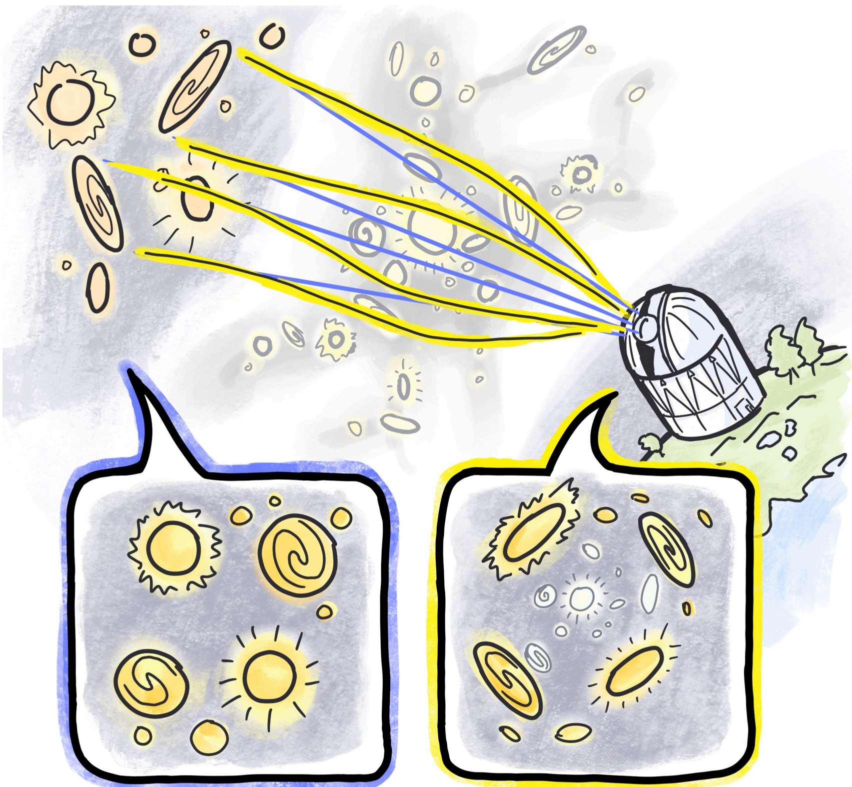
From Pixels to Parameters

- Part 1: Galaxy Surveys
  - Galaxies beyond the point-particle picture
- Part 2: From Pixels to Power Spectra
  - Systematics, estimators & covariances
- Part 3: From Power Spectra to Parameters
  - Inference & error bars you can trust
- **Part 4: Weak Lensing**
  - **Galaxies beyond the spin-2 field picture**

Weak Lensing of Galaxies



Photons emitted by distant galaxies is deflected by tidal field along line of sight.

The shape distortion of galaxies is called (gravitational) shear:
$\epsilon \approx \epsilon_{\rm int} + \gamma$

Statistical properties of the shear reflect statistical properties of the density field.

Deflection angle
$$\alpha^i(\vec{\theta}) = 2\int_0^{\chi_{\rm s}} d\chi' \, \Phi_{,i}(\mathbf{x}(\vec{\theta},\chi')) \left(1 - \frac{\chi'}{\chi_{\rm s}}\right)$$

Lensing potential
$$\psi(\vec{\theta}) \equiv 2\int_0^{\chi_{\rm s}} \frac{d\chi'}{\chi'} \Phi(\mathbf{x}(\vec{\theta},\chi')) \left(1 - \frac{\chi'}{\chi_{\rm s}}\right)$$

Born approx: evaluate along unperturbed path

Image Distortions

Image distortions occur when the deflection angle varies with position/across the image.
Consider Jacobian of transformation from source to image plane

$$A_{ij}(\boldsymbol{\theta}) \equiv \frac{\partial \beta_i}{\partial \theta_j} = \delta_{ij} - \frac{\partial \alpha_i}{\partial \theta_j}$$

Most general form: $$A_{ij} = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix}$$

$\gamma_{1,2}$ Cartesian components of **shear**

Image Distortions

Light deflection does not involve any emission or absorption processes, hence

$$I(\boldsymbol{\theta}) = I^s[\boldsymbol{\beta}(\boldsymbol{\theta})]$$

For a small source, centered on $\boldsymbol{\beta}_0 = \boldsymbol{\theta}_0 - \boldsymbol{\alpha}_0$

$$I(\boldsymbol{\theta}) = I^s[\boldsymbol{\beta}_0 + A(\boldsymbol{\theta}_0) \cdot (\boldsymbol{\theta} - \boldsymbol{\theta}_0)]$$

Hence the image of a small circular source with radius r is an **ellipse with semi-axes r $\boldsymbol{\lambda}_{1,2}$**, with $\boldsymbol{\lambda}_{1,2}$ the eigenvalues of A, and **orientation determined by the shear components $\gamma_{1,2}$**

Magnification

$$A_{ij} = \begin{pmatrix} 1-\kappa-\gamma & 0 \\ 0 & 1-\kappa+\gamma \end{pmatrix}$$

$$a_{\rm source} = \det(A)a_{\rm image} \qquad \det(A) = (1-\kappa)^2 - \gamma^2 \approx 1 - 2\kappa$$

$$a_{\rm image} = \mu a_{\rm source} \qquad \mu = \frac{1}{(1-\kappa)^2 - \gamma^2} \approx 1 + 2\kappa$$

- Sources are **magnified** by gravitational lensing.

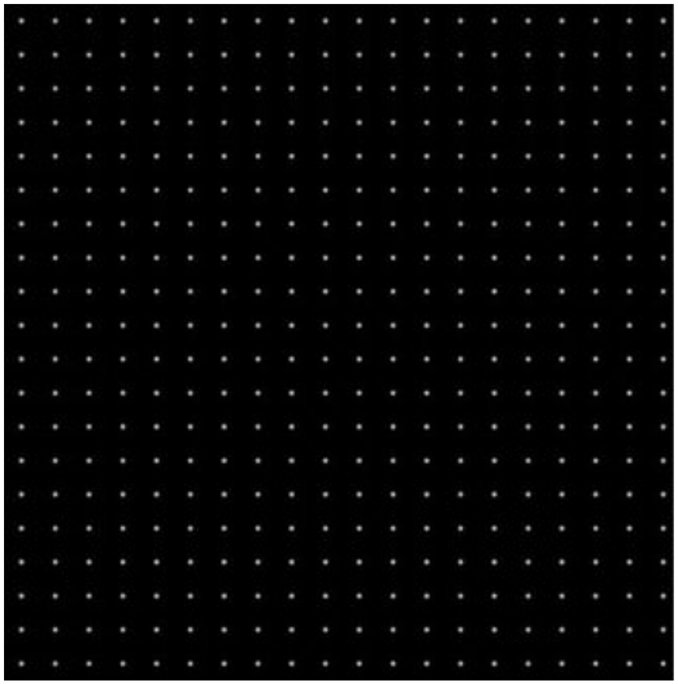
Lensing Distortions Summary

Lensing distorts a source in three ways:

- It shears the image, expanding one axis while contracting the other.
- It magnifies the image, making objects appear larger and brighter.
- Magnification

Note: lensing always preserved surface brightness.

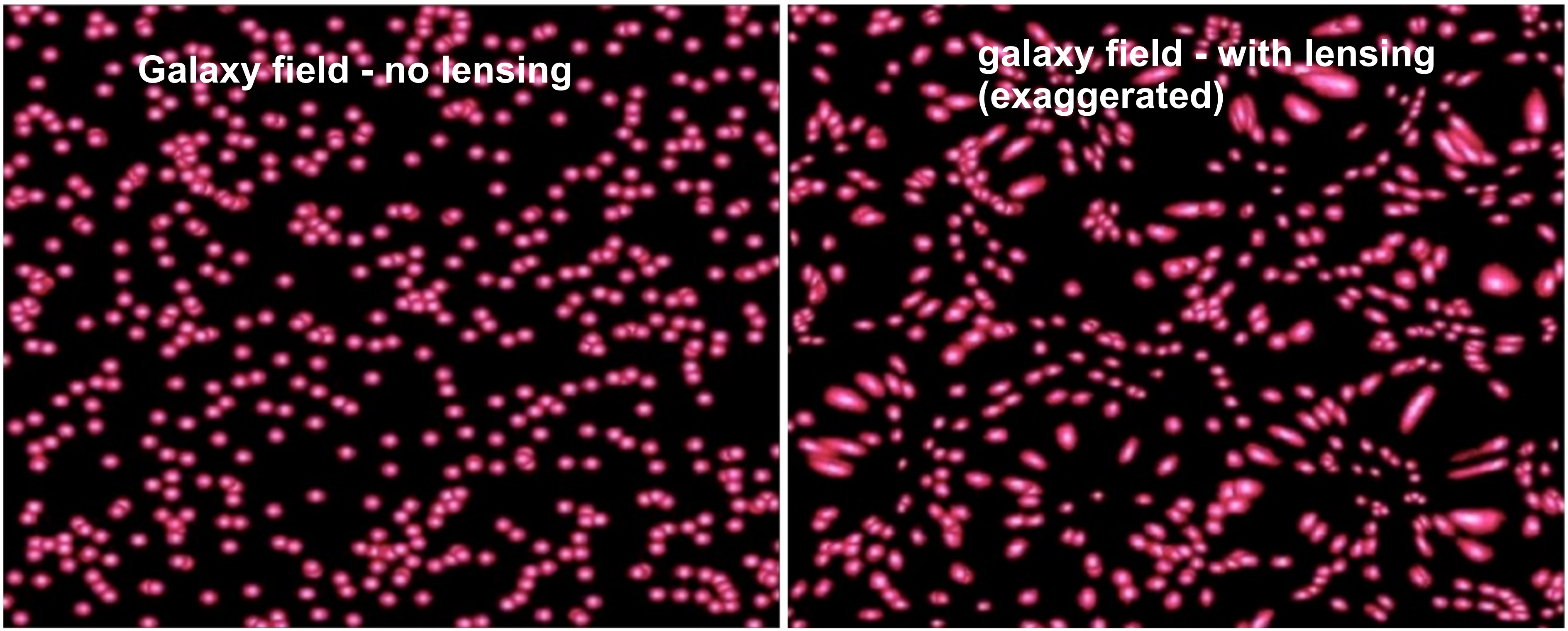
Lensing Distortions Summary



- Shear distorts the object's shape, expanding one axis while contracting the other.
- Magnification changes the size and brightness.
- Magnification changes the apparent density of sources.

Measuring Lensing

We could try to measure lensing using the various observational signatures.



What do we know about the unlensed galaxy properties?

Measuring Lensing

We could try to measure lensing using the various observational signatures:

- Magnification makes sources larger and brighter.
- Magnification changes the density of sources.
- Shear changes the ellipticity of sources.

Of these, the only one we "know" *a priori* is ellipticity: on average, galaxies have random ellipticities*!

Coherent distortions must be due to lensing*.

*Exception: intrinsic alignments

Calculating Convergence

For single source plane at z_s

$$\kappa(\boldsymbol{\theta}) = \frac{3H_0^2\Omega_m}{2}\int_0^{\chi_s} d\chi' \frac{\chi'}{a(\chi)}\left(1-\frac{\chi'}{\chi_s}\right)\delta_m(\mathbf{x}(\boldsymbol{\theta},\chi')) \equiv \int_0^{\chi_s} d\chi' W(\chi')\delta_m(\mathbf{x}(\boldsymbol{\theta},\chi'))$$

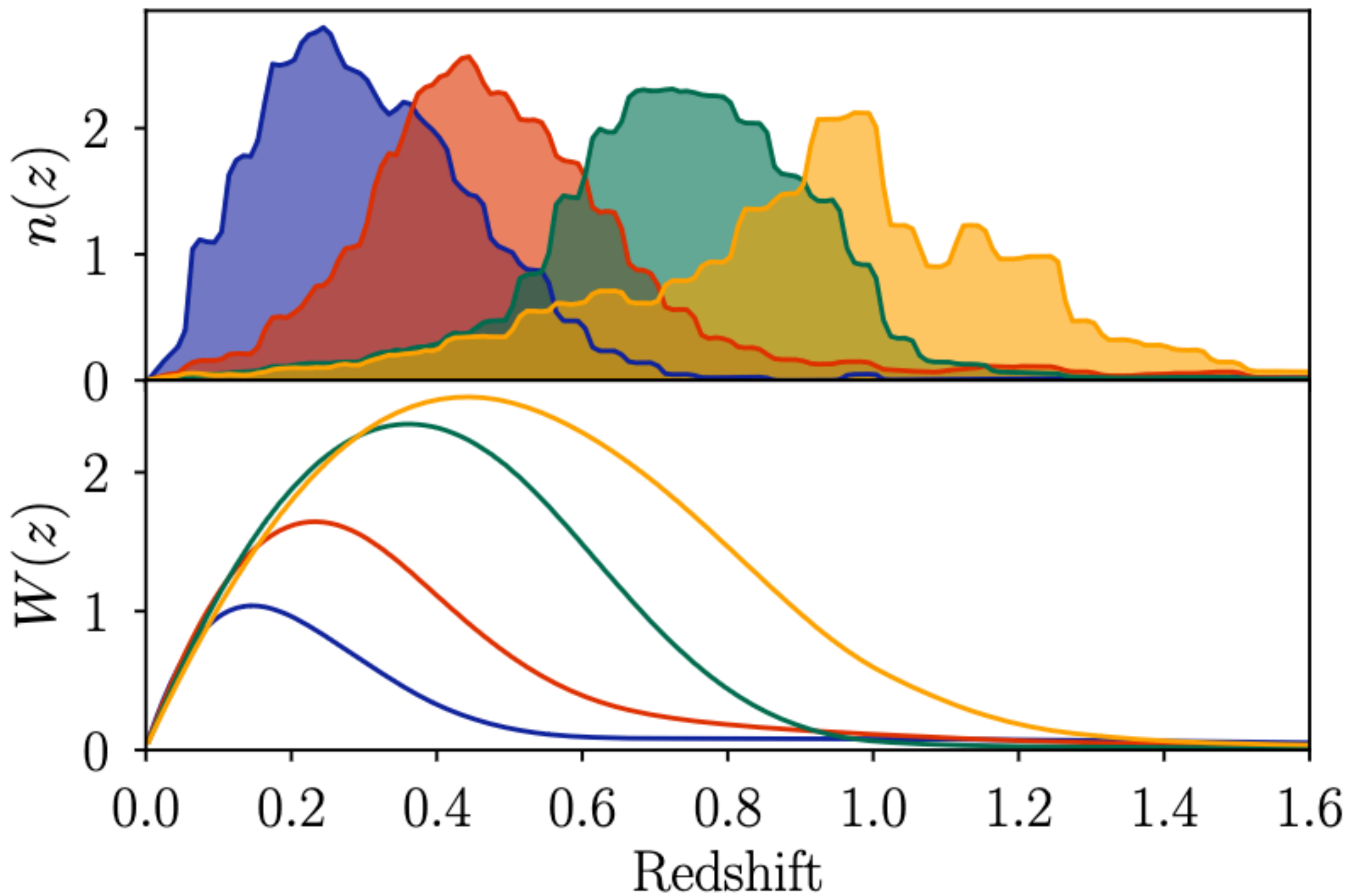
Average over tomographic source redshift distribution

$$W^i(\chi) = \frac{3H_0^2\Omega_\mathrm{m}}{2c^2}\frac{\chi}{a(\chi)}\int_\chi^{\chi_\mathrm{H}} d\chi' \, n^i\left(z(\chi')\right)\frac{dz}{d\chi'}\frac{\chi'-\chi}{\chi'}$$

