Cosmology with state-of-the-art photometric galaxy surveys: DES and LSST

Rogerio Rosenfeld
IFT-UNESP/ICTP-SAIFR/LIneA

XIV Latin American Symposium on High Energy Physics
November 14-18, 2022
Universidad San Francisco de Quito, Ecuador

What is the best model that describes our Universe?

Good old Scientific Method:

Theory (models) ⟷ Observations (data)

Theory

Modern cosmology starts in 1917:

Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie.

Von A. Einstein.

Es ist wohlbekannt, daß die Poissonsche Differentialgleichung

$$\Delta\phi = 4\pi K\rho \quad (1)$$

in Verbindung mit der Bewegungsgleichung des materiellen Punktes die Newtonsche Fernwirkungstheorie noch nicht vollständig ersetzt. Es muß noch die Bedingung hinzutreten, daß im räumlich Unendlichen das Potential ϕ einem festen Grenzwerte zustrebt. Analog ver-

Doc. 43

Cosmological Considerations in the General Theory of Relativity

This translation by W. Perrett and G. B. Jeffery is reprinted from H. A. Lorentz et al., *The Principle of Relativity* (Dover, 1952), pp. 175–188.

IT is well known that Poisson's equation

$$\nabla^2\phi = 4\pi K\rho \quad . \quad . \quad . \quad . \quad (1)$$

in combination with the equations of motion of a material point is not as yet a perfect substitute for Newton's theory of action at a distance. There is still to be taken into account the condition that at spatial infinity the potential ϕ tends toward a fixed limiting value. There is an analogous state

Einstein's equations of General Relativity: marriage of Particle Physics with Cosmology

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R + \Lambda g_{\mu\nu} = 8\pi G_N T_{\mu\nu}$$

Geometry of the universe

Space tells matter how to move
(J.A. Wheeler)

Particle Physics

Matter tells space how to curve

Cosmology is on a solid theoretical foundation: accurate predictions!

The Nobel Prize in Physics 2019

© Nobel Media. Photo: A. Mahmoud

James Peebles

Prize share: 1/2

© Nobel Media. Photo: A. Mahmoud

Michel Mayor

Prize share: 1/4

© Nobel Media. Photo: A. Mahmoud

Didier Queloz

Prize share: 1/4

The Nobel Prize in Physics 2019 was awarded "for contributions to our understanding of the evolution of the universe and Earth's place in the cosmos" with one half to James Peebles "for theoretical discoveries in physical cosmology", the other half jointly to Michel Mayor and Didier Queloz "for the discovery of an exoplanet orbiting a solar-type star."

Modern cosmology today is based on three unexpected discoveries:

- There is more matter in galaxies and cluster of galaxies than what was expected ➡ Dark Matter

- Universe is accelerating
  ➡ Dark Energy

- Universe was very homogeneous and isotropic
  ➡ Inflation

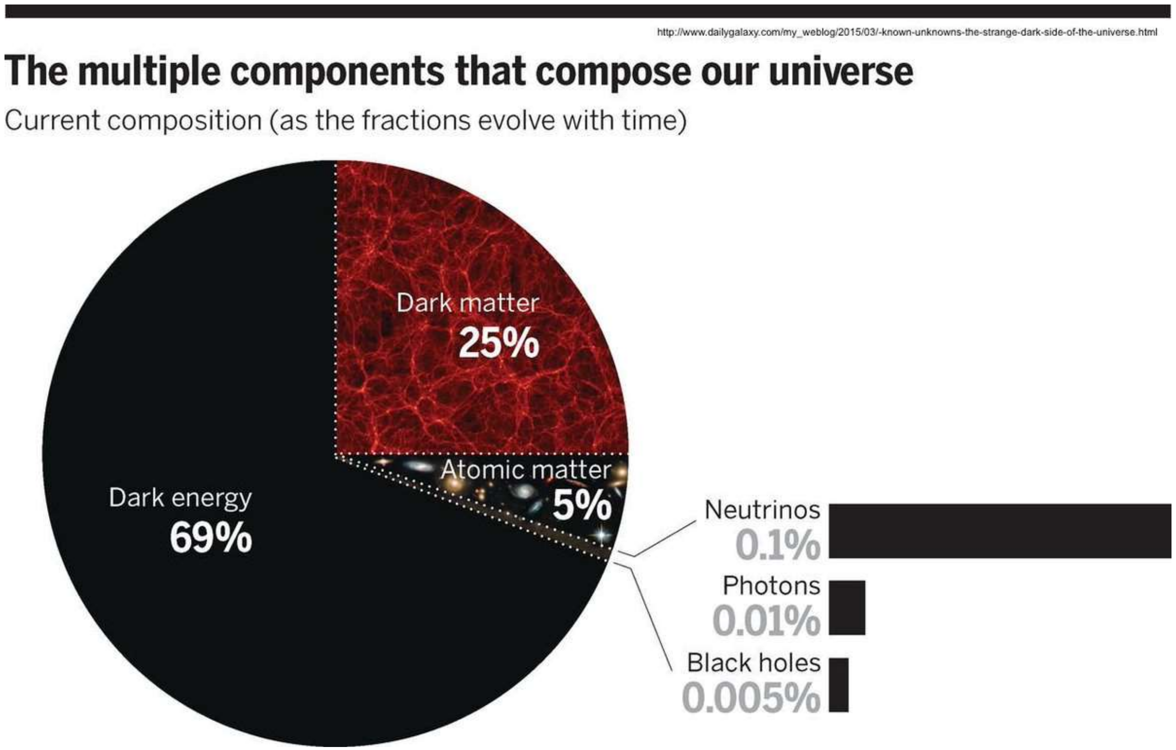
Today we have a Standard Cosmological Model (ΛCDM):

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)

BUT

We know that we don’t know what ~95% of the universe is made of!



What is dark matter ?

Cold, warm, fuzzy, self-interacting...

What is dark energy?

Cosmological constant
New degree of freedom/MG:
Quintessence, galileon, f(R), Hordensky, beyond Hordensky, massive gravity, EFTofDE...
Does it interact with matter?
Does it cluster?

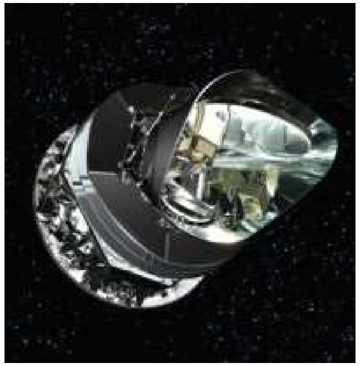
What drove inflation?

Scalar field (inflaton)
Primordial gravitational waves

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, Dark Energy Survey, LSST,...)



Planck satellite launched 2009

Rubin Observatory Legacy Survey of Space and Time 2023-2033

Summit Facility (earthcam.net)

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 (Gravitational lensing, Distribution of galaxies)

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

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

Galaxy surveys

Two main types of galaxy surveys:

- Spectroscopic: take spectra of galaxies

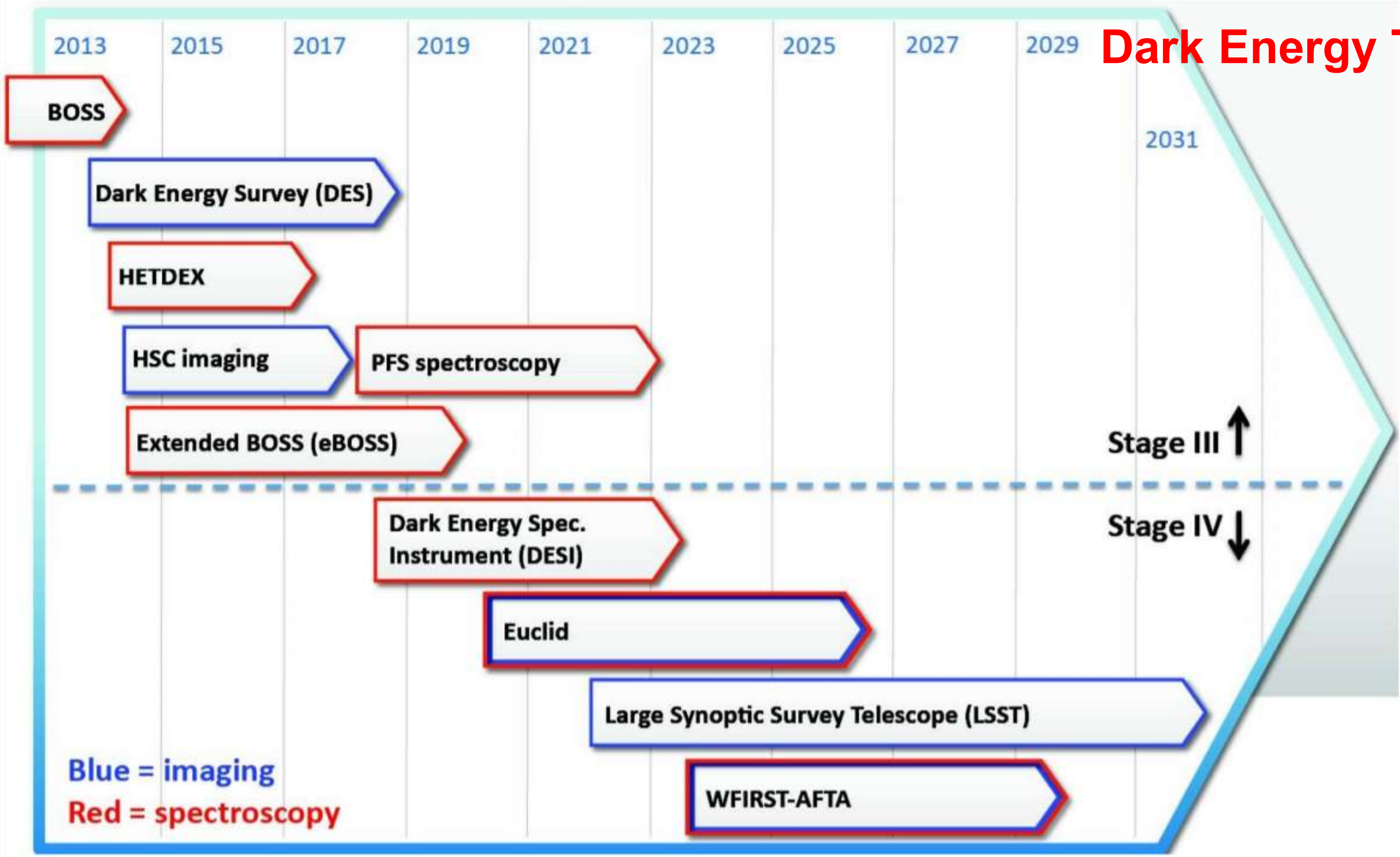
(good quality spectroscopic redshift vs smaller number of objects; no imaging)

- 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

A somewhat outdated schedule of surveys



Dark Energy Task Force

arXiV: 1401.6085

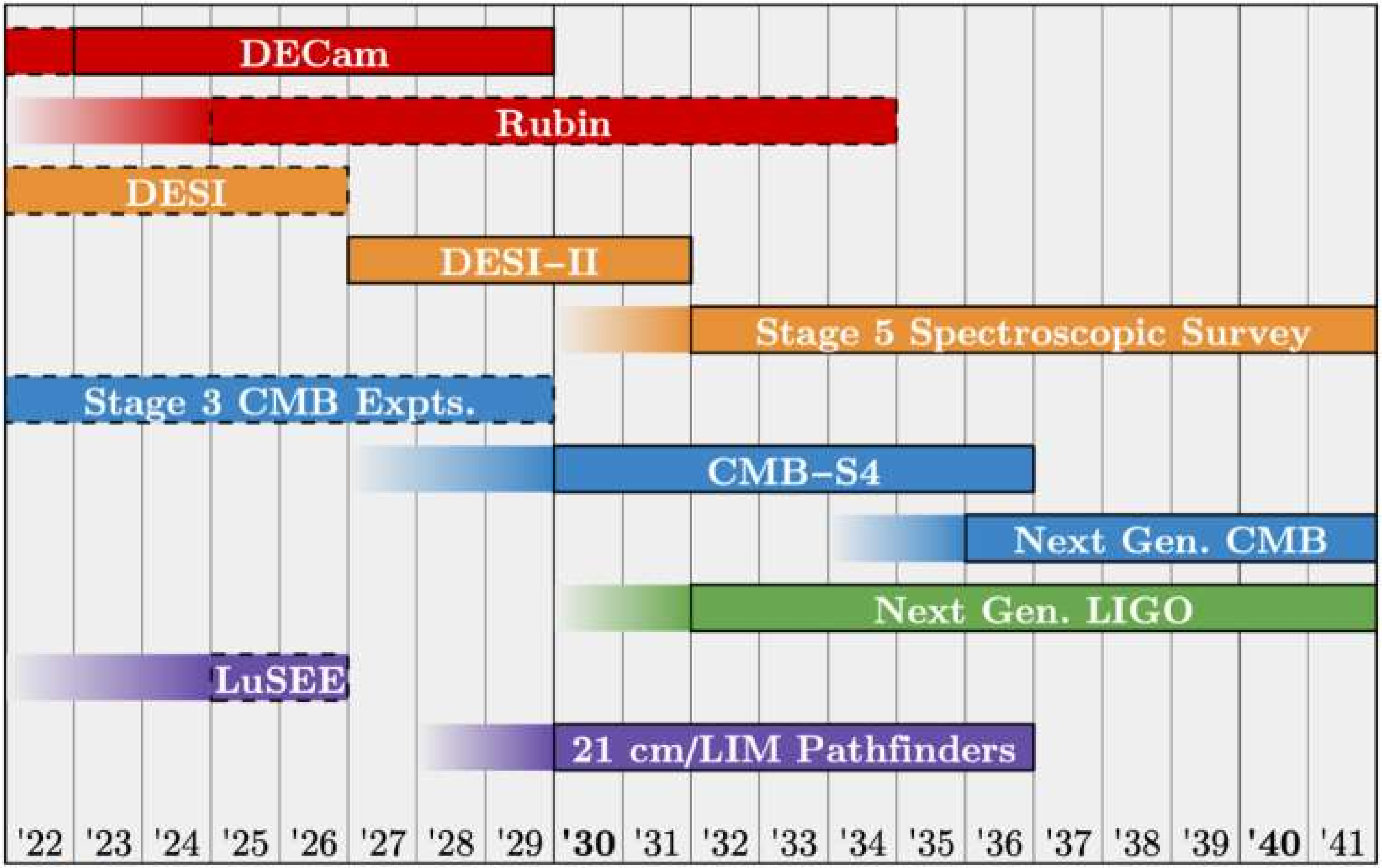


Figure 6-1. *Current and potential future facilities probing cosmic acceleration that are or may be supported by DOE or NSF. Dashed boxes indicate fully-funded facilities. Facilities in red are optical imaging, in orange are optical spectroscopy, in blue are CMB, in green are gravitational waves, and in purple are radio/mm spectroscopy. The fade-in regions indicate commissioning periods, while the boxes indicate full survey observations.*

Snowmass Report of the Topical Group on Dark Energy and Cosmic Acceleration
2209.08654

2209.08654

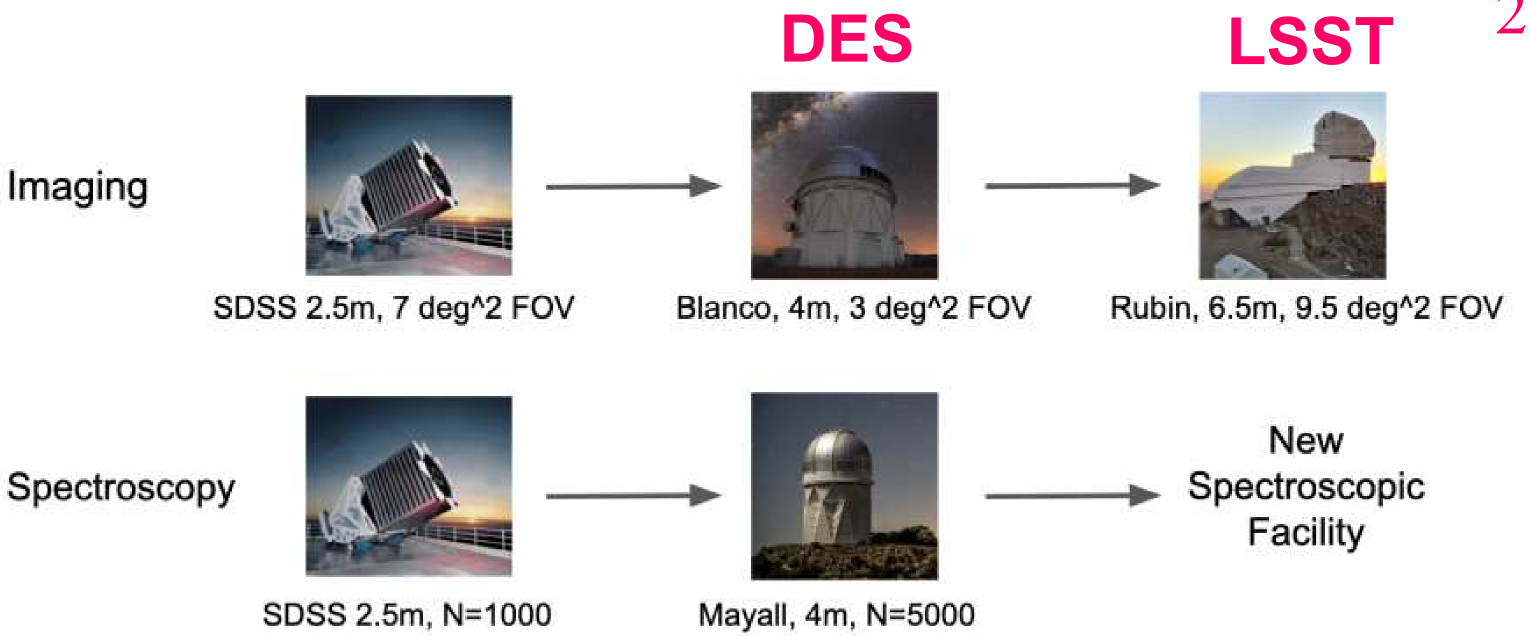


Figure 6-4. *Summary of imaging and spectroscopic surveys and facilities, ongoing and planned, that are supported by DOE/NSF partnerships. The international ground and space-based landscape of optical wide-field surveys, ongoing and planned, is very rich but for clarity is not represented here. SDSS 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.*

From A. Amon: DES-Y3 webinar

What we want to test:

Is the late time clustering consistent with the ΛCDM prediction from the CMB data?

