# DES Year 3 cosmological analysis:
## lessons learnt and challenges for LSST

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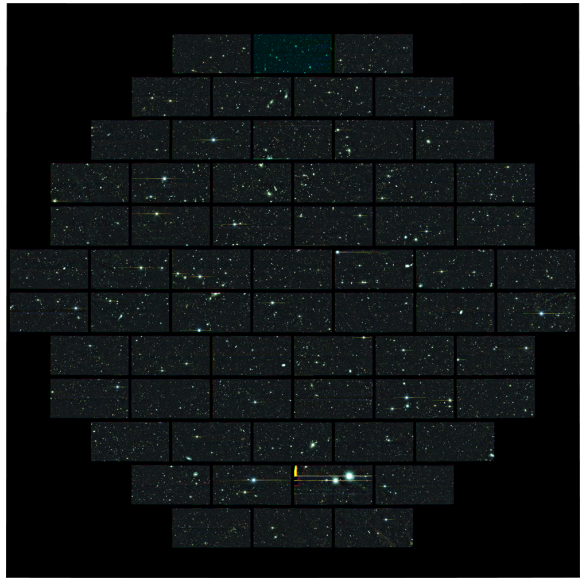
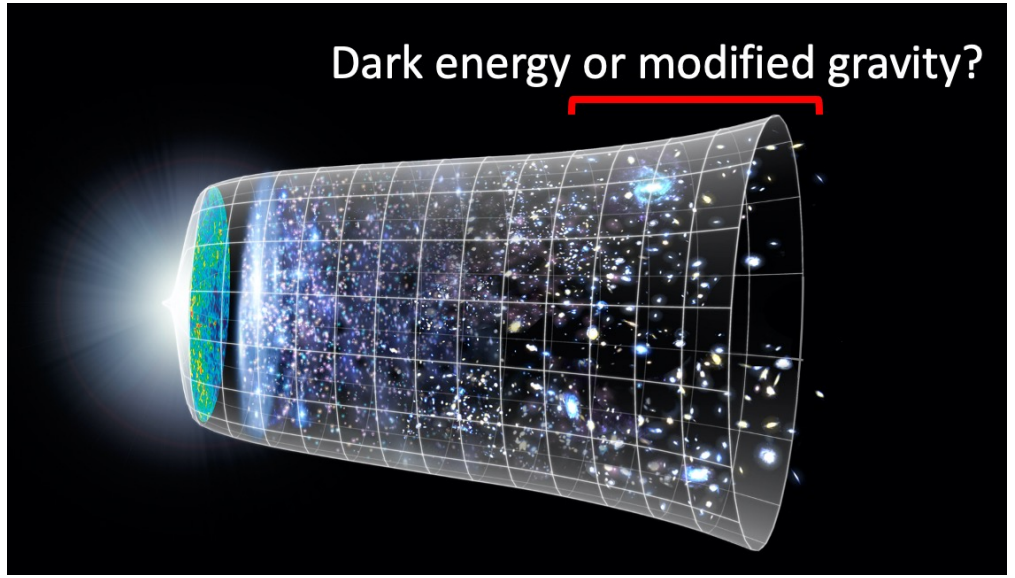
# The Dark Energy Survey

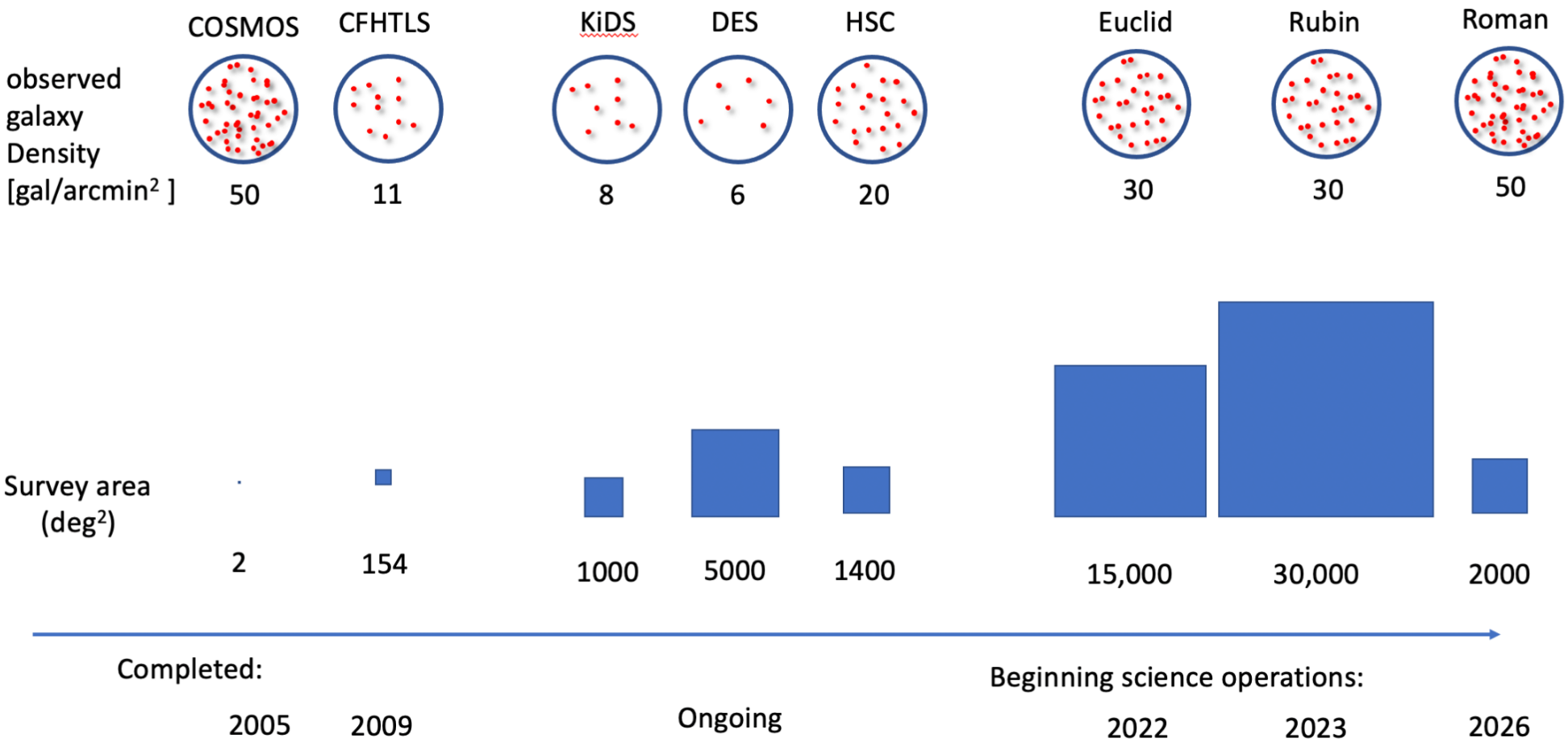



- **DECam** at CTIO Blanco-4m
  74 CCDs, 2.2° field of view, 570 Mpixels
- **10%** of the sky between 2013 and 2019
  optical/near infrared (grizY bands)
- 690 millions astronomical objects detected

