THE DARK ENERGY SURVEY

Dark Energy Survey: Cosmological Constraints from Y1

Daniel Gruen, NASA Einstein Fellow at SLAC/Stanford/KIPAC

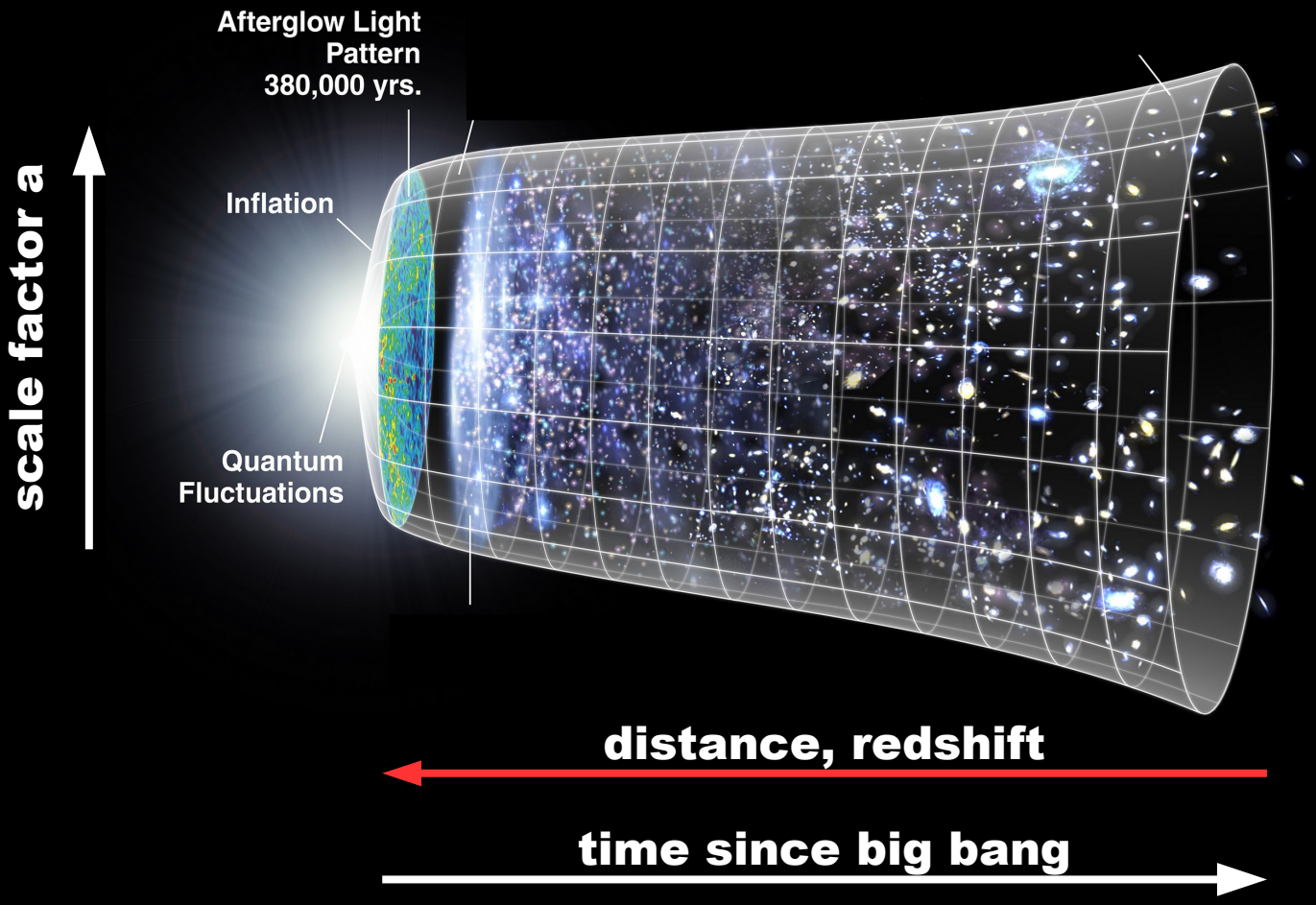
on behalf of the DES Collaboration

30th Rencontres de Blois, Jun 8 2018

Structure of this talk

- Introduction
  - Cosmology & Dark Energy from structure
  - Dark Energy Survey
- Dark Energy Survey Cosmology results from
  - Two-point correlation of matter density
  - PDF of matter density
  - Peaks of matter density

Observing our expanding Universe



Blois, June 8, 2018
Daniel Gruen / Dark Energy Survey

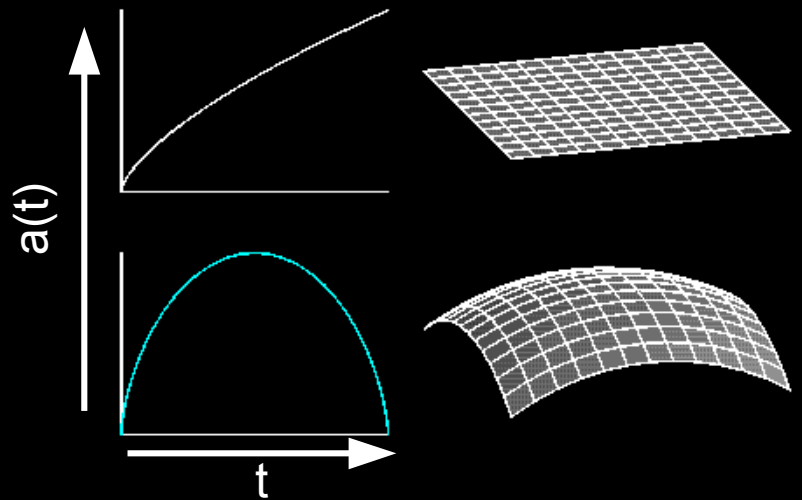
What goes up must come down?

- 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 $p \geqq 0$



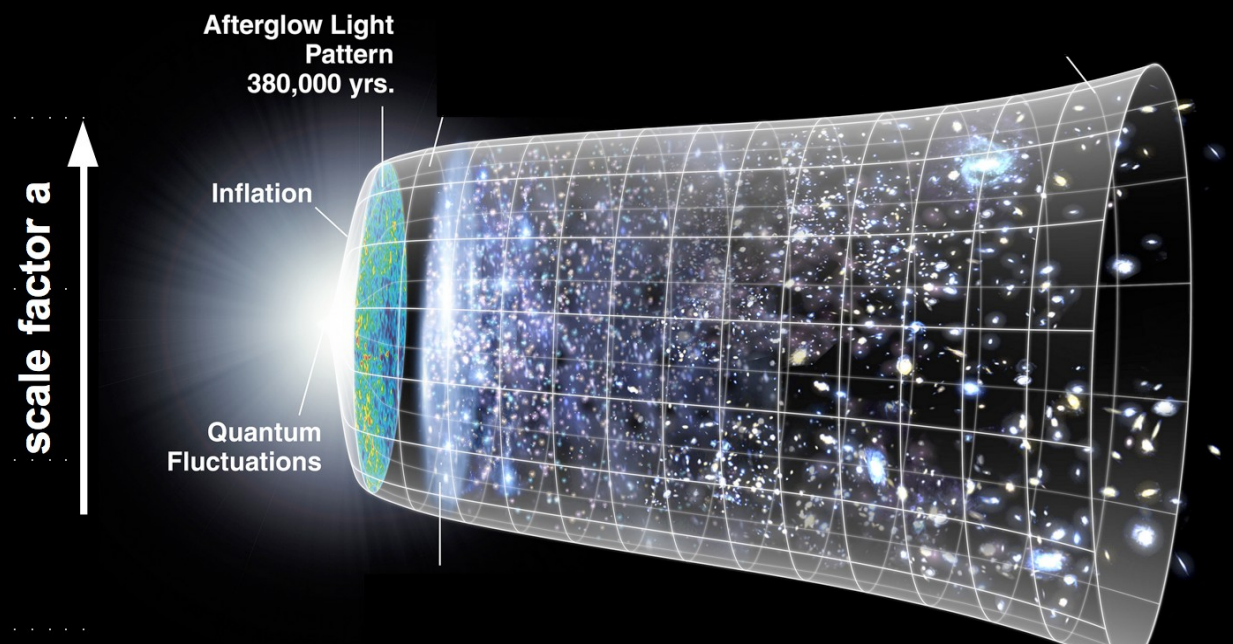
What goes up keeps getting faster!

- 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"



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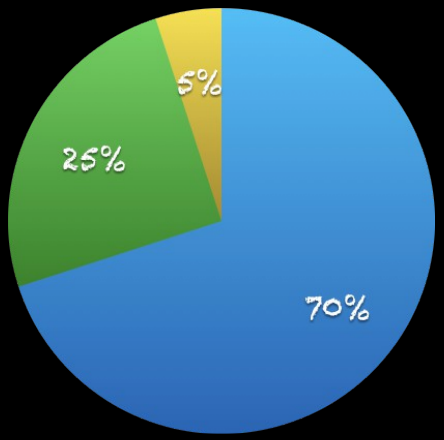
- Parameters of this universe:
  - Densities of matter (Ω_m~0.3), dark energy (Ω_Λ~0.7), baryons (~0.05), neutrinos
  - Amplitude of structure σ_8~0.8
  - Expansion rate h~0.69

"fiducial cosmology"



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 only interacts via gravitation
- We have a wide range of independent observations that cannot be explained without these assumptions; there is no other compelling, more well-founded model

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- 70% of energy content of Universe is an unknown substance that appears like vacuum energy, but 120 orders of magnitude smaller than QFT prediction
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- So let's improve our tests of its basic predictions

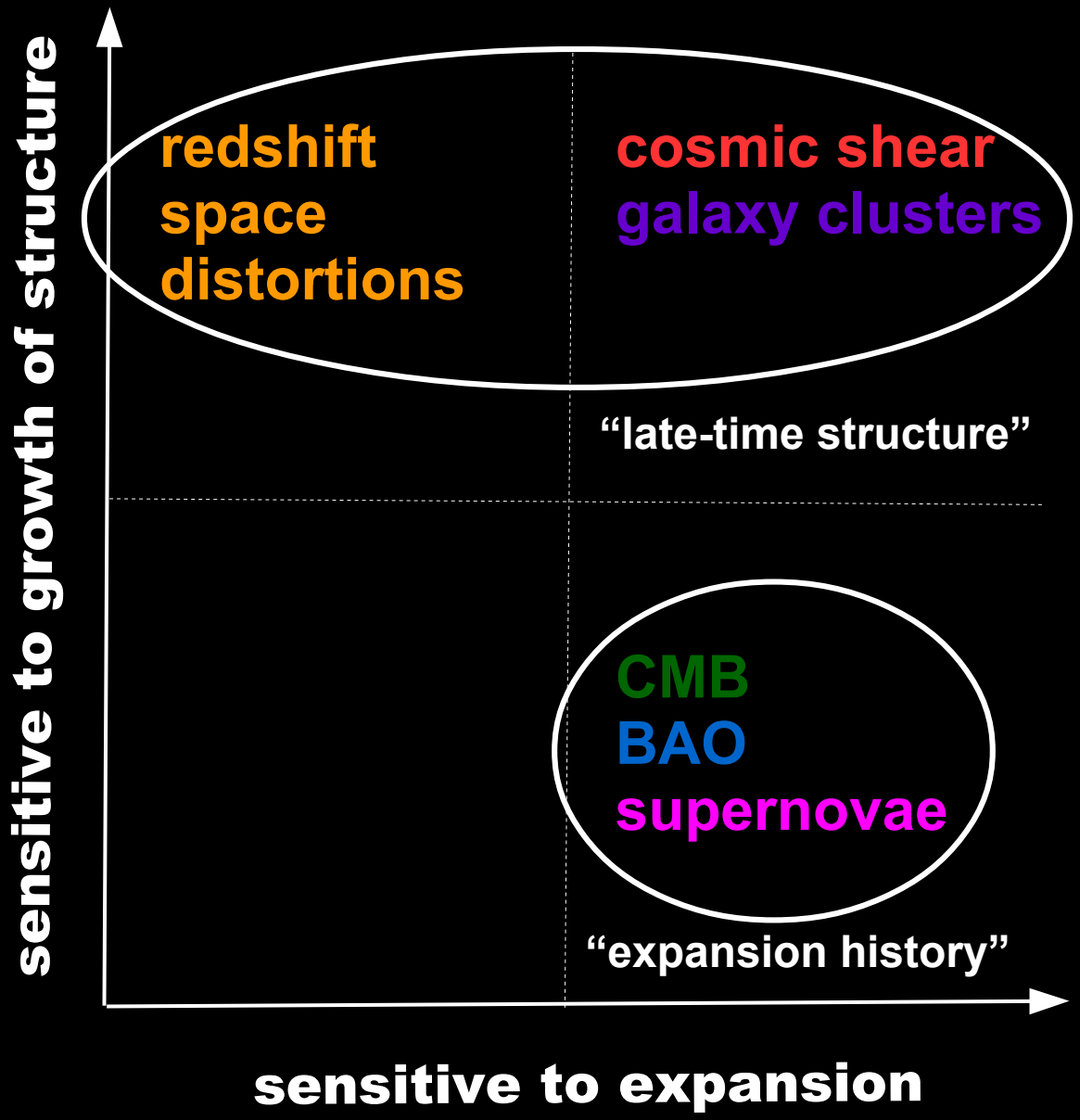
Are data from **early Universe** and **late Universe** fit by the same parameters?

Do measurements of **cosmic distances** and growth of **structure** agree?

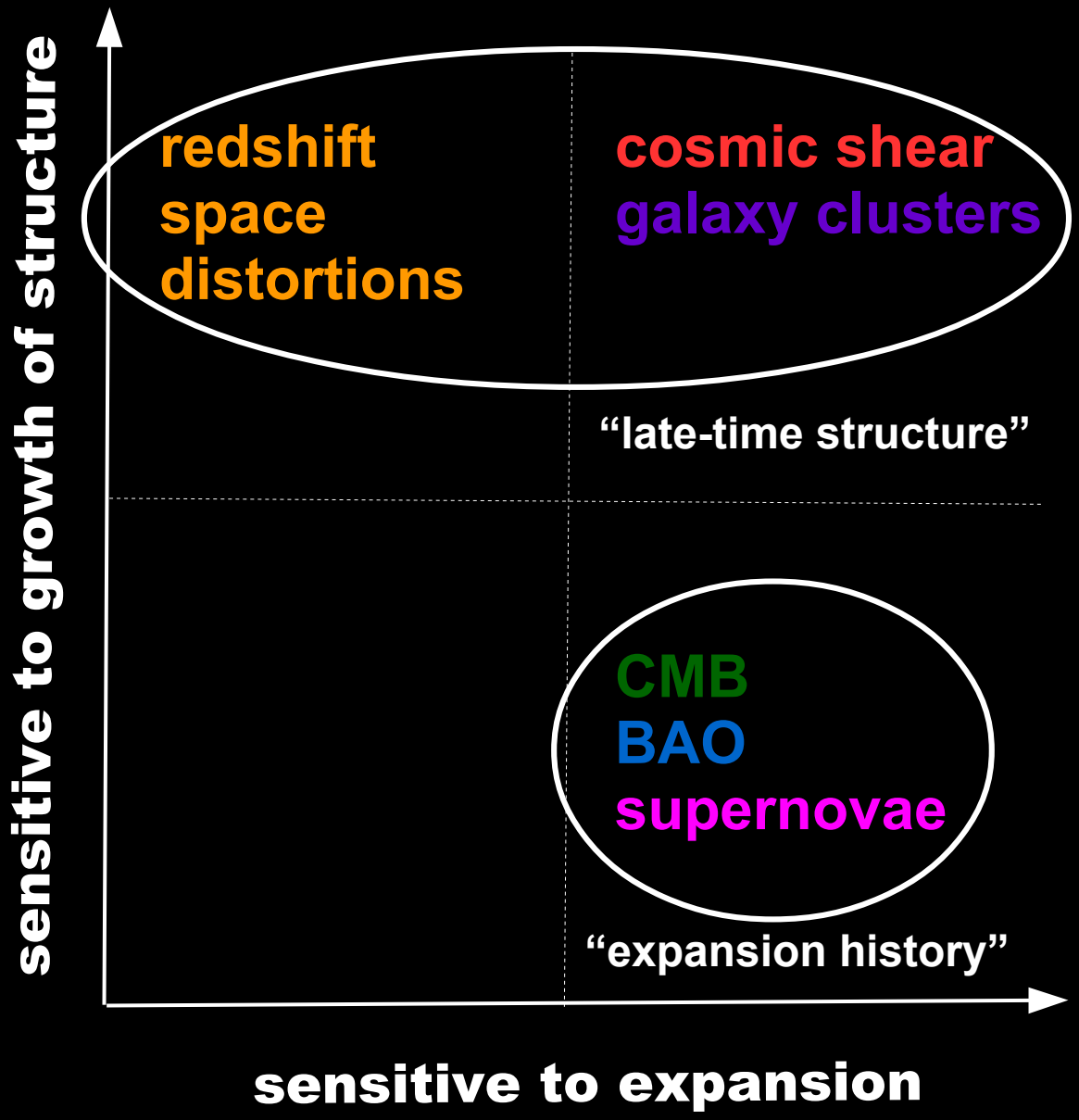
Does the dark energy density change as space expands?

