Mapping the Universe with Dark Energy Survey

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Stiftung / Foundation

Blanco telescope at Cerro Tololo, Chile

Ann Arbor, Michigan

University of Michigan

Michigan Stadium (115,000)

LSA LEINWEBER CENTER
UNIVERSITY OF MICHIGAN

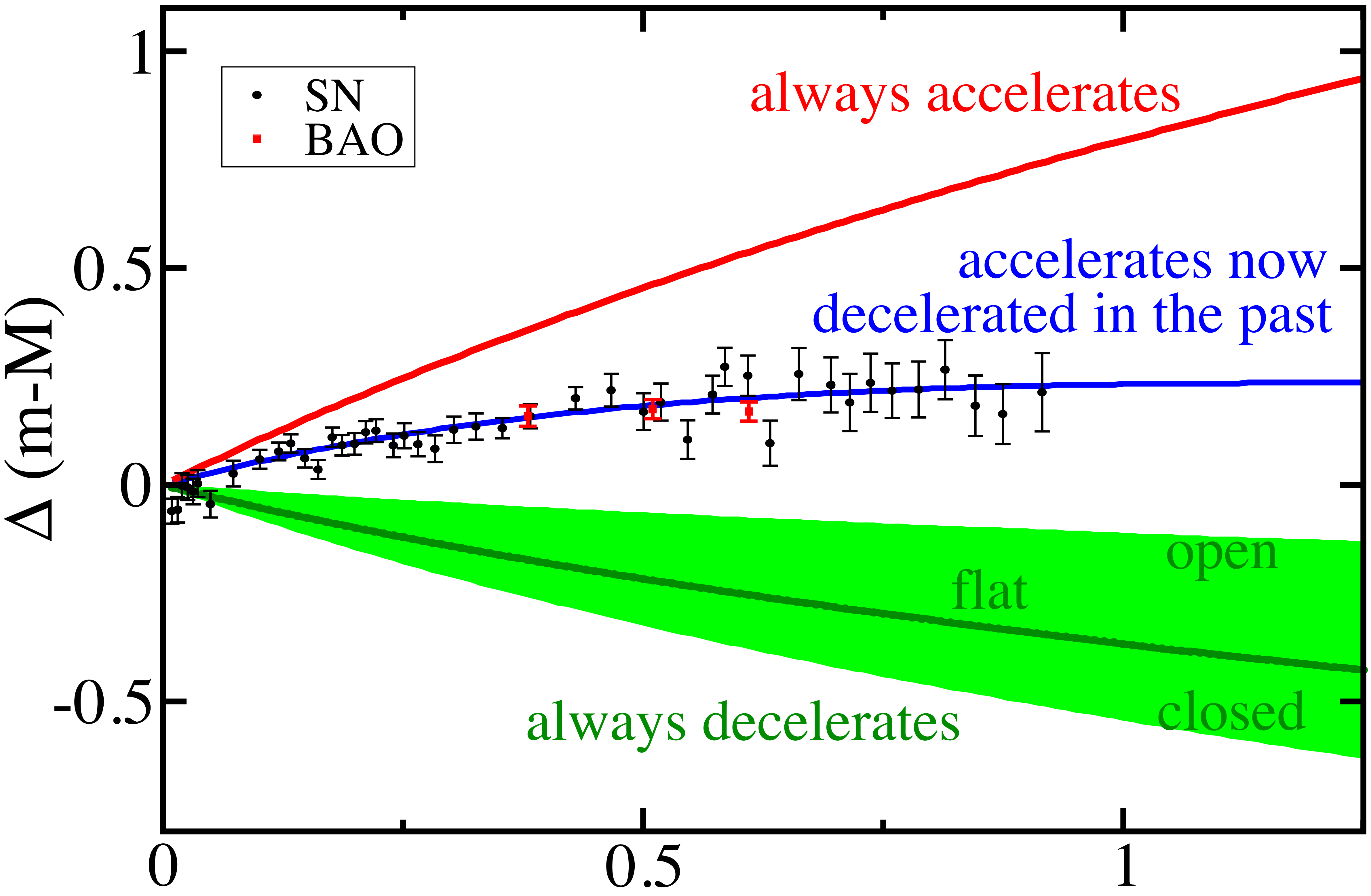
LCTP focuses on:

1. Particle theory
2. Particle pheno
3. Cosmology

Tl;dr for this talk:

- In a few weeks, DES will release Y3 results, more than tripling the area covered by any deep photometric survey
- Results will be interesting; and hopefully out in time that Michael Troxel's (Dec 17) Joint Colloquium
- Here I will present background, as well as results of some of the accompanying ("essential") Y3 papers

Evidence for Dark energy from type Ia Supernovae

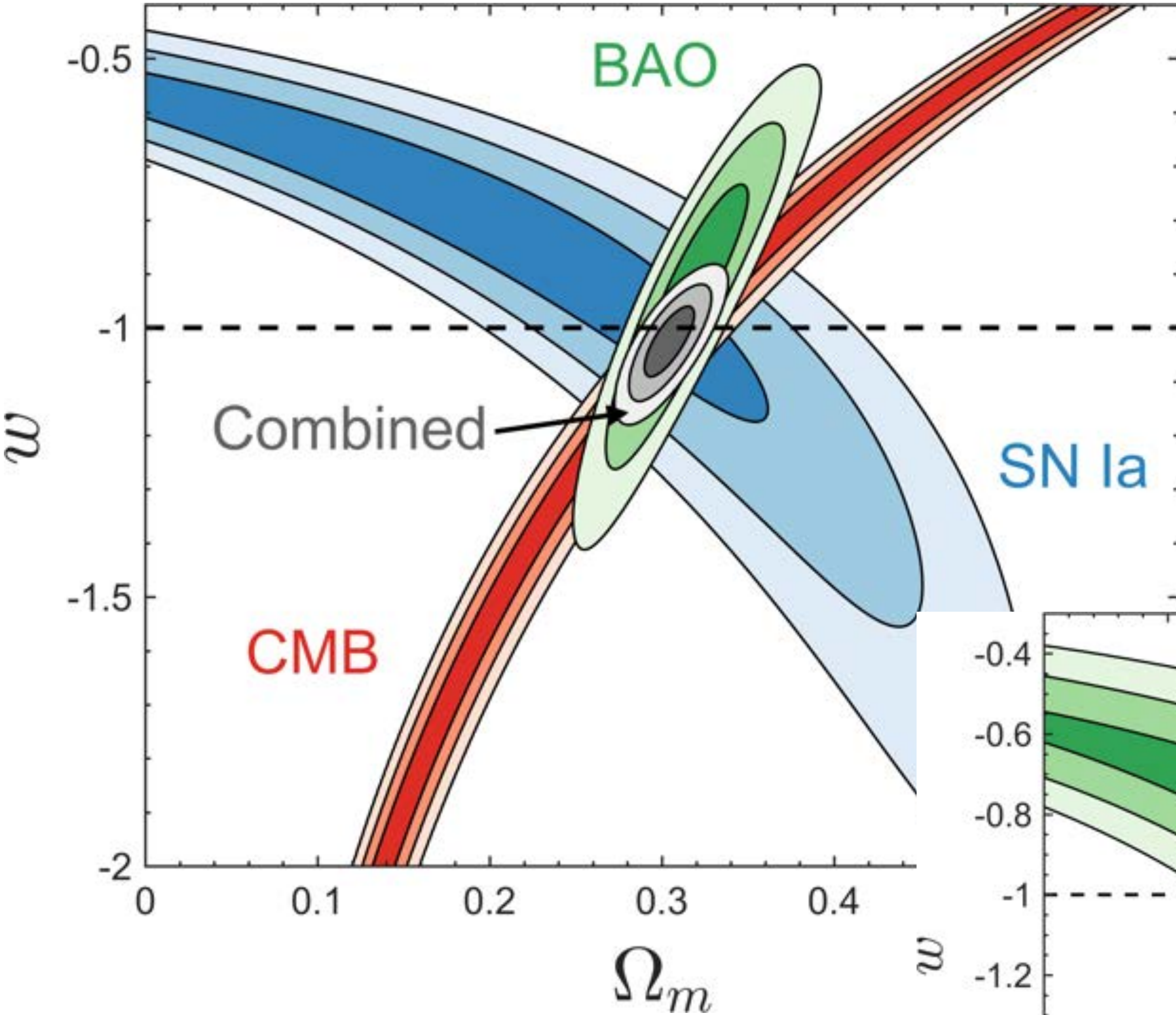


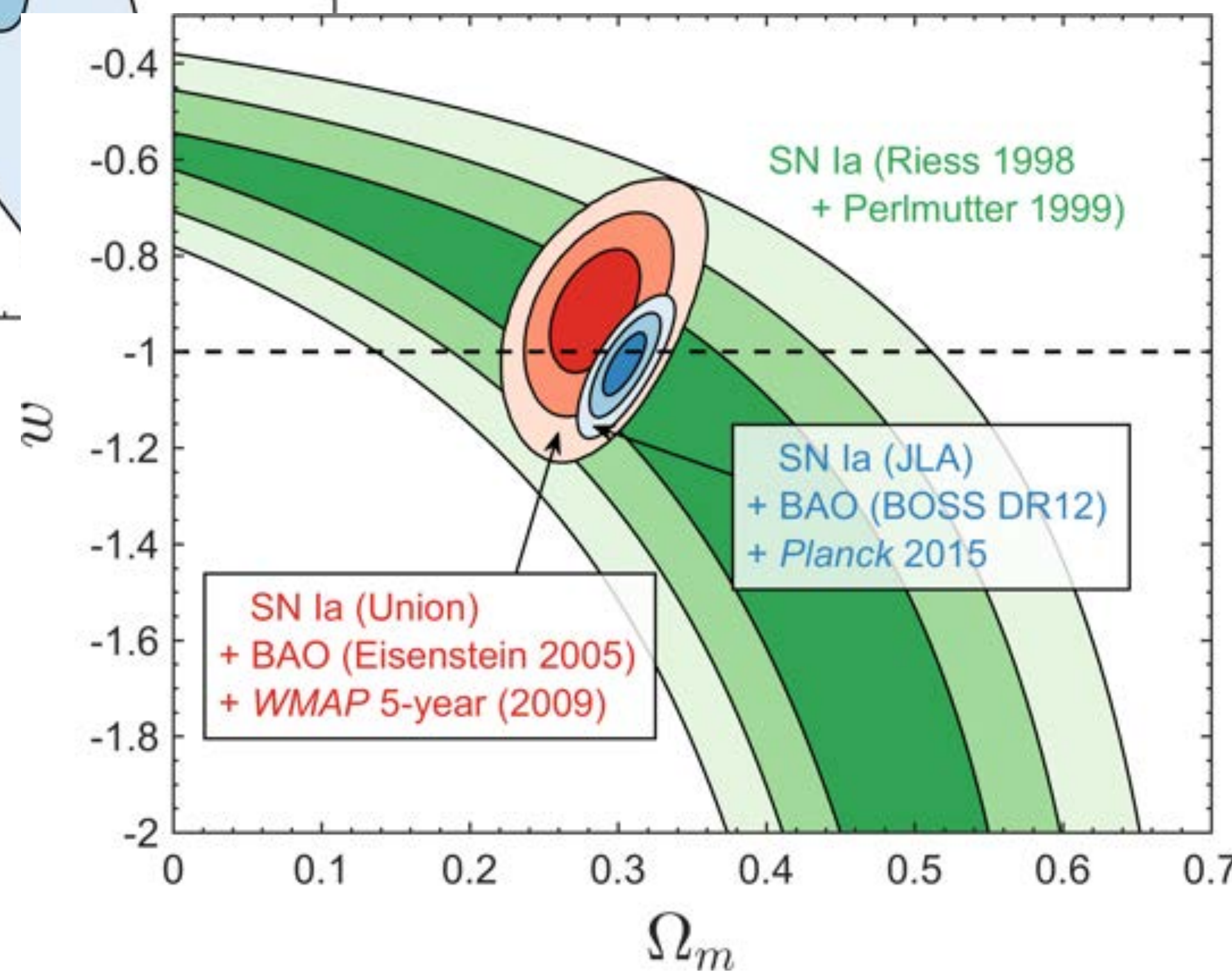
Huterer & Shafer,
Rep. Prog. Phys. 2018

$$\Omega_m = 1 - \Omega_{\rm DE}$$

$$\Omega_{\rm DE} \equiv \frac{\rho_{\rm DE}}{\rho_{\rm crit}}$$

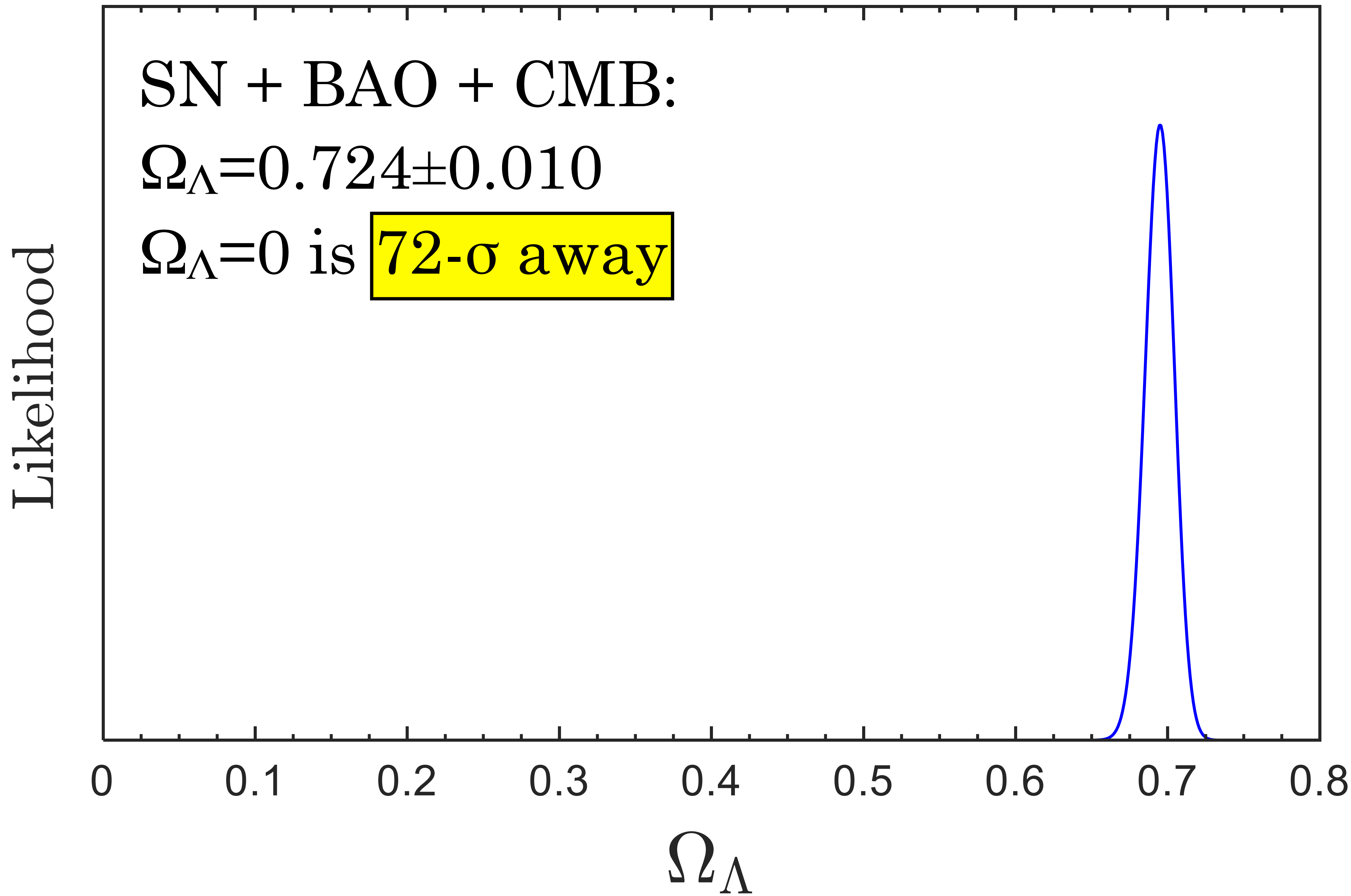
$$w \equiv \frac{p_{\rm DE}}{\rho_{\rm DE}}$$





