Rencontres des lacs alpins | January 18th 2024

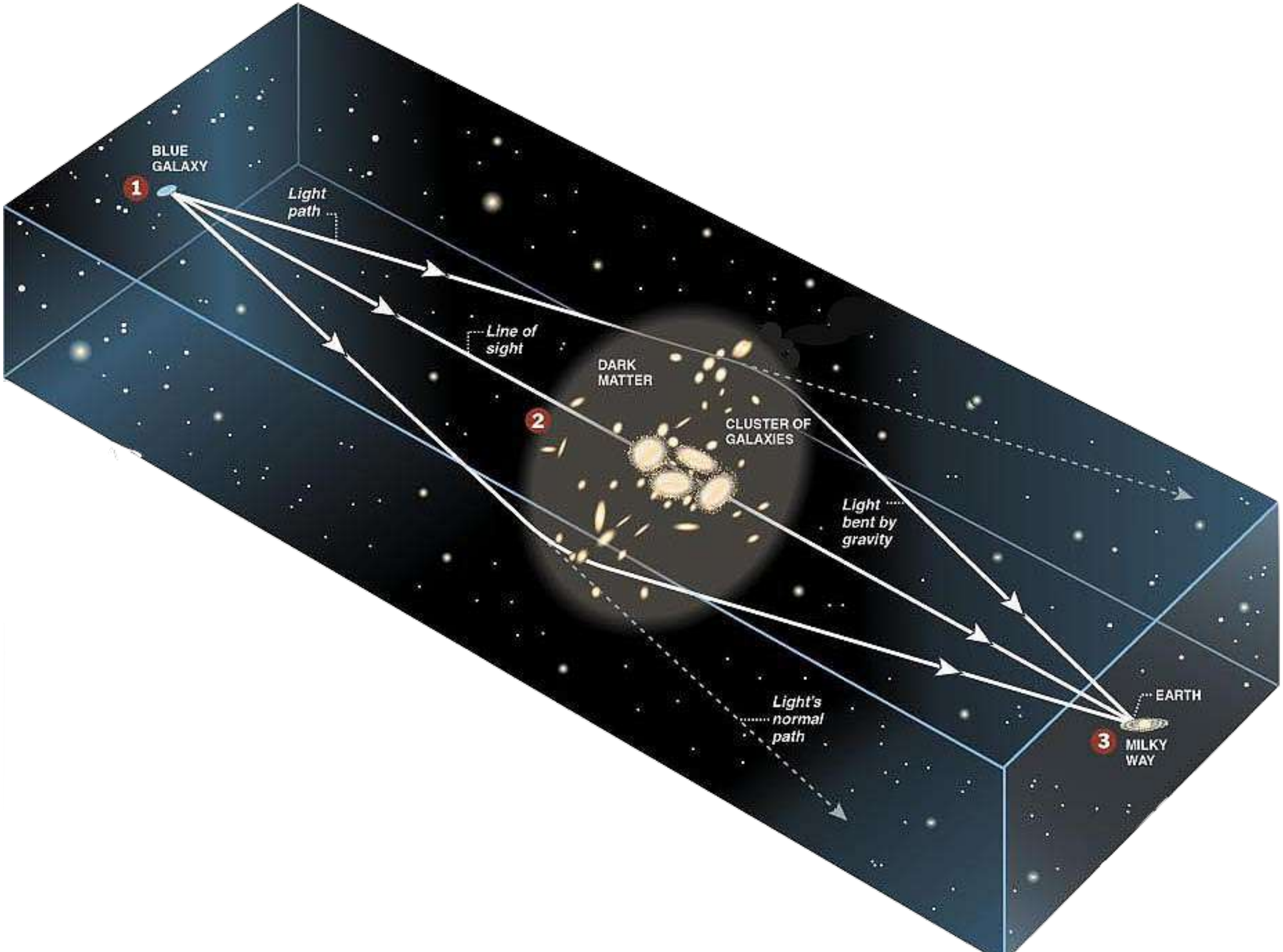
Cosmic shear: from DES to Rubin/LSST

Cyrille Doux

LPSC GRENOBLE / IN2P3 / CNRS

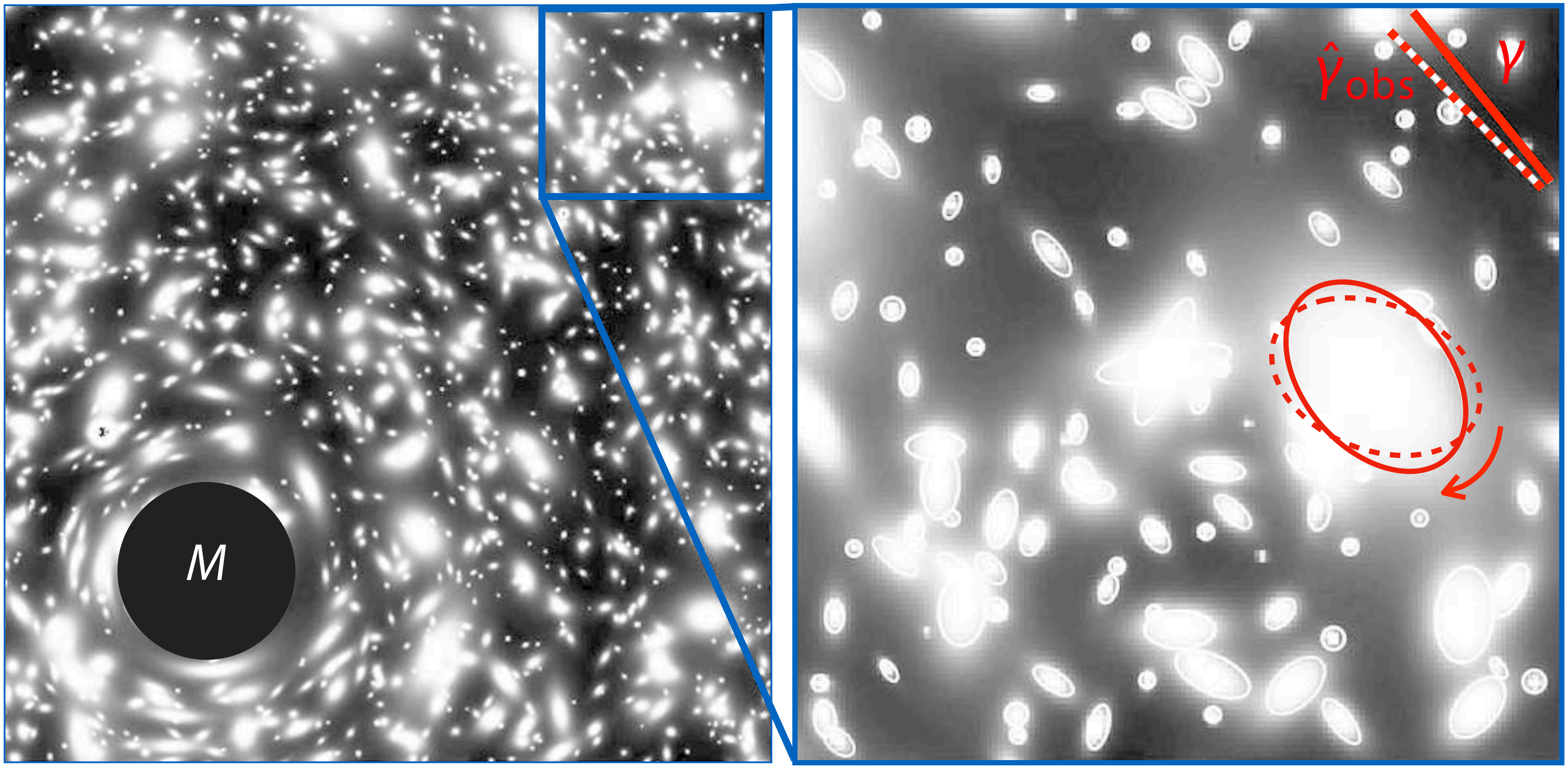
- Cosmic shear 101
- Cosmic shear in practice: DES analysis
- Cosmic shear with LSST: new challenges

Weak gravitational lensing



Weak gravitational lensing

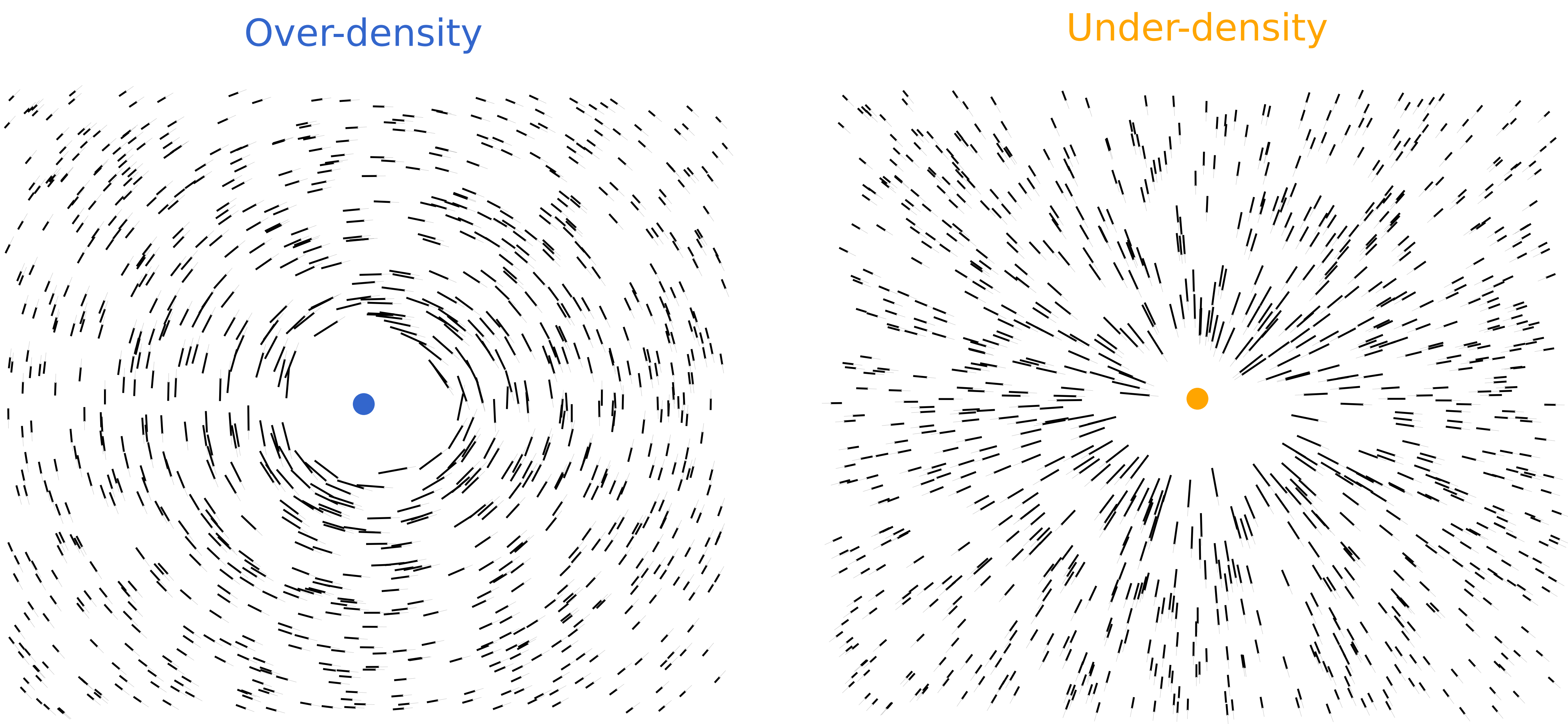
Cosmic shear



In practice, $|\gamma| \sim 0.01$ (in the field) to 0.1 (in clusters)

