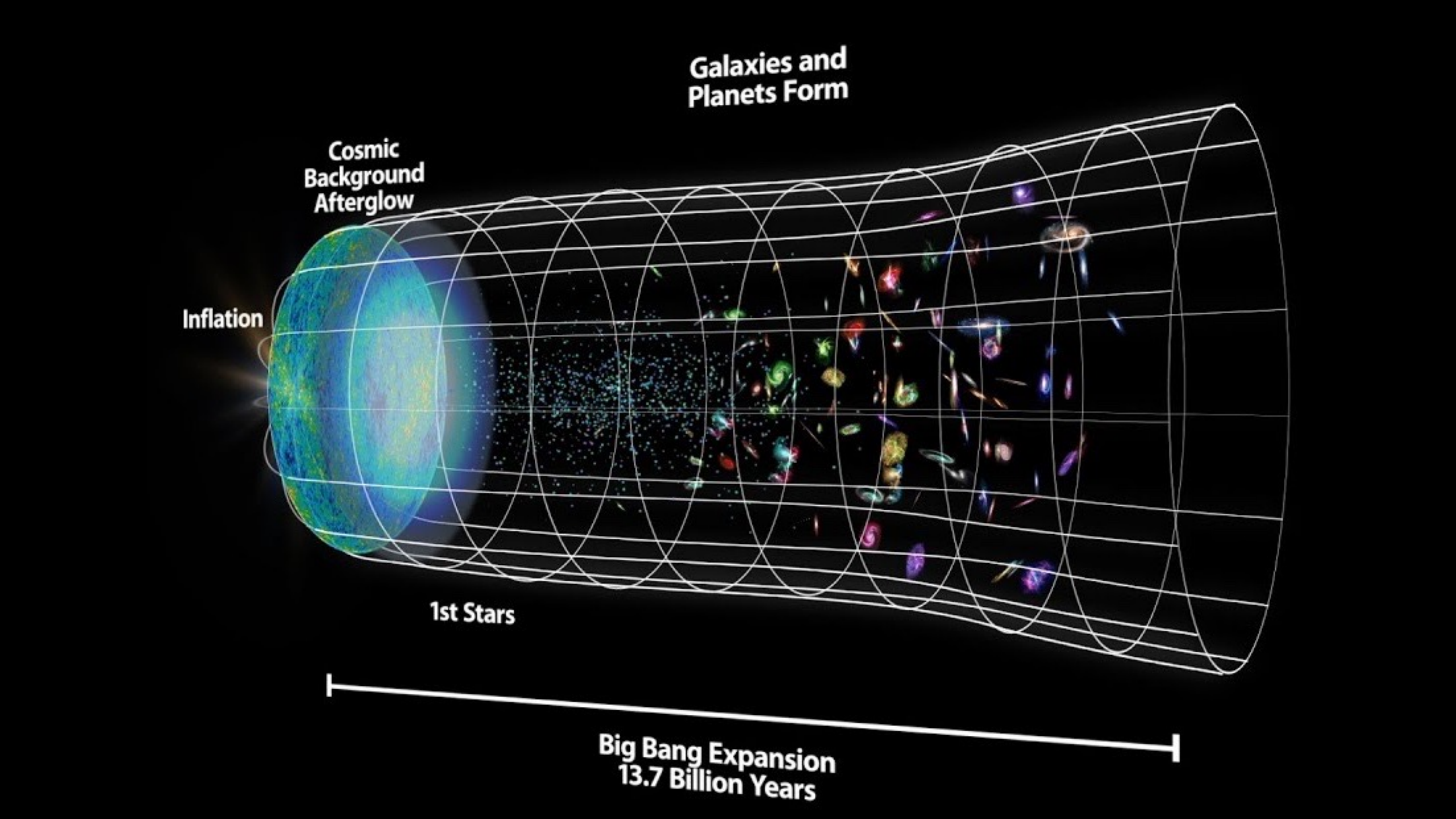
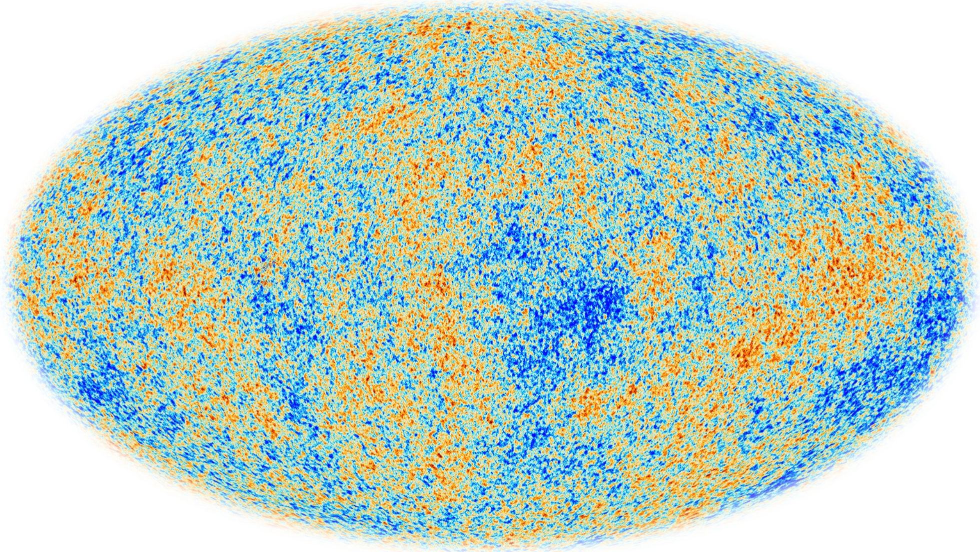
Weak Lensing Cosmology: Status and Prospects

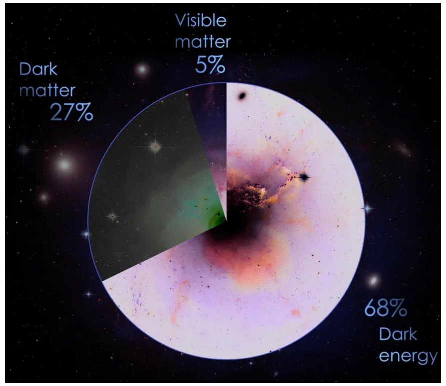
Agnès Ferté
SLAC/KIPAC

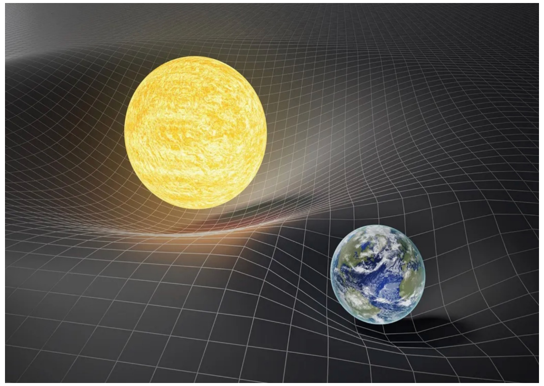

Galaxies and
Planets Form
Cosmic
Background
Afterglow
Inflation
1st Stars
Big Bang Expansion
13.7 Billion Years

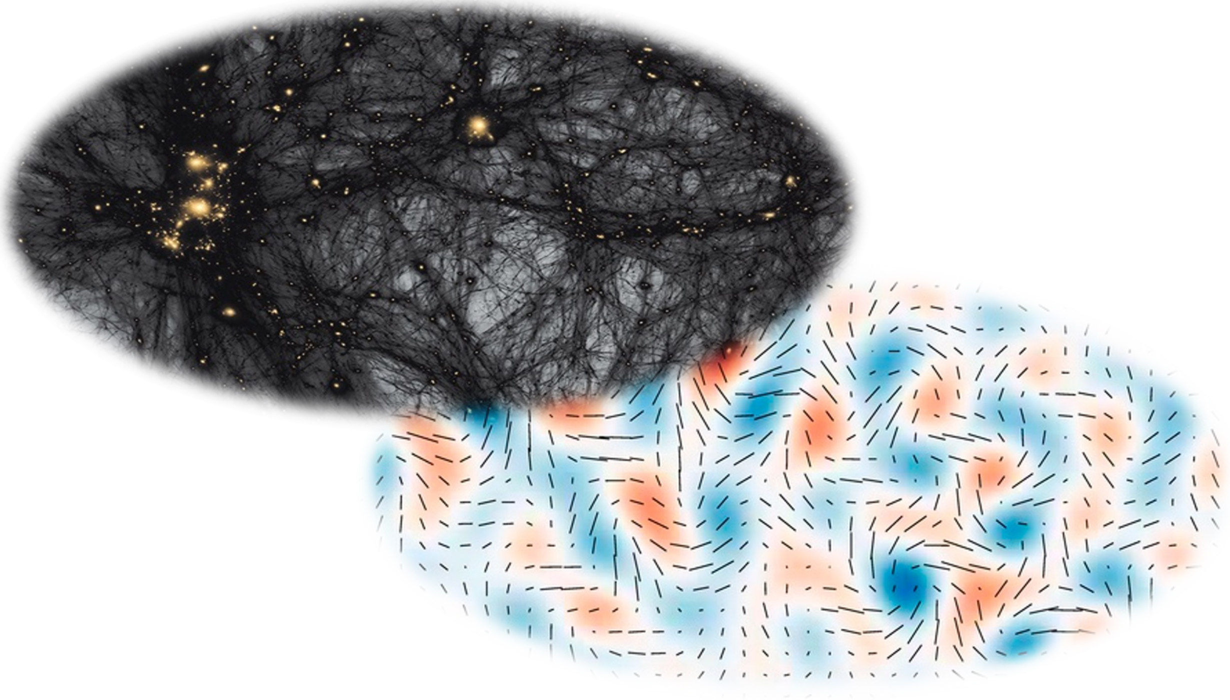
2010s 2020s



The Standard Model of Cosmology
is precisely measured



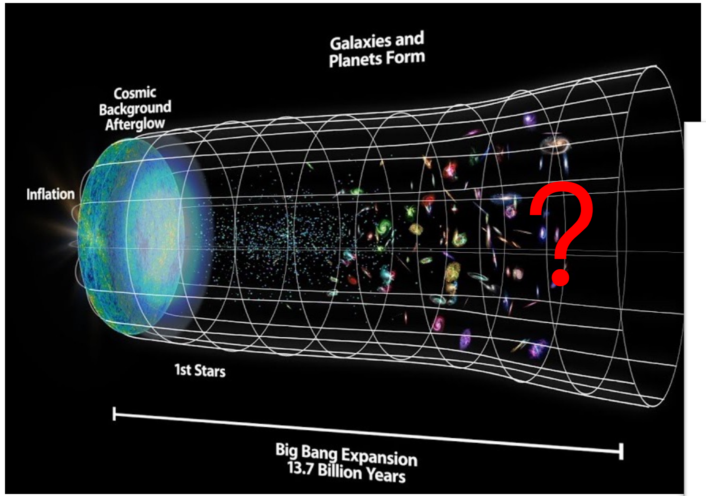




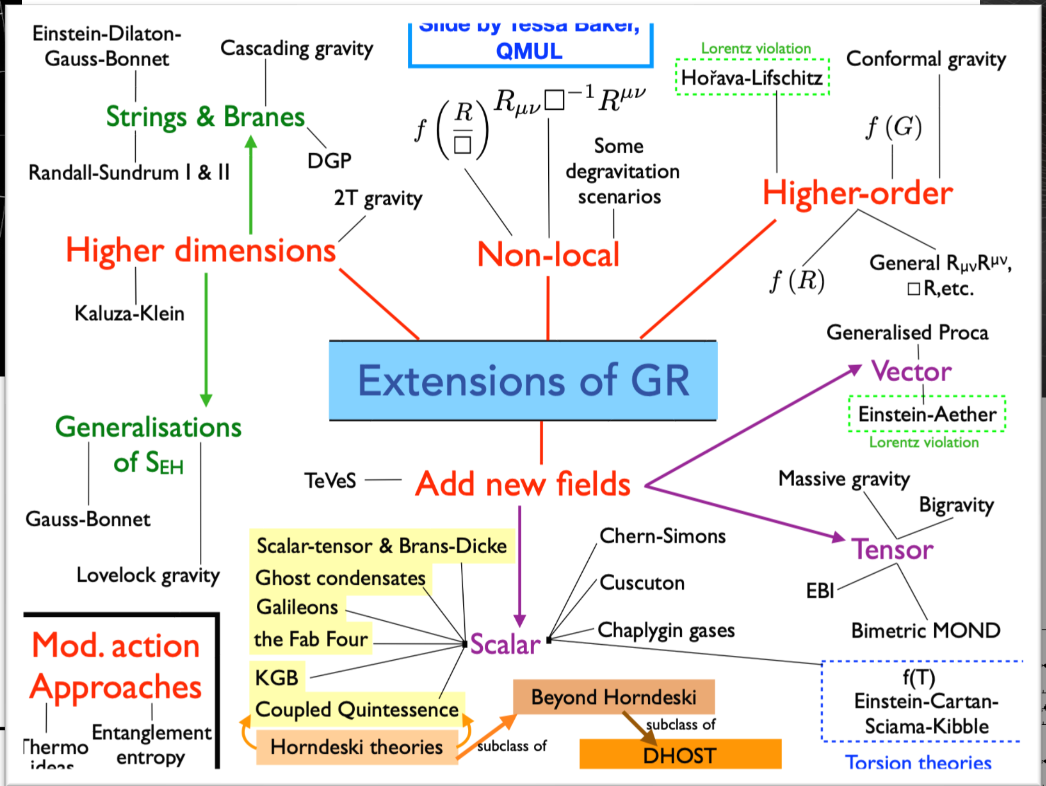
- What is causing **cosmic acceleration**?
- What is **dark matter**?
- What is the **mass of neutrinos**?
- Did **cosmic inflation** happen?

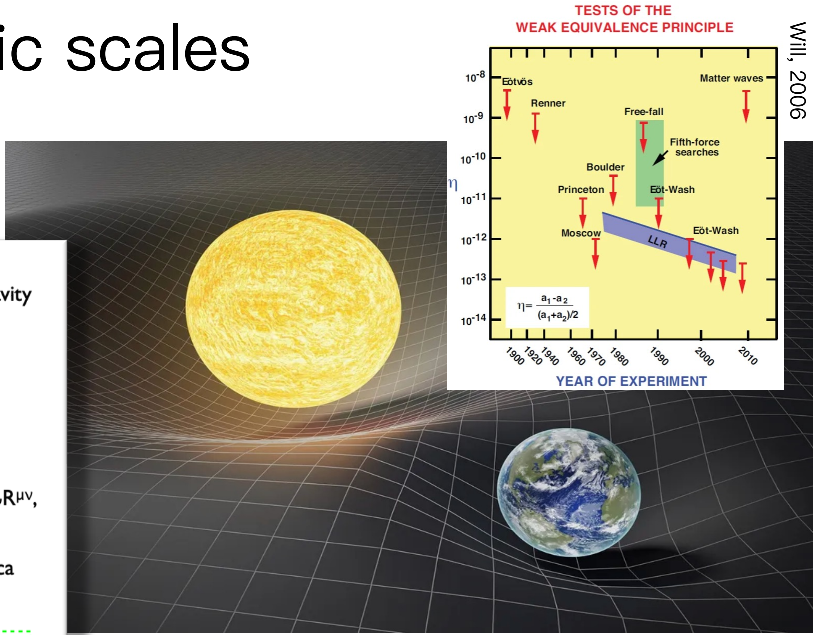
Credits: Planck collaboration, BICEP2, KIPAC/AMNH

Challenging General Relativity on cosmic scales



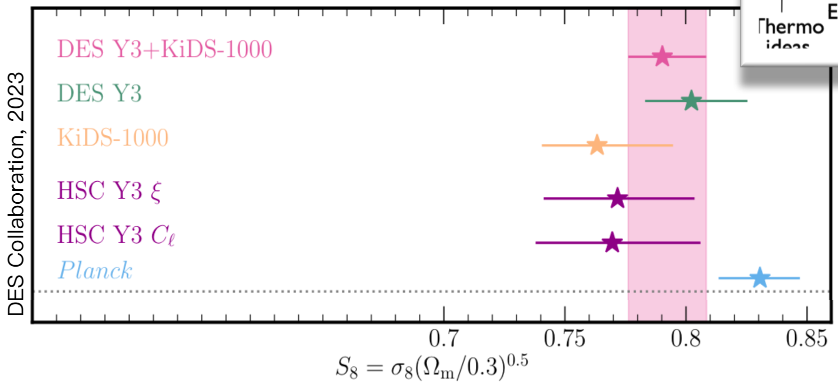
*What is causing **cosmic acceleration**?*

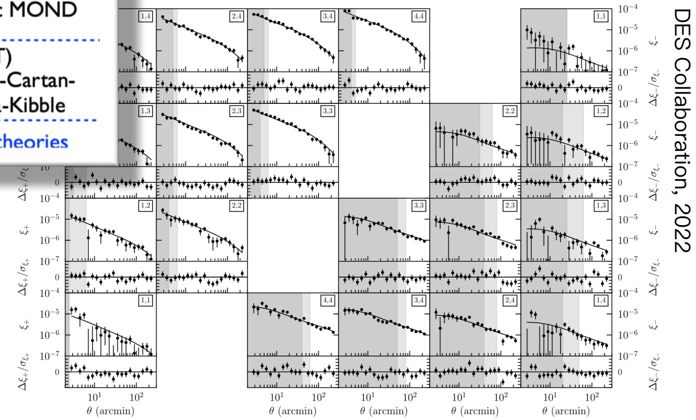




*Is General Relativity (GR) **correct** on cosmological scales?*

*Why is there a S_8 **tension**?*

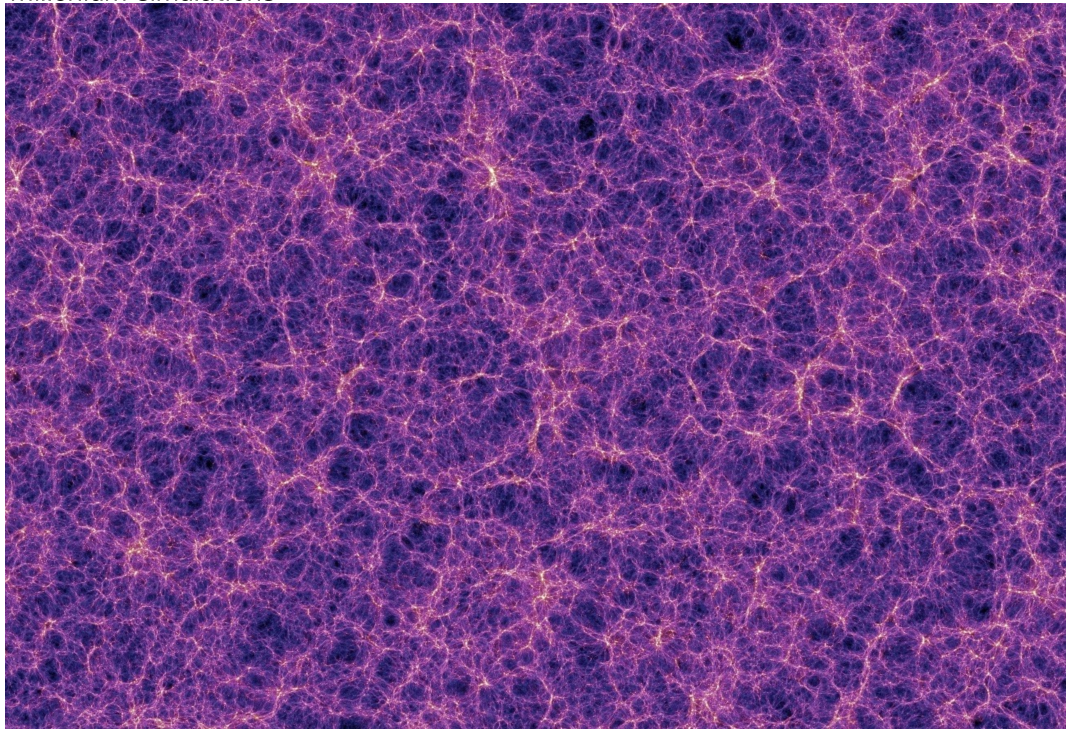




*How much can we extract from our **data**?*

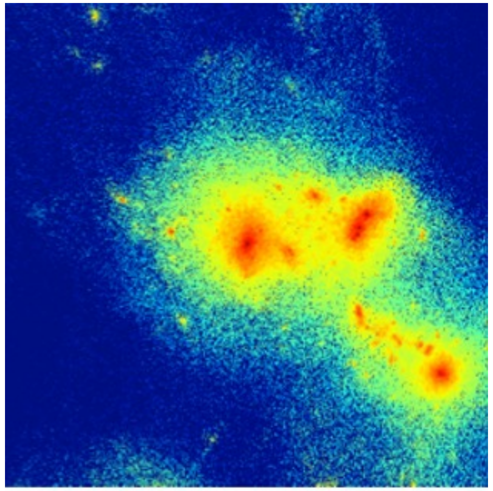
The Universe as a laboratory to test gravity

