THE DARK ENERGY SURVEY

Cosmology results from weak gravitational lensing in the Dark Energy Survey

Daniel Gruen, NASA Einstein Fellow at KIPAC/SLAC/Stanford
and the DES Collaboration

University of Melbourne, 2017-11-14

Structure of this talk

- Introduction
  - dark energy from geometry and structure
  - Dark Energy Survey
  - weak gravitational lensing
- DES Year 1 Results
  - control of systematic uncertainties
  - cosmology from lensing and galaxy clustering
  - cosmology from joint matter/galaxy PDF

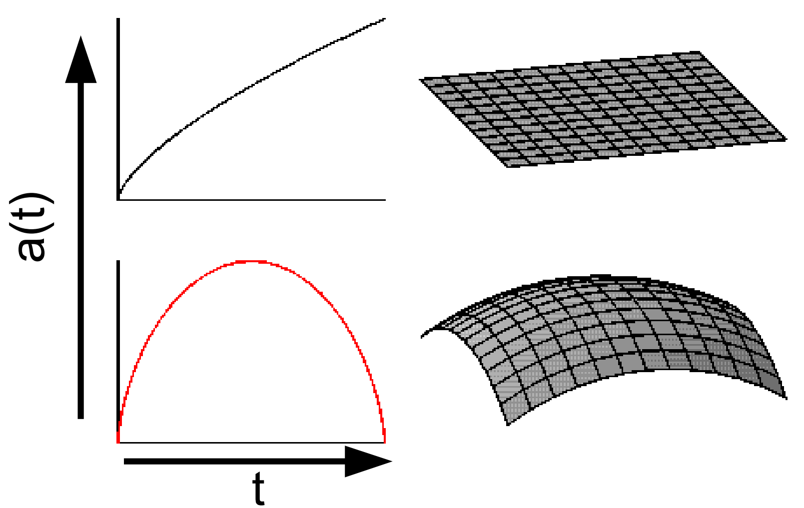
What goes up must come down?

- on large scales, Universe described as homogenous fluid in expanding space

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right)$$

scale factor of Universe

matter, radiation, relativistic species: pressure p $\geqq$ 0



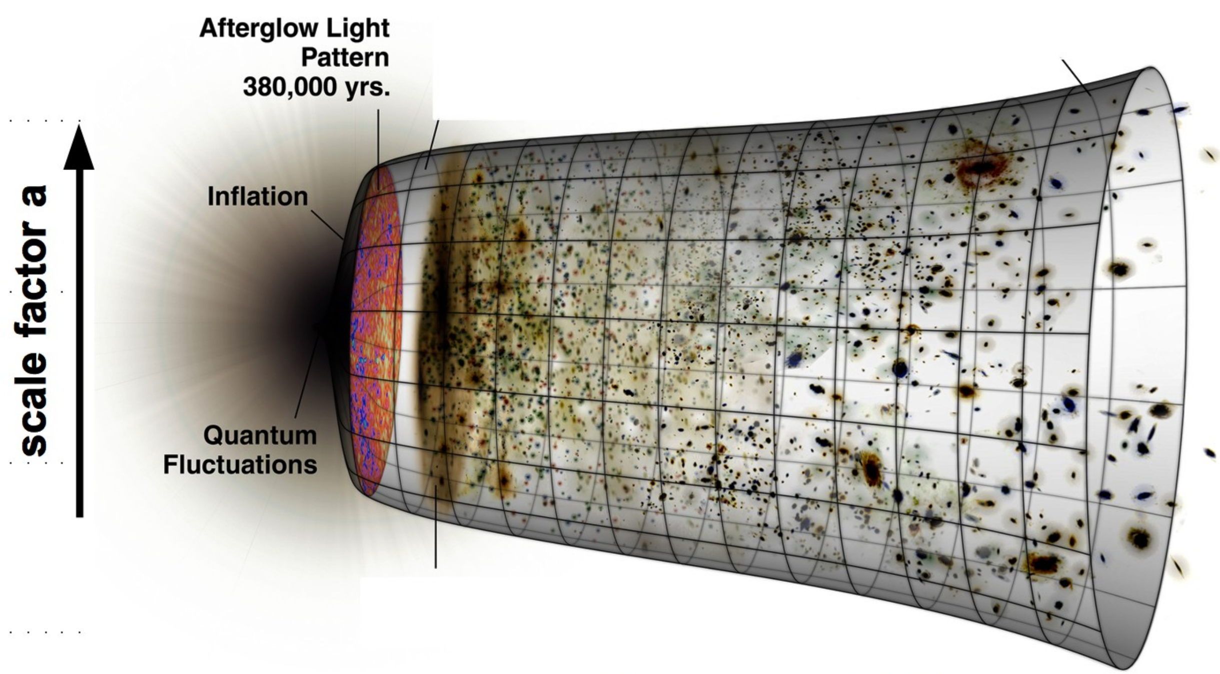
What goes up keeps getting faster!

- on large scales, Universe described as homogenous fluid in expanding space

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda c^2}{3}$$

scale factor of Universe

cosmological constant = vacuum energy = substance with negative pressure, “w= -1”



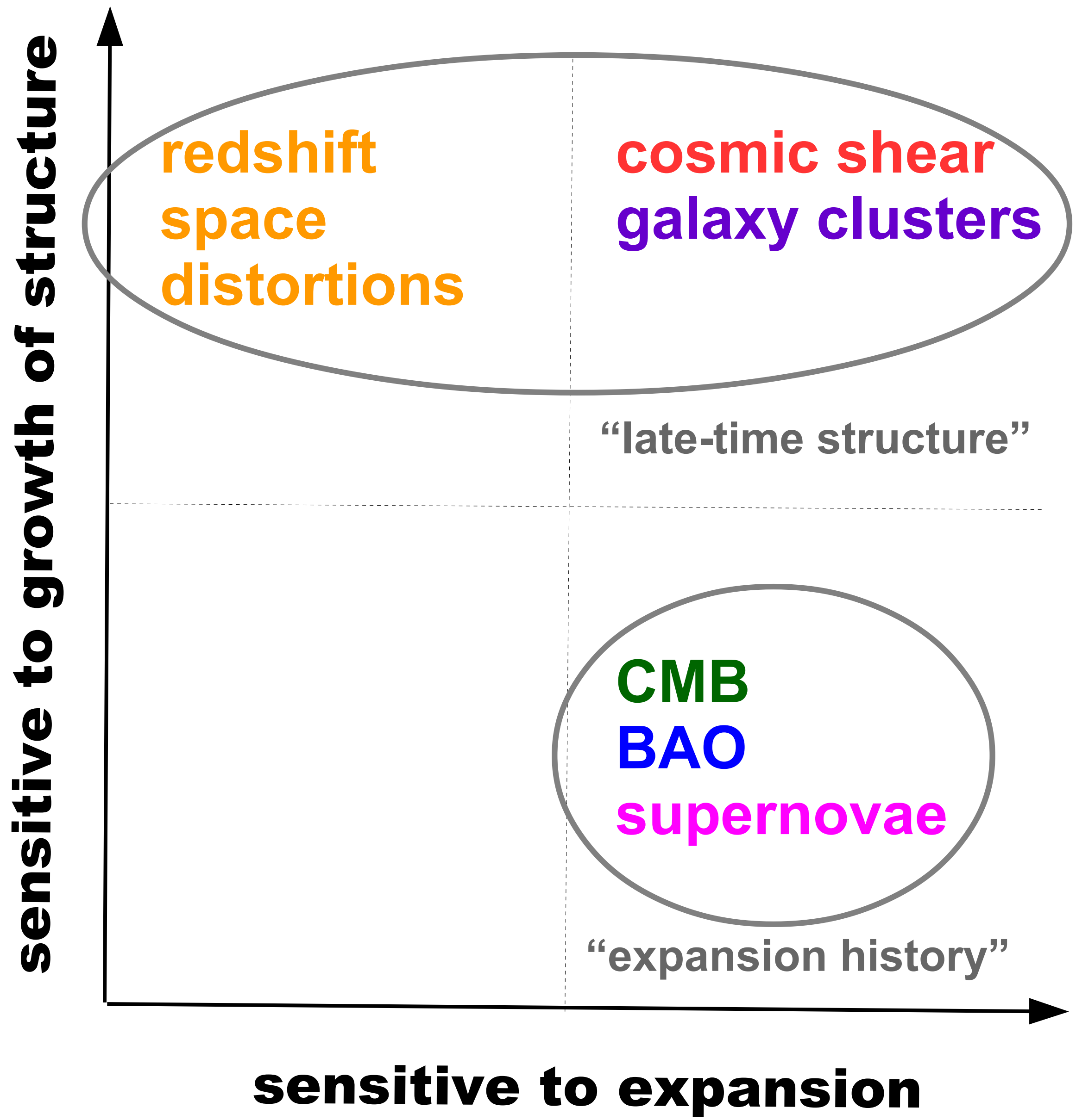
This is a remarkably odd model

- 70% of energy content of Universe is an unknown substance that appears like vacuum energy, but 120 orders of magnitude smaller than QFT prediction
- 80% of matter is an unknown matter-like substance that does only interacts via gravitation
- We have a wide range of independent observations that cannot be explained without these assumptions

Need better phenomenological tests of its predictions:

Are data from **early Universe** and **late Universe** fit by the same parameters?	Do measurements of **cosmic distances** and growth of **structure** agree?	Does the dark energy density change as space expands? “Equation of state” parameter **w=pressure/density**

How to survey Dark Energy

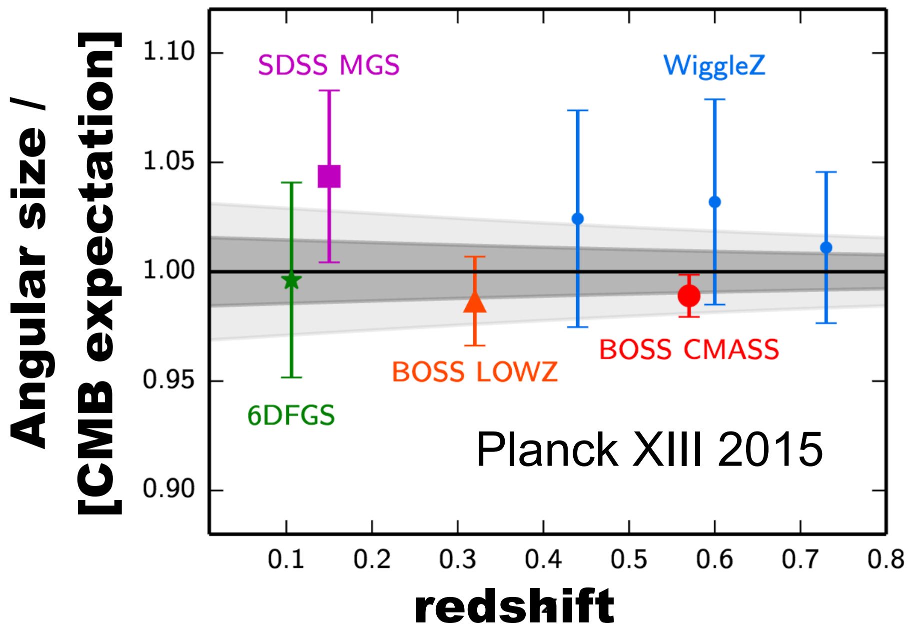


Q: Do all these measurements agree with predictions in the same, fiducial ΛCDM model?

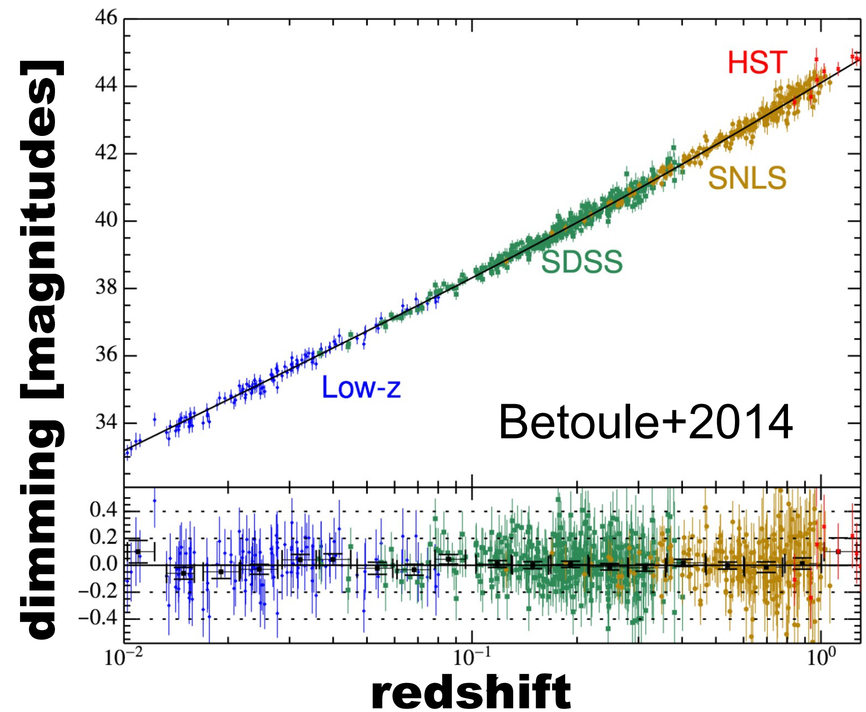
- $\Omega_m \sim 0.3$
- $\Omega_\Lambda \sim 0.7$
- $\sigma_8 \sim 0.8$
- $h \sim 0.7$

Measurements of expansion history

Standard ruler: galaxy BAO vs. CMB



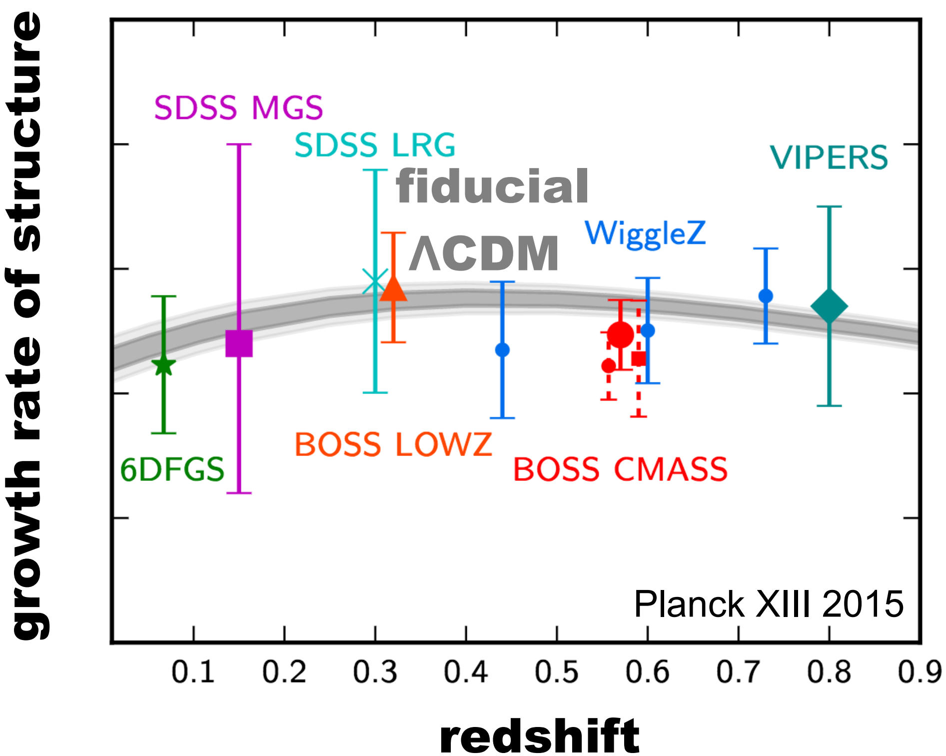
Standard candle: SNIa vs. CMB



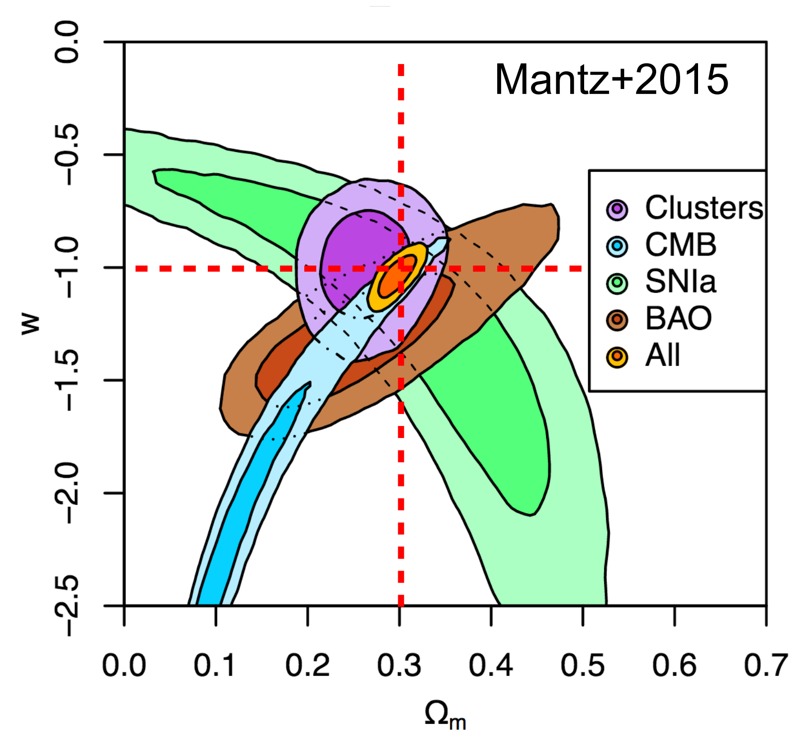
- ✔ Geometric probes are consistent and tightly constrain w=-1, Ω_m, Ω_{DE}, flatness