Weak gravitational lensing

Cosmic shear



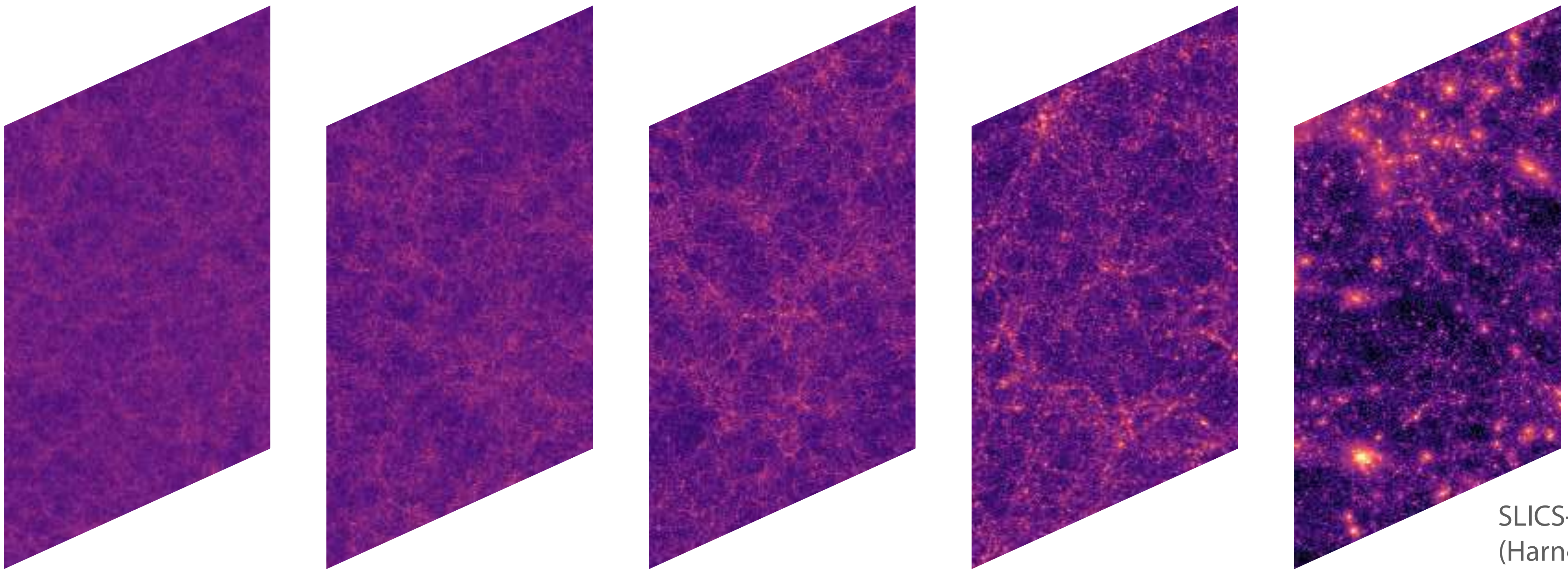
* Lengths do not scale

https://github.com/LSSTDESC/CLMM

Weak gravitational lensing

A large-scale structure probe

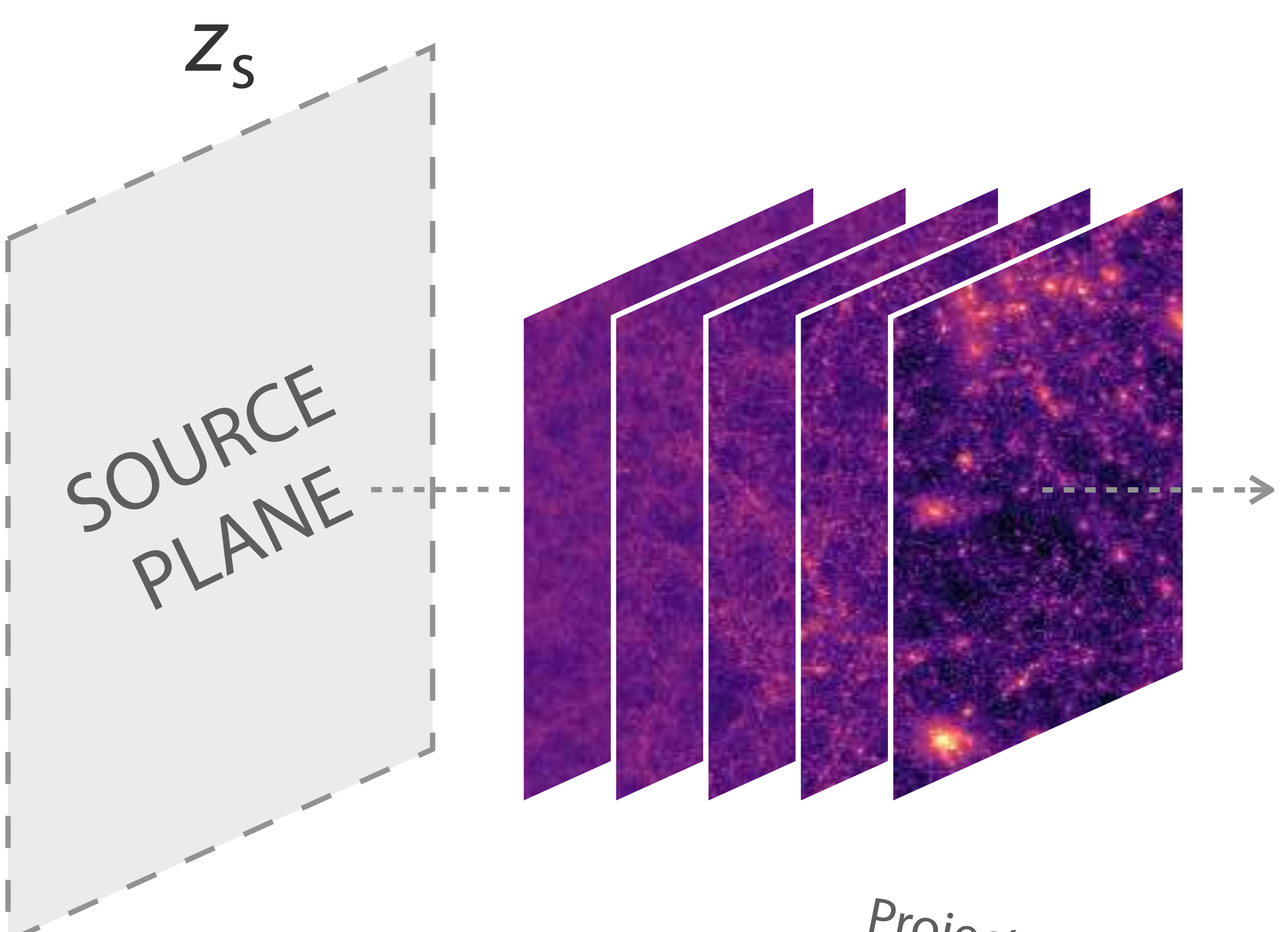
Overdensity δ

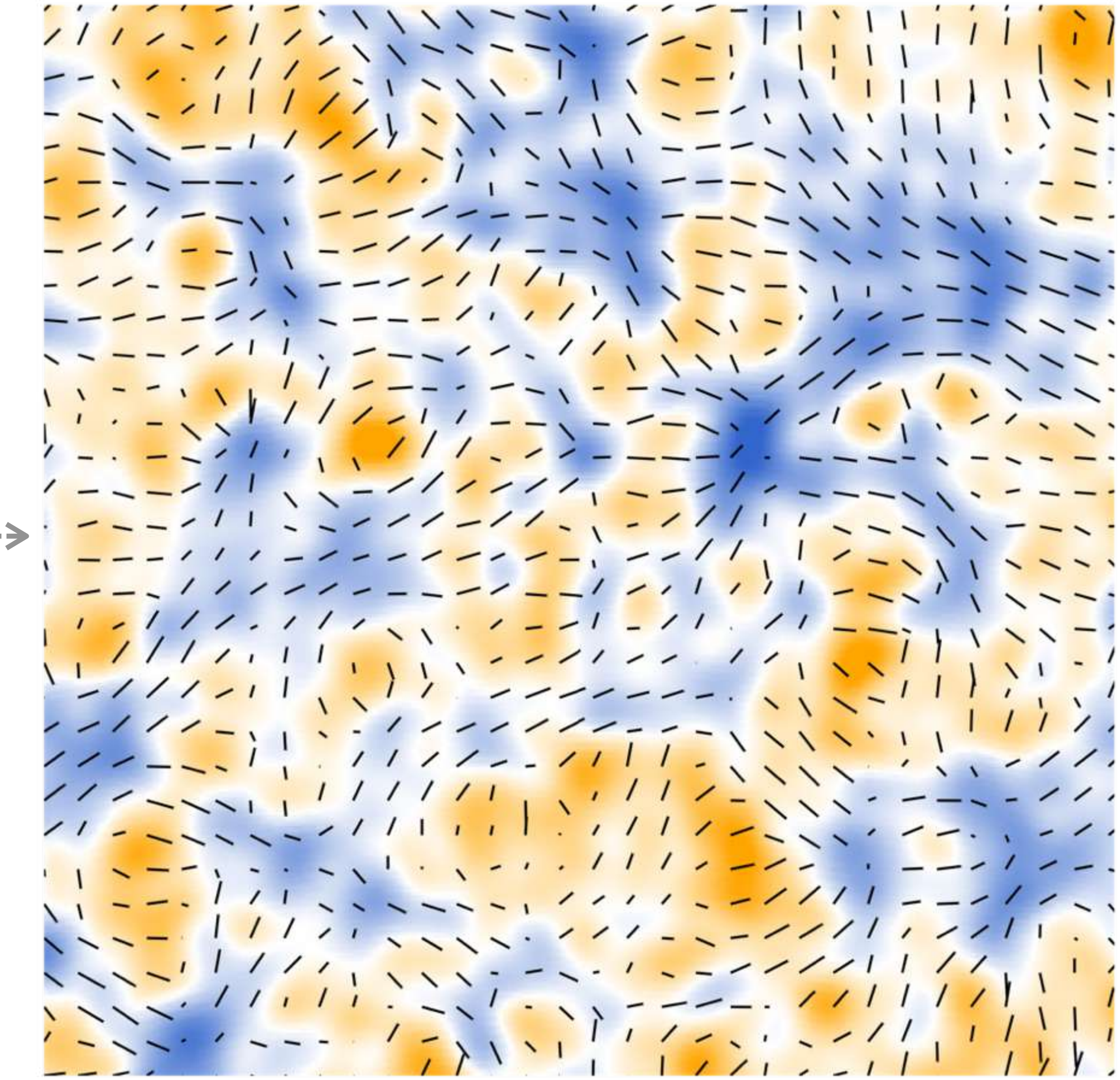


SLICS-HR
(Harnois-Déraps)

Weak gravitational lensing

A large-scale structure probe





SLICS-HR (Harnois-Déraps)

Projected gravitational potential

$$\kappa = \frac{1}{4}\left(\eth\bar{\eth} + \bar{\eth}\eth\right)\psi$$

$$\gamma = \gamma_1 + i\gamma_2 = \frac{1}{2}\eth\eth\psi$$

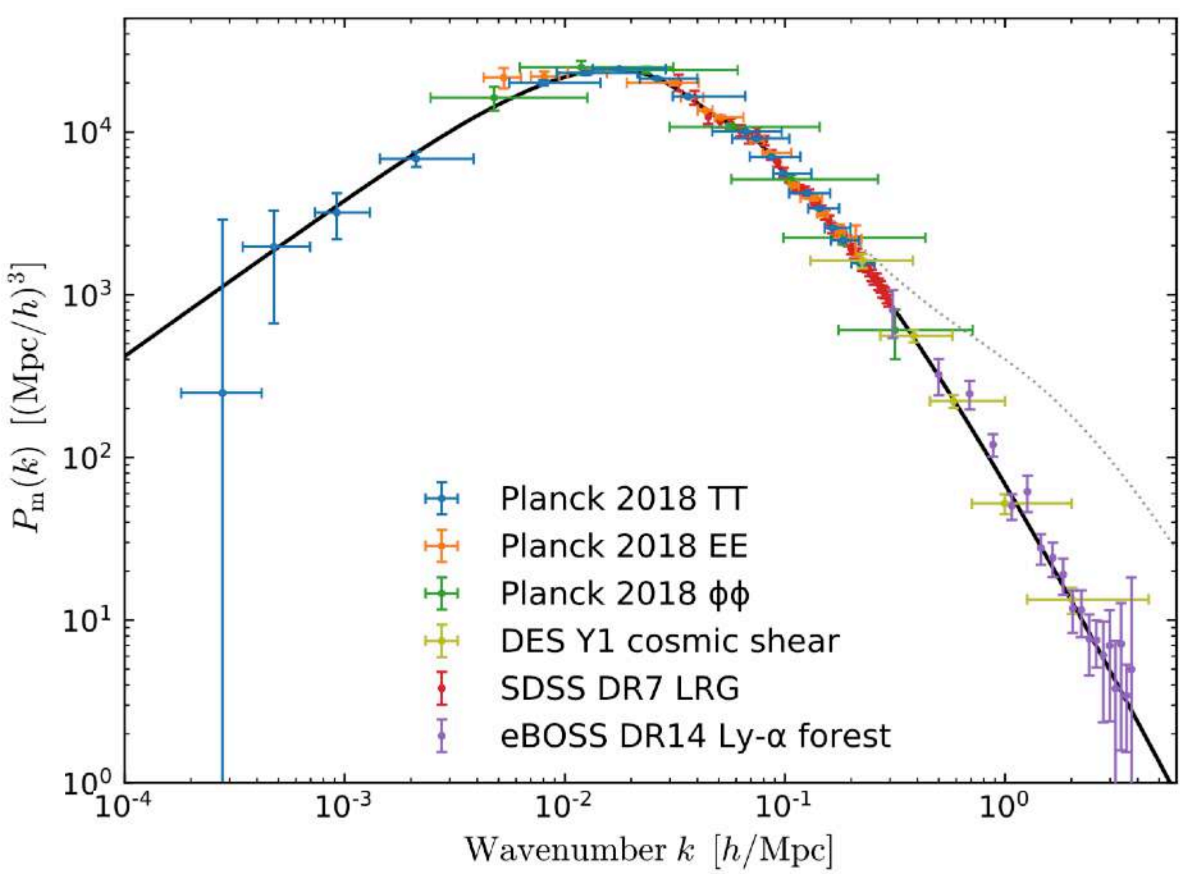
$$\kappa(\theta) = \int \mathrm{d}z\, W^{\kappa}(z, z_s)\,\delta(\theta, z)$$

Cosmic shear power spectrum

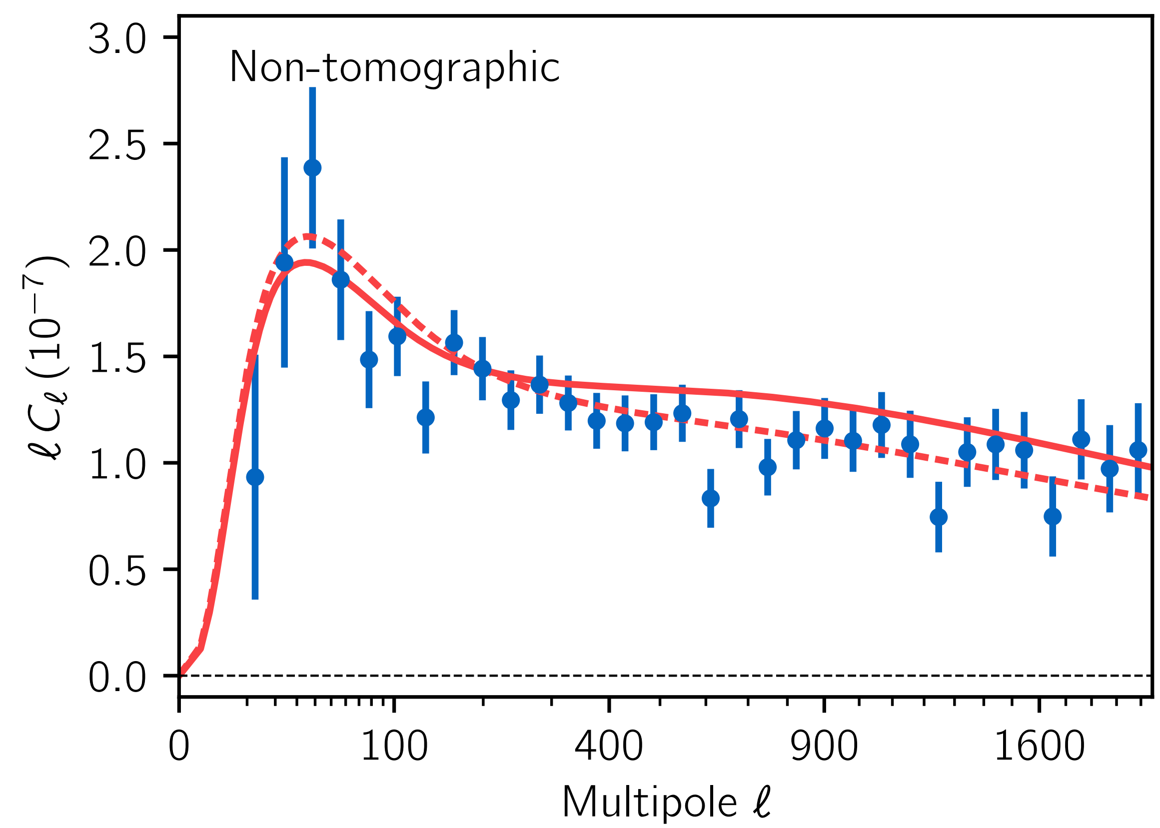
$$C_\ell^{\gamma_a \gamma_b} = \int_0^{z_\star} \mathrm{d}z \, \frac{H(z)}{c\,\chi(z)} \, W^a(z) W^b(z) \, P_\mathrm{m}\!\left(k = \frac{\ell + 1/2}{\chi(z)}, z\right)$$

GEOMETRY **GROWTH**

Matter power spectrum

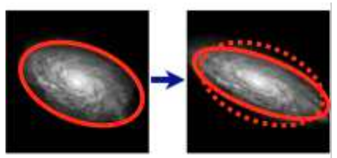


Cosmic shear power spectrum



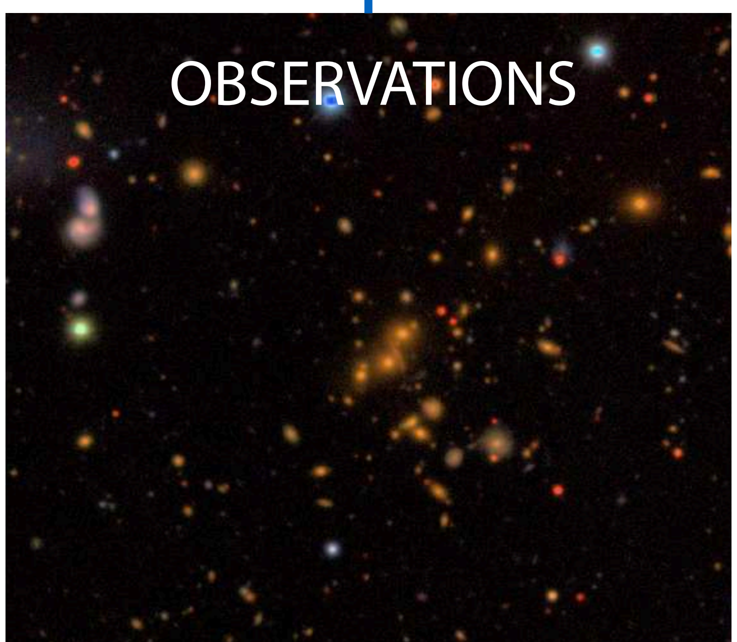
The cosmic shear power spectrum is a *projection* of the matter power spectrum !

Cosmic shear pipeline



ELLIPTICITIES

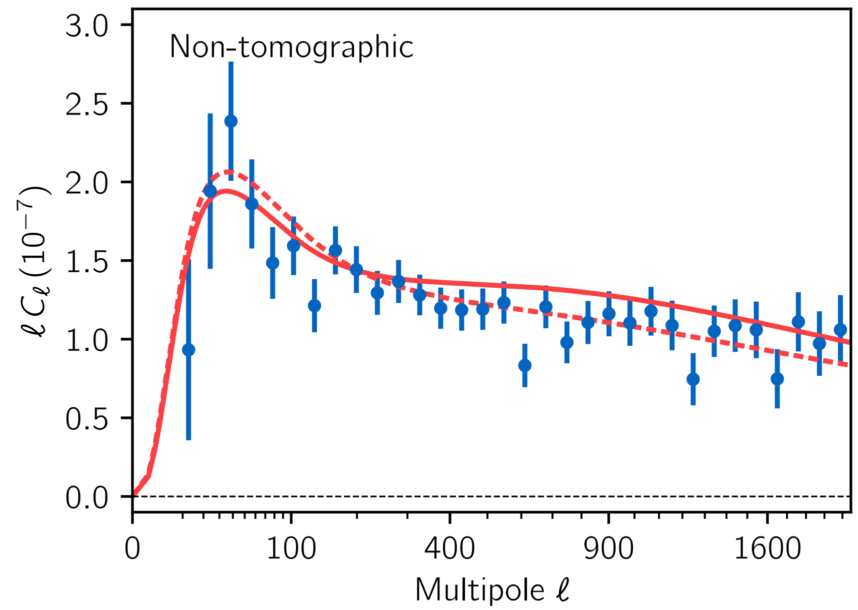
e_1/e_2



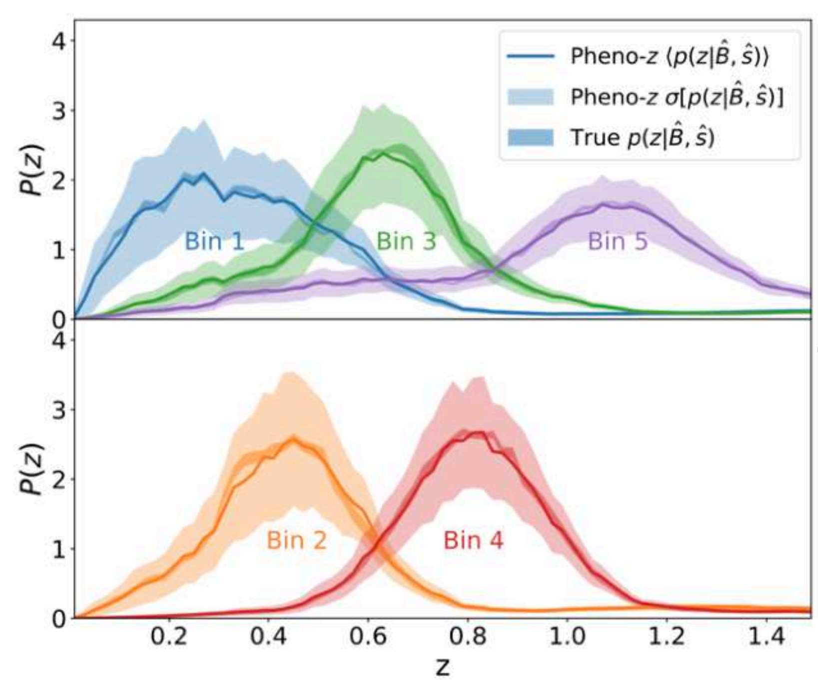
FLUXES

griz

- STATISTICS



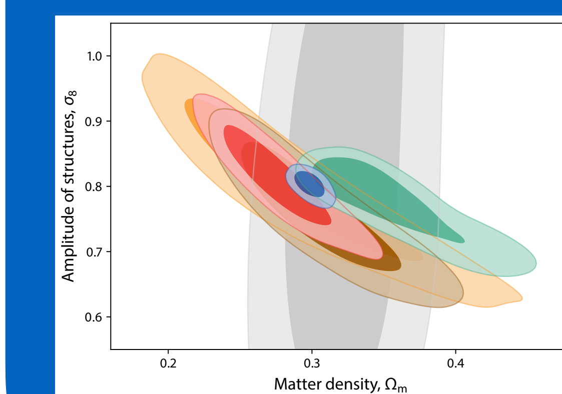
- REDSHIFT DISTRIBUTIONS



- COSMOLOGICAL SIGNAL
  - Matter power spectrum $P_{\rm NL}$
  - Lensing window functions q^i

$$C_\ell^{ij} = \int_0^{\chi_H} d\chi \, \frac{q^i(\chi) q^j(\chi)}{\chi^2} P_{\rm NL}\left(k = \frac{\ell + 1/2}{\chi}, \chi\right)$$

