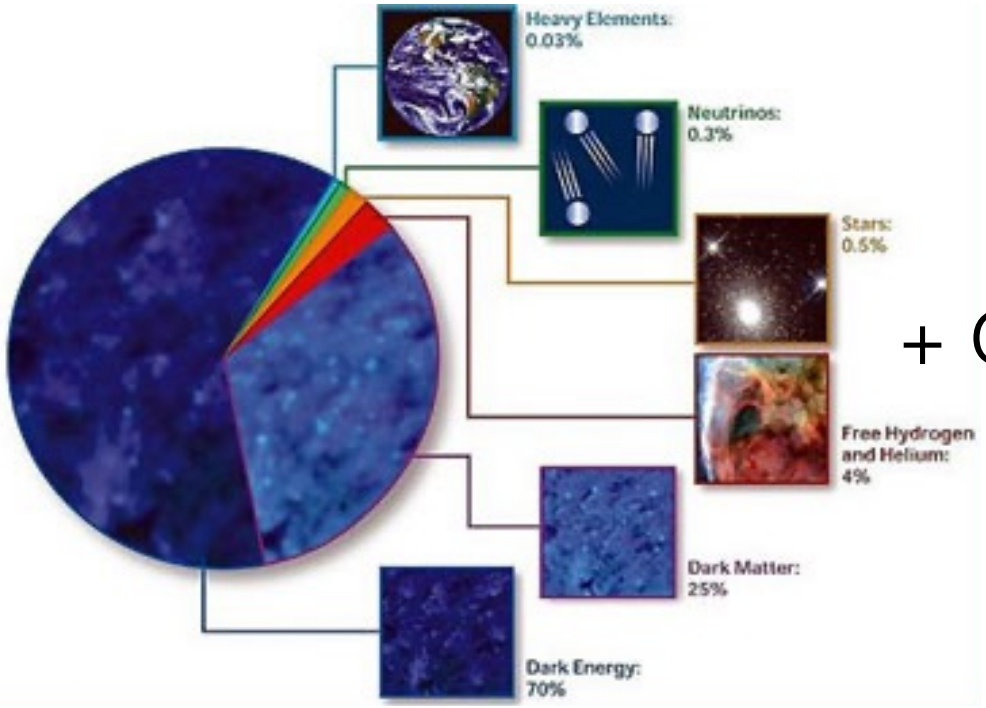
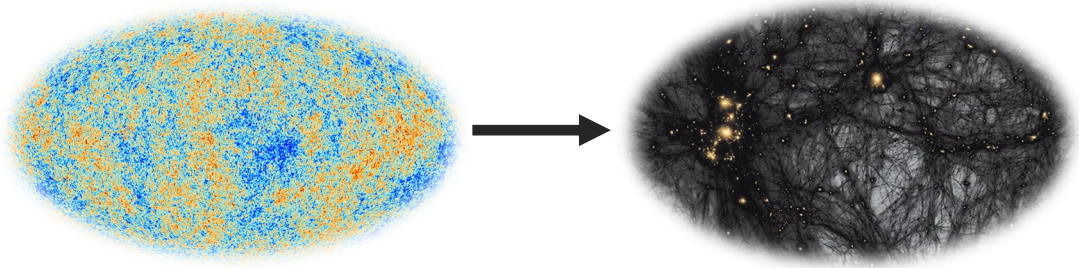
Latest results from the Dark Energy Survey

Agnès Ferté
SLAC/Stanford University

Large galaxy surveys to probe (dark) matter in the Universe



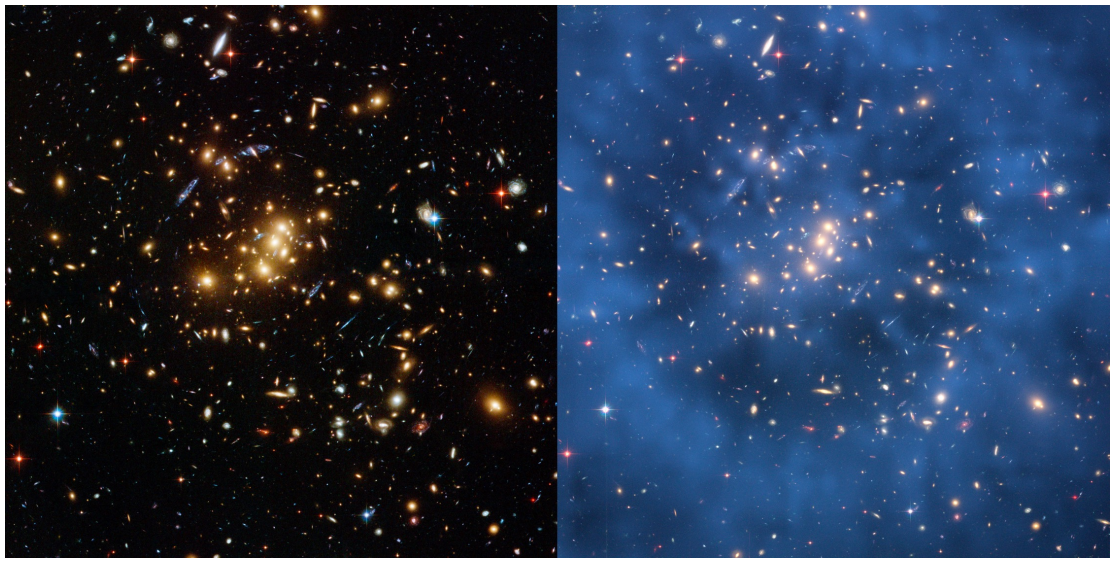
+ GR



Evolution of matter distribution since the Big Bang depends on Universe's properties

Open questions of the ΛCDM model:

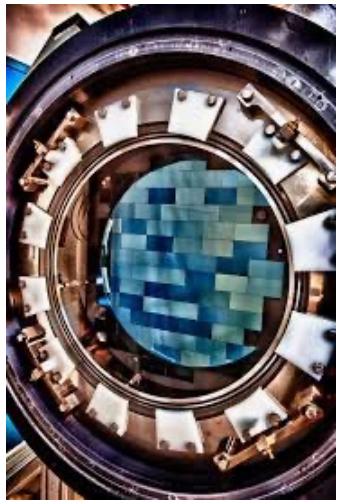
- What is **dark energy**?
- What is **dark matter**?
- Is **GR** verified at cosmic distances?