Measurements of evolved structure

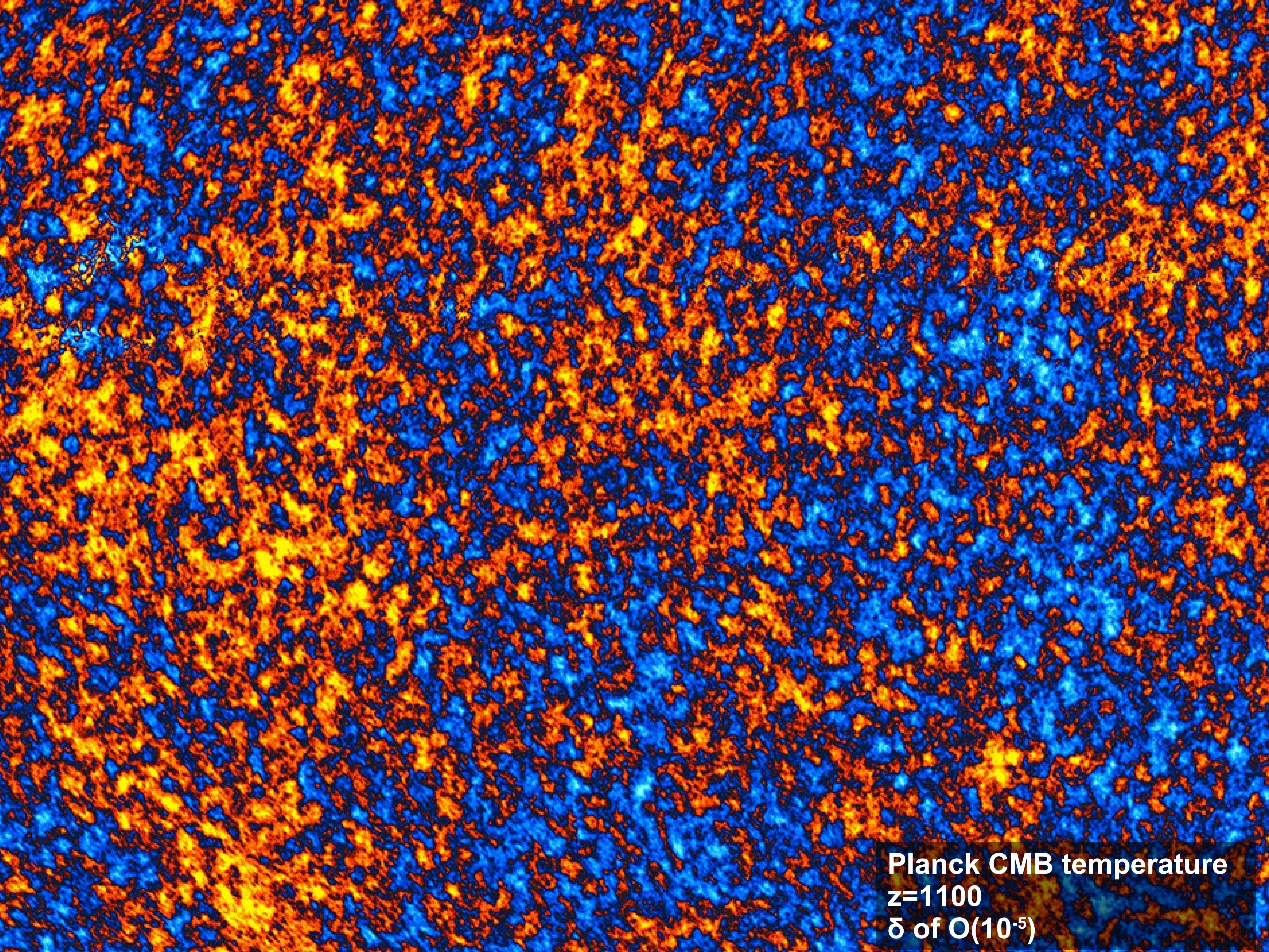
Redshift space distortions: growth in action

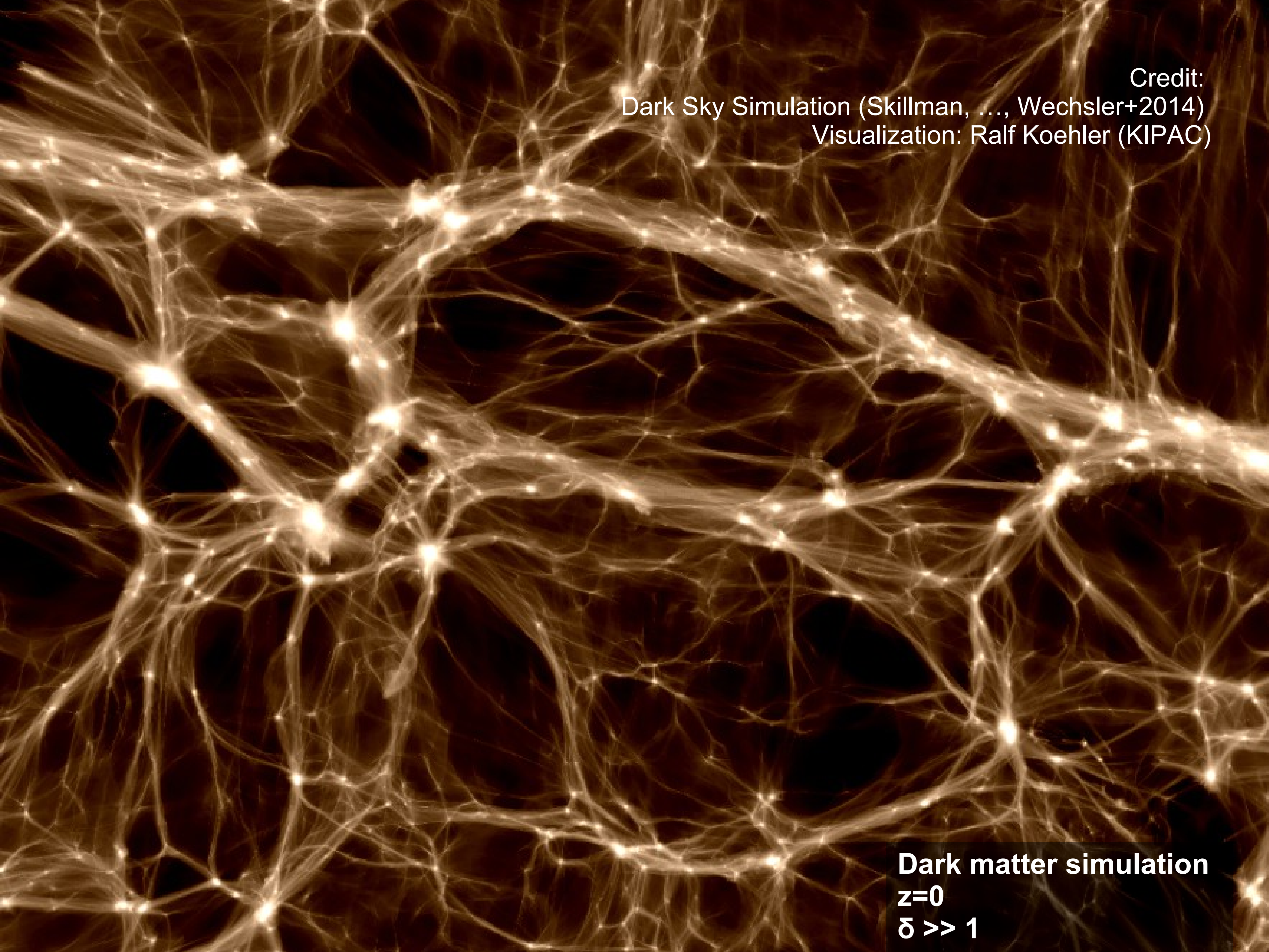


Galaxy cluster counts: final stage of growth

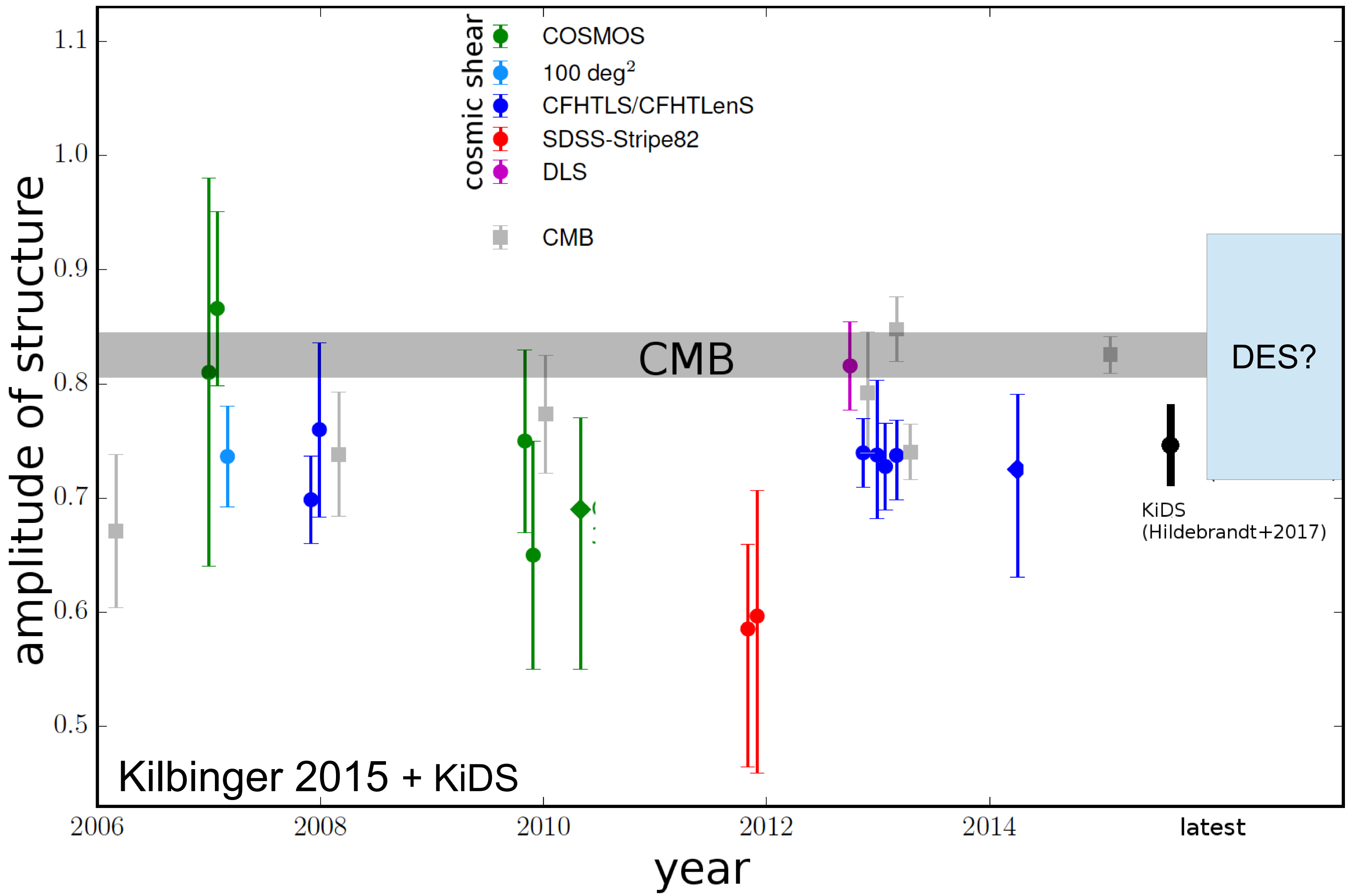


- ✔ Growth rate and count of massive, virialized haloes are consistent with geometric probes and fiducial ΛCDM model


Planck CMB temperature
z=1100
δ of O(10⁻⁵)


Credit:
Dark Sky Simulation (Skillman, …, Wechsler+2014)
Visualization: Ralf Koehler (KIPAC)
Dark matter simulation
z=0
δ >> 1

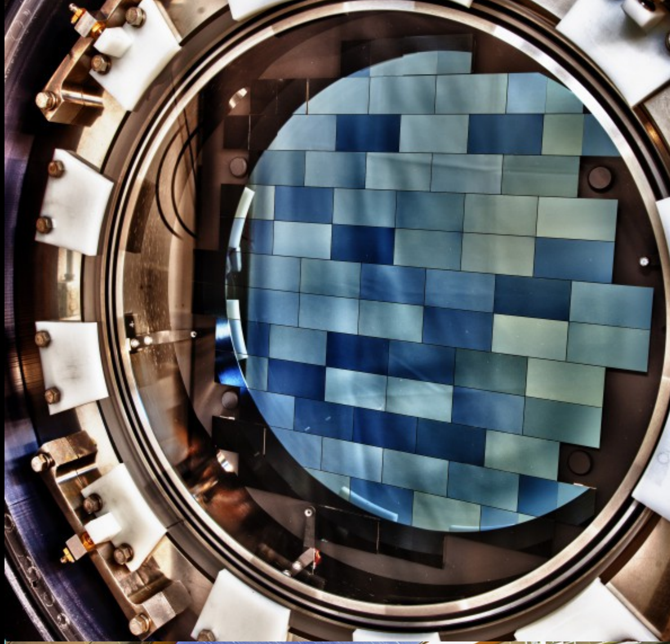
Measurements of evolved structure: Cosmic shear

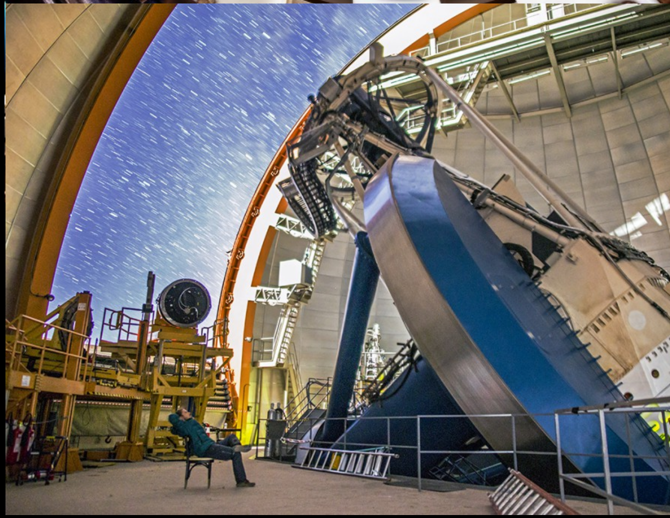


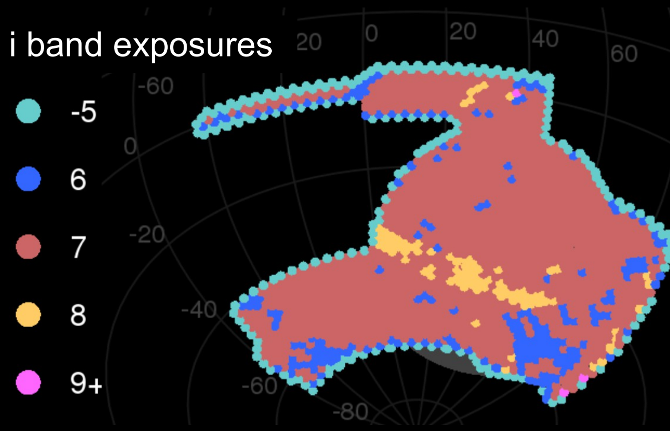
- recent studies have claimed 2-3σ offset from Planck CMB in Ω_m-σ_8
- interpretations differ – statistical fluke, systematics, crack in ΛCDM?

The Dark Energy Survey

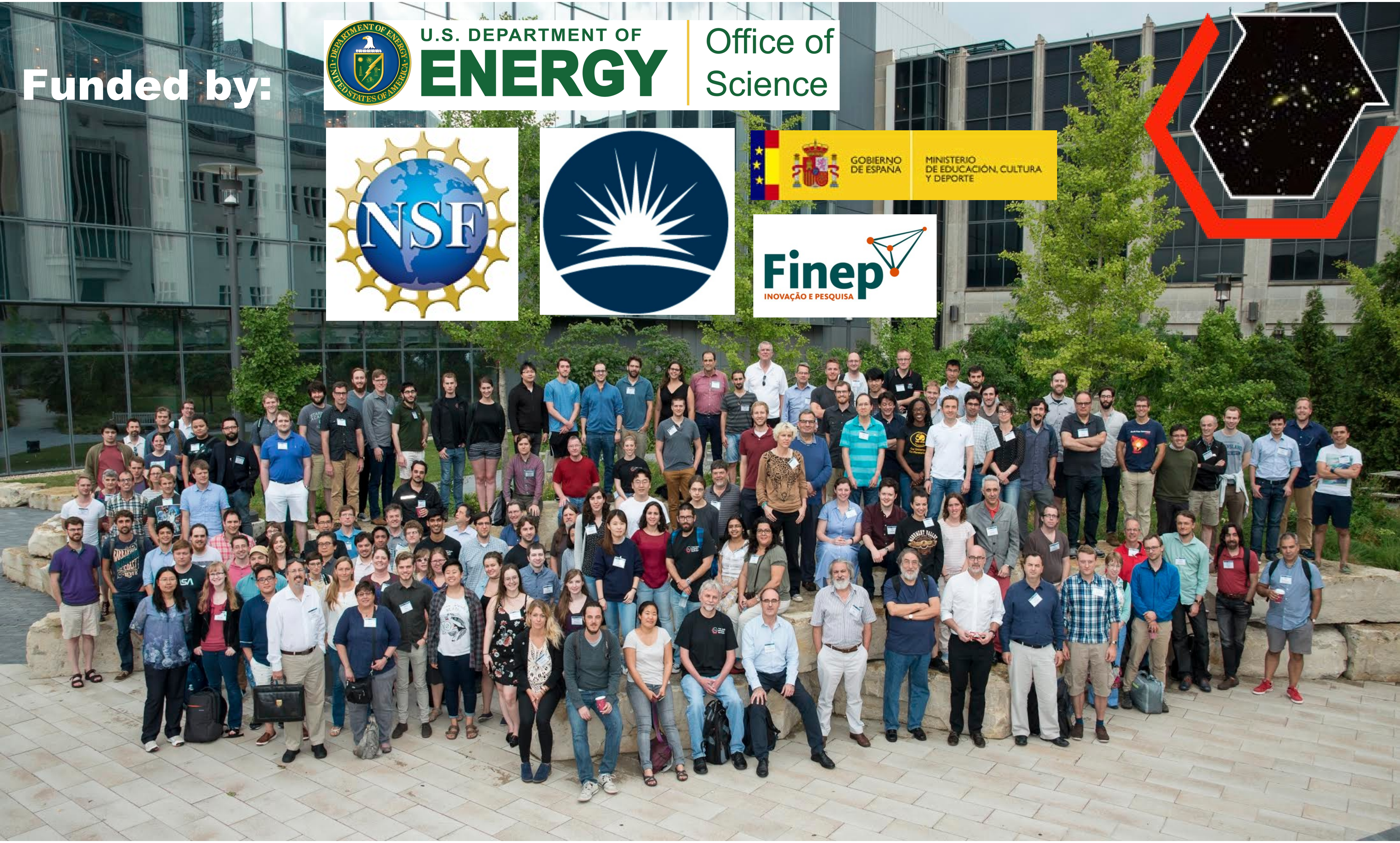
- 5000 sq. deg. survey in grizY from Blanco @ CTIO, 10 exposures, 5 years, >400 scientists
- Primary goal: dark energy equation of state
- Probes: Large scale structure, Supernovae,
  Cluster counts, Gravitational lensing
- Status:
  - SV (150 sq. deg, full depth):
    most science done, catalogs at
    http://des.ncsa.illinois.edu
  - Y1 (1500 sq. deg, 40% depth):
    data processed, results on cosmology today
  - Y3 (5000 sq. deg, 50% depth):
    data processed, vetting catalogs
  - Y4: data taking finished (70% depth)
  - Y5: in progress







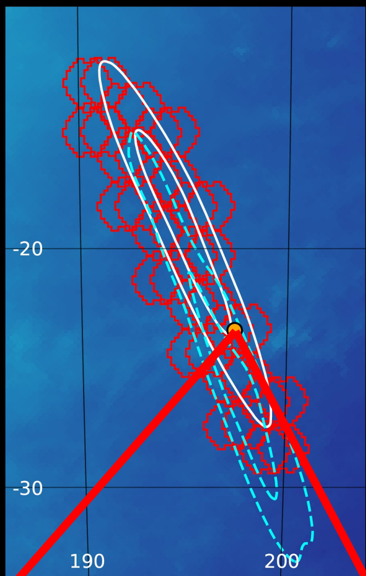
Funded by:



Collaborating institutions:

NCSA, THE OHIO STATE UNIVERSITY, LMU, BERKELEY LAB, SLAC, ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich