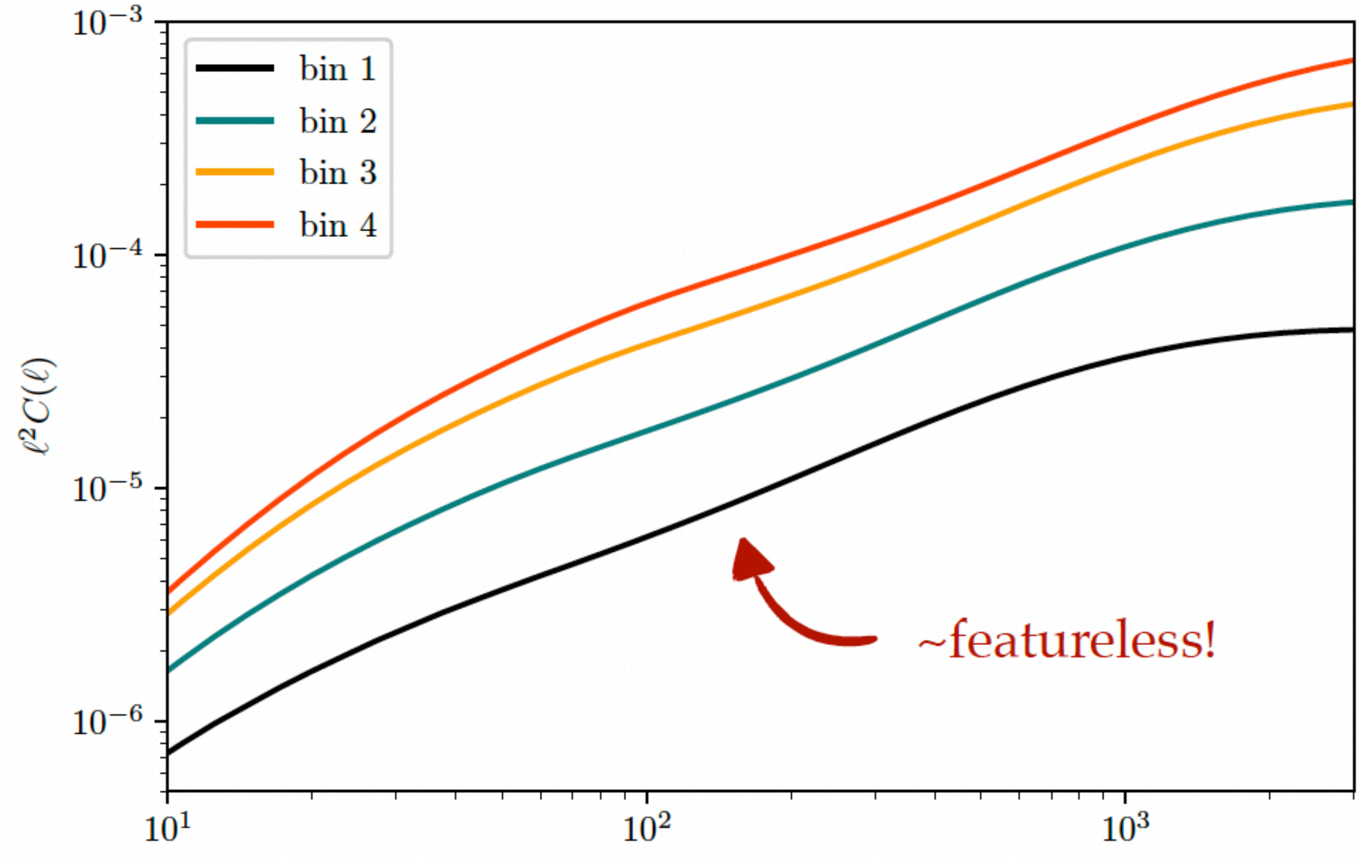
Calculate power spectrum with Limber approximation

$$C_\kappa^{ij}(\ell) = \int_0^{\chi(z_\mathrm{max})} d\chi \frac{W^i(\chi)W^j(\chi)}{\chi^2} P_\delta\left(\frac{\ell+1/2}{\chi}, z(\chi)\right)$$

Tomographic Lensing



Tomographic Lensing Power Spectra



$$C_\kappa^{ij}(\ell) = \int_0^{\chi(z_{\max})} d\chi \frac{W^i(\chi)W^j(\chi)}{\chi^2} P_\delta\left(\frac{\ell + 1/2}{\chi}, z(\chi)\right)$$

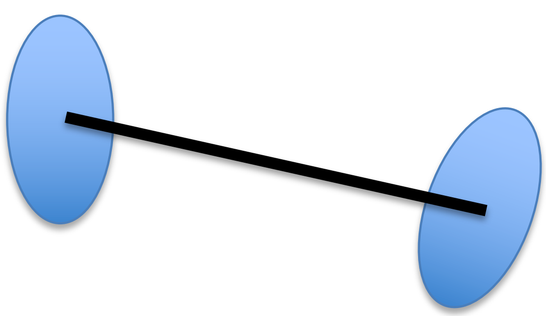
Integrate over lots of redshift slices of P(k) to get the projected 2D lensing power spectrum.

Tangential and Cross Shear

x-axis is defined by line connecting the two galaxies.

$$\gamma_{\rm T} = \text{Shear along } x - \text{axis}$$

$$\gamma_{\times} = \text{Shear perpendicular to } x - \text{axis}$$



Shear correlation function:

$$\xi_{\pm}(\theta) \equiv \langle \gamma_{\rm T} \gamma'_{\rm T} \rangle \pm \langle \gamma_{\times} \gamma'_{\times} \rangle$$

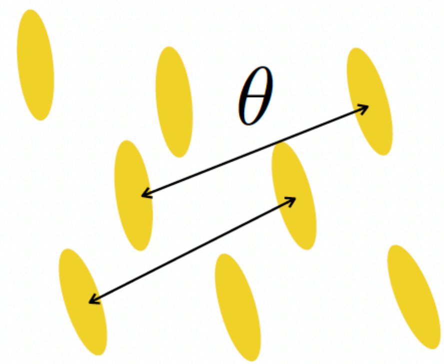
$\langle \gamma_{\rm T} \gamma'_{\times} \rangle = 0$ Parity

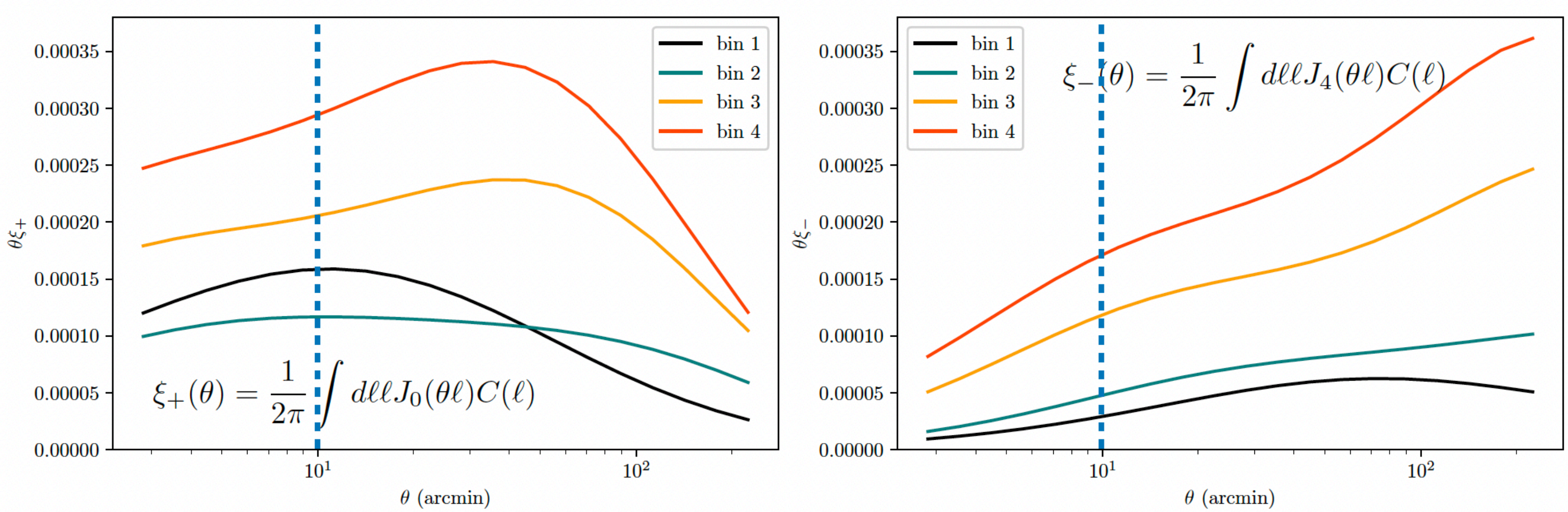
The shear correlation function is a well-defined observable!

Shear Correlation Functions

$$\xi_{\pm}(\theta) = \frac{\sum w^i w^j (\gamma_t^i(\theta_0)\gamma_t^j(\theta_0+\theta) \pm \gamma_\times^i(\theta_0)\gamma_\times^j(\theta_0+\theta))}{\sum w_i w_j}$$

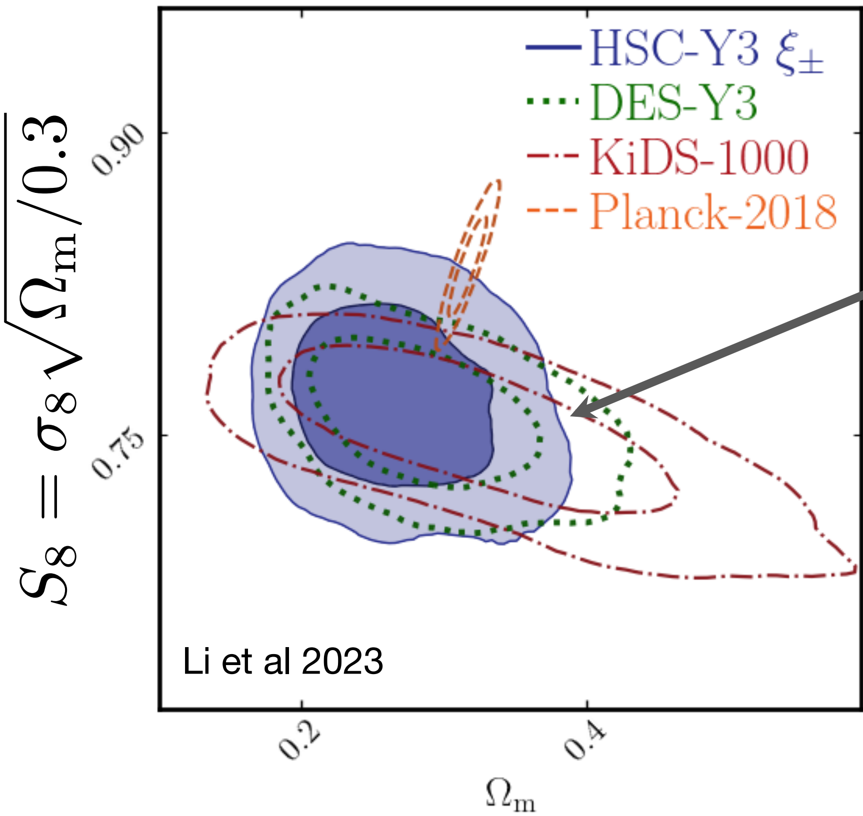
$$= \frac{1}{2\pi}\int d\ell \ell J_{0/4}(\theta\ell) C_\gamma(\ell)$$

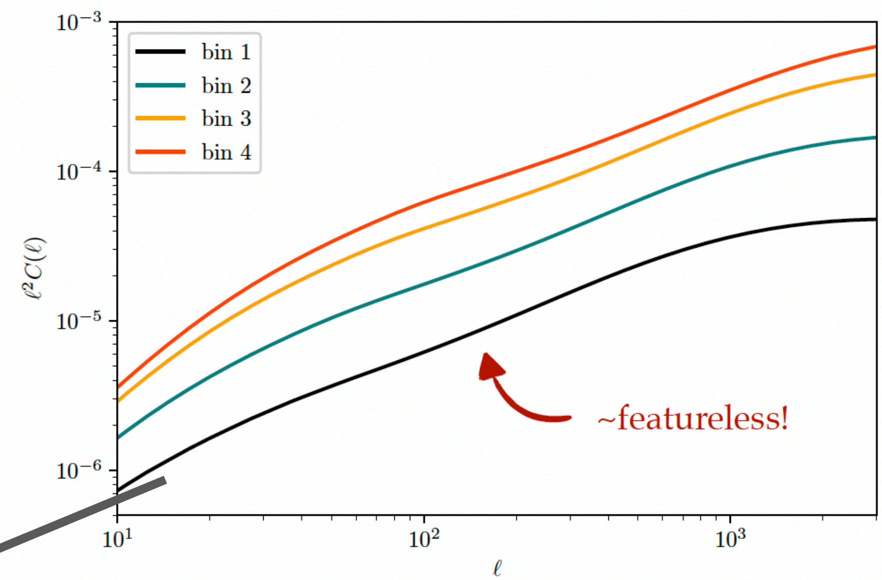




Interpreting Weak Lensing Measurements

Cosmic Shear
(lensing of galaxies)

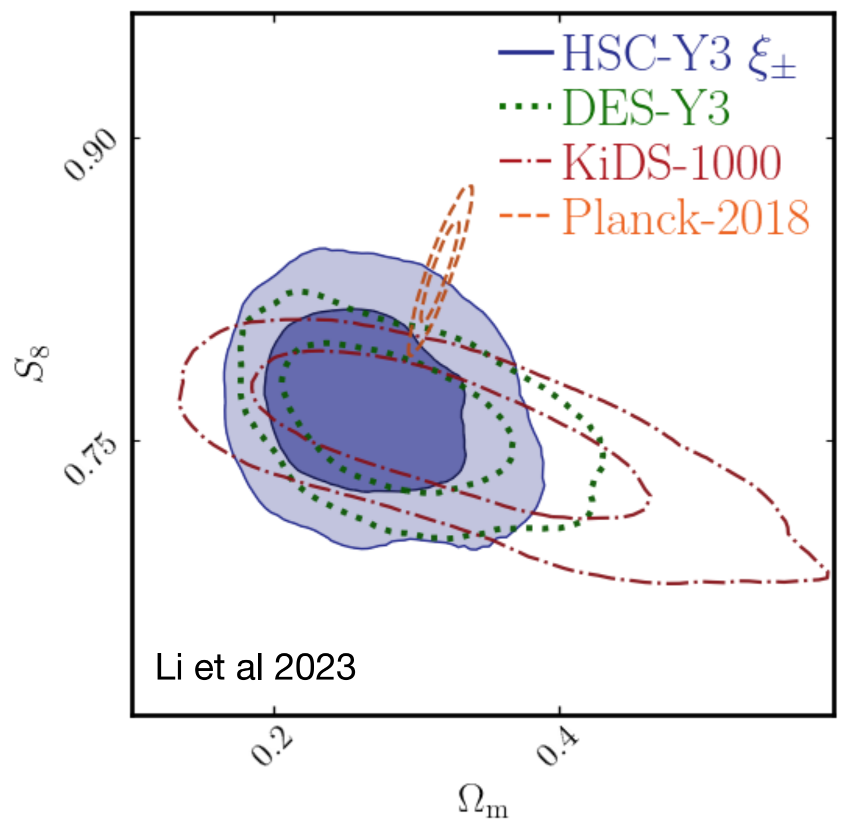




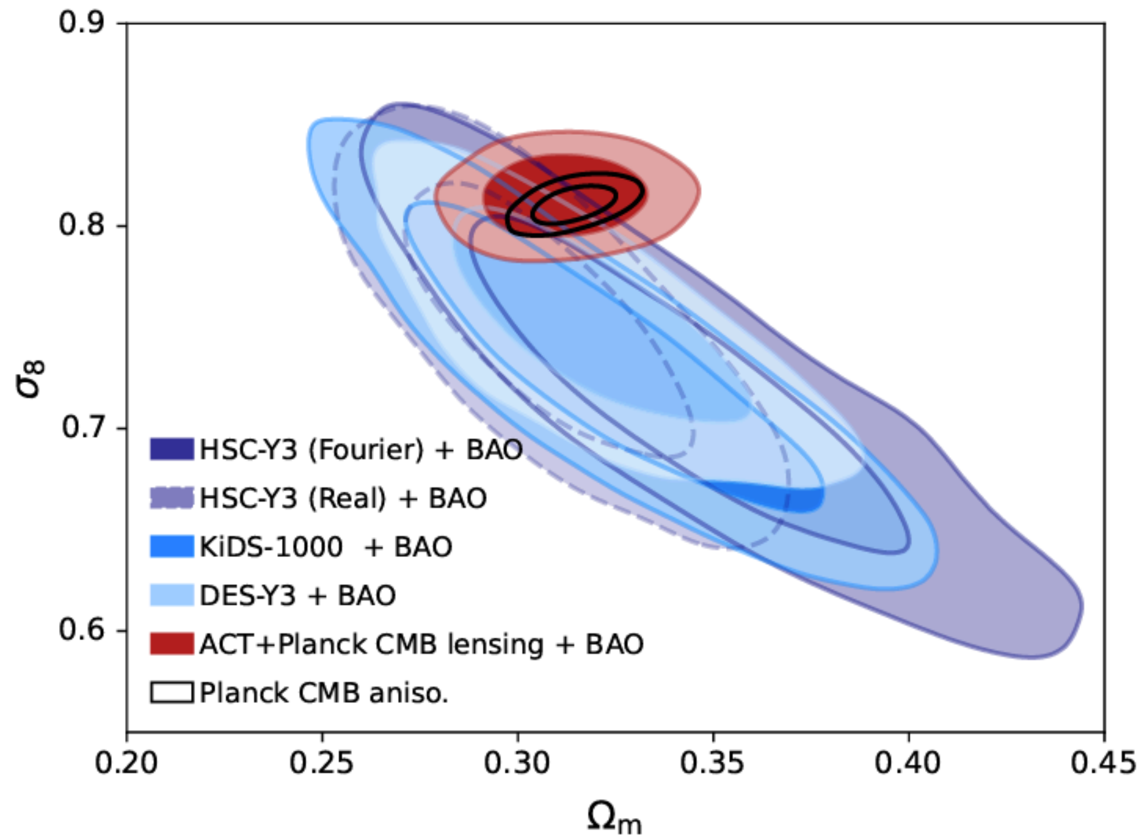
Few features, constraints mainly from amplitude of weak lensing 2pt functions

Interpreting Weak Lensing Measurements

Cosmic Shear
(lensing of galaxies)



vs. CMB lensing



New Physics? or systematics?

