Dark Energy Survey: the end game

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LSST DESC
Dark Energy Science Collaboration

LSST
LSST : Brazilian Participation Group

XV Latin American Symposium on High Energy Physics
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VERA C. RUBIN
OBSERVATORY

What is the best model that describes our Universe?

Good old Scientific Method:

Theory (models) ⟺ Observations (data)

Theory:

Modern cosmology today is based on three unexpected discoveries:

- There is more matter in galaxies and cluster of galaxies than what was expected $\Rightarrow$ Dark Matter
- Universe is accelerating $\Rightarrow$ Dark Energy
- Universe was very homogeneous and isotropic $\Rightarrow$ Inflation

Today we have a Standard Cosmological Model (ΛCDM):

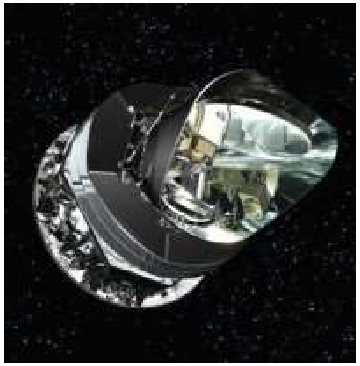
General Relativity + Cosmological Constant Λ (Dark Energy) + known elementary particles (Standard Model of Particle Physics) + Cold Dark Matter + Inflation

Explains all cosmological obervations up to now
(beware of recent tensions in measurements of the Hubble constant: systematics or new physics?)

Observations

We are the first generation with technological capability to study the universe scientifically. Cosmology became a data-driven science!

(Palomar, COBE, Hubble Sp.Tel., JWST, Planck, DES, DESI, Euclid, LSST,...)



Planck satellite launched 2009

Dark Energy Survey 2012-2019 (DES)

Many different cosmological probes and instruments:

- Cosmic Microwave Background (CMB)
- Big bang nucleosynthesis (BBN)
- Supernovae Ia
- Gravitational lensing
- Distribution of galaxies
- Number count of clusters of galaxies

This talk

COBE, WMAP, Planck
SH0ES
SDSS, BOSS, eBOSS
KiDS
HSC
DES
PAU, J-PAS
DESI
LSST
Euclid ...

Galaxy surveys

Two main types of galaxy surveys:

- Spectroscopic: take spectra of galaxies

(good quality spectroscopic redshift vs smaller number of objects; no imaging)

- Photometric (imaging): take pictures of galaxies with different color filters

(fair quality photometric redshift vs larger number of objects; imaging)
Catalogs are divided into **redshift bins**.

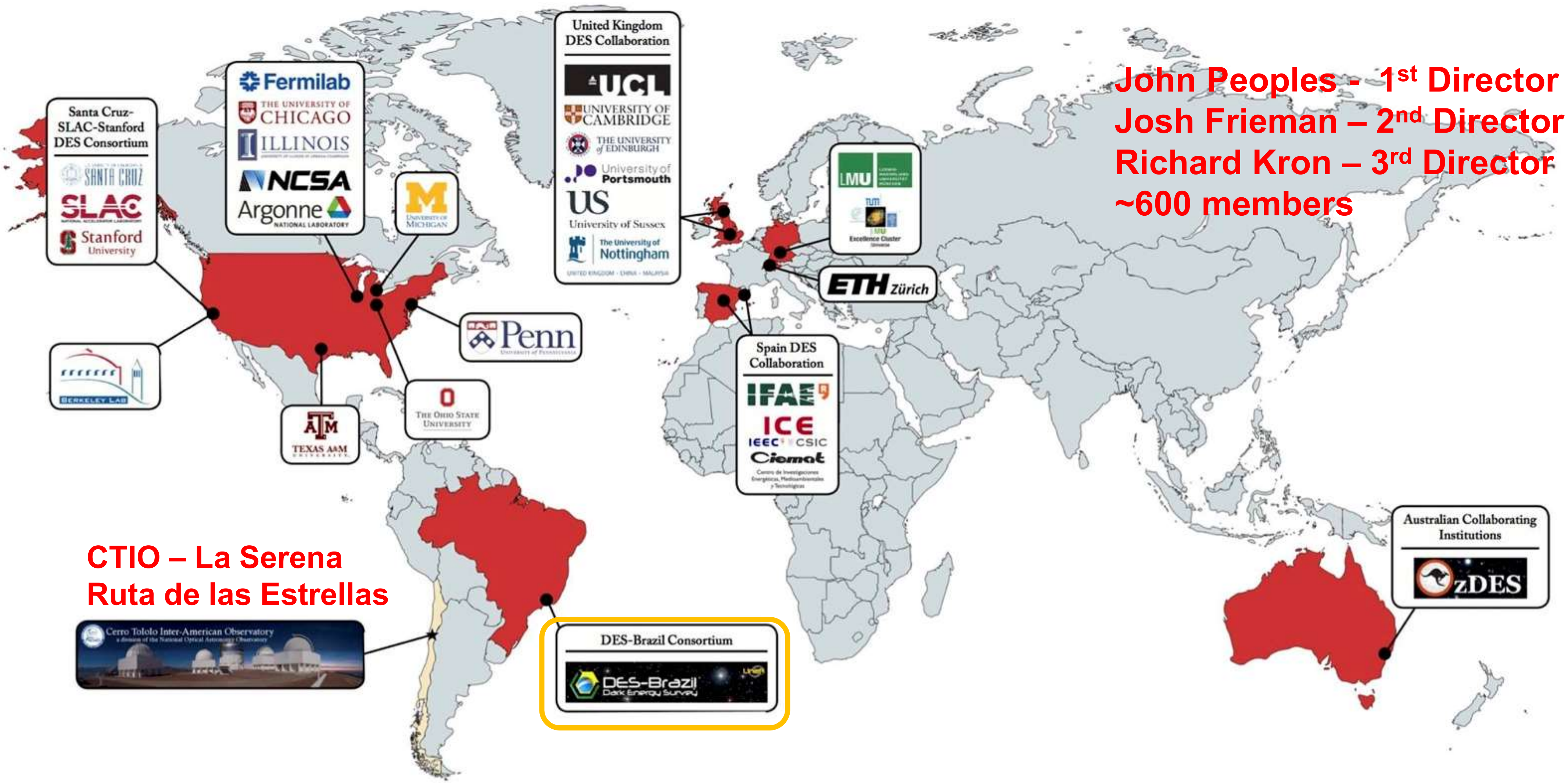
DES and LSST are photometric surveys

2209.08654

Figure 6-4. *Summary of imaging and spectroscopic surveys and facilities, ongoing and planned, that are supported by DOE/NSF partnerships. The international ground and space-based landscape of optical wide-field surveys, ongoing and planned, is very rich but for clarity is not represented here. SDSS had both imaging and spectroscopic capabilities, the Blanco telescope was used to carry out the DES, and the Mayall is currently used for DESI. In the near future, the Rubin Observatory will begin LSST. A new spectroscopic facility would open up new scientific opportunities.*

In this talk I’ll focus on observations (probes) from photometric galaxy surveys, such as the Dark Energy Survey (DES) and the future Rubin Observatory’s Legacy Survey of Space and Time (LSST).

