Year 1 Cosmology Results from the Dark Energy Survey

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on behalf of the Dark Energy Survey collaboration

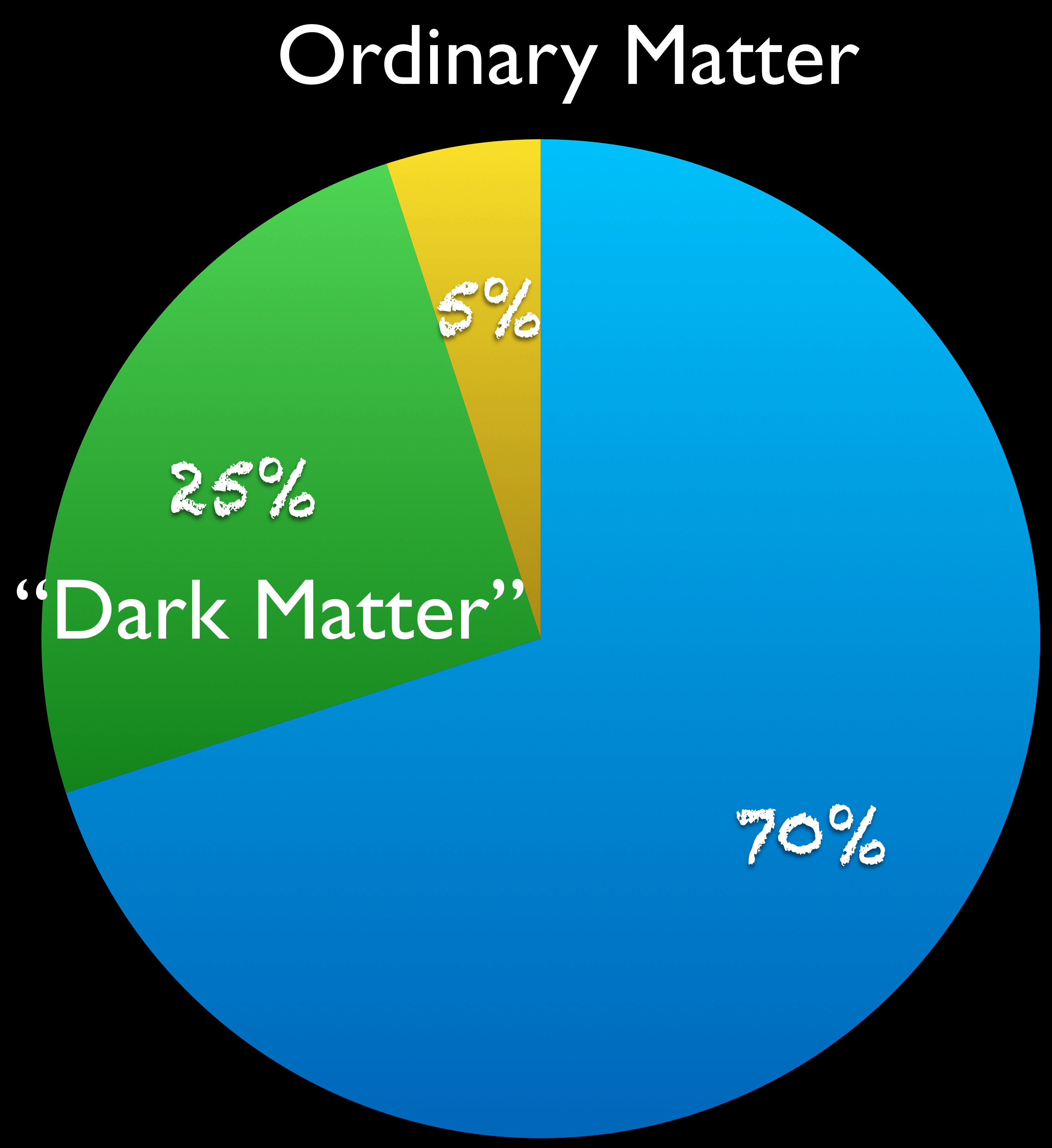
TeVPA 2017, Columbus OH

Our Simple Universe

- On large scales, the Universe can be modeled with remarkably few parameters
    - age of the Universe
    - geometry of space
    - density of atoms
    - density of matter
    - amplitude of fluctuations
    - scale dependence of fluctuations

[of course, details often not quite as simple]

Our Puzzling Universe

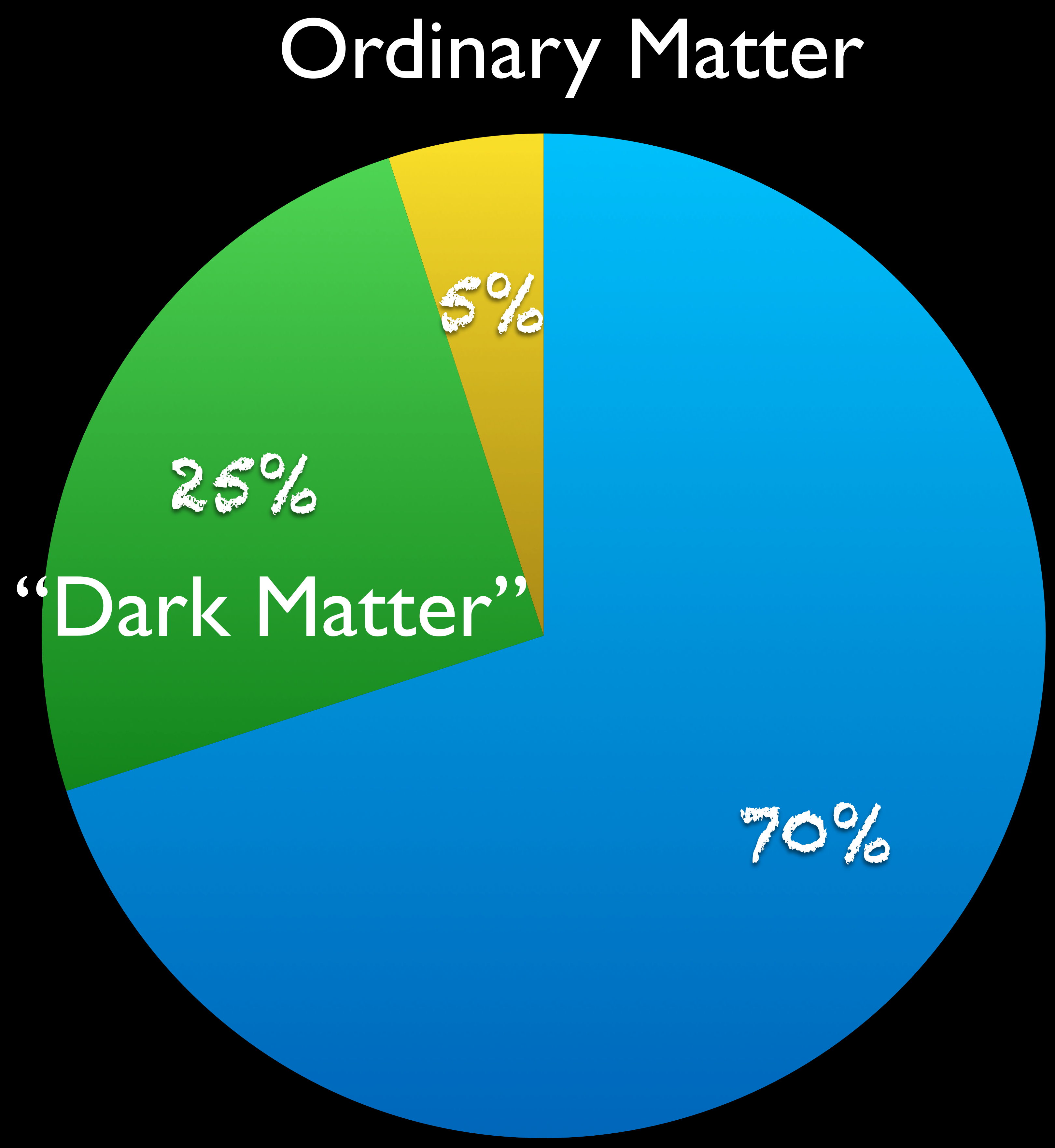


"Dark Energy"

- accelerates the expansion
- dominates the total energy density
- smoothly distributed

acceleration first measured by SN 1998

Our Puzzling Universe



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next frontier: understand

- cosmological constant Λ: $w \equiv P/\rho = -1$?
  - magnitude of Λ very surprising
- dynamic dark energy varying in time and space, $w(a)$?
- breakdown of GR?

Theoretical Alternatives to Dark Energy

Many new DE/modified gravity theories developed over last decades

Most can be categorized based on how they **break GR**:

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, are GR + Λ.

Lovelock's theorem (1969)

[subject to viability conditions]

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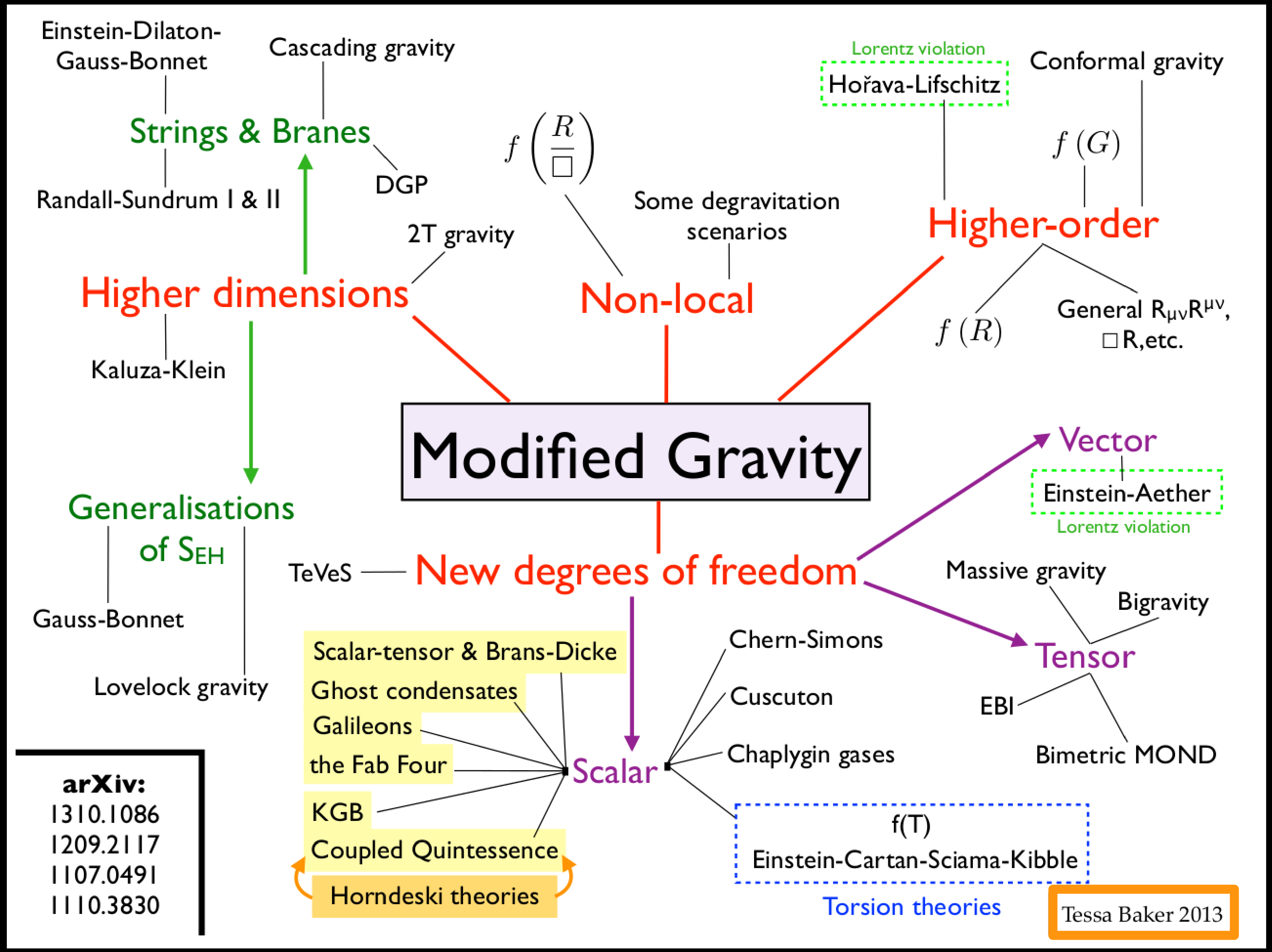

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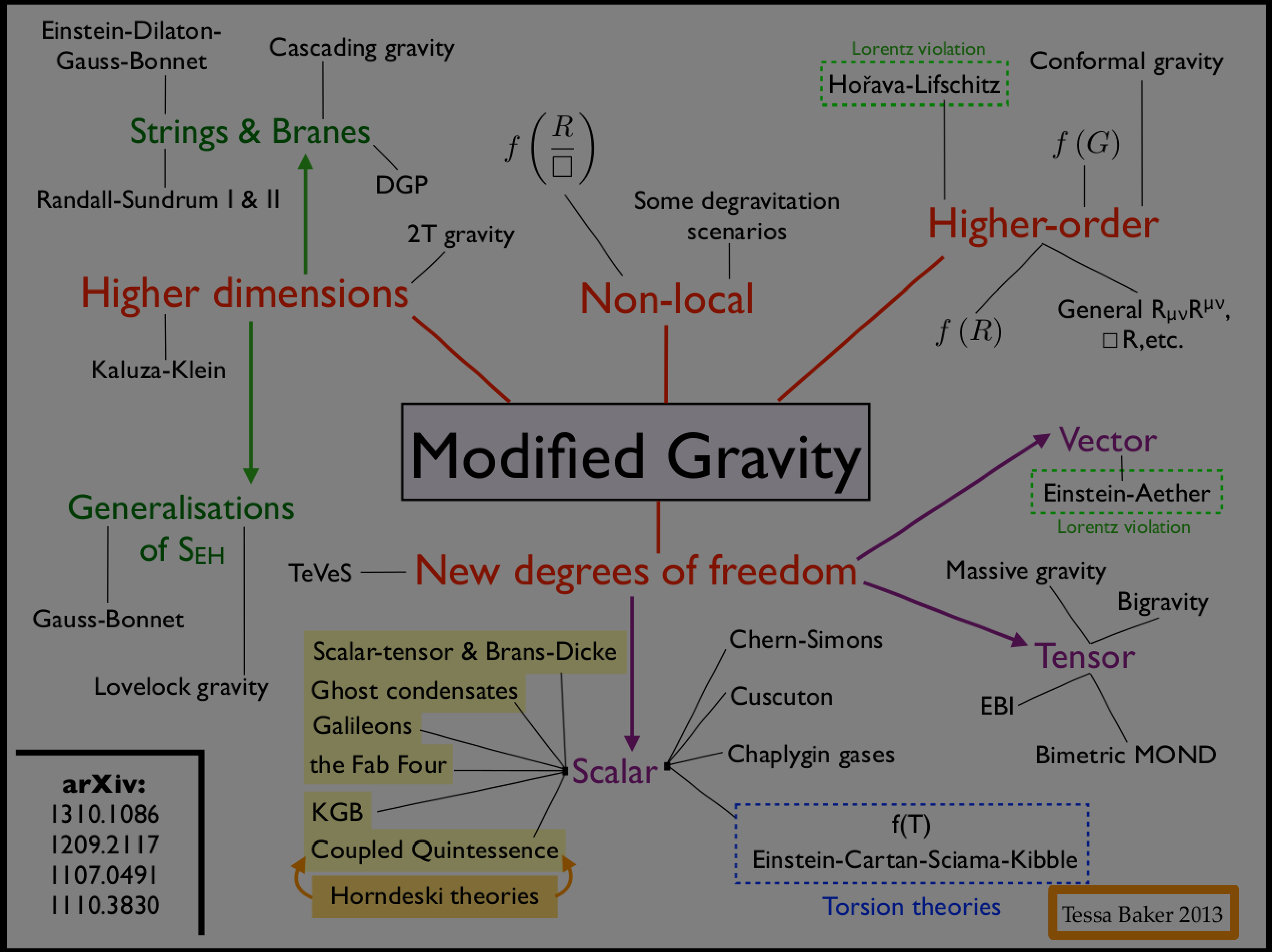


Need simple tests to confront classes of models with data

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?