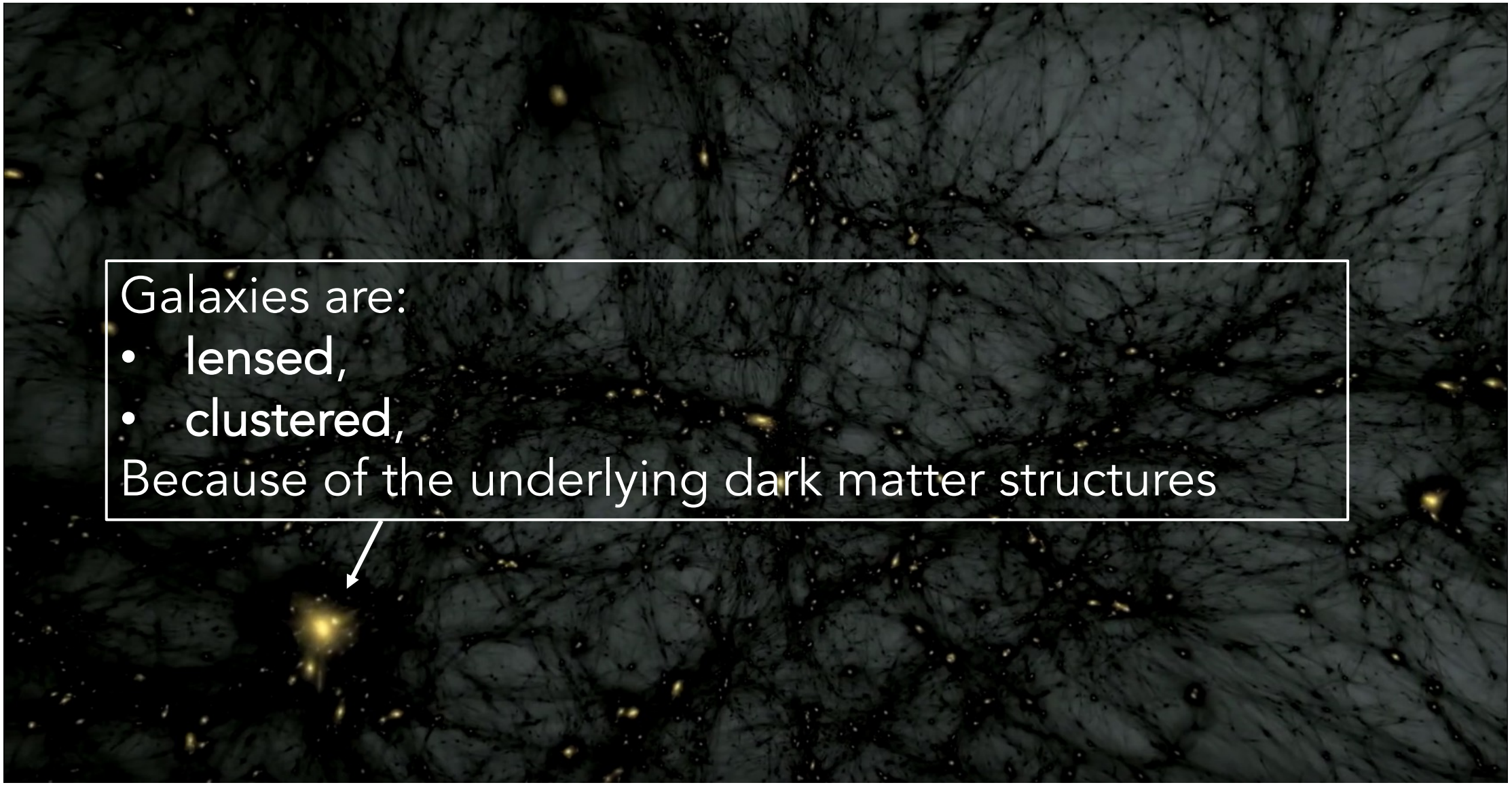


# In context

*Slide by E. Huff*

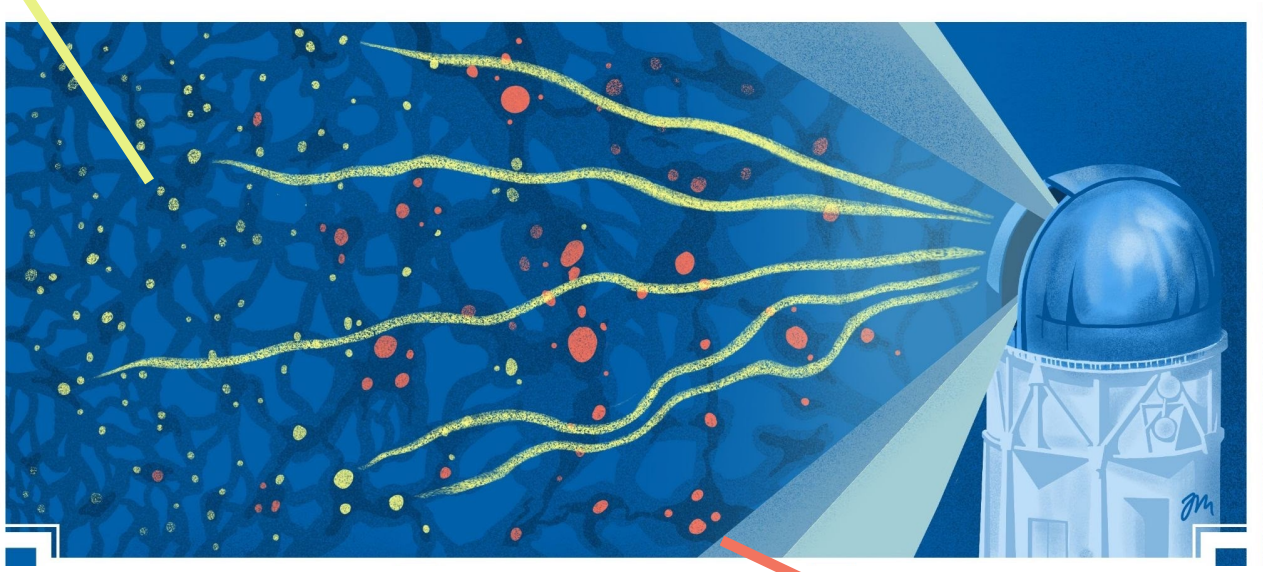


# Galaxies are the visible tip of the dark structures in the Universe



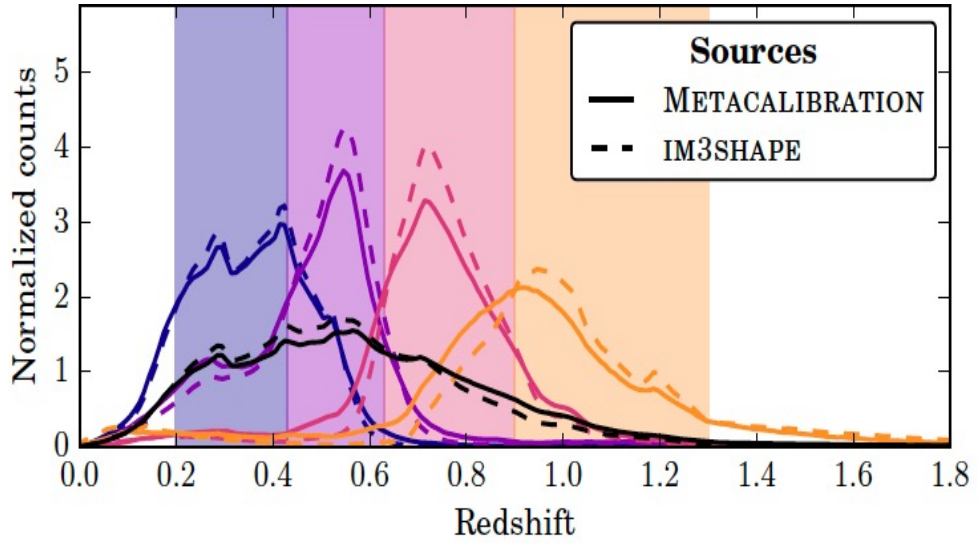
# Weak gravitational lensing and clustering

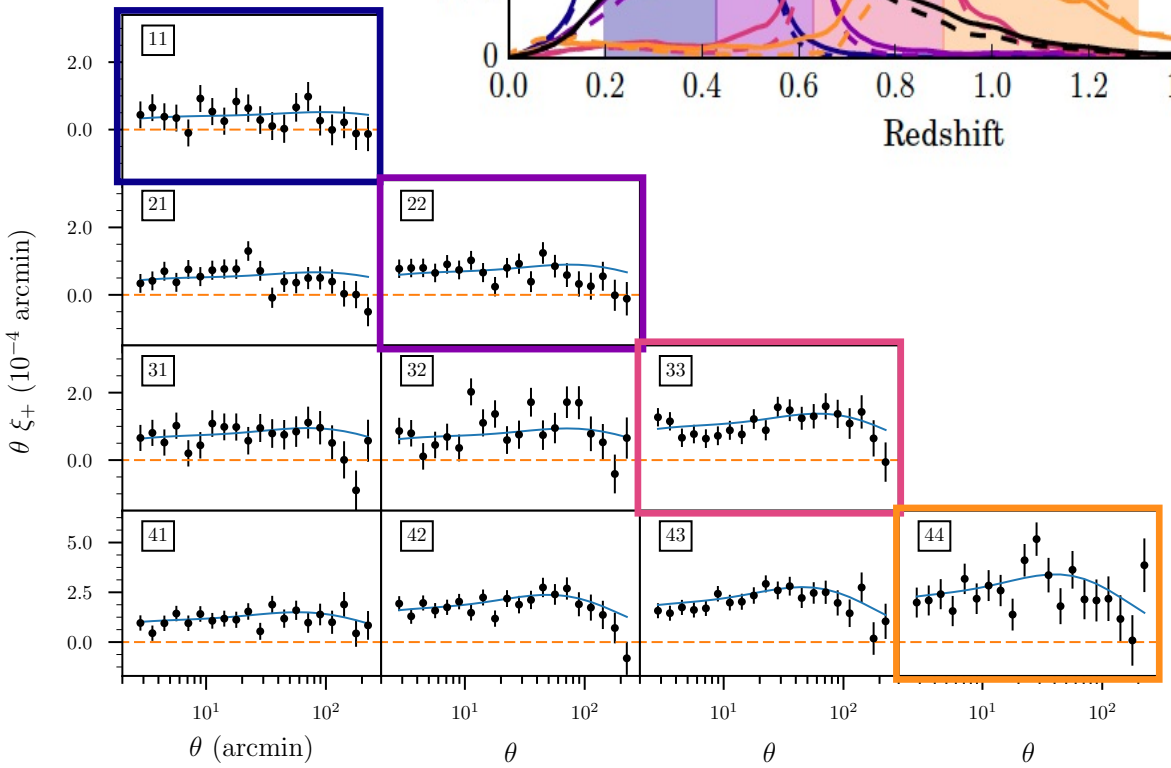
Source galaxies:
Measure shapes and redshift



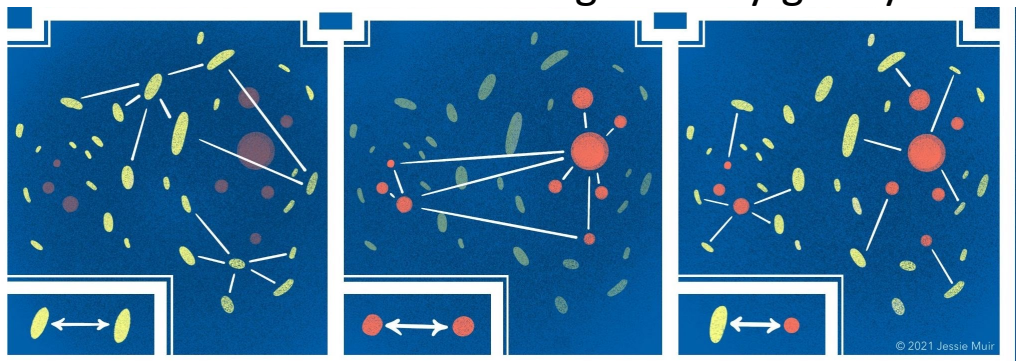
Lens galaxies:
Measure position and redshift

