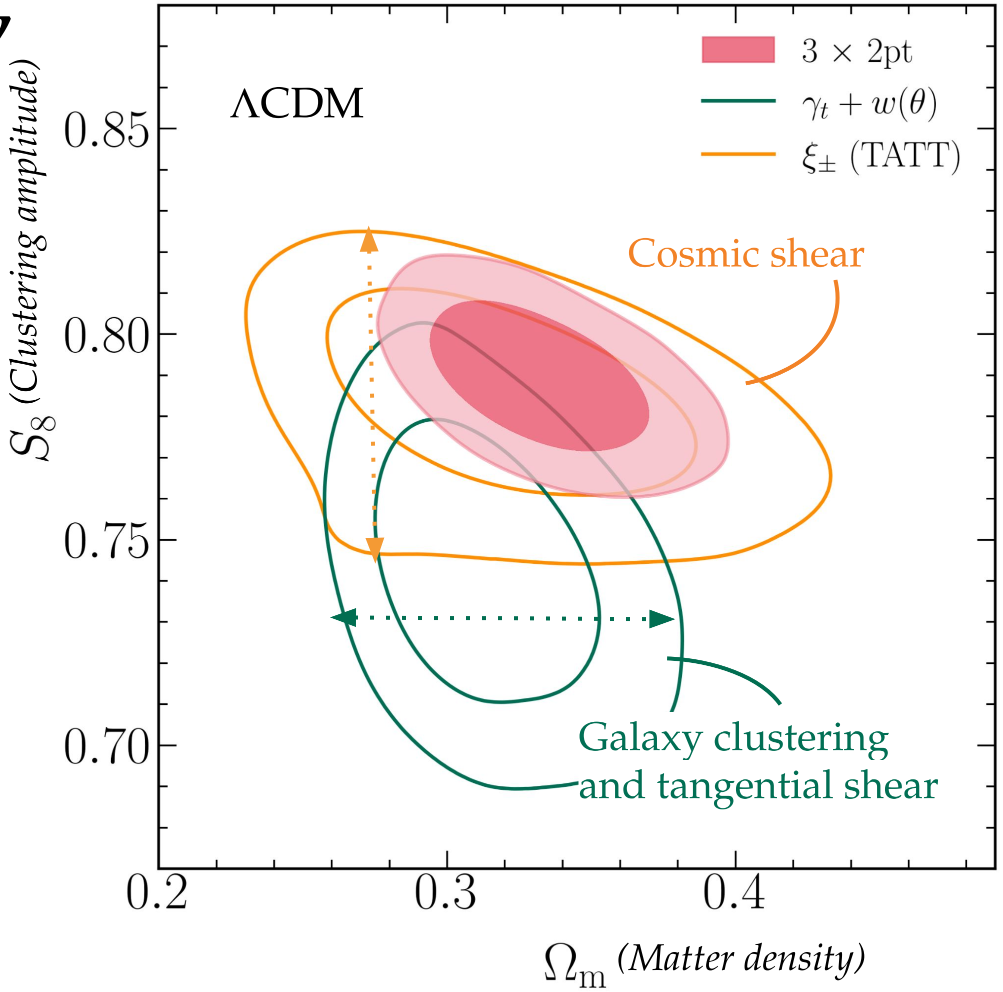
DES Y6 3x2pt cosmology

A factor of 2 improvement in FoM in this plane from DES Y3

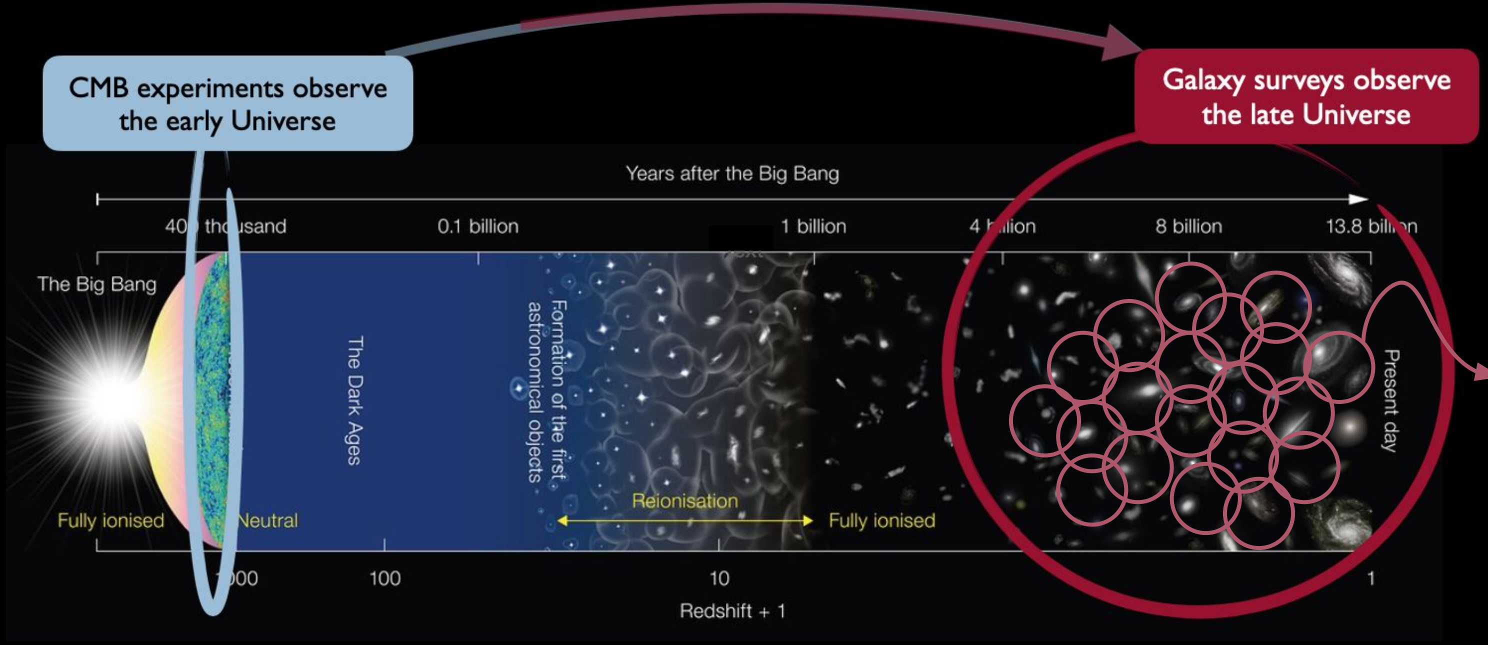
In ΛCDM:

$$S_8 = 0.789^{+0.012}_{-0.012}$$
$$\Omega_\mathrm{m} = 0.333^{+0.023}_{-0.028}$$
$$\sigma_8 = 0.751^{+0.034}_{-0.036}$$



J. Prat and M. Crocce

Can ΛCDM describe 13.8 billion years of cosmic history?



Spheres with radius 8 Mpc/h

As: Amplitude of primordial scalar density fluctuations

Image credit: NAOJ

σ_8 : Amplitude of mass fluctuations today

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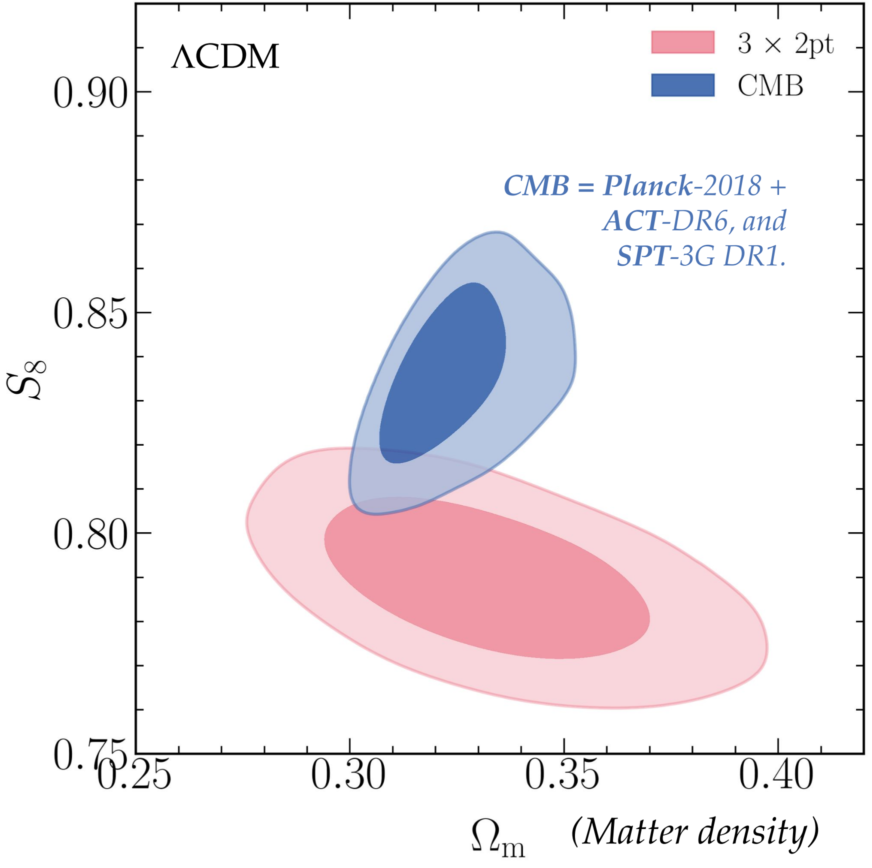
DES Y6 3x2pt cosmology vs CMB in ΛCDM

Y6 3x2pt yields similar constraining power as the CMB on the S8 direction (clustering amplitude).



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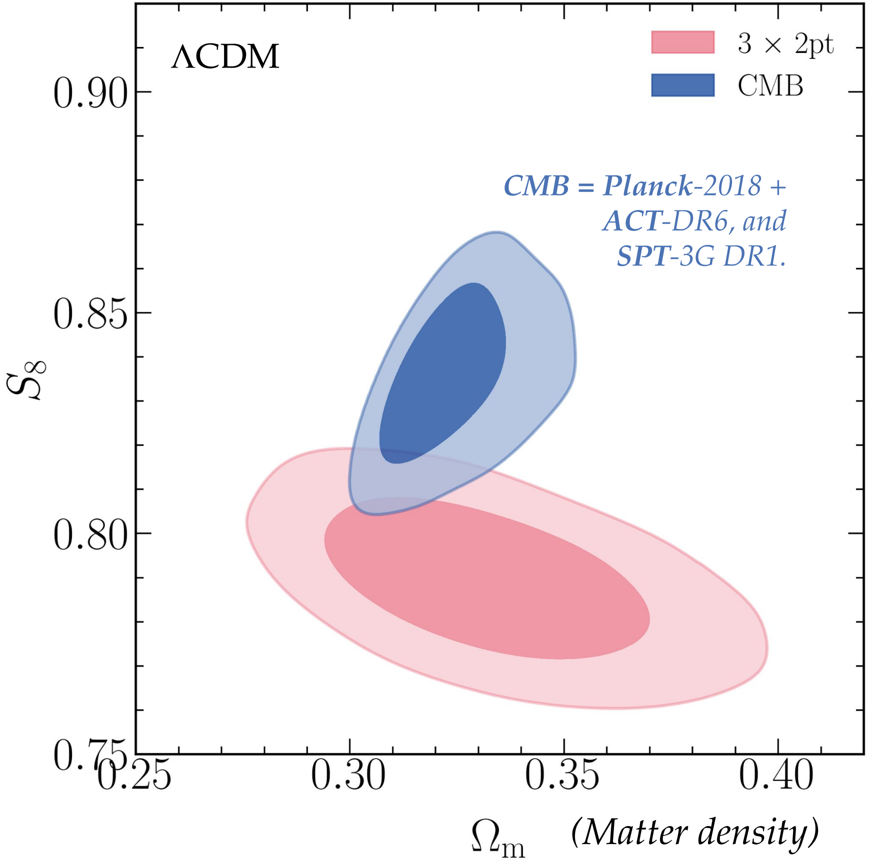
DES Y6 3x2pt cosmology vs CMB in ΛCDM

Y6 3x2pt yields similar constraining power as the CMB on the S_8 direction (clustering amplitude).

Full-parameter difference between 3×2pt and CMB is **1.8σ.**



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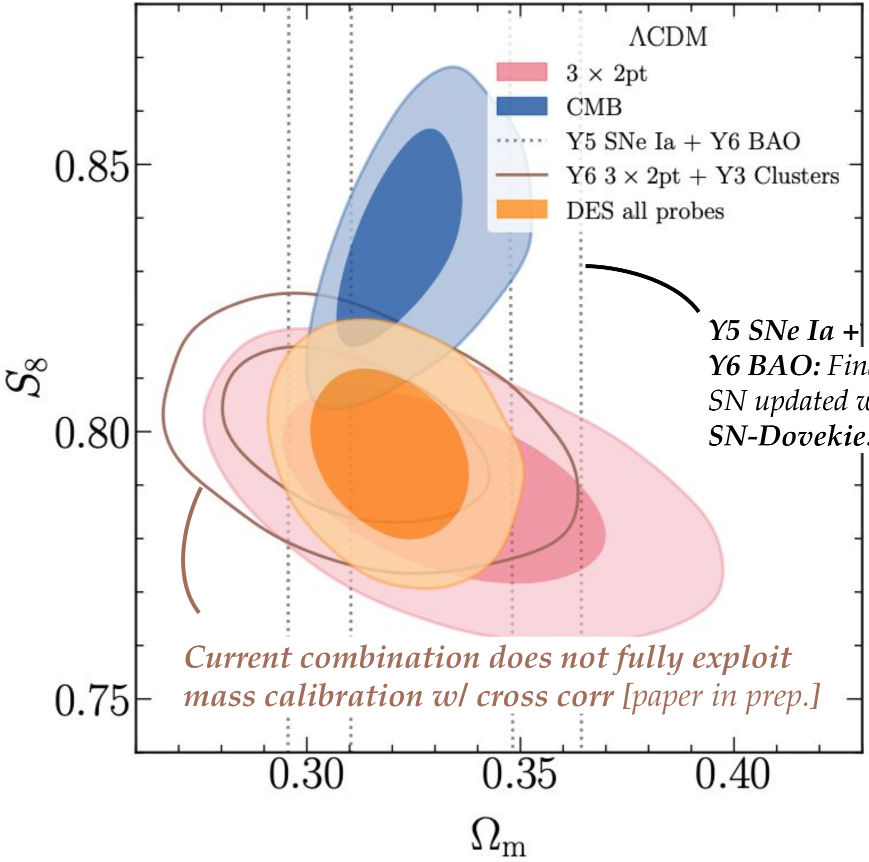
DES dark-energy probes combined: *3x2pt, BAO, SN, Clusters*

All four probes are fully consistent.



Y5 SNe Ia + Y6 BAO: *Final, SN updated with* ***SN-Dovekie****.*

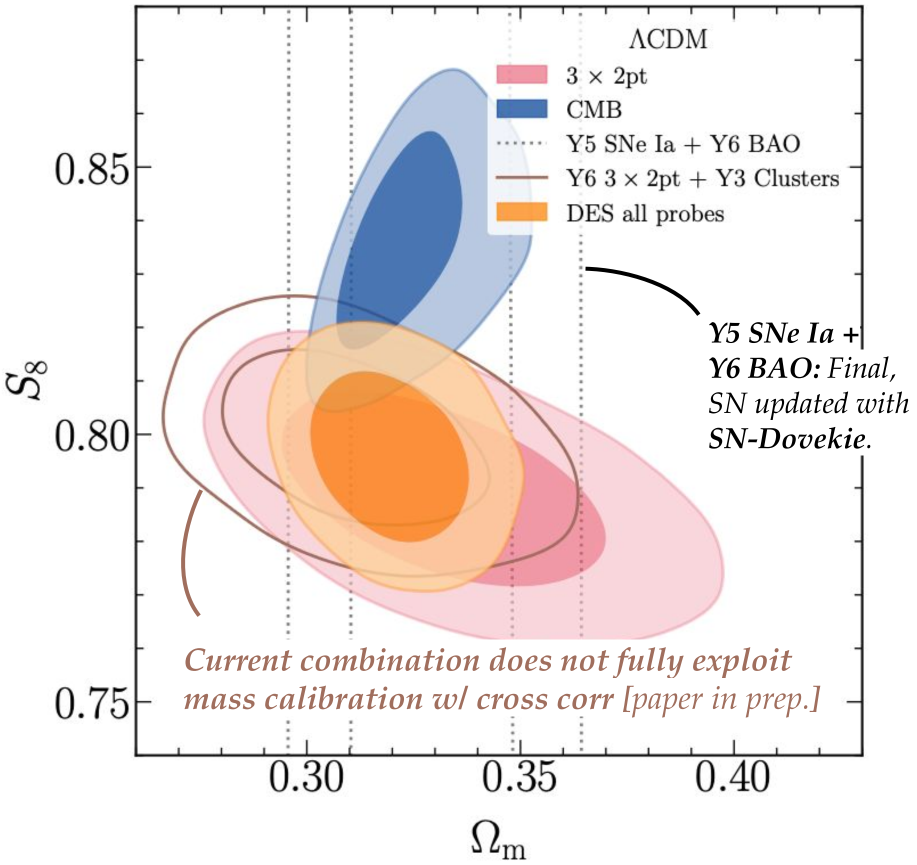
Current combination does not fully exploit mass calibration w/ cross corr *[paper in prep.]*

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**.



