Title: Gravity under Scrutiny on Cosmic Scales

Speakers: AgnÃ¨s FertÃ©

Series: Cosmology & Gravitation

Date: September 05, 2023 - 11:00 AM

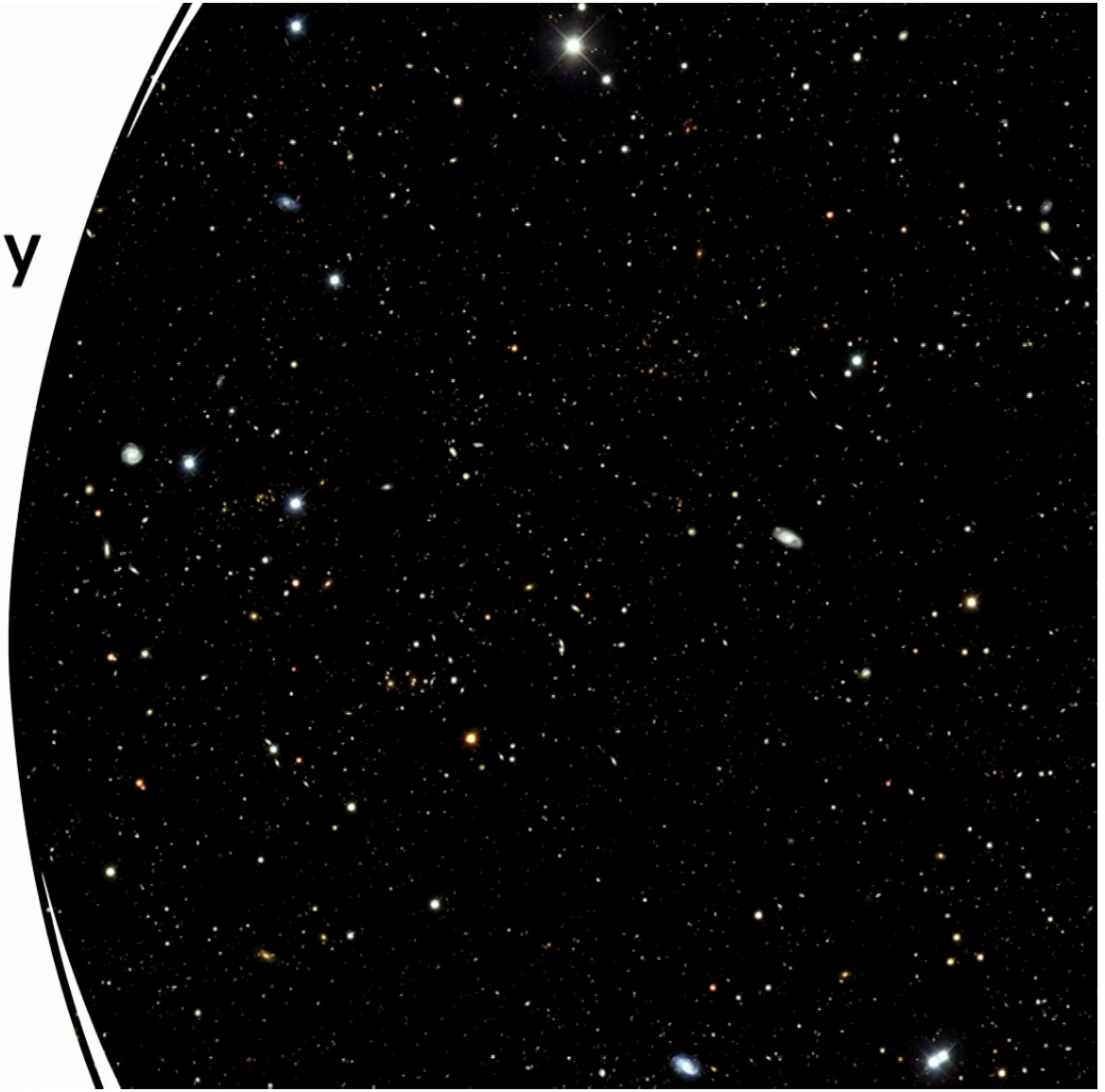
URL: https://pirsa.org/23090055

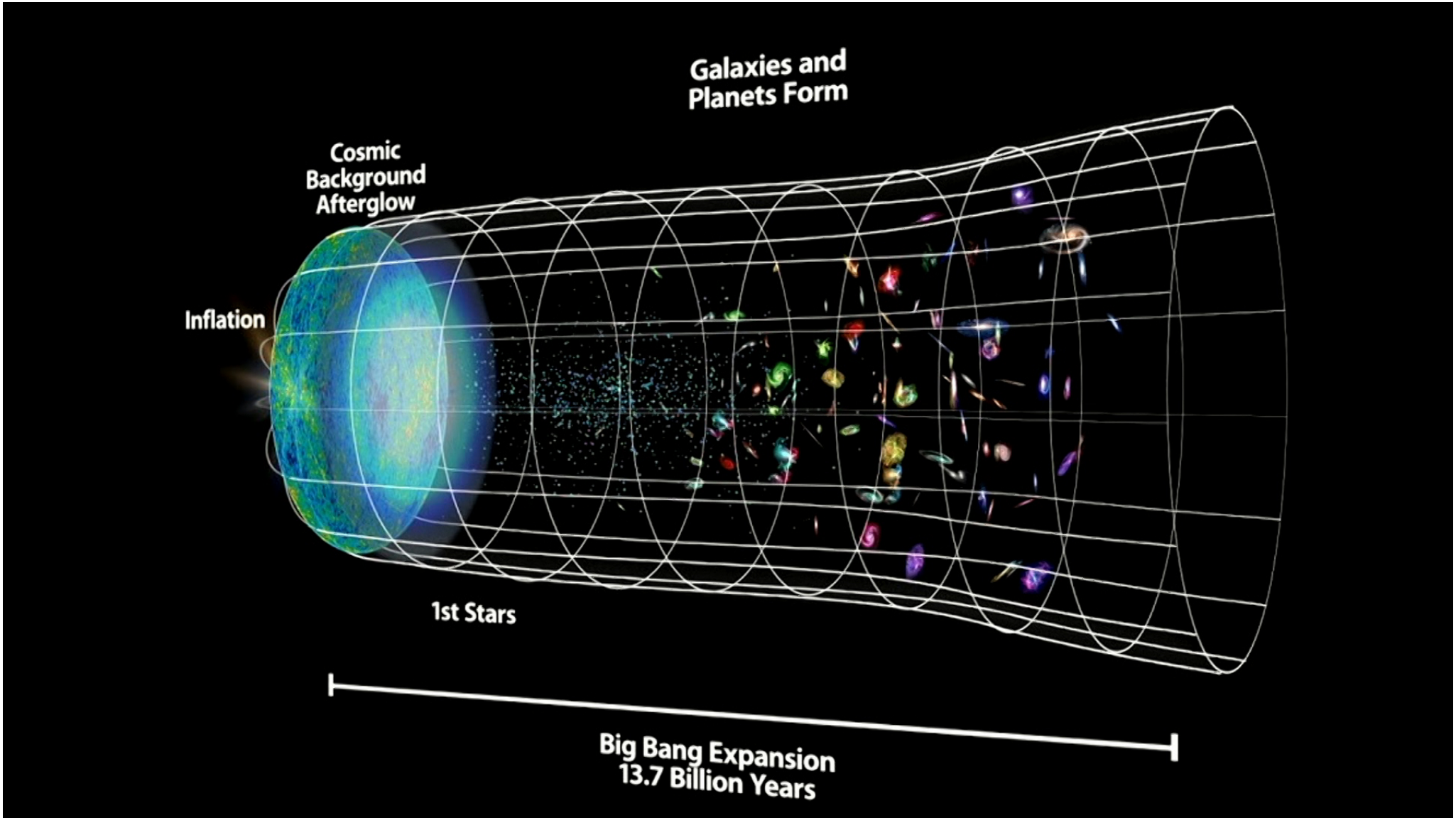
Abstract: While General Relativity has withstood tests on solar system scales, progress in observational cosmology now enables tests on the largest scales. I will present results from our tests of gravity using Dark Energy Survey Year 3 weak lensing and clustering data in addition to a variety of complementary data. One outcome of this analysis was the necessity to further explore lensing consistency so I will present preliminary results of such tests using the latest Cosmic Microwave Background (CMB) lensing data. These analyses are setting the scene for future tests of fundamental physics with CMB and galaxy surveys: I will show expected results and challenges from the Rubin Observatory. I will finally argue for the use of machine learning for theory exploration, to better organize our efforts within the future experimental landscape. As PI is a leading center in outreach, I will end my talk by sharing my experience with science content creation on various social media platforms.

Zoom link: https://pitp.zoom.us/j/96929387143?pwd=WW1CZElpMkN2U1RQUjB3VERxRVQ5dz09

Gravity under Scrutiny on Cosmic Scales

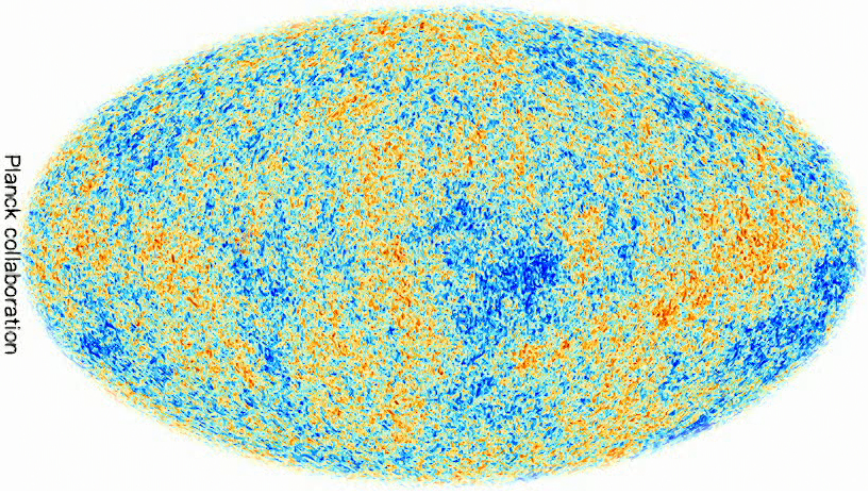
Dr Agnès Ferté
SLAC/KIPAC



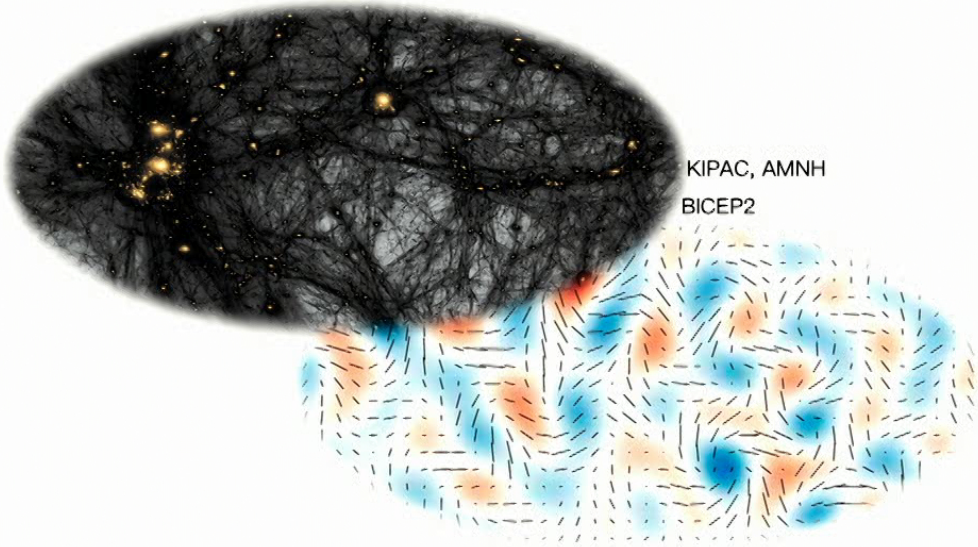

Galaxies and
Planets Form
Cosmic
Background
Afterglow
Inflation
1st Stars
Big Bang Expansion
13.7 Billion Years

2010s

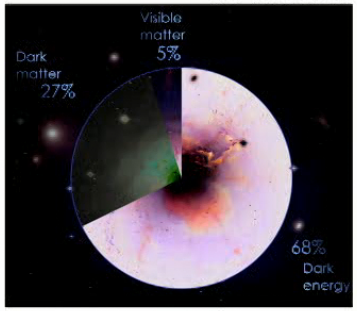
2020s

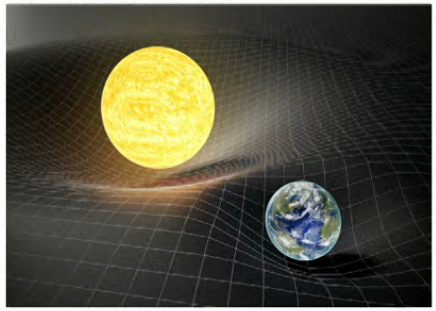


Planck collaboration



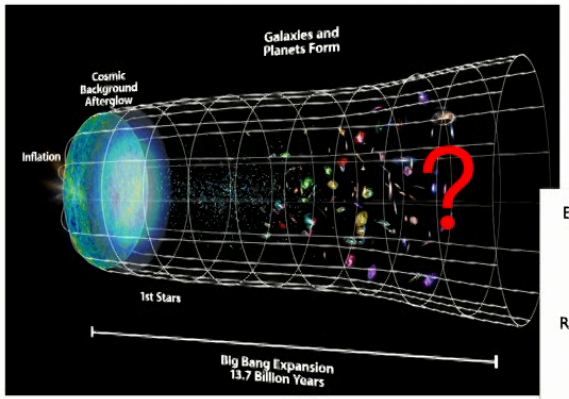
The Standard Model of Cosmology
is precisely measured





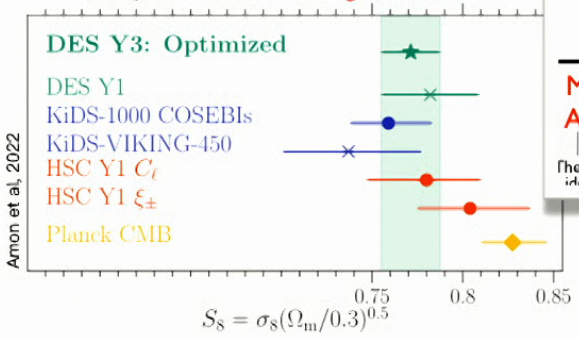
- What is causing cosmic acceleration?
- What is dark matter?
- Did cosmic inflation happen?
- What is the mass of neutrinos?

