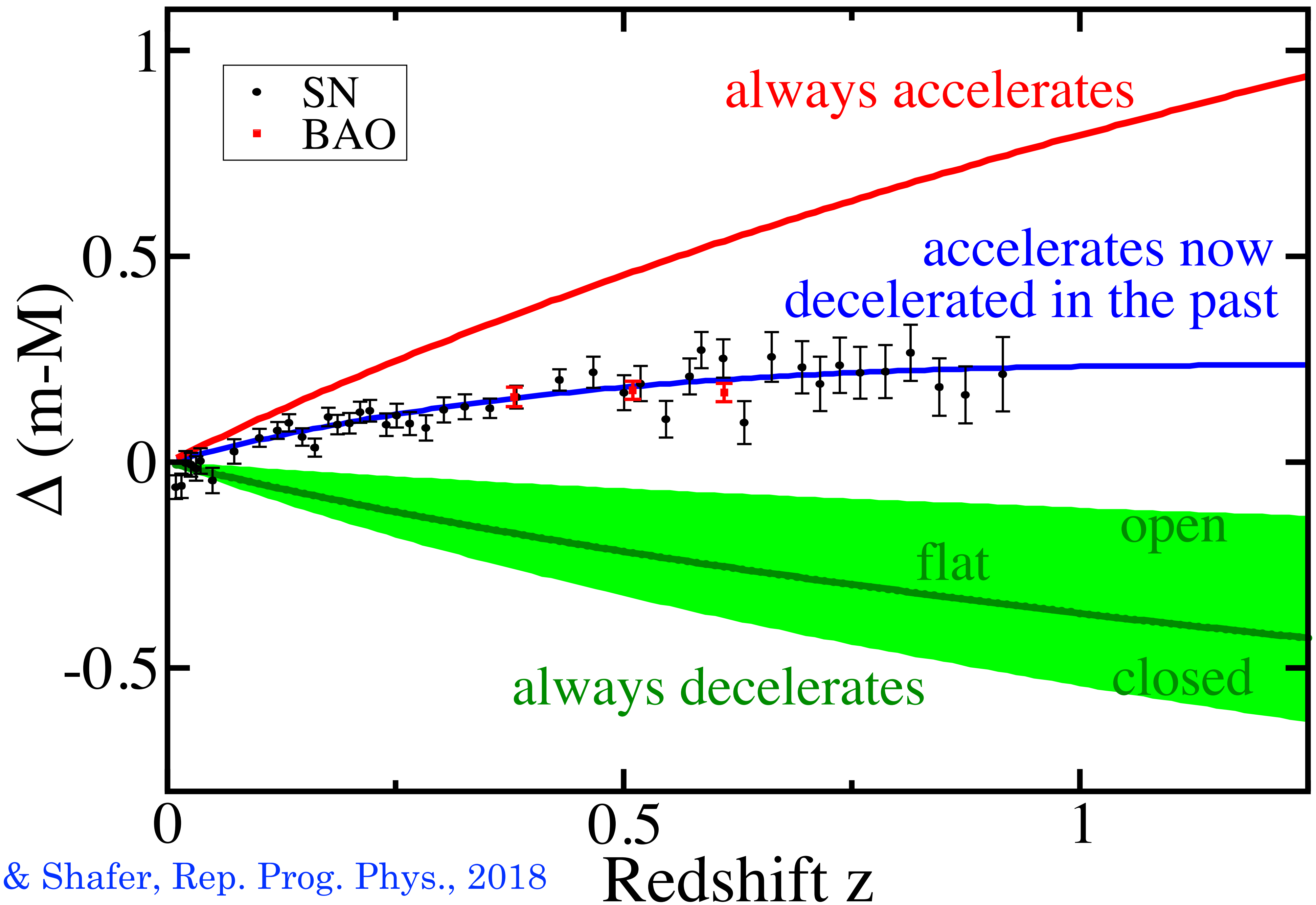
Dark Energy two decades after: Cosmological Probes and Consistency Tests

Dragan Huterer
University of Michigan



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

A bit of my background

- Theorist, but working very close to data
- First appearance of phrase “dark energy” in:

PHYSICAL REVIEW D, VOLUME 60, 081301

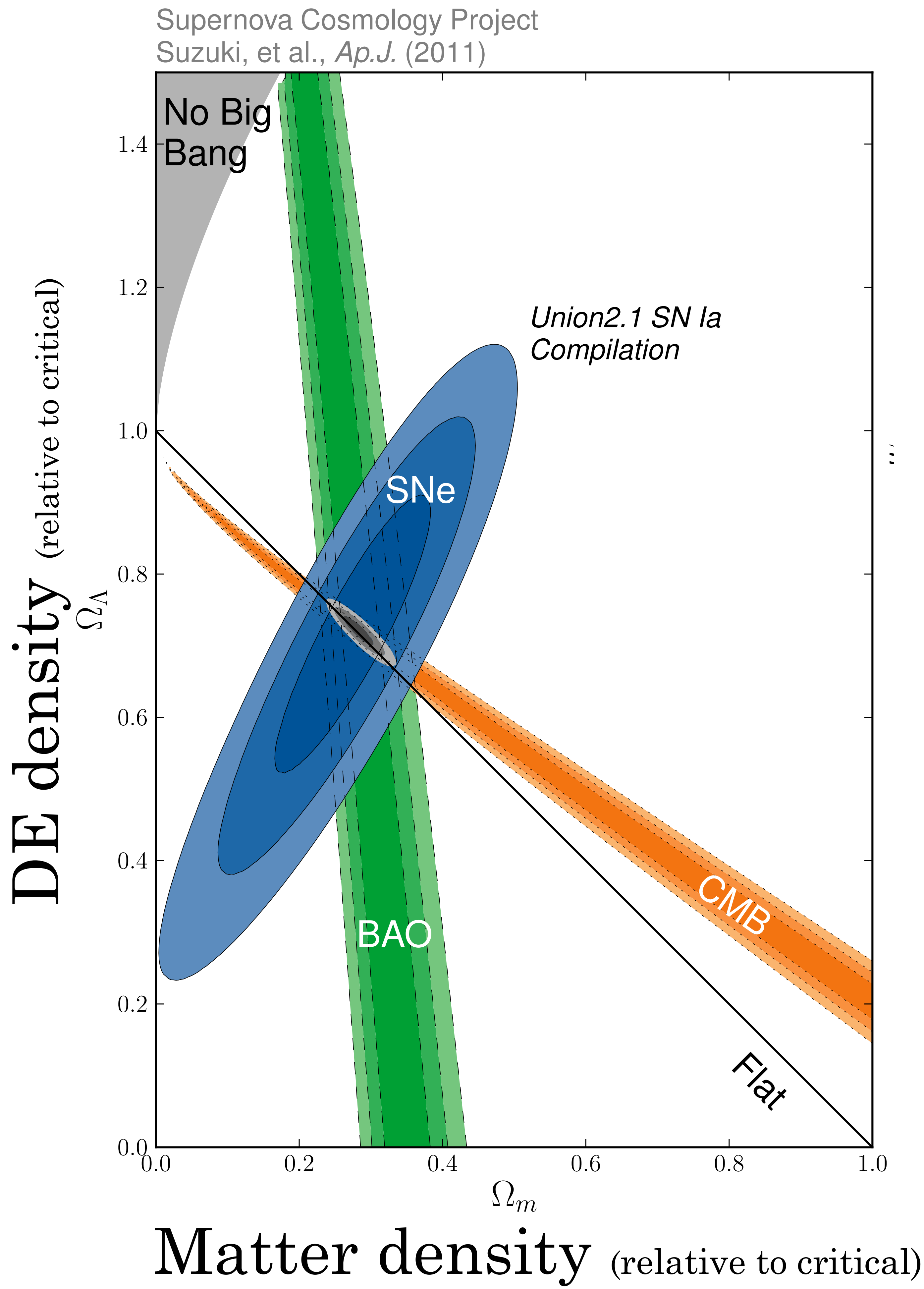
Prospects for probing the dark energy via supernova distance measurements

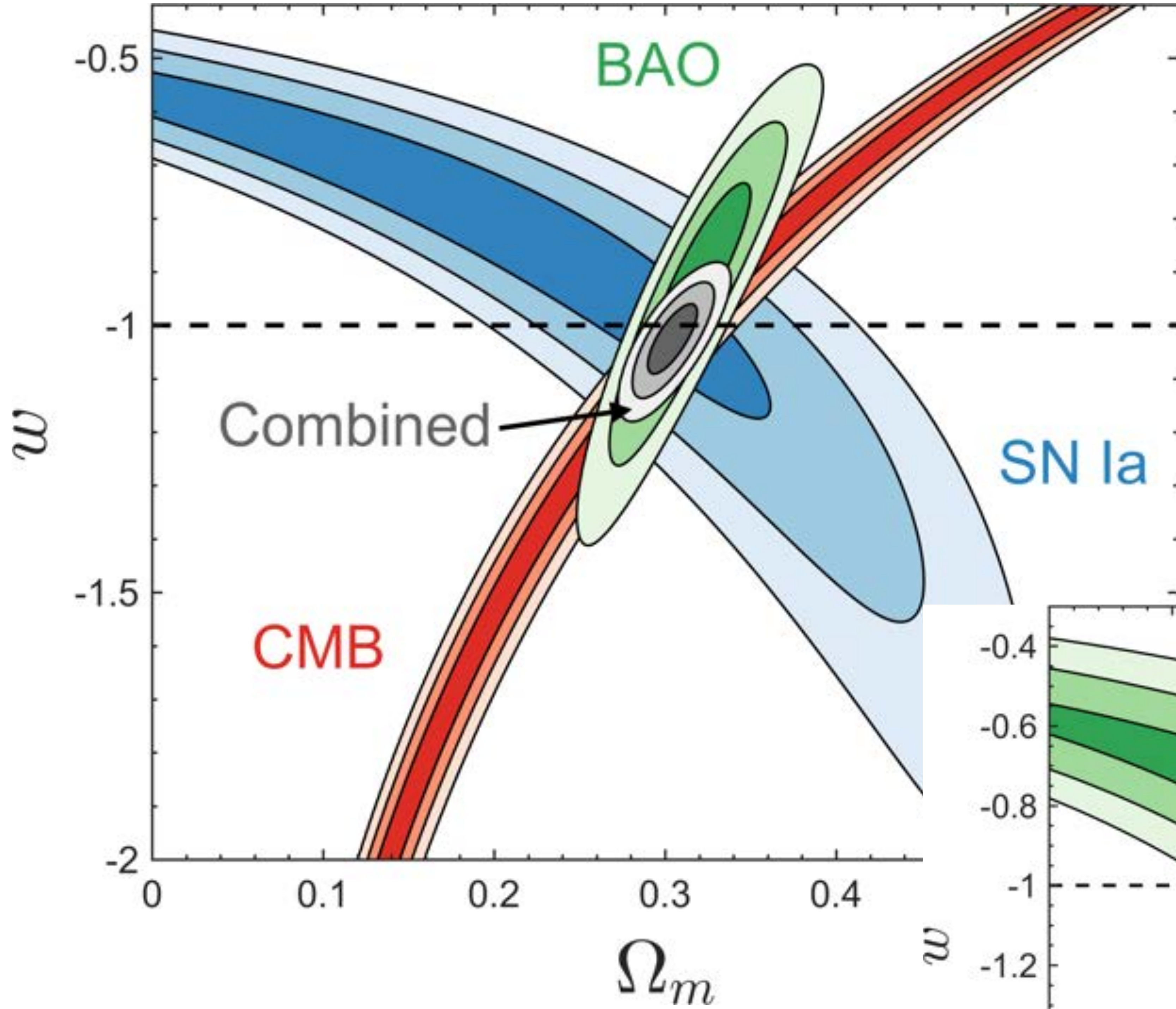
Dragan Huterer
Department of Physics, Enrico Fermi Institute, The University of Chicago, Chicago, Illinois 60637-1433