J. Prat and M. Crocce

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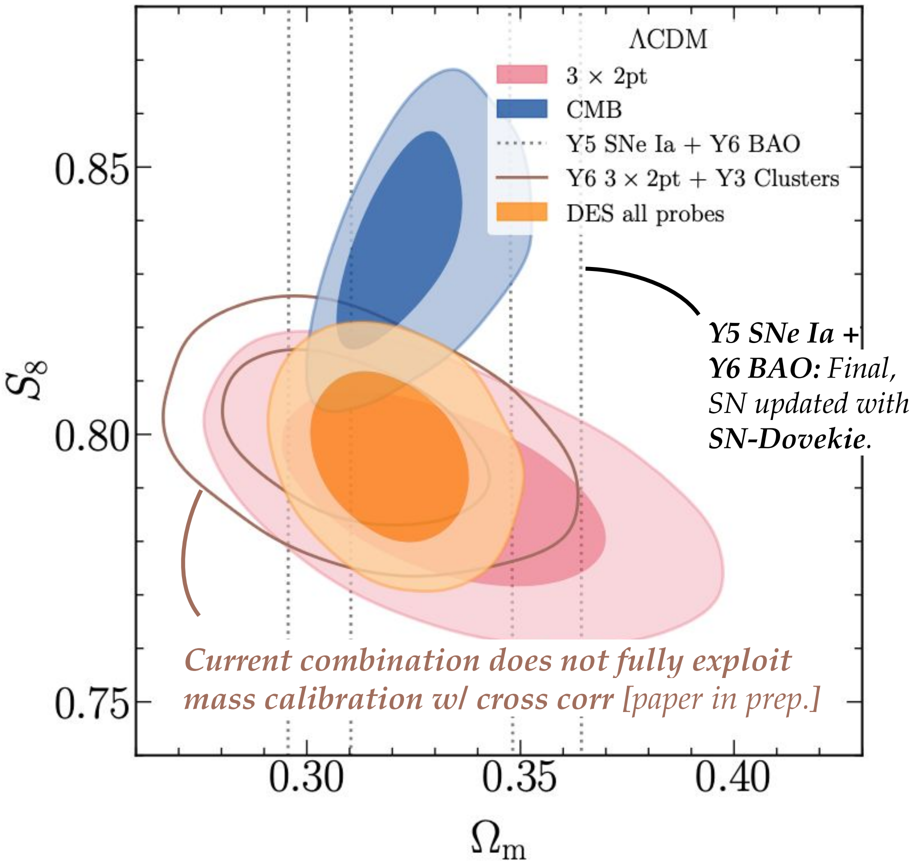
DES all-probes has similar constraining power as CMB in both S_8 and Ω_m.



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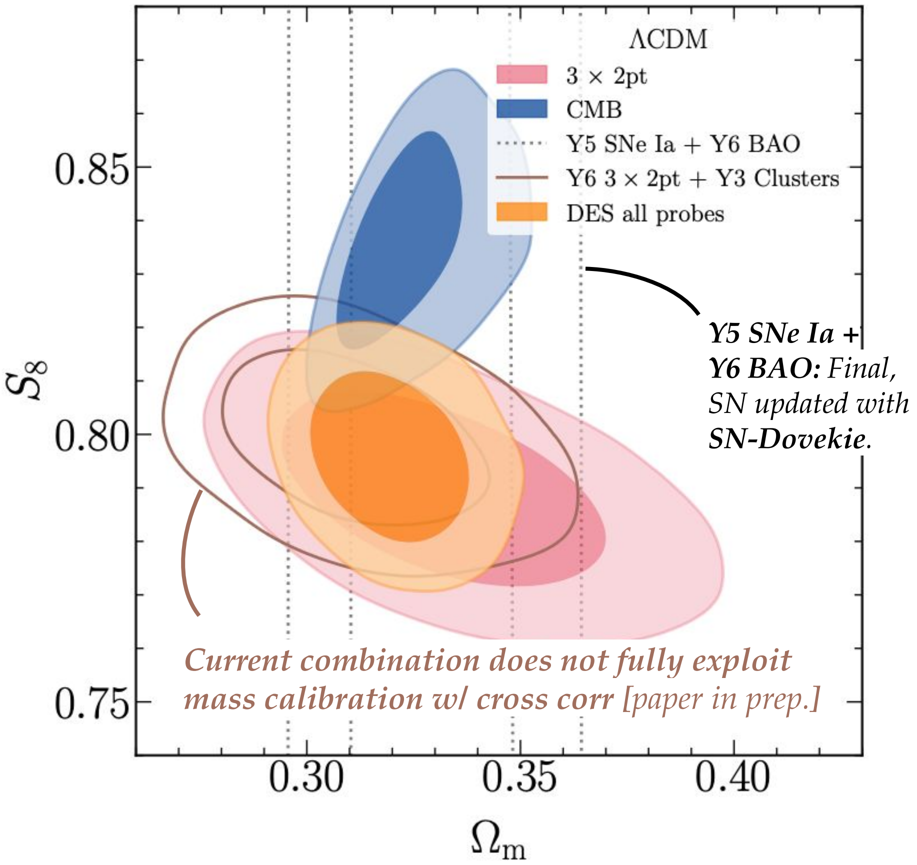
DES all-probes has similar constraining power as CMB in both S_8 and Ω_m.

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



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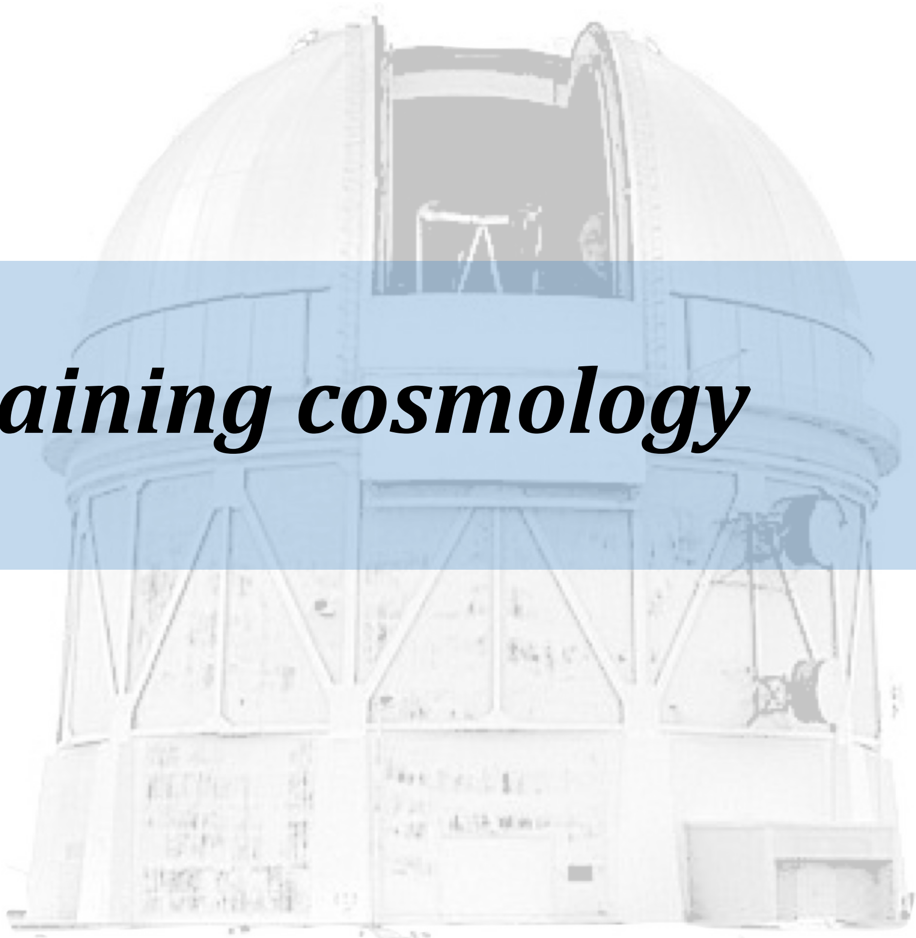
Most constraining cosmology

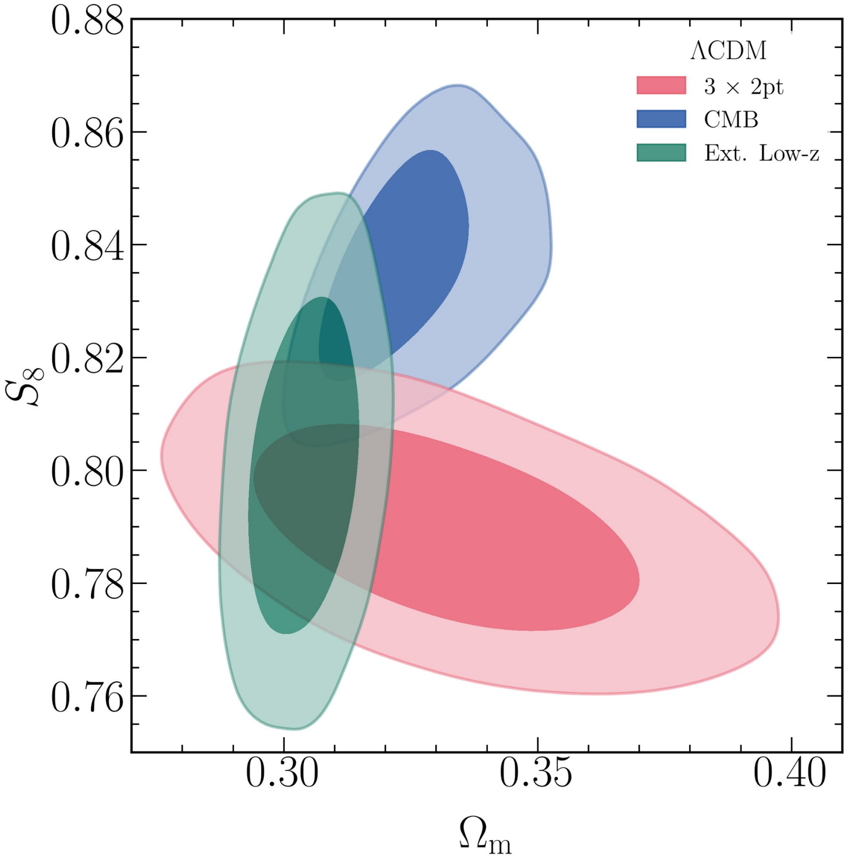


Comparison with best external probes

We constructed three independent data sets:

1. Weak lensing and clustering from DES Y6 (**3x2pt**)
2. SNIa from DES Y5
   + BAO from DESI DR2 + DES excl. DESI
   + Clusters abundance from SPT
   → **Ext. Low-z**
3. **CMB**

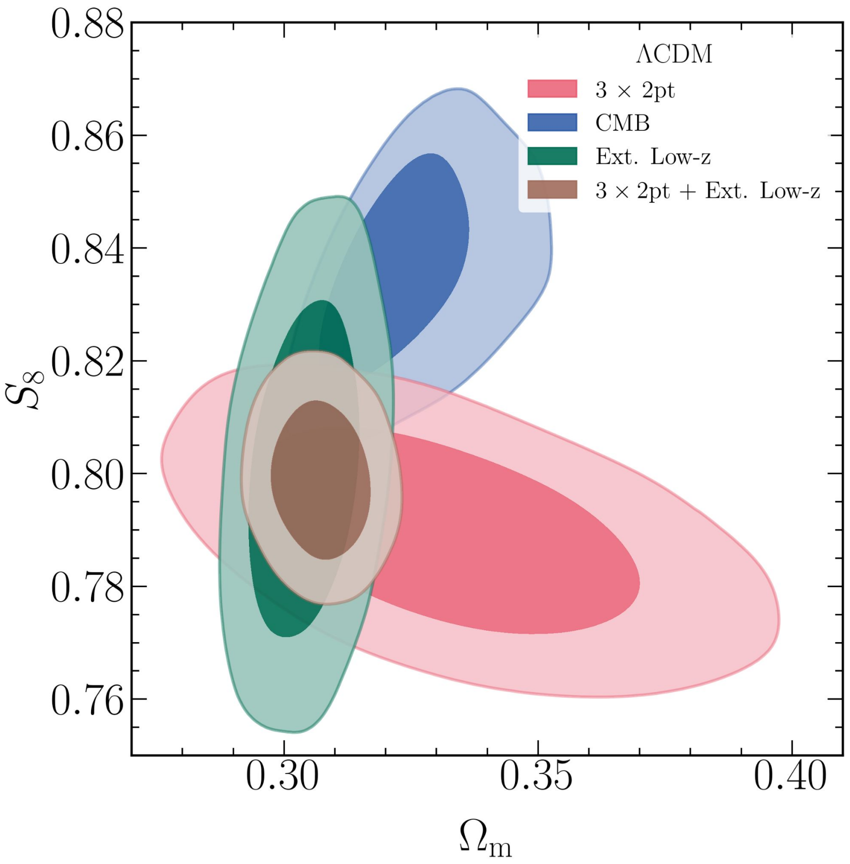
These are highly complementary.



Combination with external probes: Low-z vs CMB

DES Y6 3x2pt + Ext. Low-z has a parameter difference with respect to CMB of **2.3σ** in **ΛCDM and 2.4σ** in **wCDM**.

This represents our best understanding of the two models from the late and early universe.



Joint cosmological constraints in ΛCDM

DES Y6 3×2pt + Ext. Low-*z* + CMB yield the **tightest joint constraint** from major cosmic surveys **on ΛCDM to date**.

$$S_8 = 0.806^{+0.006}_{-0.007}$$

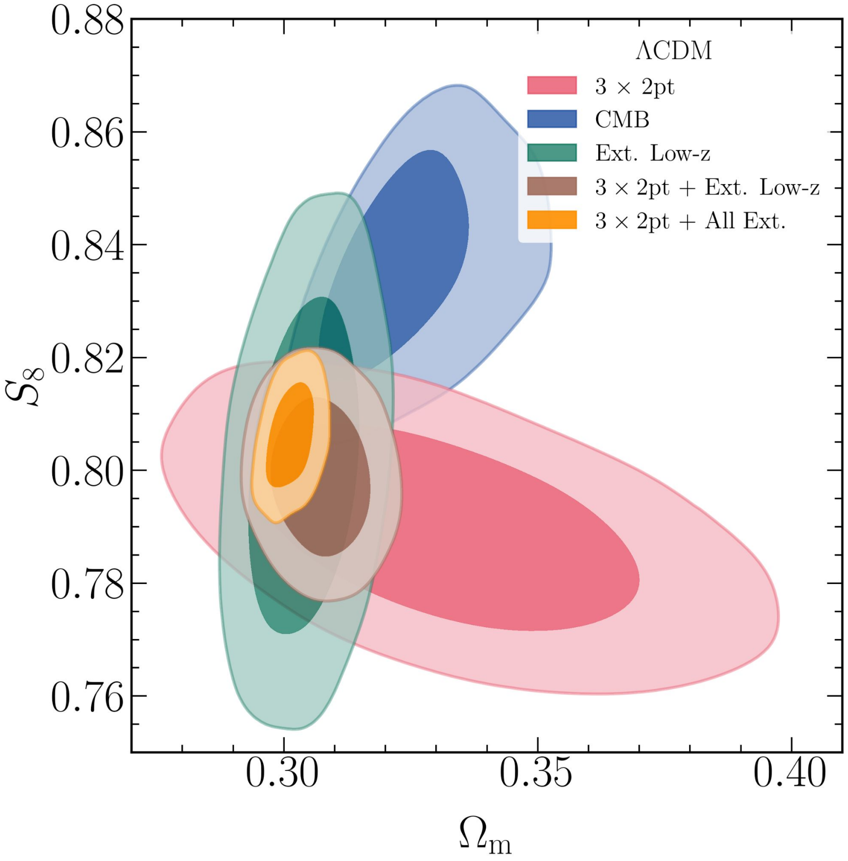
$$\Omega_\mathrm{m} = 0.302^{+0.003}_{-0.003}$$

$$\sigma_8 = 0.804^{+0.007}_{-0.006}$$

$$h = 0.683^{+0.003}_{-0.002}$$

$$\Omega_\mathrm{b} \times 10^2 = 4.83^{+0.03}_{-0.04}$$

$$\sum m_\nu < 0.14\,\mathrm{eV}\,(95\%\ \mathrm{CL})$$



Joint cosmological constraints in w0waCDM

From the best-available data sets to date:

$$w_0 = -0.82 \pm 0.05$$

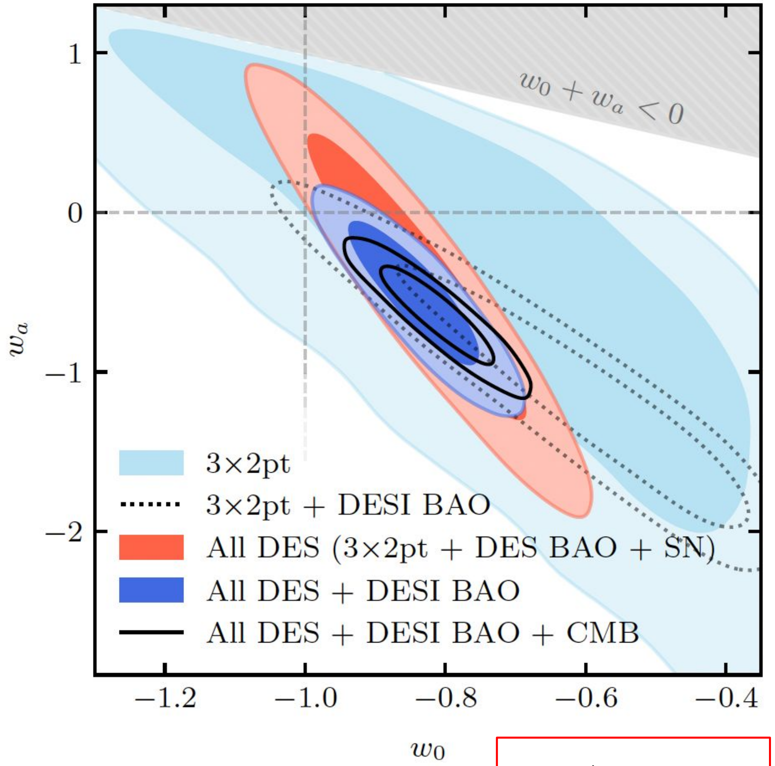
$$w_a = -0.63^{+0.21}_{-0.18}$$

$$\Omega_\mathrm{m} = 0.311 \pm 0.005$$

$$S_8 = 0.823 \pm 0.008$$

All DES is **2.2σ** away from ΛCDM.

