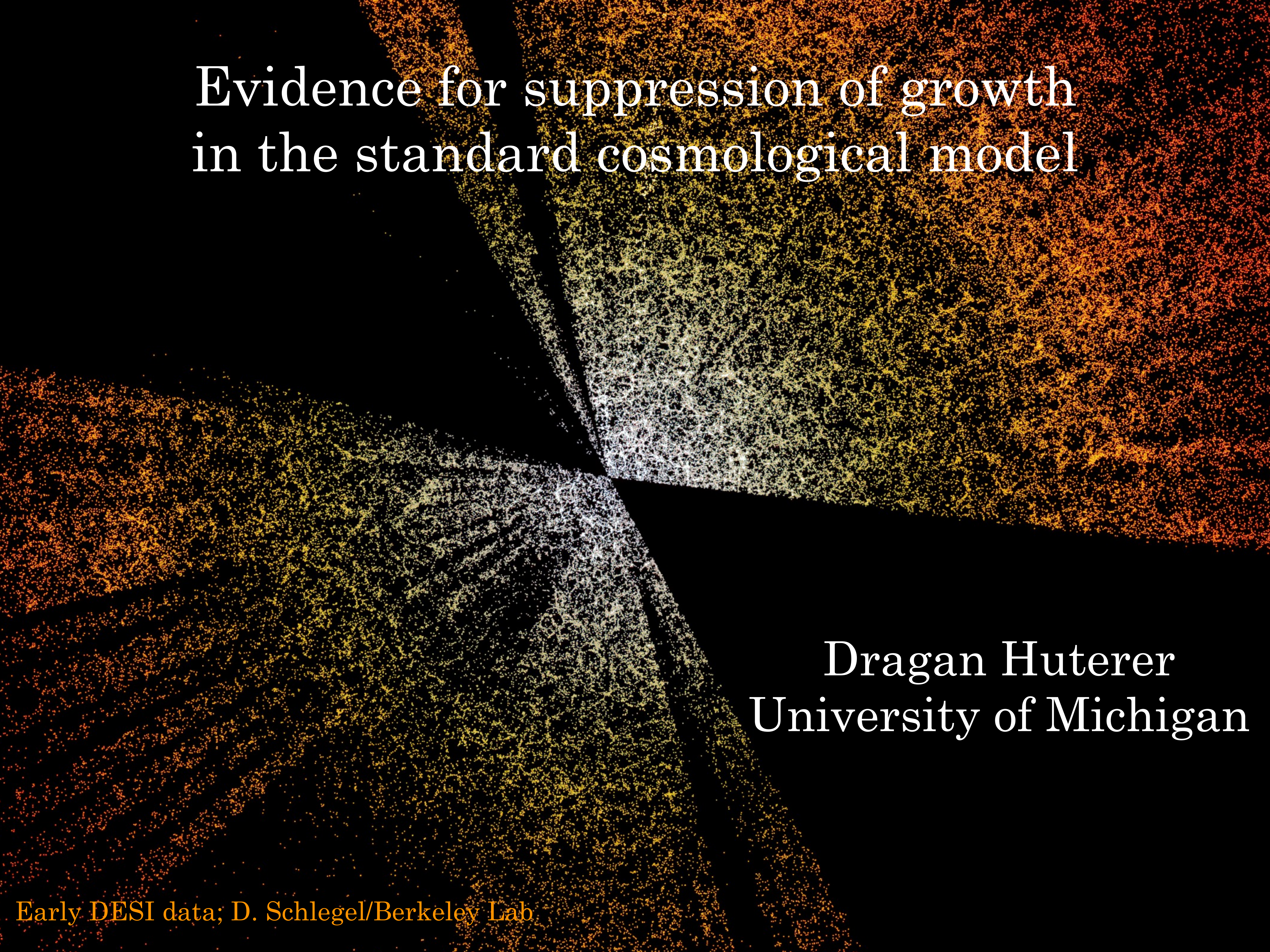
Evidence for suppression of growth in the standard cosmological model

Dragan Huterer
University of Michigan



Early DESI data; D. Schlegel/Berkeley Lab

Ross Young Scholars Program
Ohio State University, summer 1992

Timeline of the universe

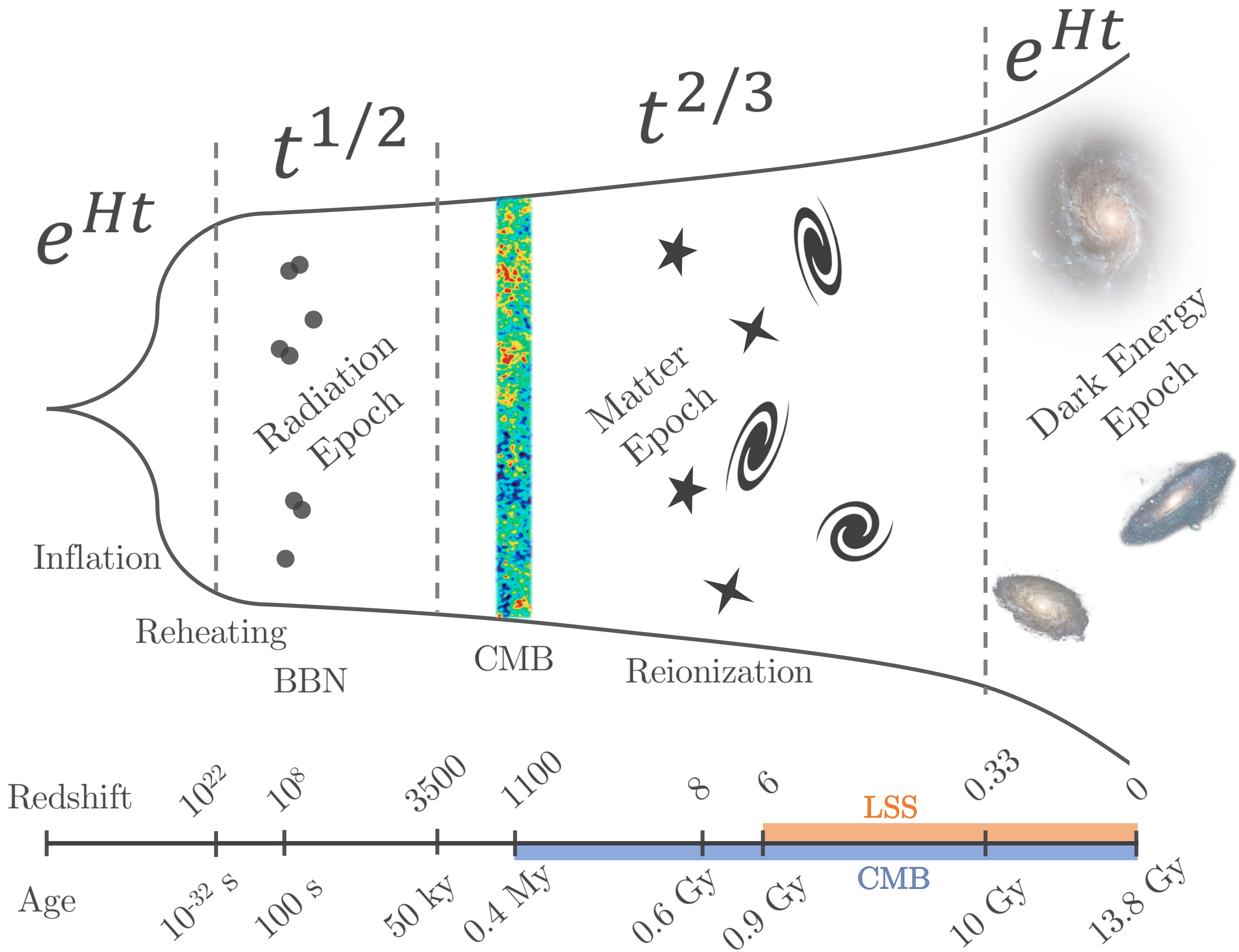
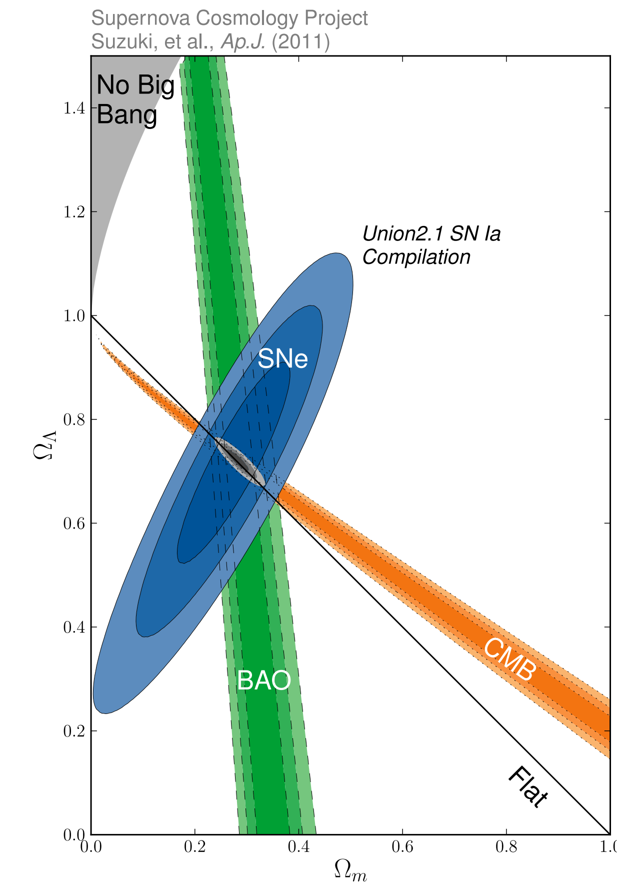
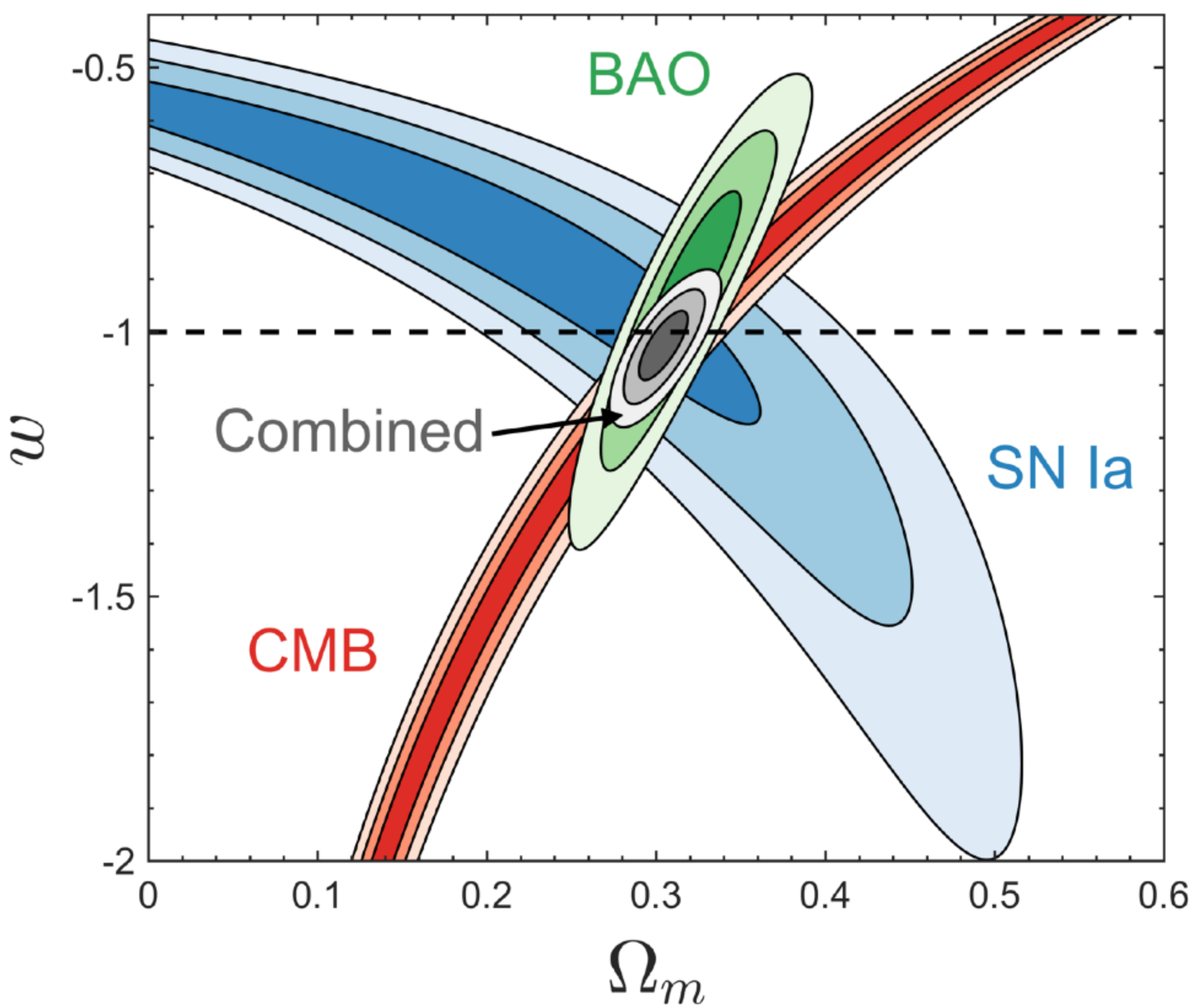
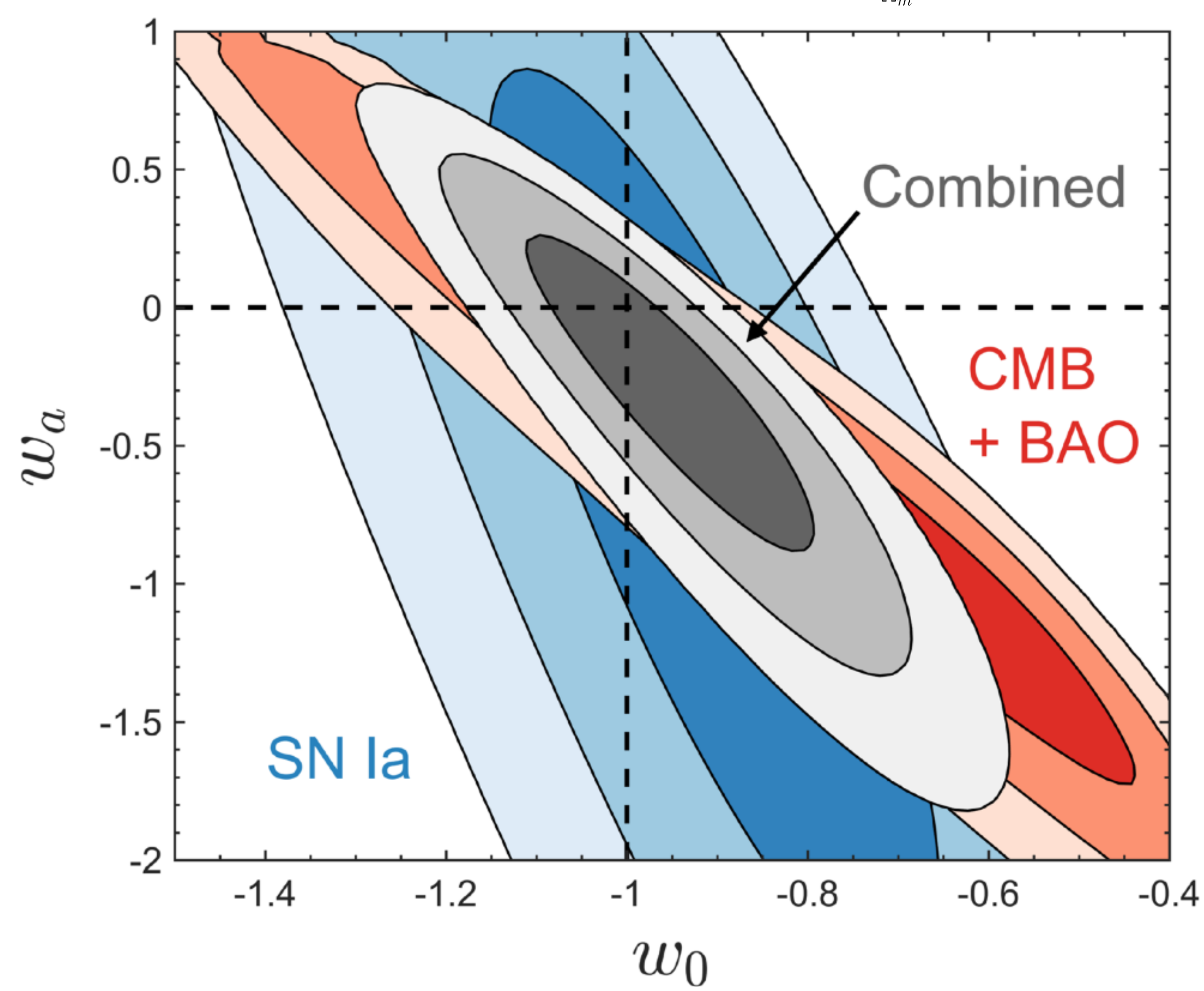