Measuring Shear (Theorist's Version)

1) Measure the centroid:

$$\bar{\boldsymbol{\theta}} \equiv \frac{\int \mathrm{d}^2\theta \, q_I[I(\boldsymbol{\theta})] \, \boldsymbol{\theta}}{\int \mathrm{d}^2\theta \, q_I[I(\boldsymbol{\theta})]}$$

2) Measure second order Brightness moments:

$$Q_{ij} = \frac{\int \mathrm{d}^2\theta \, q_I[I(\boldsymbol{\theta})] \, (\theta_i - \bar{\theta}_i) \, (\theta_j - \bar{\theta}_j)}{\int \mathrm{d}^2\theta \, q_I[I(\boldsymbol{\theta})]} \, , \quad i, j \in \{1, 2\}$$

3) Define an ellipticity measure (there exist many...)

$$\chi \equiv \frac{Q_{11} - Q_{22} + 2\mathrm{i}Q_{12}}{Q_{11} + Q_{22}}$$

and

$$\epsilon \equiv \frac{Q_{11} - Q_{22} + 2\mathrm{i}Q_{12}}{Q_{11} + Q_{22} + 2(Q_{11}Q_{22} - Q_{12}^2)^{1/2}}$$

Measuring Shear (Theorist's Version)

4) Relate observed and intrinsic ellipticities

$$Q^{(\mathrm{s})} = \mathcal{A}\,Q\,\mathcal{A}^T = \mathcal{A}\,Q\,\mathcal{A} \qquad \boxed{\mathcal{A}(\boldsymbol{\theta}) = (1-\kappa)\begin{pmatrix} 1-g_1 & -g_2 \\ -g_2 & 1+g_1 \end{pmatrix}}, \quad \boxed{g_i = \frac{\gamma_i}{(1-\kappa)}}$$

$$\chi^{(\mathrm{s})} = \frac{\chi - 2g + g^2\chi^*}{1 + |g|^2 - 2\mathcal{R}\mathrm{e}(g\chi^*)} \qquad \epsilon^{(\mathrm{s})} = \begin{cases} \dfrac{\epsilon - g}{1 - g^*\epsilon} & \text{if } |g| \le 1 \\[2ex] \dfrac{1 - g\epsilon^*}{\epsilon^* - g^*} & \text{if } |g| > 1 \end{cases}$$

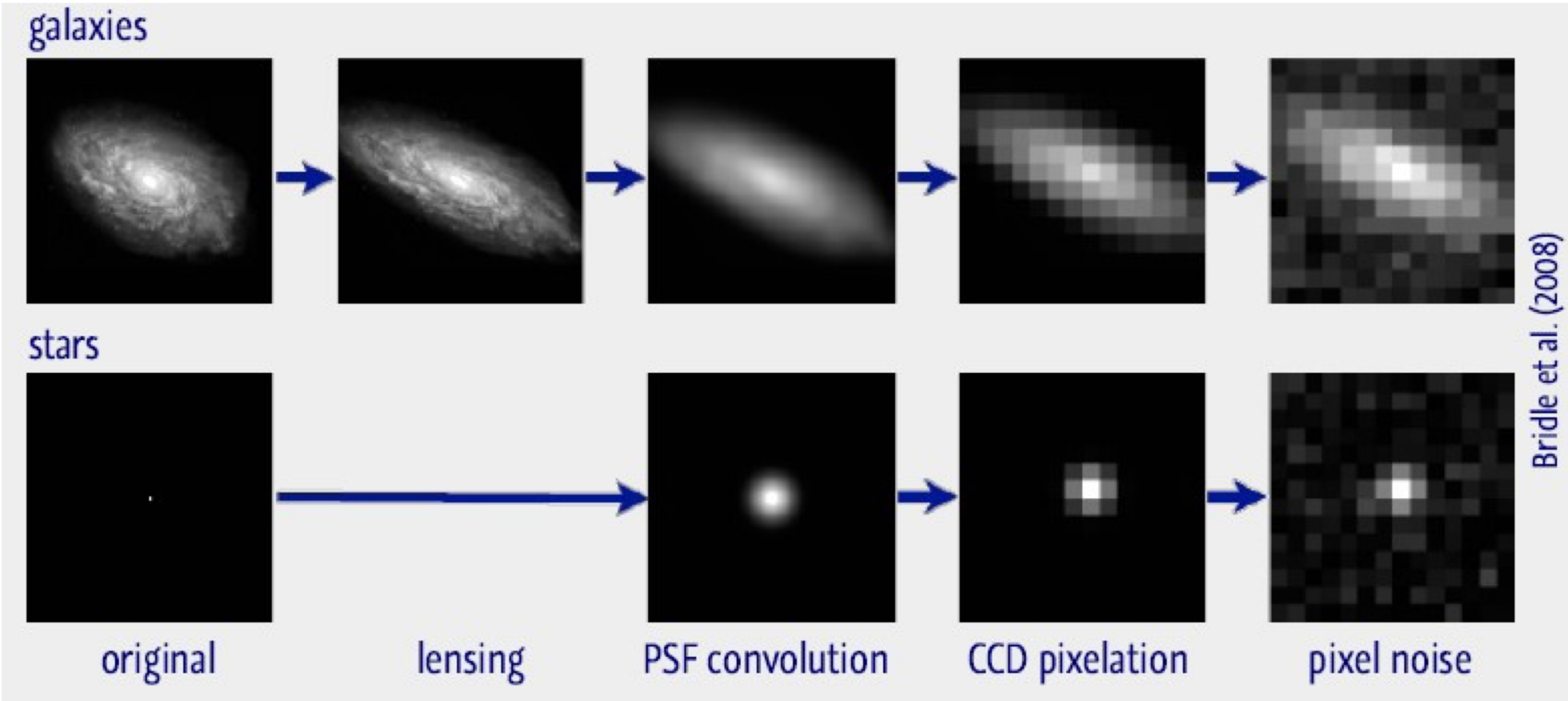
5) Assume that universe is isotropic
→ Expectation value of intrinsic ellipticity is zero

$$\boxed{\mathrm{E}\left(\chi^{(\mathrm{s})}\right) = 0 = \mathrm{E}\left(\epsilon^{(\mathrm{s})}\right)}$$

6) In the weak lensing regime....

$$\boxed{\gamma \approx g \approx \langle\epsilon\rangle \approx \frac{\langle\chi\rangle}{2}}$$

From the Source Plane to the Detector

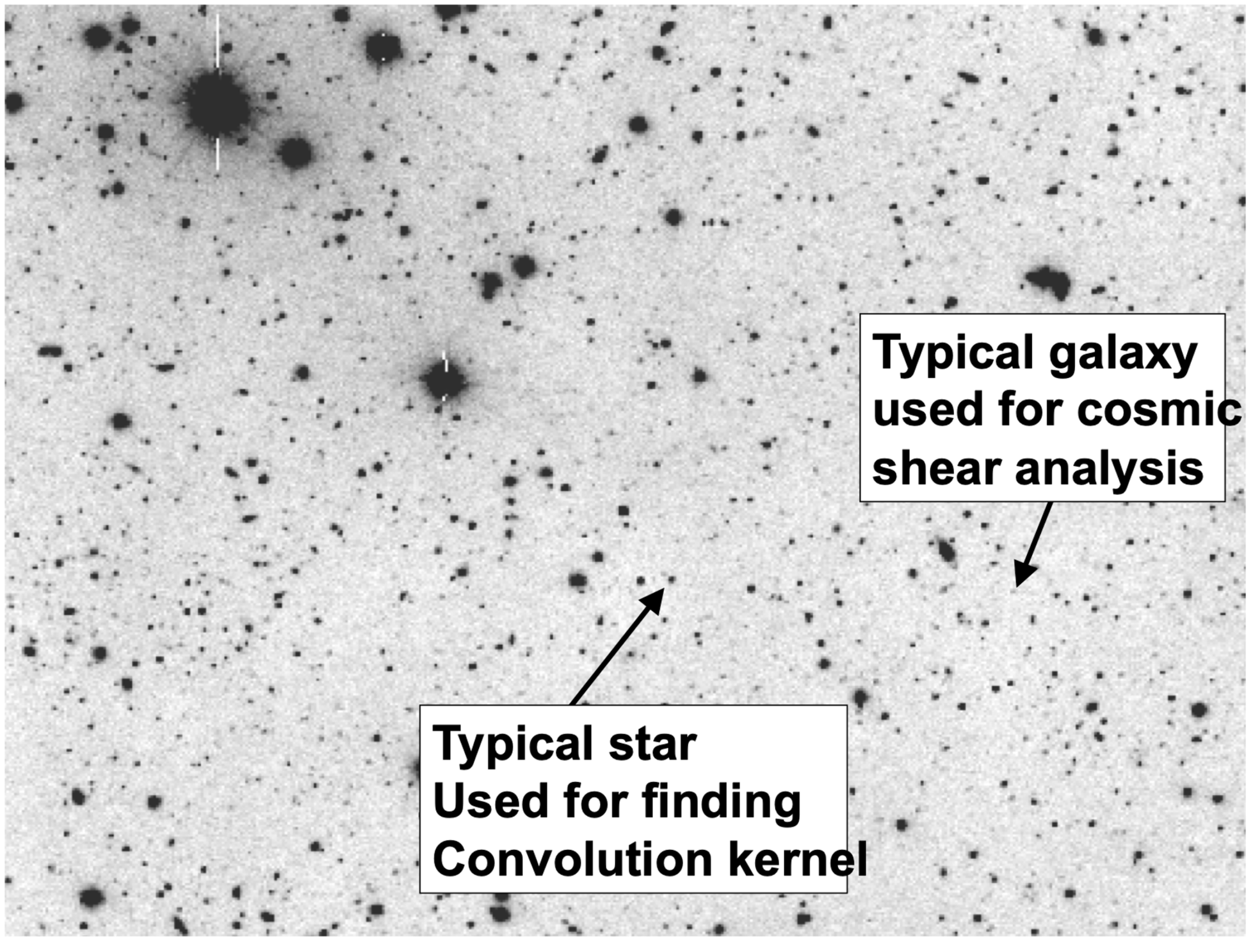


Nonlinear inverse problem

Model errors in shapes as a multiplicative bias, additive term:

$$\gamma_{meas} = (1+m)\,\gamma_{true} + c$$

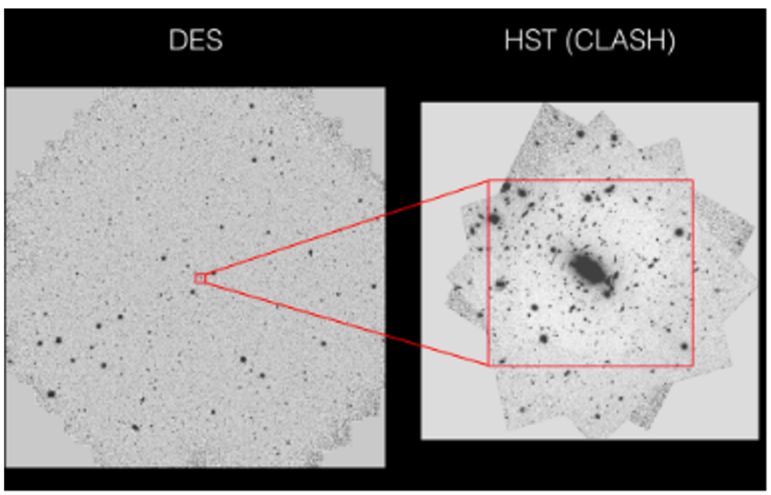
For Perspective, some real (HST) data…

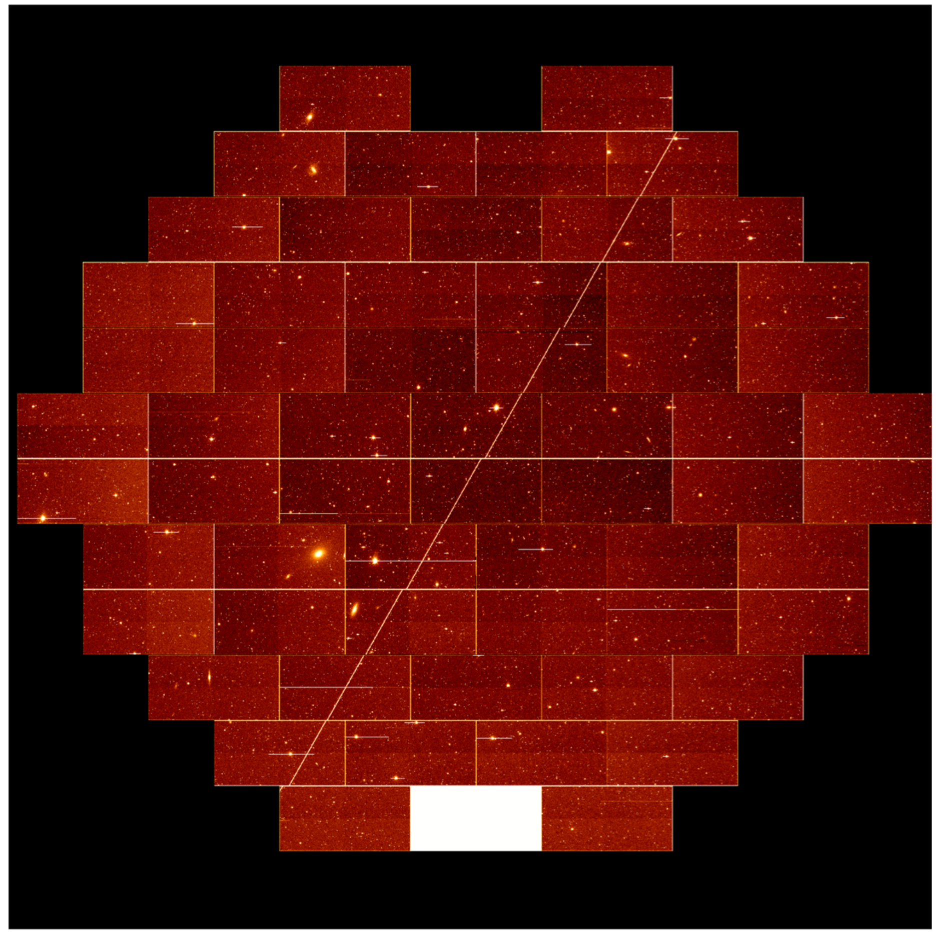


For Perspective, some real data…

Ground-based data quality is different from HST

- Raw DECam Image
- 570M pixel Dark energy Camera
- 2.2 deg^2 FoV
- HST WFC: 0.003 deg^2 FoV





Make a guess: how many source galaxies are in the right image?