# Weak lensing and clustering 2-point correlation functions = 3x2pt




Cosmic shear | Clustering | Galaxy-galaxy lensing



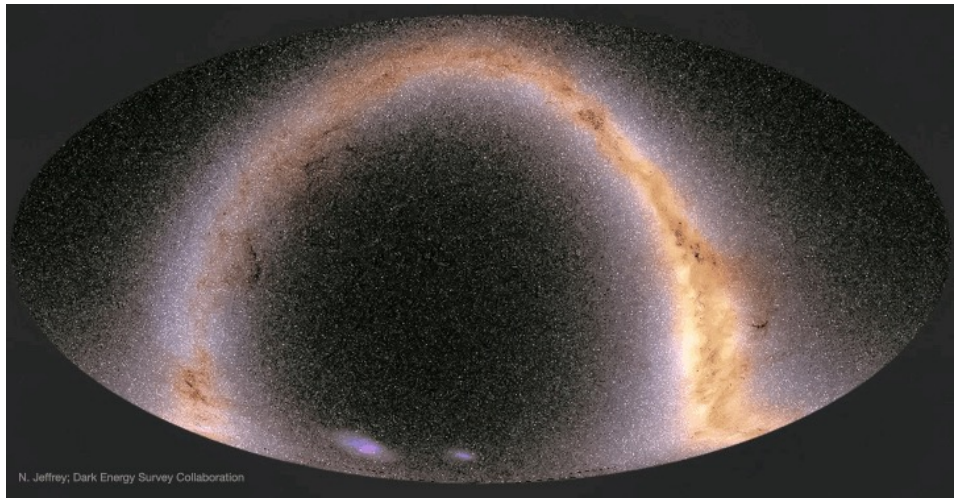

$\xi_{mm}(\theta)$ $b^2\xi_{mm}(\theta)$ $b\xi_{mm}(\theta)$

3x2pt constrains $S_8$:

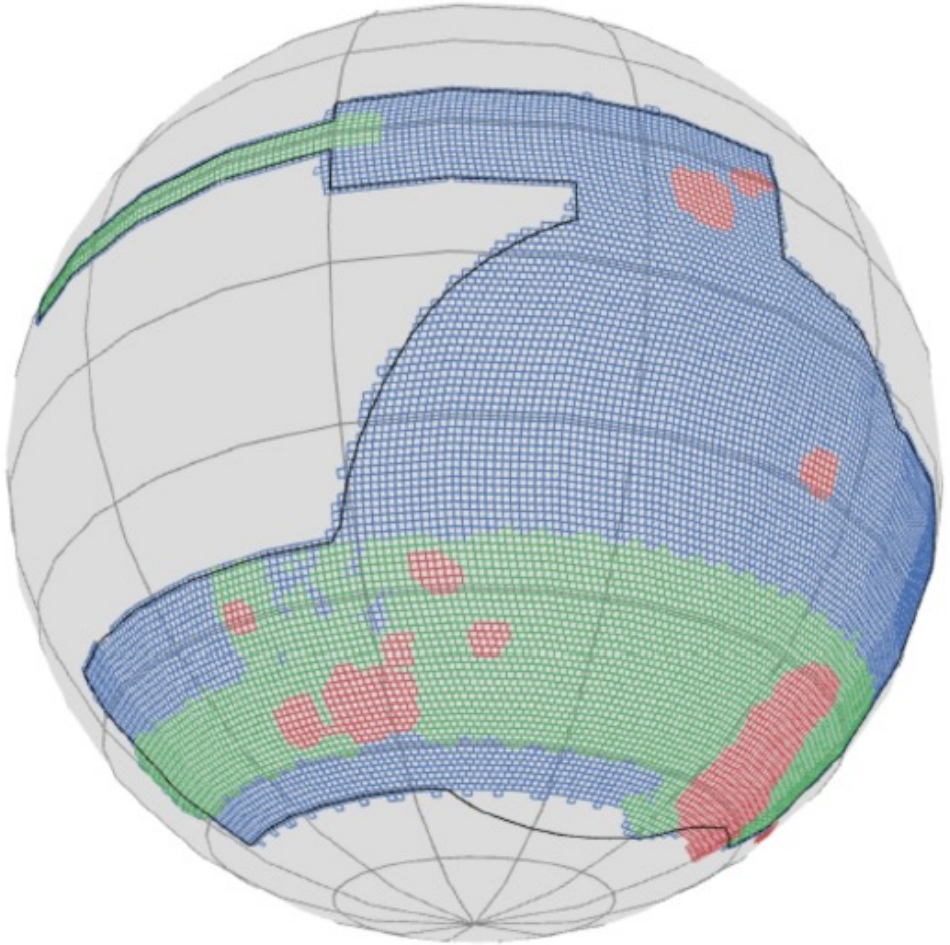
$$S_8 = \sigma_8(\Omega_m/0.3)^{0.5}$$

# 3 years of observations

- 2013-2016
- 5000 sq. deg., 50% depth
- Weak lensing:
  100 millions galaxies and $n_{eff}$ = 5.59 gal/arcmin$^2$



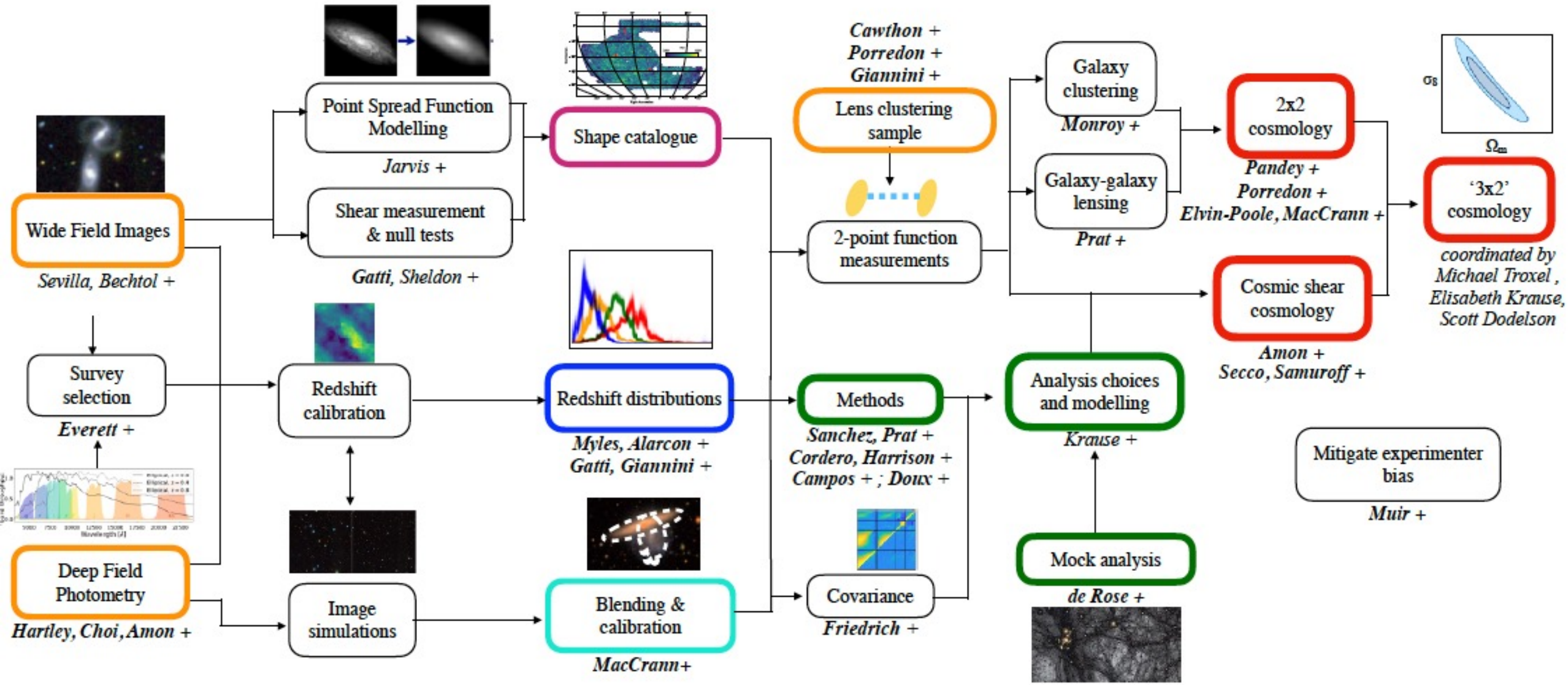

*From Jeffrey, Gatti, and the mass map team*



# 500+ pages of DES Y3 papers

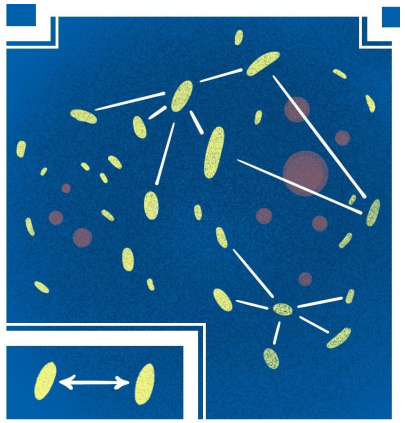
1."Blinding Multi-probe Cosmological Experiments" J. Muir, G. M. Bernstein, D. Huterer et al., arXiv: 1911.05929, MNRAS **494** (2020) 4454
2."Photometric Data Set for Cosmology", I. Sevilla-Noarbe, K. Bechtol, M. Carrasco Kind et al., arXiv:2011.03407, ApJS **254** (2021) 24
3."Weak Lensing Shape Catalogue", 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. Ferté, 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 pixel to cosmology