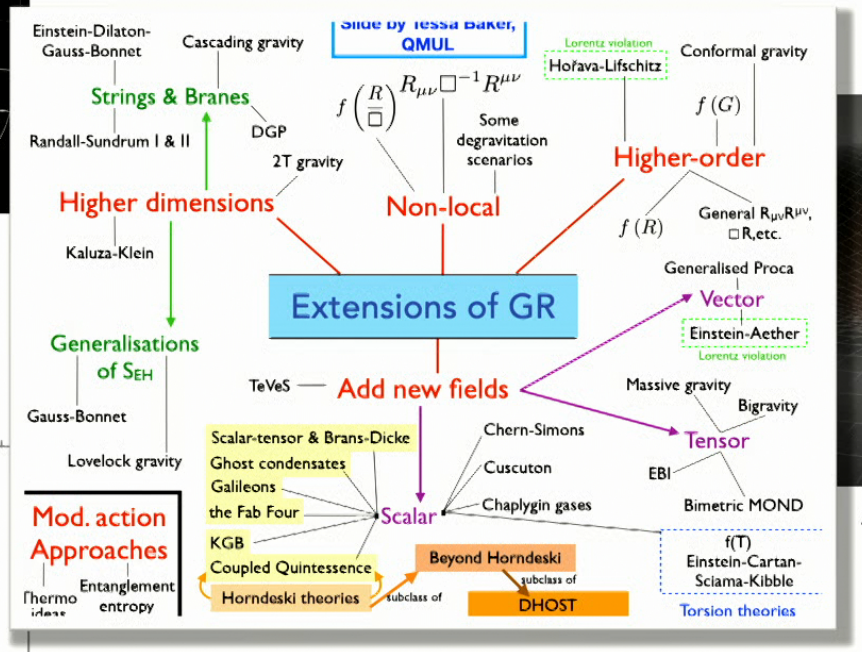
Challenging General Relativity on cosmic scales

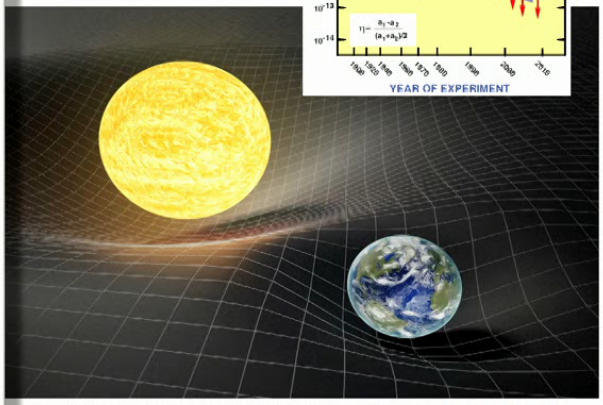


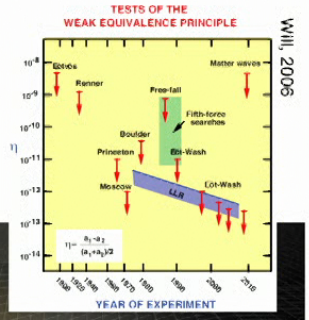
*What is causing **cosmic acceleration**?*

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





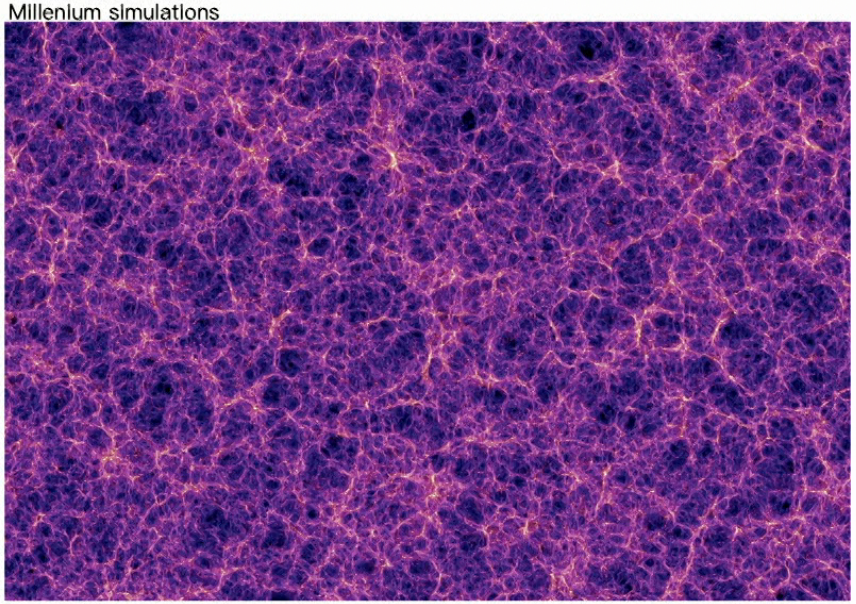




*Is General Relativity (GR) **correct** on cosmological scales?*

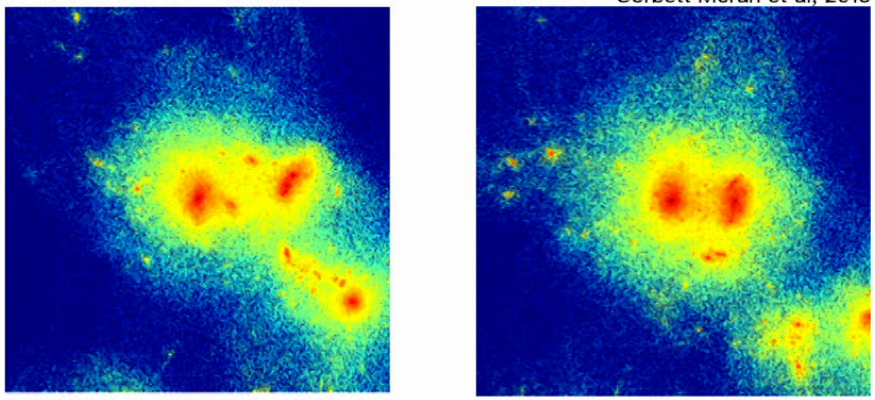
The Universe as a laboratory to test gravity

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



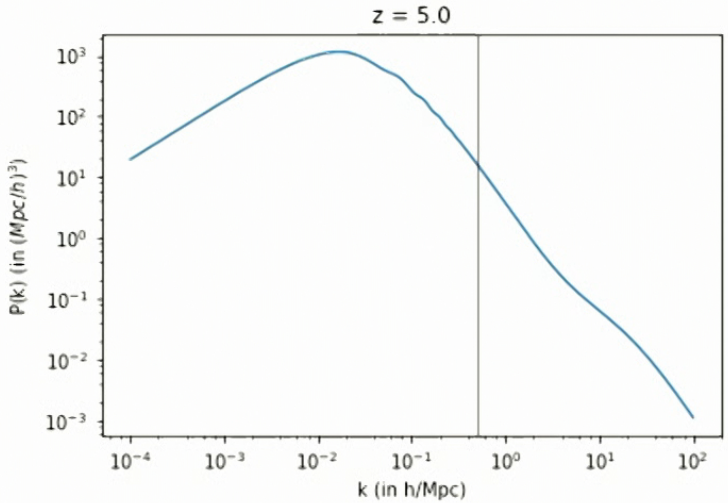
General Relativity | Modified gravity

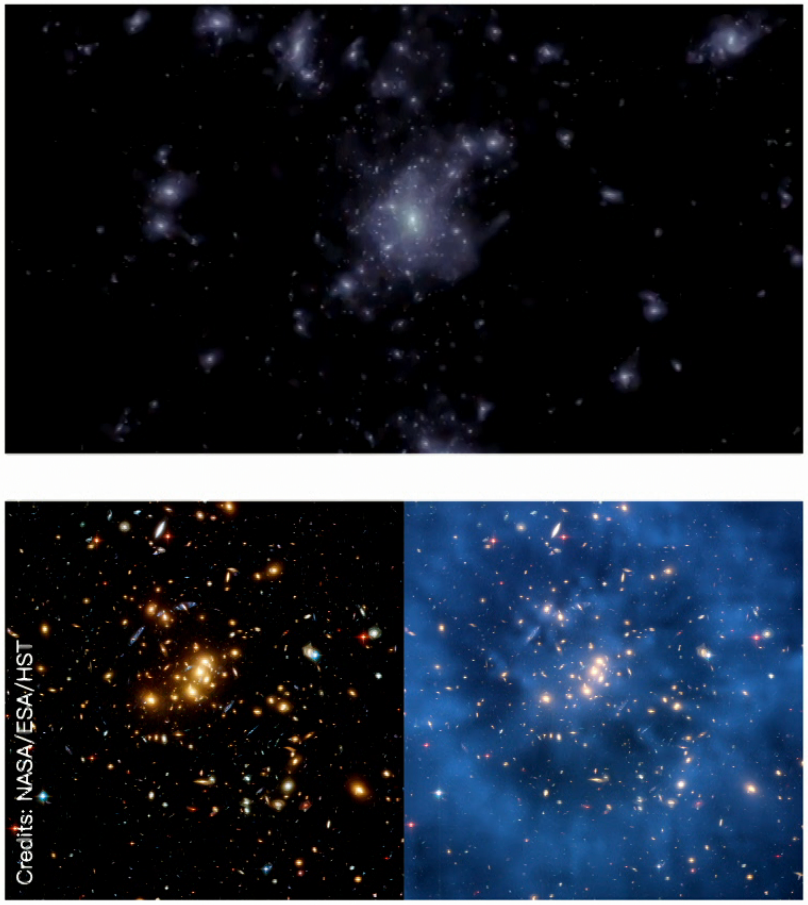
Mapping matter with galaxy surveys

Use galaxies as:

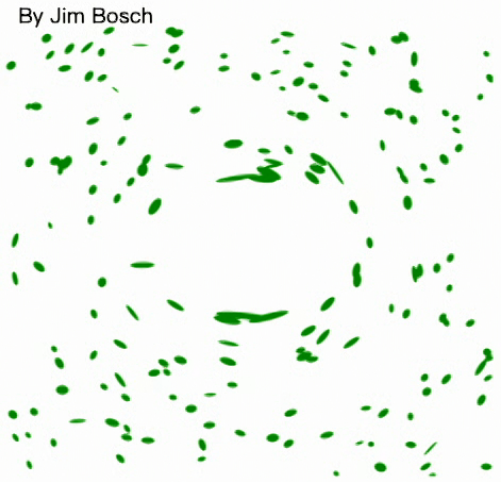
- **tracers** of (dark) matter large–scale structure,
- **background** light,

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





Cosmic shear



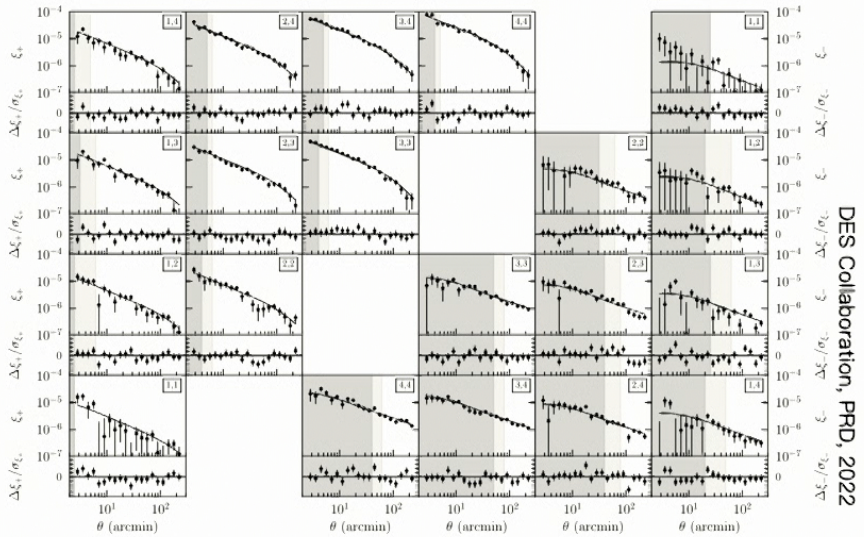
Galaxies are weakly lensed by **large-scale structures on the line of sight**

