DARK ENERGY SURVEY

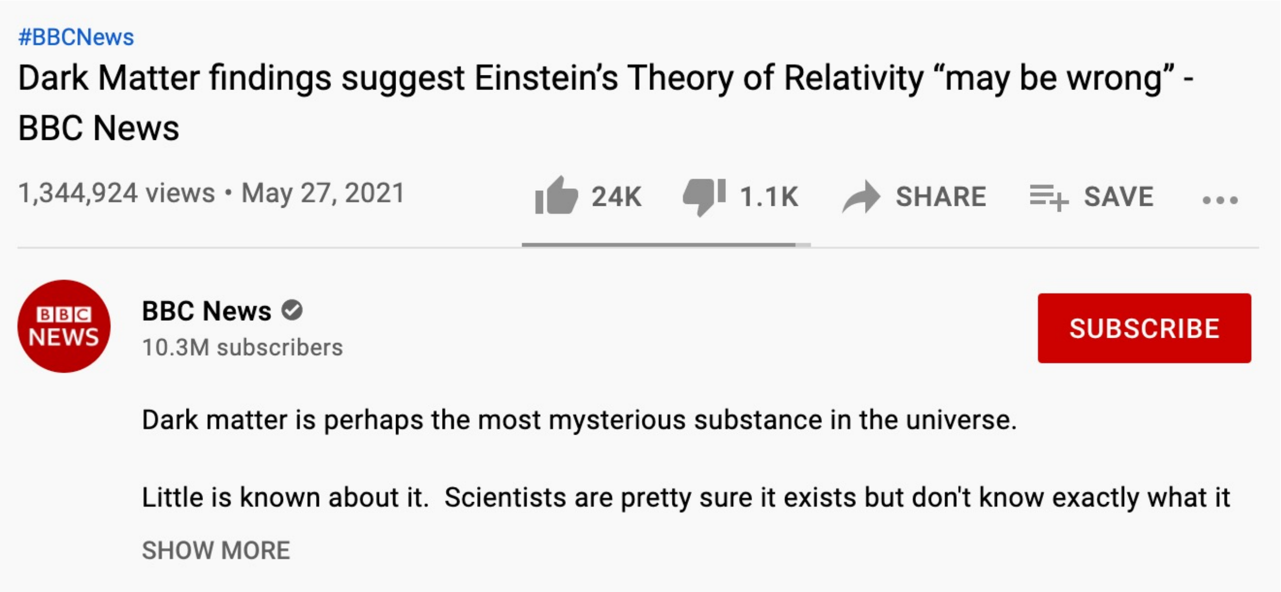
DES Year 3 Results: Cosmology from weak lensing and galaxy clustering

Niall MacCrann (DAMTP, Cambridge),

on behalf of the DES Collaboration

What I’ll talk about

- A quick large-scale structure cosmology intro
- A quick Dark Energy Survey intro
- A bit about weak gravitational lensing
- The DES Year 3 “3x2pt” analysis and challenges
- Cosmological constraints
- Was Einstein wrong? (not yet, clickbait is real…)



Large scale structure cosmology

- We have a concordance cosmological model, (flat) ΛCDM.
- Observationally solid, but what is Λ? (and what is CDM!!?)
- Strong constraints from mature geometrical probes:
  - Standard rulers (BAO in CMB/galaxies)
  - Standard candles (SN1a)
- Largely depend on background quantities e.g. Average energy densities and expansion rate of the Universe.

Large scale structure cosmology

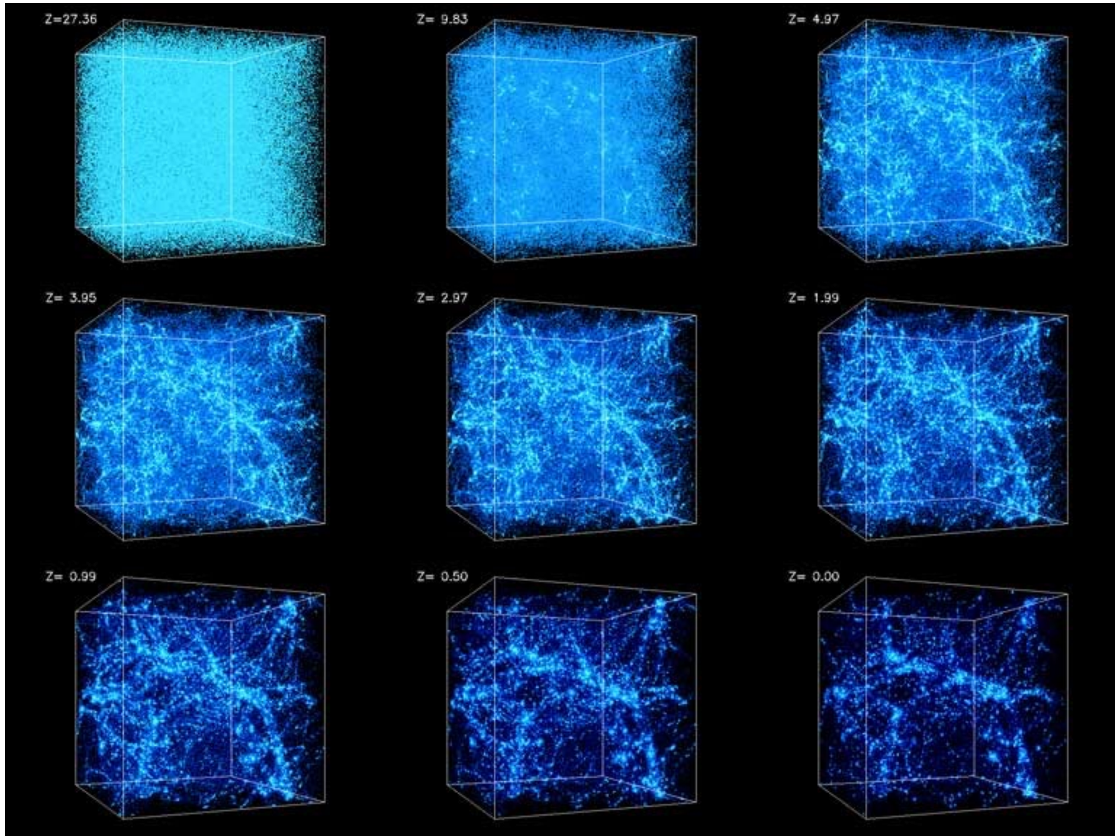
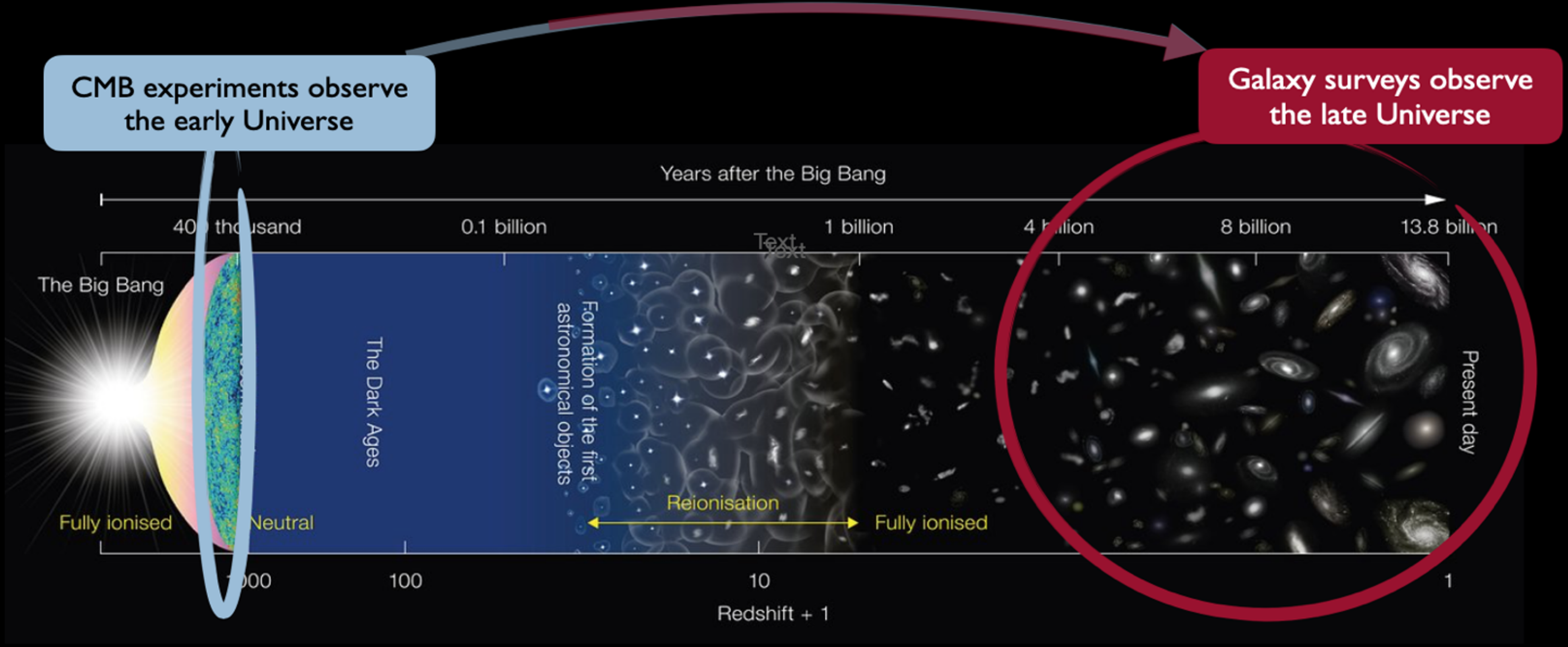


Image credit: Andrey Kravtsov and Anatoly Klypin

- What about the perturbations?
- The statistics of the density field can tell us about the growth of structure – complementary to geometrical information.