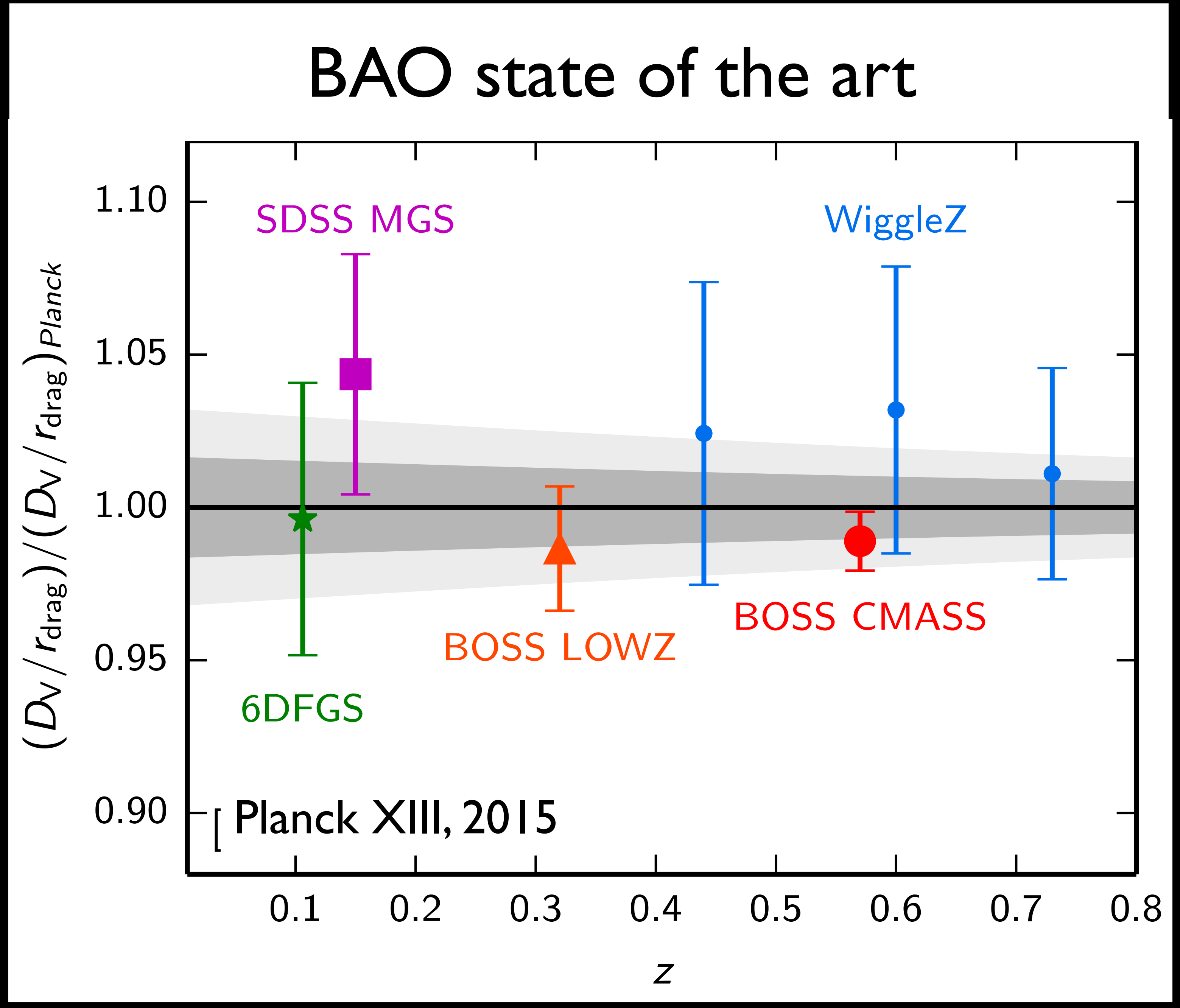
"Equation of state" parameter **w=pressure/density**

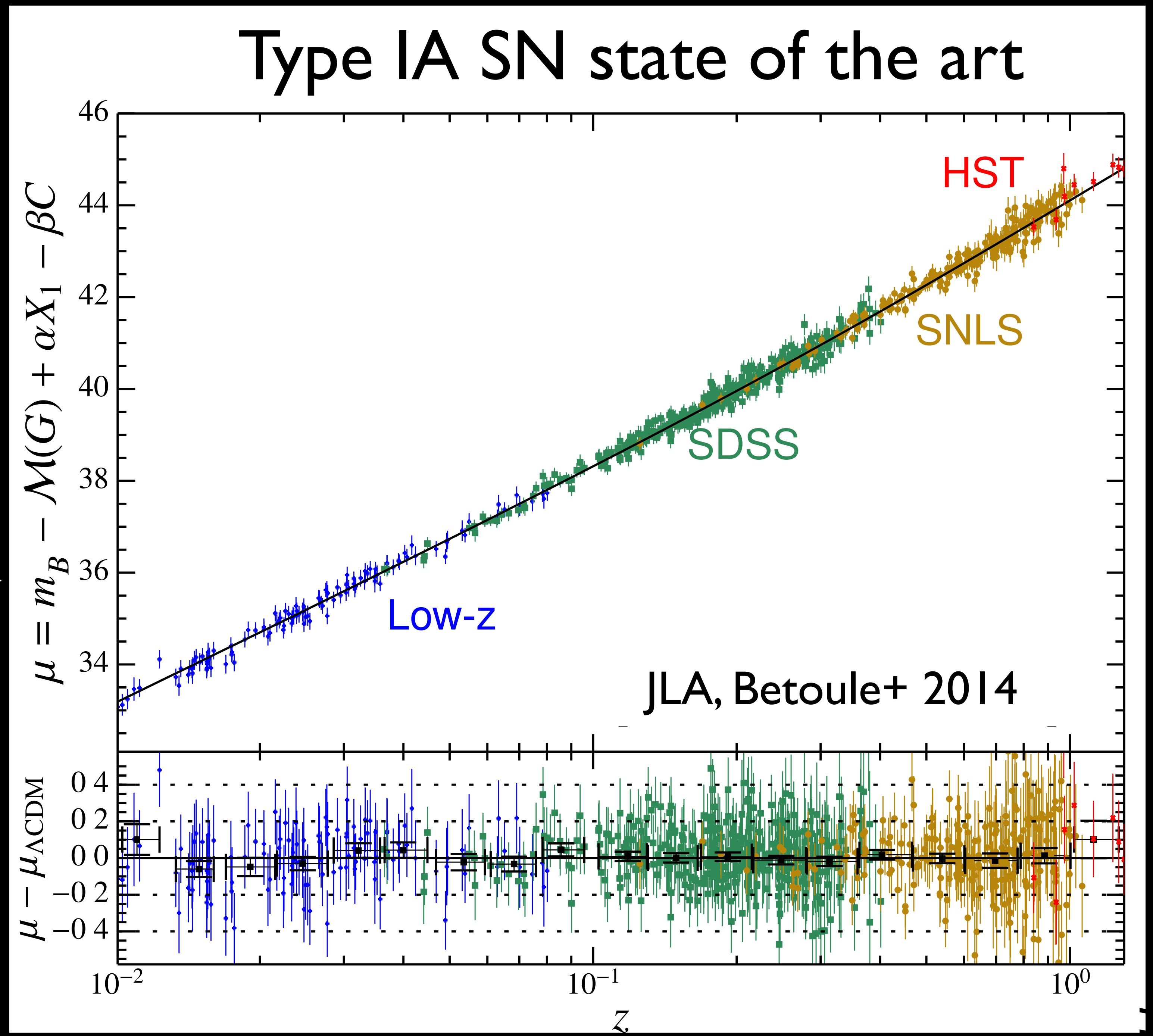
Testing Dark Energy I

Expansion history

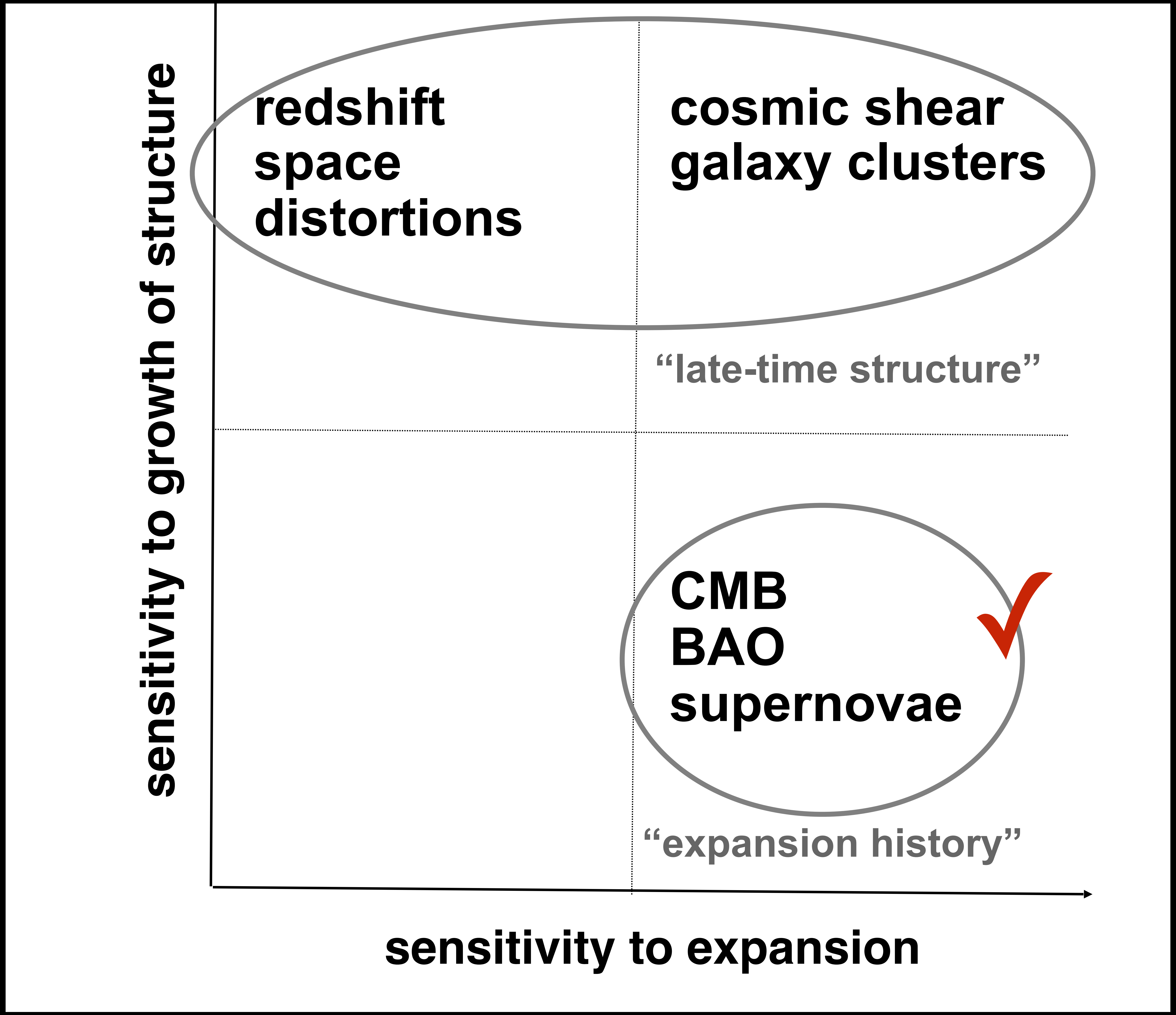
comparison of distance and redshift

- **standard rulers**: angle subtended by known scale
  - –CMB: sound horizon in early Universe
  - –BAO: same scale imprinted in late Universe
- **standard candle**: brightness of source with known luminosity
  - –supernovae
- **excellent agreement with ΛCDM**
- limited information on dark energy/modified gravity
  - –at most w0, wa



