The bright and the dark side of gravitational lensing

Daniel Gruen, NASA Einstein Fellow

with collaborators from the Dark Energy Survey

LIneA Webinar, Oct 5, 2017

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
  - matter/galaxy PDF with lensing + counts in cells

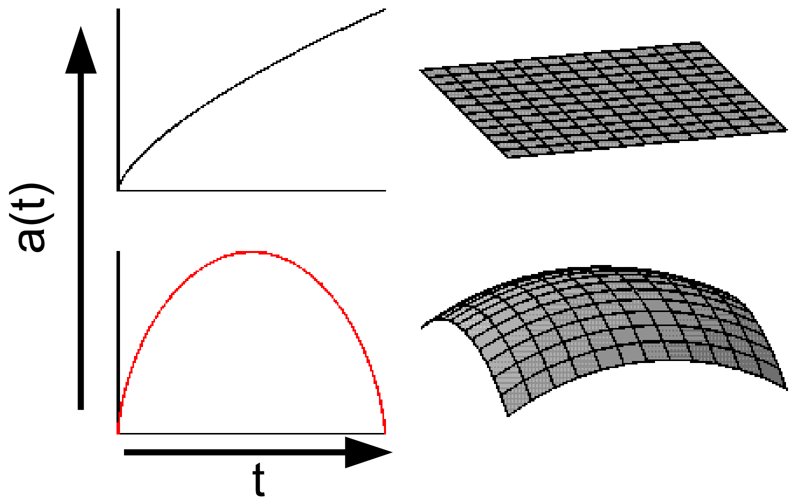
What goes up must come down?

- 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



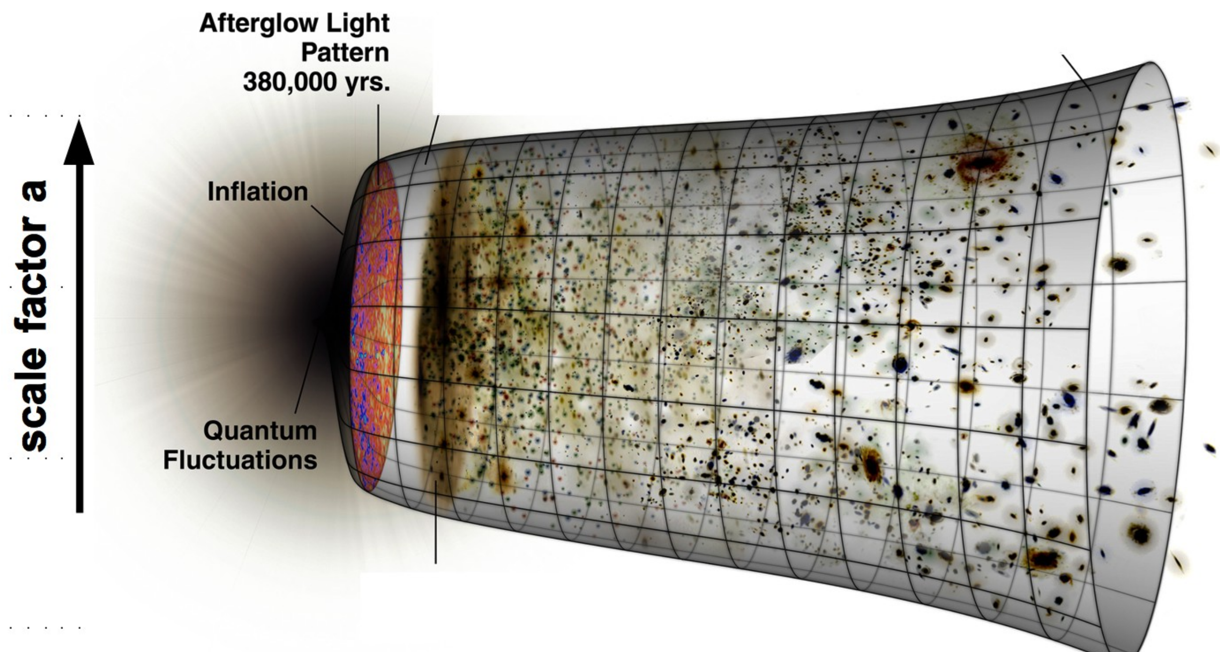
What goes up keeps getting faster!

- 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”



What goes up keeps getting faster!

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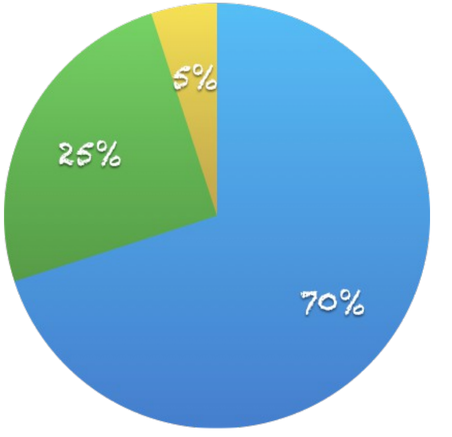
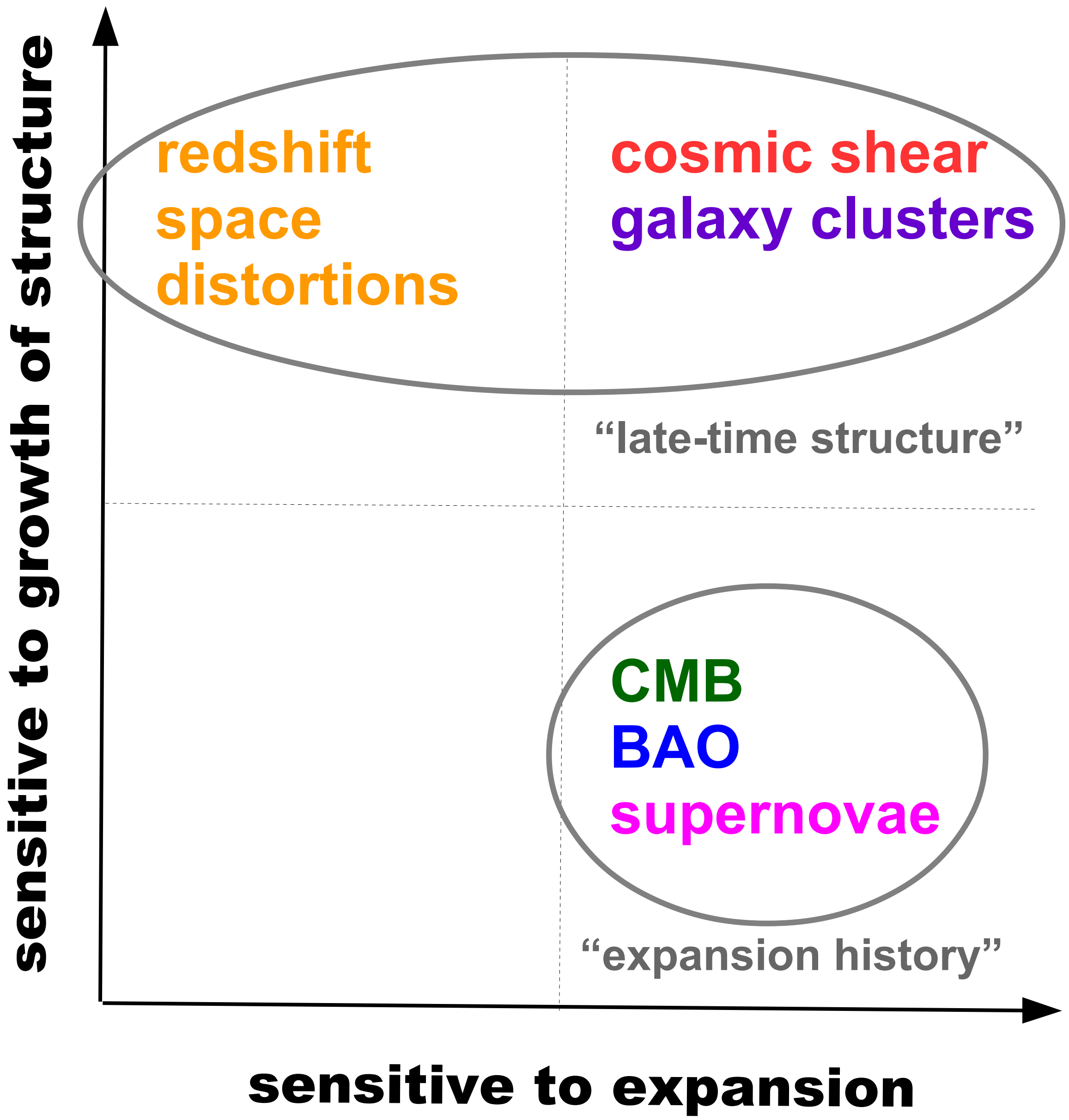
$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda c^2}{3}$$

- Parameters of this universe:
  - Densities of matter (Ω_m~0.3), dark energy (Ω_Λ~0.7), baryons (~0.05), neutrinos
  - Amplitude of structure σ_8~0.8
  - Expansion rate H

"fiducial cosmology"



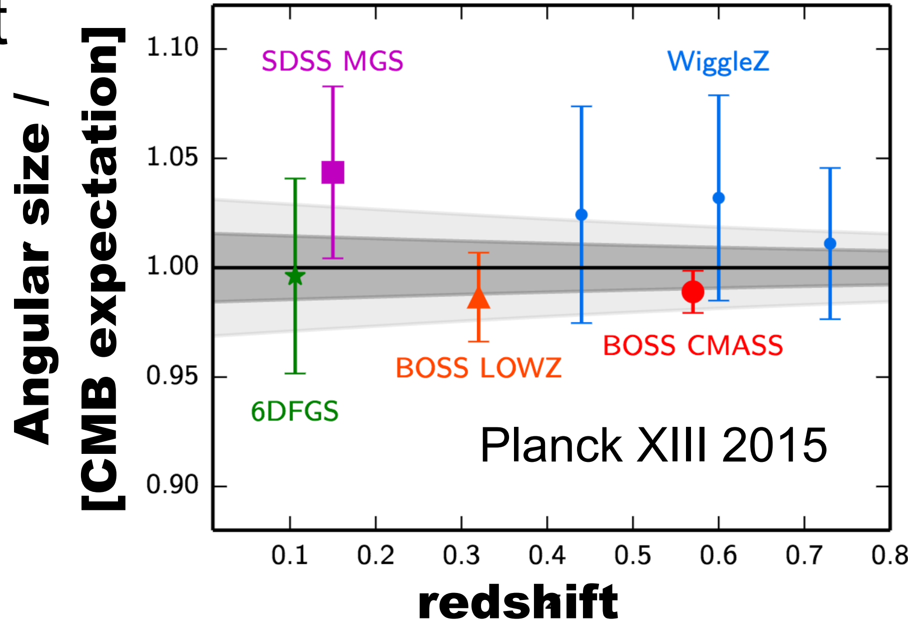
How to survey Dark Energy

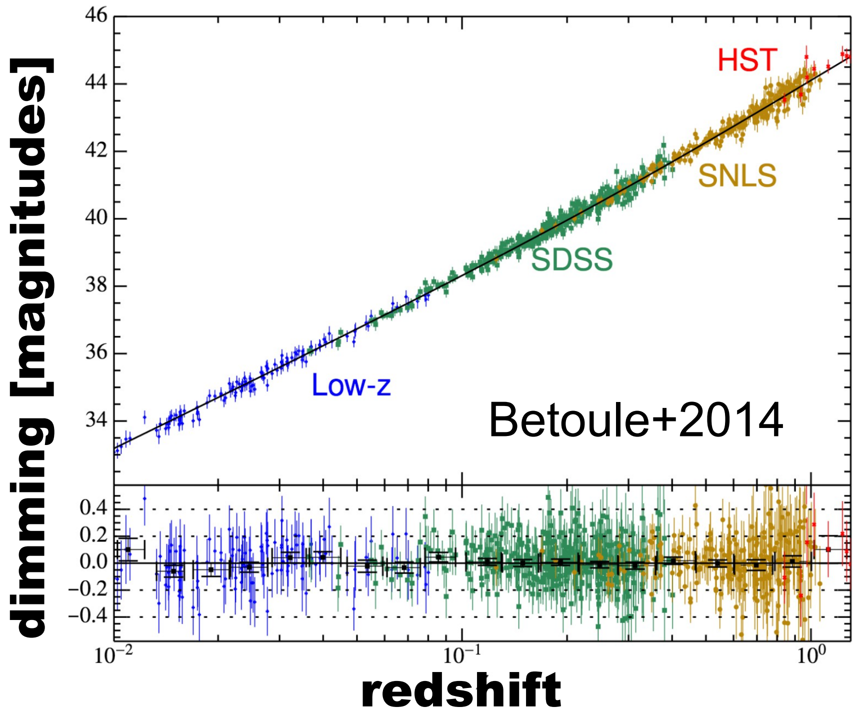


Q: Do all these measurements agree with predictions in the same, fiducial ΛCDM model?

Measurements of expansion history

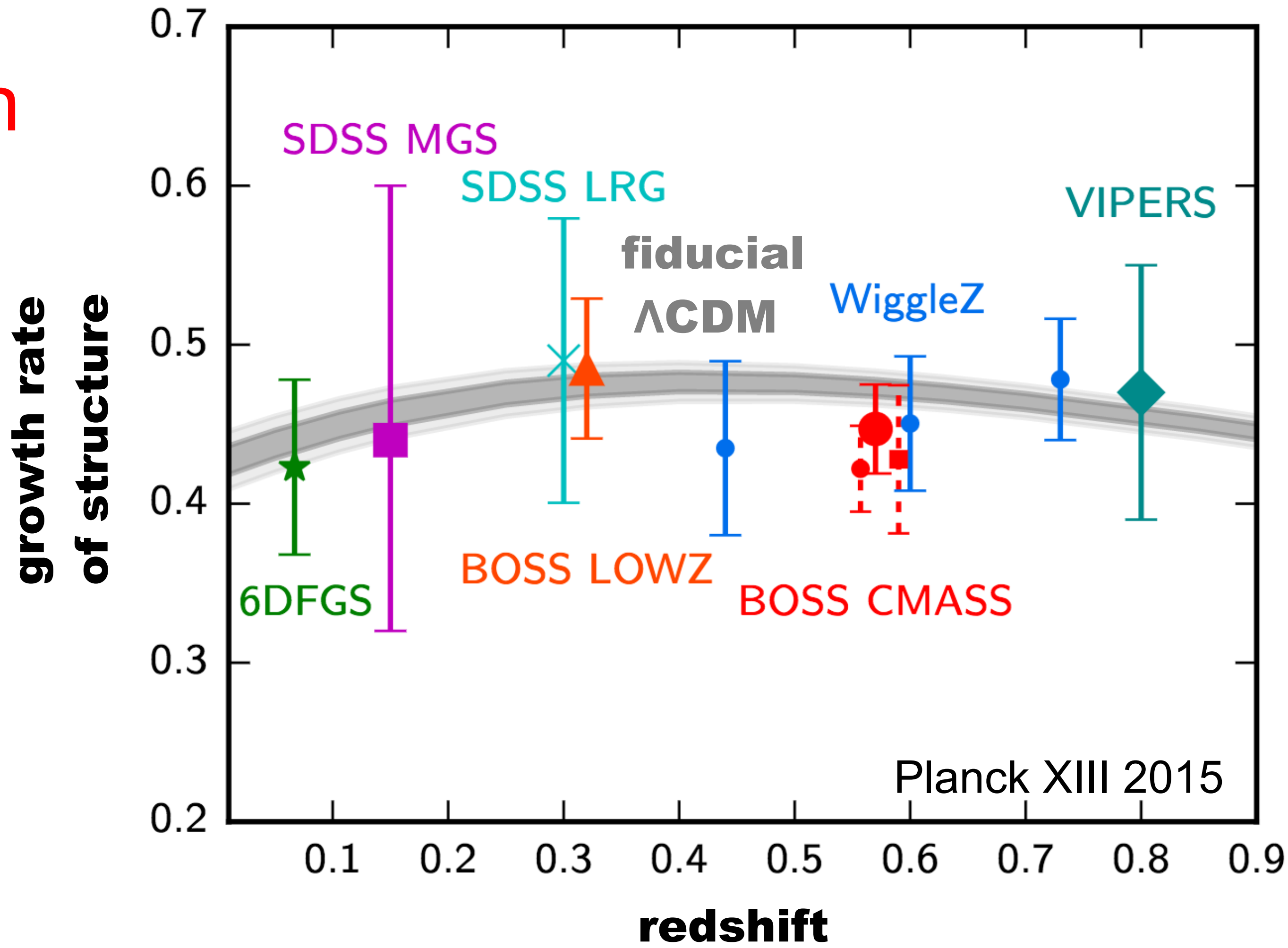
- Comparison of distance and redshift
- **Standard ruler**: angle subtended by known scale
  - **CMB**: sound horizon in early Universe (380,000 years)
  - **BAO**: same scale, but expanded at later times (billions of years)
- **Standard candle:** brightness of source with known luminosity
  - **SNe**: luminosity can be determined from duration/color
- These are consistent and very tightly constrain w=-1, Ω_m, Ω_{DE}, flatness