Figure credit: Noah Weaverdyck

Current data are in excellent consistency with LCDM model





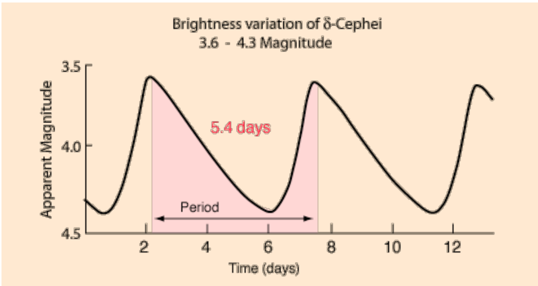


from Huterer & Shafer (2017) review

Hubble Tension:

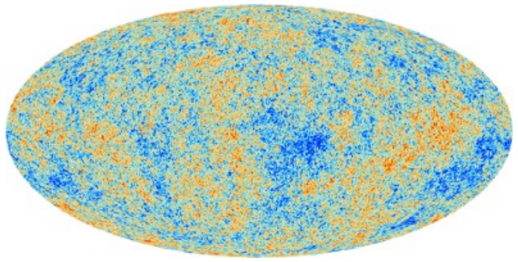
SH$_0$ES (Riess et al 2022)

$$H_0 = 73.04 \pm 1.04 \text{ (km/s/Mpc)}$$



CMB: (Planck 2018)

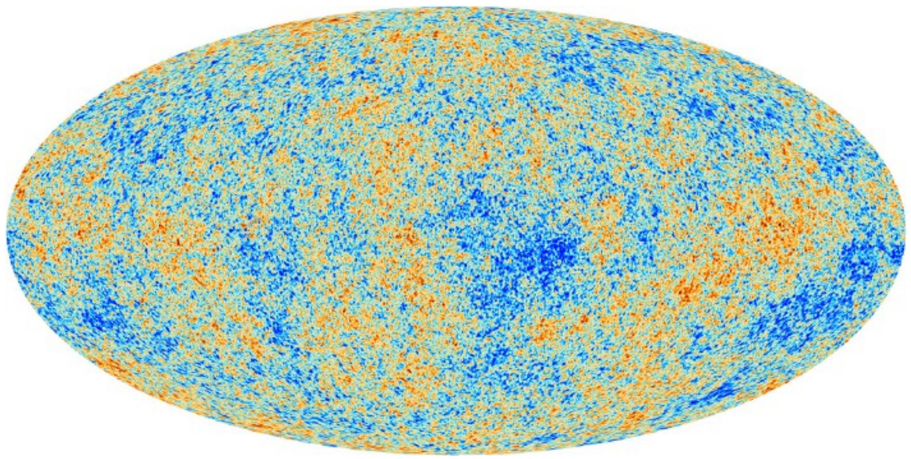
$$H_0 = 67.36 \pm 0.54 \text{ (km/s/Mpc)}$$



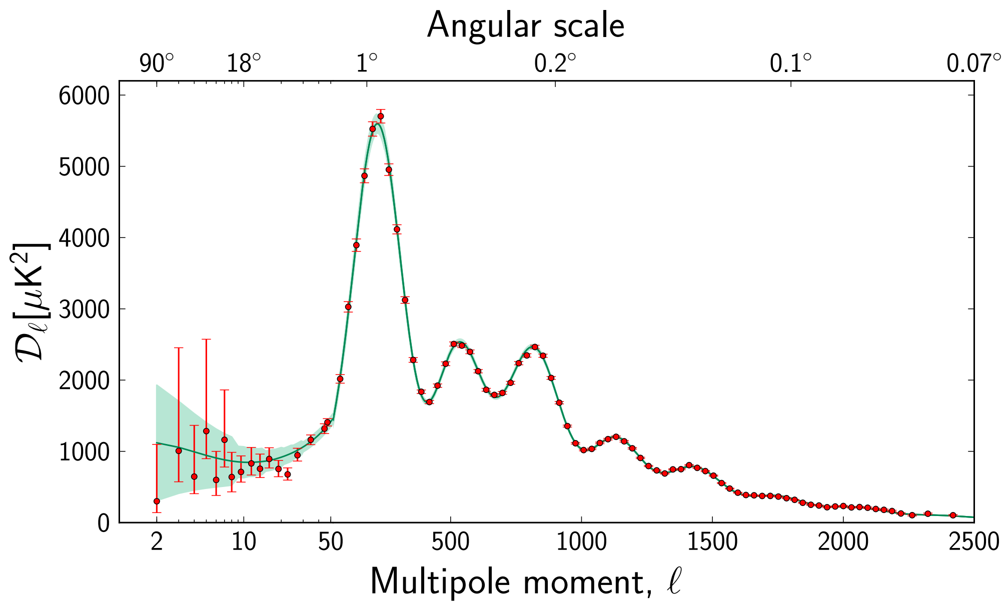
Currently the premier challenge for the standard cosmological model, and the most exciting development in cosmology (imo).

The tension recently crossed the 5-sigma threshold; this is an important step!

CMB measurement of H_0



H_0 is a "derived parameter" in the CMB - no special signature, but constrained very well.