COSMOLOGICAL PARAMETERS

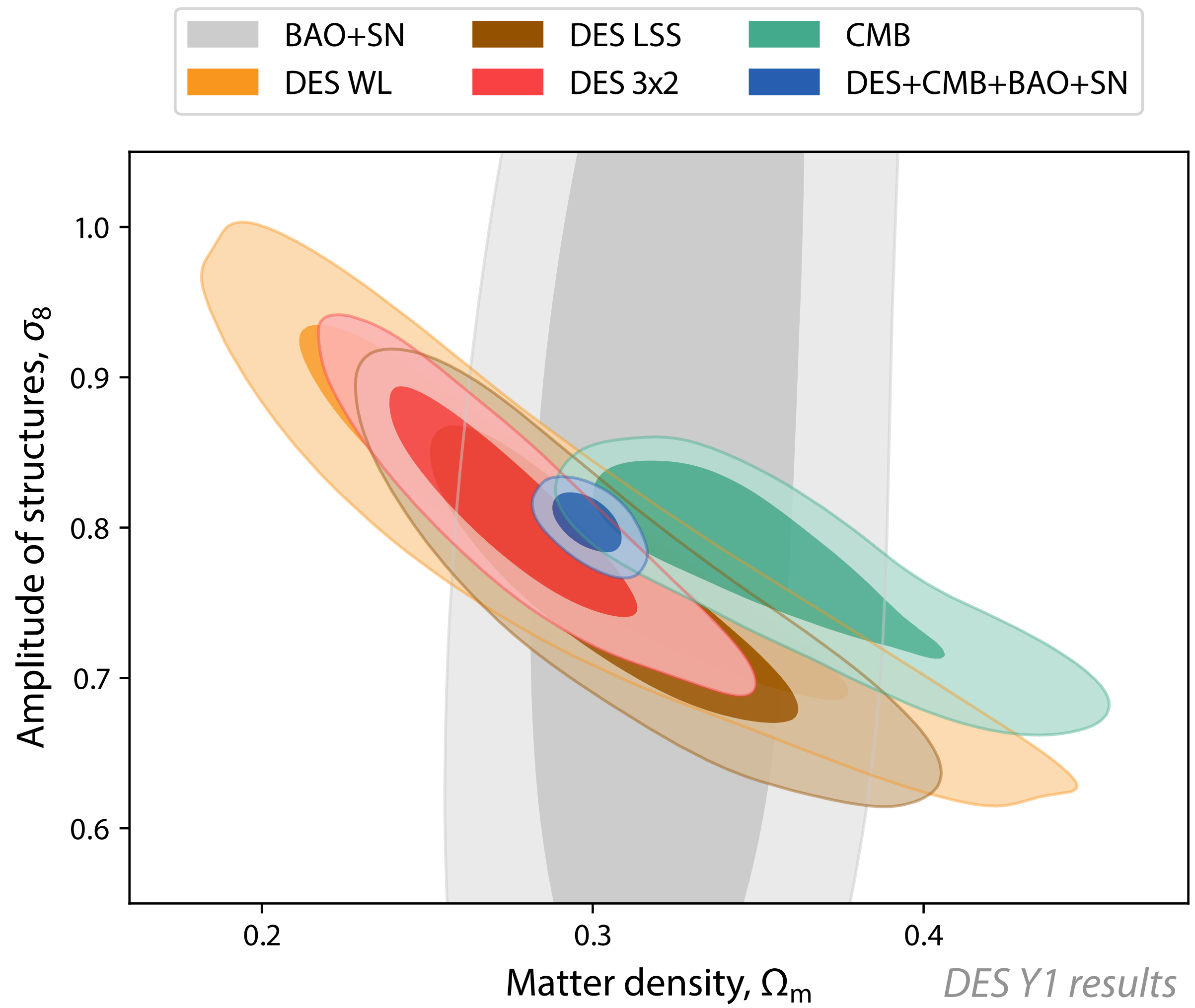


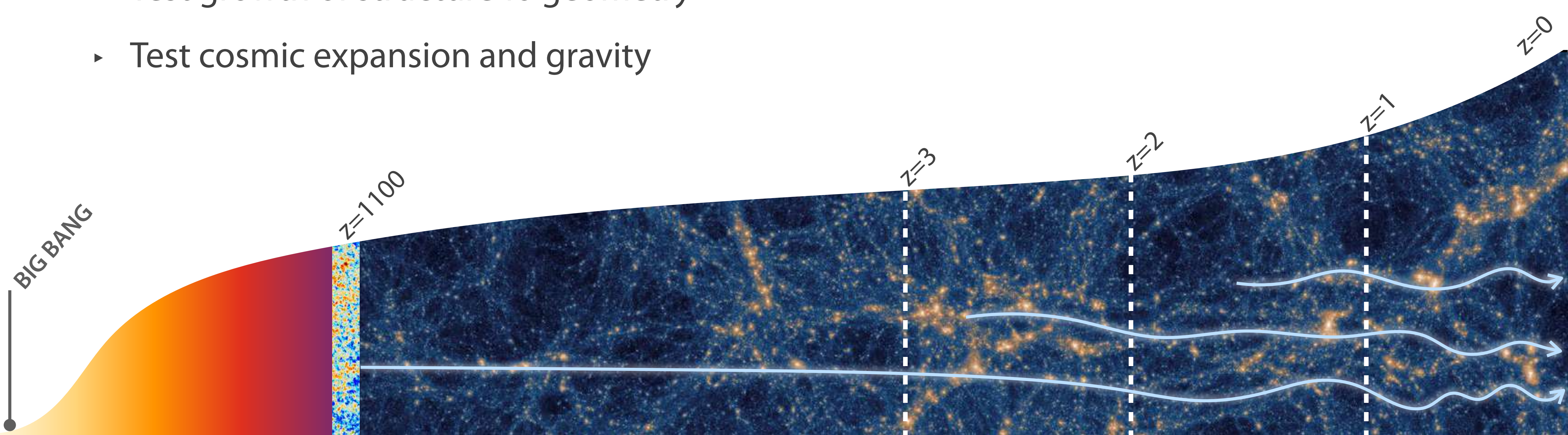
- SYSTEMATIC UNCERTAINTIES
  - Shear calibration m_i
  - Redshift uncertainties Δz_i
  - Intrinsic alignements model

Cosmic shear

A dark energy probe

- **Current ΛCDM paradigm**
  - CMB + BAO + SNIa predict flat ΛCDM…
  - Nature of dark matter and dark energy?
  - Tensions in H_0 and σ_8 : cracks in the model?
- **Cosmic shear and dark energy**
  - Test growth of structure *vs* geometry
  - Test cosmic expansion and gravity

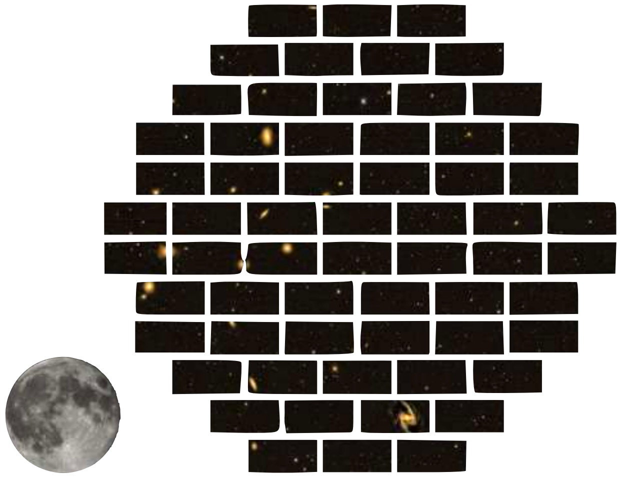


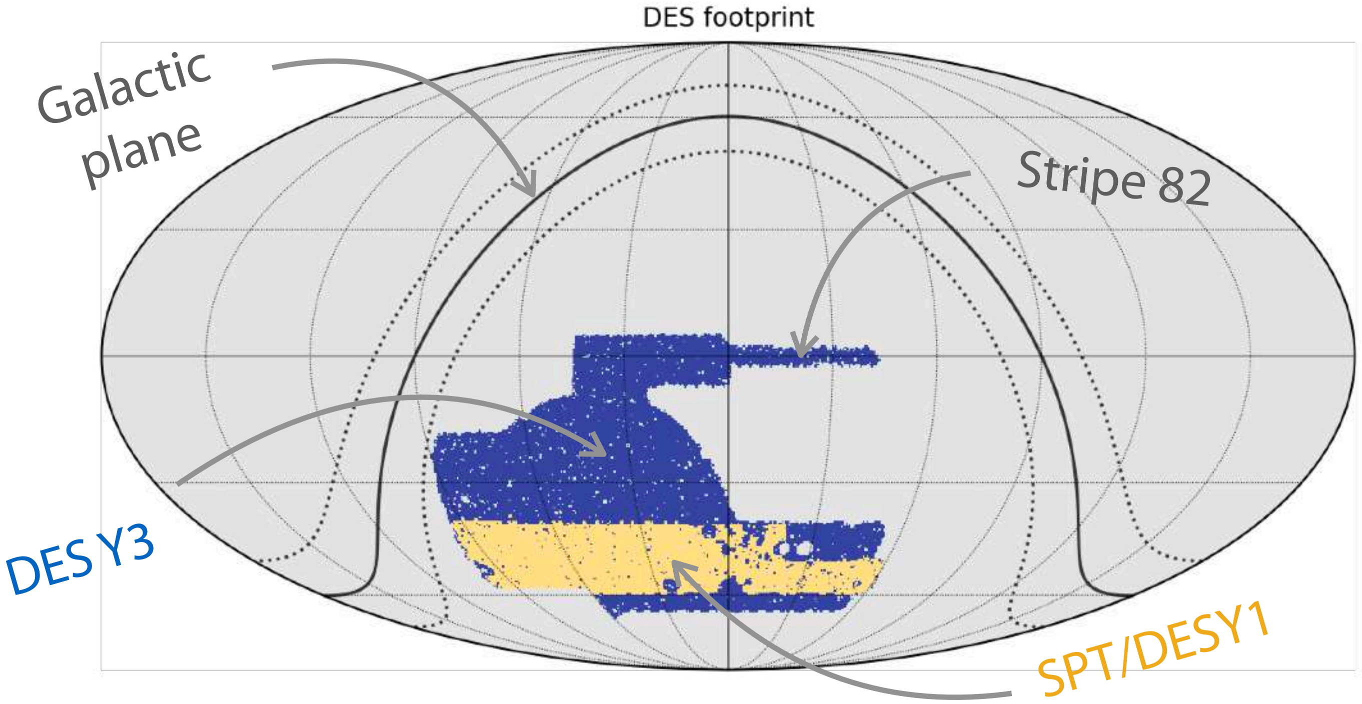


- Cosmic shear 101
- Cosmic shear in practice: DES analysis
- Cosmic shear with LSST: new challenges

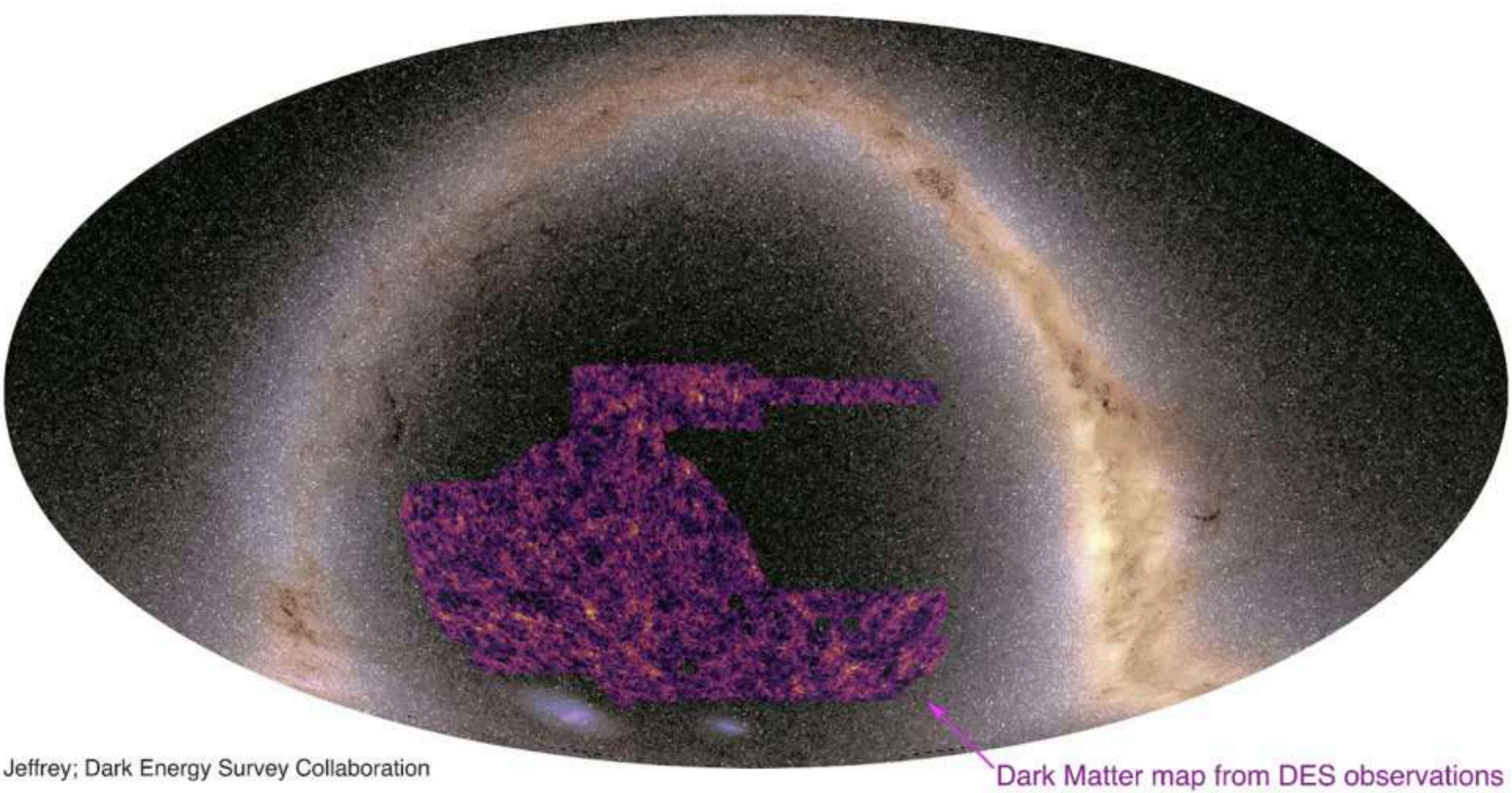
The Dark Energy Survey

- **Blanco 4-meter telescope** at Cerro Tololo (CTIO) in Chile
- **Dark Energy Camera** (DECam)
  - 3.0 deg^2 field-of-view, 70 CCD chips, 570 Mpix, *griz(Y)* filters
  - Seeing ~0.9′ in *r*-band, magnitude $i_{AB}<23.0$, $r<23.5$
- **Survey(s)**
  - 5000 deg^2 footprint + **deep fields**, observed 2013-2019