The Dark Energy Survey Collaboration

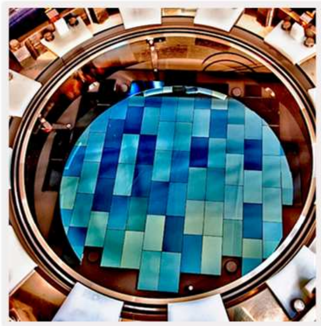


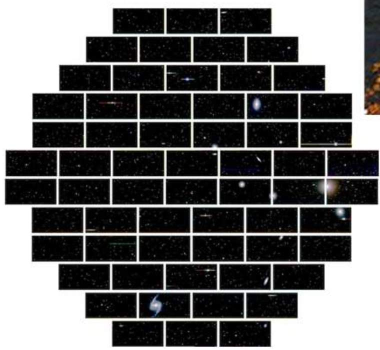
John Peoples - 1st Director
Josh Frieman – 2nd Director
Richard Kron – 3rd Director
~600 members

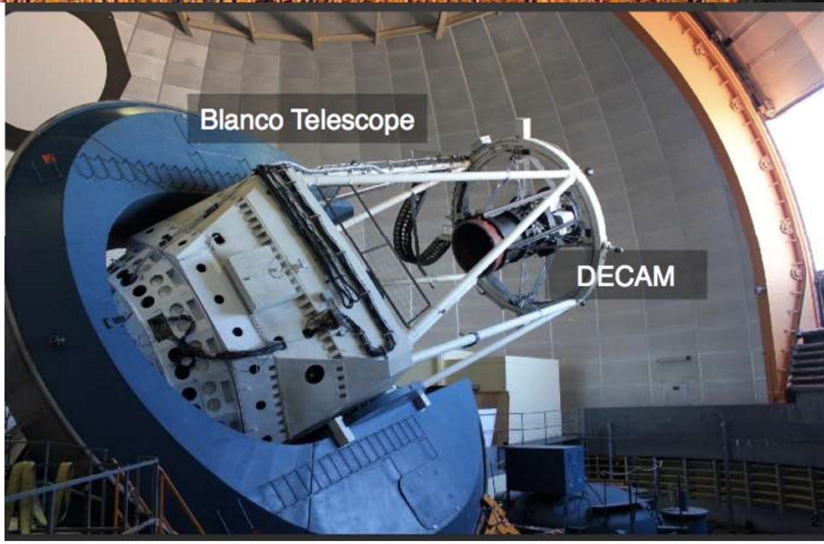
CTIO – La Serena
Ruta de las Estrellas

The Dark Energy Survey (DES)

- >600 members, 25 institutions, 7 countries
- 570 Megapixel camera for the Blanco 4m telescope in Chile.
- Full survey, ~5.5Y. 2013-2019
- Wide field: 5000 sq. deg. in 5 bands grizY. ~23 magnitude.
- DES Y3: Positions and shapes of > 300M galaxies.







DES cosmological results

Most stringent cosmological constraints from a galaxy imaging survey.

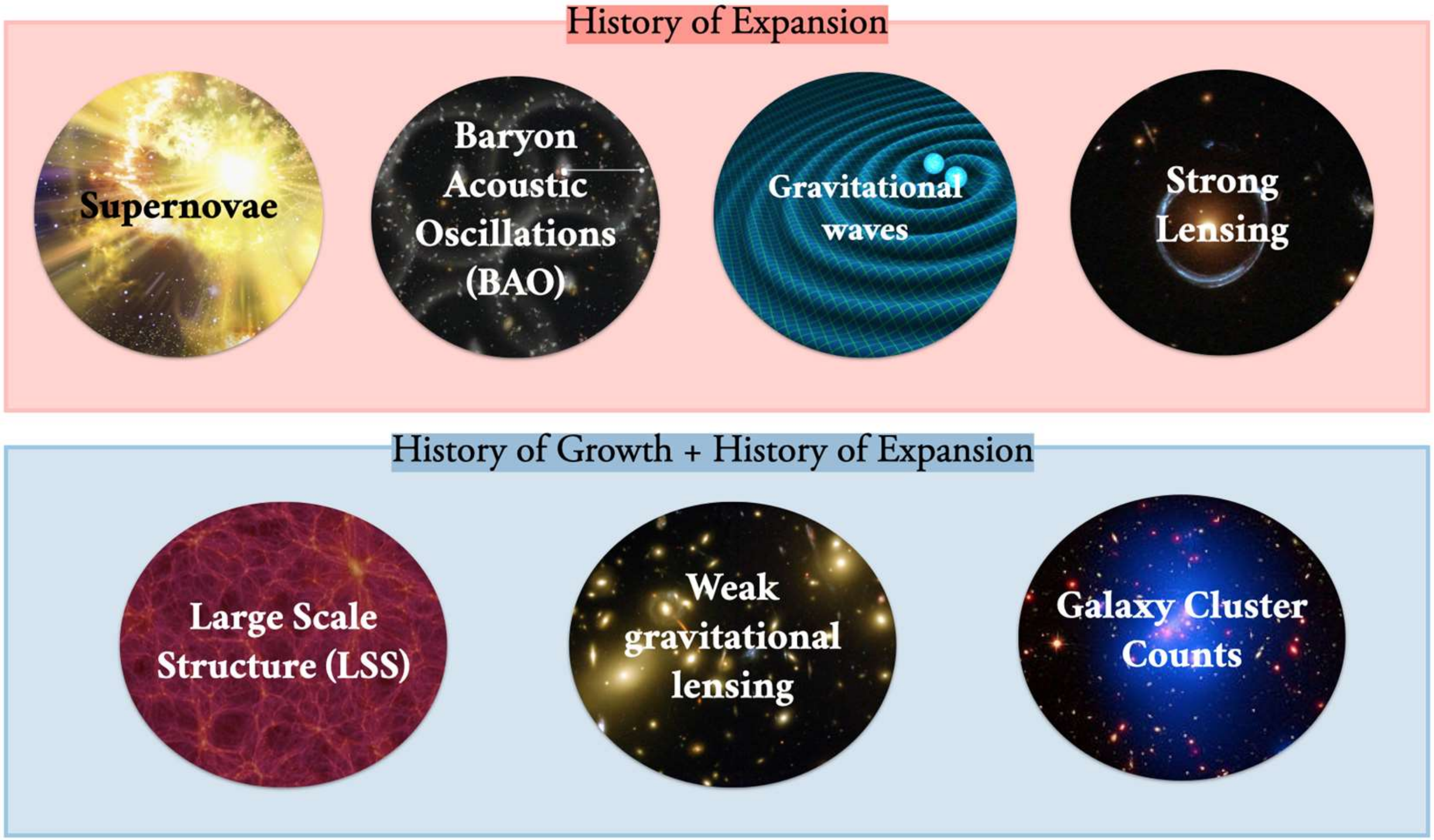
Combined with external data: most stringent constrains overall

Test the six-parameter universe – the flat ΛCDM model:

$\{A_s , n_s , h , \Omega_m , \Omega_b$ and $\Omega_\nu \}$

Small extension- flat wCDM: +w (constant equation of state)

Cosmic probes within DES



Path to cosmology

How to estimate cosmological parameters?