Millenium simulations

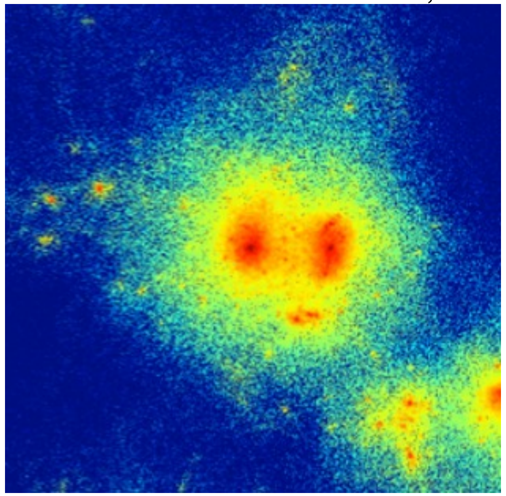


- Gravity impacts:
  - the **evolution** of matter distribution in the Universe
  - the **path of light**
- Cosmology offers a **unique** test of gravity in regime different from gravitational waves

Corbett Moran et al, 2015



General Relativity



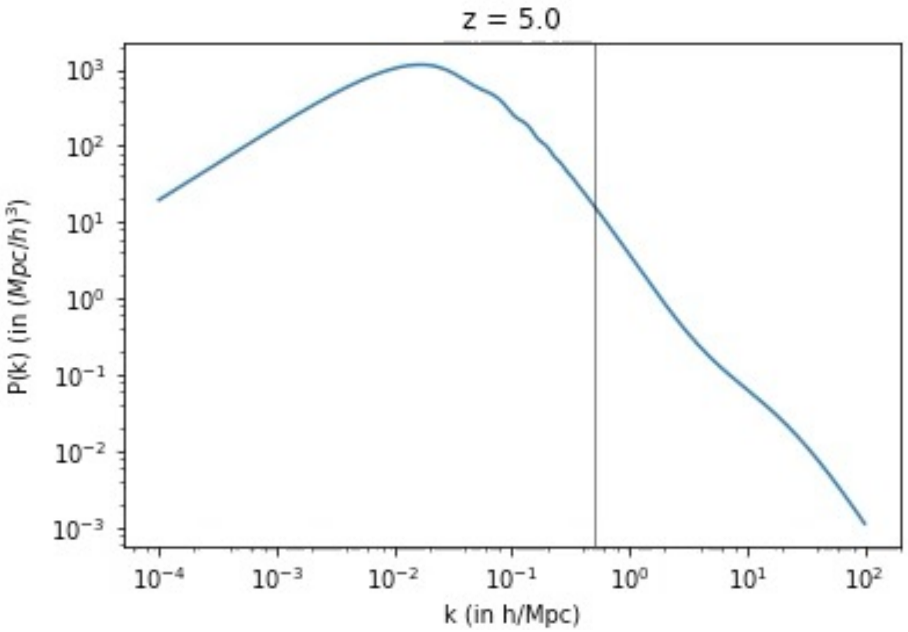
Modified gravity

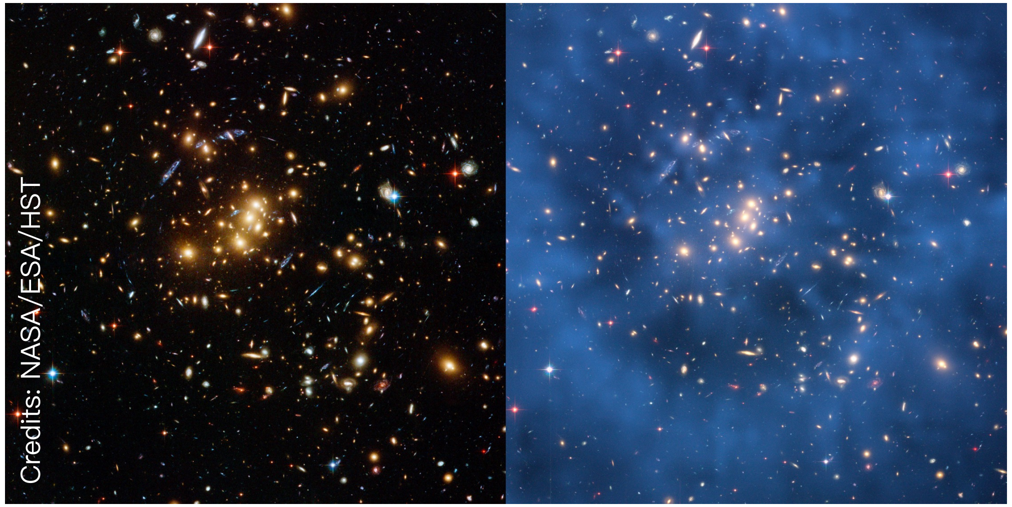
Mapping matter with galaxy surveys

Use galaxies as:

- **tracers** of (dark) matter large-scale structure,
- **background** light,

to statistically probe the matter power spectrum P(k,z)



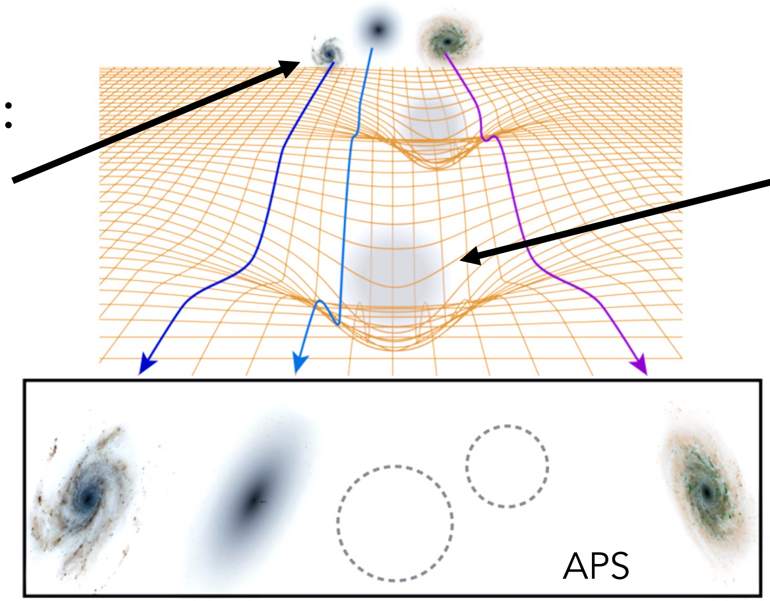


Weak lensing

By Jim Bosch

Galaxies are weakly lensed by **large-scale structures on the line of sight**
→ **Geodesics** are modified
→ **Shapes** of galaxies appear coherently more elliptical

Source galaxies ellipticities:
- ellipticity from WL <1%
- intrinsic ellipticity ~30%
- other effects



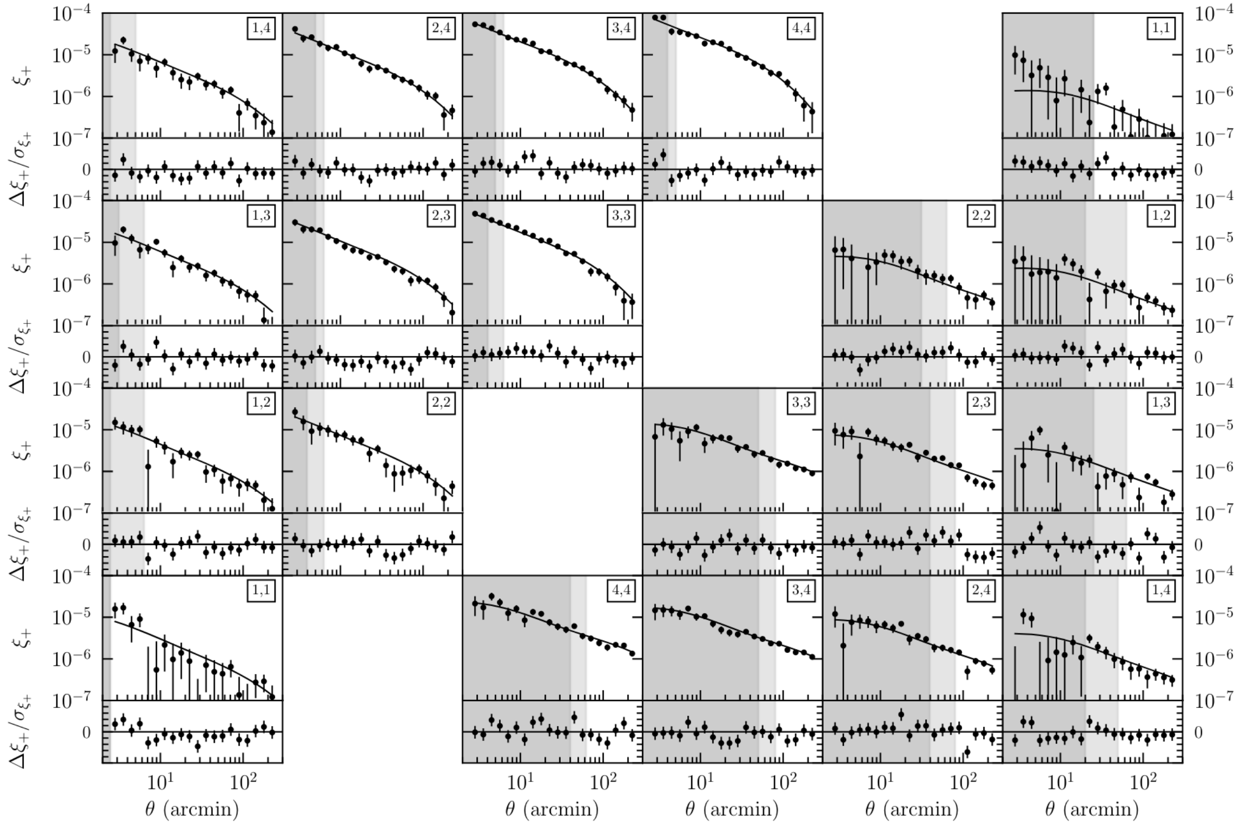
Lens galaxies position:
trace dark matter structures

Cosmic shear

Cosmic shear is summarized as:

$$\xi_{\pm}(\theta) := \langle \gamma_{\rm t}\gamma_{\rm t}\rangle \pm \langle \gamma_{\times}\gamma_{\times}\rangle$$

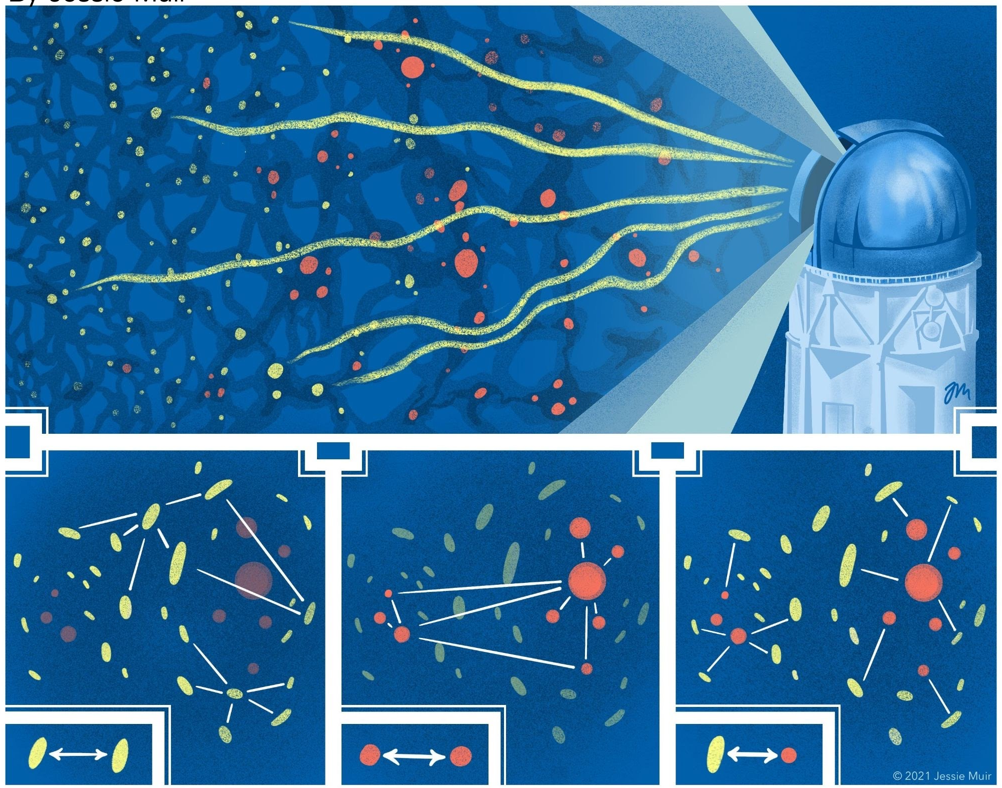
→ Directly probing the matter distribution.



DES Collaboration, PRD, 2022

Fully unlocking the growth of structures from weak lensing

By Jessie Muir



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

3x2pt is especially sensitive to S_8, dark energy, gravity.

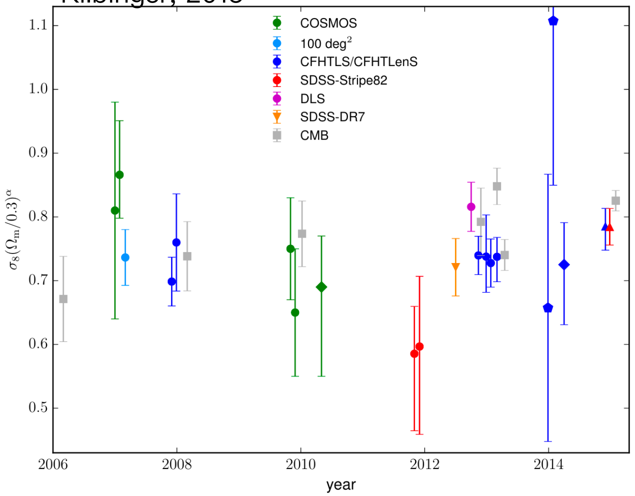
$$S_8 = \sigma_8(\Omega_\mathrm{m}/0.3)^{0.5}$$

Weak lensing experimental landscape

2000 2010 2020

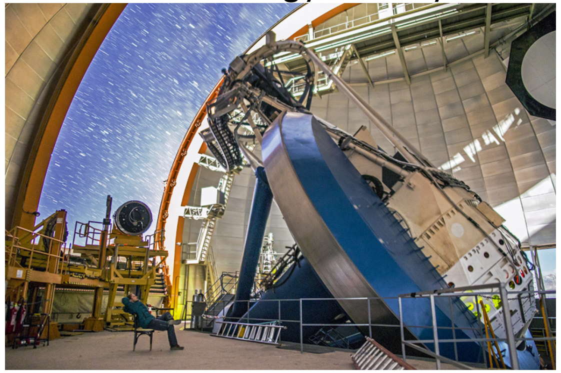
First cosmic shear measurements

Kilbinger, 2015



Stage–III surveys

Dark Energy Survey



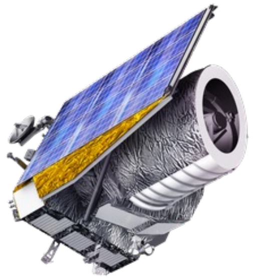
KiDS

HSC

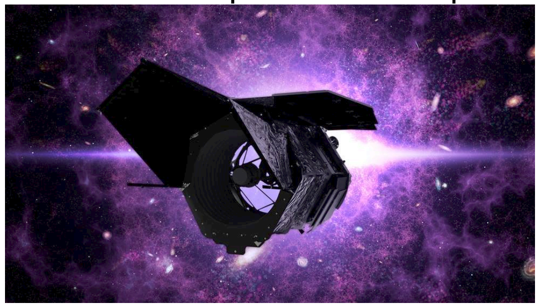
Stage–IV surveys

Vera C. Rubin Observatory

Euclid



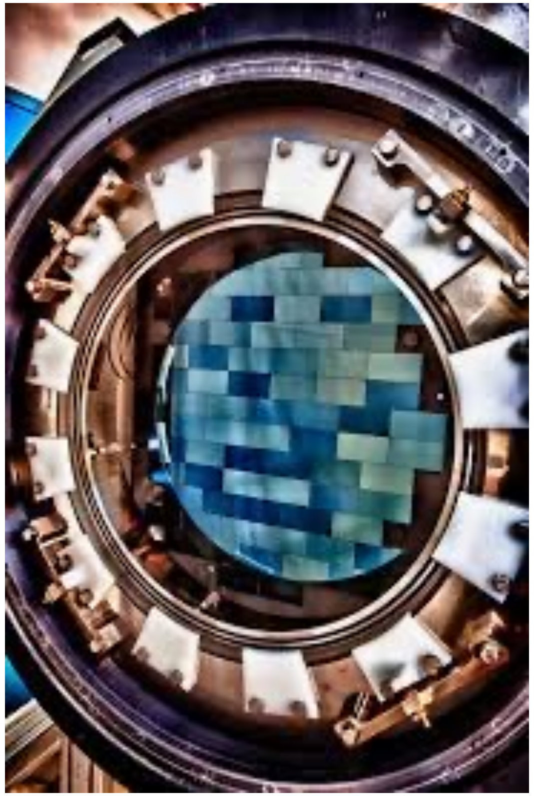
Roman space telescope

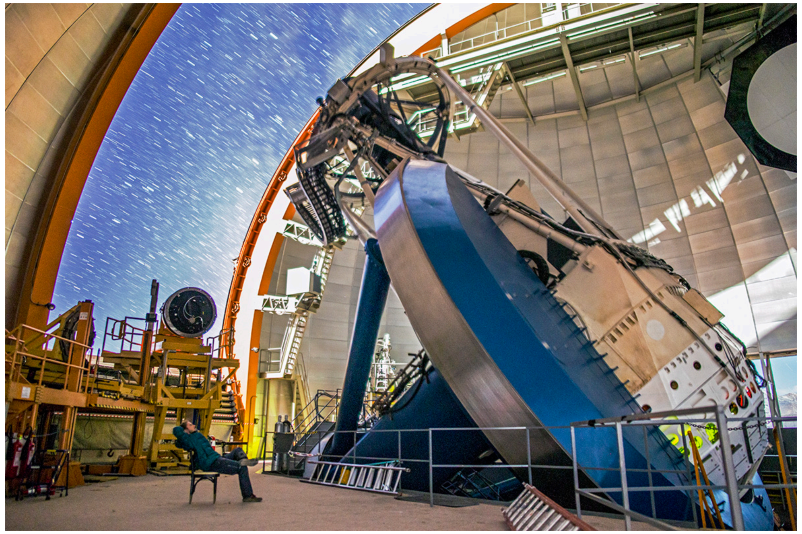


The Dark Energy Survey: precursor of stage–IV surveys

A wide photometric **map** of the Southern Sky:

- **6–year** survey by DECam at CTIO Blanco–4m in **5 optical** bands over **10%** of the sky.
- 700M objects detected.