Michael S. Turner
Department of Physics, Enrico Fermi Institute, The University of Chicago, Chicago, Illinois 60637-1433;
Department of Astronomy & Astrophysics, Enrico Fermi Institute, The University of Chicago, Chicago, Illinois 60637-1433;
and NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, Illinois 60510-0500
(Received 18 August 1998; revised manuscript received 6 April 1999; published 30 August 1999)

- These days interested in using data to “break” LCDM model and also test isotropy, tensions, etc.
- Chris Smeenk’s housemate at Oxford (summer 1994)

Recent (2011) constraints on dark energy density

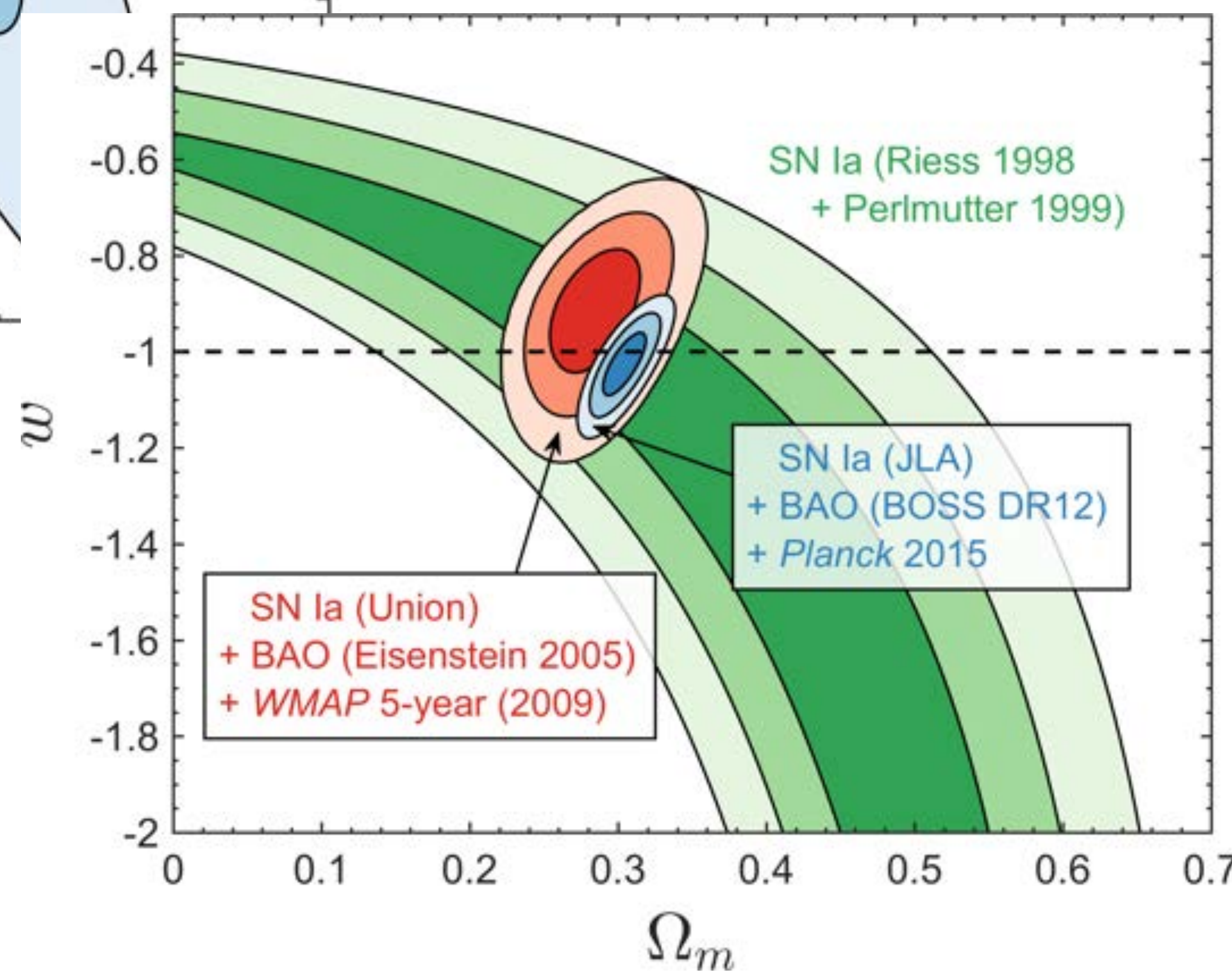




$$\Omega_m = 1 - \Omega_{\rm DE}$$

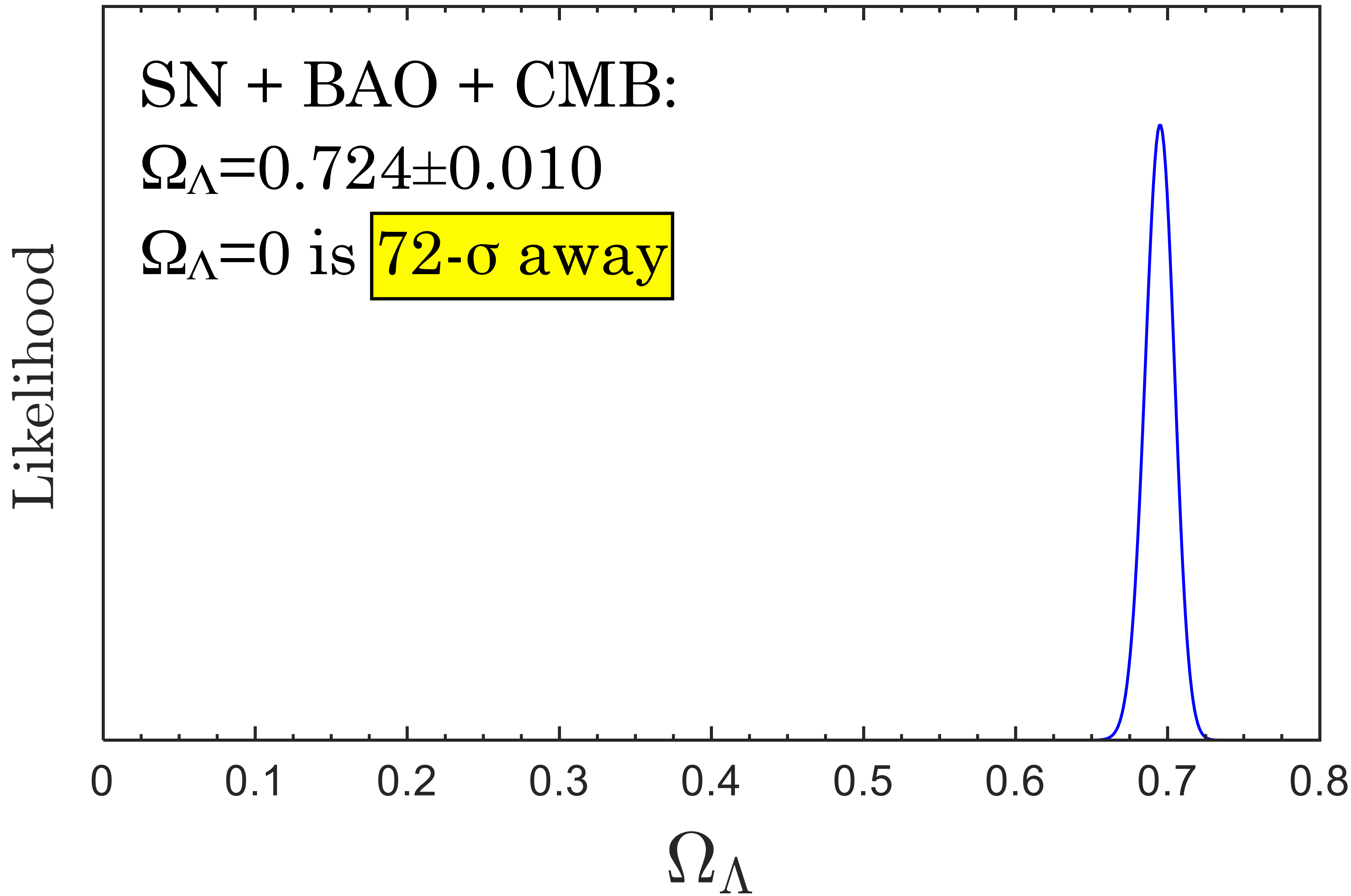
$$\Omega_{\rm DE} \equiv \frac{\rho_{\rm DE}}{\rho_{\rm crit}}$$