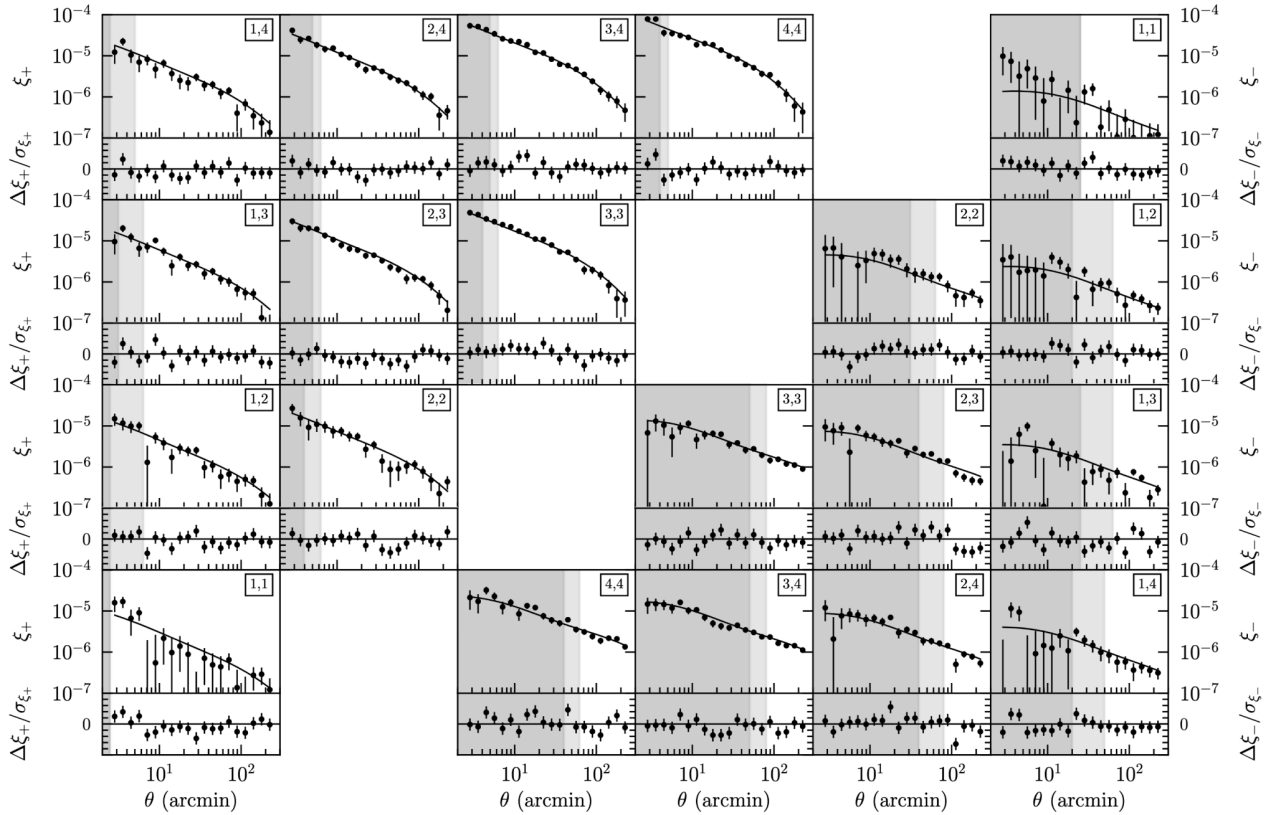



*Flowchart by Alex Amon*

# Data vector



## Cosmic shear

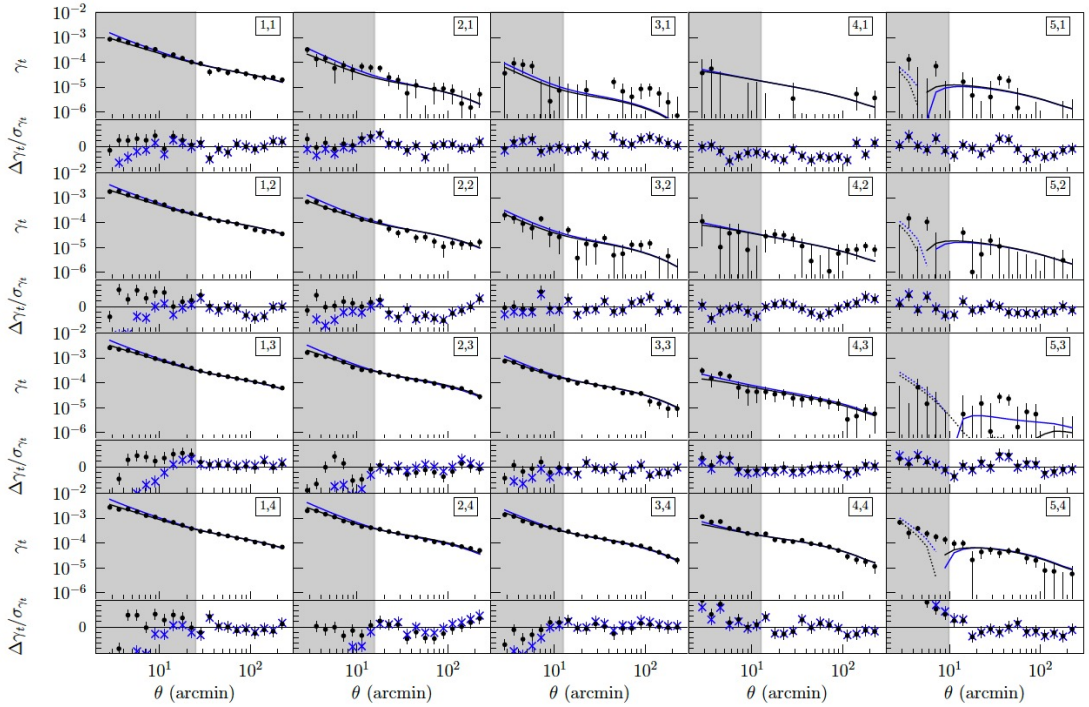


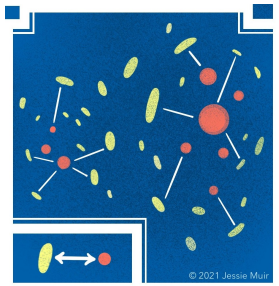

+ shear ratio = ratio of galaxy-galaxy lensing at small scales

*Sanchez, Prat et al, 2021*

# REDMAGIC

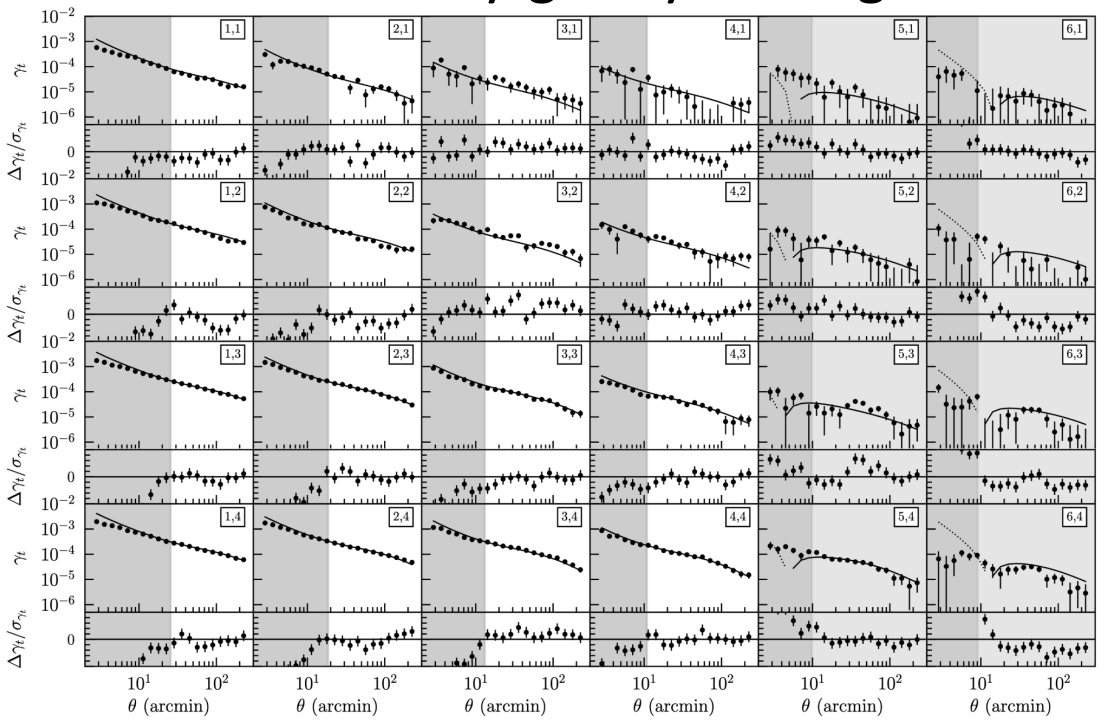
## Galaxy-galaxy lensing



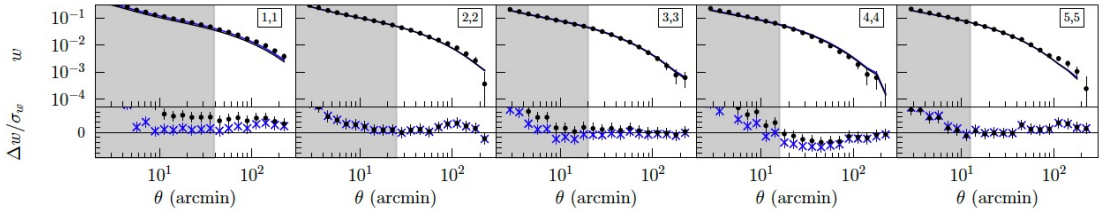



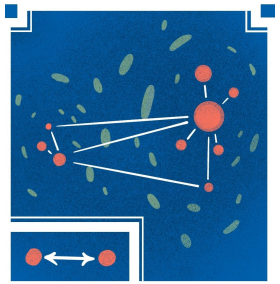

# MAGLIM

## Galaxy-galaxy lensing

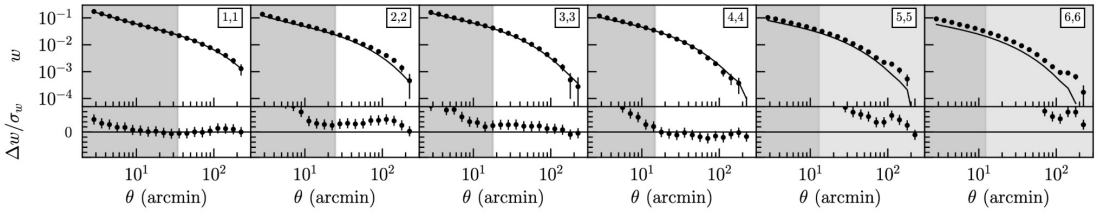



## Clustering



## Clustering

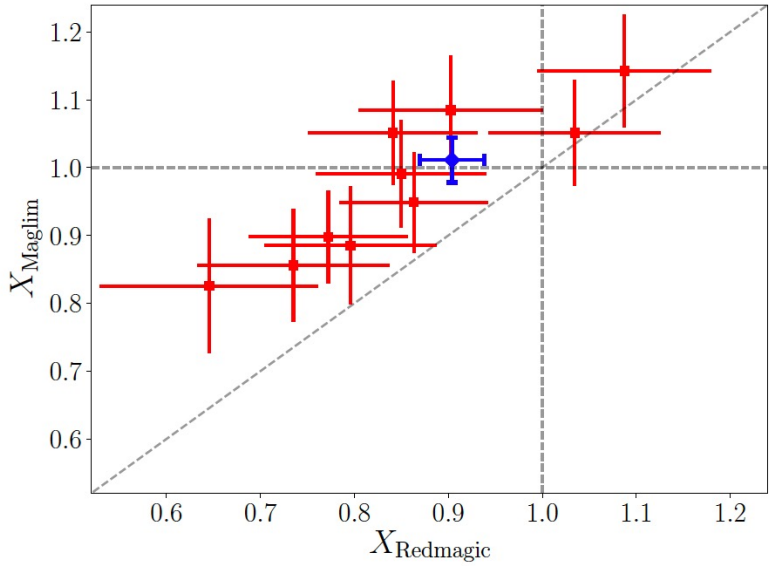


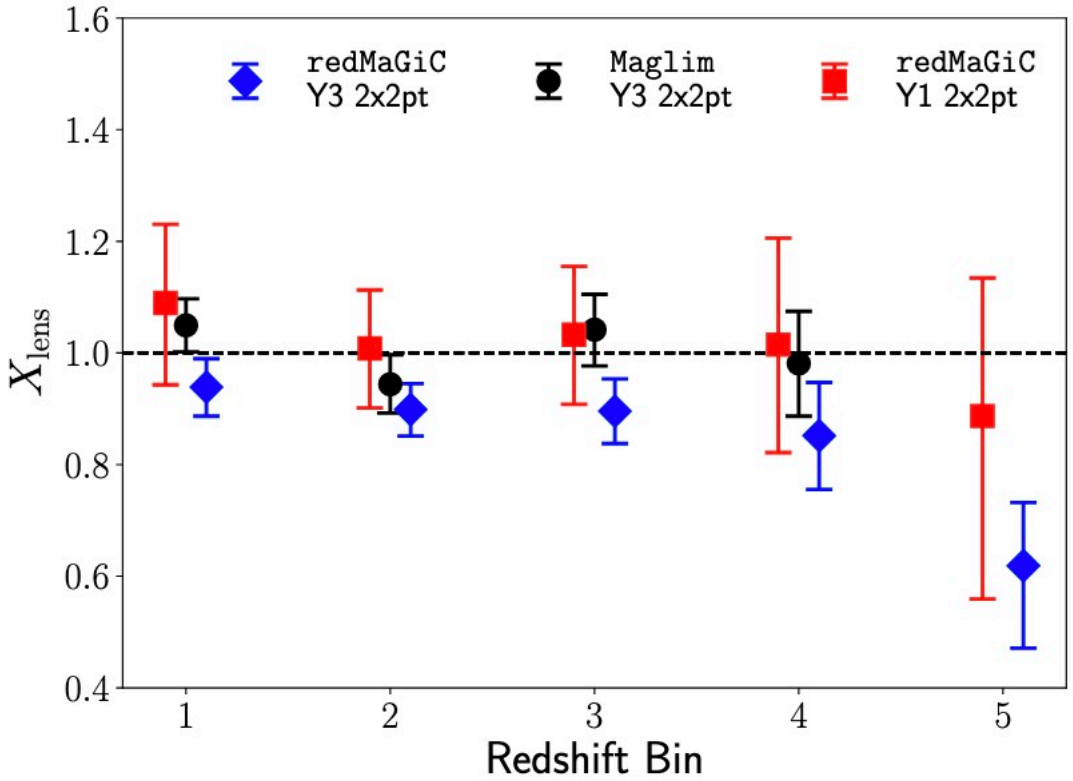
# In redmagic sample: $X_{lens}$

Galaxy-galaxy lensing inconsistent with galaxy clustering caused by unknown systematics, modeled with $X_{lens}$ :

$$w^{ii}(\theta) = b_i^2 \xi_{\rm mm}^{ii}(\theta)$$