"Equation of state" parameter **w=pressure/density**

How to survey Dark Energy



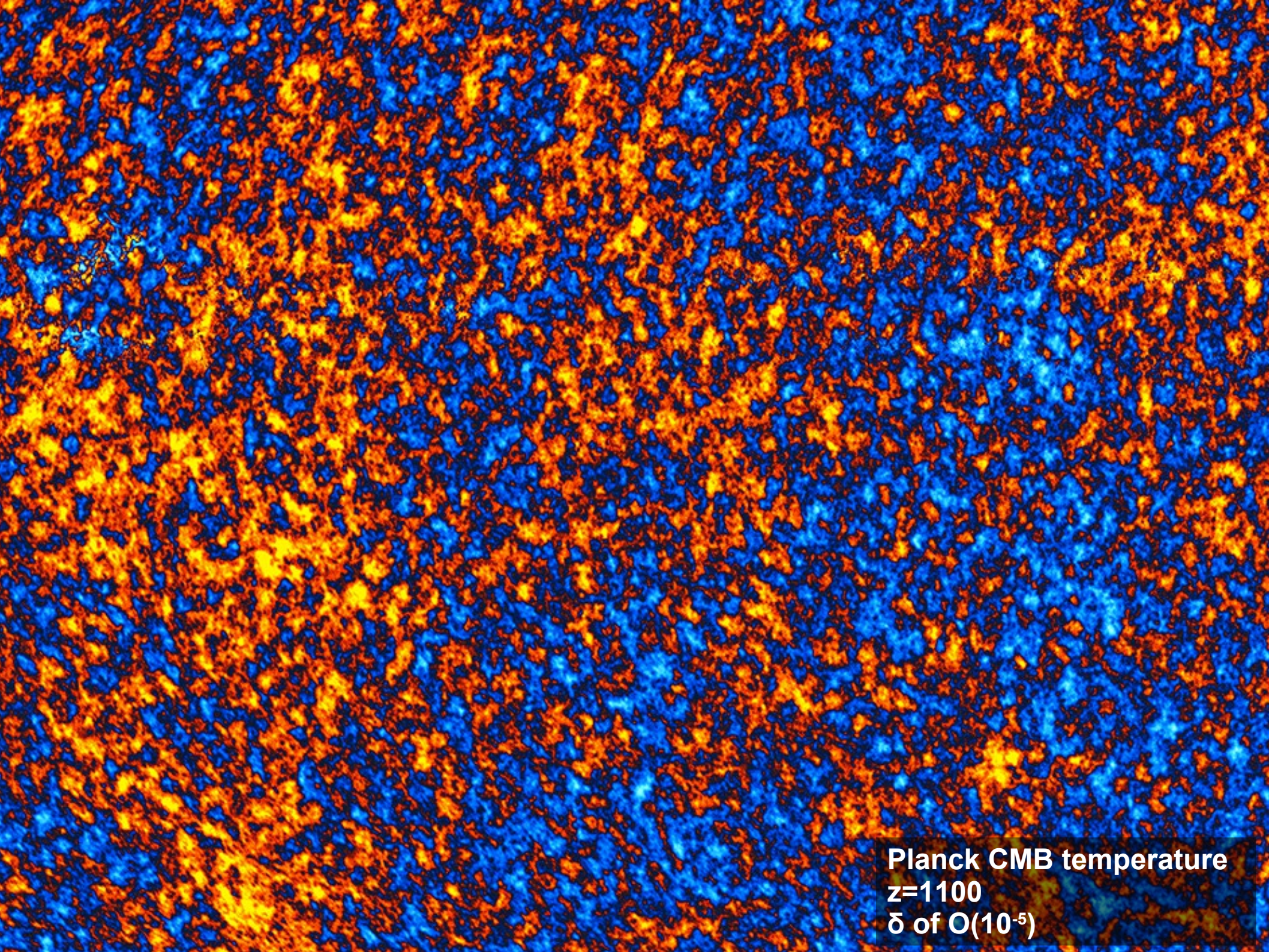
How to survey Dark Energy

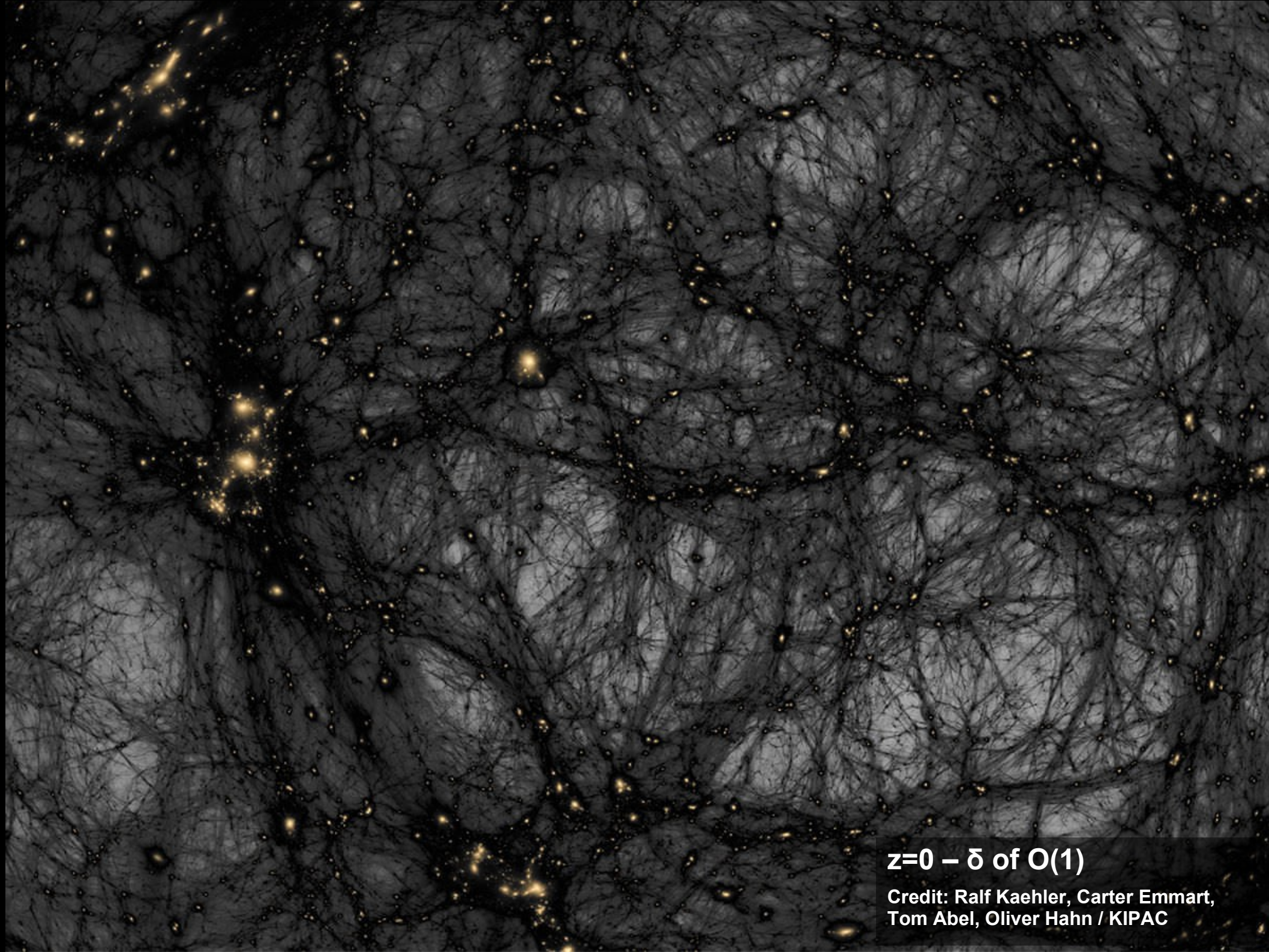


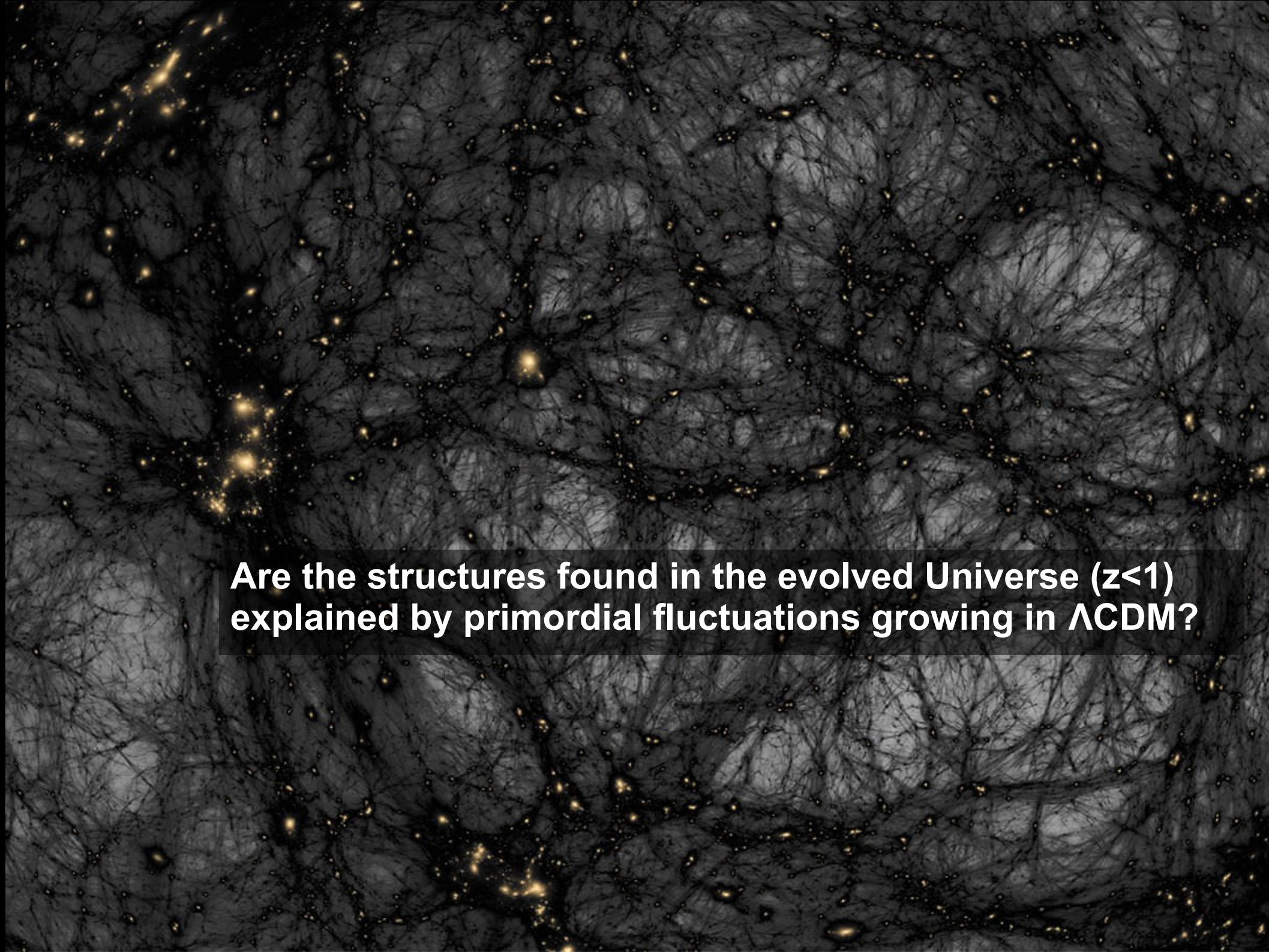
Expansion paints a consistent picture of a fiducial ΛCDM model.*

How about structure?

* except if you count the tension w.r.t. local H_0 measurements


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

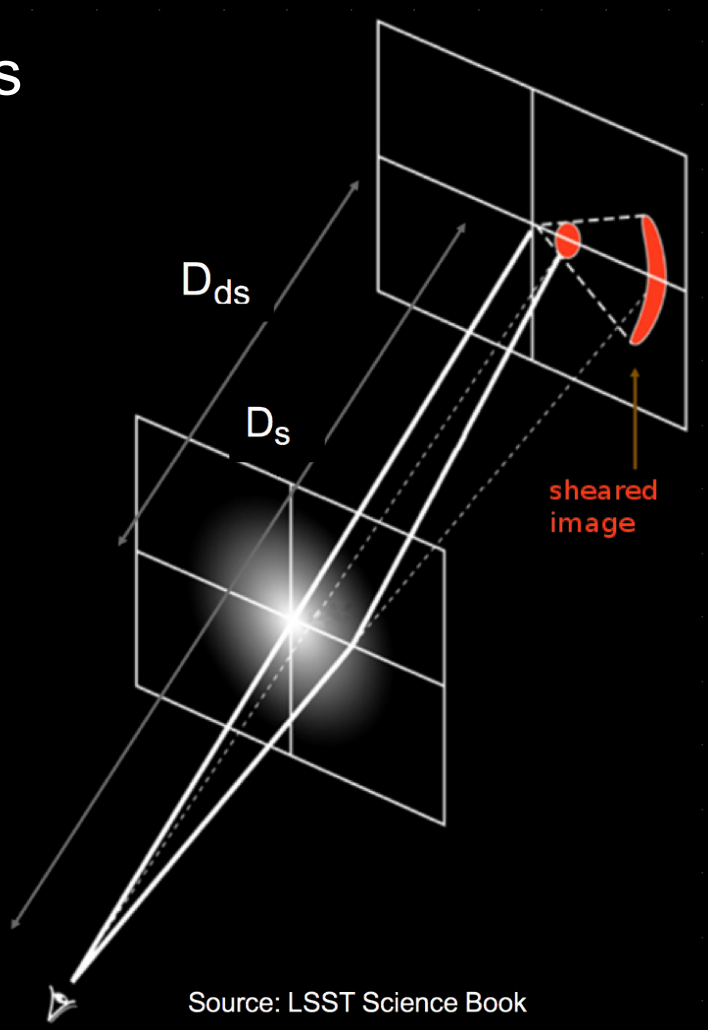

Are the structures found in the evolved Universe (z<1)
explained by primordial fluctuations growing in ΛCDM?