Measurement of late-time structure

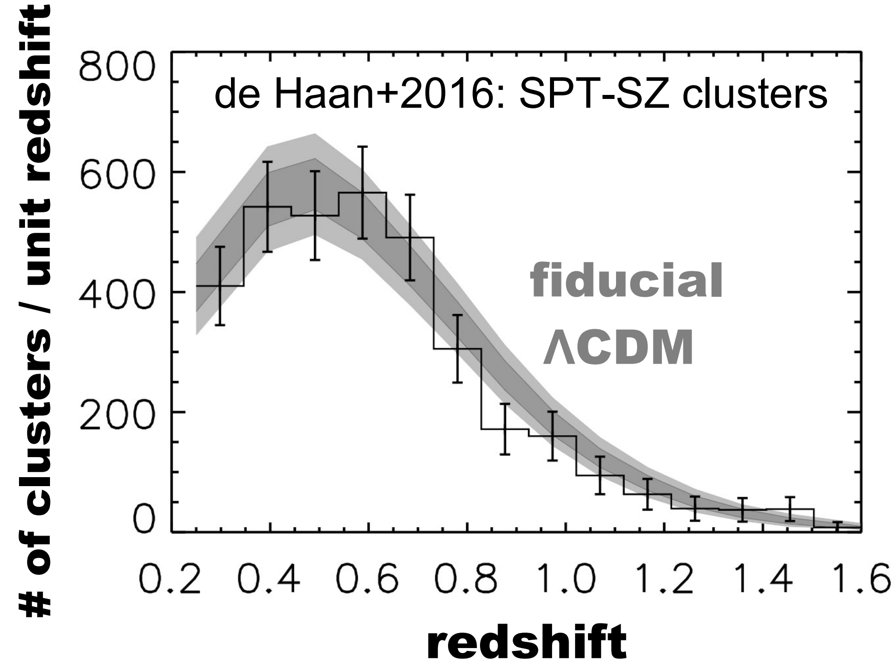
- redshift space distortions (RSD):
  growth rate
  consistent with
  fiducial ΛCDM

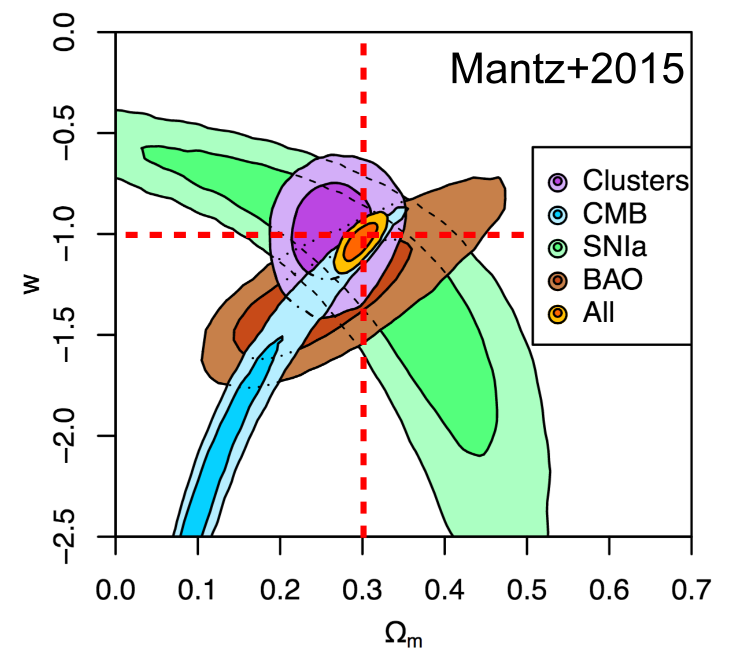


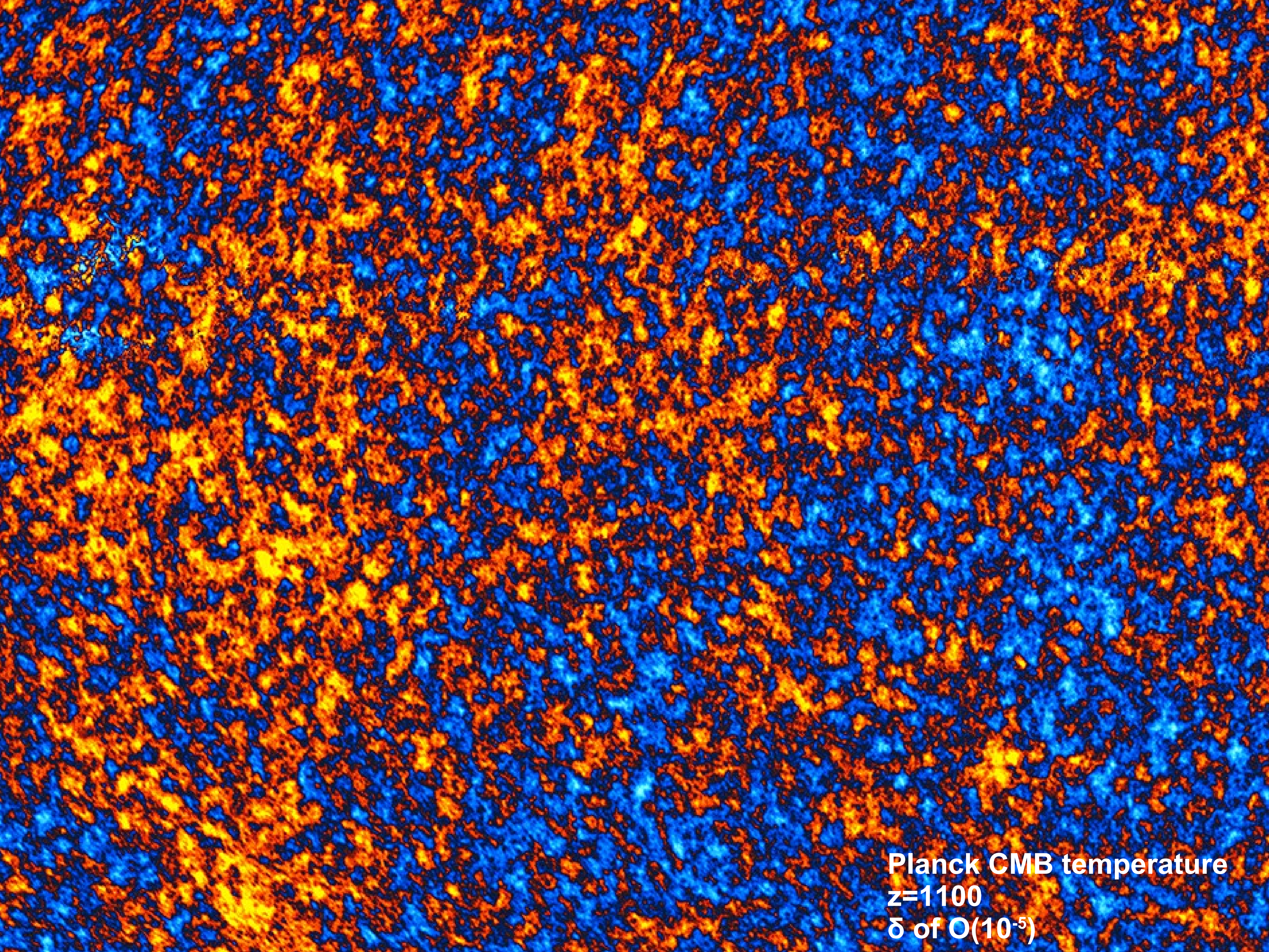
Measurement of late-time structure

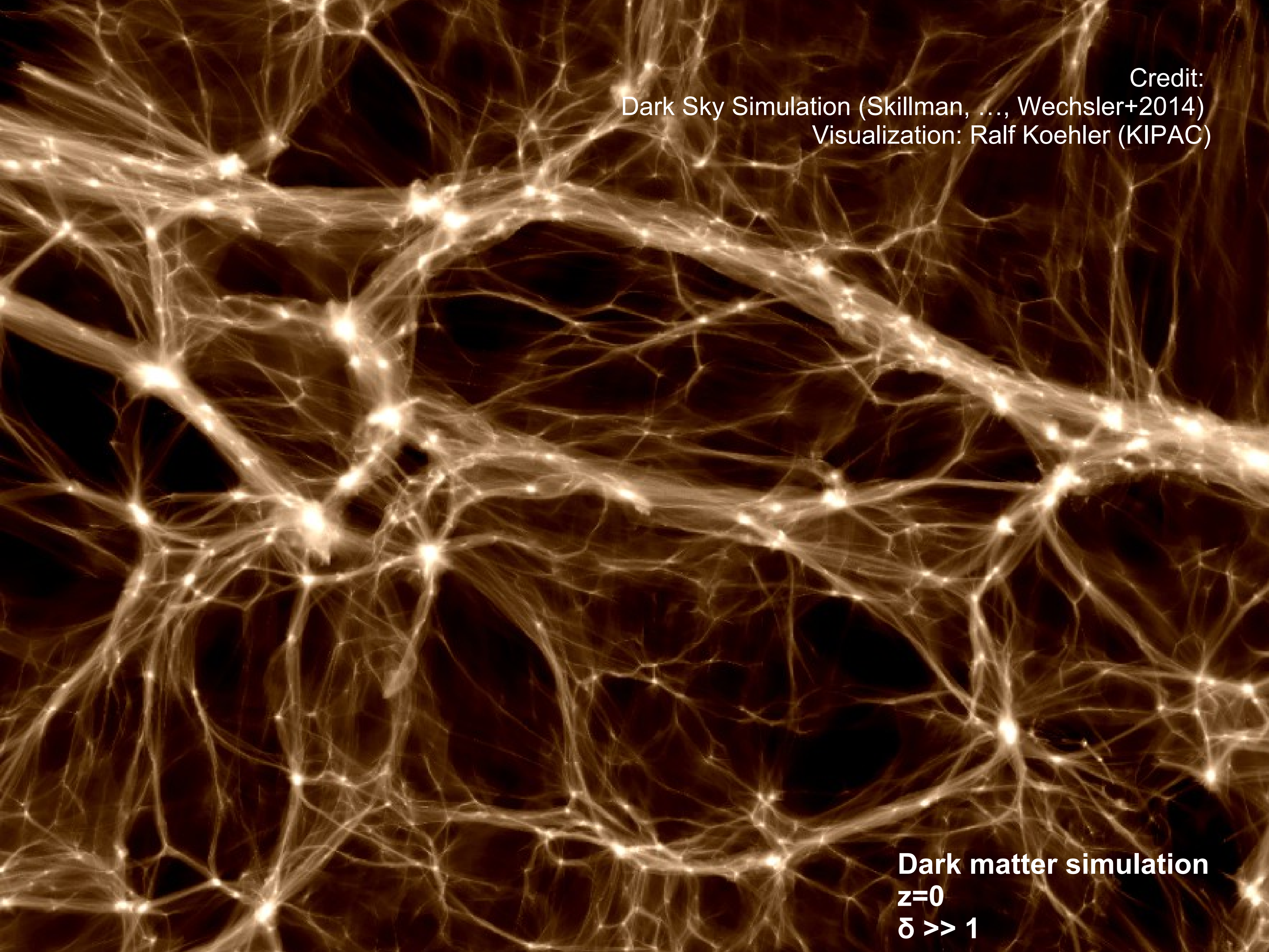
- ✔ RSD

- Galaxy clusters:
  count of clusters as a function of mass and redshift
  consistent with fiducial ΛCDM






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

Measurement of late-time structure

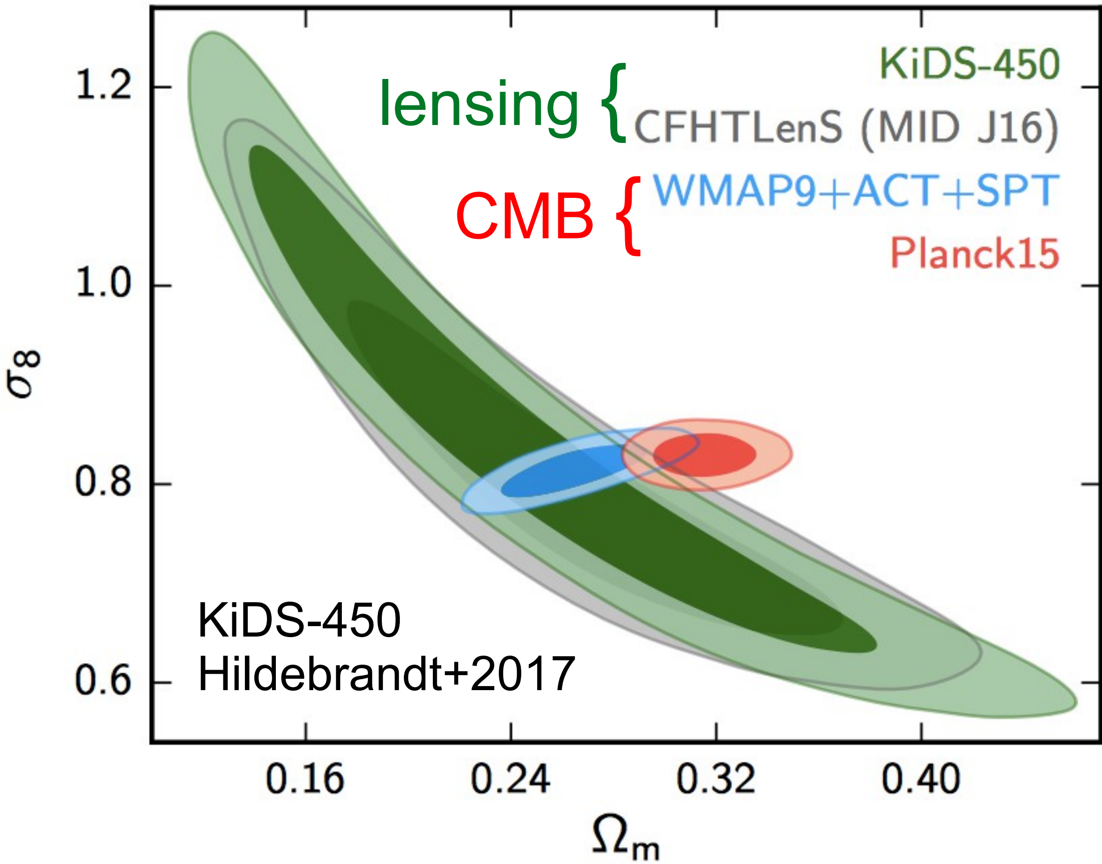
- ✔ RSD
- ✔ Galaxy clusters
- cosmic shear:

  recent studies have claimed 2-3σ offset from Planck CMB in Ω_m-σ_8

  A non-issue?

