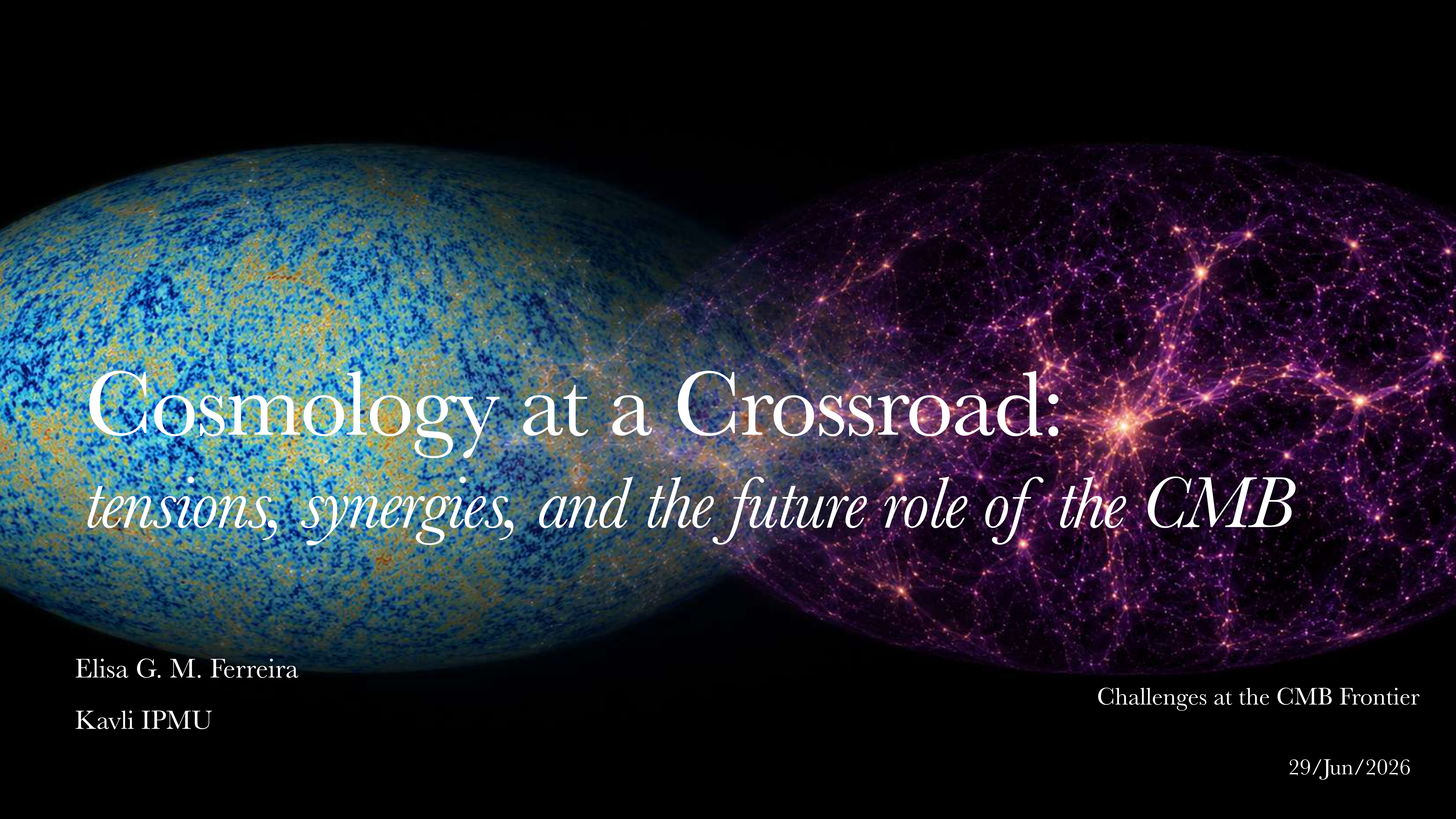


The background of the slide is a composite image. On the left, there is a map of the Cosmic Microwave Background (CMB) showing temperature fluctuations in shades of blue and yellow. On the right, there is a visualization of the large-scale structure of the universe, showing a network of galaxies and dark matter filaments in purple and orange. The title text is overlaid on this background.

Cosmology at a Crossroad: *tensions, synergies, and the future role of the CMB*

Elisa G. M. Ferreira
Kavli IPMU

Challenges at the CMB Frontier

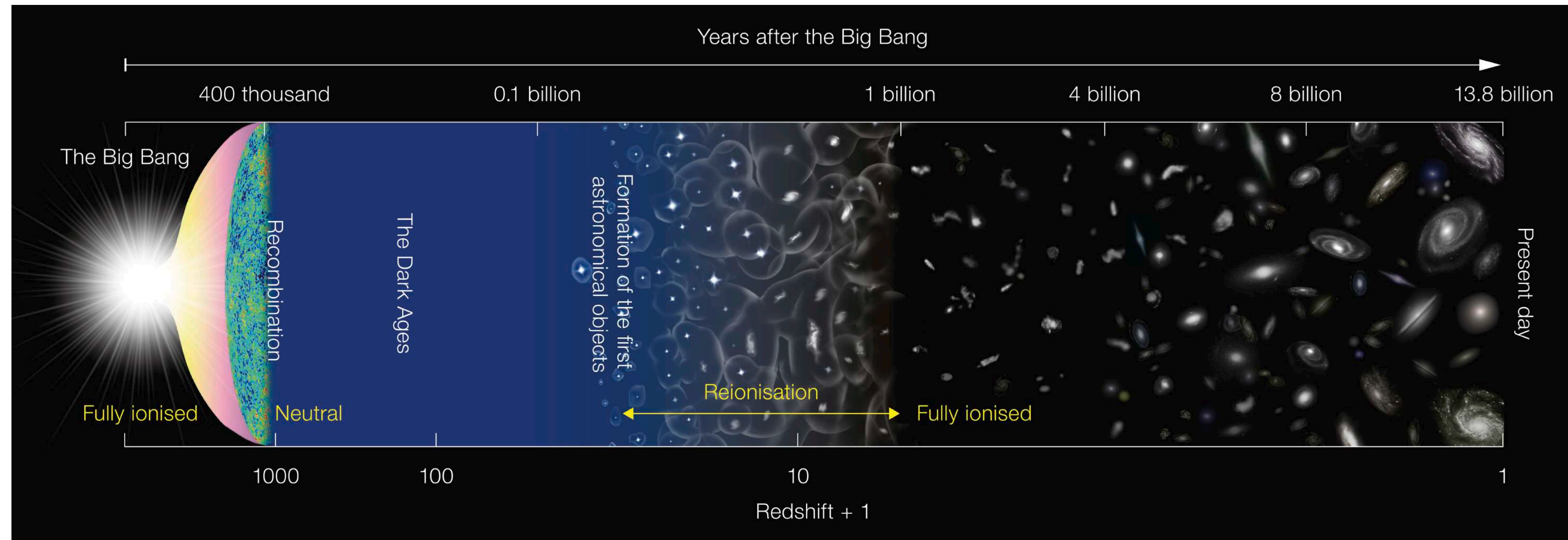
29/Jun/2026

*Standard cosmological **model***

Standard cosmological model - **LCDM model**

$$\{\Omega_b, \Omega_m, \Omega_\Lambda, n_s, A_s, \tau\}$$

GR + cosmological principle + Observational pillars

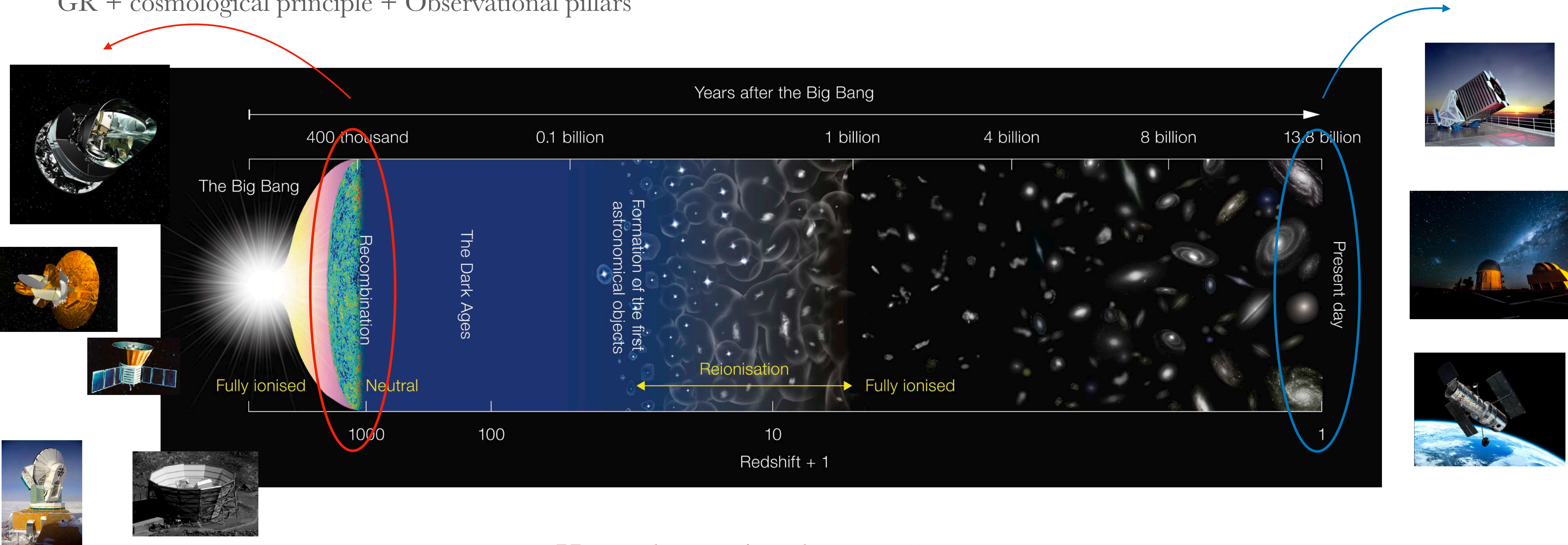


Standard cosmological *model*

Standard cosmological model - **LCDM model**

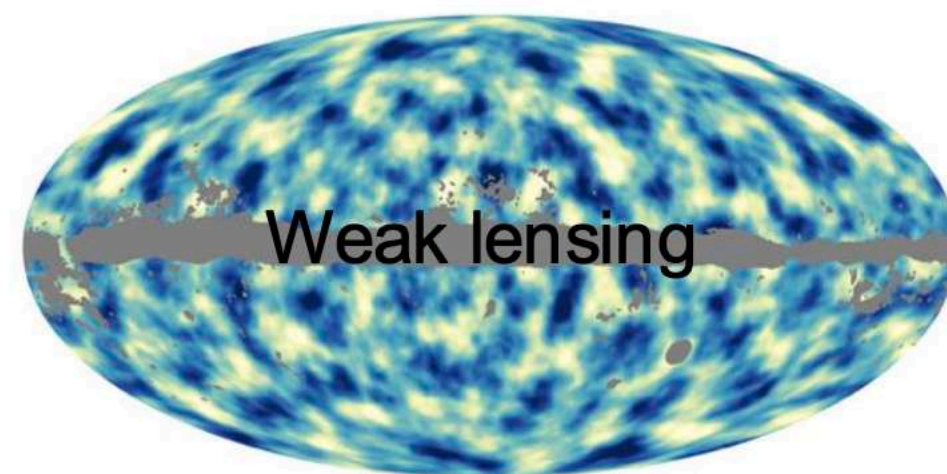
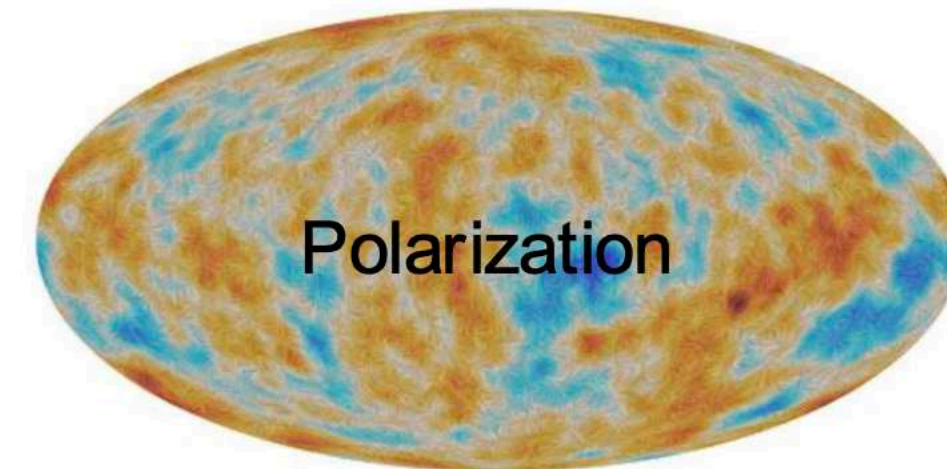
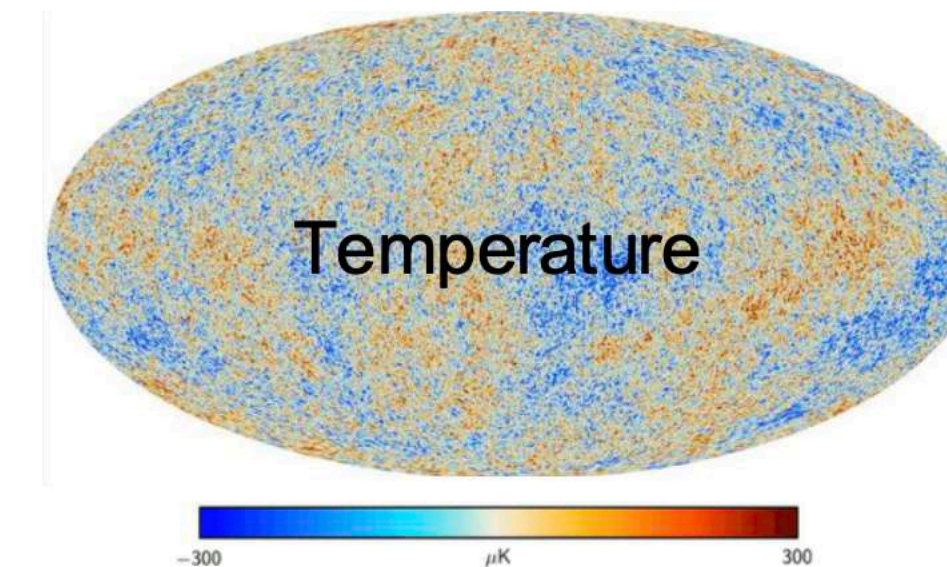
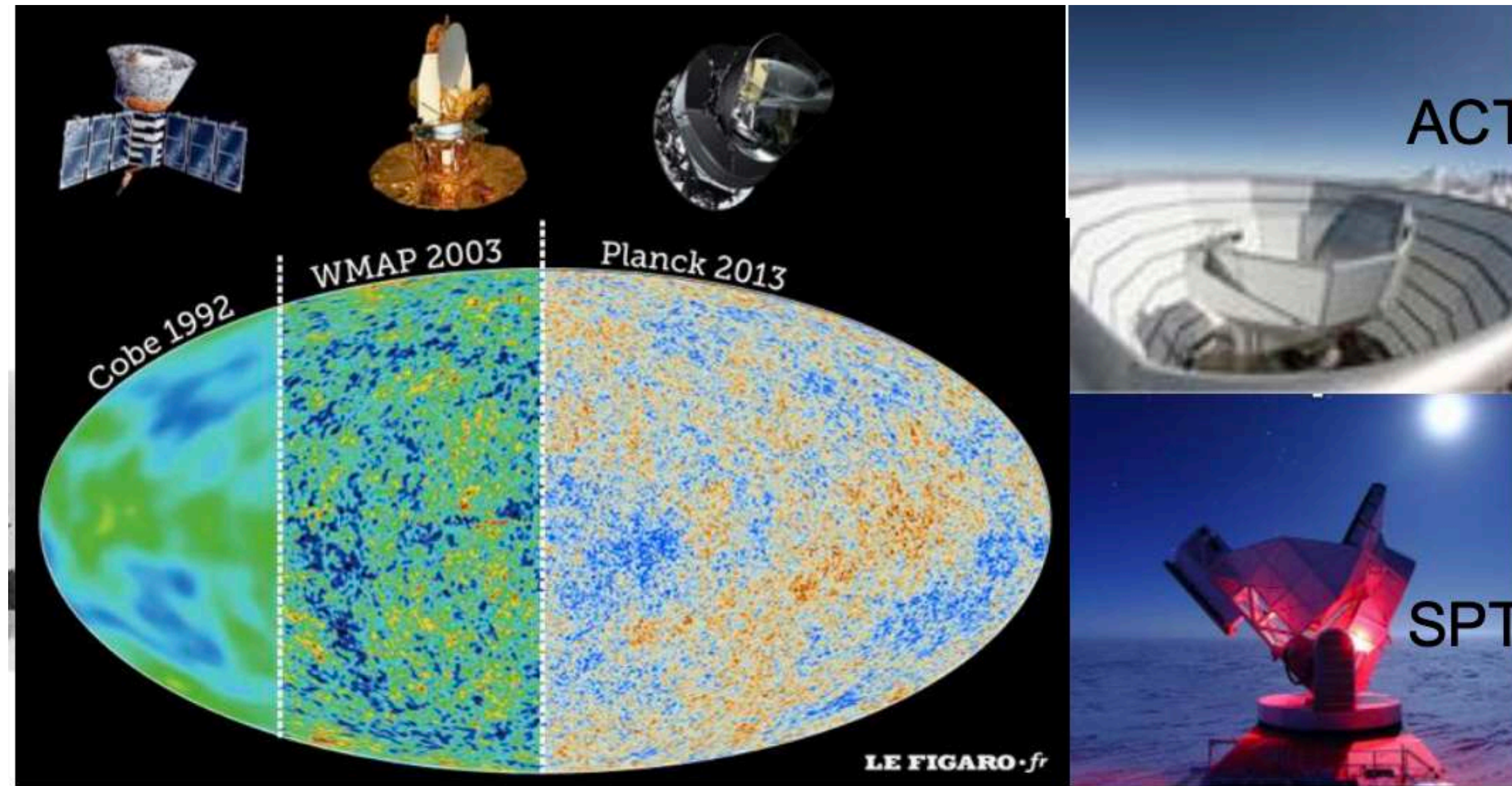
$$\{\Omega_b, \Omega_m, \Omega_\Lambda, n_s, A_s, \tau\}$$

GR + cosmological principle + Observational pillars



Huge observational success!!

Cosmic microwave background



ESA/Planck Collaboration

Cold light, 2.7K
Variations in the sky of
1 part in 100000

Initial seeds of cosmic structures
Gravitational fields
Make up of the Universe

Polarized light at the 10% level
Variations in the sky of less
than 1 part in 1000000(00)

Where and how
atoms/molecules/stars are forming
First second of Universe existence

2 arcminute ($\sim 1/15$ of the Moon)
total deflection over a 13.3
billion-year journey

Geometry and matter distribution
from early Universe to today

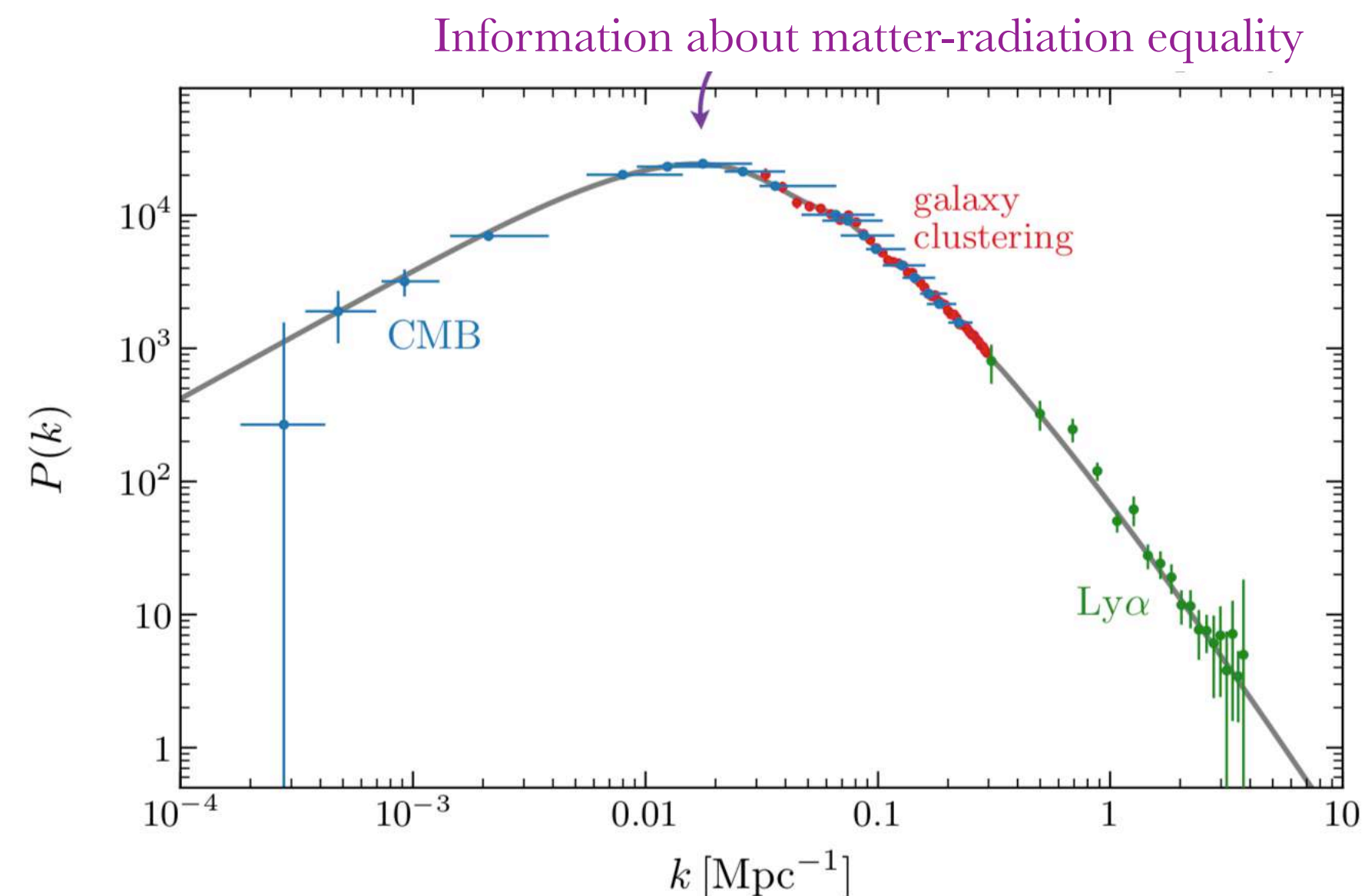
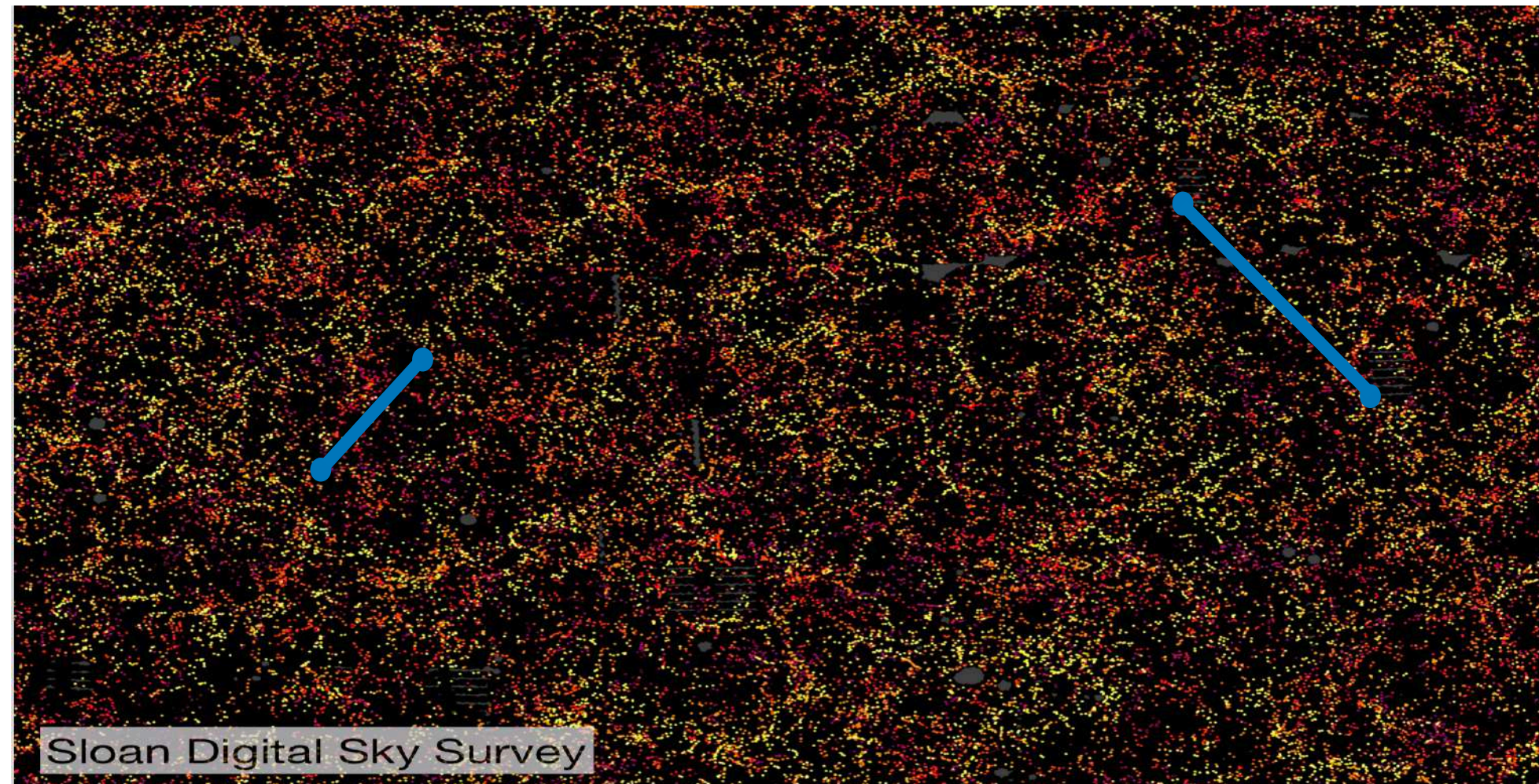
CMB shaped the LCDM

- COBE: first detection
- LCDM takes shape with WMAP
- Planck: precision era

- Beyond temperature: CMB polarization and lensing added new information: reionization, primordial tensors, projected matter fluctuations, neutrino mass, and growth.
- Today: ACT, SPT, extended to small scales, lensing, polarization

The CMB gave us the **blueprint of LCDM**; now it tests whether that blueprint predicts the Universe seen by LSS

Large scale *structure*



- **Early galaxy surveys revealed the cosmic web:** clusters, filaments, voids, and large-scale clustering.
- **Redshift surveys turned LSS into cosmology:** 2dFGRS, SDSS
→ galaxy power spectrum, $\Omega_m h$, baryon features, consistency with CMB+ Λ CDM.
- **BAO made LSS a standard-ruler experiment:** SDSS LRG, BOSS/eBOSS, DESI
→ late-time distances in units of r_d .
- **Today, LSS is no longer only BAO:**
full-shape ($P(k)$), RSD, weak lensing, galaxy–galaxy lensing, clusters, $\text{Ly}\alpha$, CMB lensing cross-correlations
→ geometry, growth, neutrino mass, dark energy, modified gravity.
- **Imaging surveys** add the matter distribution:
CFHTLenS, KiDS, DES, HSC, LSST, Euclid, Roman
→ cosmic shear, S_8 , galaxy bias, galaxy–matter connection.
- **Spectroscopic surveys** add precise 3D structure:
BOSS/eBOSS, DESI, Euclid spectroscopy, PFS, 4MOST
→ BAO, RSD, full-shape clustering, $f\sigma_8$.
- **High-redshift** and complementary probes extend the reach:
 $\text{Ly}\alpha$ forest, SPHEREx, JWST, intensity mapping
→ high-(z) structure, small-scale power, reionization-era galaxies, primordial physics.
- The story of LSS is also the story of **systematics**

LSS now tests both geometry and growth, but precision requires understanding astrophysical and observational systematics.

Standard cosmological model

Describes the universe with 6 parameters: $\{\Omega_b, \Omega_c, H_0, A_s, n_s, \tau\}$

Matter content: 2 parameters for densities

$$\Omega_b h^2$$

$$\Omega_c h^2$$

Expansion rate:

$$H_0$$

Initial conditions: 2 parameters from primordial power spectrum

$$P_{IC}(k) = A_s \left(\frac{k}{k_p}\right)^{n_s-1}$$

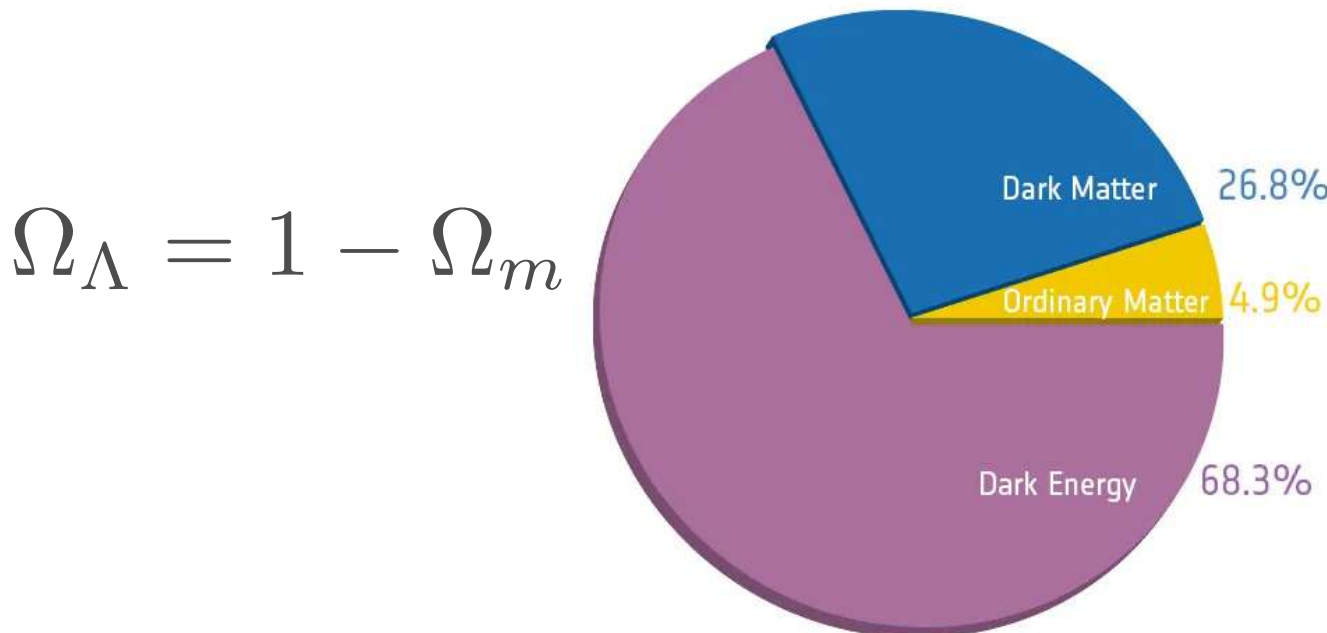
Reionization: optical depth

$$\tau$$

Huge observational success!!

ΛCDM parameters with per cent precision

Planck 2018 result VI



$$\Omega_\Lambda = 1 - \Omega_m$$

Parameter	TT,TE,EE+lowE+lensing+BAO	
	68% limits	
$\Omega_b h^2$	0.02242 ± 0.00014	(0.6%)
$\Omega_c h^2$	0.11933 ± 0.00091	(0.8%)
$100\theta_{MC}$	1.04101 ± 0.00029	(0.03%)
τ	0.0561 ± 0.0071	(12%)
$\ln(10^{10} A_s)$	3.047 ± 0.014	(0.4%)
n_s	0.9665 ± 0.0038	(0.4%)
H_0 [km s ⁻¹ Mpc ⁻¹] . .	67.66 ± 0.42	
Ω_Λ	0.6889 ± 0.0056	

Standard cosmological *model*

Matter
content

$\Omega_b = 0.0484 \pm 0.0003$ $\longrightarrow$ Amount of ordinary/visible matter

$\Omega_m = 0.308 \pm 0.012$ $\longrightarrow$ Amount of dark matter

$\Omega_\Lambda = 0.692 \pm 0.012$ $\longrightarrow$ Amount of dark energy

IC

$n_s = 0.9626 \pm 0.0057$ $\longrightarrow$ Scale dependence of the initial fluctuations

$10^9 A_s = 2.092 \pm 0.034$ $\longrightarrow$ Amplitude of the initial fluctuations

Reionization

$\tau = 0.0522 \pm 0.0080$ $\longrightarrow$ Optical depth

How opaque the universe is to photons that travel in it

Under assumptions:

- Flat universe: $\Omega_k = 0$
- 3 neutrinos: $N_{eff} = 3.046$
- Sum of neutrino mass: $\Sigma m_\nu = 0.06$
- No tensor: $P_t = 0$
- No running: $dn_s/dk = 0$

Standard cosmological *model*

Standard cosmological model - **LCDM model**

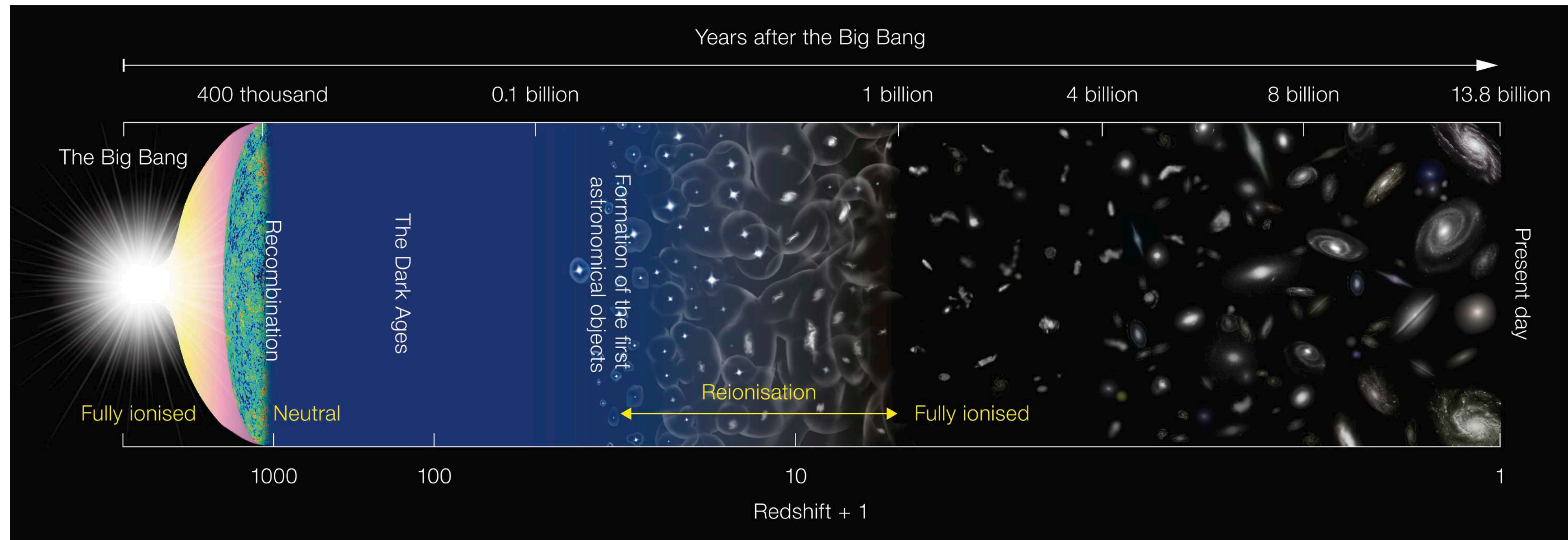
$$\{\Omega_b, \Omega_m, \Omega_\Lambda, n_s, A_s, \tau\}$$

GR + cosmological principle + Observational pillars

Early universe-
IC

Dark matter- **CDM**
Structure formation

Dark energy - **Λ**
Accelerated expansion

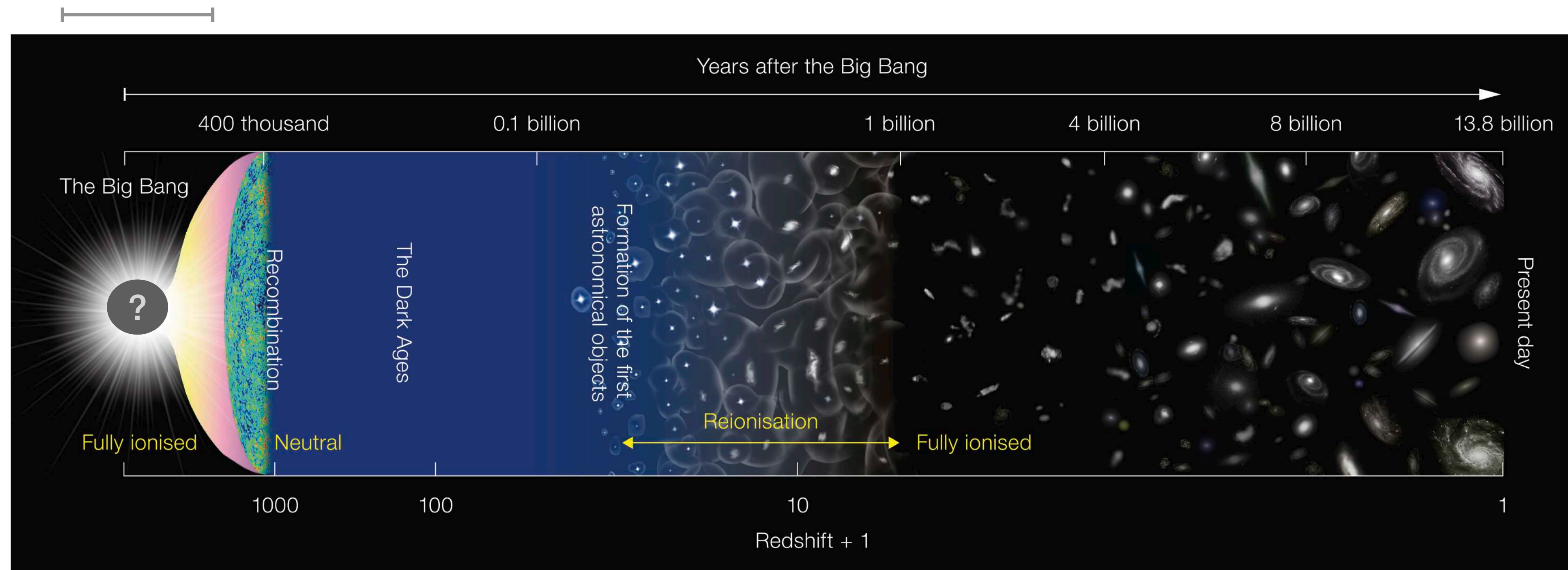


MANY fundamental open questions

Early universe
Big Bang? **What is the physics of
the early universe?**

Dark matter
What is the dark matter?

Dark energy -
What is the dark energy?



+ cosmological tensions
**Discrepancies in measured
parameters**

Precision cosmology: Concordance or Discordance?

ΛCDM model is under extreme scrutiny!

Tensions and hints of new physics are appearing.

Hypothesis and extensions *scrutinized*

CMB

Table 5. Constraints on standard cosmological parameters from *Planck* TT,TE,EE+lowE+lensing when the base- Λ CDM model is extended by varying additional parameters. The constraint on τ is also stable but not shown for brevity; however, we include H_0 (in $\text{km s}^{-1}\text{Mpc}^{-1}$) as a derived parameter (which is very poorly constrained from *Planck* alone in the $\Lambda\text{CDM}+w_0$ extension). Here α_{-1} is a matter isocurvature amplitude parameter, following [PCP15](#). All limits are 68 % in this table. The results assume standard BBN except when varying Y_{P} independently (which requires non-standard BBN). Varying A_{L} is not a physical model (see Sect. 6.2).

Parameter(s)	$\Omega_{\text{b}}h^2$	$\Omega_{\text{c}}h^2$	$100\theta_{\text{MC}}$	H_0	n_{s}	$\ln(10^{10}A_{\text{s}})$
Base ΛCDM	0.02237 ± 0.00015	0.1200 ± 0.0012	1.04092 ± 0.00031	67.36 ± 0.54	0.9649 ± 0.0042	3.044 ± 0.014
r	0.02237 ± 0.00014	0.1199 ± 0.0012	1.04092 ± 0.00031	67.40 ± 0.54	0.9659 ± 0.0041	3.044 ± 0.014
$\text{d}n_{\text{s}}/\text{d}\ln k$	0.02240 ± 0.00015	0.1200 ± 0.0012	1.04092 ± 0.00031	67.36 ± 0.53	0.9641 ± 0.0044	3.047 ± 0.015
$\text{d}n_{\text{s}}/\text{d}\ln k, r$	0.02243 ± 0.00015	0.1199 ± 0.0012	1.04093 ± 0.00030	67.44 ± 0.54	0.9647 ± 0.0044	3.049 ± 0.015
$\text{d}^2n_{\text{s}}/\text{d}\ln k^2, \text{d}n_{\text{s}}/\text{d}\ln k$.	0.02237 ± 0.00016	0.1202 ± 0.0012	1.04090 ± 0.00030	67.28 ± 0.56	0.9625 ± 0.0048	3.049 ± 0.015
N_{eff}	0.02224 ± 0.00022	0.1179 ± 0.0028	1.04116 ± 0.00043	66.3 ± 1.4	0.9589 ± 0.0084	3.036 ± 0.017
$N_{\text{eff}}, \text{d}n_{\text{s}}/\text{d}\ln k$	0.02216 ± 0.00022	0.1157 ± 0.0032	1.04144 ± 0.00048	65.2 ± 1.6	0.950 ± 0.011	3.034 ± 0.017
Σm_{ν}	0.02236 ± 0.00015	0.1201 ± 0.0013	1.04088 ± 0.00032	$67.1^{+1.2}_{-0.67}$	0.9647 ± 0.0043	3.046 ± 0.015
$\Sigma m_{\nu}, N_{\text{eff}}$	0.02223 ± 0.00023	0.1180 ± 0.0029	1.04113 ± 0.00044	$66.0^{+1.8}_{-1.6}$	0.9587 ± 0.0086	3.038 ± 0.017
$m_{\nu, \text{sterile}}^{\text{eff}}, N_{\text{eff}}$	$0.02242^{+0.00014}_{-0.00016}$	$0.1200^{+0.0032}_{-0.0020}$	$1.04074^{+0.00033}_{-0.00029}$	$67.11^{+0.63}_{-0.79}$	$0.9652^{+0.0045}_{-0.0056}$	$3.050^{+0.014}_{-0.016}$
α_{-1}	0.02238 ± 0.00015	0.1201 ± 0.0015	1.04087 ± 0.00043	67.30 ± 0.67	0.9645 ± 0.0061	3.045 ± 0.014
w_0	0.02243 ± 0.00015	0.1193 ± 0.0012	1.04099 ± 0.00031	...	0.9666 ± 0.0041	3.038 ± 0.014
Ω_K	0.02249 ± 0.00016	0.1185 ± 0.0015	1.04107 ± 0.00032	$63.6^{+2.1}_{-2.3}$	0.9688 ± 0.0047	$3.030^{+0.017}_{-0.015}$
Y_{P}	0.02230 ± 0.00020	0.1201 ± 0.0012	1.04067 ± 0.00055	67.19 ± 0.63	0.9621 ± 0.0070	3.042 ± 0.016
$Y_{\text{P}}, N_{\text{eff}}$	0.02224 ± 0.00022	$0.1171^{+0.0042}_{-0.0049}$	1.0415 ± 0.0012	$66.0^{+1.7}_{-1.9}$	0.9589 ± 0.0085	3.036 ± 0.018
A_{L}	0.02251 ± 0.00017	0.1182 ± 0.0015	1.04110 ± 0.00032	68.16 ± 0.70	0.9696 ± 0.0048	$3.029^{+0.018}_{-0.016}$

ΛCDM seems to be *stable* under extensions. No statistical signal of deviations of ΛCDM .

Hypothesis and extensions scrutinized

CMB

ΛCDM stable under extensions. No statistical signal of deviations of ΛCDM.

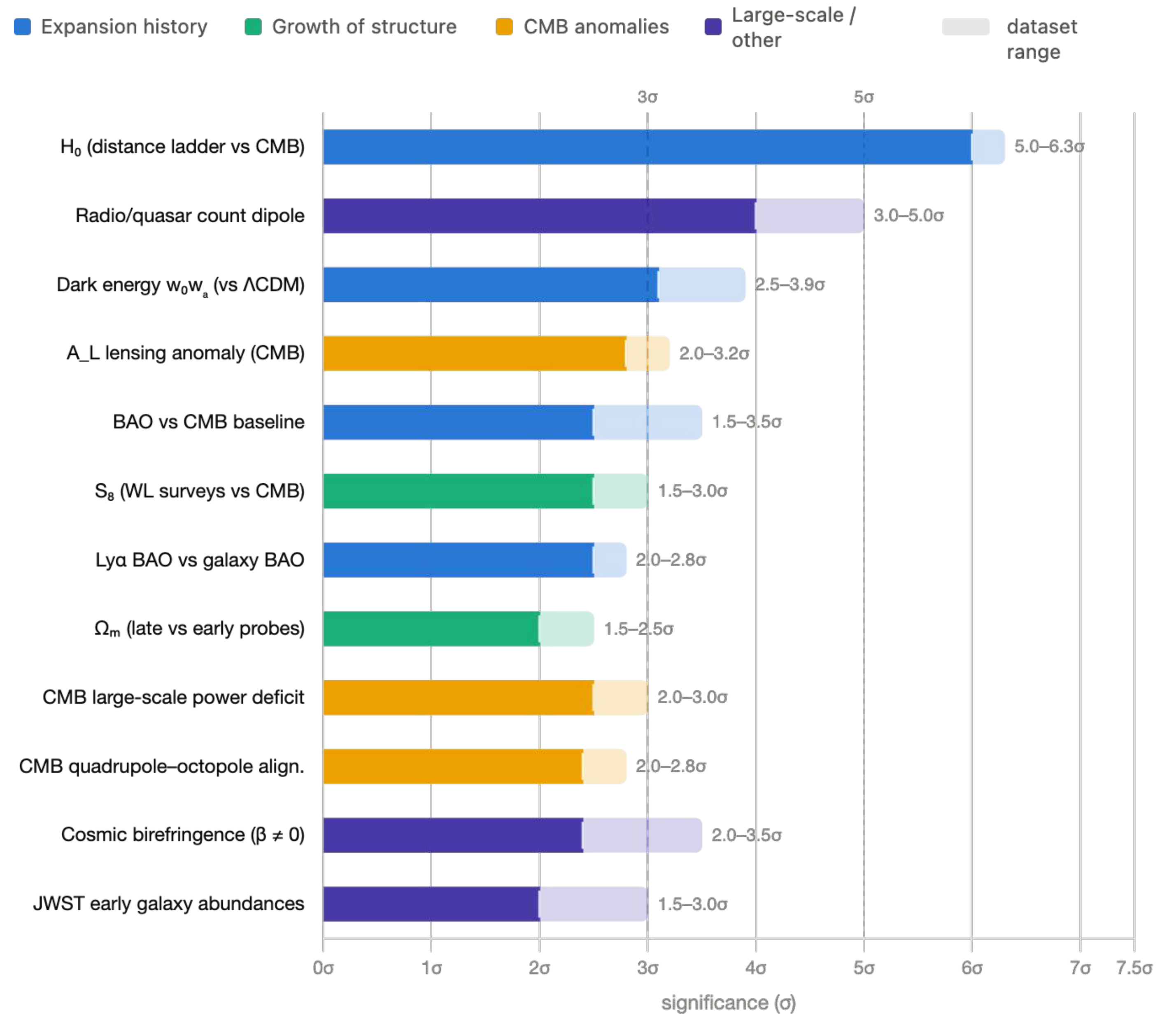
BUT, this is not the end of the story ... LSS data sets and statistical effects need to be considered

Model	Section	Theory Code	Likelihood
Running of scalar spectral index	§4.1	camb	MFLike/ACT-lite
$P_{\mathcal{R}}(k)$	§4.2	camb	ACT-lite
Isocurvature perturbations	§4.3	class	MFLike
Tensor modes	§4.4	camb	ACT-lite
Early dark energy	§5.1	class/camb/ class emulators (Qu et al. 2024a)	MFLike
Varying electron mass	§5.2.1	class	MFLike
Varying electron mass and curvature	§5.2.2	class	MFLike
Varying fine-structure constant	§5.2.3	class	MFLike
Varying fine-structure constant and curvature	§5.2.4	class	MFLike
Primordial magnetic fields	§5.3	modified class	MFLike
CMB temperature	§5.4	class	MFLike
Modified recombination history	§5.5	modified class	MFLike
Neutrino number, N_{eff}	§6.1.1	camb/ camb emulators (Jense et al. 2025)	MFLike/ACT-lite
Neutrino mass, $\sum m_\nu$	§6.1.1	camb/ camb emulators (Jense et al. 2025)	MFLike/ACT-lite
$N_{\text{eff}} + \sum m_\nu$	§6.1.1	camb/ camb emulators (Jense et al. 2025)	ACT-lite
Neutrino self-interactions	§6.1.2	modified camb	MFLike
Helium and deuterium	§6.2	camb	MFLike/ACT-lite
Axion-like particles	§6.3	modified camb/ camb emulators	ACT-lite
DM-baryon interactions	§6.4.1	modified class	MFLike
DM annihilation	§6.4.2	class	MFLike
Self-interacting DR	§6.5.1	class	MFLike
Interacting DR-DM	§6.5.2	class	MFLike
Spatial curvature	§7.1	camb	MFLike/ACT-lite
Dark energy equation of state, w	§7.2	camb	MFLike/ACT-lite
Dark energy equation of state, w_0/w_a	§7.2	camb	MFLike
Interacting DE-DM	§7.3	modified class	MFLike
Modified gravity	§7.4	modified camb	MFLike

Table 4. Summary of models explored in this paper. For each case, we list the Einstein-Boltzmann code and likelihood that are used for each model, noting when chains have been run with more than one code (for robustness tests and reproducibility). The likelihood codes and the baseline ΛCDM results are presented in L25.

Precision cosmology: Concordance or Discordance?

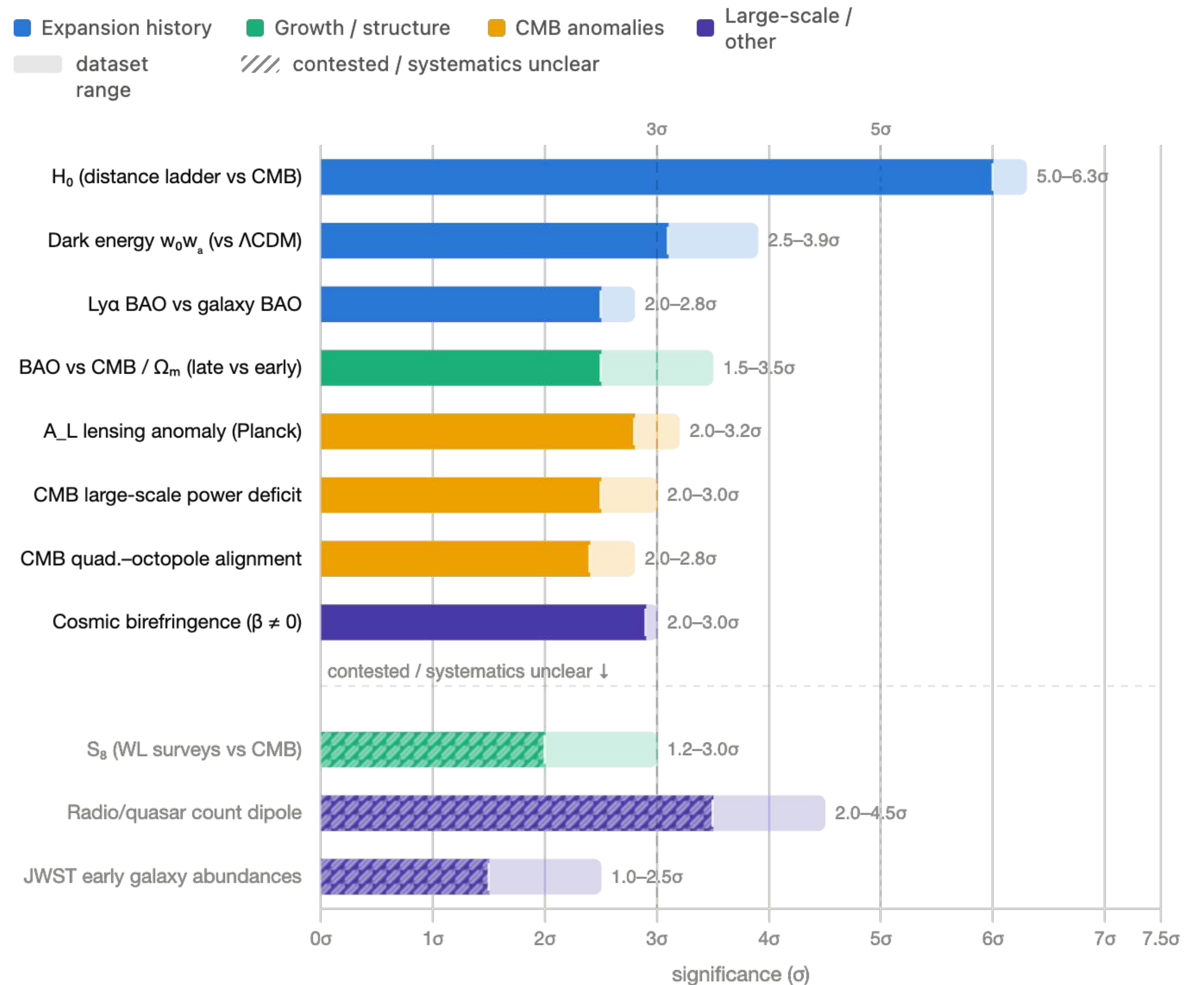
LCDM model is under
extreme scrutiny!



Solid bar = headline/most-quoted value. Light extension = range across datasets and analysis choices. H_0 : SH0ES/H0DN vs Planck/ACT/SPT. Dark energy: DESI DR1/DR2 $\pm$ SNIa/CMB combos. S_8 : KiDS-Legacy (low) $\rightarrow$ HSC Y3/DES Y3 (high). BAO vs CMB: galaxies/QSOs/Ly α /ELGs. Dashed lines at 3σ and 5σ .

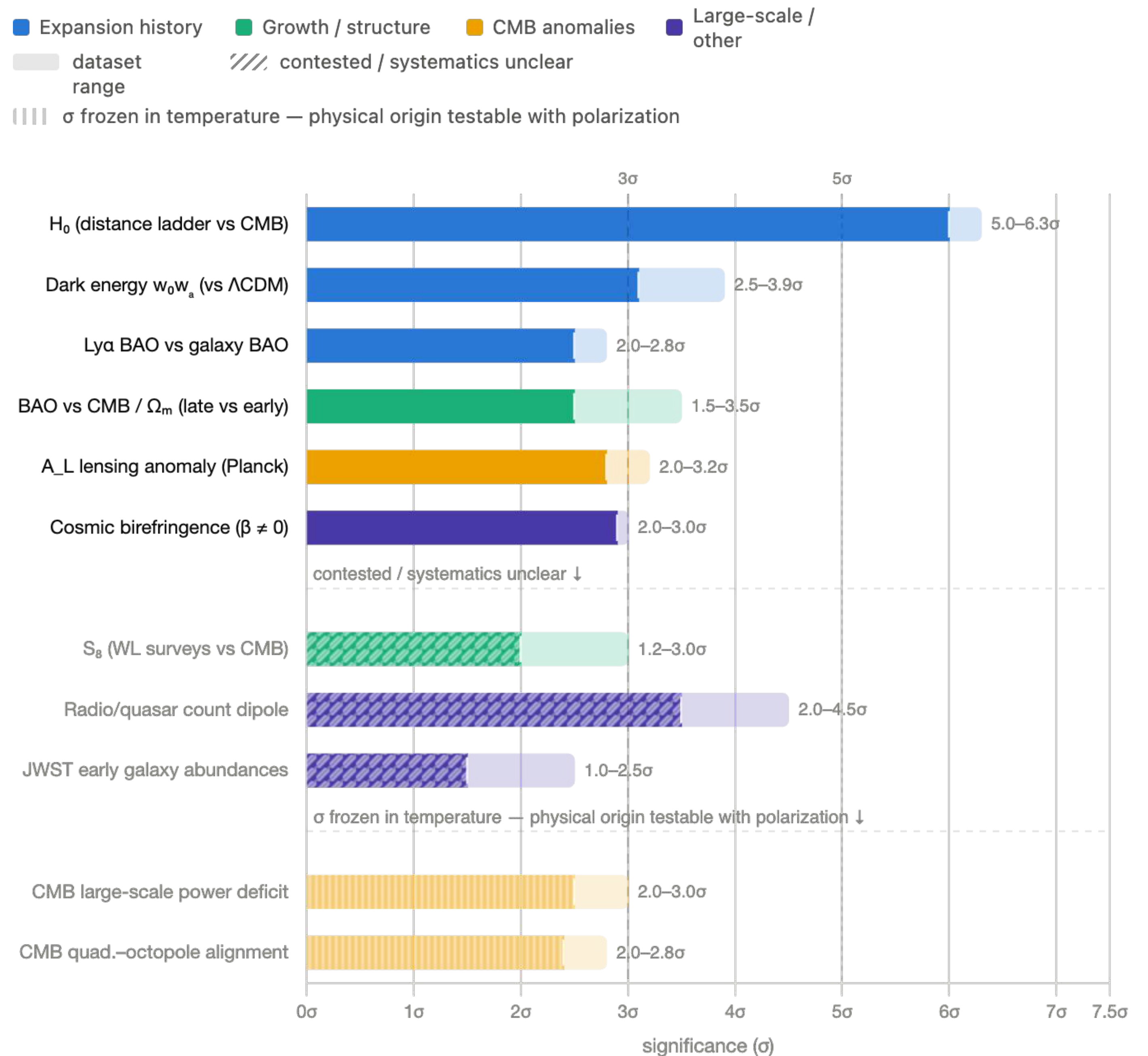
*Precision
cosmology:
Concordance or
Discordance?*

ΛCDM model is under
extreme scrutiny!



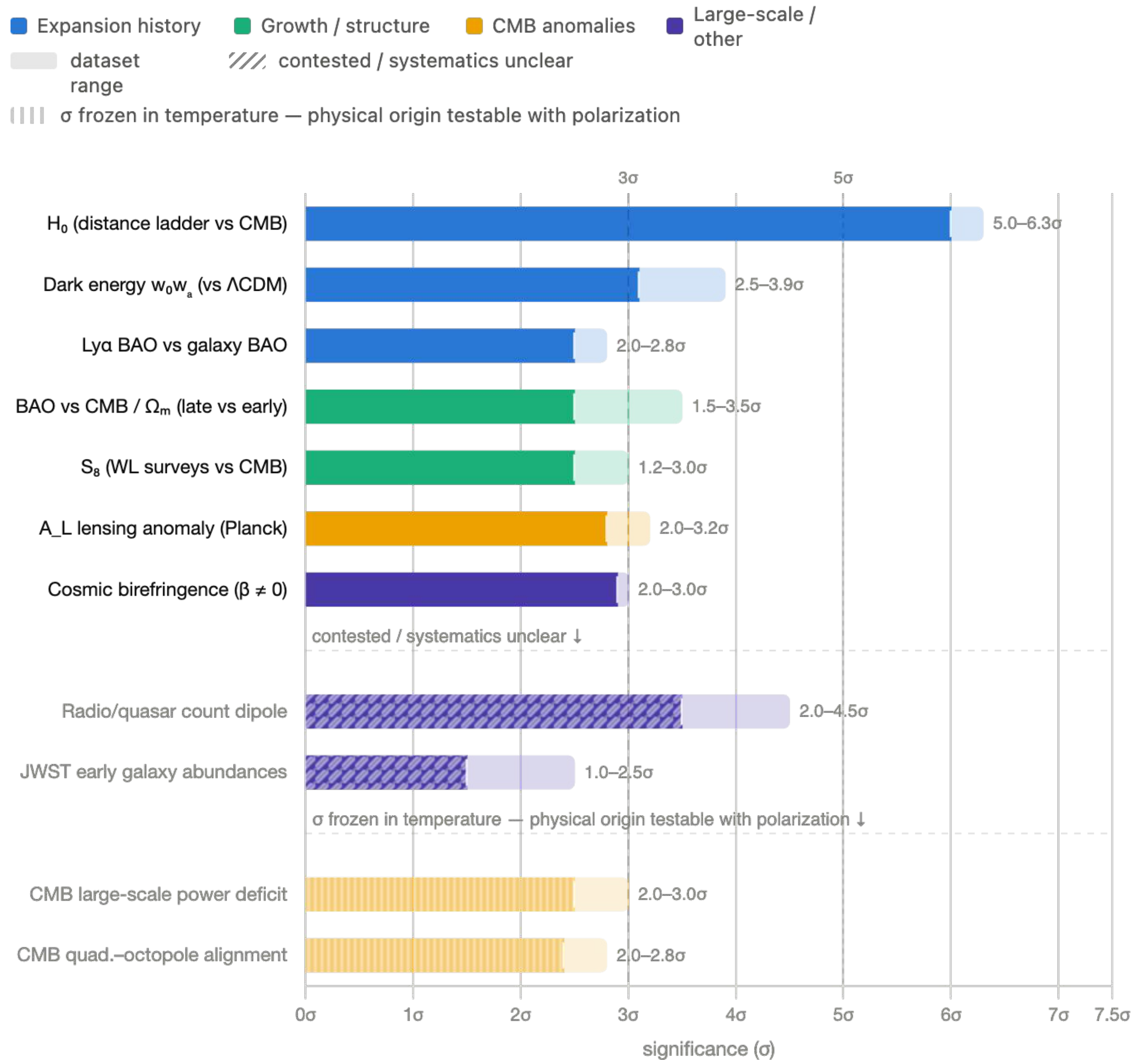
Precision cosmology: Concordance or Discordance?

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Precision cosmology: Concordance or Discordance?

LCDM model is under
extreme scrutiny!



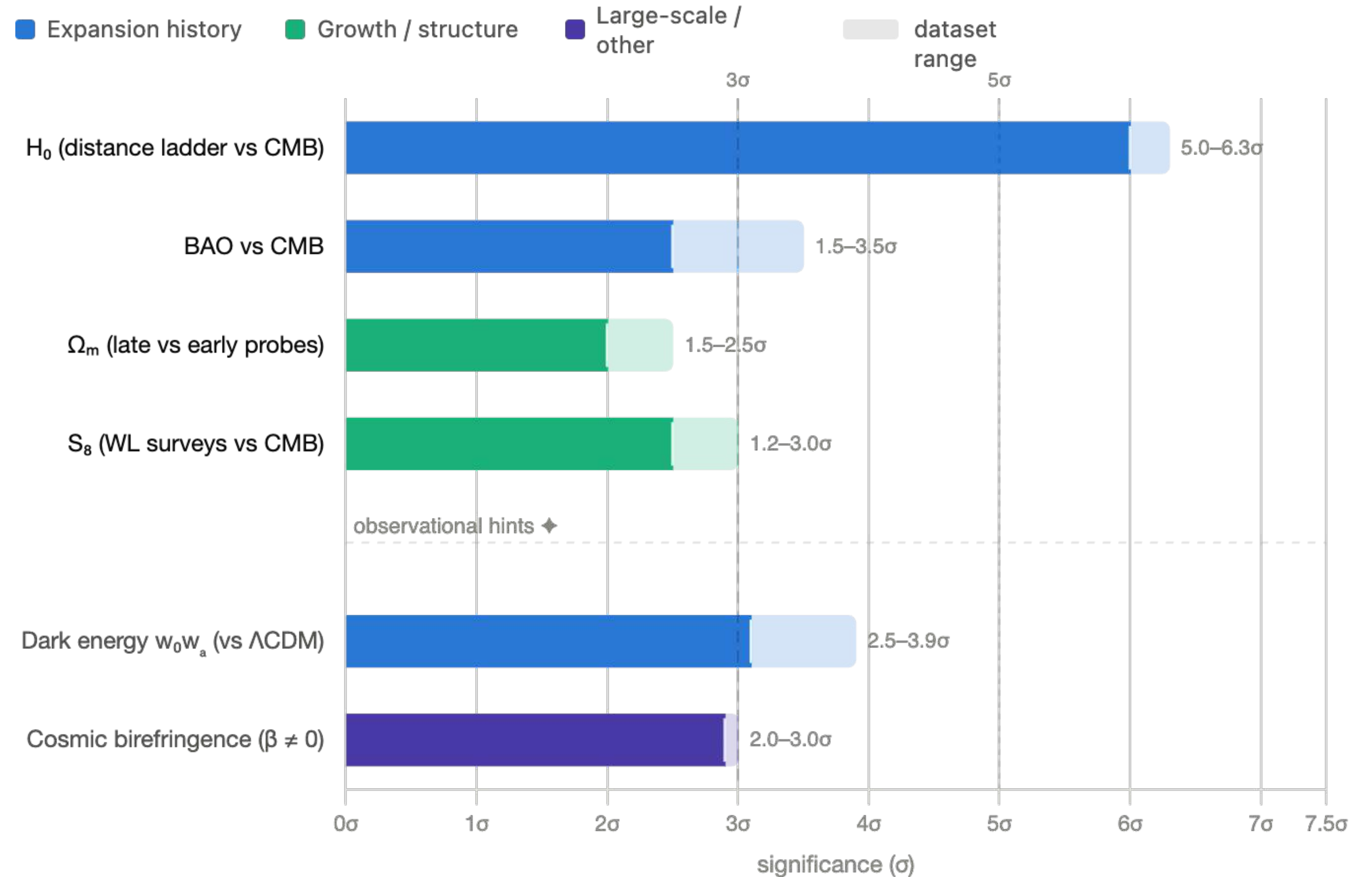
*Precision
cosmology:
Concordance or
Discordance?*

LCDM model is under
extreme scrutiny!

Are these showing LCDM break?

Are these the first signs of the true nature of DM
and DE? New physics?

A biased view of these challenges for LCDM!



observational hints

new physics(?)

Dynamical DE, birefringence

new physics(?)

Dynamical dark energy

Dynamical DE, birefringence

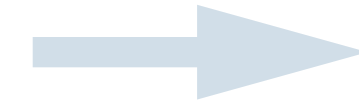
Dark energy

Observational data indicates that the universe is expanding in an **accelerated** way $\ddot{a} > 0$

Acceleration

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) > 0$$

Deceleration



$$w = \frac{p}{\rho} < -\frac{1}{3}$$

The component which is the source of this accelerated expansion we call **dark energy**

$$\ddot{a} < 0$$

Decelerated expansion

$$P > -\frac{1}{3}\rho$$

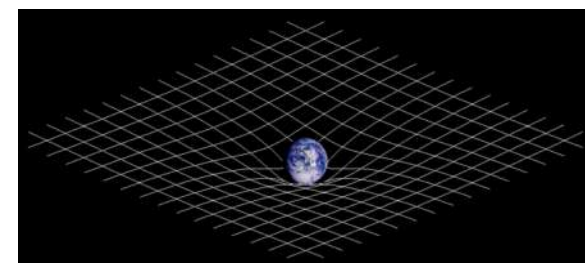
$$\ddot{a} > 0$$

Accelerated expansion

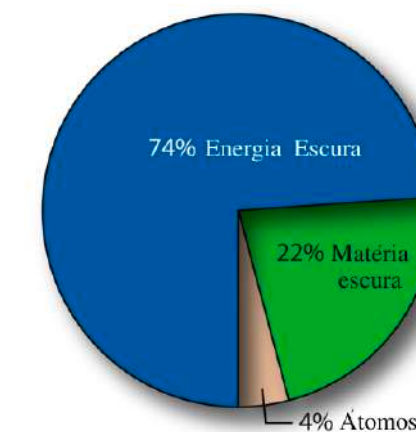
$$P < -\frac{1}{3}\rho$$

How can we explain *dark energy*

General relativity



$$\underbrace{G_{\mu\nu}}_{\text{Geometry - How the universe expands}} = \frac{8\pi G}{c^4} \underbrace{T_{\mu\nu}}_{\text{Components}}$$



The universe is accelerating: $\ddot{a} > 0$

How can we interpret the acceleration of the universe

Cosmological constant

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

New component -
dark energy

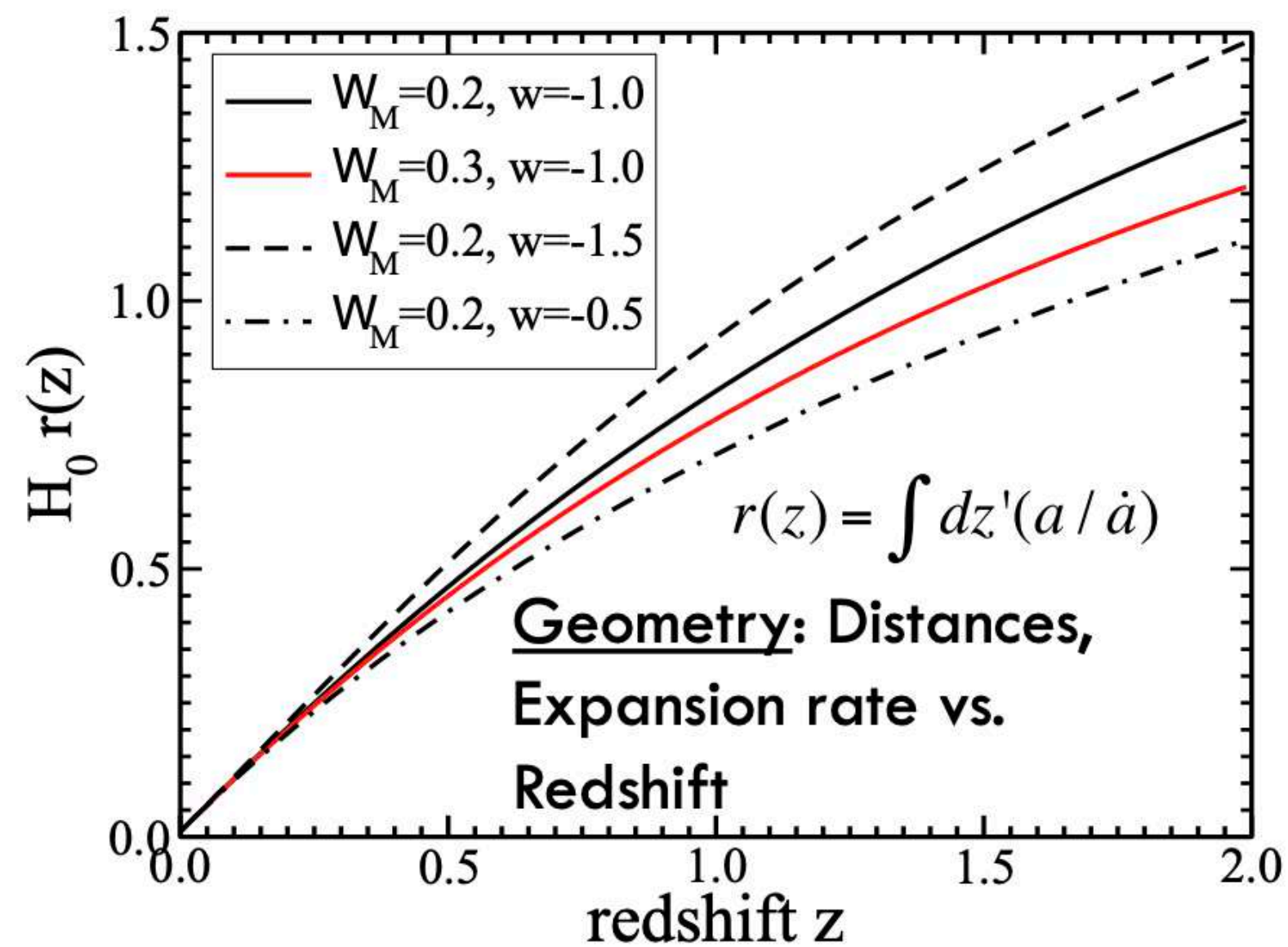
$$G_{\mu\nu} = \frac{8\pi G}{c^4} (T_{\mu\nu} - \rho_{EE} g_{\mu\nu})$$

Modify general
relativity

Backreaction

How do we probe dark energy

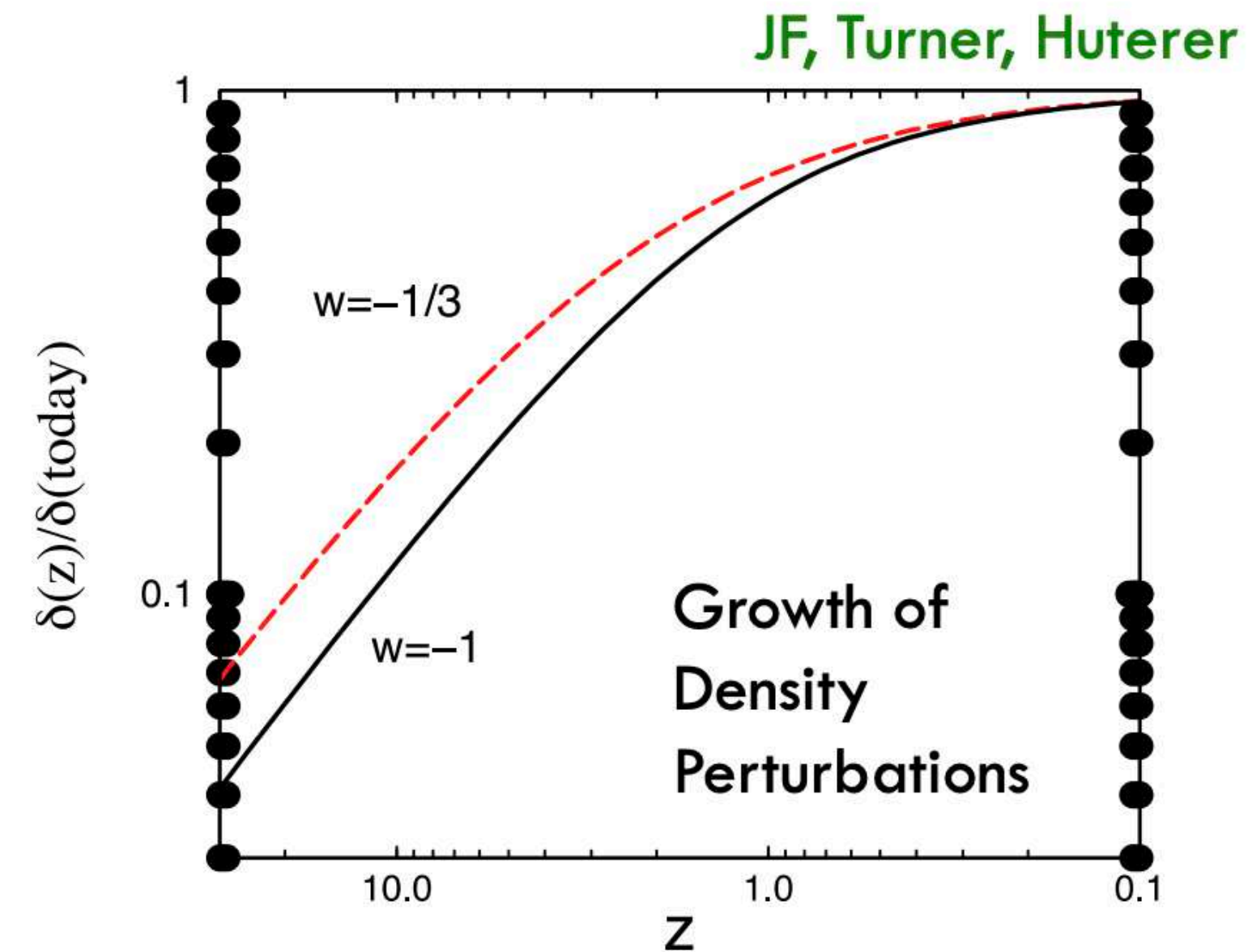
How do we probe DE?



