Evidence for accelerated expansion of the Universe: current observations

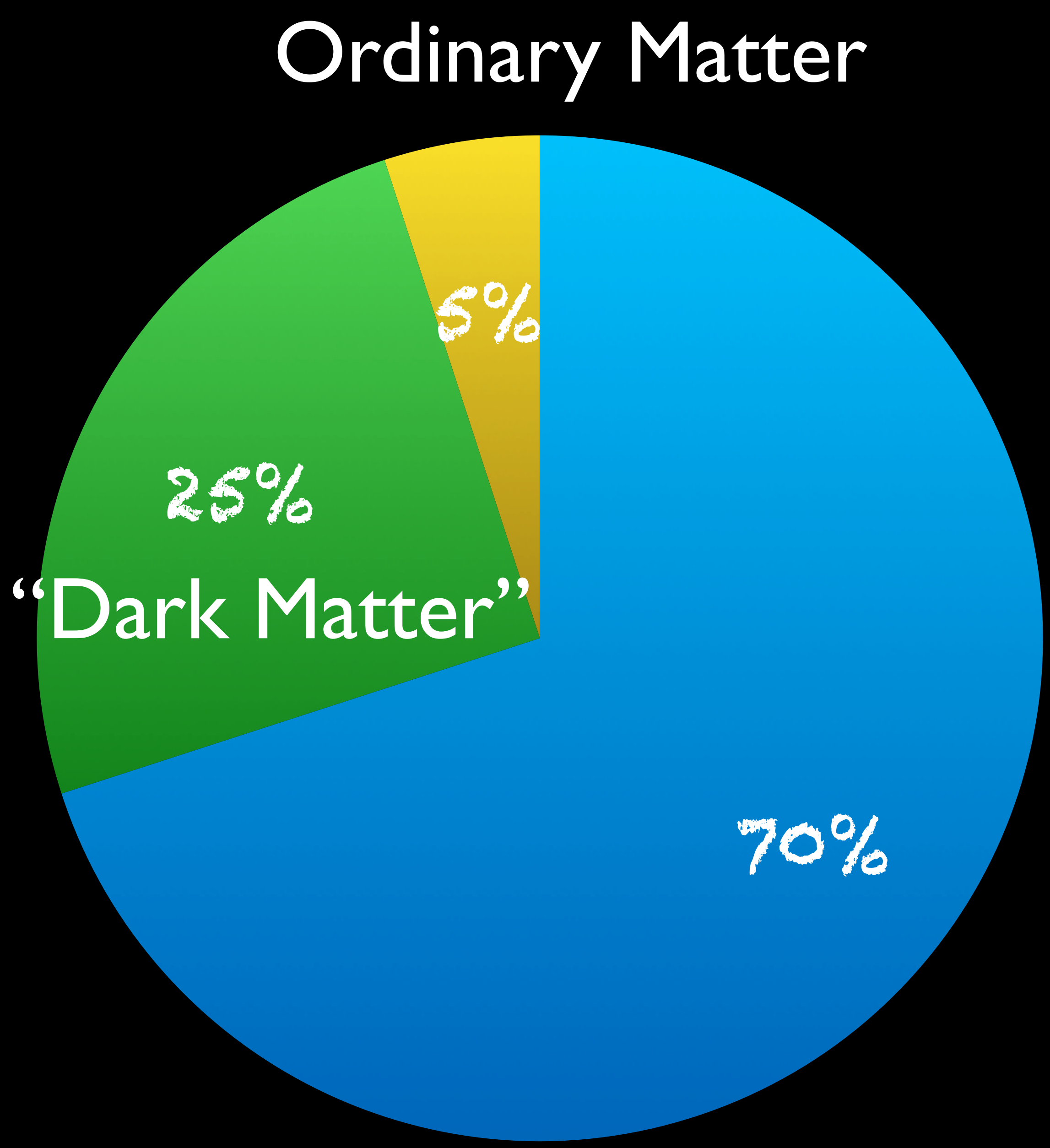
Tim Eifler
(NASA-JPL/Caltech, University of Arizona)

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

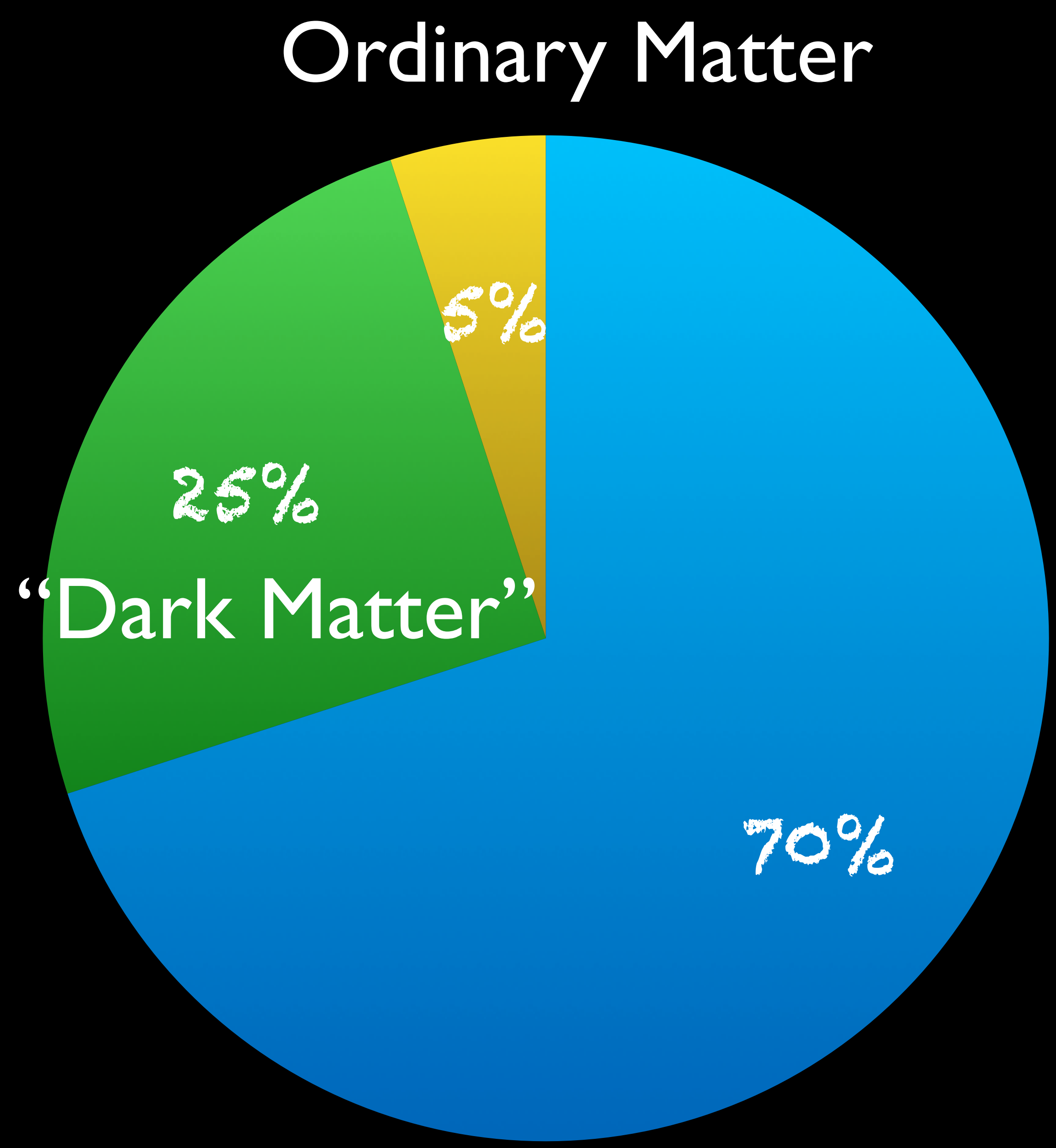


"Dark Energy"

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

acceleration first measured by SN 1998

Our Puzzling Universe



"Dark Energy"

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

acceleration first measured by SN 1998

next frontier: understand

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

Theory Space: Breaking GR

Many new DE/modified gravity theories developed over last decade

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]

Theory Space: Breaking GR

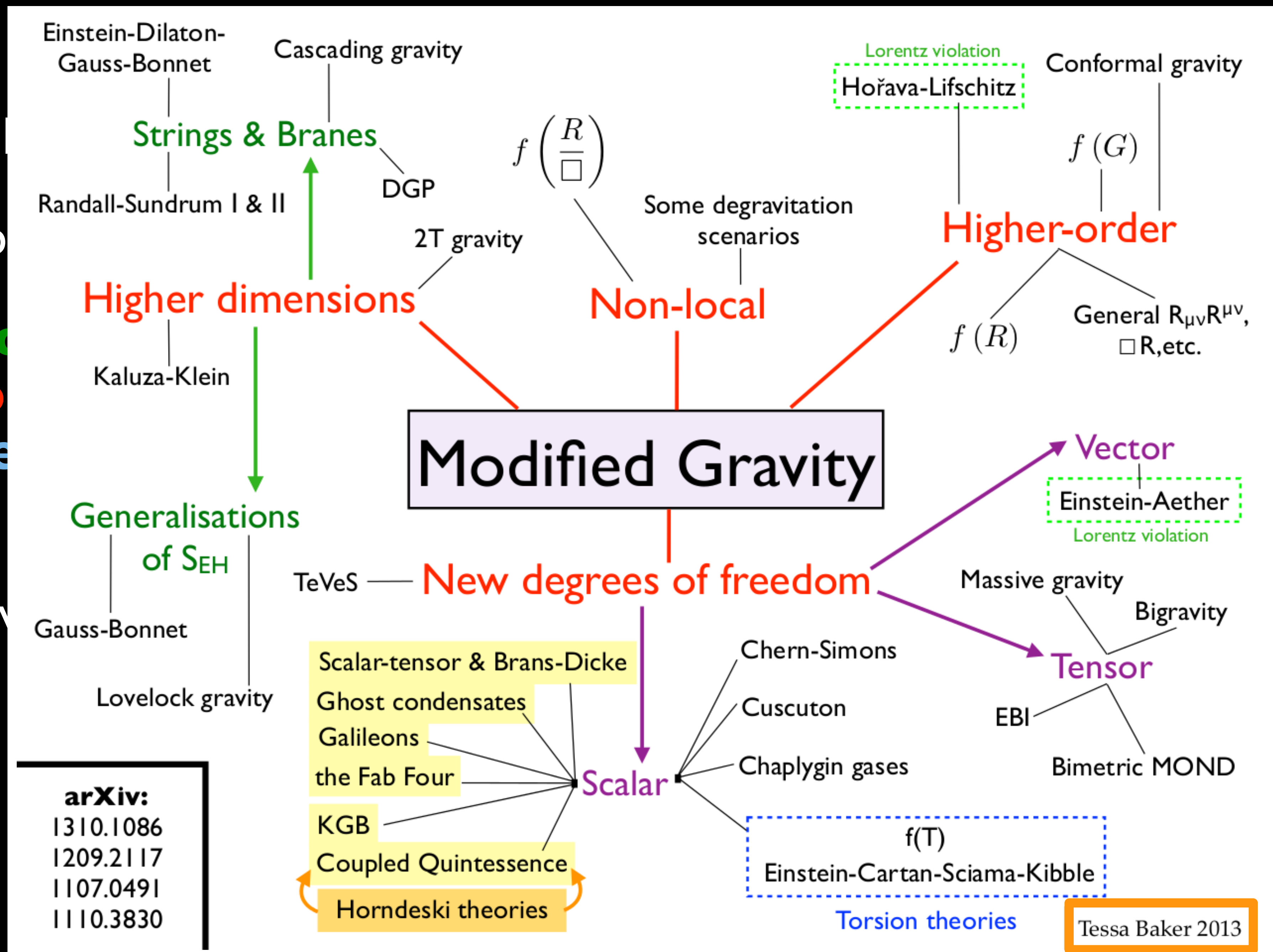
Many new

Most can b

The only **l** be derived from a **fo** **from the metric te**

theorem (1969)

subject to v



No favored alternative theory, theory space hard to summarize succinctly

Need unifying frameworks + phenomenology to compare to data

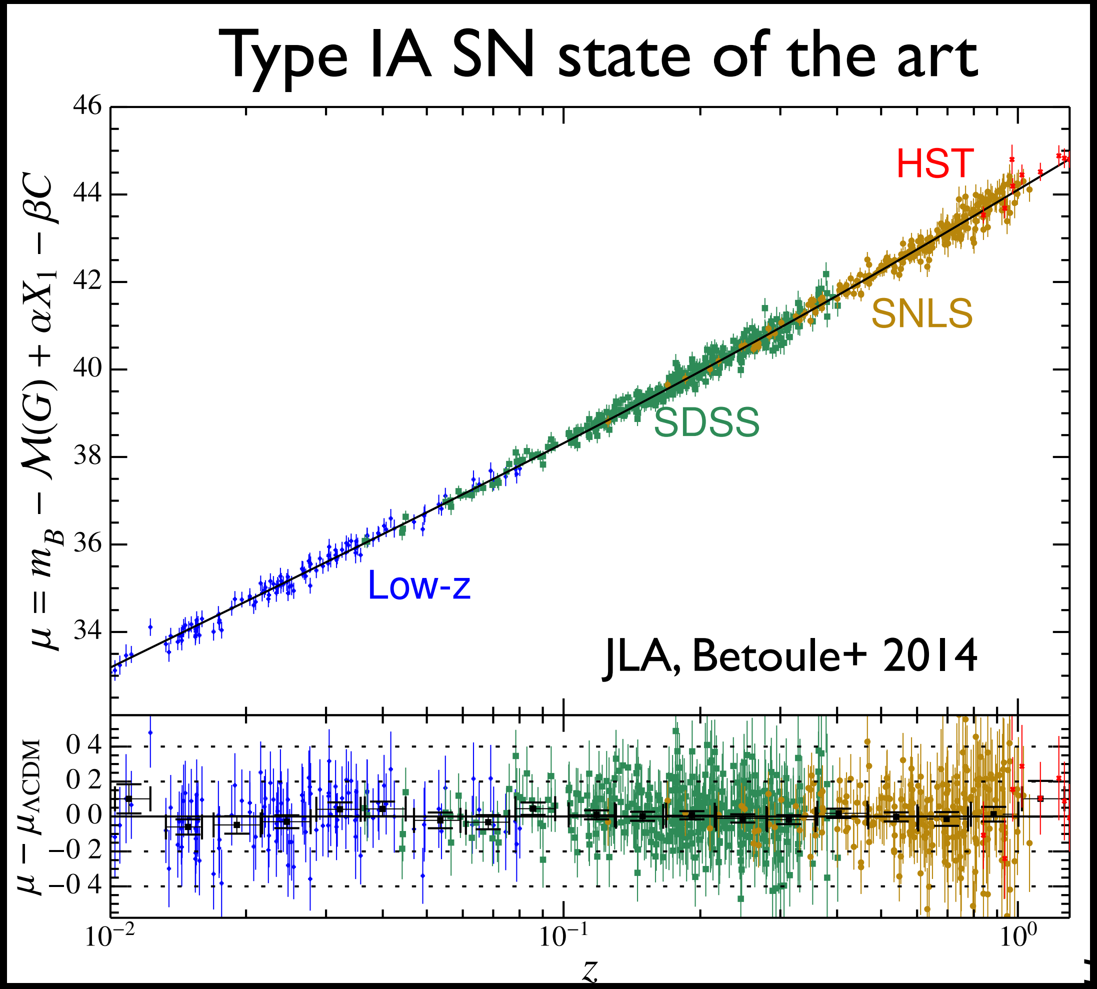
Testing Cosmic Acceleration

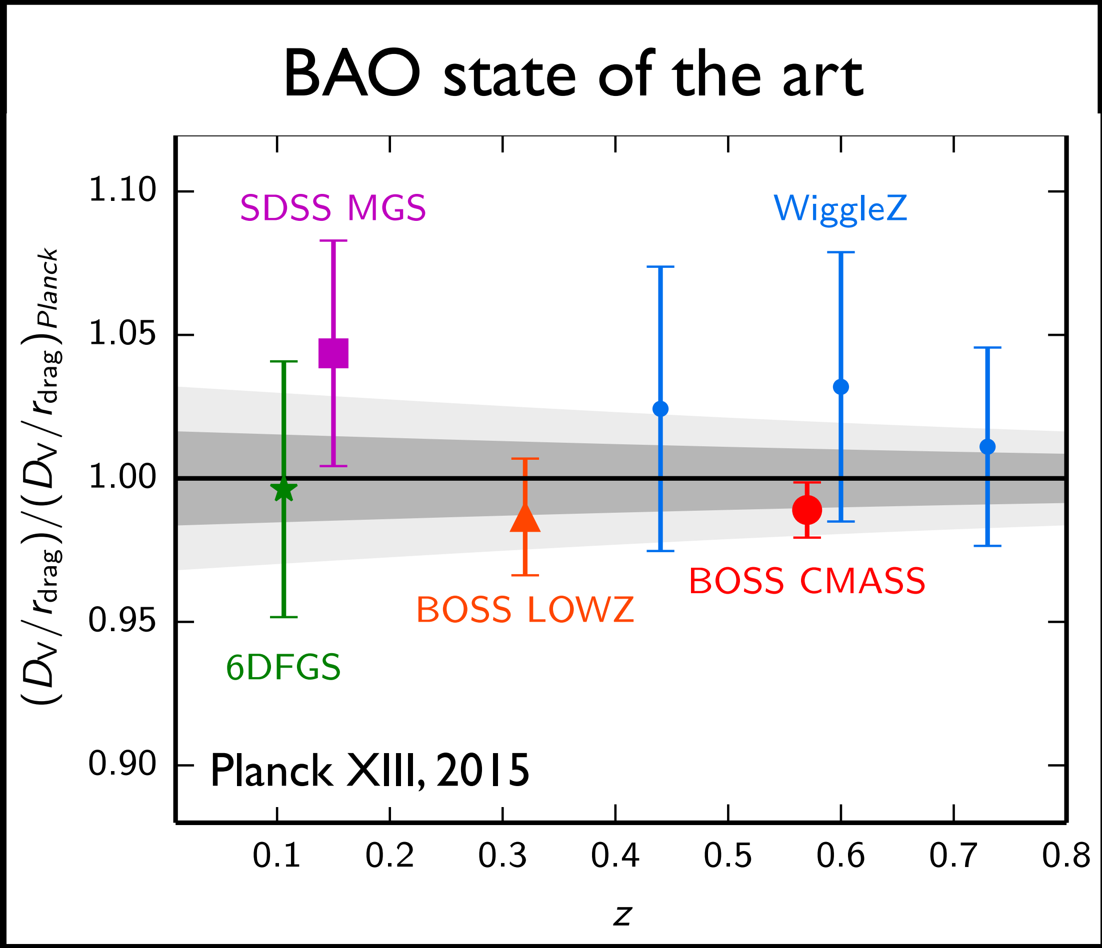
important to test GR over cosmological scales

Expansion history

$$H^2(a) = H_0^2\left(\Omega_M a^{-3} + \Omega_{DE} a^{-3(1+w_0+w_a)} e^{-3w_a(1-a)}\right)$$

- from supernovae, CMB peaks + baryonic acoustic oscillations (BAO)
- agreement with ΛCDM
- limited information on dark energy/ modified gravity: at most w0, wa