Rich science:

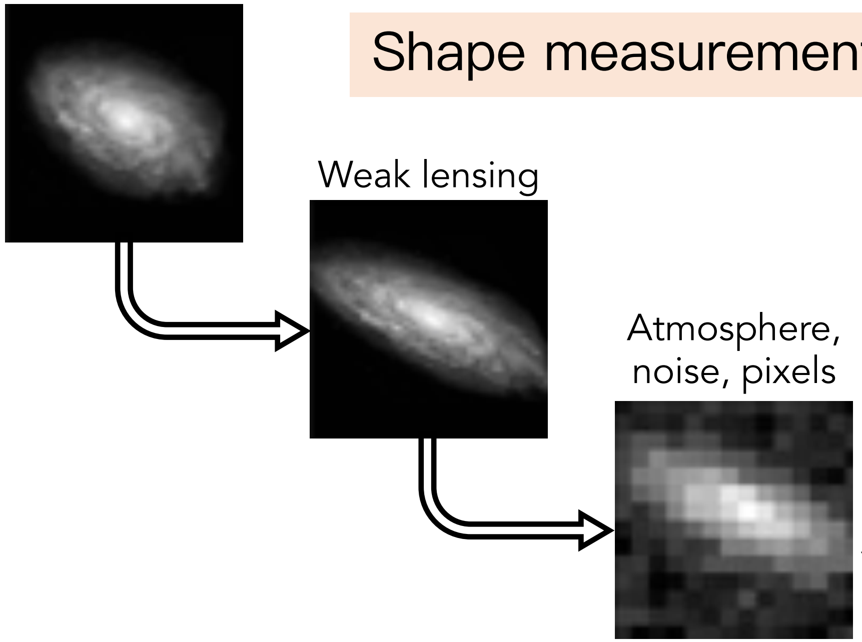
- **Multi–probe precision** Cosmology,
- **Discovery** of new solar system bodies,
- **Mapping** of surroundings of the Milky Way,
- **Follow–up** imaging,
- **Detection** of strong lensing systems.

Find our data at:
https://des.ncsa.illinois.edu/releases/y3a2

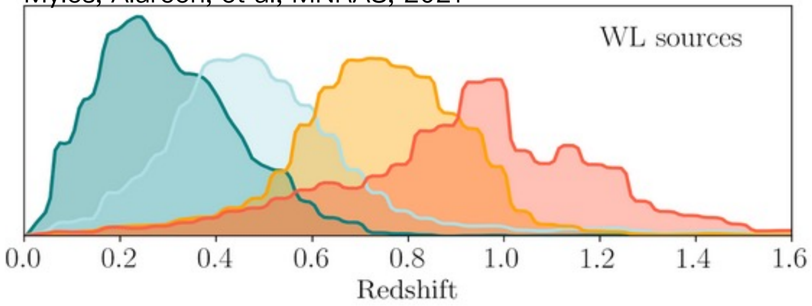
Picture credits: DES Collaboration

Cosmology from 3x2pt

Shape measurements

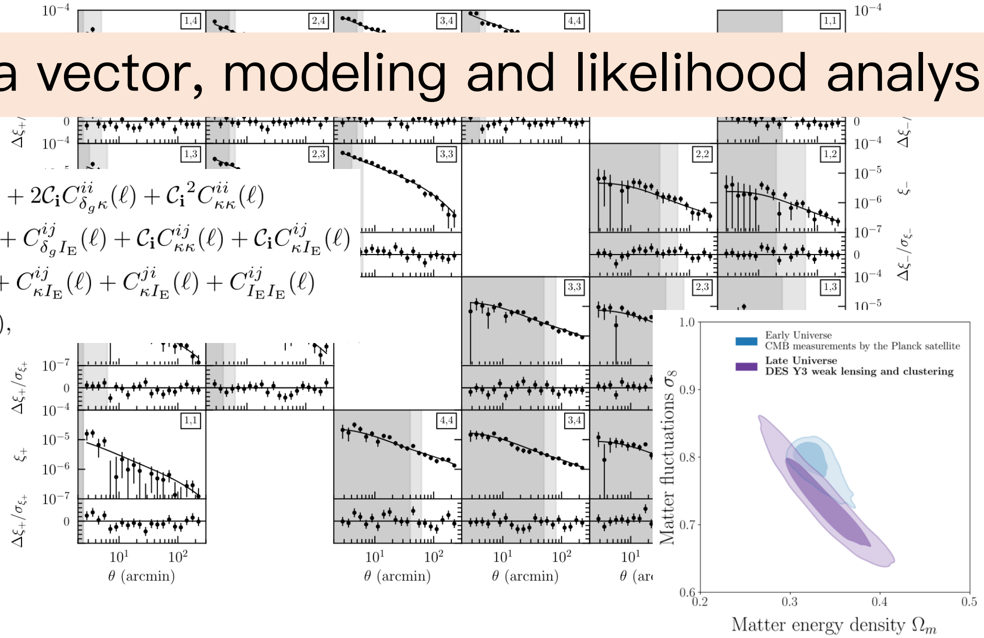


Myles, Alarcon, et al, MNRAS, 2021



Photometric redshift

Data vector, modeling and likelihood analysis

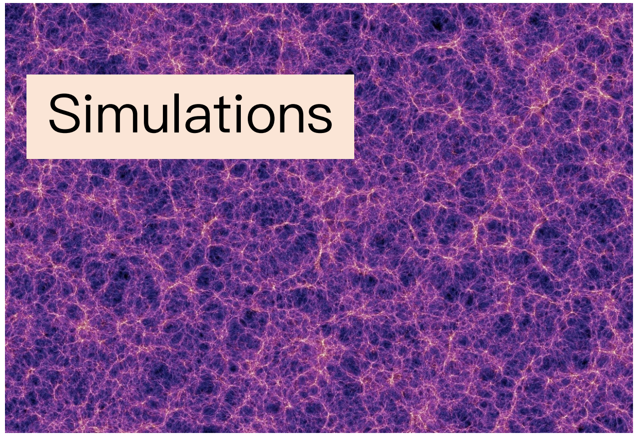


$$C^{ii}_{\delta_g\delta_g}(\ell) = C^{ii\prime}_{\delta_g\delta_g}(\ell) + 2\mathcal{C}_{\mathrm{i}} C^{ii}_{\delta_g\kappa}(\ell) + \mathcal{C}_{\mathrm{i}}^2 C^{ii}_{\kappa\kappa}(\ell)$$

$$C^{ij}_{\delta_g \mathrm{E}}(\ell) = C^{ij\prime}_{\delta_g\kappa}(\ell) + C^{ij}_{\delta_g I_{\mathrm{E}}}(\ell) + \mathcal{C}_{\mathrm{i}} C^{ij}_{\kappa\kappa}(\ell) + \mathcal{C}_{\mathrm{i}} C^{ij}_{\kappa I_{\mathrm{E}}}(\ell)$$

$$C^{ij}_{\mathrm{EE}}(\ell) = C^{ij\prime}_{\kappa\kappa}(\ell) + C^{ij}_{\kappa I_{\mathrm{E}}}(\ell) + C^{ji}_{\kappa I_{\mathrm{E}}}(\ell) + C^{ij}_{I_{\mathrm{E}} I_{\mathrm{E}}}(\ell)$$

$$C^{ij}_{\mathrm{BB}}(\ell) = C^{ij}_{I_{\mathrm{B}} I_{\mathrm{B}}}(\ell),$$

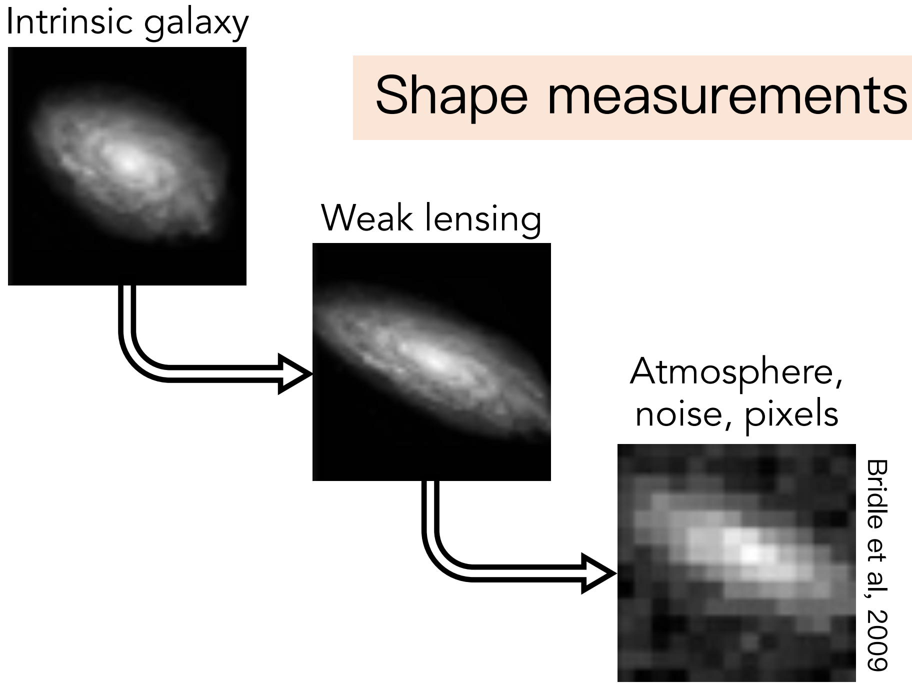


Simulations

Modeling of 3x2pt

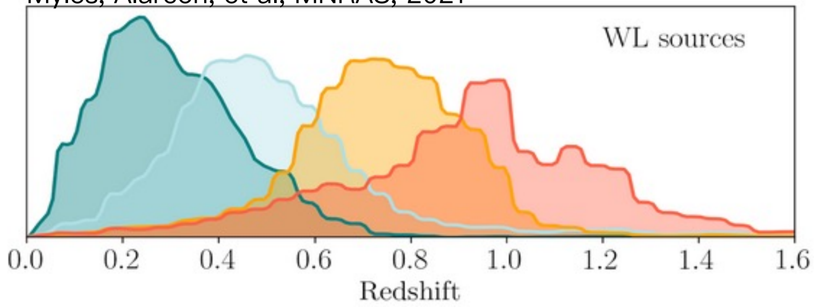
- Non–linear **matter power spectrum**: halofit + no baryonic feedback
- **Intrinsic alignment**: TATT model
- **Galaxy bias**: linear galaxy bias
- + non–limber, magnification, etc.

$$C^{ii}_{\delta_g\delta_g}(\ell) = C^{ii\prime}_{\delta_g\delta_g}(\ell) + 2\mathcal{C}_{\rm i}C^{ii}_{\delta_g\kappa}(\ell) + {\mathcal{C}_{\rm i}}^2 C^{ii}_{\kappa\kappa}(\ell)$$
$$C^{ij}_{\delta_g{\rm E}}(\ell) = C^{ij\prime}_{\delta_g\kappa}(\ell) + C^{ij}_{\delta_g I_{\rm E}}(\ell) + \mathcal{C}_{\rm i}C^{ij}_{\kappa\kappa}(\ell) + \mathcal{C}_{\rm i}C^{ij}_{\kappa I_{\rm E}}(\ell)$$
$$C^{ij}_{\rm EE}(\ell) = C^{ij\prime}_{\kappa\kappa}(\ell) + C^{ij}_{\kappa I_{\rm E}}(\ell) + C^{ji}_{\kappa I_{\rm E}}(\ell) + C^{ij}_{I_{\rm E}I_{\rm E}}(\ell)$$
$$C^{ij}_{\rm BB}(\ell) = C^{ij}_{I_{\rm B}I_{\rm B}}(\ell),$$



Shape measurements

Myles, Alarcon, et al, MNRAS, 2021

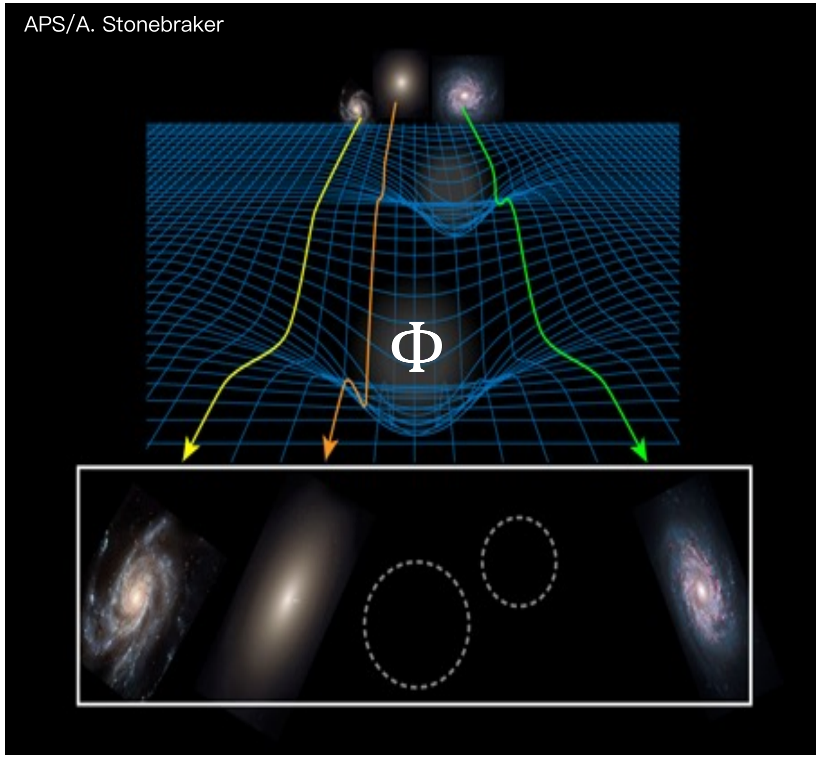


Photometric redshift

Multiplicative **shear calibration** parameter.

Shift and width of the **n(z)**.

Testing gravity through metric perturbations



Are modifications to the potential causing weak lensing as expected in GR?

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

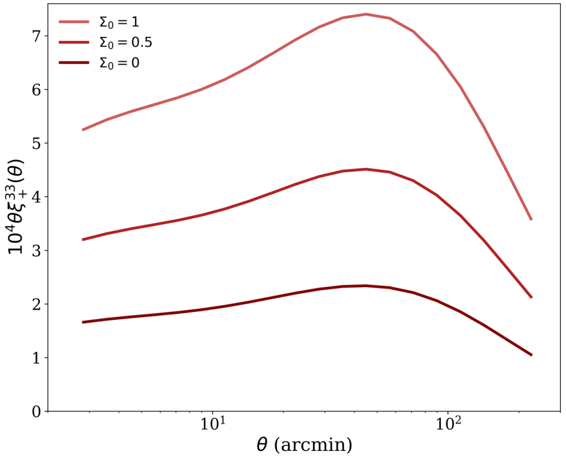
Mass = 0 : modifies **geodesics**

Σ_0 = 0 in GR

$$k^2\psi = -4\pi G a^2(1+\mu_0\Omega_\Lambda(t))\rho\delta$$

Mass ≠ 0 : modifies **dynamics**

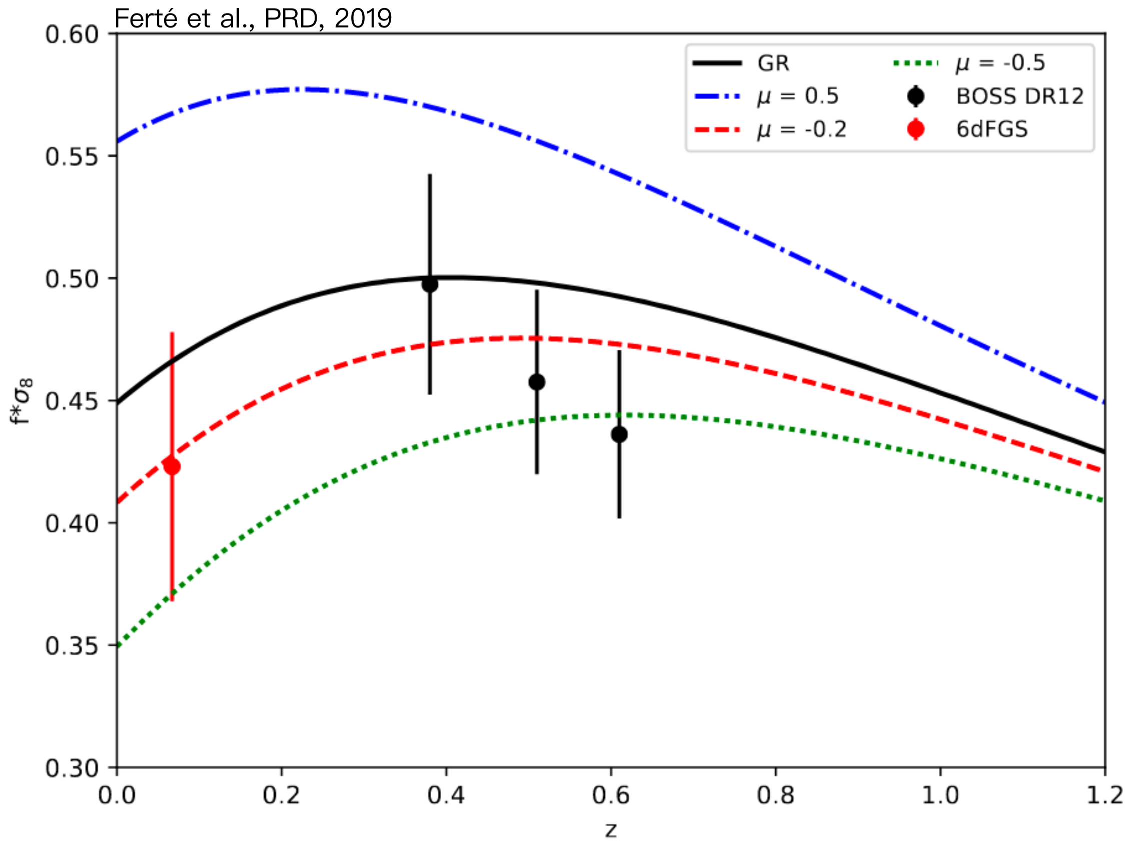
μ_0 = 0 in GR



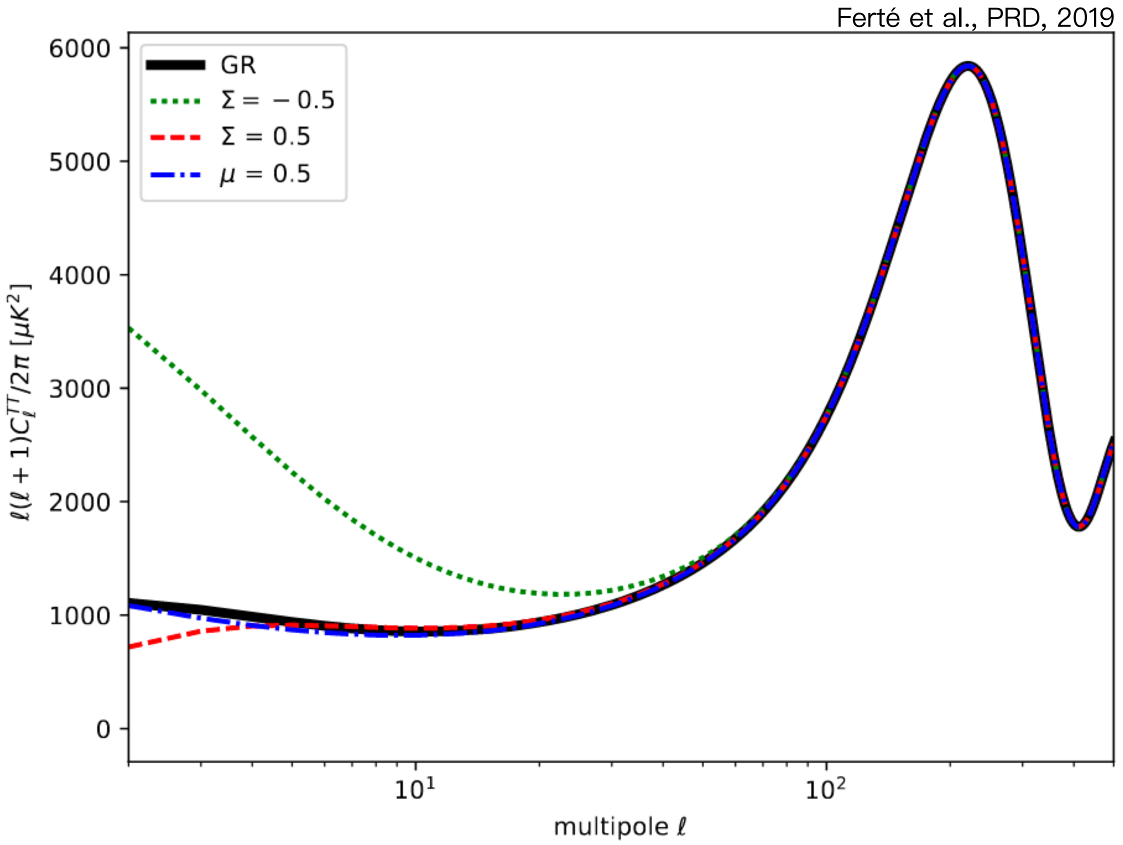
Σ_0 (stronger gravity)

