# Cosmology with DES lensing beyond the power spectrum

**Daniel Gruen**, Einstein Fellow @ Stanford / SLAC
on behalf of the Dark Energy Survey Collaboration

Kavli IPMU Tokyo, 2018-11-15

# Agenda

- Introduction

- Lensing as a high-precision survey science
  - separate discussion on photo-z tomorrow!

- DES Y1 cosmology results
  - two-point functions & joint probes
  - matter/galaxy density PDF
  - clusters of galaxies

more non-Gaussian
more information
more complex model

Questions welcome!

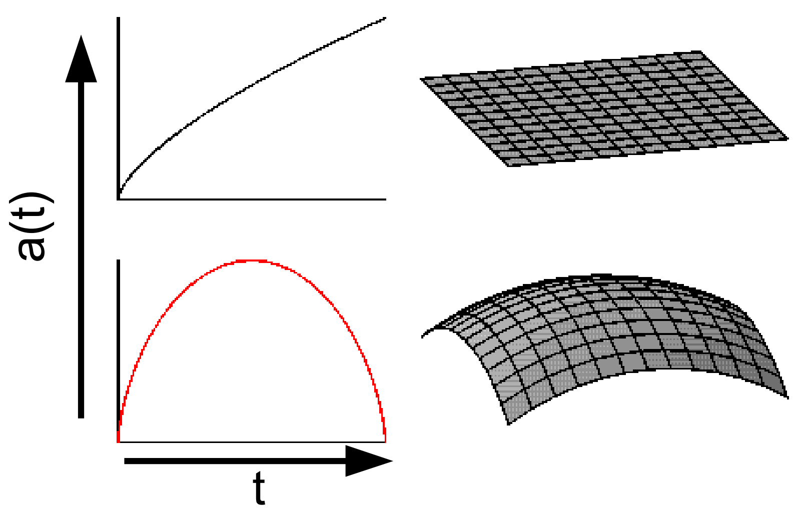
# What goes up must come down?

- 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



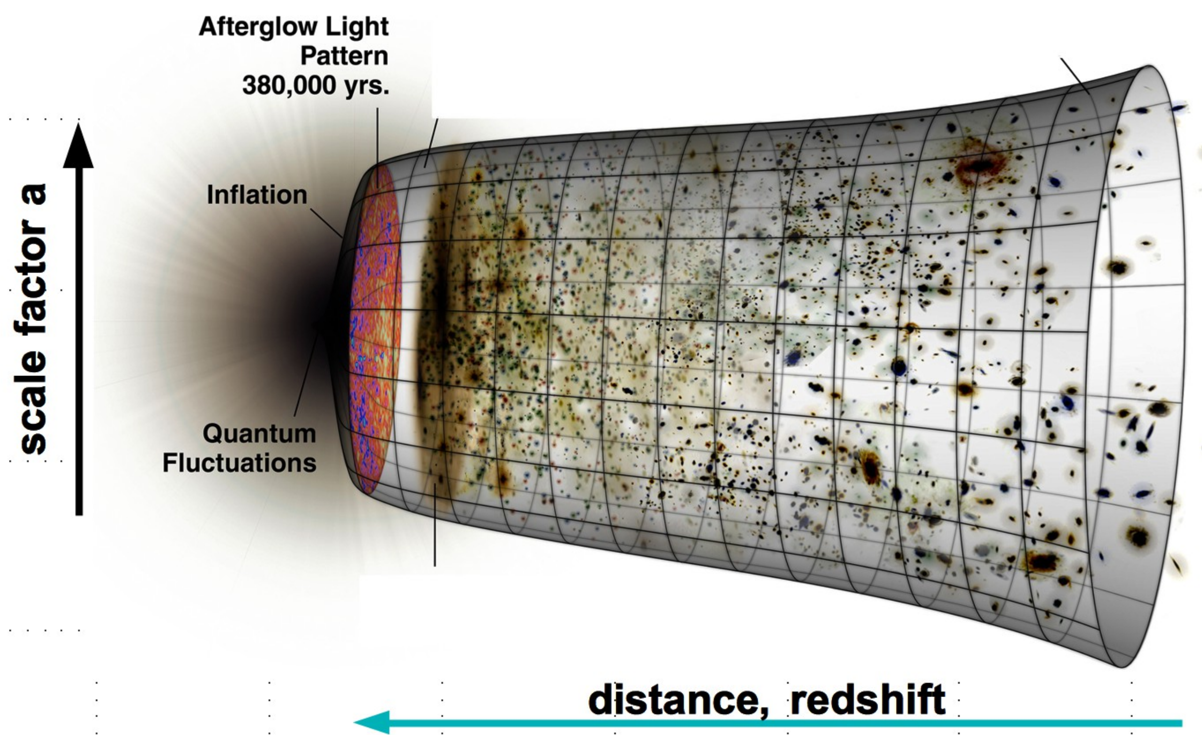
# What goes up keeps getting faster!

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

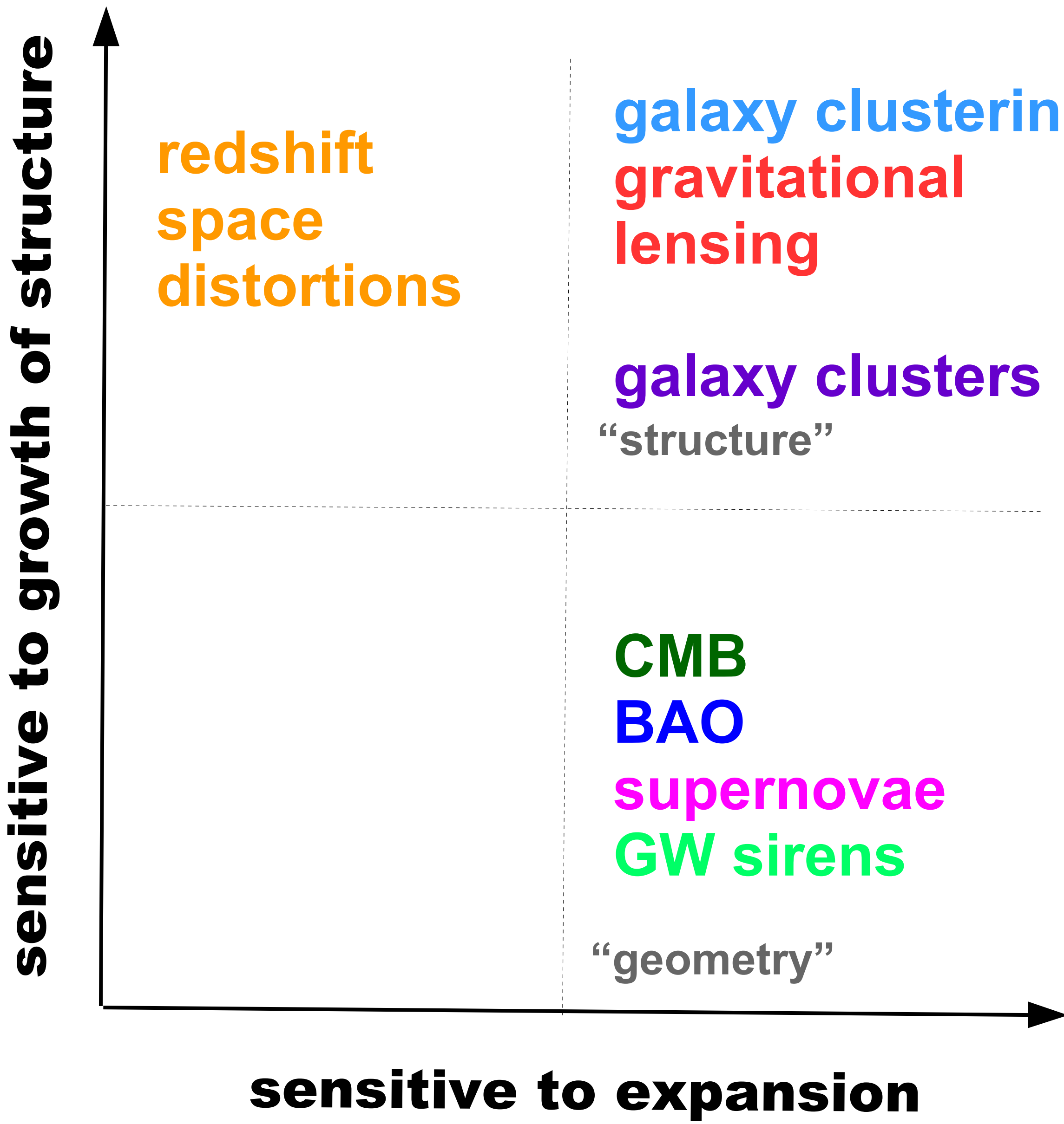
$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda c^2}{3}$$

scale factor of Universe

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



# How to survey Dark Energy




Q: Is everything we observe consistent with the same parameters in a ΛCDM universe?

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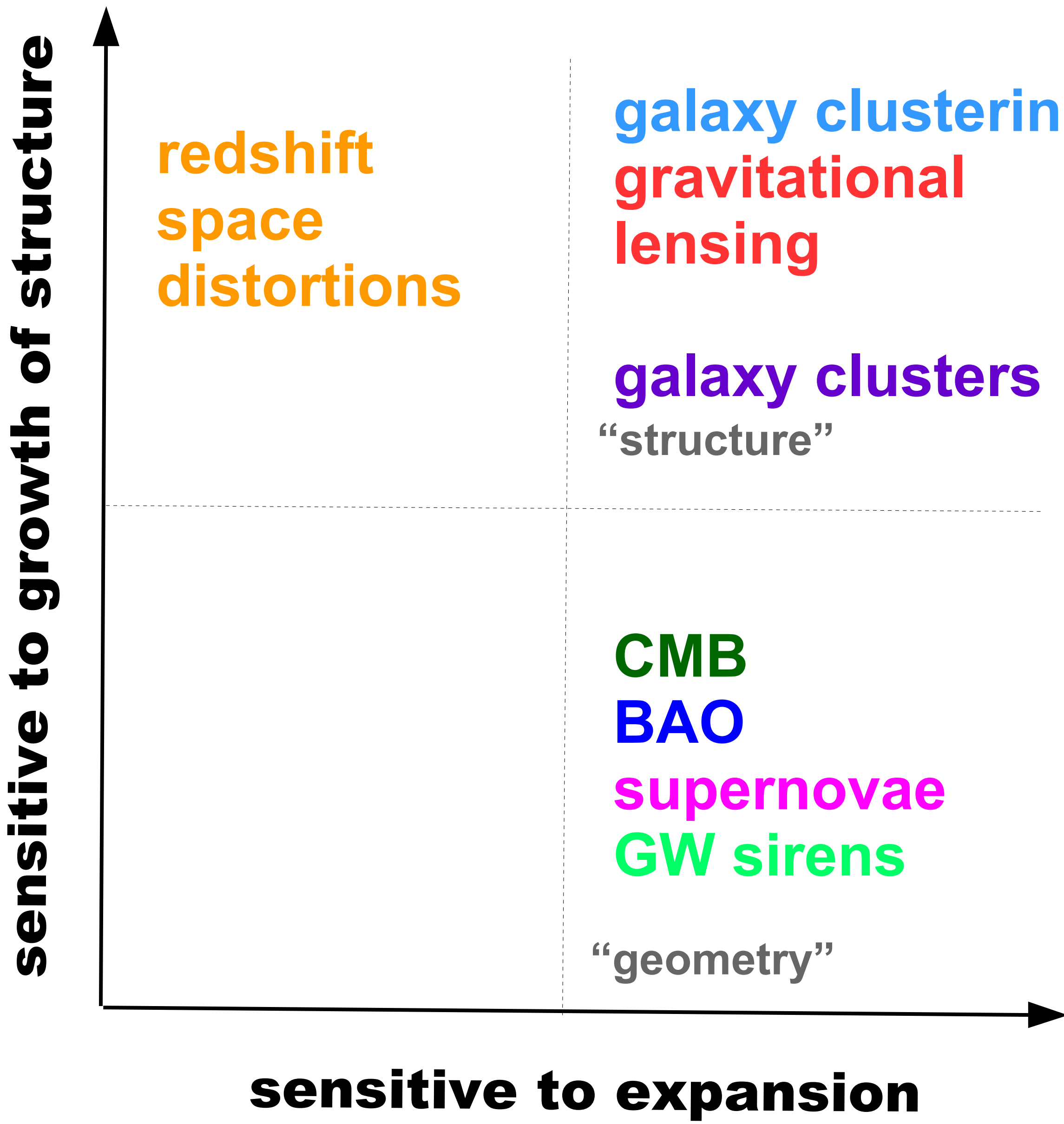



**DES results**

Elvin-Poole+2018

Prat, Sanchez+2018

Gruen+2018, Troxel+2018

DES 2018a

McClintock, Varga+2018

DES in prep.

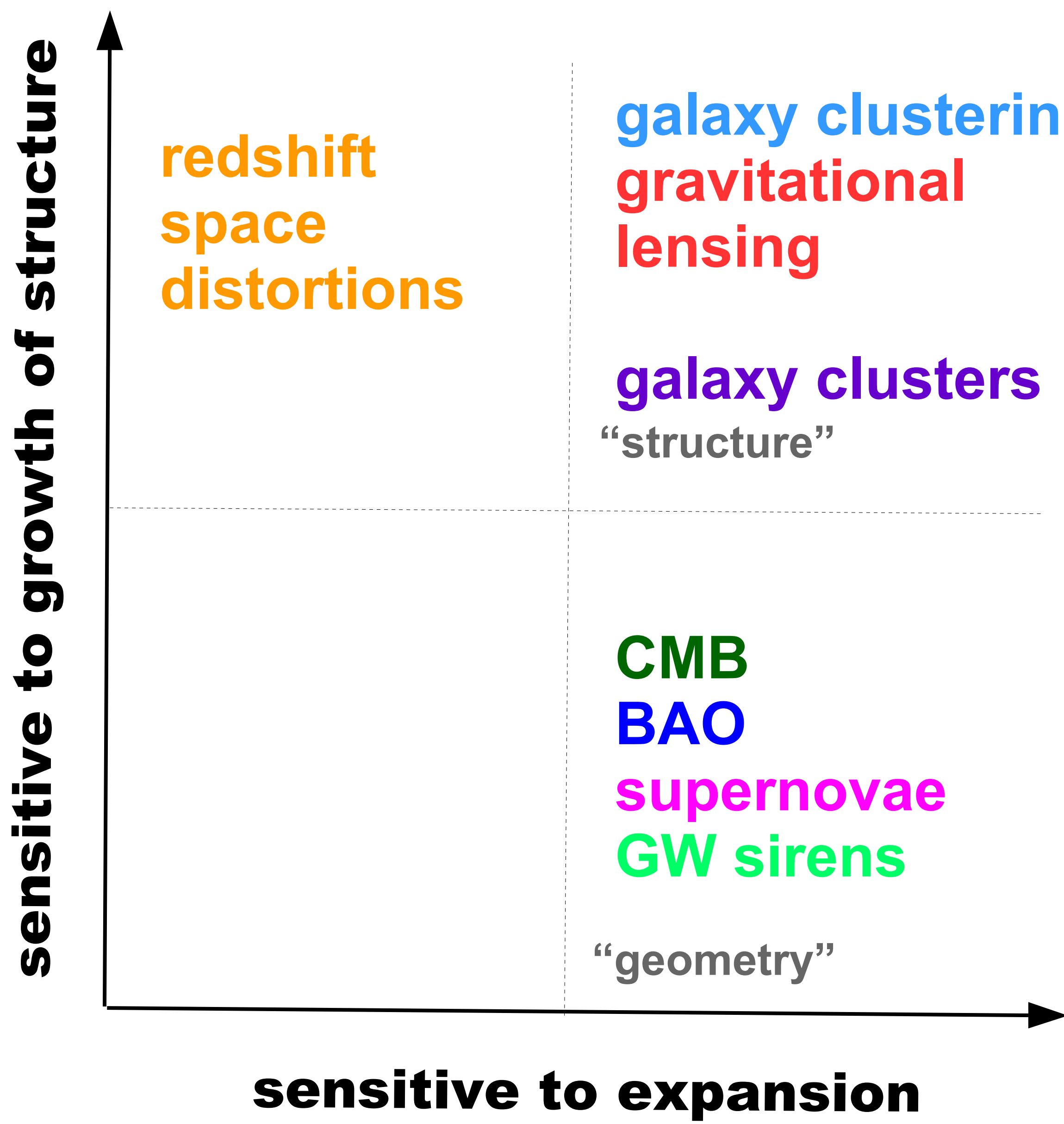
**DES WL+clustering**
**+BAO+SNe (last week)**

DES 2018b

DES (last week)