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

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

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



Source: LSST Science Book

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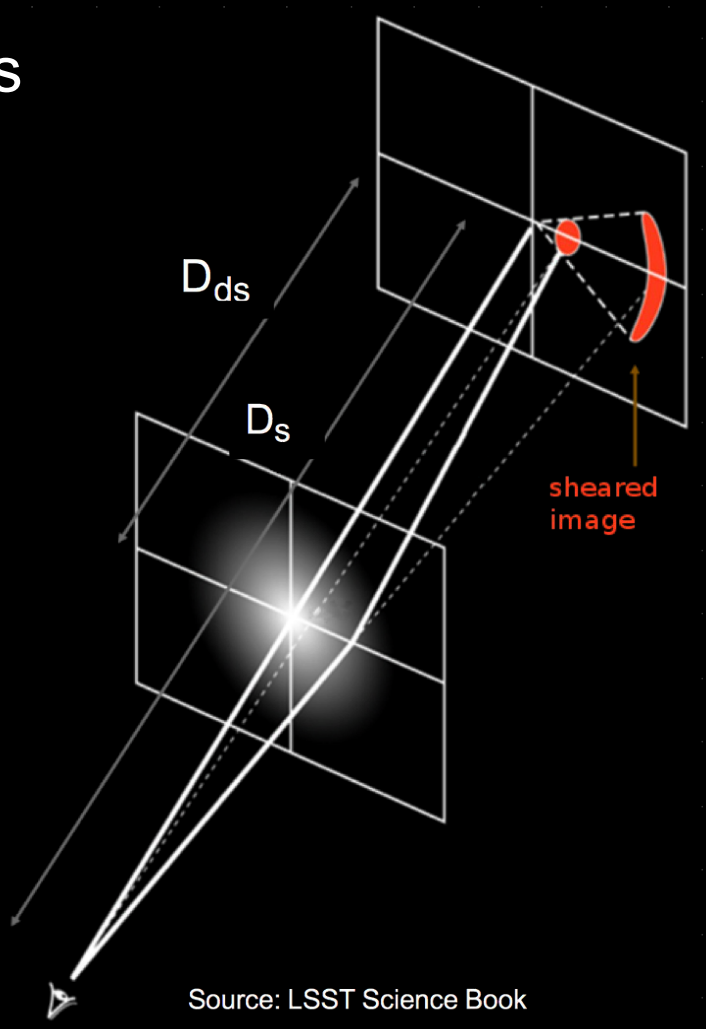


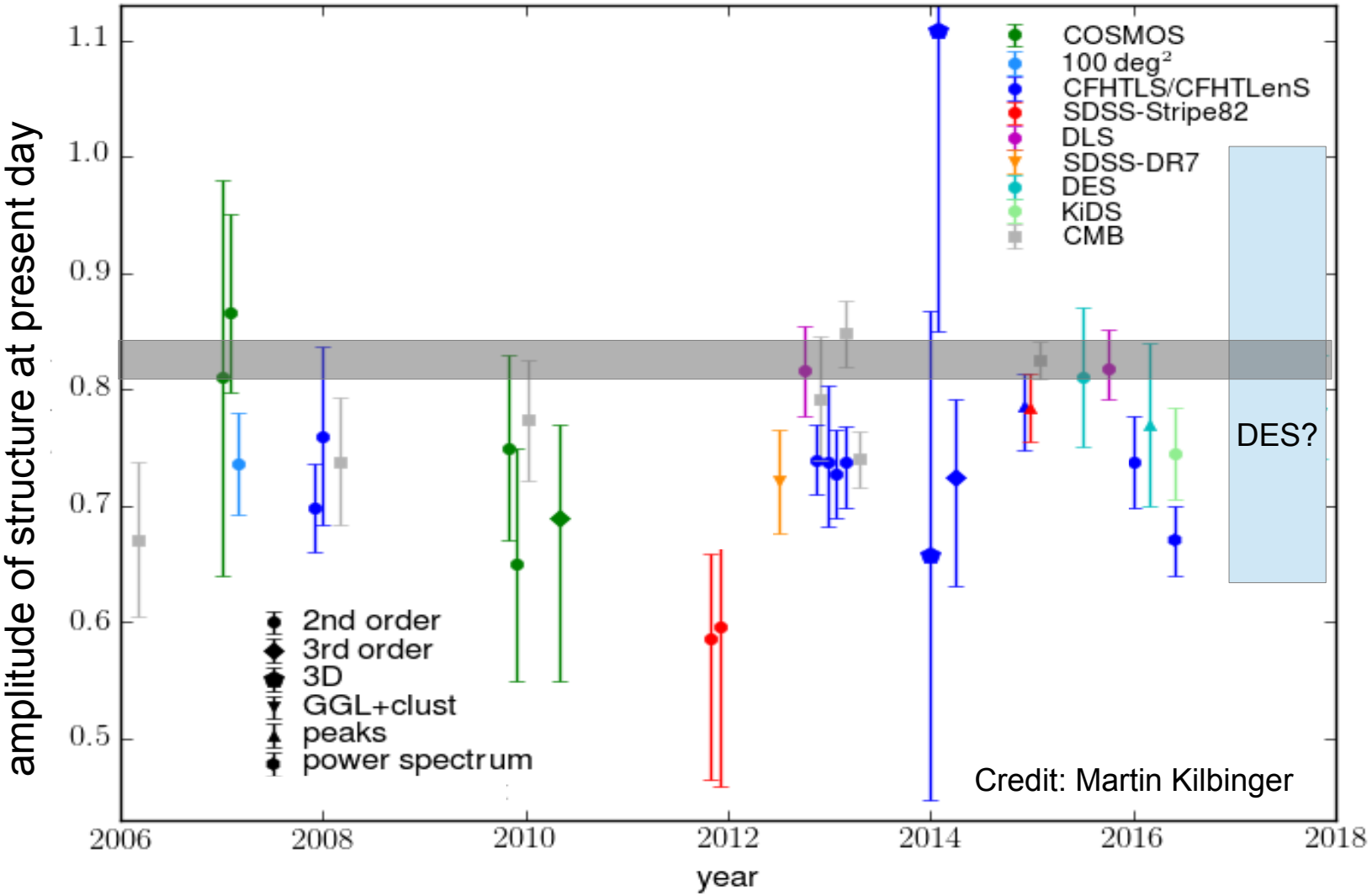
Source: LSST Science Book

Need to measure galaxy shapes and redshift distributions

Gravitational lensing by a galaxy cluster

RXC J2248.7-4431, z=0.35; DG+2014

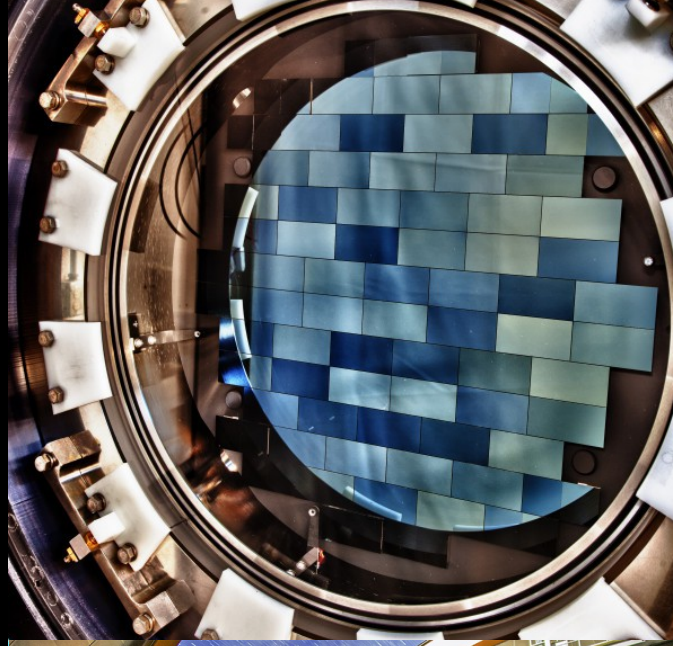
Measurements of evolved structure: Is gravitational lensing low?

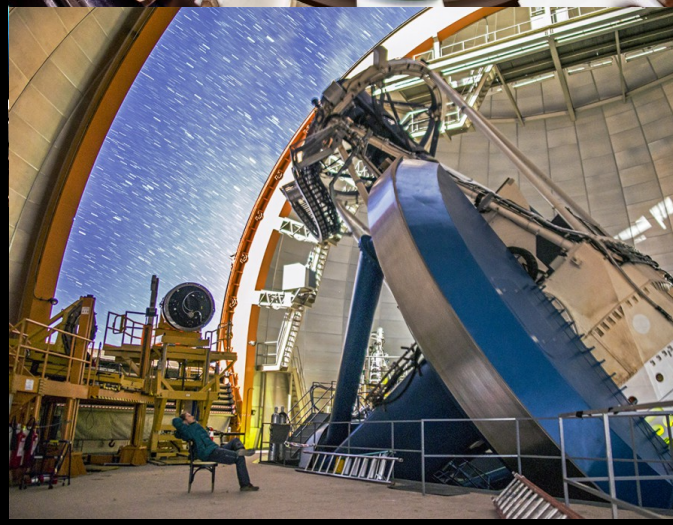


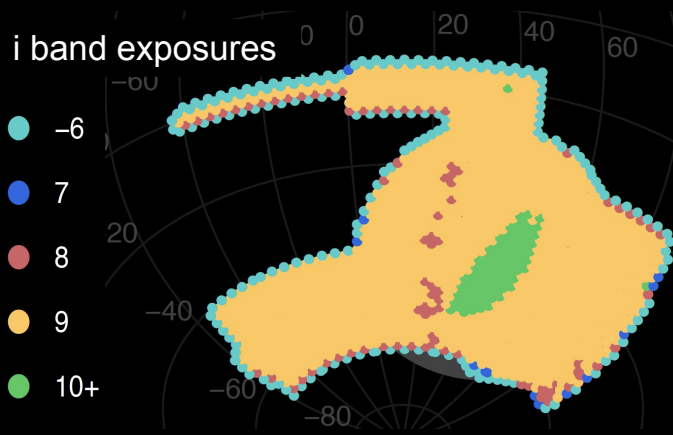
- recent studies have claimed 2-3σ offset from Planck CMB in Ω_m-σ_8
  but see Troxel&Krause, DG+ 1804.10663
- interpretations differ – statistical fluke, systematics, crack in ΛCDM?

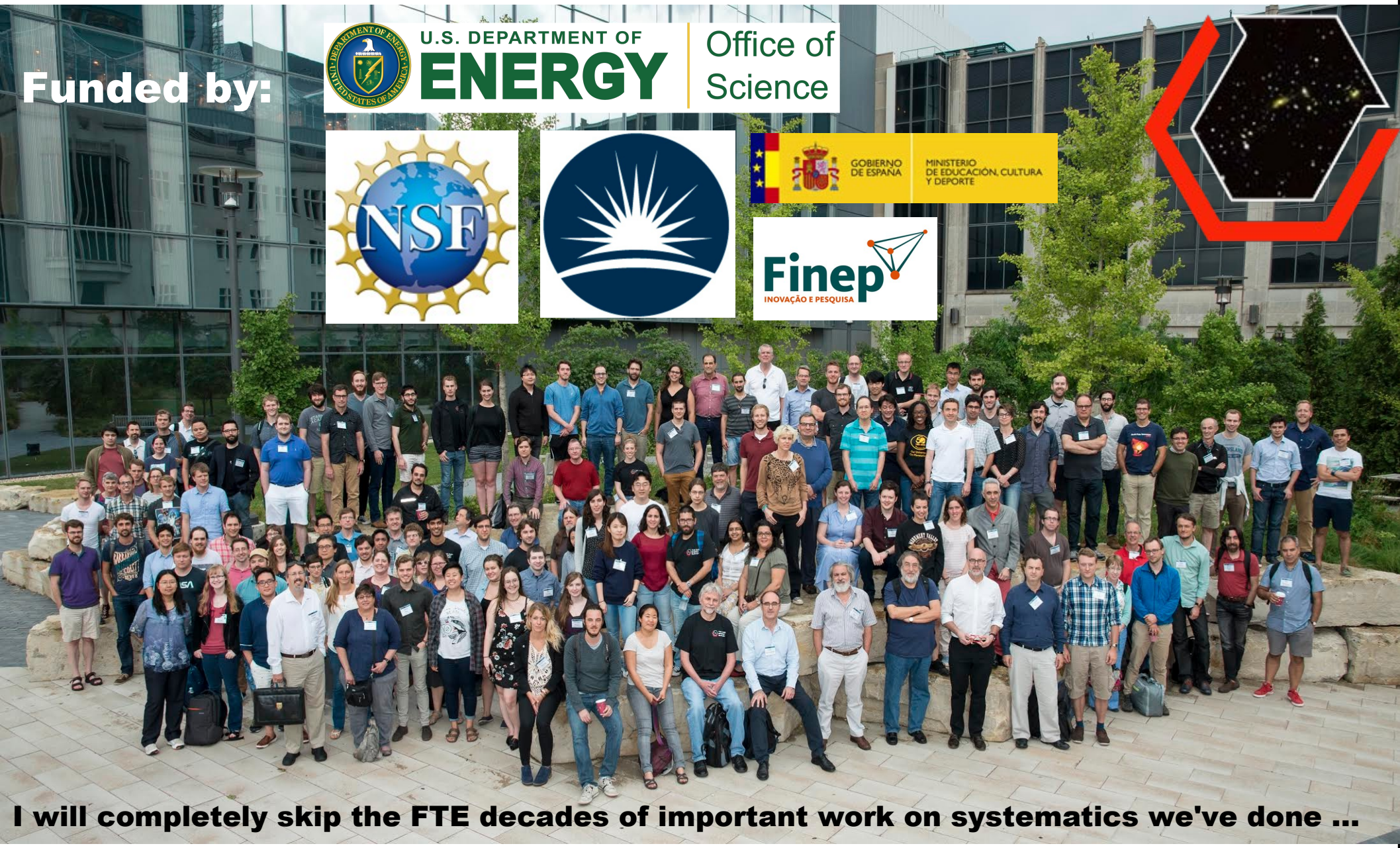
The Dark Energy Survey

- 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





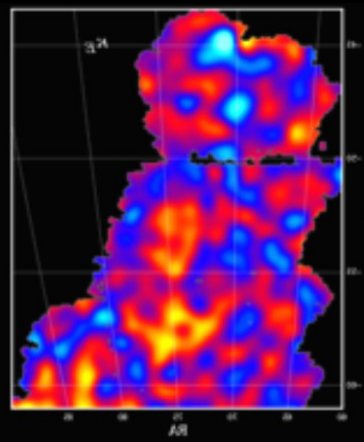




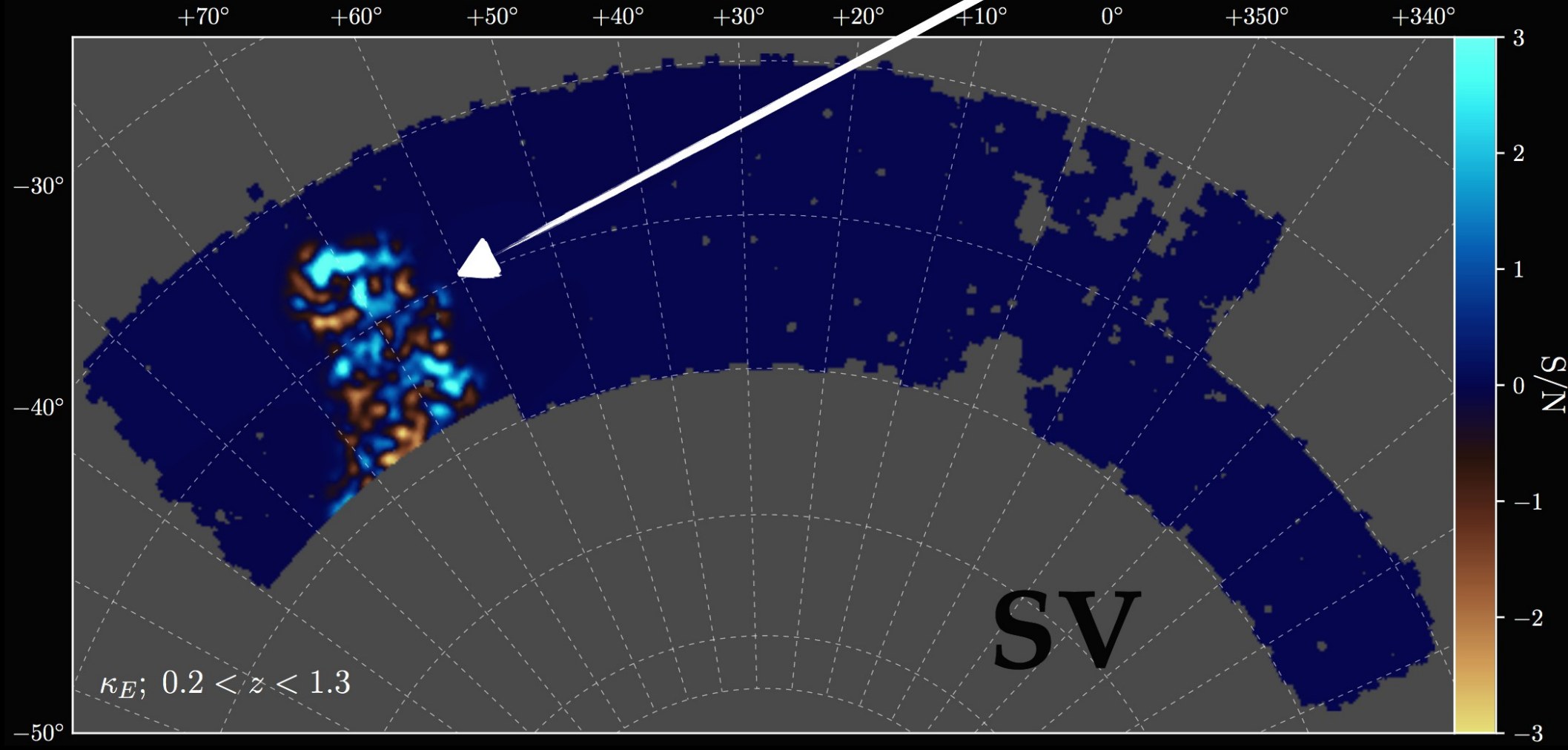
Collaborating institutions:

