Dark Energy Survey Year 1 Results

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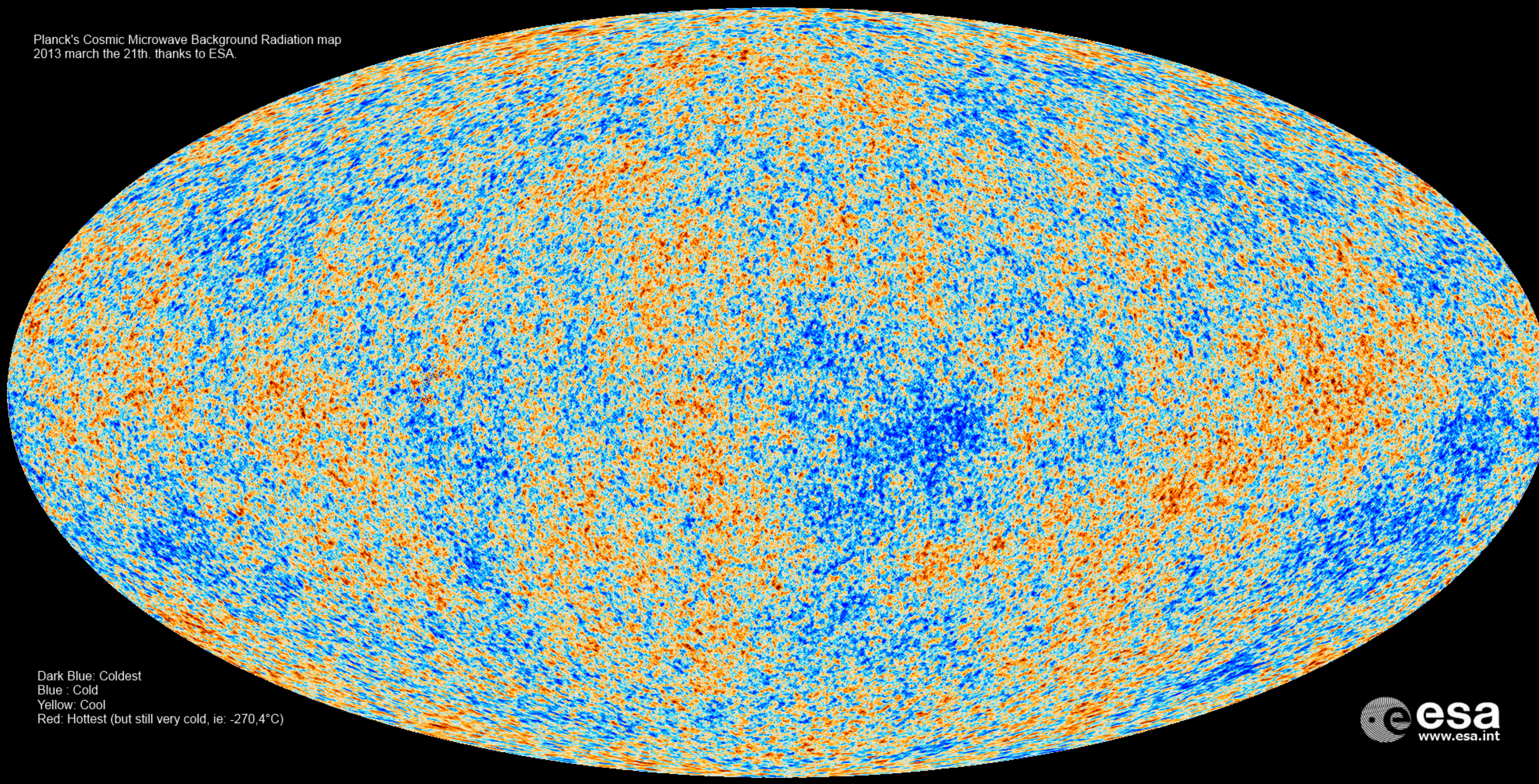
Cosmology 2017: ΛCDM

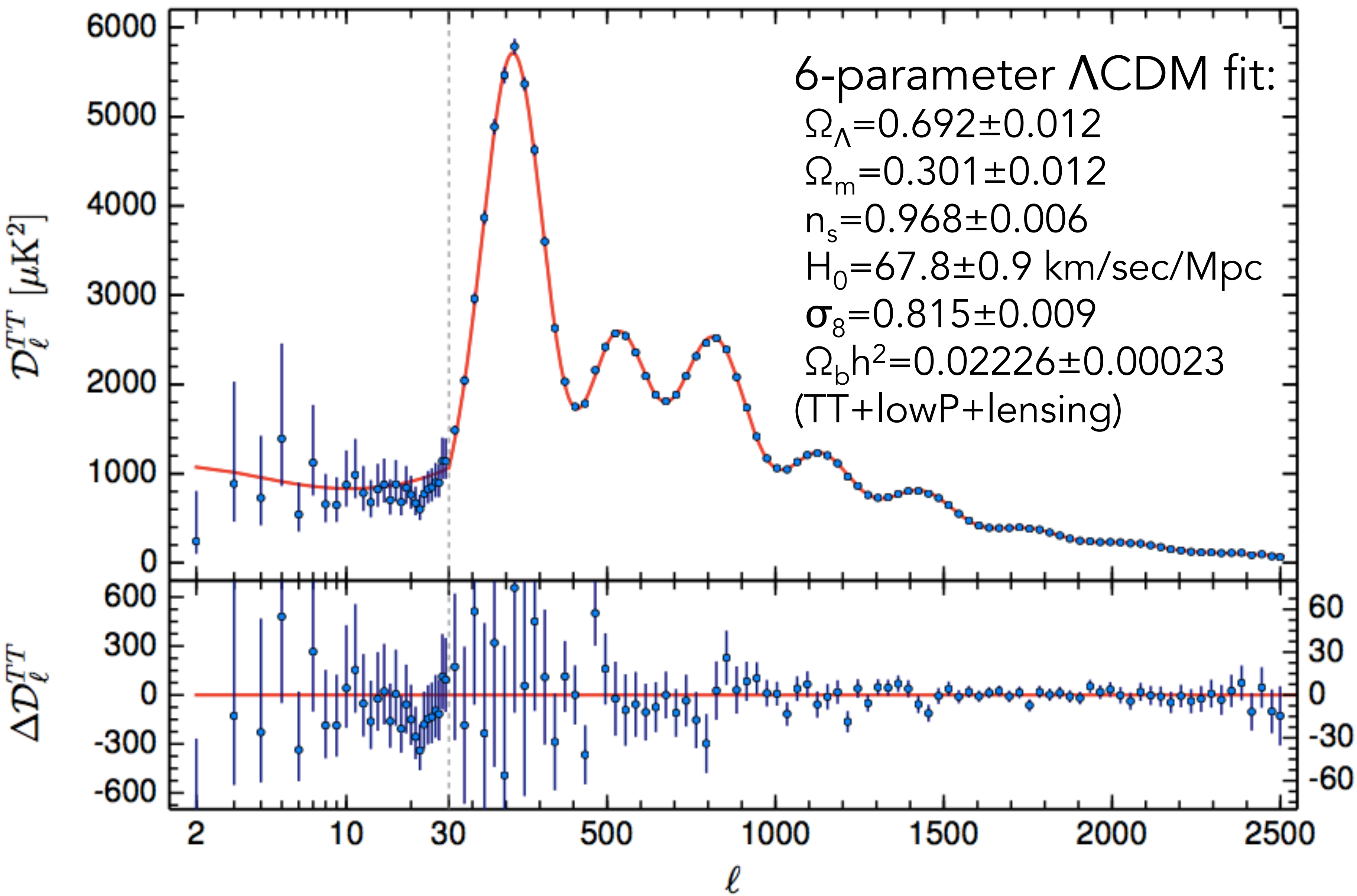
- A well-tested (6-parameter) cosmological model:
  - Universe is expanding from hot, dense early phase (Big Bang) 13.8 Gyr ago.
  - Early epoch of accelerated expansion (inflation) produced nearly flat & smooth spatial geometry and generated large-scale density perturbations from quantum fluctuations
  - From these, structure formed from gravitational instability of cold dark matter (CDM, 25%) in currently Λ-dominated (70%) universe, which is again accelerating.
- Consistent with all data from the CMB, large-scale structure, lensing, supernovae, clusters, light element abundances (BBN), …