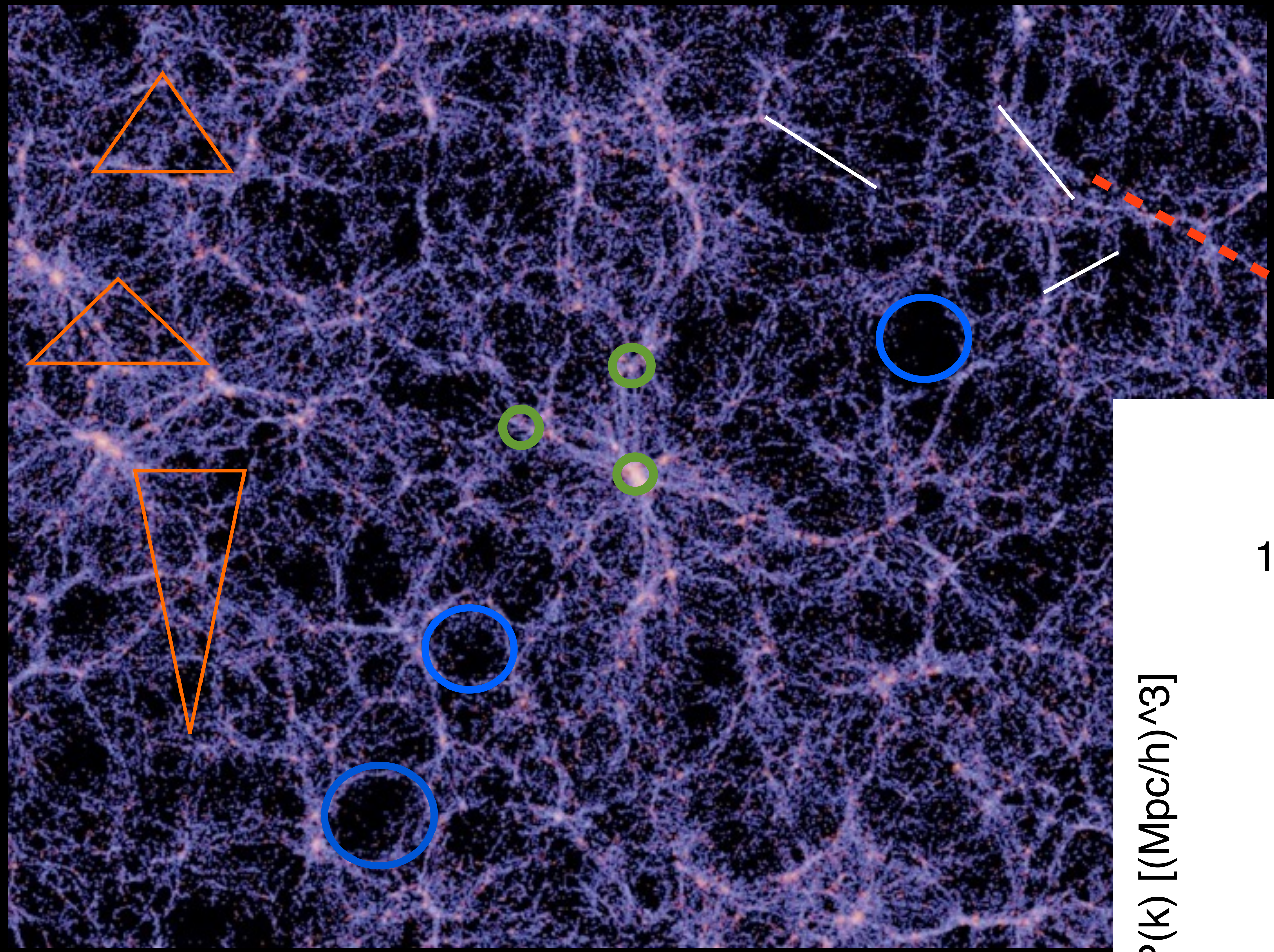


Testing Dark Energy

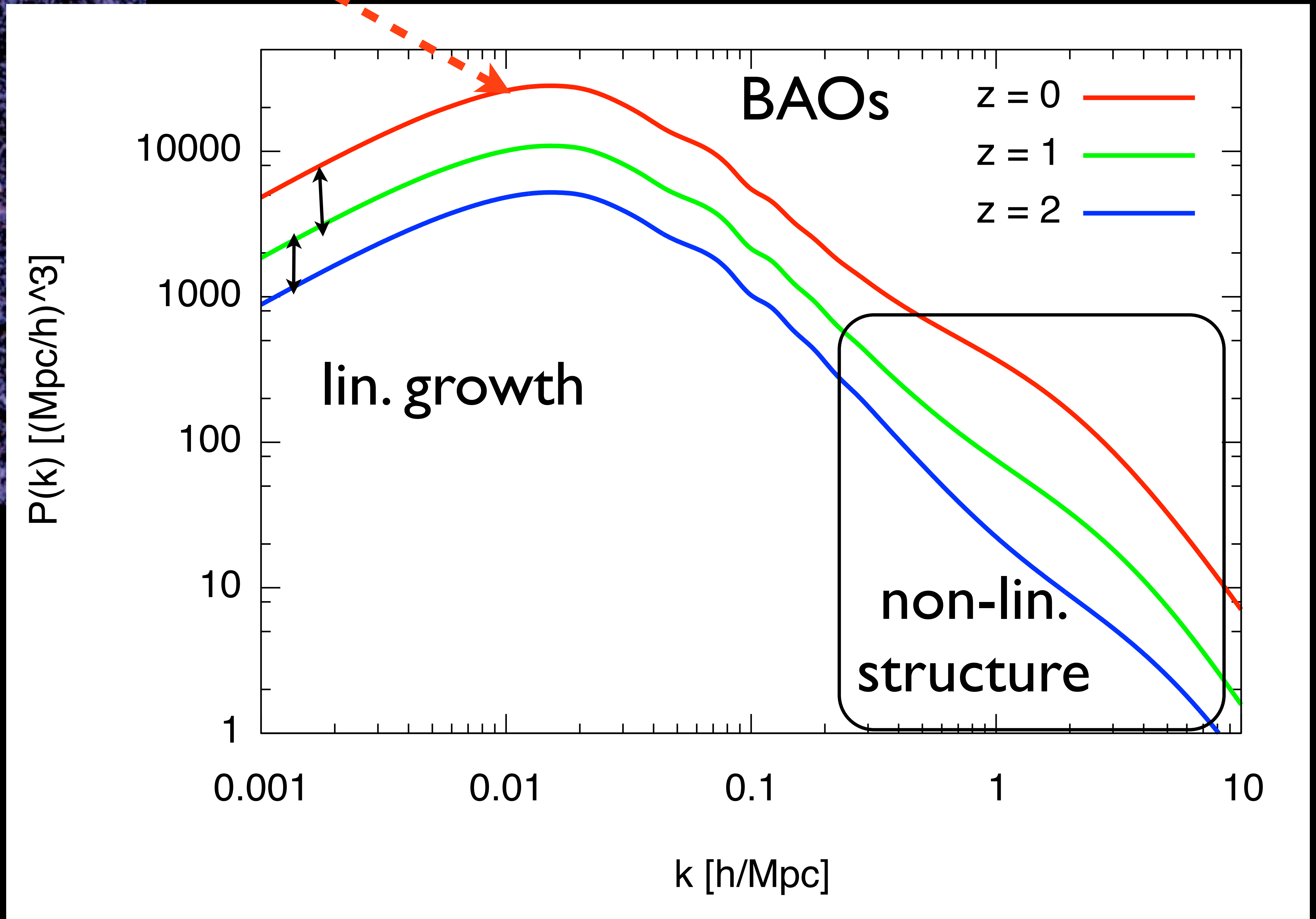


Q: Do all these measurements agree with predictions in the same, fiducial ΛCDM model?

Testing Dark Energy with Galaxies



need redshift, understand galaxy bias

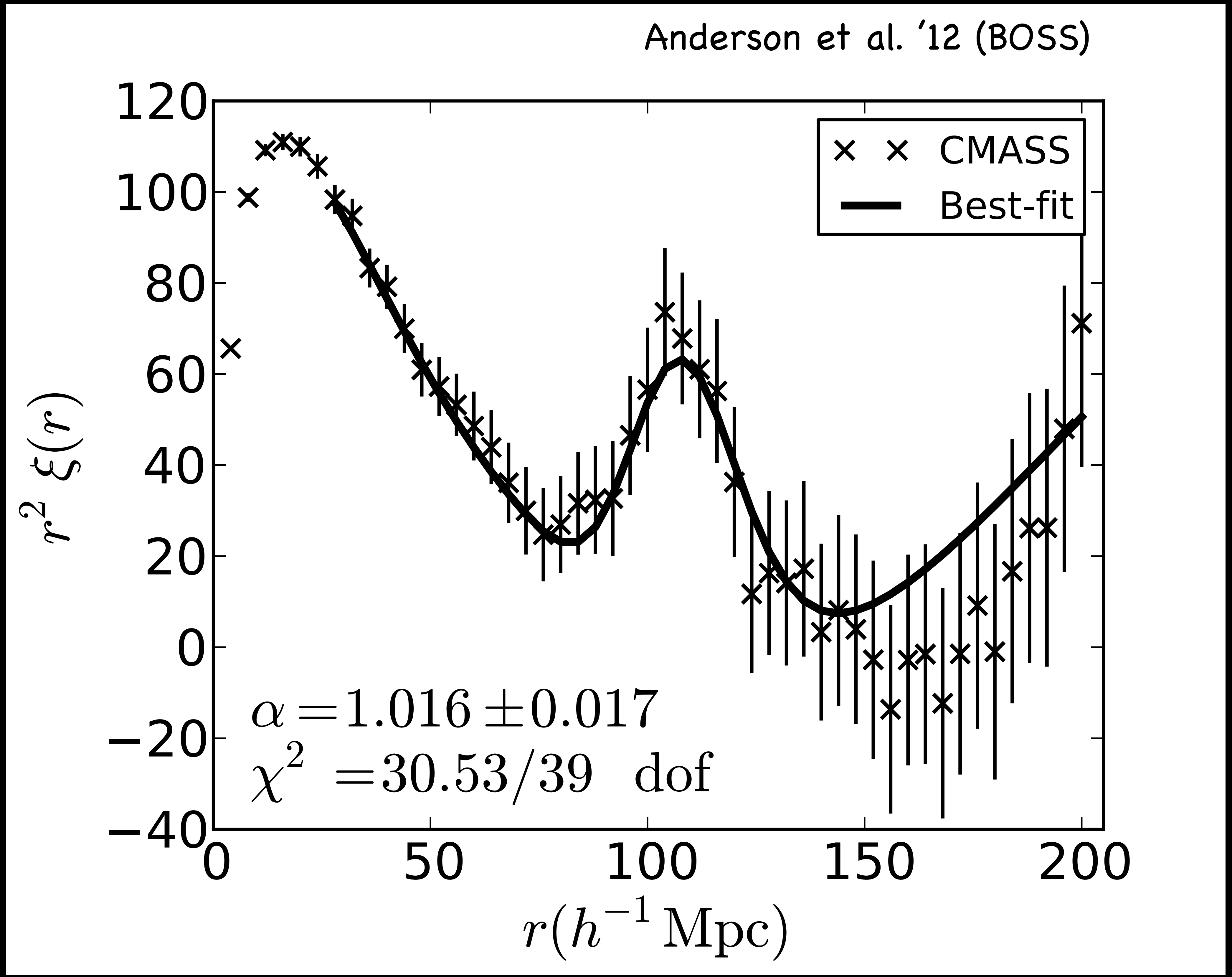


- clusters (over densities),
- voids (under densities)
- two-point correlations
- three-point correlations,...

LSS Probes of Dark Energy

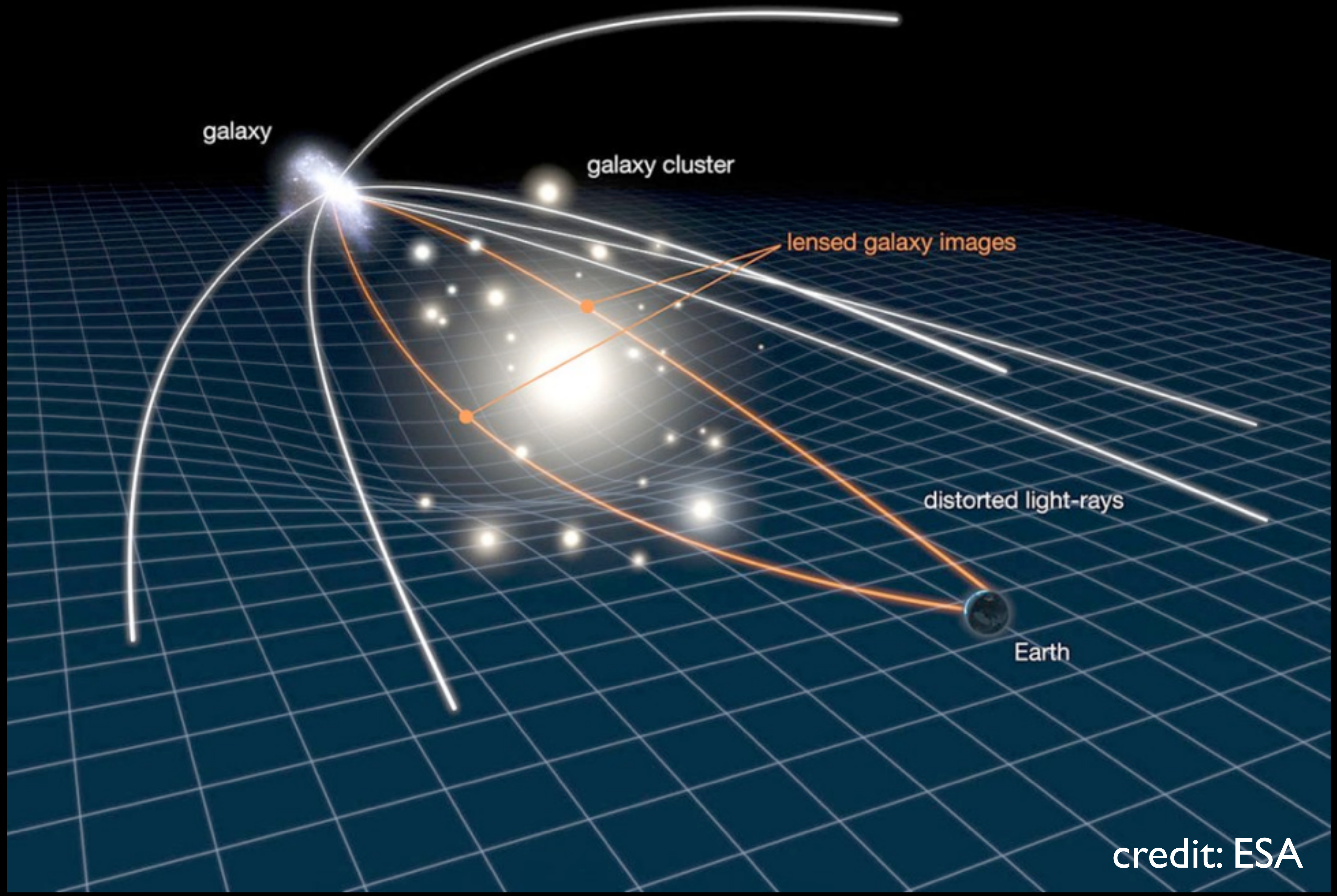
Galaxy Clustering

- measure BAOs + shape of correlation function
  - → growth of structure, expansion history
- key systematic: **galaxy bias**



LSS Probes of Dark Energy

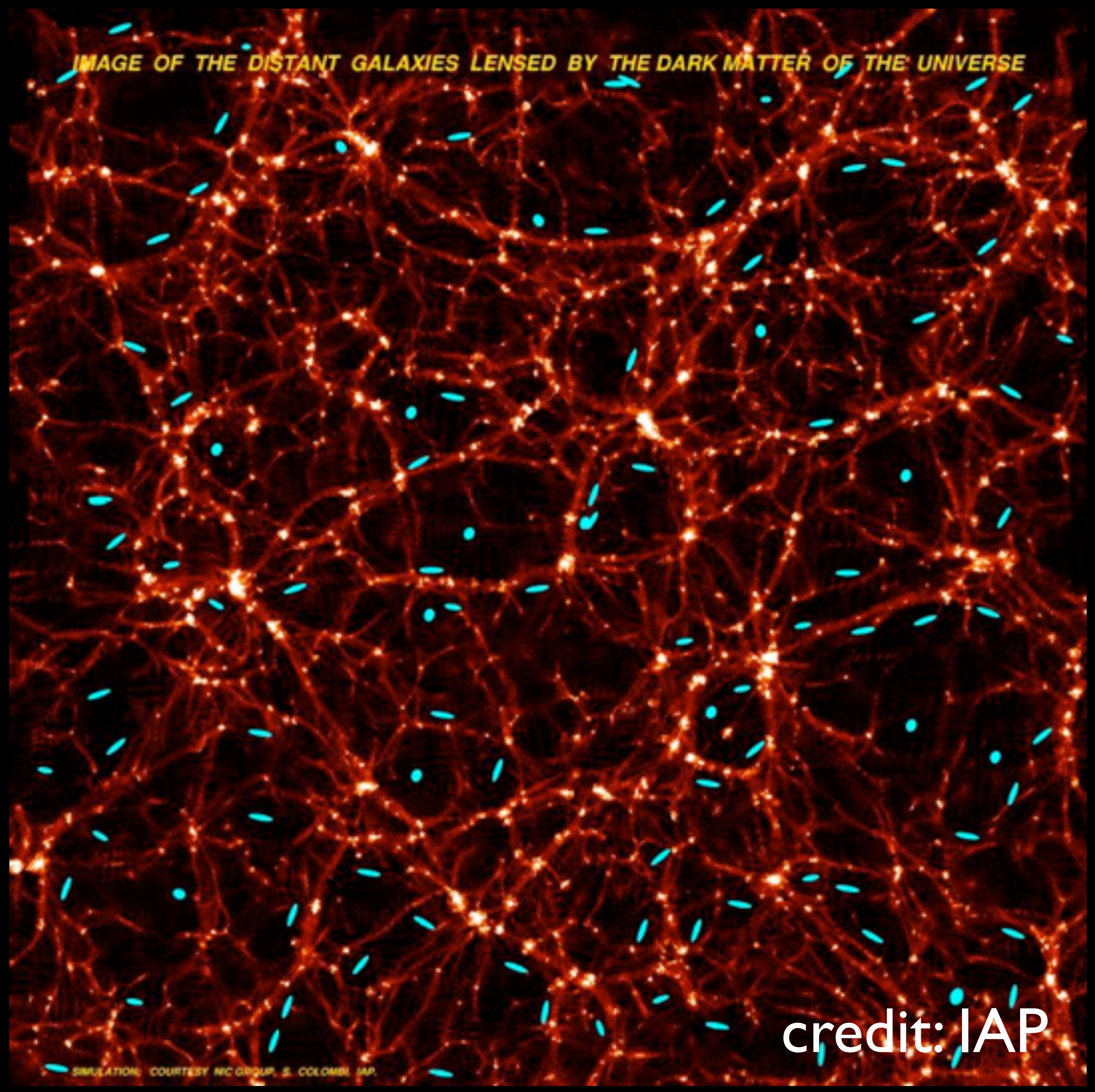
Weak Gravitational Lensing



LSS Probes of Dark Energy

Weak Gravitational Lensing

- light deflected by tidal field of LSS
  - coherent distortion of galaxy shapes "shear"
- shear related to projected matter distribution
- key systematics
  - shape measurements
  - assume random intrinsic orientation, average over many galaxies