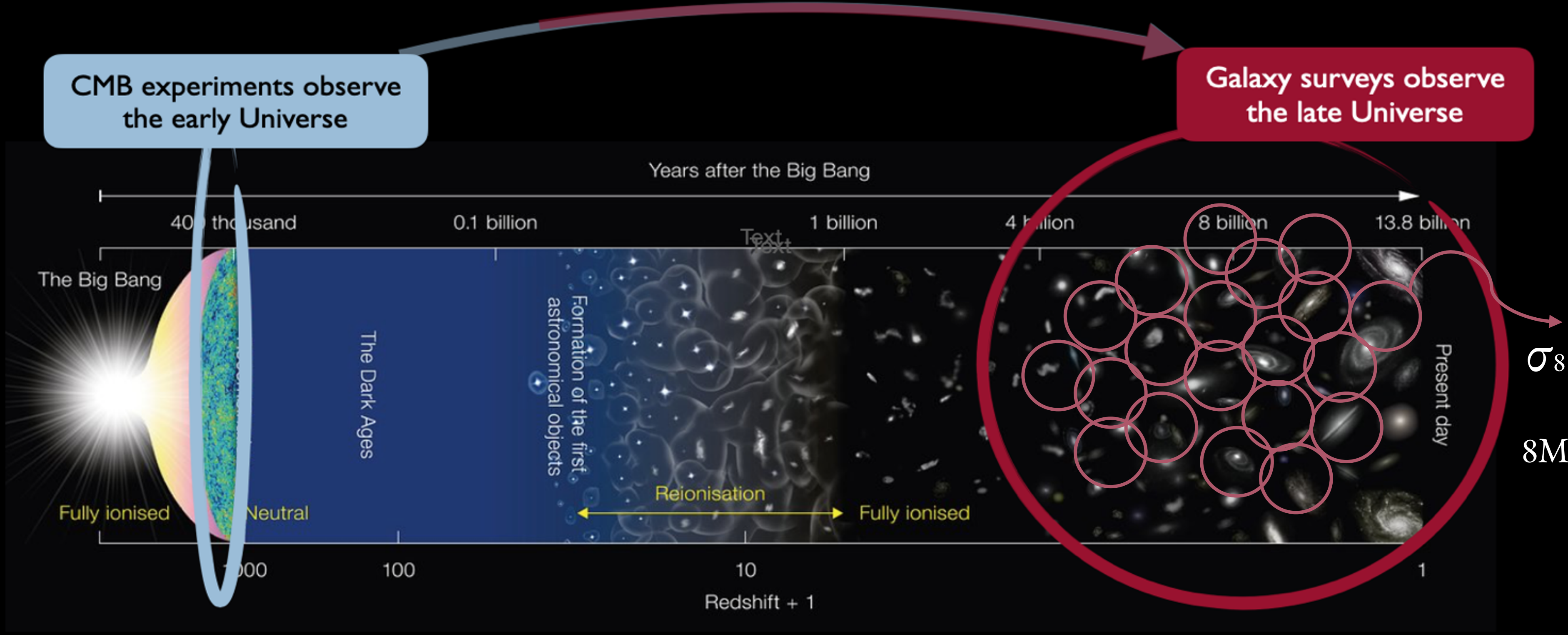
Testing ΛCDM: Is the late time clustering compatible with the ΛCDM prediction assuming initial conditions from the CMB?



As: Amplitude of primordial scalar density fluctuations.

Image credit: NAOJ

Testing ΛCDM: Is the late time clustering compatible with the ΛCDM prediction assuming initial conditions from the CMB?



σ_8: Amplitude of mass fluctuations (in 8Mpc/h spheres) today.

A_s: Amplitude of primordial scalar density fluctuations.

Image credit: NAOJ

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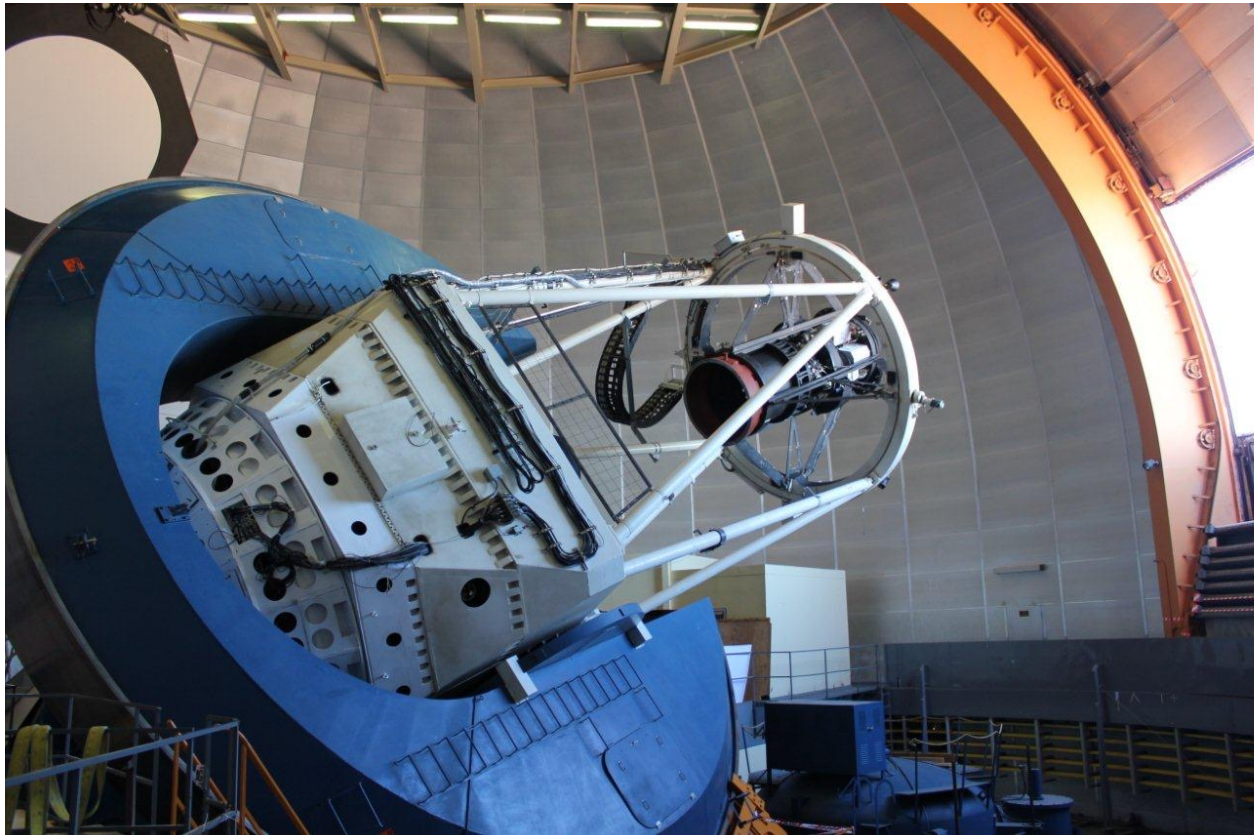
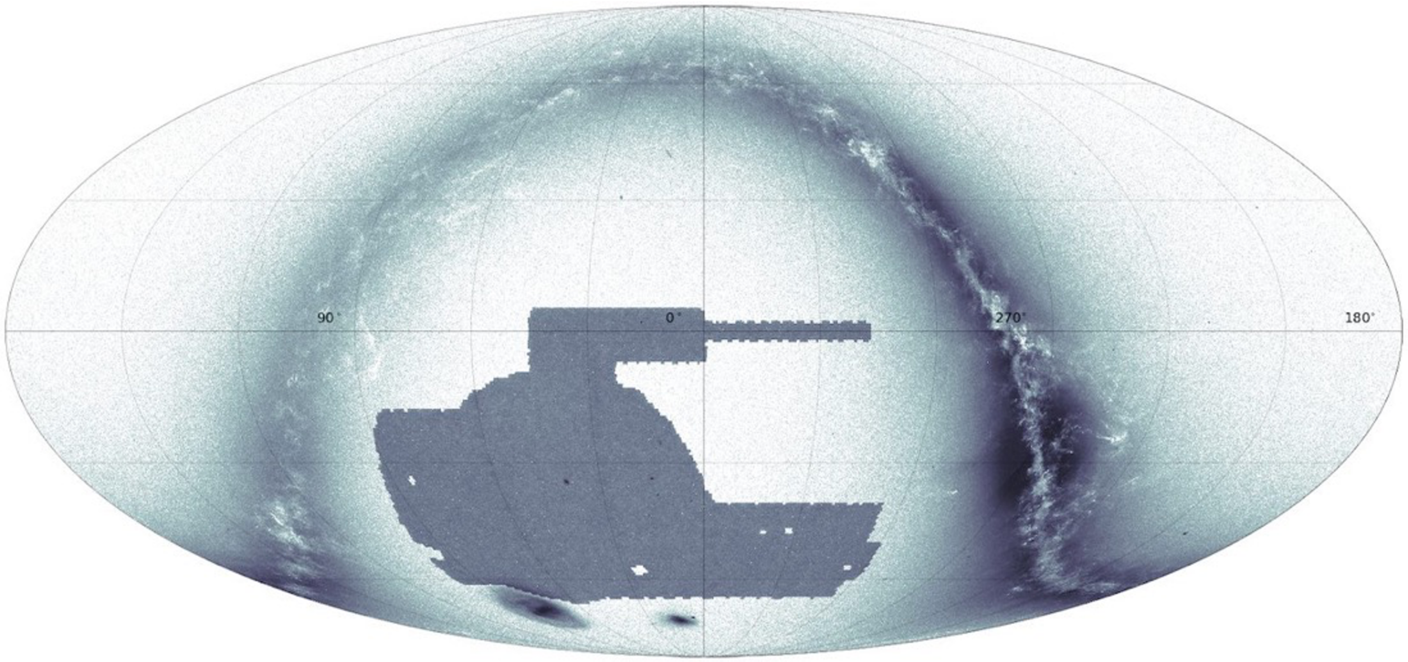
The Dark Energy Survey (DES)



The Dark Energy Survey (DES)

- 570 Megapixel camera for the Blanco 4m telescope in Chile.
- Full survey 2013-2019 (Year 3 2013-16).
- Wide field: 5000 sq. deg. in 5 bands. ~23 magnitude.
- DES Y3: Positions and shapes of > 100M galaxies.



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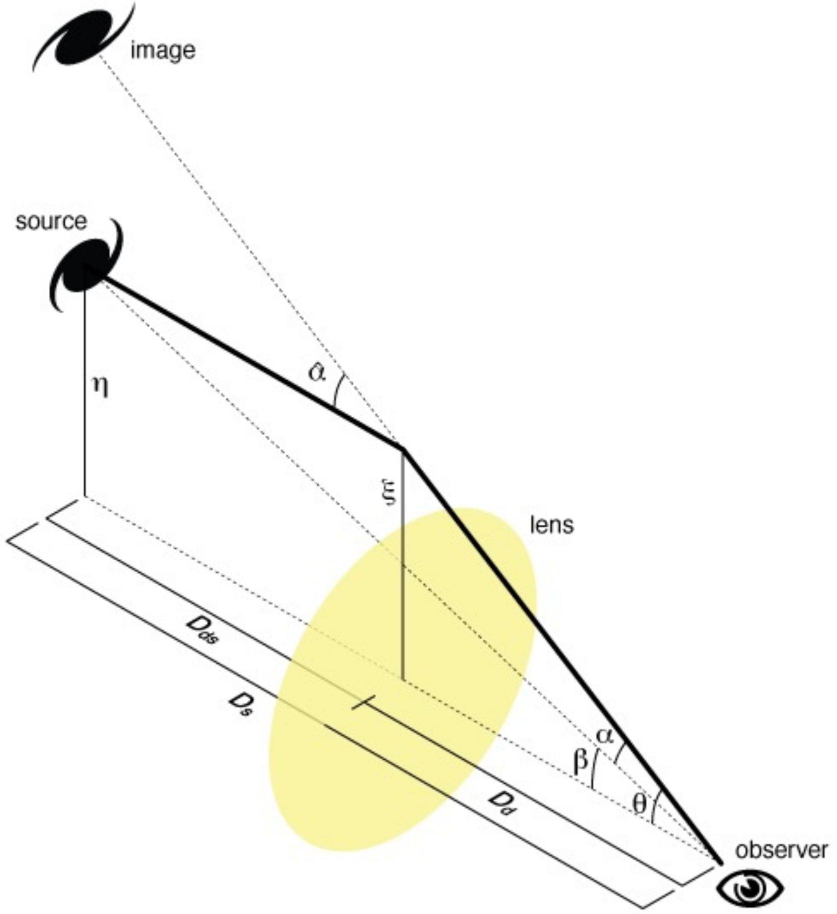
Weak Gravitational Lensing