Huterer & Shafer,
Rep. Prog. Phys., 2018

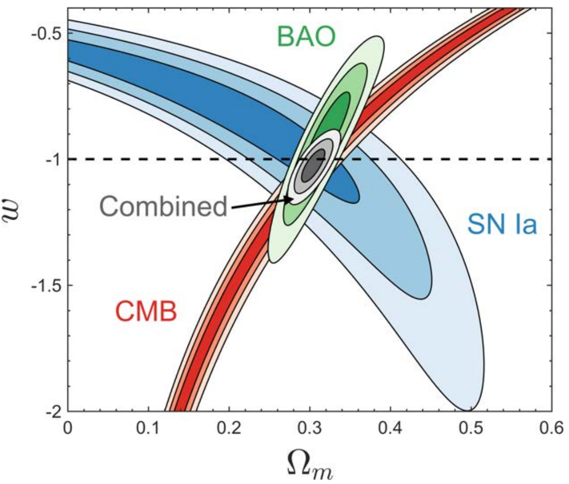
Current evidence for dark energy is impressively strong



Daniel Shafer, 2017

A difficulty:

DE theory target accuracy, in e.g. $w=p/\rho$, not known *a priori*



Contrast this situation with:

1. Neutrino masses:

$$(\Delta m^2)_{sol} \simeq 8\times10^{-5}\ \mathrm{eV}^2$$
$$(\Delta m^2)_{atm} \simeq 3\times10^{-3}\ \mathrm{eV}^2$$

$\sum m_i = 0.06$ eV* (normal)

vs.

$\sum m_i = 0.11$ eV* (inverted)

*(assuming $m_3=0$)

2. Higgs Boson mass (before LHC 2012):

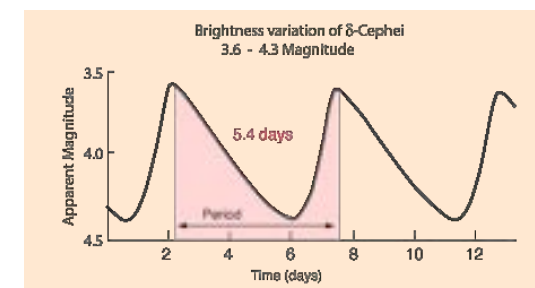
$$m_H \lesssim O(200)\ \mathrm{GeV}$$

(assuming Standard Model Higgs)

Hubble tension

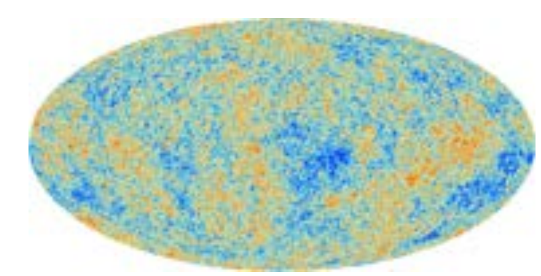
Type Ia supernovae + Cepheid distances give

$$H_0 = 74.0 \pm 1.4 \text{ (km/s/Mpc)}$$



Cosmic Microwave Anisotropies give

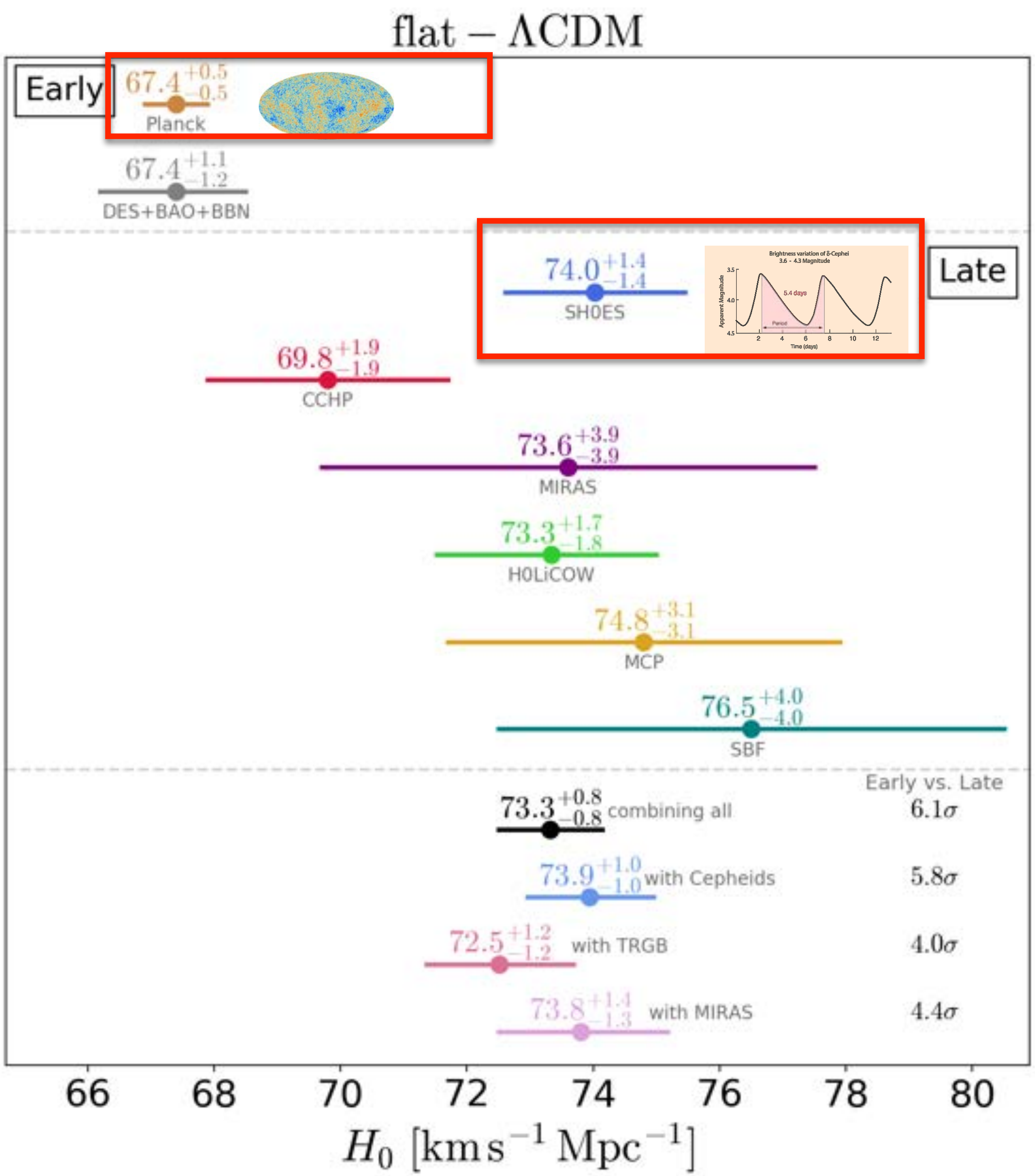
$$H_0 = 67.4 \pm 0.4 \text{ (km/s/Mpc)}$$



These two measurements are discrepant at about five sigma!*

* once strong-lensing constraints are added, which come out high ($H_0 \sim 73$)

Hubble tension - a gift to cosmology!



Verde, Treu & Riess arXiv:1907.10625

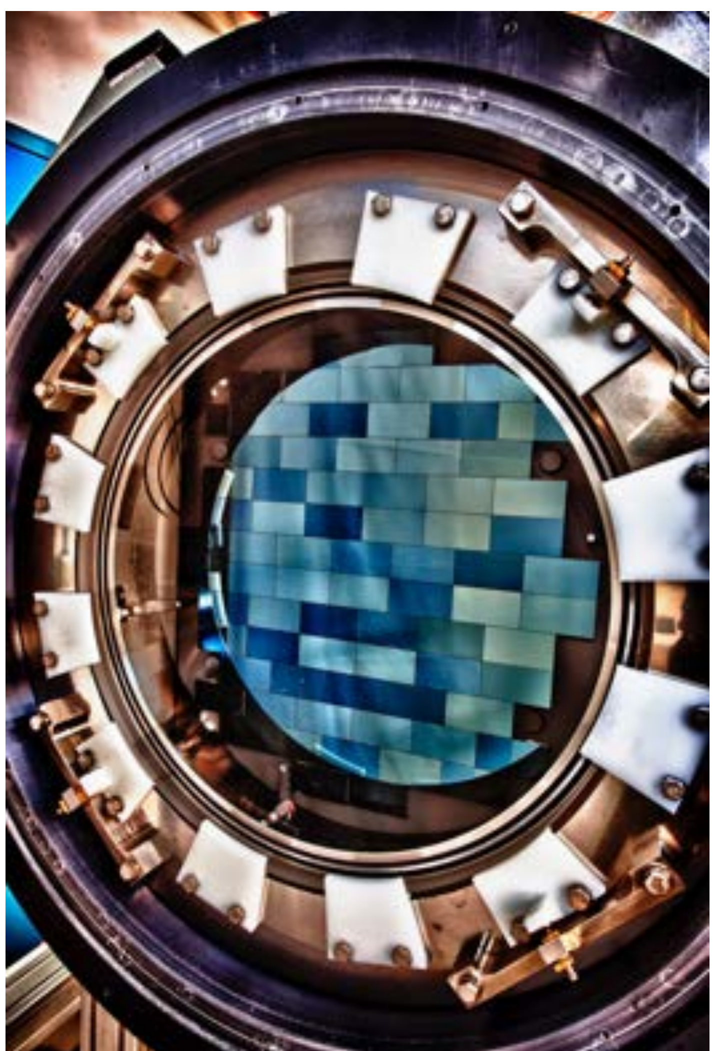
- exciting, real tension in cosmology
- all major analysis very thorough
- no obvious systematics (as yet)
- theory models surprisingly hard to concoct (e.g. very finely tuned scalar field models that *also* don't really work)

Major ongoing or upcoming DE expt's:

- **Ground photometric:**
  - Kilo-Degree Survey (KiDS)
  - Dark Energy Survey (DES)
  - Hyper Supreme Cam (HSC)
  - Large Synoptic Survey Telescope (LSST)
- **Ground spectroscopic:**
  - Hobby Eberly Telescope DE Experiment (HETDEX)
  - Prime Focus Spectrograph (PFS)
  - Dark Energy Spectroscopic Instrument (DESI)
- **Space:**
  - Euclid
  - Wide Field InfraRed Space Telescope (WFIRST)

Dark Energy Survey

- 3 sq deg camera on the Blanco 4m telescope in Chile
- 5000 sqdeg (in Y5)
- 5 filters (grizY); 10 passes on sky
- 5.5 yrs of observation
- Major cosmological probes:
  1. Galaxy Clustering
  2. Weak lensing Shear
  3. Clusters of galaxies
  4. Type Ia Supernovae
- Intern. collaboration of ~700 scientists
- in Jan 2019 finished all 5.5 yrs of obs.; Y3 analysis ~~in progress~~ almost done



Dark Energy Survey (DES)