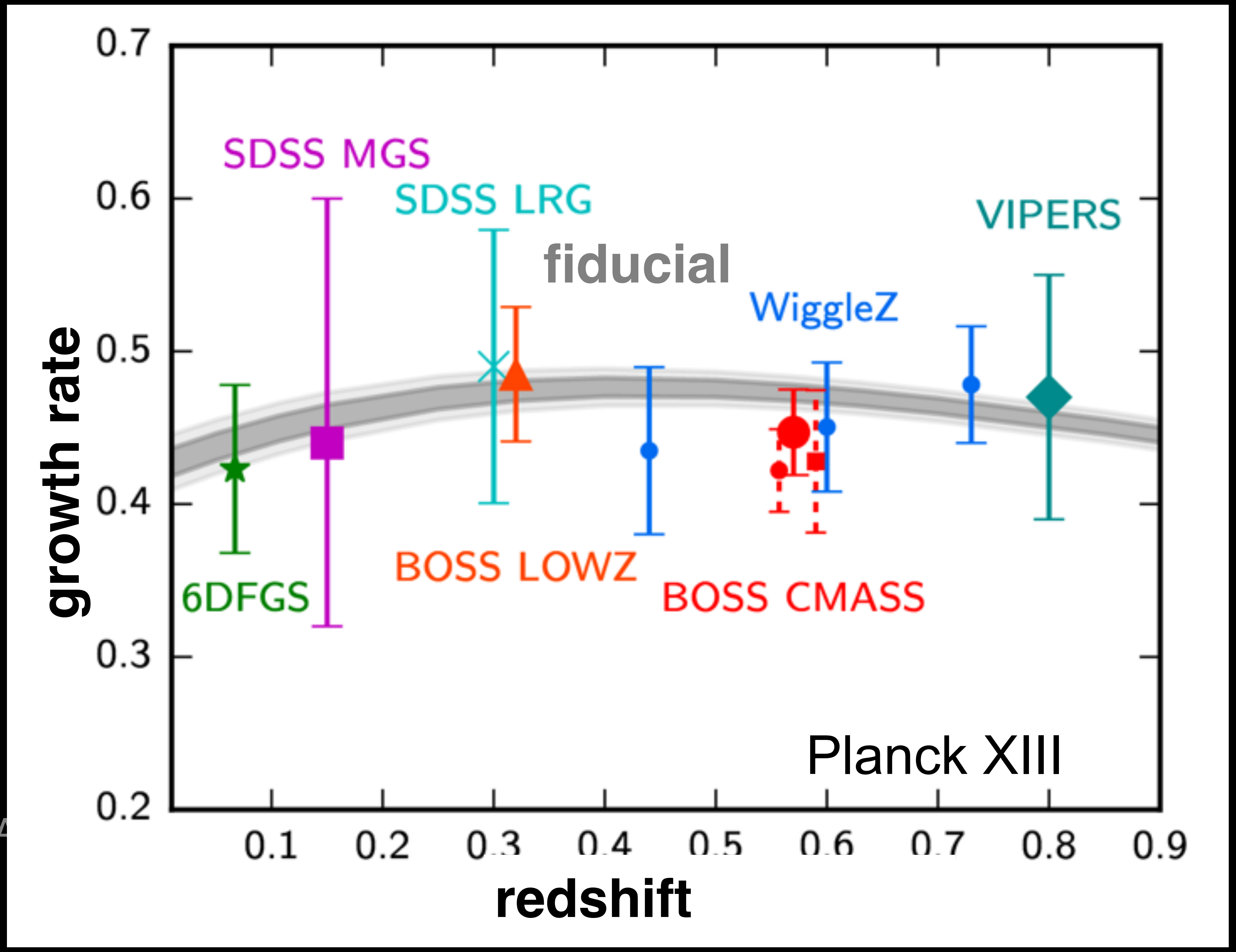


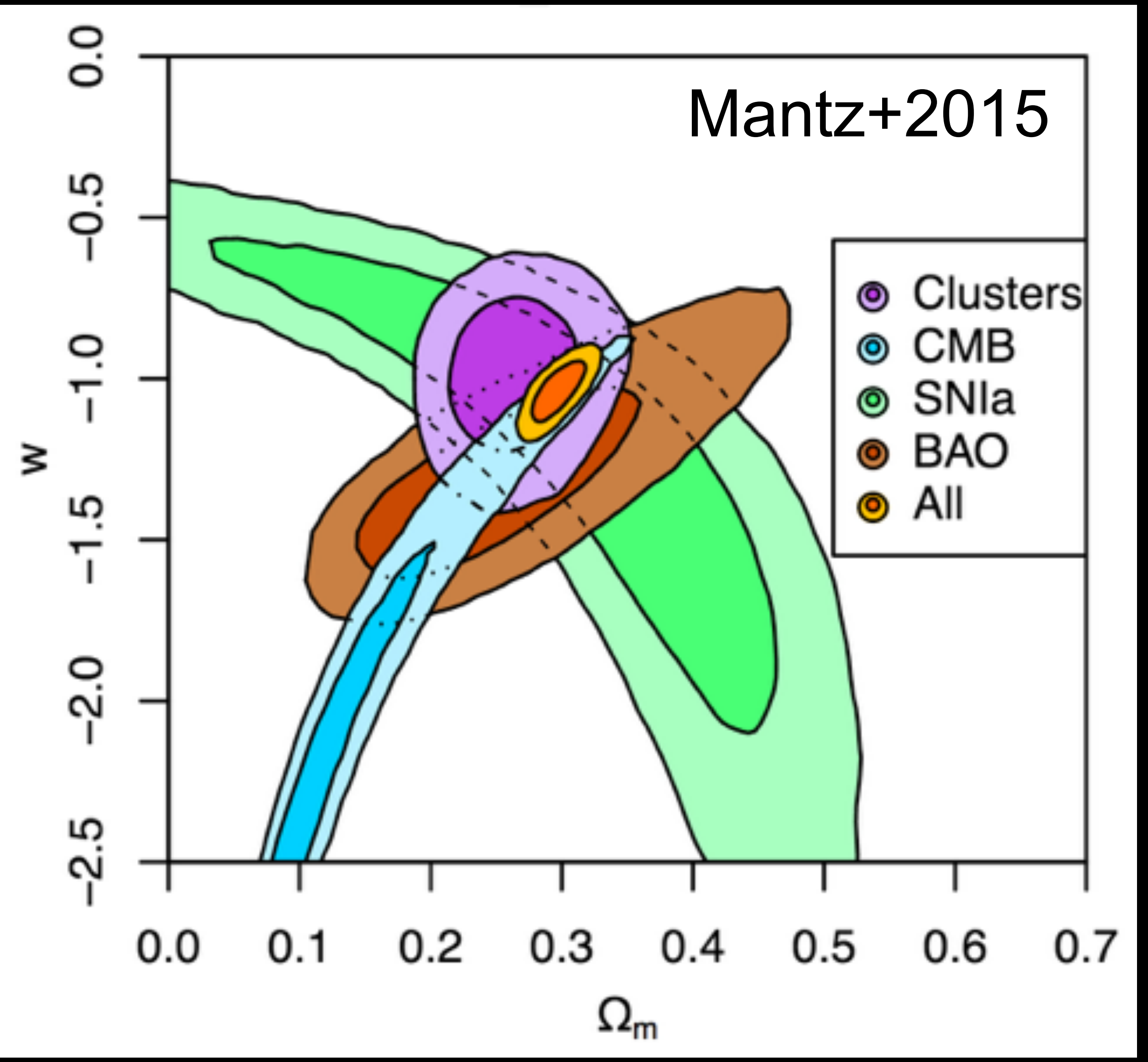
- measure **shear correlation function/power spectrum**
  - probes *total* matter power spectrum (w/ broad projection kernel)
- measure average (tangential) **shear around galaxies**
  - probes halo mass

Testing Dark Energy II

Structure Growth

- redshift space distortions ✓
- galaxy clusters (✓)
  counts as functions of mass and redshift

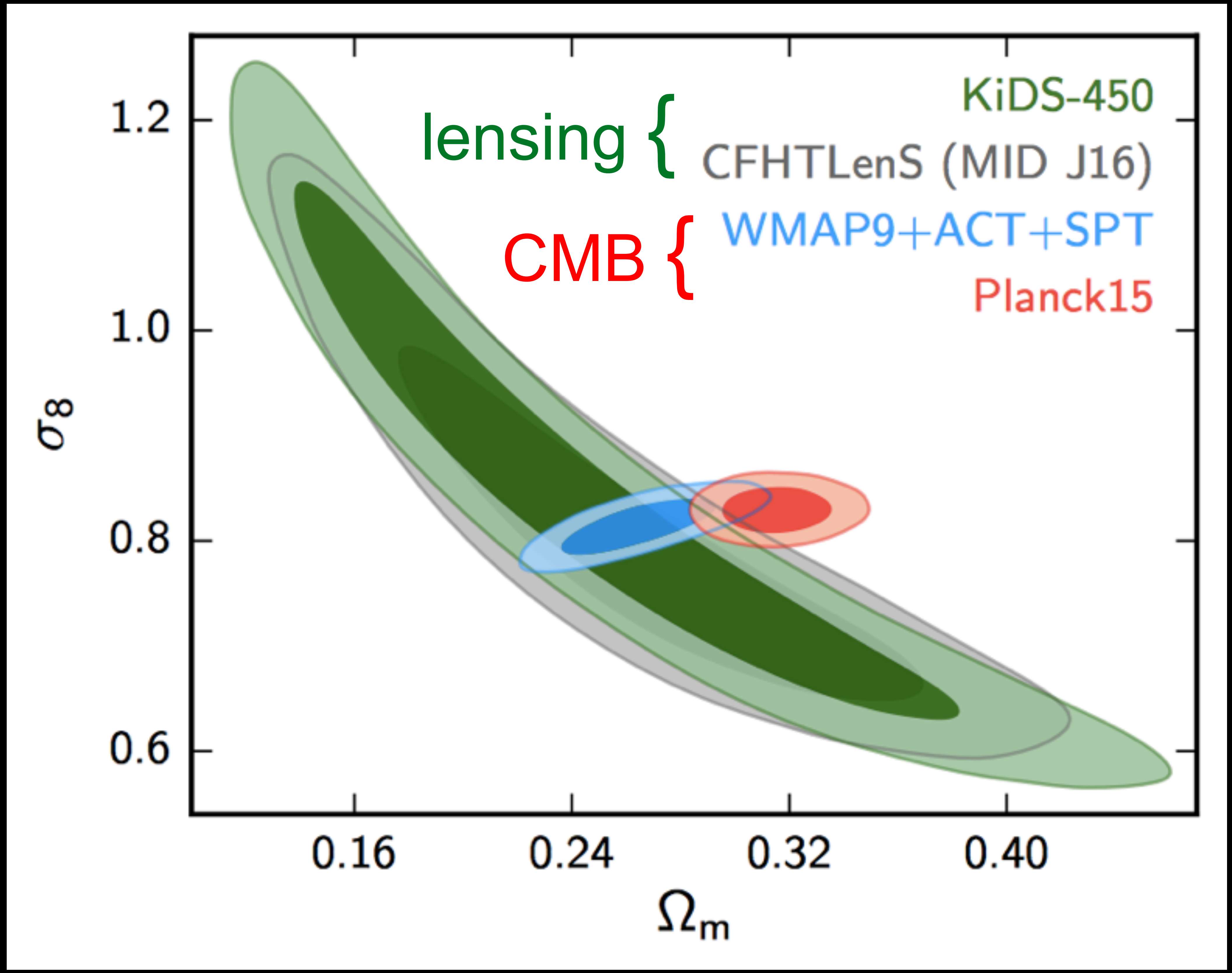




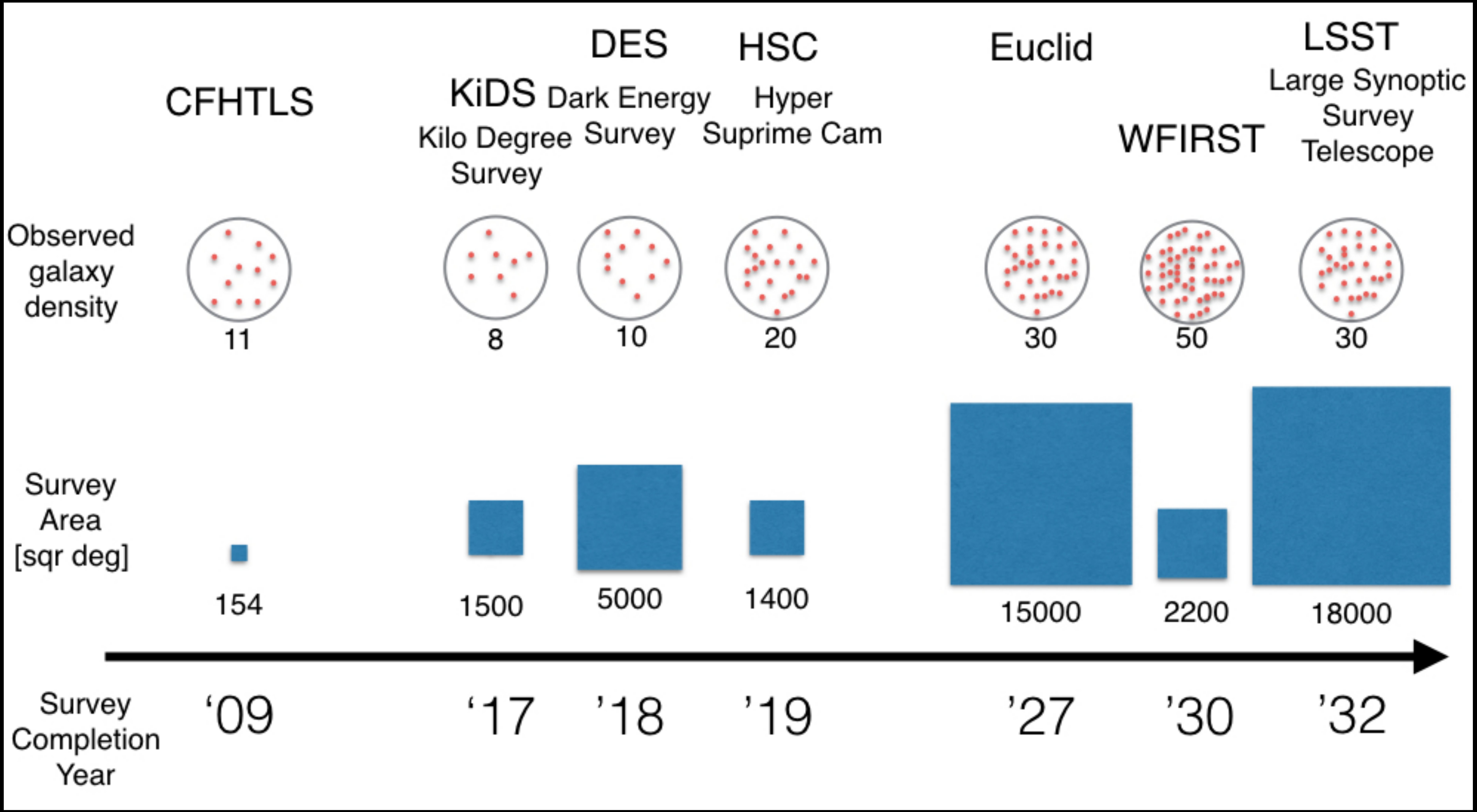
Testing Dark Energy II

Structure Growth

- **redshift space distortions** ✓
- **galaxy clusters** (✓)
  counts as functions of mass and redshift
- **weak lensing**
  recent studies have claimed 2-3σ tension with Planck
  - a fluke/non-issue?
  - a crack in LCDM?
  - a systematic error?