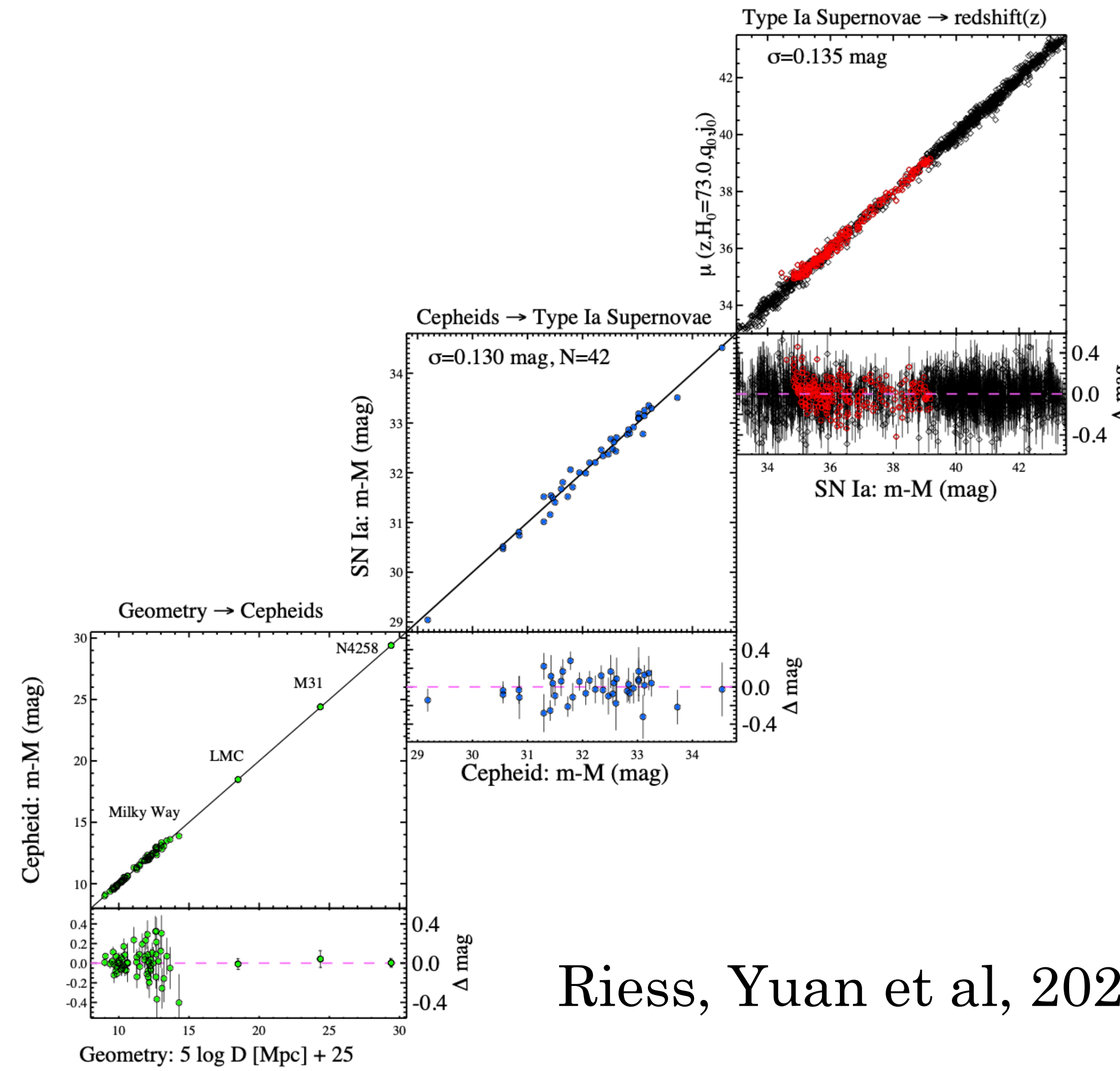


Planck (2018) finds:

$$H_0 = (67.36 \pm 0.54)\,\mathrm{km/s/Mpc} \quad \text{[flat LCDM]}$$

$$H_0 = (63.6 \pm 2.2)\,\mathrm{km/s/Mpc} \quad \text{[curved LCDM]}$$

Distance-ladder measurements of H_0



Riess, Yuan et al, 2022

starting with

$$m - M = 5\log_{10}\left(\frac{d_L}{10\text{pc}}\right)$$

we get

$$m = 5\log_{10}(H_0 d_L) + \mathscr{M}, \quad \text{where} \quad \mathscr{M} \equiv M - 5\log_{10}\left(H_0 \cdot 1\text{Mpc}\right) + 25$$

Because SNIa measure relative distances, to get at H_0 they need to be “anchored” by absolute distances from e.g. Cepheids

H_0 tension - theory

- There are literally hundreds of models out there
- However, there is only ONE simple model.

Sample/cosmic variance?

$\Rightarrow$ Global H_0 is ~67, but H_0 in our local volume is ~73

(equivalent to: “we live in a void”)

However that model is completely ruled out.

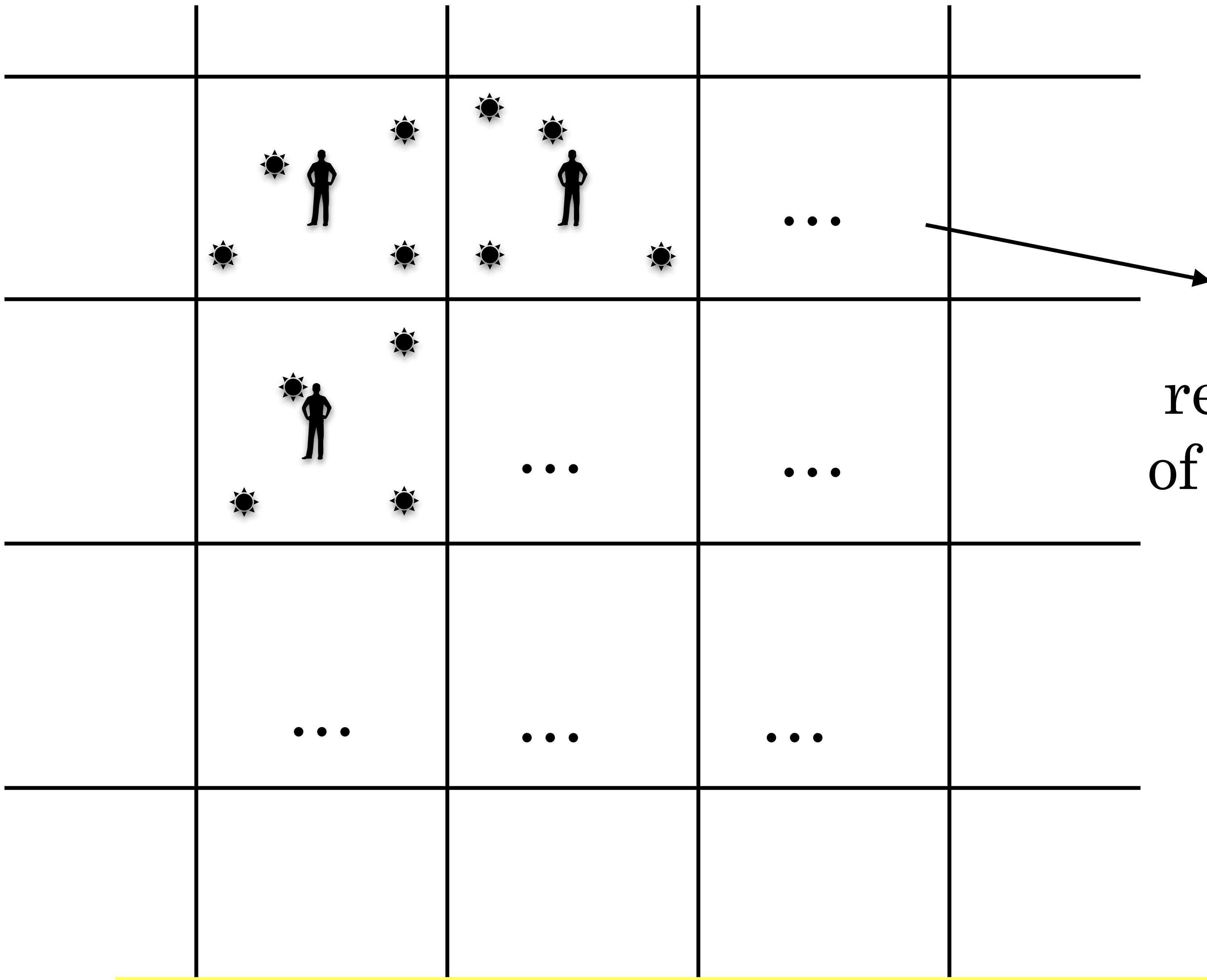
Wu & Huterer (2017), Kenworthy, Scolnic & Riess (2019)

essentially because local measurements map out a pretty
big local volume (so cosmic variance is small)

as explained on next slide…

We determined the **sample variance** of H0
from the distance-ladder measurement by repeating the analysis
~1.5 million times on numerical (Nbody) LCDM simulations

Wu & Huterer (2017)

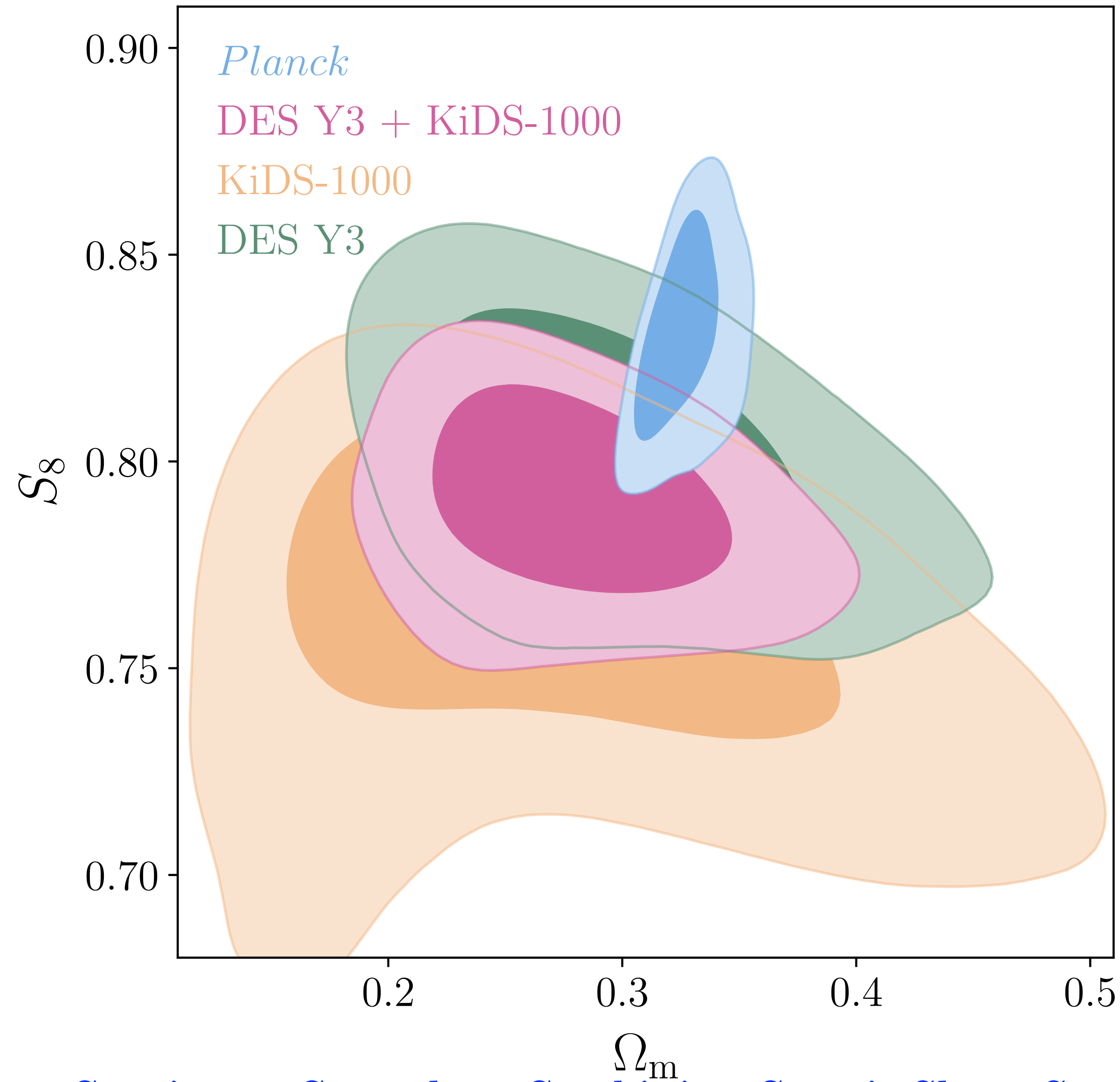


512 sub-volumes, each with ~3000 realizations (rotations) of actual SNIa positions

$$\sigma^{\mathrm{CV}}(H_0) \simeq 0.3\,\mathrm{km/s/Mpc} \simeq \frac{1}{20}\,(H_0^{\mathrm{SHOES}} - H_0^{\mathrm{CMB}})$$

There is also the S_8 tension, but it is not as significant

$$S_8 \equiv \sigma_8 \left(\frac{\Omega_m}{0.3}\right)^{0.5} ; \quad \sigma_8^2 = \int \Delta^2(k, R = 8h\mathrm{Mpc}^{-1}) W^2(kR) d\ln k$$



"DES-Y3 + KiDS 1000:Consistent Cosmology Combining Cosmic Shear Surveys", arXiv:2305.117173
(HSC also gets a similar constraint)

