Dark Energy

Daniel Gruen, NASA Einstein Fellow at SLAC/KIPAC

APS DPF Meeting, Fermilab, Aug 3 2017

THE DARK ENERGY SURVEY

Dark Energy Survey Year 1 Results: Cosmological Constraints

Daniel Gruen, NASA Einstein Fellow at SLAC/KIPAC
on behalf of the DES Collaboration

APS DPF Meeting, Fermilab, Aug 3 2017

Structure of this talk

- Dark Energy
  - Introduction
    - How to observe Dark Energy
    - How to explain Dark Energy
  - Recent results
    - geometry of expanding universe vs. growth of structure
    - early universe vs. late-time universe
- Cosmological Constraints from DES

What goes up must come down?

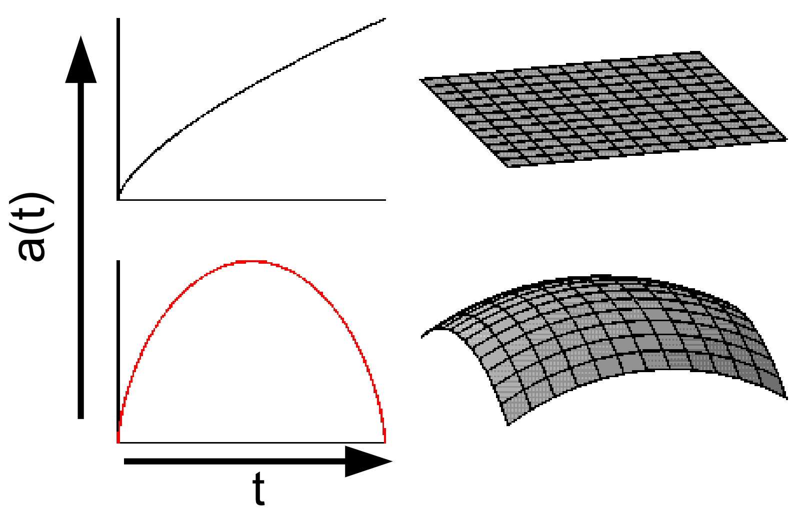
- on large scales, Universe described as homogenous fluid in expanding space

$$\left(\frac{\dot{a}}{a}\right)^2 = \Omega_{m,0}\, a^{-3}$$

scale factor of Universe

mean matter density

+ radiation
+ relativistic species
+ curvature

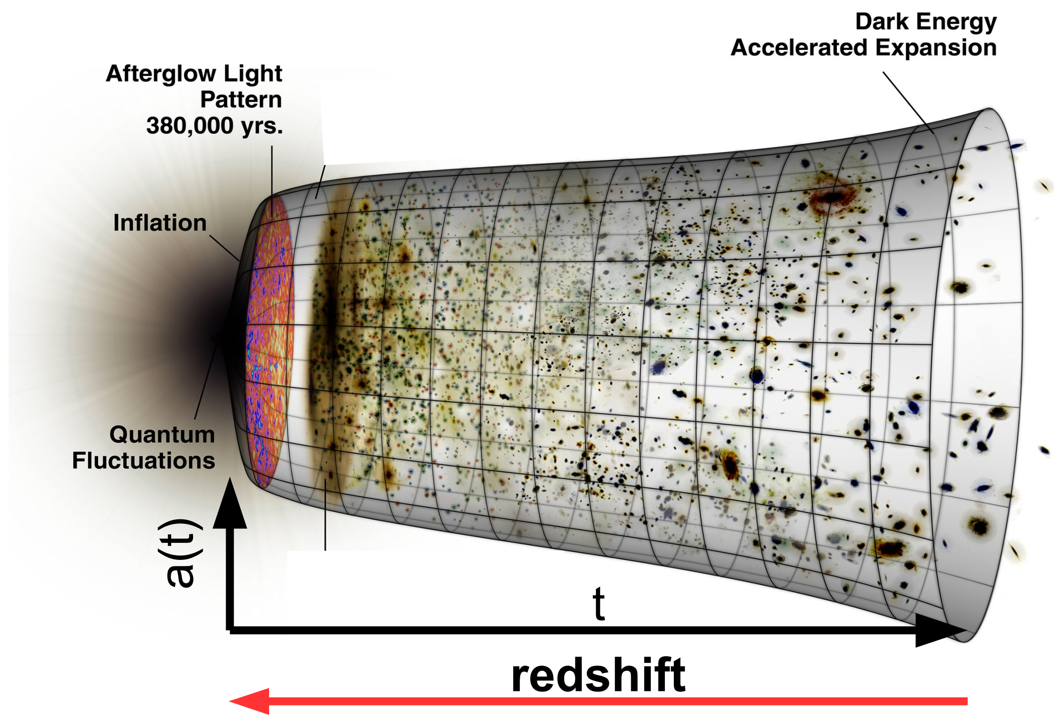


What goes up keeps getting faster!

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

$$\left(\frac{\dot{a}}{a}\right)^2 = \Omega_{m,0} a^{-3} + \Omega_\Lambda$$

constant vacuum energy density



What goes up keeps getting faster!

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

$$\left(\frac{\dot a}{a}\right)^2 = \Omega_{m,0}\, a^{-3} + \Omega_\Lambda$$

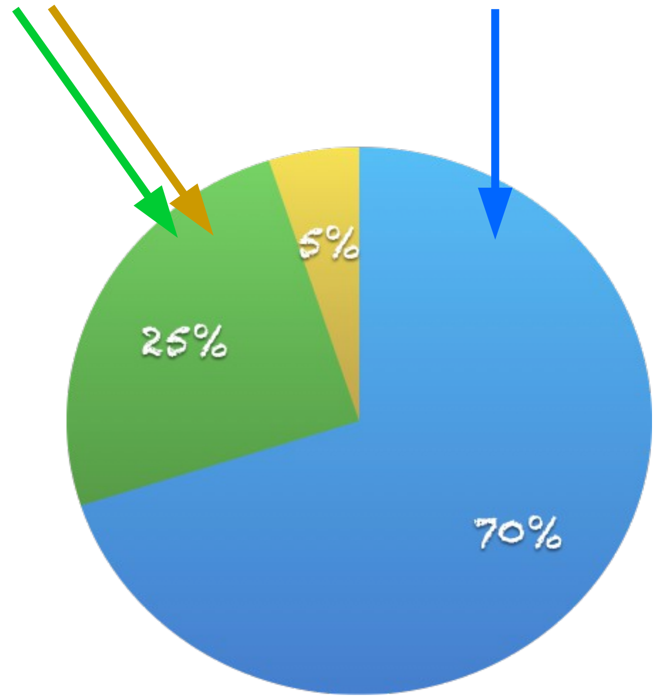
4 additional parameters:

σ_8 / S_8: amplitude of density fluctuations

m_ν / Ω_ν: mass/density of neutrinos

h / H / $\left(\frac{\dot a}{a}\right)$: rate of expansion today

n_s: scale dependence of early density fluctuations



of energy in the Universe at present

Ω_m=0.3, σ_8=0.8
"fiducial ΛCDM"

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

This is a remarkably odd model, but alternatives are even odder

Lovelock (1969) theorem:

GR + Λ are the only **local, second-order** gravitational field equations that can be derived from a **four-dimensional action** that is constructed **solely from the metric tensor**, and admitting Bianchi identities.

Theory zoo of:

- non-local field equations
- higher order field equations f(R)
- higher dimensions: e.g. strings & branes
- new degrees of freedom = substances

Credit: Elisabeth Krause, Tessa Baker

This is a remarkably odd model, but alternatives are even odder

Lovelock (1969) theorem:

GR + Λ are the only **local, second-order** gravitational field equations that can be derived from a **four-dimensional action** that is constructed **solely from the metric tensor**, and admitting Bianchi identities.

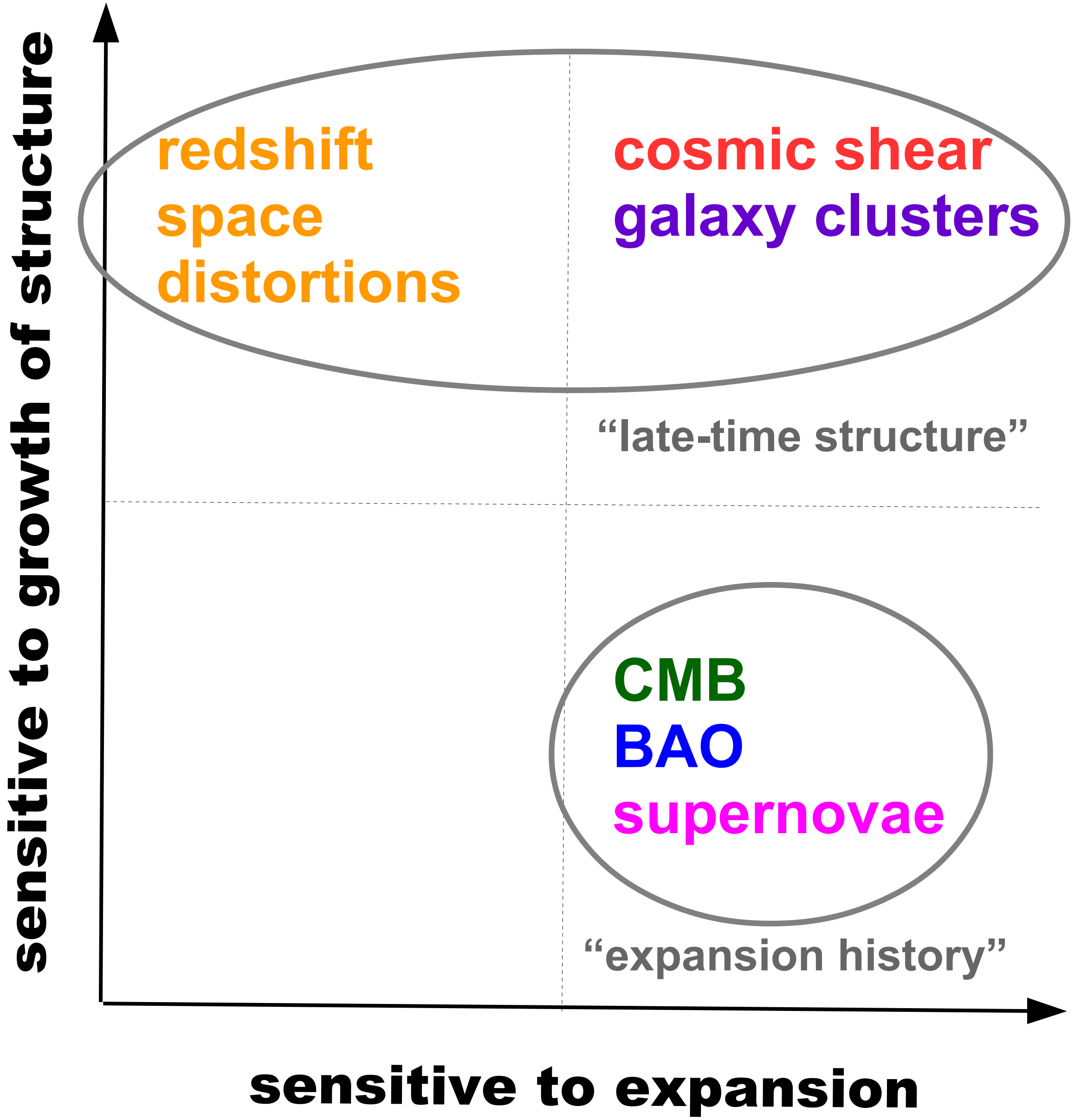
Theory zoo of:

- non-local field equations
- higher order field equations f(R)
- higher dimensions: e.g. strings & branes
- new degrees of freedom = substances

Need phenomenological tests of the most simple model:

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**

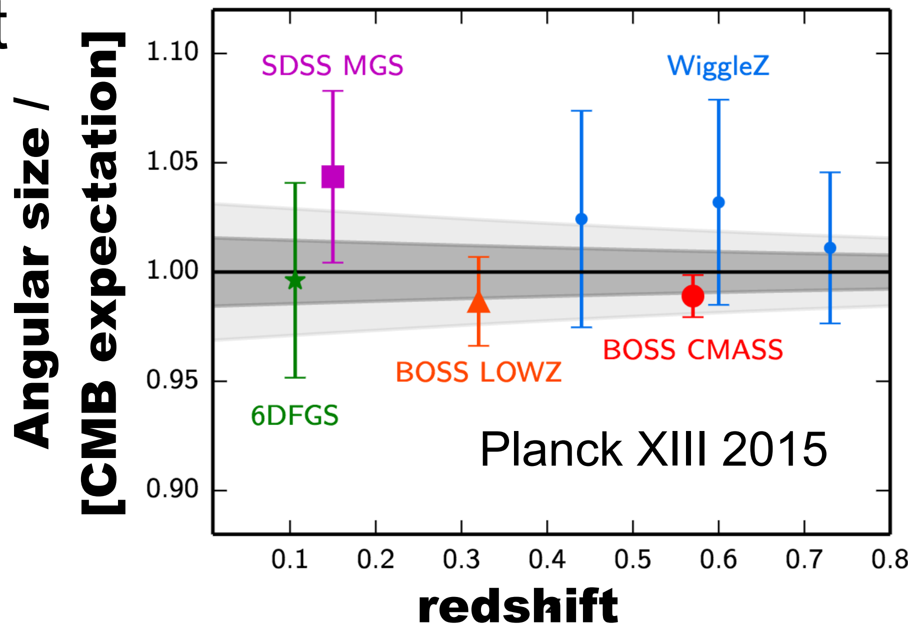
How to survey Dark Energy

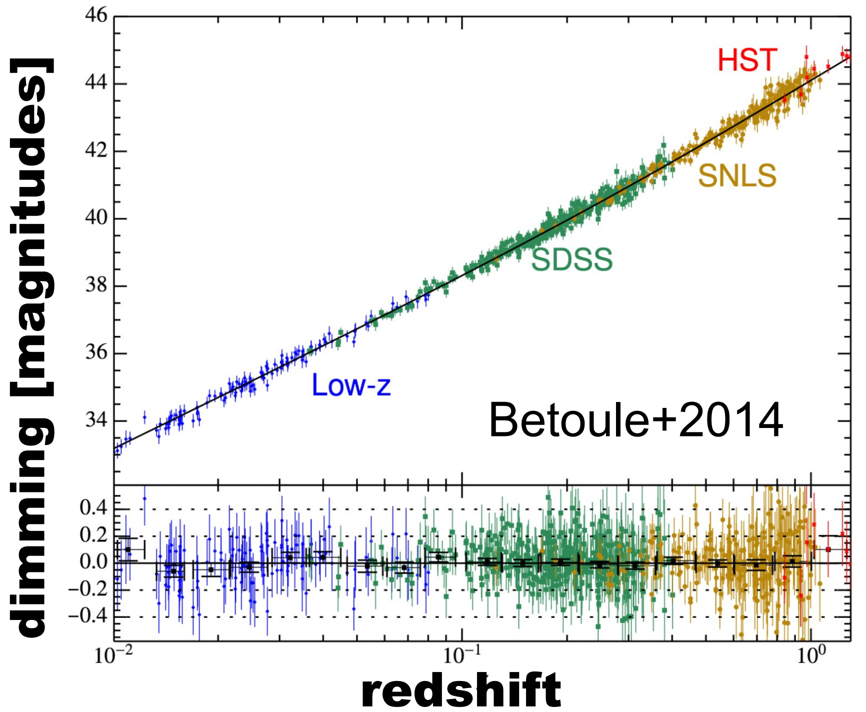


Q: Do all these measurements agree with predictions in the same, fiducial ΛCDM model?