Photometric Dark Energy Surveys



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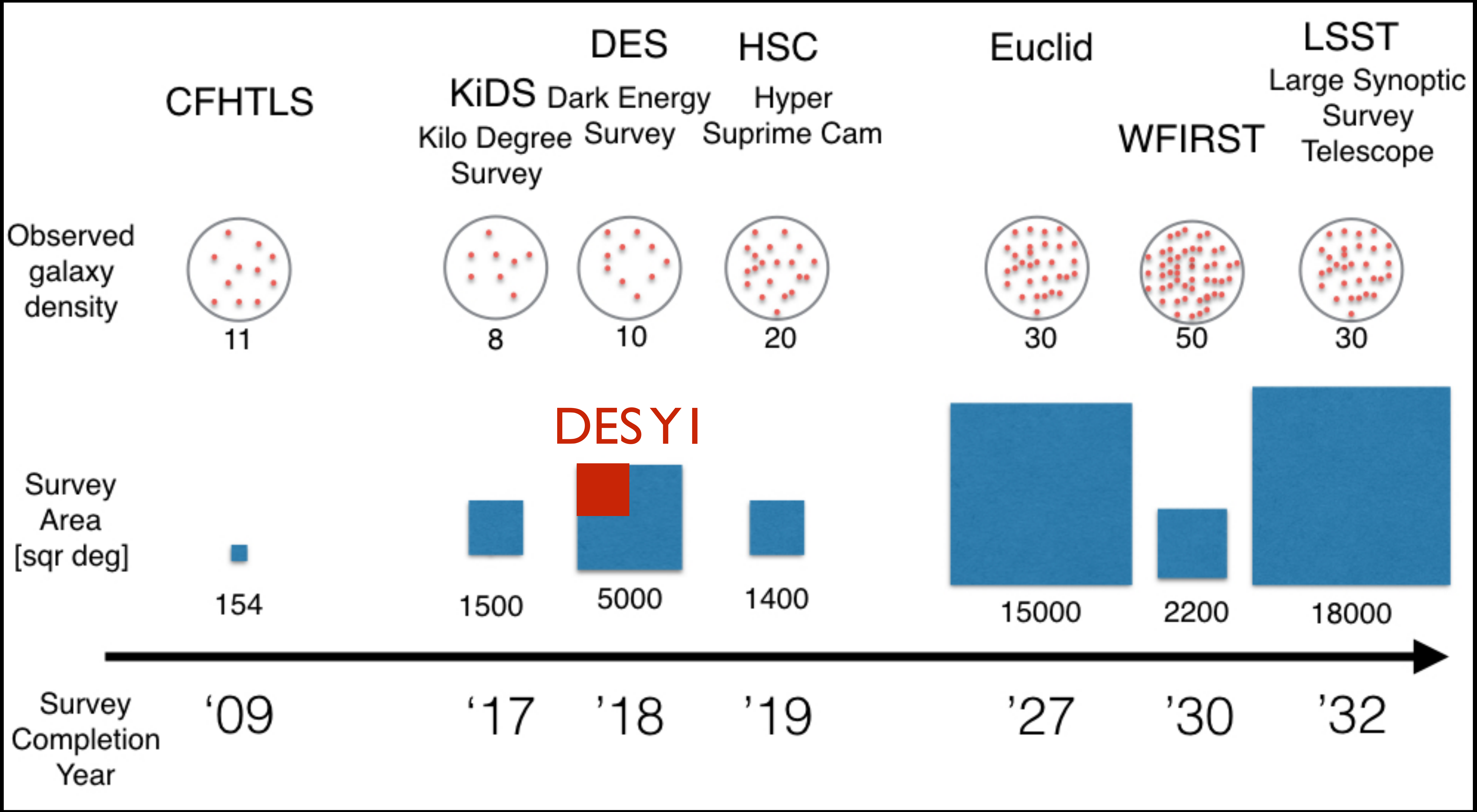
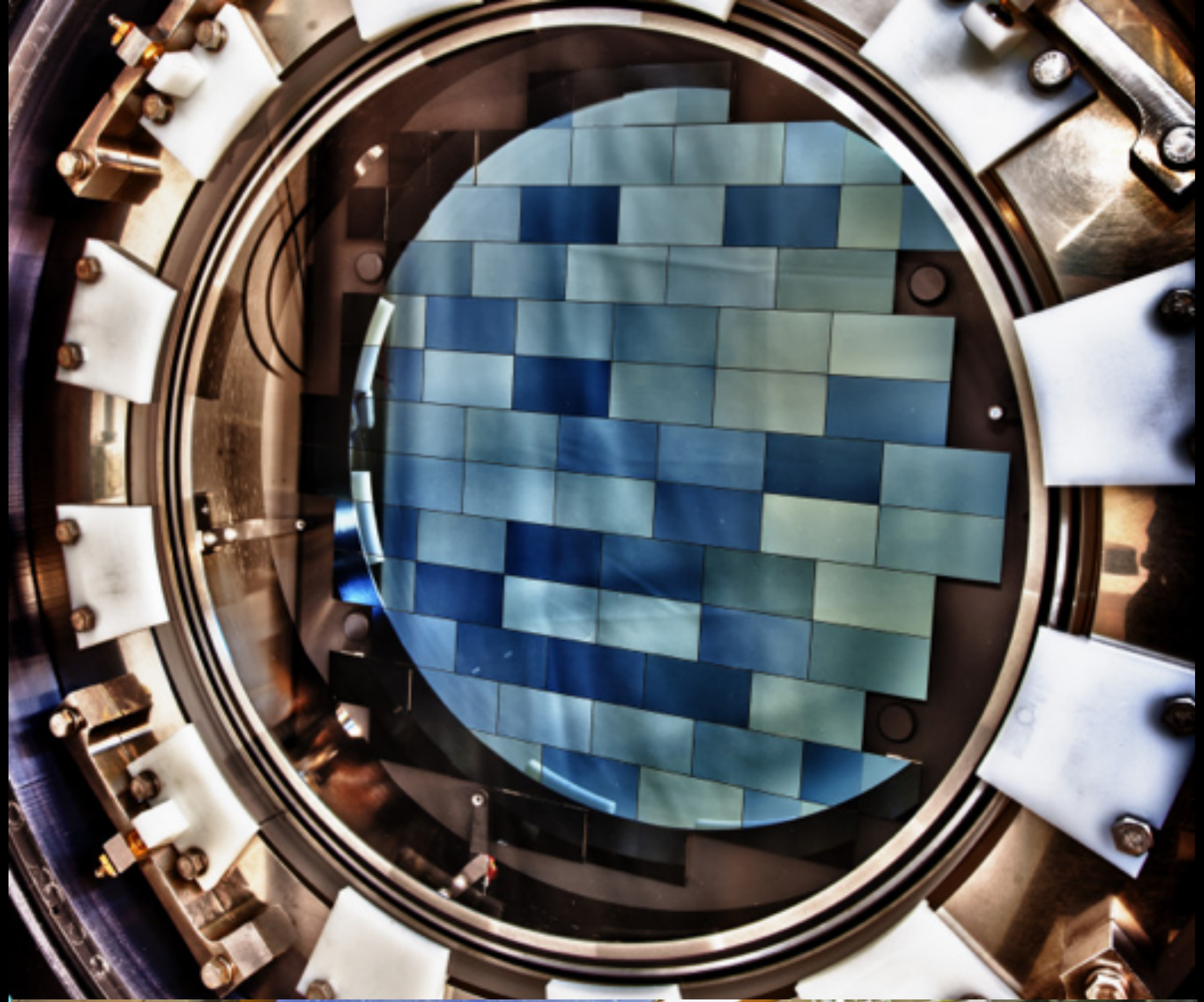
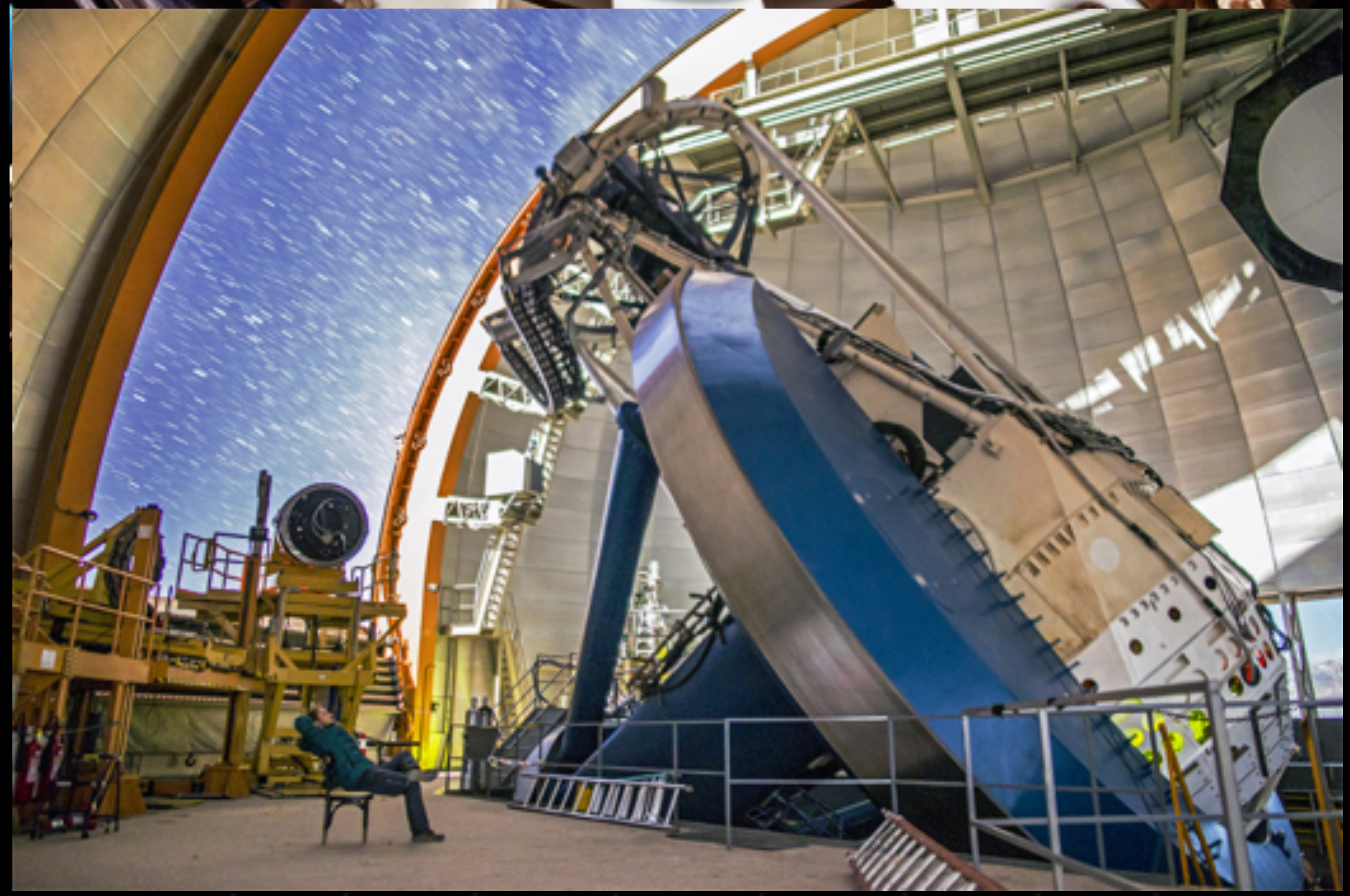
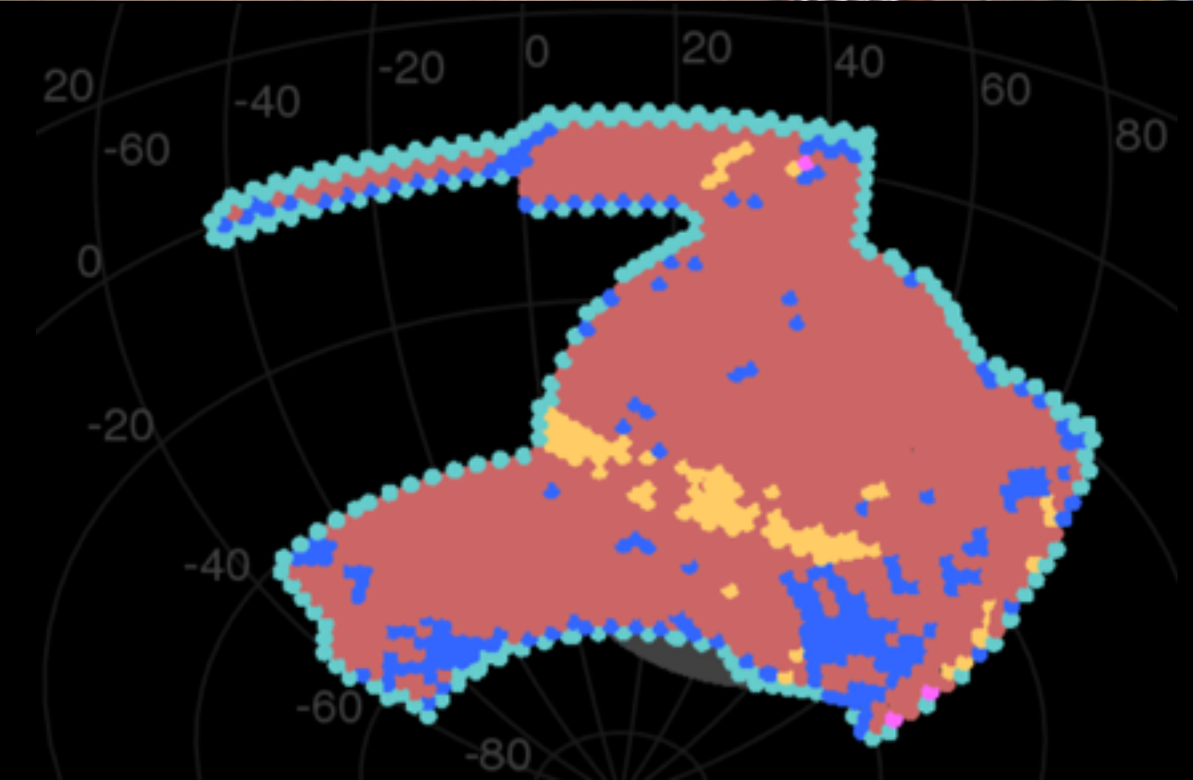


The Dark Energy Survey

- 5000 sq. deg. survey in grizY from Blanco @ CTIO
  - 10 exposures, 5 years, >400 scientists
- Primary goal: dark energy equation of state
- Probes: Galaxy Clustering, Supernovae,
  Cluster counts, Gravitational lensing
- Status:
  - SV (150 sq. deg, full depth):
    most science done, catalogs public
  - Y1 (1500 sq. deg, 40% depth):
    data processed, results on cosmology last week
  - Y3 (5000 sq. deg, 50% depth):
    data processed, vetting catalogs
  - Y4: data taking finished (70% depth)