Planck CMB Temperature Map

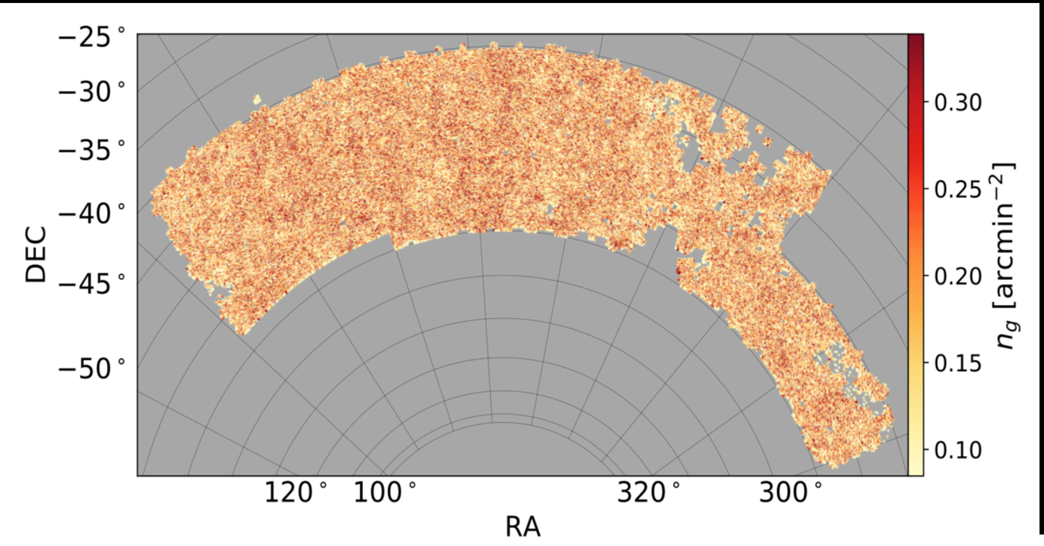


Fluctuations ~1 part in 10^5 at 380,000 years

Planck 2015 Results

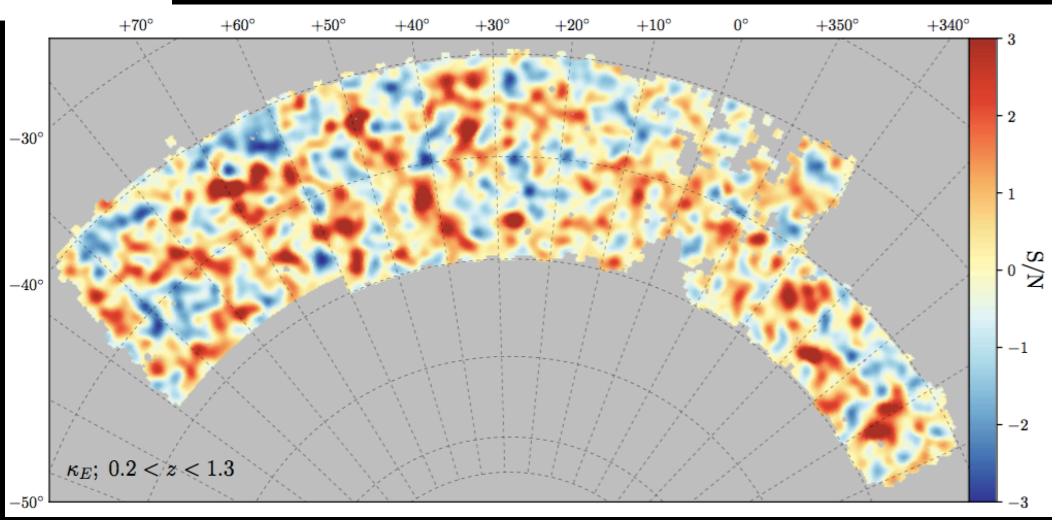


DES Year 1 Maps of Cosmic Structure



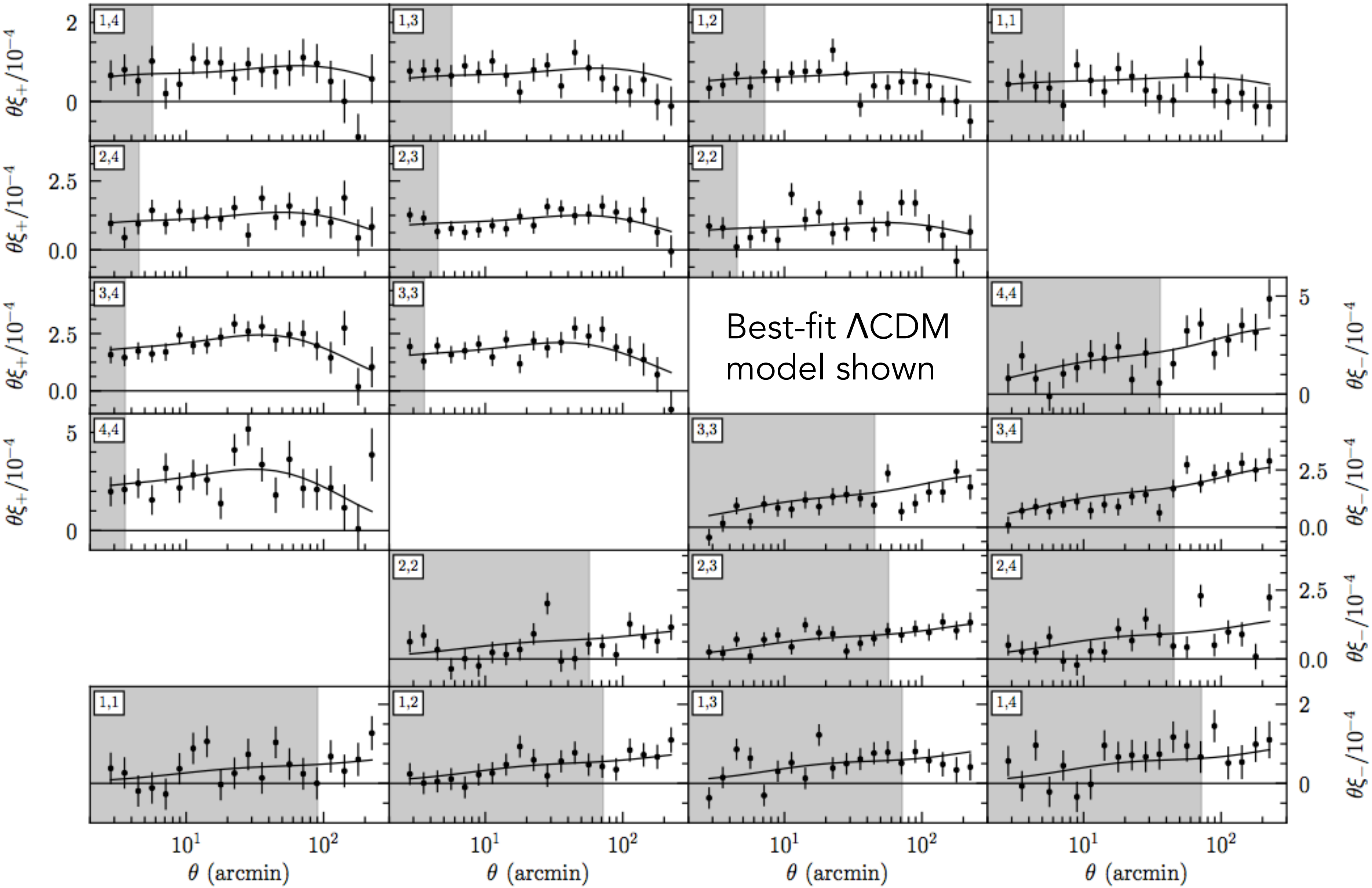
- Weak lensing mass map based on shapes of 26 million source galaxies (Chang, et al)

- 660,000 red galaxies with precise photometric redshifts (Elvin-Poole, et al)



First Year of Data: ~1800 sq. deg. out of 5000 for full survey

DES Year 1 Cosmic Shear Results



Fluctuations ~1 at 10 Gyr

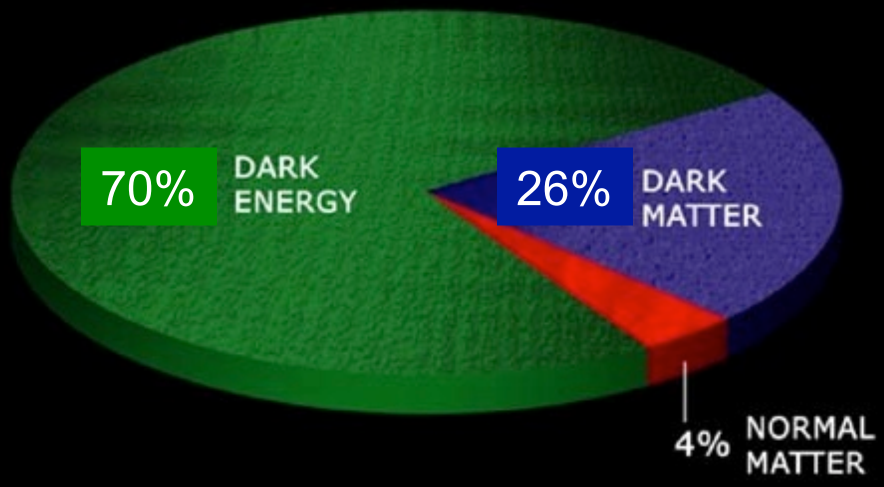
Troxel, et al

Probing the Cosmological Paradigm

- ΛCDM rests on physics beyond the Standard Model:
  - Inflation, dark energy, dark matter
- Understanding this physics constitutes 2 of the P5 science drivers (they bundled two of them).
- Are these 6 parameters all we need?
  - spatial curvature, m_ν, w [w_0, w_a], modified gravity,…
  - Tensions? Planck vs local H_0, Planck vs WL σ_8

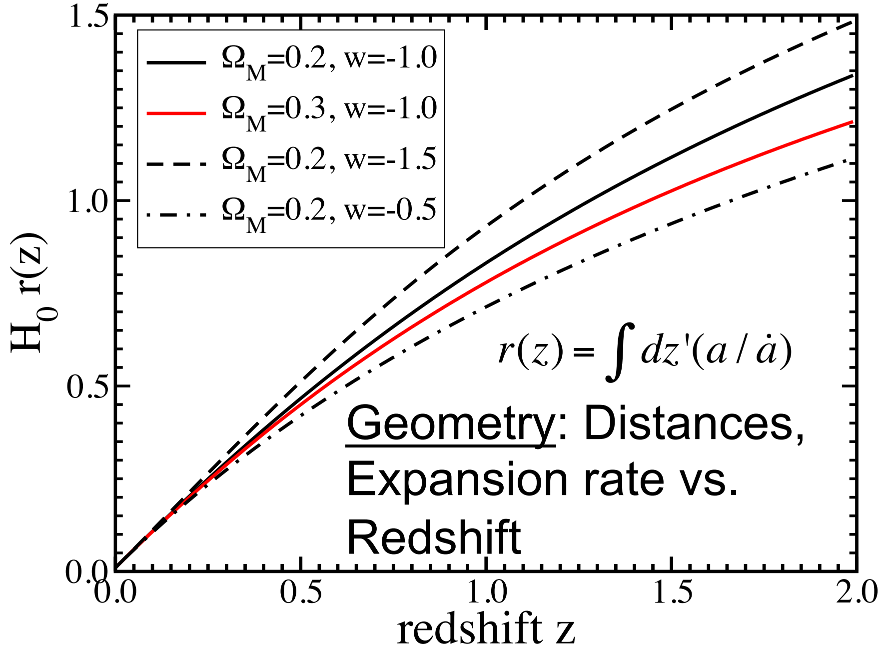
What is the physics of cosmic acceleration?