Cerro Tololo, Chile

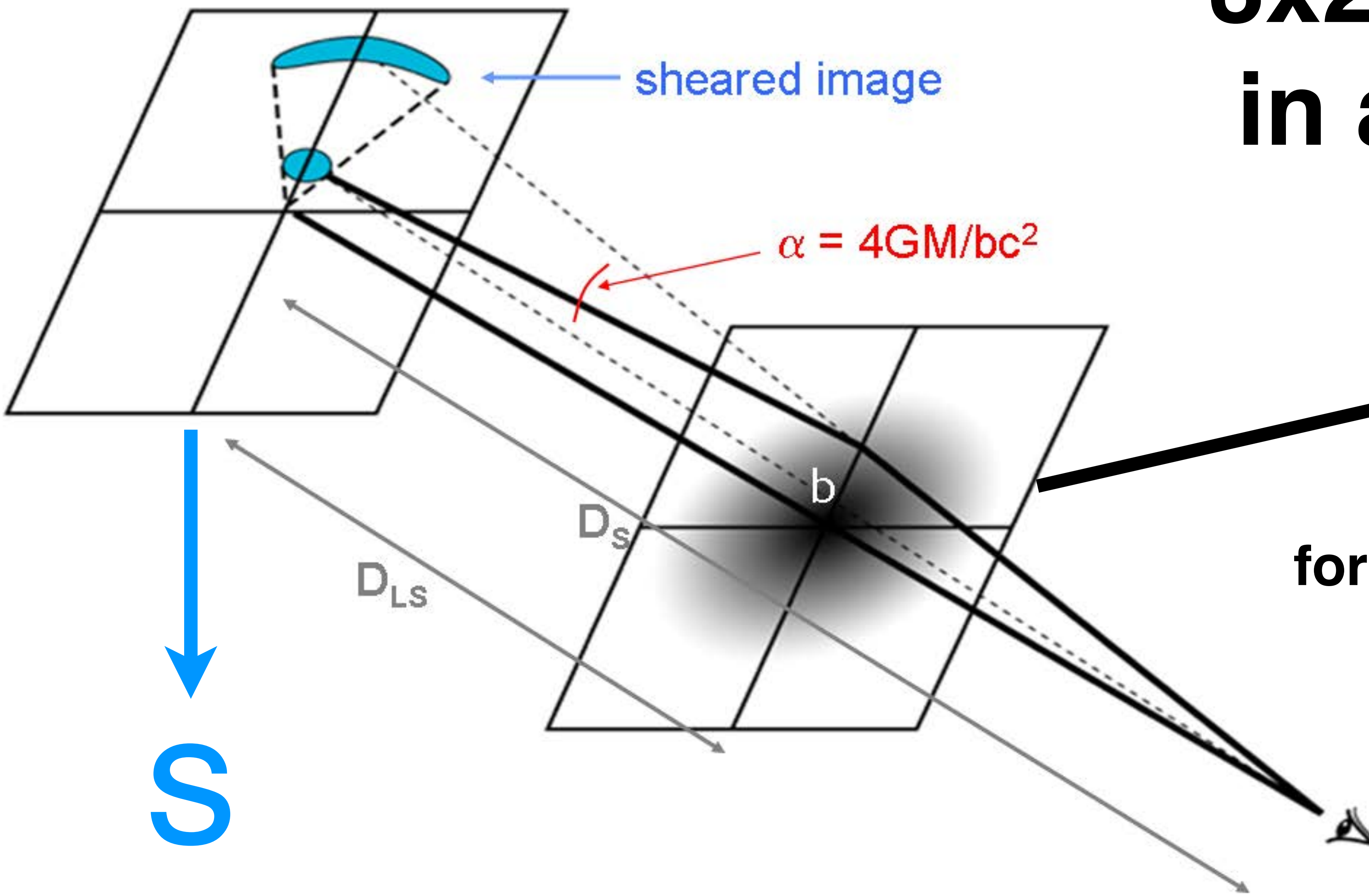
Blanco Telescope

Dark Energy Survey Y1 highlights

- About 1300 sqdeg (~1/4 of final area)
- 35 million galaxies with shear measurements
- Redshift range roughly $z<1$; photometric redshifts for all objects (two independent methods agree well)
- "3x2" analysis includes galaxy shear, galaxy-galaxy lensing, galaxy clustering (papers out; discuss next)
- blinded analysis
- **"double pipeline" for everything (next slides)**
- Supernova analysis (papers out)
- BAO: 4% distance out to $z=0.81$
- cluster counts, strong lensing
- **Over 250 papers already out**

3x2 analysis in a picture

image: LSST science book



g

(**positions** of **foreground** galaxies; 5 redshift bins)

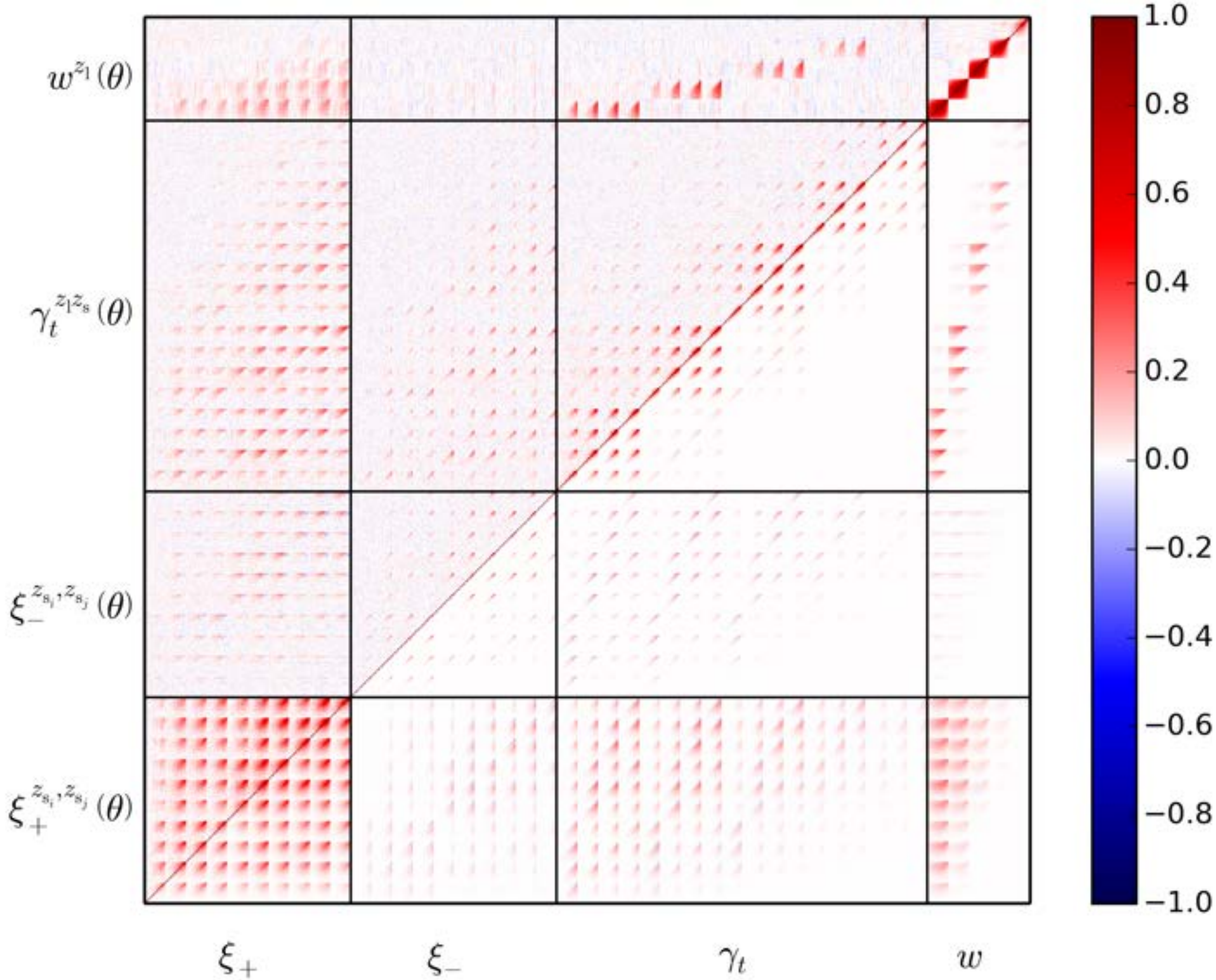
s

(**shear** of **background** galaxies; 5 redshift bins)

"3x2 (point-function)" clustering measurements:

$$\begin{bmatrix} gg & gs \\ gs & ss \end{bmatrix}$$

Covariance of 3x2 datavector



Krause, Eifler et al (2017)

DES Y1 3x2 analysis highlights

A total of ~26 parameters:
(6 cosmological, ~20 astrophysical/systematic)

and a fanatical devotion to controlling the systematic errors:

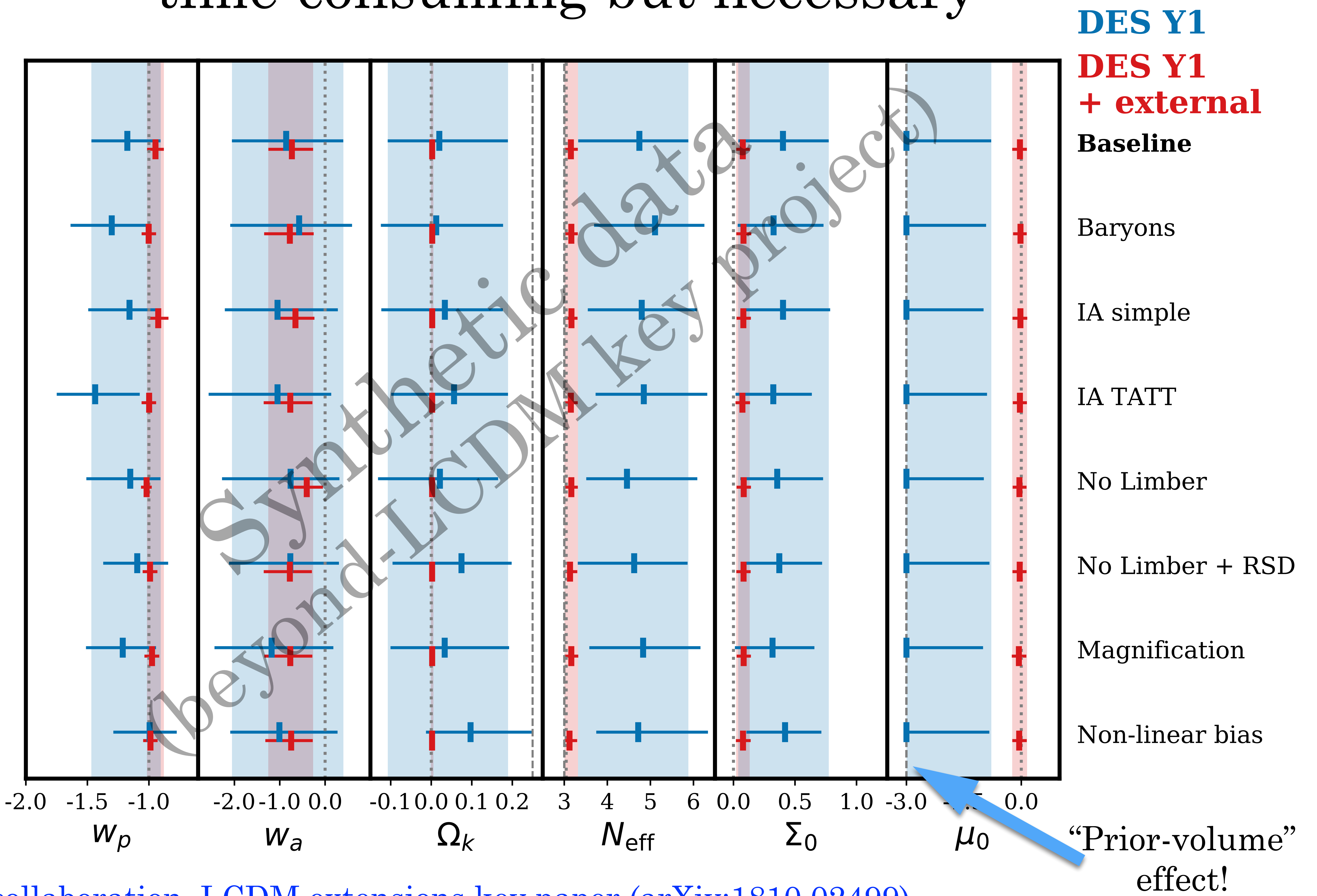
Two <u>independent</u> pipelines for everything

1. Two shear measuring/calibration pipelines
2. Two redshift-distribution algorithms
3. Two data-vector (theory) codes
4. Two parameter sampling codes

and

All cosmology results are **blinded**

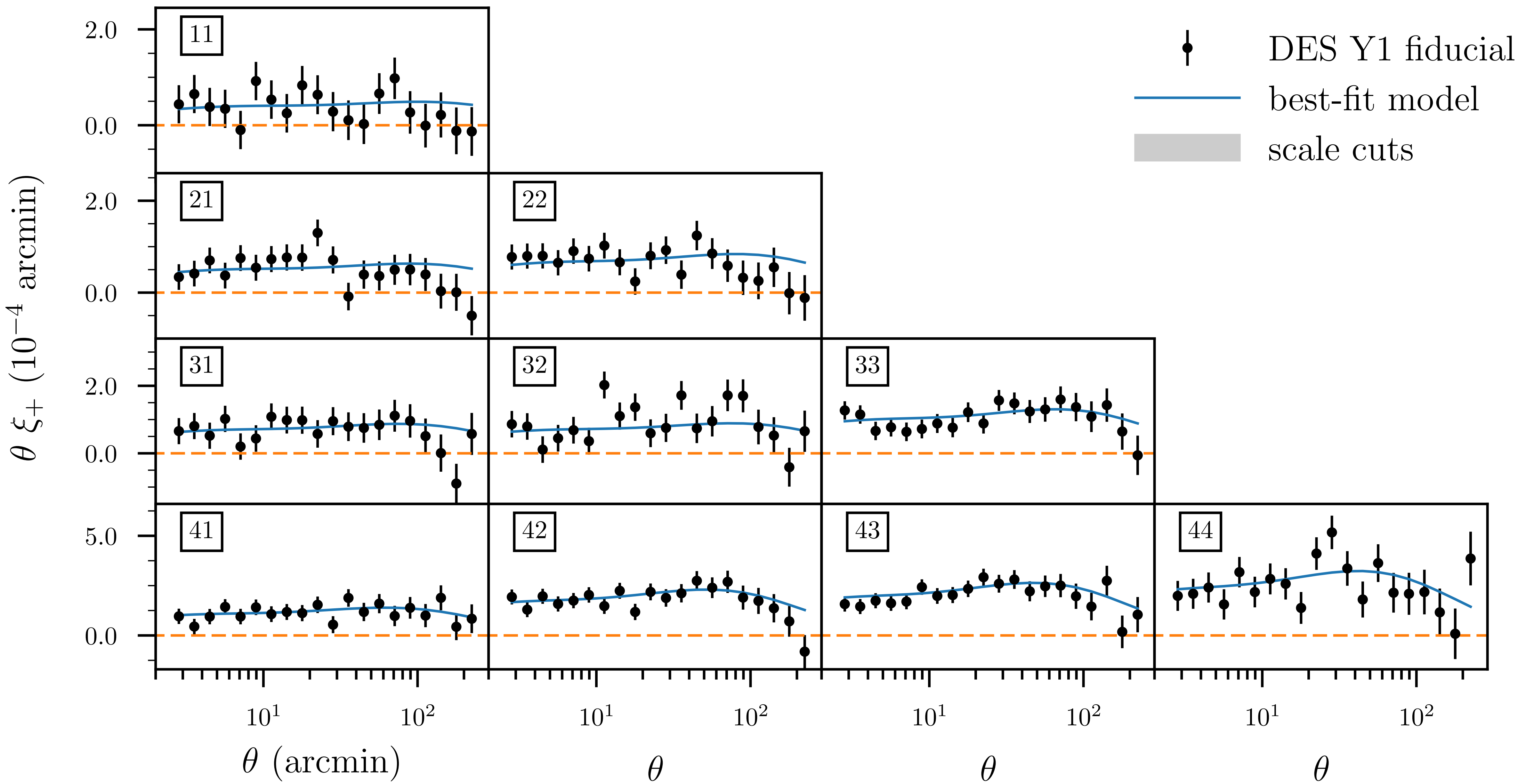
Systematic tests ("validation") are time-consuming but necessary