$$\gamma_t^{ij}(\theta) = X_{\rm lens} b_i \xi_{\rm mm}^{ij}(\theta)$$

*Pandey et al, 2021*



# DES Y3 likelihood

For 3x2pt data vector D and parameters p:

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

Sampling/MCMC
*Lemos, Weaverdyck et al, in prep*

Model of the data vector
*Krause et al, 2021*

Covariance matrix
*Friedrich et al, 2021*

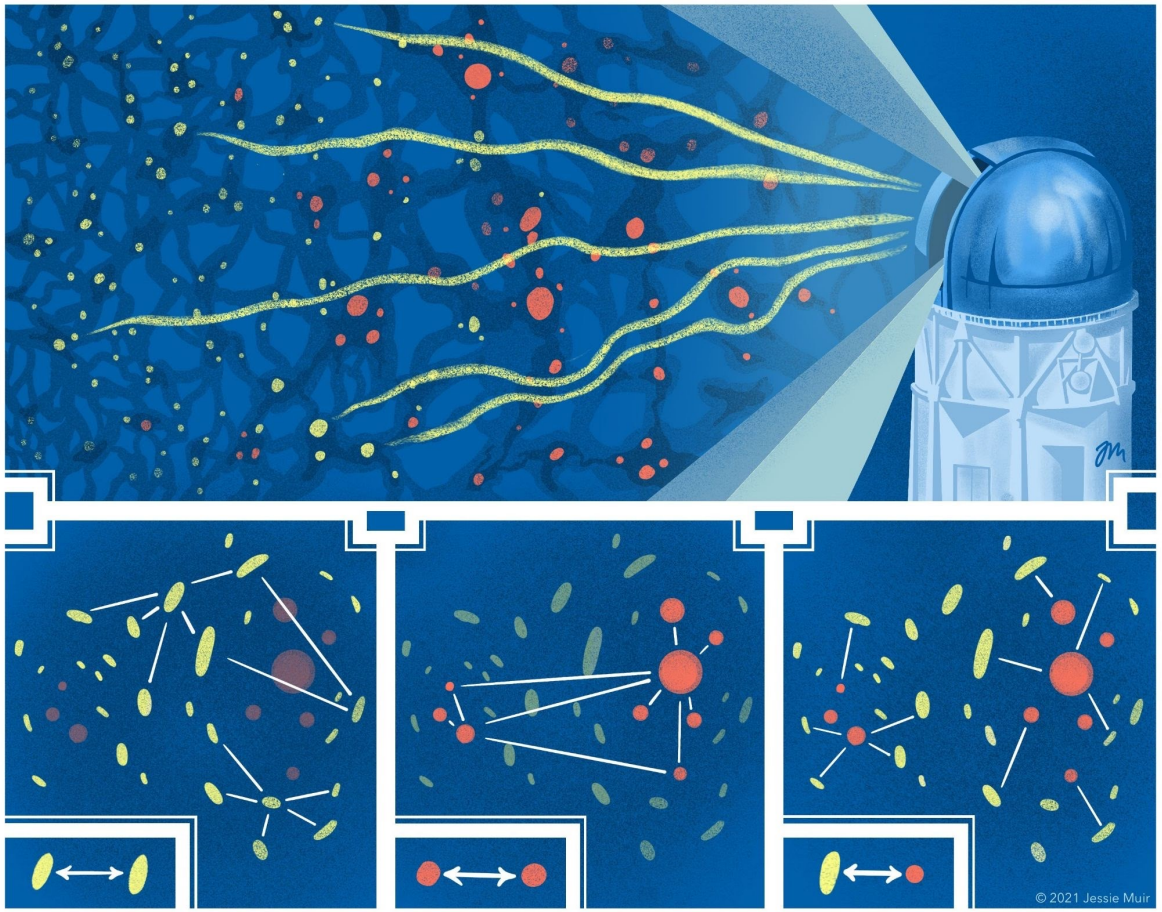
- **Blinding** procedure to avoid confirmation bias
  *Muir et al, 2020*
- **Tensions metrics**: internal consistency with PPD and external tension with suspiciousness and parameter difference
  *Doux et al, 2020, Lemos, Raveri et al, 2021*

# Modeling weak lensing and clustering

## Intrinsic alignment

Modeling the correlation of the alignment of galaxies due to their gravitational environment