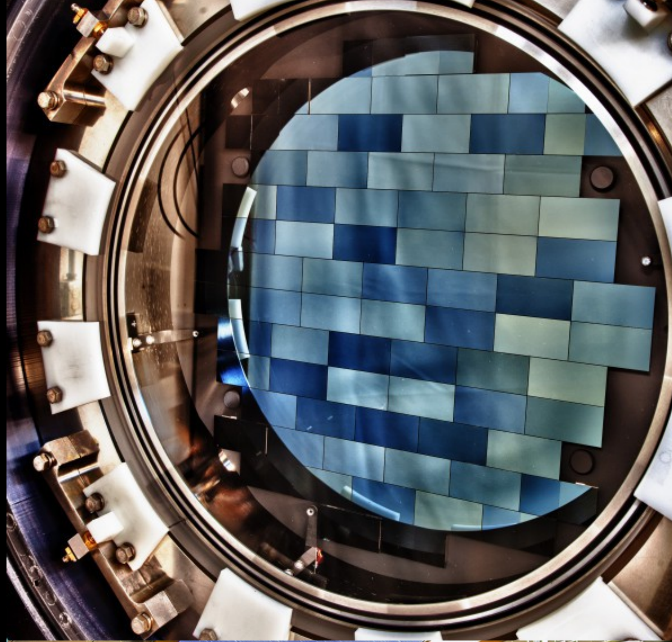
  A crack in ΛCDM?

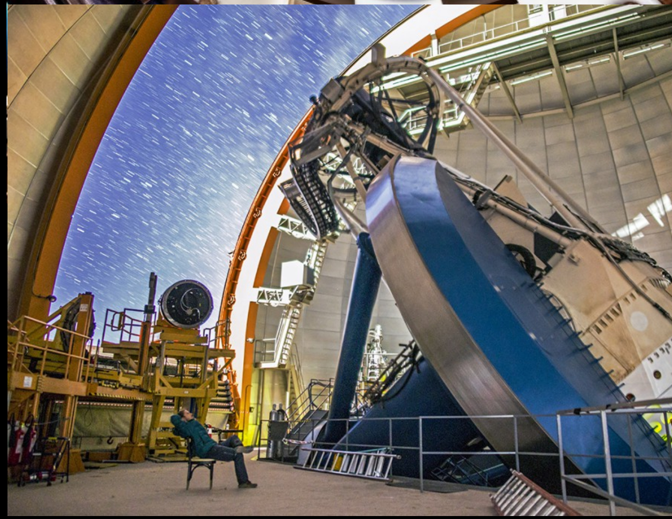
  A systematic error?

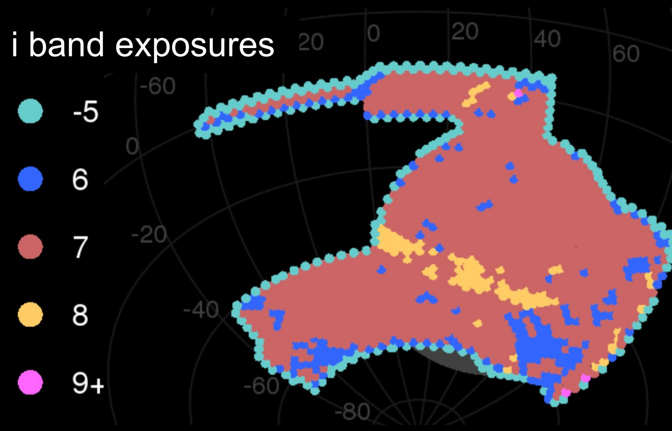


The Dark Energy Survey

- 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)







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NSF

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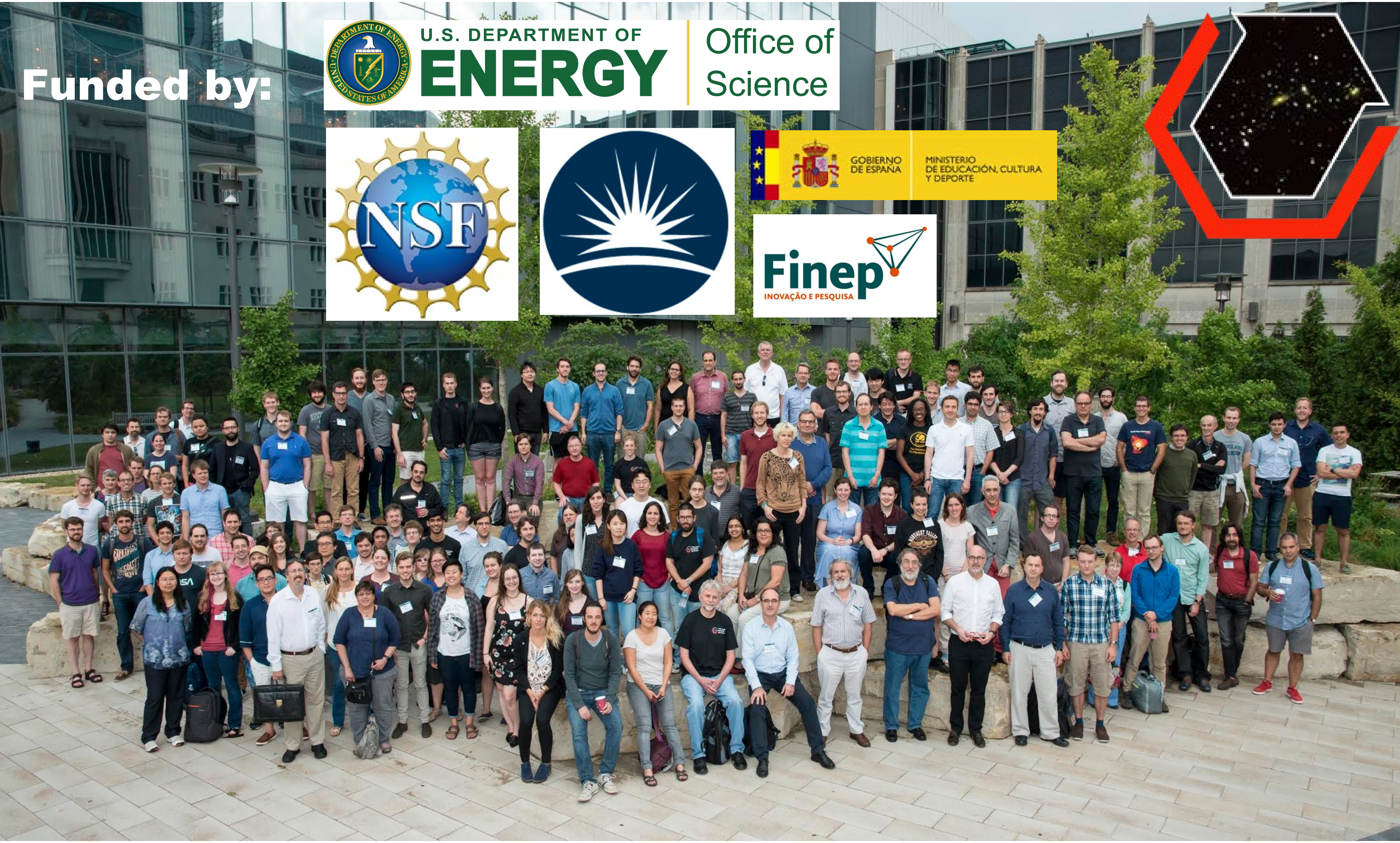
Finep INOVAÇÃO E PESQUISA



Collaborating institutions:

NCSA

THE OHIO STATE UNIVERSITY

ATM

BERKELEY LAB

LMU

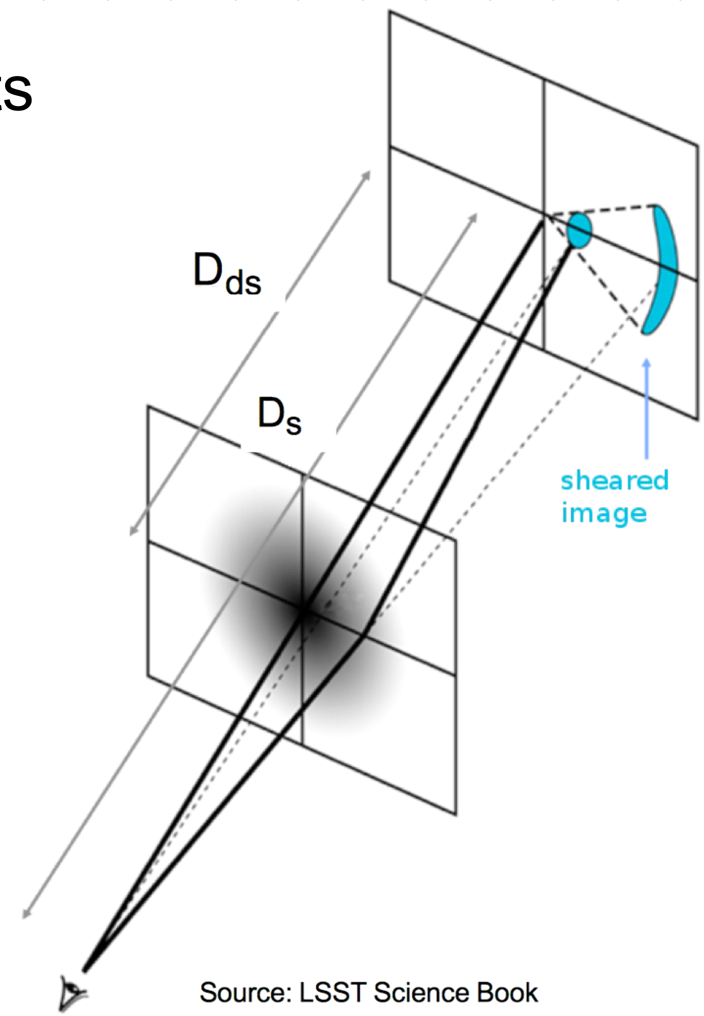
SLAC

ETH Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

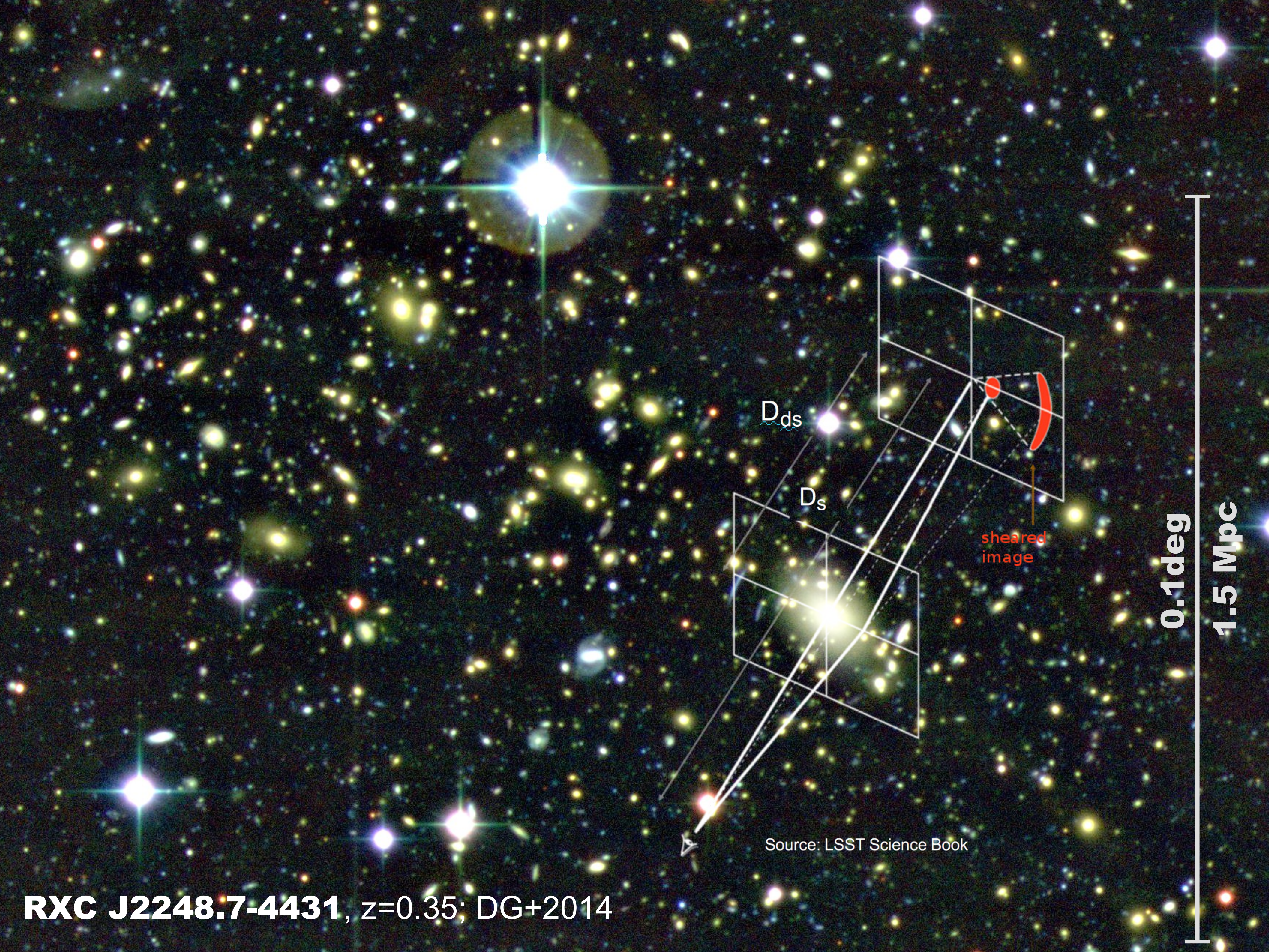
Gravitational lensing

- 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

$$\gamma_t(\theta) = \langle \kappa(\theta') \rangle_{\theta' < \theta} - \kappa(\theta)$$
$$\kappa = \Sigma / \left[\frac{c^2}{4\pi G} \frac{D_s}{D_d D_{ds}} \right]$$