Expansion history

Type Ia Supernovae

Baryon Acoustic Oscillations



Growth of structure

Weak Lensing

Galaxy Clustering

Cluster Abundance

Redshift Space Distortion

Dark energy in *Λ CDM*

- Cosmological constant

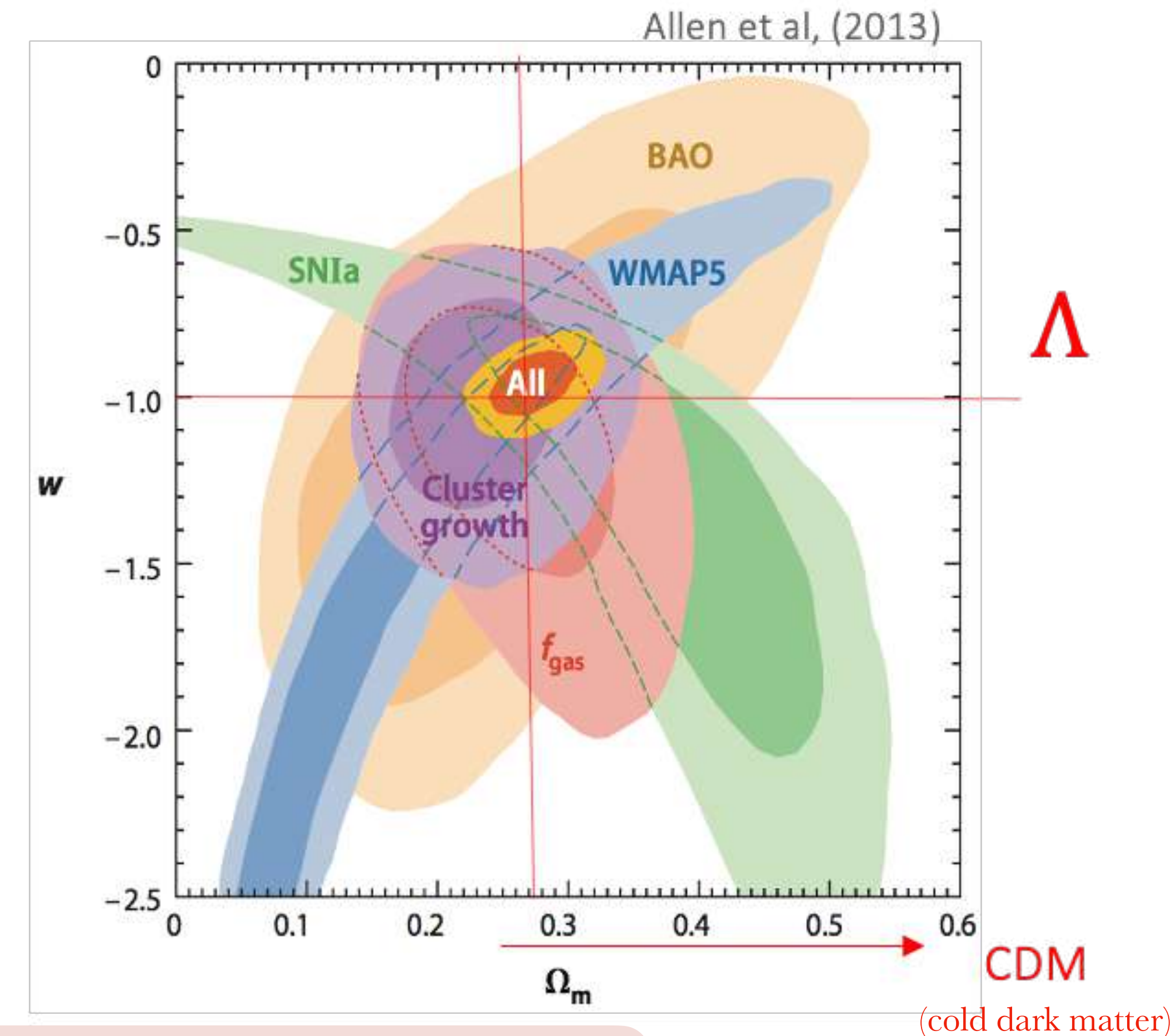
$$\underbrace{\left(\frac{\ddot{a}}{a}\right)}_{\text{acceleration}} = - \underbrace{\left(\frac{4\pi G}{3}(\rho + 3p)\right)}_{\text{decelerates the expansion}} + \underbrace{\left(\frac{\Lambda}{3}\right)}_{\text{Cosm. Constant}} \quad + \quad w = -1$$

decelerates the expansion accelerates the expansion

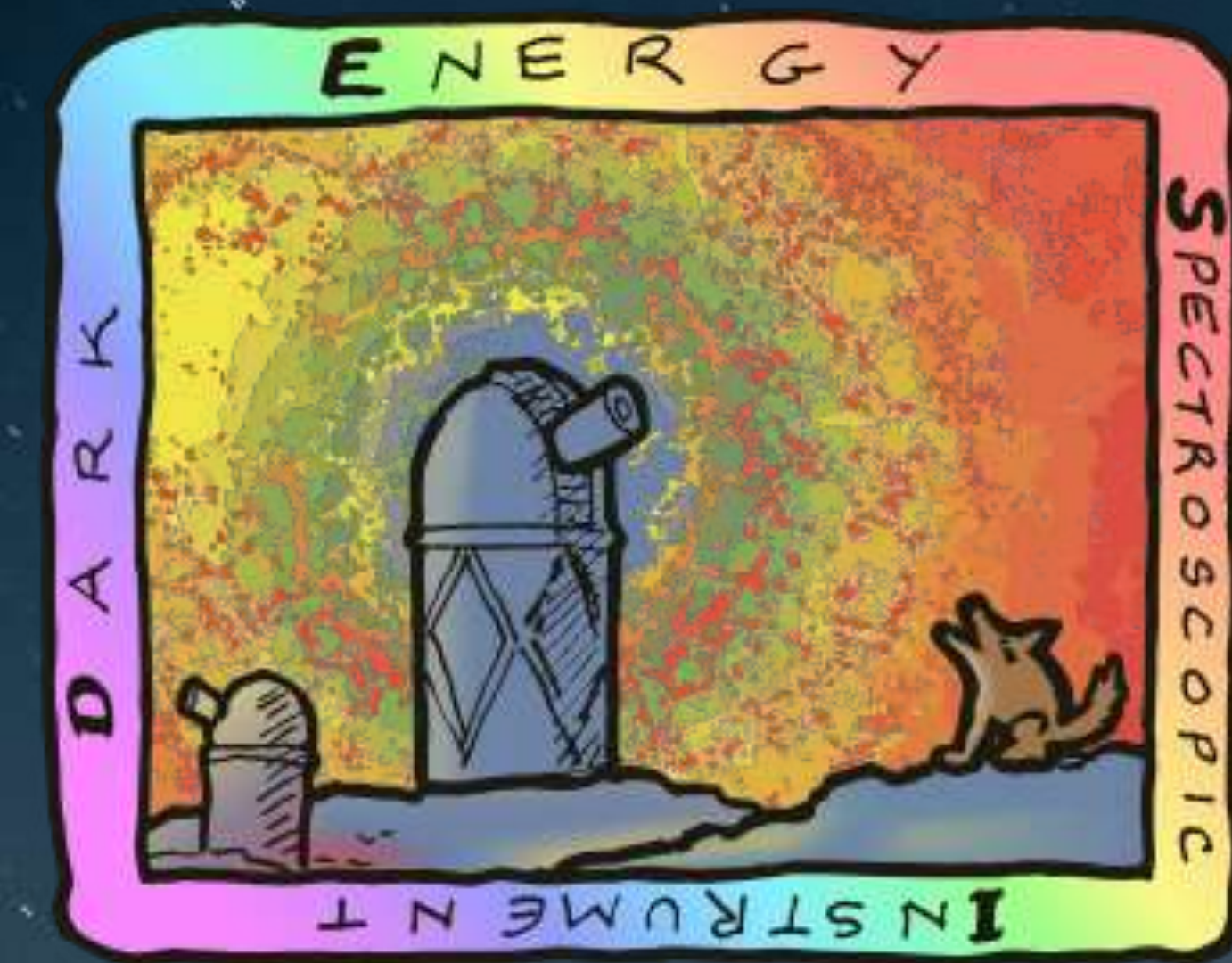
- Simplest explanation
- Not dynamical
- Preferred observationally

The cosm. constant is expected in GR!

- But, problematic theoretically: cosmological constant problems

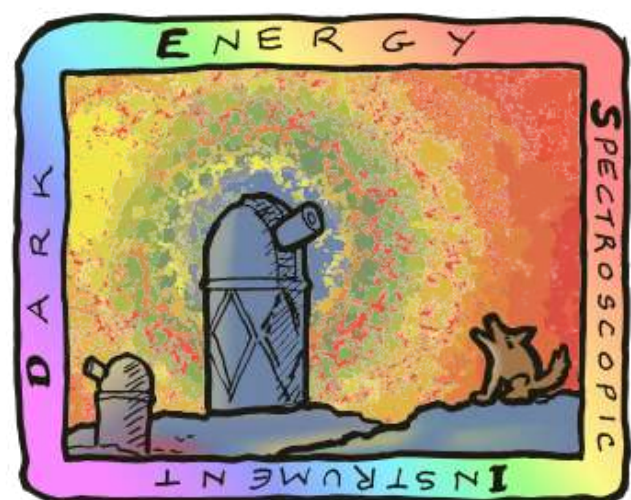


$$\rho_{\Lambda}^{\text{obs}} \simeq \rho_{\text{crit},0} \simeq (10^{-3} \text{ eV})^4$$



The Dark Energy Spectroscopic Instrument (DESI)





*The Dark Energy Spectroscopic Instrument - **DESI***

DESI galaxy samples: 40M galaxy redshifts in 5 years of observations

QSO: 3M (SDSS: 500k)

$\text{Ly}\alpha$ $1.8 < z$

Tracers $0.8 < z < 2.1$

ELG: 16M (SDSS: 200k)

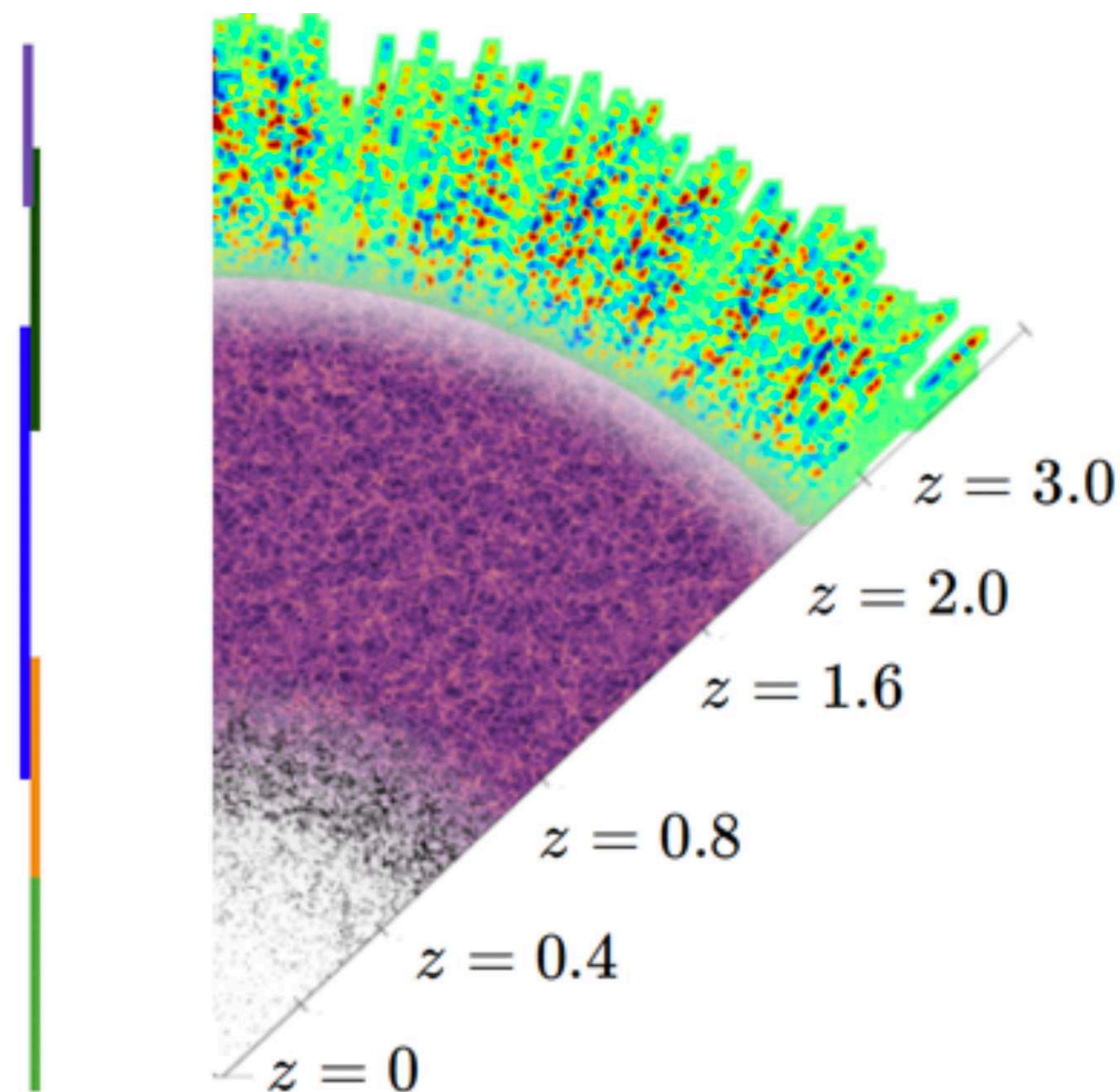
$0.6 < z < 1.6$

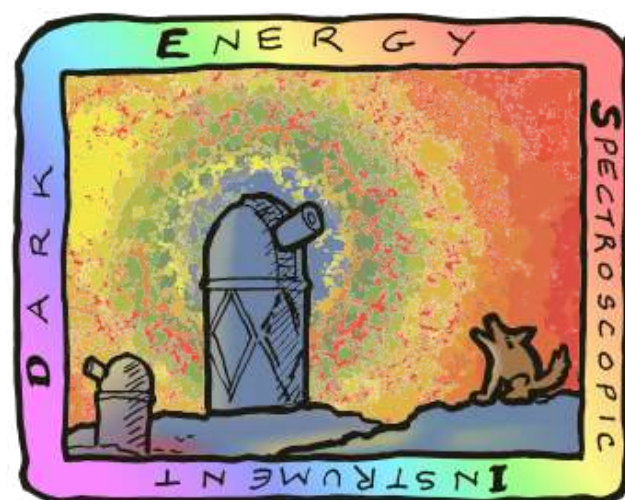
LRG: 8M (SDSS: 1M)

$0.4 < z < 0.8$

Bright Galaxies: 14M
(SDSS: 600k)

$0 < z < 0.4$

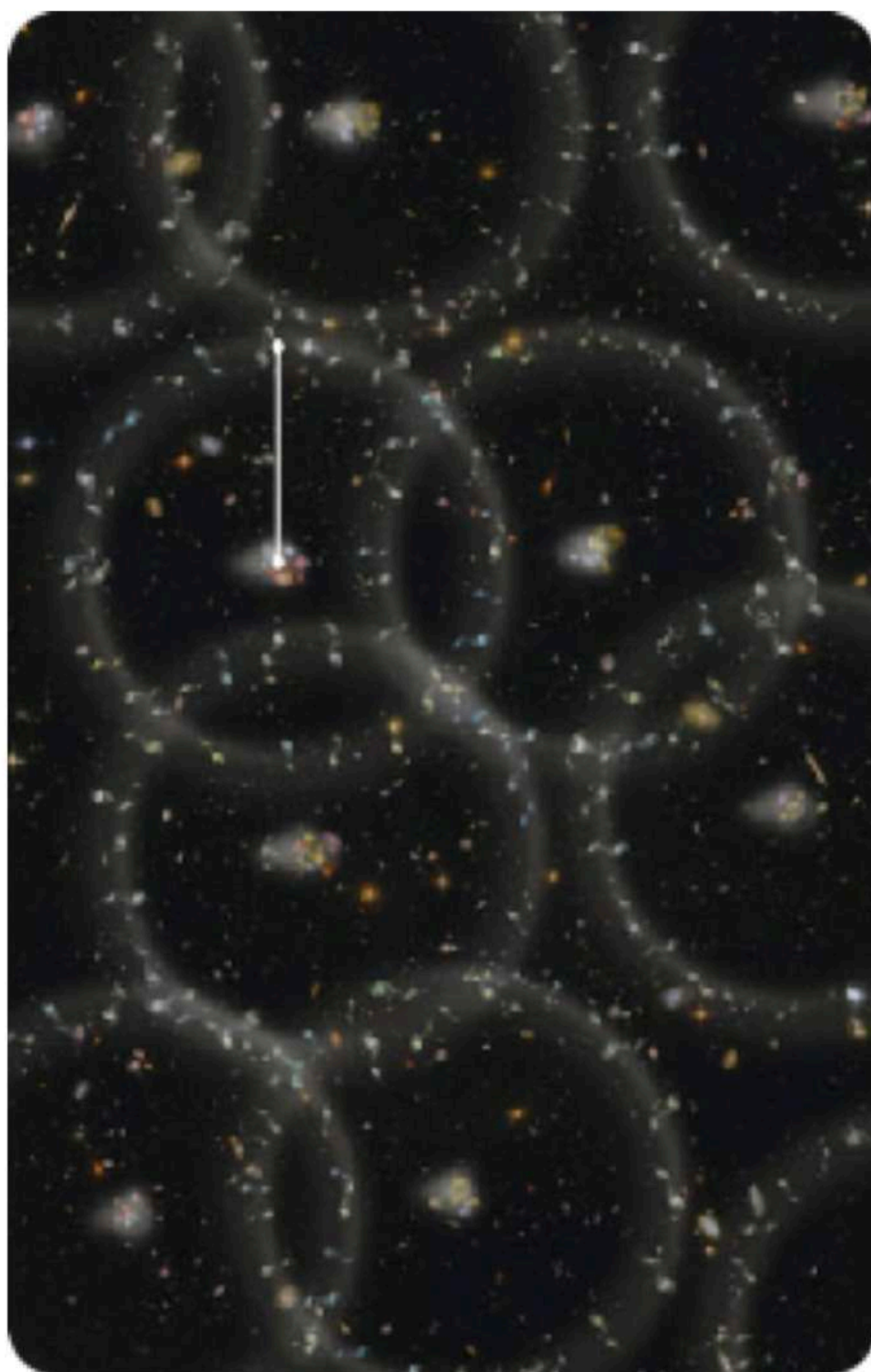




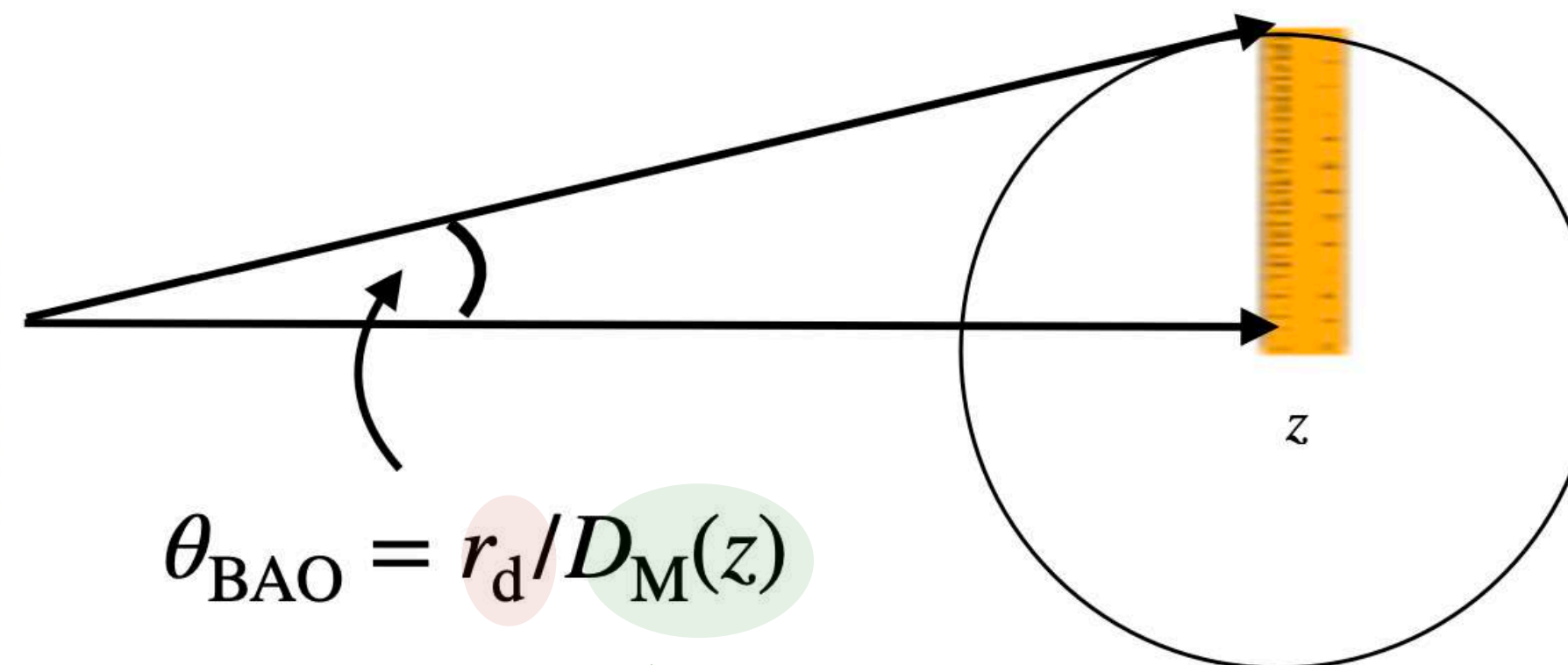
*The Dark Energy Spectroscopic Instrument - **DESI***

What DESI BAO measures

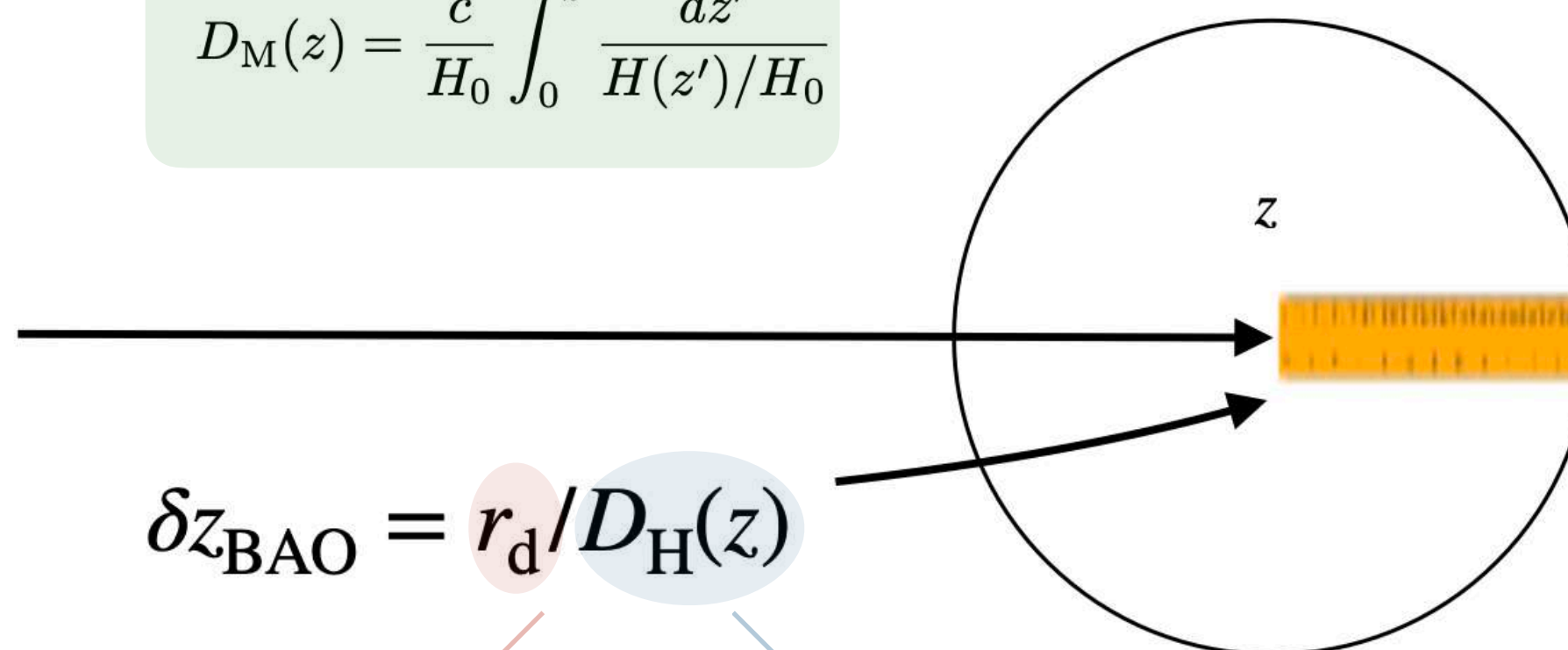
$$\omega_X = \Omega_X h^2$$



$$r_d = 147.05 \text{ Mpc} \times \left(\frac{\omega_b}{0.02236} \right)^{-0.13} \left(\frac{\omega_{bc}}{0.1432} \right)^{-0.23} \left(\frac{N_{\text{eff}}}{3.04} \right)^{-0.1}$$



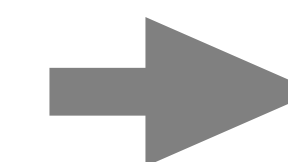
$$D_M(z) = \frac{c}{H_0} \int_0^z \frac{dz'}{H(z')/H_0}$$



$$r_d = \int_{z_d}^{\infty} \frac{c_s(z)}{H(z)} dz$$

$$D_H(z) = \frac{c}{H(z)}$$

$$+ D_V(z)/r_d$$



$$\frac{r_d h}{\Omega_M}$$

Dynamical dark energy

- DESI provides a good fit to Λ CDM and when testing w CDM, gets a w consistent to a cosmological constant
- To test if DE is evolving with time, the DESI collaboration used CPL or w_0w_a parametrization (Chevalier & Polarski 2001, Linder 2003)

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

Taylor expansion around $a = 1$

Dynamical *dark energy*

- To test if DE is evolving with time, the DESI collaboration used CPL or w_0w_a parametrization (Chevalier & Polarski 2001, Linder 2003)

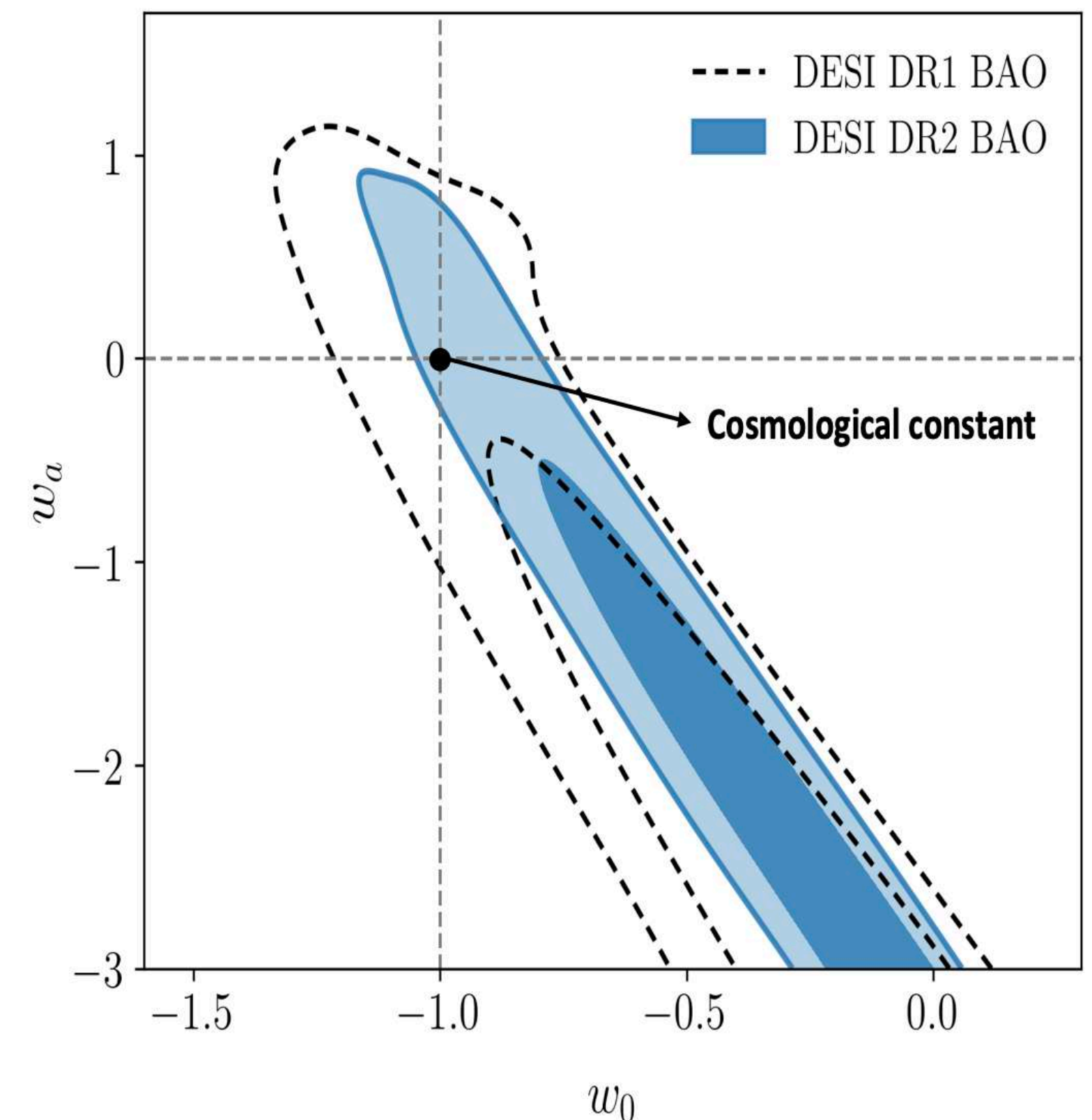
$$w(a) = w_0 + w_a(1 - a)$$

Taylor expansion around $a = 1$

DESI alone

- BAO data define a degeneracy direction in the $w_0 - w_a$ plane
- DESI DR2 within 2σ of Λ CDM
- Combine with other probes to break this degeneracy
- DESI alone cannot constrain w_0 and w_a

$$\left. \begin{array}{l} w_0 = -0.48^{+0.35}_{-0.17} \\ w_a < -1.34 \end{array} \right\} \text{DESI BAO,}$$



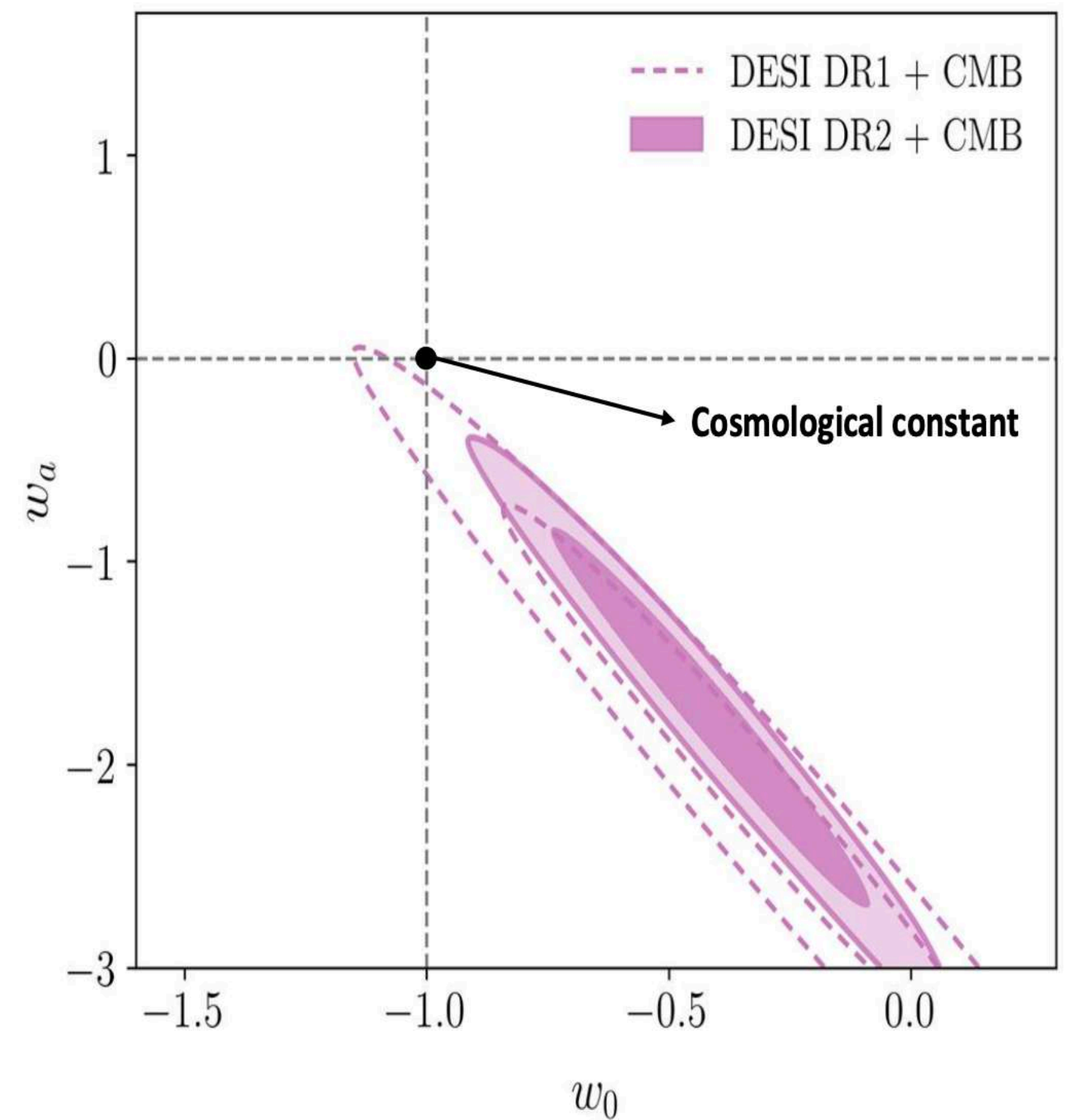
Dynamical *dark energy*

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

DESI + CMB

- DESI DR1 + CMB: 2.6σ from Λ CDM
- DESI DR2 + CMB: 3.1σ from Λ CDM

$$\left. \begin{aligned} w_0 &= -0.42 \pm 0.21 \\ w_a &= -1.75 \pm 0.58 \end{aligned} \right\} \text{DESI+CMB}$$



Dynamical *dark energy*

DESI + CMB + supernova

DESI + CMB + Pantheon+ $\Rightarrow 2.8\sigma$

$$w_0 = -0.838 \pm 0.055$$

$$w_a = -0.62^{+0.22}_{-0.19}$$

DESI + CMB + Union3 $\Rightarrow 3.8\sigma$

$$w_0 = -0.667 \pm 0.088$$

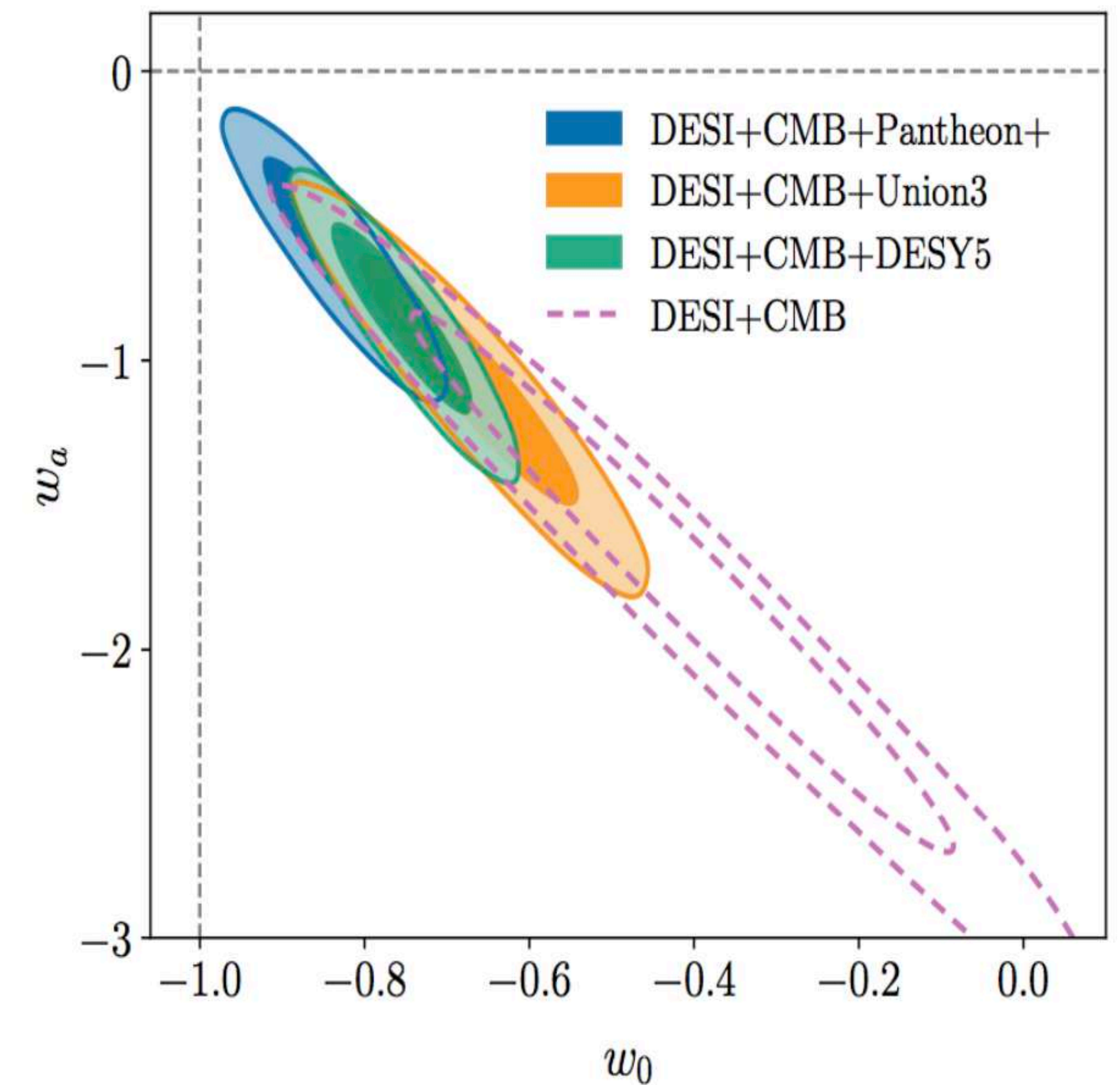
$$w_a = -1.09^{+0.31}_{-0.27}$$

DESI + CMB + DESY5 $\Rightarrow 4.2\sigma$

$$w_0 = -0.752 \pm 0.057$$

$$w_a = -0.86^{+0.23}_{-0.20}$$

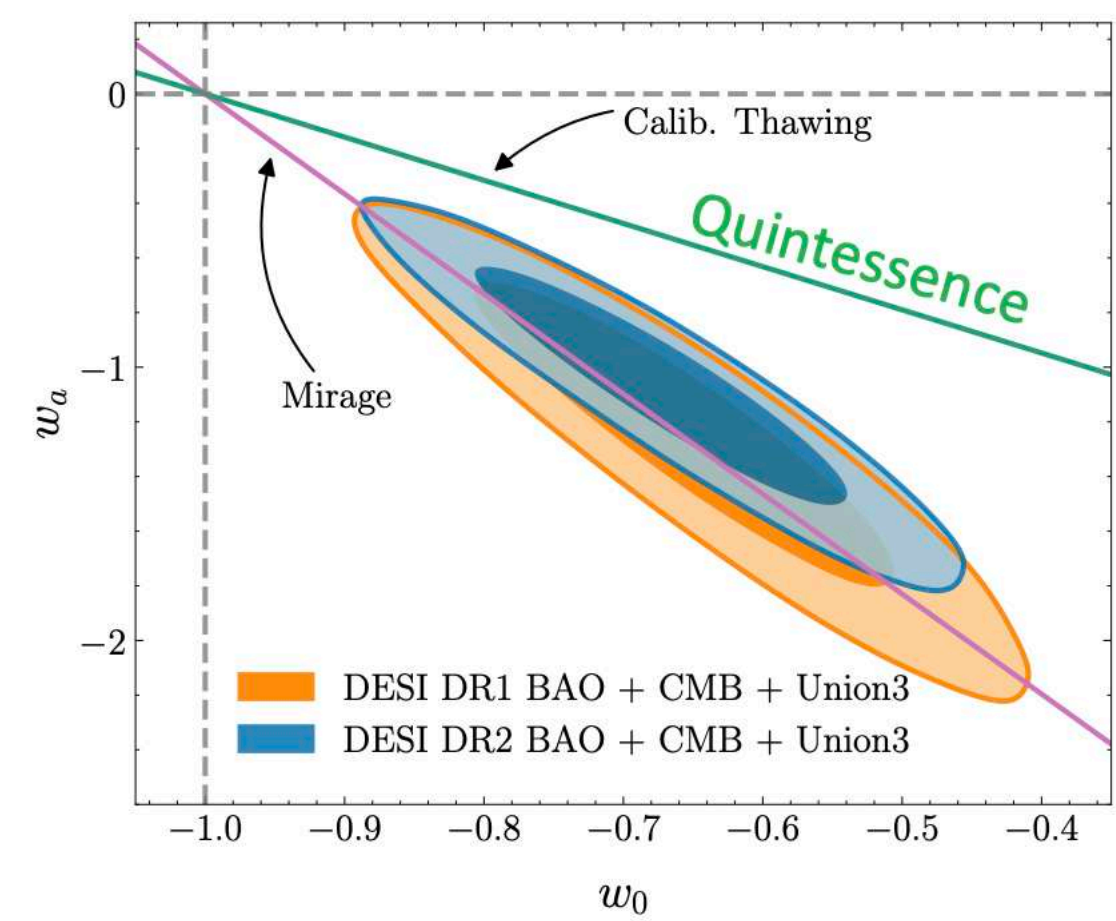
$$w(a) = w_0 + w_a(1 - a)$$



Dynamical *dark energy*

- DESI DR2 finds evidence for a dynamical DE
 - But evidence seems to be only present when combining probes (see CMB-BAO tension) - DESI BAO alone no strong evidence; compatible with LCDM.

- Result seems to be robust for different parametrizations



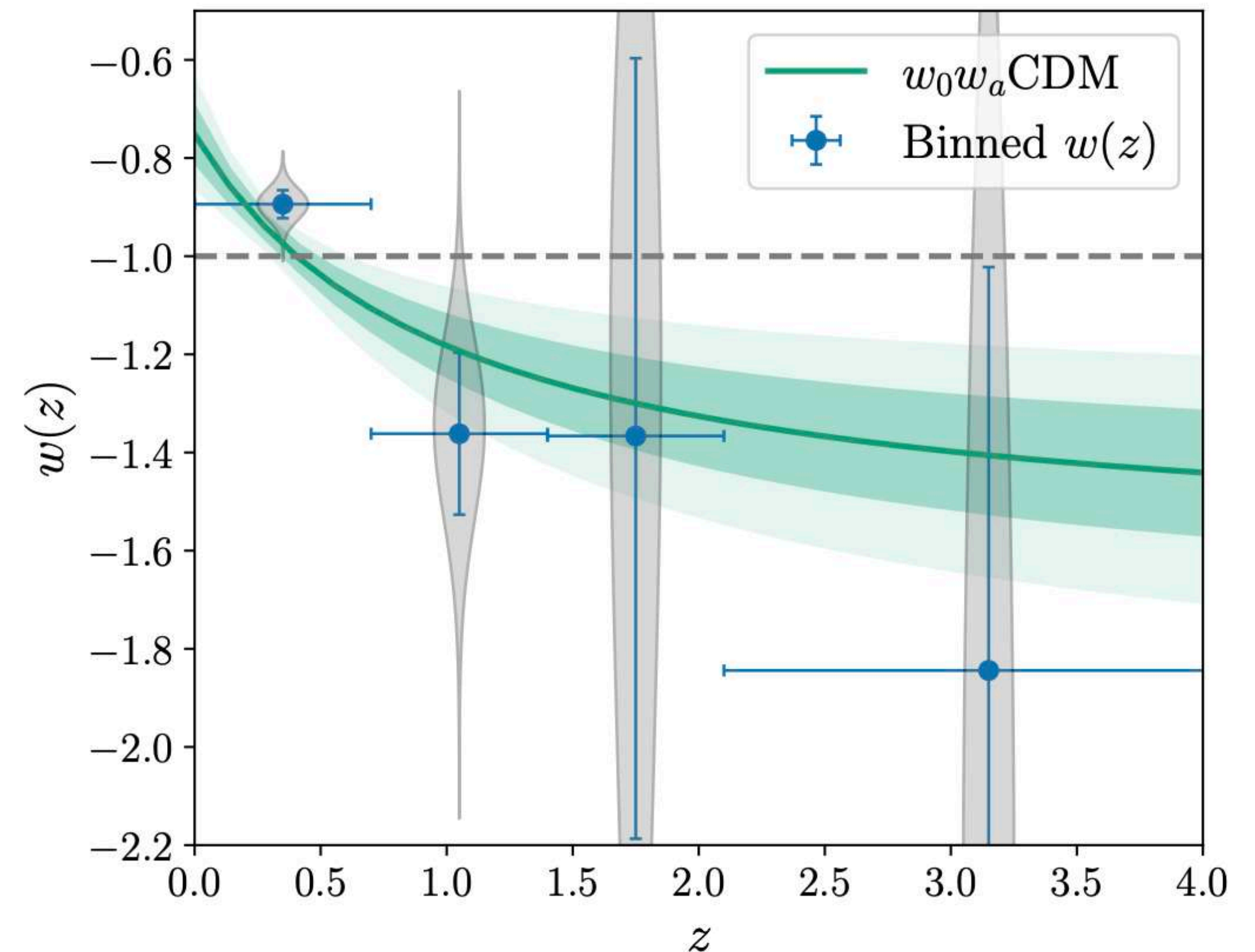
DESI+CMB: +PantheonPlus		+Union3		+DESY5	
DE classes		$\Delta\text{DIC} \ (\Delta\chi^2)$			
Thaw. (Cal.)	+0.4 (−1.6)	−0.6	(−2.5)	−5.8	(−7.1)
Thaw. (Alg.)	−1.0 (−2.9)	−4.6	(−6.9)	−10.1	(−13.2)
Emergent	+2.1 (−0.05)	+1.8	(−0.1)	+0.2	(−1.5)
Mirage	−9.1 (−10.5)	−13.8	(−16.2)	−18.7	(−20.7)
w_0w_a	−6.8 (−10.7)	−13.5	(−17.4)	−17.2	(−21.0)

Does it cross $w < -1$?

- w_0w_a model: it crosses $w < -1$
- Reconstruction still not conclusive

Important questions:

- Is this a feature of the CPL parametrization?
 - Are we using this Taylor expansion beyond its validity? Robust if one changes the pivot scale
 - Other models and parametrizations don't cross $w < -1$
- Interacting DE/DM models can show an apparent phantom crossing, without the DE fields never becoming phantom.

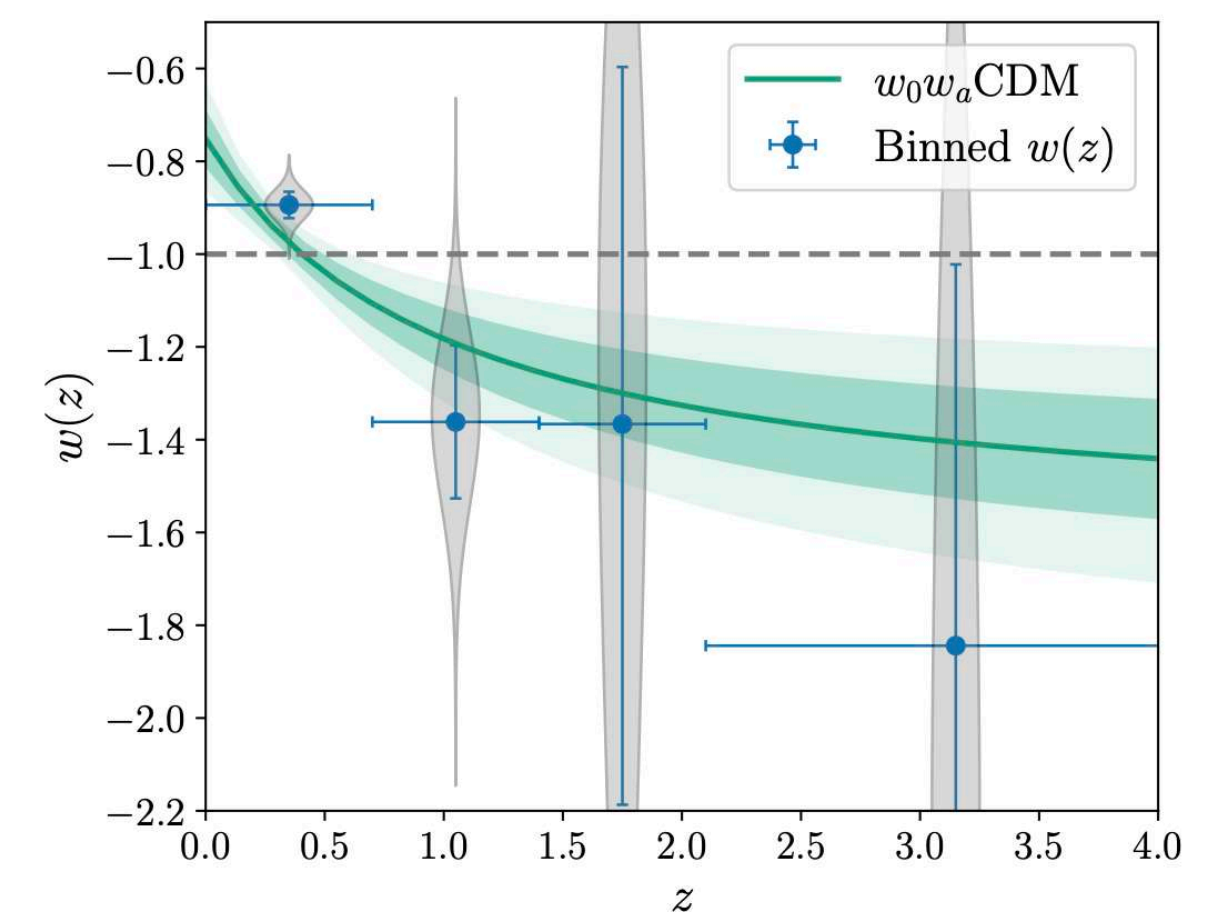
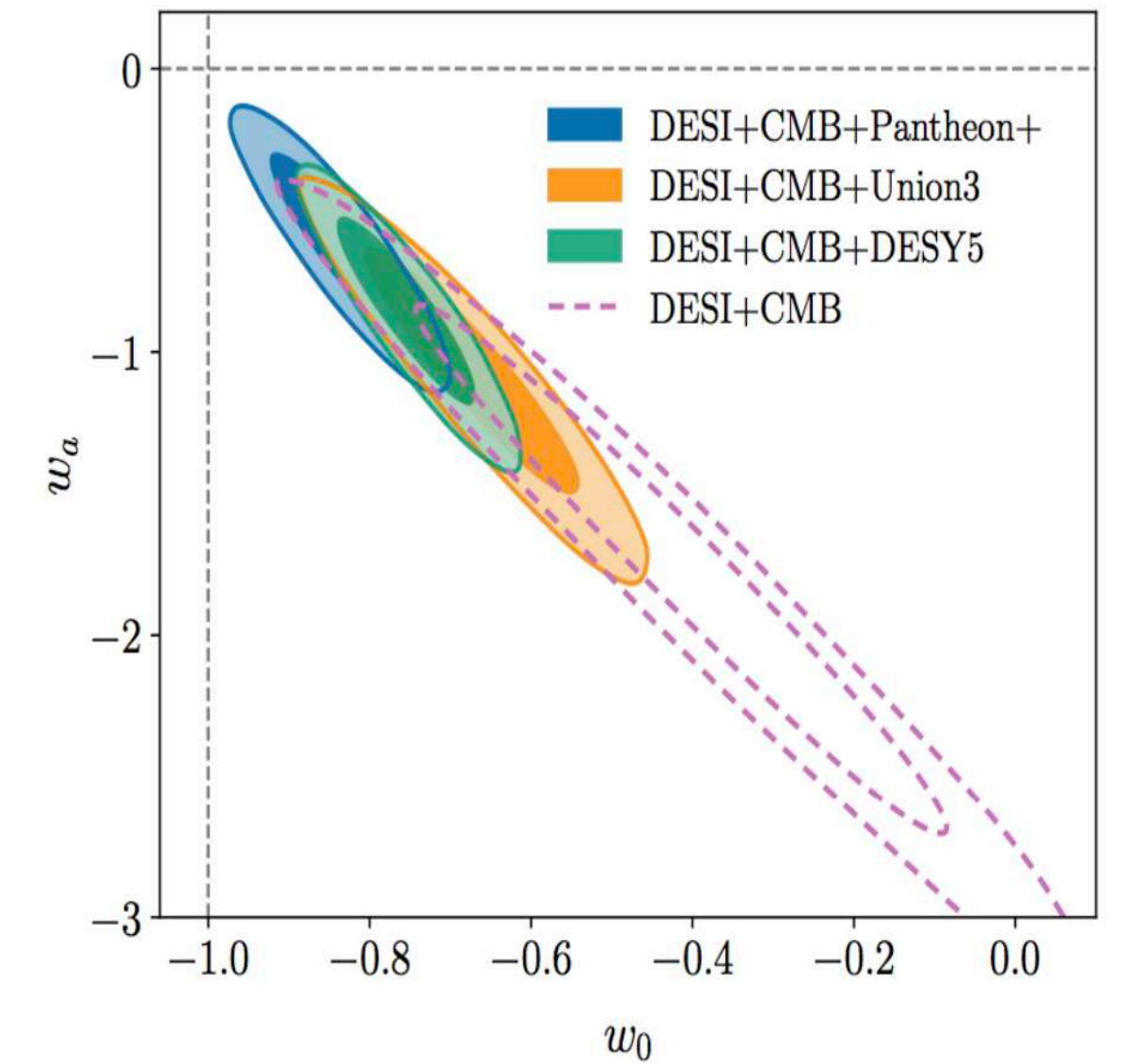


What does this mean for models of *dark energy*?

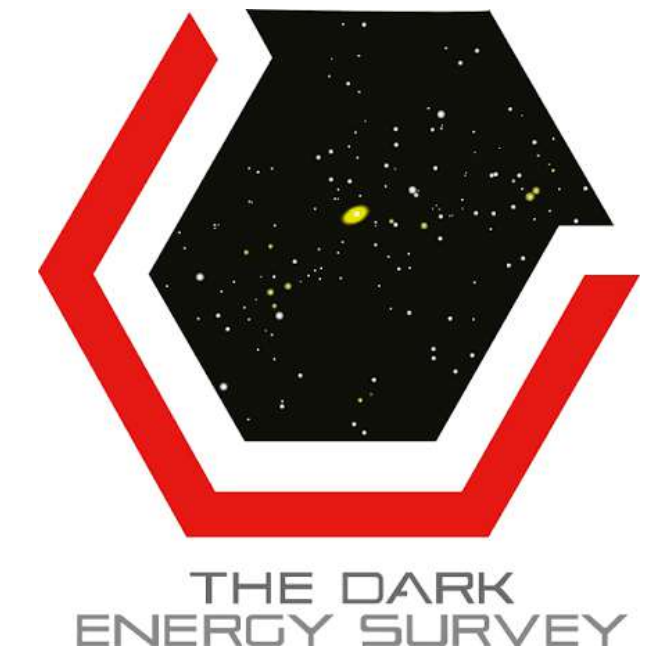
DESI DR2 Results II: BAO
measurements and Cosmology

- CPL is phenomenological:
 - w_0 and w_a are highly degenerate; degeneracy direction set by CPL
 - the inferred crossing of ($w = -1$) can depend on the parametrization;
 - different physical models can project onto similar CPL regions.
 - Some DE models don't map into CPL (see P. Ferreira et al 2025)
- Crossing ($w = -1$) is physically non-trivial:
 - this is the **phantom divide**;
 - for canonical quintessence $w_\phi \geq -1$
 - true phantom behavior can imply NEC violation and possible ghost instabilities.
- An apparent CPL crossing does not necessarily mean phantom dark energy:
 - it may be an effective description;
 - it may arise from dark-sector interactions or modified gravity;
 - it may disappear in other parametrizations.

DESI motivates dynamical dark energy, but physical interpretation requires well-motivated models beyond CPL. (See Pereira et al, including EF, to appear)



Dynamical dark energy - *Dark Energy Survey*



DES full-survey test of dynamical dark energy

- DES combines geometry and growth probes: SNe + BAO + 3×2pt

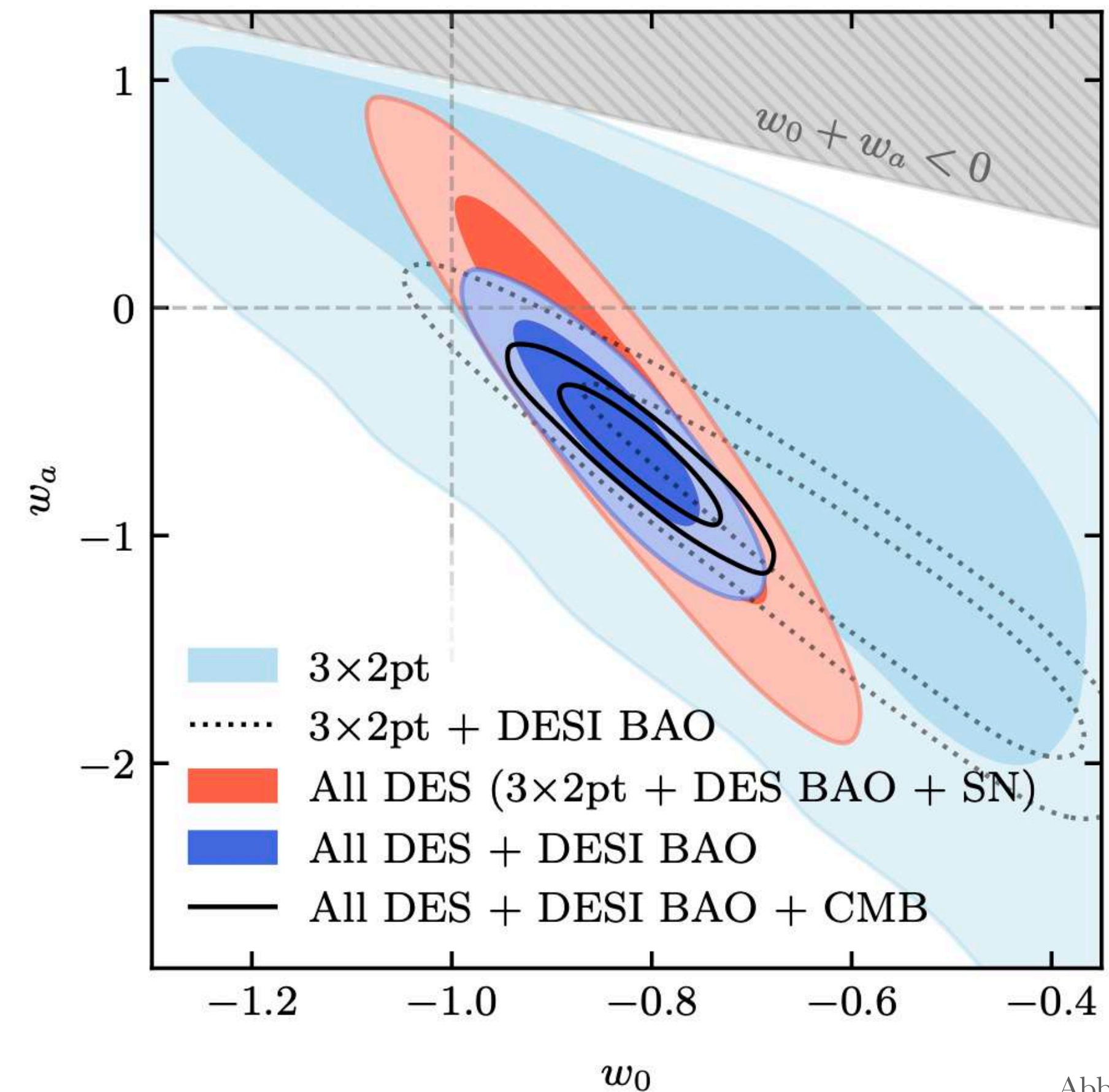
- DES-only $w_0 = -0.84 \pm 0.10$
 $w_a = -0.44^{+0.60}_{-0.55}$
 $\rightarrow 2.2\sigma$ from LCDM

- DES+DESI DR2 BAO $w_0 = -0.84^{+0.06}_{-0.07}$
 $w_a = -0.53^{+0.33}_{-0.28}$
 $\rightarrow 2.3\sigma$ from LCDM

- DES+DESI DR2 BAO+CMB $w_0 = -0.82 \pm 0.05$
 $w_a = -0.63^{+0.21}_{-0.18}$
 $\rightarrow 3.0\sigma$ from LCDM

DES 3×2pt **does not** by itself prefer dynamical DE strongly:
 3×2pt alone is consistent with Λ CDM at $\sim 1\sigma$.

Its role is to add **growth** information and sharpen the constraints.



cosmic birefringence

Cosmic *birefringence*

Cosmic Birefringence from axions

Rotation of the CMB polarization plane



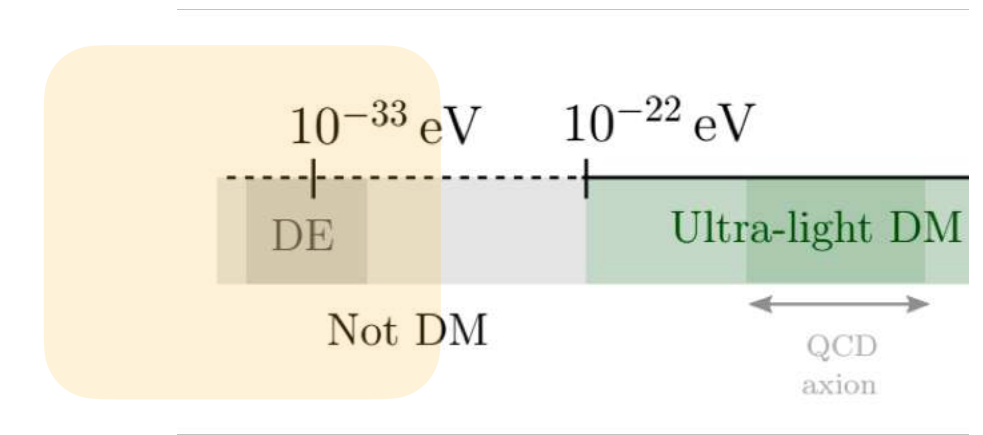
Parity-violating physics in the universe

Eskilt et al 2022

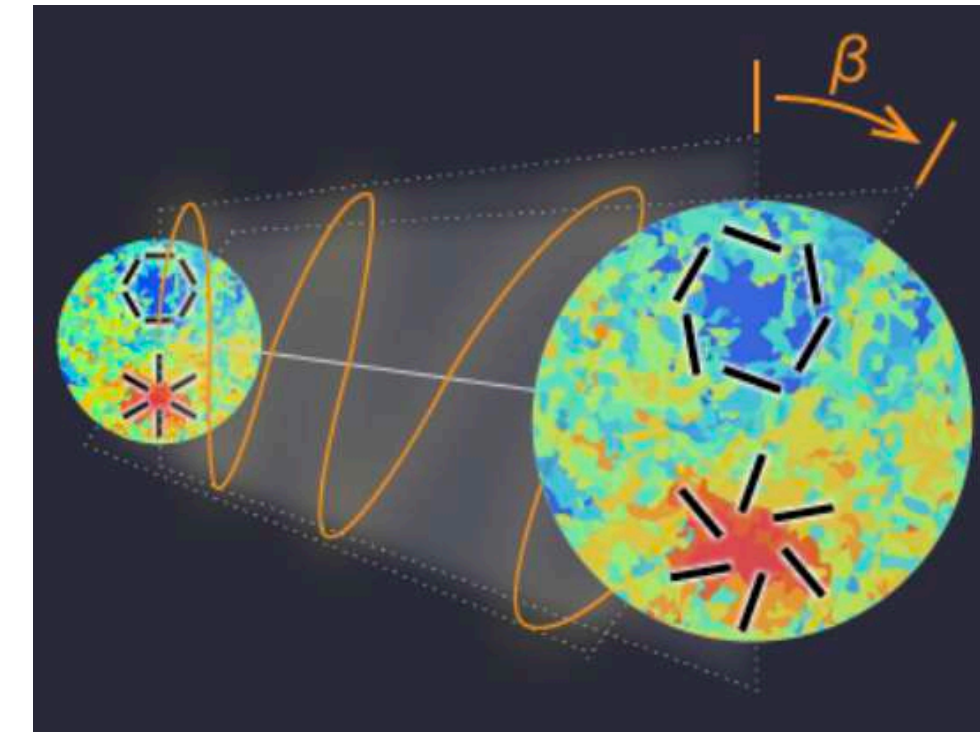
$$\beta = 0.342^\circ \substack{+0.094^\circ \\ -0.091^\circ} \longrightarrow 3.6\sigma \text{ significance}$$

Could be caused by an **ultra-light axion** that behaves like **dark energy** or **ULDM**

(Or strings, axion string loops, ...)



Minami/Komatsu



Minami, Komatsu 2020

Another hint:
4-pt correlation function (BOSS)
Found parity violation! (?)

Cosmic *birefringence*

Cosmic Birefringence from axions

For example:

Could be caused by an **ultra-light axion** that behaves like dark energy or ULDM

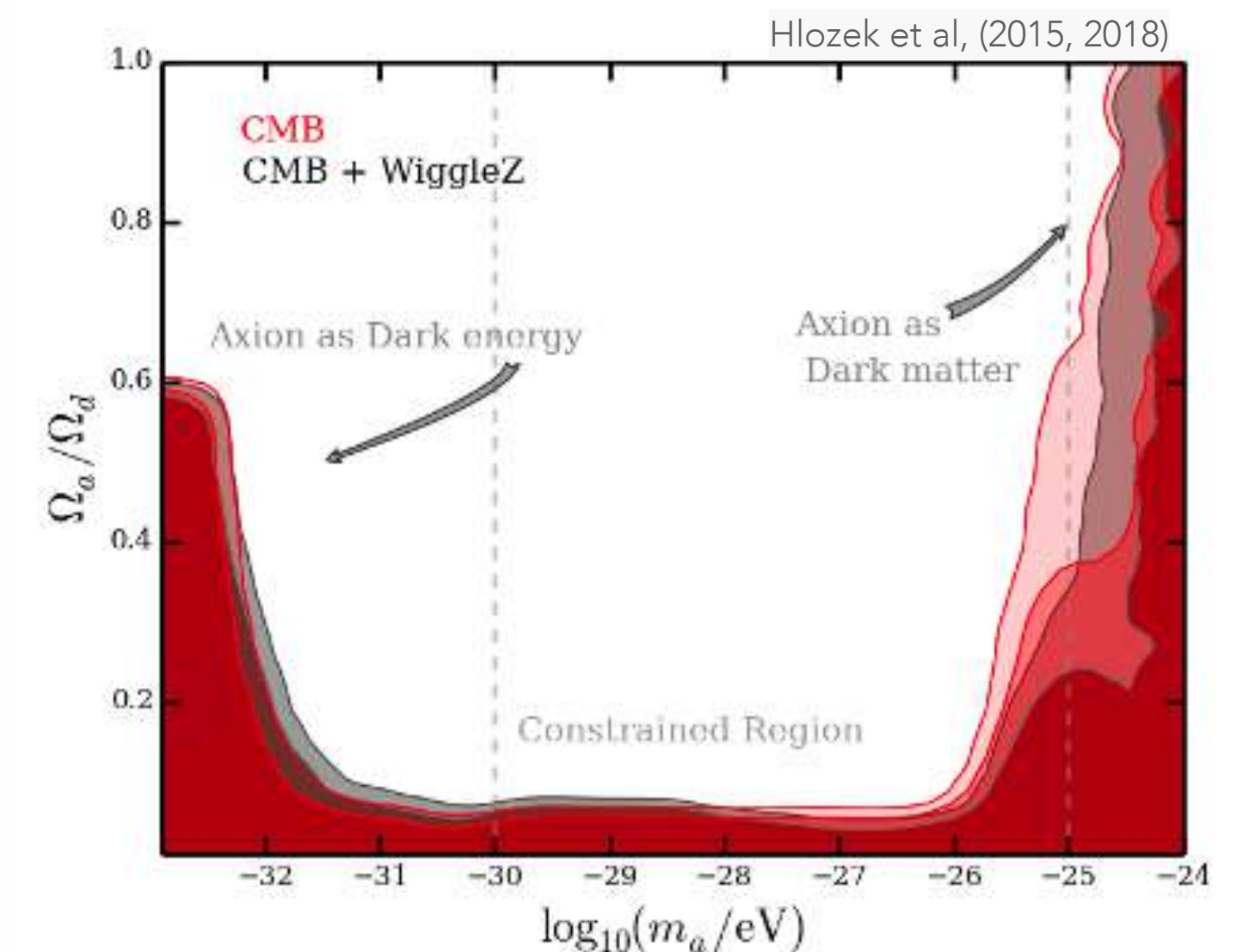
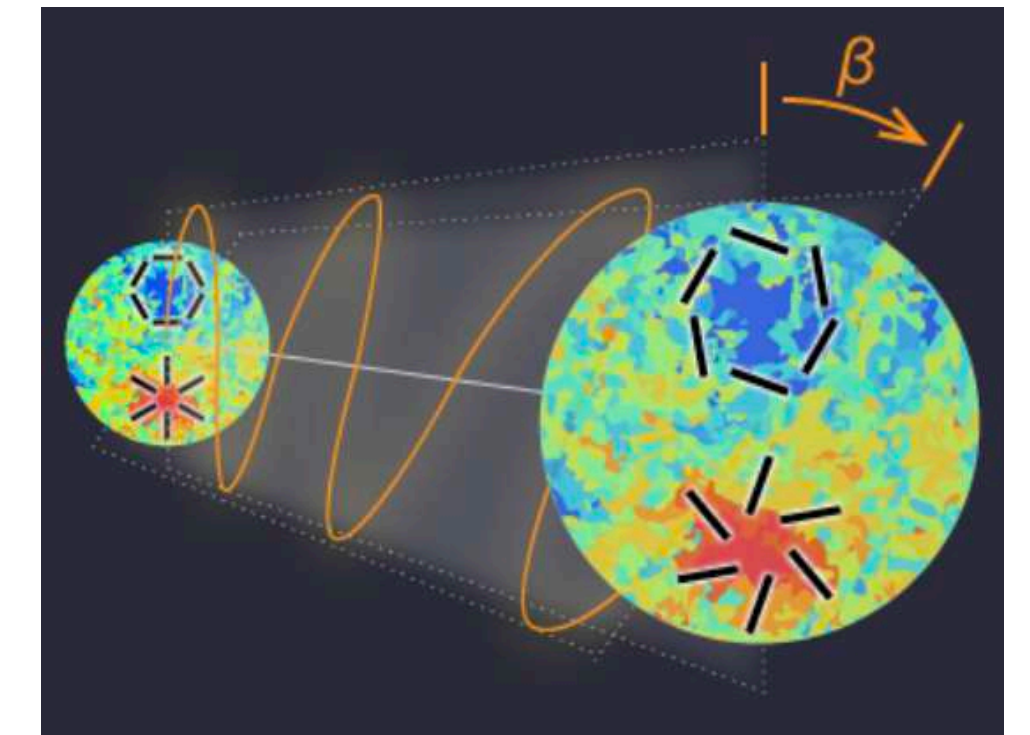
$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)^2 - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{4}g_{\phi\gamma}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Plane of polarisation of linearly polarised light is rotated with respect to the plane at emission and the amount of rotation β or $\Delta\theta_a$ depends on $\mathbf{m}$ and $\mathbf{g}$

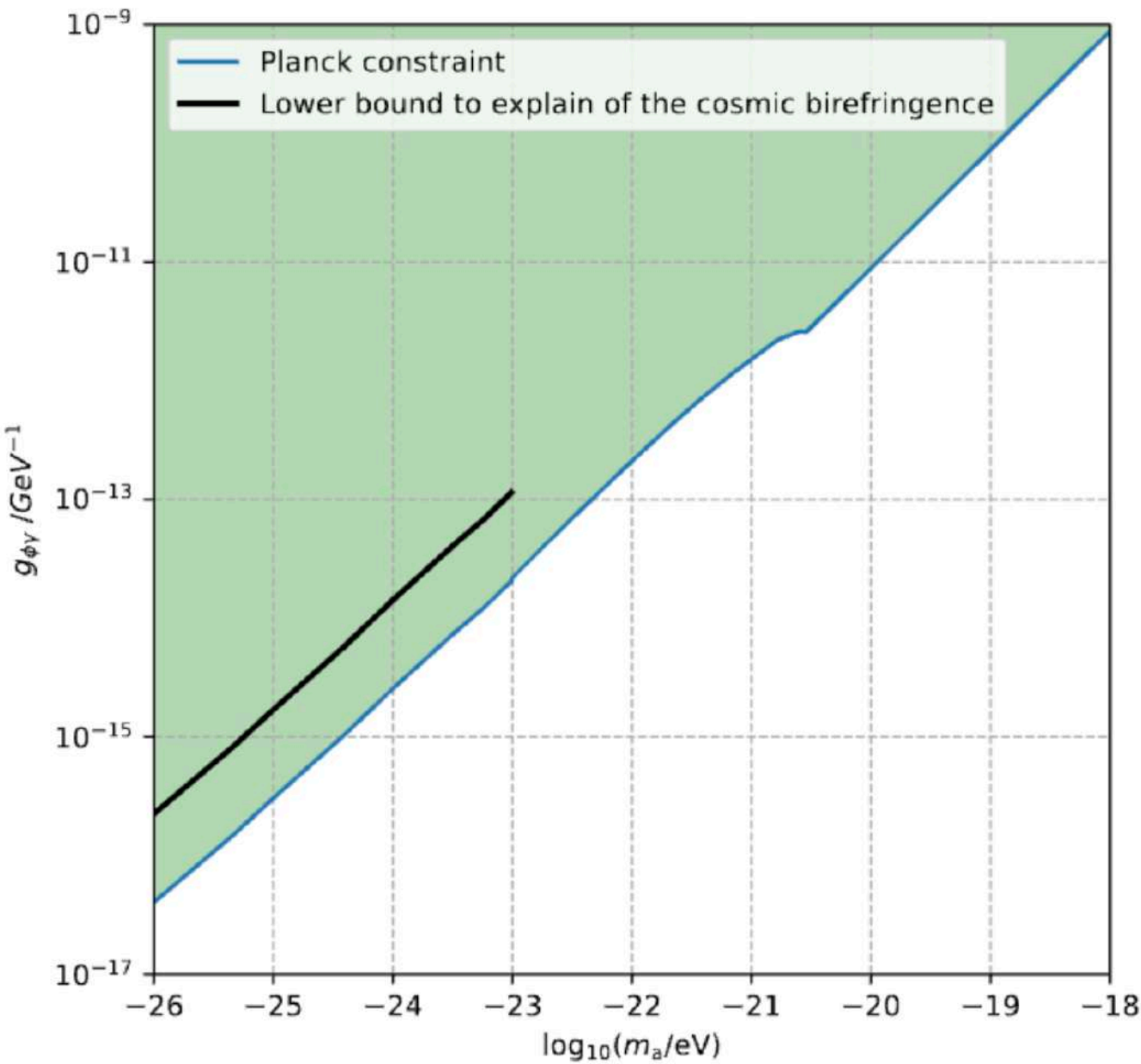
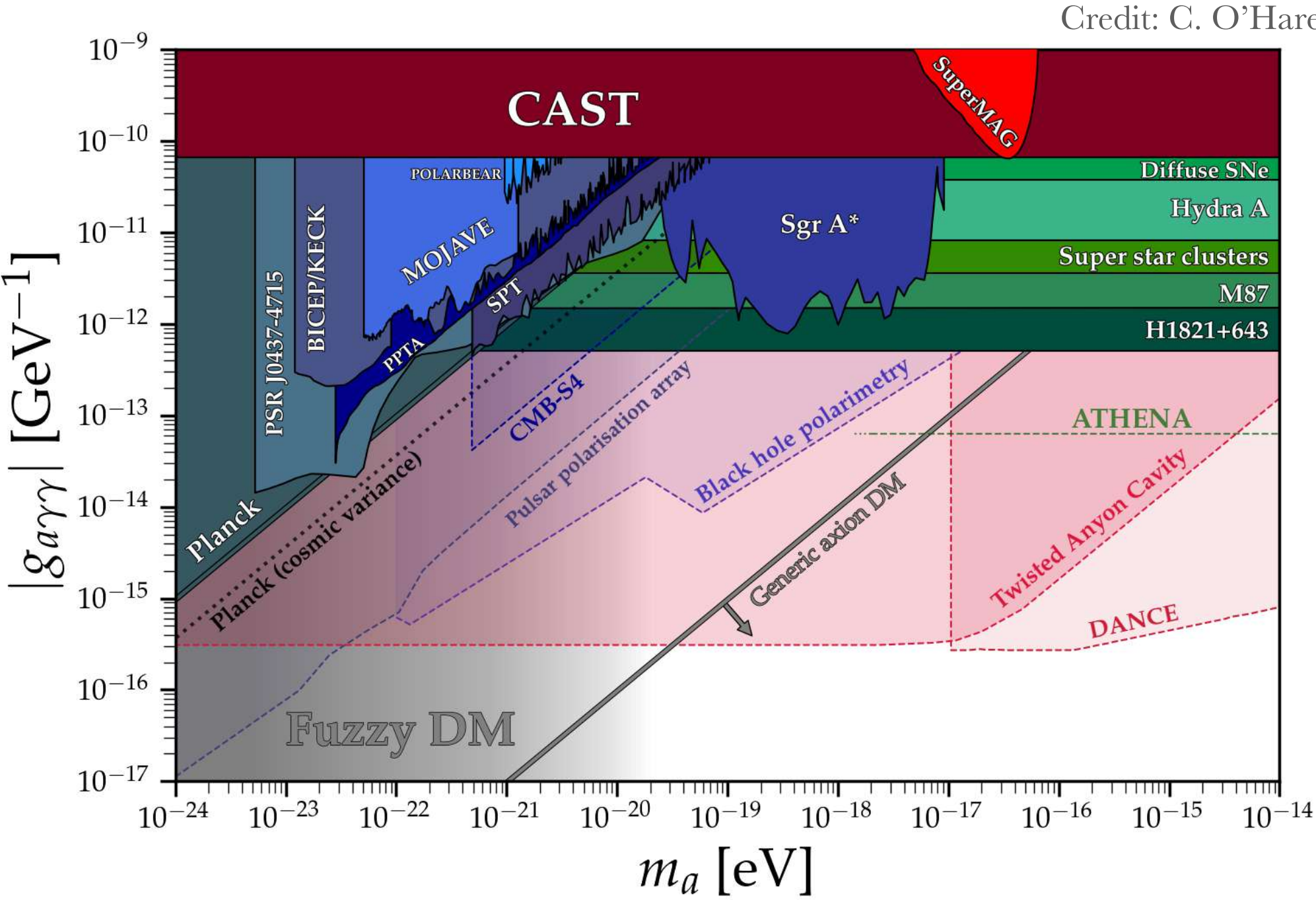
$$10^{-32} \text{ eV} < m < 10^{-22} \text{ eV}$$