Measurements of expansion history

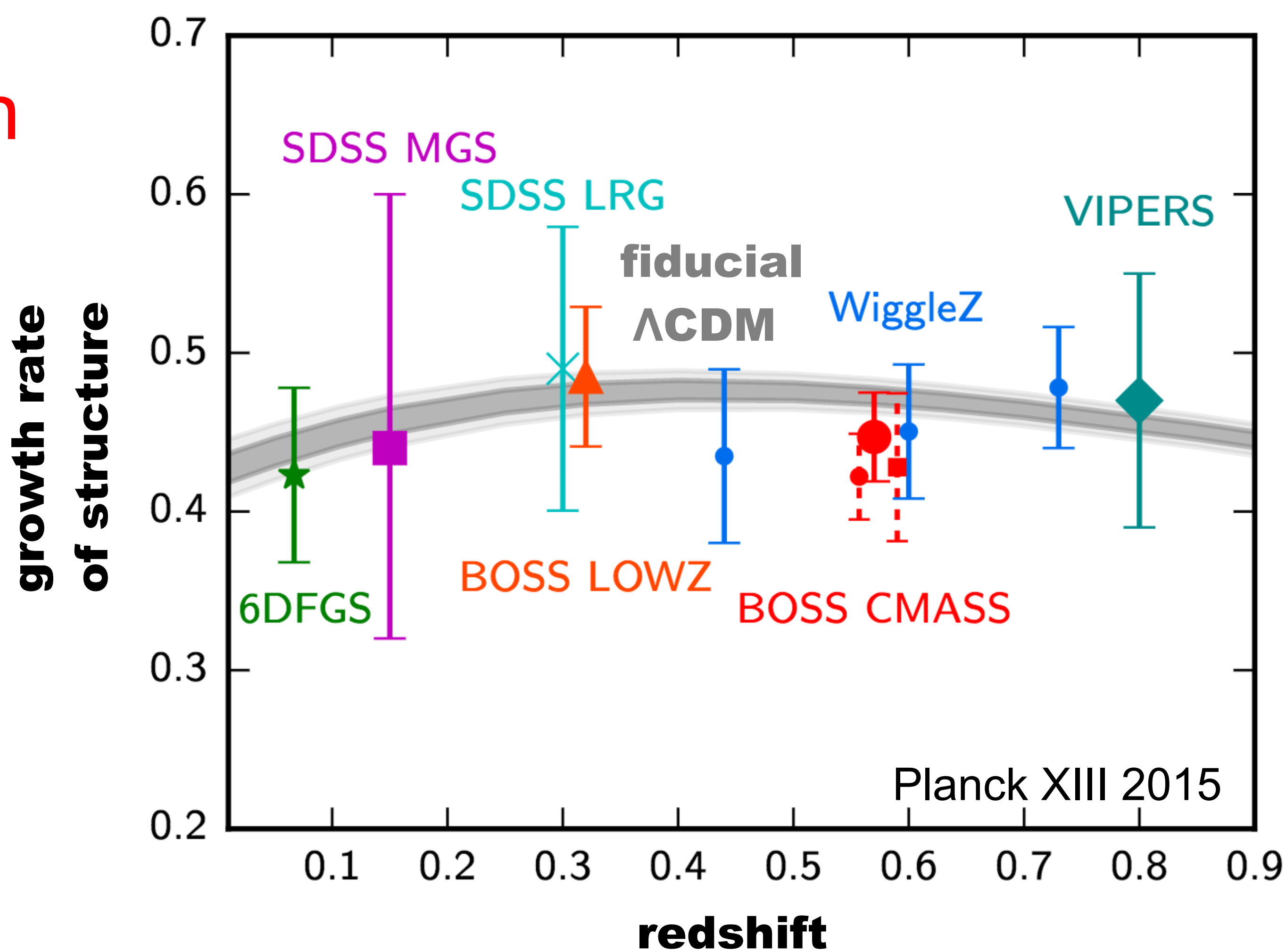
- Comparison of distance and redshift
- **Standard ruler**:
  angle subtended by known scale
  - **CMB**: sound horizon in early Universe (380,000 years)
  - **BAO**: same scale, but expanded at later times (billions of years)
- **Standard candle:** brightness of source with known luminosity
  - **SNe**: 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

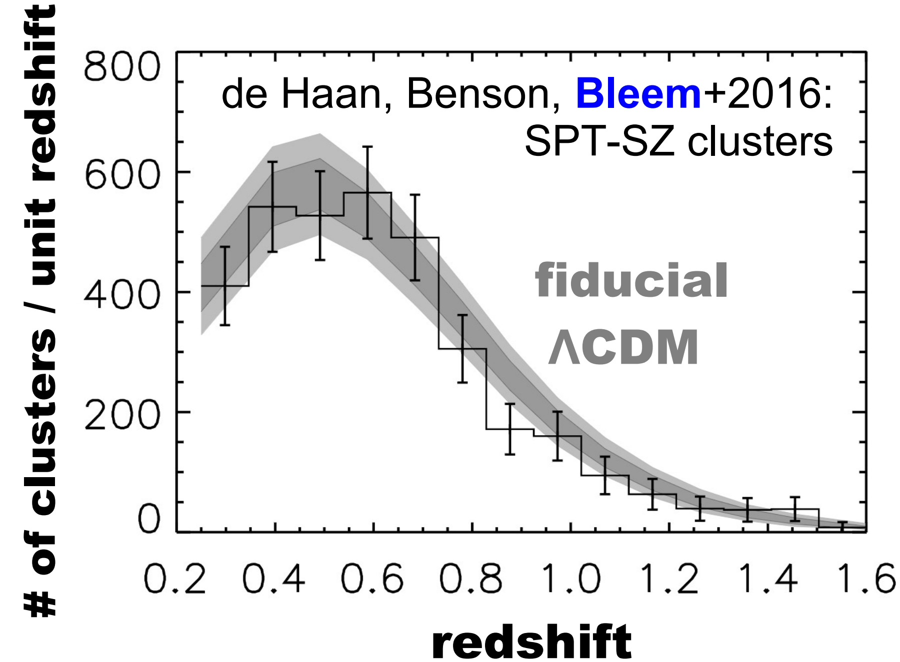
- redshift space distortions (RSD):
  growth rate
  consistent with fiducial ΛCDM