LIGO-VIRGO-DES+2018

# How to survey Dark Energy

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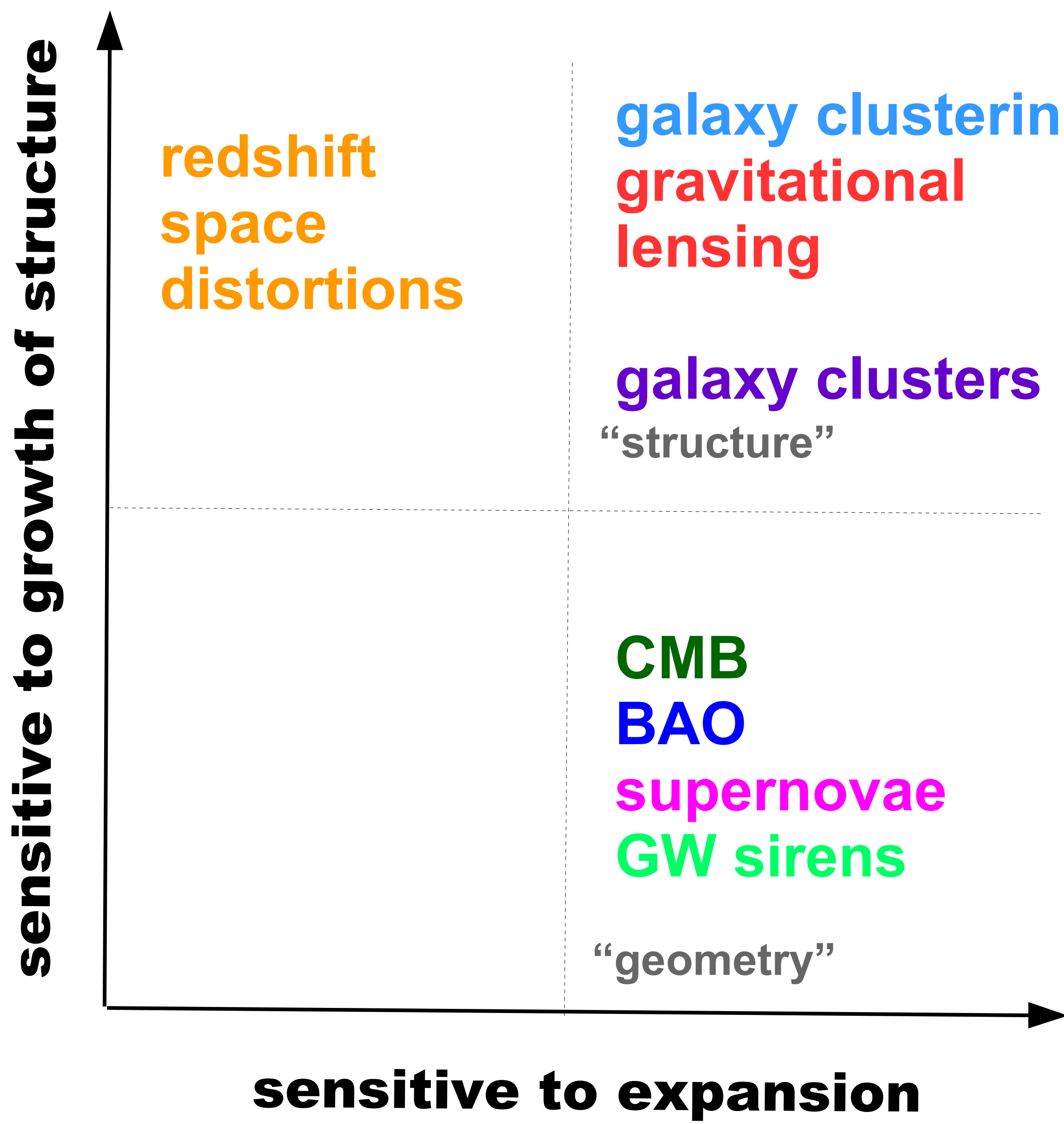
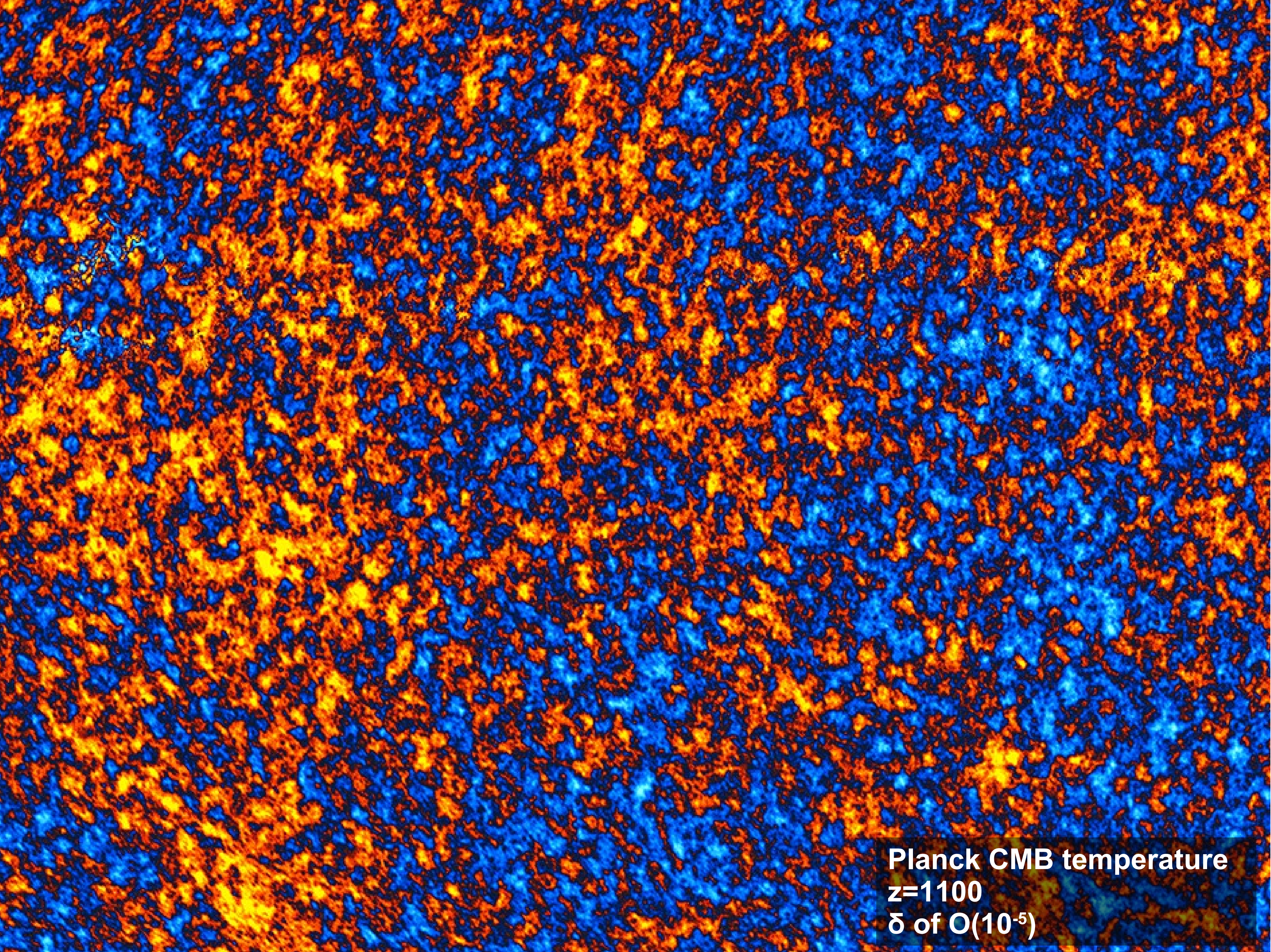
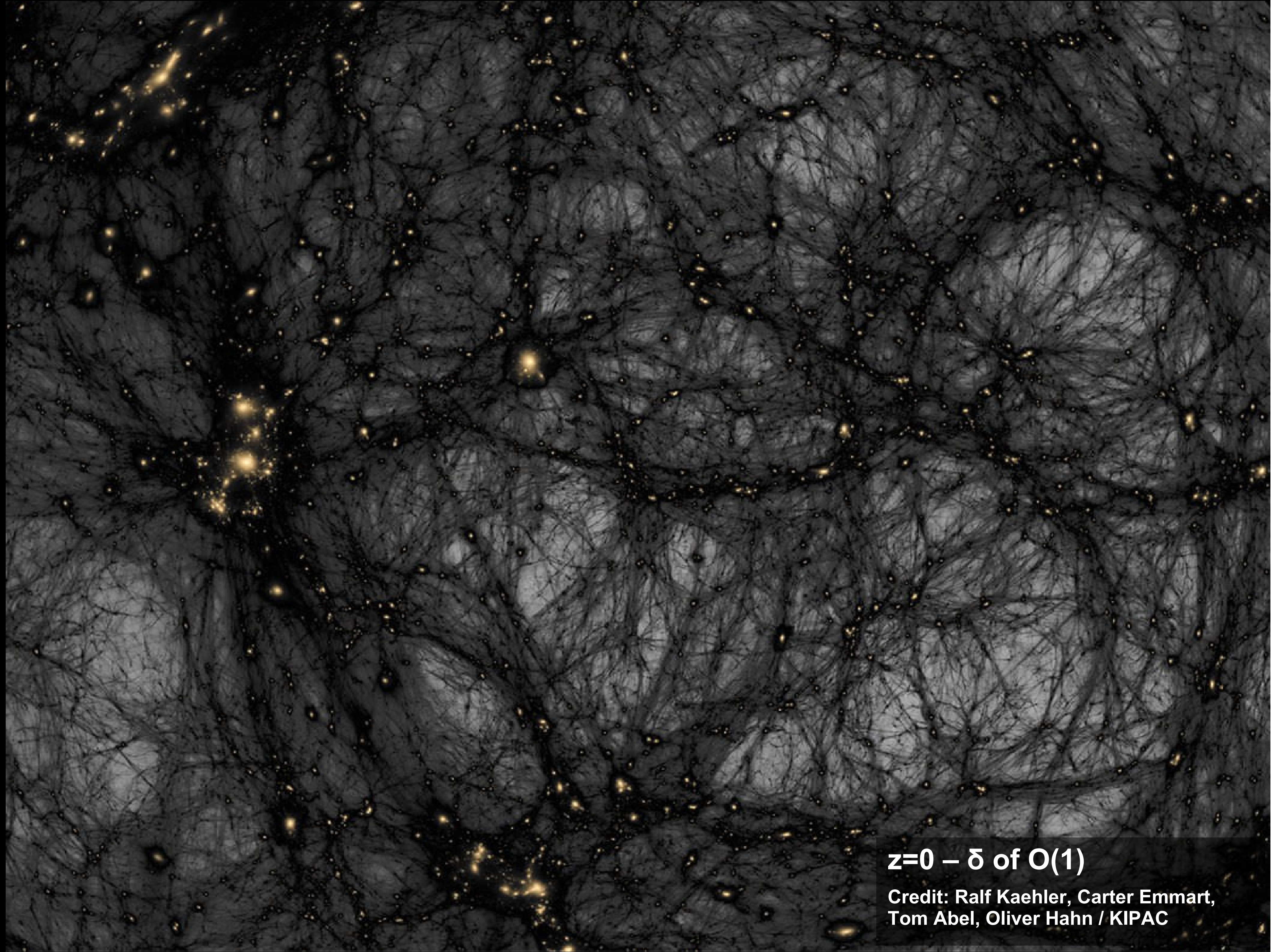


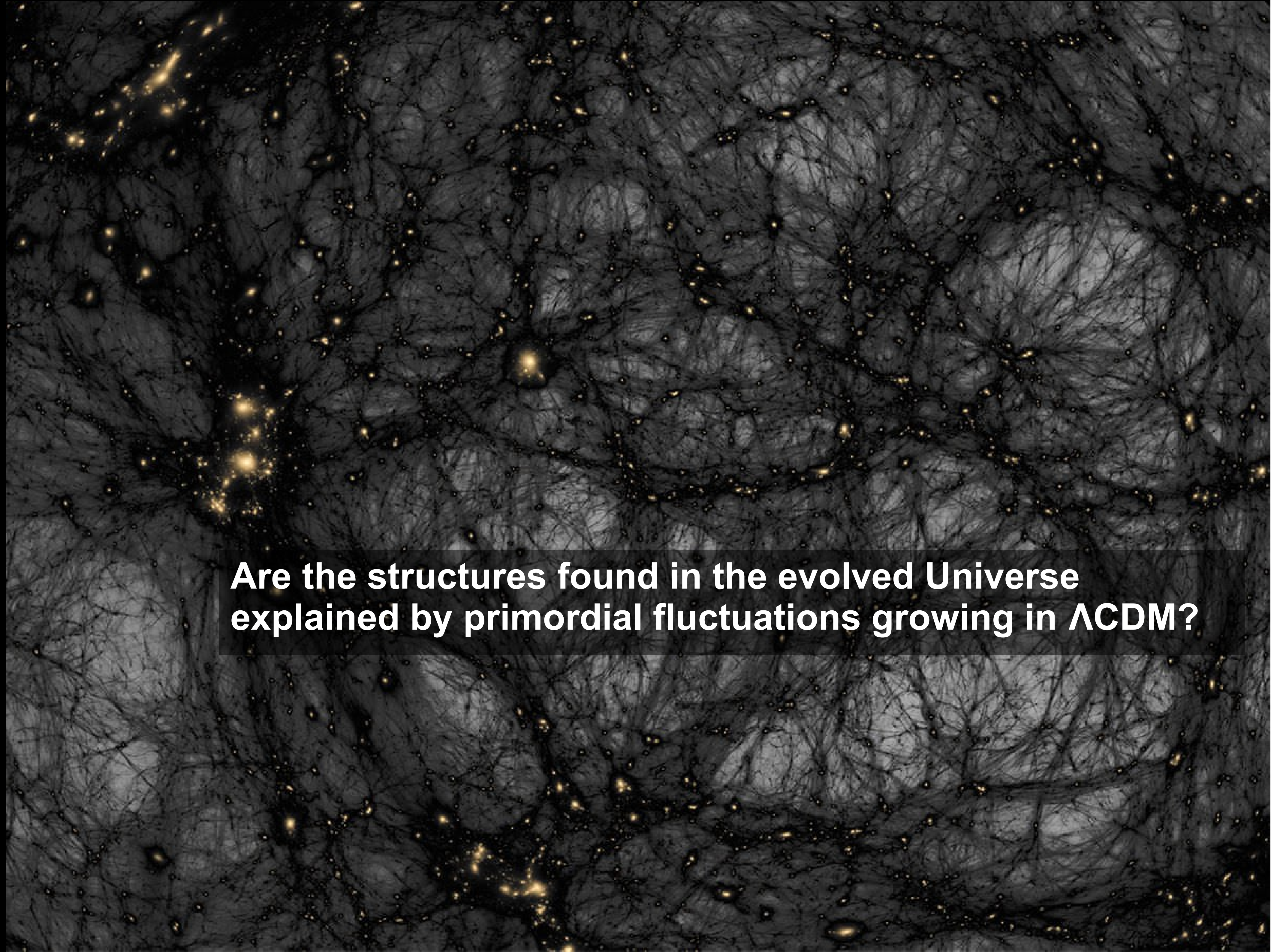

Expansion paints a consistent picture of a fiducial ΛCDM model.*

How about structure?

*except maybe $H_0$ –
can discuss what DES and HSC say about that


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

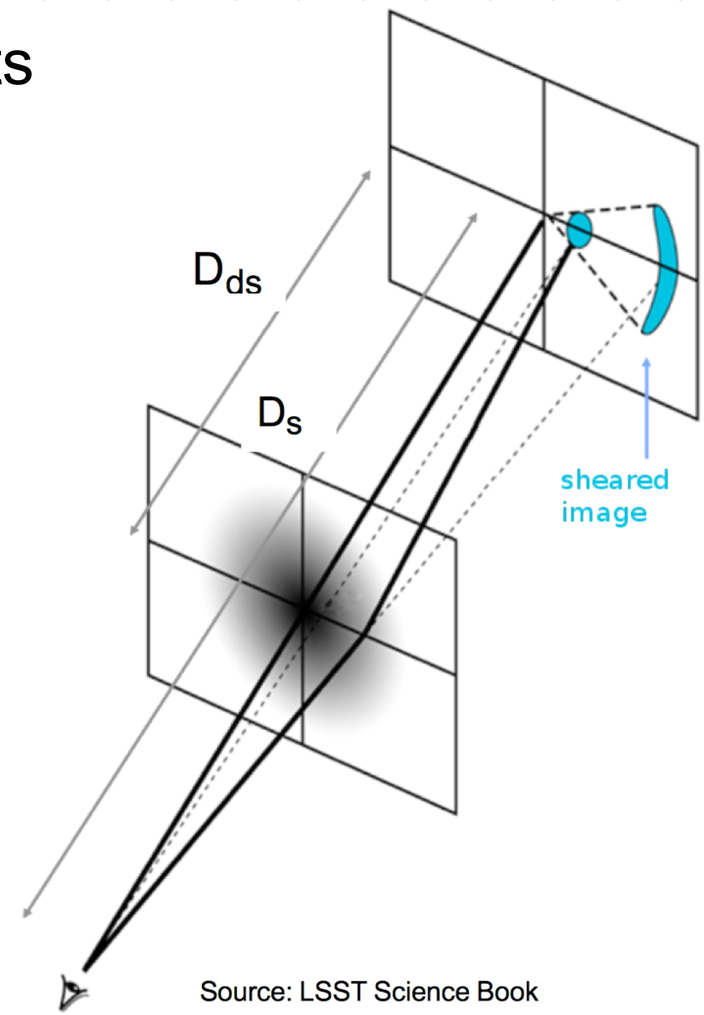

z=0 – δ of O(1)
Credit: Ralf Kaehler, Carter Emmart, Tom Abel, Oliver Hahn / KIPAC


Are the structures found in the evolved Universe
explained by primordial fluctuations growing in ΛCDM?

# 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

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




Source: LSST Science Book

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$$\gamma_t(\theta) = \langle \kappa(\theta') \rangle_{\theta' < \theta} - \kappa(\theta)$$
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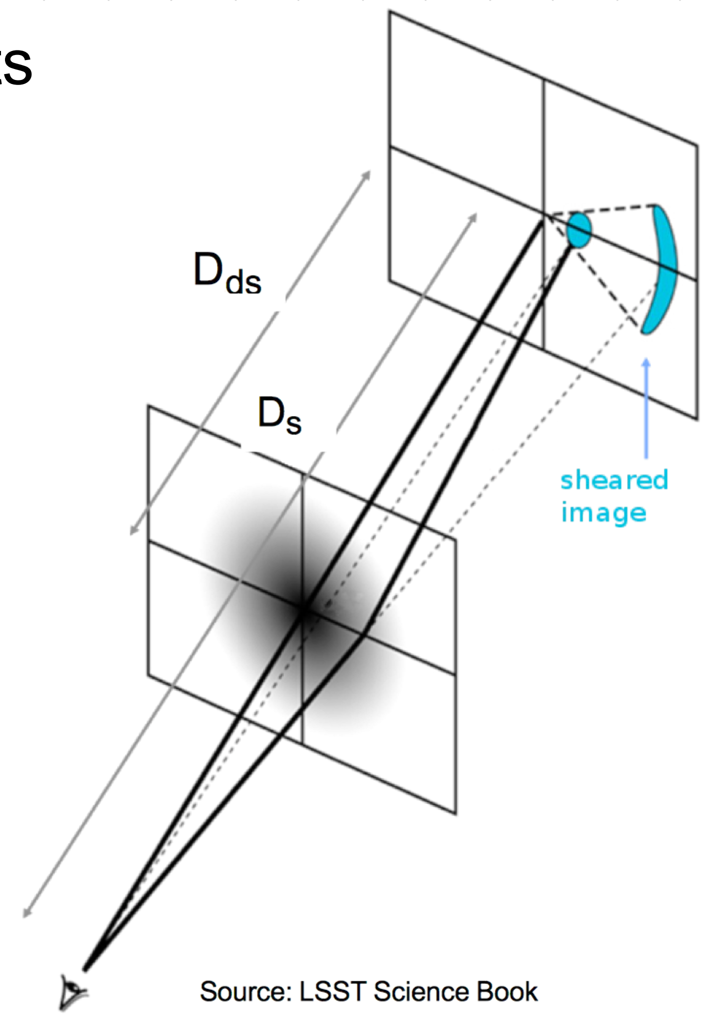
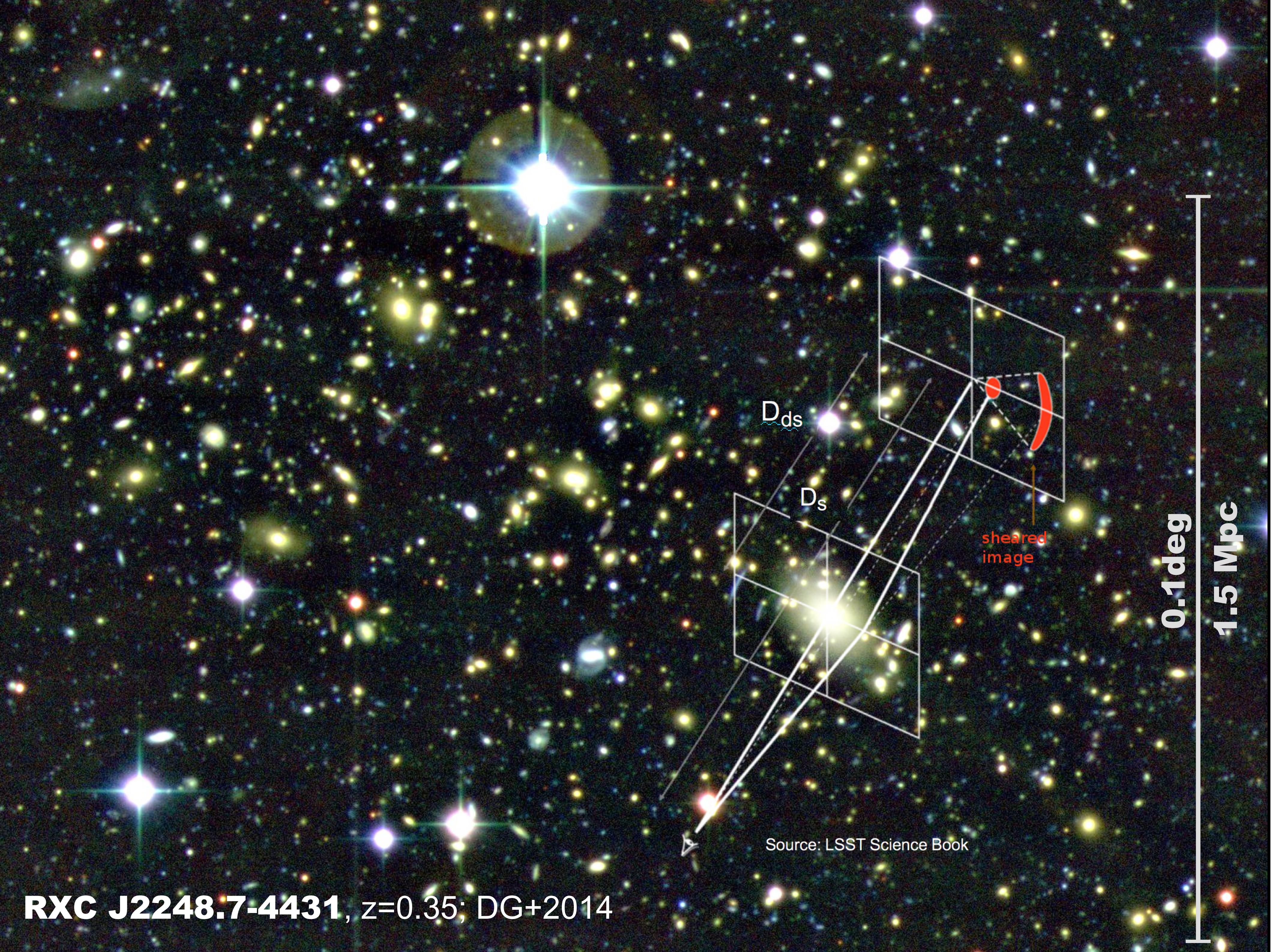
Need to measure galaxy shapes
and redshift distributions