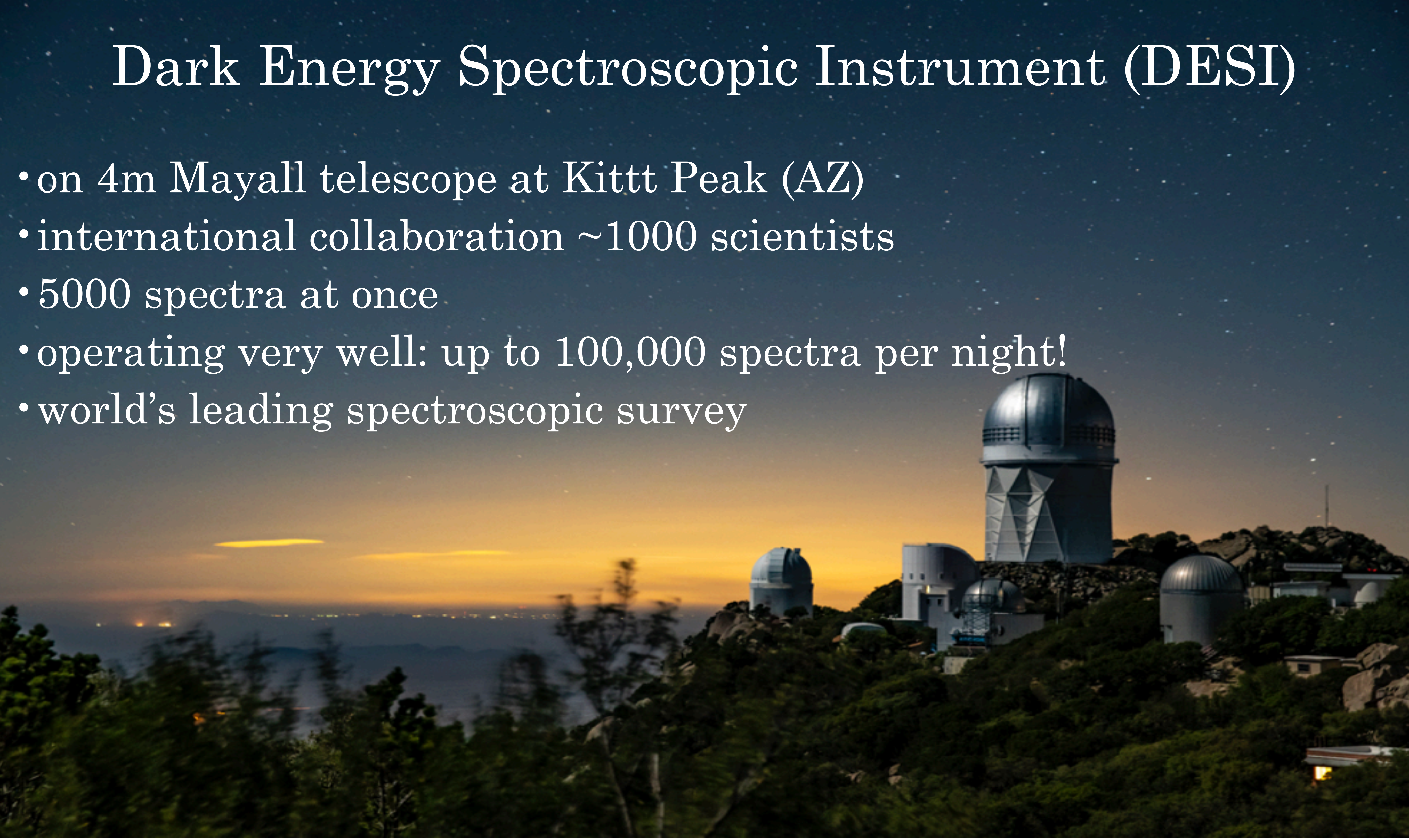
<u>However</u>, the S8 tension is also seen in other LSS data ("lensing is low" etc)

Major current or upcoming DE experiments:

- **Ground photometric:**
  - Kilo-Degree Survey (KiDS)
  - Dark Energy Survey (DES)
  - Hyper Supreme Cam (HSC)
  - Vera Rubin Telescope (and its survey LSST)
- **Ground spectroscopic:**
  - Hobby Eberly Telescope DE Experiment (HETDEX)
  - Prime Focus Spectrograph (PFS)
  - Dark Energy Spectroscopic Instrument (DESI)
- **Space:**
  - Euclid (just launched July 2023!)
  - Nancy Roman Telescope

Dark Energy Spectroscopic Instrument (DESI)

- on 4m Mayall telescope at Kittt Peak (AZ)
- international collaboration ~1000 scientists
- 5000 spectra at once
- operating very well: up to 100,000 spectra per night!
- world’s leading spectroscopic survey



DESI science:

1. dark energy
2. neutrino mass
3. primordial non-Gaussianity

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

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

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

Comparing geometry and growth ("geometry-growth split")

One approach: Double the standard DE parameter space

Instead of Ω_M and w, have:

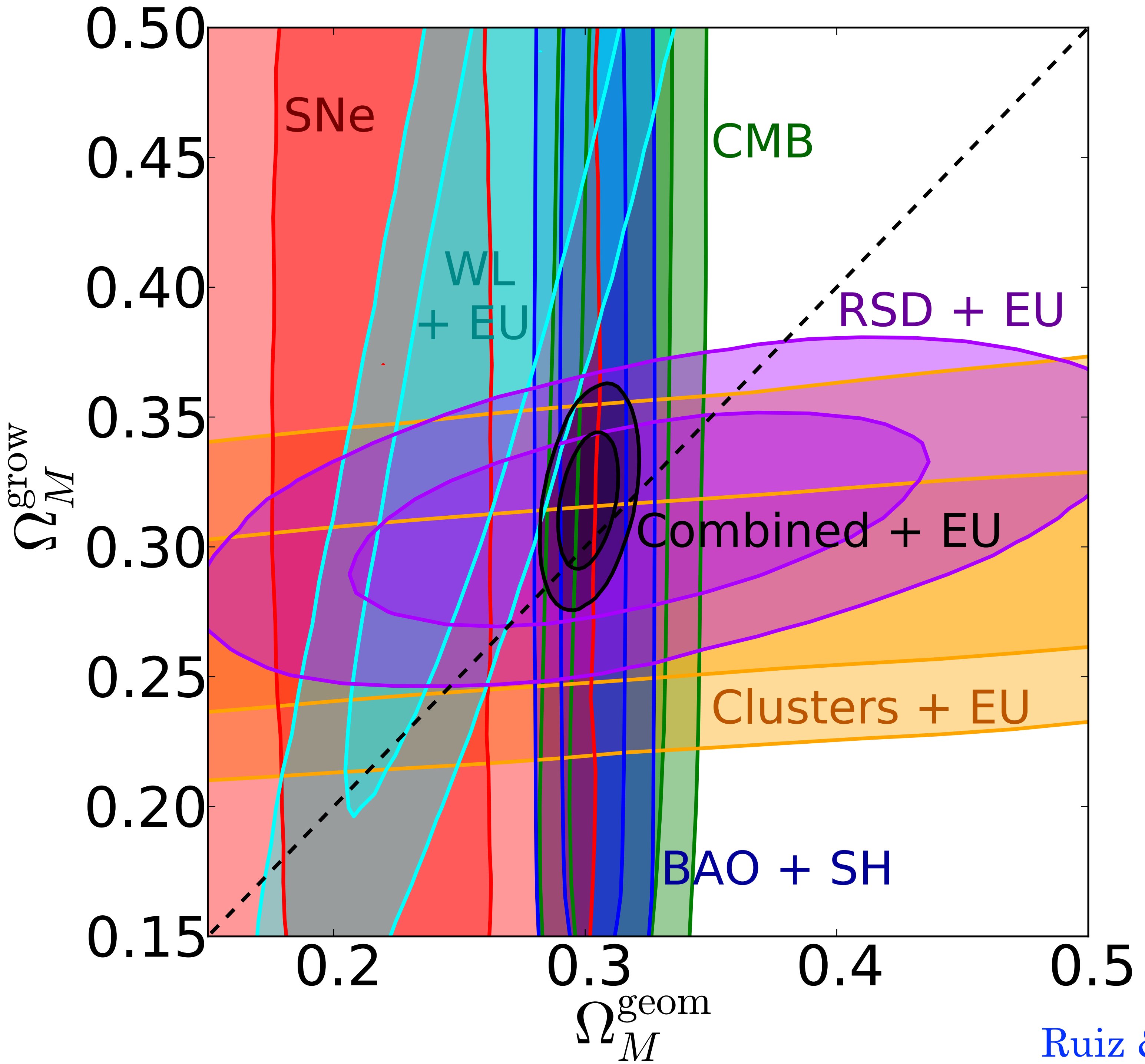
Ω_M^{geom}, w^{geom} Ω_M^{grow}, w^{grow}

[In addition to other, usual parameters]

	Cosmological Probe	Geometry	Growth
Pantheon ⟵	SN Ia	$H_0 D_L(z)$	—
eBOSS DR16 ⟵	BAO	$\{D_M(z); D_H(z)\}$	$r_d(z_d)$
Planck2018 ⟵	CMB	$j_\ell[k\chi(z)]$	$S_T(k,z)$
KiDS-1000 ⟵	Weak lensing	$\frac{d\chi(z)}{d(z)} g_i(z) g_j(z)$	$\Omega_m^2 P_\delta\left(\frac{\ell}{\chi}, z\right)$
eBOSS DR16 ⟵	RSD	—	$f(z)\sigma_8(z)$

Zhang, Hui, & Stebbins (2005)
Wang et al (2007)
Zhao, Knox & Tyson (2009)
Ruiz & Huterer (2015)
Bernal et al (2016)
Muir et al (2020) → DES
Ruiz-Zaptero et al (2021) → KIDS
Andrade et al (2021)

Comparing geometry and growth



Ruiz & Huterer (2015)

Advantages:

- physically well motivated (modified gravity)
- failure of geom=grow in measurements implies something is off <u>regardless of implementation</u>

A simpler alternative to full geometry-growth split:

growth index γ

(Peebles ~1980, Linder 2005)

$$f(a) \equiv \frac{d\ln D}{d\ln a} \simeq \Omega_m(a)^\gamma$$

then the linear growth is

$$D(a) = \exp \int_1^a d\ln a'\, \Omega_m^\gamma(a')$$

fits DE models in GR,
to very high accuracy (0.1%)

$$\gamma \simeq 0.55$$

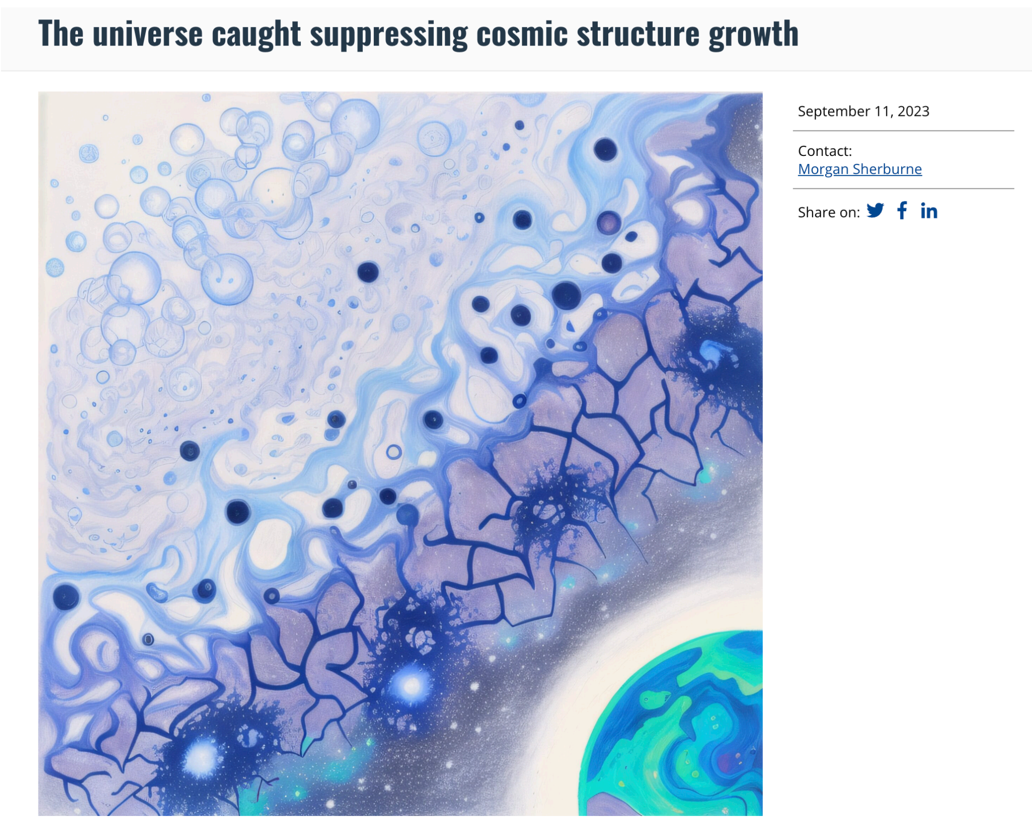
(really $\gamma \simeq 0.55[1 + 0.02w(z=1)]$)