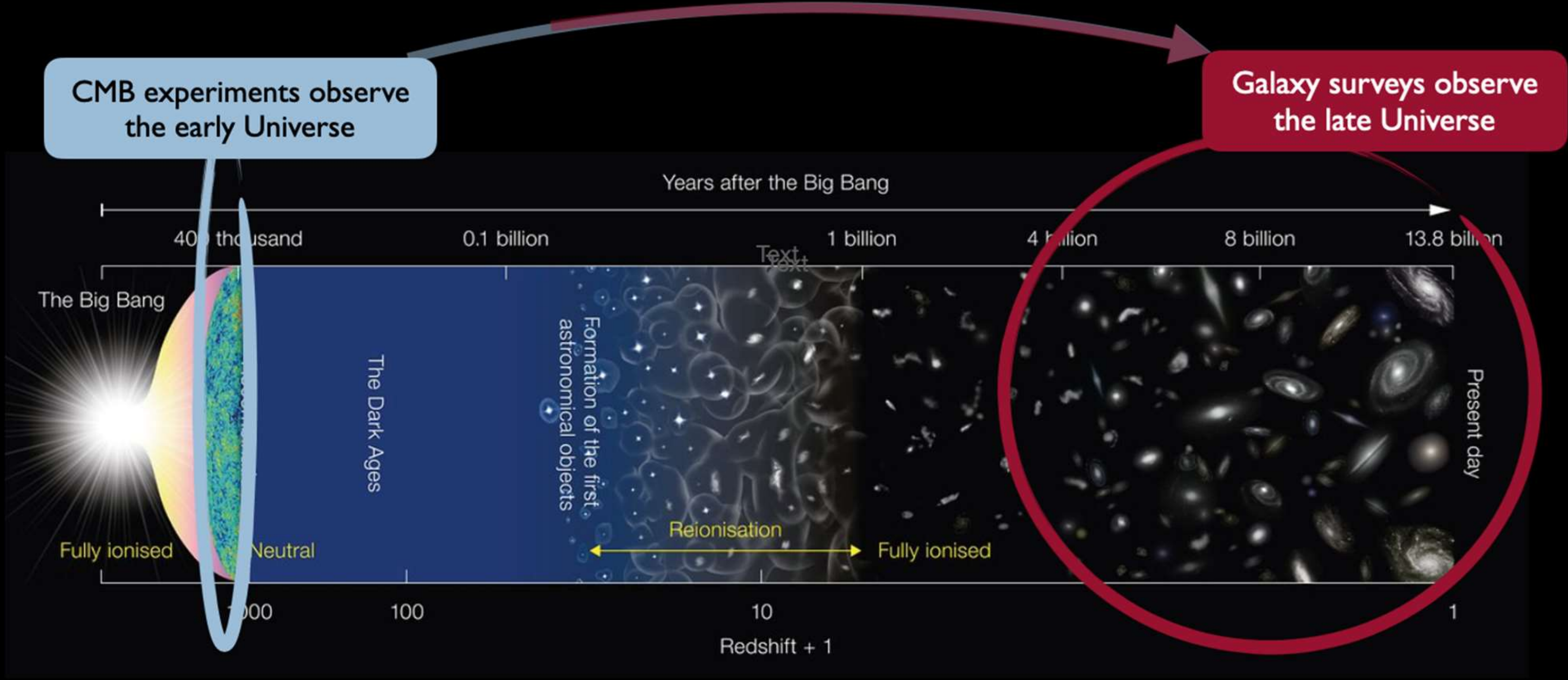
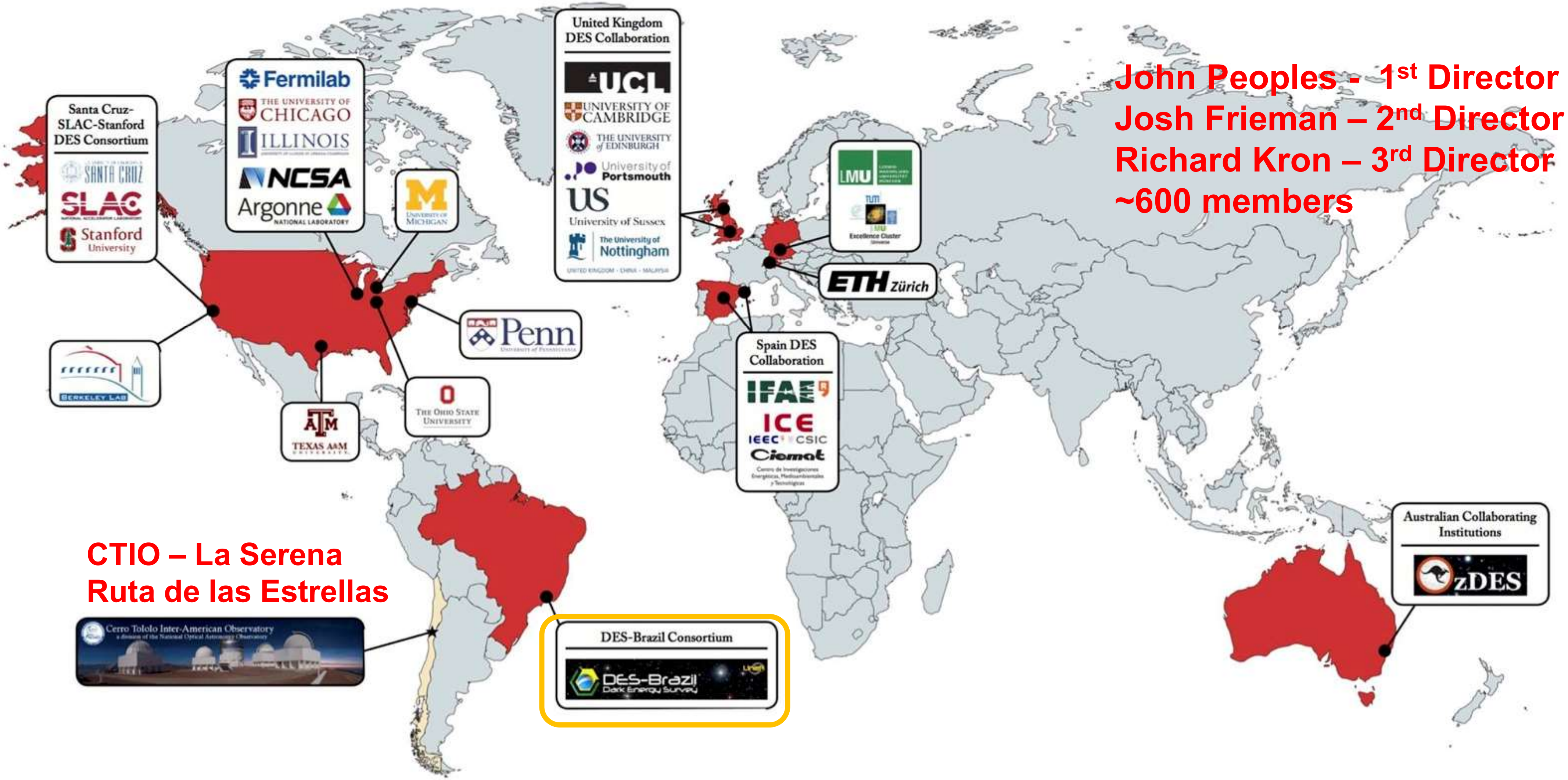
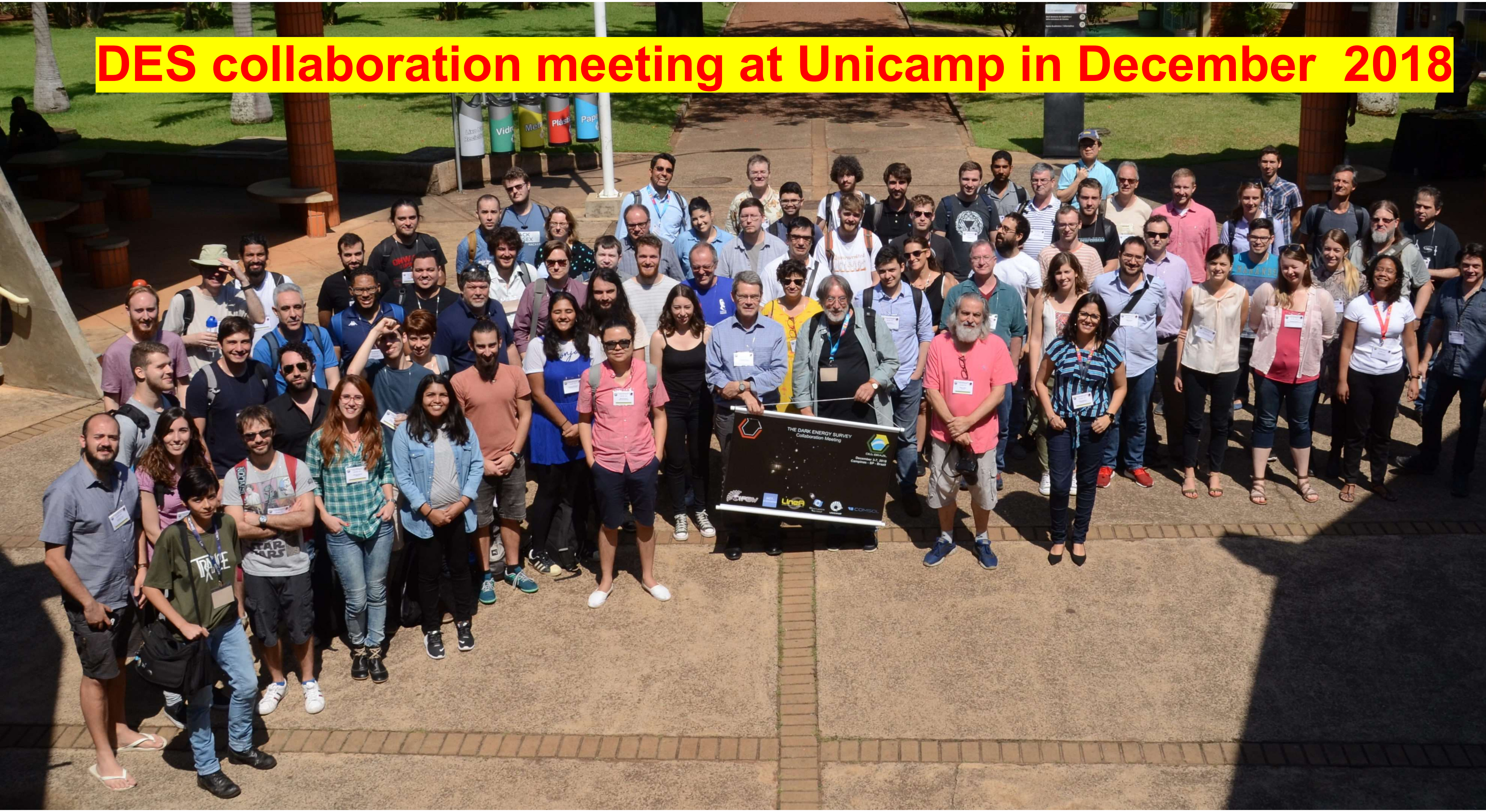


Image credit: NAOJ

The Dark Energy Survey Collaboration

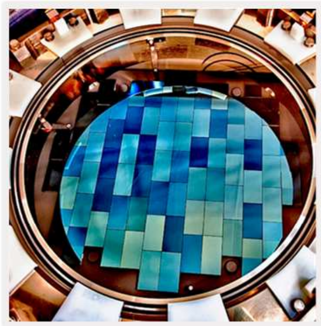


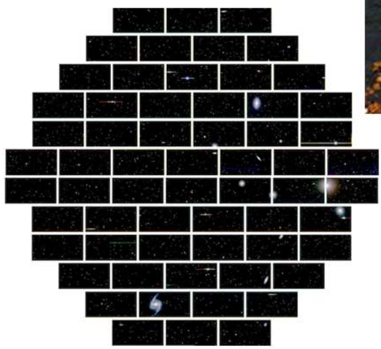
DES collaboration meeting at Unicamp in December 2018

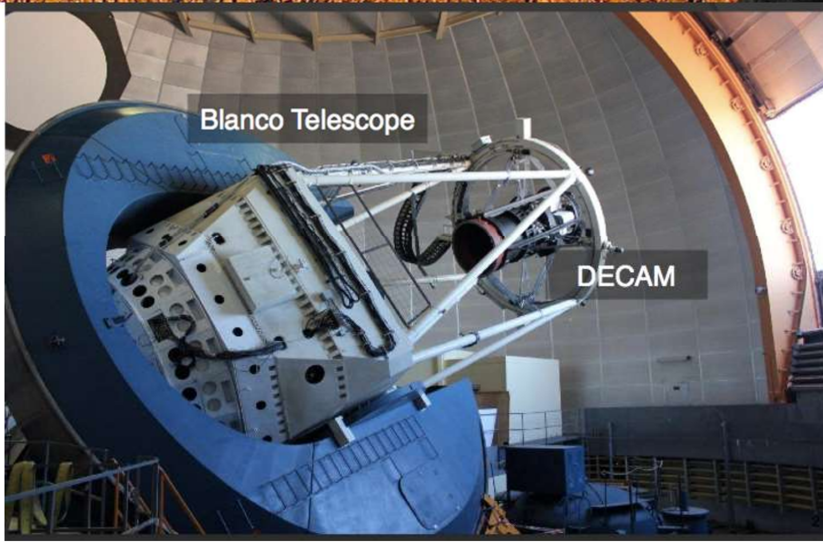


The Dark Energy Survey (DES)

- >600 members, 25 institutions, 7 countries
- 570 Megapixel camera for the Blanco 4m telescope in Chile.
- Full survey, ~5.5Y. 2013-2019 (Y3 2013-16).
- Wide field**:** 5000 sq. deg. in 5 bands grizY. ~23 magnitude.
- DES Y3: Positions and shapes of > 100M galaxies.







DES Y3

Most stringent cosmological constraints from a galaxy imaging survey.

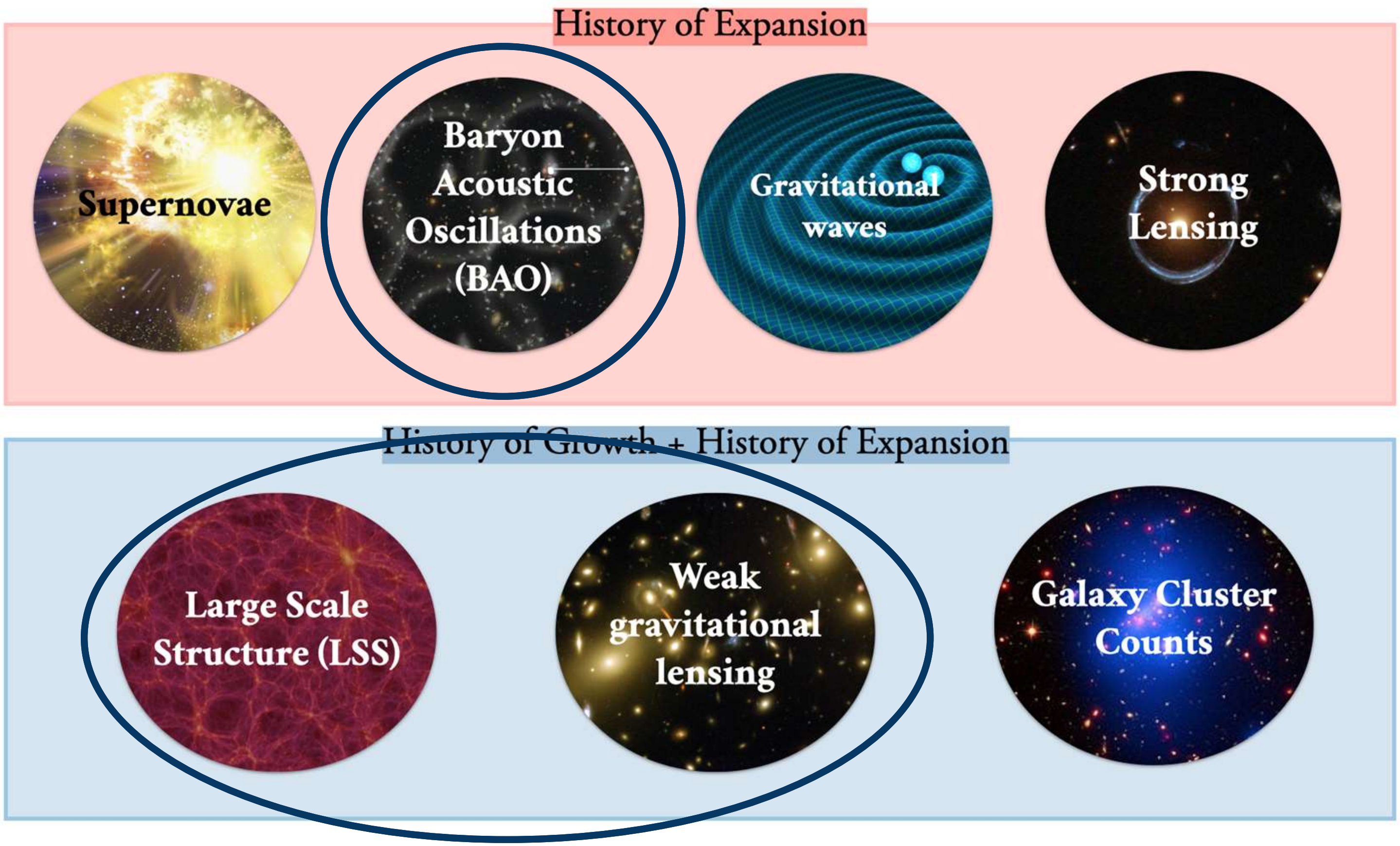
Combined with external data: most stringent constrains overall

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

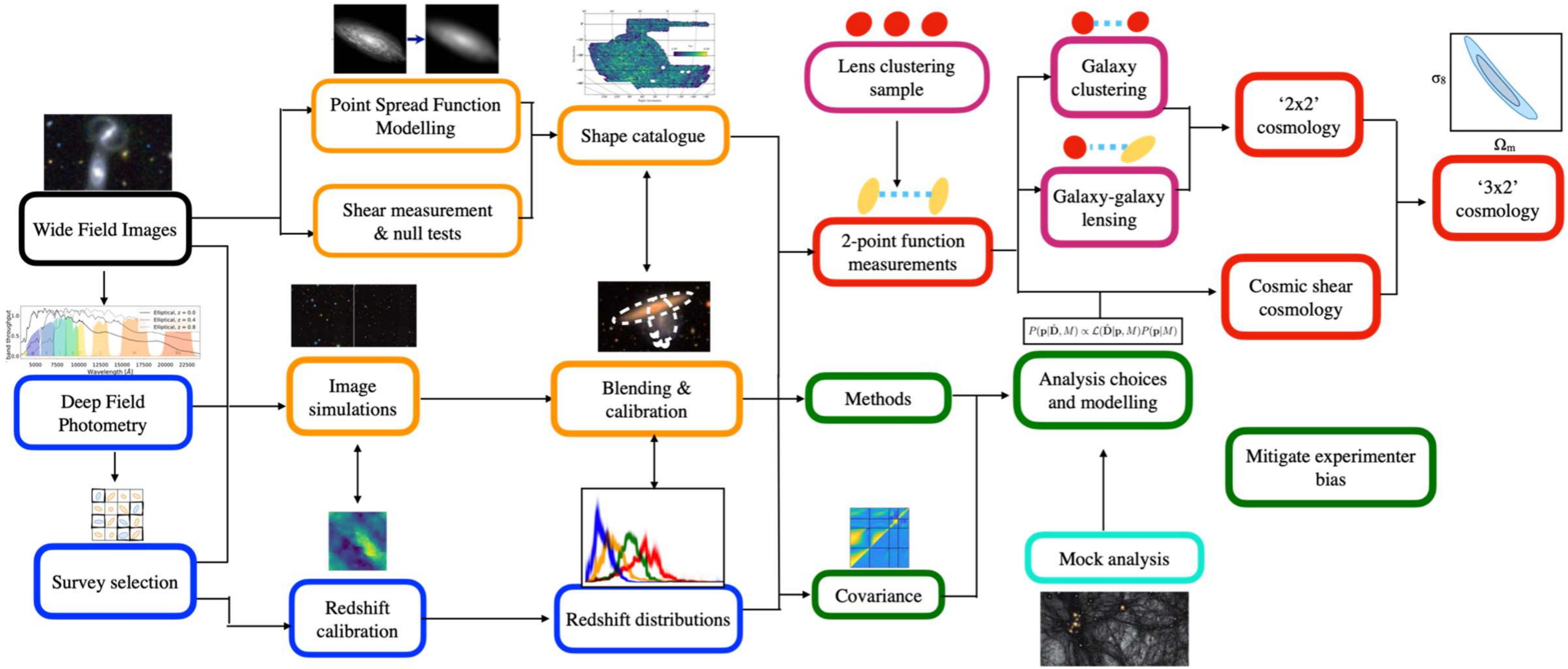
$\{A_s , n_s , h , \Omega_m , \Omega_b$ and $\Omega_\nu \}$

