The BAO-CMB tension and *implications for inflation*

Elisa G. M. Ferreira
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Frontiers of Precision Cosmology:
From the Early Universe to Observational Tensions

04/March/2026

Statistical challenges in cosmology

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

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Statistical methods in cosmology

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

LCDM →

Bayesian statistics;
MCMC techniques

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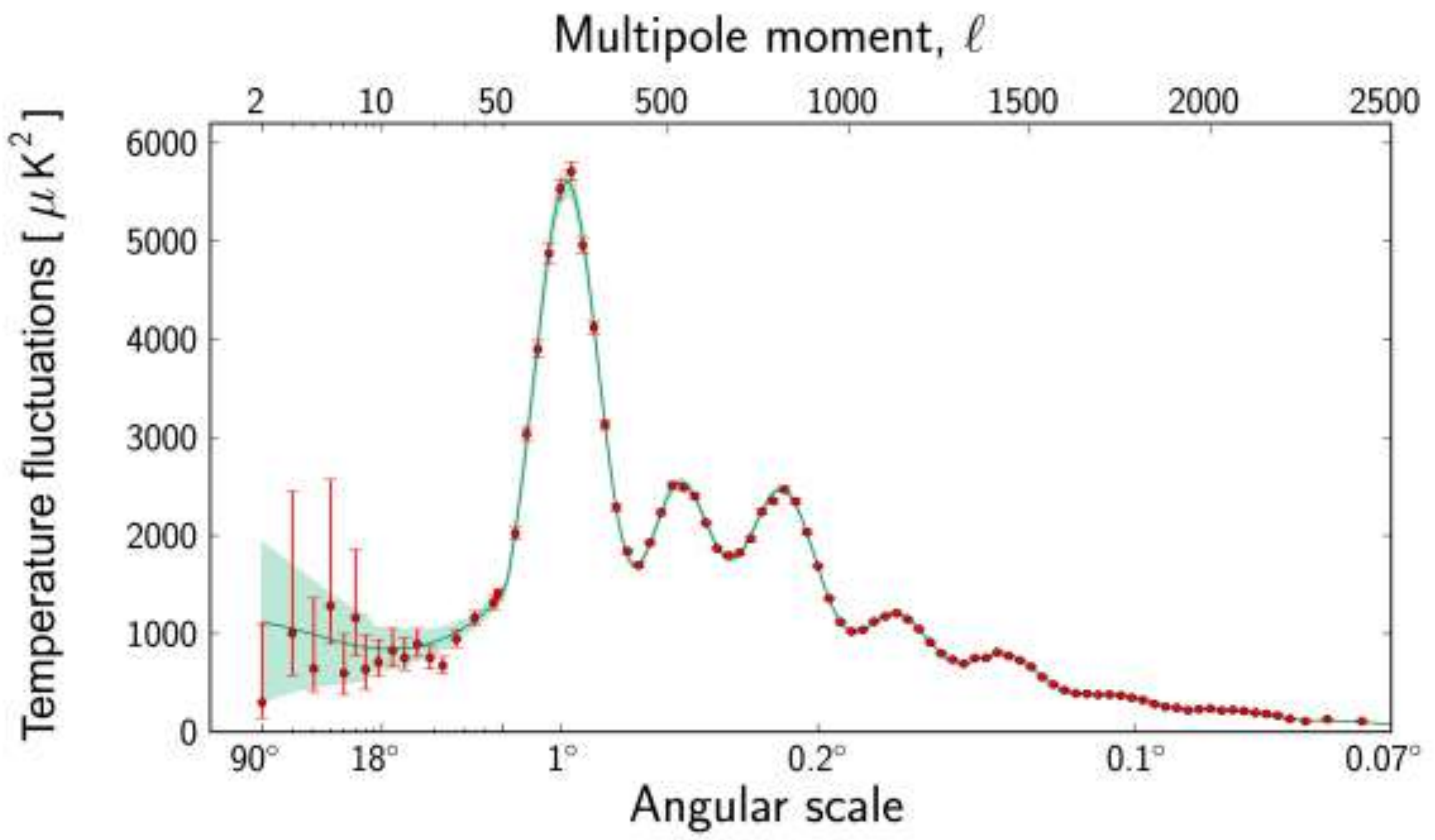
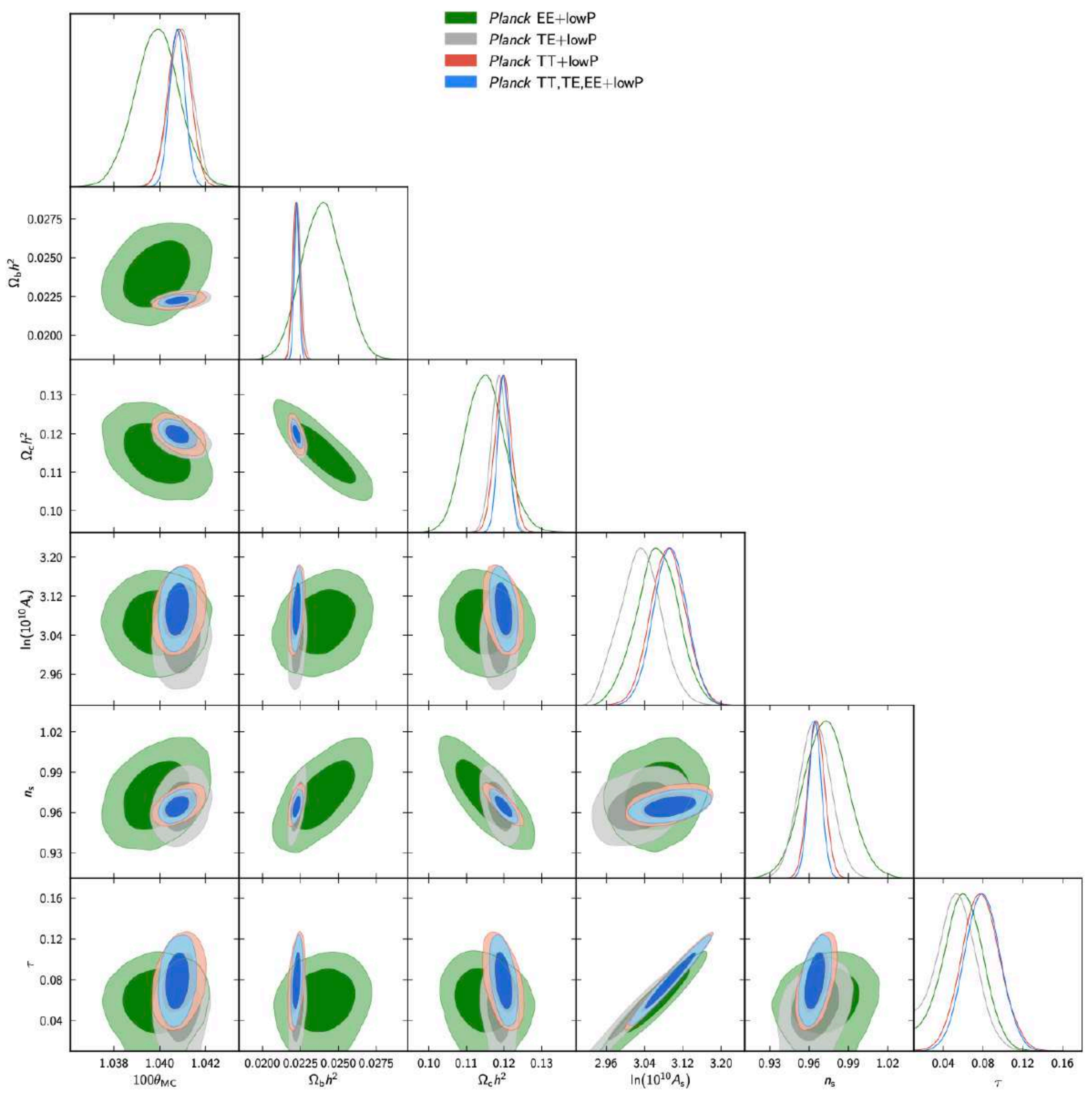




Planck analysis: **~30–40 parameters** (6 cosmological + ~25 nuisance)

Planck 2015

Statistical methods in cosmology

Cosmology as a precision science owes much of its progress to the large and precise cosmological data sets —LCDM→ Bayesian statistics; MCMC techniques

Next decade: growth of statistical power of cosmological experiments → Stress test LCDM, tensions, new physics, …

(Now!) New probes

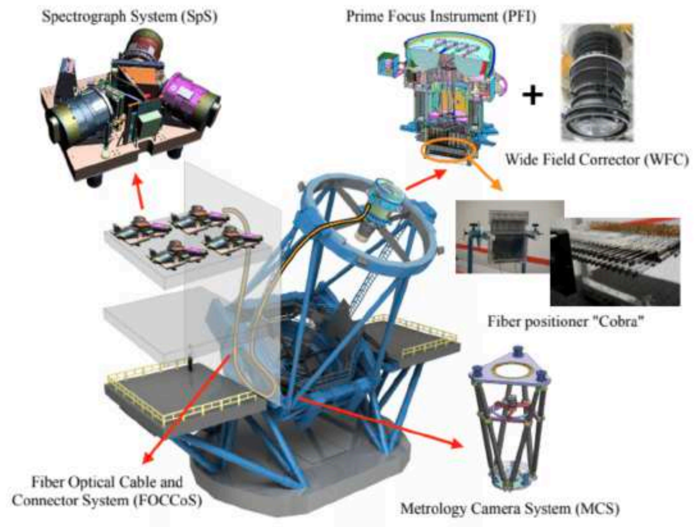
Observations - Stage 3 and 4

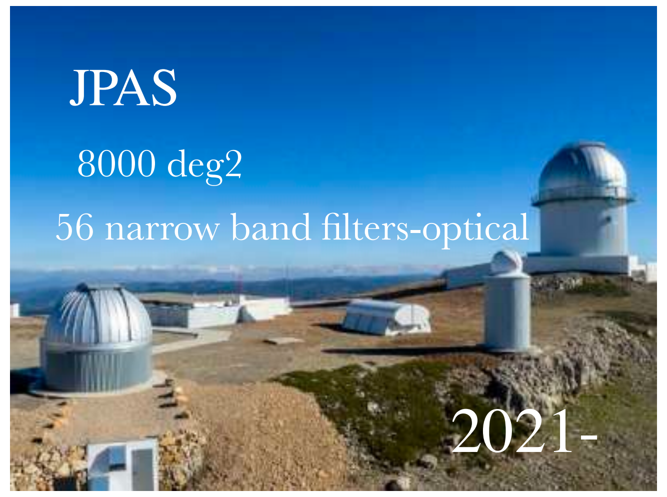
Huge amount of data coming now and in the future: incredible precision, new probes, small scales, polarization, …

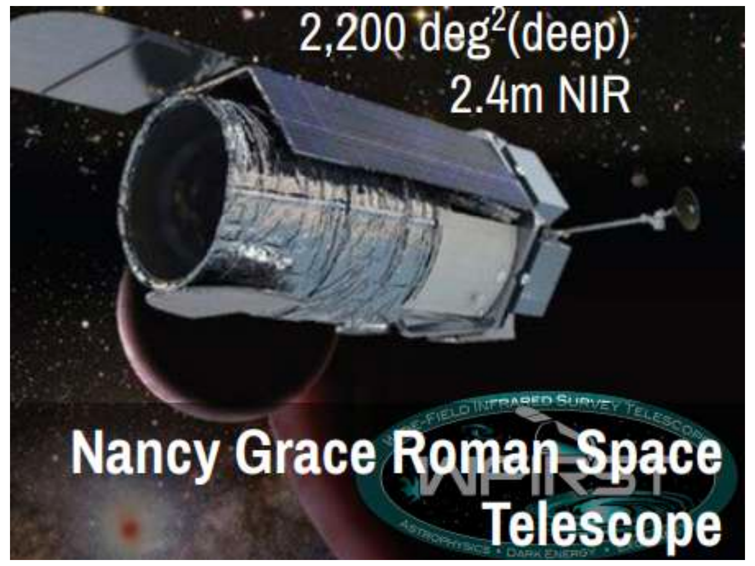
Photometric and spectroscopic surveys

DESI

Prime Focus Spectrograph (PFS)





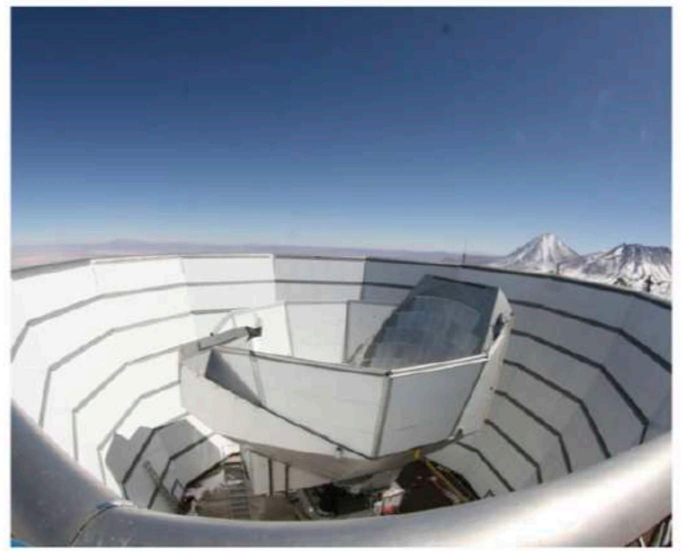


GWs

21cm

CMB

ACT



SPT

CMB-S4
Next Generation CMB Experiment

Modified from Jia Liu

Ground image
Ground spectra
Space image (+spectra)
KiDS
DES
HSC-SSP
DESI
Euclid
PFS-SSP
Rubin LSST
SPHEREx
We Are Here
Roman
Stage-V Spec
SKA
*obviously constantly evolving…
2015
2020
2025
2030
2035

Statistical methods in cosmology

Cosmology as a precision science owes much of its progress to the large and precise cosmological data sets → (LCDM) Bayesian statistics; MCMC techniques

Next decade: growth of statistical power of cosmological experiments → Stress test LCDM, tensions, new physics, break degeneracies, …
New probes

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 (ΛCDM and the total neutrino mass)
- 25 nuisance parameters

Parameter	Prior
Cosmological Parameters	
Ω_m	U[0.1, 0.9]
A_s	$U[0.5, 5.0] \times 10^{-9}$
Ω_b	U[0.03, 0.07]
n_s	U[0.87, 1.07]
h	U[0.55, 0.91]
$\Omega_\nu h^2$	$U[0.6, 6.44] \times 10^{-3}$
w	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	U[−5, 5]
a_2	U[−5, 5]
η_1	U[−5, 5]
η_2	U[−5, 5]
b_{TA}	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}	$\mathcal{N}(-0.005, 0.006)$
$\delta_{z,1}^{lens}$	$\mathcal{N}(0.975, 0.062)$
$\delta_{z,2}^{lens}$	$\mathcal{N}(1.306, 0.093)$
$\delta_{z,3}^{lens}$	$\mathcal{N}(0.870, 0.054)$
b_g^{1-3}	U[0.8, 3]

Secco et al 2021

Statistical methods in cosmology

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

LCDM →

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 thy 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

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 ns constraints from DESI and CMB data*, E McDonough, **EF**

Volume effects
&
profile likelihood in cosmology

Parameter inflation

What are those effects and how important/ how much thy 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 ΛCDM, 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

The BAO-CMB tension and Implications for Inflation

- *The BAO-CMB Tension and Implications for Inflation*, **EF**, E McDonough, L Balkenhol, R Kallosh, L Knox, and A Linde, 2025 - **Editor's suggestion**
- *The Shifting Spectrum of ns constraints from DESI and CMB data*, E McDonough, **EF**, 2025

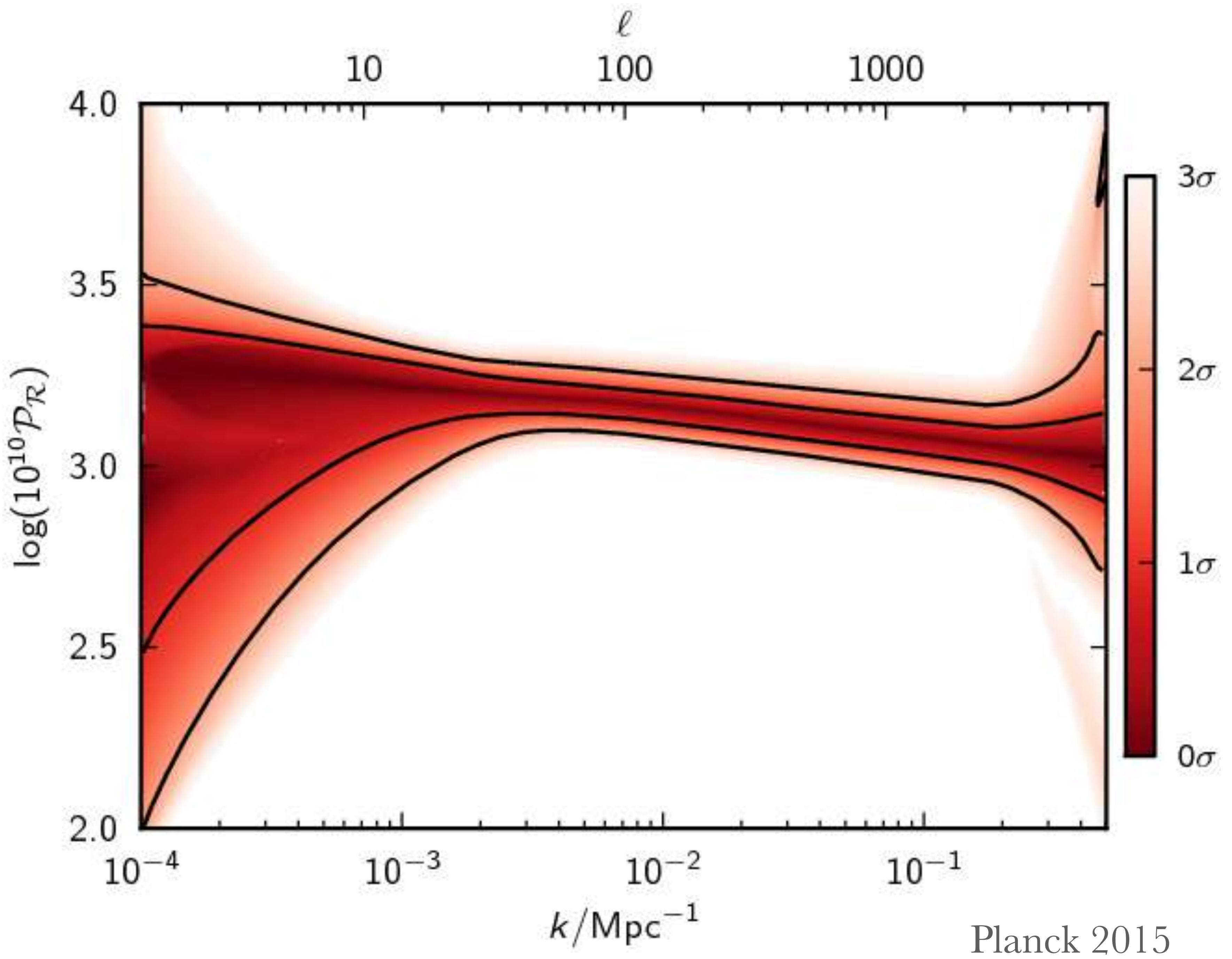
Early universe and the spectral index

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!

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

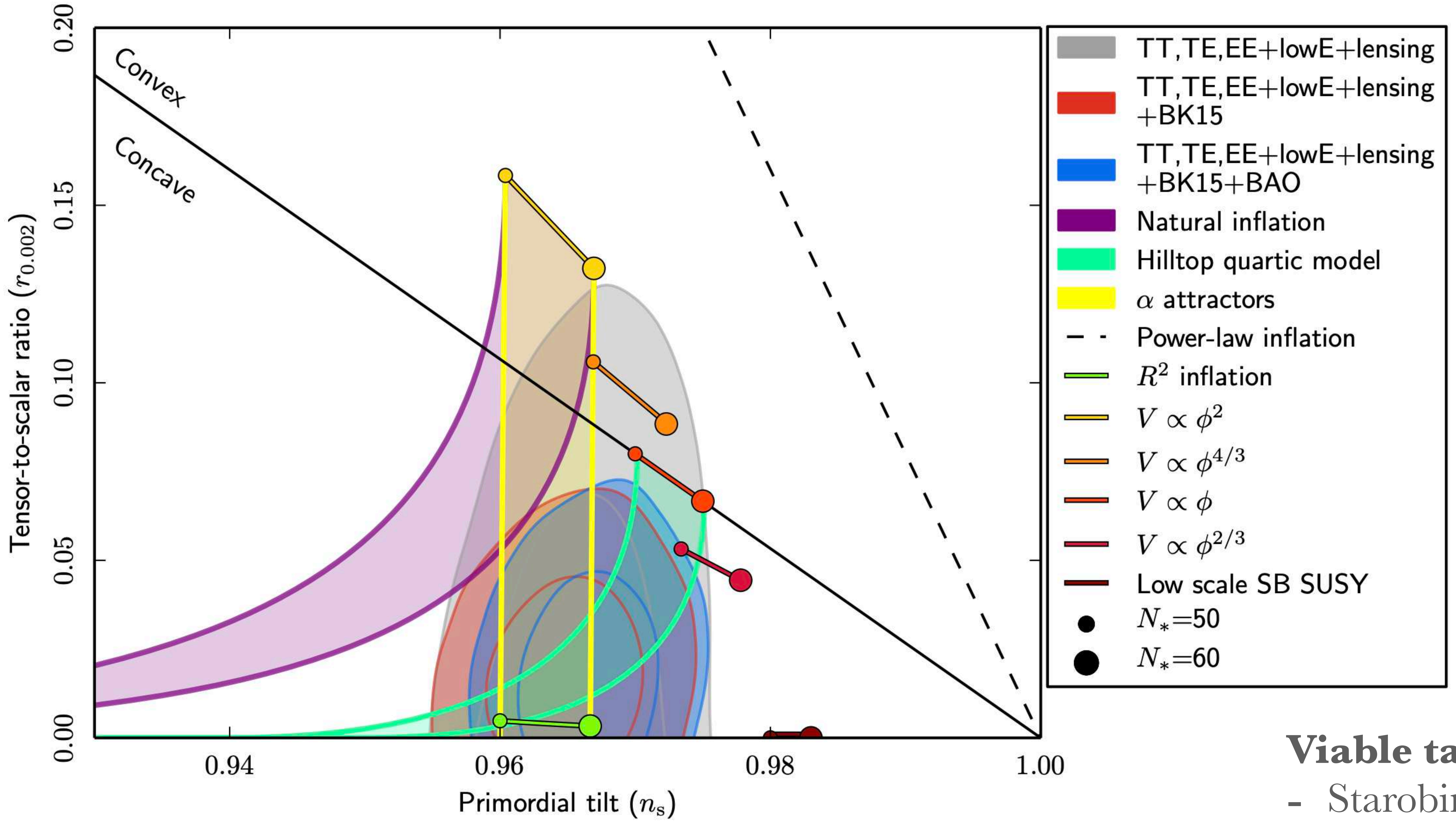
Value of n_s: great discriminator of inflationary (and early universe) models



Planck 2015

Early universe and the spectral index

Current status:



Planck 2018

$n_s = 0.9626 \pm 0.0057$ (68 % CL, *Planck* TT+lowE)

$\tau = 0.052 \pm 0.008$

$n_s = 0.9649 \pm 0.0044$ (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:

CMB-S4
Next Generation CMB Experiment

+ LSS experiments
+ GW wxperiments
+ New probes

BUT…

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

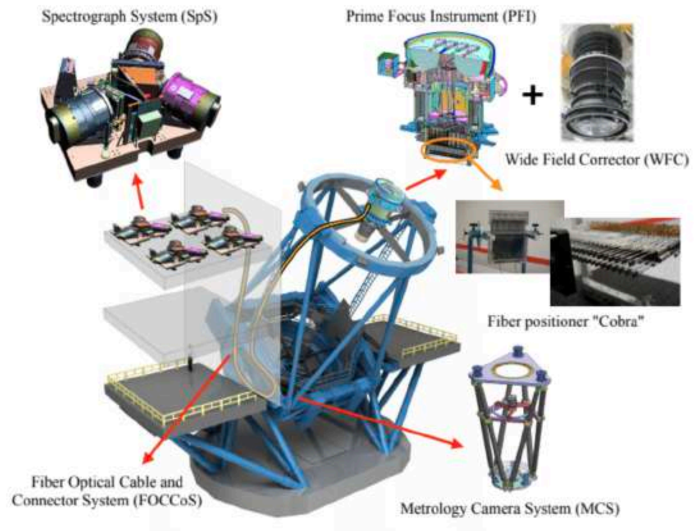
Observations - Stage 3 and 4

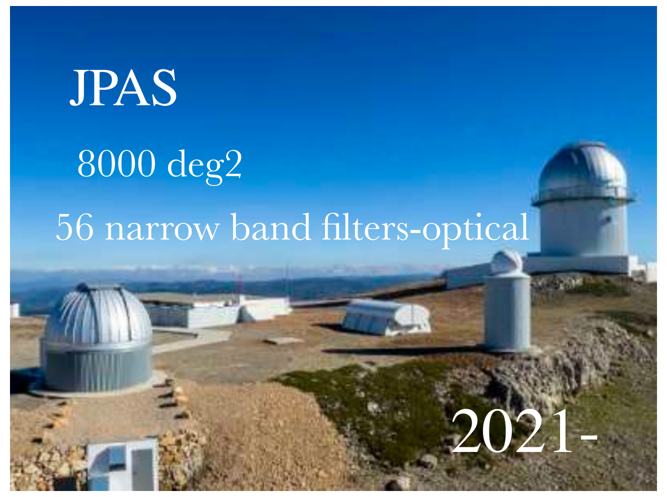
From the ones we already have results, we already learned a lot of new things!!!

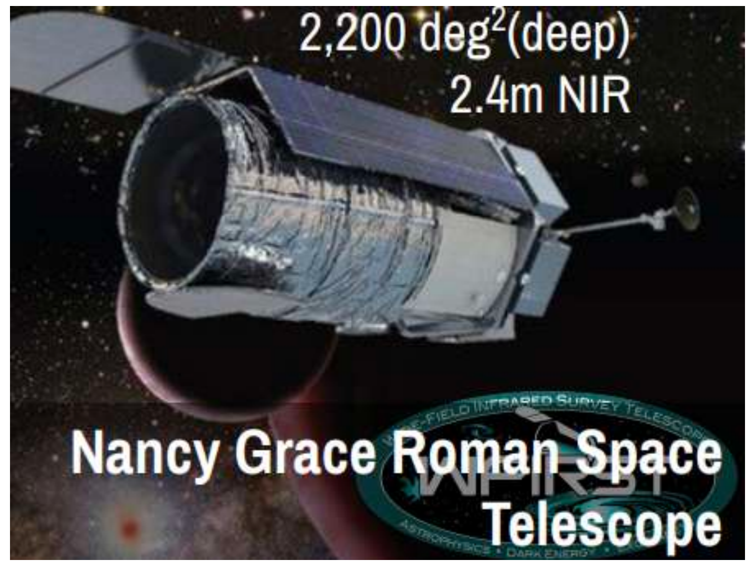
Photometric and spectroscopic surveys

DESI

Prime Focus Spectrograph (PFS)





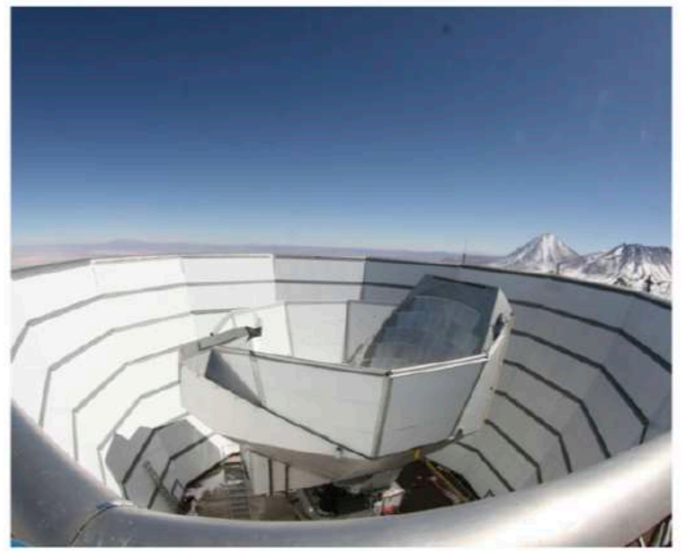


GWs

21cm

CMB

ACT



SPT

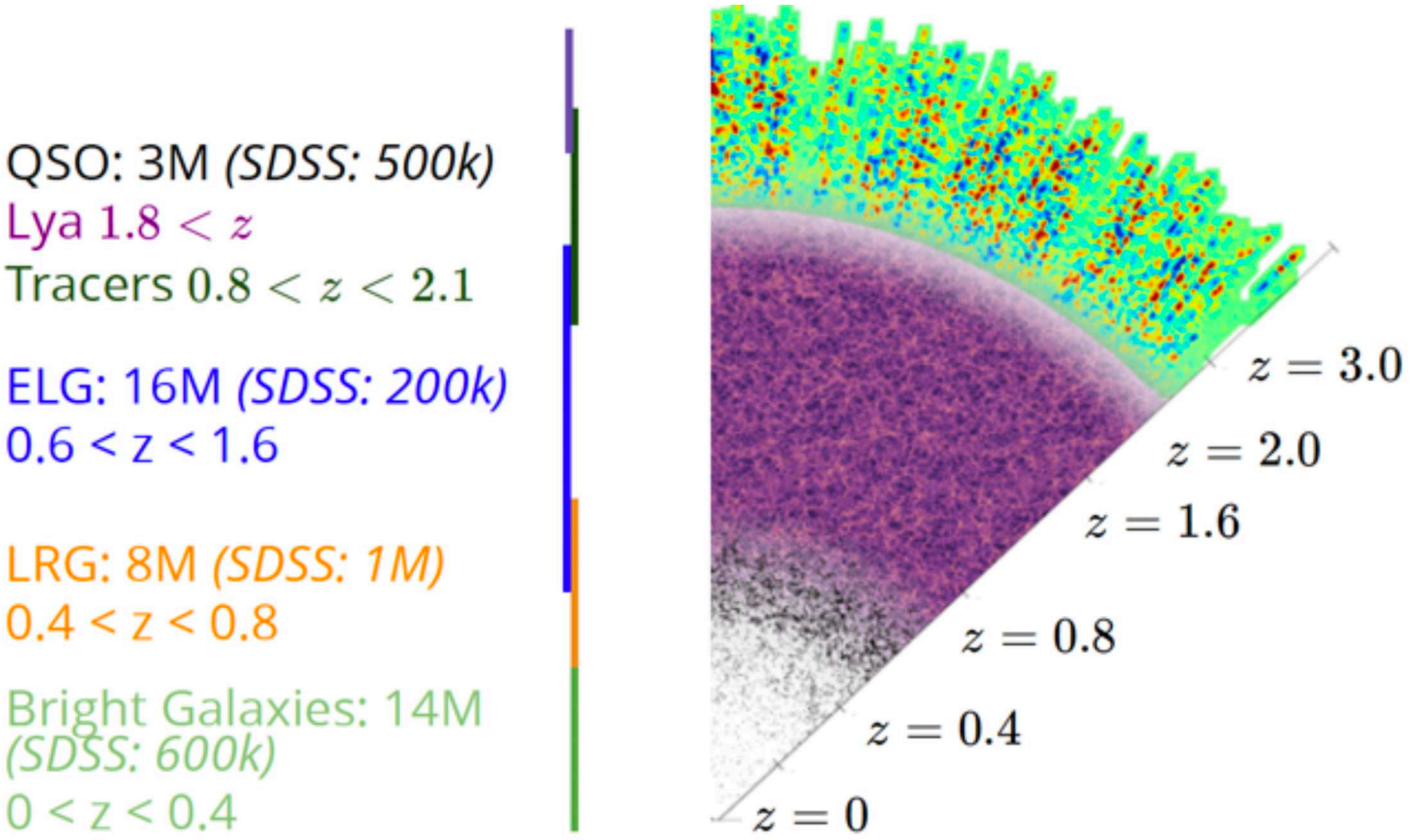
CMB-S4
Next Generation CMB Experiment

Modified from Jia Liu

The Dark Energy Spectroscopic Instrument (DESI)

The Dark Energy Spectroscopic Instrument - DESI

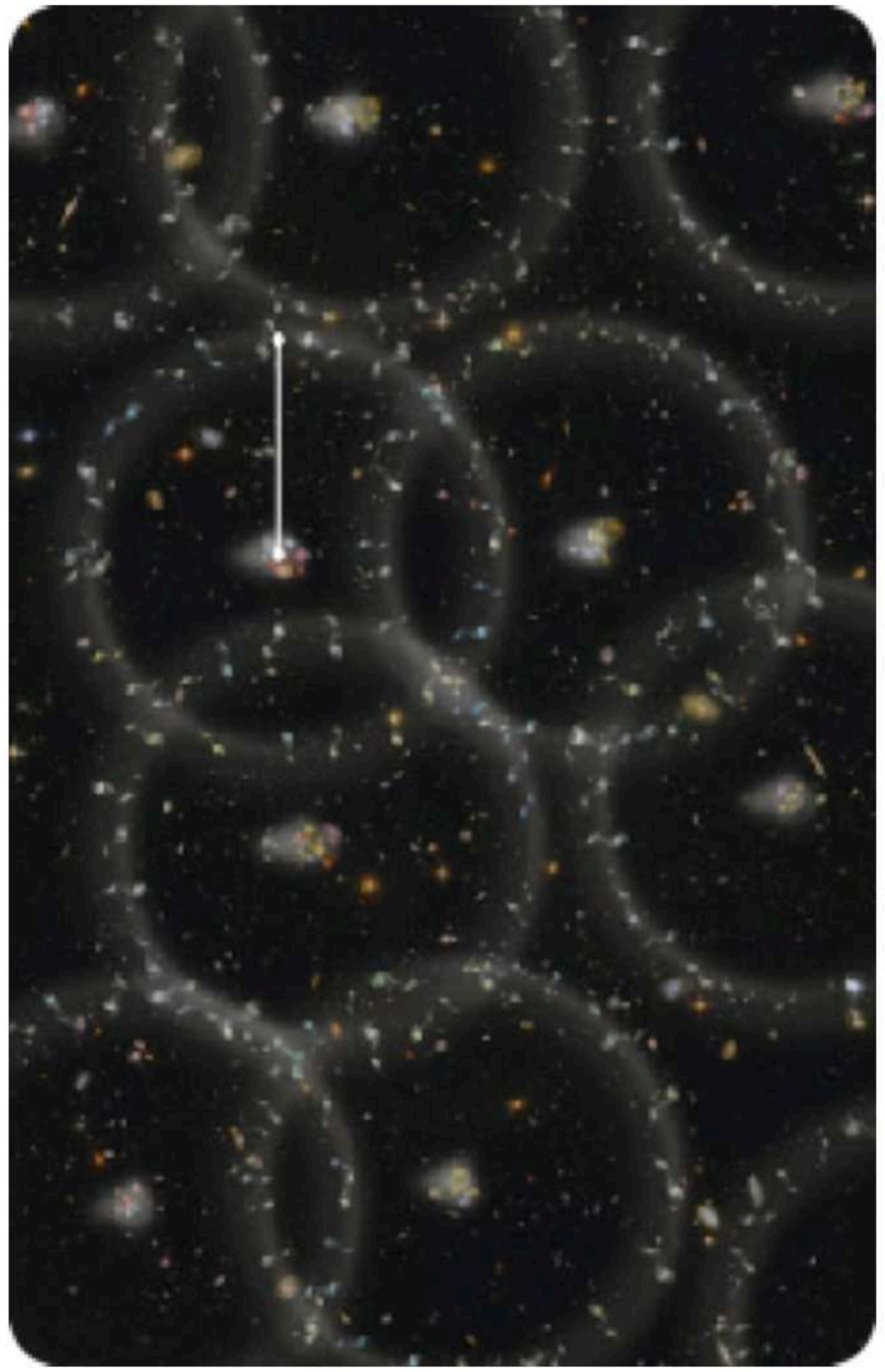
DESI galaxy samples: 40M galaxy redshifts in 5 years of observations



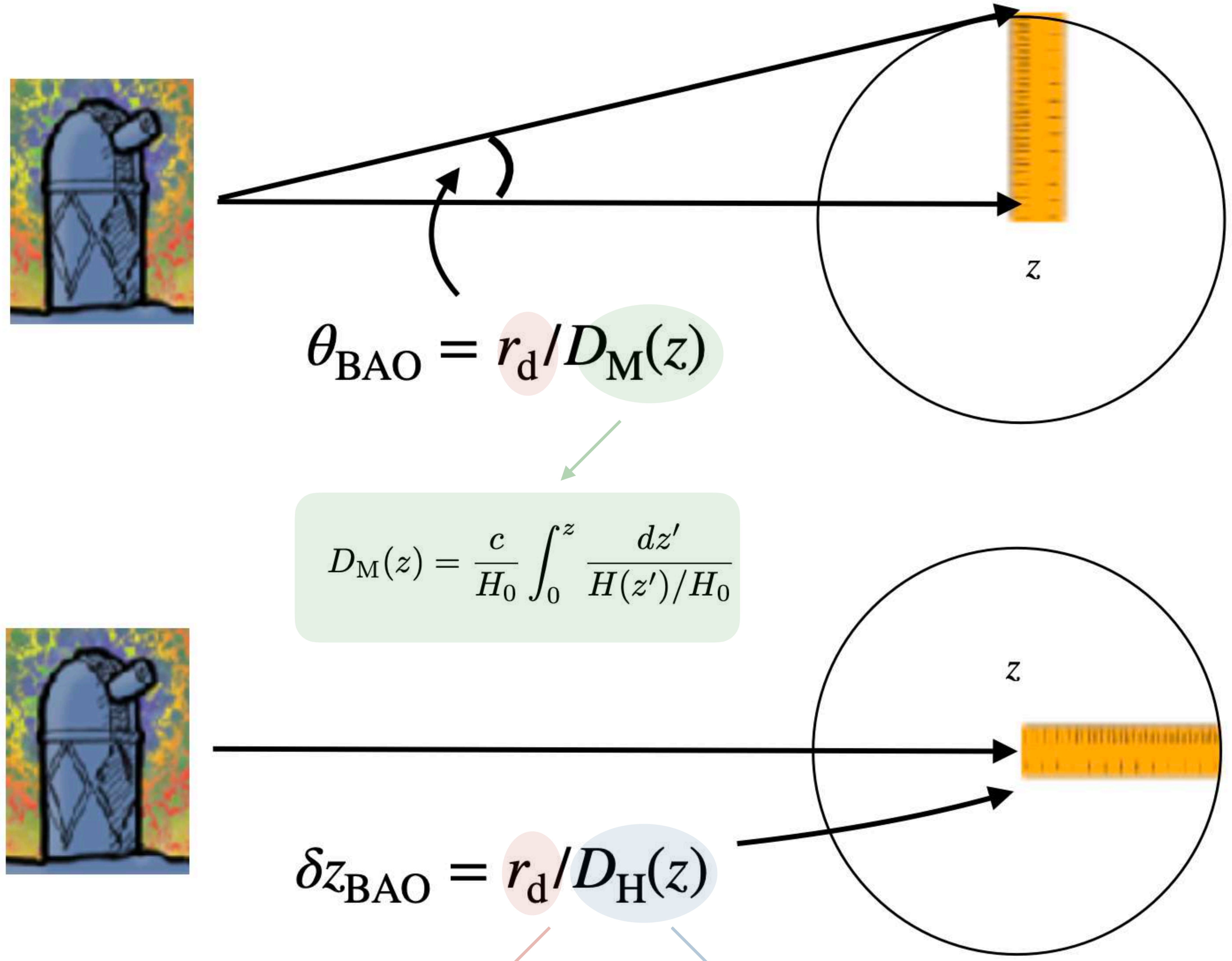
The Dark Energy Spectroscopic Instrument - DESI