All data is **3.0σ** away from ΛCDM.



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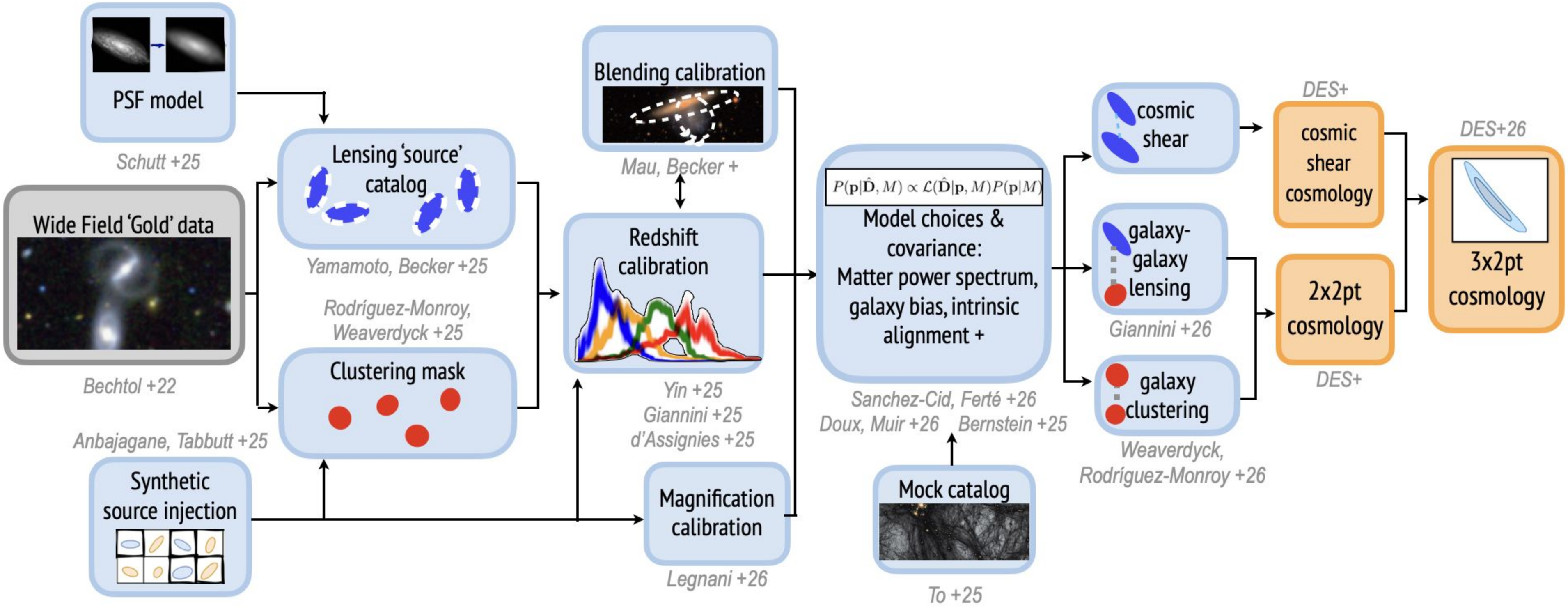
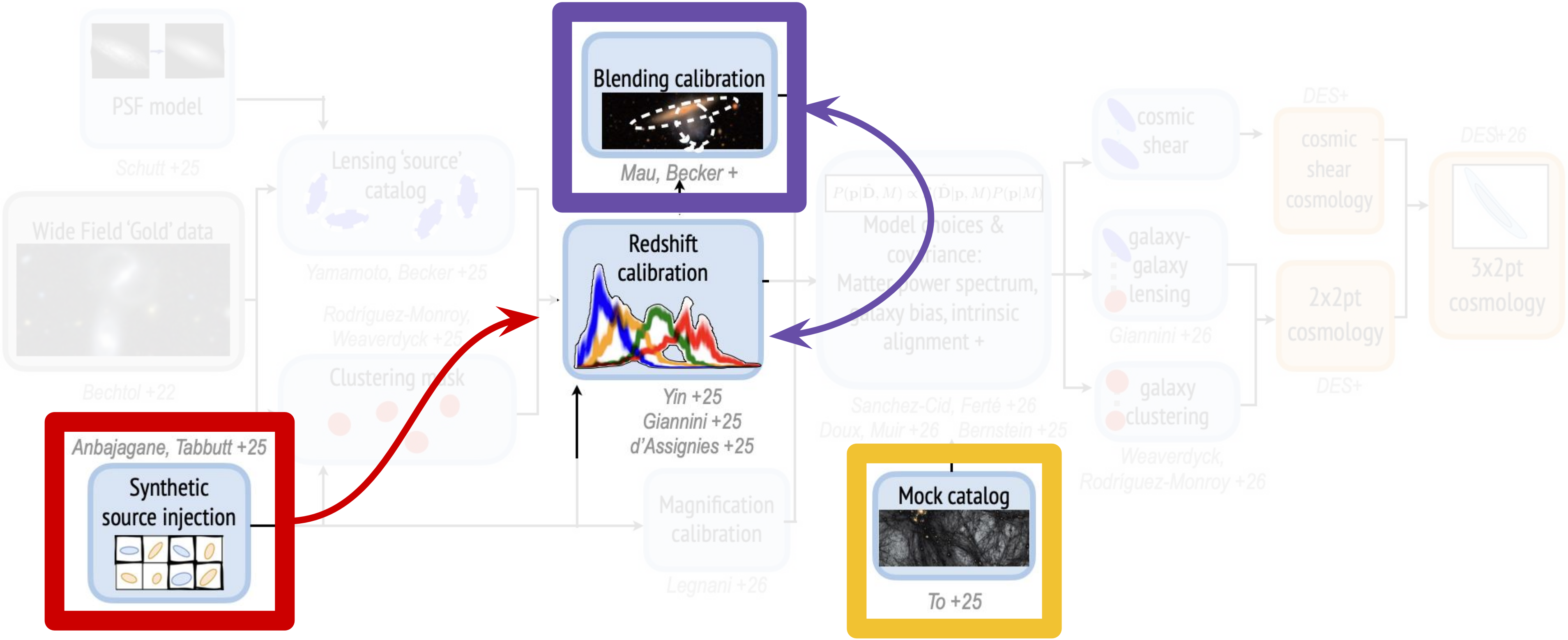
What Goes Into a Cosmology Result?