Nakatsuka, et al 2022

Minami/Komatsu

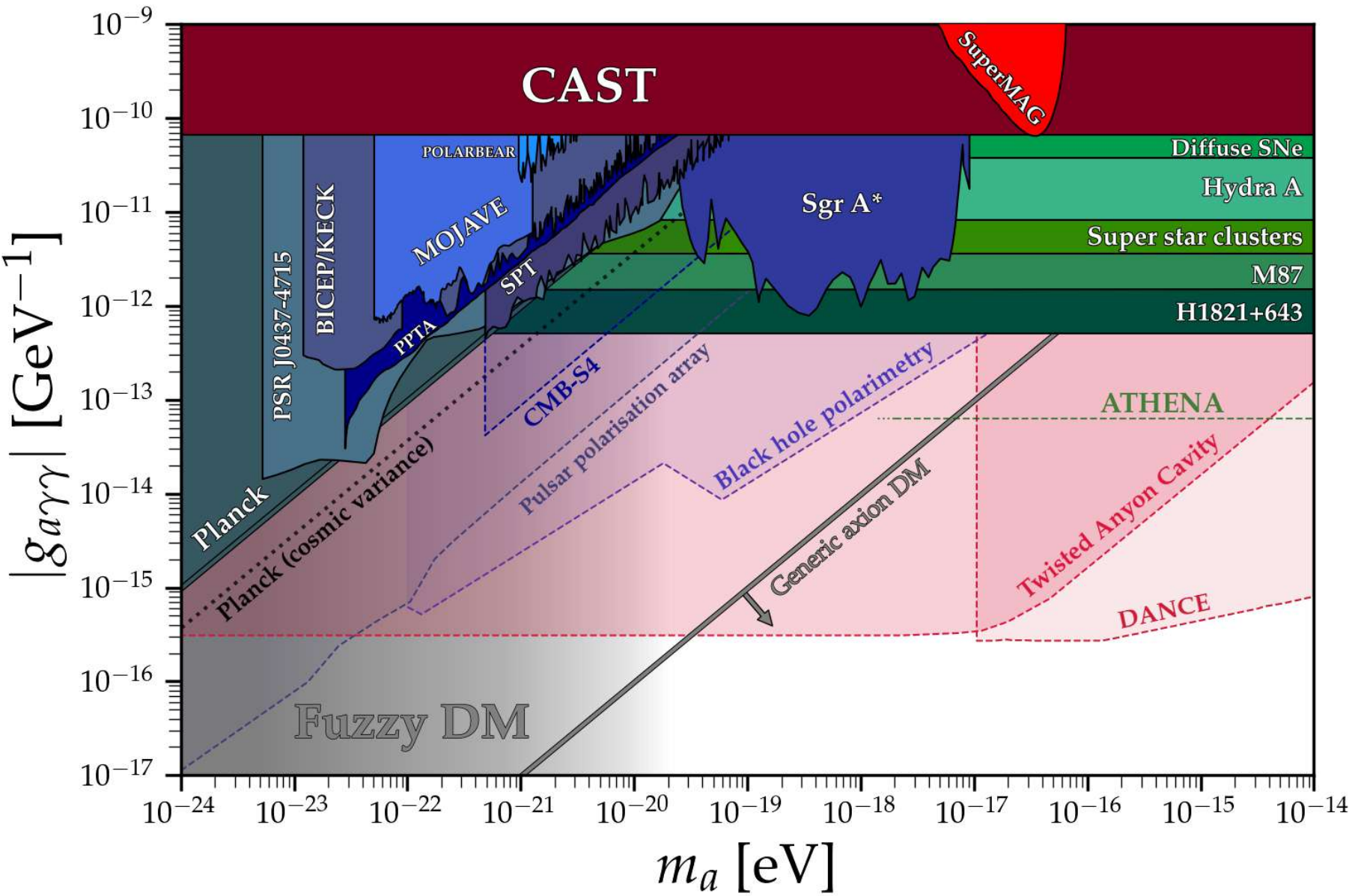


Bounds on interaction with *SM*



CMB isotropic
birefringence

D. Zhang, EF, I. Obata,
T. Namikawa,
2408.08063



Birefringence w/ strong
lensing

(Work in progress)
In collaboration with Simona
Vegetti and Devon Powell

Standard cosmological *model*

Matter
content

$\Omega_b = 0.0484 \pm 0.0003$ $\longrightarrow$ Amount of ordinary/visible matter

$\Omega_m = 0.308 \pm 0.012$ $\longrightarrow$ Amount of dark matter

$\Omega_\Lambda = 0.692 \pm 0.012$ $\longrightarrow$ Amount of dark energy

IC

$n_s = 0.9626 \pm 0.0057$ $\longrightarrow$ Scale dependence of the initial fluctuations

$10^9 A_s = 2.092 \pm 0.034$ $\longrightarrow$ Amplitude of the initial fluctuations

Reionization

$\tau = 0.0522 \pm 0.0080$ $\longrightarrow$ Optical depth

How opaque the universe is to photons that travel in it

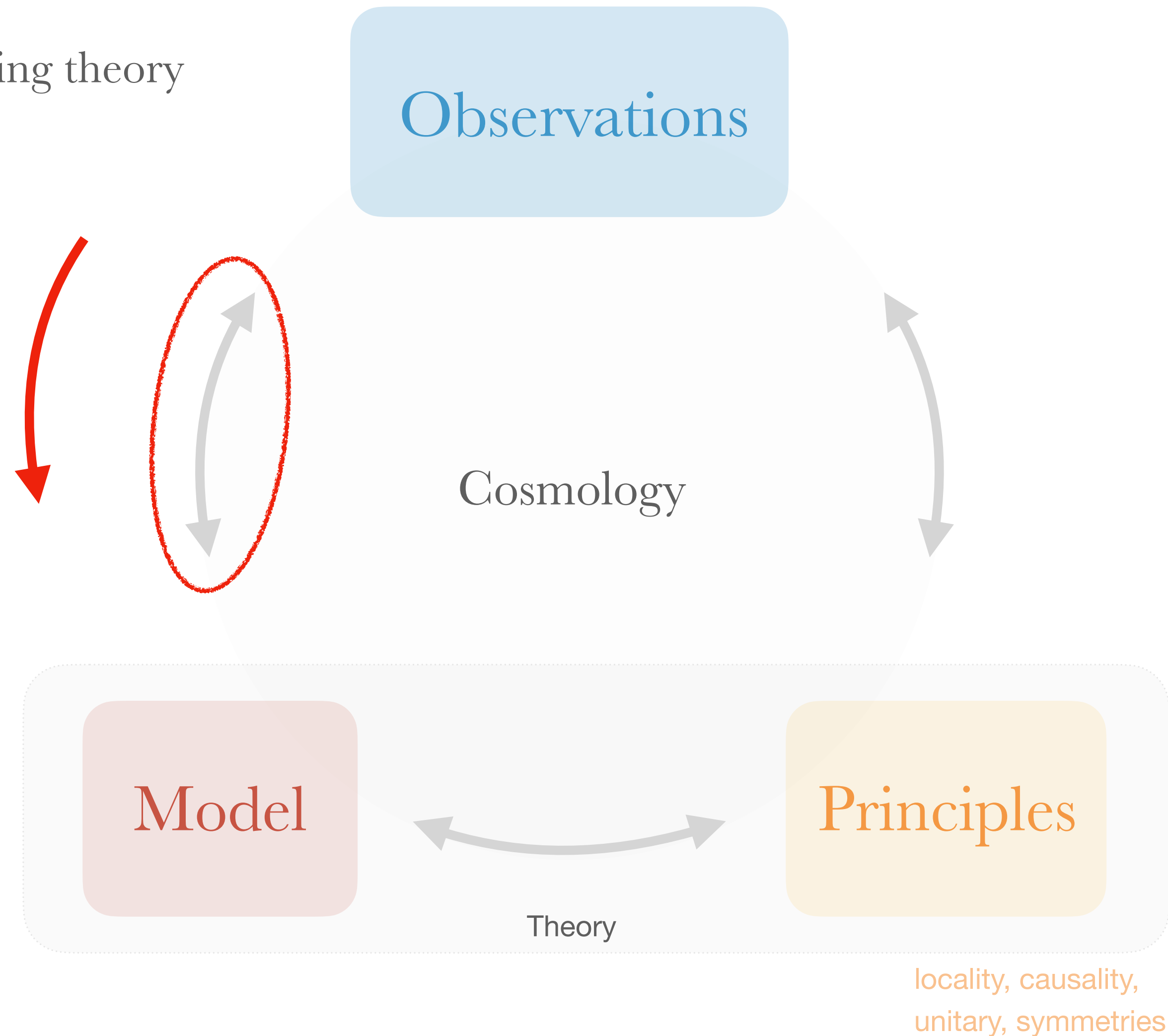
Under assumptions:

- Flat universe: $\Omega_k = 0$
- 3 neutrinos: $N_{eff} = 3.046$
- Sum of neutrino mass: $\Sigma m_\nu = 0.06$
- No tensor: $P_t = 0$
- No running: $dn_s/dk = 0$

*New physic from **observations** → **theory***

Observations inspiring and informing theory

DDE, cosmic birefringence, H0 tension

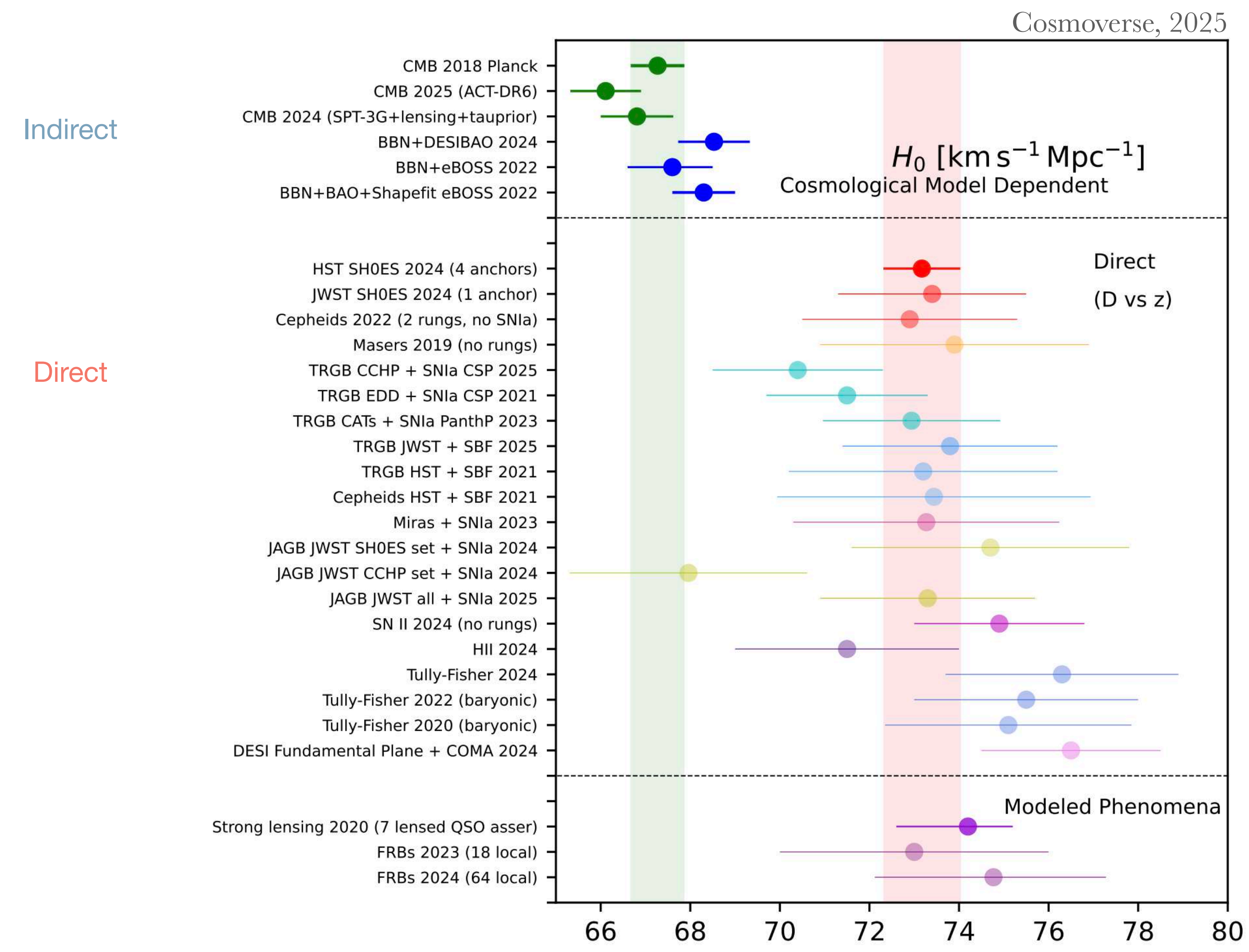


tensions

H_0 tension, S_8 tension, BAO-CMB tension and Ω_m tension

the H_0 tension

The Hubble tension



→ Depends on the cosmological model

New SHOES result (*Riess et al 2021*):

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

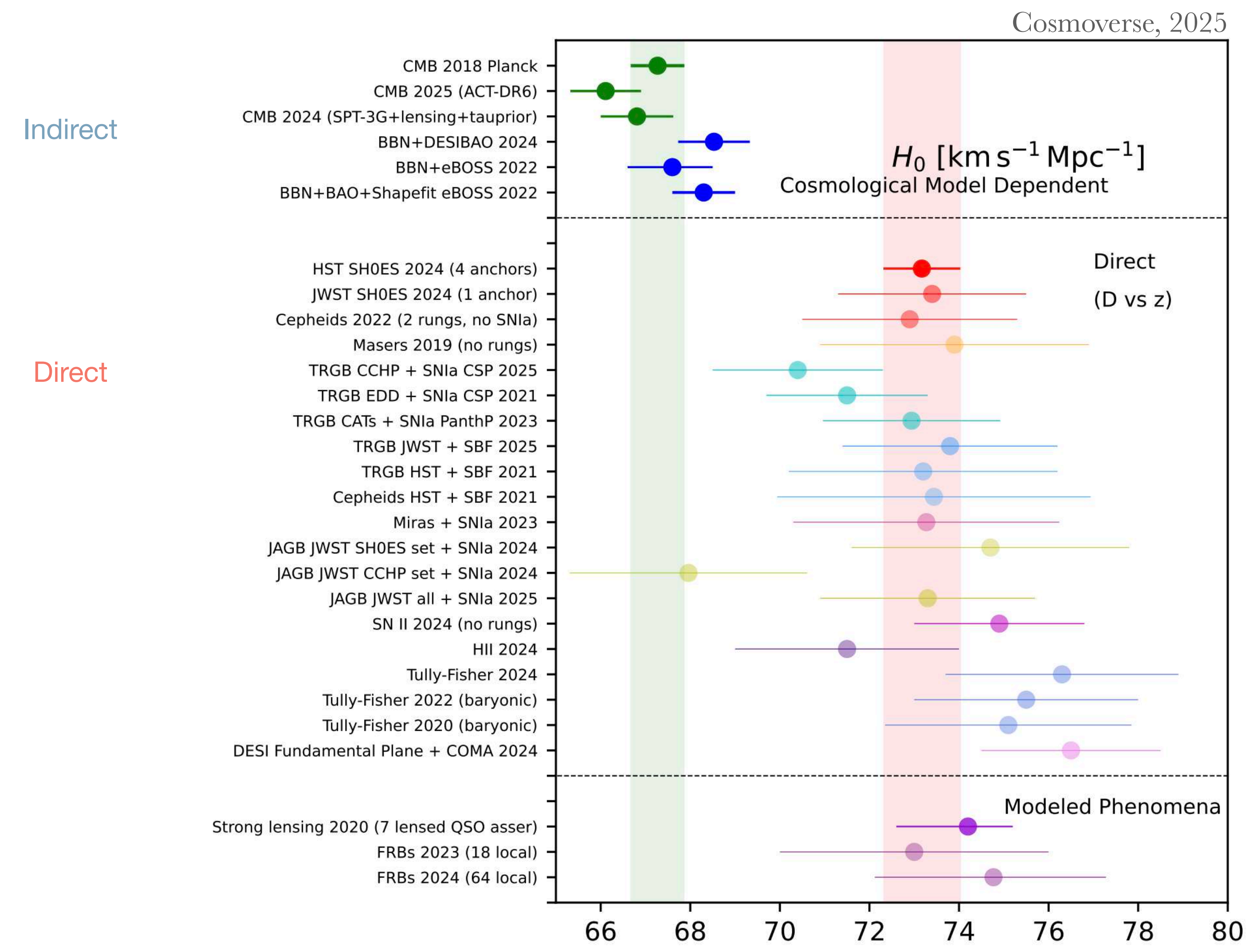
5 σ tension with Planck!

$$H_0 = 67.71 \pm 0.40 \text{ km/s/Mpc}$$

(Planck+BAO+Sn)

Systematics or new physics?

The Hubble tension



Depends on the cosmological model

New SHOES result (*Riess et al 2021*):

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

5 σ tension with Planck!

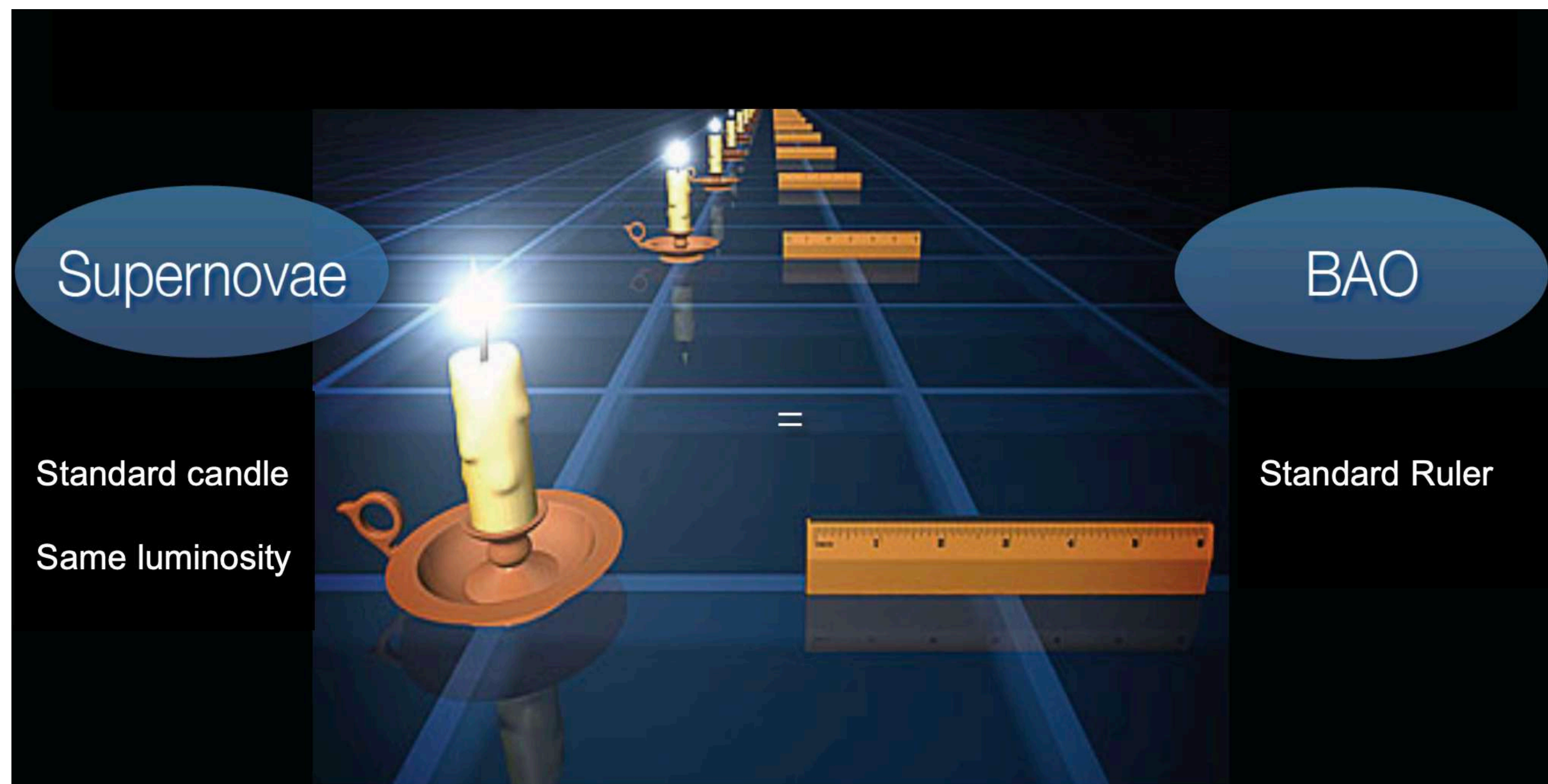
$$H_0 = 67.71 \pm 0.40 \text{ km/s/Mpc}$$

(Planck+BAO+Sn)

Systematics or new physics?

*The Hubble **tension***

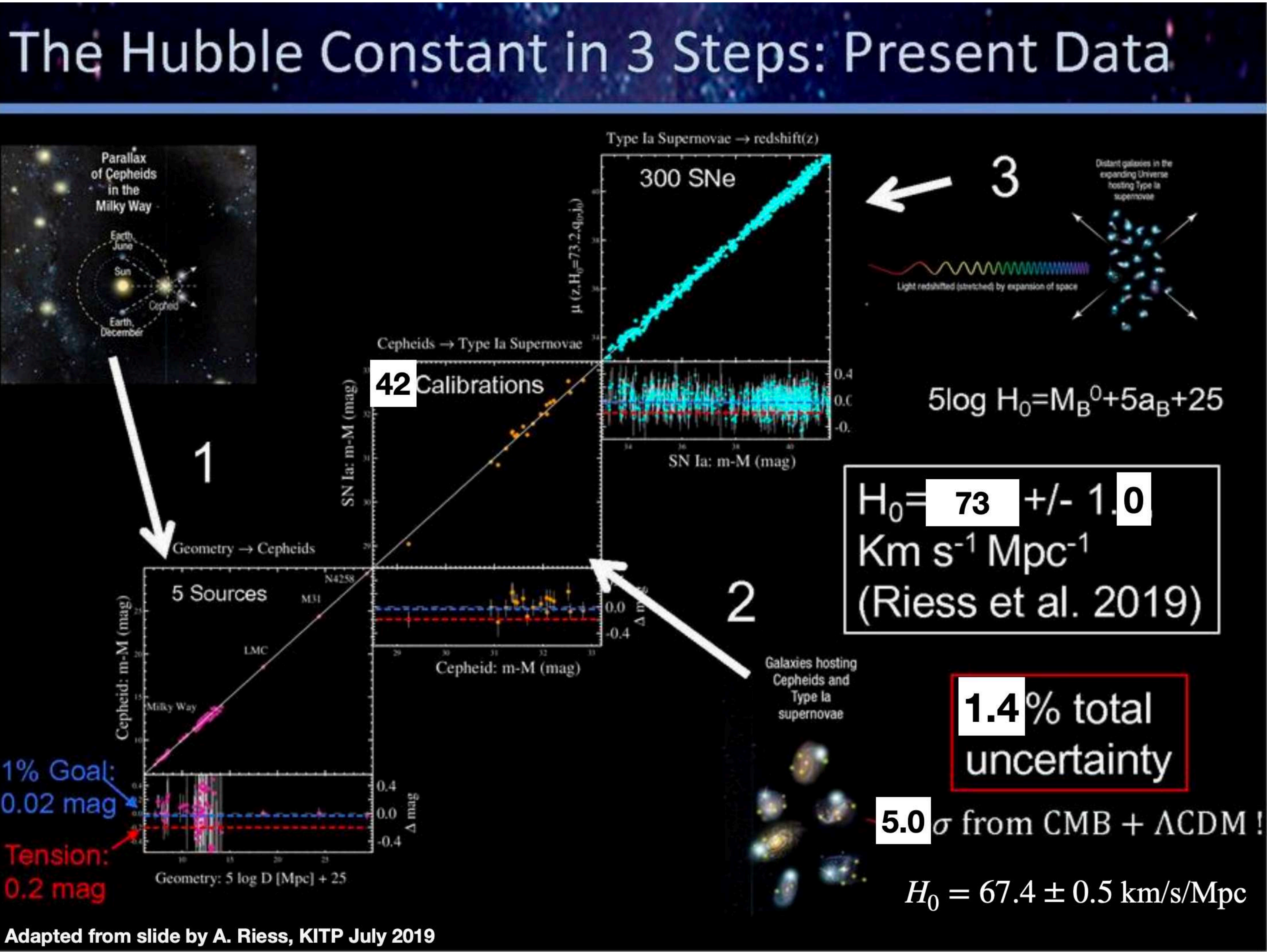
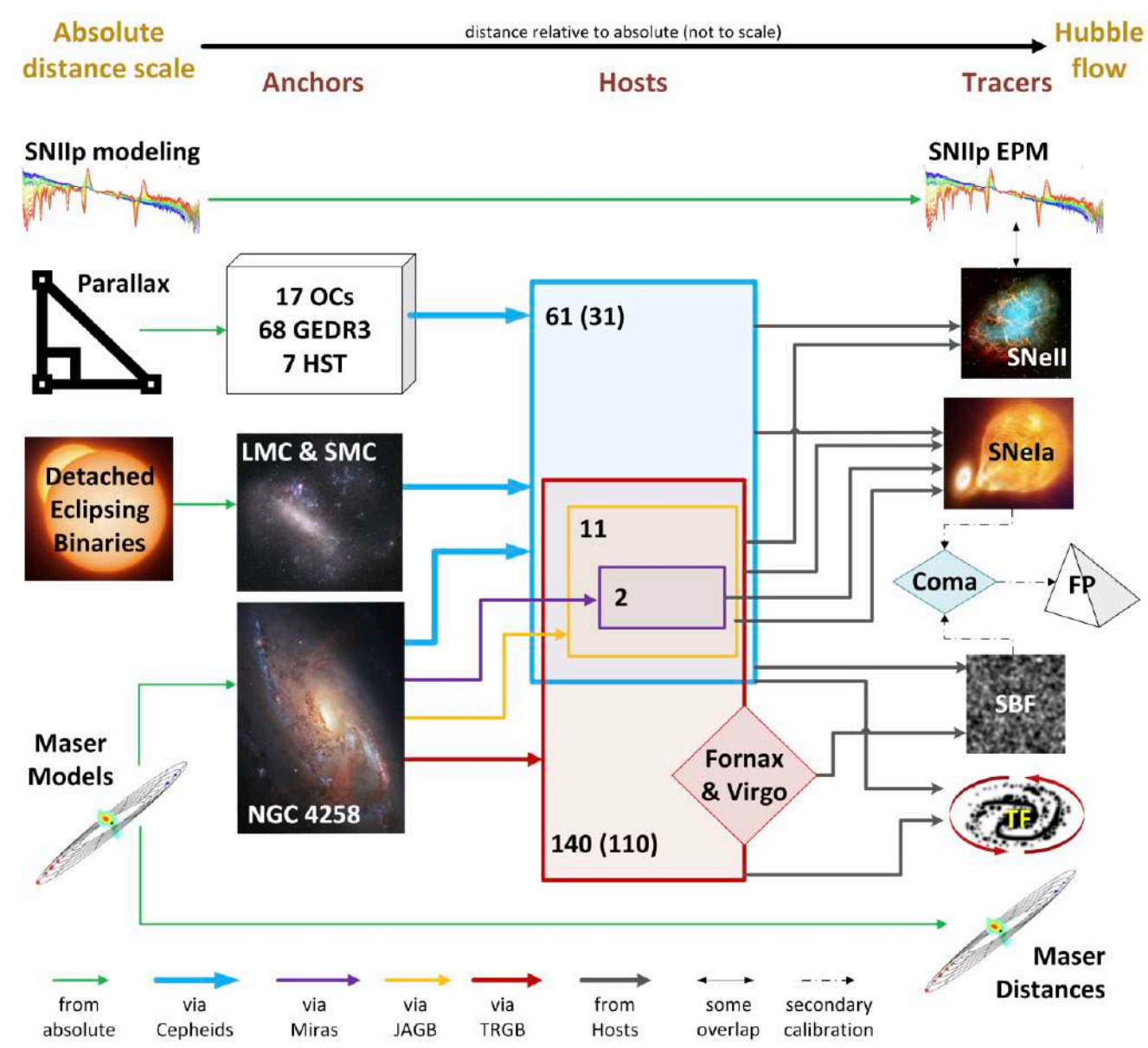
- Discrepancy in the indirect and direct measured value of H_0
- Discrepancy between the direct and indirect **calibrations** of the cosmic distance ladder



Measuring H_0

DIRECT

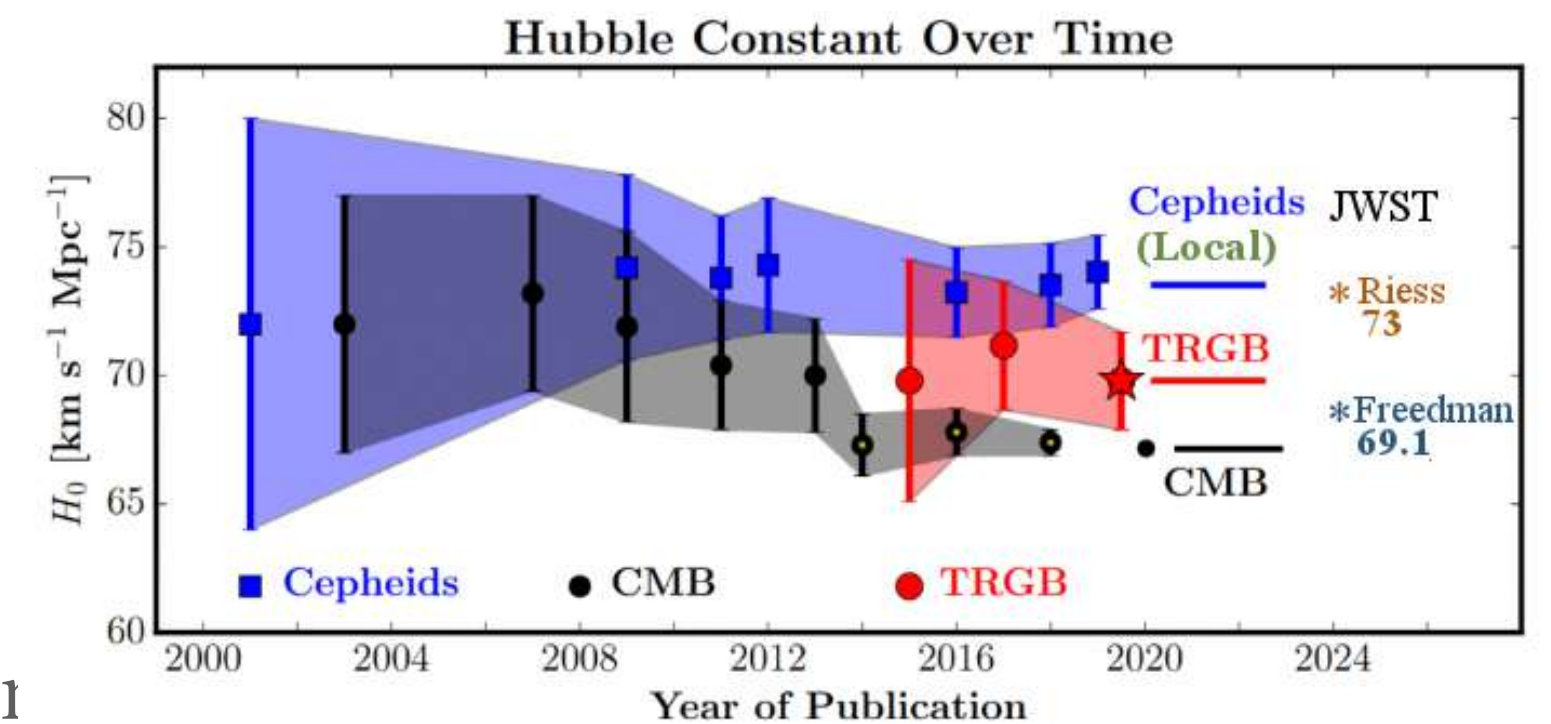
Possible pathways to directly calibrate the distance ladder



Measuring H_0

Update

- Local H_0 is measured through the distance ladder:
geometric anchors $\rightarrow$ Cepheids/TRGB $\rightarrow$ SNe Ia $\rightarrow H_0$
- The old framing was “Cepheids vs TRGB”: **Cepheids high, TRGB lower**
- **JWST**: sharper near-IR imaging, reduced crowding, lower dust sensitivity - we can cross-check and higher precision
 - Allows multiple indicators in the same galaxies: *Cepheids*, *TRGB*, *JAGB*, *Miras*
- The current situation is subtler: *distances in common hosts are increasingly consistent*
- A major issue is now:
which nearby SNe Ia enter the calibration sample - selection!



Not “Cepheids vs TRGB” anymore!

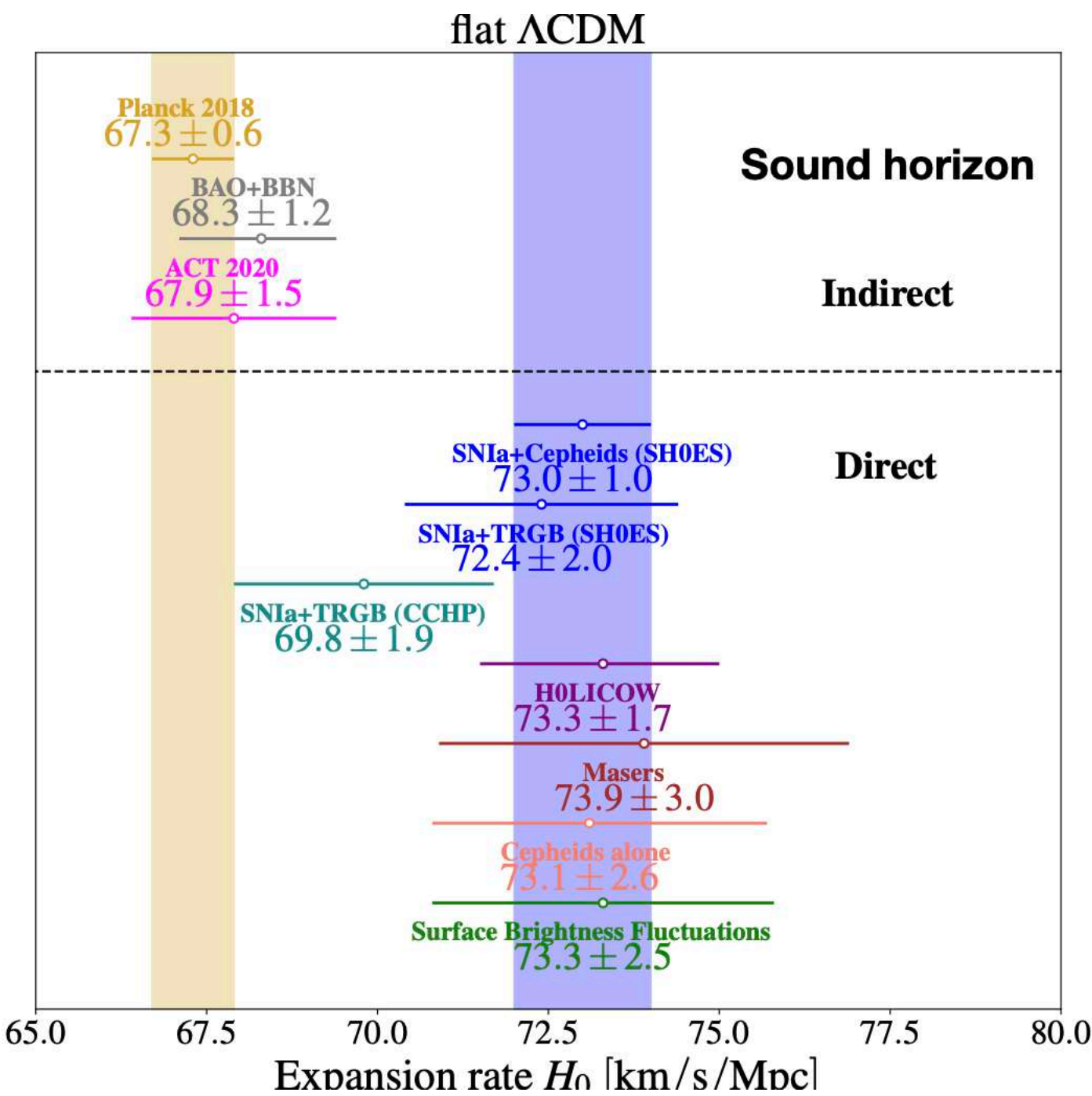
Status

- JWST has not removed the Hubble tension; it has sharpened where the systematics must be tested
- local distance ladders remain high compared with CMB+LCDM, but the internal consistency tests are becoming much stronger

Measuring H_0

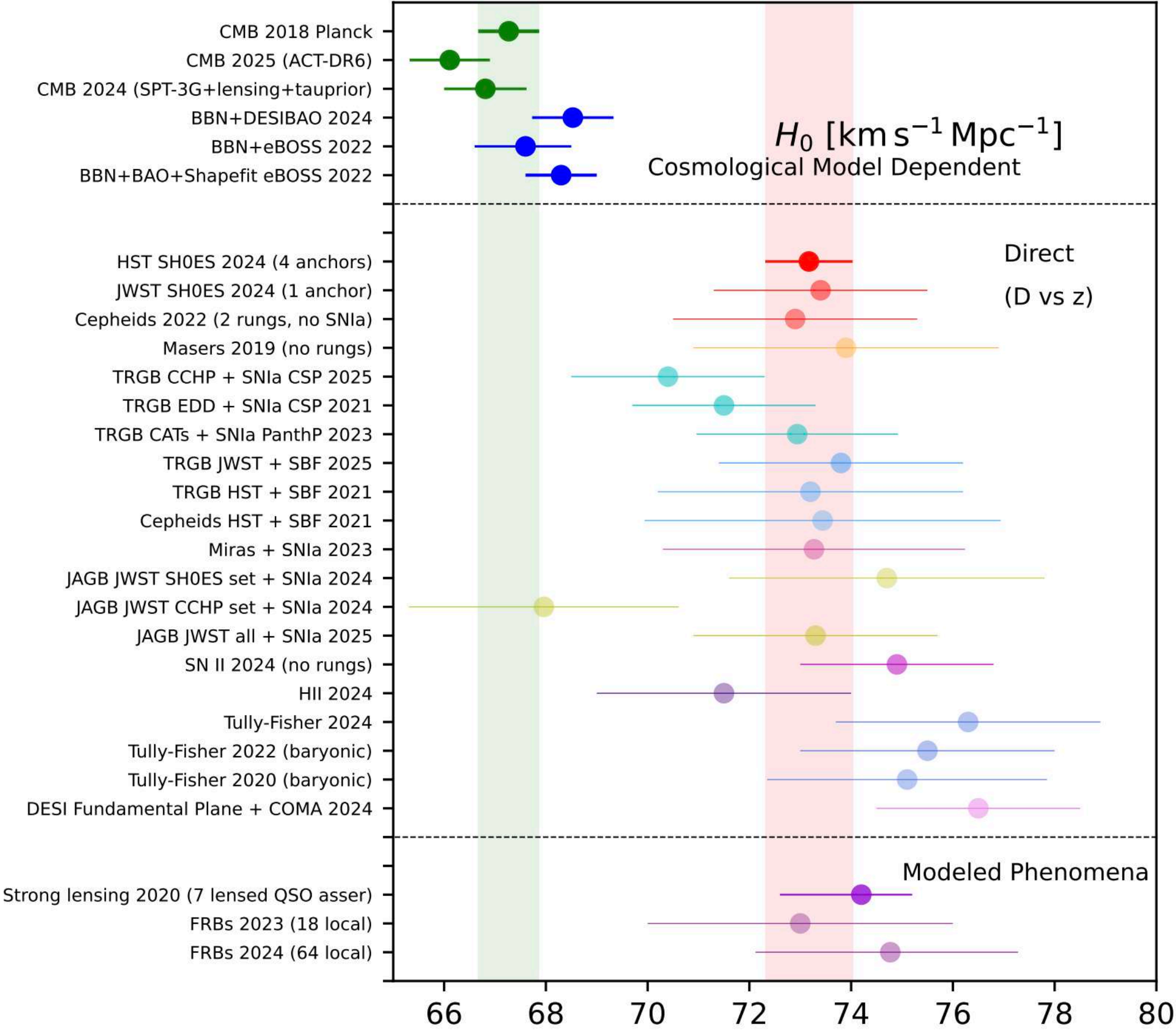
DIRECT

Tension seems to be beyond SHOES only



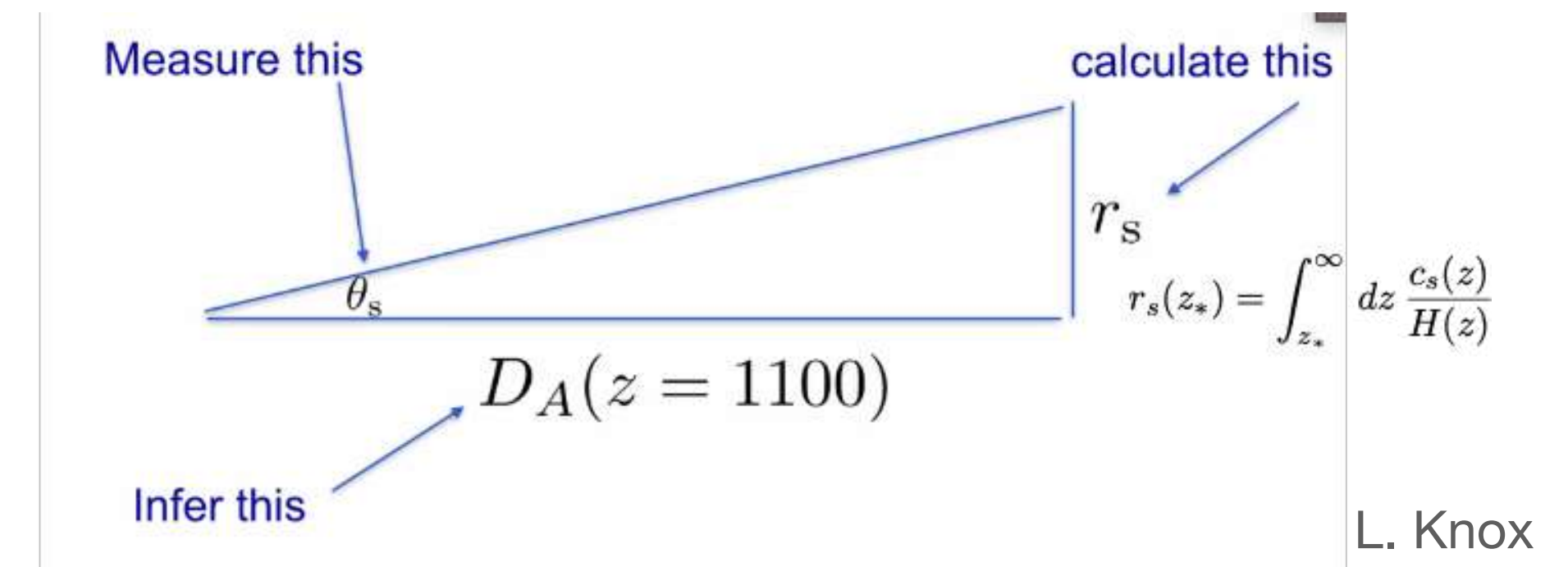
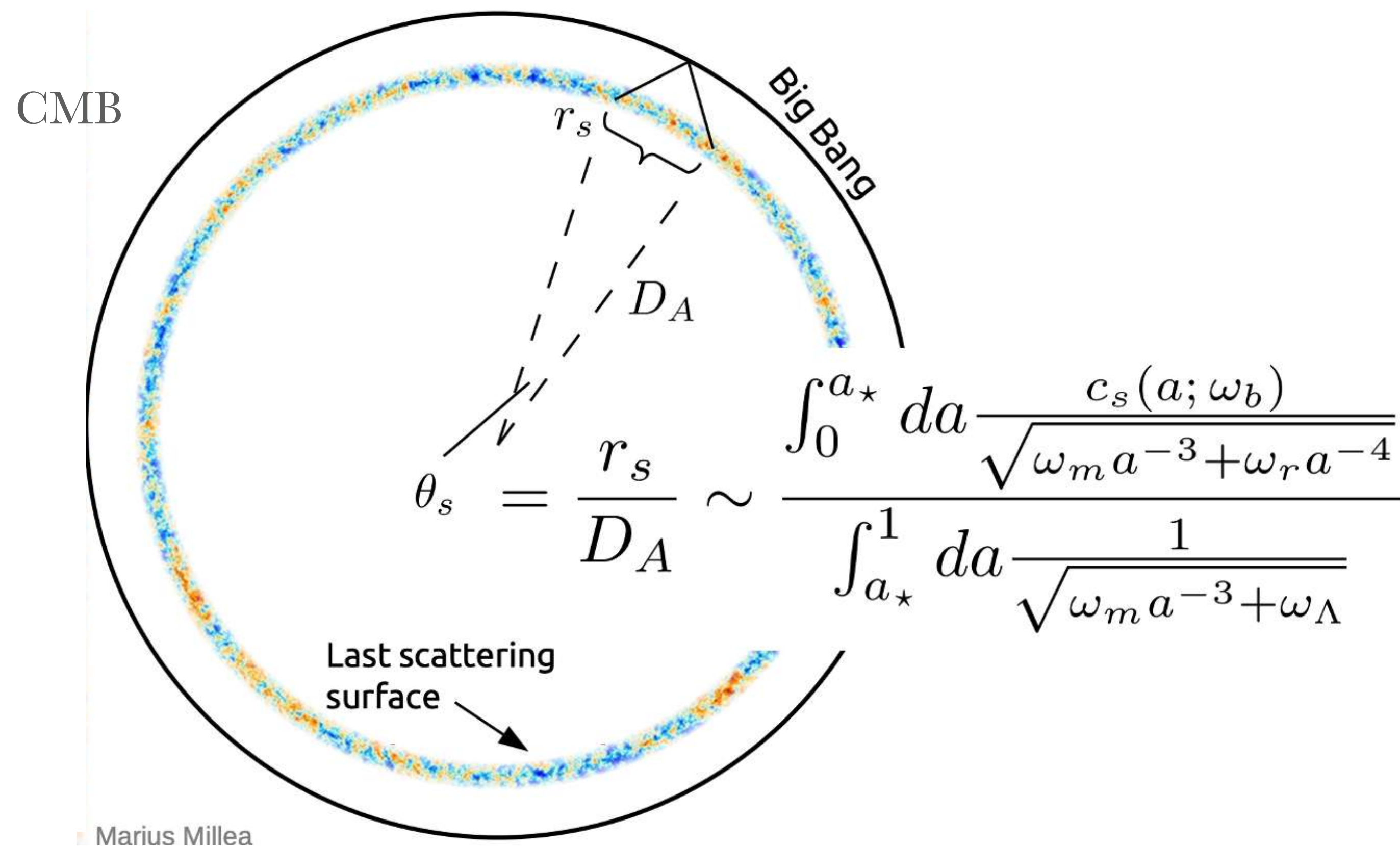
Snowmass, 2022

Cosmoverse, 2025



Measuring H_0

INDIRECT



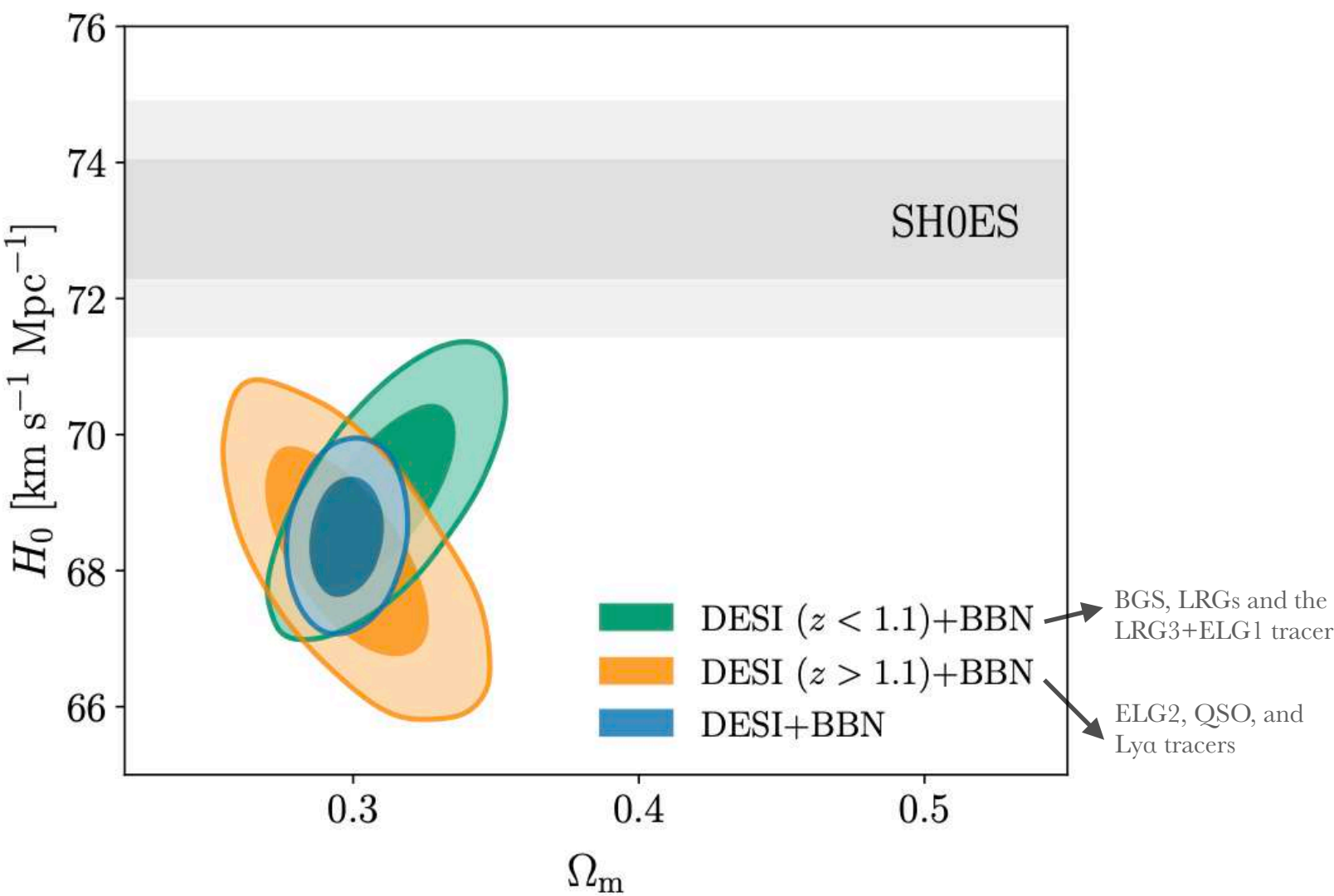
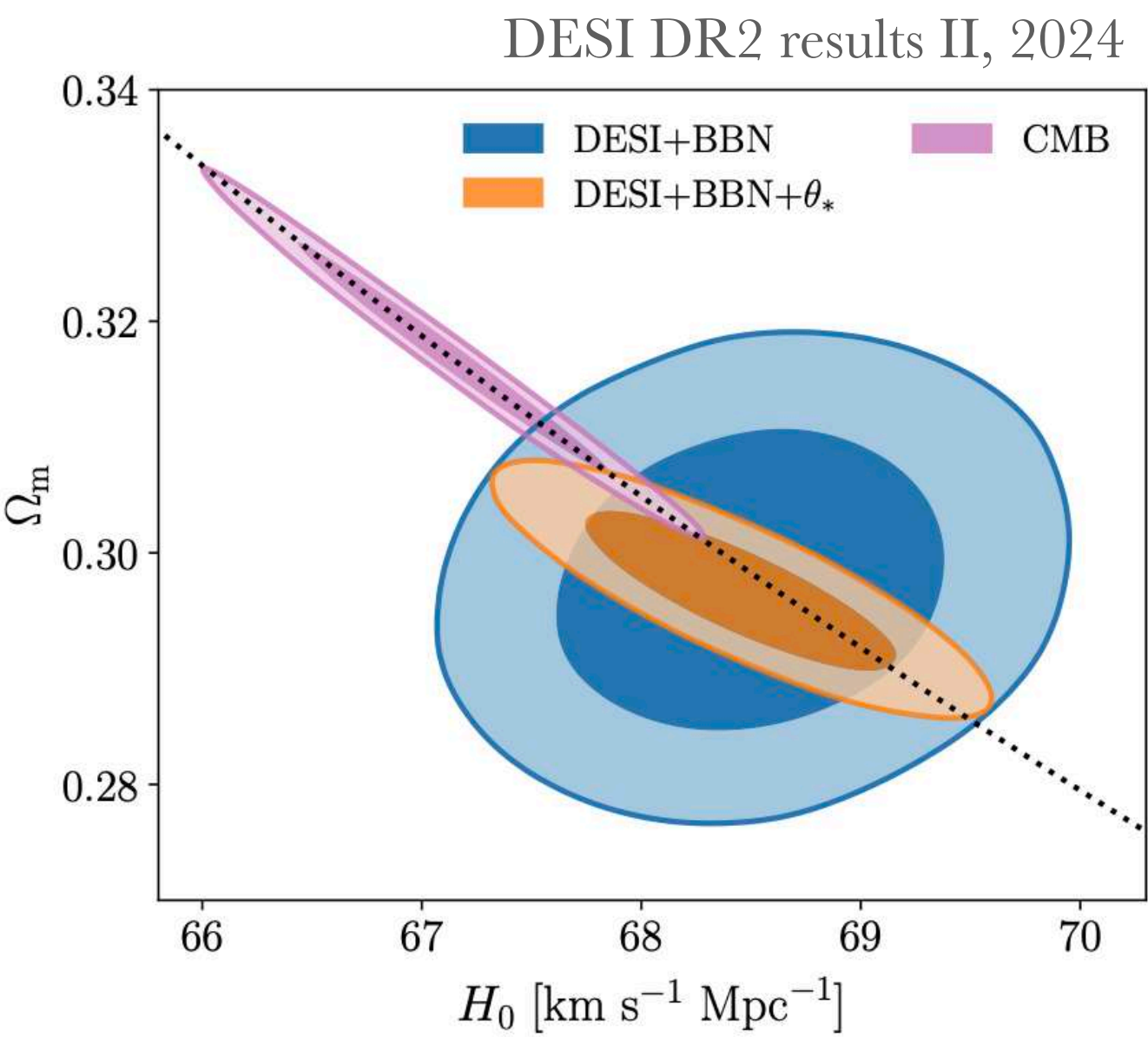
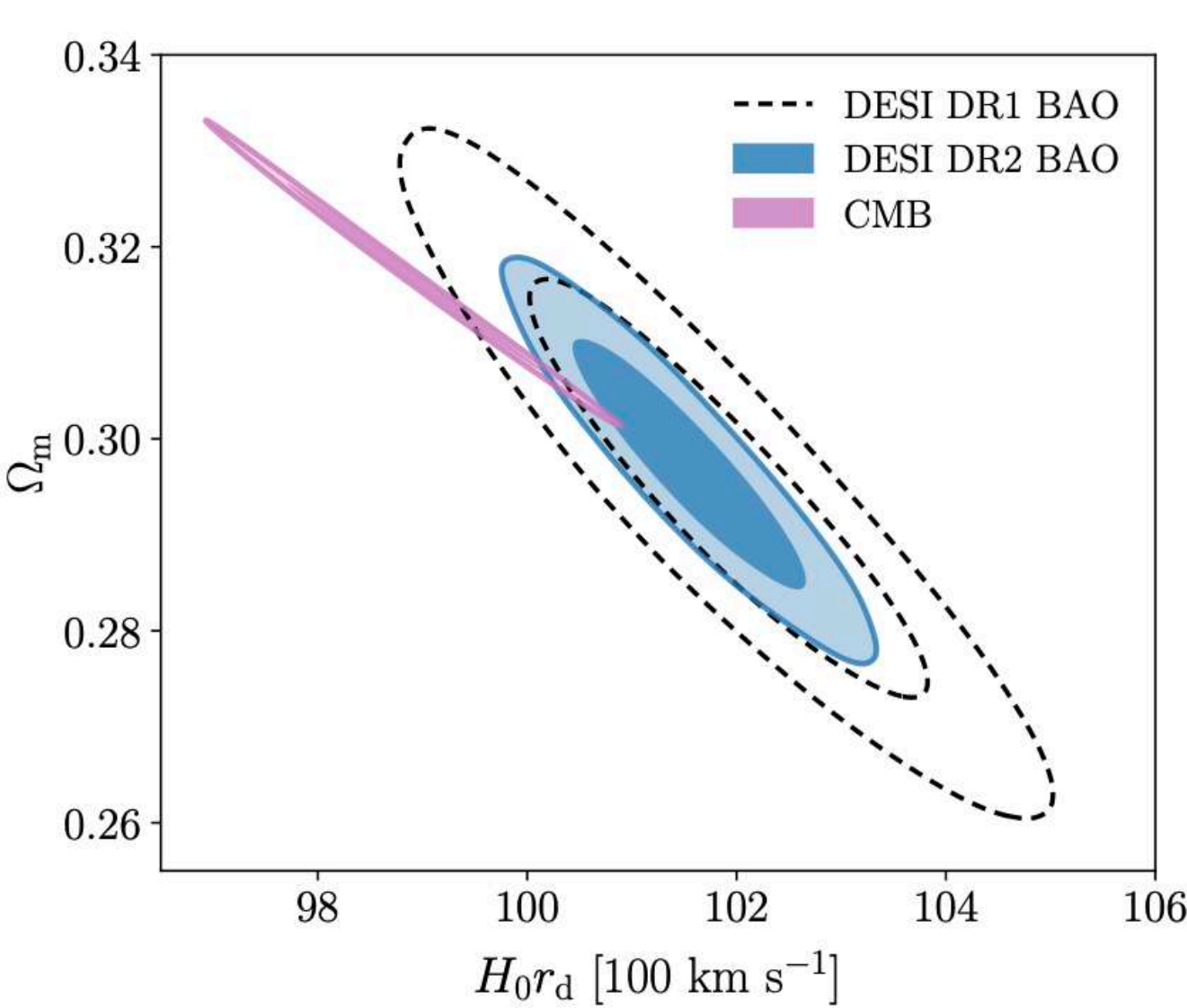
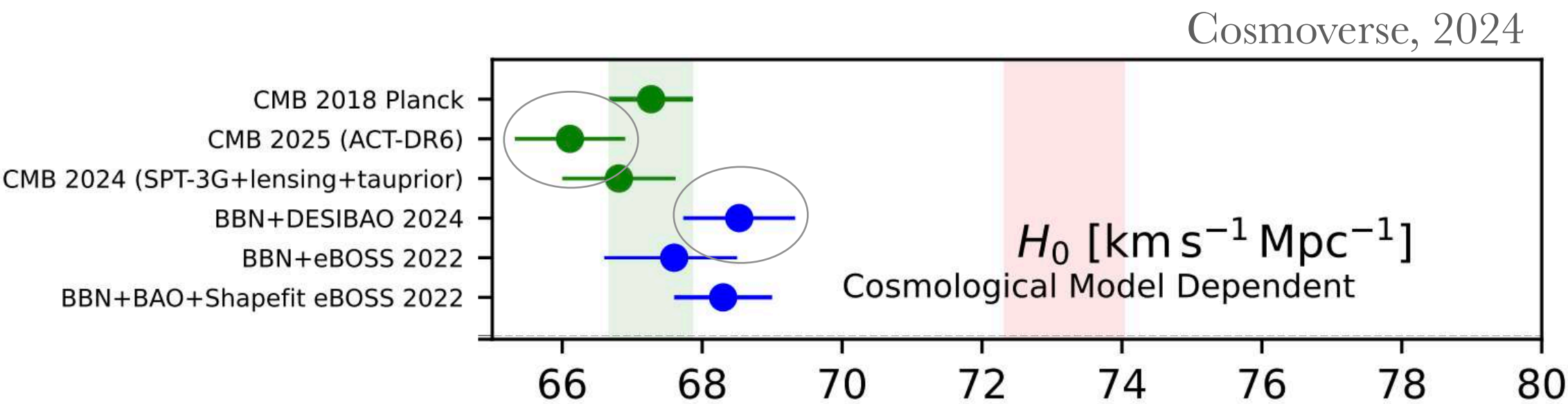
$r_s(z_*) \rightarrow$ Sound horizon at lss
 $D_A(z_*) \rightarrow$ Angular diameter distance
 $\theta_s(z_*) \rightarrow$ Angular scale of the sound horizon

- θ_s is measured with a 0.04% precision by *Planck* 2018 (@ $z \sim 1000$) and with 1% precision by LSS (@ $z \sim 1-2$)
- H is determined as a model-dependent calibration of the sound horizon

Measuring H_0

INDIRECT

CMB and LSS H_0 in agreement!



DESI does not measure H_0 directly: BAO gives distances relative to r_d ; BBN calibrates r_d through $\Omega_b h^2$, allowing an inferred H_0

How to solve the *H0* tension?

INDIRECT

The diagram illustrates the equation for the angular scale of the sound horizon, $\theta_s(z_*)$, which is measured with a 0.03% precision by *Planck* 2018. The equation is:

$$\theta_s(z_*) = \frac{r_s(z_*)}{D_A(z_*)} = \frac{\int_{z_*}^{\infty} c_s(z) dz / H(z)}{\int_0^{z_*} c dz / H(z)}$$

Annotations for the terms in the equation:

- r_s : *pre-recombination* physics $\longrightarrow$ depend on physical densities (b, r, cdm, ν)
- D_A : *post-recombination* physics $\longrightarrow$ information on H0

Measured with a 0.03% precision by *Planck* 2018

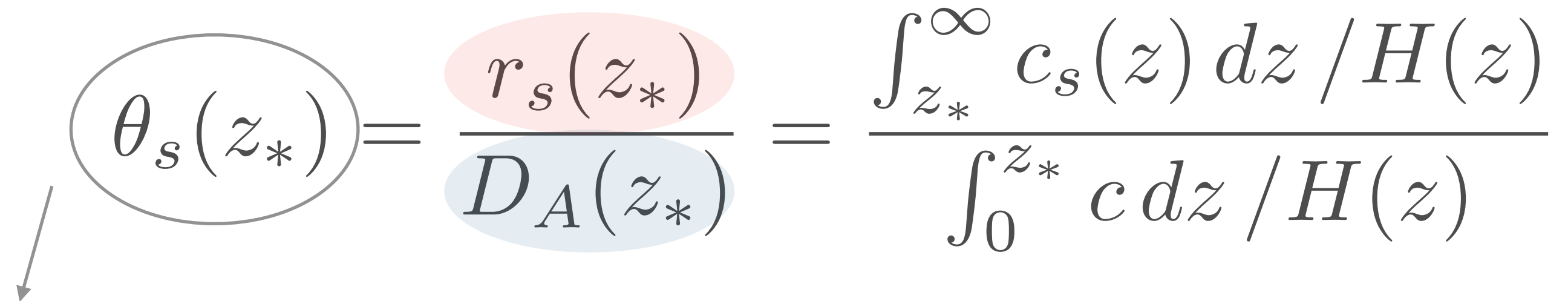
$r_s(z_*) \rightarrow$ Sound horizon at lss

$D_A(z_*) \rightarrow$ Angular diameter distance

$\theta_s(z_*) \rightarrow$ Angular scale of the sound horizon

Early vs late time solutions to the *Hubble tension*

To increase H_0 :

$$\theta_s(z_*) = \frac{r_s(z_*)}{D_A(z_*)} = \frac{\int_{z_*}^{\infty} c_s(z) dz / H(z)}{\int_0^{z_*} c dz / H(z)}$$


Measured with a 0.03% precision by *Planck* 2018

LATE UNIVERSE SOLUTIONS

Change only late time physics: early universe unaffected

Little room for changes in the physics (?)

Shown to not solve the tension, only alleviates!

EARLY UNIVERSE SOLUTIONS

Change only early time physics, late time almost unaffected

$\theta_s(z_*)$: decrease $r_s(z_*) \implies$ decreases $D_A(z_*)$
Fixed

$\Downarrow$
Increases H_0

Hubble tension solving *models*

tension $\leq 1\sigma$ “Excellent models”	tension $\leq 2\sigma$ “Good models”	tension $\leq 3\sigma$ “Promising models”
Early Dark Energy [228, 235, 240, 250] Exponential Acoustic Dark Energy [259] Phantom Crossing [315] Late Dark Energy Transition [317] Metastable Dark Energy [314] PEDE [394] Vacuum Metamorphosis [402] Elaborated Vacuum Metamorphosis [401, 402] Sterile Neutrinos [433] Decaying Dark Matter [481] Neutrino-Majoron Interactions [509] IDE [637, 639, 657, 661] DM - Photon Coupling [685] $f(\mathcal{T})$ gravity theory [812] BD- Λ CDM [851] Über-Gravity [59] Galileon Gravity [875] Unimodular Gravity [890] Time Varying Electron Mass [990] Λ CDM [995] Ginzburg-Landau theory [996] Lorentzian Quintessential Inflation [979] Holographic Dark Energy [351]	Early Dark Energy [212, 229, 236, 263] Rock ‘n’ Roll [242] New Early Dark Energy [247] Acoustic Dark Energy [257] Dynamical Dark Energy [309] Running vacuum model [332] Bulk viscous models [340, 341] Holographic Dark Energy [350] Phantom Braneworld DE [378] PEDE [391, 392] Elaborated Vacuum Metamorphosis [401] IDE [659, 670] Interacting Dark Radiation [517] Decaying Dark Matter [471, 474] DM - Photon Coupling [686] Self-interacting sterile neutrinos [711] $f(\mathcal{T})$ gravity theory [817] Über-Gravity [871] VCDM [893] Primordial magnetic fields [992] Early modified gravity [859] Bianchi type I spacetime [999] $f(\mathcal{T})$ [818]	DE in extended parameter spaces [289] Dynamical Dark Energy [281, 309] Holographic Dark Energy [350] Swampland Conjectures [370] MEDE [399] Coupled DM - Dark radiation [534] Decaying Ultralight Scalar [538] BD- Λ CDM [852] Metastable Dark Energy [314] Self-Interacting Neutrinos [700] Dark Neutrino Interactions [716] IDE [634–636, 653, 656, 663, 669] Scalar-tensor gravity [855, 856] Galileon gravity [877, 881] Nonlocal gravity [886] Modified recombination [986] Effective Electron Rest Mass [989] Super Λ CDM [1007] Axi-Higgs [991] Self-Interacting Dark Matter [479] Primordial Black Holes [545]

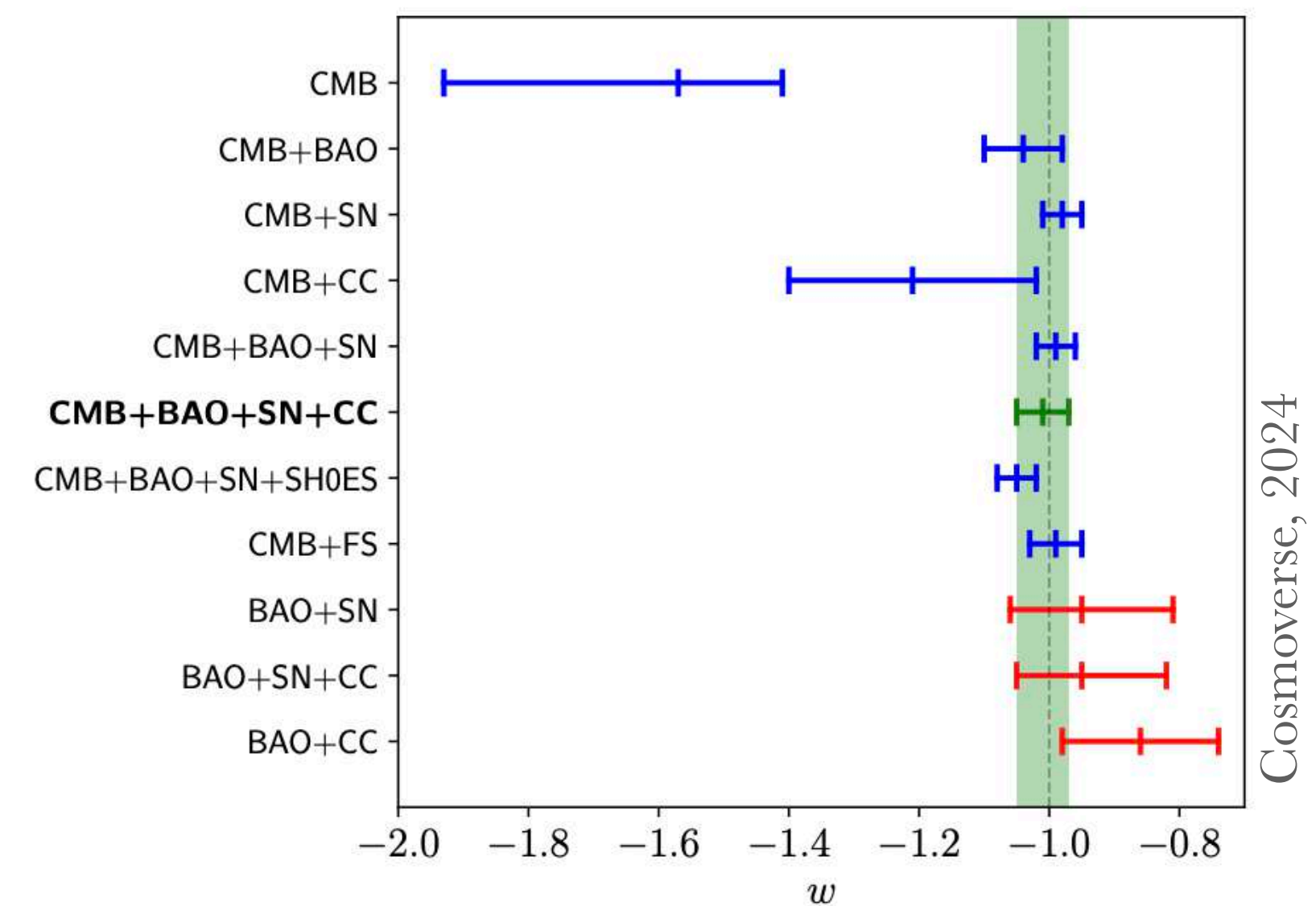
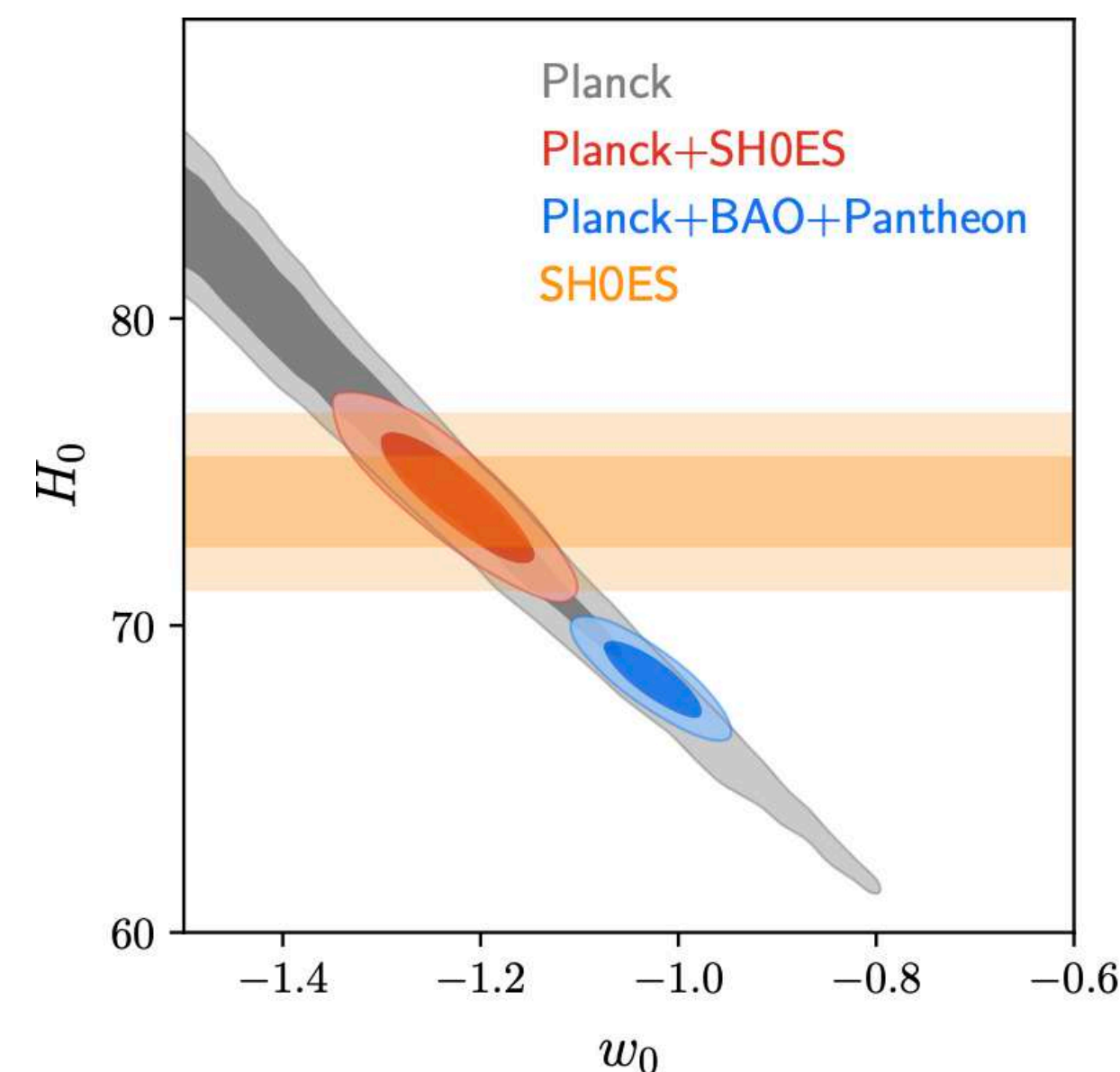
Late time solutions to the *Hubble tension*

- These solutions include: interacting DM/DE, "phantom" DE, rapid change DE, decaying DM, ...
- They usually can only **alleviate** the tension

Late-time fixes are constrained by late-time data

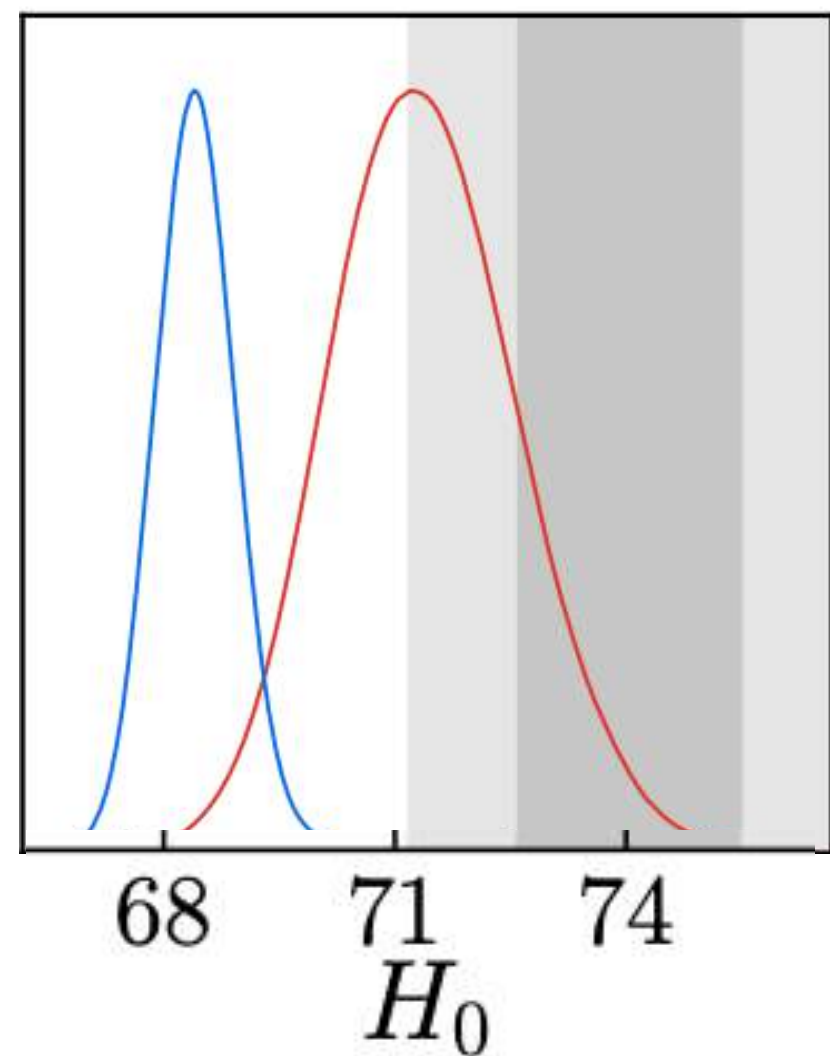
- Although from CMB alone, one can get a higher H_0 from these models, LSS and Sn data
 - BAO + uncalibrated SNe already reconstruct the low-(z) distance ladder.
- If (r_d) is unchanged, raising (H_0) requires a sharp/exotic feature in ($H(z)$) or in SN calibration.

wCDM model



Cosmoverse, 2024

Early time solutions to the *Hubble tension*



ΛCDM

EDE

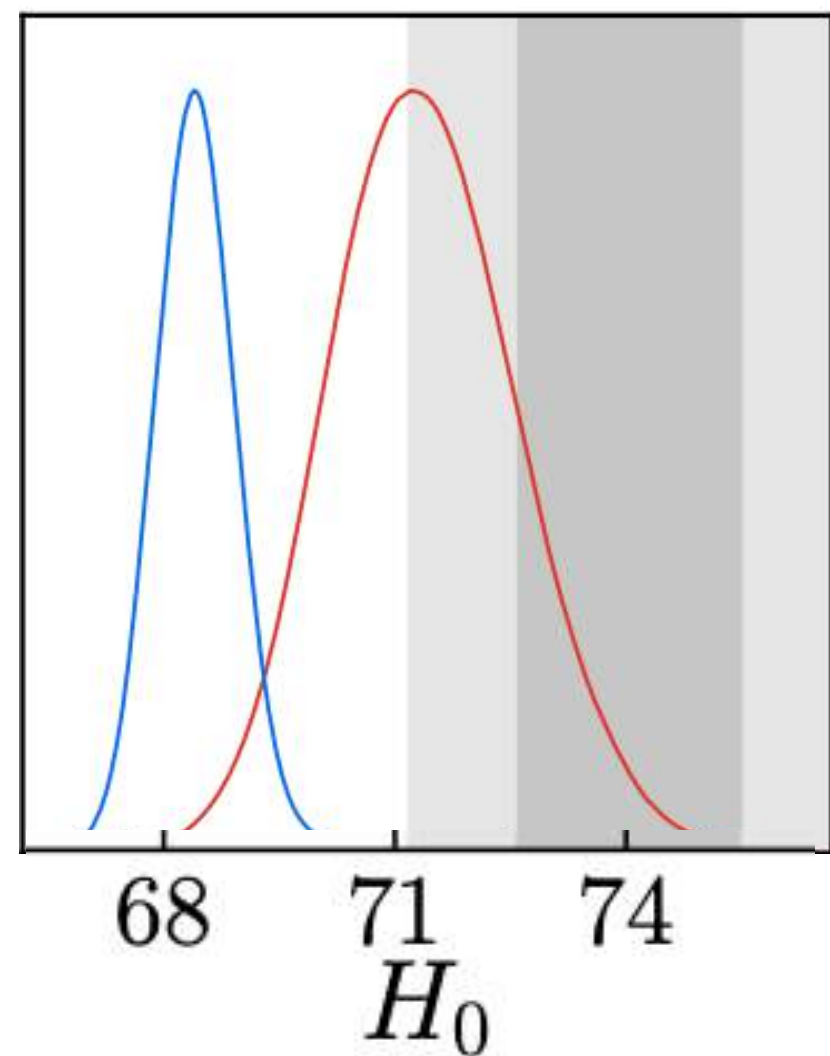
$\theta_s(z_*)$: decrease $r_s(z_*) \implies$ decreases $D_A(z_*) \implies$ Increases H_0
Fixed

$$r_s(z_*) = \int_{z_*}^{\infty} \frac{dz}{H(z)} c_s(t)$$

- Sound horizon at last scattering dominated by contributions near the lower bound of the integral
- Sensitive to $H(z)$ at times shortly after recombination

$\implies$ If we **decrease r_s by 10 Mpc** (keeping r_s/r_d and r_s/r_{eq} fixed) we can *solve the H_0 tension*

Early time solutions to the *Hubble tension*



ΛCDM

EDE

$\theta_s(z_*)$: decrease $r_s(z_*) \implies$ decreases $D_A(z_*) \implies$ Increases H_0
Fixed

$\implies$ If we **decrease r_s by 10 Mpc** (keeping r_s/r_d and r_s/r_{eq} fixed) we can *solve the H_0 tension*

Many ideas on how to do this:

$$r_s(z_*) = \int_{z_*}^{\infty} \frac{dz}{H(z)} c_s(t)$$

Change $H(z)$: increasing $H(z)$ before recombination with additional components

- Light Relics
- Early Dark Energy (*Karwal+ 2016, ...*)

Change z_* : change recombination physics - primordial B (*Jedamzik + 2020*); change m_e or m_e, Ω_k (*Sekiguchi+ 2020*)

Change c_s (*e.g. Boddy + 2018*)

The H_0 Olympics

Schöneberg, 2107.10291



See also the Hubble Hunter's guide, Mile+Knox, 2019

The H_0 Olympics

Contestants - finalists



Varying electron mass (m_e)



Varying electron mass and curvature ($m_e + \Omega_k$)



Early dark energy



New Early dark energy



Primordial magnetic field



Self interacting dark radiation



Early Modified Gravity model



Majoron

Rules

To reach the podium, a model must pass three events:

1. The SH0ES event

Reduce the local-vs-CMB tension to an acceptable level. ladder?