What DESI BAO measures

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



$$r_{\rm d} = 147.05\,\text{Mpc} \times \left(\frac{\omega_{\rm b}}{0.02236}\right)^{-0.13} \left(\frac{\omega_{\rm bc}}{0.1432}\right)^{-0.23} \left(\frac{N_{\rm eff}}{3.04}\right)^{-0.1}$$



$$\theta_{\rm BAO} = r_{\rm d}/D_{\rm M}(z)$$

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

$$\delta z_{\rm BAO} = r_{\rm d}/D_{\rm H}(z)$$

$$r_{\rm d} = \int_{z_{\rm d}}^{\infty} \frac{c_s(z)}{H(z)} dz$$

$$D_{\rm H}(z) = \frac{c}{H(z)}$$

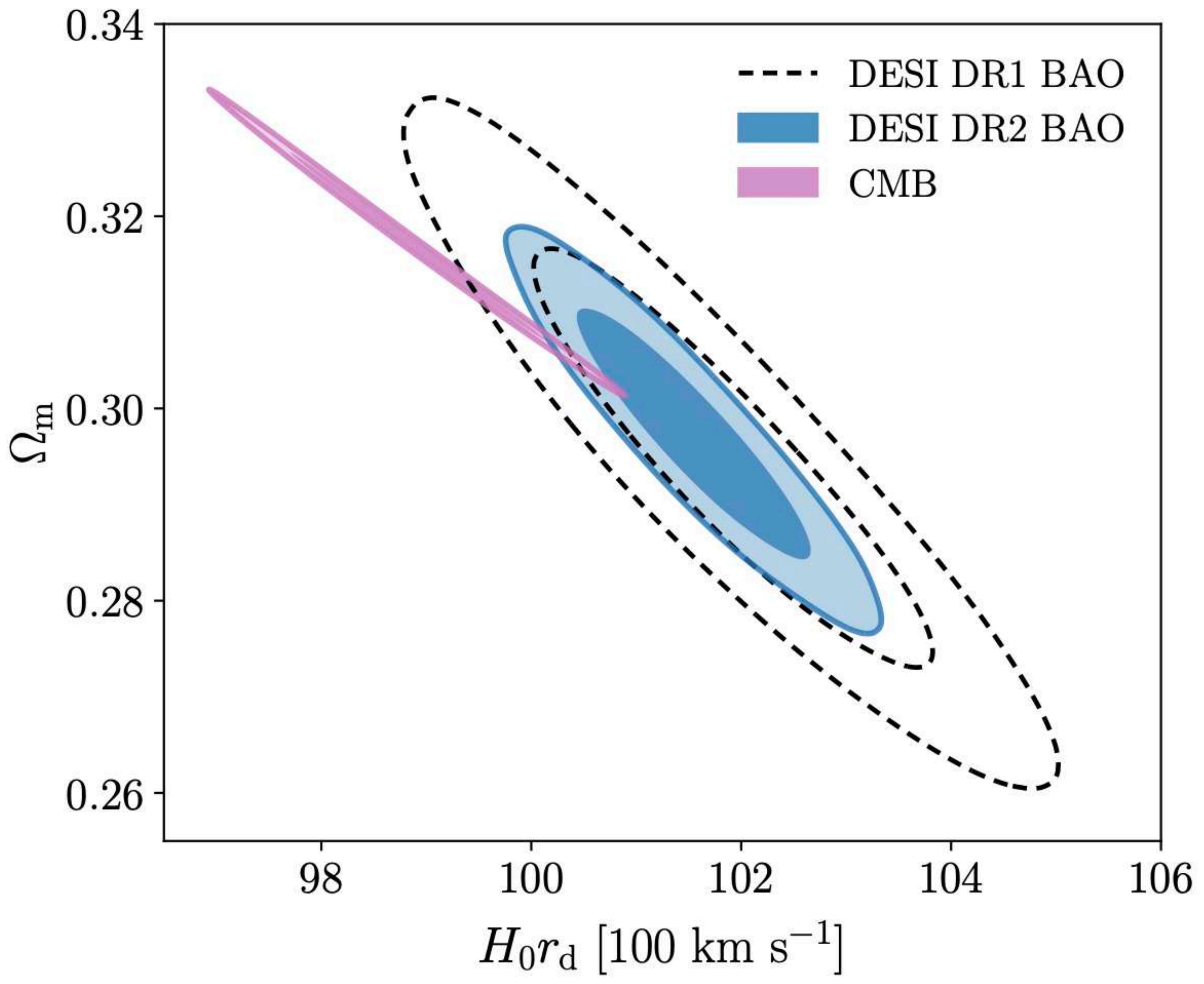
→ $r_d \, h$

Ω_M

$+ \;\; D_V(z)/r_d$

The Dark Energy Spectroscopic Instrument - DESI

Results: LCDM



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

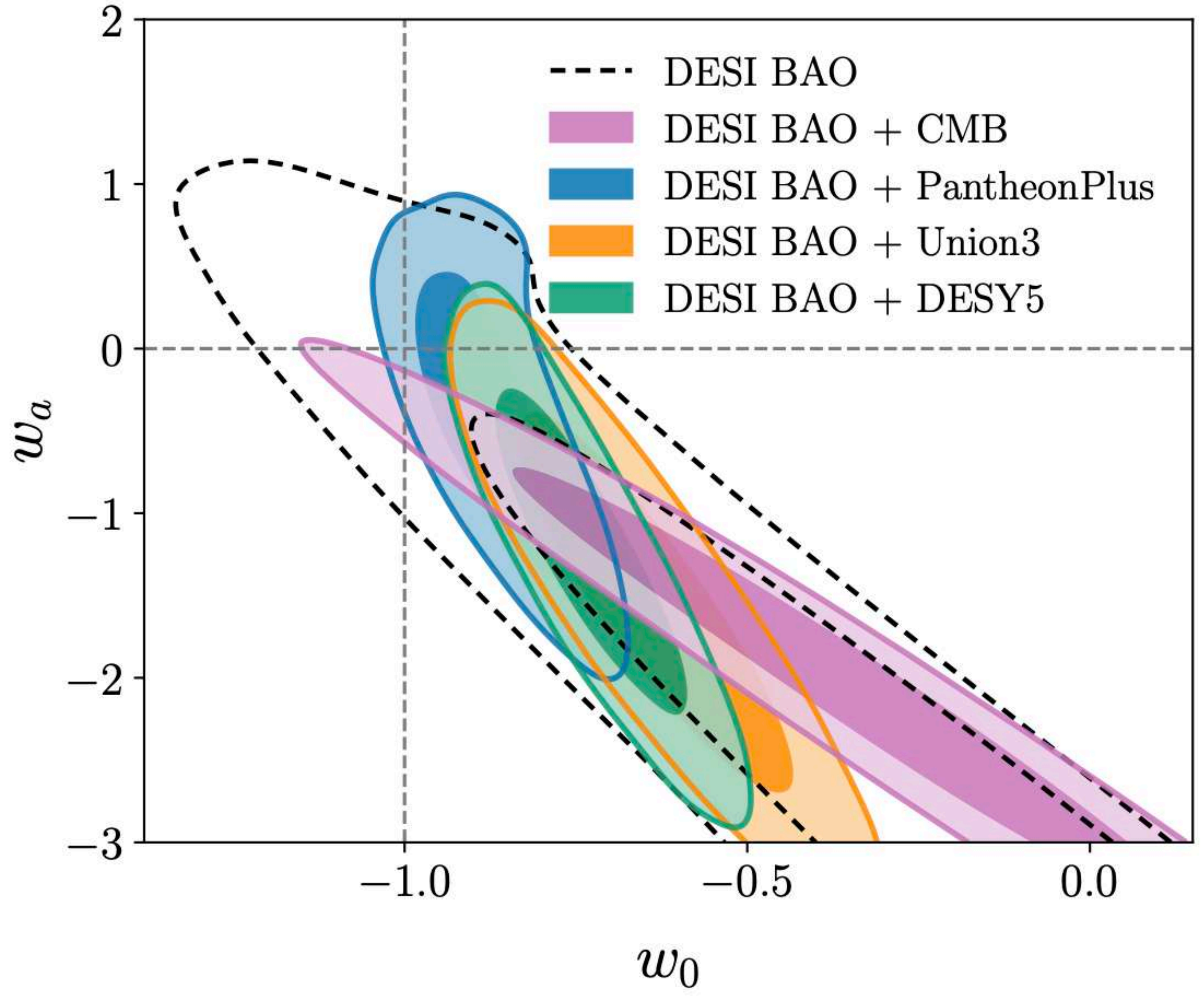
$$\left.\begin{aligned} \Omega_m &= 0.295 \pm 0.015, \\ r_d h &= (101.8 \pm 1.3)\,\mathrm{Mpc}, \end{aligned}\right\} \text{DESI BAO}$$

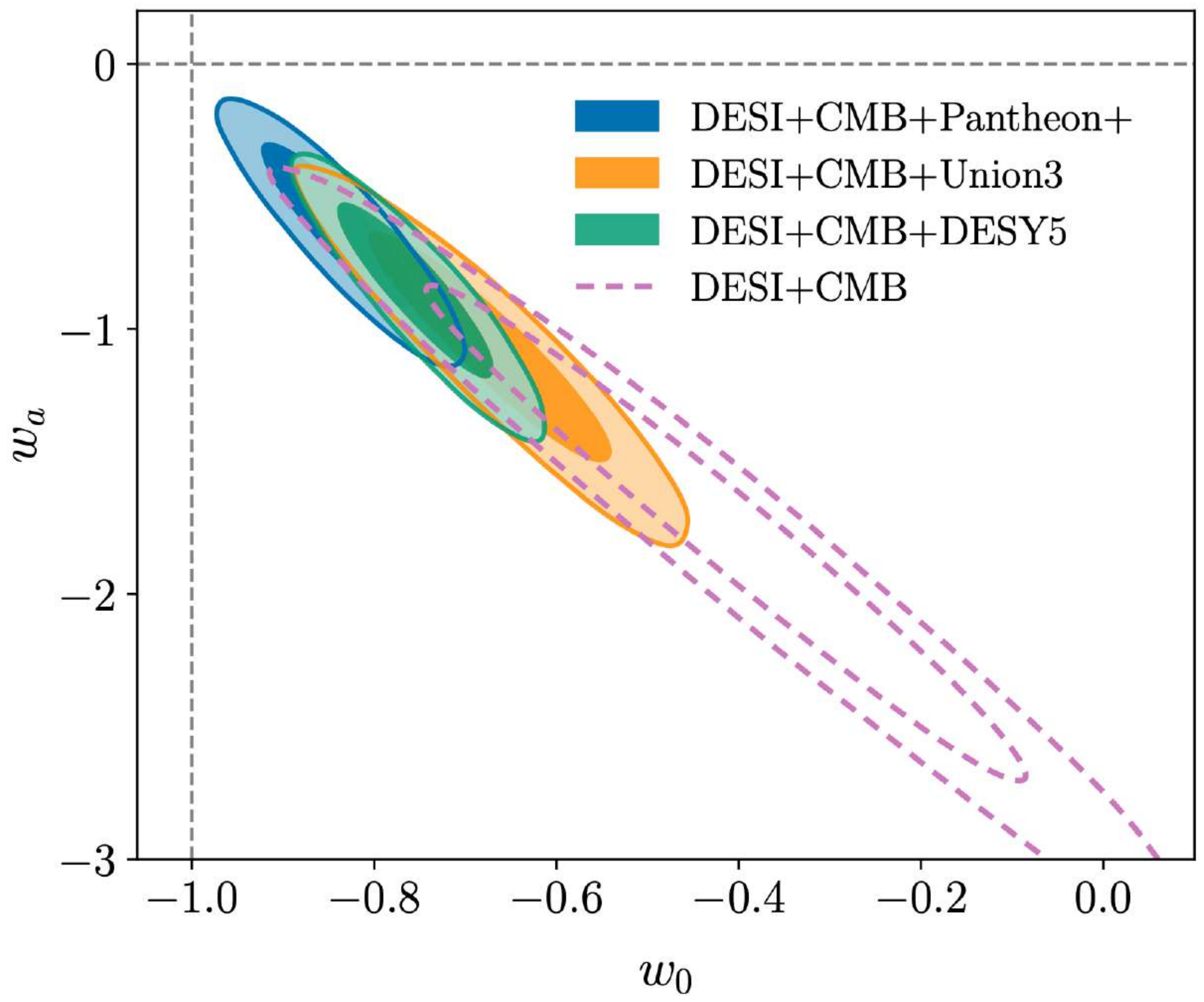
- Constraint: $\sim 2.3\sigma$ away from *Planck (DR1: $\sim 1.9\sigma$)*

The Dark Energy Spectroscopic Instrument - DESI

Results: w0wa model

DR1





- DESI alone cannot constrain w0 and wa

$$w_0 = -0.48^{+0.35}_{-0.17}$$
$$w_a < -1.34$$

DESI BAO, DR2

- Combining with other data sets, hint for dynamical DE

$$w_0 = -0.42 \pm 0.21$$
$$w_a = -1.75 \pm 0.58$$

DESI+CMB DR2

$$w_0 = -0.838 \pm 0.055$$
$$w_a = -0.62^{+0.22}_{-0.19}$$

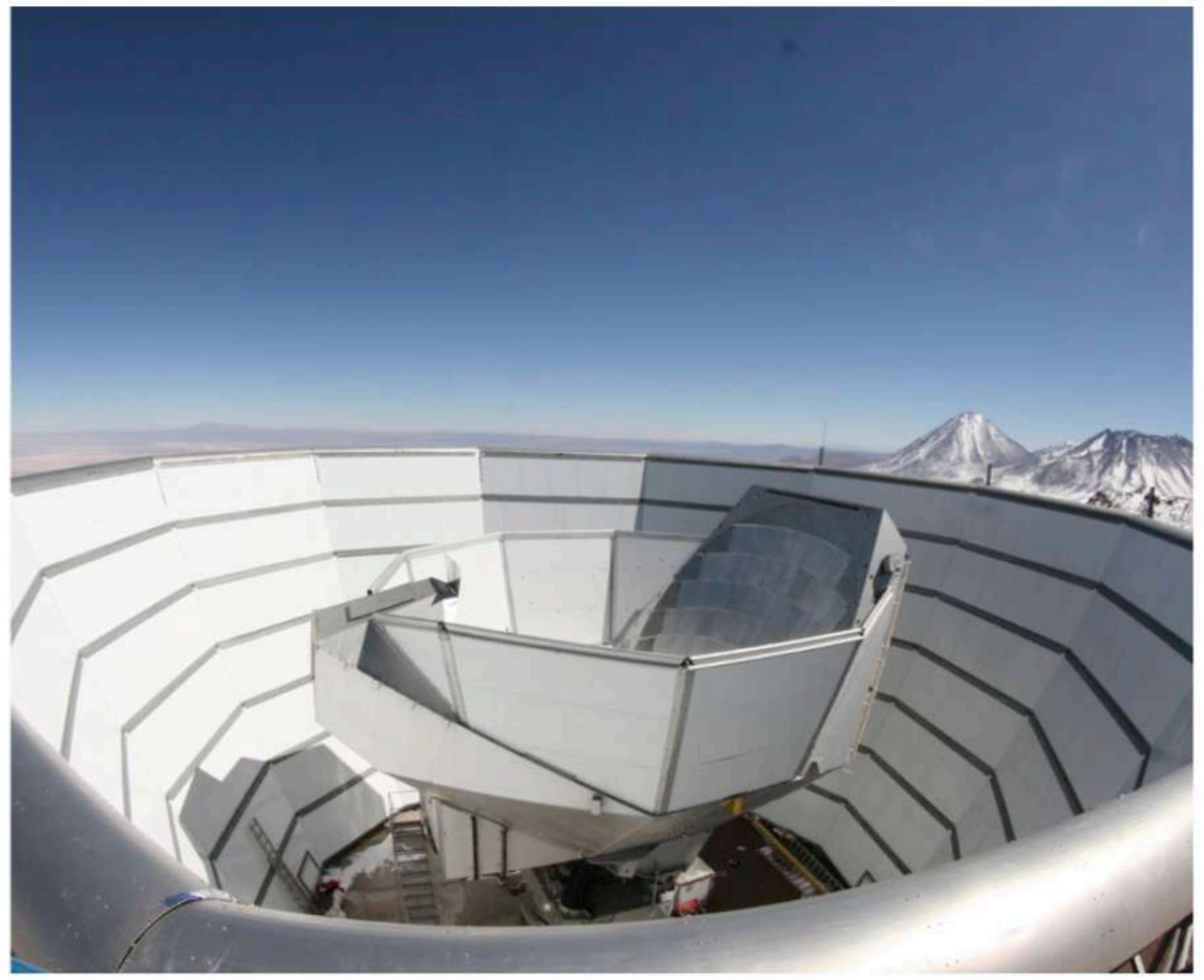
DESI+CMB+ Pantheon+,

Stage 3 CMB experiments

Planck

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

ACT



Observations **2008-2022**
f_{sky}~30% for science
5x Planck resolution
⅓ Planck white noise RMS
Precise polarization measurements

March 2025- DR6 Biggest data improvement since Planck!

SPT

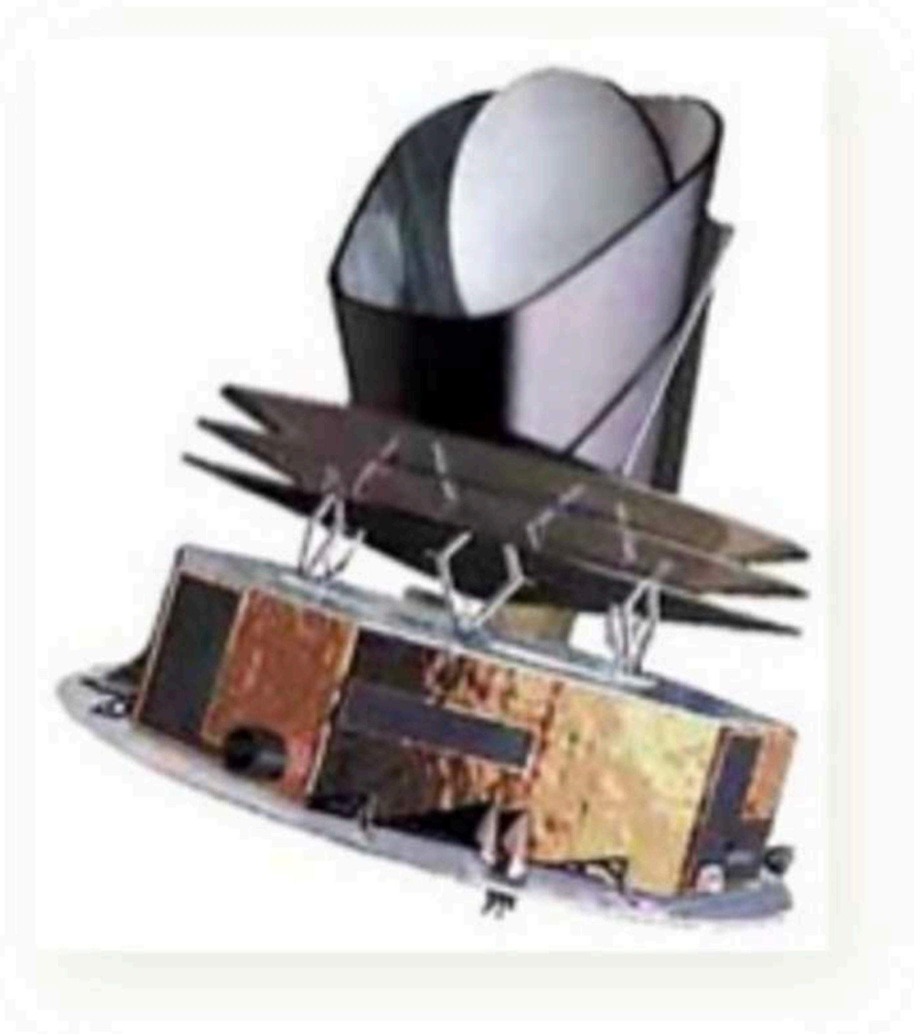
Observations **2007-2024(27)**
f_{sky} ~4-10% for science
Noise 6-17x lower than Planck
1-1.6 arcmin resolution
90, 150, 220 GHz

Credit: Calabresi

Atacama Cosmology Telescope (ACT)

Atacama Cosmology Telescope - ACT

Planck



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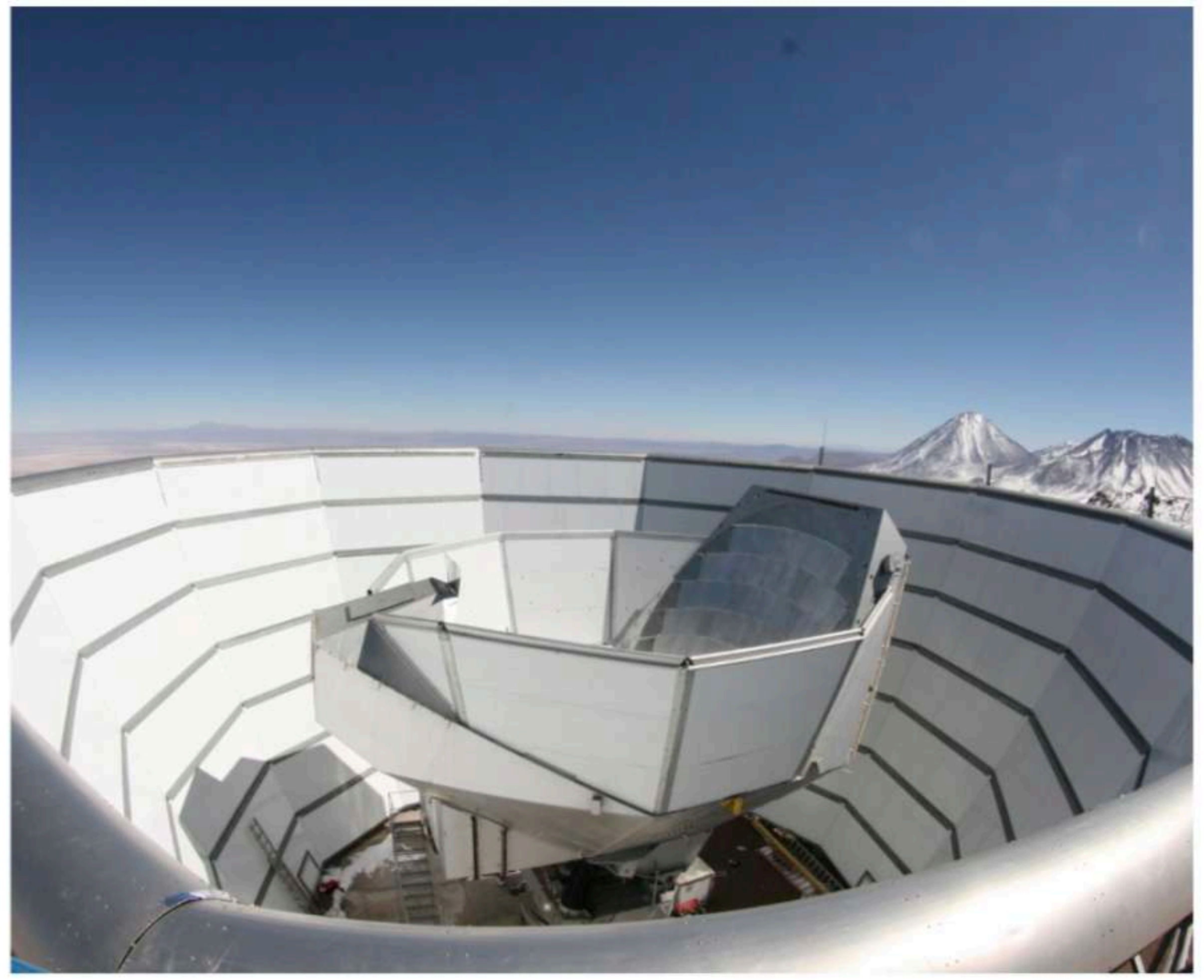


Observations **2008-2022**
f_{sky}~30% for science
Noise 3-6x lower than Planck
1-2 arcmin resolution
98, 150, 220 GHz (+30, 40 GHz)

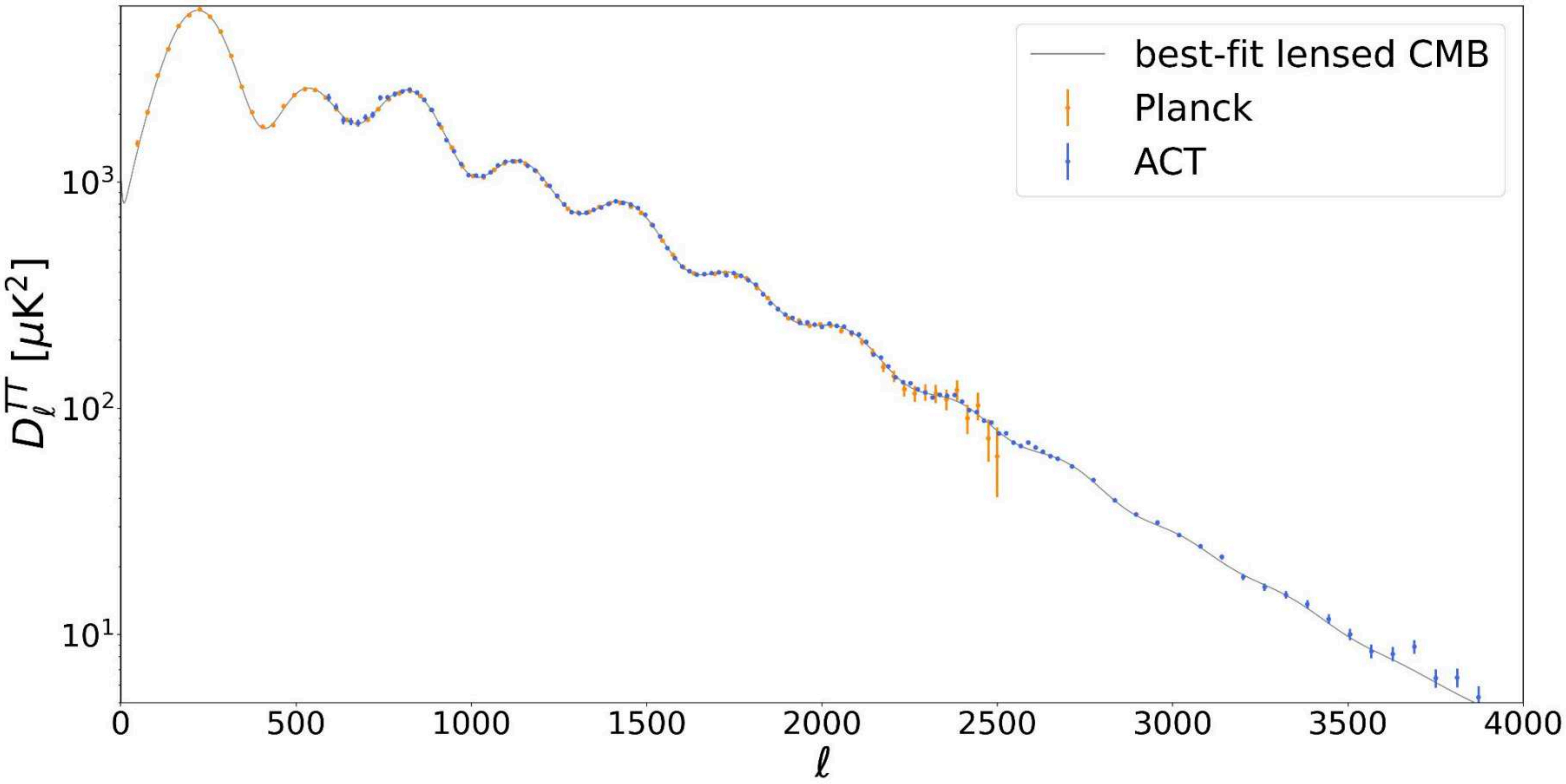
- 5x Planck resolution
- ⅓ Planck white noise RMS
- Small scales!!
- Precise polarization measurements

↓

March 2025- DR6
Biggest data improvement since Planck!

Atacama Cosmology Telescope - ACT

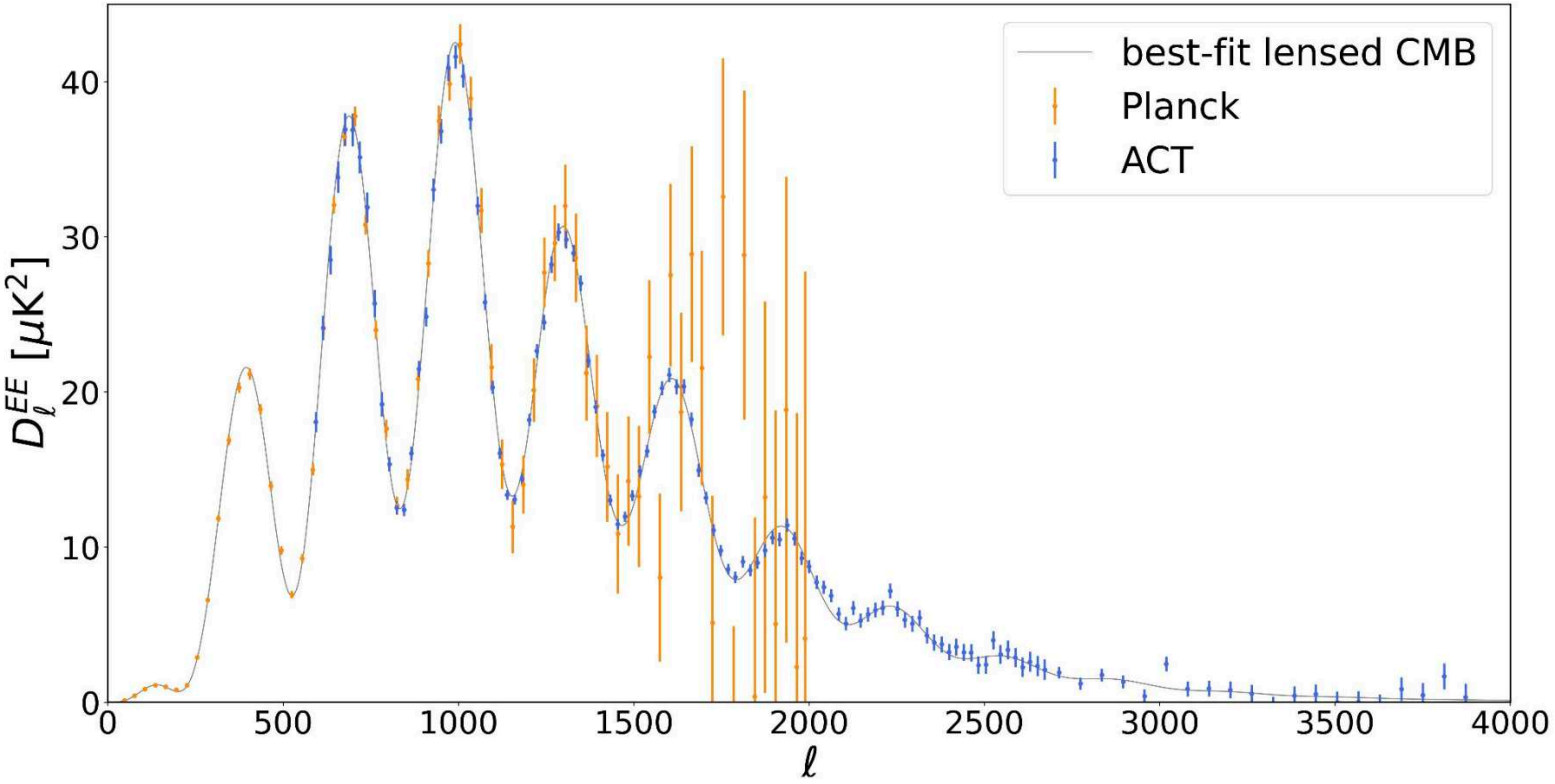
What ACT measures



ACT data
1) Extend Planck measurement to small angular scales
2) Consistent with Planck data on overlapping angular scales

Atacama Cosmology Telescope - ACT

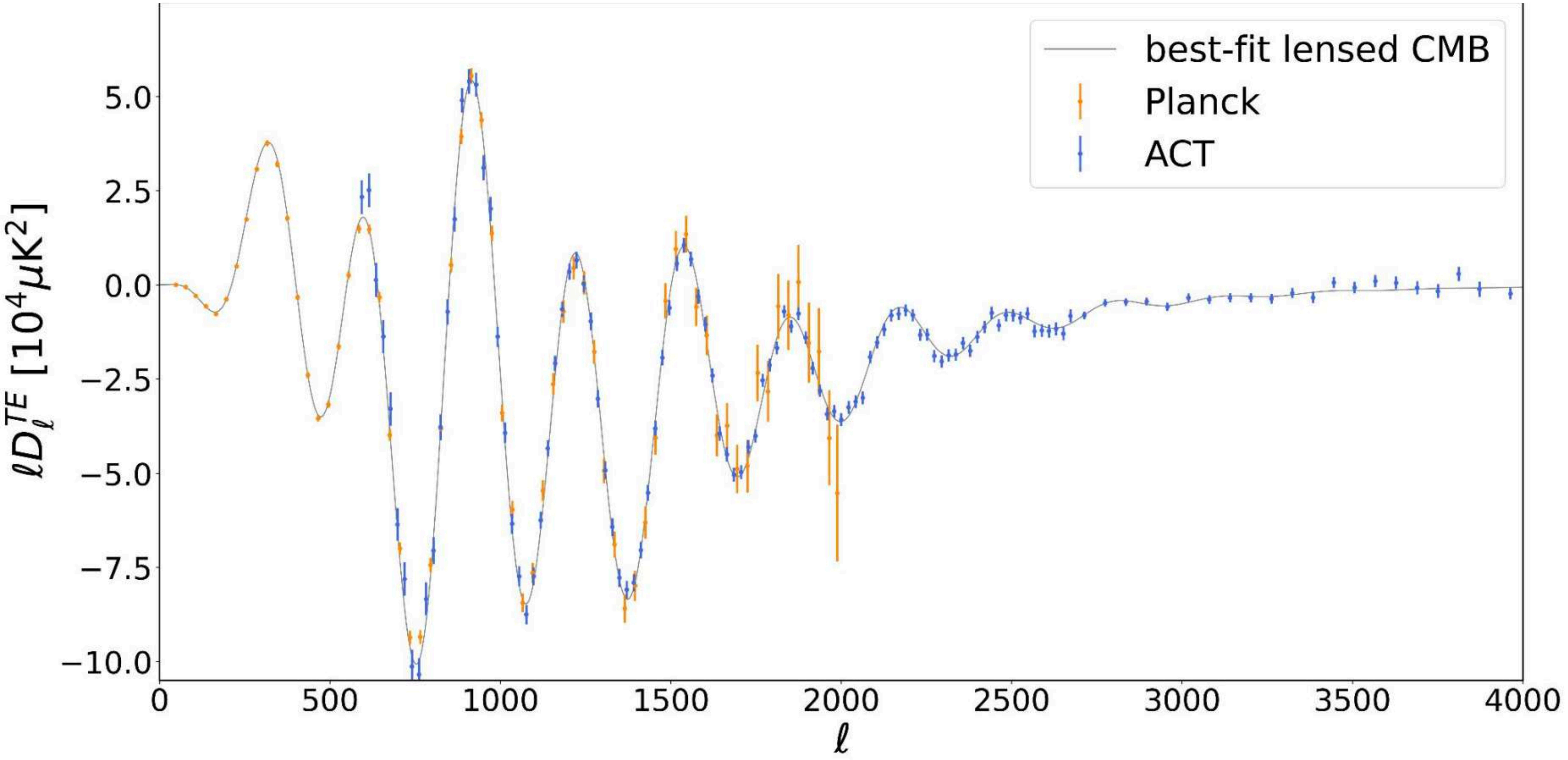
What ACT measures



ACT DR6 EE is more sensitive than Planck for multipoles $\ell > 600$

Atacama Cosmology Telescope - ACT

What ACT measures



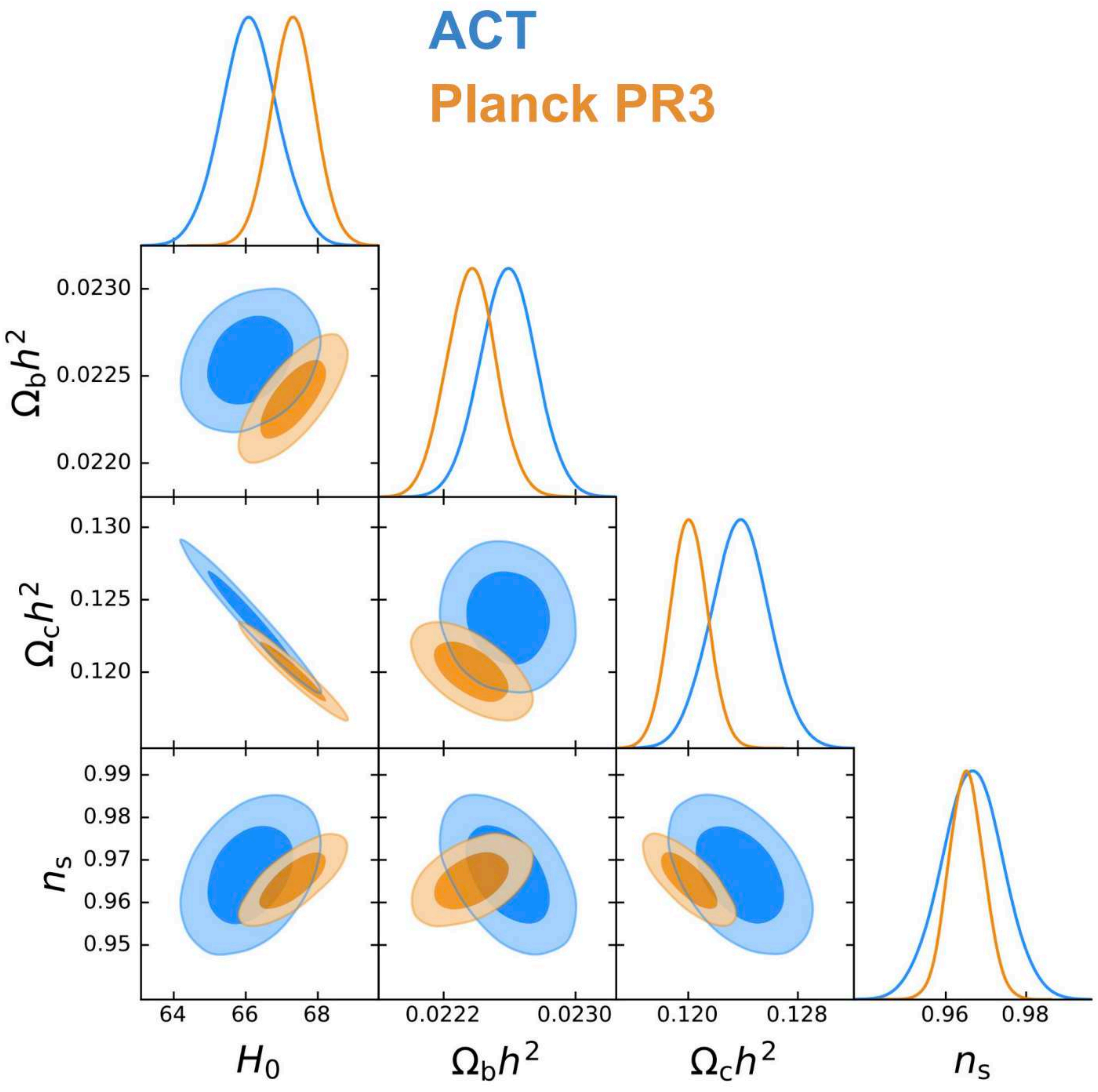
1.1 % constraint on H0 from TE alone

Atacama Cosmology Telescope - ACT

LCDM

Concordance with Planck (PR3): 1.6σ

Parameter	ACT
Sampled	
θ_{MC}	0.0104056 ± 0.0000031
$\Omega_b h^2$	0.02259 ± 0.00017
$\Omega_c h^2$	0.1238 ± 0.0021
$\log(10^{10} A_s)$	3.053 ± 0.013
n_s	0.9666 ± 0.0077
τ	$0.0562^{+0.0053}_{-0.0063}$
Derived	
H_0	66.11 ± 0.79
Ω_m	0.337 ± 0.013
σ_8	0.8263 ± 0.0074



How collaborations assess the compatibility between data sets

Ex.: ACT and Planck

- Calibration and transfer-function checks:
ACT maps were cross-correlated with Planck to measure scale-dependent calibration and power-loss. After applying conservative ℓ -cuts and updated calibration factors, ACT and Planck agree at the ≲0.3 % level.