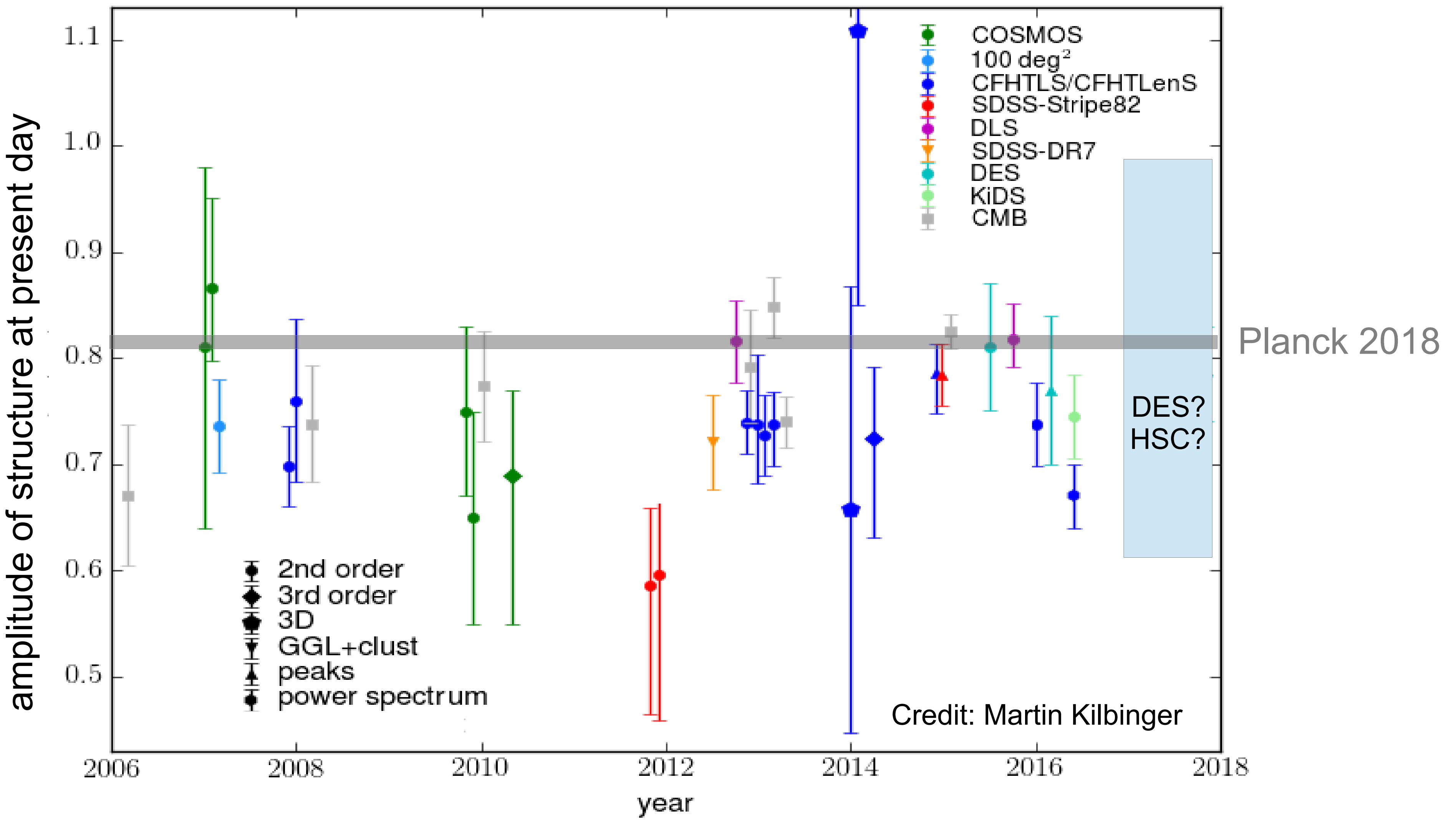


Source: LSST Science Book



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

# Is there evidence for tension from gravitational lensing?




- recent studies have claimed 2-3σ offset from Planck CMB in $\Omega_m$-$\sigma_8$

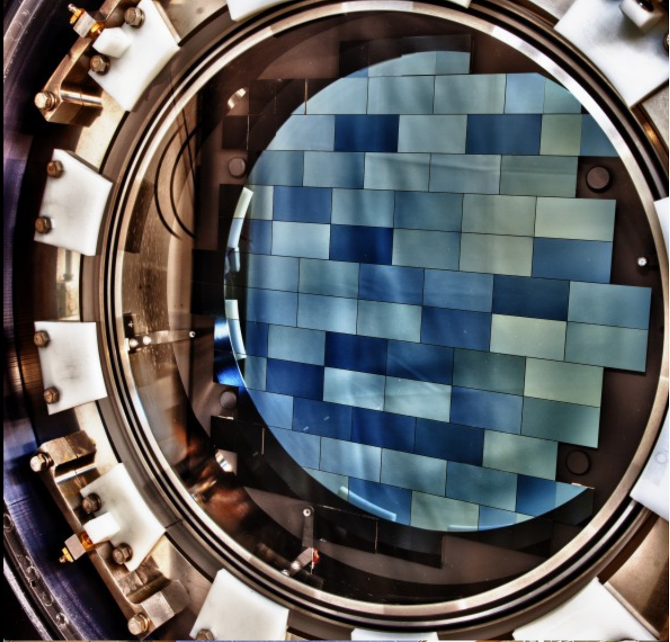
  but see Troxel&Krause, DG+2018
- interpretations differ – statistical fluke, systematics, crack in ΛCDM?

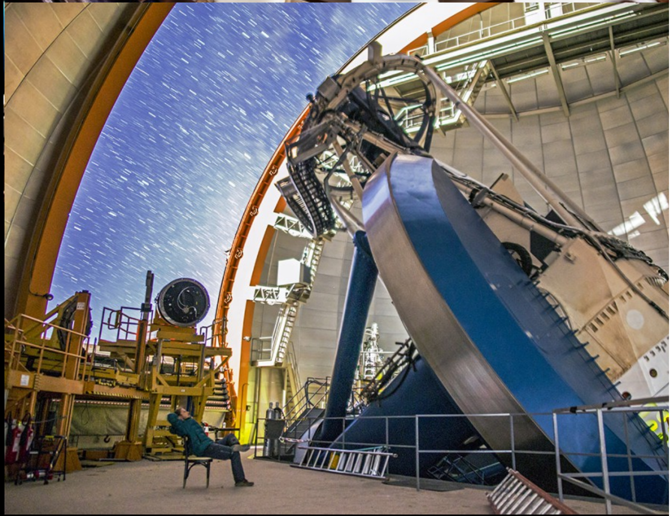
# The Dark Energy Survey

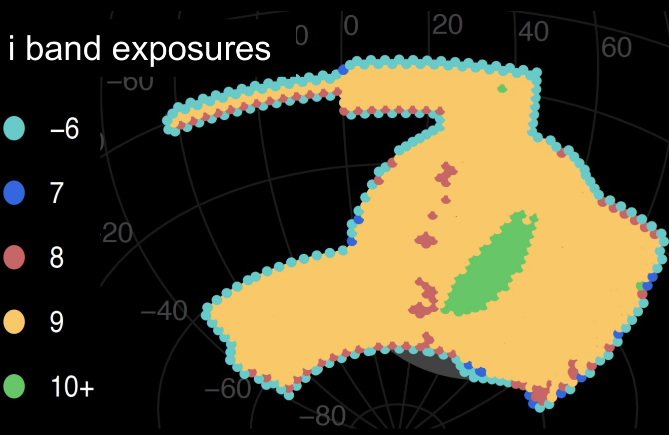
- 5000 sq. deg. survey in grizY from Blanco @ CTIO, 10 exposures, 5.5 years, >400 scientists
- Primary goal: dark energy equation of state
- Probes: Large scale structure, Supernovae,
  Cluster counts, Gravitational lensing
- Status:
  - Y1 (1500 sq. deg, 40% depth):
    key results published / in internal review
  - Y3 (5000 sq. deg, 50% depth):
    data processed, vetting catalogs
  - Y5: data taking finished (90% depth)
  - Y6: homogeneous survey at planned depth

  basic Y3 data released 01/10/18

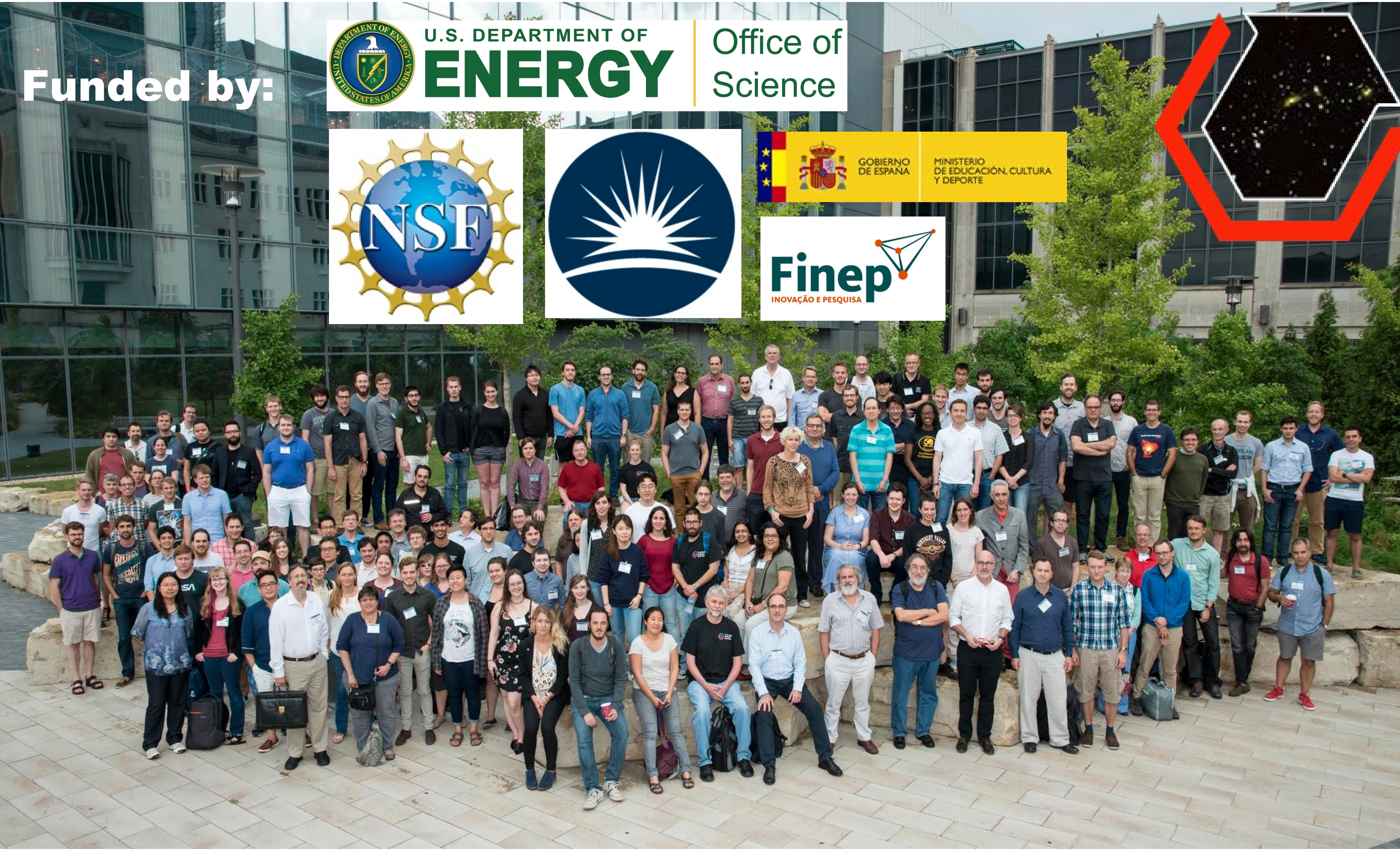
  full Y1 value added data released 10/01/18





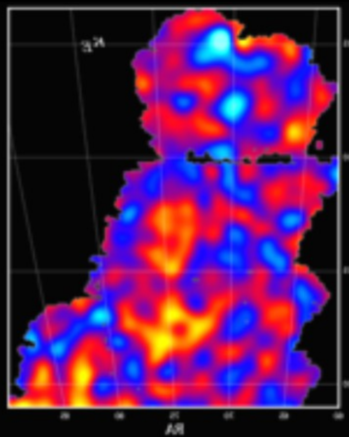


**Funded by:**

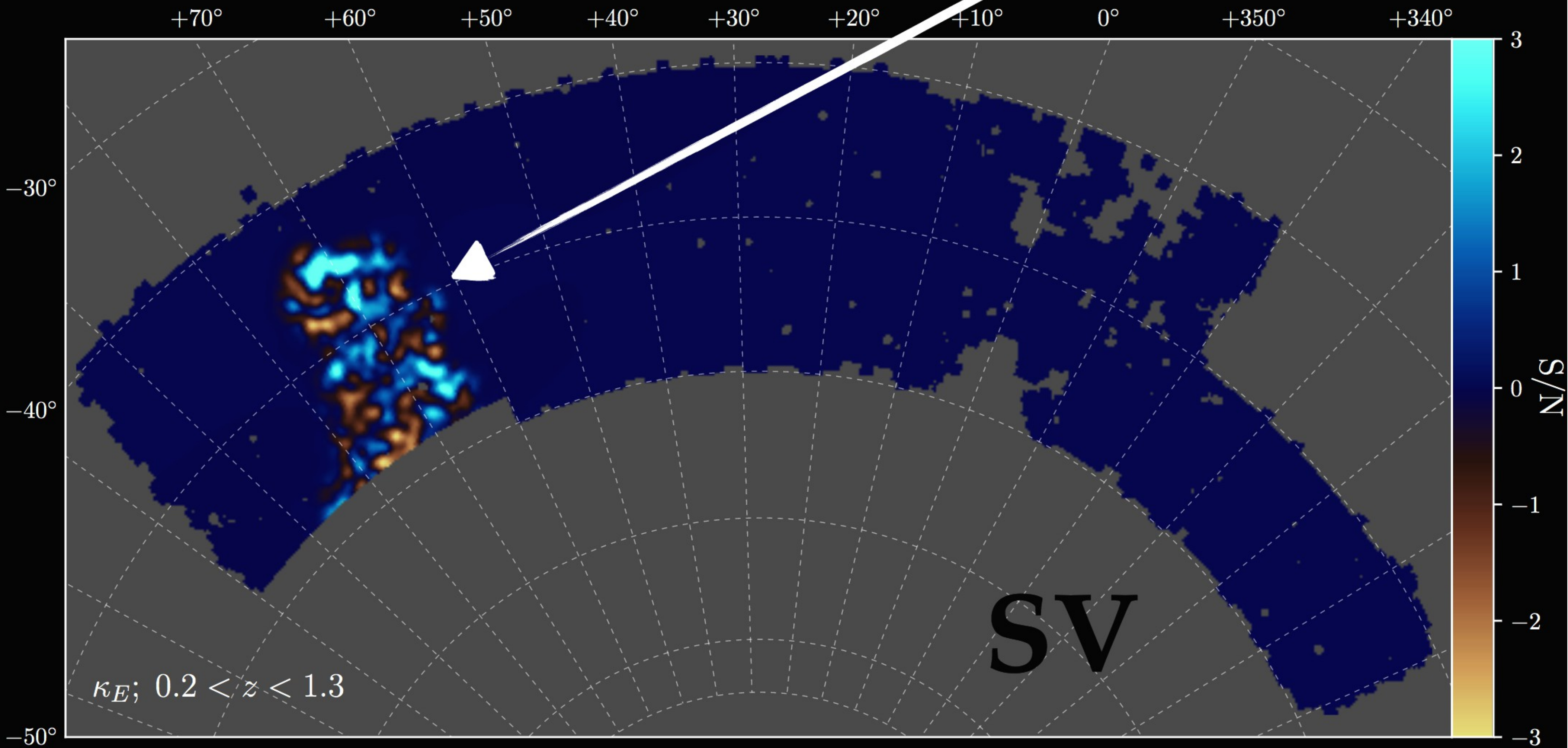


**Collaborating institutions:**

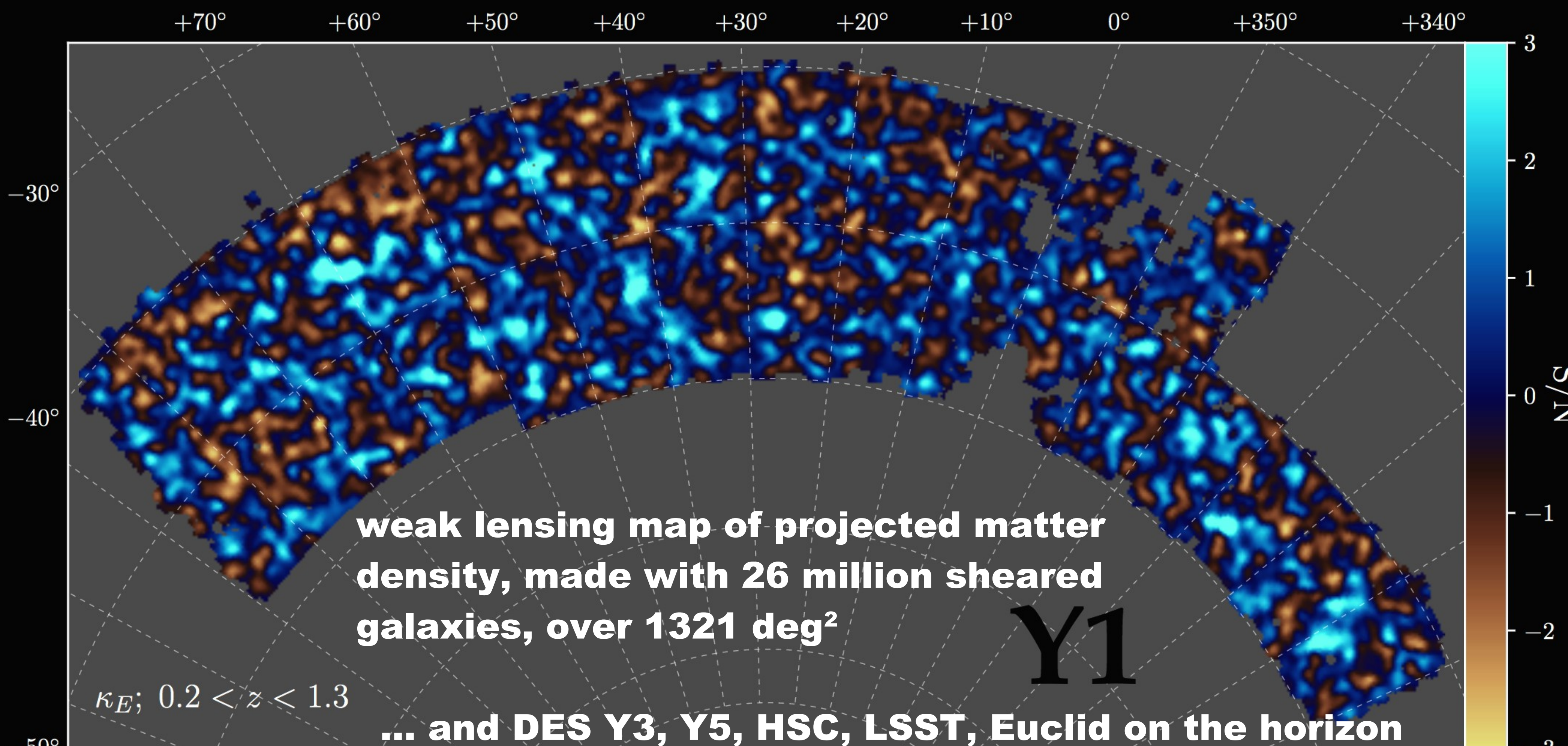
# DES SV …



Chang+; Vikram+ 2016



# DES SV ... to Y1




**weak lensing map of projected matter density, made with 26 million sheared galaxies, over 1321 deg²**

**... and DES Y3, Y5, HSC, LSST, Euclid on the horizon**

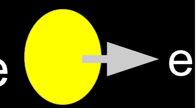
Chang, DG+2018

# With great statistical power comes great systematic responsibility

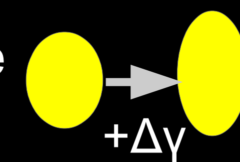
- two independent galaxy shape measurements, including metacalibration algorithm, bias<1.3% (68 c.l.) (Zuntz, Sheldon, DG+2018)