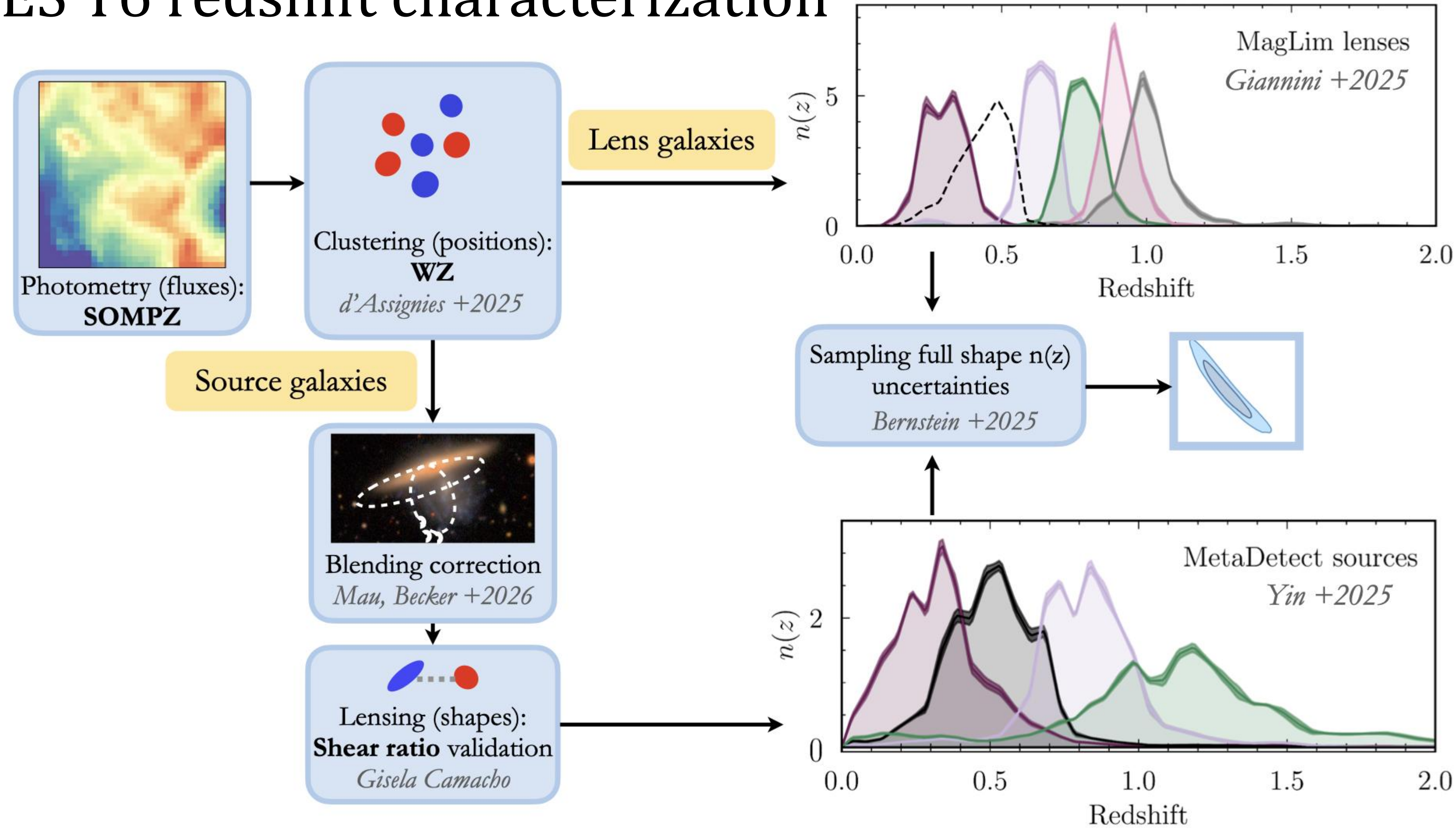


A. Amon

Redshift and Shear calibration

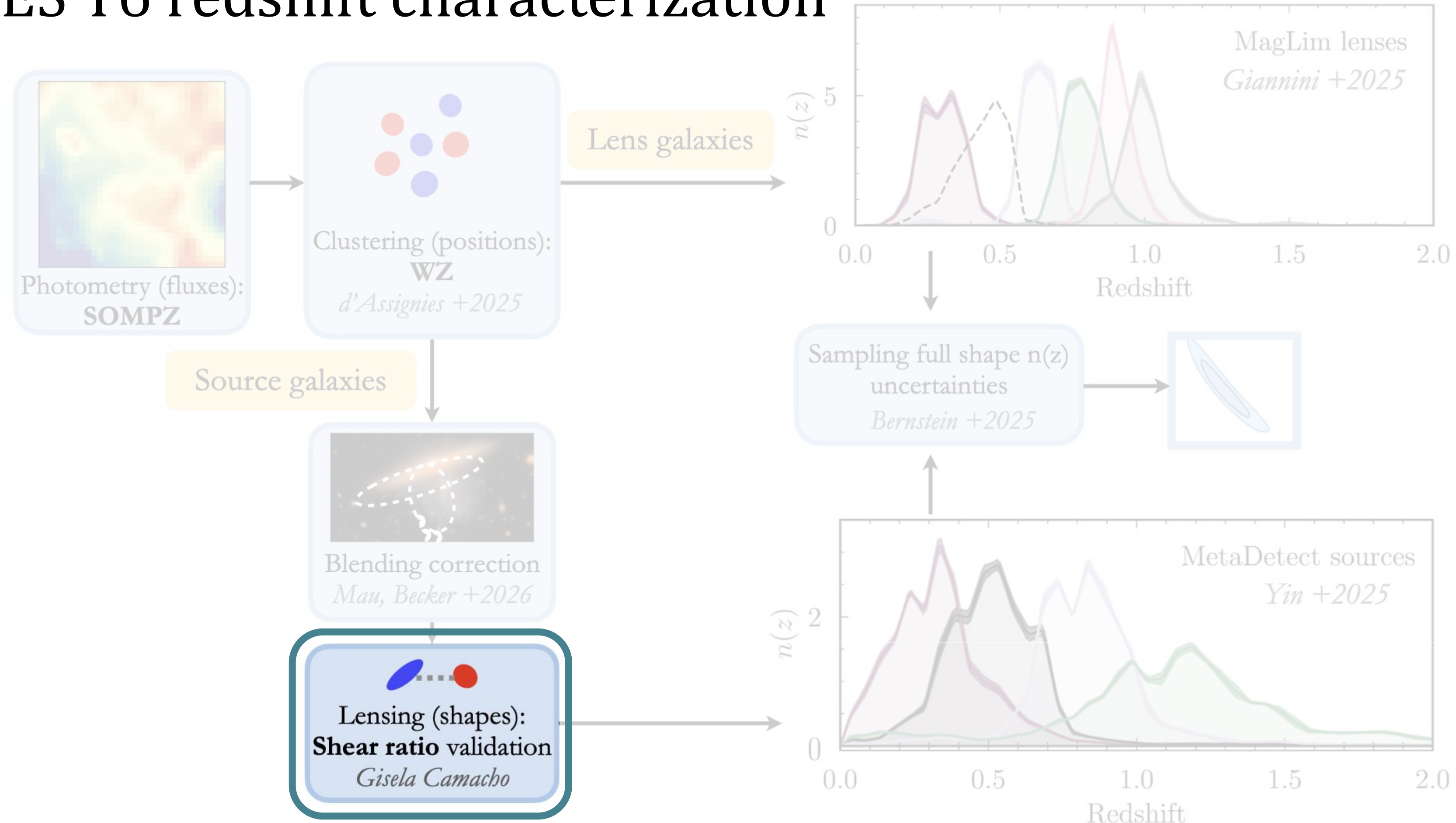


DES Y6 redshift characterization



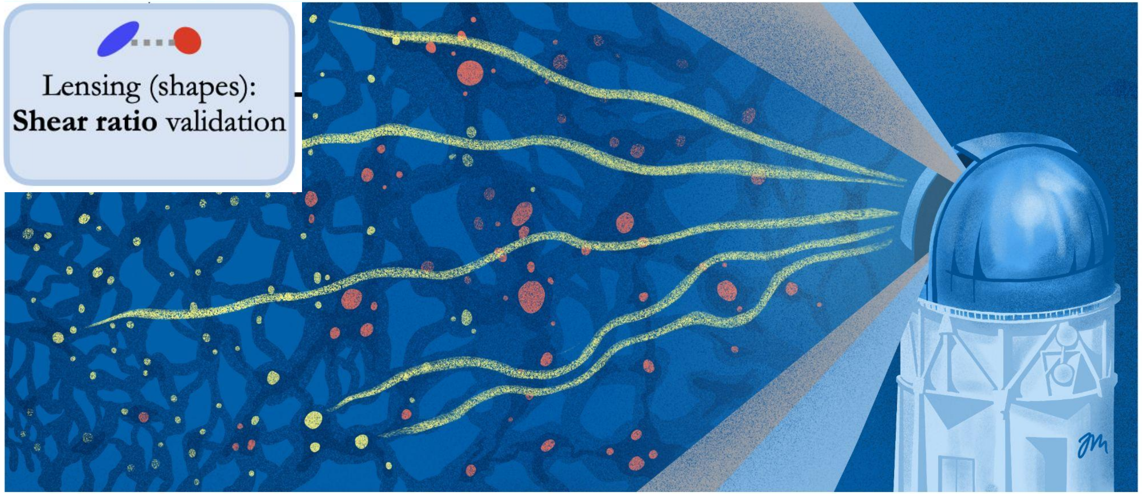
B. Yin

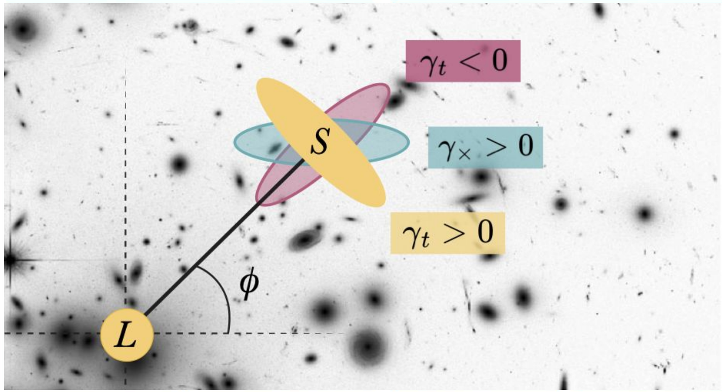
DES Y6 redshift characterization

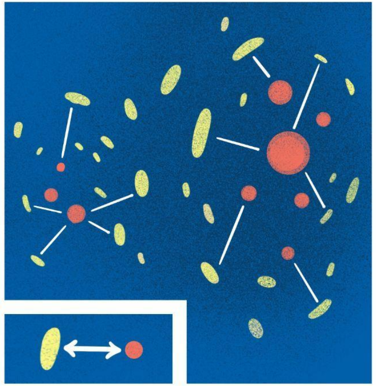


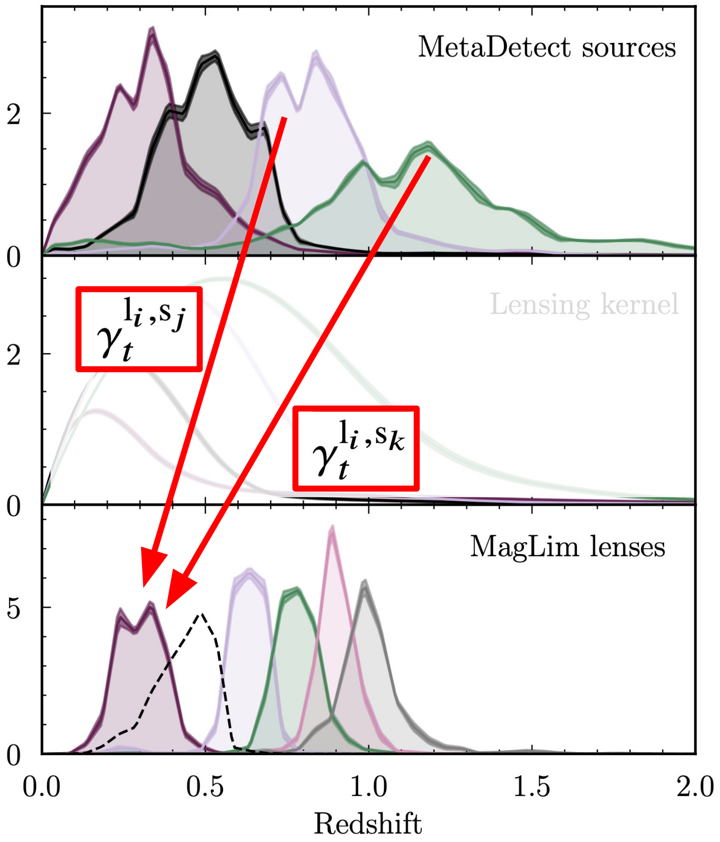
Dark Energy Survey Y6: Shear Ratios

DESY6 GGL: 2601.15175









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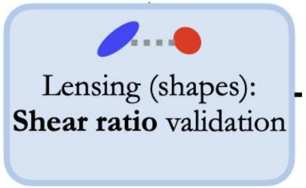
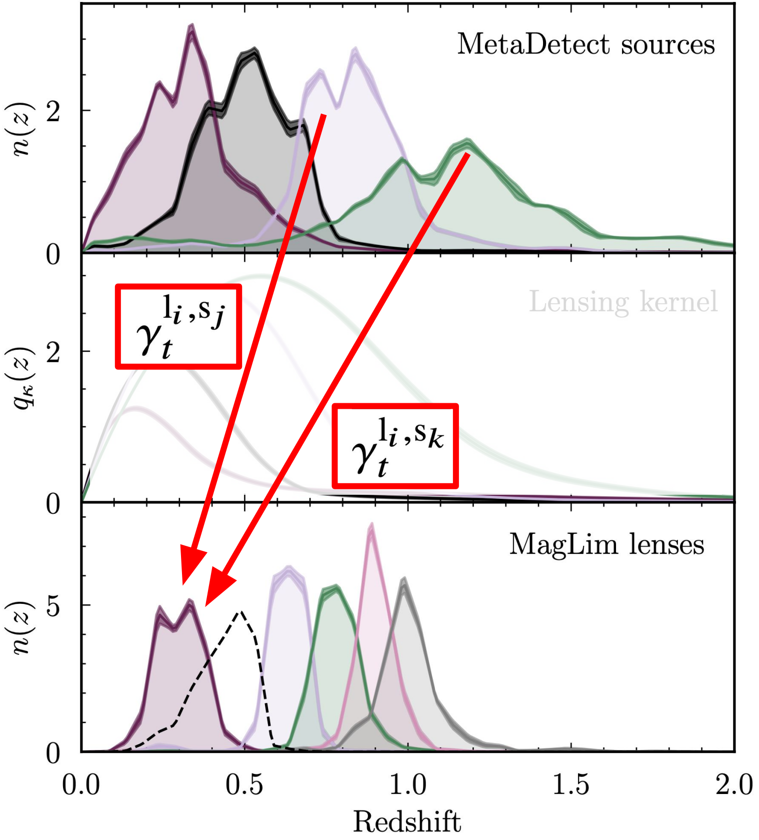


$$\gamma_t(\theta) = \frac{\Delta\Sigma(\theta)}{\Sigma_{\rm crit}}$$

excess surface mass density

$$\Sigma_{\rm crit}^{-1}(z_{\rm l}, z_{\rm s}) = \frac{4\pi G}{c^2}\frac{D_{ls}\,D_l}{D_s}$$



Dark Energy Survey Y6: Shear Ratios

DESY6 GGL: 2601.15175

Lensing (shapes):
Shear ratio validation

What is Shear Ratio (SR)?

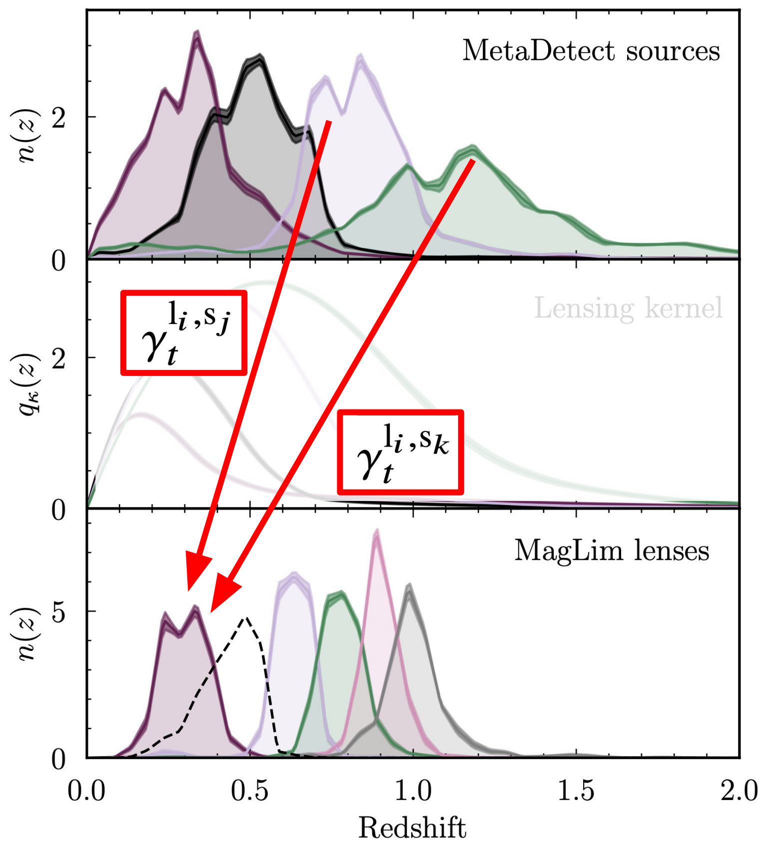
Ratio between two galaxy-galaxy lensing (lensing position x source shape) **using the same lens and different sources**

$$\gamma_t(\theta) = \frac{\Delta\Sigma(\theta)}{\Sigma_{\text{crit}}}$$

excess surface mass density

$$\Sigma_{\text{crit}}^{-1}(z_{\text{l}}, z_{\text{s}}) = \frac{4\pi G}{c^2}\frac{D_{ls}\,D_l}{D_s}$$

$$\text{SR} \longrightarrow \frac{\gamma_t^{\text{l}_i,\text{s}_j}}{\gamma_t^{\text{l}_i,\text{s}_k}} = \frac{\Sigma_{\text{crit}}^{-1}(z_{\text{l}_i}, z_{\text{s}_j})}{\Sigma_{\text{crit}}^{-1}(z_{\text{l}_i}, z_{\text{s}_k})}$$



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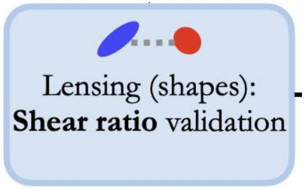
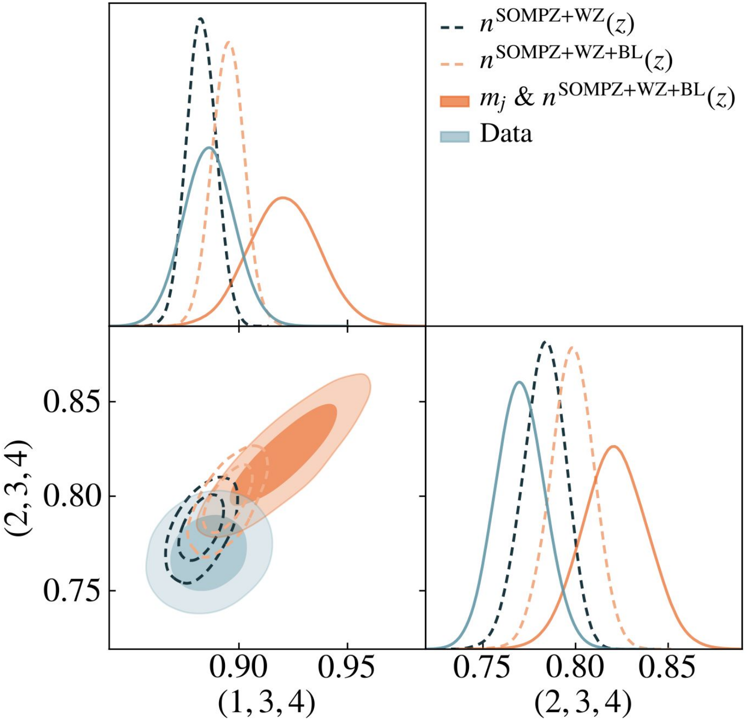
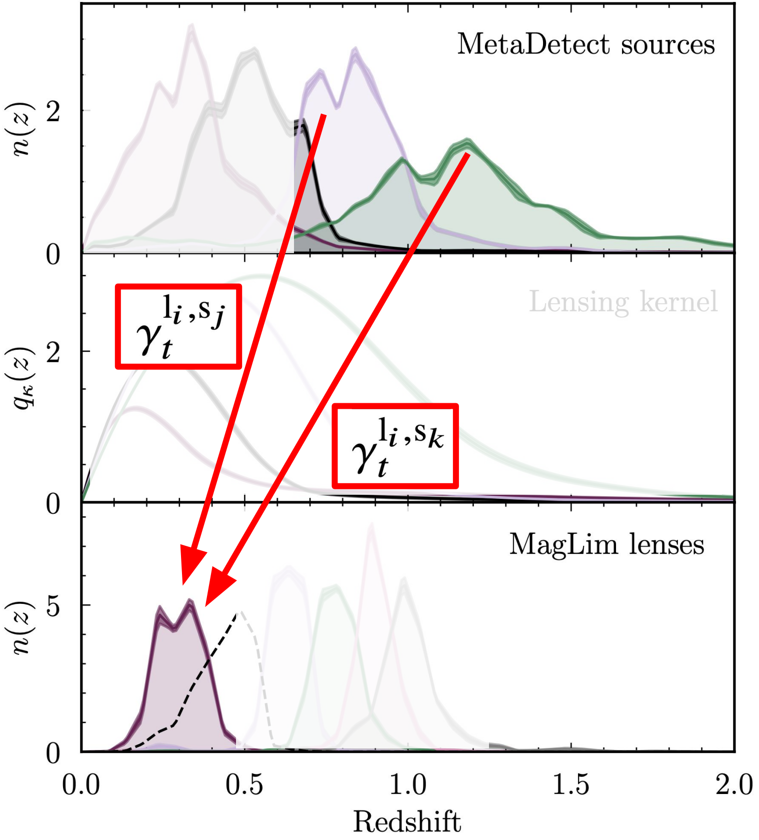


Shear ratios: Redshift+Shear calibration

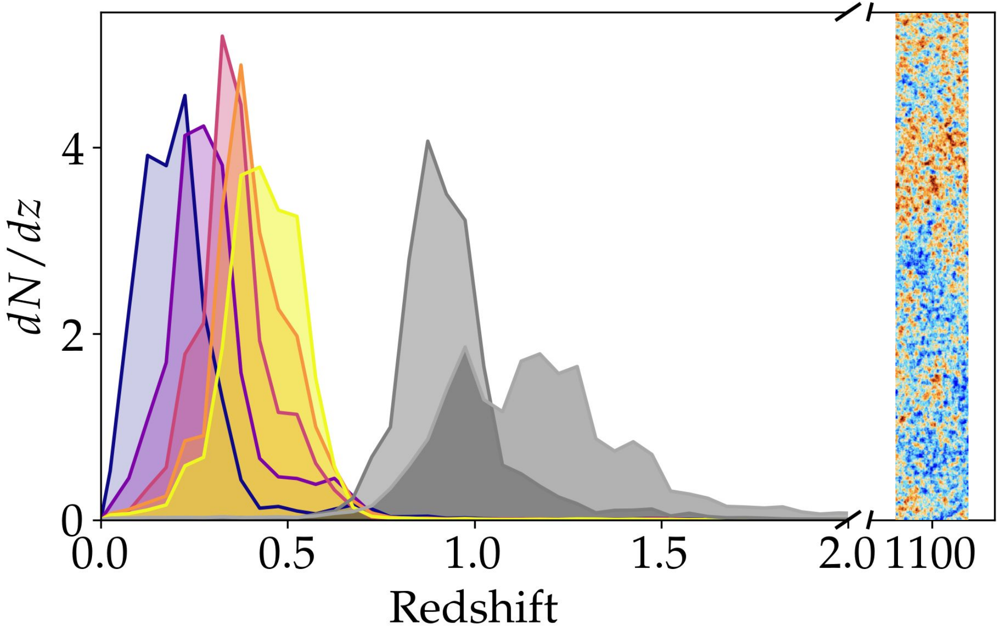




What more can shear/lensing ratios offer?

Lensing Ratios: Towards Cosmology

What more can shear/lensing ratios offer?

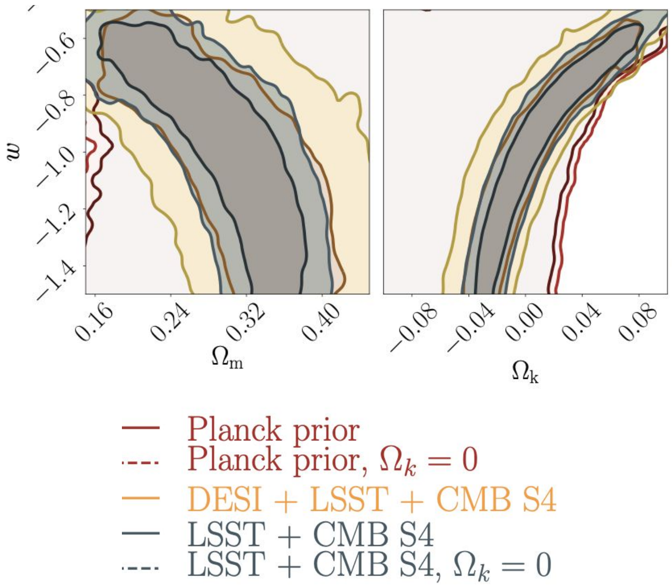


Currently using DESY6 galaxies + CMB lensing from ACT to obtain cosmological constraints with shear ratios.