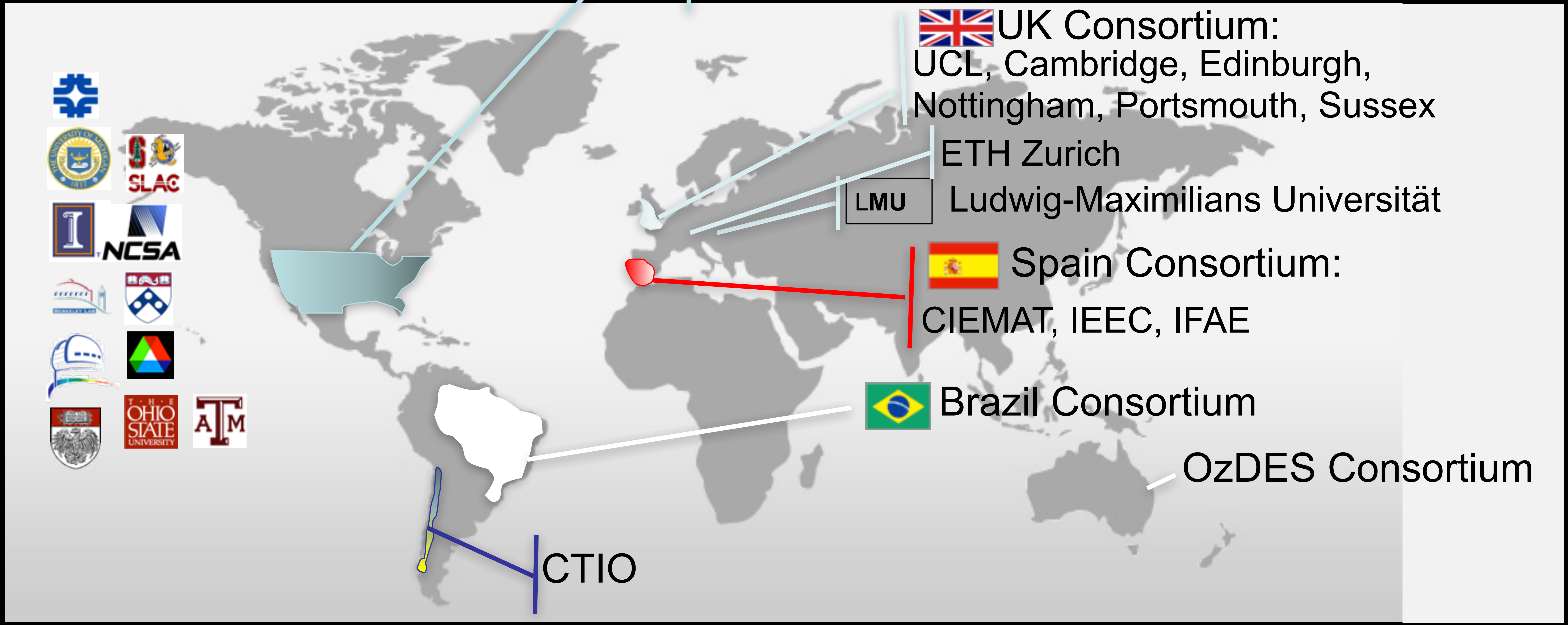




The Dark Energy Survey Collaboration

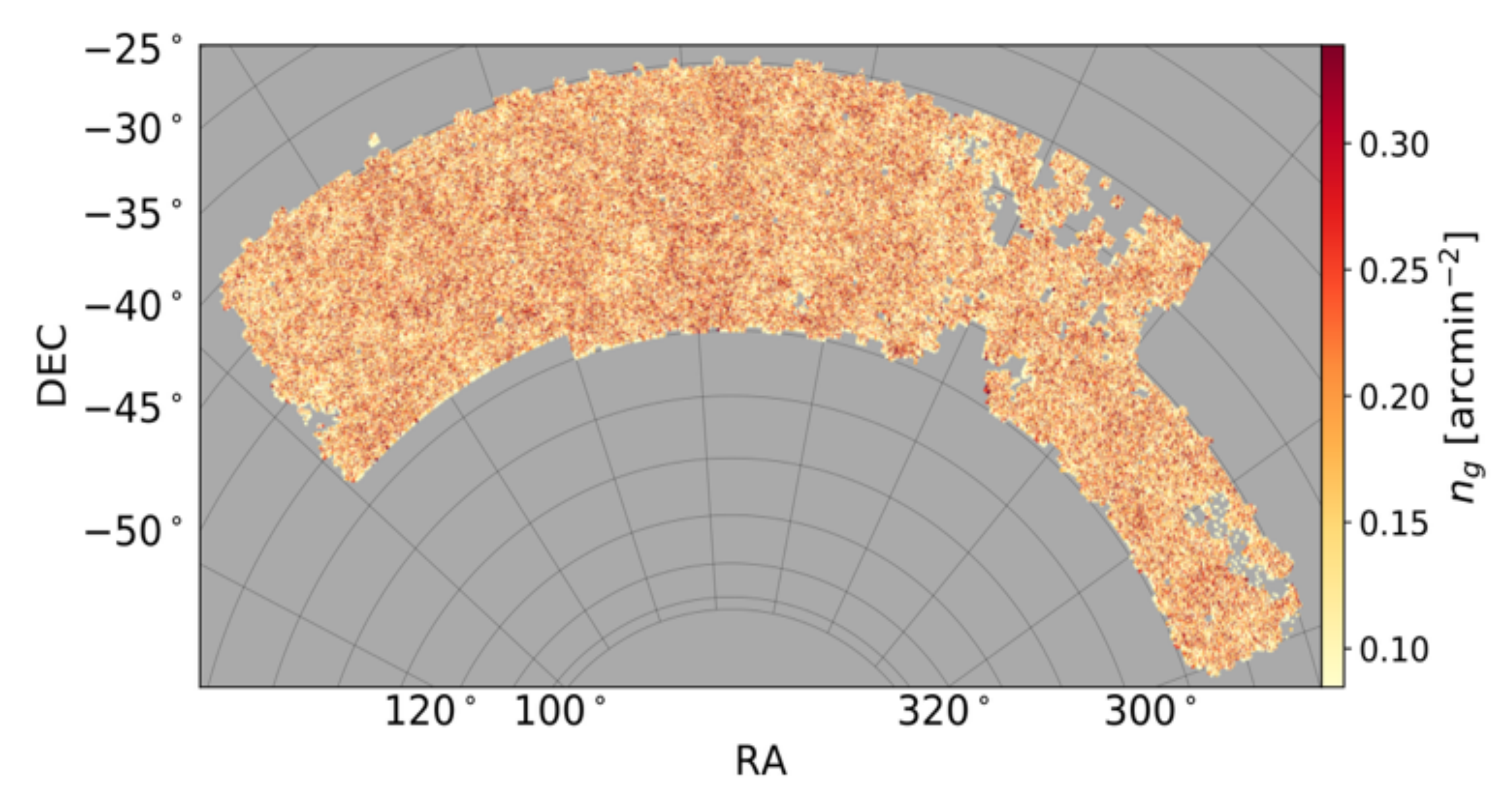
~400 scientists;
US support from
DOE & NSF

Fermilab, UIUC/NCSA, University of Chicago, LBNL, NOAO, University of Michigan, University of Pennsylvania, Argonne National Lab, Ohio State University, Santa-Cruz/SLAC/Stanford, Texas A&M

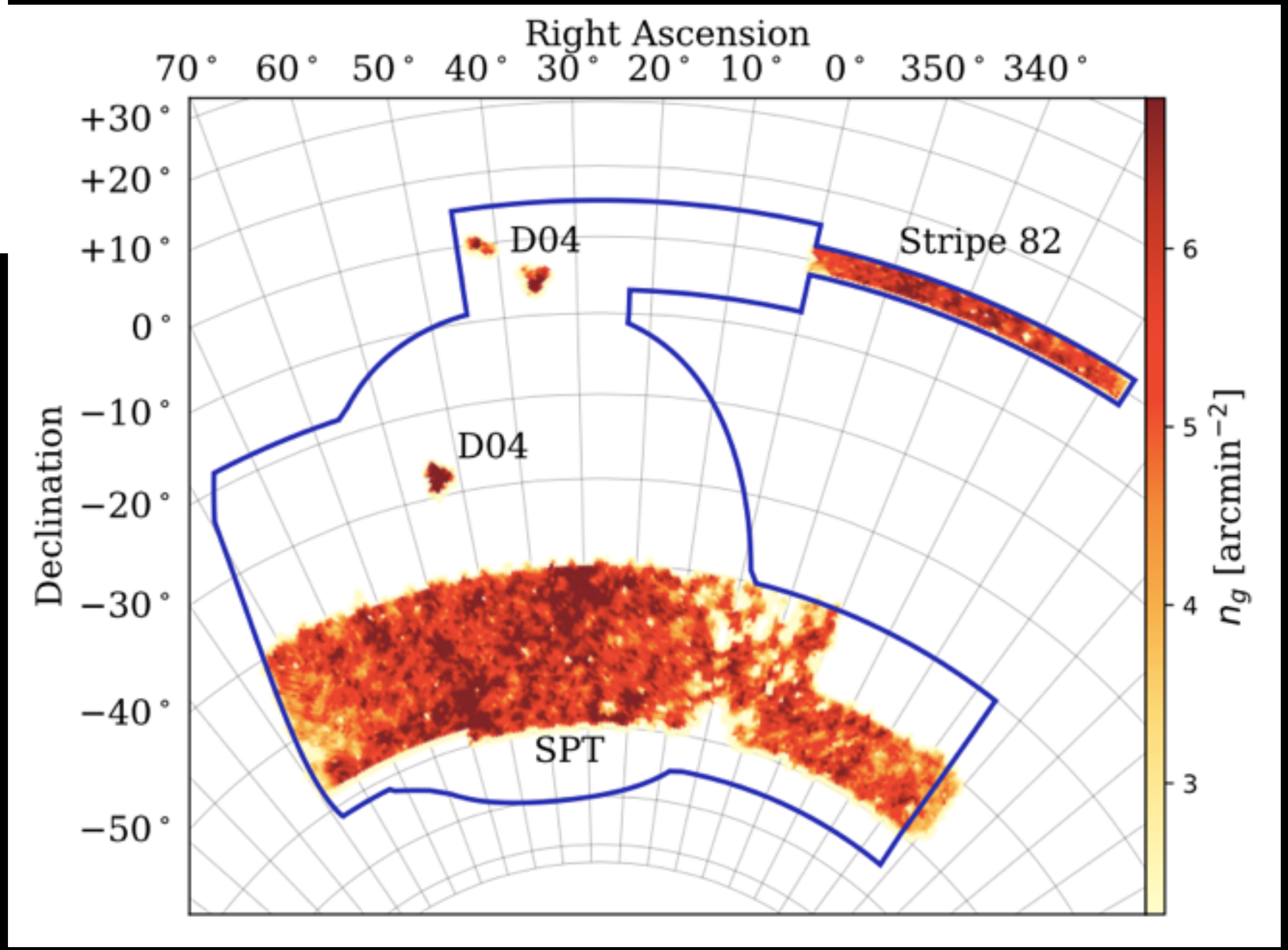


Dark Energy Survey @ OSU

DES Year 1 Galaxy Samples



- 26 million source galaxies
- 4 redshift bins
- Sources for cosmic shear & galaxy-galaxy lensing

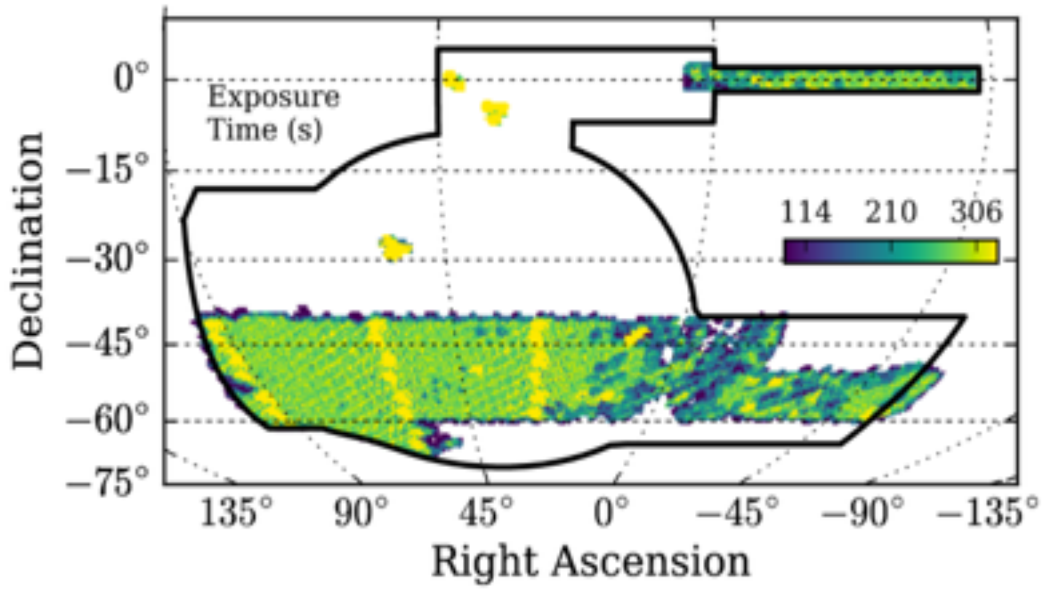


- 660,000 redMaGiC galaxies with excellent photo-z's
- Measure angular clustering in 5 redshift bins
- Use as lenses for galaxy-galaxy lensing

First Year of Data: ~1800 sq. deg. Analyzed 1321 s.d. after cuts

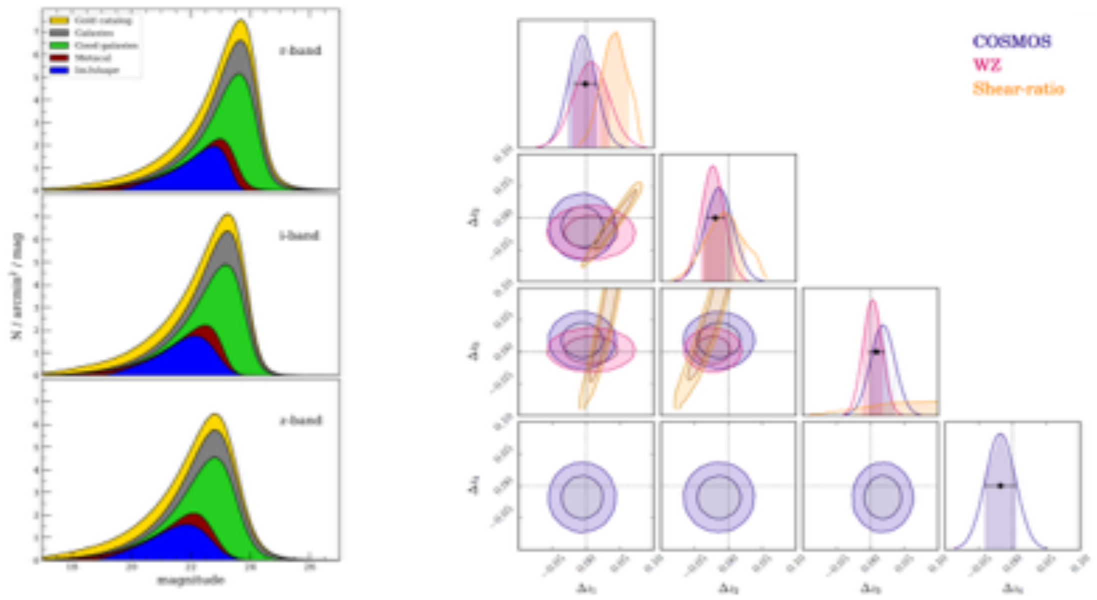
With great statistical power comes great systematic responsibility

Unprecedented size and depth of photometric data



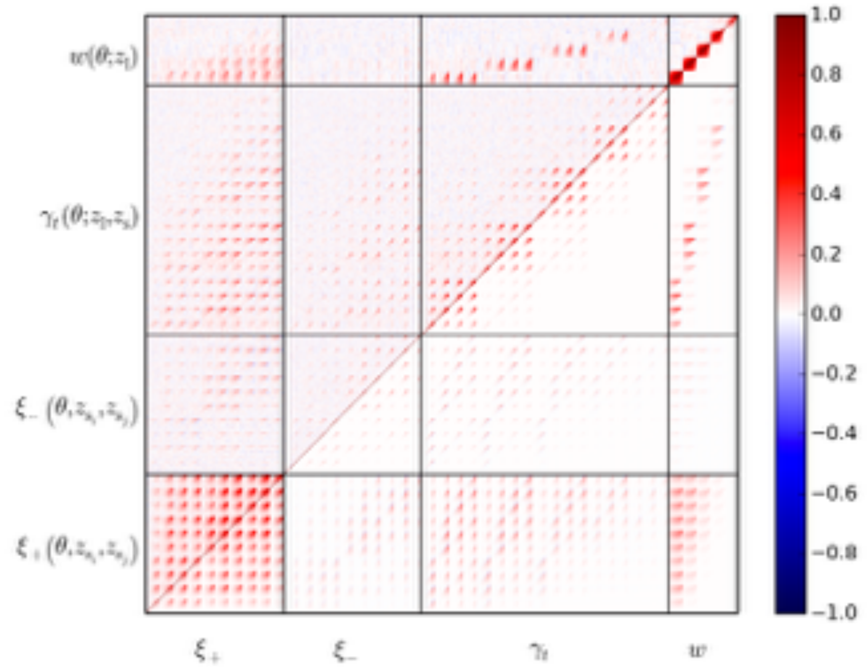
Drlica-Wagner, Rykoff, Sevilla+ 2017

Two independent shape & photo-z catalogs and calibrations

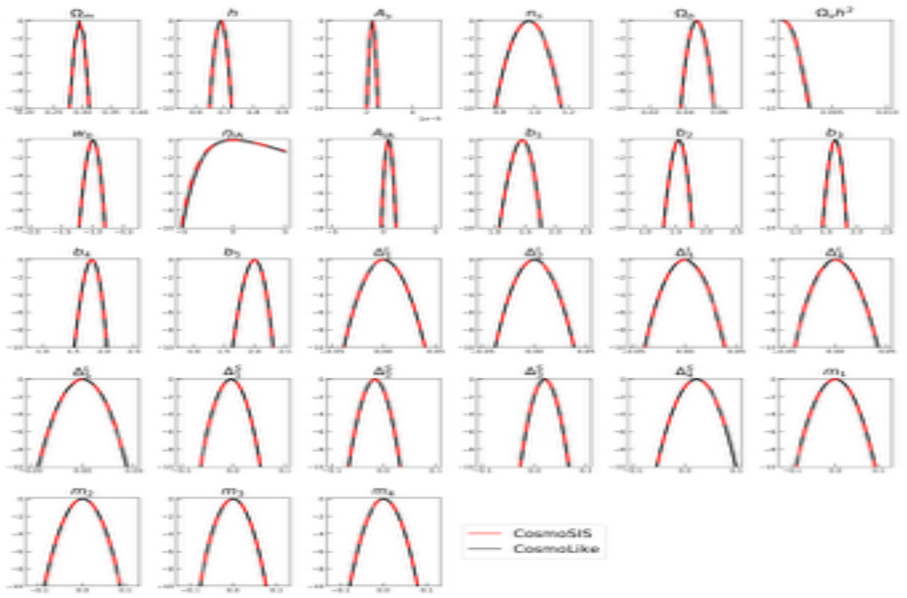


Zuntz, Sheldon+; Samuroff+; Hoyle, Gruen+ 2017; Davis+, Gatti, Vielzeuf+, Cawthon+ in prep.