$$\hat{\alpha} = \frac{4GM}{c^2 \xi}$$

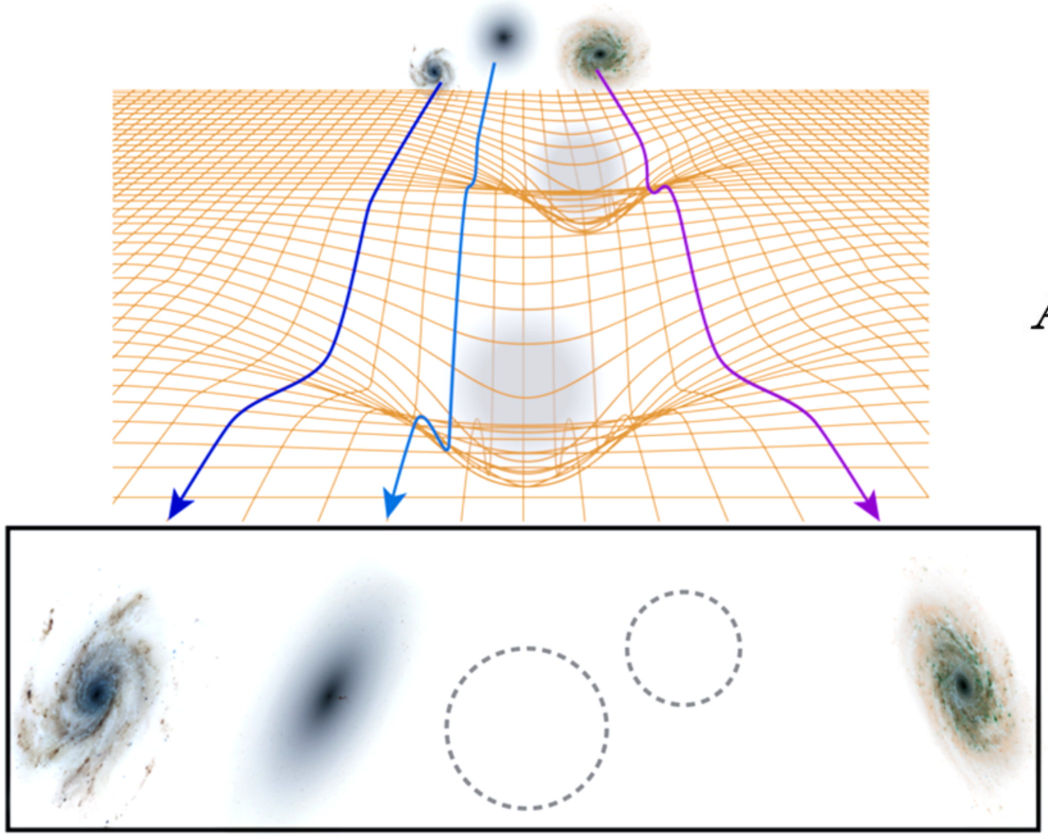
<- For a point mass

$$\vec{\alpha}(\vec{\theta}) = \vec{\nabla}\psi(\vec{\theta})$$

<- In general

$$\psi(\vec{\theta}) = \frac{2D_{ds}}{D_d D_s c^2} \int \Phi(D_d \vec{\theta}, z) dz$$

Weak Gravitational Lensing



APS/Alan Stonebraker; galaxy images from STScI/AURA, NASA, ESA, and the Hubble Heritage Team

To first order, unlensed coordinates are transformed to the lensed coordinates according to the lensing Jacobian

$$A_{ij} = \delta_{ij} - \frac{\partial\psi}{\partial\theta_i\partial\theta_j} = \begin{bmatrix} 1-\kappa-\gamma_1 & \gamma_2 \\ \gamma_2 & 1-\kappa+\gamma_1 \end{bmatrix}$$

Galaxy ellipticities transform as

$$\epsilon \approx \epsilon_s + \gamma$$

Galaxies are randomly oriented (before lensing) so:

$$\langle\epsilon\rangle = \langle\epsilon_s\rangle + \langle\gamma\rangle = \langle\gamma\rangle$$

Weak Gravitational Lensing

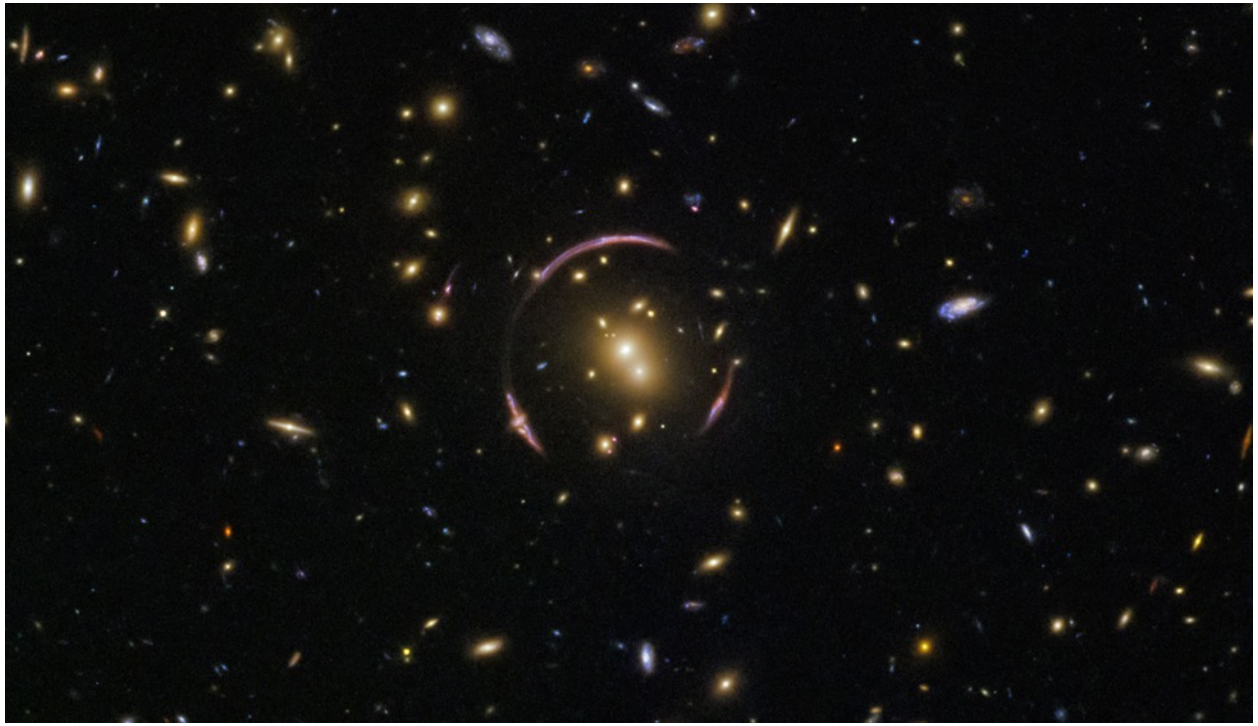


Image credit: ESA/Hubble & NASA

Strong gravitational lensing:

- Prettier
- Much rarer!

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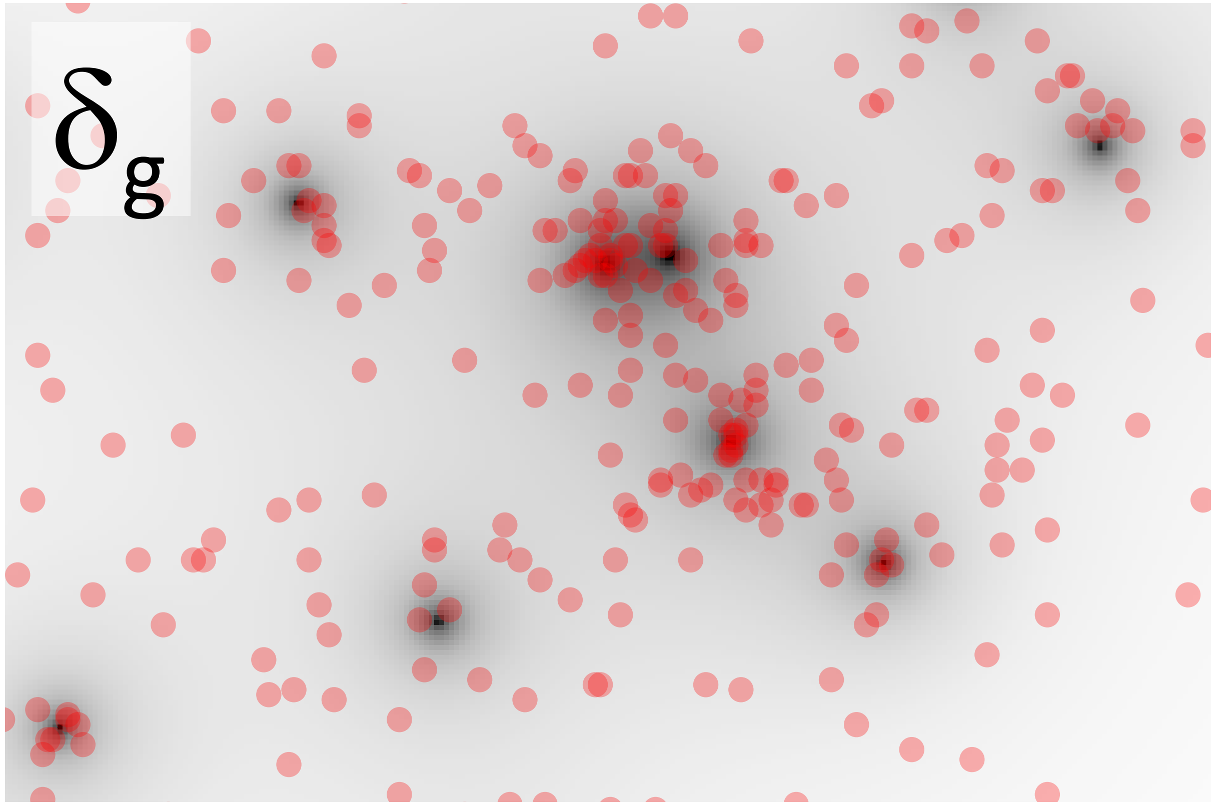
The Observables

We want to access the matter perturbations δ_m (because their e.g. 2-point statistics are sensitive to cosmology)

The Observables



We use two observables to do this:

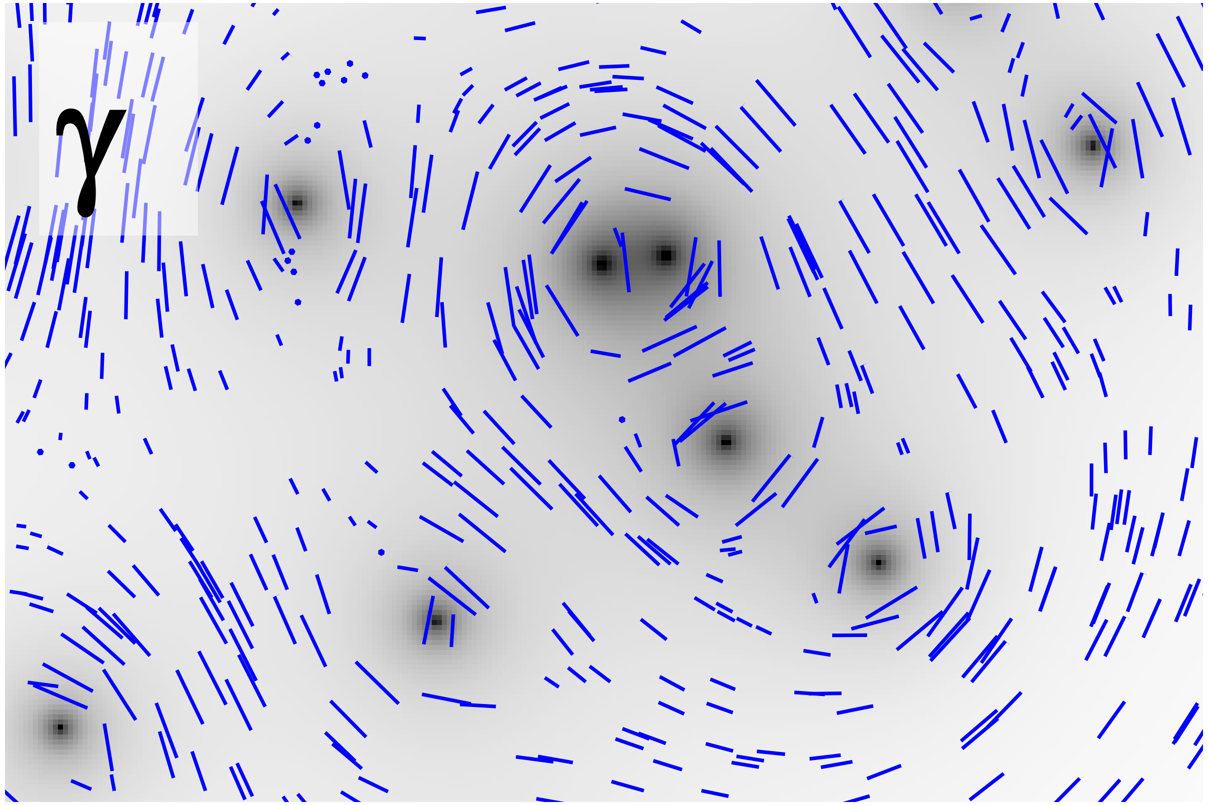
1. δ_g : Counts of galaxies:

$$< \delta_g \delta_g > = b^2 < \delta_m \delta_m >$$

b is the galaxy bias and is unknown…

"galaxy clustering"

The Observables



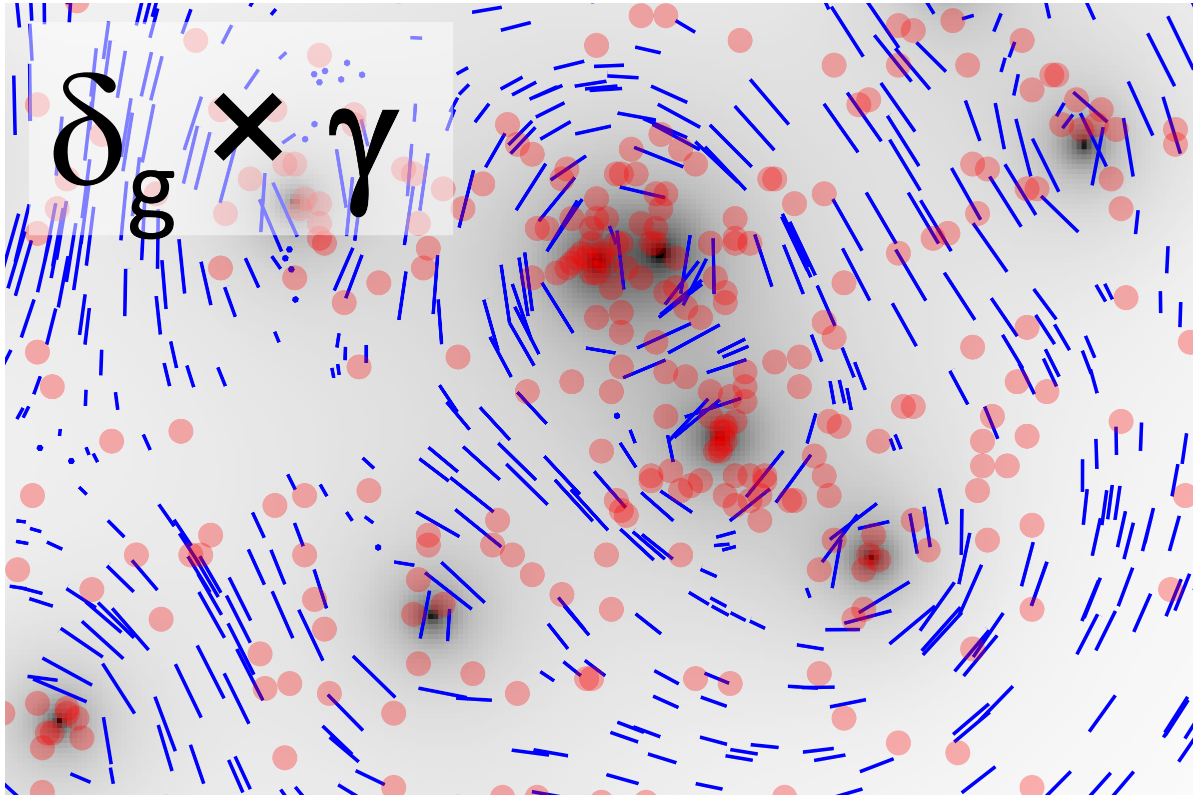
We use two observables to do this:

2. Weak lensing shear, γ:
    - Produces coherent galaxy ellipticities.
    - Depends directly on projected δ_m:

$$< \gamma\gamma > \sim < \delta_m \delta_m >$$

"cosmic shear"

The Observables



We can also use the cross-correlation:

$$< \delta_g \gamma > \sim b < \delta_m \delta_m >$$

Also sensitive to galaxy bias

"galaxy-galaxy lensing"

"Lens galaxies"

"Source galaxies"

The Observables

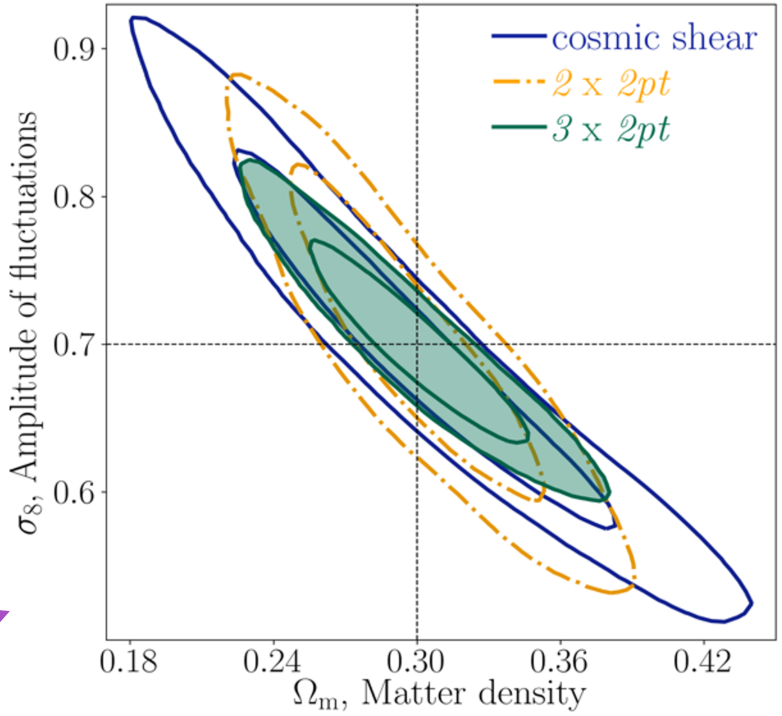
Summarizing, we use…

1. Galaxy number density field δ_g
2. The weak lensing shear field γ

i) $< \gamma\gamma > \sim < \delta_m \delta_m >$

ii) $< \delta_g \delta_g > = b^2 < \delta_m \delta_m >$

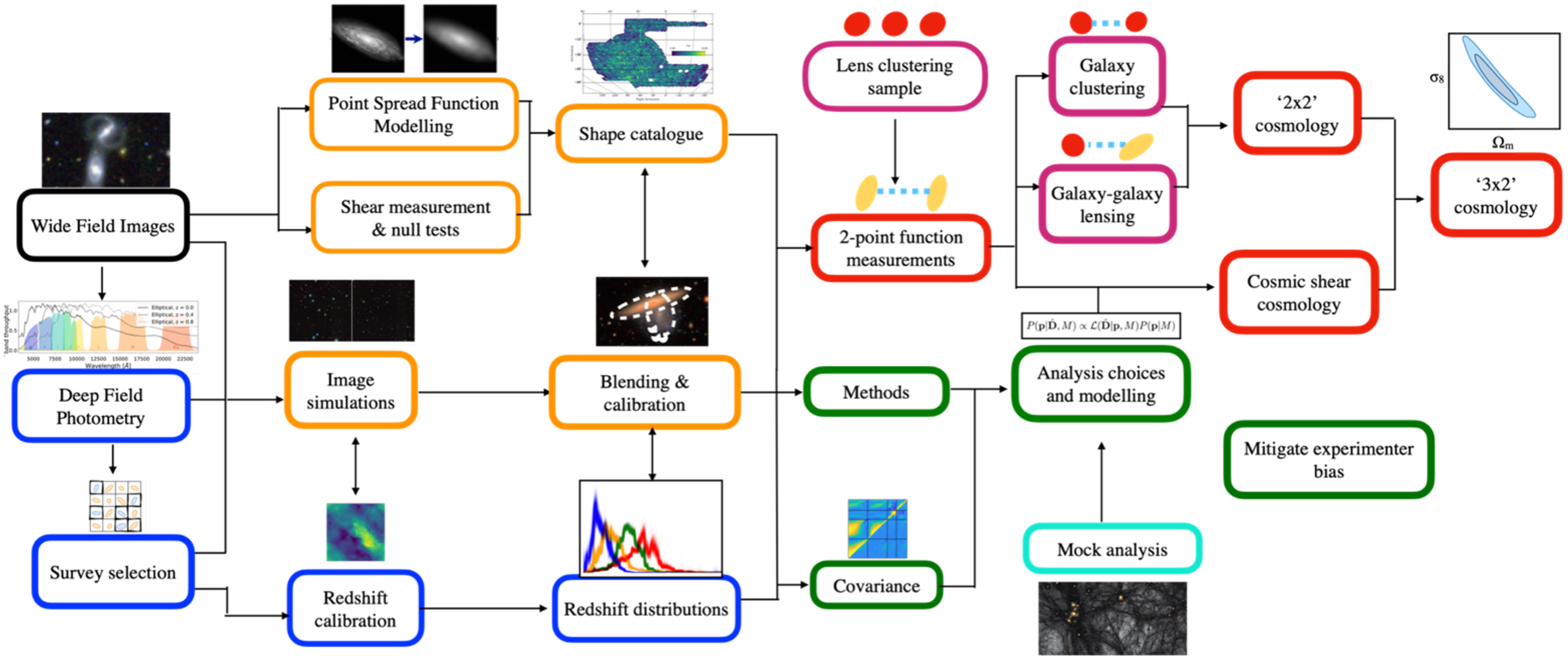
iii) $< \delta_g \gamma > \sim b < \delta_m \delta_m >$