Growth index also fits MG models (e.g. γ≃0.67 in DGP),
though see Wen, Nguyen & Huterer, JCAP 2023

- Pros: γ is easy to implement
- Cons: not "physical" (but neither is S_8)
- Pros: very robust - if $\gamma \neq 0.55$ then *something* is wrong

Evidence for suppression of growth in the standard cosmological model

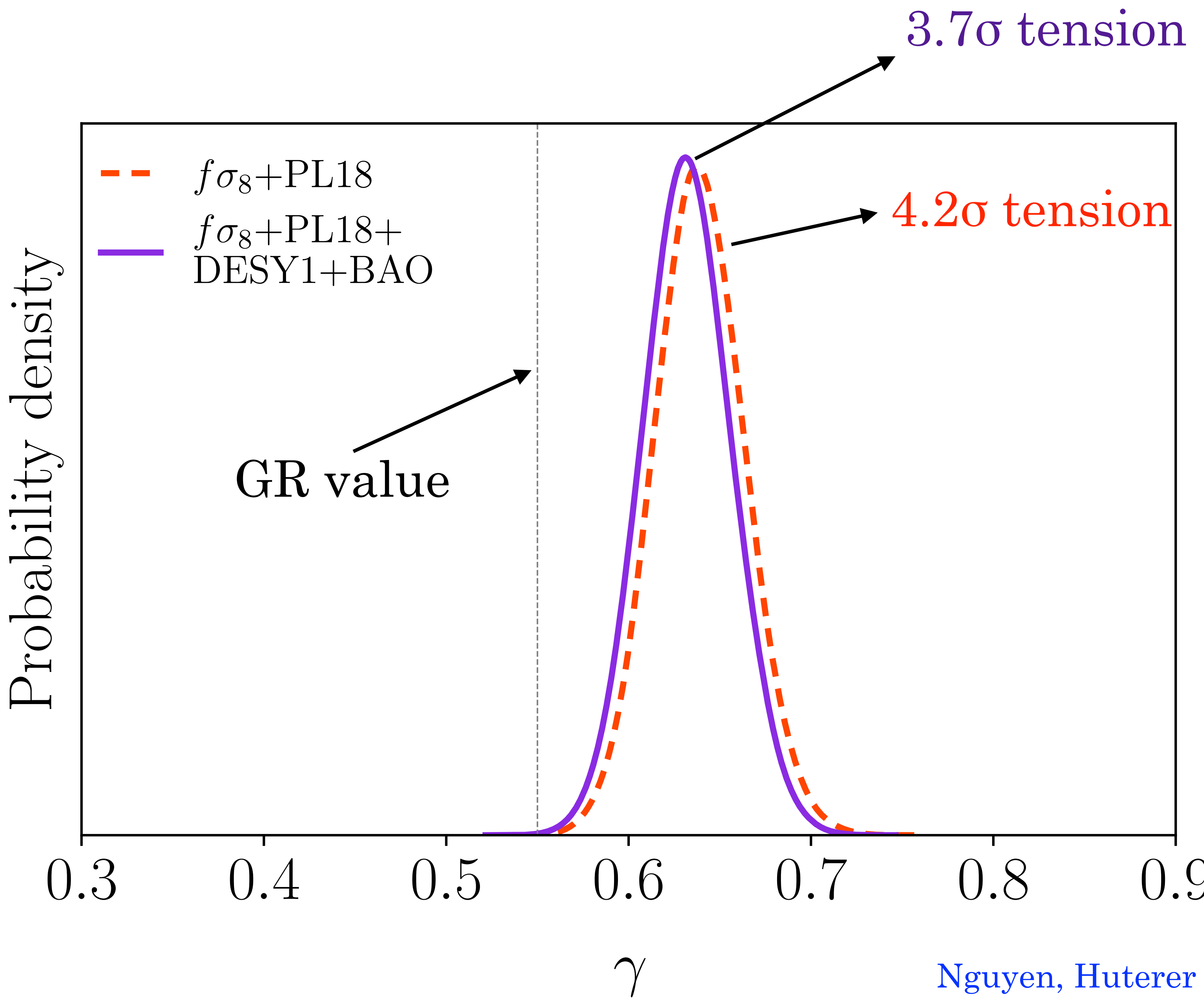
Nguyen, Huterer & Wen, PRL 131, 111001 (2023);
PRL Editor's Suggestion



(Nhat-)Minh Nguyen

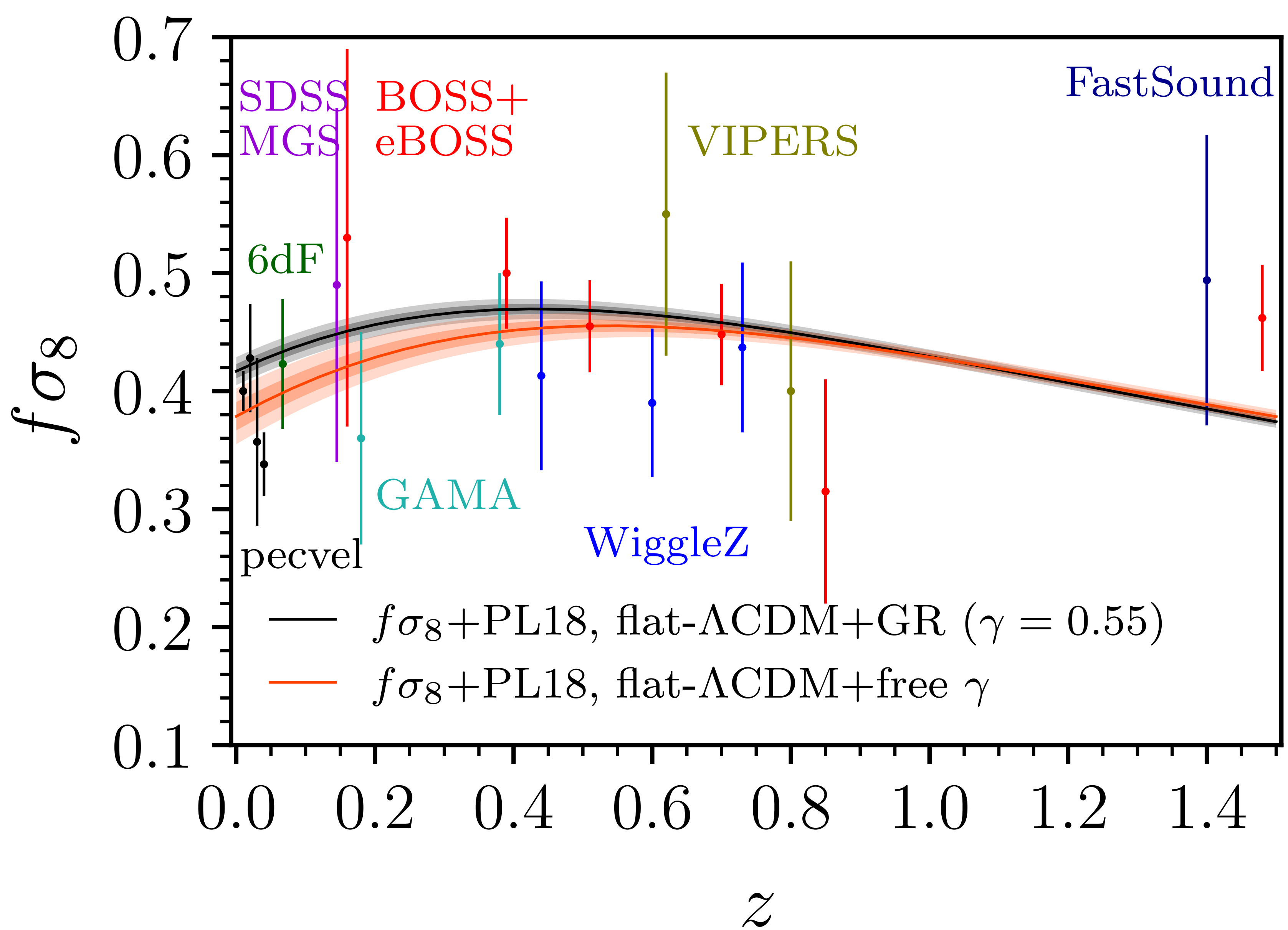
1. Implemented, validated growth index to theory pipeline. CMB affected by γ only via lensing.
2. Applied to analysis of CMB+fs8+DESY1+BAO data

Basic result:



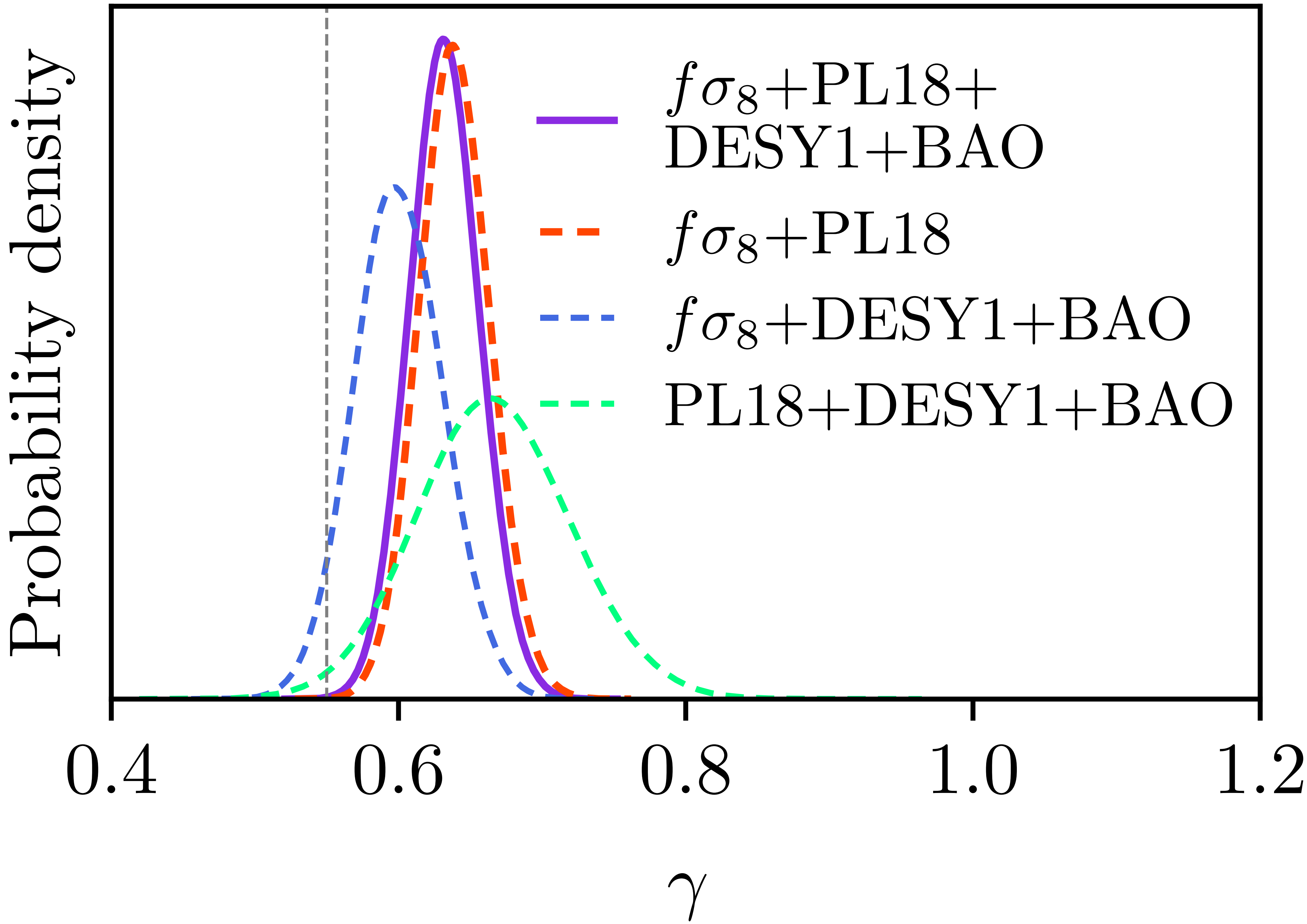
Nguyen, Huterer & Wen (2023)