Cosmic Structure Formation

gravity drives **formation of cosmic structure,** dark energy slows it down

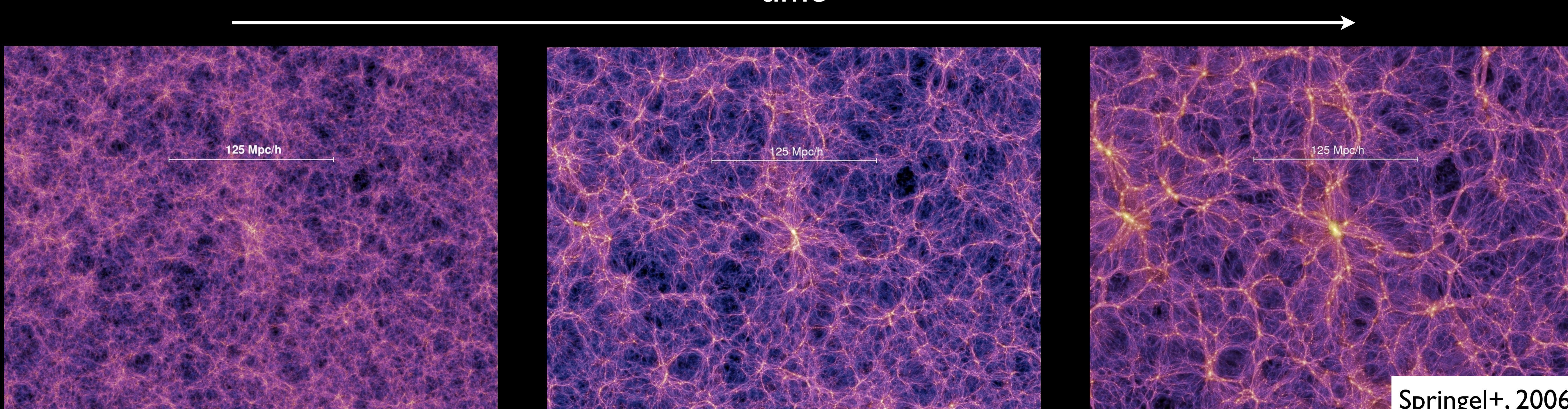
growth of structure contains much more information than expansion rate

linear level: perturbation theory

non-linear evolution: numerical simulations

- reliably predict *dark matter distribution, for wCDM cosmologies + individual MG models*

time

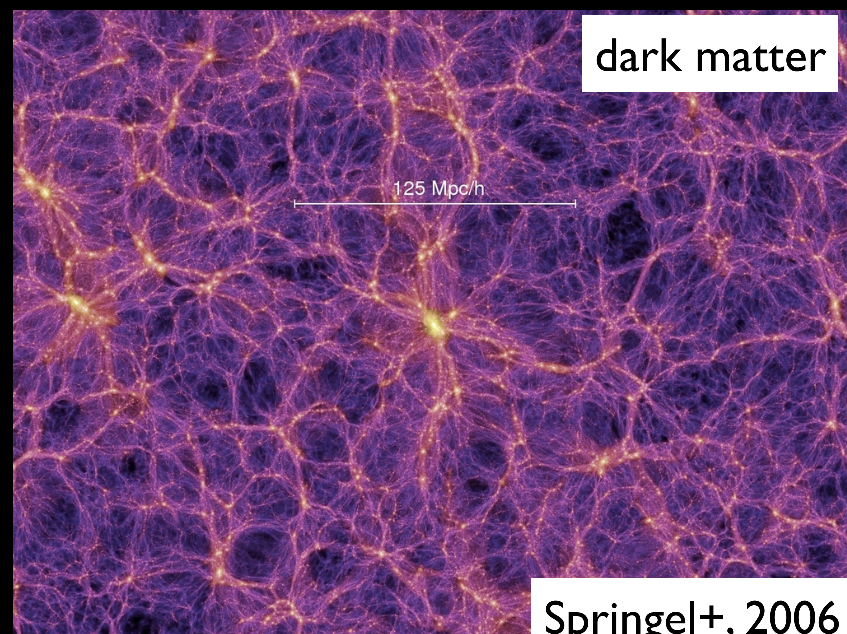


Springel+, 2006

Connect theory to data

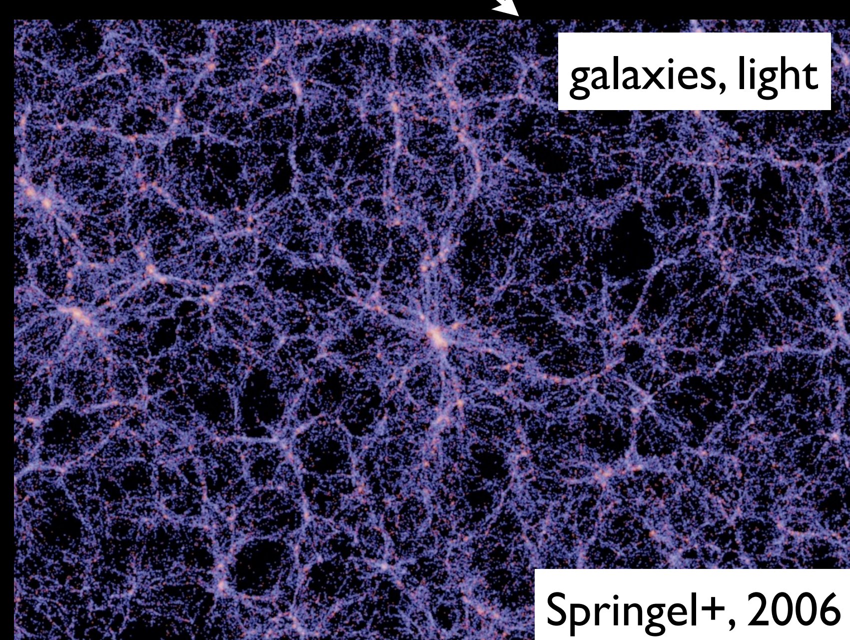
fundamental physics
+ model parameters

generate initial conditions, evolve



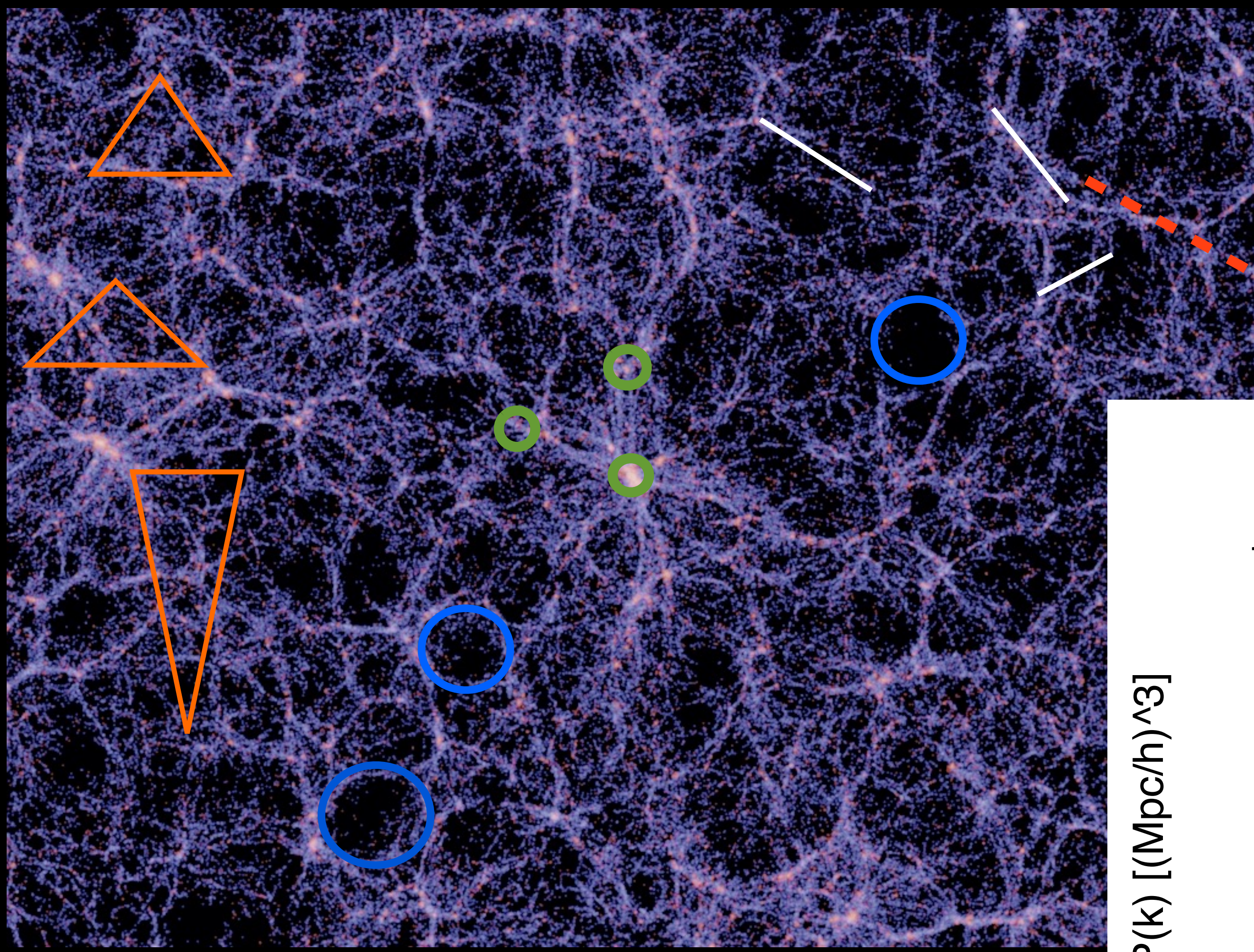
galaxy formation models

?

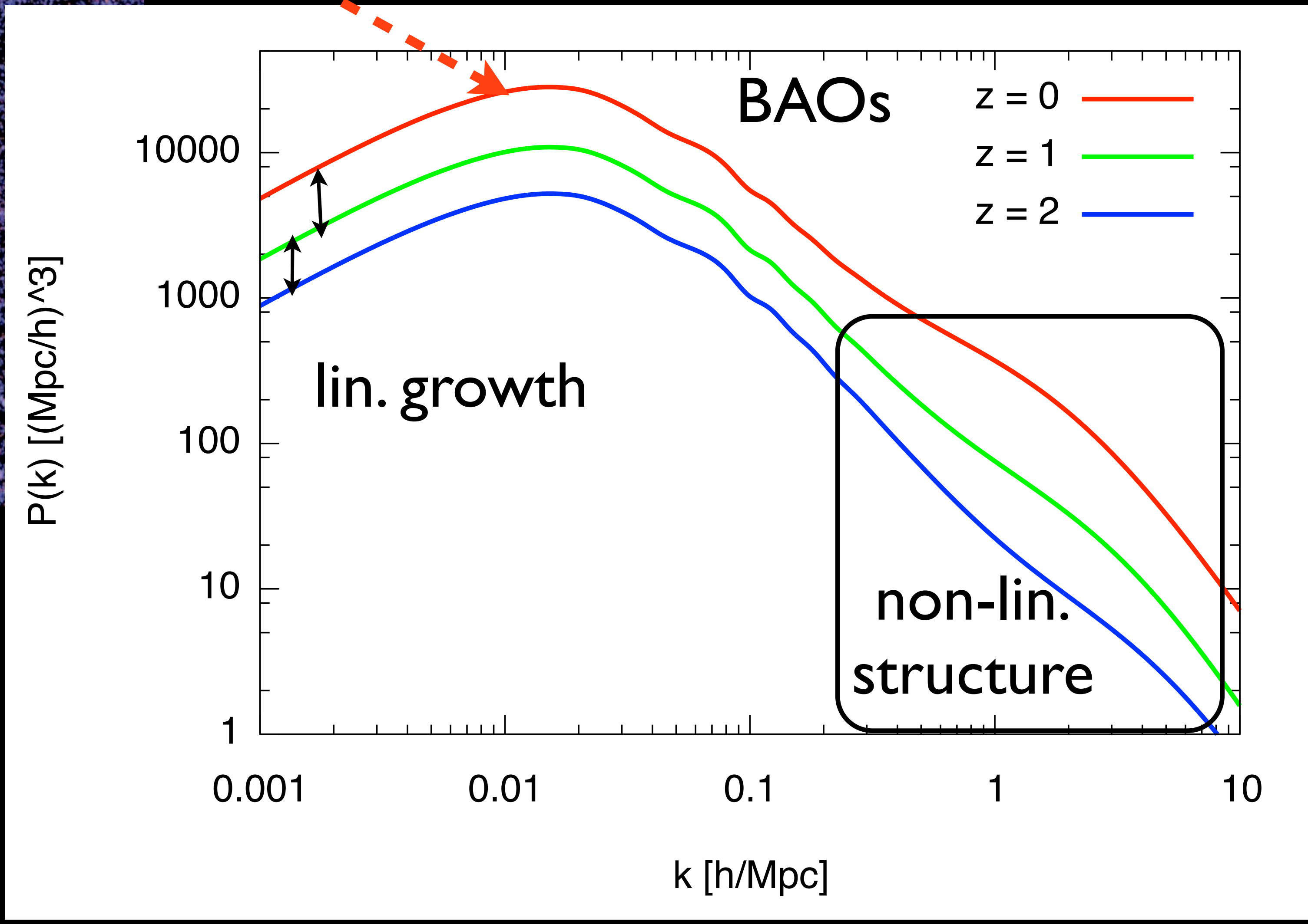


?

What to look for in the galaxy distribution?



need redshift, understand galaxy bias



clusters (over densities),

voids (under densities)

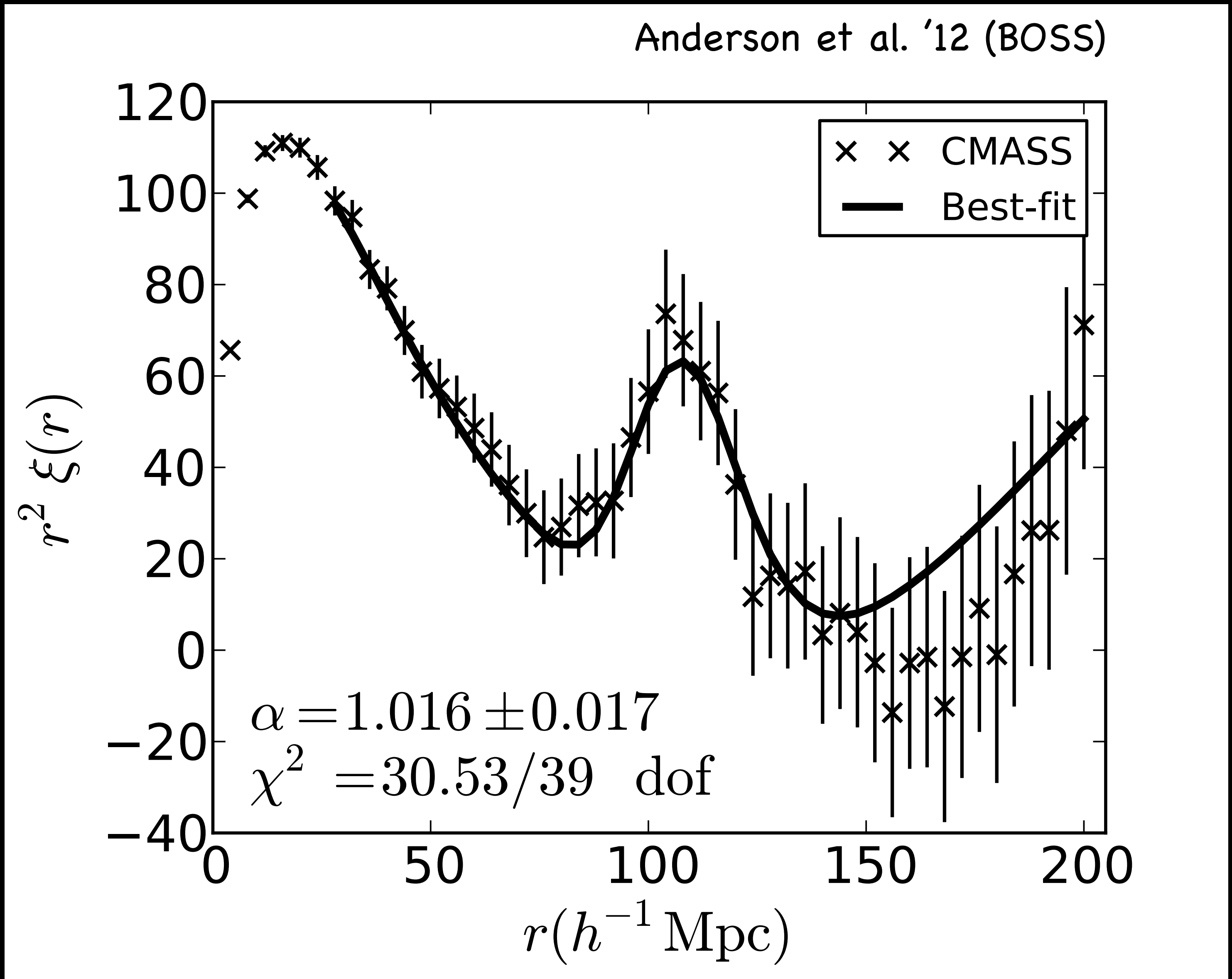
two-point correlations

three-point correlations,...

LSS Probes of Dark Energy

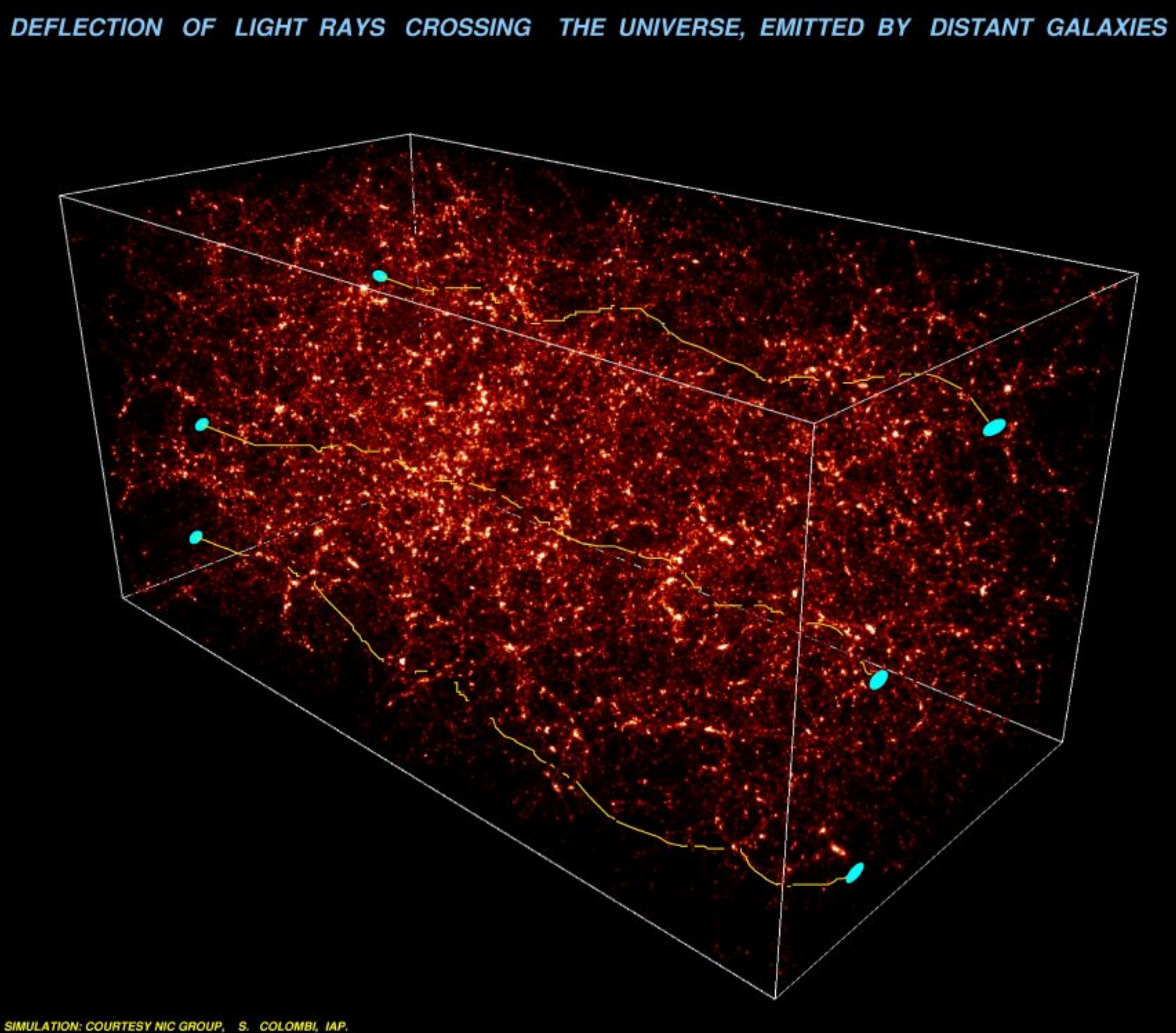
Galaxy Clustering

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



LSS Probes of Dark Energy

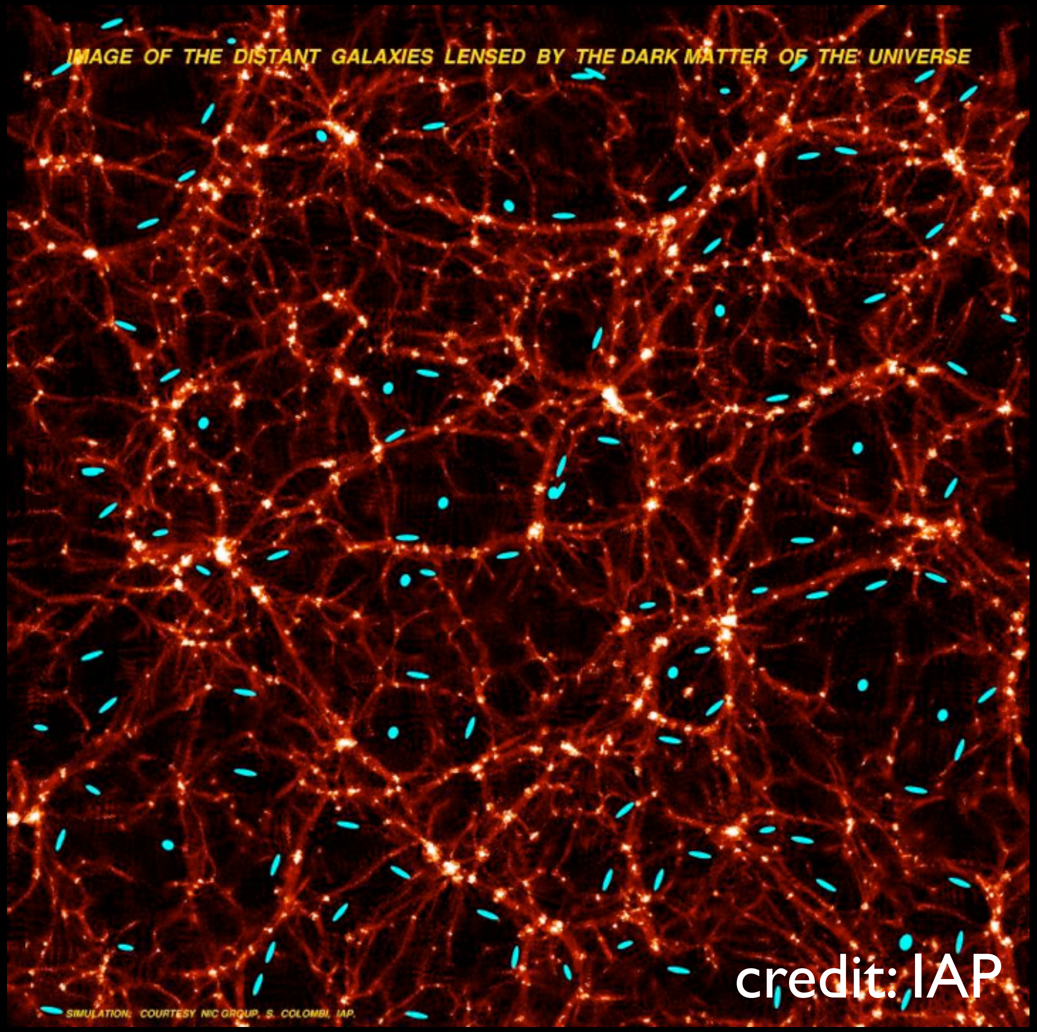
Weak Gravitational Lensing



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/clusters**
  - probes halo mass