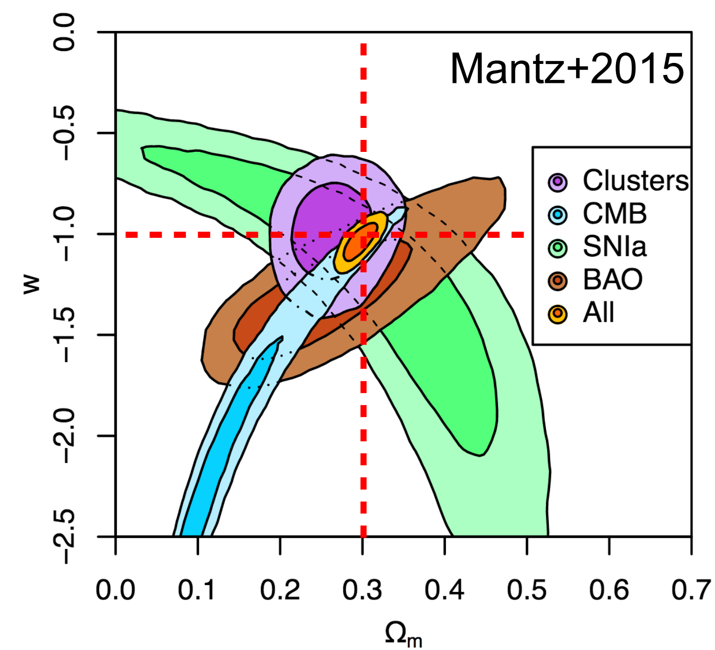


Measurement of late-time structure

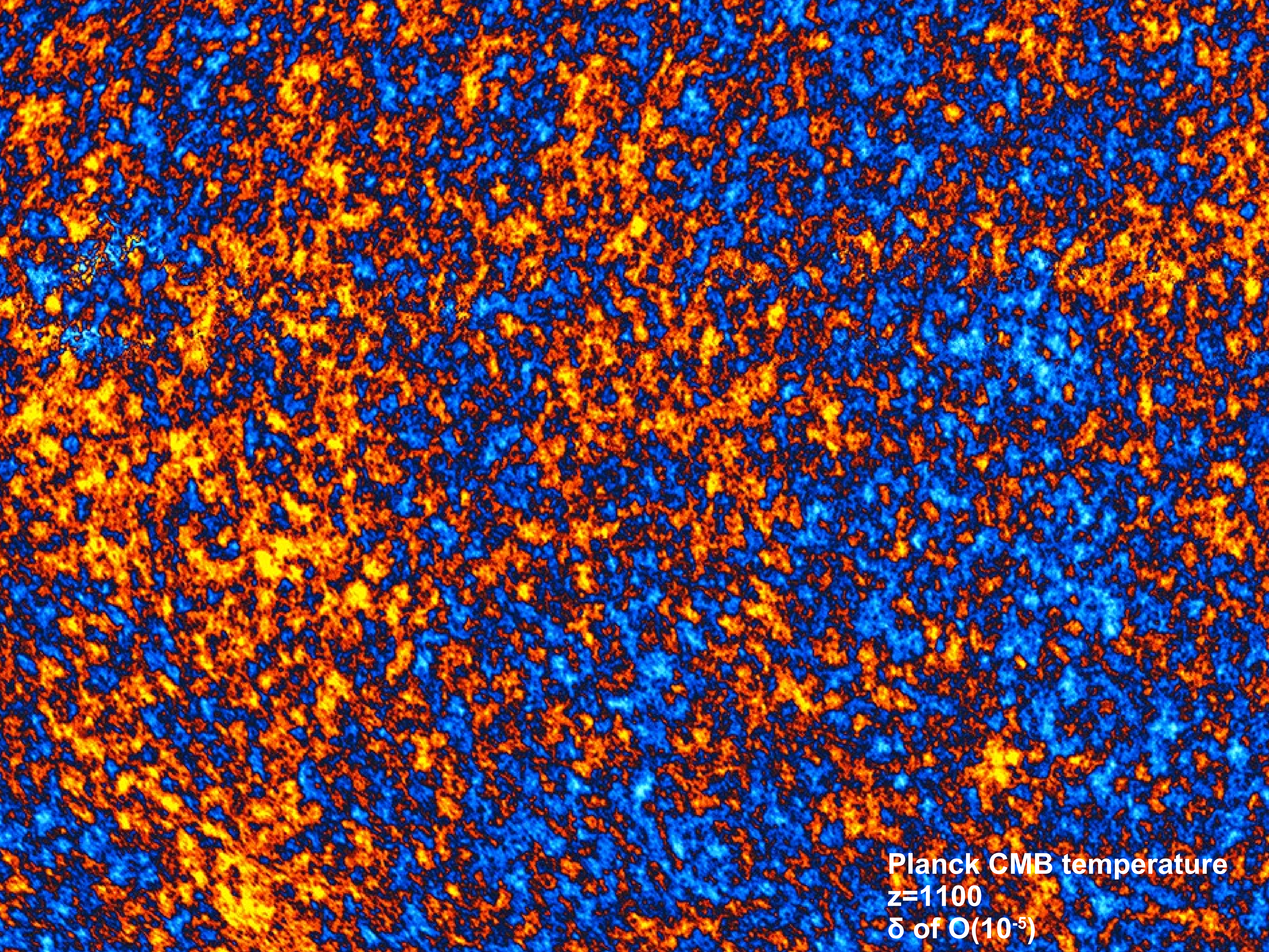
✔ RSD

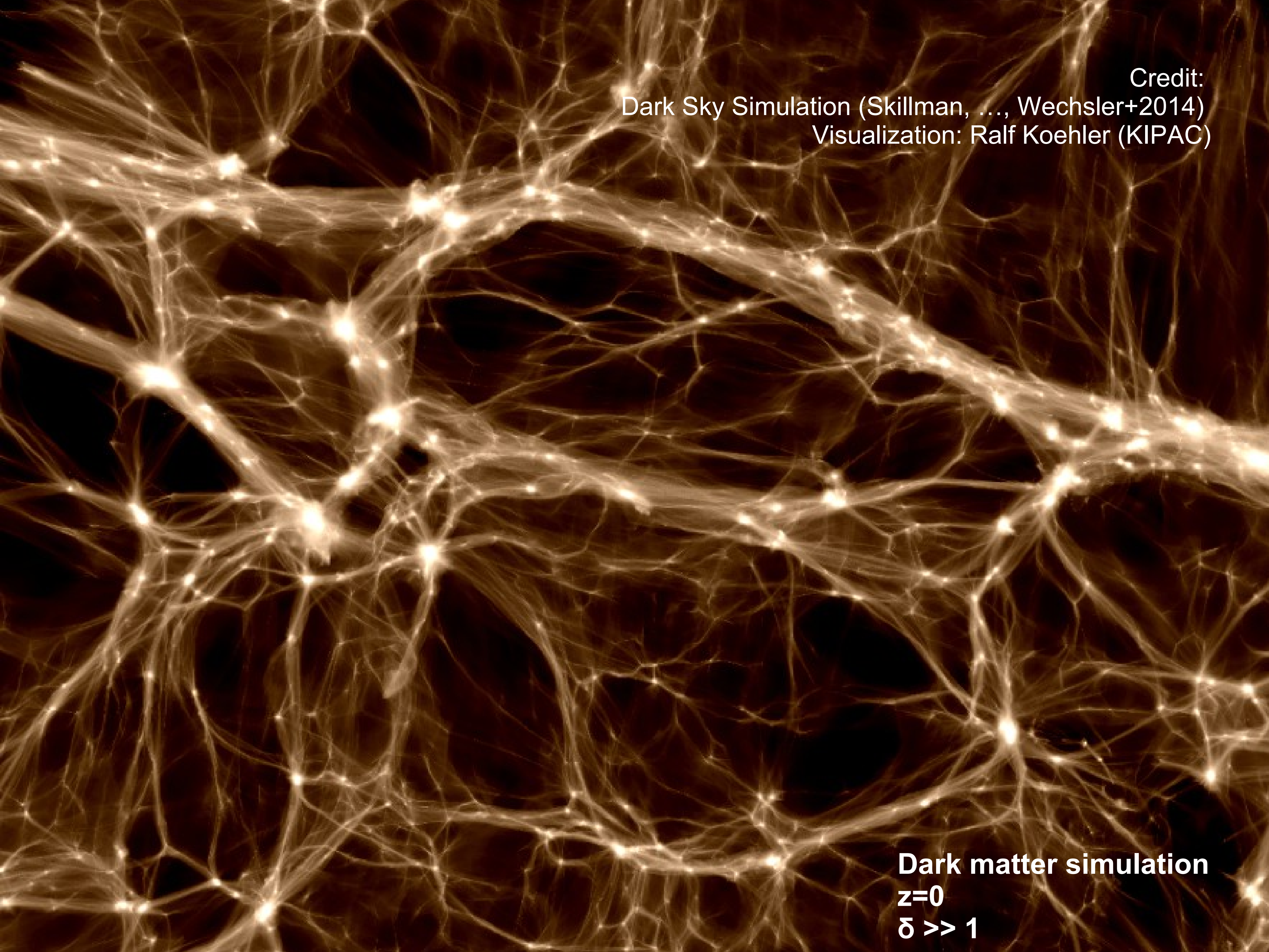
- Galaxy clusters:
  count of clusters as a function of mass and redshift consistent with fiducial ΛCDM





see also: talks by Antonella Palmese & Huan Lin, Yuanyuan Zhang, Mathew Madhavacheril


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

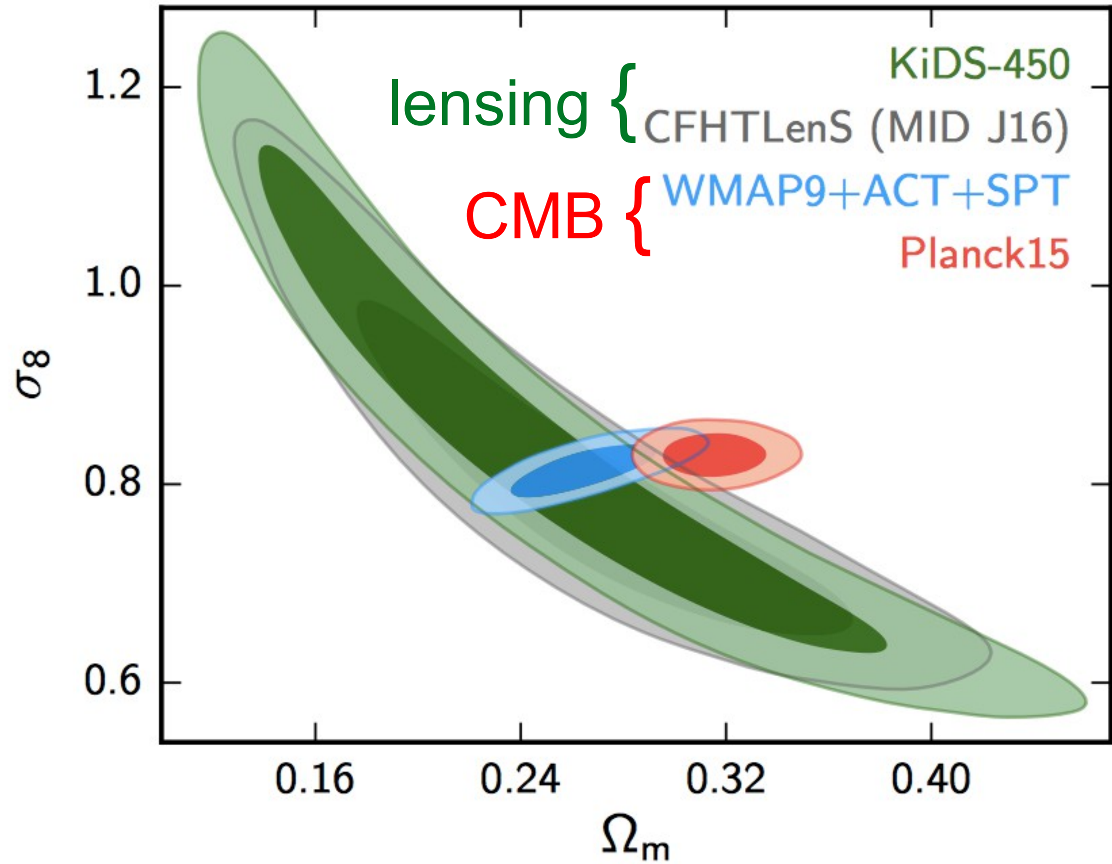
- ✔ RSD
- ✔ Galaxy clusters
- cosmic shear:

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

  A non-issue?

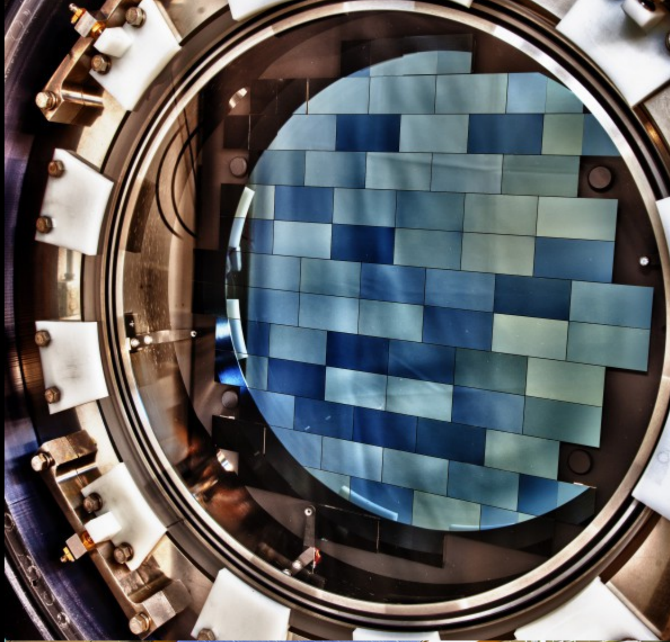
  A crack in ΛCDM?

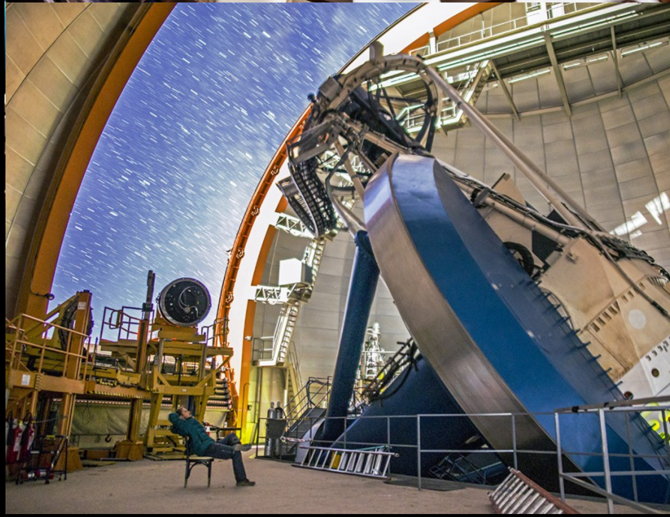
  A systematic error?

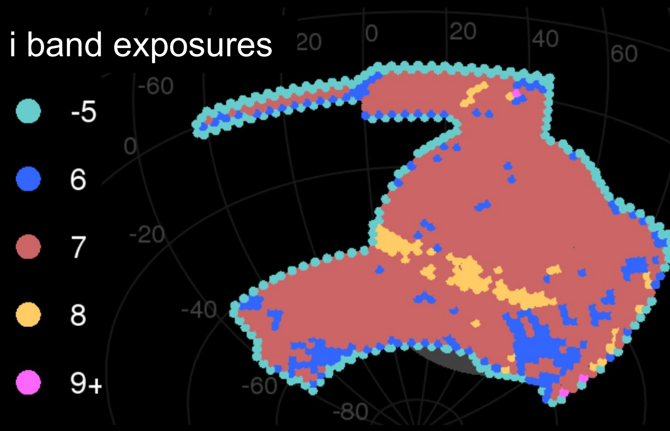


The Dark Energy Survey

- 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)







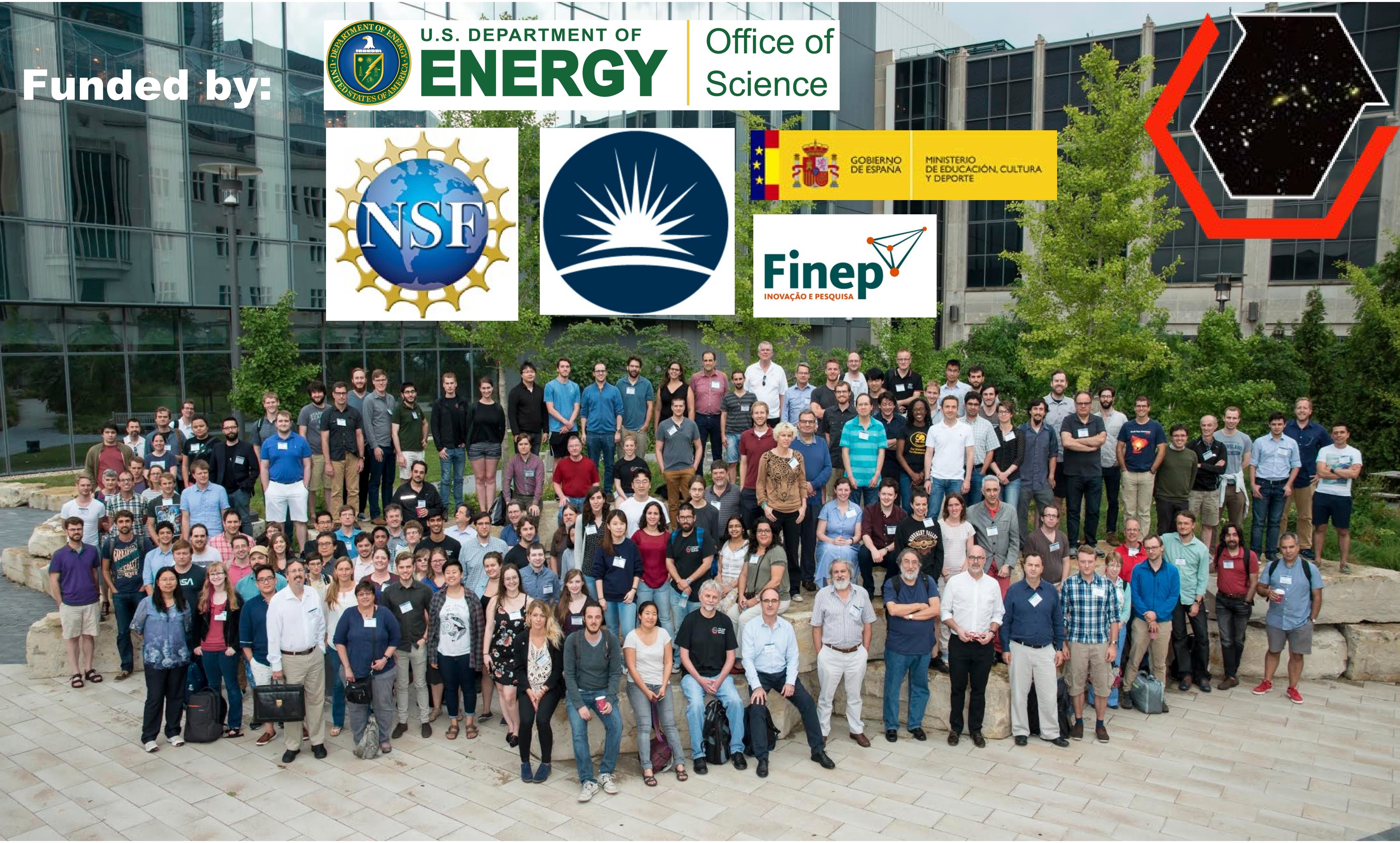
Funded by:

U.S. DEPARTMENT OF ENERGY | Office of Science

NSF

GOBIERNO DE ESPAÑA | MINISTERIO DE EDUCACIÓN, CULTURA Y DEPORTE

Finep INOVAÇÃO E PESQUISA



Collaborating institutions:

NCSA

THE OHIO STATE UNIVERSITY

A M

BERKELEY LAB

LMU

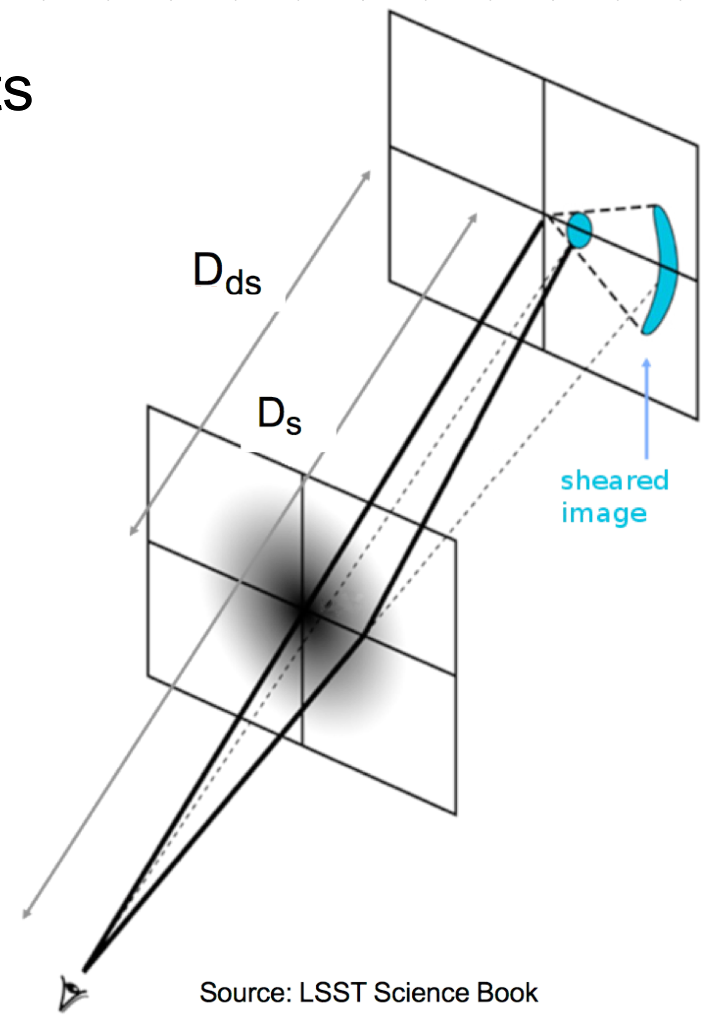
SLAC

ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich

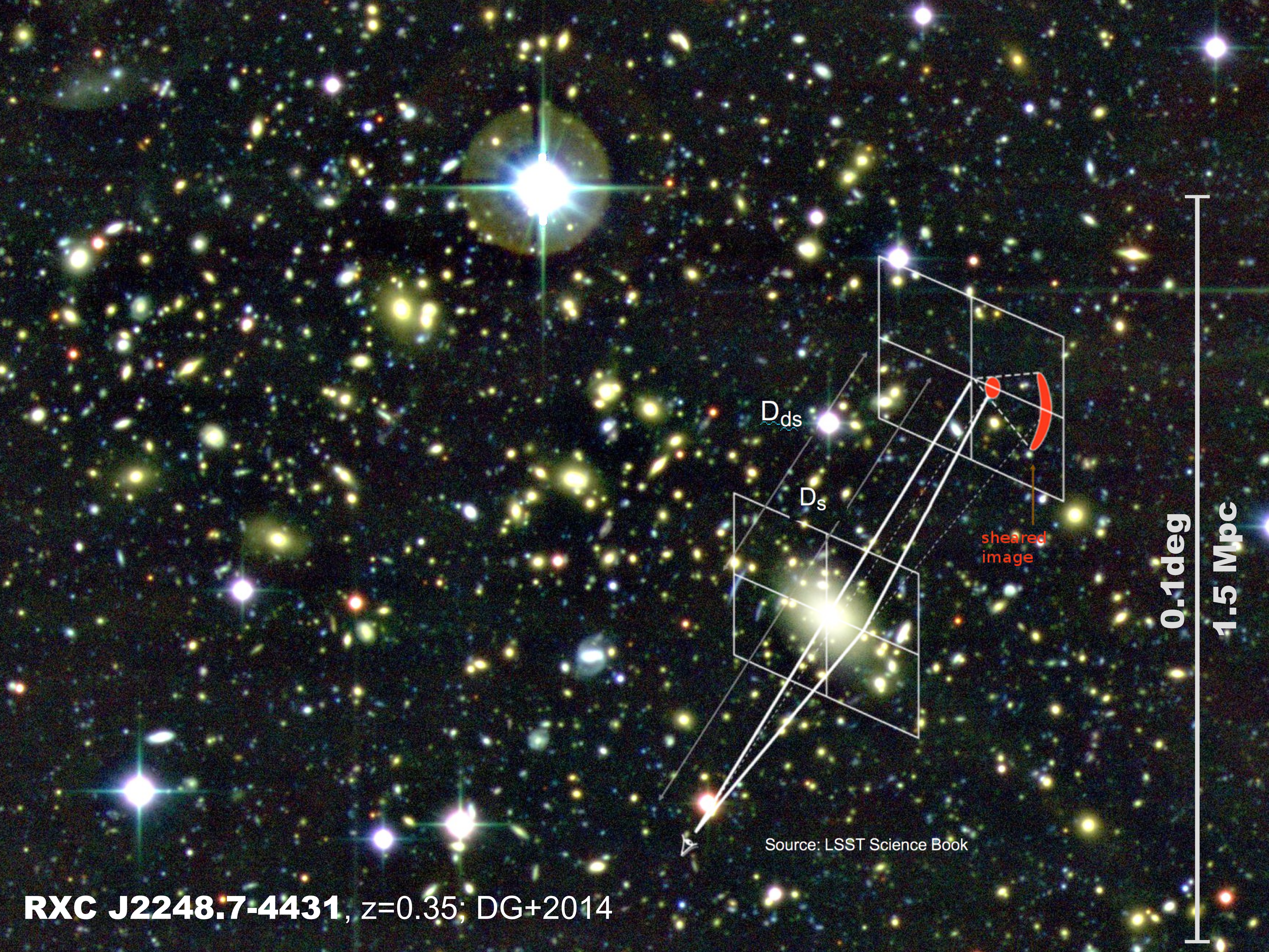
Gravitational lensing

- 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

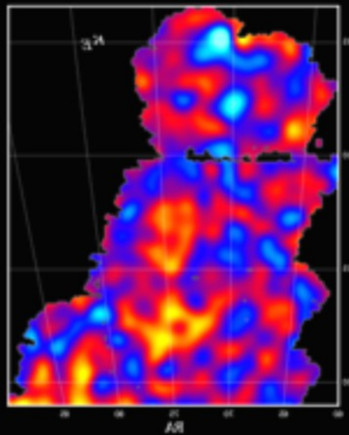
$$\gamma_t(\theta) = \langle\kappa(\theta')\rangle_{\theta'<\theta} - \kappa(\theta)$$
$$\kappa = \Sigma / \left[\frac{c^2}{4\pi G}\frac{D_\mathrm{s}}{D_\mathrm{d}D_\mathrm{ds}}\right]$$



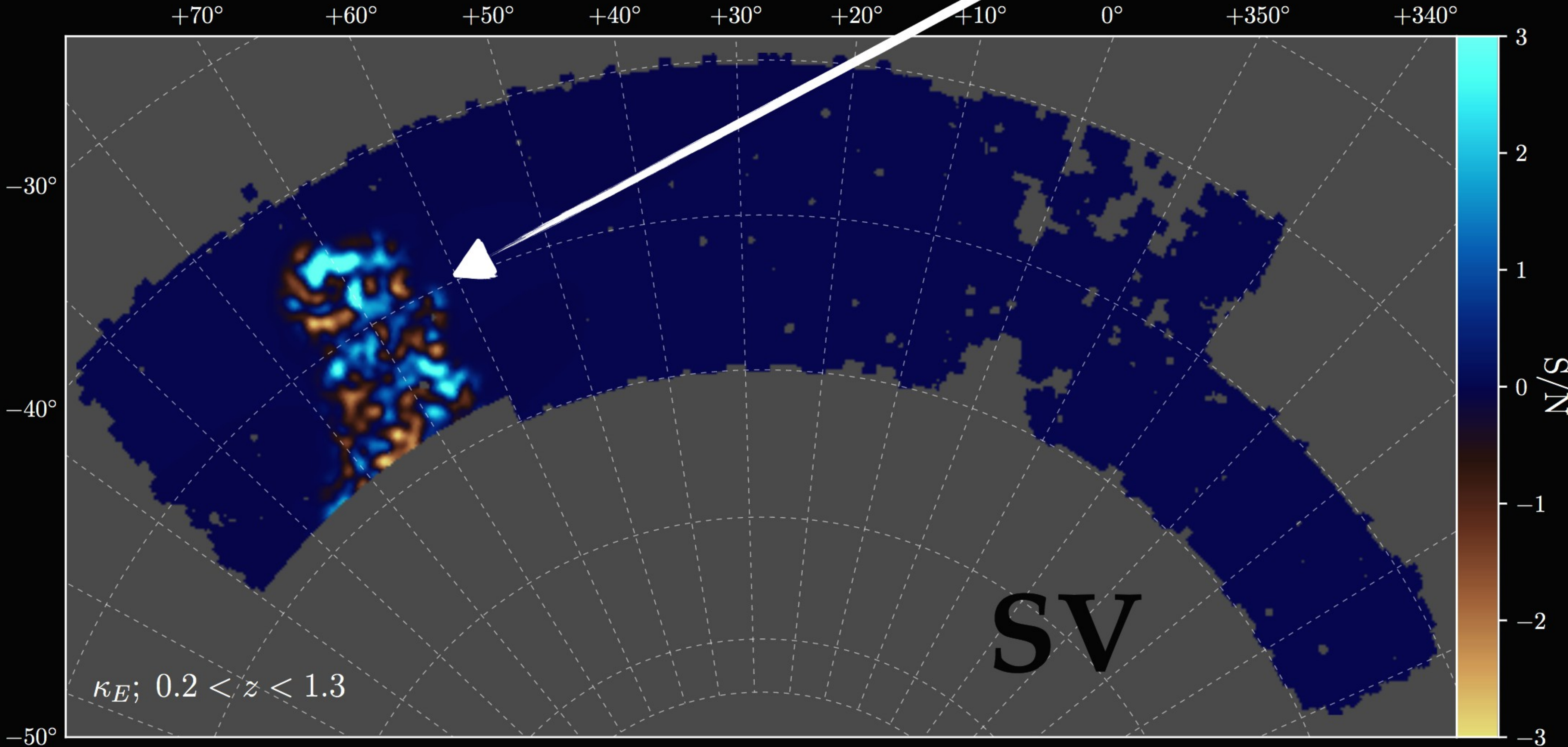
Source: LSST Science Book


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

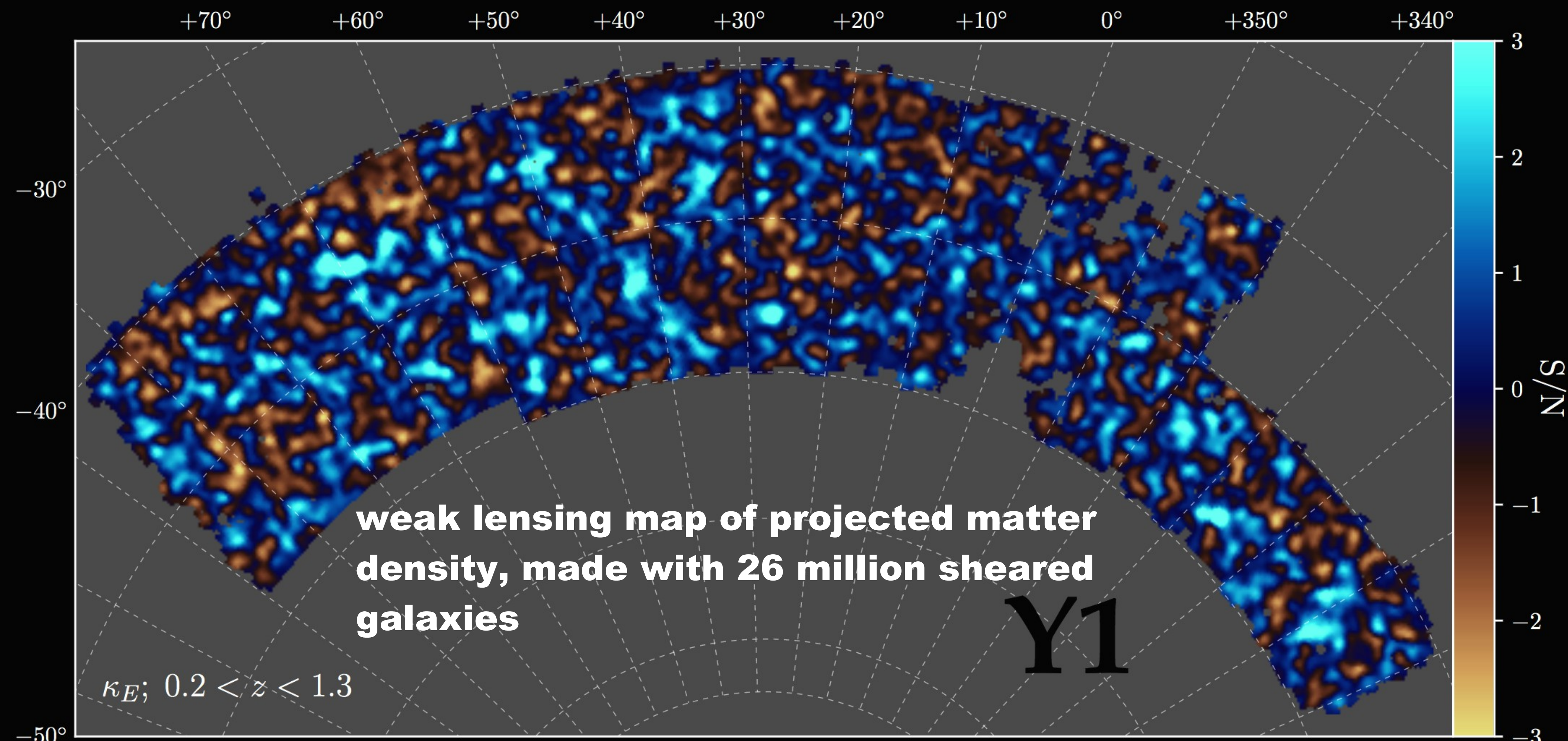
DES SV ...