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

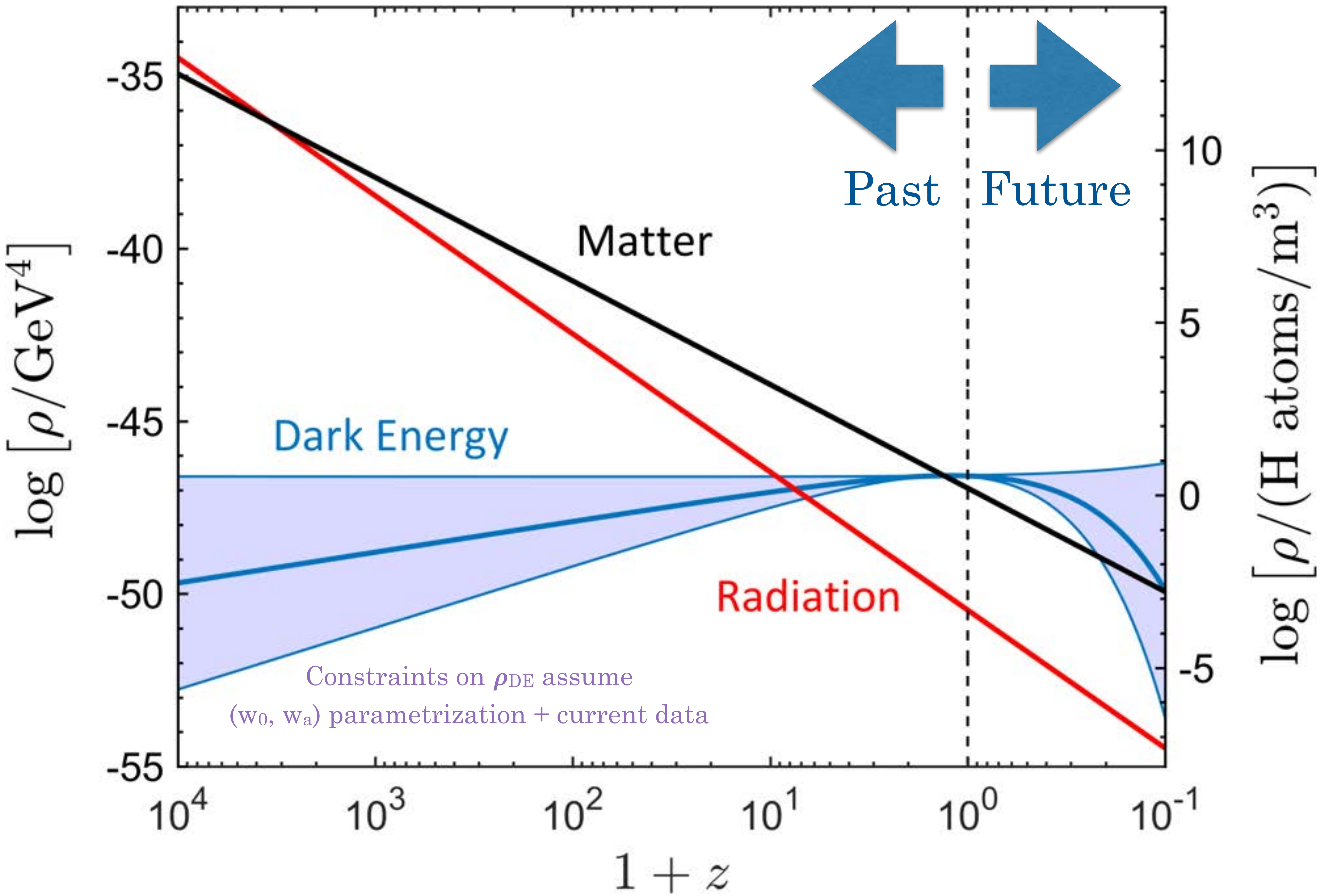


Huterer & Shafer,
Rep. Prog. Phys., 2018

Current evidence for dark energy is impressively strong



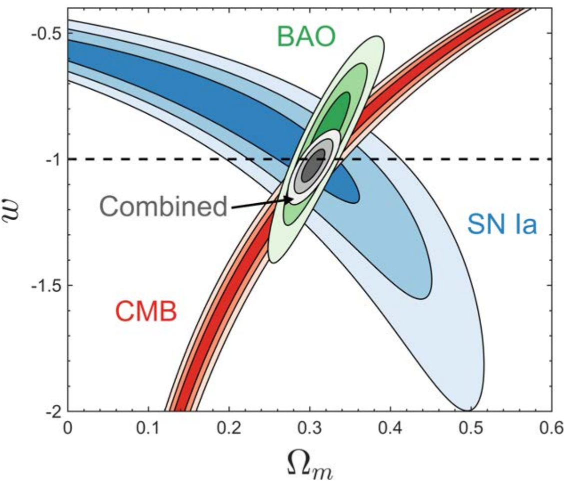
Daniel Shafer, 2017



Huterer & Shafer,
Rep. Prog. Phys 2018

A difficulty:

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



Contrast this situation with:

1. Neutrino masses:

$$\left.\begin{array}{l}(\Delta m^2)_{sol} \simeq 8\times10^{-5}\ \mathrm{eV}^2 \\ (\Delta m^2)_{atm} \simeq 3\times10^{-3}\ \mathrm{eV}^2\end{array}\right\}$$

$\sum m_i = 0.06\ \mathrm{eV}^*$ (normal)

vs.

$\sum m_i = 0.11\ \mathrm{eV}^*$ (inverted)

*(assuming $m_3=0$)

2. Higgs Boson mass (before LHC 2012):

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

(assuming Standard Model Higgs)

Fine Tuning Problem: "Why so small"?

Vacuum Energy: Quantum Field Theory predicts it to be determined by cutoff scale

$$\rho_{\rm VAC} = \frac{1}{2}\sum_{\rm fields} g_i \int_0^\infty \sqrt{k^2+m^2}\,\frac{d^3k}{(2\pi)^3} \simeq \sum_{\rm fields} \frac{g_i k_{\rm max}^4}{16\pi^2}$$

Measured: $(10^{-3}{\rm eV})^4$

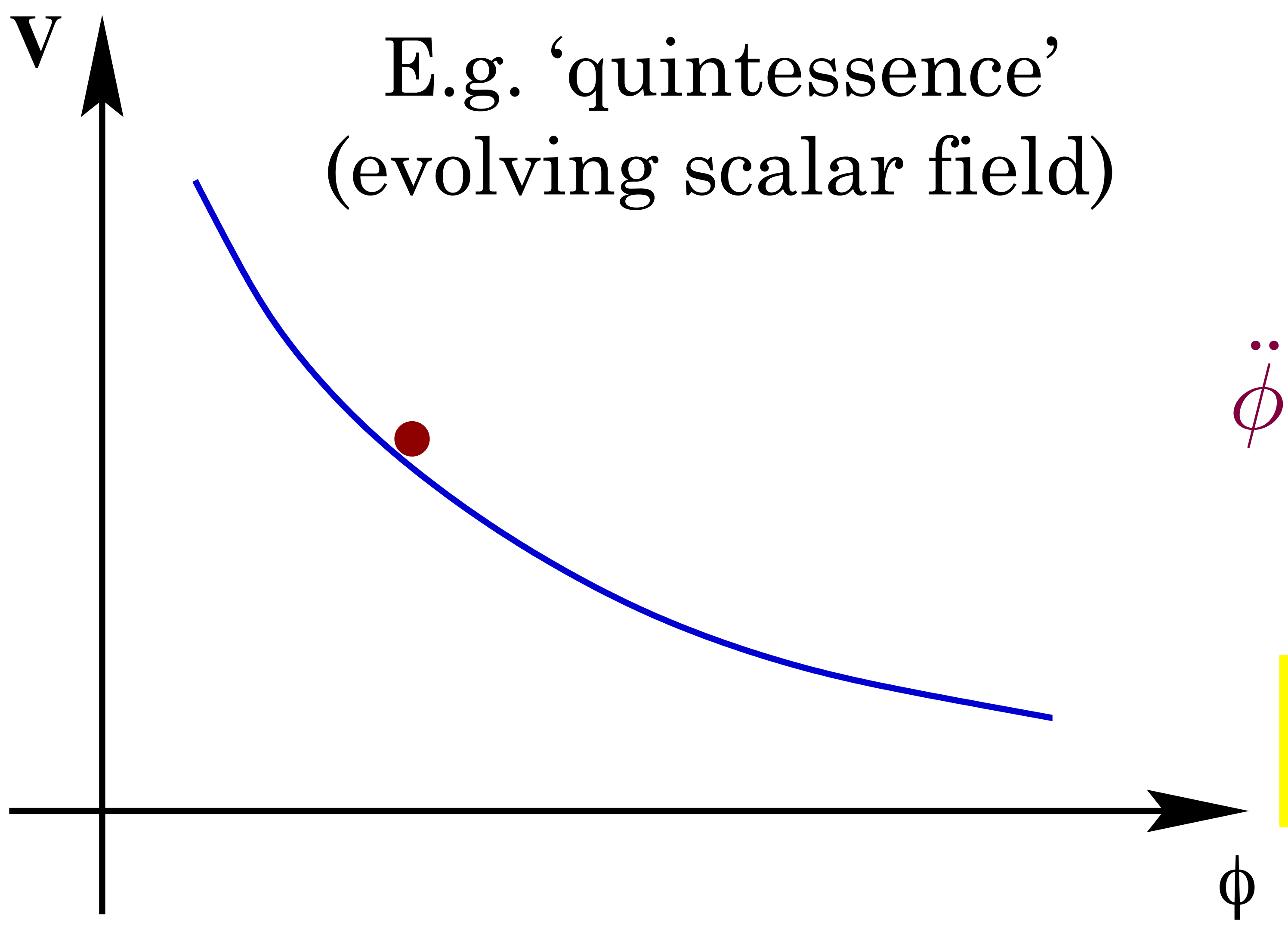
SUSY scale: $(1\,{\rm TeV})^4$

Planck scale: $(10^{19}\,{\rm GeV})^4$

} 60-120 orders of magnitude smaller than expected!

Lots of theoretical ideas, few compelling ones:

Very difficult to motivate DE **naturally**

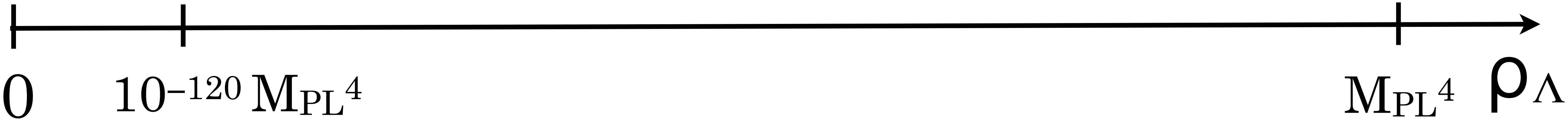


$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0$$

$m_\phi \simeq H_0 \simeq 10^{-33}$ eV

For DE, data are well ahead of theory at the moment

String landscape?