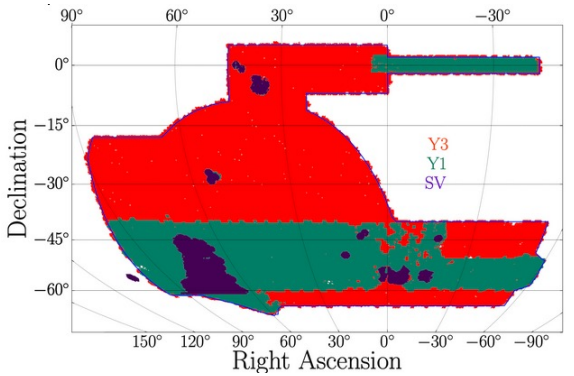
But most of the matter is dark…

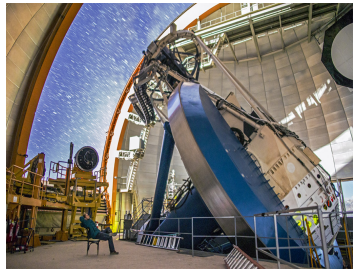
⇒ Use galaxies as tracers of large-scale structures

The Dark Energy Survey, a pivotal photometric galaxy survey

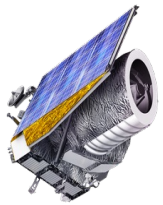


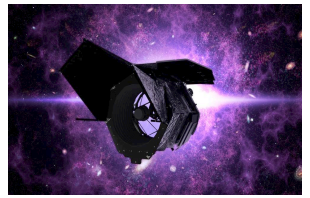
- DECam on the Blanco–4m in Chile:
  74 CCDs, 2.2° field of view, 570 Mpixels
- Mapped 10% of the sky from 2011 until 2019
  in 5 optical bands (g,r,i,z,Y)
- International collaboration working on
  3–stage cosmological analyses: Y1, Y3, Y6





+ KiDS, HSC





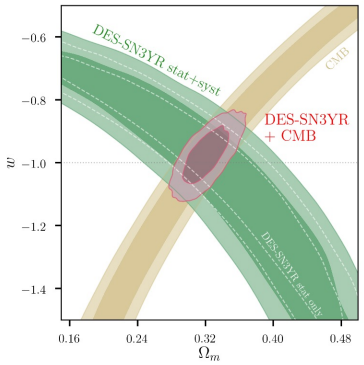
DES cosmological probes and main current results

Expansion

Supernovae

Cosmology from 207 supernovae from DES–SN Y3

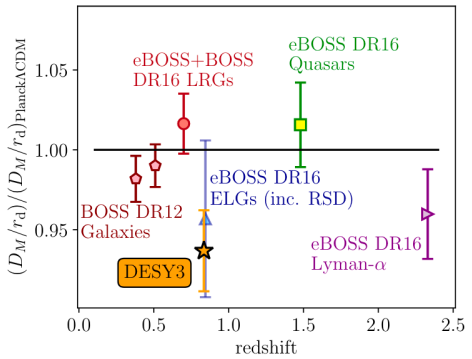
DES Collaboration, ApJL, 2019



Baryonic Acoustic Oscillation

Cosmology from 2.7% measurement of BAO scale using DES Y3 data

DES Collaboration, PRD, 2022

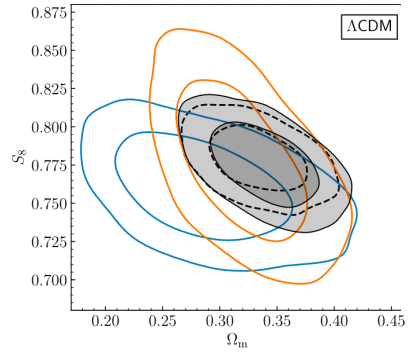


Growth

Weak lensing and clustering

Cosmology with 4% precision from DES Y3 data

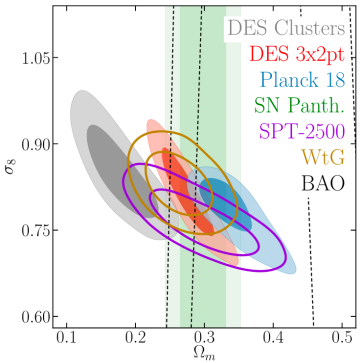
DES Collaboration, PRD, 2022



Clusters of galaxies

Cosmology from 6054 clusters using DES Y1 data

DES Collaboration, PRD, 2020



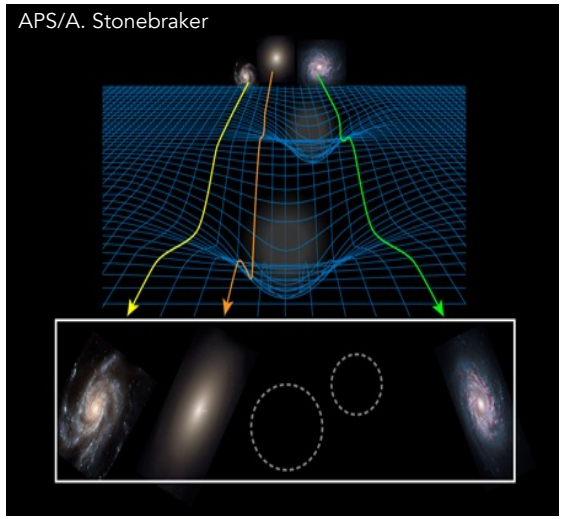
Focus on weak lensing and clustering

Statistical properties of galaxies:
- Galaxies are clustered on large scales
- Galaxies are weakly lensed
  by large–scale structures on the line of sight
  → **Geodesics** are modified
  → **Shapes** of galaxies appear:

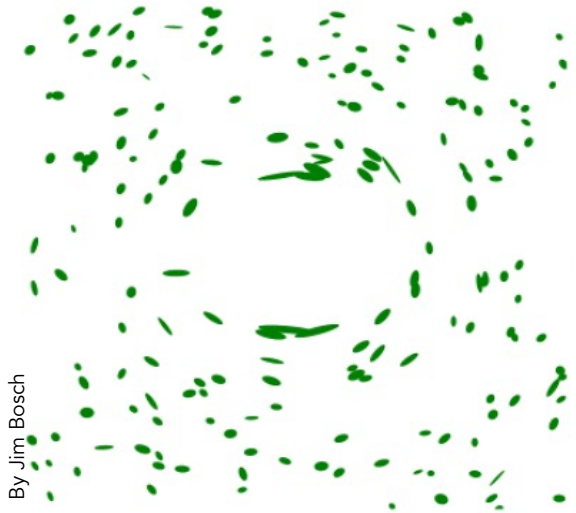
Clustering $b^2\xi_{mm}(\theta)$ | Galaxy–galaxy lensing $b\xi_{mm}(\theta)$ | Cosmic shear $\xi_{mm}(\theta)$

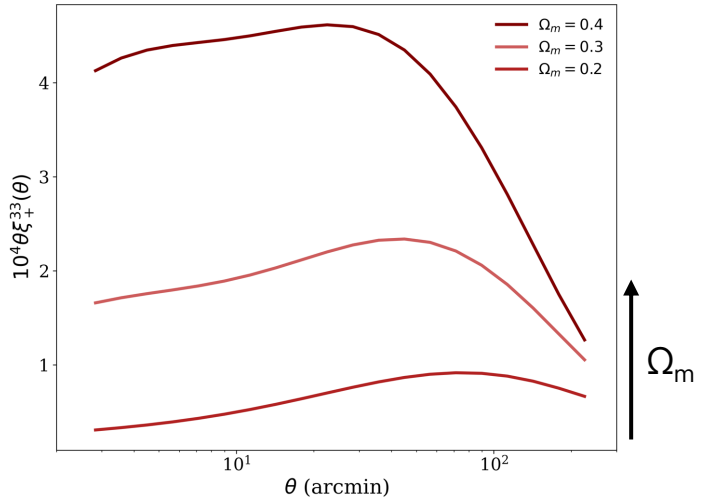
Measurements of 2–pt correlation functions of shape and position of galaxies in tomographic redshift bins
⇒ Probe the expansion and the growth of structures
⇒ Sensitive to the parameter S8