Chang+; Vikram+ 2016



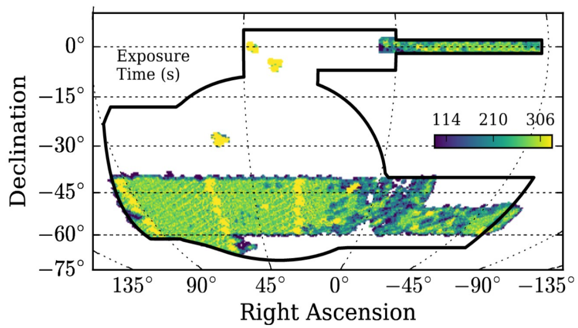
DES SV ... to Y1



Chang et al. (released today)

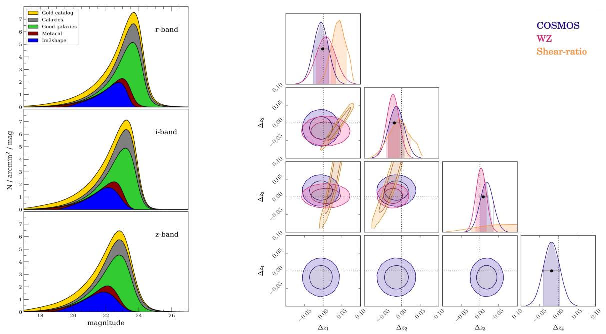
With great statistical power comes great systematic responsibility

Unprecedented size and depth of photometric data



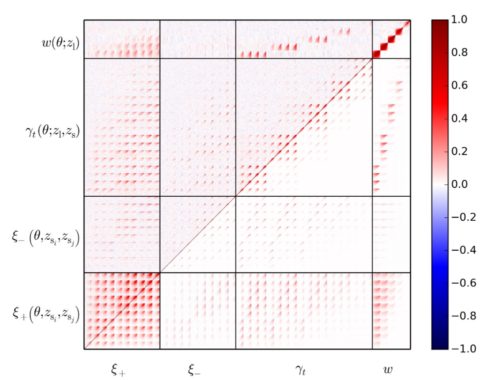
Drlica-Wagner, Rykoff, Sevilla+ released today

Two independent shape & photo-z catalogs and calibrations

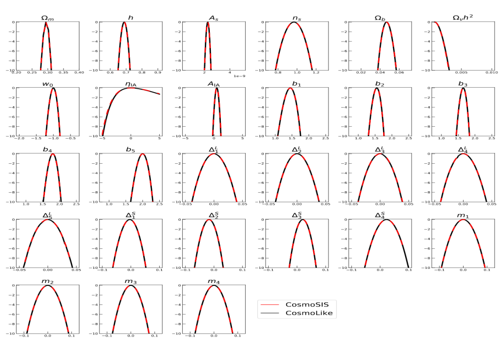


Zuntz, Sheldon+; Samuroff+; Hoyle, Gruen+ released today; Davis+, Gatti, Vielzeuf+, Cawthon+ in prep.

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



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

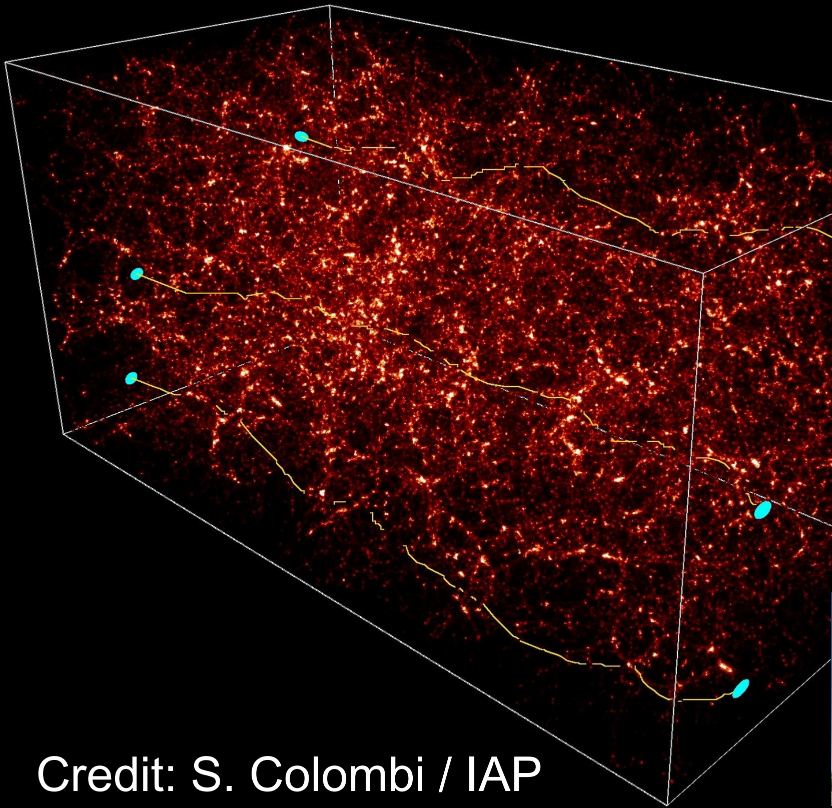


Krause, Eifler+2017; MacCrann, DeRose+ in prep

Measurements: cosmic shear

Troxel+ released today

- Light from distant galaxies passes the same foreground structure

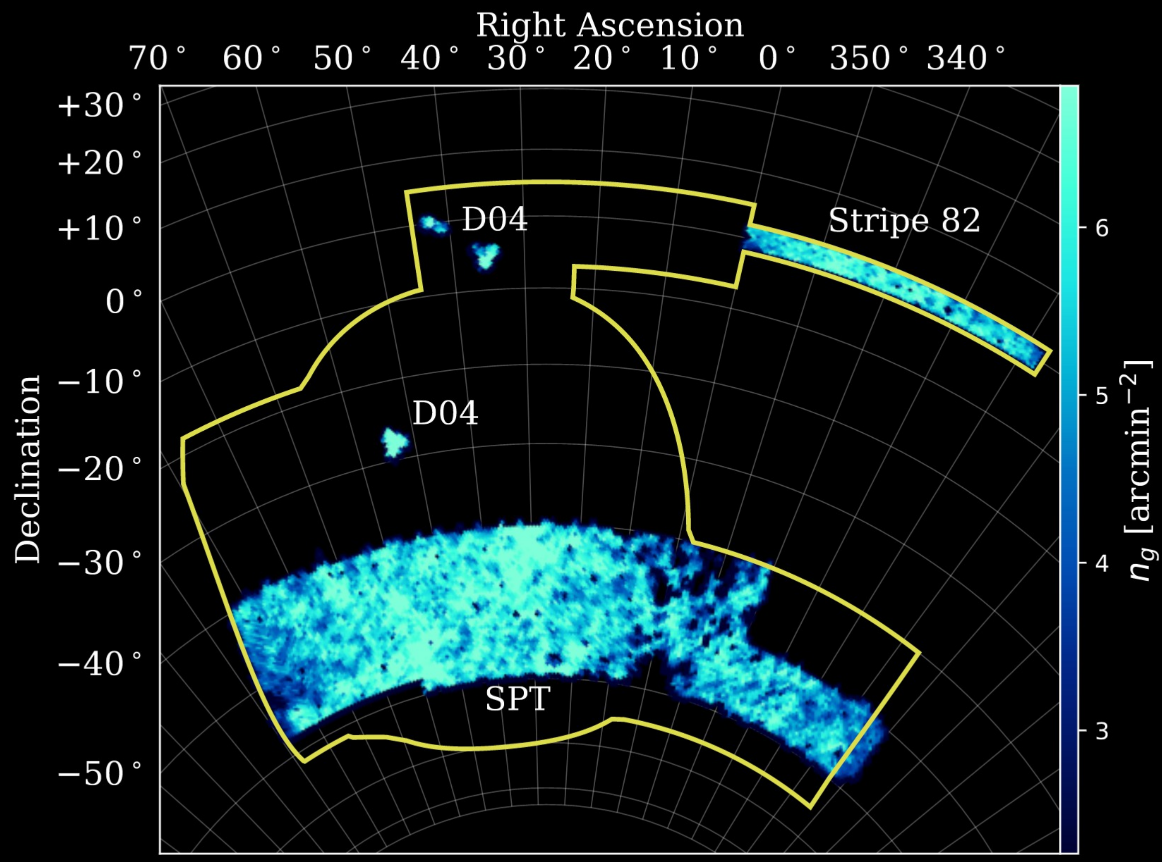


Credit: S. Colombi / IAP

Measurements: cosmic shear

Troxel+ released today

- Light from distant galaxies passes the same foreground structure
- We measure their shapes



35 million shapes in primary catalog with metacalibration (Sheldon+2017; Huff+2017) with multiplicative bias |m| below 1.3% (68% C.L.)

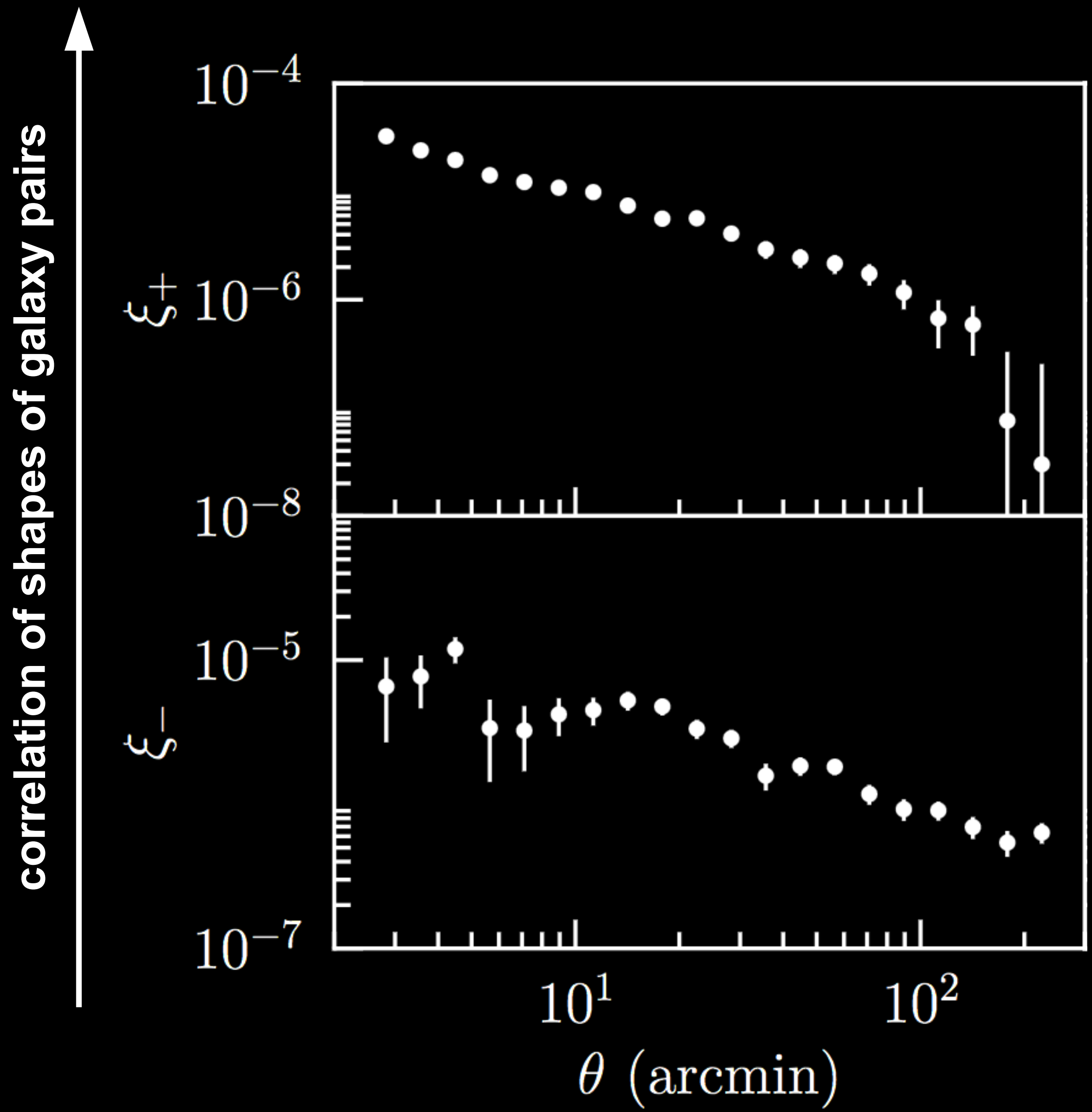
Independent im3shape (Zuntz+2013) catalog, calibrated with image simulations (Samuroff+ released today)

