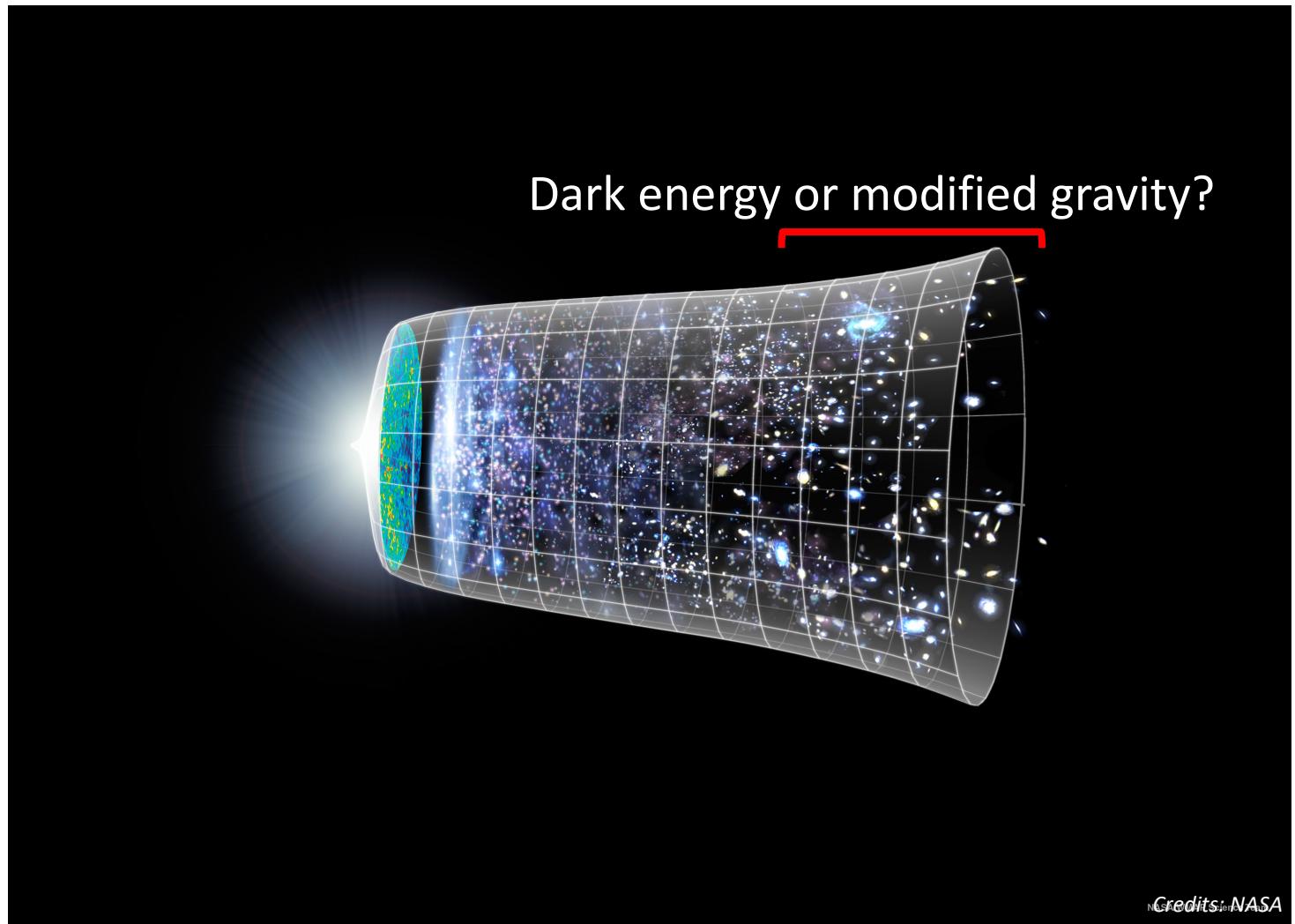
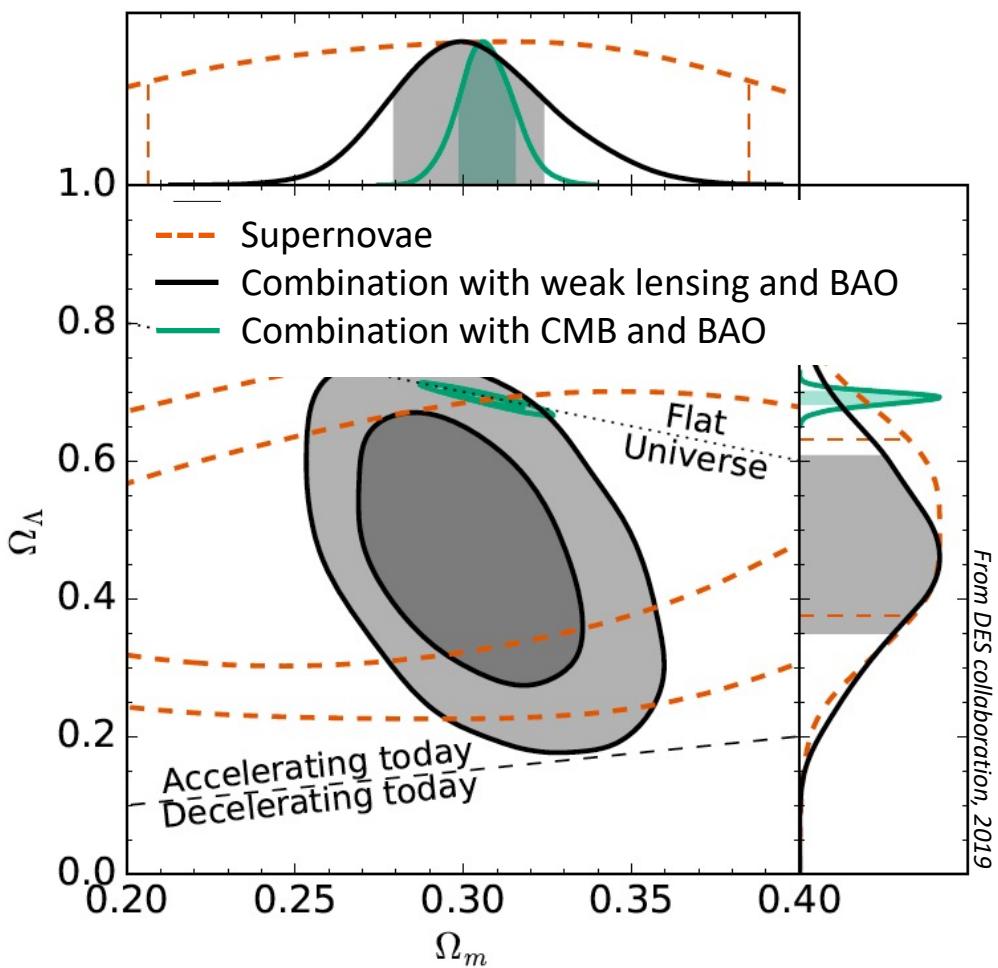


Dark Energy Survey Year 3 cosmology results



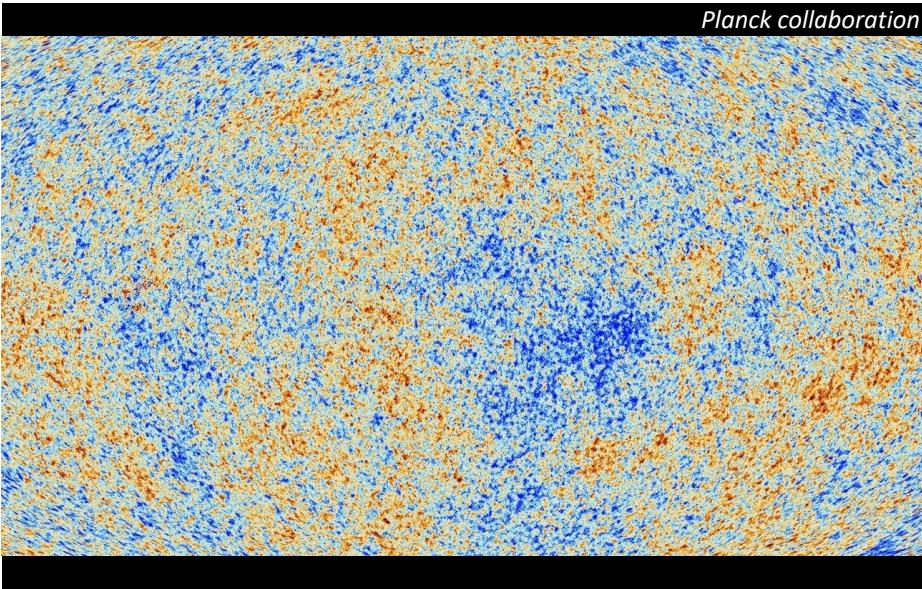
Agnès Ferté
On behalf of the DES collaboration