→ **Geodesics** are modified

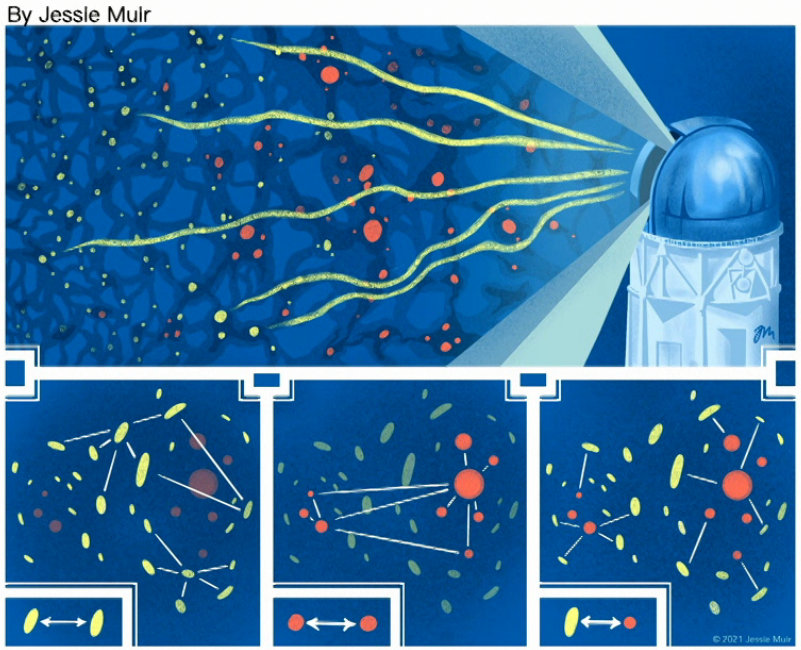
→ **Shapes** of galaxies appear coherently more elliptical

Cosmic shear is summarized as: $\xi_{\pm}(\theta) := \langle \gamma_t \gamma_t \rangle \pm \langle \gamma_\times \gamma_\times \rangle$

→ Directly probing the matter distribution.



Fully unlocking the growth of structures from weak lensing



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

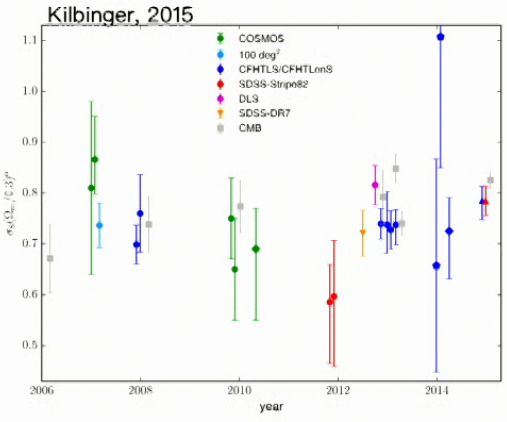
$$S_8 = \sigma_8(\Omega_m/0.3)^{0.5}$$

Weak lensing surveys

2000 — 2010 — 2020

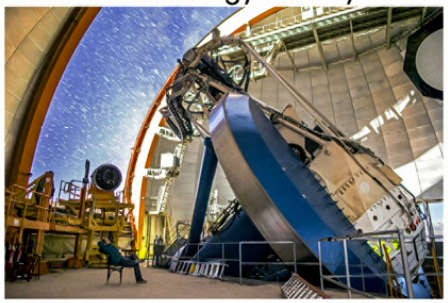
First cosmic shear measurements

Kilbinger, 2015



Stage–III surveys

Dark Energy Survey



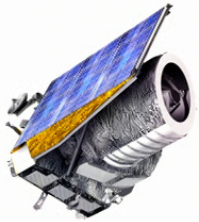
KiDS

HSC

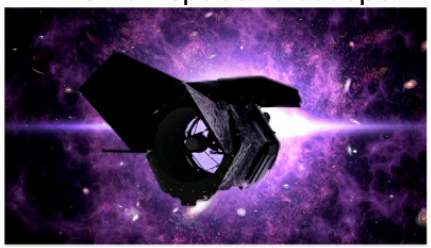
Stage–IV surveys

Vera C. Rubin Observatory

Euclid

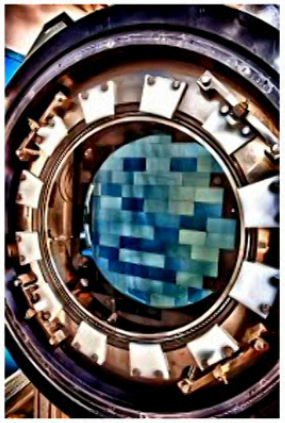


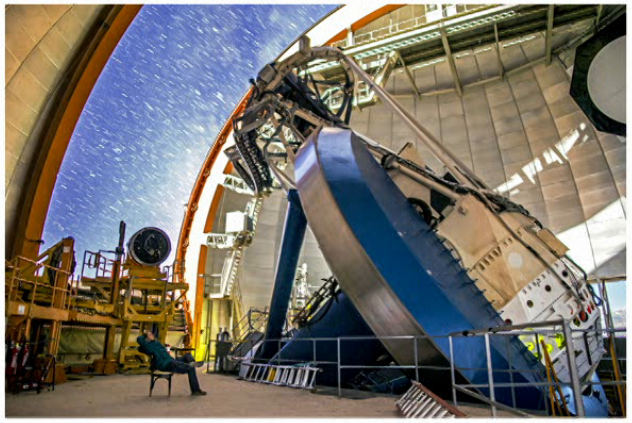
Roman space telescope

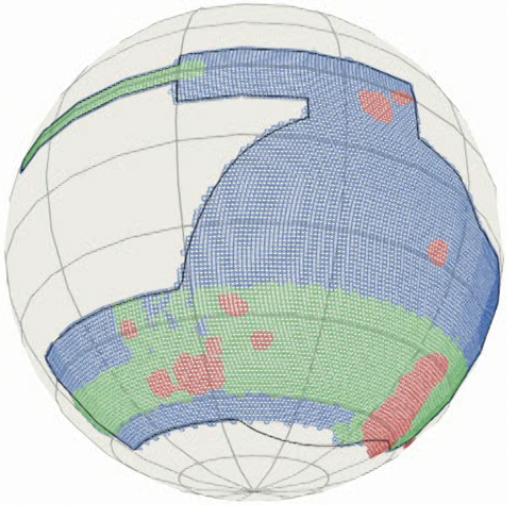


The Dark Energy Survey

- **DECam** at CTIO Blanco–4m
  74 CCDs, 2.2° field of view, 570 Mpixels
- **10%** of the sky between 2013 and 2019
  5 optical bands (grizY)
- International collaboration
- Cosmology from:
  - supernovae, BAO
  - **3x2pt**, clusters





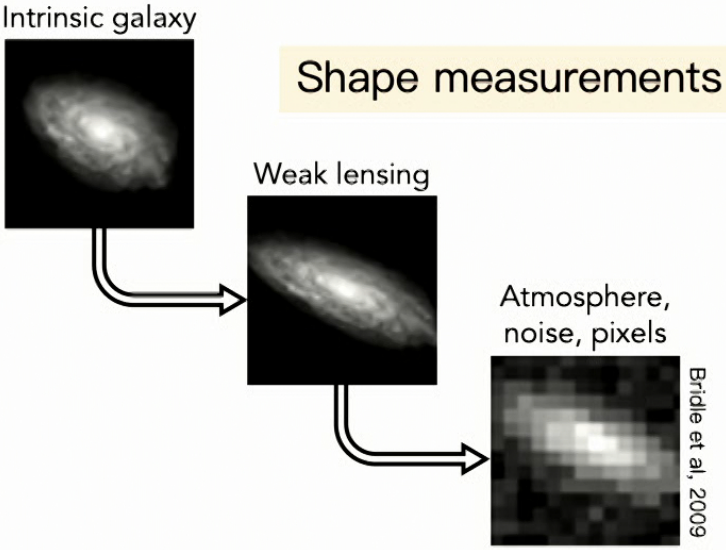


From Gatti et al, MNRAS, 2022

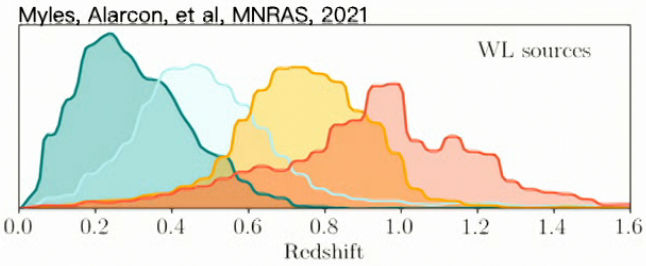
My roles:

- 2 weeks for the **observing** campaign
- **Pipeline** developments for DES Y1/Y3 LCDM, extensions
- 2018–2022: Y3 **extensions** analysis co–lead
- 2021–2022: Theory and Combined Probes **working group co–convener**
- Prepare **Year 6 cosmological analysis**