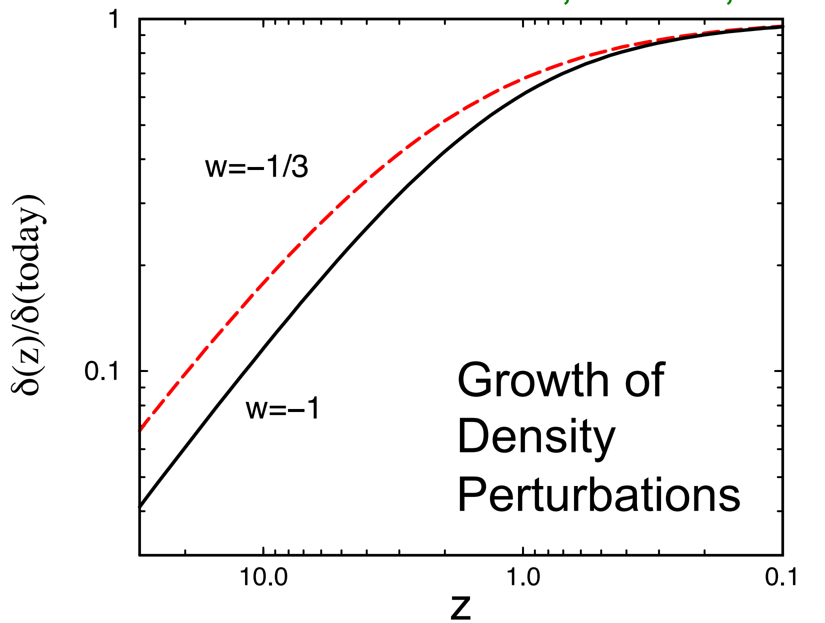
- Dark Energy or modification of General Relativity?
  - If Dark Energy, is it Λ (the vacuum) or something else?
    - What is the DE equation of state parameter w and (how) does it evolve? (For Λ, $w = -1$.)



What can we probe?

JF, Turner, Huterer



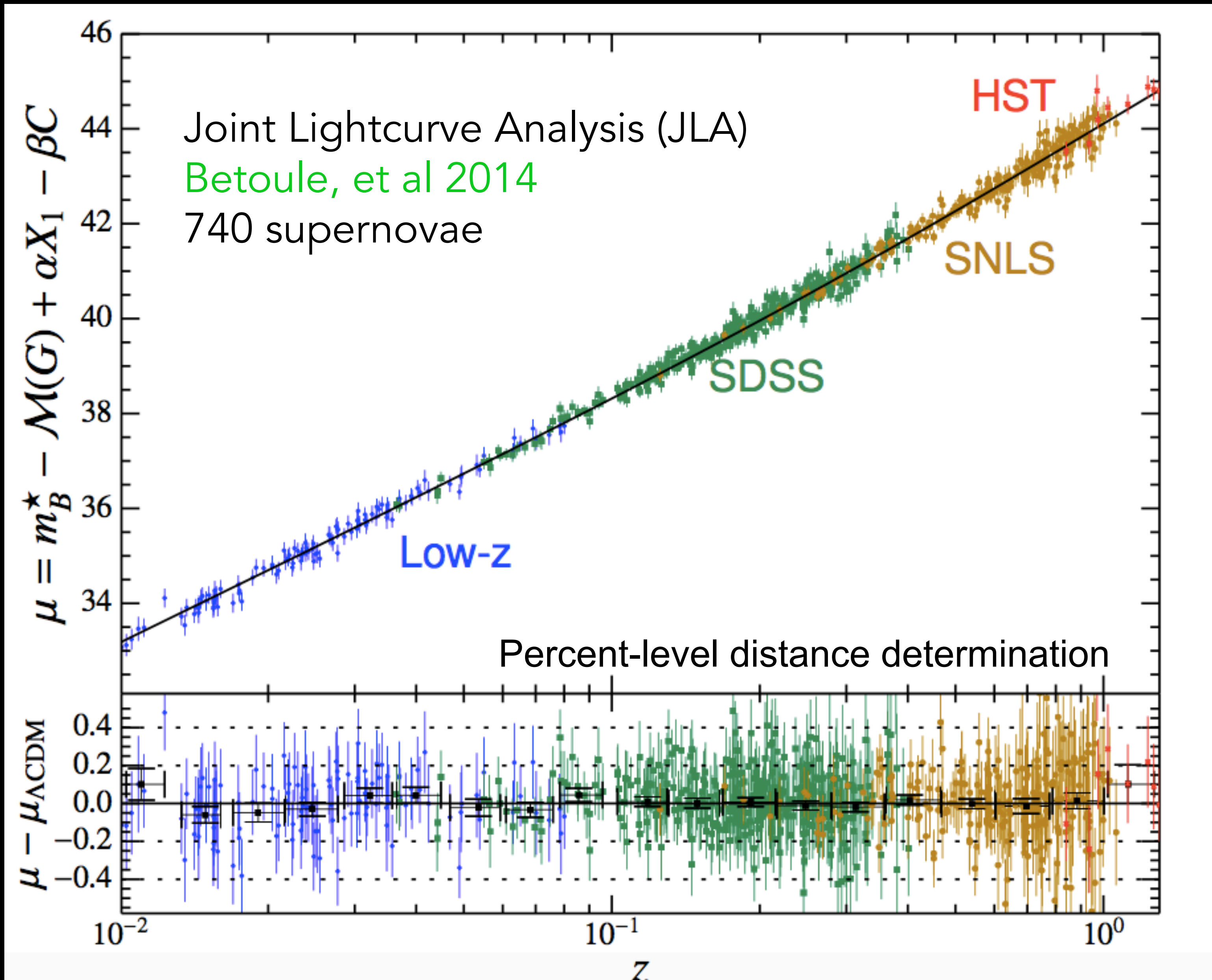


Expansion History

Growth of Structure

Require both to distinguish Dark Energy from Modified Gravity.
Aiming toward %-level measurements of geometry & structure.

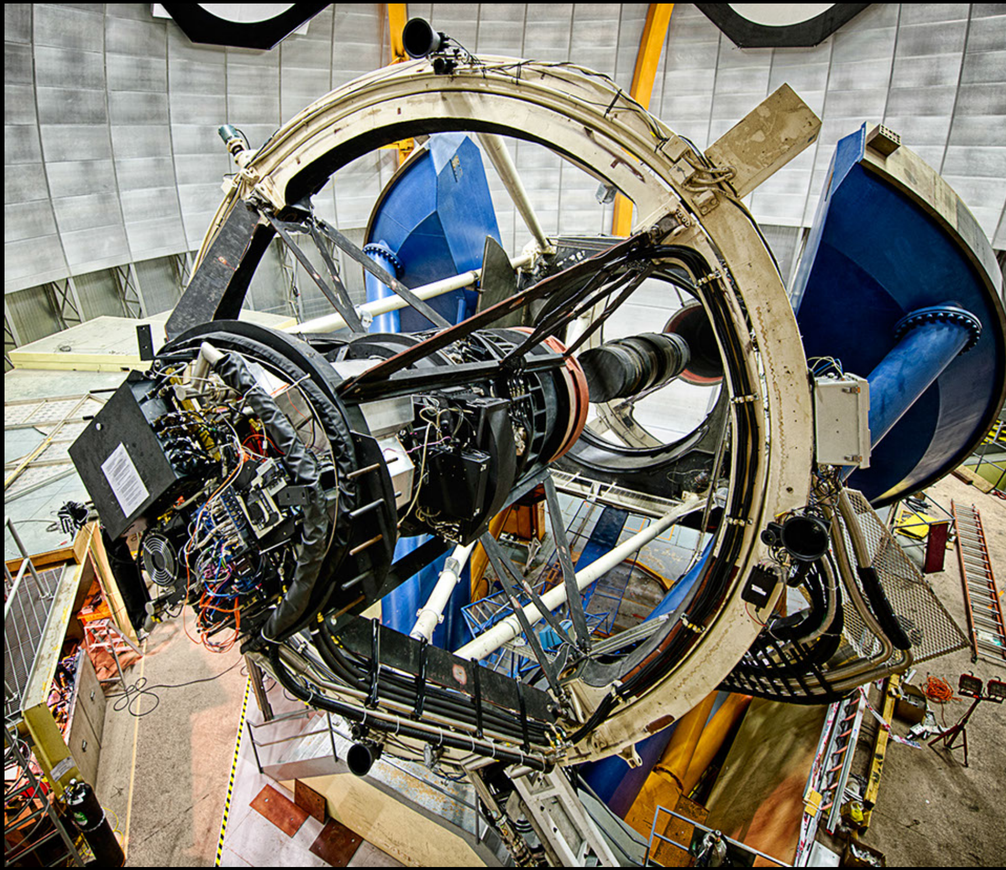
Supernova Ia Hubble Diagram



The Dark Energy Survey

- Probe origin of Cosmic Acceleration:
  - Clusters, Weak Lensing, Galaxy clustering, Supernovae
- Two multicolor surveys:
  - 300 M galaxies over 5000 sq deg, grizY to 24th mag
  - 3000 supernovae (27 sq deg)
- New camera for CTIO Blanco 4m telescope
  - DECam Facility instrument
- Survey started Aug. 2013
  - Now in 5th of 5 seasons, 105 nights per season (Aug-Feb)