Λ CDM model: great fit but open questions



Probing the recent universe through growth of structures

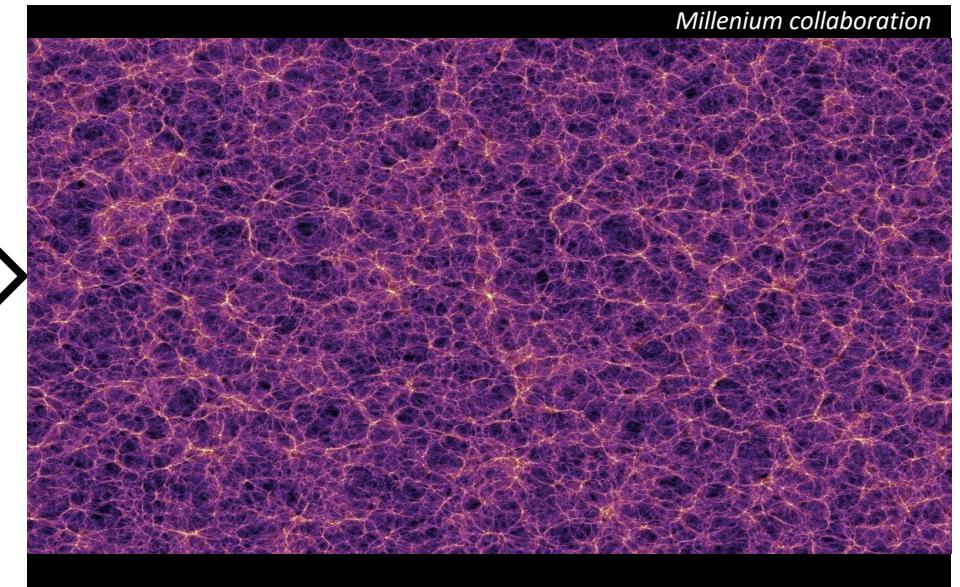
Cosmic Microwave Background



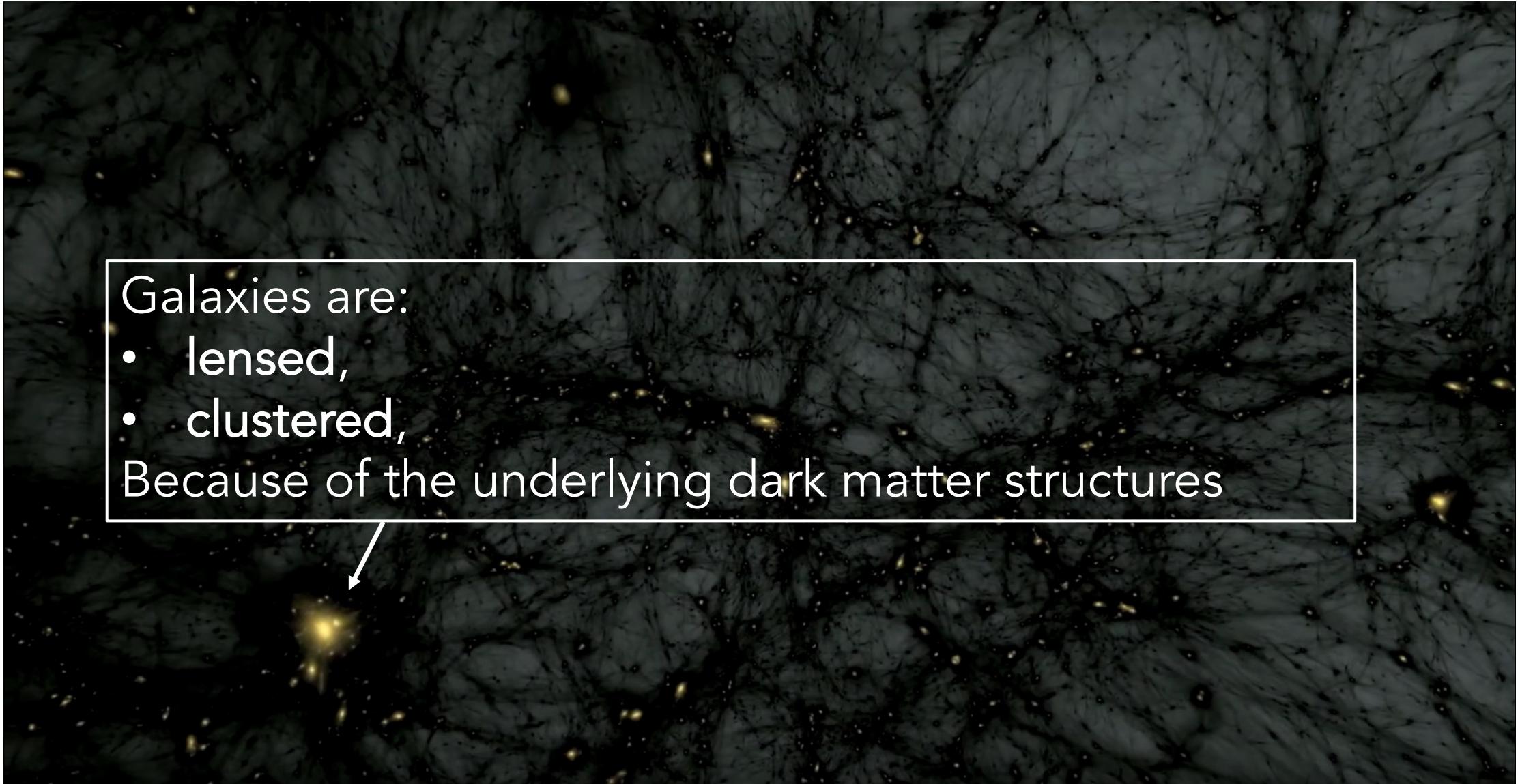
13 billions years



Large scale structures



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



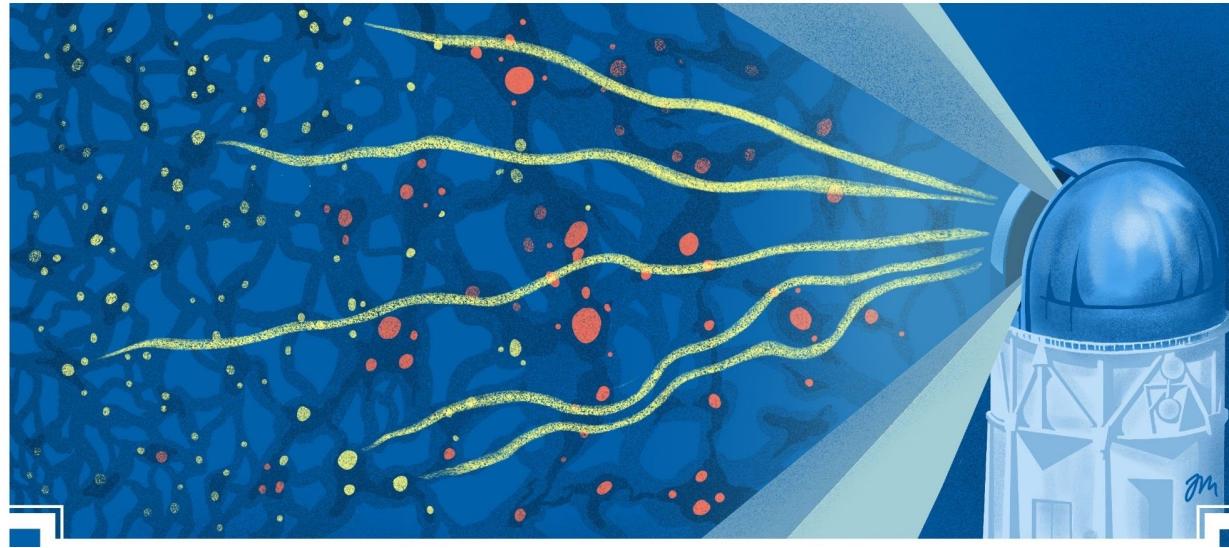
Galaxies are:

- lensed,
- clustered,

Because of the underlying dark matter structures



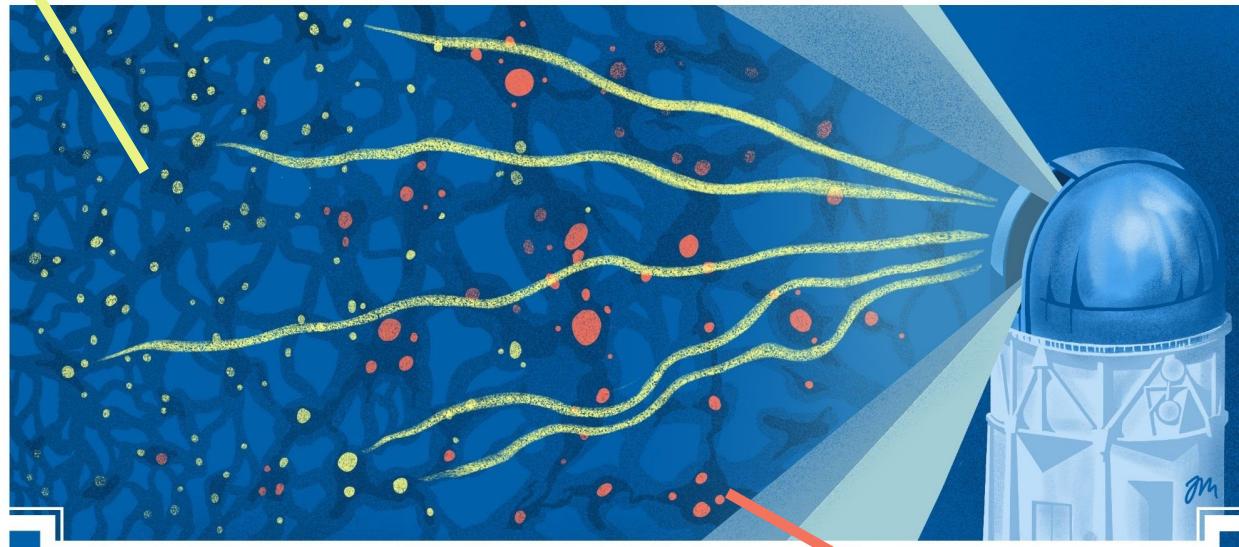
Weak gravitational lensing and clustering



Weak gravitational lensing and clustering

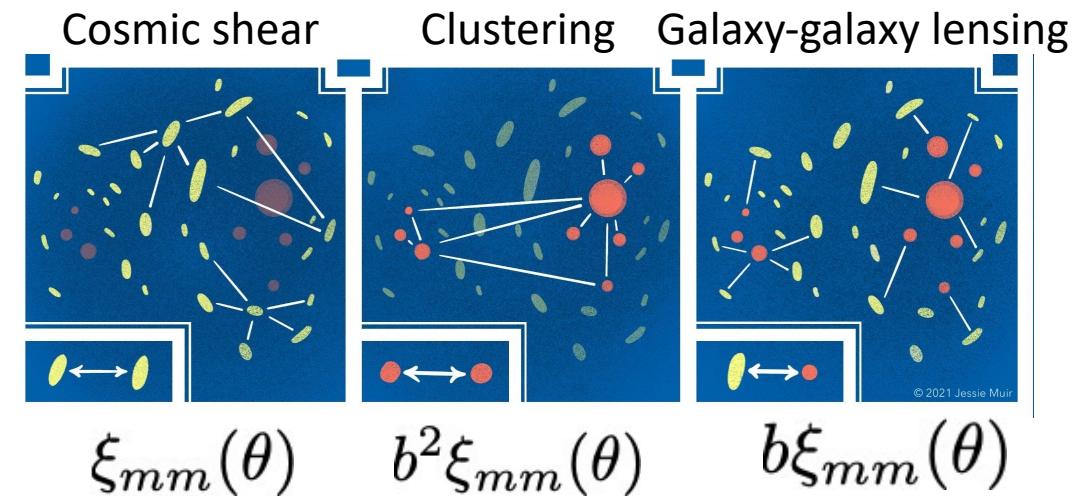
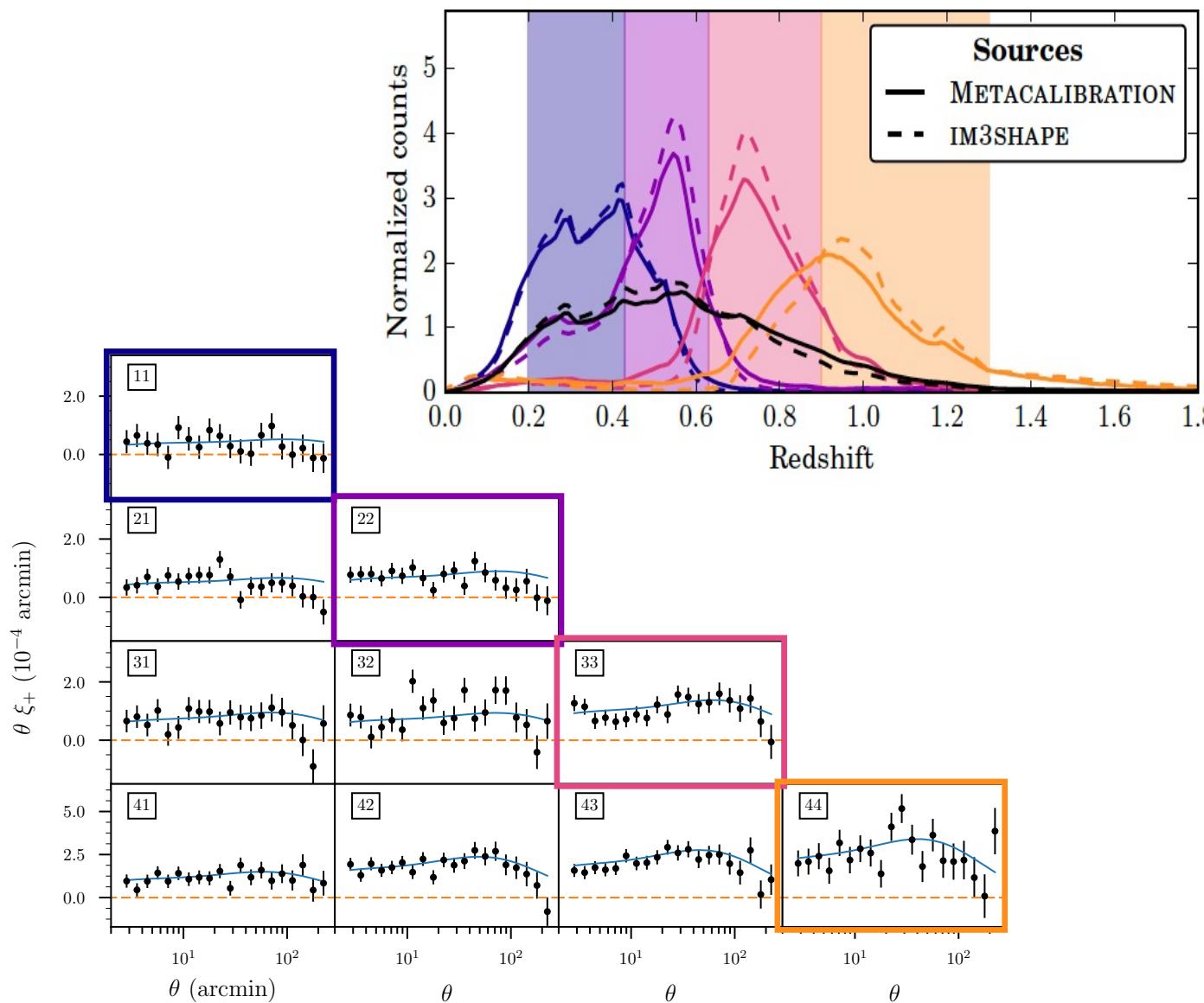
Source galaxies:

Measure shapes and redshift

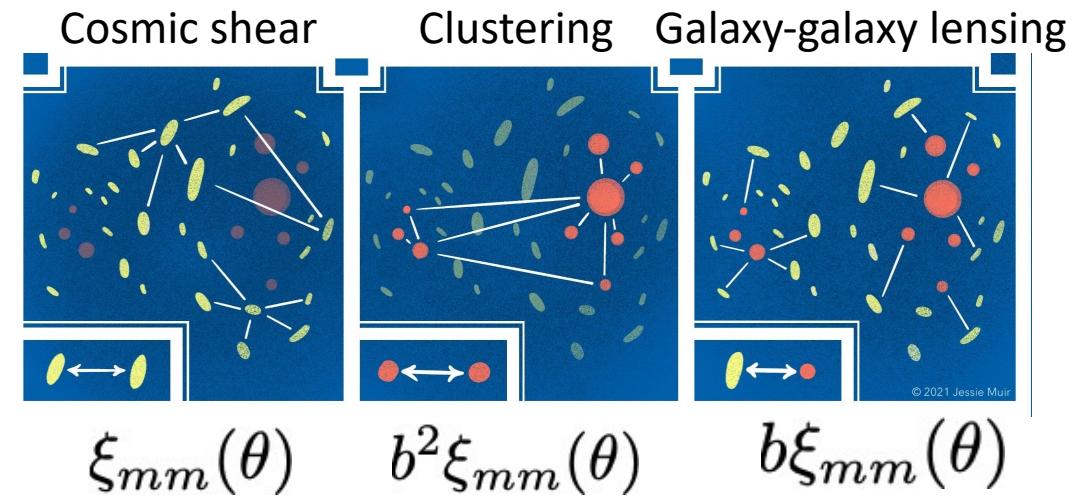
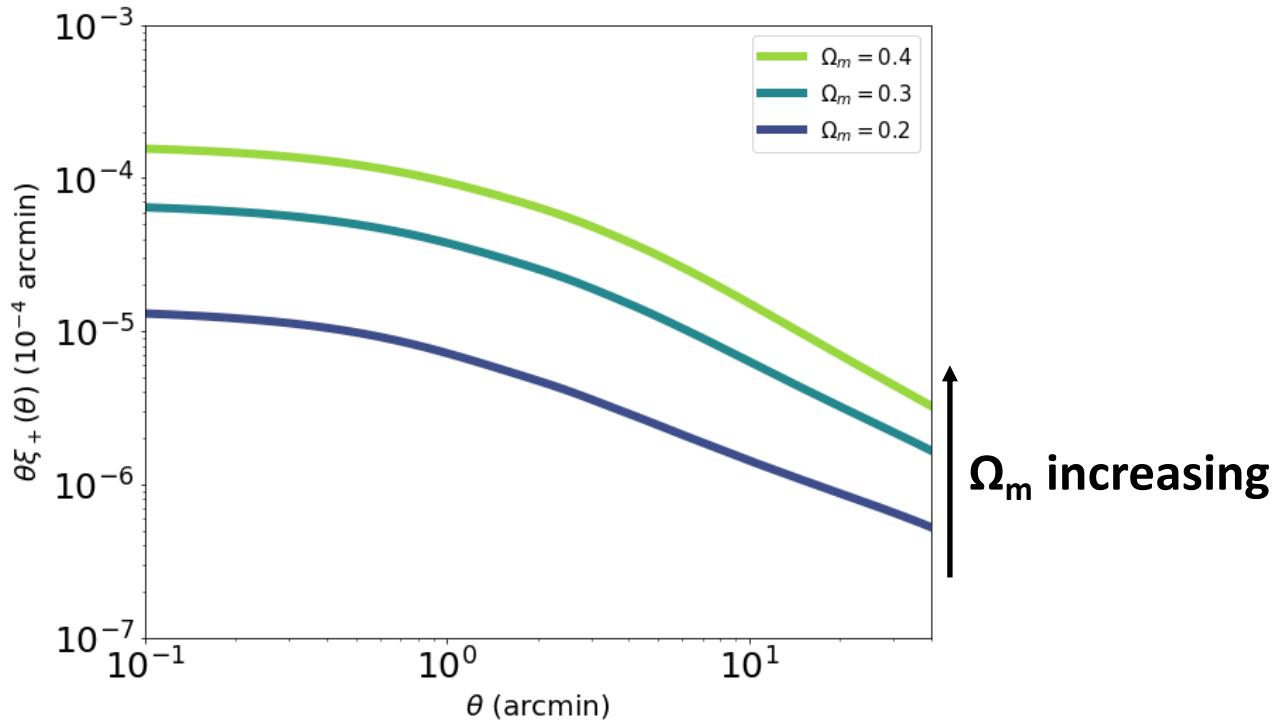