Complementary observables

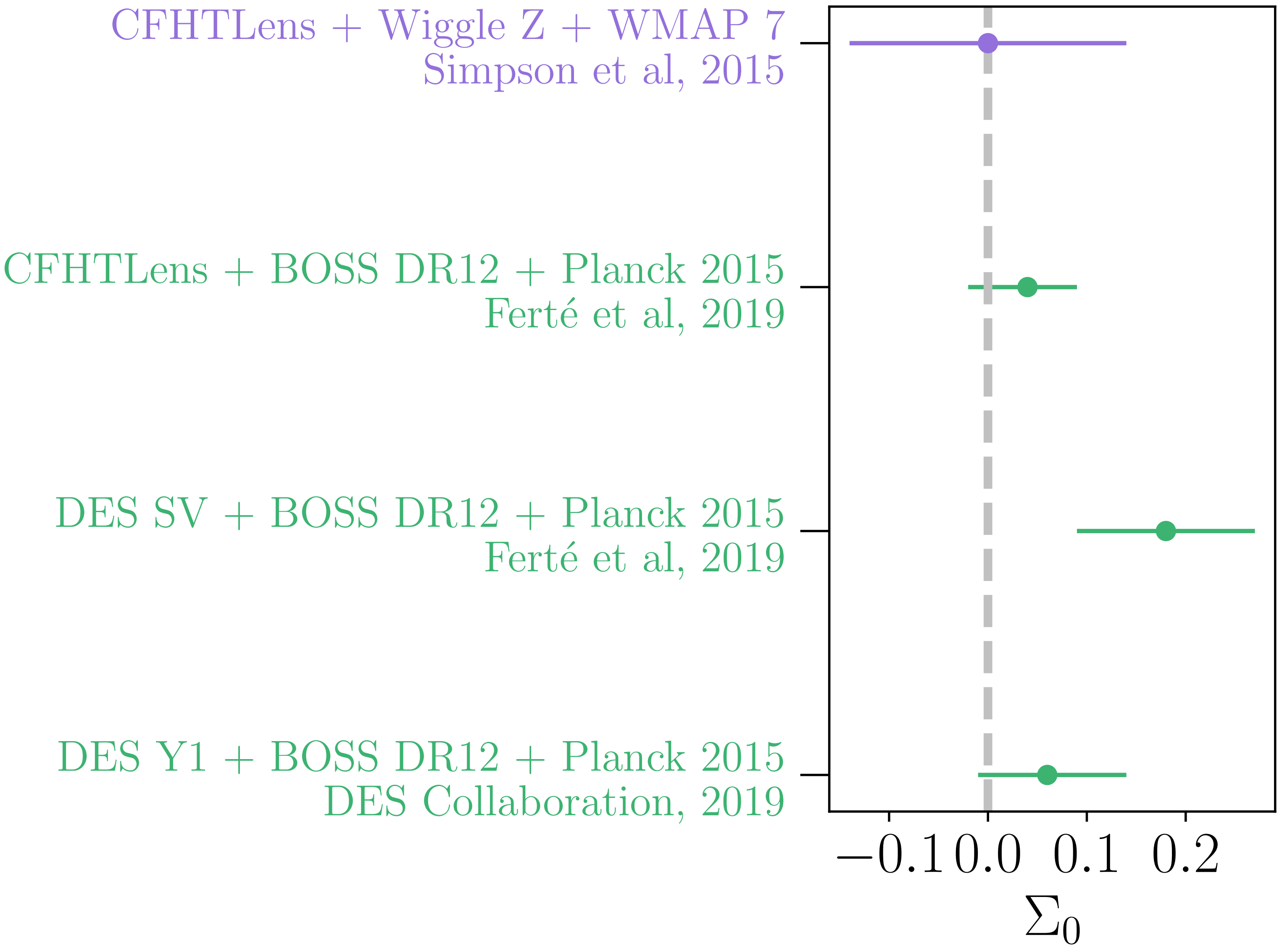
RSD → μ_0



CMB Temperature and polarization power spectra → Σ_0,μ_0



History of Σ_0 measurements



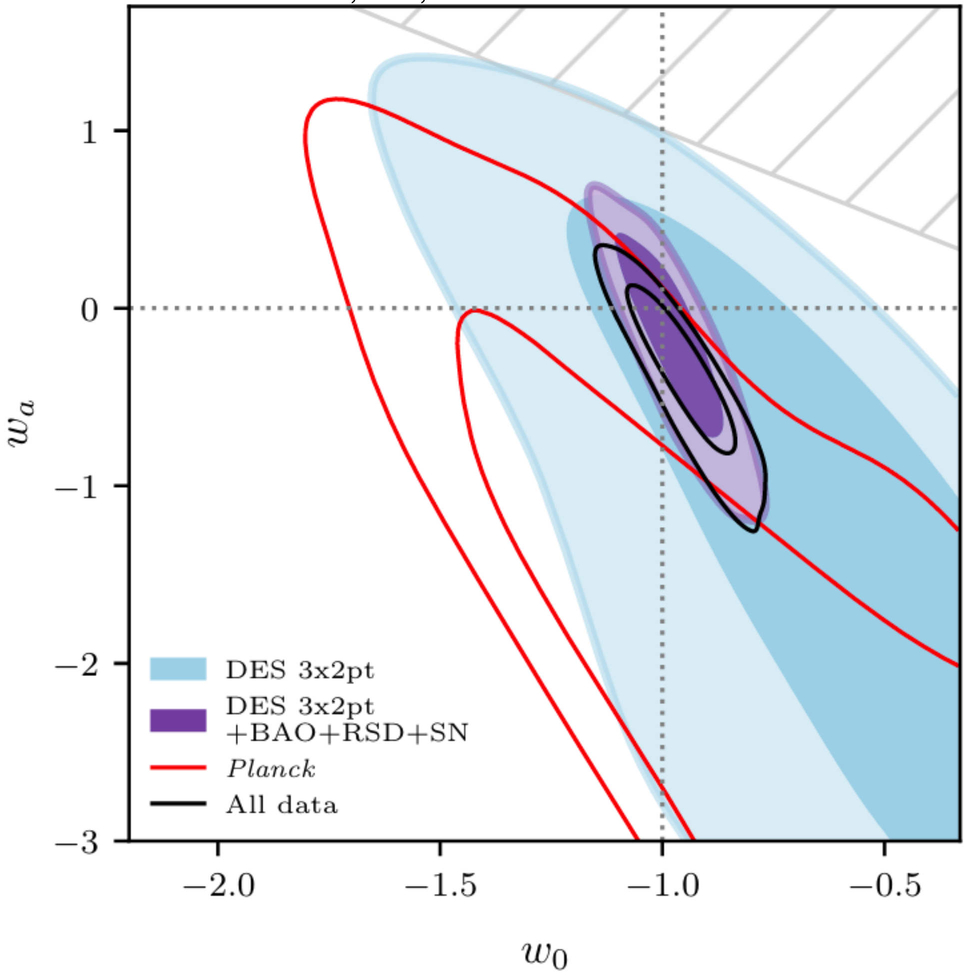
Σ_0 with DES Year 3 3x2pt

- DES extensions team
  Co–leads: AF and Jessie Muir

  Noah Weaverdyck, Otávio Alves, Sujeong Lee, Paul Rogozenski, Danielle Leonard, Angela Chen, David Sanchez–Cid, Anderson Souza, Marco Raveri, Andrew Liddle, Dragan Huterer, Leonardo Giani, Eleonora Di Valentino, Jonathan Blazek, Cyrille Doux, Vivian Miranda, Ken Herner, …

- **Extensions to ΛCDM considered:**
  - Time dependent dark energy equation of state
  - Non–zero spatial curvature
  - Sterile neutrinos
  - Phenomenological $\sigma_8(z)$ test
  - **Σ,μ test of gravity**

DES collaboration, PRD, 2023

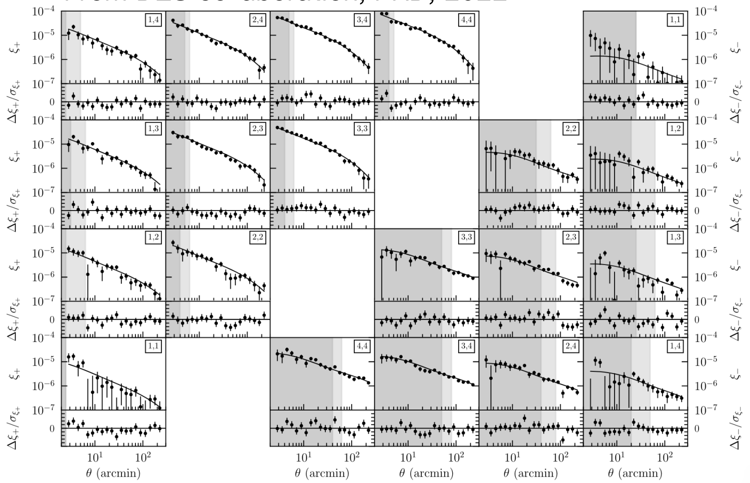


DES Year 3 3x2pt data

$$L(D|p) \sim \exp\left(-\frac{1}{2}[(D - M(p))^T C^{-1}(D - M(p))]\right)$$

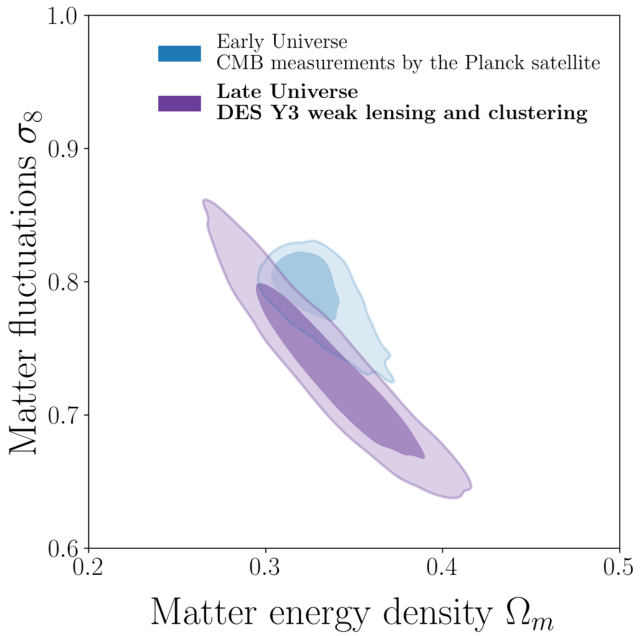
Precise measurements of the 3x2pt data vector

From DES collaboration, PRD, 2022



- **Source** galaxies:
  Largest shape catalog to date = **100M galaxies**
- **Lens** galaxies:
  Optimized for w, 4 z–bins used out of 6.

- DES Y3 3x2pt measurements and ΛCDM results:
  → Cosmology with 4% **precision**
  DES collaboration, PRD, 2022 + 29 papers



Estimation of non-standard physics parameters through Bayesian analysis

$$L(D|p) \sim \exp\left(-\frac{1}{2}[(D - M(p))^T C^{-1}(D - M(p))]\right)$$

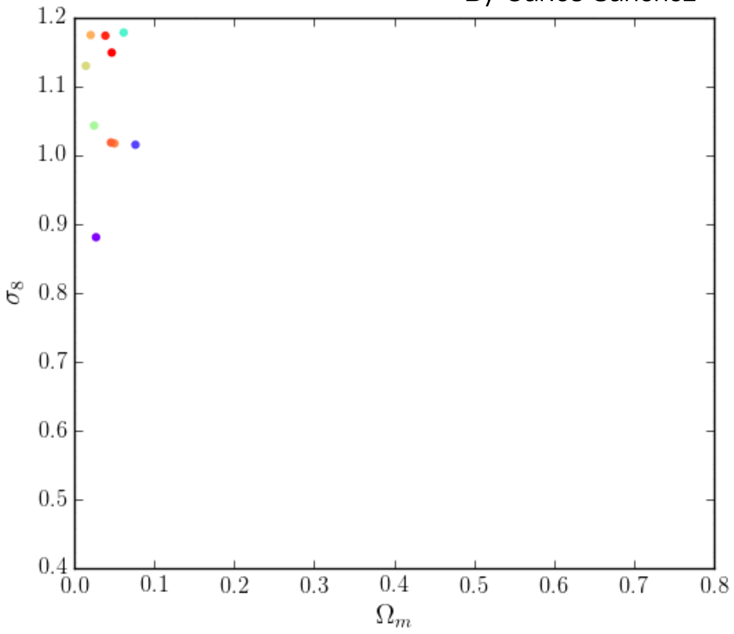
Sampling of the likelihood

- Use CosmoSIS with the **Polychord** sampler.
  validated for DES in ***Lemos, Weaverdyck et al (incl. AF), arxiv:2202.08233***

- 6 cosmological parameters + **extended parameters**
  + 22 nuisance parameters

- Run 700+ chains on HPC
  Use of NERSC, TACC, Sherlock @ Stanford U, GATTACA @ JPL

By Carles Sánchez

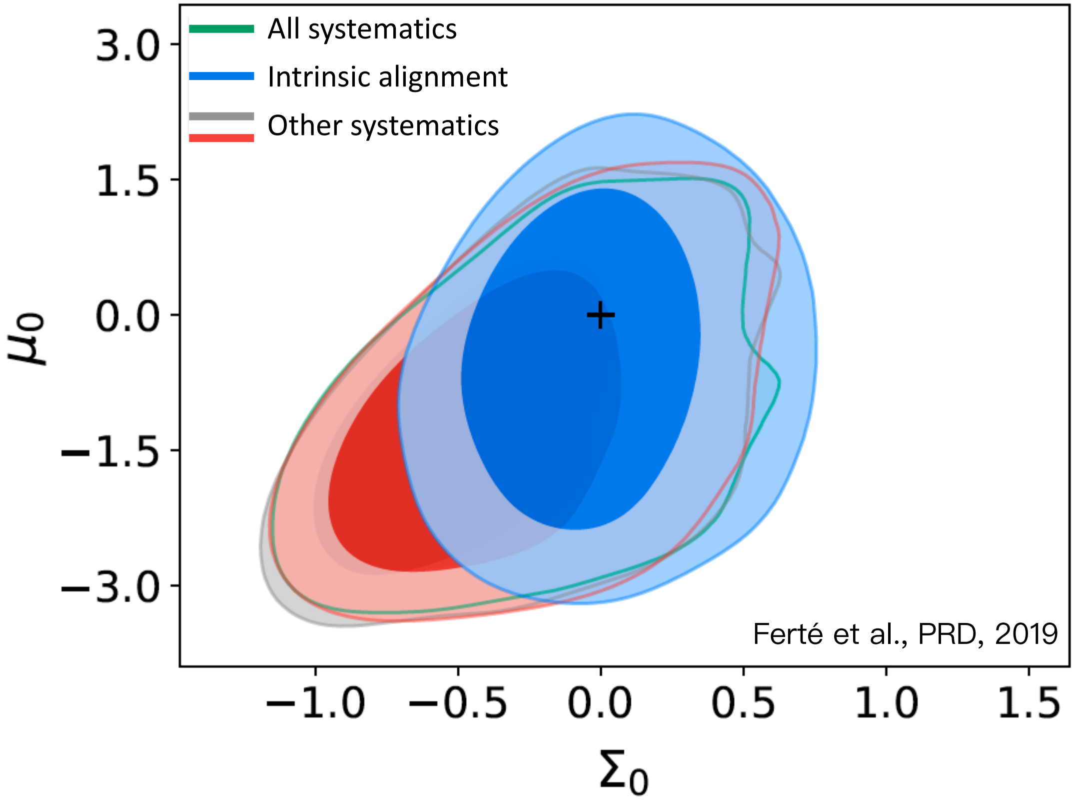


3x2pt modeling in Σ,μ

$$L(D|p) \sim \exp\left(-\frac{1}{2}[(D-M(p))^T C^{-1}(D-M(p))]\right)$$

Accurate modeling of the data vector in extended models

- **Propagation** of the Weyl and matter power spectra to 3x2pt in Σ,μ:
  MGCamb P(k,z) → 3x2pt
- Consistent modeling of intrinsic alignment, galaxy bias, observational effects.
- Impact of non-linearities & baryonic feedback mitigated through **scale cuts**.
- Analysis **blinded** at the level of the parameters and validated against systematics.