- Power-spectrum consistency tests:
ACT×ACT, ACT×Planck, and Planck×Planck TT/TE/EE spectra were compared on the same sky region. Residuals and PTEs show no significant discrepancies.

- Checks for residual tilts or scale dependence:
Ratios of ACT and Planck spectra to best-fit ΛCDM models show no significant relative tilt or scale-dependent mismatch once the transfer-function cuts are applied.

- Parameter-shift tests:
ACT-only and Planck-only posteriors overlap well. A single ΛCDM model fits both datasets with high goodness of fit, indicating statistical compatibility.

Atacama Cosmology Telescope - ACT

LCDM

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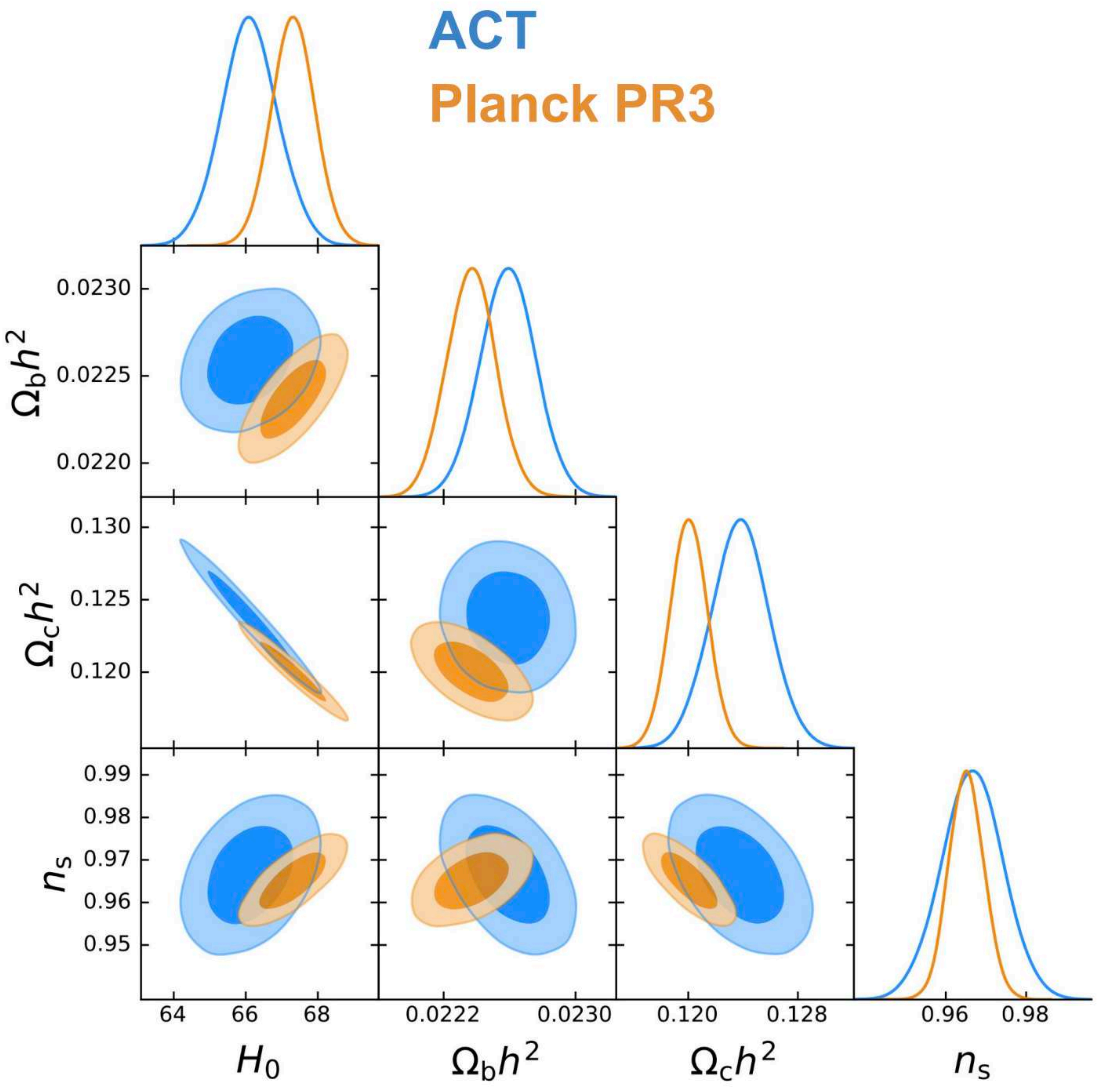
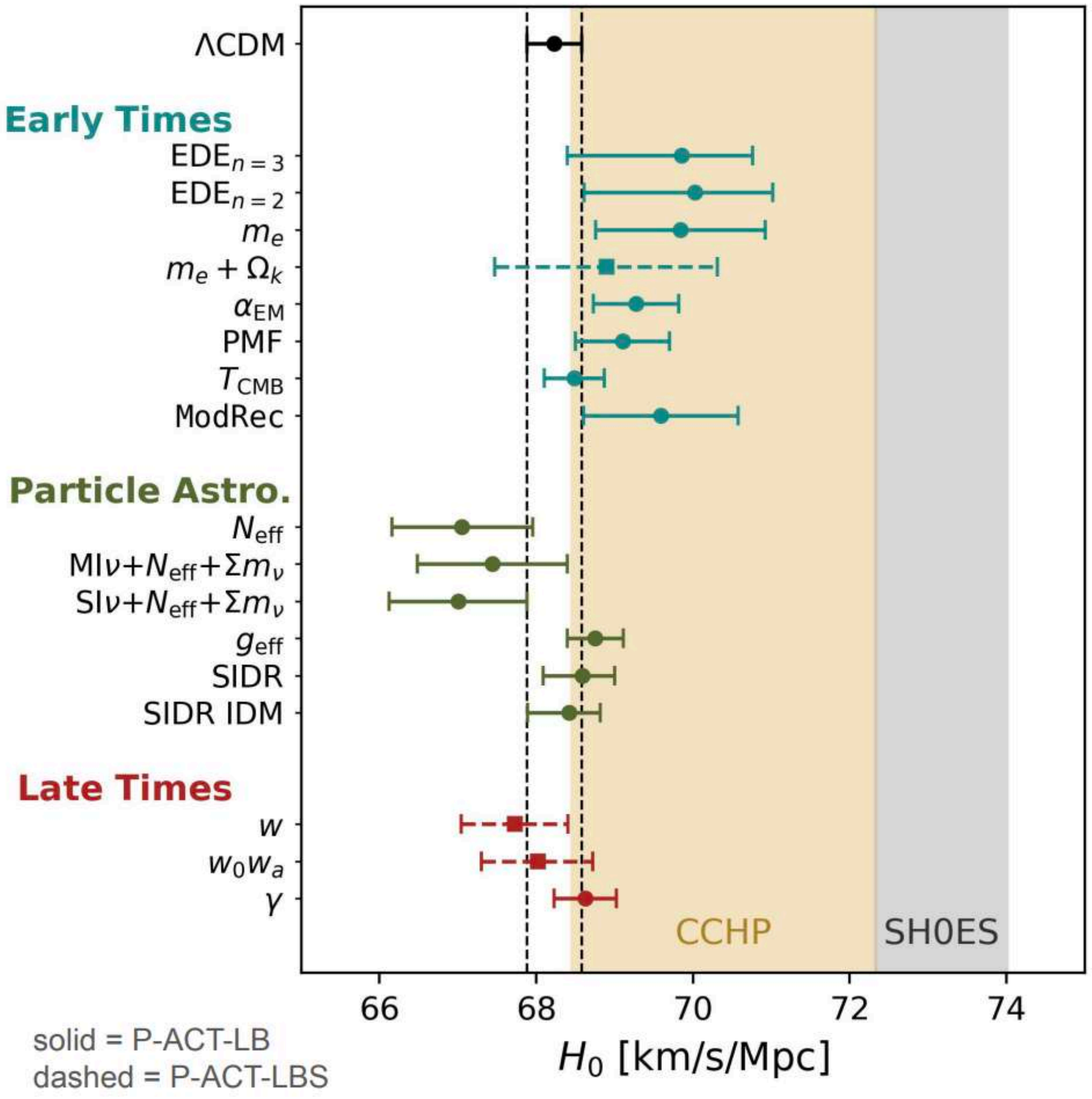


Atacama Cosmology Telescope - *ACT*

Extensions to LCDM:

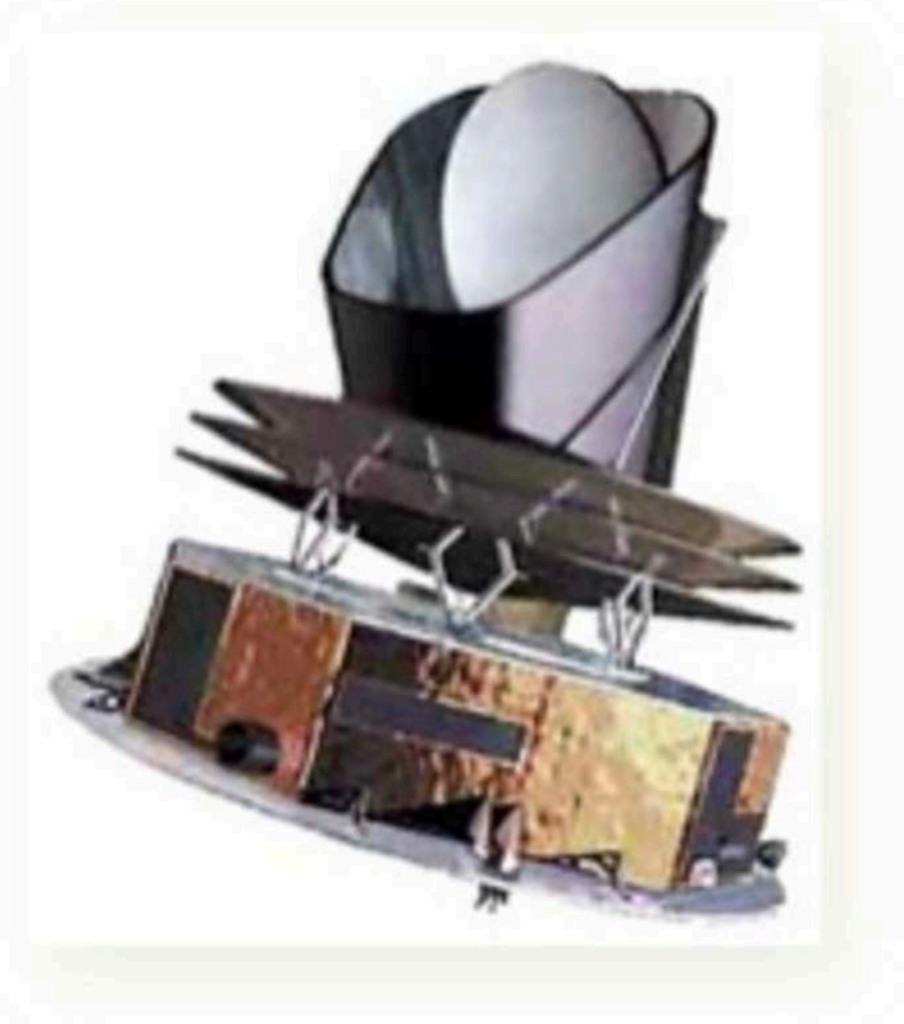
More than 30 extension of LCDM tested:
no preference over LCDM!



South Pole Telescope - SPT3G

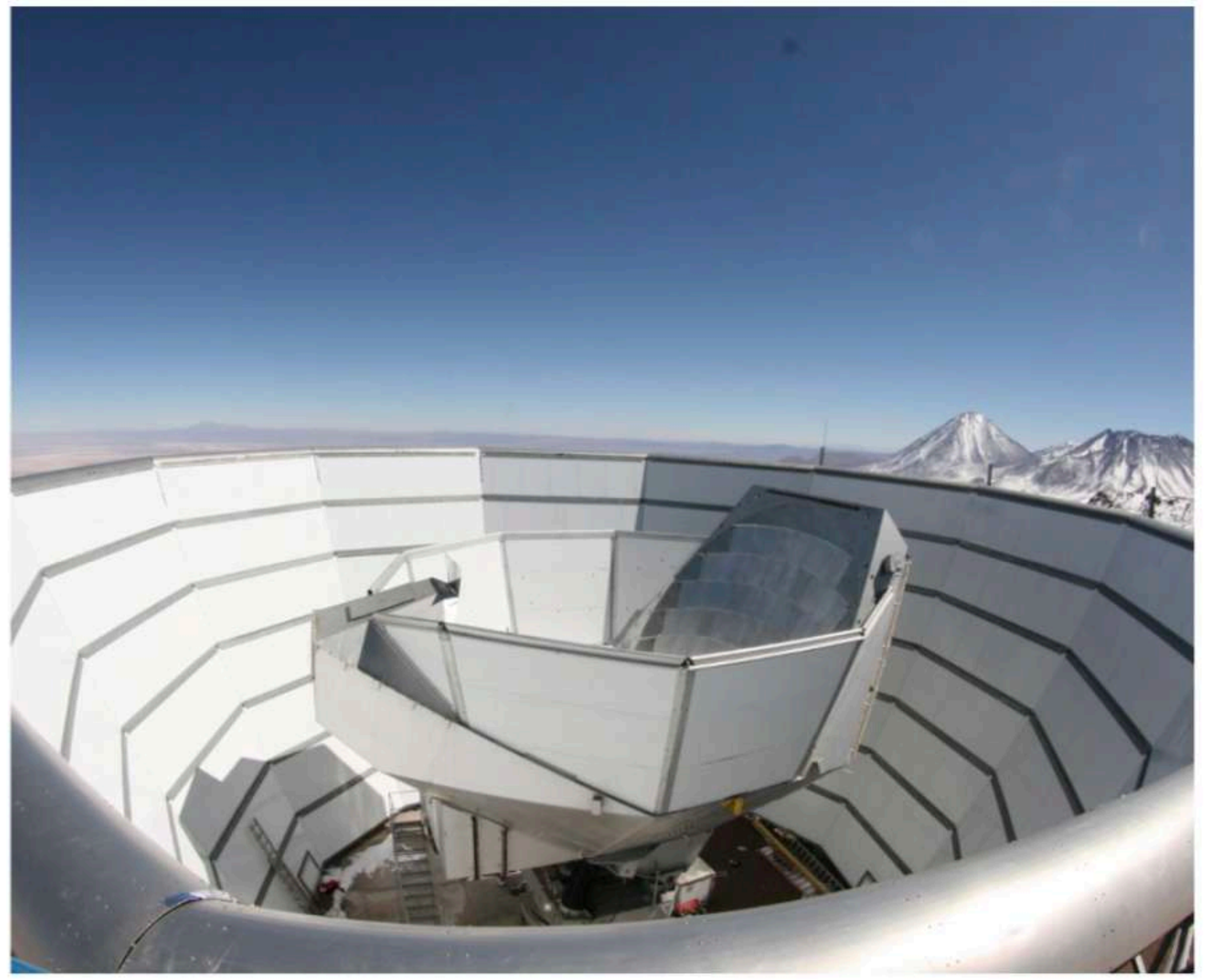
Stage 3 CMB experiments

Planck



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

ACT



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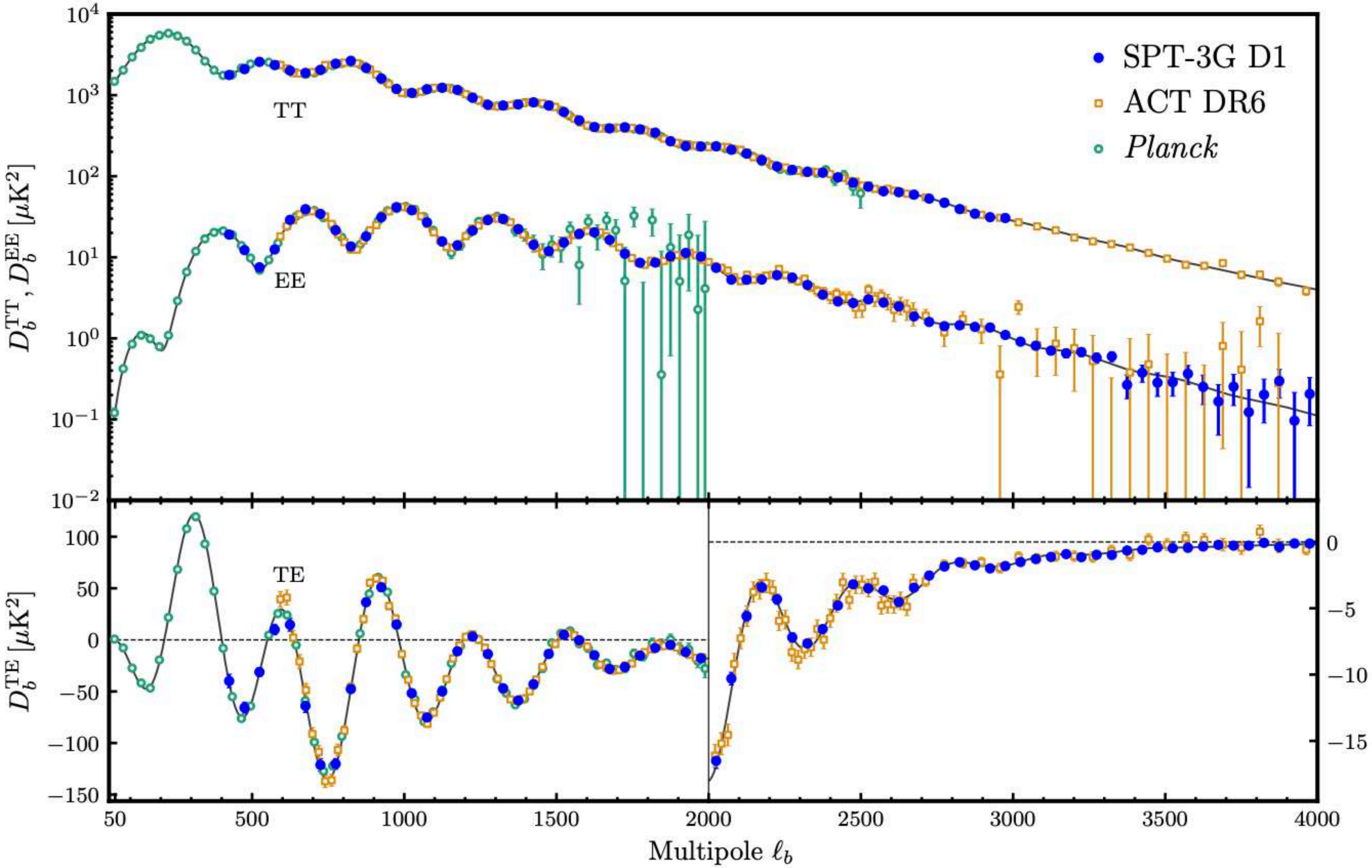
Noise 6-17x lower than Planck
1-1.6 arcmin resolution
90, 150, 220 GHz

Credit: Calabresi

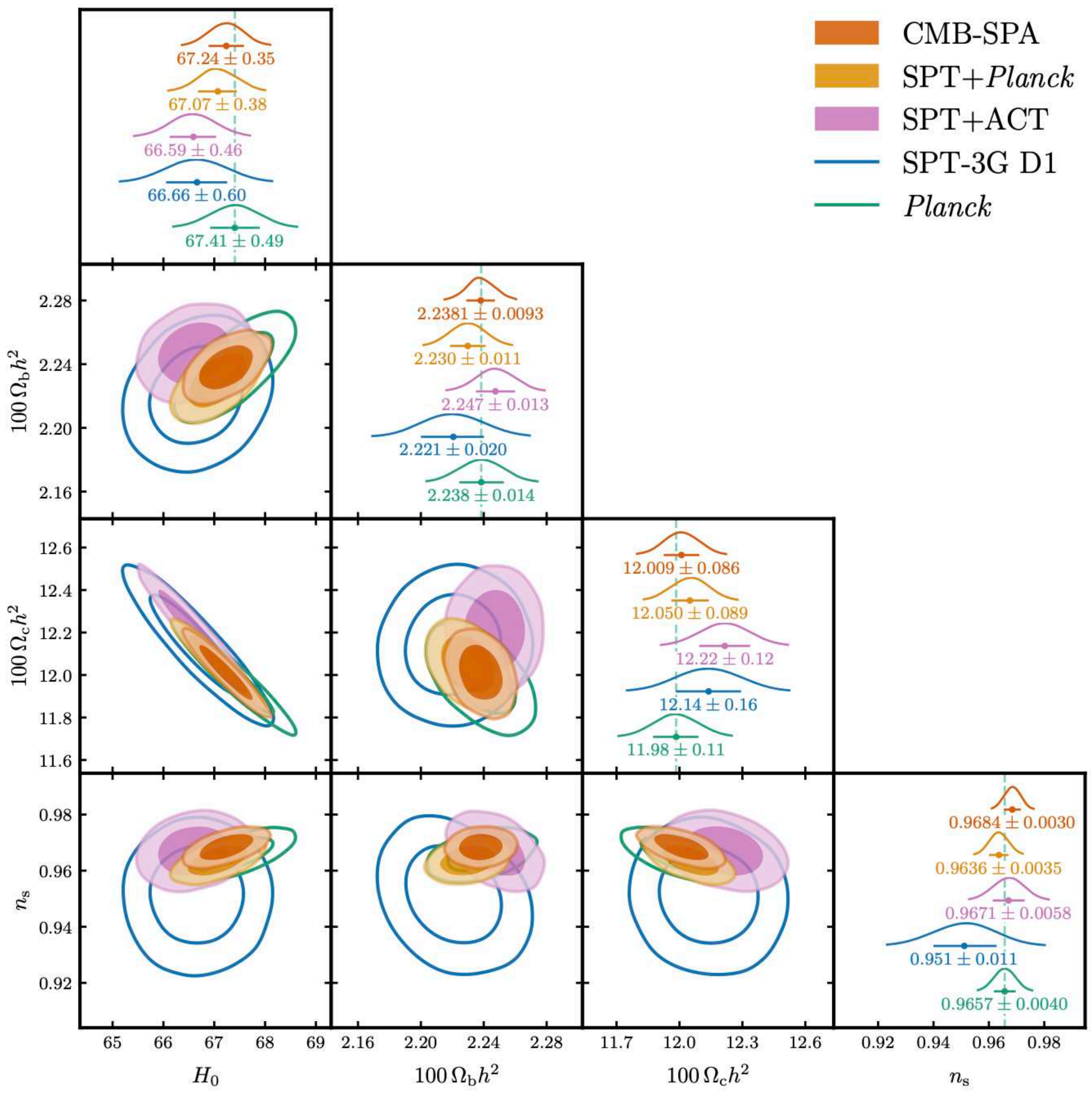
South Pole Telescope - SPT3G

June 2025: Latest data release



South Pole Telescope - SPT3G

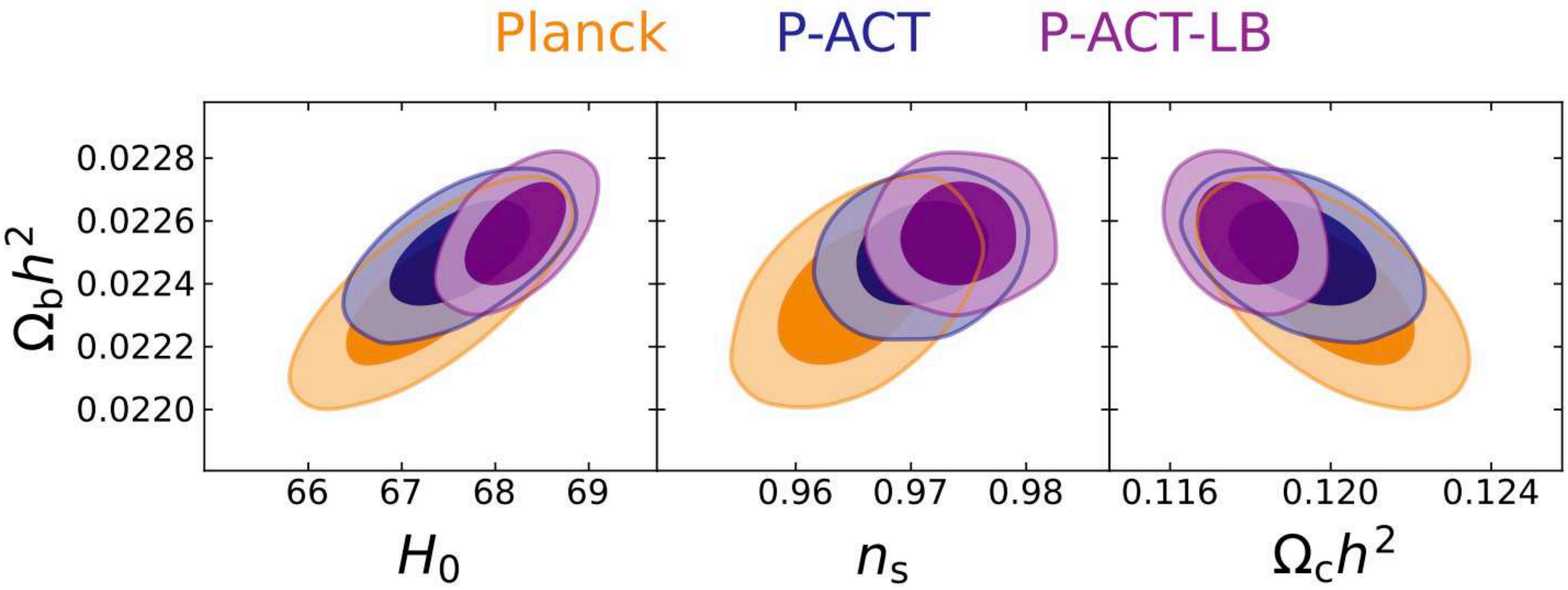
Concordance with Planck and ACT



Next obvious step:

combine these data sets

Combining CMB and LSS data



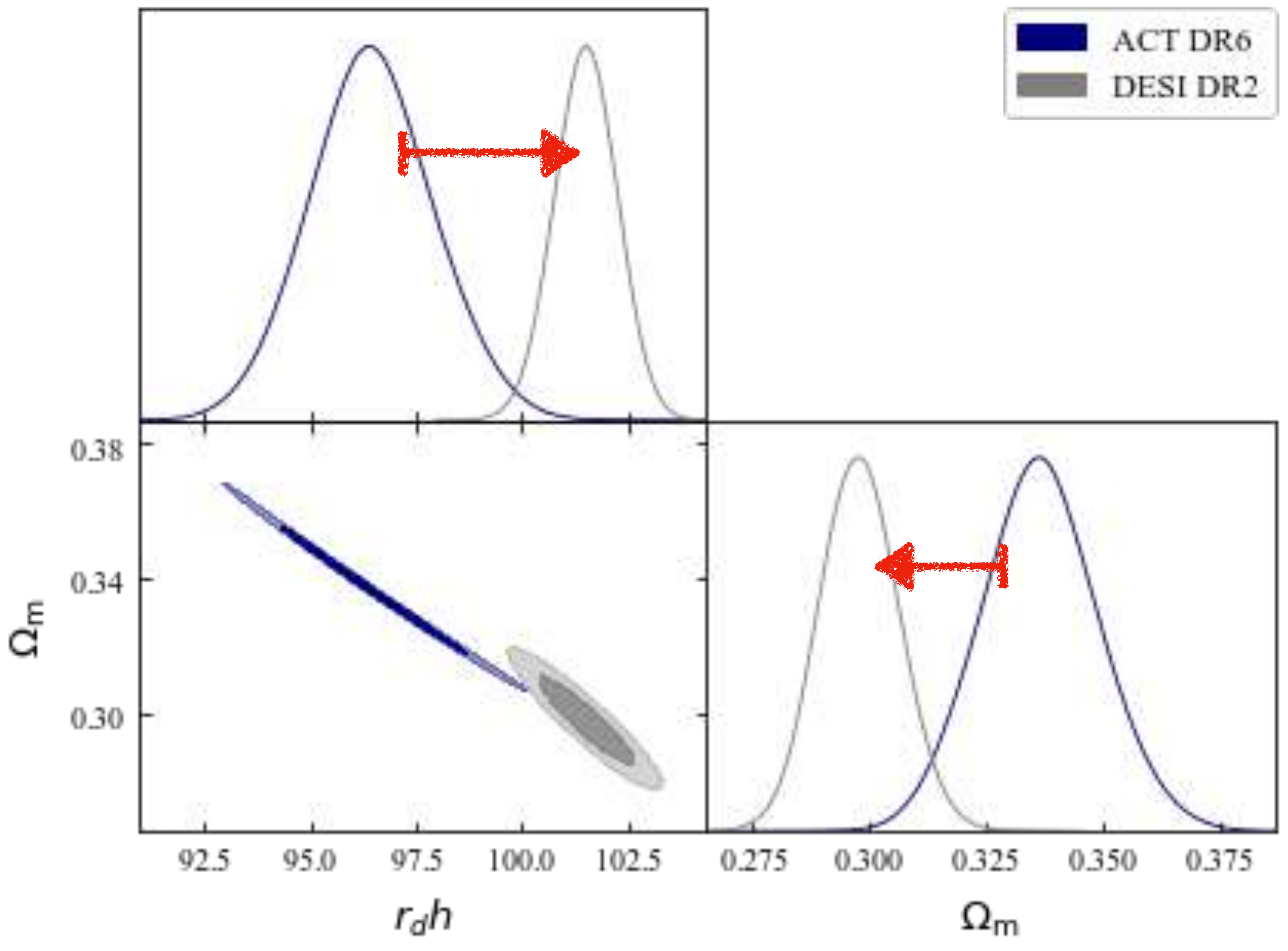
P: Planck
L: ACT lensing
B: BAO from DESI

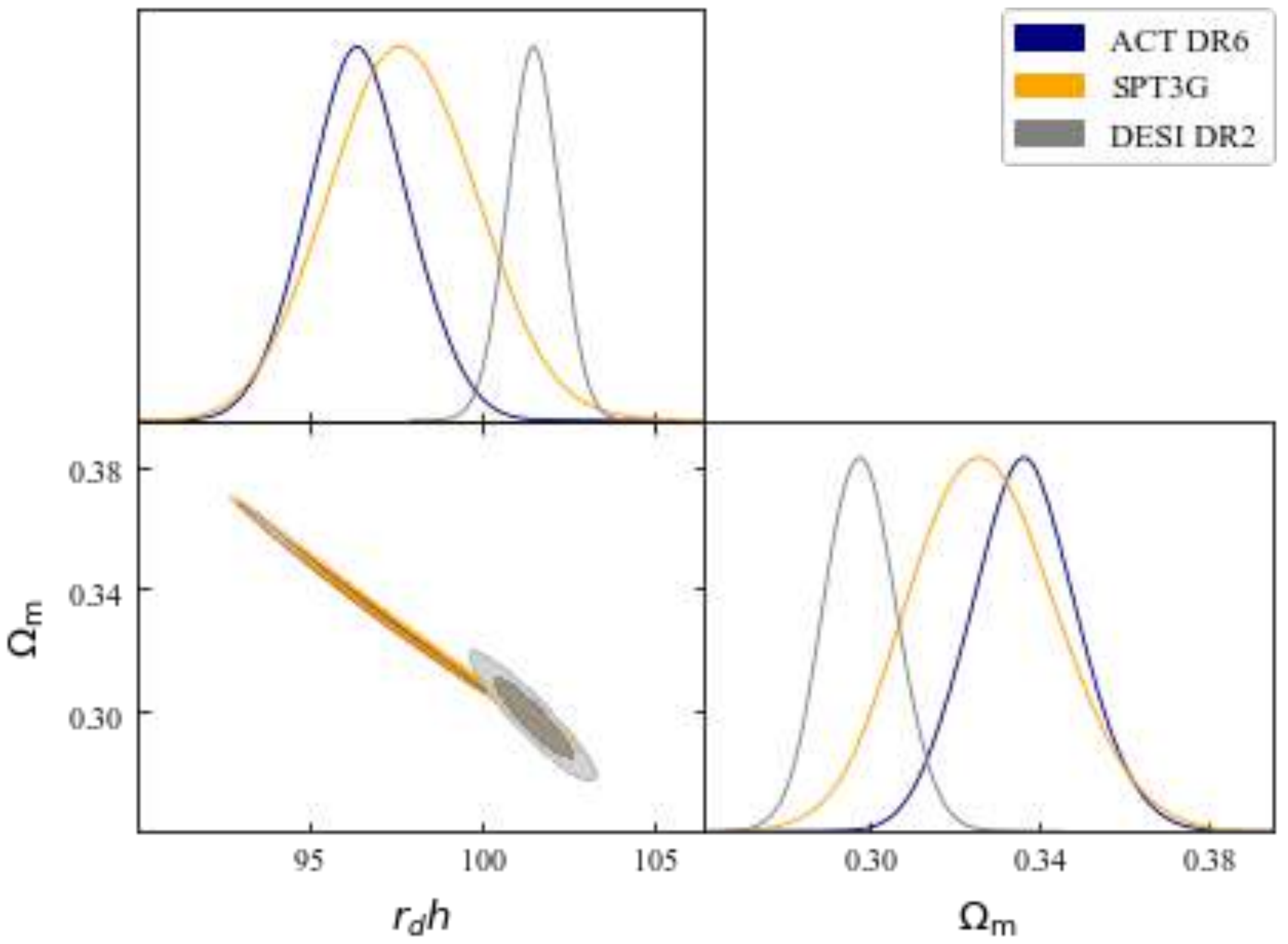
BAO - CMB tension

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)





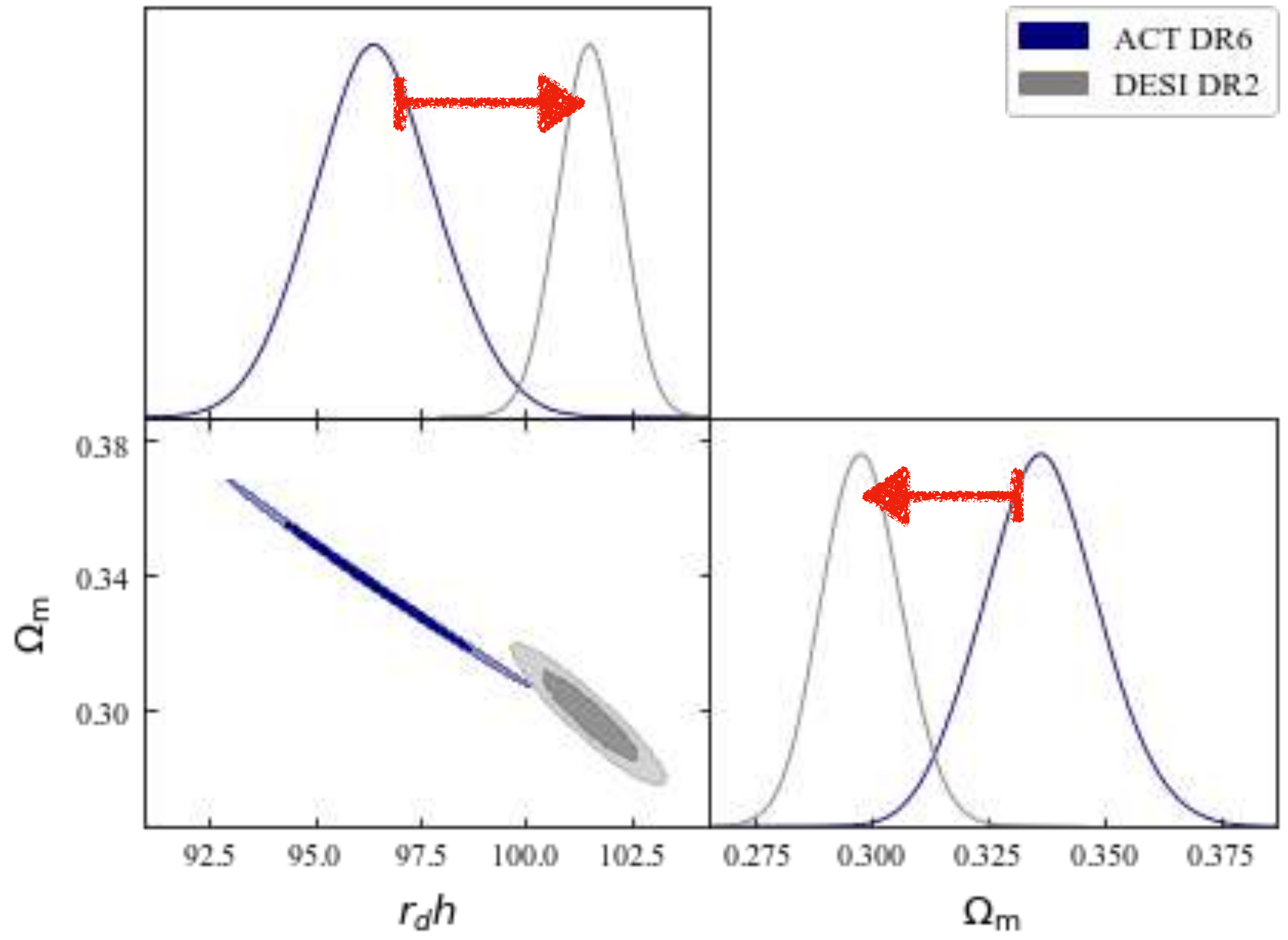
- 2d posteriors show small overlap
- 1d posterior shifted

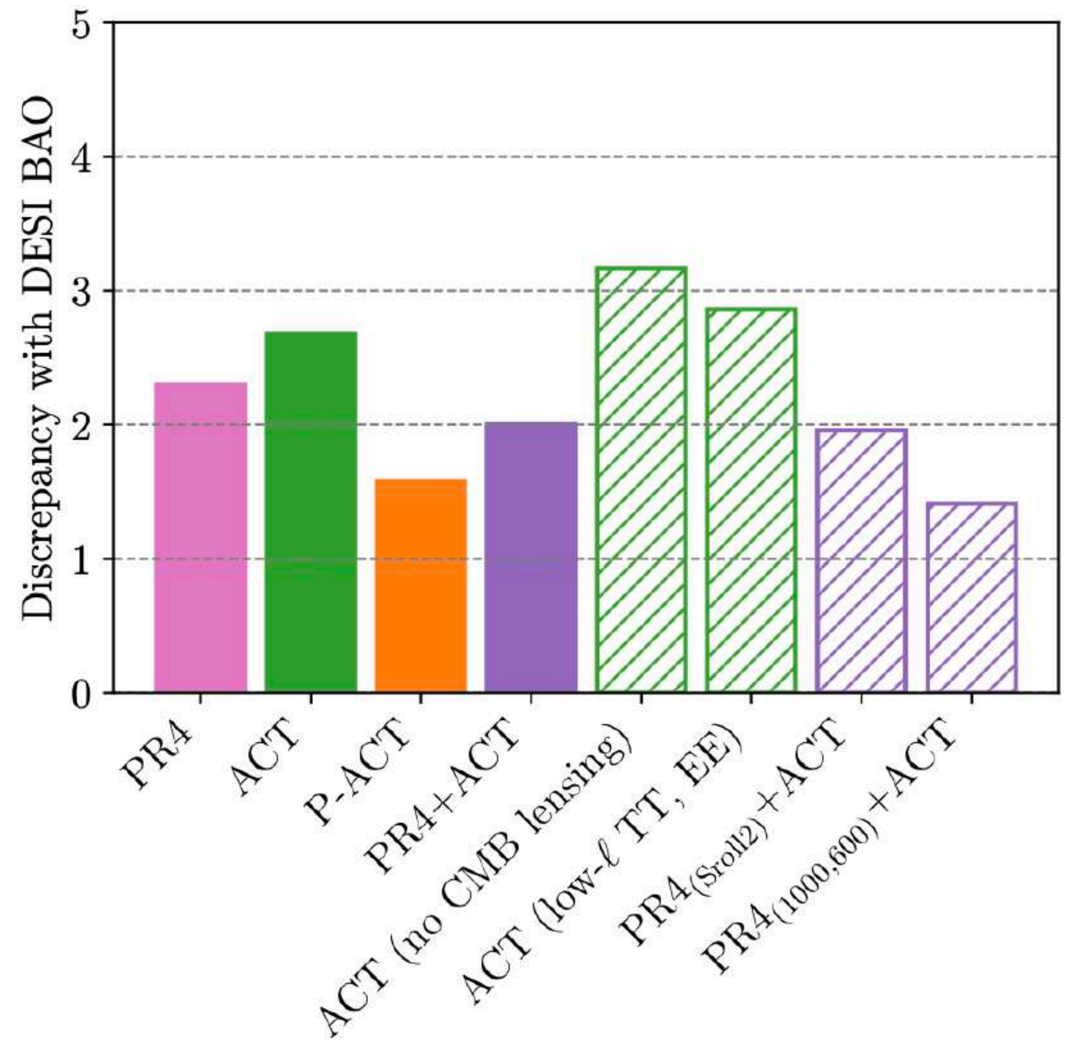
Discrepancy (or tension) in the values of $r_d h$ and Ω_M measured from CMB and DESI BAO!