Lens galaxies:
Measure position and redshift

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



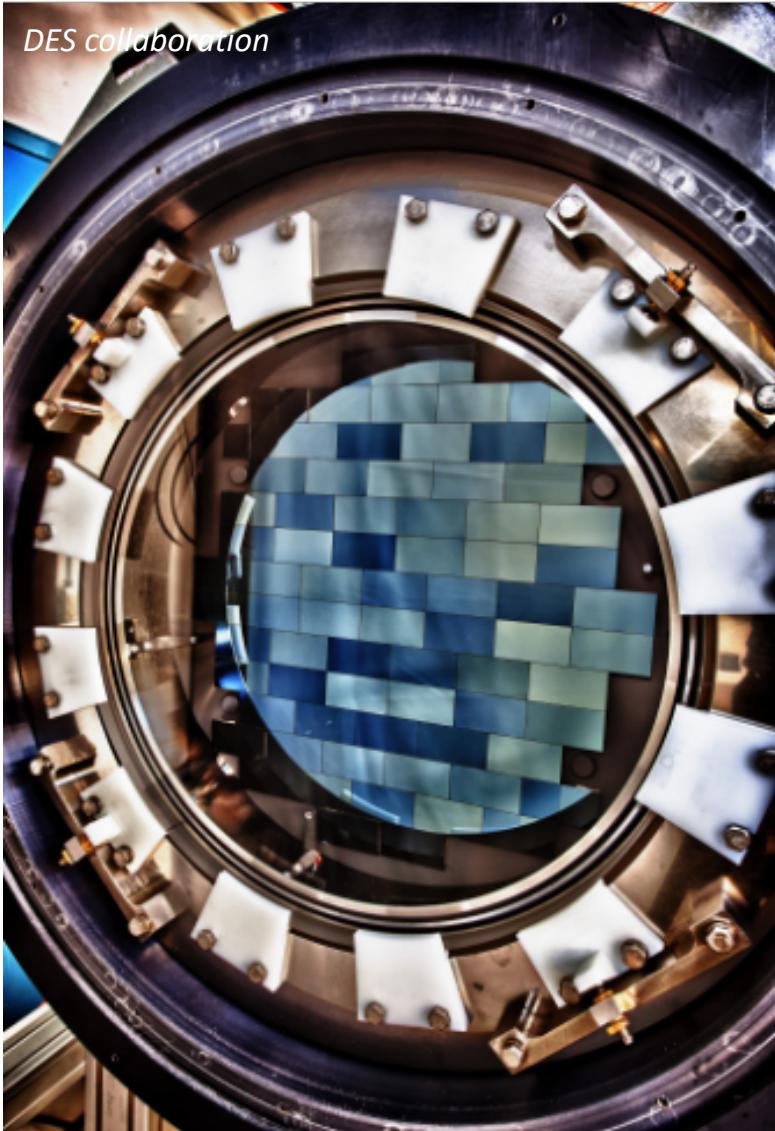
Cosmology in 3x2pt



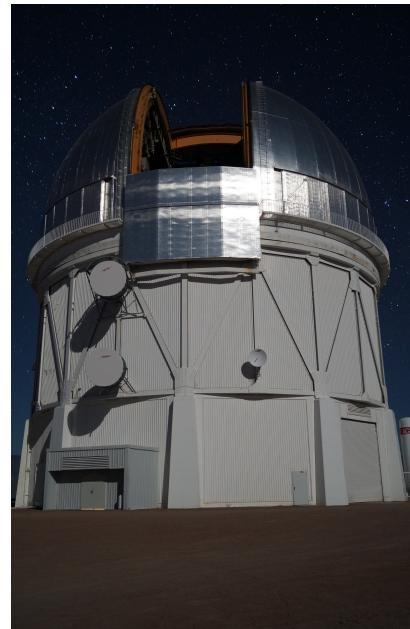
3x2pt constrains S_8 :

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

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



A collaborative effort

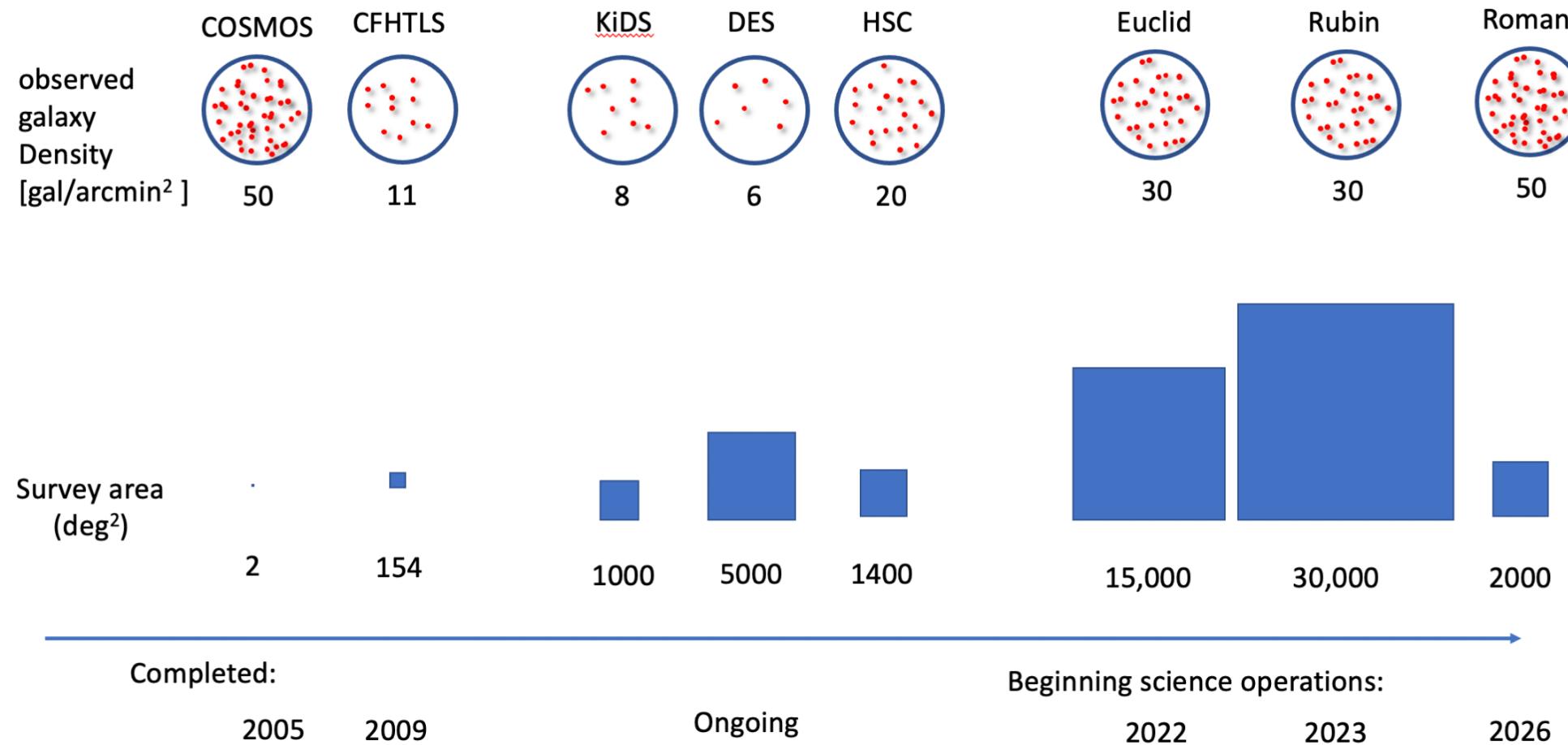


- International collaboration
700+ participants around the world
- Cosmological probes:
 - Geometry: supernovae, BAO
 - Growth: 3x2pt, galaxy clusters
- 3 cosmological analysis using weak lensing:
Year 1 **done** - Year 3 **done** - Year 6 **ongoing**



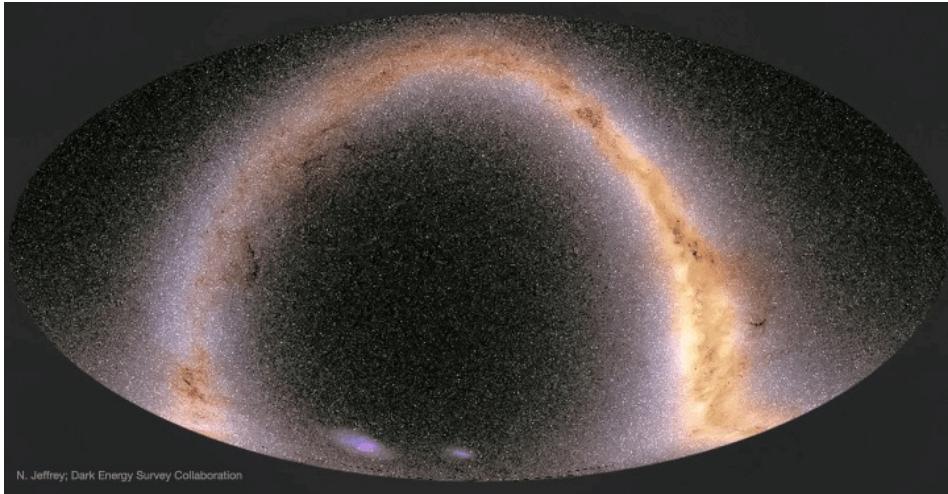
In context

Slide by E. Huff

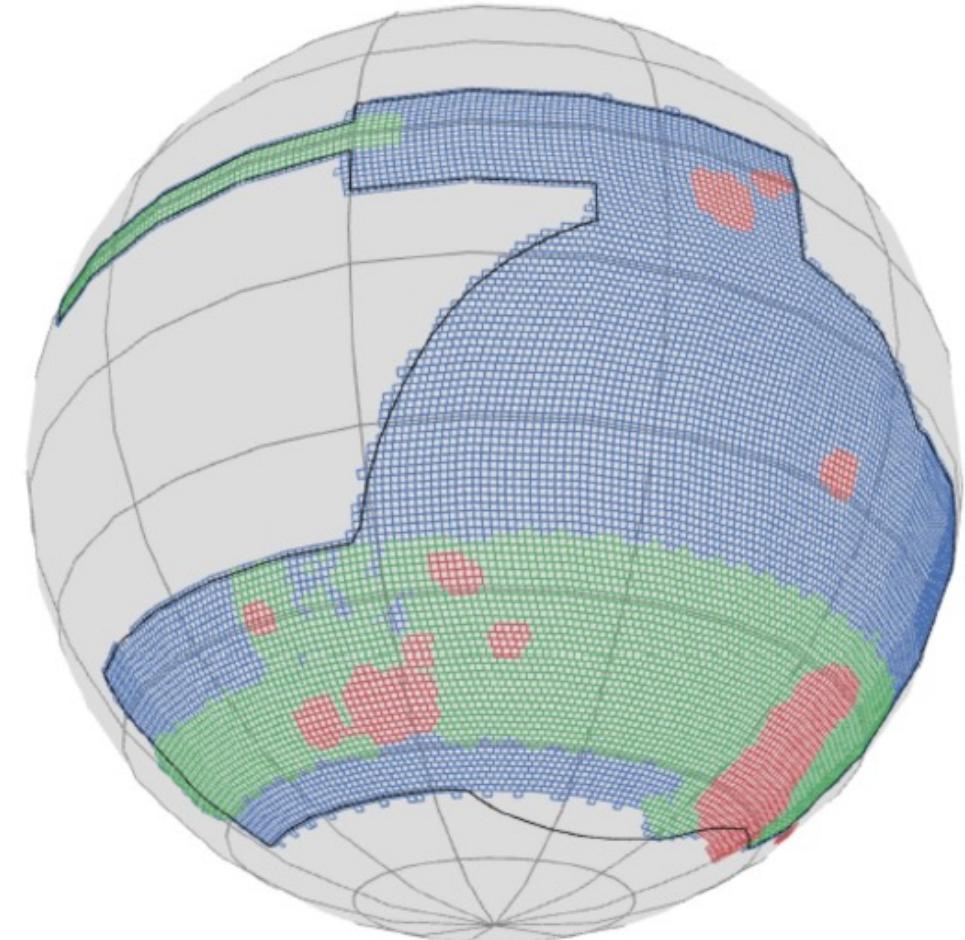


3 years of observations

- 2013-2019
- 5000 sq. deg., 50% depth
- Weak lensing:
100 millions galaxies and $n_{\text{eff}} = 5.59$
gal/arcmin²



From Jeffrey, Gatti, and the mass map team



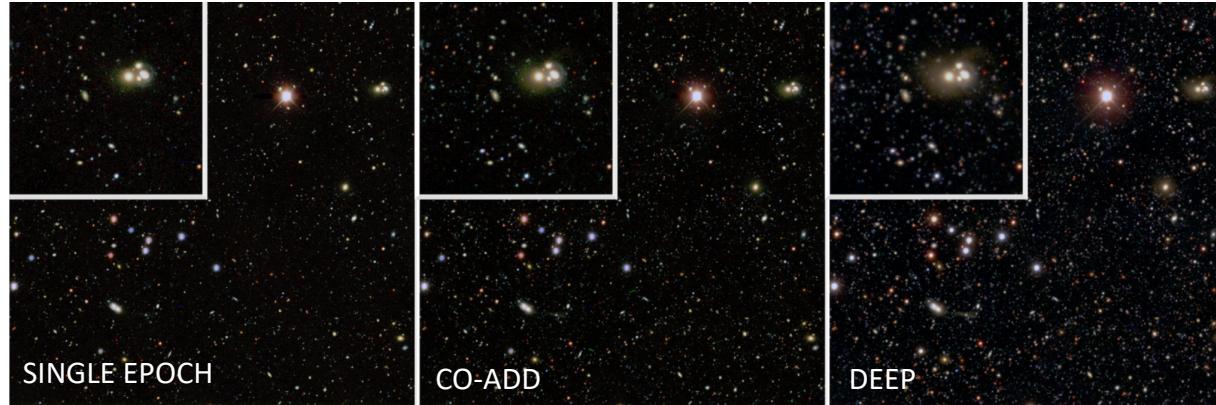
~500 pages of DES Y3 papers

- 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.