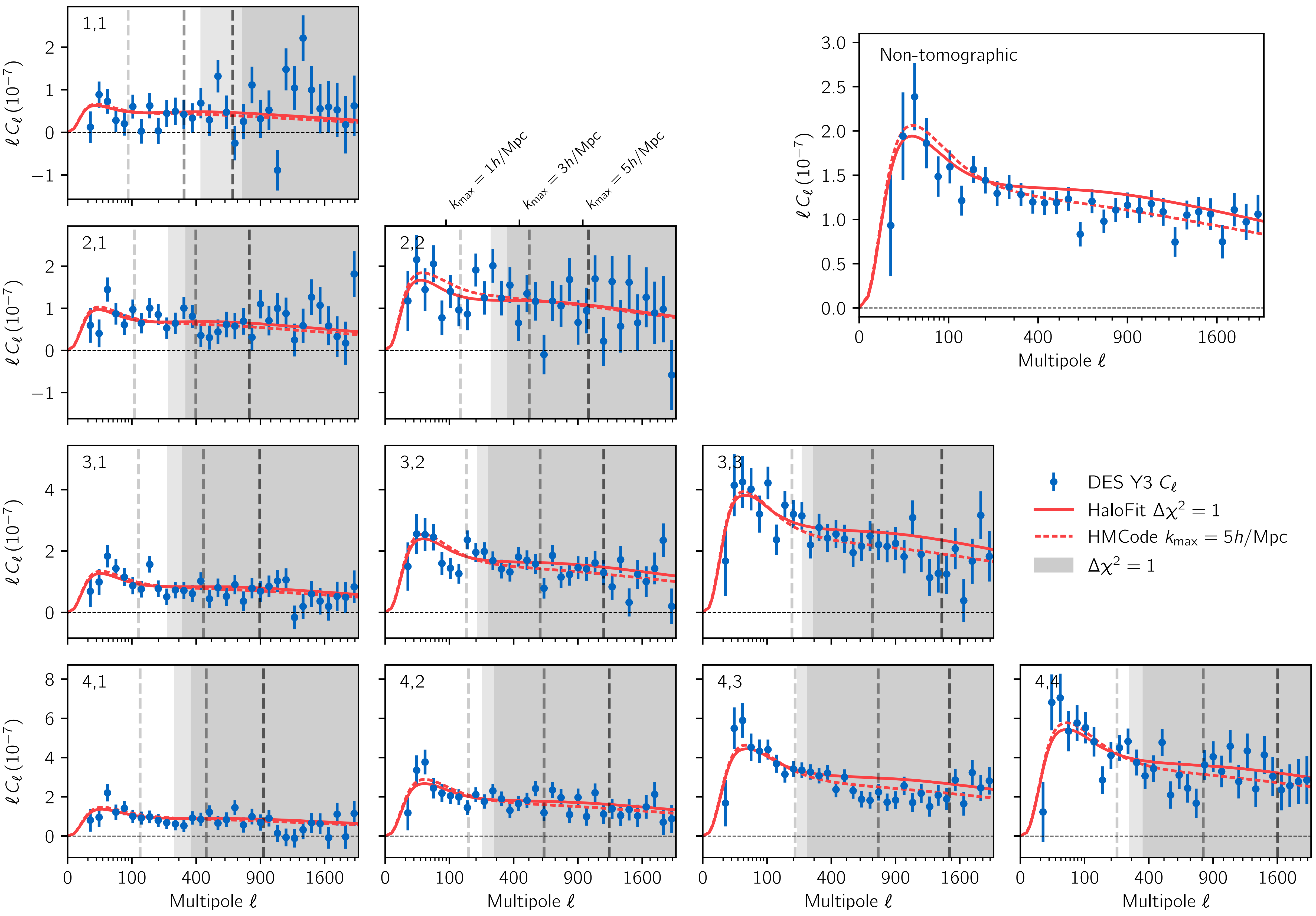


Dark Energy Survey mass maps

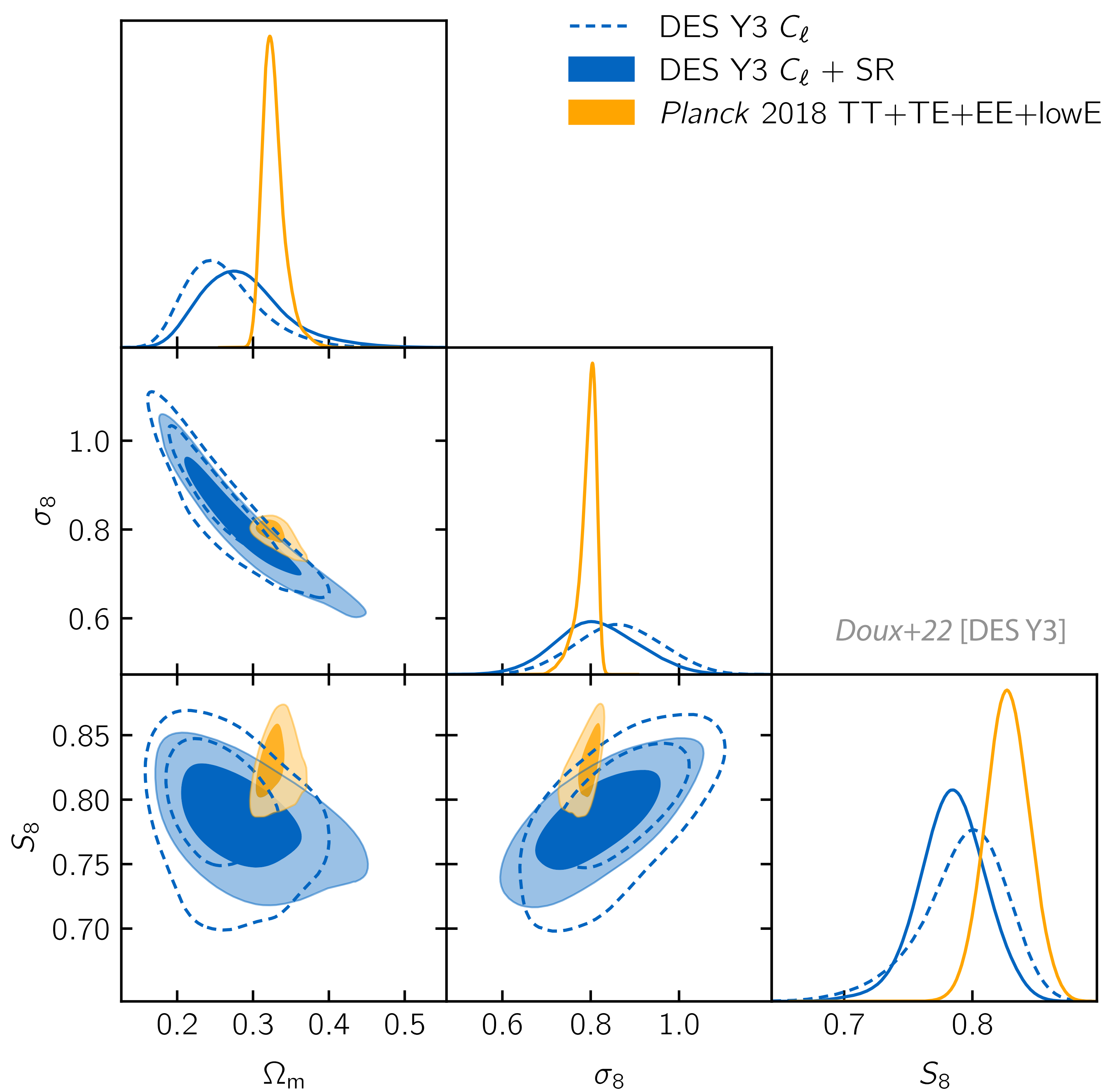


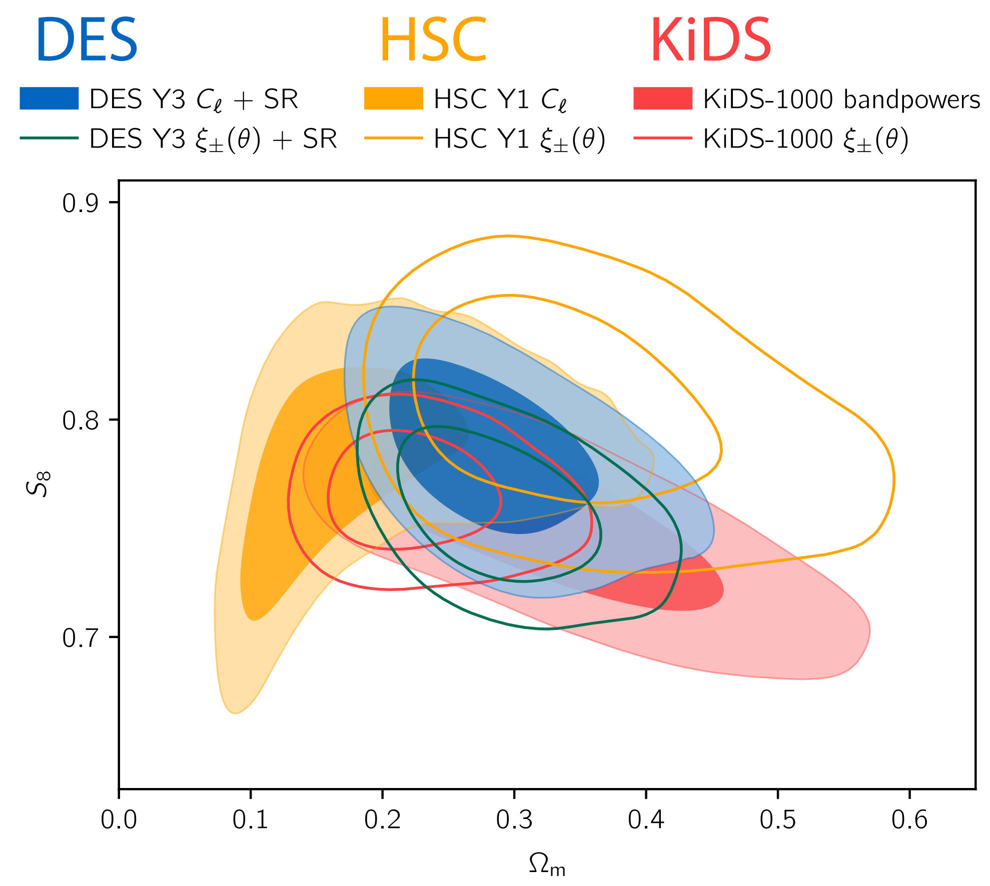
N. Jeffrey; Dark Energy Survey Collaboration

DES Y3 cosmic shear power spectra



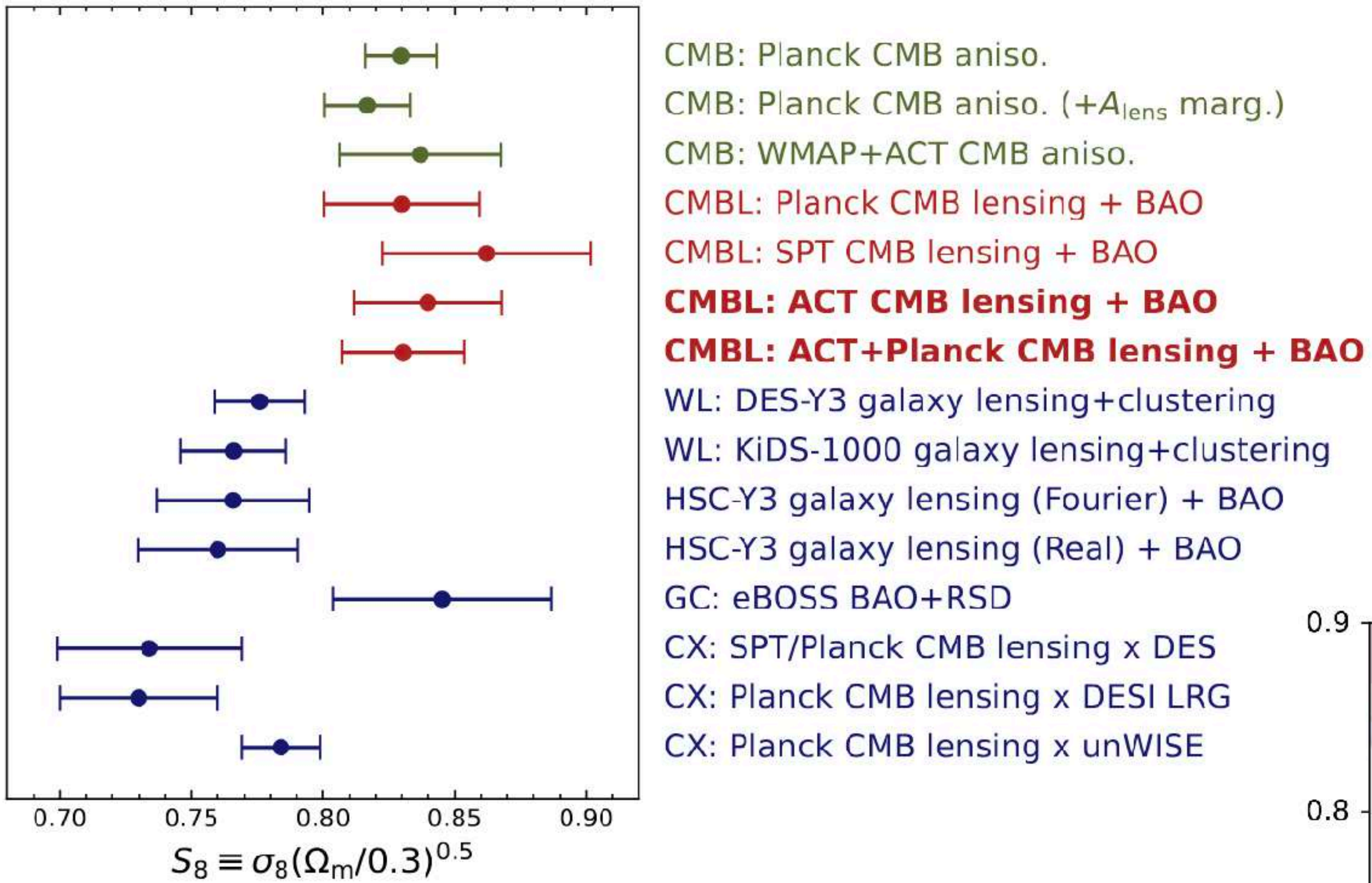
Cosmological constraints: shear *vs* CMB



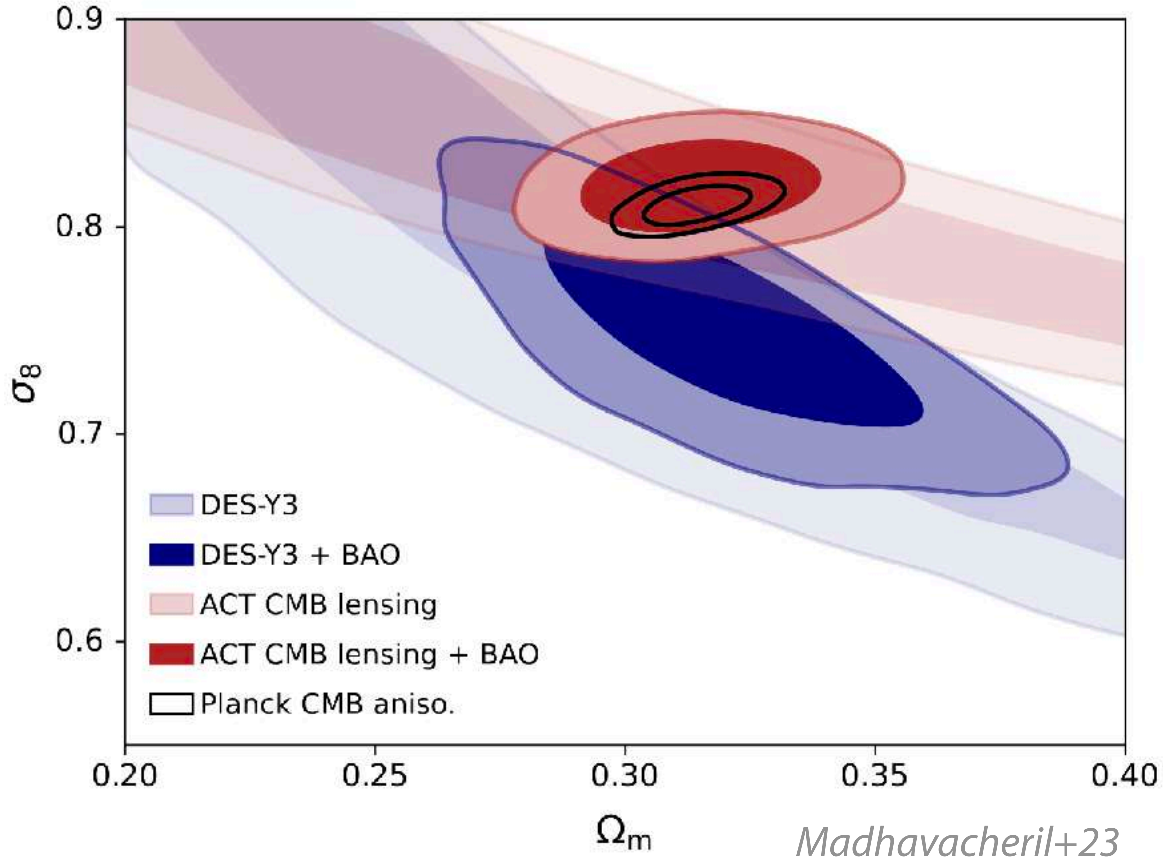


Lensing surveys *consistently* find lower S_8 than Planck CMB

Galaxy/CMB lensing and the σ_8 tension



- **Late-time Universe appears more *clumpy* than expected from the CMB**
  1. Unknown systematics?
  2. Theory predictions off?
  3. New physics?



Madhavacheril+23

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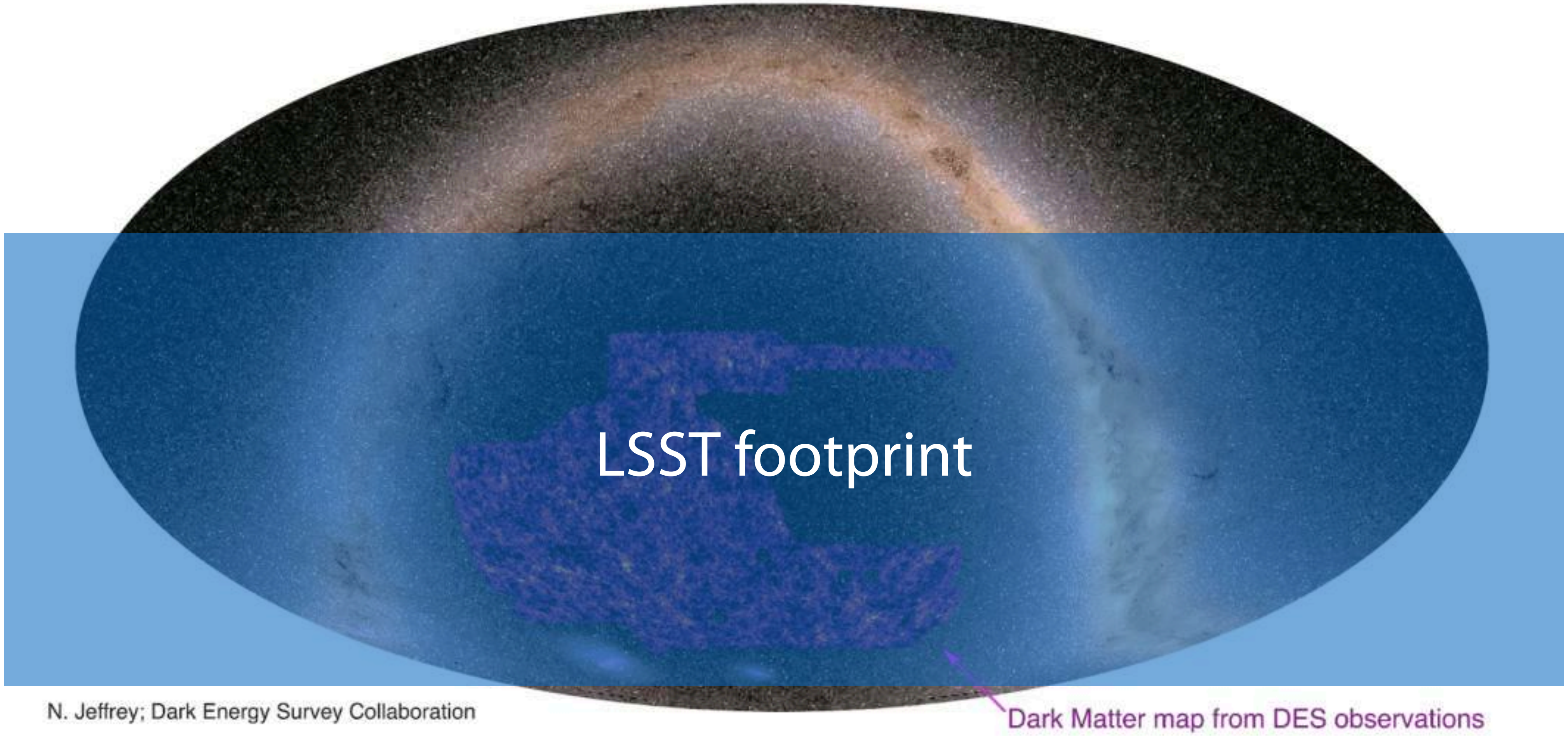
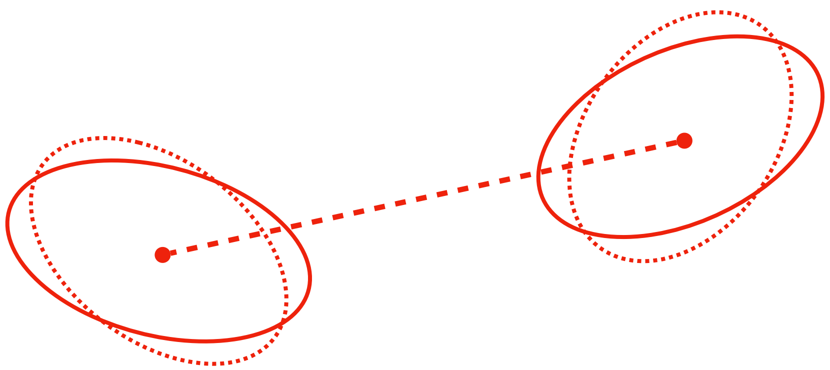
DES *vs* LSST

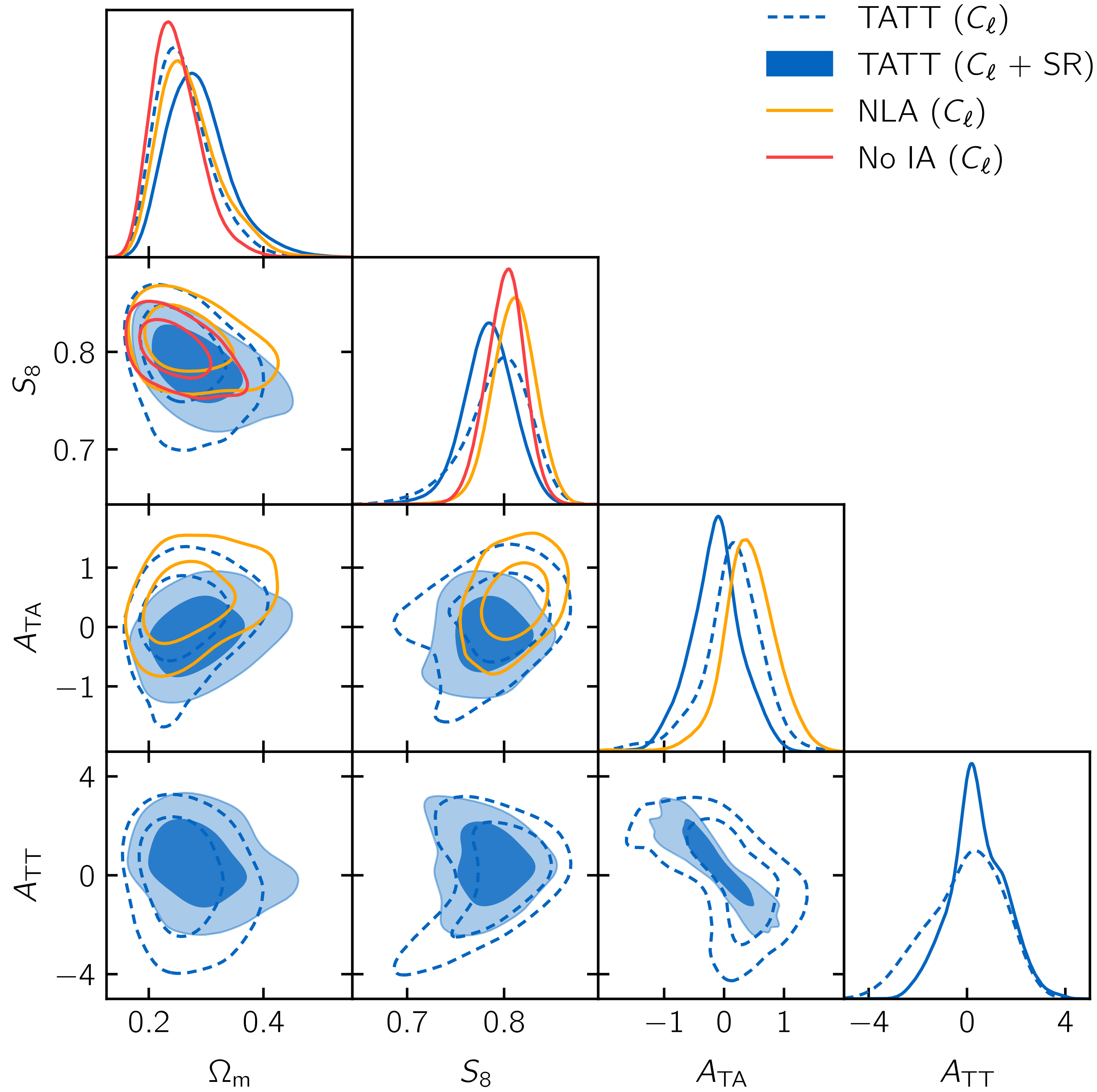


	DES	LSST
Dates	2013-2019	2025-2035
Footprint	5000 deg^2	18000 deg^2
Galaxies for WL	150 millions	Few billions
Density for WL	6 gal/arcmin^2	30 gal/arcmin^2