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

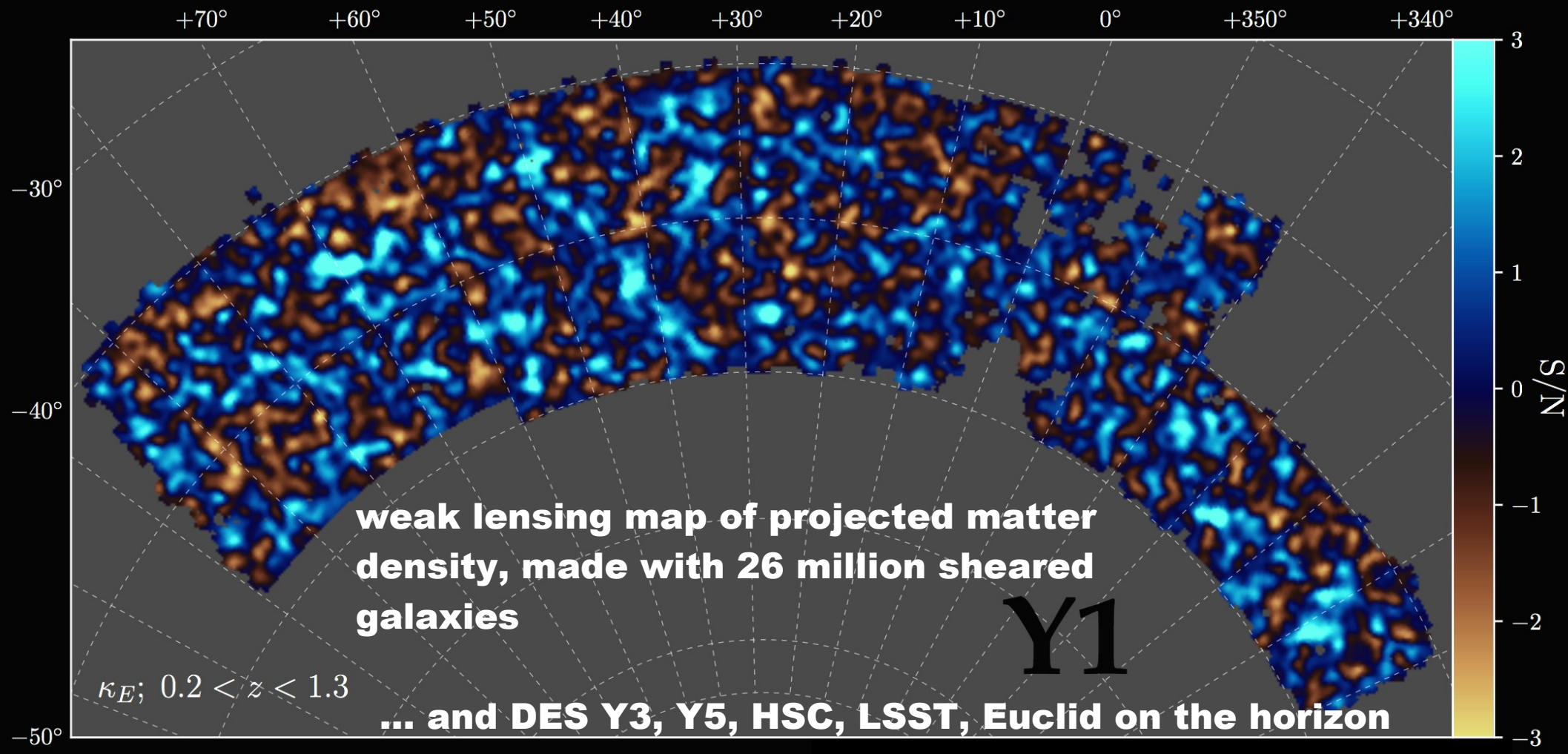
DES SV ...



Chang+; Vikram+ 2016

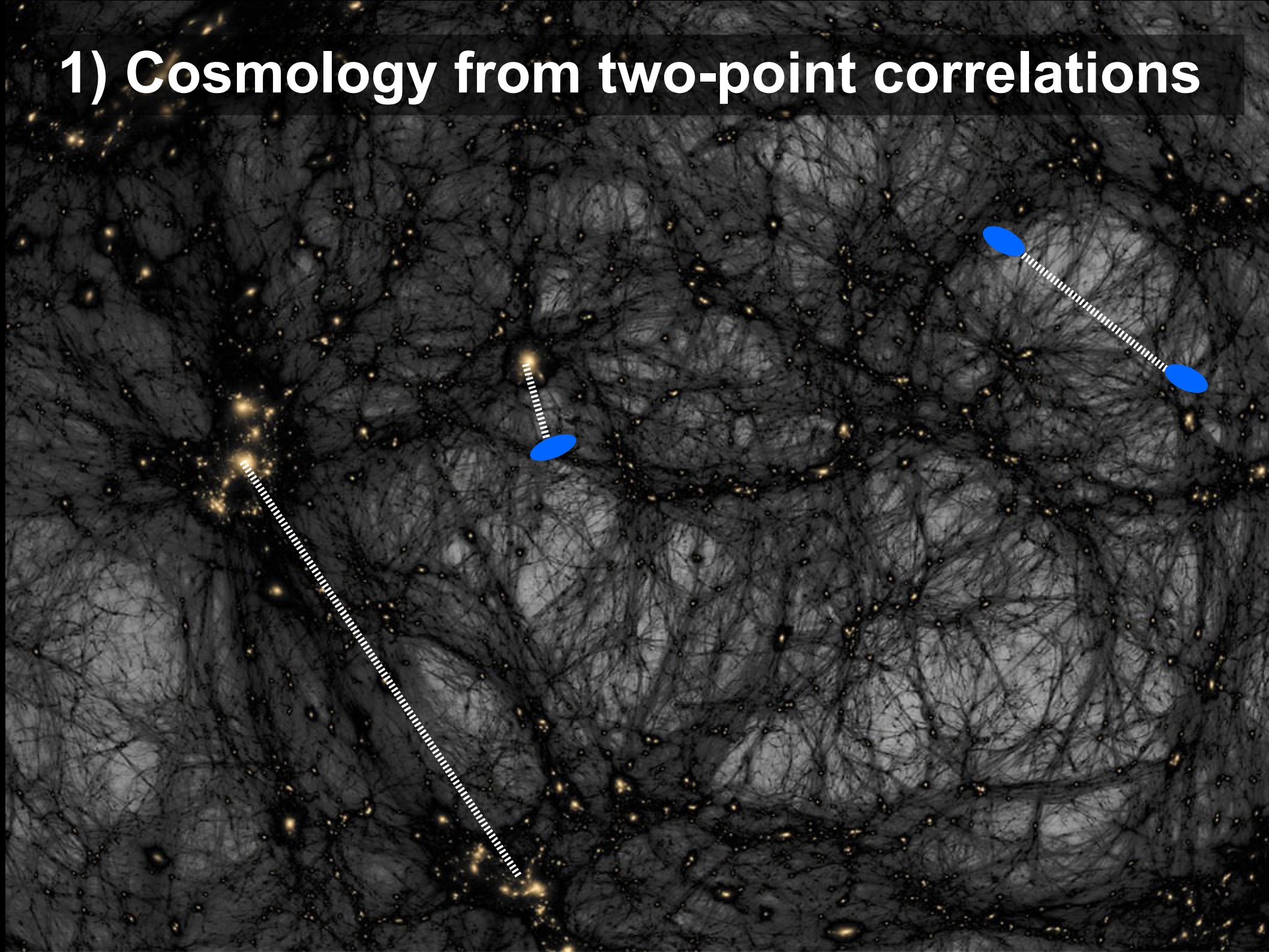


DES SV … to Y1



Chang, DG et al. 2017 (arXiv:1708.01535)

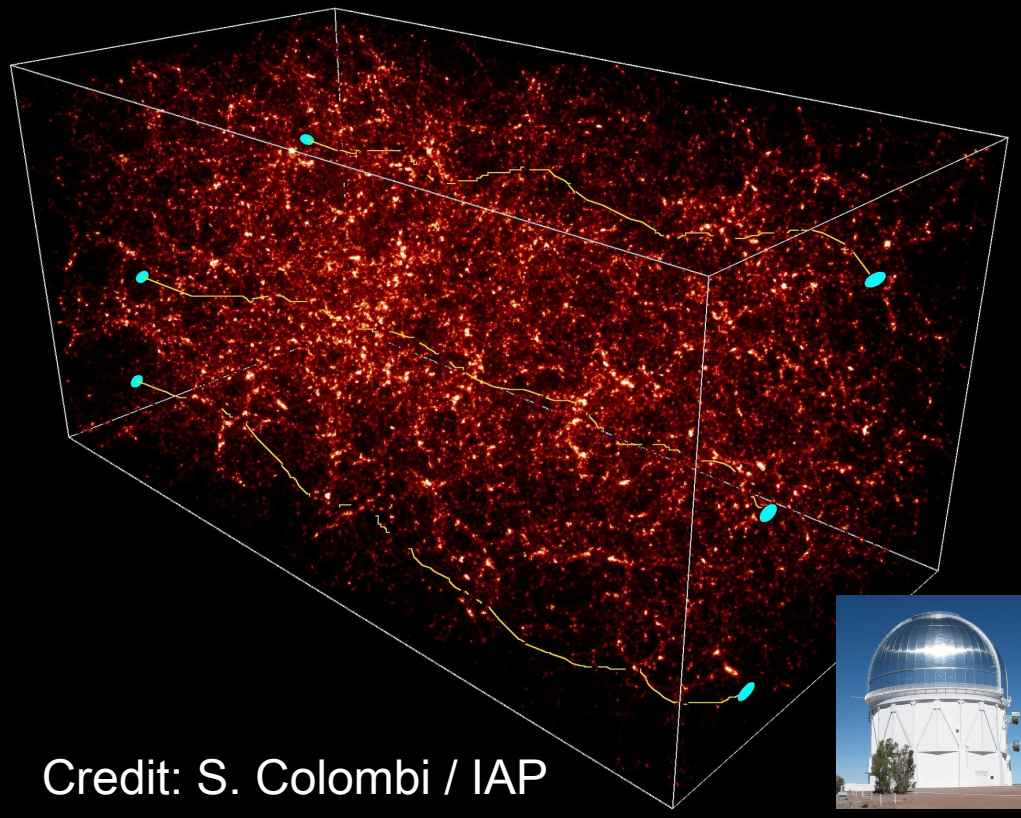
1) Cosmology from two-point correlations



Measurements: cosmic shear

Troxel+ (1708.01538)

- Light from distant galaxies passes the same foreground structure

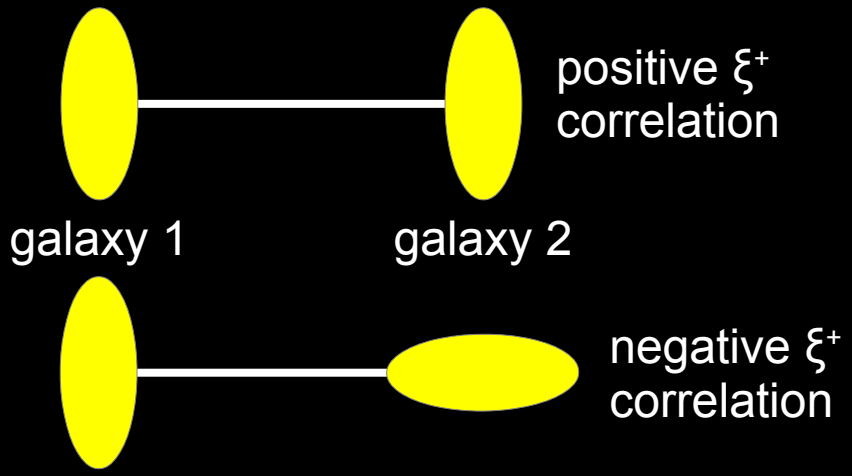


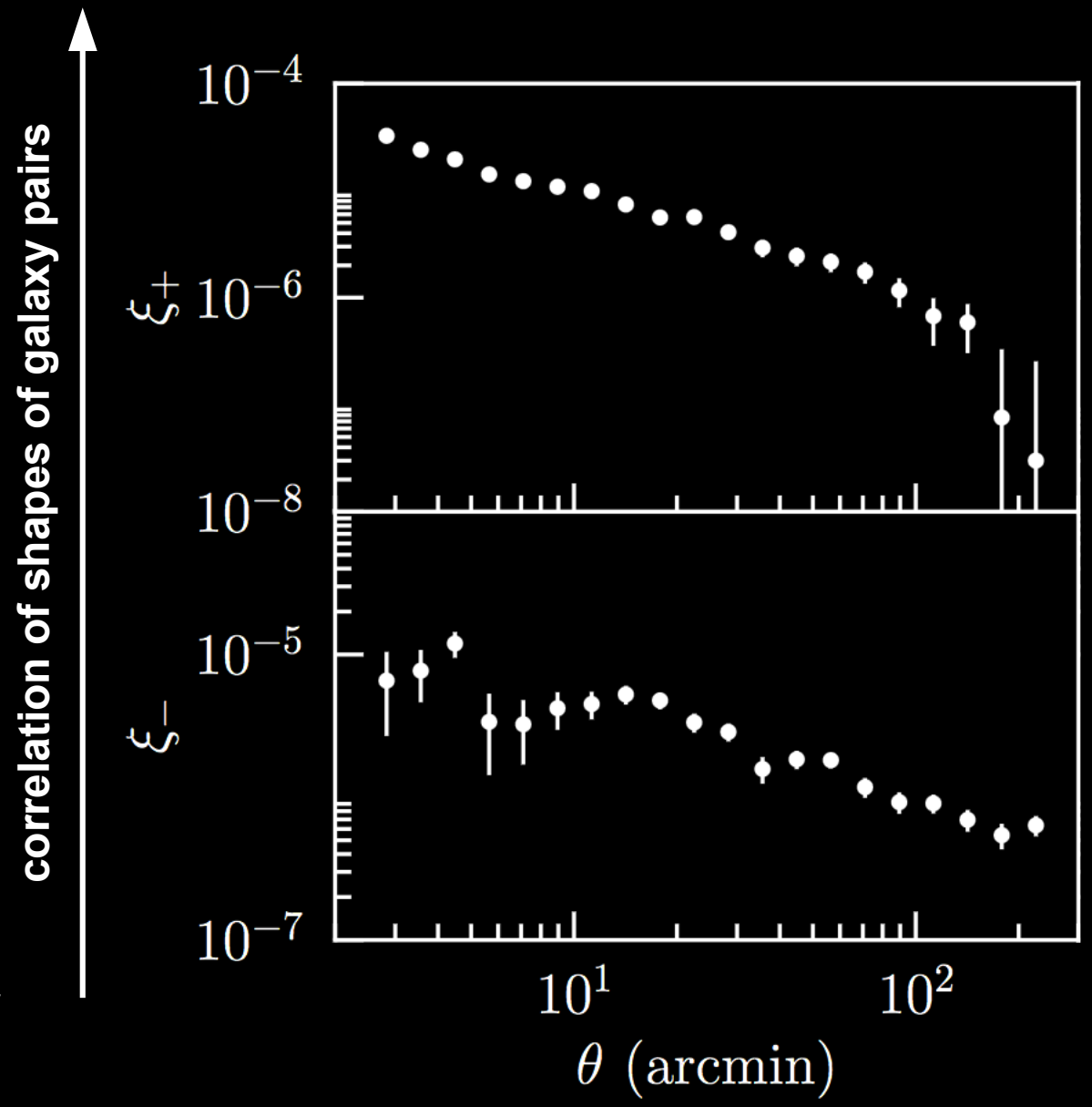
Credit: S. Colombi / IAP

Measurements: cosmic shear

Troxel+ (1708.01538)

- Light from distant galaxies passes the same foreground structure
- We measure the correlation of shapes of galaxy pairs
- We do this in source redshift bins