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

Cosmic probes within DES



DES Year 3: from pixels to cosmology



From A. Amon - DES-Y3 webinar


#Darkbites
IMAGES
SIM.
1011
0011
1010
Models
SHAPES
mcmc
COV
PHOTO-Z
σ_8
Ω_m

DES-Y3 cosmology: 30+3 papers

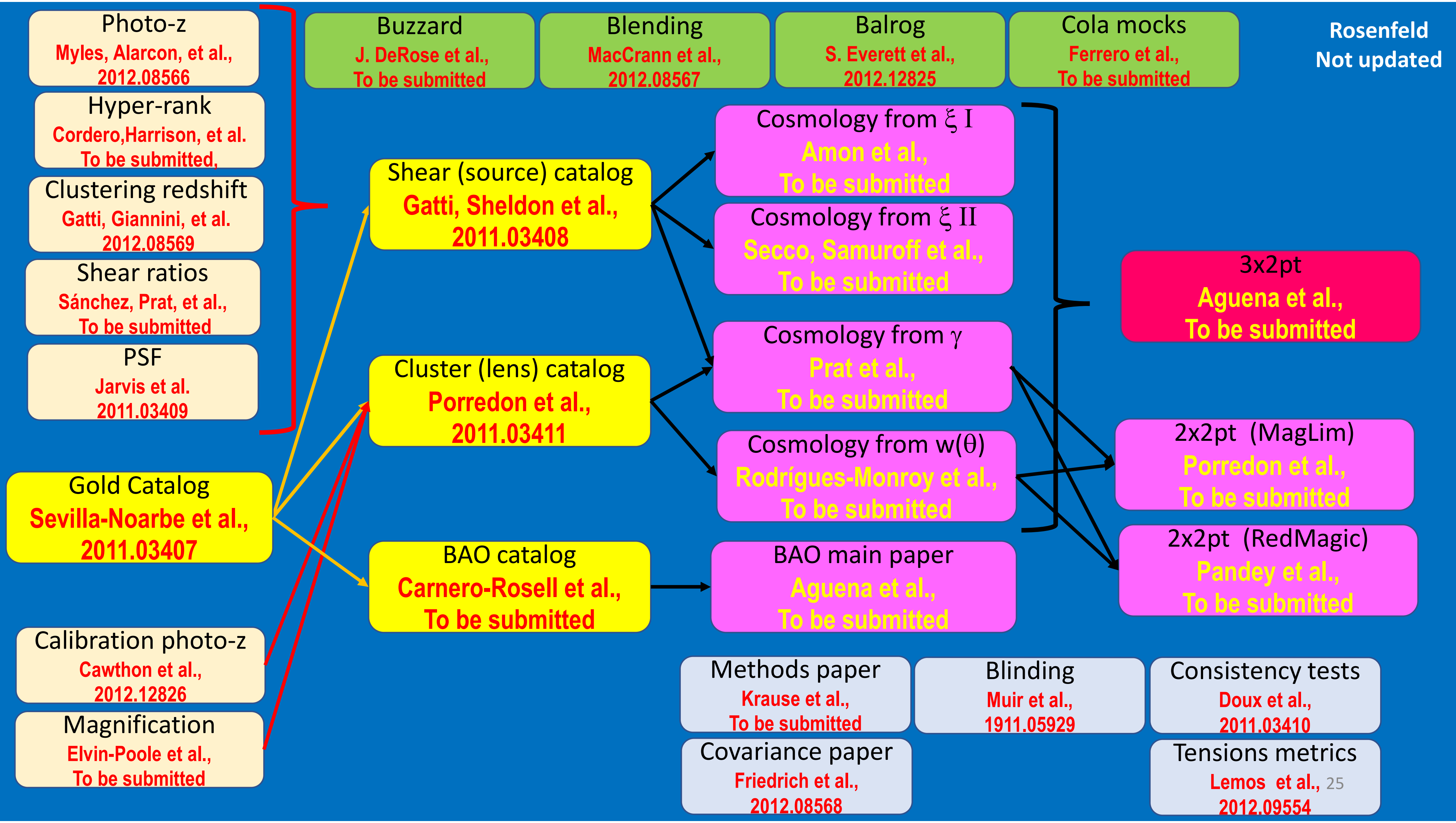


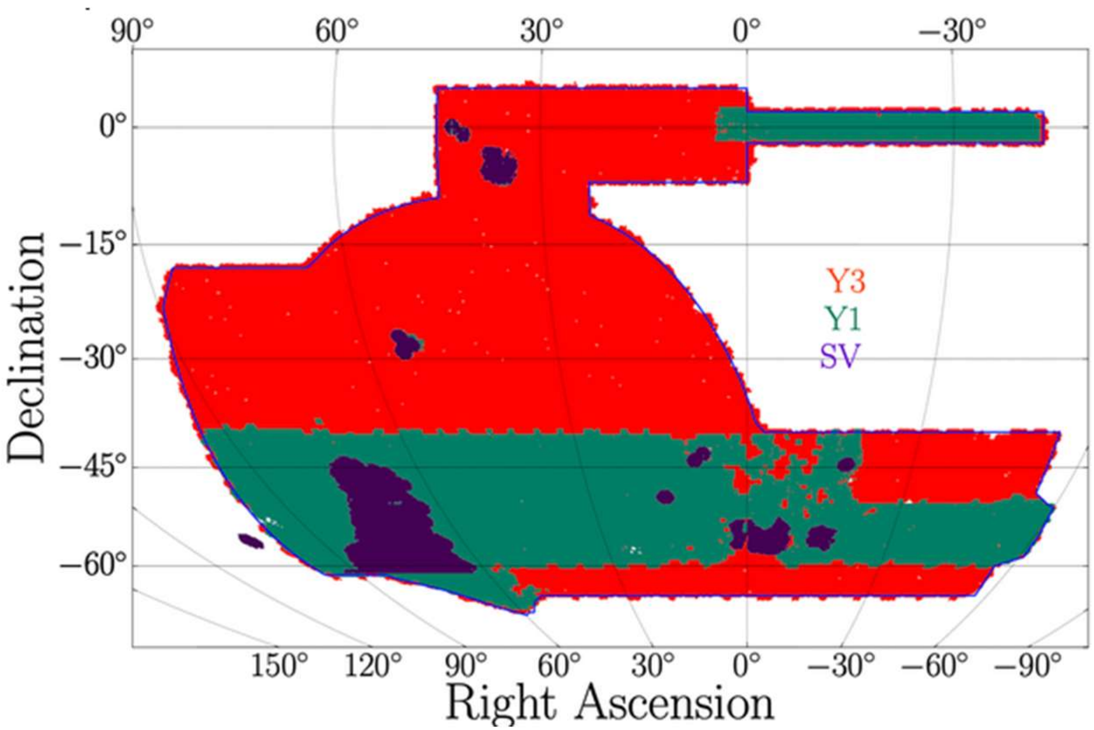
Photo-z
Myles, Alarcon, et al., 2012.08566
Hyper-rank
Cordero,Harrison, et al. To be submitted,
Clustering redshift
Gatti, Giannini, et al. 2012.08569
Shear ratios
Sánchez, Prat, et al., To be submitted
PSF
Jarvis et al. 2011.03409
Buzzard
J. DeRose et al., To be submitted
Blending
MacCrann et al., 2012.08567
Balrog
S. Everett et al., 2012.12825
Cola mocks
Ferrero et al., To be submitted
Rosenfeld
Not updated
Shear (source) catalog
Gatti, Sheldon et al., 2011.03408
Cluster (lens) catalog
Porredon et al., 2011.03411
Gold Catalog
Sevilla-Noarbe et al., 2011.03407
BAO catalog
Carnero-Rosell et al., To be submitted
Cosmology from ξ I
Amon et al., To be submitted
Cosmology from ξ II
Secco, Samuroff et al., To be submitted
Cosmology from γ
Prat et al., To be submitted
Cosmology from w(θ)
Rodrígues-Monroy et al., To be submitted
BAO main paper
Aguena et al., To be submitted
3x2pt
Aguena et al., To be submitted
2x2pt (MagLim)
Porredon et al., To be submitted
2x2pt (RedMagic)
Pandey et al., To be submitted
Calibration photo-z
Cawthon et al., 2012.12826
Magnification
Elvin-Poole et al., To be submitted
Methods paper
Krause et al., To be submitted
Blinding
Muir et al., 1911.05929
Consistency tests
Doux et al., 2011.03410
Covariance paper
Friedrich et al., 2012.08568
Tensions metrics
Lemos et al., 2012.09554

Y3 Gold Catalog (Sevilla-Noarbe et al., 2011.03407)

- The data included in Y3 Gold spans 345 distinct nights of observations with at least one observation passing quality tests from 2013 August 15 to 2016 February 12

- Gold sample: selection of objects from multi-epoch images passing quality cuts, photometric calibration, masking, signal-to-noise>10, objects brighter than i>23, star-galaxy separation, survey property maps, ...
  Total of 319 million objects.

DES footprint (Science Verification, Y1 and Y3)



Sevilla-Noarbe, Bechtol et al., 2011.03407

Science Verification: 139 deg^2

Y1: 1786 deg^2 (1321 deg^2 for 3x2pt cosmological analyses)

Y3: 4946 deg^2 (4143 deg^2 for 3x2pt cosmological analyses)

- Gold sample is used to produce science-ready catalogues:
    1. Shear catalog (Metacalibration)
    2. Position catalogs (RedMagic and MagLim)
    3. BAO-optimized catalog

I will present DES-Y3 (and some DES-Y1) results for:

1. 3x2pt correlation functions [Our group contributed with covariance matrix study]

2. Baryon acoustic oscillation [Our group contributed to the harmonic space analyis]

3. Harmonic space analysis [Led by our group + C. Doux]

Hugo Camacho
PhD IFUSP
Post-doc UNESP

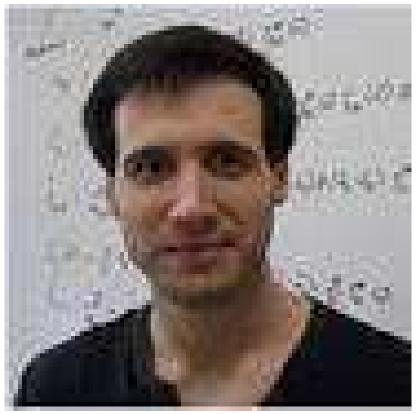
Felipe Andrade-Oliveira
PhD IAG-USP
Post-doc UNESP
Post-doc University of Michigan

Antonino Troja
PhD Milano
Post-doc SAIFR
Post-doc Padua

Lucas Faga
MSc IFUSP
PhD student @ IFUSP

Prof. Marcos Lima
IFUSP

Nick Kokron
BSc at USP
IC at IFT
PhD student at Stanford



Fabien Lacasa
PhD Orsay
Post-doc SAIFR
Post-doc Geneva
Post-doc Padua

1. 3x2pt correlation functions

Observables are:

- Positions of galaxies (clustering)
- Shapes of galaxies (shear)

From DES-Y3 webinar

Weak lensing

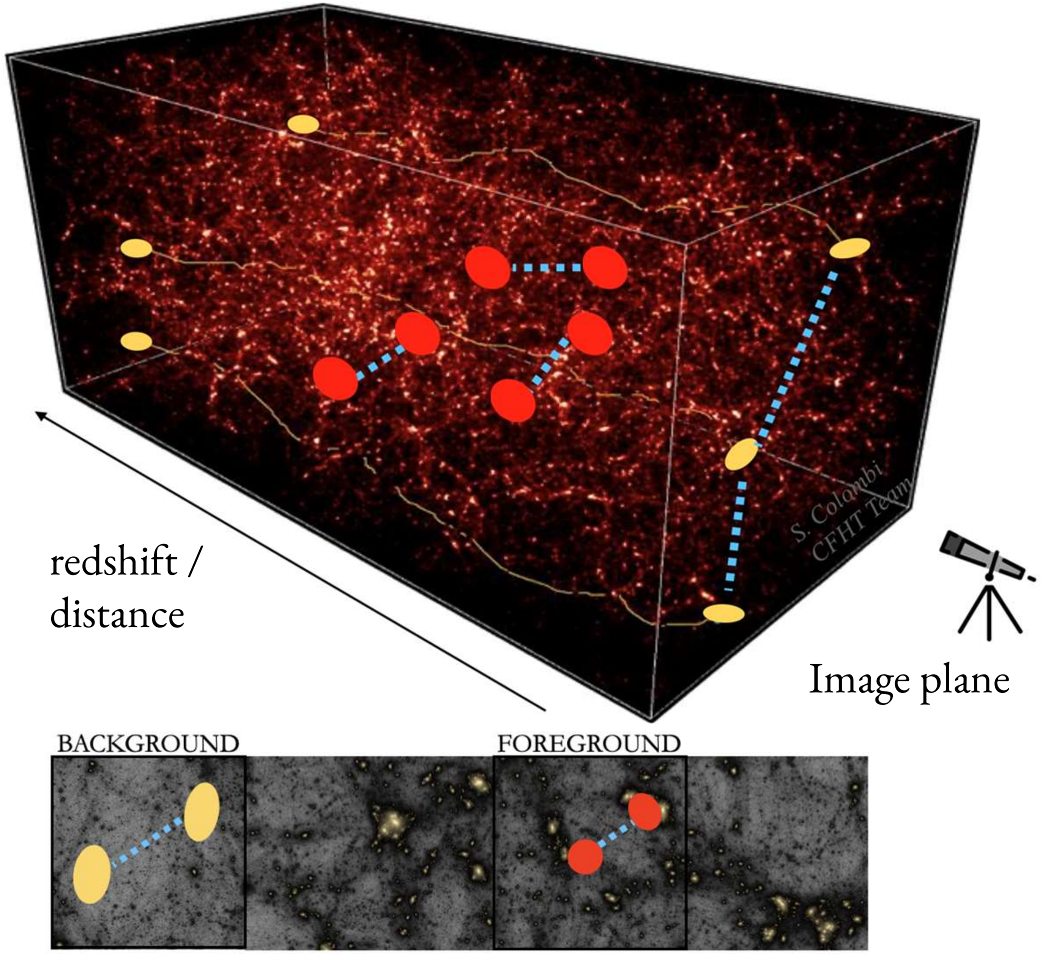
Light from distant galaxies passes the same foreground structure and acquires coherent distortions : they are observe to be *lensed*.

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.



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.

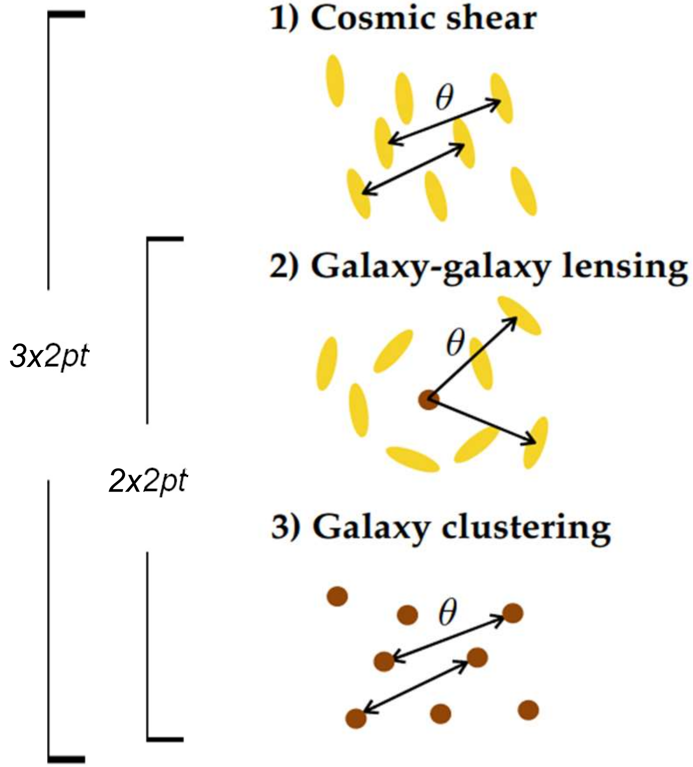
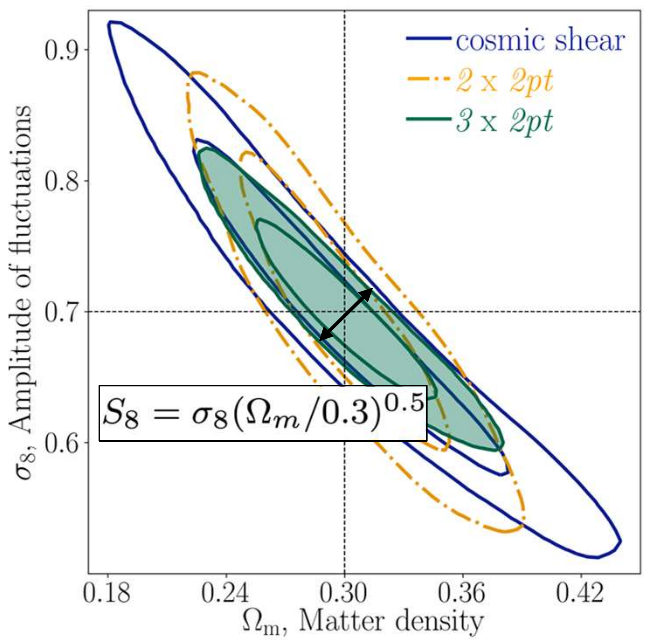


Image credit: Chihway Chang



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

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

Posterior distribution of the parameters that depend on priors: MCMC

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

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

Issues in modeling are dealt with:

- Introduction of nuisance parameters to parametrize uncertainties
- Scale cuts designed to leave out small scales where nonlinear bias and baryonic effects are important.

These mitigation methods have to be implemented and tested against realistic simulations, with a requirement of accuracy in recovering cosmological parameters.

JOURNAL ARTICLE

Mitigating baryonic effects with a theoretical error covariance

Maria G Moreira ✉, Felipe Andrade-Oliveira, Xiao Fang, Hung-Jin Huang, Elisabeth Krause, Vivian Miranda, Rogerio Rosenfeld ✉, Marko Simonović

Monthly Notices of the Royal Astronomical Society, Volume 507, Issue 4, November 2021, Pages 5592–5601, https://doi.org/10.1093/mnras/stab2481

Published: 03 September 2021 **Article history ▾**

Maria Gabriela Cota Moreira

B.S. in Physics, 2017, Federal University of Minas Gerais, Brazil

M.S. in Physics, 2020, São Paulo State University, Brazil

Areas of Interest: *Cosmology, Extragalactic Astronomy, Galaxy Formation and Evolution*

PhD student at the University of Arizona

Work in progress: Mitigation of galaxy bias uncertainties

Abdias Aires
MSc student at IFT

Nick Kokron
BSc at USP
IC at IFT
PhD student at Stanford

Felipe Andrade-Oliveira
PhD IAG-USP
Post-doc UNESP
Post-doc University of Michigan

Cosmological parameters (7)

Nuisance parameters (30)

Parameter	Prior	
Cosmology		
Ω_{m}	Flat	(0.1, 0.9)
$10^9 A_s$	Flat	(0.5, 5.0)
n_s	Flat	(0.87, 1.07)
Ω_{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_l^1	Fixed	1.21
C_l^2	Fixed	1.15
C_l^3	Fixed	1.88
C_l^4	Fixed	1.97
Lens photo-z		
$\Delta z_l^1 \times 10^2$	Gaussian	$(-0.9, 0.7)$
$\Delta z_l^2 \times 10^2$	Gaussian	$(-3.5, 1.1)$
$\Delta z_l^3 \times 10^2$	Gaussian	$(-0.5, 0.6)$
$\Delta z_l^4 \times 10^2$	Gaussian	$(-0.7, 0.6)$
$\sigma_{z,l}^1$	Gaussian	(0.98, 0.06)
$\sigma_{z,l}^2$	Gaussian	(1.31, 0.09)
$\sigma_{z,l}^3$	Gaussian	(0.87, 0.05)
$\sigma_{z,l}^4$	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_{TA}	Flat	(0, 2)
z_0	Fixed	0.62
Source photo-z		
$\Delta z_s^1 \times 10^2$	Gaussian	(0.0, 1.8)
$\Delta z_s^2 \times 10^2$	Gaussian	(0.0, 1.5)
$\Delta z_s^3 \times 10^2$	Gaussian	(0.0, 1.1)
$\Delta z_s^4 \times 10^2$	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	$(-3.7, 0.8)$

Main results from DES-Y3 3x2pt correlation functions

2105.13549

Andresa Campos

MSc student at IFT.
PhD student at Carnegie Mellon with Scott Dodelson.
Current y6 weak lensing photo-z coordinator.