Collaborators: C. Sanchez, J. Prat, M. Gatti + DES

Lensing Ratios: Towards Cosmology

Previous forecasting for LSST and Simons Observatory



From Prat+18 (1810.02212)

Collaborators: C. Sanchez, J. Prat, M. Gatti + DES

Lensing Ratios: Towards Cosmology

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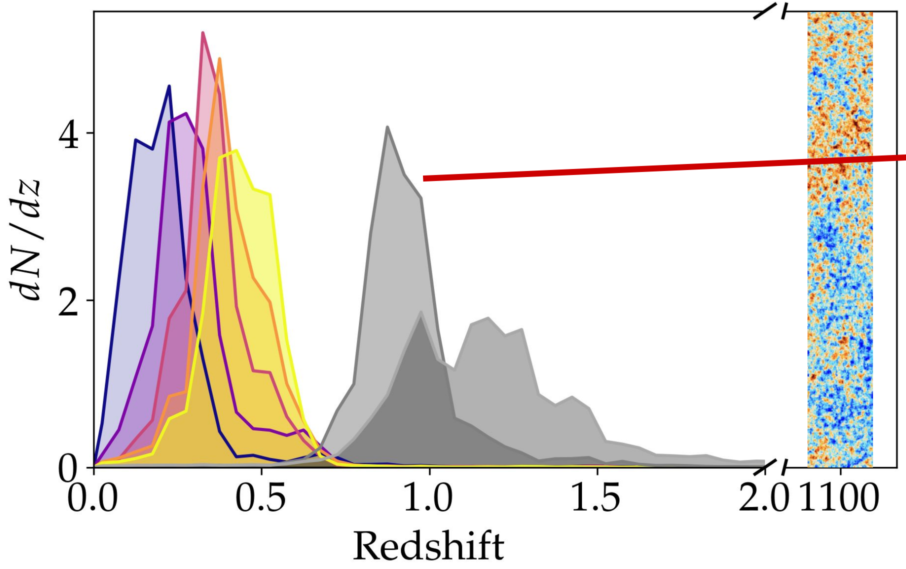

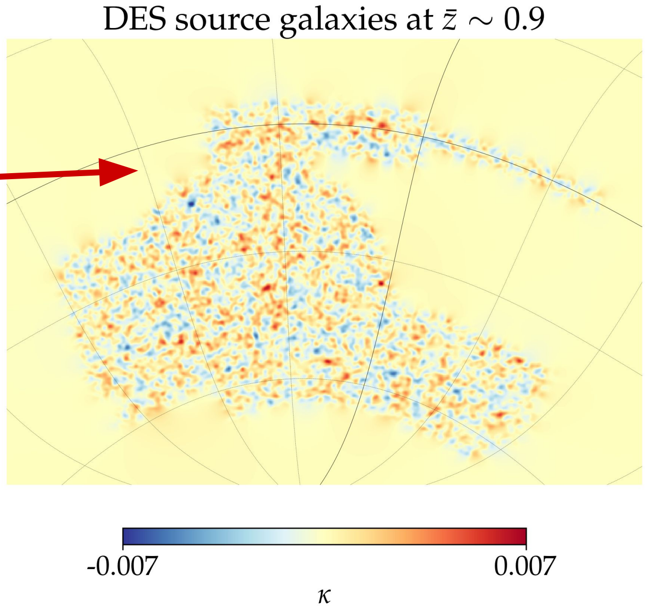

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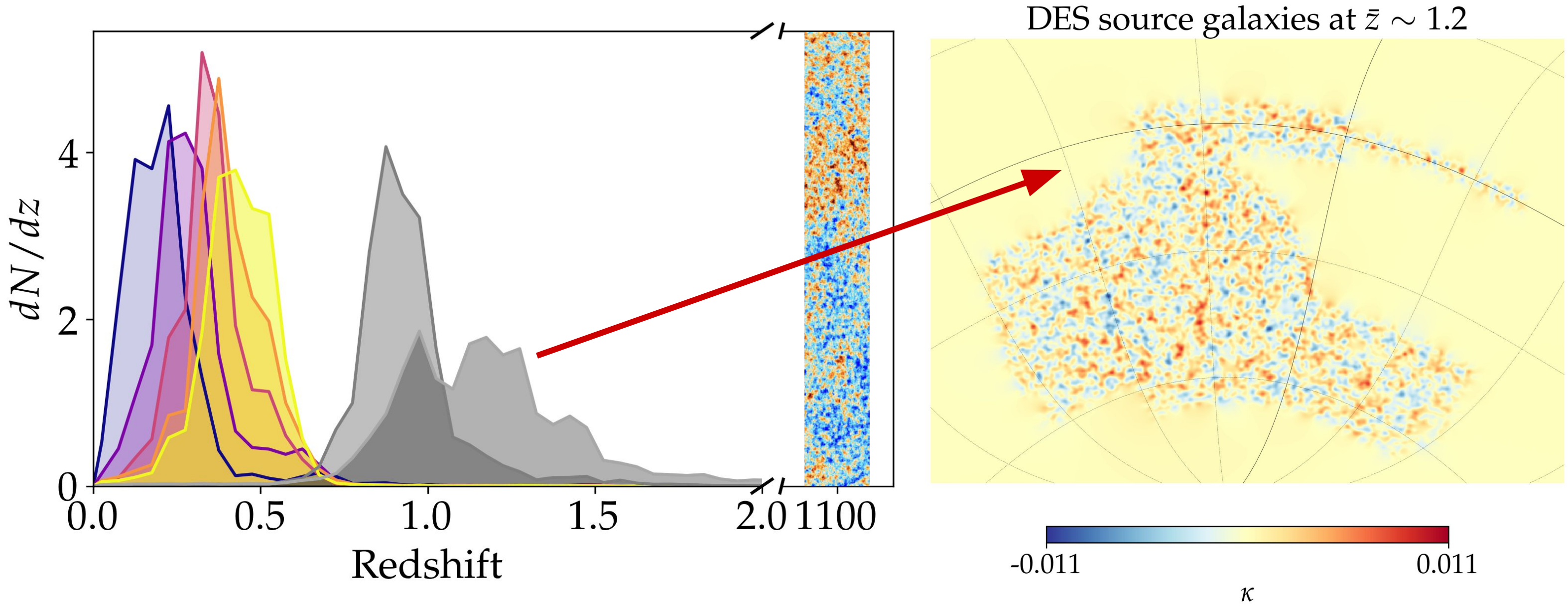

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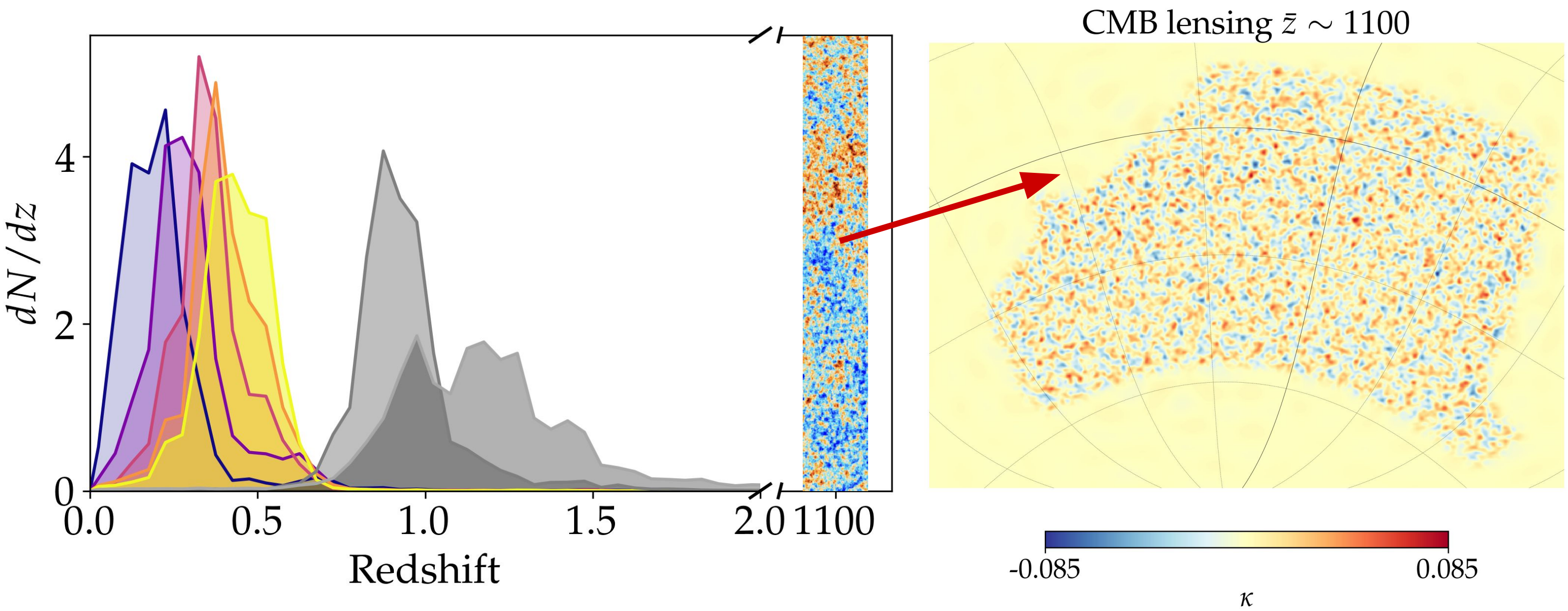

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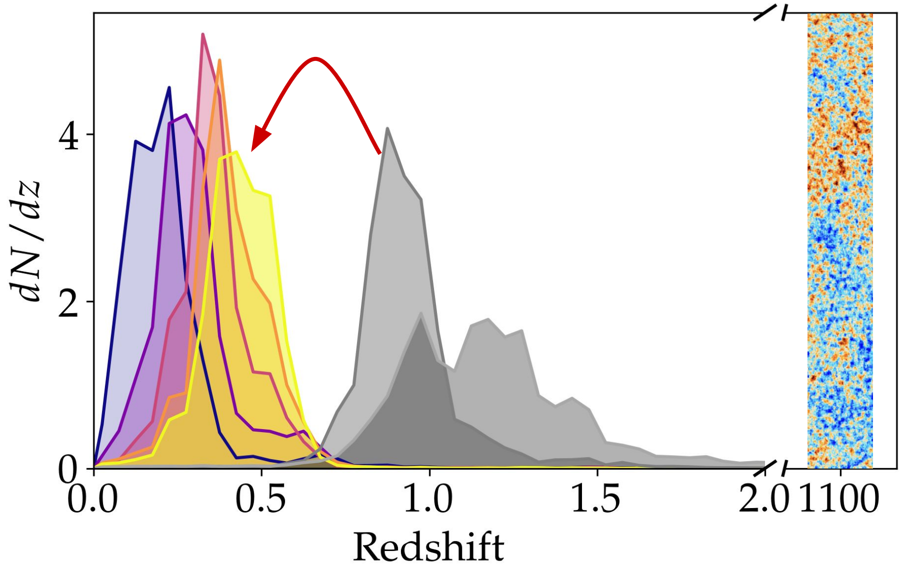
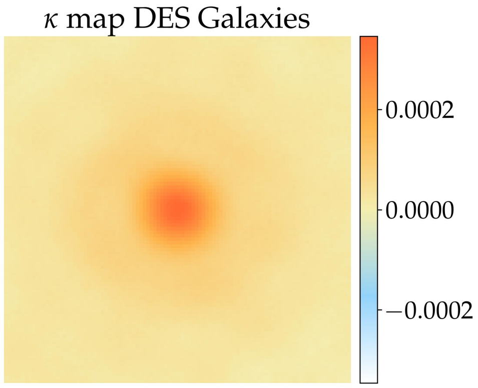
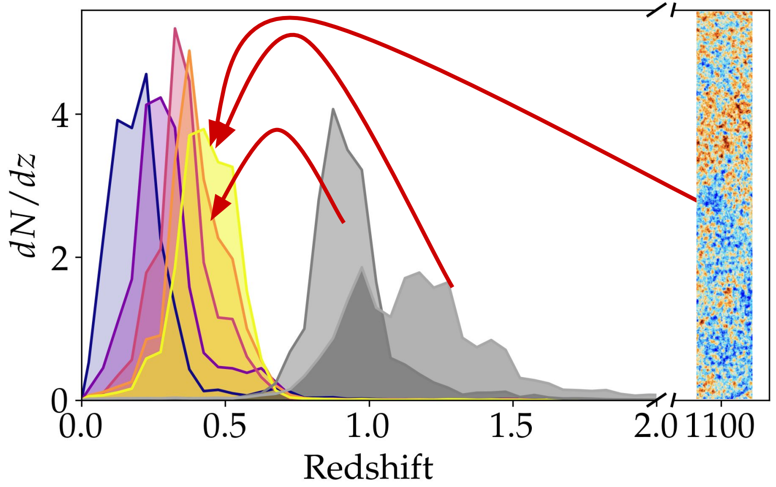




Collaborators: C. Sanchez, J. Prat, M. Gatti + DES

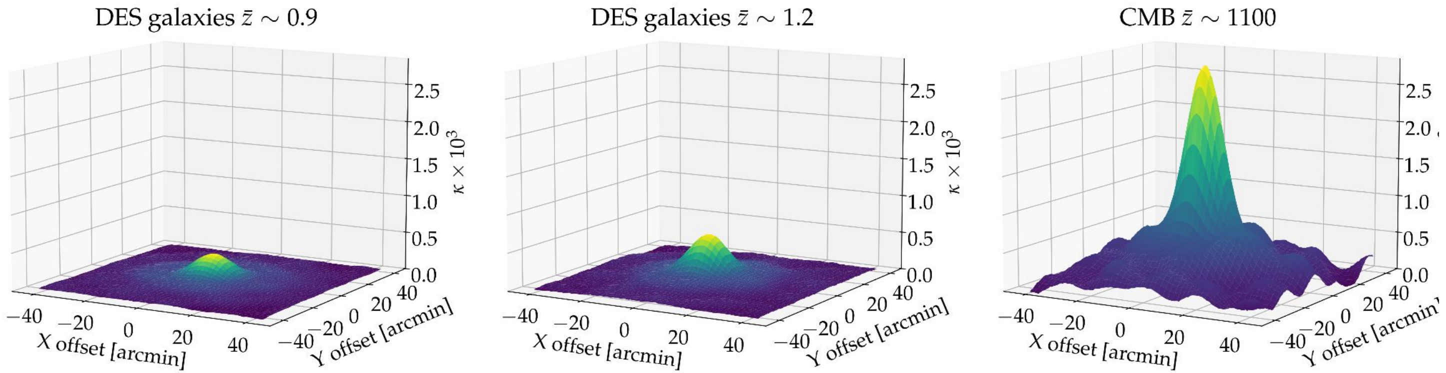
Lensing Ratios: Towards Cosmology



$$\frac{w^{g\kappa_{s_1}}(\theta)}{w^{g\kappa_{s_2}}(\theta)} = \frac{\Sigma_{gm}(R)/\Sigma_{\mathrm{crit}}(z_l, z_{s_1})}{\Sigma_{gm}(R)/\Sigma_{\mathrm{crit}}(z_l, z_{s_2})} = \frac{\Sigma_{\mathrm{crit}}(z_l, z_{s_2})}{\Sigma_{\mathrm{crit}}(z_l, z_{s_1})}$$

The relative heights of the stacked κ profiles encode the geometric information and cosmology!

κ map profiles around the same lens at $\bar{z} \sim 0.45$, different sources



Collaborators: C. Sanchez, J. Prat, M. Gatti + DES

Summary

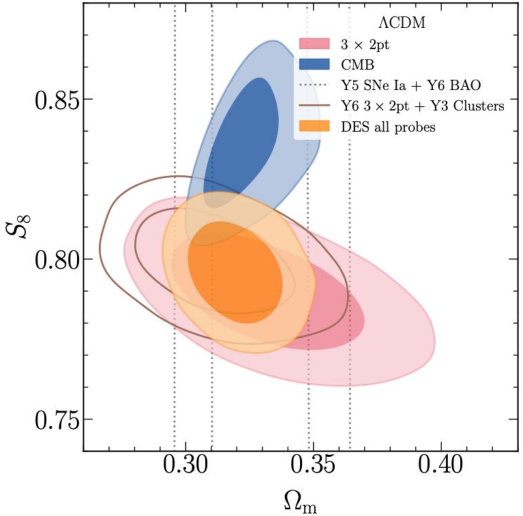
Novel methods and data leading to legacy cosmological results from the DES Y6.