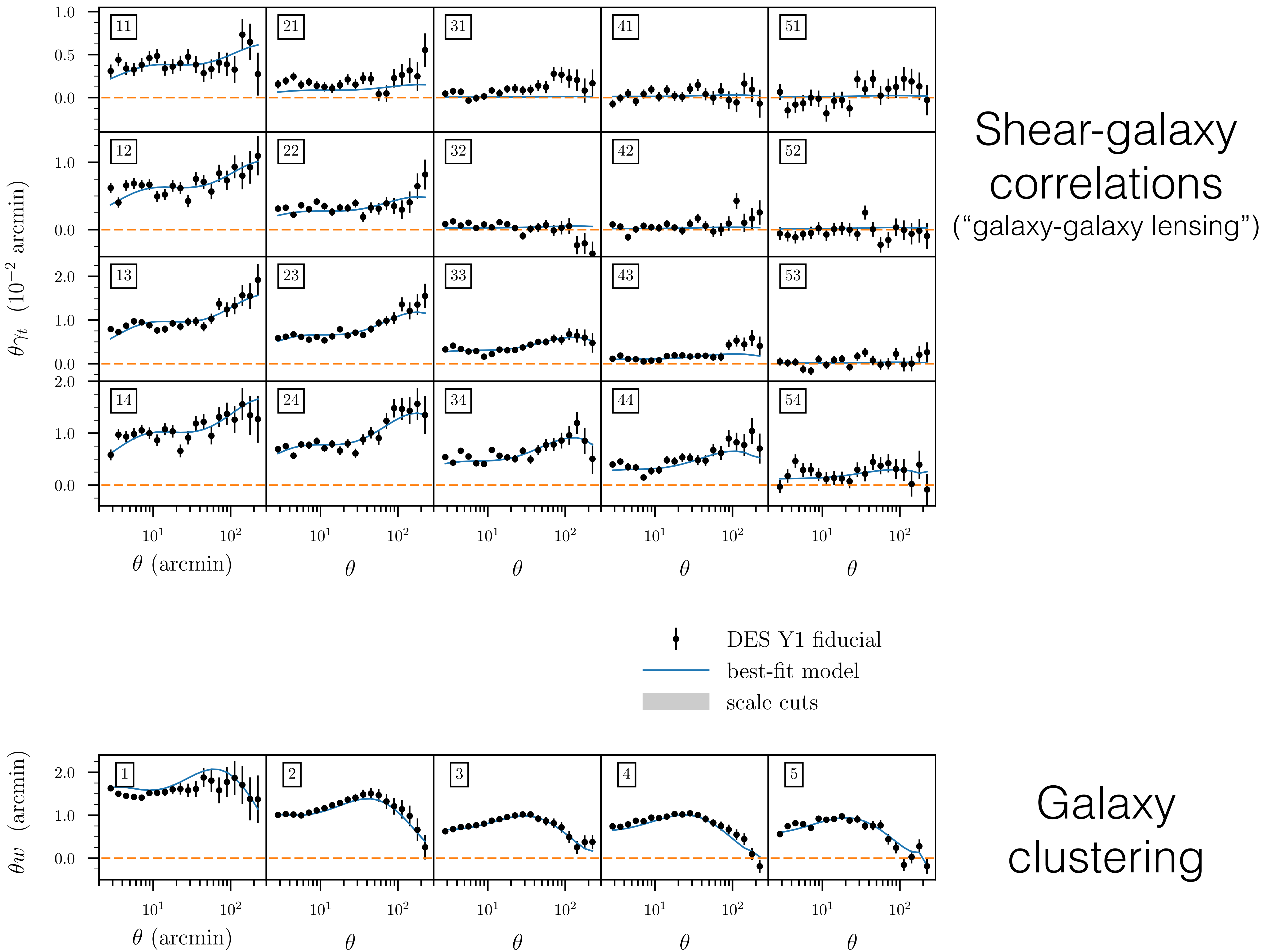


DES collaboration, LCDM extensions key paper (arXiv:1810.02499)

DES Y1 Measurements:
shear clustering, galaxy-galaxy lensing, gal clustering

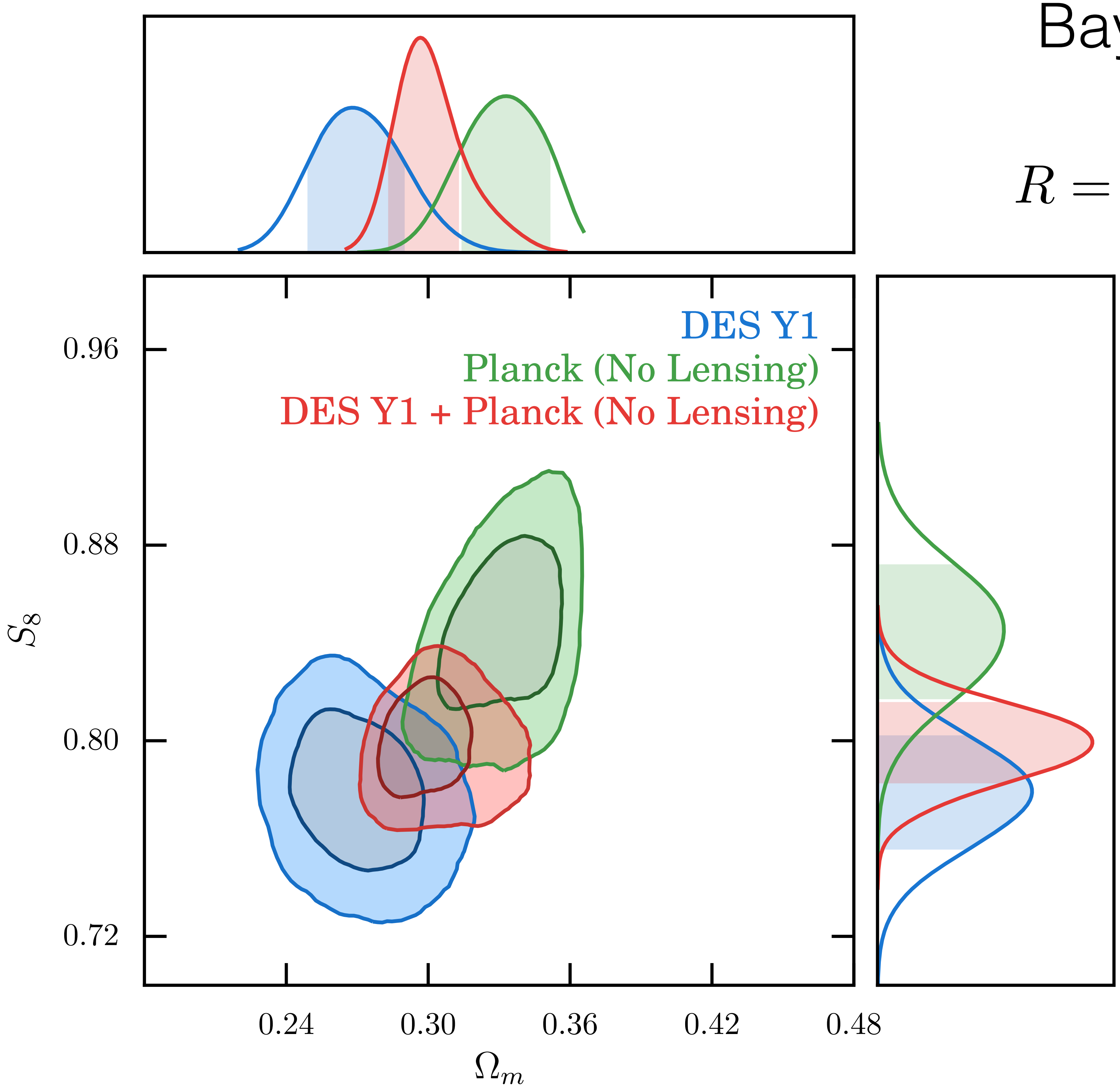
Shear clustering:





Shear-galaxy correlations
("galaxy-galaxy lensing")
Galaxy clustering
DES Y1 fiducial
best-fit model
scale cuts
θγ_t (10^-2 arcmin)
θw (arcmin)
θ (arcmin)
θ

DES Y1 3x2 results: Ω_m-S_8 plane



Bayes factor (in 26D space):

$$R = \frac{P\left(\vec{D}_1, \vec{D}_2|M\right)}{P\left(\vec{D}_1|M\right) P\left(\vec{D}_2|M\right)} = 6.6$$

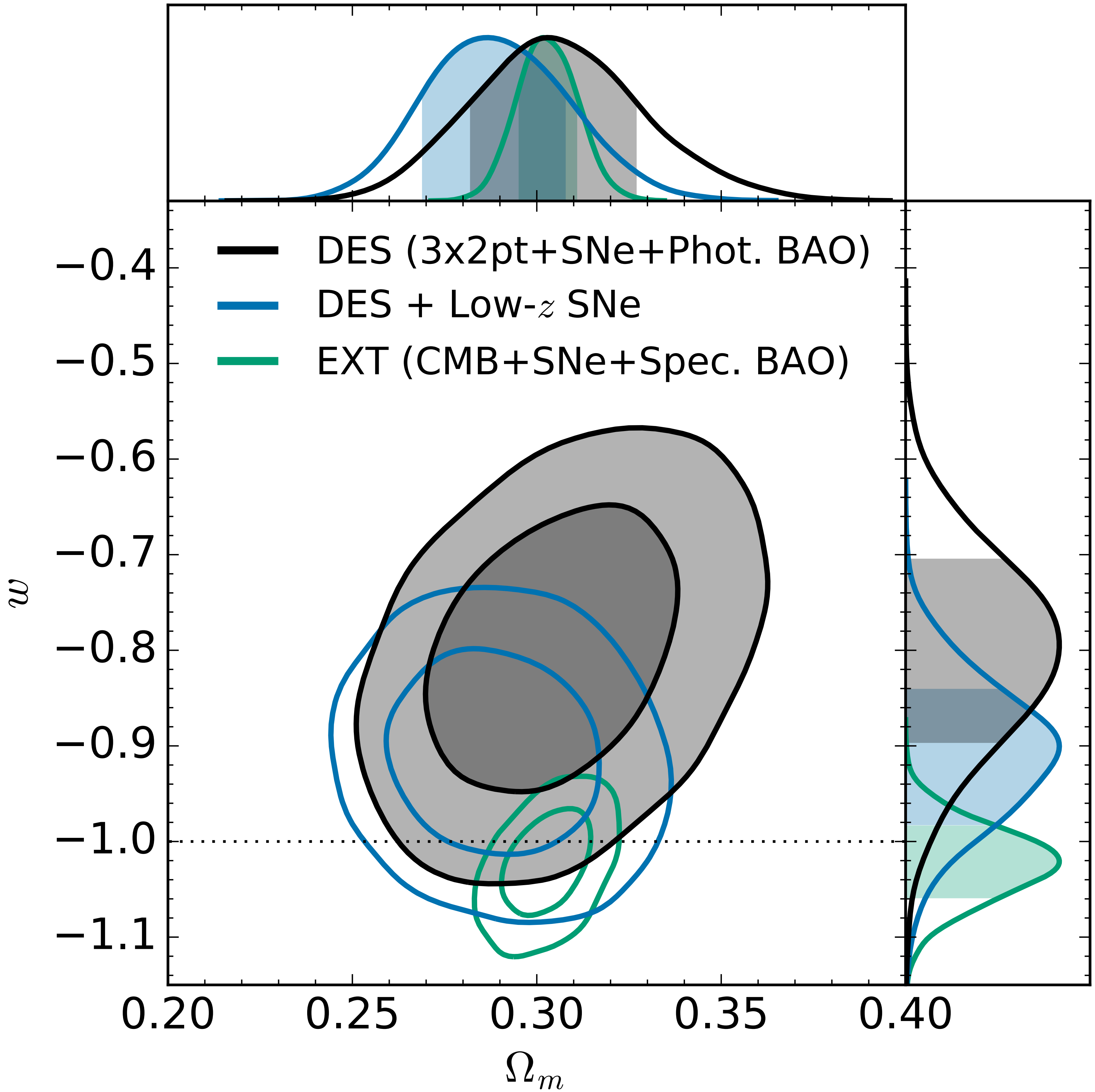
$\Rightarrow$ "substantial" agreement (DES,Planck)

$$\Omega_m = 0.267^{+0.030}_{-0.017}$$

$$S_8 = 0.773^{+0.026}_{-0.020}$$

DES collaboration, arXiv:1708.01530

DES-only Y1 constraints on DE



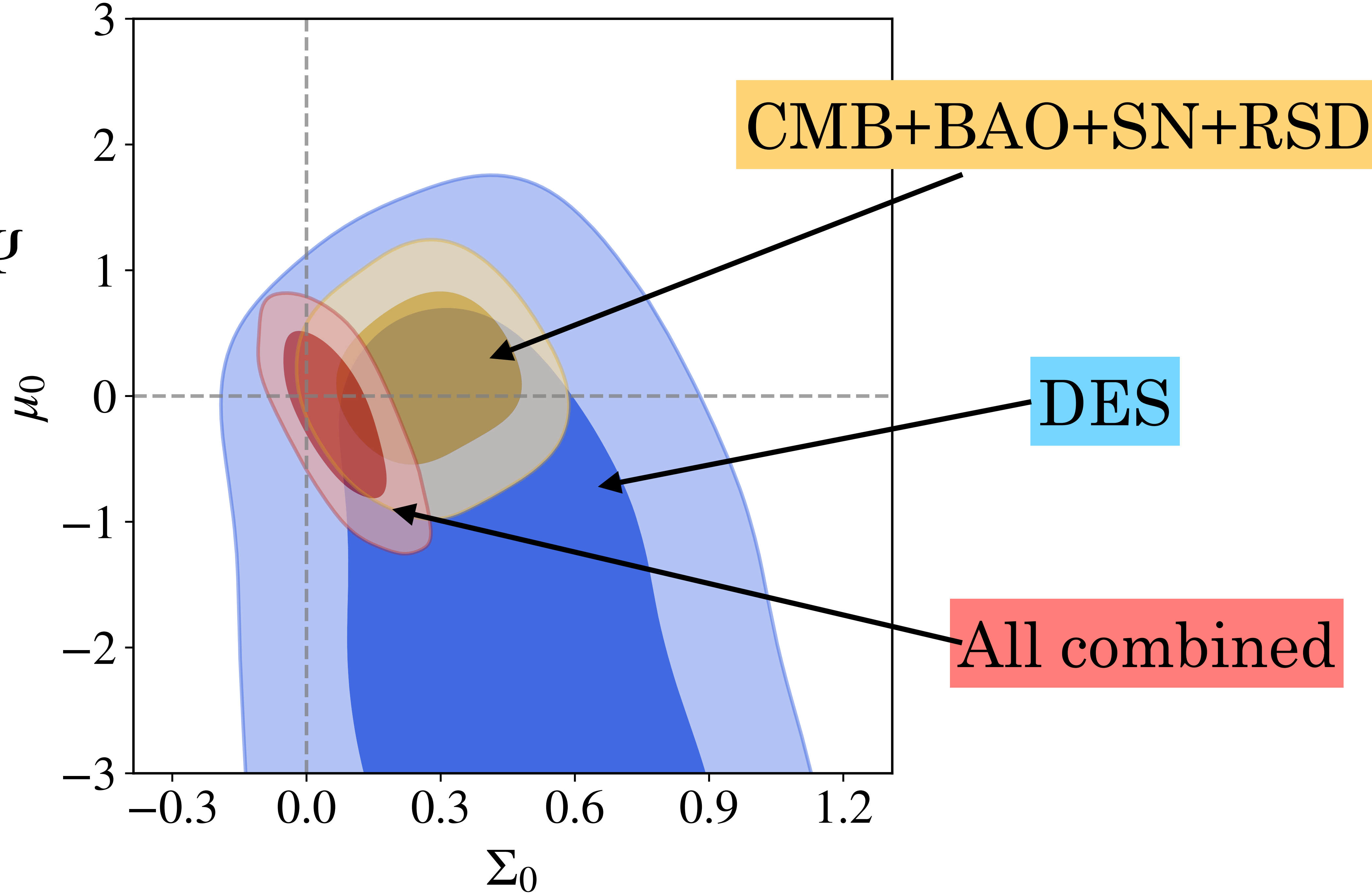
"This is the first time a low-redshift survey has been capable of independently constraining these properties of dark energy to this level of precision"

DES collaboration, arXiv:1811,02375 PRL 2019

DES Year1 results:
extensions to ΛCDM, incl. modified gravity

$1+\mu \sim \Psi$

$1+\Sigma \sim \Phi+\Psi$



DES collaboration, arXiv:1810.02499;
PRD Editor's suggestion

What if gravity deviates from GR?