~Optical Dark Energy Surveys

Spectroscopic galaxy surveys

determine redshifts of select galaxies

Galaxy Clustering

galaxy positions, types, redshifts

Supernovae

light curve, redshift

Galaxy Clusters

cluster centers, redshifts, member galaxies

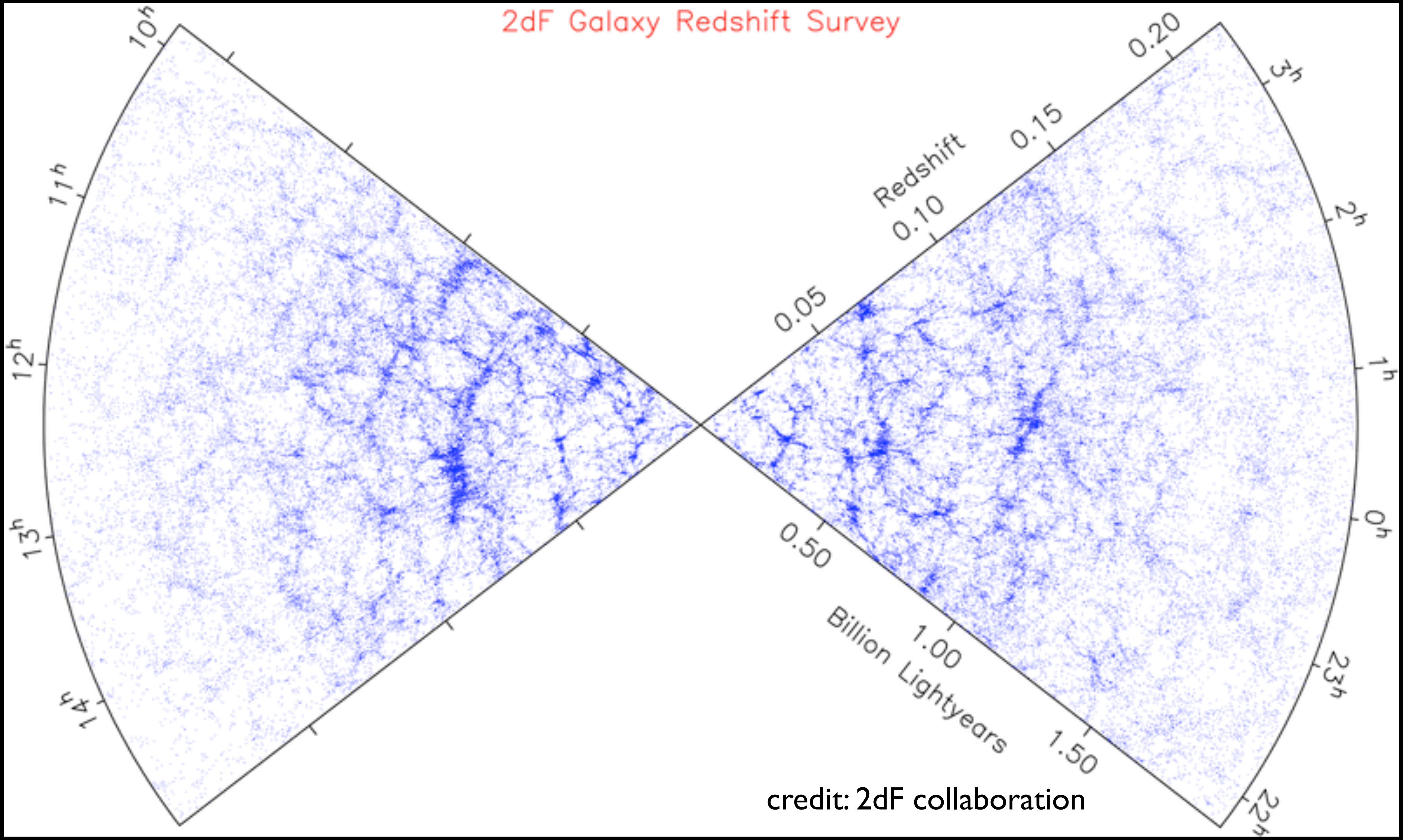
Weak Lensing

galaxy positions, shapes, types, redshifts

Spectroscopic Dark Energy Surveys

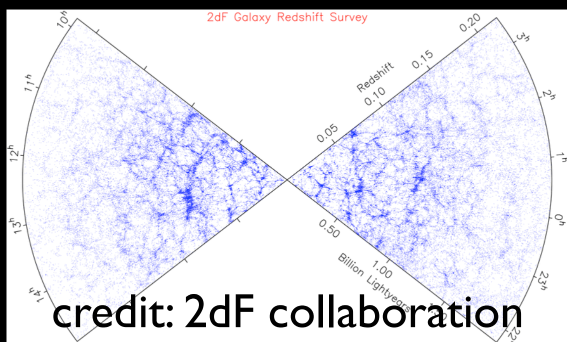
the early days: SDSS, 2-degree Field survey(2dF):

$\mathcal{O}(10^5 - 10^6)$ low-redshift galaxies



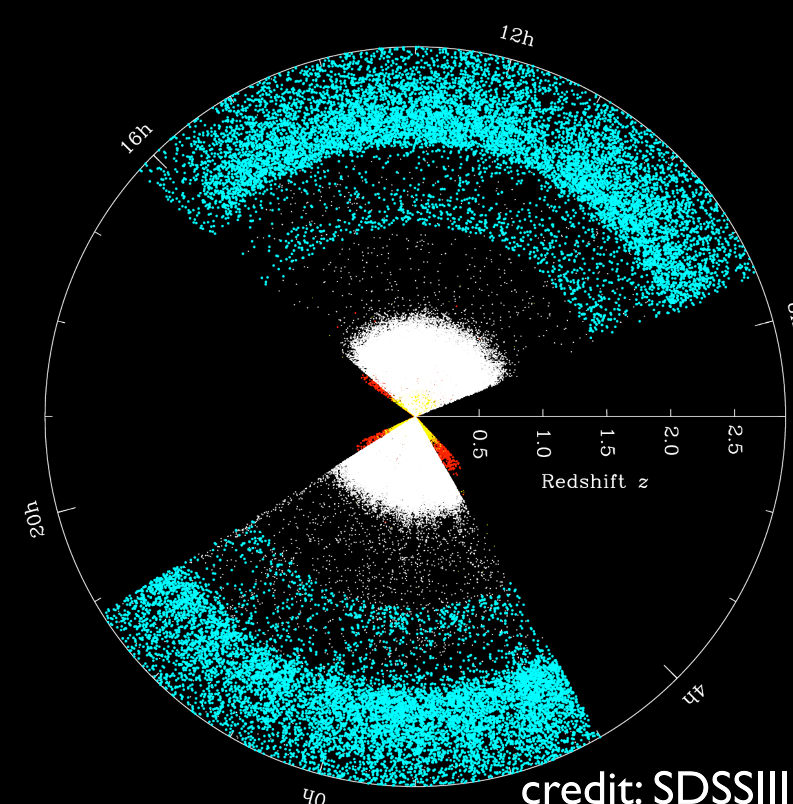
credit: 2dF collaboration

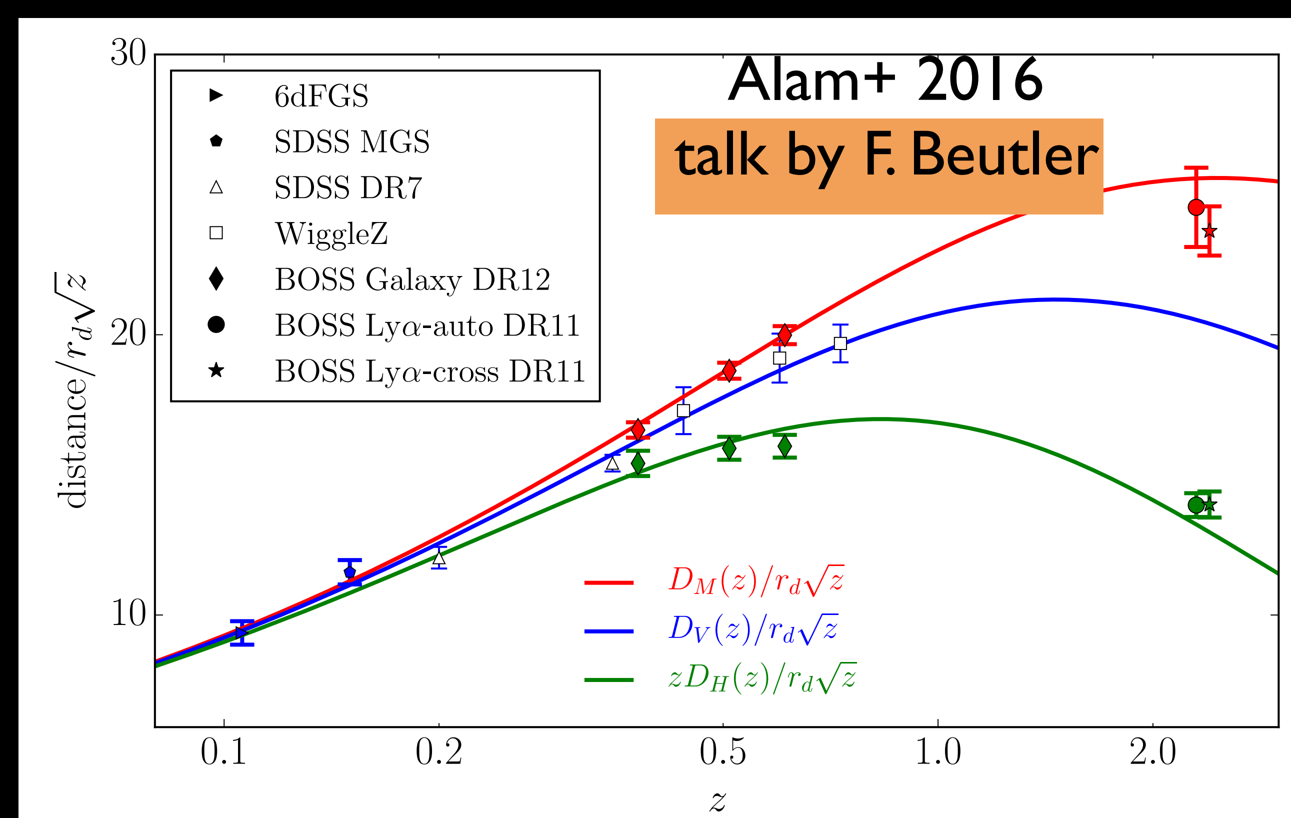
Spectroscopic Dark Energy Surveys



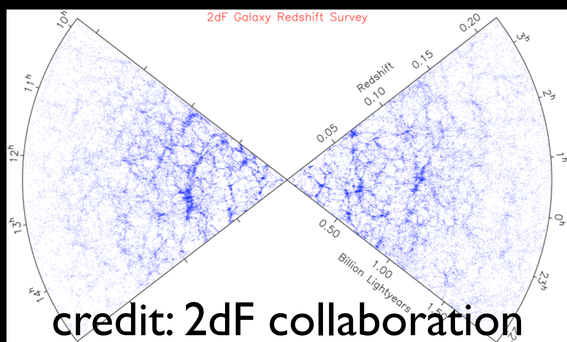
the present: BOSS, WiggleZ, …

$\mathcal{O}(10^6)$ intermediate-redshift galaxies



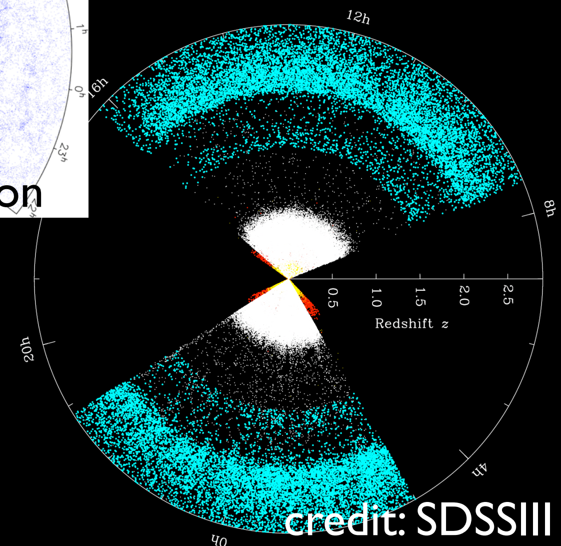


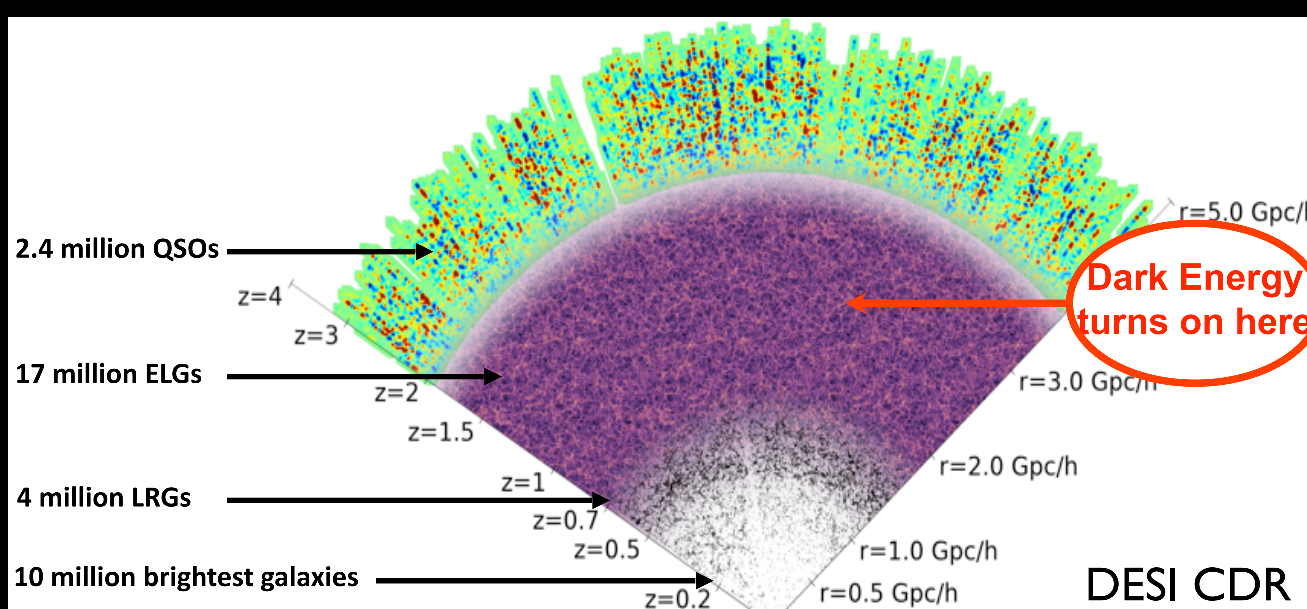
Spectroscopic Dark Energy Surveys

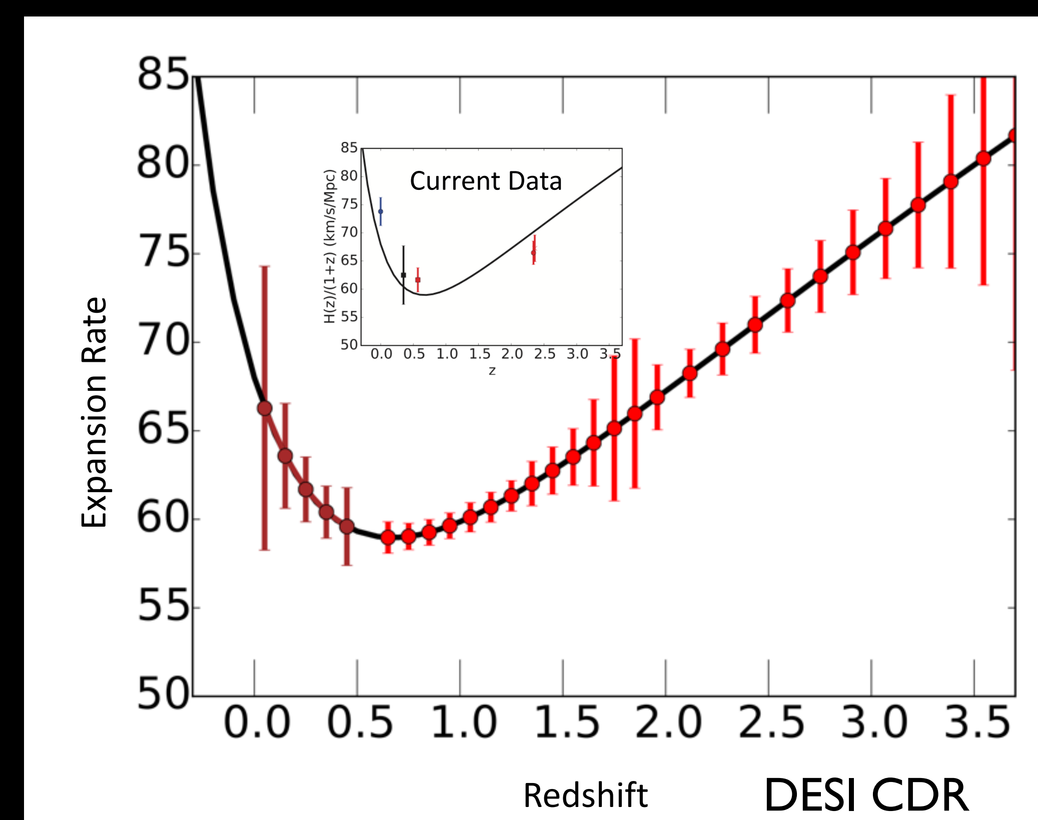


the future: Dark Energy Spectroscopic Instrument (DESI)