→ residual tension below ($\sim 3\sigma$)

2. Data marathon event

Fit CMB + BAO + SNe + LSS without creating new tensions.

→ no large degradation of the global fit

3. The elegance event (Pay the parameter tax)

Is the improvement large enough to justify the extra parameters?

Gold medal: passes all three.

Silver/Bronze: improves some events, but not others.

The H_0 Olympics

Schöneberg, 2107.10291



Model ranking

Gold: (Varying m_e and $m_e + \Omega_k$)

Best overall balance: tension reduced below (2σ) in both GT and DMAP, with strong statistical preference over LCDM.

Silver: Early Dark Energy, new early DE (and EMG)

Strong global-fit improvement and ($<2\sigma$) DMAP, but still under pressure from the Gaussian tension criterion.

Bronze: Primordial magnetic fields

Better than LCDM in model comparison, but not enough to remove the tension: GT/DMAP remain ($>3\sigma$).

Close contenders: Majoron and SIDR

Mild improvement only, with residual tension at roughly (3σ).

See also the Hubble Hunter's guide, Mile+Knox, 2019

The H_0 Olympics

Model	ΔN_{param}	M_B	Gaussian Tension	Q_{DMAP} Tension		$\Delta\chi^2$	ΔAIC		Finalist
ΛCDM	0	-19.416 ± 0.012	4.4σ	4.5σ	$\textcolor{red}{X}$	0.00	0.00	$\textcolor{red}{X}$	$\textcolor{red}{X}$
ΔN_{ur}	1	-19.395 ± 0.019	3.6σ	3.8σ	$\textcolor{red}{X}$	-6.10	-4.10	$\textcolor{red}{X}$	$\textcolor{red}{X}$
SIDR	1	-19.385 ± 0.024	3.2σ	3.3σ	$\textcolor{red}{X}$	-9.57	-7.57	✓	✓ 
mixed DR	2	-19.413 ± 0.036	3.3σ	3.4σ	$\textcolor{red}{X}$	-8.83	-4.83	$\textcolor{red}{X}$	$\textcolor{red}{X}$
DR-DM	2	-19.388 ± 0.026	3.2σ	3.1σ	$\textcolor{red}{X}$	-8.92	-4.92	$\textcolor{red}{X}$	$\textcolor{red}{X}$
SI ν +DR	3	$-19.440^{+0.037}_{-0.039}$	3.8σ	3.9σ	$\textcolor{red}{X}$	-4.98	1.02	$\textcolor{red}{X}$	$\textcolor{red}{X}$
Majoron	3	$-19.380^{+0.027}_{-0.021}$	3.0σ	2.9σ	✓	-15.49	-9.49	✓	✓ 
primordial B	1	$-19.390^{+0.018}_{-0.024}$	3.5σ	3.5σ	$\textcolor{red}{X}$	-11.42	-9.42	✓	✓ 
varying m_e	1	-19.391 ± 0.034	2.9σ	2.9σ	✓	-12.27	-10.27	✓	✓ 
varying $m_e + \Omega_k$	2	-19.368 ± 0.048	2.0σ	1.9σ	✓	-17.26	-13.26	✓	✓ 
EDE	3	$-19.390^{+0.016}_{-0.035}$	3.6σ	1.6σ	✓	-21.98	-15.98	✓	✓ 
NEDE	3	$-19.380^{+0.023}_{-0.040}$	3.1σ	1.9σ	✓	-18.93	-12.93	✓	✓ 
EMG	3	$-19.397^{+0.017}_{-0.023}$	3.7σ	2.3σ	✓	-18.56	-12.56	✓	✓ 
CPL	2	-19.400 ± 0.020	3.7σ	4.1σ	$\textcolor{red}{X}$	-4.94	-0.94	$\textcolor{red}{X}$	$\textcolor{red}{X}$
PEDE	0	-19.349 ± 0.013	2.7σ	2.8σ	✓	2.24	2.24	$\textcolor{red}{X}$	$\textcolor{red}{X}$
GPEDE	1	-19.400 ± 0.022	3.6σ	4.6σ	$\textcolor{red}{X}$	-0.45	1.55	$\textcolor{red}{X}$	$\textcolor{red}{X}$
DM $\rightarrow$ DR+WDM	2	-19.420 ± 0.012	4.5σ	4.5σ	$\textcolor{red}{X}$	-0.19	3.81	$\textcolor{red}{X}$	$\textcolor{red}{X}$
DM $\rightarrow$ DR	2	-19.410 ± 0.011	4.3σ	4.5σ	$\textcolor{red}{X}$	-0.53	3.47	$\textcolor{red}{X}$	$\textcolor{red}{X}$

Table 1: Test of the models based on dataset $\mathcal{D}_{\text{baseline}}$ (Planck 2018 + BAO + Pantheon), using the direct measurement of M_b by SH0ES for the quantification of the tension (3rd column) or the computation of the AIC (5th column). Eight models pass at least one of these three tests at the 3σ level.

the H_0 tension

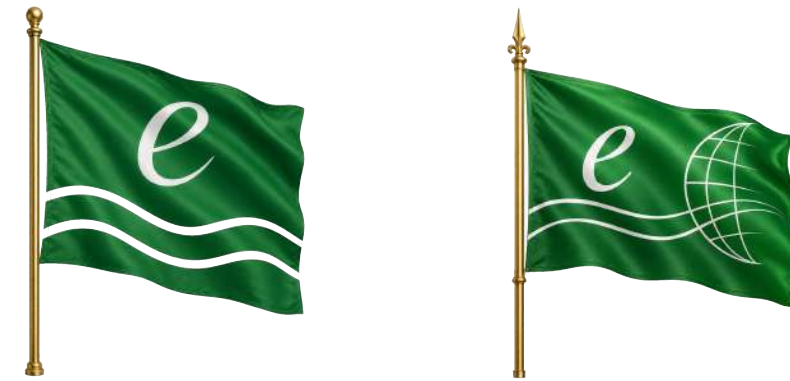
models

Early time solutions to the *Hubble tension*

$$r_s(z_*) = \int_{z_*}^{\infty} \frac{dz}{H(z)} c_s(t)$$

Change z_*

Change m_e or m_e, Ω_k (Sekiguchi+ 2020)



A variation of the fundamental properties of the hydrogen/helium atom, such as the electron mass or the fine structure constant, is one of the most effective ways to shift the time of recombination in the early Universe.

Shifting the energy gap between successive excitation levels one directly changes the temperature at which photo-dissociation of hydrogen/helium becomes inefficient - change of fundamental parameters $\sim$ **change in z_***



phenomenologically parameterize the impact of light species in such models - specify the spacetime dependence of each parameter

$$\delta m_e \equiv \frac{m_e^{\text{early}}(z)}{\text{locally observed } m_{e,\text{late}}} - 1$$

Change in fundamental parameters - **change in z_***
Reduces the sound horizon at recombination.
Can alleviate the H0 tension!

Early time solutions to the *Hubble tension*

$$r_s(z_*) = \int_{z_*}^{\infty} \frac{dz}{H(z)} c_s(t)$$

Change z_*

Change recombination physics



Primordial B (*Jedamzik + 2020*)

Primordial magnetic fields (PMFs) in the plasma before recombination: induce small-scale, mildly non-linear inhomogeneities in the baryon density

Scales much smaller than the photon mean free path the effective speed of sound is far lower than that of a relativistic plasma

- PMFs of ~ 0.1 nano-Gauss (nG) strength can generate baryon inhomogeneities on $\sim$ kpc scales

Do not directly source CMB temperature and polarization anisotropies



recombination rate (electron density), the mean free electron fraction modified in the presence of an inhomogeneous plasma

Modifying the ionization history of the Universe

This type of clumpy plasma recombines earlier, and thus reduces the sound horizon at recombination.

Can alleviate the H_0 tension!

Early time solutions to the *Hubble tension*

$$r_s(z_*) = \int_{z_*}^{\infty} \frac{dz}{H(z)} c_s(t)$$

Change c_s (e.g. Boddy + 2018)

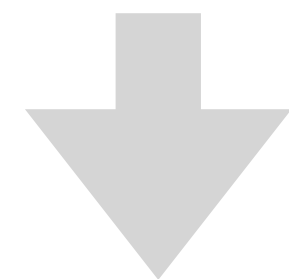
The adiabatic sound speed is related to the baryon/photon plasma density and pressure $c_s^2 = \partial P / \partial \rho$

Inertia of the baryons reduces the pressure from the pure relativistic gas case $P = \frac{\rho}{3} \longrightarrow P = \frac{\rho}{3(1+R)}, R = \frac{3\rho_b}{4\rho_\gamma}$

IF:

The sound speed could potentially be reduced further by introduction of a new non-relativistic species tightly coupled either to the photons or to the baryons, species x

$$\implies R = \frac{3(\rho_b + \rho_x)}{4\rho_\gamma}$$



$$\downarrow c_s \longrightarrow \downarrow r_s$$

BUT: if c_s changes, we already have its influence included in to our estimate of the sound speed from CMB data
 $\Rightarrow$ less than 0.4% to be consistent with the 2015 Planck temperature, polarization, and lensing data

Early time solutions to the *Hubble tension*

$$r_s(z_*) = \int_{z_*}^{\infty} \frac{dz}{H(z)} c_s(t)$$

Change $H(z)$:

Increasing $H(z)$ before recombination with additional components; **energy injection** before recombination

Many ways of doing this!!!



*The H_0 Olympics: A fair ranking
of proposed models,
Schöneberg + (2021)*

	ΔN_p	
Majoron	3	2
primordial B	1	3
varying m_e	1	1
varying $m_e + \Omega_k$	2	1
EDE	3	2
NEDE	3	2
EMG	3	2

Early dark energy

Based on Laura Herold, EF 2210.1629

& Laura Herold, EF and Eiichiro Komatsu 2112.12140,

& A. Reeves, L. Herold, S. Vagnozzi, B. Sherwin, EF 2207.01501

Early dark energy

Idea: add an extra component (to increase $H(z)$) that starts acting around equality, behaves as DE and dilutes faster than matter

↓
 ϕ_i

↓
Initially frozen
Slow-rolls

Early dark energy

Idea: add an extra component (to increase $H(z)$) that starts **acting around equality**, behaves as **DE** and **dilutes faster than matter**

$$V(\phi) = V_0 [1 - \cos(\phi/f)]^n$$

3 free parameters: $\{m, f, n\}$ + IC: ϕ_i

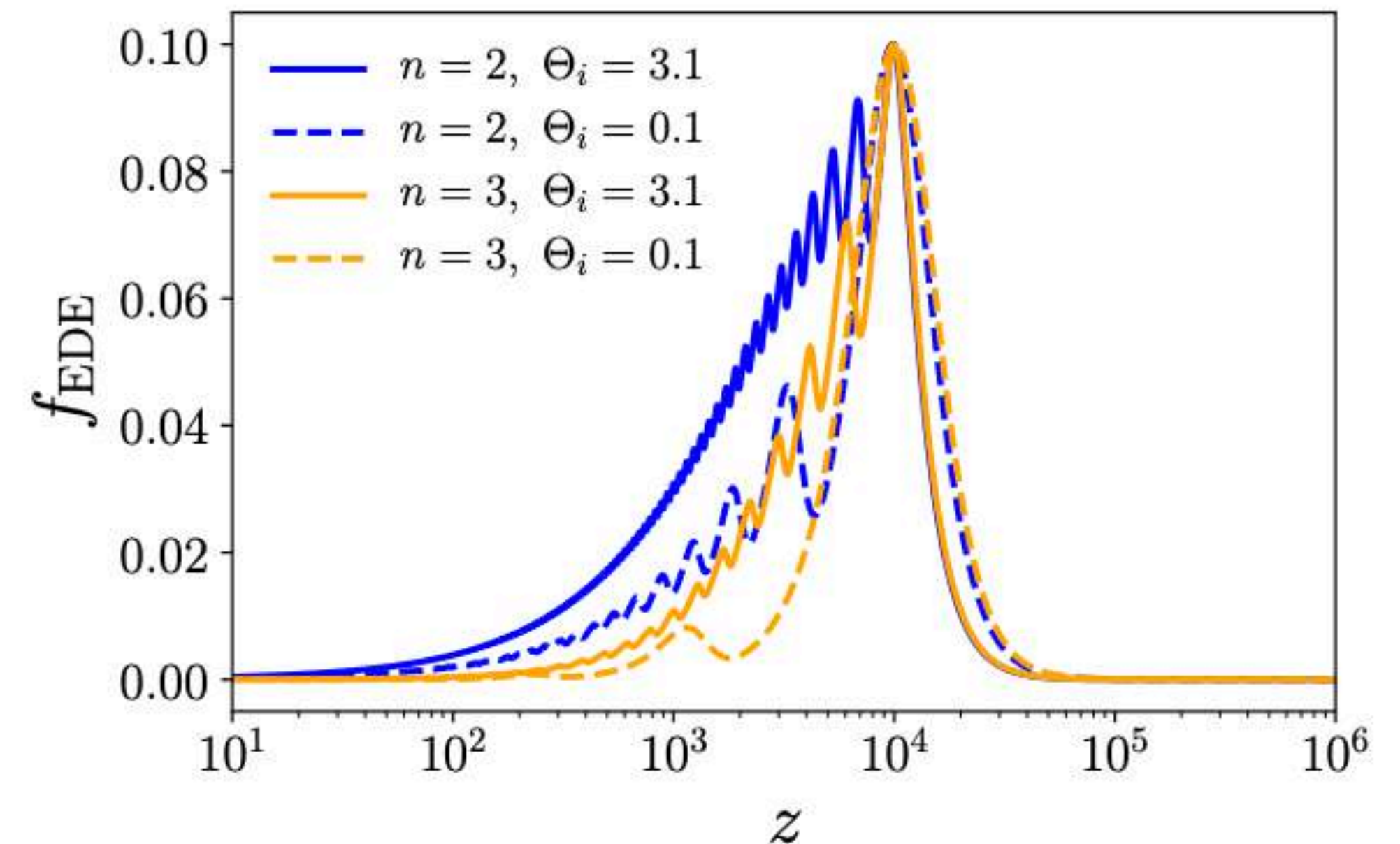
- V_0 or m ($V_0 = m^2 f^2$): the field is ultra-light $m \sim H(z_{eq}) \sim 10^{-27}$ eV
- f (spont. sym. breaking scale)
- n : controls the decay $\rightarrow$ needs to be hidden at late times

$$n \geq 2 \quad (w \geq 1/3)$$

Phenomenological parameters $\{f_{\text{EDE}}(z_c), z_c, n, \theta_i = \phi_i/f\}$

$$f_{\text{EDE}}(z_c) \equiv \frac{\rho_{\text{EDE}}}{\rho_{\text{tot}}} \Big|_{z_c} = \frac{\rho_{\text{EDE}}}{(3M_{\text{pl}}^2 H^2)} \Big|_{z_c}$$

Smith et al 2019



We usually fix $n = 3$

$\Rightarrow \{f_{\text{EDE}}(z_c), z_c, \theta_i\}$

*Early dark **energy***

Does EDE really solves the H_0 tension?

2019

Early dark energy can resolve the *Hubble tension*

EDE from CMB

V. Poulin, T. Smith, T. Karwal,
M. Kamionkowski, 2019

- For: *Planck* + *BOSS DR12 BAO/RSD* + *6dFGS* + *Pantheon*
+ *SHOES 2016*

$$H_0 = 71.49 \pm 1.20 \text{ km/s/Mpc}$$

Solves the tension!

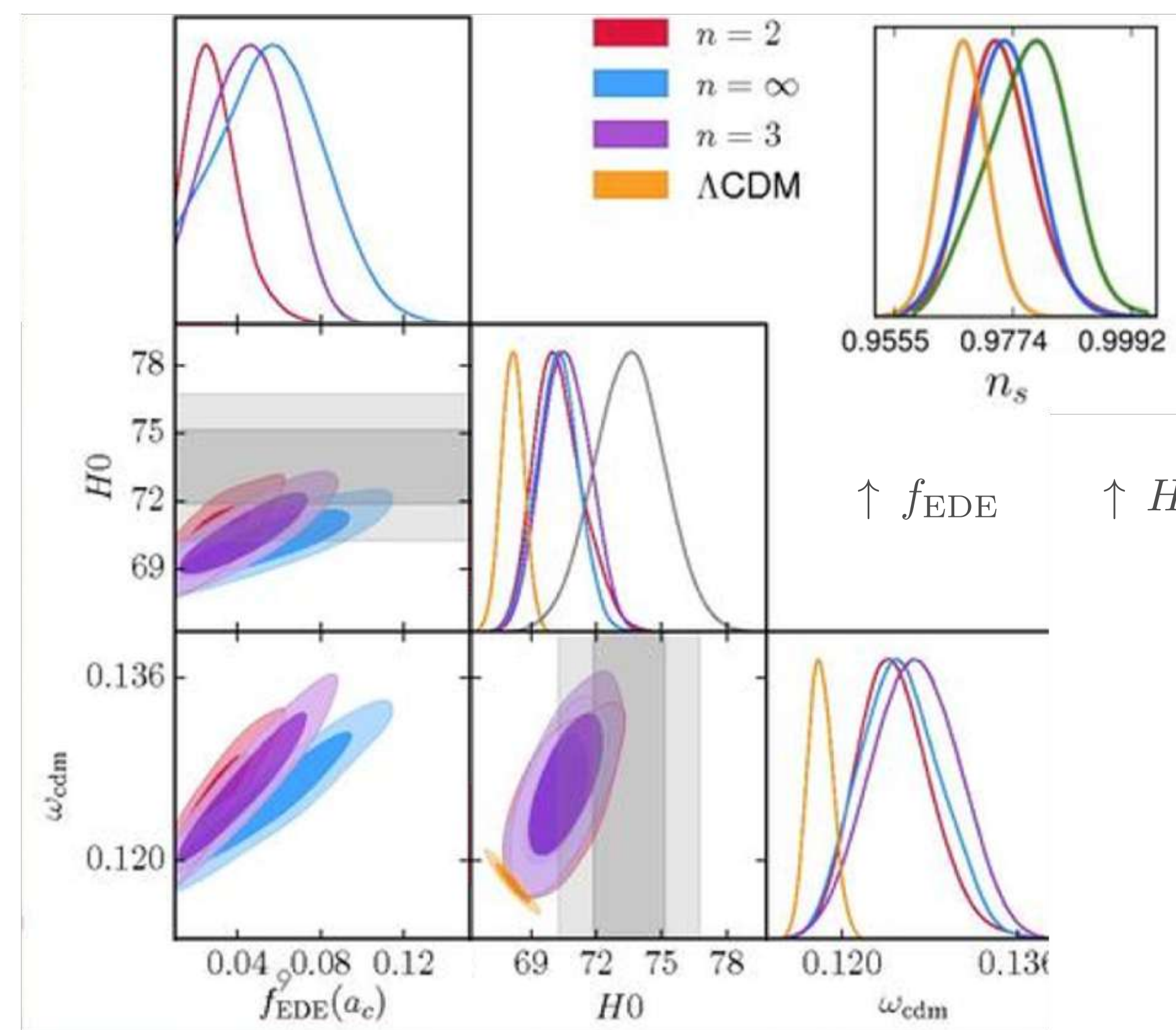
$\uparrow f_{\text{EDE}}$

$\uparrow H_0$

But with:

- More DM

- Higher n_s



$$w_{\text{cdm}} = \Omega_{\text{cdm}} h^2$$

Early dark energy does NOT restore cosmological concordance

EDE from LSS

2020

Use LSS to constrain EDE

- CMB: *Planck* 2018 TT, TE, EE
- LSS
 - *Planck* lensing
 - “Compressed” likelihood
 - BAO
 - Weak lensing from KIDS+VIKING-450 + HSC
- FULL SHAPE OF THE PS

Early Dark Energy Does Not Restore Cosmological Concordance

J. COLIN HILL,^{1,2} EVAN McDONOUGH,³ MICHAEL W. TOOMEY,⁴ AND STEPHON ALEXANDER³

Constraining Early Dark Energy with Large-Scale Structure

Mikhail M. Ivanov,^{1,2} Evan McDonough,³ J. Colin Hill,^{4,5} Marko Simonović,⁶
Michael W. Toomey,⁷ Stephon Alexander,⁷ and Matias Zaldarriaga⁸

Uniform prior in the phenomenological parameters

$$f_{\text{EDE}}, z_c, \theta_i$$

Early dark energy does NOT restore *cosmological concordance*

EDE from LSS

- For: *Planck* + *BOSS DR12 BAO/RSD* + ~~*SHOES 2016*~~ + *full-shape of PS*

Constraints from *Planck* 2018 data + BOSS DR12

Parameter	Λ CDM	EDE ($n = 3$)
f_{EDE}	—	< 0.072 (0.047)
H_0 [km/s/Mpc]	67.70 (67.56) ± 0.42	68.54 (68.83) $^{+0.52}_{-0.95}$
Ω_m	0.3105 (0.3112) $^{+0.0053}_{-0.0058}$	0.3082 (0.3120) $^{+0.0056}_{-0.0057}$

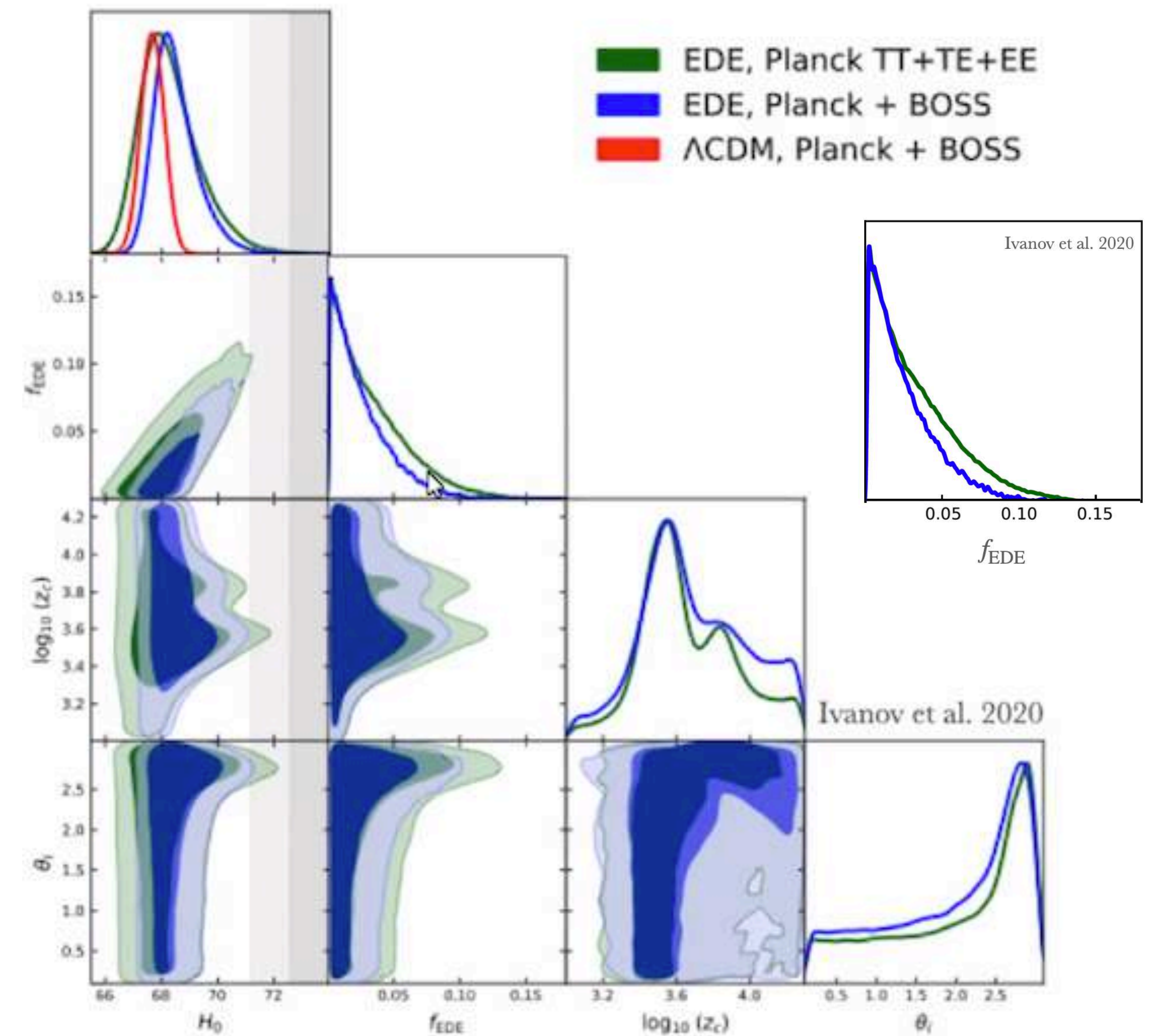
$$H_0 = 68.54^{+0.52}_{-0.95} \text{ km/s/Mpc}$$

$$f_{\text{EDE}} < 0.072 \text{ (95 \% CL)}$$

3.6 σ tension with SHOES !!

Adding S_8 prior $\longrightarrow f_{\text{EDE}} < 0.058$

Early dark energy does NOT solve **Hubble tension**!



Wait...

Not all groups agree with this result

Volume effects?

- Previous result can be a consequence of choice of priors of the EDE parameters

Volume effects: $f_{\text{EDE}} \rightarrow 0$, any value of $\log(z_c)$ and θ_i , degenerate with ΛCDM



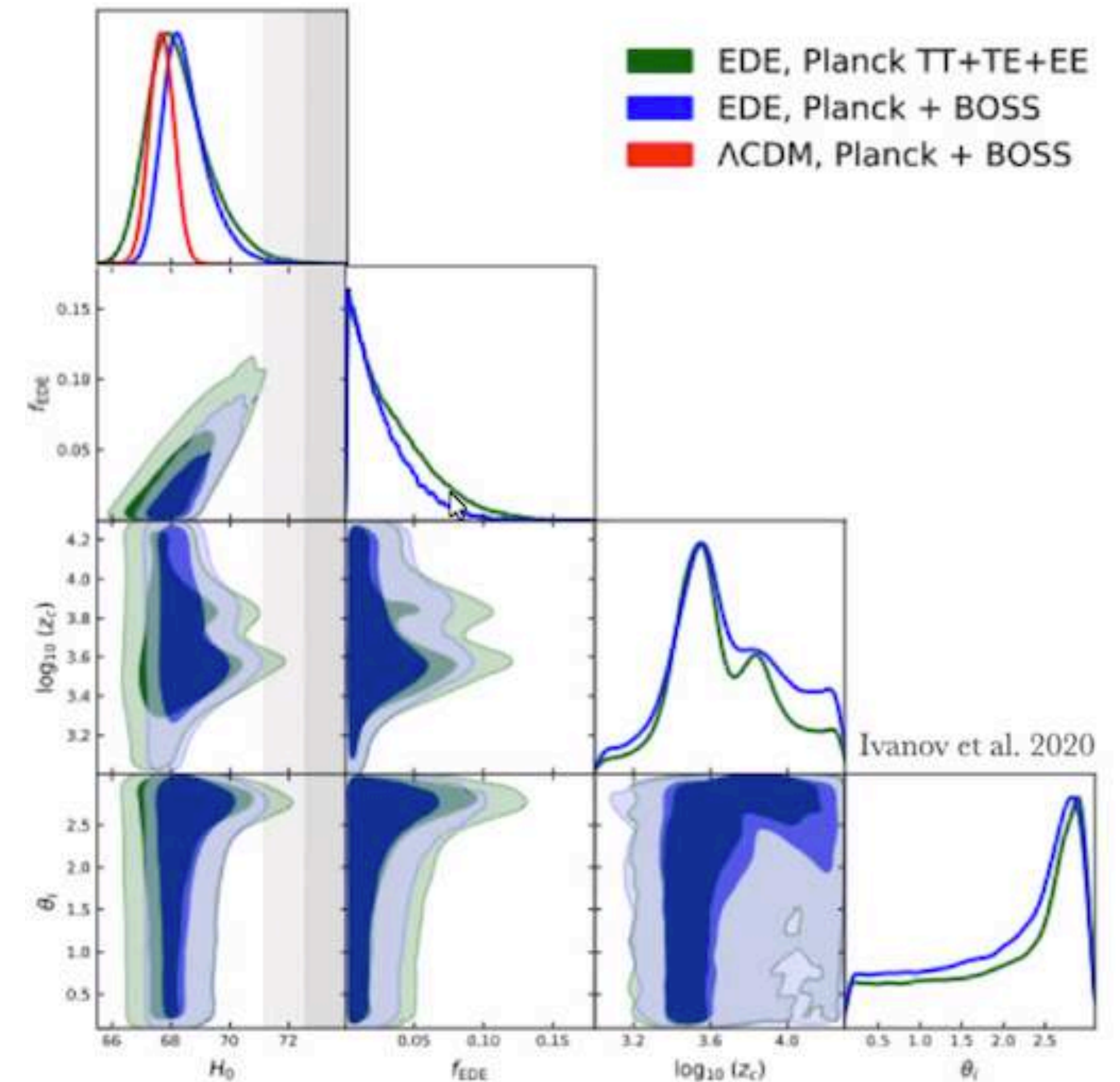
Marginalization: preference for $f_{\text{EDE}} \sim 0$

- $\log(z_c)$ and θ_i are not well constrained by data

Early dark energy is **NOT** excluded by current LSS data

T. Smith et al (2020)

Niedermann, Sloth (2019)



Prior volume effects

Bayesian marginalization of the full-dimensional posterior involves integrating out the nuisance dimensions and other cosmological parameters

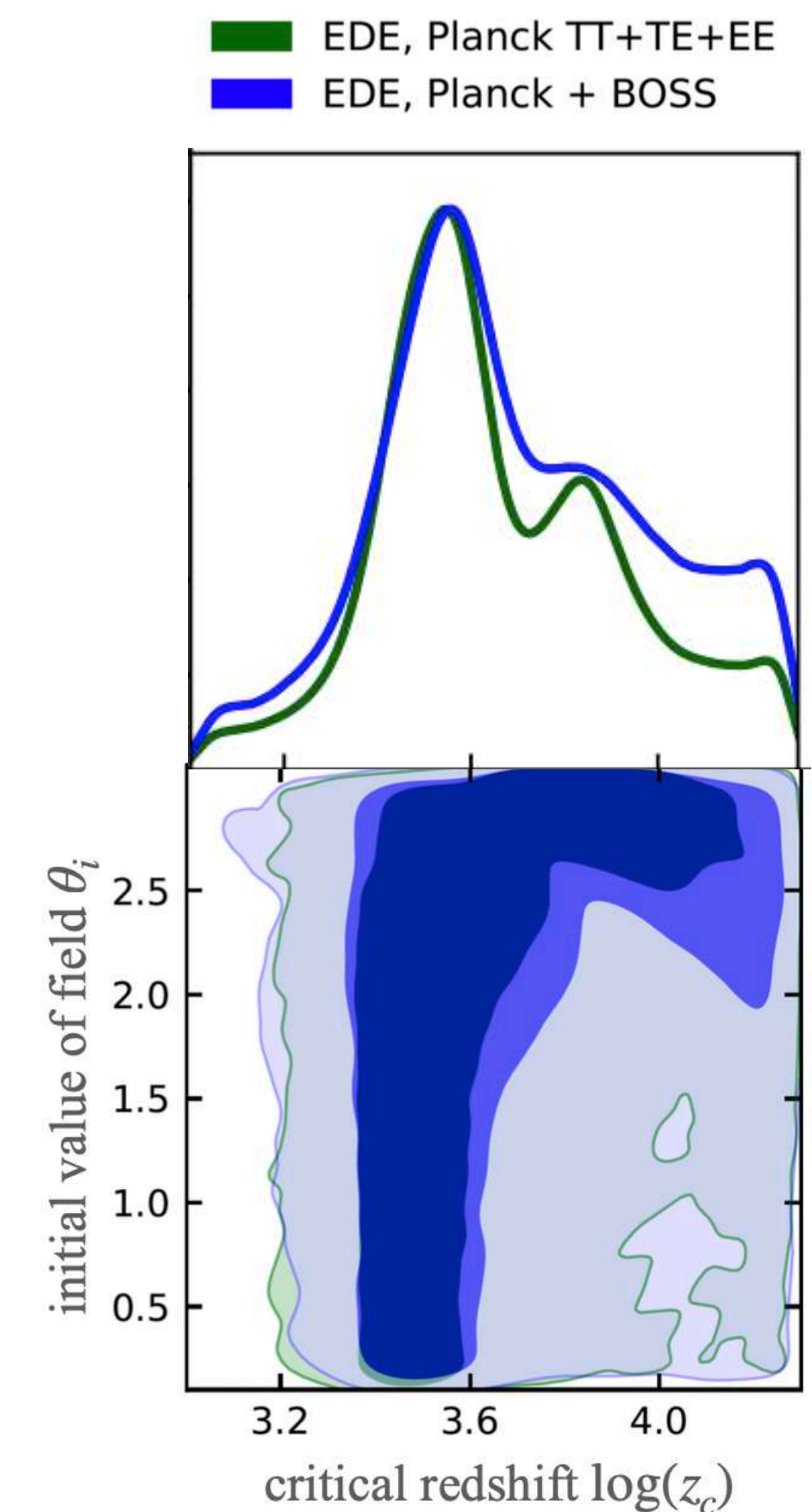
Since in addition to the value of the posterior, an integral is sensitive to the prior volume

→ **Large parameter regions** (of possibly non-maximal posterior values) are emphasized compared to **smaller regions** (of possibly larger posterior values).

Inescapable feature of the Bayesian method!!

(volume effect can occur even with flat priors)

And if this is true, does it bias the parameter so much that we don't know if the Hubble tension is solved or not by EDE.



Ivanov et al. 2020

Prior volume *effects*

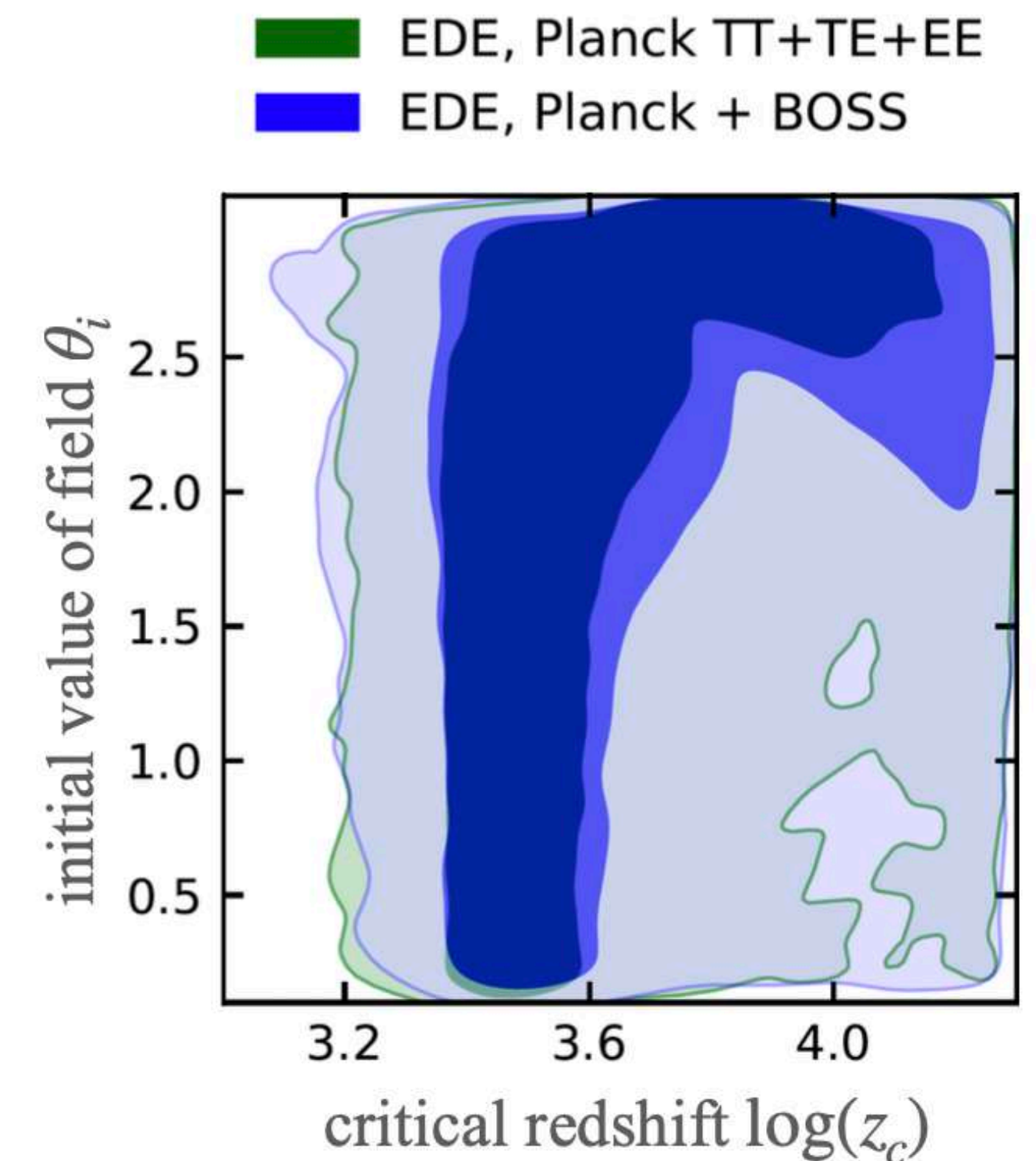
Prior volume effects or marginalization effects: ...appear if the posterior is dominated by the prior volume

When they appear:

- Model has too many parameters / data is not constraining.
- Posterior is very non-Gaussian.
- Parameter structure of the model generates large volume differences.

Leads to:

- **Bias/shifts** in the marginalized posterior
- Inefficiencies in sampling
- Incorrect assessment of the effect of errors, such as systematic errors

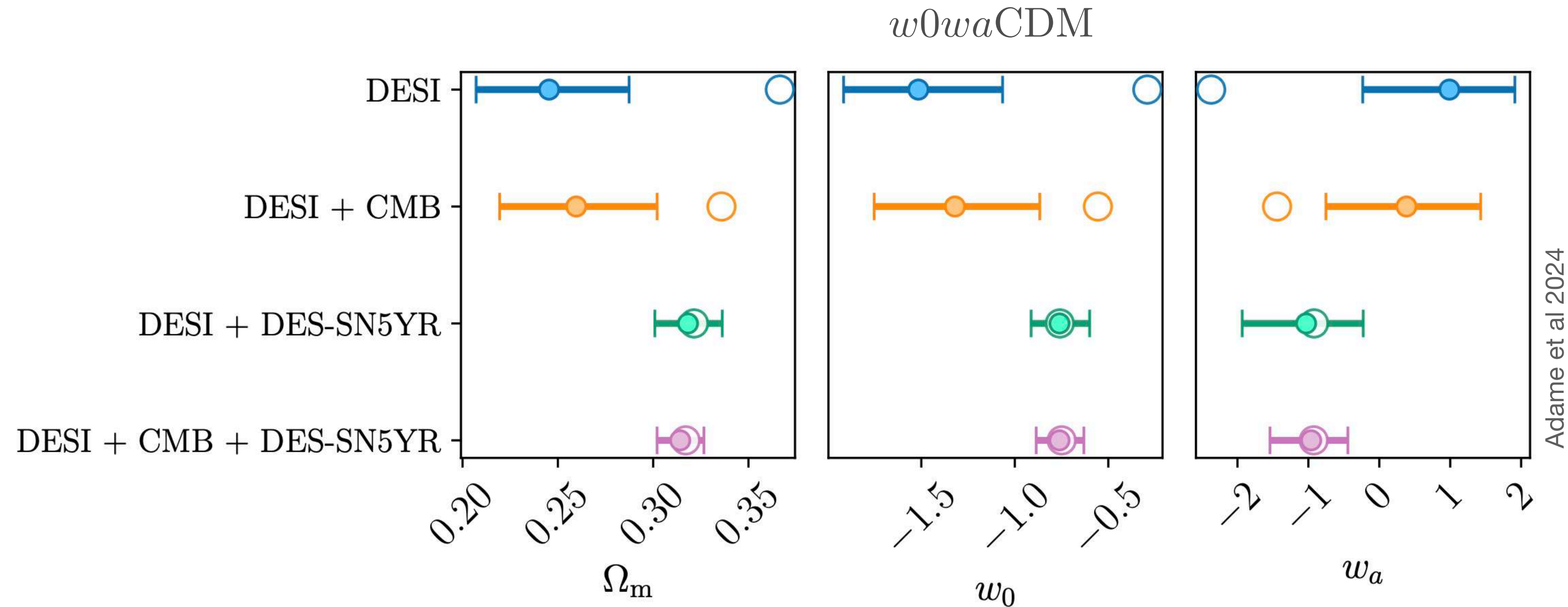


Elisa Ferreira to appear

Ivanov et al. 2020

Important to understand to what extent the results are affected by volume effects!

DESI DR1 full shape analysis



Solid horizontal lines: 95% marginalised posteriors, $\bullet$: mean

$\bigcirc$: MAP (maxima of the corresponding posteriors)

DESI collaboration *doesn't even quote* the DESI and DESI+CMB values since this result is dominated by prior volume effects!

Bayesian and frequentist

Bayesian statistics

Bayesian inference: derive the posterior probability as a consequence of two antecedents: a prior probability and a "likelihood function" derived from a statistical model for the observed data.

$$\text{Posterior } P(H | E) = \frac{\text{Likelihood } P(E | H) \cdot \text{Prior } P(H)}{P(E)}$$

H: hypothesis
E: evidence

- **Likelihood**: probability of observing E *given* H
- **Prior**: Probability of H *before* E is observed
- **Posterior**: probability of H *given* E, i.e., *after* E is observed. Probability of a hypothesis *given* the observed evidence.

Frequentist approach

$$\mathcal{L}(x|\theta)$$

data model
 parameters

Frequentist statistics never uses or calculates the probability of the hypothesis, while Bayesian uses probabilities of data and probabilities of both hypothesis.

Frequentist methods do not demand construction of a prior and depend on the probabilities of observed and unobserved data.

Profile *likelihood*

Profile Likelihoods in Cosmology: When, Why and How
illustrated with Λ CDM, Massive Neutrinos and Dark Energy,
L. Herold, **EF**, L. Heinrich

Motivation:

Frequentist method for comparison with Bayesian to check for prior or marginalization effects

What is the profile likelihood $\chi^2(\theta)$?

- **Fix** the parameters of interested θ to different values
- **Maximize** the likelihood L (**minimize** $\chi^2 = -2 \ln L$) wrt to the other parameters for different values of the parameter of interest
- For **Gaussian** distribution this gives a **parabola** $\rightarrow$ fit a parabola

Confidence interval:

- A confidence region, can be extracted from the likelihood ratio statistic:

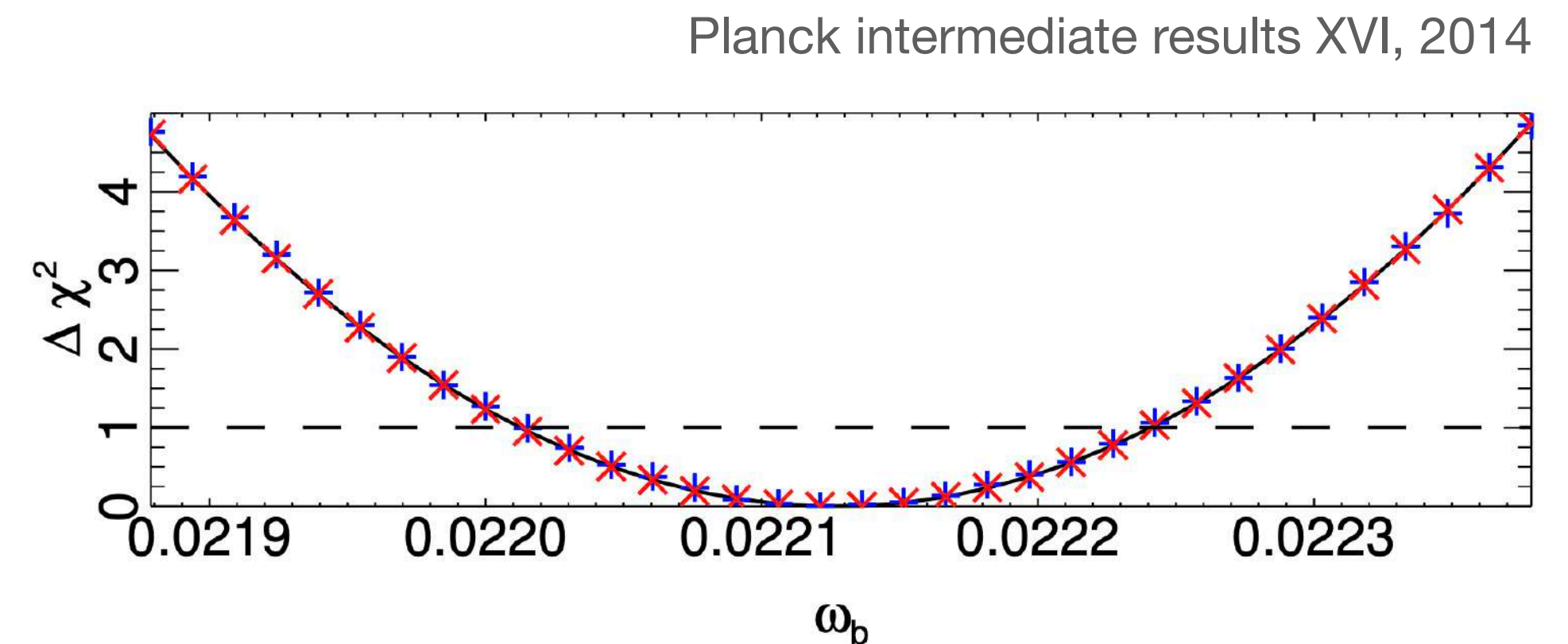
$$\Delta\chi^2(\theta) = \chi^2(\theta) - \chi_{\min}^2 = -2 \ln(\mathcal{L}/\mathcal{L}_{\max})$$

- For parabolic $\chi^2(\theta)$, and one dof, the c.i. is given by:

$$\Delta\chi^2 = 1, 2.7, 3.84 \text{ for } 68, 90 \text{ and } 95\%, \text{ respectively} \longrightarrow \text{Graphical profile likelihood method}$$

(Only valid in the asymptotic limit)

$\chi_{\min}^2$ is obtained from global maximum likelihood estimate given the entire set of parameters



Profile likelihood

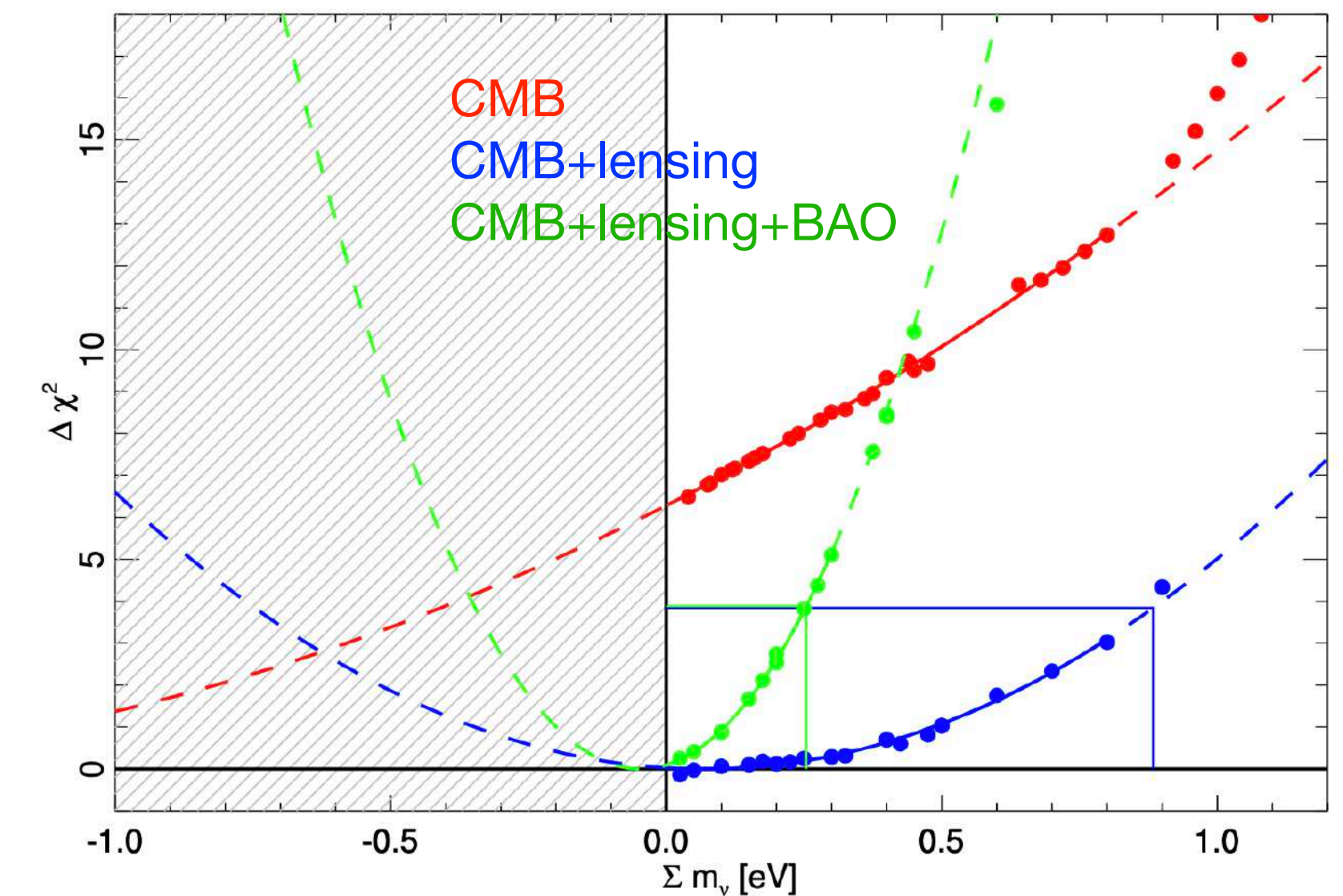
Profile Likelihoods in Cosmology: When, Why and How illustrated with Λ CDM, Massive Neutrinos and Dark Energy,
L. Herold, EF, L. Heinrich

Advantages:

- Not affected by **volume effects** (no priors)
- Invariant under reparametrizations (since $L(\theta)$ is a MLE)
- Allows construction of confidence intervals close to boundaries

Disadvantages:

- Computationally expensive
- When can be used $\rightarrow$ asymptotic limit
- Insensitive to parameter volume; prefer cosmology small parameters volume ("fine tuning")



Planck intermediate results XVI, 2014

*Going back to our case of **EDE** and the H_0 tension...*

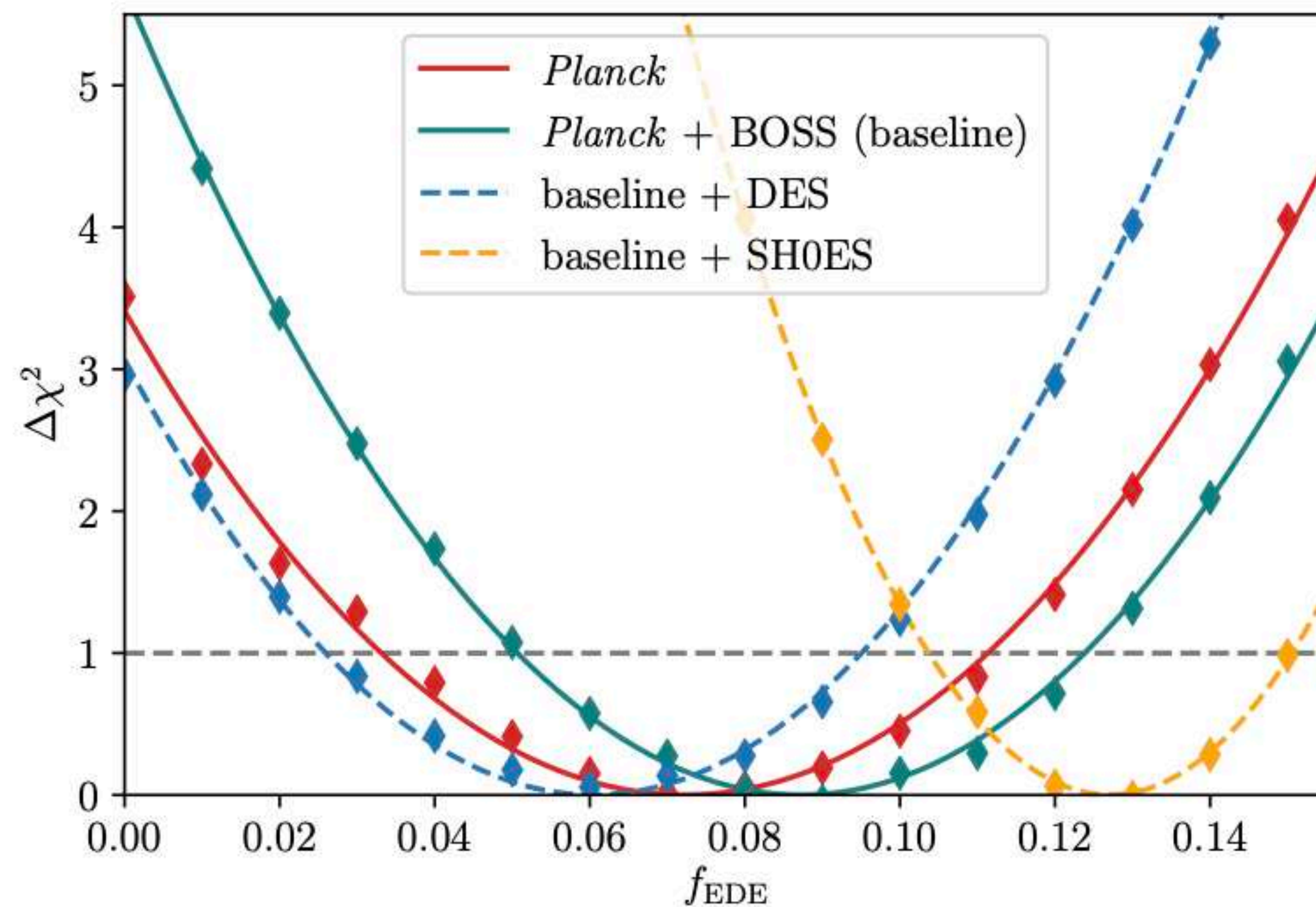
YES

Profile likelihood *for* f_{EDE}

Check for *volume effects*:
comparison to previous results

Bayesian result:

$$f_{\text{EDE}} < 0.072 \quad (95\%CL)$$

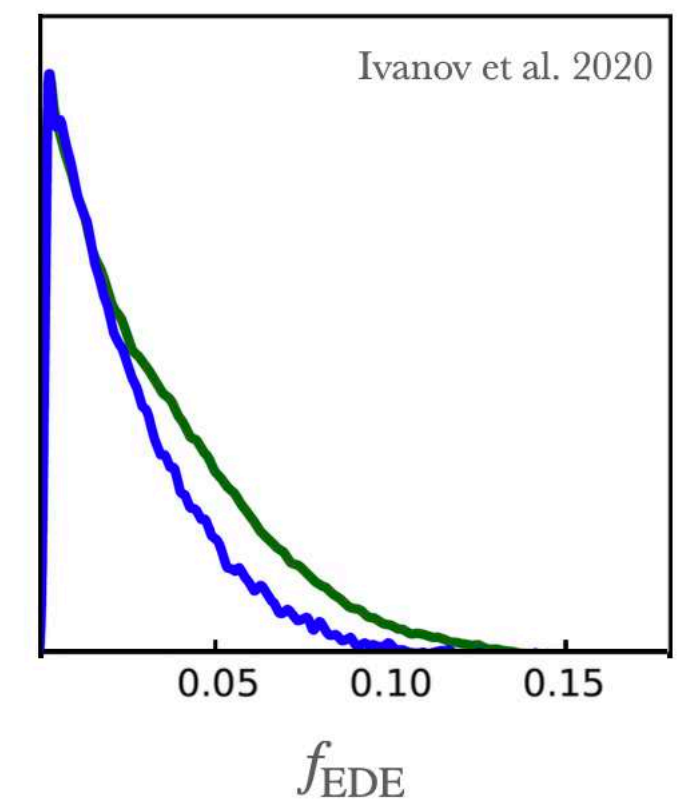


$$f_{\text{EDE}}^{(\text{base})} = 0.087 \pm 0.037$$

(68%CL)

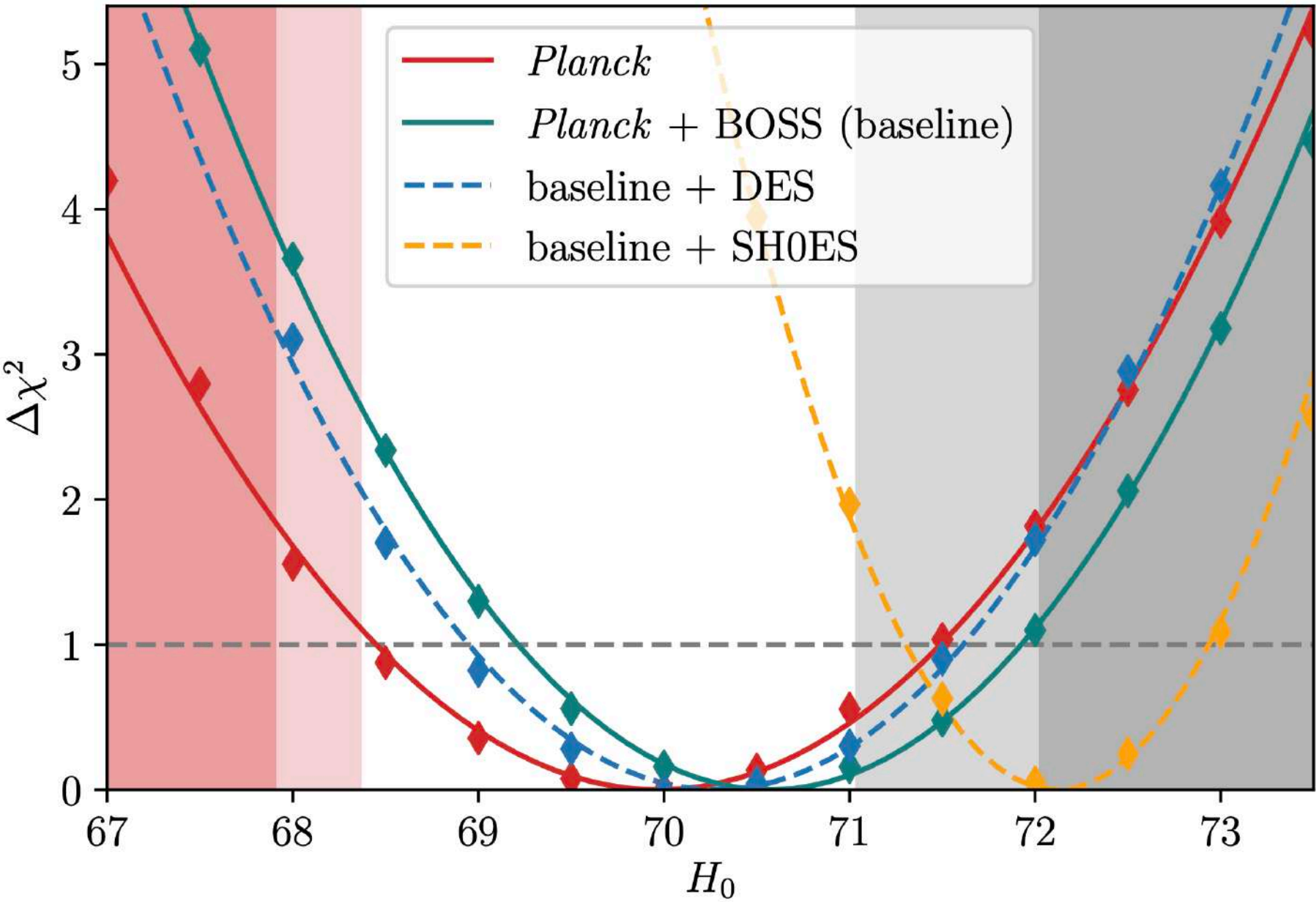
Baseline: Planck+BOSS FS

EDE, Planck TT+TE+EE
EDE, Planck + BOSS



Profile likelihood for H_0

Baseline: Planck+BOSS FS



PL analysis: could show that there indeed is was a prior volume effect in the MCMC analysis.

$$H_0^{\text{EDE},(\text{base})} = 70.57 \pm 1.36$$

(68%CL)

Data set	$\chi^2(\Lambda\text{CDM})$	$\chi^2(\text{EDE})$	$\Delta\chi^2$	f_{EDE}	H_0 (consistency w. SH0ES)
Planck	2774.24	2770.72	-3.52	0.072 ± 0.039	69.97 ± 1.52 (1.7σ)
Planck+BOSS (base)	3045.65	3039.98	-5.67	0.087 ± 0.037	70.57 ± 1.36 (1.4σ)
Baseline + DES	3052.06	3049.13	-2.93	$0.061^{+0.035}_{-0.034}$	70.28 ± 1.33 (1.6σ)
Baseline + SH0ES	3068.44	3042.08	-26.36	0.127 ± 0.023	72.12 ± 0.82 (0.69σ)

Consistent with SHOES at $< 1.4\sigma$!

No H_0 tension with EDE
(For this dataset)

Solve the confusion in the field and proposed new method

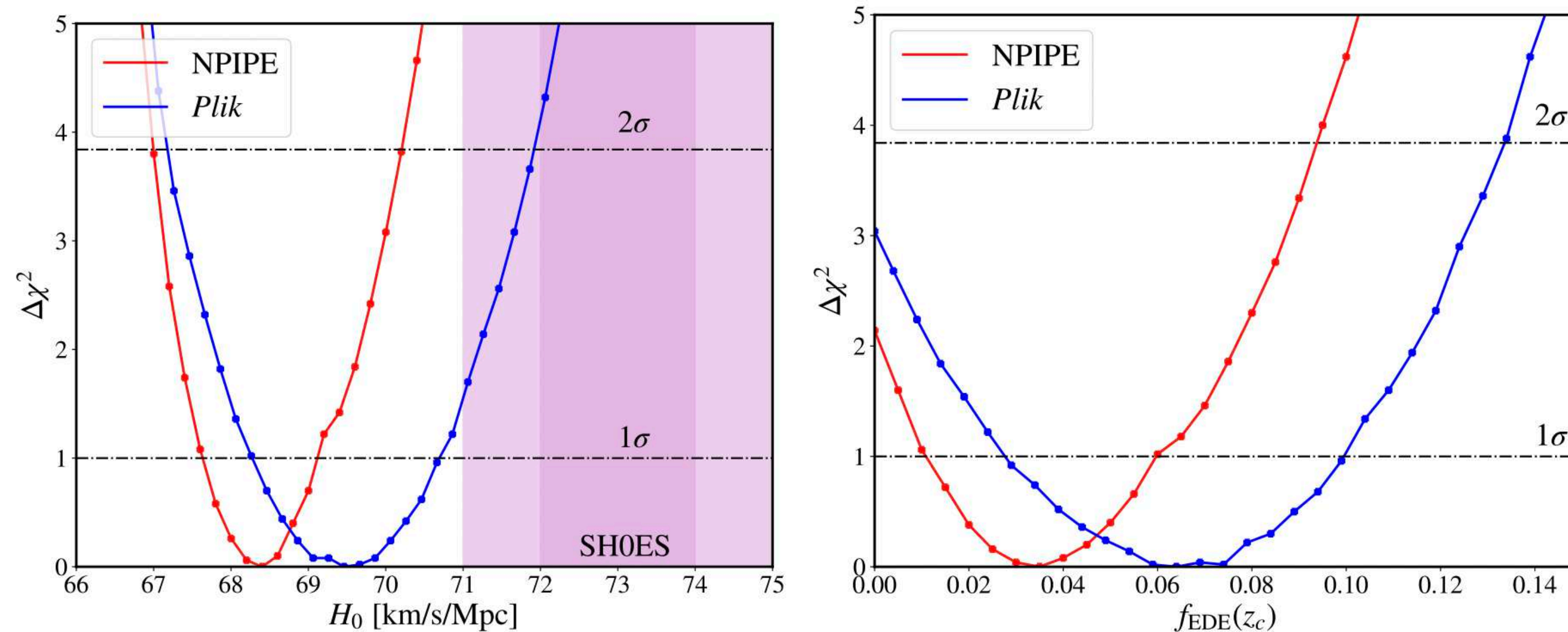
NO

Early dark energy - *reanalysis*

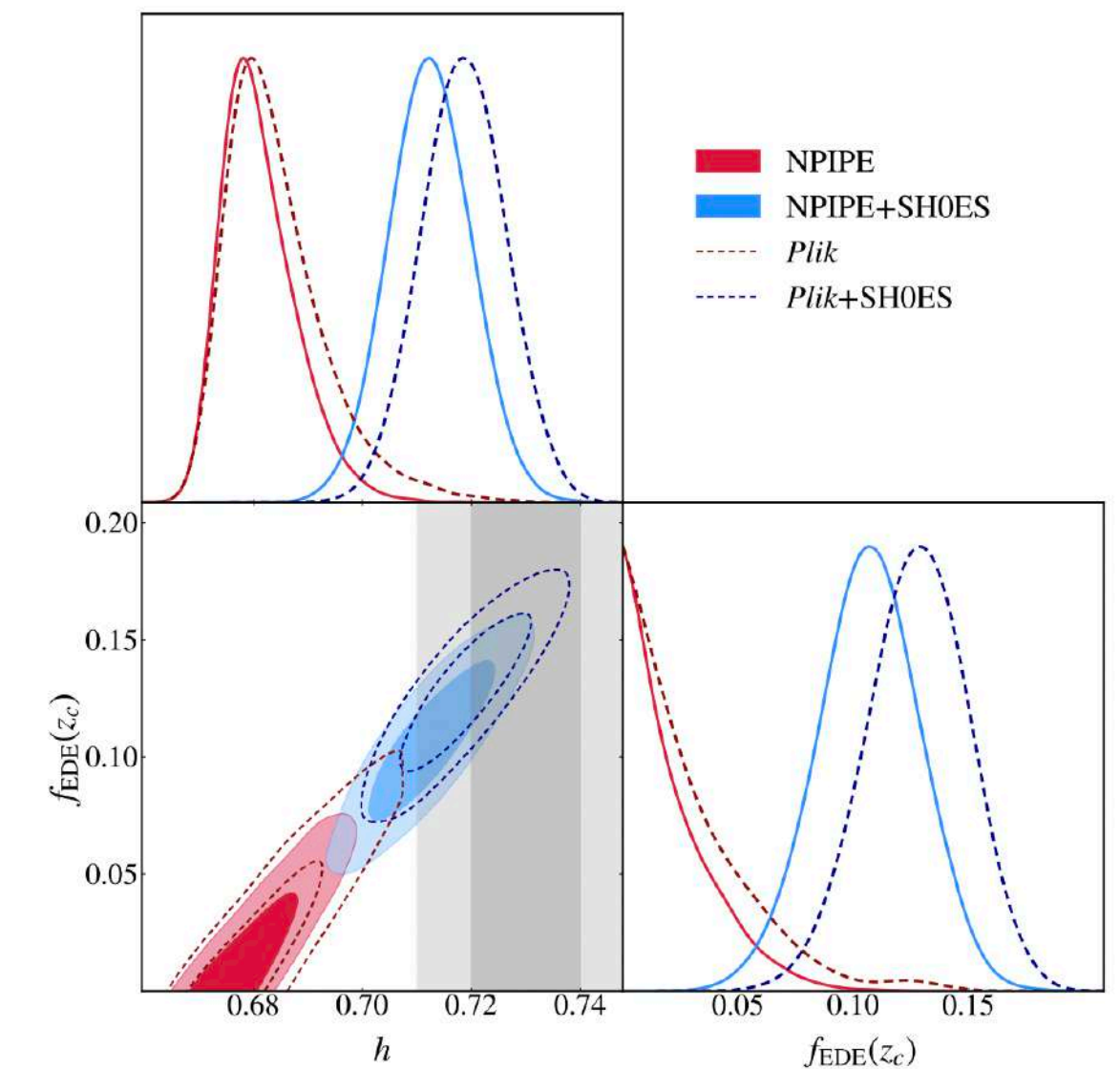
George Efstathiou, Erik Rosenberg,, and Vivian Poulin 2023,
*Improved Planck constraints on axion-like early dark energy as a resolution
of the Hubble tension*

Reanalysis using **new** *Planck* likelihood (NPIPE)+CamSpec: different analysis choices, more data

Profile likelihood:



MCMC:



PL (MCMC) analysis: $H_0^{\text{EDE},(\text{NPIPE})} = 68.37 \pm 0.0075$ ($68.11^{+0.0047}_{-0.0082}$)

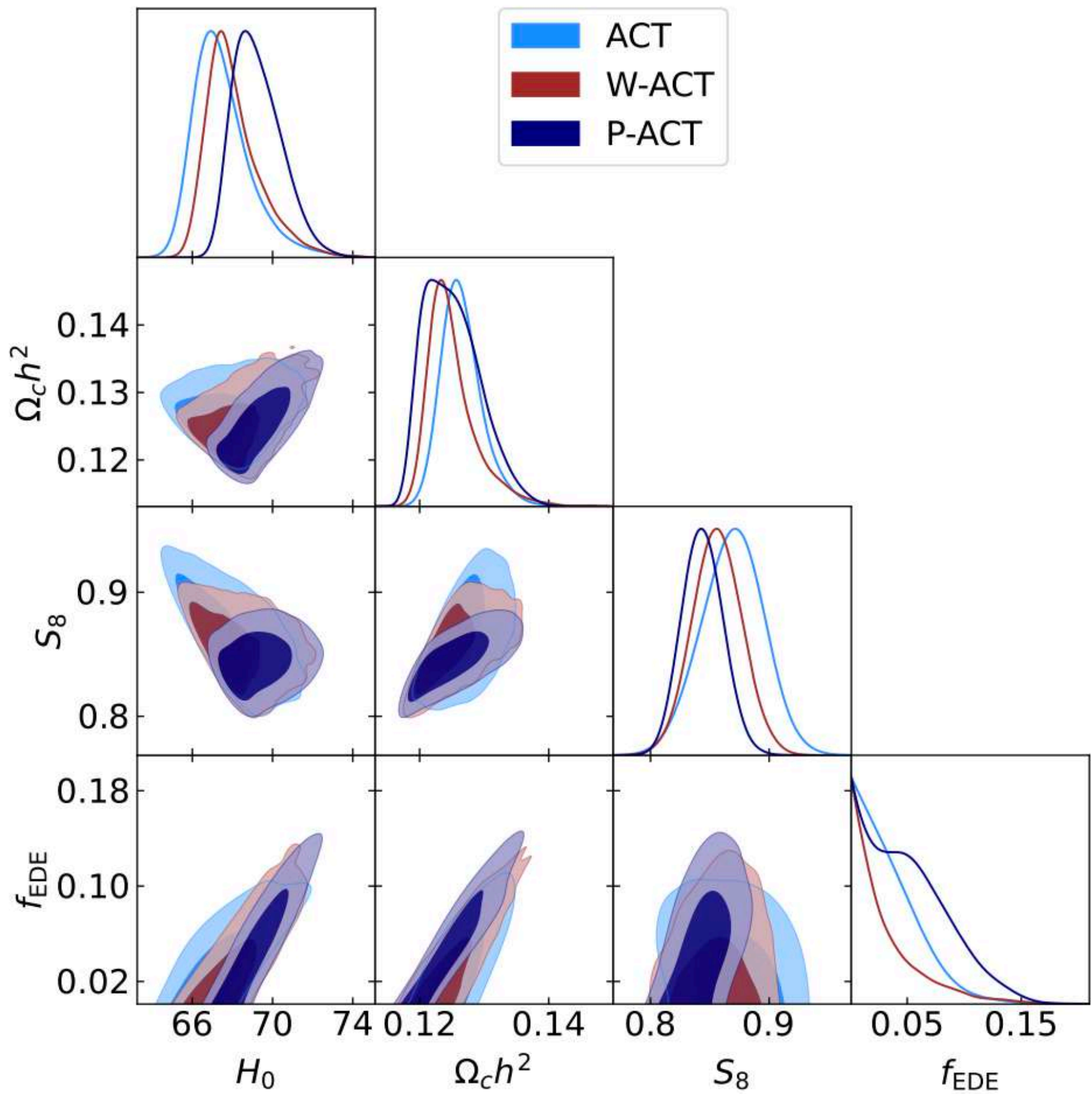
Distance from SHOES at 3.7σ

Volume effects present in the old likelihood.
NO volume effects with new likelihood!