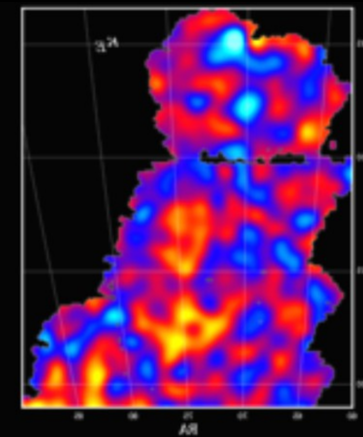


Source: LSST Science Book

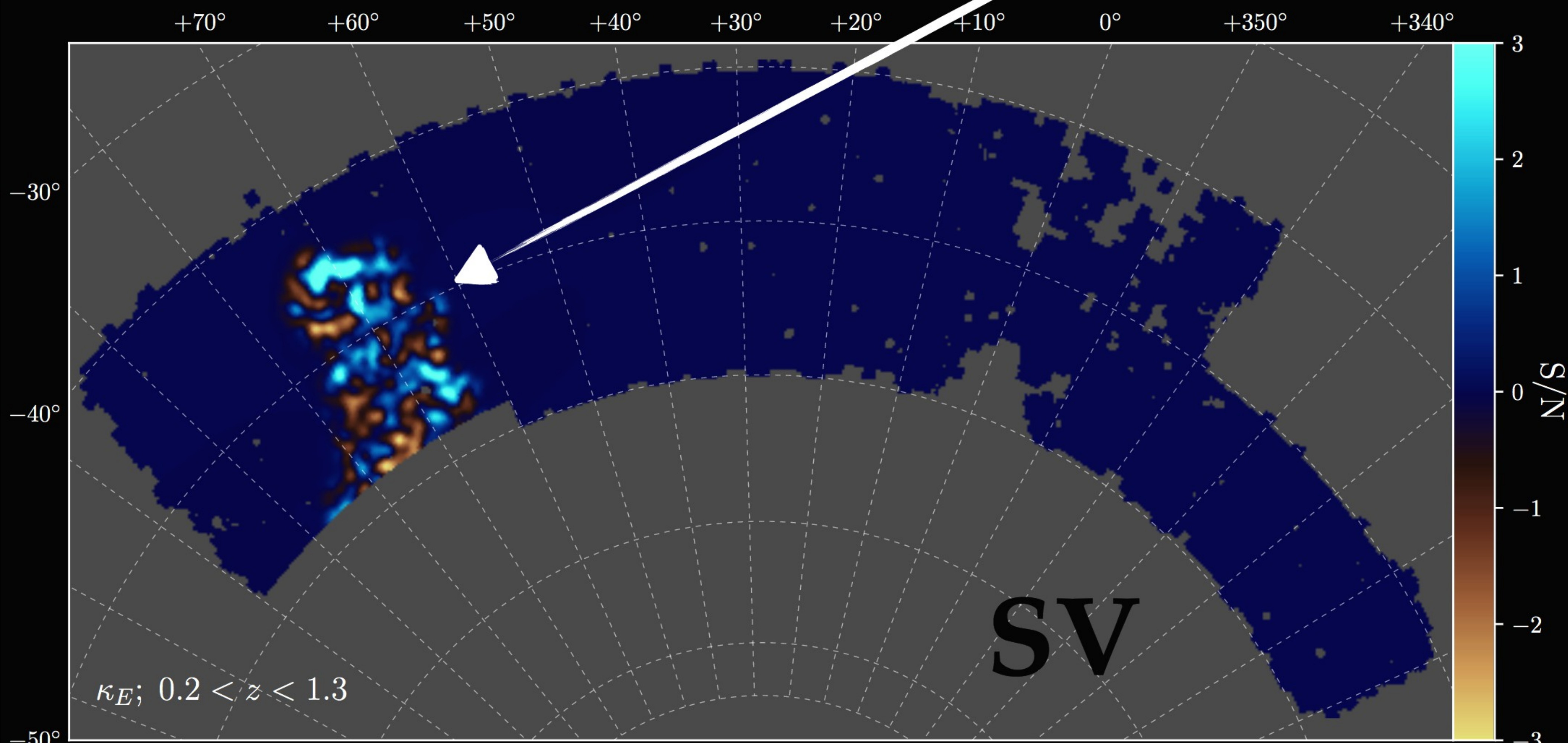


D_{ds}
D_s
sheared image
0.1deg
1.5 Mpc
Source: LSST Science Book
RXC J2248.7-4431, z=0.35; DG+2014

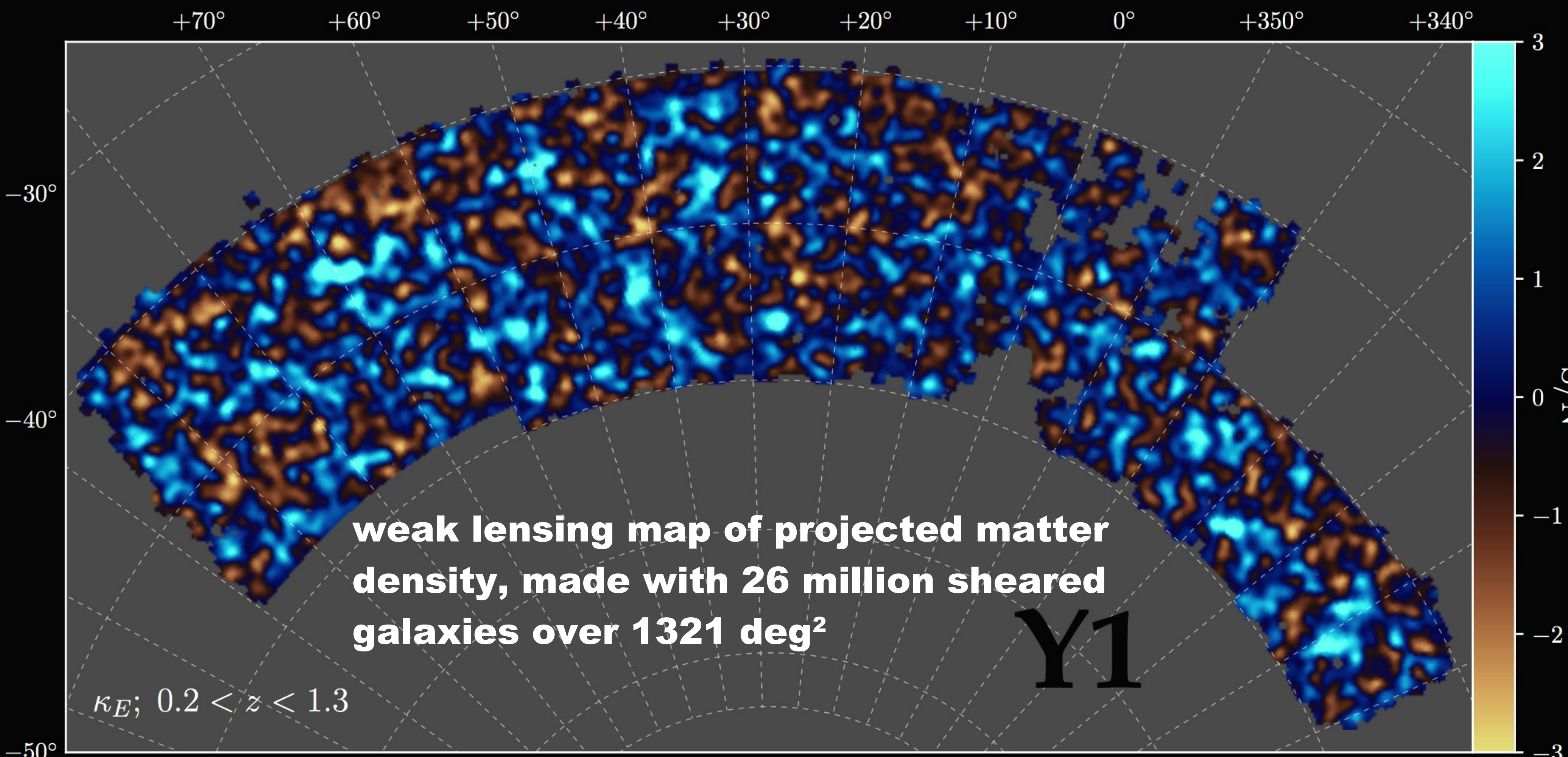
DES SV ...



Chang+;
Vikram+
2016



DES SV … to Y1



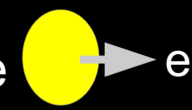
Chang et al. 2017 (arXiv:1708.01535)

With great statistical power comes great systematic responsibility

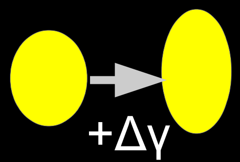
- two independent galaxy shape measurements, including novel metacalibration algorithm

Metacalibration:

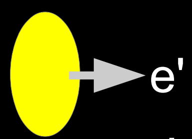
i. apply biased estimator to image



ii. manipulate image to include artificial (shear) signal



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



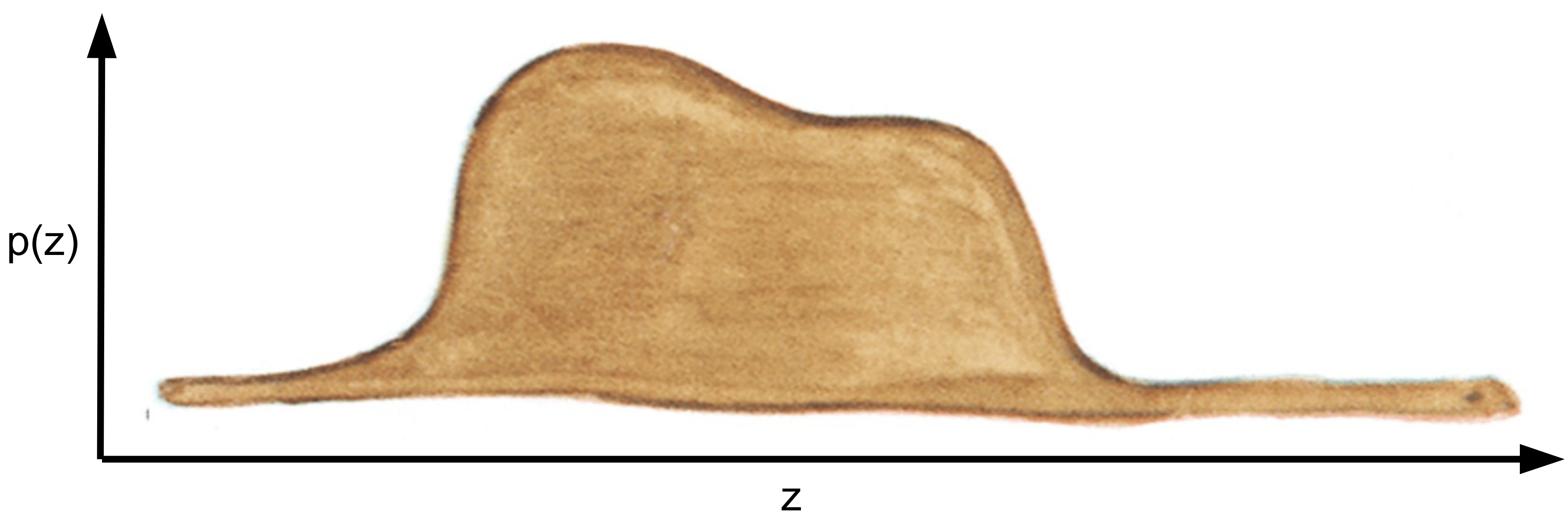
$$\text{response} = \frac{e'-e}{\Delta\gamma}$$

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)

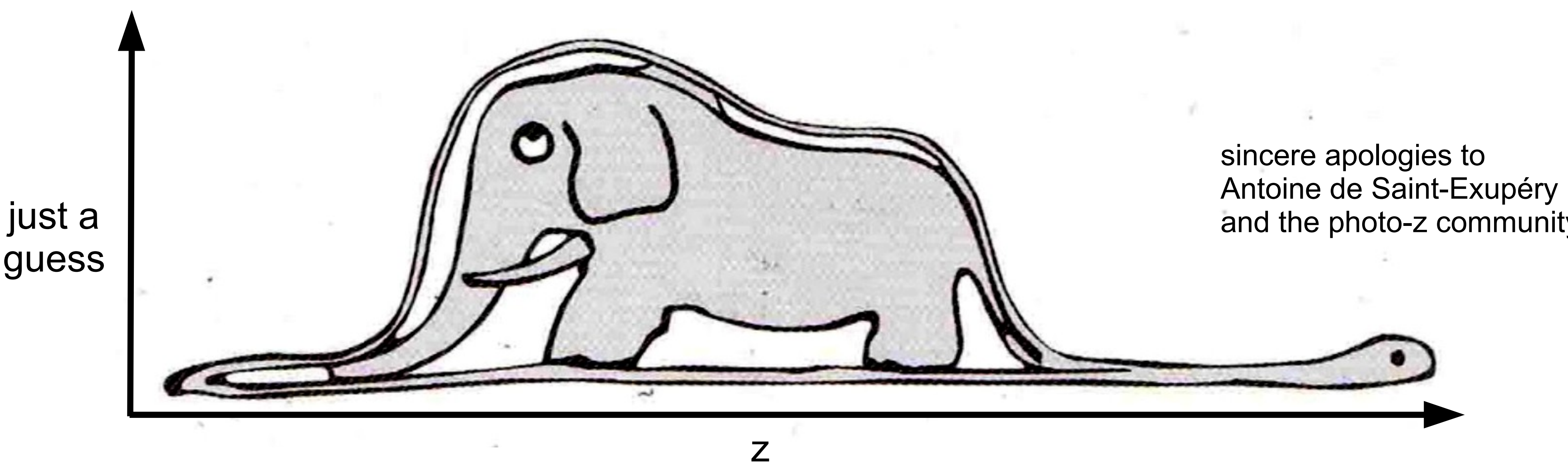
Photometric redshifts detour



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]
- If you are working on photo-z without fixing those things – please reconsider



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Three ways out:

- **Clustering redshifts** – angular correlation with galaxies at known z $\propto$ n(z)
- **Fully representative samples + unbiased matching** [Masters, Capac+2015 for spec-z, COSMOS/Alhambra/J-PAS/PAU for photo-z, DG+2017 for a matching method]
- **Bayesian hierarchical scheme** of priors+templates+n(z) [Leistedt+2016]

Simplification: for DES Y1 and current errors on <z>, n(z) shape error subdominant

Calibration of DES photo-z

COSMOS photo-z (Hoyle, DG+)

- For each source galaxy, pick closest matching COSMOS galaxy (χ^2 of griz, size)
- Run BPZ on COSMOS galaxy to assign to bin
- Use mean $z_{COSMOS30}$ of bin as estimate of <z> of DES bin
- Uncertainty from cosmic variance + systematics of matching (sims), flux calibration, size match (data)
- ~0.02 mean z uncertainty

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- Uncertainty from cosmic variance + systematics of matching (sims), flux calibration, size match (data)
- ~0.02 mean z uncertainty