$\mathcal{O}(10^7)$ intermediate+high-z galaxies







~Optical Dark Energy Surveys

Spectroscopic galaxy surveys

determine redshifts of select galaxies

Photometric galaxy surveys

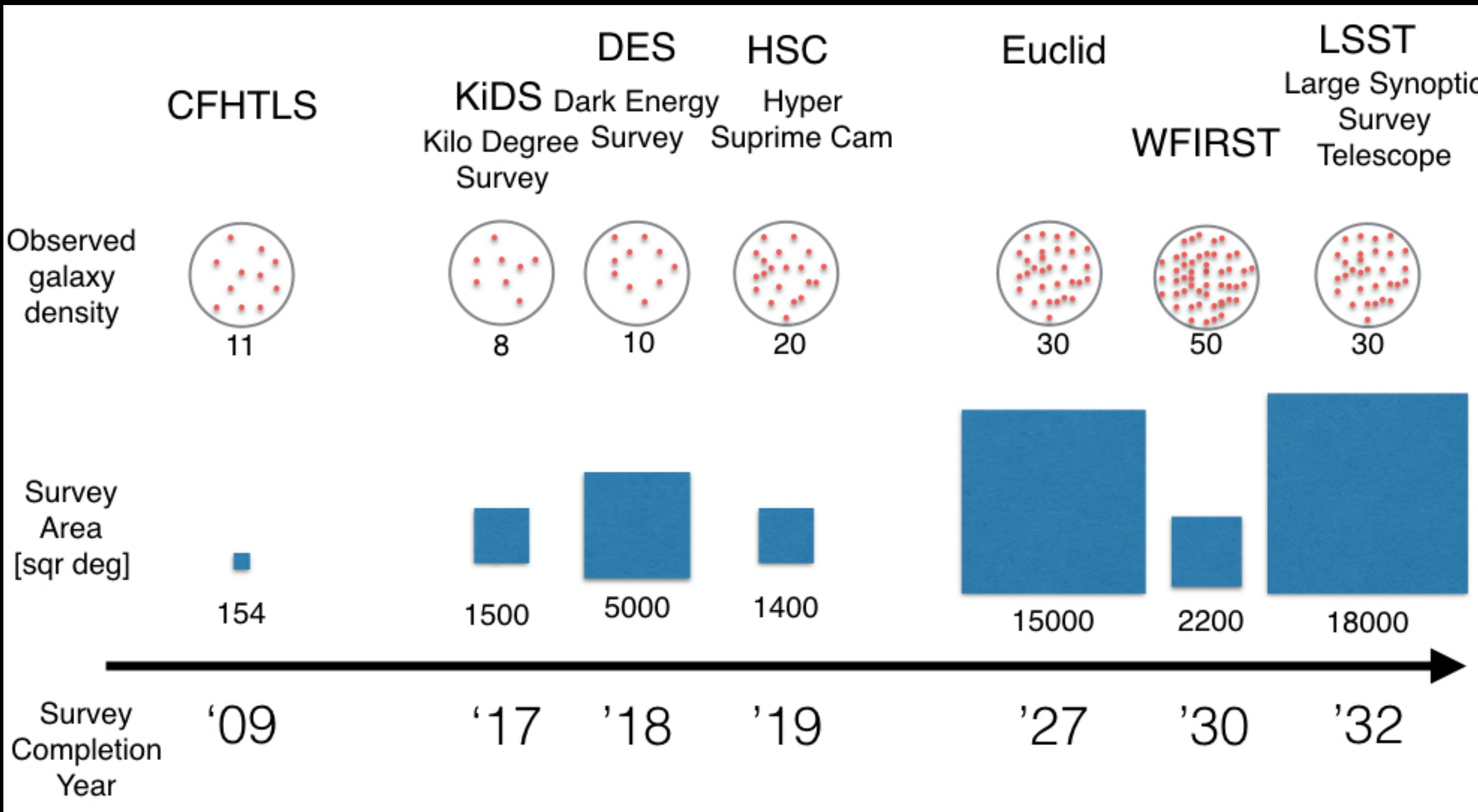
image all galaxies to lim. brightness, in multiple bands

Time domain surveys

repeated observations with suitable cadence

Galaxy Clustering galaxy positions, types, redshifts	Supernovae + Strong Lensing light curve, redshift
Galaxy Clusters cluster centers, redshifts, member galaxies	Weak Lensing galaxy positions, shapes, types, redshifts

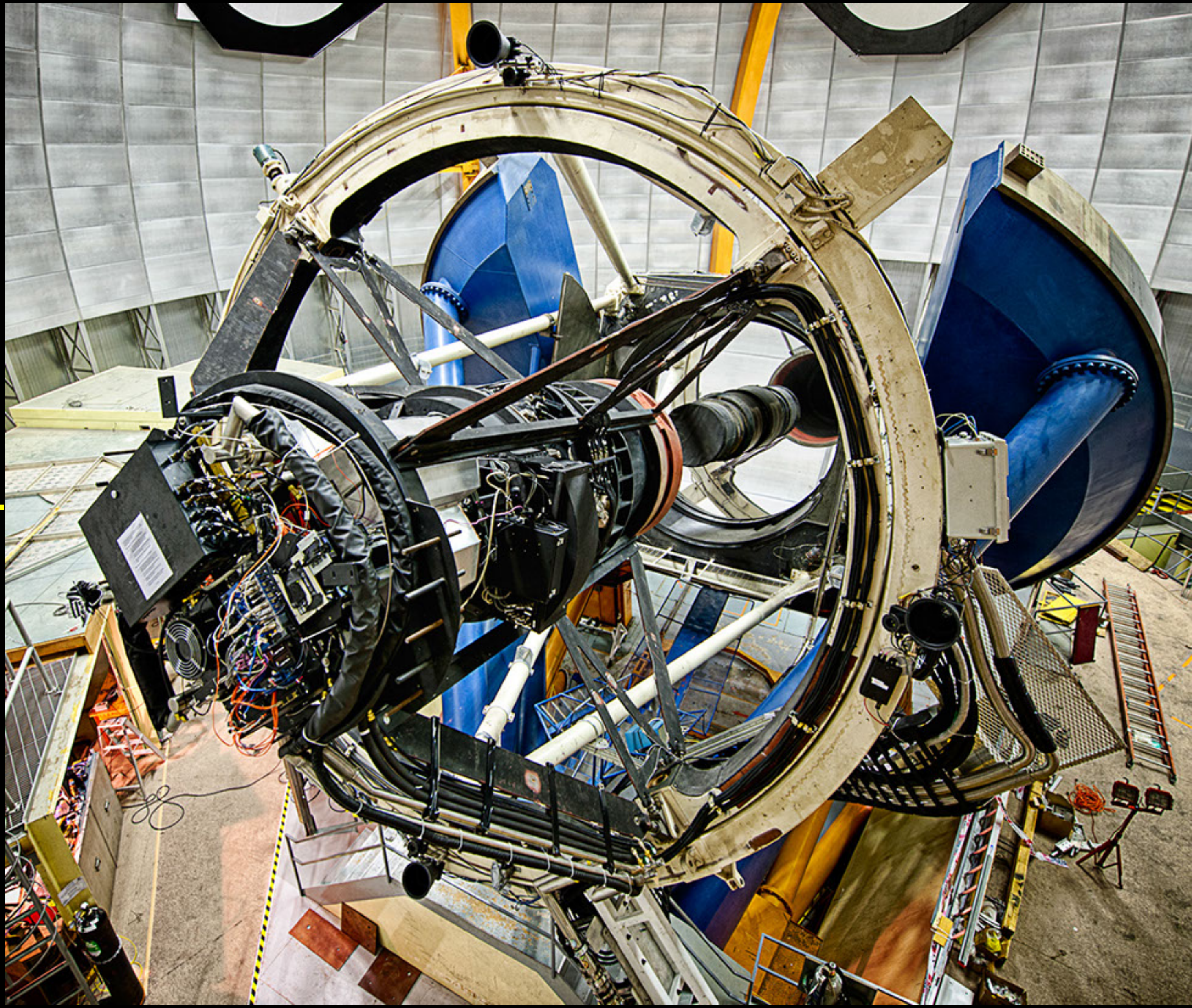
Photometric Dark Energy Surveys



The Dark Energy Survey

- Probe origin of Cosmic Acceleration:
  - Distance vs. redshift
  - Growth of Structure
- Two multicolor surveys:
  - 300 M galaxies over 5000 sq deg, grizY to 24th mag
  - 3000 supernovae (27 sq deg)
- New camera for CTIO Blanco 4 telescope
  - DECam Facility instrument
- Survey started Aug. 2013
  - Finished 5 seasons, 105 nights per season (Aug-Feb)

DECam on the CTIO Blanco 4m



www.darkenergysurvey.org

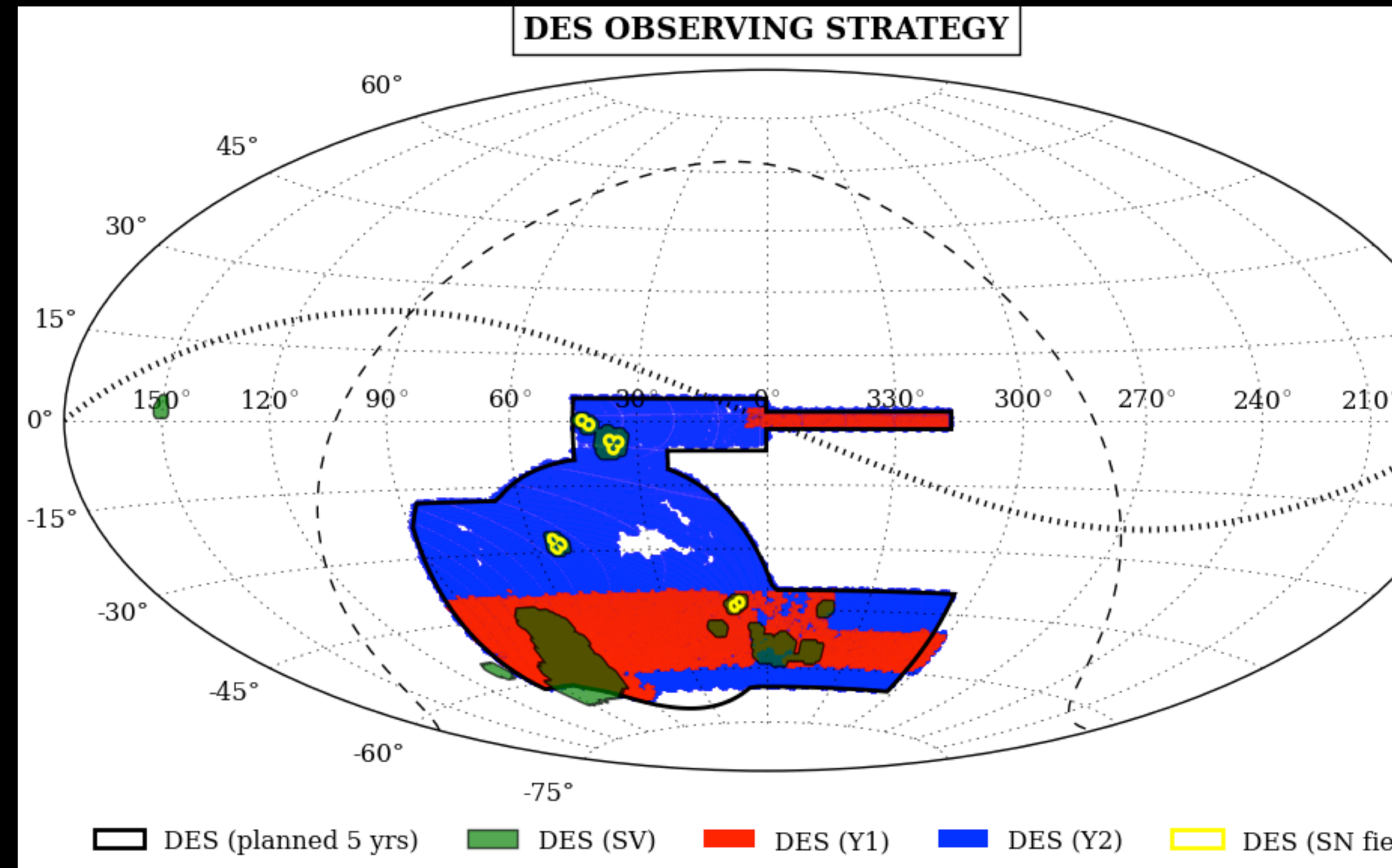
Dark Energy Survey: Progress

SV (150 sq .deg., full depth)
science done, catalogs public

Y1 (1500 sq. deg., 40% depth)

Y3 (5000 sq. deg., 50% depth)
data processed, vetting catalogs

Y5 observations completed
Y5.5 in 2018B

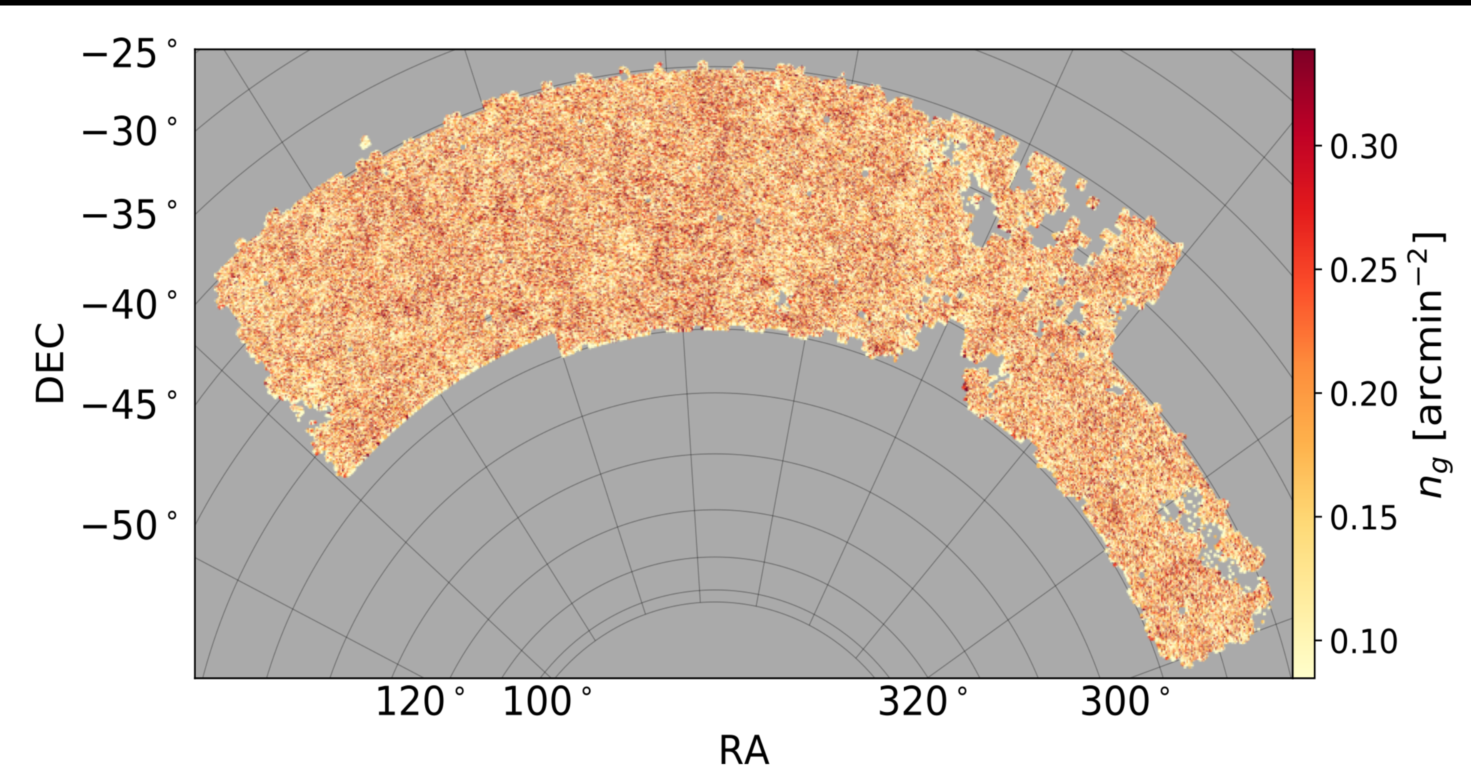


	Area (deg²)	Exposure time (s) (per visit for SNe) Specified median PSF FWHM (arcsec)					Dithering	Cadence
		g	r	i	z	Y		
Wide	5000	10x90 -	10x90 0.9"	10x90 0.9"	10x90 0.9"	10x45 -	10 fully interlaced tilings	10 tilings over 5 years
SN Shallow	24	1x175 -	1x150 -	1x200 -	2x200 -	-	Minimal dithers	Seeing >1.1" or 7 days since last observed
SN Deep	6	3x200 -	3x400 -	5x360 -	10x330 -			

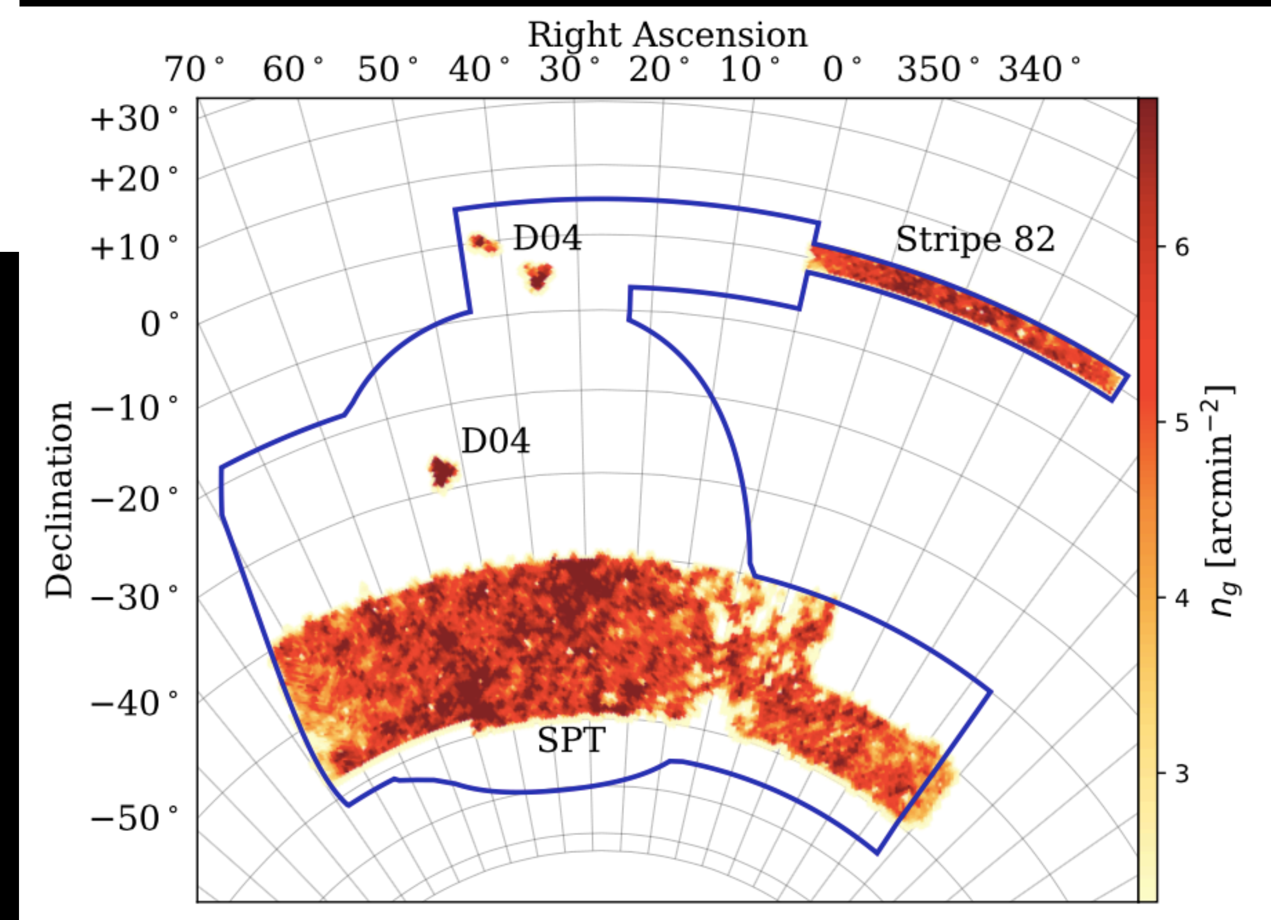
Major El Nino affected Year 3

Dark Energy Survey Collaboration

DES Year 1 Galaxy Samples



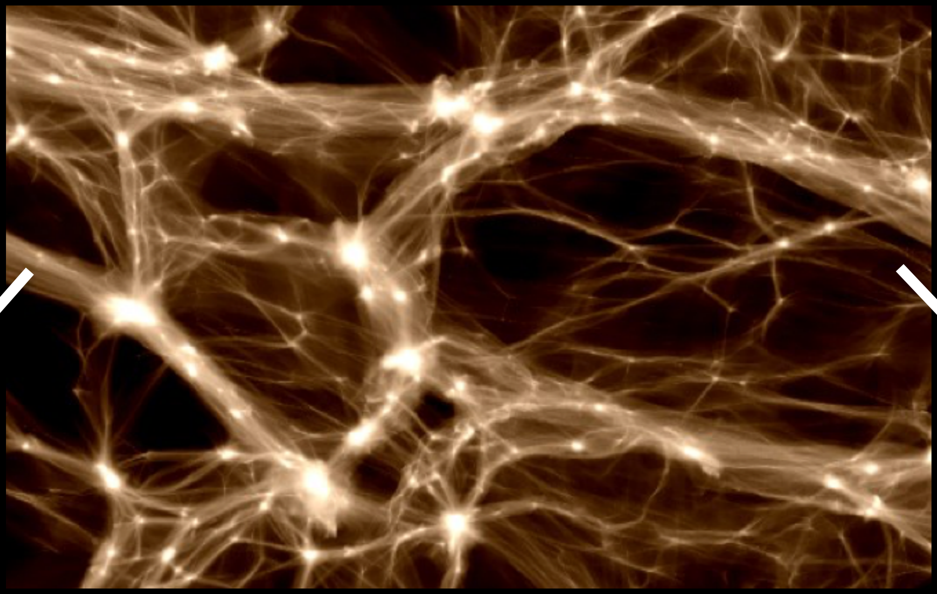
- 26 million source galaxies
- 4 redshift bins
- Sources for cosmic shear & galaxy-galaxy lensing