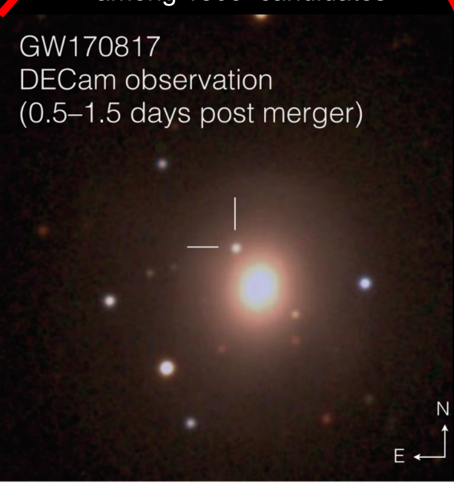
Looking for more than dark energy: Discovery* of GW170817 counterpart



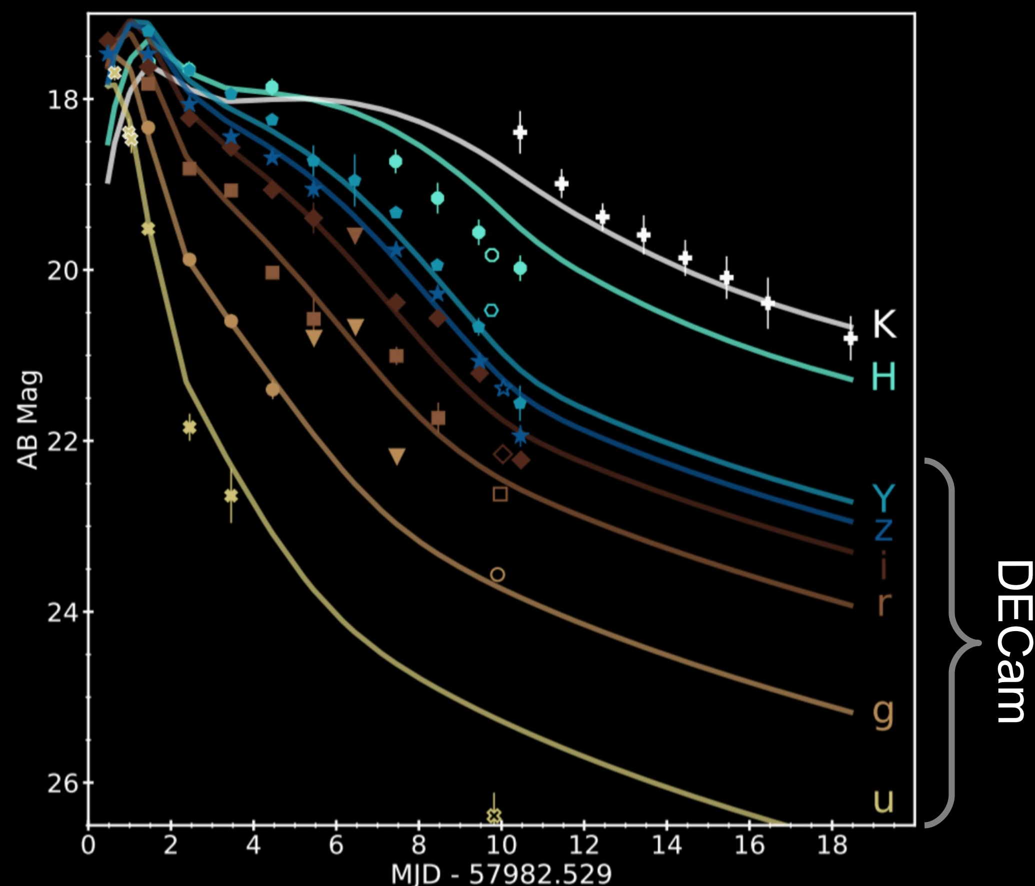
10.5 hours post-merger
among 1500 candidates

25 deg^2 LIGO/VIRGO positional constraint (90 % C.L.)
>90% covered by DECam

Soares-Santos, … DG+
ArXiv:1710.05459



Above left: DECam discovery image *grz* color co-add for the optical counterpart of GW170817. Above right: template image. From Soares-Santos et al (2017).



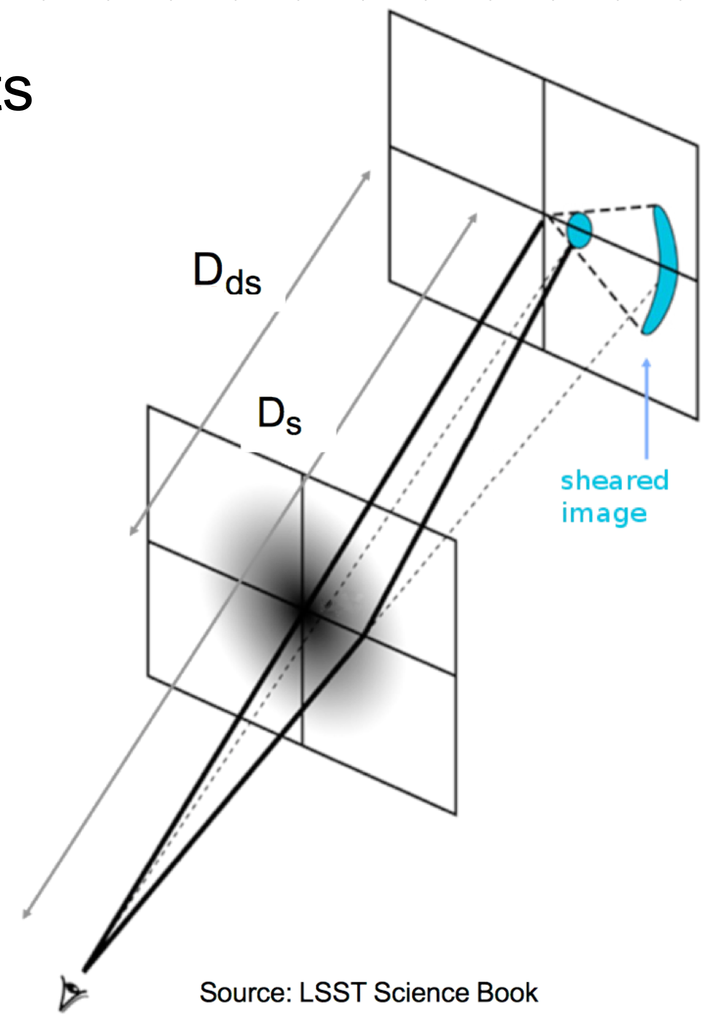
UV, optical, and NIR light curves of the GW170817 source. Cowperthwaite et al (2017).

* fine print here

Gravitational lensing

- When light passes massive structures, it feels gravity and its path gets bent
- This causes shifting, and magnification, and shearing of the galaxy image

$$
\begin{aligned}
\gamma_t(\theta) &= \langle \kappa(\theta') \rangle_{\theta' < \theta} - \kappa(\theta) \\
\kappa &= \Sigma / \left[\frac{c^2}{4\pi G} \frac{D_{\rm s}}{D_{\rm d} D_{\rm ds}} \right]
\end{aligned}
$$



Source: LSST Science Book

Gravitational lensing

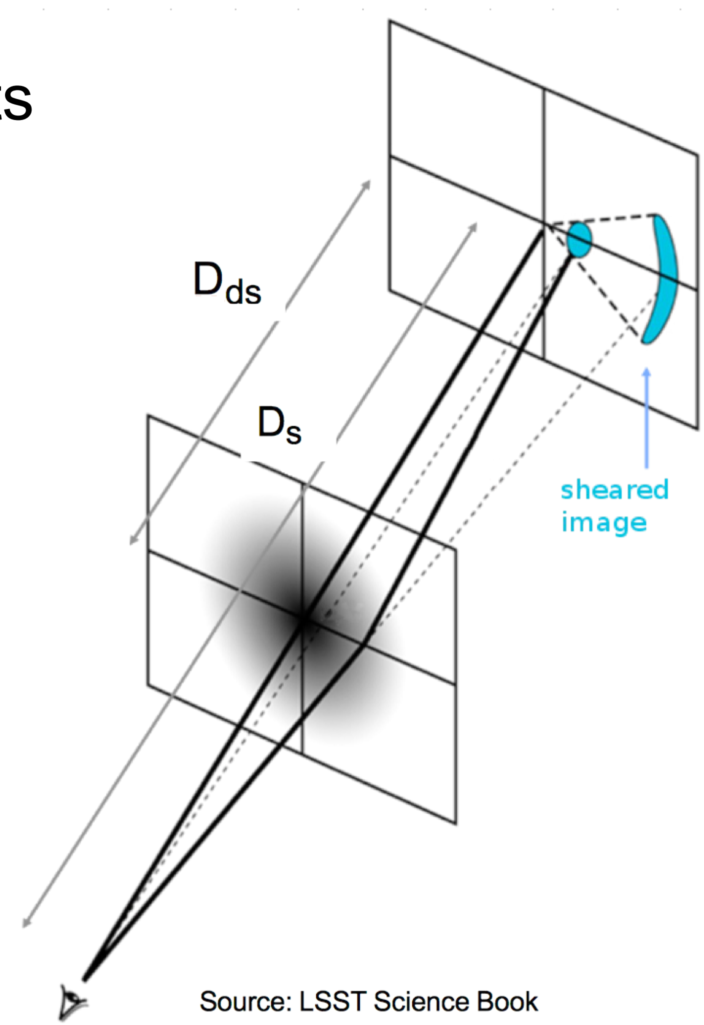
- When light passes massive structures, it feels gravity and its path gets bent
- This causes shifting, and magnification, and <u>shearing</u> of the galaxy image

need galaxy shapes

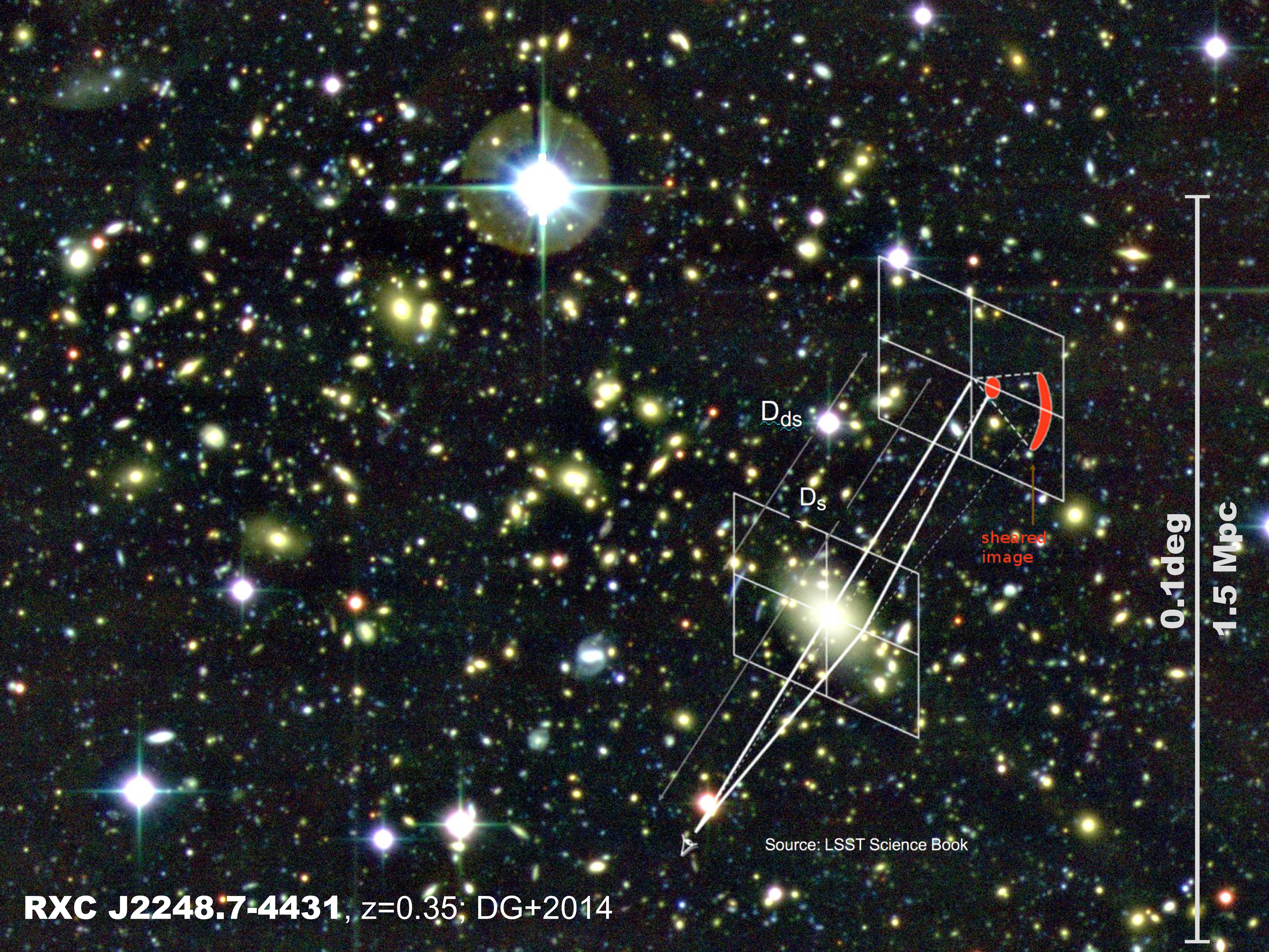
$$\gamma_t(\theta) = \langle \kappa(\theta') \rangle_{\theta' < \theta} - \kappa(\theta)$$

$$\kappa = \Sigma / \left[\frac{c^2}{4\pi G} \frac{D_s}{D_d D_{ds}} \right]$$

need galaxy redshift distributions

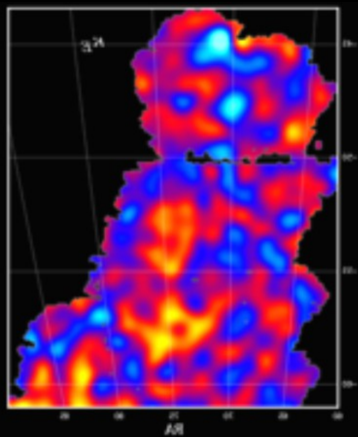


Source: LSST Science Book

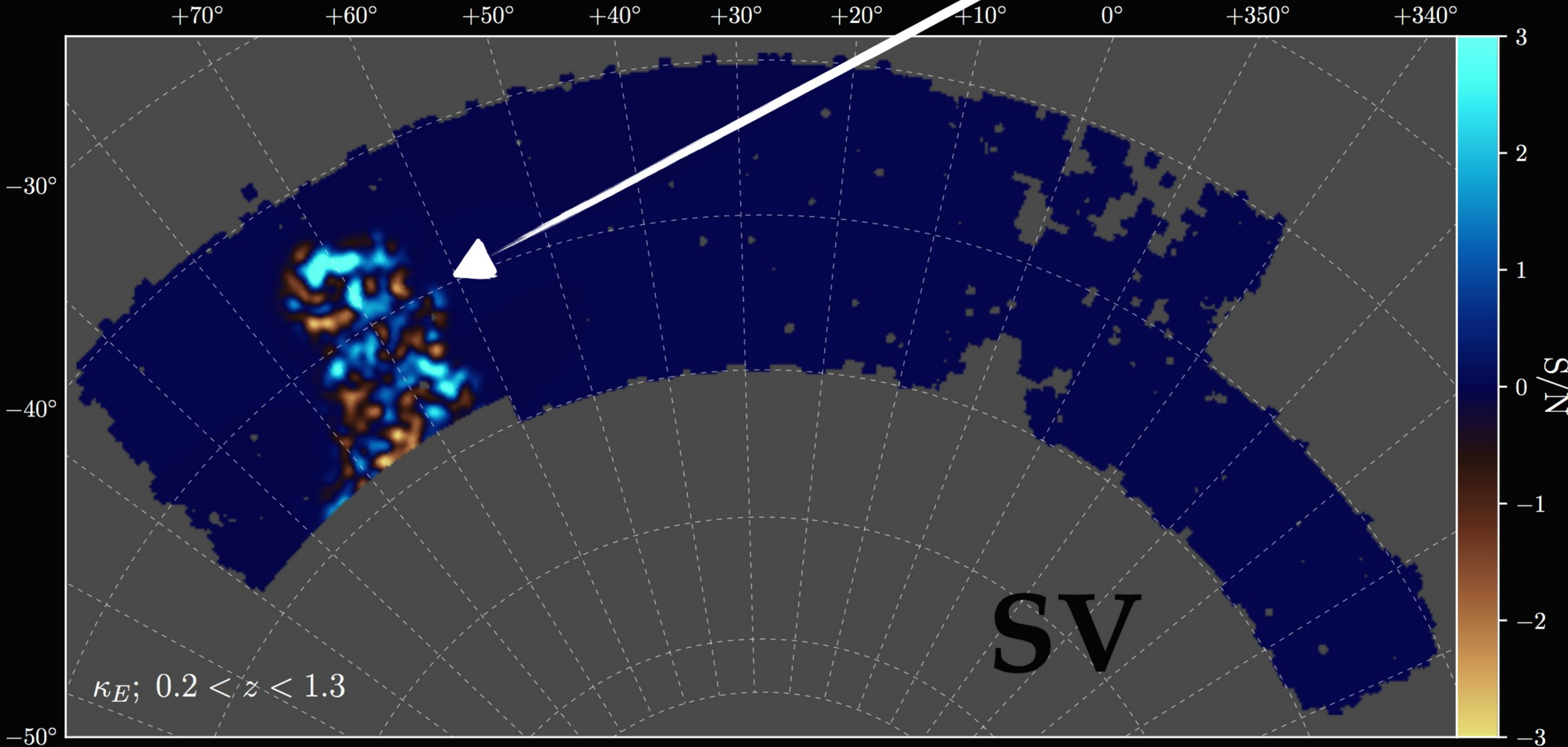


D_ds
D_s
sheared image
0.1deg
1.5 Mpc
Source: LSST Science Book
RXC J2248.7-4431, z=0.35; DG+2014

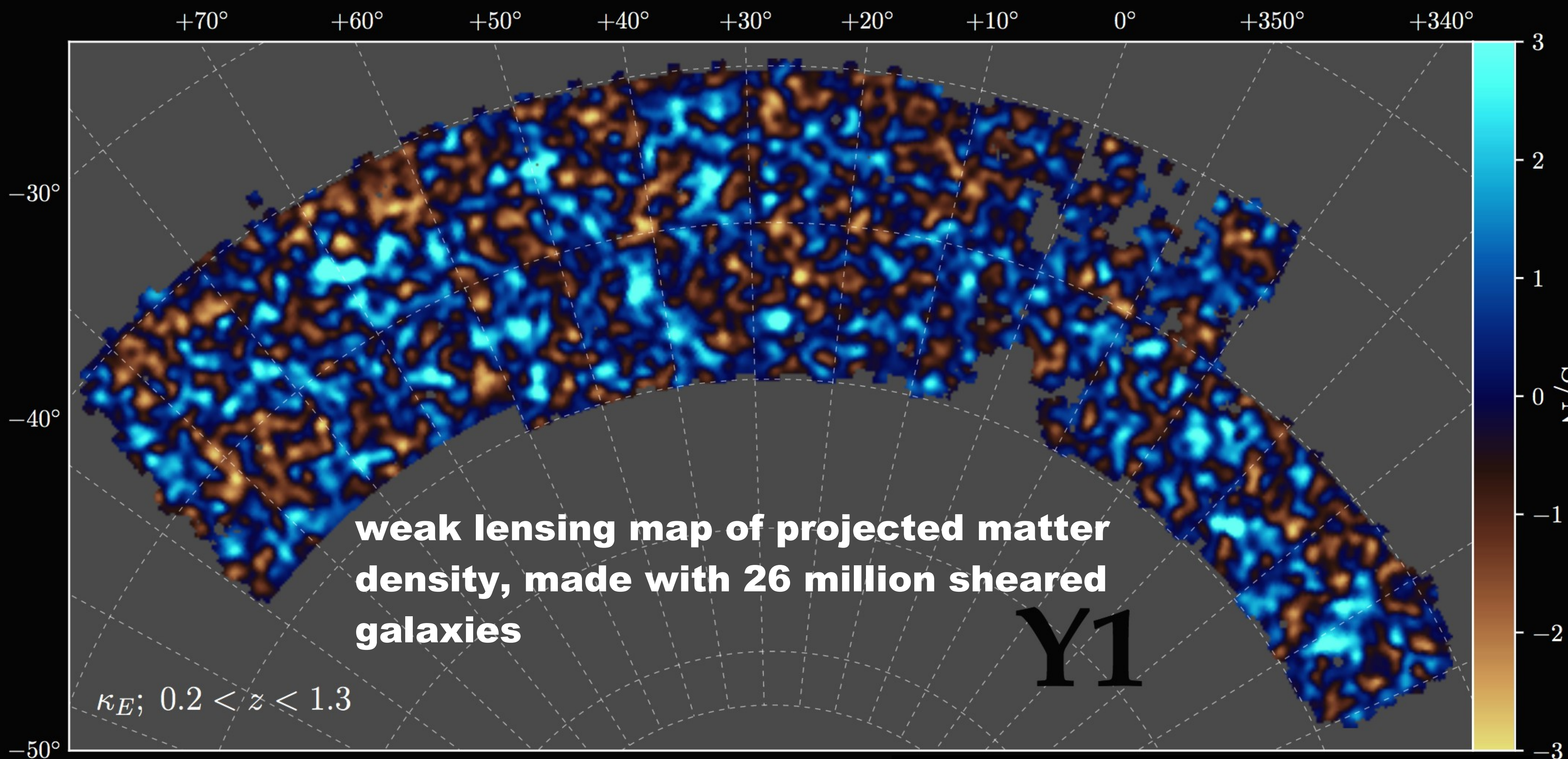
DES SV ...