Suite of detailed tests: Zuntz, Sheldon+ released today

Measurements: cosmic shear

Troxel+ released today

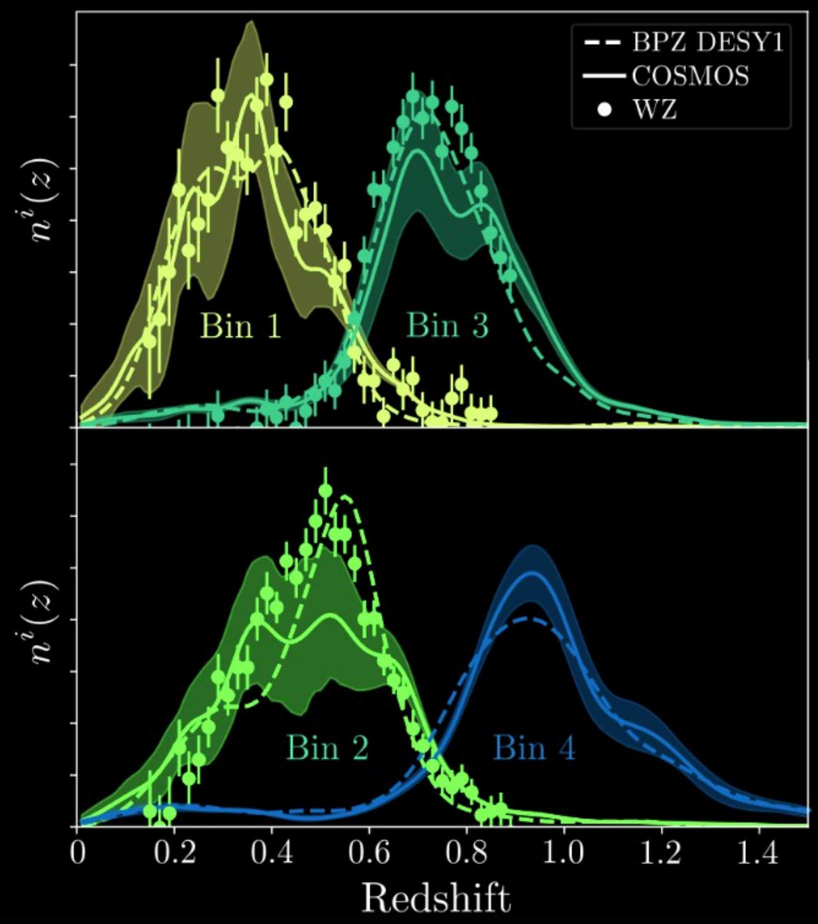
- Light from distant galaxies passes the same foreground structure
- We measure their shapes
- We measure the correlation of shapes of galaxy pairs



Measurements: cosmic shear

Troxel+ released today

- Light from distant galaxies passes the same foreground structure
- We measure their shapes
- We measure the correlation of shapes of galaxy pairs
- Using photometric redshifts, we do this tomographically



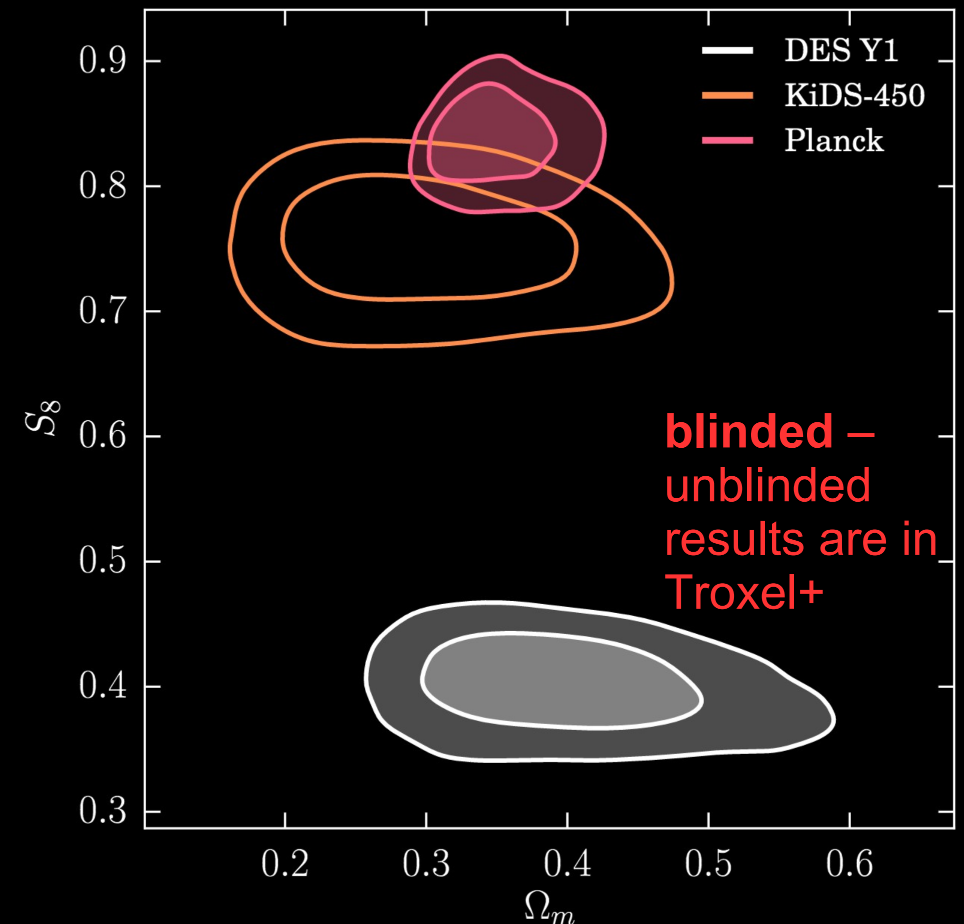
Redshift distributions n(z) measured with independent methods
[BPZ, Benitez+2000; DNF, de Vicente+2016; COSMOS, Laigle+2016]

Bias in redshifts independently calibrated with COSMOS photometry and cross-correlations with LRGs (WZ).
Hoyle, Gruen+ released today; Cawthon+, Davis+, Gatti, Vielzeuf+ in preparation

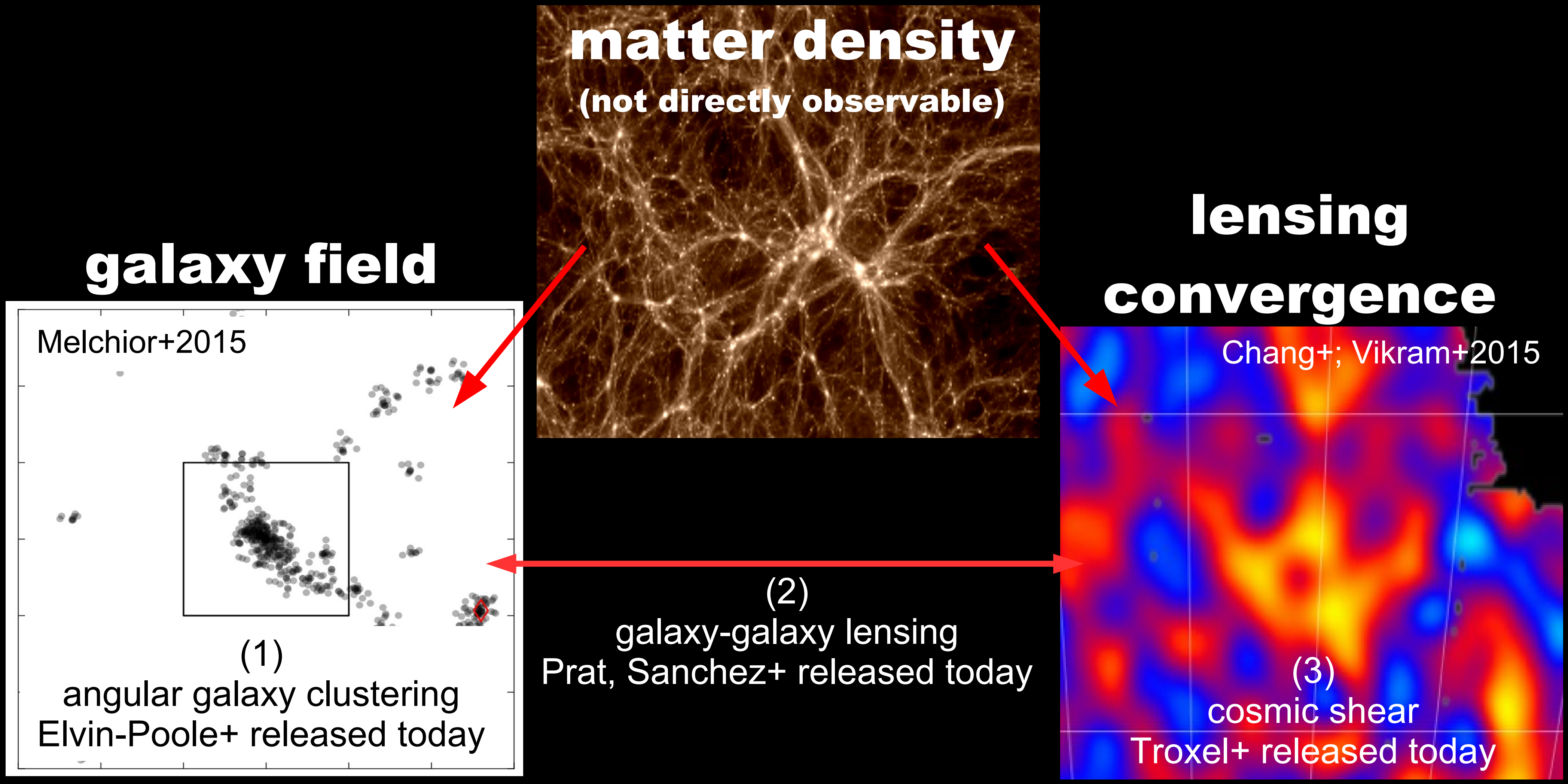
Measurements: cosmic shear

Troxel+ released today

- Light from distant galaxies passes the same foreground structure
- We measure their shapes
- We measure the correlation of shapes of galaxy pairs
- Using photometric redshifts, we do this tomographically
- We constrain cosmological parameters – blindly first, before we pass all tests



most precise cosmic shear experiment to date!



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]

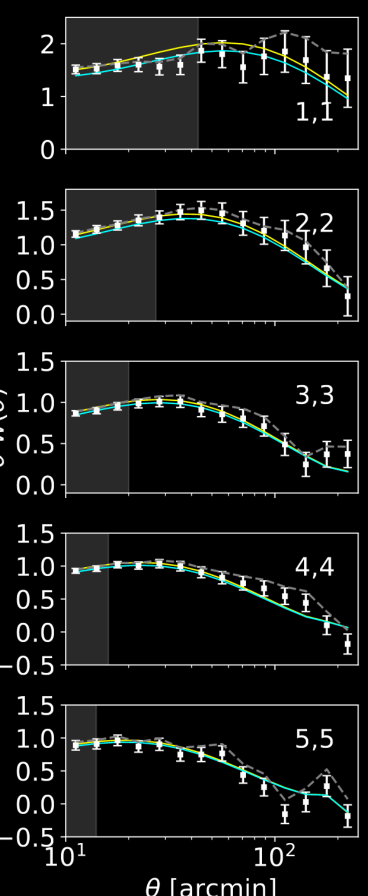
largest individual data sets and joint constraints from these three probes for the first time: DES Collaboration+ released today