More elliptic



Correlated

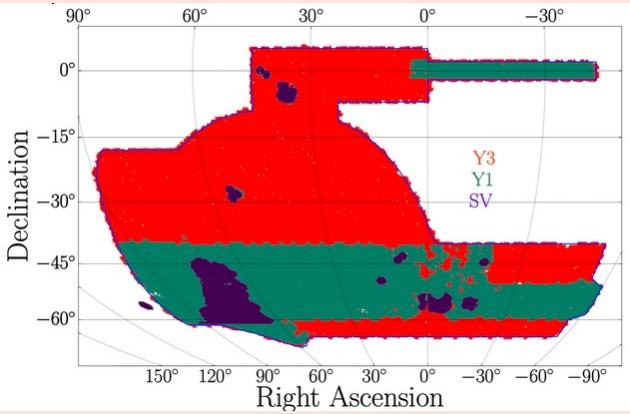




DES Y3: cosmological analysis of 3x2pt is a data challenge

Images over **10%** of the sky

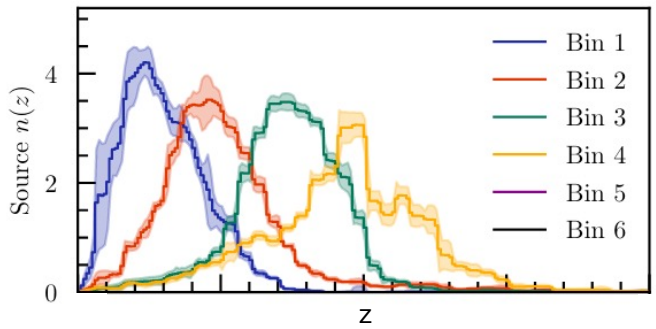
Sevilla – Noarbe, Bechtol, Carrasco Kind, et al, ApJ, 2021



Sevilla – Noarbe, Bechtol, Carrasco Kind, et al, 2021
Hartley, Choi, et al, 2021
MacCrann et al, 2021
Everett et al, 2021

Shape of **100 millions** galaxies and redshift estimation

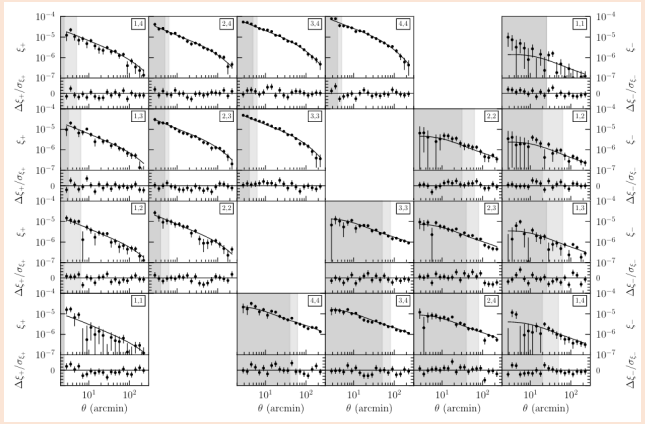
DES collaboration, PRD, 2022



Jarvis et al, 2021
Gatti, Sheldon, et al, 2021
Cawthon et al, 2021
Giannini et al, in prep
Myles, Alarcon, et al, 2021
Gatti, Giannini, et al, 2021
Cordero, Harrison, et al, 2021
Elvin–Poole, MacCrann, et al, in prep

Precise measurements of correlation functions (S/N = 87)

DES collaboration, PRD, 2022



DeRose et al, 2021
Porredon et al, 2021
Pandey et al, 2021
Rodriguez–Monroy et al, 2021
Prat et al, 2021
Sánchez, Prat, et al, 2021
Amon et al, 2021
Secco, Samuroff, et al, 2021
Jeffrey, Gatti, et al, 2021

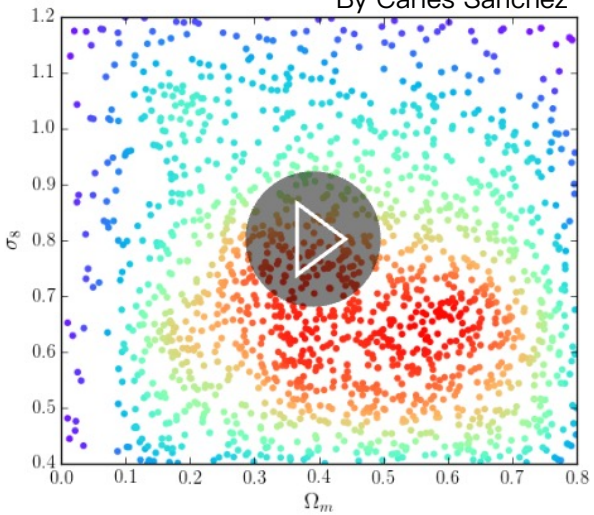
and also a modeling challenge

Estimation of cosmological parameters by sampling the likelihood:

$$\mathcal{L}(\mathbf{D}|\Theta) \sim [\mathbf{D} - \mathbf{M}(\Theta)]^T C^{-1} [\mathbf{D} - \mathbf{M}(\Theta)]$$

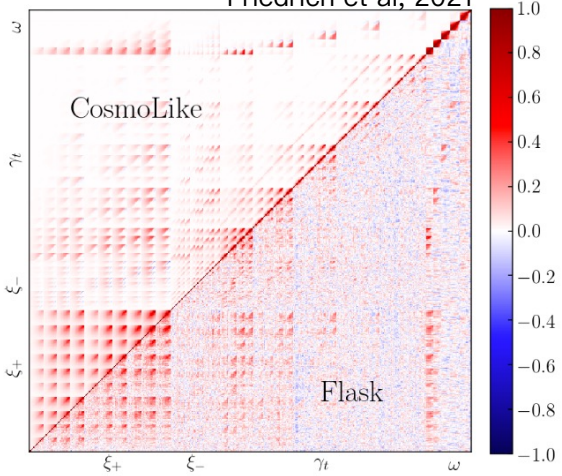
Gaussian **likelihood**: Sampling with polychord
Lemos, Weaverdyck (incl. **AF**) et al, 2022

By Carles Sánchez



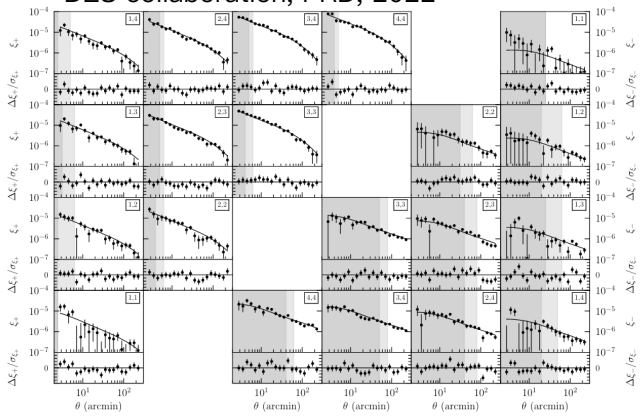
Covariance matrix between measurements
Friedrich et al, 2021

Friedrich et al, 2021



Data: Weak lensing and clustering measurements (462 data points)