Chang+; Vikram+ 2016



DES SV ... to Y1



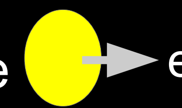
Chang et al. 2017 (arXiv:1708.01535)

With great statistical power comes great systematic responsibility

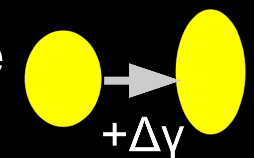
- two independent galaxy shape measurements, including novel metacalibration algorithm

Metacalibration:

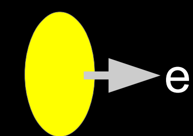
i. apply biased estimator to image



ii. manipulate image to include artificial (shear) signal



iii. apply biased estimator to manipulated image
→ derivative w.r.t. signal



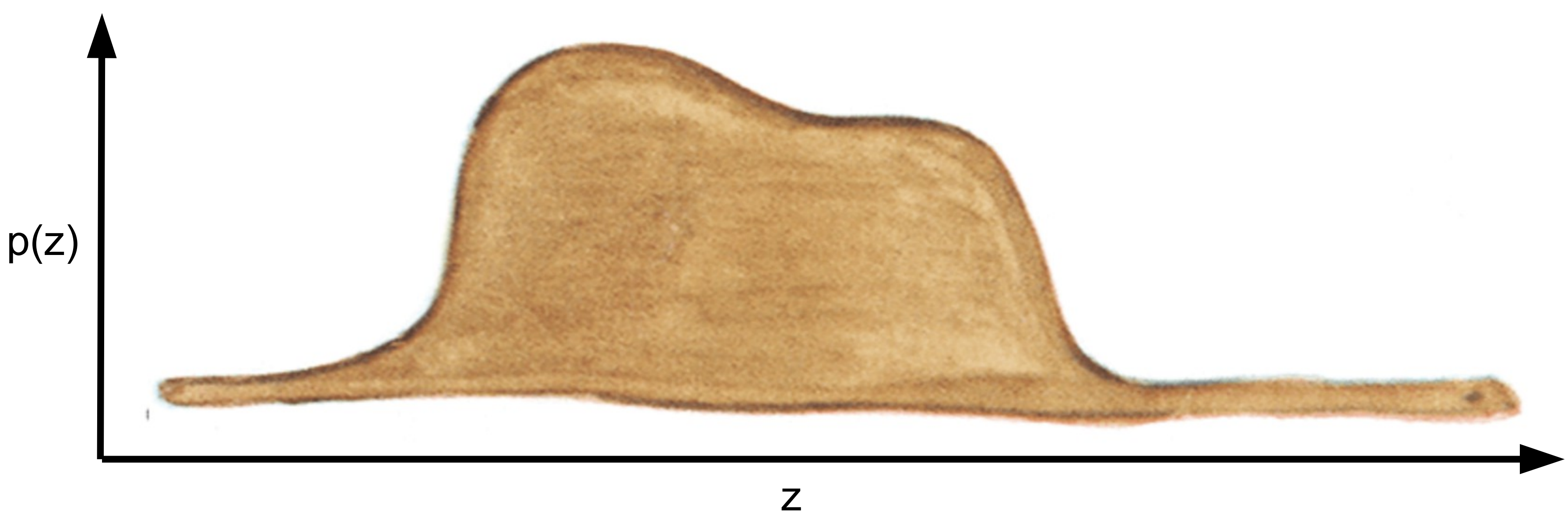
$$\text{response} = \frac{e' - e}{\Delta\gamma}$$

iv. related tricks to also correct *selection* bias

35 million galaxy shapes with systematic error <1.3% (68% C.L.)

Huff & Mandelbaum, Sheldon & Huff (2017); Zuntz, Sheldon+ (1708.01533)

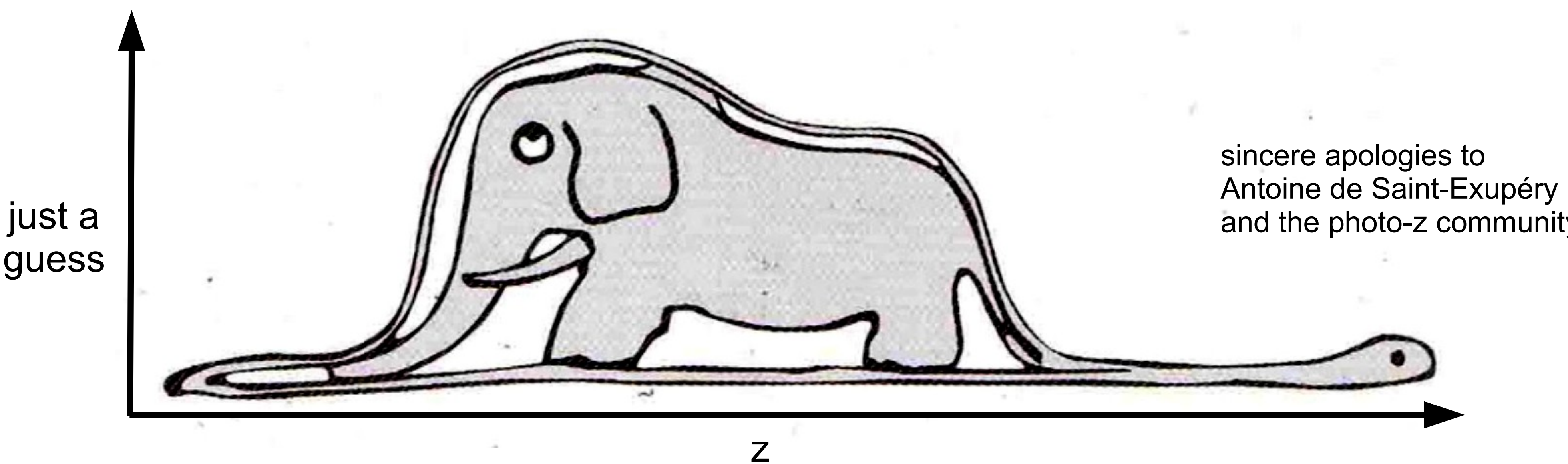
Photometric redshifts



Photometric redshifts are the elephant in the room

There is no “correct” photometric redshift estimate as of today:

- **template fitting** codes make arbitrary/wrong choices of templates and priors
  - no estimate for this systematic error – but it's surely O(few %)!
- **machine learning** codes / **spec-z validation** uses non-representative sample
  - What is essential is invisible to the eye: these are **selected** by redshift, not just by color/magnitude → biases at O(few %) [Bonnett+2016, DG+2017]

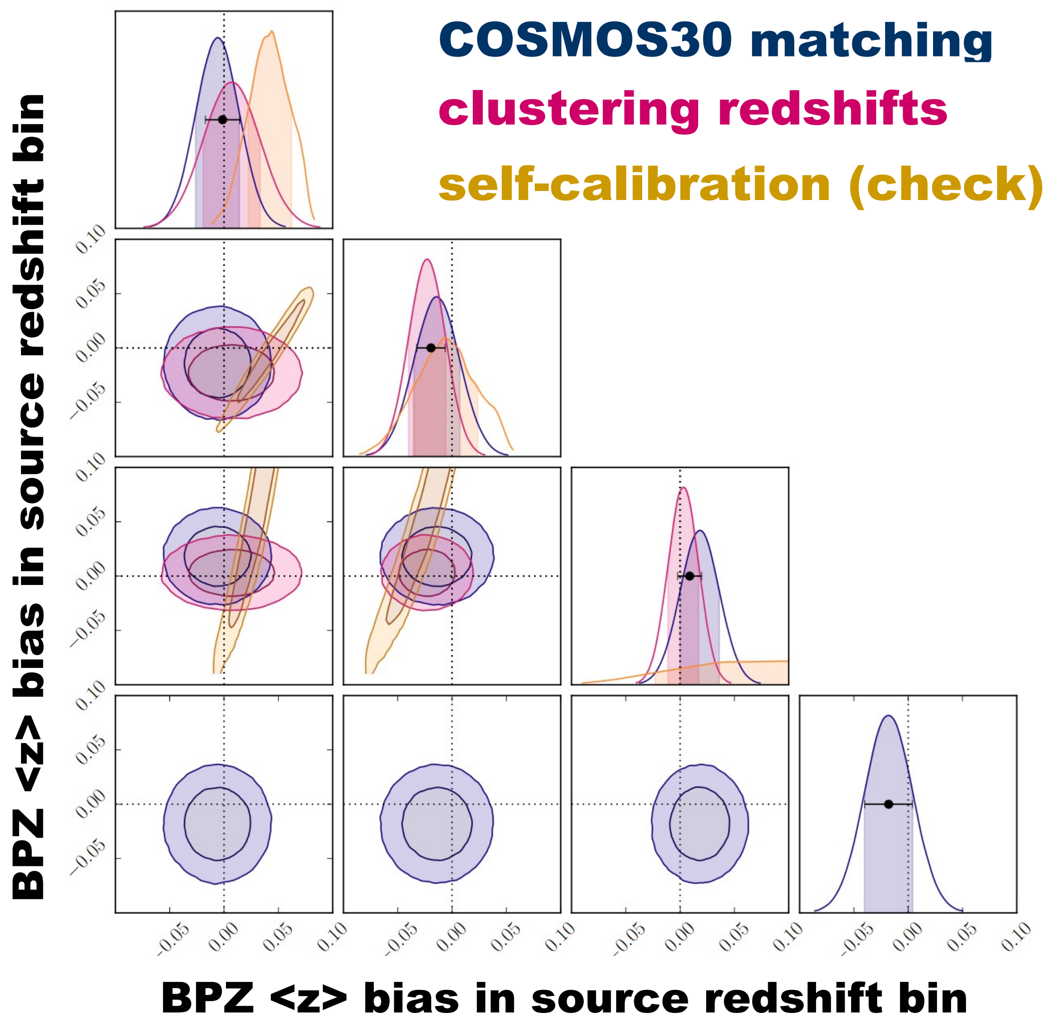


Photometric redshifts: four ways forward

- Calibration with complete, matched reference samples of known redshift
  - DES Y1: COSMOS photo-z; dominant uncertainty from cosmic variance and details of matching algorithm
- Clustering with reference sample at z is proportional to n(z)
  - DES Y1: redMaGiC LRGs as reference; dominant uncertainty from bias evolution and redshift range of redMaGiC
- Self-calibration/shear ratio+marginalization of errors with a parameter <z> in likelihood
  - DES Y1: done in all likelihoods

- Full Bayesian schemes

(Leistedt+2016; Bernstein+2016; Herbel+2017)

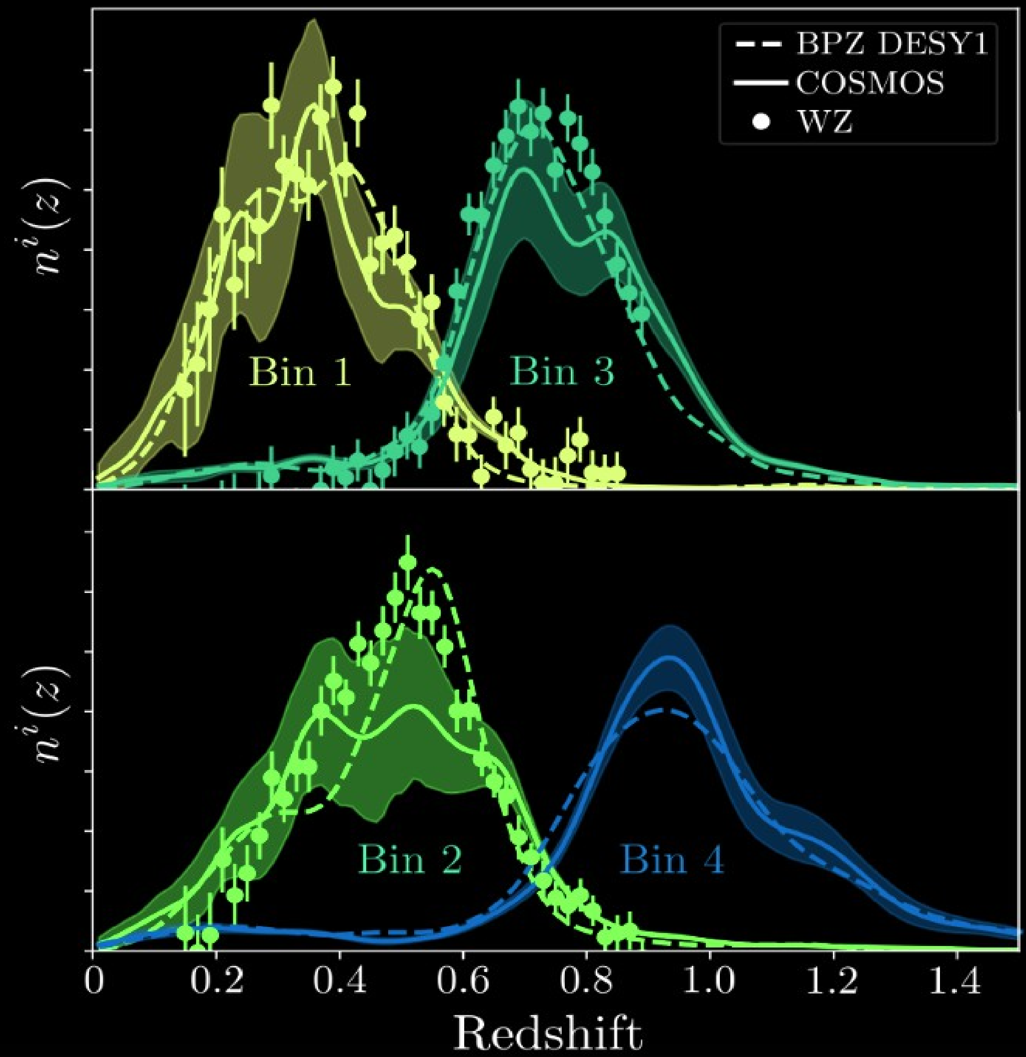


Hoyle, DG+ 1708.01532
Gatti, Vielzeuf+ 1709.00992; Davis+ 1710.02517

With great statistical power comes great systematic responsibility

- two independent galaxy shape measurements, including novel metacalibration algorithm
- two independent calibrations of photometric redshifts of four source bins

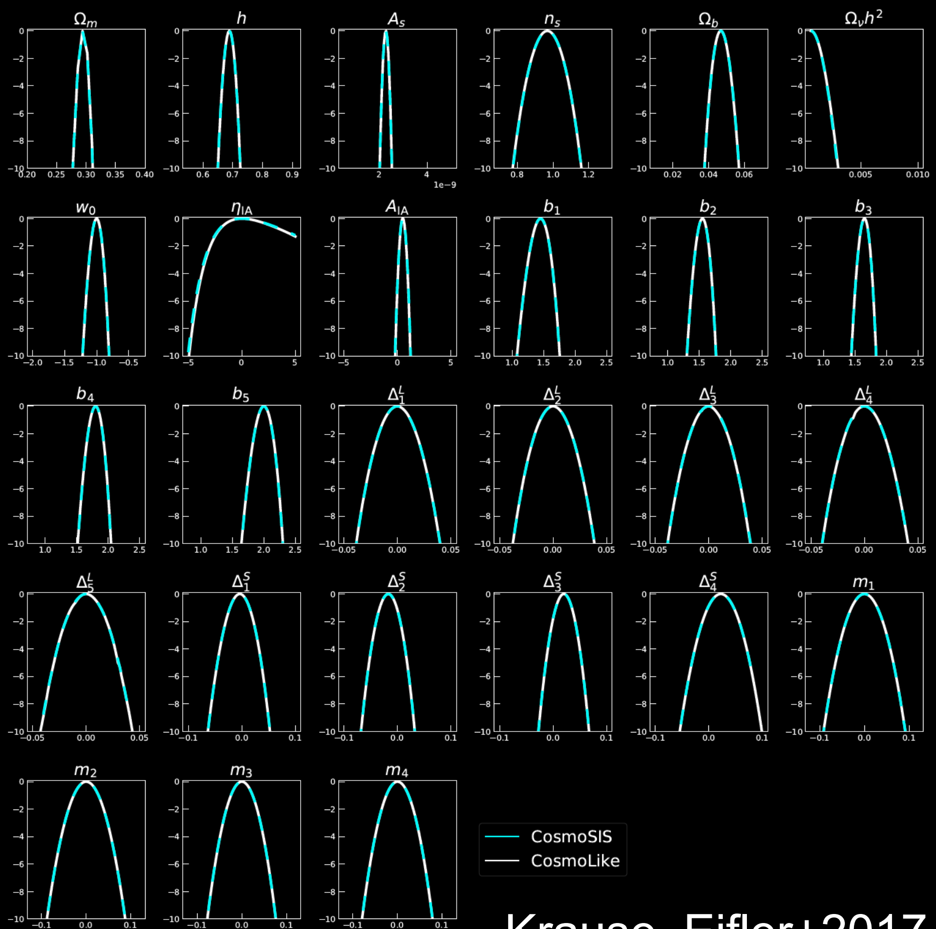
COSMOS + clustering methods agree, ~0.015 joint errors!