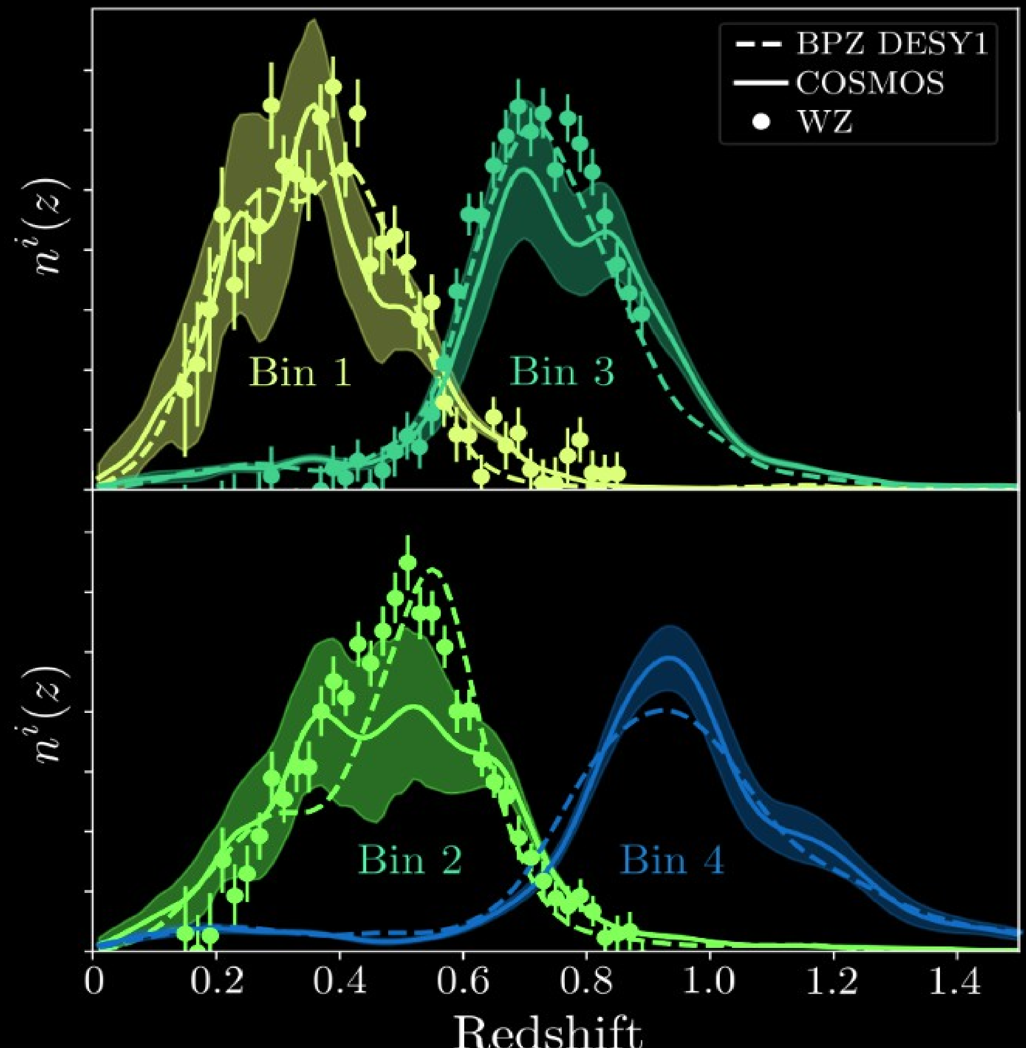
Clustering (Gatti, Vielzeuf+; Davis+)

- Measure clustering of lensing sources with redMaGiC LRGs as function of their redshift
- Shift BPZ estimate of source n(z) to match these signals → <z> of DES bin
- Uncertainty from simulations: dominated by z-evolution of galaxy bias and n(z) shape mismatch
- ~0.02 mean z uncertainty

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

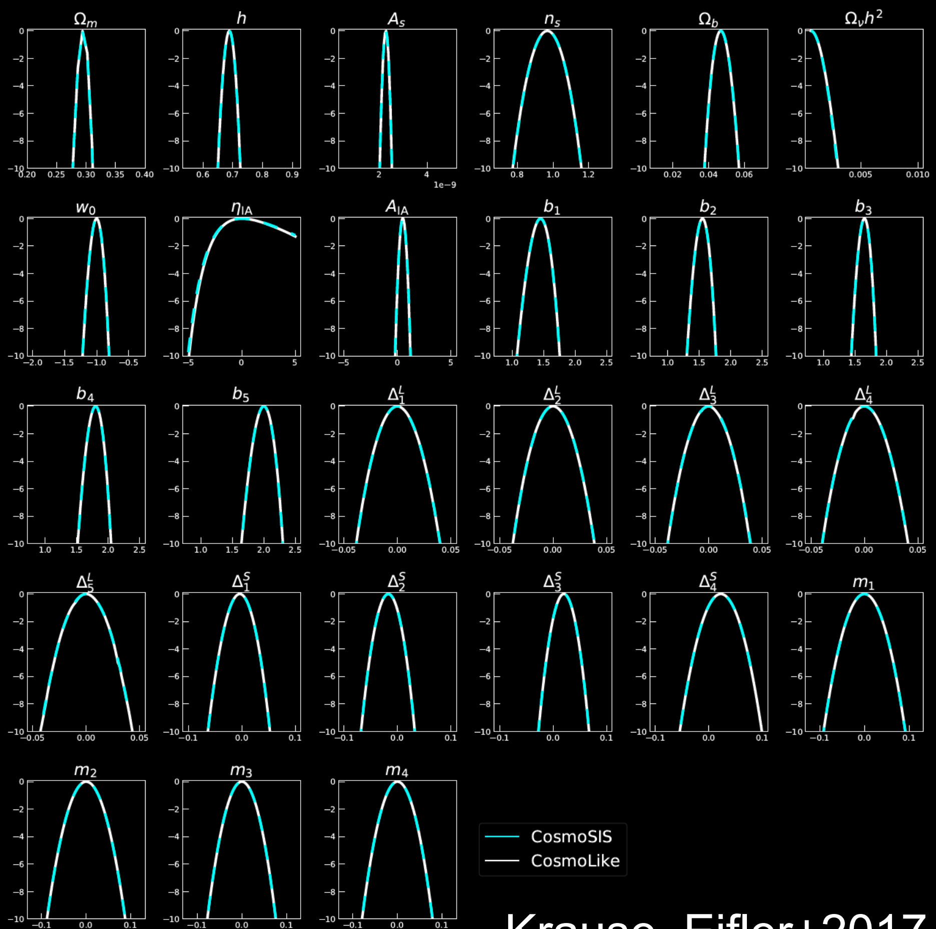
COSMOS + clustering methods agree, ~0.015 joint errors!



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

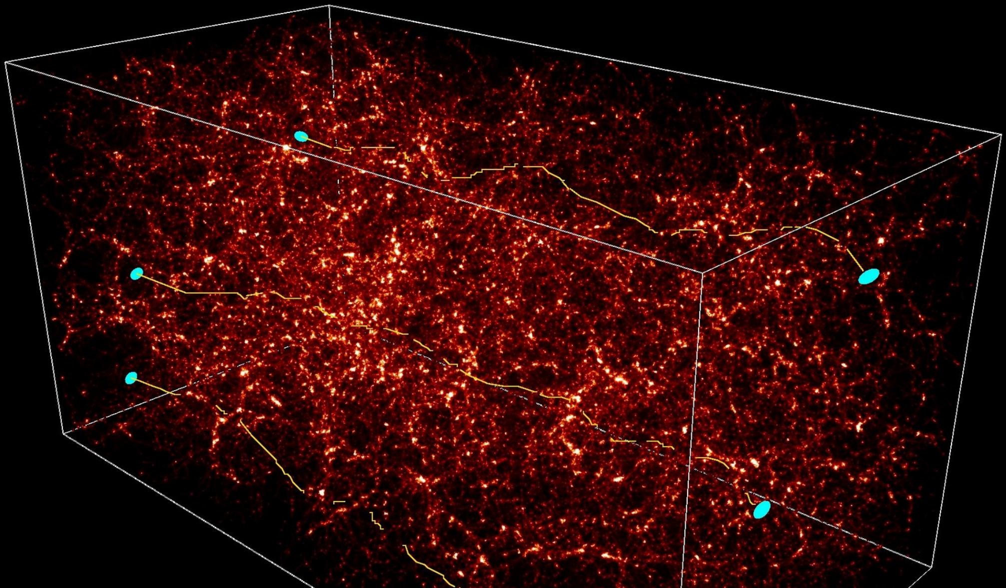


Krause, Eifler+2017

Measurements: cosmic shear

Troxel+ (1708.01538)