ACT DR6

Early dark energy

Calabrese et al 2025



$$V(\phi) = \Lambda^4 [1 - \cos(\phi/f_a)]^3$$

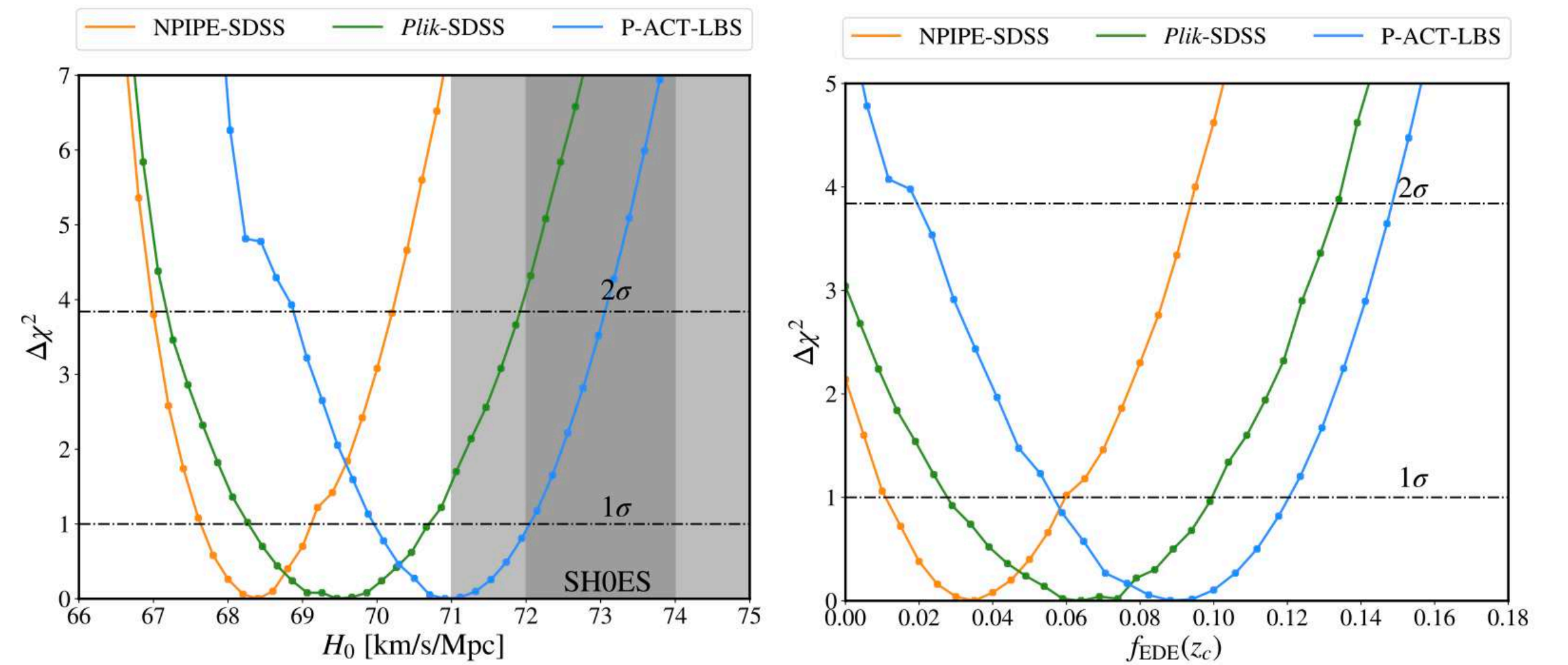
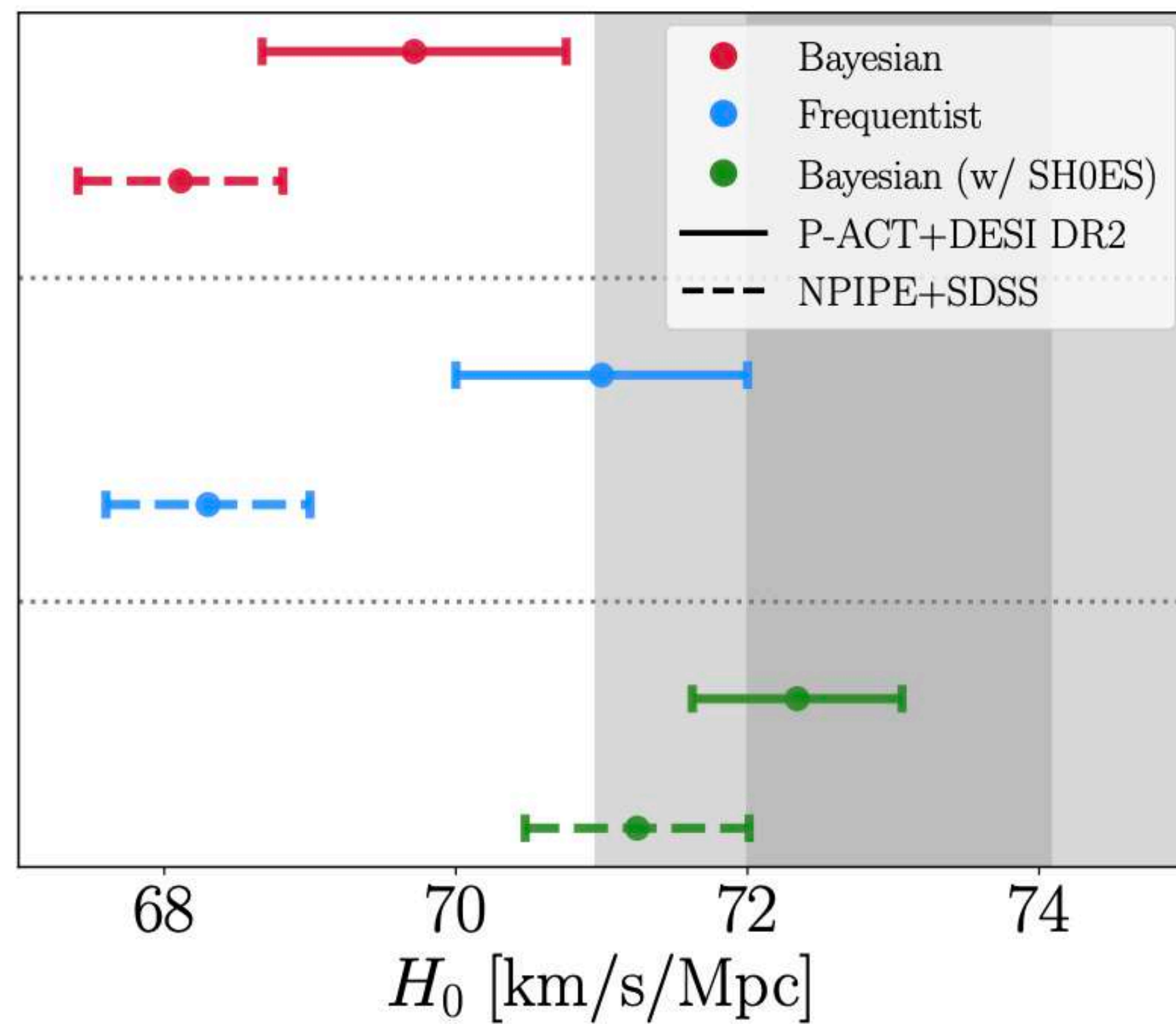
$$f_{\text{EDE}} < 0.088 \quad (95\%, \text{ACT}),$$
$$f_{\text{EDE}} < 0.12 \quad (95\%, \text{P-ACT}),$$

$$H_0 = 67.5^{+0.9}_{-1.7} \quad (68\%, \text{ACT}),$$
$$H_0 = 69.3^{+0.9}_{-1.5} \quad (68\%, \text{P-ACT}),$$

ACT DR6 - *profile likelihood*

Early dark energy

Poulin et al 2025



a residual tension with SH0ES of $\sim 2\sigma$ for the combination of *Planck* at $\ell < 1000$ + ACT DR6 + lensing + Pantheon-plus + DESI DR2, a significant decrease from 3.7σ for analyses that use NPIPE and SDSS BAO data. A profile likelihood analysis reveals significant prior-volume effects in Bayesian analyses which do not include SH0ES, with confidence intervals of $f_{\text{EDE}} = 0.09 \pm 0.03$ and $H_0 = 71.0 \pm 1.1$ km/s/Mpc. When including DESI data, the EDE model with $H_0 = 73$ km/s/Mpc provides a better fit than the Λ CDM model with $H_0 = 68.4$ km/s/Mpc. The inclusion of SH0ES data rises the preference well above 5σ , with $\Delta\chi^2 = -35.4$. Our work demonstrates that after ACT DR6 and DESI DR2, EDE remains a potential resolution to the Hubble tension.

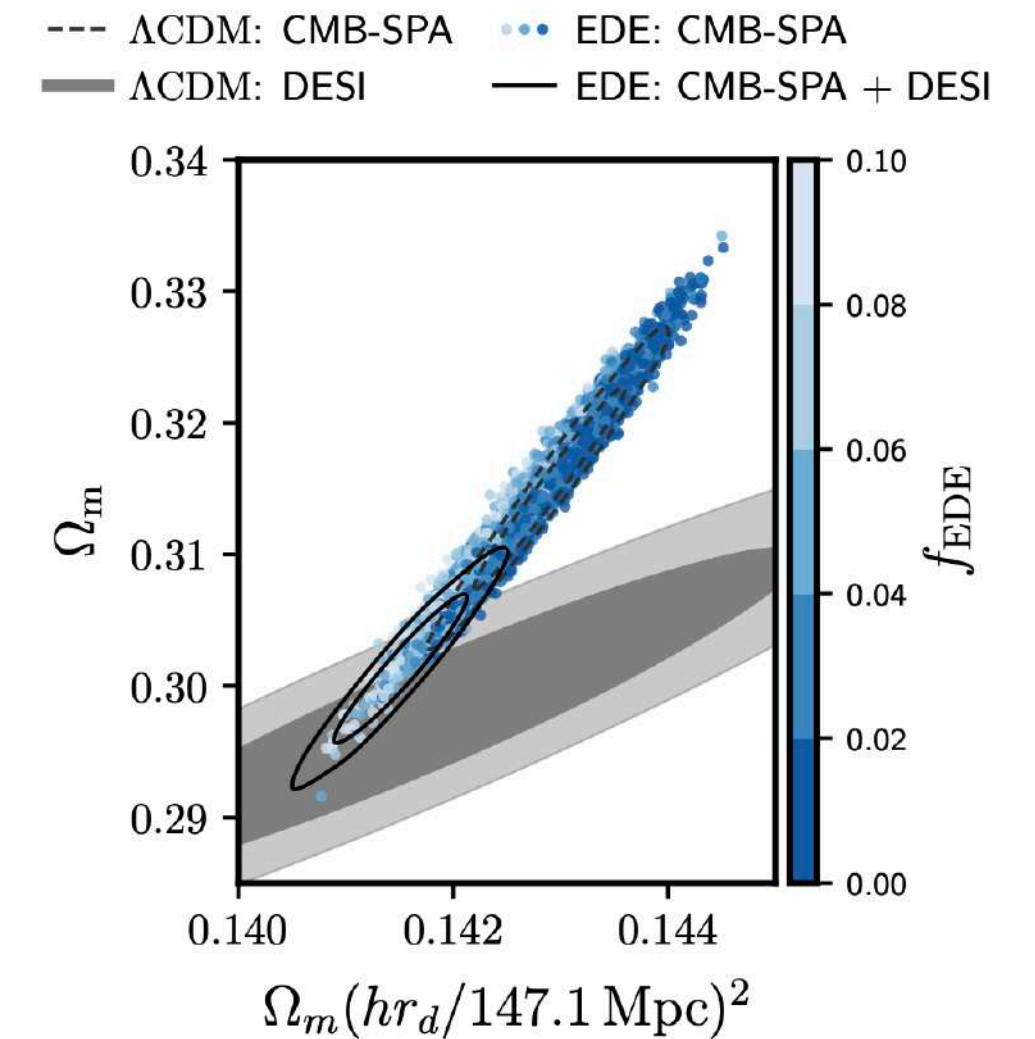
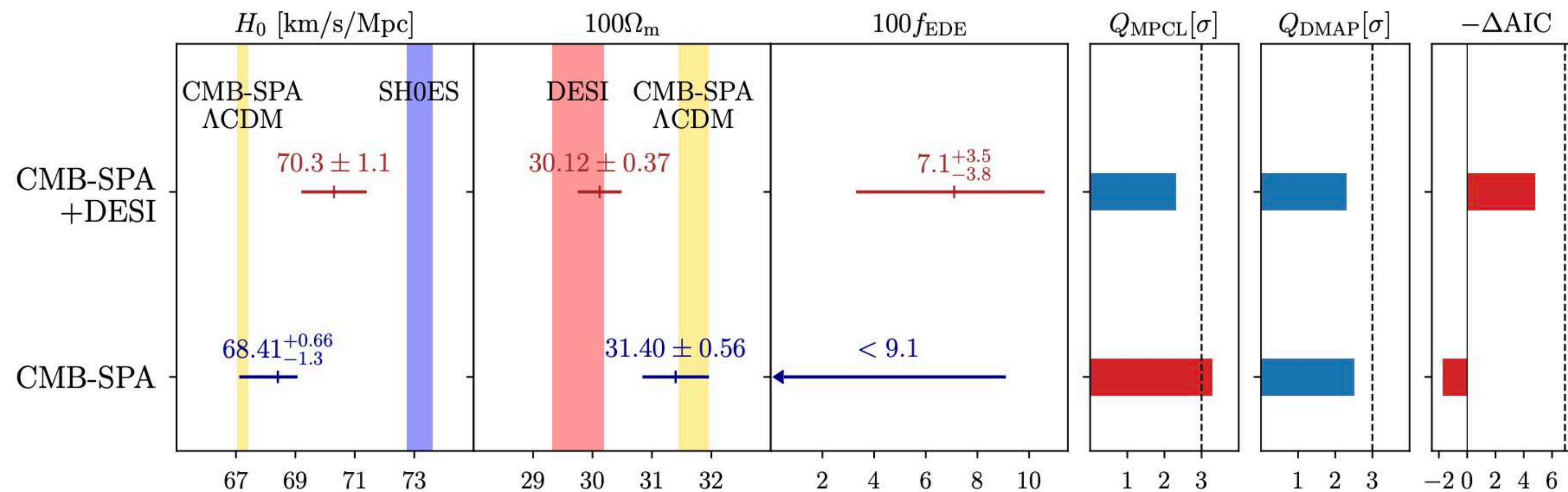
SPT 3g

Early dark energy

SPT-3G D1: Axion Early Dark Energy with CMB experiments and DESI

A. R. Khalife ¹ L. Balkenhol ¹ E. Camphuis ¹ A. J. Anderson ^{2,3,4} B. Ansarinejad,⁵ M. Archipley ^{4,3}

Instrument (DESI) has on these constraints. From CMB data alone, we do not find statistically significant evidence for the presence of AEDE, and we find only moderate reduction in the Hubble tension. From the latest SPT data alone, we find the maximal fractional contribution of AEDE to the cosmic energy budget is $f_{\text{EDE}} < 0.12$ at 95% confidence level (CL), and the Hubble tension between the SPT and SH0ES results is reduced to the 2.3σ level. When combining the latest SPT, ACT, and *Planck* datasets, we find $f_{\text{EDE}} < 0.091$ at 95% CL and the Hubble tension at the 3.3σ level. In contrast, adding DESI data to the CMB datasets results in mild preference for AEDE and, in some cases, non-negligible reduction in the Hubble tension. From SPT+DESI, we find $f_{\text{EDE}} = 0.081^{+0.037}_{-0.052}$ at 68% CL, and the Hubble tension reduces to 1.5σ . From the combination of DESI with all three CMB experiments, we get $f_{\text{EDE}} = 0.071^{+0.035}_{-0.038}$ at 68% CL and a weak preference for AEDE over ΛCDM . This data combination, in turn, reduces the Hubble tension to 2.3σ . We highlight that this shift in parameters when adding the DESI dataset is a manifestation of the discrepancy currently present between DESI and CMB experiments in the concordance model ΛCDM .



The discrepancy between CMB and DESI BAO data in ΛCDM projects onto a preference for higher values of f_{EDE} .

SPT 3g

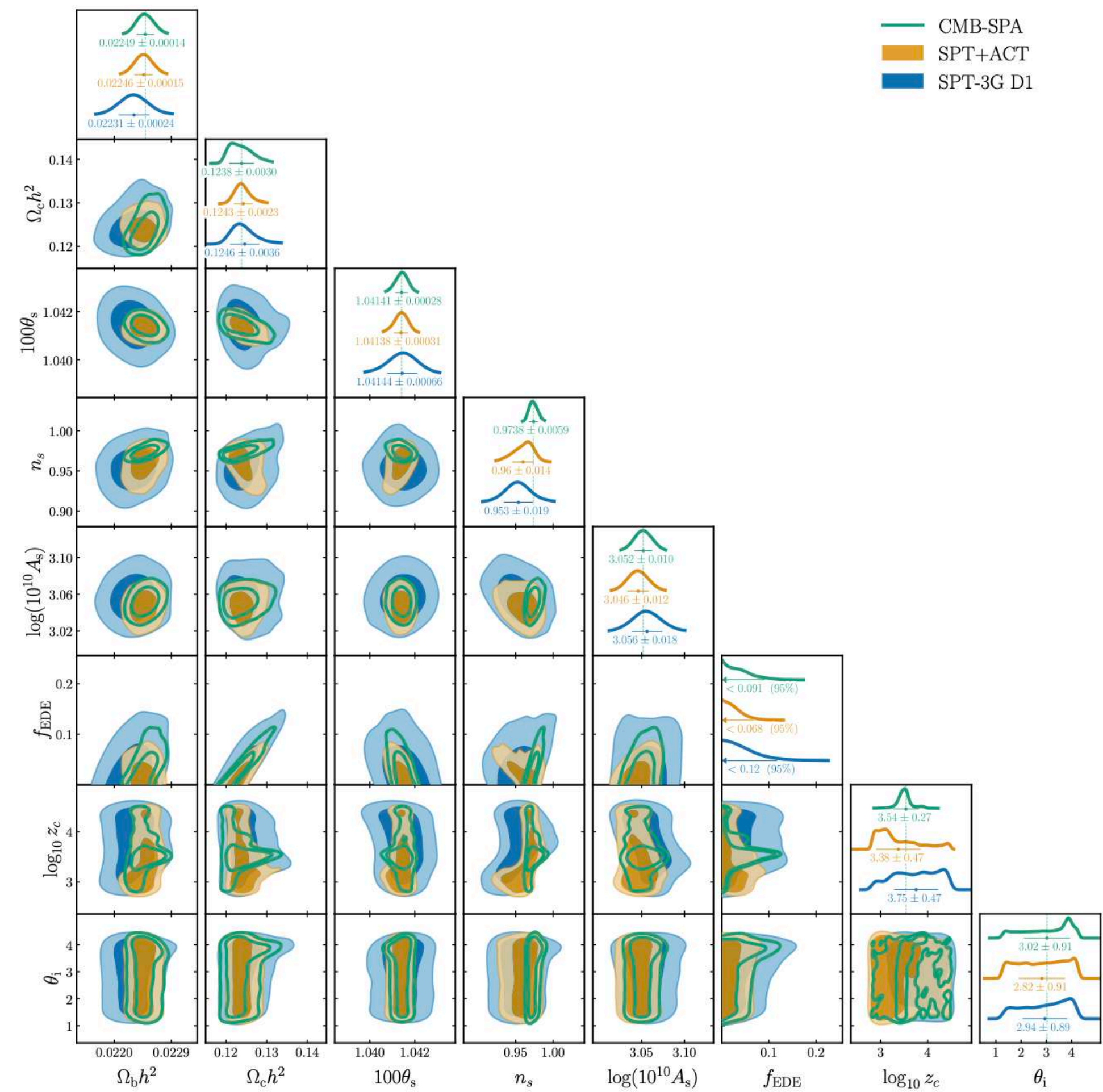
Early dark energy

Khalife et al 2025

YES/NO

SPT-3G D1: Axion Early Dark Energy with CMB experiments and DESI

A. R. Khalife ¹ L. Balkenhol ¹ E. Camphuis ¹ A. J. Anderson ^{2,3,4} B. Ansarinejad,⁵ M. Archipley ^{4,3}



Volume effects might be present

$$r_s(z_*) = \int_{z_*}^{\infty} \frac{dz}{H(z)} c_s(t)$$

*Early time solutions to the **Hubble tension***

What is the current status?

The H_0 World Cup

Someone should do it! :-p

- I don't think we are ready for podium yet. Still in the quarter finals...
- A lot has changed with new probes (ACT, ...)
- Also, more complex analysis: more nuisance parameters, and modelling choices that can impact result. Plus, tensions like the CMB-BAO tension.
- In general, all models lost a bit of the significance after ACT
- EDE and NEDE come and go depending on the analysis. Current status (imo): still a viable solution to H_0 tension, but maybe solves less than expected before. Maybe the best model now.
- We **do not** currently have a good model that solve the Hubble tension.

the S_8 tension

The S_8 tension

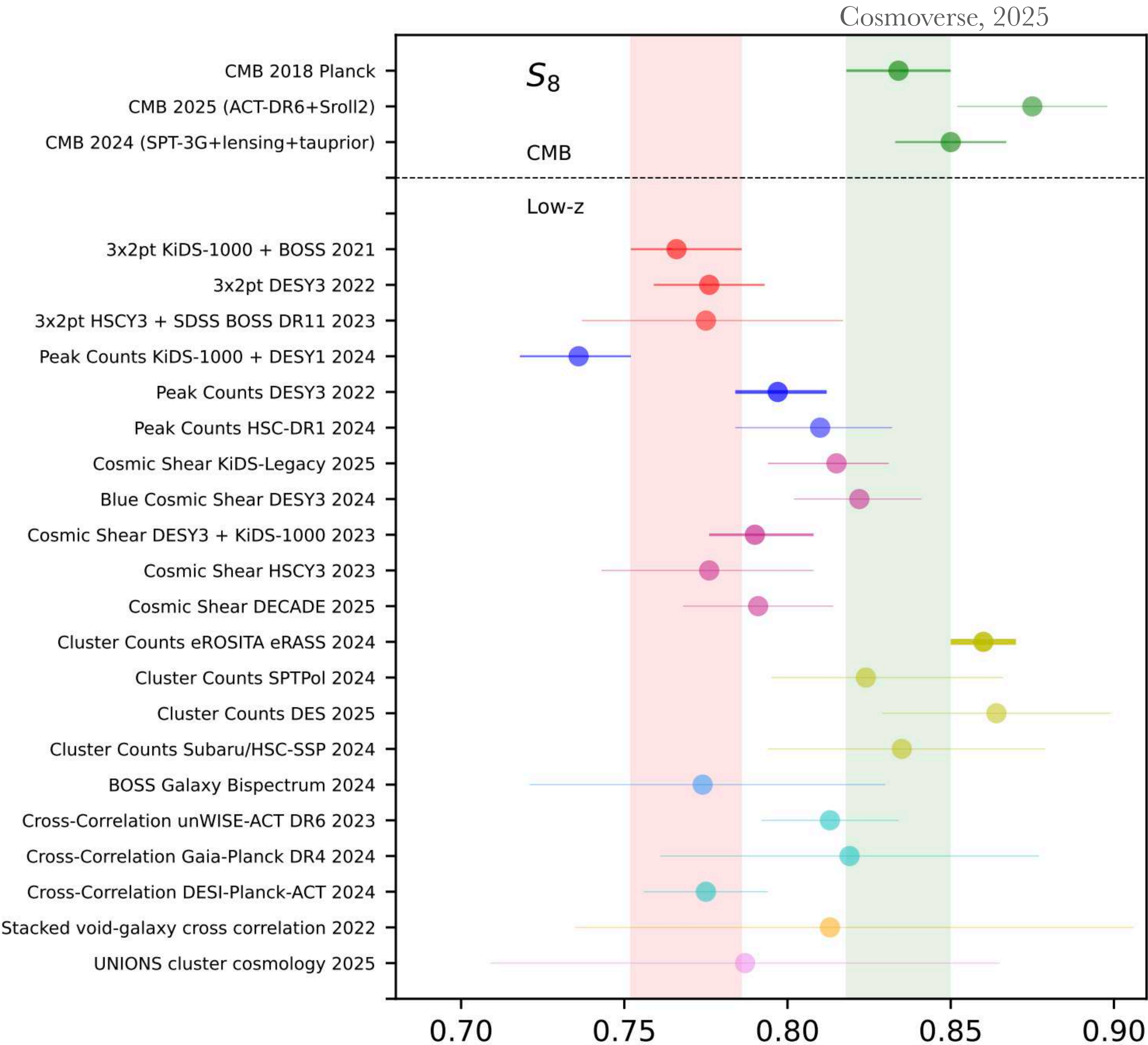
Discrepancy between the value of S_8 measure from weak lensing (WL) probes and Planck.

- While BAO/CMB are geometrical probes, WL measures the projected **clustering** of matter
- S_8 describes the inhomogeneity of the matter distribution now; WL is sensitive to this quantity

$$S_8 \equiv \sigma_8 \sqrt{\Omega_m/0.3}$$

- Max. 3σ tension

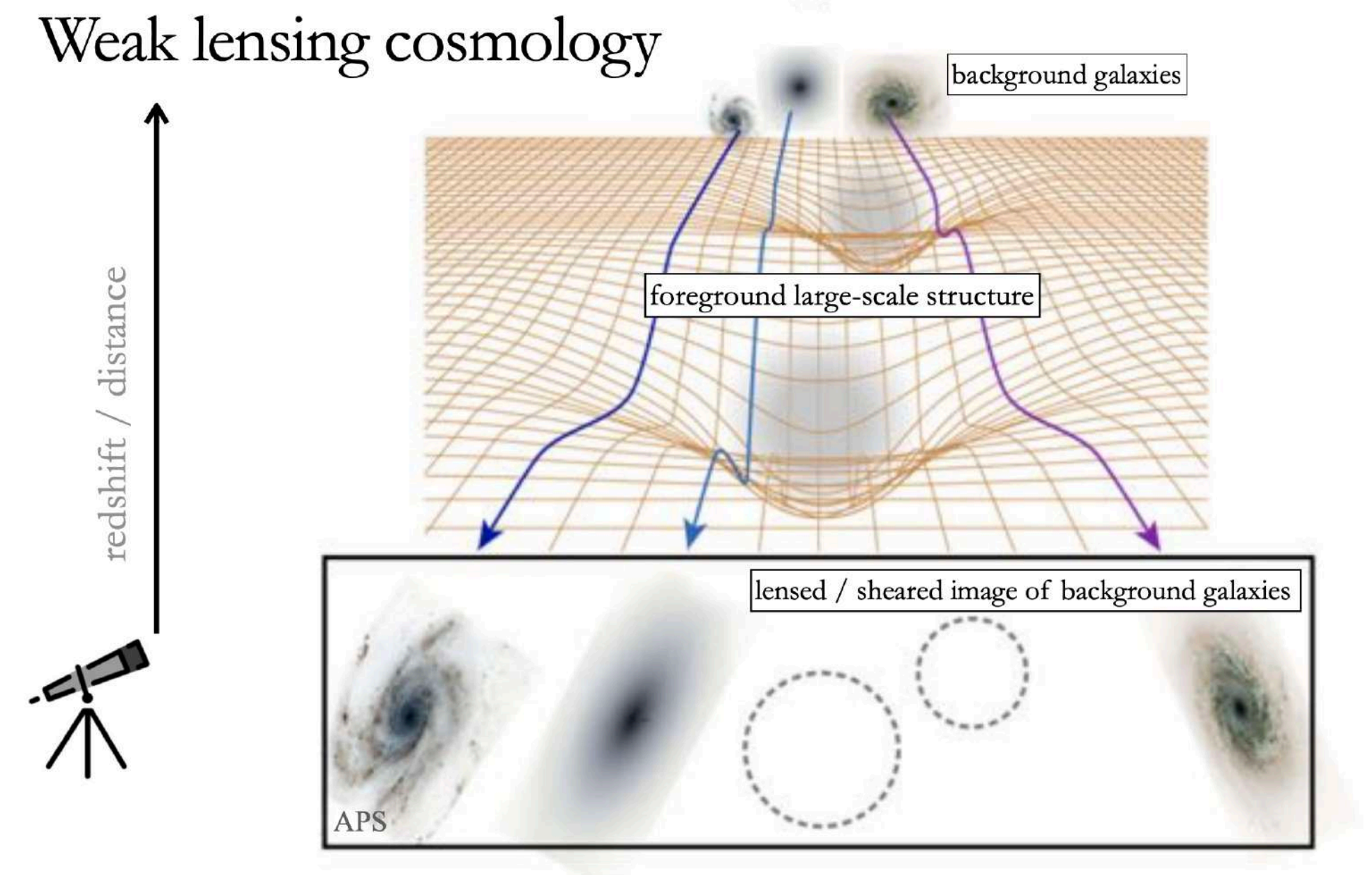
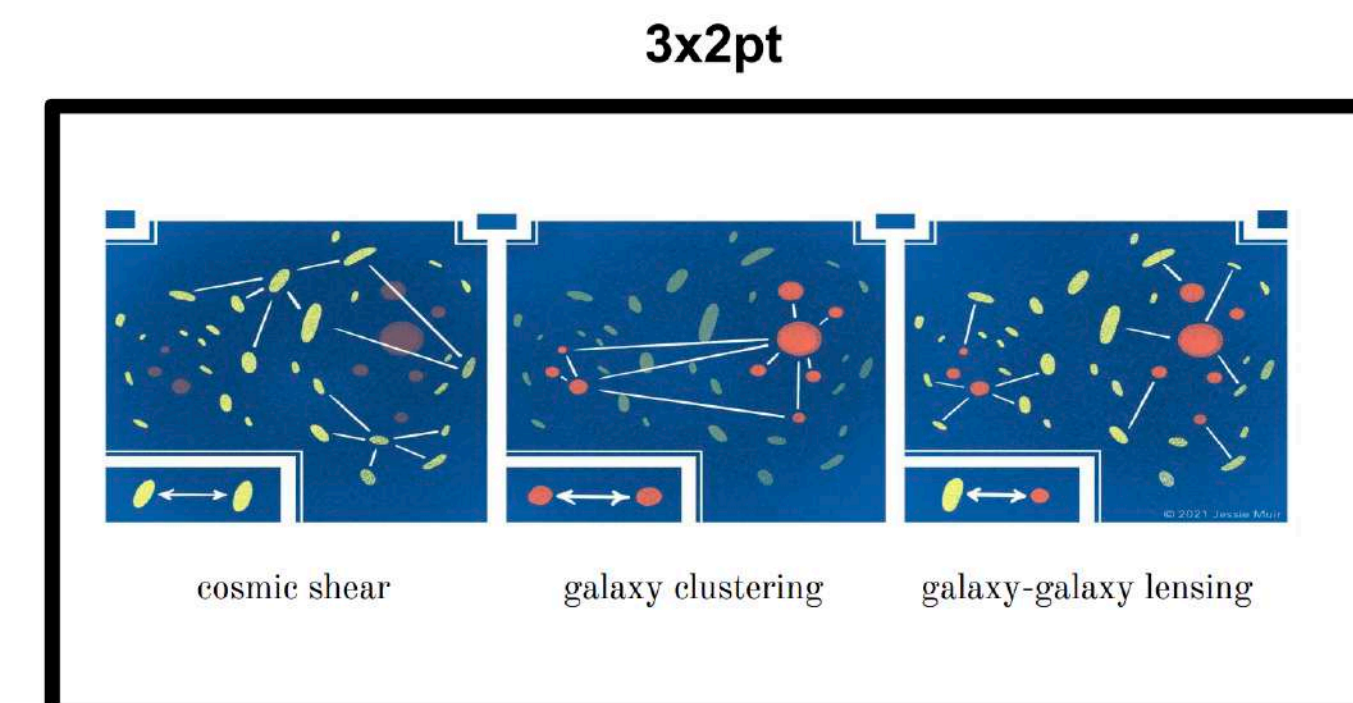
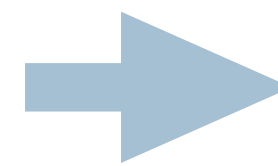
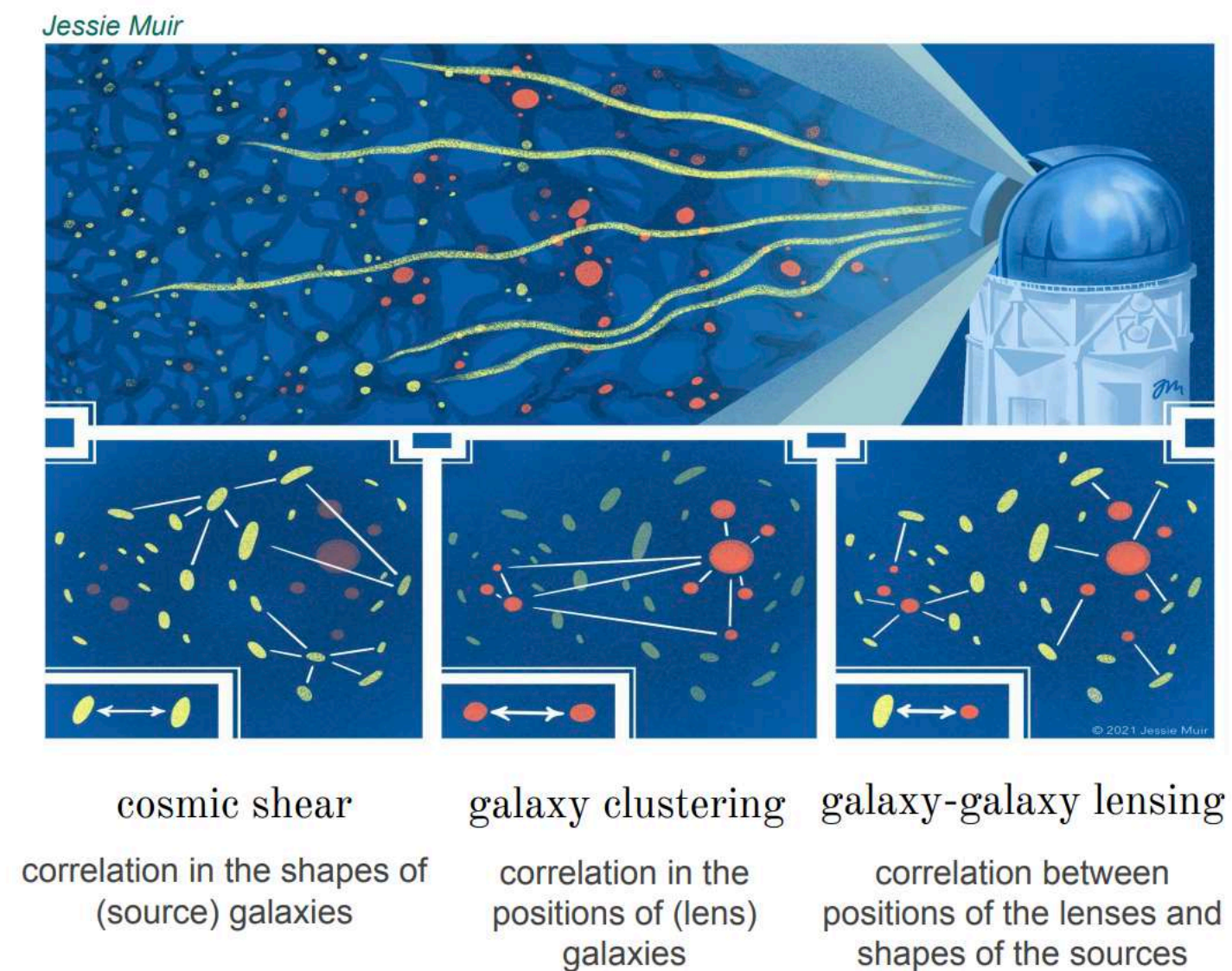
σ_8 : RMS fluctuation of the linear density field within a sphere of radius 8 Mpc/h



Weak *lensing*

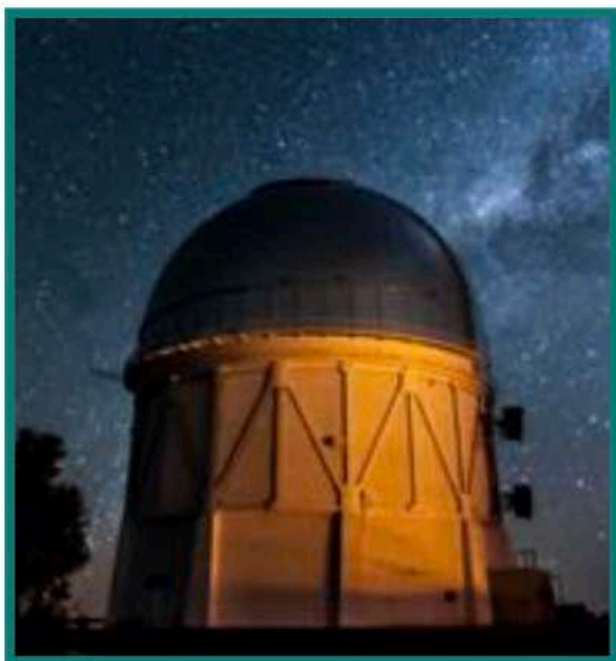
- Foreground matter coherently distorts the shapes of background galaxies.
- Weak lensing measures correlations of galaxy ellipticities, for source-bin pairs $([i,j])$ as a function of angular separation
- The signal depends on the redshift distributions of the source samples.
- Tomography: split galaxies into redshift bins and measure auto- and cross-correlations between bins.

Measures:

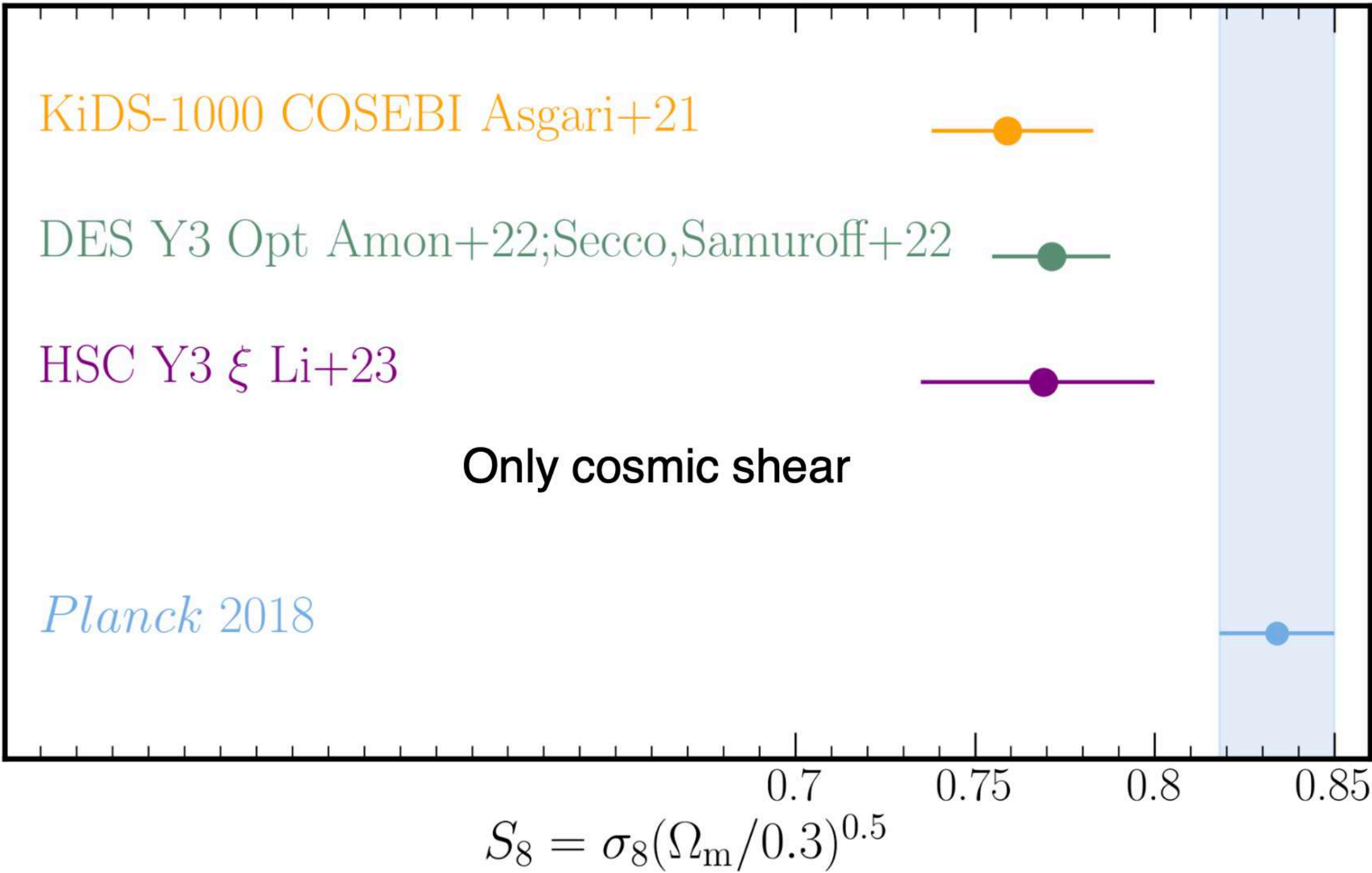


Based on A. Amon

The S_8 tension



Dark Energy Survey

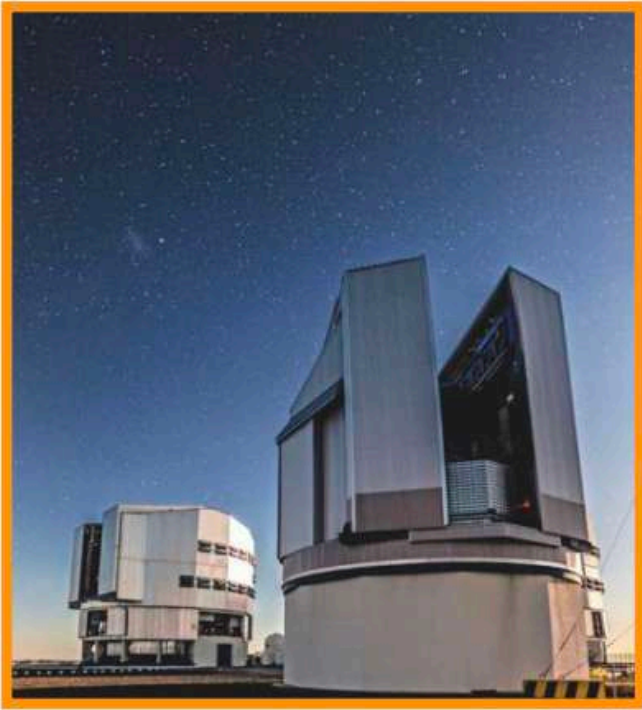


DES and KiDS Collaborations, arXiv:2305.17173

Hyper-Supreme Camera Survey



Kilo-Degree Survey



The S_8 tension

Many analysis choices and possible sources of systematics!

Huge effort from the collaborations to test them. Joint analysis!

For example:

- Redshift calibration
- Shear calibration: blending
- Intrinsic alignments
- Scale cuts & baryonic effects

The S_8 tension

Many analysis choices and possible sources of systematics!

Huge effort from the collaborations to test them. Joint analysis!

KiDS legacy

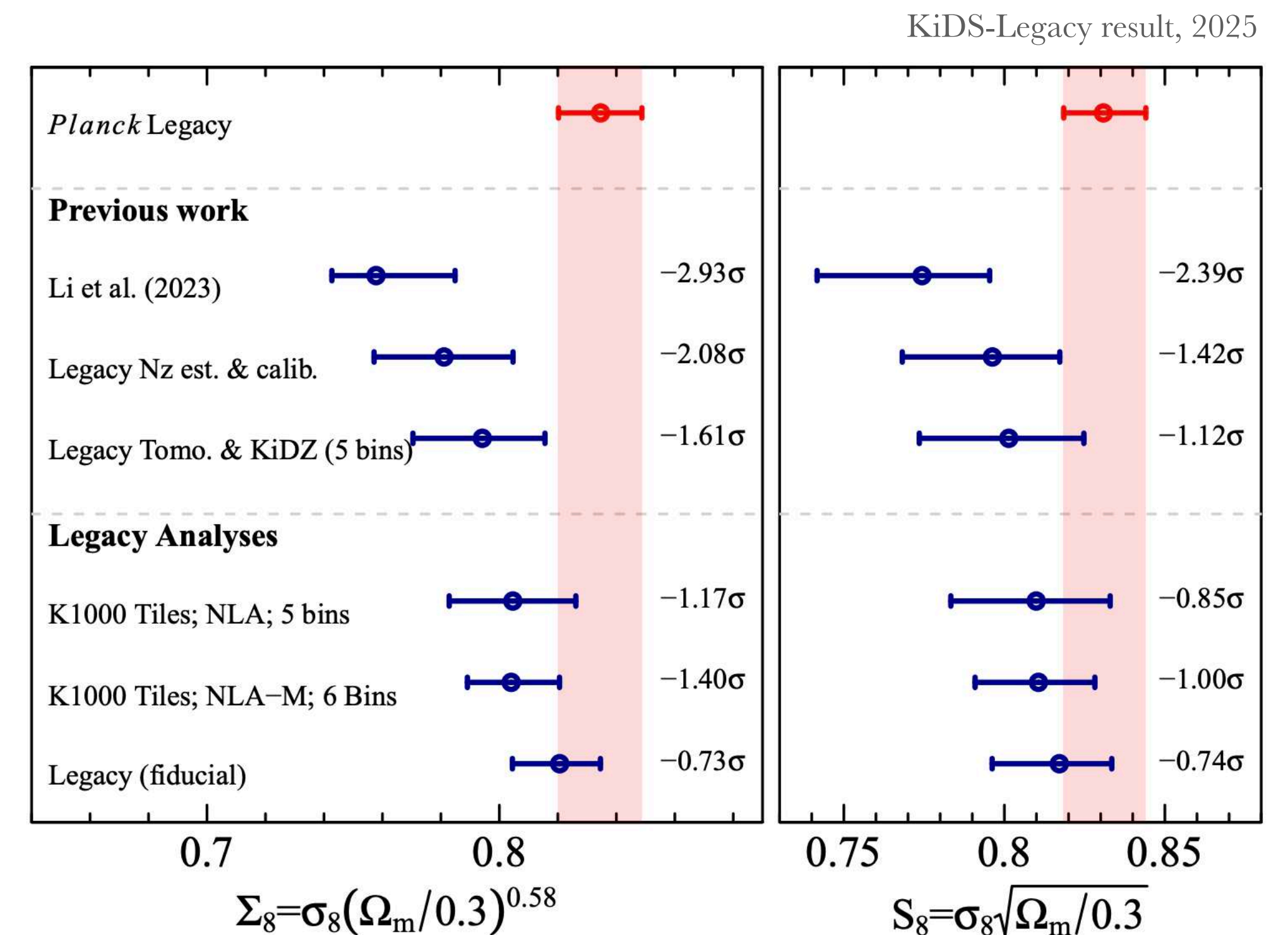
- Previous KiDS-1000-like result: lower S_8 , more tension with Planck;
- update redshift estimation/calibration: moves S_8 upward;
- update tomography + KiDZ calibration sample: moves further toward Planck;
- restrict/use Legacy footprint and analysis variations: remaining shifts;

Final KiDS-Legacy result $S_8 = 0.815^{+0.016}_{-0.021}$

compatible with Planck at $\sim 0.7\sigma$

For example:

- Redshift calibration
- Shear calibration: blending
- Intrinsic alignments
- Scale cuts & baryonic effects



The S_8 tension

Many analysis choices and possible sources of systematics!

Huge effort from the collaborations to test them. Joint analysis!

DES Y6

- Much larger dataset: full 6-year DES footprint, $\sim 5000 \text{ deg}^2$
- Higher signal-to-noise cosmic shear measurement: about a factor of 2 higher than Y3.
- Improved shear and redshift calibration.
- More conservative treatment of small scales, baryons, and intrinsic alignments.

$$S_8 = 0.789 \pm 0.012 \quad \text{for } 3 \times 2pt$$

$$S_8 = 0.798^{+0.014}_{-0.015} \quad \text{for cosmic shear only}$$

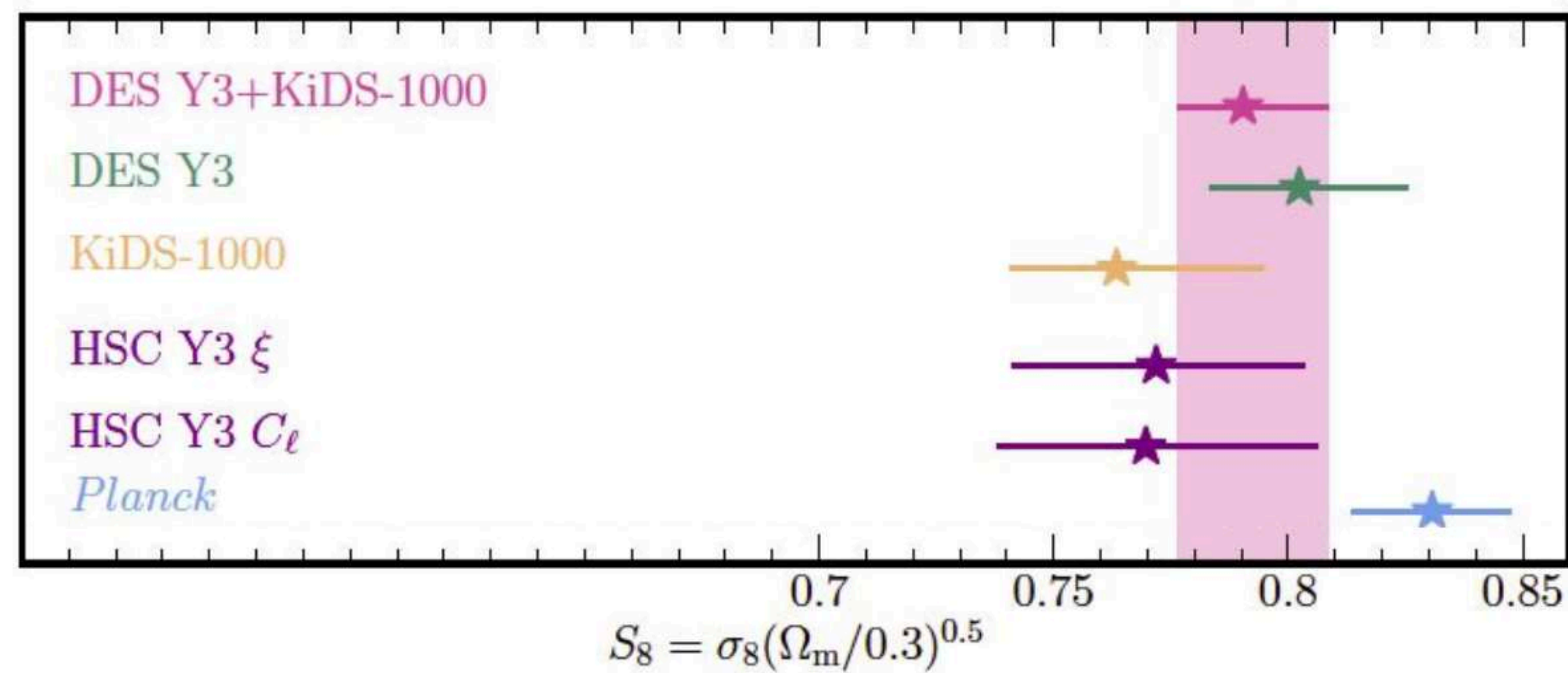
$$S_8^{\text{Y3}} \sim 0.76 - 0.77 \quad \rightarrow \quad S_8^{\text{Y6}} \sim 0.79 - 0.80.$$

Final DES Y6 result, the distance from Planck is 2σ (NLA).
For the full parameter space, the distance is 1.1σ .

The S_8 tension

Combined DES+KiDS

- Reanalysis having a hybrid pipeline



Cosmic shear and S_8

- DES x KIDS analysis

DES Y3 + KIDS-1000: CONSISTENT COSMOLOGY COMBINING COSMIC SHEAR SURVEYS

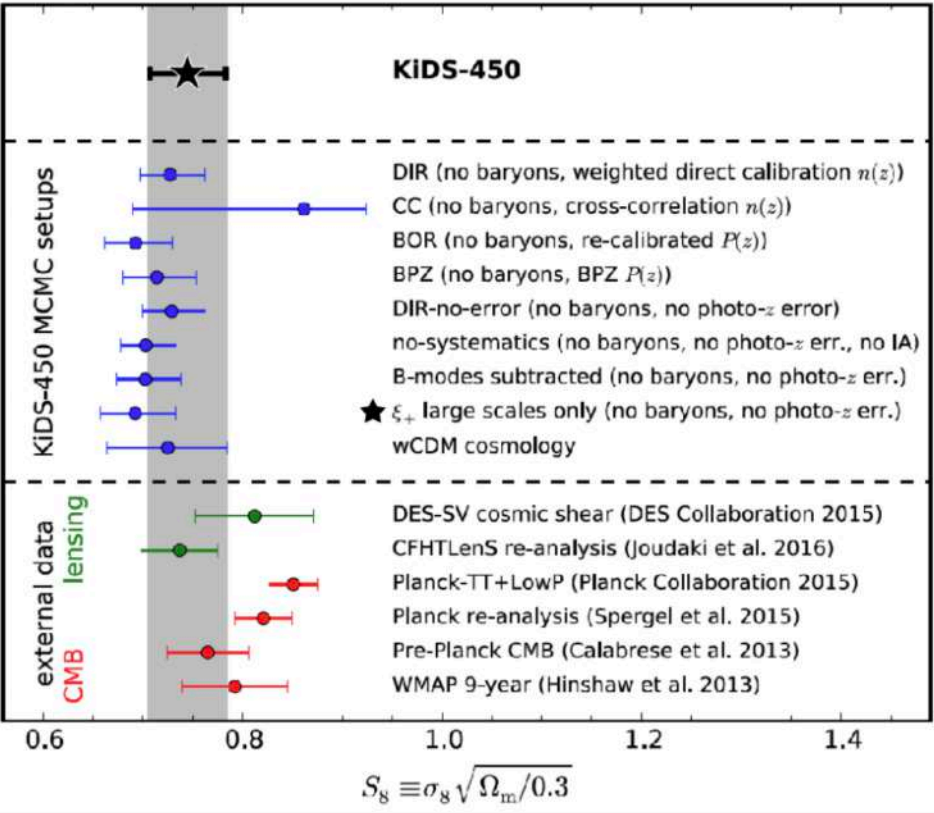
DARK ENERGY SURVEY AND KILO-DEGREE SURVEY COLLABORATION:
T. M. C. ABBOTT,¹ M. AGUENA,² A. ALARCON,³ O. ALVES,⁴ A. AMON,^{5,6} F. ANDRADE-OLIVEIRA,⁴ M. ASGARI,⁷ S. AVILA,⁸ D. BACON,⁹
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F. J. CASTANDER,^{27,28} R. CAWTHON,²⁹ C. CHANG,^{30,31} R. CHEN,³² A. CHOI,³³ C. CONSELICE,^{34,35} J. CORDERO,³⁴ L. N. DA COSTA,²
M. E. S. PEREIRA,³⁶ R. DALAL,³⁷ C. DAVIS,¹⁹ J. T. A. DE JONG,^{38,39} J. DEROSE,⁴⁰ S. DESAI,⁴¹ H. T. DIEHL,⁴² S. DODELSON,^{22,43}
P. DOEL,¹⁷ C. DOUX,^{11,44} A. DRLICA-WAGNER,^{30,42,31} A. DVORNIK,⁴⁵ K. ECKERT,¹¹ T. F. EIFLER,^{46,47} J. ELVIN-POOLE,⁴⁸ S. EVERETT,⁴⁷
X. FANG,^{49,46} I. FERRERO,⁵⁰ A. FERTÉ,²⁰ B. FLAUGHER,⁴² O. FRIEDRICH,⁶ J. FRIEMAN,^{42,31} J. GARCÍA-BELLIDO,⁵¹ M. GATTI,¹¹
G. GIANNINI,⁸ B. GIBLIN,^{52,53} D. GRUEN,¹⁶ R. A. GRUENDL,^{25,26} G. GUTIERREZ,⁴² I. HARRISON,⁵⁴ W. G. HARTLEY,⁵⁵ K. HERNER,⁴²
C. HEYMANS,^{53,45} H. HILDEBRANDT,⁴⁵ S. R. HINTON,⁵⁶ H. HOEKSTRA,³⁸ D. L. HOLLOWOOD,⁵⁷ K. HONSCHIED,^{58,59} H. HUANG,^{46,60}
E. M. HUFF,⁴⁷ D. HUTERER,⁴ D. J. JAMES,⁶¹ M. JARVIS,¹¹ N. JEFFREY,¹⁷ T. JELTEMA,⁵⁷ B. JOACHIMI,⁶² S. JOUDAKI,⁶³ A. KANNAWADI,⁶⁴
E. KRAUSE,⁴⁶ K. KUEHN,^{65,66} K. KUIJKEN,³⁸ N. KUROPATKIN,⁴² P.-F. LEGET,¹⁹ P. LEMOS,^{67,68,69,70} S. LI,³⁸ X. LI,^{71,72} A. R. LIDDLE,⁷³
M. LIMA,^{74,2} C. LIN,^{45,75} H. LIN,⁴² N. MACCRANN,⁷⁶ C. MAHONY,⁴⁵ J. L. MARSHALL,⁷⁷ J. MCCULLOUGH,¹⁹ J. MENA-FERNÁNDEZ,⁷⁸
F. MENANTEAU,^{25,26} R. MIQUEL,^{79,8} J. J. MOHR,^{80,16} J. MUIR,⁸¹ J. MYLES,^{82,19,20} N. NAPOLITANO,⁸³ A. NAVARRO-ALSINA,⁸⁴
R. L. C. OGANDO,⁸⁵ A. PALMESE,²² S. PANDEY,¹¹ Y. PARK,⁸⁶ M. PATERNO,⁴² J. A. PEACOCK,⁵³ D. PETRAVICK,²⁵ A. PIERES,^{2,85}
A. A. PLAZAS MALAGÓN,⁸⁷ A. PORREDON,^{58,59,53} J. PRAT,^{30,31} M. RADOVICH,⁸⁸ M. RAVERI,⁸⁹ R. REISCHKE,⁴⁵ R. P. ROLLINS,³⁴
A. K. ROMER,⁹⁰ A. ROODMAN,^{19,20} E. S. RYKOFF,^{19,20} S. SAMUROFF,¹⁵ C. SÁNCHEZ,¹¹ E. SANCHEZ,⁷⁸ J. SANCHEZ,⁹¹ P. SCHNEIDER,¹⁸
L. F. SECCO,³¹ I. SEVILLA-NOARBE,⁷⁸ H. SHAN,^{92,93,94} E. SHELDON,⁹⁵ T. SHIN,⁹⁶ C. SIFÓN,⁹⁷ M. SMITH,⁹⁸ M. SOARES-SANTOS,⁴
B. STÖLZNER,⁴⁵ E. SUCHYTA,⁹⁹ M. E. C. SWANSON,⁴ G. TARLE,⁴ D. THOMAS,⁹ C. TO,⁵⁸ M. A. TROXEL,³² T. TRÖSTER,¹⁰⁰
J. TUCKER,^{101,27,28} D. TURNER,⁴⁵ T. VAN DEN BEEK,^{102,80,103} A. VAN DER BEEK,¹⁰⁴ M. VAN DEN KUIP,⁴ D. VAN DYK,^{82,19,20}

Identified and quantified the marginalization (prior volume or projection) effects given some choices in the analysis.

Using MAP (maximum a posteriori)

Prior volume effects might be biasing σ_8 from cosmic shear

Analysis in preparation!



Cosmic shear and S_8

- DES x KIDS analysis

Identified and quantified the prior volume effects given some choices in the analysis - using mocks

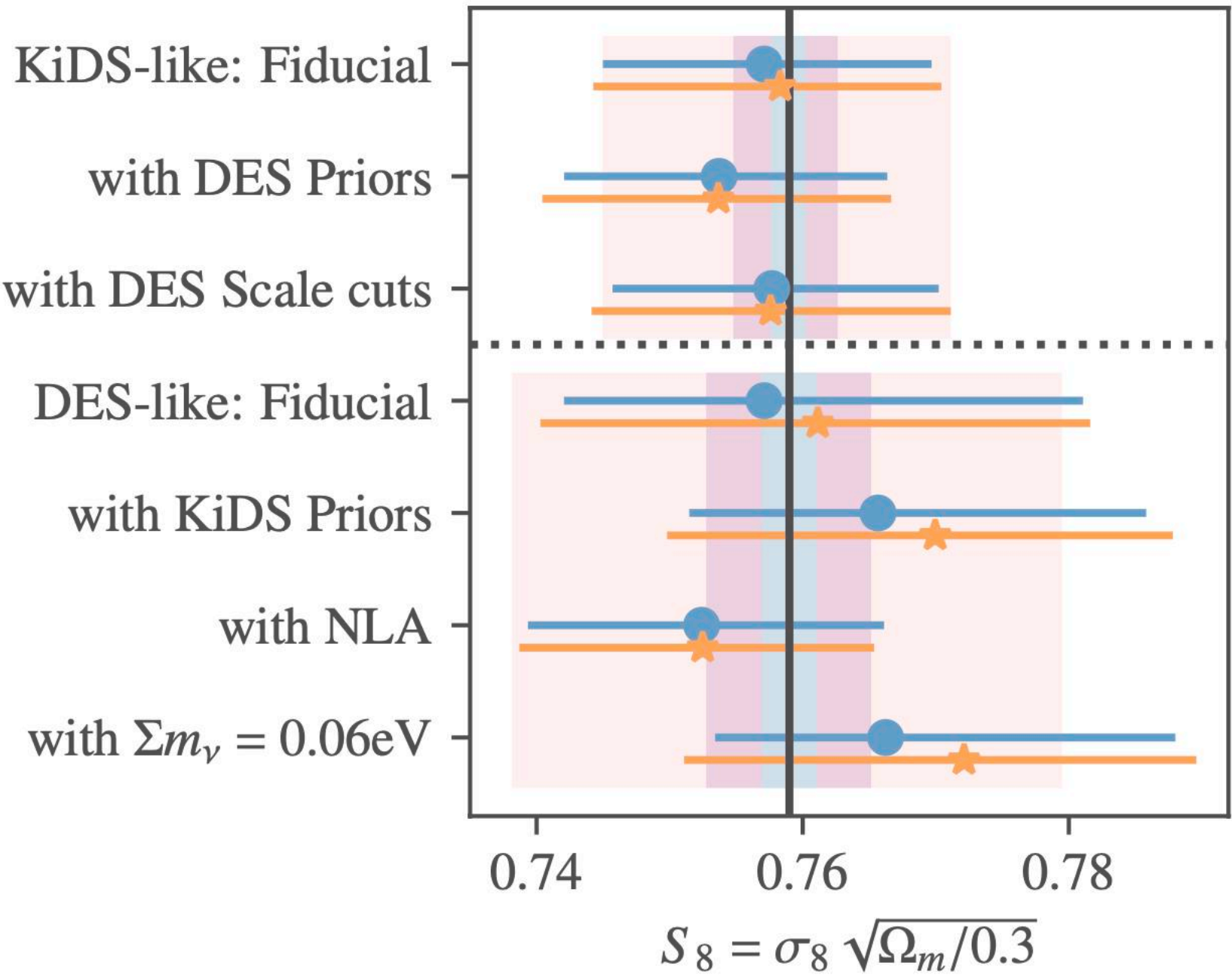
ΔS_8 = bias of the recovered S_8 relative to the true S_8 = 0.759, as a fraction of the 1σ error

Analysis	KiDS		DES	
Non-linear	HMCode2020		HALOFIT	
IA	NLA		TATT	
Baryons	$T_{\text{AGN}} = 7.8$		Scale Cuts	
Quoted S_8	Max	Mean	Max	Mean
S_8^{KiDS}	$0.752^{+0.022}_{-0.023}$	$0.747^{+0.026}_{-0.017}$	$0.758^{+0.028}_{-0.033}$	$0.748^{+0.036}_{-0.018}$
S_8^{DES}	$0.758^{+0.018}_{-0.017}$	$0.758^{+0.016}_{-0.017}$	$0.758^{+0.026}_{-0.028}$	$0.753^{+0.030}_{-0.020}$
S_8^{J1IA}	$0.758^{+0.012}_{-0.014}$	$0.757^{+0.013}_{-0.012}$	$0.761^{+0.020}_{-0.021}$	$0.757^{+0.024}_{-0.015}$
S_8^{Joint}	$0.757^{+0.013}_{-0.013}$	$0.757^{+0.011}_{-0.011}$	$0.764^{+0.016}_{-0.019}$	$0.759^{+0.019}_{-0.014}$
ΔS_8^{KiDS}	-0.31σ	-0.55σ	-0.02σ	-0.42σ
ΔS_8^{DES}	-0.08σ	-0.04σ	-0.04σ	-0.26σ
ΔS_8^{J1IA}	-0.05σ	-0.15σ	0.10σ	-0.10σ
$\Delta S_8^{\text{Joint}}$	-0.12σ	-0.14σ	0.27σ	0.01σ

Maximum-marginal credible intervals are $\sim 10\%$ larger than the reported mean-marginal credible intervals

DES Y3 + KIDS-1000: CONSISTENT COSMOLOGY COMBINING COSMIC SHEAR SURVEYS

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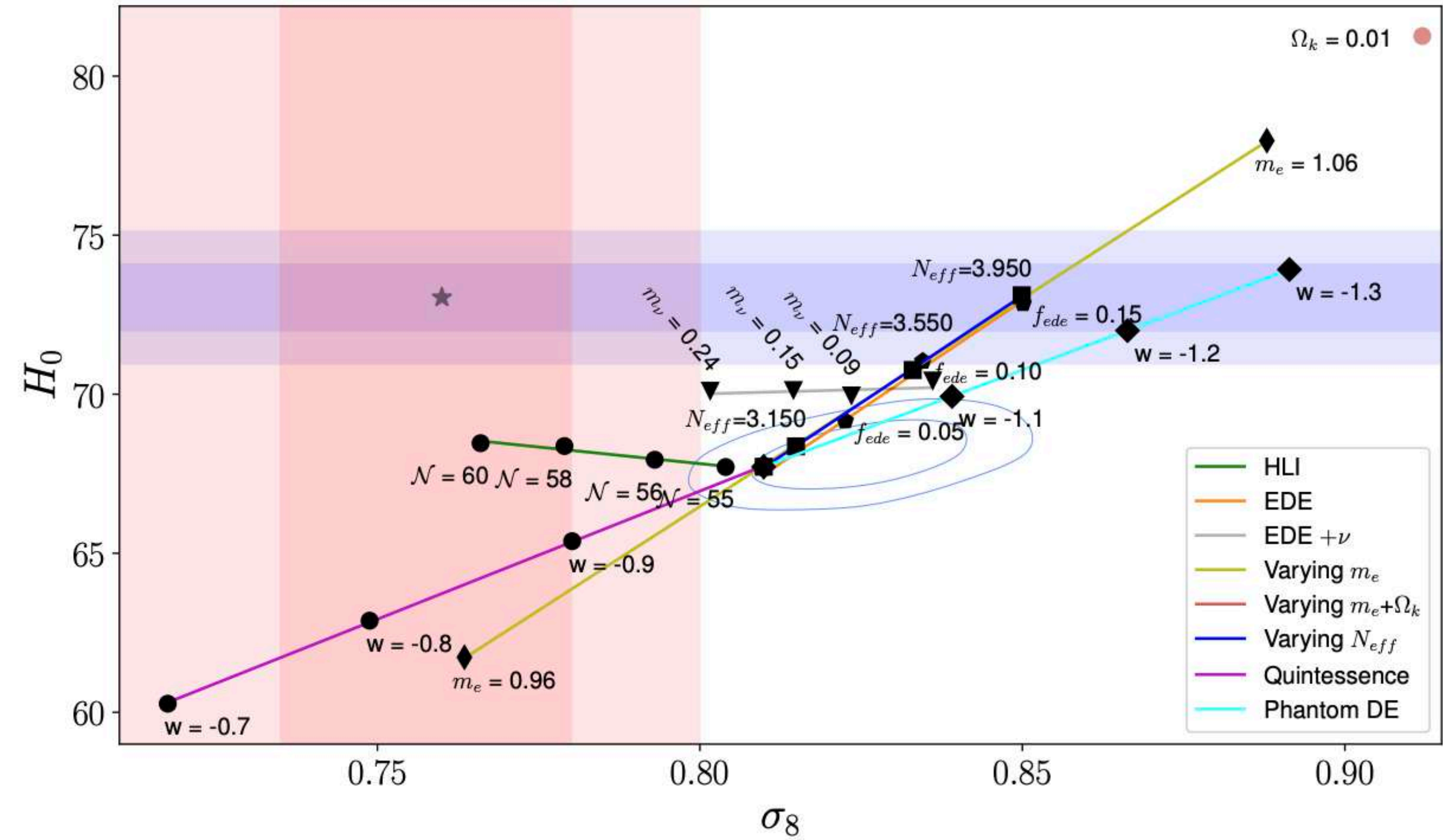
Maximum-marginal posterior is the KiDS-preferred alternative to their fiducial (MAP+PJ-HPD estimate. credible intervals are defined using a 1D kernel density estimator (KDE))

Mean-marginal posterior is the DES-preferred estimator.

S_8 tension

Pedreira, Benetti, **EF**, Graef, Herold, 2023

Usually H0 solutions worsen the S8 distance



Solutions to the S_8 tension

- Planck+BAO+SNIa+SH0ES
- Planck+BAO+SNIa
- Planck+SNIa+SH0ES
- Planck+BAO+SNIa+SH0ES
- Planck+BAO+BBN+SNIa+SH0ES
- Planck+BAOtr+DESY5 SN+CC+f σ_{12} +SH0ES
- Planck+BAO+SH0ES
- Planck+BAO
- Planck+BAO+RSD+SNIa
- ★

 Planck+BAO+SNIa+S8
- ★

 Planck
- ★

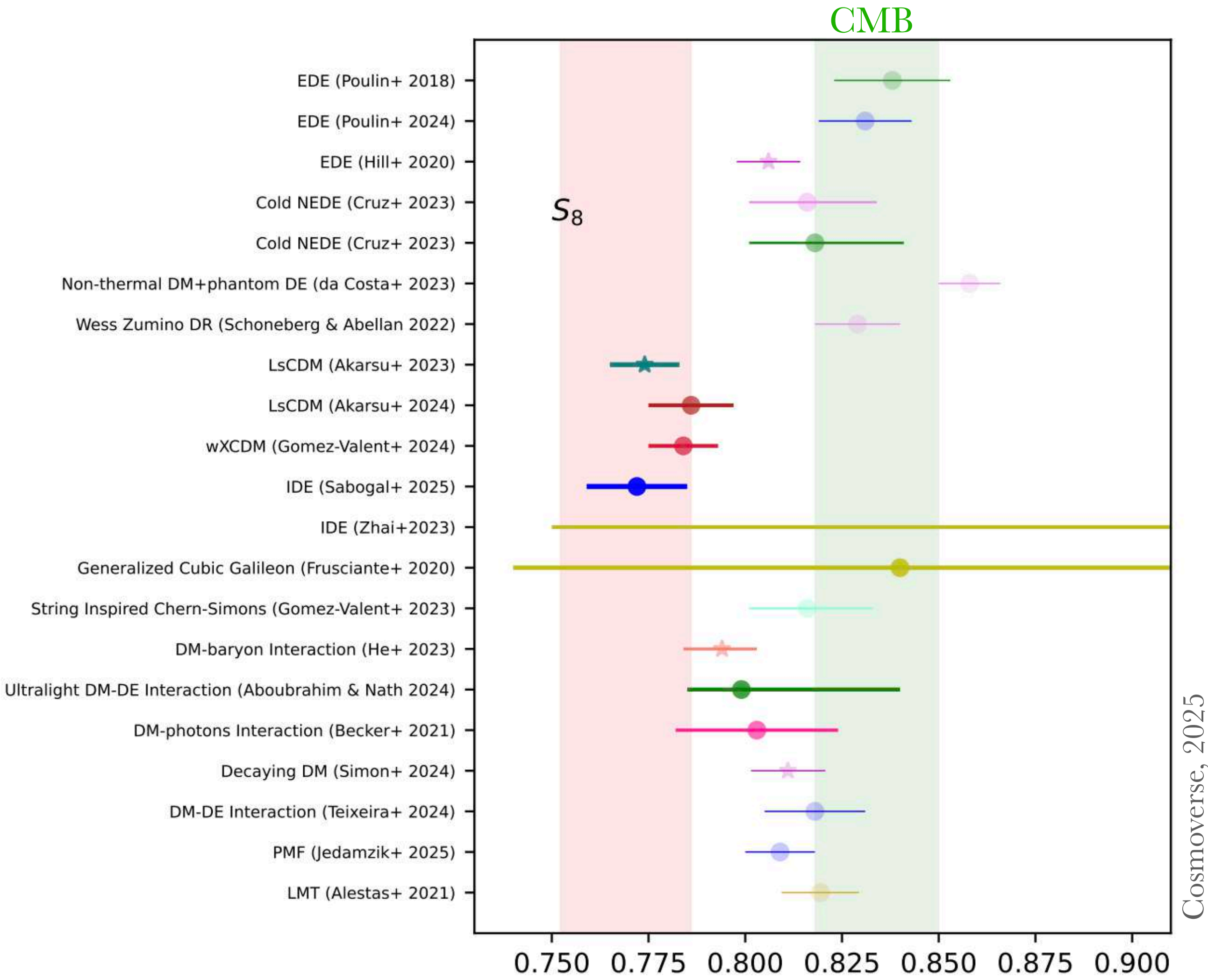
 Planck+BAO+CC+SNIa+SH0ES
- ★

 Planck+BAO+S8
- ★

 Planck+BAOtr+KiDS1000+SNIa+SH0ES
- ★

 Planck+BAO+DES

Summary of possible solutions to the S_8 tension, if present (and models that make it worse)



Solutions to the S_8 tension

Ref.: K. Rogers et al 2023

Changes in the small scale paradigm can change the behaviour of DM in many scales, including cosmology

Fuzzy DM

$$\sigma_8 = \int d\ln k \frac{k^3}{2\pi} W^2(k) P^{\text{linear}}(k)$$

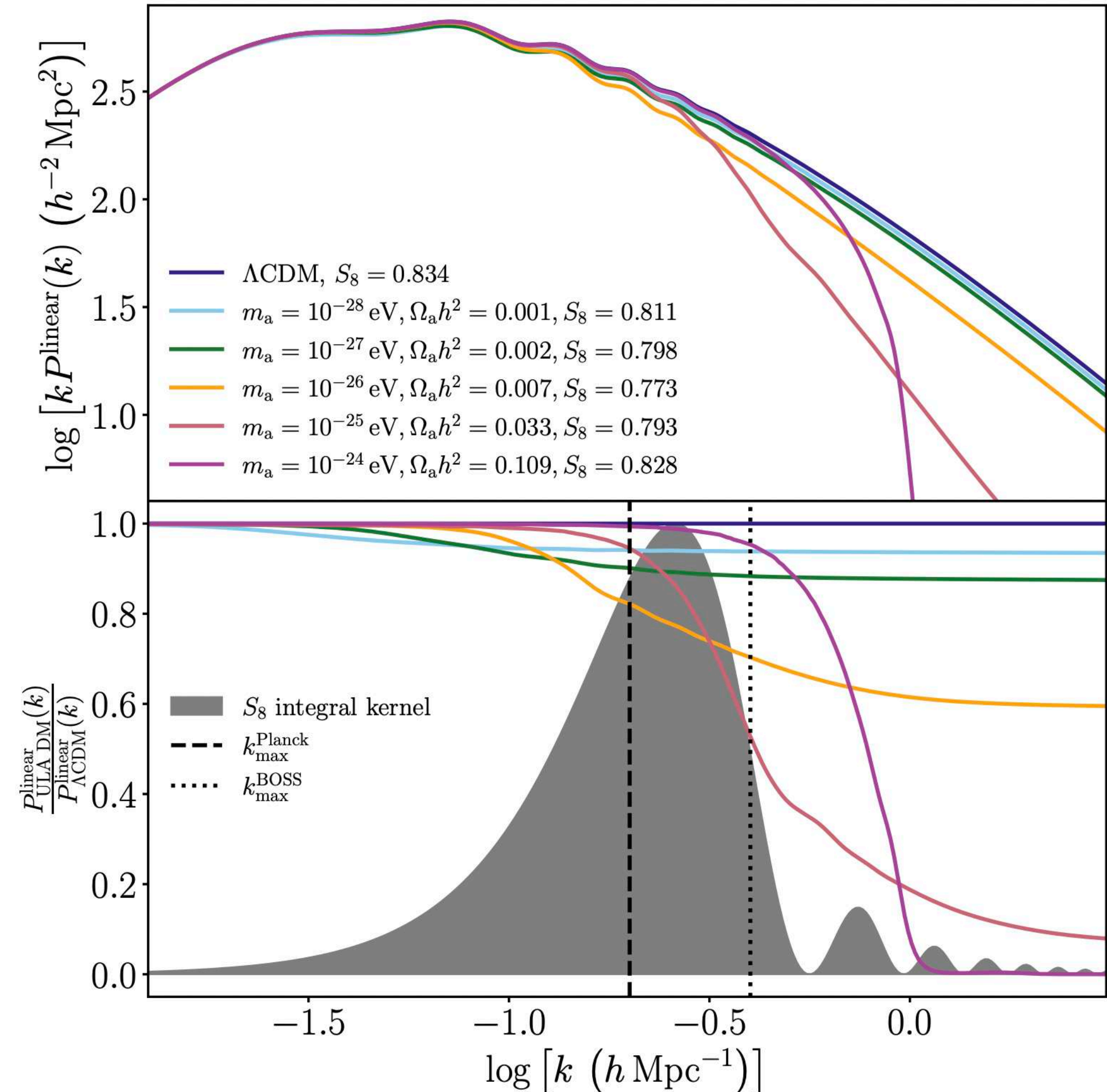
$$S_8 = \sqrt{\frac{\Omega_m}{0.3}} \sigma_8$$

The presence of ULAs can significantly lowers S_8 for:

$$m_a \in [10^{-27}, 10^{-25}] \text{ eV}$$

S_8 is lowered because the Jeans scale today for $m_a = 10^{-25} - 10^{-26} \text{ eV}$ is about $\lambda_J = 4 - 12 h^{-1} \text{ Mpc}$

from 2.6σ to 1.7σ



*Is there a S8 **tension**?*

The jury is still out, but the evidence from some collaborations have been dropping; KiDS compatible with Planck.

Hard systematics and modelling. Huge effort from the collaborations to sort this, including joint analysis.

Future

Improved analysis; combined/hybrid; improved modeling

DESI

Future LSS probes: Euclid

the CMB-BAO tension

Observations - Stage 3 and 4

From the ones we already have results, we already learned a lot of new things!!!