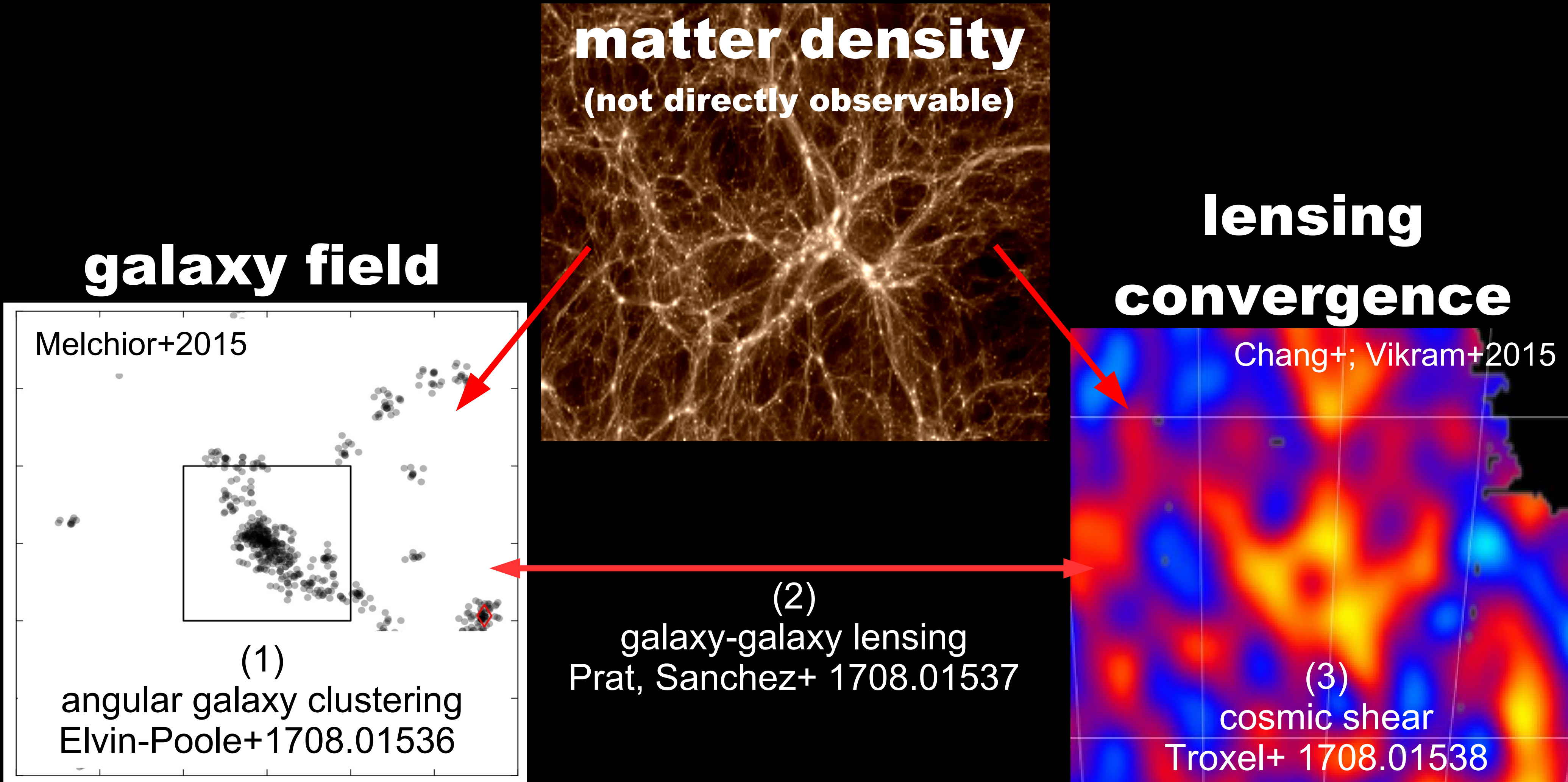
With great statistical power comes great systematic responsibility

- two independent galaxy shape measurements, including novel metacalibration algorithm
- two independent calibrations of photometric redshifts of four source bins
- two independent inference pipelines

CosmoLike (Krause+Eifler) and CosmosSIS (Zuntz+):
equal predictions / equal constraints



Krause, Eifler+2017



combination of these three two-point functions maximizes use of information and jointly and robustly constrains nuisance parameters

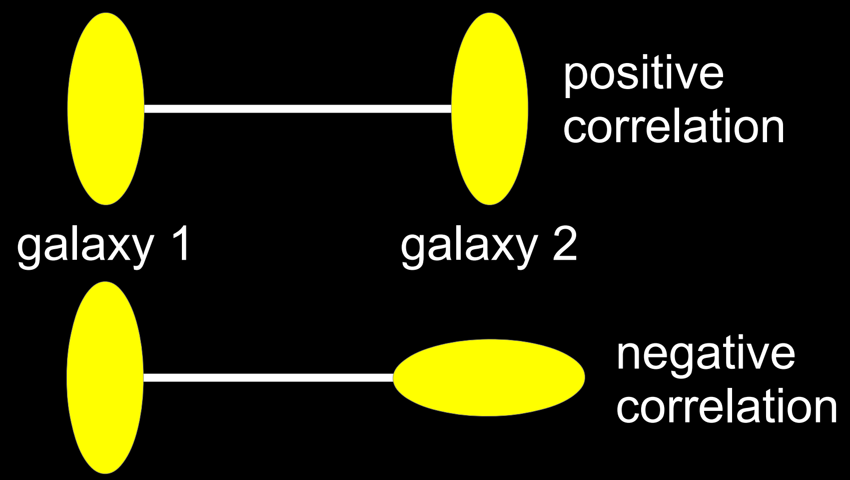
[Hu&Jain 2004, Huterer+2006, Bernstein+2009, Joachimi&Bridle 2010, van Uitert+2017, Joudaki+2017]

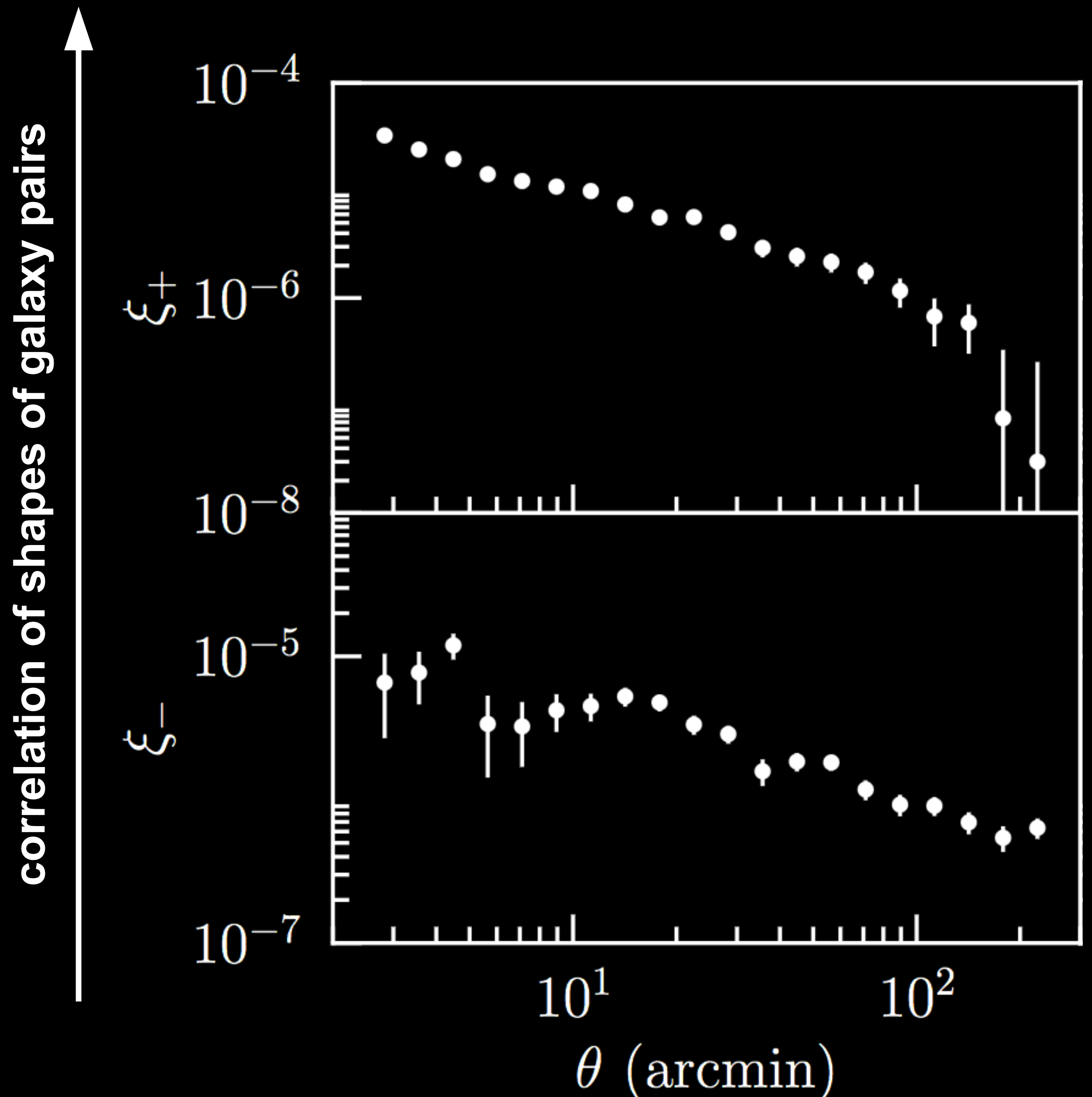
joint constraints from these three probes in a photometric survey for the first time: DES Collaboration+ 1708.01530

Measurements: cosmic shear

Troxel+ (1708.01538)

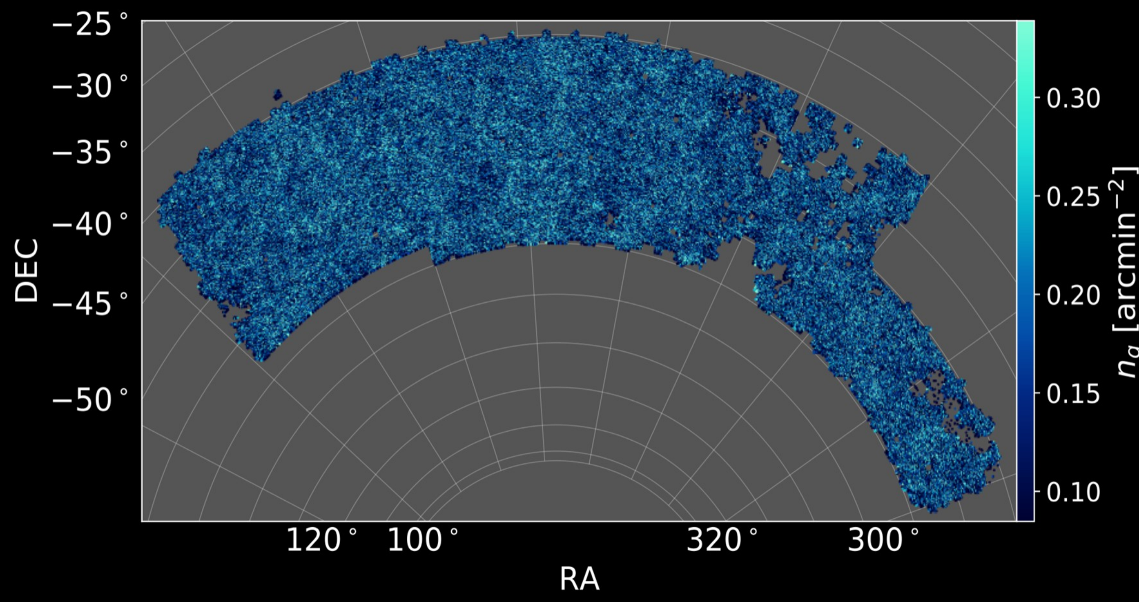
- Light from distant galaxies passes the same foreground structure
- We measure their shapes
- We measure the correlation of shapes of galaxy pairs



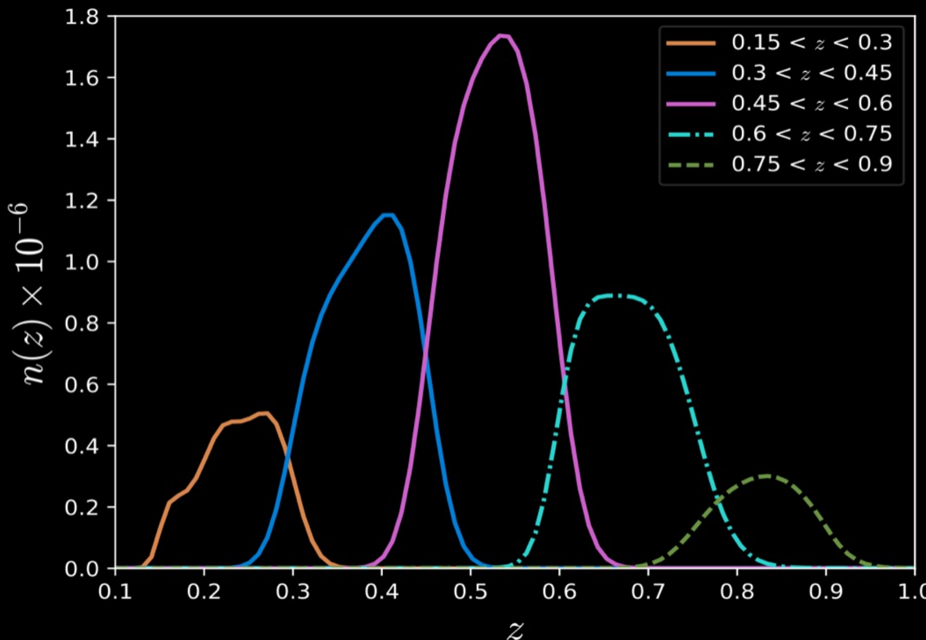


DES Year 1 Lens Galaxy Sample: redMaGiC

- 660,000 redMaGiC (bright, red) galaxies with excellent redshifts
  Rozo, Rykoff+2016



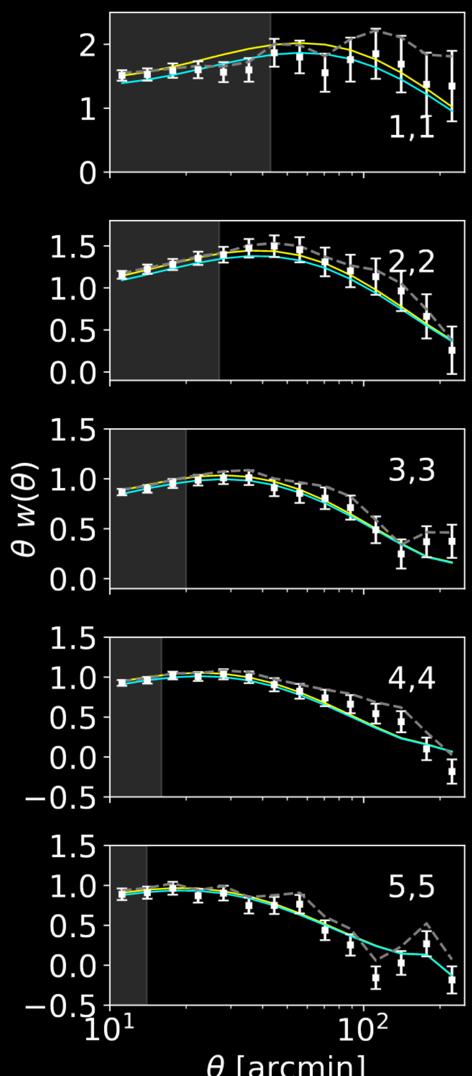
- Measure angular clustering in 5 redshift bins
- Use as lenses for galaxy-galaxy lensing



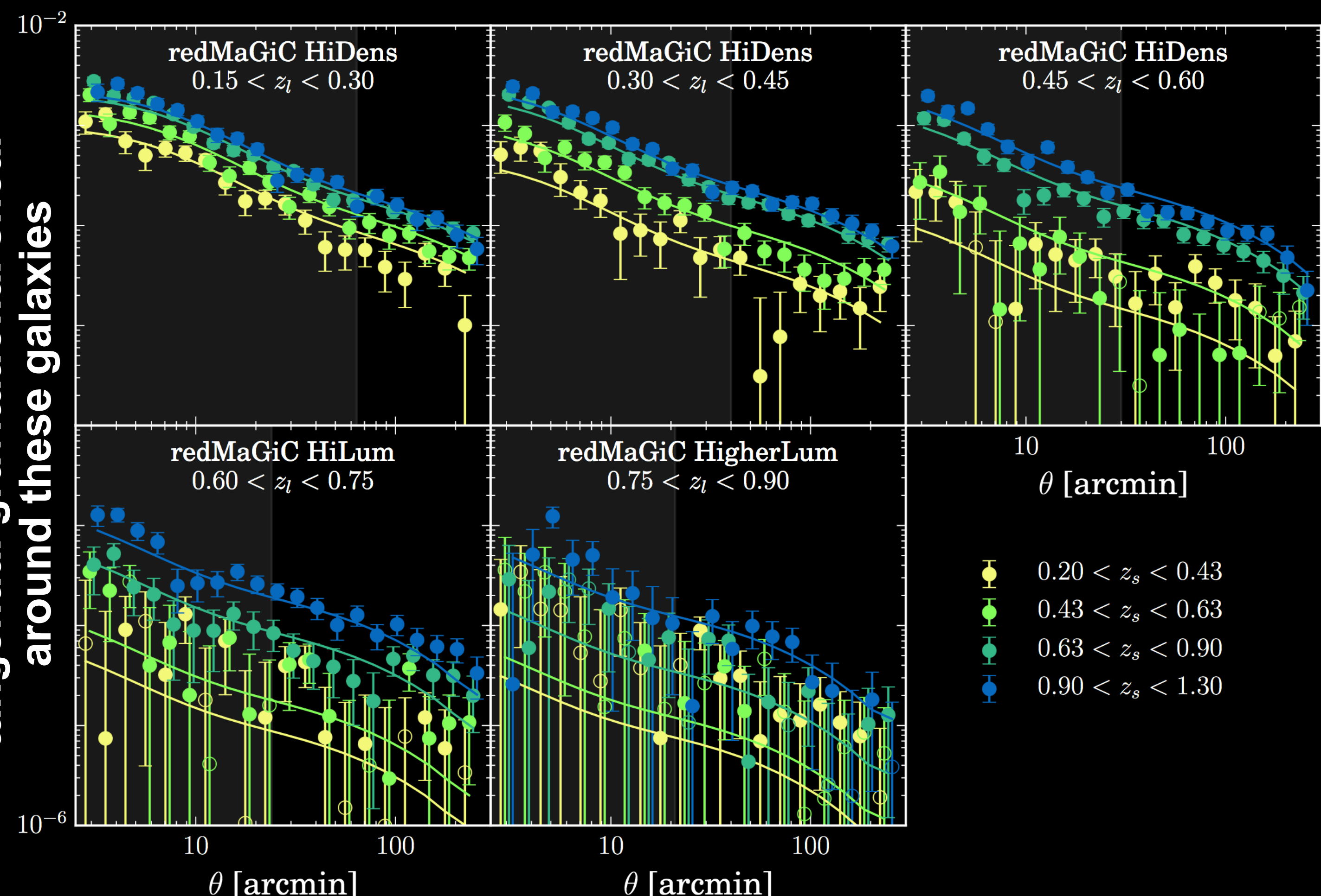
Measurements: galaxy clustering and galaxy-galaxy lensing