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

DES Y1 Shear Catalogs

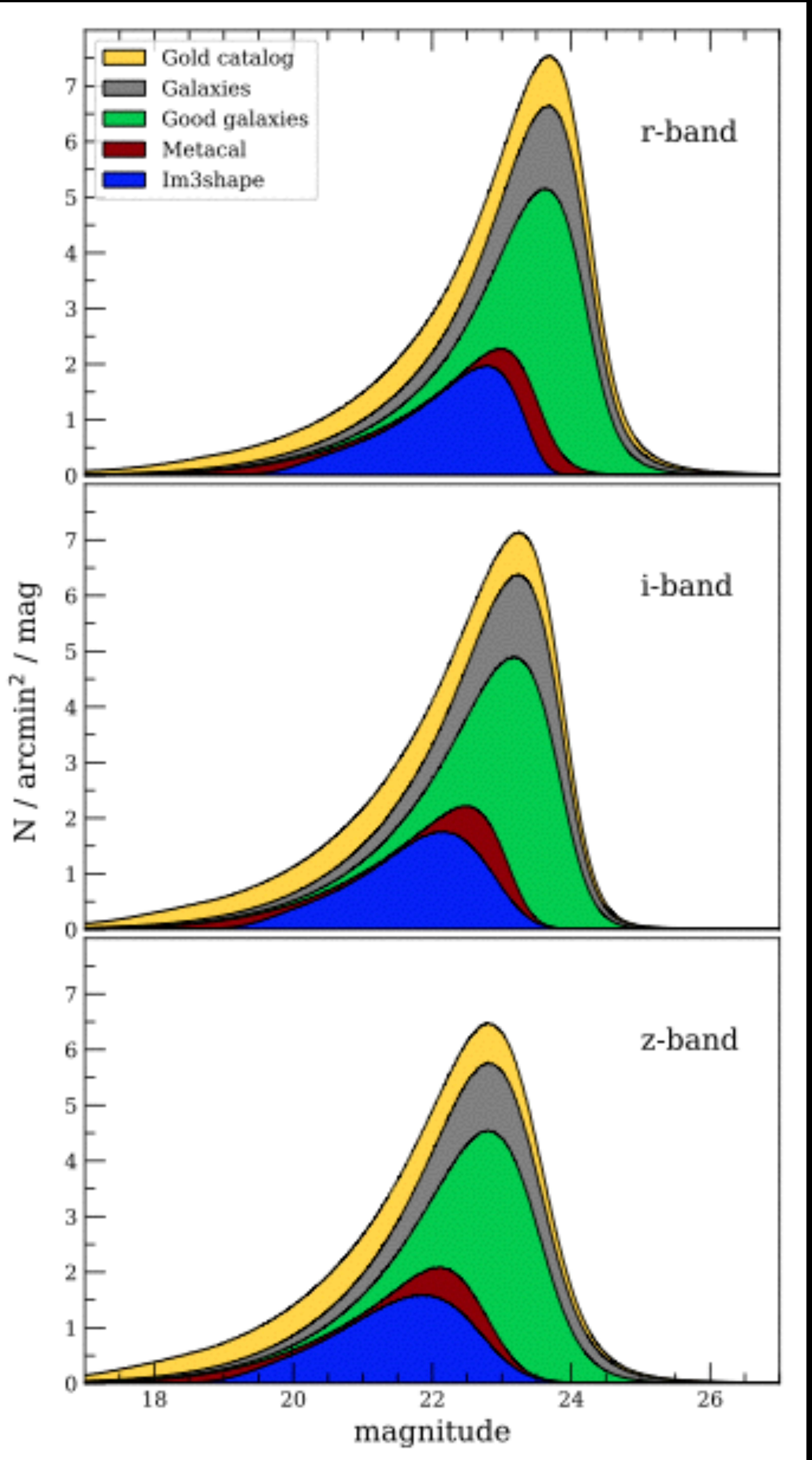
(Zuntz+17)

Metacalibration *(Huff+17, Sheldon+17)* **:**

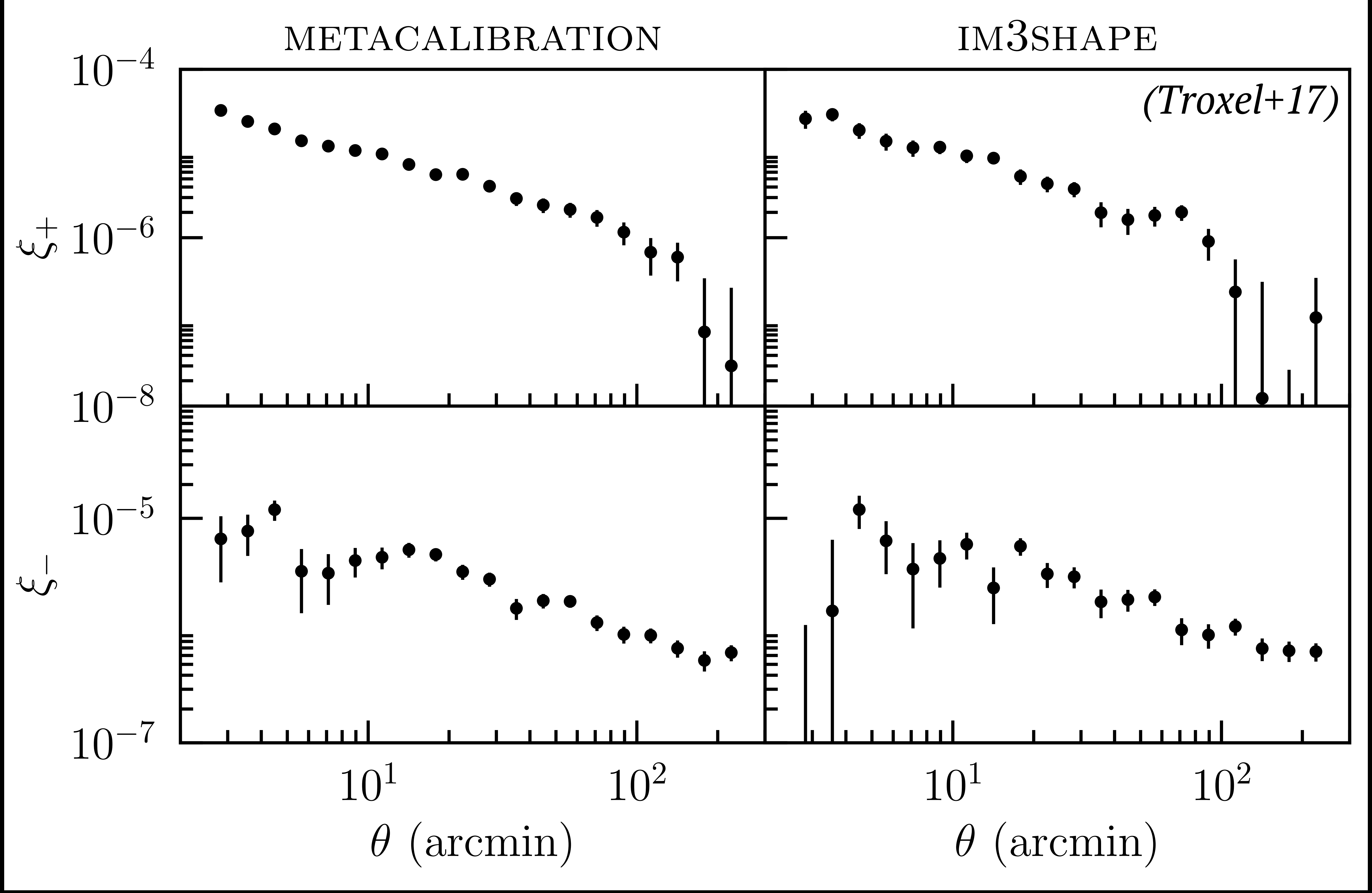
- New method measuring estimator shear response internally by deconvolving, shearing, deconvolving.
- It uses g, r, i bands.
- 35 M galaxies (26 M for cosmology).

im3shape:

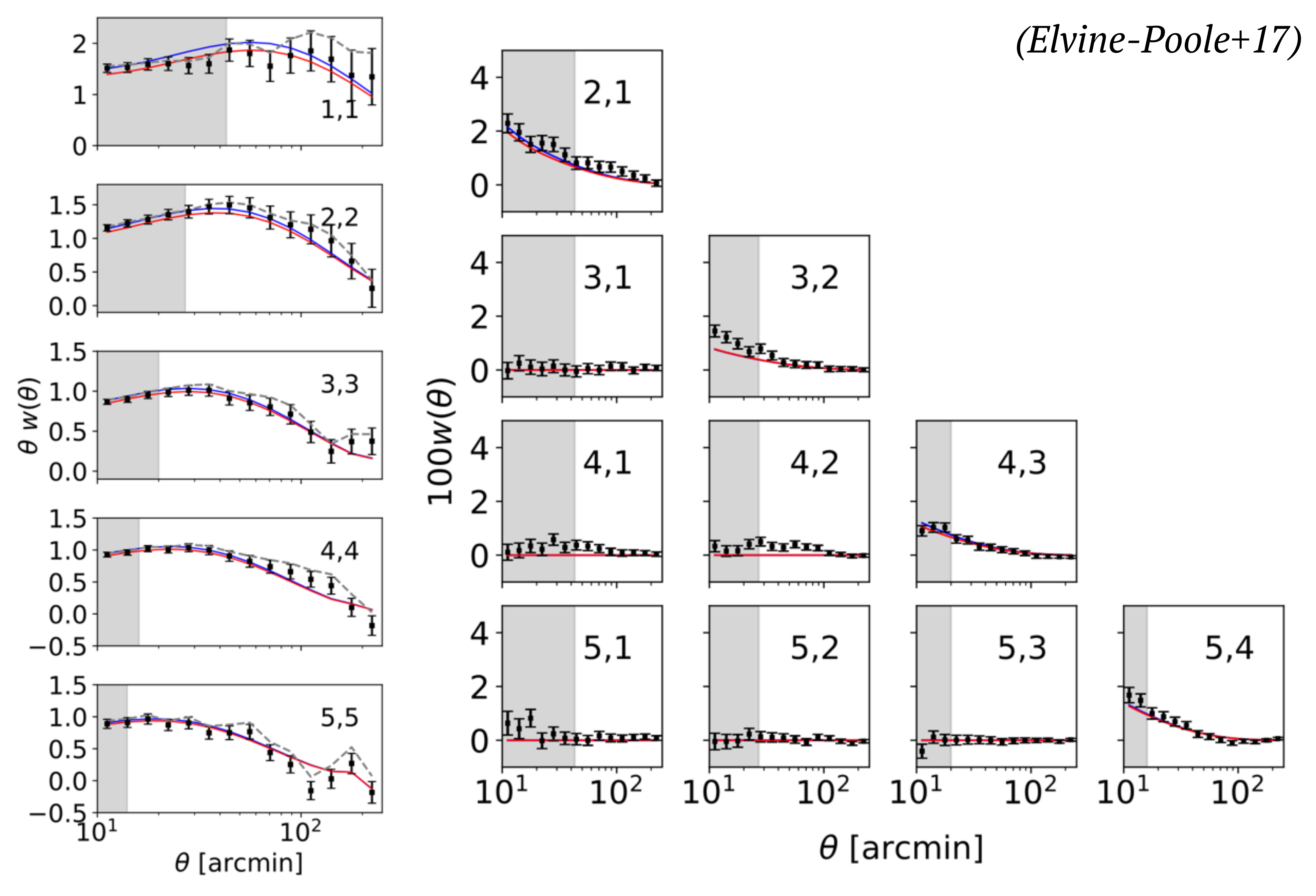
- Best-fit bulge & disc models, calibrated with simulations.
- Only r-band.
- 22 M galaxies (18 M for cosmology).



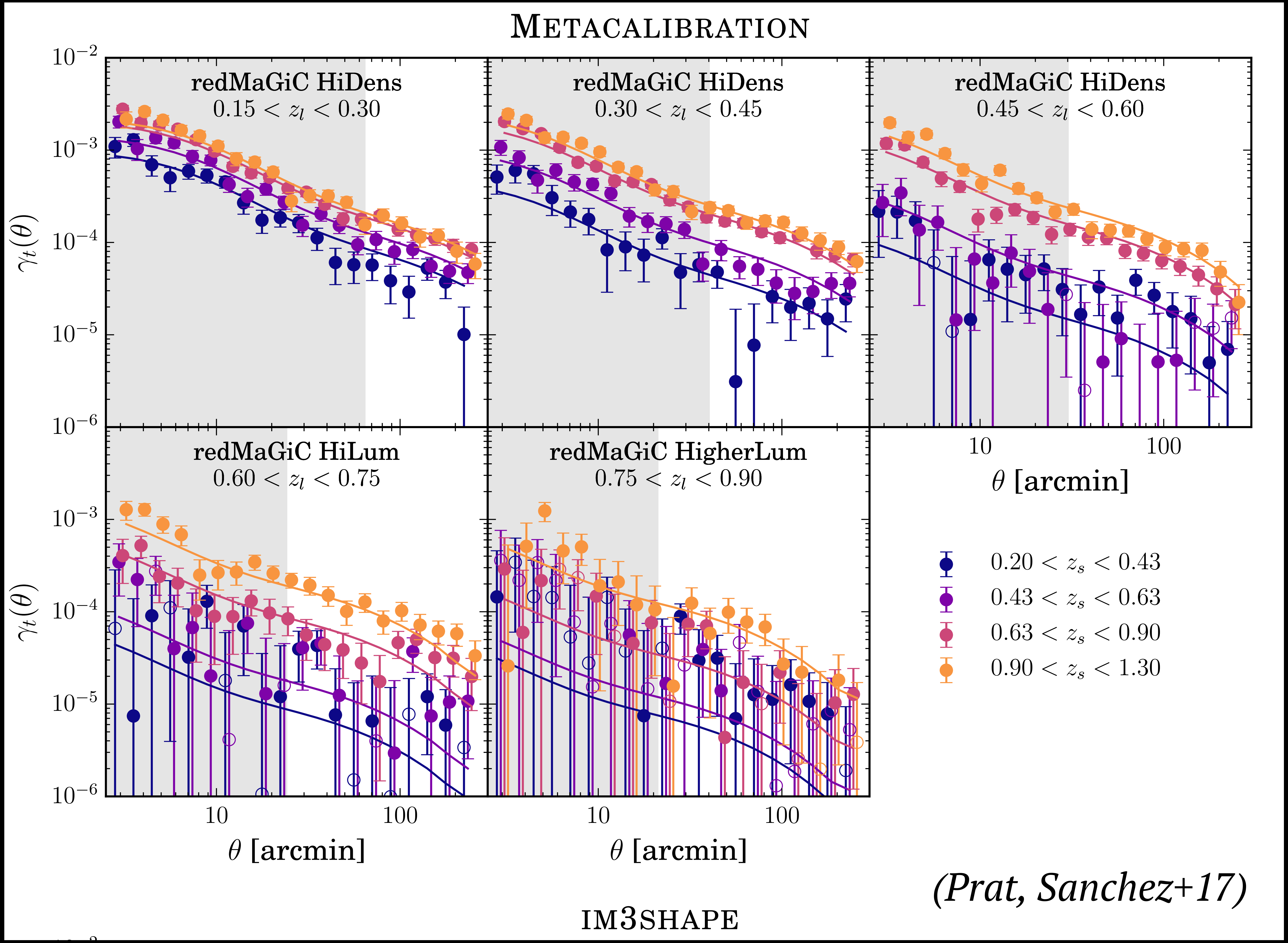
DESY1 Measurements: Cosmic Shear



DESY1 Measurements: Galaxy Clustering



DESY1 Measurements: Galaxy-Galaxy Lensing



(Prat, Sanchez+17)

Multi-Probe Methodology

(Krause, Eifler+17)

from data vector D to parameters p

$$L(\mathbf{D}|\mathbf{p}) \propto \exp\left(-\frac{1}{2}\left[(\mathbf{D}-\mathbf{M}(\mathbf{p}))^T \mathbf{C}^{-1}(\mathbf{D}-\mathbf{M}(\mathbf{p}))\right]\right)$$

- model data vector, incl. relevant systematics
  - implementation details should not contribute to error budget
  - are the systematics parameterizations sufficient for DES-Y1?
- covariance for ~450 data points
- sampler - don't get the last step wrong...

methods paper: validate model + implementation, covariance, sampling

Multi-Probe Blinding

(DES Collaboration 17)

Goal: minimize confirmation bias

Implementation: two-staged blinding process

- shear catalogs scaled by unknown factor, until catalogs fixed
- cosmo params shifted by unknown vector, until full analysis fixed
- (do not overplot measurement + theory)
- (clearly state any post-unblinding changes in paper)