#Darkbites
IMAGES
SIM.
1011
0011
1010
Models
SHAPES
mcmc
COV
PHOTO-Z
JM
σ_8
Ω_m

3x2pt results

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:

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

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

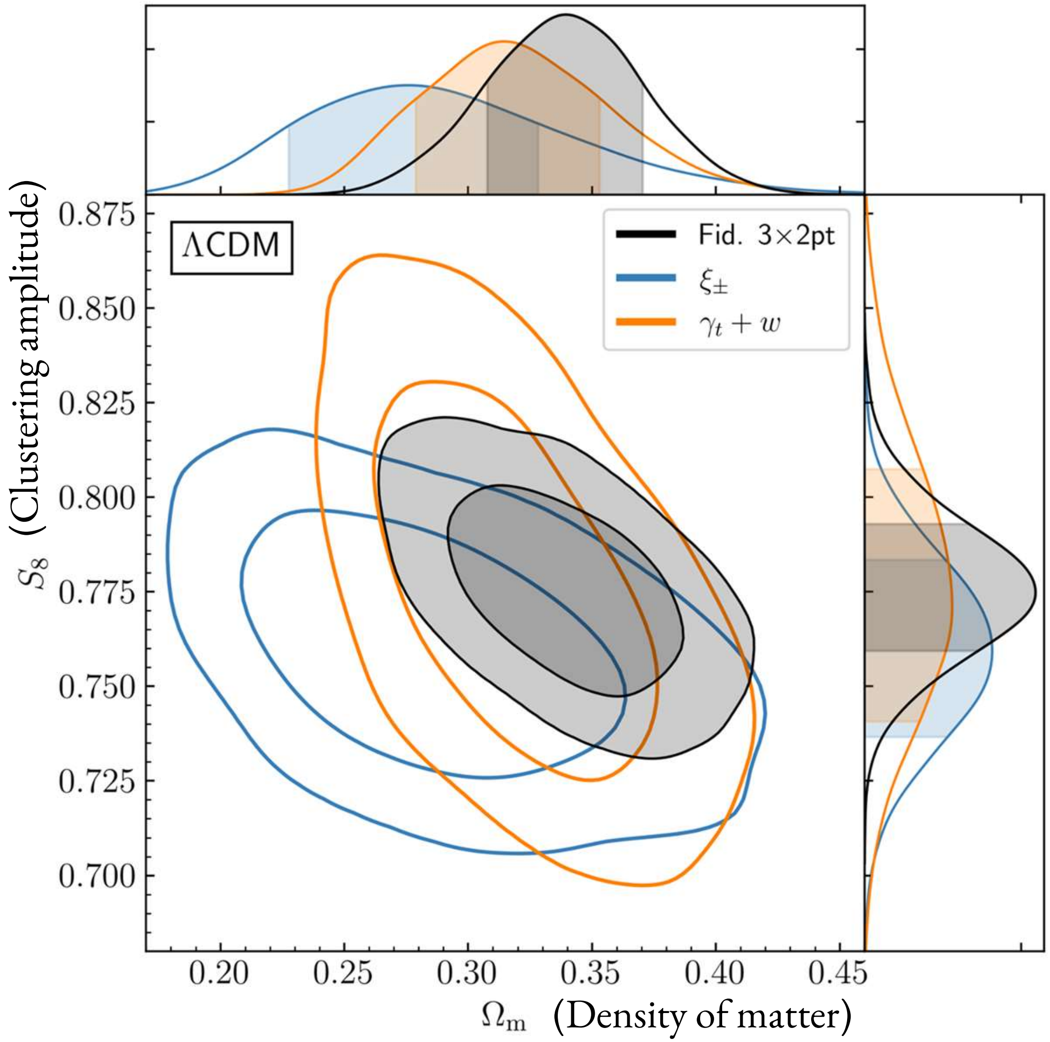
$$\sigma_8 = 0.733^{+0.039}_{-0.049} \quad (0.696)$$

In wCDM:

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

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

From DES-Y3 webinar



Consistency with Planck results

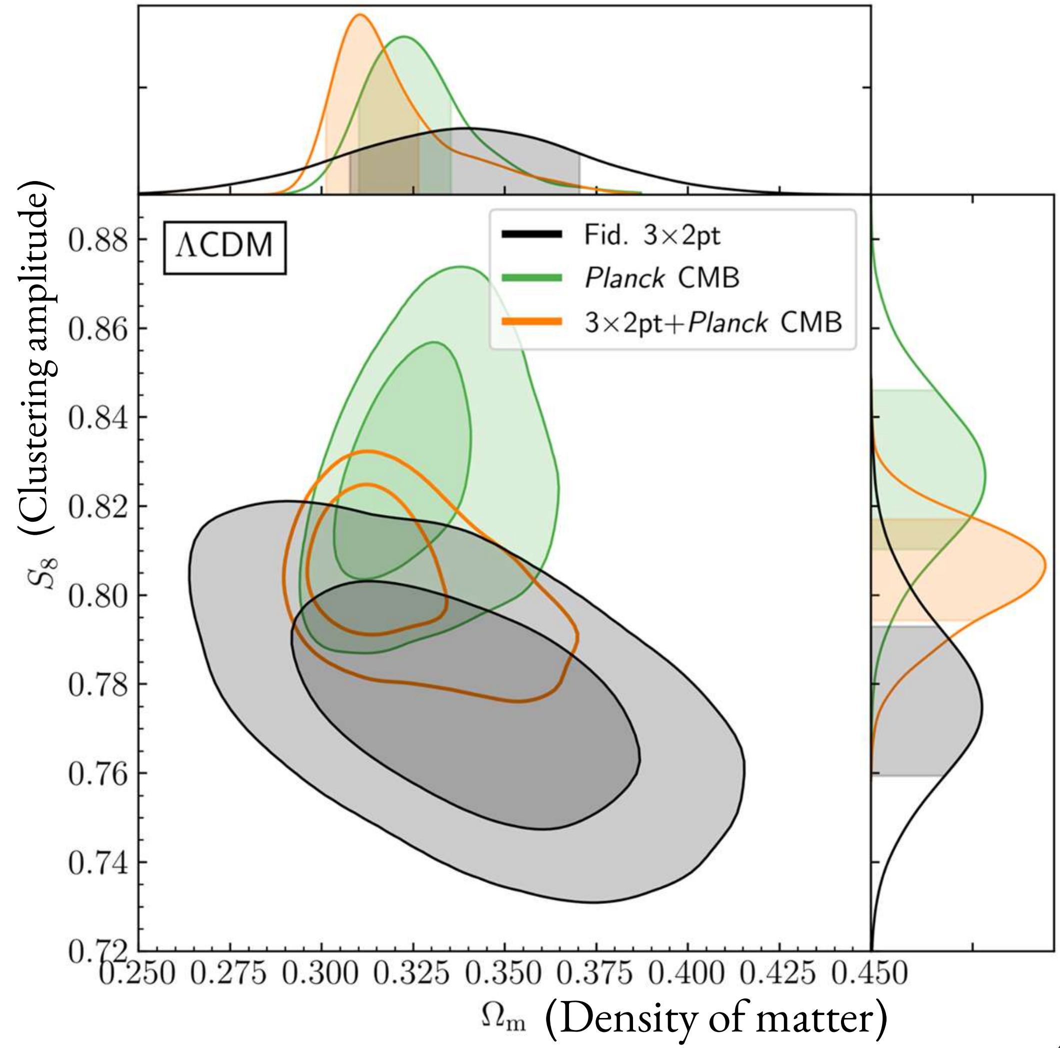
From DES-Y3 webinar

Low-z vs High-z in ΛCDM

We test the robustness of ΛCDM by comparing measurements of the clustering amplitude at low-redshift to the prediction from the cosmic microwave background (CMB) at high-redshift.

We find no significant evidence of inconsistency between **DES Y3 3×2pt** and *Planck* CMB at 0.7-1.5σ or p=0.13-0.48.

Combining the results we find the orange contour.



From DES-Y3 webinar

Joint constraints

Combining all these data sets we find:

In ΛCDM

$$S_8 = 0.812^{+0.008}_{-0.008} \quad (0.815)$$

$$\Omega_m = 0.306^{+0.004}_{-0.005} \quad (0.306)$$

$$\sigma_8 = 0.804^{+0.008}_{-0.008} \quad (0.807)$$

$$h = 0.680^{+0.004}_{-0.003} \quad (0.681)$$

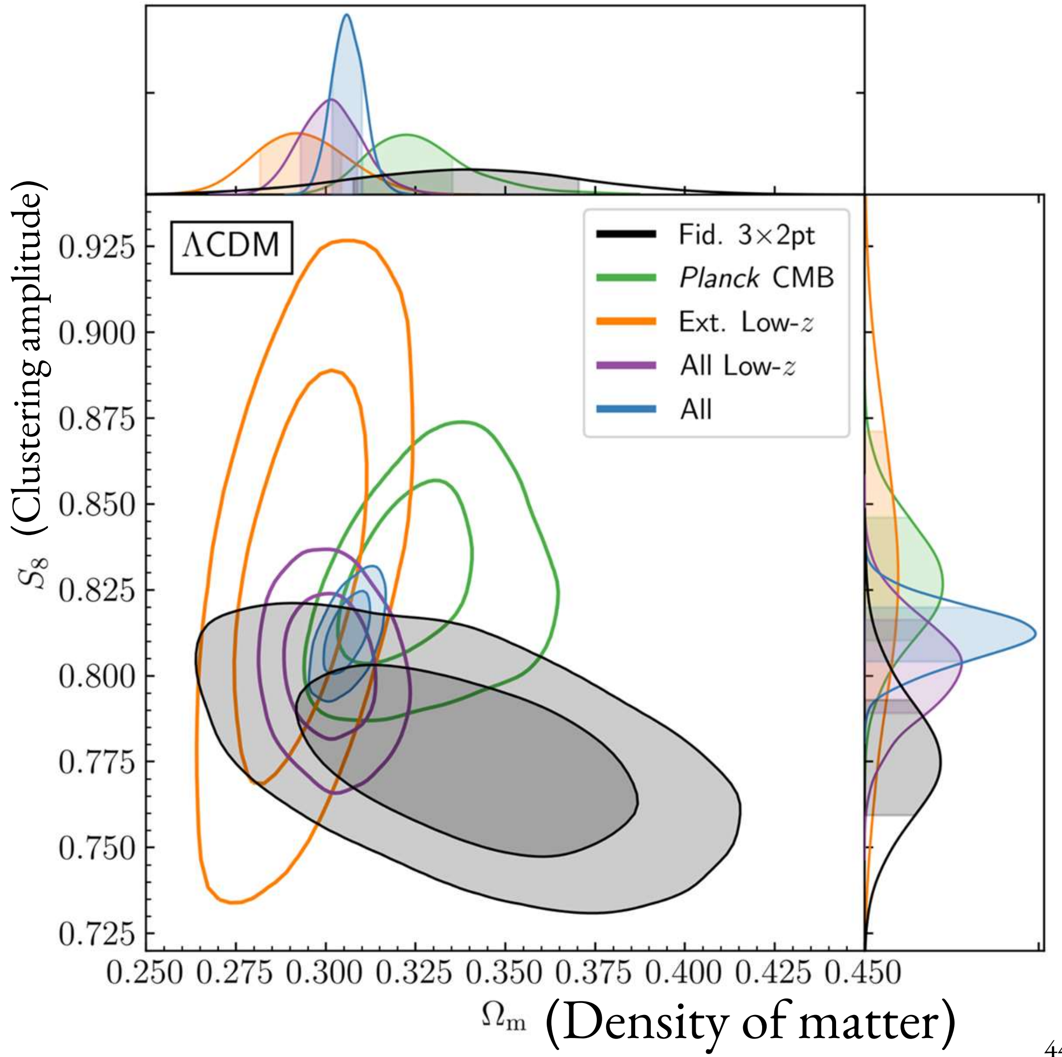
$$\sum m_\nu < 0.13 \text{ eV (95\% CL)}$$

In wCDM:

$$\sigma_8 = 0.810^{+0.010}_{-0.009} \quad (0.804);$$

$$\Omega_m = 0.302^{+0.006}_{-0.006} \quad (0.298);$$

$$w = -1.03^{+0.03}_{-0.03} \quad (-1.00)$$



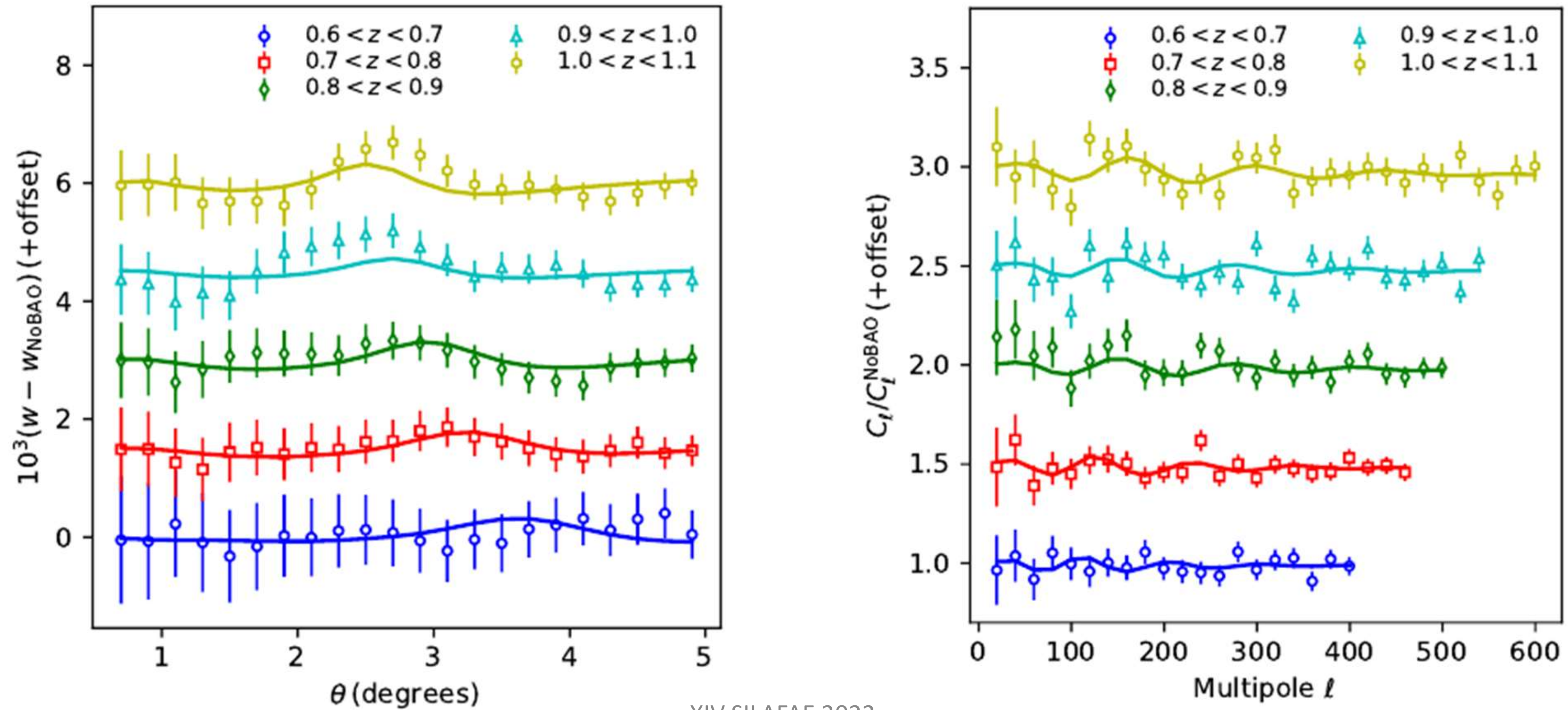
2. DES-Y3 Baryon Acoustic Oscillation

1. “Dark Energy Survey Year 3 Results: Galaxy Sample for BAO Measurement” A. Carnero et. al.

2. “Dark Energy Survey Year 3 Results: Galaxy mock catalogs for BAO analysis”, I. Ferrero et. al. (2021)

3. “Dark Energy Survey Year 3 Results: A 2.7% measurement of Baryon Acoustic Oscillation distance scale at redshift 0.835”, DES Collaboration (2021)

BAO feature was measured in both angular correlation function (single peak) and in angular power spectrum (oscillations)

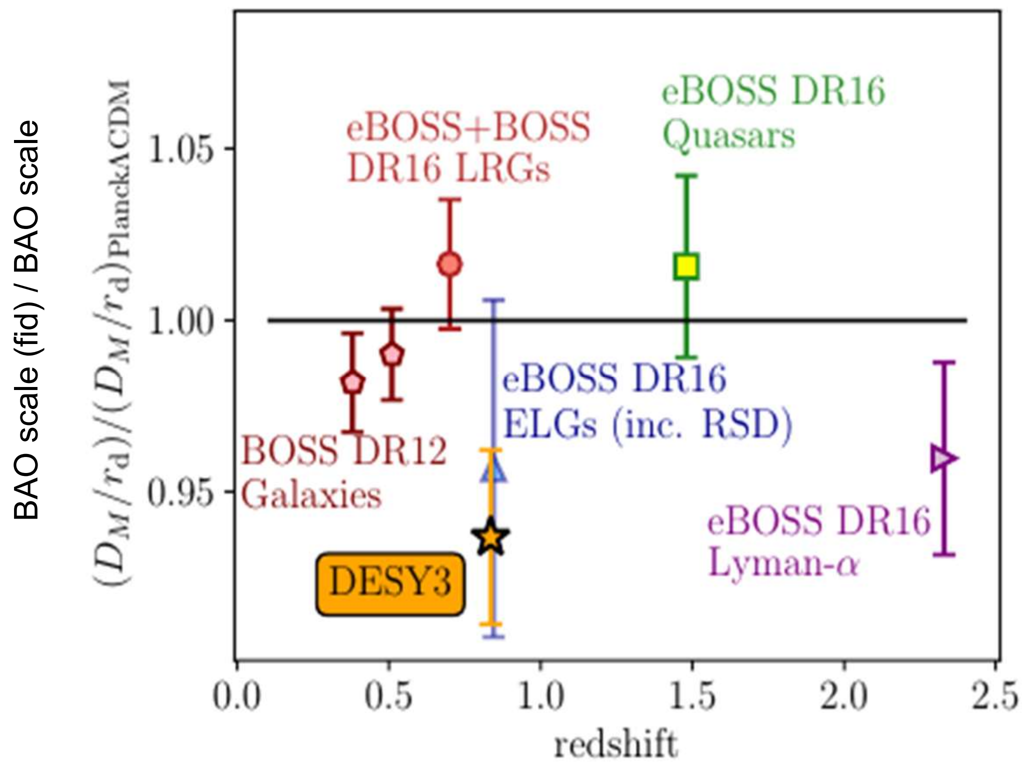


Key result: BAO Feature detection

2.7% detection at z=0.835 (Improved from 4% in Y1) at a significance level of 2.3σ.

The most precise BAO distance measurement from imaging data to date. Competitive with the latest transverse ones from spectroscopic samples at z > 0.75

Robust under a battery of tests specially designed for pre-unblinding procedure.