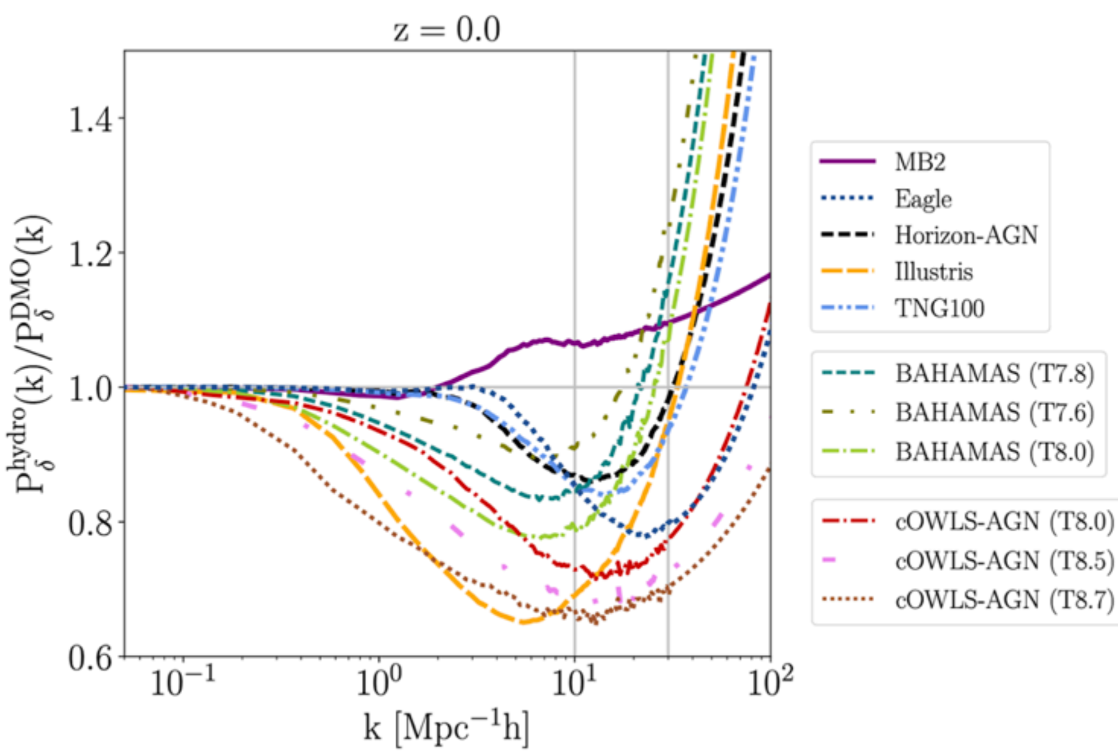
Weak Lensing Systematics

$$C_{\kappa}^{ij}(\ell) = \int_0^{\chi(z_{\max})} d\chi \frac{W^i(\chi)W^j(\chi)}{\chi^2} P_\delta\left(\frac{\ell+1/2}{\chi}, z(\chi)\right)$$

We glanced over a lot of details there…

- signal depends on redshift distribution of galaxies
- source galaxies may not be randomly oriented
- P_δ is the total matter power spectrum, including non-linear evolution and baryonic feedback effects

Weak Lensing Systematics
Matter Power Spectrum



Baryonic feedback suppresses matter power spectrum

Mitigation options:

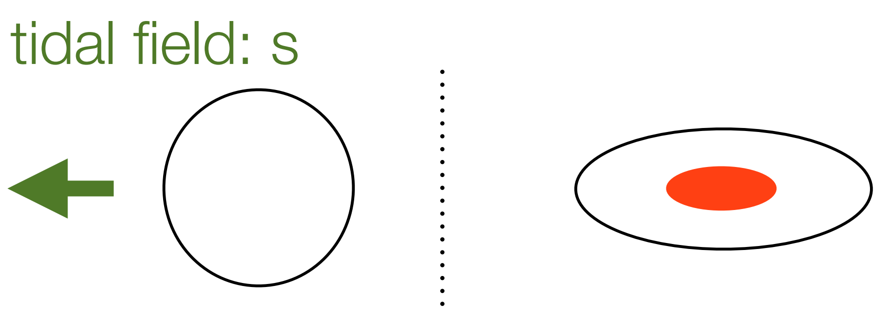
- include in model
- throw out small-scale data

Additional uncertainty in gravity-only non-linear matter power spectrum

Weak Lensing Systematics
Intrinsic Alignments

For elliptical galaxies, intrinsic shape ~aligned with halo shape.

Consider a halo forming in a tidal field



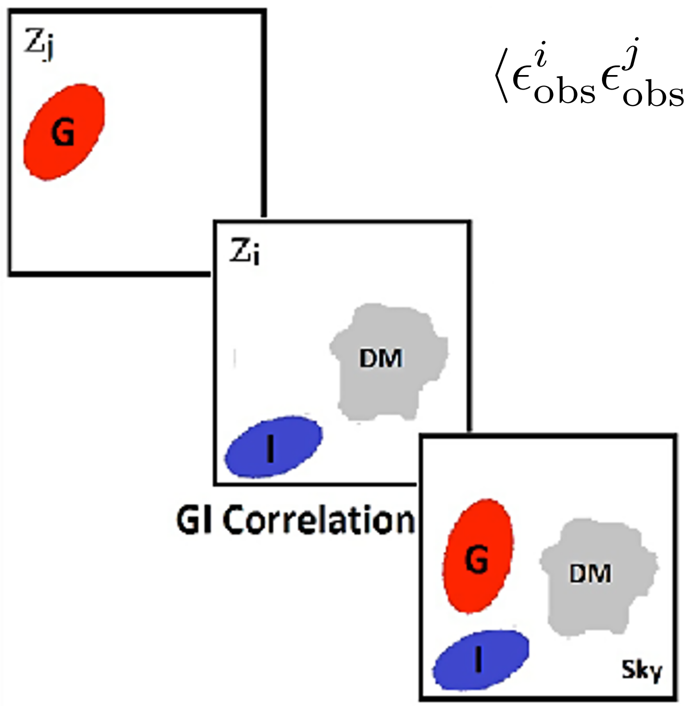
For two source galaxies at the same redshift:

Both align with the tidal field, **boost shape correlation.**

If not accounted in modeling, inferred S8 biased high.

spiral galaxies may align through tidal torqueing
see Laman et al. 2309.08605 for review

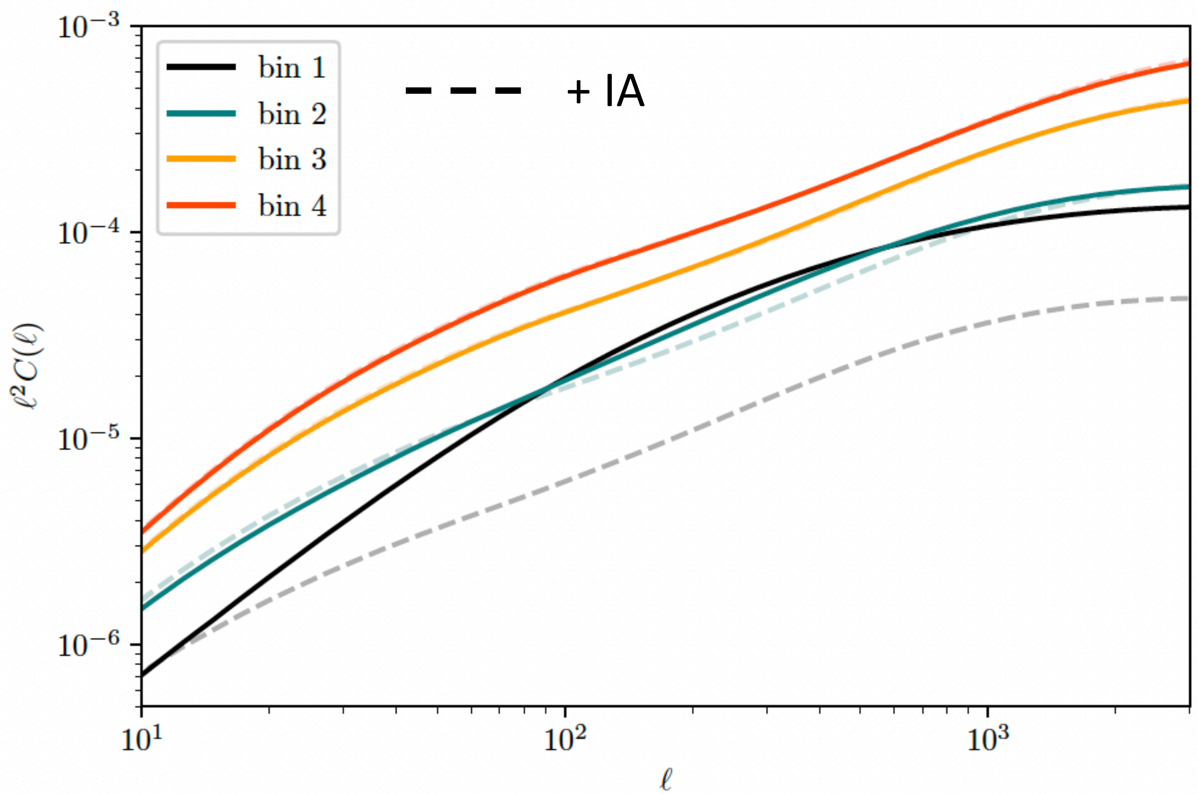
Weak Lensing Systematics
Intrinsic Alignments



$$\langle \epsilon^i_{\rm obs} \epsilon^j_{\rm obs} \rangle = \langle \gamma^i \gamma^j \rangle + \boxed{\langle \gamma^i \epsilon^j_{\rm IA} \rangle + \langle \gamma^j \epsilon^i_{\rm IA} \rangle} + \langle \epsilon^i_{\rm IA} \epsilon^j_{\rm IA} \rangle$$

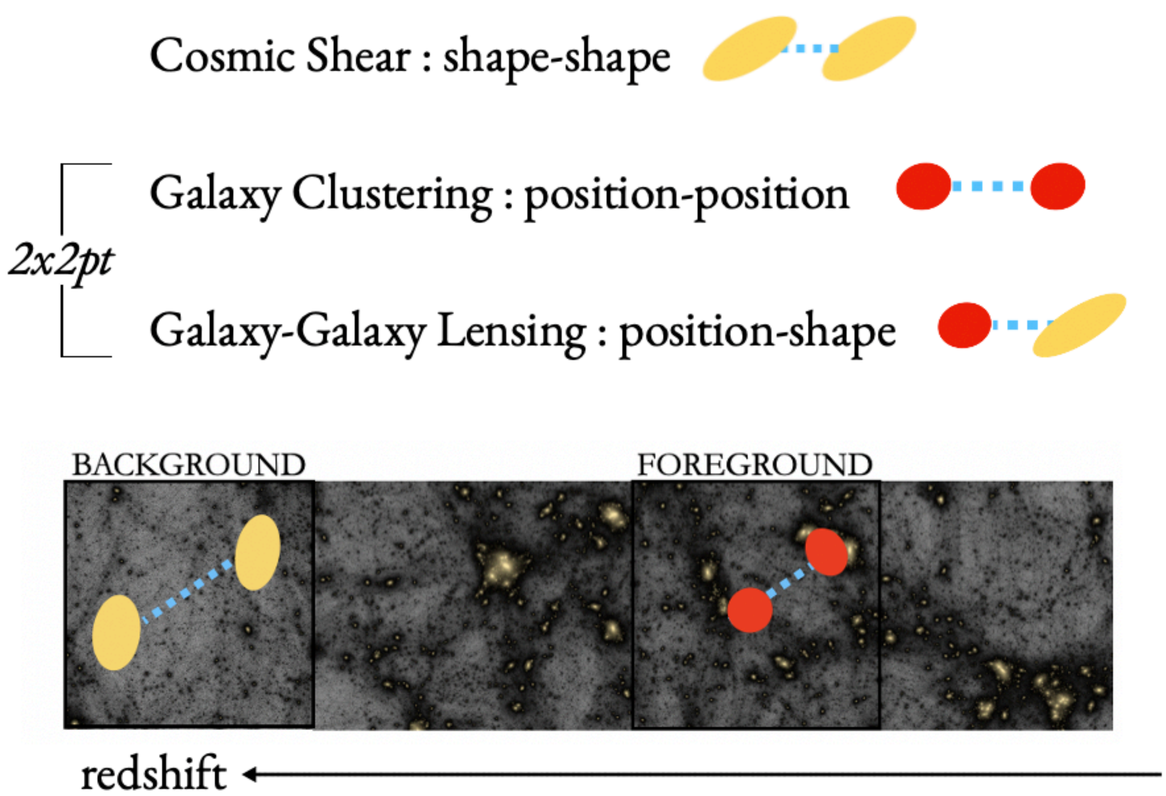
Anticorrelation between shape of foreground source and shear of background source

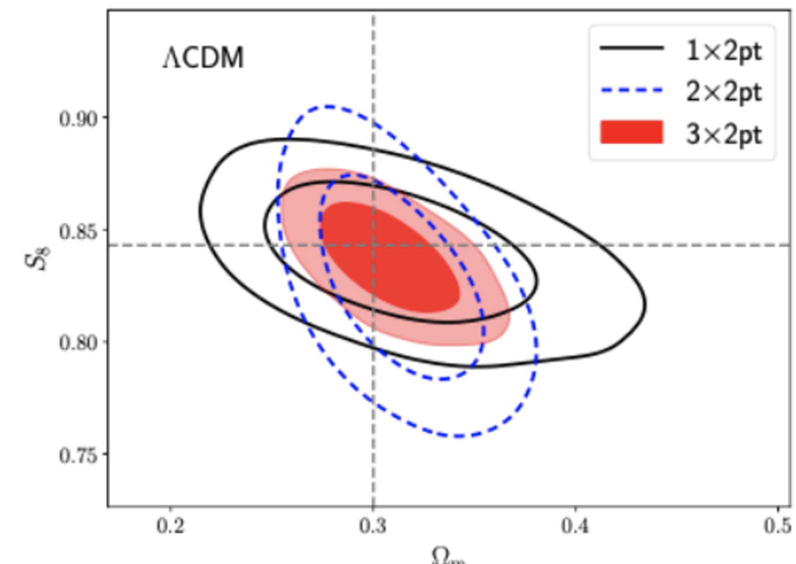
Weak Lensing Systematics
Intrinsic Alignments



Intrinsic alignments most affect low redshift source bins, across all scales.
Unless we throw out all low-z galaxies, IA must be included in the model.

3x2pt Analyses





A joint analysis maximises the cosmological information and robustly constrains astrophysical & observational systematic priors in the analysis!