BAO - CMB *tension*

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

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





Garcia-Quintero et al (DESI collaboration) 2024

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

Translating the differences in the Ωm and rdh constraints from CMB and DESI data to equivalent statistical significances for a one-dimensional Gaussian distribution:

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

Camphuis et al (SPT collaboration) 2025

$2 - 4\sigma$ discrepancy between CMB and BAO datasets

$\Rightarrow$ Implication for other cosmological parameters

BAO - CMB discrepancy

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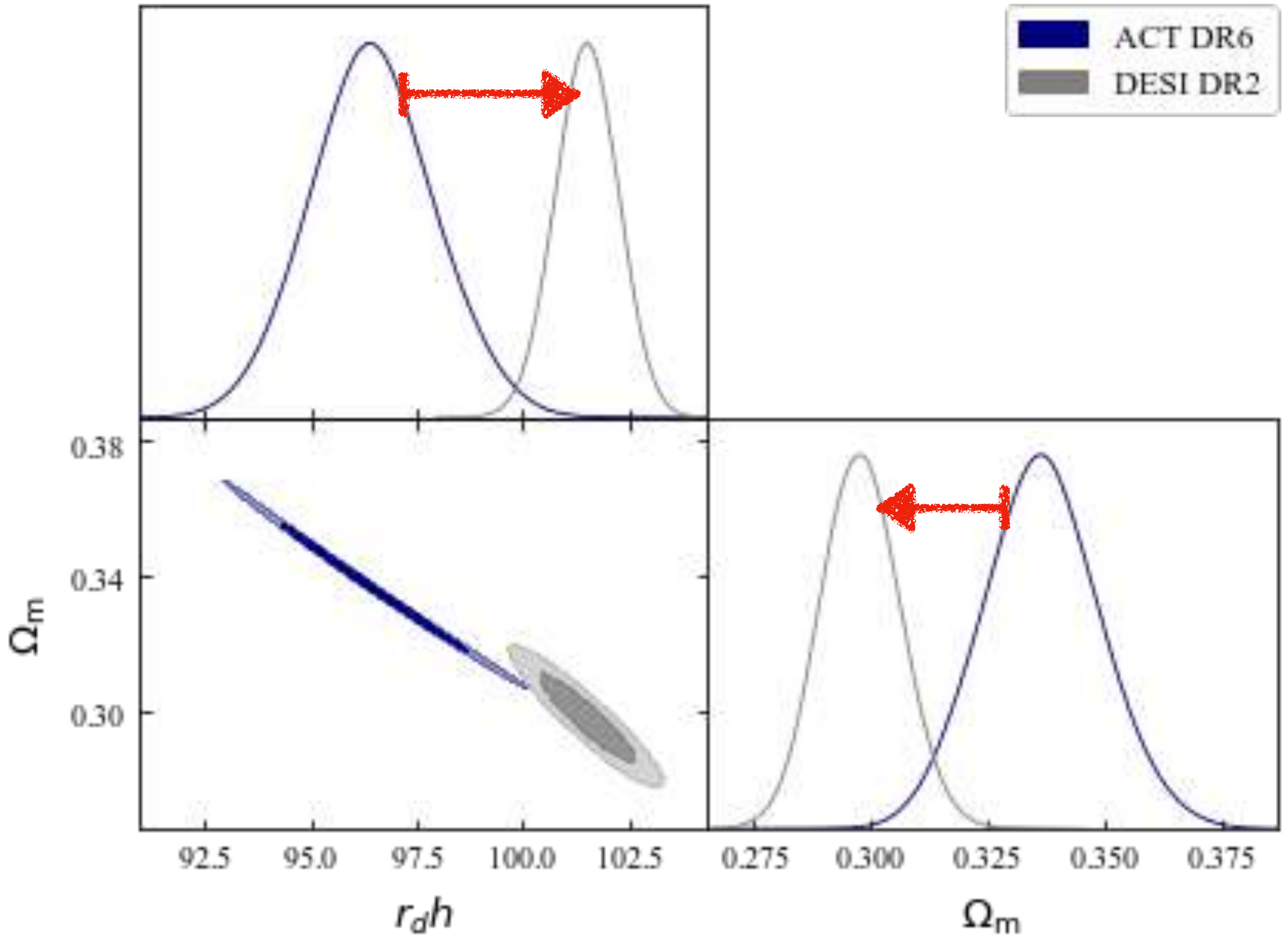

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DESI	29.76 ± 0.87	101.52 ± 0.73	

Camphuis et al (SPT collaboration) 2025

Is it even valid to combine them?

ACT and SPT might not be compatible with DESI !

$2 - 4\sigma$ discrepancy between CMB and BAO datasets

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 ΛCDM 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 ~38σ (ACT only) and ~50σ (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 ΛCDM 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 3 σ consistency requirement; if we were to do so, differences in the favored Ωm and hrd 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 ΛCDM, we report a growing inconsistency with the BAO results from DESI DR2"

Consequences for the spectral index ns

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

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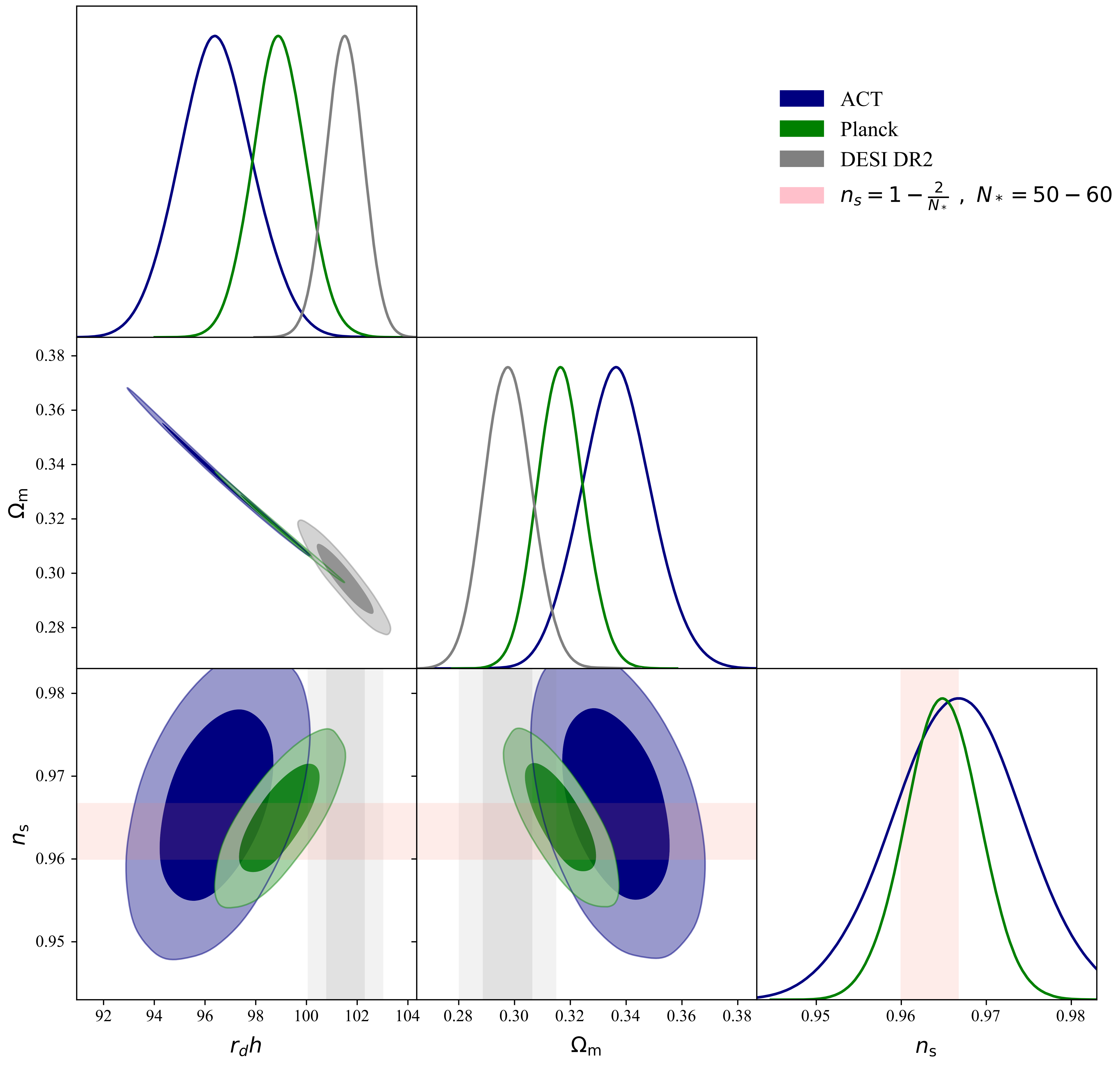
The BAO-CMB tension has important consequences for ns

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

  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 ns 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 ns

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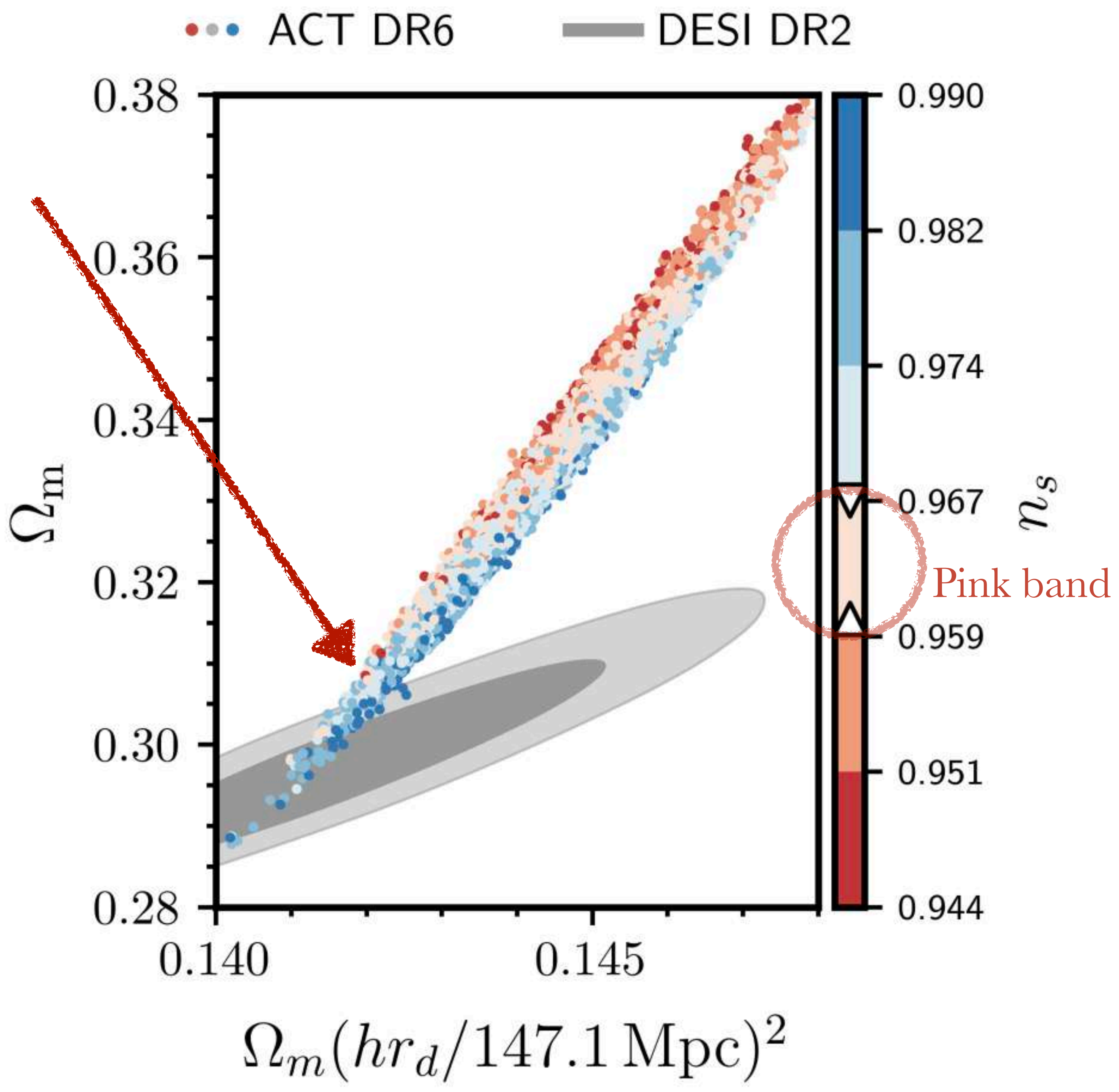
The BAO-CMB tension has important consequences for ns

- 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 lage values of ns

In the $n_s - r_d\, h$ plane: there is **no simultaneous overlap** between the ACT 2σ contour, the 2σ DESI constraint on rdh, and the band of ns values predicted by benchmark inflation scenarios!



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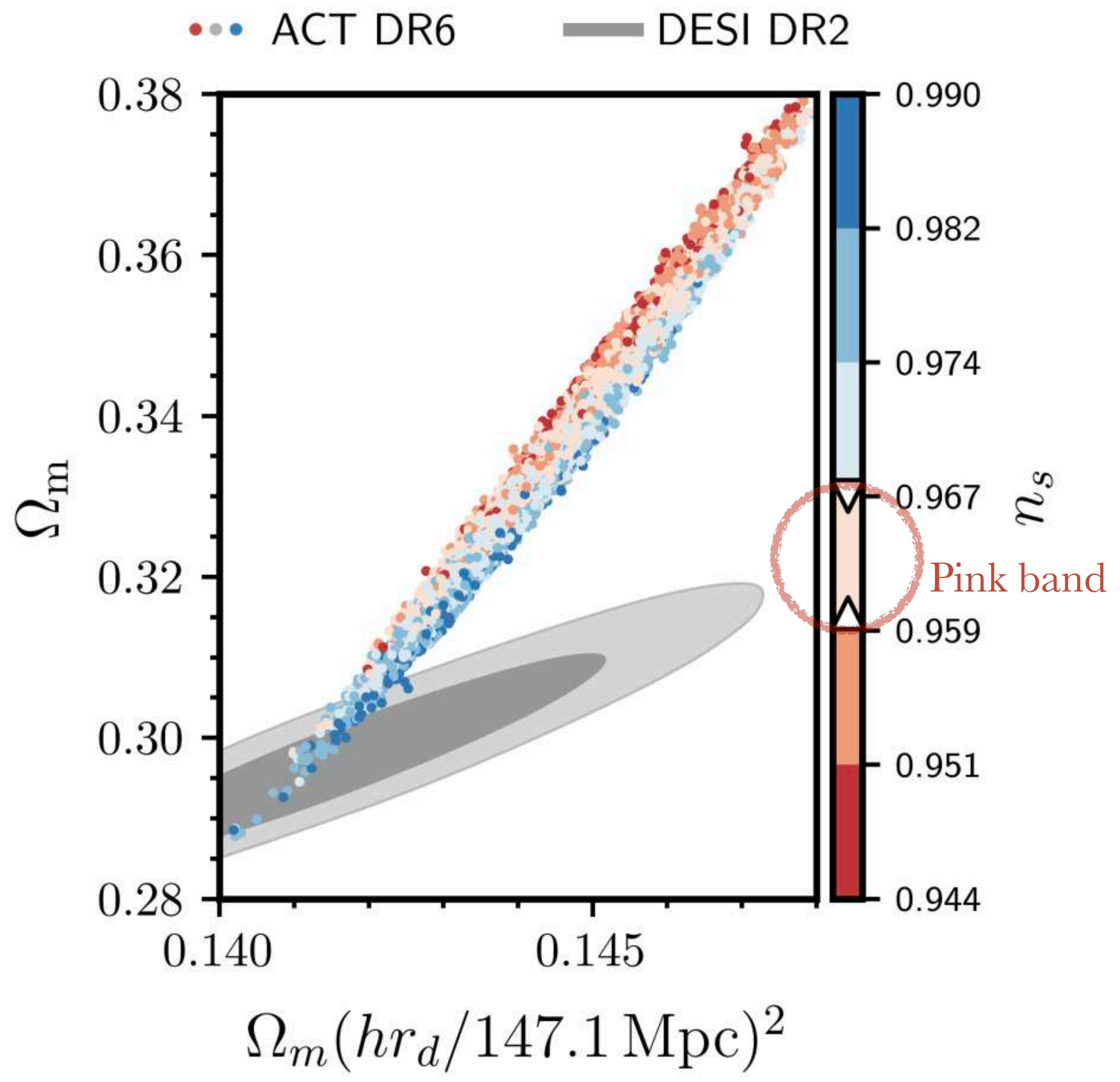
In the $n_s - r_d h$ plane: there is **almost no simultaneous overlap** between the

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

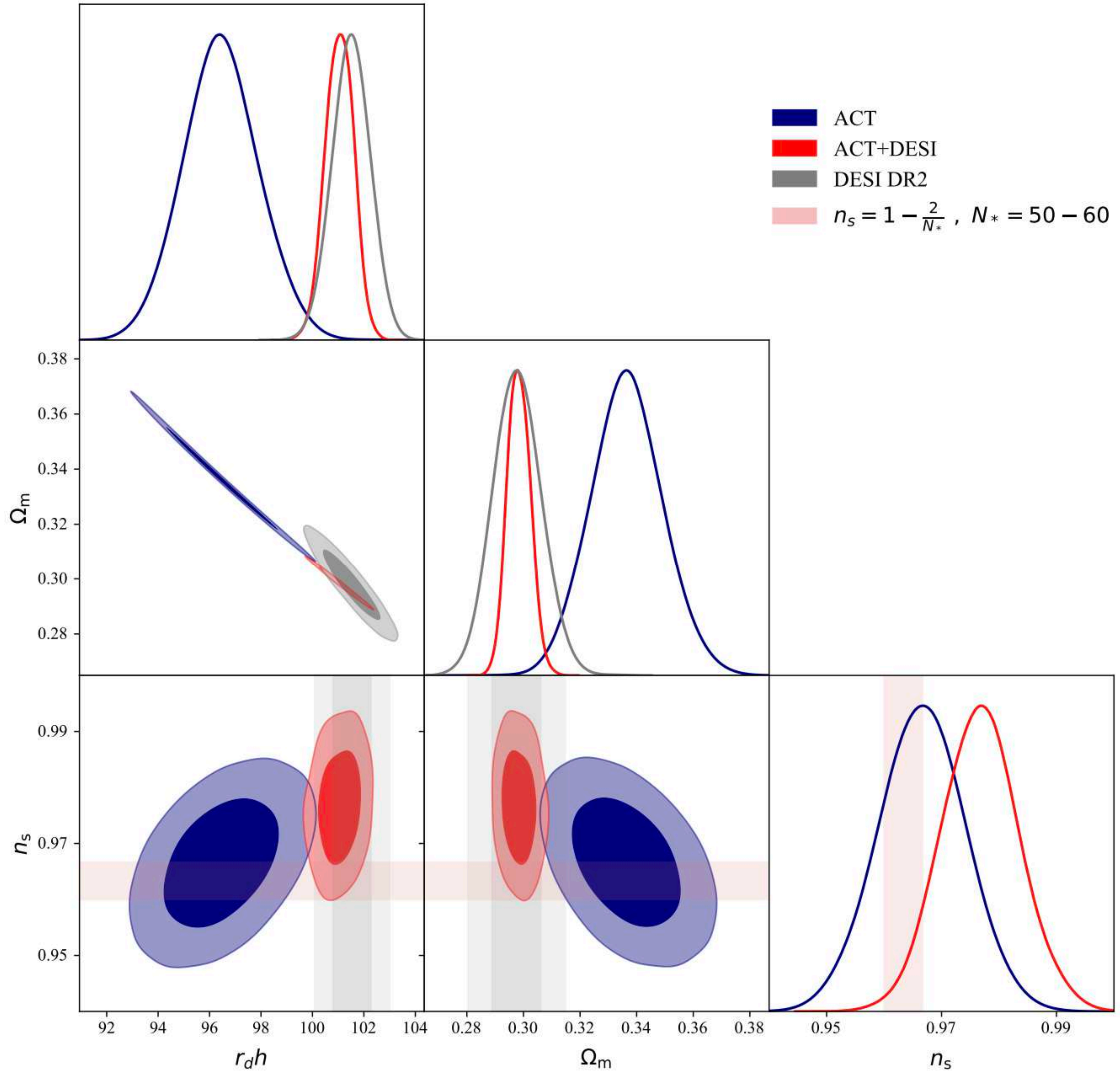


*This **discrepancy** suggests that there is little evidence that ACT and DESI constraints are both right, while at the same time ΛCDM with a benchmark inflation scenario holds true; something has to give.*

Consequences for the spectral index ns

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 ns

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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

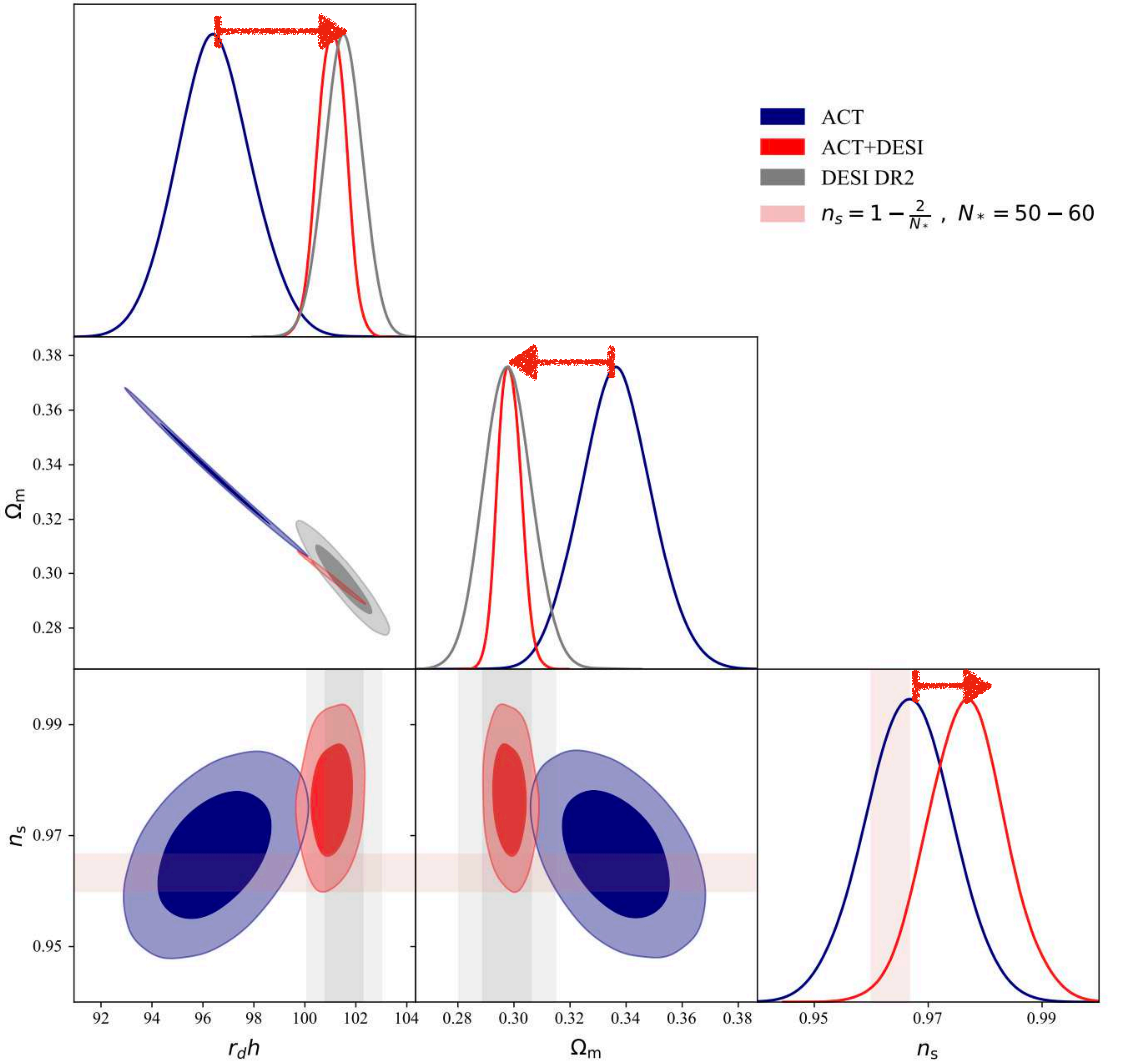
Constraints from ACT DR6 CMB and DESI DR2 BAO Data

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

$\sim 3.34\sigma$ distance

(translating into a one-dimensional Gaussian difference)

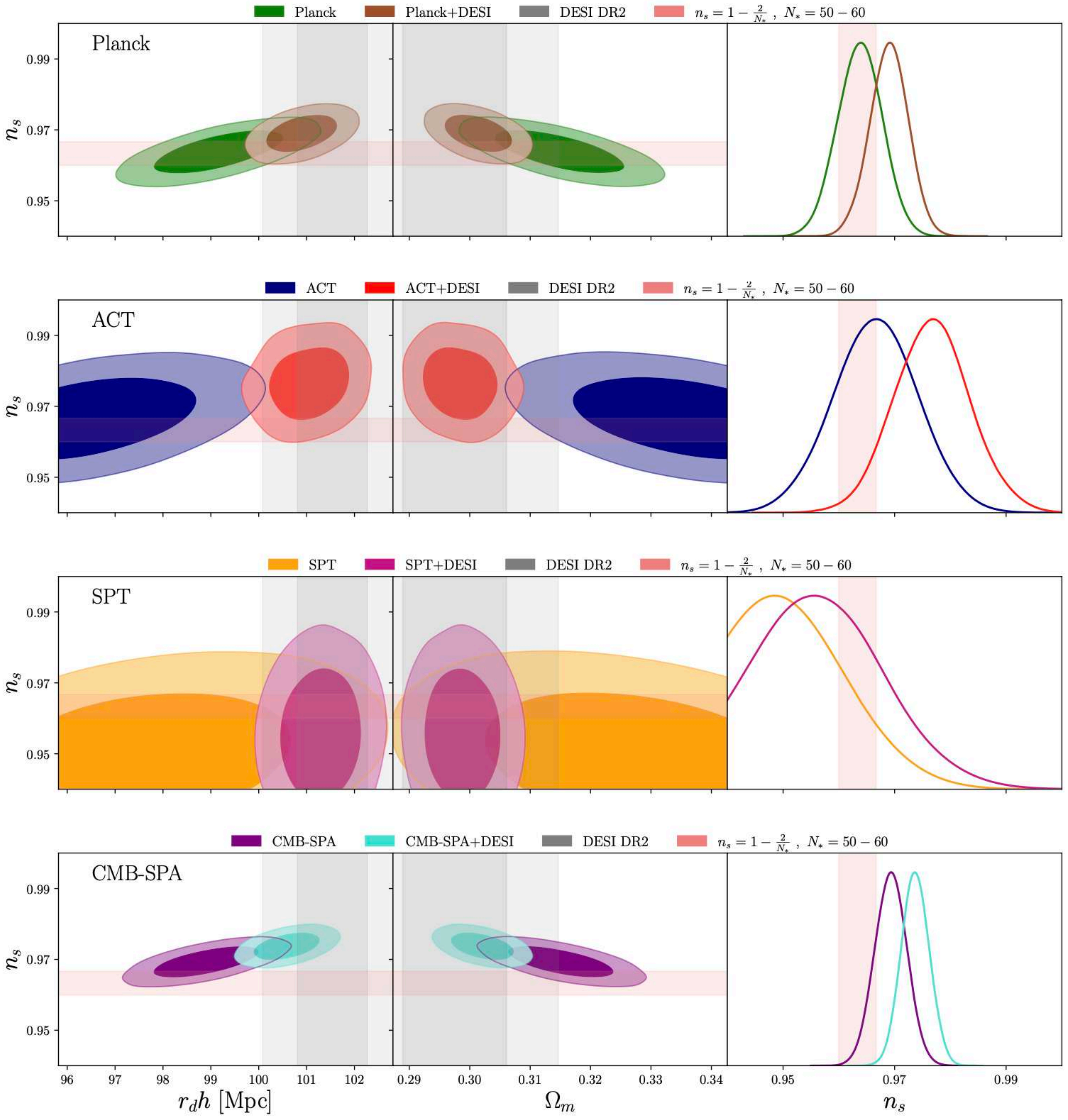
For n_s alone, the discrepancy is from $\sim 3.5\sigma$
(Correlated data - dependent on the metric used)



highly significant shift

Consequences for the spectral index ns - SPT

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



SPA: SPT+Planck+ACT

Planck + DESI

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

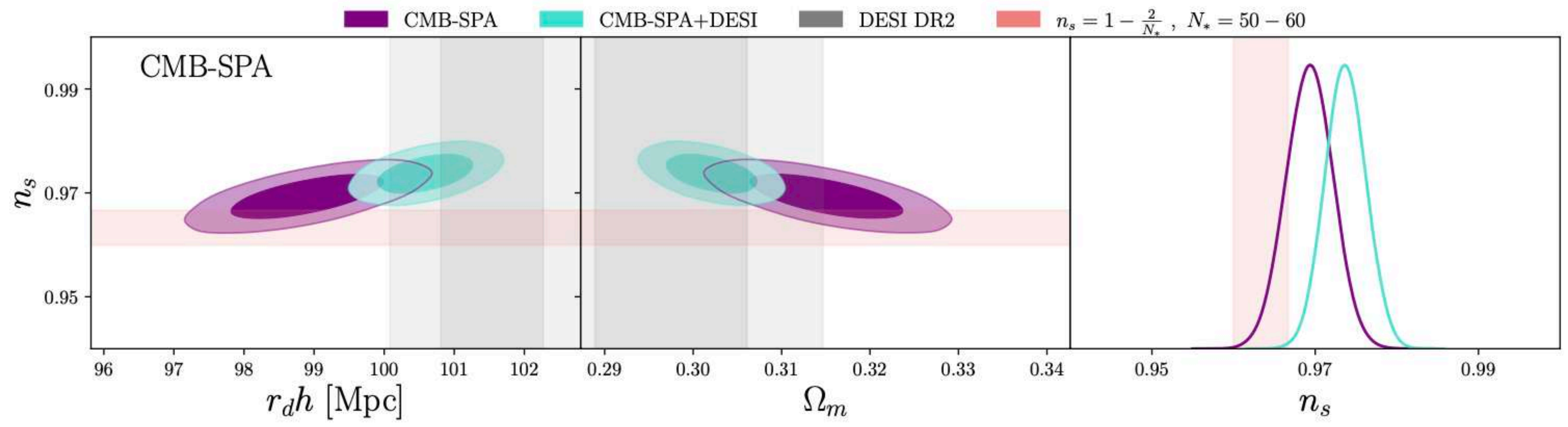
SPT + DESI (full SPT likelihood, no lensing)

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

Consequences for the spectral index ns - Planck, ACT, SPT

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



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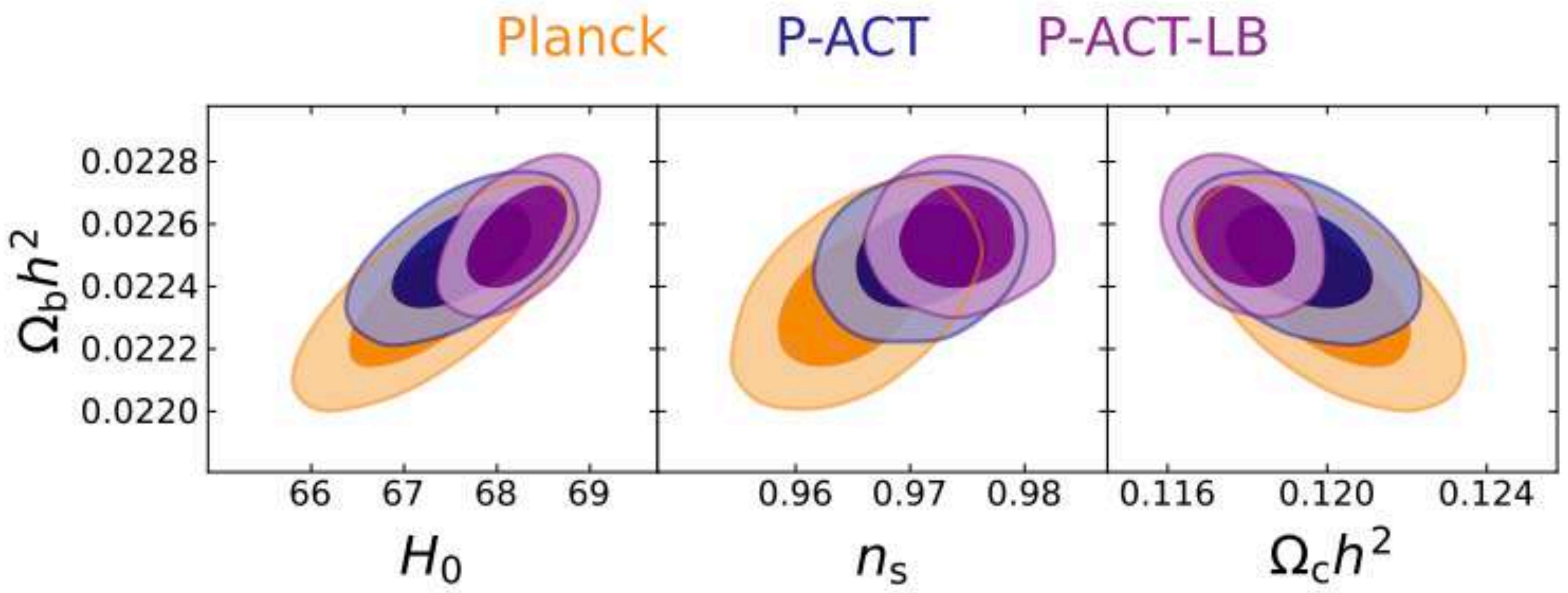


$$
\begin{aligned}
n_s &= 0.9666 \pm 0.0077 (\mathrm{ACT}) \\
&= 0.9709 \pm 0.0038 (\mathrm{P-ACT}) \\
&= 0.9743 \pm 0.0034 (\mathrm{P-ACT-LB})
\end{aligned}
$$

SPA: SPT+Planck+ACT

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

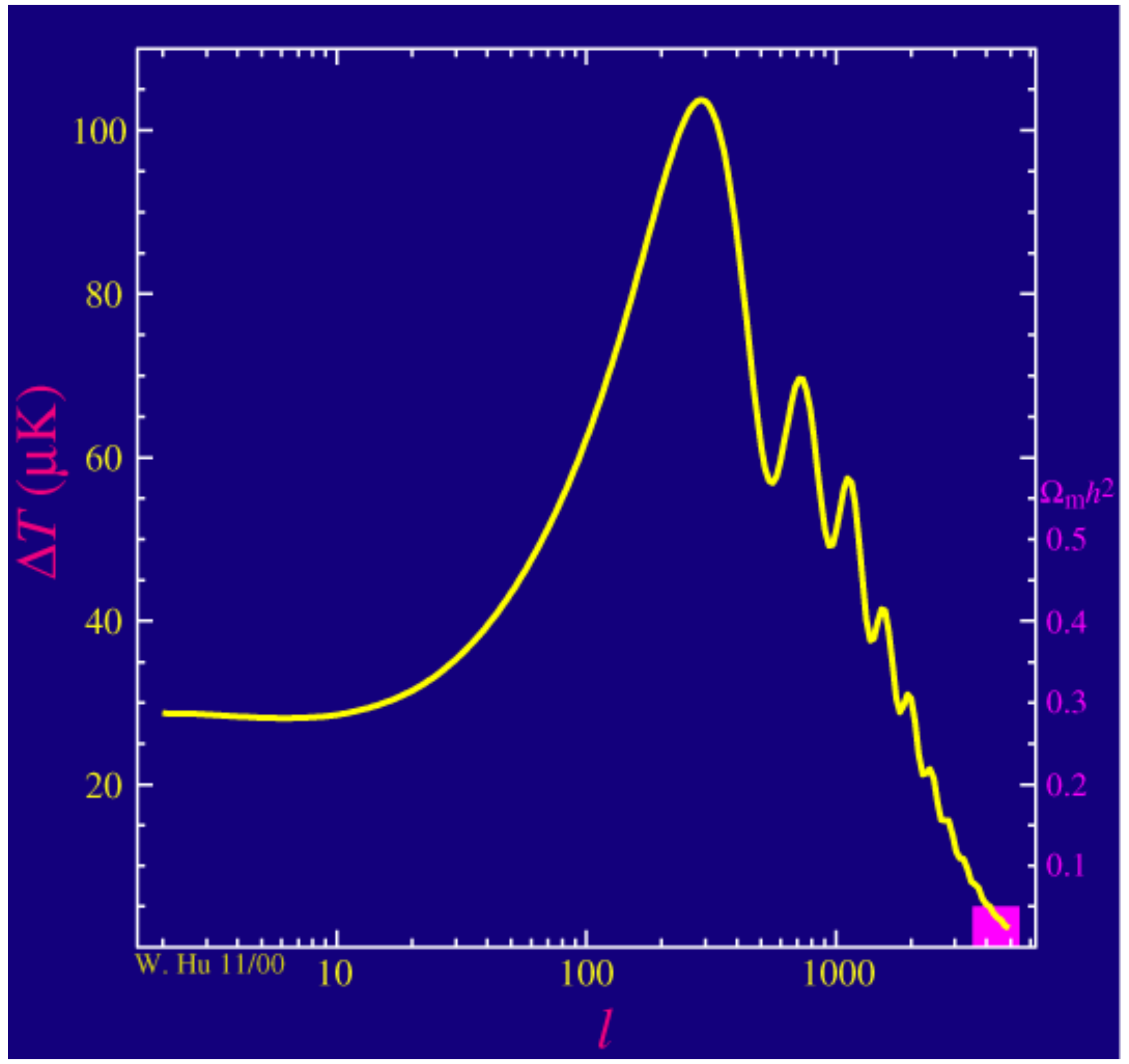
The “high" value of ns comes only when combined with DESI

Consequences for the spectral index n_s

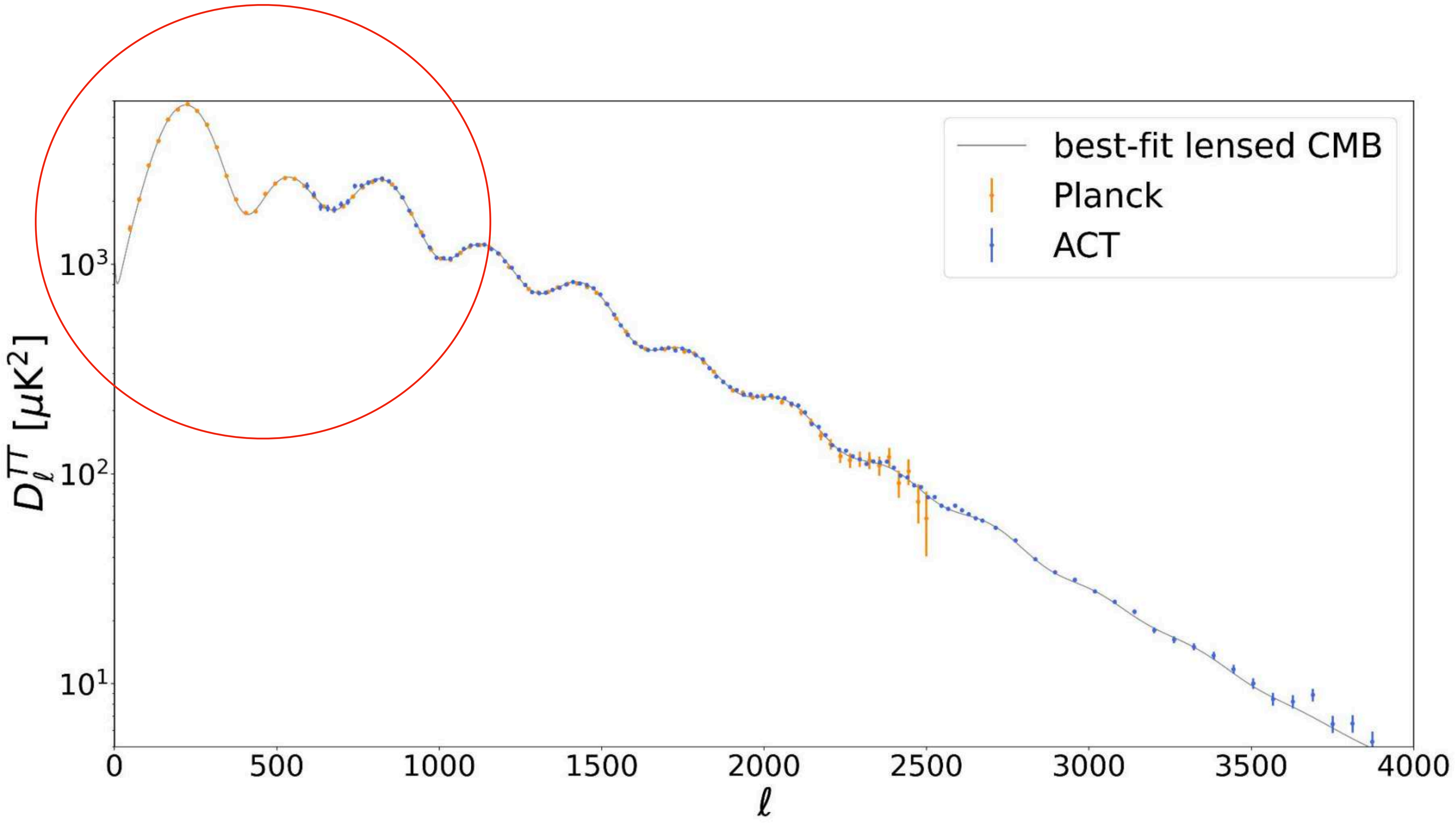
Understanding these shifts and significance:

Why ACT shifts so much when including DESI?