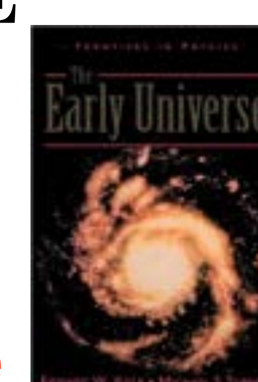


Among the ~10^{500} minima,

we live in one that allows structure/galaxies to form

(selection effect) (anthropic principle)

Landscape + anthropic "predicts" the observed Ω_{DE}



Kolb & Turner, "Early Universe", footnote on p. 269:

"**It is not clear to one of the authors how a concept as lame as the "anthropic idea" was ever elevated to the status of a principle**"

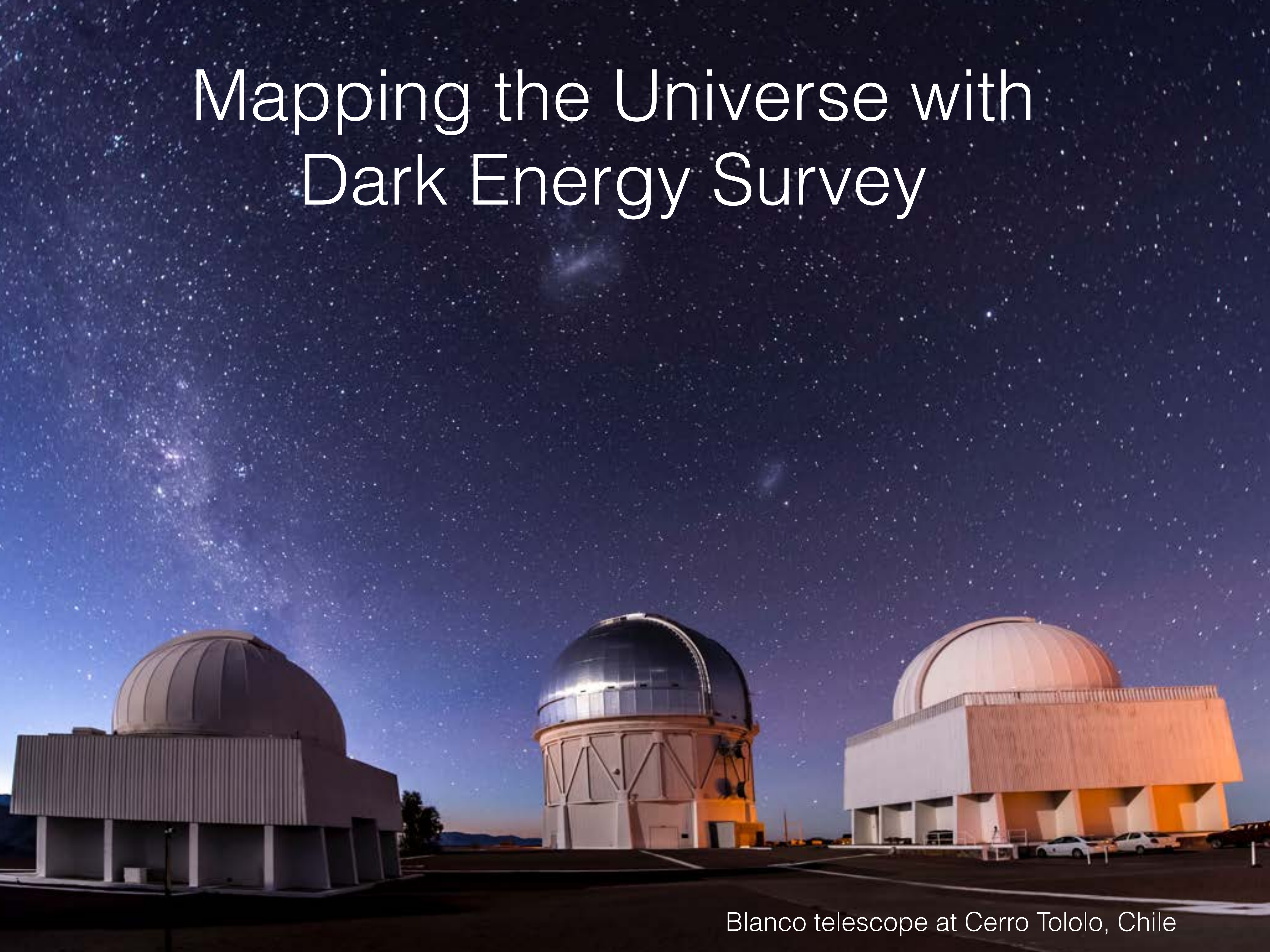
Current status of DE measurements

- Excellent precision on DE already
- However, CMB is "done", while SNe and BAO are already pretty well-developed $\Rightarrow$ future improvements using standard DE probes will be ever-more challenging
- Most promise is in **large-scale structure**: galaxy clustering, weak lensing, redshift-space distortions
- Key challenges:
  - Theory modeling on small spatial scales
  - Systematic errors from sky and instrument (atmosphere, dust, observing-induced, etc etc)

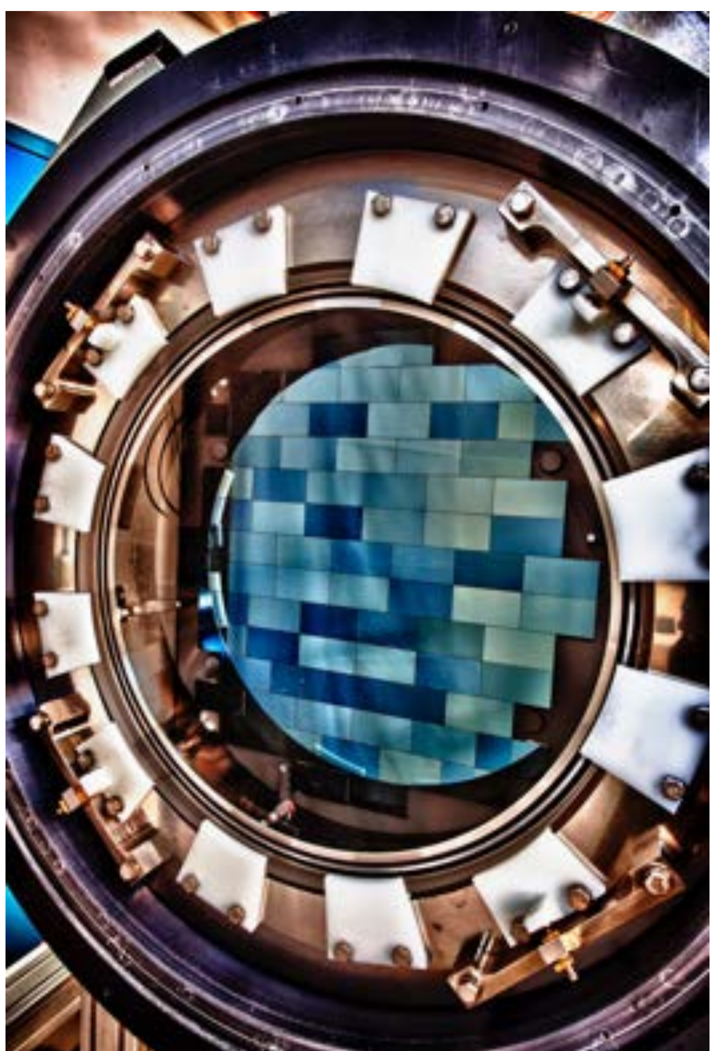
Major ongoing or upcoming DE expt's:

- **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)

Mapping the Universe with Dark Energy Survey



Blanco telescope at Cerro Tololo, Chile



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
- collaboration of >400 scientists
- just (Jan 2019) finished all 5.5 yrs of observing; Y3 analysis in progress

Dark Energy Survey (DES)

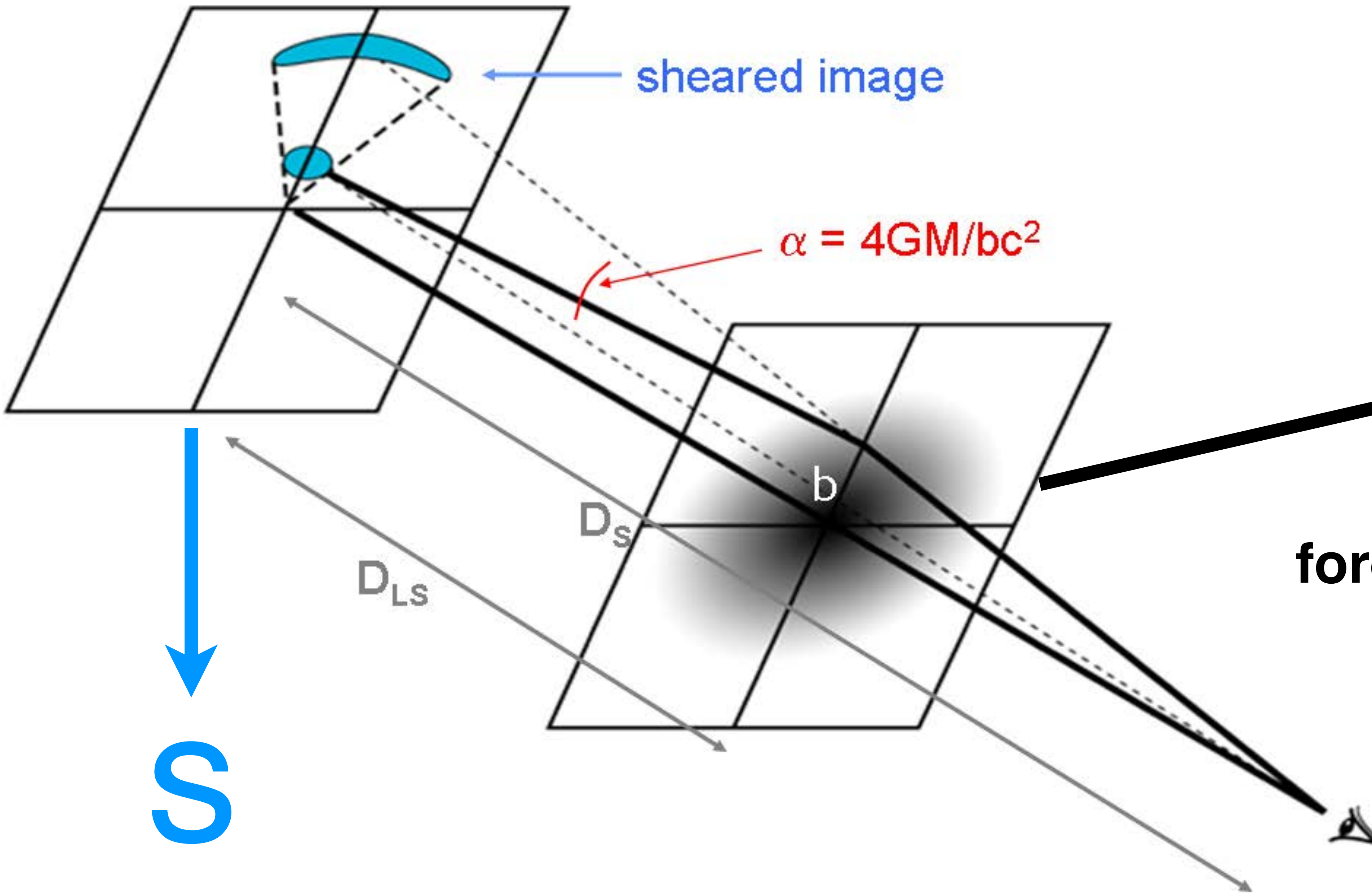
Cerro Tololo, Chile

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**
- Supernova analysis (papers out)
- BAO: 4% distance out to z=0.81 (paper out)
- cluster counts, strong lensing (papers coming soon)
- **Close to 200 papers already out**

image: LSST science book



g

(**positions** of **foreground** galaxies; 4 redshift bins)