3. Harmonic space analysis

Galaxy clustering in harmonic space from the dark energy survey year 1 data: compatibility with real-space results FREE

F Andrade-Oliveira ✉, H Camacho, L Faga, R Gomes, R Rosenfeld, A Troja, O Alves, C Doux, J Elvin-Poole, X Fang ... Show more

Monthly Notices of the Royal Astronomical Society, Volume 505, Issue 4, August 2021, Pages 5714–5724, https://doi.org/10.1093/mnras/stab1642

JOURNAL ARTICLE

Cosmic shear in harmonic space from the Dark Energy Survey Year 1 Data: compatibility with configuration space results Get access >

H Camacho ✉, F Andrade-Oliveira, A Troja, R Rosenfeld ✉, L Faga, R Gomes, C Doux, X Fang, M Lima, V Miranda ...
Show more

Monthly Notices of the Royal Astronomical Society, Volume 516, Issue 4, November 2022, Pages 5799–5815, https://doi.org/10.1093/mnras/stac2543

Published: 11 September 2022 **Article history ▾**

Dark energy survey year 3 results: cosmological constraints from the analysis of cosmic shear in harmonic space

C Doux ✉, B Jain, D Zeurcher, J Lee, X Fang, R Rosenfeld, A Amon, H Camacho, A Choi, L F Secco ... Show more

Monthly Notices of the Royal Astronomical Society, Volume 515, Issue 2, September 2022, Pages 1942–1972, https://doi.org/10.1093/mnras/stac1826

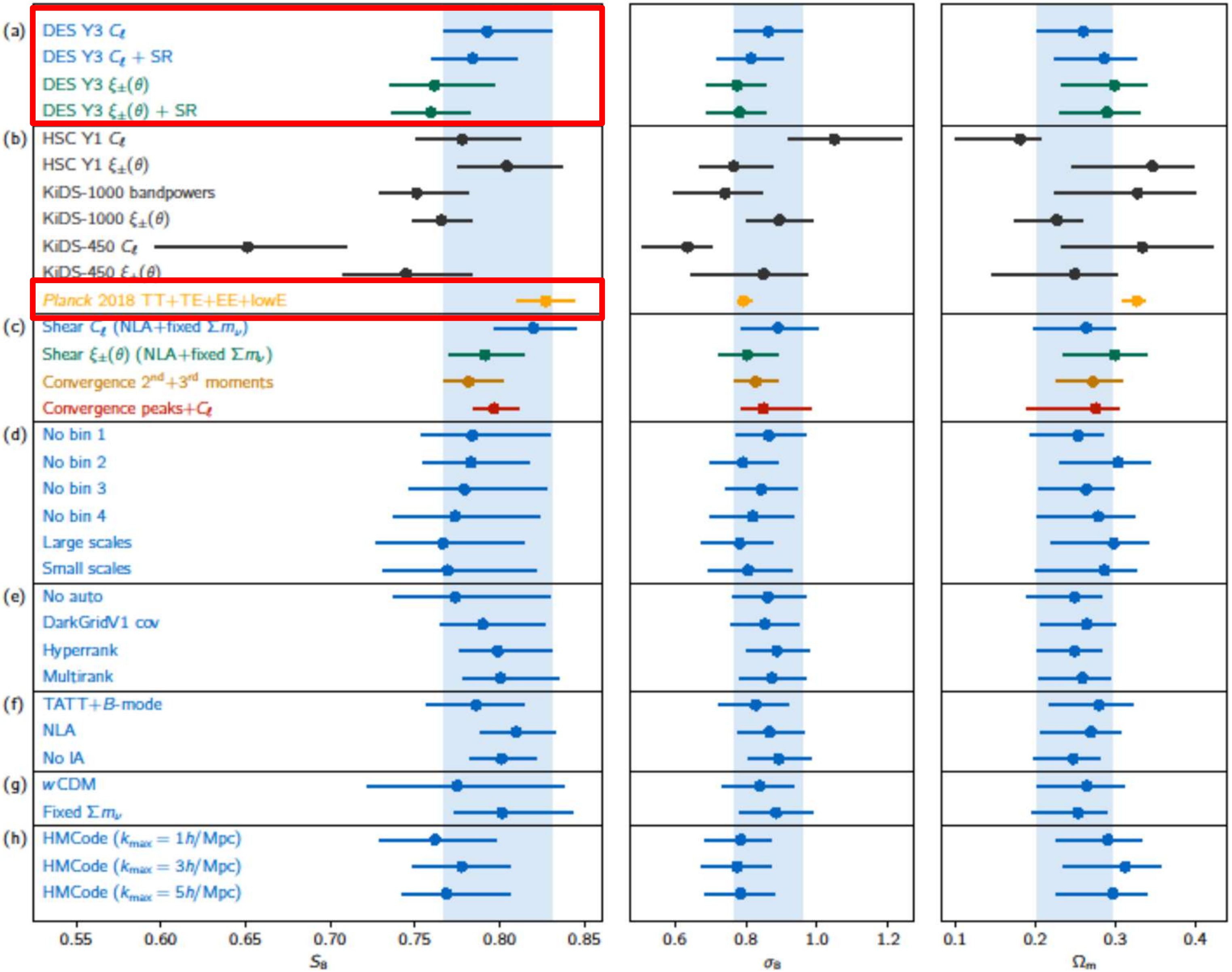
Published: 01 July 2022 **Article history ▾**

Why harmonic space?

- One can use either angular correlation functions in real space or angular power spectra in harmonic space for coemological analysis.
- In principle (full sky, no systematic effects, exact covariances, etc) the information is the same.
- However, in reality these conditions are not met – independent analysis.
- Covariance matrix is more diagonal in harmonic space.
- Theoretical predictions are more readily made in harmonic space.
- Footprint of survey introduces mode-coupling – pseudo-Cl method.


#Darkbites
IMAGES
SIM.
1011
0011
1010
Models
SHAPES
MCMC
COV
PHOTO-Z
σ_8
Ω_m

S_8 tension



(a)
DES Y3 C_ℓ
DES Y3 C_ℓ + SR
DES Y3 $\xi_\pm(\theta)$
DES Y3 $\xi_\pm(\theta)$ + SR
(b)
HSC Y1 C_ℓ
HSC Y1 $\xi_\pm(\theta)$
KiDS-1000 bandpowers
KiDS-1000 $\xi_\pm(\theta)$
KiDS-450 C_ℓ
KiDS-450 $\xi_\pm(\theta)$
Planck 2018 TT+TE+EE+lowE
(c)
Shear C_ℓ (NLA+fixed Σm_ν)
Shear $\xi_\pm(\theta)$ (NLA+fixed Σm_ν)
Convergence 2nd+3rd moments
Convergence peaks+C_ℓ
(d)
No bin 1
No bin 2
No bin 3
No bin 4
Large scales
Small scales
(e)
No auto
DarkGridV1 cov
Hyperrank
Multirank
(f)
TATT+B-mode
NLA
No IA
(g)
wCDM
Fixed Σm_ν
(h)
HMCode ($k_{max} = 1h$/Mpc)
HMCode ($k_{max} = 3h$/Mpc)
HMCode ($k_{max} = 5h$/Mpc)
0.55 0.60 0.65 0.70 0.75 0.80 0.85
S_8
0.6 0.8 1.0 1.2
σ_8
0.1 0.2 0.3 0.4
Ω_m

We are going towards a full 3x2pt analysis in harmonic space!

What about new physics?

- One can use DES data to study models beyond ΛCDM
- DES has published a paper on “extensions”: (w0,wa), modified gravity, curvature - arXiv:2207.05766

Otávio Alves

Physics graduate student, University of Michigan
Verified email at umich.edu

cosmology

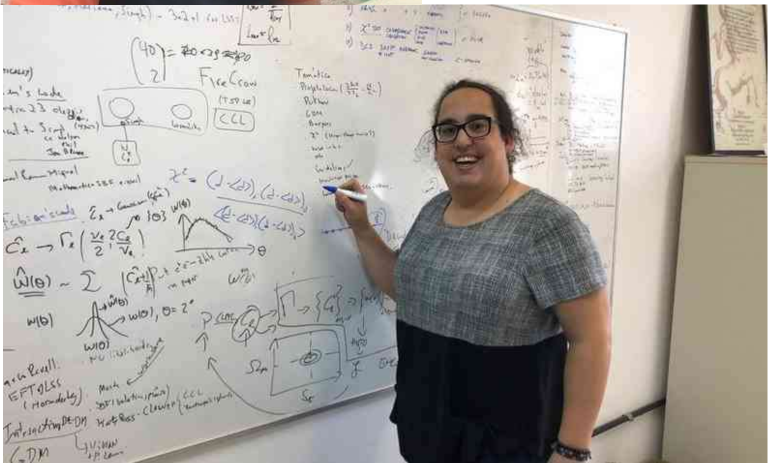
MSc student at IFT
Worked with Importance Sampling for the Extensions paper.
PhD student at University of Michigan with Dragan Huterer.
Current y6 extension co-convenor.

What about new physics?

Work in progress on Early Dark Energy models (motivated by H0 tension)

João Victor Rebouças
PhD student at IFT

Diogo Henrique Francis de Souza
PhD student at IFT



Vivian Miranda
Professor
Stony Brook

To study new models is computationally very demanding – high performance computing is a must to be competitive. Must run many MCMC chains with different data sets, analysis choices, etc.

A project on Early Dark Energy in collaboration with Vivian Miranda and PhD students requires >100 chains!

The next state-of-the-art photometric survey:

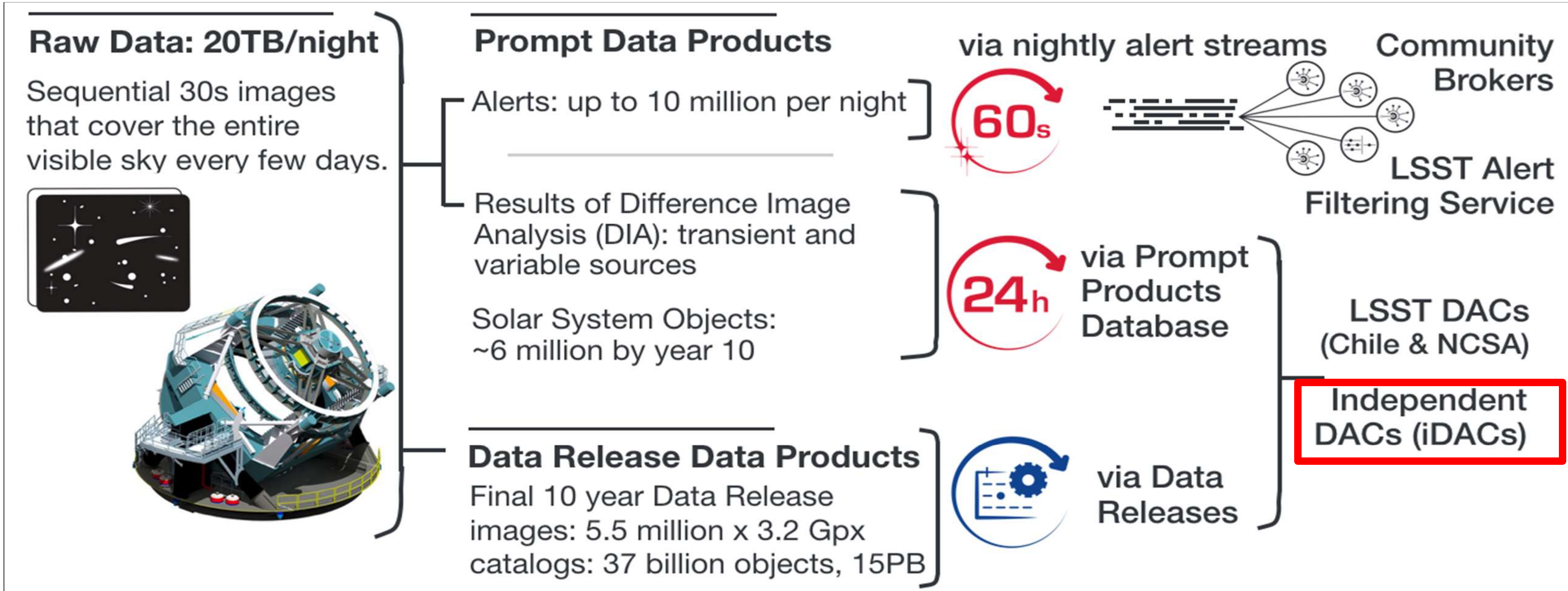
LSST

Legacy Survey of Space and Time

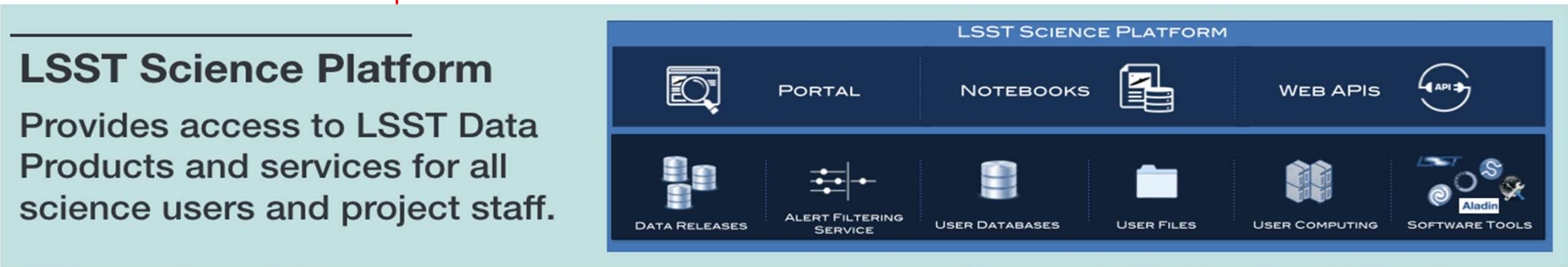
LSST is a 10-year survey to be conducted at the
Vera Rubin Observatory in Chile (CTIO)
using the
Simonyi Survey Telescope – 8.4 meters primary mirror
9.6 deg2 field of view
with the
LSSTCam
largest digital camera ever built (SLAC) – 3.2 Gigapixels
189 science CCDs
6 filters: ugrizy

Construction started in 2015
10 years of observations are planned – 2024 to 2034

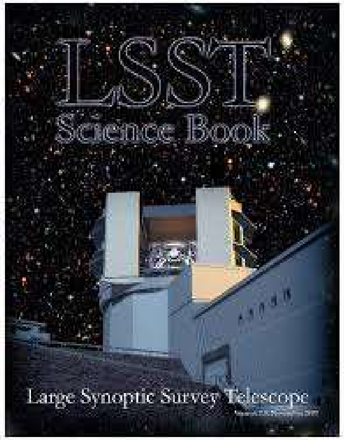
https://www.lsst.org/news/see-whats-happening-cerro-pachon



Slide from Melissa Graham's presentation at PCW22



LSST Science



www.lsst.org/scientists/scibook

LSST can do much more than study Dark Energy: unprecedent amount of data for multiple science goals

Science Topics are addressed within
LSST Science Collaborations
(autonomous, self-managed teams)

LSST Science Collaborations

8 Science Collaborations

- Active Galactic Nuclei
- Dark Energy
- Informatics and Statistics
- Transients and Variable Stars
- Stars, Milky Way, and Local Volume
- Strong Lensing
- Galaxies
- Solar System

LSST - Brazilian Participation Group

I'm the current coordinator
Tassia Ferreira: spokesperson

LSST : Brazilian Participation Group

MoA with Brazil signed in 2015 – 10 PIs (+40 juniors)

LIneA

LNA LABORATÓRIO NACIONAL DE ASTROFÍSICA

FAPESP 60
CIÊNCIA, CULTURA E DESENVOLVIMENTO | 1962 - 2022

RNP
REDE NACIONAL DE ENSINO E PESQUISA

LIneA activities (including LSST) are supported by:

L. da Costa is the coordinator
and I’m the vice-coordinator

LIneA is an Institutional Member of the LSST Corporation – LSSTC: L. da Costa is the representative.

An additional 15 PIs (+60 juniors) were secured by LIneA through in-kind contribution: an IDAC and contribution to the photometric redshift effort.

They were selected through a public call and results were announced in July 2022.

At the moment the BPG has 25 PIs and 61 young researchers.

Argentina joined LSST
Chile is a native member of LSST

Challenges and Opportunities in DESC

DESC

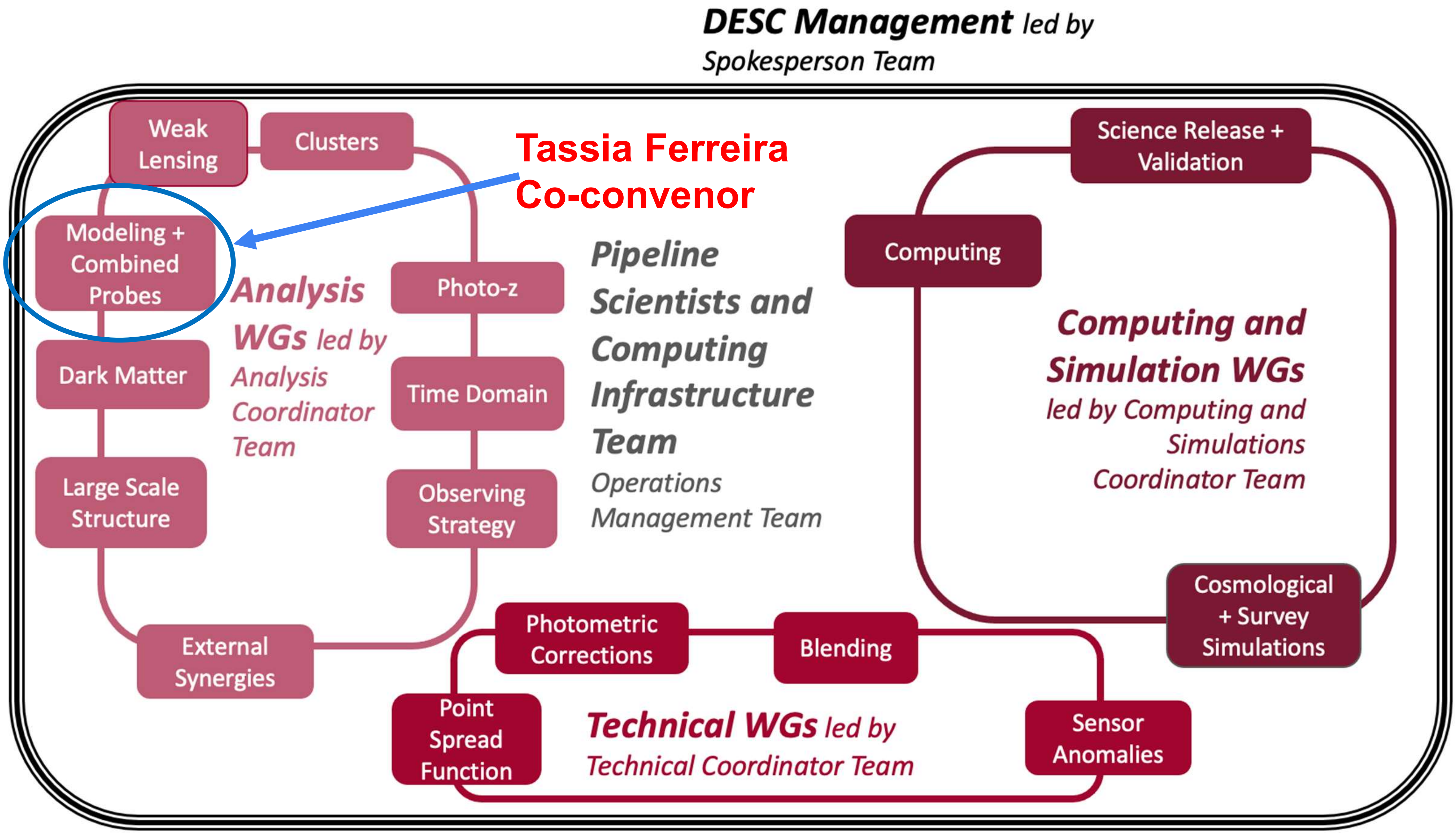
LSST DESC

Dark Energy Science Collaboration

1100+ members in **20+** countries,

Lear about Dark Energy mainly from the (combination of) observables:

- Distribution of galaxies (including BAO)
- Distribution of the shapes of galaxies
- SNIa
- Cluster counts


DESC Management led by Spokesperson Team
Weak Lensing
Clusters
Tassia Ferreira Co-convenor
Modeling + Combined Probes
Analysis WGs led by Analysis Coordinator Team
Photo-z
Dark Matter
Time Domain
Large Scale Structure
Observing Strategy
External Synergies
Pipeline Scientists and Computing Infrastructure Team
Operations Management Team
Science Release + Validation
Computing
Computing and Simulation WGs led by Computing and Simulations Coordinator Team
Cosmological + Survey Simulations
Photometric Corrections
Blending
Point Spread Function
Technical WGs led by Technical Coordinator Team
Sensor Anomalies

DESC challenges

- Large volume of data requires efficient modelling, codes and pipelines

Sandro Vitenti (LSST pipeline scientist): co-leading the development of the Firecrown pipeline for likelihood estimation.

Mariana Penna-Lima: participating in the development of the Cluster weak Lensing Mass Modeling (CLMM) library for cosmology. Non-Limber computations of cross-correlations. NumCosmo library for validation of LSST's Core Cosmology Library (CCL).

Felipe Andrade-Oliveira (LSST pipeline scientist): co-leading the development of the MCPCovariance pipeline.

- Cosmology with LSST Type Ia Supernovae

Valerio Marra: Machine learning for SN classification, Strong Lensing of SN; tests of FLRW, isotropy of the universe, reconstruction of the metric from observations, cosmic variance from local structure,..