- Smaller BAO-CMB discrepancy for Planck
- Different degree of correlation of BAO parameters with ns for these data sets. Correlation structure depends non-trivially on:
  - Angular scales covered by the power spectrum measurements:
    - Experiment with more of its information coming from large angular scales (Planck) has the higher correlation: more information about $\Omega_m h^2$
  - Weighting of the data towards temperature or polarization set by the noise level
  - Relative weight of gravitational lensing information: gravitational lensing is more important on smaller scales, and is another source of information about $\Omega_m h^2$, one we expect to be relatively uncorrelated with ns.



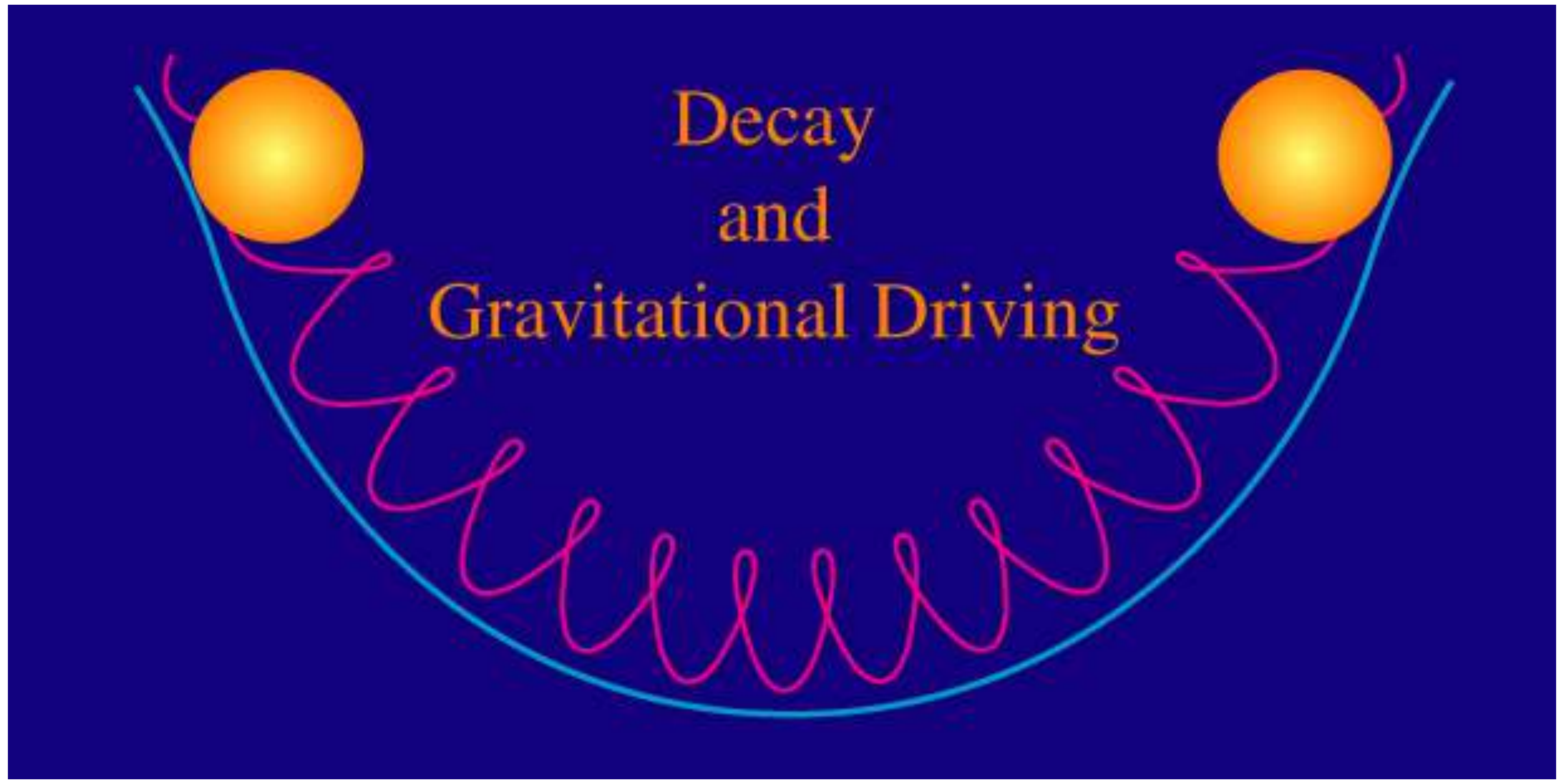
ACT allows more variation of Ω_m than Planck!



BAO parameters in the CMB

BAO parameters $r_d\,h$ and Ω_m can also be inferred from CMB data

- $\omega_m = \Omega_m h^2$ is determined primarily by the imprint of the 'radiation driving' effect
    - 'Radiation driving': boosting of acoustic oscillation amplitude due to potential decay at horizon crossing
- The amplitude depends on the matter-to-radiation ratio at horizon crossing and hence changes smoothly over a wide range of angular scales, with some similarity to changes in n_s
    - Leads to a partial degeneracy between n_s and ω_m.
- Determination of Ω_m comes from combining ω_m and the angular size of the sound horizon, θ_s (→ best measure quantity in cosmology)
- Ω_m determination is correlated with n_s since $\Omega_m h^2$ is correlated with n_s and θ_s is not



Implications to inflation

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

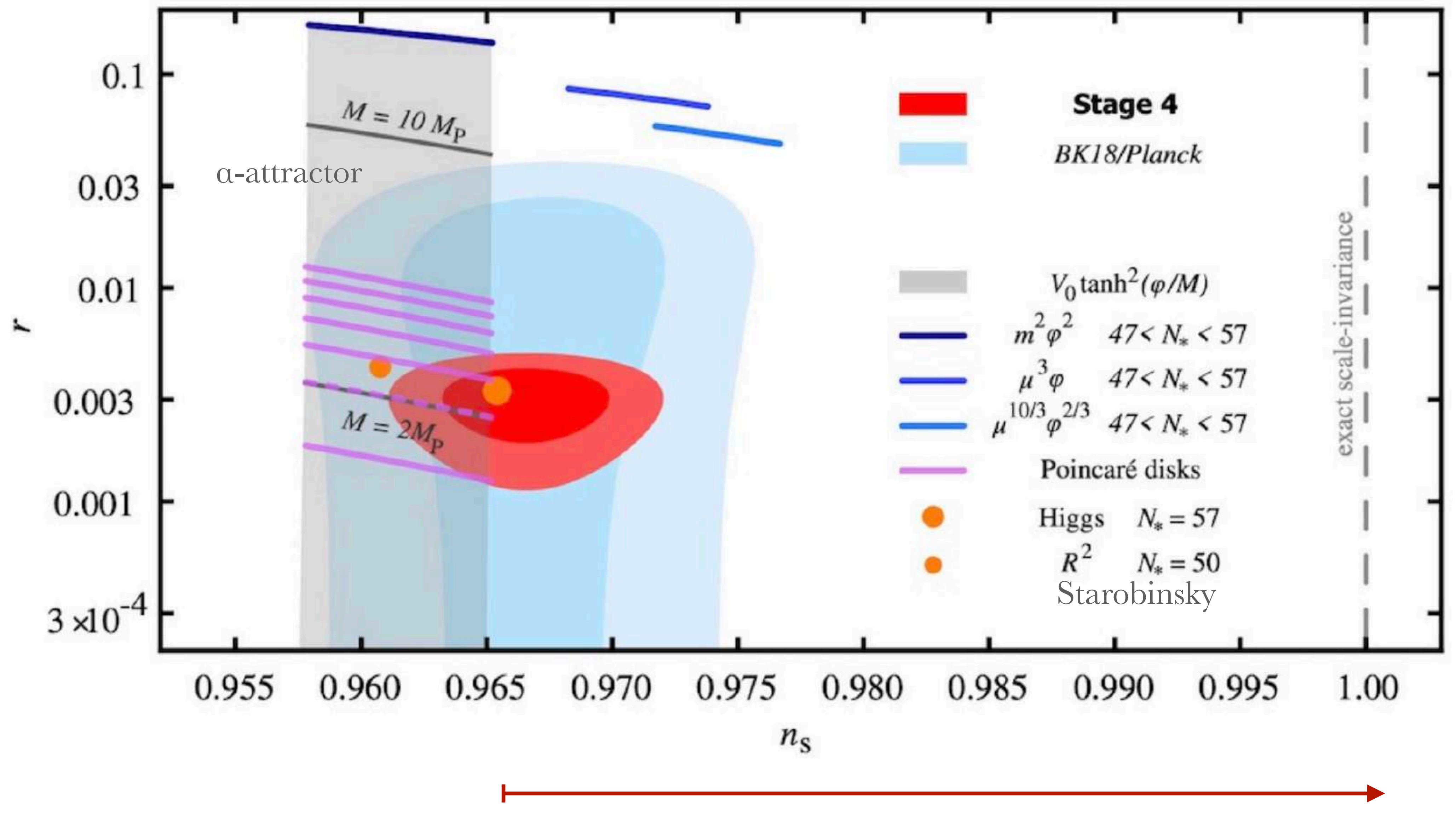
Does this shift has consequences for inflationary models?

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)

From CMB White Paper and LiteBIRD



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

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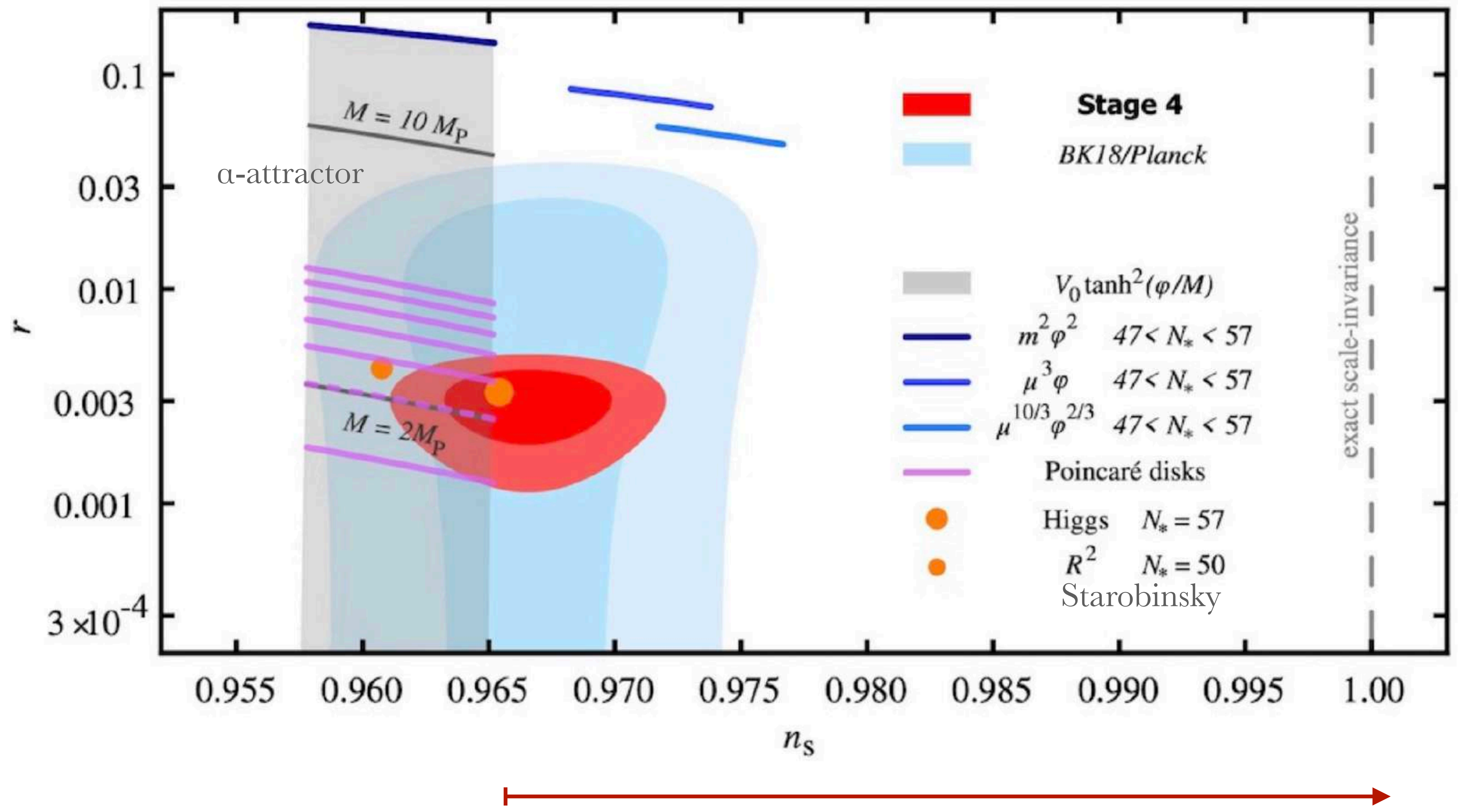
- α-attractors (exponential - T and E α-attractor)

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



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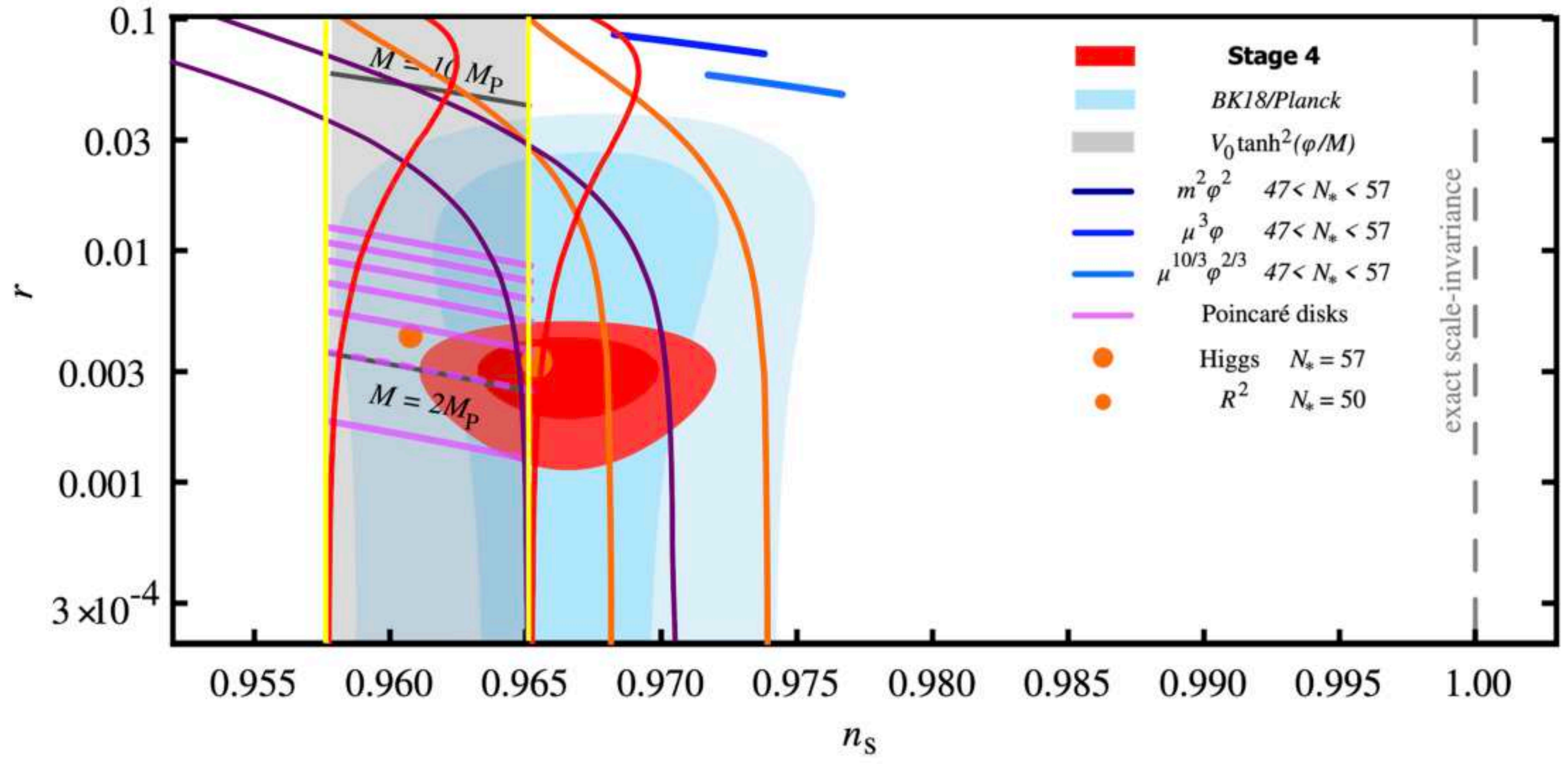
Does this shift has consequences for inflationary models?

Taking the high value of ns from ACT+DESI (or P-ACT-LB result ns = 0.9739±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, KKLTI models, polynomial α-attractors, chaotic inflation with nonminimal coupling to gravity ($N_* = 60$)

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

Red lines represent the E-model α-attractors, while the purple and orange lines show the predictions of the polynomial attractors with k = 4 and k = 2
Predictions of the simplest models with k = 4 and k = 2 in the small r area have 0.965 < ns < 0.974 for 47 < N∗ < 50

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

- Shift comes from the BAO-CMB discrepancy (within LCDM); can we rely in these combinations?

***Remember**: many of the current hints are only present when combining datasets e.g. dynamical DE*

- CAUTION when interpreting these constraints until the BAO-CMB discrepancy is resolved

- These shifts in n_s can strongly impact the viable inflationary scenarios in accordance to data

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

* Interesting interplay between *tau, the CMB-BAO tension and ns.*

Interplay of ns and 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 As 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 Ω_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 primodial power spectrum from inflation

τ is measured from:

1. **Low- ℓ E-mode polarization bump** from rescattering during reionization

   → *main observable;* $C_\ell^{EE} \propto \tau^2$
2. **Suppression of high- ℓ TT/TE/EE acoustic peaks**

   → *gives τ only via and is highly degenerate with A_s*
3. **Low- ℓ TE correlations**

   → *secondary constraint*

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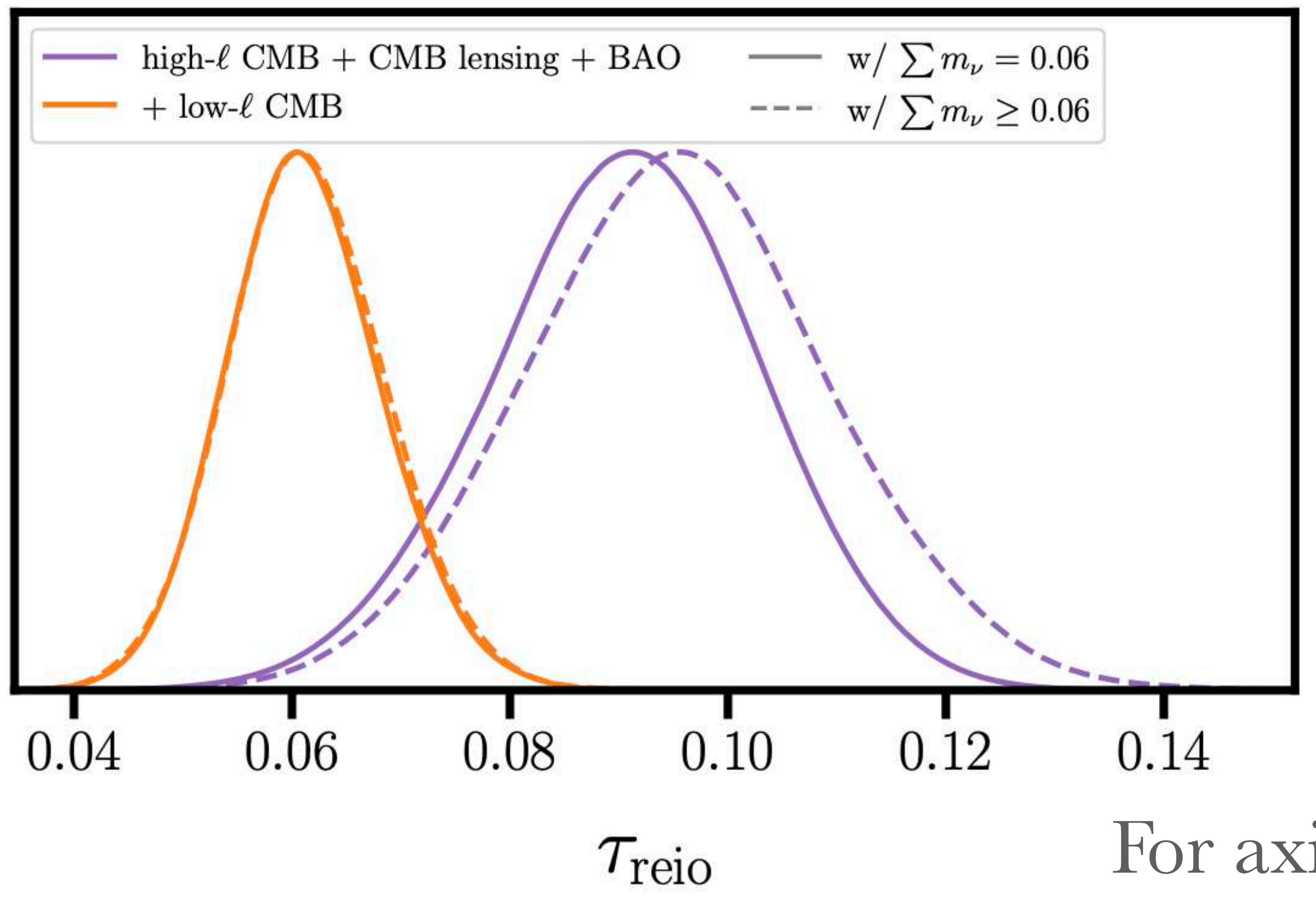
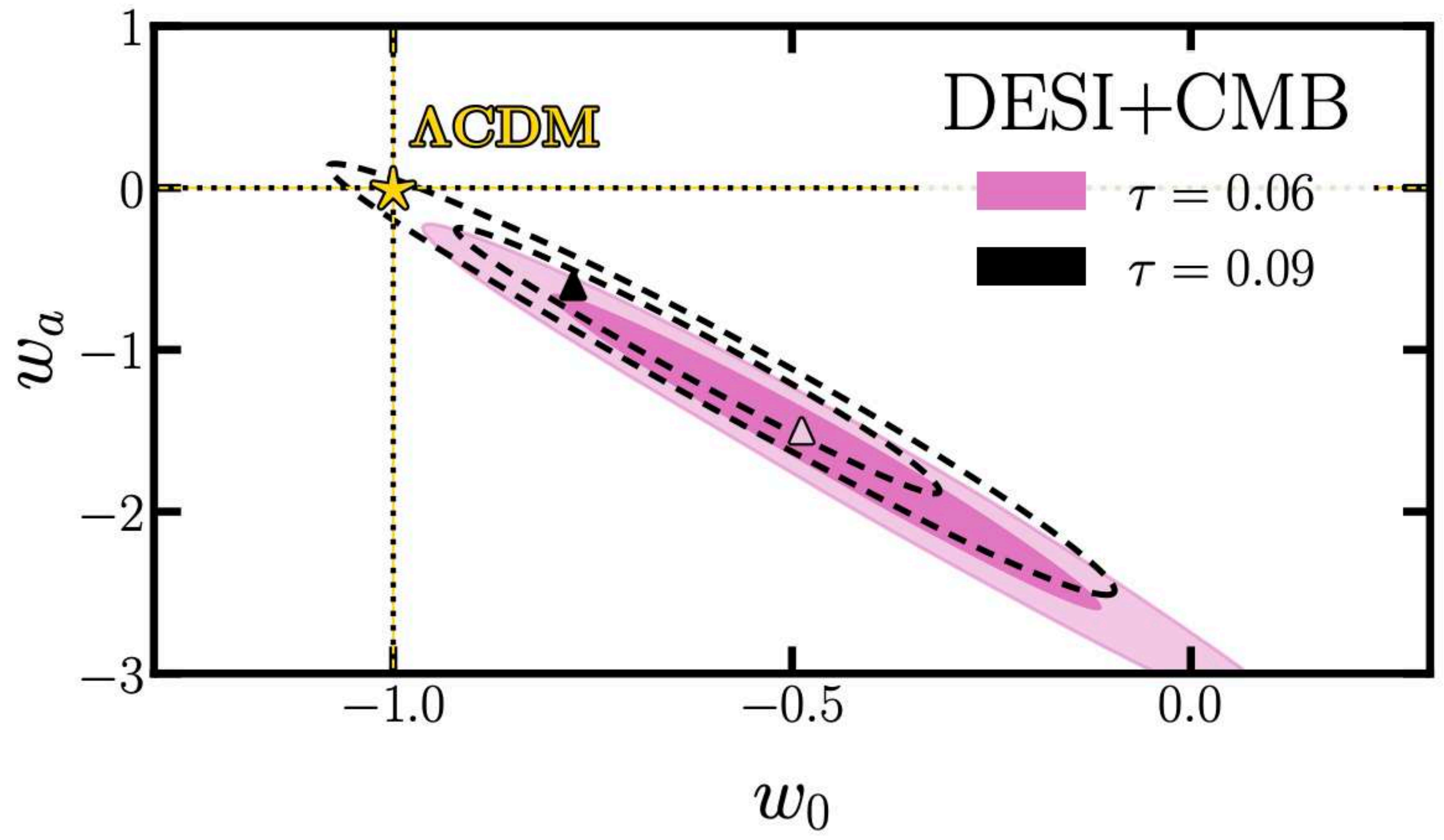
Influence of τ for sum of neutrino mass and DE constraints

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 w0 − wa phantom dark energy

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

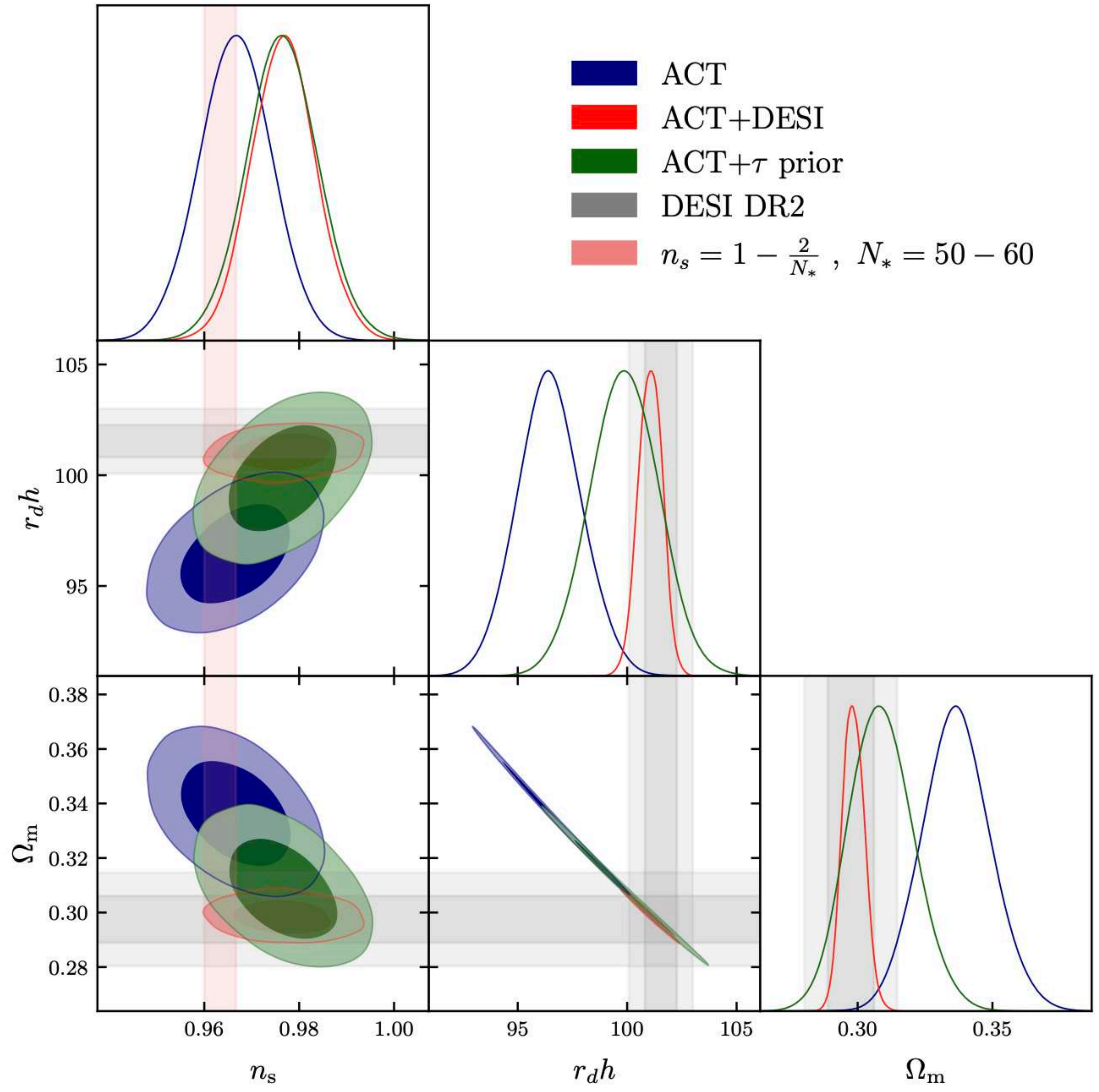
Interplay of ns and tau

The Shifting Spectrum of ns constraints from DESI and CMB data, E McDonough, **EF**, 2512.05108

Exercise:

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

Expected: τ tightly correlated to As and ns

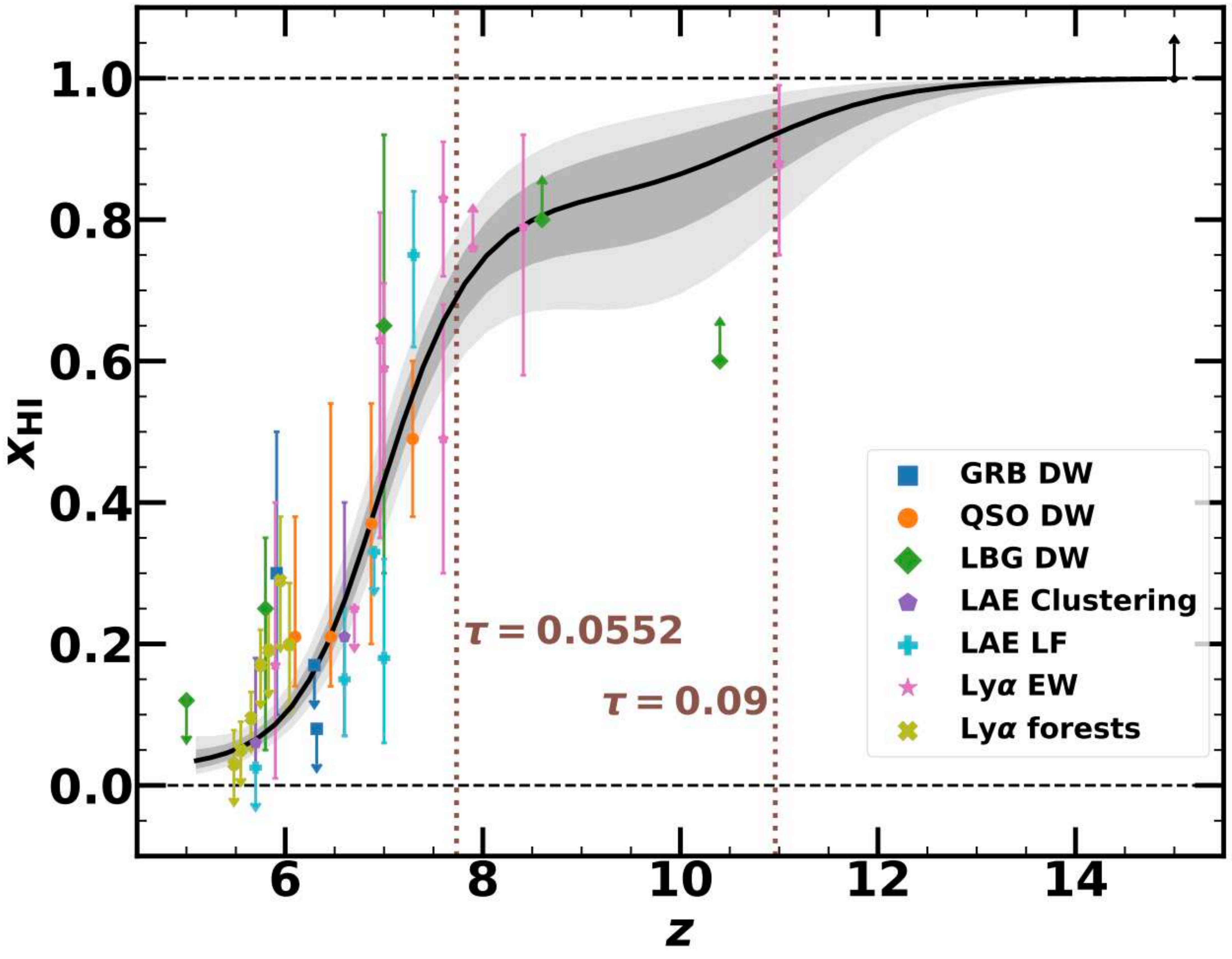


There might be systematics in the measurements of low l polarization and in the determination of τ - important goal of LiteBIRD

Interplay of ns and tau

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 tau?



- Lyα damping-wing absorption of GRBs at $z = 5.9 - 6.3$ (Totani et al. 2006, 2014; Fausey et al. 2025)
- Lyα damping-wing absorption of QSOs at $z = 6.0 - 7.5$ (Greig et al. 2022; Ďurovčíková et al. 2024)
- Lyα damping-wing absorption of LBGs at $z = 5 - 13$ (Umeda et al. 2025a)
- Clustering properties of Lyα emitters at $z = 5 - 7$ (Umeda et al. 2025b)
- Evolution of the Lyα luminosity function at $z = 5 - 7$ (Wold et al. 2022; Umeda et al. 2025b)
- Evolution of the Lyα 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 Lyβ 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)

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 ΛCDM with a benchmark inflation scenario holds true; something has to give.

But this goes beyond inflation. It affects: dynamical DE, neutrinos, …
Important!

Also alerts us for to be careful when combining datasets

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

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 ns constraints from DESI and CMB data,* E McDonough, **EF**

Volume effects
&
profile likelihood in cosmology

Parameter inflation

What are those effects and how important/ how much thy 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 ΛCDM, 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

Profile likelihood in cosmology

Statistical methods in cosmology

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

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

Statistical tools center stage! *Bayesian, frequentist, ML,* …

Important:

MCMC effect: Prior volume effect ⟶ when large, affects the results

➡ *Profile likelihood*

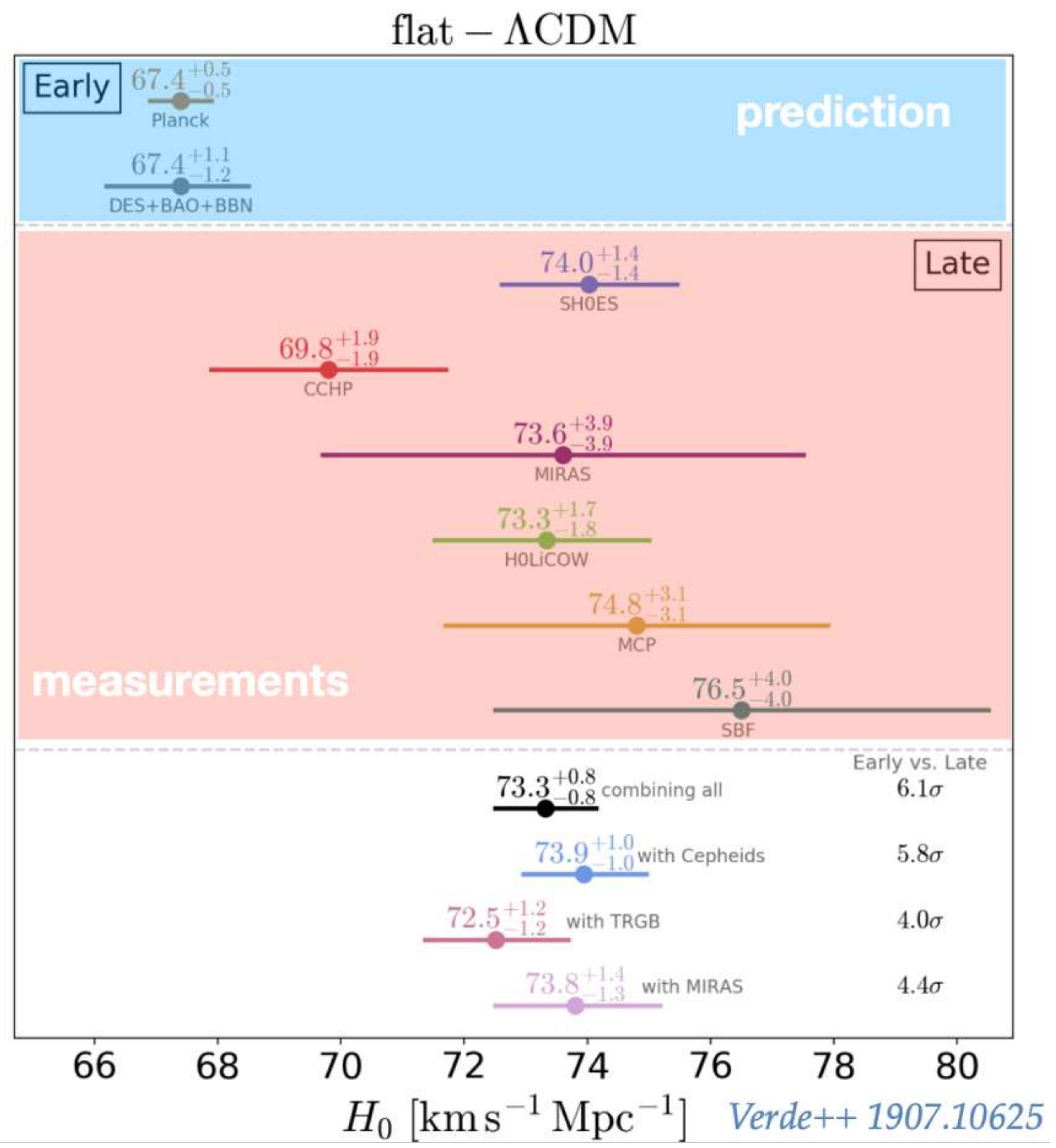
Cosmological tensions and early dark energy

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

Hubble tension

Indirect

Direct



→ Depends on the cosmological model

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

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

5σ tension with Planck!