Calibration

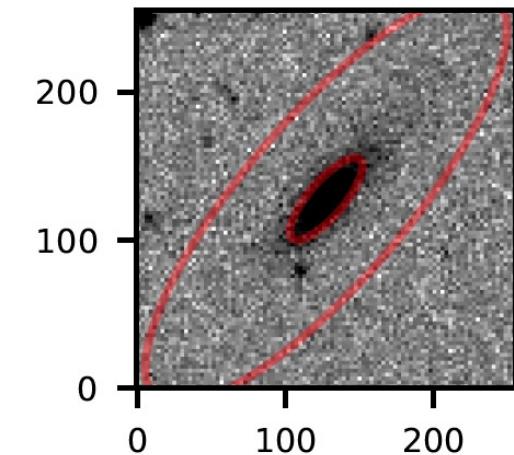
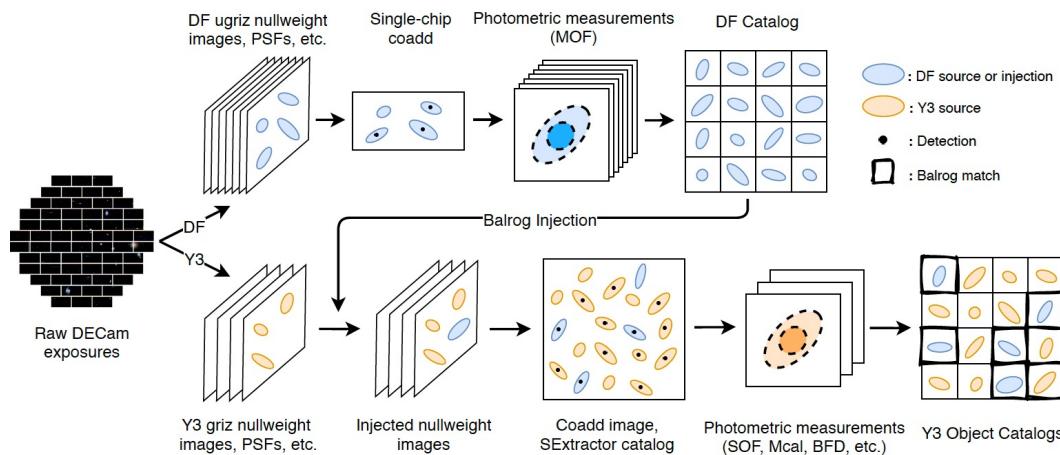
Deep fields: set of multi-wavelength images (DECam + VISTA)

Hartley *et al*, 2021



Balrog: injections of realistic galaxies to real data to measure DES transfer functions

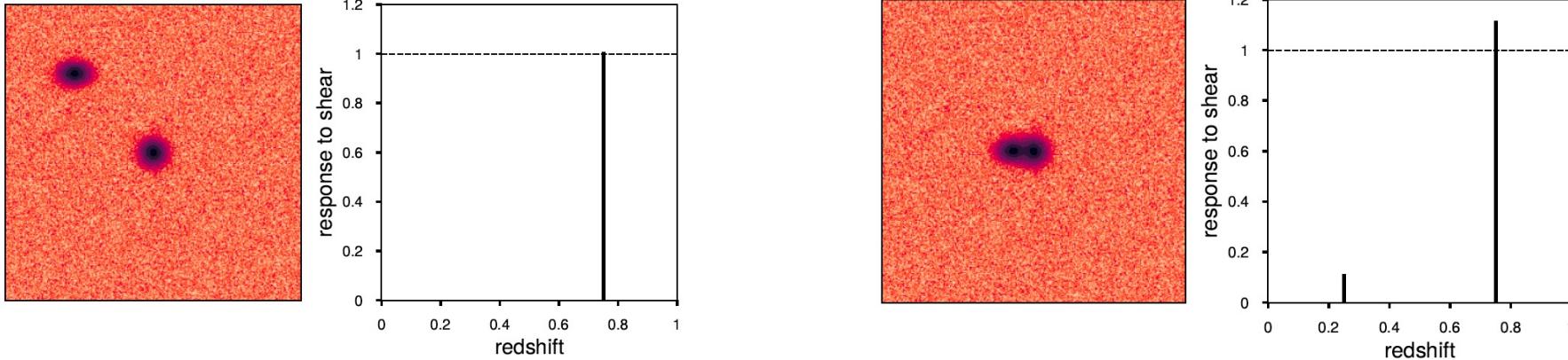
Everett *et al*, 2021



Simulations

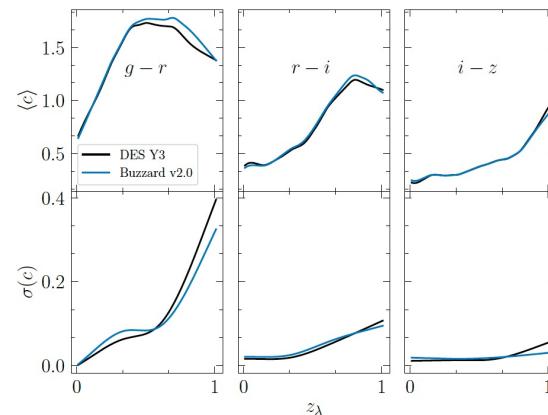
Image simulations: performance of the shear estimation pipeline

McCrann et al, 2021

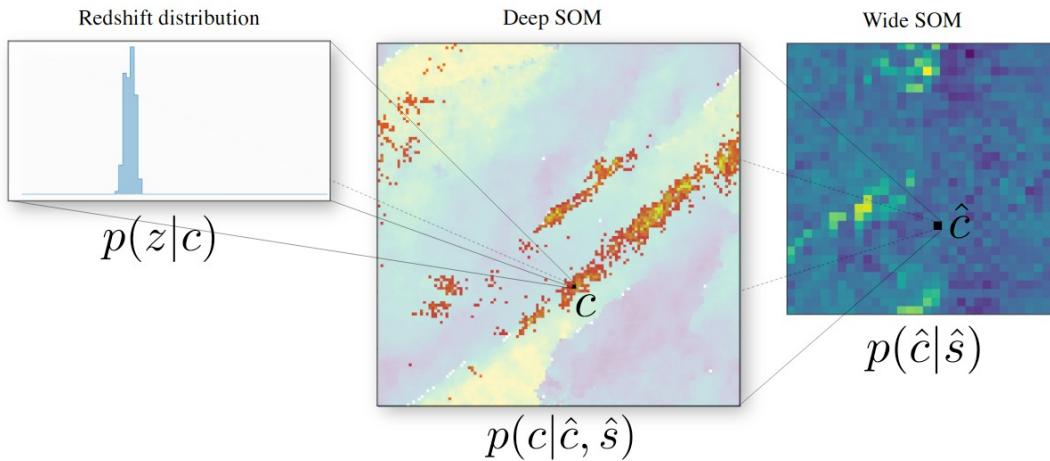


Buzzard: n-body simulations to validate modelling of 3x2pt correlation functions

DeRose et al, 2021



Photometric redshift



$$n_i(z) = p(z|\hat{b}_i) \approx \sum_{\hat{c} \in \hat{b}_i} \sum_c \underbrace{p(z|c)}_{\text{Redshift}} \underbrace{p(c)}_{\text{Deep}} \underbrace{\frac{p(c, \hat{c})}{p(c)p(\hat{c})}}_{\text{Balrog}} \underbrace{p(\hat{c})}_{\text{Wide}} .$$

Combination of 3 redshift characterization:

- SOMPZ
 - Clustering redshift
 - Shear ratio
- Ensemble of redshift distribution

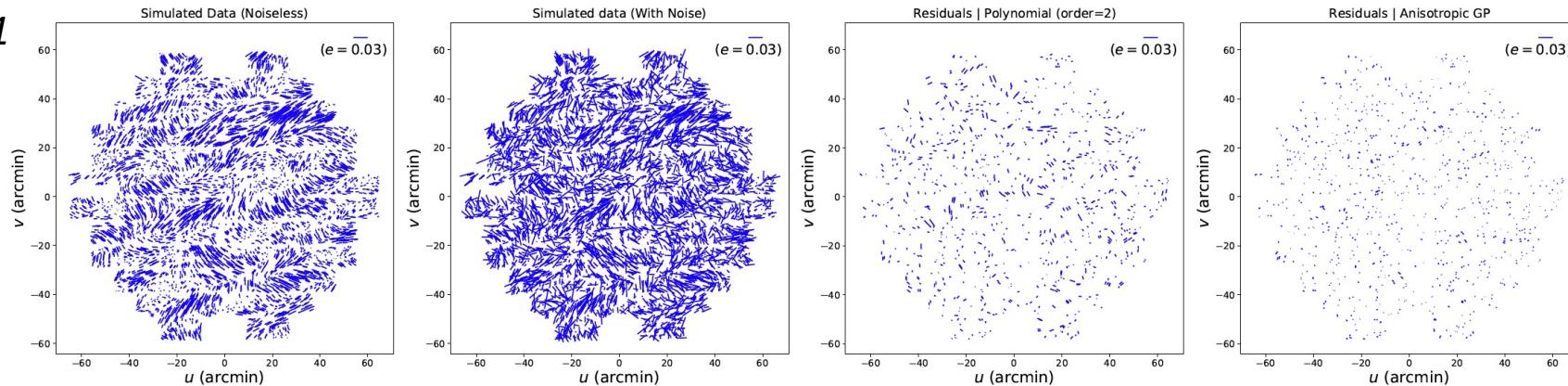
In cosmological analysis, marginalize over stretch and shift to mean

Myles, Alarcon, et al, 2021, Cordero, Harrison, et al, 2021, Buchs et al, 2021, Gatti et al, 2021, Cawthon et al, 2021, Giannini et al, in prep

Source catalog: PSF and shape measurements

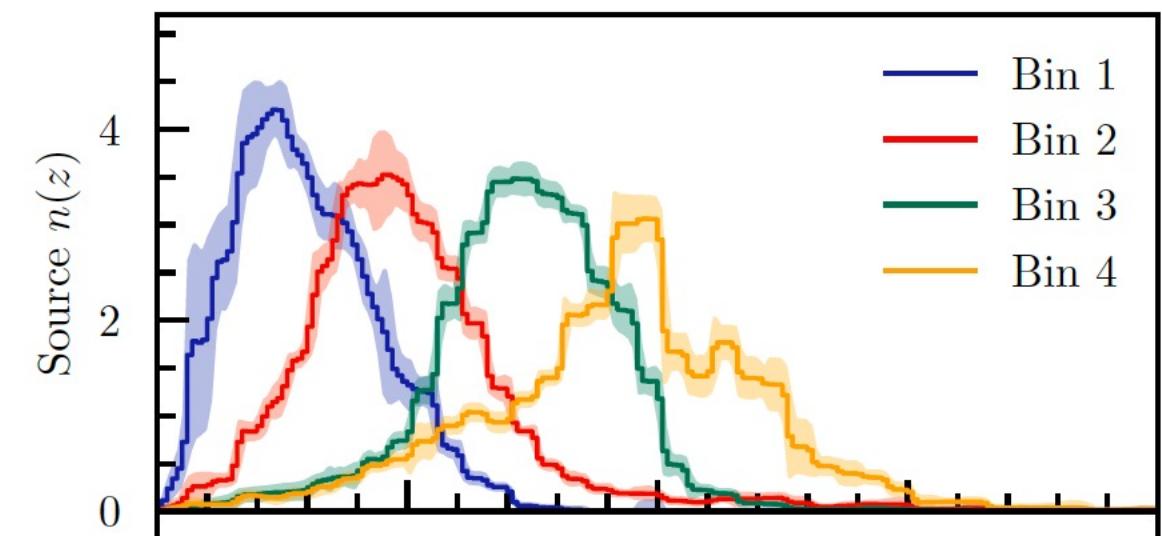
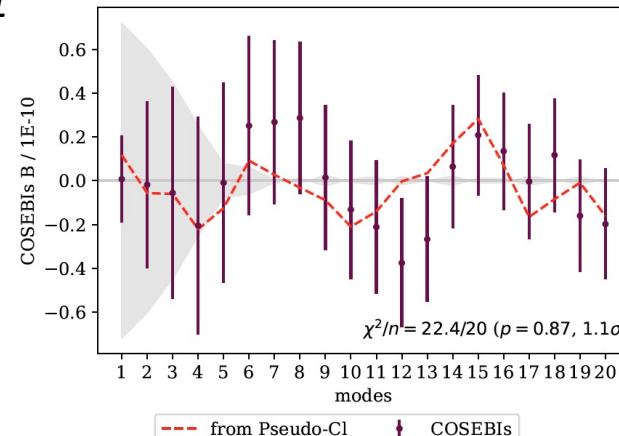
PSF modeled across the field of view with PIFF