$< \delta_m \delta_m >$

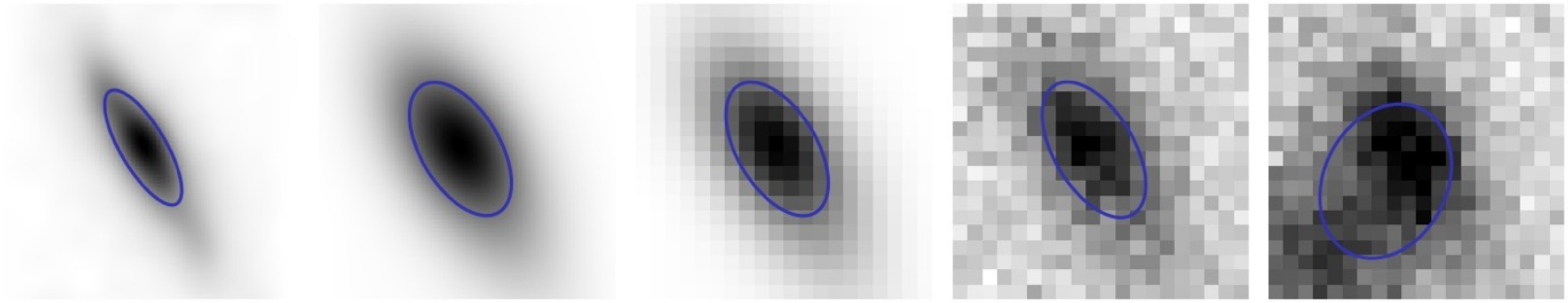
(where <> means 2 point correlation function or power spectrum)

The DES Year 3 analysis



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

The Challenges: Shear estimation



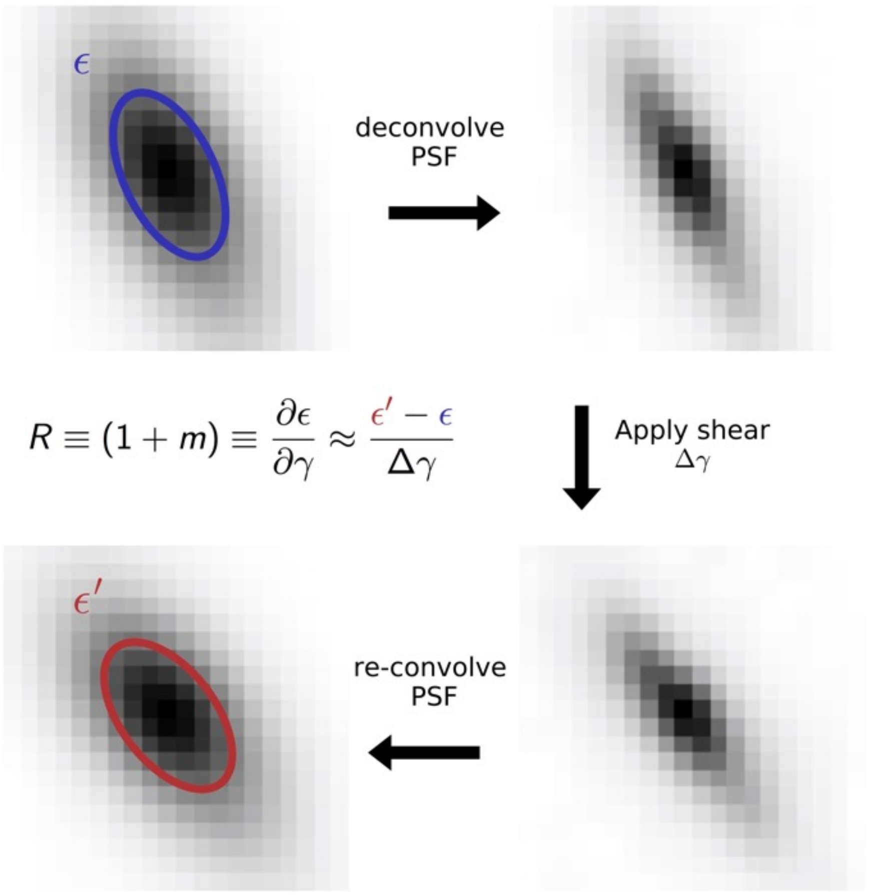
Galaxy images have:

- Complex morphologies (ellipticity not uniquely defined)
- Blurring due to the atmosphere / telescope optics
- Noise
- Blending

Shear estimation biases parameterized as

$$\left\langle \epsilon^{\mathrm{obs}} \right\rangle = (1+m)\left\langle \gamma \right\rangle + c$$

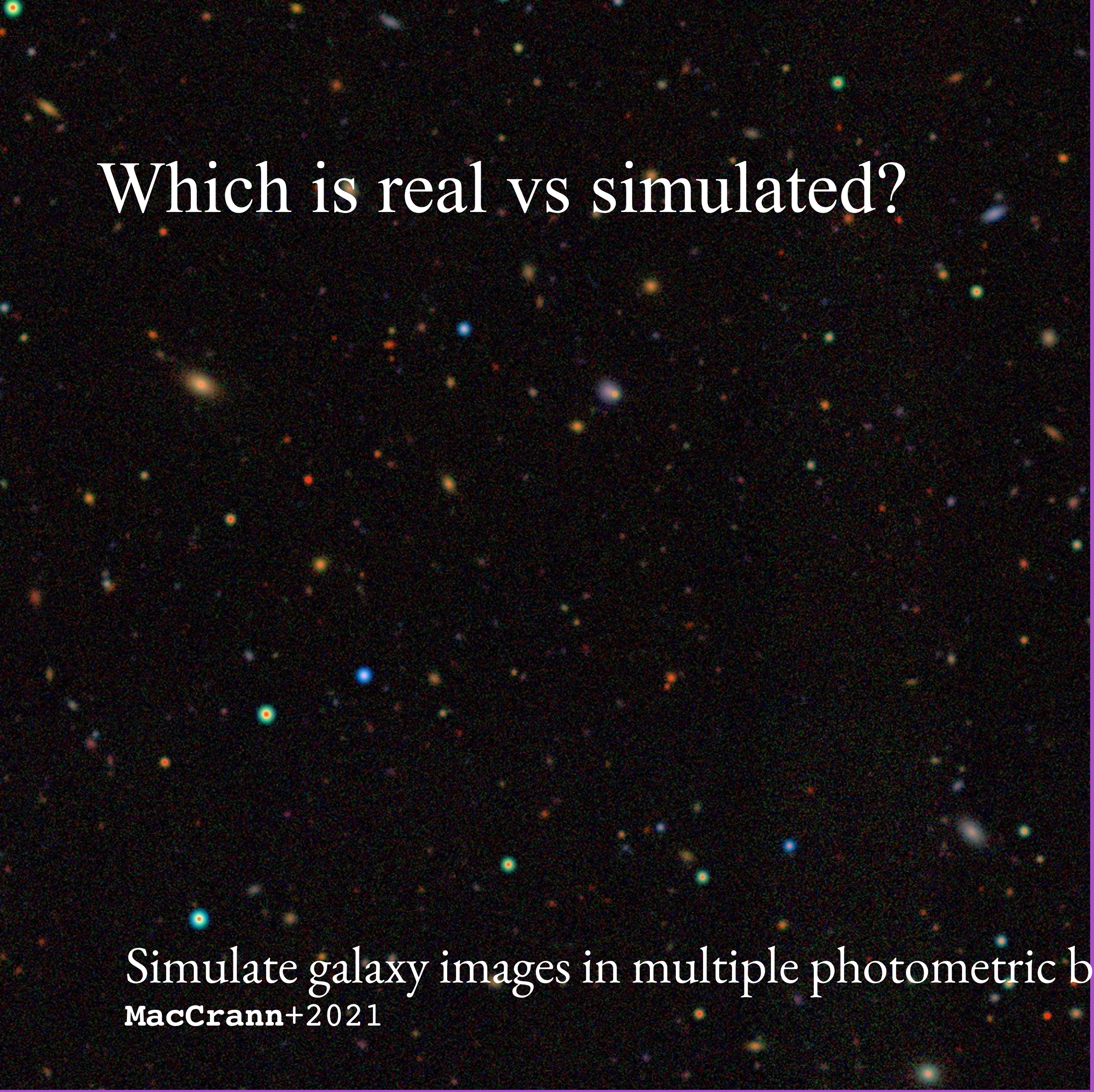
The Challenges: Shear estimation

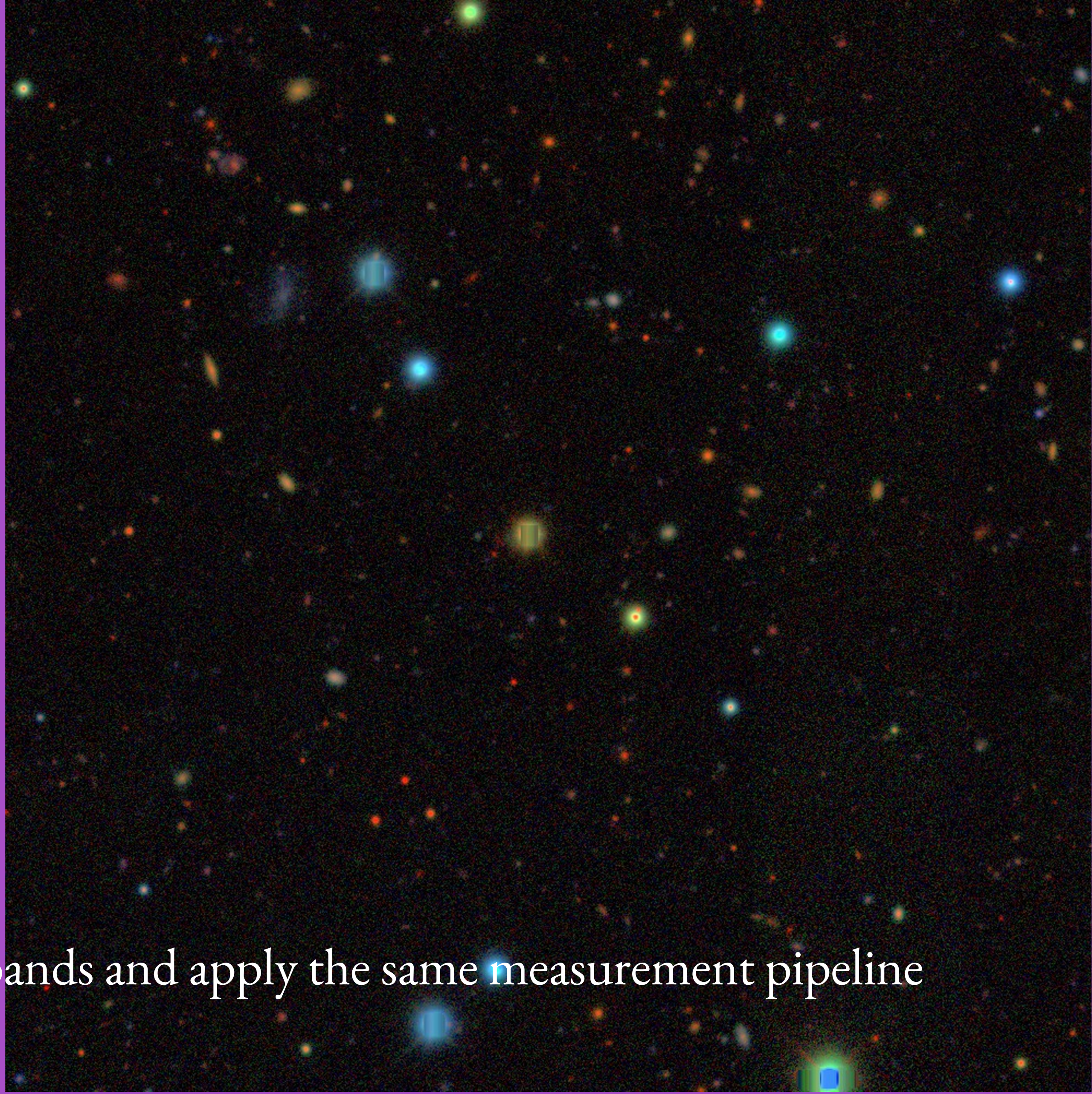


Metacalibration

- A method for calibrating the shear estimate without requiring complex calibration simulations (Huff & Mandelbaum 2017, Sheldon & Huff 2017).
- Generalized to full scenes in Sheldon, Becker, NM et al. 2020.
- But for blends between galaxies at different redshifts, calibration simulations still required.