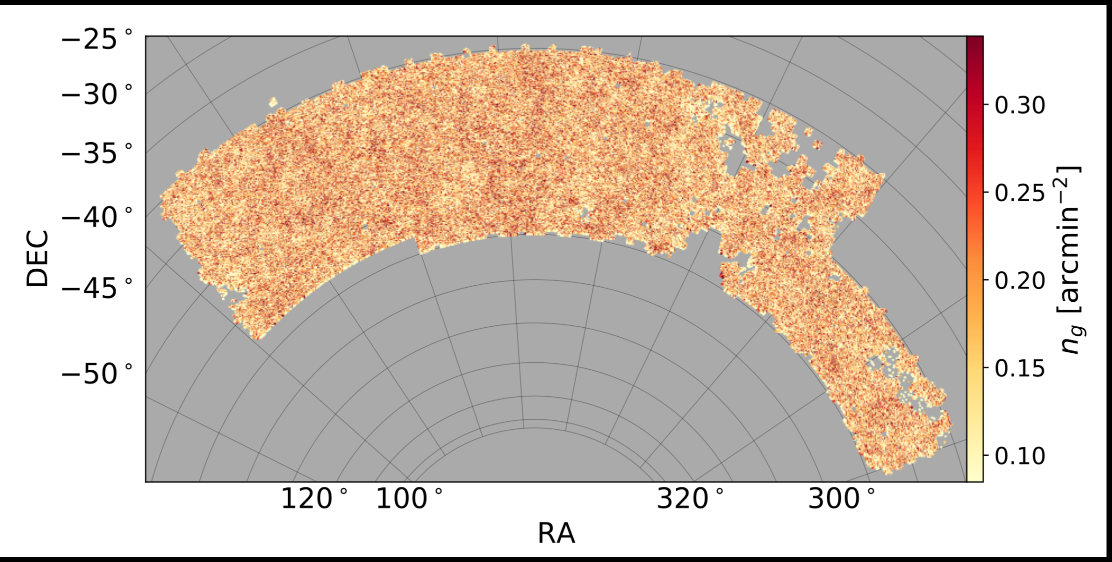


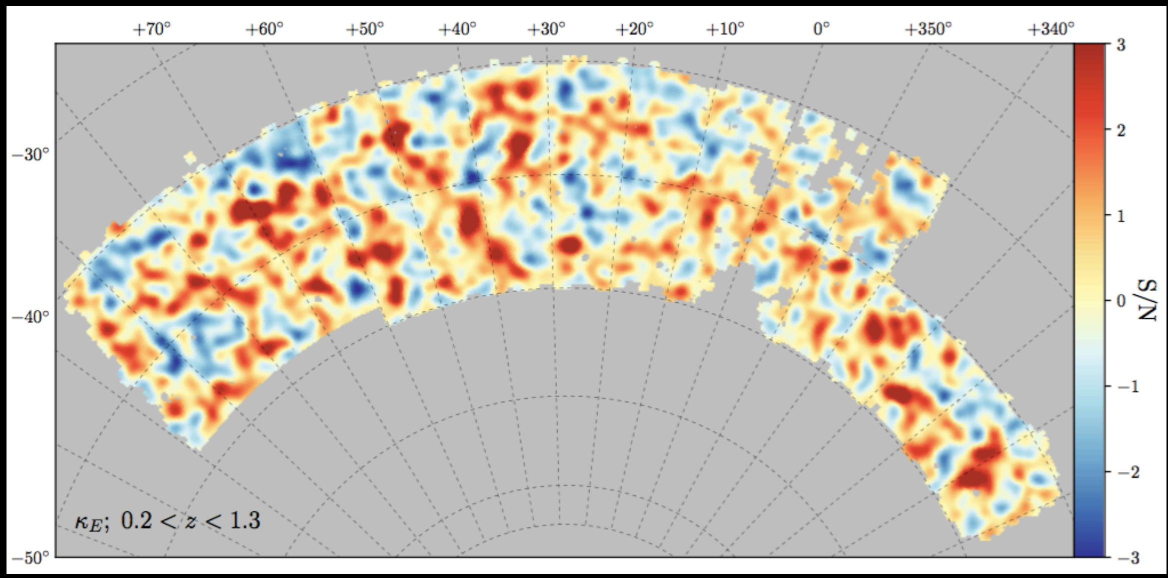
- 660,000 redMaGiC galaxies with excellent photo-z's
- Measure angular clustering in 5 redshift bins
- Use as lenses for galaxy-galaxy lensing

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

DES Year 1 Cosmology Analysis







galaxies x galaxies:
angular clustering

galaxies x lensing:
galaxy-galaxy lensing

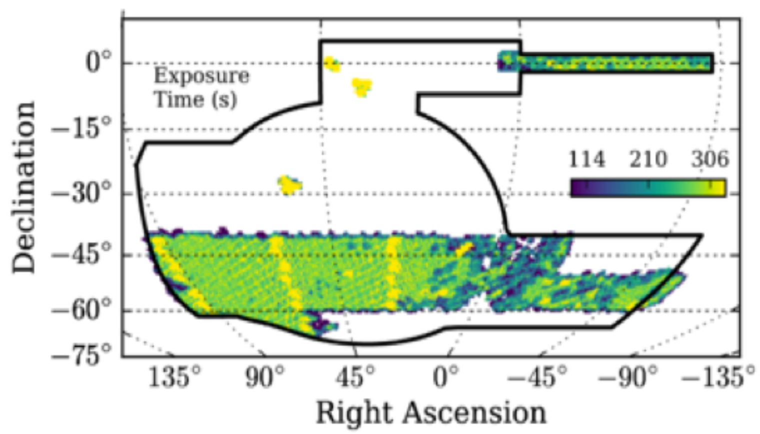
lensing x lensing:
cosmic shear

DES Year 1 Cosmology Analysis

- Angular clustering: autocorrelation of 660,000 luminous red galaxies with excellent photo-z's, in 5 redshift bins
- Cosmic shear weak lensing: shear-shear correlation functions from 26 million galaxy shapes in 4 redshift bins
- Galaxy-galaxy lensing: correlate red galaxy positions (foreground lenses) with source galaxy shear

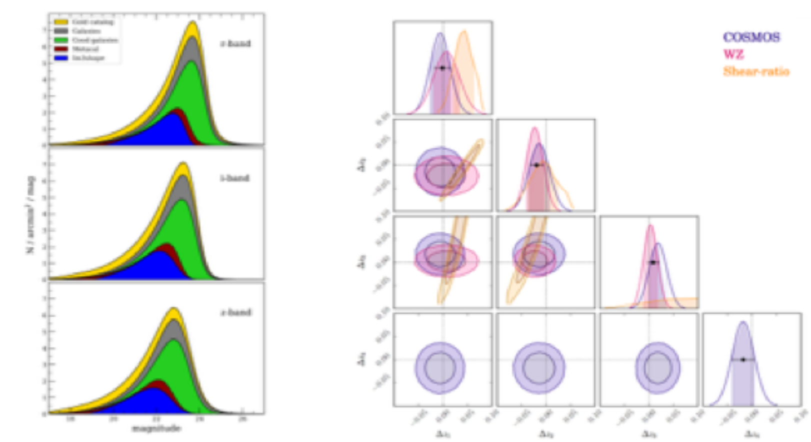
With great statistical power comes great systematic responsibility

Unprecedented size and depth of photometric data



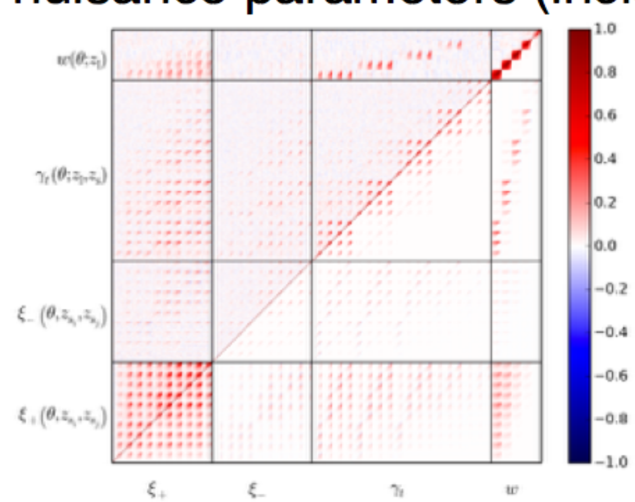
Drlica-Wagner, Rykoff, Sevilla+

Two independent shape & photo-z catalogs and calibrations

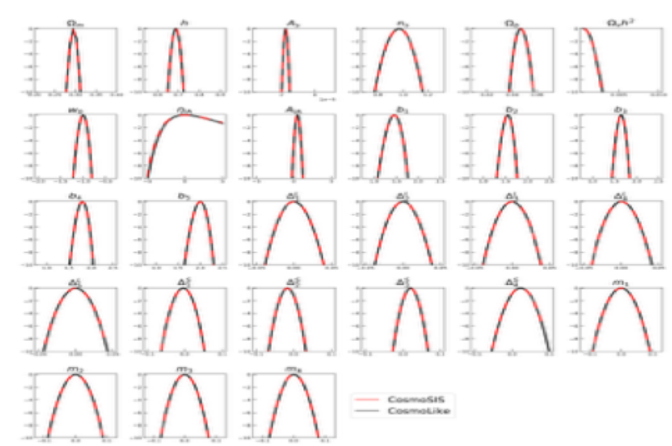


Zuntz, Sheldon+, Samuroff+
Cawthon+, Davis+, Gatti, Vielzeuf+, Hoyle, Gruen+

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+, MacCrann, DeRose+

Measurements: shear catalogs

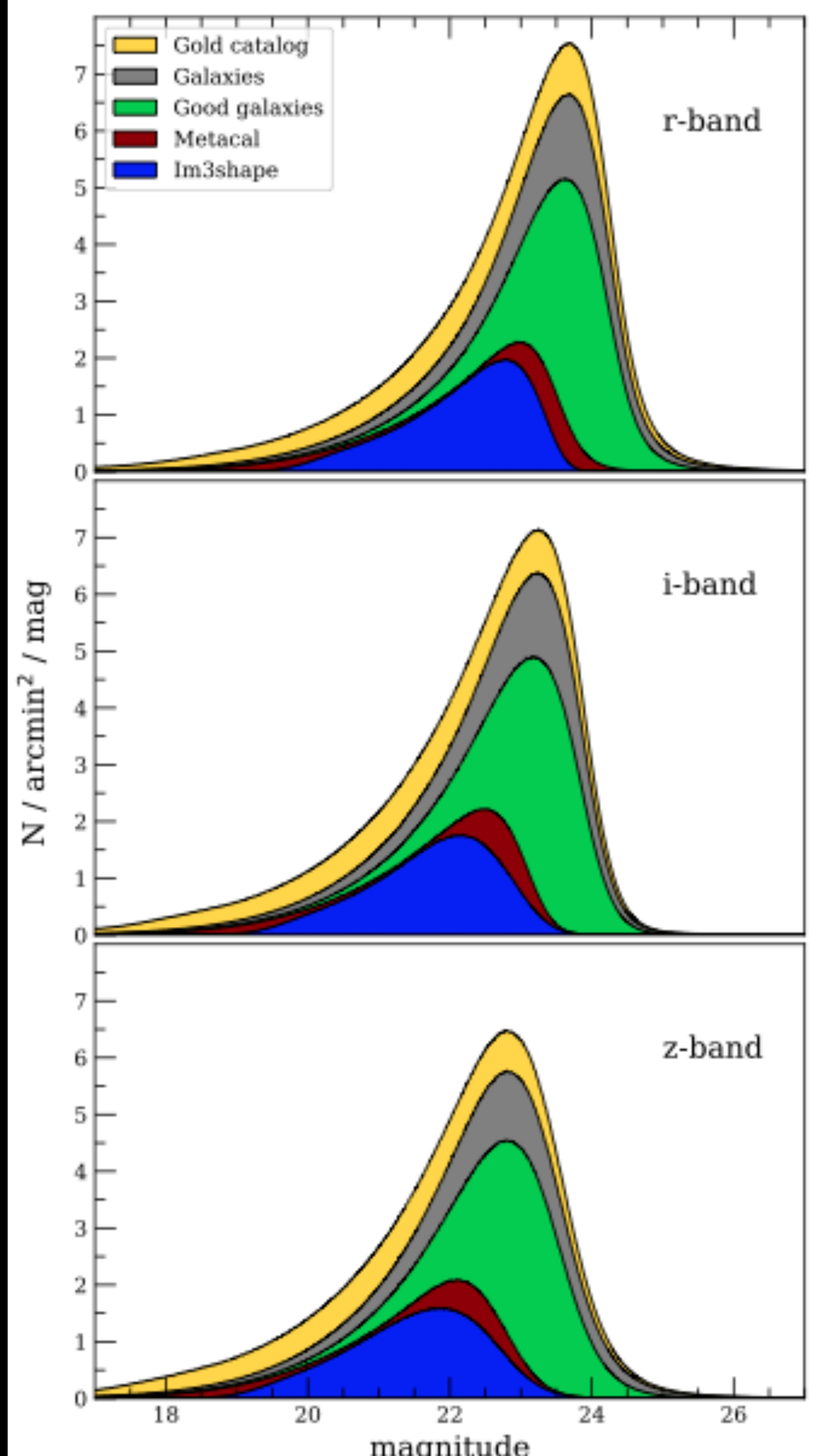
(Huff+17, Sheldon+17, Zuntz+17)

Metacalibration

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

im3shape

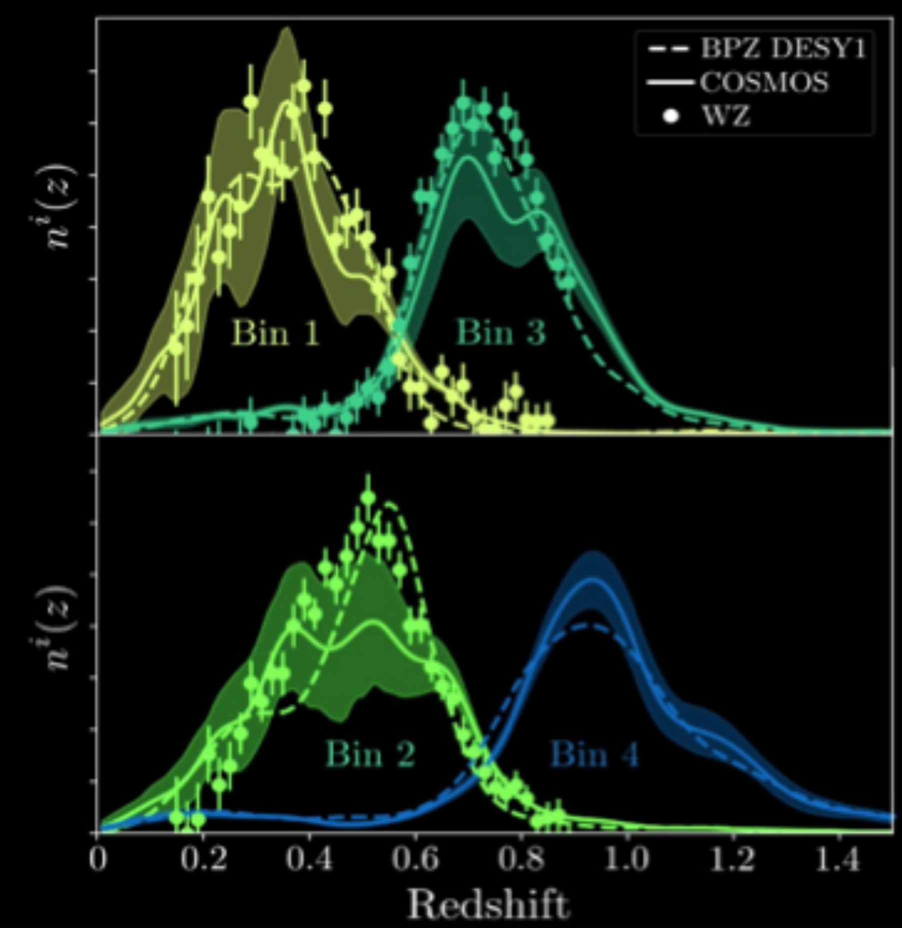
- Best-fit bulge & disc models, calibrated with simulations.
- Uses only r-band.
- 22 M galaxies (18 M for cosmology).



With great statistical power comes great systematic responsibility

- unprecedented combination of area and depth
- two independent galaxy shape measurements, including novel metacalibration algorithm
- two independent calibrations of photometric redshifts

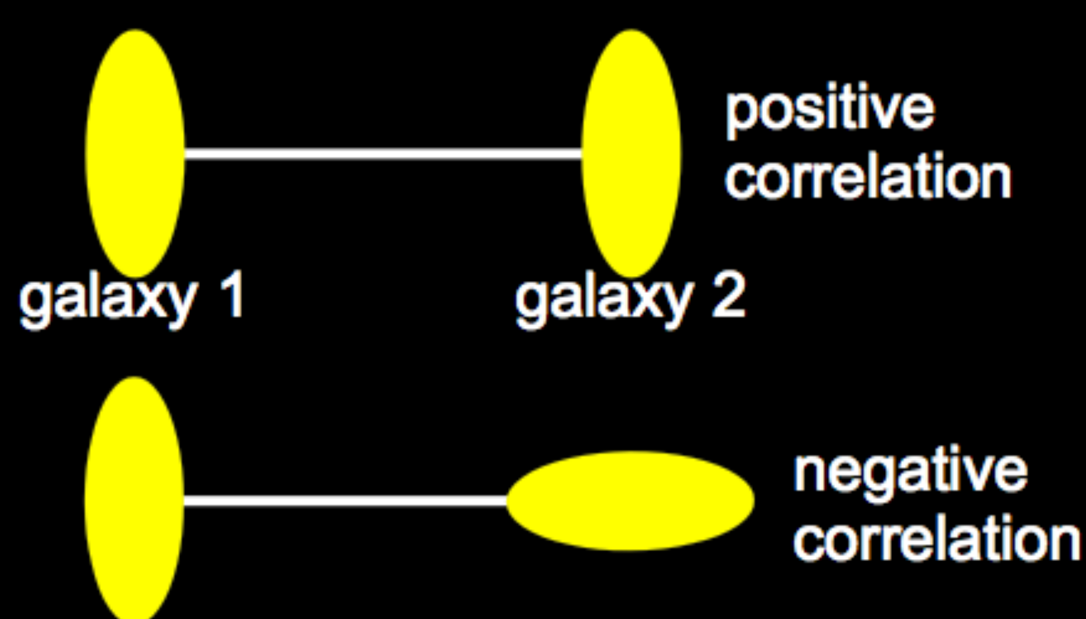
- Matching galaxy population to COSMOS galaxies with known redshift: Hoyle, **Gruen+** (1708.01532)
- Clustering of galaxy population with galaxies with known redshift: **Davis+** (1707.08256)
- Methods agree, ~0.015 joint errors!