**Metacalibration**:

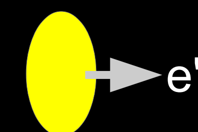
i. apply biased estimator to image




ii. manipulate image to include artificial (shear) signal




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




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

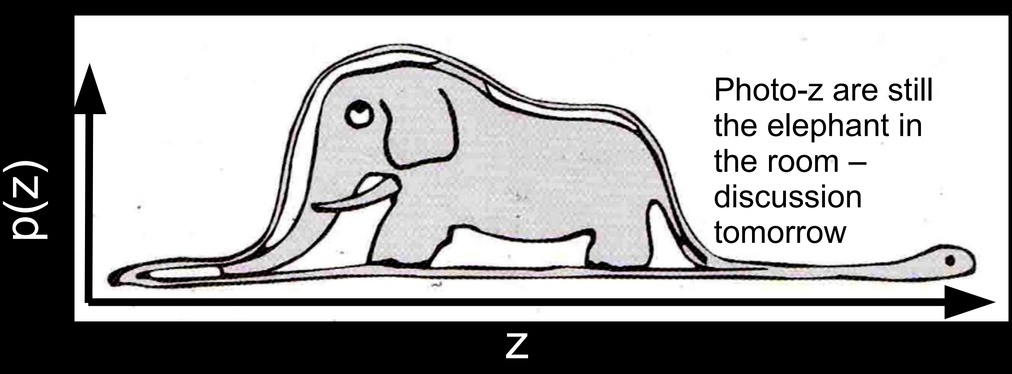
iv. related tricks to also correct selection bias

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

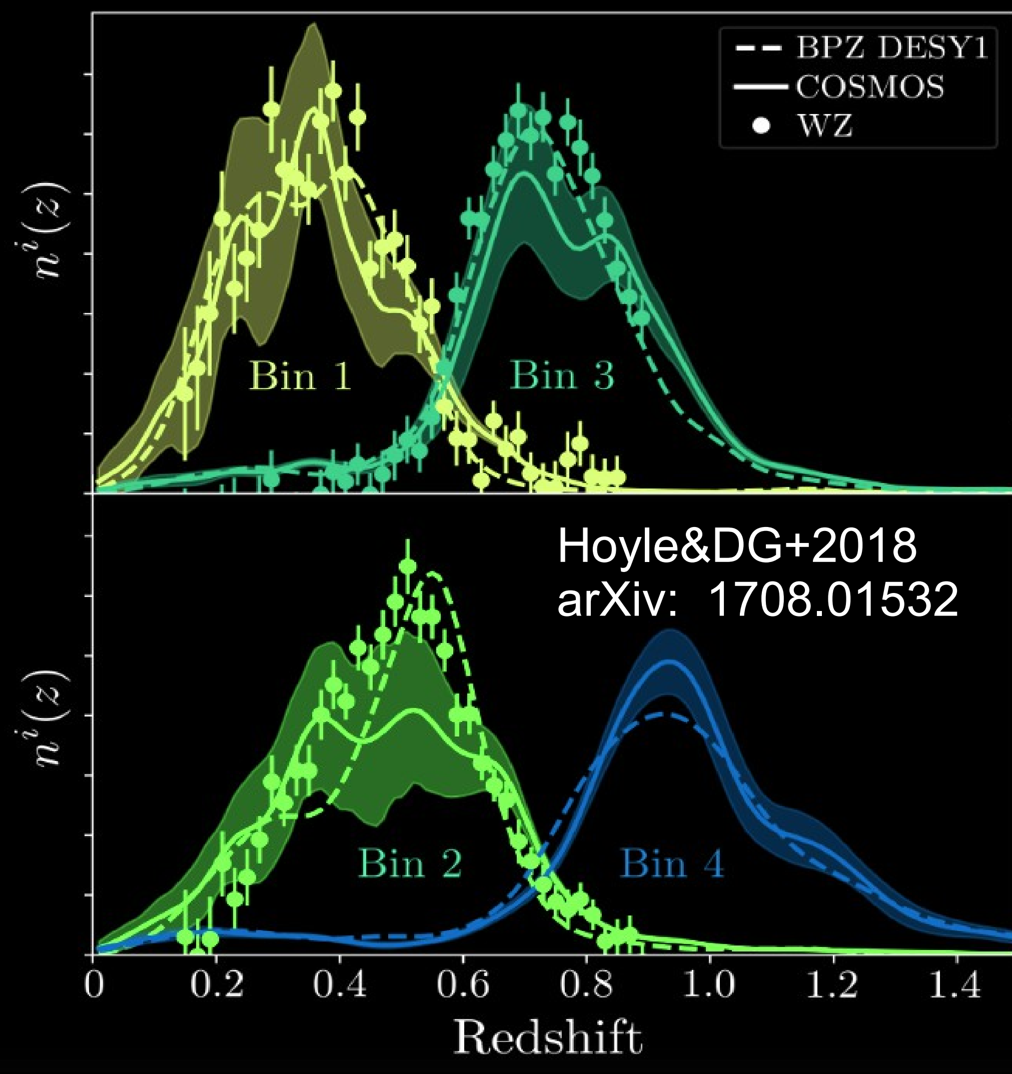
Huff & Mandelbaum, Sheldon & Huff 2017; Zuntz, Sheldon, DG+2018

# With great statistical power comes great systematic responsibility

- two independent galaxy shape measurements, including metacalibration algorithm, bias<1.3% (68 c.l.) (Zuntz, Sheldon, DG+2018)
- two independent calibrations of photometric redshifts of four source bins (Hoyle&DG+2018)

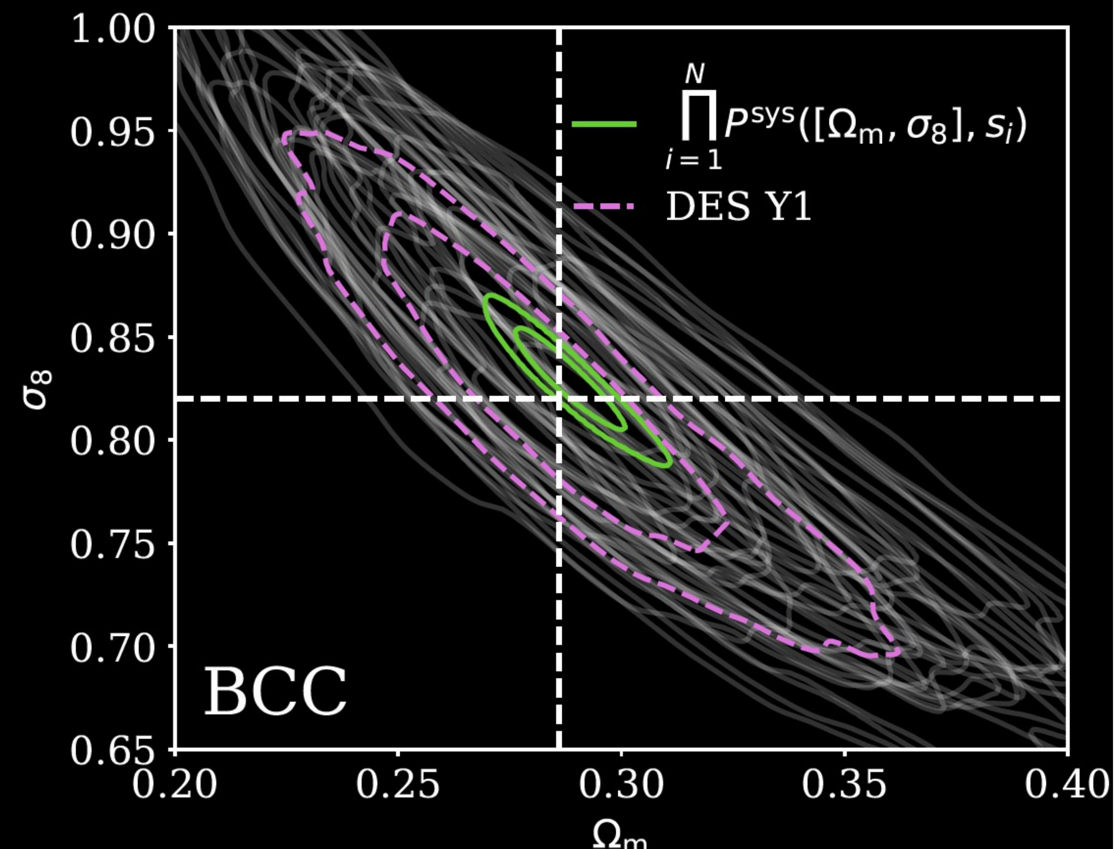



COSMOS + clustering methods agree, ~0.015 uncertainty on <z>

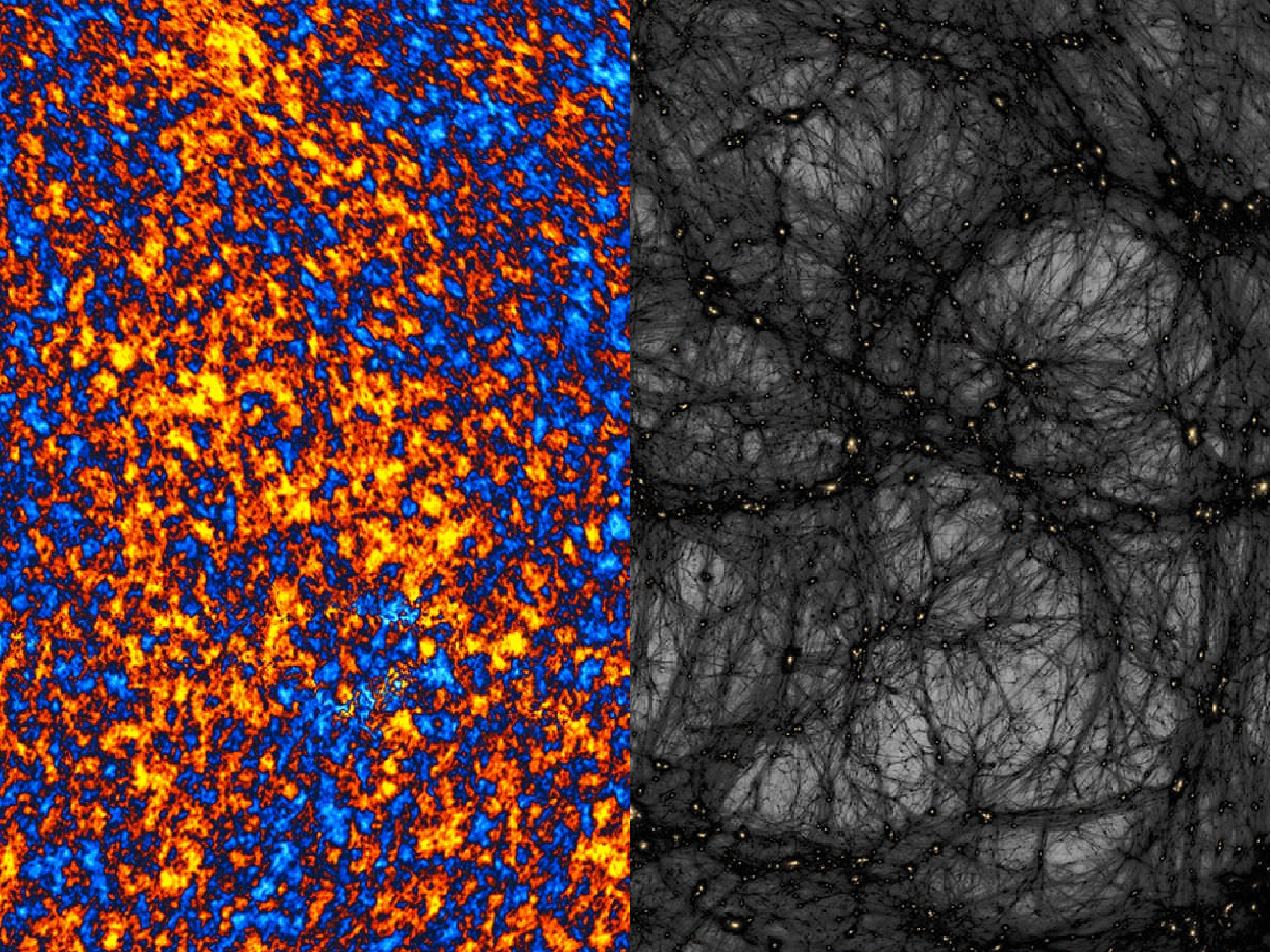


# With great statistical power comes great systematic responsibility

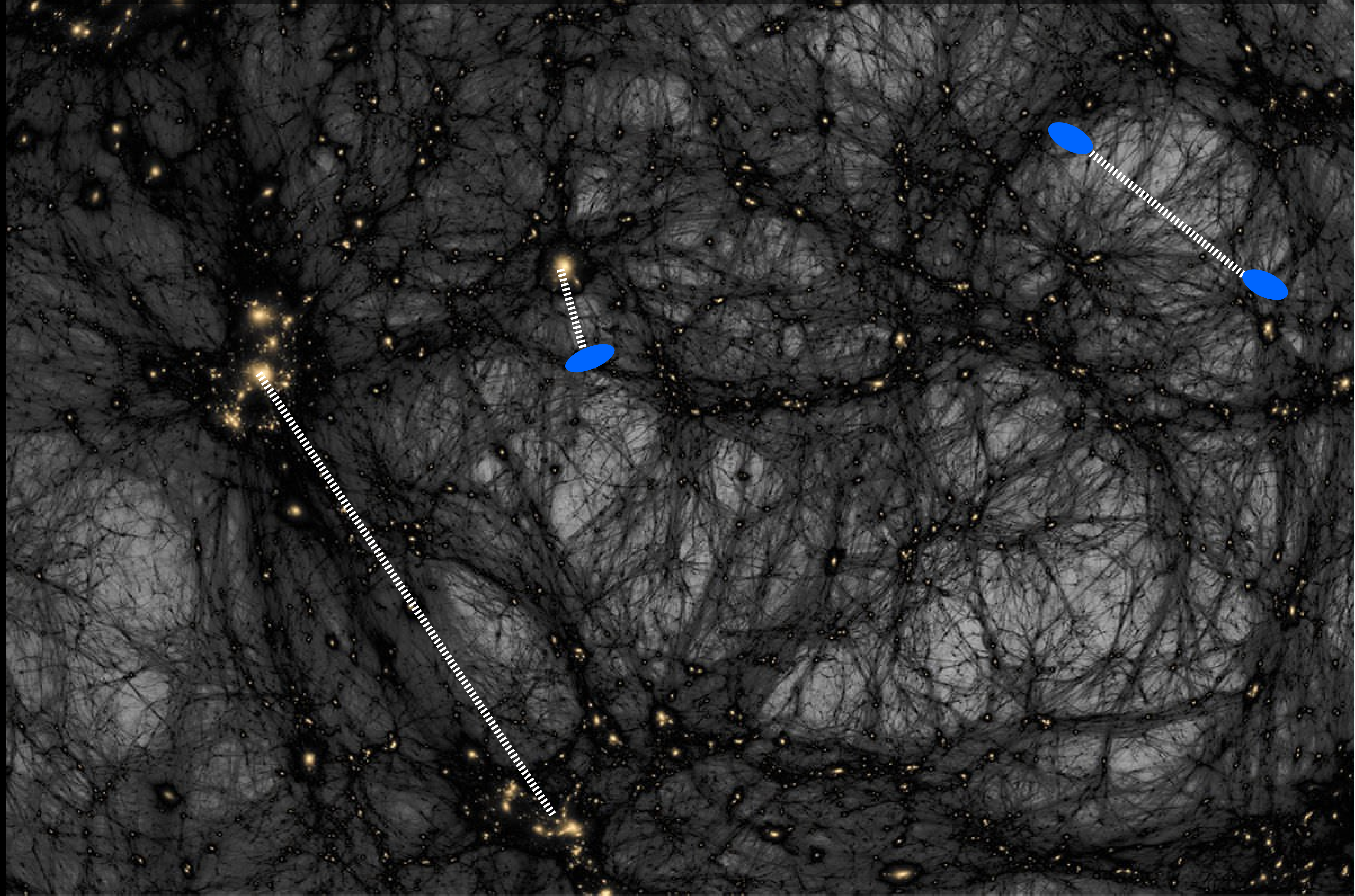
- two independent galaxy shape measurements, including metacalibration algorithm, bias<1.3% (68 c.l.) (Zuntz, Sheldon, DG+2018)
- two independent calibrations of photometric redshifts of four source bins (Hoyle&DG+2018)
- two independent cosmological inference pipelines, tested with simulations (Krause, Eifler+2018; MacCrann, DeRose+2018)