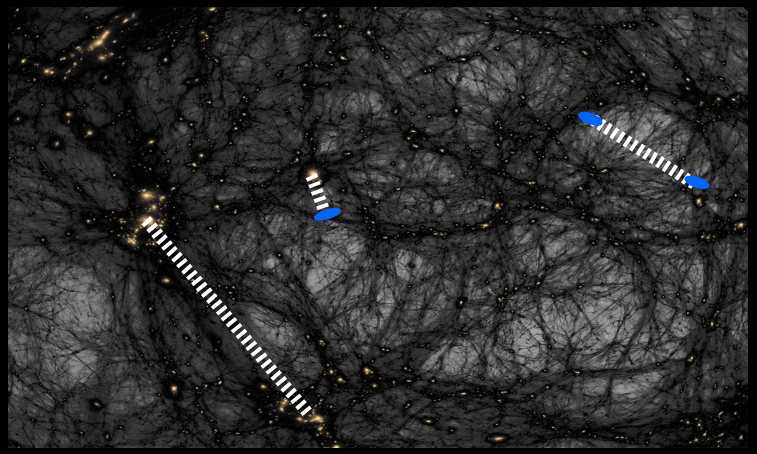


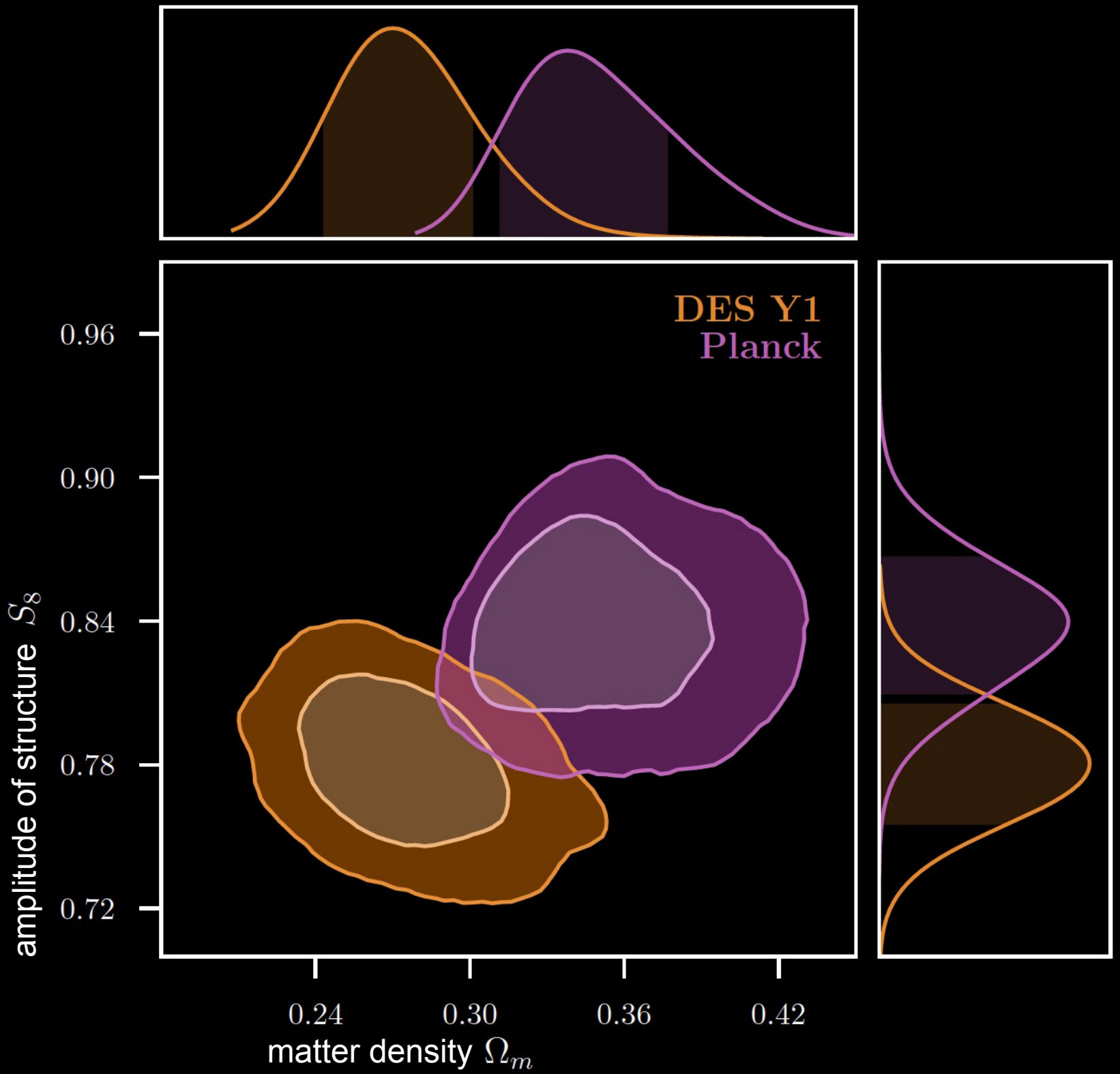
Consistency of the cosmic shear & galaxy clustering + lensing in ΛCDM

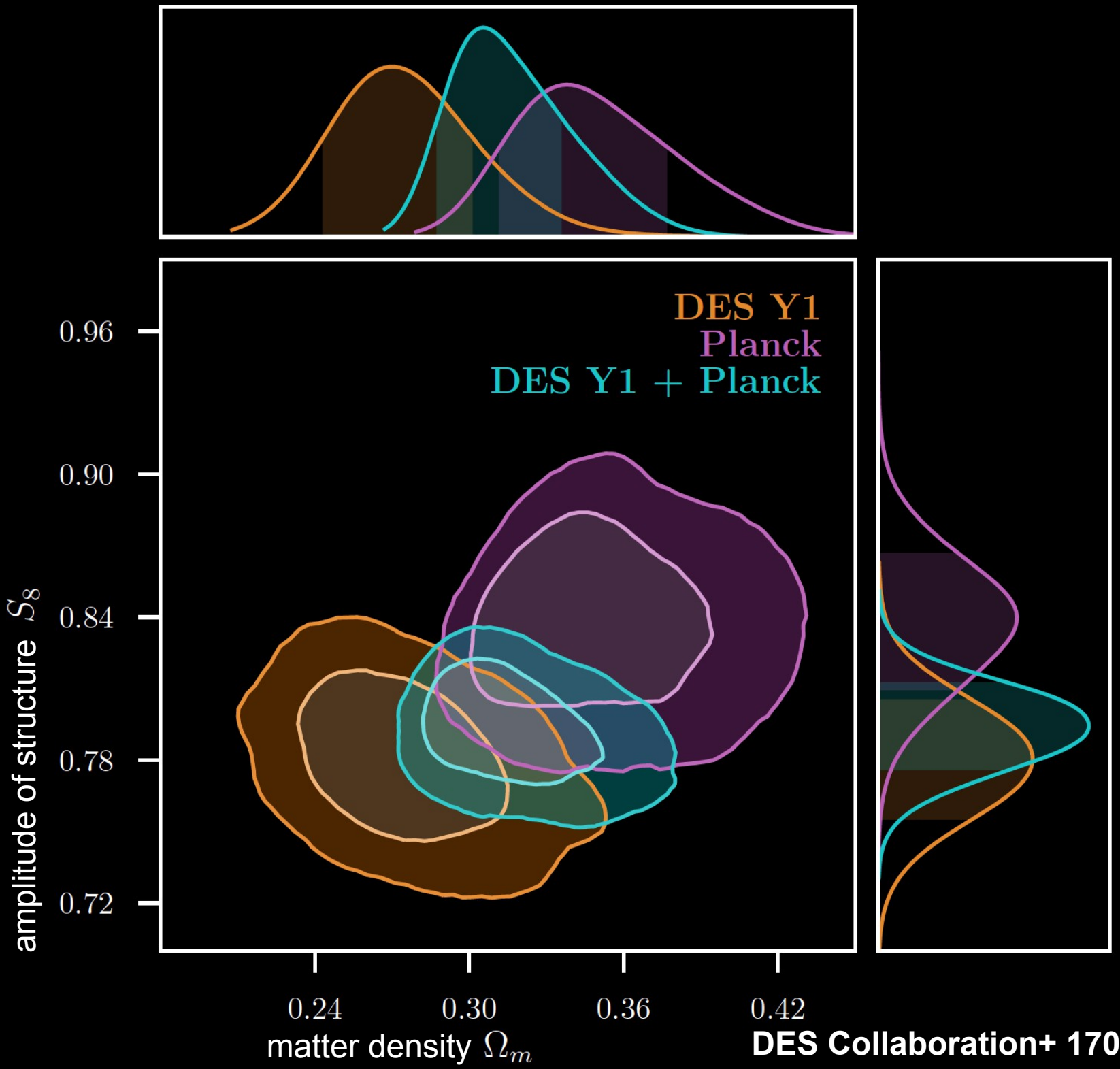
- Cosmic shear and galaxy clustering + lensing yield consistent cosmological constraints
- Criterion: Bayes Factor

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

- passing 11 other null tests, we unblind



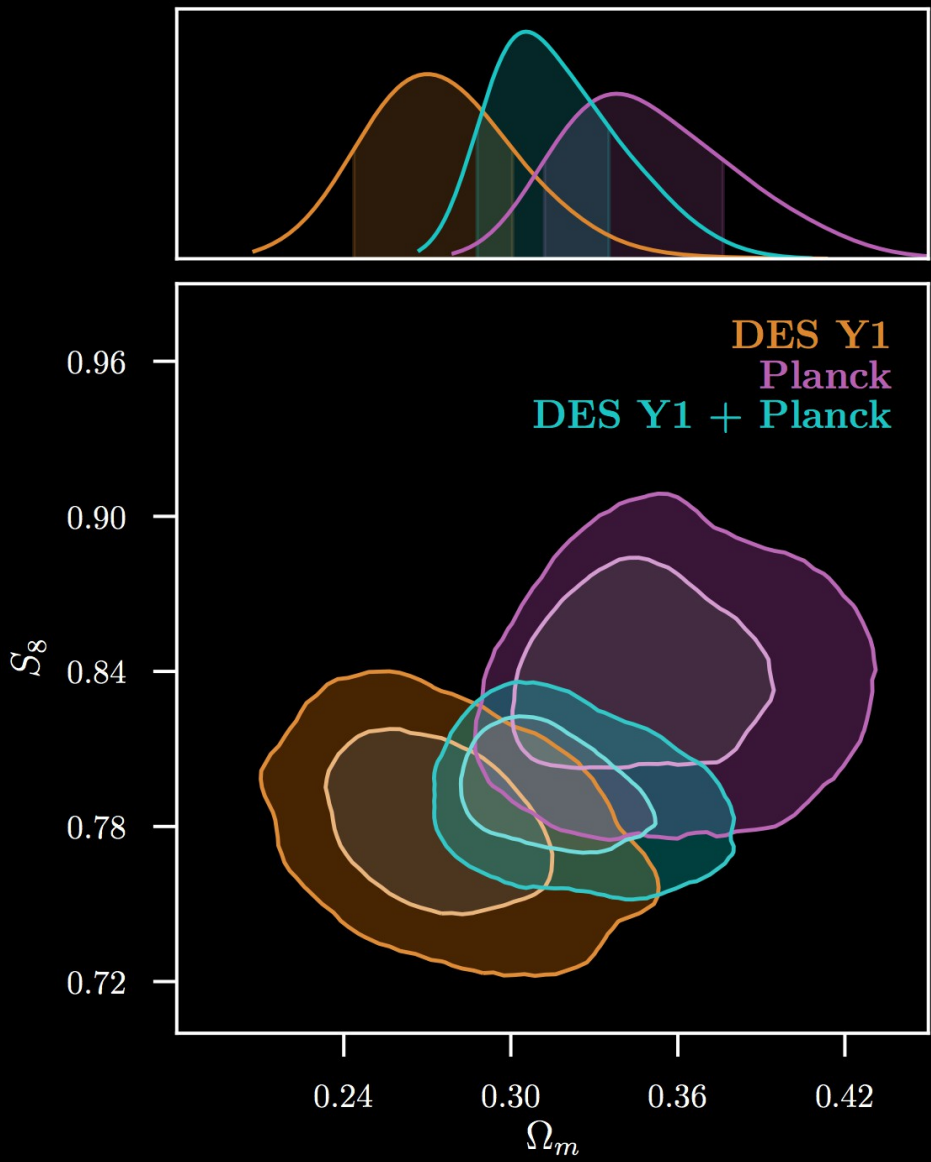

DES Y1
Planck
0.96
0.90
0.84
0.78
0.72
amplitude of structure S_8
0.24
0.30
0.36
0.42
matter density Ω_m



DES Collaboration+ 1708.01530

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



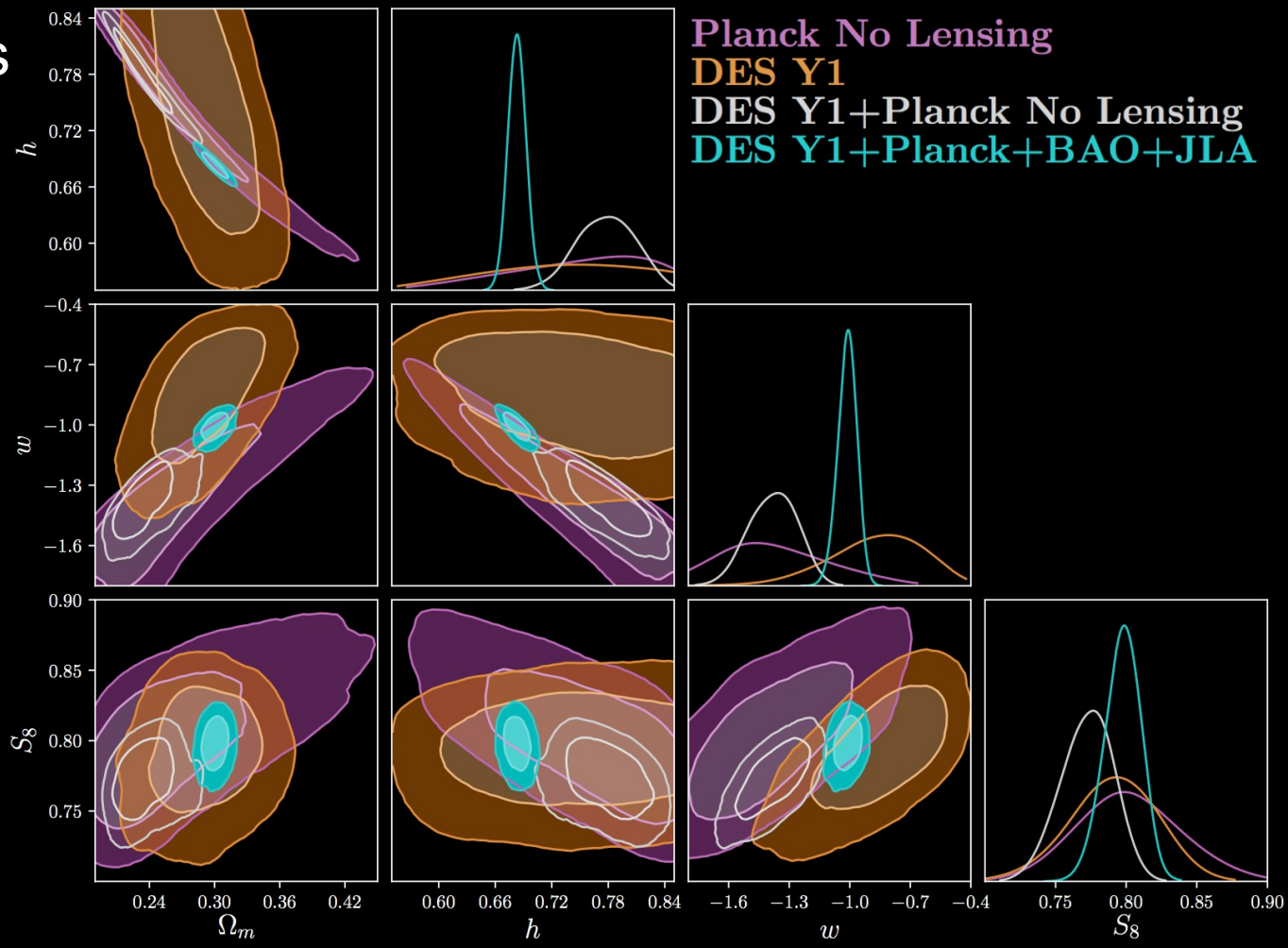
Key result: DES + geometry + CMB yields consistent, tightest constraints