DES collaboration, PRD, 2022

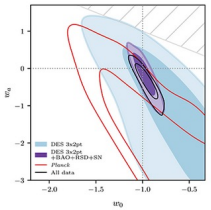


Model: **Analytic** prediction of weak lensing and clustering signal,
pipeline and **validation** of modeling choices
Krause et al (incl. **AF**), 2021

Tests of beyond–ΛCDM models with DES Y3 weak lensing and clustering data

DES Y3 extensions team
led by Jessie Muir & **Agnès Ferté**
from 2018 to 2022:

- Dynamical dark energy
- Curvature
- Sterile massive neutrinos
- Phenomenological $\sigma_8(z)$ test
- **Test of gravity**



EDITORS' SUGGESTION

Dark Energy Survey Year 3 results: Constraints on extensions to ΛCDM with weak lensing and galaxy clustering

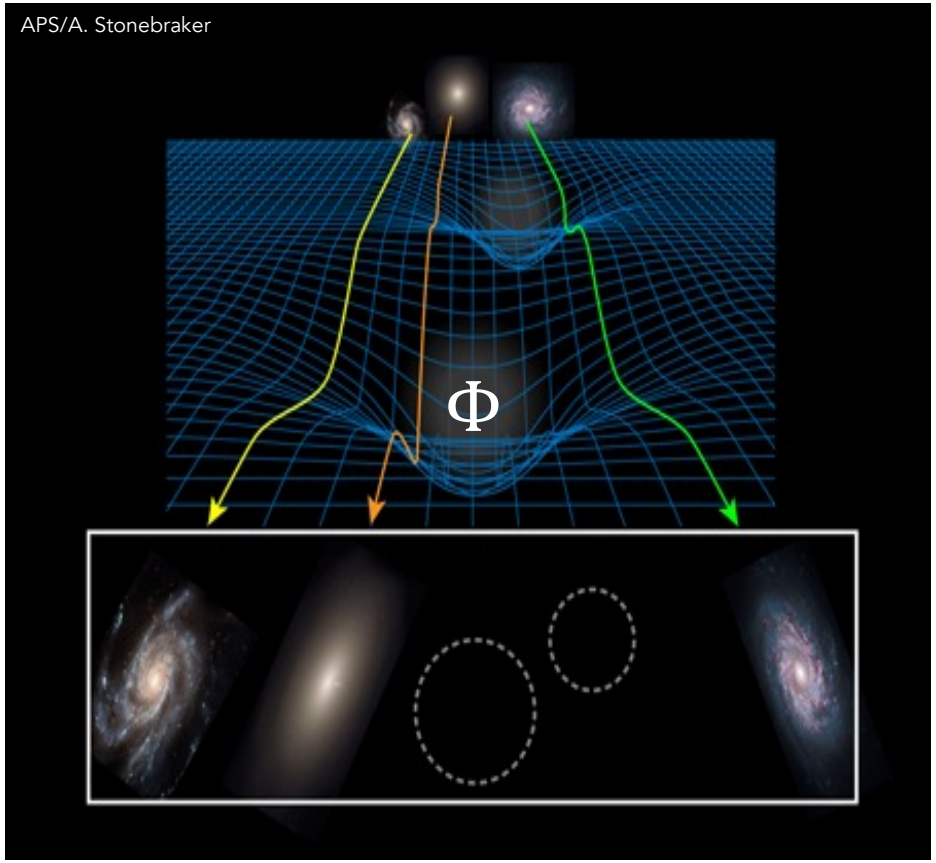
The authors use Dark Energy Survey data on galaxy clustering and lensing from the first three years of observations combined with five prominent external datasets. They robustly constrain six potential extensions to the currently prevalent cosmological paradigm of ΛCDM (Cold Dark Matter with a cosmological constant). All extensions would add significant new physics, such as deviations from General Relativity or non-zero spatial curvature, but no significant evidence for new physics is found.

T.M.C. Abbott *et al.* (DES Collaboration)
Phys. Rev. D **107**, 083504 (2023)

Results released:

- DES collaboration, PRD, 2023 as **editor's suggestion**
- Public data
  https://dev.des.ncsa.illinois.edu/releases/y3a2/Y3key-extensions

Phenomenological tests of gravity



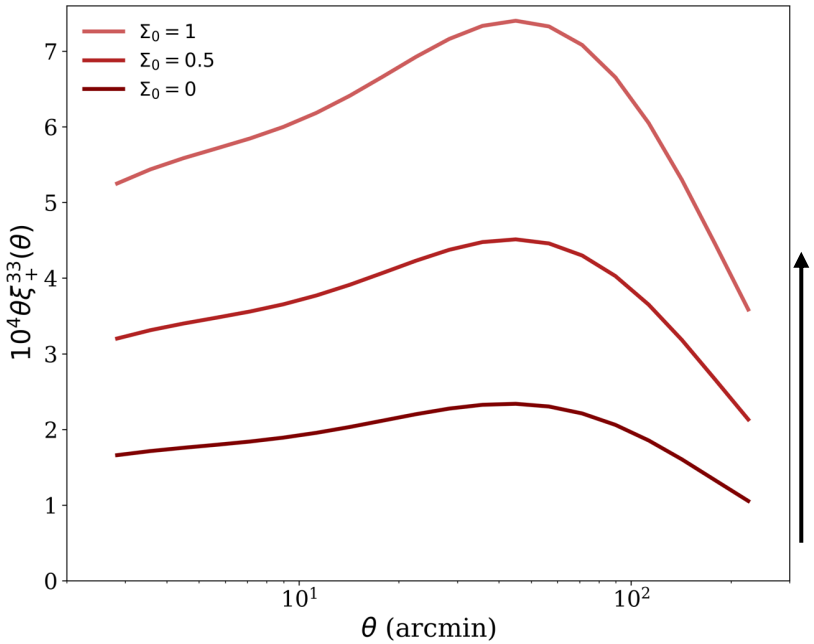
Are modifications to geodesics caused by weak lensing as expected in GR?

$$k^2\Phi = -8\pi G a^2 (1 + \Sigma_0 \Omega_\Lambda(t))\rho\delta$$

⇒ Test for deviations of Σ_0 from 0 (GR)

⇒ Similarly for clustering with the parameter μ_0

See Camille Bonvin's talk for more about Σ,μ



Approach to test of gravity

$$w^i(\theta) = \sum_\ell \frac{2\ell+1}{4\pi} P_\ell(\cos\theta) C^{ii}_{\delta_g\delta_g}(\ell)$$