Data vector: $\hat{\mathbf{D}} \equiv \{\hat{w}^i(\theta), \hat{\gamma}_t^{ij}(\theta), \hat{\xi}_\pm^{ij}(\theta)\}$

Theoretical modelling that depends on model M and parameters p $\mathbf{T}_M(\mathbf{p}) \equiv \{w^i(\theta, \mathbf{p}), \gamma_t^{ij}(\theta, \mathbf{p}), \xi_\pm^{ij}(\theta, \mathbf{p})\}$

Gaussian likelihood that depends on the covariance matrix C

$$\mathcal{L}(\hat{\mathbf{D}}|\mathbf{p}, M) \propto e^{-\frac{1}{2}\left[(\hat{\mathbf{D}}-\mathbf{T}_M(\mathbf{p}))^{\mathrm{T}}\mathbf{C}^{-1}(\hat{\mathbf{D}}-\mathbf{T}_M(\mathbf{p}))\right]}$$

Posterior distribution of the parameters that depend on priors: MCMC

$$P(\mathbf{p}|\hat{\mathbf{D}}, M) \propto \mathcal{L}(\hat{\mathbf{D}}|\mathbf{p}, M)P(\mathbf{p}|M)$$

DES-Y3 cosmology: 30+3 papers
Released in 2021/2022

Dark Energy Survey Year 3 results: Cosmological constraints from galaxy clustering and weak lensing

T. M. C. Abbott *et al.* (DES Collaboration)
Phys. Rev. D **105**, 023520 – Published 13 January 2022

DES-Y6: the final analysis
Almost there!

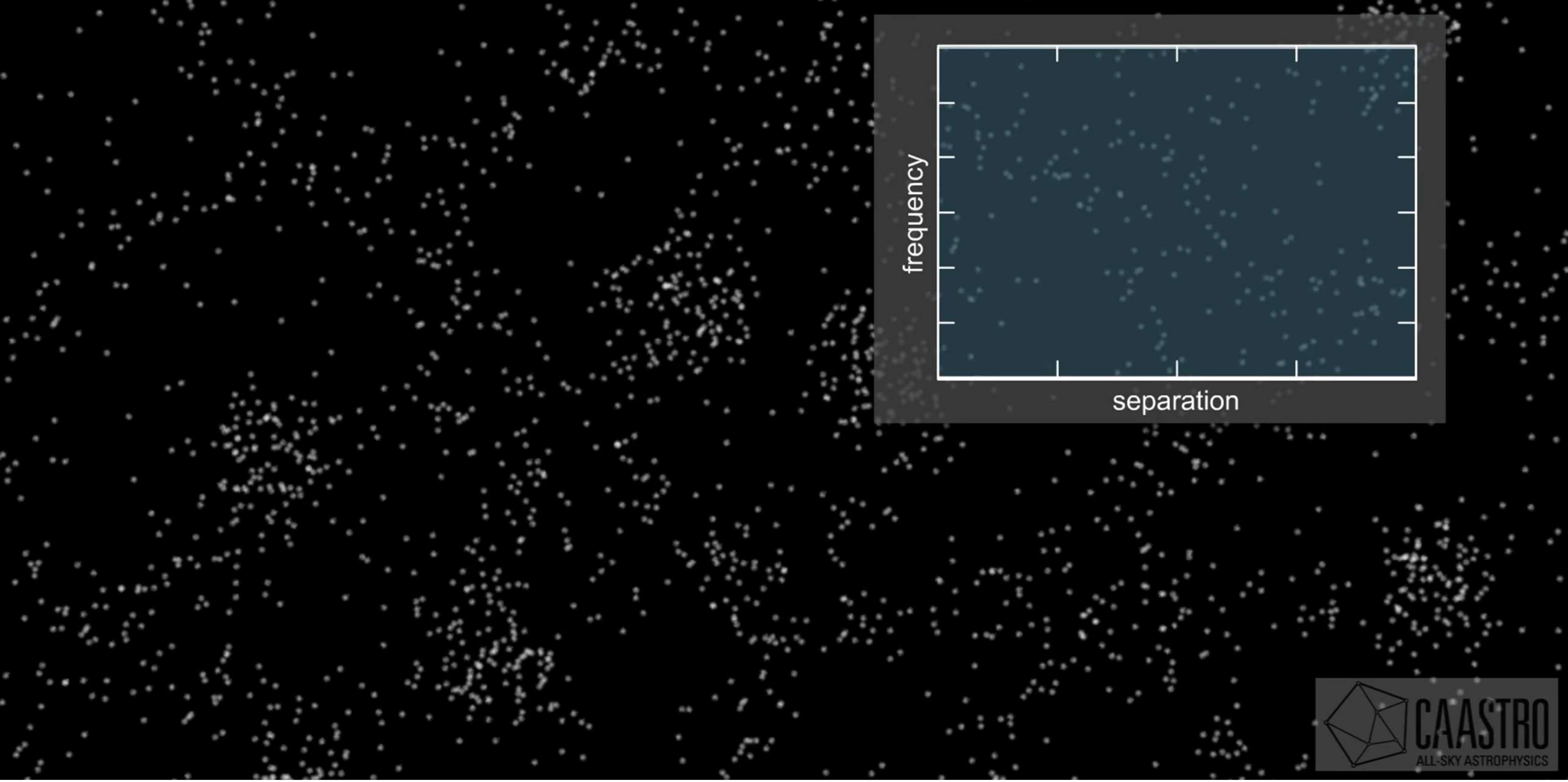
DES cosmological constraints analysis

Main observables are:

- Positions of galaxies (clustering)
- Baryon Acoustic Oscillation
- Shapes of galaxies (shear)
- Type Ia Supernovae

2-point correlation function:
angular correlation function
or
angular power spectrum

Two-point correlation function



From DES-Y3 webinar

Weak lensing

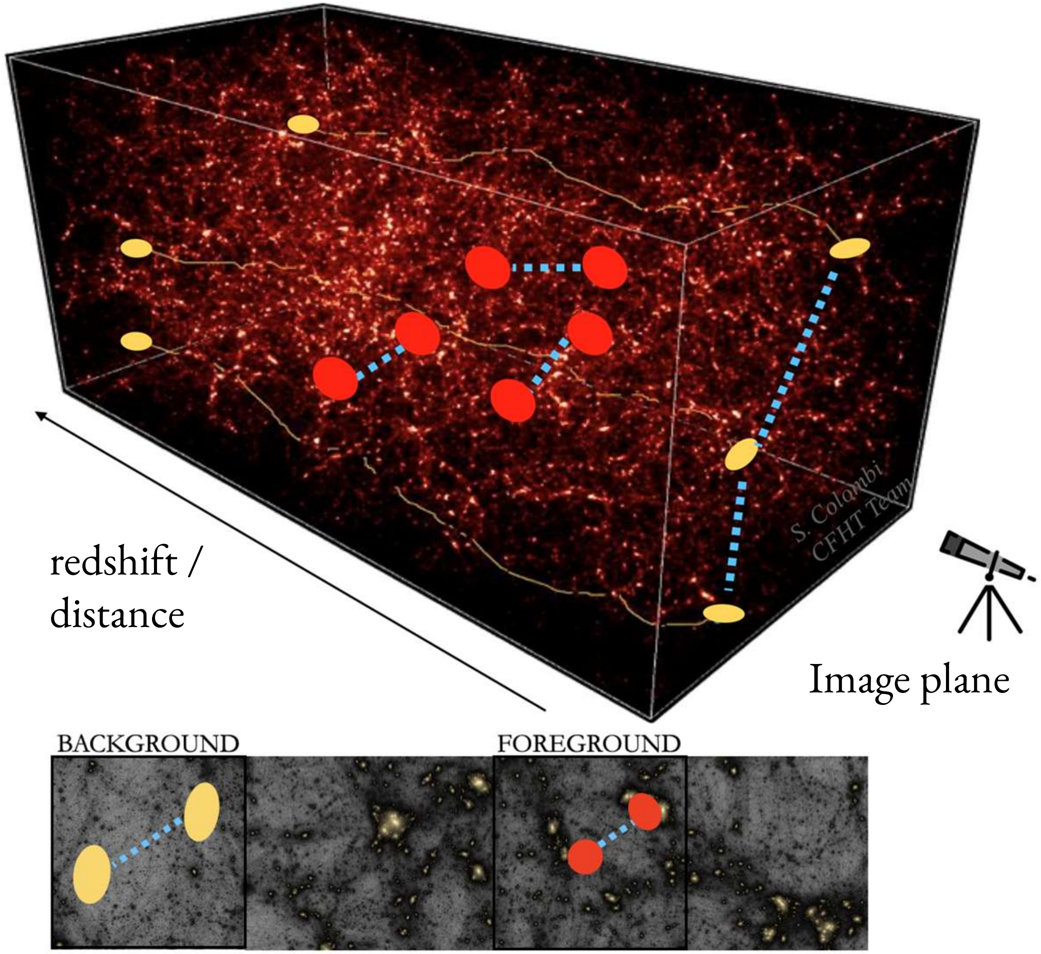
Light from distant galaxies passes the same foreground structure and acquires coherent distortions : they are observe to be *lensed*.