DECam on the CTIO Blanco 4m



International collaboration led by FNAL; DOE+NSF support

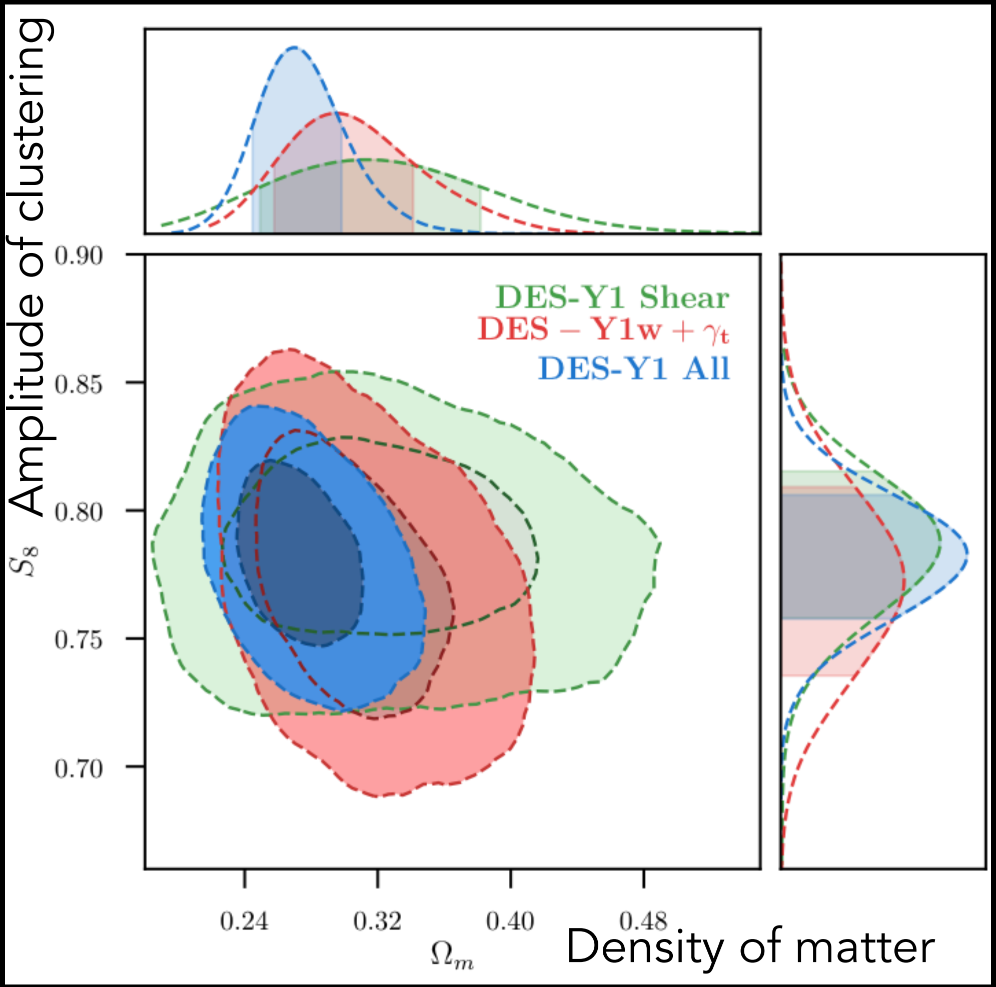
DES Year 1 Cosmology Analysis: 3x2

- Compare & consistently combine three 2-point correlation function measurements:
  - Angular clustering: autocorrelation of 660,000 luminous red galaxies in 5 redshift bins
  - Cosmic shear weak lensing: shear correlation of 26 million galaxy shapes in 4 redshift bins
  - Galaxy-galaxy lensing: correlate red galaxy positions (foreground lenses) with source galaxy shear
- Fully blind analysis, 10 papers released Aug. 3

Multi-Probe Constraints: ΛCDM

DES Year 1 results:

- Weak Lensing Cosmic Shear
- Galaxy-galaxy lensing+galaxy clustering
- Detailed modeling of covariance between probes

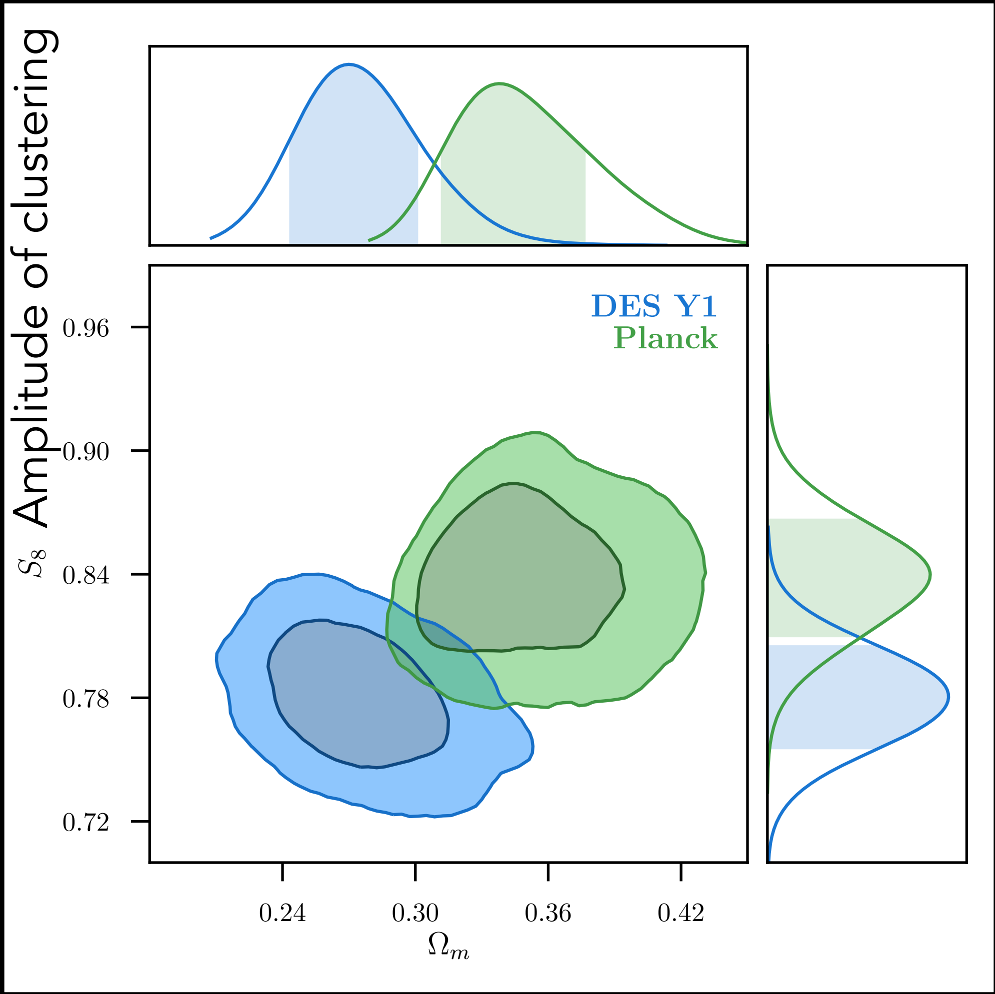


DES Collaboration 2017

$S_8 = \sigma_8(\Omega_m/0.3)^{0.5}$

Comparison of DES Y1 with Planck: low-z vs high-z in ΛCDM

- DES and Planck constrain S_8 and Ω_m with comparable strength!
- Differ in central values by >1σ, but consistent according to Bayesian evidence
- DES final analysis will include 4x Y1 data and additional probes (clusters, supernovae)



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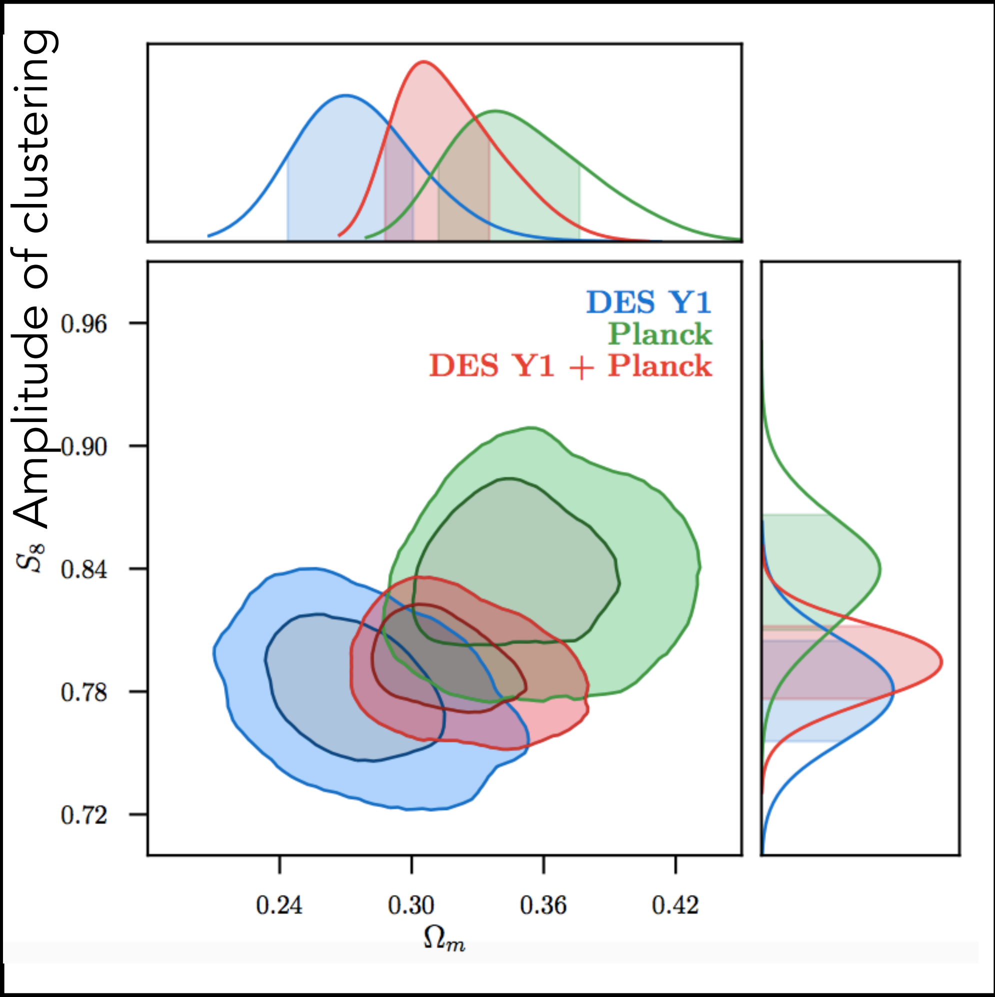
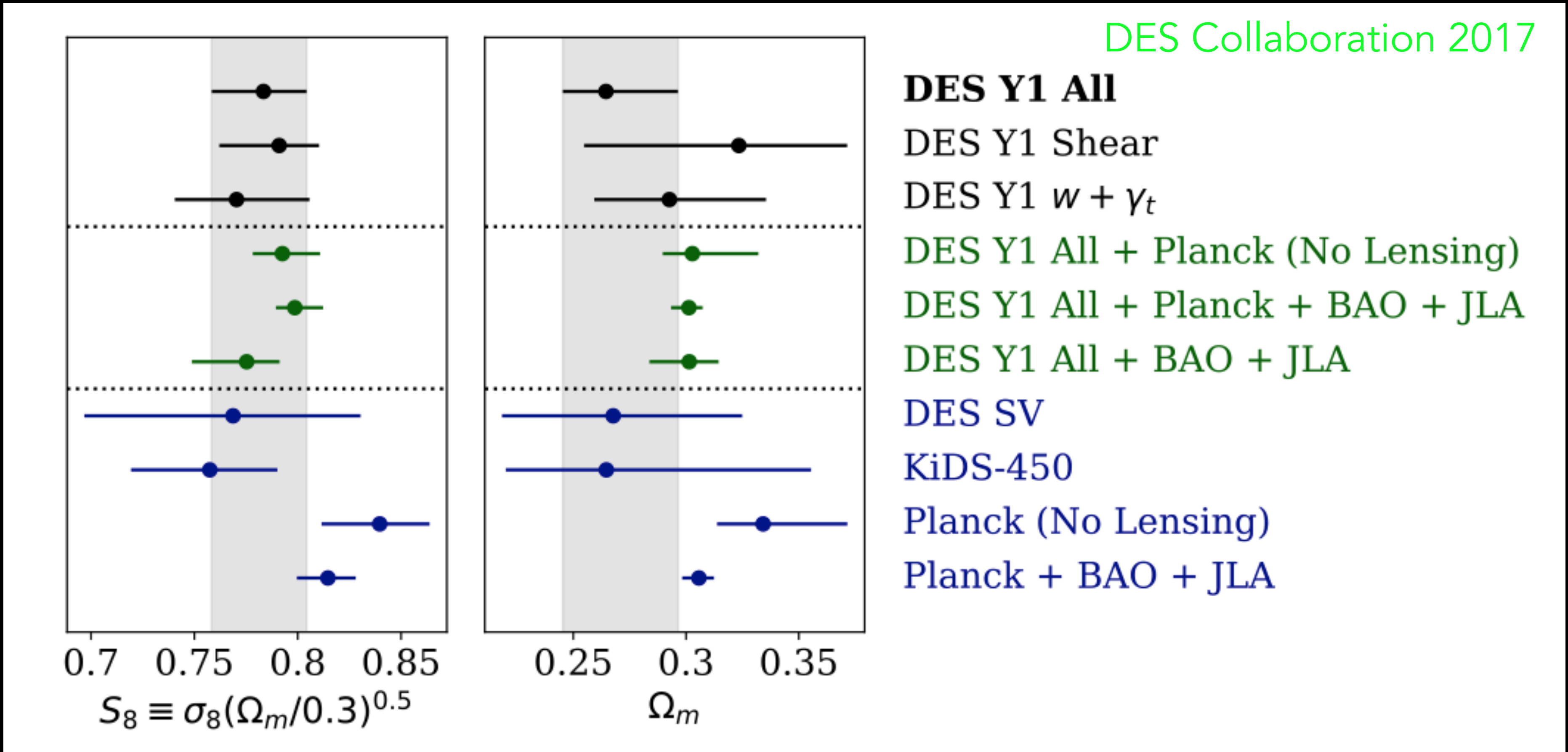