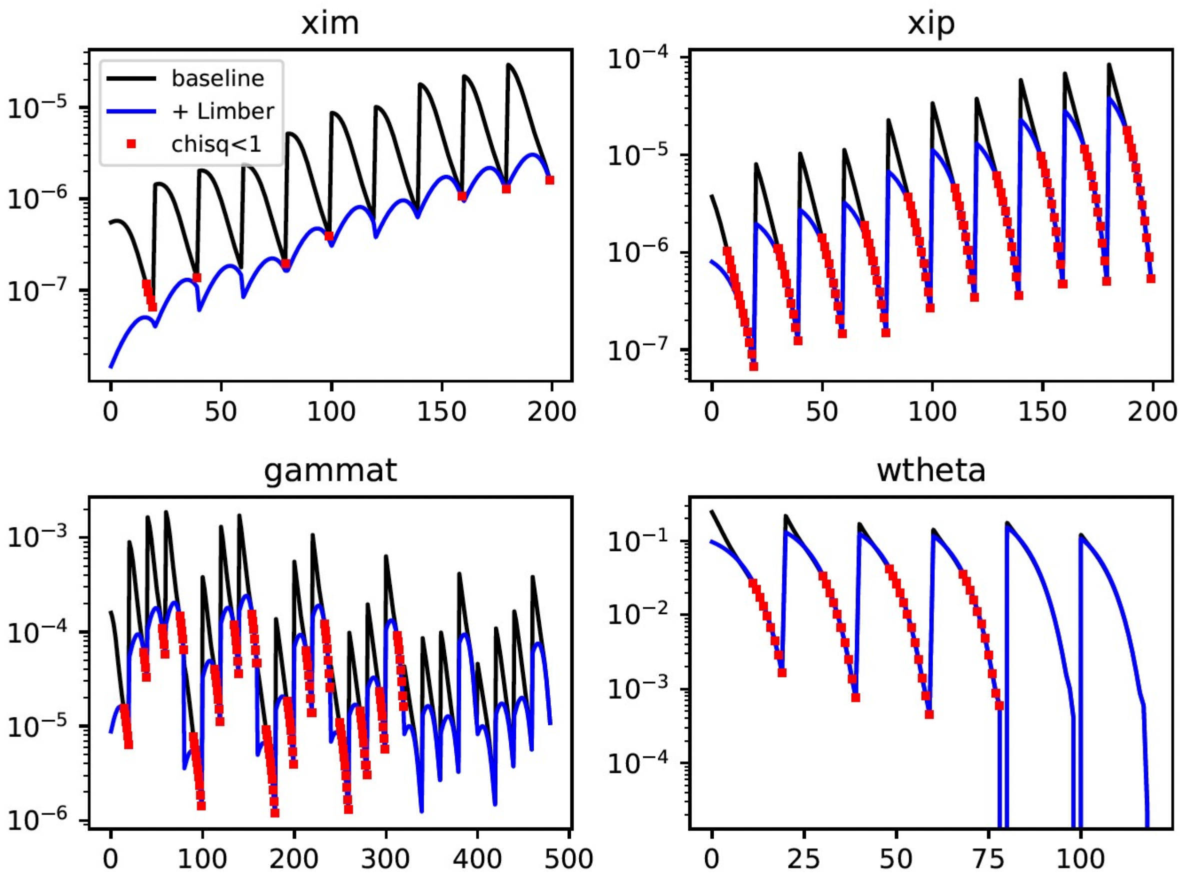


Non–linear power spectrum

Non–linear evolution of matter distribution is described using N–body simulations in LCDM.
Approach:

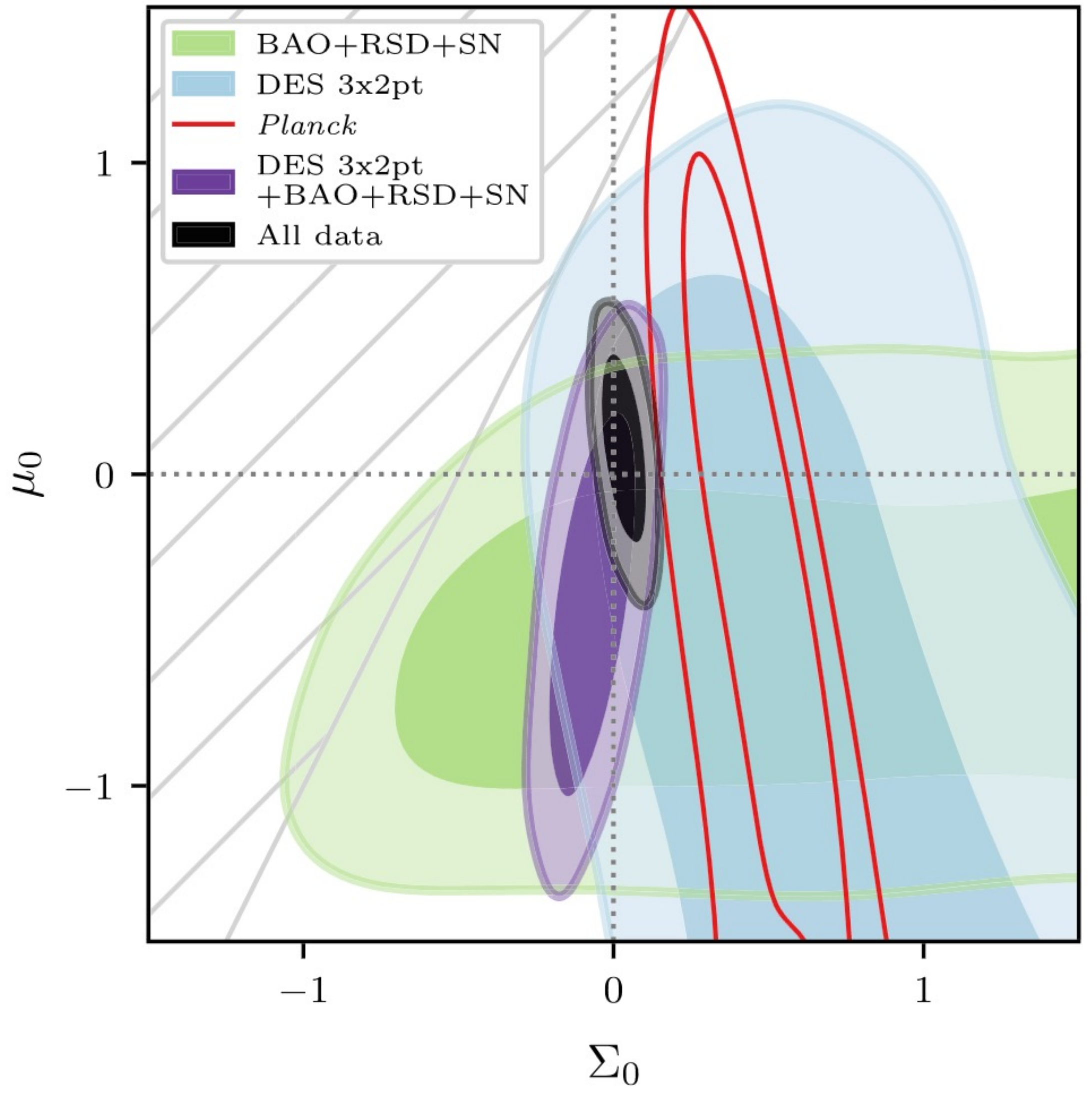
$$\Delta\chi^2 \equiv (\mathbf{D}_{\rm NL} - \mathbf{D}_{\rm lin})^{\rm T}\, \mathbf{C}^{-1}\, (\mathbf{D}_{\rm NL} - \mathbf{D}_{\rm lin}) < 20$$

→ Use **255 data points** from 462 data points used in the LCDM analysis.

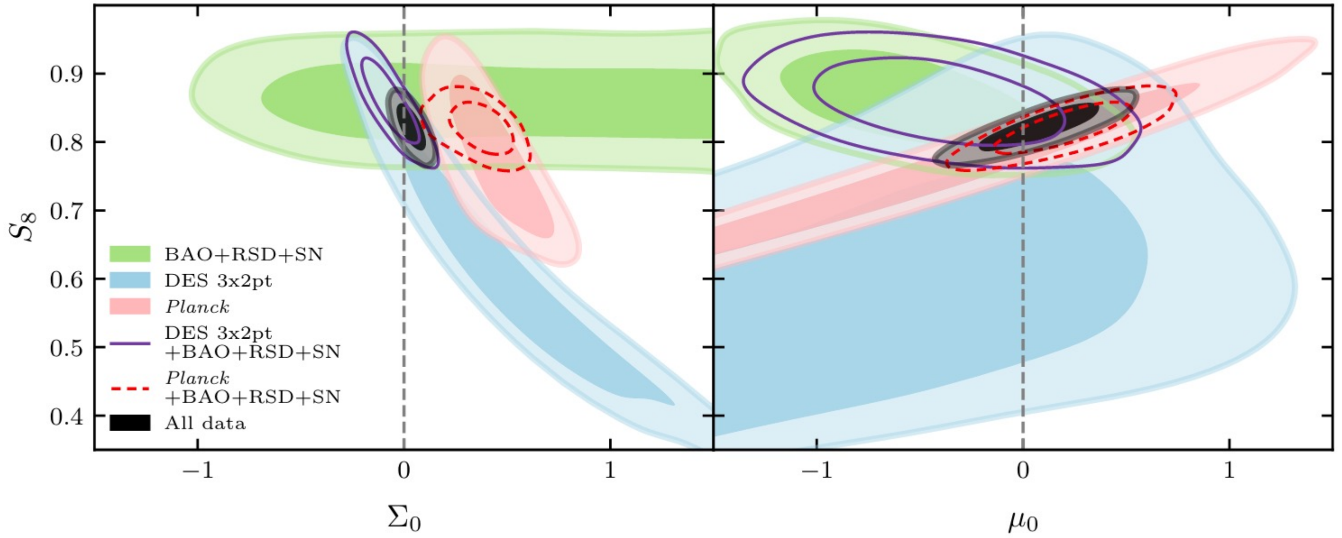


DES Year 3 results on tests of gravity

DES collaboration, PRD, 2023



- DES Year 3 3x2pt constrain Σ_0:
  - **consistent with GR,**
  - limited by scale cuts.
- Planck 2018 in tension?
- Our chains are available at https://dev.des.ncsa.illinois.edu/releases/y3a2/Y3key-extensions

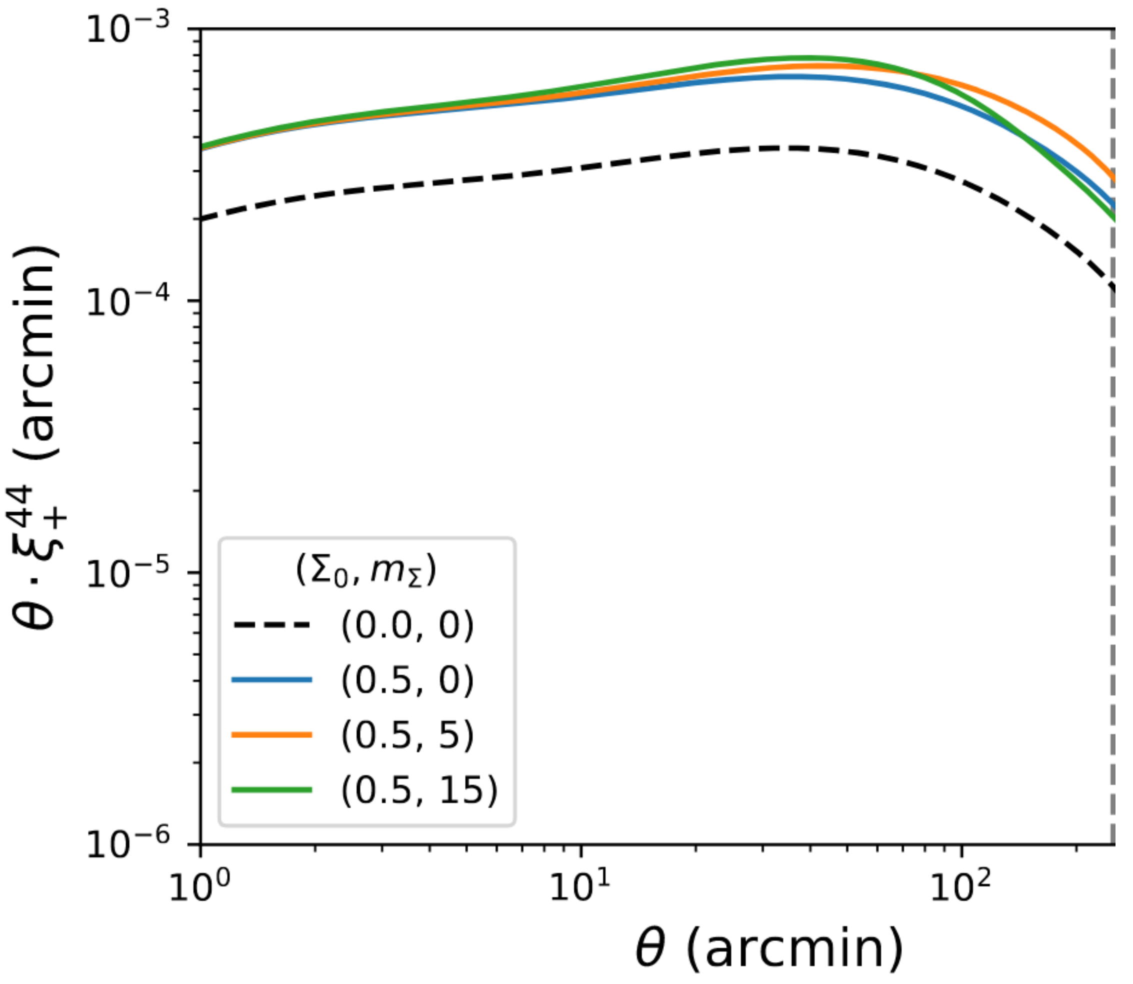


Further tests of gravity

- **Scale**–dependant Σ,μ(a,k):
  Work with student David Shlivko in 2019.
  Model added to MGCamb and validation.

$$\Sigma(a,k) = 1 + \Sigma_0 \cdot \frac{\Omega_\Lambda^{GR}(a)}{\Omega_{\Lambda 0}^{GR}} \cdot \left[1 + \left(\frac{M_\Sigma}{k}\right)^2\right]$$

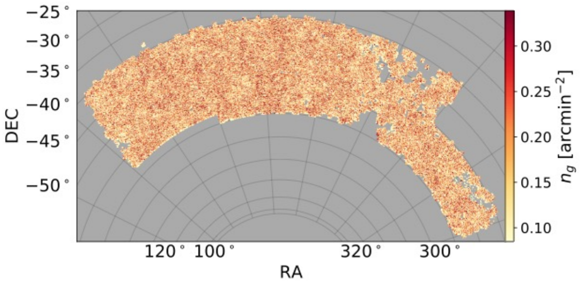
Shlivko, AF et al, in prep

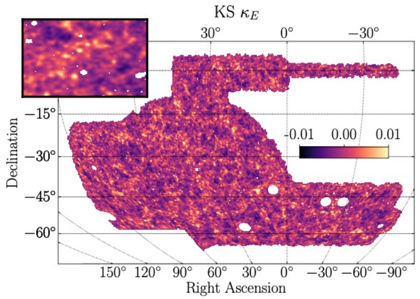


- Other **time** dependence of Σ,μ.
- Other **theories**: f(R), dilaton, …

→ Application to DES Y3 3x2pt *AF et al, in prep*

Final analysis of DES 3x2pt





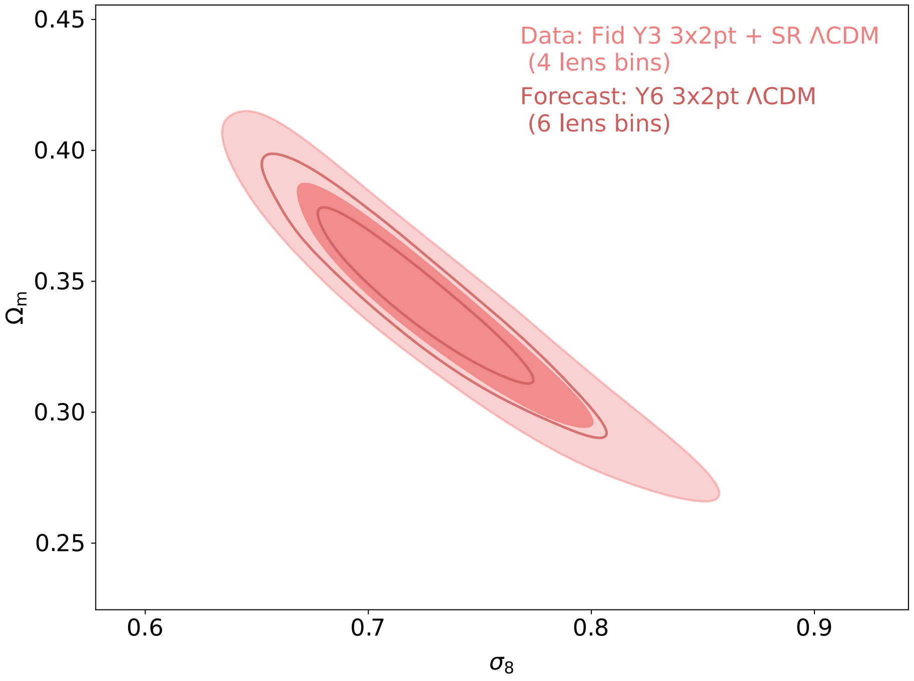
Y1 cosmology | Y3 cosmology | Y6 cosmology

2013 — 2019 — 2023

Data taking

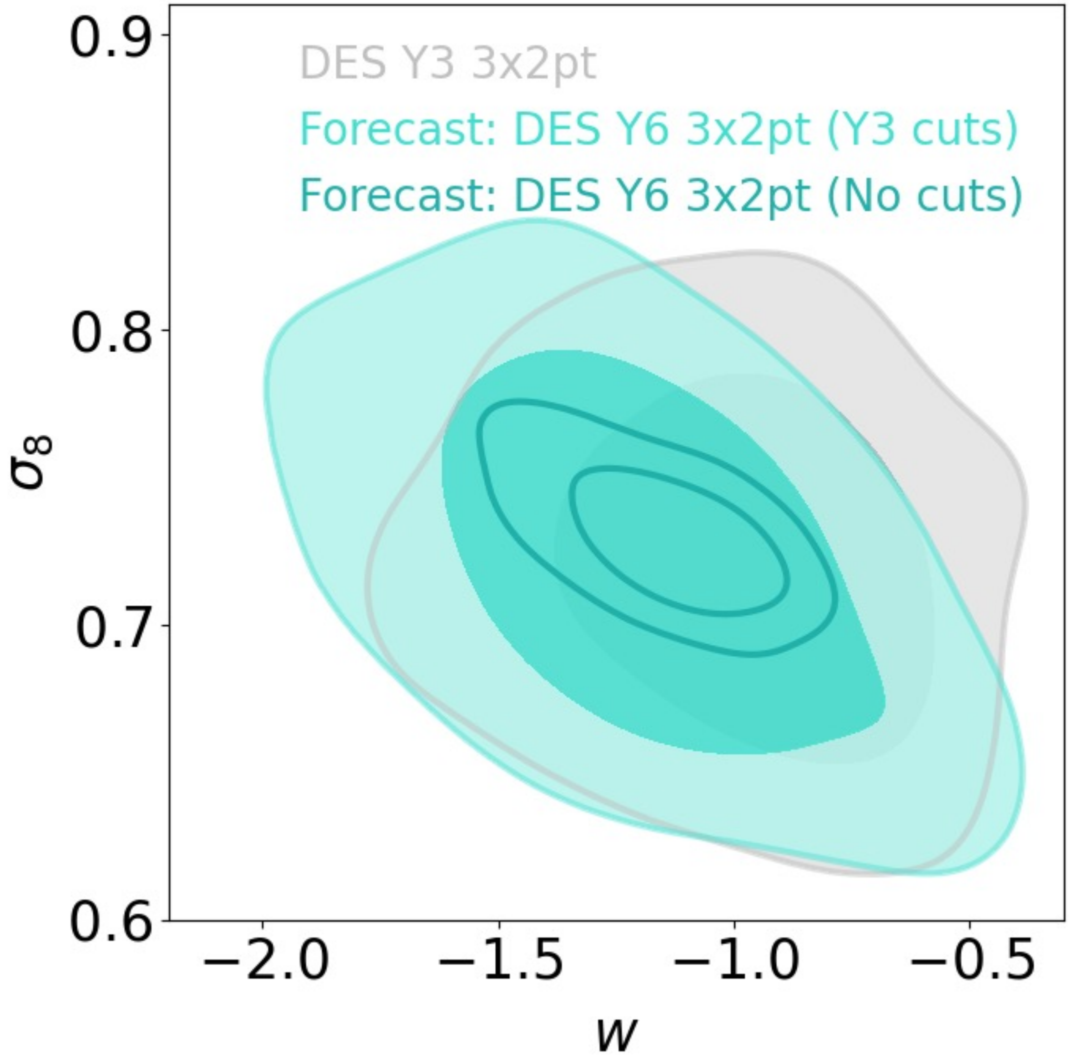
DES Y6:

- The largest shape catalogs with expected **150M source galaxies**
- The only **3x2pt from same survey**



Picture credits:
J. Elvin-Poole, M. Crocce et al, PRD, 2018
Jeffrey, N., Gatti et al., MNRAS, 2021

Solving challenges for DES Y6 cosmology



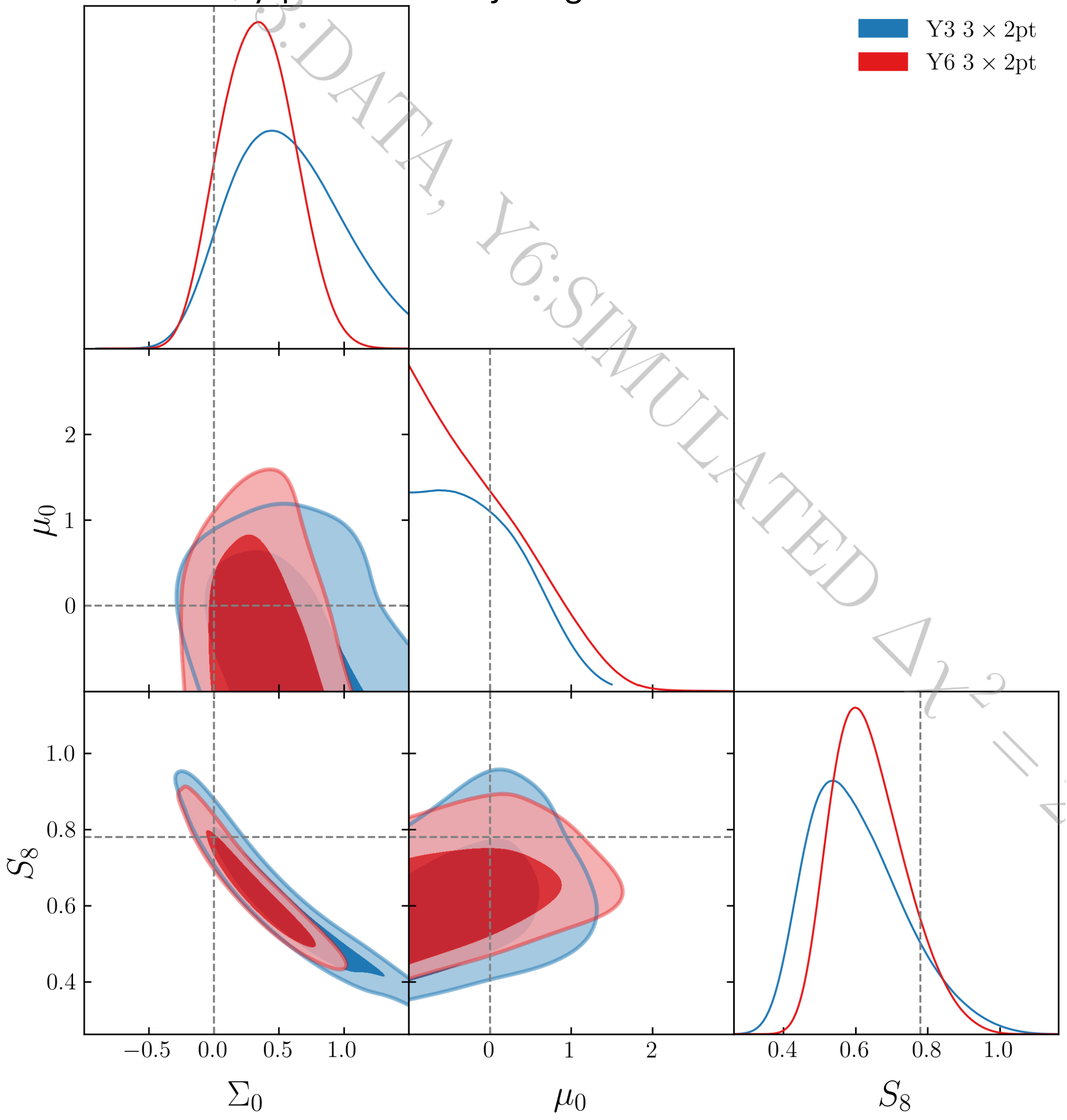
Y6 modeling team **co-leads**:
David Sanchez-Cid, Jonathan Blazek

New **precise** data also means pushing modeling **choices**:

- HMCode for baryonic feedback,
- use of **non-linear galaxy bias model** is one of the planned improvements from DES Y3.

DES Y6 tests of gravity

Preliminary plot from Sujeong Lee

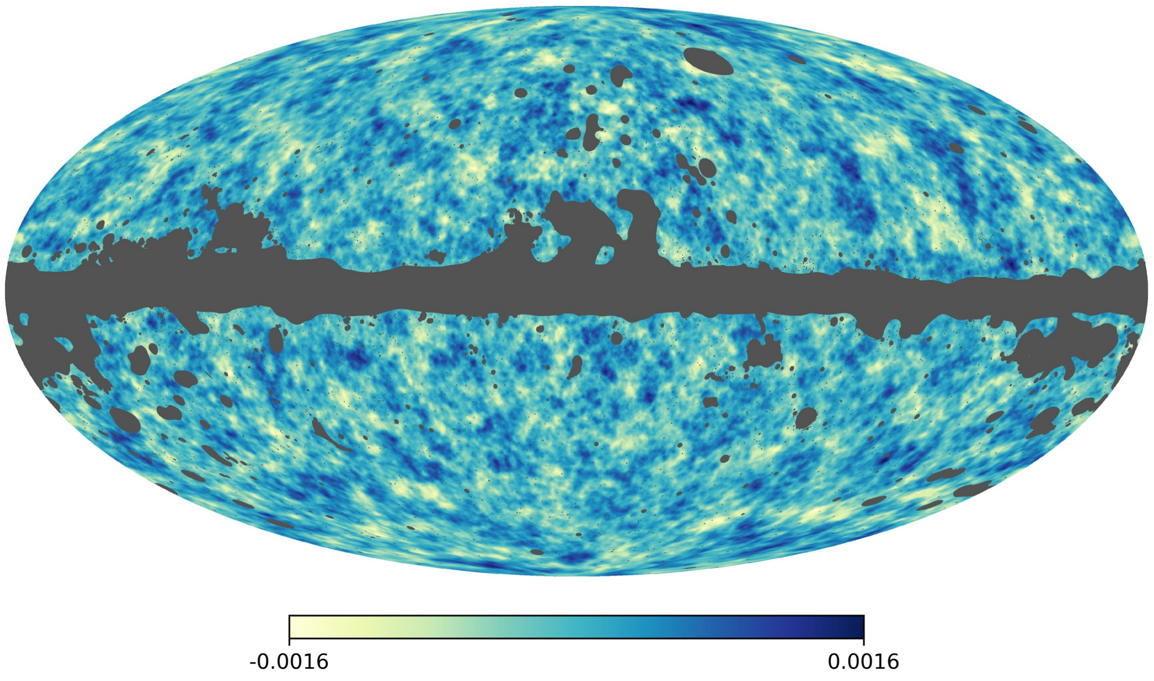


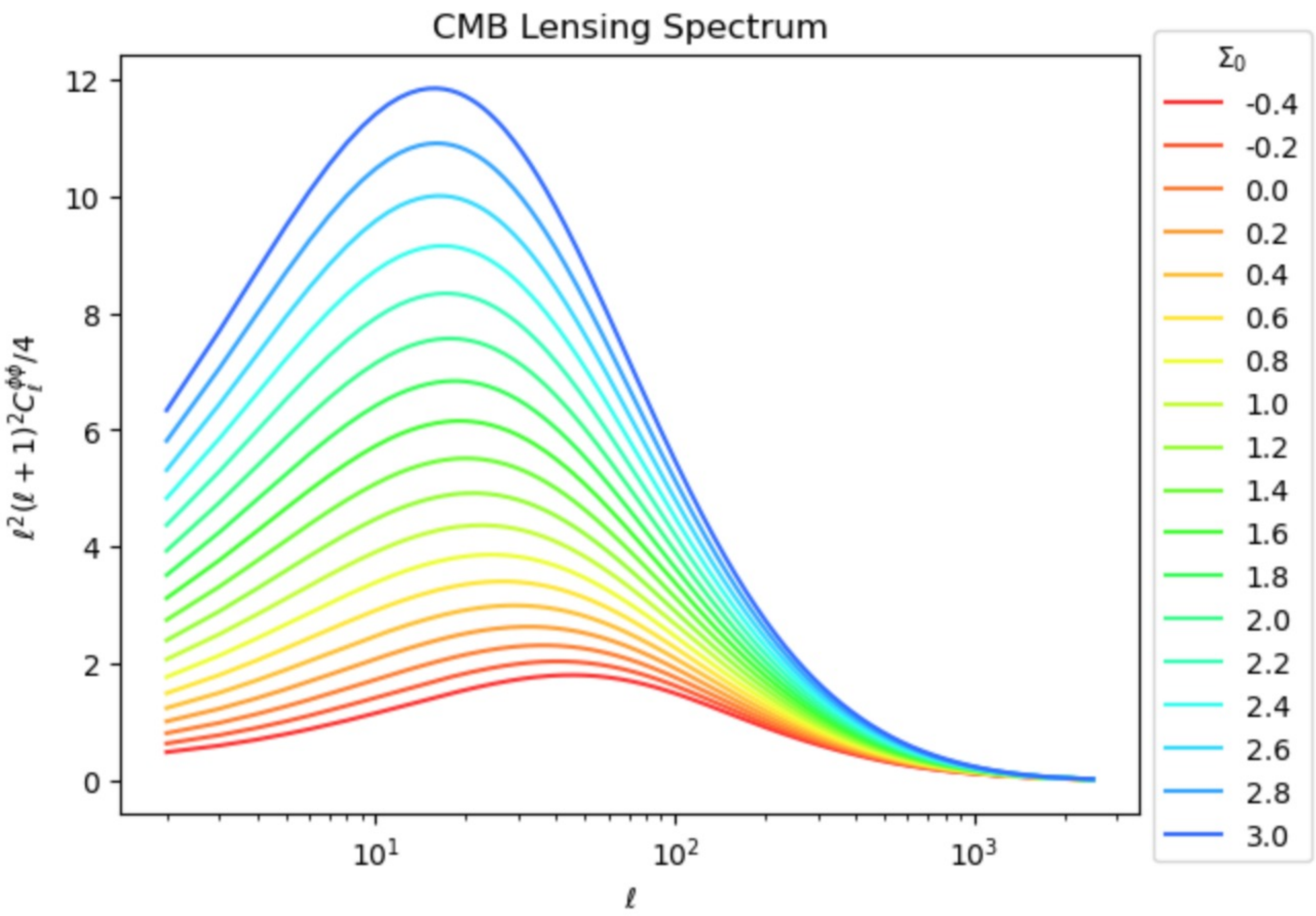
Promising results for tests of Σ,μ and early dark energy

Y6 Extensions team **co-leads**:
Sujeong Lee, Otávio Alves, Marco Raveri

CMB lensing to test gravity

Planck collaboration, A&A, 2020



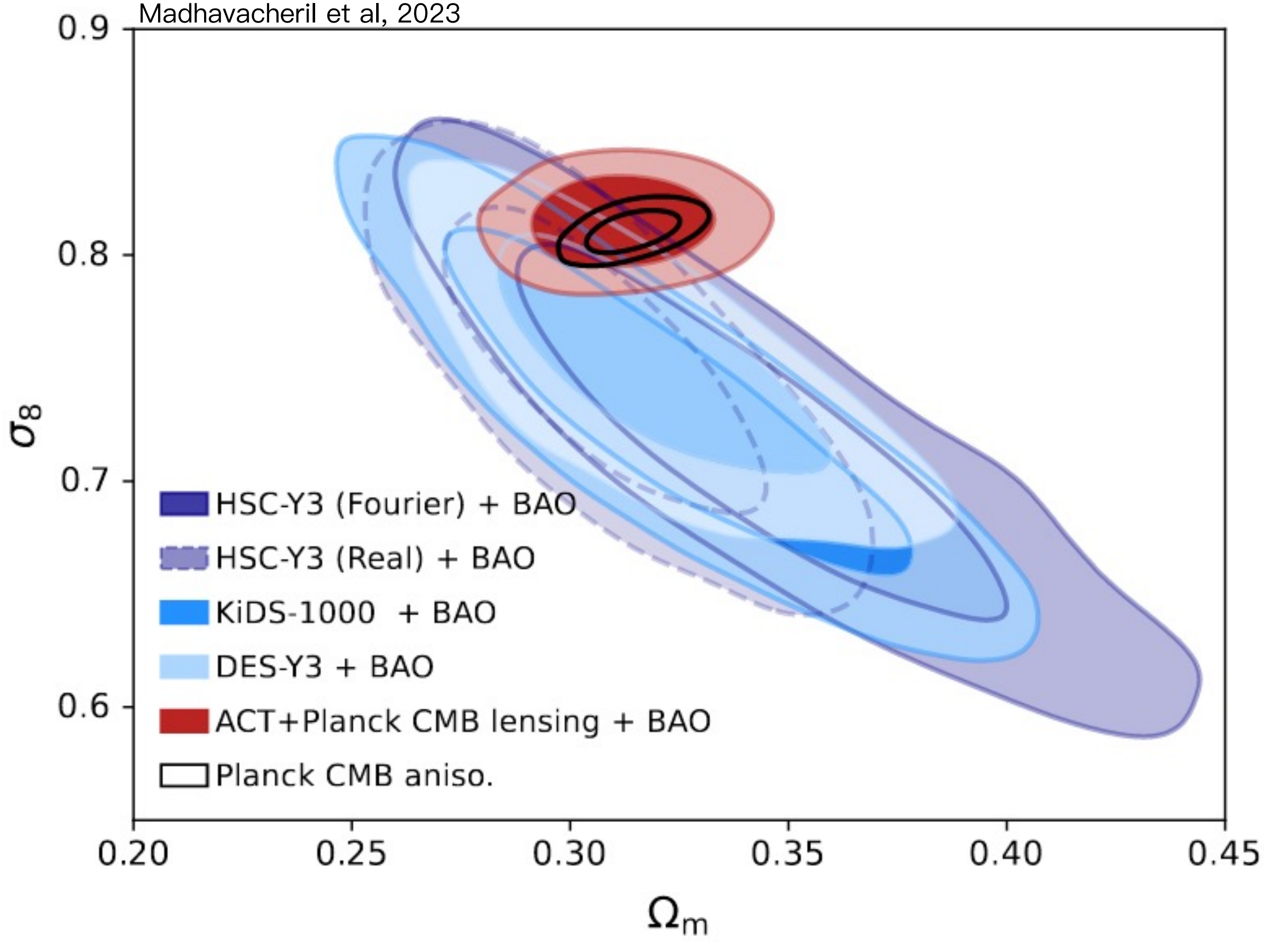


- Lensing of the Cosmic Microwave Background: sensitive to Σ_0
- More and more **precise** measurements of CMB lensing