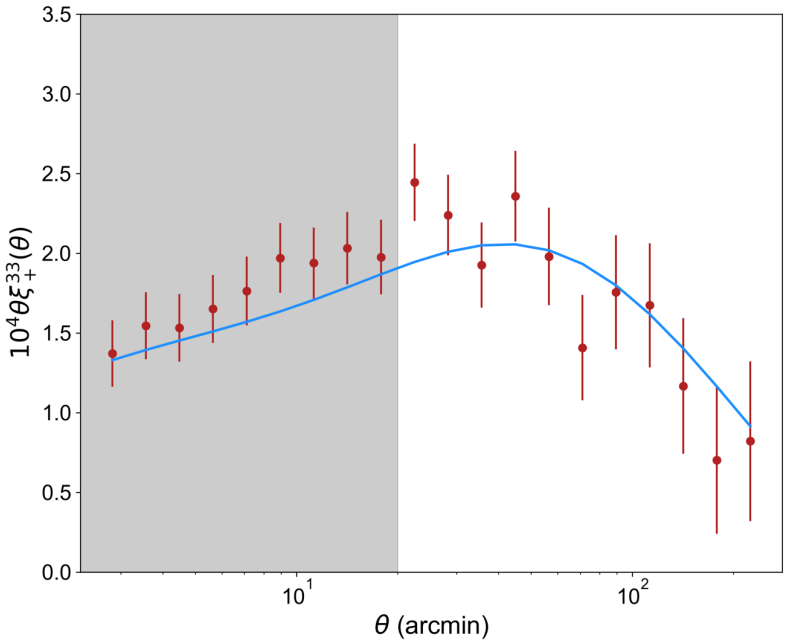
$$\gamma_t^{ij}(\theta) = \sum_\ell \frac{2\ell+1}{4\pi} \frac{P_\ell^2(\cos\theta)}{\ell(\ell+1)} C^{ij}_{\delta_g \mathrm{E}}(\ell)$$

$$\xi_\pm^{ij}(\theta) = \sum_{\ell\geqslant 2} \frac{2\ell+1}{4\pi} \frac{2(G^+_{\ell,2}(x) \pm G^-_{\ell,2}(x))}{\ell^2(\ell+1)^2} \times [C^{ij}_{\mathrm{EE}}(\ell) \pm C^{ij}_{\mathrm{BB}}(\ell)],$$

$$\mathcal{L}(\mathbf{D}|\Theta) \sim [\mathbf{D} - \mathbf{M}(\Theta)]^T C^{-1} [\mathbf{D} - \mathbf{M}(\Theta)]$$

Estimate Σ_0 by sampling the likelihood

Adapt the model of 3x2pt to add the impact of Σ_0,μ_0



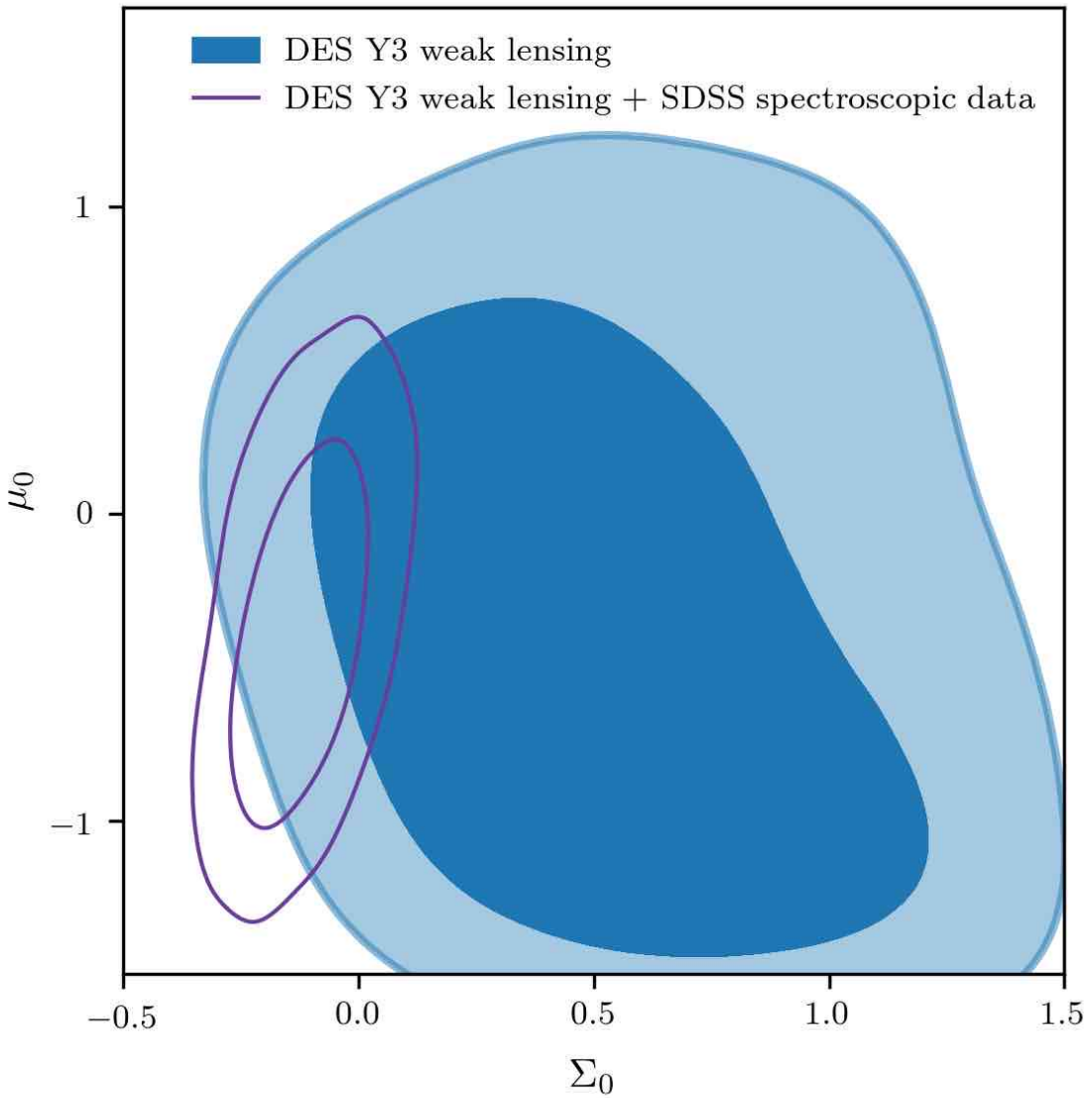
Safeguard against false detection of beyond–ΛCDM physics:

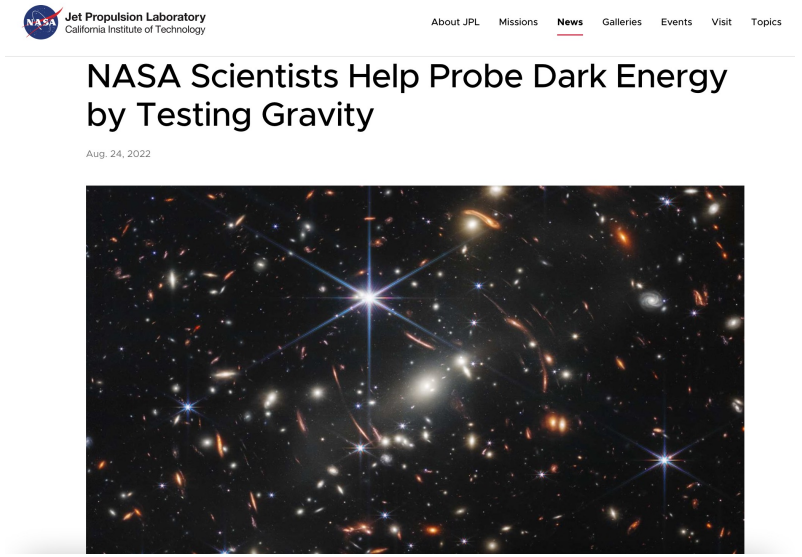
- Scale cuts: data points where we don't trust our model are removed. 50% of data point removed for tests of gravity.
- Blinded analysis: validation of our modeling choices on P(k,z) modeling, intrinsic alignment, baryonic feedback, etc. on **simulated** data and real data **without looking at real results** to avoid confirmation bias