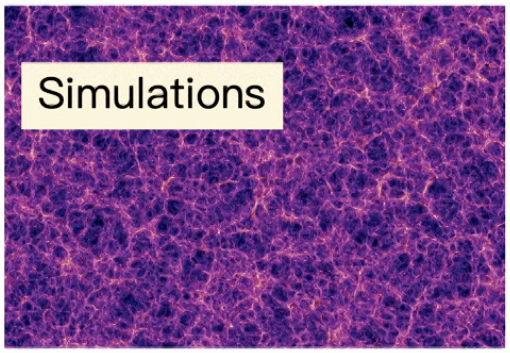
Cosmology from weak lensing



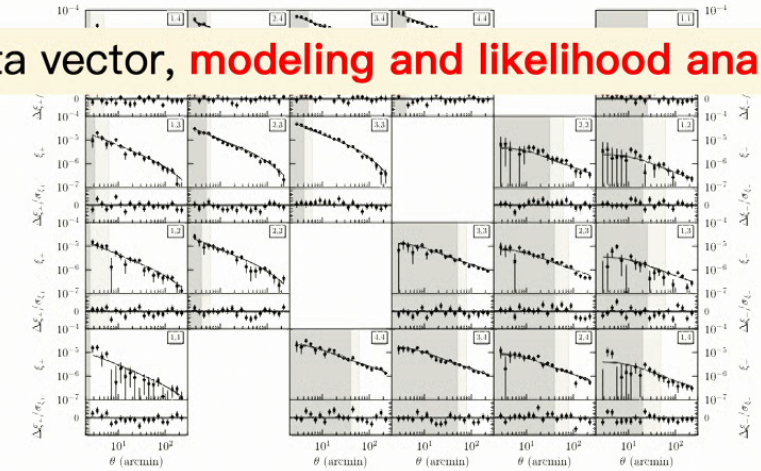
Shape measurements



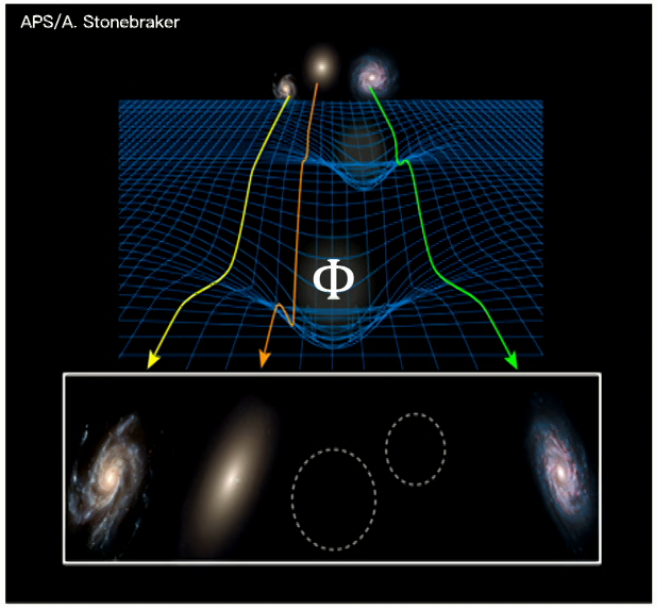
Photometric redshift



Data vector, **modeling and likelihood analysis**



Testing gravity through metric perturbations



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

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

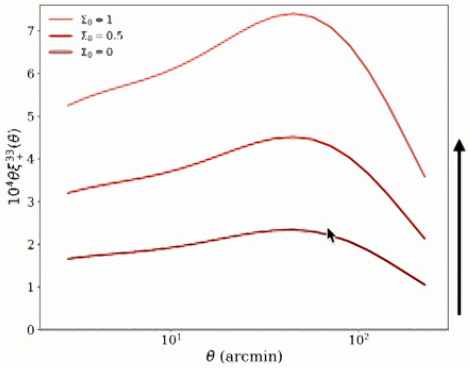
Mass = 0 : modifies **geodesics**

$\Sigma_0 = 0$ in GR

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

Mass ≠ 0 : modifies **dynamics**

$\mu_0 = 0$ in GR

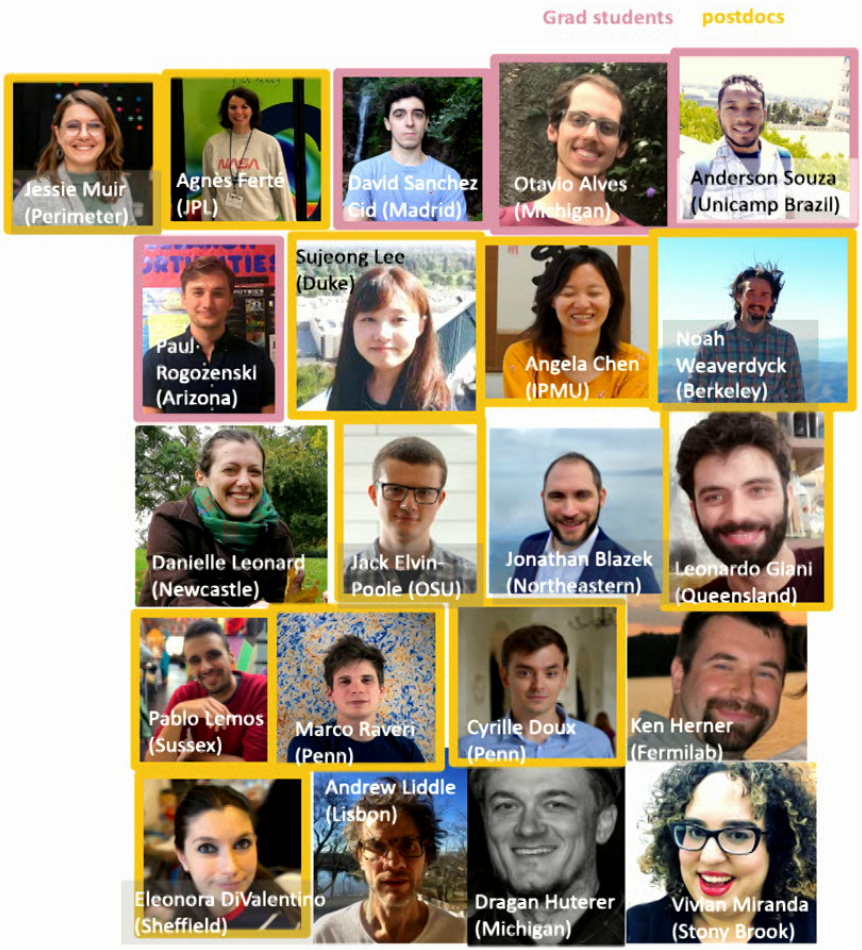


Σ_0 (stronger gravity)

Tests of cosmological models with DES Year 3 3x2pt

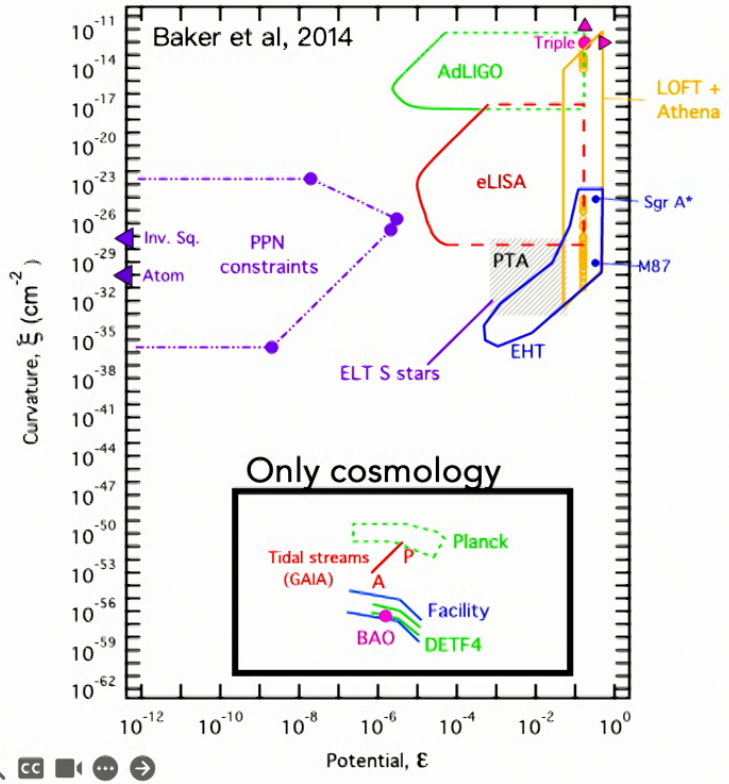
- DES **extensions** team:
  - Co–leads: AF and Jessie Muir
    ~20 scientists including many early career
- Extensions to ΛCDM considered:
  - Time dependent dark energy equation of state
  - Non–zero spatial curvature
  - Sterile neutrinos
  - Phenomenological $\sigma_8(z)$ test
  - **Tests of gravity**

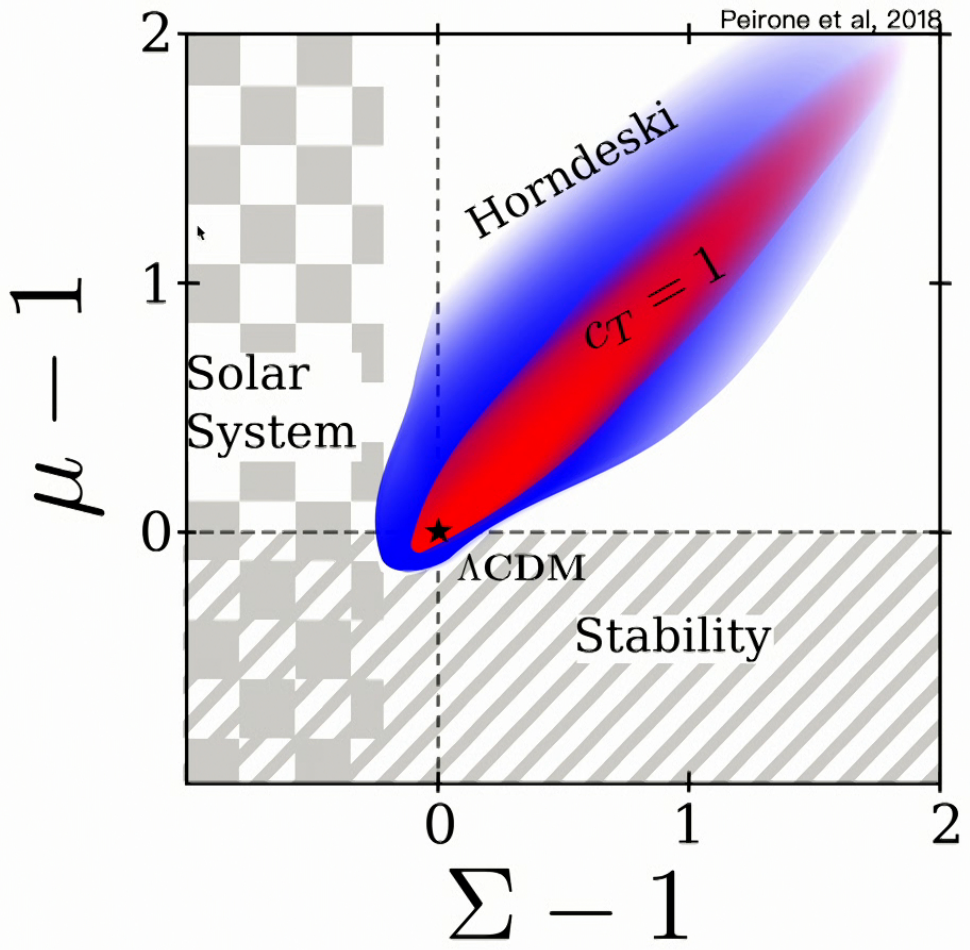
DES Collaboration (incl. Ferté), PRD, 2023



Cosmological tests of gravity

Measurements of speed of GW:
Tensor theories not viable
Space for other theory





Estimation of non-standard physics parameters through Bayesian analysis

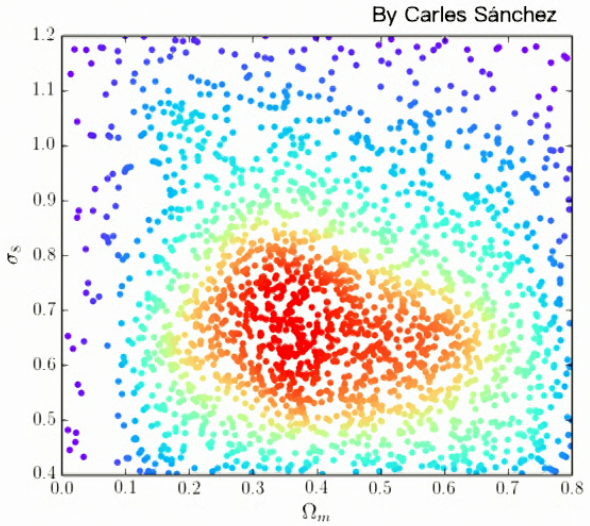
$$L(D|p) \sim \exp\left(-\frac{1}{2}[(D-M(p))^T C^{-1}(D-M(p))]\right)$$

Sampling of the likelihood

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

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

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



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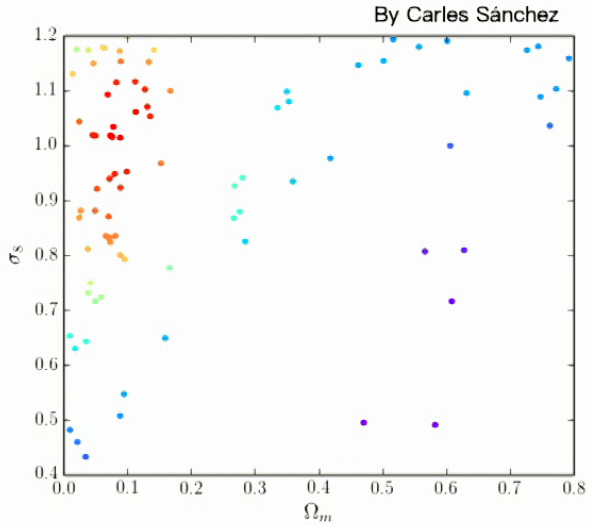

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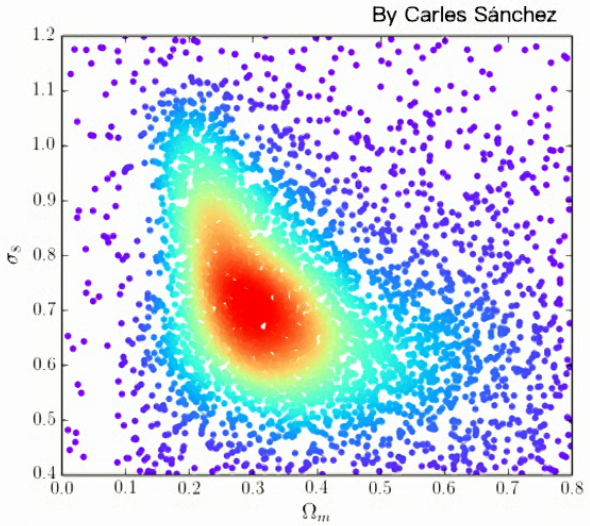


DES Year 3 3x2pt data

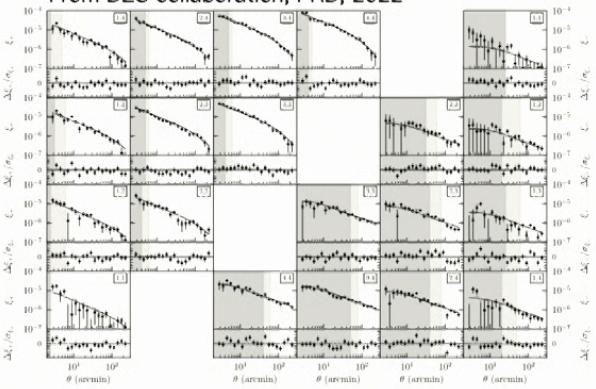
$$L(D|p) \sim \exp\left(-\frac{1}{2}[(D - M(p))^T C^{-1}(D - M(p))]\right)$$

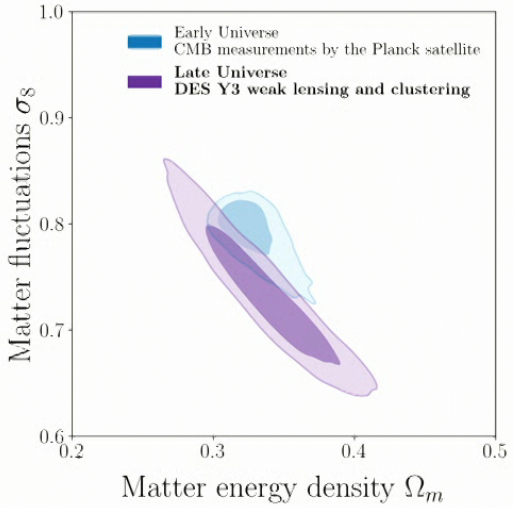
Precise measurements of the 3x2pt data vector