Intrinsic alignments



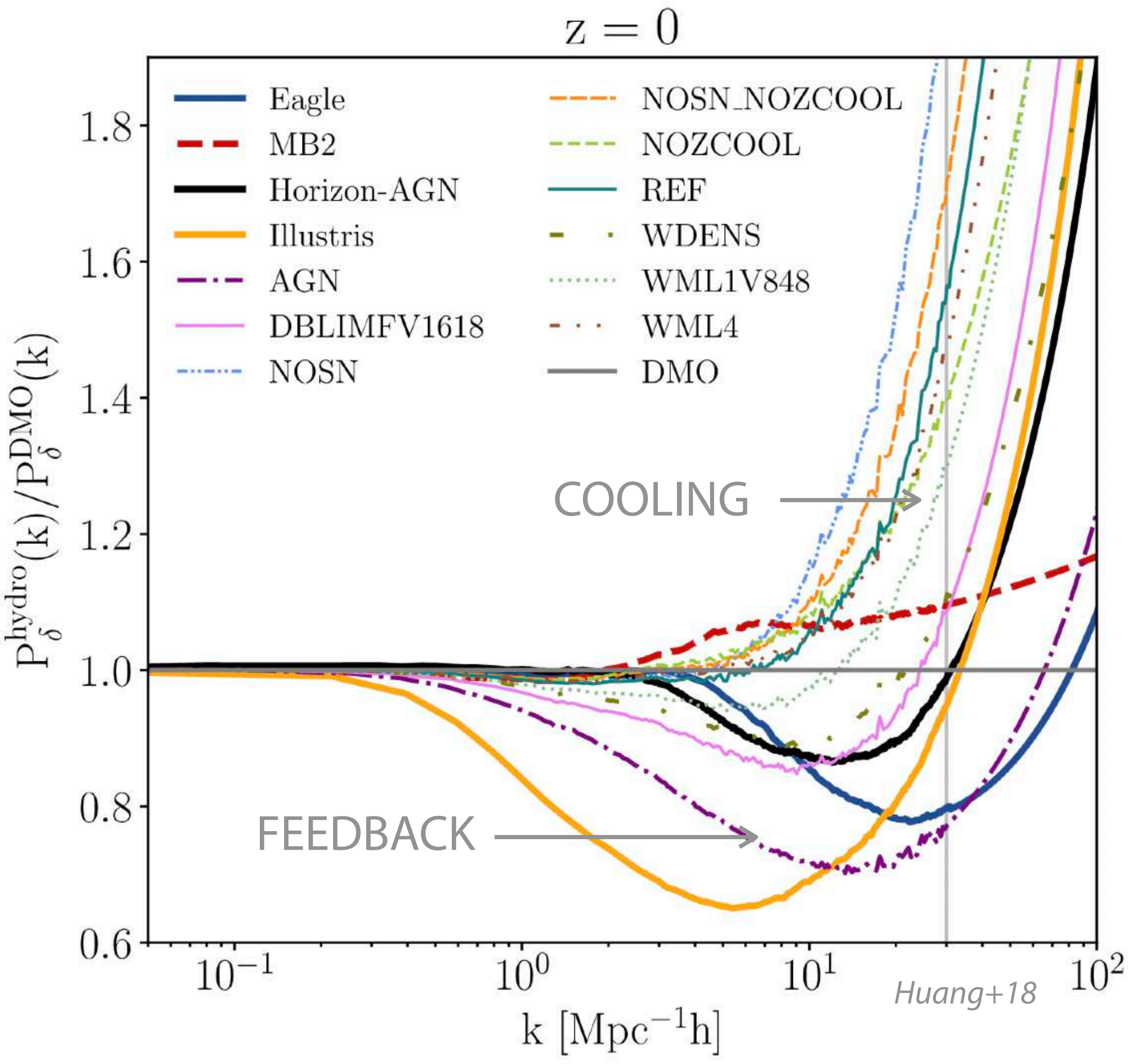
- **IA modelling**
  - Tidal alignment (TA) $\propto A_{TA}$
  - Tidal torquing (TT) $\propto A_{TT}$
- **DES Y3 results**
  - Degeneracy partially broken by geometric *shear ratios*
  - More complex model (TATT) not favored by data over simpler one (NLA)



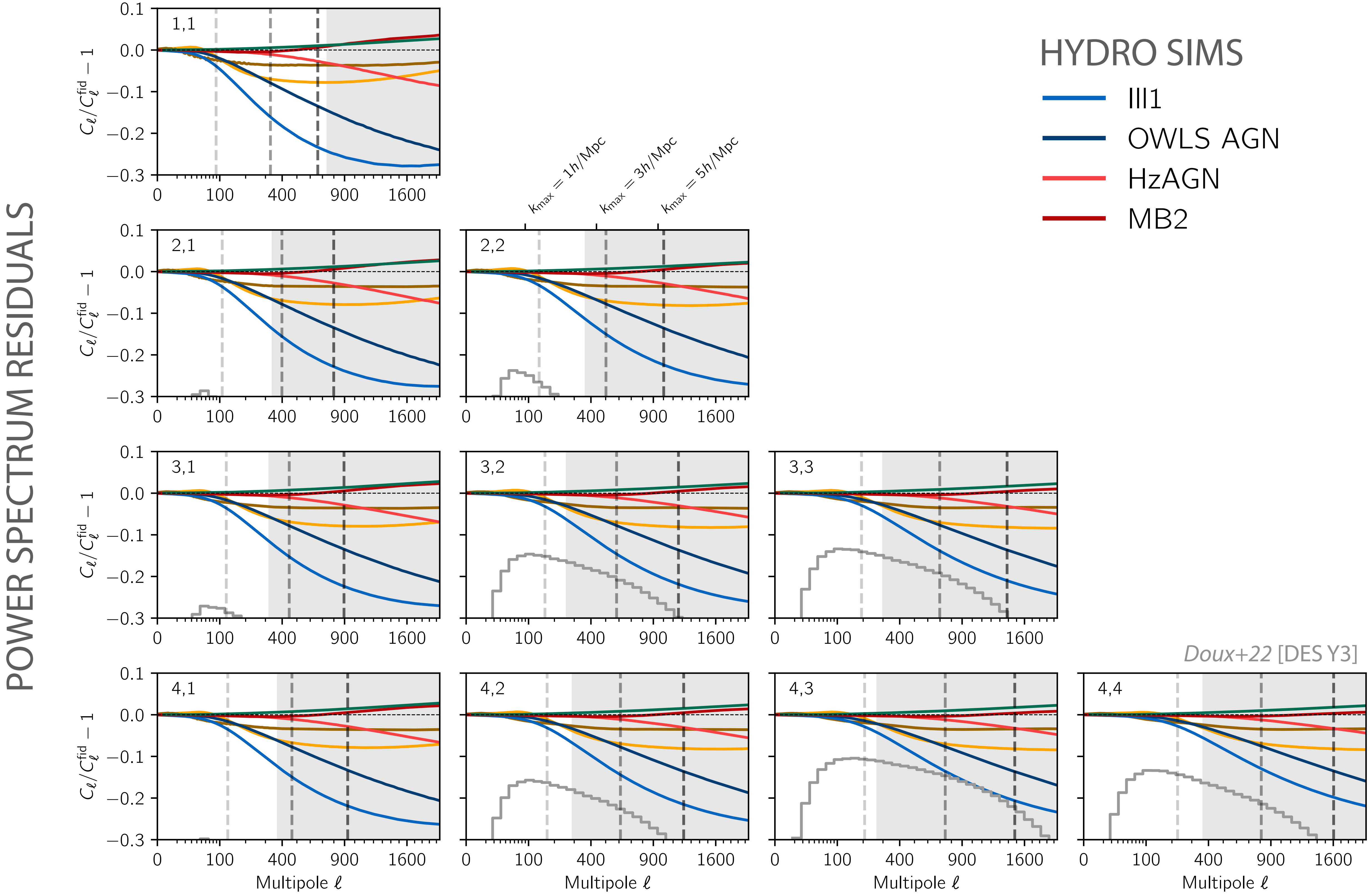
Doux+22 [DES Y3]

Impact of baryons

- **Baryonic effects?**
  - Feedback from AGN and SN explosions, cooling mechanism
  - Redistribute matter
- **Impact on the power spectrum**
  - Brooooaaaad variations across hydrodynamical simulations…

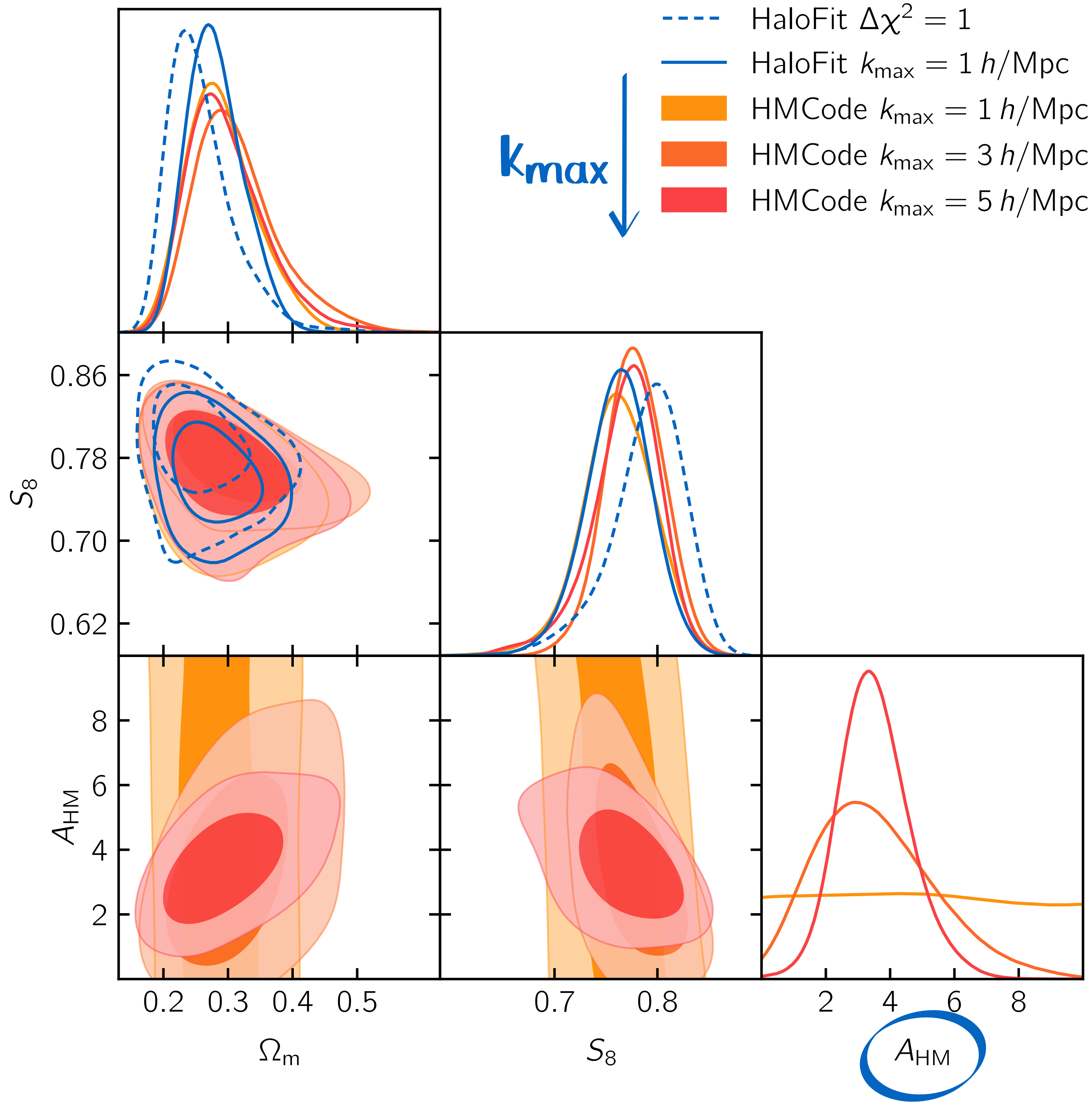


Baryons *vs* scale cuts



Baryons *vs* scale cuts

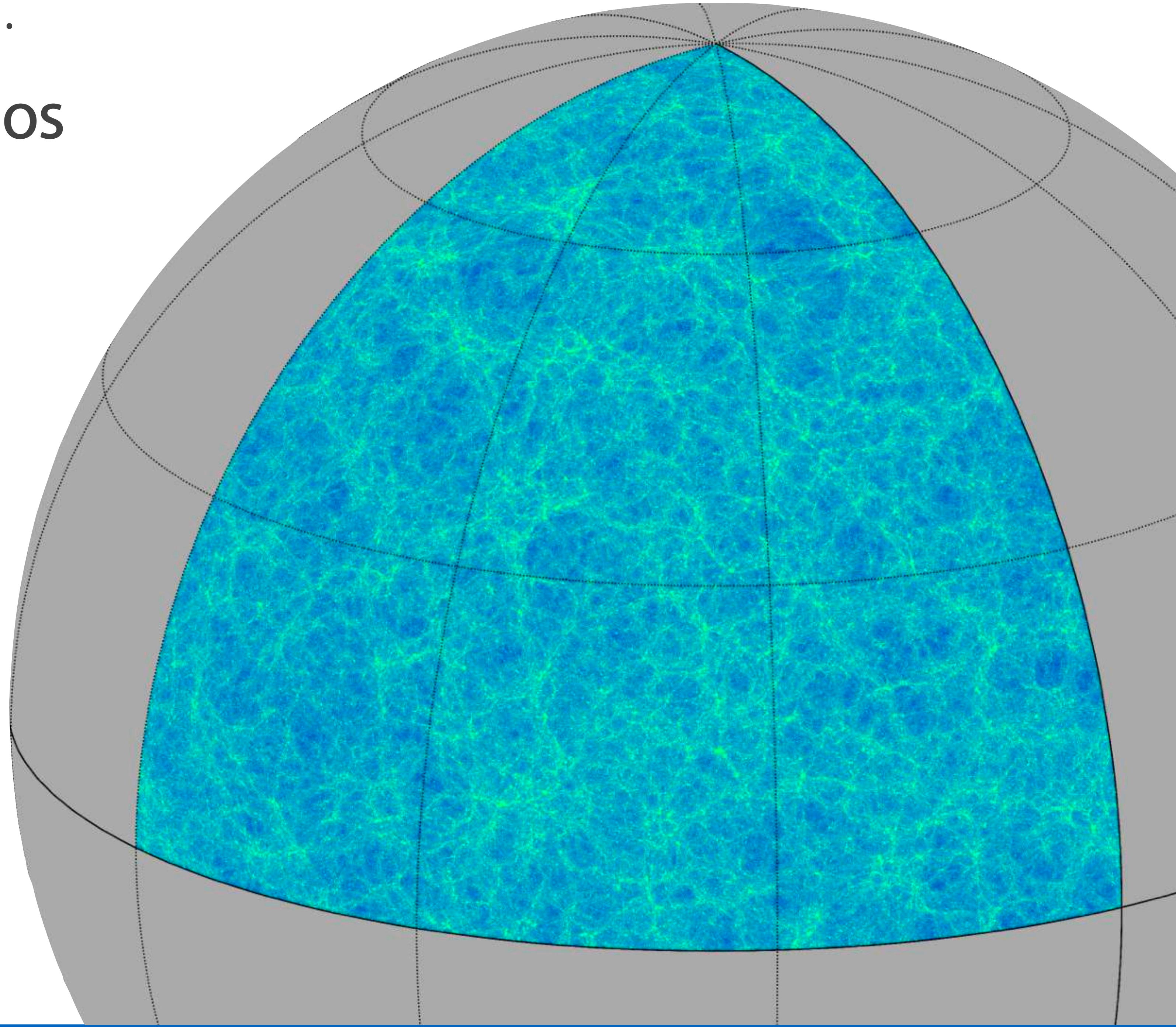
- **Discarding small scales?**
  - DES Y3 fiducial approach
- **Modeling baryons**
  - Halo model of baryonic feedback
  - DES Y3 results: small-scale constraining power goes to baryonic feedback parameter
  - LSST: higher density means extra cosmological information reachable (+cross-correlations with CMB tSZ)



Doux+22 [DES Y3]

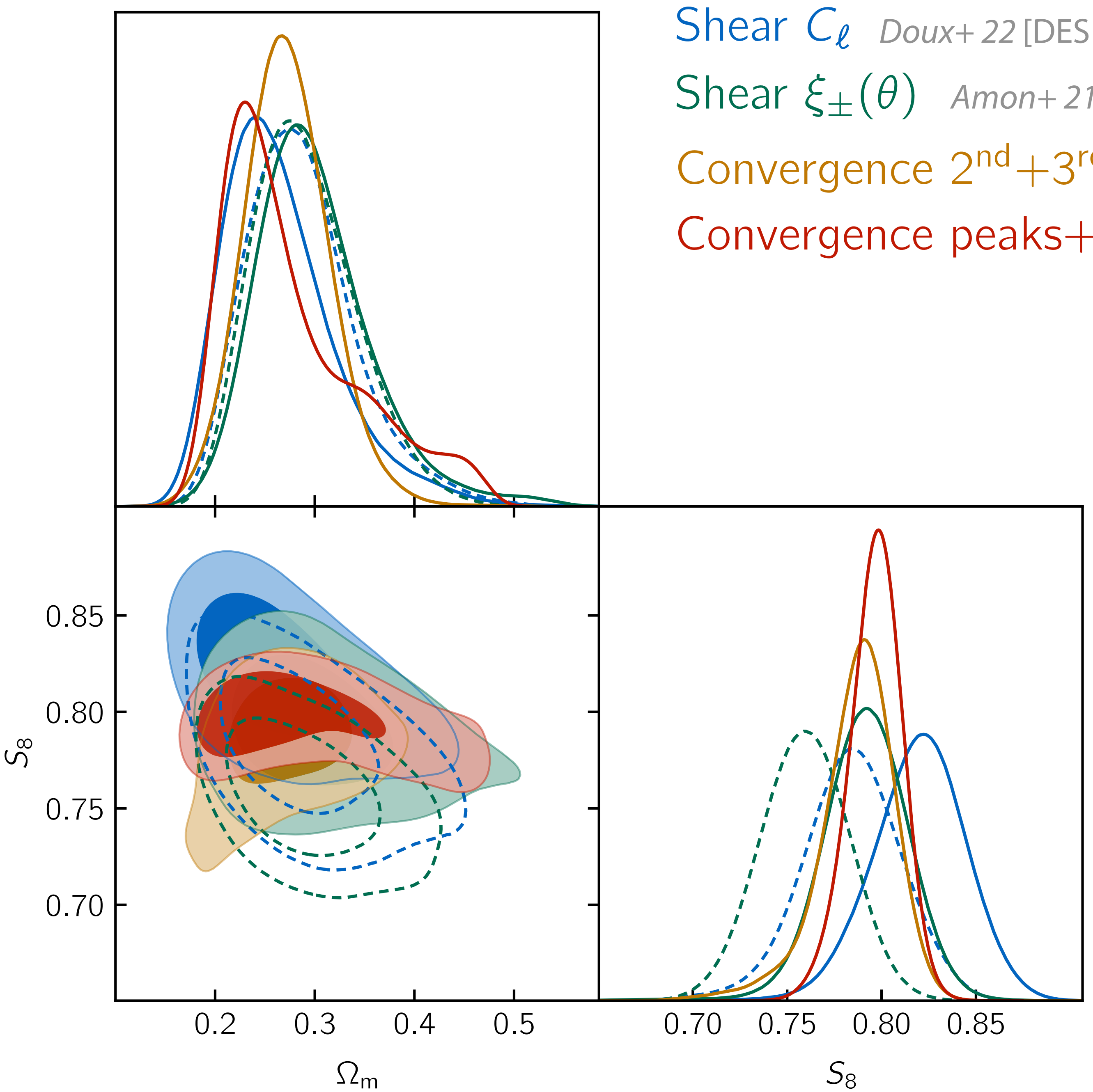
Beyond two-point statistics

- **Higher-order statistics?**
  - N-point functions, peaks, voids, 1D PDF, topological features, etc.
  - Theoretical predictions are tricky…
- **Simulation-based modelling of HOS**
  1. Sample parameter space
  2. Generate *N*-body sims, turn into lightcone and lensing maps
  3. Include all known *astrophysical uncertainties* and *observational systematics*…
  4. Measure HOS on sims and "compare" to data!