Measurements: galaxy clustering and galaxy-galaxy lensing

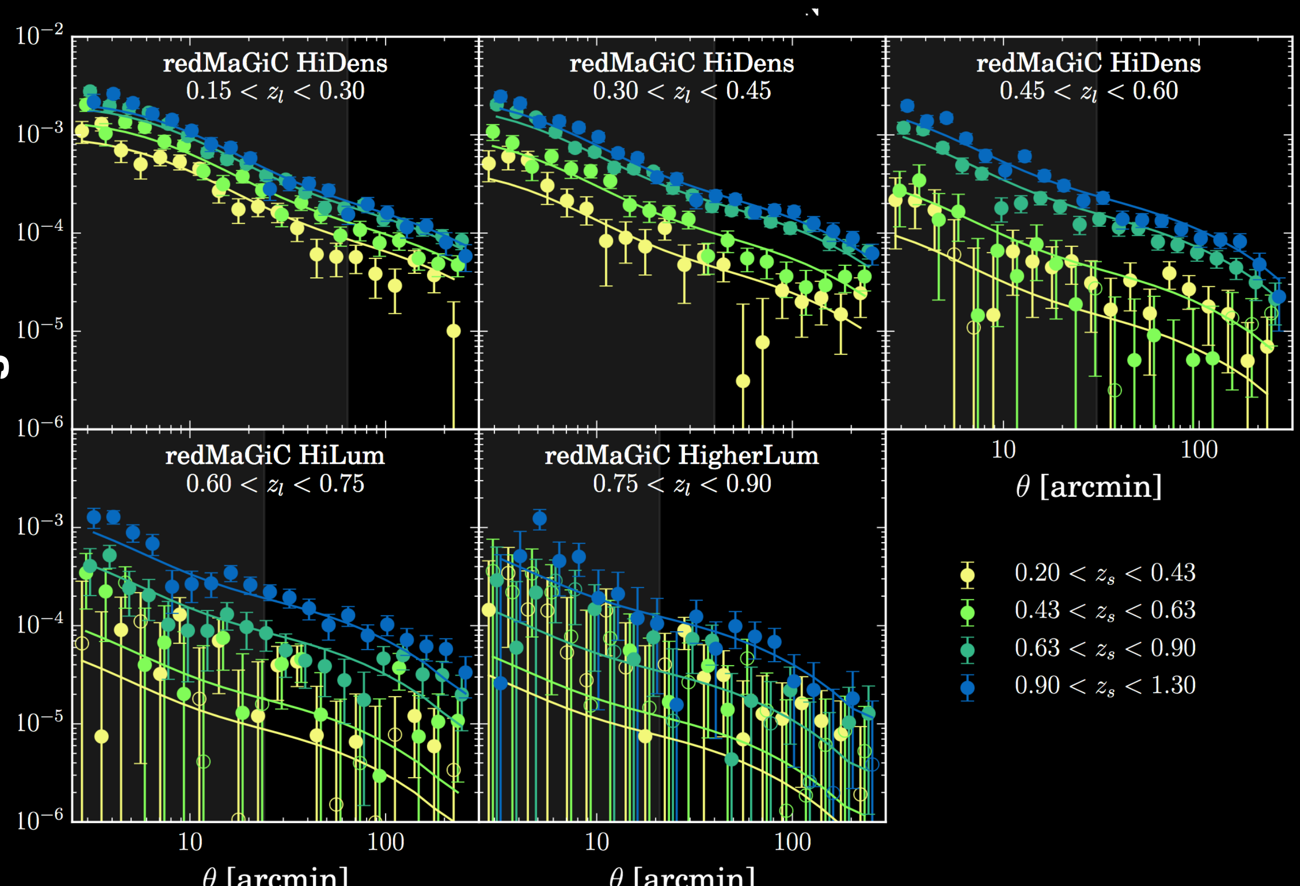
Elvin-Poole+; Prat, Sanchez+ released today

- Lens galaxies: redMaGiC LRGs with high-quality photometric redshift estimates (Rozo, Rykoff+2016)

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



tangential gravitational shear around these galaxies

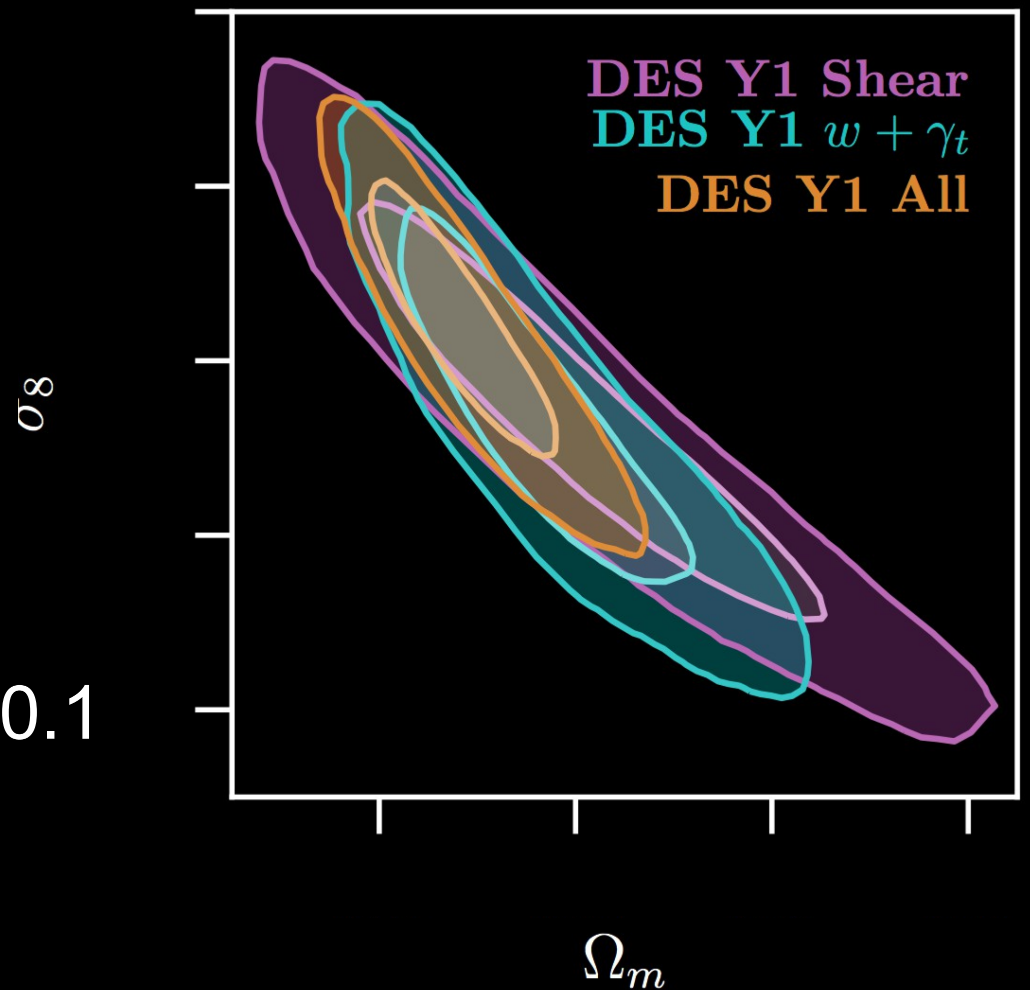


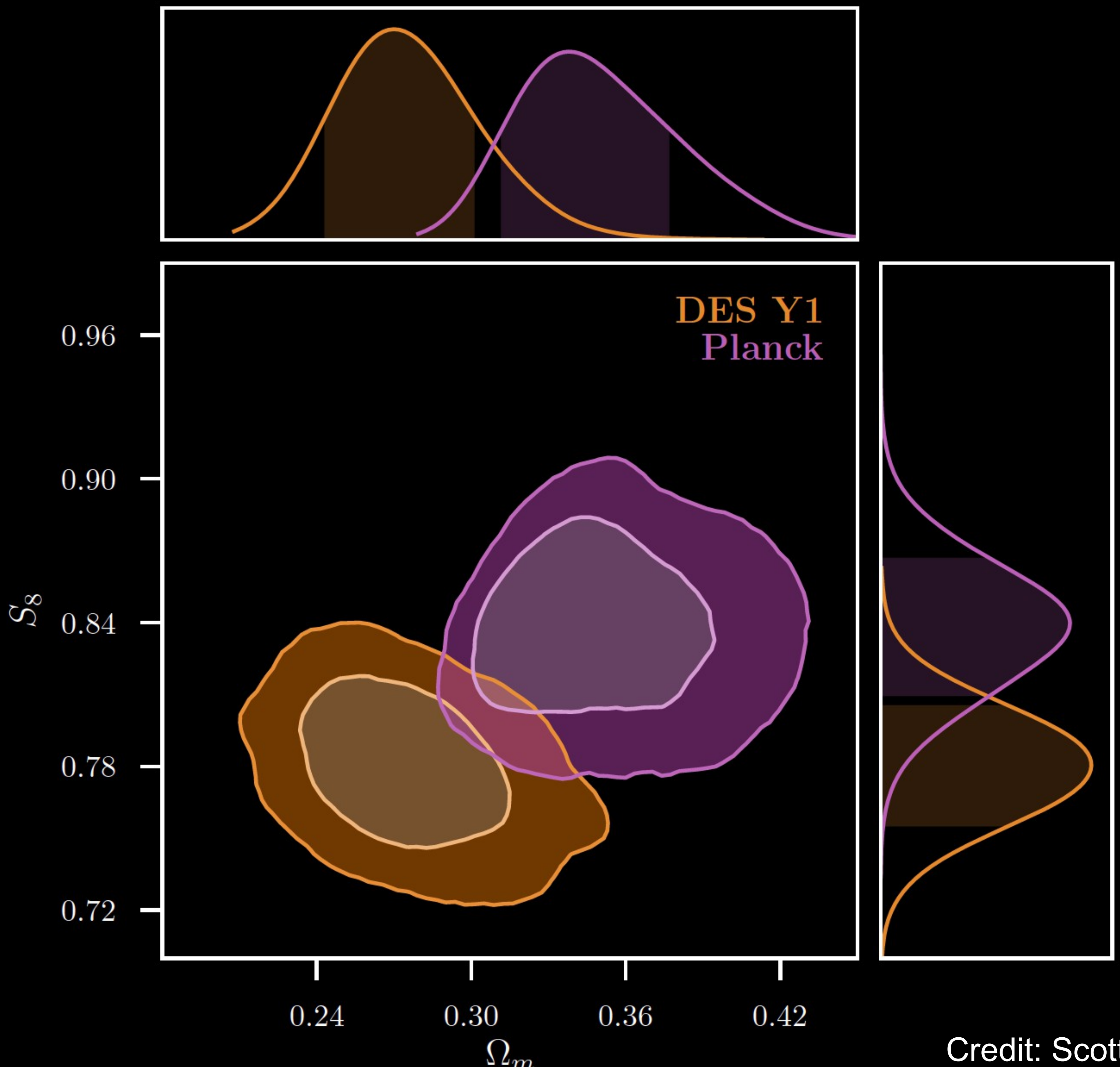
Consistency of the individual constraints in ΛCDM