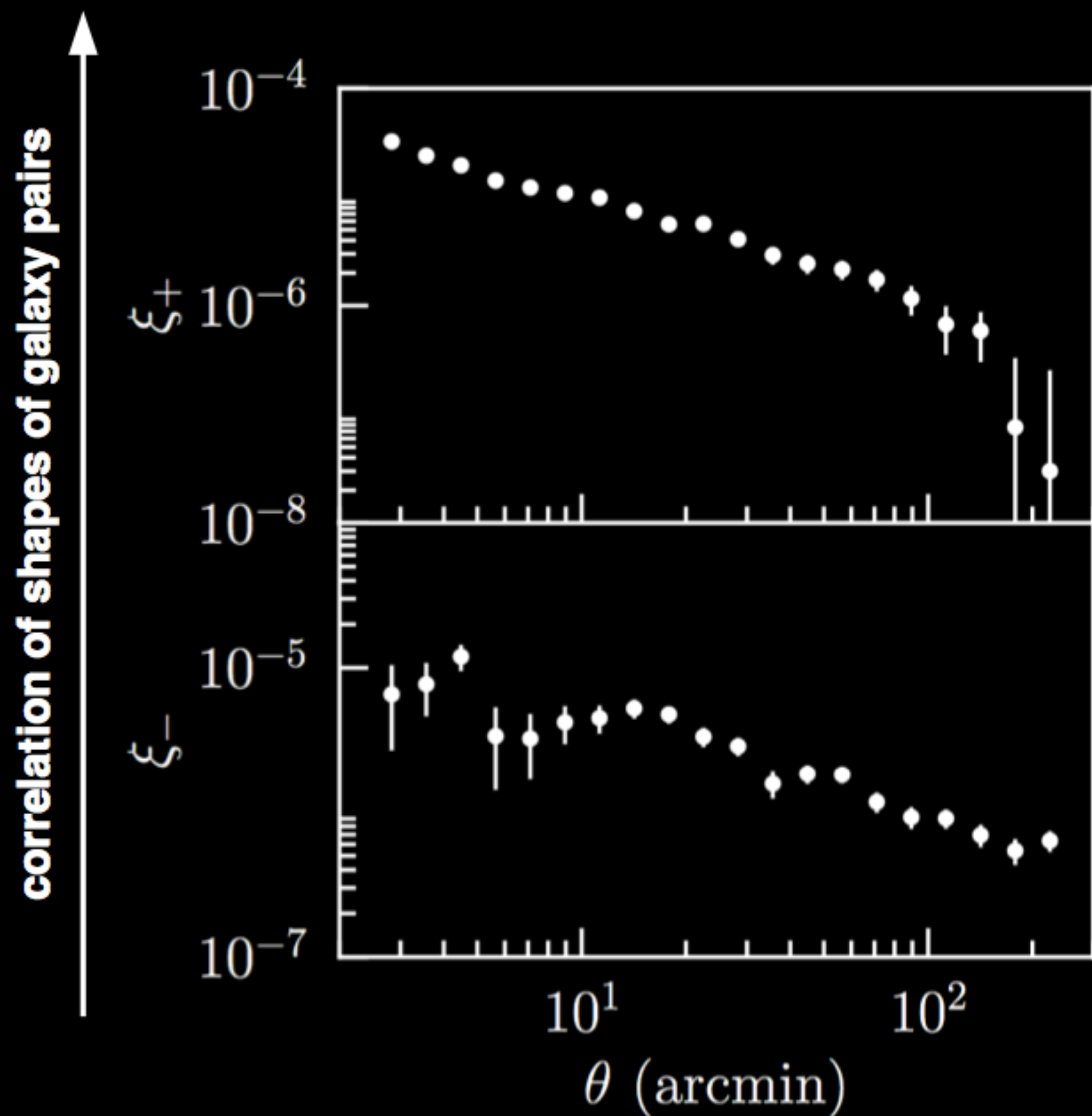


Measurements: cosmic shear

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



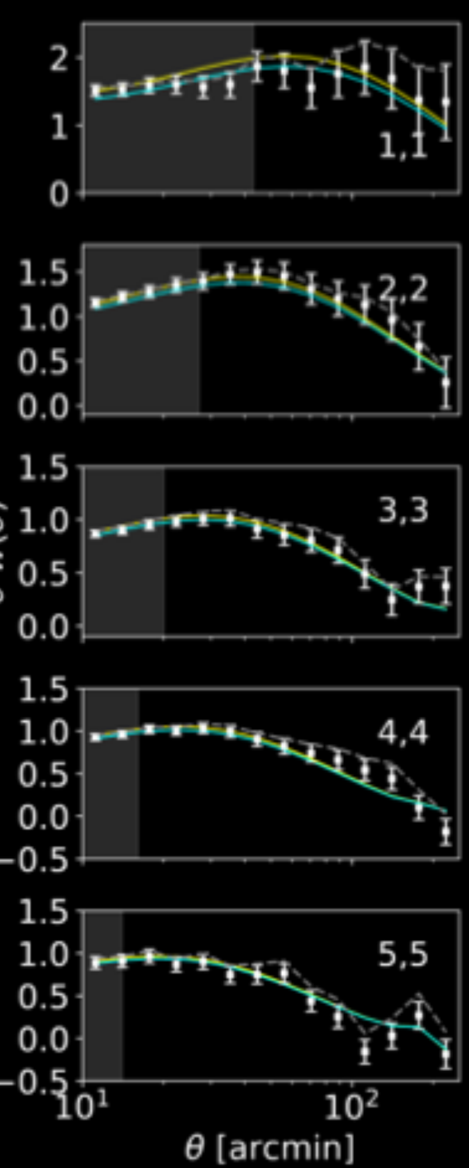


Measurements: galaxy clustering and galaxy-galaxy lensing

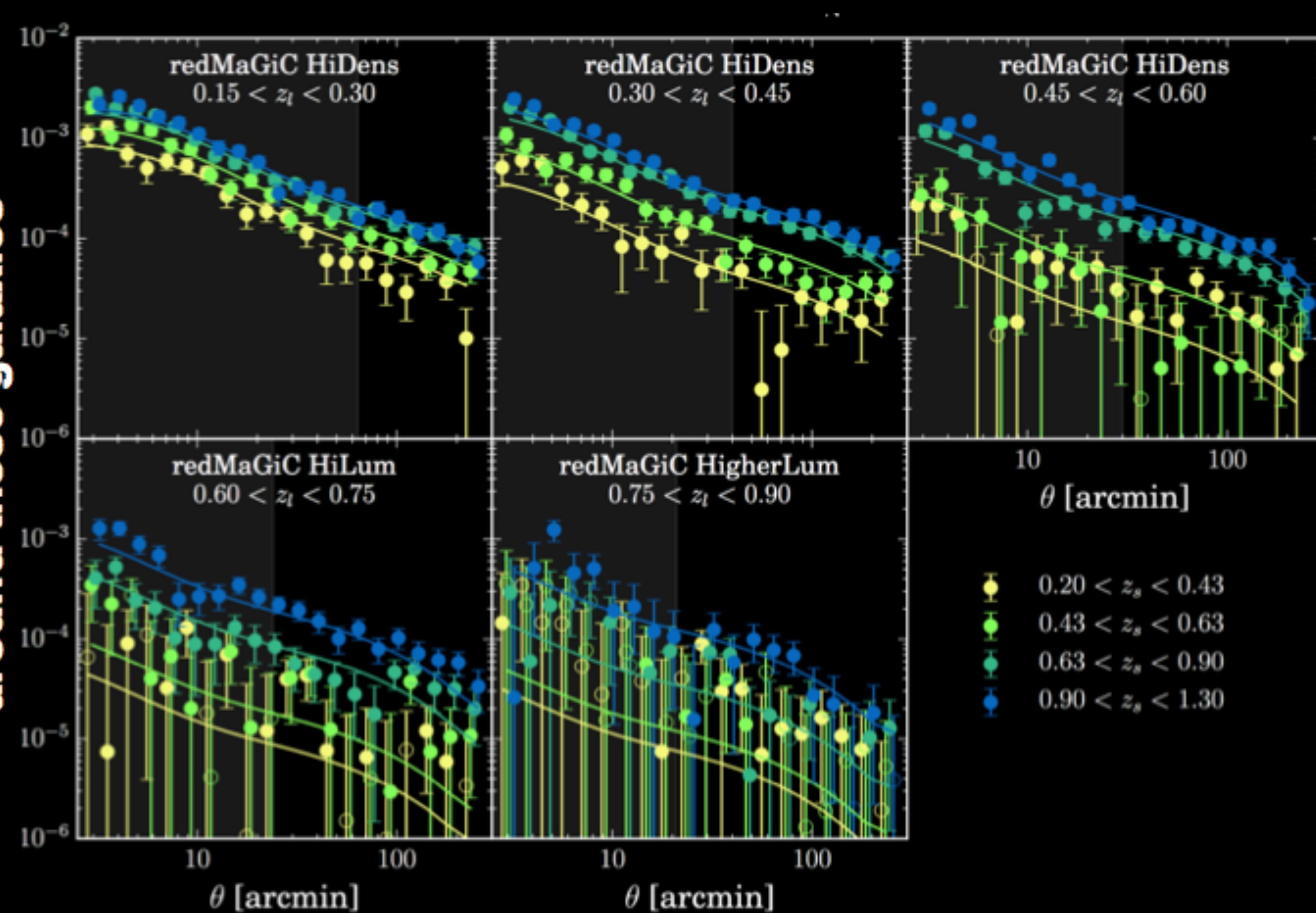
Elvin-Poole+ (1708.01536); Prat, Sanchez+ (1708.01537)

- Lens galaxies: redMaGiC LRGs with high-quality photometric redshift estimates

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

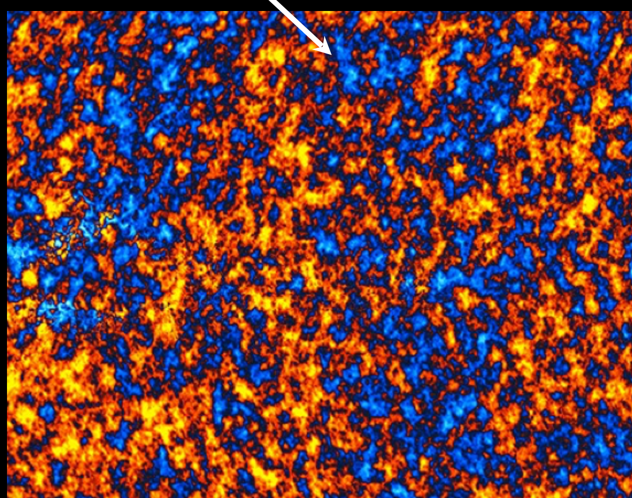


tangential gravitational shear around these galaxies

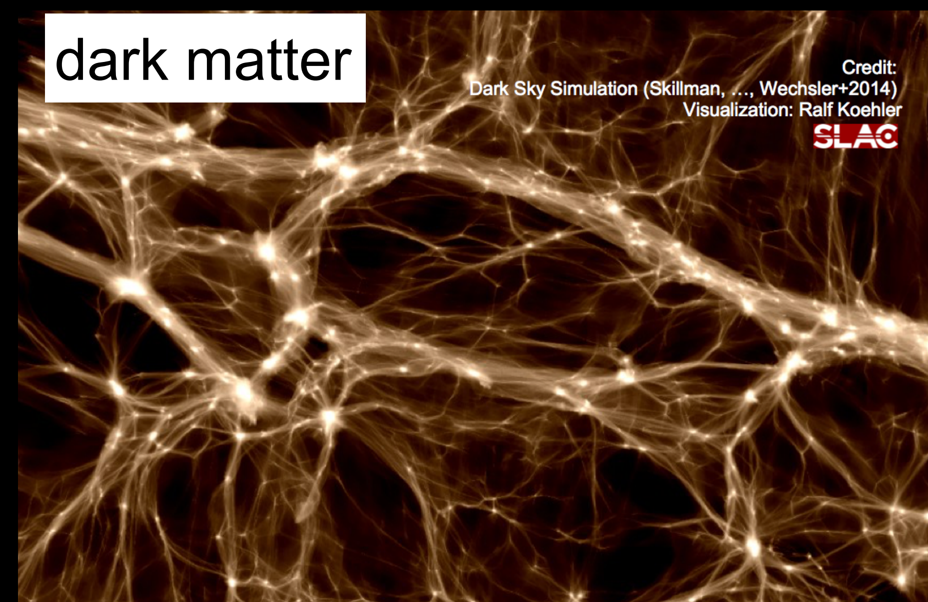


Cosmology Analysis: Modeling

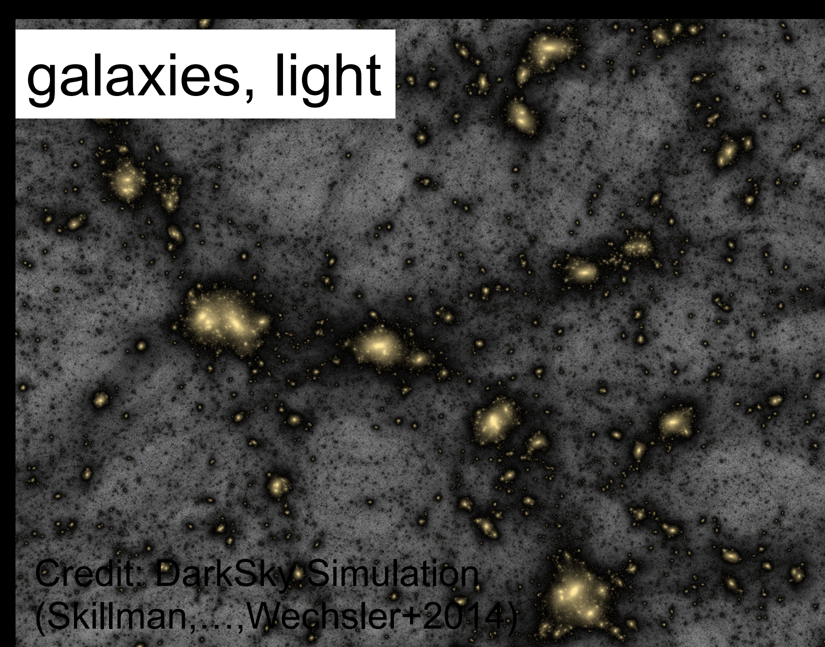
Cosmological model
+ model parameters



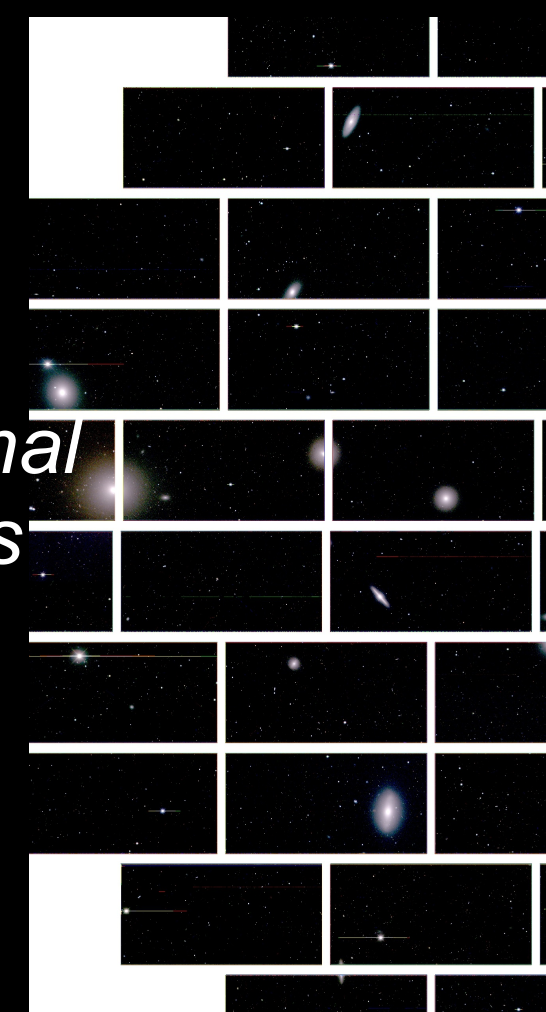
evolve



galaxy formation



observational systematics



Multi-Probe Methodology

from data vector D to parameters p

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

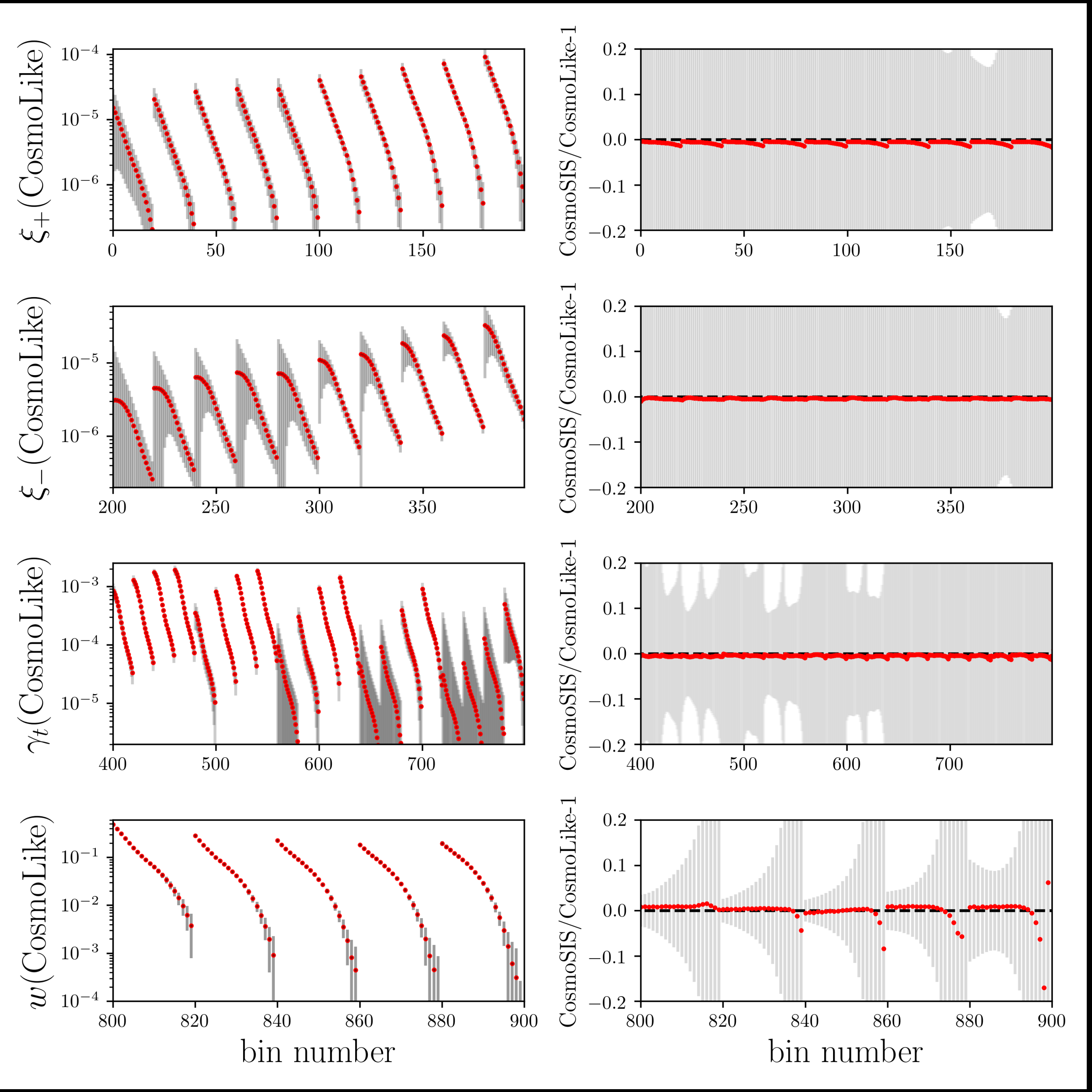
- model data vector, incl. relevant systematics
  - implementation details should not contribute to error budget
  - are the systematics parameterizations sufficient for DES-Y1?
- covariance for ~450 data points
- sampler - don't get the last step wrong...