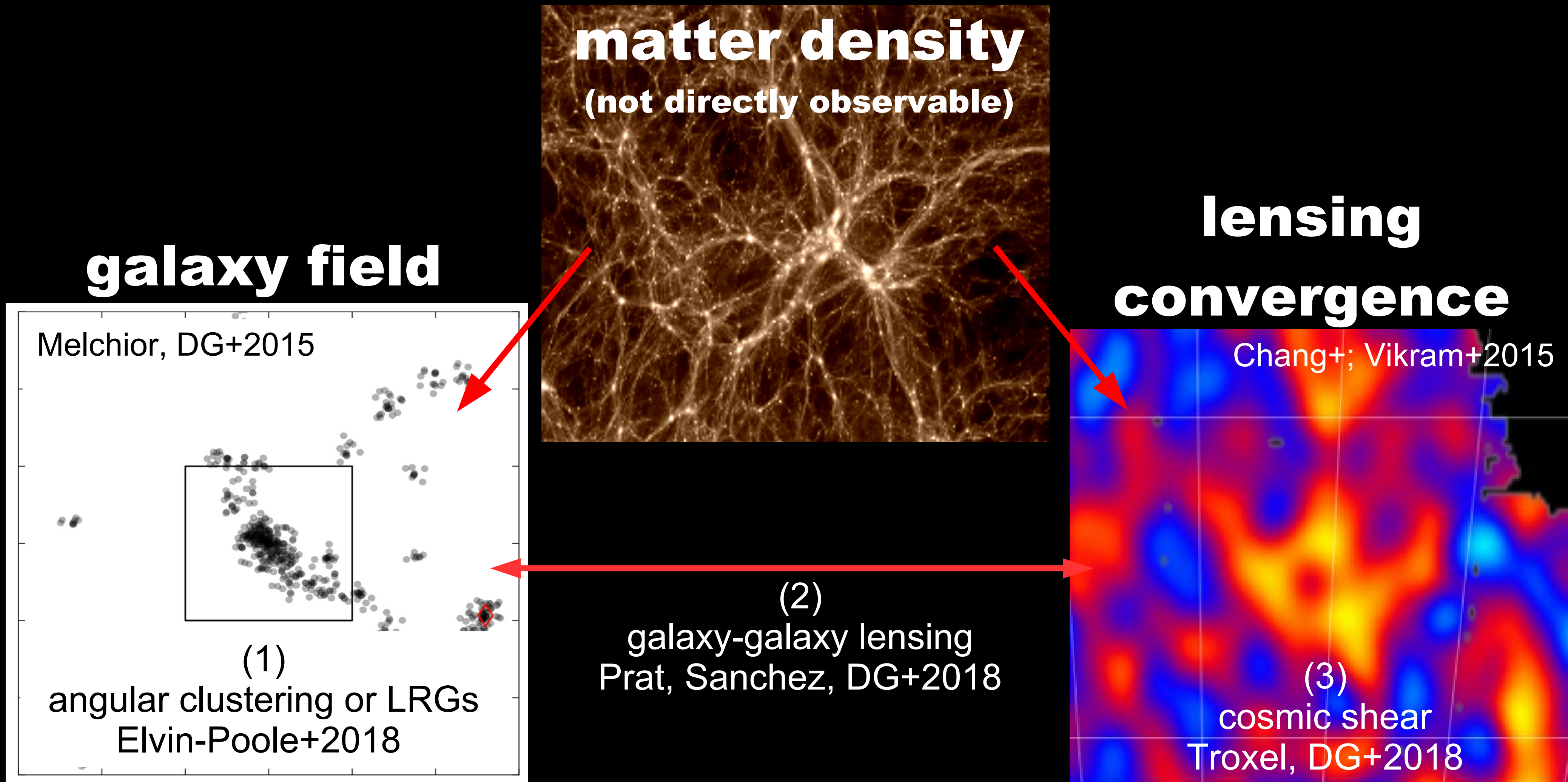



MacCrann & DeRose+2018:
DES likelihoods accurate enough for 18x the (simulated) Y1 volume



# 1) Cosmology from two-point correlations

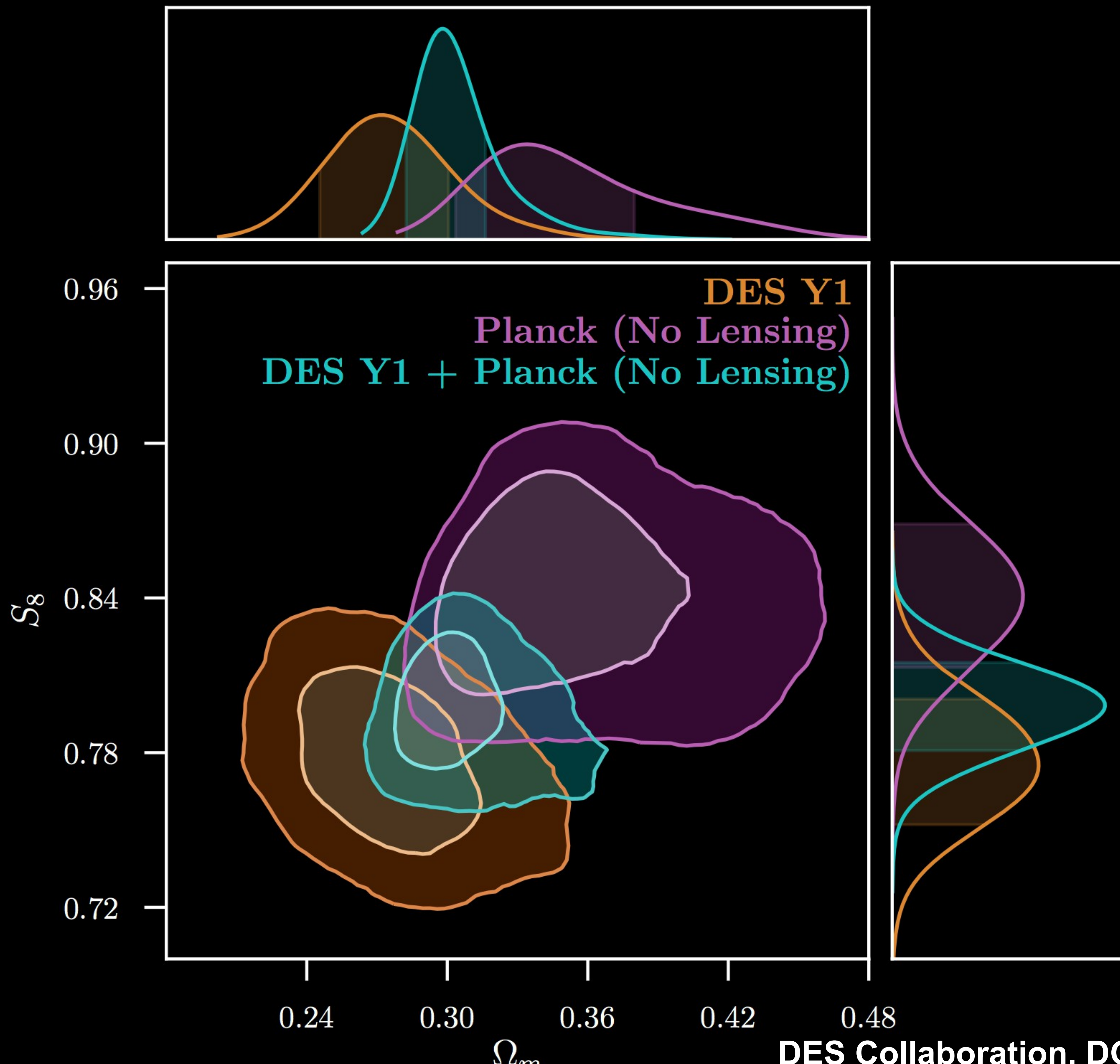




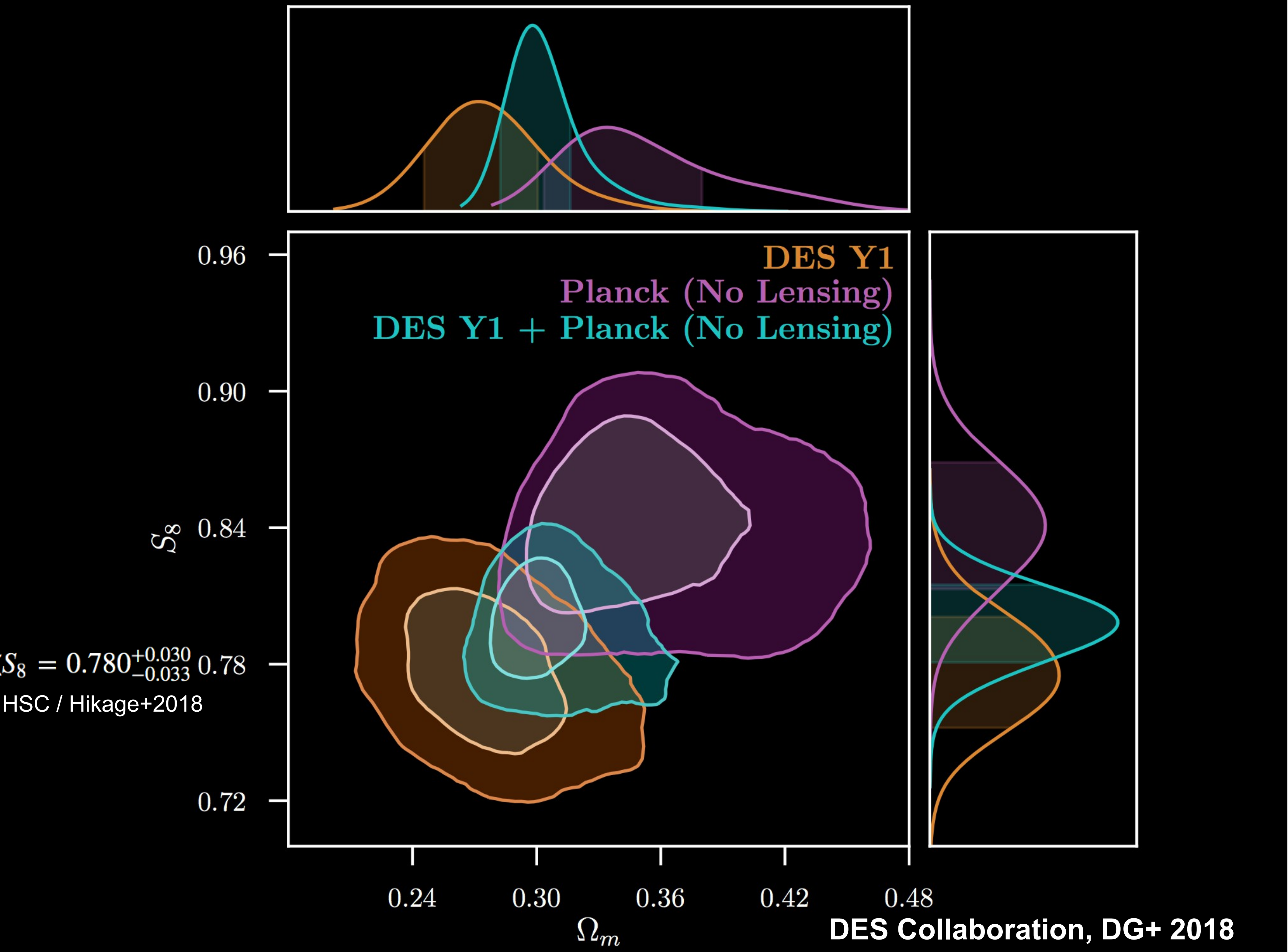

**combination of these three two-point functions maximizes use of information and jointly and robustly constrains nuisance parameters**

[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, DG+2018**



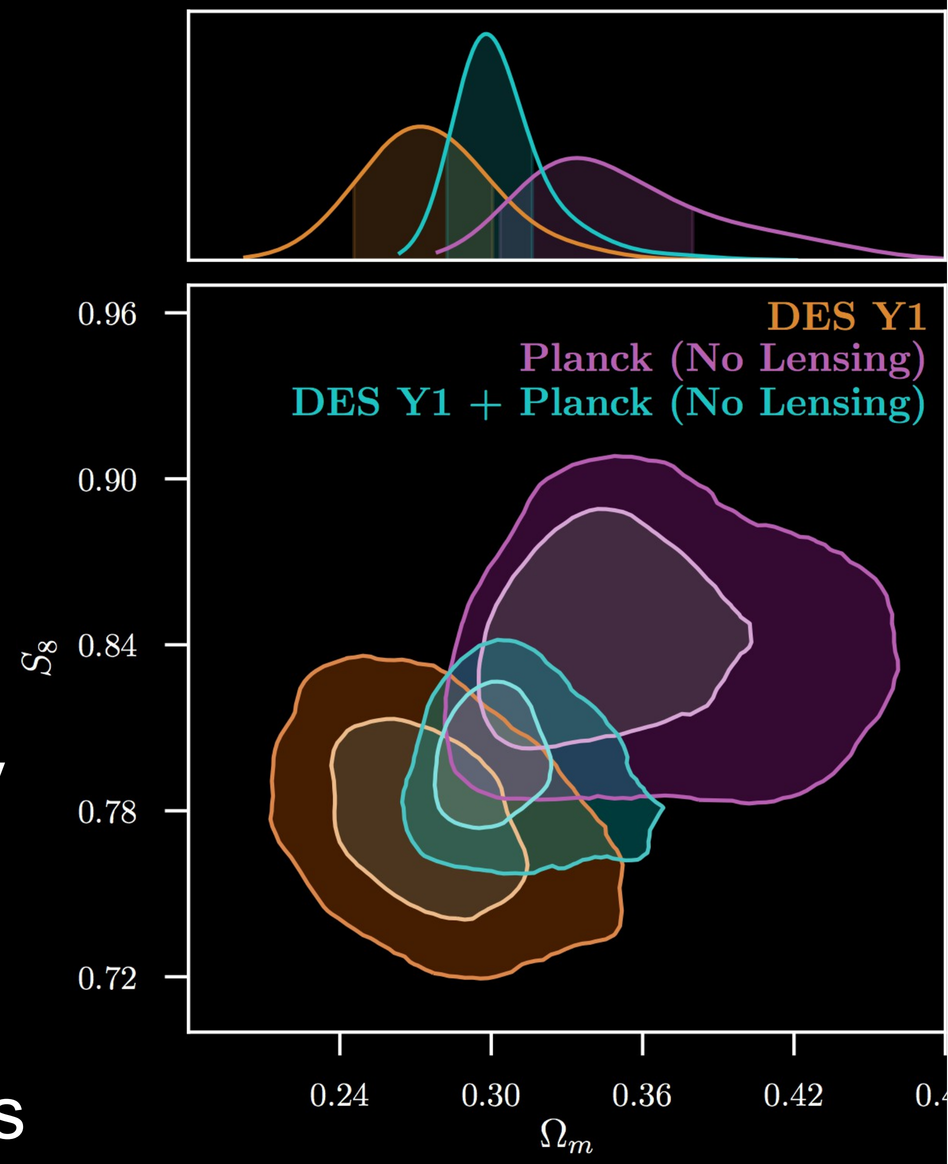

DES Collaboration, DG+ 2018



DES Y1
Planck (No Lensing)
DES Y1 + Planck (No Lensing)
0.96
0.90
0.84
0.78
0.72
$S_8$
0.24
0.30
0.36
0.42
0.48
$\Omega_m$
$S_8 = 0.780^{+0.030}_{-0.033}$
HSC / Hikage+2018
DES Collaboration, DG+ 2018

# 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 good – no evidence for inconsistency
- Combination with CMB/BAO/SNe yields consistent, tightest constraints



# Released last week: Cosmology from DES 2pt+BAO+SNe

First joint constraint from structure + geometry in an imaging survey

**SNe Ia:**
207 DES SNe
(no low-z)

**Phot. BAO:**
angular clustering of 1.6m DES Y1 galaxies at z=0.6-1

**DES 3x2pt:**
DES Y1 galaxy/shear 2pt functions

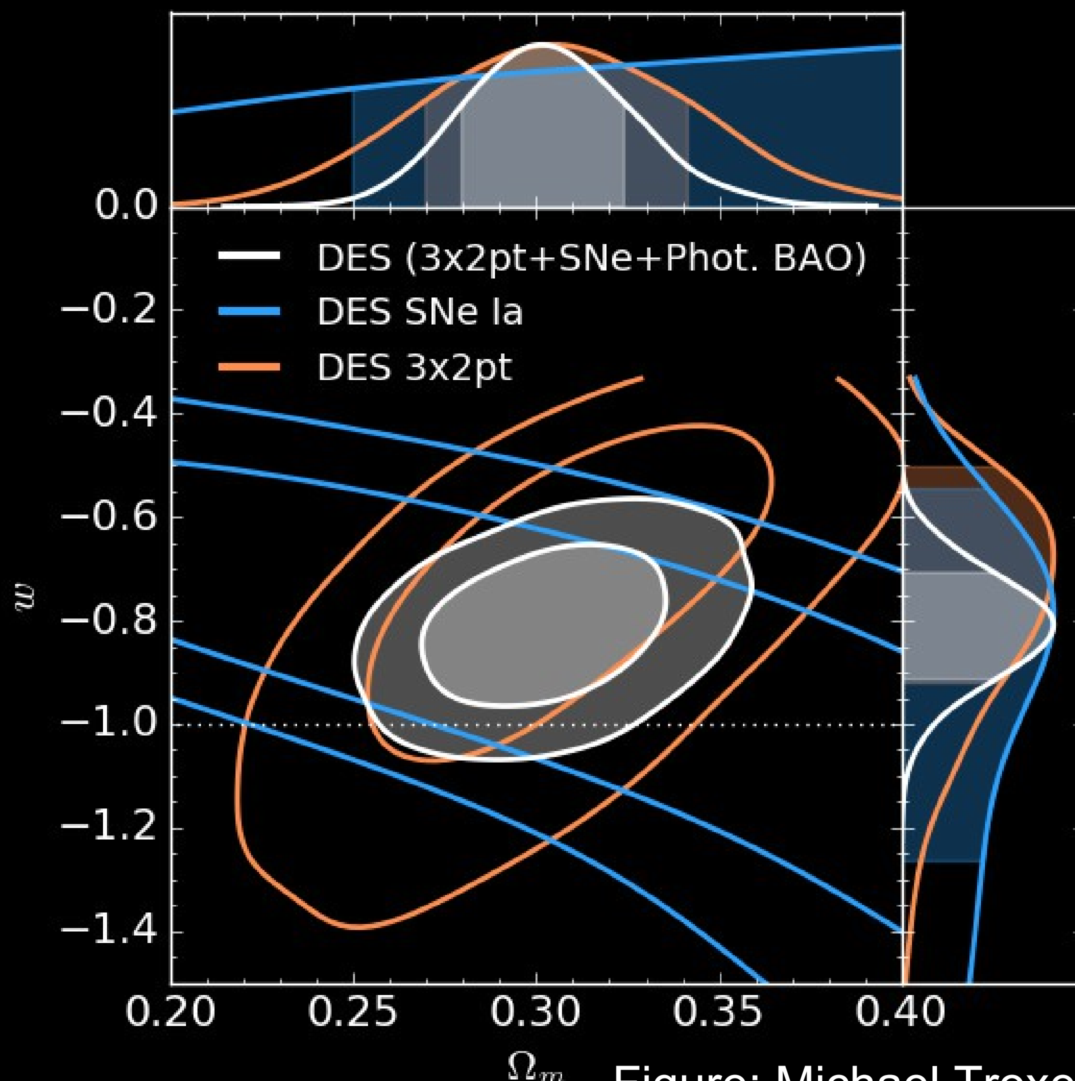



Figure: Michael Troxel

On arXiv last week:

1811.02374
...
1811.02381

# Released last week:
# Cosmology from DES 2pt+BAO+SNe

First joint constraint from structure + geometry in an imaging survey

DES against the rest:

consistent in wCDM

| Parameter | $w$CDM |
|---|---|
| $\Omega_m$ | $0.300^{+0.023}_{-0.021}$ |
| $\Omega_b$ | $0.064^{+0.013}_{-0.009}$ |
| $\Omega_k$ | 0 |
| $\Omega_\Lambda$ | $0.700^{+0.021}_{-0.023}$ |
| $w$ | $-0.80^{+0.09}_{-0.11}$ |
| $S_8$ | $0.786^{+0.029}_{-0.019}$ |

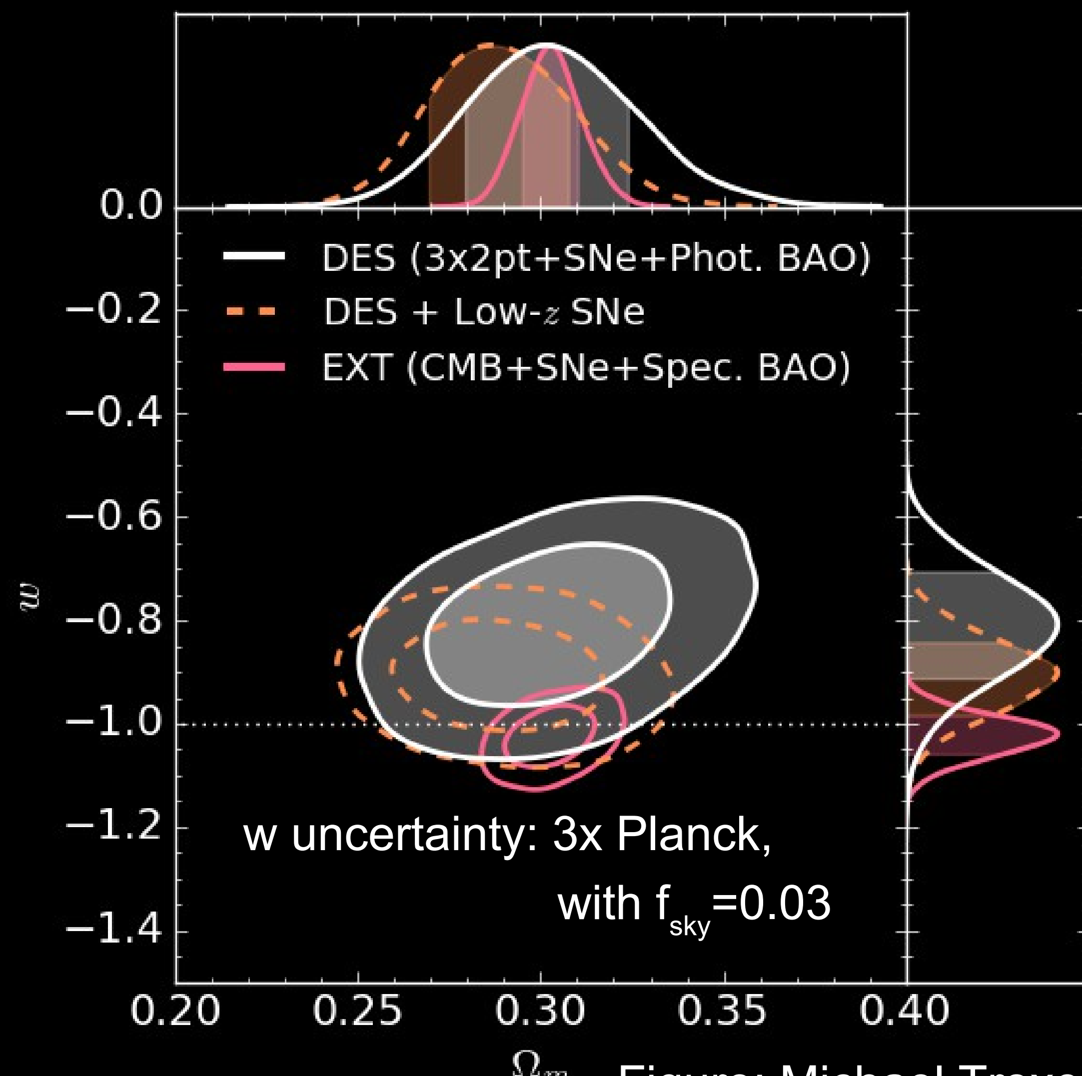



Figure: Michael Troxel

On arXiv last week:

1811.02374

...

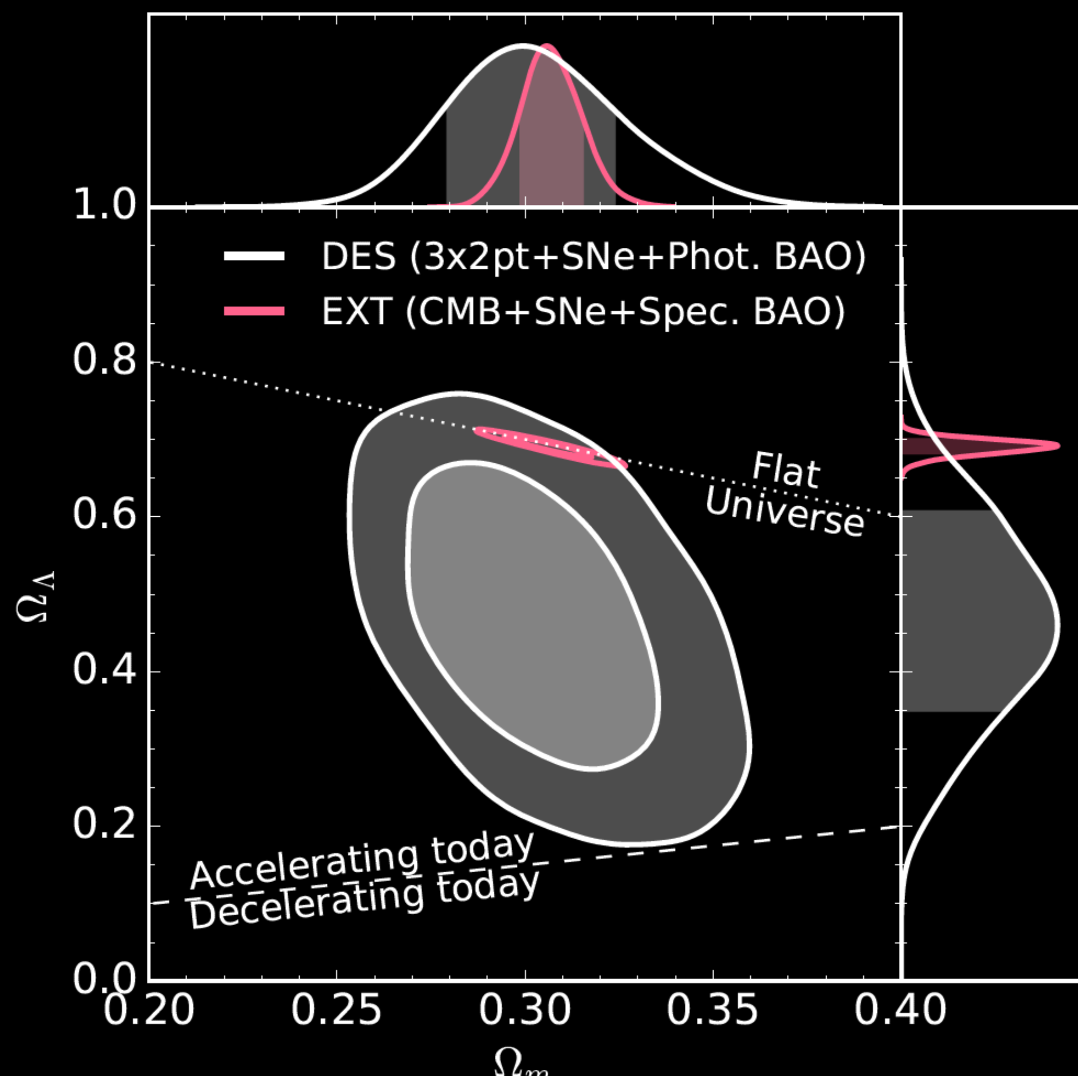
1811.02381

# Released last week:
# Cosmology from DES 2pt+BAO+SNe

First joint constraint from structure + geometry in an imaging survey

DES against the rest:
consistent in open ΛCDM

| Parameter | $o$CDM |
|---|---|
| $\Omega_m$ | $0.299^{+0.024}_{-0.020}$ |
| $\Omega_b$ | $0.069^{+0.009}_{-0.012}$ |
| $\Omega_k$ | $0.252^{+0.095}_{-0.14}$ |
| $\Omega_\Lambda$ | $0.47^{+0.14}_{-0.12}$ |
| $w$ | $-1$ |
| $S_8$ | $0.801^{+0.028}_{-0.026}$ |

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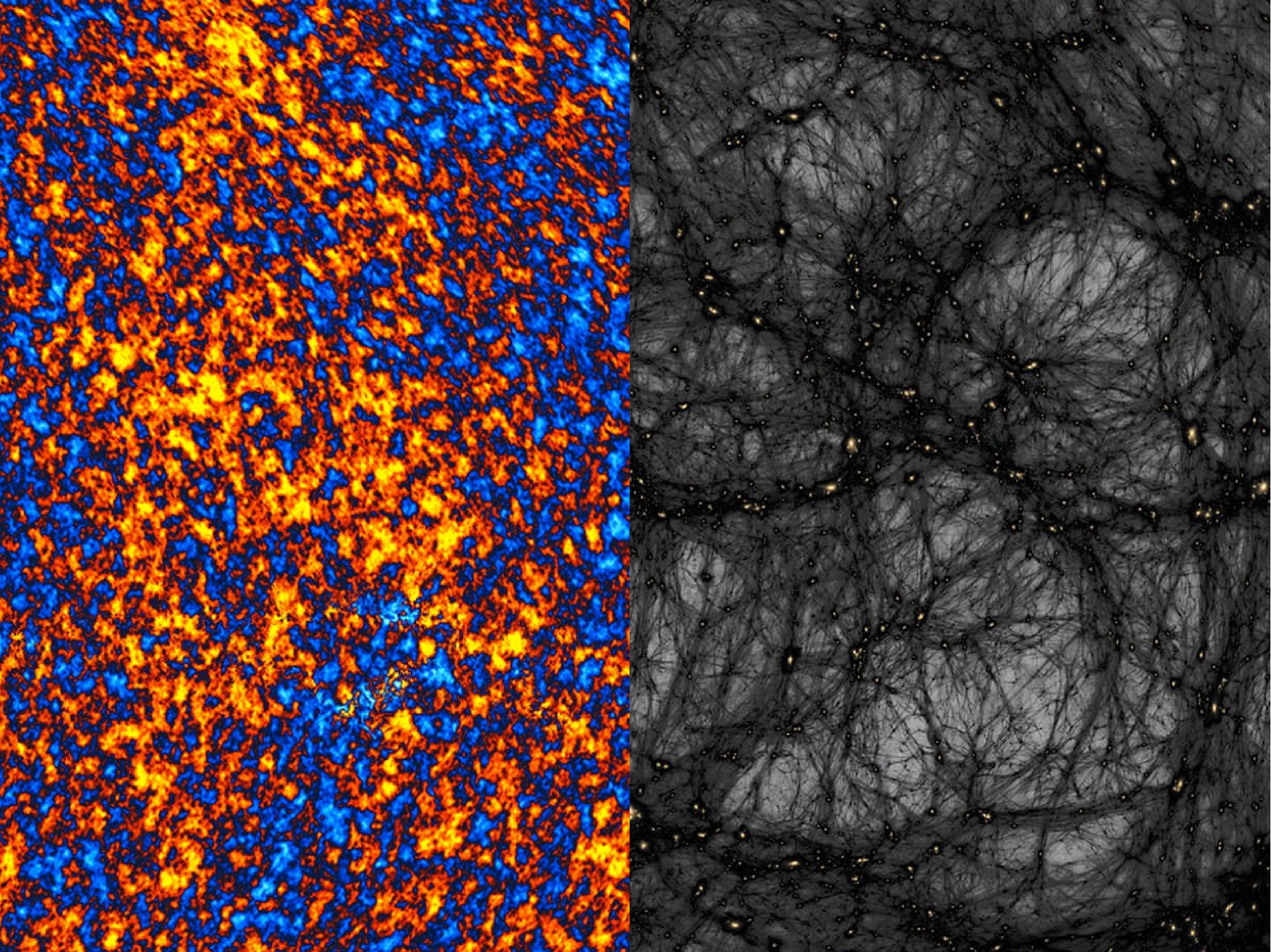
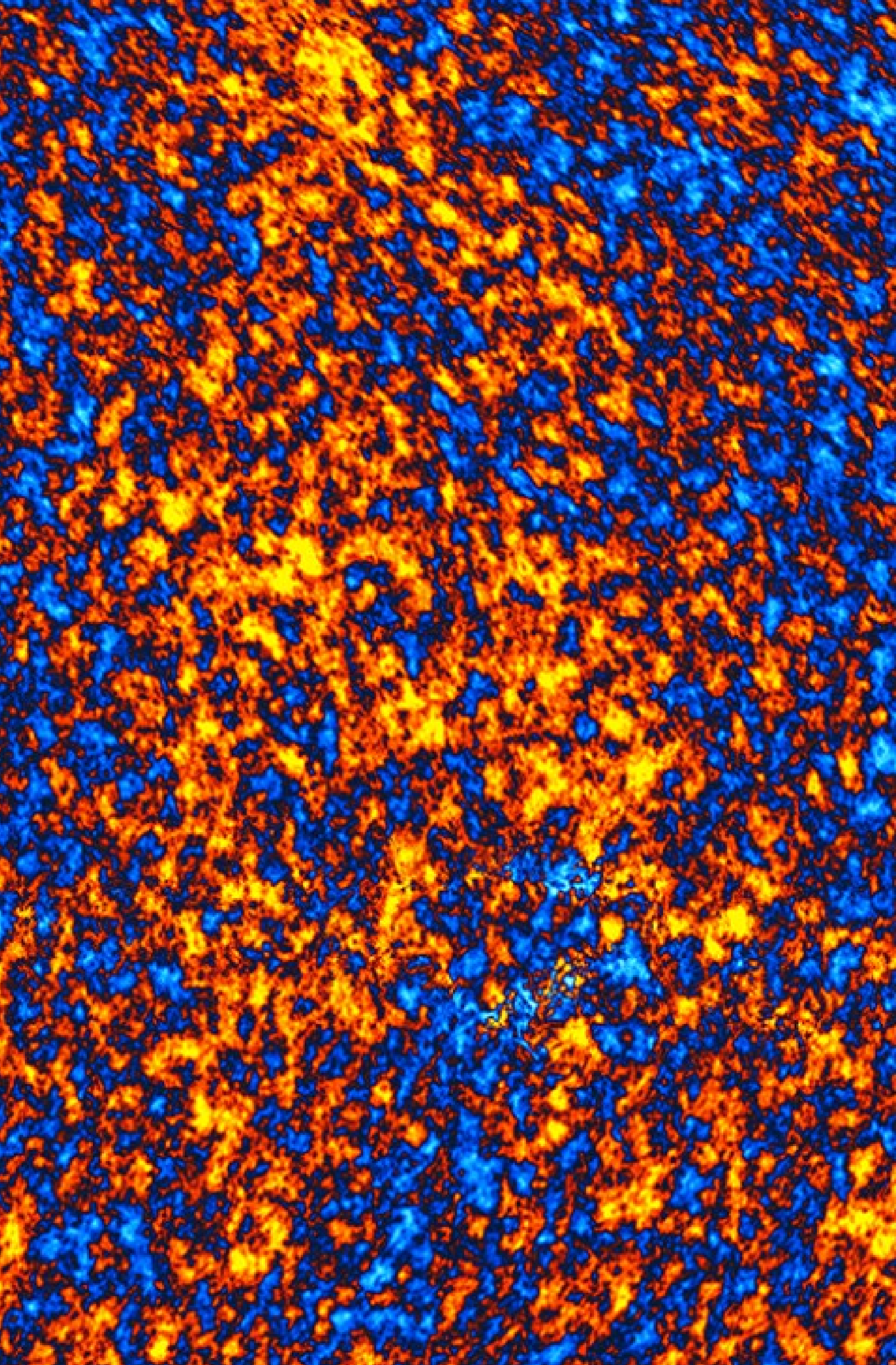
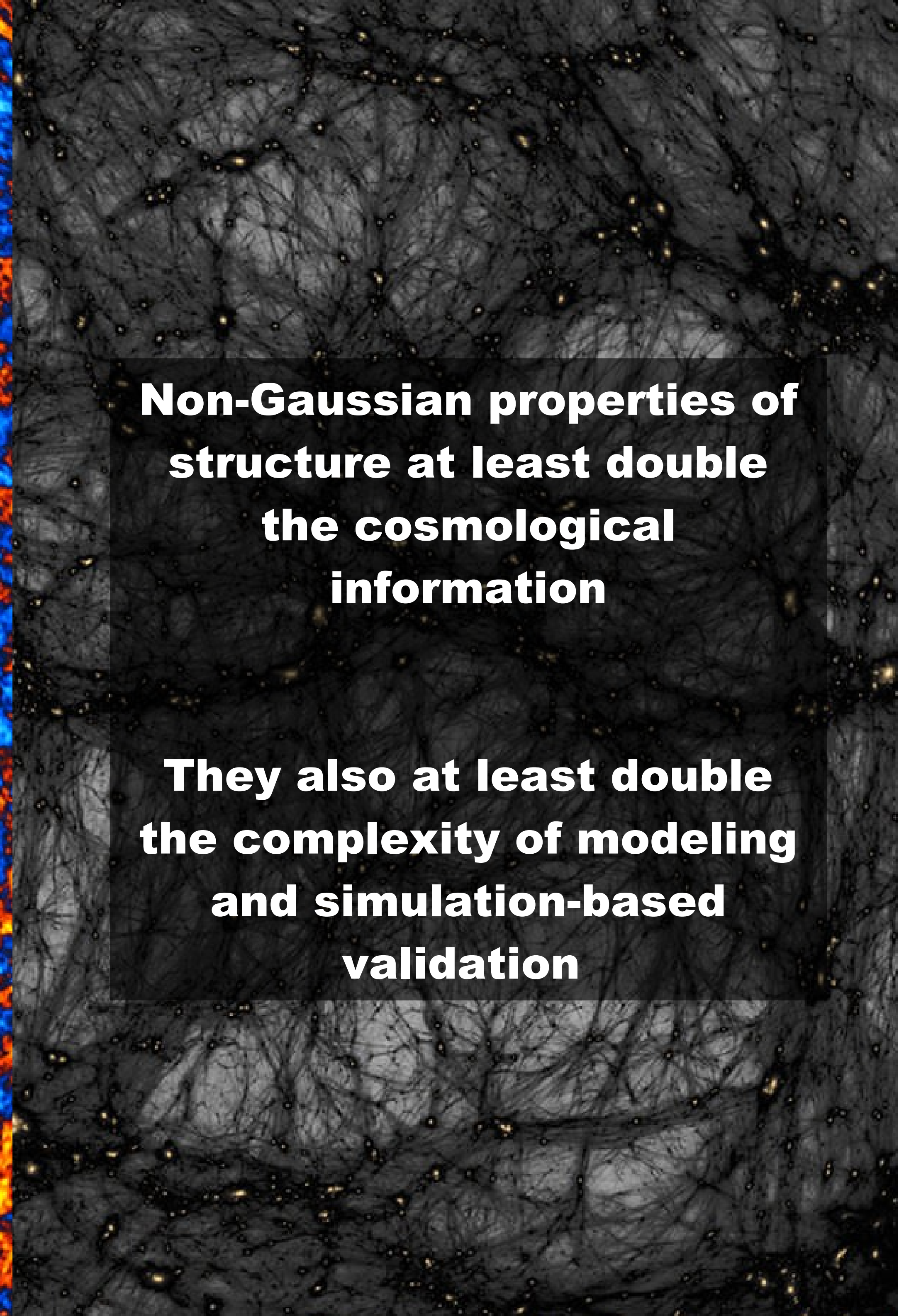
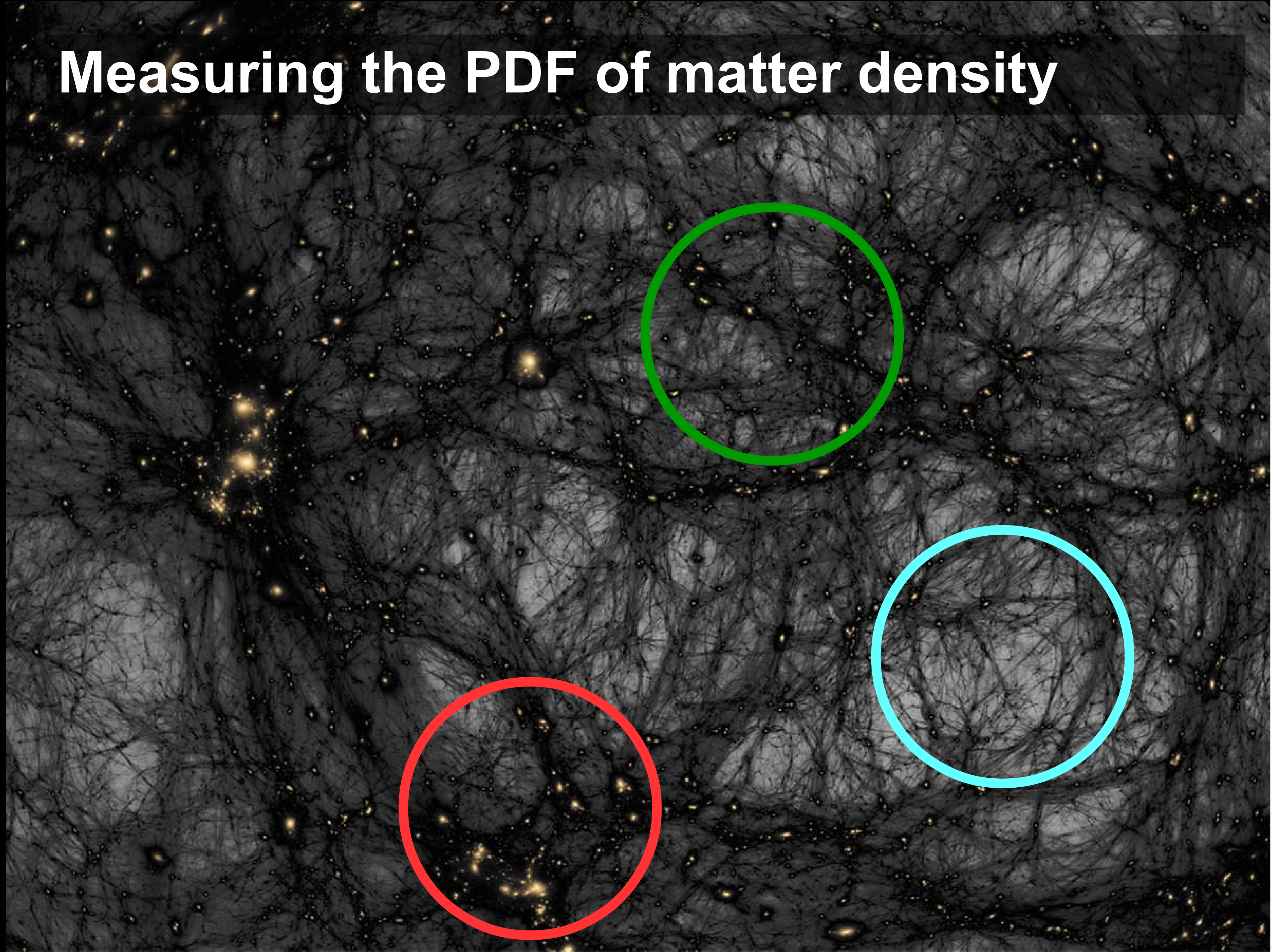