- Light from distant galaxies passes the same foreground structure

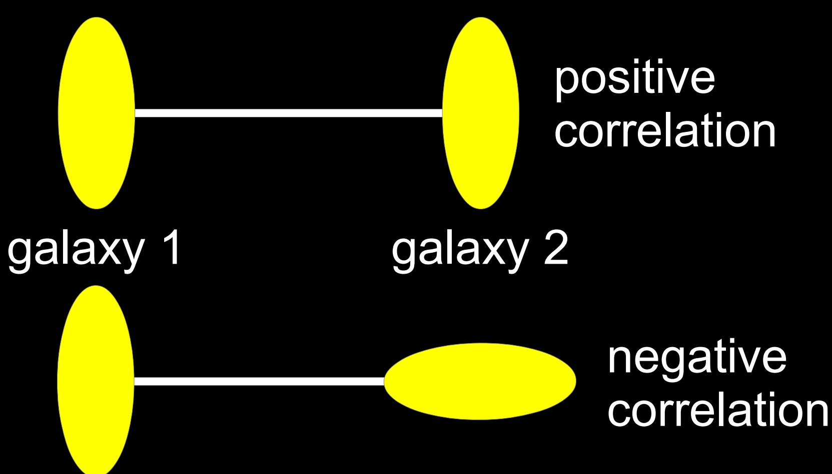


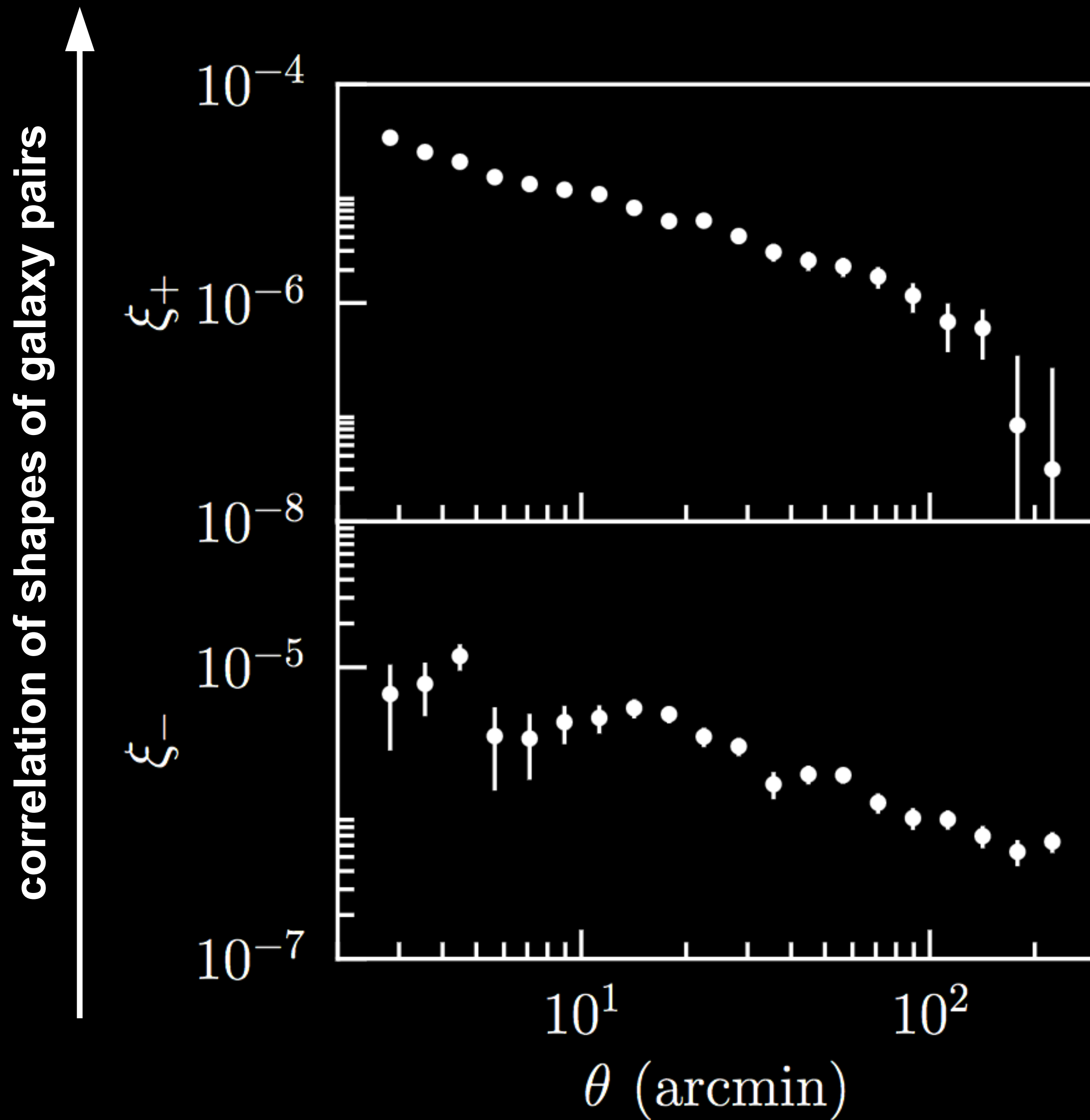
Credit: S. Colombi / IAP

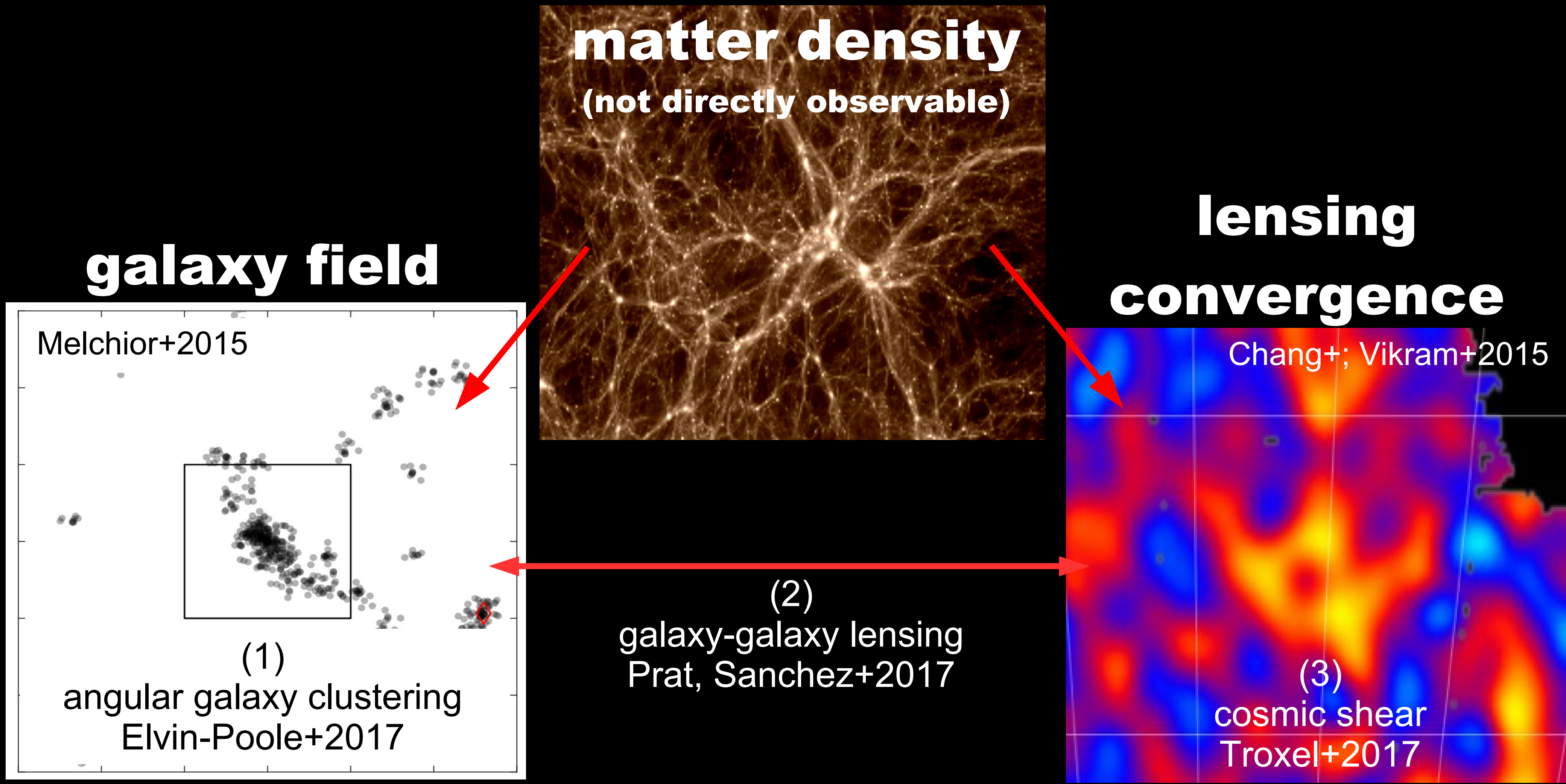
Measurements: cosmic shear

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







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

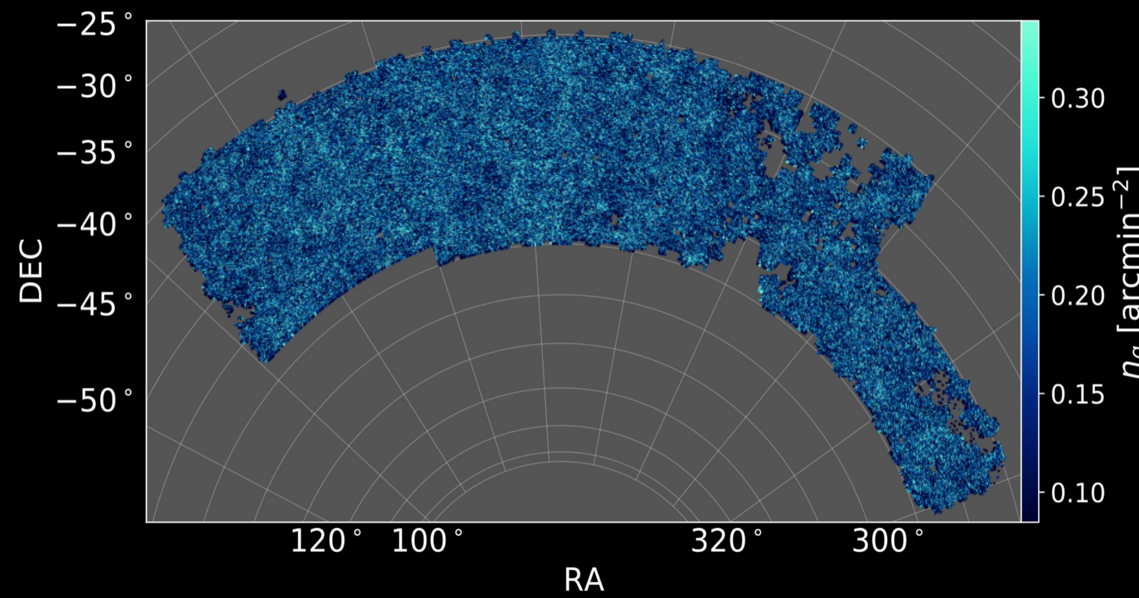
[Hu&Jain 2004, Huterer+2006, Bernstein+2009, Joachimi&Bridle 2010, van Uitert+2017, Joudaki+2017]

largest individual data sets and joint constraints from these three probes for the first time: DES Collaboration+2017

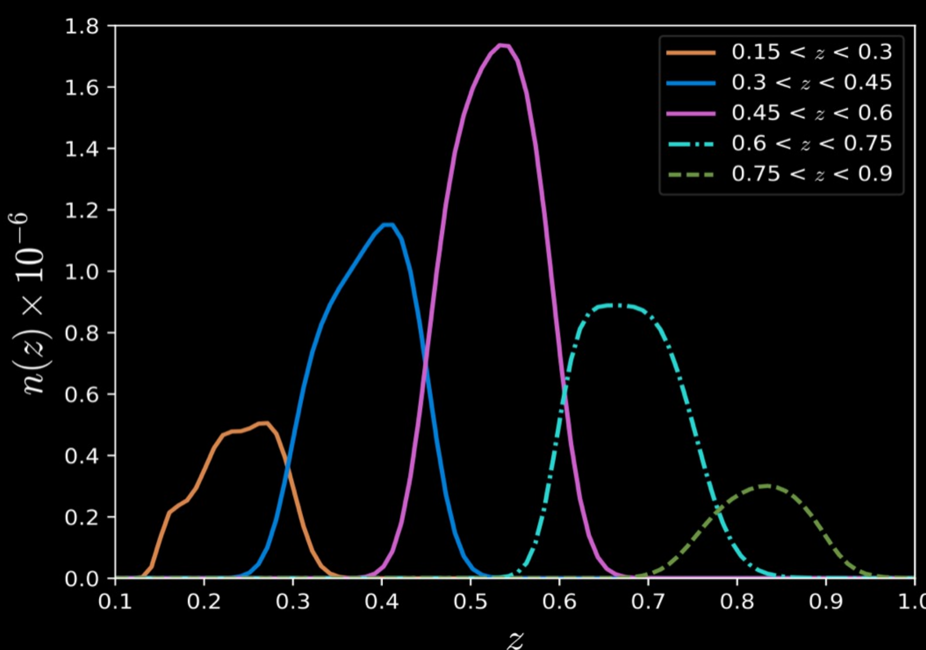
DES Year 1 Lens Galaxy Sample: redMaGiC

- 660,000 redMaGiC (bright, red) galaxies with excellent redshifts

  Rozo, Rykoff+2016



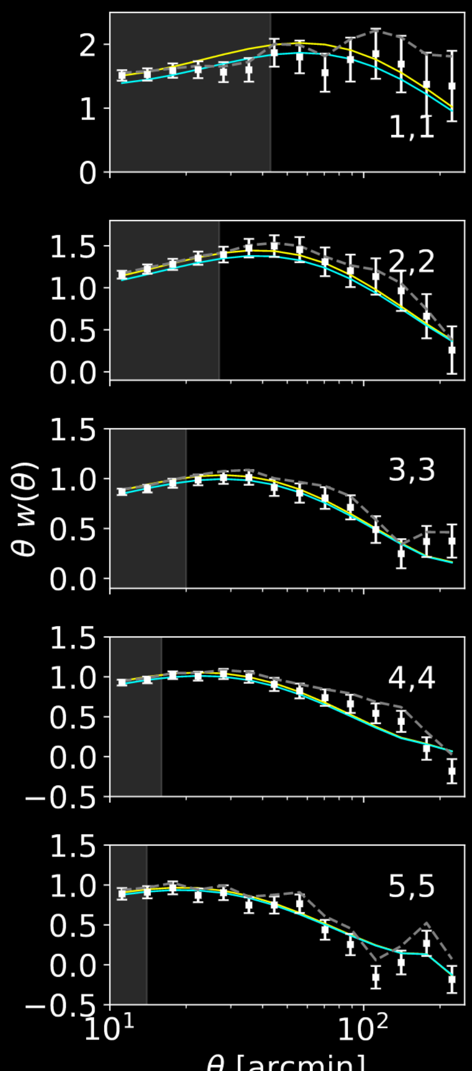
- Measure angular clustering in 5 redshift bins
- Use as lenses for galaxy-galaxy lensing



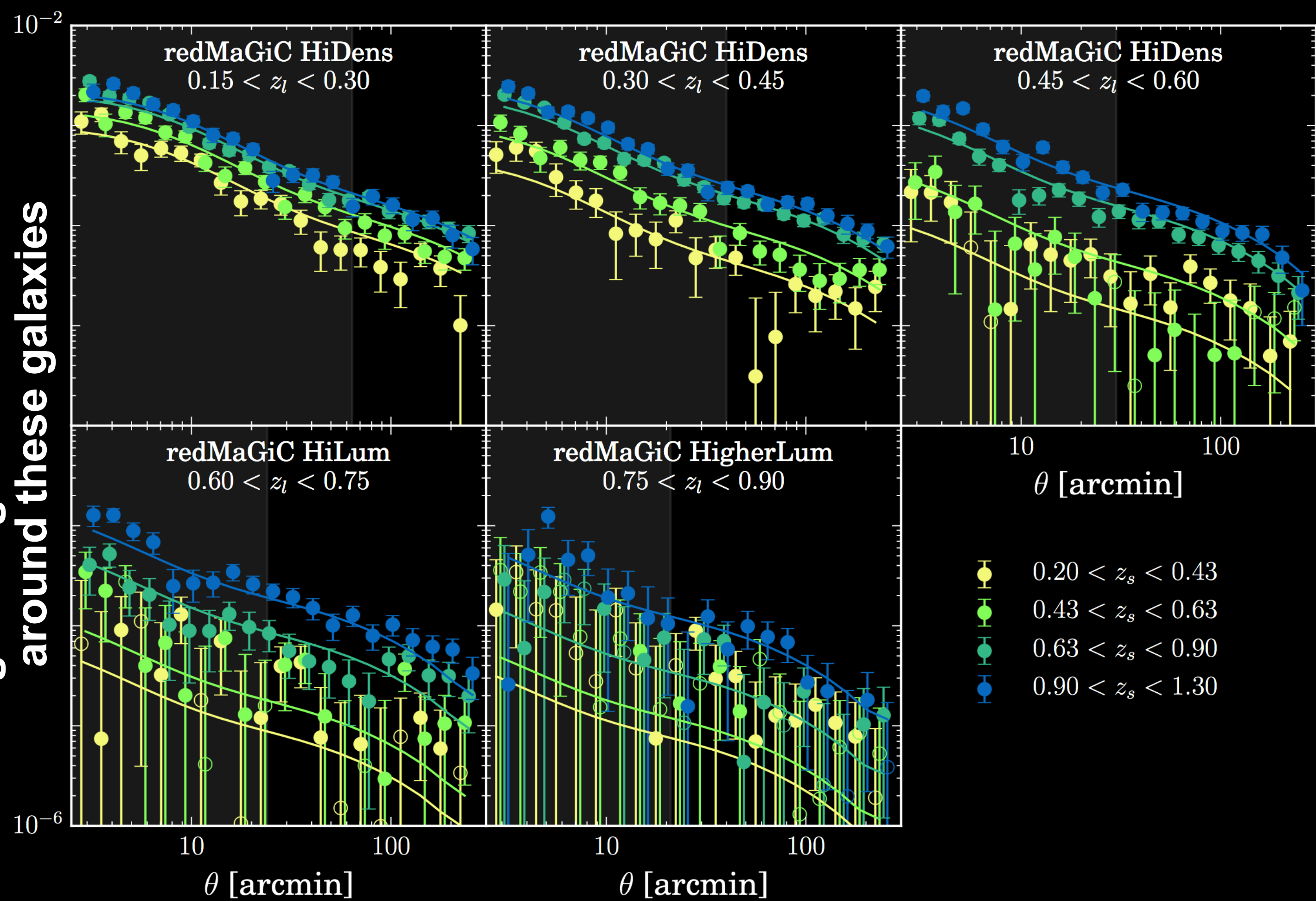
Measurements: galaxy clustering and galaxy-galaxy lensing