Which is real vs simulated?

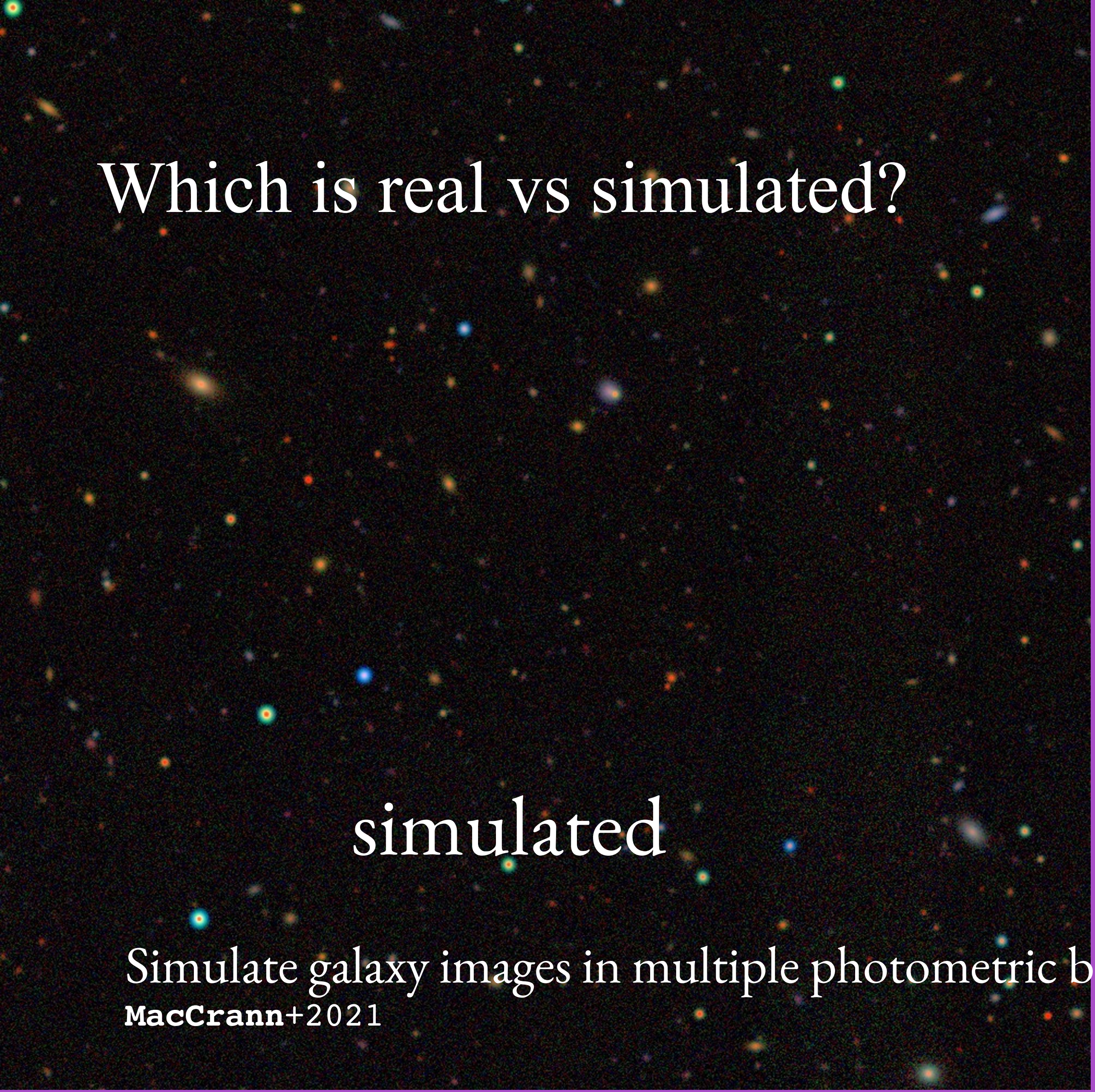


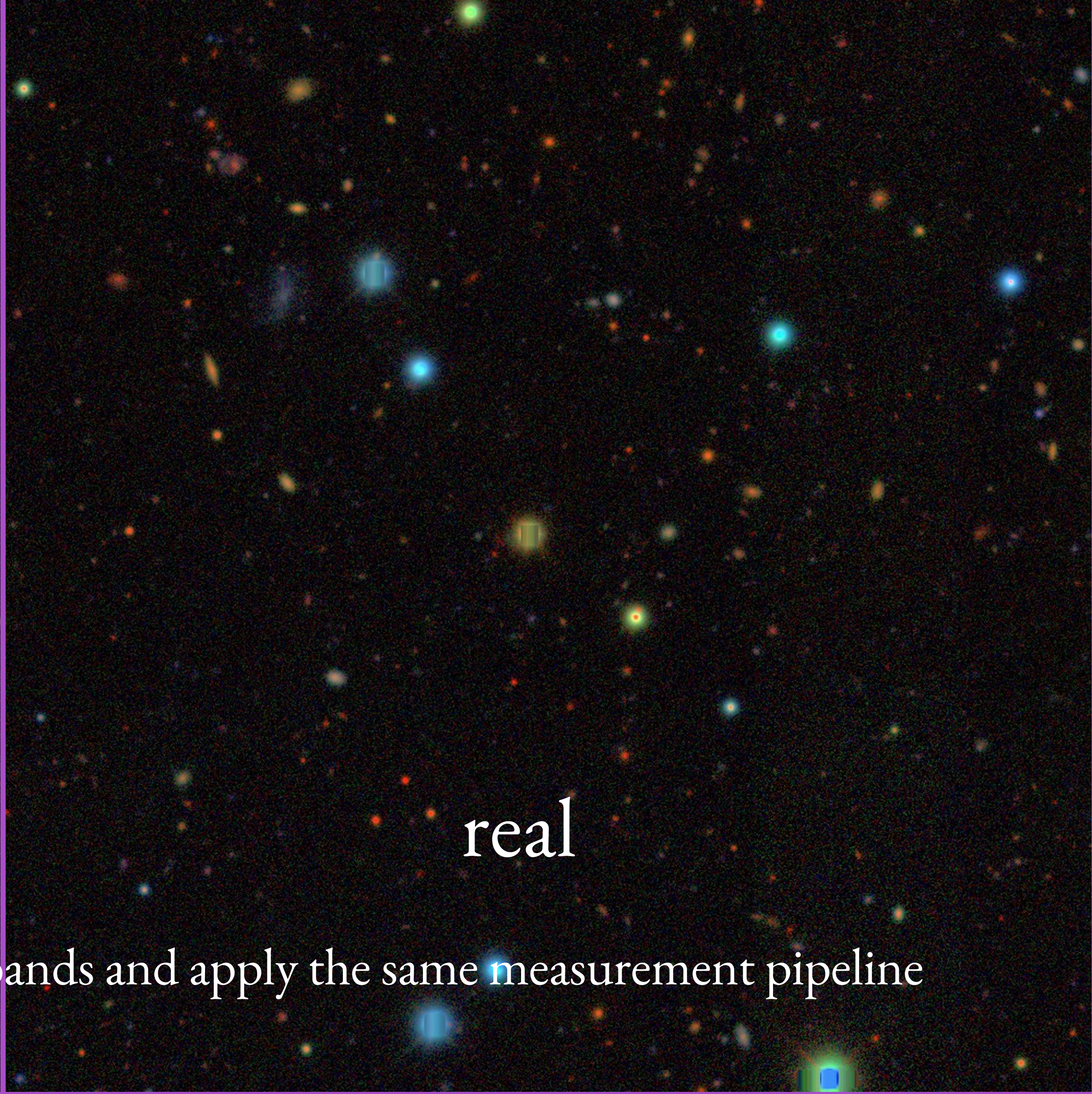


Simulate galaxy images in multiple photometric bands and apply the same measurement pipeline

MacCrann+2021

Which is real vs simulated?





Simulate galaxy images in multiple photometric bands and apply the same measurement pipeline
MacCrann+2021

Calibrate shear biases with image simulations

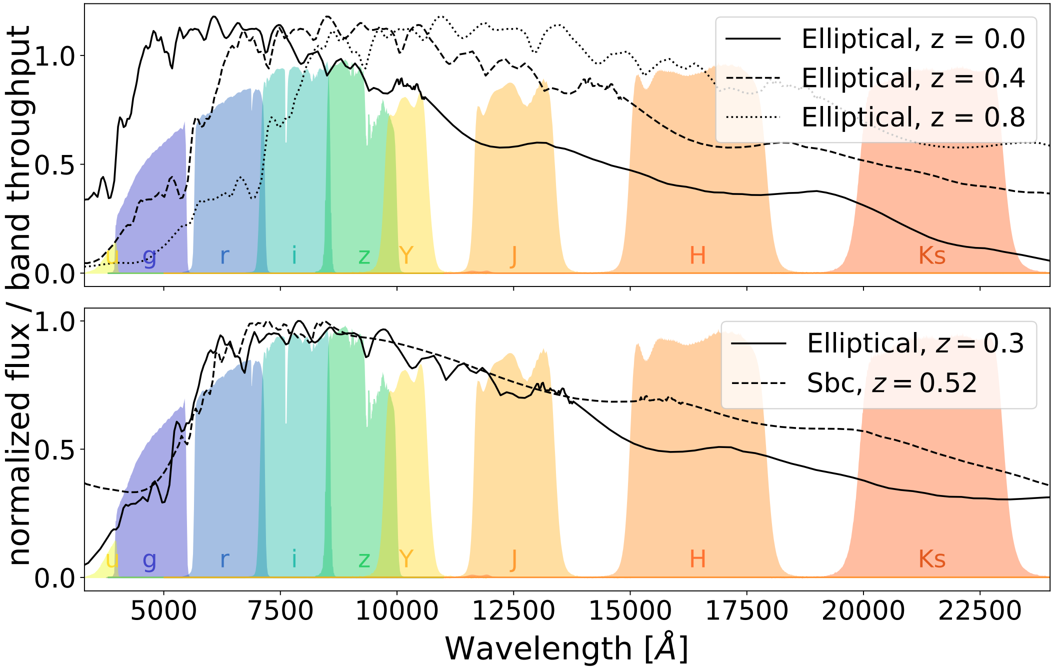
$$\underbrace{\bar{\epsilon}^{\text{obs}}}_{\textit{observed ellipticity}} = (1 + \underbrace{m}_{\textit{multiplicative error}})\ \overbrace{\bar{\gamma}}^{\textit{lensing shear}} + \underbrace{c}_{\textit{additive error}}$$

- Few percent multiplicative biases **due to blending** (-1.5 to -4% depending on redshift bin)
- Joint impact of blending on shear and photo-z characterized by **effective redshift distribution**

$$\bar{\epsilon}^{\text{obs}} = \int \mathrm{d}z\, n_\gamma(z)\gamma^{\text{true}}(z) + c + \text{noise}$$

MacCrann+2021

The Challenges: Redshift estimation



Buchs et al. 2019

- Accurate redshift distributions n(z) required for theoretical predictions.
- Imaging surveys have a limited number of bands.
- Redshifts estimated from this very crude spectrum.
- Degeneracy between galaxy type and redshift

The Challenges: Redshift estimation

- In Year 3 we used a novel "SOMPZ" method (see Buchs et al. 2019, Alarcon et al. 2019, Myles et al. 2021).