S

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

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

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

DES 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

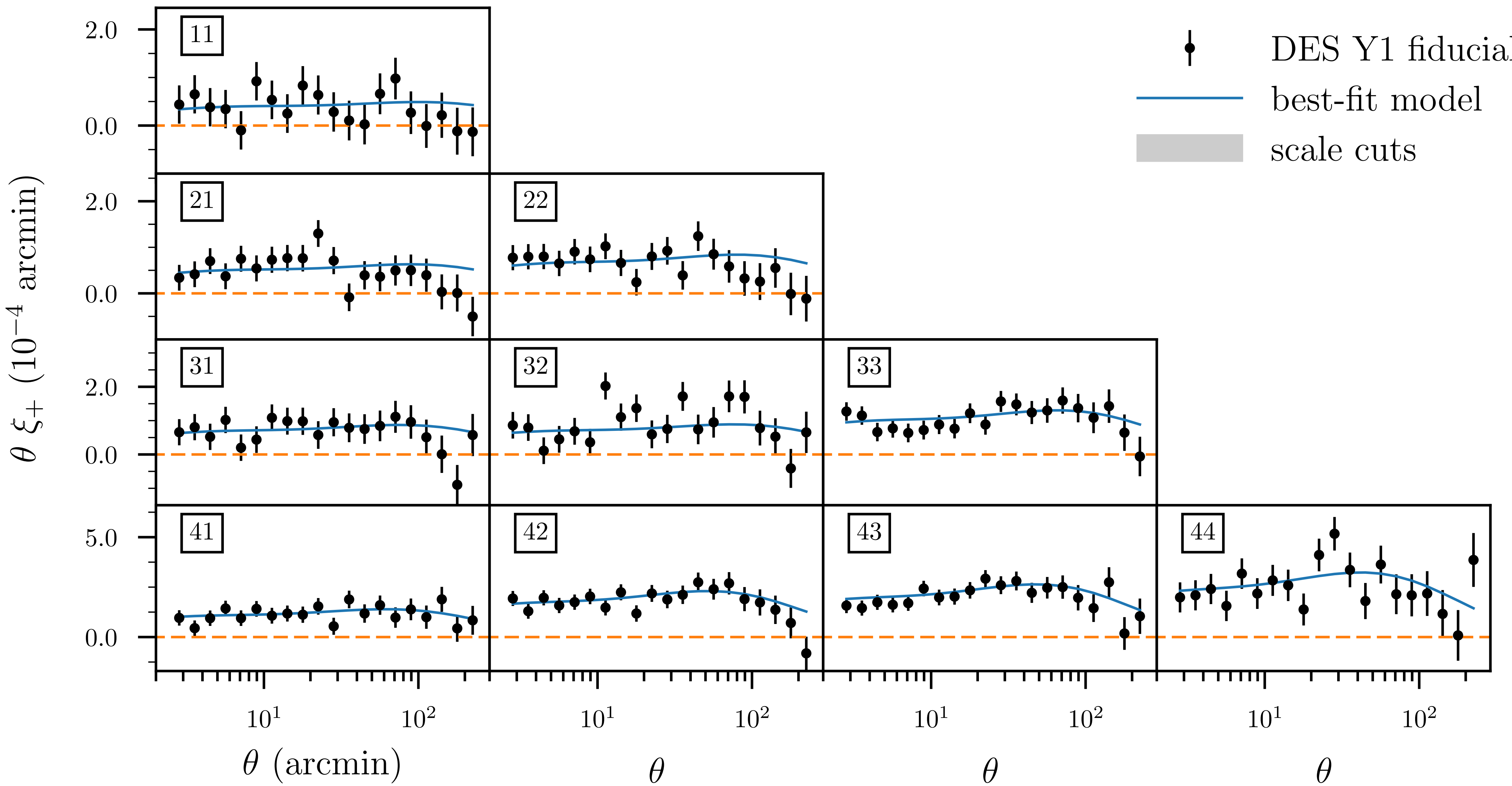
1. Two shear measuring/calibration pipelines
2. Two redshift calibration algorithms
3. Two theory covariance matrices
4. Two parameter sampling (likelihood) codes

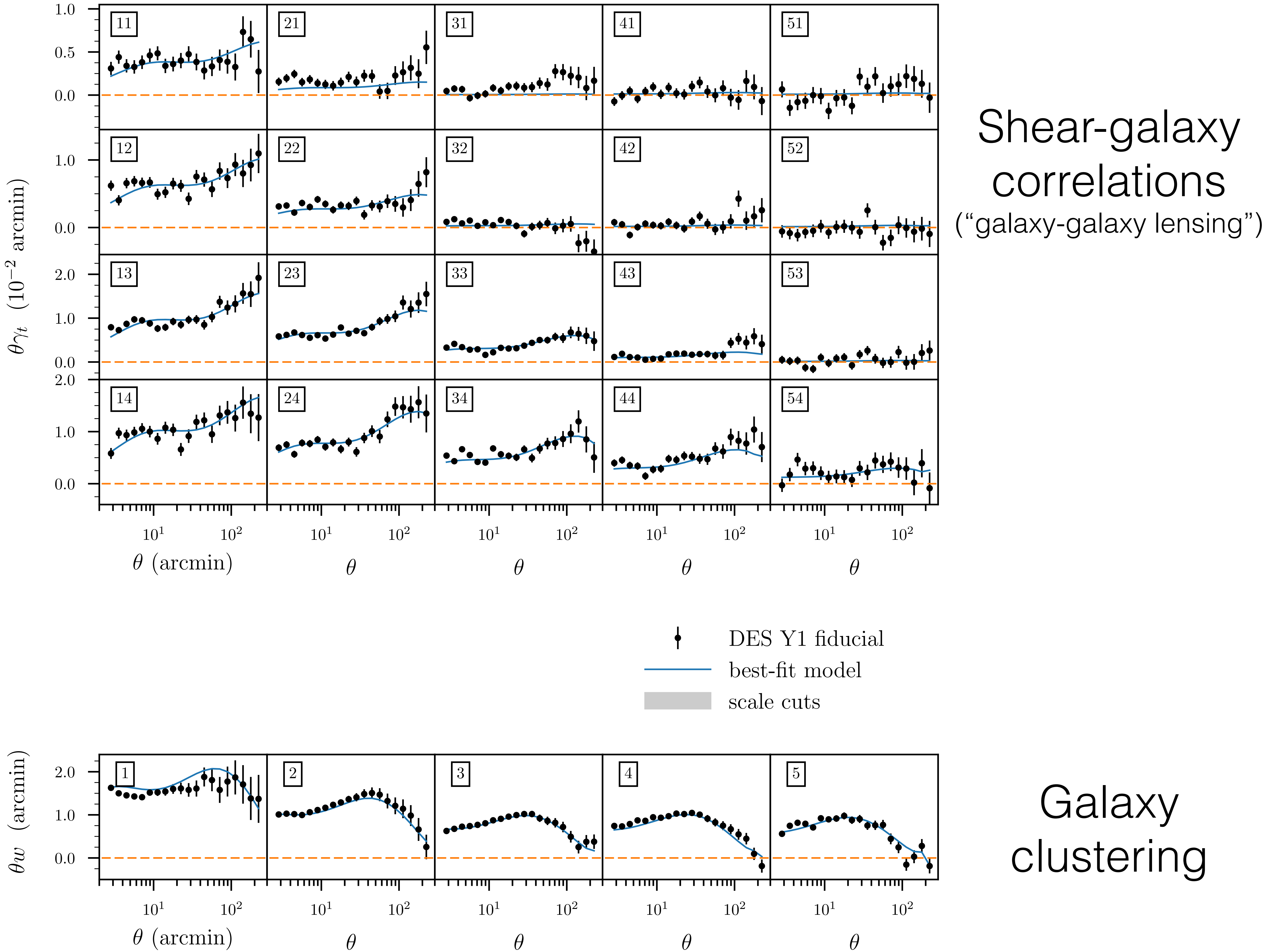
and

All cosmology results are **blinded**

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

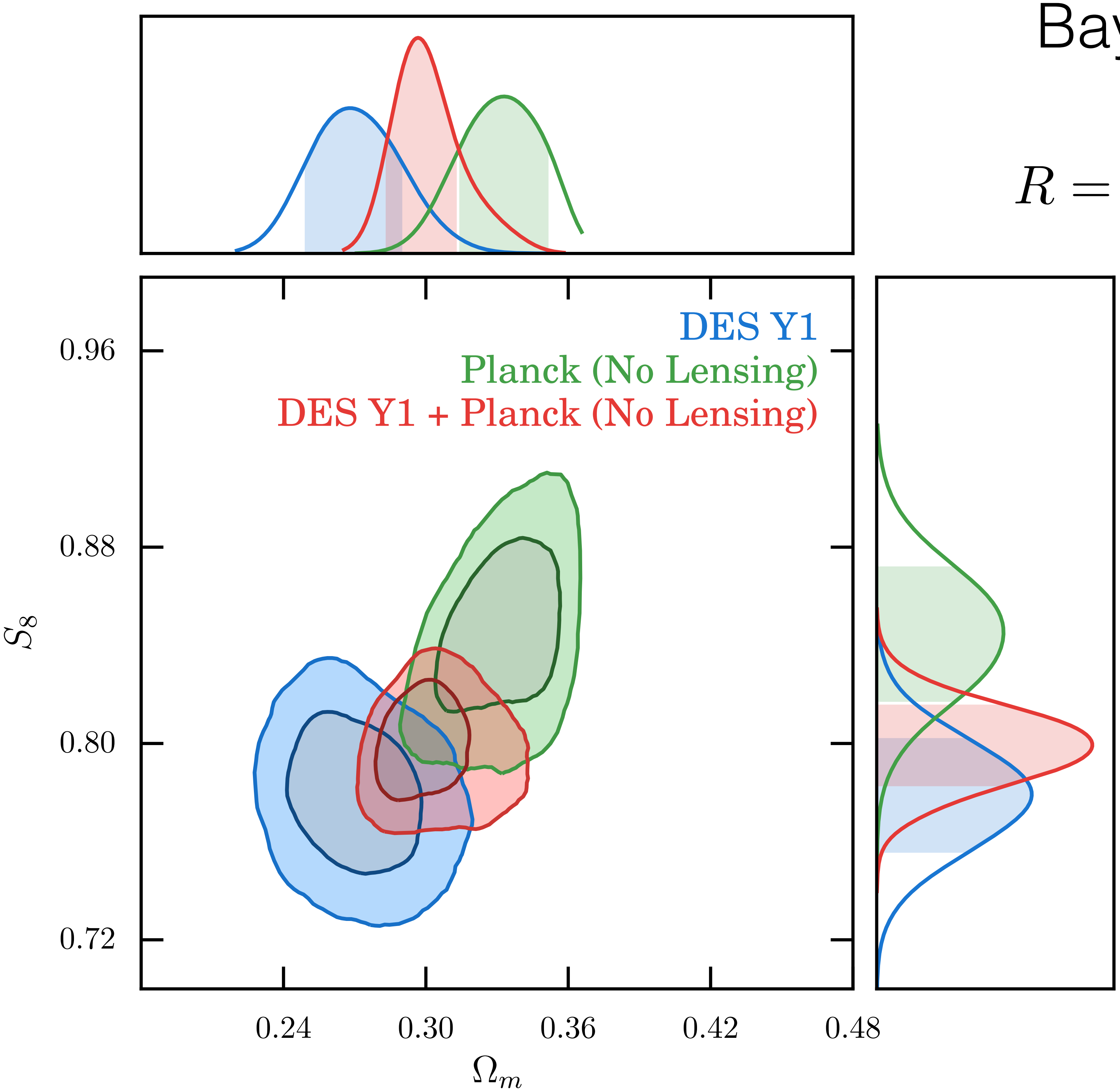
Shear clustering:





Shear-galaxy correlations
("galaxy-galaxy lensing")
Galaxy clustering
$\theta\gamma_t$ (10^{-2} arcmin)
θw (arcmin)
θ (arcmin)
11
21
31
41
51
12
22
32
42
52
13
23
33
43
53
14
24
34
44
54
1
2
3
4
5
DES Y1 fiducial
best-fit model
scale cuts

DES 3x2 results: Ω_m-S_8 plane



Bayes factor (in 26D space):

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

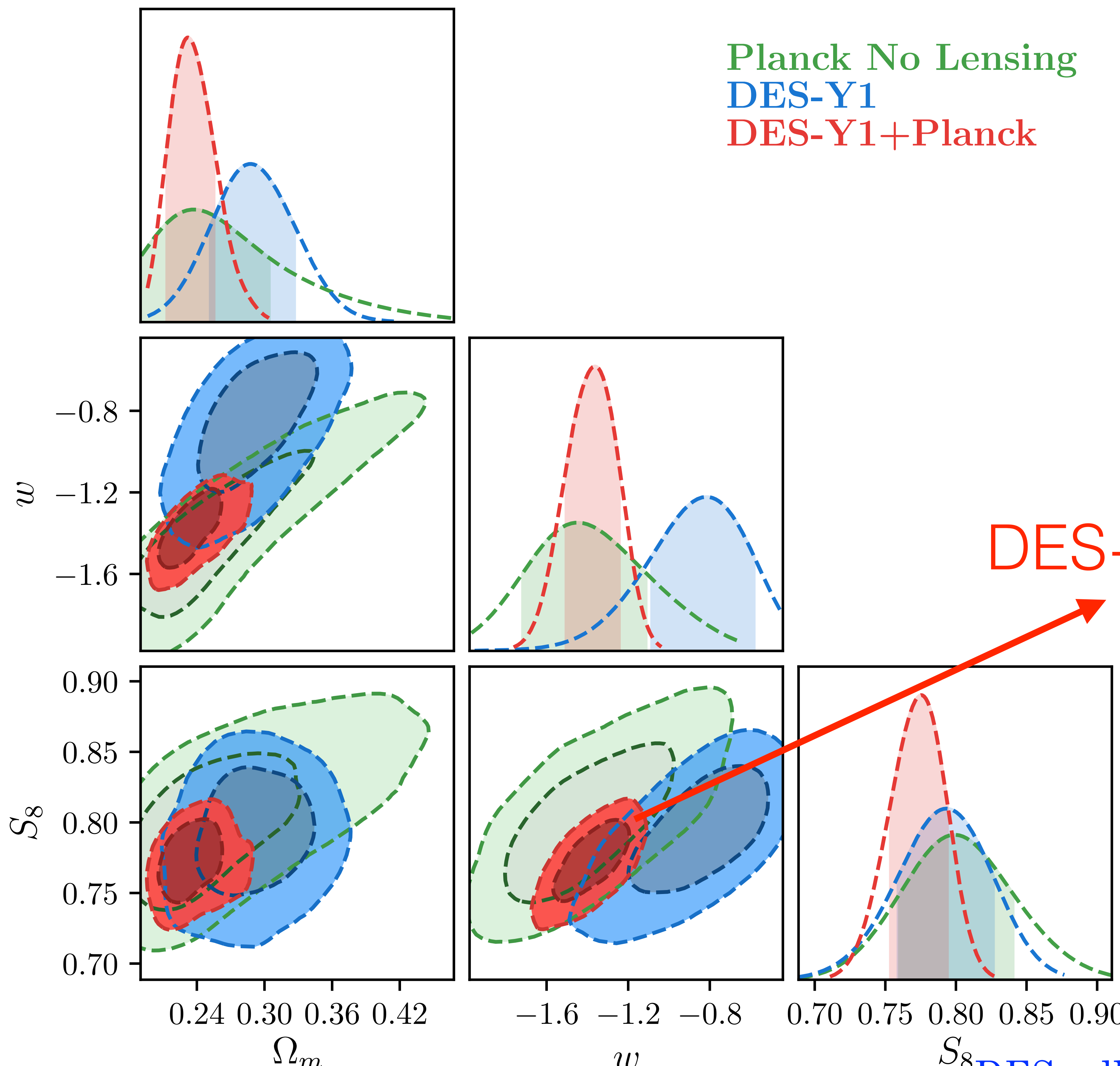
$\Rightarrow$ "substantial" agreement (DES,Planck)

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

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

DES collaboration, arXiv:1708.01530

DES 3x2 results: constraints on w



DES+Planck:

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

DES+Planck+
SN+BAO:

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

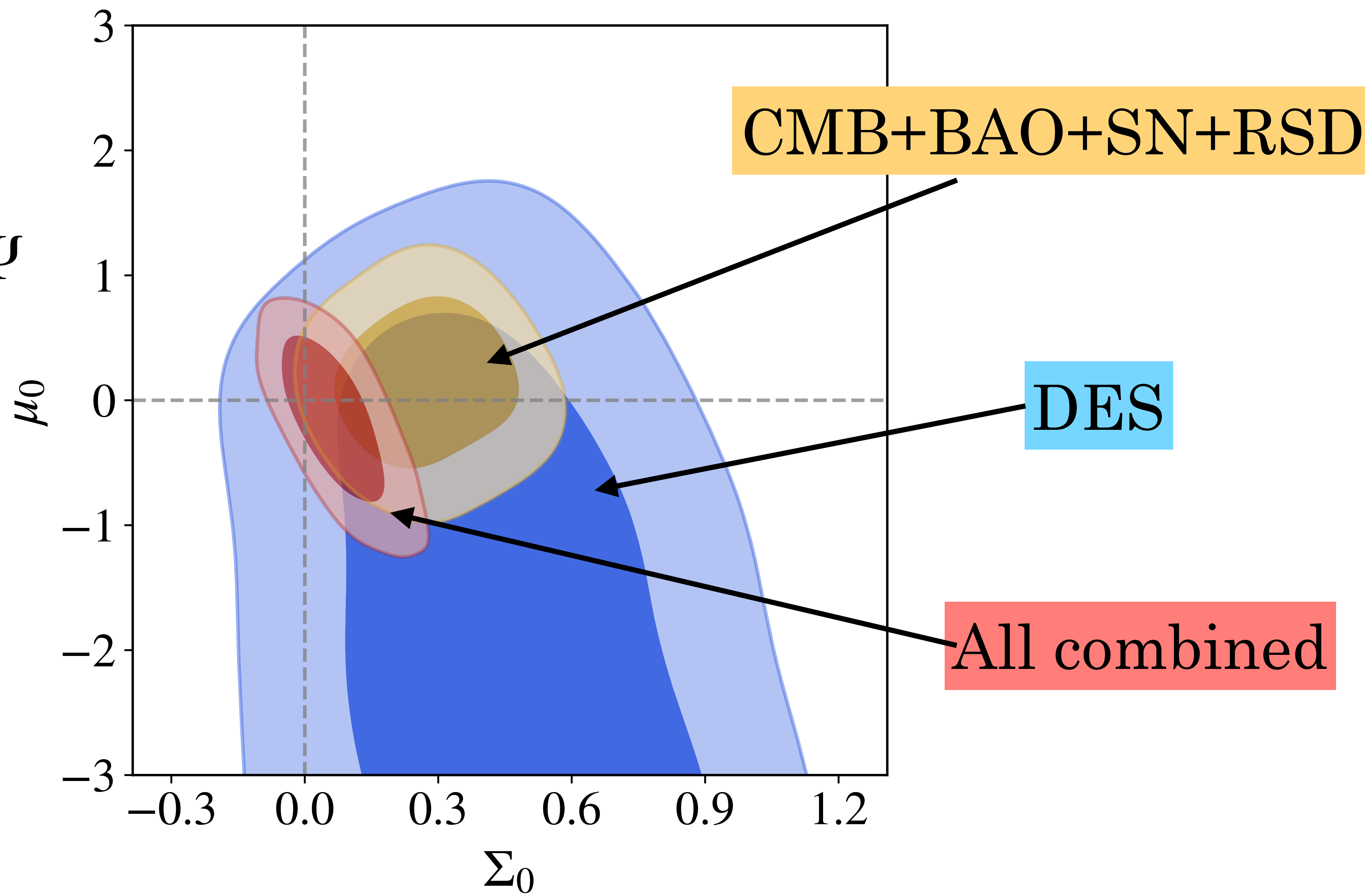
DES collaboration, arXiv:1708.01530

DES Year1 results (October 2018)

extensions to ΛCDM, incl. modified gravity

$1+\mu \sim \Psi$

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



Watch out for
DES Y3 results (out in 2019)!