DES Y3: From Pixels to Parameters in 30 papers

How it started

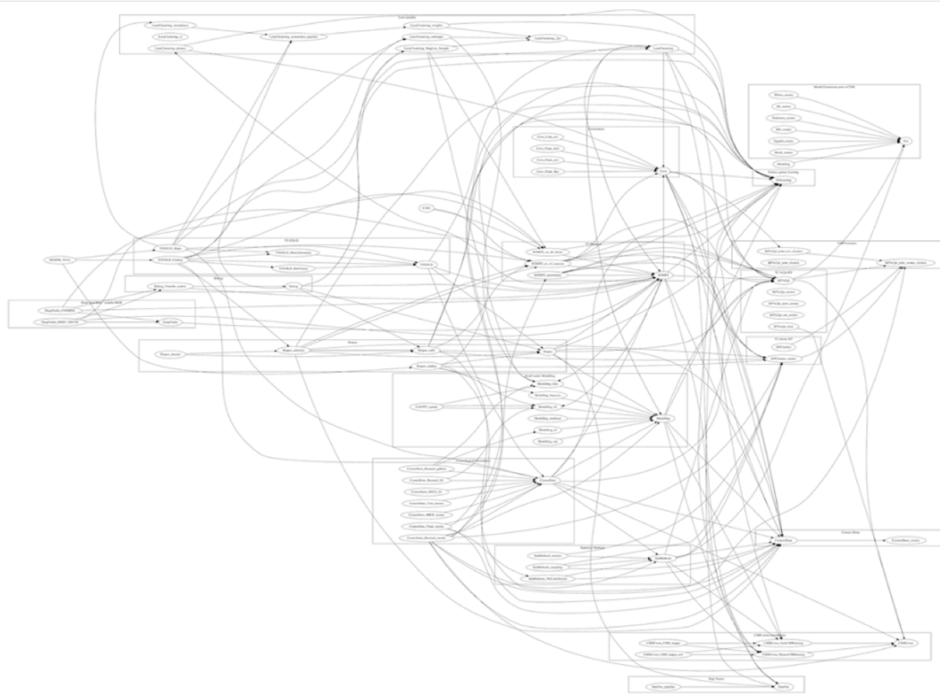


image credit: Troxel (Y3KP coordinator)

How it's going

1. “Blinding Multi-probe Cosmological Experiments” J. Muir, et al.
2. “Photometric Data Set for Cosmology”, I. Sevilla-Noarbe, et al.
3. “Weak Lensing Shape Catalogue”, M. Gatti et al.
4. “Point Spread Function Modelling”, M. Jarvis et al.
5. “Measuring the Survey Transfer Function with Balrog”, S. Everett et al.
6. “Deep Field Optical + Near-Infrared Images and Catalogue”, W. Hartley et al.
7. “Blending Shear and Redshift Biases in Image Simulations”, N. MacCrann et al.
8. “Redshift Calibration of the Weak Lensing Source Galaxies”, J. Myles , et a.
9. “Redshift Calibration of the MagLim Lens Sample using Self-Organizing Maps and Clustering Redshifts”, G. Giannini et al.
10. “Clustering Redshifts – Calibration of the Weak Lensing Source Redshift Distributions with redMaGiC and BOSS/eBOSS”, M. Gatti, et al.
11. “Calibration of Lens Sample Redshift Distributions using Clustering Redshifts with BOSS/eBOSS”, R. Cawthon et al
12. “Phenotypic Redshifts with SOMs: a Novel Method to Characterize Redshift Distributions of Source Galaxies for Weak Lensing Analysis” R. Buchs, et al.
13. “Marginalising over Redshift Distribution Uncertainty in Weak Lensing Experiments”, J. Cordero, et al.
14. “Exploiting Small-Scale Information using Lensing Ratios”, C. Sánchez, J. Prat et al.
15. “Cosmology from Combined Galaxy Clustering and Lensing - Validation on Cosmological Simulations”, J. de Rose et al.
16. “Unbiased fast sampling of cosmological posterior distributions”, P. Lemos et al., in prep.
17. “Assessing Tension Metrics with DES and Planck Data”, P. Lemos, et al.,
18. “DES Internal Consistency Tests of the Joint Cosmological Probe Analysis with Posterior Predictive Distributions”, C. Doux et al.
19. “Covariance Modelling and its Impact on Parameter Estimation and Quality of Fit”, O. Friedrich, et al.
20. “Multi-Probe Modeling Strategy and Validation”, E. Krause et al.
21. “Curved-Sky Weak Lensing Map Reconstruction”, N. Jeffrey, M. Gatti, C. Chang et al.
22. “Galaxy Clustering and Systematics Treatment for Lens Galaxy Samples”, M.Rodríguez-Monroy, et al.
23. “Optimizing the Lens Sample in Combined Galaxy Clustering and Galaxy-Galaxy Lensing Analysis”, A. Porredon, et al.
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.
26. “Cosmological Constraints from Galaxy Clustering and Galaxy-Galaxy Lensing using the Maglim Lens Sample” A. Porredon, et al.
27. “Cosmology from Cosmic Shear and Robustness to Data Calibration”, A. Amon, et al.
28. “Cosmology from Cosmic Shear and Robustness to Modeling Assumptions”, L. Secco, S. Samuroff, et al.
29. “Magnification modeling and impact on cosmological constraints from clustering and g-g lensing”, J. Elvin-Poole, et al.
30. “Cosmological Constraints from Galaxy Clustering and Weak Lensing” The DES Collaboration

DES Year 3 redshift characterization

Imaging surveys need an accurate characterization of their redshift distributions, for both lens and source galaxies, in order to yield unbiased cosmological constraints.

For the redshift characterization of lensing sources, we use three independent sources of information:

Photometry (colors):
SOMPZ

Myles, Alarcon et al. (2021)

Clustering (positions):
WZ

Gatti, Giannini et al. (2021)

Lensing (shapes):
Shear Ratio (SR)

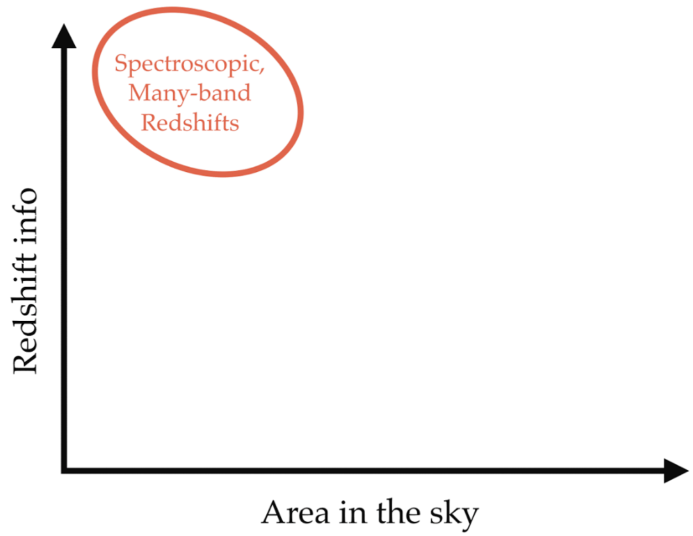
Sánchez, Prat, et al. (2021)

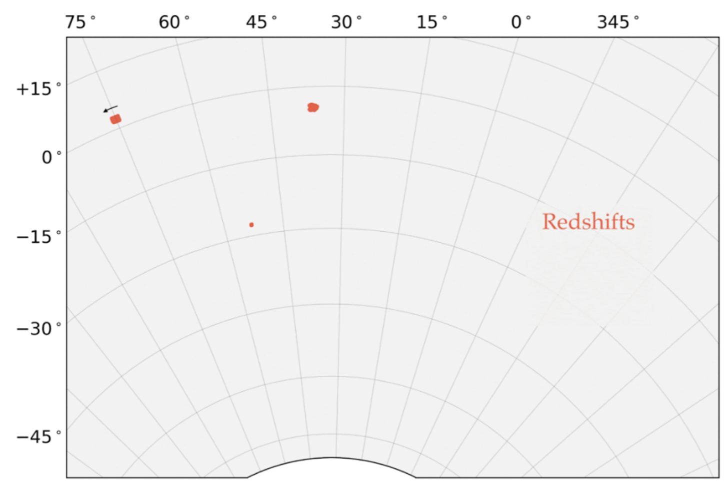
SOMPZ: Redshift distributions from galaxy colors

DF: **Hartley, Choi,** et al. (2021)
Balrog: **Everett** et al. (2021)
SOMPZ: **Myles, Alarcon,** et al. (2021)

SOMPZ is a Bayesian redshift scheme to use the DES deep fields as an intermediate step between small redshift samples and the wide-field DES sample.

We use artificial galaxy injections (Balrog) to characterize how deep-field galaxies would look like in the noisier wide-field conditions.





SOMPZ: Redshift distributions from galaxy colors

DF: 2012.12824
Balrog: 2012.12825
SOMPZ: 2012.08566

To characterize the deep and wide photometric spaces, we create two different SOMs. The Bayesian formalism allows us to connect the two, and to separate different pieces.

Likelihood of deep and wide-field color

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

$$c = \begin{cases} \text{Deep SOM cell index:} \\ (u,g,r,i,z,J,H,K) \end{cases}$$

$$\hat{c} = \begin{cases} \text{Wide SOM cell index:} \\ (r,i,z) \end{cases}$$

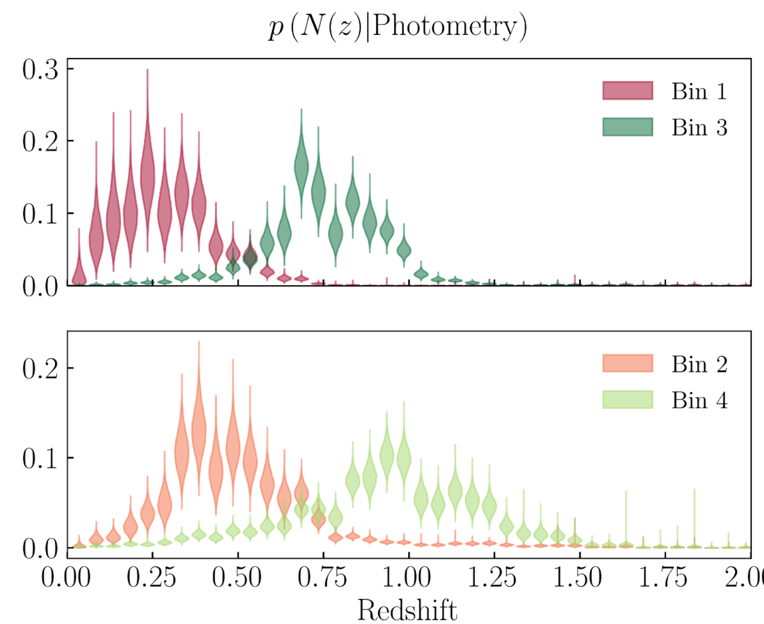
$\hat{s}$ = weak lensing sample selection

$\hat{b}$ = tomographic bin selection

z = redshift bin index

Redshift at a given deep photometric color

Probabilistic mapping between deep and wide photometric colors



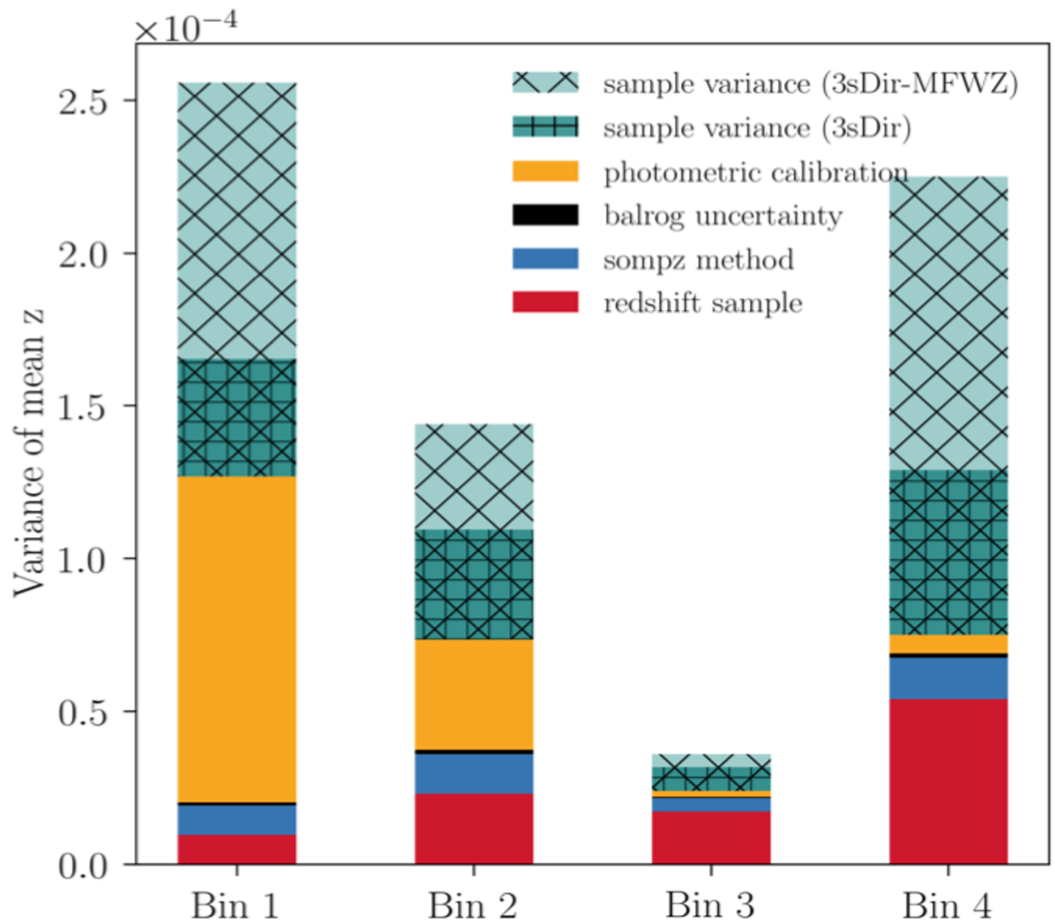
SOMPZ

Hyperrank: **Cordero, Harrison** et al. (2021)
SOMPZ: **Myles, Alarcon**, et al. (2021)

We separate source galaxies into four redshift bins, and produce realizations of their redshift distributions.

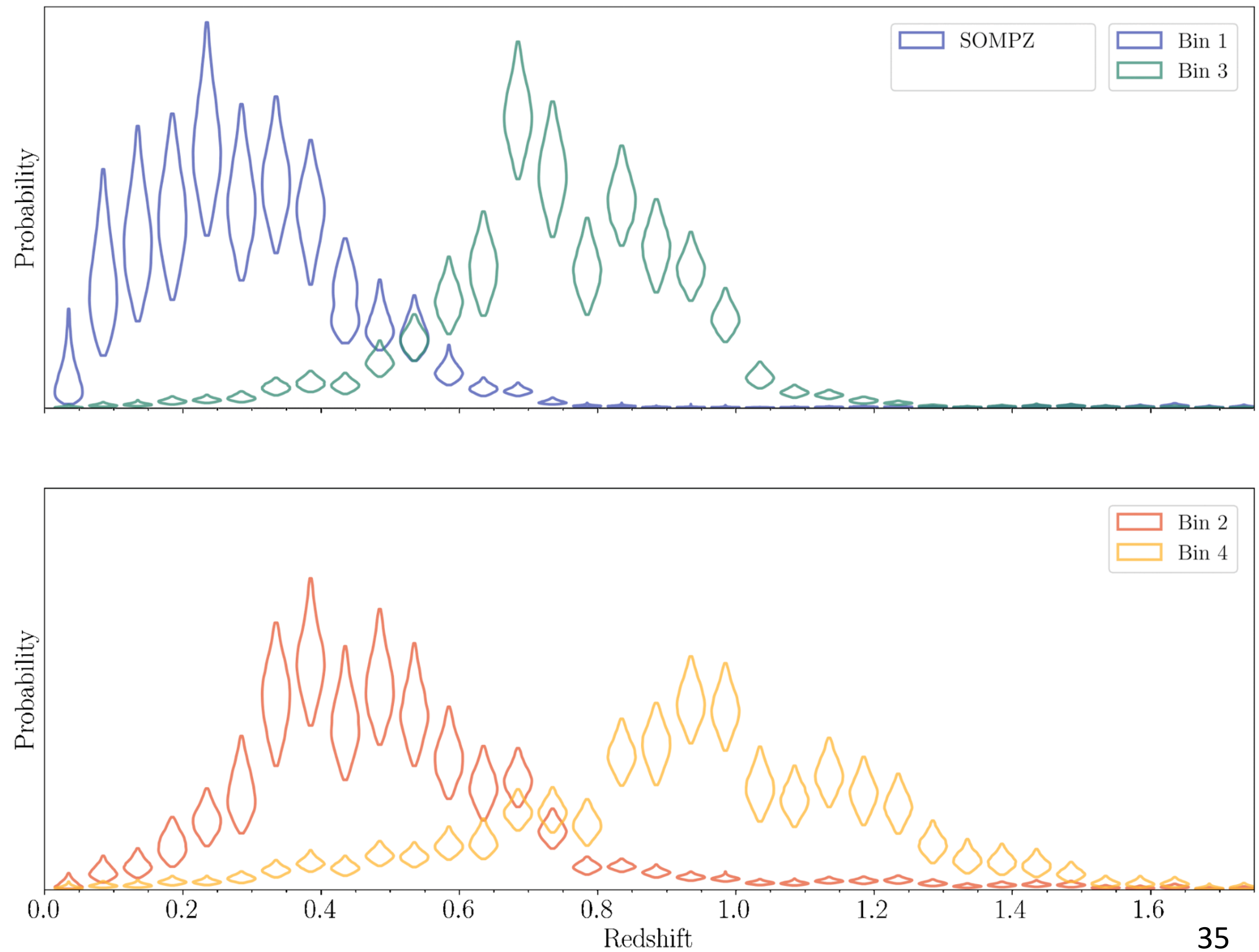
Such realizations include several sources of uncertainty coming from:

- Redshift samples.
- Shot noise and sample variance.
- Photometric calibrations.
- Transfer function.
- Assumptions in the method.