Elvin-Poole+ (1708.01536); Prat, Sanchez+ (1708.01537)

clustering of galaxies in 5 redshift bins between z=0.15 … 0.90



tangential gravitational shear around these galaxies

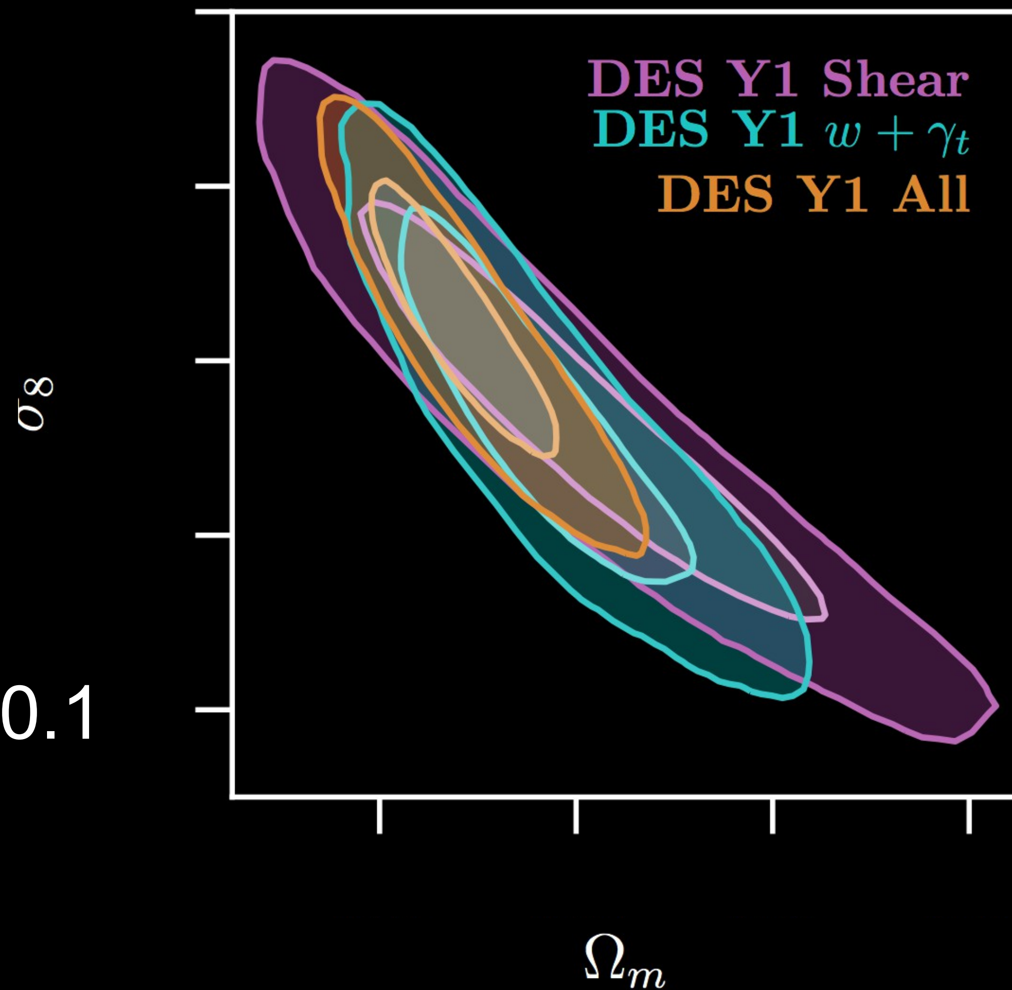


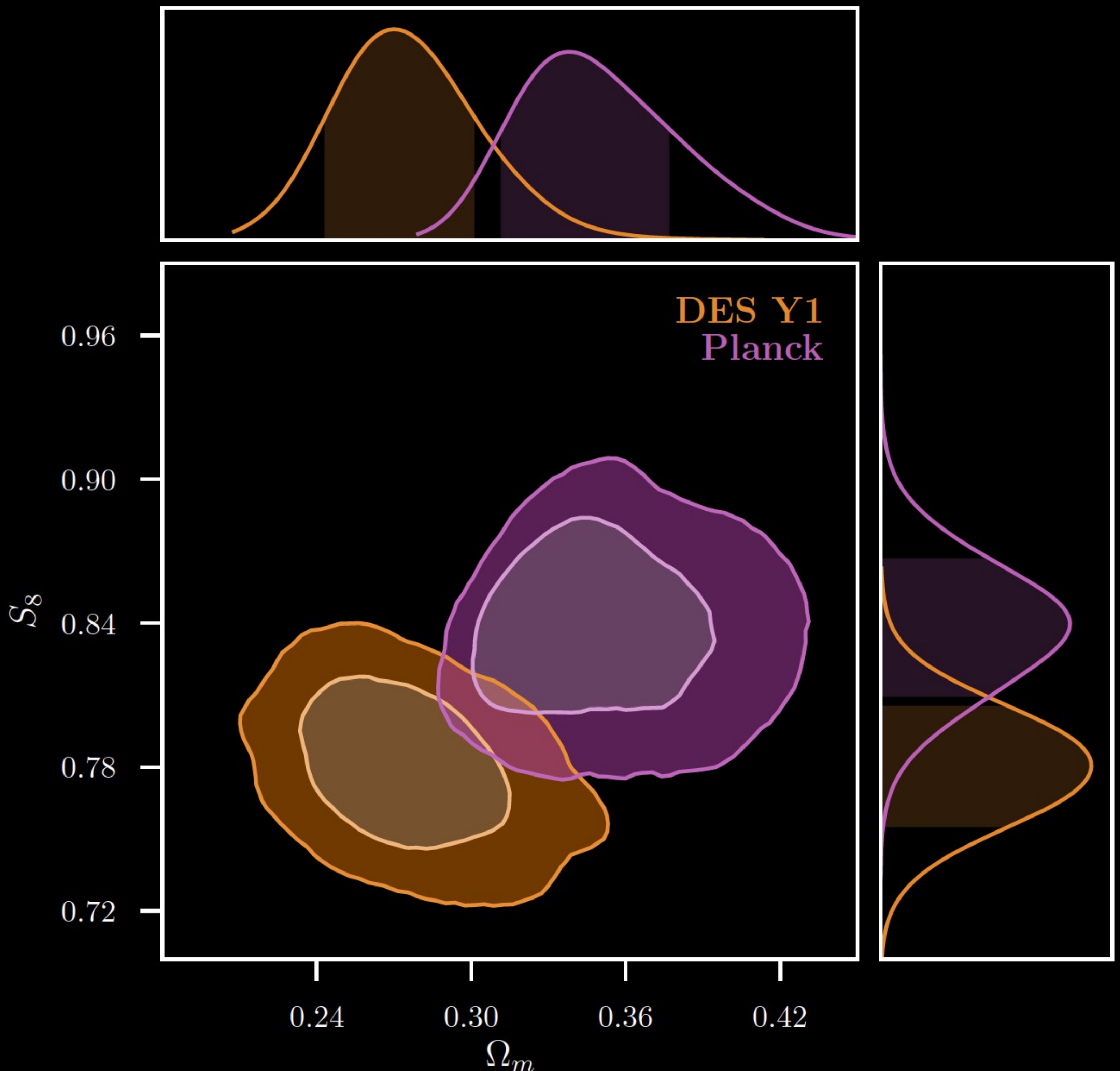
Consistency of the individual constraints in ΛCDM

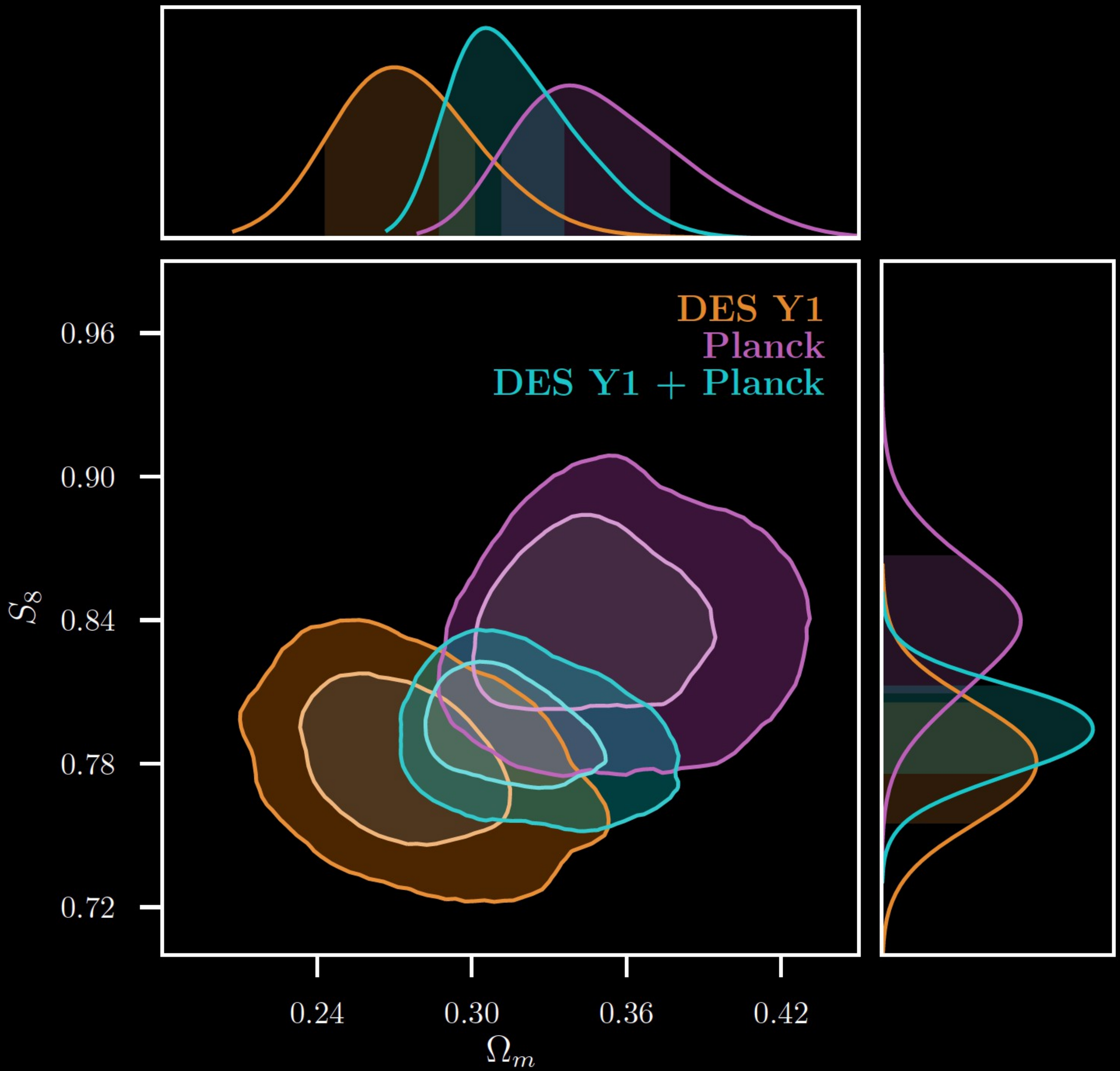
- Cosmic shear and redMaGiC clustering + lensing yield consistent cosmological constraints
- Criterion: Bayes Factor

$$R = \frac{P\left(\vec{D}_1, \vec{D}_2 | M\right)}{P\left(\vec{D}_1 | M\right) P\left(\vec{D}_2 | M\right)} = 2.8 > 0.1$$

- passing 11 other null tests, we unblind

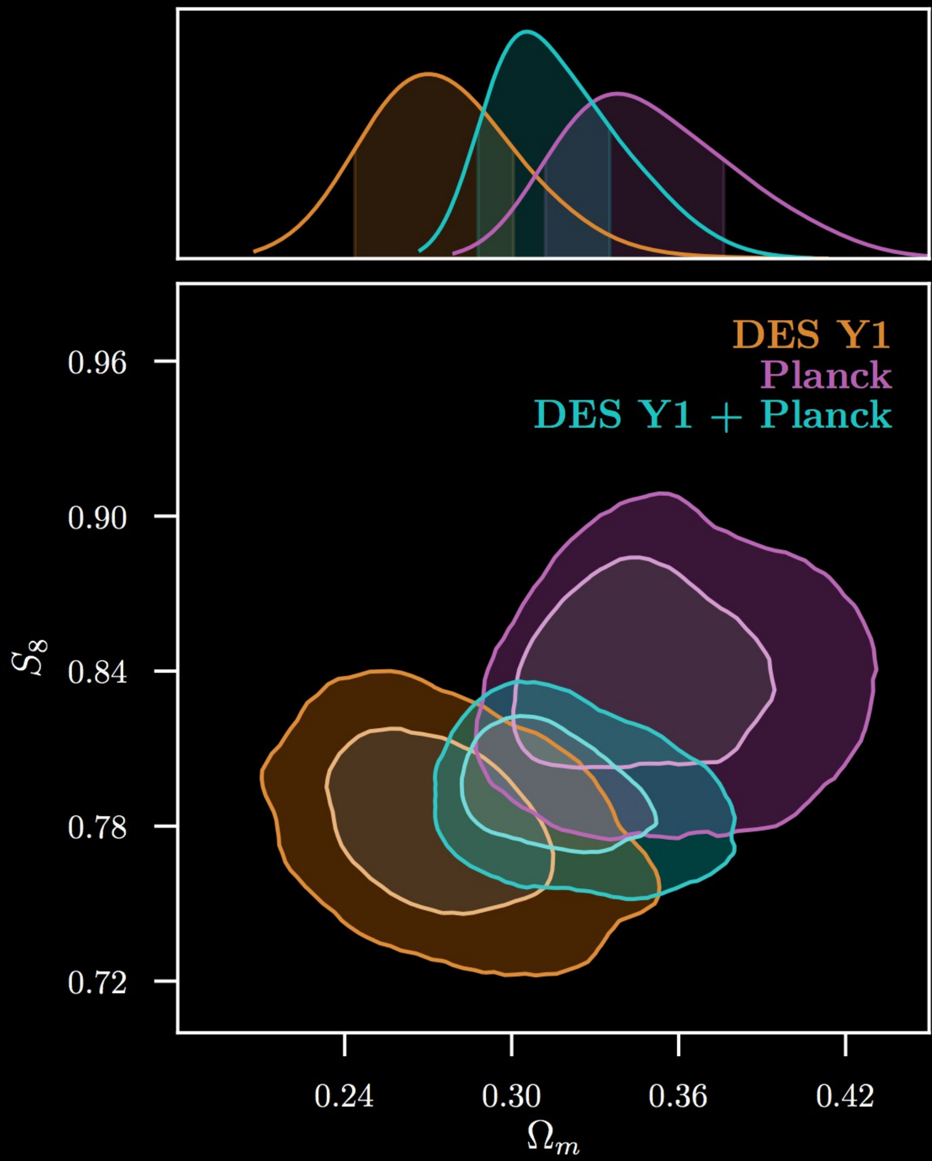



DES Y1
Planck
0.96
0.90
0.84
0.78
0.72
S_8
0.24
0.30
0.36
0.42
Ω_m


DES Y1
Planck
DES Y1 + Planck
0.96
0.90
0.84
0.78
0.72
S_8
0.24
0.30
0.36
0.42
Ω_m

Key result: Consistency of late Universe with Planck in ΛCDM

- DES and Planck constrain matter density and S_8 with equal strength
- Difference in central values 1-2σ in the same direction as earlier lensing results
- Bayes Factor 4.2 – no evidence for inconsistency



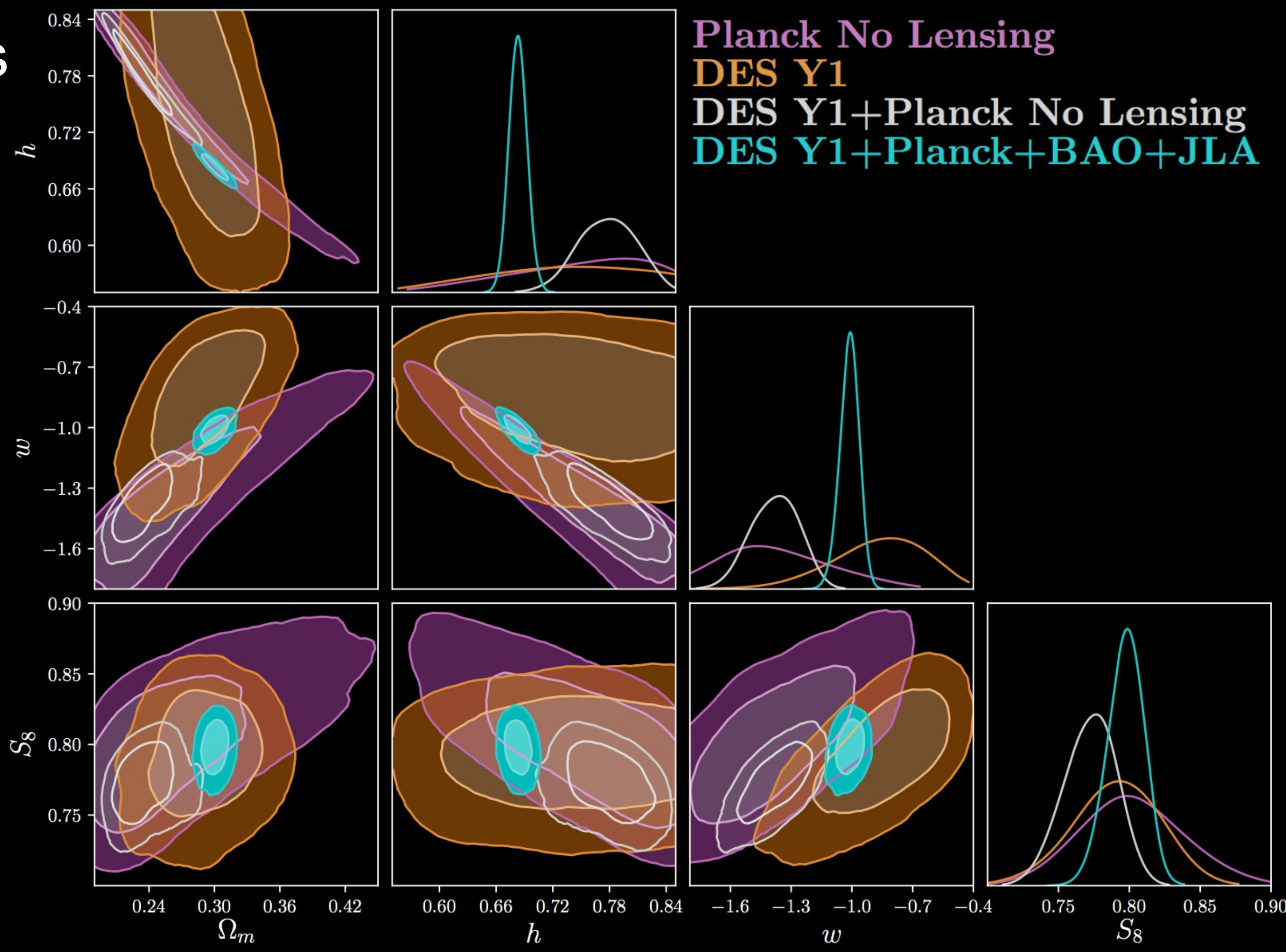
Key result: DES + geometry + CMB yields consistent, tightest constraints