- 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

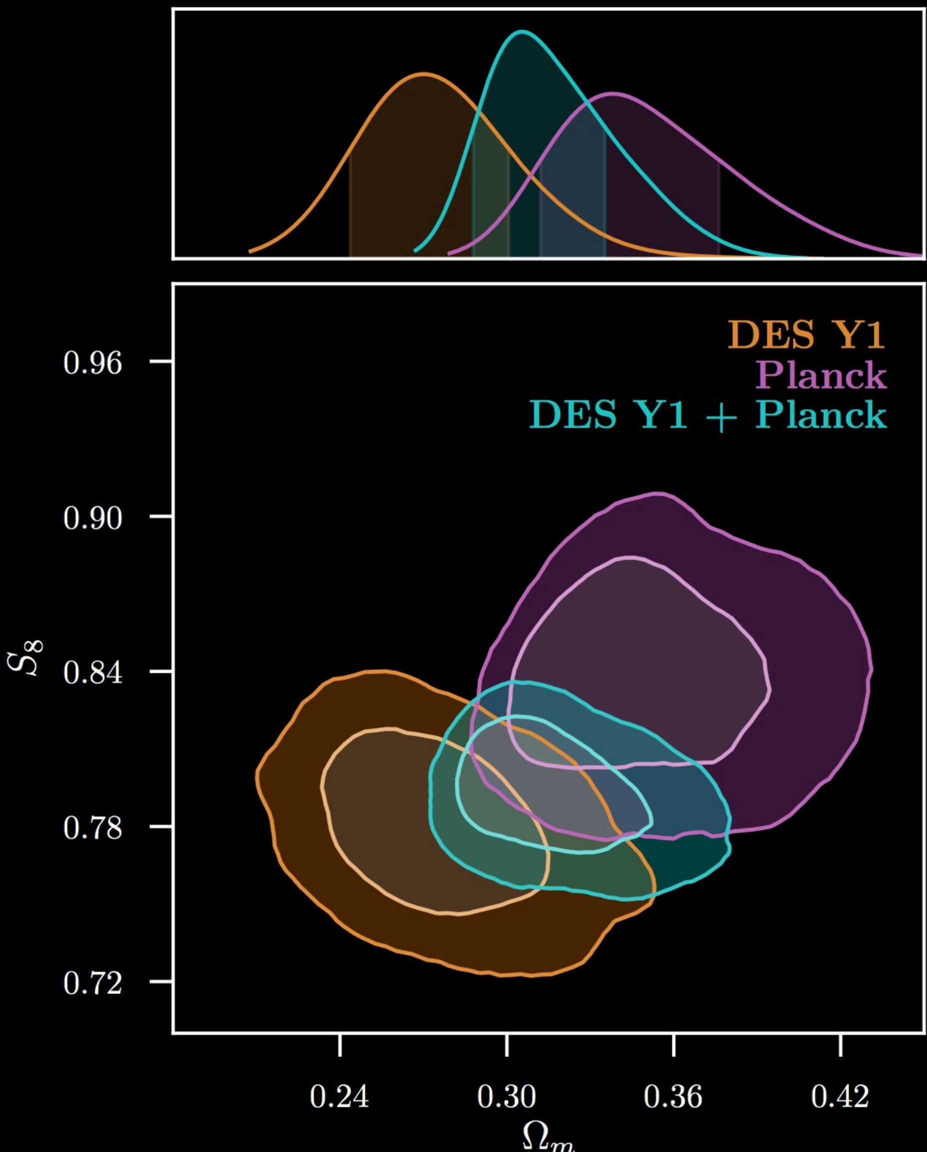




Credit: Scott Dodelson

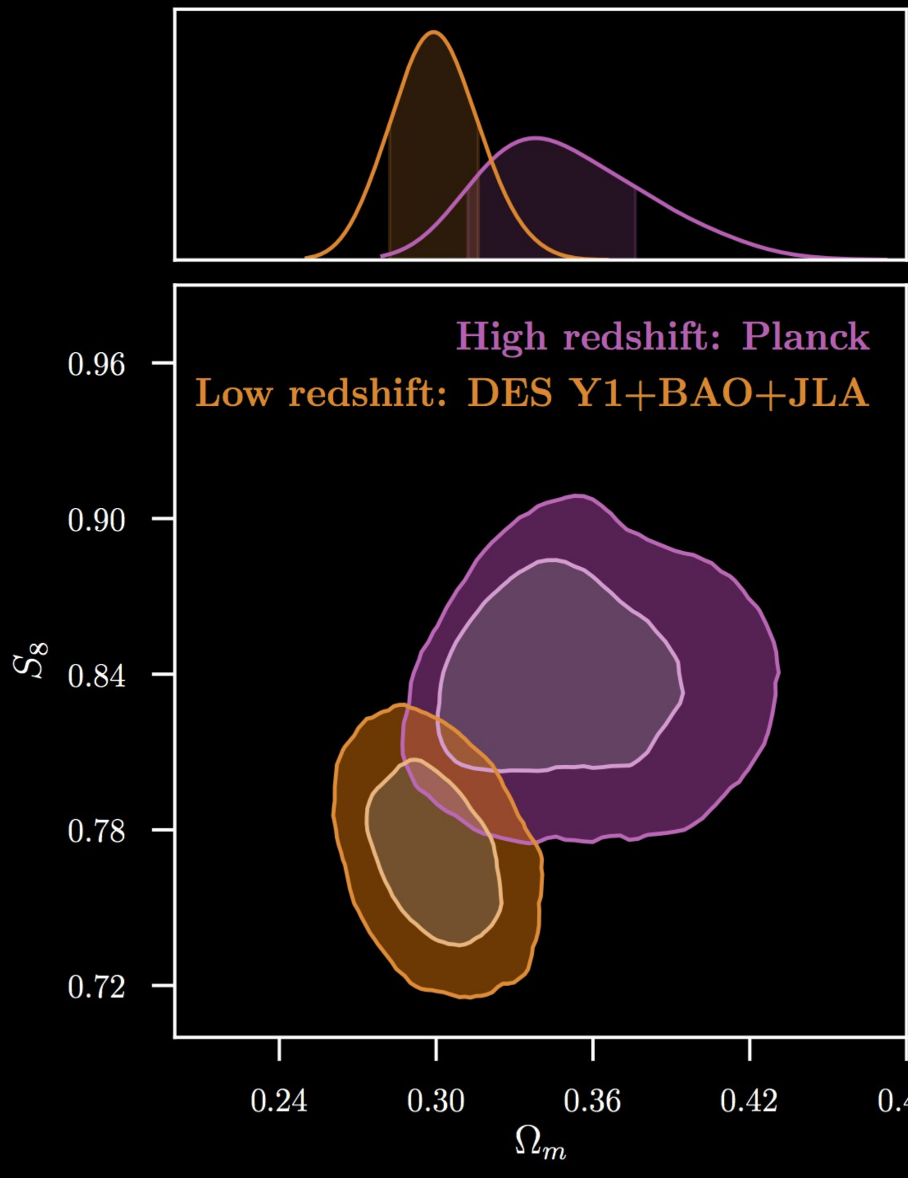
Key result: Consistency of late Universe with Planck in ΛCDM

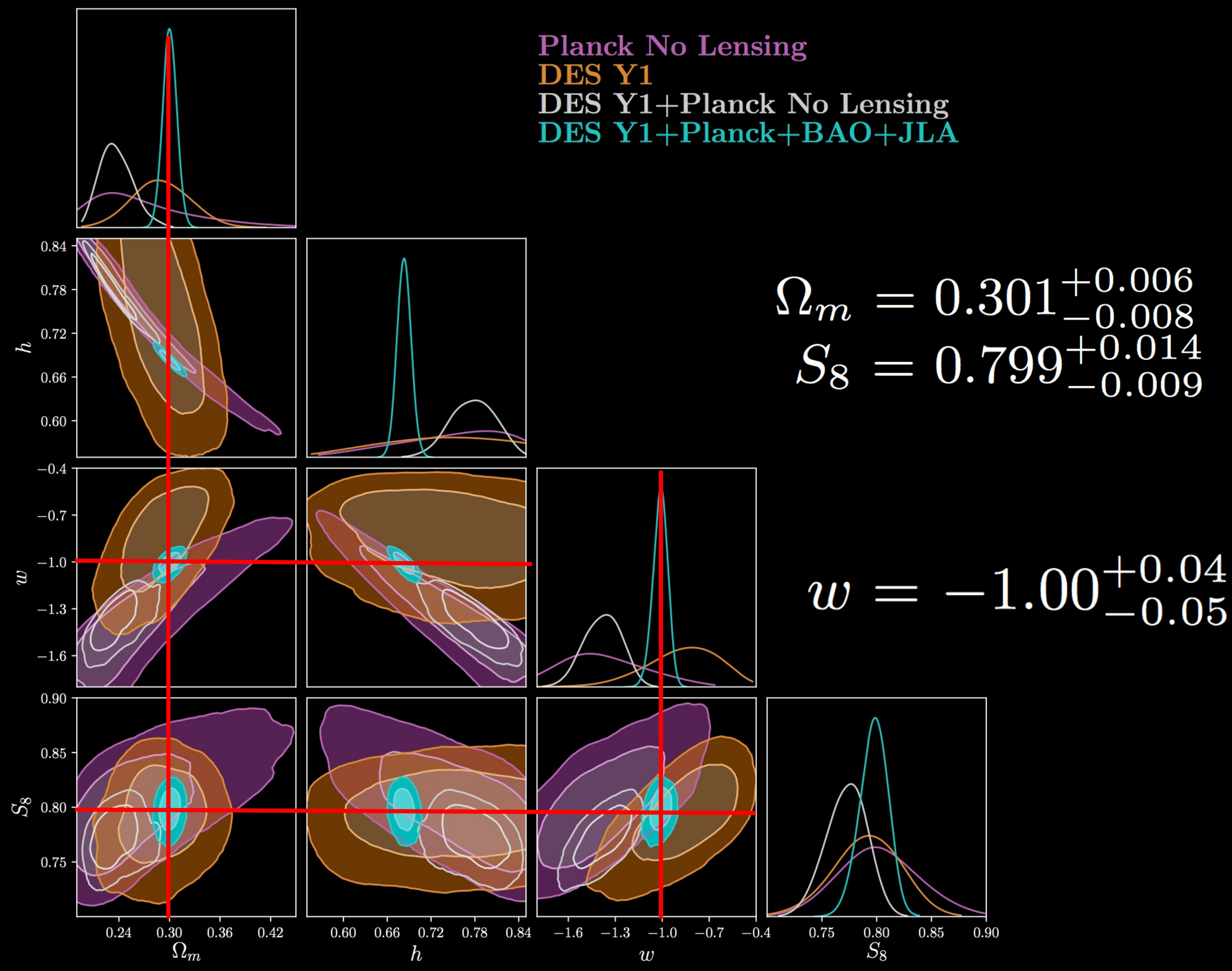
- DES and Planck constrain matter density and S_8 with equal strength
- Difference in central values 1-2σ in the same direction as earlier lensing results
- Bayes Factor 4.2 – no evidence for inconsistency



Key result: 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
- Still consistent (R=9.0) for joint low-z results + Planck, which is why we combine...





Planck No Lensing
DES Y1
DES Y1+Planck No Lensing
DES Y1+Planck+BAO+JLA
$\Omega_m = 0.301^{+0.006}_{-0.008}$
$S_8 = 0.799^{+0.014}_{-0.009}$
$w = -1.00^{+0.04}_{-0.05}$
Ω_m
h
w
S_8

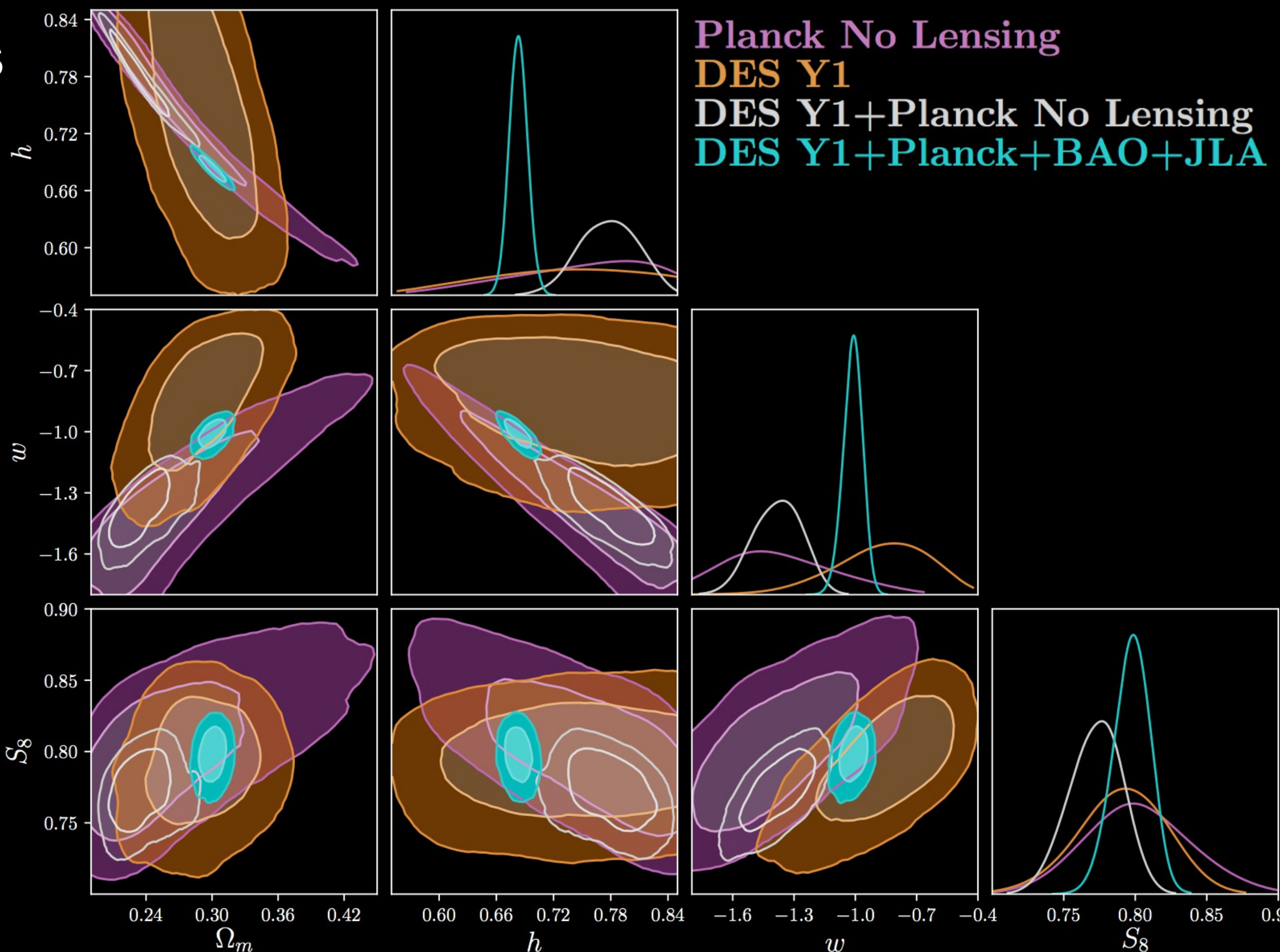
Key result: DES + geometry + CMB yields consistent, tightest constraints

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

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

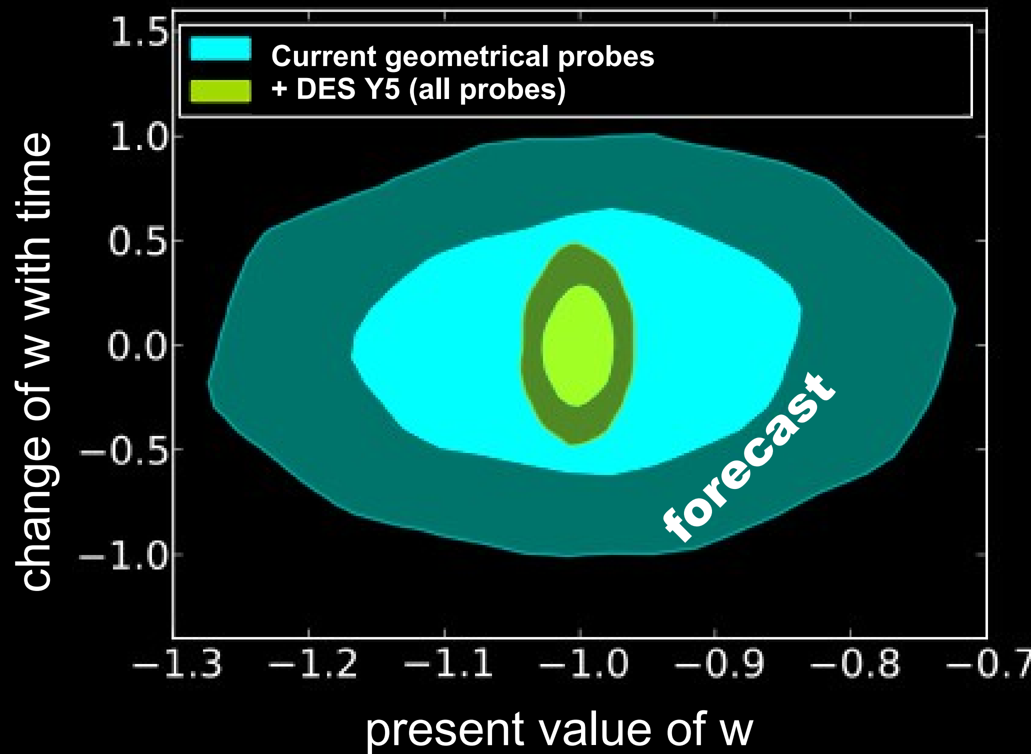
- no evidence for w≠-1 in any combination

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



Steps forward: more precise tests of broader range of models

- This is a precise test of ΛCDM, and it shows any potential discrepancies are smaller than its uncertainty
- It does not explain ΛCDM
- It is 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
  - 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
  - Papers released now on http://www.darkenergysurvey.org/
  - DES Collaborators in the audience happy to discuss later!
- Need even more precise & different model tests to understand Dark Energy – work in progress!