We measure the correlation of the **shapes** of source galaxy pairs as a function of angle and in source **redshift** bins or tomographically.

Galaxy distribution

Galaxies trace the underlying dark matter structure : they are observed to be spatially *clustered*.

We measure the correlation of the **positions** of foreground (lens) galaxy pairs as a function of angle and in lens **redshift** bins or tomographically.



Main issues in modelling correlation functions

- Photometric redshift uncertainties
- Galaxy bias relating galaxy with matter distributions

(does not affect shear)

- Intrinsic alignment of galaxies (does not affect clustering)
- Shear calibration (does not affect clustering)
- Baryonic effects in power spectrum of galaxies
- Nonlinear (gravity) clustering in the power spectrum

3x2pt cosmology

A self-consistent combined analysis maximises the cosmological information and robustly constrains astrophysical & observational systematic priors in the analysis! Most sensitive to Ω_m and S_8.

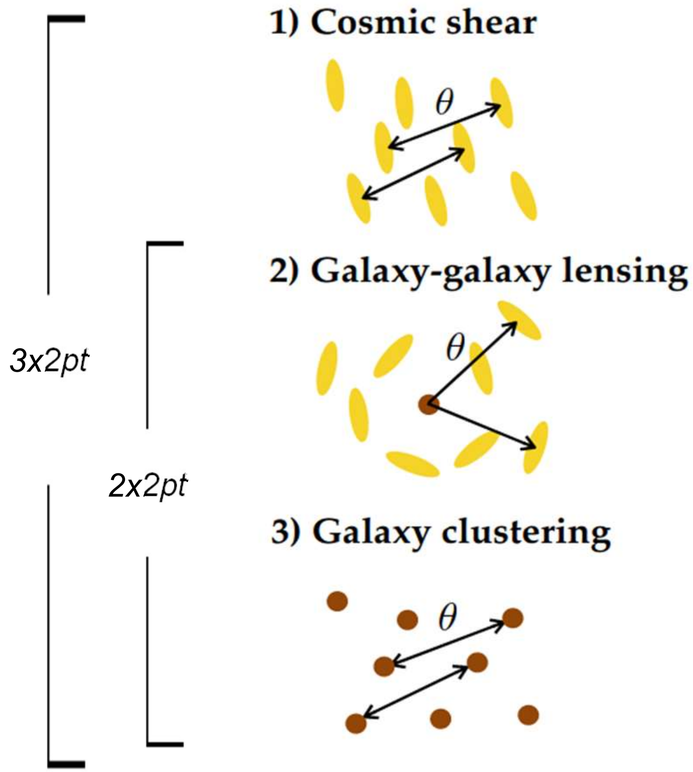
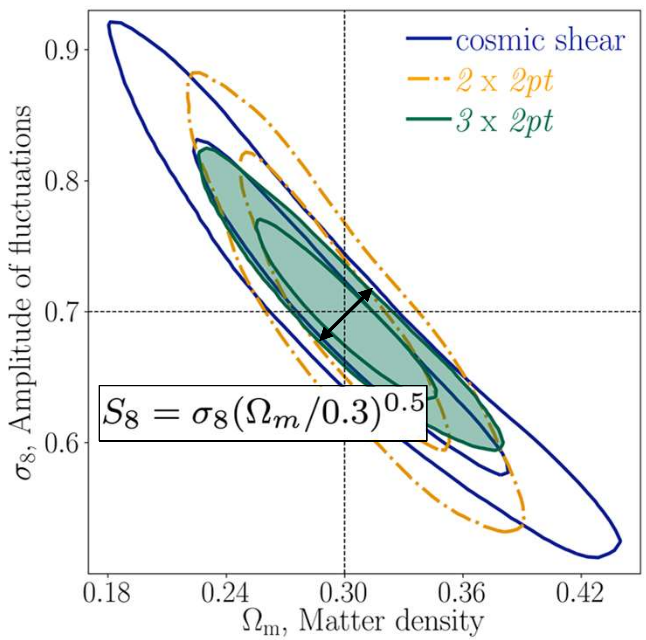


Image credit: Chihway Chang



Cosmological parameters (7)

Nuisance parameters (30)

Parameter	Prior	
Cosmology		
$\Omega_{\rm m}$	Flat	$(0.1, 0.9)$
$10^9 A_s$	Flat	$(0.5, 5.0)$
n_s	Flat	$(0.87, 1.07)$
$\Omega_{\rm b}$	Flat	$(0.03, 0.07)$
h	Flat	$(0.55, 0.91)$
$10^3 \Omega_\nu h^2$	Flat	$(0.60, 6.44)$
w	Flat	$(-2.0, -0.33)$
Lens Galaxy Bias		
$b_i (i \in [1, 4])$	Flat	$(0.8, 3.0)$
Lens magnification		
$C_{\rm l}^1$	Fixed	1.21
$C_{\rm l}^2$	Fixed	1.15
$C_{\rm l}^3$	Fixed	1.88
$C_{\rm l}^4$	Fixed	1.97
Lens photo-z		
$\Delta z_{\rm l}^1 \times 10^2$	Gaussian	$(-0.9, 0.7)$
$\Delta z_{\rm l}^2 \times 10^2$	Gaussian	$(-3.5, 1.1)$
$\Delta z_{\rm l}^3 \times 10^2$	Gaussian	$(-0.5, 0.6)$
$\Delta z_{\rm l}^4 \times 10^2$	Gaussian	$(-0.7, 0.6)$
$\sigma_{z,{\rm l}}^1$	Gaussian	$(0.98, 0.06)$
$\sigma_{z,{\rm l}}^2$	Gaussian	$(1.31, 0.09)$
$\sigma_{z,{\rm l}}^3$	Gaussian	$(0.87, 0.05)$
$\sigma_{z,{\rm l}}^4$	Gaussian	$(0.92, 0.05)$
Intrinsic Alignment		
$a_i \ (i \in [1, 2])$	Flat	$(-5, 5)$
$\eta_i \ (i \in [1, 2])$	Flat	$(-5, 5)$
$b_{\rm TA}$	Flat	$(0, 2)$
z_0	Fixed	0.62
Source photo-z		
$\Delta z_{\rm s}^1 \times 10^2$	Gaussian	$(0.0, 1.8)$
$\Delta z_{\rm s}^2 \times 10^2$	Gaussian	$(0.0, 1.5)$
$\Delta z_{\rm s}^3 \times 10^2$	Gaussian	$(0.0, 1.1)$
$\Delta z_{\rm s}^4 \times 10^2$	Gaussian	$(0.0, 1.7)$
Shear calibration		
$m^1 \times 10^2$	Gaussian	$(-0.6, 0.9)$
$m^2 \times 10^2$	Gaussian	$(-2.0, 0.8)$
$m^3 \times 10^2$	Gaussian	$(-2.4, 0.8)$
$m^4 \times 10^2$	Gaussian	$(-3.7, 0.8)$

3x2pt results from DES-Y3

We combine these into the **3×2pt** probe of large-scale structure.