Photometric and spectroscopic surveys

2022-
18,000 deg²
8.4m
ugrizy

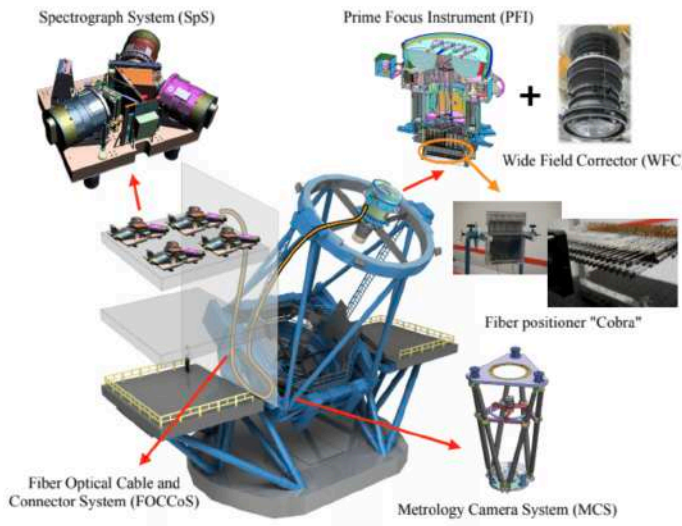


Vera Rubin Observatory
Legacy Survey of Space & Time

DESI



Prime Focus Spectrograph (PFS)

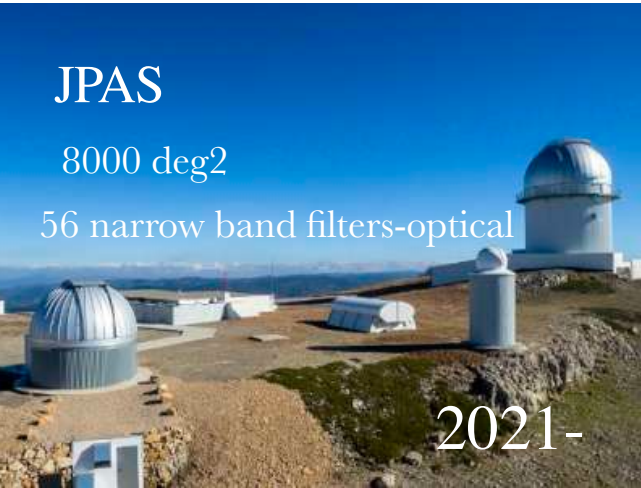


2022-
15,000 deg²
1.2m Optical/NIR



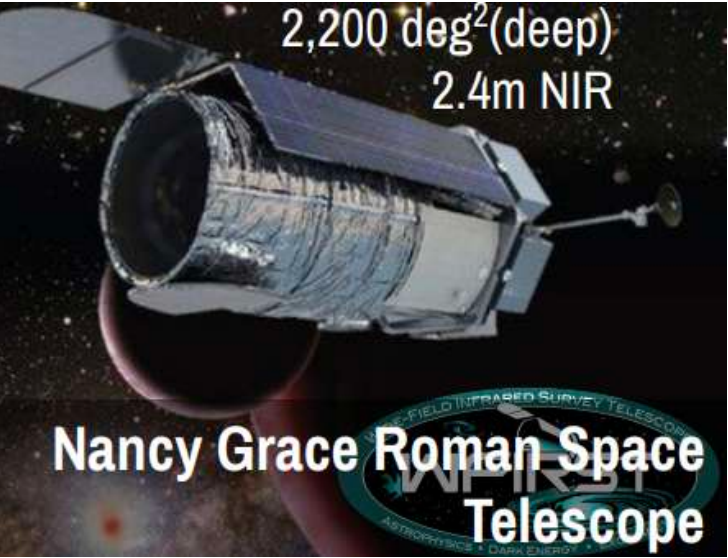
Euclid Mission

JPAS
8000 deg²
56 narrow band filters-optical



2021-

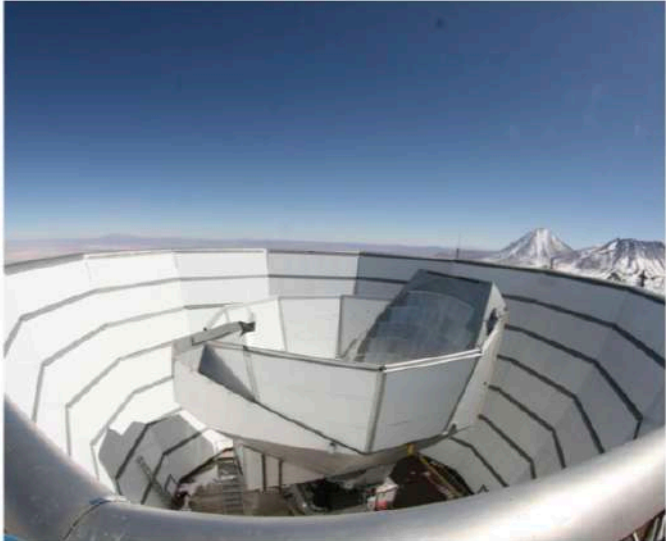
2,200 deg²(deep)
2.4m NIR



Nancy Grace Roman Space Telescope

CMB

ACT



SPT



AliCPT



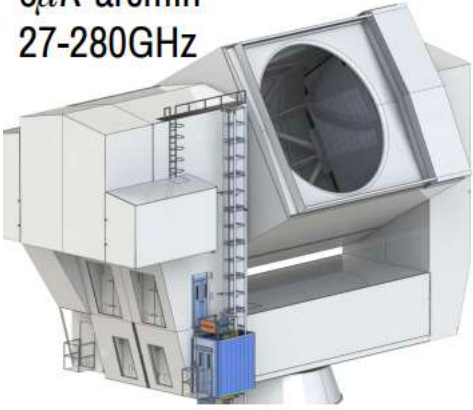
GWs

LiteBIRD



Full sky
100 μK-arcmin
40-402GHz

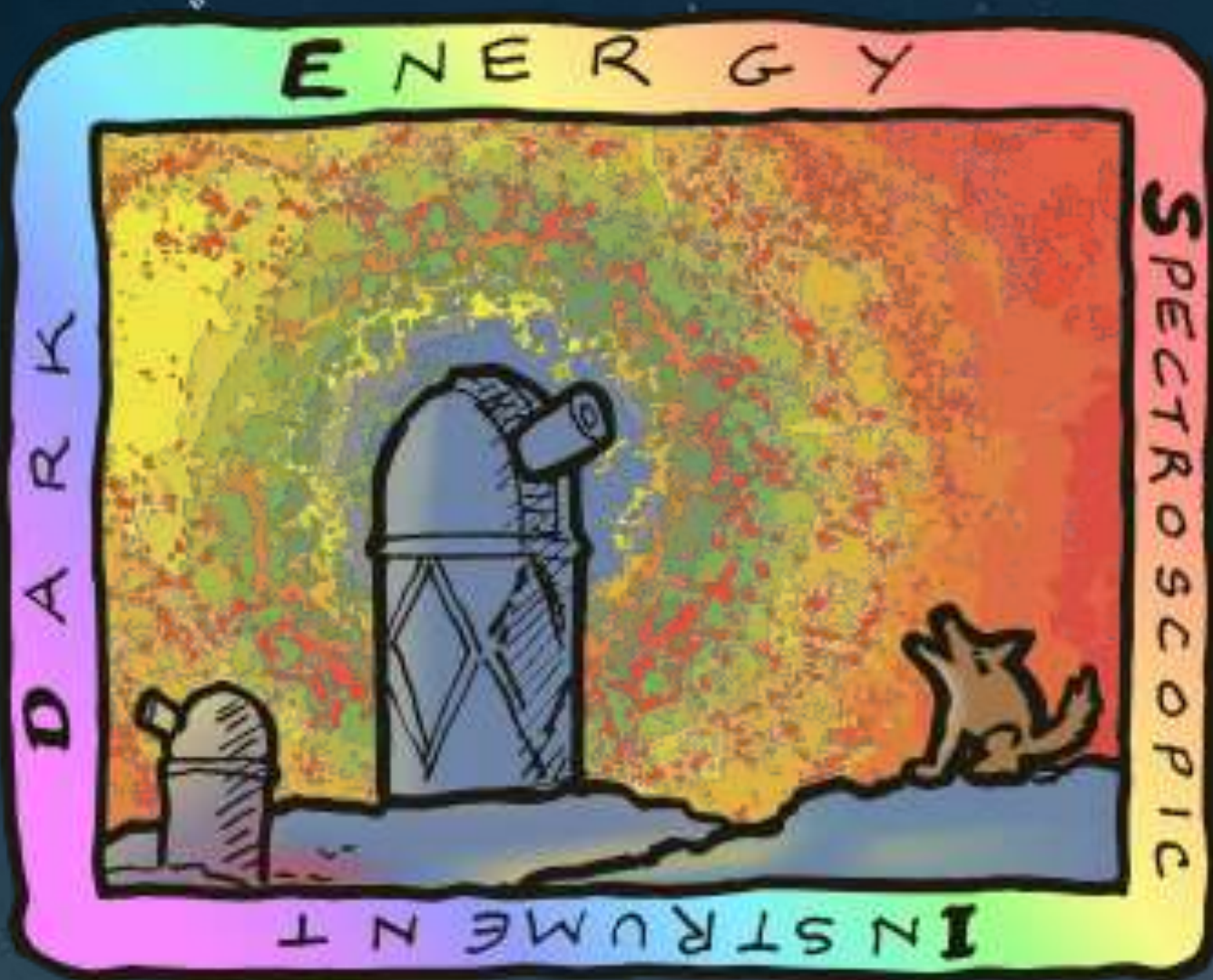
2021
16,000 deg²
6 μK-arcmin
27-280GHz



SIMONS OBSERVATORY

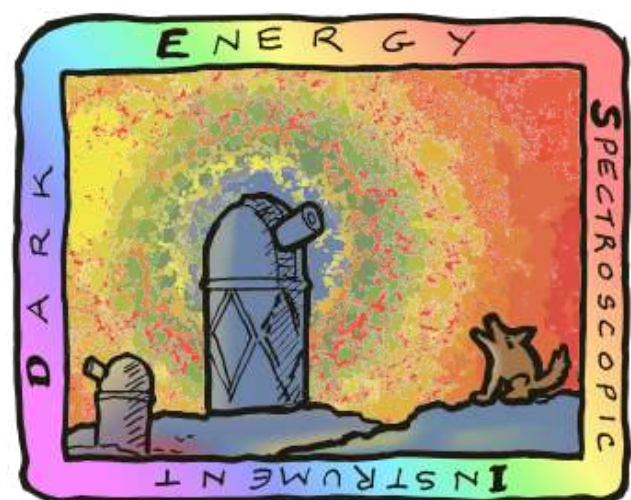
CMB-S4
Next Generation CMB Experiment

21cm



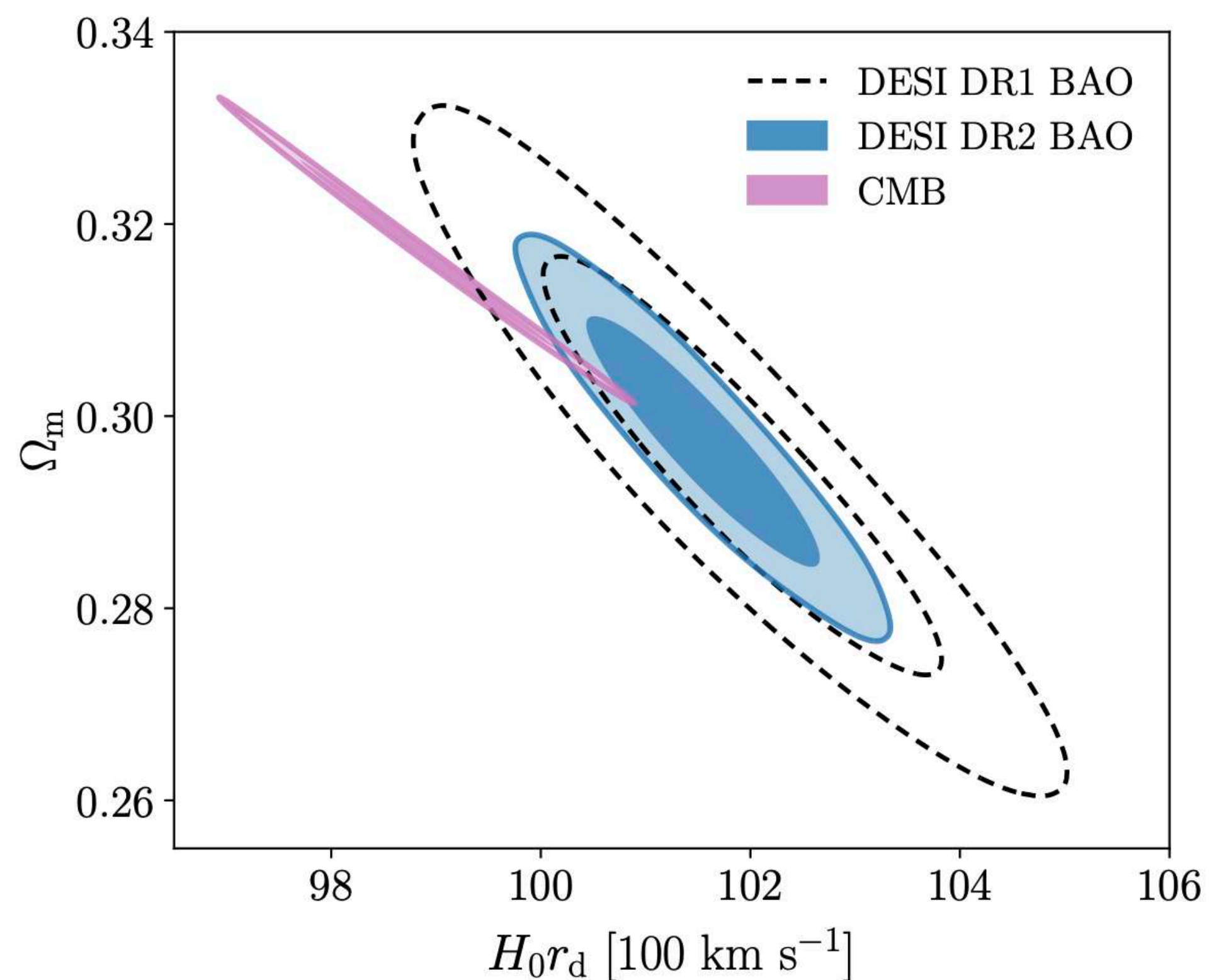
The Dark Energy Spectroscopic Instrument (DESI)





*The Dark Energy Spectroscopic Instrument - **DESI***

Results: LCDM



- DR2: 40% Improvement in the precision on and compared to DR1

$$\left. \begin{aligned} \Omega_m &= 0.295 \pm 0.015, \\ r_d h &= (101.8 \pm 1.3) \text{ Mpc}, \end{aligned} \right\} \text{ DESI BAO}$$

- Constraint: $\sim 2.3\sigma$ away from *Planck* (*DR1*: $\sim 1.9\sigma$)

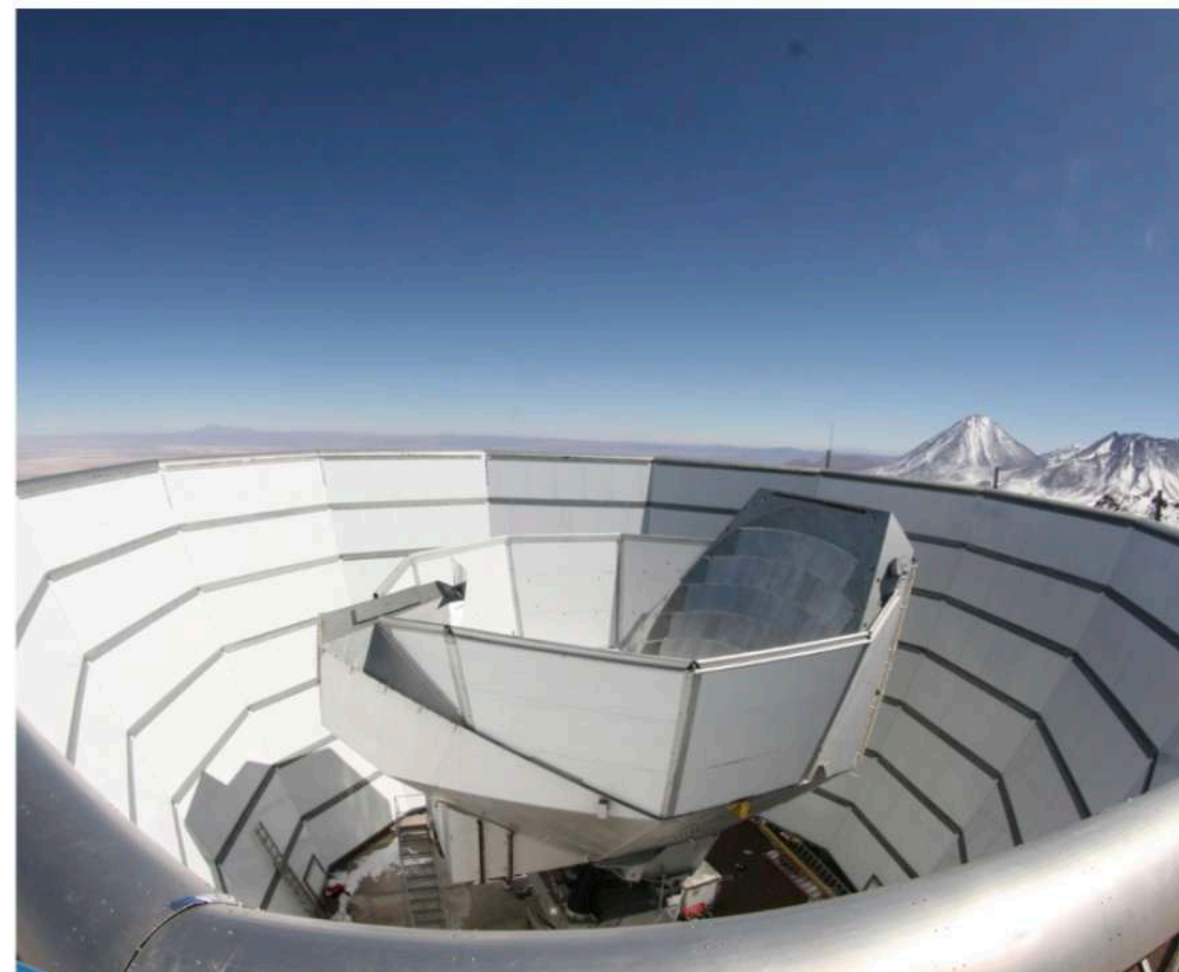
Stage 3 *CMB* experiments

Planck



Final release **2018**
 $f_{\text{sky}} = 70\%$ for science
5-10 arcmin resolution
9 bands from 30-857 GHz

ACT



Observations **2008-2022**
 $f_{\text{sky}} \sim 30\%$ for science
5x Planck resolution
 $\frac{1}{3}$ Planck white noise RMS
Precise polarization measurements

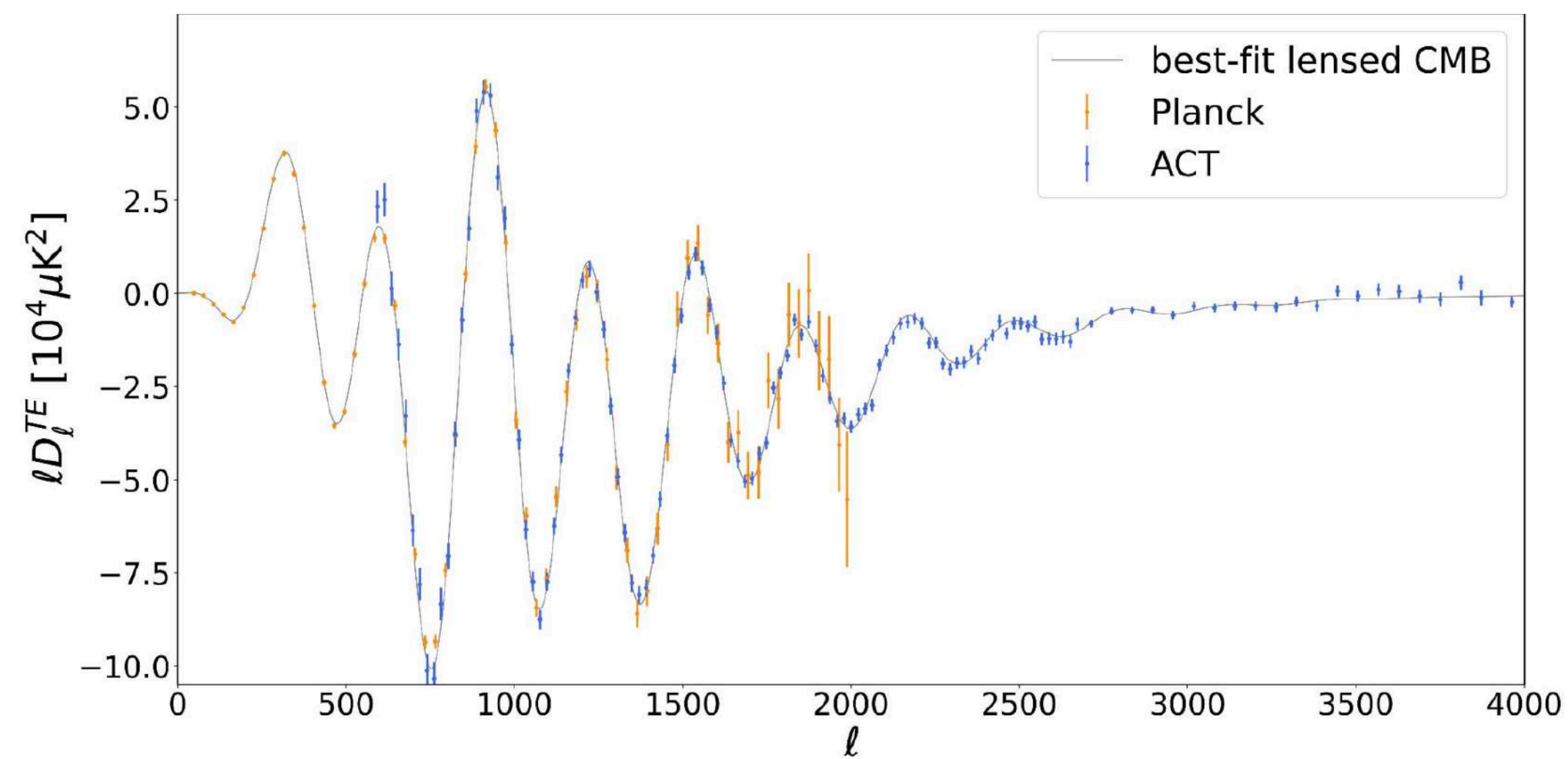
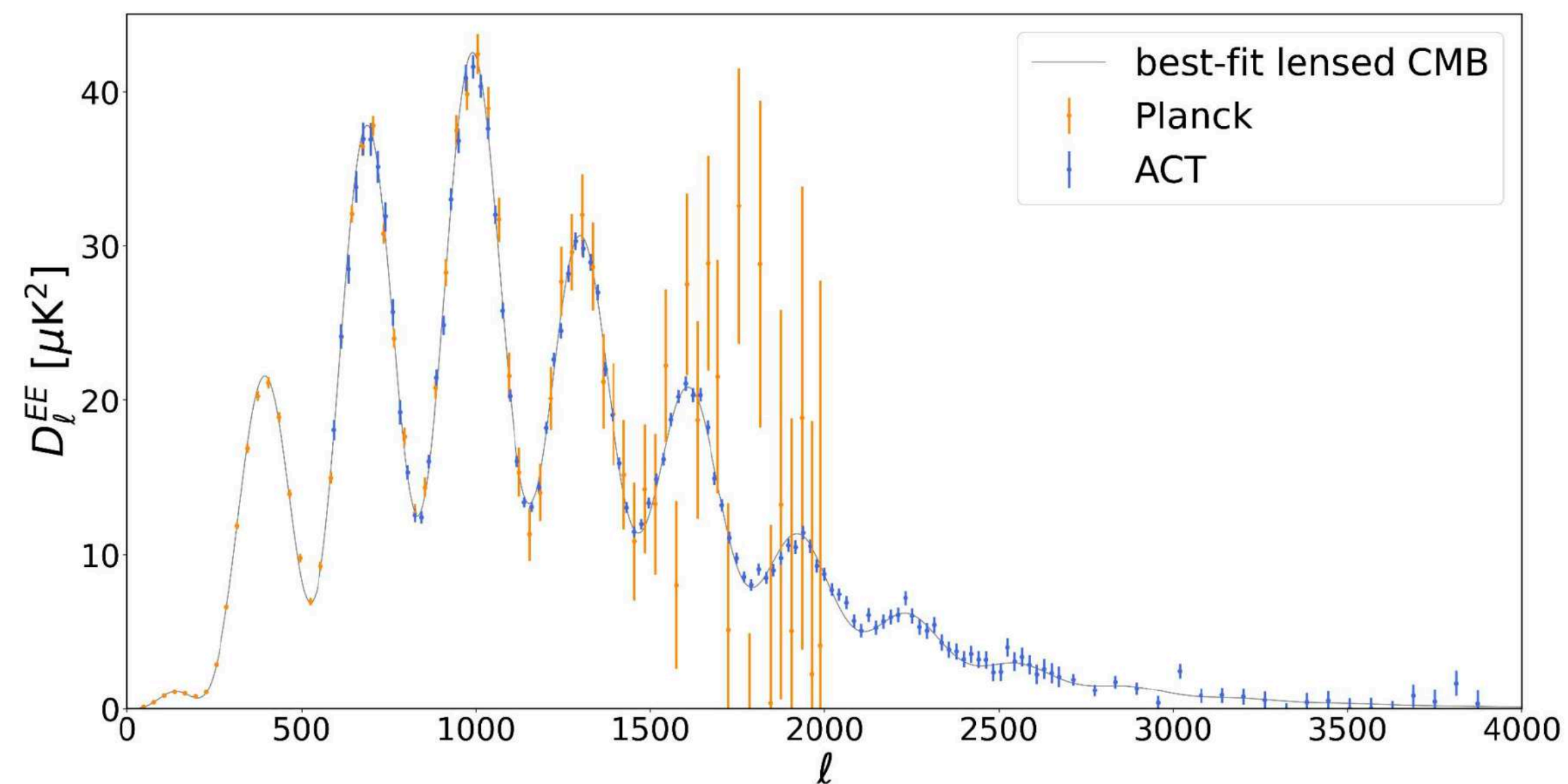
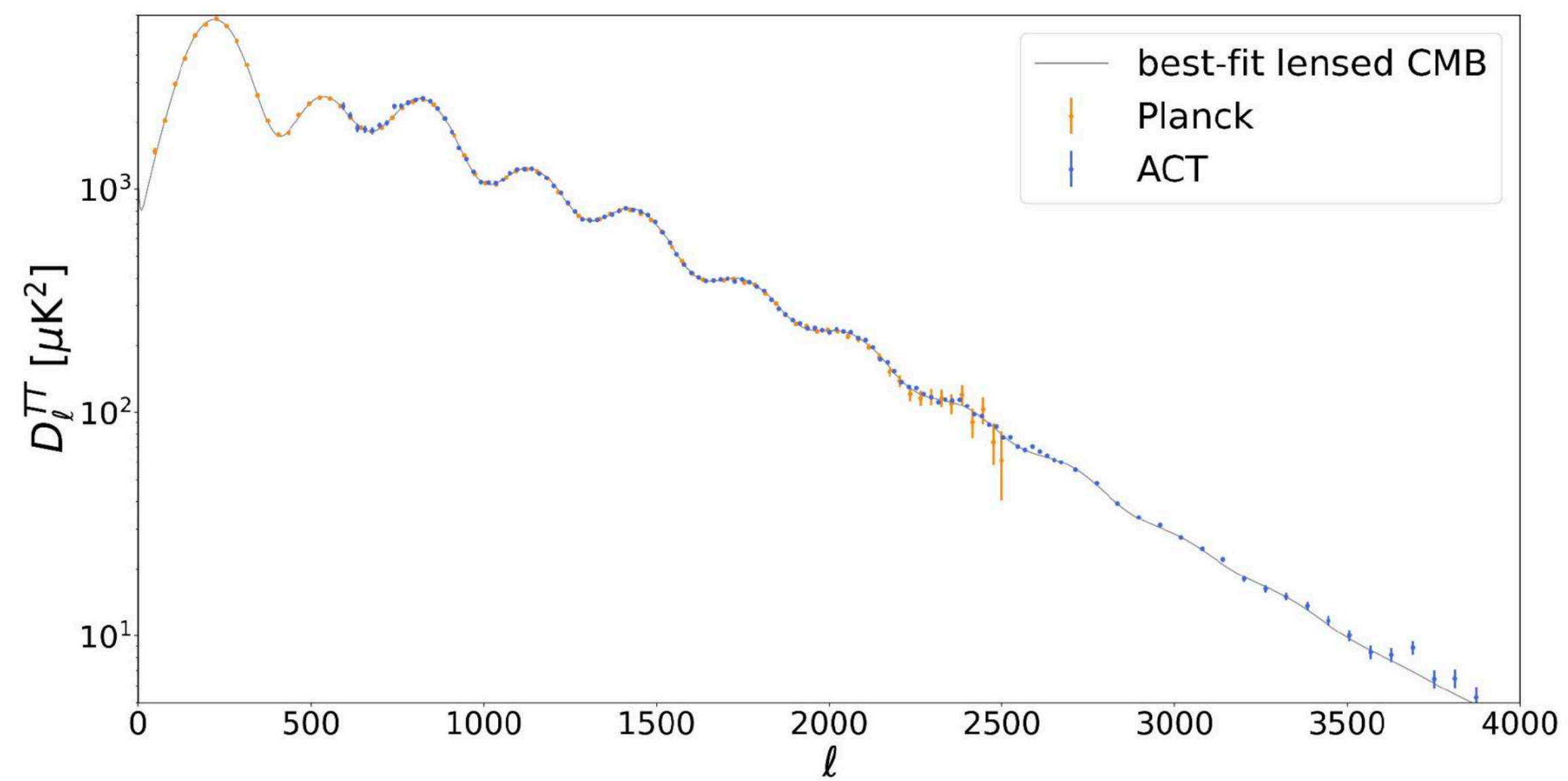
March 2025- DR6 Biggest
data improvement since Planck!

SPT



Observations **2007-2024(27)**
 $f_{\text{sky}} \sim 4-10\%$ for science
Noise 6-17x lower than Planck
1-1.6 arcmin resolution
90, 150, 220 GHz

Atacama Cosmology Telescope - *ACT*



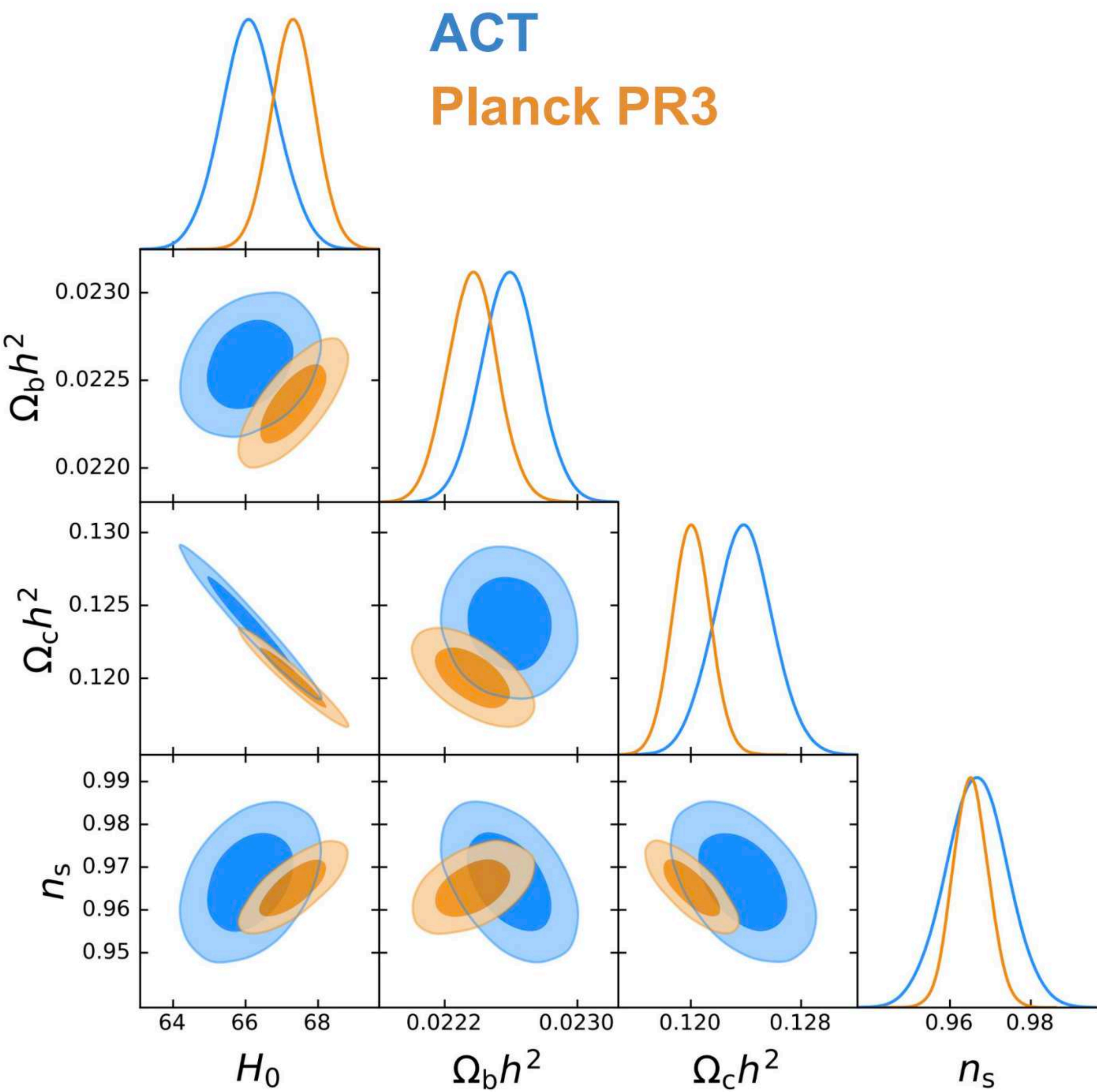
Atacama Cosmology Telescope

- ACT

ΛCDM

Concordance with Planck (PR3): 1.6σ

ACT	
Parameter	
<i>Sampled</i>	
θ_{MC}	0.0104056 ± 0.0000031 ..
$\Omega_{\text{b}} h^2$	0.02259 ± 0.00017
$\Omega_{\text{c}} h^2$	0.1238 ± 0.0021
$\log(10^{10} A_{\text{s}})$	3.053 ± 0.013
n_{s}	0.9666 ± 0.0077
τ	$0.0562^{+0.0053}_{-0.0063}$
<i>Derived</i>	
H_0	66.11 ± 0.79
Ω_{m}	0.337 ± 0.013
σ_8	0.8263 ± 0.0074

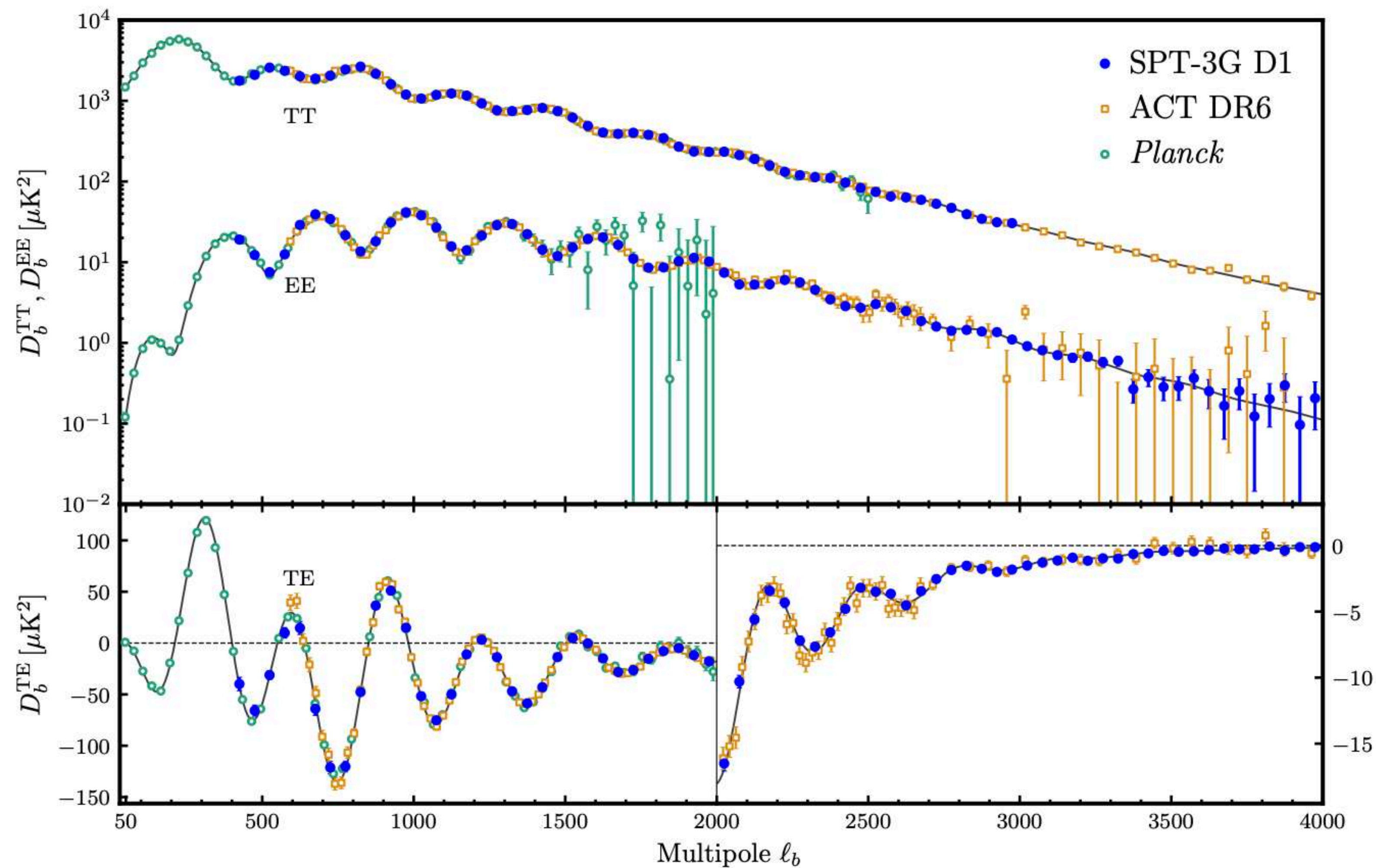


South Pole Telescope - SPT3G



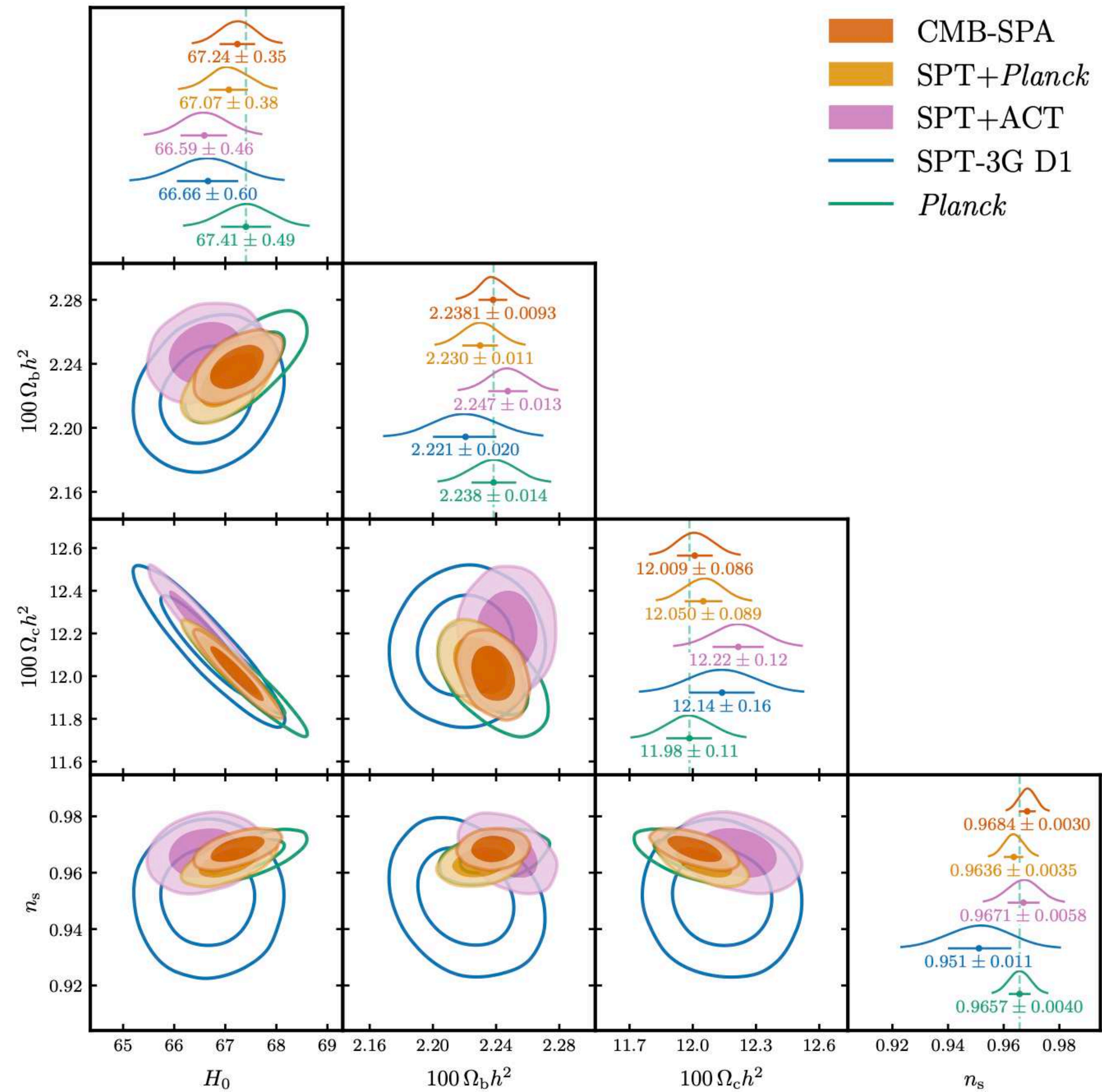
South Pole Telescope - *SPT3G*

June 2025: Latest data release



South Pole Telescope - *SPT3G*

Concordance with Planck and ACT

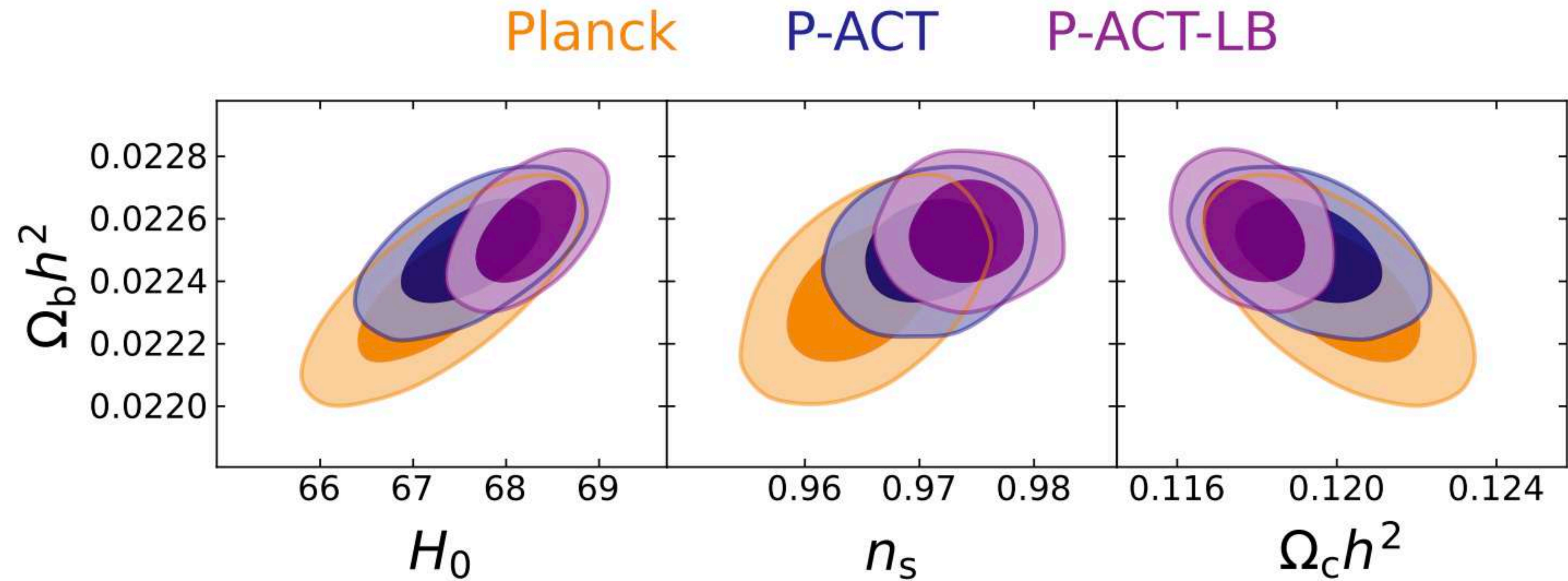


These new CMB and LSS data showed amazing constraining power

Next obvious step:

combine these data sets

Combining CMB and *LSS* data



P: Planck
L: ACT lensing
B: BAO from DESI

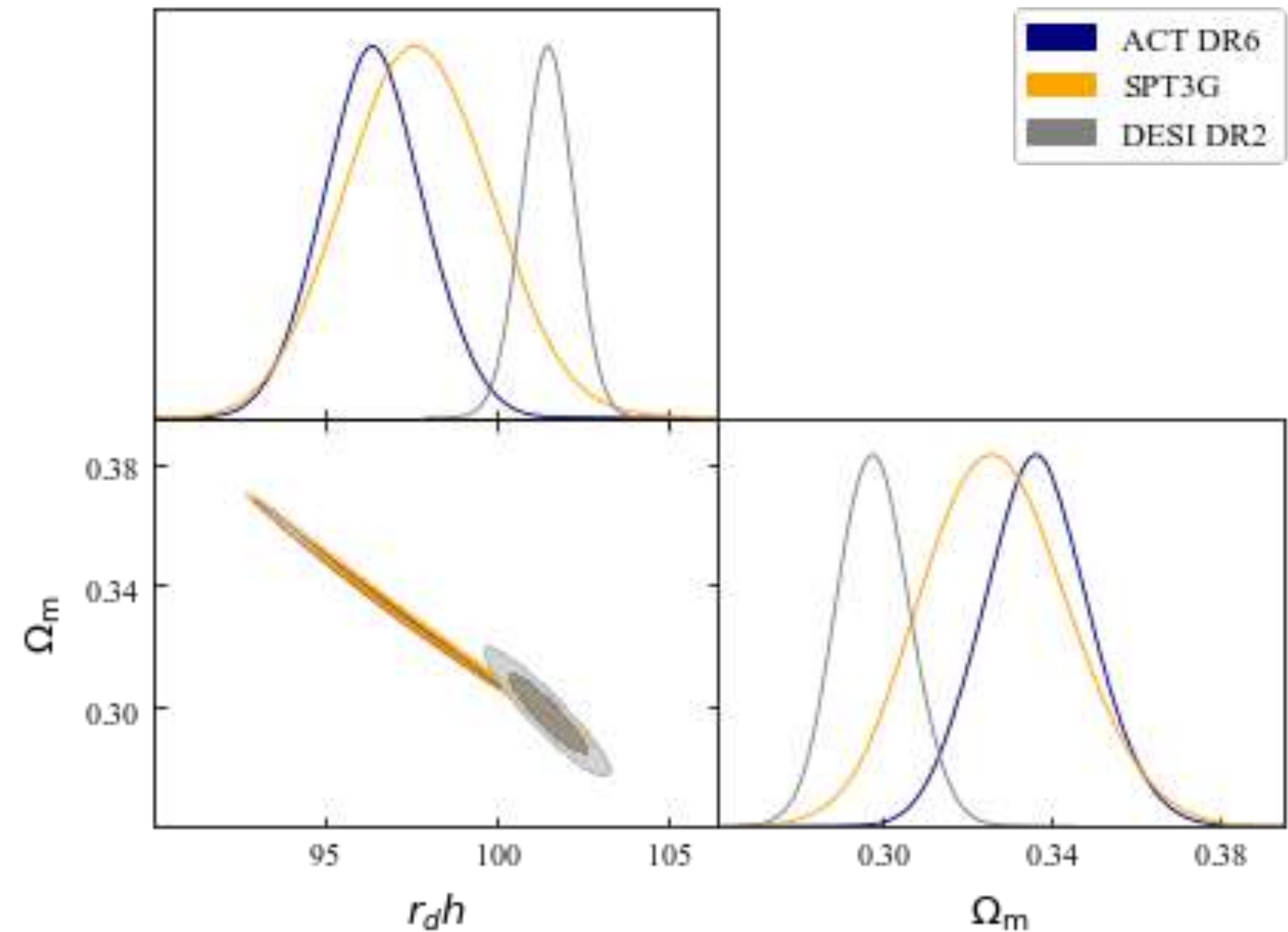
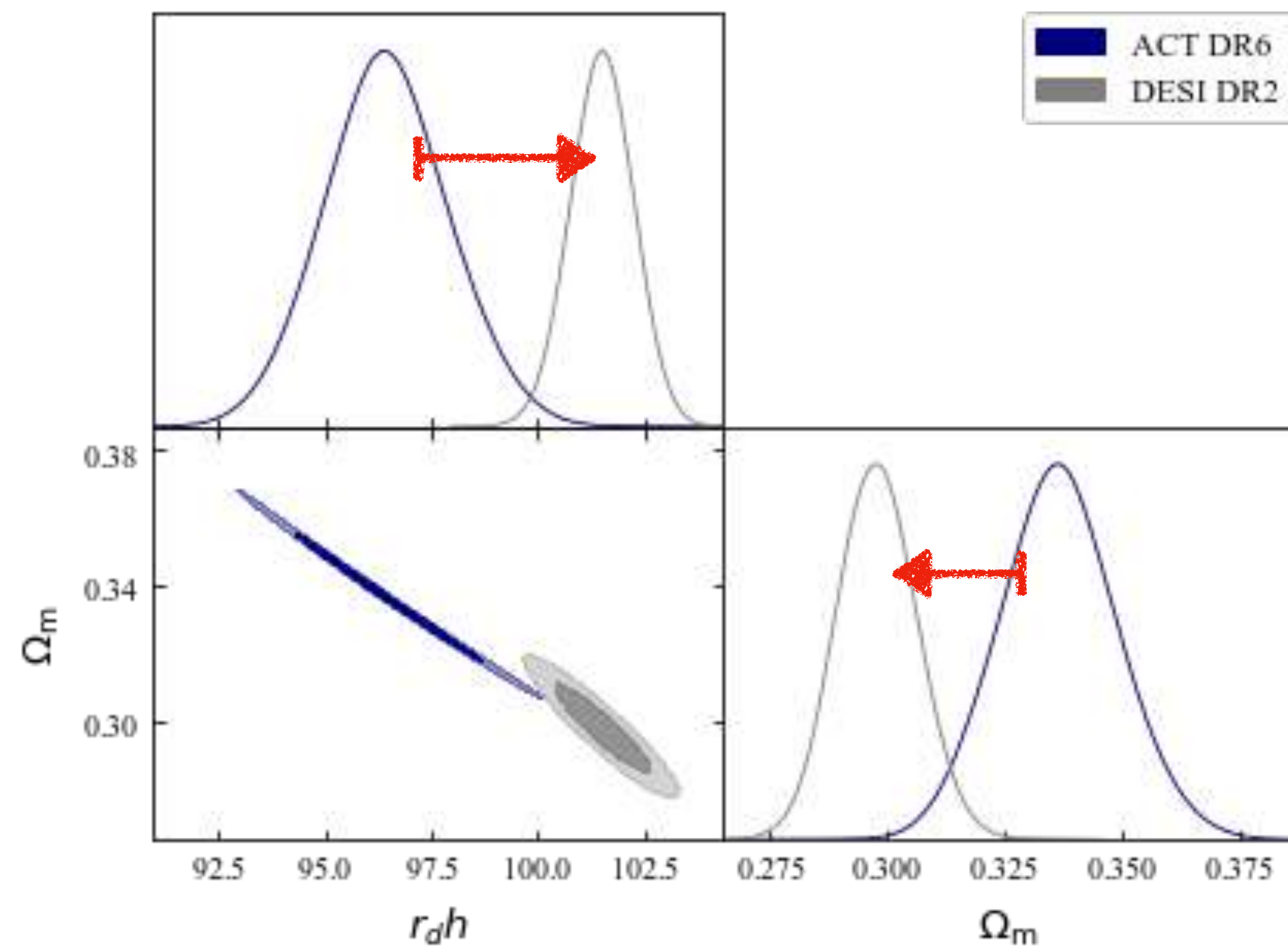
BUT...

BAO - CMB *tension*

The BAO-CMB Tension and Implications for Inflation
EF, E McDonough, L Balkenhol, R Kallosh, L Knox, and A Linde,
2507.12459

Are **ACT** and **SPT** compatible with **DESI** ?

(or BAO-CM tension or Ω_M tension)

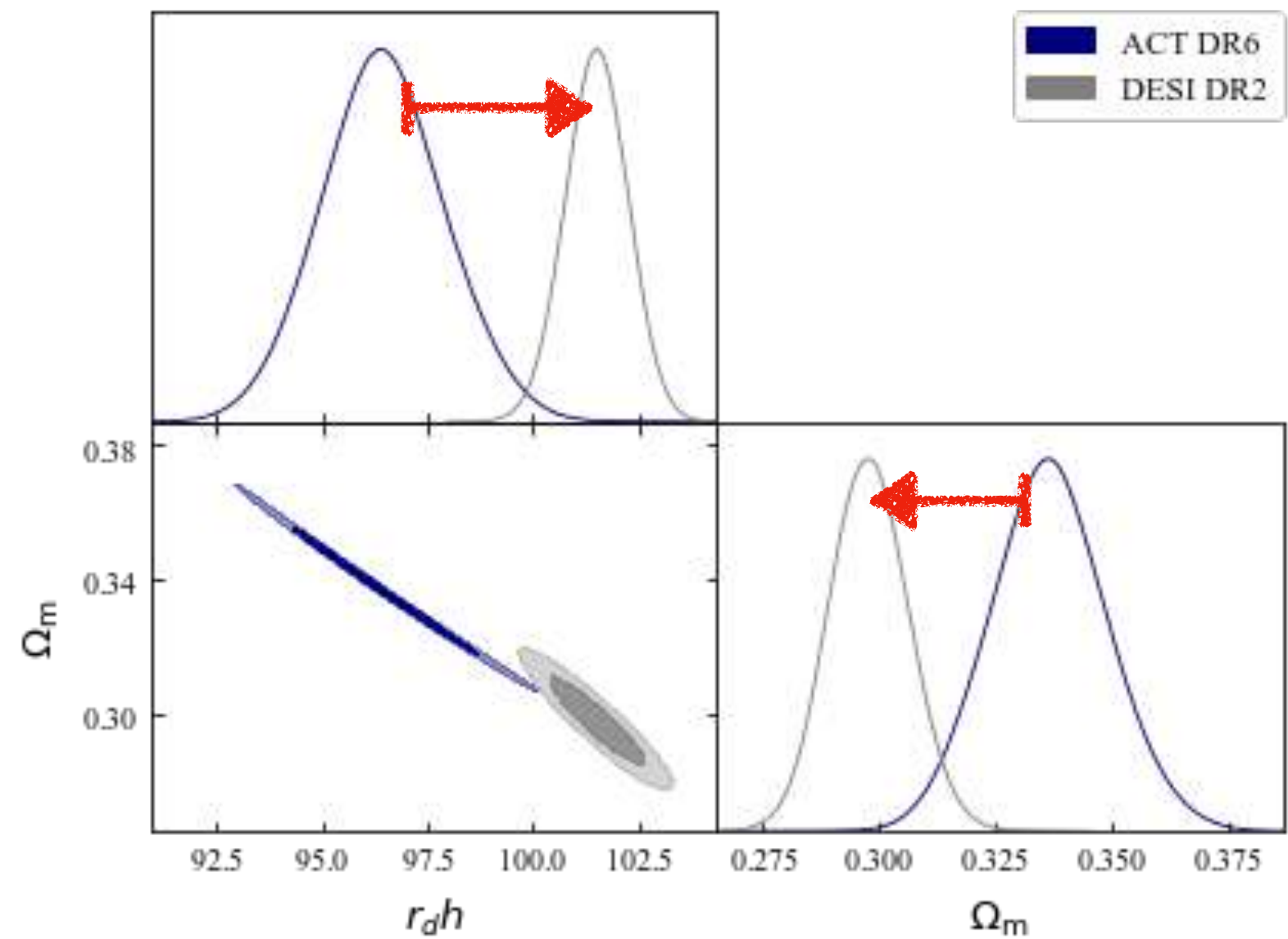


- 2d posteriors show small overlap
- 1d posterior shifted

Discrepancy (or tension) in the values of $r_d h$ and Ω_M measured from CMB and DESI BAO!

BAO - CMB *tension*

Discrepancy or tension in the values of $r_d h$ and Ω_M measured from CMB and DESI BAO!

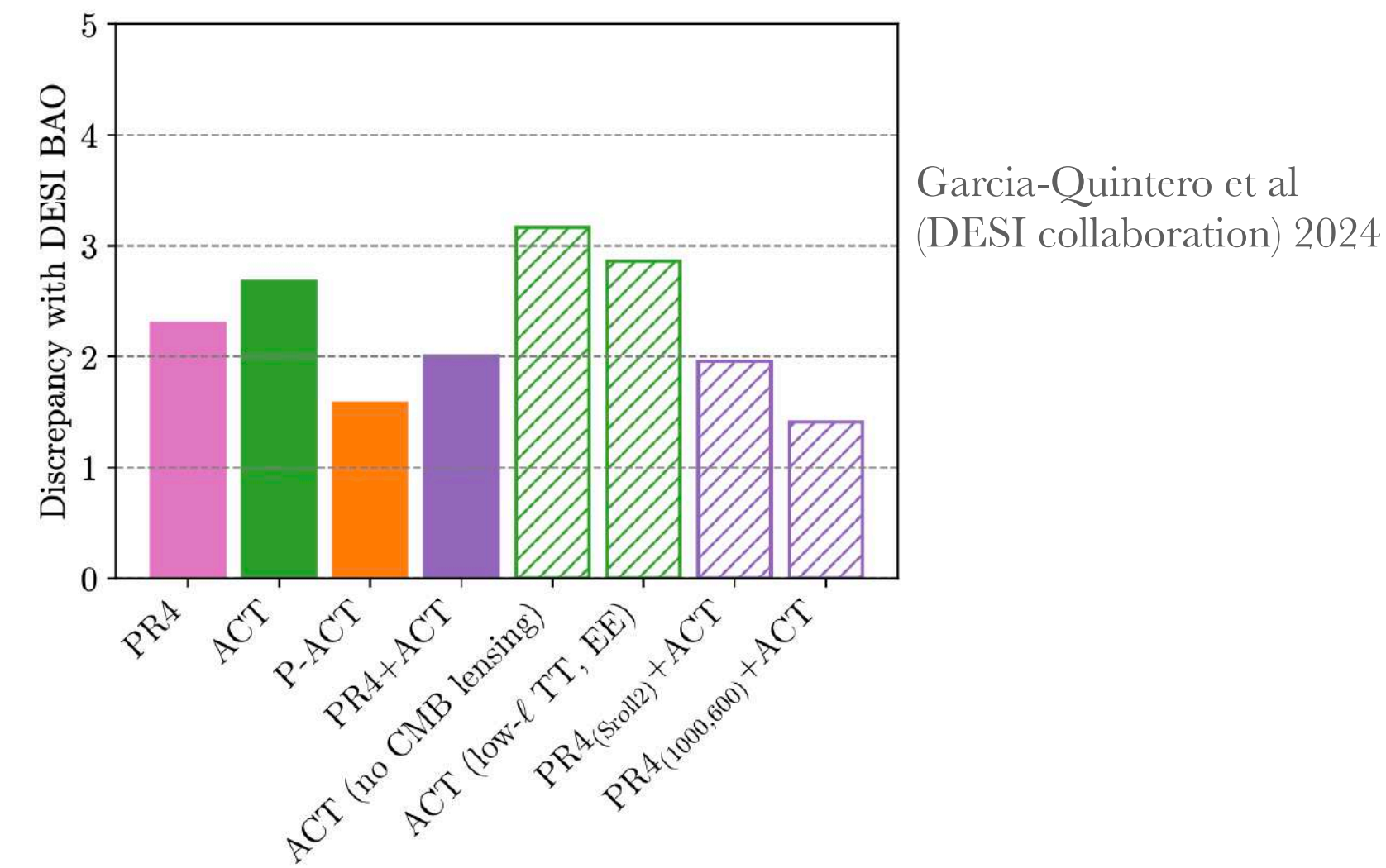


ACT and SPT present parameter-level offset wrt to DESI !

Translating the differences in the Ω_m and $r_d h$ constraints from CMB and DESI data to equivalent statistical significances for a one-dimensional Gaussian distribution:

2 – 4 σ discrepancy between CMB and BAO datasets

The BAO-CMB Tension and Implications for Inflation
Elisa G.M. Ferreira et al, 2507.12459



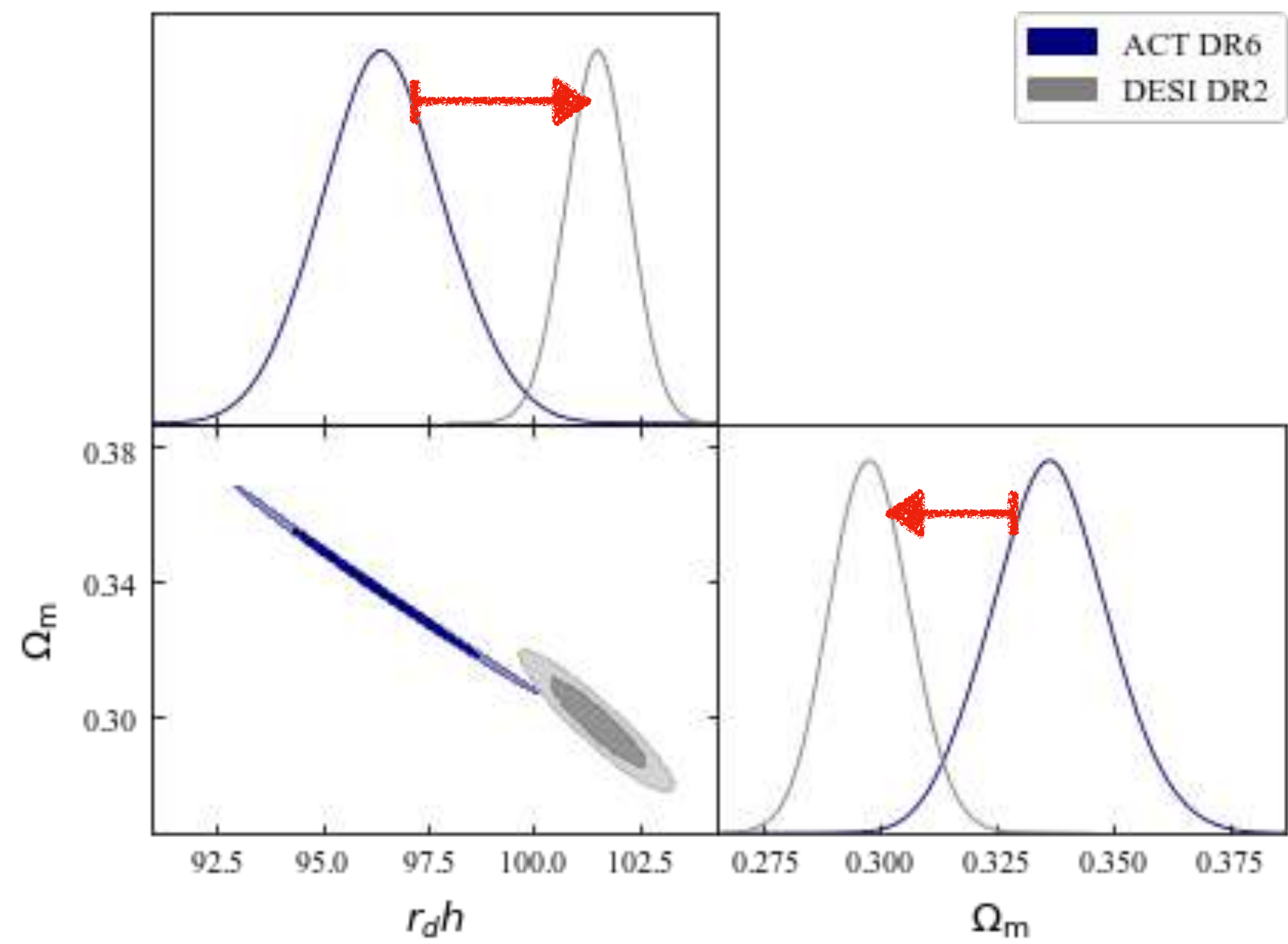
	$100 \Omega_m$	$h r_d$ [Mpc]	Distance to DESI
CMB-SPA	31.66 ± 0.50	98.89 ± 0.63	2.8σ
SPT+ACT	32.77 ± 0.72	97.51 ± 0.87	3.7σ
SPT+Planck	31.89 ± 0.54	98.63 ± 0.67	3.0σ
ACT DR6	33.0 ± 1.0	97.2 ± 1.2	3.1σ
SPT-3G D1	32.47 ± 0.91	97.9 ± 1.1	2.5σ
Planck	31.45 ± 0.67	99.18 ± 0.84	2.0σ
DESI	29.76 ± 0.87	101.52 ± 0.73	

Camphuis et al (SPT collaboration) 2025

BAO - CMB *tension*

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Discrepancy or tension in the values of $r_d h$ and Ω_M measured from CMB and DESI BAO!

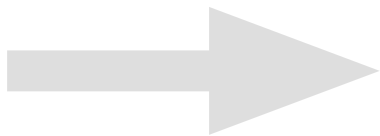


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Camphuis et al (SPT collaboration) 2025

ACT and SPT might not be compatible with DESI !

2 – 4 σ discrepancy between CMB and BAO datasets



Is it even valid to combine them?

SPT collaboration doesn't combine their data with DESI for this reason

Caution required!

*How collaborations assess the compatibility between **data sets***

ACT and DESI

- Parameter-shift test or parameter level consistency tests: compare Λ CDM posteriors (ACT vs DESI BAO)
- BAO distance comparison: ACT-inferred distances vs DESI BAO measurements; ACT+Planck fully consistent.
- Cross-correlation study between ACT DR6 CMB-lensing maps and DESI Luminous Red Galaxies (LRGs) (redshift range ~ 0.4 – 1.0) detects the signal at $\sim 38\sigma$ (ACT only) and $\sim 50\sigma$ (ACT + Planck Collaboration PR4) level.

Caveats:

- Parameter-shift test:
 - Shift in the BAO and other parameters
 - Posterior 2d overlap (or one-dimensional posterior)
 - Goodness of fit
- Covariance

PS: Other cosmological parameters might present smaller shift than the BAO ones, which might lead to not noticing this discrepancy.

- The BAO-CMB Tension and Implications for Inflation

Elisa G.M. Ferreira et al, 2025

- Cosmological implications of DESI DR2 BAO measurements in light of the latest ACT DR6 CMB data, DESI collaboration 2025

"While ACT alone exhibits a tension with DESI exceeding 3σ within the Λ CDM model, this discrepancy is reduced when ACT is analyzed in combination with Planck."

- Camphuis et al (SPT collaboration) 2025

"We forego reporting the combination of DESI with SPT+ACT as it does not meet our 3σ consistency requirement; if we were to do so, differences in the favored Ω_m and h_{rd} values would also lead to sizeable shifts in other cosmological parameters in the joint constraints compared to the CMB-preferred values."

"...while we find that the results from SPT-3G, Planck, and ACT DR6 are in excellent agreement and consistent with Λ CDM, we report a growing inconsistency with the BAO results from DESI DR2"

Consequences for *the spectral index n_s*

The BAO-CMB Tension and Implications for Inflation
Elisa G.M. Ferreira et al, 2507.12459

The BAO-CMB tension has important consequences for n_s

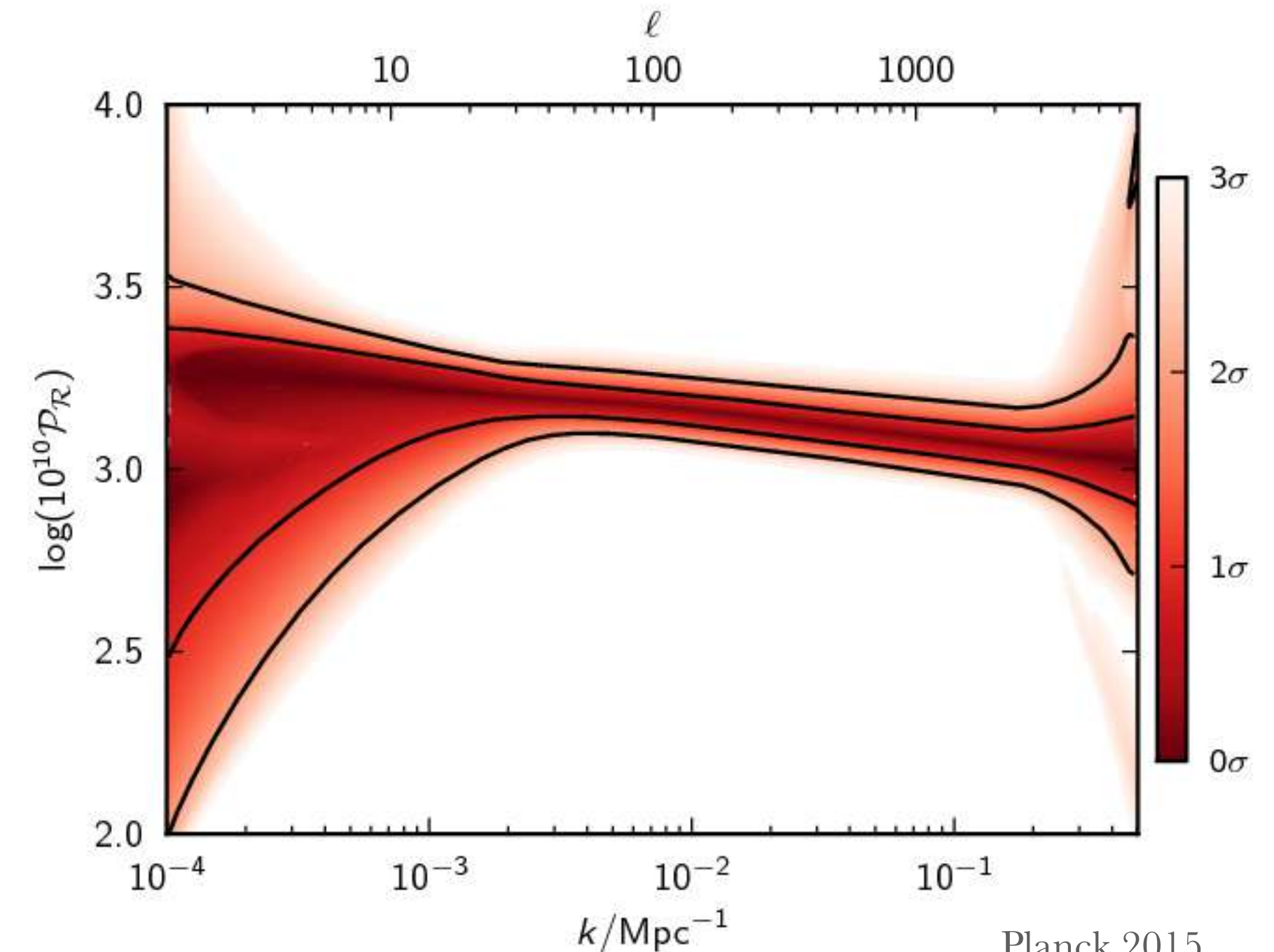
Early universe and the *spectral index*

Prediction from inflation: primordial density fluctuations that are nearly Gaussian and adiabatic and are described by a nearly scale-invariant power spectrum

- Confirmed by observations (CMB and LSS)
- Scale invariant excluded!

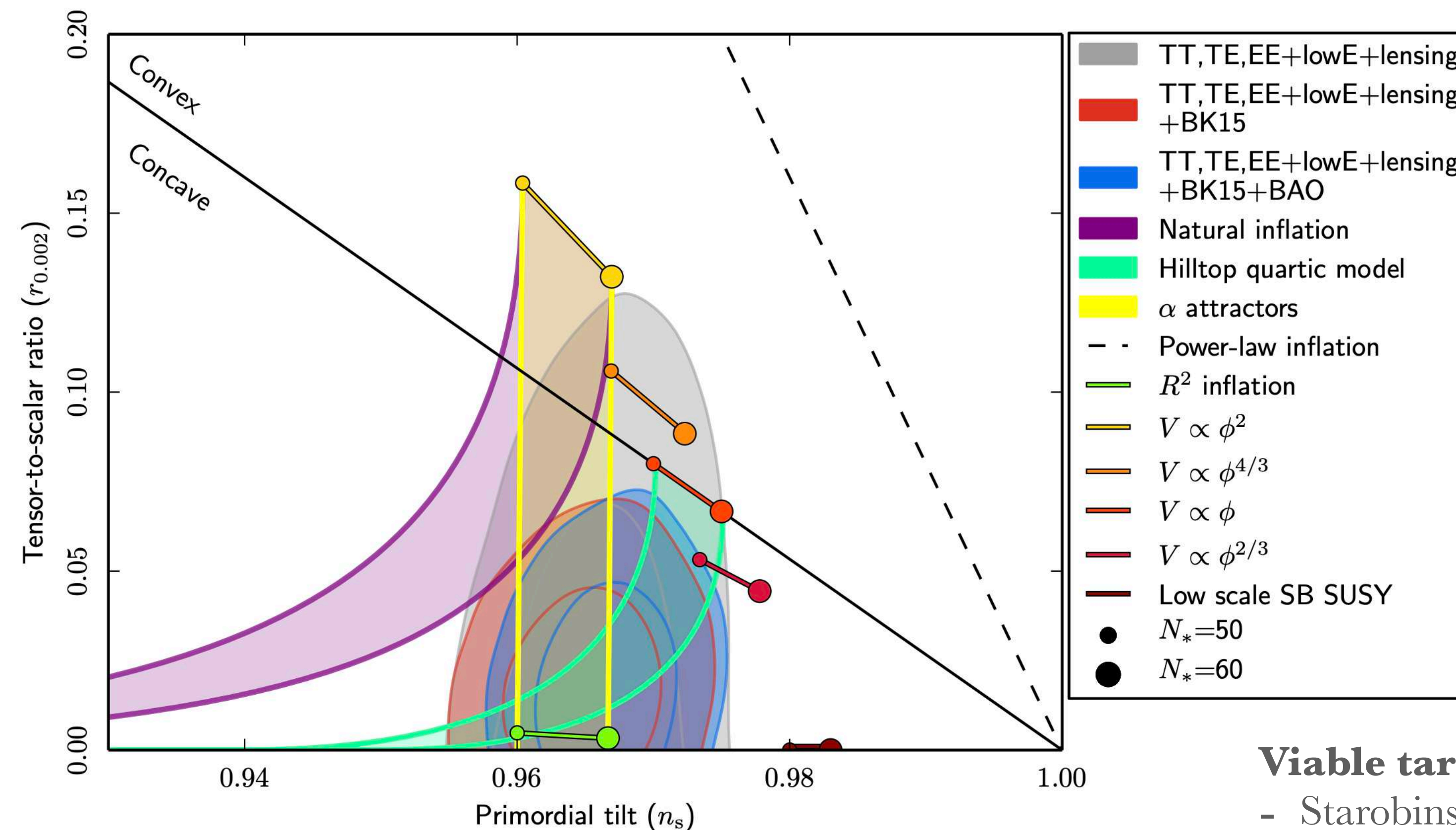
$$P(k) = A_S \left(\frac{k}{k_*} \right)^{n_S - 1}$$

Value of n_s : great discriminator of inflationary (and early universe) models



Early universe and the *spectral index*

Current status:



Planck 2018

$$n_s = 0.9626 \pm 0.0057 \quad (68 \% \text{ CL, } \textit{Planck} \text{ TT+lowE})$$

$$n_s = 0.9649 \pm 0.0044 \quad \tau = 0.052 \pm 0.008$$

(68 % CL, *Planck* TT,TE,EE+lowE)

Planck 2018 + lensing

$$n_s = 0.9634 \pm 0.0048$$

(68 % CL, *Planck* TT+lowE+lensing),

$$n_s = 0.9649 \pm 0.0042$$

(68 % CL, *Planck* TT,TE,EE+lowE+lensing).

Planck 2018 + lensing + BAO (BOSS)

$$n_s = 0.9665 \pm 0.0038$$

(68 % CL, *Planck* TT,TE,EE+lowE+lensing+BAO).

A_s and n_s determined with great precision ($< 1 \%$)!

Viable targets (Planck/BICEP/Keck/ACT/SPT data):

- Starobinsky model ,
- Higgs inflation and
- α -attractors (exponential - T and E α -attractor)
- Polynomial, ...

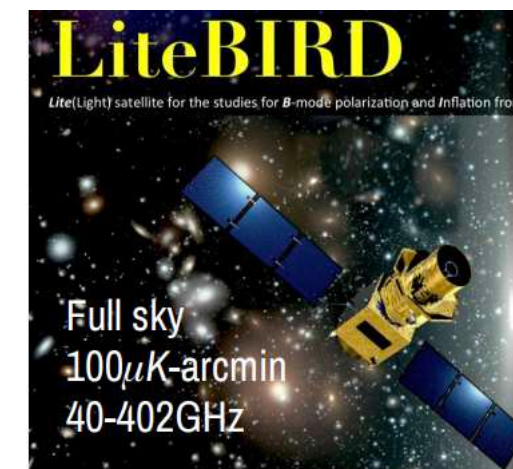
Early universe and the *spectral index*

Given that we determined A_s and n_s with great precision, ...