- consistent constraints from geometric probes + DES
- most precise measurements in ΛCDM:

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

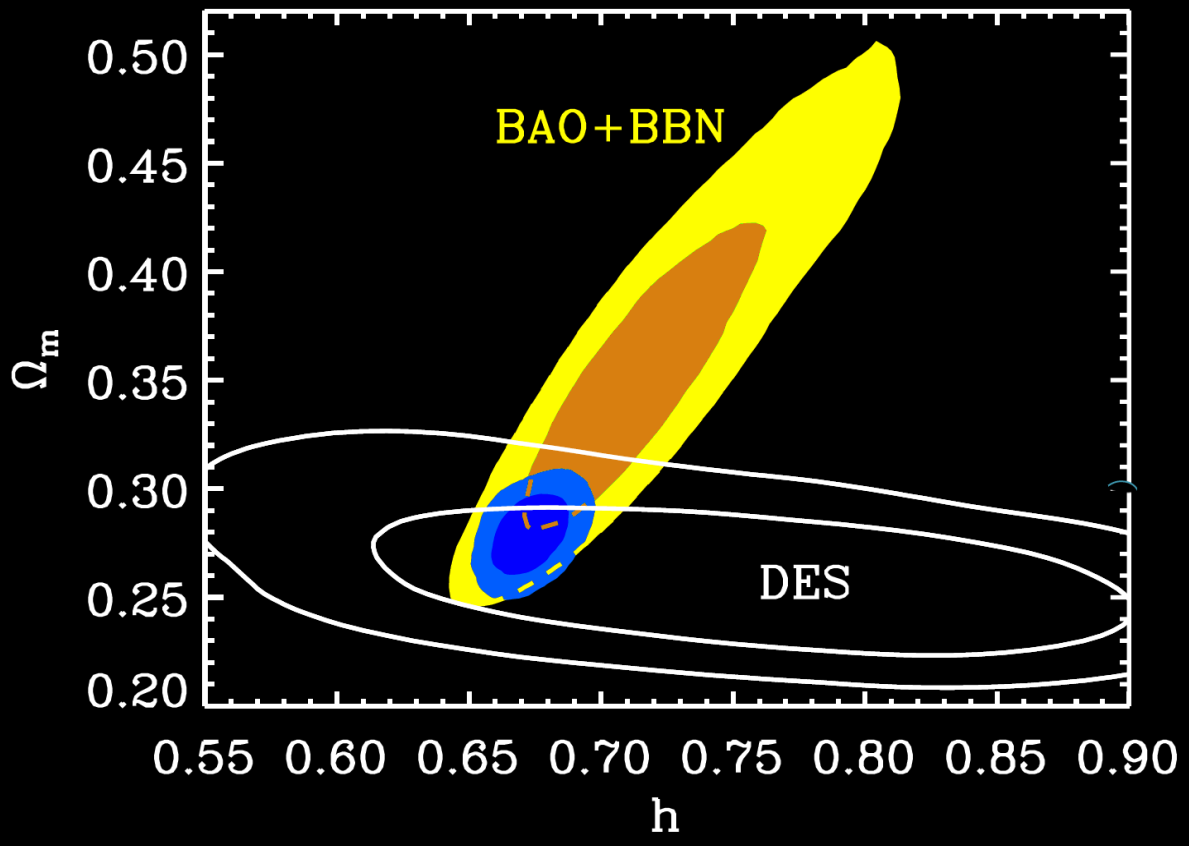
- no evidence for w≠-1 in any combination

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



Bonus key result: DES constraints on Hubble parameter

- 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

Bonus key result: DES constraints on Hubble parameter

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

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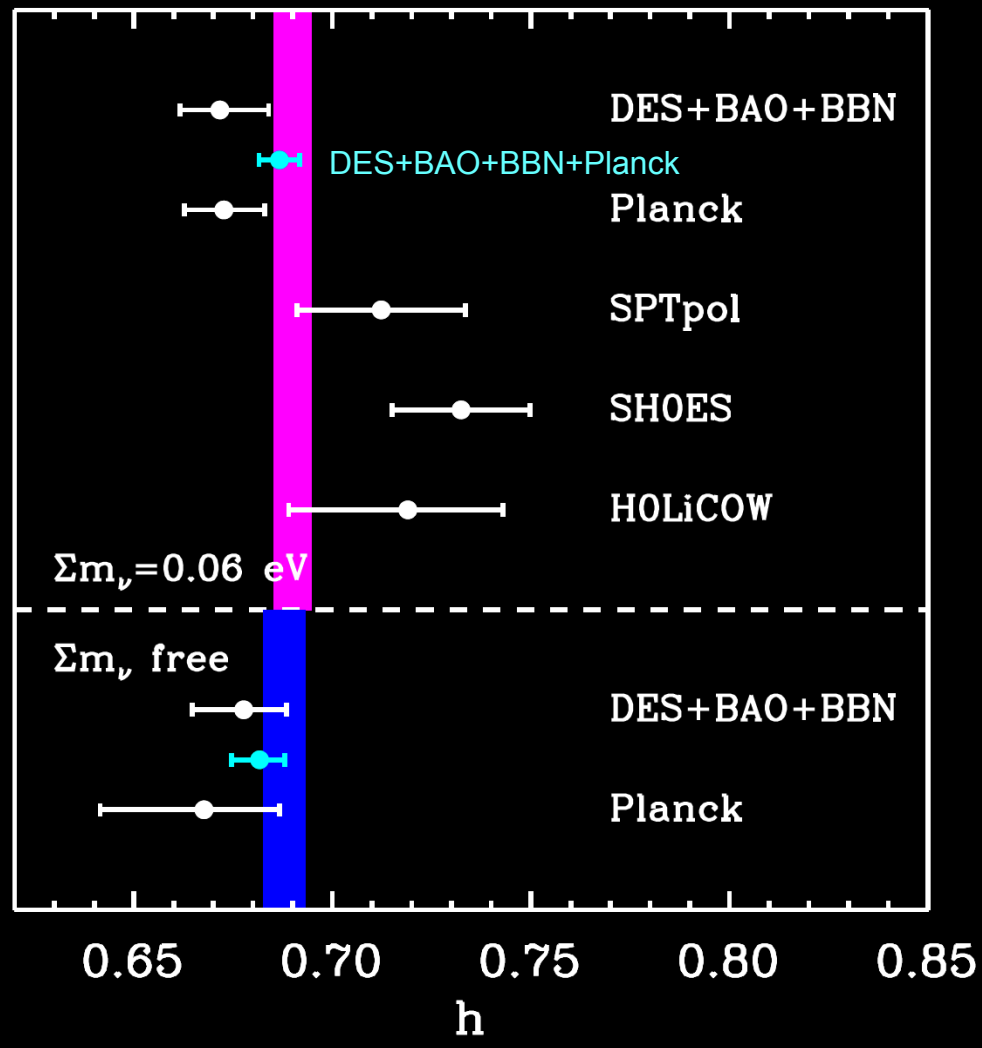
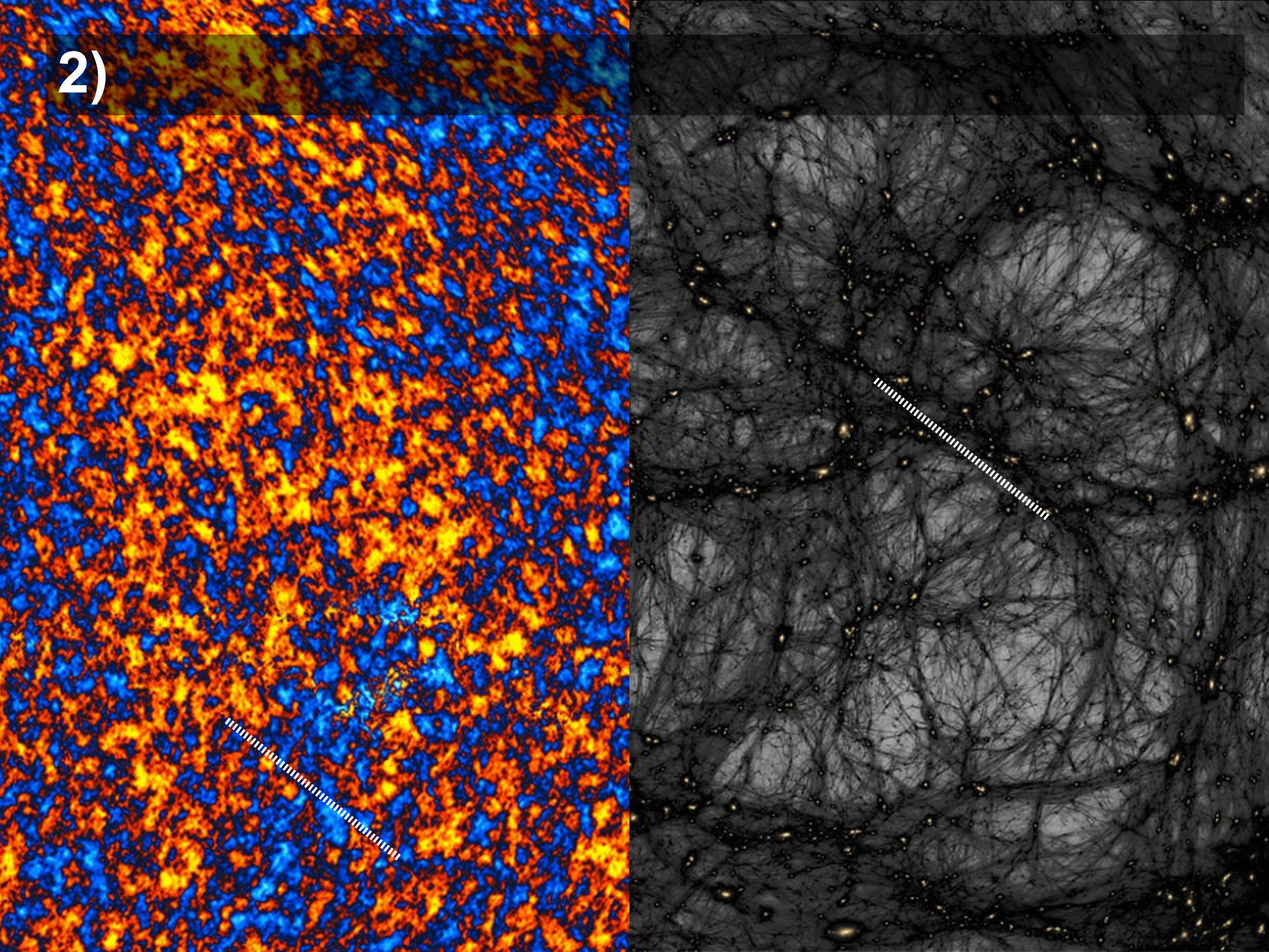
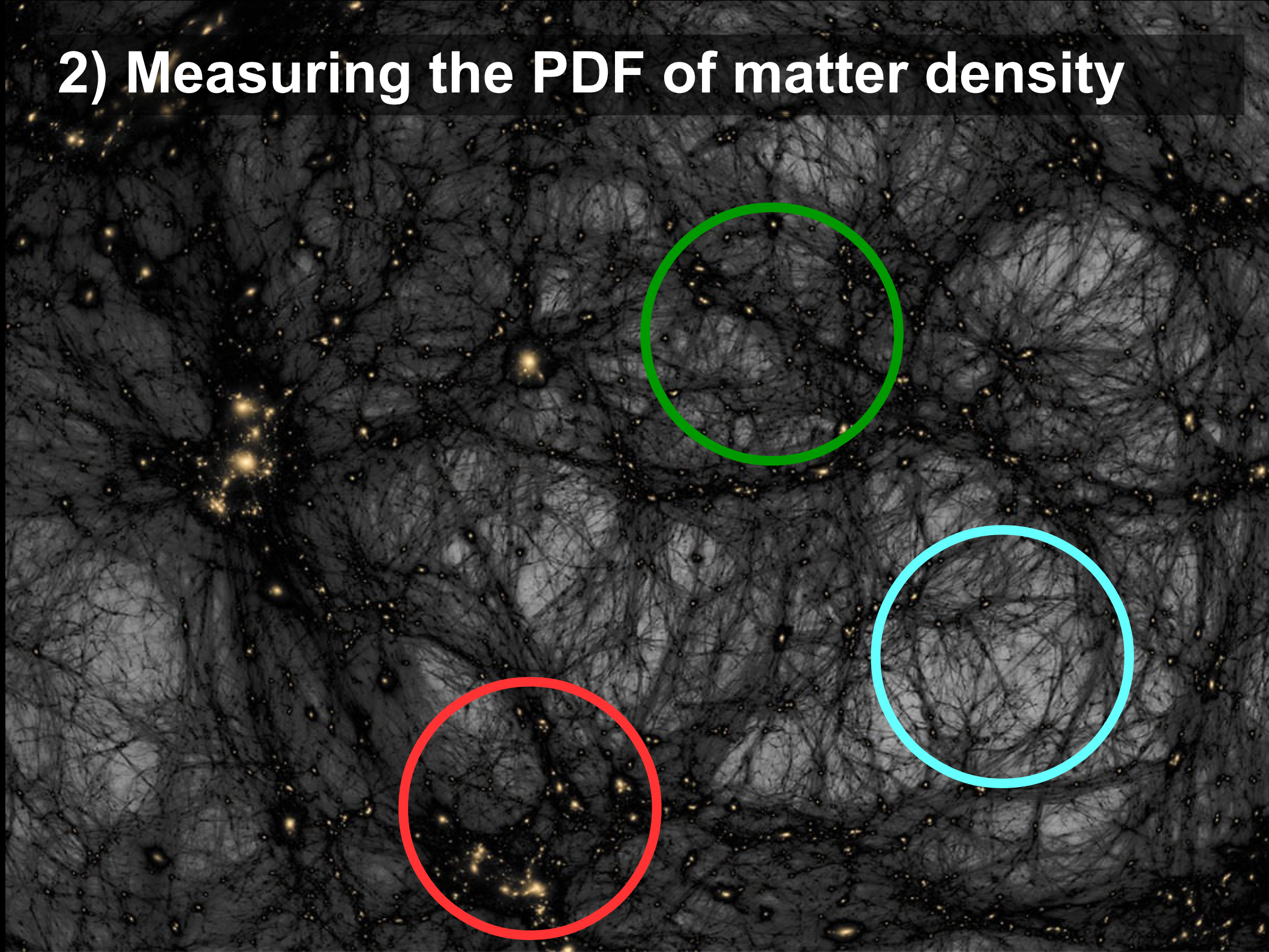


- 5 measurements with ~expected scatter (p~4%) around $H_0 = 69.1^{+0.4}_{-0.6}$ km/s/Mpc

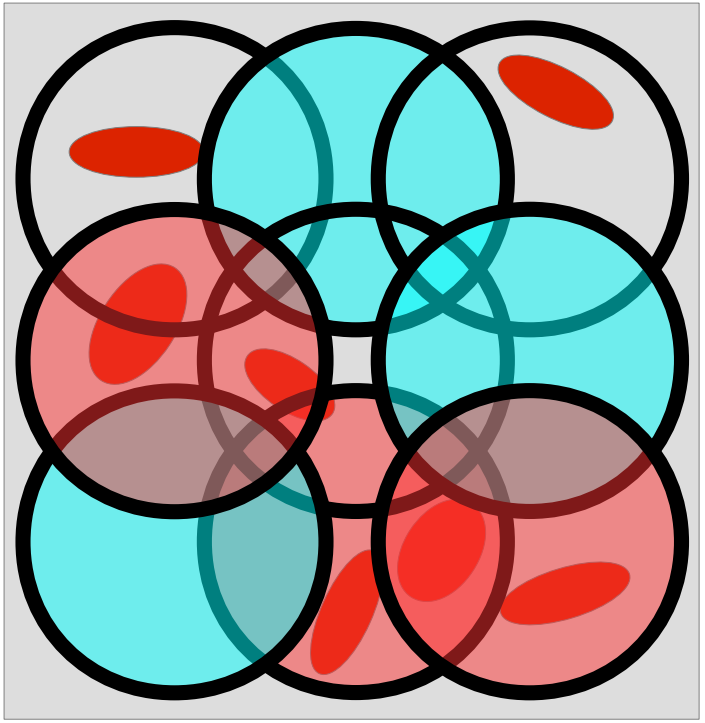

2)