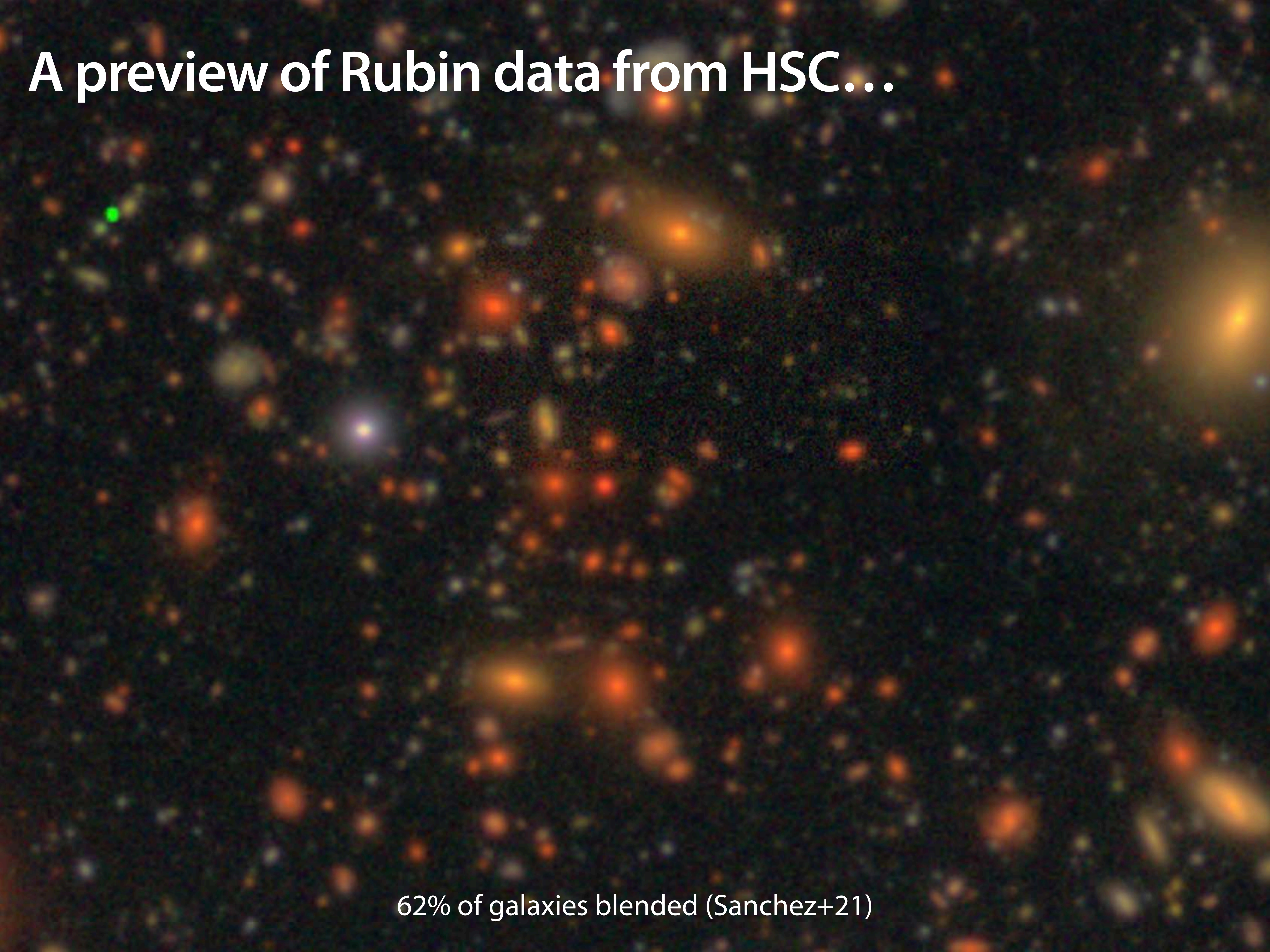
Beyond two-point statistics

- **What's the point?**
  - DES Y3 ~30% improvement ⟶ factor 2 (or more) for LSST/Euclid?



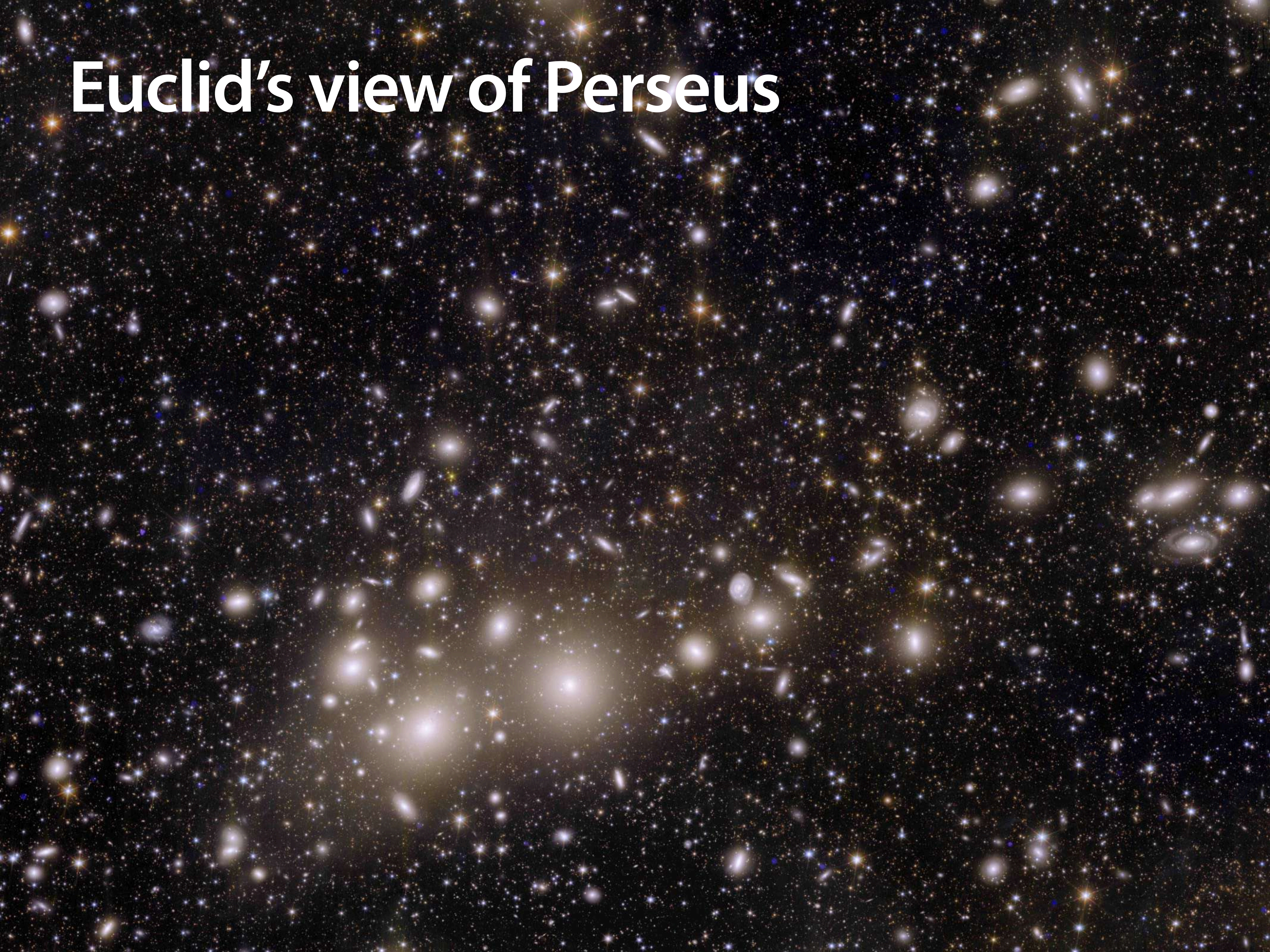
- **Best HOS?**
  - Robustness to systematics? 😅
  - Interpretability? CNNs 😱
  - Theoretical predictions? 😵

A preview of Rubin data from HSC…



62% of galaxies blended (Sanchez+21)

Euclid’s view of Perseus



Take-away messages

1. Galaxy weak lensing allows to test ΛCDM+GR
2. Current constraints on σ_8 on par with CMB constraints, with mild tension
3. Many challenges and opportunities with future surveys


Thanks!

Back-up slides

METACALIBRATION/METADETECT in a nutshell

- **Recipe**

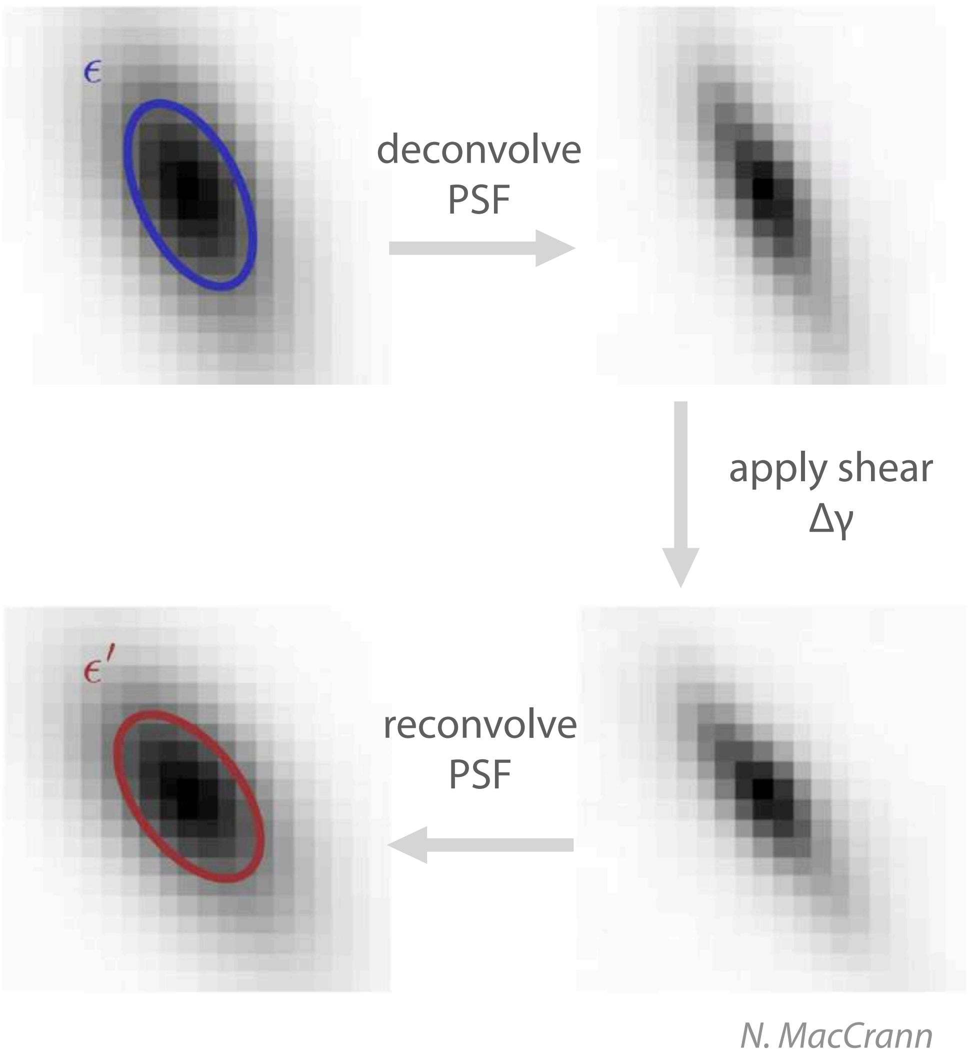
1. For any *biased* shear estimator **e**,

$$\mathbf{e} = \mathbf{e}|_{\gamma=0} + \gamma \cdot \underbrace{\frac{\partial \mathbf{e}}{\partial \gamma}\bigg|_{\gamma=0}}_{\mathbf{R}_\gamma} + \mathcal{O}(\gamma^3)$$

2. Response $\mathbf{R}_\gamma$ estimated by applying shear to images

$$\mathbf{R}_\gamma = \frac{\mathbf{e}^+ - \mathbf{e}^-}{2\Delta\gamma}$$

3. Estimator $\langle\hat{\gamma}\rangle \approx \langle \mathbf{R}_\gamma \rangle^{-1} \langle \mathbf{e} \rangle$ is *unbiased* 👍



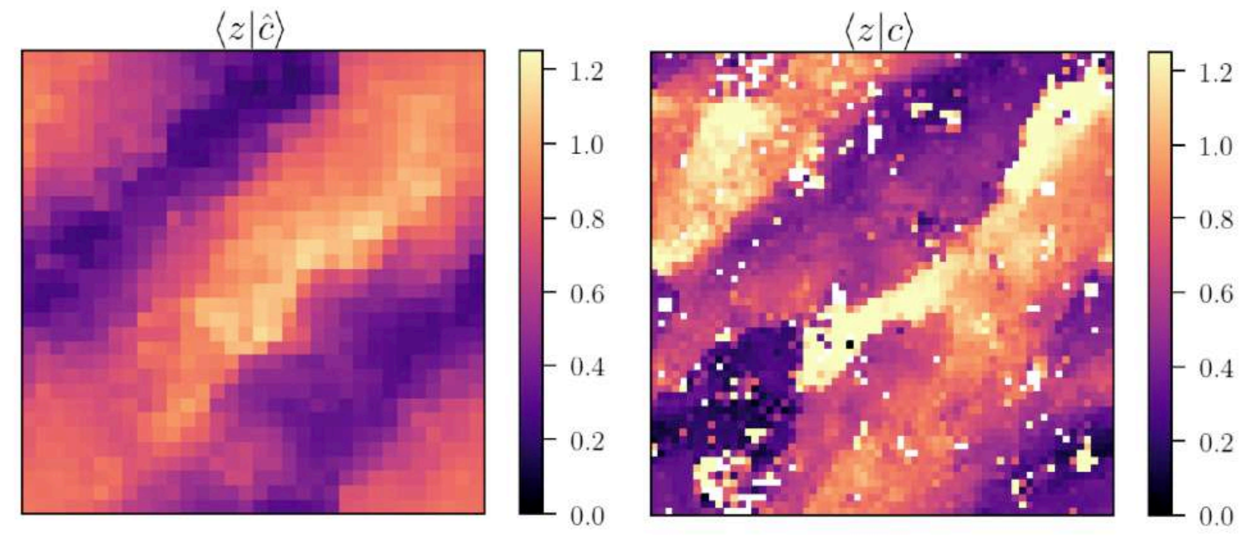
- **Pros/cons**

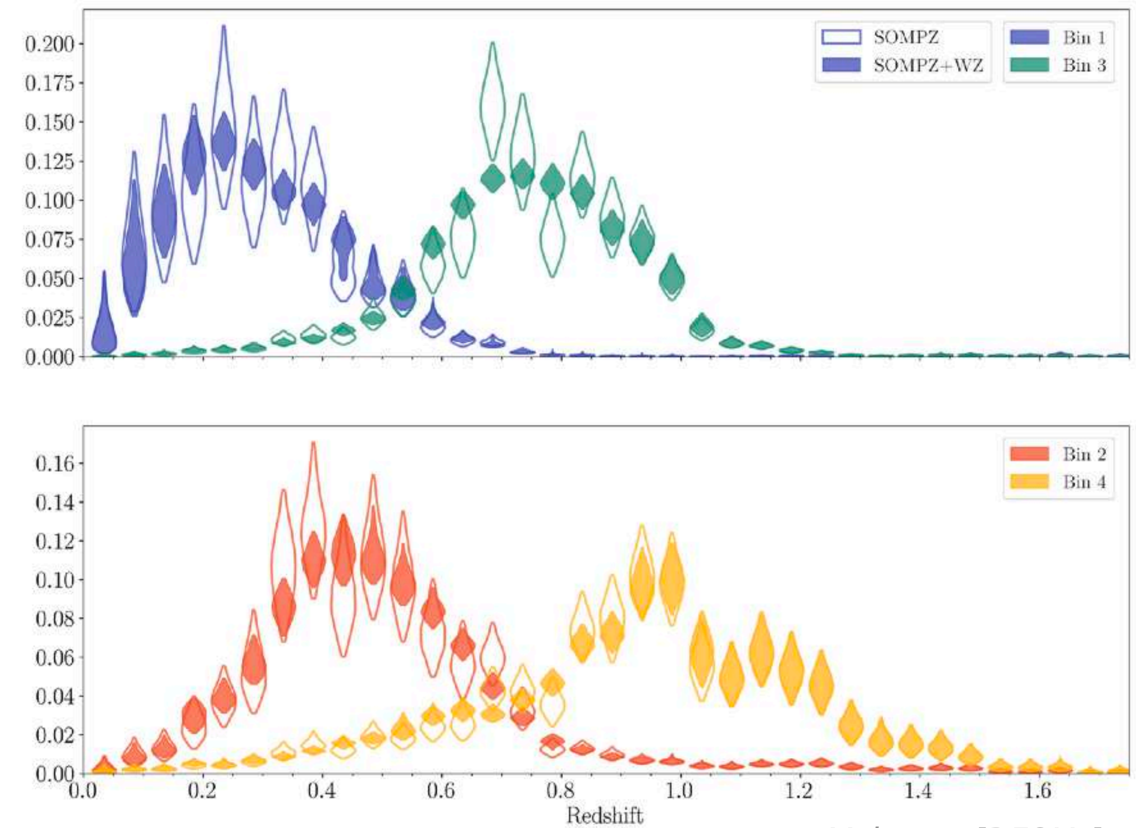
✓ Mitigates *shear-dependent* biases from model, noise, detection and selection