Next steps for early universe cosmology:

- Primordial gravitational waves
- Non-Gaussianity
- Features in the power spectrum
- New phenomenology

Main goal of the next generation of experiments:



- + LSS experiments
- + GW wxperiments
- + New probes

BUT...

In 2025, n_s comes back to the light and a new discrepancy arises

Consequences for *the spectral index n_s*

The BAO-CMB Tension and Implications for Inflation
Elisa G.M. Ferreira et al, 2507.12459

The BAO-CMB tension has important consequences for n_s

- From the correlation between Ω_m and $r_d h$, and the correlation of each of these with n_s :

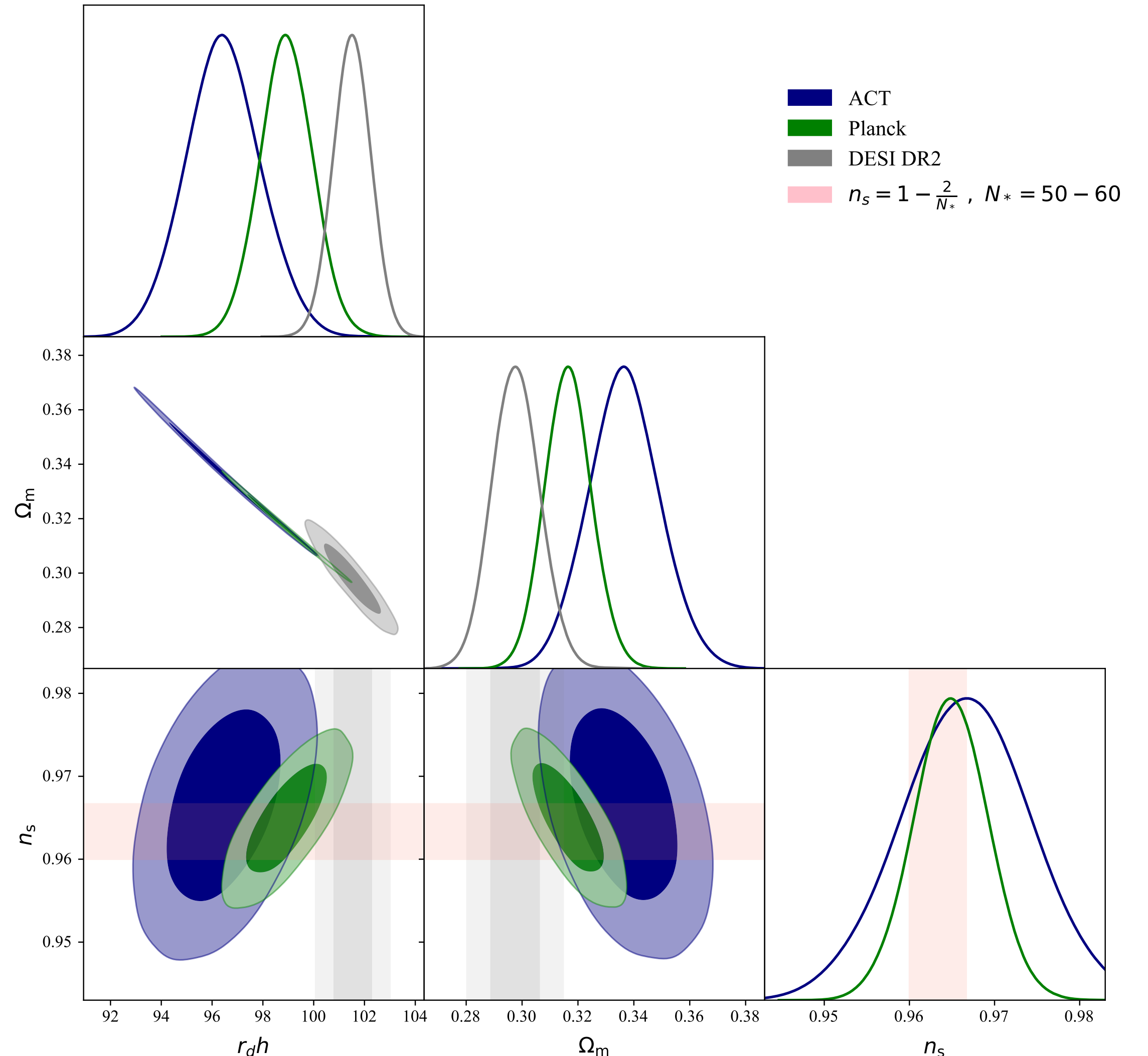
Moving Ω_m and $r_d h$, towards the DESI-preferred region, while maintaining the fit to the data, requires a **equivalent increase in n_s** .

Pink band:

To help contextualize we compare with the predicted n_s from inflation (Mukhanov & Chibisov 1981; Starobinsky 1983) compatible with 'benchmark' models

$$n_s = 1 - 2/N_*$$

$$\Rightarrow N_* = [50, 60], n_s = [0.9600, 0.9667]$$



Consequences for *the spectral index n_s*

The BAO-CMB Tension and Implications for Inflation
Elisa G.M. Ferreira et al, 2507.12459

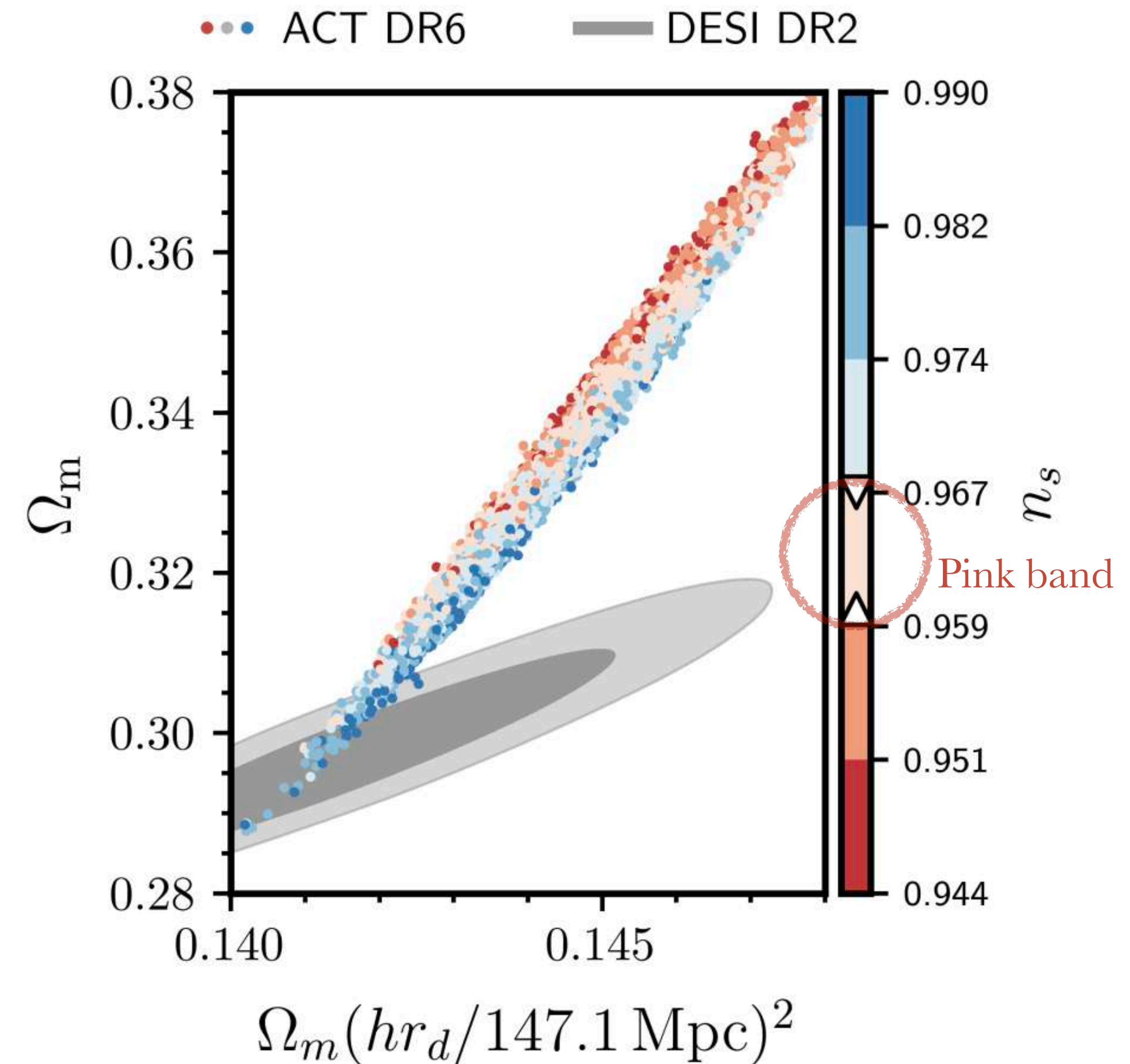
The BAO-CMB tension has important consequences for n_s

- To illustrate, I show constraints on Ω_m and $r_d h$, from ACT DR6 and DESI DR2.
- ACT barely enters DESI, and when it does $n_s > 0.97$
- DESI only overlaps with ACT for large values of n_s

In the $n_s - r_d h$ plane: there is **almost no simultaneous overlap** between the

- ACT 2σ contour,
- the 2σ DESI constraint on rdh , and
- the band of n_s values predicted by benchmark inflation scenarios!

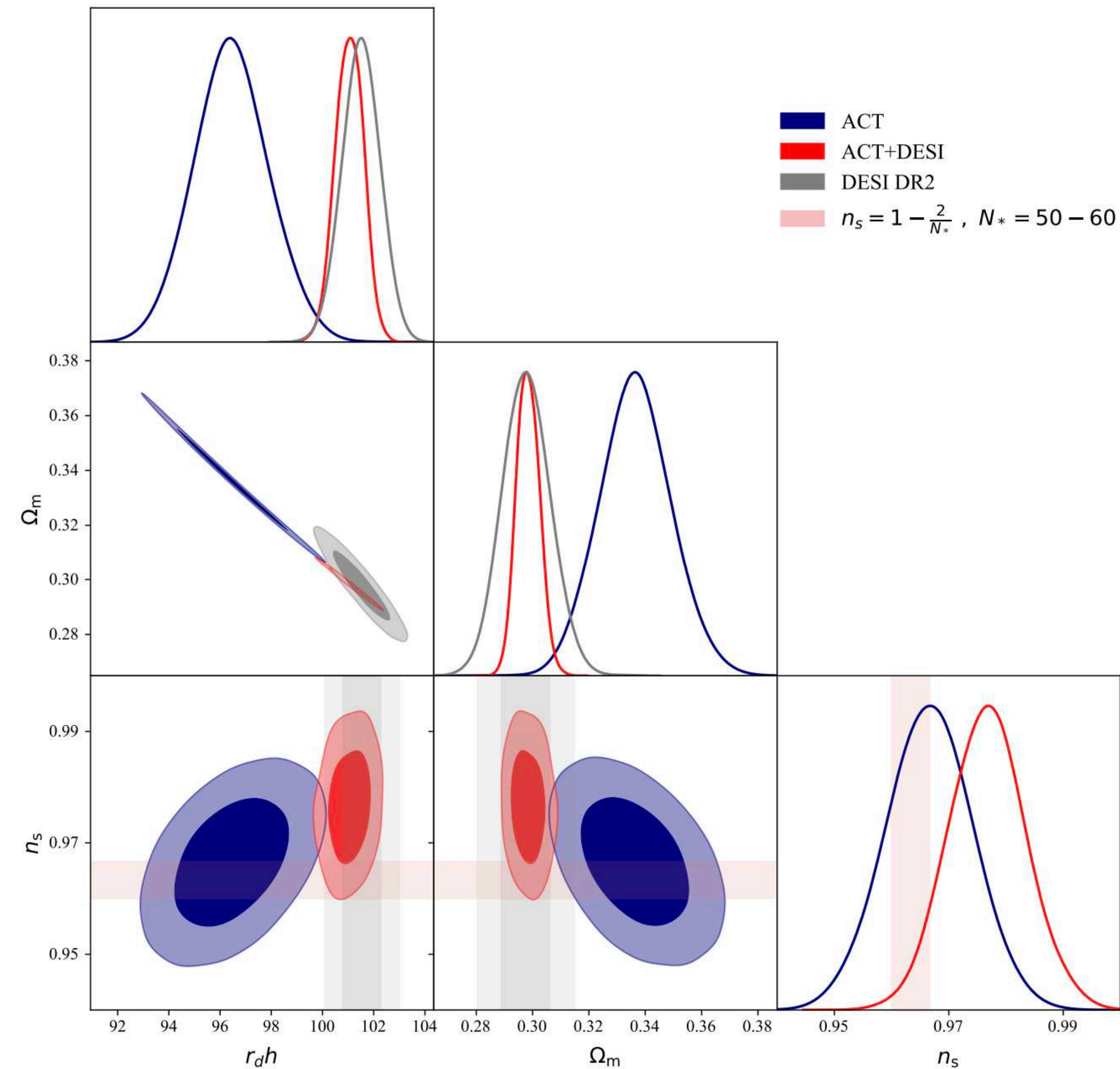
*This **discrepancy** suggests that there is little evidence that **ACT** and **DESI** constraints are **both right**, while at the same time Λ CDM with a benchmark inflation scenario holds true; **something has to give**.*



Consequences for *the spectral index n_s*

The BAO-CMB Tension and Implications for Inflation
Elisa G.M. Ferreira et al, 2507.12459

Combining ACT DR6 and DESI DR2



Consequences for *the spectral index n_s*

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Elisa G.M. Ferreira et al, 2507.12459

Combining ACT DR6 and DESI DR2

- Significant shift in the BAO parameters Ω_m and $r_d h$,
→ corresponding shift of n_s along the degeneracy direction of the fit to ACT alone

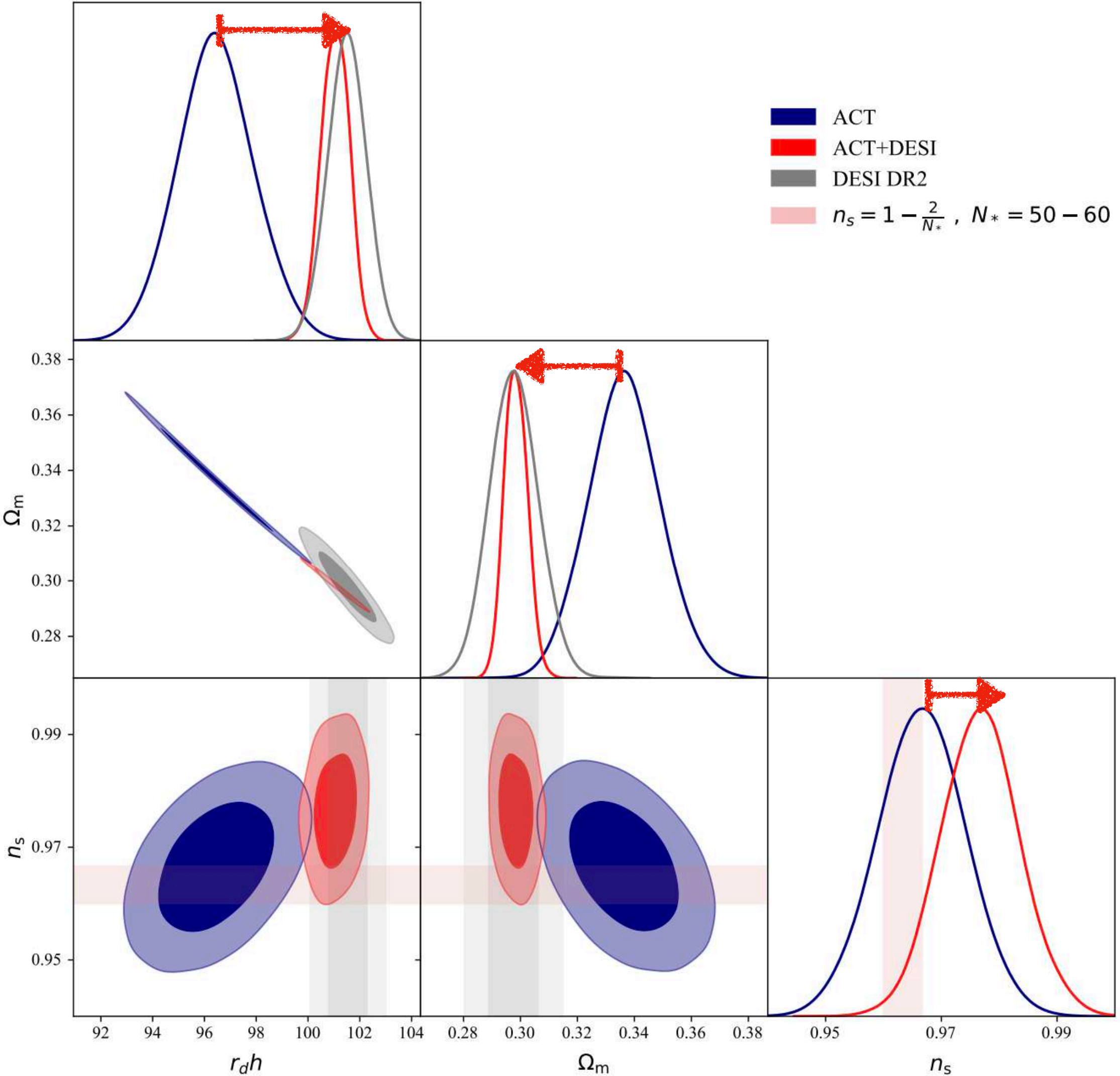
Constraints from ACT DR6 CMB and DESI DR2 BAO Data

Parameter	ACT	ACT + DESI
n_s	0.9666 (0.9664) $\pm$ 0.0076	0.9770 (0.9754) $\pm$ 0.0070
$r_d h$ [Mpc]	96.5 (96.27) $\pm$ 1.5	101.04 (101.05) $\pm$ 0.54
Ω_m	0.337 (0.338) $\pm$ 0.013	0.2999 (0.2996) $\pm$ 0.0040

$\sim 3.34\sigma$ distance

(translating into a one-dimensional Gaussian difference)

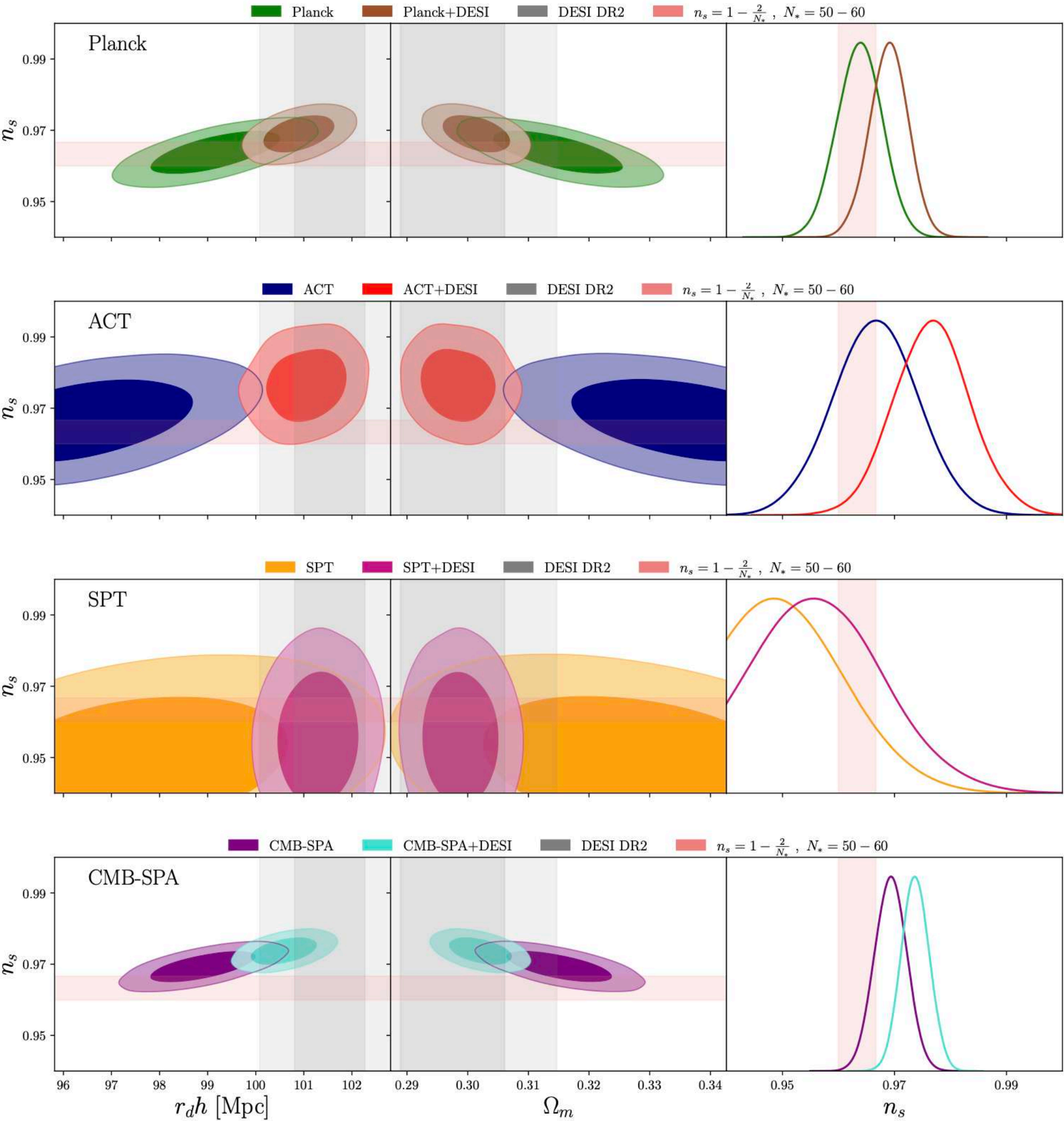
For n_s alone, the discrepancy is from $\sim 3.5\sigma$
(Correlated data - dependent on the metric used)



highly significant shift

Consequences for the spectral index n_s - SPT

*The Shifting Spectrum of n_s constraints from DESI and CMB data, E McDonough, **EF**, 2025*



Planck + DESI

- Planck has the **tightest** constraint on n_s and the **strongest correlation** between n_s and BAO parameters.
- Planck and DESI differ at the level of **$\sim 2.0\sigma$** .
- Adding DESI shifts n_s **slightly upward**, but Planck remains **fully compatible** with pink band
- Even after adding DESI, n_s stays **strongly correlated** with BAO parameters due to Planck's constraining power.

SPT + DESI (full SPT likelihood, no lensing)

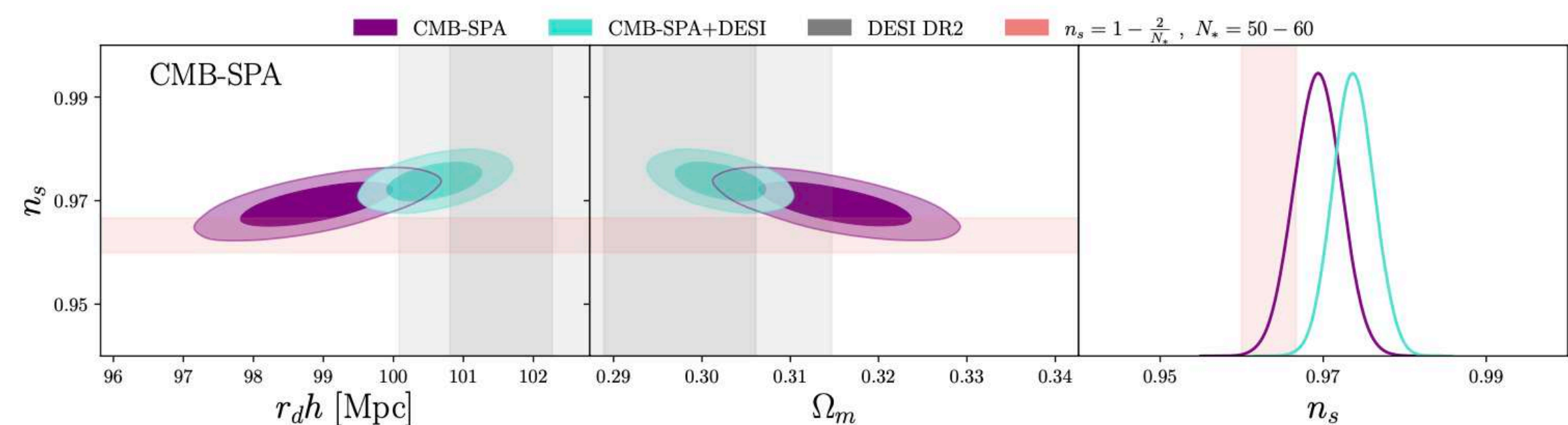
- SPT has a **weaker intrinsic correlation** between n_s and the BAO parameters, so the upward shift in n_s is **smaller** than for ACT.
- SPT prefers a **lower n_s** than ACT, so DESI acts to move SPT **toward** the pink band
- As with ACT, DESI causes a **re-orientation** and **decorrelation** of the n_s –BAO contours.

Data set	n_s	$r_d h$ [Mpc]	Ω_m	τ
DESI	–	101.54 ± 0.73	0.2975 ± 0.0086	–
Planck	0.9638 ± 0.0040	99.16 ± 0.88	0.3149 ± 0.0070	0.0516 ± 0.0078
Planck + DESI	0.9690 ± 0.0035	100.90 ± 0.49	0.3014 ± 0.0037	0.0554 ± 0.0076
ACT	0.9666 ± 0.0076	96.5 ± 1.5	0.337 ± 0.013	$0.0562^{+0.0053}_{-0.0063}$
ACT + DESI	0.9767 ± 0.0068	101.05 ± 0.55	0.2984 ± 0.0041	0.0636 ± 0.0064
SPT	0.948 ± 0.012	97.6 ± 2.1	0.328 ± 0.017	0.0506 ± 0.0059
SPT + DESI	0.955 ± 0.012	101.30 ± 0.56	0.2988 ± 0.0042	0.0529 ± 0.0059
CMB-SPA	0.9693 ± 0.0029	98.90 ± 0.72	0.3151 ± 0.0057	0.0557 ± 0.0036
CMB-SPA + DESI	0.9737 ± 0.0025	100.59 ± 0.45	0.3021 ± 0.0034	0.0575 ± 0.0036

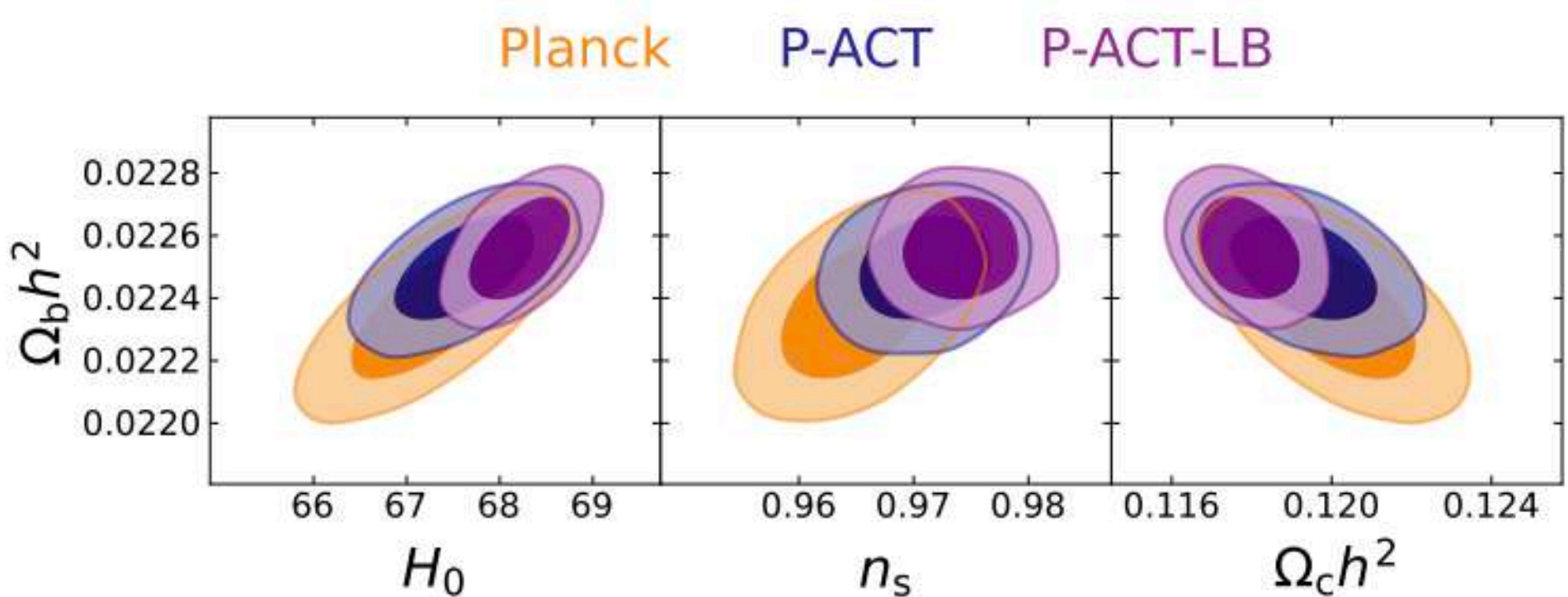
SPA: SPT+Planck+ACT

Consequences for the spectral index n_s – Planck, ACT, SPT

*The Shifting Spectrum of n_s constraints from DESI and CMB data, E McDonough, **EF**, 2025*



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$$\begin{aligned} n_s &= 0.9666 \pm 0.0077(\text{ACT}) \\ &= 0.9709 \pm 0.0038(\text{P} - \text{ACT}) \\ &= 0.9743 \pm 0.0034(\text{P} - \text{ACT} - \text{LB}) \end{aligned}$$

SPA: SPT+Planck+ACT

- CMB-SPA shows excellent alignment with Planck (and ACT) in the structure of the n_s correlations.
- Adding DESI to CMB-SPA mirrors the behavior seen in the other data sets: an upward shift in n_s and reduced correlation with BAO parameters.

The “high” value of n_s comes only when combined with DESI

Implications to *inflation*

The BAO-CMB Tension and Implications for Inflation
Elisa G.M. Ferreira et al, 2507.12459

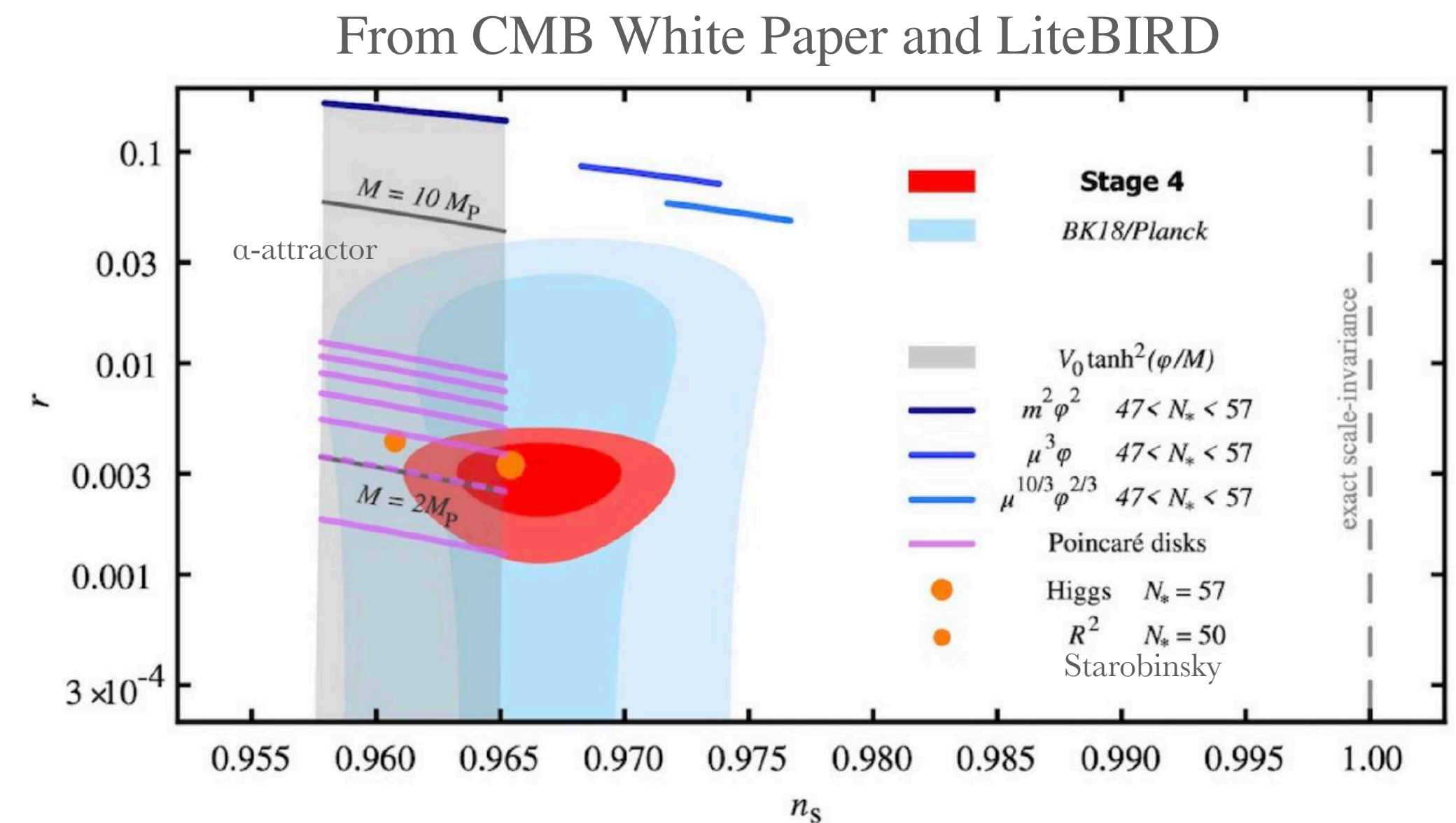
Does this shift has consequences for inflationary models?

Lessons from *Planck*:

Plateau potentials are preferable to monomial potentials. Moreover, over the last 10 years, the data have supported models approaching the plateau exponentially

Viable targets (Planck/BICEP/Keck/ACT/SPT data):

- Starobinsky model ,
- Higgs inflation and
- α -attractors (exponential - T and E α -attractor)



No viable targets at $n \gtrsim 0.967$

The predictions are for $47 < N_* < 57$.

If one plots the model predictions in the often used range $50 < N_* < 60$, they would shift to the right by about 0.002

Implications to *inflation*

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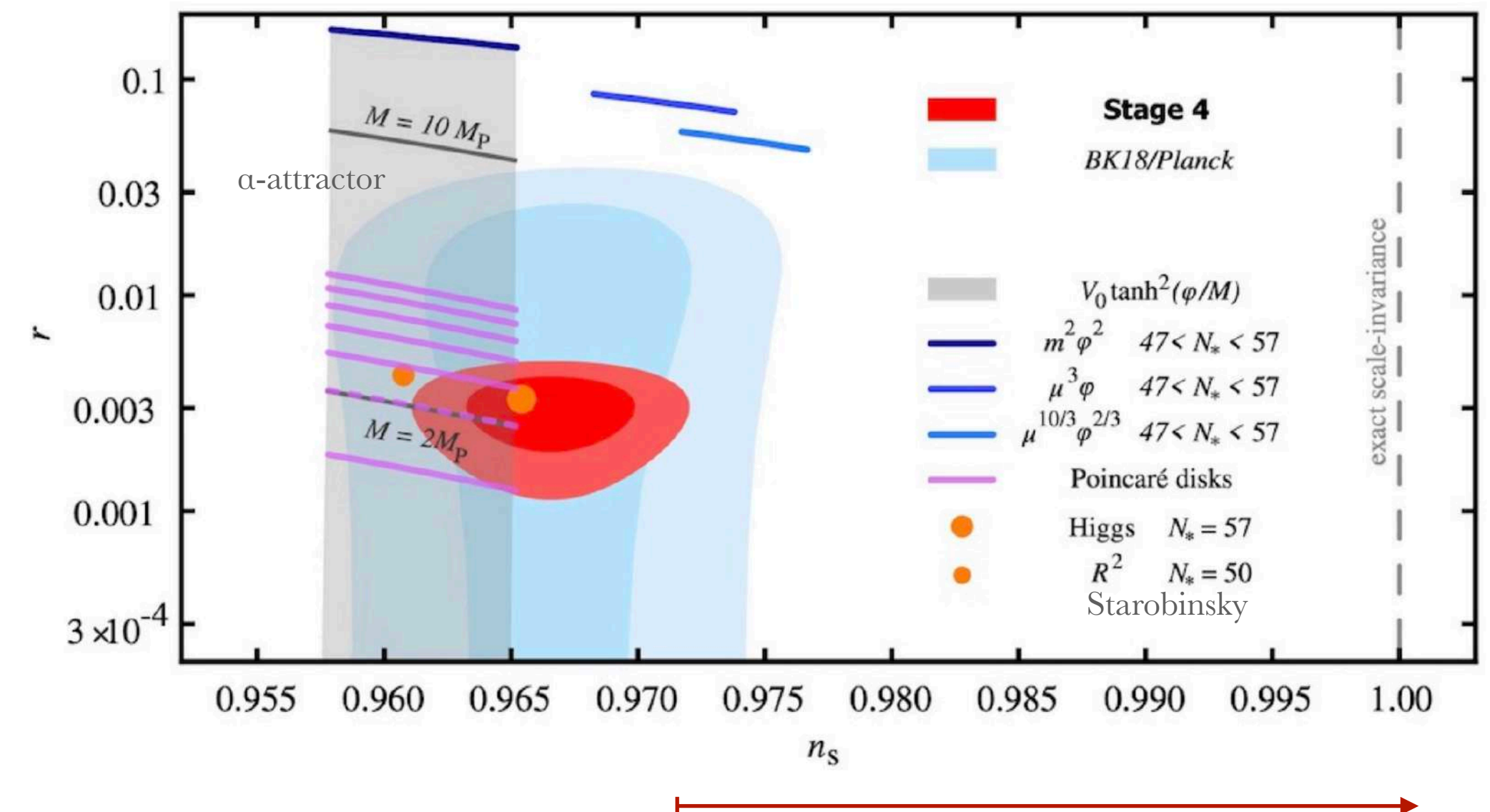
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- α -attractors (exponential - T and E α -attractor)

Hard to change conditions of these models to have $n \gtrsim 0.967$ -
e.g. changing *reheating*

- Starobinsky model: not very efficient $n_s \sim 0.962 - 0.963$
- Higgs inflation: very efficient $n_s \sim 0.966$
- α -attractors: $\max \Delta n_s \sim 0.006$

From CMB White Paper and LiteBIRD



The predictions are for $47 < N^* < 57$.

If one plots the model predictions in the often used range $50 < N^* < 60$, they would shift to the right by about 0.002

Implications to *inflation*

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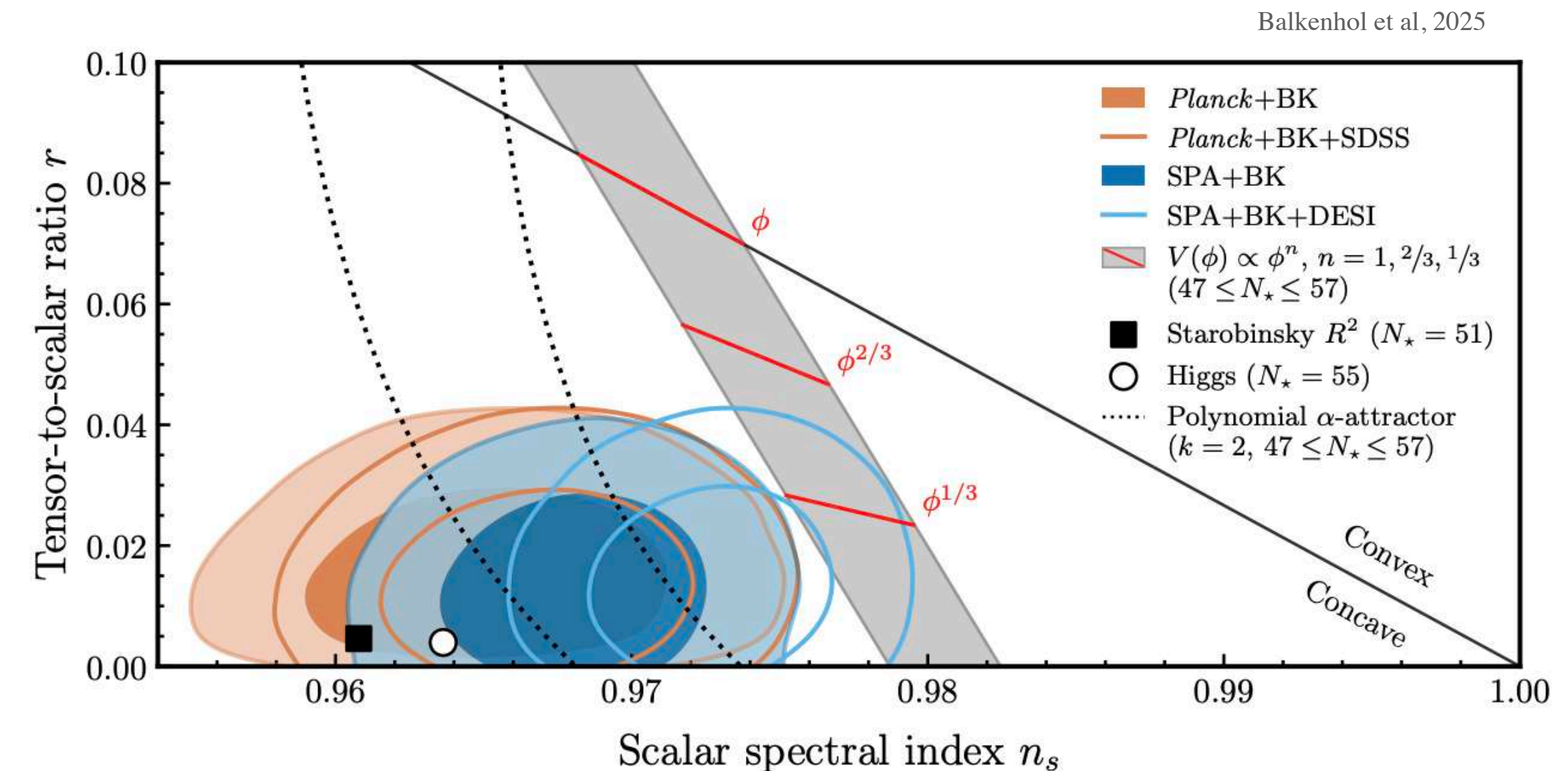
Taking the high value of n_s from ACT+DESI (or P-ACT-LB result $n_s = 0.9739 \pm 0.0034$) **at face value**:

- Starobinsky model, Higgs inflation and α -attractors **NOT *viable*** anymore!
- Would need models that allow $n_s > 0.97$

Ex.: simple inflationary models with polynomial potentials- e.g. pole inflation, D-brane inflation, KKLT models, polynomial α -attractors, chaotic inflation with nonminimal coupling to gravity ($N_* = 60$)

- Polynomial attractors with $k = 1, 2$ compatible with P-ACT-LB

If we confirm that data prefers $n_s \sim 0.973 - 0.974$:
data prefer potentials approaching the plateau polynomially rather than exponentially



Implications to inflation

The BAO-CMB Tension and Implications for Inflation
Elisa G.M. Ferreira et al, 2507.12459

- Large value of n_s only appears for the data combinations that add BAO DESI data to CMB (ACT or SPT, with or without Planck)
- These shifts in n_s can strongly impact the viable inflationary scenarios in accordance to data
- Shift comes from the BAO-CMB discrepancy (within LCDM); can we rely in these combinations?
- CAUTION when interpreting these constraints until the BAO-CMB discrepancy is resolved

At this point, we **don't know** what is the final value of n_s

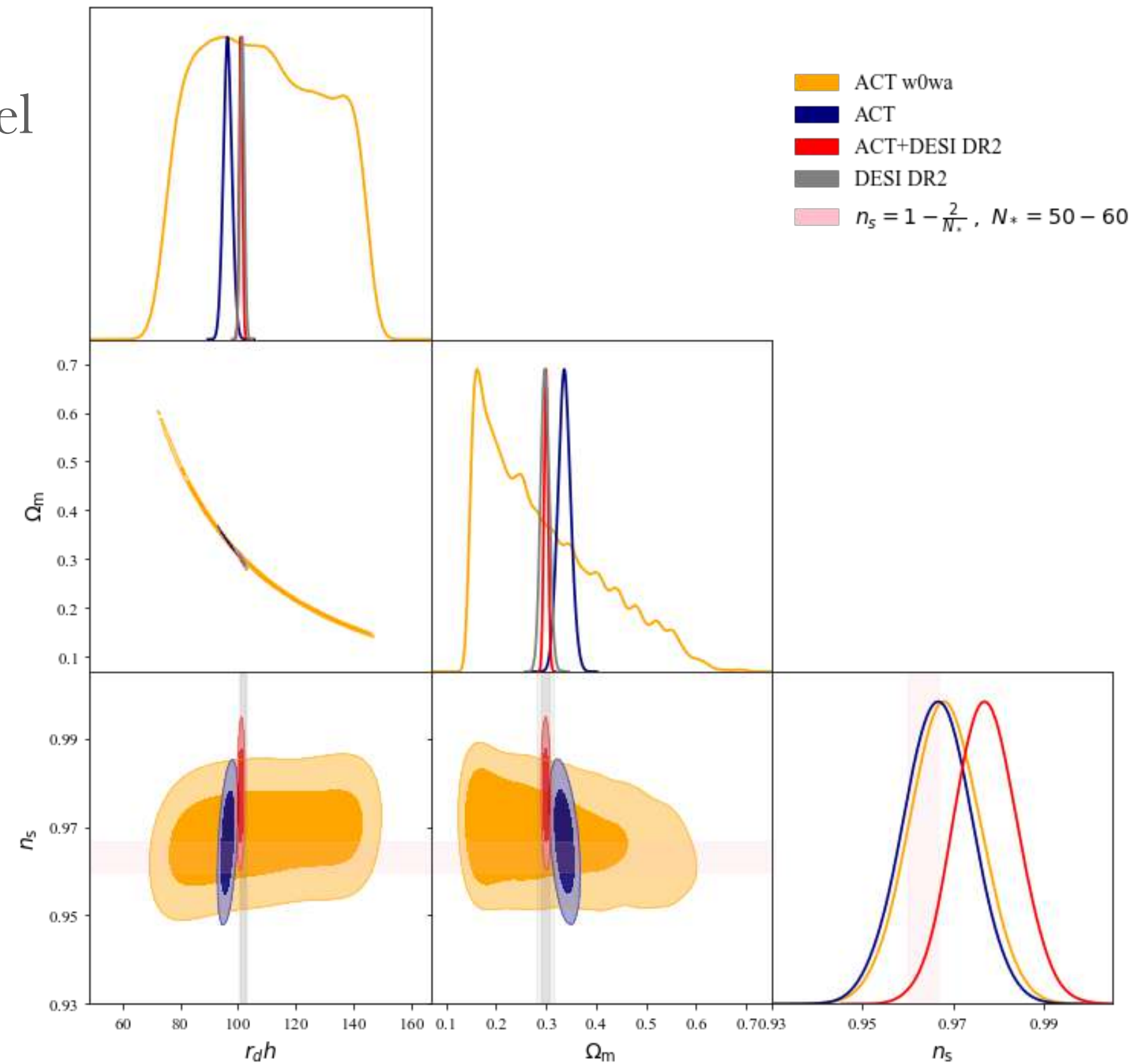
Since we don't know what this tension is indicating - systematics, new insights on the analysis, new physics - we need to be careful when combining data sets

BAO - CMB tension

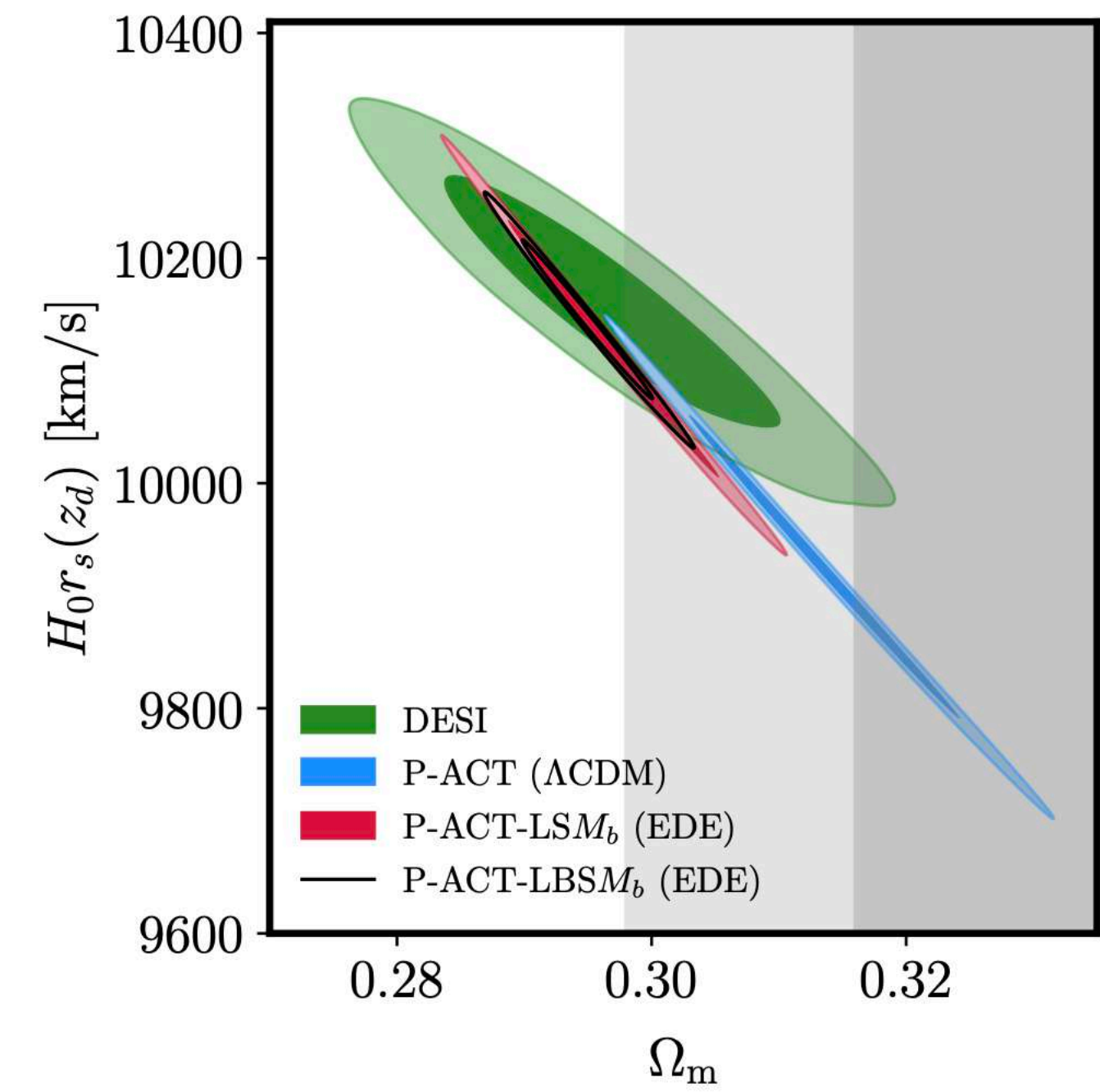
Careful:

one should be careful when it is said that either w_0w_a model or EDE resolves the BAO-CMB tension. They "solve" it making the error bars larger (more parameters).

w_0w_a model



EDE model



Poulin et al, 2025

Interesting effect of *tau*

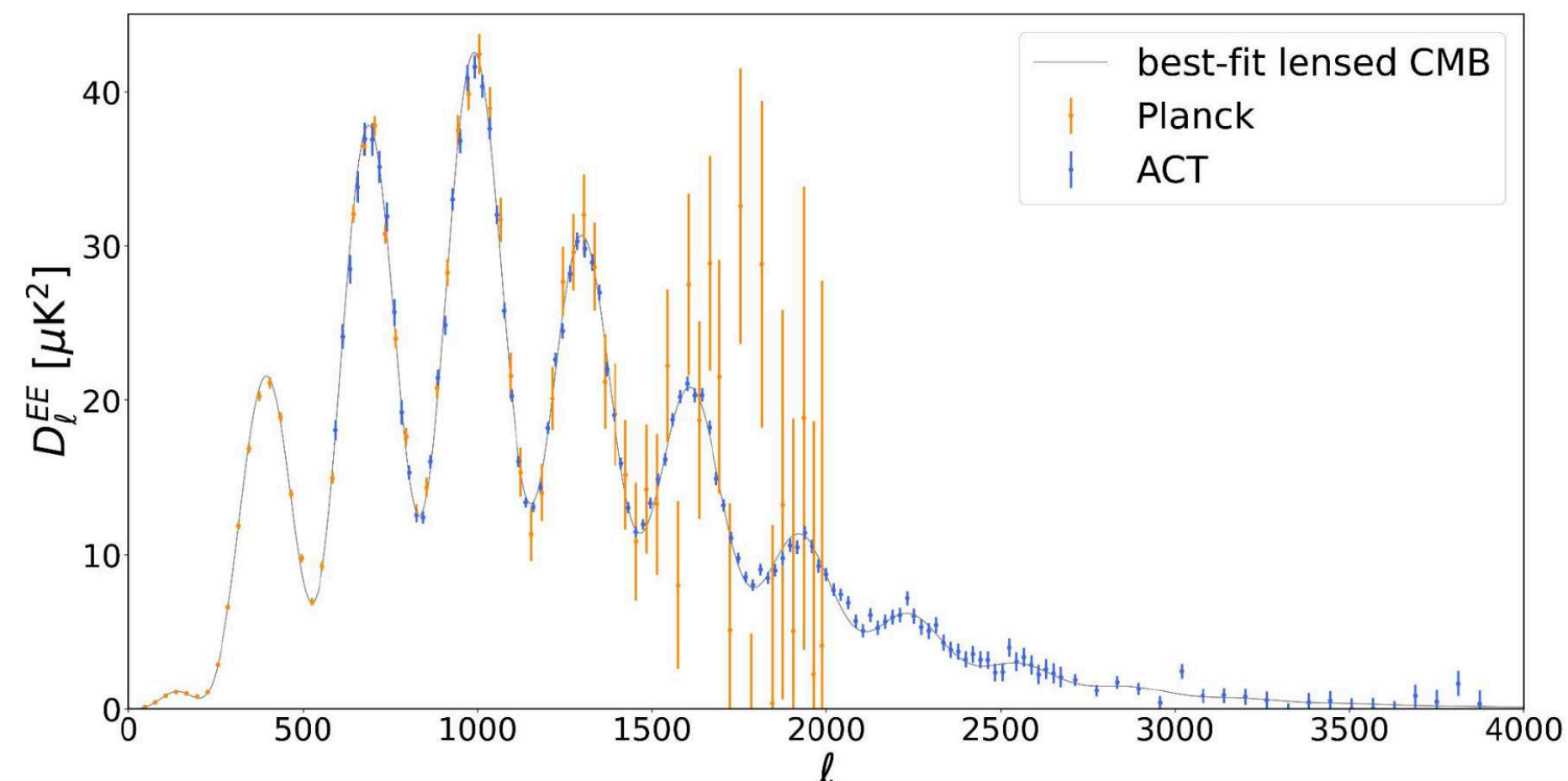
Sailer et al, 2504.16932;
Jhaveri et al 2504.21813;
Liu et al 2510.14957

τ - optical depth to reionization

CMB-BAO tension: inability to change the cold dark matter density $\Omega_c h^2$ given the measurements of the CMB lensing once the optical depth to reionization τ is constrained by the Planck lowE polarization data

Optical depth constraint prevents the amplitude A_s of the curvature power spectrum, $A_s e^{-2\tau}$, from adjusting the lensing amplitude to fit the data and instead fixes $\Omega_c h^2 \rightarrow$ fixes $\Omega_m (D_m)$

If it is not systematics, what would happen if these constraints on τ can be somewhat **relaxed** in extended reionization models or alternately by reducing the large scale primordial power spectrum from inflation



τ is measured from:

- 1. Low- ℓ E-mode polarization bump** from rescattering during reionization
 $\rightarrow$ main observable; $C_\ell^{EE} \propto \tau^2$
- 2. Suppression of high- ℓ TT/TE/EE acoustic peaks**
 $\rightarrow$ gives τ only via and is highly degenerate with A_s
- 3. Low- ℓ TE correlations**
 $\rightarrow$ secondary constraint

Interesting effect of *tau*

Sailer et al, 2504.16932;
Jhaveri et al 2504.21813;
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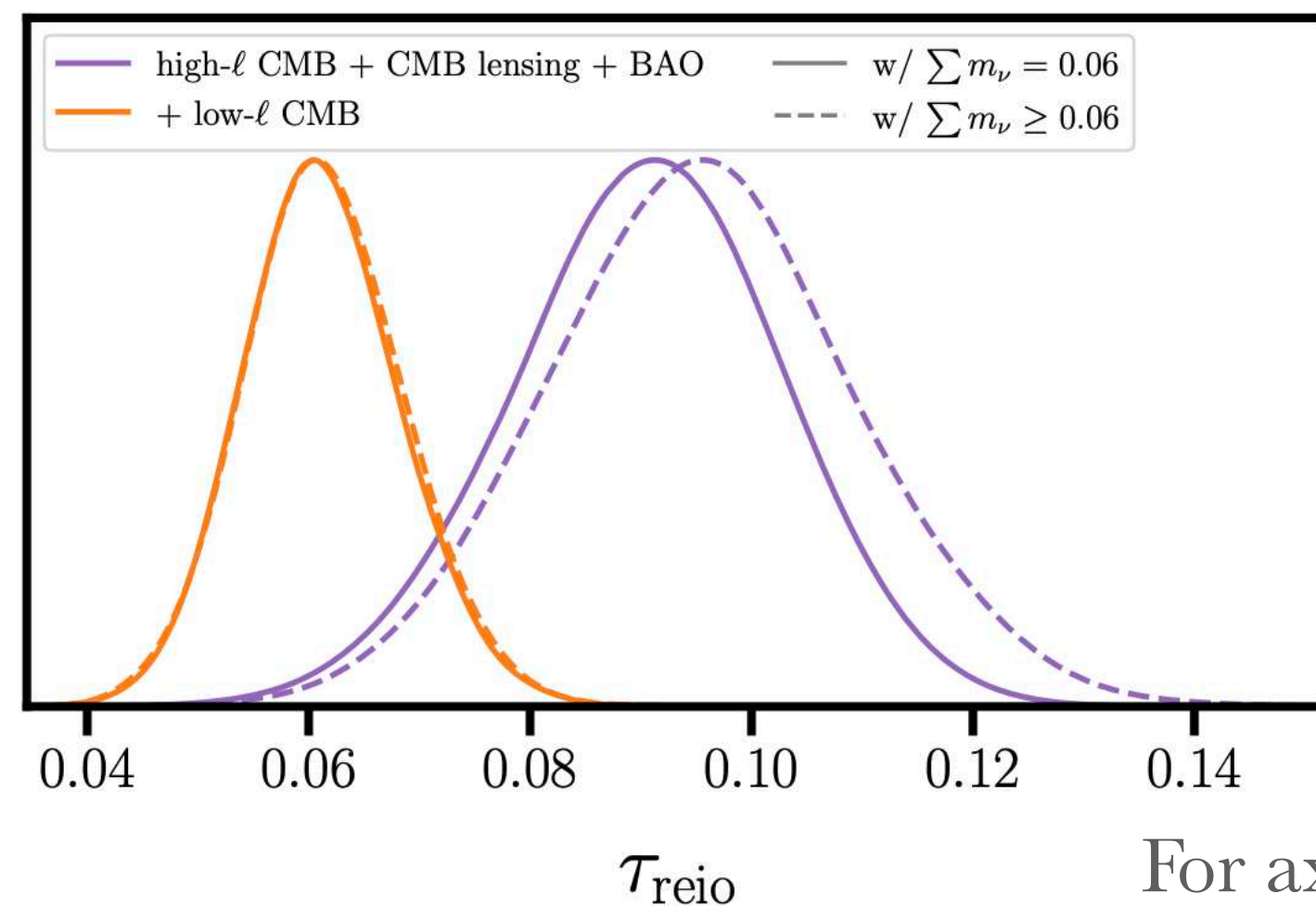
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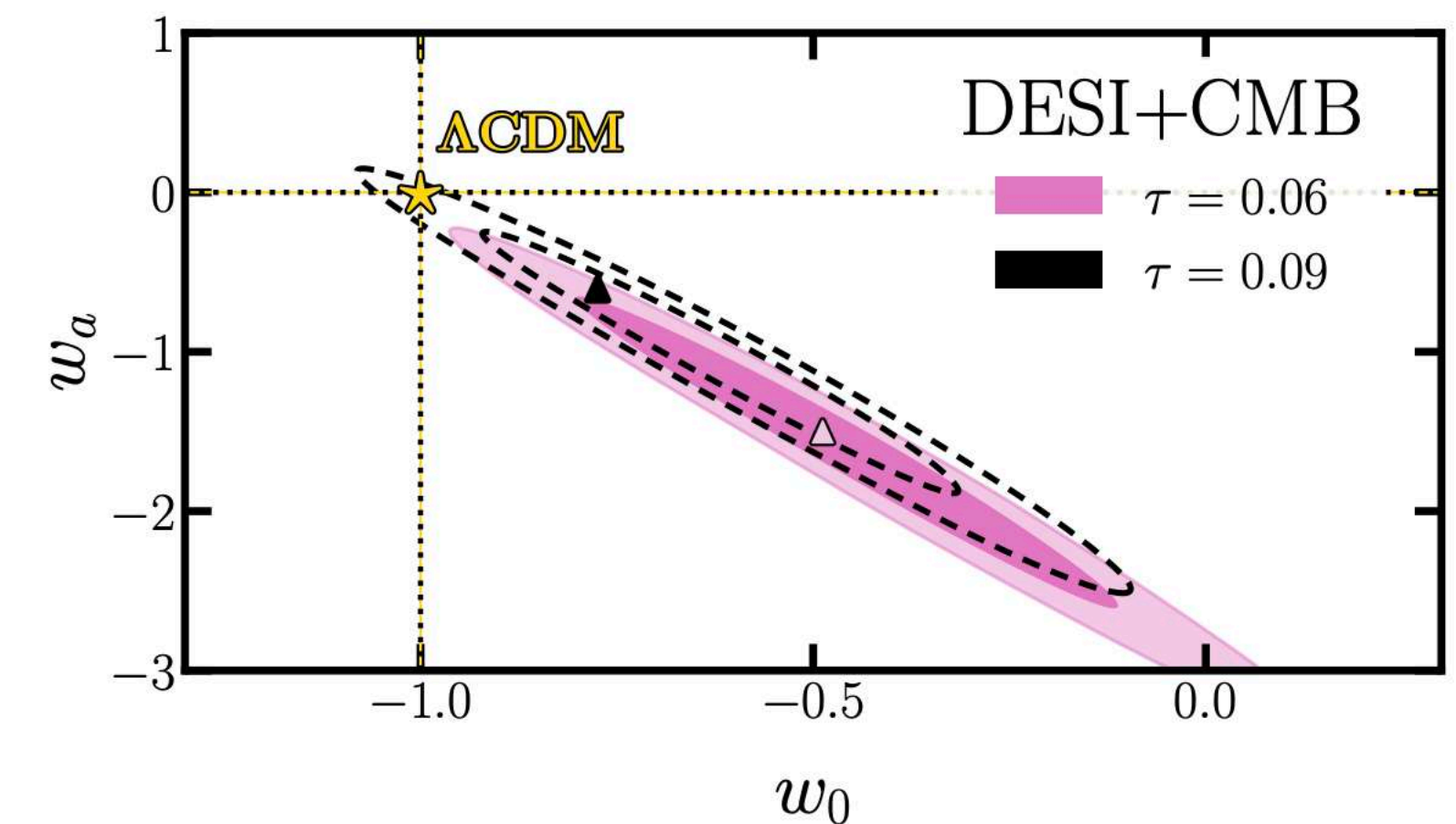
If it is not systematics, what would happen if these constraints on τ can be somewhat **relaxed** in extended reionization models or alternately by reducing the large scale primordial power spectrum from inflation

Influence of τ for sum of neutrino mass and DE constraints

CMB-BAO discrepancy can be resolved by **raising** τ_{reio} from 0.054 to a higher value, $\sim 0.09 - 0.1$ (in the absence of low- ℓ EE data)



Reduces preference for dynamical DE from 3σ to 1.5σ



For axion DE, if one had $\tau = 0.1$, this would fit the data as well as $w_0 - w_a$ phantom dark energy

However, the required increase in τ is in $\approx 3 - 5\sigma$ tension with Planck low- ℓ E-mode polarization

Interplay of n_s and τ

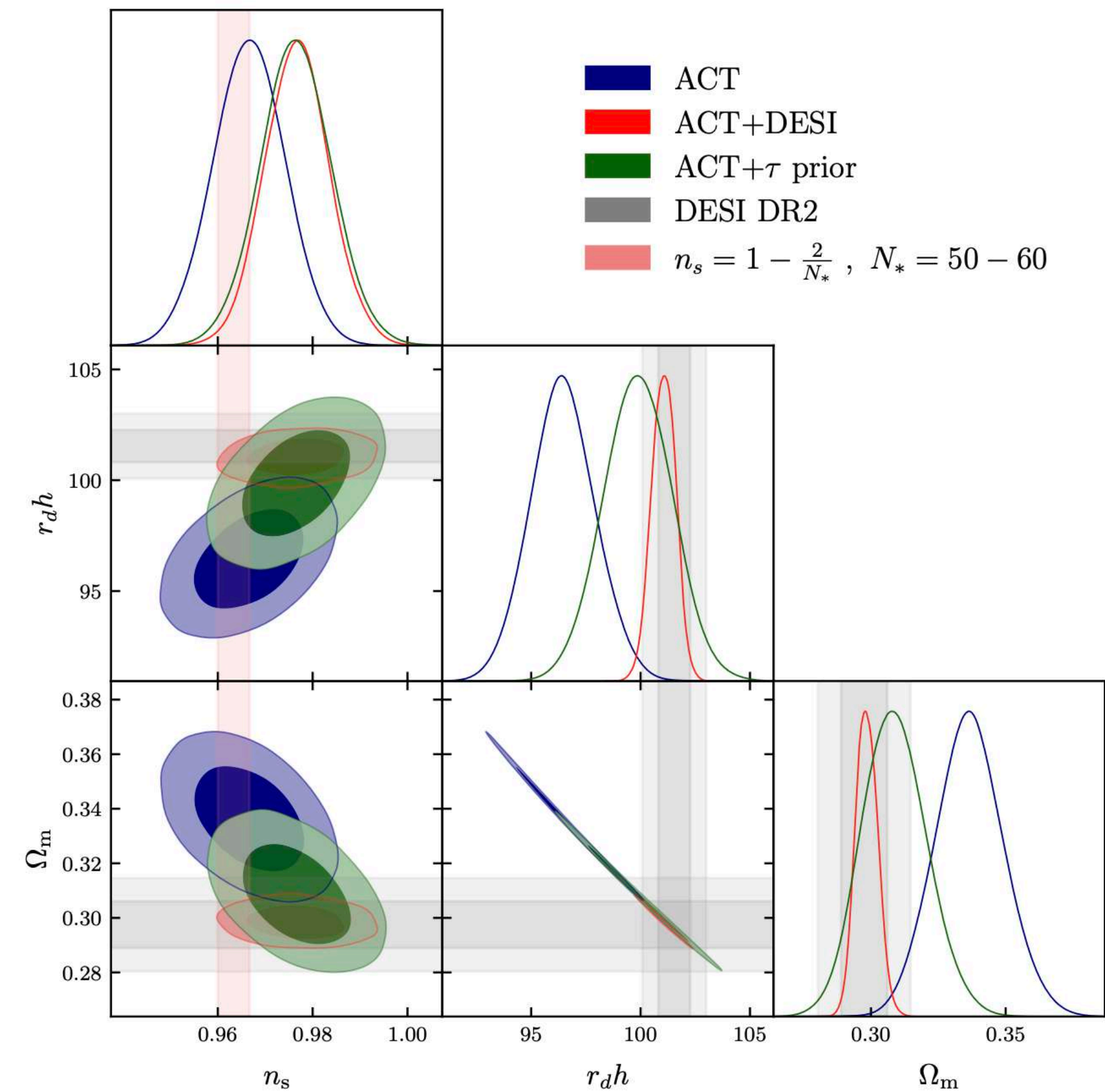
The Shifting Spectrum of n_s constraints from DESI and CMB data, E McDonough, **EF**, R Kallosh, and A Linde, to appear

Exercise:

Force τ to be large, ~ 0.1 , has the **same effect** in the constraints in the BAO parameters and n_s as combining with DESI

Expected: τ tightly correlated to A_s and n_s

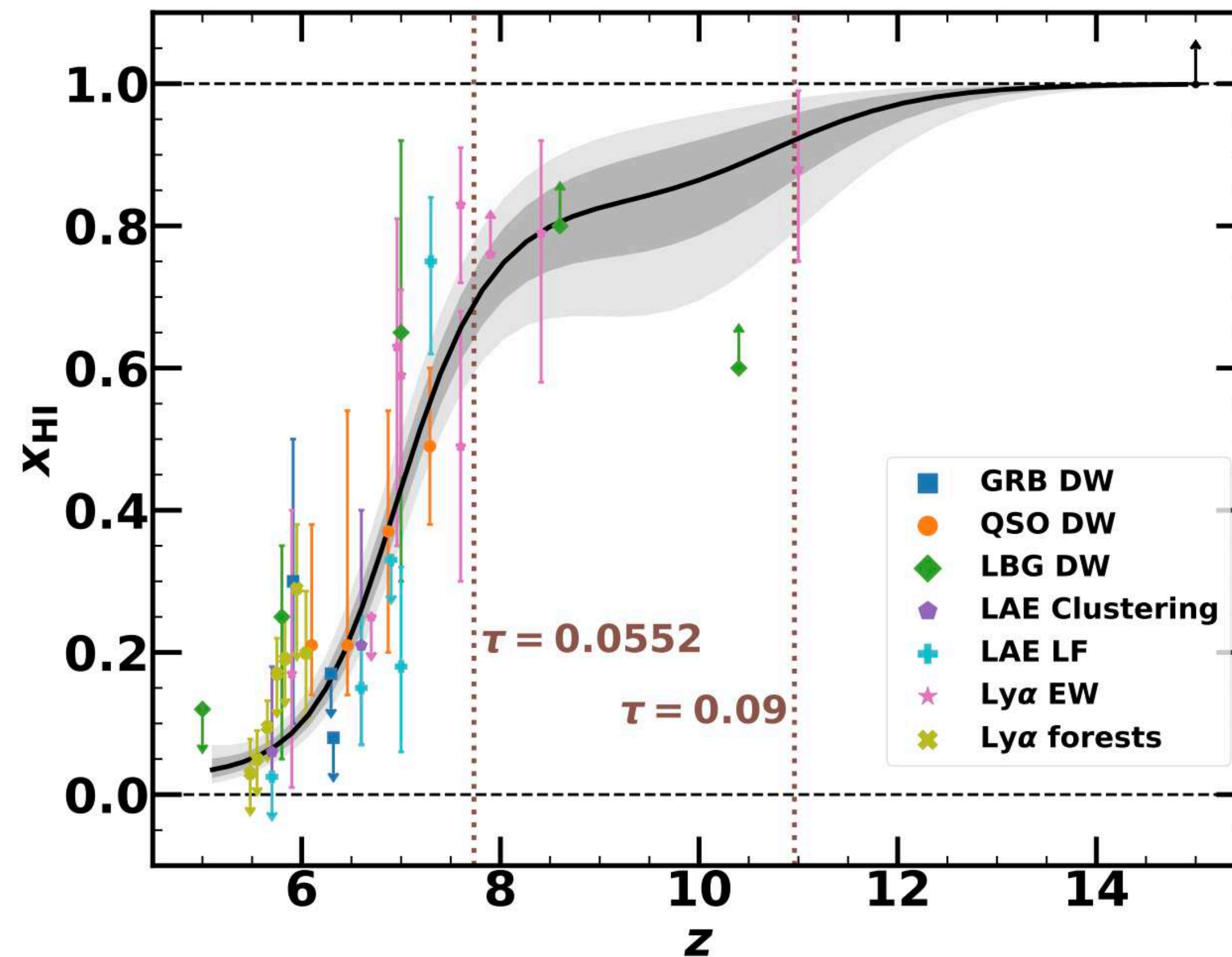
There might be systematics in the measurements of low l polarization and in the determination of τ - important goal of LiteBIRD



Interplay of n_s and τ

A New Constraint on the Optical Depth from the Reionization History Independent of CMB Large-Scale E-Mode Polarization, Y. Kageura, M. Ouchi, F. Naokawa, H. Umeda, A. Matsumoto, Y. Harikane, M. Nakane and T Thi Thai

Can we really have a large value for τ ?



- $\text{Ly}\alpha$ damping-wing absorption of GRBs at $z = 5.9 - 6.3$ (Totani et al. 2006, 2014; Fausey et al. 2025)
- $\text{Ly}\alpha$ damping-wing absorption of QSOs at $z = 6.0 - 7.5$ (Greig et al. 2022; Ďurovčíková et al. 2024)
- $\text{Ly}\alpha$ damping-wing absorption of LBGs at $z = 5 - 13$ (Umeda et al. 2025a)
- Clustering properties of $\text{Ly}\alpha$ emitters at $z = 5 - 7$ (Umeda et al. 2025b)
- Evolution of the $\text{Ly}\alpha$ luminosity function at $z = 5 - 7$ (Wold et al. 2022; Umeda et al. 2025b)
- Evolution of the $\text{Ly}\alpha$ EW distribution at $z = 5 - 14$ (Mason et al. 2019b; Jung et al. 2020; Whitler et al. 2020; Bolan et al. 2022; Kageura et al. 2025)
- Dark gaps in the $\text{Ly}\beta$ forest at $z = 5.5 - 6.0$ (Zhu et al. 2022)
- Fraction of dark pixels in the Lyman-series forests at $z = 4.9 - 6.2$ (Davies et al. 2026)

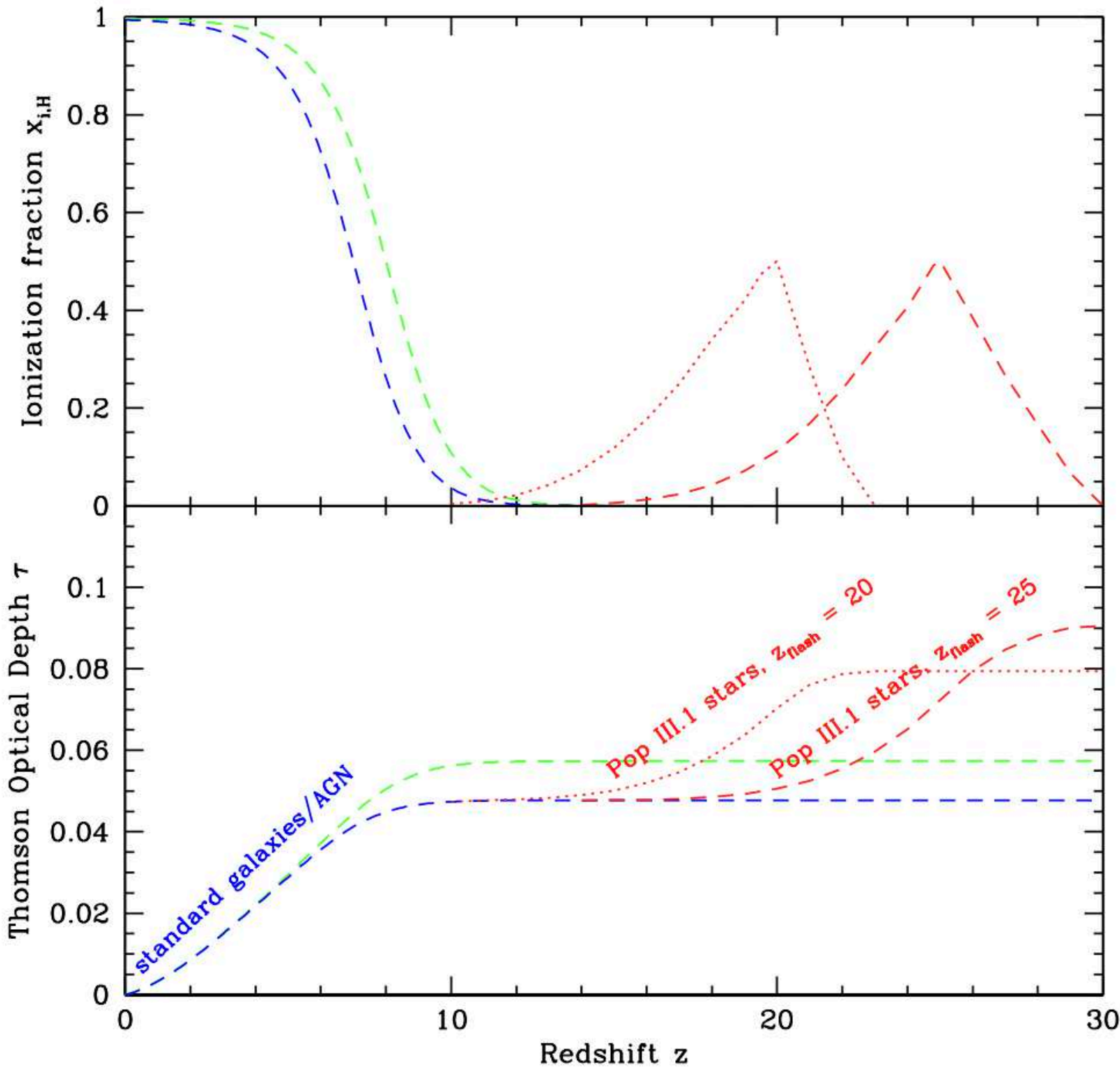
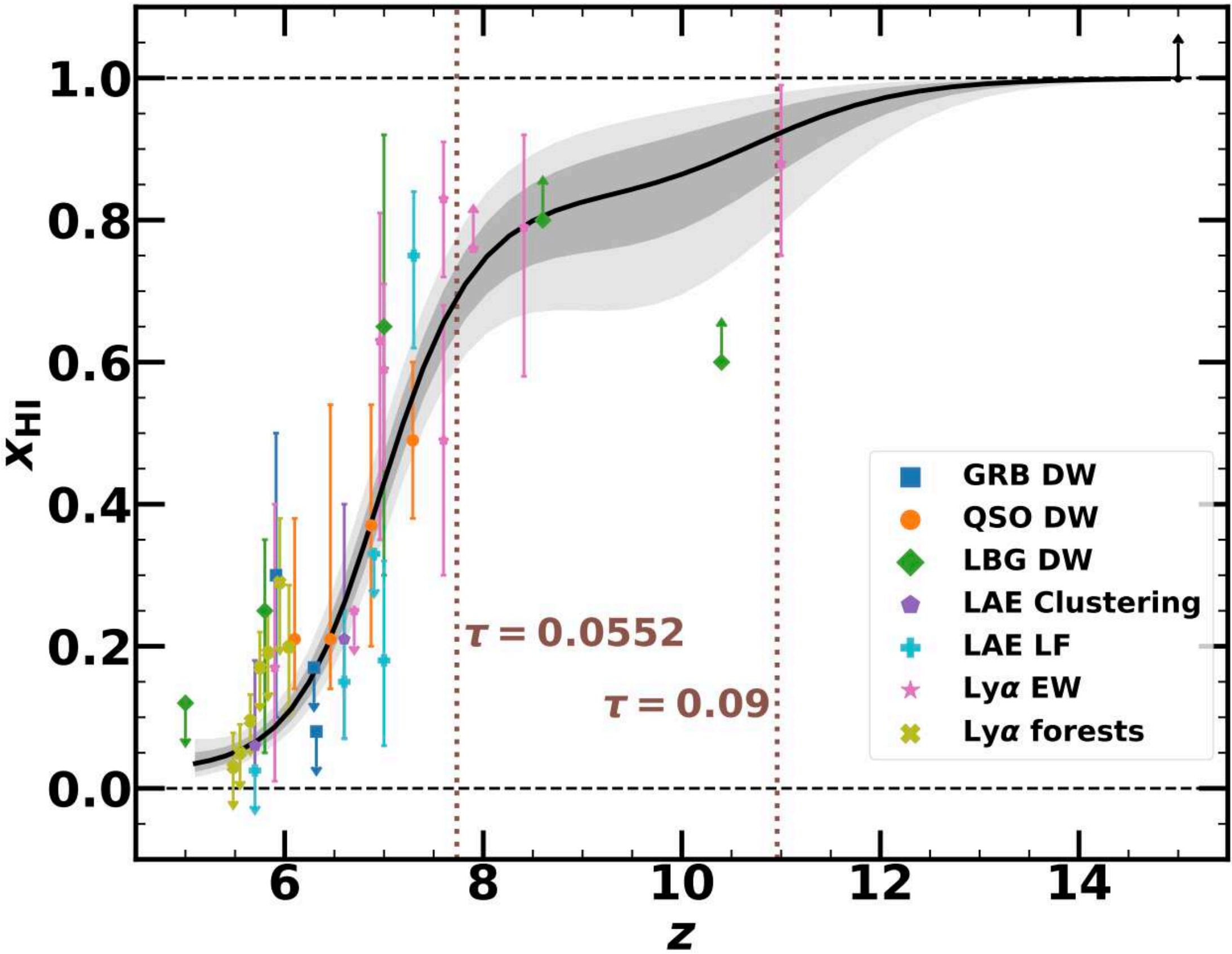
Interplay of n_s and τ

A New Constraint on the Optical Depth from the Reionization History Independent of CMB Large-Scale E-Mode Polarization, Y. Kageura, M. Ouchi, F. Naokawa, H. Umeda, A. Matsumoto, Y. Harikane, M. Nakane and T Thi Thai

Can we really have a large value for τ ?