Jarvis et al, 2021

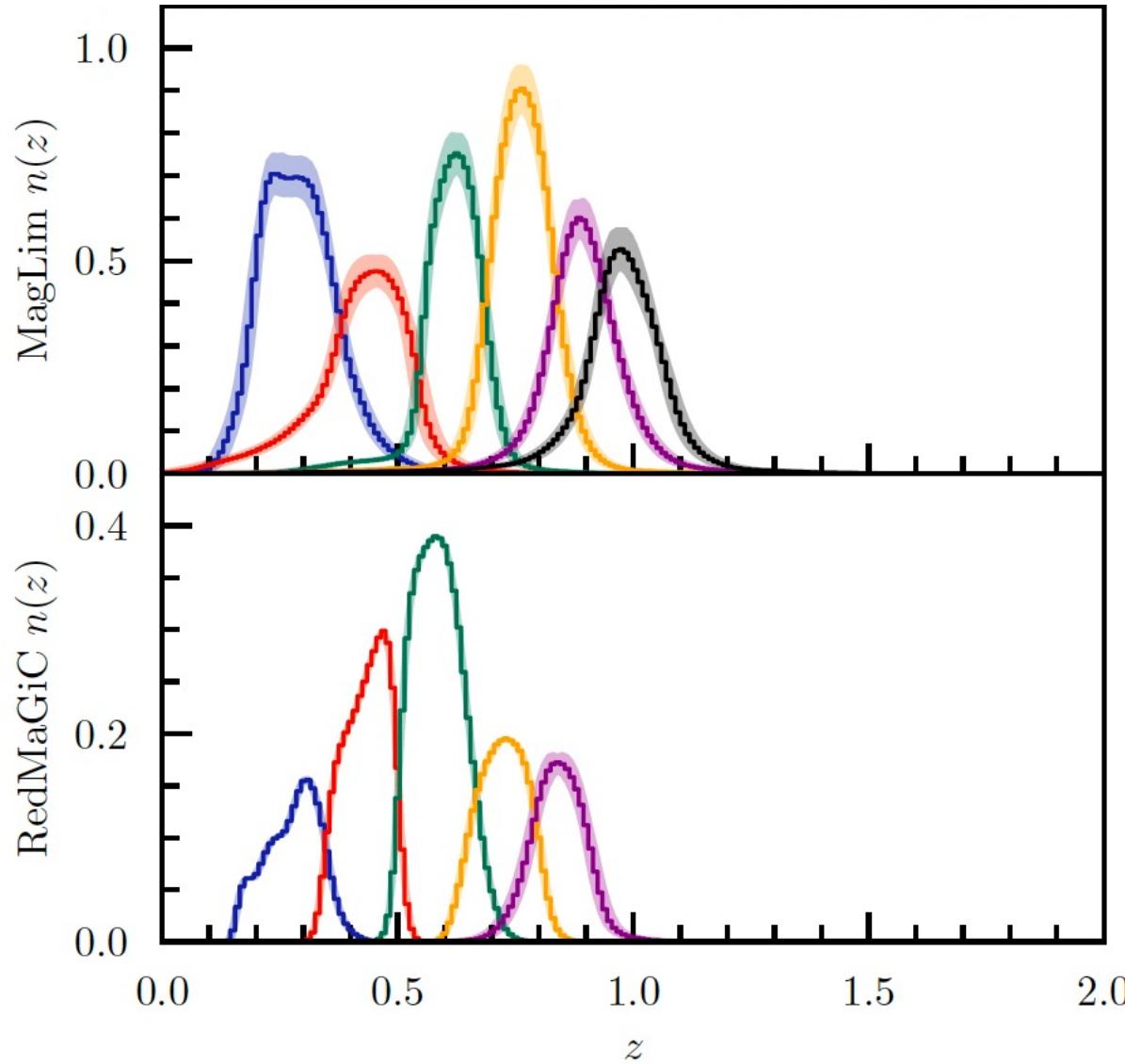


Shape measurements with metacalibration

Gatti, Sheldon et al, 2021



Lens catalog: clustering samples

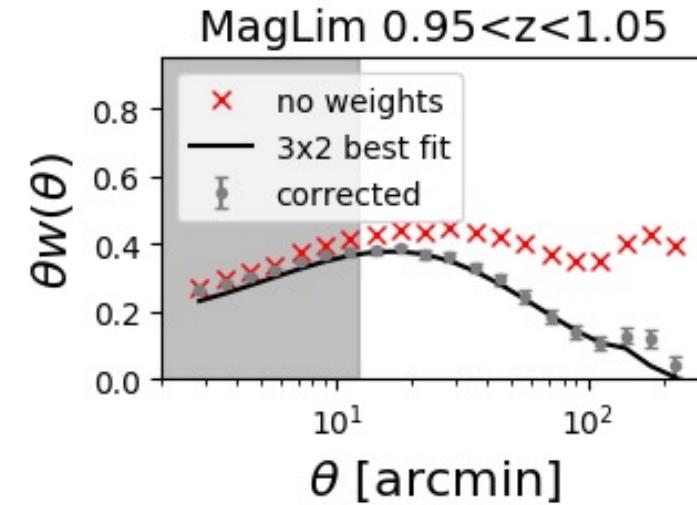


- Maglim lens sample
 $i < 18 + 4 z_{phot}$
→ 11 million galaxies
Porredon et al., 2021

- Redmagic lens sample
red-sequence template fit
→ 3 million galaxies
Rodriguez-Monroy et al., 2021

Clustering systematics

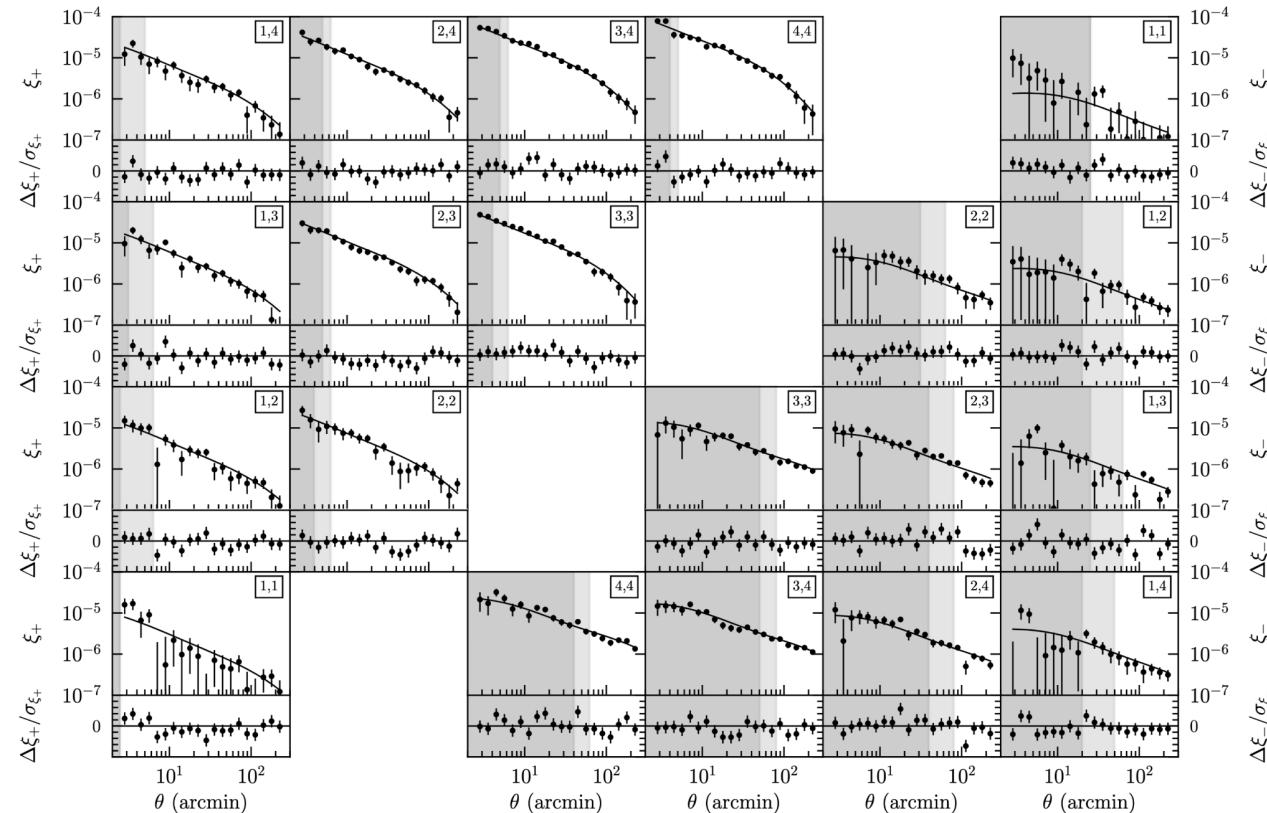
Quantity	Units	Statistics
airmass	0	WMEAN, MIN, MAX
fwhm	arcsec	WMEAN, MIN, MAX
fwhm_fluxrad	arcsec	WMEAN, MIN, MAX
exptime	seconds	SUM
t_eff	0	WMEAN, MIN, MAX
t_eff_exptime	seconds	SUM
skybrite	electrons/CCD pixel	WMEAN
skyvar	(electron s/CCD pixel) ²	WMEAN, MIN, MAX
skyvar_sqrt	electrons/CCD pixel	WMEAN
skyvar_uncertainty	electrons/ s · coadd pixel	
sigma_mag_zero	mag	QSUM
fgcm_gry	mag	WMEAN, MIN
maglim	mag	
sof_depth	mag	
magauto_depth	mag	
stars_1620	# stars	
stellar_dens	stars/deg ²	
sfd98	mag	



- 30 maps of variability of survey properties in each band
Rodríguez-Monroy et al, 2021
- Fit and remove impact of full set of maps on galaxy clustering by reweighting

Data vector

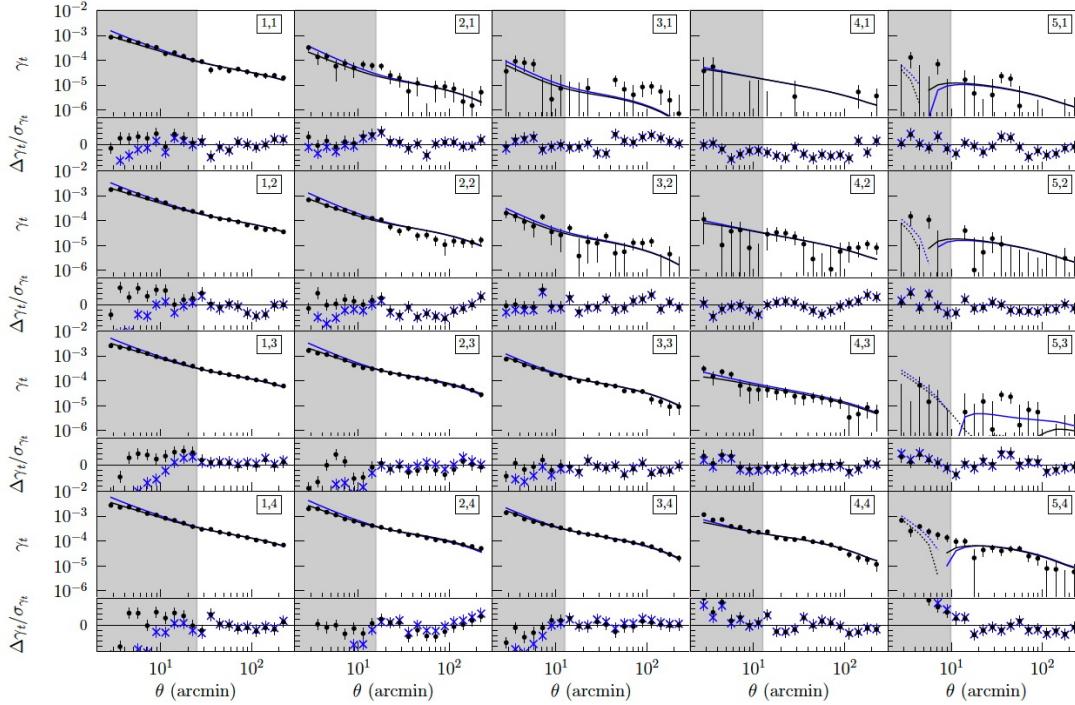
Cosmic shear



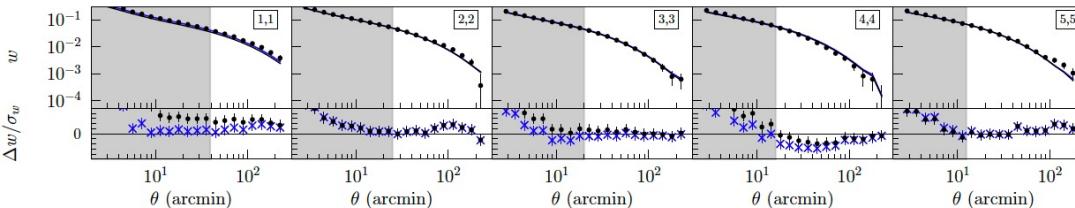
+ shear ratio = ratio of galaxy-galaxy lensing at small scales
Sanchez, Prat et al, 2021