Data	γ	S_8	H_0 [kms^{-1}Mpc^{-1}]	$\lvert\log_{10}\mathrm{BF}_{10}\rvert$	$\Delta\chi^2 \equiv \chi^2_\gamma - \chi^2_{\gamma=0.55}$
PL18	$\mathbf{0.668^{+0.068}_{-0.067}}$	$0.807^{+0.019}_{-0.019}$	$68.1^{+0.7}_{-0.7}$	0.4	-2.8
PL18+$f\sigma_8$	$\mathbf{0.639^{+0.024}_{-0.025}}$	$0.814^{+0.011}_{-0.011}$	$67.9^{+0.5}_{-0.5}$	1.7	-13.6
PL18+$f\sigma_8$+DESY1+BAO	$\mathbf{0.633^{+0.025}_{-0.024}}$	$0.802^{+0.008}_{-0.008}$	$68.4^{+0.4}_{-0.4}$	1.2	-13.2
PL18+$f\sigma_8$+DESY1+BAO (flat ΛCDM+GR)	**0.55**	$0.803^{+0.008}_{-0.008}$	$68.5^{+0.4}_{-0.4}$	-	0



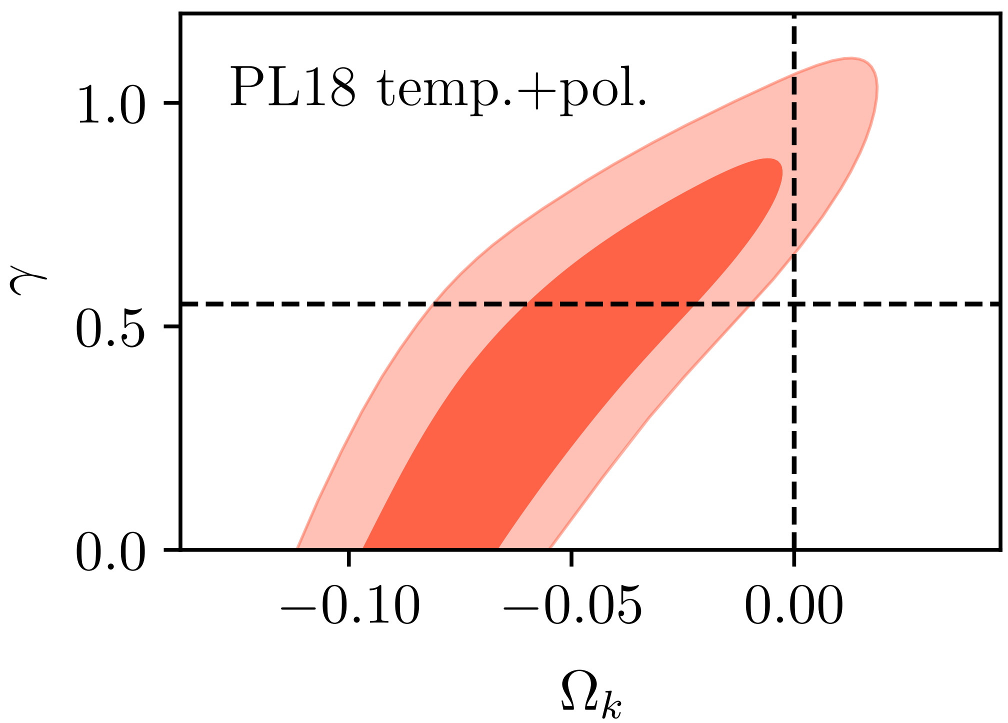
Nguyen, Huterer & Wen (2023)

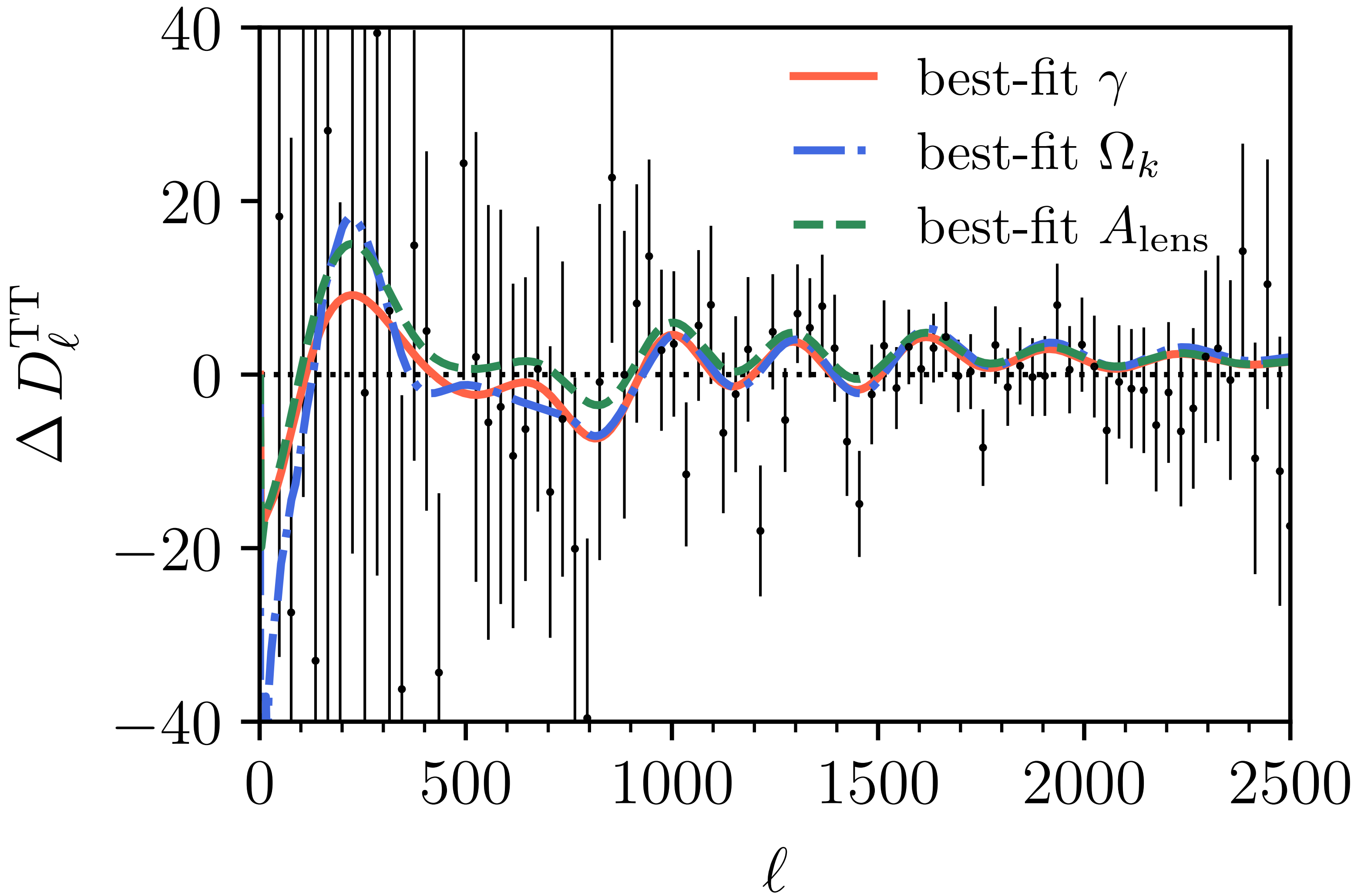
More details



Nguyen, Huterer & Wen (2023)

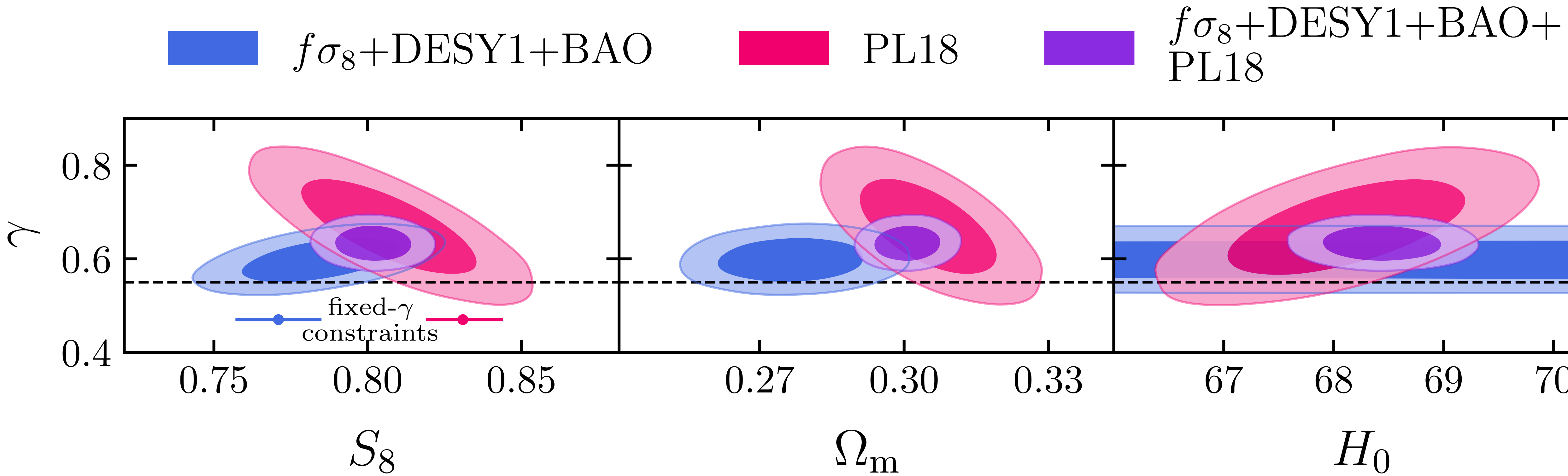
Signature of suppressed growth in CMB





Nguyen, Huterer & Wen (2023)