Interesting field!

Check: The Impact of Population III.1 Flash Reionization for CMB Polarization and Thomson Scattering Optical Depth, Jonathan C. Tan, Eiichiro Komatsu, 2025



*The resolution of the **BAO-CMB tension** remains an open question,
and so too does the fate of n_s !*

*Little evidence that ACT and DESI constraints are both right, while at the same time Λ CDM with a benchmark
inflation scenario holds true; something has to give.*

*But this goes beyond inflation. It affects: dynamical DE, neutrinos,
features in the power spectrum, curvature ... **Important!***

*Also alerts us for to be careful when **combining datasets***

the Ω_m tension

Ω_m *tension*

Different probes prefer different Ω_m when interpreted in Λ CDM - like a parameter space symptom

BAO/DESI

$$\Omega_m^{\text{DESI BAO}} \simeq 0.295 \pm 0.015$$

CMB/Planck

$$\Omega_m^{\text{Planck}} \simeq 0.315 \pm 0.007,$$

Supernova

$$\Omega_m^{\text{Pantheon+, SNe alone}} = 0.334 \pm 0.018$$

SNe constrain Ω_m through the shape of $D_L(z)$; BAO through distances relative to r_d ; and CMB through early-universe physics and the acoustic scale $\Rightarrow$ SNe provide the shape; BAO provides the ruler.

Ω_m “tug of war”:

$$\Omega_m^{\text{BAO}} < \Omega_m^{\text{CMB}} < \Omega_m^{\text{SNe}}$$

- Since $\Omega_m(1+z)^3$ controls the redshift dependence of $H(z)$, even $\Delta\Omega_m \sim 0.03$ changes the inferred expansion history.
- This can lead to an **apparent** preference for **dynamical dark energy** when datasets are combined

Attention: BAO–CMB tension is a mismatch between the CMB-calibrated sound horizon and the BAO distance scale; it is a ruler/geometry tension, not a Ω_m parameter discrepancy.

Ω_m *tension*

Different probes prefer different Ω_m when interpreted in Λ CDM - like a parameter space symptom

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- This can lead to an **apparent** preference for **dynamical dark energy** when datasets are combined

Connection to S_8 : Weak lensing adds the **growth** side of the story. Weak lensing often prefers a lower clustering amplitude. Is the same Λ CDM Ω_m able to fit both distances and structure?

synergies and future

Observations - Stage 3 and 4

From the ones we already have results, we already learned a lot of new things!!!

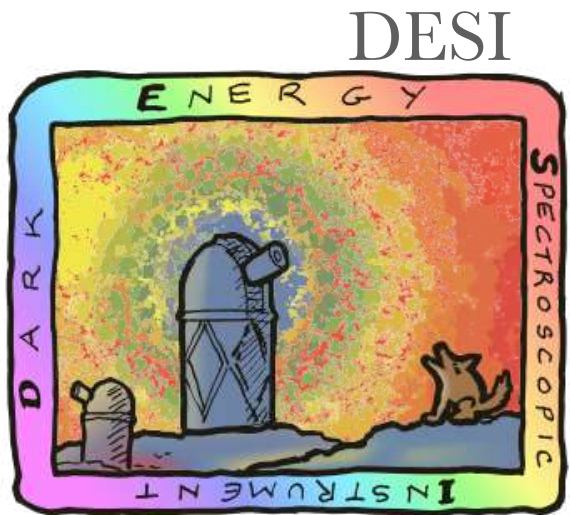
Photometric and spectroscopic surveys

CMB

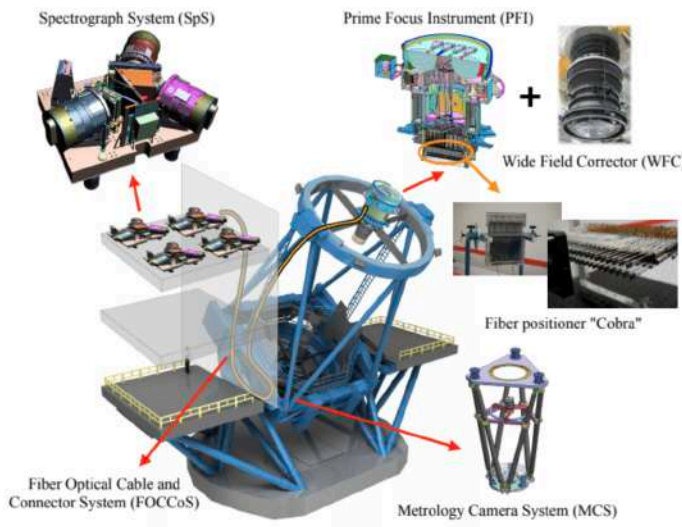
2022-
18,000 deg²
8.4m
ugrizy



Vera Rubin Observatory
Legacy Survey of Space & Time



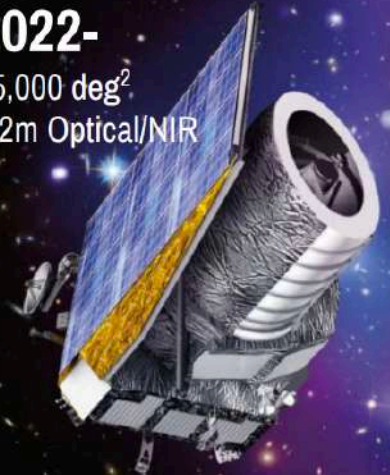
Prime Focus Spectrograph (PFS)



GWs

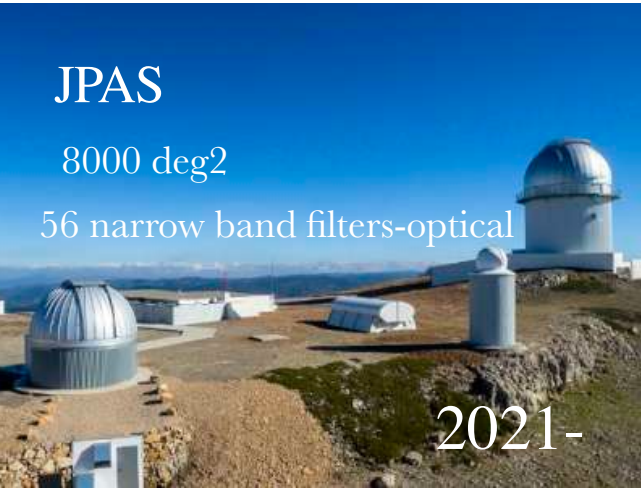


2022-
15,000 deg²
1.2m Optical/NIR



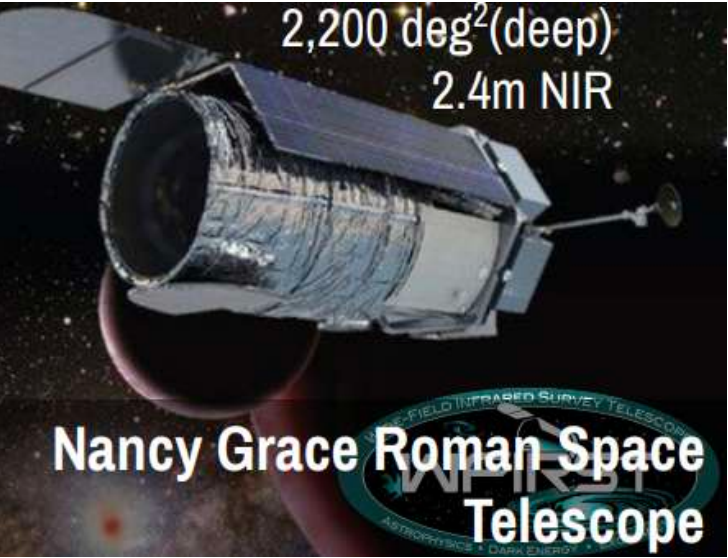
Euclid Mission

JPAS
8000 deg²
56 narrow band filters-optical



2021-

2,200 deg²(deep)
2.4m NIR



Nancy Grace Roman Space Telescope

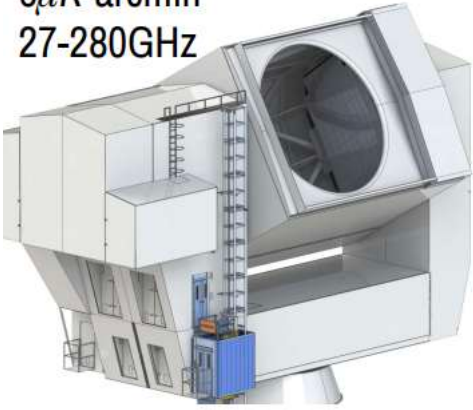
21cm

LiteBIRD



Full sky
100 μK-arcmin
40-402GHz

2021
16,000 deg²
6 μK-arcmin
27-280GHz



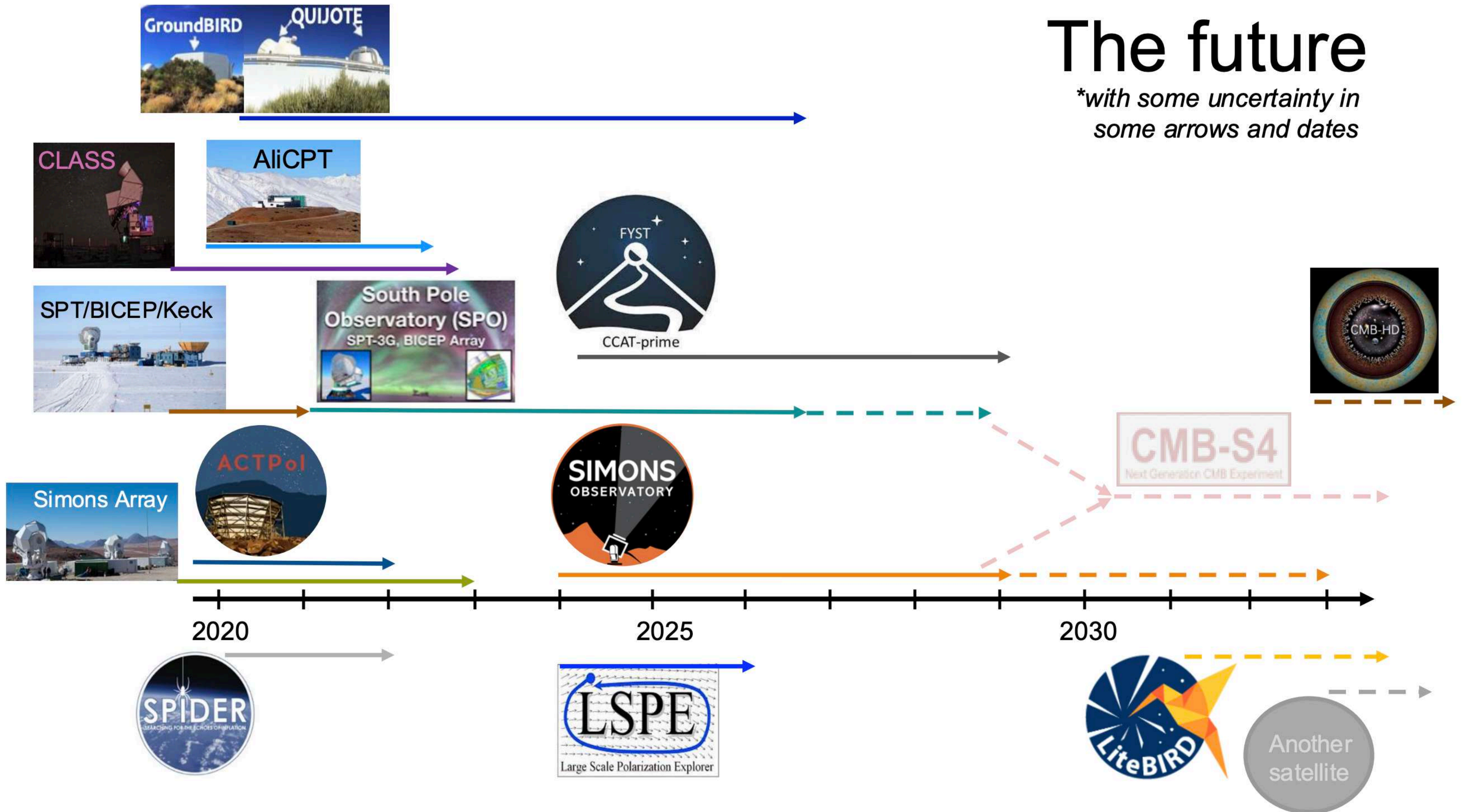
SIMONS OBSERVATORY

CMB-S4
Next Generation CMB Experiment

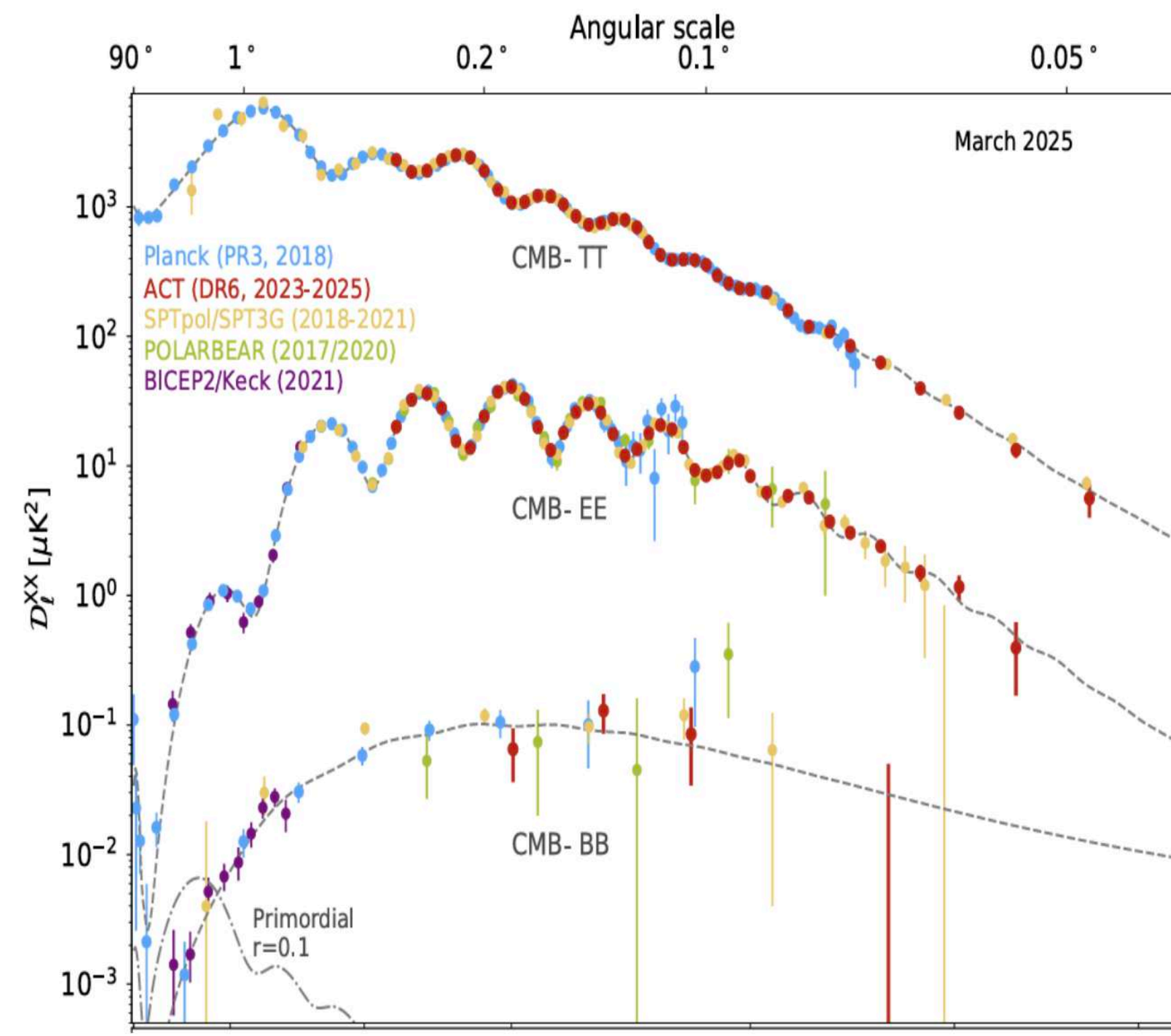
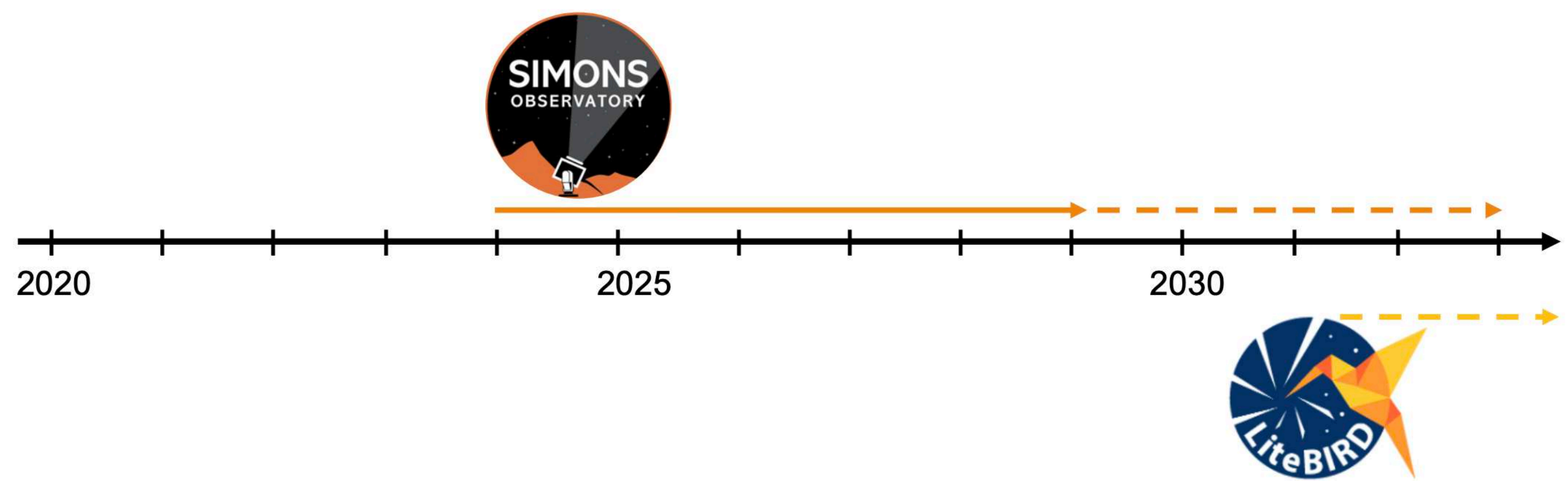
future of CMB

The future

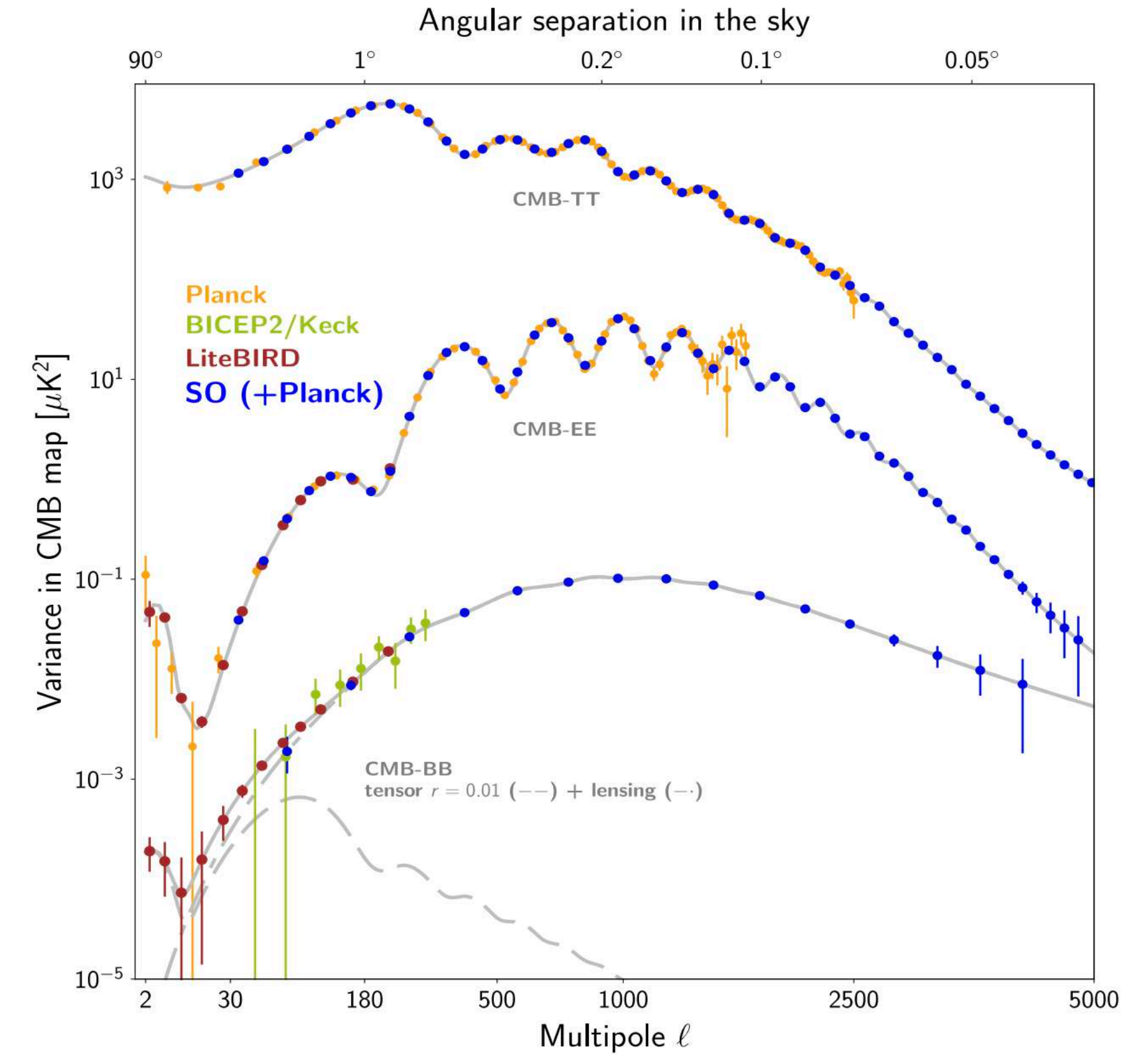
**with some uncertainty in
some arrows and dates*



Future of *CMB*



High sensitivity and high precision CMB polarization



Future of *CMB*



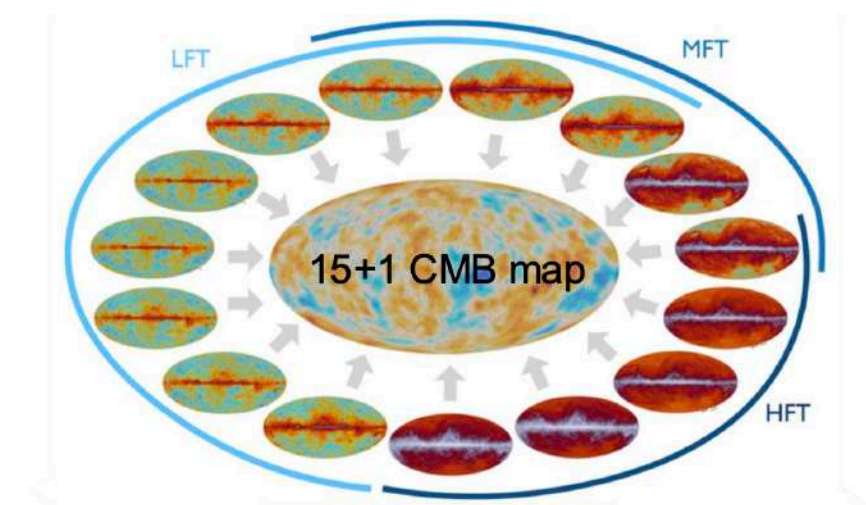
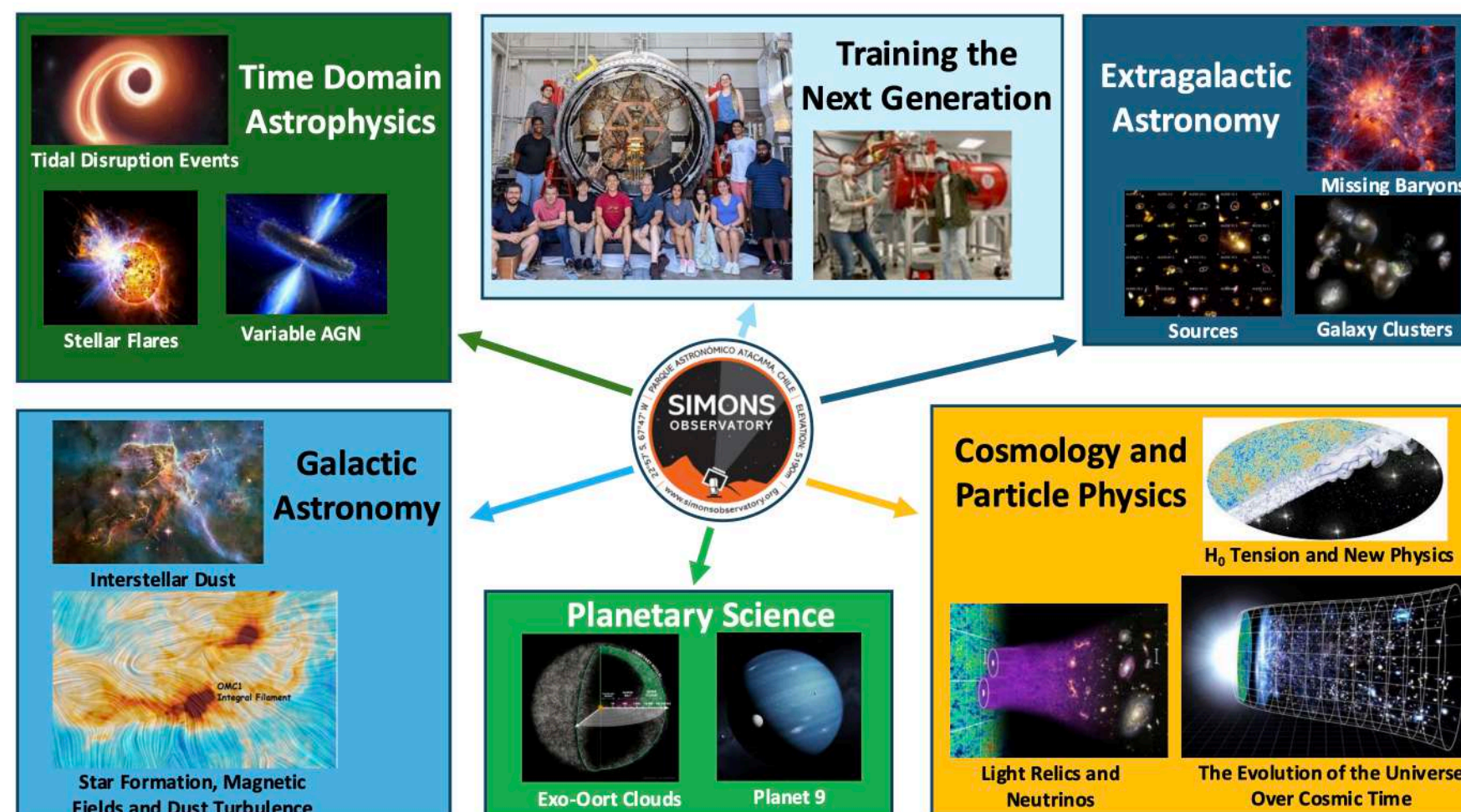
Diverse science:

- Cosmology
- Particle physics
- Extragalactic astronomy
- Galactic astronomy
- Time domain astrophysics
- Planetary physics



Diverse science:

- New Physics:
 - Neutrino Masses
 - Cosmic Birefringence
 - Large Scale Anomalies
 - Spectral Distortions
- Early Universe
 - Inflation: Beyond r , n_s
 - B-Mode De-Lensing
 - Primordial Non-Gaussianity
 - Primordial Magnetic Fields
- Dark Ages
 - Cosmic Reionization
- Structure Formation & Dark Cosmological Components
 - Cross-Correlations
 - Weak Lensing Reconstruction
 - Hot Gas in the Universe
- Extra-Galactic Astrophysics
 - Polarized Point Source Catalogues
 - Science of Transients
- Galactic Astrophysics
- Galactic Science
- LiteBIRD legacy maps



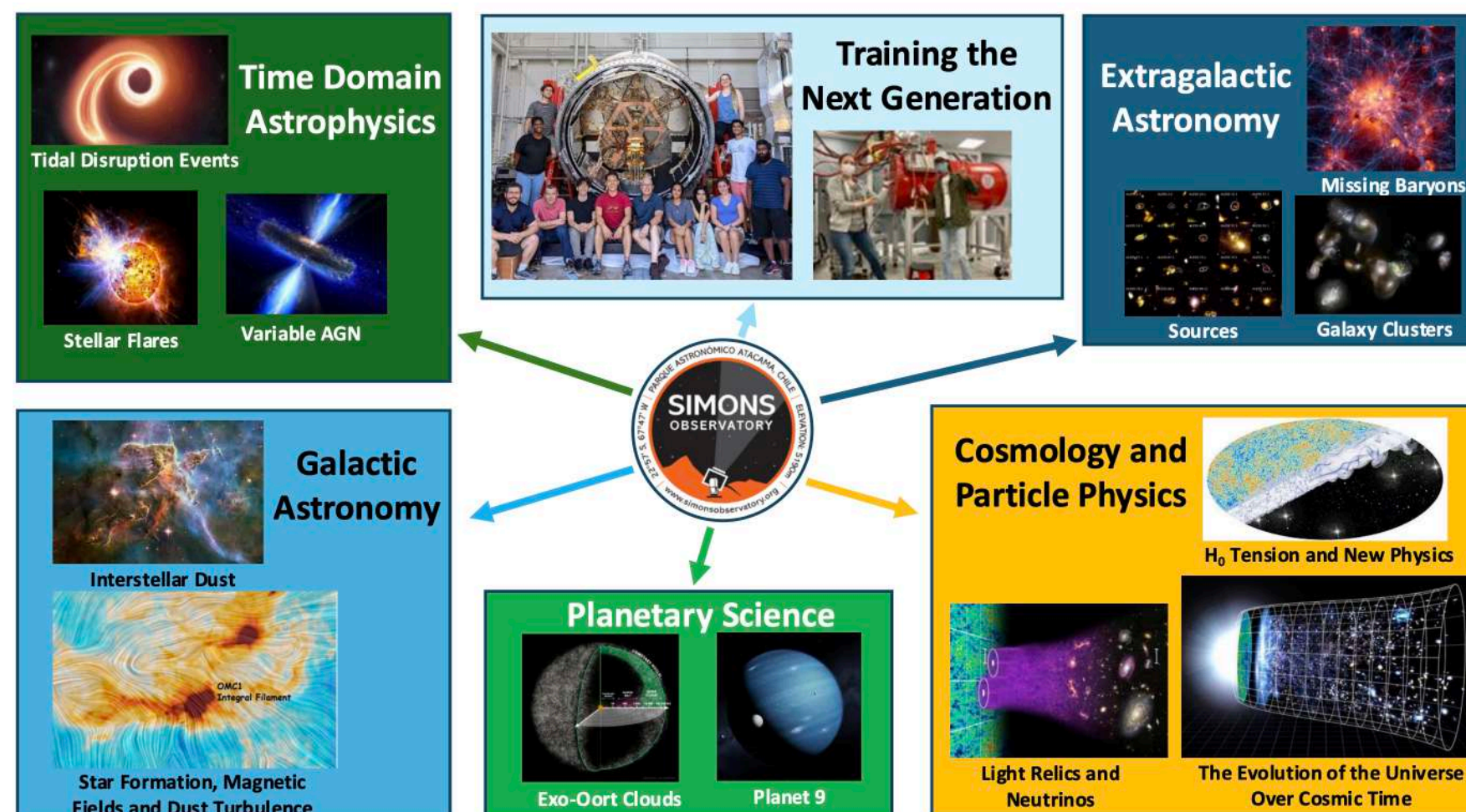
Credit: Ludovic Montier

Future of *CMB*



Diverse science:

- Cosmology
- Particle physics
- Extragalactic astronomy
- Galactic astronomy
- Time domain astrophysics
- Planetary physics

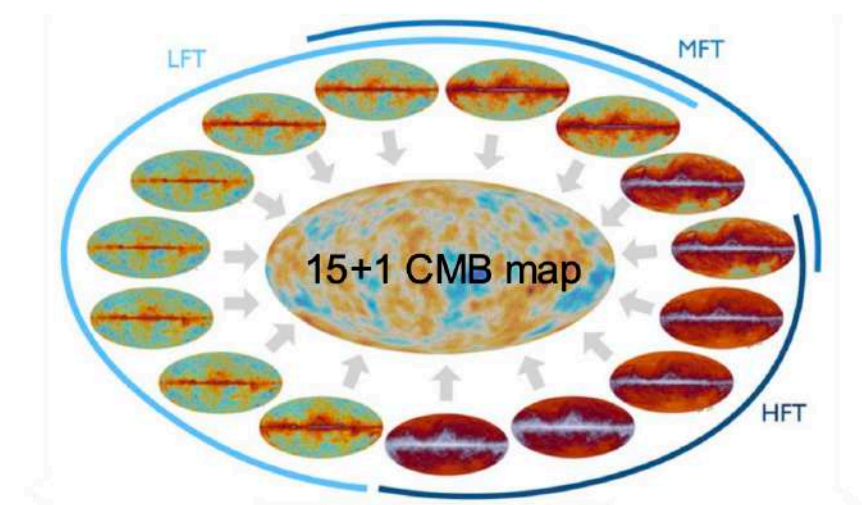


We will see much more this week!!



Diverse science:

- New Physics:
 - Neutrino Masses
 - Cosmic Birefringence
 - Large Scale Anomalies
 - Spectral Distortions
- Early Universe
 - Inflation: Beyond r , n_s
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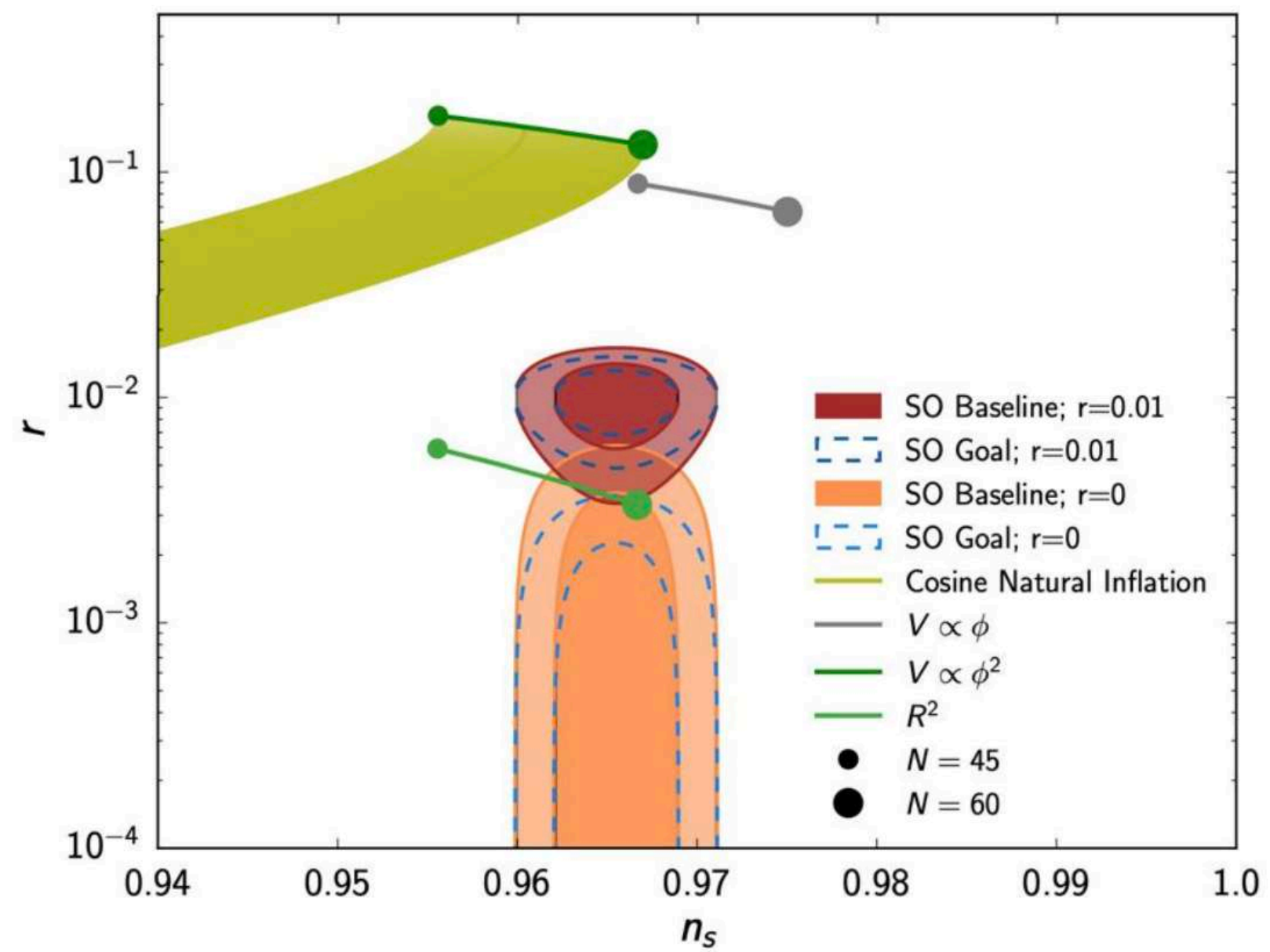


Credit: Ludovic Montier

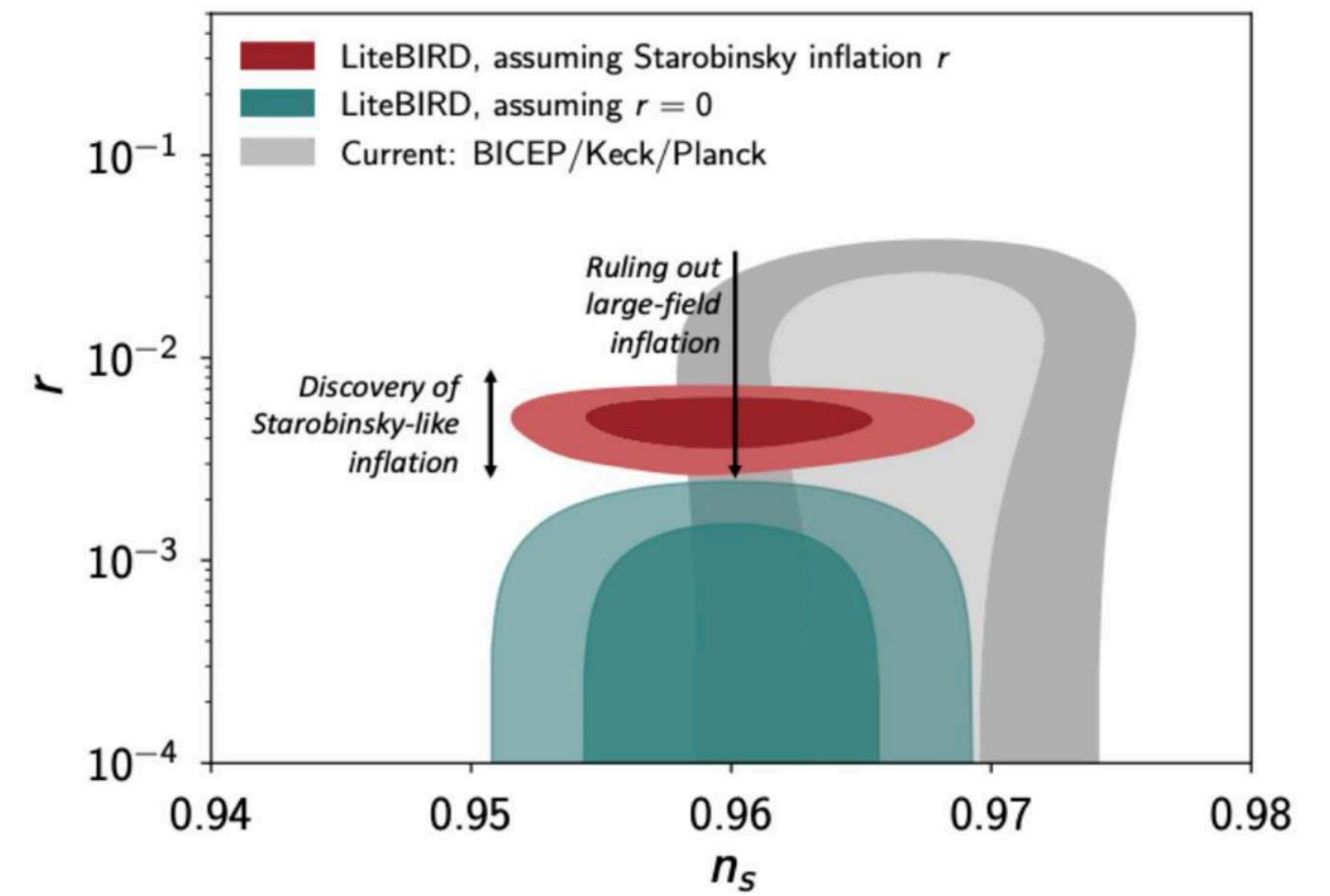
Future of *CMB*



Tensor to scalar ratio

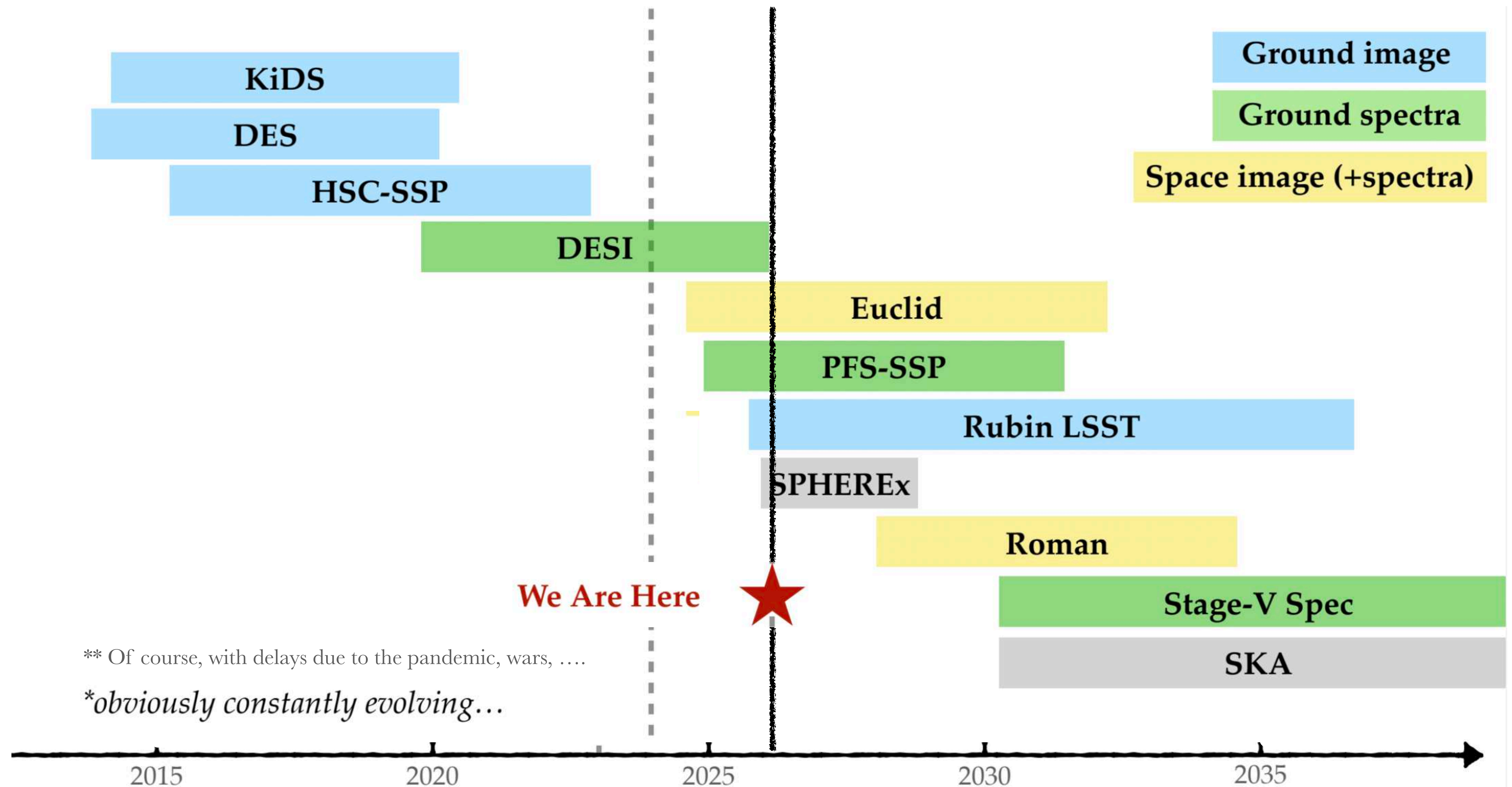


Tensor to scalar ratio



future of LSS

*Future of **LSS***



** Of course, with delays due to the pandemic, wars, ...

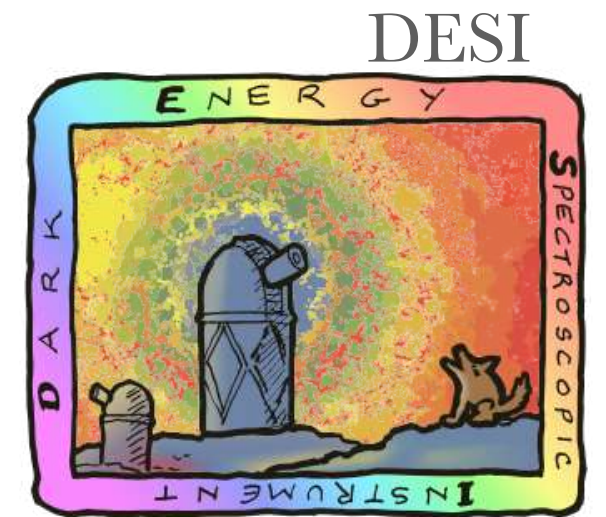
**obviously constantly evolving...*

*Future of **LSS***

Unprecedented amount of data:

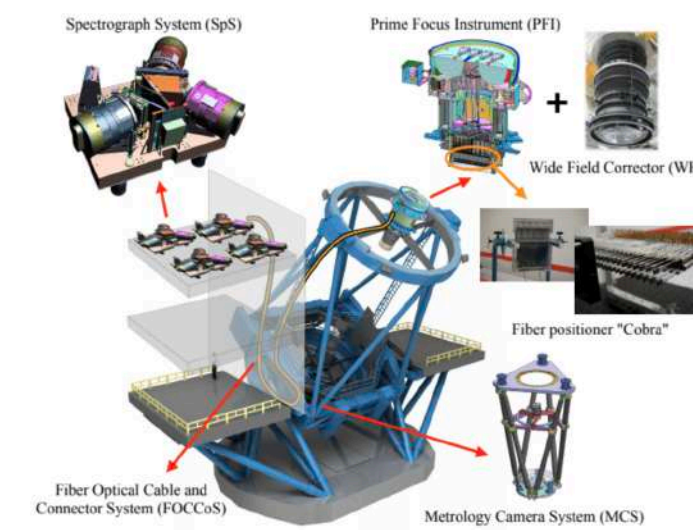
- Galaxy surveys
 - Spectroscopic surveys: e.g. DESI, Euclid spectroscopic, PFS, 4MOST
 - Photometric surveys: e.g. LSST/Rubin, DES, HSC, Euclid photometric
- Weak lensing / cosmic shear: LSST, Euclid, Roman
- Galaxy clusters: eROSITA, SPT, ACT, DES, LSST, Euclid
- CMB lensing as an LSS probe: Simons Observatory, LiteBIRD cross-correlations
- Intensity mapping: 21 cm, CO, [CII], Ly α intensity mapping - SPHEREX
- Lyman- α
- High-redshift galaxy formation: JWST
- Gravitational waves: LIGO/Virgo/KAGRA, LISA, ET/CE

Observations - Stage 4



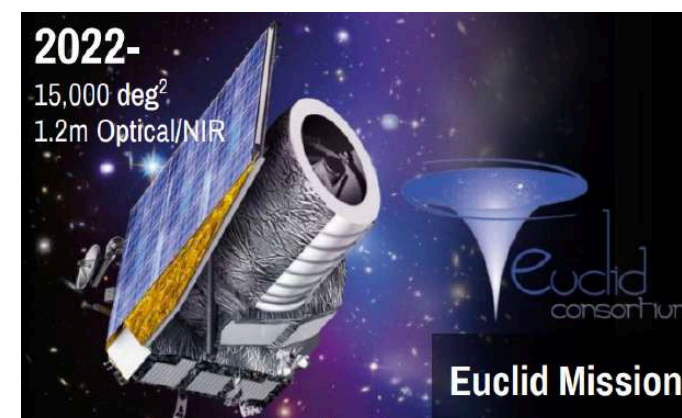
Vera C. Rubin Observatory LSST
Science driver: WL, CL, SNe, solar system, transients, Milky Way
Final data products: image of 37 billion sources, >2 billion WL galaxies, 10 million alerts per night, 18,000 deg²

Prime Focus Spectrograph (PFS)



Prime Focus Spectrograph (PFS)
Science driver: BAO, PNG, galaxy evolution, IGM
Final data products: 2400 fibers, spectra of 4 million galaxies (target selected for HSC), 1,400 deg²
Timeline: engineering first light now

See Jingjing's talk



Euclid
Science driver: WL, CL, BAO
Final data products: images of 10 billion sources, >1 billion WL galaxies, spectra of 35 million galaxies, 15,000 deg²



Nancy Grace Roman Telescope
Science driver: WL, CL, SNe, exoplanets
Final data products (High Latitude Survey): image of 380 million WL galaxies, 2700 SNe, 22 million ELG spectra at $1 < z < 3$, 2,000 deg²
Timeline: launch by May 2027

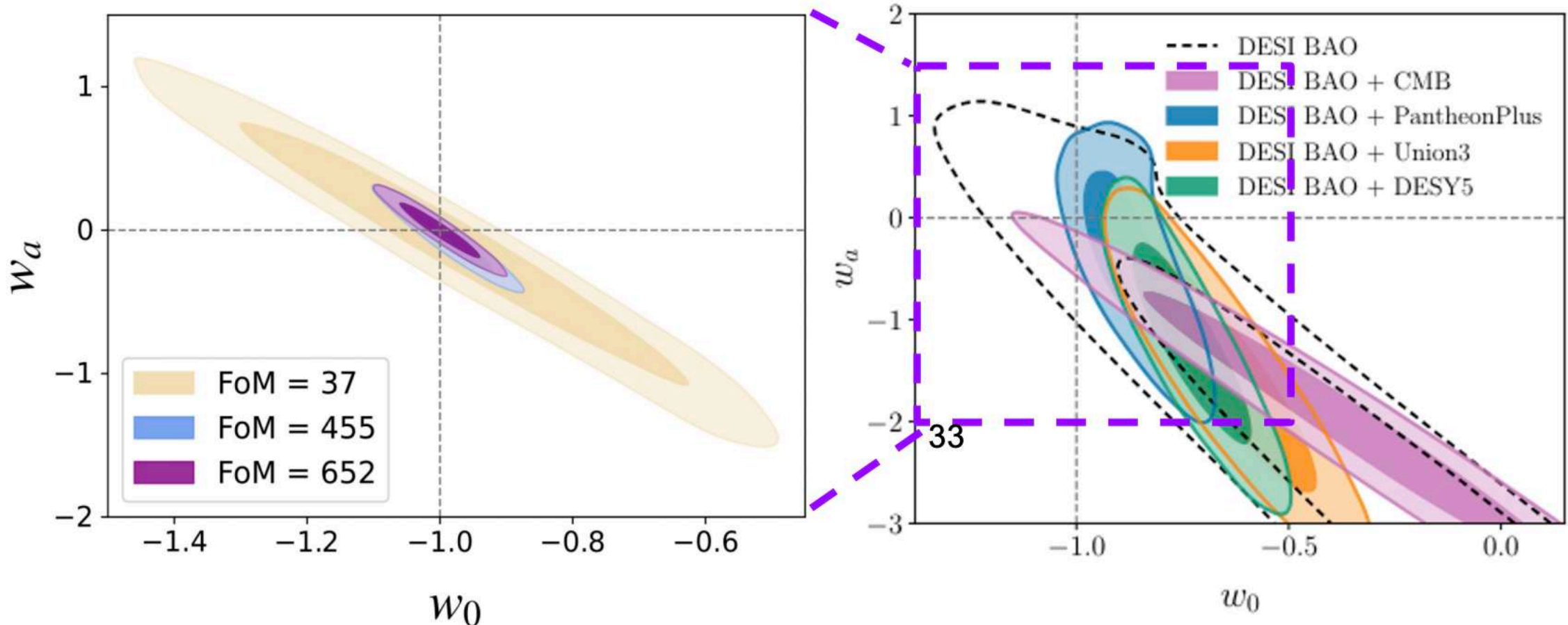


SPHERE_x (Spectro-Photometer for the History of the Universe, Epoch of Reionization, and Ices Explorer)
Science driver: PNG, BAO
Final data products: all-sky survey with 102 fine photometric bands at $0.2 < z < 2.5$
Timeline: launch Spring 2025

Future of *LSS*

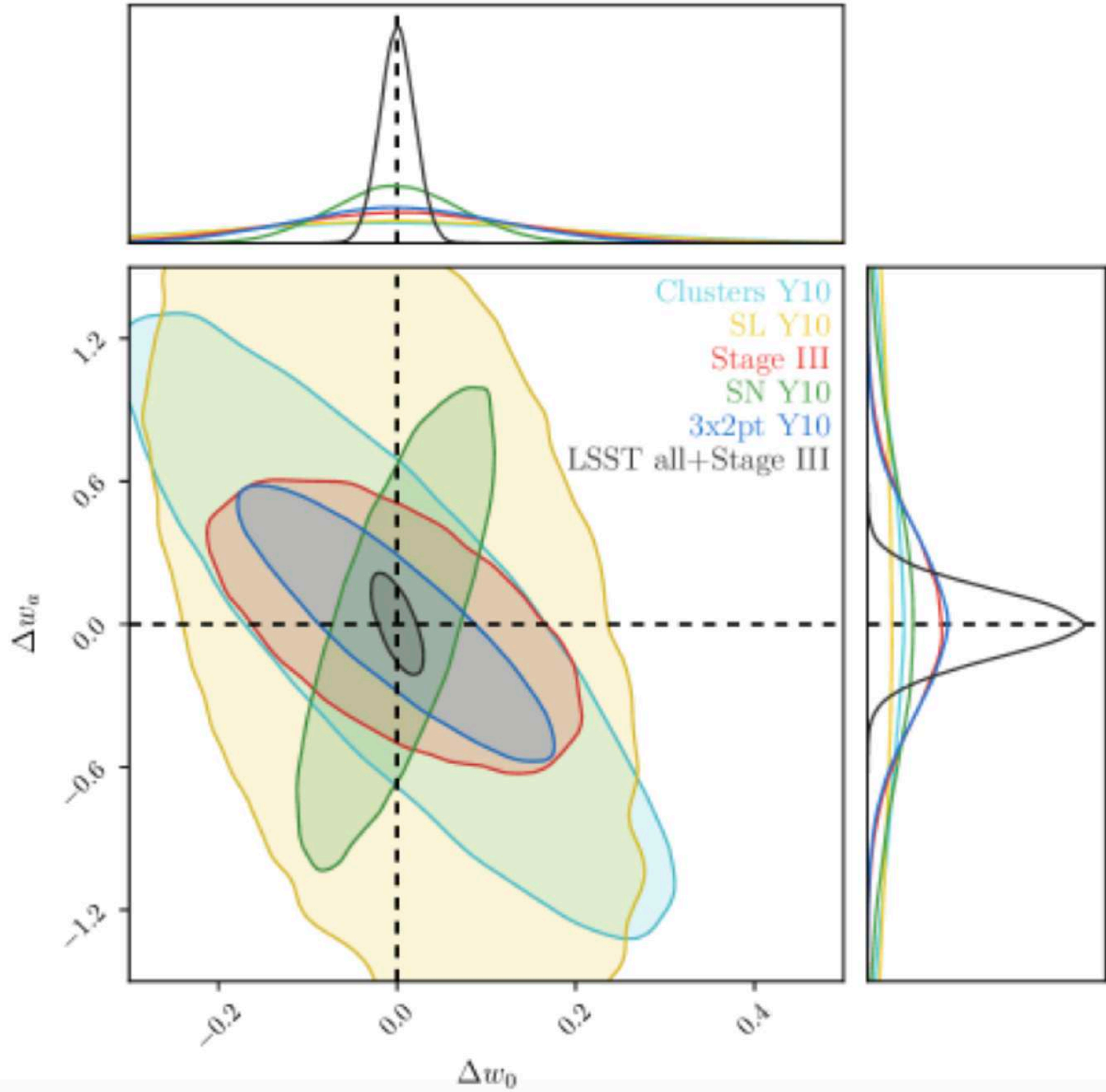


- w_0w_a CDM (GCsp)
- w_0w_a CDM (3x2pt)
- w_0w_a CDM (3x2pt + GCsp)



Euclid Forecast
(Mellier et al 2024)

DESI Collaboration 2024



Considerable improvement in testing DDE, beyond DESI

CMB x LSS

CMB $\times$ *LSS*

CMB:

early-Universe calibration, initial conditions, acoustic scale

LSS:

late-time distances, growth of structure, nonlinear matter distribution

Together:

- test the same cosmological model across cosmic time
- break parameter degeneracies
- compare geometry and growth
- calibrate galaxy bias and lensing systematics
- constrain dark energy, neutrino mass, modified gravity

But combining probes requires care:

- shared assumptions: Λ CDM, GR, flatness, standard recombination, standard rd
- correlated information: CMB lensing, galaxy lensing, clustering, BAO
- nuisance parameters: galaxy bias, intrinsic alignments, photo-z, baryons
- different redshift ranges and physical scales
- possible tensions should not be averaged away

Synergy will help us tighter contours through more information and breaking degeneracies, but it is also a consistency test between probes

CMB x LSS

Example: Simons observatory X LSST

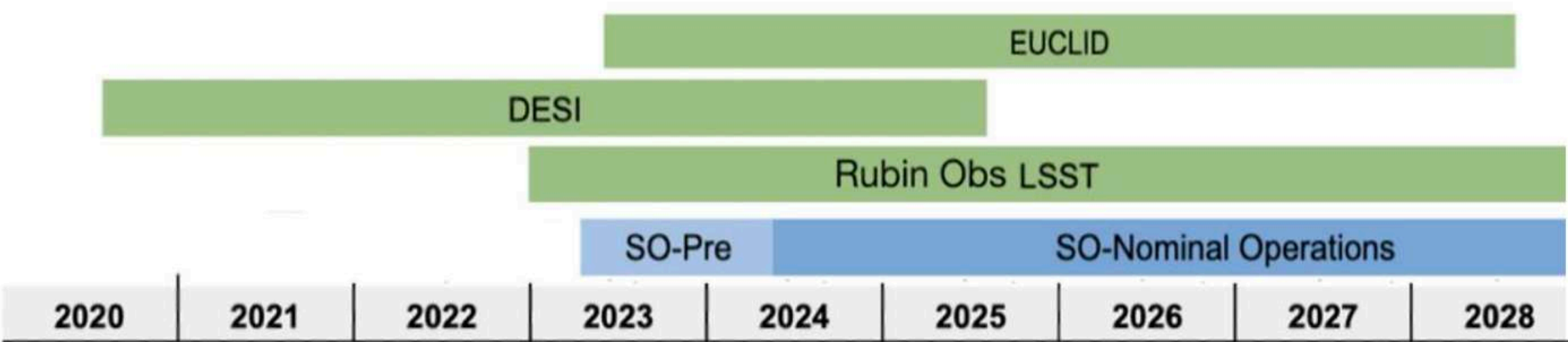
CMB lensing, tSZ, kSZ

X

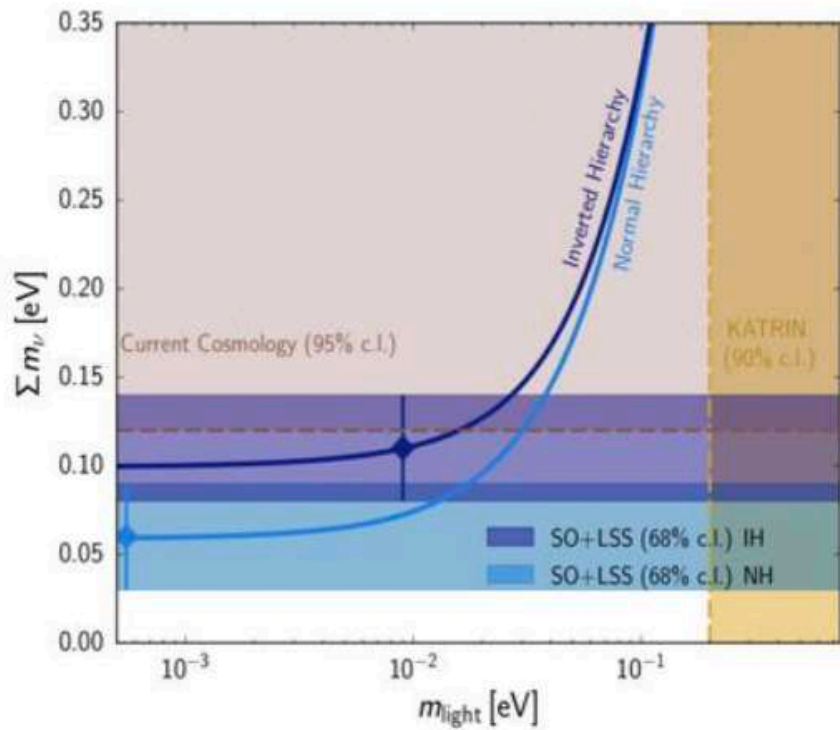
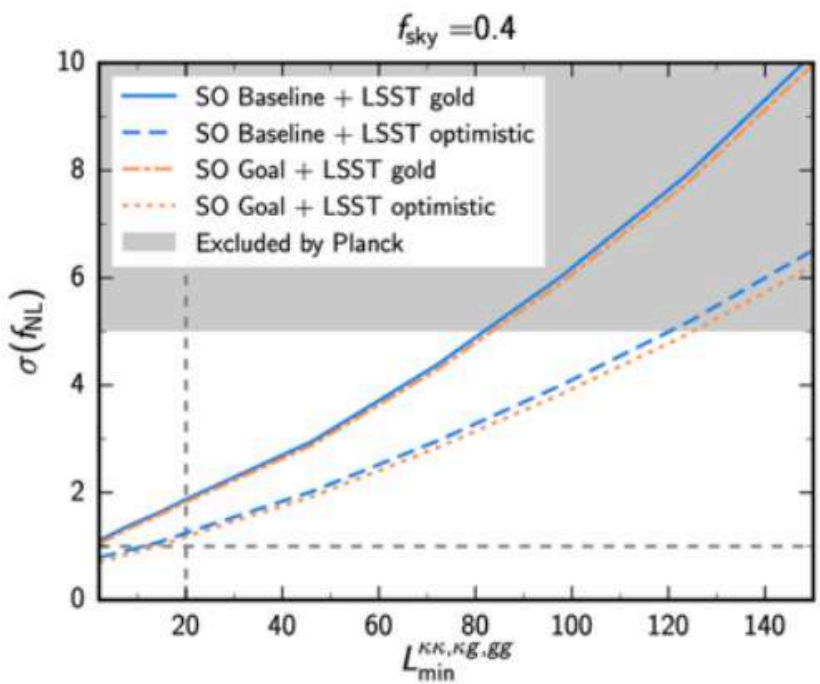
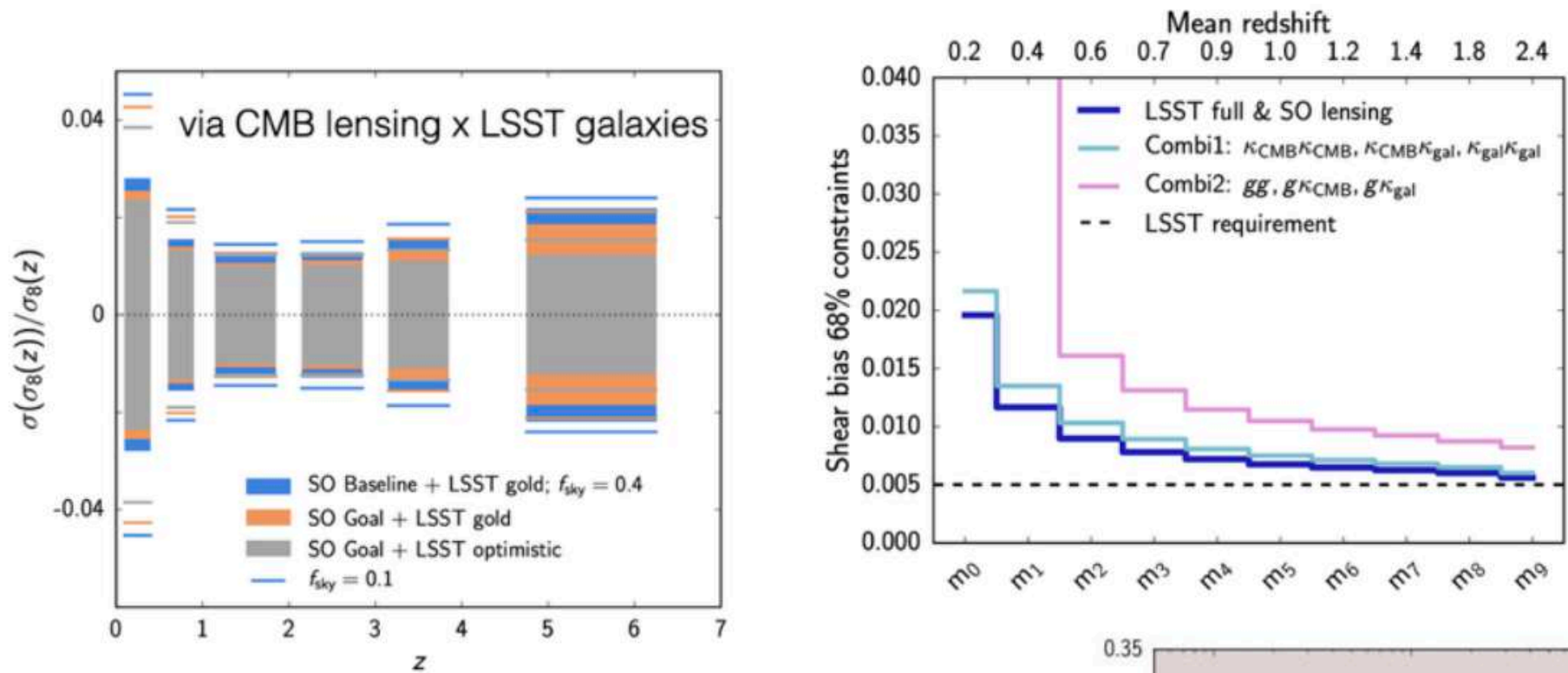
Optical galaxy shear, clustering,
clusters

Can help improve constraints on:

- Neutrino mass
- Structure growth: σ_8 at $z > 1$
- Non-Gaussianity: fnl
- Cluster mass calibration
- Shear bias calibration
- Constraints on baryonic feedback



* with some post-pandemic and war updates



Statistical challenges in cosmology

Exploring the growth of parameter spaces, statistical effects, data combination and their impact on cosmological inference and tensions in cosmology

Statistical methods in cosmology

Cosmology as a precision science owes much of its progress to the large and precise cosmological data sets

ΛCDM →

Bayesian statistics;
MCMC techniques

Next decade: growth of statistical power of cosmological experiments
(Now!) New probes

→

Stress test ΛCDM,
tensions, new physics, ...

Statistical methods in cosmology

Cosmology as a precision science owes much of its progress to the large and precise cosmological data sets

→
ΛCDM

Bayesian statistics;
MCMC techniques

Next decade: growth of statistical power of cosmological experiments
New probes

→

Stress test ΛCDM,
tensions, new physics,
break degeneracies, ...

However...

Increased statistical power and complexity from new observational, theoretical, and systematic uncertainties introduce additional **nuisance parameters**, making statistical inference more challenging.

Particularly important with the increase of high quality data, where systematics will play important role:
stage IV (even stage III), cosmological tensions, ...

LSS surveys: large number of observational and “astrophysical systematics”

Statistical methods in *cosmology*

LSS surveys: large number of observational and “astrophysical systematics”

Photometric surveys - avenue for addressing important questions in cosmology

- Ex: galaxy clustering + weak gravitational lensing (DES) -
- 6 cosmological parameters (Λ CDM and the total neutrino mass)
 - 25 nuisance parameters

Parameter	Prior
Cosmological Parameters	
Ω_{m}	$\text{U}[0.1, 0.9]$
A_{s}	$\text{U}[0.5, 5.0] \times 10^{-9}$
Ω_{b}	$\text{U}[0.03, 0.07]$
n_{s}	$\text{U}[0.87, 1.07]$
h	$\text{U}[0.55, 0.91]$
$\Omega_{\nu} h^2$	$\text{U}[0.6, 6.44] \times 10^{-3}$
w	$\text{U}[-2, -0.333]$
Calibration Parameters	
m_1	$\mathcal{N}(-0.0063, 0.0091)$
m_2	$\mathcal{N}(-0.0198, 0.0078)$
m_3	$\mathcal{N}(-0.0241, 0.0076)$
m_4	$\mathcal{N}(-0.0369, 0.0076)$
Δz_1	$\mathcal{N}(0.0, 0.018)$
Δz_2	$\mathcal{N}(0.0, 0.015)$
Δz_3	$\mathcal{N}(0.0, 0.011)$
Δz_4	$\mathcal{N}(0.0, 0.017)$
Intrinsic Alignment Parameters	
a_1	$\text{U}[-5, 5]$
a_2	$\text{U}[-5, 5]$
η_1	$\text{U}[-5, 5]$
η_2	$\text{U}[-5, 5]$
b_{TA}	$\text{U}[0, 2]$
Shear Ratio Parameters	
Δz_1^{lens}	$\mathcal{N}(-0.009, 0.007)$
Δz_2^{lens}	$\mathcal{N}(-0.035, 0.011)$
Δz_3^{lens}	$\mathcal{N}(-0.005, 0.006)$
$\delta_{z,1}^{\text{lens}}$	$\mathcal{N}(0.975, 0.062)$
$\delta_{z,2}^{\text{lens}}$	$\mathcal{N}(1.306, 0.093)$
$\delta_{z,3}^{\text{lens}}$	$\mathcal{N}(0.870, 0.054)$
b_g^{1-3}	$\text{U}[0.8, 3]$

Statistical methods in *cosmology*

Cosmology as a precision science owes much of its progress to the large and precise cosmological data sets

ΛCDM
→

Bayesian statistics;
MCMC techniques

Increased statistical power and complexity from new observational, theoretical, and systematic uncertainties introduce additional **nuisance parameters**, making statistical inference more challenging.

This **inflation of parameters** can lead to statistical artefacts or inefficient data analysis that can **bias** the cosmological parameter inference, affecting how powerful these data sets can be

Statistical tools at center stage! *Bayesian, frequentist, ML, ...*

Questions:

*What are those effects and how important/how much they affect *parameter inference*?*

*Can we combine data sets to improve *parameter constraints*?*

*Cosmological *tensions*?*

Statistical methods in cosmology - challenges for current and next generation of experiments

Volume effects & profile likelihood in cosmology

Parameter inflation

*What are those effects and how important/
how much they affect parameter inference?*

Challenges for new experiments

- Laura Herold, **EF** 2210.1629
- Laura Herold, **EF** and Eiichiro Komatsu 2112.12140,
- Reeves, L. Herold, S. Vagnozzi, B. Sherwin, **EF** 2207.01501
- *Profile Likelihoods in Cosmology: When, Why and How illustrated with Λ CDM, Massive Neutrinos and Dark Energy*, L. Herold, **EF**, L. Heinrich, 2025
- E. Holm, L. Herold, T. Simon, **EF**, S. Hannestad, V. Poulin, T. Tram 2023

Combining data sets & tension in cosmology

*Can we combine data sets to improve
parameter constraints?*

Cosmological tensions?

- *The BAO-CMB Tension and Implications for Inflation*, **EF**, et al - **PRD Editor's suggestion**
- *The Shifting Spectrum of n_s constraints from DESI and CMB data*, E McDonough, **EF**

Next-generation cosmological surveys

Large volumes, different probes, different wavelengths

With statistical precision rapidly improving, systematic uncertainties will set the frontier

New, creative and complementary statistical analysis necessary to achieve this frontier

Opportunity for new analysis

Careful modelling of astrophysical systematics

Combining surveys and probes

Understand systematic effects

Opportunity to maximize constraining power

Careful! Need proper framework (avoid improper claims)

A lot work to be done...

Λ CDM remains an extraordinarily successful baseline.

But precision data are now testing its assumptions, not only its parameters:

early-universe ruler, late-time geometry, growth of structure, dark energy, gravity.

Current tensions are not all equally significant:

H_0 remains sharp; S_8 is survey/systematics dependent;

Hints on new physics:

DESI hints at evolving dark energy but interpretation is model dependent. Cosmic birefringence

The key question is shifting:

not simply “is there a tension?” but “which physical assumption is being tested?”

CMB + LSS synergies are essential:

CMB fixes initial conditions and the early ruler; LSS maps geometry, growth, and nonlinear structure across cosmic time.

But combining data sets is hard!

Stage IV surveys will decide whether today’s hints are:

systematics, astrophysics, parameter degeneracies, or the first signs of new dark-sector physics.

Future very exciting!!

Are we confirming or going beyond the standard model; learning about fundamental physics of the universe



Thank you!