$S_8=\sigma_8(\Omega_m/0.3)^{0.5}$

Combine multiple data sets: ΛCDM



Combined constraints:

$$\Omega_m = 0.301^{+0.006}_{-0.008}.$$

$$h = 0.682^{+0.006}_{-0.006}$$

$$\sigma_8 = 0.801 \pm 0.014$$

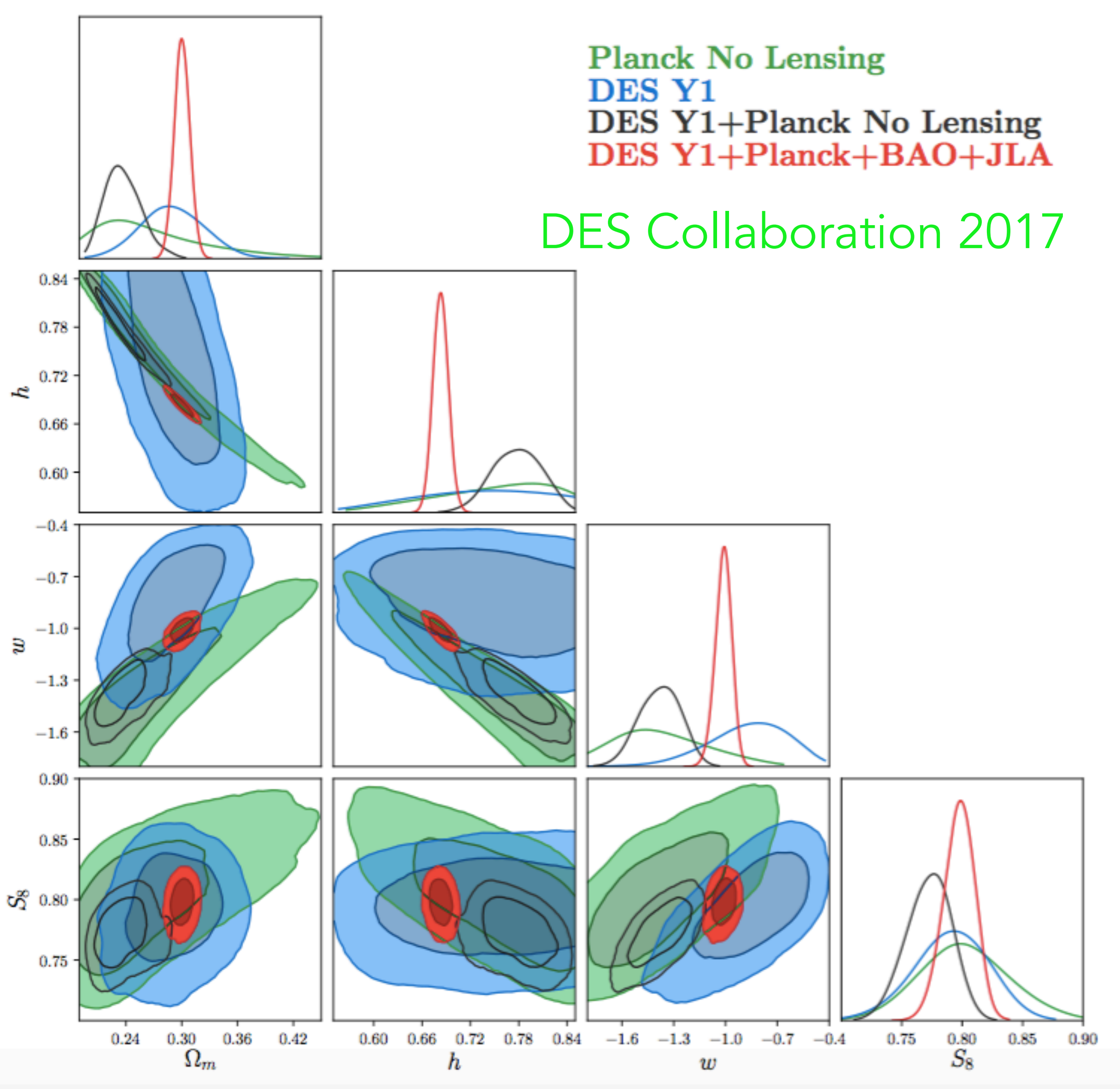
$$S_8 = 0.799^{+0.014}_{-0.009}.$$

Combine multiple data sets: wCDM

- Combine to achieve very stringent parameter constraints:

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

- Haven't yet tested model with time-varying *w*

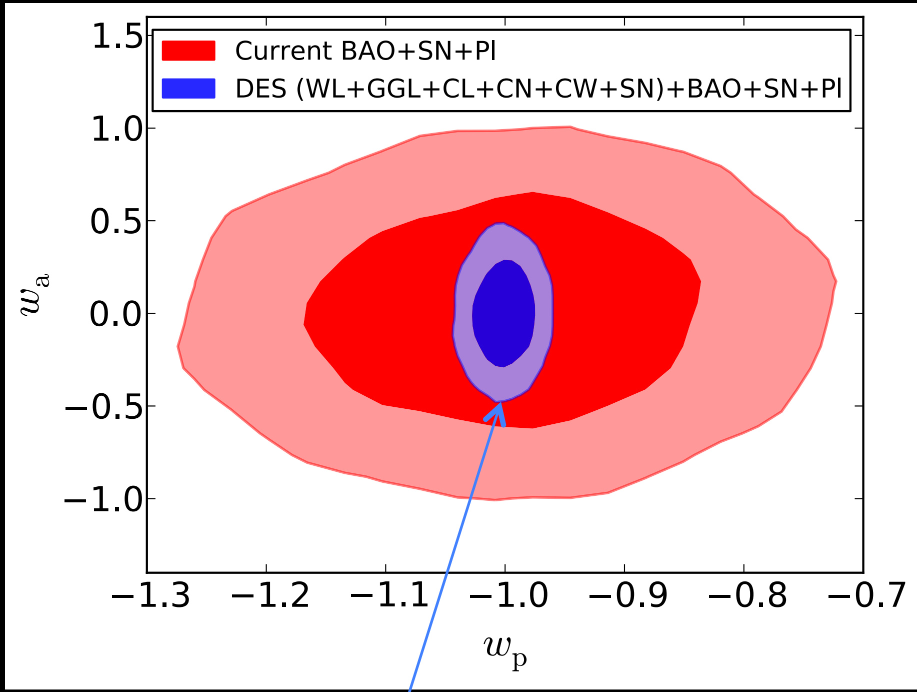


Where do we go from here? Y3-Y5 analyses

5000 sq. deg. with increasing depth

- Galaxy Clusters
  - Tens of thousands of clusters to z~1
- Weak Lensing
  - Shape measurements of ~200 million galaxies
- Galaxy Clustering
  - ~300 million galaxies to z ~ 1
- Supernovae
  - 3000 well-sampled SNe Ia to z ~1
- Strong Lensing
  - ~30 QSO lens time delays
  - Arcs with multiple source redshifts
- Cross-correlations
  - Galaxies, WL x CMB lensing