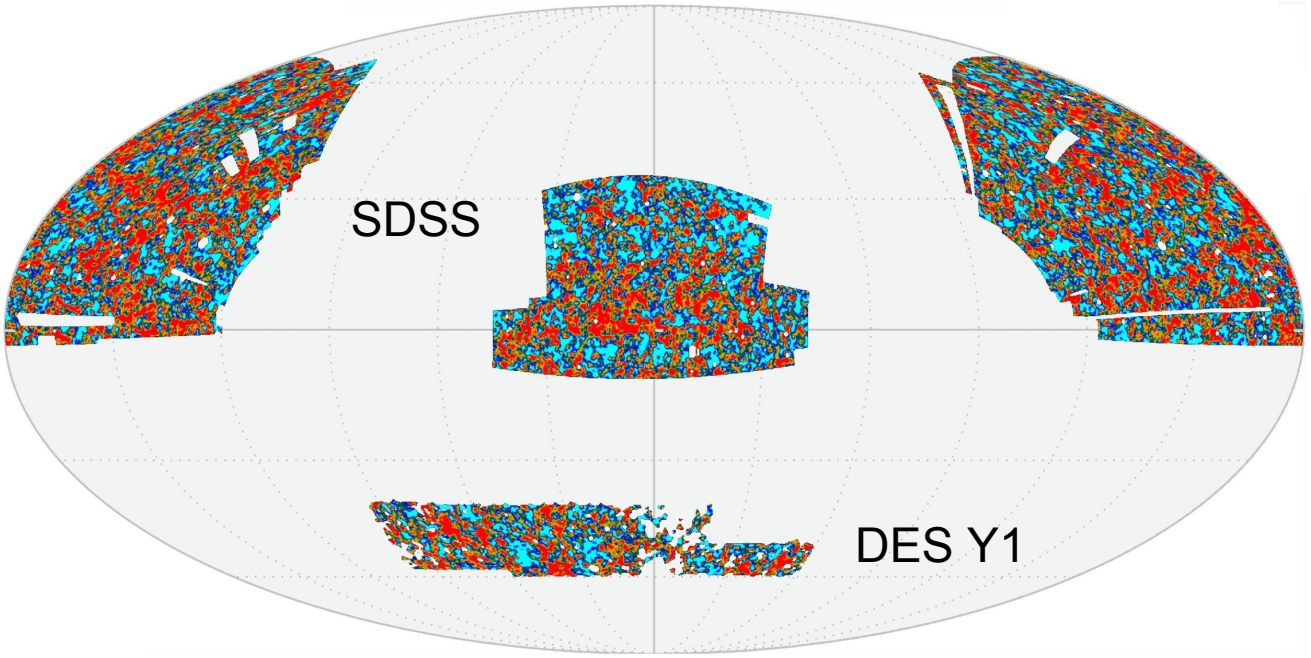
2) Measuring the PDF of matter density



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

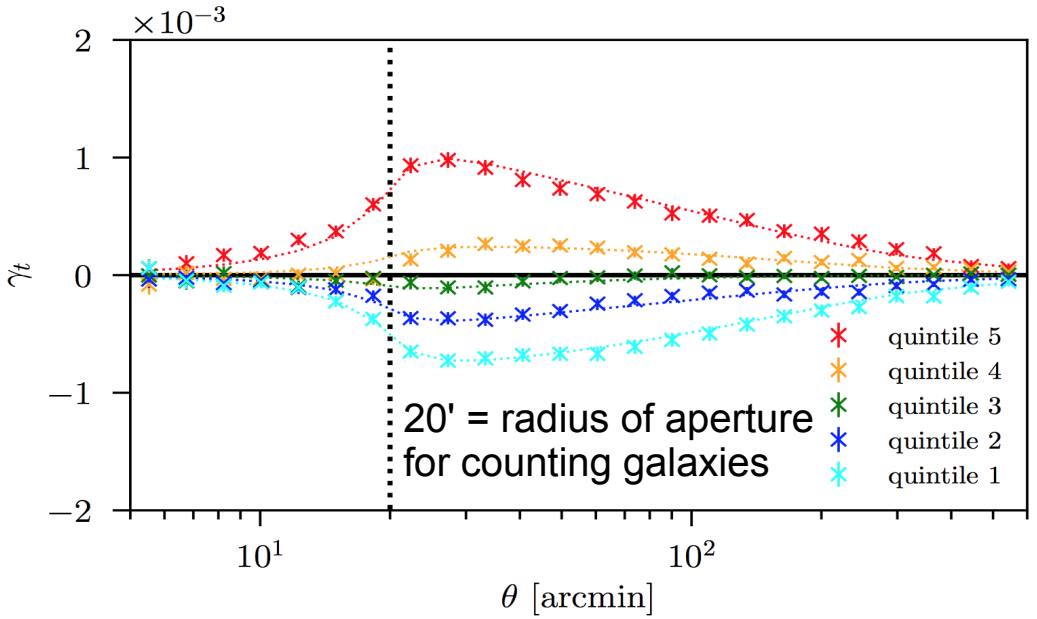


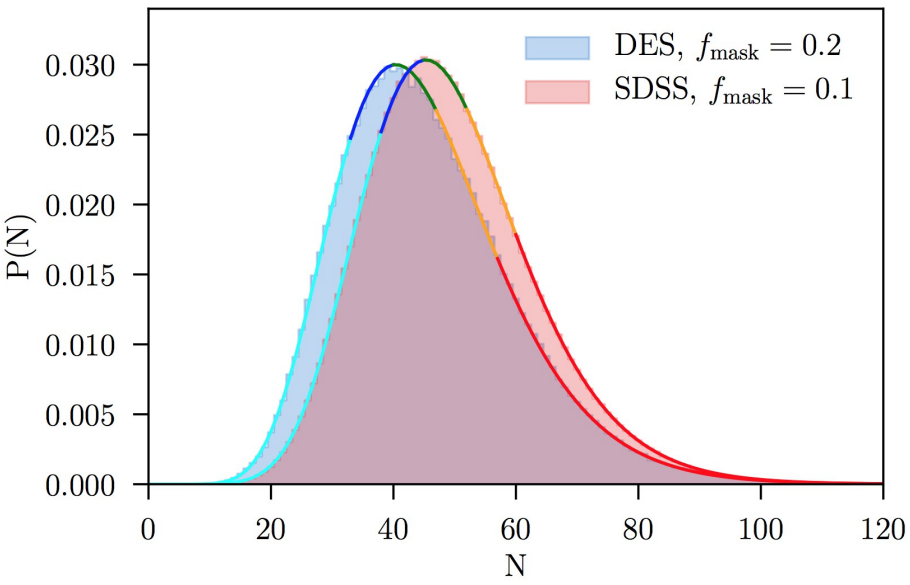


DG+ 1710.05045

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

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





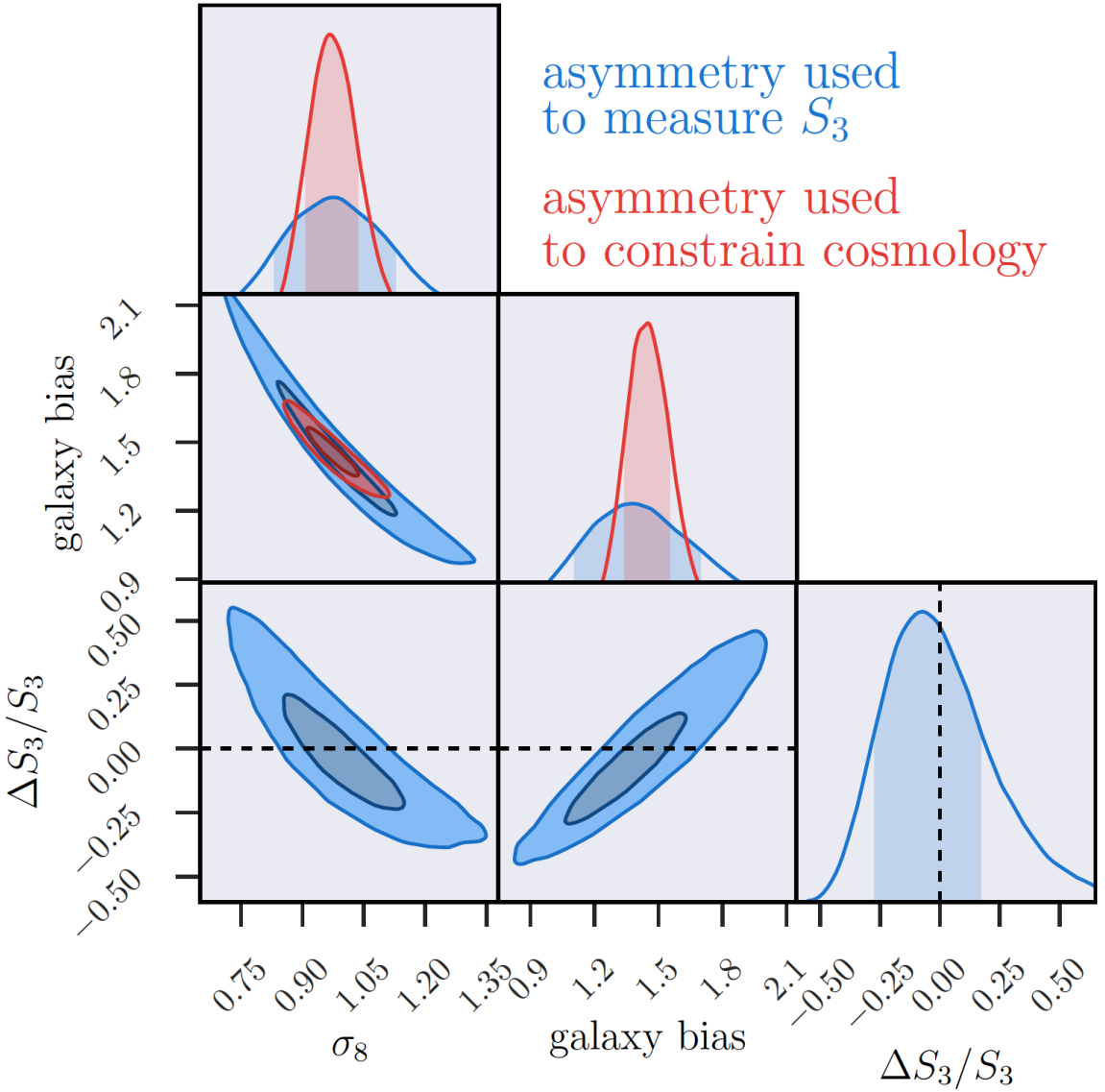
DG+ 1710.05045

Cosmology from matter/galaxy PDF: skewness of matter density

- Step 3: model with matter density PDF (Friedrich, DG+ 1710.05162)
- Lensing + counts in cells jointly constrain:
  - Cosmology
  - Bias + Stochasticity
  - Skewness of matter density:

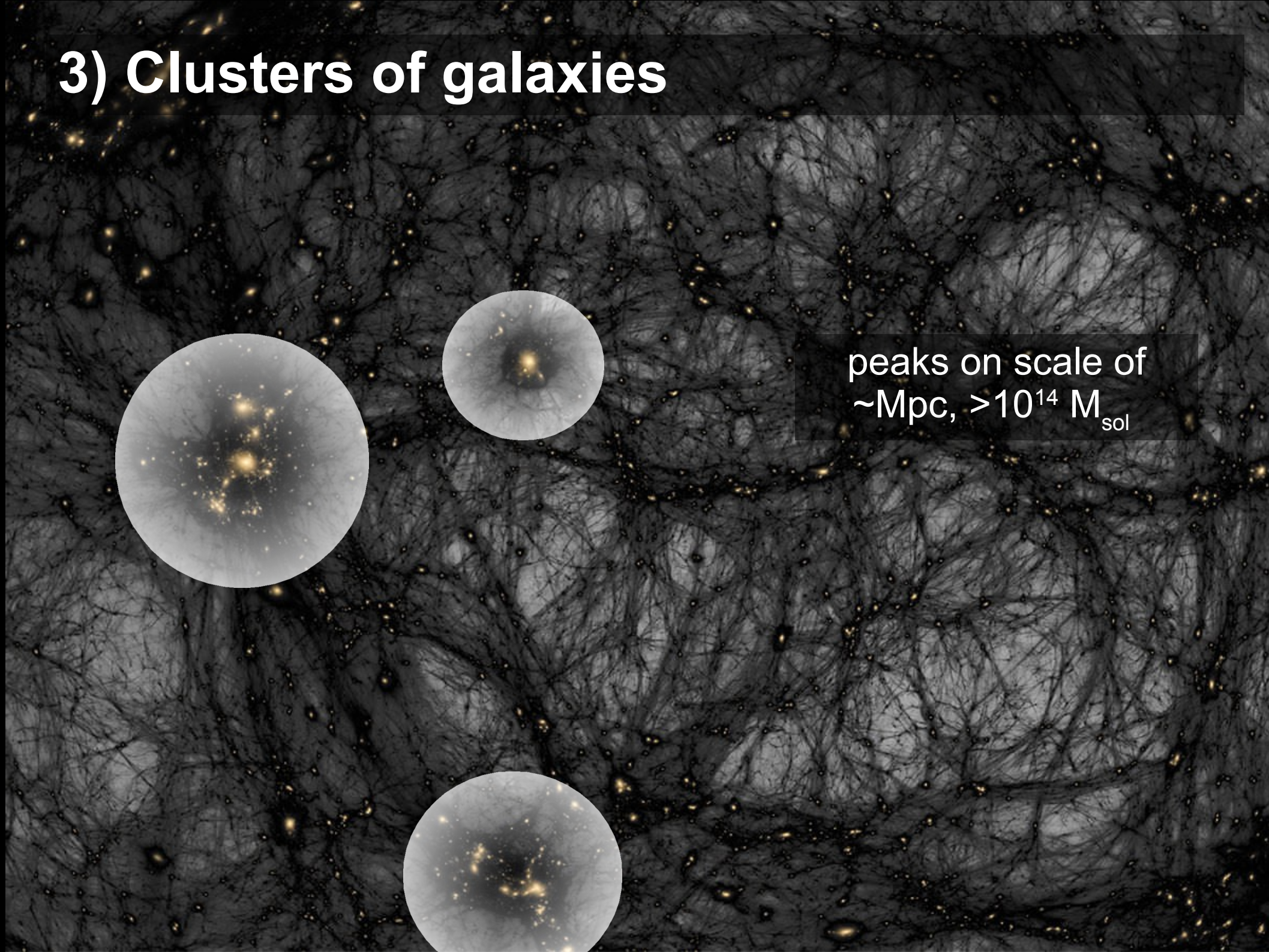
$$S_3 \equiv \frac{\langle \delta^3 \rangle}{\langle \delta^2 \rangle^2}$$

- Skewness is consistent with CDM theory & adds significant constraining power



DG+ 1710.05045

3) Clusters of galaxies



peaks on scale of ~Mpc, $>10^{14}$ M_{sol}

3) Clusters of galaxies
… allow for an equally strong, largely independent test of cosmological models