For example:

$$H^2 - F(H) = \frac{8\pi G}{3}\rho, \qquad \text{or} \qquad H^2 = \frac{8\pi G}{3}\left(\rho + \frac{3F(H)}{8\pi G}\right)$$

↓ Modified gravity

↓ Dark energy

Notice: there is no way to distinguish these two possibilities just by measuring expansion rate H(z)!

Growth of structure comes to the rescue: in standard GR, H(z) determines distances **and** growth of structure

$$\ddot{\delta} + 2H\dot{\delta} - 4\pi\rho_M\delta = 0$$

⇒ measure geometry [D(z), Vol(z)] and growth [Pk(z)]

Sensitivity to geometry and growth

Cosmological Probe	Geometry	Growth
SN Ia	$H_0 D_L(z)$	—
BAO	$\left(\frac{D_A^2(z)}{H(z)}\right)^{1/3} / r_s(z_d)$	—
CMB peak loc.	$R \propto \sqrt{\Omega_m H_0^2}\, D_A(z_*)$	—
Cluster counts	$\frac{dV}{dz}$	$\frac{dn}{dM}$
Weak lens 2pt	$\frac{r^2(z)}{H(z)} W_i(z) W_j(z)$	$P\left(k = \frac{\ell}{r(z)}\right)$
RSD	$F(z) \propto D_A(z) H(z)$	$f(z)\sigma_8(z)$

Ruiz & Huterer, 2015

Specifically: compare geometry and growth in order to stress-test the LCDM model and see if it "breaks"

Our approach:

Double the standard DE parameter space

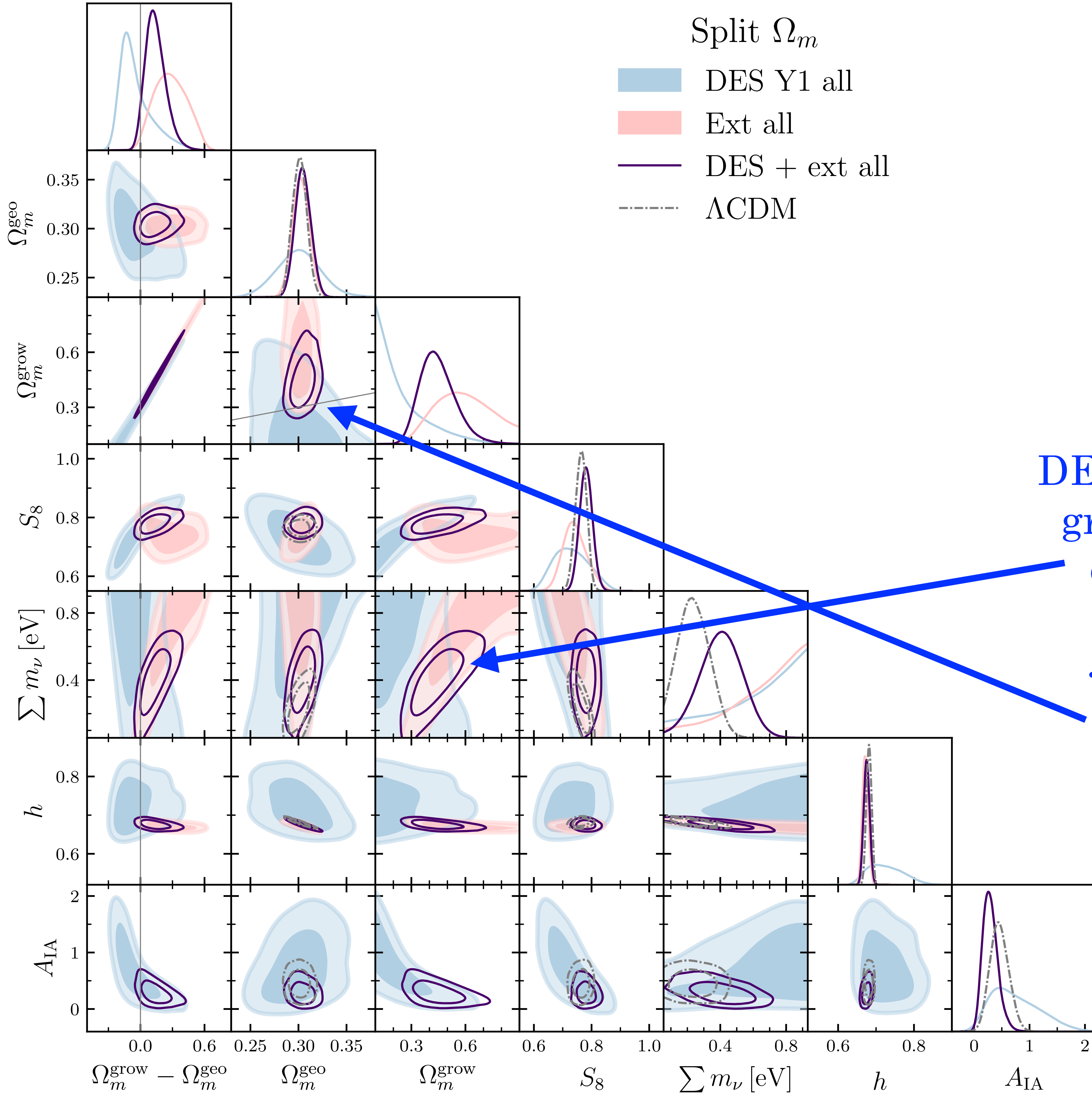
($\Omega_M = 1 - \Omega_{DE}$ and w):

$\Rightarrow \Omega_M^{geom}, w^{geom}\ \Omega_M^{grow}, w^{grow}$

[In addition to other, usual parameters]

Zhang et al (2005); Wang et al (2007); Ruiz & Huterer (2015); Bernal et al (2016)

Geometry-growth tests with DES Y1



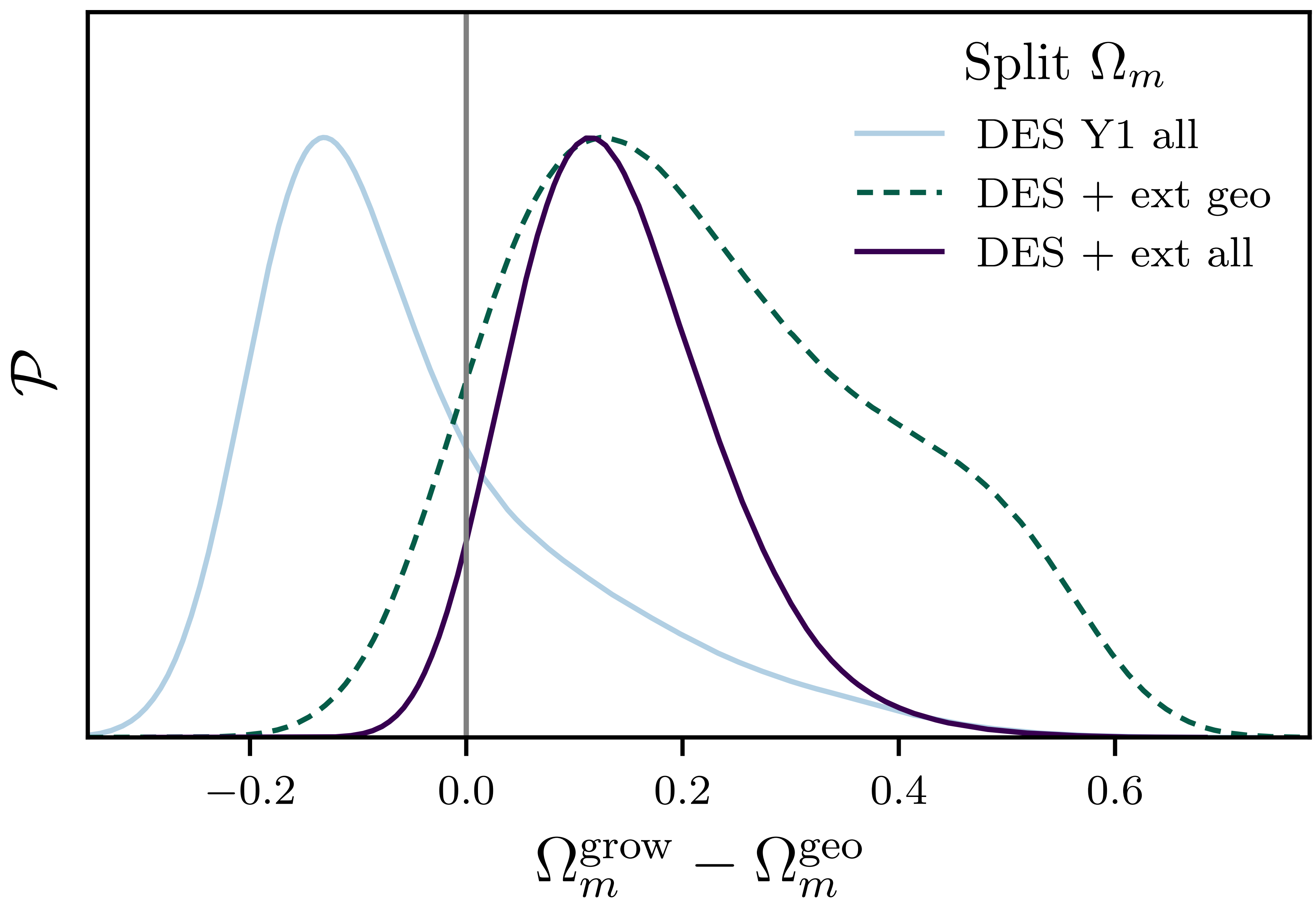
Jessie Muir
(Stanford)

DES can break the growth-neutrino degeneracy…

…and get interesting constraints in geom-grow plane

Muir et al (DES collab.), arXiv:2010.05935

Geometry-growth tests with DES Y1



Jessie Muir
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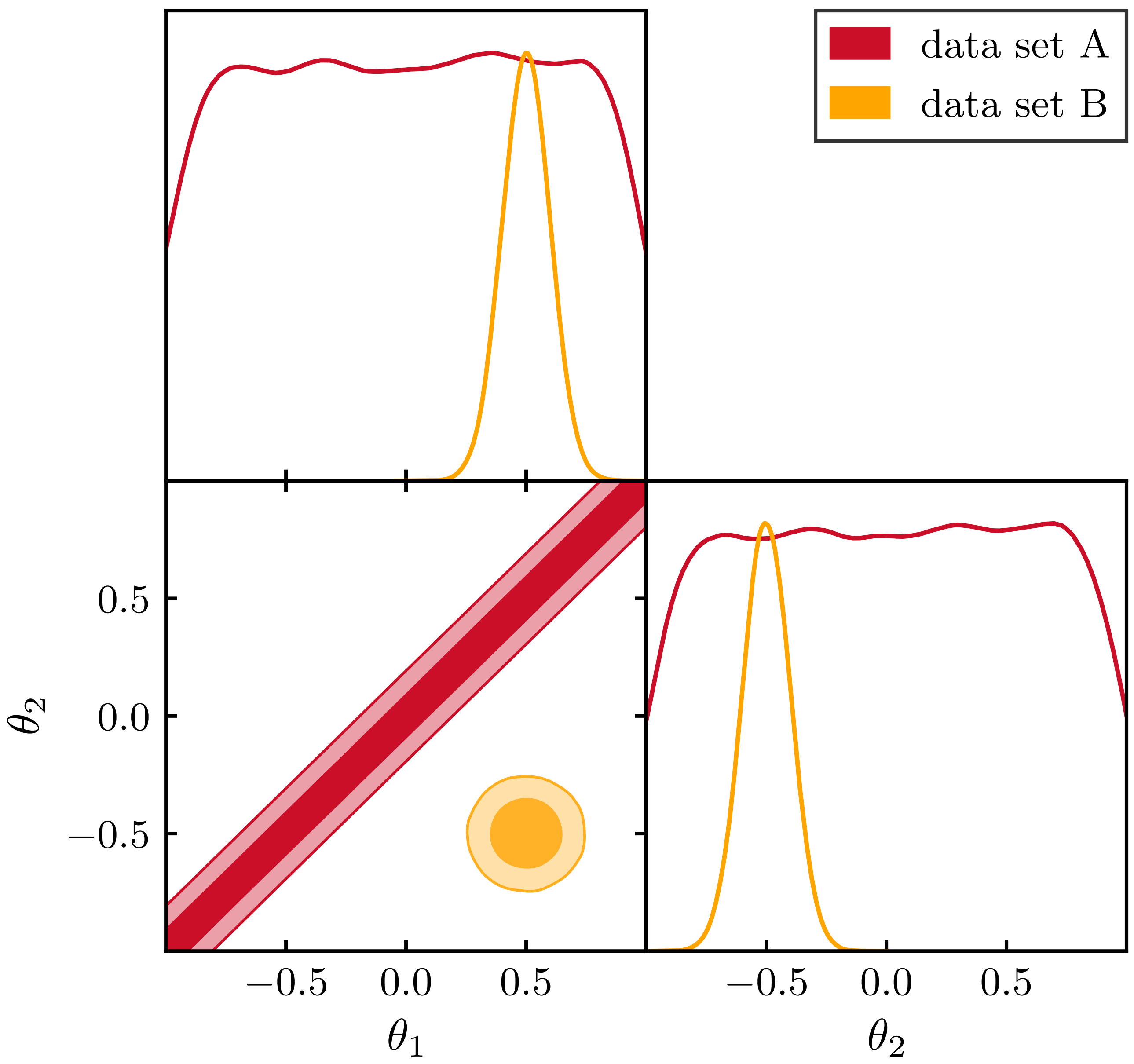
Muir et al (DES collab.), arXiv:2010.05935

How do you measure (N-dim) tensions?