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

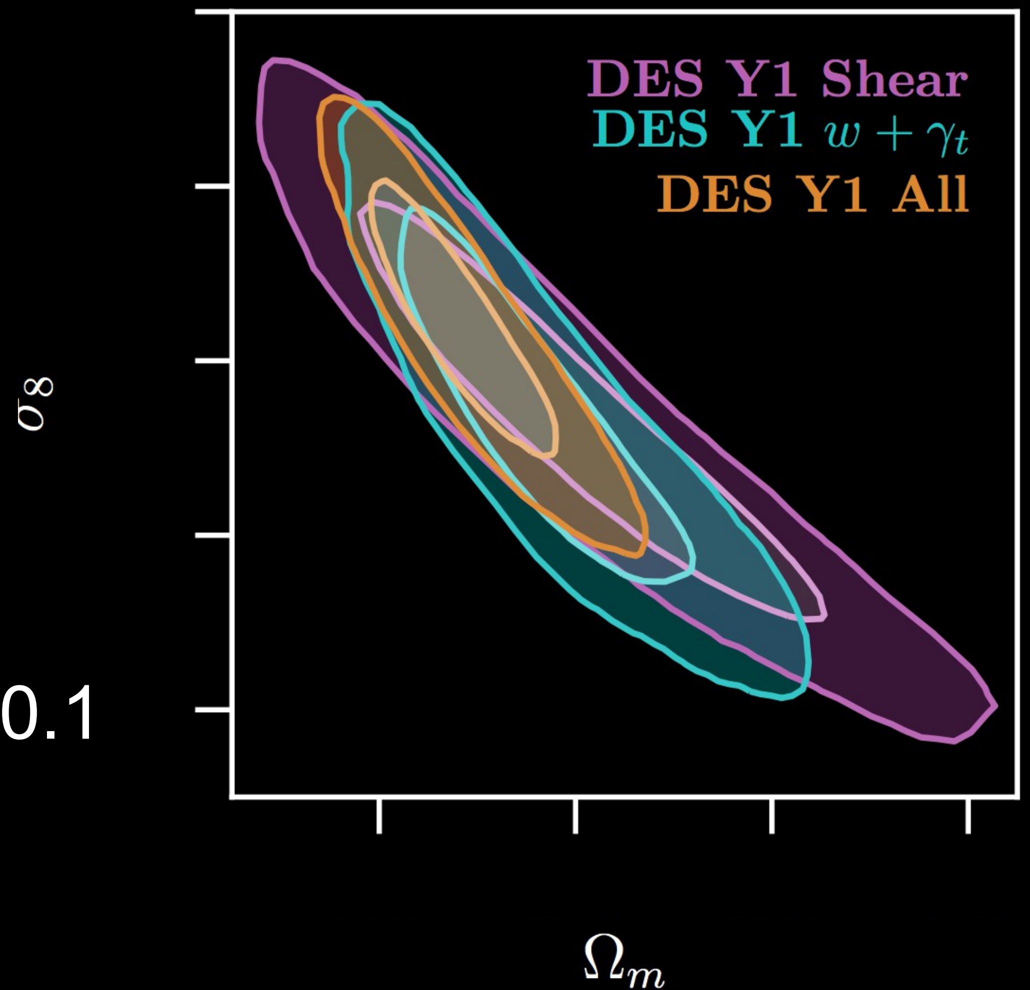


Consistency of the individual constraints in ΛCDM

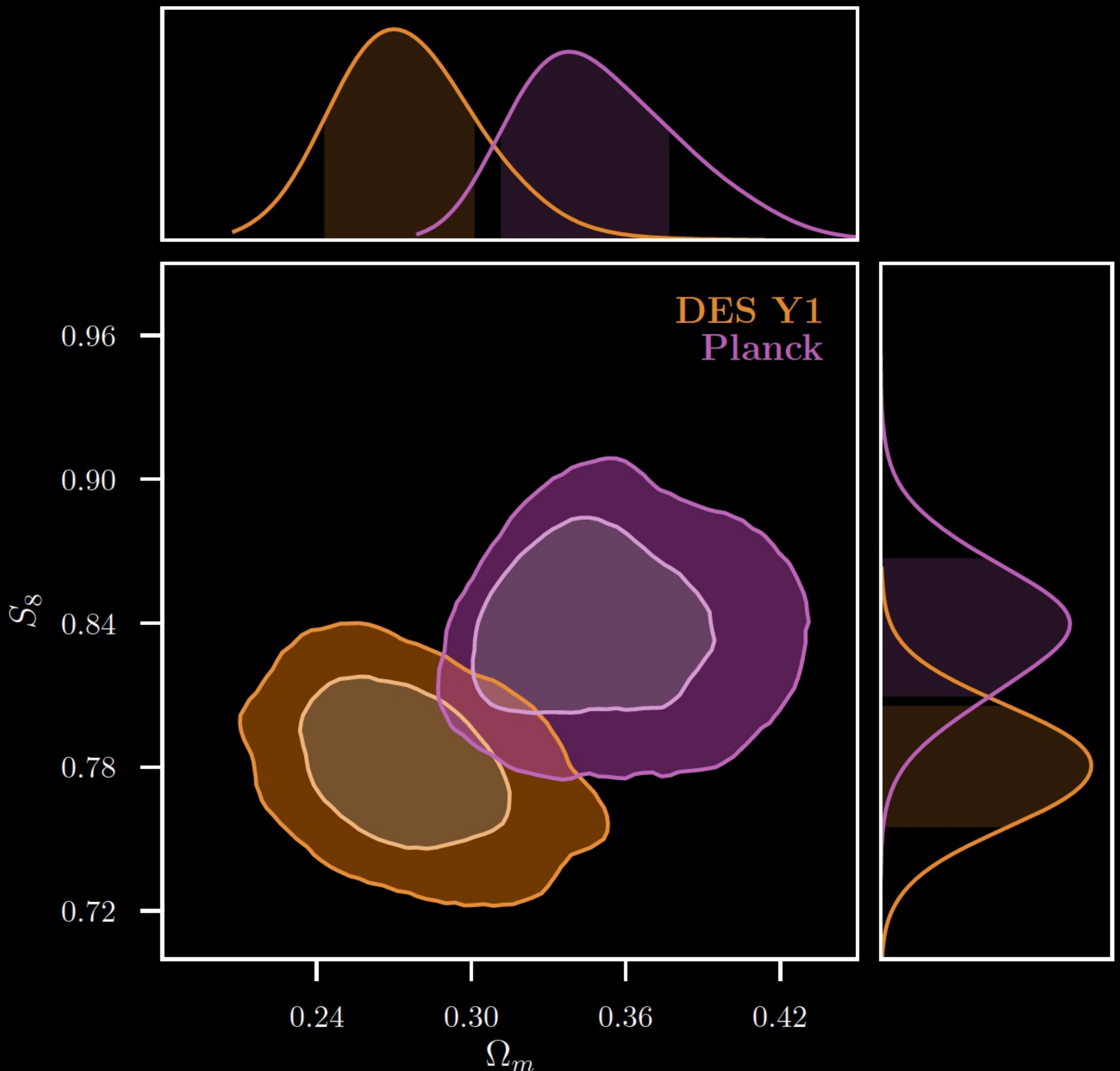
- Cosmic shear and redMaGiC clustering + lensing yield consistent cosmological constraints

- 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



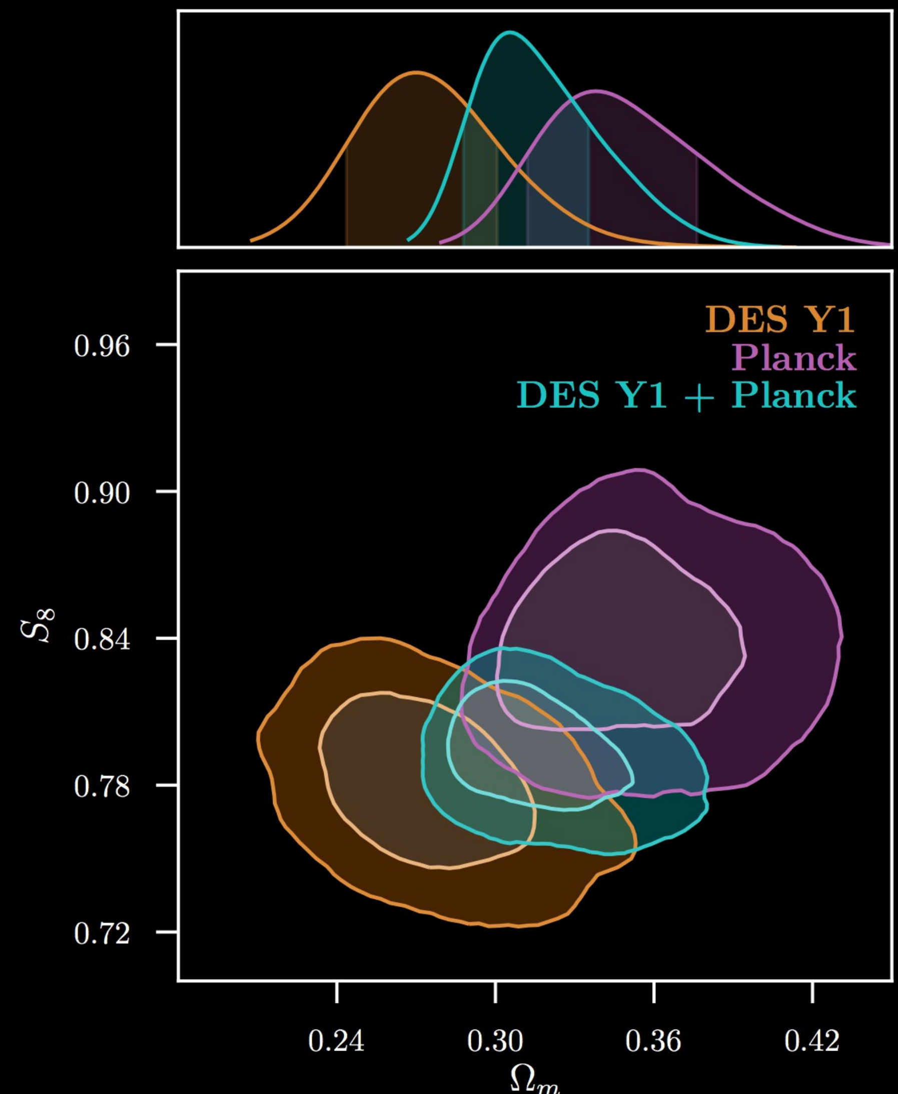
- passing 11 other null tests, we unblind



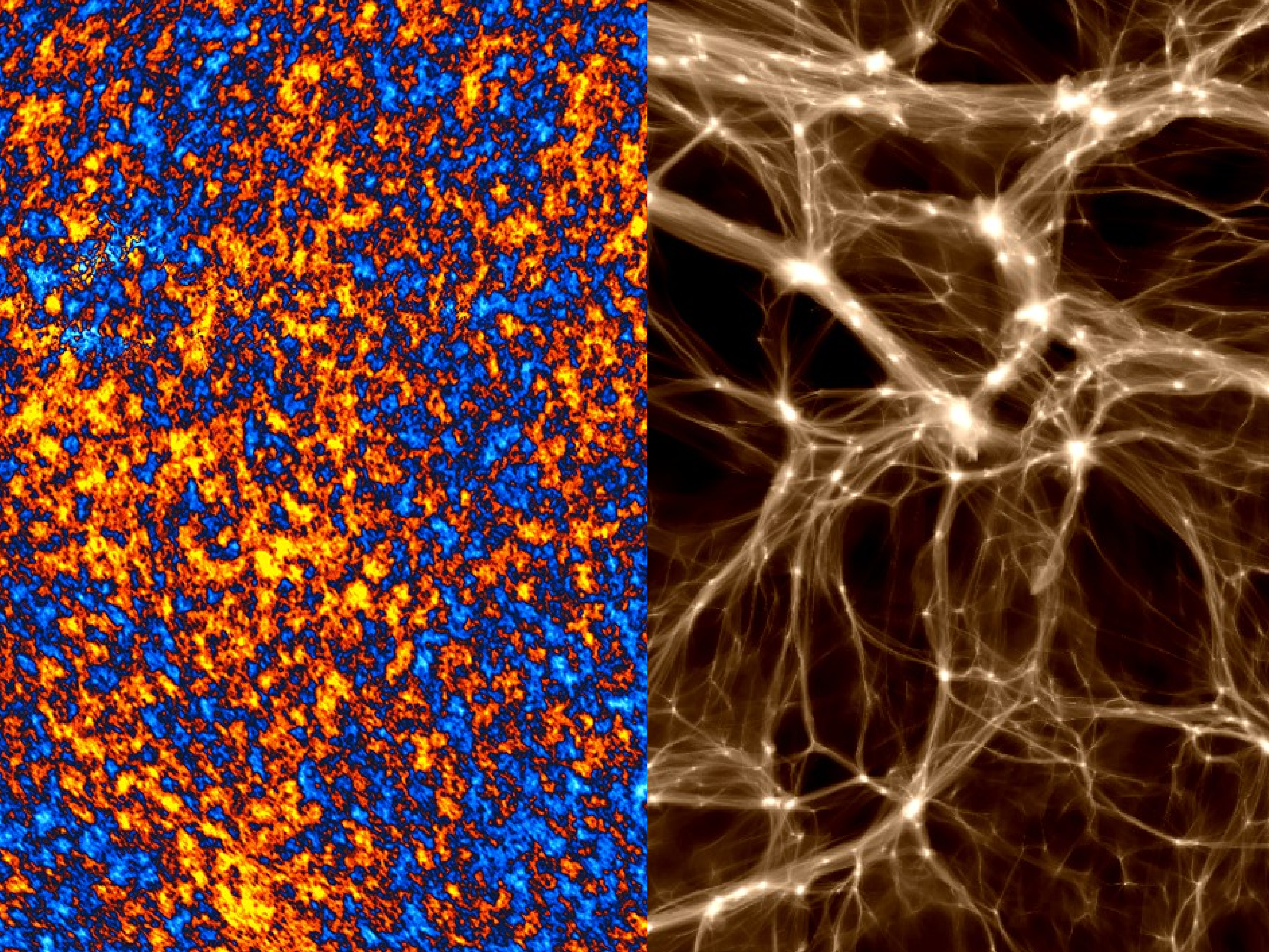
DES Y1
Planck
0.96
0.90
0.84
0.78
0.72
S_8
0.24
0.30
0.36
0.42
Ω_m

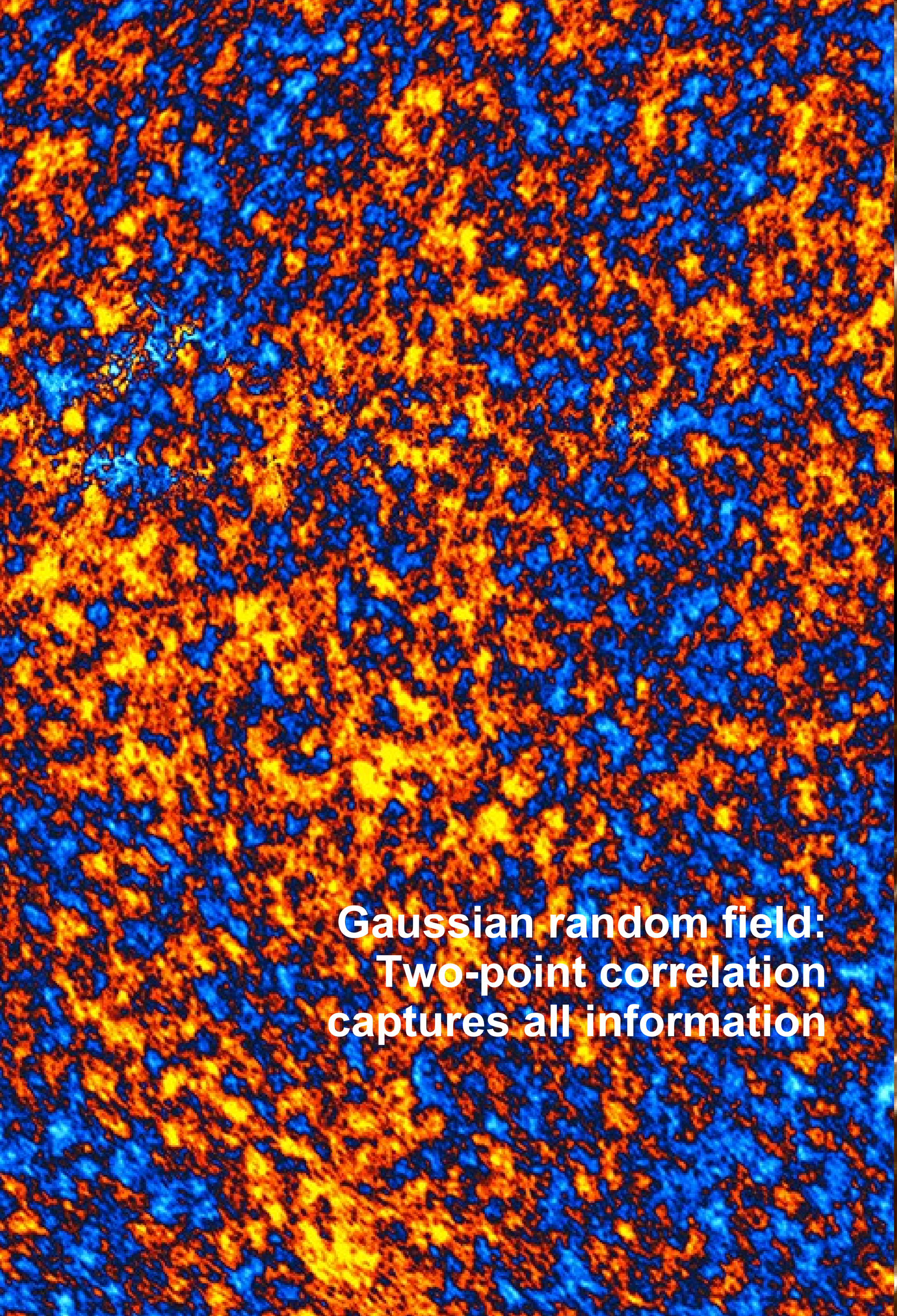
Key result: Consistency of late Universe with Planck in ΛCDM