Clustering (WZ)

Hyperrank: **Cordero, Harrison** et al. (2021)
SOMPZ: **Myles, Alarcon**, et al. (2021)
WZ: **Gatti, Giannini**, et al. (2021)



Estimate the redshift distribution of a sample with unknown redshifts by measuring the cross-correlation signal with "reference" samples.

DES Year 3 approach: produce a likelihood for the observed WZ data as function of *N(z)* by computing a prediction of the WZ signal for each of the SOMPZ realizations.

WZ acts as a smoothing of the SOMPZ realizations.

Galaxy shapes measured using *Metacalibration*

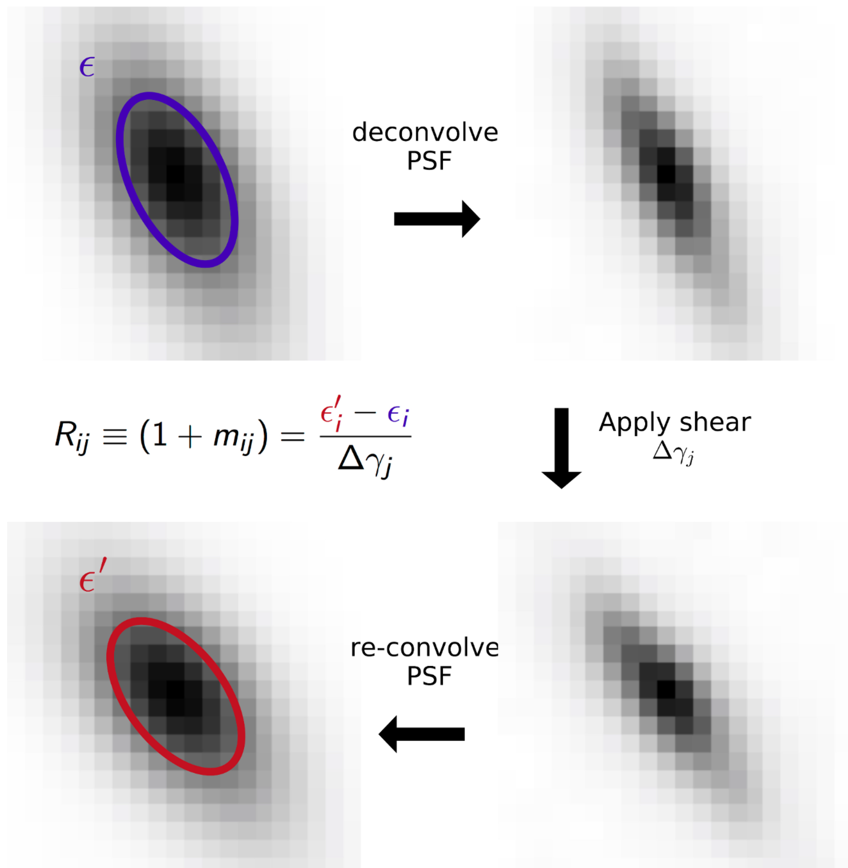


Image credit: **Niall MacCrann**

Measure response on ellipticity estimator to artificially-applied shear
(Huff & Mandelbaum 2017, Sheldon & Huff 2017)

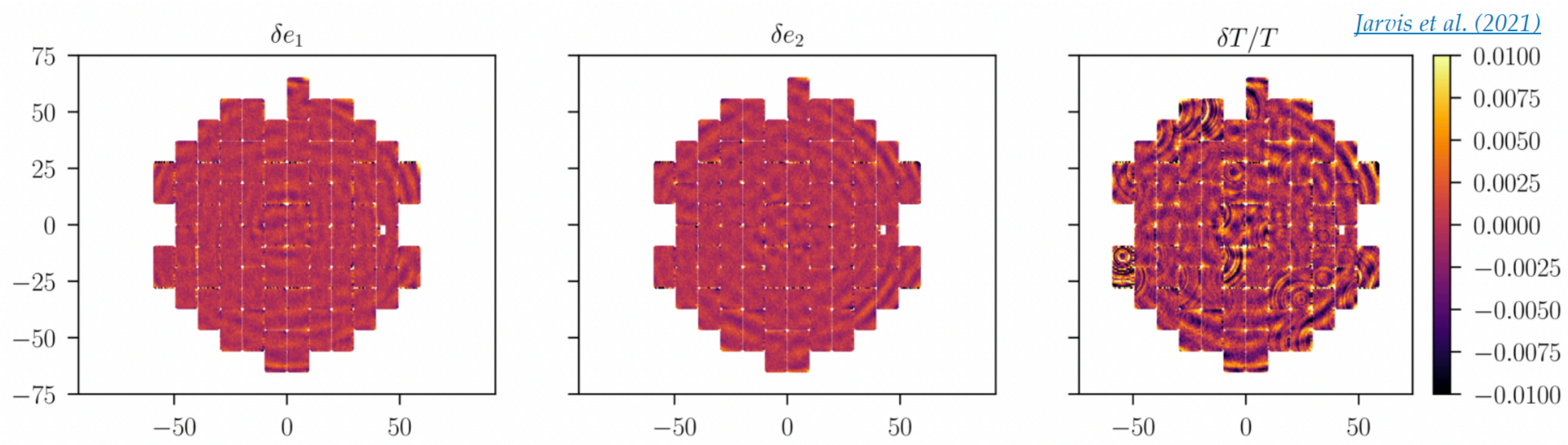
Unbiased in limit of:

- weak shear
- isolated galaxy images
- perfect knowledge of PSF

Use **simulations to calibrate bias** from, e.g., **blending** of galaxy images

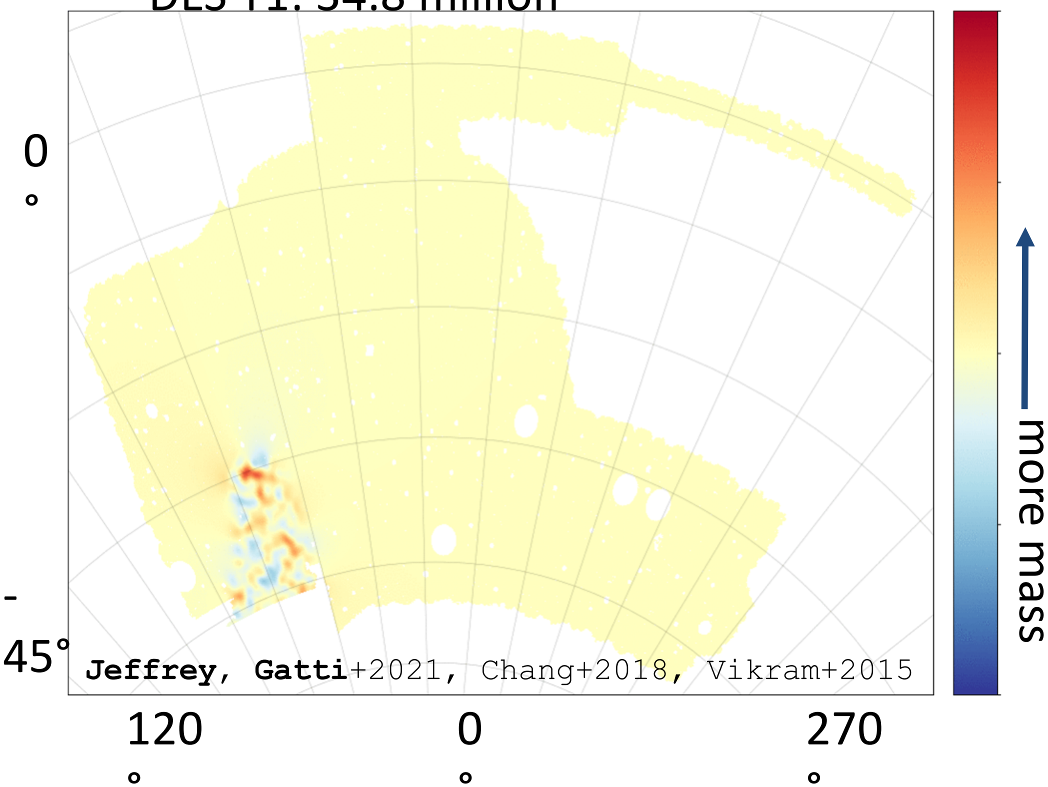
How do we know the shear measurements are cosmological?

The main contamination comes from imperfect PSF modeling.
Use cross-correction with star ellipticity to characterize PSF.



100.2 million galaxy shapes for DES Y3

cf. DES SV: 2-3 million shapes
DES Y1: 34.8 million

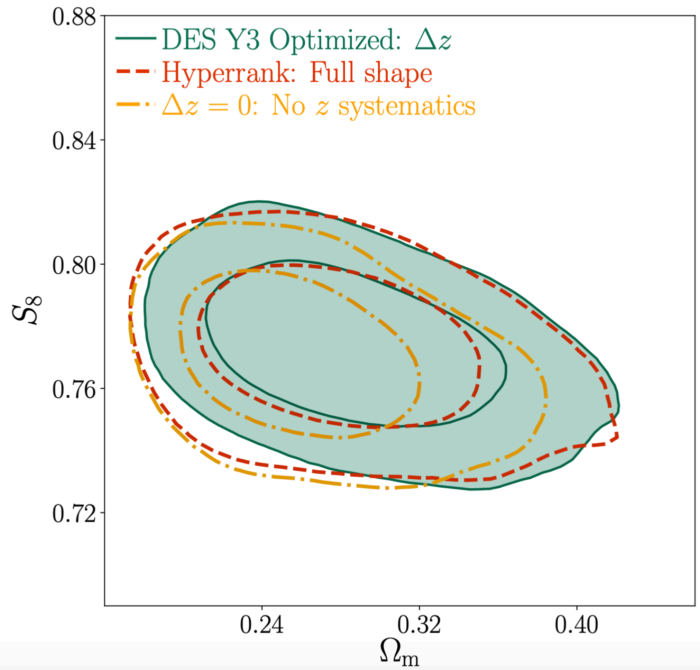


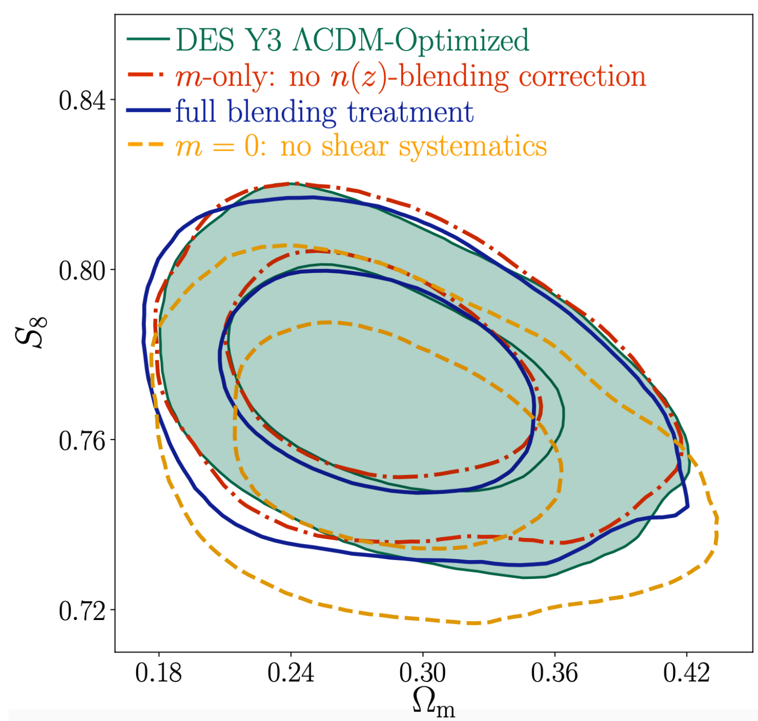
Key improvements over DES Y1:

- More accurate **PSF modeling** (Jarvis+2021)
- Improved astrometry
- Expanded suite of **null tests** (**Gatti**, Sheldon+2021)
- Calibration using realistic image simulations that characterize the impact of **blending** on both shear and redshifts (**MacCrann**+2021)

# galaxies	n_{eff}	σ_e
100 204 026	5.590	0.268

Impact of Calibration Modeling (Amon+ 2021)





Galaxy clustering and Lens samples

Galaxy clustering measured in two foreground samples

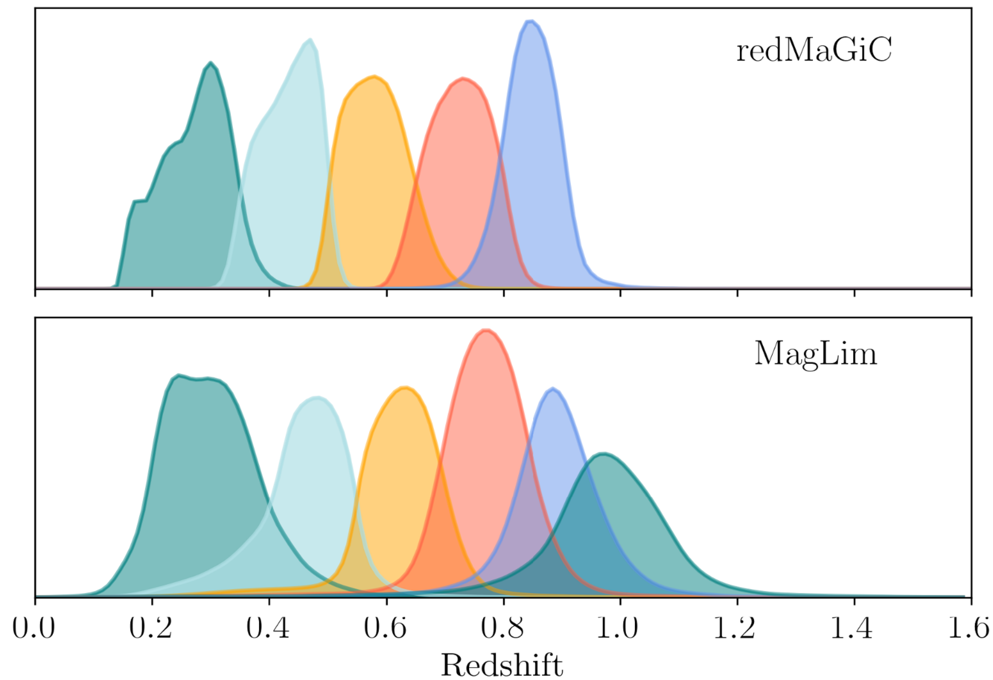
redMaGiC

LRG selection also used in Y1 analysis

MagLim

$$i_{\text{mag}} < 4z + 18$$

Bright selection



Position-Position auto-correlations measured on large scales

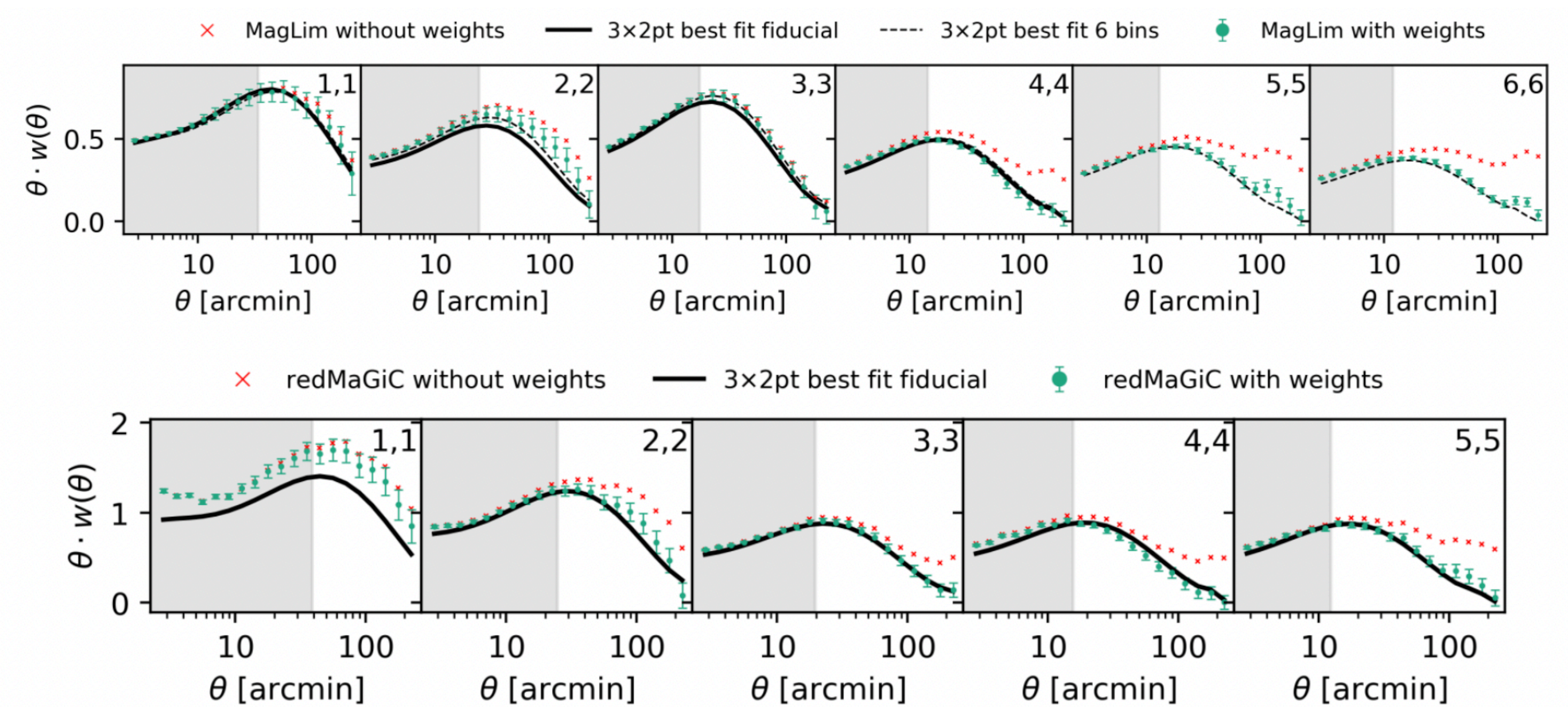
Combination with galaxy-galaxy lensing calibrates linear galaxy bias