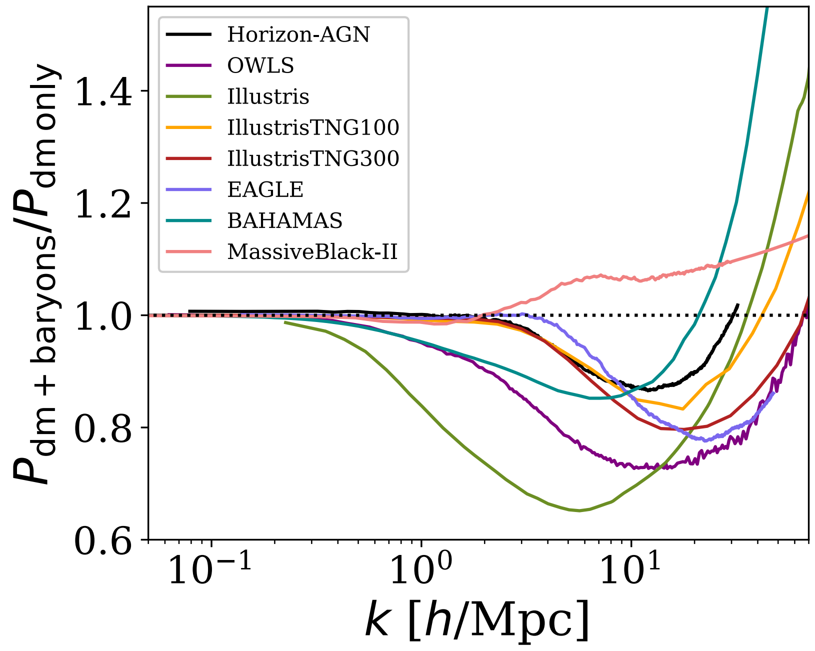
- DES also has a smaller (~30 deg^2) deep survey which has overlap with near infrared data (J, H, Ks bands – see Hartley, Choi et al. 2021). In this area, highly accurate and precise redshift estimation is possible. One can leverage this information via

$$\underbrace{P(z|\text{wide flux})}_{\text{Accurate redshifts in wide fields}} = \int dz \underbrace{P(\text{wide flux}|\text{deep flux})}_{\text{Survey transfer function}} \underbrace{P(z|\text{deep flux})}_{\text{Precise redshifts in deep fields}}$$

The Challenges: Theoretical Predictions

- Weak lensing observables are sensitive to the small-scale matter power spectrum (k>1 h/Mpc). Galactic astrophysics ("Baryonic effects"), affects the matter distribution here, much harder to simulate than gravity-only sims.
- Nonlinear galaxy bias and intrinsic alignments becoming important:

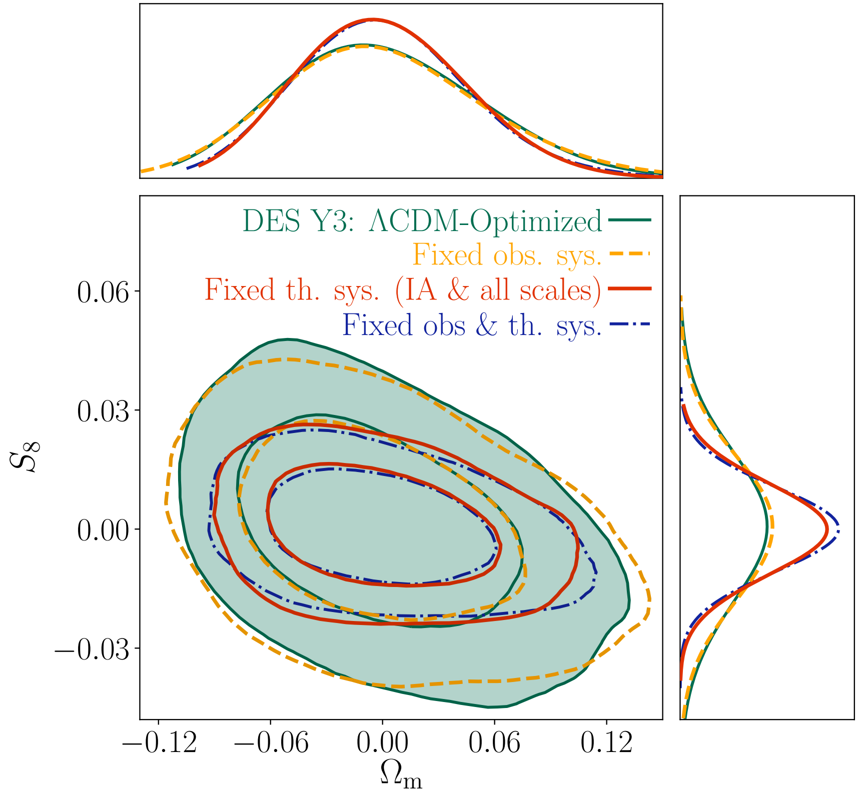
$$\delta_g = b_1\delta_m + b_2^2\delta_m^2 + \text{other } O(\delta_m^2) + O(\delta_m^3) + \ldots$$



Chisari et al. 2019

The Challenges: Theory Predictions

- We largely address these issues by throwing away information!
  - Conservative scale cuts (see Krause et al. 2021 and Secco & Samuroff 2021)
  - Extra nuisance parameters (see Pandey et al. 2019 for nonlinear bias model)
  - Analytic marginalization schemes (see NM et al. 2019 for "point-mass" marginalization)
- Theoretical uncertainties were our limiting systematics for DES Y3 cosmic shear



Amon et al. 2021

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Drumroll….

The Results: Internal consistency

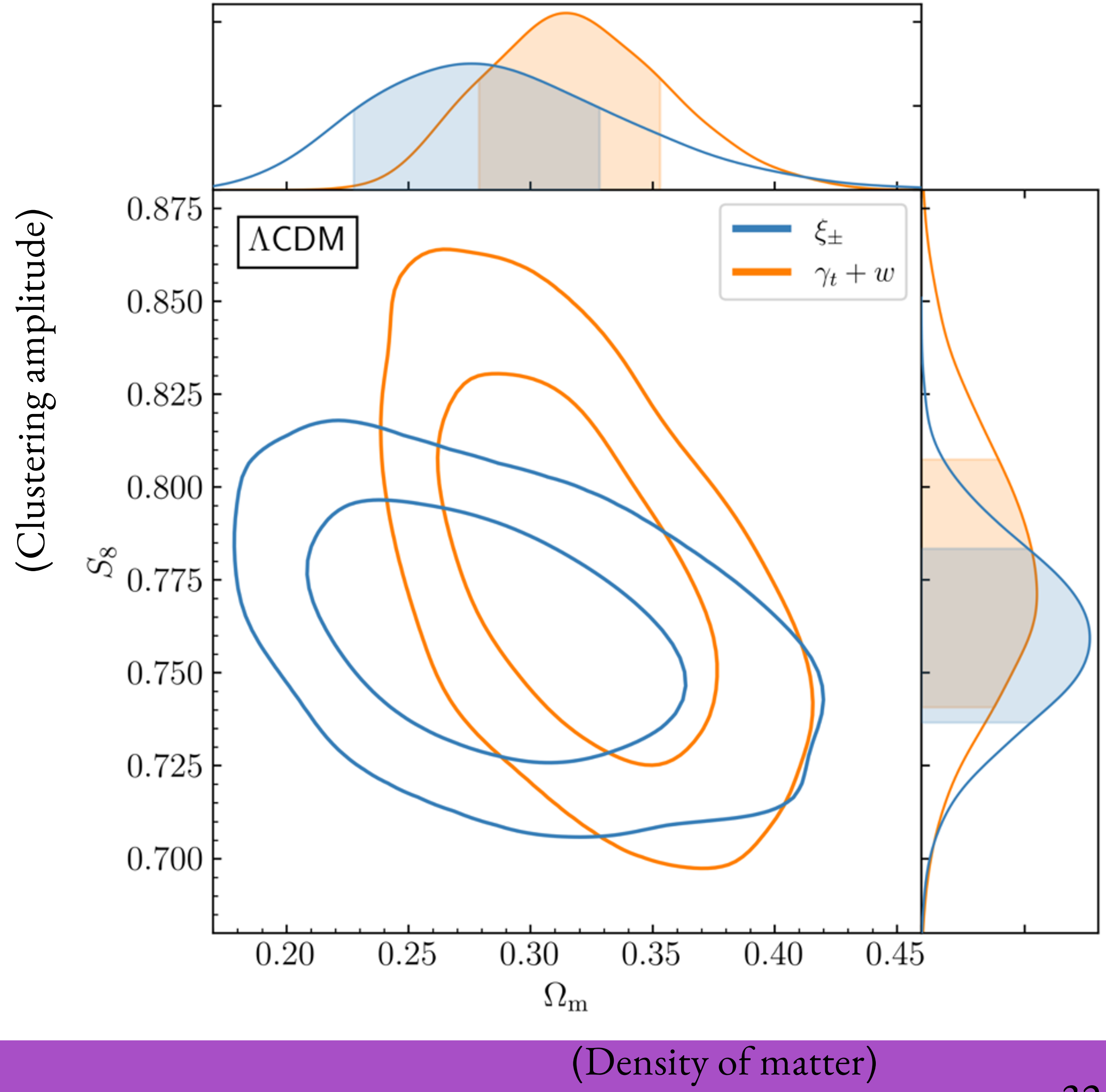
Two correlated cosmological probes:

1. **Cosmic shear** (blue)
2. **Galaxy clustering** and **tangential shear** (orange)

We find consistency between them.

Cosmic shear most sensitive to clustering amplitude.

Galaxy clustering and tangential shear more sensitive to total matter density.



The Results: 3x2pt

- Combine these into the **3x2pt** probe of large-scale structure.
- Factor of 2 improvement in constraining power w.r.t. DES Year 1.