- Modelling challenges

Tassia Ferreira, Rogerio Rosenfeld, Mariana Penna-Lima, Marcos Lima... : extensions of ΛCDM, non-Limber computations, mitigation of baryonic effects, non-linear power spectrum and galaxy bias (scale cuts, theoretical errors,...).

- New observables

Valerio Marra: Dark sirens correlated with LSST catalogues.

- ## Parameter estimation challenges

Effficient samplers to be included in likelihood code Firecrown to find posterior distributions of the many parameters (cosmological + nuisance). At the moment testing extensions with the cocoa framework (UNESP collaboration with Vivian Miranda).

- ## Mock challenges

Fast mock generation beyond lognormal (for 3x2pt+clusters) in order to validate covariance matrices and pipelines.

Conclusions

DES presented results from 3 years of data – DES-Y3:

- Combination of correlations among galaxy positions and galaxy shapes: 3x2pt
- Baryon acoustic oscillation

Most precise results from imaging surveys to-date (will be surpassed by LSST)

Results are an improvement of ~2 with respect to DES-Y1

No statistical significant inconsistencies with Planck were found within the Standard Cosmological Model (ΛCDM) and wCDM: can combine the data to obtain the strongest constraints in cosmology.

DES-Y6 final analysis of full data set under way. Amazing opportunities to work with state-of-the-art data. Valuable experience for LSST!

ΛCDM still is the best model to describe the Universe. No evidence of a need to go beyond it so far.

New upcoming surveys (DESI, LSST, Euclid,...) will continue to test ΛCDM at an unprecedent level

If ΛCDM breaks – new physics! Hubble tension may be the first indication.

Exciting times ahead!!

Obrigado

Gracias

Thank you

Lens sample comparison

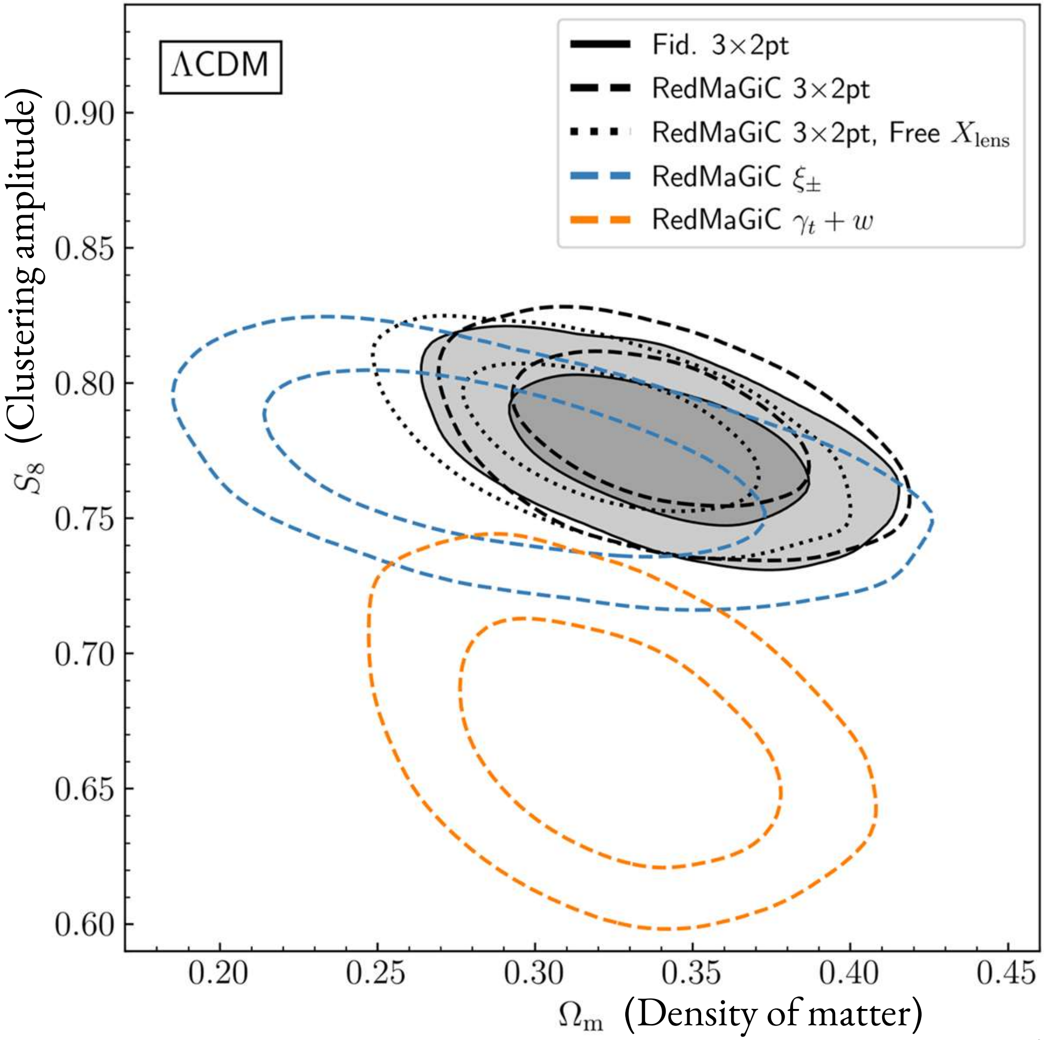
We introduce a parameter $X_{\rm lens}$ to model this, which decorrelates the clustering and lensing amplitudes: $w^{ii}(\theta) = b_i^2 \xi_{\rm mm}^{ii}(\theta)$

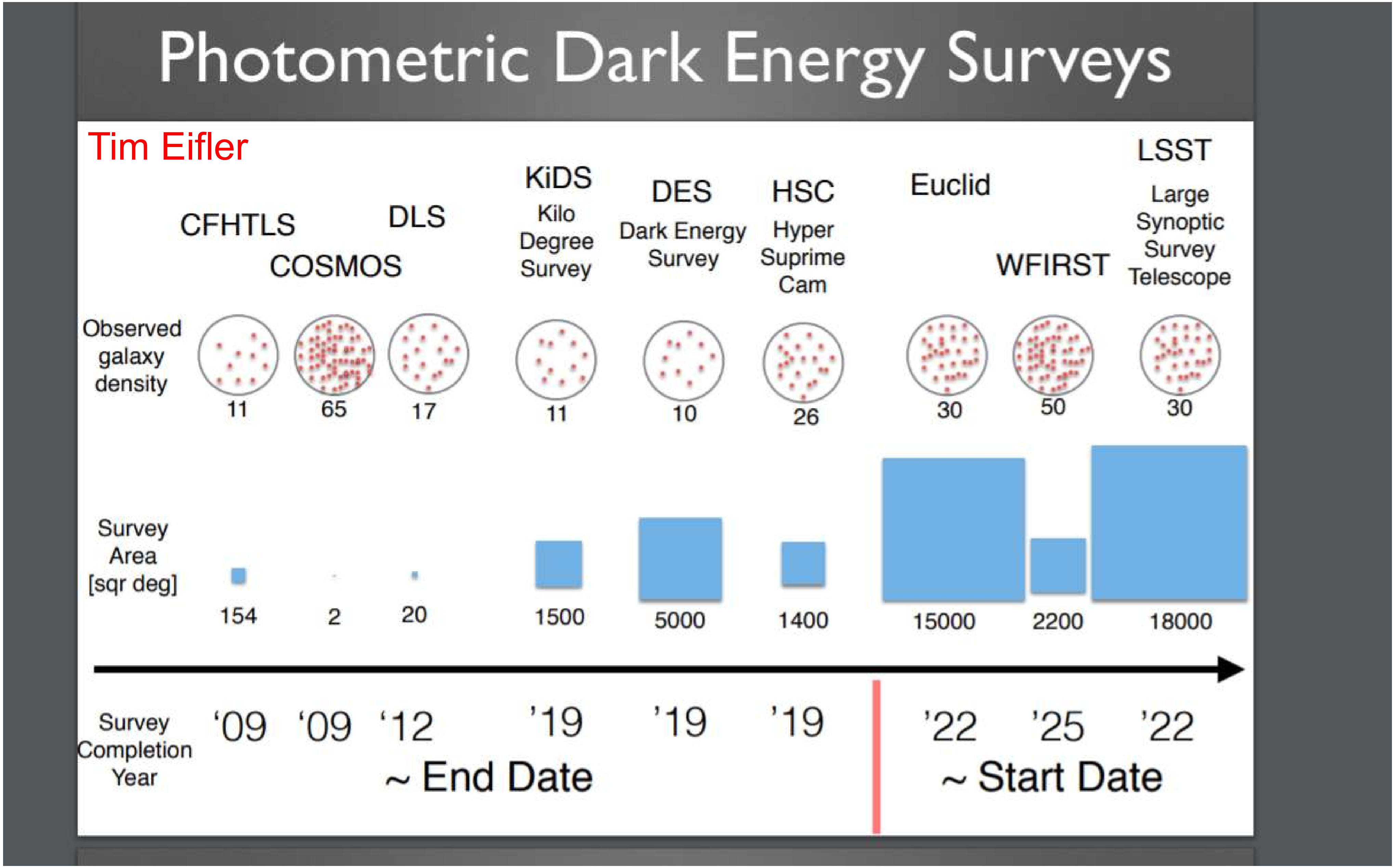
$$\gamma_t^{ij}(\theta) = X_{\rm lens} b_i \xi_{\rm mm}^{ij}(\theta)$$

We measure $X_{\rm lens} = 0.877^{+0.026}_{-0.019}$ for redMaGiC with **3×2pt** in ΛCDM ($X_{\rm lens}$ should be consistent with 1; it is in fiducial redshift range for MagLim).

$X_{\rm lens}$ does not strongly impact ΛCDM results, but is highly correlated with *w* in redMaGiC *w*CDM.

... but what is $X_{\rm lens}$?

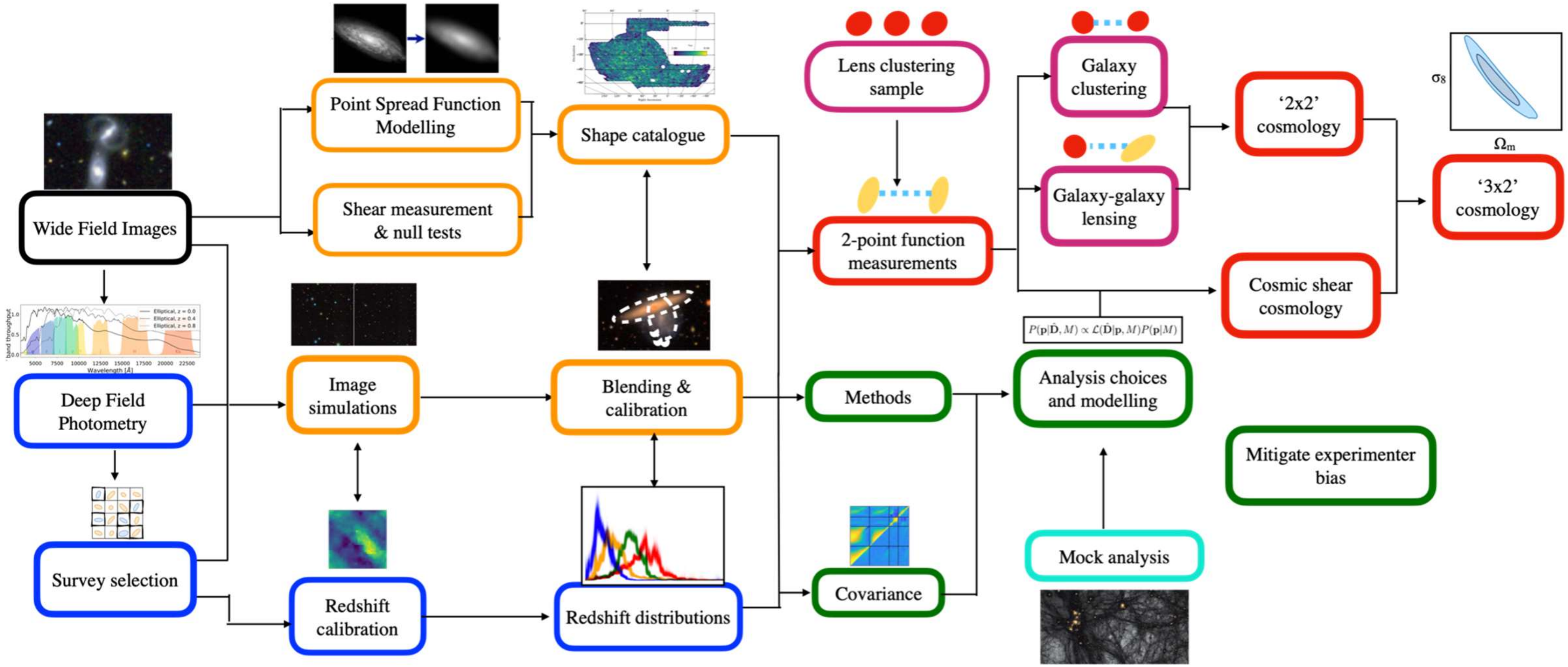




Photometric Dark Energy Surveys
Tim Eifler
CFHTLS
COSMOS
DLS
KiDS
Kilo Degree Survey
DES
Dark Energy Survey
HSC
Hyper Suprime Cam
Euclid
WFIRST
LSST
Large Synoptic Survey Telescope
Observed galaxy density
11
65
17
11
10
26
30
50
30
Survey Area [sqr deg]
154
2
20
1500
5000
1400
15000
2200
18000
Survey Completion Year
‘09
‘09
‘12
’19
’19
’19
’22
’25
’22
~ End Date
~ Start Date

DES Year 3: from pixels to cosmology

From DES-Y3 webinar



LCDM —— WL+LSS —— Redshifts —— Shapes —— Clustering —— Simulations —— Theory —— Results

Dark Energy Survey Year 3 results. List of key and supporting papers

1. “Blinding Multi-probe Cosmological Experiments” J. Muir, G. M. Bernstein, D. Huterer et al., arXiv: 1911.05929, MNRAS **494** (2020) 4454
2. “Photometric Data Set for Cosmology”, I. Sevilla-Noarbe, K. Bechtol, M. Carrasco Kind et al., arXiv:2011.03407, ApJS **254** (2021) 24
3. “Weak Lensing Shape Catalogue”, M. Gatti, E. Sheldon, A. Amon et al., arXiv:2011.03408, MNRAS **504** (2021) 4312
4. “Point Spread Function Modelling”, M. Jarvis, G. M. Bernstein, A. Amon et al., arXiv:2011.03409, MNRAS **501** (2021) 1282
5. “Measuring the Survey Transfer Function with Balrog”, S. Everett, B. Yanny, N. Kuropatkin et al., arXiv:2012.12825
6. “Deep Field Optical + Near-Infrared Images and Catalogue”, W. Hartley, A. Choi, A. Amon et al., arXiv:2012.12824
7. “Blending Shear and Redshift Biases in Image Simulations”, N. MacCrann, M. R. Becker, J. McCullough et al., arXiv:2012.08567
8. “Redshift Calibration of the Weak Lensing Source Galaxies”, J. Myles, A. Alarcon, A. Amon et al., arXiv:2012.08566
9. “Redshift Calibration of the MagLim Lens Sample using Self-Organizing Maps and Clustering Redshifts”, G. Giannini et al., in prep.
10. “Clustering Redshifts – Calibration of the Weak Lensing Source Redshift Distributions with redMaGiC and BOSS/eBOSS”, M. Gatti, G. Giannini, et al., arXiv:2012.08569
11. “Calibration of Lens Sample Redshift Distributions using Clustering Redshifts with BOSS/eBOSS”, R. Cawthon et al. arXiv:2012.12826
12. “Phenotypic Redshifts with SOMs: a Novel Method to Characterize Redshift Distributions of Source Galaxies for Weak Lensing Analysis” R. Buchs, C.Davis, D. Gruen et al. arXiv:1901.05005, MNRAS **489** (2019) 820
13. “Marginalising over Redshift Distribution Uncertainty in Weak Lensing Experiments”, J. Cordero, I. Harrison et al., in prep.
14. “Exploiting Small-Scale Information using Lensing Ratios”, C. Sánchez, J. Prat et al., in prep.
15. “Cosmology from Combined Galaxy Clustering and Lensing - Validation on Cosmological Simulations”, J. de Rose et al., in prep.
16. “Unbiased fast sampling of cosmological posterior distributions”, P. Lemos, R. Rollins, N. Weaverdyck, A. Ferte, A. Liddle et al., in prep.
17. “Assessing Tension Metrics with DES and Planck Data”, P. Lemos, M. Raveri, A. Campos et al., arXiv:2012.09554
18. “Dark Energy Survey Internal Consistency Tests of the Joint Cosmological Probe Analysis with Posterior Predictive Distributions”, C. Doux, E. Baxter, P. Lemos et al. arXiv:2011.03410, MNRAS **503** (2021) 2688
19. “Covariance Modelling and its Impact on Parameter Estimation and Quality of Fit”, O. Friedrich, F. Andrade-Oliveira, H. Camacho et al., arXiv:2012.08568
20. “Multi-Probe Modeling Strategy and Validation”, E. Krause et al., in prep.
21. “Curved-Sky Weak Lensing Map Reconstruction”, N. Jeffrey, M. Gatti, C. Chang et al., in prep.
22. “Galaxy Clustering and Systematics Treatment for Lens Galaxy Samples”, M.Rodríguez-Monroy, N. Weaverdyck, J. Elvin-Poole, M. Crocce et al., in prep.
23. “Optimizing the Lens Sample in Combined Galaxy Clustering and Galaxy-Galaxy Lensing Analysis”, A. Porredon, M. Crocce et al., arXiv:2011.03411 PhRvD **103** (2021) 043503
24. “High-Precision Measurement and Modeling of Galaxy-Galaxy Lensing”, J. Prat, J. Blazek, C. Sánchez et al., in prep.
25. “Constraints on Cosmological Parameters and Galaxy Bias Models from Galaxy Clustering and Galaxy-Galaxy Lensing using the redMaGiC Sample”, S. Pandey et al., in prep.
26. “Cosmological Constraints from Galaxy Clustering and Galaxy-Galaxy Lensing using the Maglim Lens Sample” A. Porredon, M. Crocce et al., in prep.
27. “Cosmology from Cosmic Shear and Robustness to Data Calibration”, A. Amon, D. Gruen, M. A. Troxel et al., in prep.
28. “Cosmology from Cosmic Shear and Robustness to Modeling Assumptions”, L. Secco, S. Samuroff et al., in prep.
29. “Magnification modeling and impact on cosmological constraints from galaxy clustering and galaxy-galaxy lensing”, J. Elvin-Poole, N. MacCrann et al., in prep.
30. “Cosmological Constraints from Galaxy Clustering and Weak Lensing” The DES Collaboration in prep.

From DES-Y3 webinar

Dark Energy Survey:

- Imaging survey using a digital camera (DECam) of 570 megapixels with 62 CCDs
- DECam mounted on the focal plane of the 4-meter Blanco Telescope at CTIO
- Images taken in 5 filters gryzY (~10 exposures in each filter)
- 6-year survey – first light September 12, 2012 and last observation night January 9, 2019.
- Covered an area of 5000 square degrees (~1/8 of the sky)
- Takes a lot of work to go from data to results
- Main results from the first year of observations (DES-Y1) published in 2017.
- We released the main results from the first three years (DES-Y3) in May 2021.
- Main cosmological analysis based on galaxy clustering combined with weak lensing
- Main paper + 29 key papers – huge amount of work from the ~400 members
- Also results from Baryon Acoustic Oscillations (BAO) (+3 papers)
- Our group was mostly involved in the Covariance Matrix validation and in the BAO detection in harmonic space

All results are available at:

www.darkenergysurvey.org/des-year-3-cosmology-results-papers

I will sumarize the results in this talk.

Ingredients for Dark Energy Survey Y3 analysis

- Gold sample: selection of objetcs passing quality cuts, photometric calibration, masking, signal-to-noise>10, objects brighter than i>23, star-galaxy separation,..