- **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 (incl. Ferté), PRD, 2022 + 29 papers

From DES collaboration, PRD, 2022



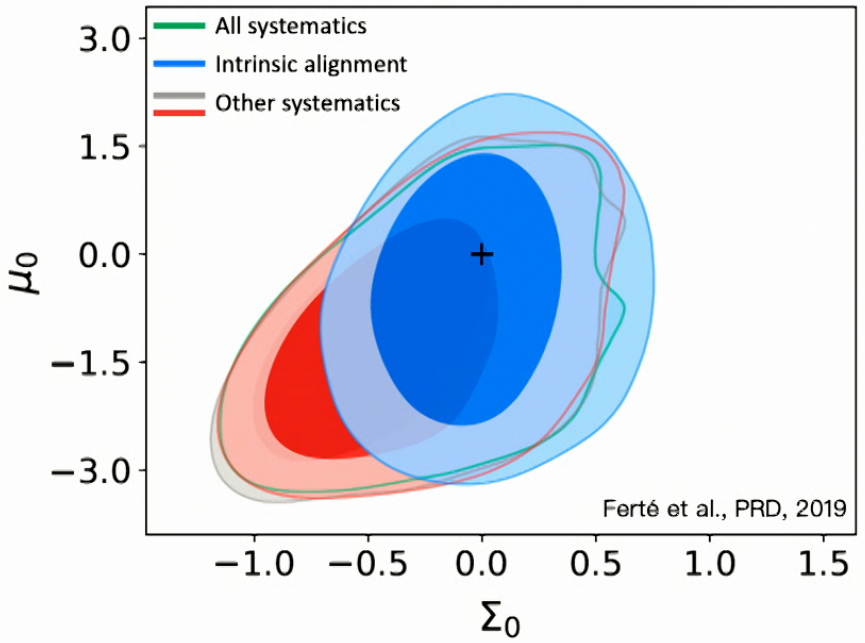


3x2pt modeling in Σ,μ

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

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.

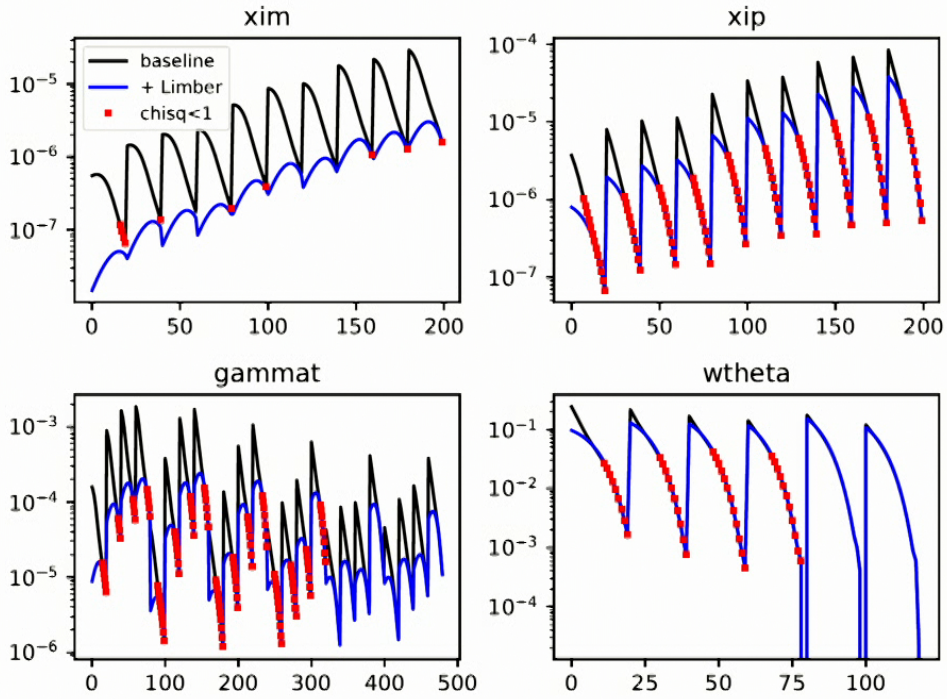


Non–linear power spectrum

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

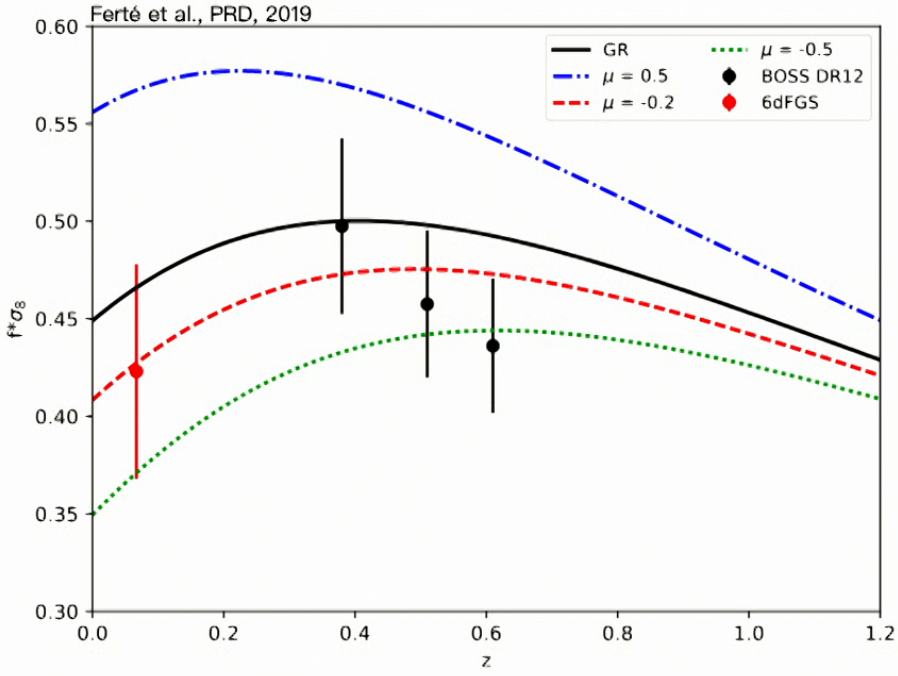
$$\Delta\chi^2 \equiv (\mathbf{D}_{\rm NL} - \mathbf{D}_{\rm lin})^{\rm T}\, \mathbf{C}^{-1}\, (\mathbf{D}_{\rm NL} - \mathbf{D}_{\rm lin}) < 1$$

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

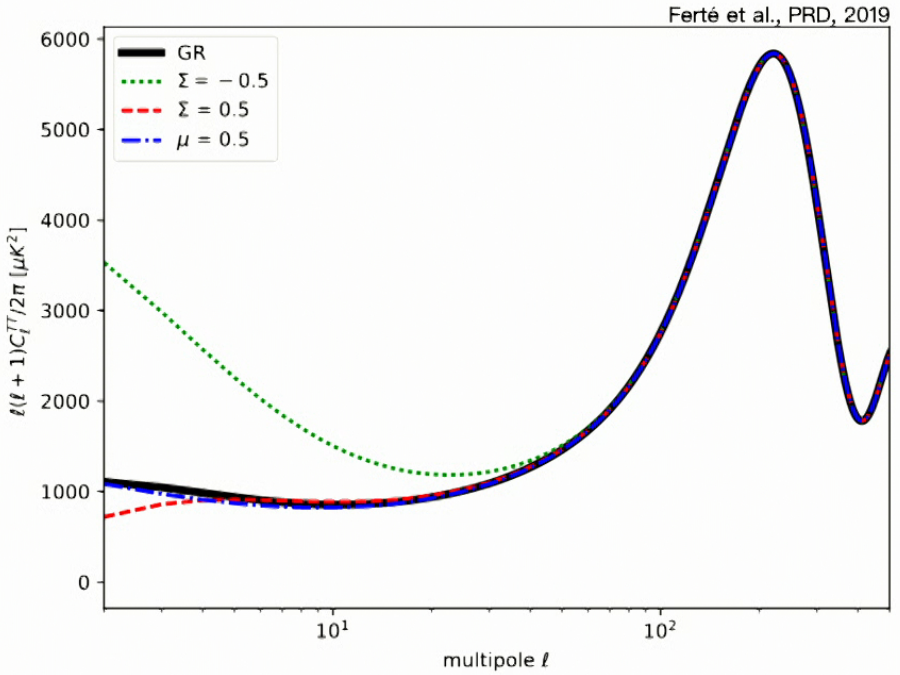


Complementary data to test gravity

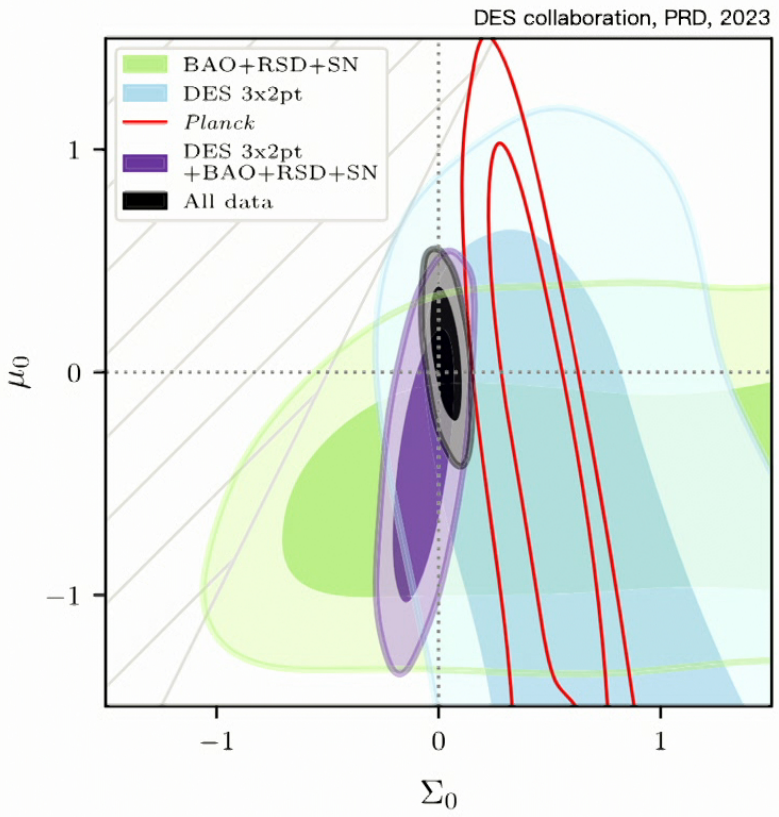
RSD → μ_0



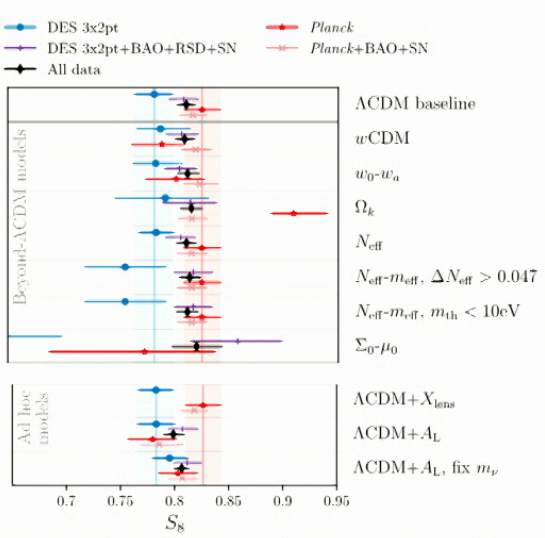
CMB Temperature and polarization power spectra → Σ_0,μ_0