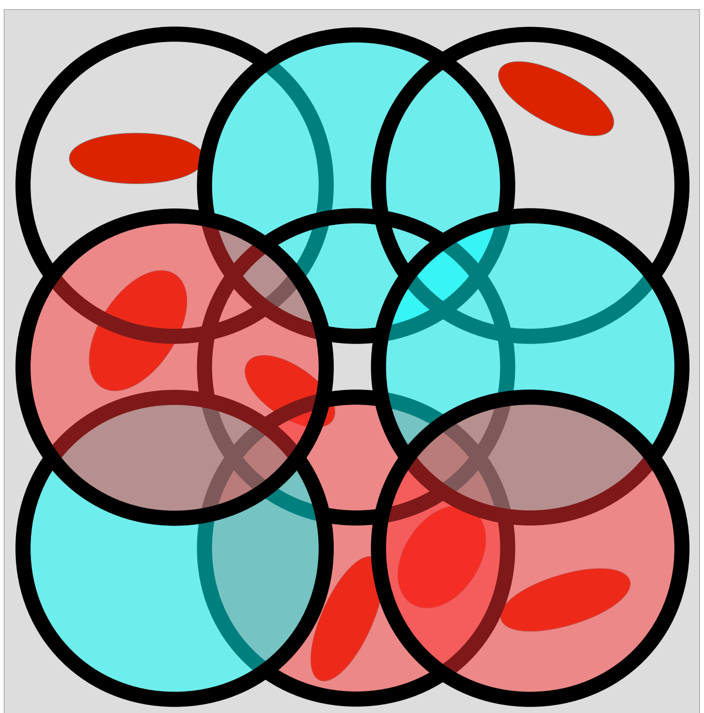
Non-Gaussian properties of structure at least double the cosmological information
They also at least double the complexity of modeling and simulation-based validation

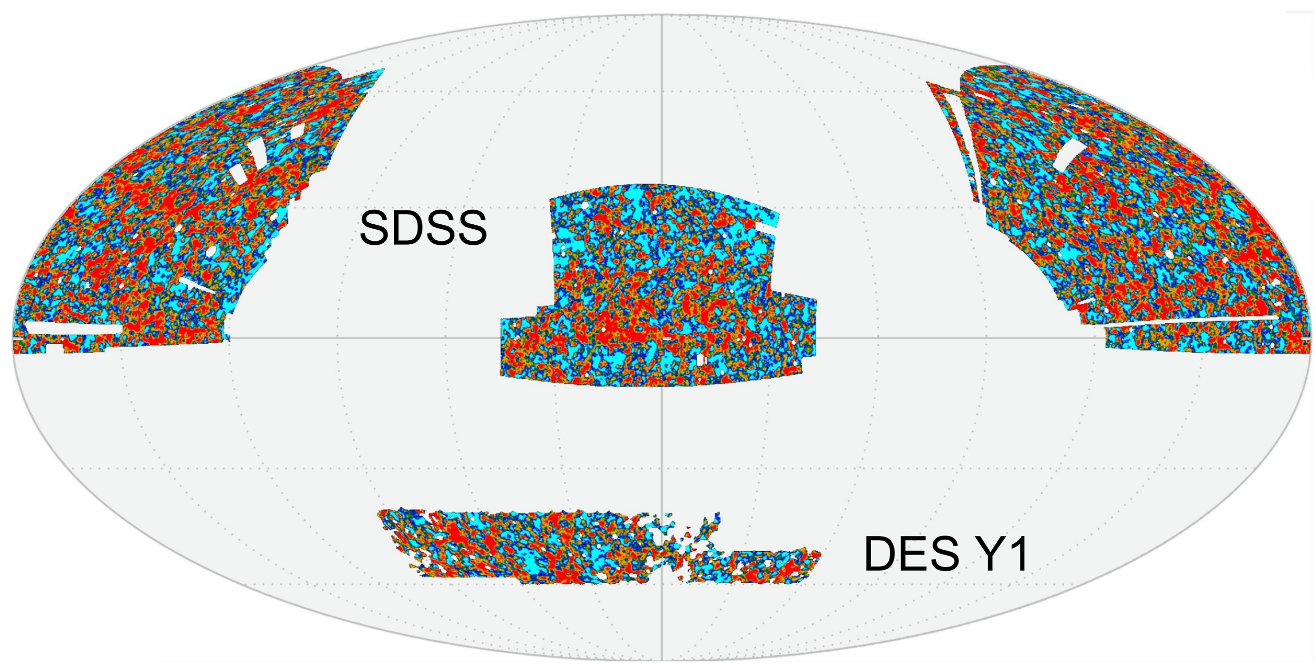
# Measuring the PDF of matter density



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

- Step 1: split lines of sight into quintiles of LRG count – underdense ("troughs") to overdense

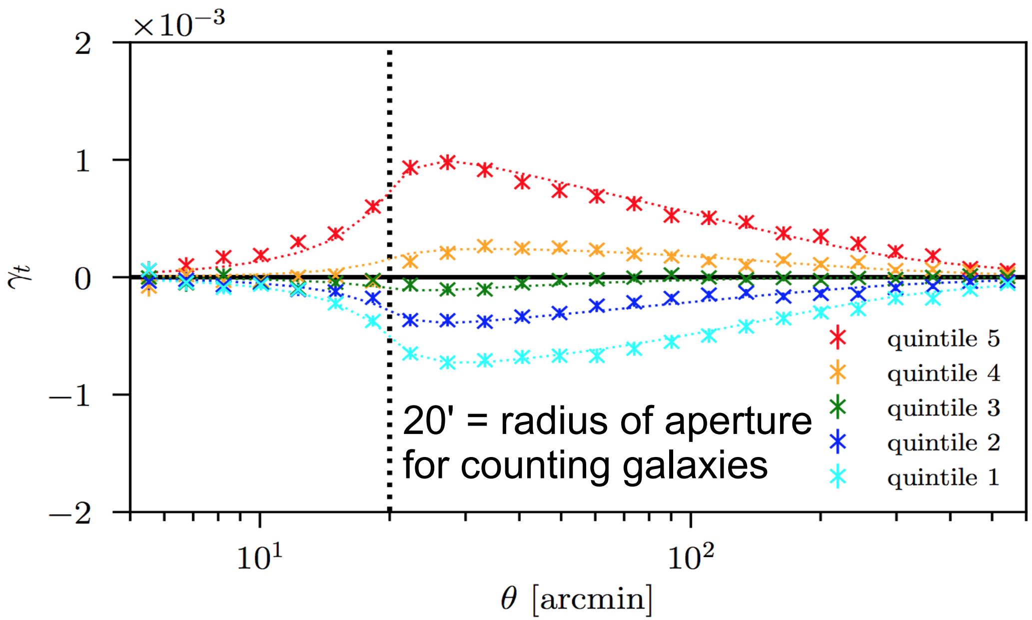


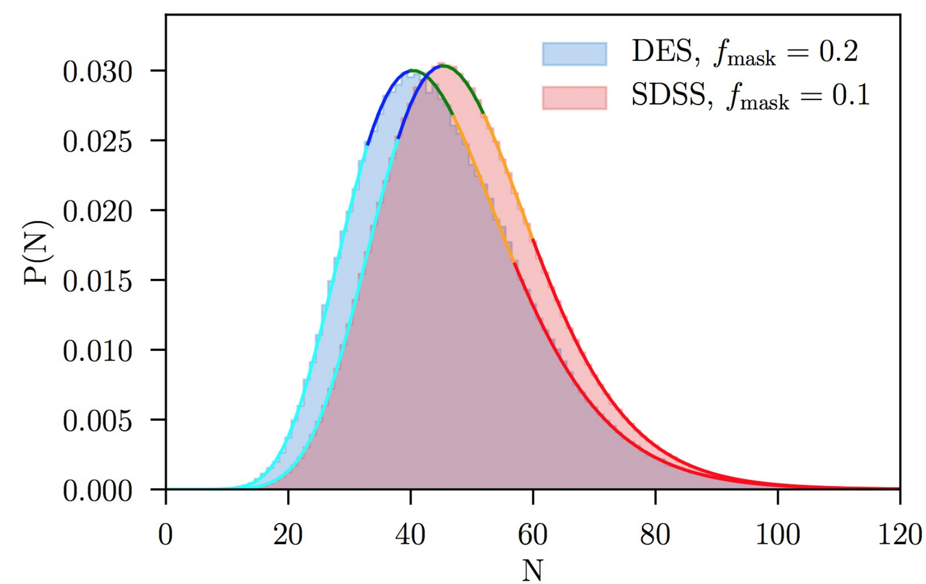



DG+ 2018

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

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

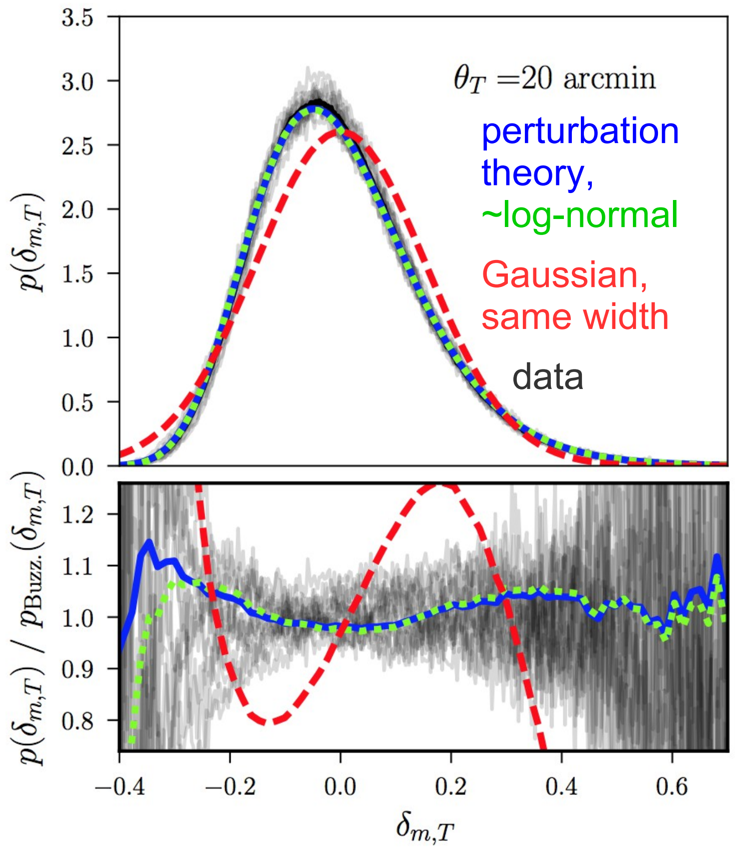



DG+ 2018

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

- Step 1: split lines of sight into quintiles of LRG 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

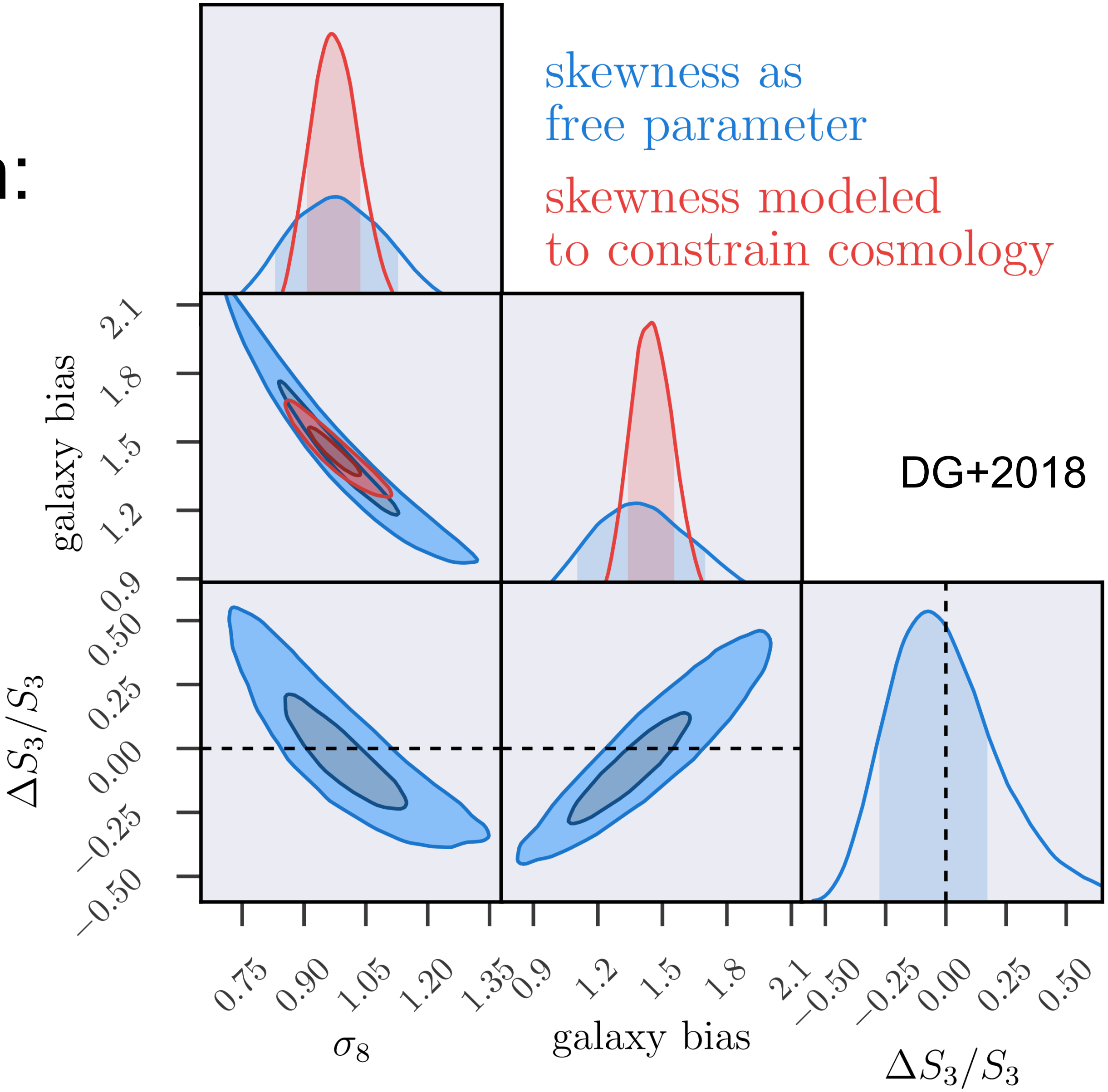



$$\langle\gamma_t\rangle(N) = \int p(\delta_m|N)\,\langle\gamma_t\rangle(\delta_m)\,\mathrm{d}\delta_m$$