In ΛCDM:

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

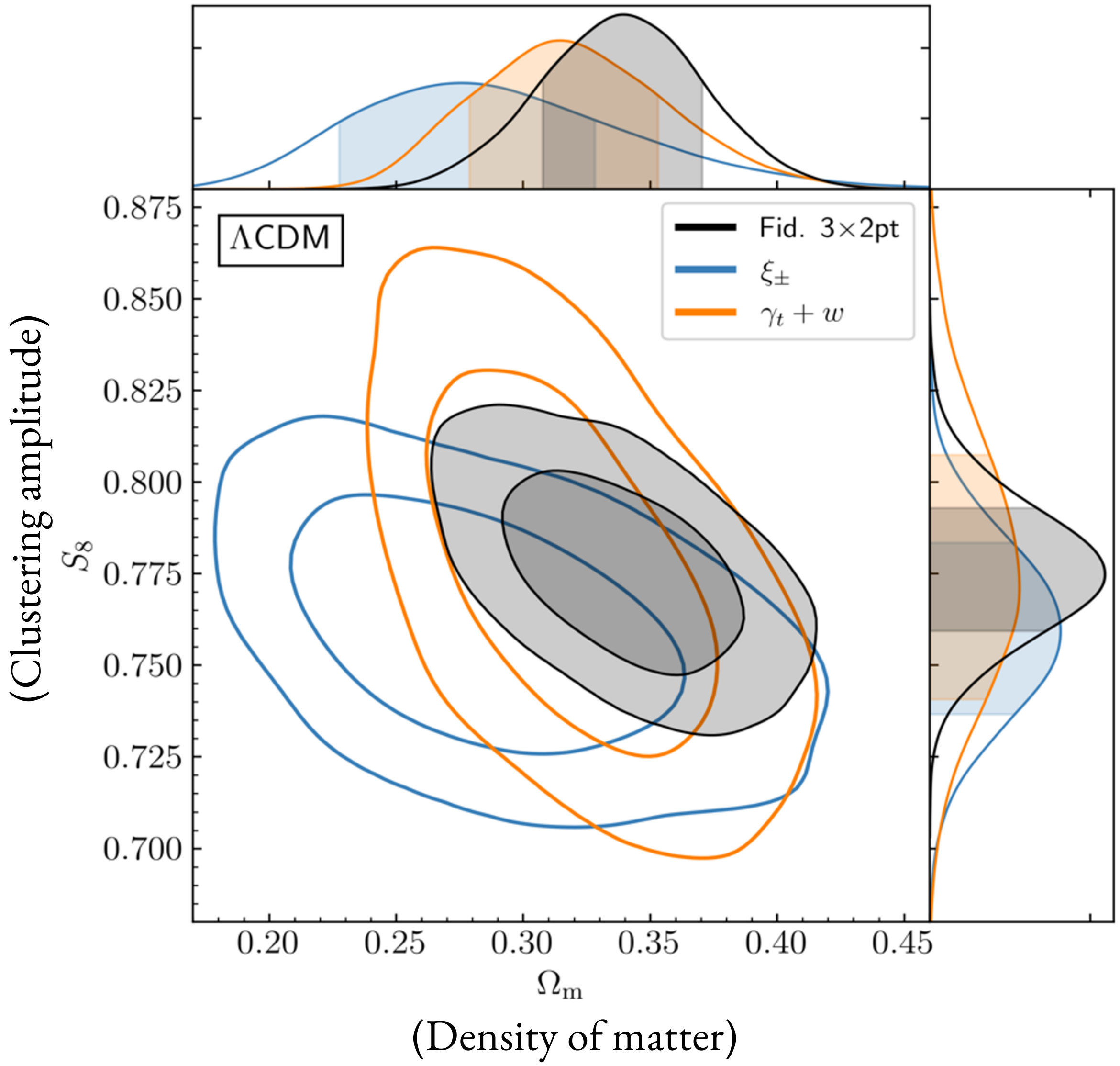
$$\Omega_\mathrm{m} = 0.339^{+0.032}_{-0.031} \quad (0.372)$$

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

In *w*CDM:

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

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

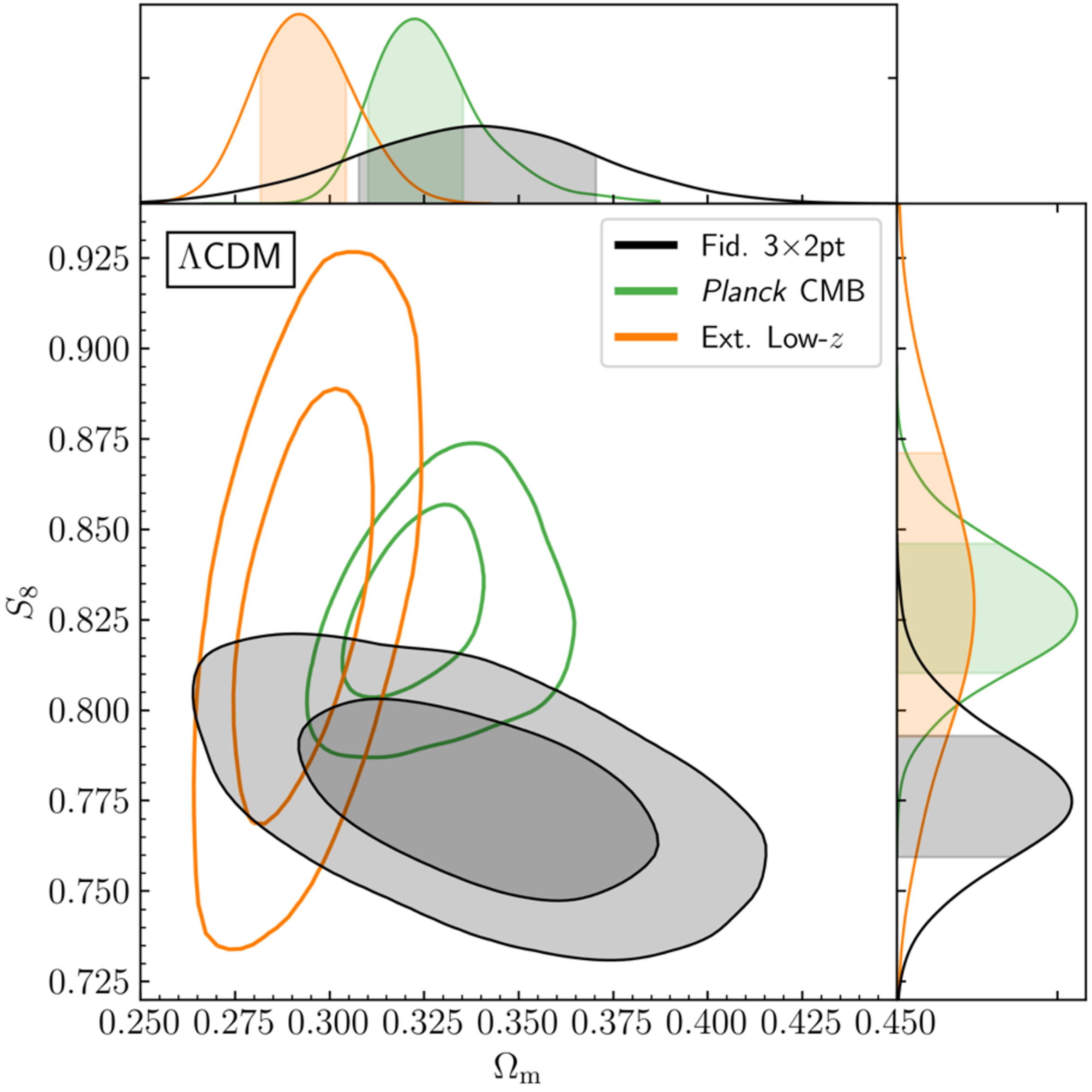


The Results: Consistency in ΛCDM

We construct three independent data sets:

1. Weak lensing and clustering from DES (**3x2pt**)
2. The combination of other low-redshift **non-lensing** data (Ext. Low-*z*): SNe Ia, BAO, RSD.
3. Planck CMB

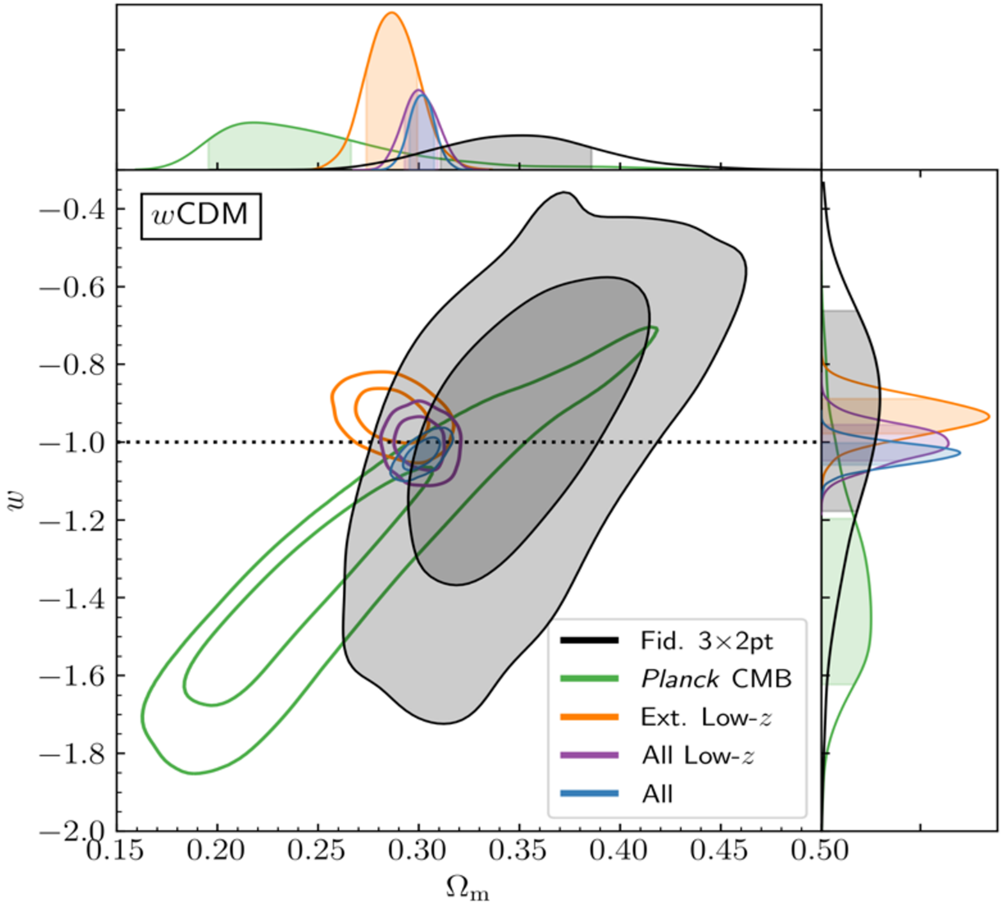
- No significant evidence of inconsistency between **DES Y3 3x2pt** and *Planck* CMB (0.7-1.5σ or p=0.13-0.48)



The Results: Dark Energy

- 3% constraint on *w* when combined with external datasets
- No evidence for *w*!=-1 (i.e. consistent with cosmological constant)

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



Open Questions….

- We found indications of systematic effects in some of the lens redshift bins. More work required on sample selection and characterization for **angular** clustering analyses
- Meanwhile the weak lensing constraints are significantly degraded by our conservative intrinsic alignment modeling choice – can we use priors from simulations or external data to improve on this for Y6 / LSST?
- How much can going beyond 2-point statistics improve constraining power to further test ΛCDM? Some papers exploring this are in prep.

Papers available at: https://www.darkenergysurvey.org/des-year-3-cosmology-results-papers/

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.

List of participants
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Eleonora di Valentino
Lucas Secco
Ji Won Park
Andrew Pace

Alex Drlica-Wagner
Simon Birrer
Brian Yanny
Sahar Allam
Scott Dodelson
Jim Annis
Andras Kovacs
Hugo Camacho
Kai Hoffmann
Mandeep Gill
Jonathan Blazek
Lucas James Faga
Joe Zuntz
Steve Kent
Martin Crocce
Spencer Everett
Juan Estrada
Donald Petravick
Hung-Jin Huang
Yuanyuan Zhang
Georgios Zacharegkas
Shivam Pandey
Helen Qu
Eric Baxter
Jack Odonnell
Sebastian Bocquet