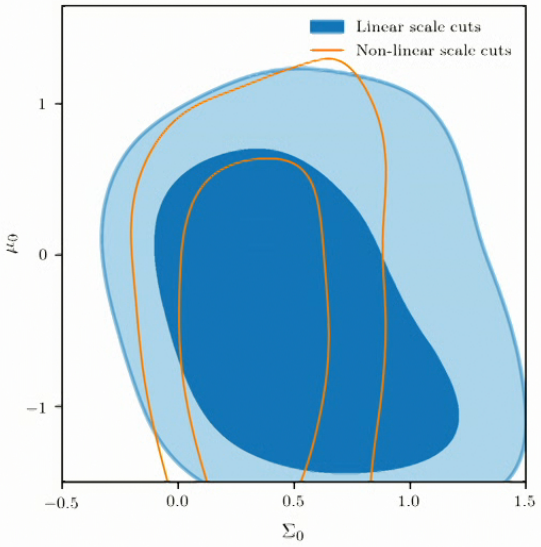


DES Year 3 results on tests of gravity



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





Further tests of gravity

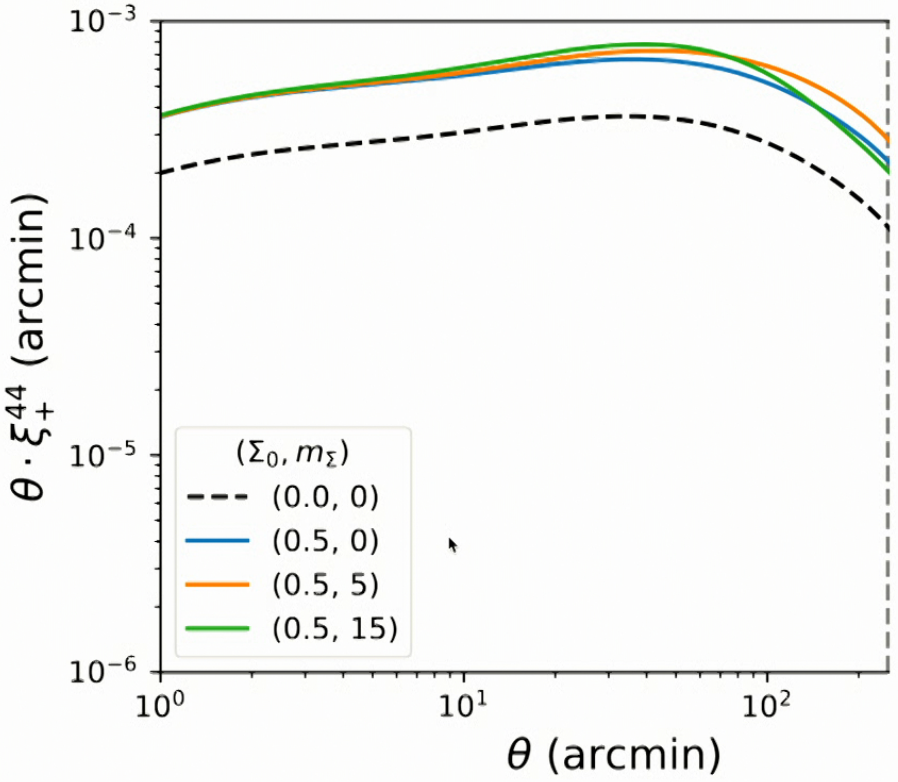
- **Scale**–dependant Σ,μ(a,k):
  Work with student David Shlivko in 2019.
  Model added to MGCamb and validation.

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

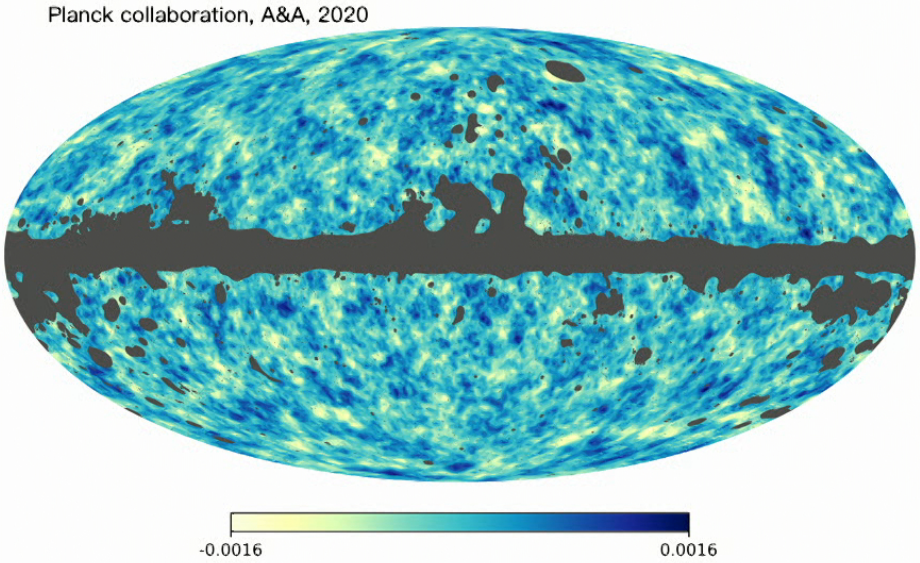
Shlivko, Ferté et al, in prep

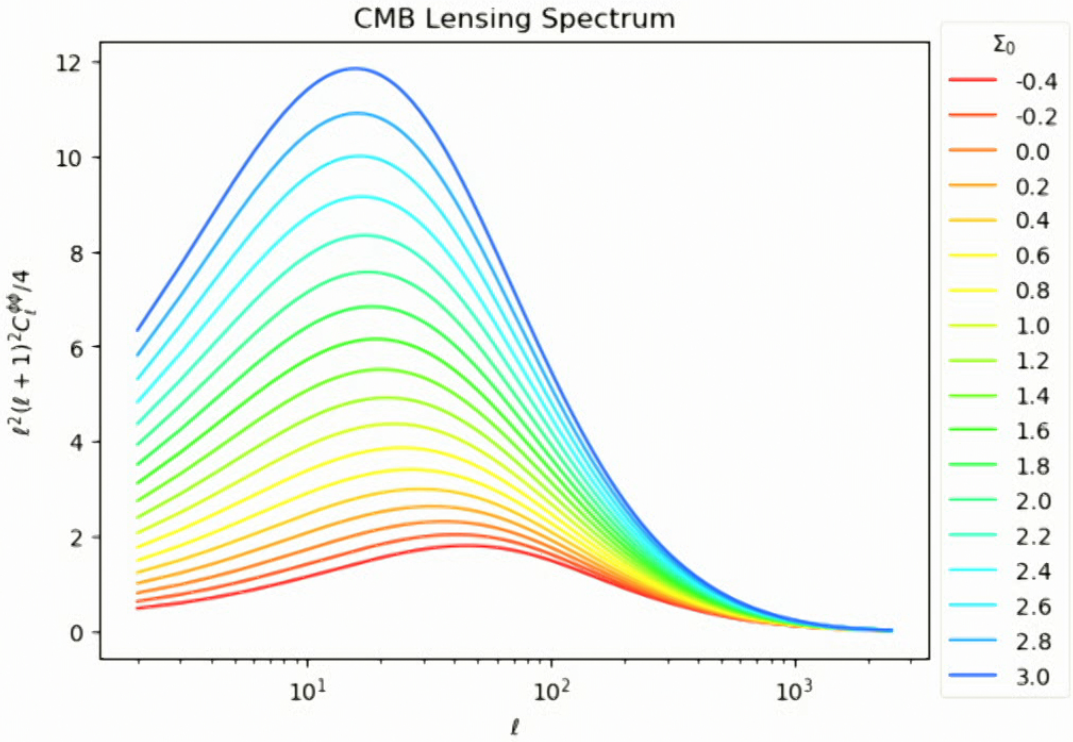
- Other **time** dependence of Σ,μ.
- Other **theories**: f(R), dilaton, ...

→ Application to DES Y3 3x2pt ***Ferté et al, in prep***
=> work this week @ PI.



CMB lensing to test gravity

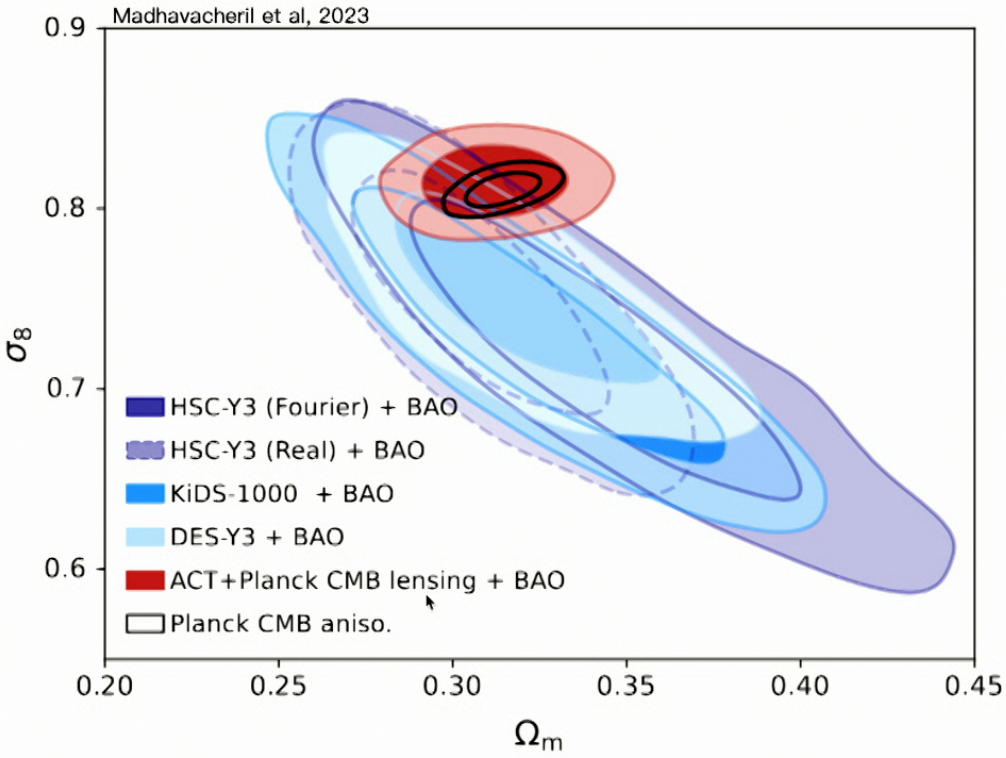




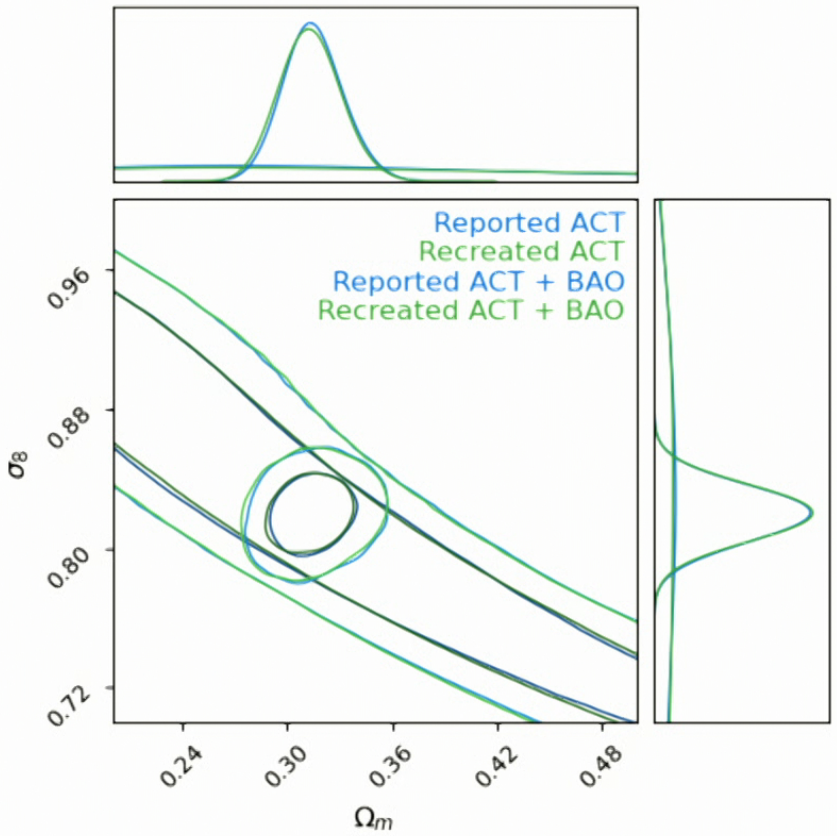
- Lensing of the Cosmic Microwave Background: sensitive to Σ_0
- More and more **precise** measurements of CMB lensing