A factor of 2.1 improvement in signal-to-noise from DES Year 1.

In ΛCDM:

$$S_8 = 0.776^{+0.017}_{-0.017} \quad (0.776)$$

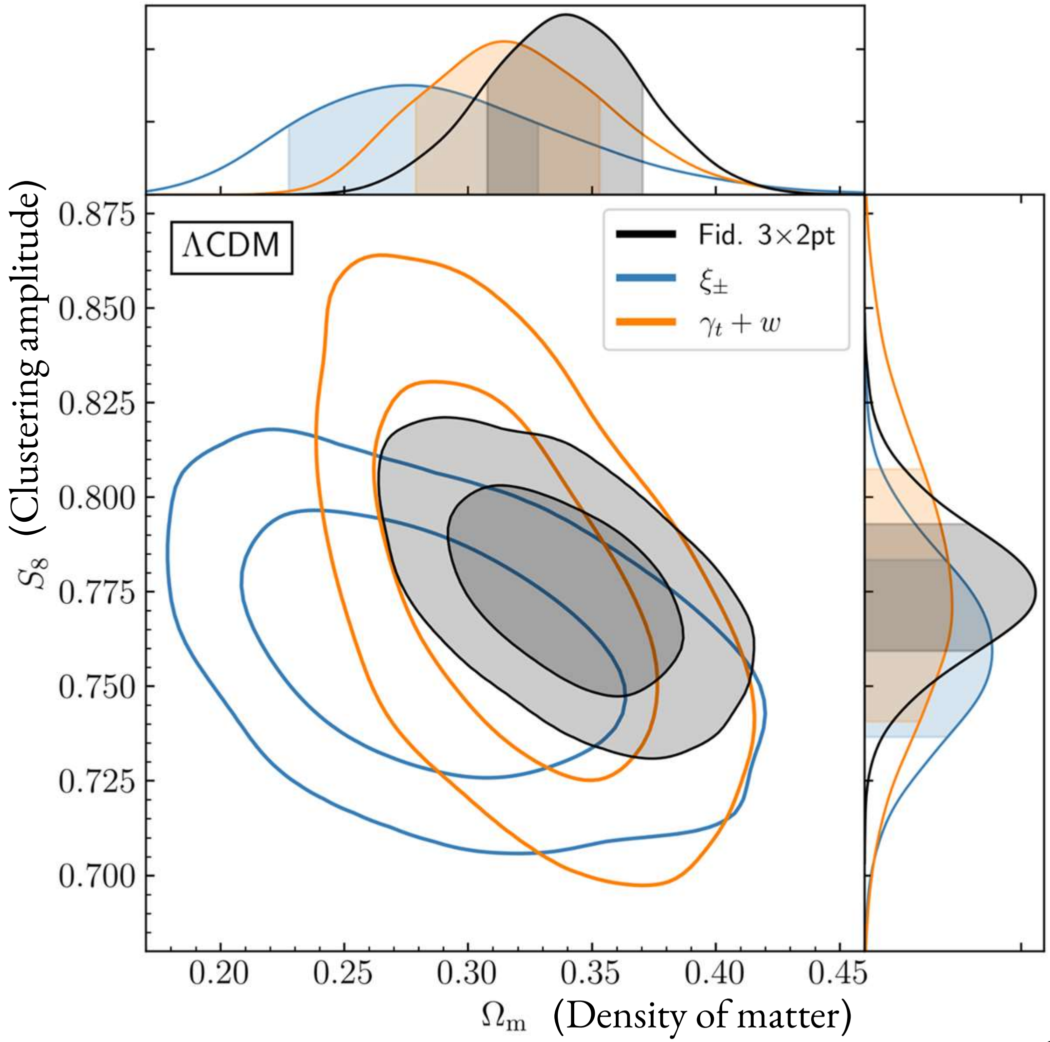
$$\Omega_{\rm m} = 0.339^{+0.032}_{-0.031} \quad (0.372)$$

$$\sigma_8 = 0.733^{+0.039}_{-0.049} \quad (0.696)$$

In wCDM:

$$\Omega_{\rm m} = 0.352^{+0.035}_{-0.041} \quad (0.339)$$

$$\boxed{w = -0.98^{+0.32}_{-0.20} \quad (-1.03)}$$

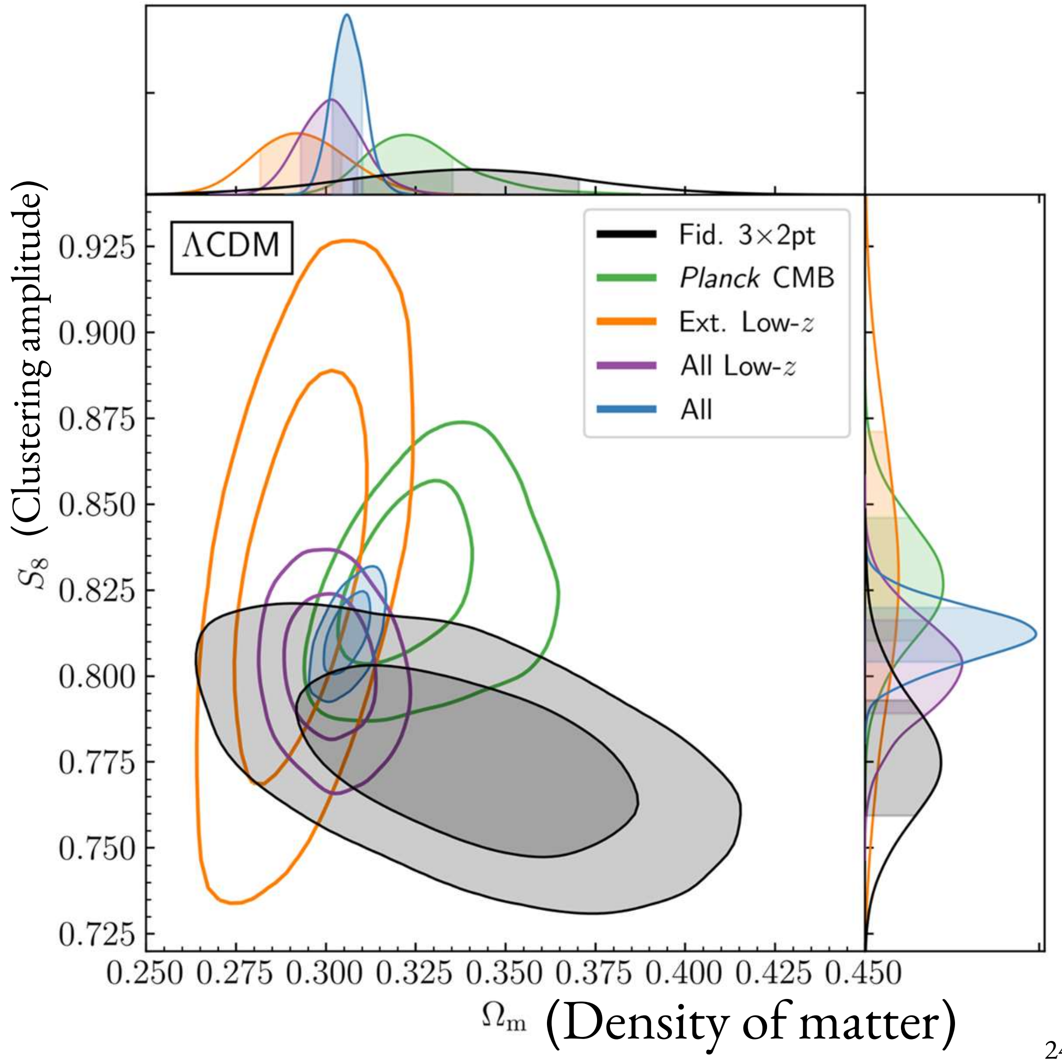


Joint constraints – 3x2pt + Planck

Combining all these data sets we find:

In ΛCDM
$$S_8 = 0.812^{+0.008}_{-0.008} \quad (0.815)$$
$$\Omega_m = 0.306^{+0.004}_{-0.005} \quad (0.306)$$
$$\sigma_8 = 0.804^{+0.008}_{-0.008} \quad (0.807)$$
$$h = 0.680^{+0.004}_{-0.003} \quad (0.681)$$
$$\sum m_\nu < 0.13 \text{ eV (95\% CL)}$$

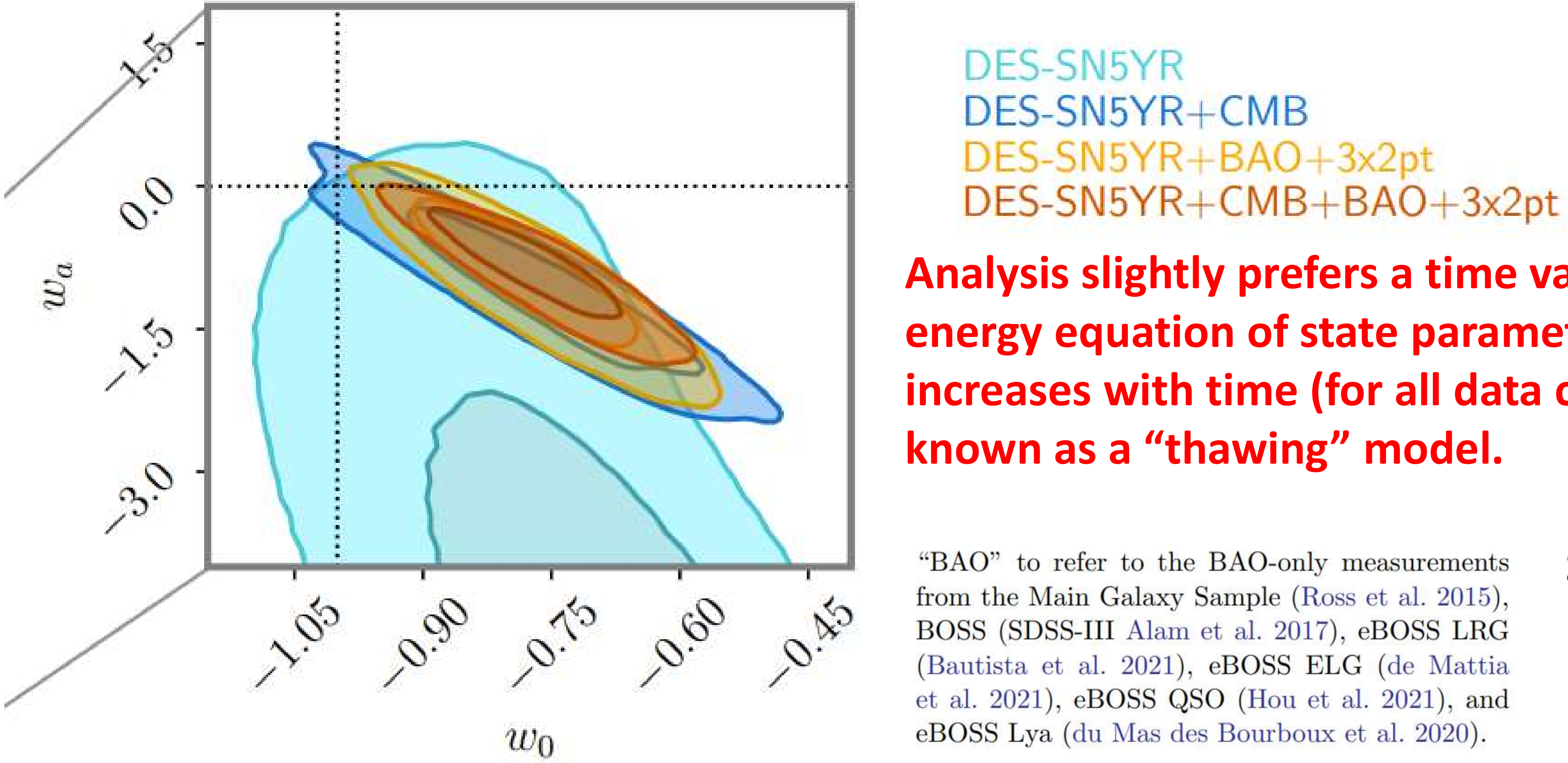
In wCDM:
$$\sigma_8 = 0.810^{+0.010}_{-0.009} \quad (0.804),$$
$$\Omega_m = 0.302^{+0.006}_{-0.006} \quad (0.298),$$
$$\boxed{w = -1.03^{+0.03}_{-0.03} \quad (-1.00)}$$



New results from type Ia Supernovae

The Dark Energy Survey: Cosmology Results With ∼1500 New High-redshift Type Ia Supernovae Using The Full 5-year Dataset

2401.02929



Analysis slightly prefers a time varying dark energy equation of state parameter that increases with time (for all data combinations), known as a "thawing" model.

"BAO" to refer to the BAO-only measurements from the Main Galaxy Sample (Ross et al. 2015), BOSS (SDSS-III Alam et al. 2017), eBOSS LRG (Bautista et al. 2021), eBOSS ELG (de Mattia et al. 2021), eBOSS QSO (Hou et al. 2021), and eBOSS Lya (du Mas des Bourboux et al. 2020).