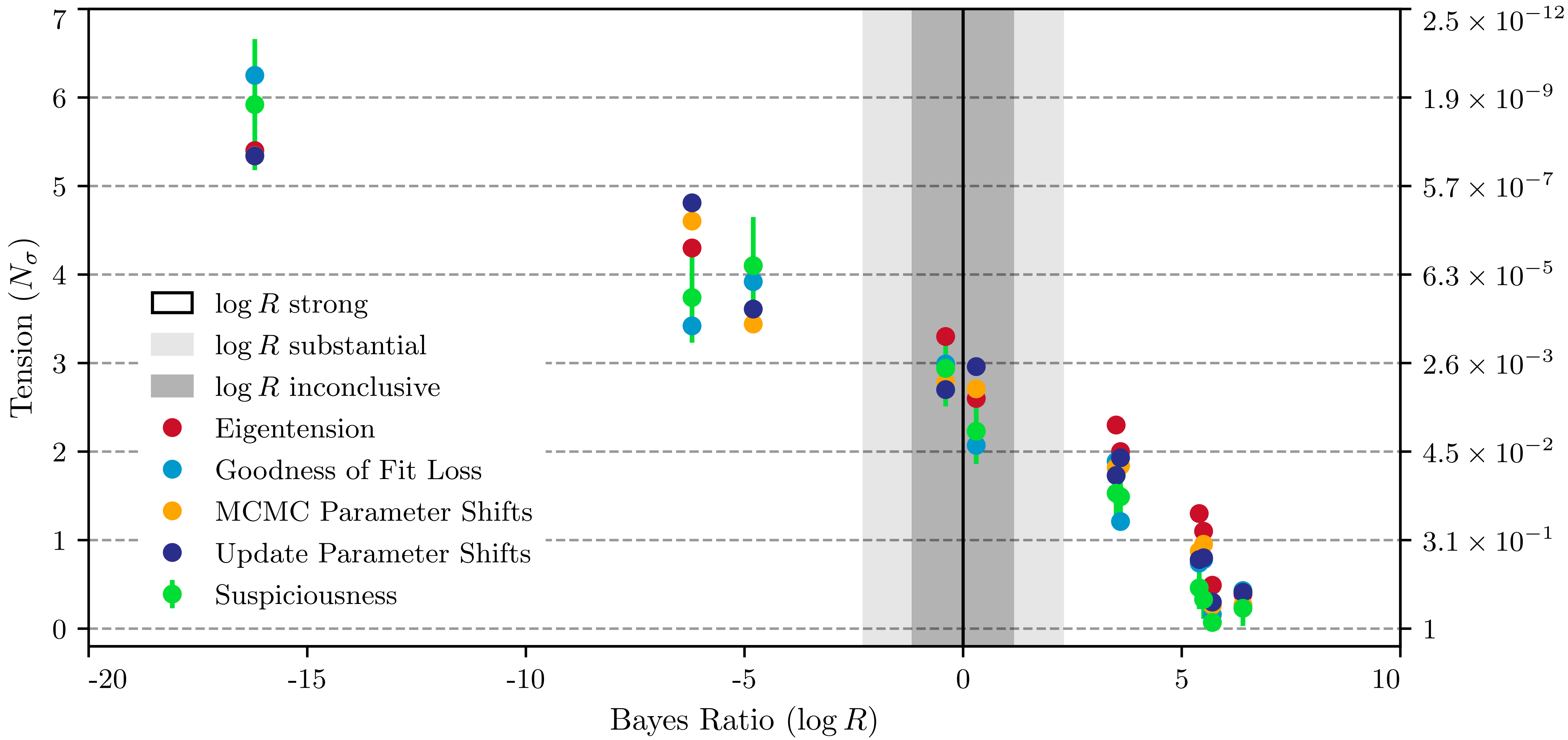
In 1D it's easy, but in ≥2D, ambiguous how to estimate



Lemos, Raveri et al (DES collab.),
in prep (arXiv in ~2 weeks)

How do you measure (N-dim) tensions?

Principal result: tension metrics (roughly) agree



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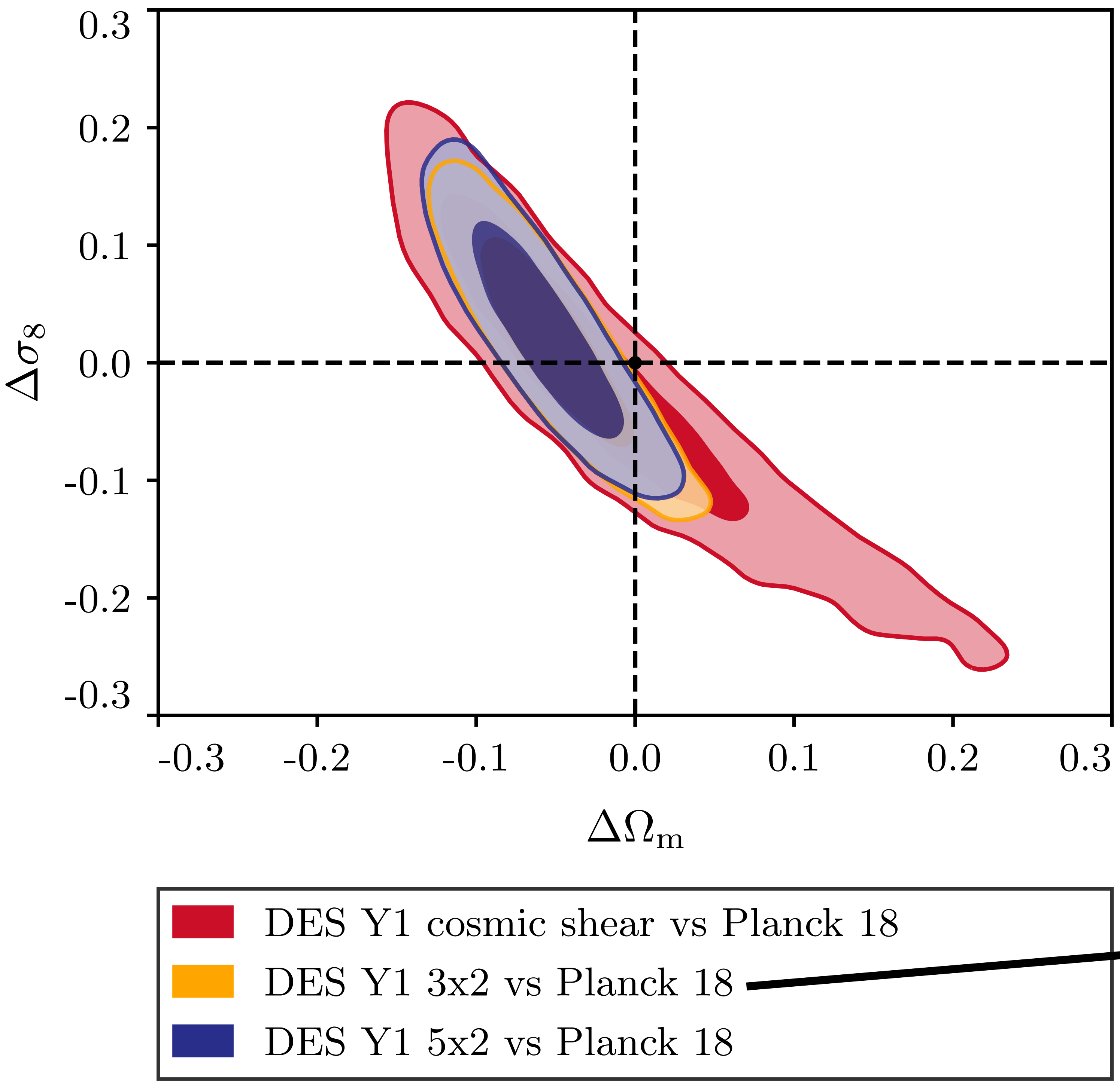
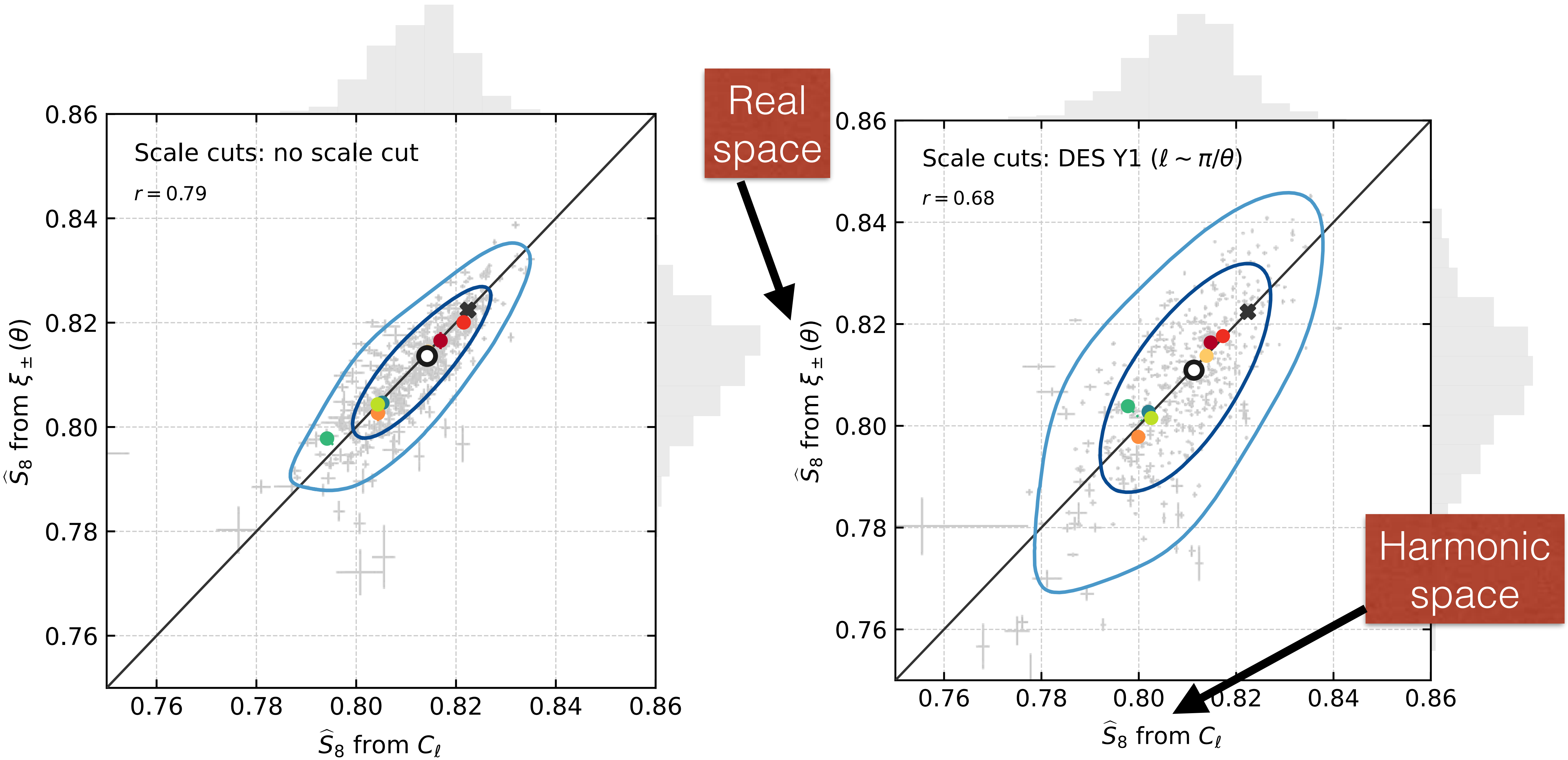
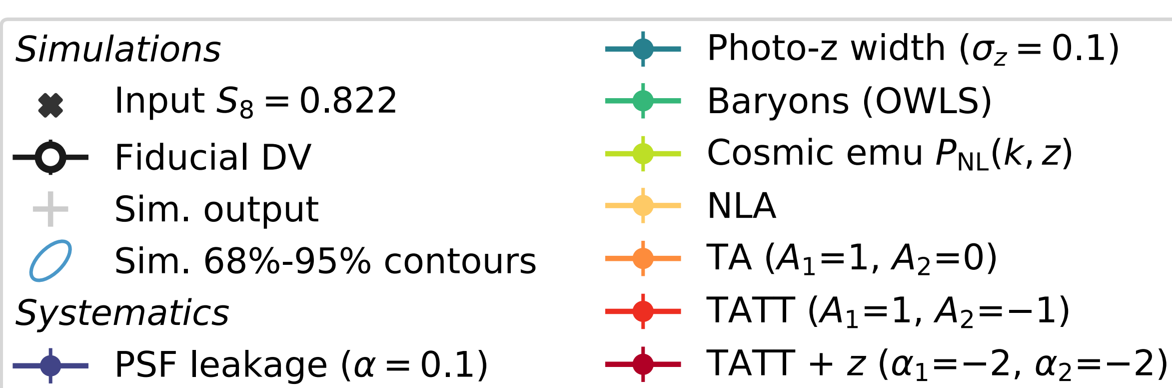


2-ish sigma tension

Lemos, Raveri et al (DES collab.), in prep (arXiv in ~2 weeks)

Harmonic vs real space analysis - same information??