ACT DR6 lensing data

43σ measurement of CMB lensing with ACT data

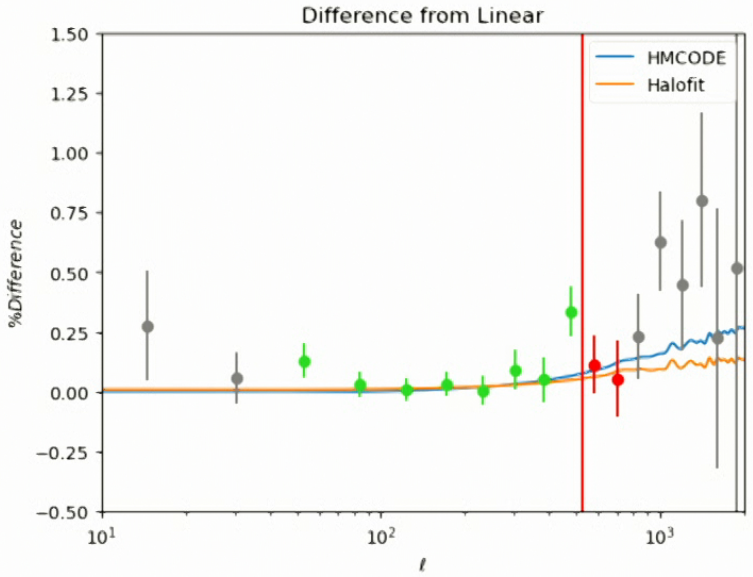


Preparing Σ,μ analysis of ACT DR6 lensing

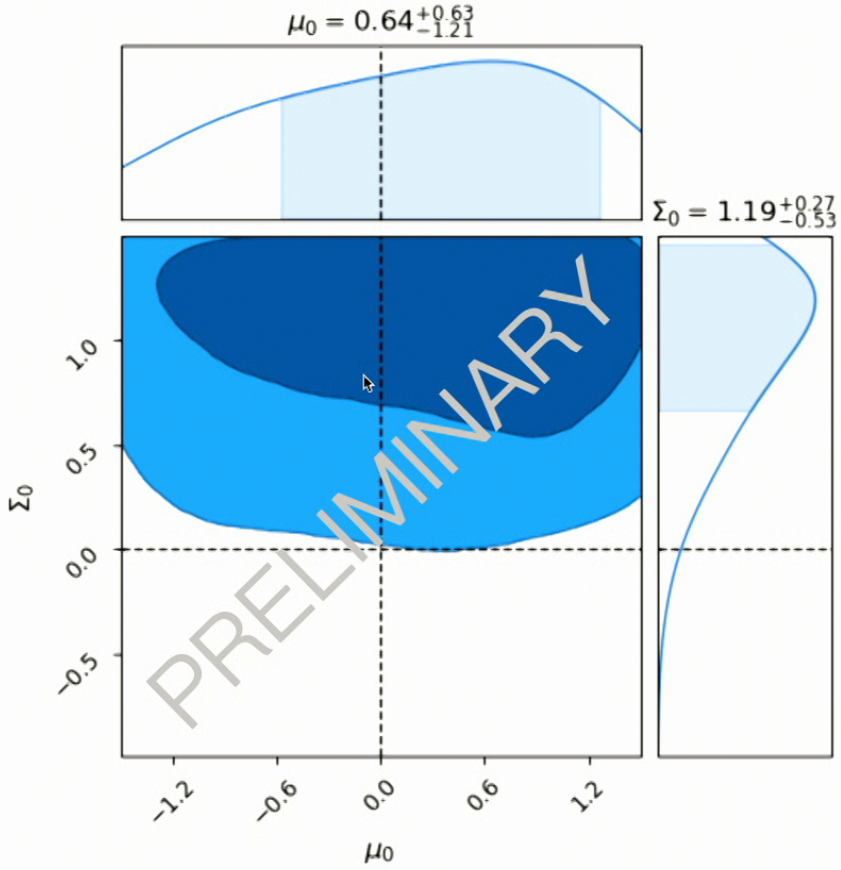


Work with student David Dzingeleski

- Re-doing the **cosmological analysis with CosmoSIS** using ACT DR6 module from Mat Madhavacheril, Renée Hlozek, Joe Zuntz.
  => Validation against the official ACT DR6 chains in LCDM.
- Non-linear **scale cuts**: remove 2 data points.



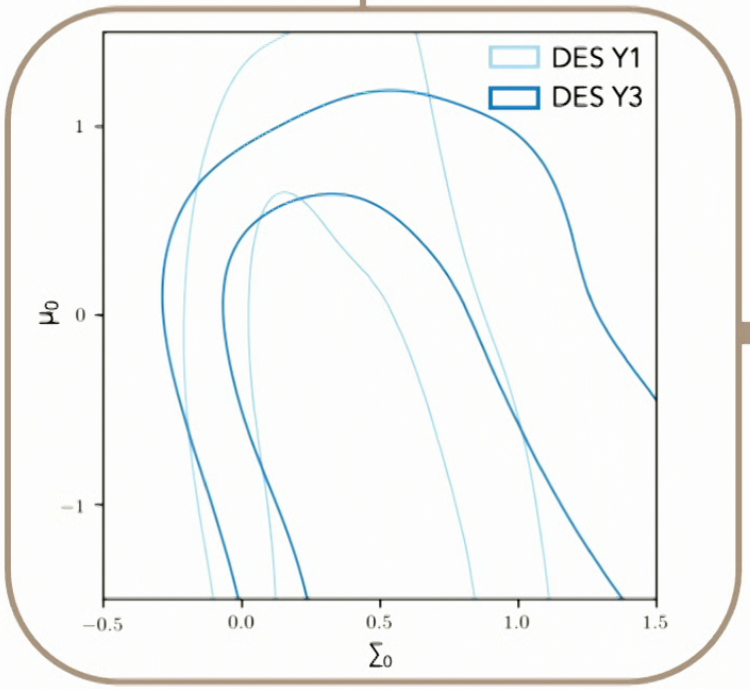
ACT DR6 lensing results on Σ,μ



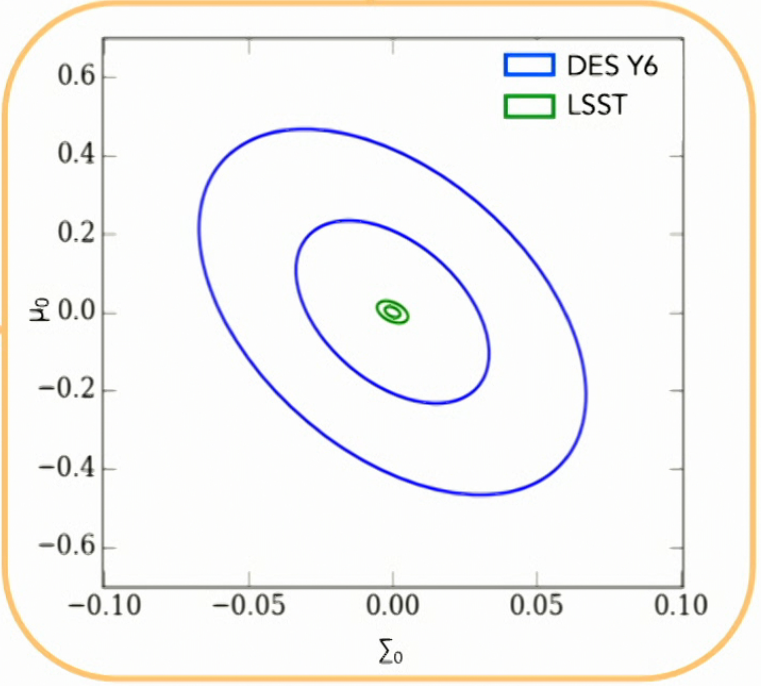
- Intriguing results: ongoing work.
- Combination with other datasets:
  - Adding RSD: consistent GR.
- Exciting prospects to test Σ_0 with **SO and CMB–S4** in parallel to **LSST and Euclid**.

Dark Energy Survey → Legacy Survey of Space and Time

2023 2025 2030



observed f_{sky} x5
galaxies x10
$\sigma(\Sigma_0,\mu_0)$ /10



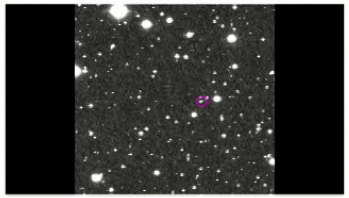
DES Collaboration (incl. **Ferté**), PRD, 2019
DES Collaboration (incl. **Ferté**), PRD, 2023

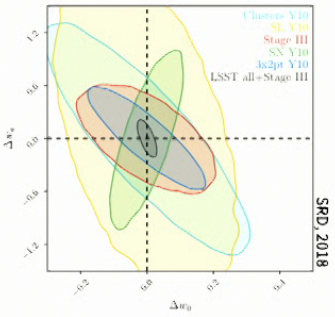
Ferté, Kirk, Zuntz, Liddle, PRD, 2019

Rubin Observatory will map the entire Southern sky every 3 nights

LSST = a fast wide deep survey to do:

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



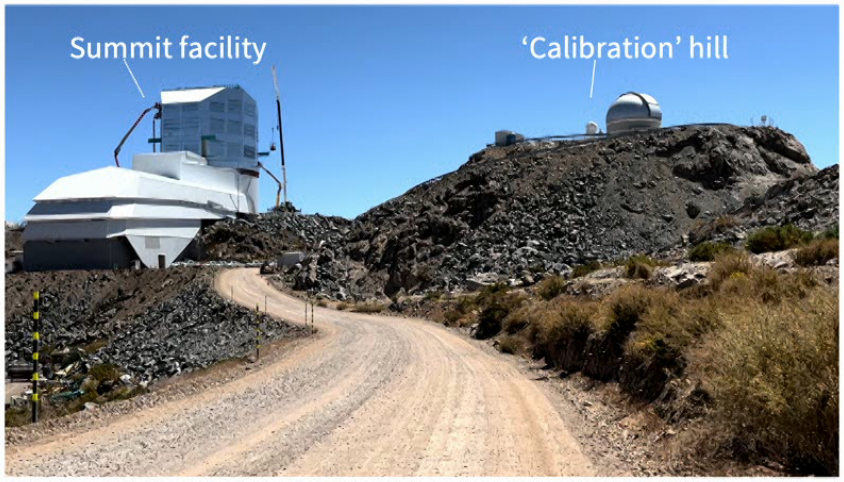


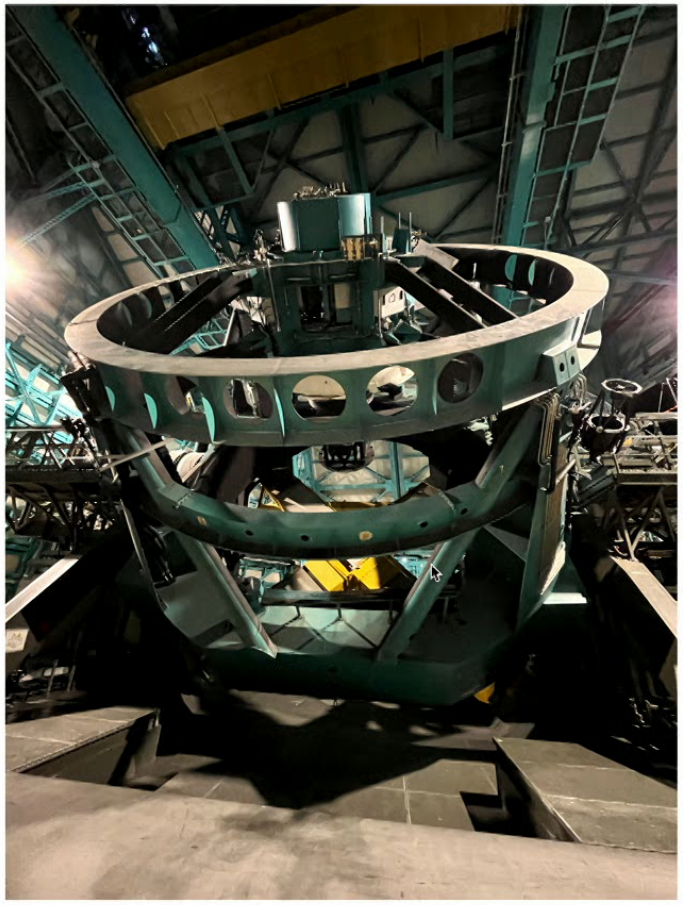
Rubin Observatory & **you**:

- Science Collaborations: organized efforts around science with LSST data.
- Community forum:
- The Rubin Observatory is a US and Chilean Project with in-kind contributions:
  - From the US and Chile
  - From the international community including Canada through the IDAC and software contribution

A new addition to Cerro Pachón

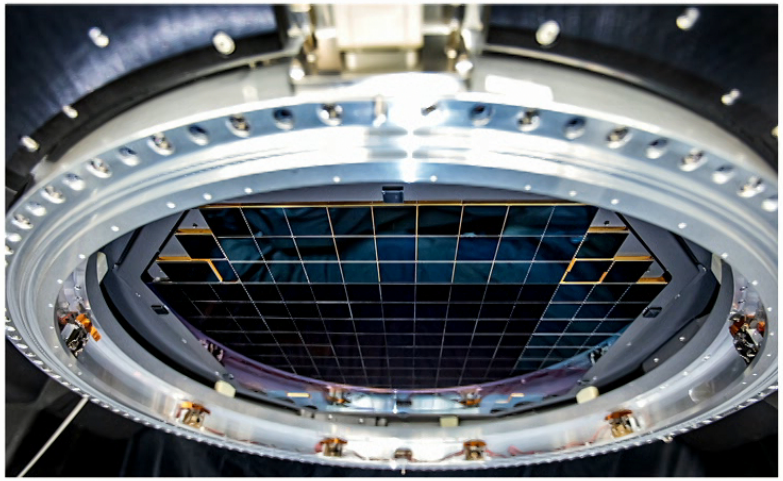
- The Rubin Observatory under **construction** since 2015 at Cerro Pachón at 2,660m elevation
- The Simonyi Survey Telescope Mount Assembly:
  - On and moving.
  - **Mirrors** cells are on the telescope.
  - **Camera**: ComCam on the telescope, the camera LSSTCam is still at SLAC: shipping soon!
- Currently taking data with the software at the summit with AuxTel.