Total of 319 million objects (Sevilla-Noarbe et al., 2011.03407)

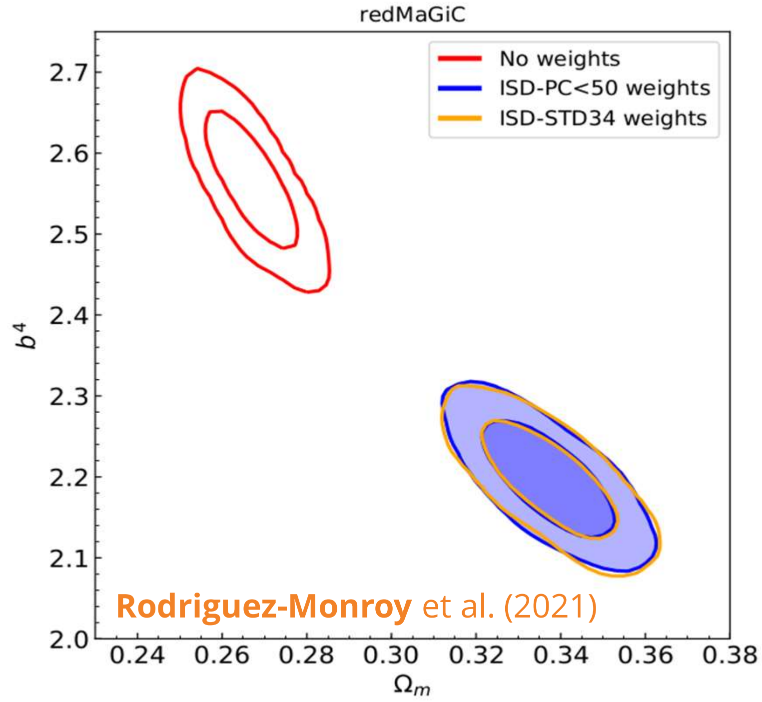
- Gold sample is used to produce science-ready catalogues:
  1. Position catalogues (RedMagic and MagLim)
  2. Shear catalogue (Metacalibration)
  3. BAO-optimized catalogue
- Measurements of 2-point correlation functions are performed using these catalogues
- Theoretical modelling of the 2-point correlation functions given a cosmological model is developed taking into account several effects (discussed later)
- Analysis choices (scale cuts, effects to be modelled, nuisance parameters for systematic uncertainties, etc) are set in a Methods paper and validated using simulations
- Analytical covariance matrix validation
- Blinded likelihood analysis
- Unblinding
- Quality of the results (chi2, ppd), robustness tests
- Cosmological parameters
- Comparison with other experiments (measure of tension)
- Final results

Main issues in measuring correlation functions

- Systematic errors:

Airmass, seeing, exposure time, depth, stellar density, dust, sky brightness, calibration residuals

Mitigated with a weighting scheme that decorrelates galaxy maps from these systematic maps. Also need a model for point spread function (PSF).



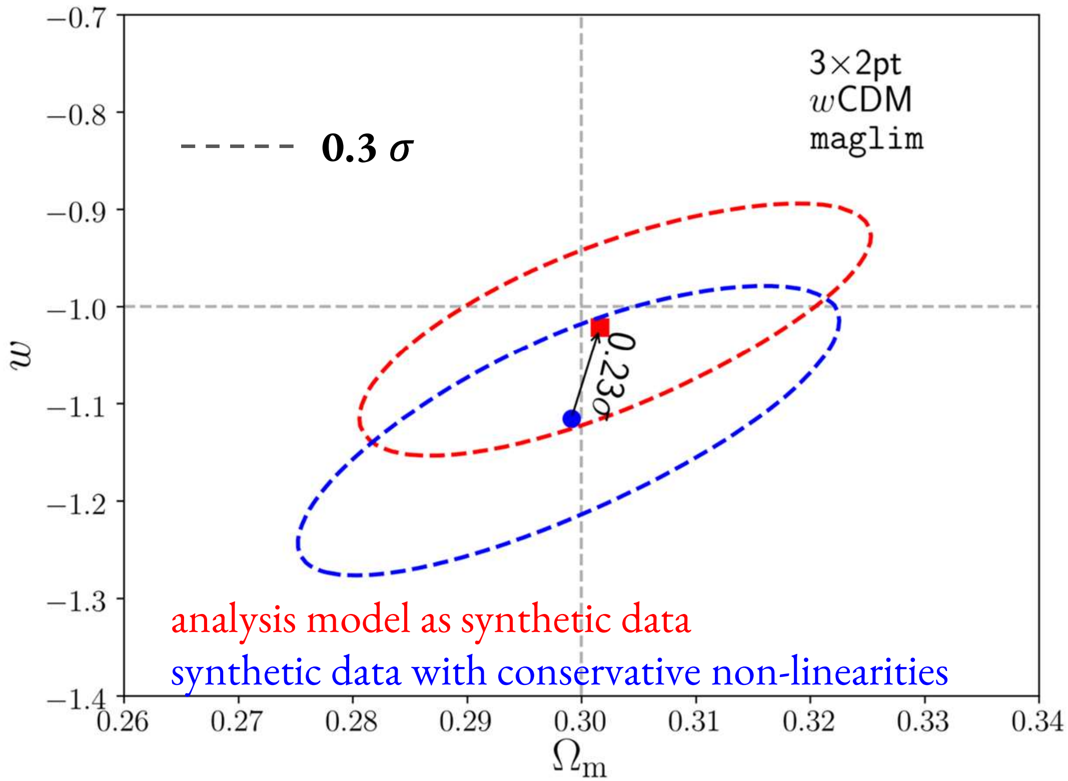
"With great statistical power comes great systematic responsibility"

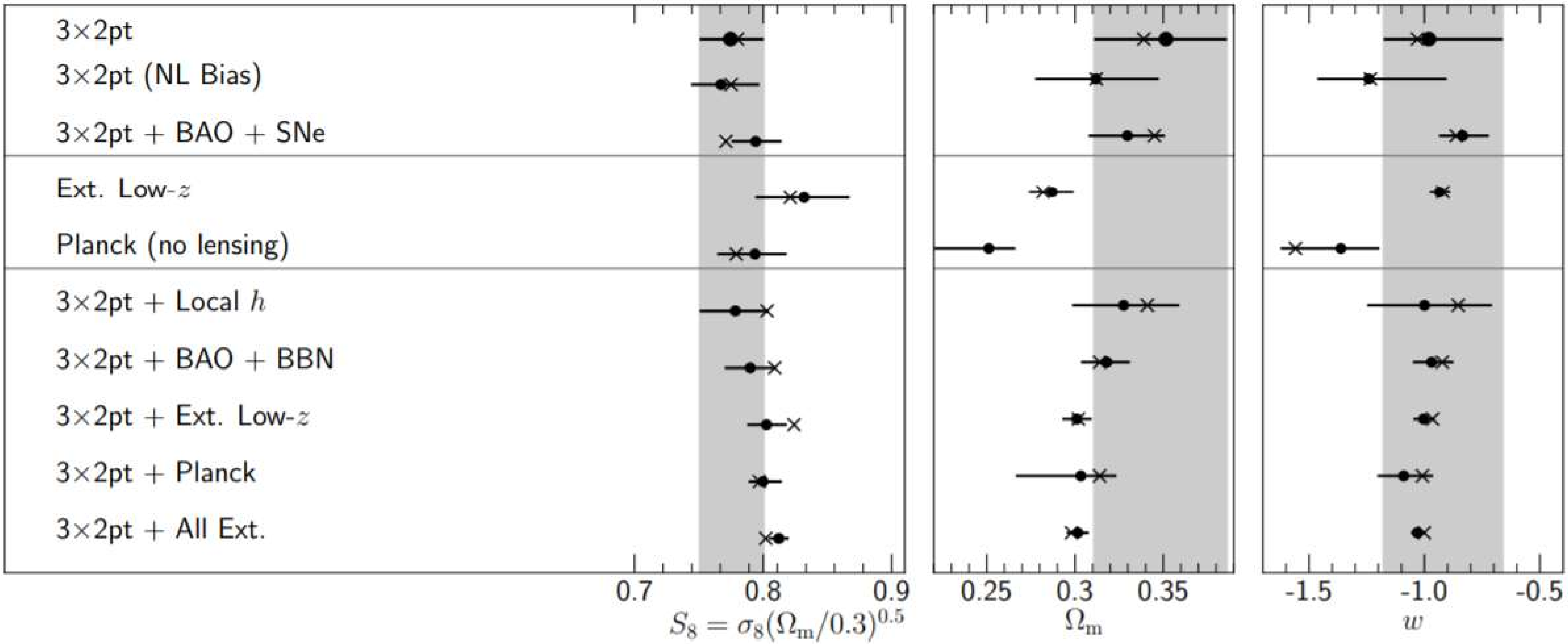
3x2pt Modeling

DES-Y3 analysis restricted to angular scales such that non-linear modeling uncertainties bias cosmology constraints by < 0.3σ.

(Krause+, DeRose+)

Krause+





3×2pt
3×2pt (NL Bias)
3×2pt + BAO + SNe
Ext. Low-z
Planck (no lensing)
3×2pt + Local h
3×2pt + BAO + BBN
3×2pt + Ext. Low-z
3×2pt + Planck
3×2pt + All Ext.
0.7
0.8
0.9
$S_8 = \sigma_8(\Omega_m/0.3)^{0.5}$
0.25
0.3
0.35
Ω_m
-1.5
-1.0
-0.5
w

From clustering measurements to the BAO feature

We are interested in the location of the BAO peak on the correlation function, not in its full-shape, we then use a template-fitting approach

- Configuration space
  $M(x) = BT_{\mathrm{BAO}}(x\alpha) + A(x)$
- Harmonic space
  $C(\ell) = BT_{\mathrm{BAO}}(\ell/\alpha) + A(\ell)$

Having a single parameter (so-called shift parameter):

$$\alpha = \frac{D_A(z_{\mathrm{eff}})r_{\mathrm{d}}^{\mathrm{fid}}}{D_A^{\mathrm{fid}}(z_{\mathrm{eff}})r_{\mathrm{d}}}$$

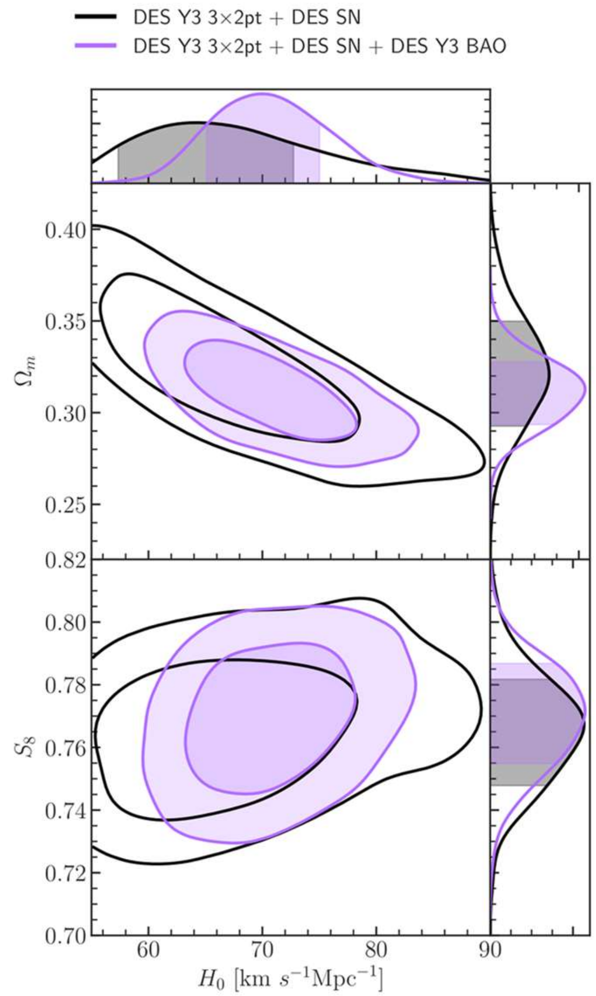
Final result is from a combination of real and harmonic space analysis!

Combination of 3x2pt, BAO and SNIa in DES

Pure history of growth constraints from DES are consistent with 3x2pt and can be combined to have:

$$h = 0.691^{+0.138}_{-0.043},$$
$$\Omega_m = 0.344^{+0.029}_{-0.025},$$
$$S_8 = 0.773^{+0.018}_{-0.019},$$

$$h = 0.72^{+0.090}_{-0.053},$$
$$\Omega_m = 0.317^{+0.021}_{-0.020},$$
$$S_8 = 0.778^{+0.016}_{-0.017}.$$



New PIs possible through LIneA in-kind contributions which are essential for doing science with LSST:

- Photometric redshift

Julia Gschwend et al:

- ➢ Photo-z Server – data and metadata photo-z related repository
- ➢ Training Set Maker – pipeline to generate training and validation sets for photo-z estimation from public spectroscopic data
- ➢ Complementary data products – photo-z measurements for all objects in public data releases.

- Independent Data Access Center (IDAC)

LIneA IT team:

- Access of proprietary LSST data to members
- Access of public data using the Science Server
- 5 PB storage, 500 TB database, 500 cores
- Process photo-z measurements
- Accquisition of equipment has started

29 de julho de 2022 | LIneA

A pedido da Comissão de Seleção para o Grupo de Participação Brasileiro no projeto *Legacy Survey Space and Time* (BPG-LSST), a diretoria do LIneA tem o prazer de anunciar os nomes dos pesquisadores selecionados para preencher as 15 vagas de PIs oferecidas pelo LIneA à comunidade brasileira.

Na tabela abaixo listamos os nomes dos novos membros em ordem alfabética, instituto de origem e área de pesquisa.

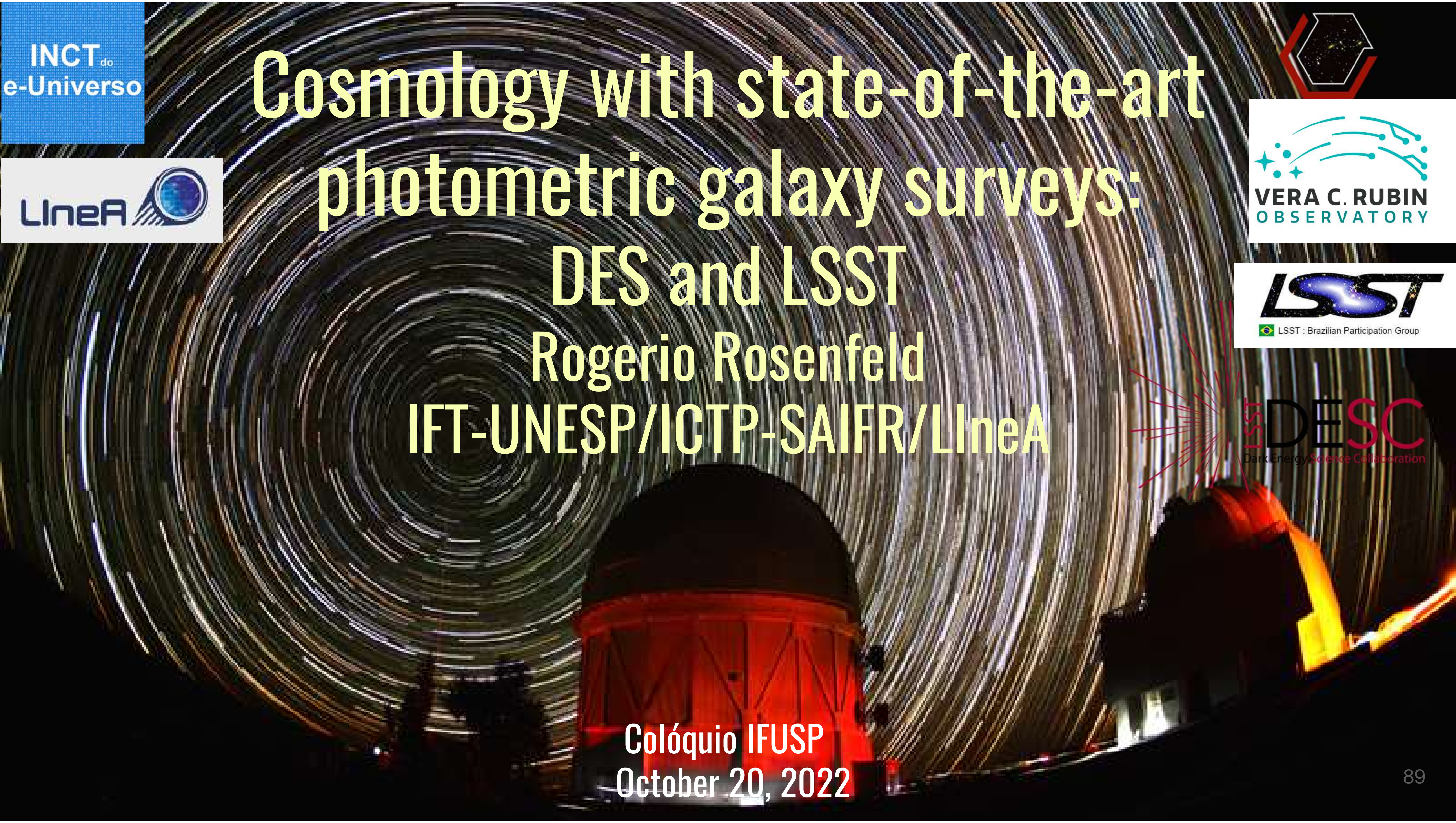
Nome	**Instituto**	**Área**
Altair Ramos Gomes Júnior	UFU	Solar System
Ana Leonor Chies Santiago Santos	UFRGS	Milky Way
Bruno Azevedo Lemos Moraes	UFRJ	Dark Energy
Charles J. Bonato	UFRGS	Milky Way
Daniel Cardoso Moraes de Oliveira	UFF	Informatics
Felipe Braga Ribas	UTFPR	Solar System
Jaderson da Silva Schimoia	UFSM	AGN
Kepler de Souza Oliveira Filho	UFRGS	Milky Way
Rafael Izbicki	UFSCar	Dark Energy
Reinaldo Roberto Rosa	INPE	Informatics
Rogemar André Riffel	UFSM	AGN
Rogério Riffel	UFRGS	AGN
Sandro Barboza Rembold	UFSM	AGN
Thaisa Storchi Bergmann	UFRGS	AGN
Valerio Carruba	UNESP	Solar System

https://linea.org.br/2022/07/linea-anuncia-os-novos-membros-do-grupo-de-participacao-brasileiro-no-lsst-bpg-lsst/