↓

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

(Planck+BAO+Sn)

Systematics or new physics?

Early vs late time solutions to the Hubble tension

To increase H_0:

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

r_s: *pre-recombination* physics ⟶ depend on physical densities (b, r, cdm, ν)

Measured with a 0.03% precision by *Planck* 2018

D_A: *post-recombination* physics ⟶ information on H0

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

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 $r_s(z_*)$ $\Longrightarrow$ decreases $D_A(z_*)$

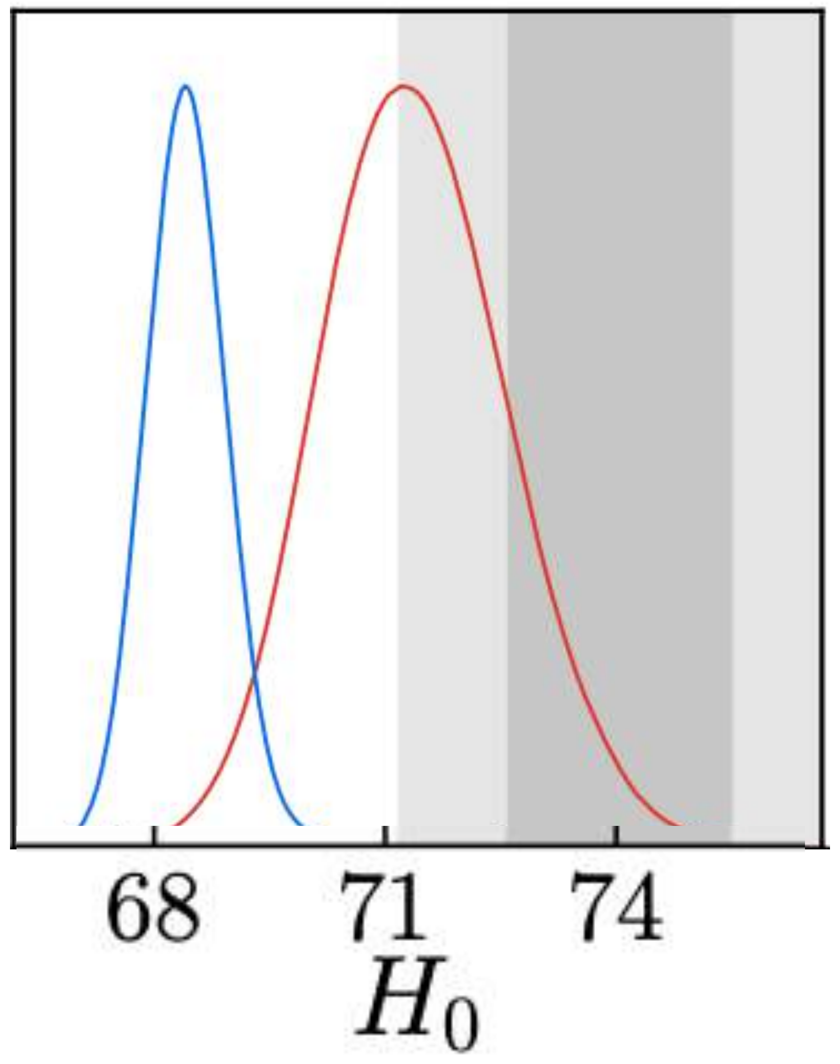
Fixed

$\Downarrow$

Increases H_0

Verde + (2019),Poulin (2019), Agrawal + (2019), Lin +(2019), Smith + (2019), Knox and Milea (2019)

Early time solutions to the Hubble tension



ΛCDM

EDE

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

Fixed

$\Longrightarrow$ 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:

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

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

	ΔN_p
Majoron	3
primordial B	1
varying m_e	1
varying m_e+Ω_k	2
EDE	3
NEDE	3
EMG	3

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

- Light Relics
- Early Dark Energy

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: A fair ranking of proposed models,
Schöneberg + (2021)

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

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

acting around equality ↓ ϕ_i

behaves as DE ↓ 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

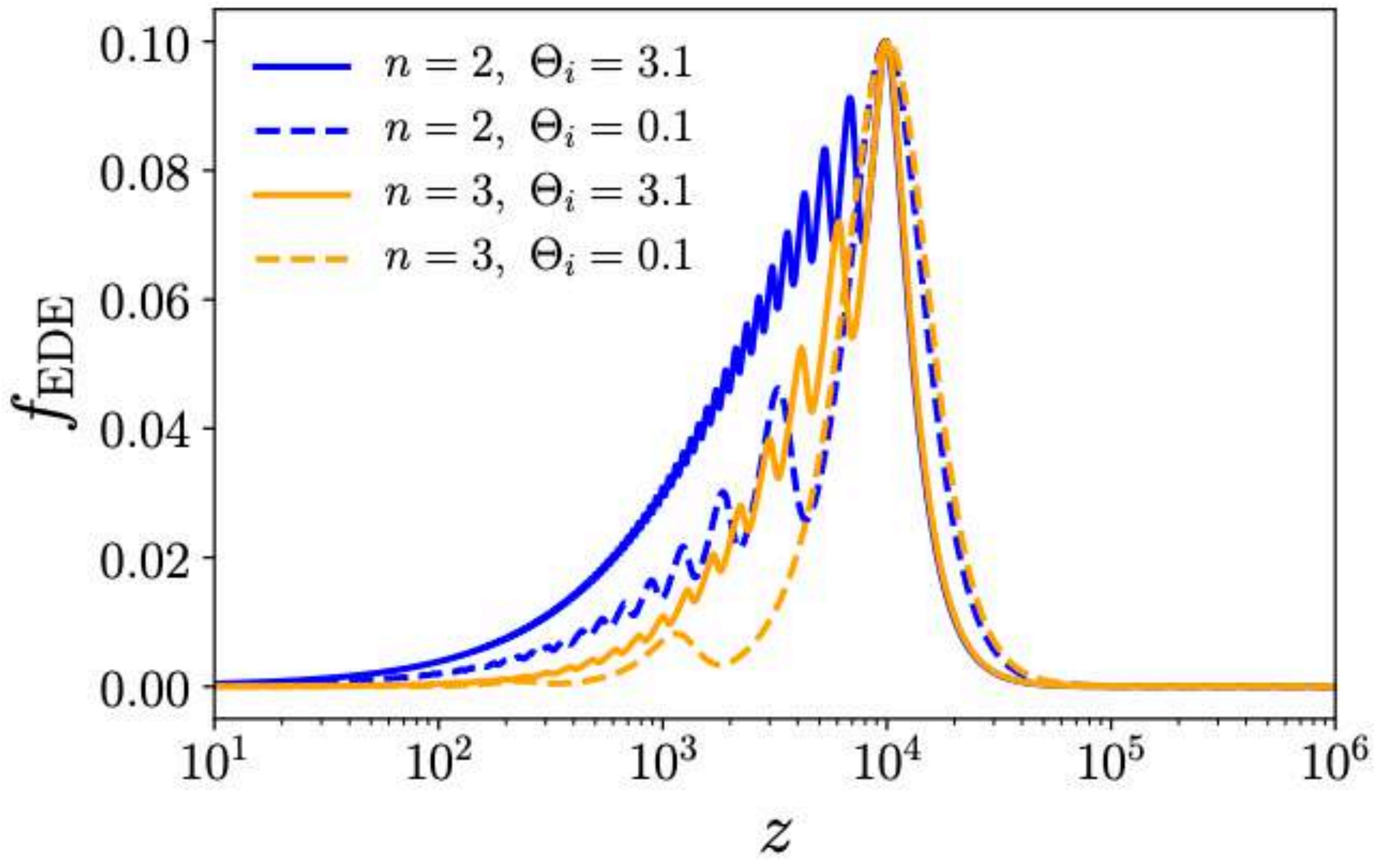
$$V(\phi) = V_0 \, [1 - \cos(\phi/f)]^n$$

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 → needs to be hidden at late times

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

Smith et al 2019



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

$$f_{\rm EDE}(z_c) \equiv \left.\frac{\rho_{\rm EDE}}{\rho_{\rm tot}}\right|_{z_c} = \left.\frac{\rho_{\rm EDE}}{(3M_{pl}^2 H^2)}\right|_{z_c}$$

We usually fix $n = 3$

$$\Longrightarrow \{f_{\rm EDE}(z_c),\ z_c,\ \theta_i\}$$

Matteo Braglia et al 2020, Adrià Gómez-Valent et al 2021, …

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*

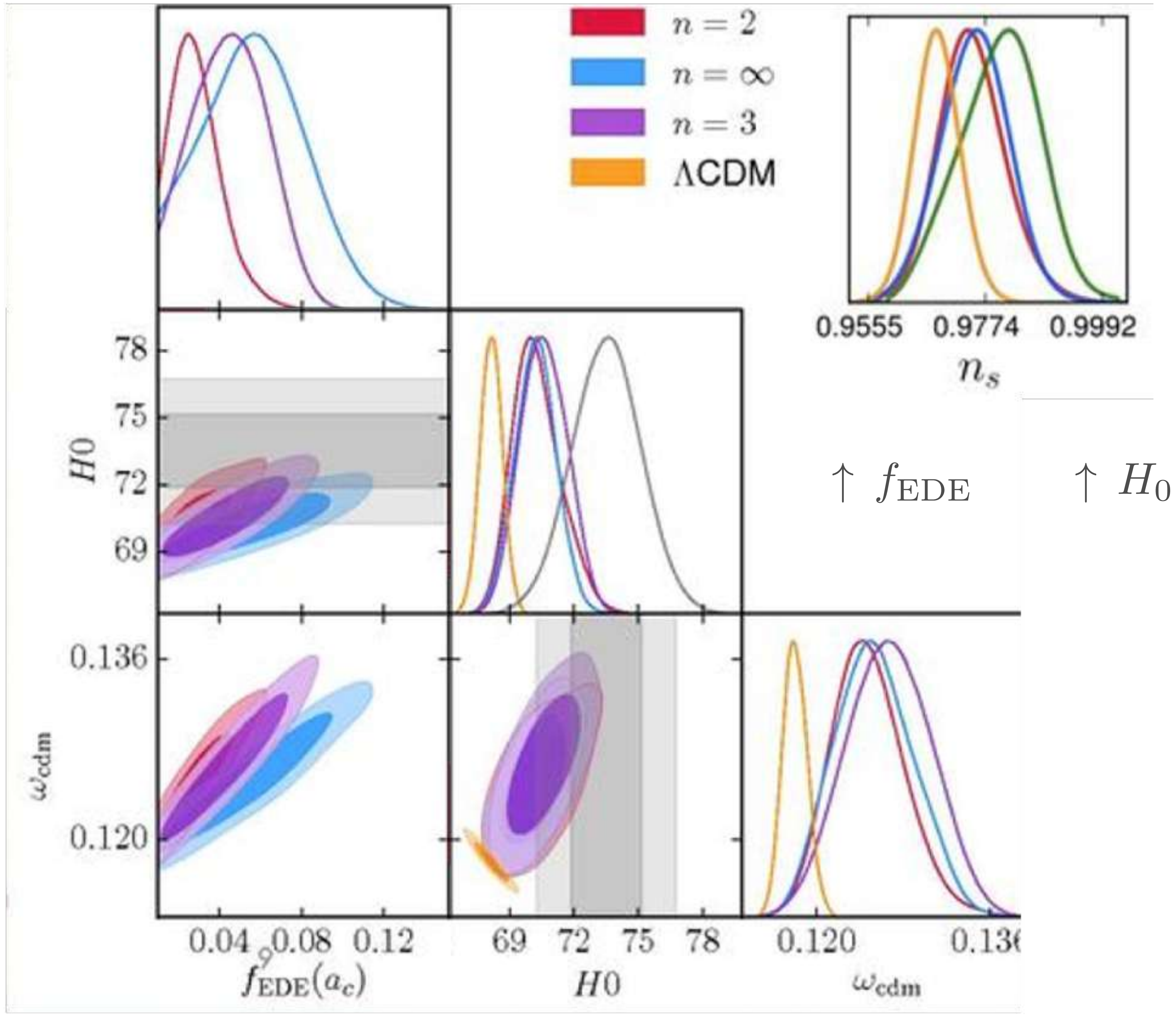
$$H_0 = 71.49 \pm 1.20\,\mathrm{km/s/Mpc}$$

Solves the tension!

$\uparrow f_{\rm EDE}$ $\uparrow H_0$

But with:

- More DM
- Higher n_s



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

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 Alexander[3]

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 Zaldarriaga[8]

Uniform prior in the phenomenological parameters

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

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

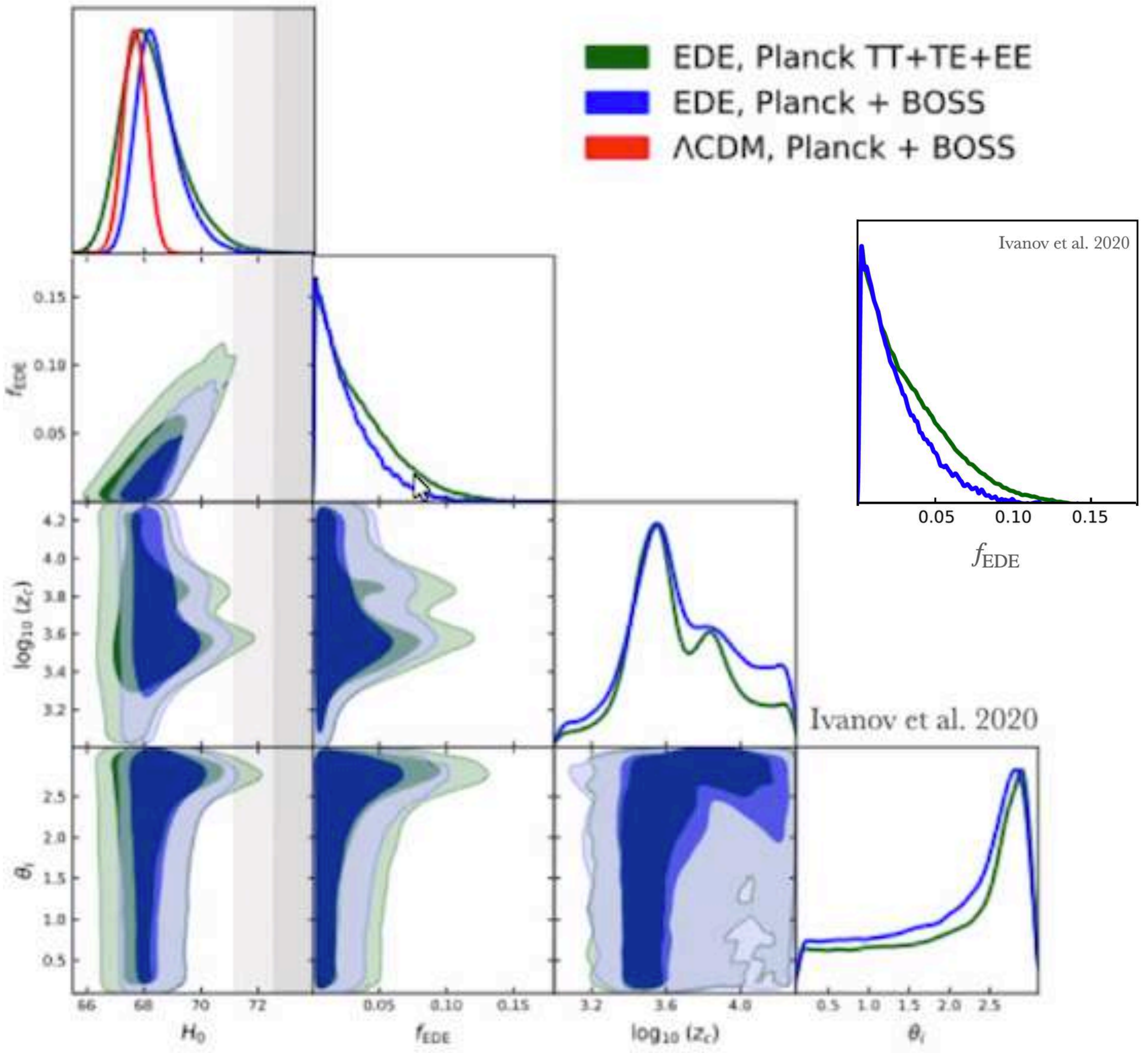
Parameter	ΛCDM	EDE ($n = 3$)
f_{EDE}	−	$< 0.072\ (0.047)$
H_0 [km/s/Mpc]	$67.70\,(67.56)\ \pm 0.42$	$68.54\,(68.83)^{+0.52}_{-0.95}$
Ω_{m}	$0.3105\,(0.3112)^{+0.0053}_{-0.0058}$	$0.3082\,(0.3120)^{+0.0056}_{-0.0057}$

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

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

3.6σ tension with SHOES !!

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



Early dark energy does NOT solve Hubble tension!

Wait…

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

T. Smith et al (2020)

Niedermann, Sloth (2019)

Not all groups agree with this result Volume effects?

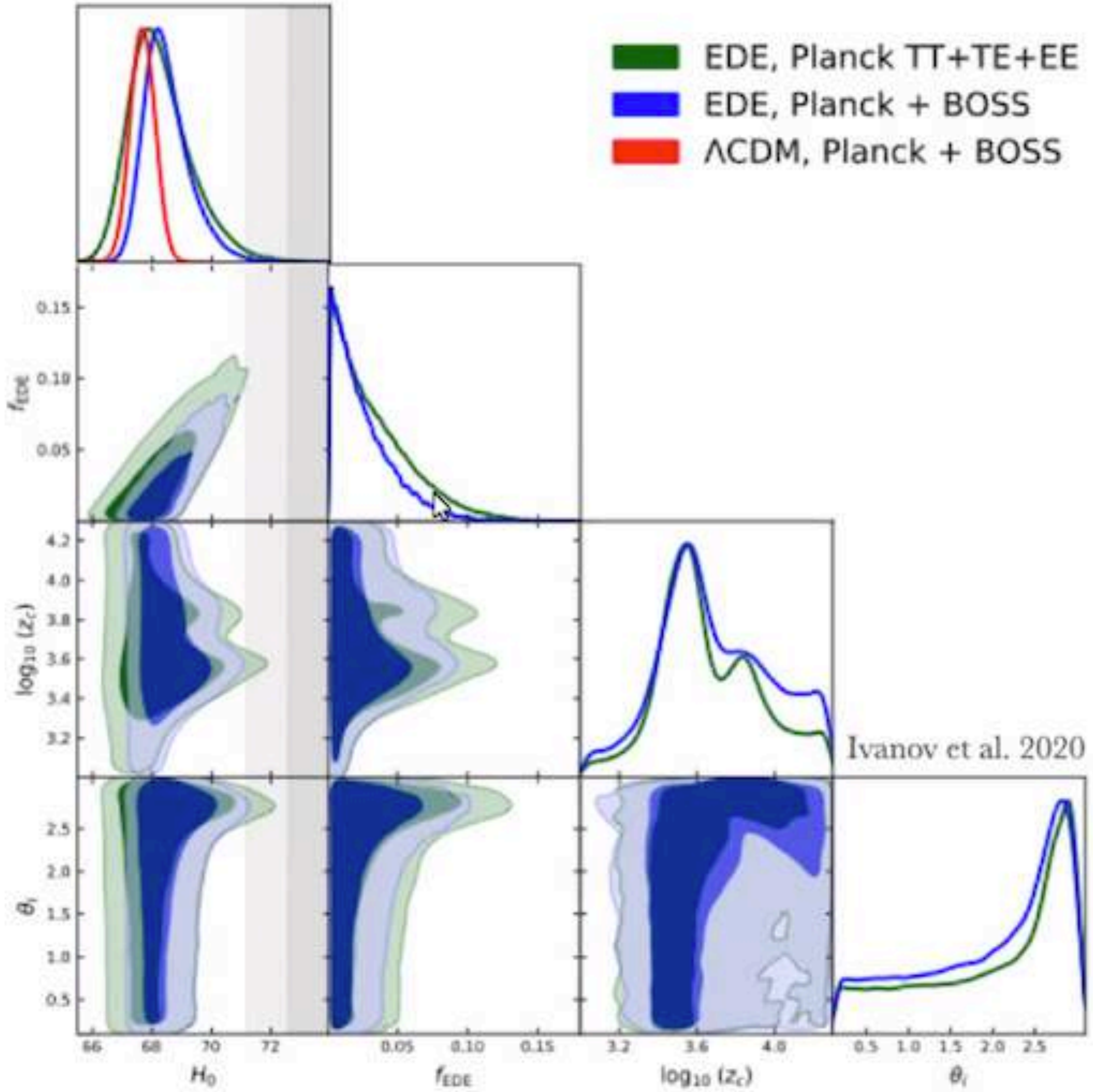
- Previous result can be a consequence of choice of priors of the EDE parameters

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

↓

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

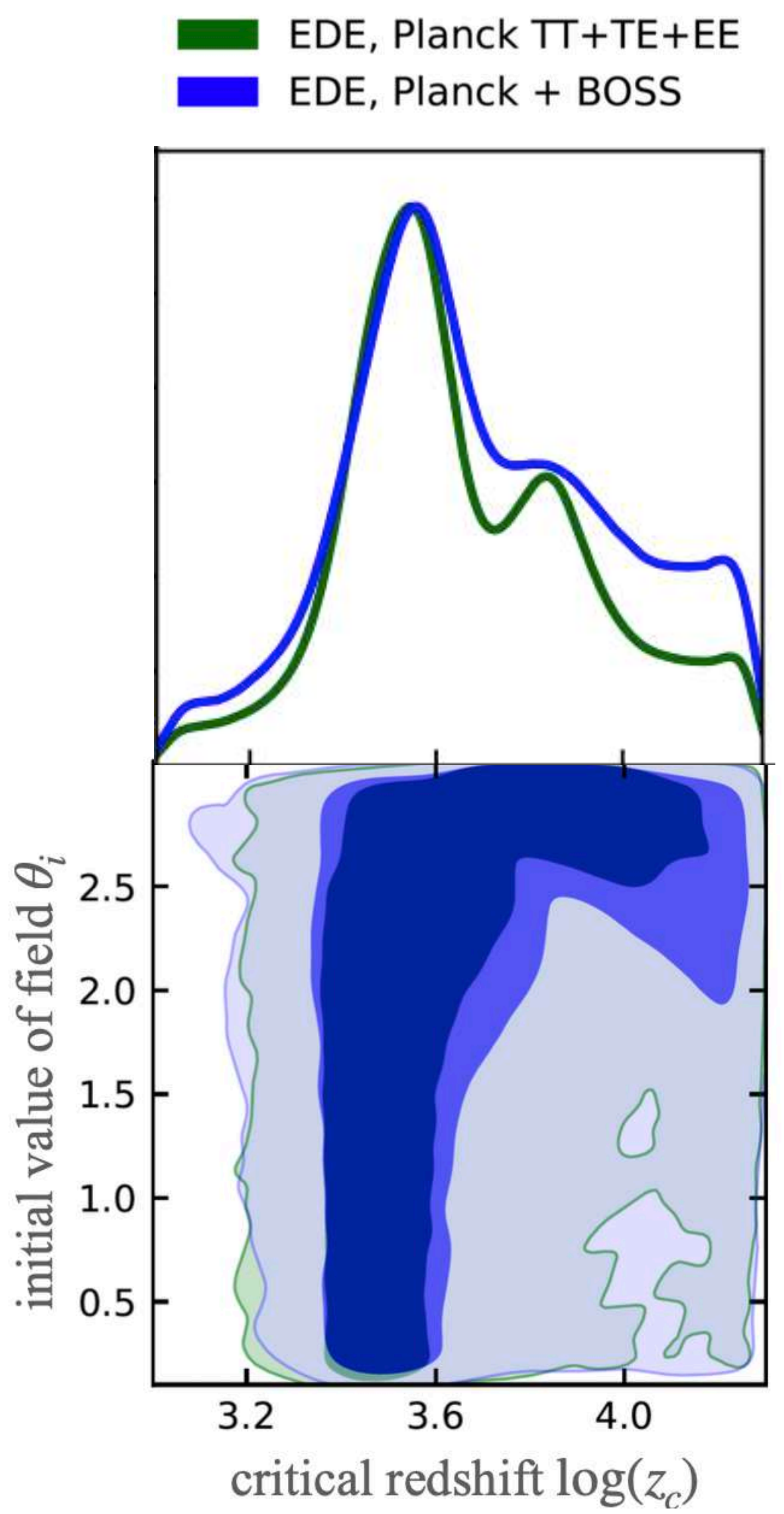
• $\log(z_c)$ and θ_i are not well constrained by data



Ivanov et al. 2020

Prior volume effects

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



Ivanov et al. 2020

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.

Prior volume effects

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

When they appears:

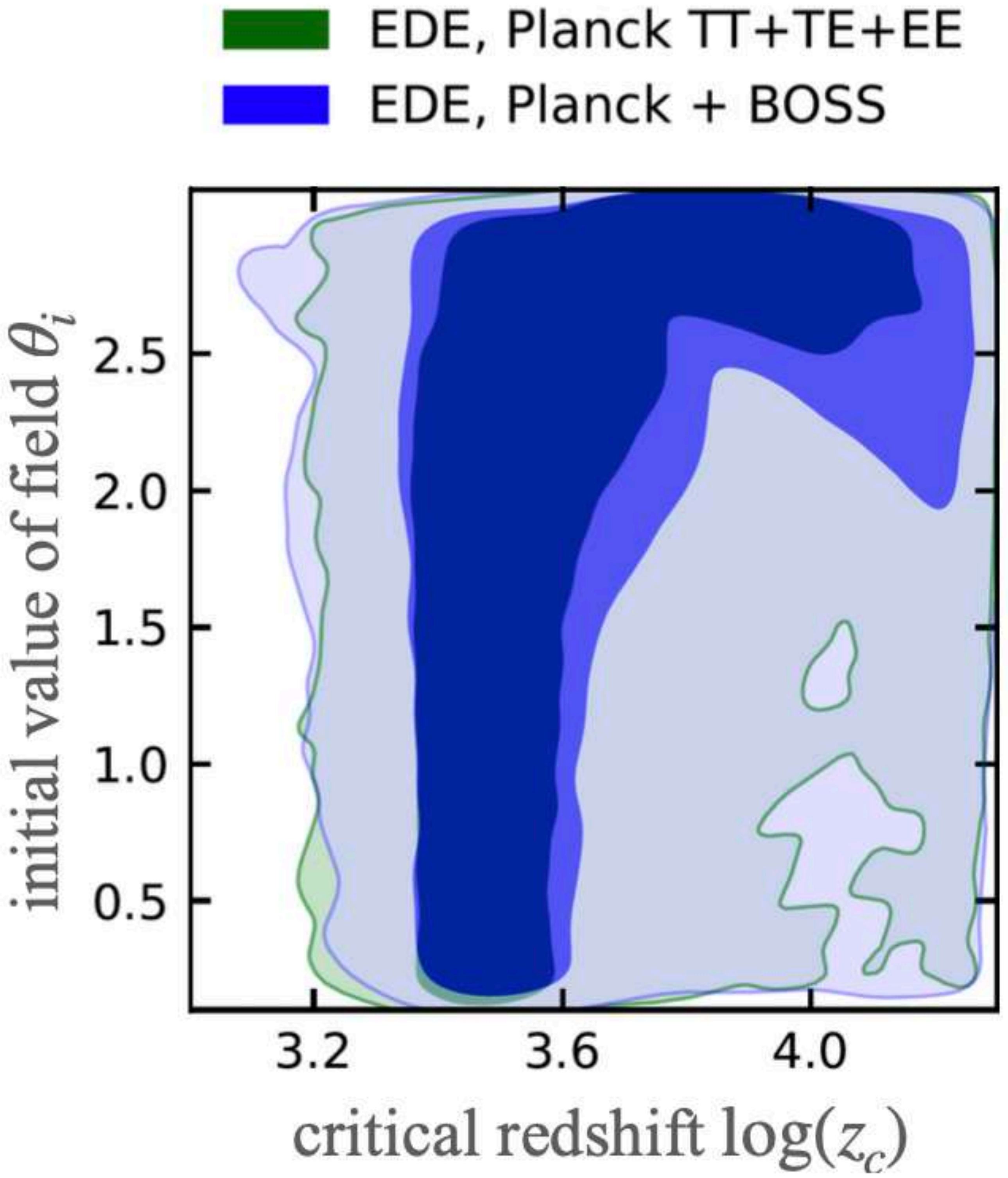
- Model has too many parameters / data is not constraining.
- Posterior is very non-Gaussian.
- Parameter structure of the model generates large volume differences.

Leads to:

⟶ Bias/shifts in the marginalized posterior

⟶ Inefficiencies in sampling

⟶ Incorrect assessment of the effect of errors, such as systematic errors

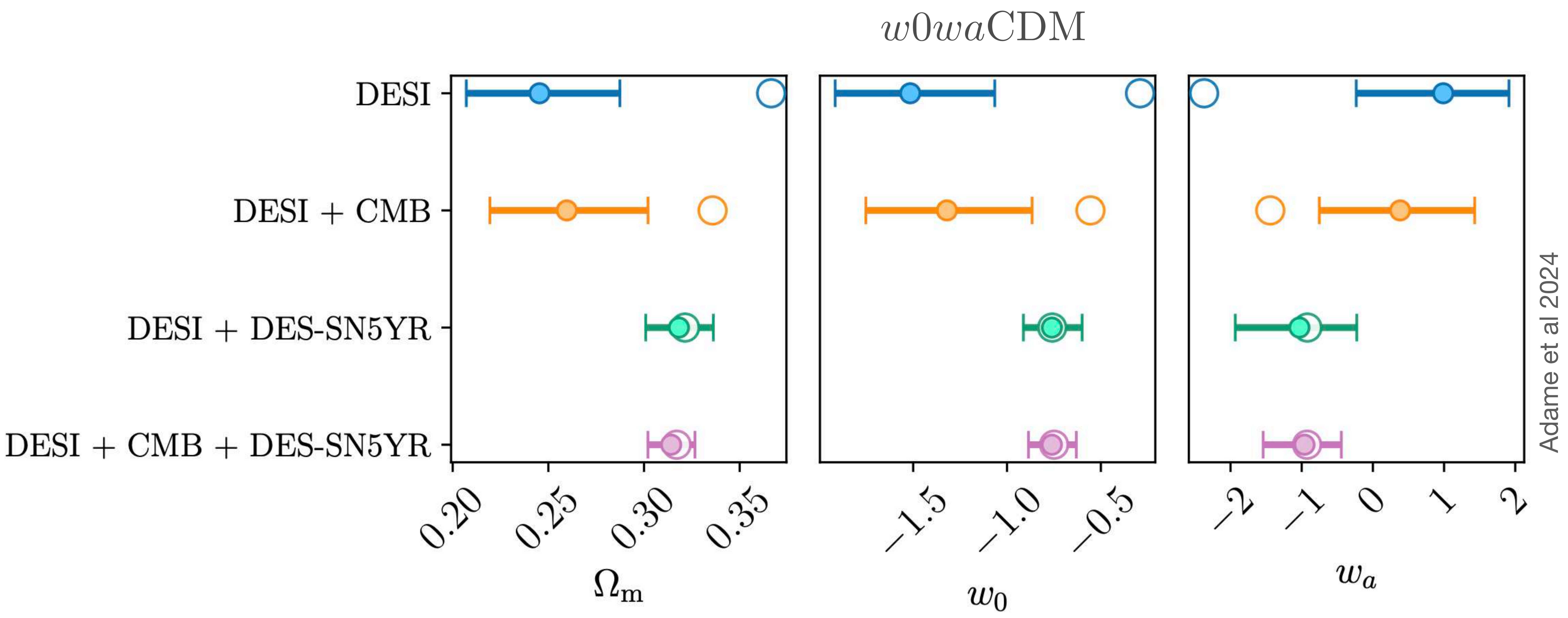


Elisa Ferreira to appear

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, •: mean
◯ : 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!

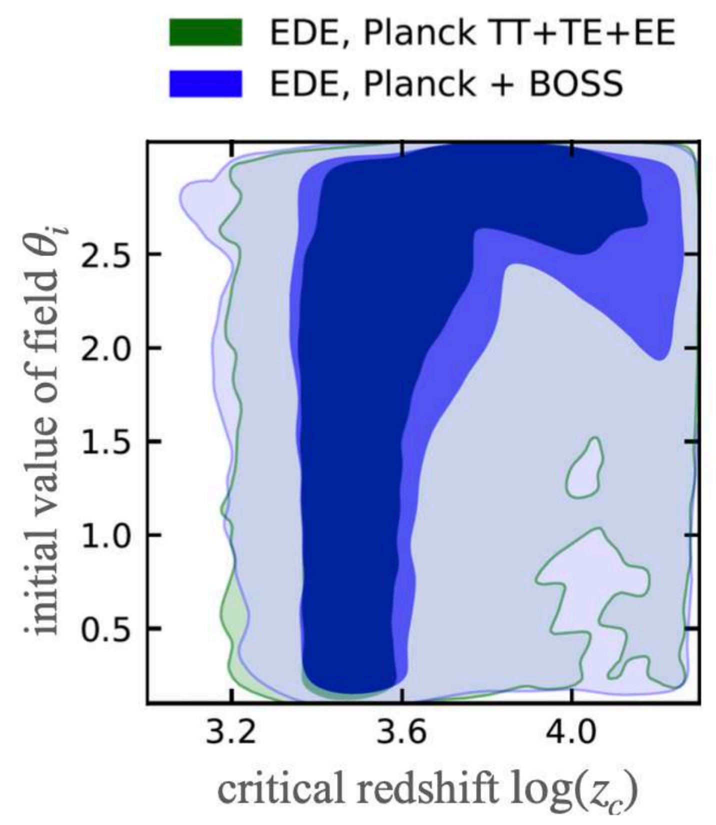
Challenges for data analysis

Statistical challenges for parameter inference:

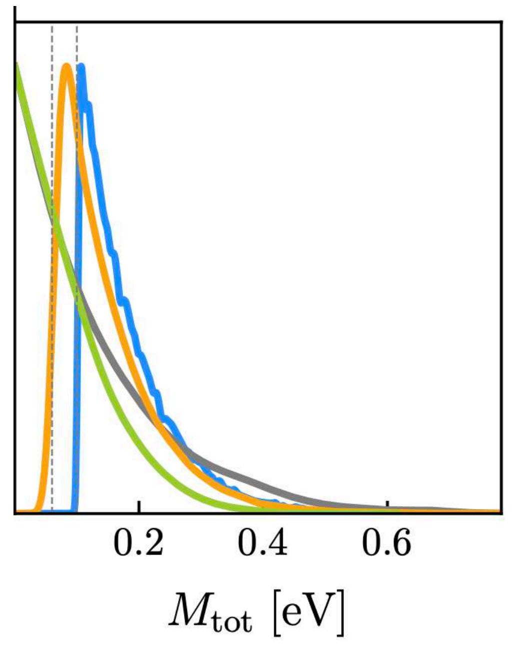
- Prior volume/marginalization/projection effect
- Prior weight effect
- Parameters at the border of the prior volume
- Very non-Gaussian likelihoods
- …