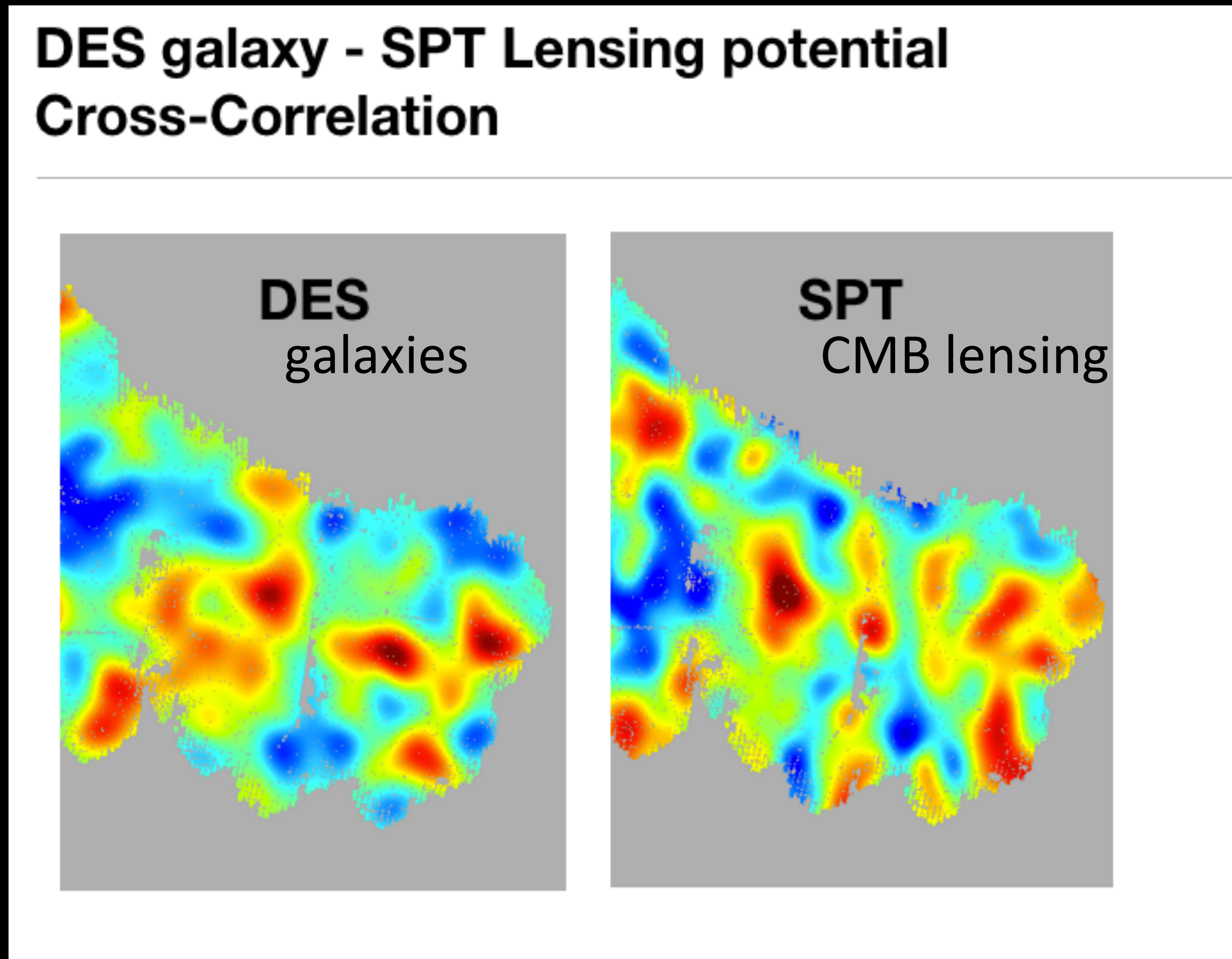
$$w(a) = w_0 + w_a(1 - a(t))$$



DES forecast
T. Eifler, E. Krause

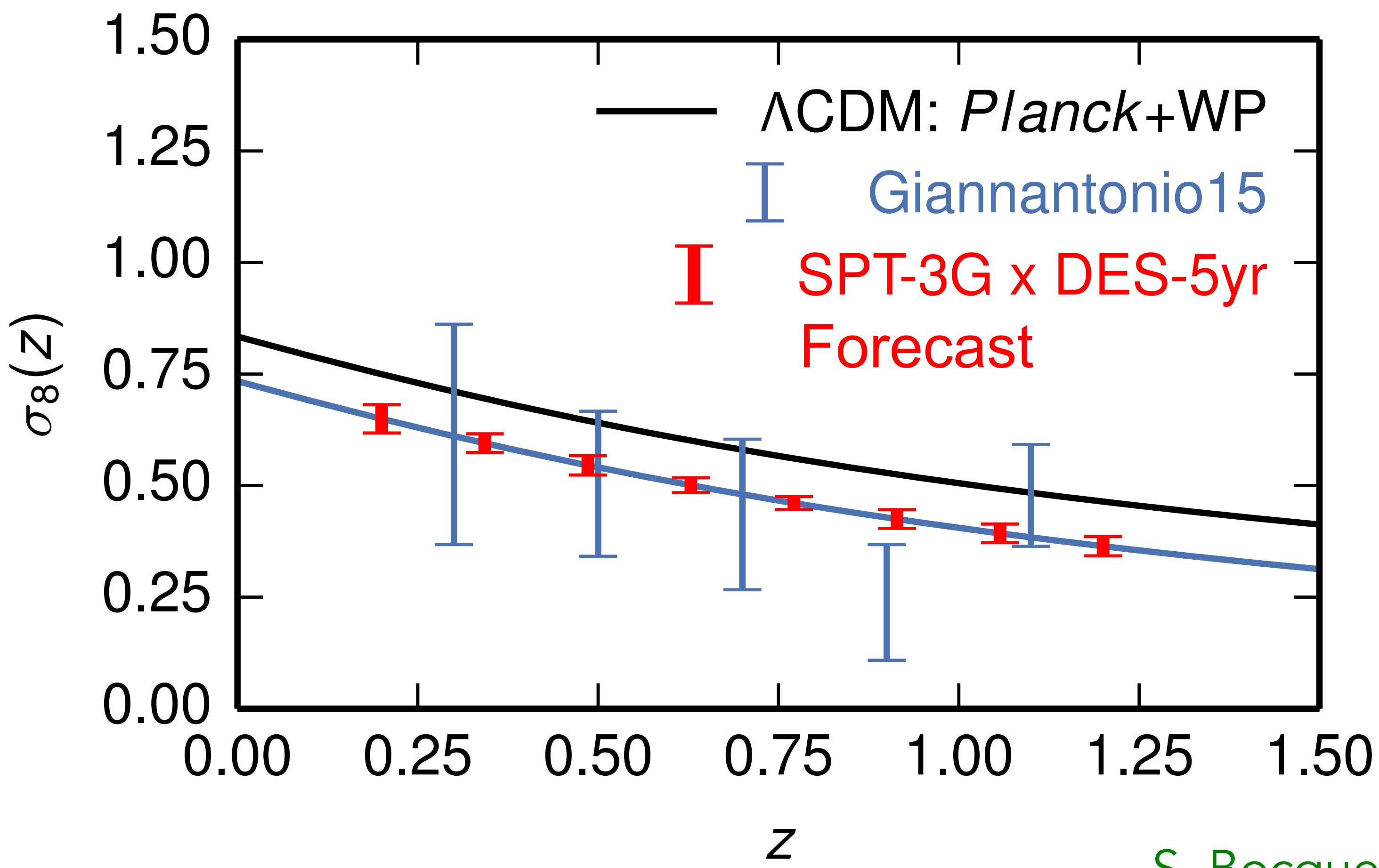
DES Galaxies X CMB Lensing

- DES galaxies associated with projected mass partly responsible for CMB lensing
- Additional cosmological information in this cross-correlation



Giannantonio, Fosalba, Cawthon et al (earlier DES SV data)

Constraining Growth Function of Perturbations



S. Bocquet

Powerful test of ΛCDM and GR
(complements Redshift Space Distortions)

What new techniques, technology, or data enabled this?

- Technology: DECam on the Blanco: highly efficient, red-sensitive CCDs (LBNL), wide-field imager (3 sq. deg., 570 megapixels) w/ excellent optical design on 4m telescope: unprecedented survey power (depth x area)/time. 525 nights awarded in exchange for facility instrument.
- Techniques: control systematics of photo-z's; new weak lensing shape methodologies; model complex covariance matrices, test with realistic N-body simulations.
- Data: DES Y1, extensively vetted for systematics; NCSA-led production system for data management, augmented by collaboration-produced value-added catalogs for analysis.