⚠ Reprocessing each image + issue with deblending

Redshift distributions *n*(*z*)'s

- **How to estimate the *n*(*z*) of a sample of galaxies?**
  - Stacking individual *p*(*z*)'s is sub-optimal
  - *Uncertainty* of sample's *n*(*z*), eg on $\langle z \rangle$
- **SOMPZ in DES Y3/Y6**
  - Samples of *n*(*z*)=*P*({*z*}|{noisy colors}) using
    1. *p*(true colors|z)* from deep fields + spectroscopic data
    2. *p*(noisy colors|true colors)* from synthetic source injection
  - Marginalization over distribution of distributions?? 🫠



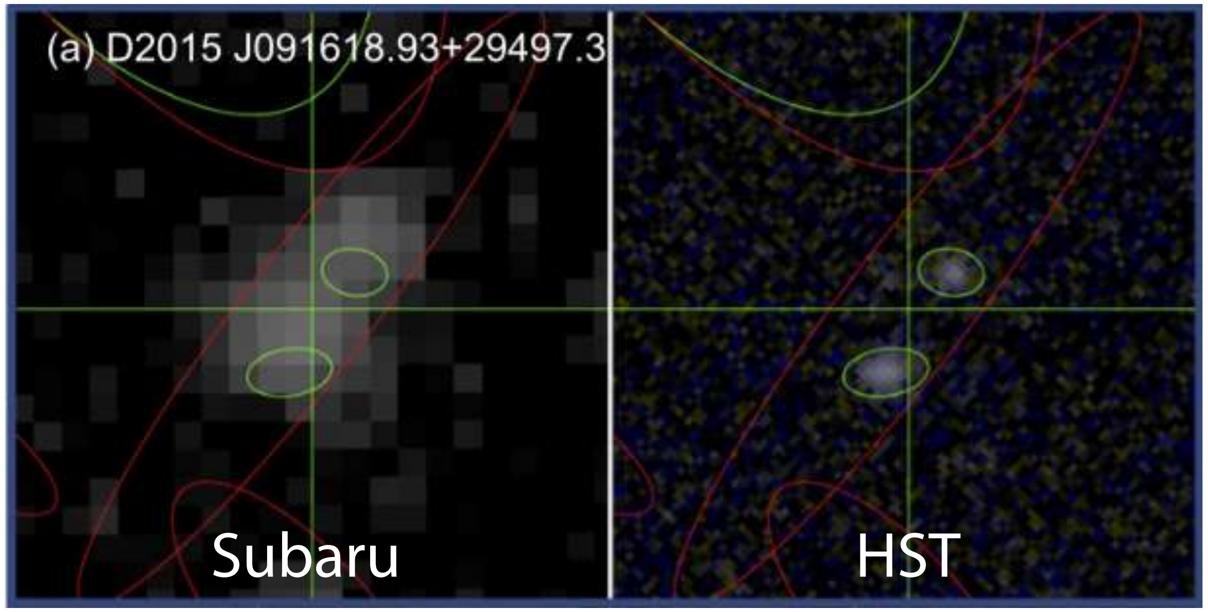


Myles+20 [DES Y3]

* conditional distributions parametrised with self-organizing maps (SOM)

(De)blending

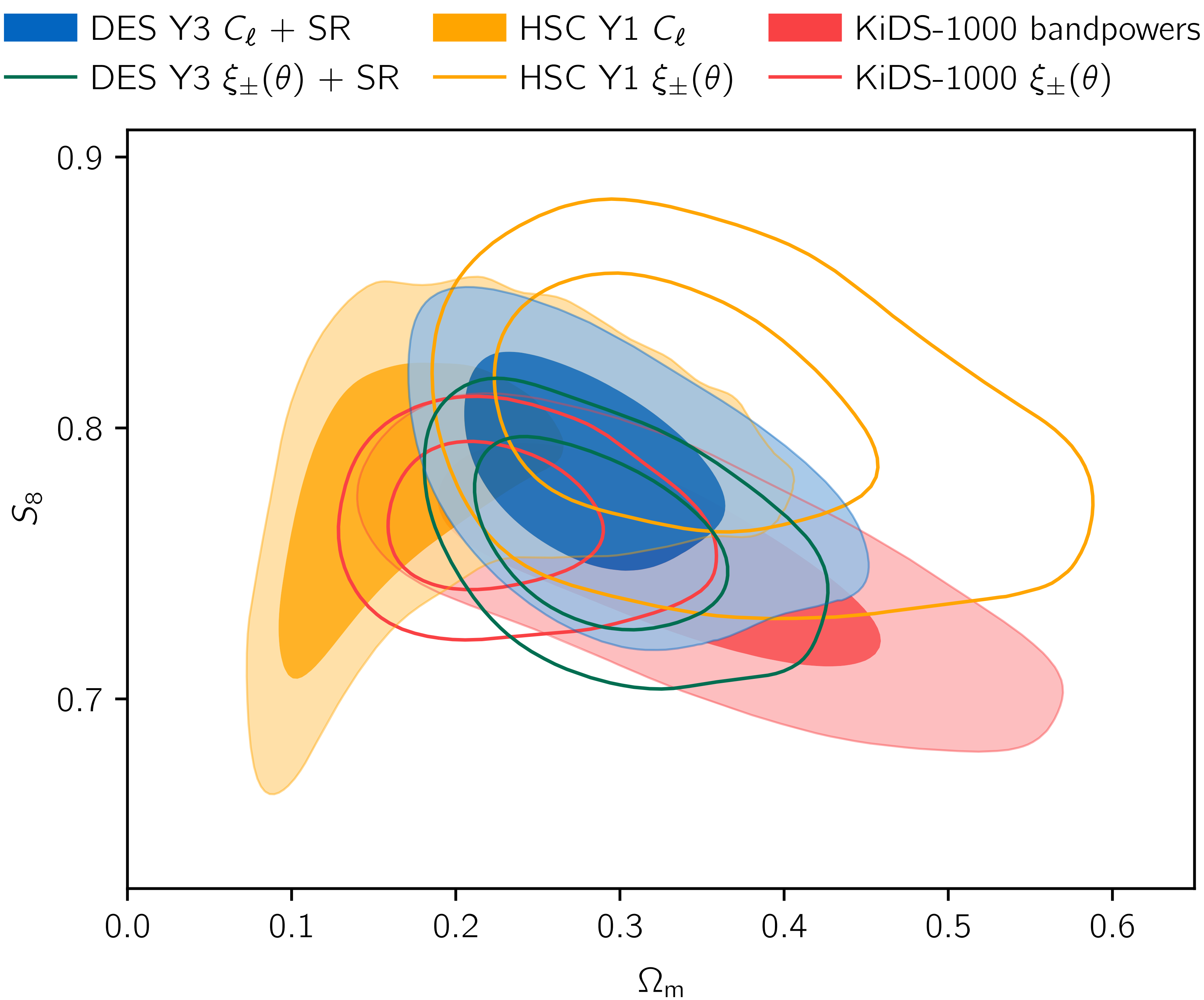
- **Why is it an issue?**
  - 2/3 galaxies are blended at LSST's depth
  - Impacts detection and shape/flux measurements, *ie* all weak lensing science!



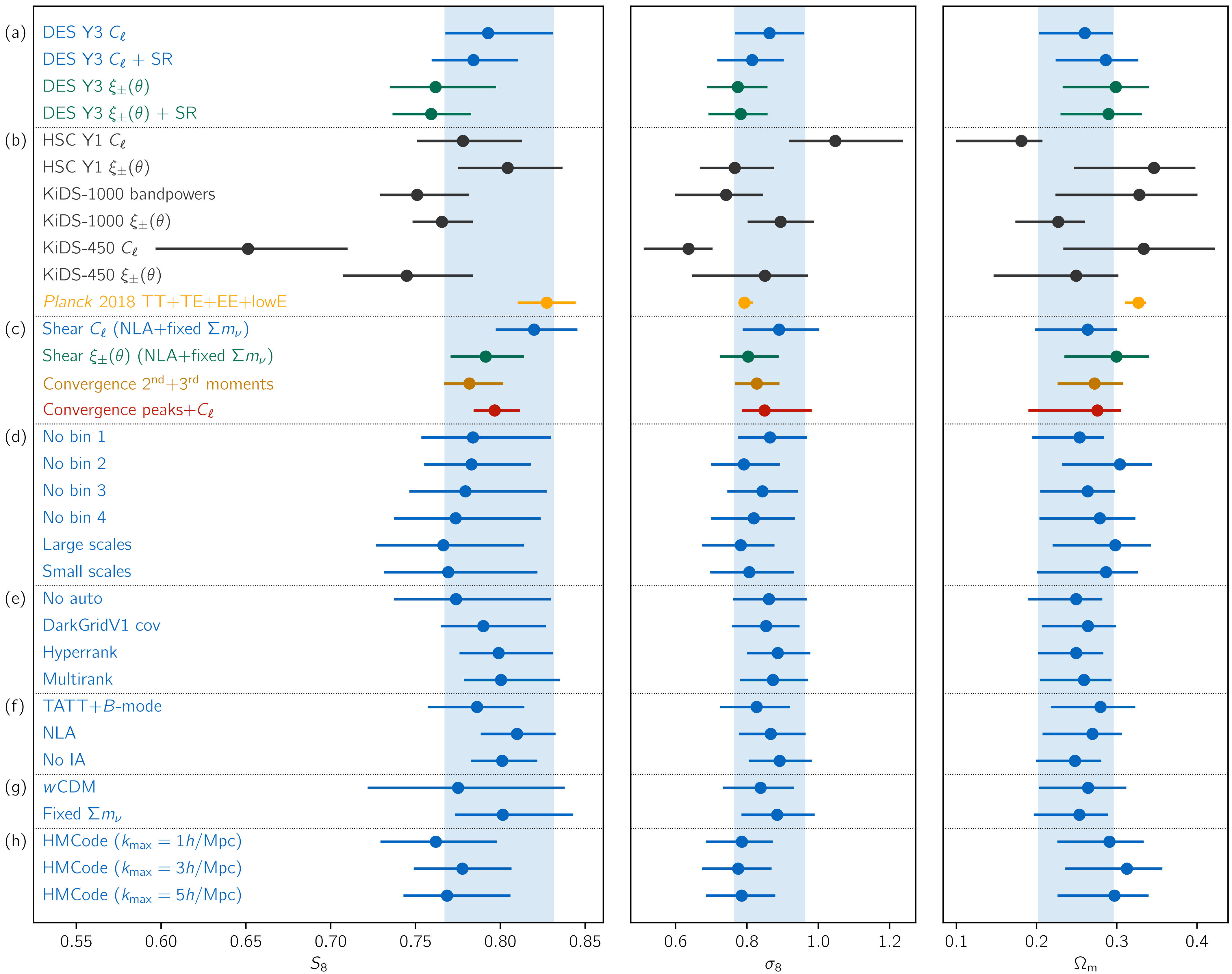
Dawson+15

- **Why is it difficult?**
  - 20% of *unrecognised* blends
  - Highly non-linear operation, so METACAL goes 🤯
  - Requires heavy image simulations to calibrate biases (~2%)
  - Joint pixel-level analysis of LSST + Euclid + Roman

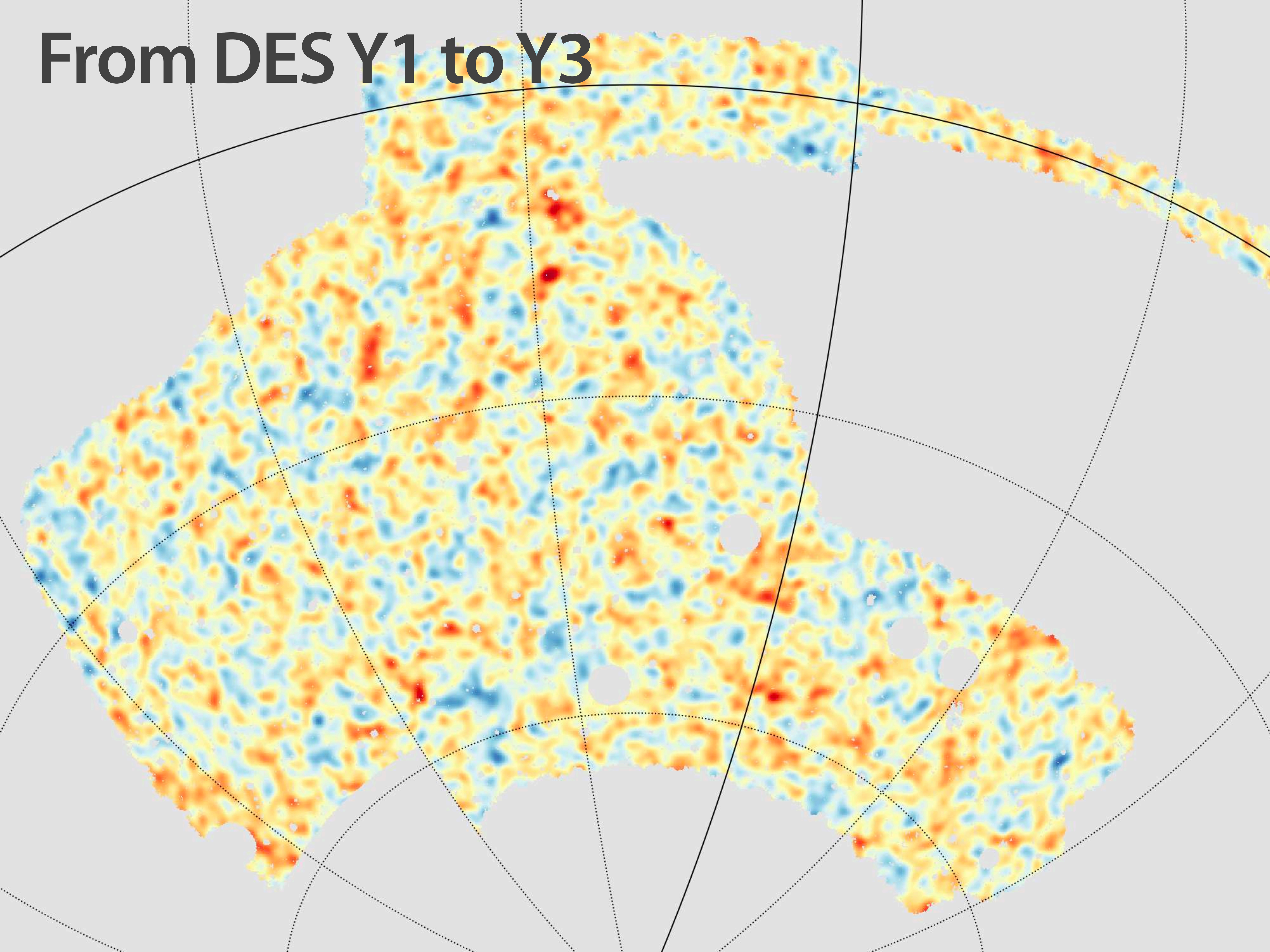
DES *vs* HSC *vs* KiDS



Doux+22 [DES Y3]


(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 $2^{nd}+3^{rd}$ 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

From DES Y1 to Y3



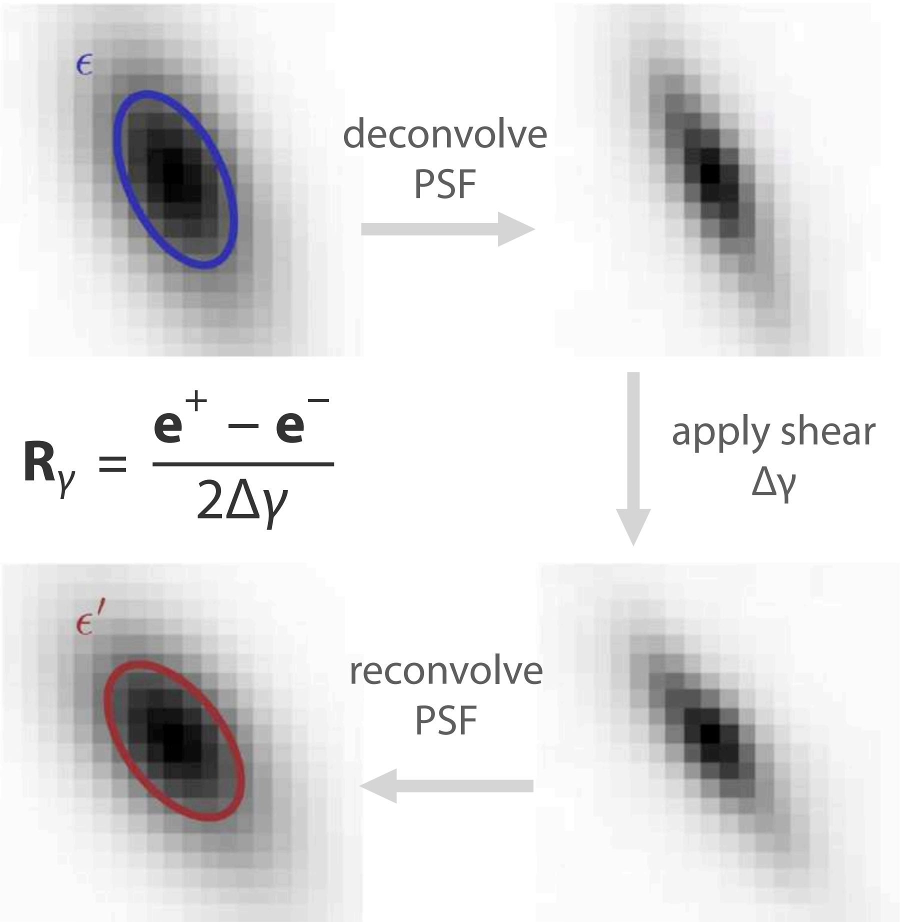
DES Y3 METACALIBRATION shape catalogue

- **METACALIBRATION in a nutshell**
  - For any *biased* shear estimator **e**,

$$\mathbf{e} = \mathbf{e}|_{\gamma=0} + \gamma \cdot \underbrace{\frac{\partial \mathbf{e}}{\partial \gamma}\bigg|_{\gamma=0}}_{\mathbf{R}_\gamma} + \mathcal{O}(\gamma^3)$$

such that $\langle \hat{\gamma} \rangle \approx \langle \mathbf{R}_\gamma \rangle^{-1} \langle \mathbf{e} \rangle$ is *unbiased* 👍

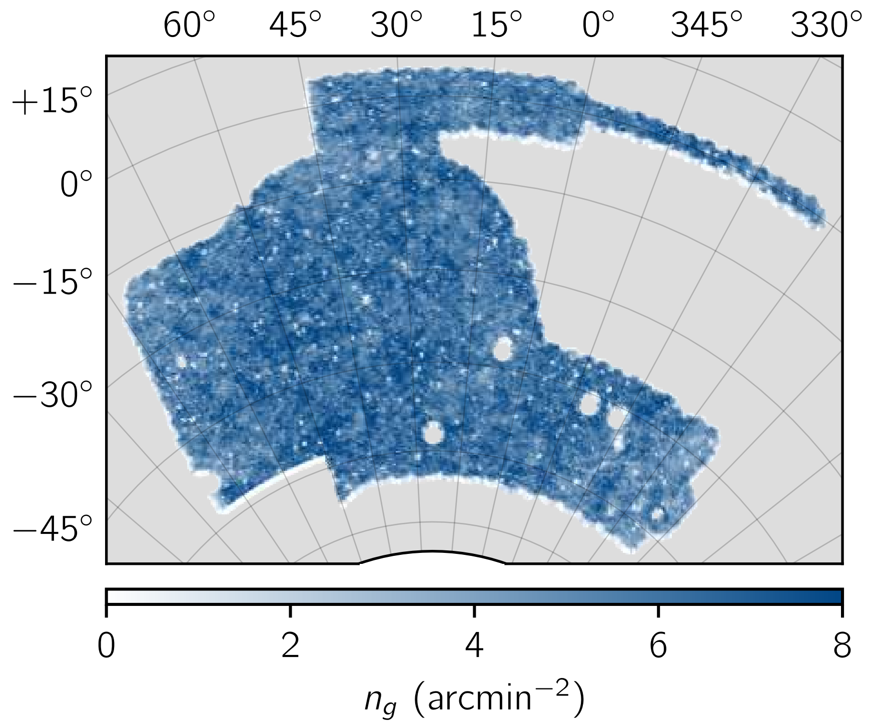
  - Mitigates model+noise biases and *shear-dependent* selection