Marginalization

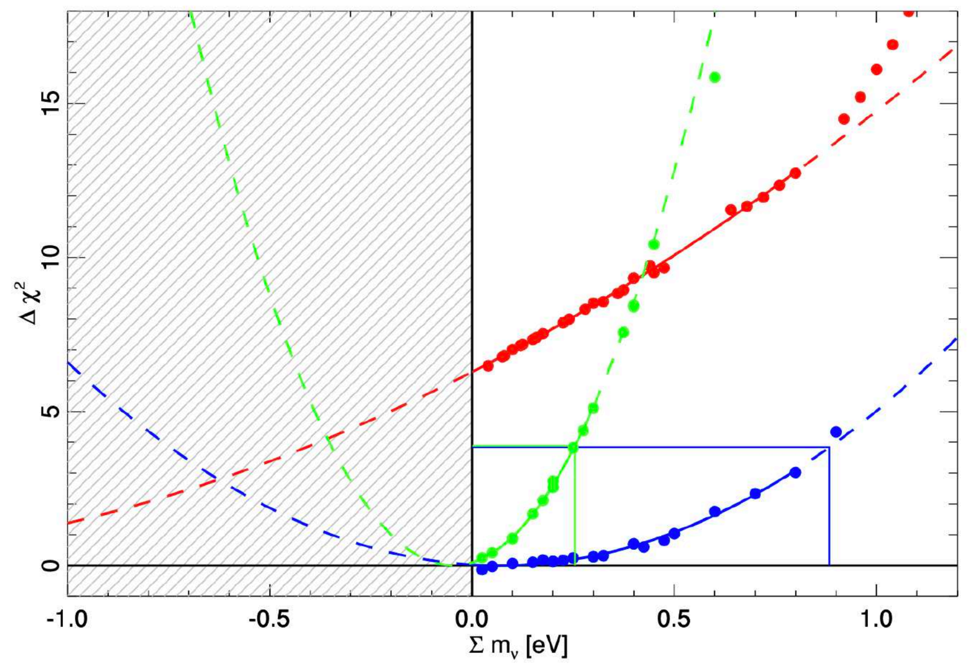
Prior



Ivanov et al. 2020



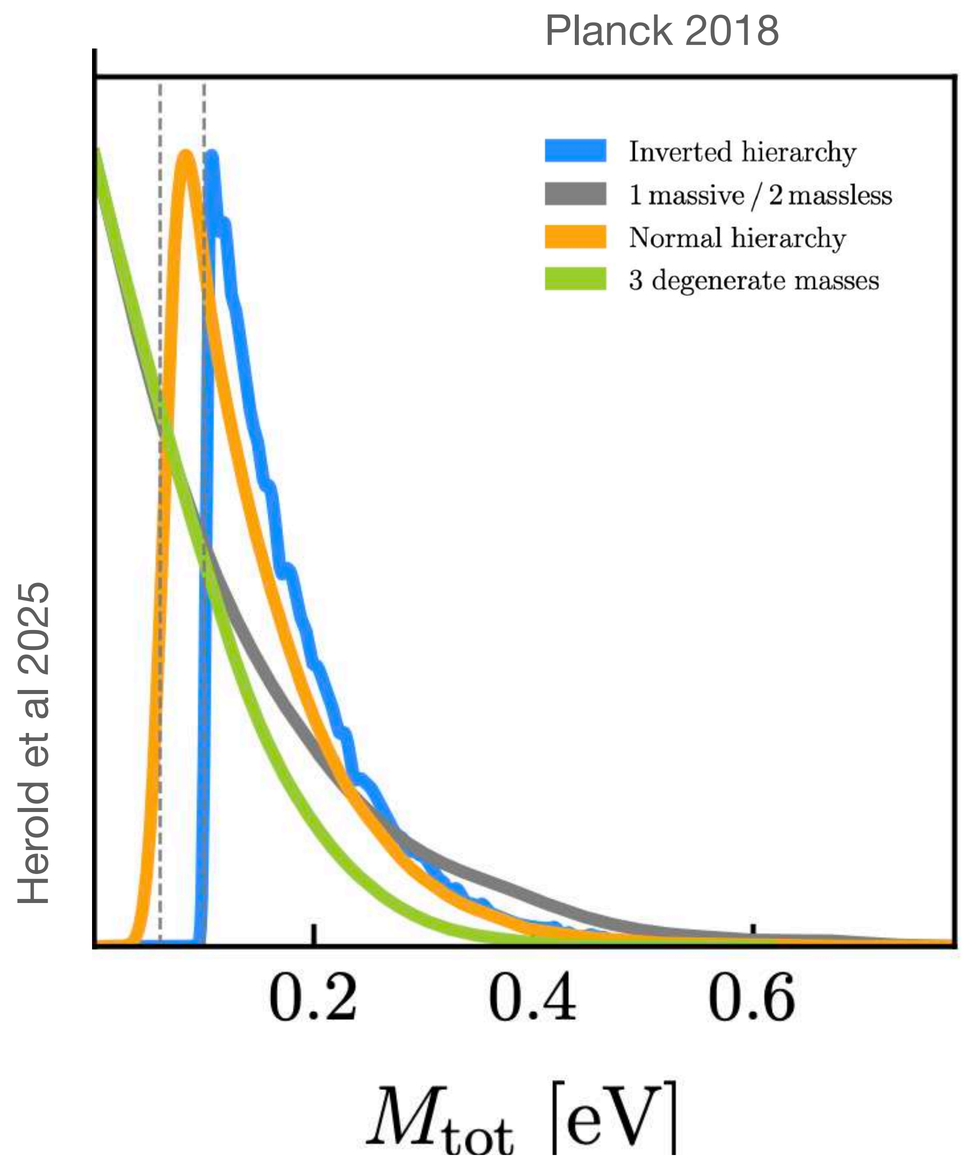
Herold et al 2025



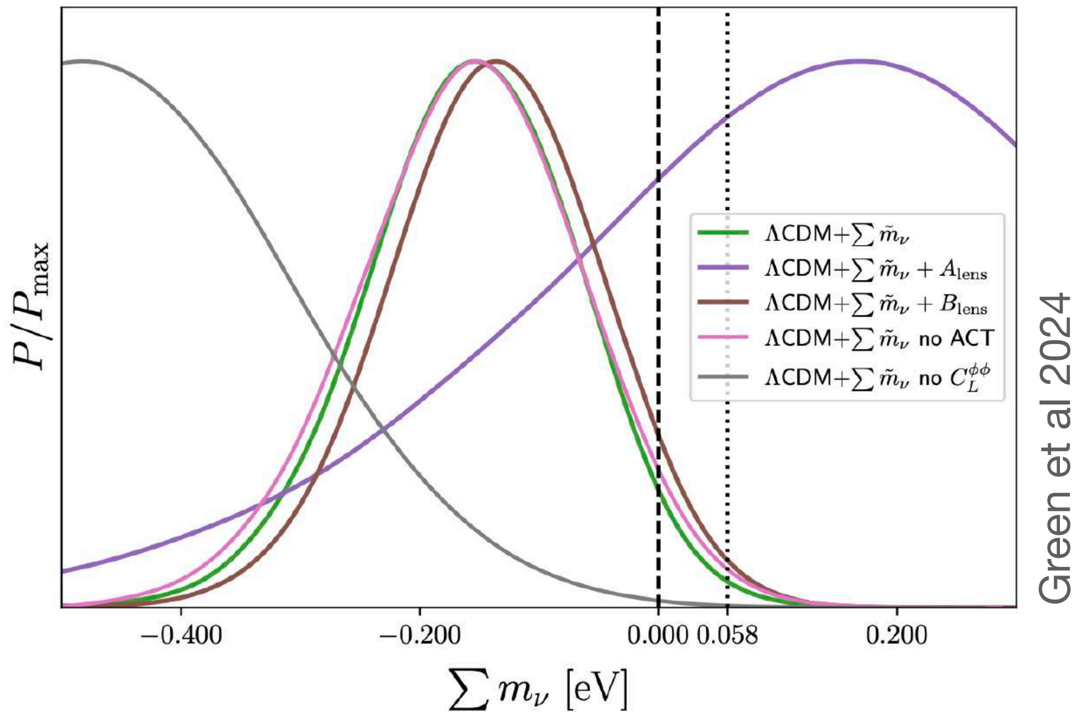
Planck intermediate results XVI, 2014

Parameters at the border of the prior

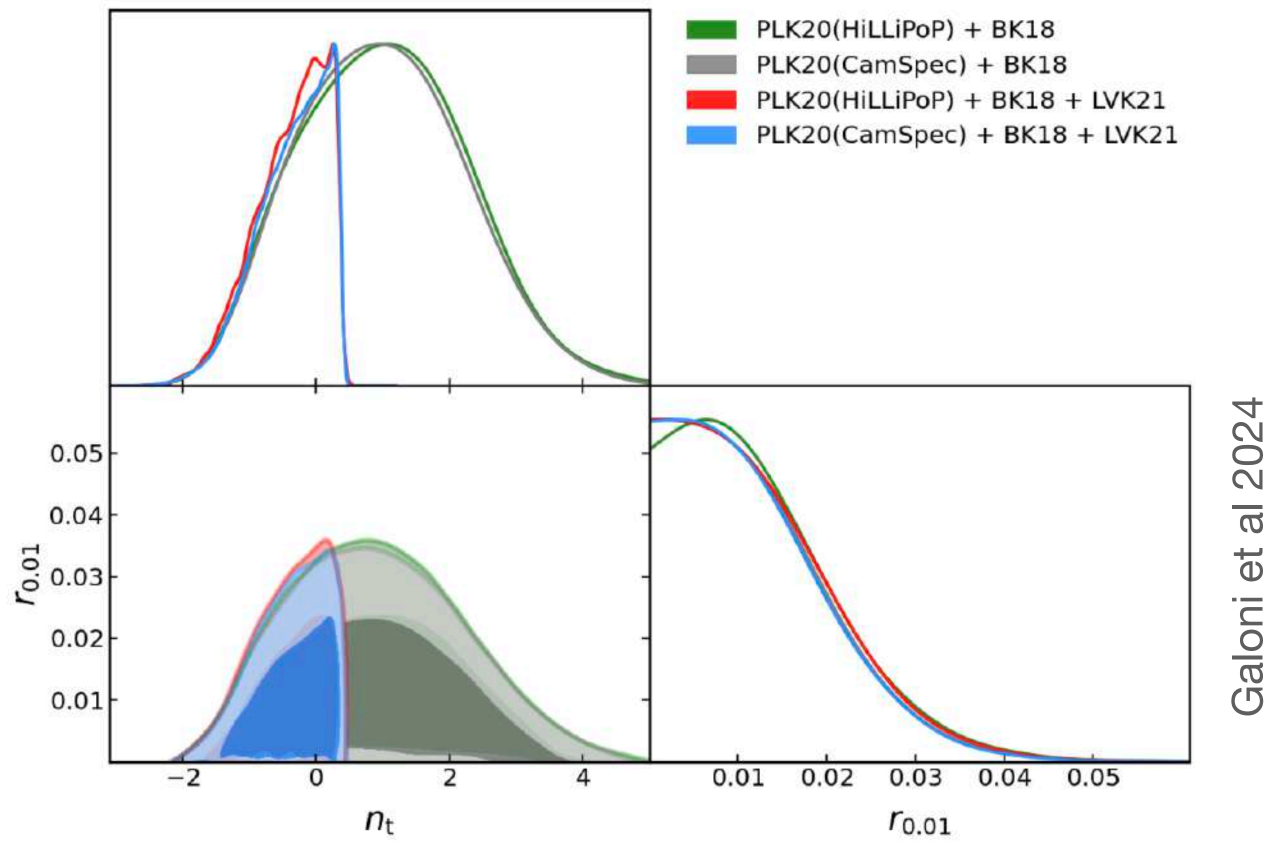
Neutrino mass:



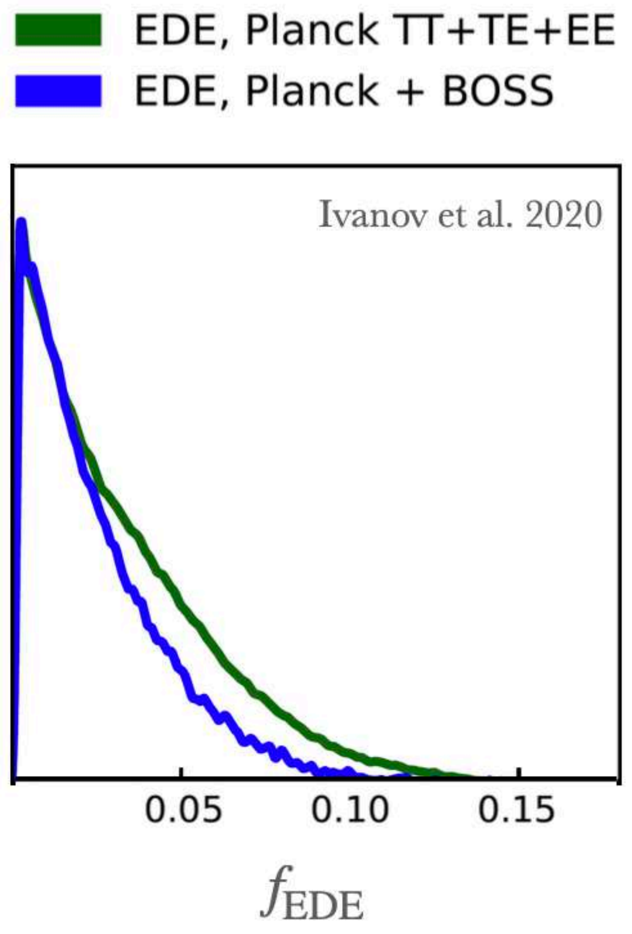
Negative neutrino mass



Tensor to scalar ratio (r):



$f_{\rm EDE}$:



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.

Posterior / Likelihood / Prior

$$P(H \mid E) = \frac{P(E \mid H) \cdot P(H)}{P(E)}$$

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 ΛCDM, Massive Neutrinos and Dark Energy,
L. Herold, **EF**, L. Heinrich

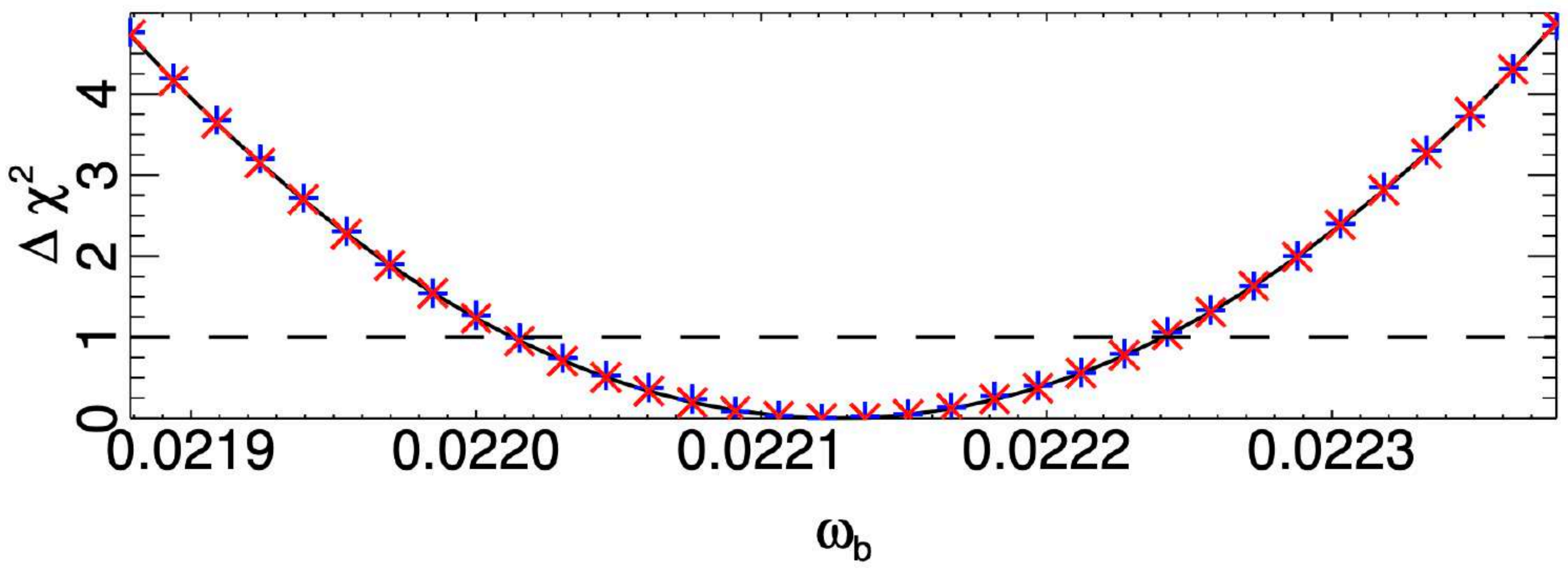
Motivation:

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 → fit a parabola

Planck intermediate results XVI, 2014



Confidence interval:

- A confidence region, can be extracted from the likelihood ratio statistic:
  $\Delta\chi^2(\theta) = \chi^2(\theta) - \chi^2_{\rm min} = -2\ln(\mathscr{L}/\mathscr{L}_{\rm max})$
- For parabolic $\chi^2(\theta)$, and one dof, the c.i. is given by:

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

(Only valid in the asymptotic limit)

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

Profile likelihood

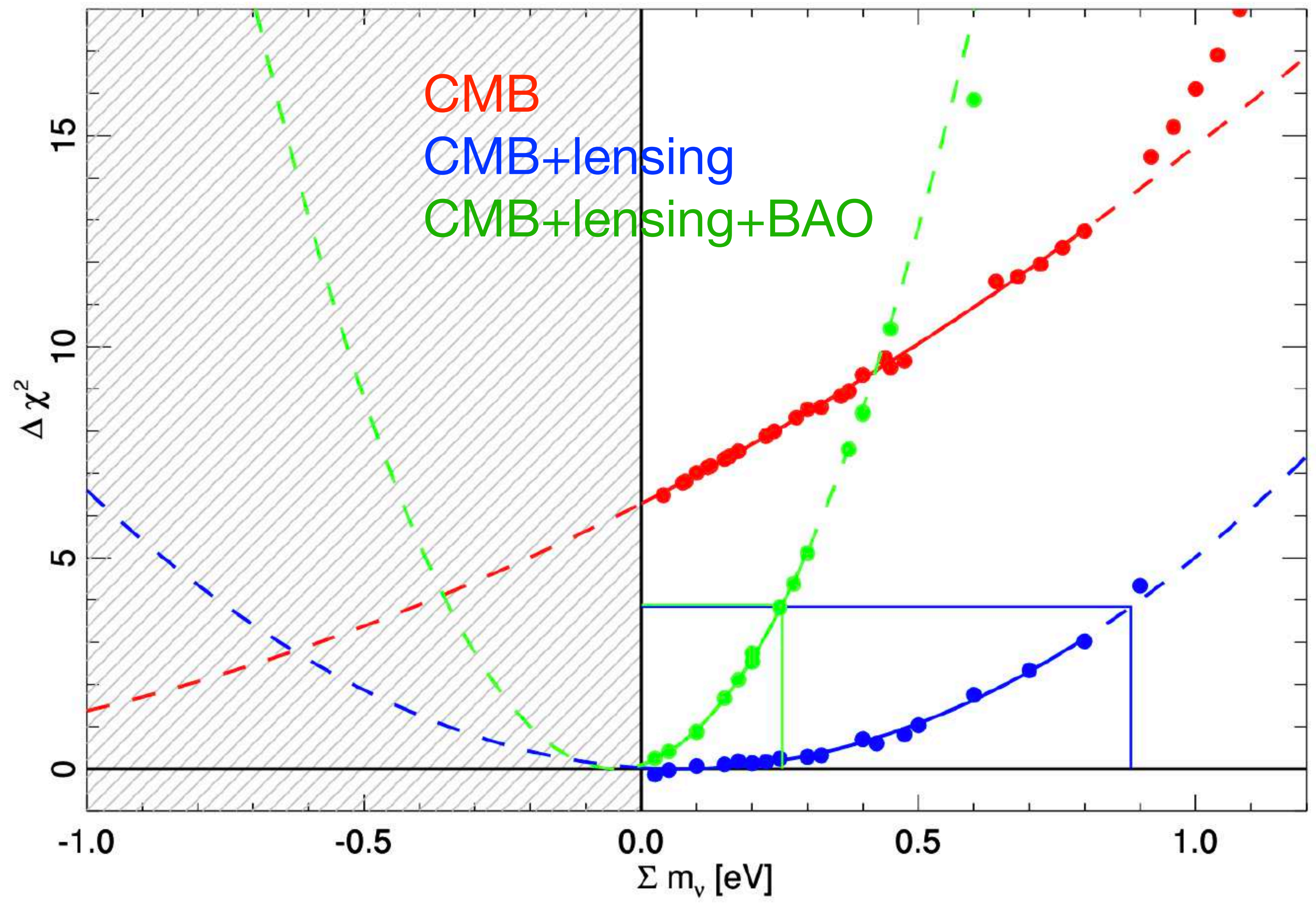
Profile Likelihoods in Cosmology: When, Why and How illustrated with ΛCDM, Massive Neutrinos and Dark Energy,
L. Herold, EF, L. Heinrich

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 → asymptotic limit
- Insensitive to parameter volume; prefer cosmology small parameters volume ("fine tuning")

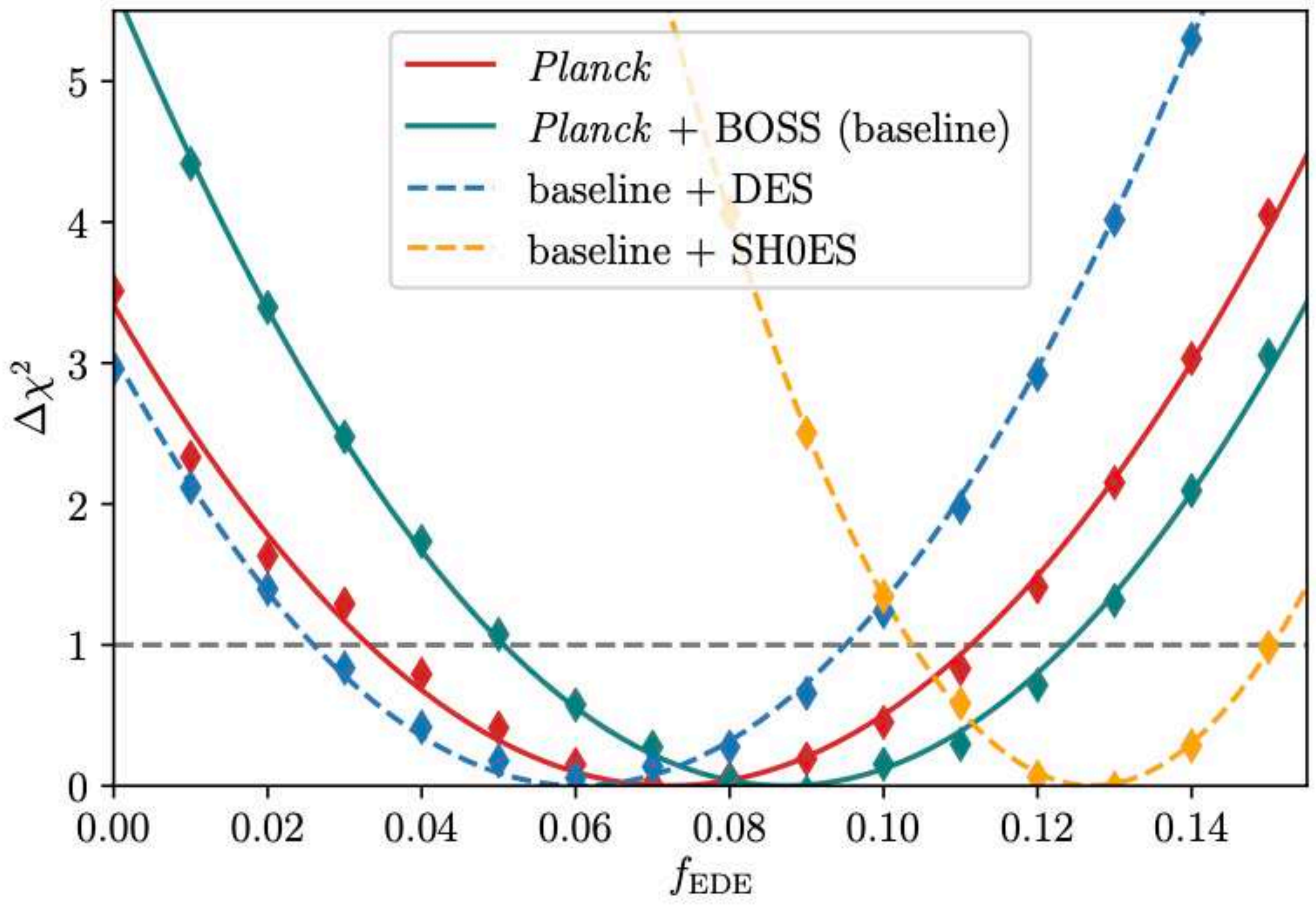


Planck intermediate results XVI, 2014

Going back to our case of EDE and the H0 tension…

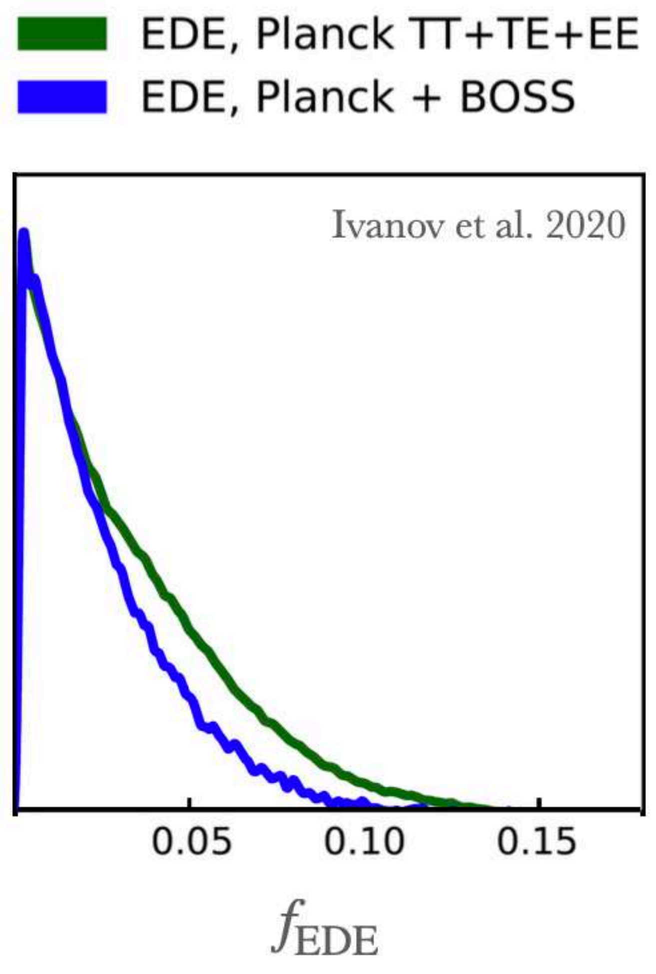
Profile likelihood for $f_{\rm EDE}$

Check for *volume effects:*
comparison to previous results



Bayesian result:

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



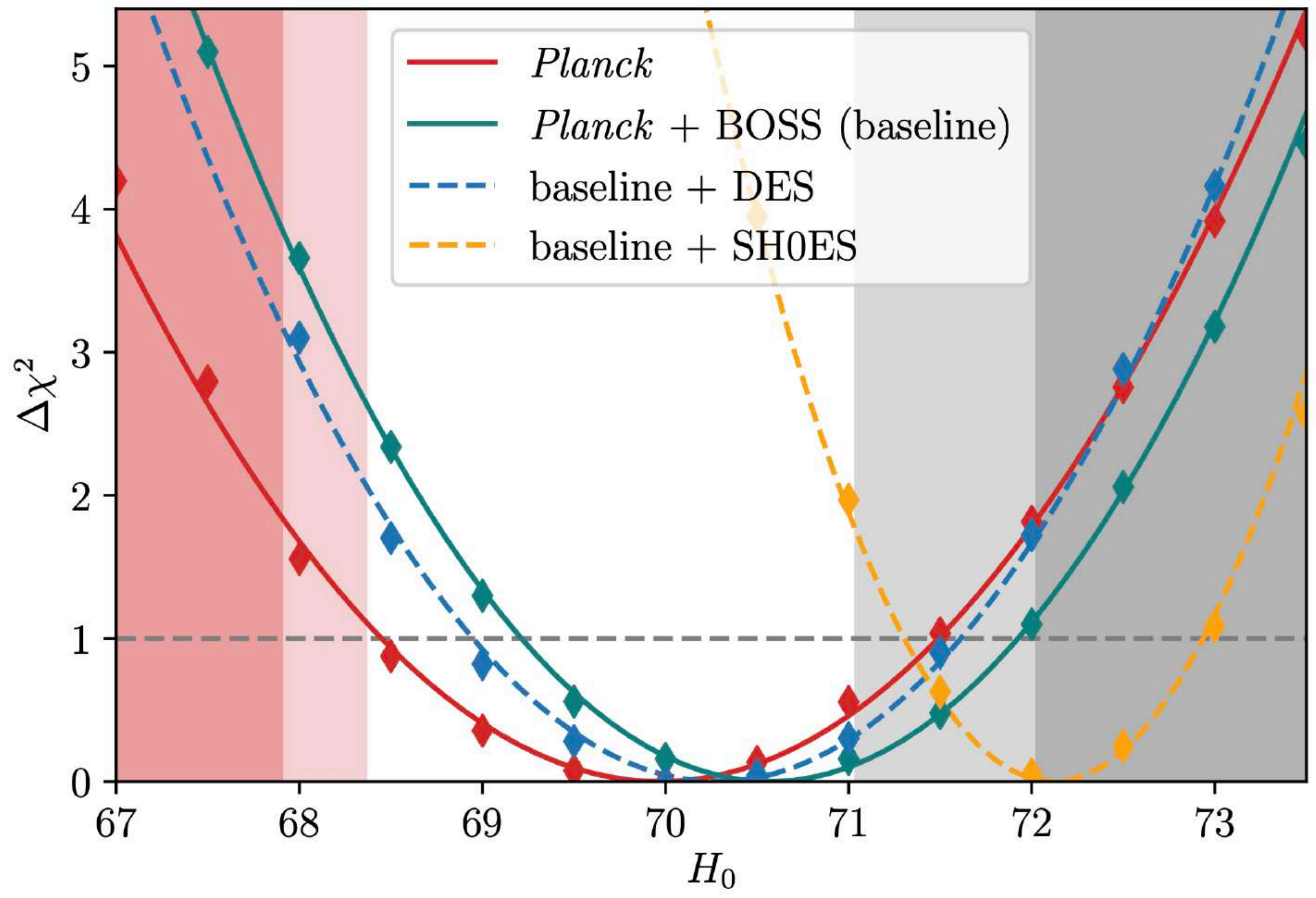
$$f_{\rm EDE}^{\rm (base)} = 0.087 \pm 0.037$$
(68%CL)

Baseline: Planck+BOSS FS

Profile likelihood for H0

Laura Herold, EF 2210.1629
Laura Herold, EF and Eiichiro Komatsu 2112.12140

Baseline: Planck+BOSS FS



$$H_0^{\mathrm{EDE,(base)}} = 70.57 \pm 1.36$$
(68%CL)

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

Consistent with SHOES at $< 1.4\sigma$!

No H0 tension with EDE
(For this dataset)

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

Solve the confusion in the field and proposed new method

Profile likelihood - advantages

Profile likelihood useful tool:

- Very informative for **diagnosis** and knowledge of your likelihood and parameter space
- Provides *complementary* statistical methods to deal with volume effects
- Useful and informative for parameters close to a physical boundary (e.g. Forecasts in LiteBIRD)
- Valuable when priors strongly influence results
- In some cases yields tighter constraints (e.g., neutrinos, r)

Profile likelihood: when, how, why

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

PL cookbook - practical guide

Why compute frequentist confidence intervals?

How to compute the profile likelihood and frequentist confidence intervals?

When does the graphical profile likelihood construction give constraints with correct coverage?

Goal to be the main guide for researcher on PL in cosmology

Profile likelihood: when, how, why

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

PL cookbook - practical guide

Why compute frequentist confidence intervals?

Run the MCMC. If…

- Some of the parameters of the model are not well constrained; OR
- At a physical boundary

Check:

1. Assess the sensitivity of the results on the choice of prior
2. Compute point estimates like the maximum likelihood estimate (MLE) or maximum a posteriori (MAP)

Compute PL if:

1. Dependence of the results on the choice of prior
2. MLE/MAP strongly deviates from the mean

→ Hint that volume effects might be strong!

How to compute the profile likelihood and frequentist confidence intervals?

When does the graphical profile likelihood construction give constraints with correct coverage?

Profile likelihood: when, how, why

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

PL cookbook - practical guide

Why compute frequentist confidence intervals?

How to compute the profile likelihood and frequentist confidence intervals?

Assume that the Gaussian approximation or Wilks' theorem holds, and the graphical profile likelihood method is used *(acknowledging that correct coverage might not be fulfilled)*

1. Compute a profile likelihood using an efficient minimizer (ex. pinc)
2. Construct a confidence interval. For that, it is relevant whether the parameter is near a physical boundary.
   (i) If far away from boundary, one can use the simple graphical profile likelihood method
   (ii) If the parameter is near a physical boundary, one needs to use the boundary-corrected graphical construction

When does the graphical profile likelihood construction give constraints with correct coverage?

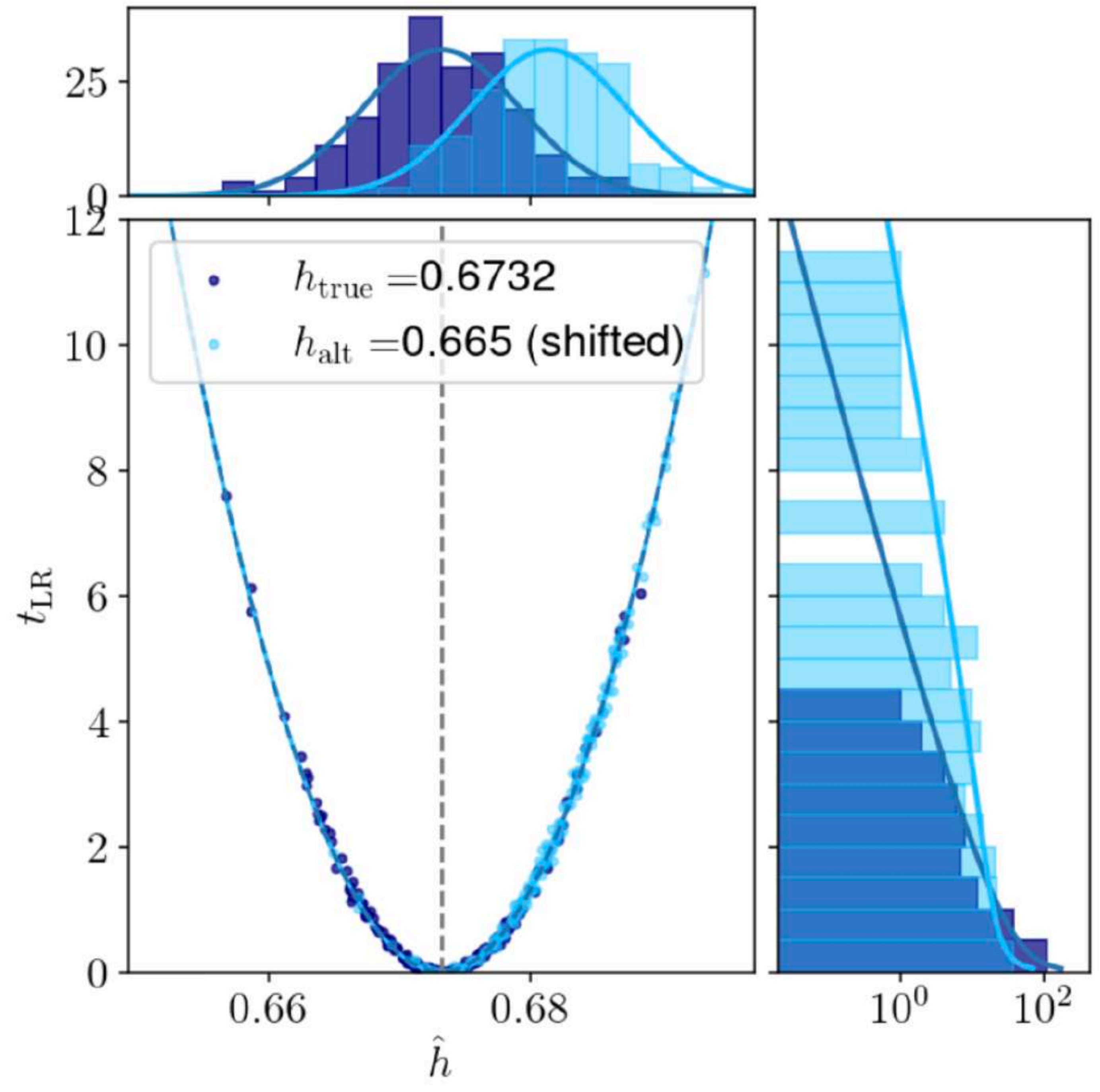
Profile likelihood: when, how, why

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

When does the graphical profile likelihood construction give constraints with correct coverage?

Verify wether the mocks follow the predictions in the asymptotic limit

- ΛCDM: tests indicate that asymptotic assumptions hold → *graphical profile likelihood method*
- ΛCDM + Mν: tests indicate consistency with Gaussian near boundary → *boundary-corrected graphical method (Feldman-Cousins)*
- wCDM: tests indicate violation asymptotic assumptions → *should use full Neyman construction*



Profile likelihood: codes

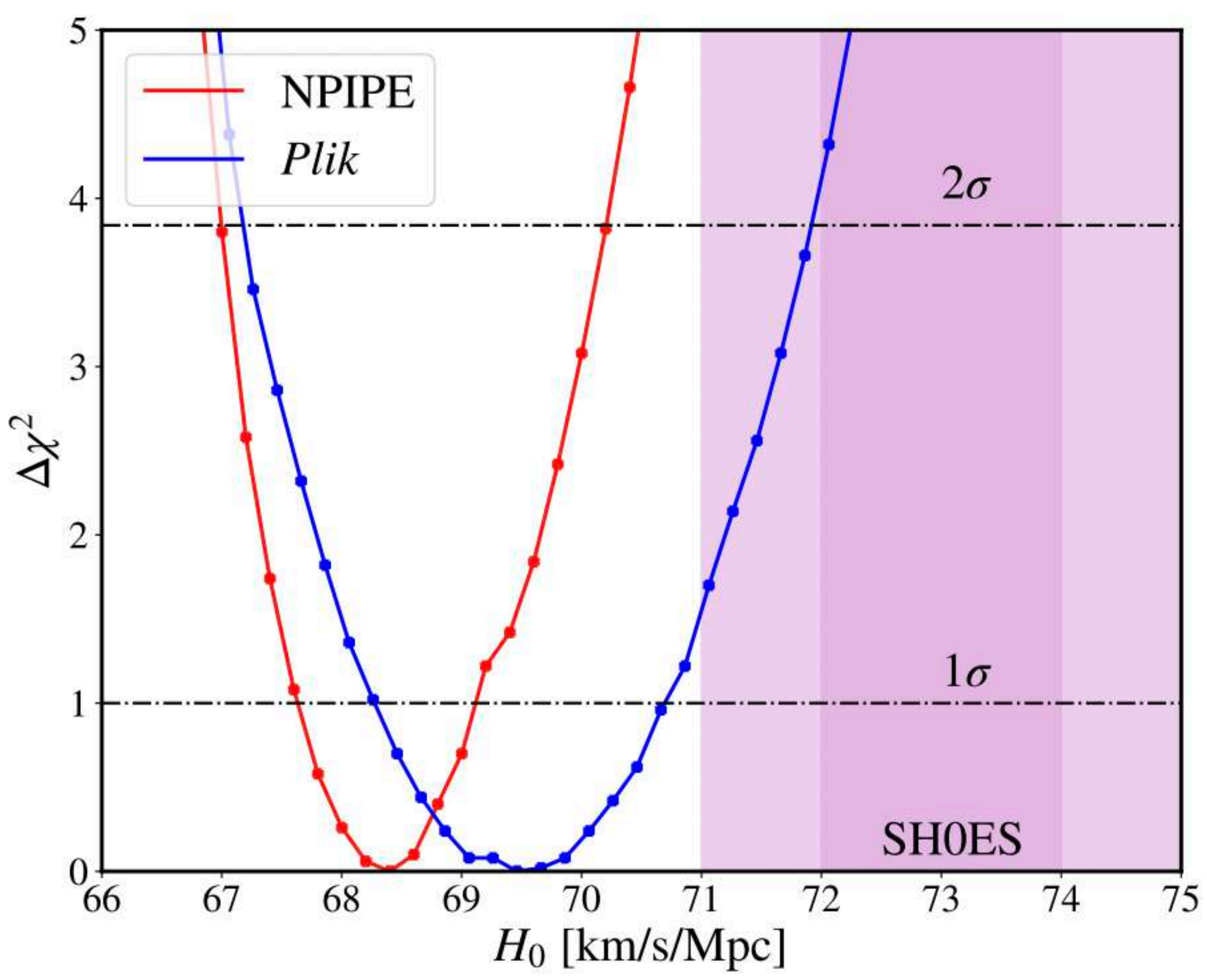
- CAMEL (Henrot-Versillé et al 2016)
- PROSPECT (Holm et al 2023)
- PROCOLI (Karwal et al 2024)
- **pinc (Herold, EF 2024)**
- CONNECT (Nygaard et al 2022)
- …