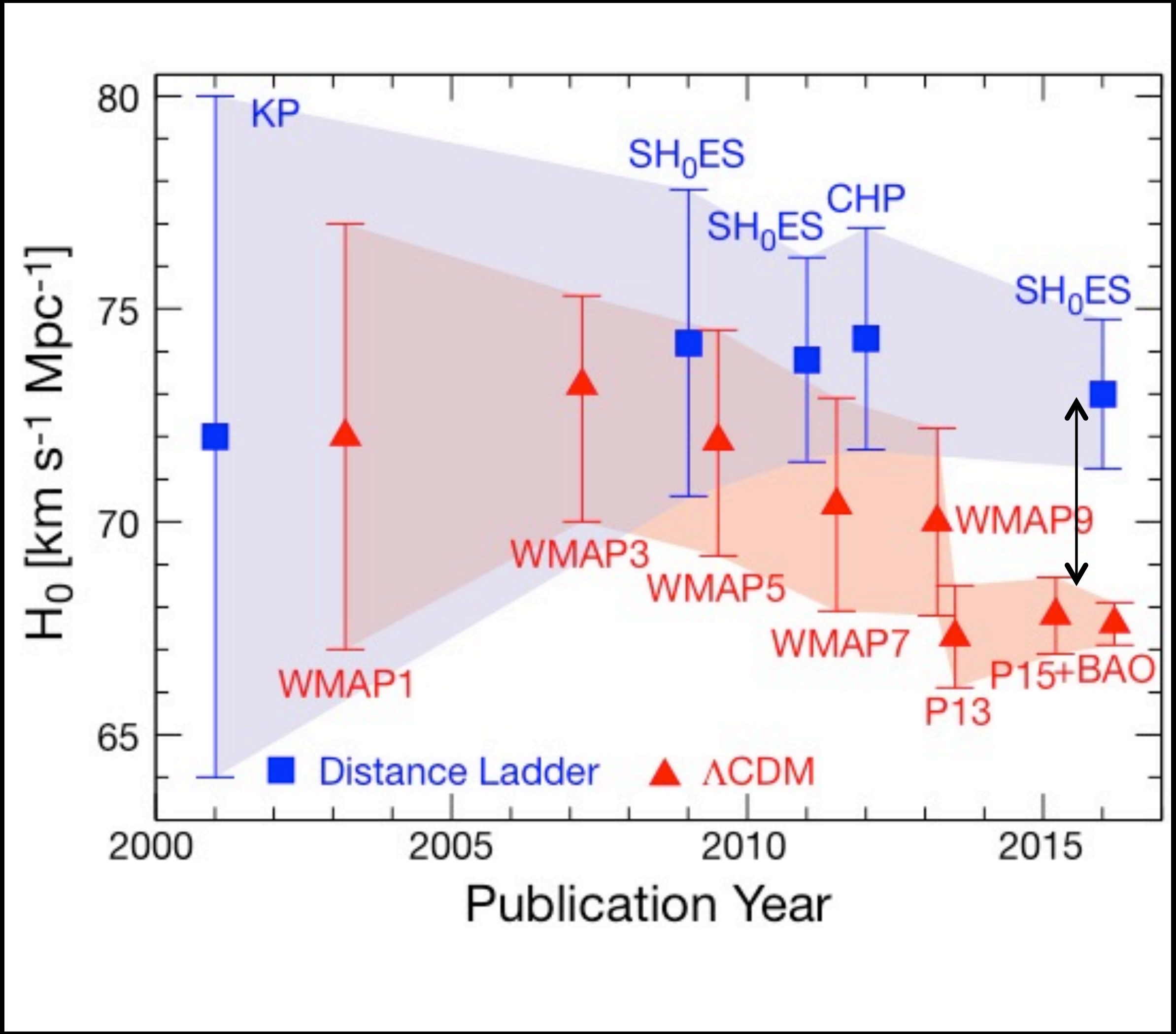
Meaning & Impact

- Measurements from galaxy surveys now rival precision of CMB for certain cosmological parameters (and exceed it for some others): compare low- and high-z Universe to obtain complementary constraints (break parameter degeneracies).
- DES Y1 consistent with Planck CMB in context of ΛCDM. Quite remarkable for simple 6-parameter model.
- DES Y1 in combination with Planck, BAO, JLA SN provide most stringent constraints on ΛCDM parameters to date.
- Precision will increase with larger data sets (Y1→Y3→Y5) and by using more probes (clusters, SNe, CMB cross-correlations), enabling tests of more complex models ($w_0 w_a$CDM, modified gravity), and eventually will be even better with LSST, DESI, Euclid, WFIRST.

Extra Slides

H_0: CMB vs. Local Measurements

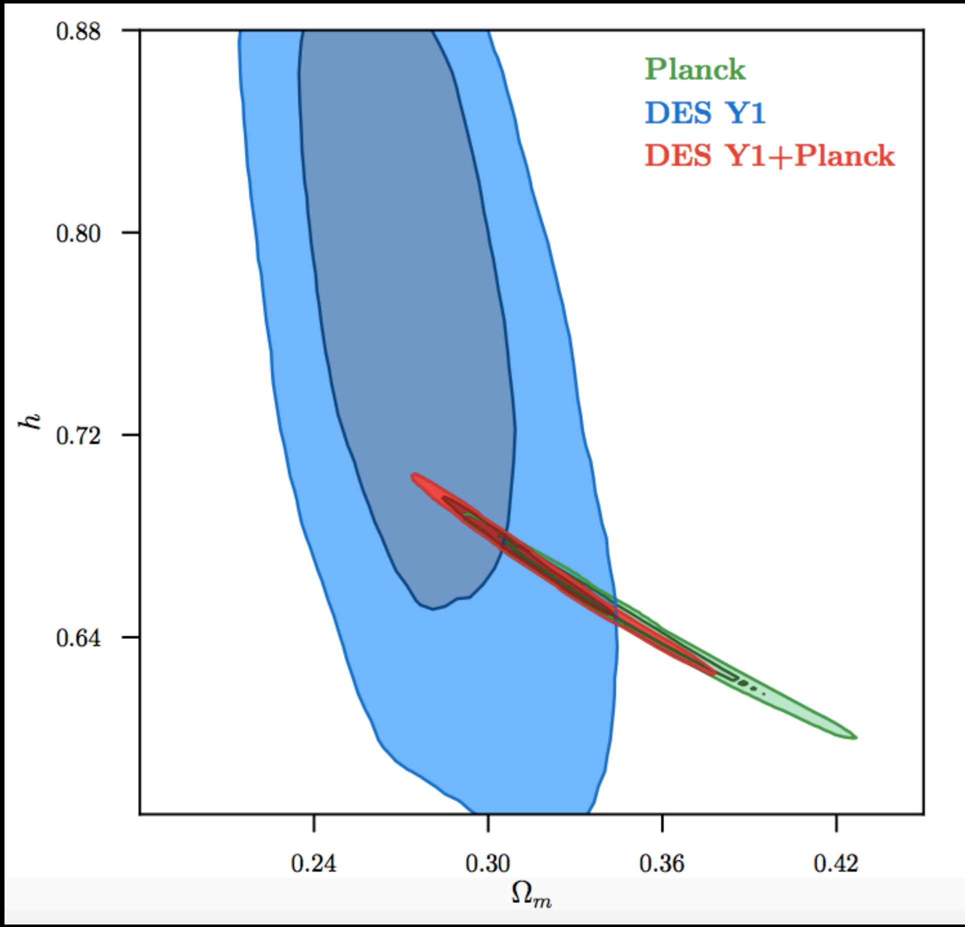
CMB results *assume* ΛCDM model



3.4σ discrepancy

What about H_0?

- DES 3x2 doesn't constrain H_0 on its own
- DES ΛCDM constraint on Ω_m combined with Planck shifts *h* up by >1σ from Planck central value, toward but not reaching local H_0 values



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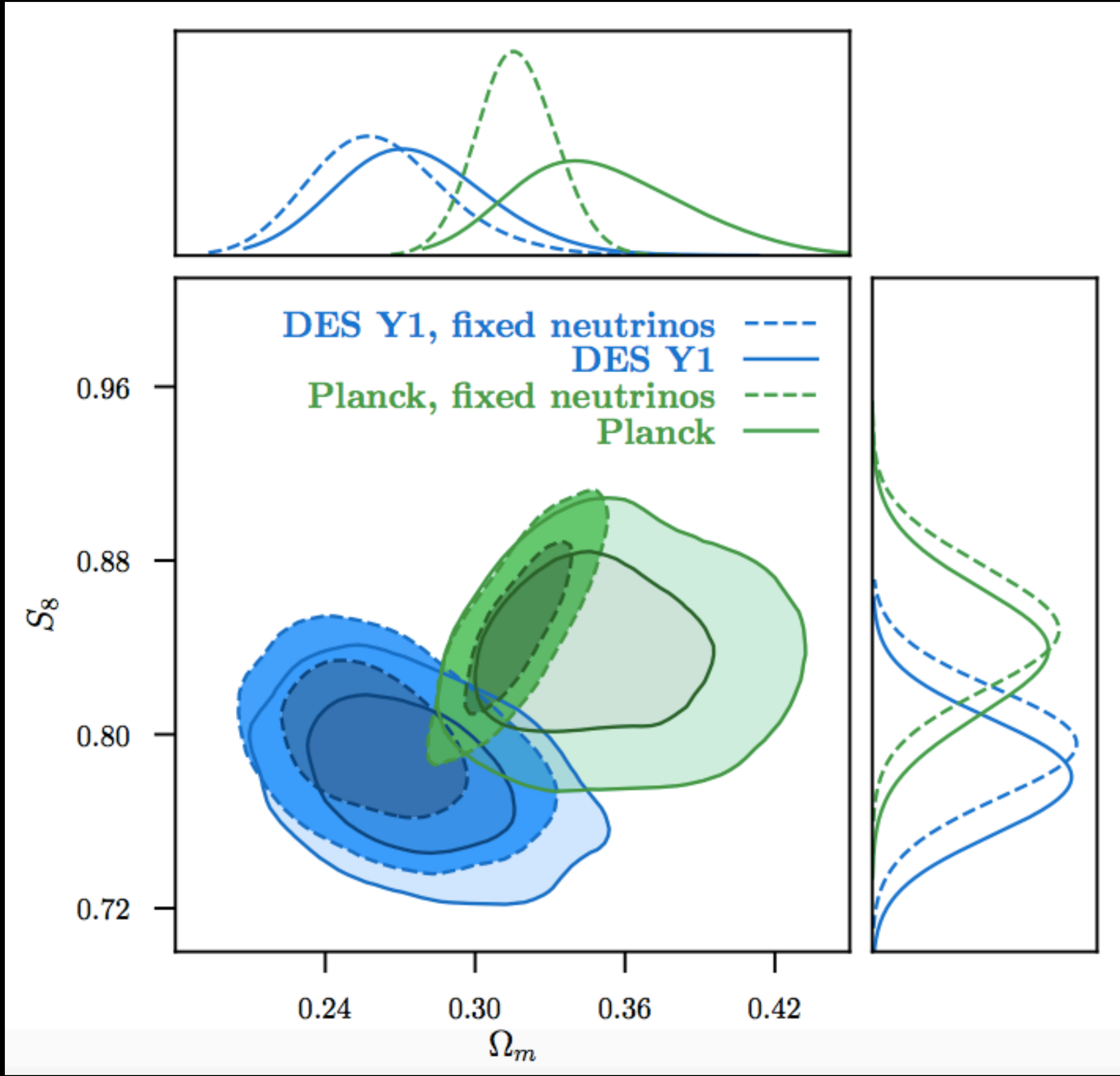
What if we fix neutrino mass?