DES collaboration, arXiv:1810.02499

Current notable tensions in cosmology

1. The amplitude of mass fluctuations (σ_8) is higher in the CMB (σ_8=0.83) than in cluster abundance / weak lens (σ_8=0.80)

2. Hubble constant measured by the Planck collaboration (H_0=67.3±1.0) disagrees with that from the distance ladder measurements (H_0=73.52±1.62); the two are **3.8 sigma** apart

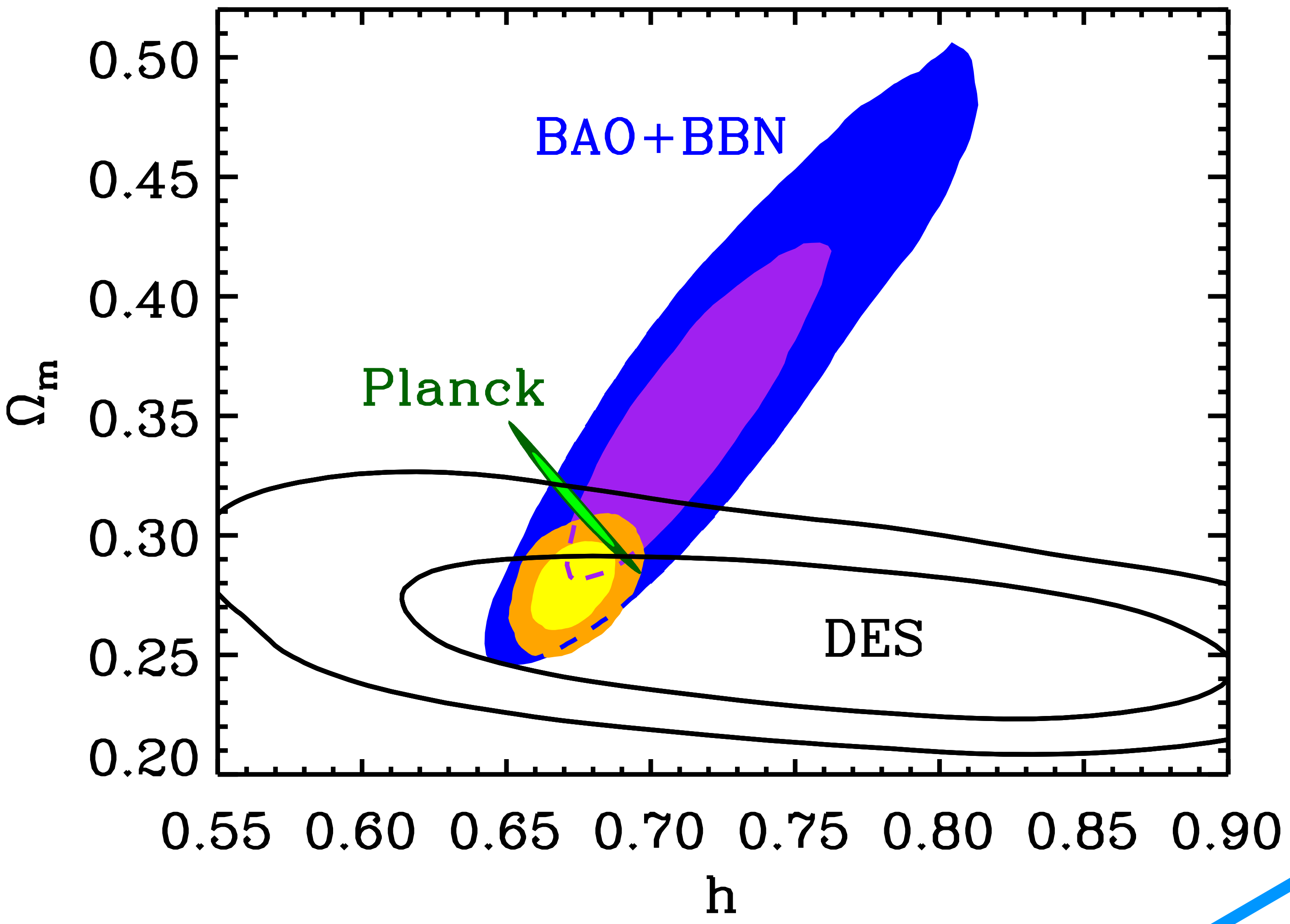
My totally personal view of these:

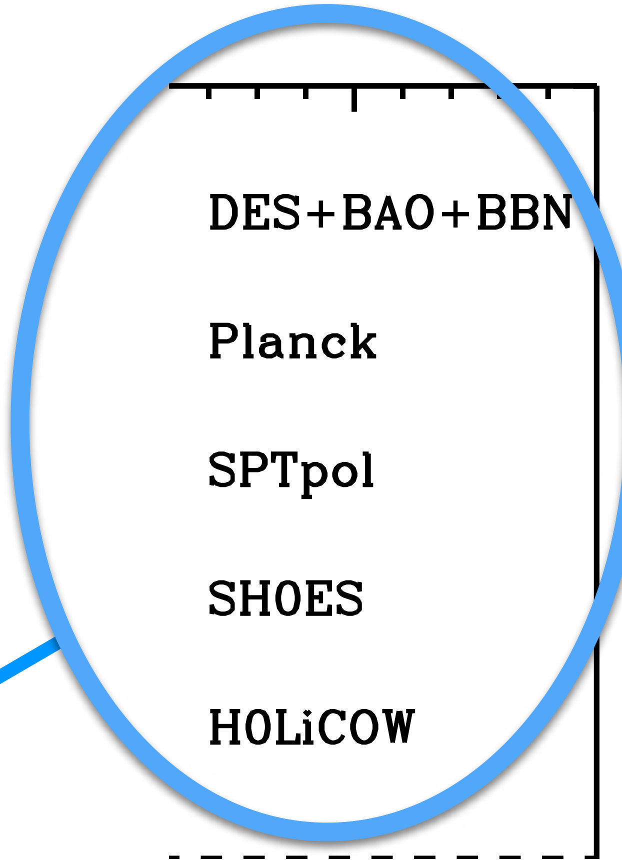
1. is an accidental “scattering around central value” and will go away basically

2. is much more serious, because of excellent, rigorous analyses by CMB **and** distance ladder teams, and may be pointing toward new physics (or non-trivial systematics). Moreover, cosmic variance (fact we live in a “high local H_0” part of universe) contributes negligibly to the (H_0^{local} –H_0^{CMB}) difference (Wu & Huterer 2017)

DES H_0 constraints

DES collaboration, arXiv:1711.00403





$$H_0 = 67.2^{+1.2}_{-1.0}$$

Amazing fact:
these 5 measurements of H0 are basically independent

All 5 combined give: $H_0 = 69.1^{+0.4}_{-0.6}$

More general comments regarding confronting DE data with theory

- We are doing our best to use statistics properly and treat systematics thoroughly. [This area has undergone huge development over the past ~20 yrs.]
- We are not trying to sweep under the rug any reasonable explanations for DE - many are simply ruled out by data!
- [We could of course be missing some essential ingredient in the underlying theory model.]
- In my opinion, the most promising direction is to test the internal consistency of the model (LCDM, FRW, isotropy…) using data and hope for “bumps”
- Also a big fan of measuring general Lagrangian-level functions (e.g. Luca’s $h_i(k, z)$), but realistically you can only expect data on a few DE parameters from cosmology, not functions

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)!

Can we distinguish between DE and MG?

Yes; here is how:

- In standard GR, H(z) determines distances and growth of structure

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

- So check if this is true by measuring separately

Geometry
(as known as kinematic probes)
(a.k.a. 0^{th} order cosmology)

Probed by supernovae, CMB, weak lensing, cluster abundance

Growth
(a.k.a. dynamical probes)
(a.k.a. 1^{st} order cosmology)

Probed by galaxy clustering, weak lensing, cluster abundance

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]

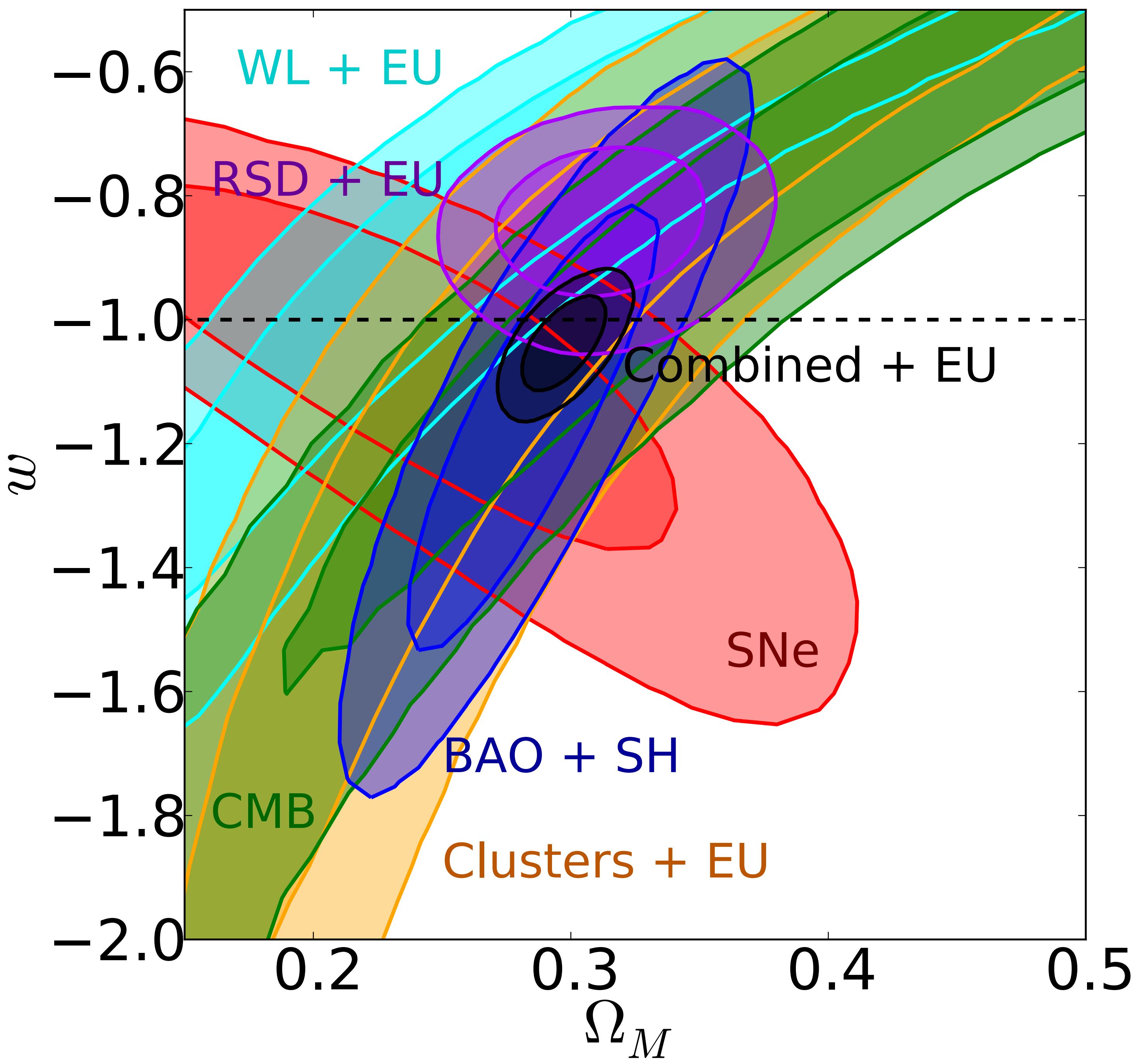
Ruiz & Huterer, PRD 2015

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	$F(z) \propto D_A(z) H(z)$	$f(z)\sigma_8(z)$