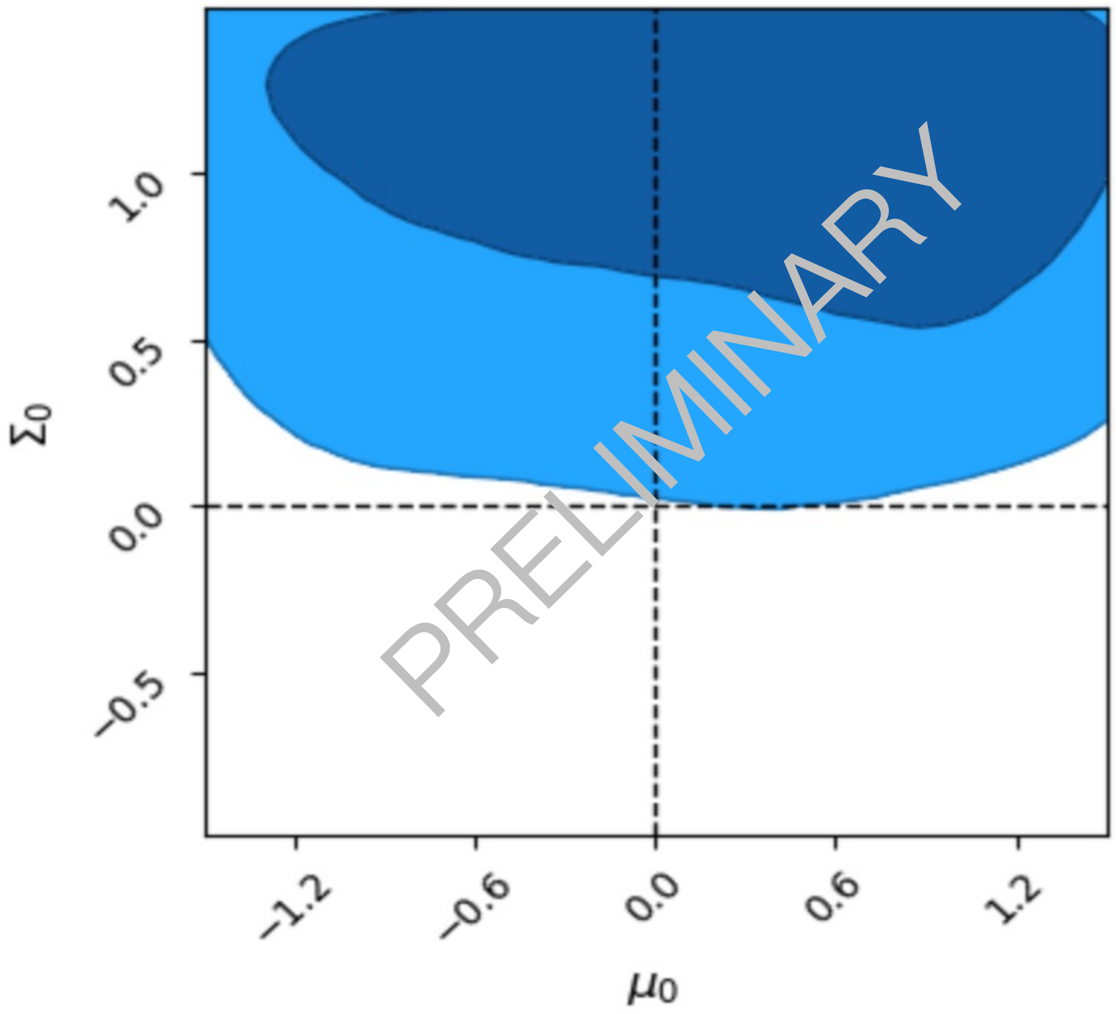
ACT DR6 lensing data

43σ measurement of CMB lensing with ACT data

Madhavacheril et al, 2023

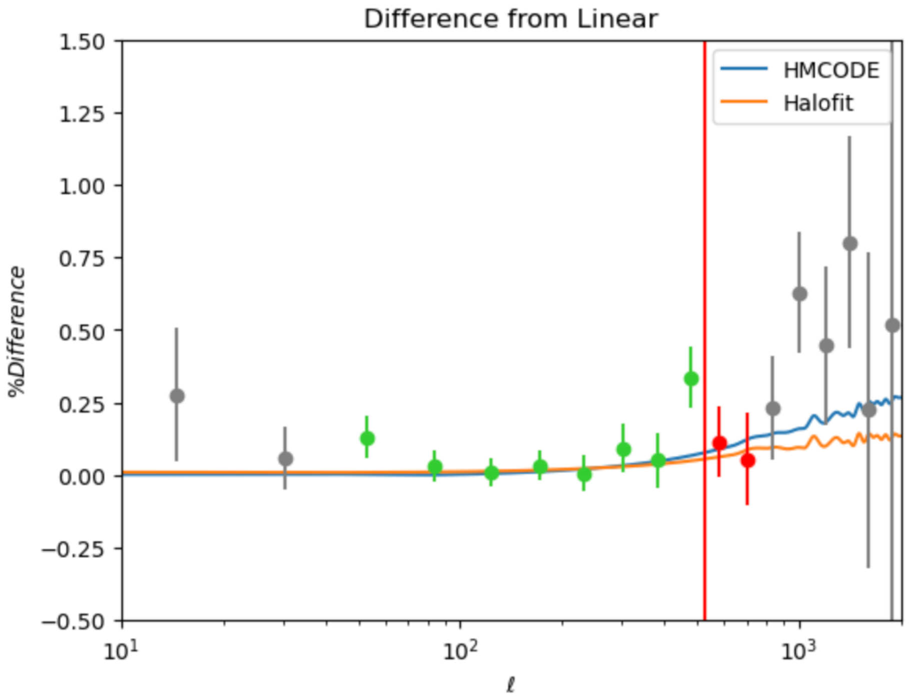


ACT DR6 lensing results on Σ,μ

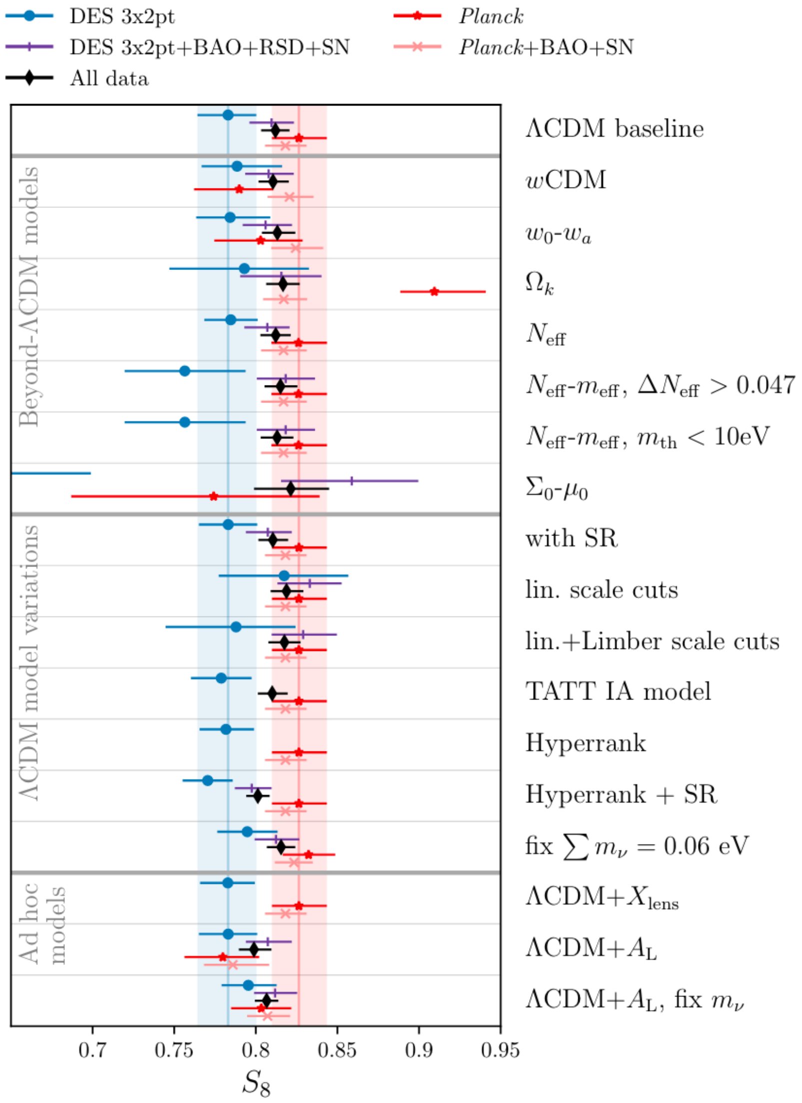


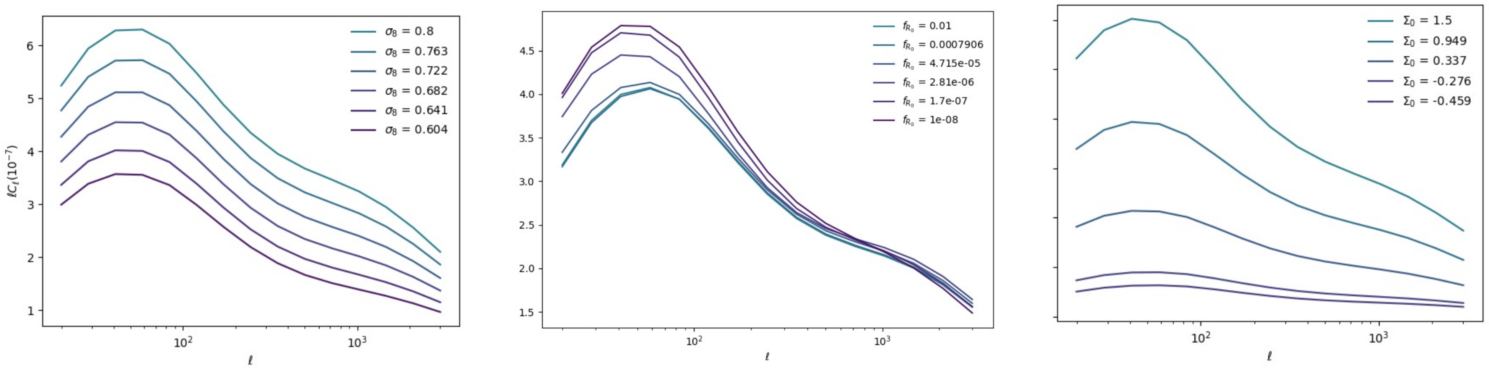
Work with student David Dzingeleski

- Non-linear **scale cuts**: remove 2 data points.
- Results from ACT DR6 lensing:
  - High Σ_0 from ACT data
  - Adding RSD: consistent GR.
- Exciting prospects to test Σ_0 in the future



The σ8 tension





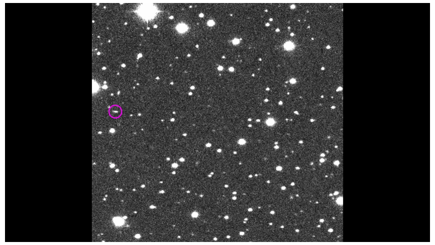
σ8 tension between CMB from Planck and Weak lensing measurements:

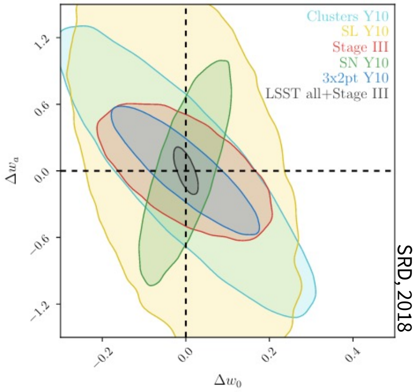
- No clear solutions to σ8 tension from beyond–ΛCDM models.
- Data not precise enough.

Rubin Observatory will map the entire Southern sky every 3 nights

LSST = a fast wide deep survey:

- Galaxy survey **cosmology** (static sky)
- **Changing** phenomena:
  solar system bodies, asteroids, SN, AGN, etc (transient sky)





Rubin Observatory & **you**:

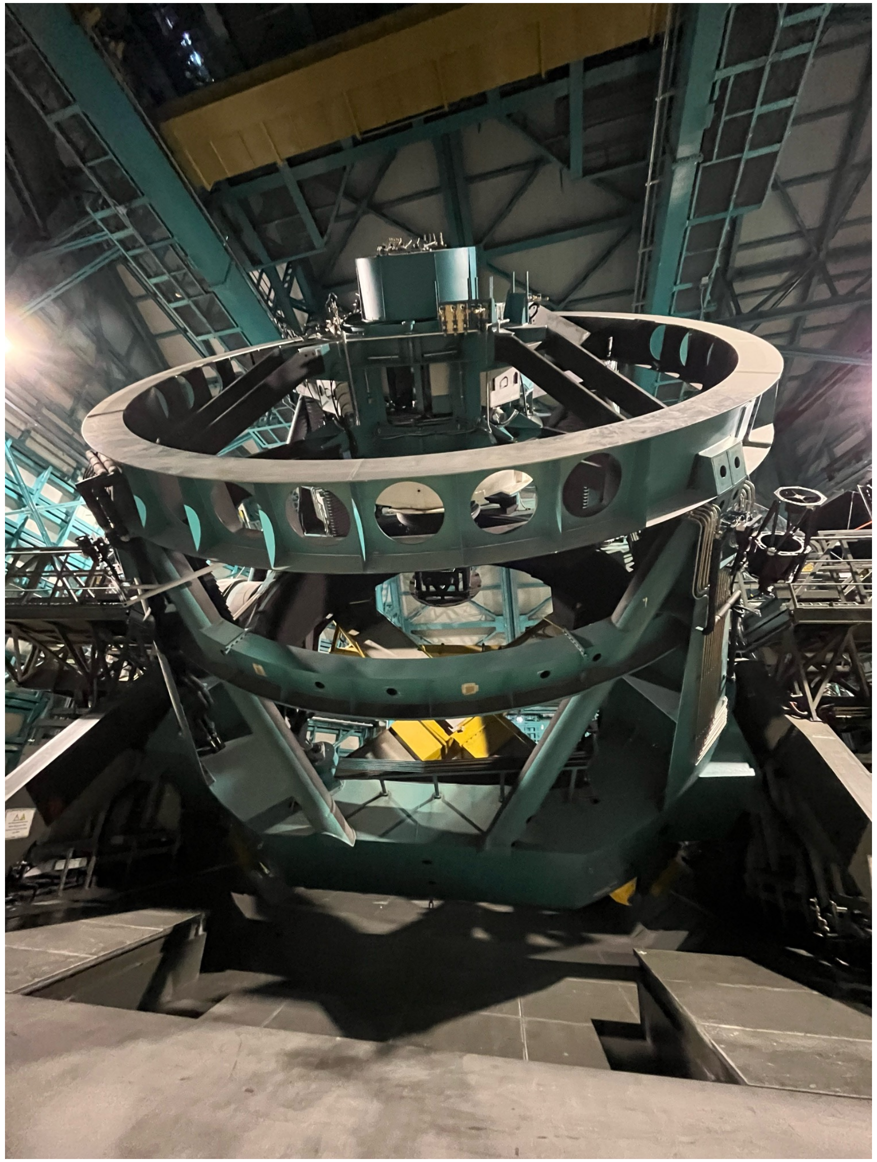
- Science Collaborations: organized efforts around science with LSST data.
- Community forum: https://community.lsst.org/
- The Rubin Observatory is a US and Chilean Project with in-kind contributions:
  - From the US and Chile
  - From the international community including France through IN2P3—CC and software contribution

A new addition to Cerro Pachón

- The Rubin Observatory under **construction** since 2015 at Cerro Pachón at 2,660m elevation

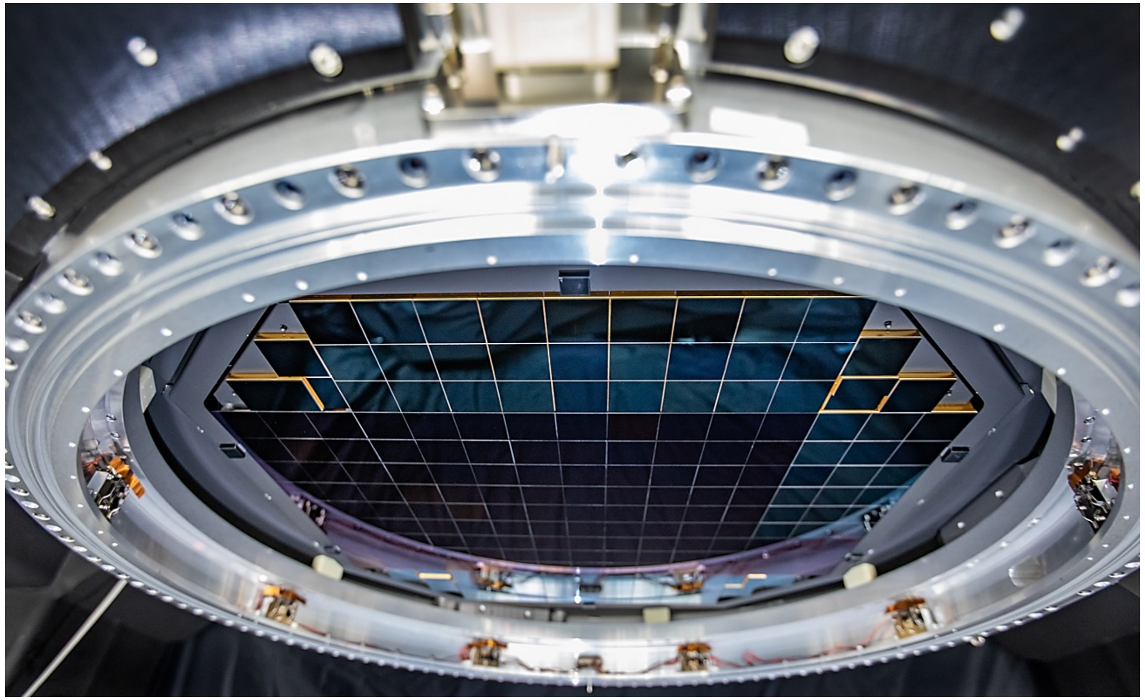
- The Simonyi Survey Telescope Mount Assembly:
  - On and moving.
  - **Camera**: ComCam on the telescope, the camera LSSTCam is still at SLAC: shipping soon!

- Currently taking data with the software at the summit with AuxTel.

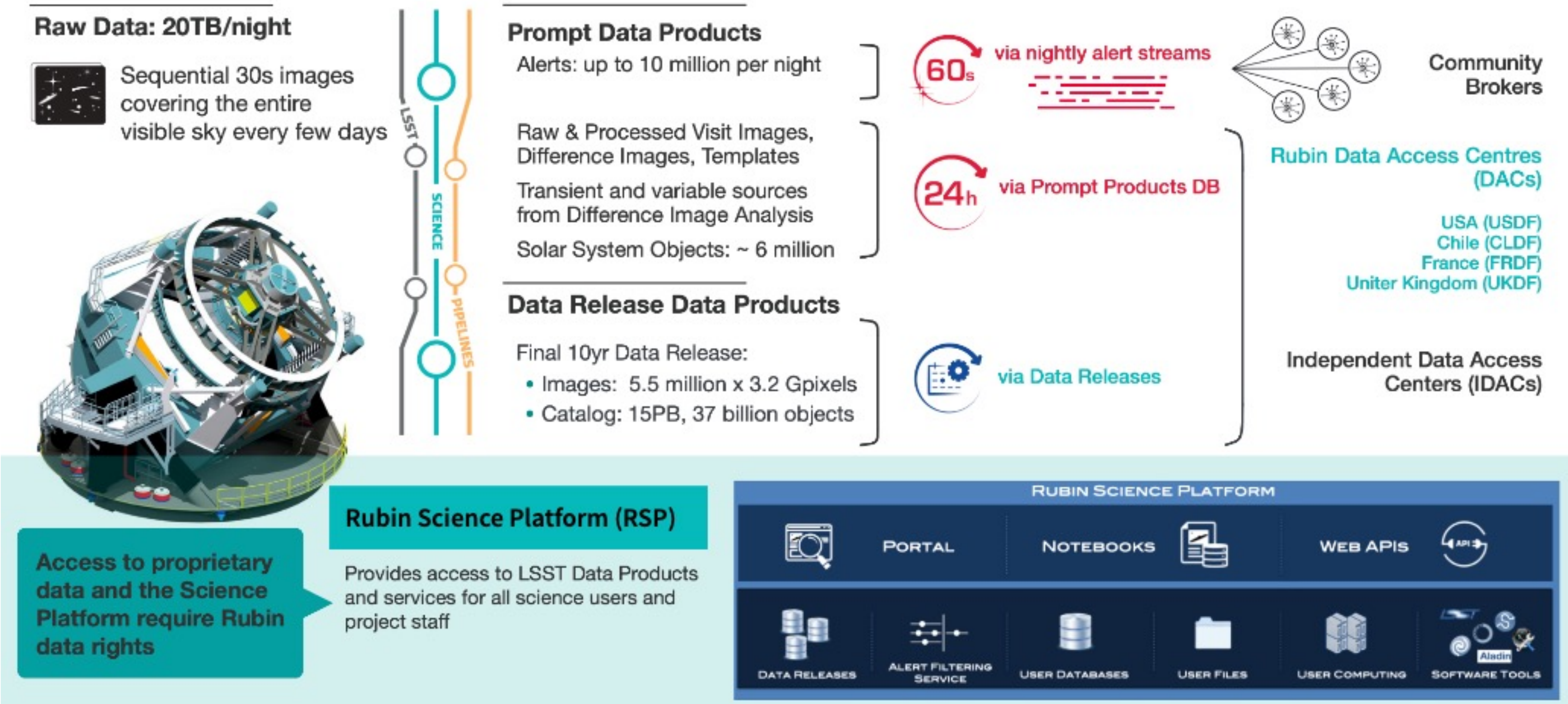


LSSTCam: the largest digital camera

- **189 4k x4k CCDs** (ITL and e2v) of 16 amplifiers.
- All assembled with lenses and filters @ SLAC.
- Last tests before shipping by air and road to the summit.
- Correction of detector effects and calibration in Rubin DM.