- consistent constraints from geometric probes + DES (R=244)
- most precise measurements in ΛCDM:

$$\Omega_m = 0.301^{+0.006}_{-0.008}$$
$$S_8 = 0.799^{+0.014}_{-0.009}$$

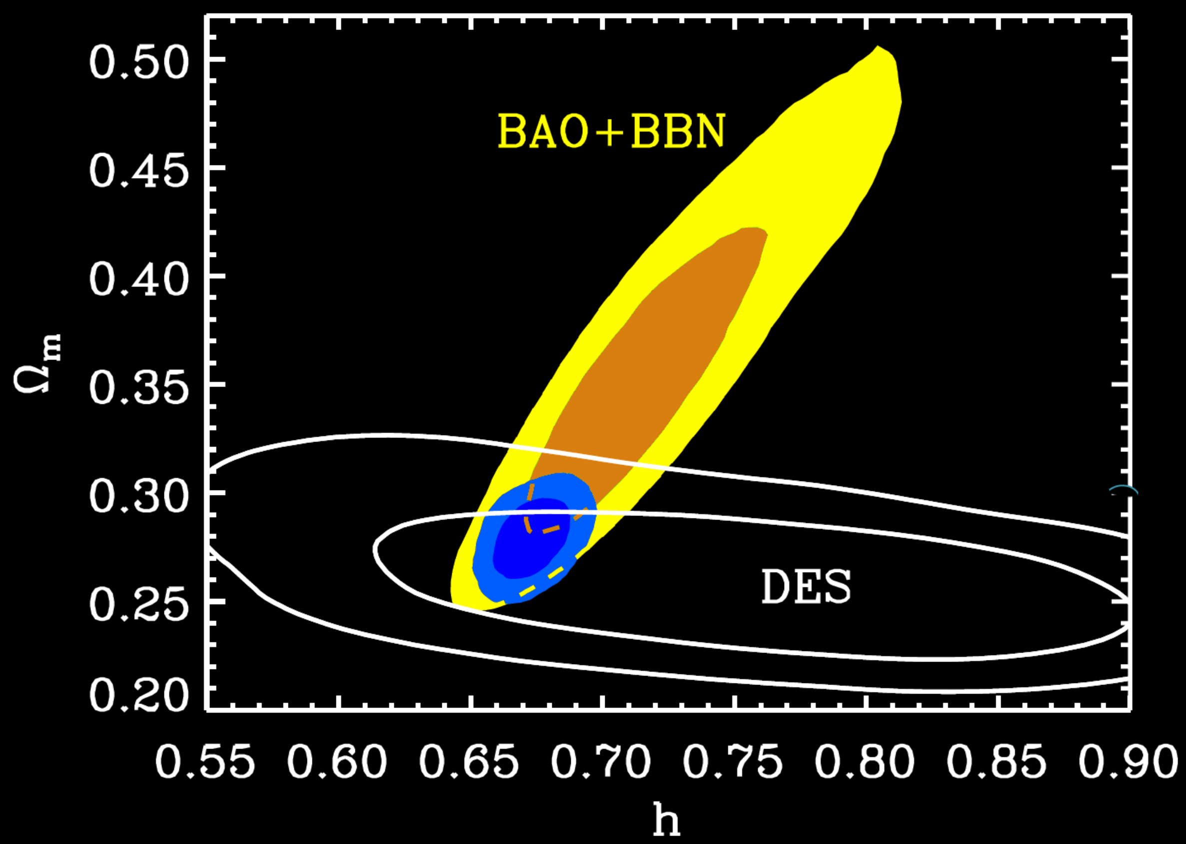
- no evidence for w≠-1 in any combination

$$w = -1.00^{+0.04}_{-0.05}$$



Bonus key result:
DES constraints on Hubble parameter

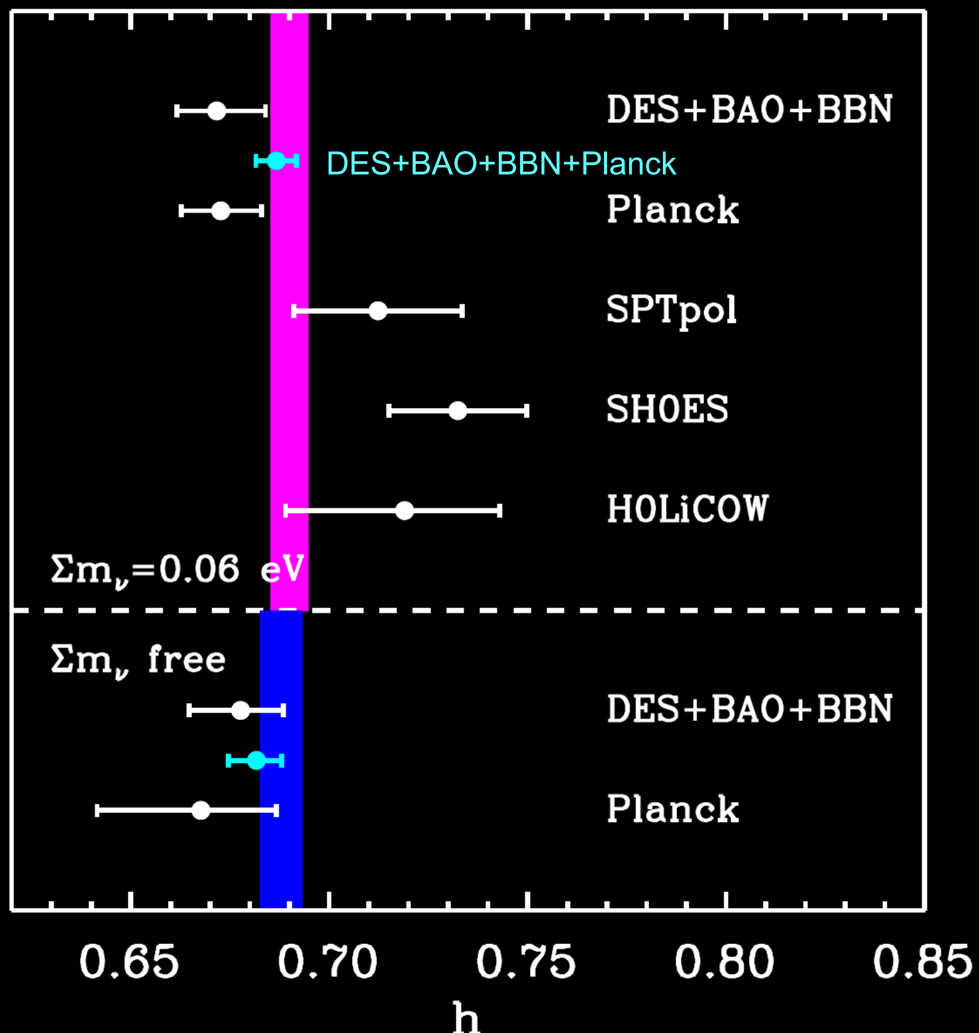
- Mild tension between local and CMB constraints on expansion rate
- Independent measurement of Ω_m, Ω_b, $\mathbf{H_0}$ from:
  - Best measurement of matter density from DES
  - Baryon density from Big Bang Nucleosynthesis
  - and BAO scale



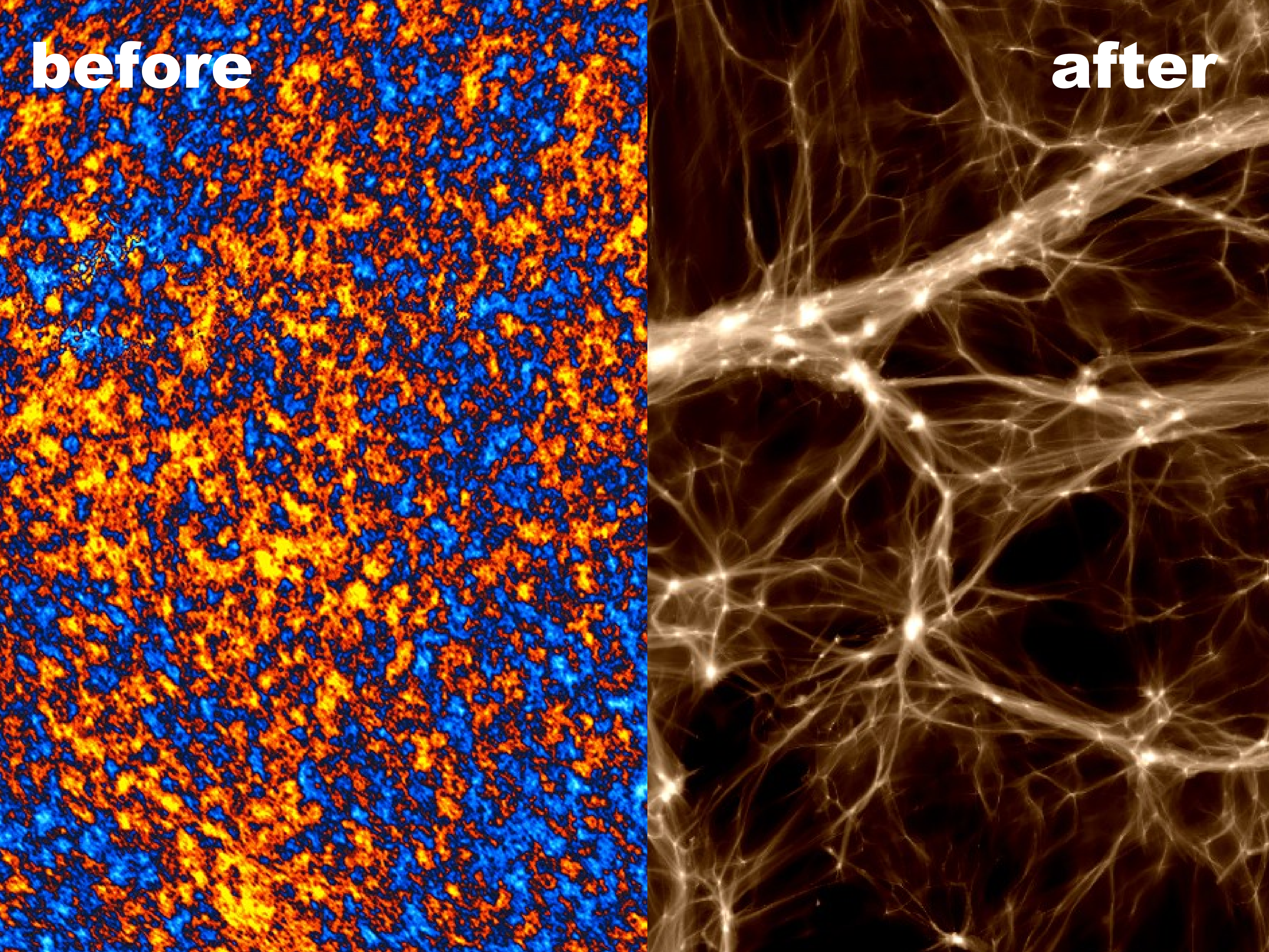
DES Collaboration 1711.00403
figure: E. Rozo

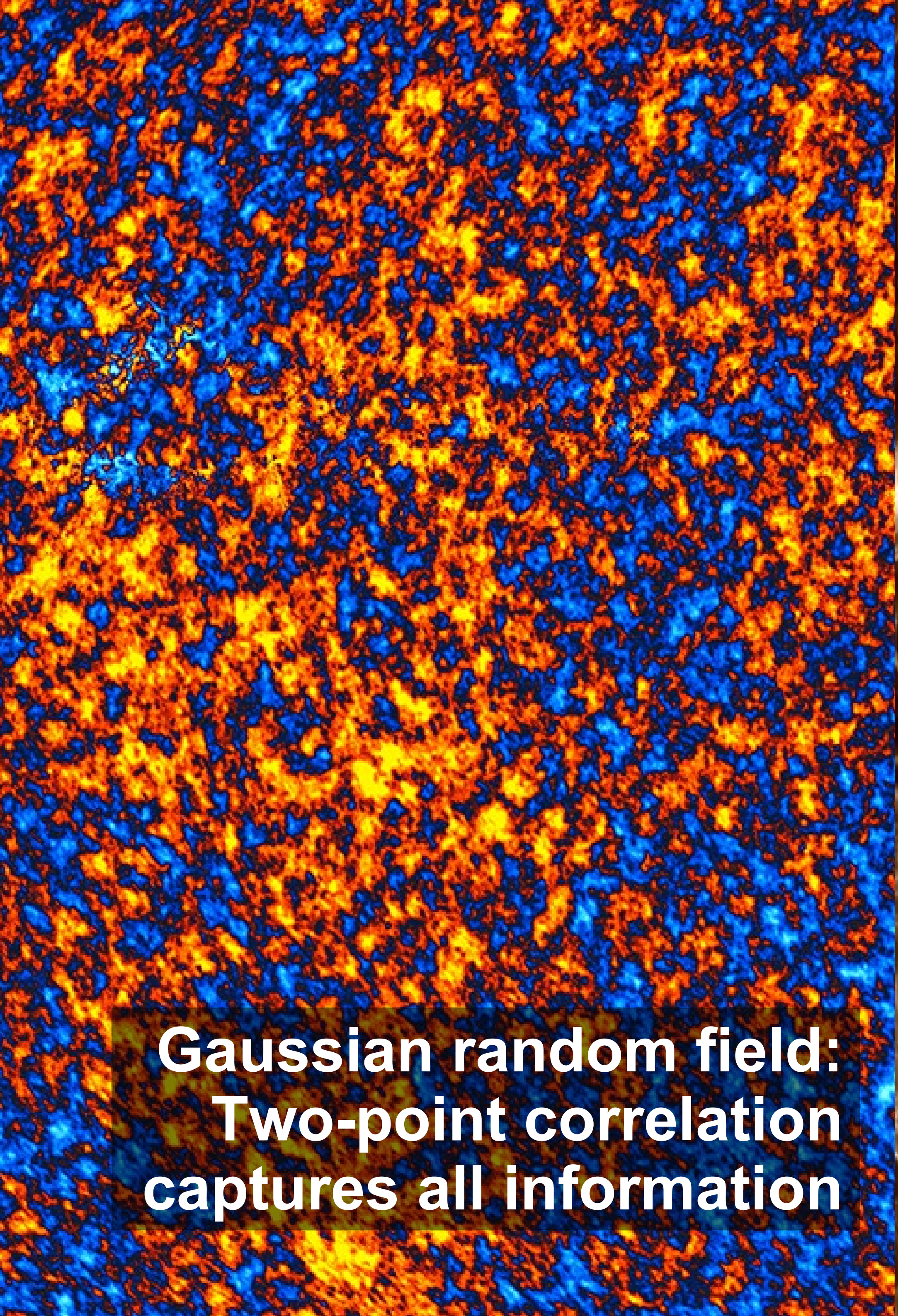
Bonus key result: DES constraints on Hubble parameter

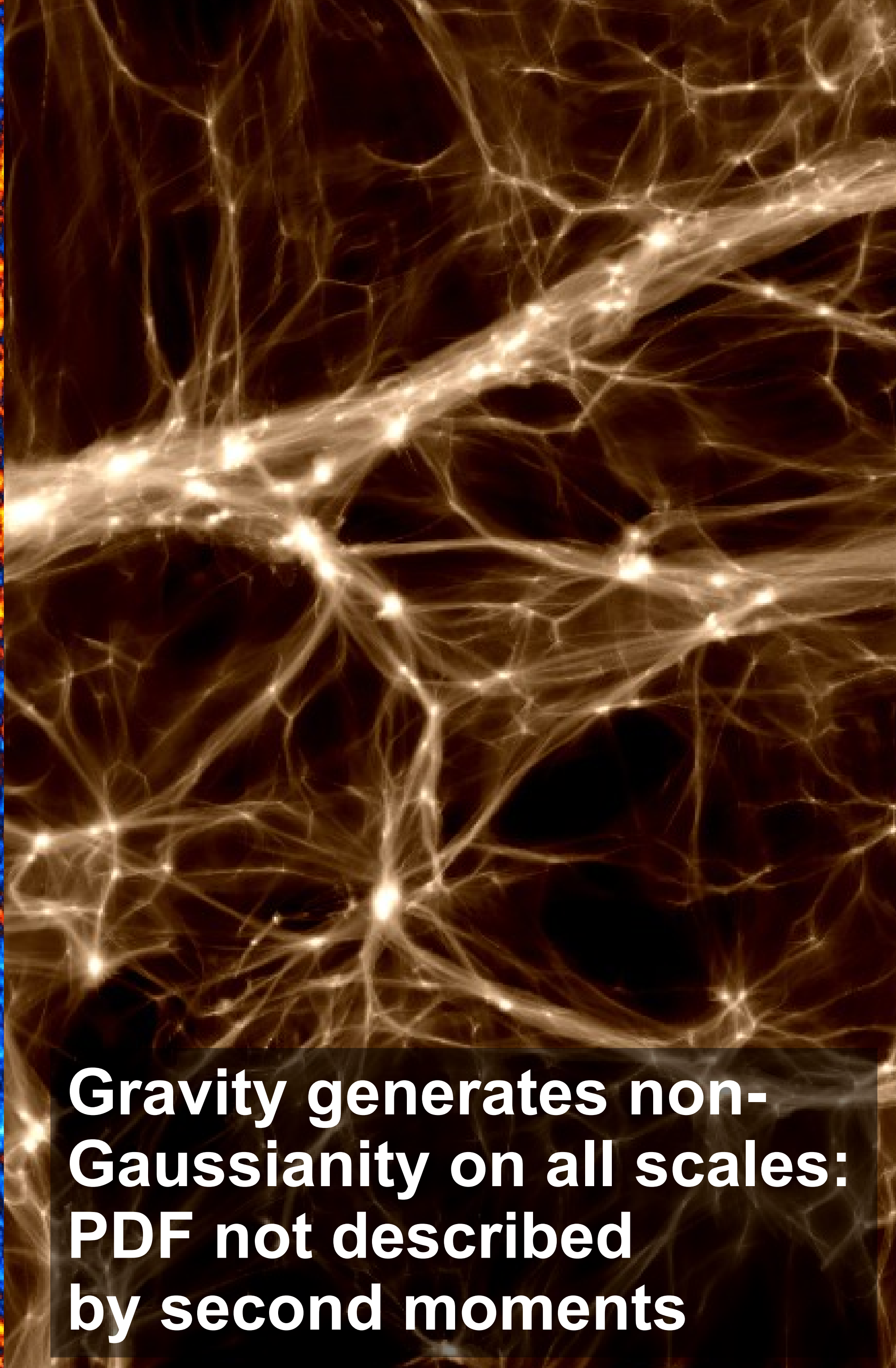
$67.2^{+1.2}_{-1.0}$ km/s/Mpc



- Independent measurement of Ω_m, Ω_b, H_0 from:
  - best measurement of matter density from DES
  - Baryon density from Big Bang Nucleosynthesis
  - and BAO scale
- 5 measurements with ~expected scatter around $H_0 = 69.1^{+0.4}_{-0.6}$ km/s/Mpc