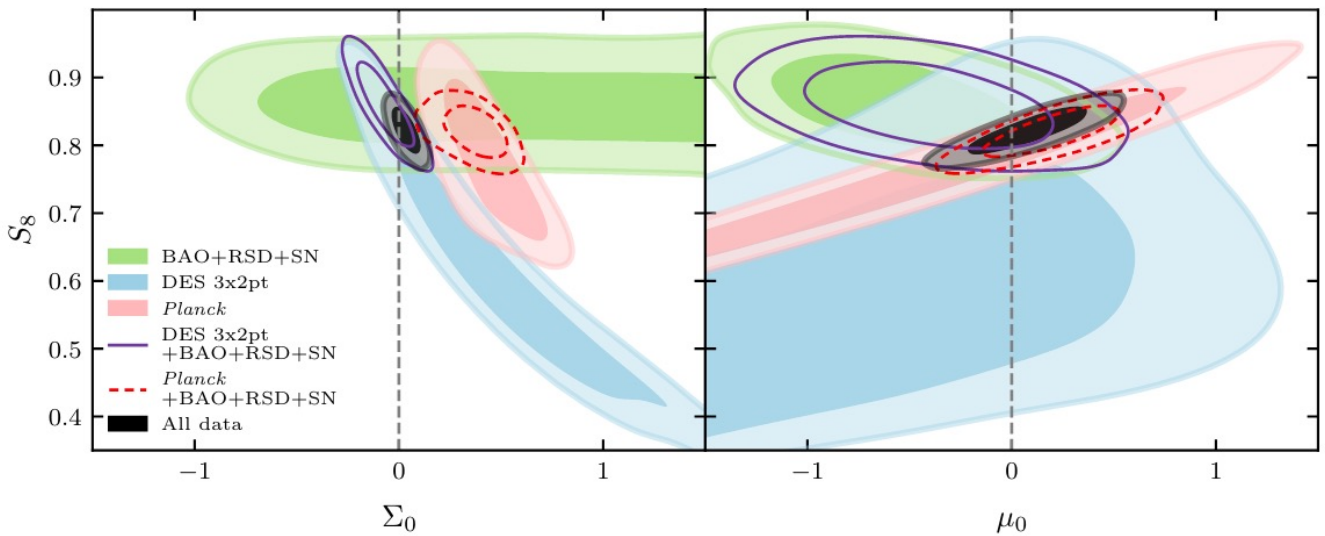
  Muir et al, PRD, 2020

  Weaverdyck, Alves et al, in prep

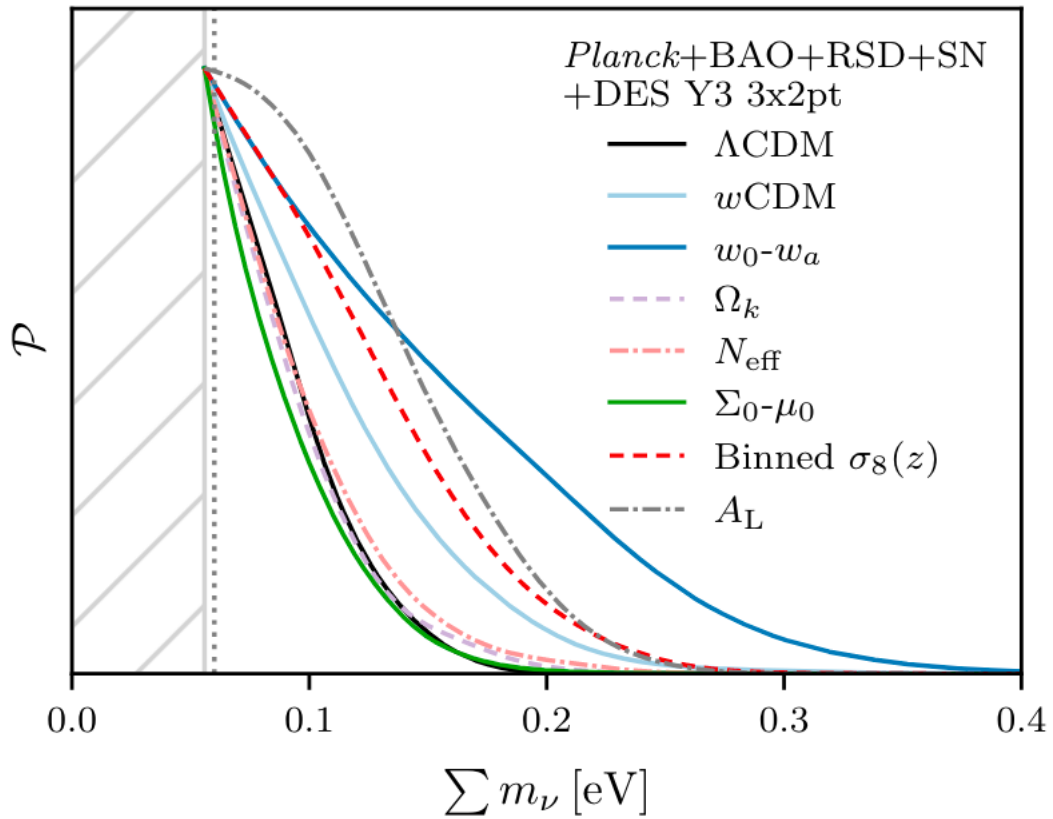
DES Y3 weak lensing tells us that General Relativity still holds…