REDMAGIC

Galaxy-galaxy lensing

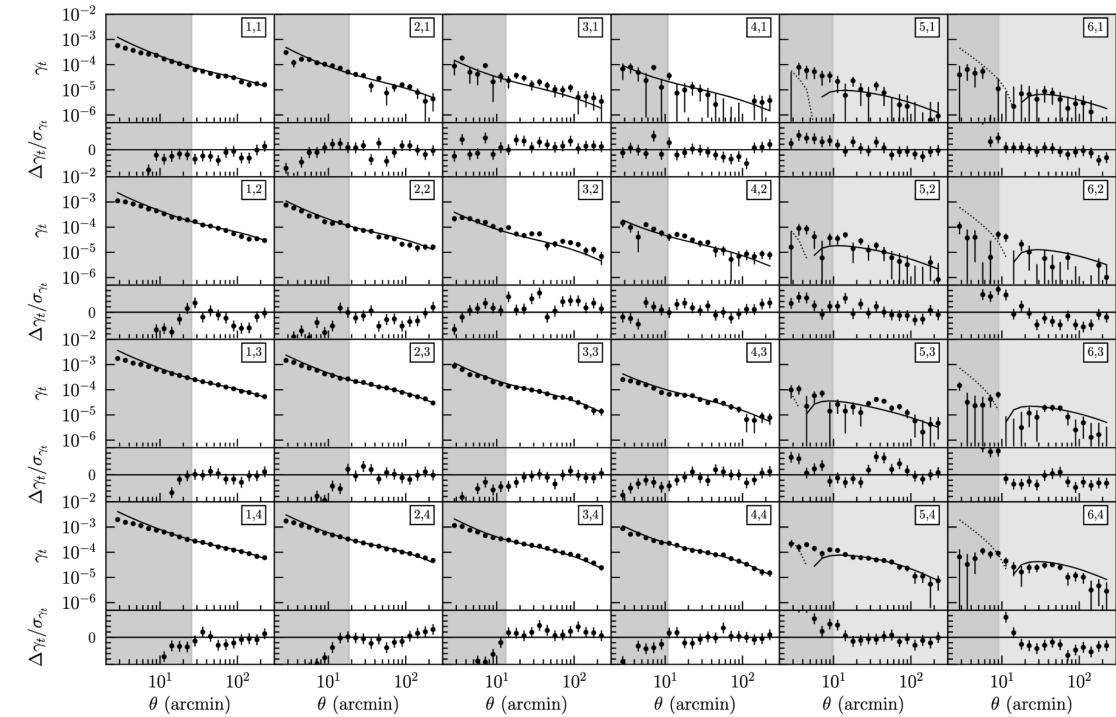


Clustering

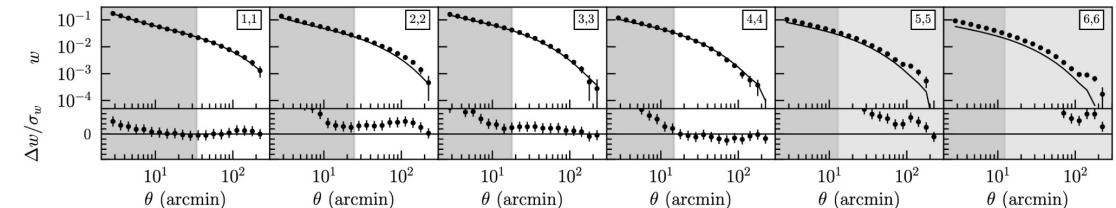


MAGLIM

Galaxy-galaxy lensing



Clustering



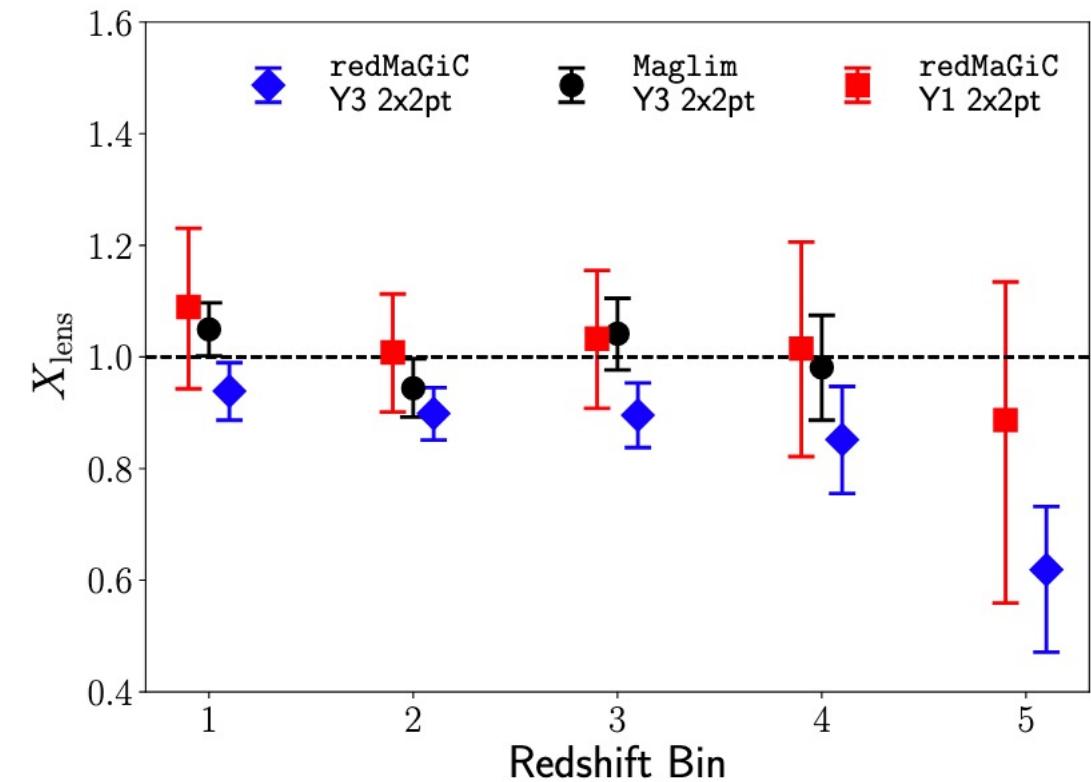
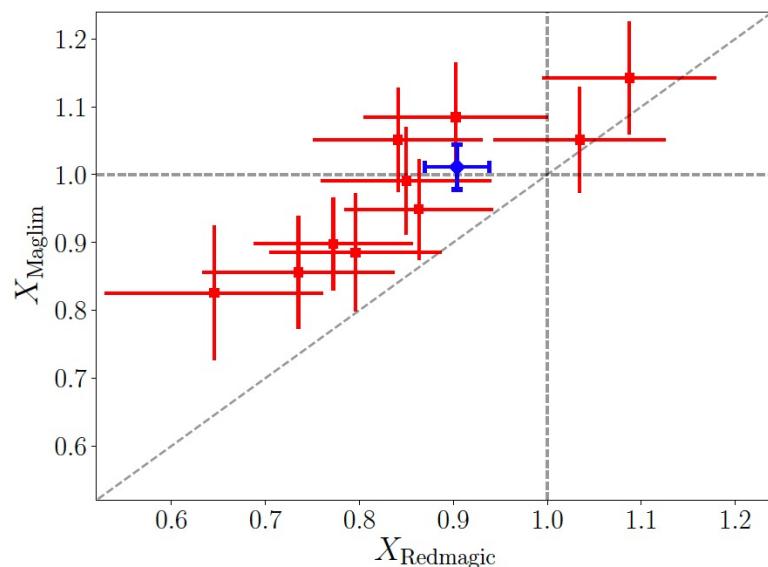
In redmagic sample: X_{lens}

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

$$w^{ii}(\theta) = b_i^2 \xi_{\text{mm}}^{ii}(\theta)$$

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

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

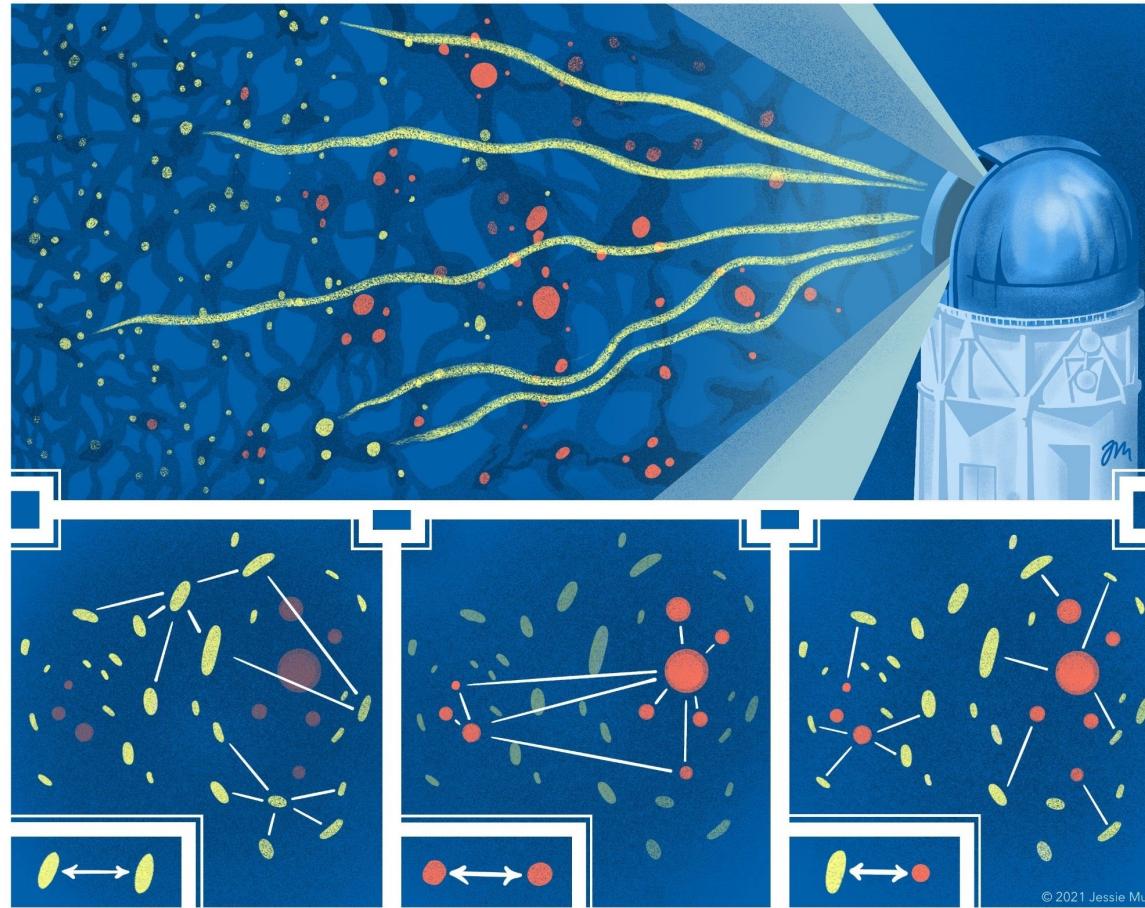
Analysis:

- 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



Matter power spectrum

Modeling the underlying total matter distribution

Galaxy bias

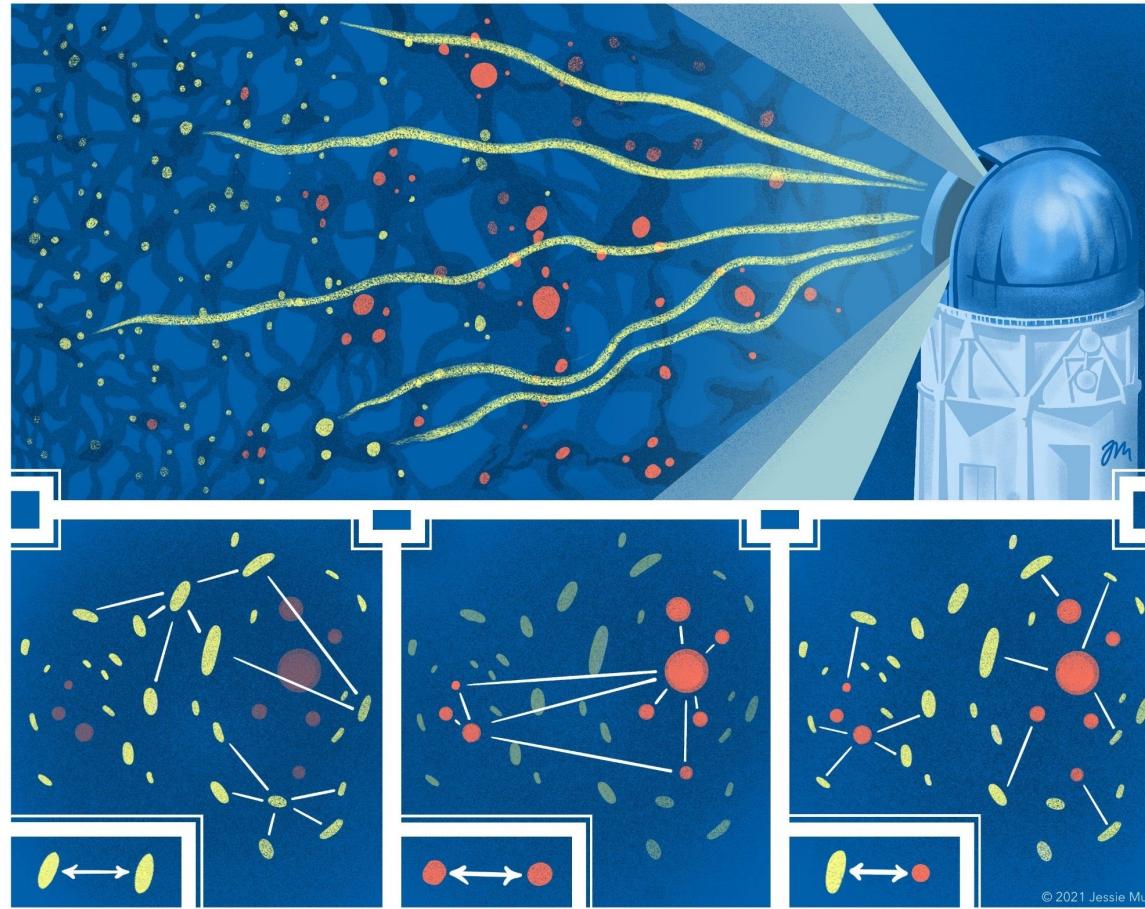
Modeling how galaxies trace the underlying matter distribution