methods paper: validate model + implementation, covariance, sampling

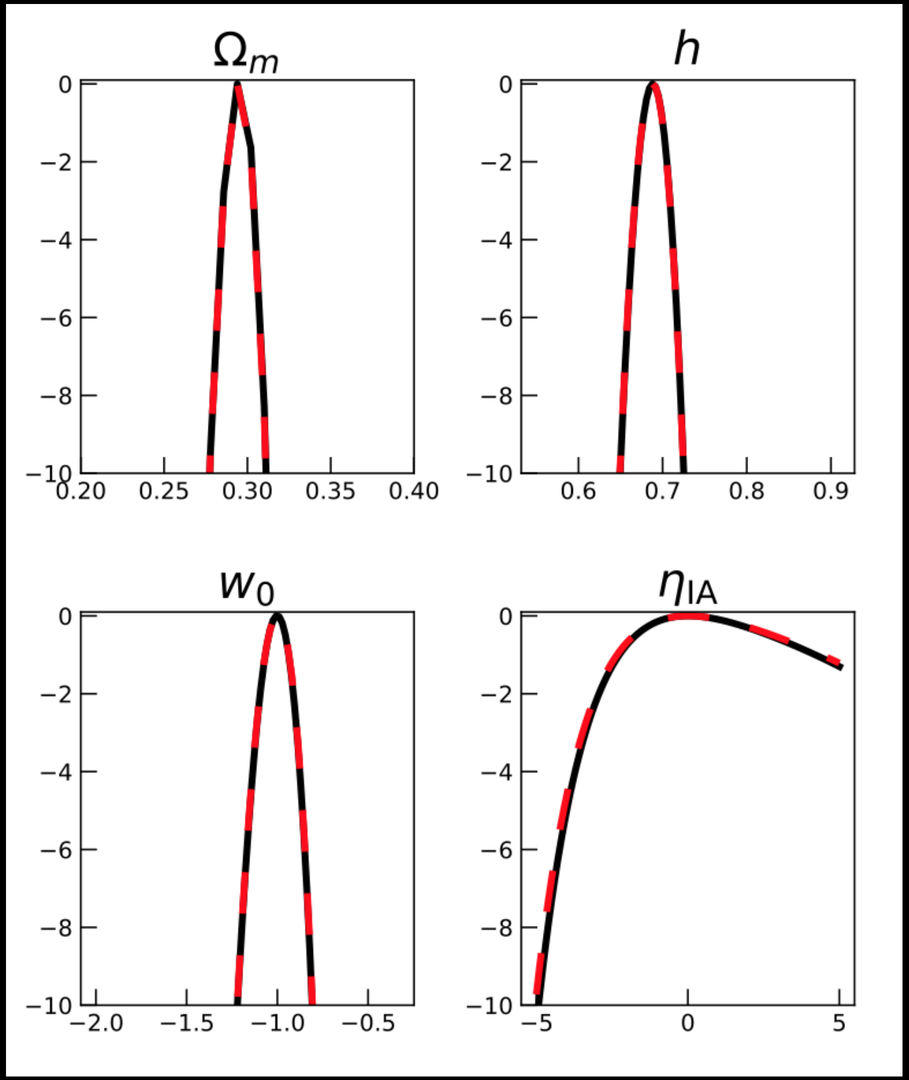
Krause, Eifler+ 1706.09359

Cosmology Pipeline Validation

data vector



log(L) for variation of 1 parameter



(+22 other parameters)

Systematics Modeling + Mitigation

baseline systematics marginalization (20 parameters)

- linear bias of lens galaxies, per lens z-bin
- lens galaxy photo-zs, per lens z-bin
- source galaxy photo-zs, per source z-bin
- multiplicative shear calibration, per source z-bin
- intrinsic alignments, power-law/free amplitude per per source z-bin

Krause, Eifler+ 1706.09359

Systematics Modeling + Mitigation

baseline systematics marginalization (20 parameters)

- linear bias of lens galaxies, per lens z-bin
- lens galaxy photo-zs, per lens z-bin
- source galaxy photo-zs, per source z-bin
- multiplicative shear calibration, per source z-bin
- intrinsic alignments, power-law/free amplitude per per source z-bin

-> this list is known to be incomplete

how much will known, unaccounted-for systematics bias Y1 results?

-> choice of parameterizations ≠ universal truth

are these parameterizations sufficiently flexible for Y1 analyses?

Krause, Eifler+ 1706.09359

Angular Scale Cuts: remove known, unaccounted-for systematics

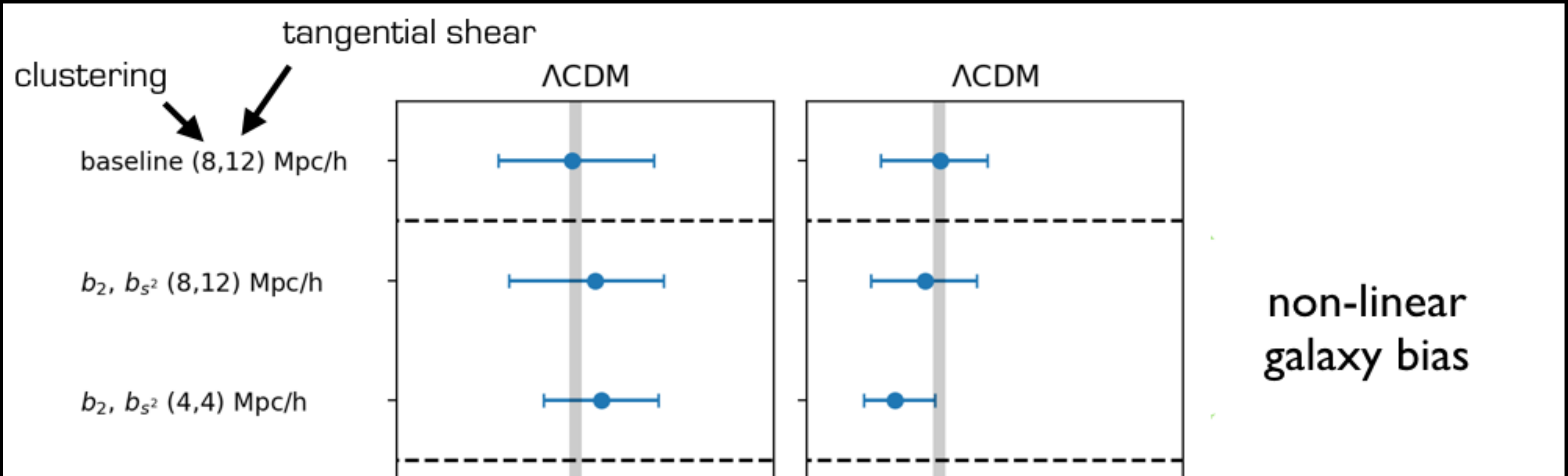
-> this list is known to be incomplete

how much will known, unaccounted-for systematics bias Y1 results?

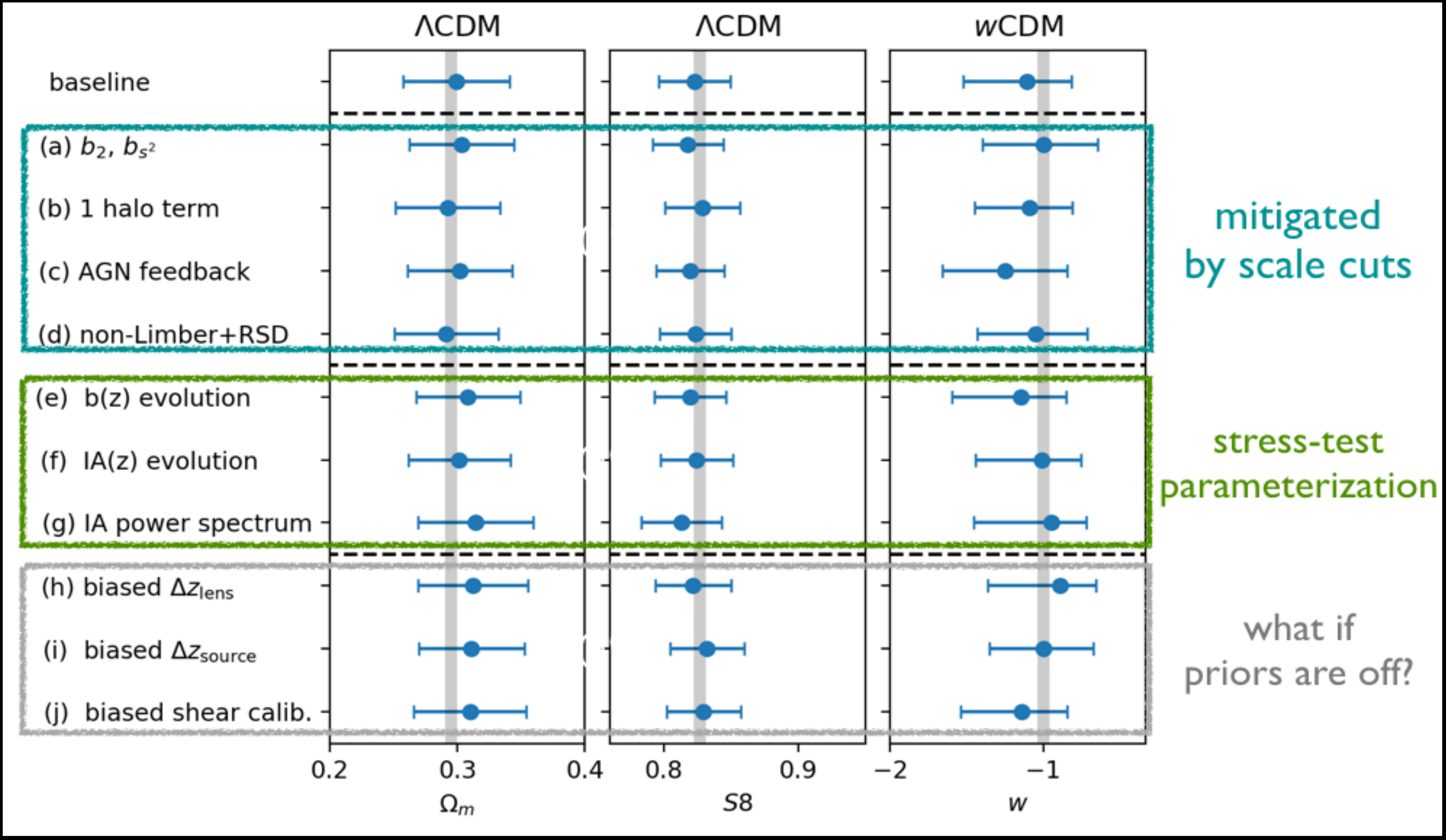
Example: generate input 'data' incl. 2nd order galaxy bias

enhances clustering signal on small physical scales

determine scale cuts to minimize parameter biases



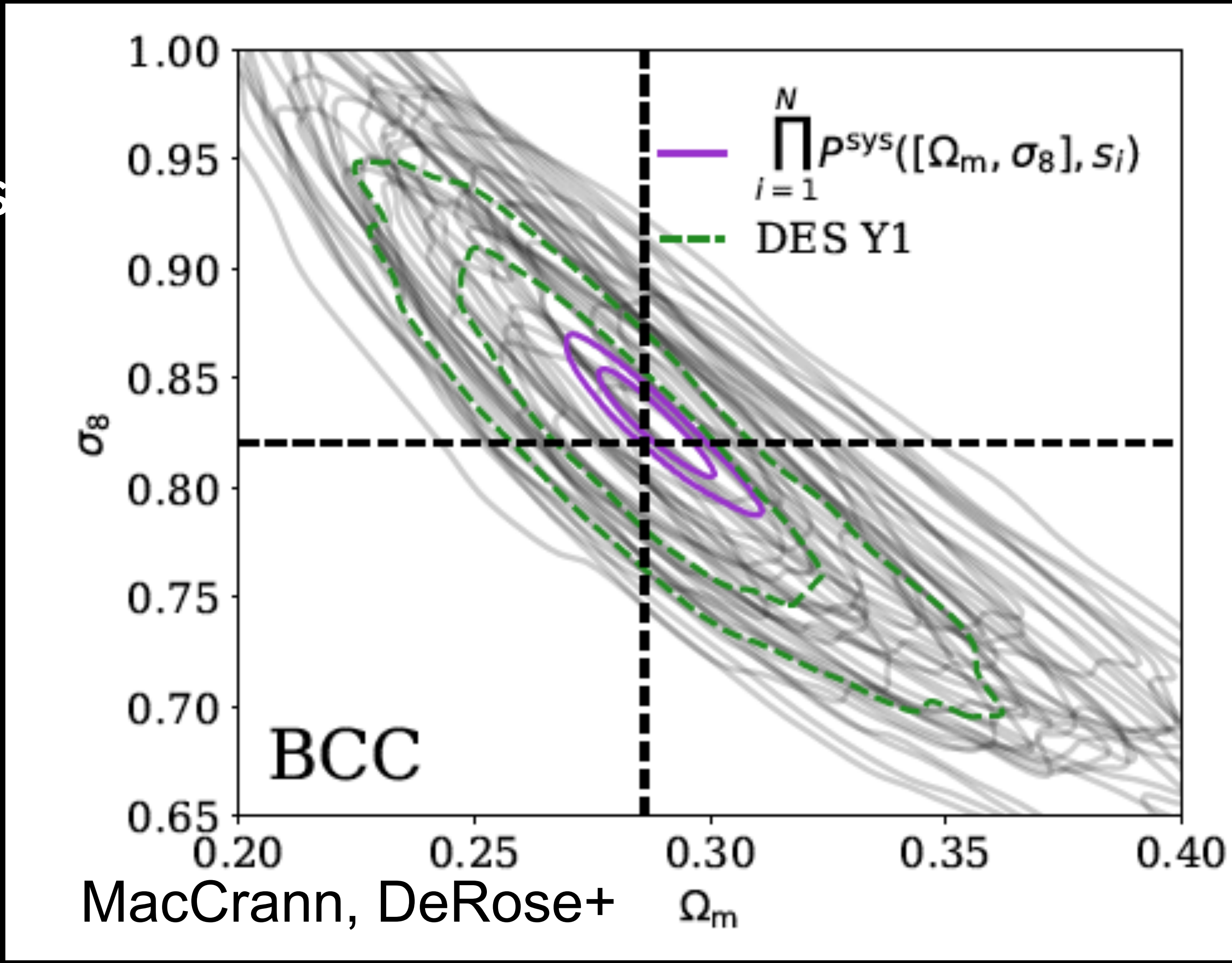
Systematics Mitigation: imperfect parameterizations



Analysis Validation: Mock Catalogs -> Cosmology

DeRose+ (in prep.):
Realistic DES mock catalogs including galaxy properties and DES-specific observational effects

MacCrann, DeRose+ 2018:
- Measure 3x2pt on mock catalogs (with known cosmology)
- Analyze with DES cosmology pipeline
- Recover input cosmology!



Covariance Validation

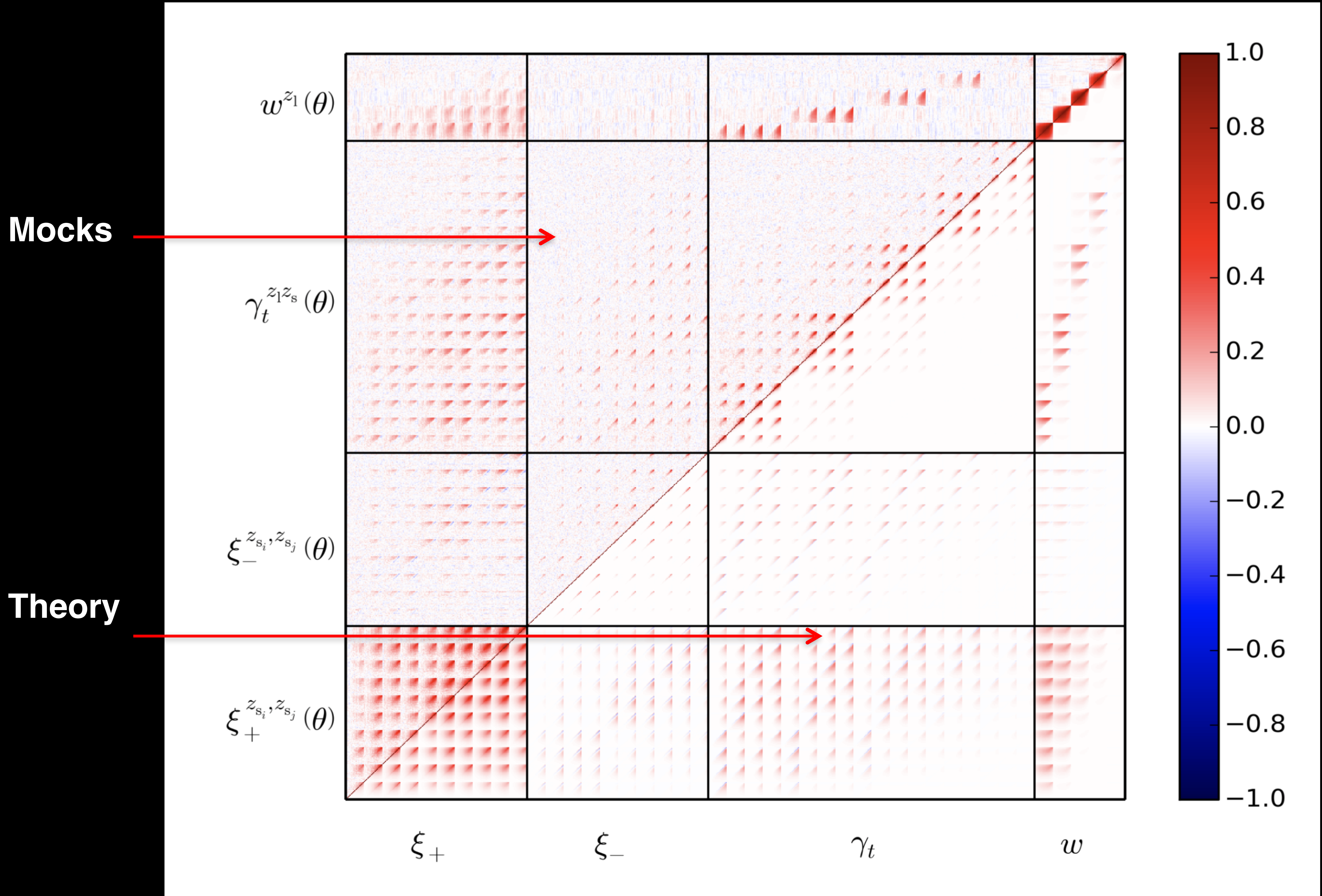
Oliver Friedrich, Lucas Seco, Nick Kokron, Rogerio Rosenfeld, many others

DES-Y1 analysis uses halo model covariance matrix

- Validation method:
  - produce 1200 DES-like areas mocks with different geometries: circular and DES-like mask
  - estimate covariance matrix from these mocks

- Validation metric:
  - parameter uncertainties, determined in simulated analyses

Covariance Validation



Multi-Probe Blinding

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)

DES Collaboration 1708.01530

Multi-Probe Blinding

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)

Post-Unblinding Updates

- shear catalog blinding removed by meta-calibration
  - best-kept secret in DES

- include survey footprint in shot/shape noise model
  - updates to evidence ratios, χ^2
    - χ^2/dof =1.16
  - parameter values ~unaffected

DES Collaboration 1708.01530

When to Combine Probes?