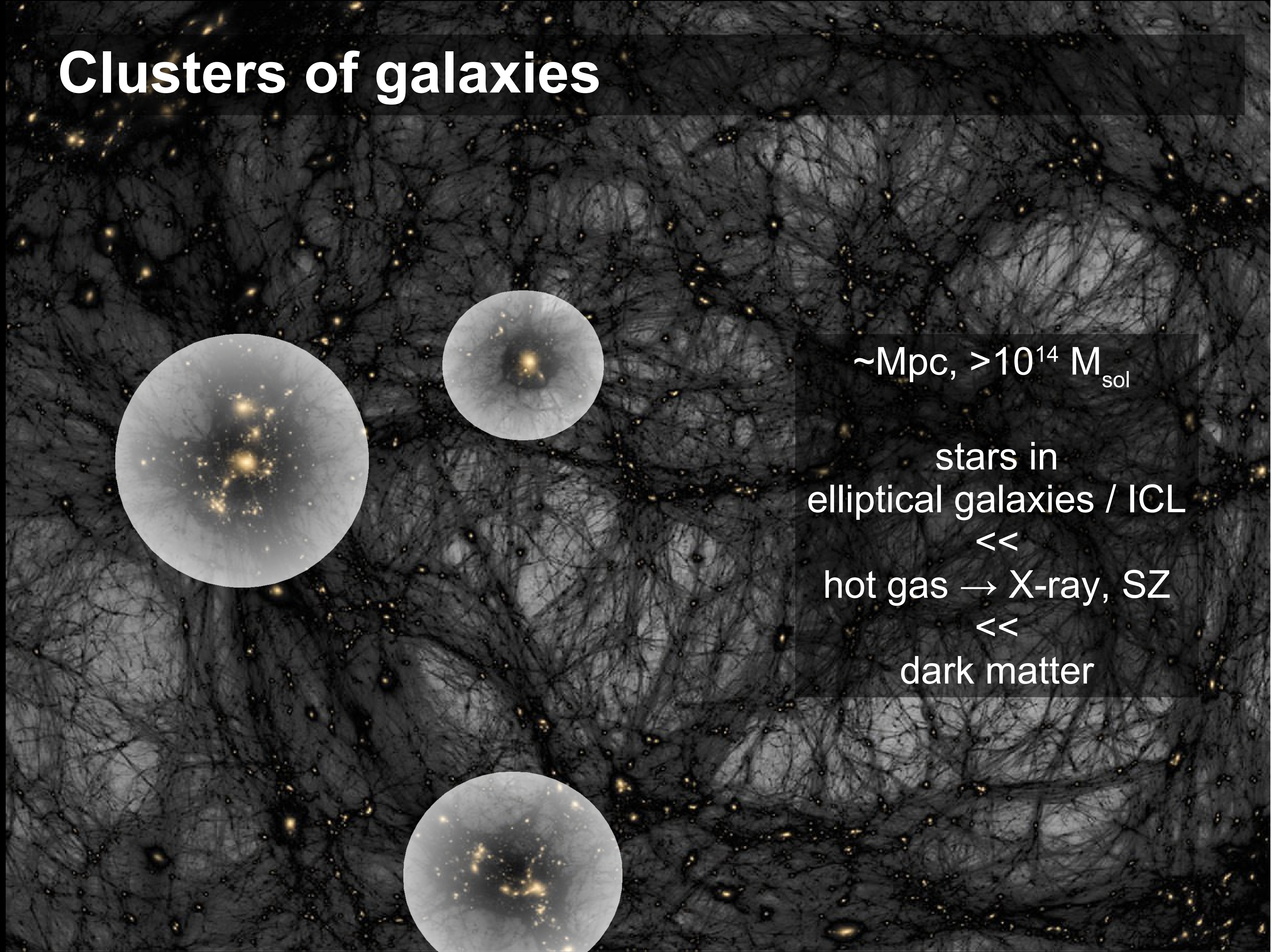
perturbation theory model:
Friedrich, DG+ 2018

# Cosmology from matter/galaxy PDF: constraining skewness of 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 adds significant constraining power
- Limited by stochasticity = higher order bias



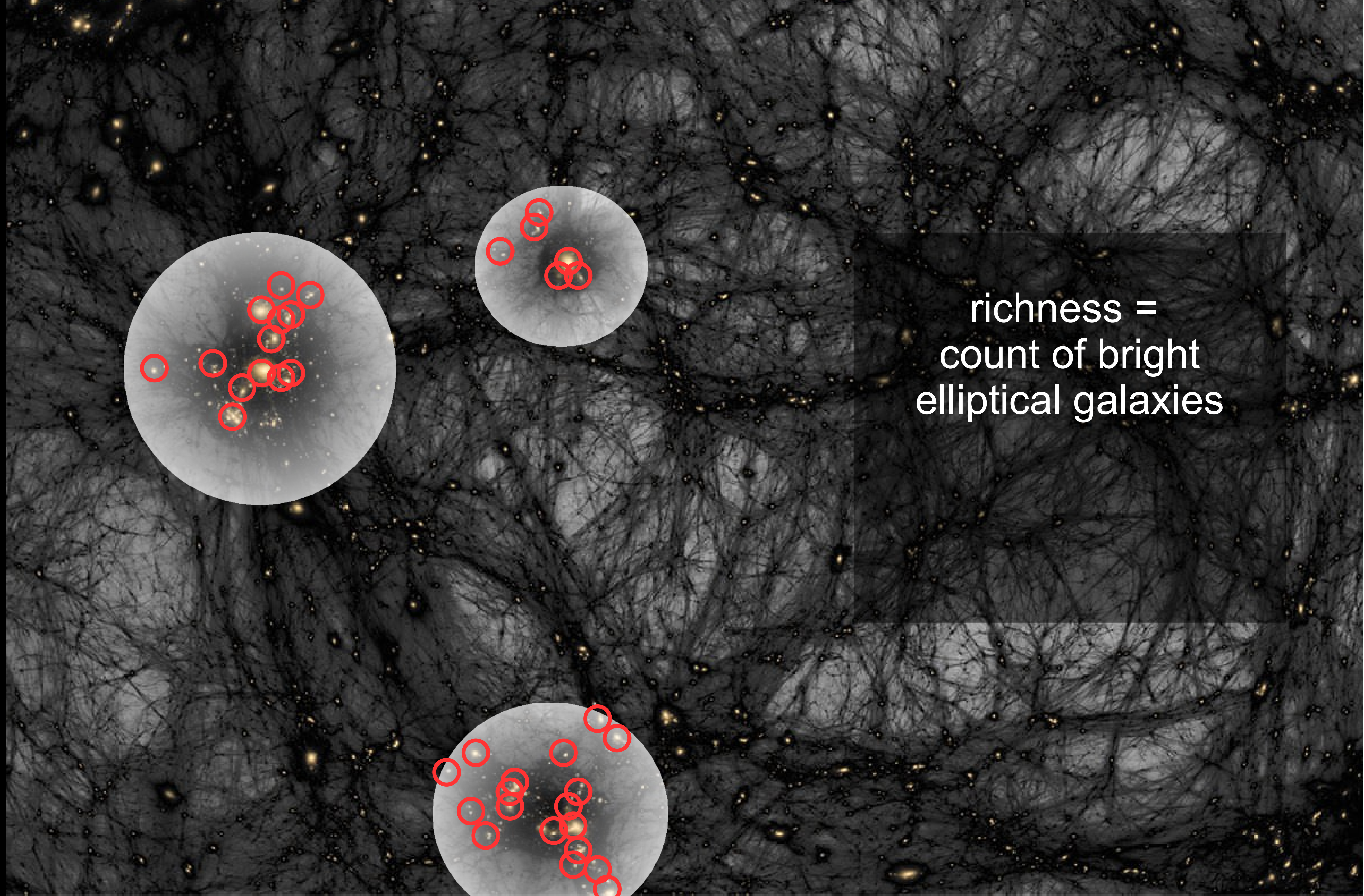
# Clusters of galaxies



~Mpc, $>10^{14}\ M_{sol}$

stars in
elliptical galaxies / ICL
<<
hot gas → X-ray, SZ
<<
dark matter

# Counting clusters of galaxies

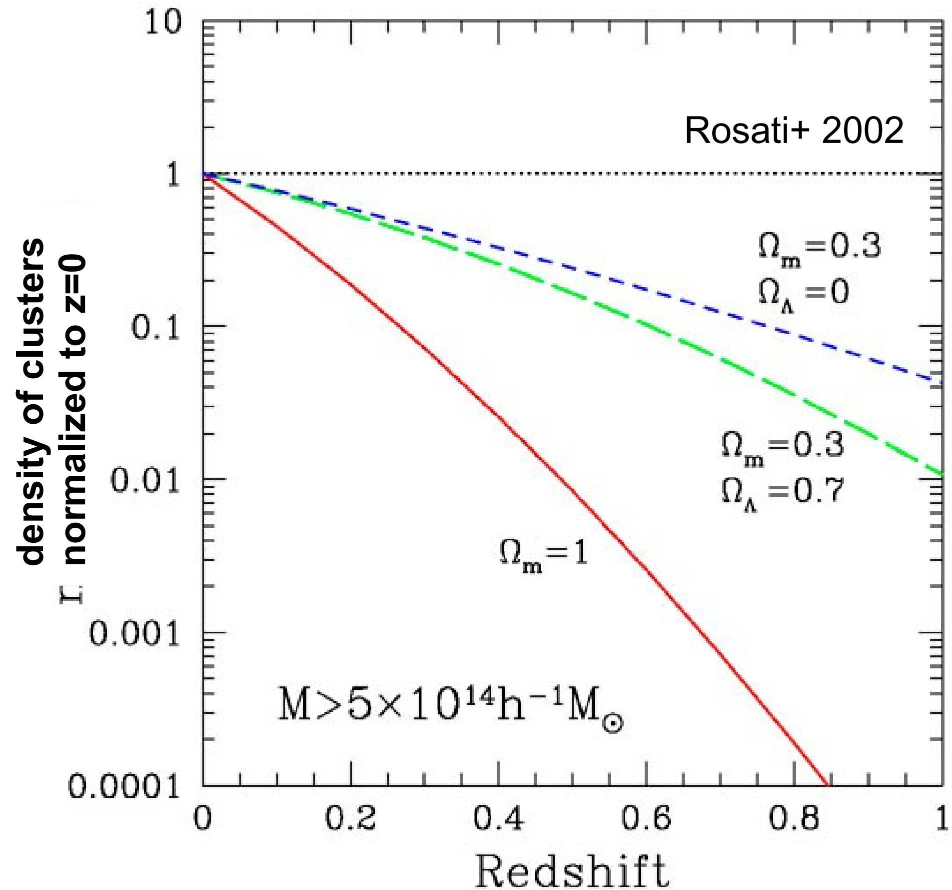


# Cosmology with clusters of galaxies

Simply ...

- Count clusters in an optical survey

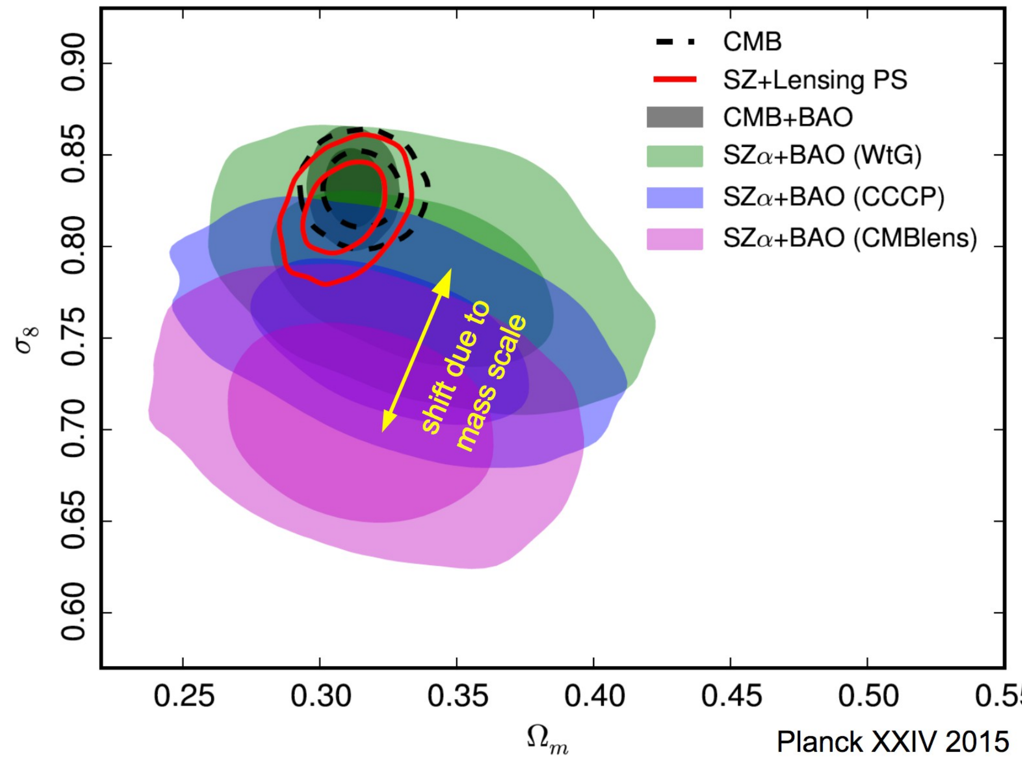
- Compare count to predictions as function of cosmology
  - M dependence: $S_8$, new physics
  - z dependence: Dark Energy



# Cosmology with clusters of galaxies: MOR calibration is key

Simply ...

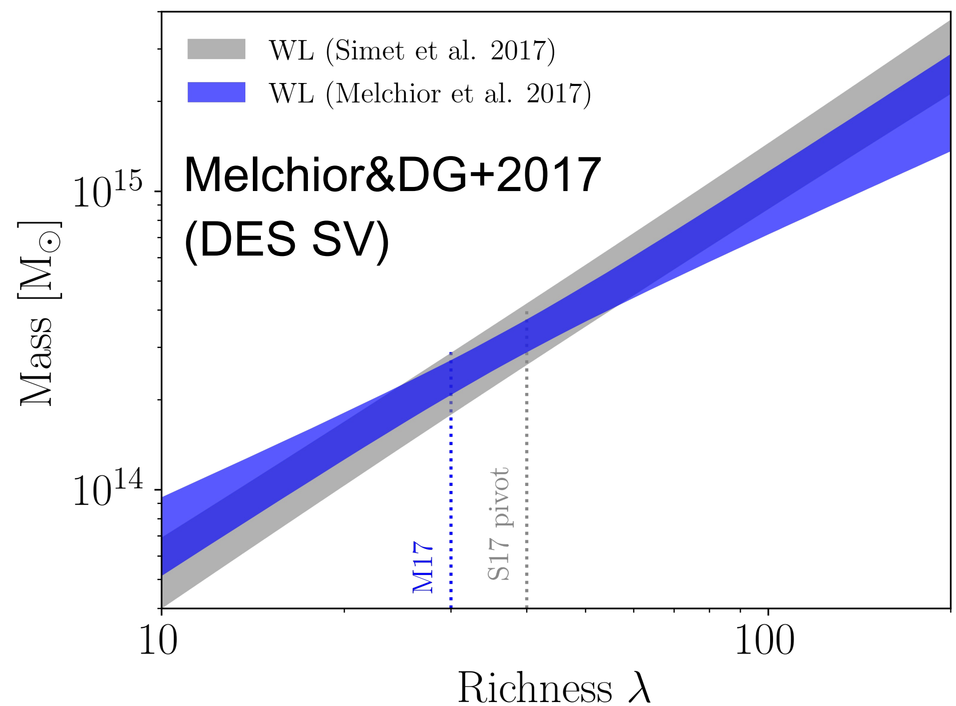
- Count clusters in an optical survey
- Calibrate MOR (mass-observable relation)
- Compare count to predictions as function of cosmology
  - M dependence: $S_8$, new physics
  - z dependence: Dark Energy




Planck XXIV 2015

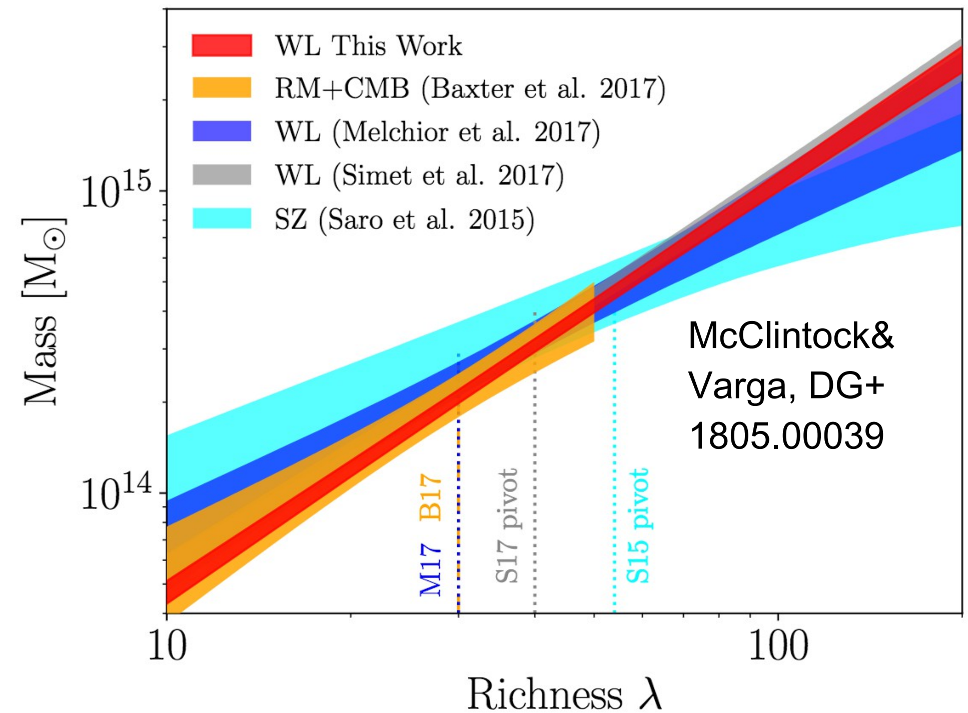
# MOR calibration with lensing surveys

- Large area lensing surveys are now by far the best way of calibrating the MOR of cluster samples (mean mass!)



# Ways forward: MOR calibration with lensing surveys

- Large area lensing surveys are now by far the best way of calibrating the MOR of cluster samples (mean mass!)
- Self-calibration helps [Murata+2018]
- Uncertainties limited by modeling and photo-z




McClintock&
Varga, DG+
1805.00039

| Source of systematic | SV Amplitude uncertainty | Y1 Amplitude Uncertainty |
|---|---|---|
| Shear measurement | 4% | 1.7% |
| Photometric redshifts | 3% | 2.6% |
| Modeling systematics | 2% | 0.73% |
| Cluster triaxiality | 2% | 2.0% |
| Line-of-sight projections | 2% | 2.0% |
| Membership dilution + miscentering | $\leqslant$ 1% | 0.78% |
| **Total Systematics** | 6.1% | 4.3% |
| **Total Statistical** | 9.4% | 2.4% |
| **Total** | 11.2% | 5.0% |

photo-z

modeling (galaxy-matter connection)

# Mass-observable relation: We are limited by scatter prior

- greatly improved model for scatter due to projection effects [Costanzi&Rozo+2018a]
- <u>intrinsic</u> scatter is a free parameter
- prior motivated by dedicated & archival X-ray and SZ data
- daily telecons, unblinding next week?
- DES Y1 clusters will significantly add to $S_8$ issue – we need to get this right

**preliminary and blind**

DES in prep.

see also Costanzi&Rozo+2018ab, McClintock&Varga, DG+2018, DG+2018b, Zhang+2018, Varga+in prep., Farahi+in prep., von der Linden&Mantz+in prep.

# Summary

- The Dark Energy Survey tests cosmology competitively, with lensing-empowered measurements of structure.
  - Consistency with Planck CMB, but intriguingly low $S_8$
  - Different, almost fully independent, views of Gaussian and non-Gaussian properties of density field with full PDF and cluster counts
- Geometry and growth of structure are complementary. DES is the first photometric survey to join them. Both are consistent with the simple yet crazy $\Lambda$CDM.
- Stay tuned for 5x more DES, HCS, and the next generation.