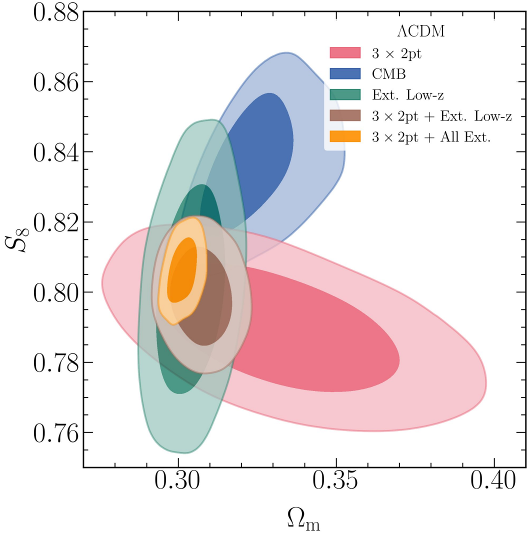
In Λ**CDM: no significant evidence for inconsistency** between DES and CMB, or between DES + other complementary low-redshift probes and CMB

First time **we combine all four DE probes** proposed at the DES inception: 3×2pt, BAO, SNIa and Clusters. Similar constraining power as CMB *in both* Ωm and S8.

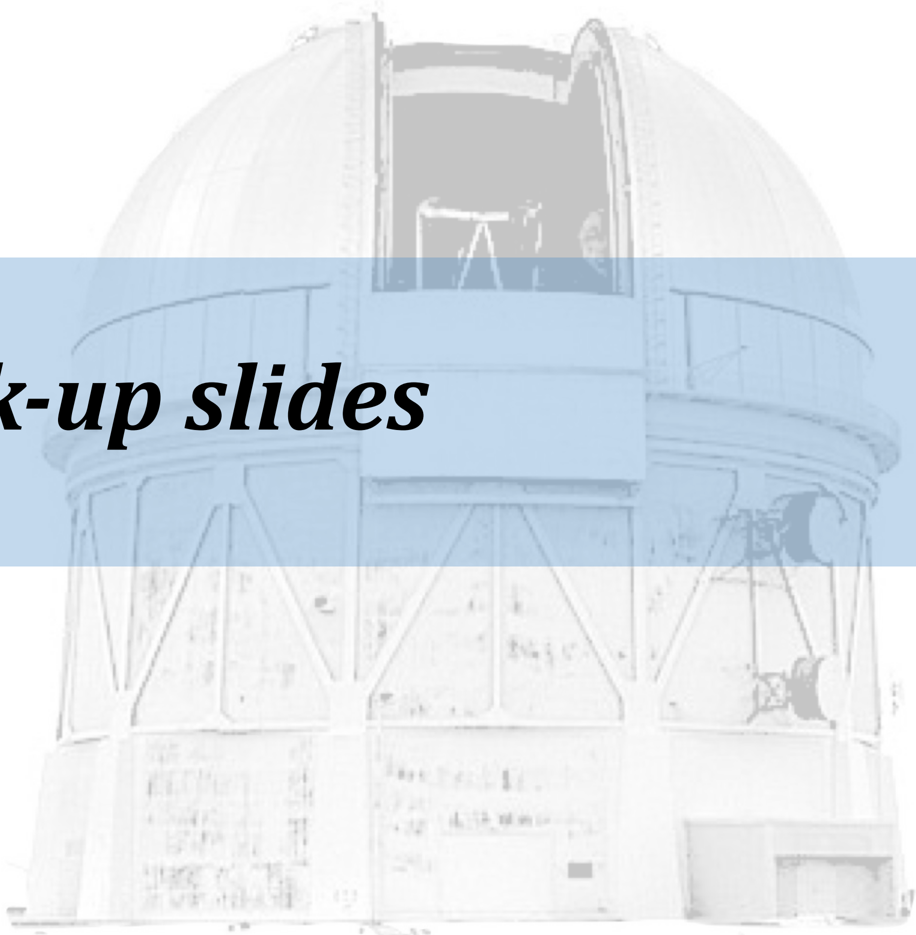
Lensing ratios are a promising lensing probe for dark energy cosmology.

Email: gcamacho@ice.csic.es





Back-up slides

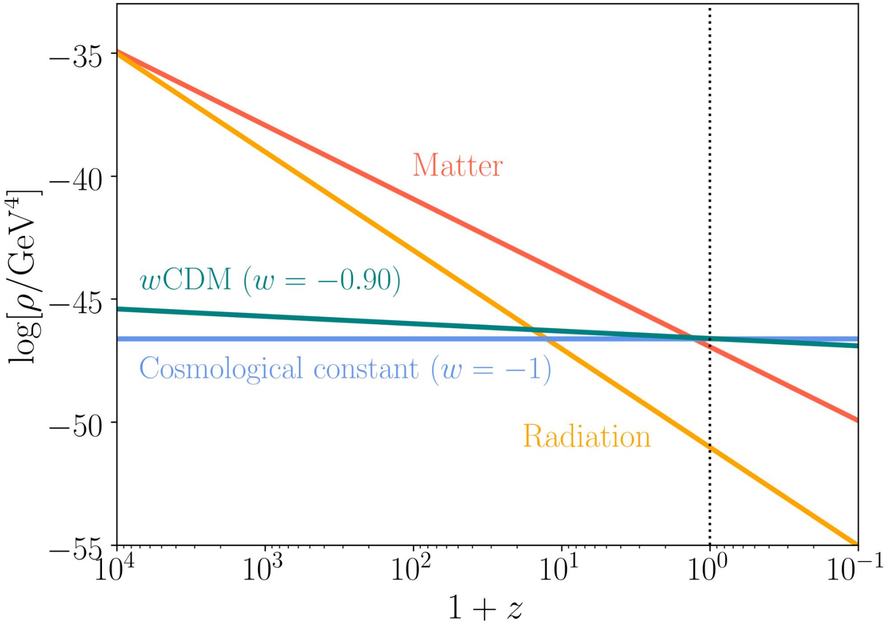


Alternatives to a cosmological constant: wCDM model

The dark energy component might not be a cosmological constant Λ

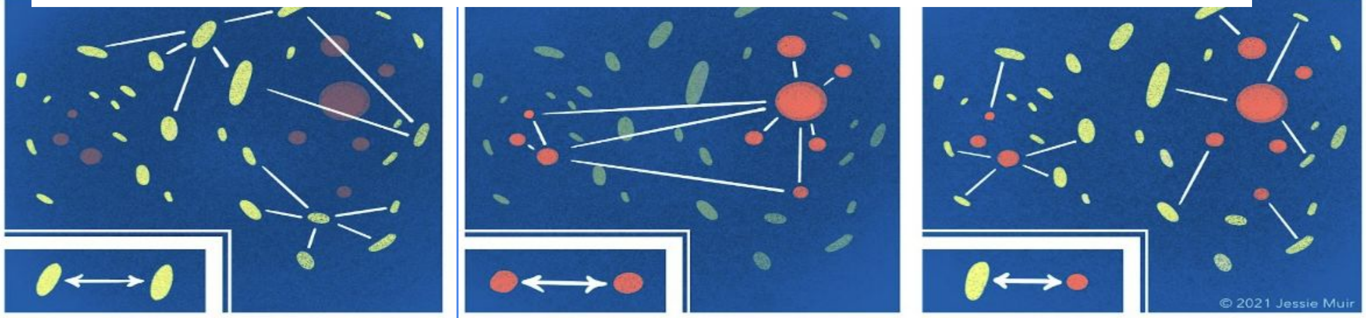
$$w \equiv \frac{\mathcal{P}}{\rho}$$

We can open up the parameter space to measure w, which defines the **equation of state** of dark energy



3x2 Cosmology

Drawing credit: J. Muir

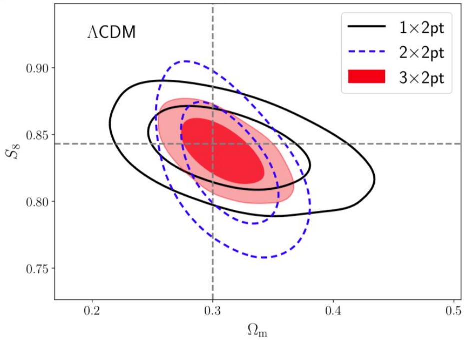


cosmic shear	galaxy clustering	galaxy-galaxy lensing
correlation in the shapes of (source) galaxies	correlation in the positions of (lens) galaxies	correlation between positions of the lenses and shapes of the sources
$\xi_\pm = \langle e_t(\theta')e_t(\theta'+\theta)\rangle - \langle e_x(\theta')e_x(\theta'+\theta)\rangle$	$w(\theta) = \langle \delta(\theta')\delta(\theta'+\theta)\rangle$	$\gamma_t(\theta) = \langle \delta(\theta')e_t(\theta'+\theta)\rangle$
$\propto \sigma_8^2$	$\propto b^2\sigma_8^2$	$\propto b\sigma_8^2$

1x2pt

2x2pt

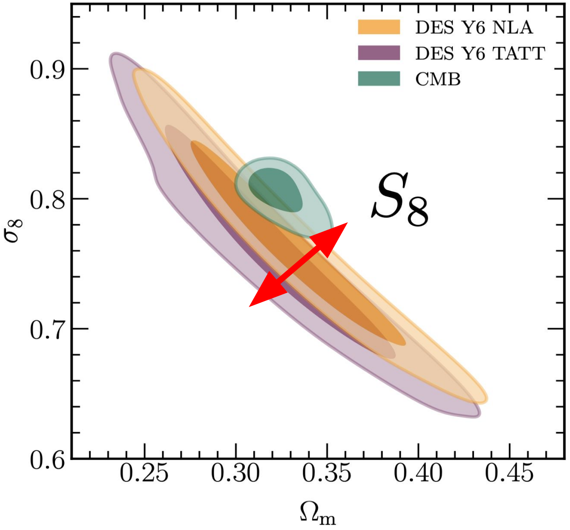
3x2pt



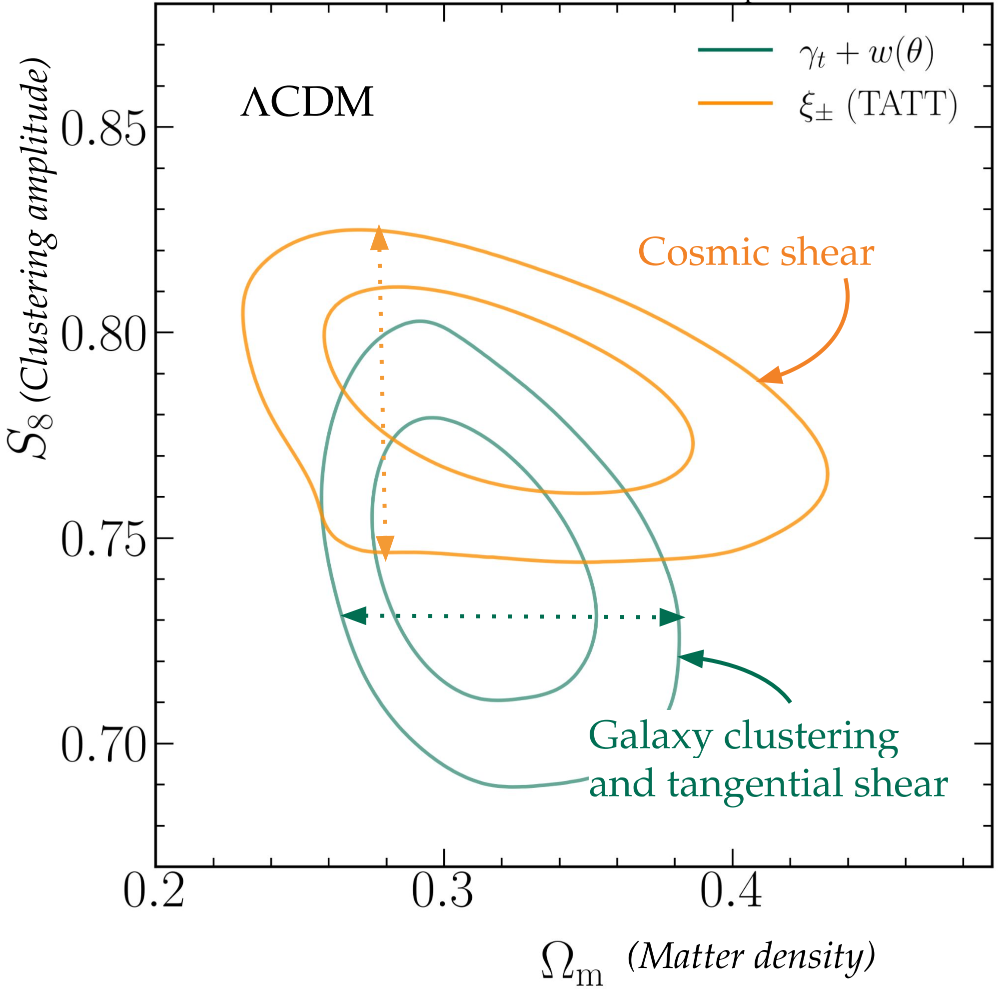
Slide credit: M. Crocce

DES Y6 3×2pt cosmology

$$\boxed{S_8 = \sigma_8(\Omega_m/0.3)^{0.5}}$$



DESY6 3x2pt: 2601.14559



J. Prat and M. Crocce

DES 3x2pt vs CMB: *evolution across releases*

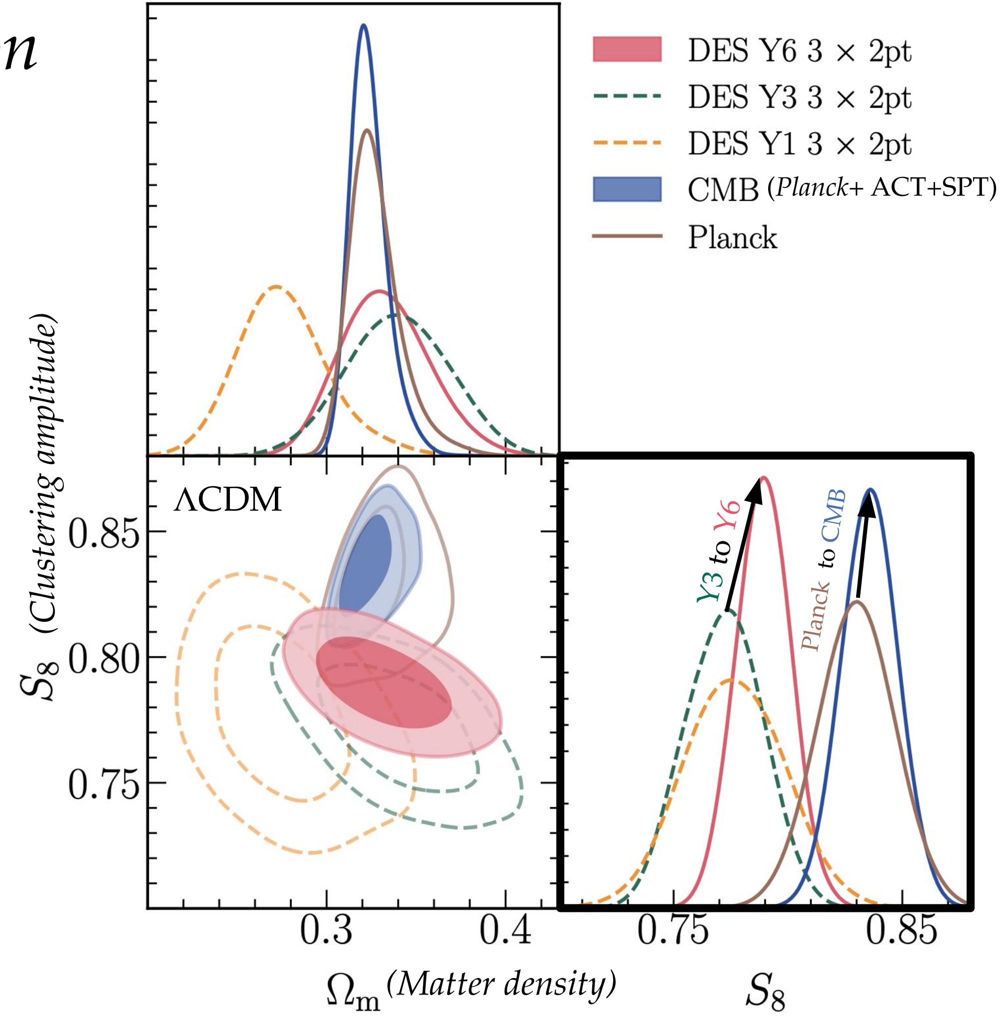
DES 3x2pt S8 constraints are consistent across releases.