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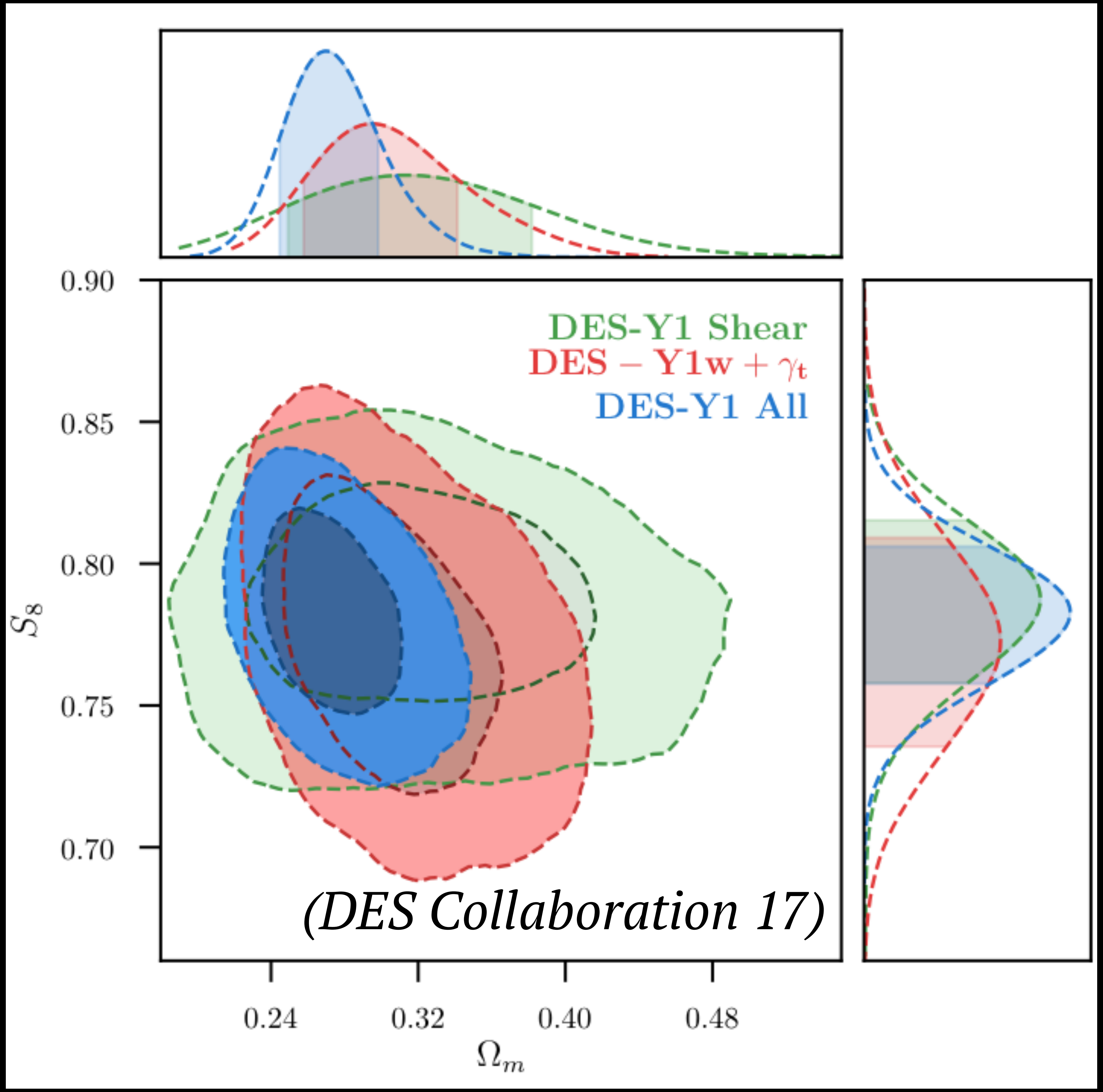
Lessons

- clearly define scope of blinding
  - e.g., parameter measurements vs. model testing
- make sure blinding scheme allows null tests
  - for parameter measurements, this may include consistency between probe
- someone not knowing what they're doing, shouldn't be able to unblind intentionally; someone knowing what they're doing, shouldn't be able to unblind unintentionally

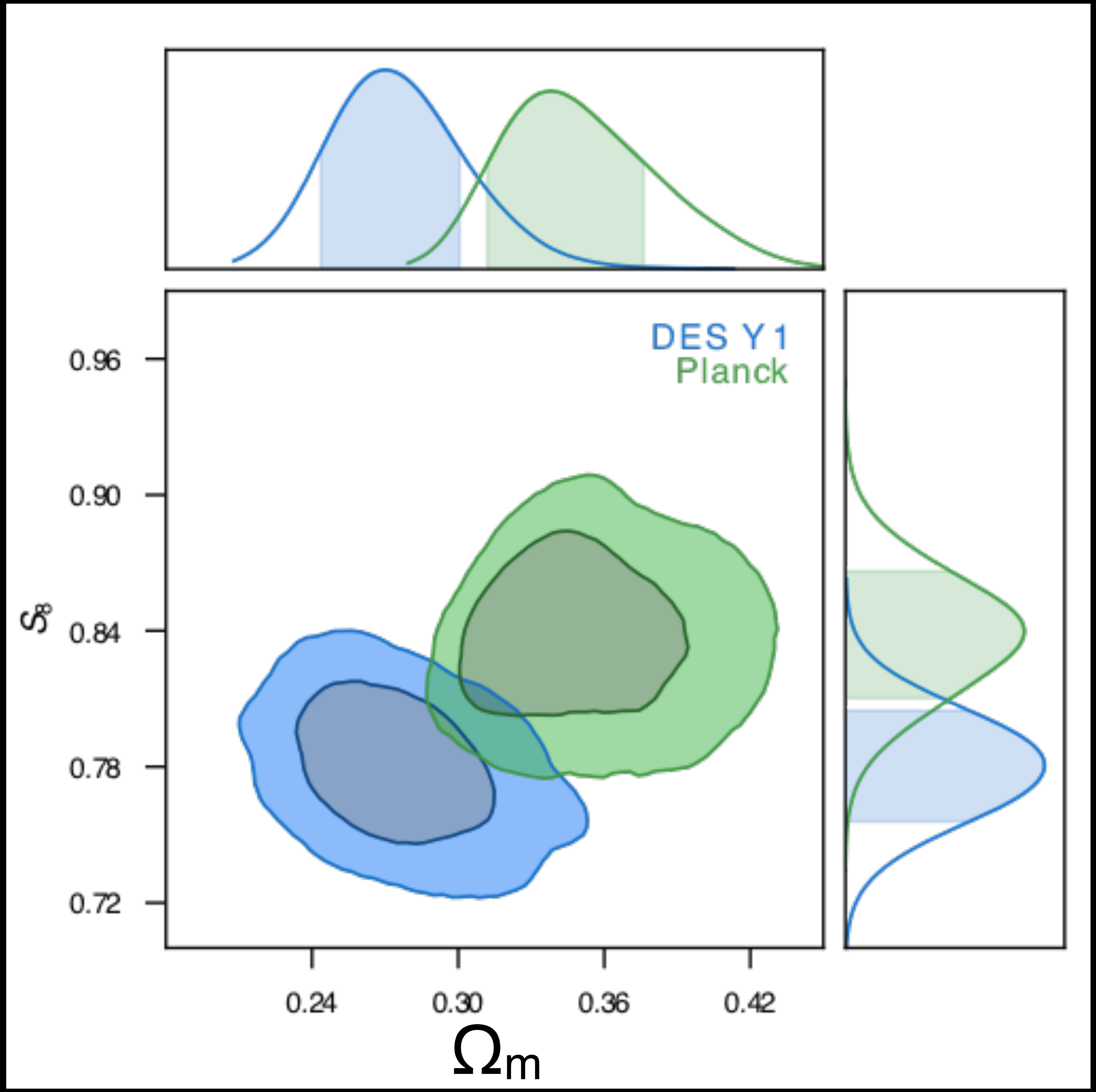
Multi-Probe Constraints: LCDM



- DES-Y1 weak lensing: factor ~2 increase in constraining power
- marginalized 4 cosmology parameters, 10 clustering nuisance parameters, and 10 lensing nuisance parameters
- consistent (Bayes Factor R = 2.8) cosmology constraints from weak lensing and clustering in configuration space

Key Result: Consistency of late Universe with Planck in ΛCDM

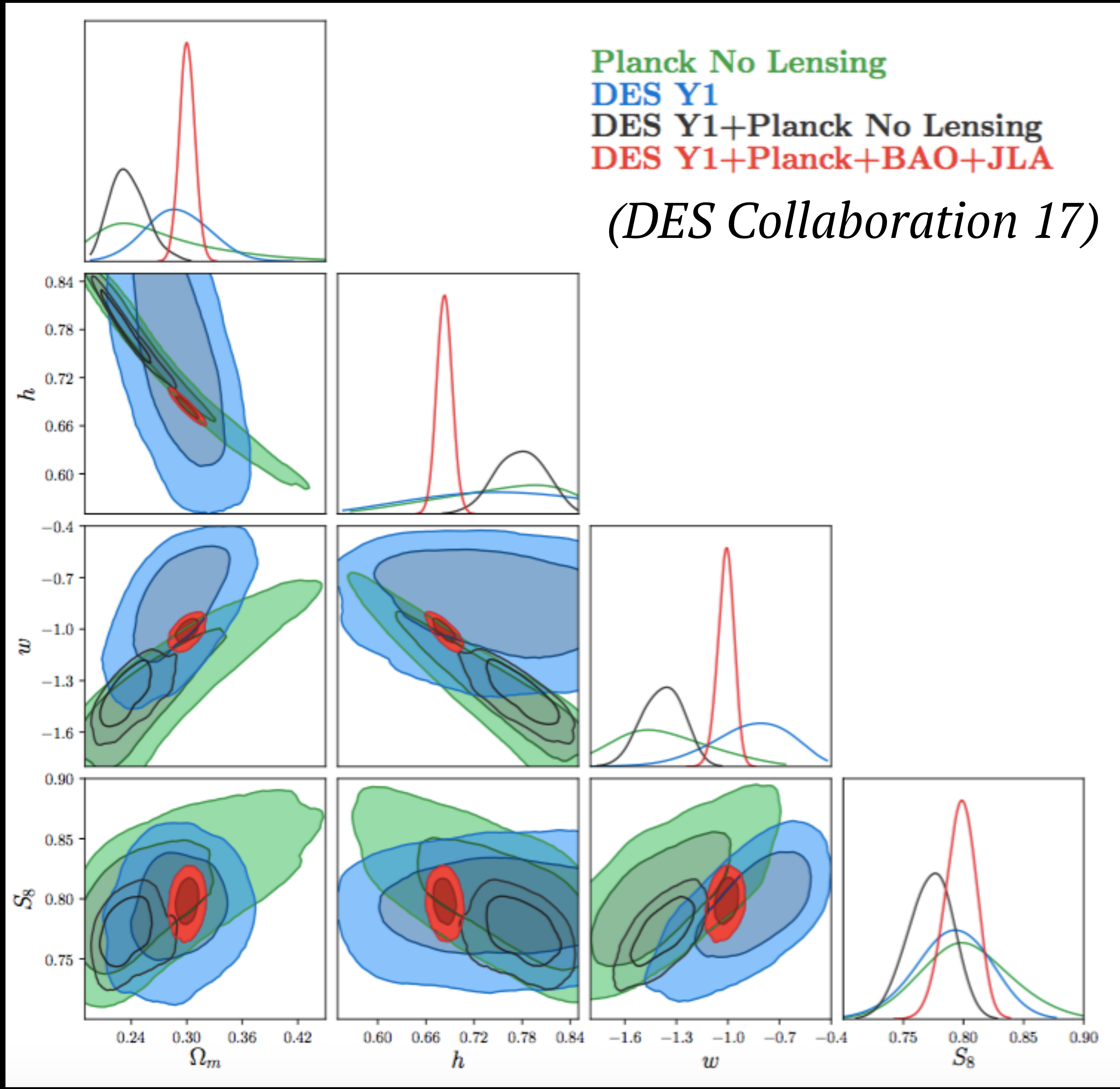
- DES and Planck constrain matter density and S_8 with equal strength
- Difference in central values 1-2σ in the same direction as earlier lensing results
- Bayes Factor 4.2 –
  no evidence for inconsistency
- Still consistent (R=9.0)
  for joint low-z results + Planck, which is why we combine...



Key Result: Combined Constraints in wCDM

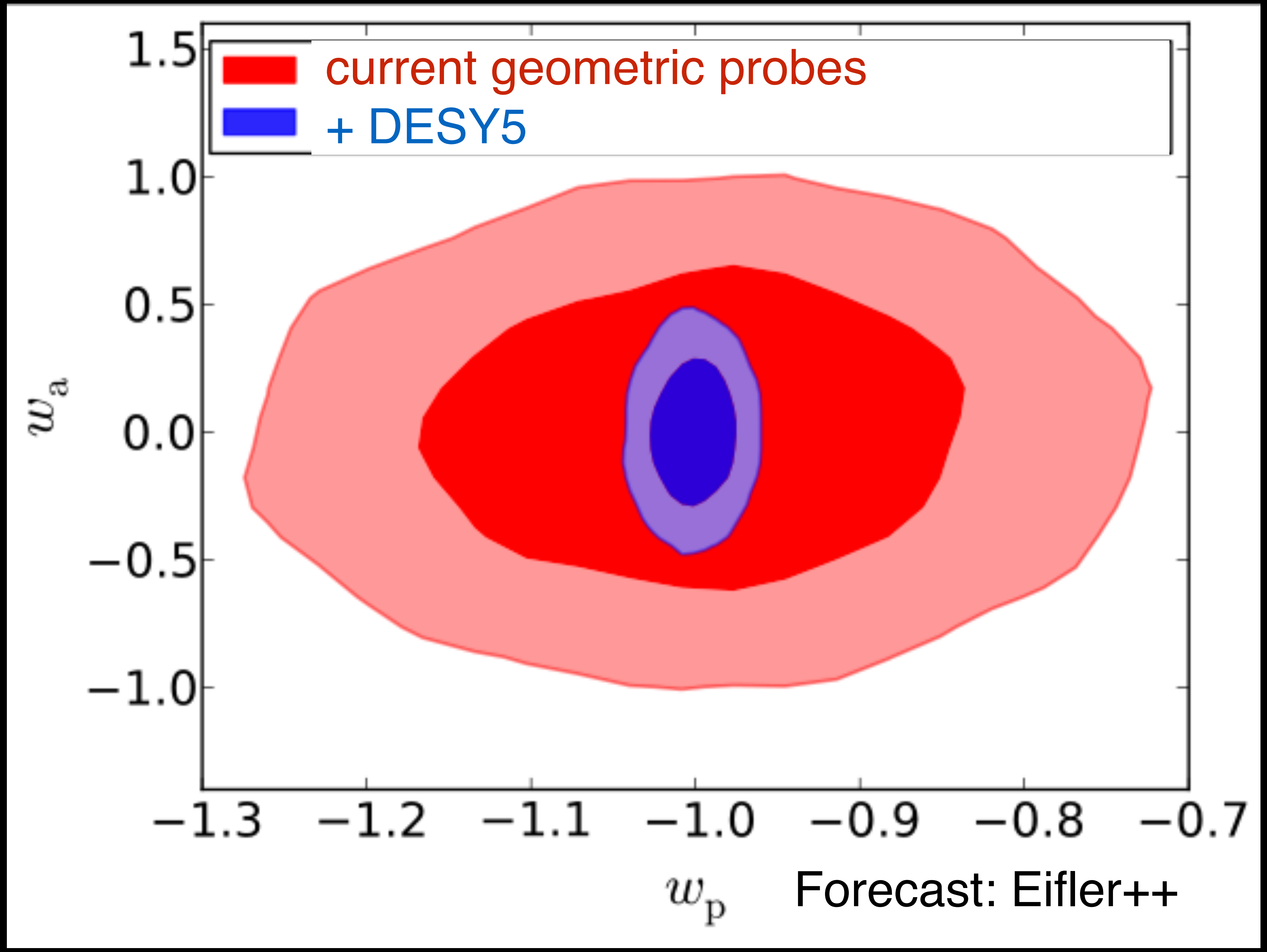
- consistent constraints from geometric probes (R=244)
- most precise parameter constraints from DES+Planck +BAO (BOSS) +SN (JLA)
- no evidence for w ≠-1

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



Steps forward: more precise tests of broader range of models

- DESY1++ is a precise test of ΛCDM. 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!



Conclusions

- DES Y1 Cosmology results from galaxy clustering, galaxy-galaxy lensing, and cosmic shear (3x2) are now out: 10 papers, with more to follow.
- In context of ΛCDM, these measurements from galaxy surveys now rival precison of Planck CMB results for certain parameters: can compare low- and high-z Universe.
- Precision will increase with larger data sets (Y1->Y3->Y5) and by bringing in more probes (clusters, SN, cross-correlations…), enabling tests of more complex models (w_0w_aCDM, modified gravity,…)
- DES Y1 results consistent with Planck CMB in context of ΛCDM.
- DES Y1 results in combination with Planck, BAO, JLA SN provide stringent constraints on ΛCDM parameters.