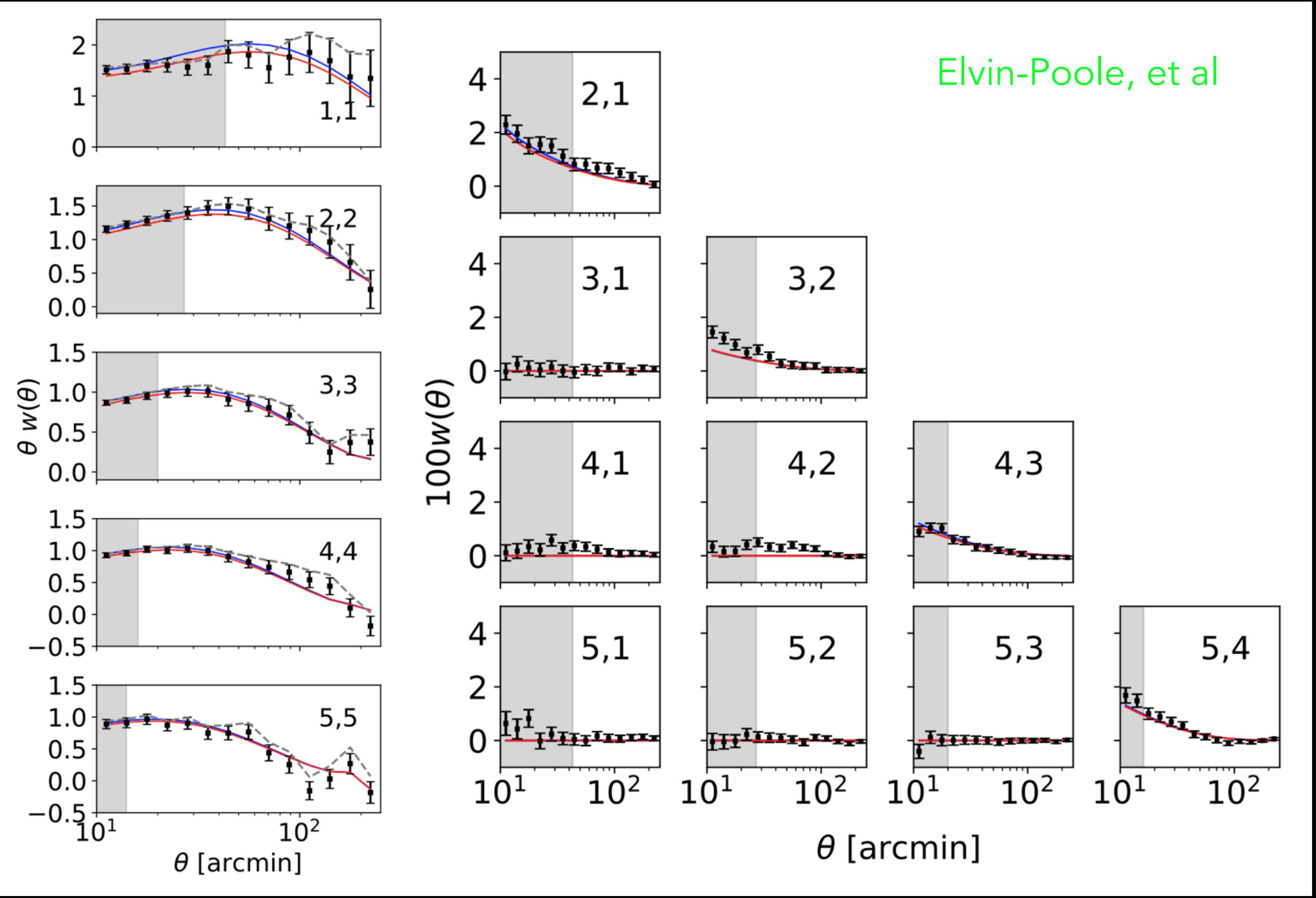
- Hold neutrino mass at 0.06 eV (lower limit from oscillation experiments)
- DES 3x2 still consistent with Planck in ΛCDM

S_8	$= 0.797 \pm 0.022$	DES Y1
	$= 0.801 \pm 0.032$	KiDS+GAMA [62]
	$= 0.742 \pm 0.035$	KiDS+2dFLenS+BOSS

DES Collaboration 2017

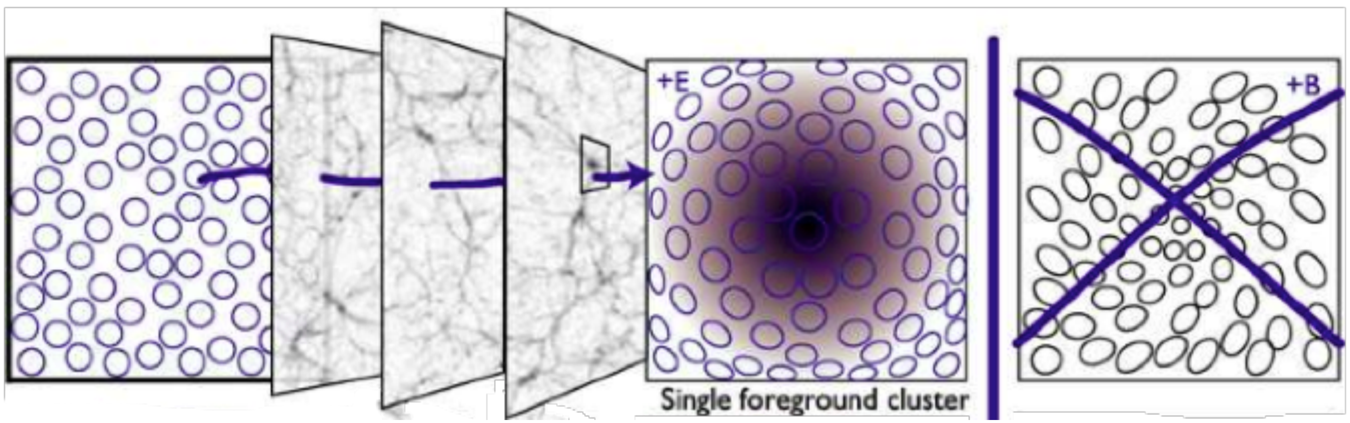


DES Y1 Galaxy Clustering

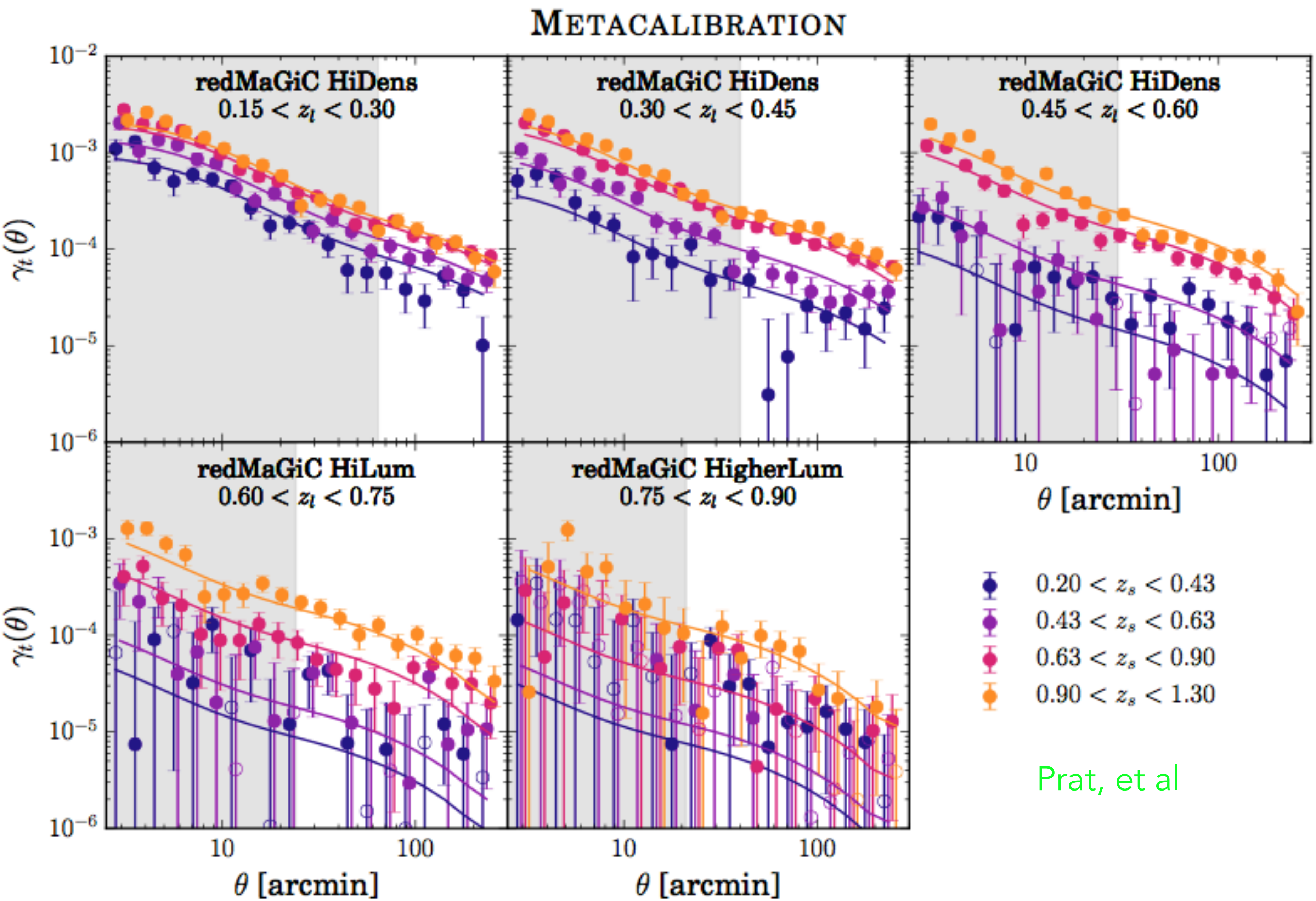


Galaxy-Galaxy Lensing

- Measurement of the tangential shear of background (source) galaxies around foreground (lens) galaxies.



$$\gamma_t^{ij}(\theta) = b^i \, \frac{3}{2} \, \Omega_m \left(\frac{H_0}{c}\right)^2 \int \frac{d\ell}{2\pi} \, \ell \, J_2(\theta \ell) \times$$
$$\times \int dz \left[\frac{g^j(z) \, n_l^i(z)}{a(z) \, \chi(z)} \, P_{\delta\delta}\left(k = \frac{\ell}{\chi(z)}, \chi(z)\right)\right],$$



METACALIBRATION
redMaGiC HiDens
$0.15 < z_l < 0.30$
redMaGiC HiDens
$0.30 < z_l < 0.45$
redMaGiC HiDens
$0.45 < z_l < 0.60$
redMaGiC HiLum
$0.60 < z_l < 0.75$
redMaGiC HigherLum
$0.75 < z_l < 0.90$
$\gamma_t(\theta)$
θ [arcmin]
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10
100
$0.20 < z_s < 0.43$
$0.43 < z_s < 0.63$
$0.63 < z_s < 0.90$
$0.90 < z_s < 1.30$
Prat, et al

Covariance Matrix

Krause, et al

Mocks

Theory