- Adopted Bayesian Evidence Ratio R as criterion to compare hypotheses H_0 and H_1

$$R = \frac{P(\mathbf{D}|H_0)}{P(\mathbf{D}|H_1)} = \frac{P(H_0|\mathbf{D})\,P(H_1)}{P(H_1|\mathbf{D})\,P(H_0)}$$

equal prior on H_0, H_1

- H_0 is favored with R:1 odds over H_1 .
- Jeffreys scale: R > 3.2 substantial evidence, R > 10 strong evidence
- For combining probes:

H_0 = 'data sets described by same model parameters'

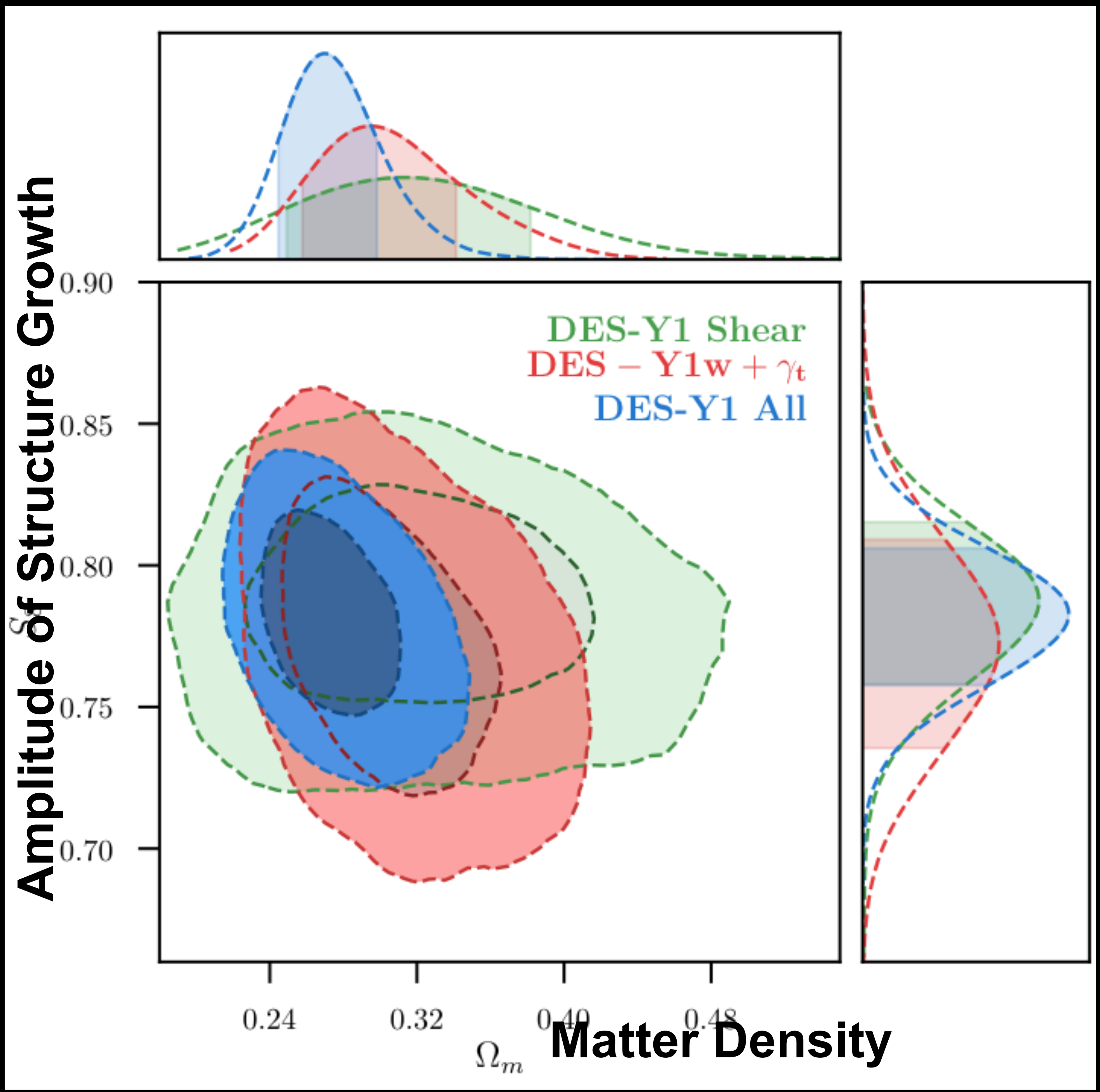
H_1 = 'data sets described by different model parameters

$$R = \frac{P(\mathbf{D_1}, \mathbf{D_2}|H)}{P(\mathbf{D_1}|H)P(\mathbf{D_2}|H)}$$

Combine iff R > 0.1

(R< 0.1: strong evidence for inconsistency)

Multi-Probe Constraints: LCDM



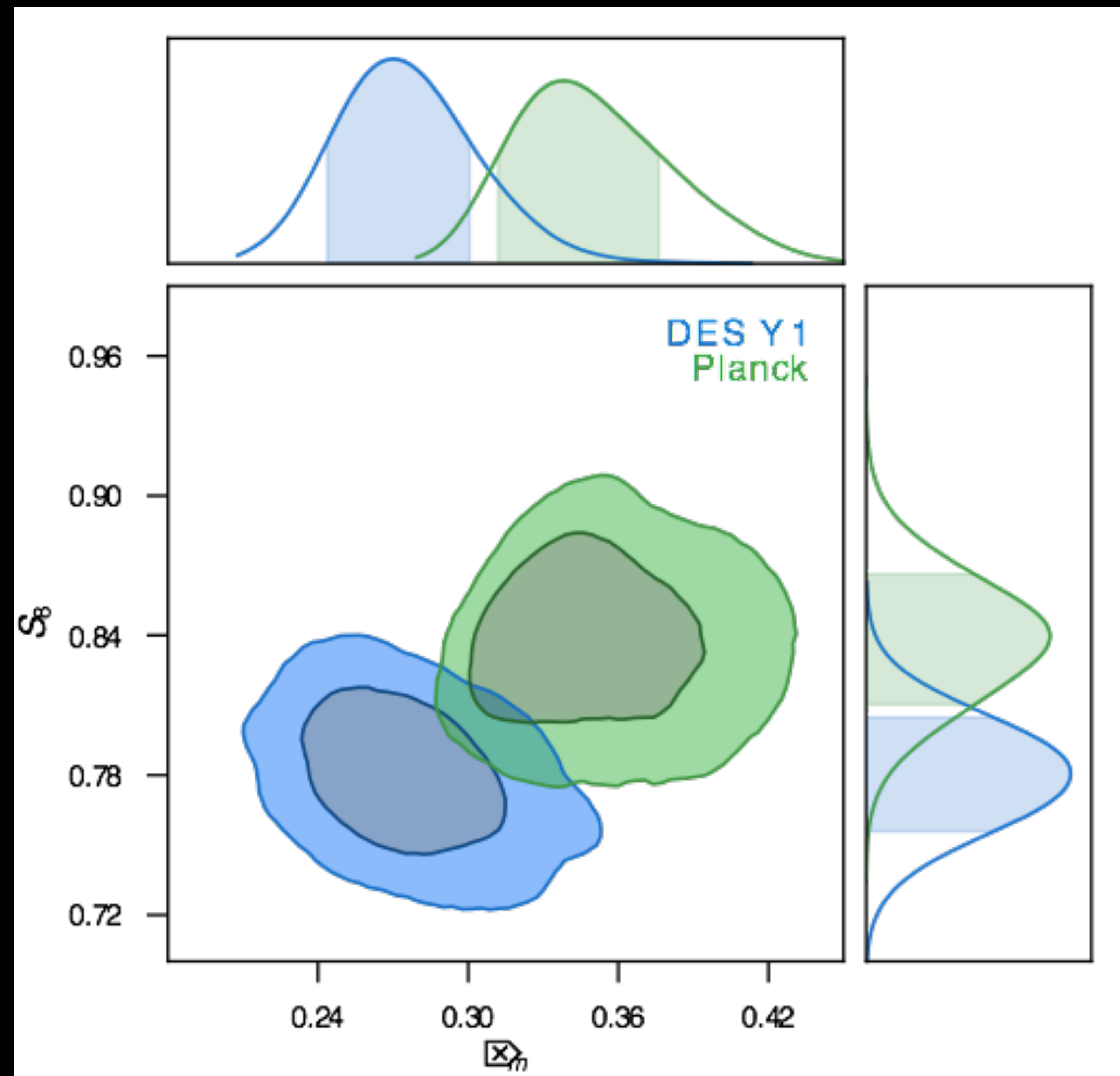
- DES-Y1 most stringent constraints from weak lensing
- marginalized 4 cosmology parameters, 10 clustering nuisance parameters, and 10 lensing nuisance parameters
- consistent (R = 583) cosmology constraints from weak lensing and clustering in configuration space

DES Collaboration 1708.01530
(numbers from revised version)

Comparison of DES 3x2 with Planck CMB: low-z vs high-z in ΛCDM

- note: contours marginalized over M_ν=[0.06,1]eV
- DES-3x2pt and Planck (TT+lowP, without CMB lensing) constrain S8 and Ω_m with comparable strength
- Central values differ by >1σ, in same direction as KiDS
- Bayes factor R = 6.6, “substantial” evidence for consistency in ΛCDM

Amplitude of Structure Growth



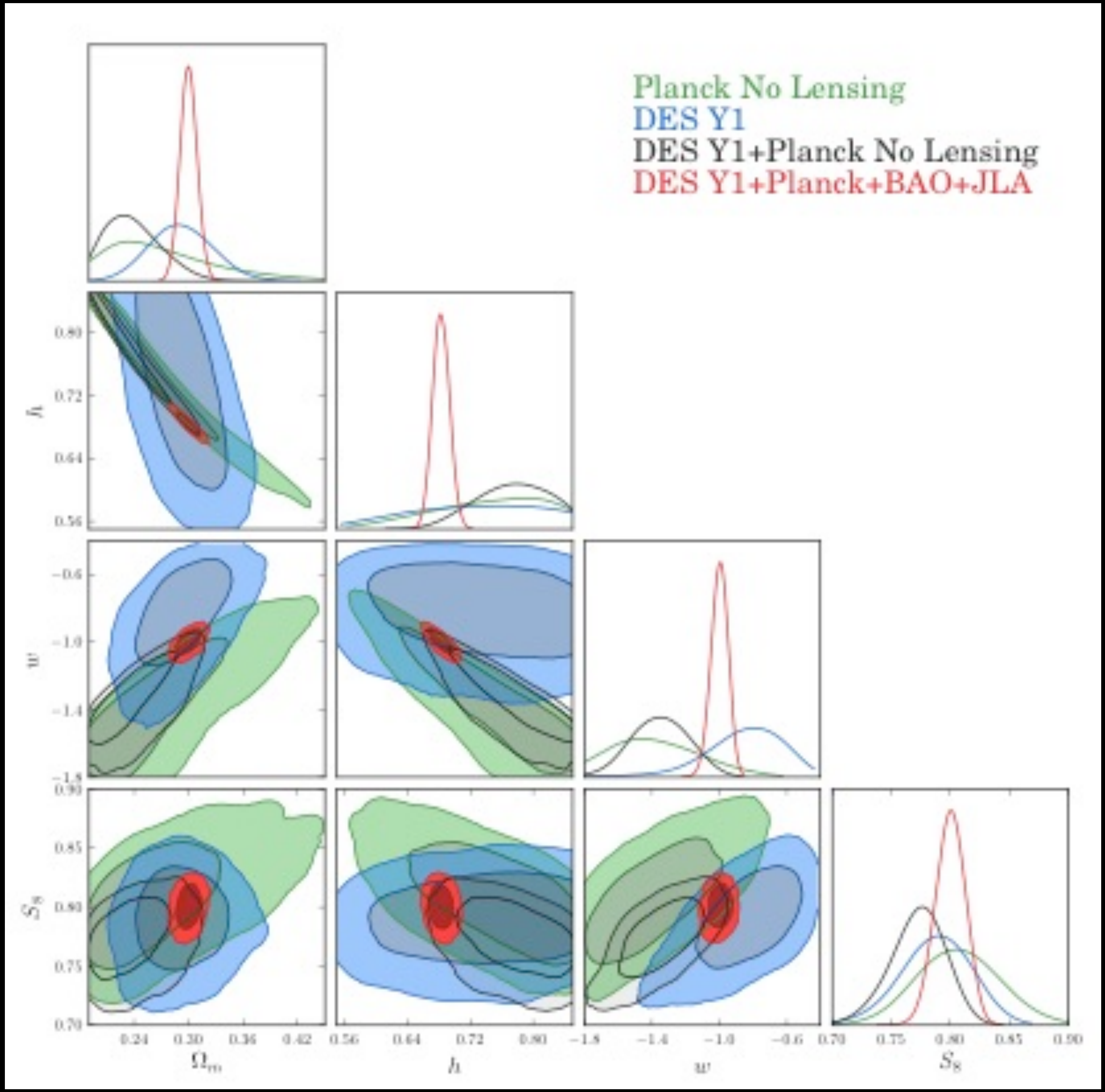
Matter Density

DES Collaboration 1708.01530
(numbers from revised version)

Combine multiple data sets: wCDM

- DES-3x2pt+Planck does not favor wCDM
- (w,h, M_ν) highly degenerate for DES-3x2pt/Planck alone
- DES-3x2pt+BAO+SN consistent with Planck in wCDM
- combination disfavors wCMD (R_w =0.1), yields

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

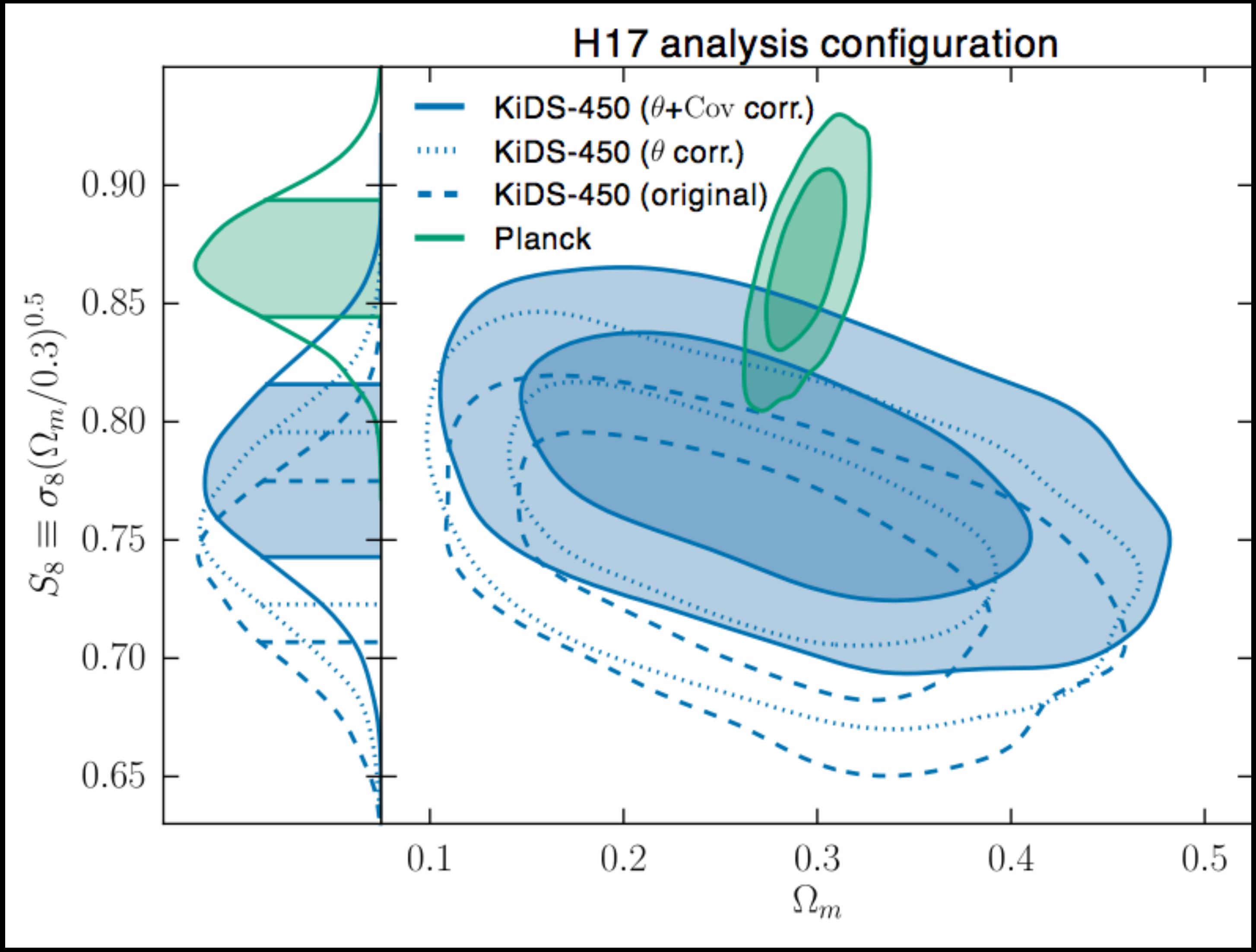


DES Collaboration 1708.01530 – revised numbers

Consistency of Cosmic Shear Measurements

- applied shape noise correction from DES-Y1 revision to KiDS-450 (Hildebrandt+2017)
  - **χ^2 = 121 (118 dof)**

    before: χ^2 =161
- updated marginalization of multiplicative shear calibration
- applied known update to effective angular bin centers

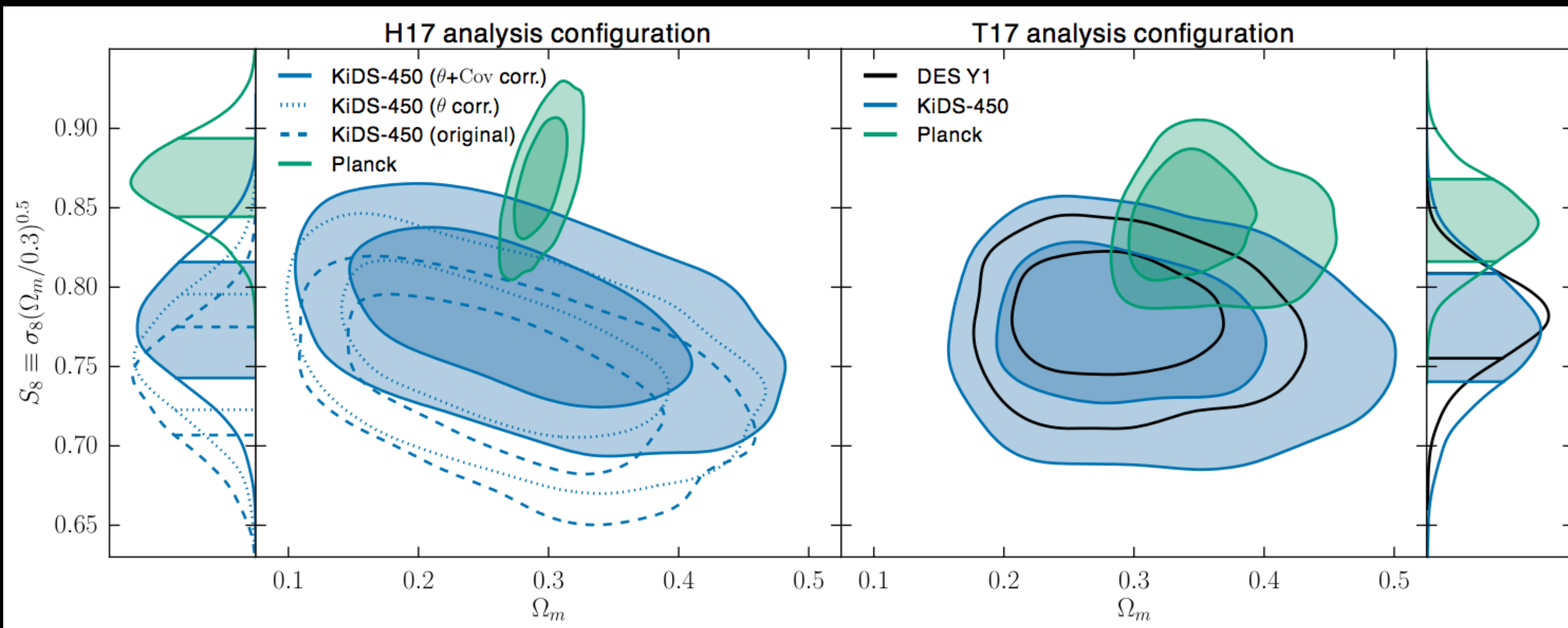


Troxel, Krause+ 1804.10663

Consistency of Cosmic Shear Measurements

Modeling, priors + scale cuts as in KiDS-450 (Hildebrandt+ 2017)

Modeling, priors + scale cuts as in DES-Y1 (Troxel+ 2017)



Troxel, Krause+ 1804.10663

Conclusions

- LCDM is a minimal and robust model and hard to break
- Only ~2 sigma tensions (except for perhaps H_0), e.g. DES Y1 results consistent with Planck CMB in ΛCDM.
- DES Y1 has published 20 papers on the first 20% of the total DES volume -> 60% data volume analysis is ongoing
- Information gain for DES will not just come from data volume but even more so from methodology… it's early days for optical multi-probe analyses
- The future with JWST, LSST, Euclid, WFIRST, DESI, 4MOST, ELTs, and many others optical/NIR instruments is extremely **exciting/challenging** for cosmology