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

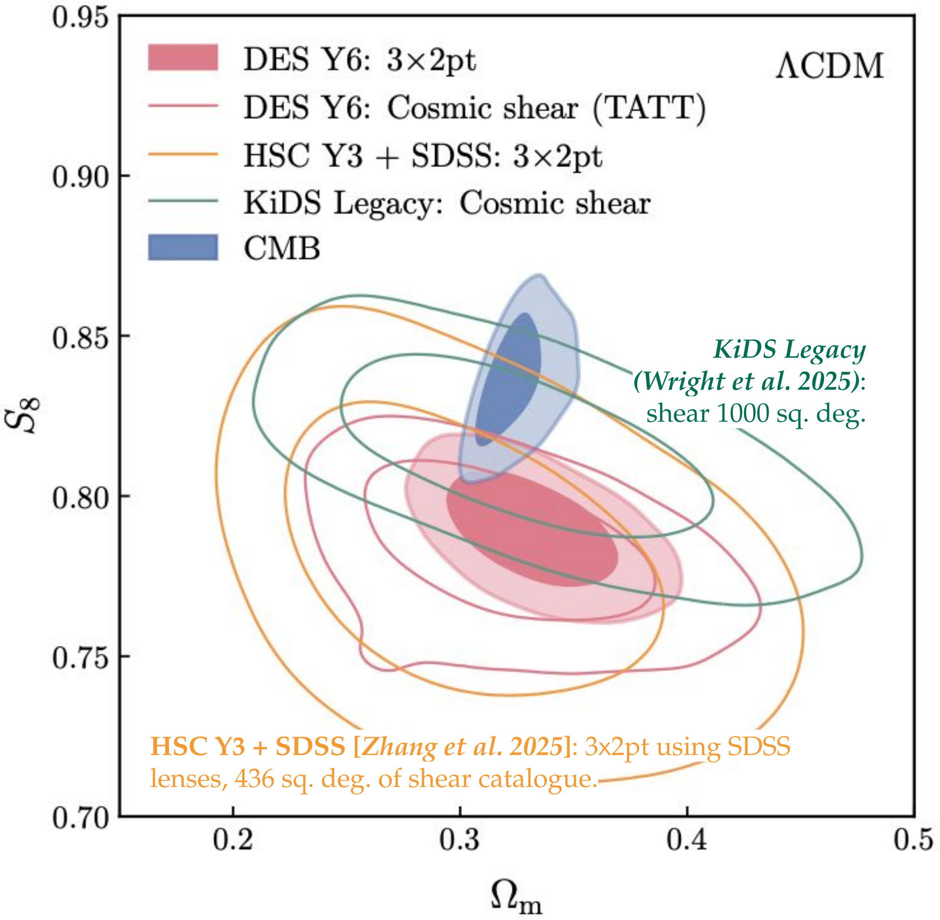
so **with respect to *Planck* the difference has decreased,** even with tighter constraints.



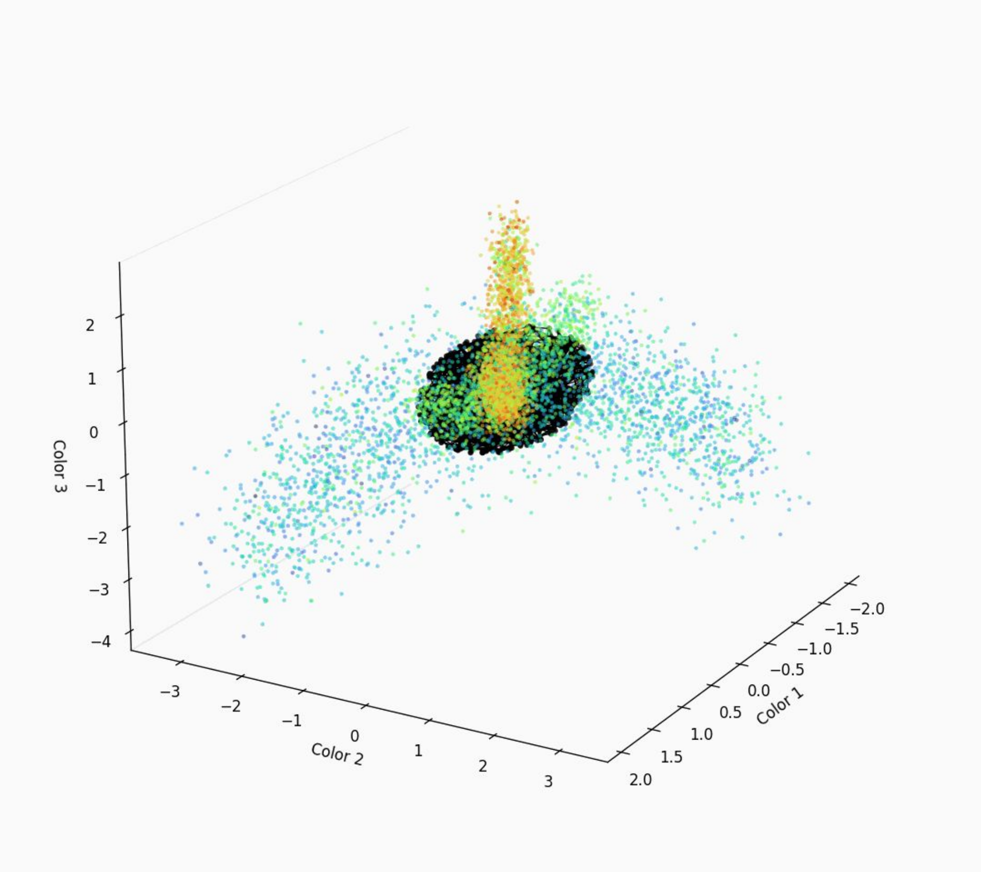
Comparison of lensing probes

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.

Status of "S8 tension": Various estimates of tension metrics across weak lensing experiments with the CMB still range from ~ 1σ to ≲ 3σ.



SOMPZ



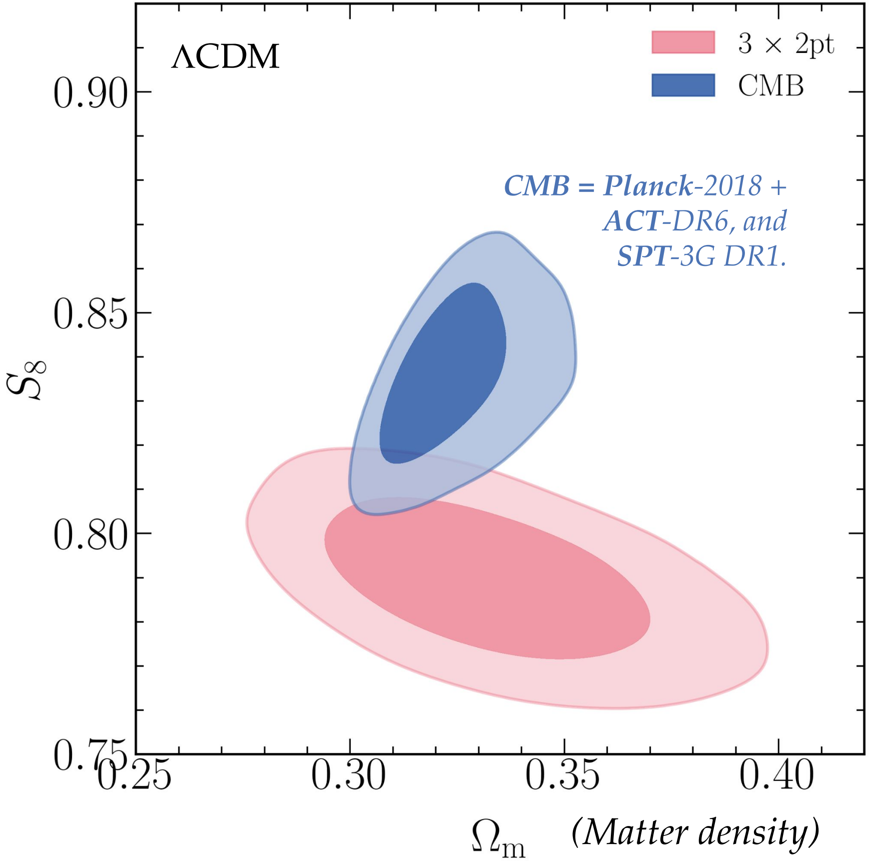
Credit figure: Tyann Dumerchat

DES Y6 3x2pt cosmology vs CMB in ΛCDM

Y6 3x2pt yields similar constraining power as the CMB on the S8 direction (clustering amplitude).

Full-parameter difference between 3×2pt and CMB is **1.8σ.**

In the **2D plane** of the clustering amplitude-matter density is **2.2σ** and in **S8**, it is **2.6σ**.



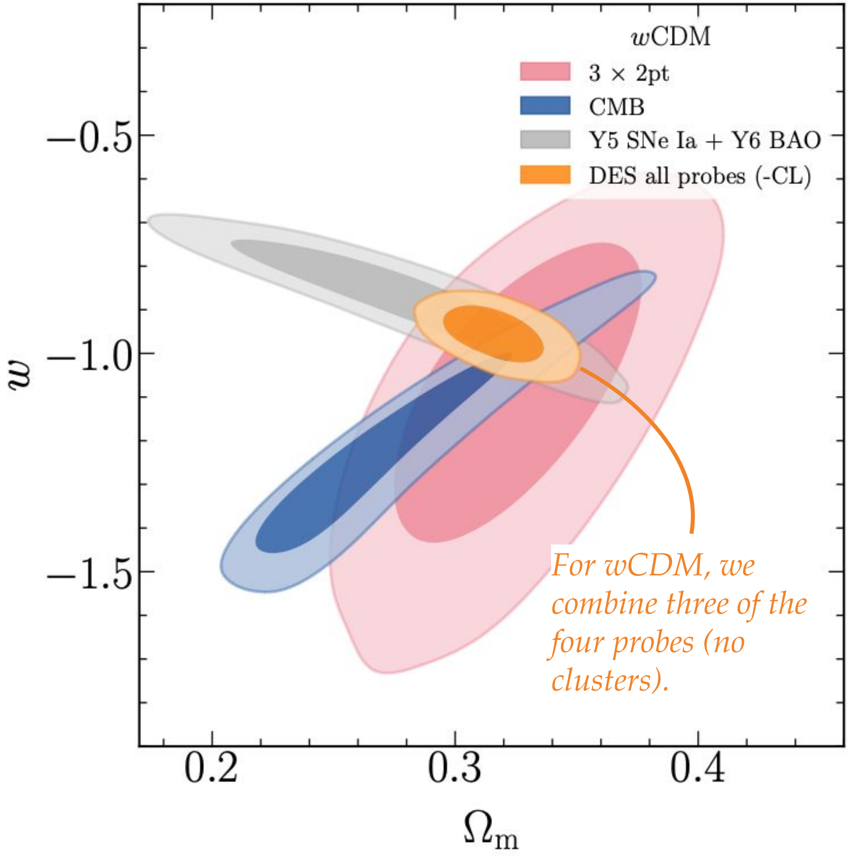
J. Prat and M. Crocce

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

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

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

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

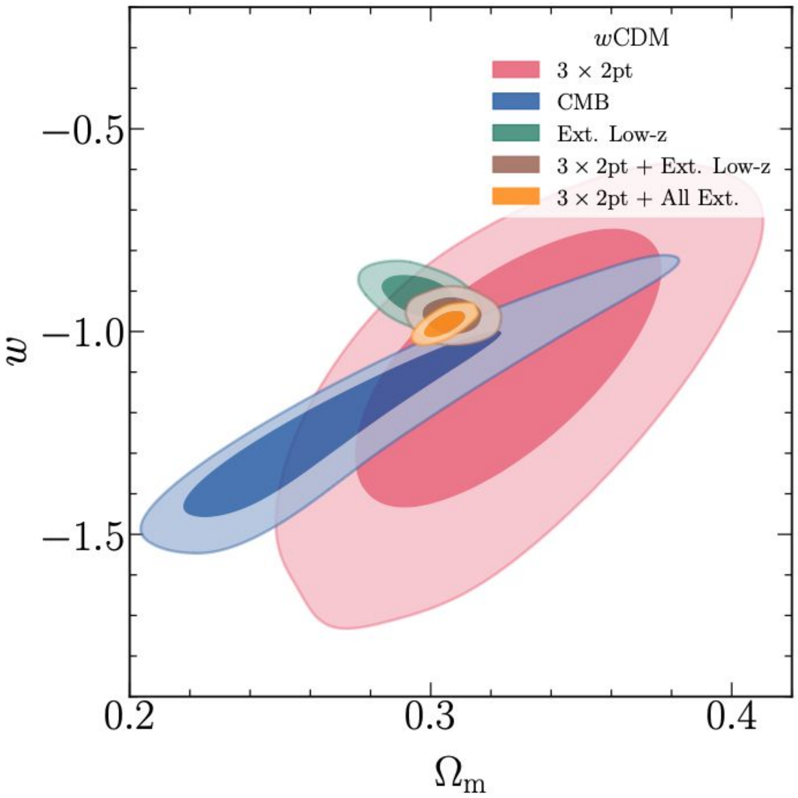


Joint cosmological constraints in wCDM

From the best-available data sets to date:

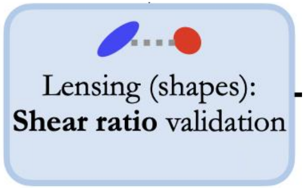
$$S_8 = 0.807^{+0.007}_{-0.007}$$
$$\Omega_\mathrm{m} = 0.305^{+0.004}_{-0.005}$$
$$w = -\,0.981^{+0.021}_{-0.022}$$

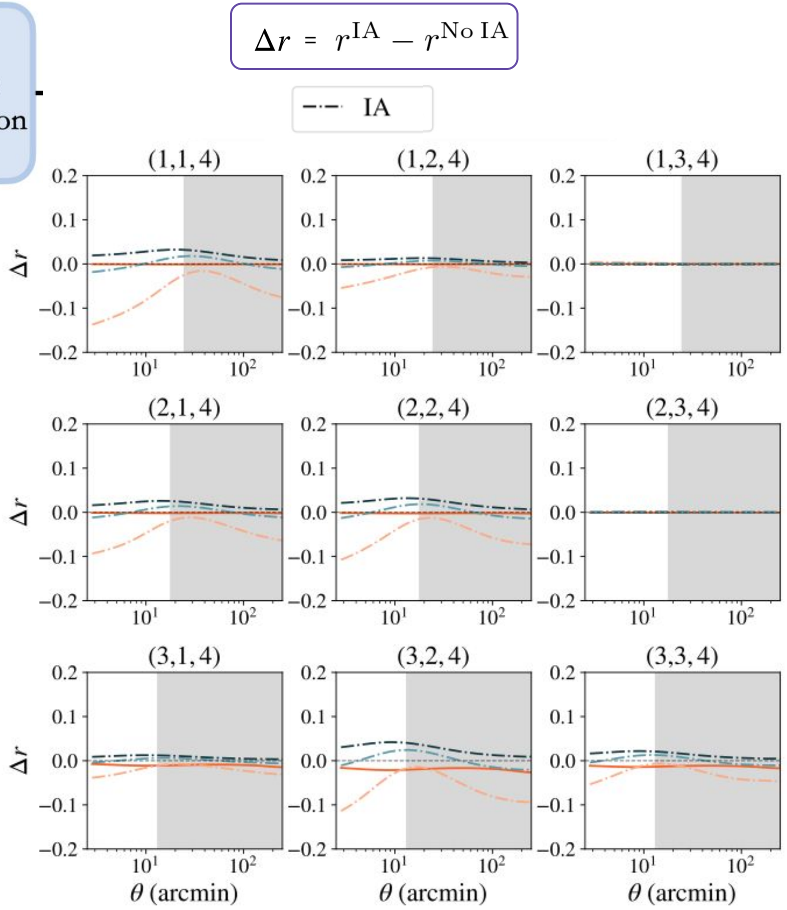
We find no significant preference of *w*CDM over ΛCDM.