DESI results: ~4 σ
2404.03002

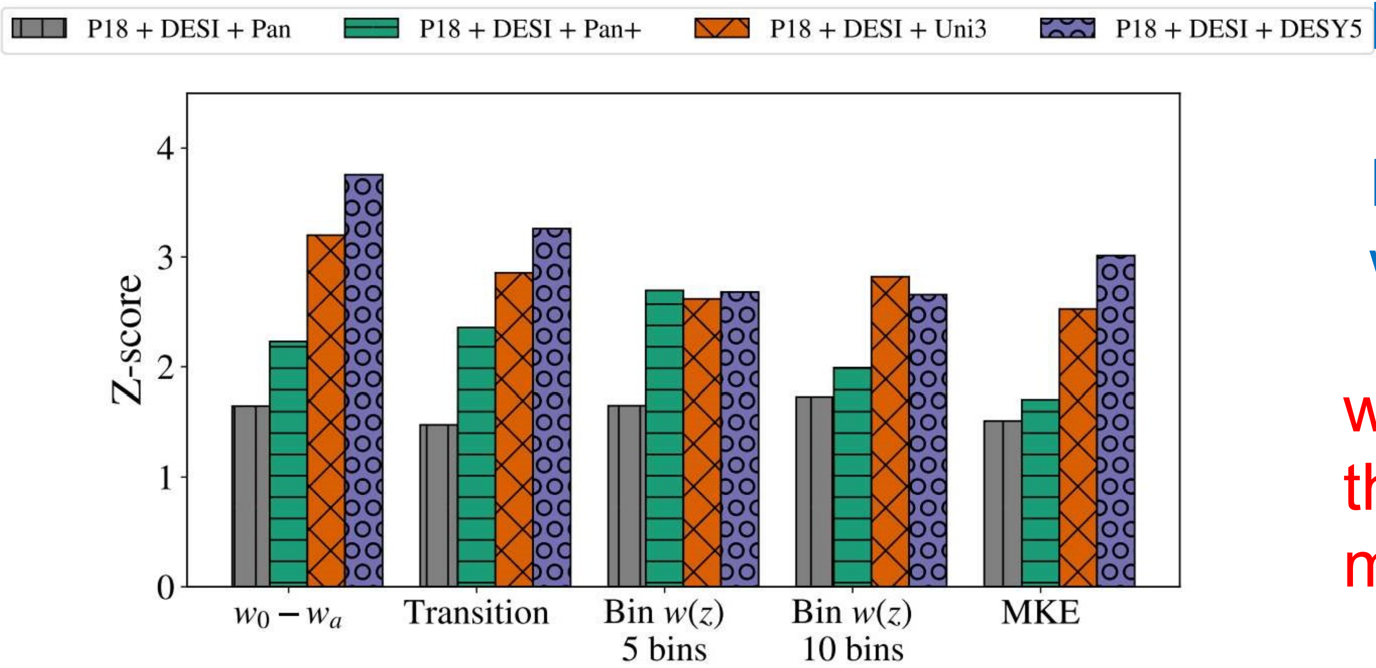
arXiv > astro-ph > arXiv:2408.14628

Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 26 Aug 2024]

Investigating Late-Time Dark Energy and Massive Neutrinos in Light of DESI Y1 BAO

João Rebouças, Diogo H. F. de Souza, Kunhao Zhong, Vivian Miranda, Rogerio Rosenfeld



We studied different models with different data sets. We compare different models with use the so-called z-score. This measure was also used by DESI.

Higher z-score: better fit with respect to ΛCDM.

w_0-w_a parametrization is still the best “cost-effective” model

First batch of DES-Y6 papers in January 2025.

Final DES-Y6 cosmology results only in March 2025.

I’ll focus now on two results from DES-Y3 that are more recent and involved our group.

(By the way, DES-Y3 data is publicly available)

I. Primordial non-Gaussianity

JOURNAL ARTICLE

Primordial non-Gaussianity with angular correlation function: integral constraint and validation for DES FREE

Walter Riquelme ✉, Santiago Avila ✉, Juan García-Bellido ✉, Anna Porredon, Ismael Ferrero, Kwan Chuen Chan, Rogerio Rosenfeld, Hugo Camacho, Adrian G Adame, Aurelio Carnero Rosell ... Show more

Monthly Notices of the Royal Astronomical Society, Volume 523, Issue 1, July 2023, Pages 603–619,

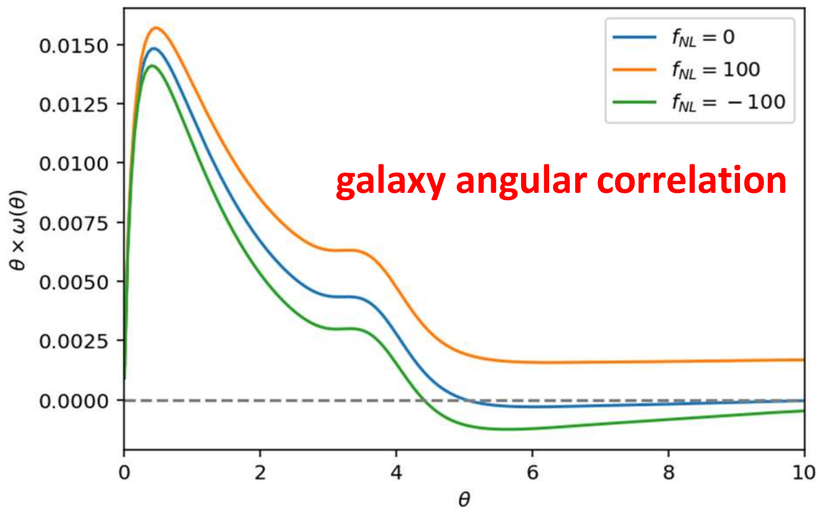
Posdoc in São Paulo since 2024

Primordial perturbations are predicted to be very close to gaussian in single-field inflation models

Non-gaussianities can be parametrized by a parameter f_{NL}.

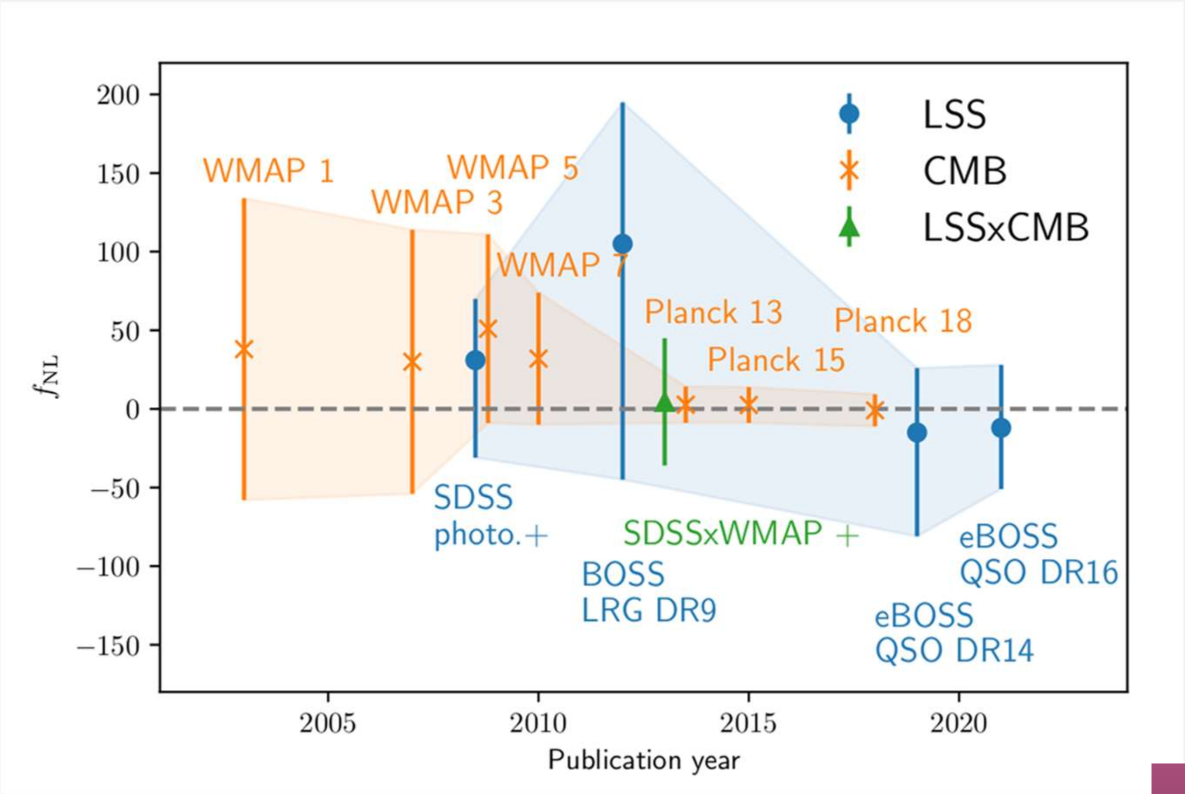
Galaxies form in regions with large concentration of dark matter (serve as potential wells): galaxy bias

Galaxy distribution is changed by the presence of f_{NL}.