Modeling weak lensing and clustering

Intrinsic alignment

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

- + RSD and non-limber computation for clustering
- + mitigating effect of non-locality of gg lensing



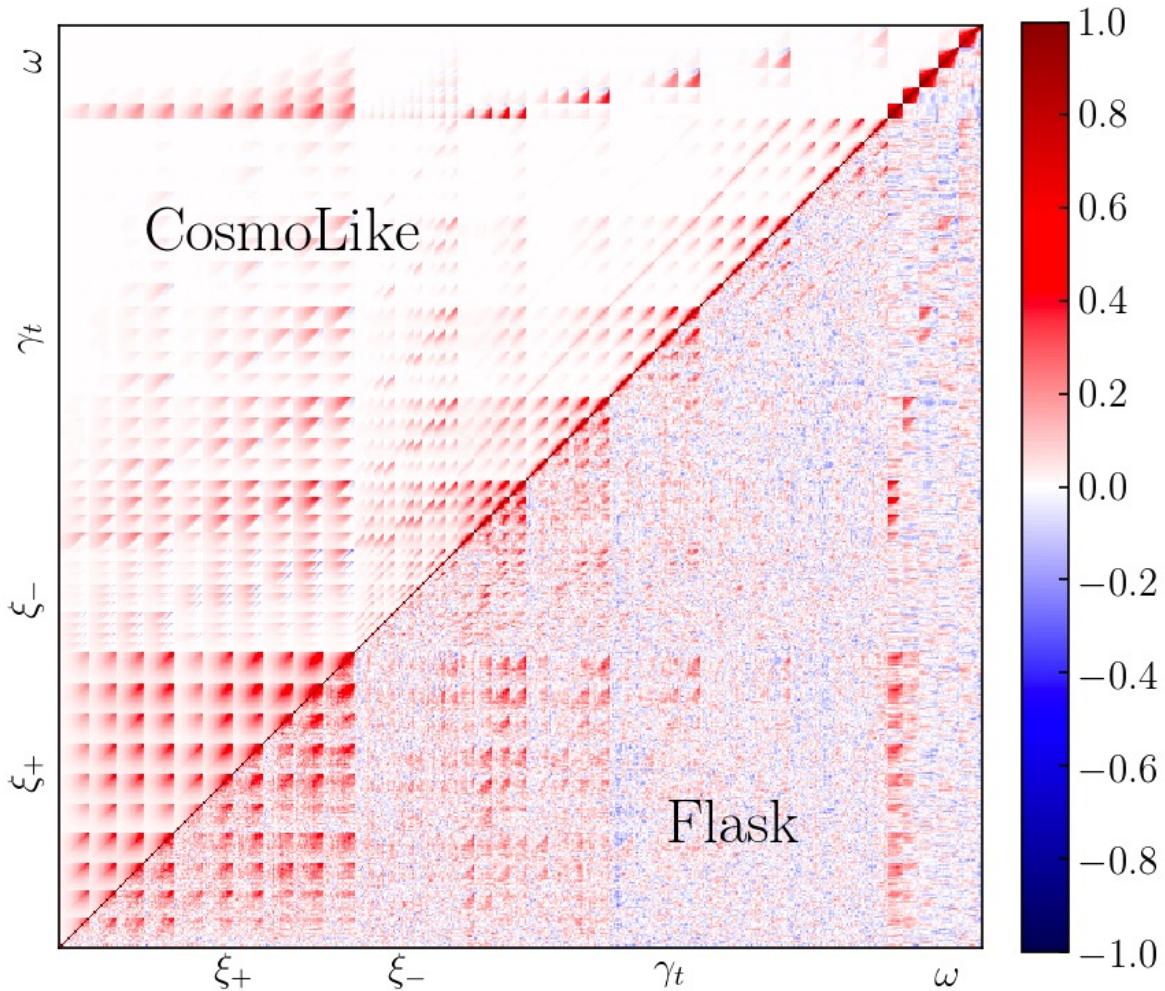
Matter power spectrum

Halofit

Galaxy bias

Linear galaxy bias model
⇒ 4 parameters

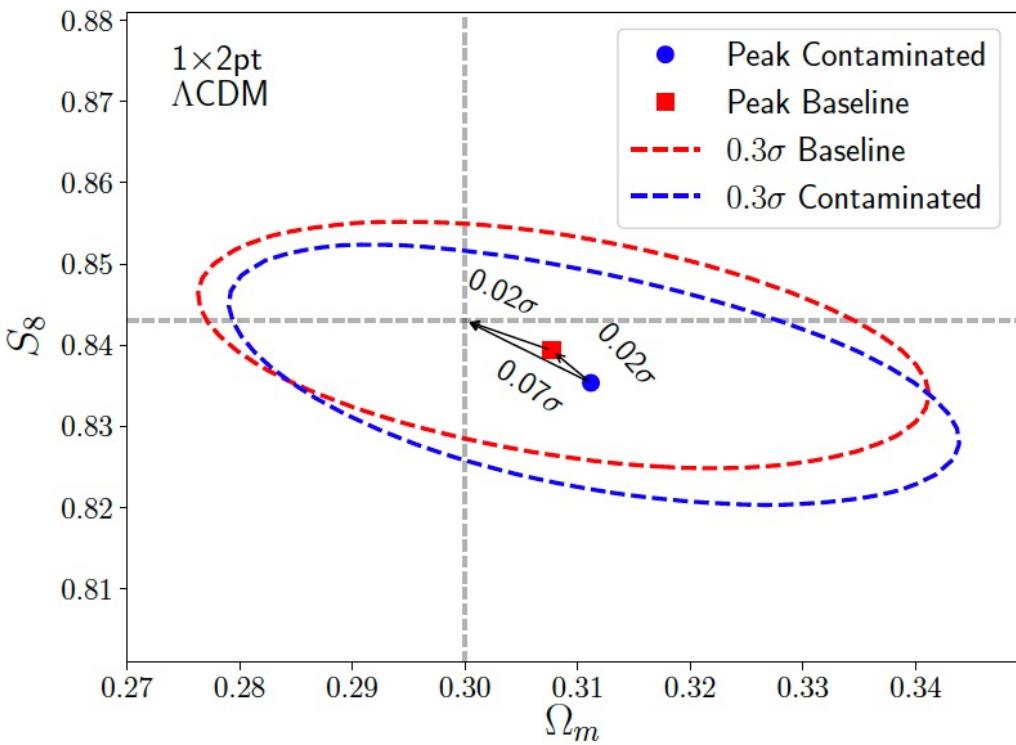
3x2pt covariance



Covariance matrix

- Analytical: Cosmolike
Krause, Eifler 2017
- Validated on simulations
- Many effects tested:
shot noise, non-gaussian terms, mask, etc.
Friedrich et al, 2020

Testing limitations of modeling



Scale cuts

Keep only 462 data points out of 1300, removing the impact from:

- Baryons in the matter power spectrum
- Non-linear galaxy bias

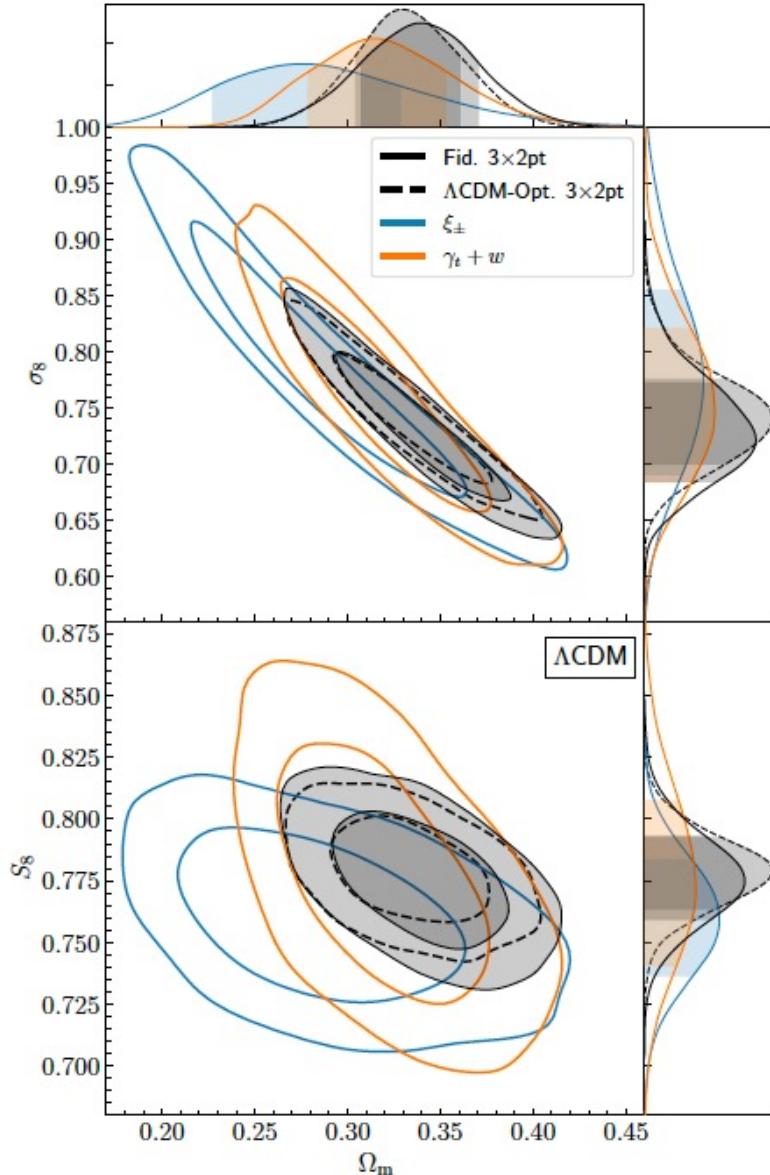
Krause+ 2021

Validation tests

Test the impact of mismodeling on constraints from cosmic shear, galaxy-galaxy lensing, clustering

Amon+ 2021, DeRose+ 2021, Krause+ 2021, Pandey+ 2021, Porredon+ 2021, Prat 2021 Secco+ 2021 [DES Y3]

DES Y3 weak lensing and clustering cosmological results



Unblinding telecon 100+ participants

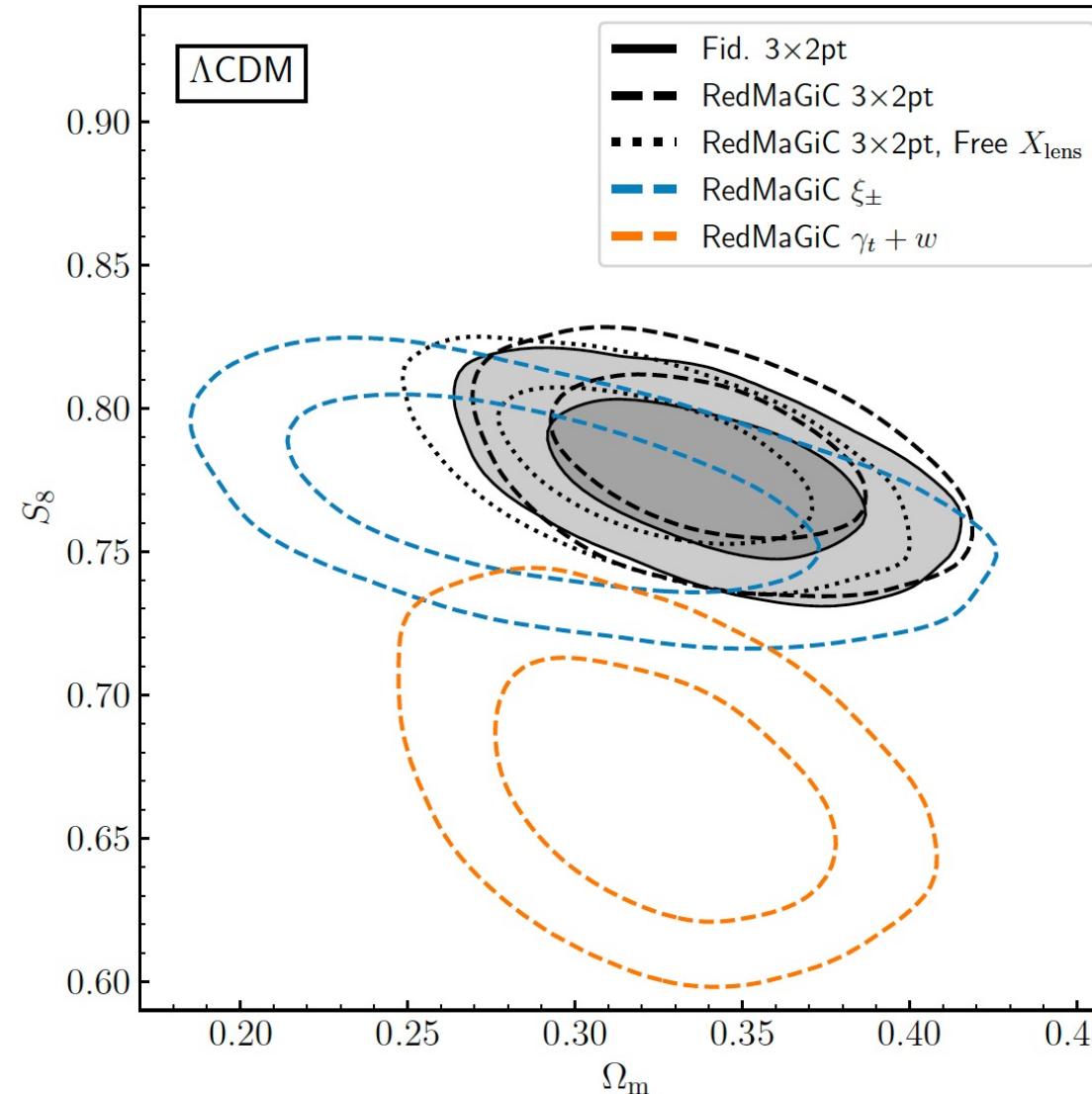
- Redmagic sample: November 3, 2020
- Maglim sample: March 15, 2021