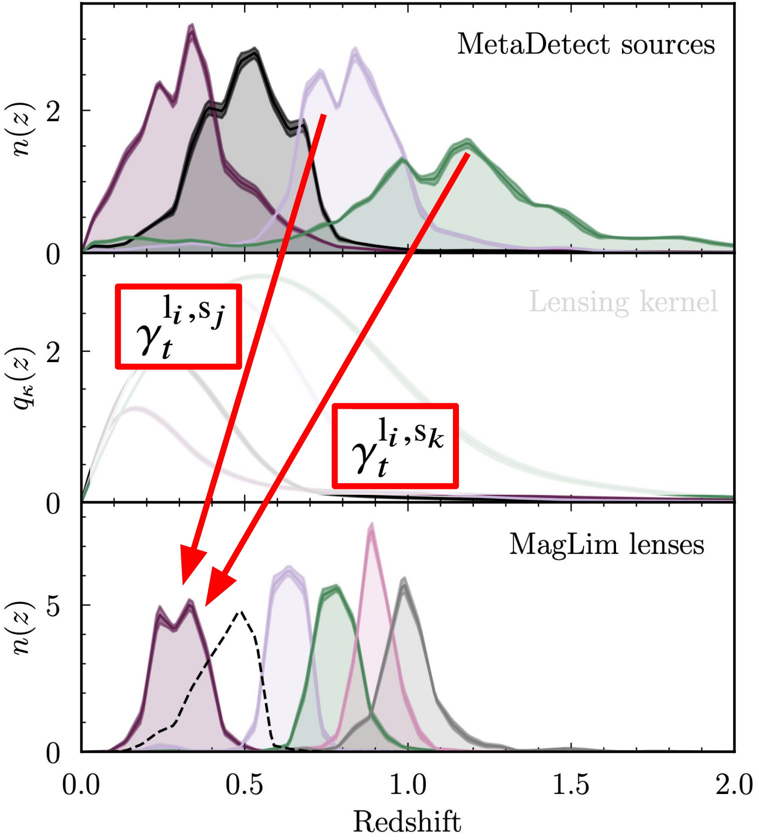


Dark Energy Survey Y6: Shear Ratios

DESY6 GGL: 2601.15175







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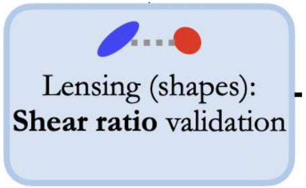
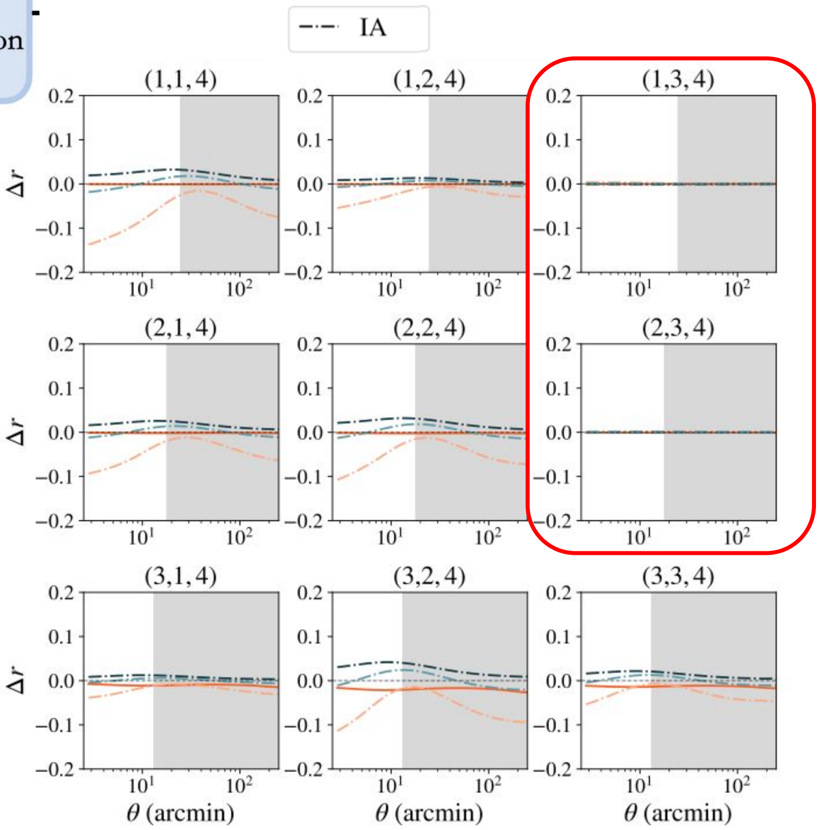
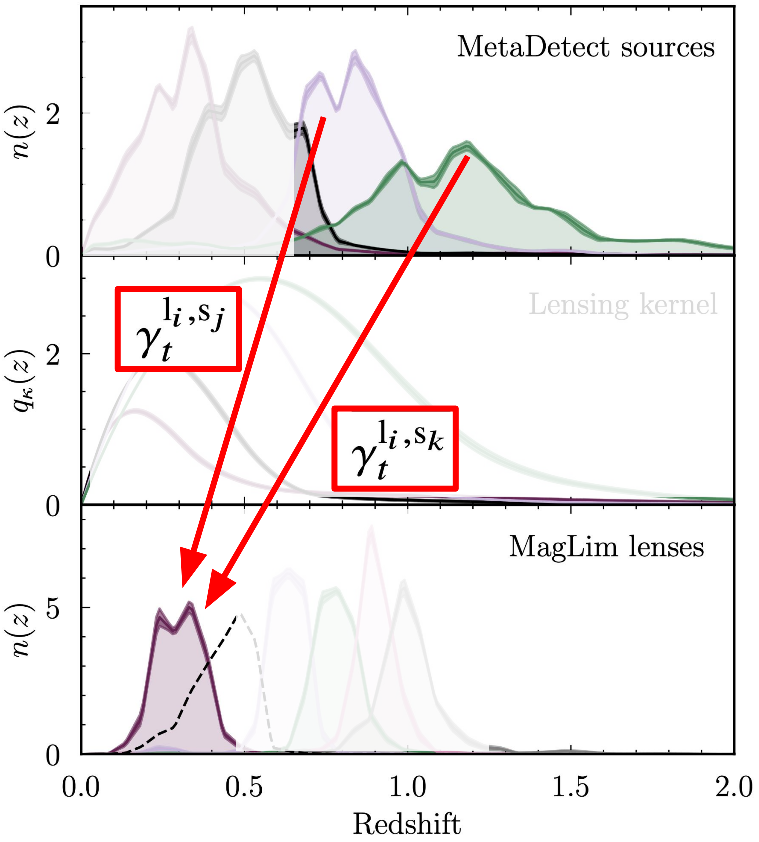
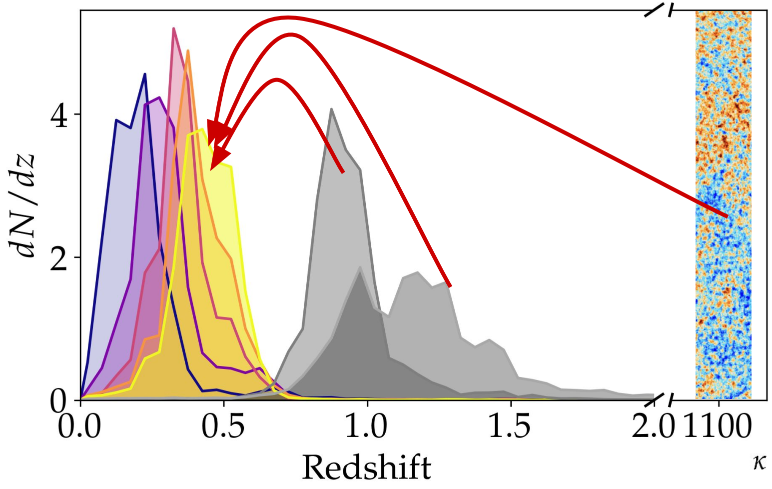


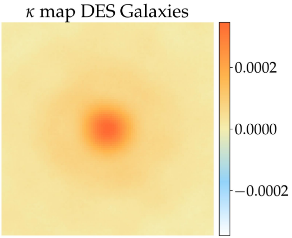
$$\Delta r = r^{\mathrm{IA}} - r^{\mathrm{No\ IA}}$$





Lensing Ratios: Towards Cosmology

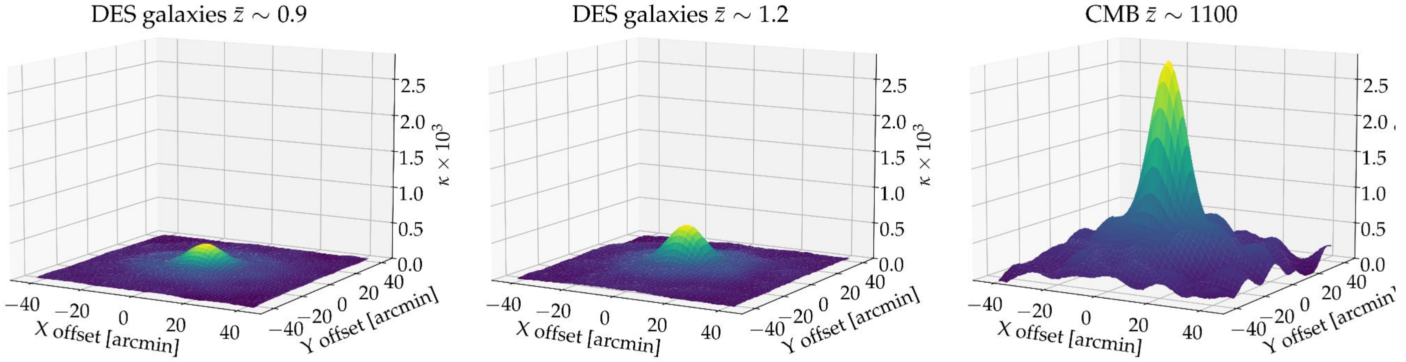




$$\kappa(\theta) = \frac{\Sigma(\theta)}{\Sigma_{\rm crit}}$$

$$\frac{w^{g\kappa_{s_1}}(\theta)}{w^{g\kappa_{s_2}}(\theta)} = \frac{\Sigma_{gm}(R)/\Sigma_{\rm crit}(z_l, z_{s_1})}{\Sigma_{gm}(R)/\Sigma_{\rm crit}(z_l, z_{s_2})} = \frac{\Sigma_{\rm crit}(z_l, z_{s_2})}{\Sigma_{\rm crit}(z_l, z_{s_1})}$$

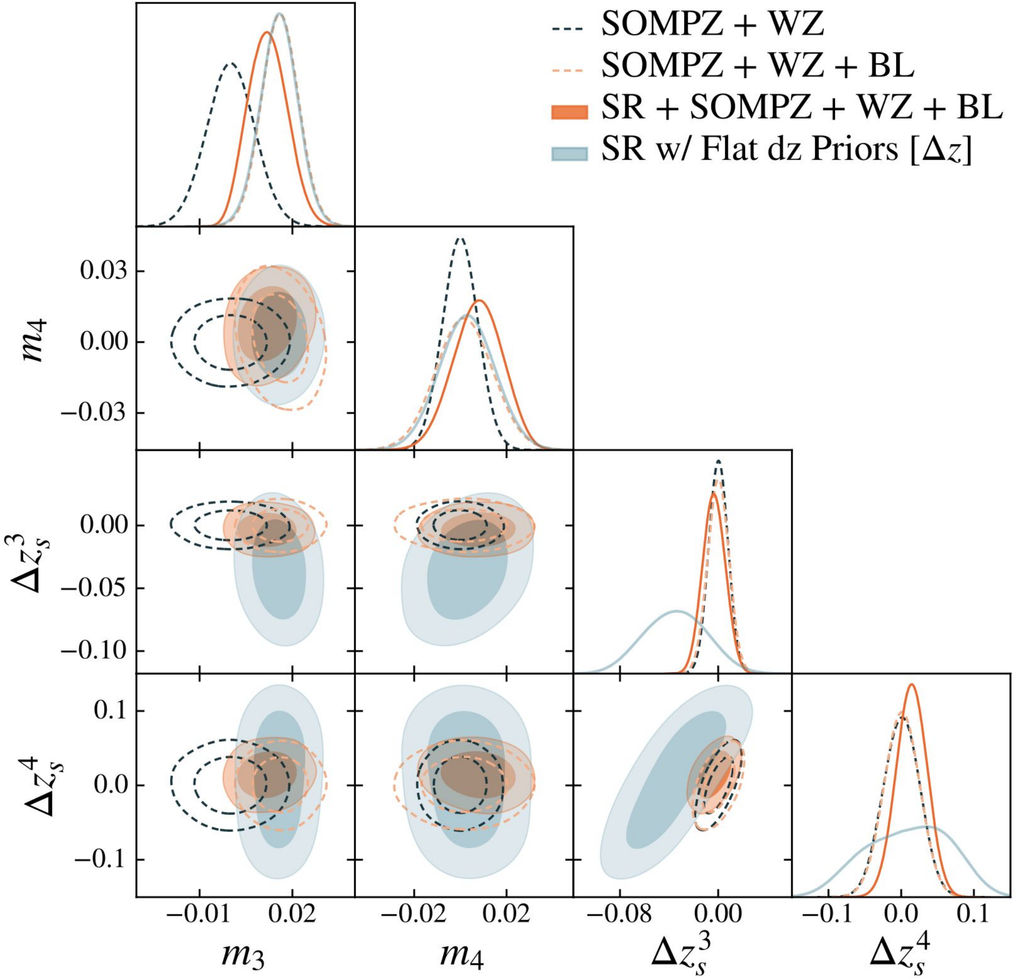
κ map profiles around the same lens at $\bar{z} \sim 0.45$, different sources

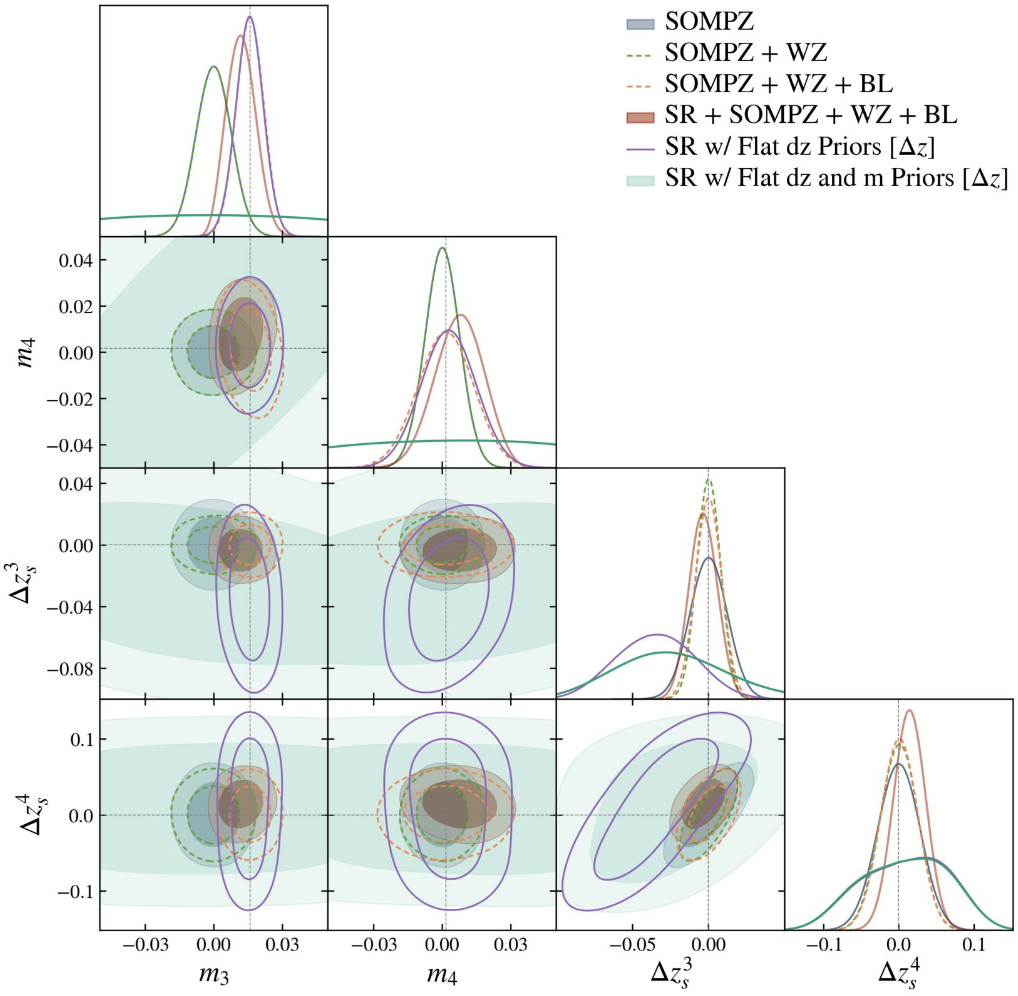


The relative heights of the stacked κ profiles encode the geometric information and cosmology!

Collaborators: C. Sanchez, J. Prat, M. Gatti + DES

Datasets	Distance to ΛCDM (σ)	$\Delta\chi^2$ (σ)	FoM
3×2pt	1.0	1.0	6
SN + DES BAO	1.5	1.6	11
All DES (3×2pt + SN + DES BAO)	2.2	2.0	48
All data (All DES + DESI BAO + CMB)	3.0	3.0	222
SN + BAO	2.4	2.3	61
3×2pt + DESI BAO	1.7	1.5	32
CMB + DESI BAO	2.9	2.9	61
All DES + DESI BAO (All except CMB)	2.3	2.2	110
SN + BAO + CMB (All except 3×2pt)	3.2	3.3	202
3×2pt + BAO + CMB (All except SN)	2.6	2.5	66
3×2pt + SN + CMB (All except BAO)	2.4	2.4	96
All DES + CMB (All except DESI BAO)	2.8	2.8	102


SOMPZ + WZ
SOMPZ + WZ + BL
SR + SOMPZ + WZ + BL
SR w/ Flat dz Priors [Δz]
m_4
0.03
0.00
−0.03
Δz_s^3
0.00
−0.05
−0.10
Δz_s^4
0.1
0.0
−0.1
−0.01
0.02
m_3
−0.02
0.02
m_4
−0.08
0.00
Δz_s^3
−0.1
0.0
0.1
Δz_s^4



SOMPZ
SOMPZ + WZ
SOMPZ + WZ + BL
SR + SOMPZ + WZ + BL
SR w/ Flat dz Priors [Δz]
SR w/ Flat dz and m Priors [Δz]
m_4
Δz_s^3
Δz_s^4
m_3

Summary

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In Λ**CDM: no significant evidence for inconsistency** between DES and CMB, or between DES + other complementary low-redshift probes and CMB, although we find *systematically lower values* of the $\mathbf{S_8}$ parameter.

First time **we combine all four DE probes** proposed at the DES inception: 3×2pt, BAO, SNIa and Clusters. Similar constraining power as CMB *in both* Ω_m and S_8.

In ***w*****CDM**: DES constraints equation of state to 4% (consistent with Λ**CDM). Full joint constraints** find a 2% result on *w*, no preference for *w*CDM over ΛCDM.

Lensing ratios are a promising lensing probe for dark energy cosmology.