Slide borrowed from Riquelme

f_{NL} through the years



[E-M Mueller et al. 2021]

- CMB experiments had reached the **cosmic variance limit**.
- Current constraints are obtained from **spectroscopic** surveys.
- ***Photometric surveys*** could play a big role in **breaking the $\sigma(f_{NL})$~1** barrier.
  Larger number of objects → More fourier modes
  (R. de Putter, O. Doré, 2014)

➔ ***f_{NL} << 1*** implies **single-field** inflation
➔ ***f_{NL} ~ 1*** implies **beyond standard** inflation

Riquelme et al forecast ***$\sigma(f_{NL})$~31*** when using the **Y3 BAO sample**

Works in progress:

- Select a ***galaxy sample*** using Y6 **DES data** that lowers the $\boldsymbol{f_{NL}}$ errors

- Forecasts for LSST

arXiv > astro-ph > arXiv:2406.12675

Search...

Help | Adv

Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 18 Jun 2024]

Dark Energy Survey Year 3 Results: Cosmology from galaxy clustering and galaxy-galaxy lensing in harmonic space

L. Faga, F. Andrade-Oliveira, H. Camacho, R. Rosenfeld, M. Lima, C. Doux, X. Fang, J. Prat, A. Porredon, M. Aguena, A. Alarcon, S. Allam, O. Alves, A. Amon, S. Avila, D.

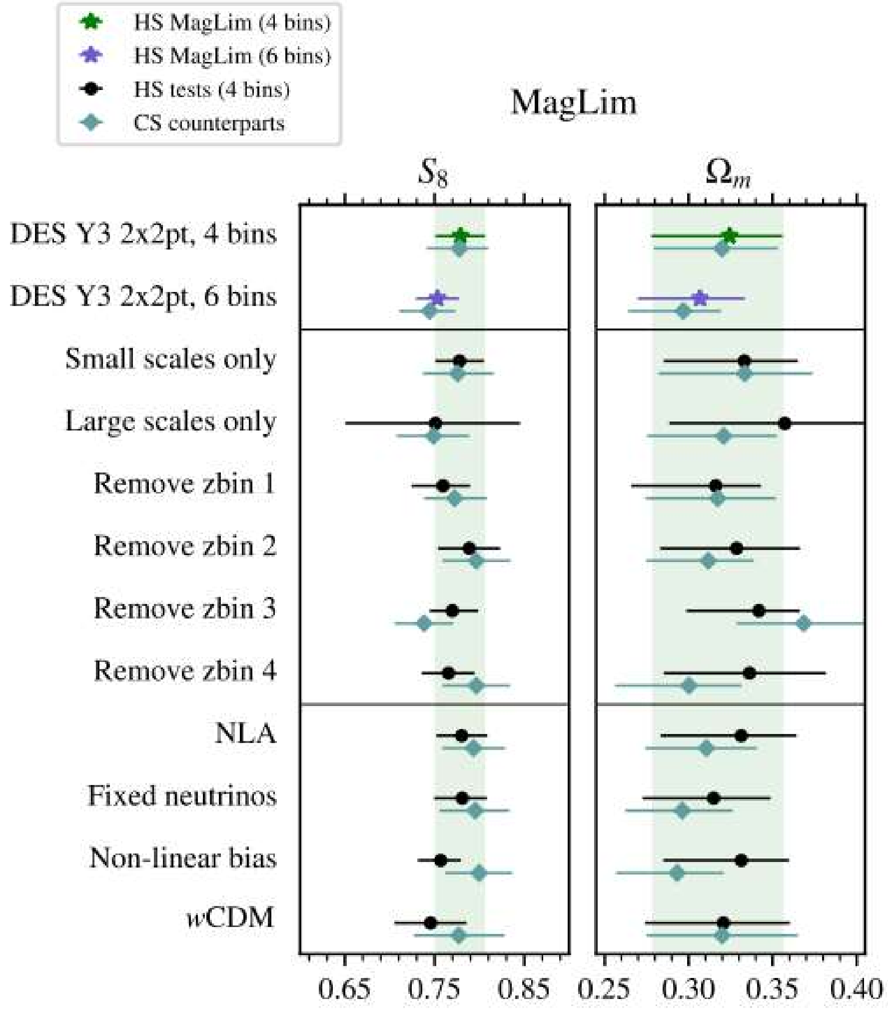
Fresh from the oven

PhD student in São Paulo

The DES main analysis are in real space using angular correlation functions. We obtain similar results with an analysis in harmonic space using angular power spectra as a consistency test. In LSST the default resulst will be in harmonic space!

The measurements of angular power spectra are performed using the pseudo-C_ℓ method, and our theoretical modelling follows the fiducial analyses performed by DES Y3 in configuration space, accounting for galaxy bias, intrinsic alignments, magnification bias, shear magnification bias and photometric redshift uncertainties.

Good agreement between real and harmonic space analysis.



HS MagLim (4 bins)
HS MagLim (6 bins)
HS tests (4 bins)
CS counterparts
MagLim
S_8
Ω_m
DES Y3 2x2pt, 4 bins
DES Y3 2x2pt, 6 bins
Small scales only
Large scales only
Remove zbin 1
Remove zbin 2
Remove zbin 3
Remove zbin 4
NLA
Fixed neutrinos
Non-linear bias
wCDM
0.65 0.75 0.85
0.25 0.30 0.35 0.40

Final analysis of the full 6 years (2013-2019) due in early 2025.

What’s after the Dark Energy Survey?

The Legacy Survey of Space and Time

LSST is a 10-year survey to be conducted at the
Vera Rubin Observatory in Chile (NOIRLab, AURA, SLAC)
using the
Simonyi Survey Telescope – 8.4 meters primary mirror
9.6 deg2 field of view
with the
LSSTCam
largest digital camera ever built (SLAC) – 3.2 Gigapixels
189 science CCDs
6 filters: ugrizy

Chile, Brazil, Argentina and Mexico participate in LSST

Rubin Team Installs Primary Mirror

October 14, 2024

In early October, the team on Cerro Pachón installed Rubin Observatory's 8.4-meter combined primary/tertiary mirror (M1M3) on the Simonyi Survey Telescope for the first time. This is a huge achievement in itself, and — with all three mirrors and the commissioning camera (ComCam) now in place — Rubin Observatory officially has a complete telescope! After getting this configuration of the telescope on-sky and conducting several months of testing, the summit team will remove the 144-megapixel ComCam and install the final science component: the car-sized, 3200 megapixel LSST Camera.

Conclusions and challenges

- We are living exciting times! Several tensions are putting the standard cosmology model under stress: Hubble tension, S8 tension, recent DESI BAO results

- Dark Energy Survey final analysis early 2025
- New surveys are taking data - DESI and Euclid. Roman Space Telescope in 2027.
- LSST is starting soon! Data from ComCam by end of this year. Full LSSTCam data in May 2025.
- Science collaborations have been active for years already building pipelines and simulations to test them
- Strong Latin American participation in LSST (and DESI)
- New data will bring more information on the nature of Dark Energy and Dark Matter