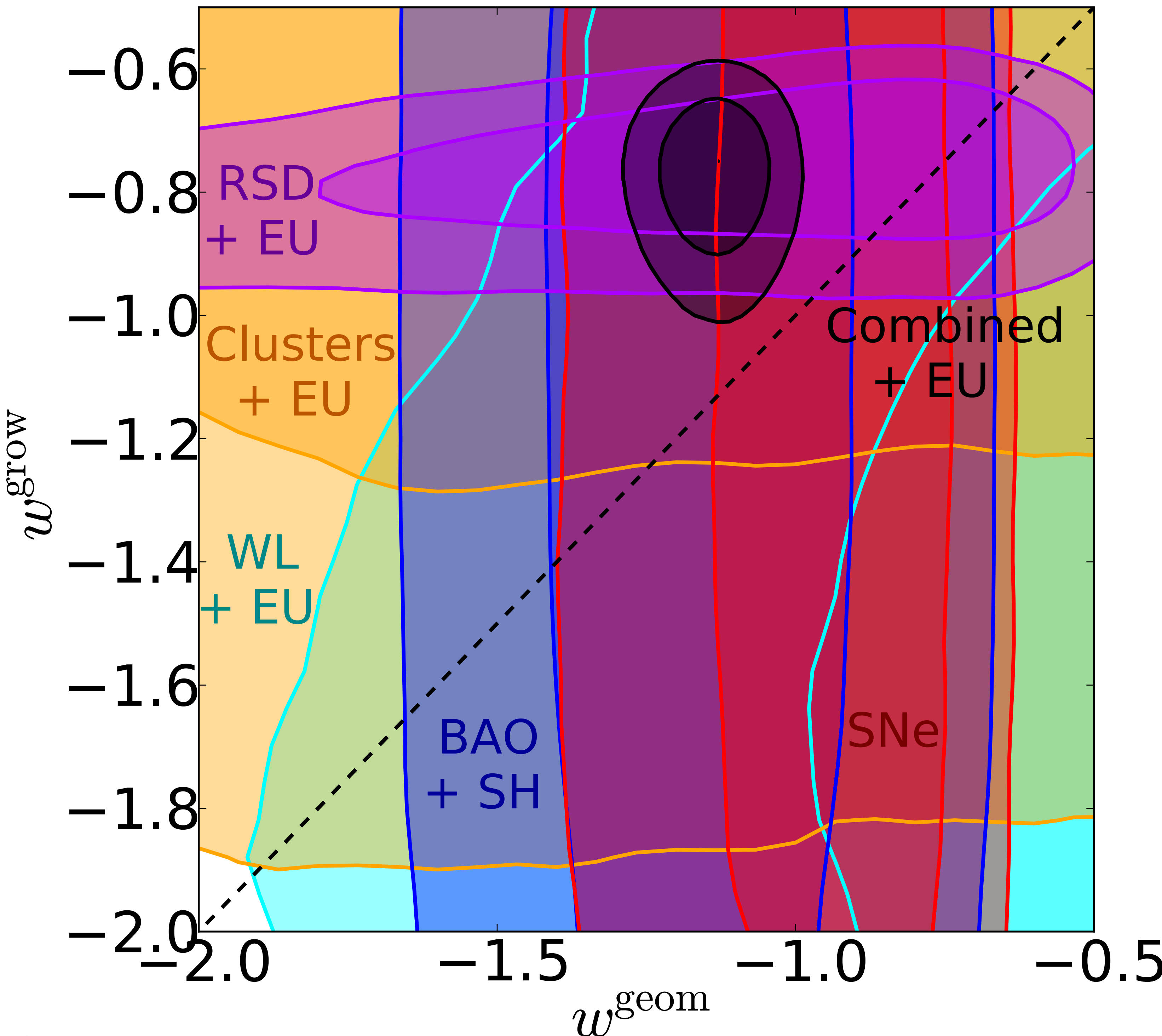
Resolves the S_8 tension, alleviates the H_0



- Planck's S8 is ~lower than for fixed ɣ
- fs8+DESY1+BAO S_8 is ~higher than for fixed ɣ
- (and the error bars are larger with ɣ varied, so)
- $\Longrightarrow$ S8 tension is resolved
- H0 tension is somewhat alleviated

Nguyen, Huterer & Wen (2023)

The same effect (suppressed late-time growth) has been seen before in some geometry-growth-split analyses

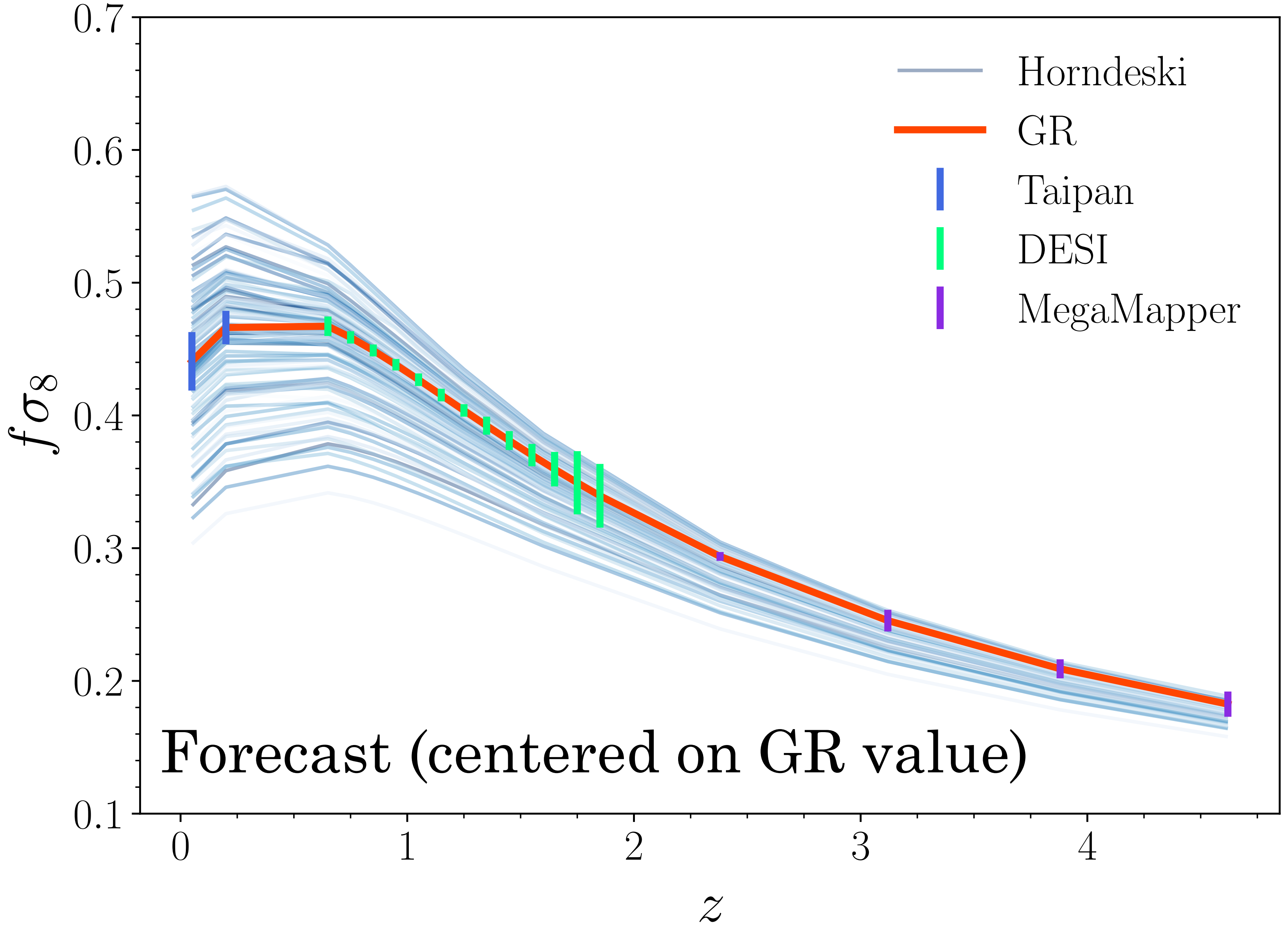


note: high $w_{\rm growth}$ is equivalent to suppressed late-time growth

Ruiz & Huterer (2015); also see Bernal, Verde & Cuesta (2015)

So:

- A new intriguing piece of evidence that growth is suppressed, building upon previous work which found the same
- Will be *very* sharply tested with forthcoming data!



Conclusions

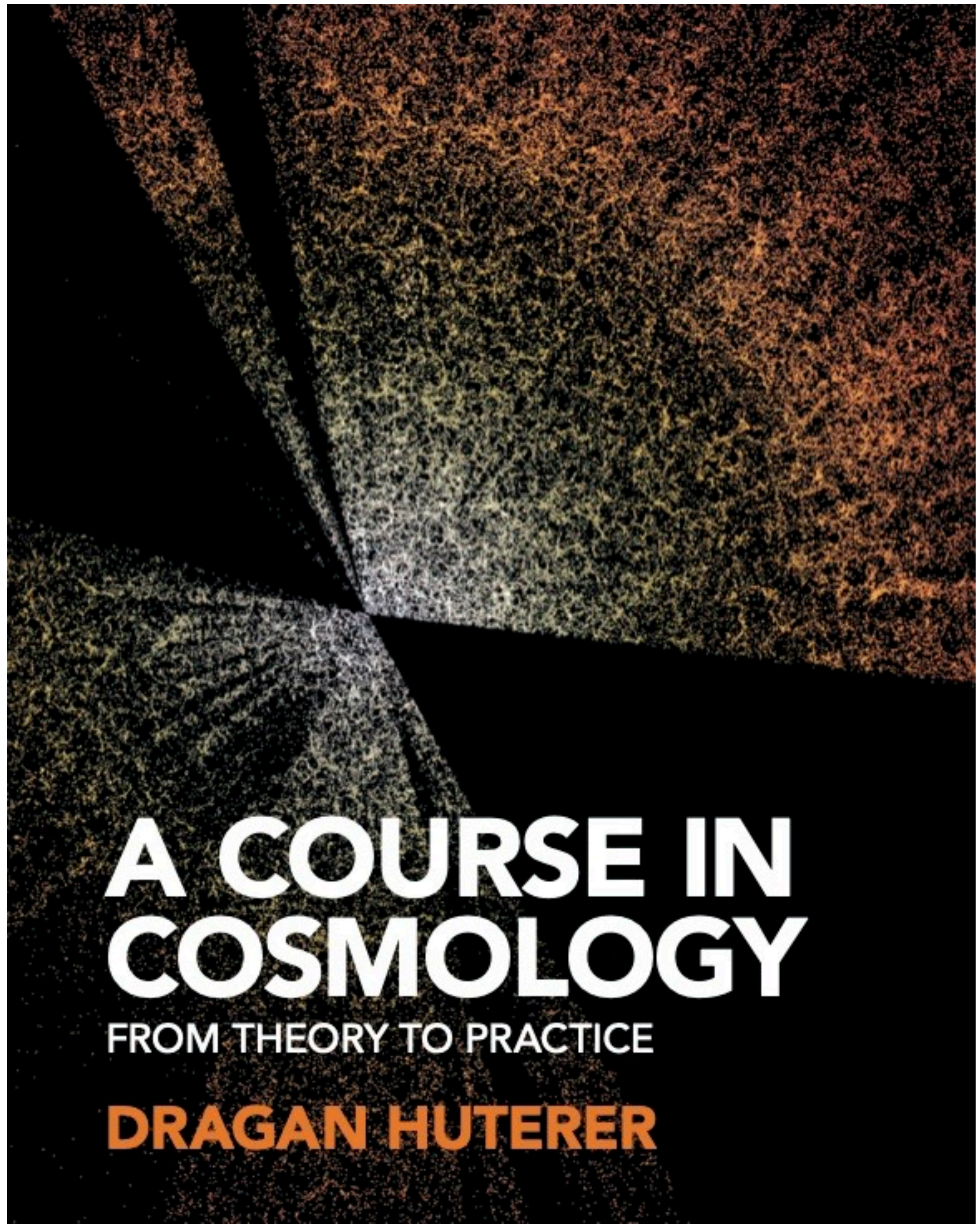
- Current status of DE: excellent consistency with ~70% dark energy ~30% matter flat universe

- Like particle physicists, we would really like to see some “bumps” in the data ⇒ H_0 tension, maybe S_8 tension