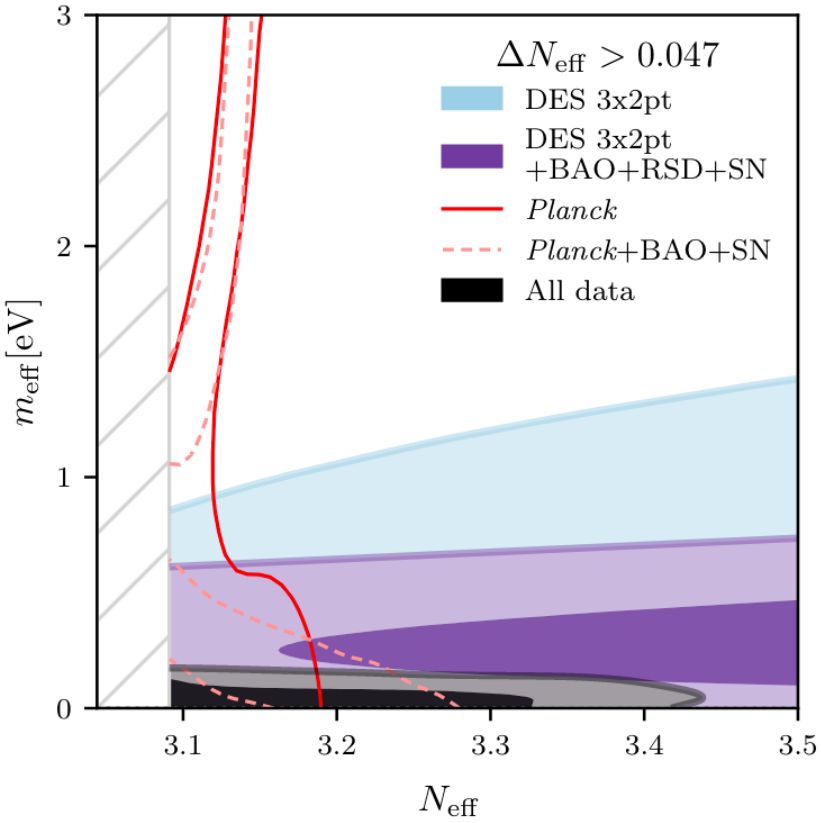




Neutrinos mass constraints



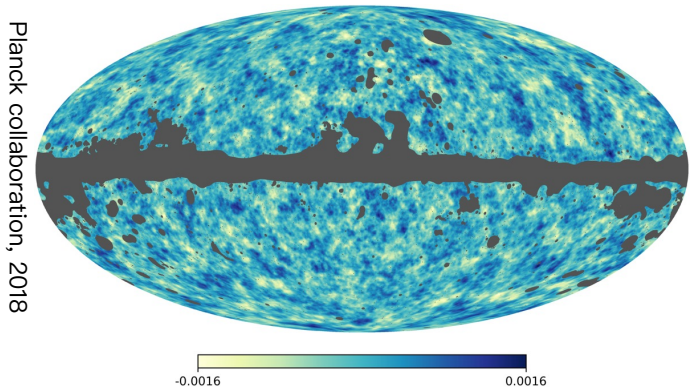
⇒ Weak lensing will give important constraints on the sum of neutrino masses in the coming years.



⇒ Weak lensing helps constrain sterile massive neutrinos when added to CMB data

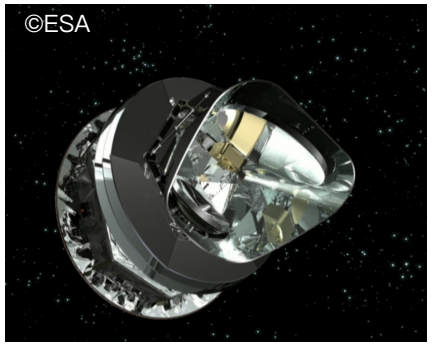
Combination of DES weak lensing with CMB lensing

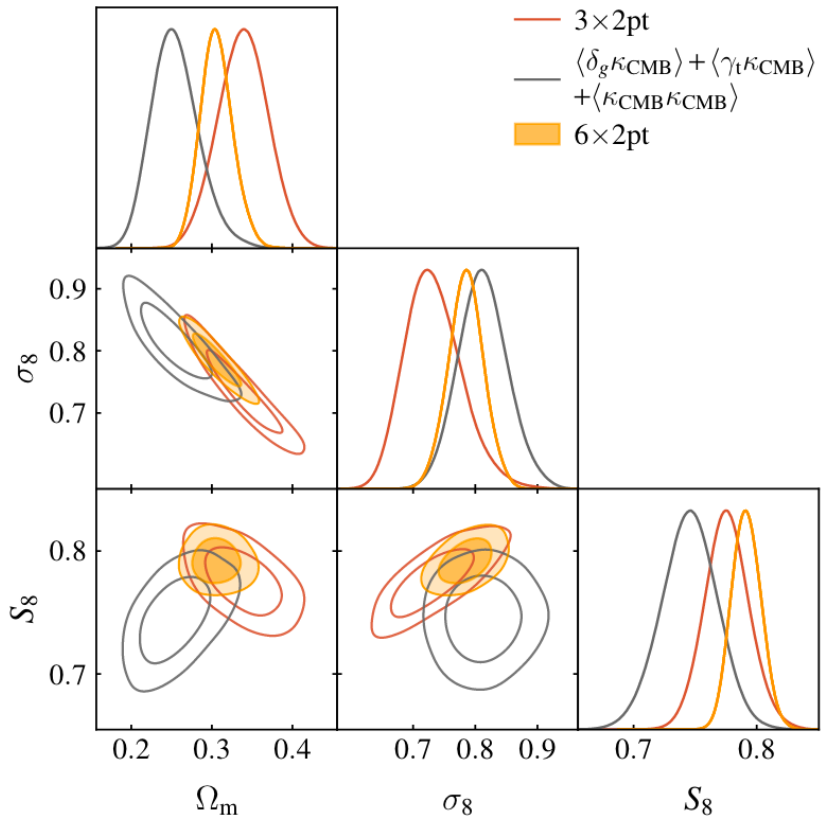
The Cosmic Microwave Background is also lensed:



⇒ Are 3x2pt and CMB lensing consistent?
Consistency and combination of

- CMB lensing power spectrum from SPT–SZ and the Planck satellite,
- 3x2pt from DES Y3.