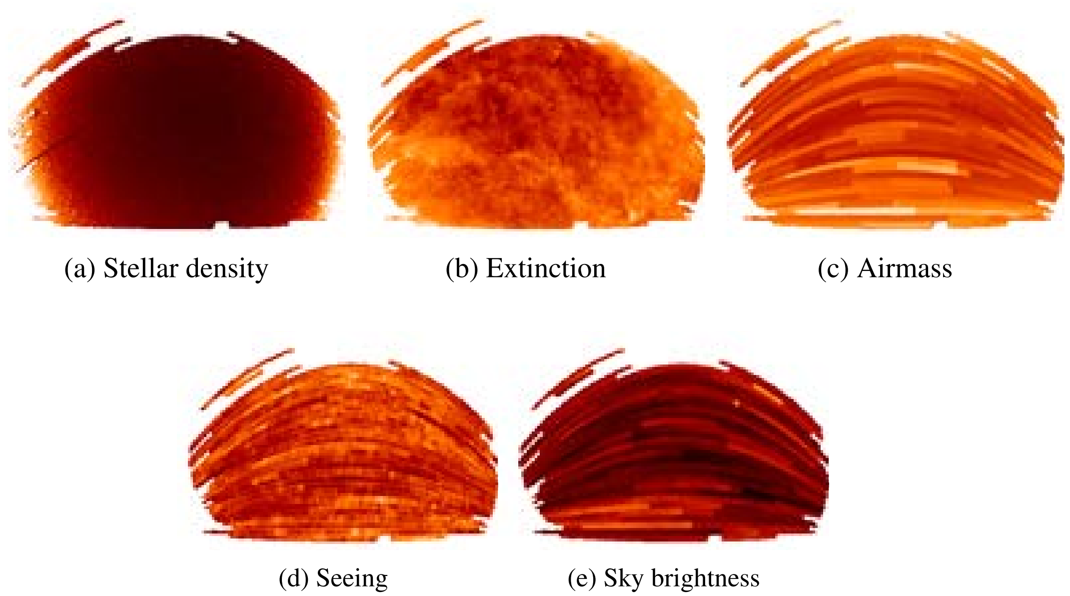




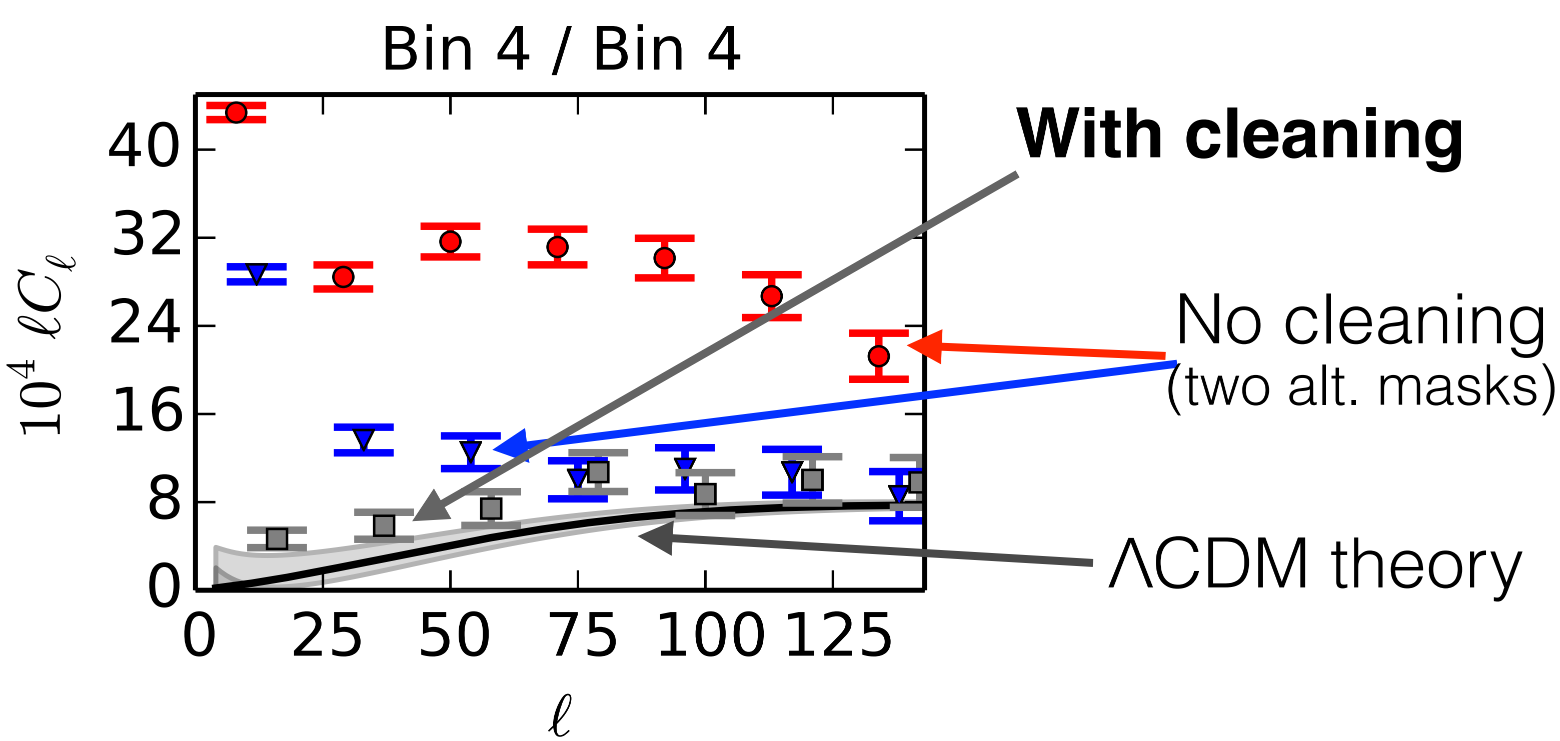
Doux et al (DES collab.), arXiv.2011.06469

Systematics cleaning (of LSS maps)

- **Map contamination: a key systematic in LSS**
- due to variety of observ/astro/instrumental reasons
- visible “by eye” at large scales
- important for all galaxy-clustering, shear etc
- esp important for large-spatial-scale science (f_{NL})
- multiplicative, so small scales affected too



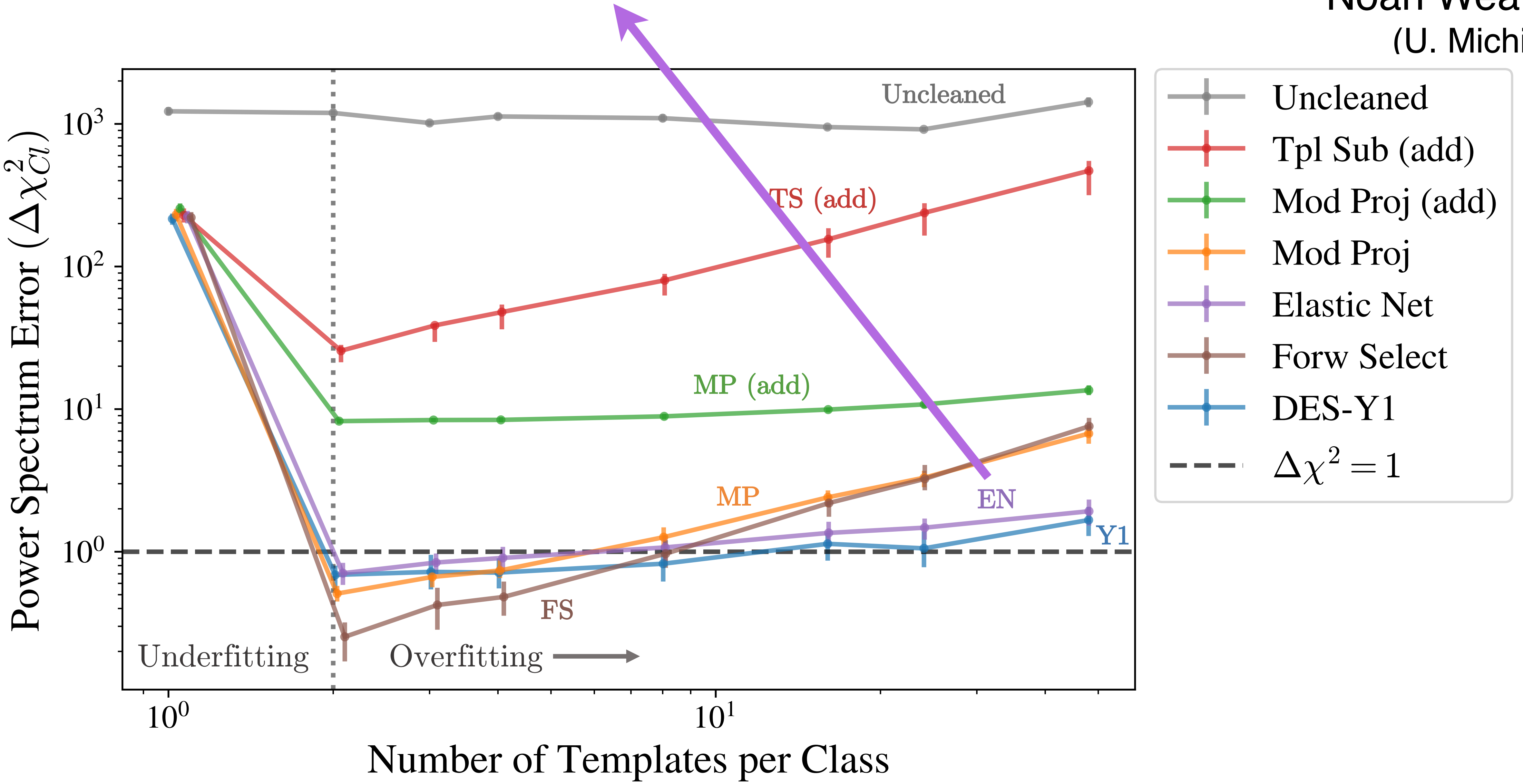
Leistedt & Peiris 2015



Systematics cleaning (of LSS maps)

$$\text{Loss} = \underbrace{\frac{1}{2N_{\text{pix}}}||d_{\text{obs}} - \sum_i^{N_{\text{tpl}}} t_i\alpha_i||_2^2}_{\text{Least Squares Loss}} + \lambda_1 \underbrace{\left(\sum_i^{N_{\text{tpl}}} |\alpha_i|\right)}_{\text{Prefer fewer templates}} + \frac{\lambda_2}{2} \underbrace{\left(\sum_i^{N_{\text{tpl}}} |\alpha_i^\dagger \alpha_i|\right)^2}_{\text{Shrink imprecise estimates}},$$

Noah Weaverdyck
(U. Michigan)



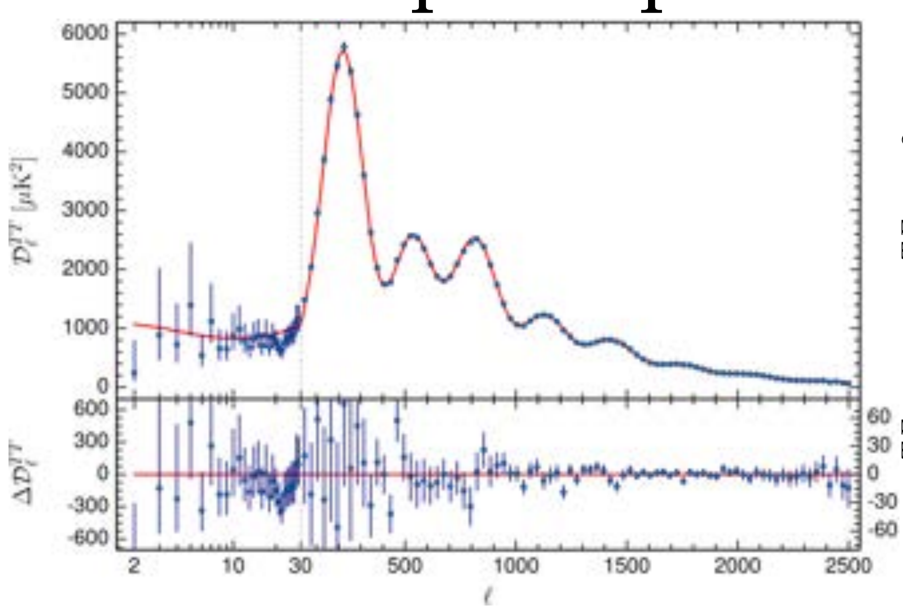
Weaverdyck & Huterer, arXiv:2007.14499

Story so far:

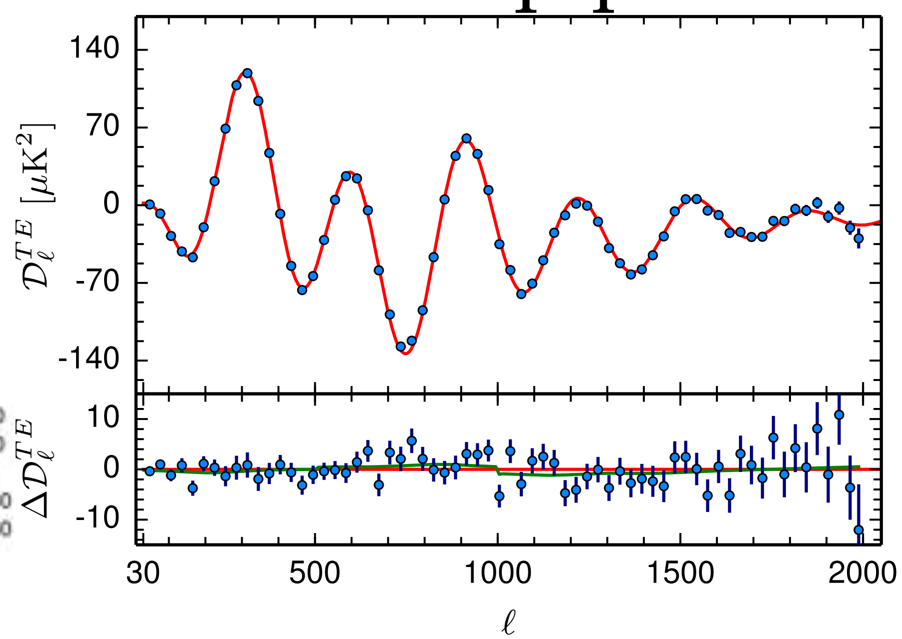
- Cosmology definitely in the precision regime
- Impressive constraints on DM, DE and inflation…
- …but some big questions unanswered
- Lots of potential from upcoming surveys

But are Planck++ constraints *so* good that they bias us?