TATT model: tidal alignment, torque and z-dependence
⇒ 5 parameters




## Matter power spectrum

Modeling the underlying total matter distribution

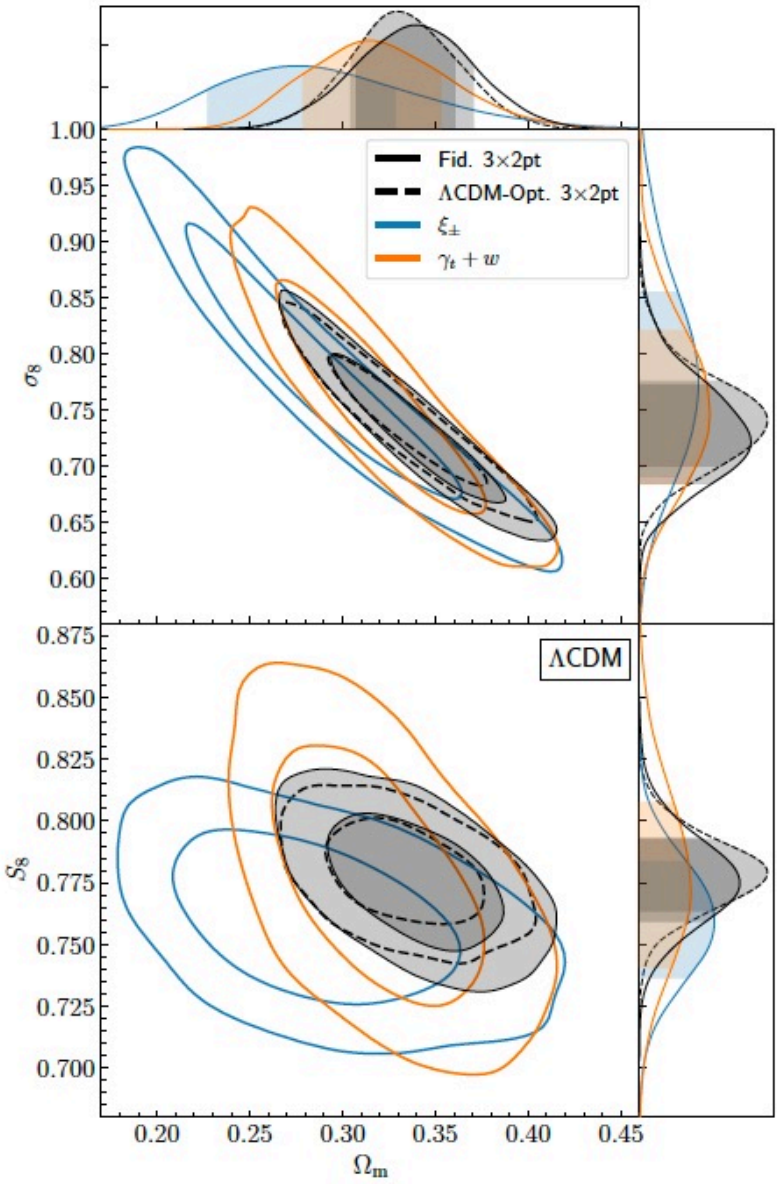
Halofit

## Galaxy bias

Modeling how galaxies trace the underlying matter distribution

Linear galaxy bias model
⇒ 4 parameters

# DES Y3 weak lensing and clustering cosmological results




Unblinding telecon 100+ participants

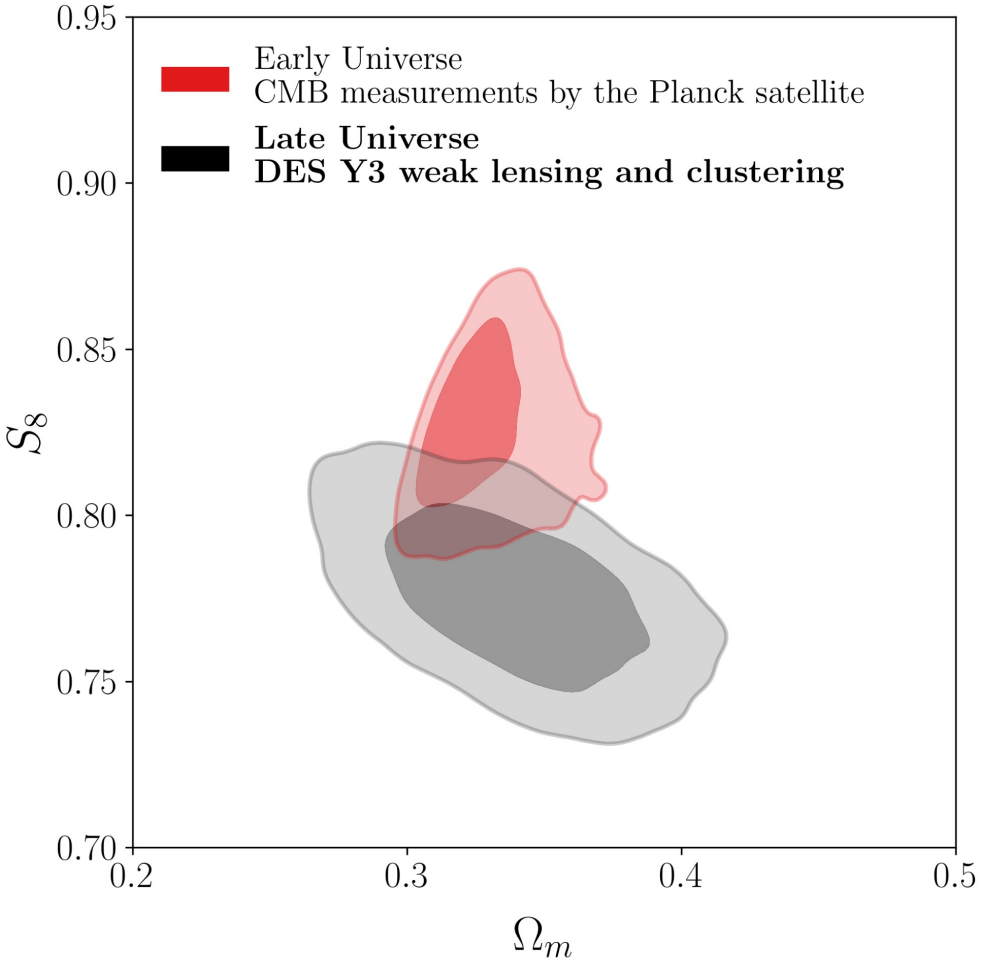
- Redmagic sample: November 3, 2020
- Maglim sample: March 15, 2021

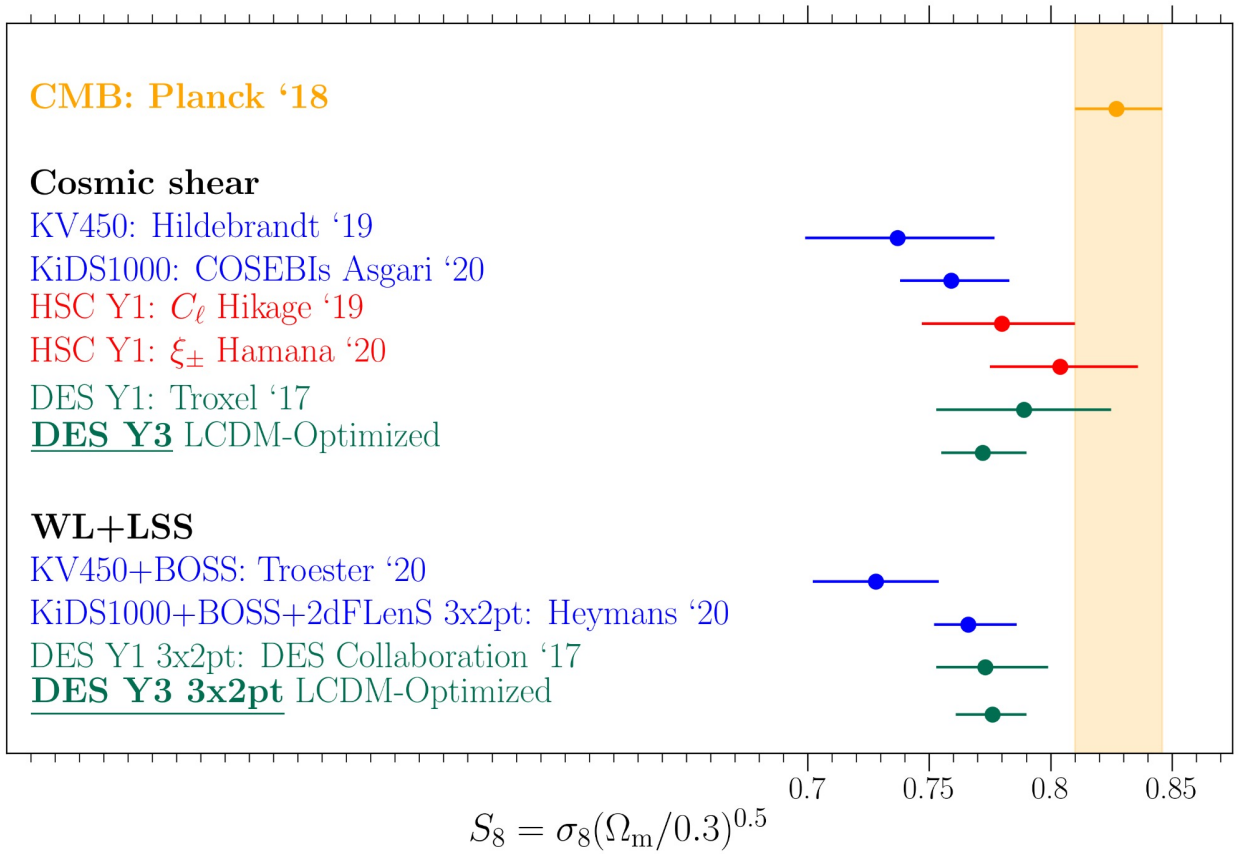
Constraints combining DES Y3 cosmic shear, galaxy-galaxy lensing and clustering measurements:

- **Most powerful** constraints from 3x2pt of same survey
- **x2** more constraining than Y1
- No evidence for deviations from w = -1