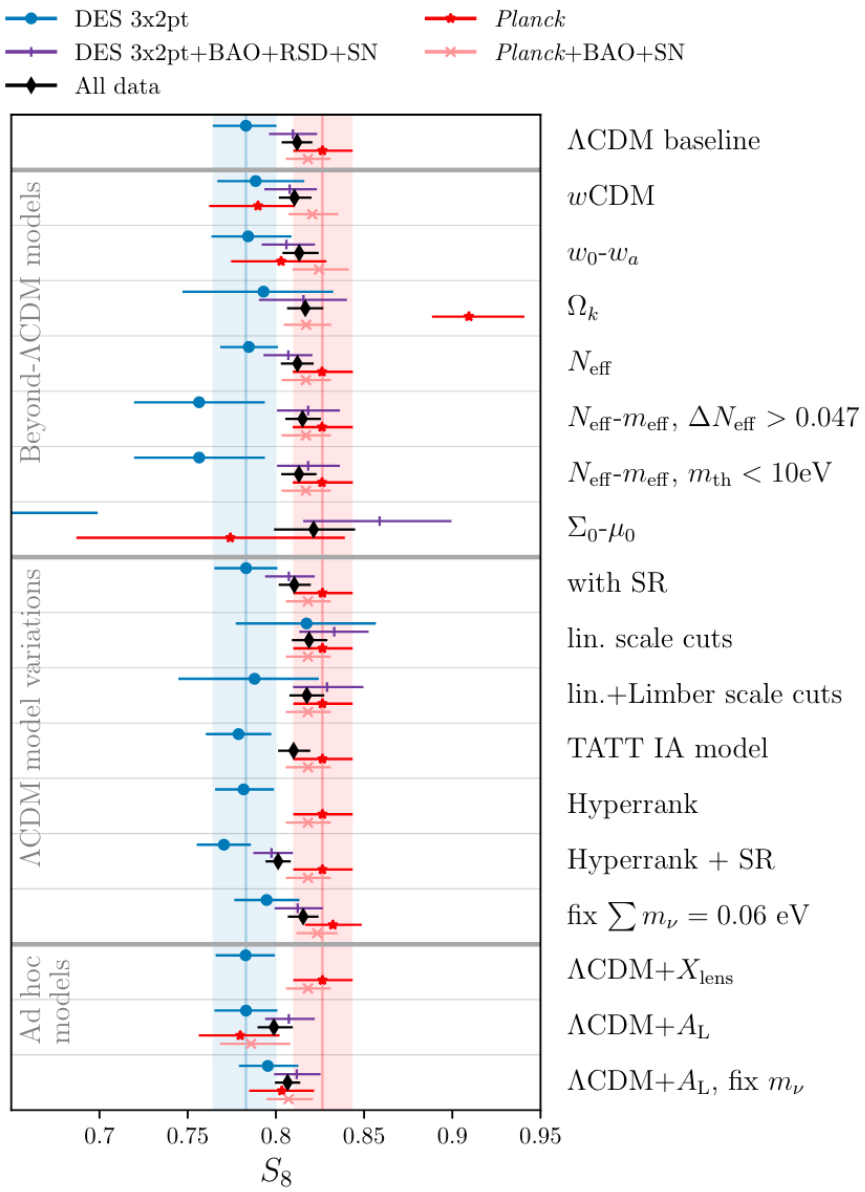


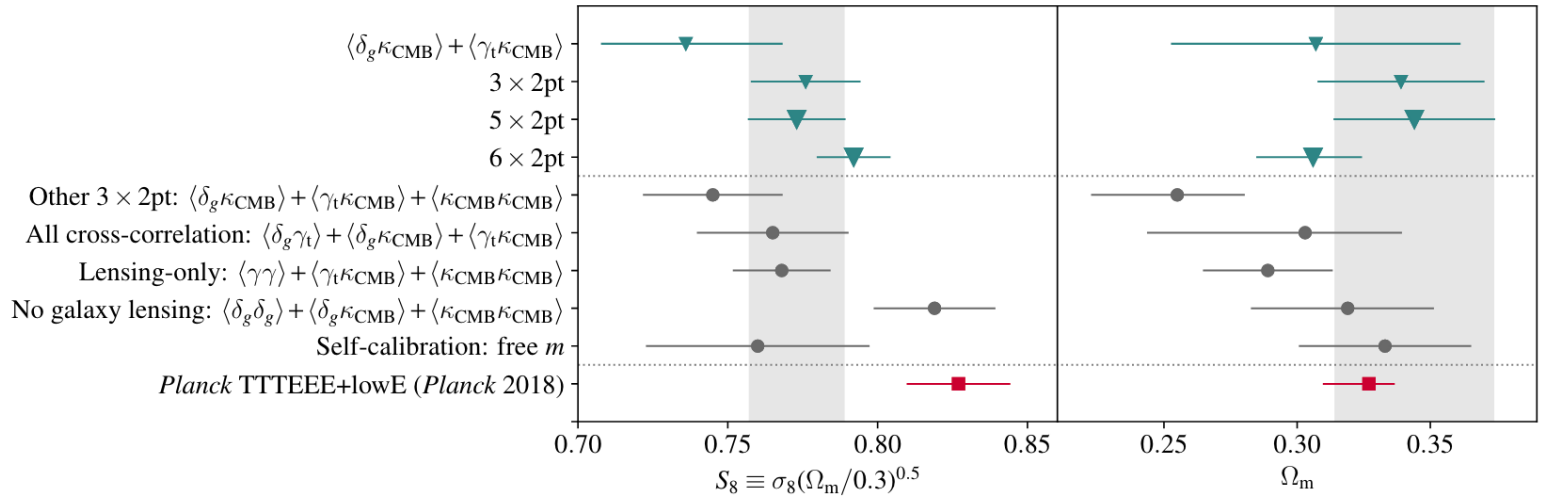


Results released in

- Y. Omori, E. J. Baxter, C. Chang et al., PRD, 2023
  C. Chang, Y. Omori, E. J. Baxter, PRD, 2023
  DES Collaboration, PRD, 2023

Tensions: S_8 tension and tensions with ΛCDM





S_8 tension: weak lensing surveys systematically measure S_8 to be lower than what CMB experiments measure.

- Not alleviated by beyond ΛCDM models we tested.
- Not alleviated by combination with CMB lensing.

See Pedro Carrilho's talk for more about the S_8 tension

Tension with ΛCDM: used many tensions metrics and no evidence of tension.

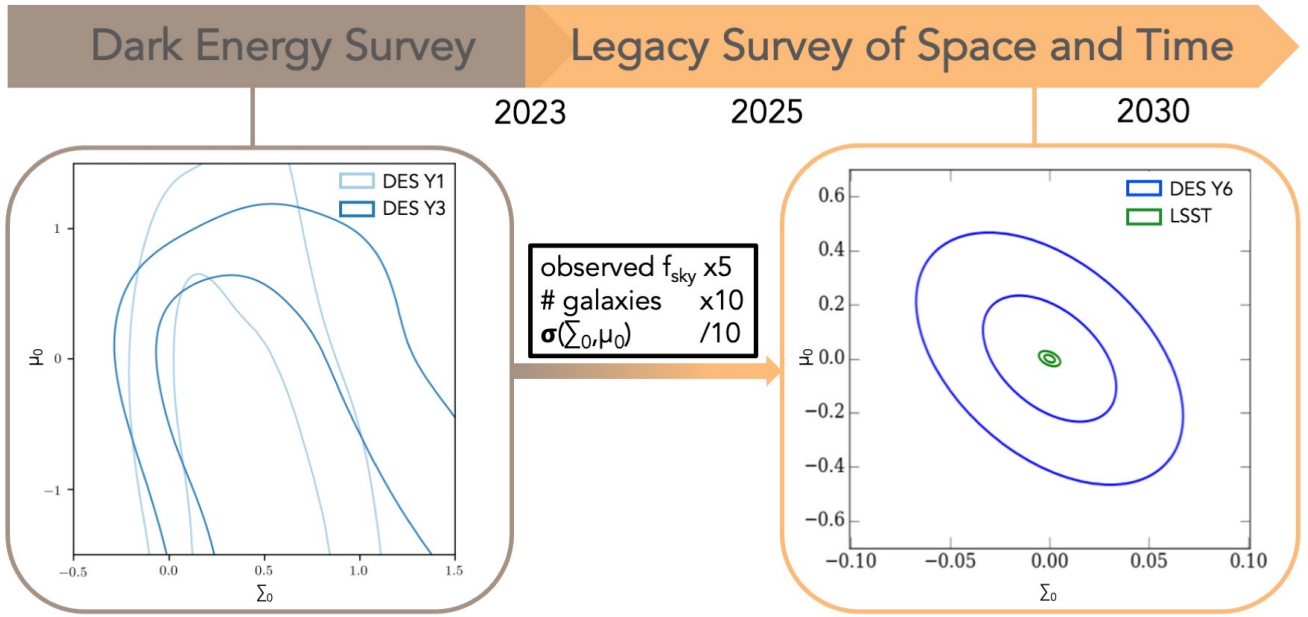
Lemos, Raveri et al, MNRAS, 2021

Preparing for the DES legacy and the new weak lensing surveys

- DES Y3 results in 2022/2023:
  - No deviation from ΛCDM detected.
  - Results of combination with CMB lensing data.
- Many challenges need to be solved for the future:
  X_{lens} issue, improve modeling of 3x2pt in beyond ΛCDM models, …
- Exploration beyond 3x2pt: cosmology from deep learning.
  AF co–PI with Tomasz Kacprzak of NERSC NESAP proposal to develop deep learning algorithms parallelized on GPUs on NERSC Perlmutter.
- We are working hard on DES Y6 data to do the final cosmological analyses of DES probes.

DES Y6 workshop in Chicago last week

The future of tests of gravity



Rubin Observatory (LSST) in March