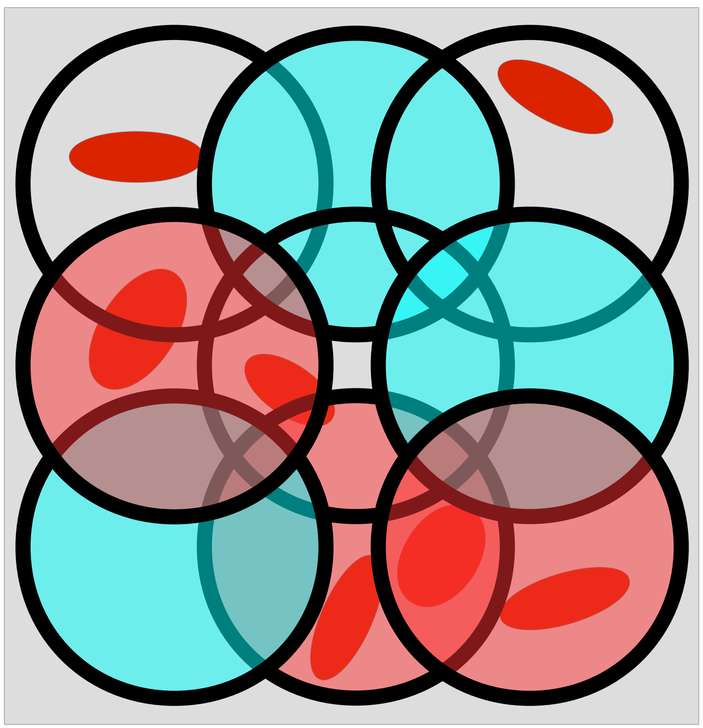

before
after

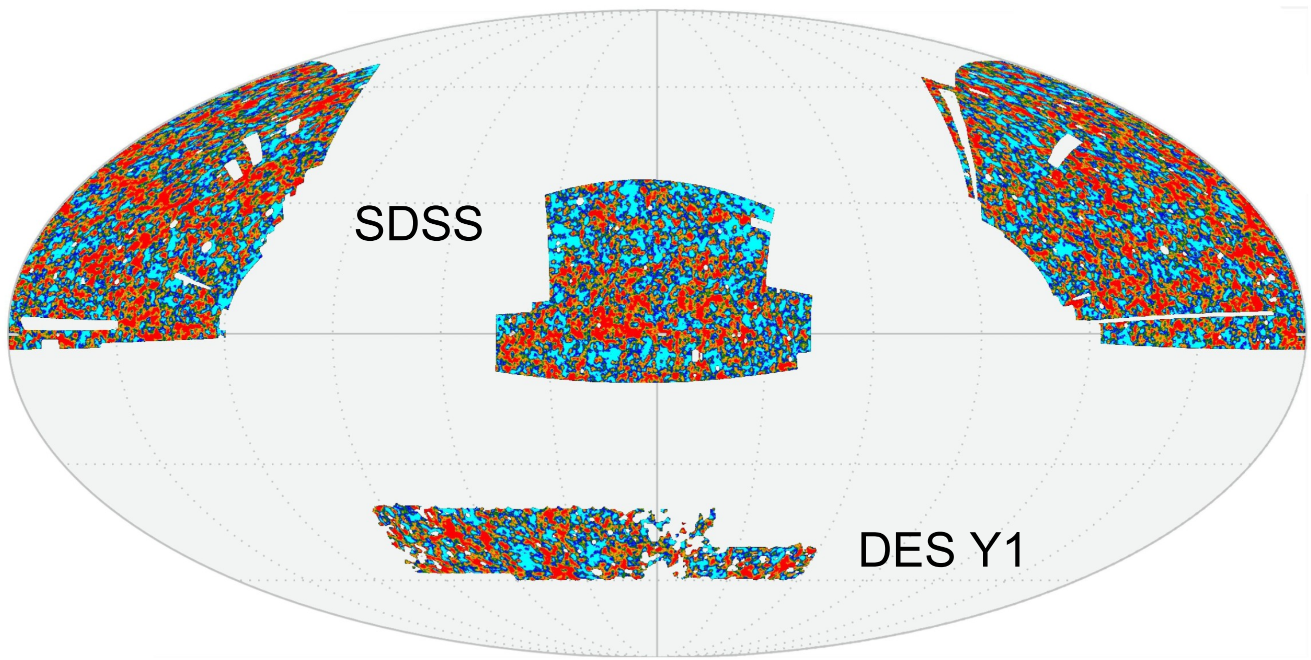

Gaussian random field:
Two-point correlation
captures all information


Gravity generates non-
Gaussianity on all scales:
PDF not described
by second moments

Cosmology from matter/galaxy PDF with lensing and counts in cells

- Step 1: split lines of sight into quintiles of redMaGiC galaxy count – underdense to overdense





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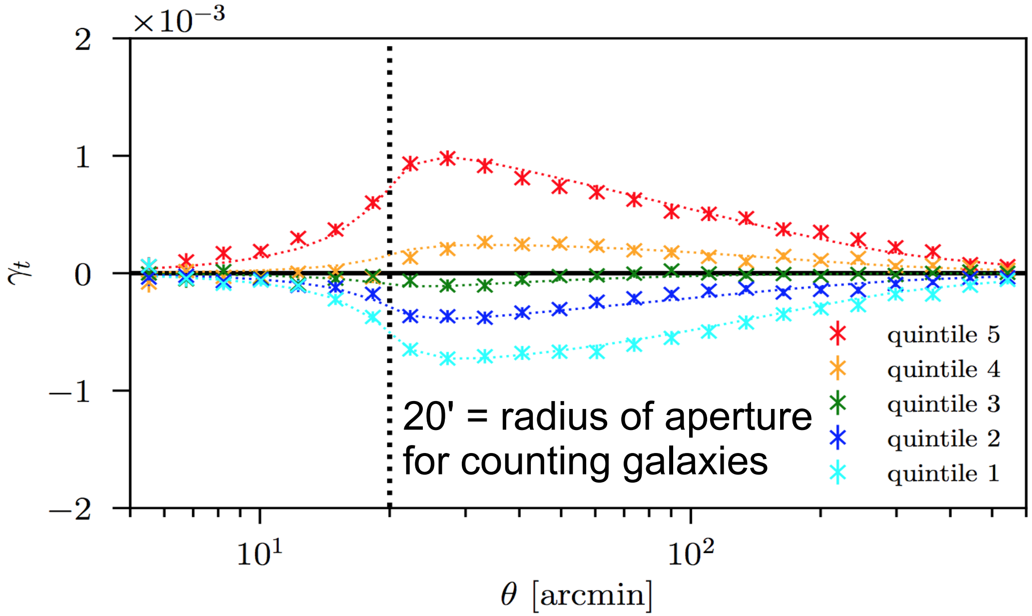
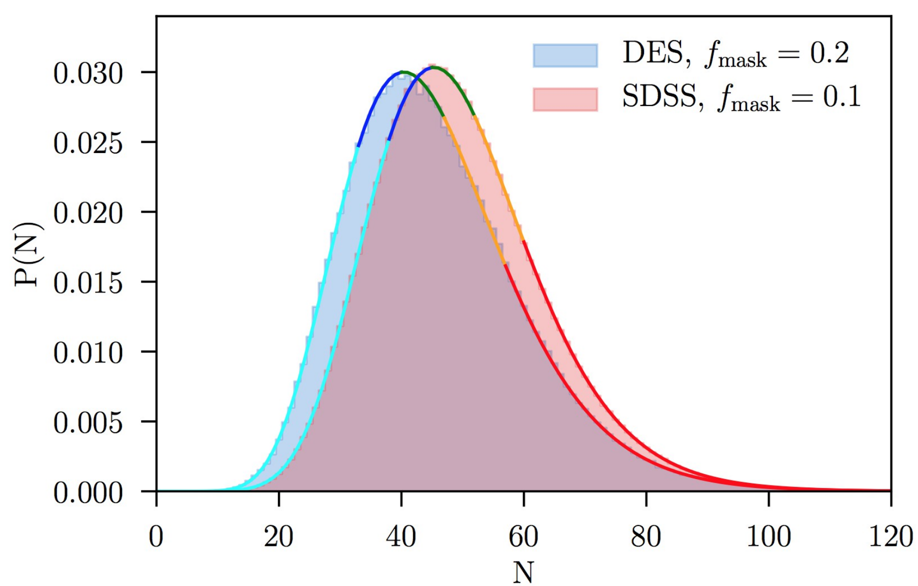
Cosmology from matter/galaxy PDF with lensing and counts in cells

- Step 1: split lines of sight into quintiles of redMaGiC galaxy count
- Step 2: measure shear around and mean counts in quintiles – there is an asymmetry / skewness!





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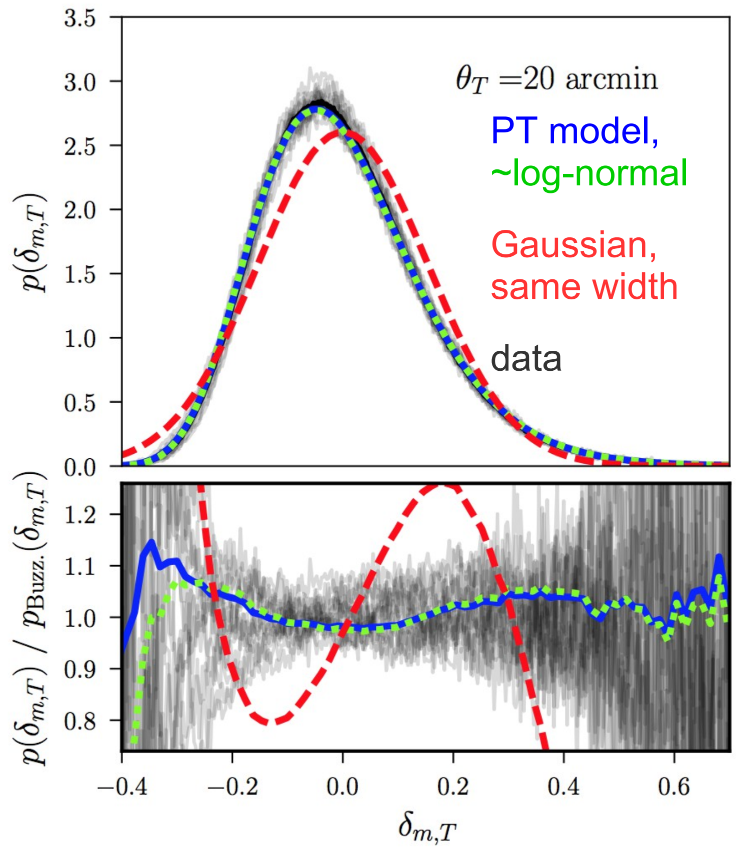
Cosmology from matter/galaxy PDF with lensing and counts in cells

- Step 1: split lines of sight into quintiles of redMaGiC galaxy count N
- Step 2: measure shear around and mean counts in quintiles
- Step 3: model these signals via joint PDF of matter and galaxy density

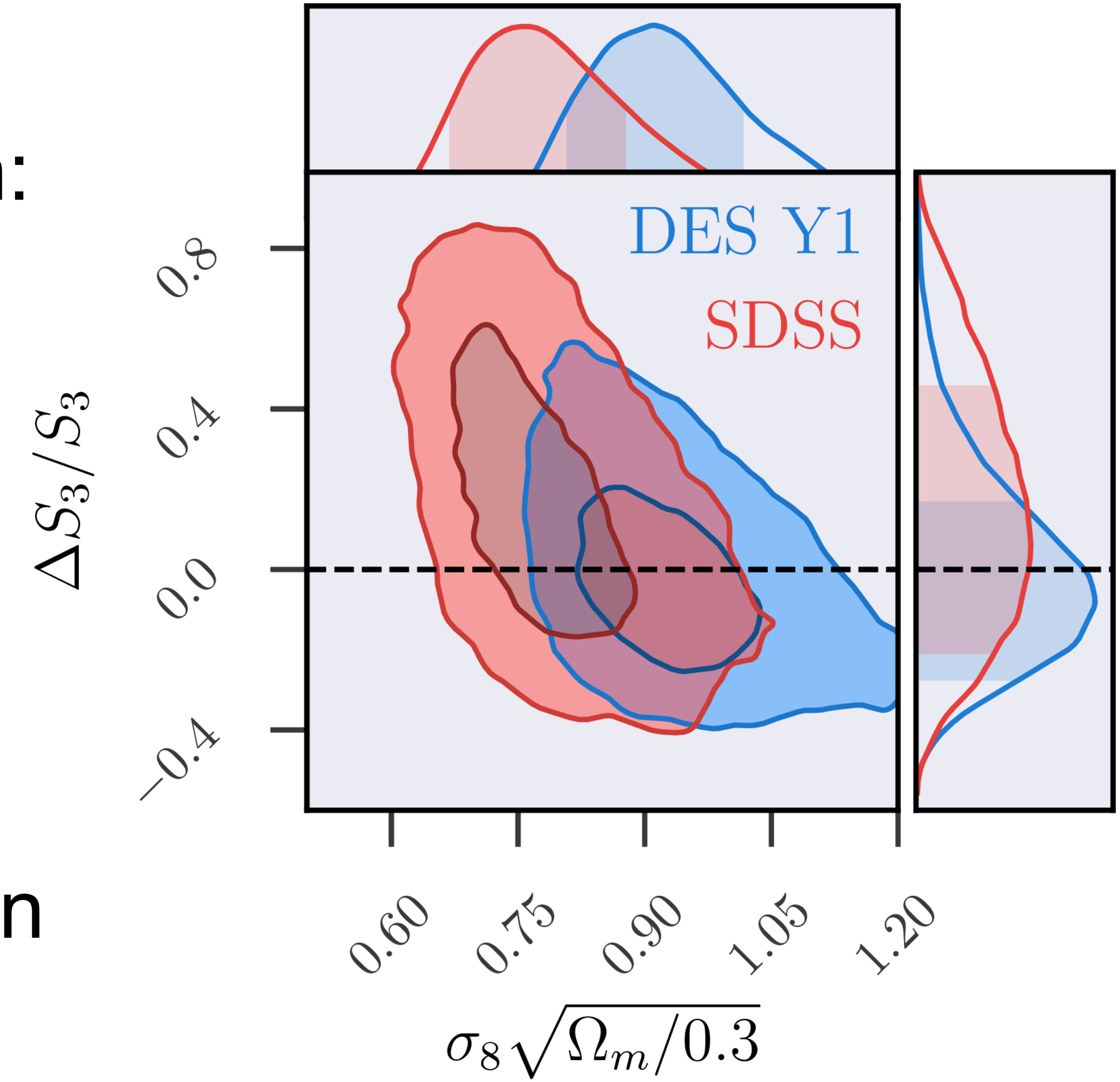


$$\langle \gamma_t \rangle (N) = \int p(\delta_m | N) \, \langle \gamma_t \rangle (\delta_m) \, \mathrm{d}\delta_m$$

perturbation theory model:
Friedrich, DG+ 1710.05162

Cosmology from matter/galaxy PDF: skewness of matter density

- Lensing + counts in cells jointly constrain:
  - Cosmology
  - Bias + Stochasticity
  - Skewness of matter density: $S_3 \equiv \frac{\langle \delta^3 \rangle}{\langle \delta^2 \rangle^2}$
- Skewness agrees with ΛCDM prediction at ~20% uncertainty



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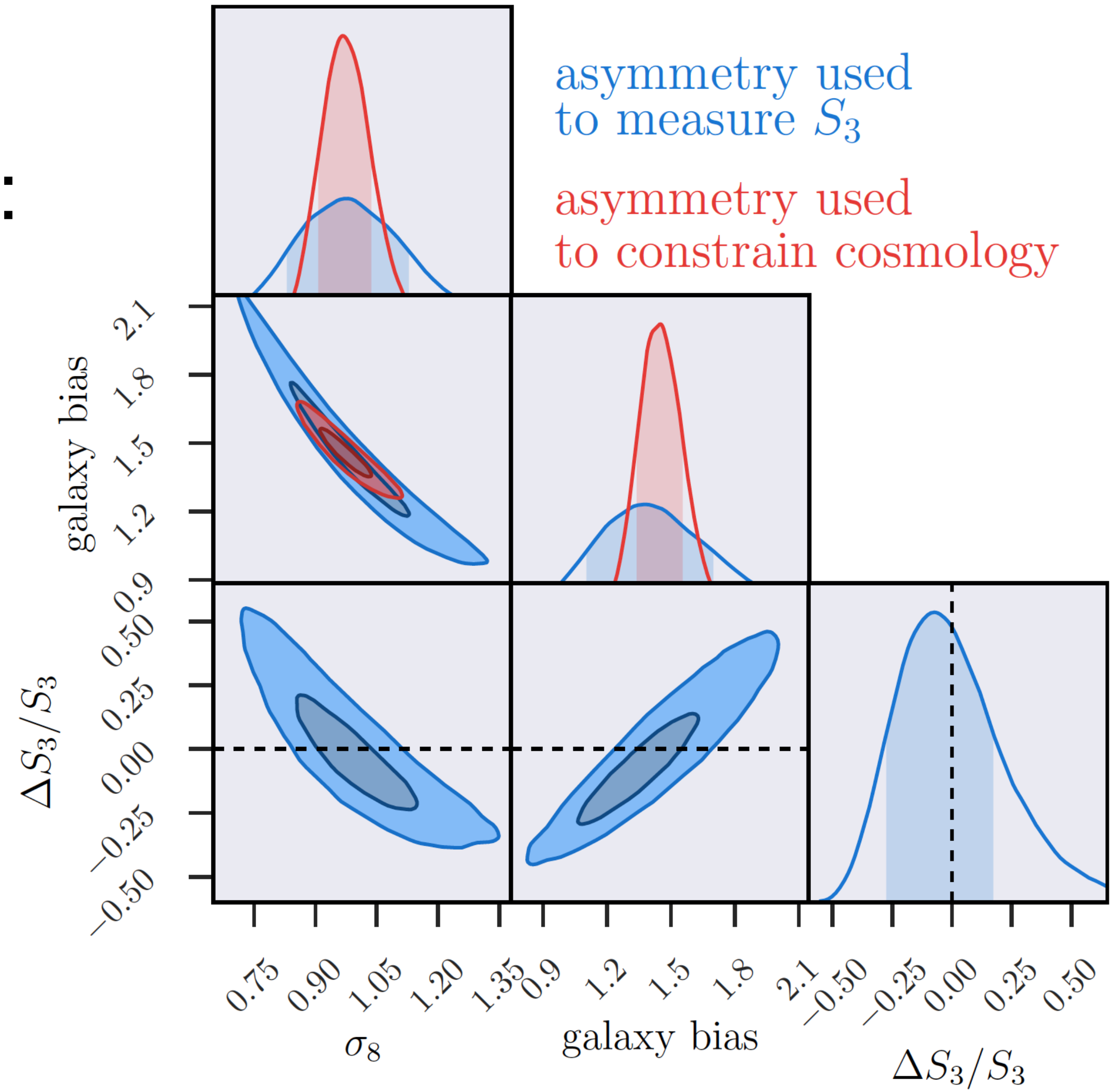
Cosmology from matter/galaxy PDF: skewness of matter density

- Lensing + counts in cells jointly constrain:
  - Cosmology
  - Bias + Stochasticity

- Skewness adds significant constraining power



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Summary

- Wide range of probes from early & late Universe, geometry & structure, agree on fiducial ΛCDM cosmology
- DES has added the most precise measurement of structure in the evolved Universe
  - Control of systematics with improved, independent methods
  - Competitiveness and consistency with Planck CMB in ΛCDM, insignificant offset, but in the direction of other lensing studies
  - Joint constraints close to Ω_m=0.30, σ_8=0.80, w=-1.0, h=0.69
- Different statistics (matter PDF, clusters of galaxies) and much more data (Y3) soon!