*DES collaboration 2021*

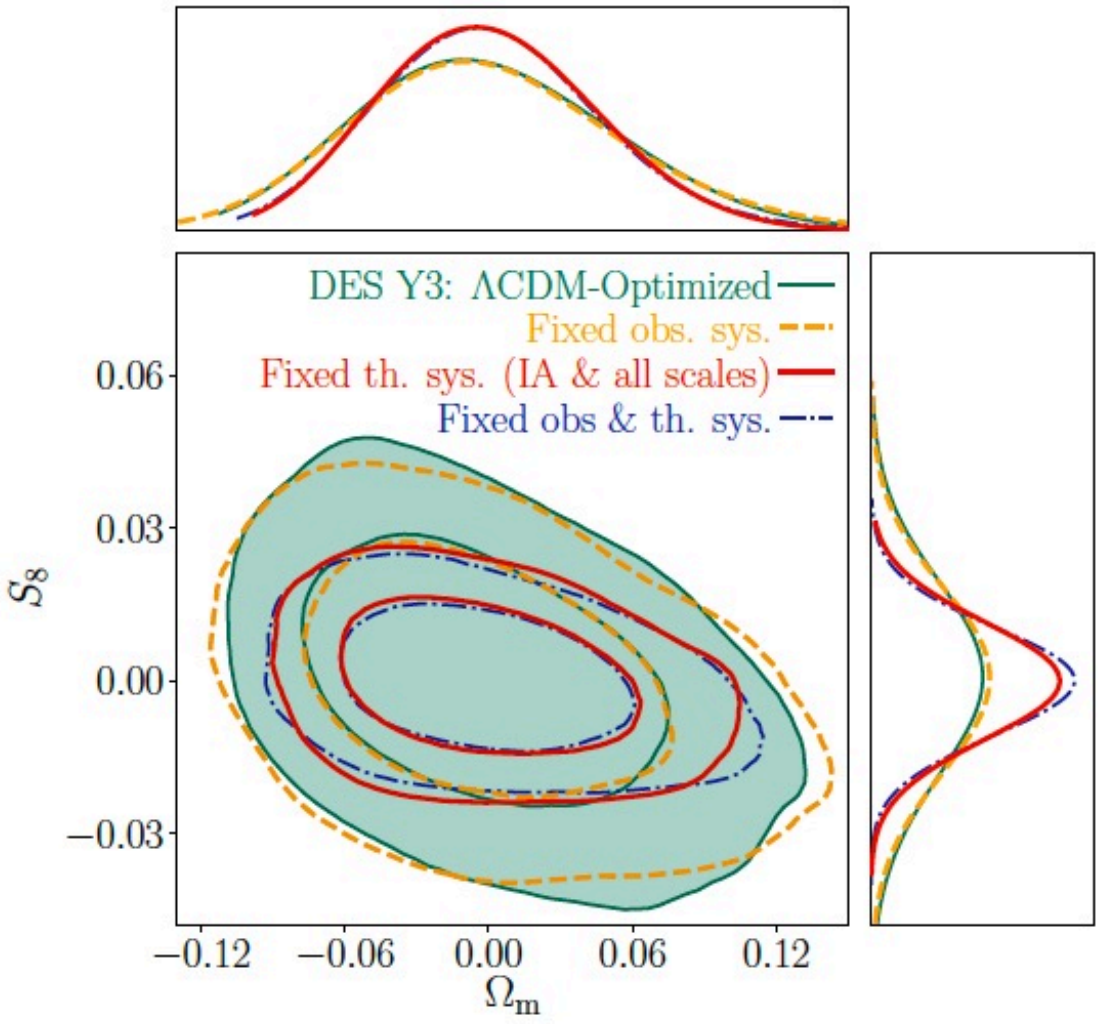
# Comparison with CMB measurements



# Lessons learnt

- **Robust** analysis and results
- Not immune to **unknown systematics**
- Important **developments** on modeling, calibration, simulations
  ➔ Limitations are ‘theoretical systematics’
  *Amon et al, 2021*
- **Transparency, communication, collaboration** have to be central

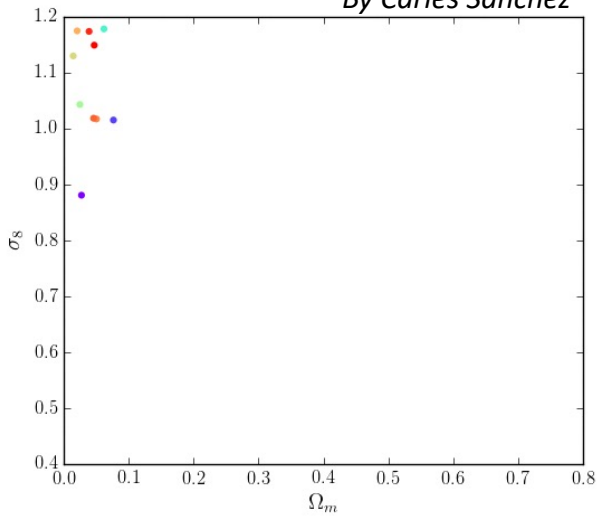


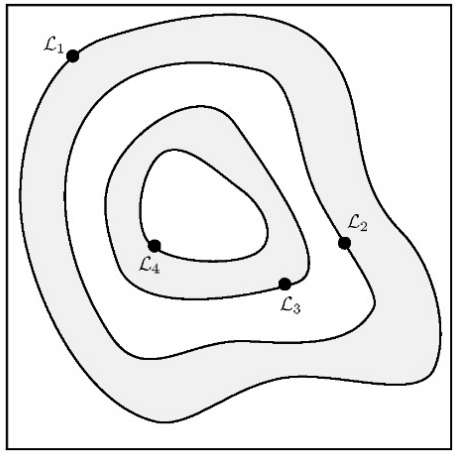
# Challenge for LSST Bayesian analysis I – accurate results from samplers

Samplers to estimate:

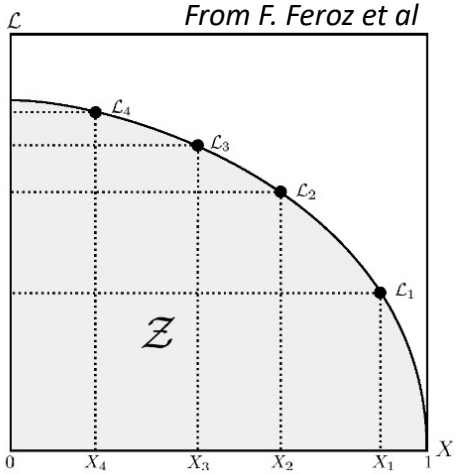
- Constraints on cosmological parameters
- Metrics to compare models or data

*By Carles Sánchez*




*From F. Feroz et al*



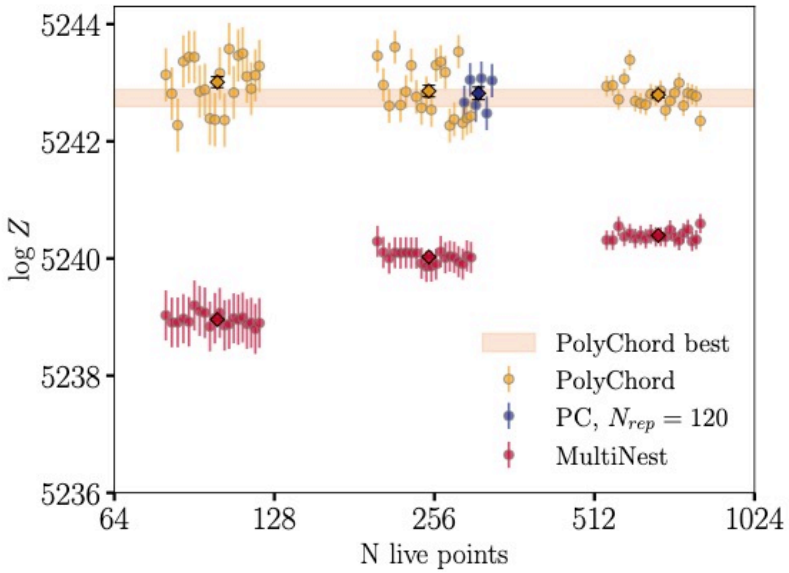

→ MCMC: Metropolis-Hastings

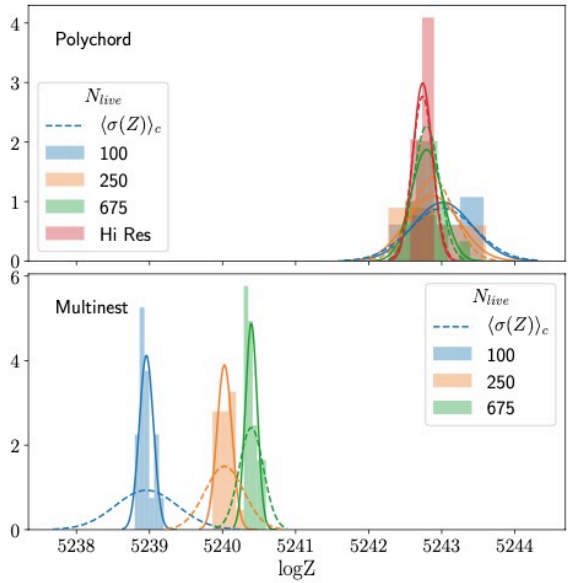
→ Nested sampling:

- Multinest: ellipsoidal
- Polychord: slice

# Comparison of samplers

Comparing samplers efficiency and accuracy to determine reliable samplers and settings for publication results -- *Lemos, Weaverdyck et al, in prep*




→ Multinest not reliable for Bayesian evidence computation and error estimates
→ Polychord recommended with specific settings, although time consuming
→ Approach can be used in LSST

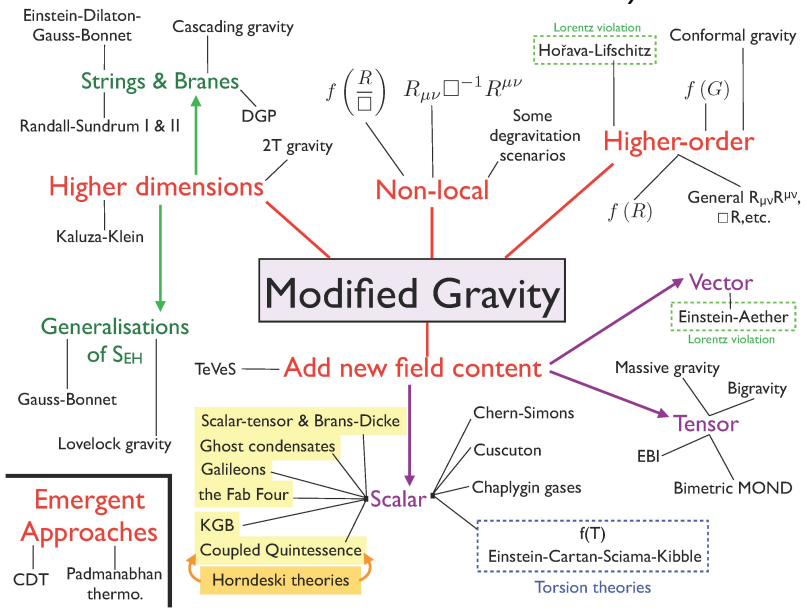
# Future of parameter estimation

- New samplers developed:
  - Zeus
  - Bayefast
  - Etc.
- Differentiable likelihoods
- Emulators – e.g. to bypass Boltzmann code computing time
- Likelihood free inference