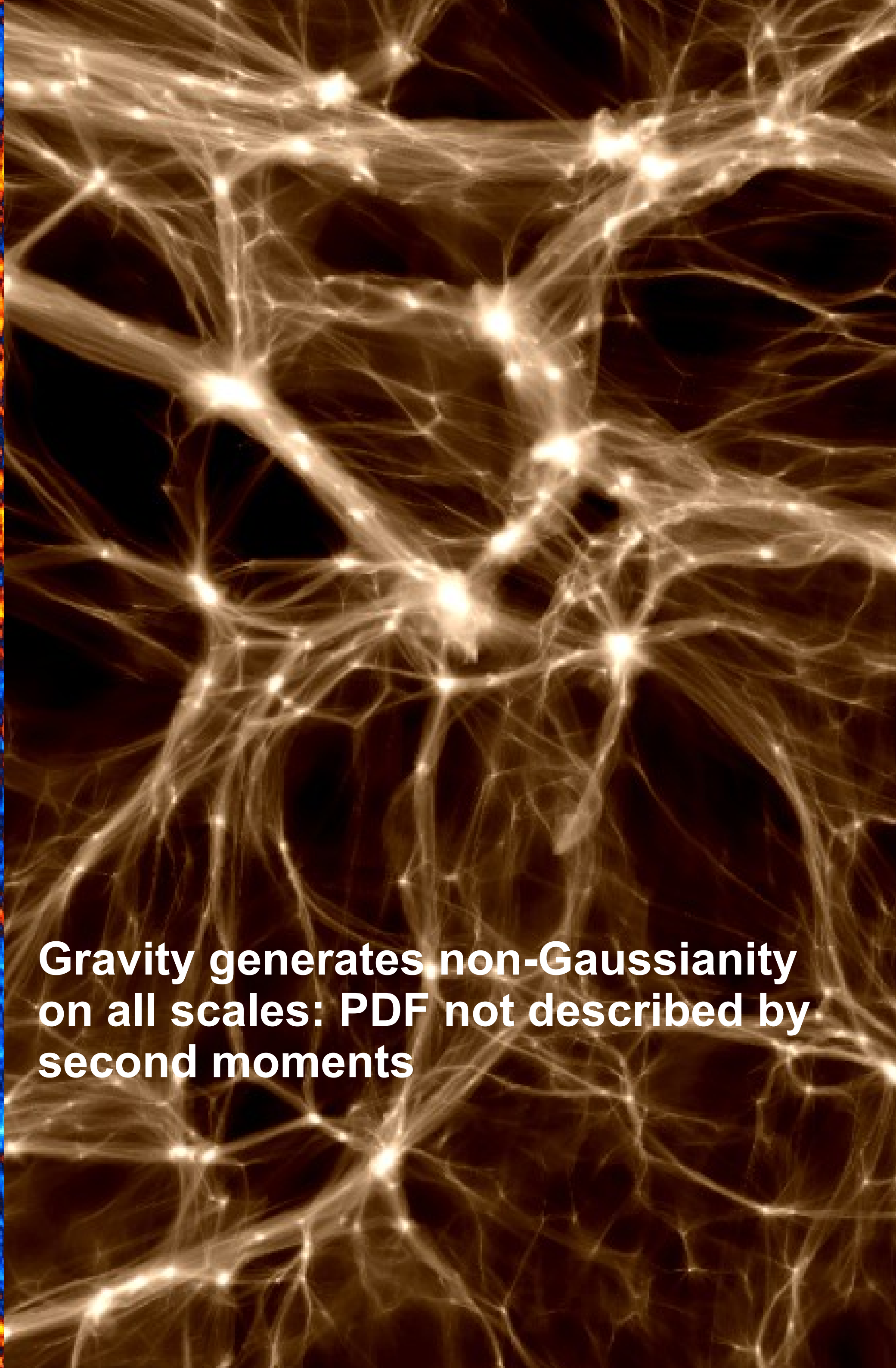
- DES and Planck constrain matter density and S_8 with equal strength
- Difference in central values 1-2σ in the same direction as earlier lensing results
- Bayes Factor 4.2 – no evidence for inconsistency
- Combination with Planck + BAO + SNe yields



$$\Omega_m = 0.301^{+0.006}_{-0.008} \quad S_8 = 0.799^{+0.014}_{-0.009} \quad w = -1.00^{+0.04}_{-0.05}$$

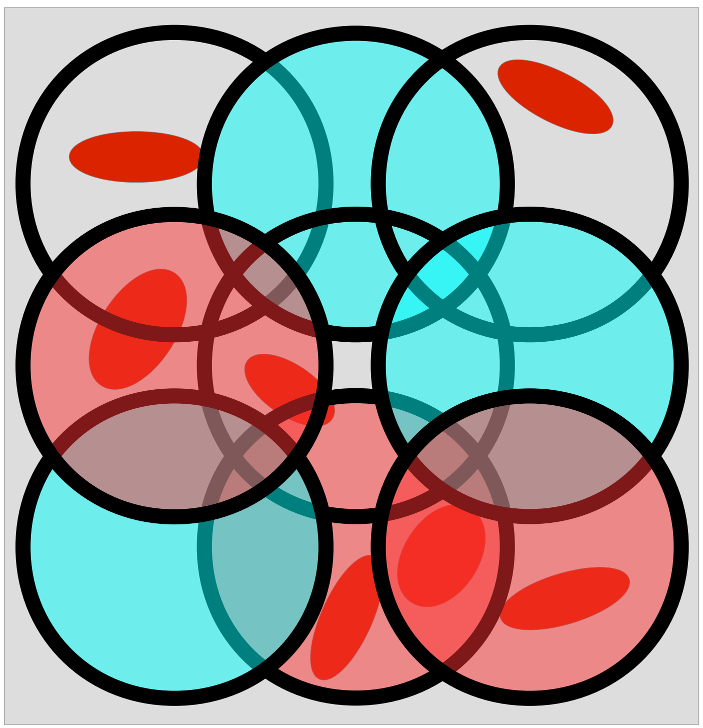


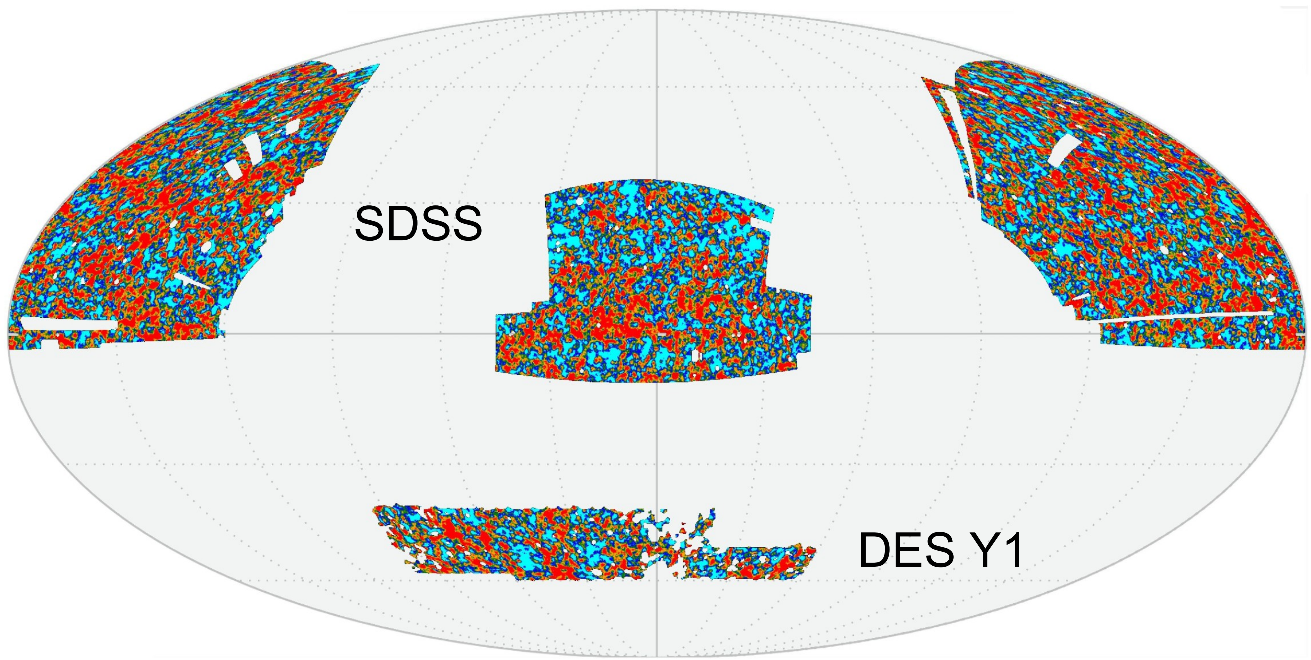

Gaussian random field:
Two-point correlation
captures all information


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

Going beyond two-point functions: Density PDF from lensing + counts in cells

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

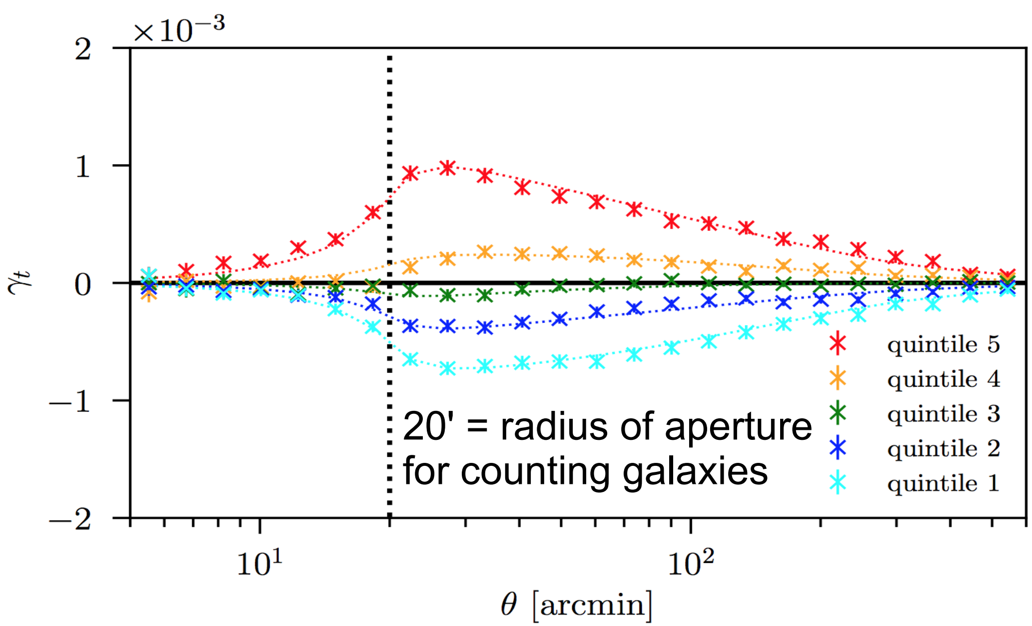


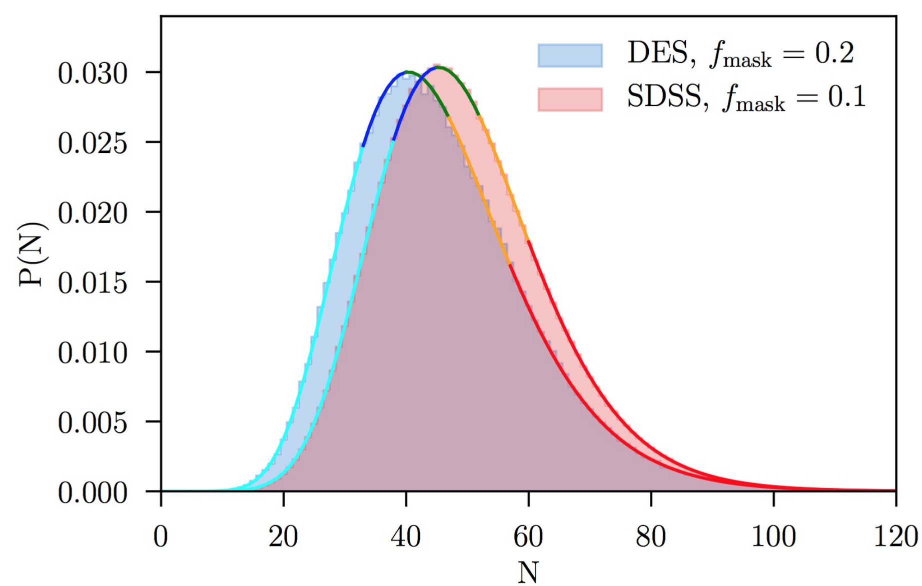


DG+ in prep. / preliminary
cf. arXiv:1507.05090

Going beyond two-point functions:
Density PDF from lensing + 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!





DG+ in prep. / preliminary

Going beyond two-point functions:
Density PDF from lensing + counts in cells

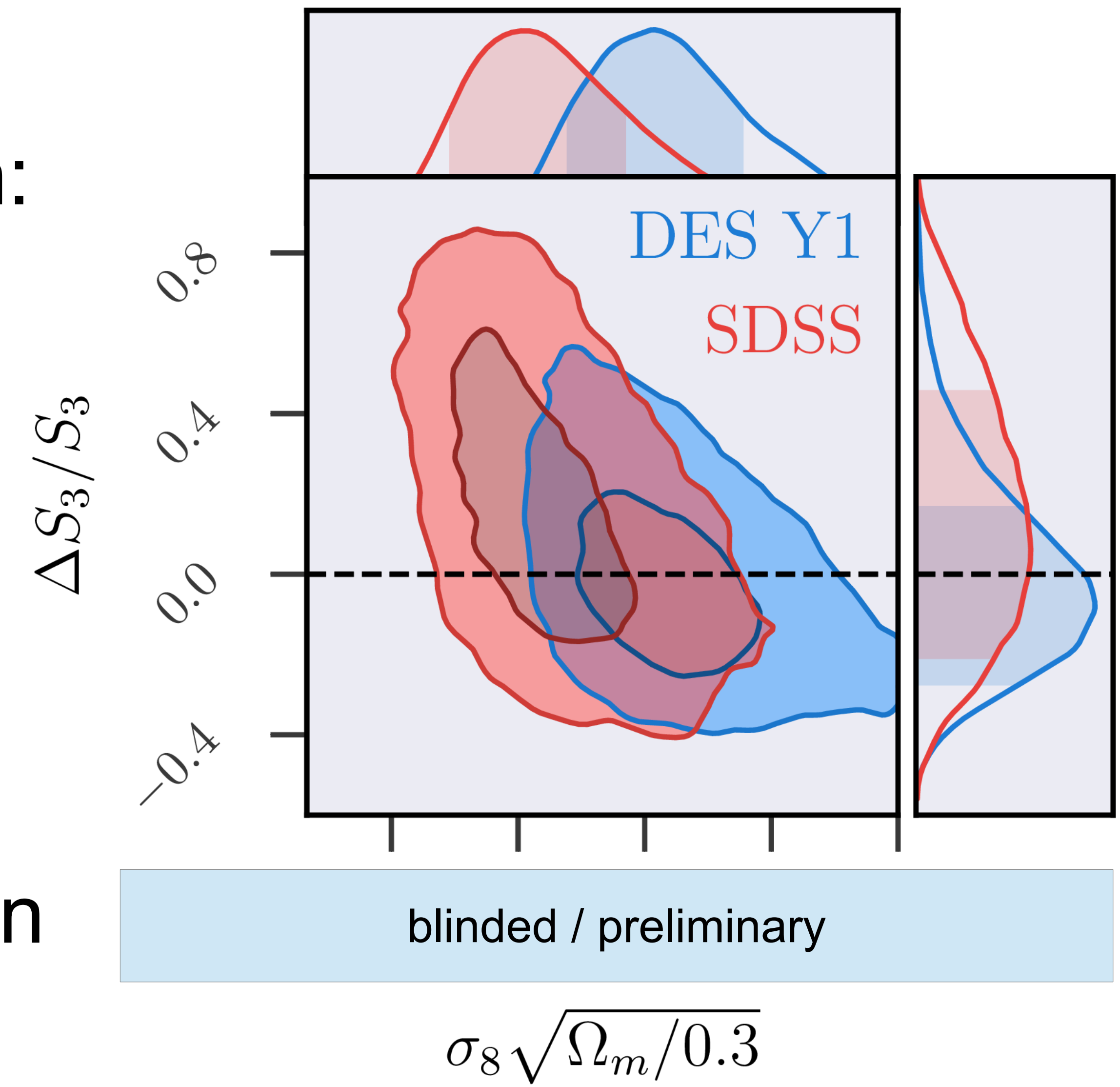
- Step 1: split lines of sight into quintiles of redMaGiC galaxy count N
- Step 2: measure shear around and mean counts in quintiles
- Step 3: model these signals via joint PDF of matter and galaxy density

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

perturbation theory model: Friedrich, DG+ in prep.

Lensing + counts in cells: skewness of matter PDF

- 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



DG+ in prep

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 in the direction of other lensing studies
  - Precise joint measurements close to Ω_m=0.30, σ_8=0.80, w=-1.0
- Different statistics (matter PDF!) and much more data (Y3!) soon
- Even the dark side (systematics, studies of underdensities) of lensing looks rather bright!