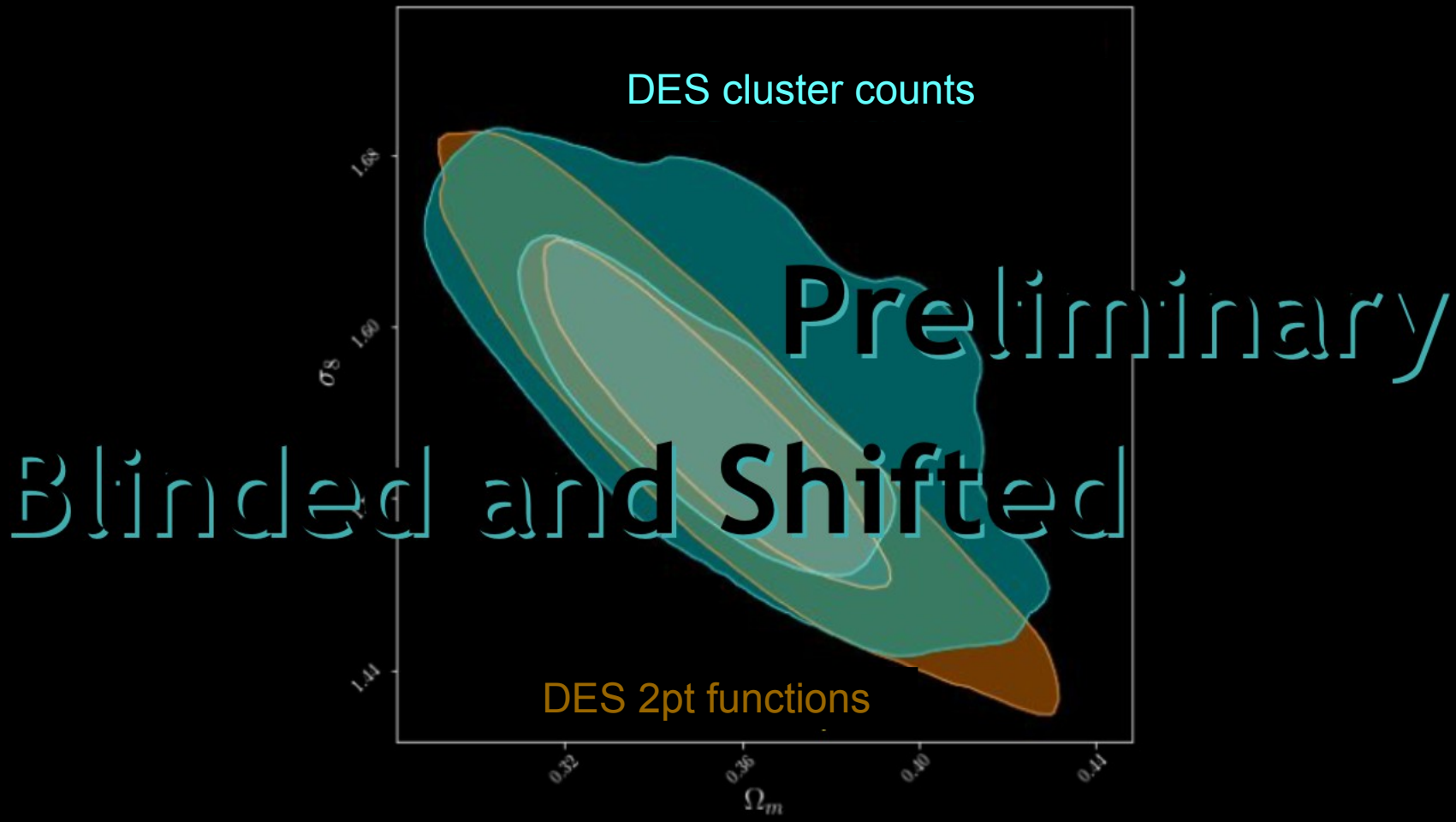
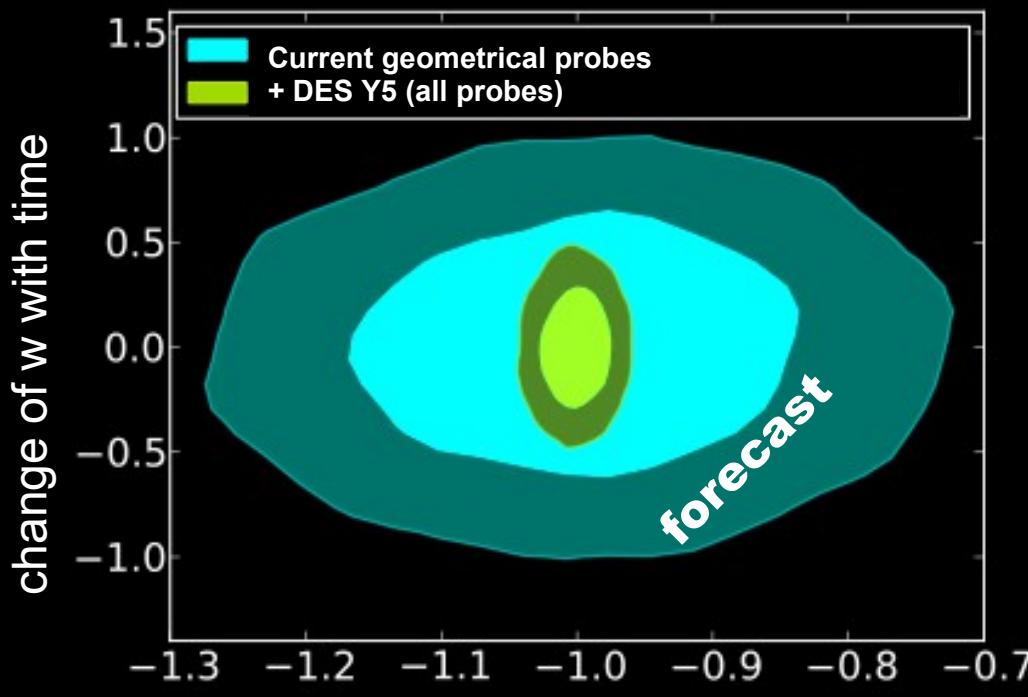


Figure: Matteo Costanzi, Eduardo Rozo
Weak lensing cluster mass calibration:
McClintock, Varga, DG+ 1805.00039

Way forward: more precise tests of more general dark energy model

- These are precise tests of ΛCDM, and they shows any potential discrepancies are < their uncertainty
- They do not 'confirm' or 'explain' ΛCDM
- They are not very sensitive to models with time-varying Dark Energy equation of state (among others)
- Future joint analyses will be!



Credit:
T. Eifler, E. Krause, J. Frieman

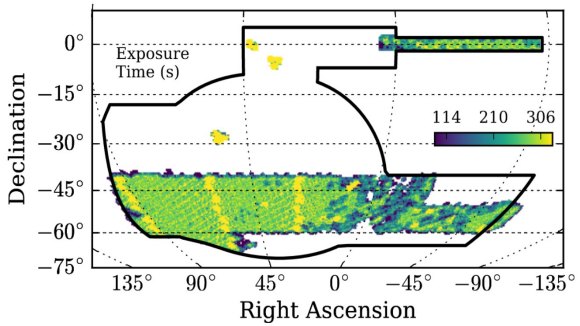
Summary

- 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. We do not find a tension with the CMB.
  - Competetiveness 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
  - Complementary, consistent results from matter density PDF
  - Complementary measurement of cluster counts: very soon
- Even more precise measurements, accurate modeling, and joint analysis of different probes in progress – greatly improved tests for tensions & alternate models to come soon!

backup

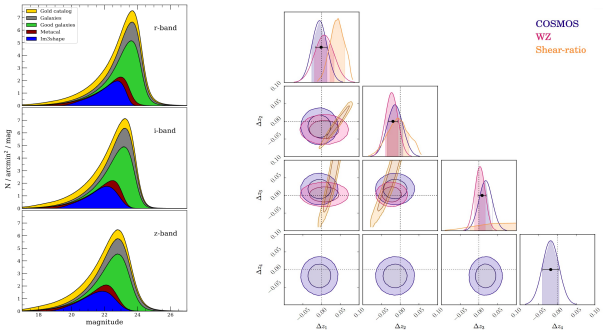
With great statistical power comes great systematic responsibility

Unprecedented size and depth of photometric data



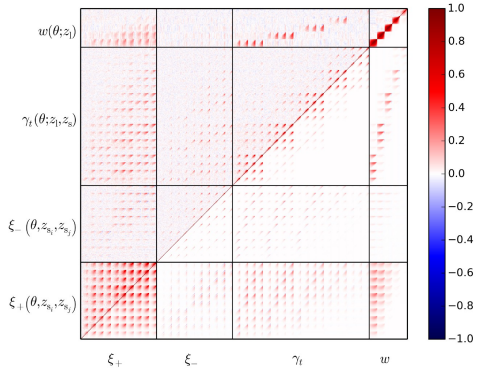
Drlica-Wagner, Rykoff, Sevilla+

Two independent shape & photo-z catalogs and calibrations

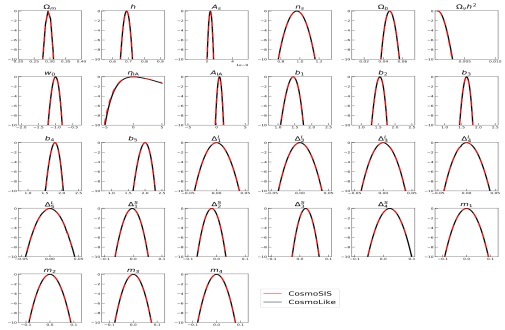


Zuntz, Sheldon+; Samuroff+; Hoyle, Gruen+; Davis+; Gatti, Vielzeuf+; Cawthon+

Full, validated treatment of covariance and nuisance parameters (including v)

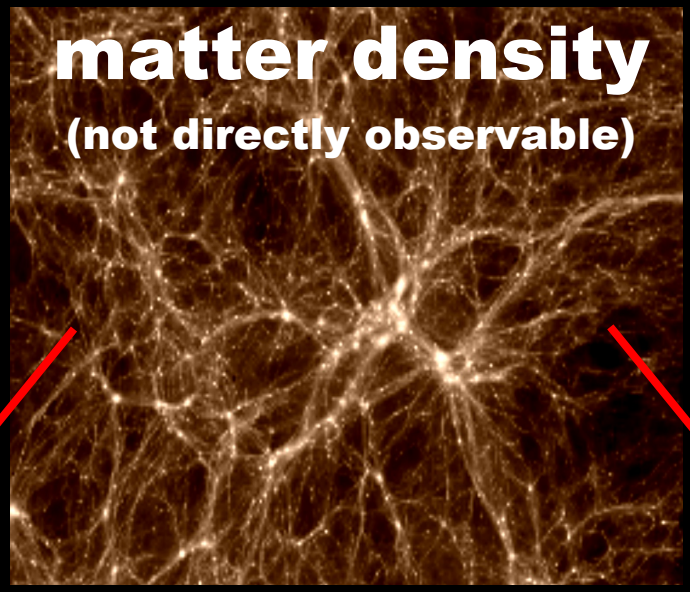


Theory and simulation tested, blind, analysis with two independent codes, CosmoLike and CosmoSIS

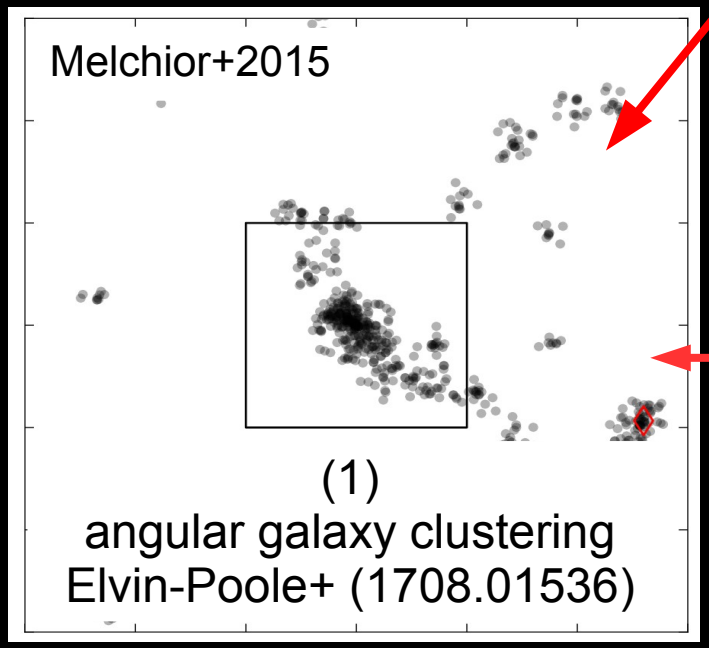


Krause, Eifler+; MacCrann, DeRose+

matter density
(not directly observable)



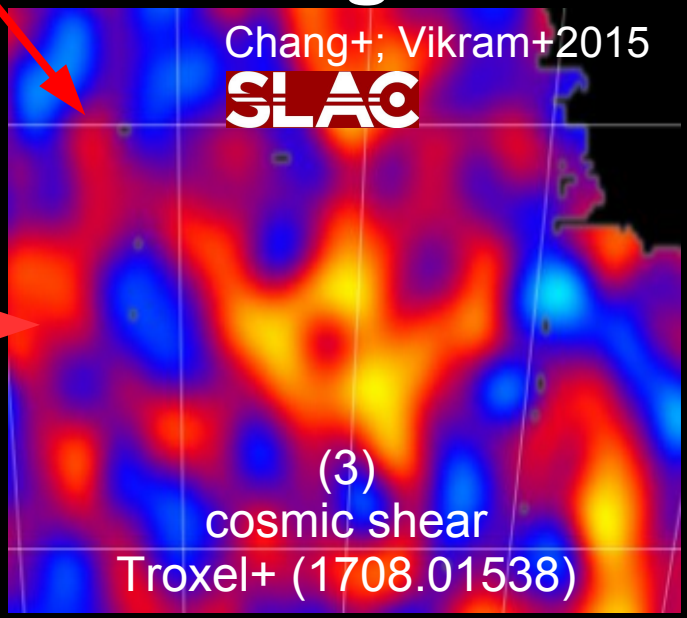
galaxy field



(1)
angular galaxy clustering
Elvin-Poole+ (1708.01536)

(2)
galaxy-galaxy lensing
Prat, Sanchez+ (1708.01537)

lensing convergence



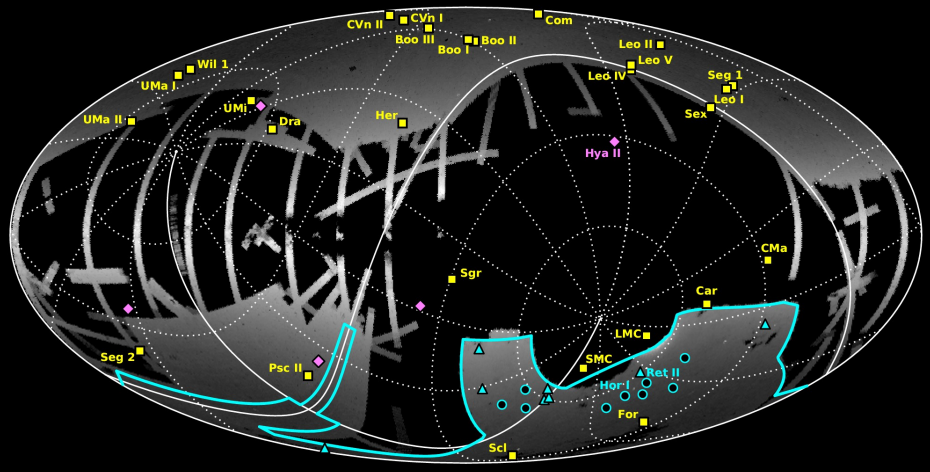
(3)
cosmic shear
Troxel+ (1708.01538)

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

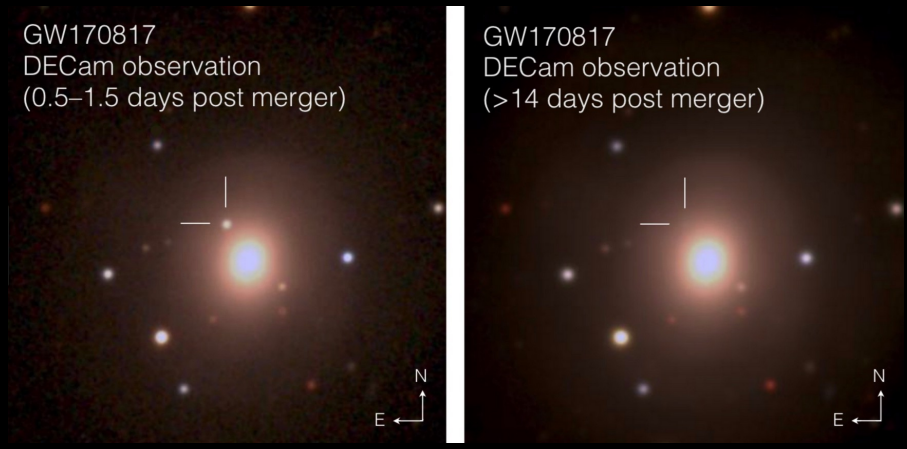
[Hu&Jain 2004, Huterer+2006, Bernstein+2009, Joachimi&Bridle 2010, van Uitert+2017, Joudaki+2017, **Krause**&Eifler 2017]

DES is much more than just a Dark Energy Survey

DES finds Milky Way satellites (Drlica-Wagner+)



DES uniquely identifies NS+NS GW host rapidly (Soares-Santos+)



DES measures the matter density profiles of cluster satellite galaxies

in prep.: Varga+

Fermi/LAT gamma rays cross-correlated with DES galaxies/lensing

in prep.: Ammazzalorso+