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

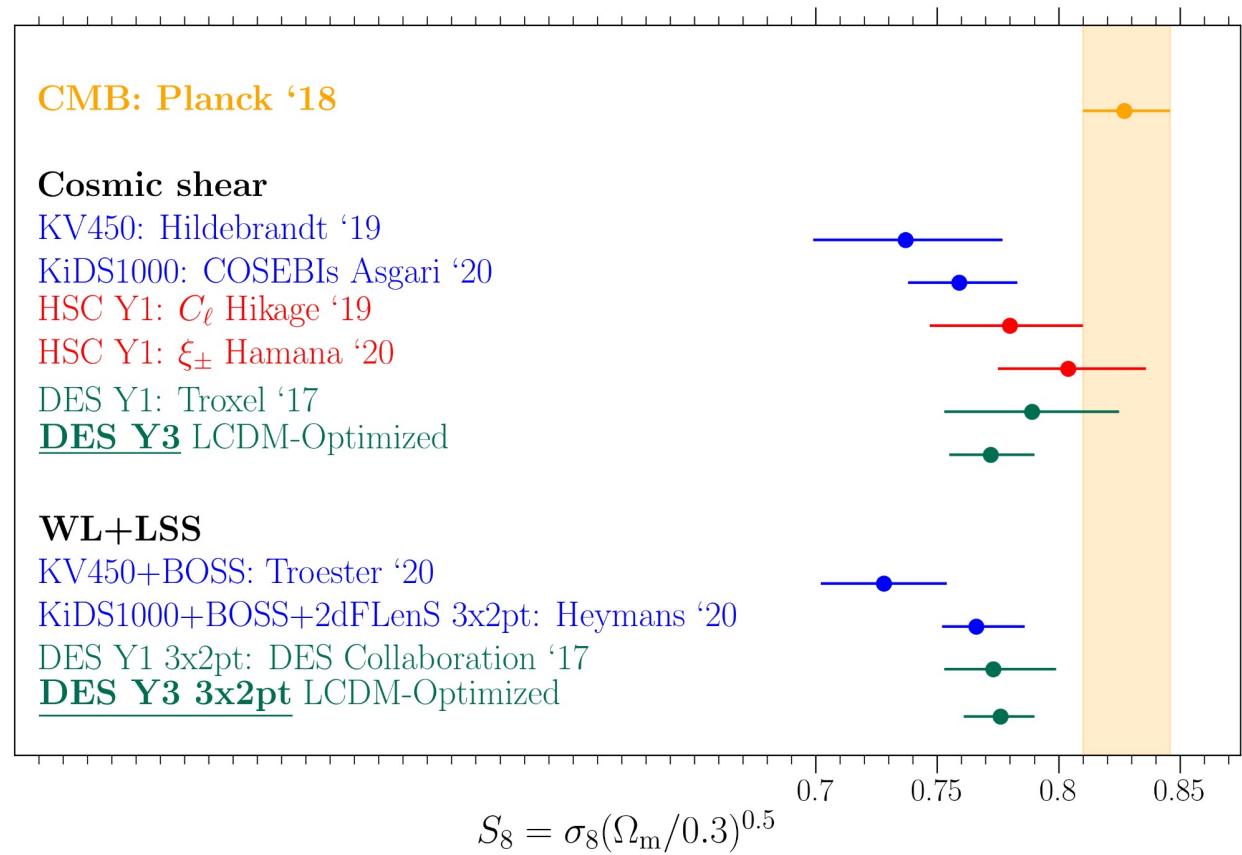
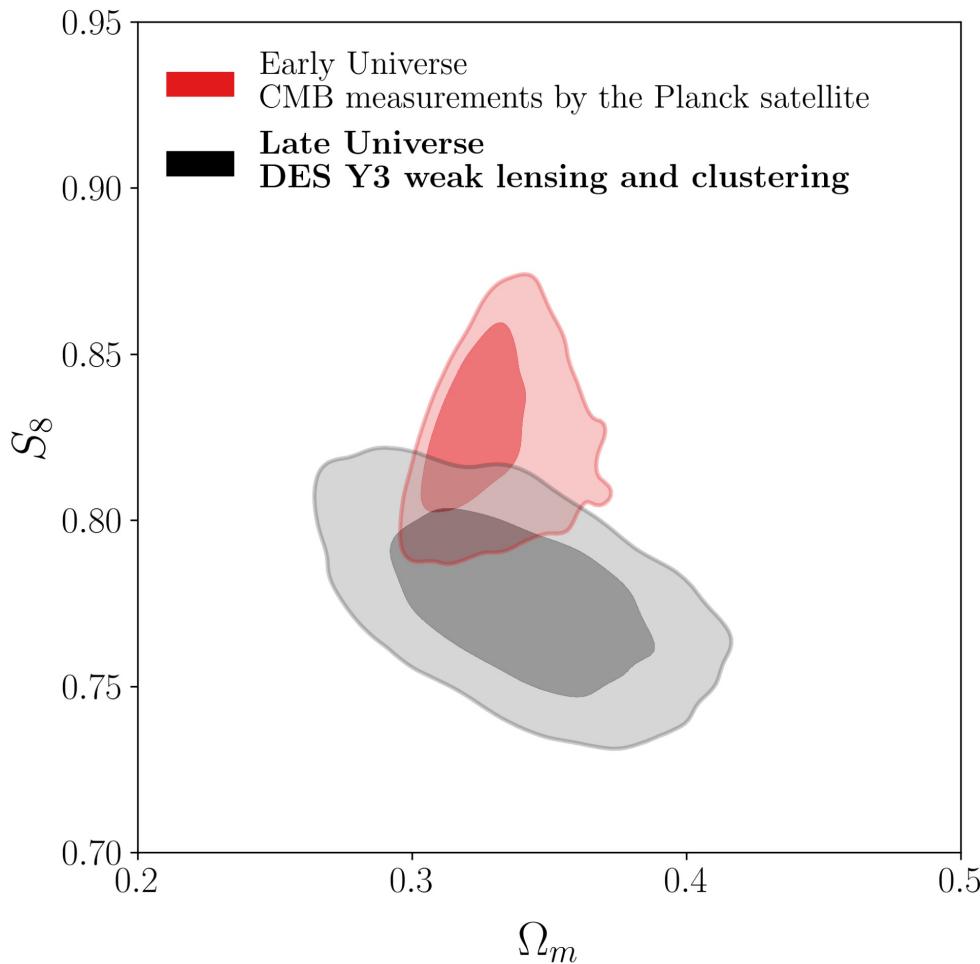
- **Most powerful** constraints from 3x2pt of same survey
- **x2** more constraining than Y1
- No evidence for deviations from $w = -1$

DES collaboration 2021

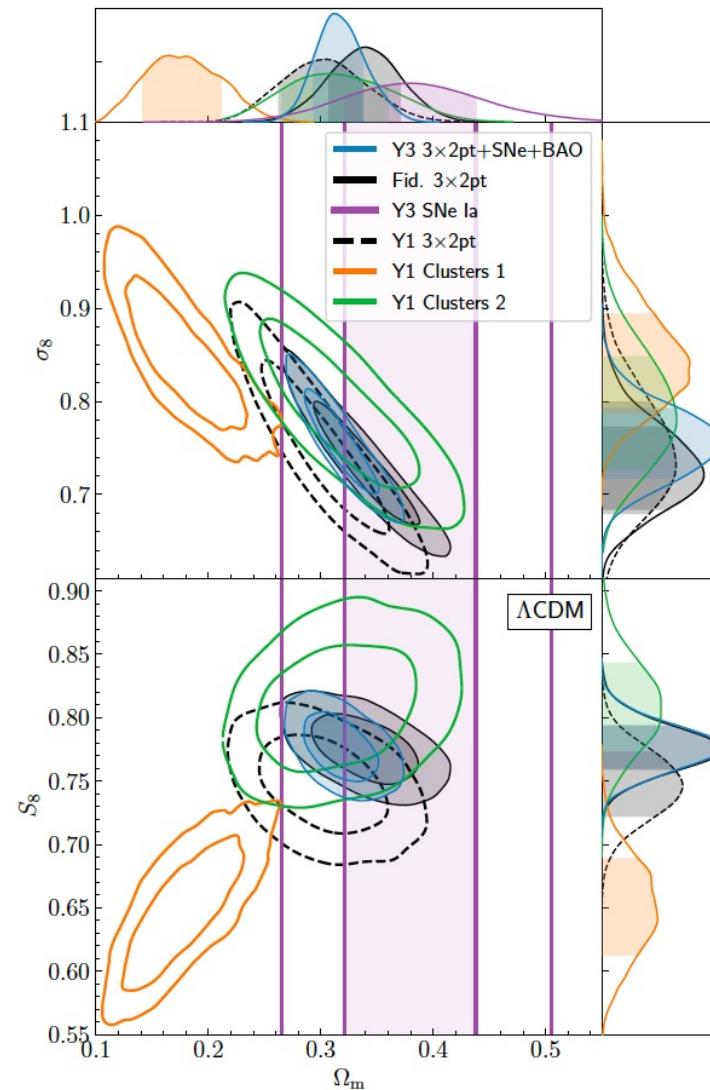
Impact of X_{lens} (unknown systematics) on cosmological results



Comparison with CMB measurements

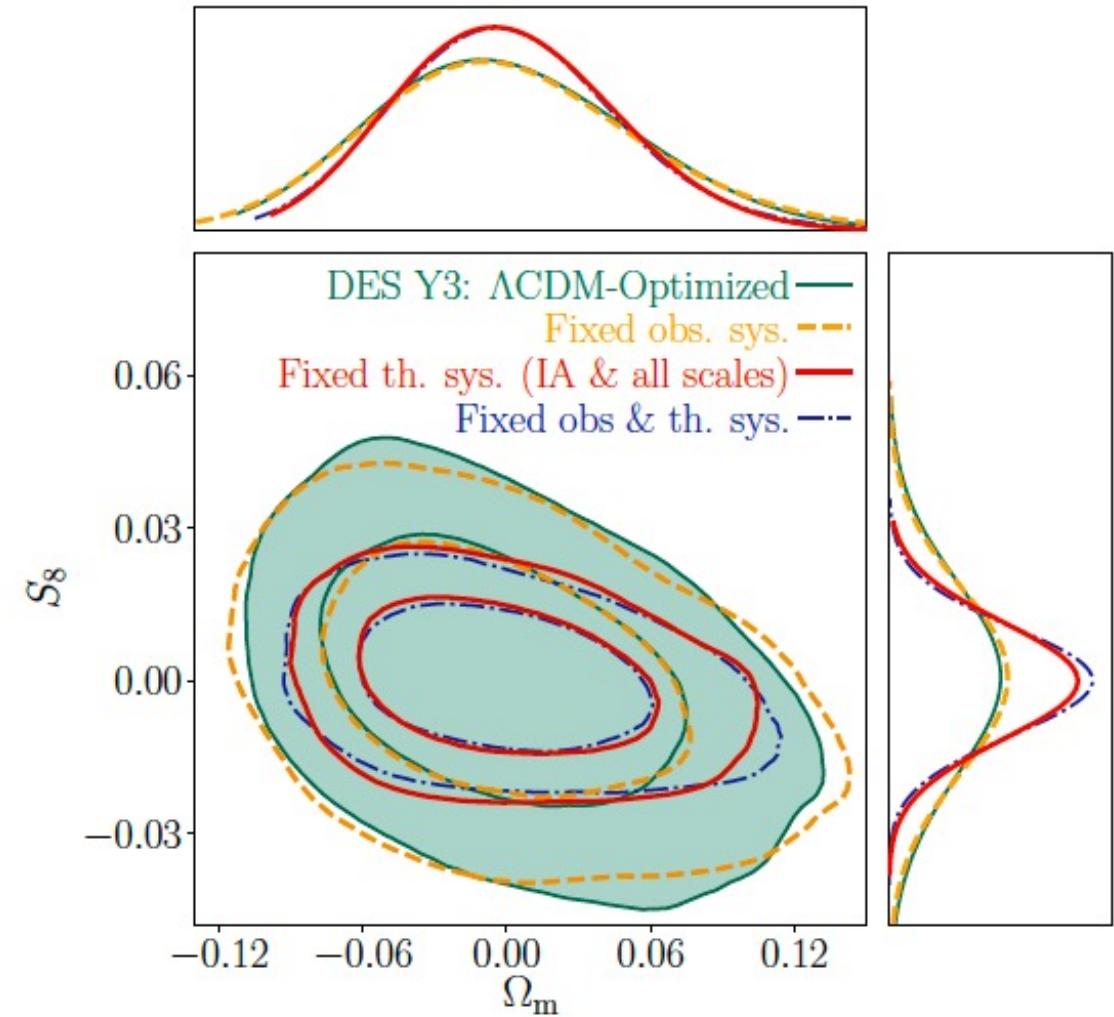


Cosmology from all DES



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



What's next for the Dark Energy Survey

Other results from DES Y3:

- Cosmology from clusters
DES collaboration, in prep
- Analysis in harmonic space
Doux et al, in prep
- Non-gaussian statistics in weak lensing: peak statistics and 3rd moments of mass map
Zeurcher et al, Gatti et al, in prep
- Constraints on models beyond Λ CDM
 - Dynamical dark energy, curvature, neutrinos, tests of gravity
DES collaboration, in prep
 - Modified gravity constraints
Ferté et al, in prep

DES Y6 ongoing