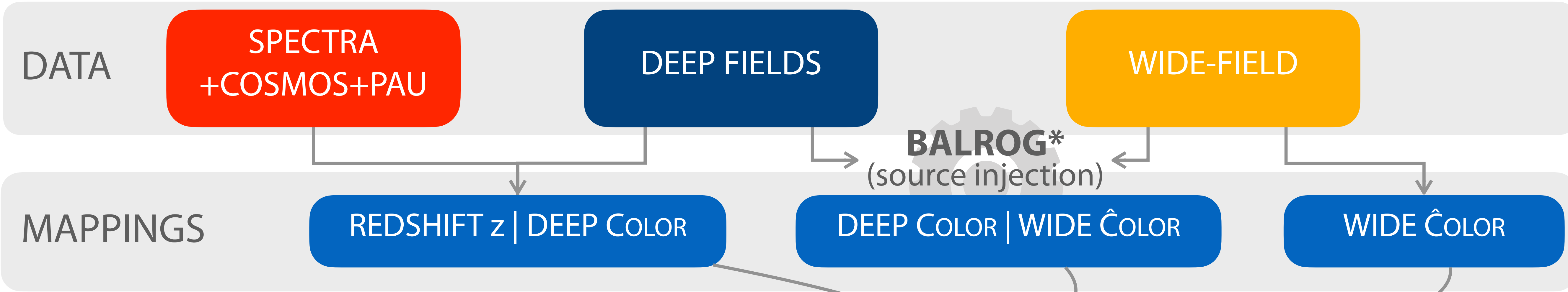
$$\mathbf{R}_\gamma = \frac{\mathbf{e}^+ - \mathbf{e}^-}{2\Delta\gamma}$$

N. MacCrann

- **DES Y3 METACALIBRATION catalogue**
  - Cuts: 10<S/N<1000, T/TPSF>0.5 + color cuts in *riz*
    - 100,204,026 galaxies from Y3 GOLD
    - $\sigma_e = 0.261$ with inverse-variance weights$(S/N, T/T_{PSF})$
    - $n_{eff} = 5.59$ gal/arcmin^2
  - Catalogue found to be very robust *Gatti…CD+20* [DES Y3]



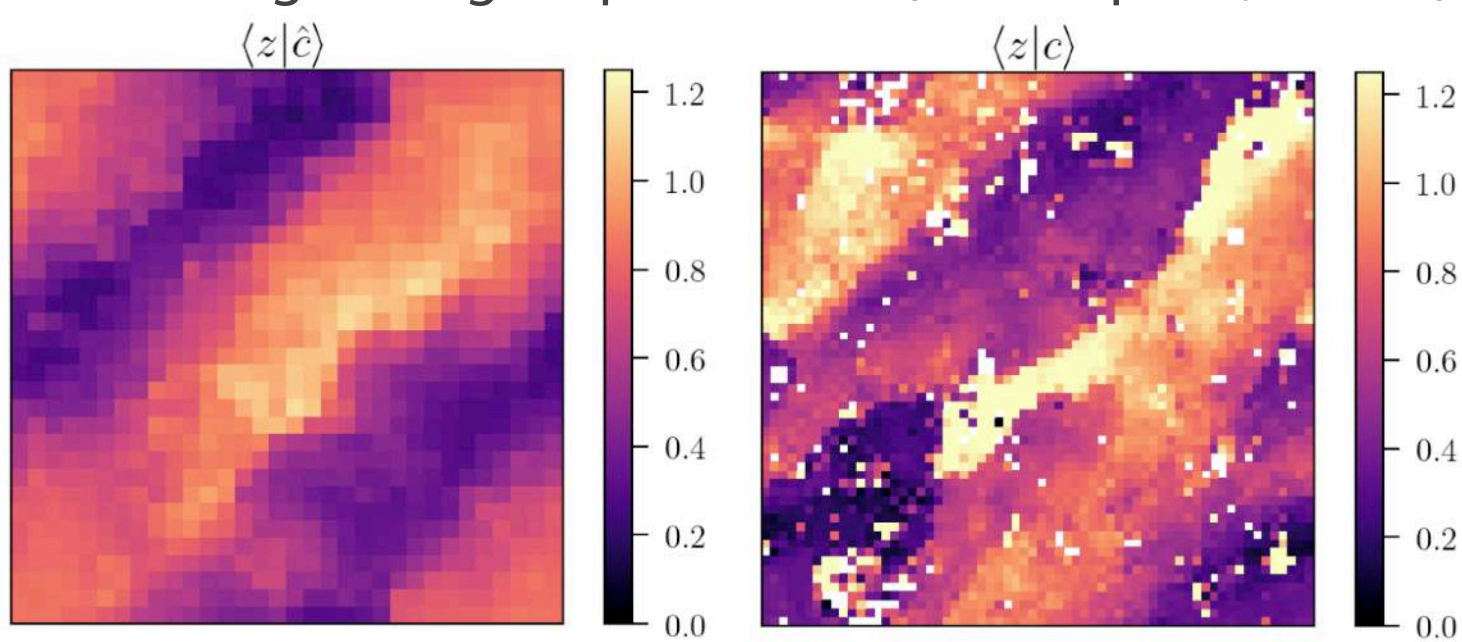
DES Y3 redshift distributions with SOMPZ



- Marginal photo-z for bin $\hat{b}$ is

$$p(z|b) = \sum_{\hat{c} \in b} \sum_{c} p(z|c)\, p(c|\hat{c})\, p(\hat{c})$$

- Bayesian mapping with self-organizing maps method (no template, no ML) from Buchs+19



Myles+20 [DES Y3]

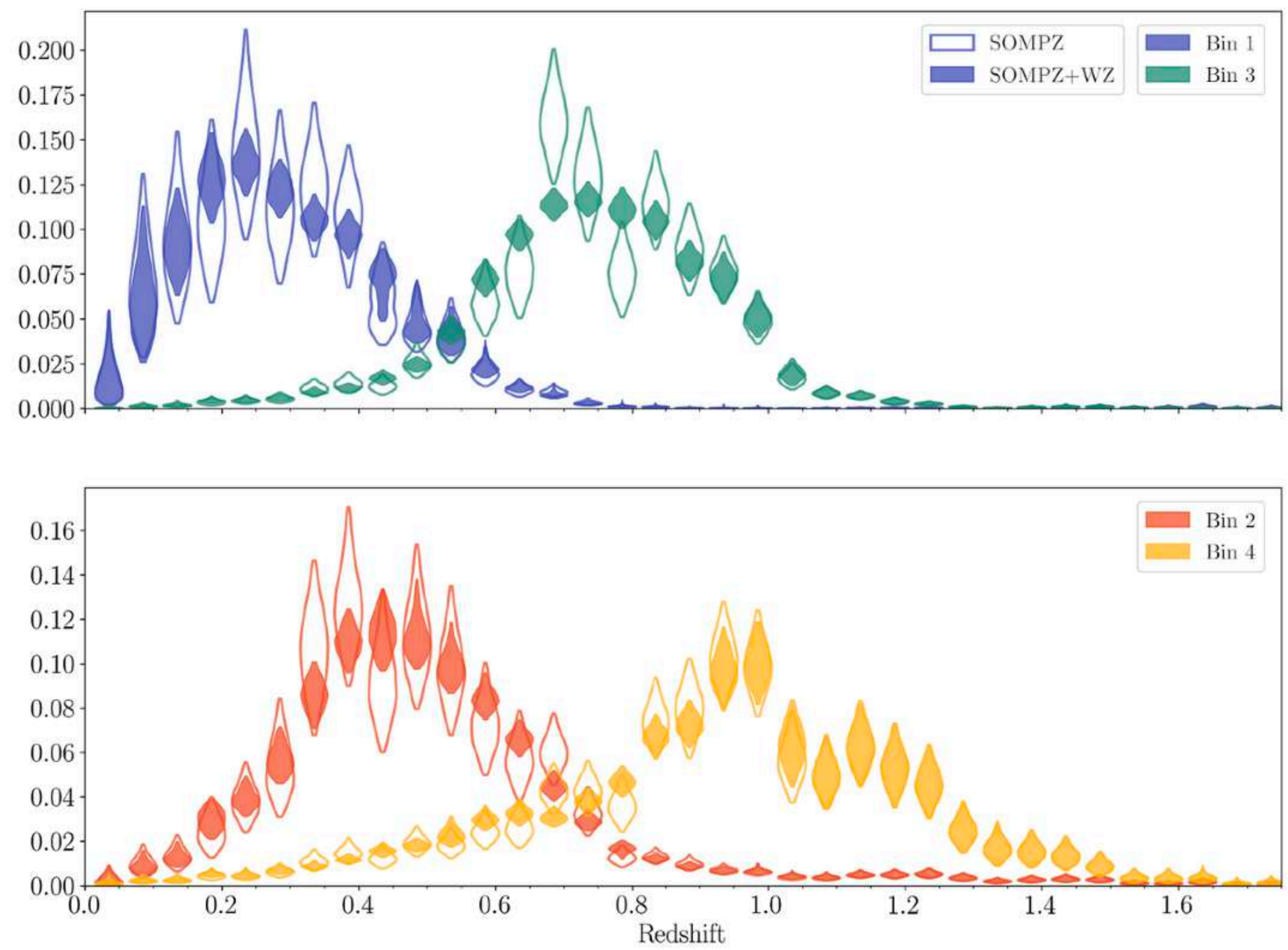
- **RESULT**: produces *posterior samples* of $n(z)$ for each redshift bin

**Everett+20* [DES Y3]

DES Y3 redshift distributions with SOMPZ

- **3 sources of information**
  1. **SOMPZ** method calibrated with Balrog
  2. **Constraints from clustering**
  3. **Shear-ratio**

Myles+20 [DES Y3]



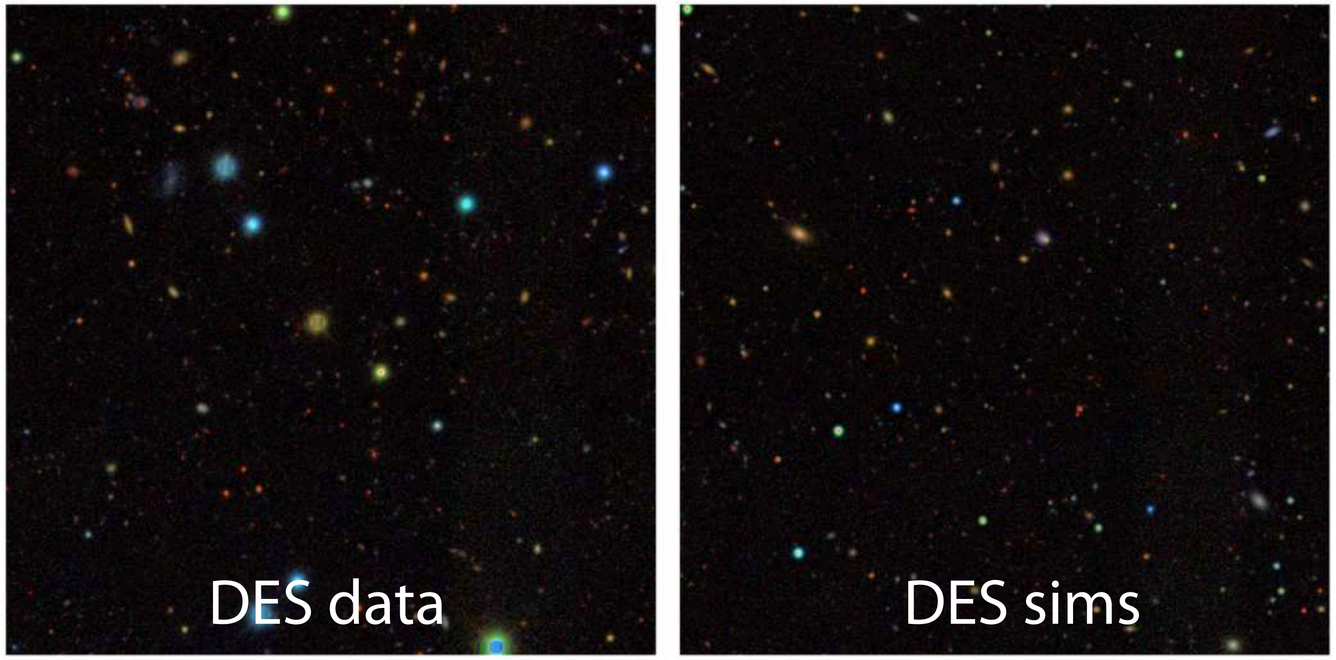
- **DES Y3 *n*(*z*)'s**
  - Effective combined ⟨*z*⟩ uncertainties between 0.008 and 0.015
  - Error dominated by
    - photo-calibration at low *z*
    - sample variance at higher *z*
- **Marginalisation over n(z)'s with HYPERRANK** *Cordero+ 21* [DES Y3]
  - *Posterior samples* of *n*(*z*)*'s* instead of usual shift n′(z) = n(z+Δz)
  - HYPERRANK ranks *n*(*z*)'s to allow marginalisation over both ⟨*z*⟩ *and n*(*z*) *shape*

Joint calibration of shears and redshifts

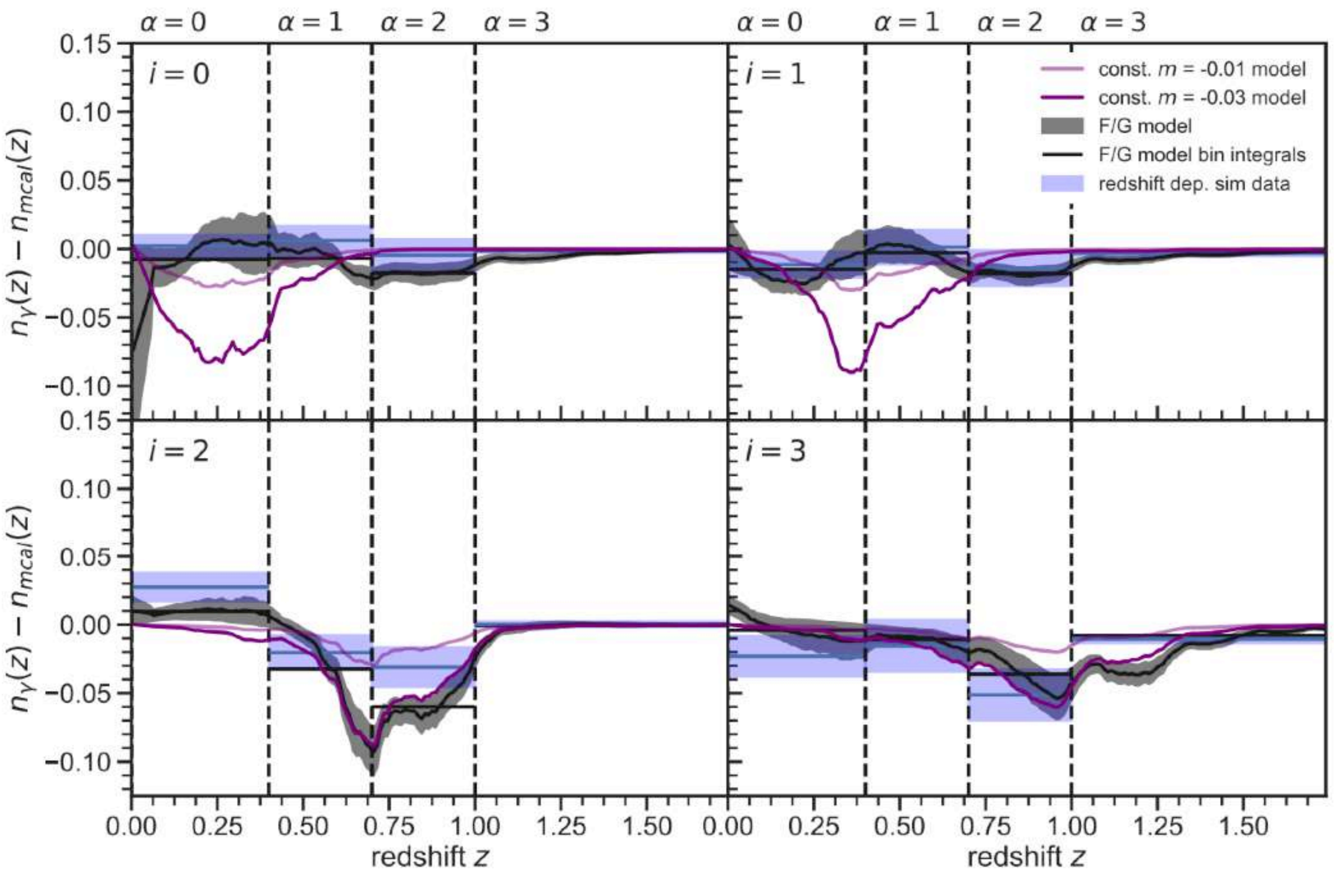
- **Redshift distributions as *shear response***
  - Consider $n(z)$ as *response of data ensemble to shear* at redshift z

$$\langle \mathbf{e}_{\rm obs} \rangle = \int n_\gamma(z) \gamma_{\rm true}(z)\, {\rm d}z + c + {\rm noise}$$

  - Distorsion $n(z) \rightarrow n_\gamma(z)$ measured by sims
    - $n_\gamma(z)$ has norm $1+m$
    - Very realistic simulations matching deep field colors and blending
- **DES Y3 results**
  - $m \sim -2\%$ dominated by blending
  - Distorted/calibrated SOMPZ $n_\gamma(z)$ samples to be used for cosmology



MacCrann+20 [DES Y3]



Weak lensing surveys

Survey	Area	Bands	Depth	Density
SDSS-II and III	~ 10 000 deg^2 [8]	*ugriz*	$r \sim 23.5$	~ 2 gal/$arcmin^2$
DES	**5 000 deg^2**	*grizY*	$r \sim 24.3$ (10σ)	~ 6 gal/$arcmin^2$
KiDS (+VIKING)	1 350 deg^2	***ugri*(+*ZYJHK*$_s$)** [9]	$r \sim 24.9$ (5σ)	~ 6 gal/$arcmin^2$
HSC	1 400 deg^2	*grizy*	**$r \sim 26.1$ (5σ)**	~ 20 gal/$arcmin^2$
LSST	**18 000 deg^2**	*ugrizY*	**$r \sim 27.5$** (5σ)	~ 30 gal/$arcmin^2$
Euclid	**15 000 deg^2**	**Visible+*YJH*** [10]	$m_{AB} \sim 24.5$ (10σ, ext)	~ 30 gal/$arcmin^2$
Roman HLS	2 000 deg^2	***YJH***	**$Y \sim 26.5$**	~ 30 gal/$arcmin^2$