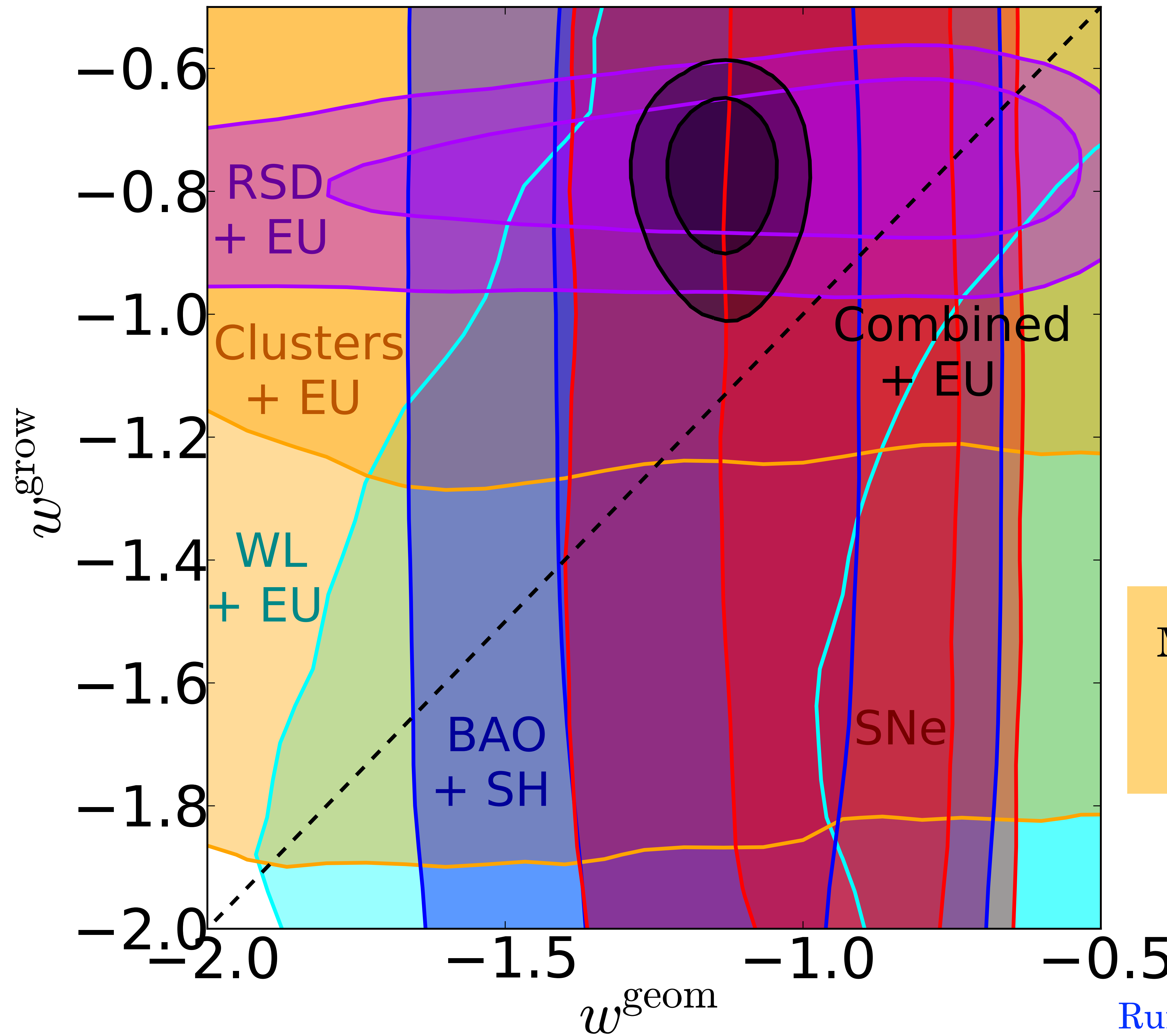
Ruiz & Huterer, 2015

Standard parameter space



EU = Early Universe prior from Planck ($\Omega_M h^2$, $\Omega_B h^2$, n_s, A)
SH = Sound Horizon prior from Planck ($\Omega_M h^2$, $\Omega_B h^2$)

w (eq of state of DE): geometry vs. growth

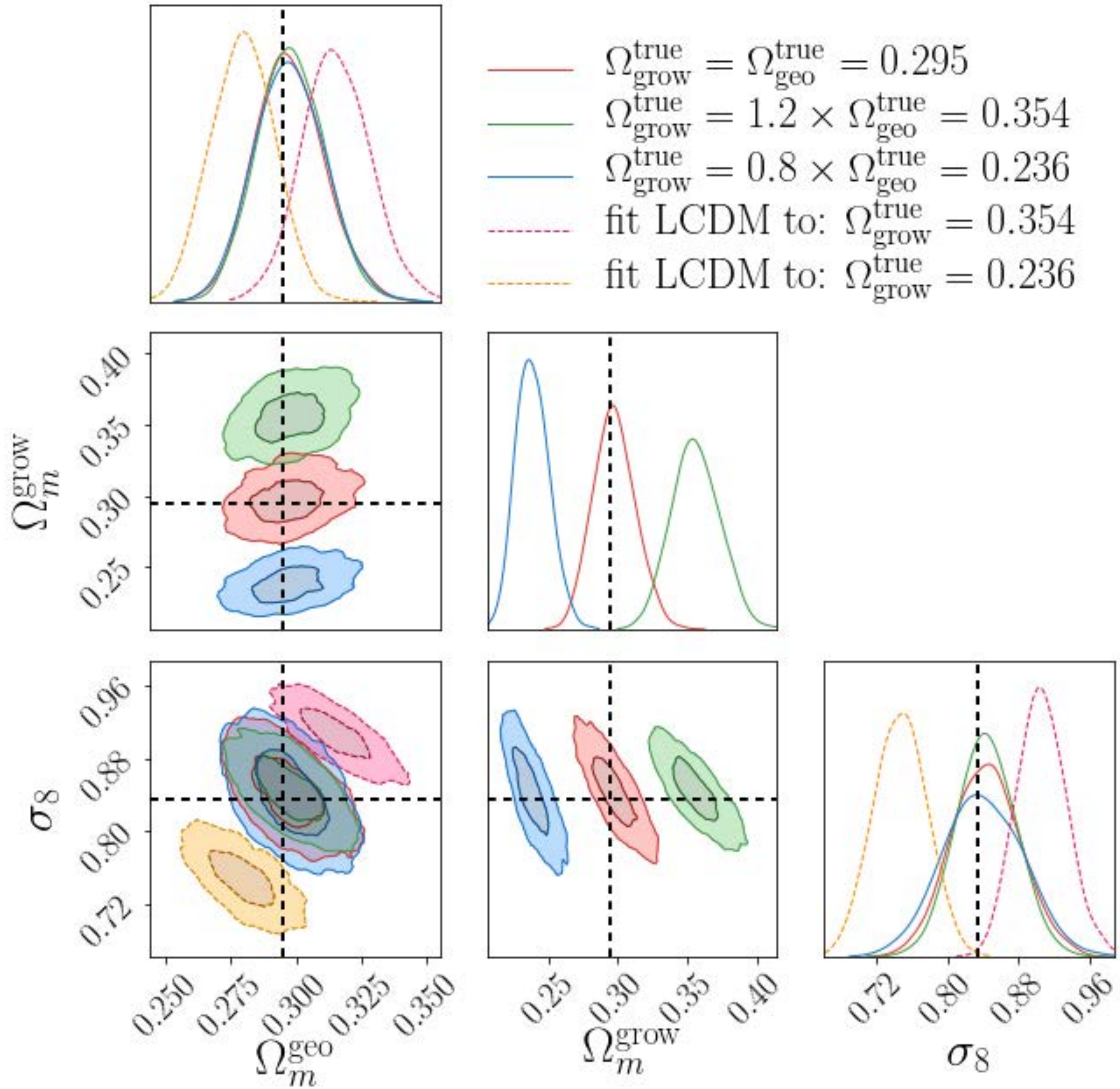


Evidence for $w^{\mathrm{grow}} > w^{\mathrm{geom}}$: 3.3-σ

Method currently being applied to DES data

Ruiz & Huterer 2015

Coming up: geometry-growth tests with DES



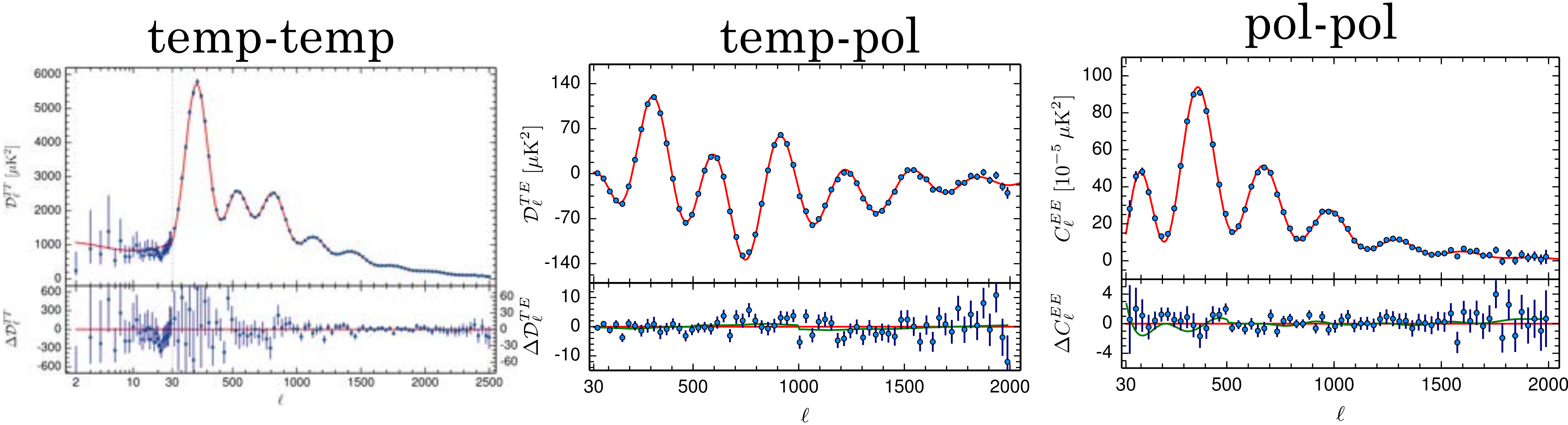
Jessie Muir
Michigan ⇒ Stanford

(synthetic tests shown…)

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?



Danger of declaring currently favored model to be the truth

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

Blinding the DES analysis

Muir, Elsner, Bernstein,
Huterer, and DES collab.

Our requirements:

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

Our choice is specifically:

$$\xi_{ij}^{\text{blinded}}(k) = \xi_{ij}^{\text{measured}}(k) \left[\frac{\xi_{ij}^{\text{model 1}}(k)}{\xi_{ij}^{\text{model 2}}(k)} \right]$$

Tests passed, black-box code ready.

First application expected for clustering measurements in DES year-3 data.

Conclusions

- Impressive variety of new constraints on DE; current frontier is large-scale structure
- Dark energy is definitely out there! w(z), DE vs MG, and ultimately DE's nature are of course open questions
- More likely than not, game-changing new insight from theory needed, but none found yet
- Regarding data: sophisticated statistical tools, as well as blinding in analysis, will be key
- Like particle physicists, we would really like to see some "bumps" in the data (e.g. Hubble tension?)