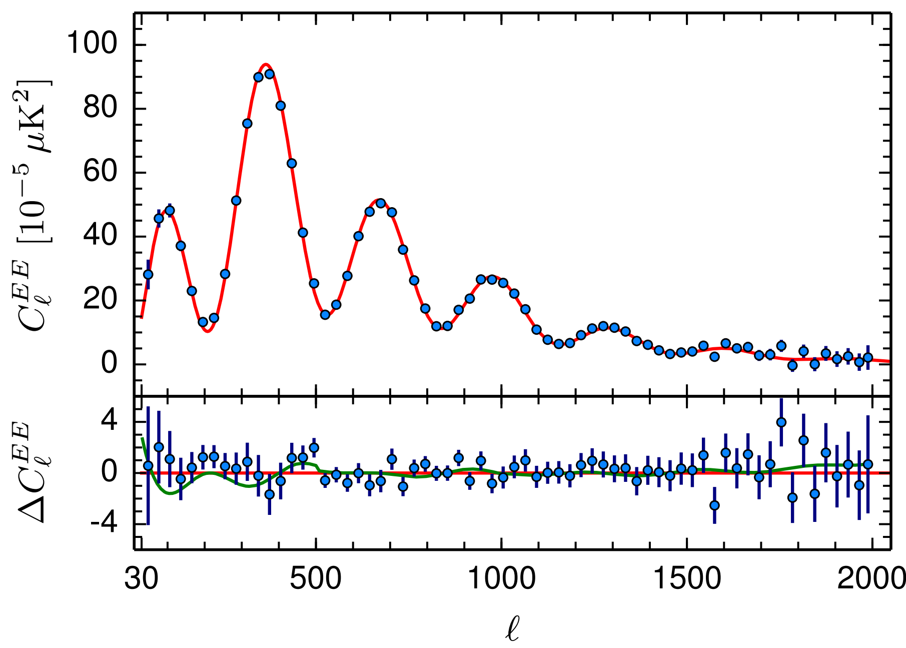
temp-temp



temp-pol



pol-pol



Danger of declaring currently favored model to be the truth

$\Longrightarrow$ **blinding new data is key**

Blinding the DES analysis

Jessie Muir
(Stanford)

Our requirements:

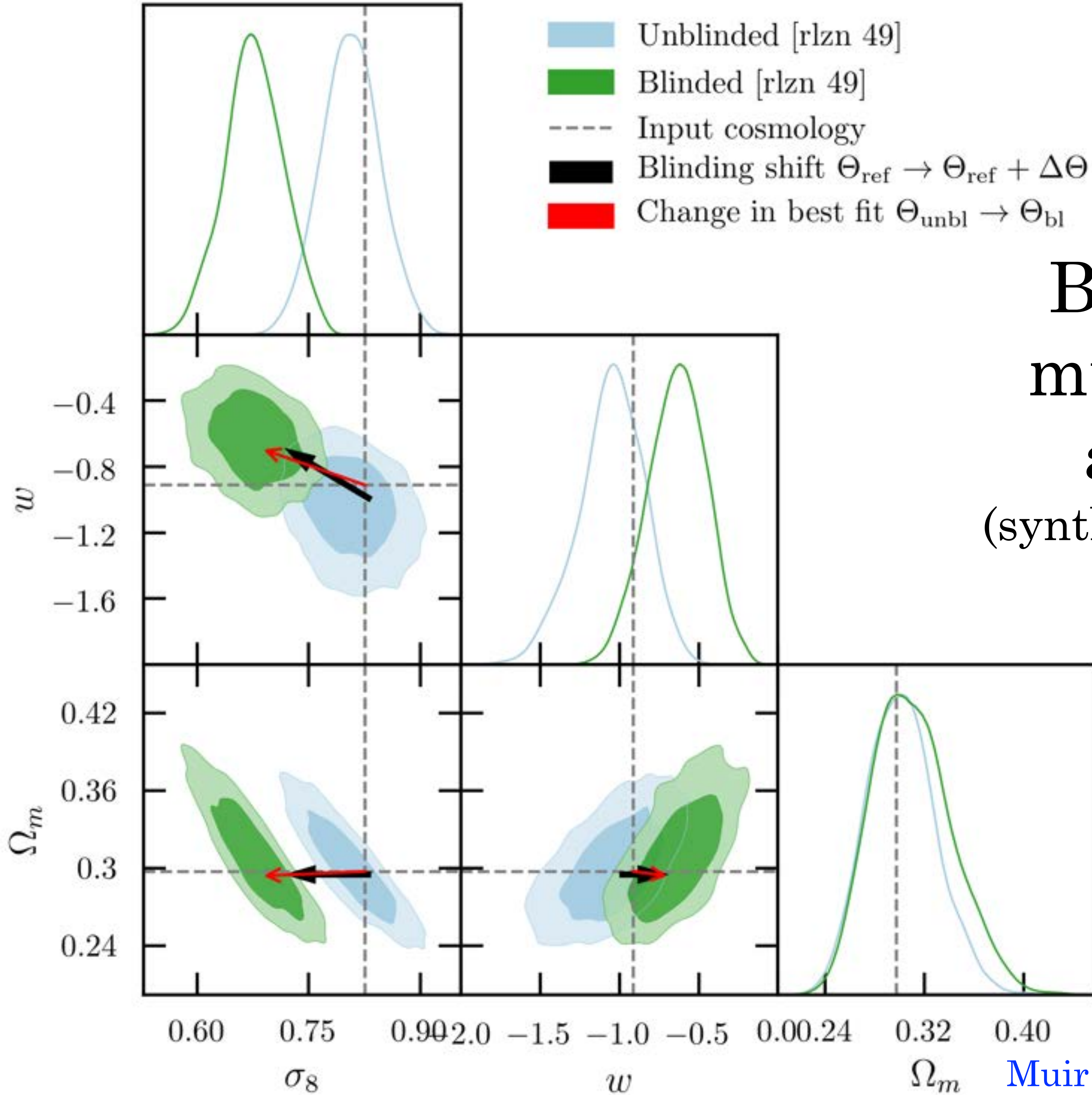
- Preserve inter-consistency of cosmological probes
- Preserve ability to test for systematic errors

Our choice is specifically:

$$\xi_{ij}^{\mathrm{blinded}} = \xi_{ij}^{\mathrm{measured}} + [\xi_{ij}^{\mathrm{th\,model\,1}} - \xi_{ij}^{\mathrm{th\,model\,2}}]$$

Applied to DES Y3!

Muir, Bernstein, Huterer, et al., arXiv:1911.05929



Blinding a multi-probe analysis

(synthetic test shown)

Muir et al, arXiv:1911:15929

DES Y3 key paper: cosmological results

- Almost 5000 sqdeg
- ~100 million source galaxies for lensing
- Improved methodology across board
- Analysis was 3 years in the making
- **Results unblinded, out in ~few weeks**

Conclusions

- Dark Energy is a premier mystery in physics/cosmology; physical reason for accelerating universe still an open question

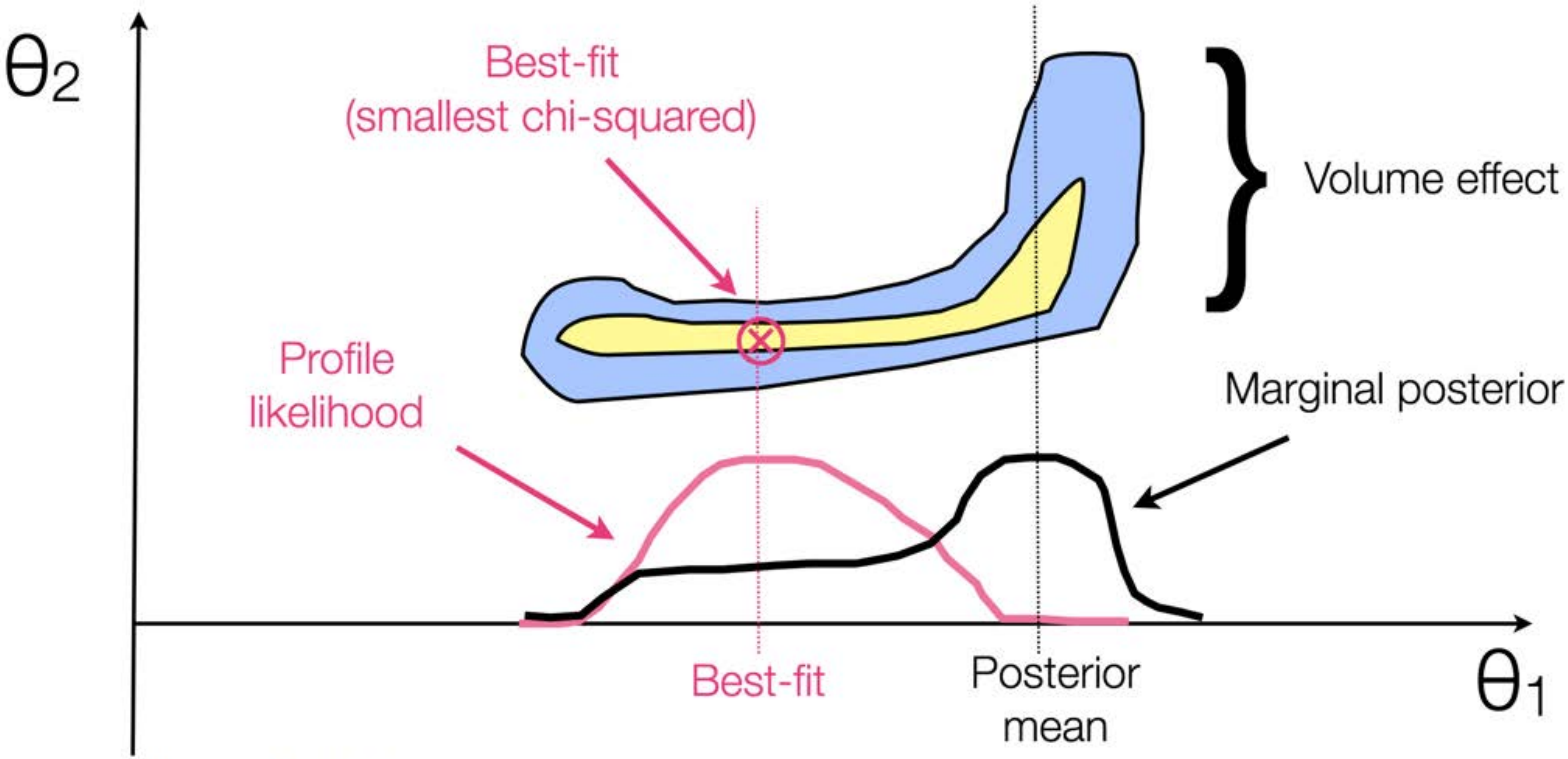
- Impressive variety of new data; new telescopes planned

- Like particle physicists, we would really like to see some "bumps" in the data (e.g. Hubble tension!).

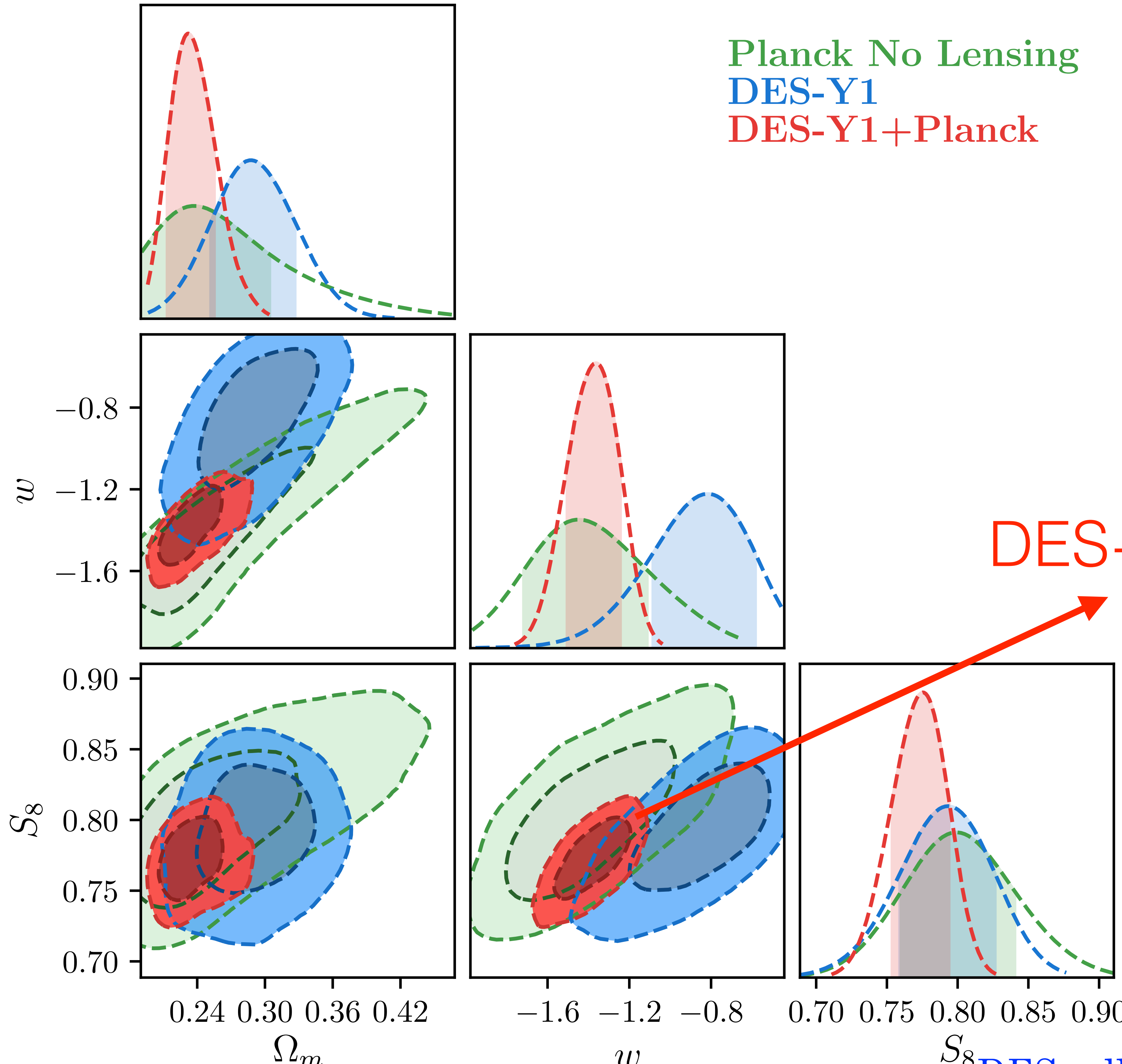
- Forthcoming DES Y3 results will dramatically improve constraints from photometric LSS, may hold surprises

Extra slides

Prior-volume effect illustrated



DES Y1 3x2 results: constraints on w



DES+Planck:

$$w = -1.47^{+0.31}_{-0.22}$$

DES+Planck+
SN+BAO:

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

DES collaboration, arXiv:1708.01530