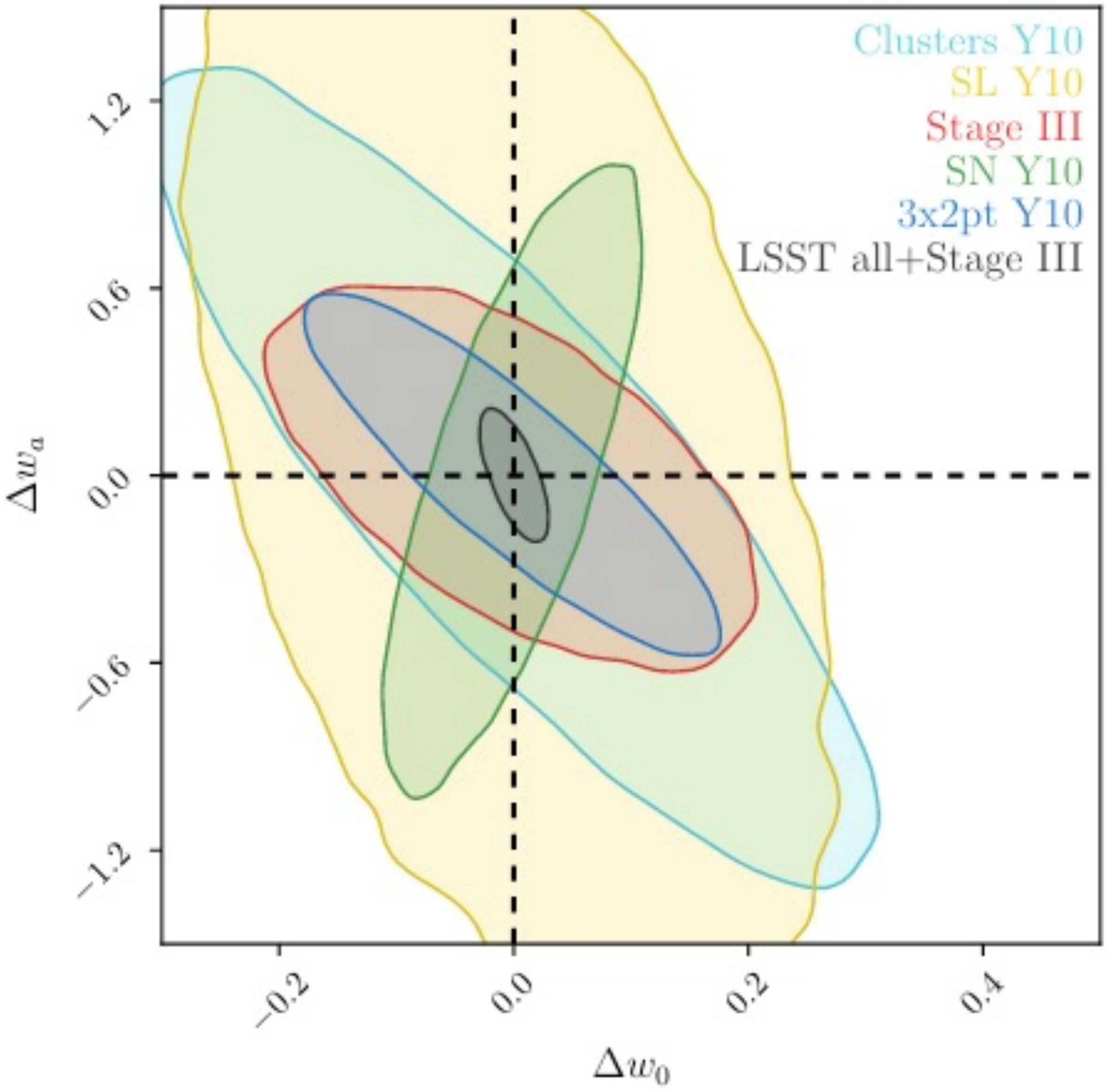
Processing and releasing TB of data



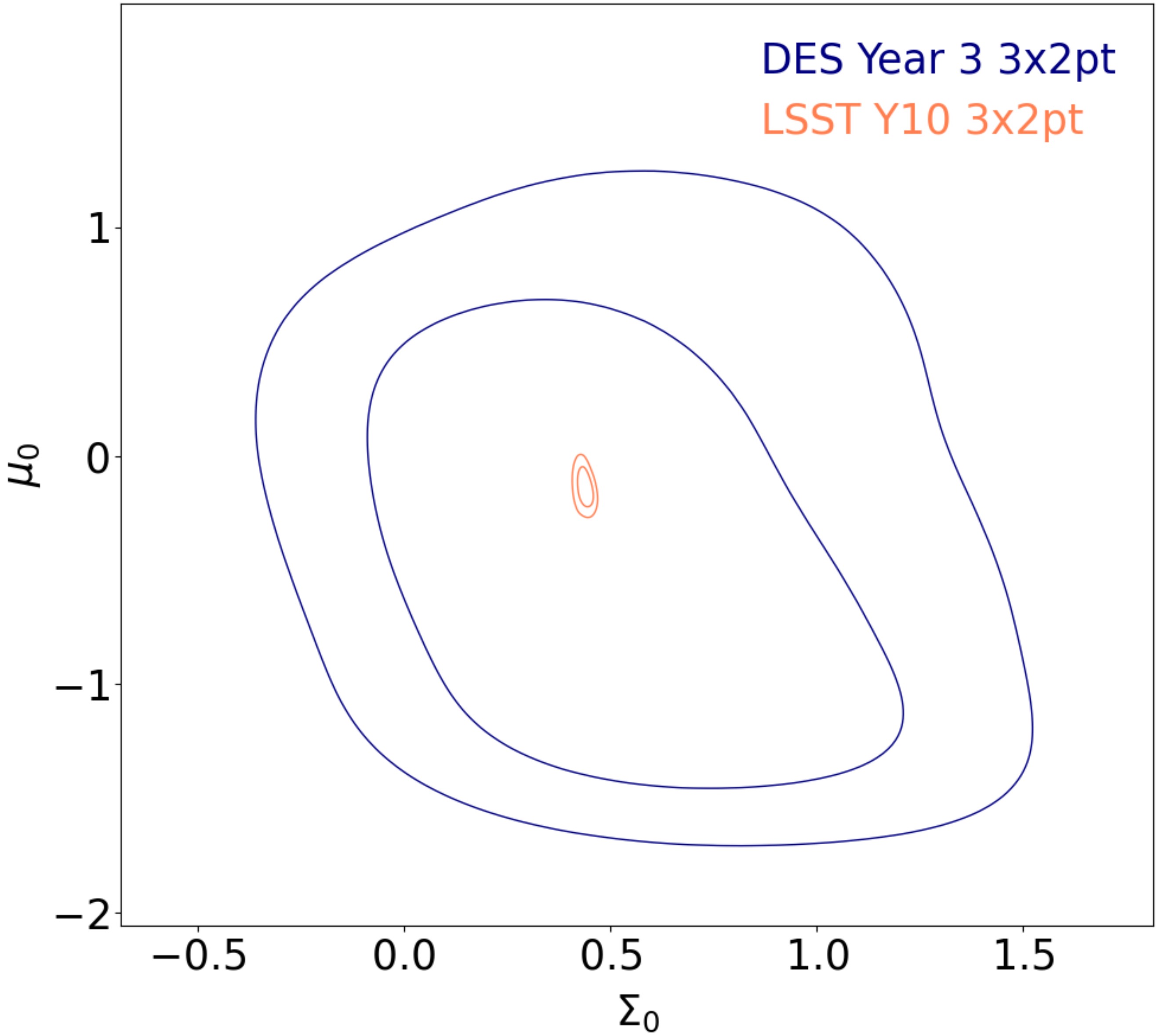
Slide by Leanne Guy

LSST multi-probes for dark energy

DESC SRD, 2018



Future of weak lensing and tests of gravity



Observed f_{sky}	x 5
# galaxies	x 10
➔ **σ**(Σ,μ)	/ 10

Forecasts updated from ***AF*** et al, 2019

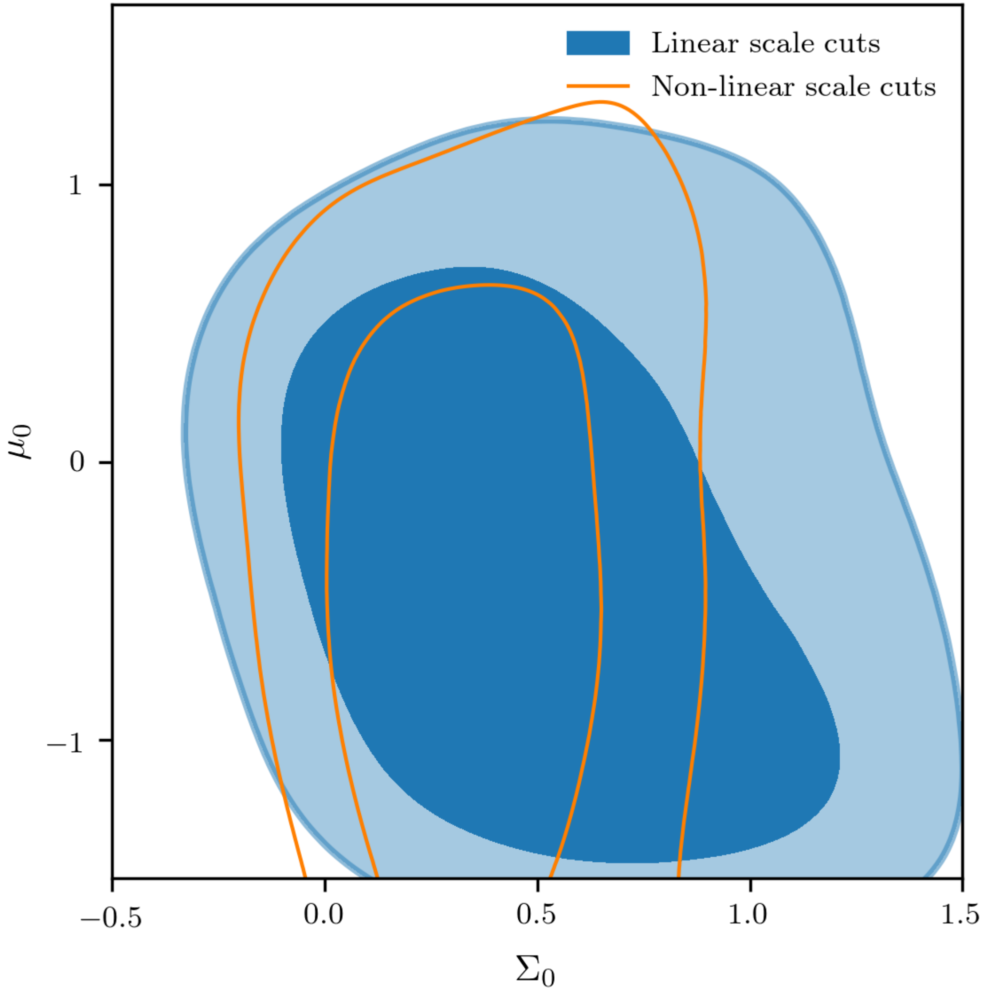
Challenges to test gravity with stage–IV surveys

Analyzing the **data**:

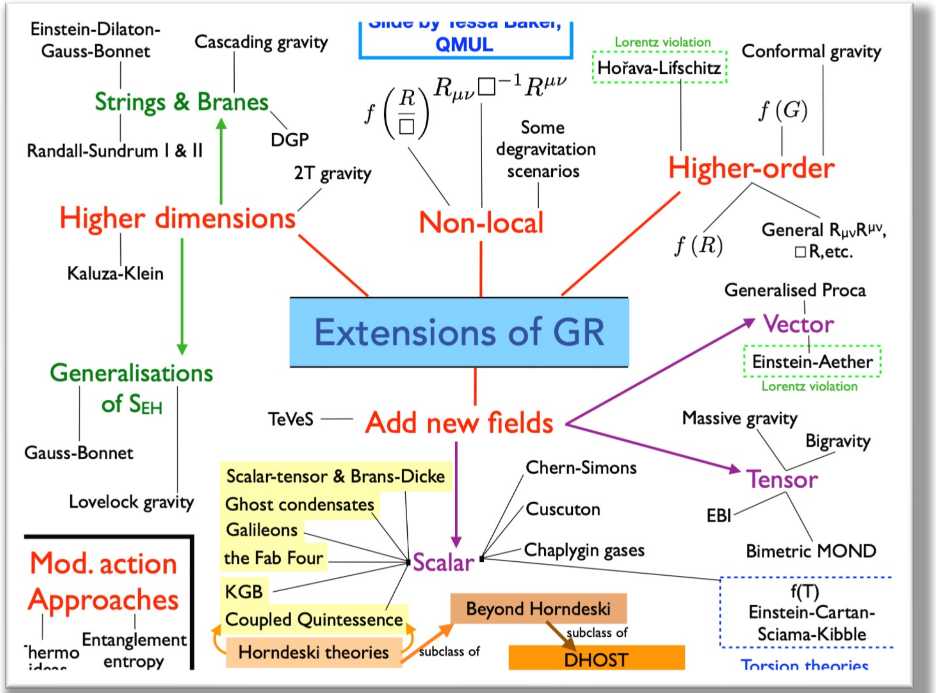
- Computationally Expensive:
  - More efficient parameter estimation algorithms,
  - Emulators,
  - Data compression.

- How to describe physical systematics in modified gravity?

- Need to use smaller scales.



Challenges to test gravity with stage–IV surveys



Not a clear direction in **theory** space:

- (Σ,μ) is a great to explore,
  but we must assume a parametrization.
- Community seems to focus on f(r) and EFT.

In ***AF*** et al, OJA, 2023 we propose to compare theories at the level of observables.

It will be important to be creative in looking at the data:

- New probes,
- Deep learning, SBI.

Exciting prospects with weak lensing and CMB

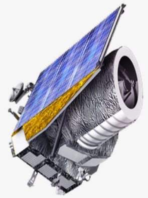
CMB

- SO
- CMB-S4
- ADV-ACT, SPT-3G, BICEP 3, BA

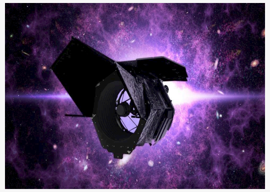
Weak lensing surveys

- Rubin Observatory
- Euclid
- Roman

2023



2025



Cosmic inflation

Up to now, **CMB B–modes** experiments mainly use:

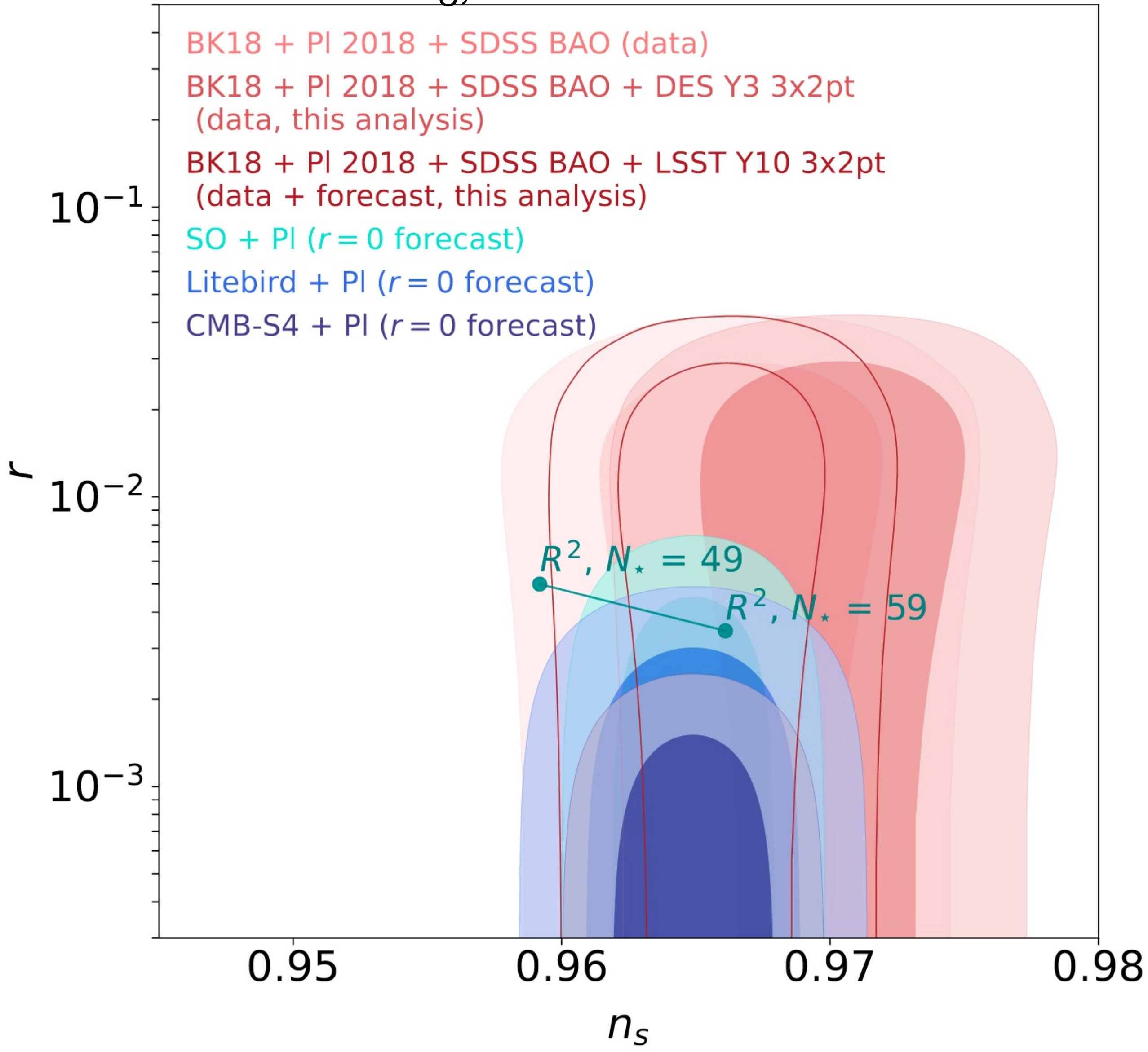
- BAO,
- CMB temperature and polarization,

to test cosmic inflation.

Galaxy surveys should be added as well in the future.

Galaxy surveys also have access to f_{NL}.

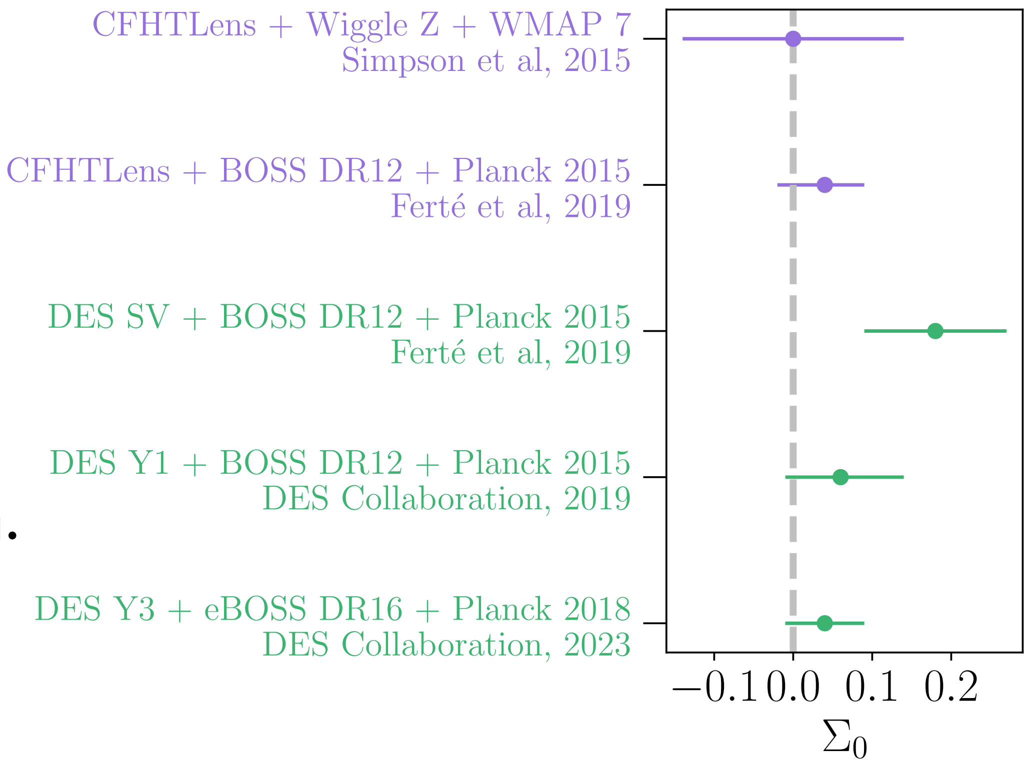
From ***AF*** & Hong, submitted



Outlooks

- DES is precursor of stage–IV surveys: ongoing work on DES Y6

- Cosmology from weak lensing:
  - More and more **precise tests of Σ,μ**: DES Year 3 consistent with GR + preliminary test with ACT DR6 lensing data.
  - **Modeling observables accurately** is a very important challenge.



Rich synergies between cosmological surveys in the 2020s.