Lens WZ: **Cawthon** et al. (2021)
MagLim: **Porredon,** et al. (2020)
Clustering: **Rodriguez-Monroy** et al. (2021)
Lens SOMPZ (alt. method): **Giannini** et al. (in prep)
DNF: **de Vicente** et al (2015)

~Cosmological Clustering Signal

Rodriguez-Monroy+

Iterative reweigh galaxy catalogs to decorrelate foregrounds and galaxy density – significant correction!



From 2PCF Measurements to Cosmology Constraints

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

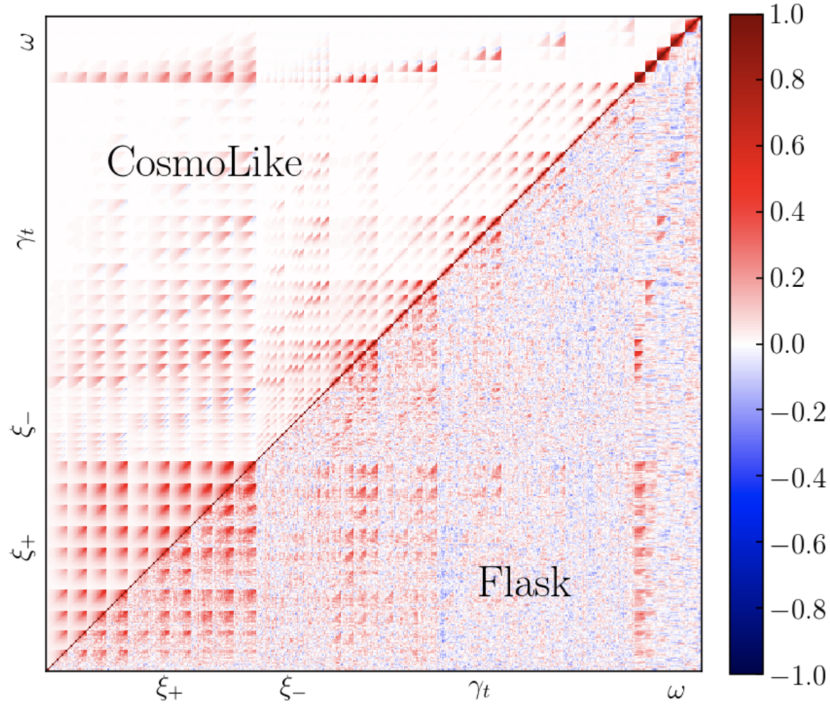
$$P(\mathbf{p}|\hat{\mathbf{D}}, M) \propto \mathcal{L}(\hat{\mathbf{D}}|\mathbf{p}, M)P(\mathbf{p}|M)$$

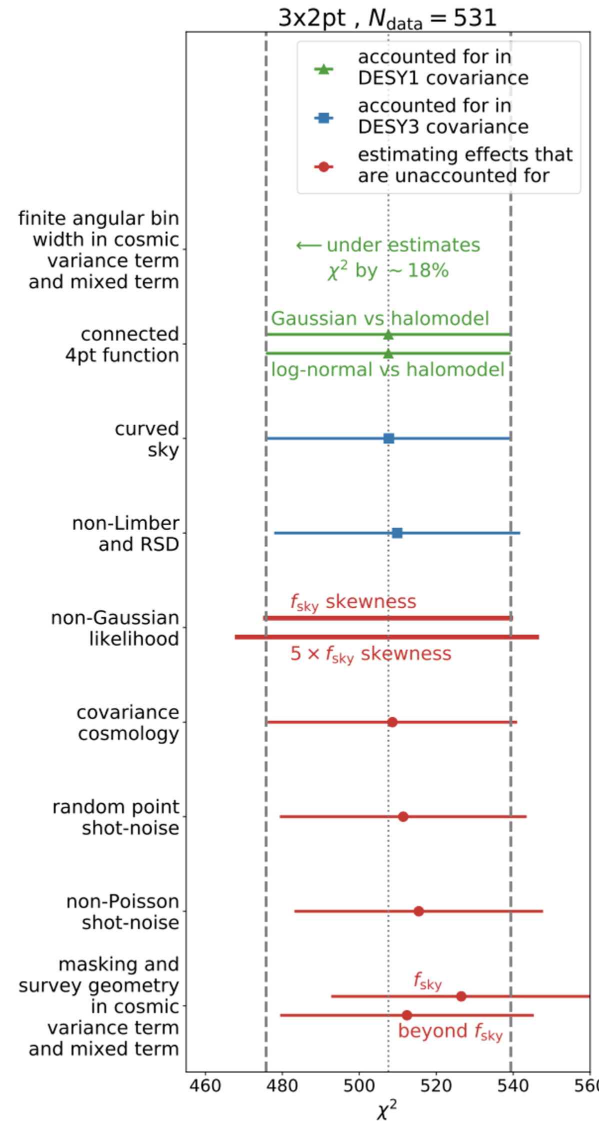
Required Ingredients

- Data likelihood $\mathcal{L}(\hat{\mathbf{D}}|\mathbf{p}, M)$ with data covariance **C**
    - `Friedrich+2020`: Gaussian data likelihood ✓, halo model covariance ✓
- Model M with parameters **p**, and prior $P(\mathbf{p}|M)$
- Criteria which measurements to combine
- Blinding scheme to minimize observer bias

Covariance (Gaussian+cNG+SSC)

Computed with CosmoCov based on halomodel and validated with FLASK lognormal simulations





Model Validation: Strategy

Krause+

- **Identify modeling choices**

  write down general formalism for computing 3x2pt data vector

  then fill in non-linear+astrophysics choices (+approximations)

- **Validate that each choice biases inferred parameters by < 0.3σ**

Consider two types of systematics

- **Known, but unmodeled systematics** (baryons, non-linear modelling)

  mitigated by scale cuts

- **Imperfect parameterizations** (~everything else, e.g., piece-wise constant b(z))

  stress test scale + redshift dependence

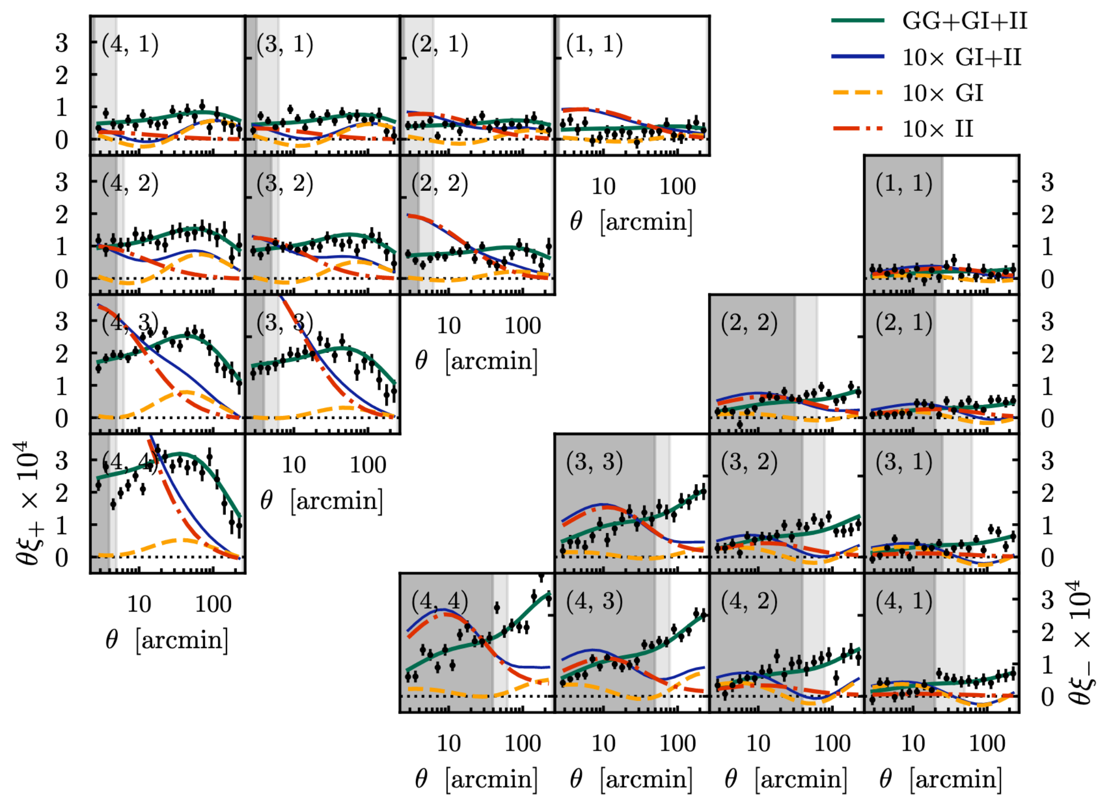
Model Validation: Scale Cuts

- **Cosmic shear**: requires nonlinear matter power spectrum, model does not incl. baryonic feedback

- **Galaxy clustering**: linear bias model, need to remove data points where non-linear biasing significan

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

Removes >40% of weak lensing S/N!

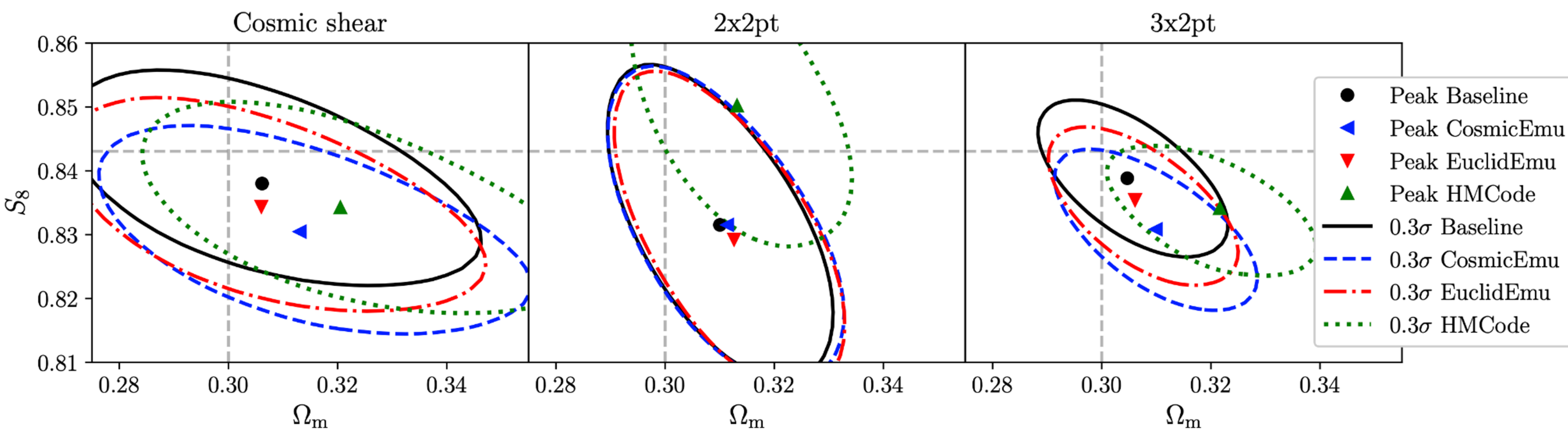


Model Validation: Stress Tests

Generate simulated input "data" from alternate parameterizations

- *aim to bracket reasonable-conservative range - requires priors from sims/observations*

P_{NL}: CosmicEmu, Euclid Emulator (most accurate, but limited parameter support)

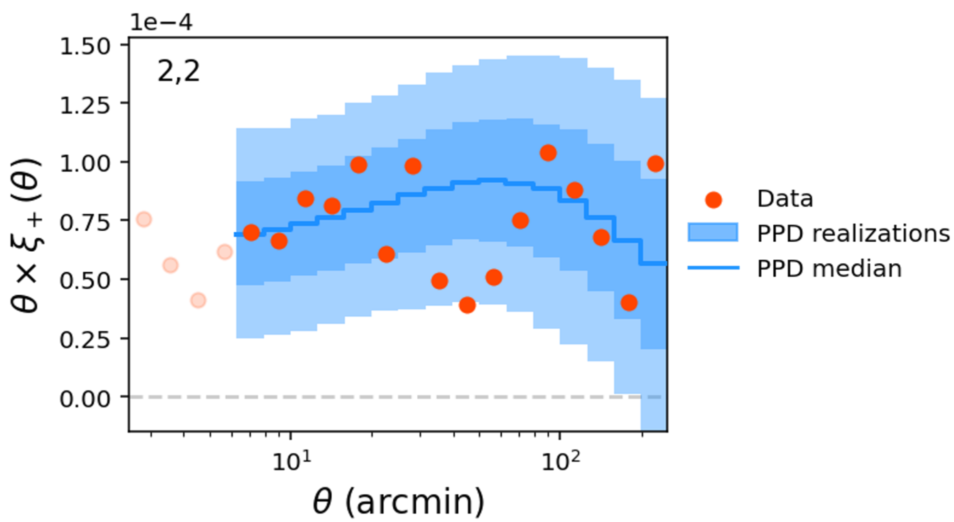


Consistency/Tension Metrics

Doux, Baxter+2020

Internal consistency of 3x2pt data quantified in data space using Posterior Predictive Distribution (PPD)

Accept model fit if p>0.01



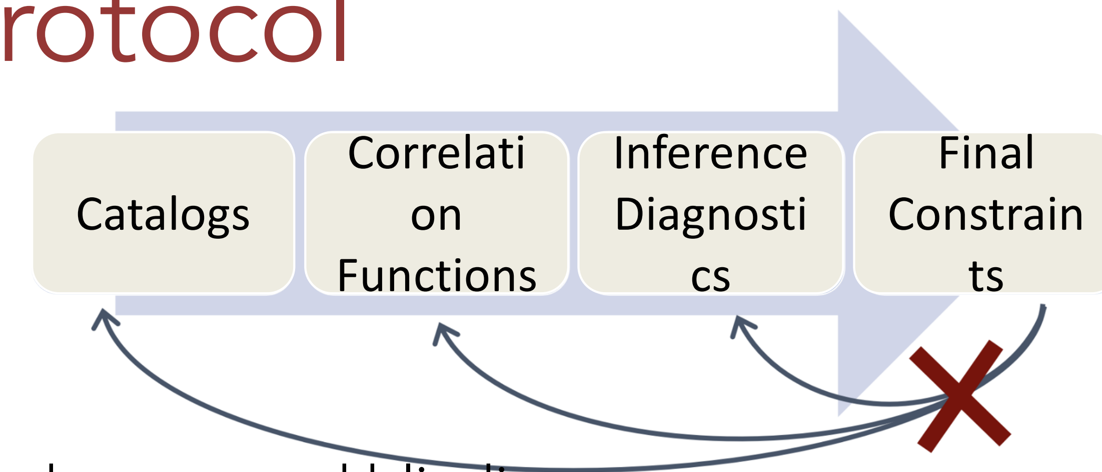
Best cosmology constraints from combining DES with Planck, SN, BAO - only allowed to combine if data sets are consistent.