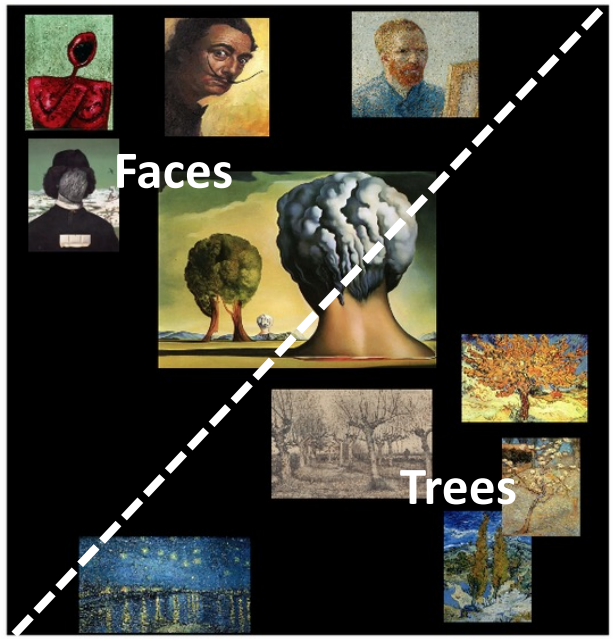
# Challenge for LSST Bayesian analysis II – large theory space

Self-Organization Maps represent **multidimensional** data in low dimension: closest neurons correspond to data that looks the most alike

*By T. Baker*

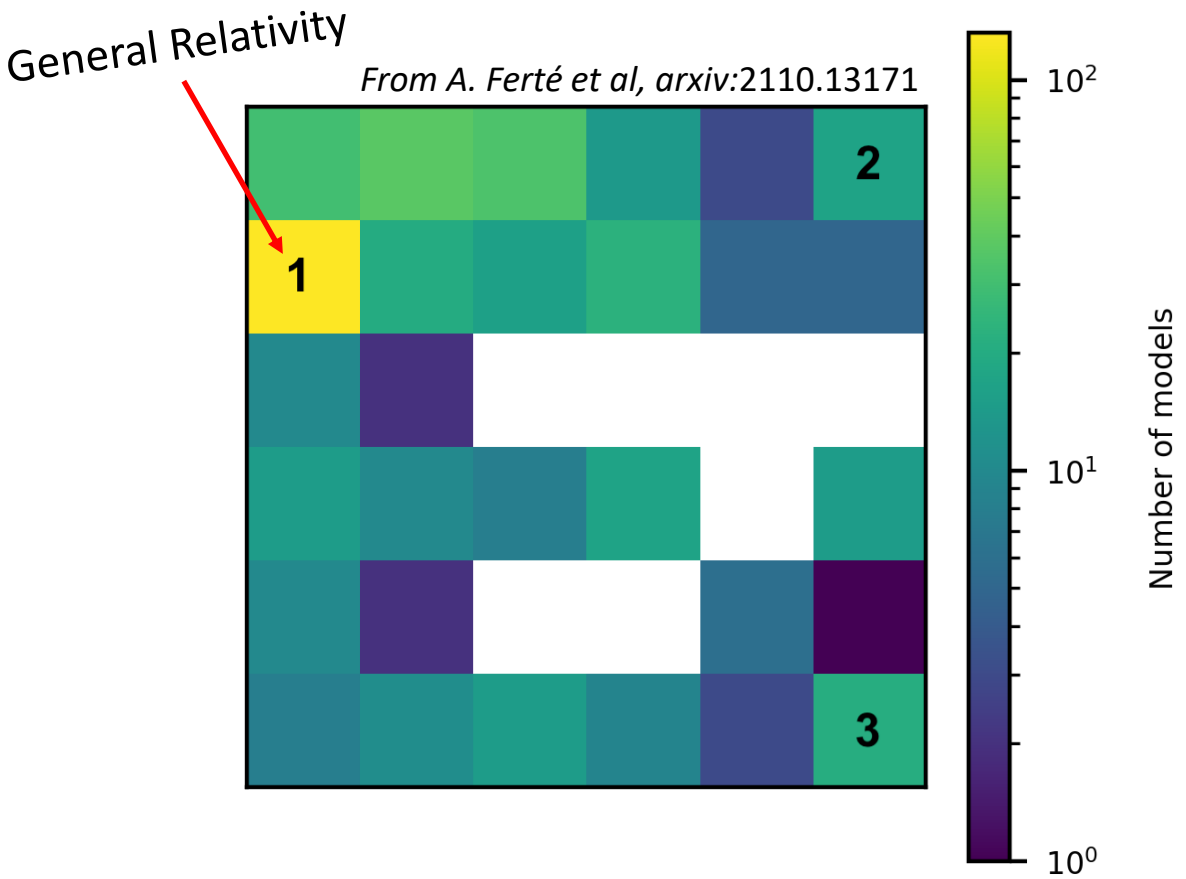


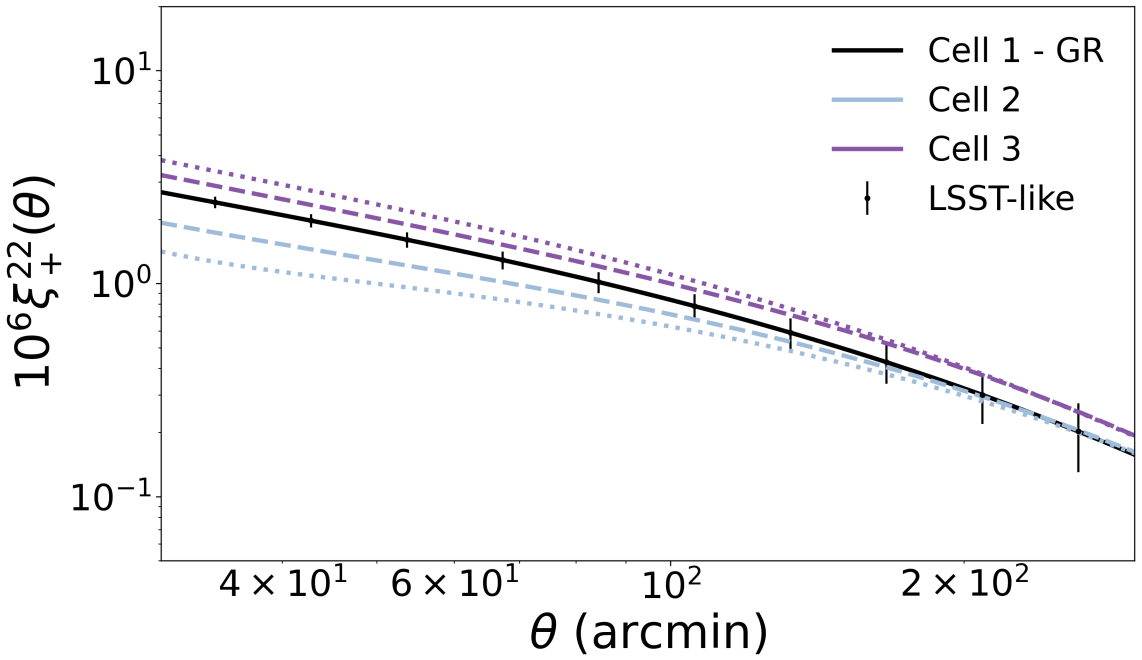

*Made by Shoubaneh Hemmati*




Expensive sampling in beyond-LCDM models
→Which direction in theory space should we explore?

# Map theory space using unsupervised learning




- Collaborators: Shoubaneh Hemmati, Daniel Masters, Brigitte Montminy, Peter Taylor, Jason Rhodes, Eric Huff
- **arxiv:2110.13171**

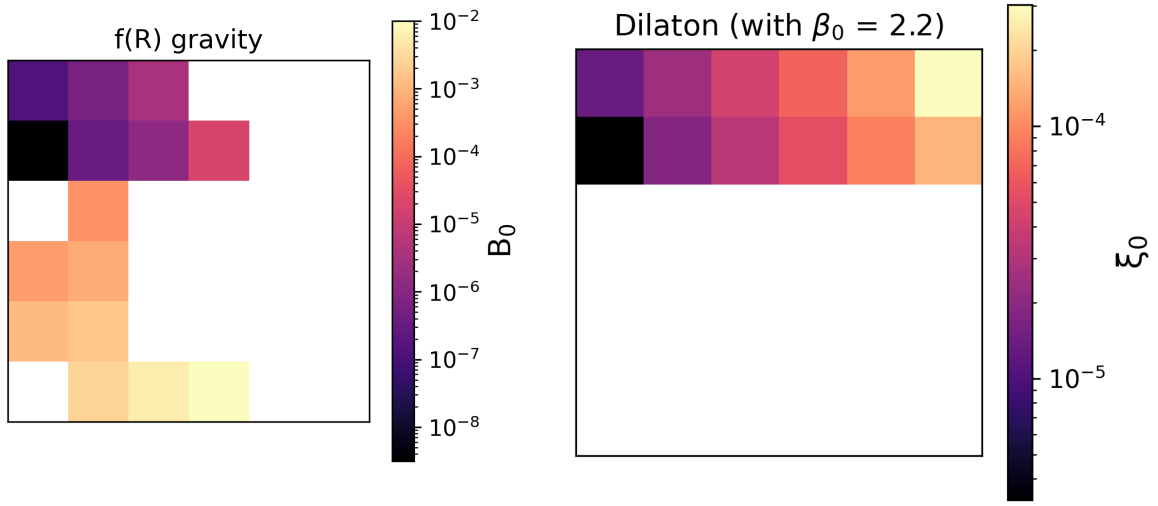
# Application to LSST-like 3x2pt measurements

Compute theoretical predictions of 3x2pt in beyond-LCDM models, based on arxiv:1905.09687

Compute LSST Y1 and Y10 covariance matrix

- Use of CCL and other LSST codes
- Vary corresponding parameters

TJPCov




→

- Train SOM
- Propagate error bars to SOM

→ Overlapping, distinguishable models

DESC project 217 (awaiting WG approval) - Beyond wCDM models distinguishable with LSST 3x2pt

# From DES to LSST

## DES

- Still work on Y3

  Constraints on models beyond ΛCDM
  - Dynamical dark energy, curvature, neutrinos, tests of gravity

    *DES collaboration, in prep*
  - Modified gravity constraints

    *Ferté et al, in prep*
- Beyond 2pt statistics
- Started effort for the full DES survey

## Preparing LSST cosmological analysis

- Samplers
- Exploring new directions with LSS and weak lensing data