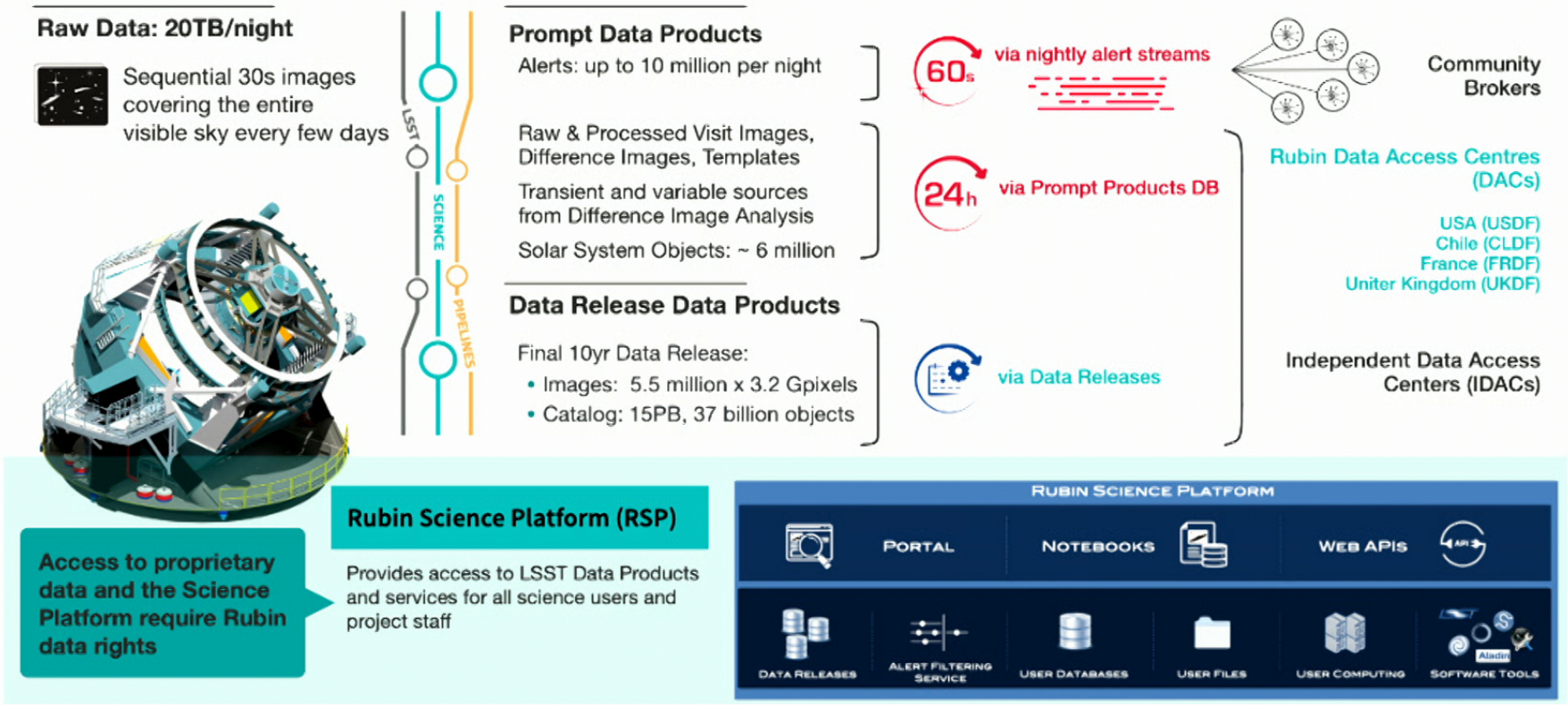


LSSTCam: the largest digital camera

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

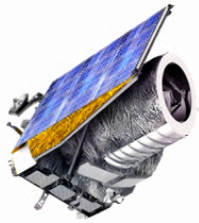


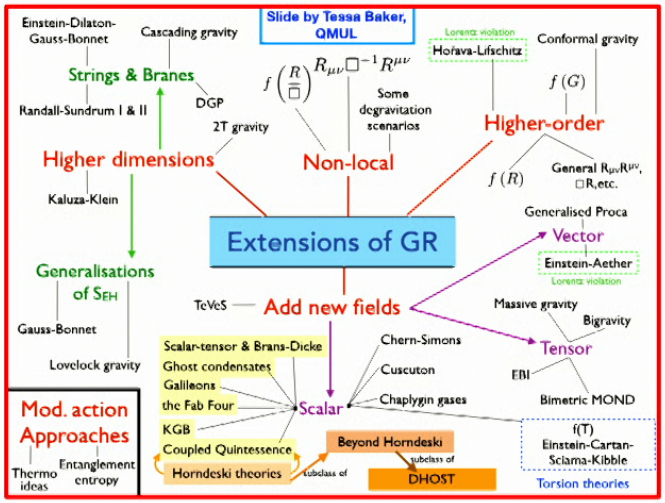
Processing and releasing TB of data



Slide by Leanne Guy

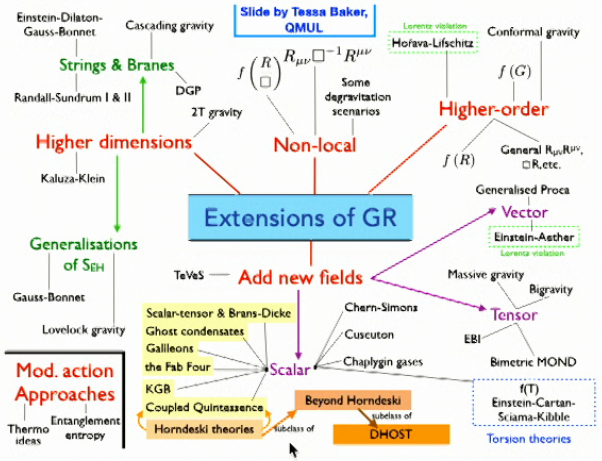
Increase of volume of data and large theory space

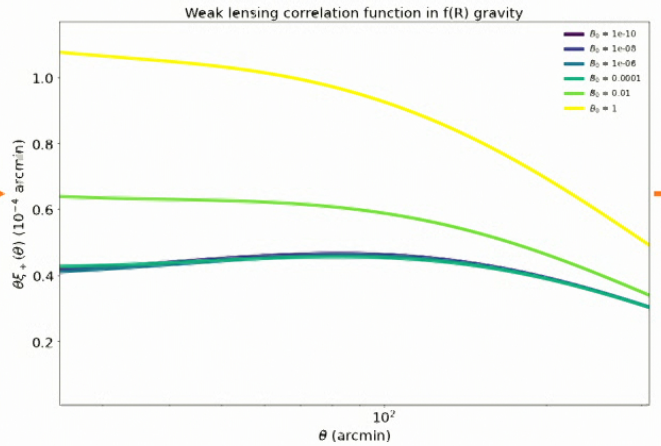


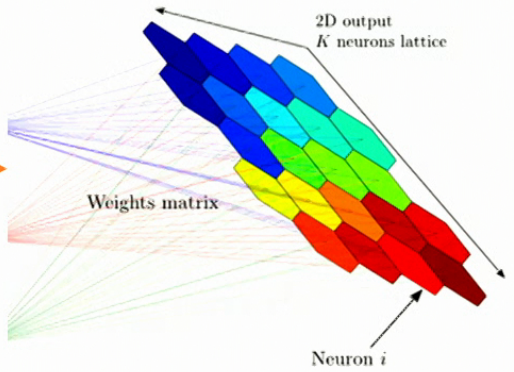


- A few models are preferred by the community and tools developed to model them.
- Mainly theoretical motivations.

Machine learning to help us explore theory space

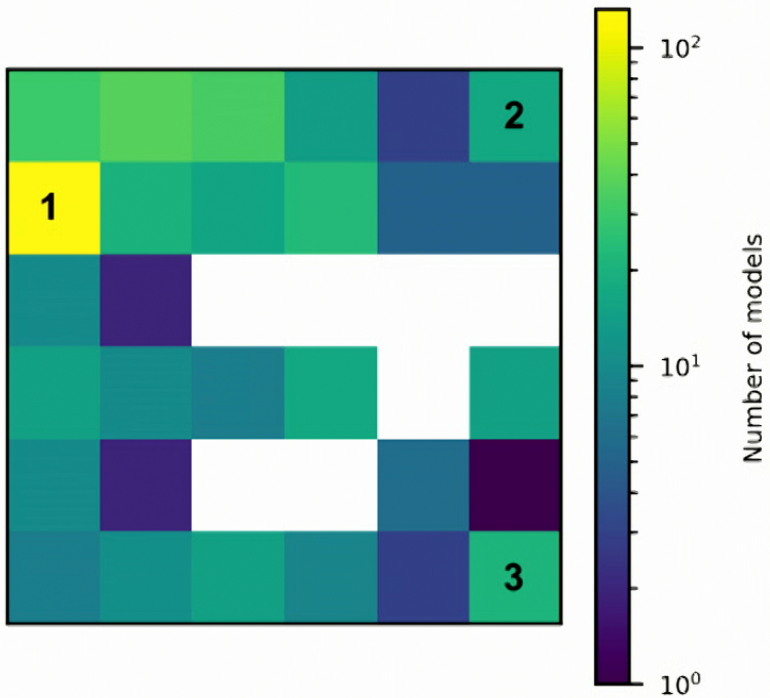


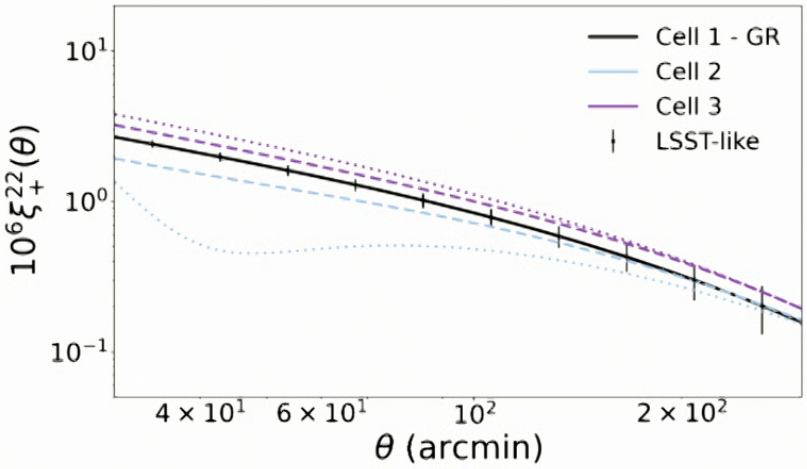


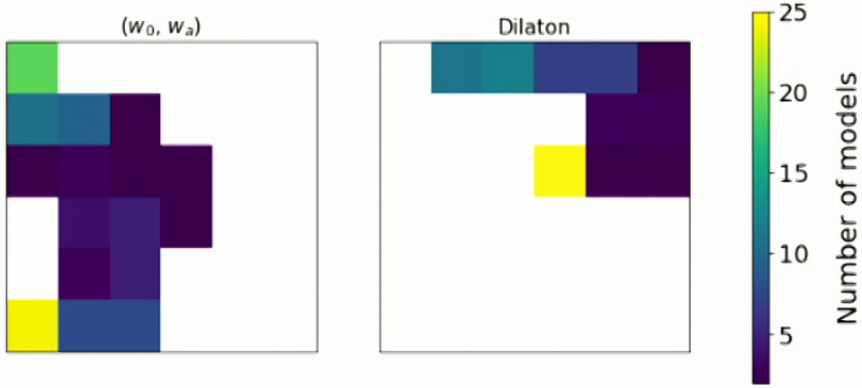


THEORY → **OBSERVABLE** → **SELF-ORGANIZING MAP**

Modified gravity search to complete dark energy search





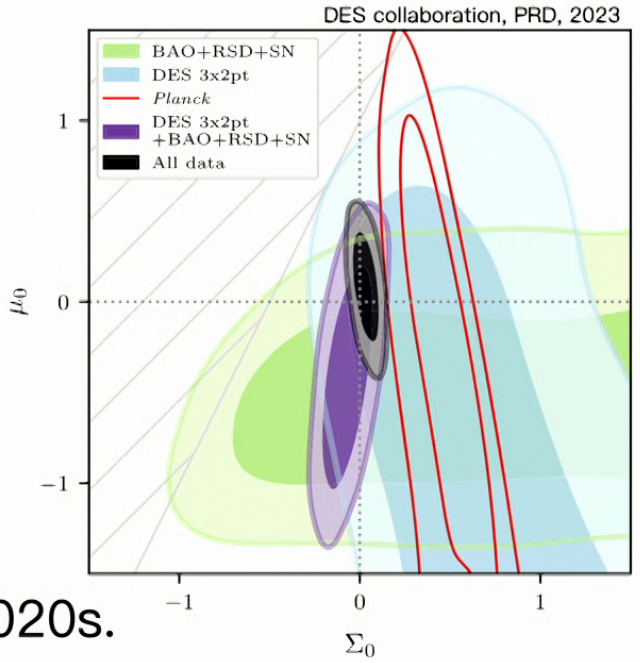


Outlooks

Visiting Jessie Muir this week:
- DES Y3 Modified Gravity
- Preparing for DES Y6 LCDM analysis
- Σ,μ from ACT

Outreach:
- Public talks
- Sharing videos: creation, filming, editing (science, climate change)

- **Gravity under scrutiny**:
  - Σ,μ results: DES Year 3 consistent with GR + preliminary test with ACT DR6 lensing data.
  - Cosmological tests of gravity are more and more precise.
  - **Modeling observables accurately** is the largest challenge.
- ML can be used for theory exploration.



Rich synergies between cosmological surveys in the 2020s.