Lemos, Raveri+2020

Quantify **consistency with external data** using parameter differences and evidence-based methods.

Agreed to combine if p>0.01

Blind Analysis Protocol



Minimize observer bias through three-staged blinding

1. Catalog: rescaling of galaxy ellipticities by unknown factor
2. Correlation functions: transformation of summary statistics corresponding to unknown change in wCDM parameters (Muir+2020)
3. Parameters: shift of parameter values, axes of posterior plots by unknown offset

Unblinded parameter constraints after data vectors and modeling were frozen.

Finalized list of model tests and combinations with external data before unblinding.

In practice, these last steps were quite a rollercoaster ride!

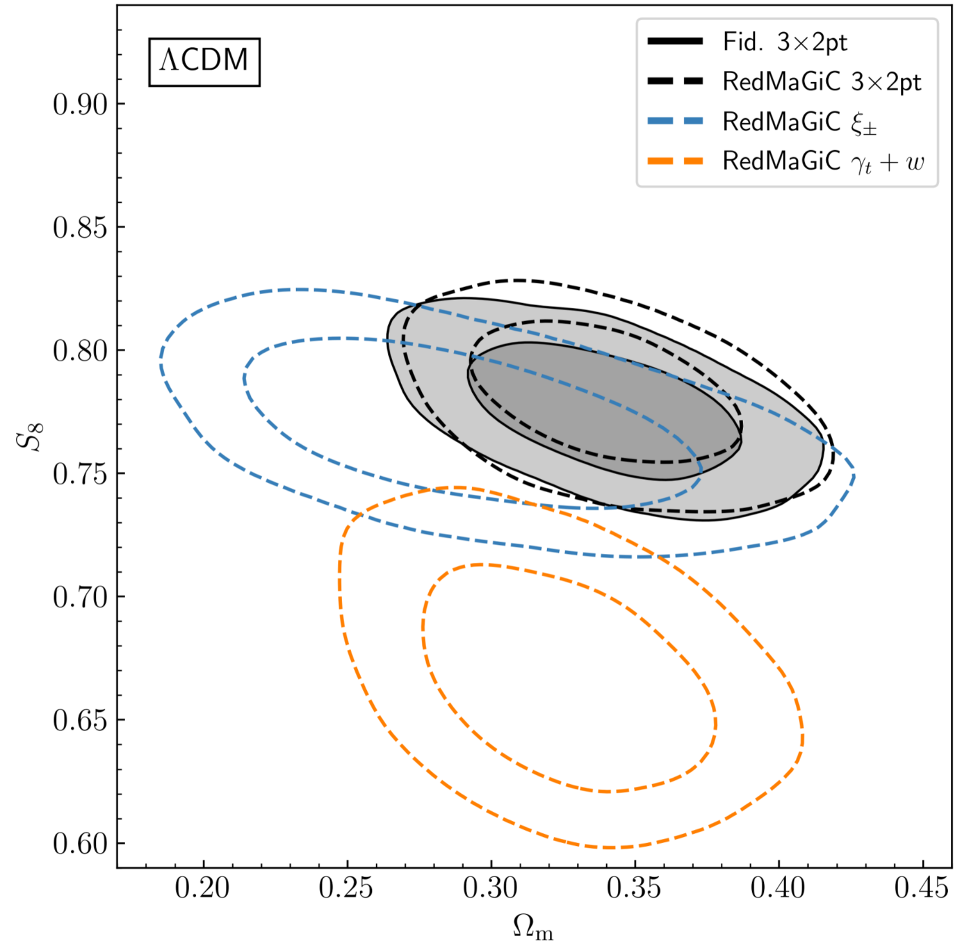
A Surprise at Unblinding

Cosmic shear and galaxy clustering+tangential shear (2x2pt) for redMaGiC are also formally consistent and combine to give the **3x2pt** result.

2x2pt prefers lower S8 and higher galaxy bias. Combination with cosmic shear brings S8 up and bias down to agree with DES Y1.

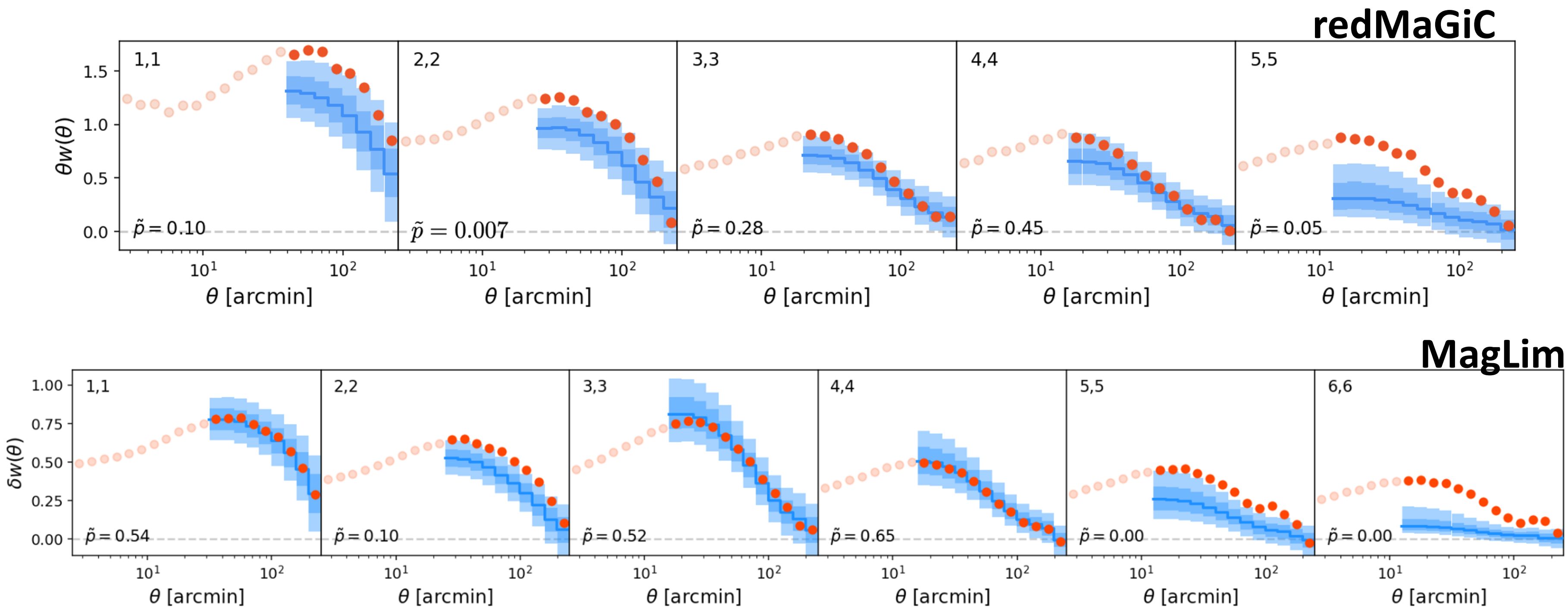
Evidence for potential systematics in the redMaGiC clustering data vector at all redshifts and above the fiducial lens redshift range for MagLim.

Two highest-redshift bins removed in MagLim.



Inconsistency of galaxy clustering and gg-lensing

Investiage internal (in)consistency of measurements with PPD p-value of clustering given the parameter posteriors from cosmic shear + gg-lensing



Credit: Cyrille Doux

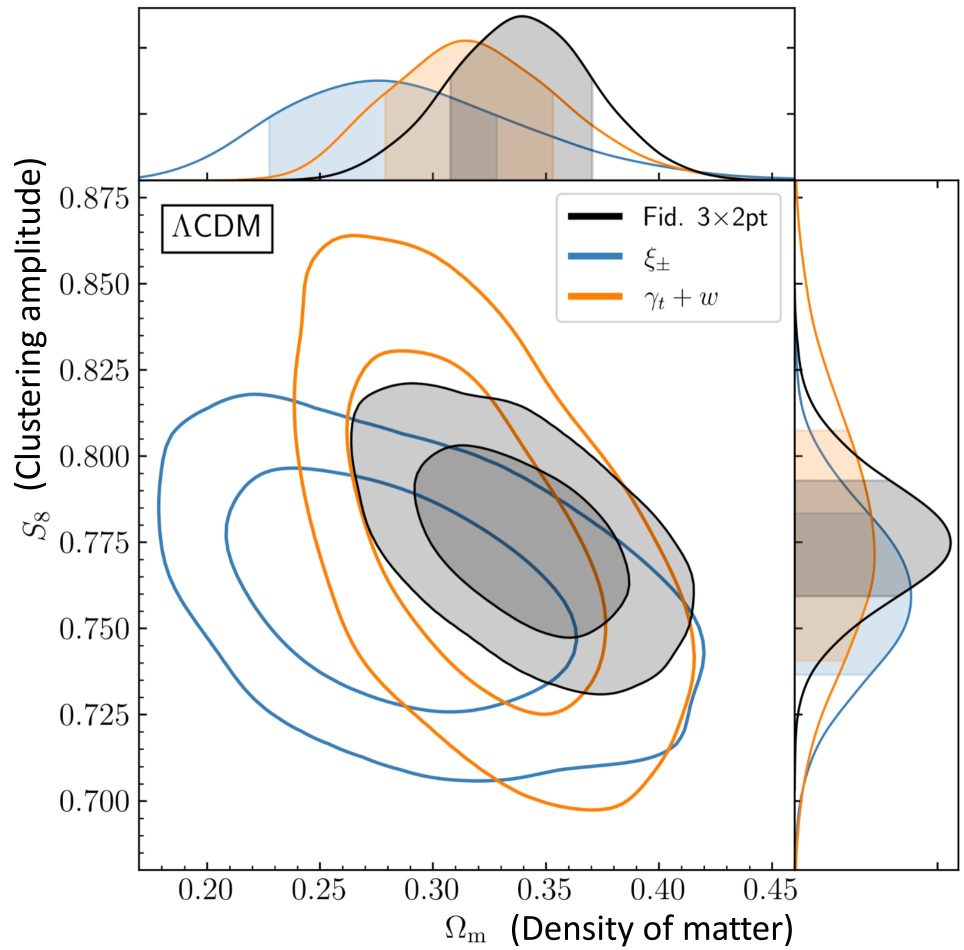
3x2pt Results

We combine these into the **3x2pt** probe of large-scale structure.

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

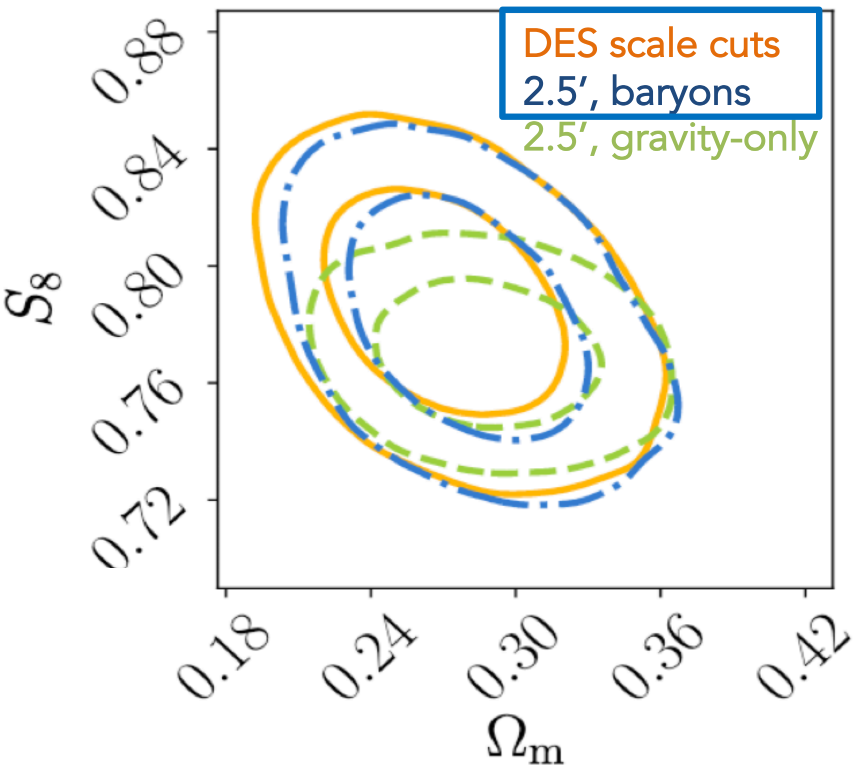
In **Λ**CDM:
$$S_8 = 0.776^{+0.017}_{-0.017} \quad (0.776)$$
$$\Omega_m = 0.339^{+0.032}_{-0.031} \quad (0.372)$$
$$\sigma_8 = 0.733^{+0.039}_{-0.049} \quad (0.696)$$

In *w*CDM:
$$\Omega_m = 0.352^{+0.035}_{-0.041} \quad (0.339)$$
$$w = -0.98^{+0.32}_{-0.20} \quad (-1.03)$$

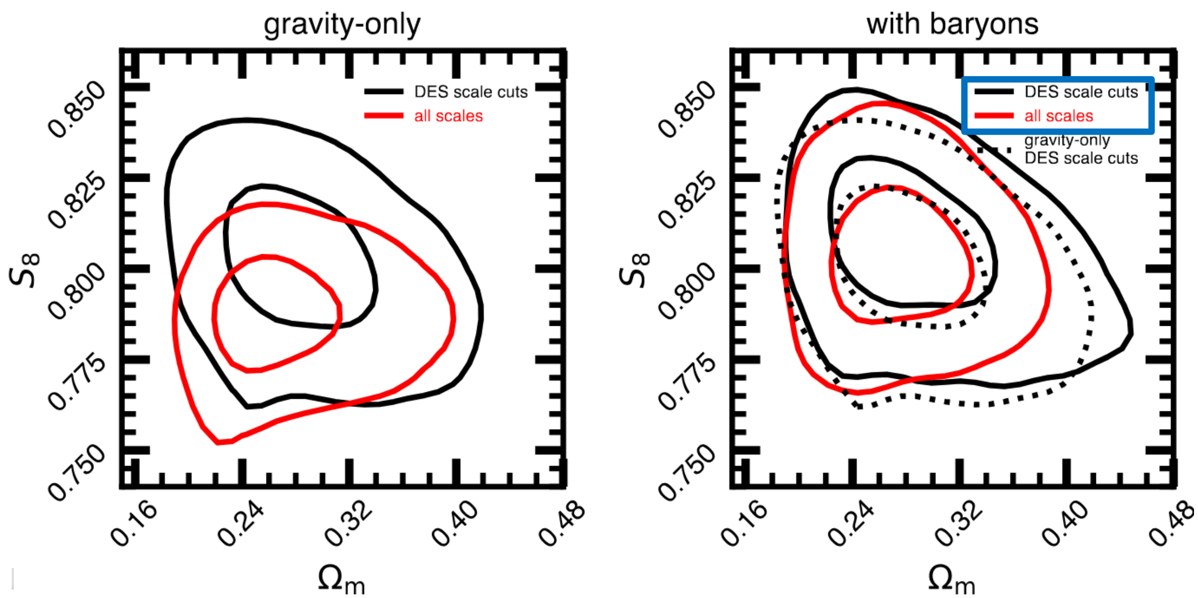


S8 Tension or Baryon Feedback?

Huang+2021: DES-Y1 3x2pt
shear to 2.5′, PCA-based baryon marginalization



Arico+2023: DES-Y3 shear
shear to 2.5′, baryonification-based baryon marginalization (+lots of other model changes)



All-scale+baryon analyses agree well with DES scale cuts+gravity-only model!