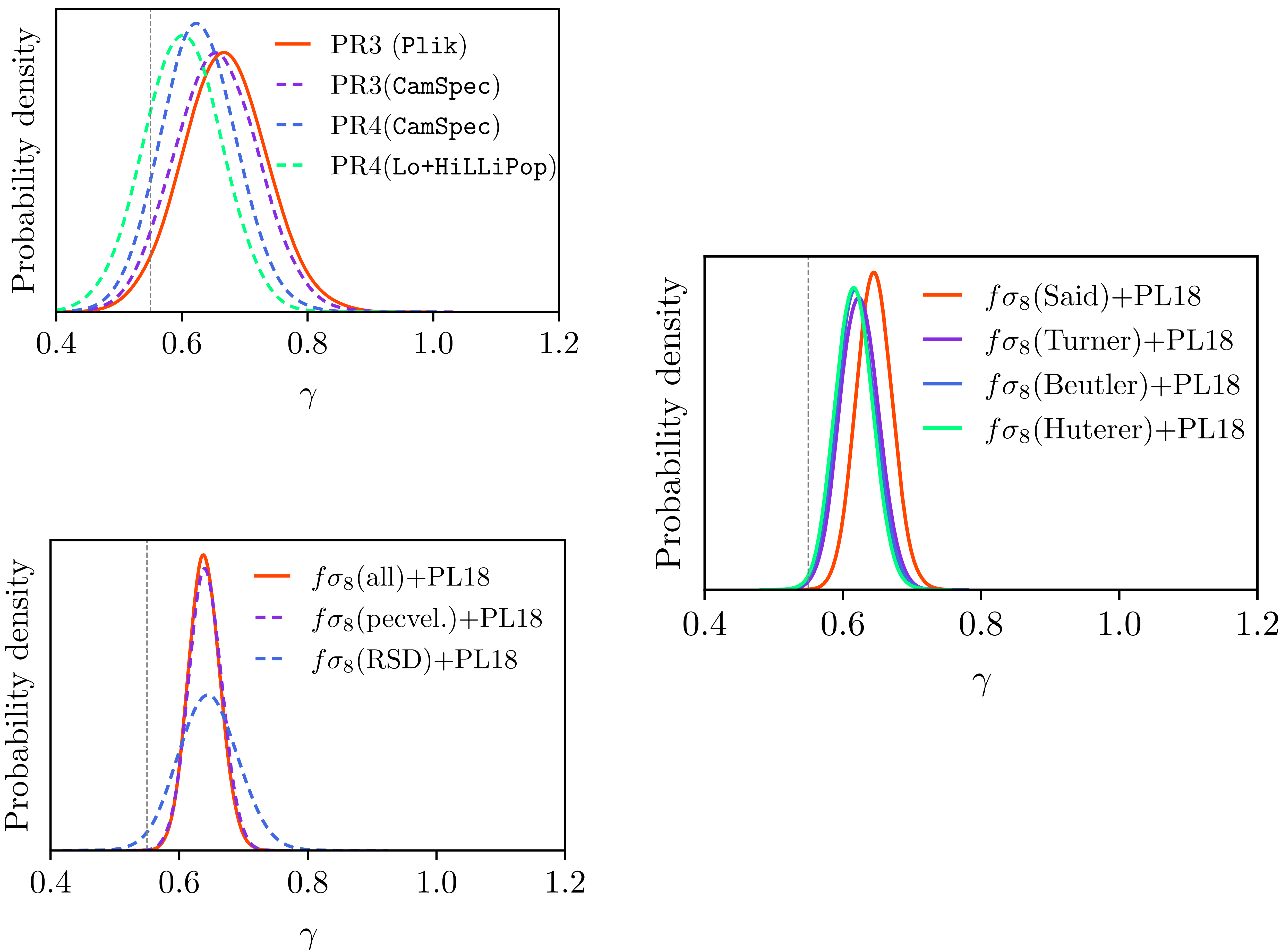
- ~4-sigma evidence that growth is suppressed (relative to LCDM expectation)

- This, along with other DE and DM science, will be sharply tested with forthcoming experiments

New textbook, out May 2023 (Cambridge University Press)
Emphasis: pedagogy, computation
Level: lower graduate

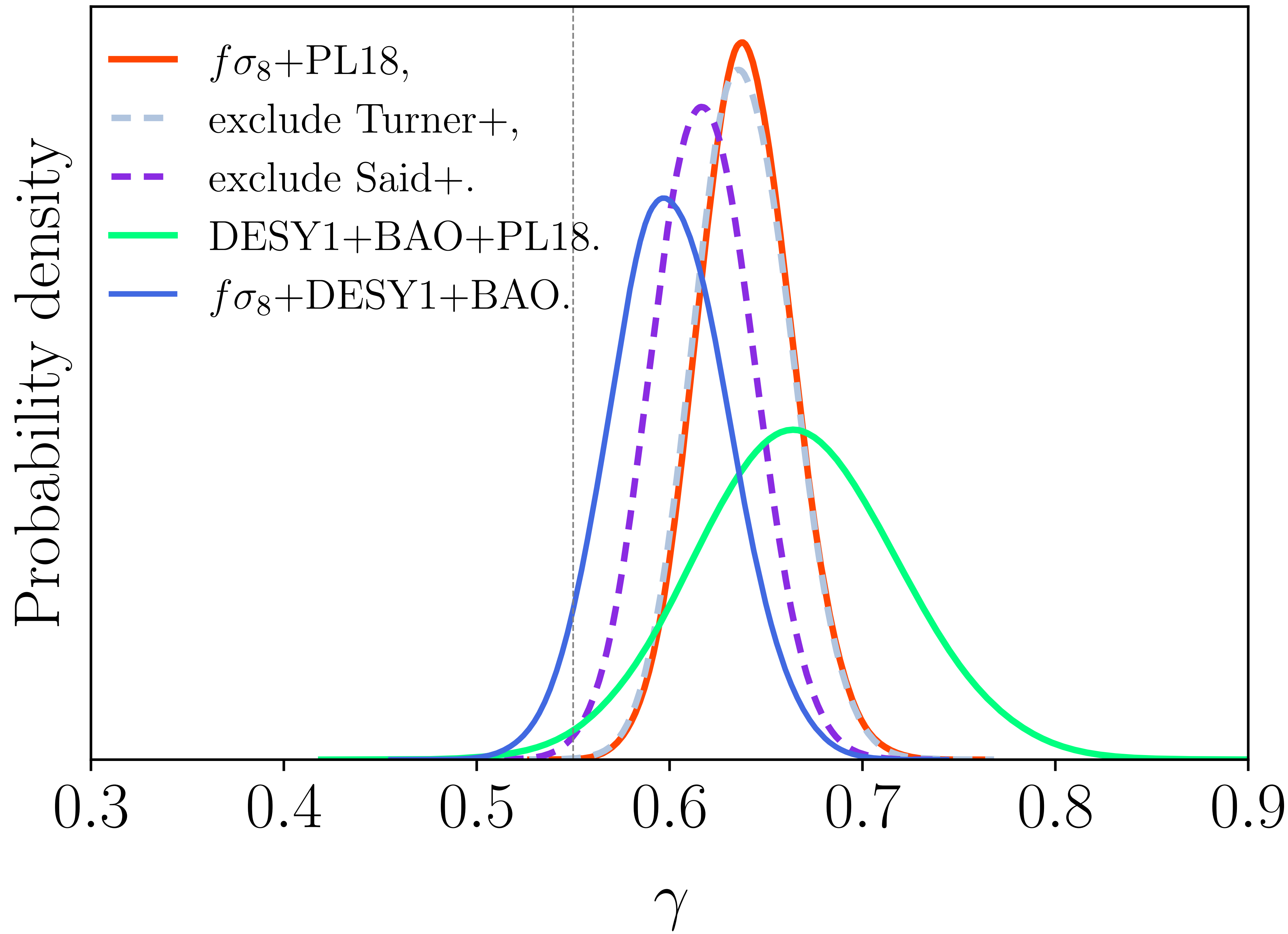


Extra slides

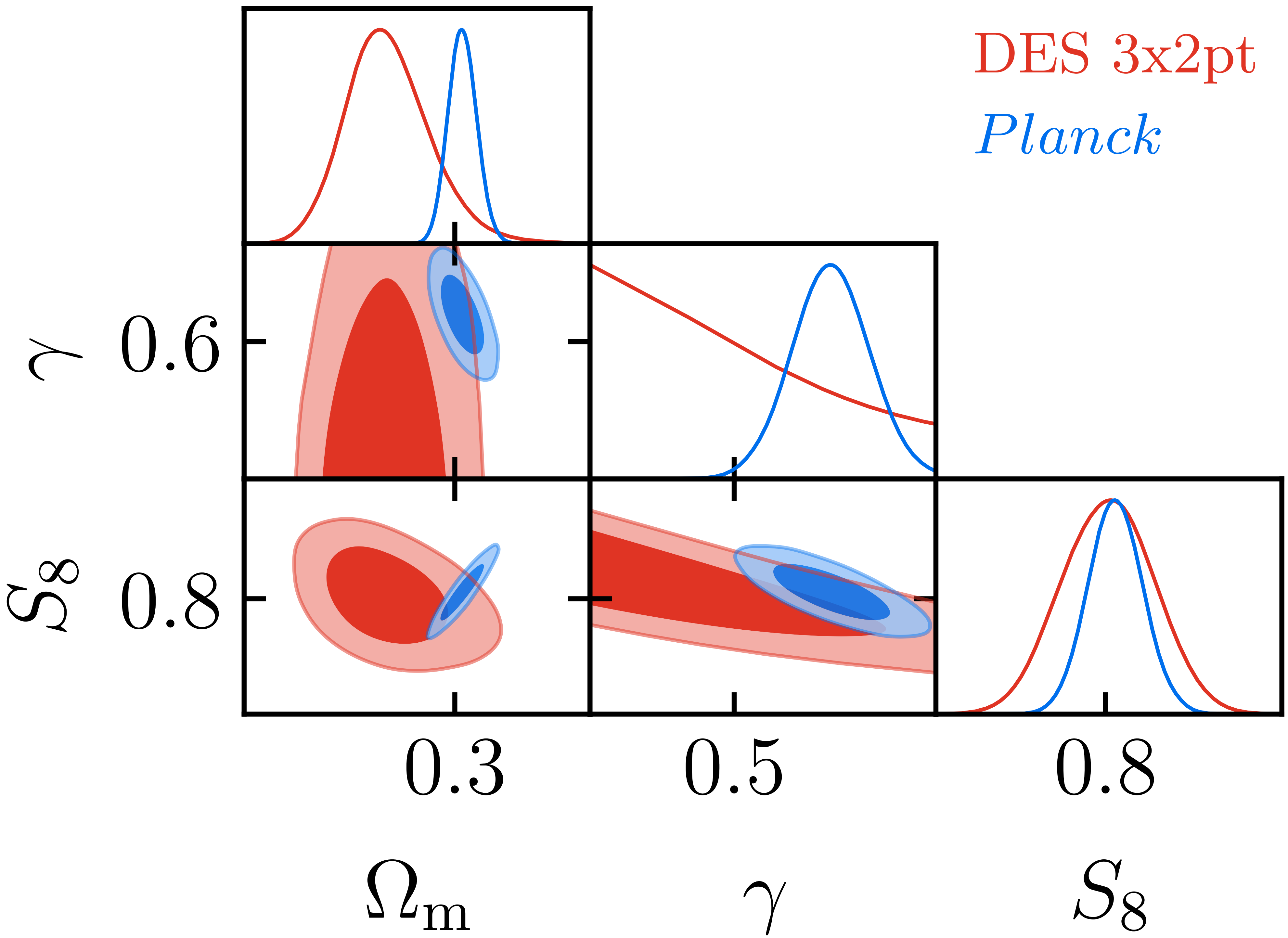


Probability density
PR3 (Plik)
PR3(CamSpec)
PR4(CamSpec)
PR4(Lo+HiLLiPop)
0.4
0.6
0.8
1.0
1.2
γ
Probability density
fσ8(Said)+PL18
fσ8(Turner)+PL18
fσ8(Beutler)+PL18
fσ8(Huterer)+PL18
0.4
0.6
0.8
1.0
1.2
γ
Probability density
fσ8(all)+PL18
fσ8(pecvel.)+PL18
fσ8(RSD)+PL18
0.4
0.6
0.8
1.0
1.2
γ

More details



Nguyen, Huterer & Wen (2023)



DES 3x2pt
Planck
γ
0.6
S_8
0.8
0.3
0.5
0.8
Ω_m
γ
S_8

Data	$\Delta\chi^2 \equiv \chi^2_\gamma - \chi^2_{\gamma=0.55}$							
	low-ℓ TT	**low-ℓ EE**	**high-ℓ TTTEEE**	**lensing**	$f\sigma_8$	**DESY1**	**BAO**	**total**
PL18 temp.+pol.	-1.1	-0.4	-7.0	-	-	-	-	-8.5
PL18	-1.0	-0.1	-3.1	$+1.4$	-	-	-	-2.8
PL18+$f\sigma_8$	$+0.1$	-0.3	-5.6	$+0.5$	-8.3	-	-	-13.6
PL18+DESY1+BAO	-0.6	-0.8	-3.7	$+0.3$	-	-0.7	$+0.8$	-4.7
$f\sigma_8$+DESY1+BAO	-	-	-	-	-1.2	-2.9	-2.2	-6.3
PL18+$f\sigma_8$+DESY1+BAO	-0.2	-1.1	-5.3	-0.7	-6.8	$+0.8$	$+0.1$	-13.2