Cosmology with state-of-the-art photometric galaxy surveys: DES and LSST

Rogerio Rosenfeld
IFT-UNESP/ICTP-SAIFR/LIneA

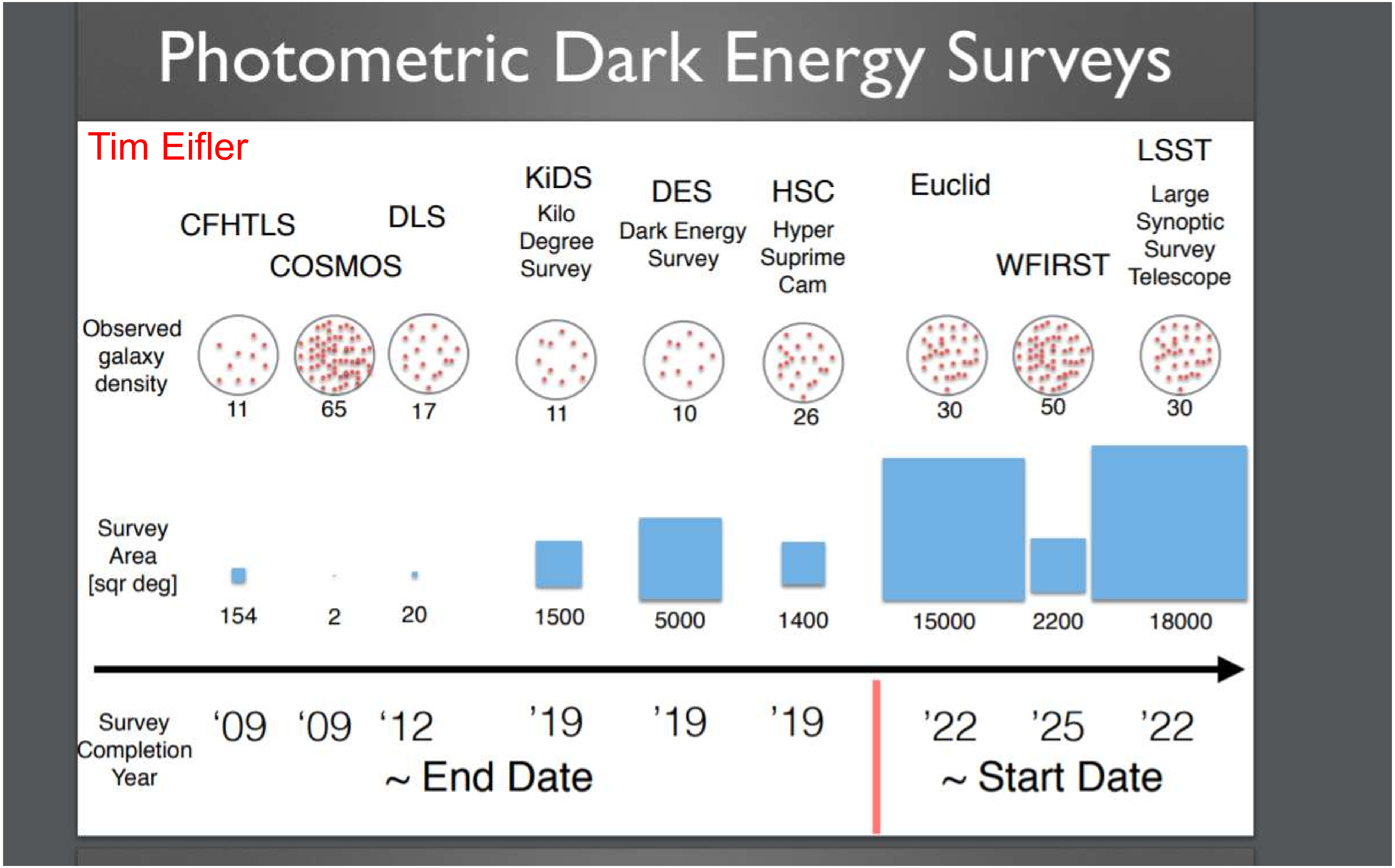
Colóquio IFUSP
October 20, 2022



Cosmology with state-of-the-art photometric galaxy surveys: DES and LSST

Rogerio Rosenfeld
IFT-UNESP/ICTP-SAIFR/LIneA

Colóquio IFUSP
October 20, 2022



Photometric Dark Energy Surveys
Tim Eifler
CFHTLS
COSMOS
DLS
KiDS
Kilo Degree Survey
DES
Dark Energy Survey
HSC
Hyper Suprime Cam
Euclid
WFIRST
LSST
Large Synoptic Survey Telescope
Observed galaxy density
11
65
17
11
10
26
30
50
30
Survey Area [sqr deg]
154
2
20
1500
5000
1400
15000
2200
18000
Survey Completion Year
'09
'09
'12
'19
'19
'19
'22
'25
'22
~ End Date
~ Start Date

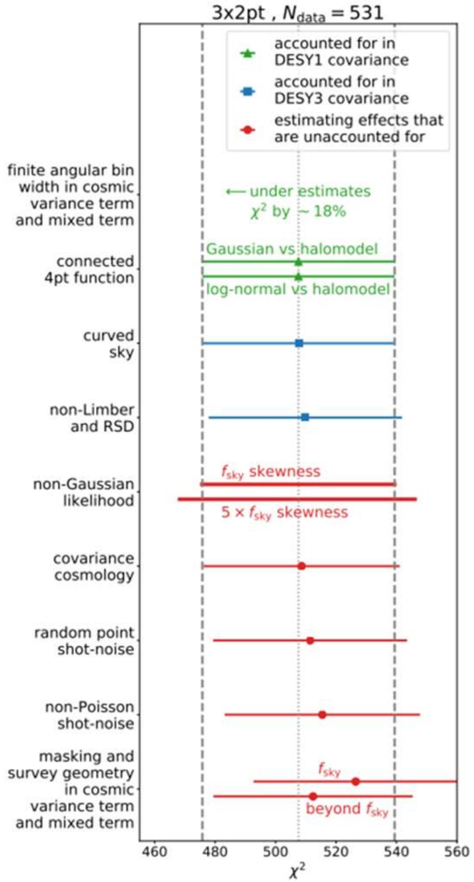
How to estimate cosmological parameters?

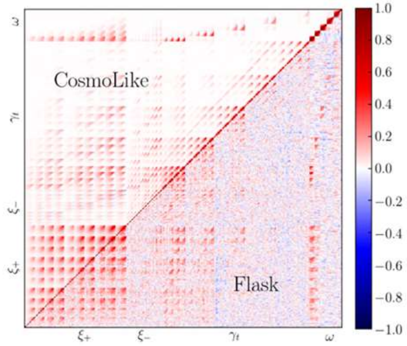
Infer parameter posterior $P(\mathbf{p}|\hat{\mathbf{D}}, M)$ within model M using Bayes' theorem

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

Required Ingredients

- Data likelihood $\mathcal{L}(\hat{\mathbf{D}}|\mathbf{p}, M)$ with data covariance **C**
- Model M with parameters **p**, and prior, $P(\mathbf{p}|M)$
- Criteria for which measurements to combine
- Blinding scheme to minimize observer bias





Covariance matrix paper
Friedrich, Andrade-Oliveira, Camacho et. al. (2021)

Model for 2-point binned angular correlation functions

$$w^i(\theta) = \sum_\ell \mathcal{G}_0\left(\ell, \theta_{\rm min}, \theta_{\rm max}\right) C^{ii}_{\delta_{\rm obs}\delta_{\rm obs}}(\ell)$$

$$\gamma^{ij}_{\rm t}(\theta) = \sum_\ell \mathcal{G}_2\left(\ell, \theta_{\rm min}, \theta_{\rm max}\right) C^{ij}_{\delta_{\rm obs}{\rm E}}(\ell) \qquad (13)$$

$$\xi^{ij}_\pm(\theta) = \sum_\ell \mathcal{G}_{4,\pm}\left(\ell, \theta_{\rm min}, \theta_{\rm max}\right) \left[C^{ij}_{\rm EE}(\ell) \pm C^{ij}_{\rm BB}(\ell)\right] ,$$

Selection functions

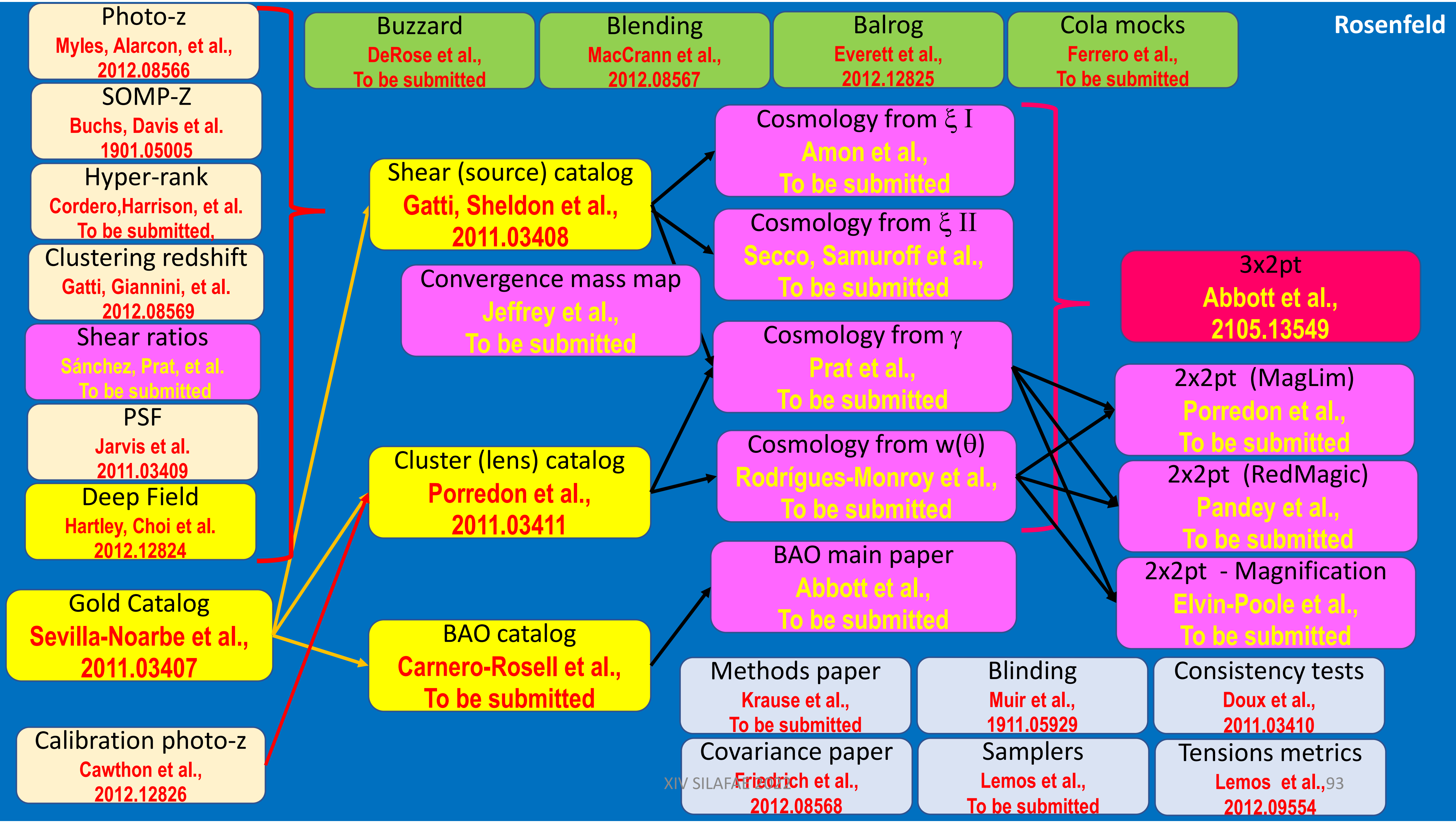
$$C^{ij}_{AB}(\ell) = \int d\chi \frac{W^i_A(\chi) W^j_B(\chi)}{\chi^2} P_{AB}\left(k = \frac{\ell + \frac{1}{2}}{\chi}, z(\chi)\right)$$

Angular power spectrum

Comoving distance Geometry

3-d power spectrum

Cosmological parameters


Rosenfeld
Photo-z
Myles, Alarcon, et al., 2012.08566
SOMP-Z
Buchs, Davis et al. 1901.05005
Hyper-rank
Cordero,Harrison, et al. To be submitted,
Clustering redshift
Gatti, Giannini, et al. 2012.08569
Shear ratios
Sánchez, Prat, et al. To be submitted
PSF
Jarvis et al. 2011.03409
Deep Field
Hartley, Choi et al. 2012.12824
Gold Catalog
Sevilla-Noarbe et al., 2011.03407
Calibration photo-z
Cawthon et al., 2012.12826
Buzzard
DeRose et al., To be submitted
Blending
MacCrann et al., 2012.08567
Balrog
Everett et al., 2012.12825
Cola mocks
Ferrero et al., To be submitted
Shear (source) catalog
Gatti, Sheldon et al., 2011.03408
Convergence mass map
Jeffrey et al., To be submitted
Cluster (lens) catalog
Porredon et al., 2011.03411
BAO catalog
Carnero-Rosell et al., To be submitted
Cosmology from ξ I
Amon et al., To be submitted
Cosmology from ξ II
Secco, Samuroff et al., To be submitted
Cosmology from γ
Prat et al., To be submitted
Cosmology from w(θ)
Rodrígues-Monroy et al., To be submitted
BAO main paper
Abbott et al., To be submitted
3x2pt
Abbott et al., 2105.13549
2x2pt (MagLim)
Porredon et al., To be submitted
2x2pt (RedMagic)
Pandey et al., To be submitted
2x2pt - Magnification
Elvin-Poole et al., To be submitted
Methods paper
Krause et al., To be submitted
Blinding
Muir et al., 1911.05929
Consistency tests
Doux et al., 2011.03410
Covariance paper
Friedrich et al., 2012.08568
Samplers
Lemos et al., To be submitted
Tensions metrics
Lemos et al., 2012.09554

What is our main goal?

Find the best cosmological model that explains observations.

What is our main goal?

Find the best cosmological model and its parameters that explains observations.

How?

Easy steps:

. Pick a probe
. Pick a model
. Compute predictions from the model for a given set of parameters
. Get some data
. Compare model predictions with data
. Find the best model with the corresponding values of parameters

Put all steps together in the so-called likelihood function:

$$\mathcal{L}(\{p\}) \propto \exp\left\{-\frac{1}{2}\left(\mathcal{O}^{\rm th}-\mathcal{O}^{\rm obs}\right)^T_i \mathrm{Cov}^{-1}_{ij}\left(\mathcal{O}^{\rm th}-\mathcal{O}^{\rm obs}\right)_j\right\}$$

Theoretical prediction depends on the model and its parameters.

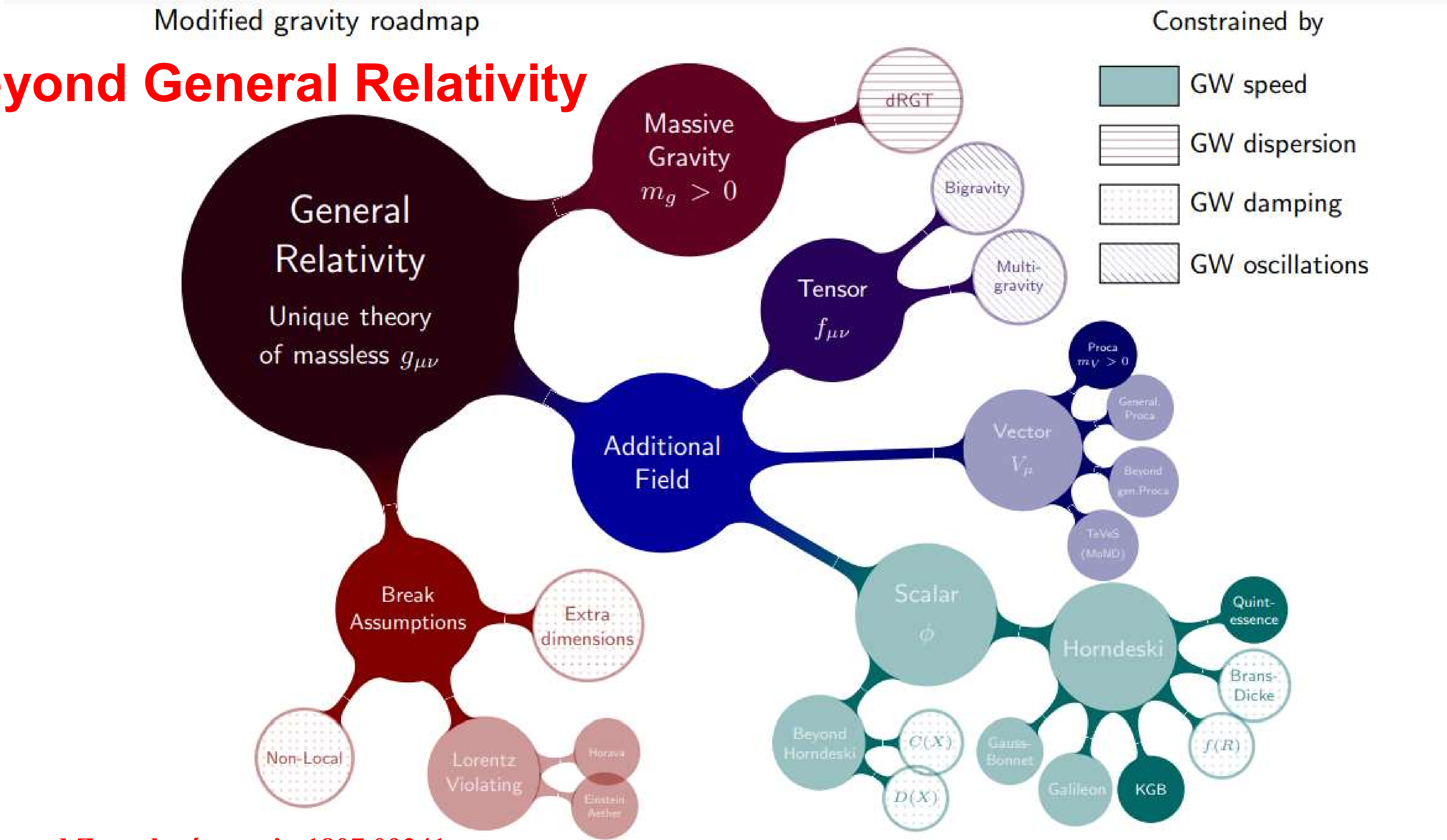
Observations depend on the experiment.

The covariance matrix basically reflects the uncertainty in the experimental measurement.

Best model: maximize likelihood

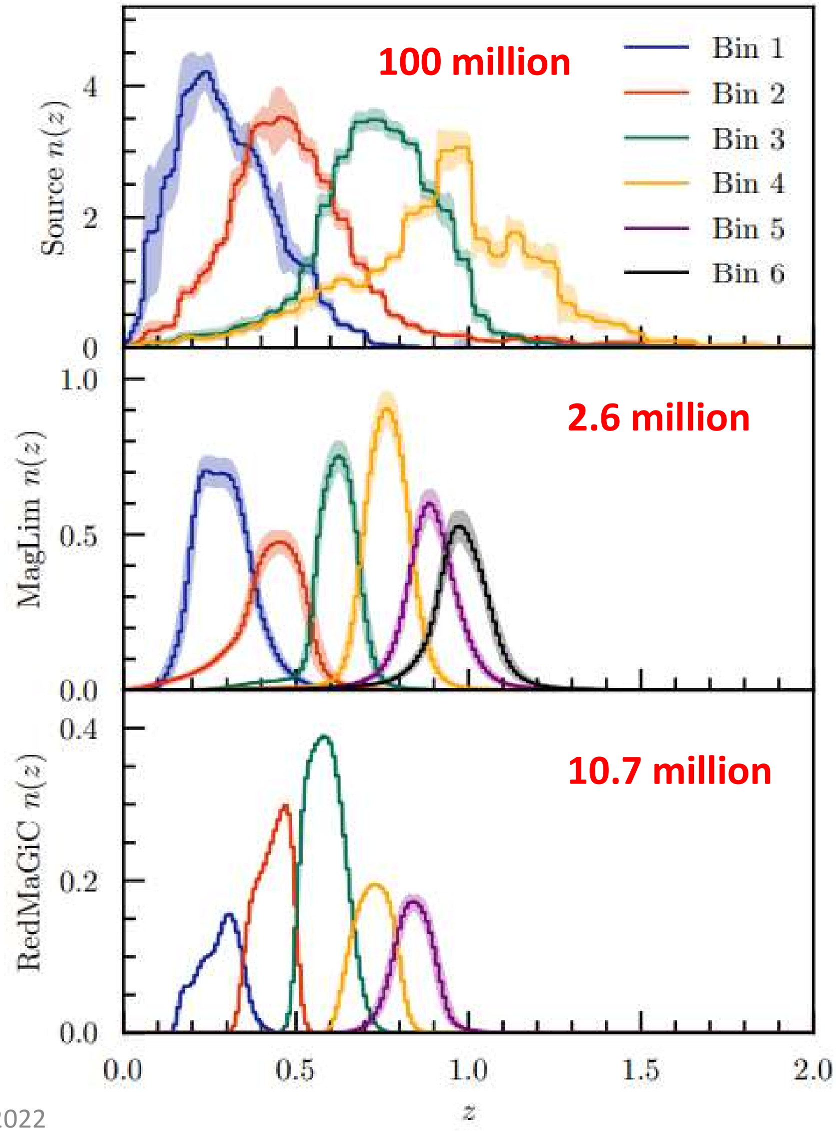
Sounds pretty easy!   I'll show challenges later in the talk.

Beyond General Relativity



Ezquiaga and Zumalacárregui - 1807.09241

Redshift distributions of galaxies



BRA-LIN in-kind contribution program for LSST:

- Lite IDAC
- Software + Data Products for Photo-z
- Pipeline Scientist

BRA-LIN key-people:

- Program Lead: Luiz da Costa
- Program Manager: Julia Gschwend
- IDAC Contribution Lead: Carlos Adean
- PZ Contribution Lead: Julia Gschwend
- DESC Pipeline Scientist: Sandro Vitenti
- In-kind Program Coordinator (from Rubin): Aprajita Verma