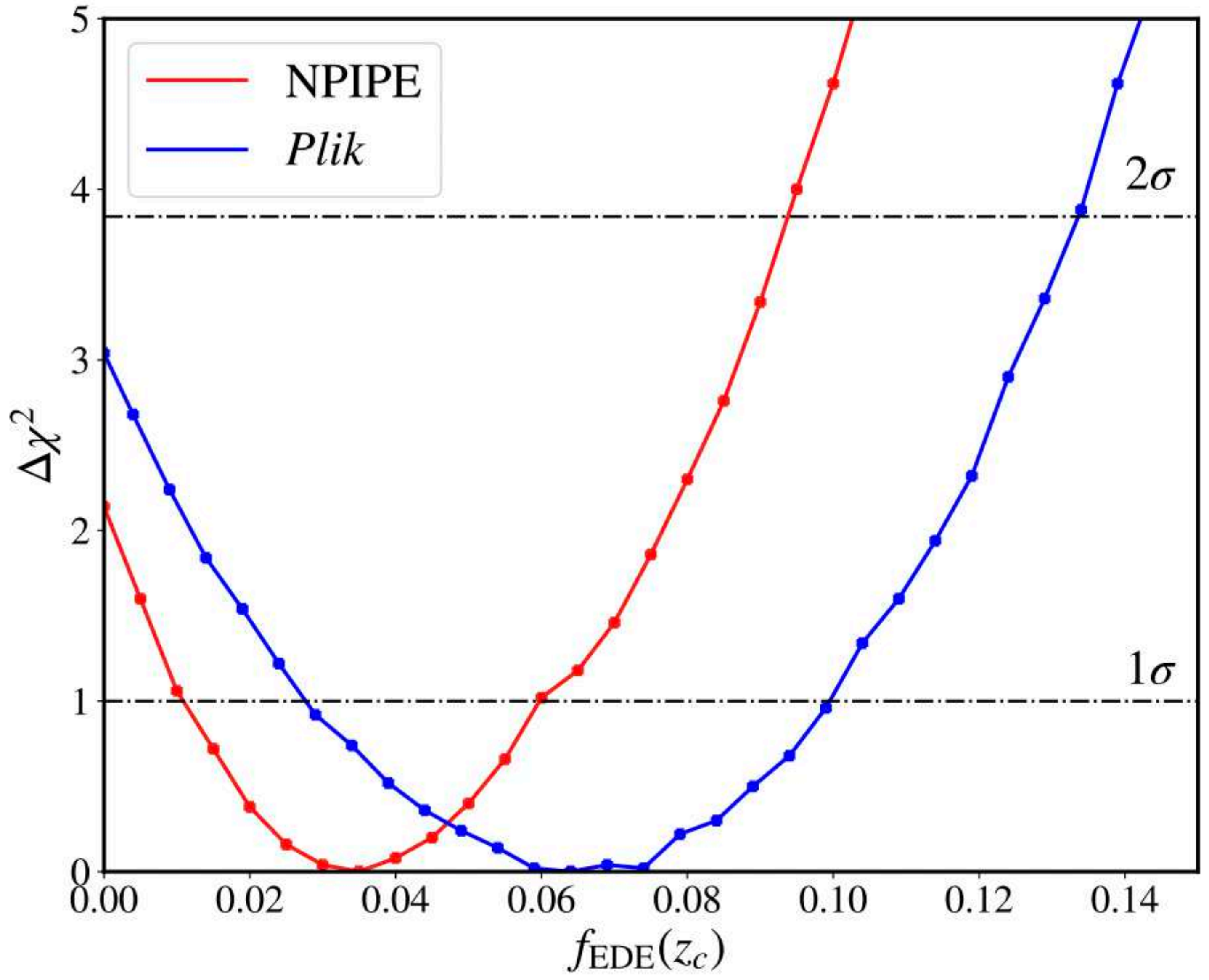
Early dark energy - reanalysis

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

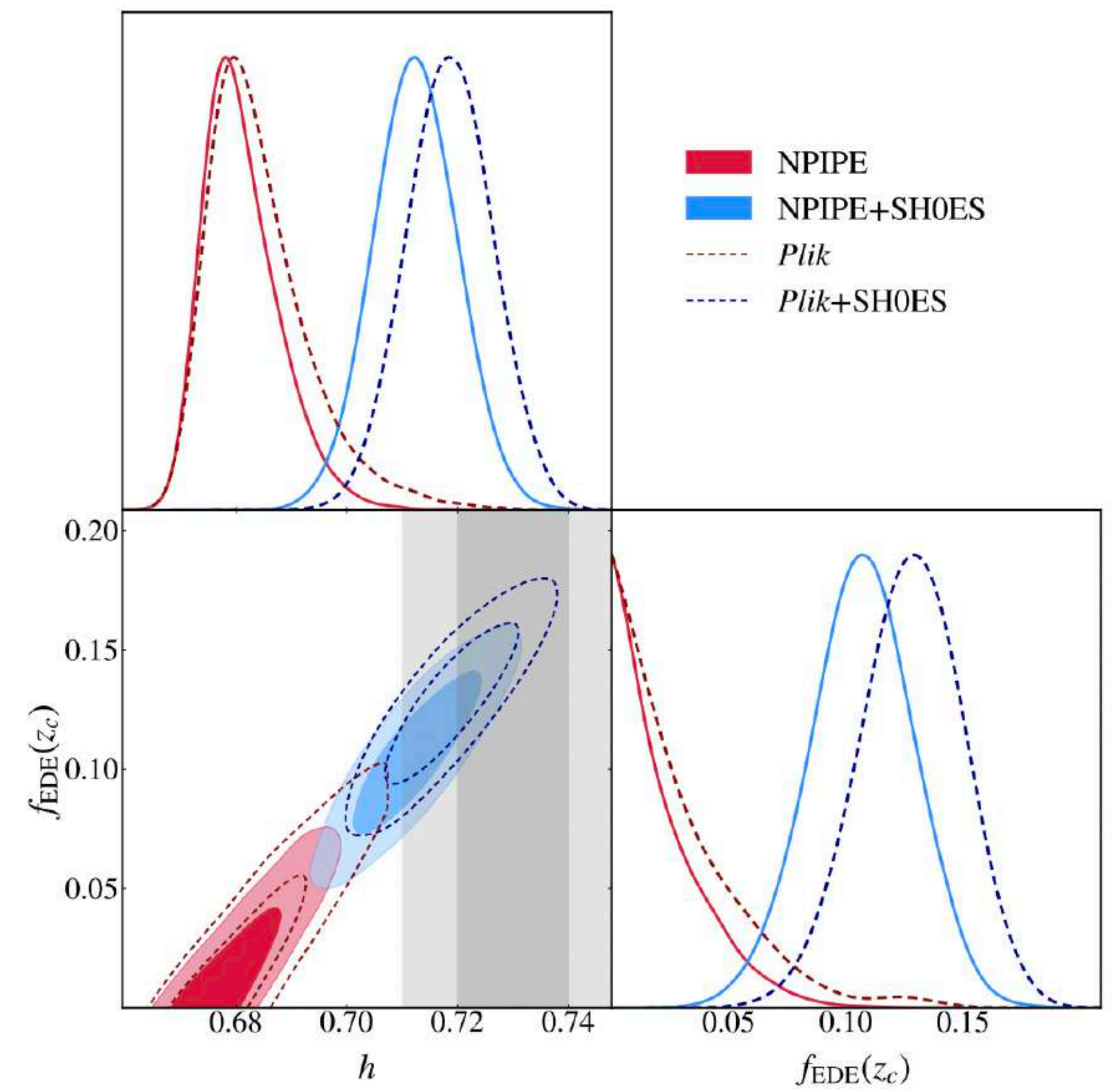
Reanalysis using new *Planck* likelihood (NPIPE)+CamSpec: different analysis choices, more data

Profile likelihood:





MCMC:



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

Distance from SHOES at 3.7σ

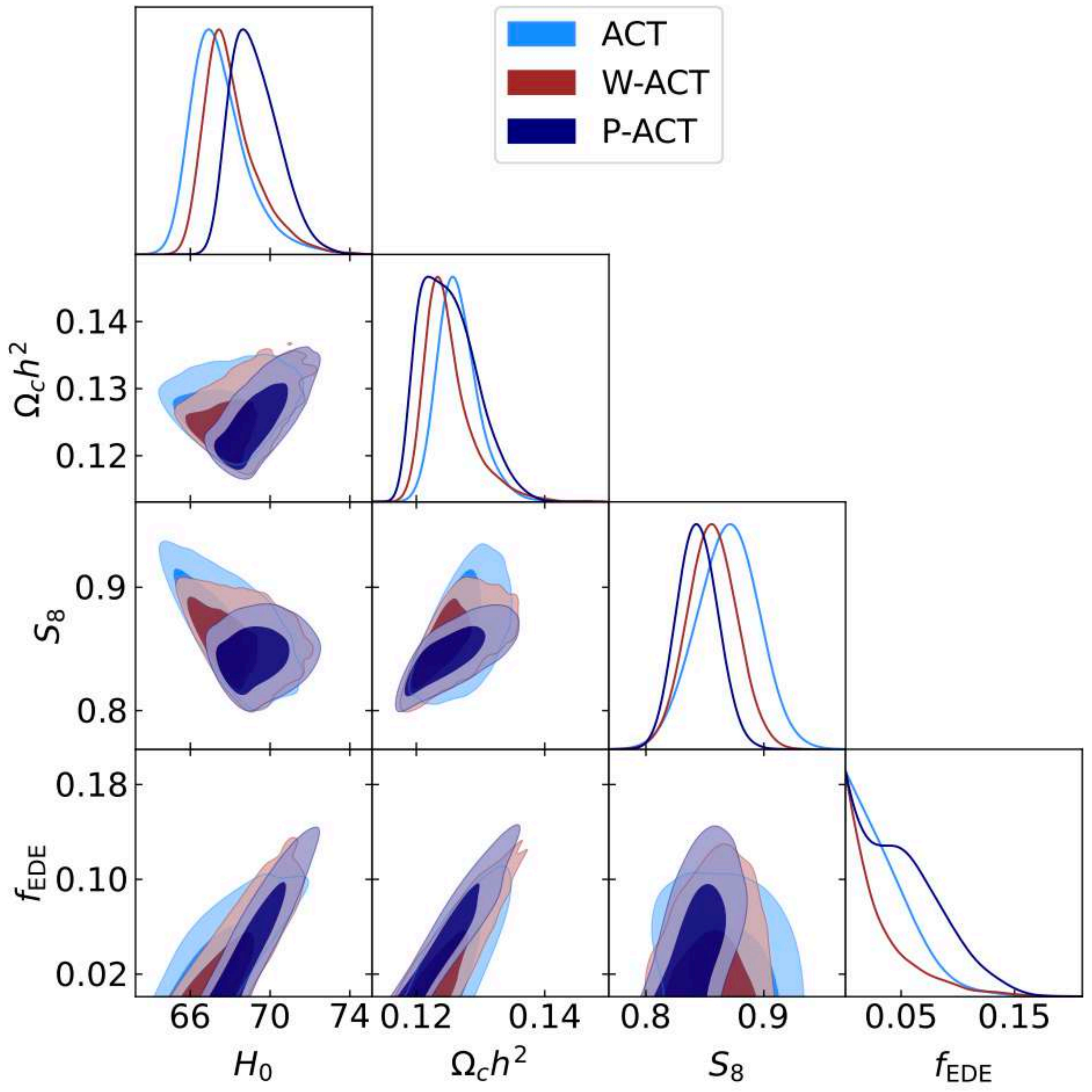
Volume effects present in the old likelihood.

NO volume effects with new likelihood!

ACT DR6

Early dark energy

Calabrese et al 2025



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

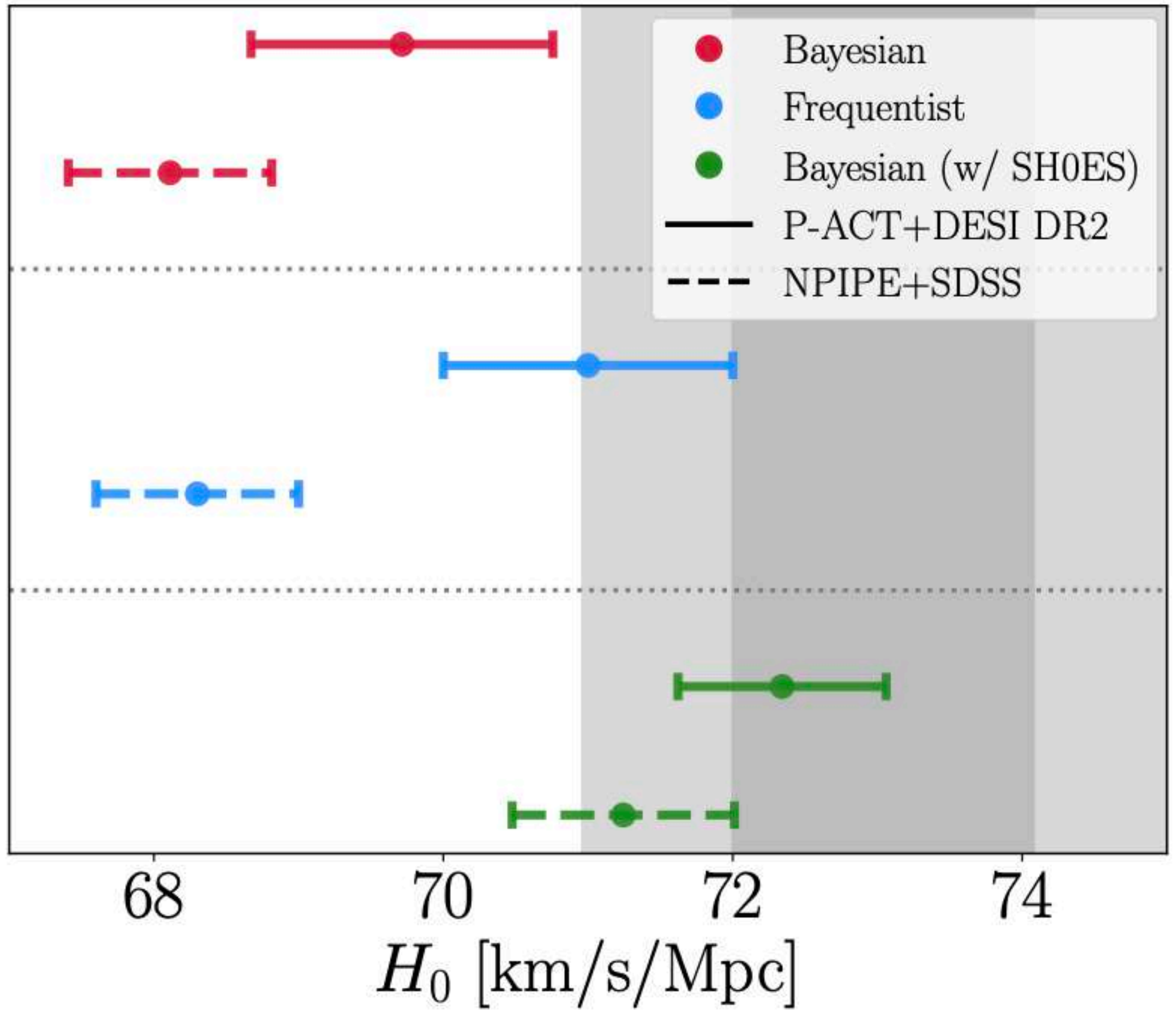
$f_{\rm EDE} < 0.088$ (95%, ACT),
$f_{\rm EDE} < 0.12$ (95%, P-ACT),

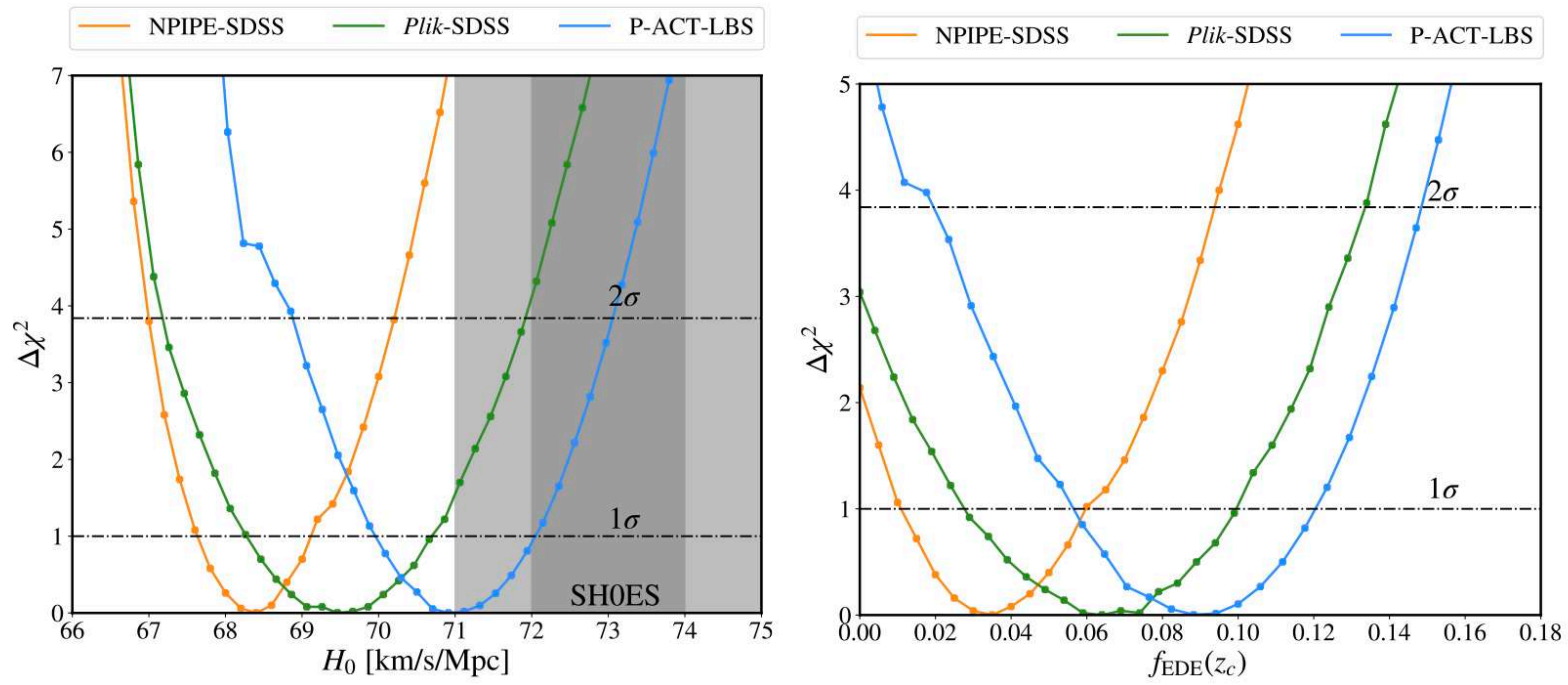
$H_0 = 67.5^{+0.9}_{-1.7}$ (68%, ACT),
$H_0 = 69.3^{+0.9}_{-1.5}$ (68%, P-ACT) ,

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 $f_{\rm EDE} = 0.09 \pm 0.03$ 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 ΛCDM 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.

Application to other cases

Prior effects in EFTofLSS analyses of full-shape BOSS and eBOSS data

E.Holm, L. Herold, T. Simon, **EF**, S. Hannestad, V. Poulin, T. Tram 2023

- Discrepancy between MCMC and PL results for both parametrizations of full-shape: WC and EC - prior volume effects!
- Profile likelihoods from WC and EC coincide - no more discrepancy

Strong prior dependence!

- Use this tool carefully!

Main tool for next generation of surveys

- Show that more constraining power reduces the difference between the Bayesian and frequentist approaches.

Sum of neutrino masses

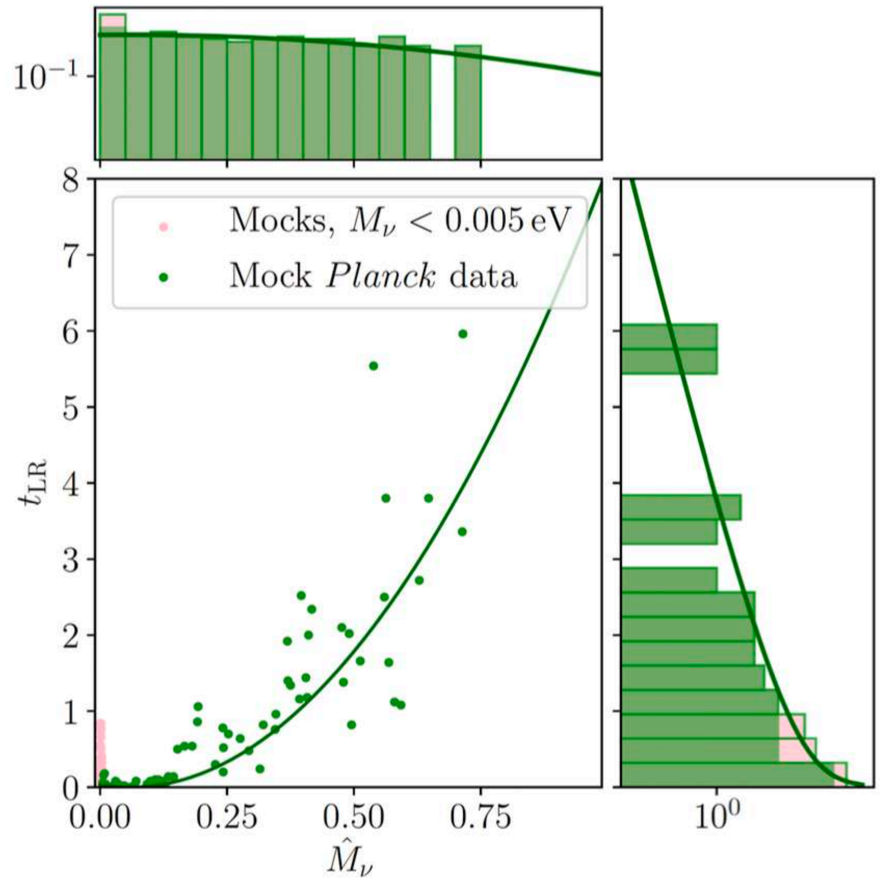
Profile Likelihoods in Cosmology: When, Why and How illustrated with ΛCDM, Massive Neutrinos and Dark Energy, L. Herold, **EF**, L. Heinrich

Sum of neutrino mass is close to a physical boundary $\sum m_\nu = M_\nu > 0$ → strong prior dependence

Perfect target for profile likelihood

The presence of the physical border, Mν ≥ 0, leads to an **accumulation of points** near Mν = 0.

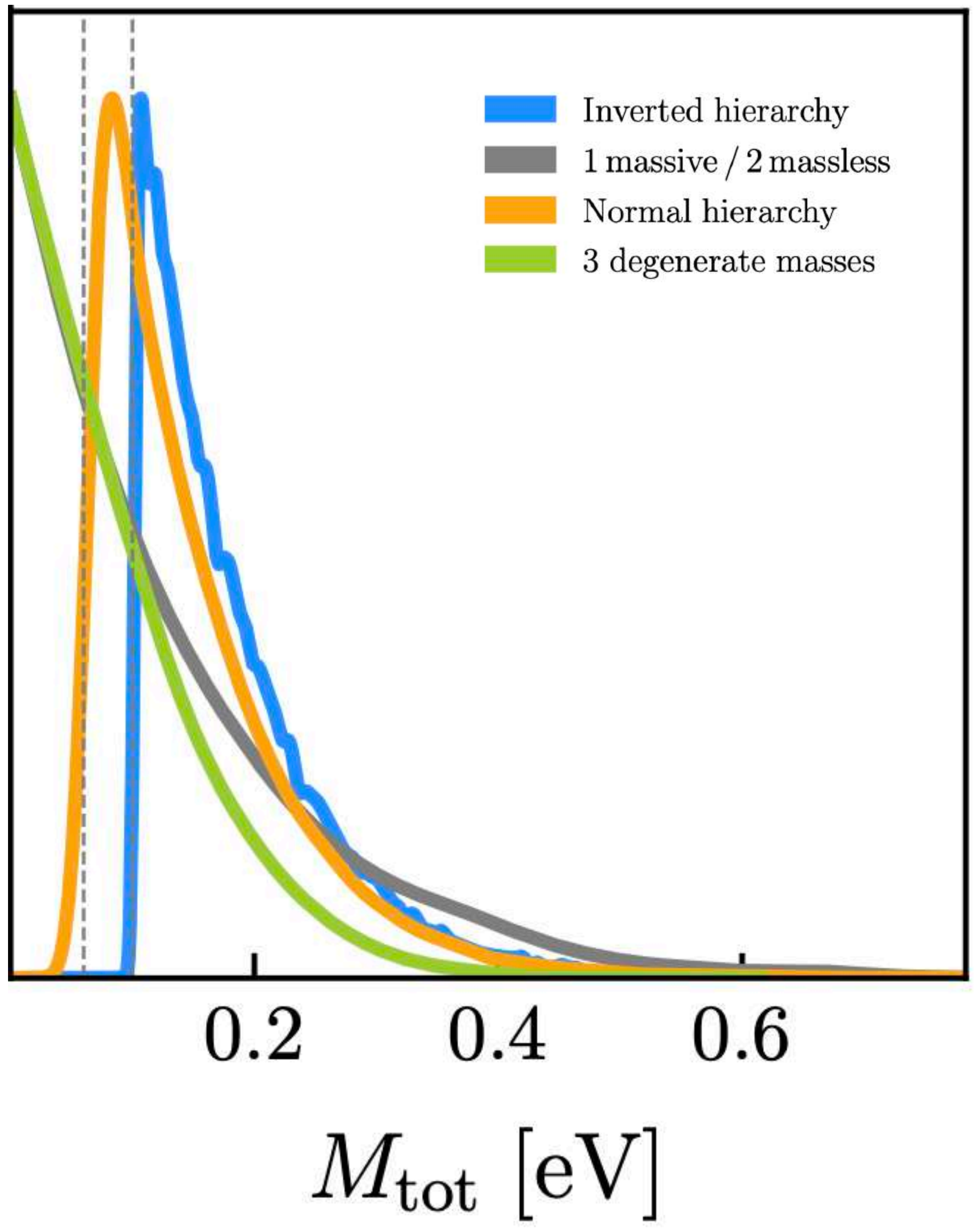
Using PL can help yield correct results in this case!



Neutrino mass

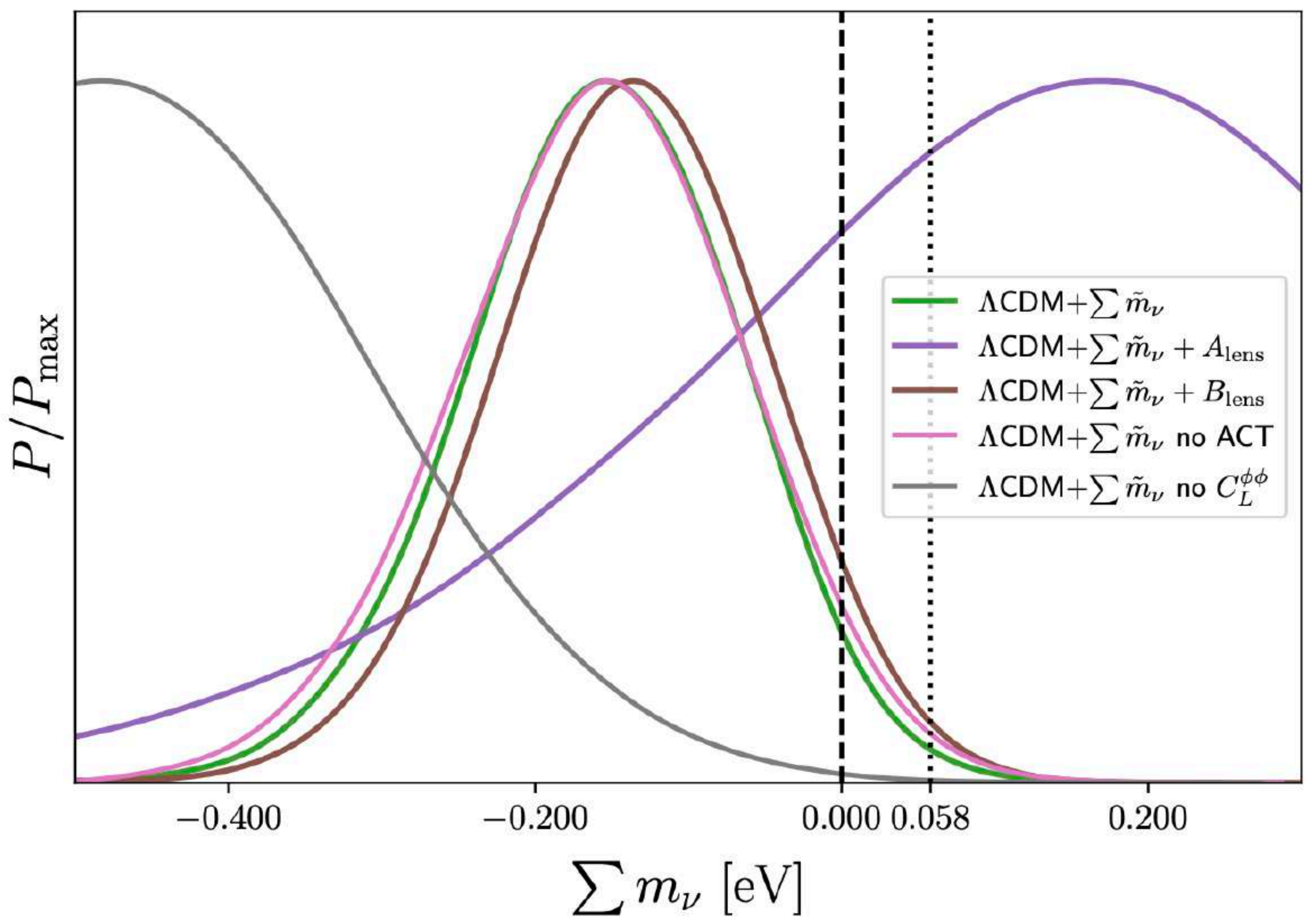
Sum of neutrino mass is close to a physical boundary $\sum m_\nu = M_\nu > 0$ → strong dependence on the prior

Planck 2018



Herold et al 2025

Negative neutrino mass



Green et al 2024

Neutrino mass

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

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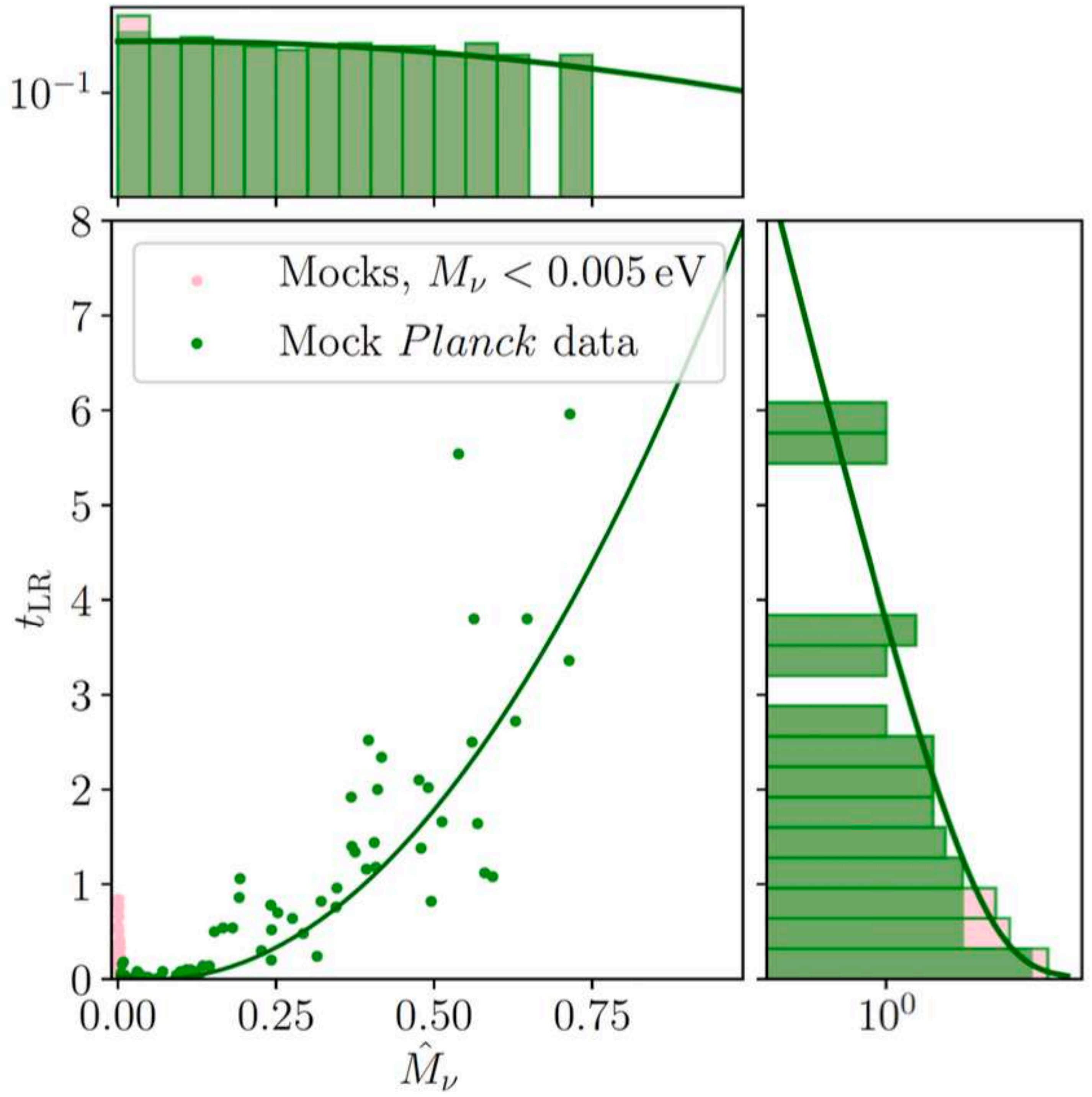


For all checks we did in ΛCDM+M_ν:

- large scatter: more complex model or intrinsic? Distribution of M_ν deviates from Gaussian?
- Deviation from Wilks & Walds

→ Indicates that boundary-corrected graphical method (Feldman-Cousins construction) gives correct coverage ✔ *ok to use PL!*

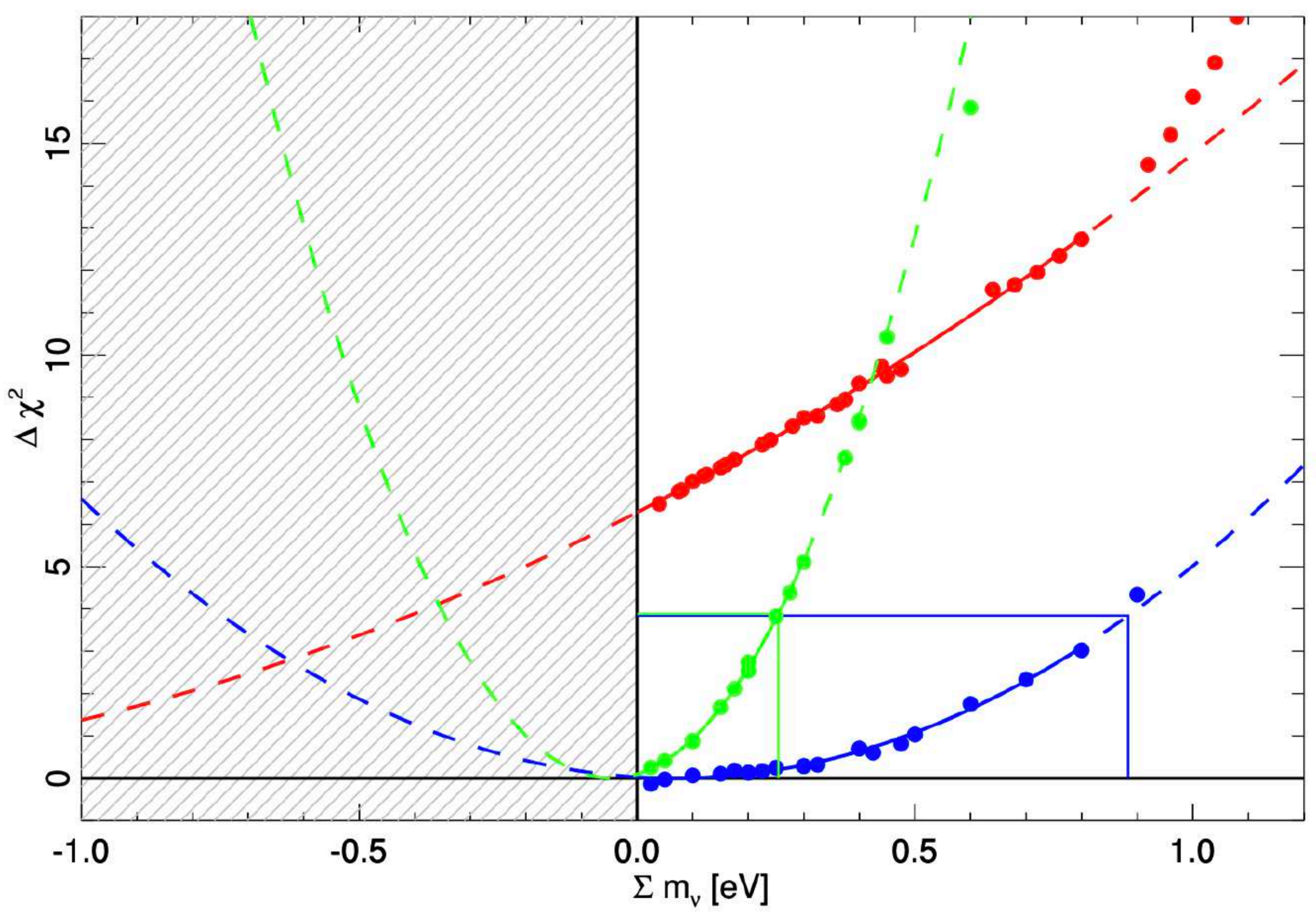
Neutrino mass

Planck intermediate results XVI, 2014
Naredo-Tuero et al 2024
Green et al 2024
Noriega et al 2024
Herold et al 2024
Chebat et al 2025

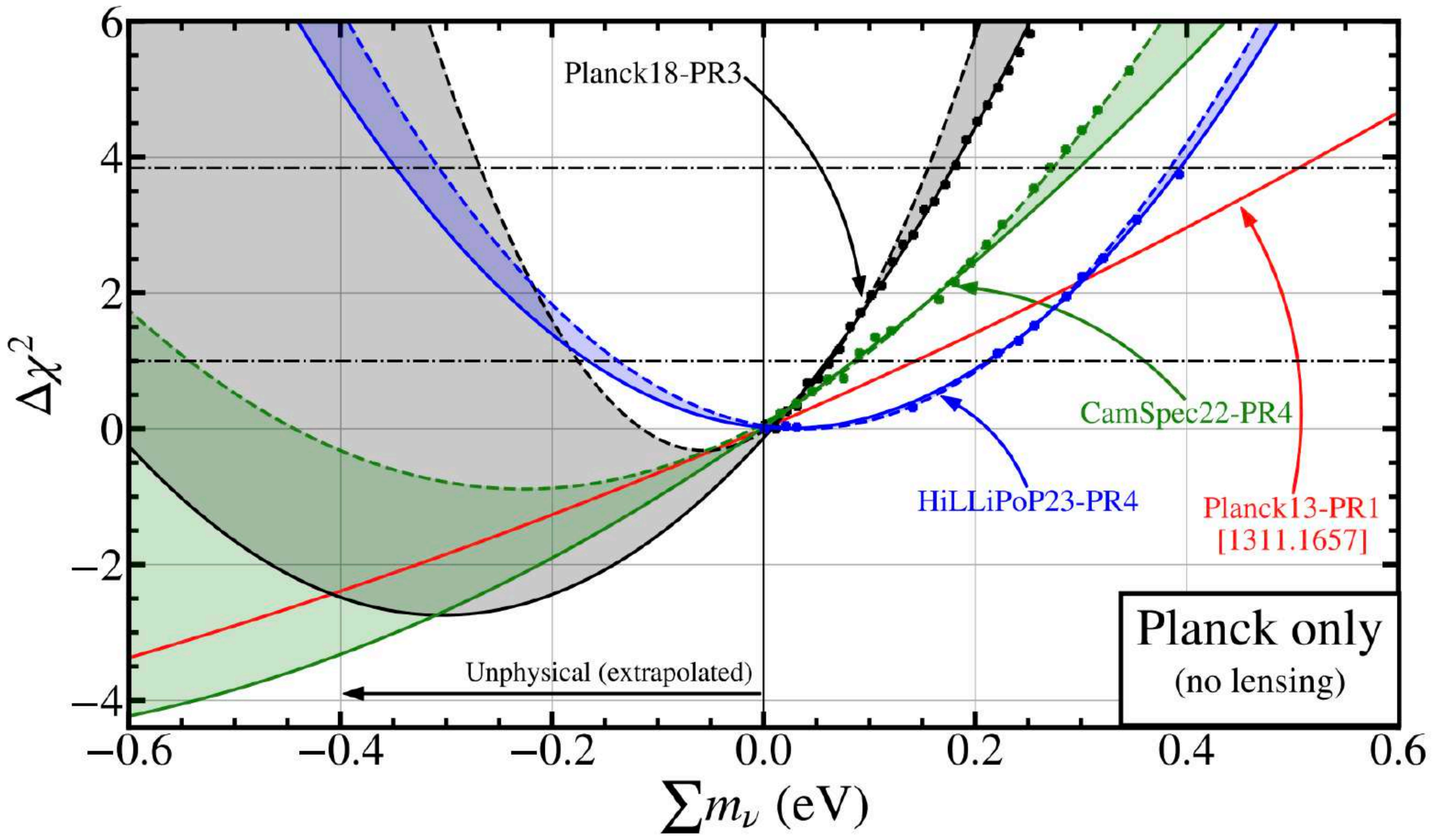
Sum of neutrino mass is close to a physical boundary $\sum m_\nu = M_\nu > 0$ → strong dependence on the prior

Perfect target for profile likelihood

Indeed, the <u>PL has its minimum (or the Likelihood peaks) in negative values</u> for all current data sets:



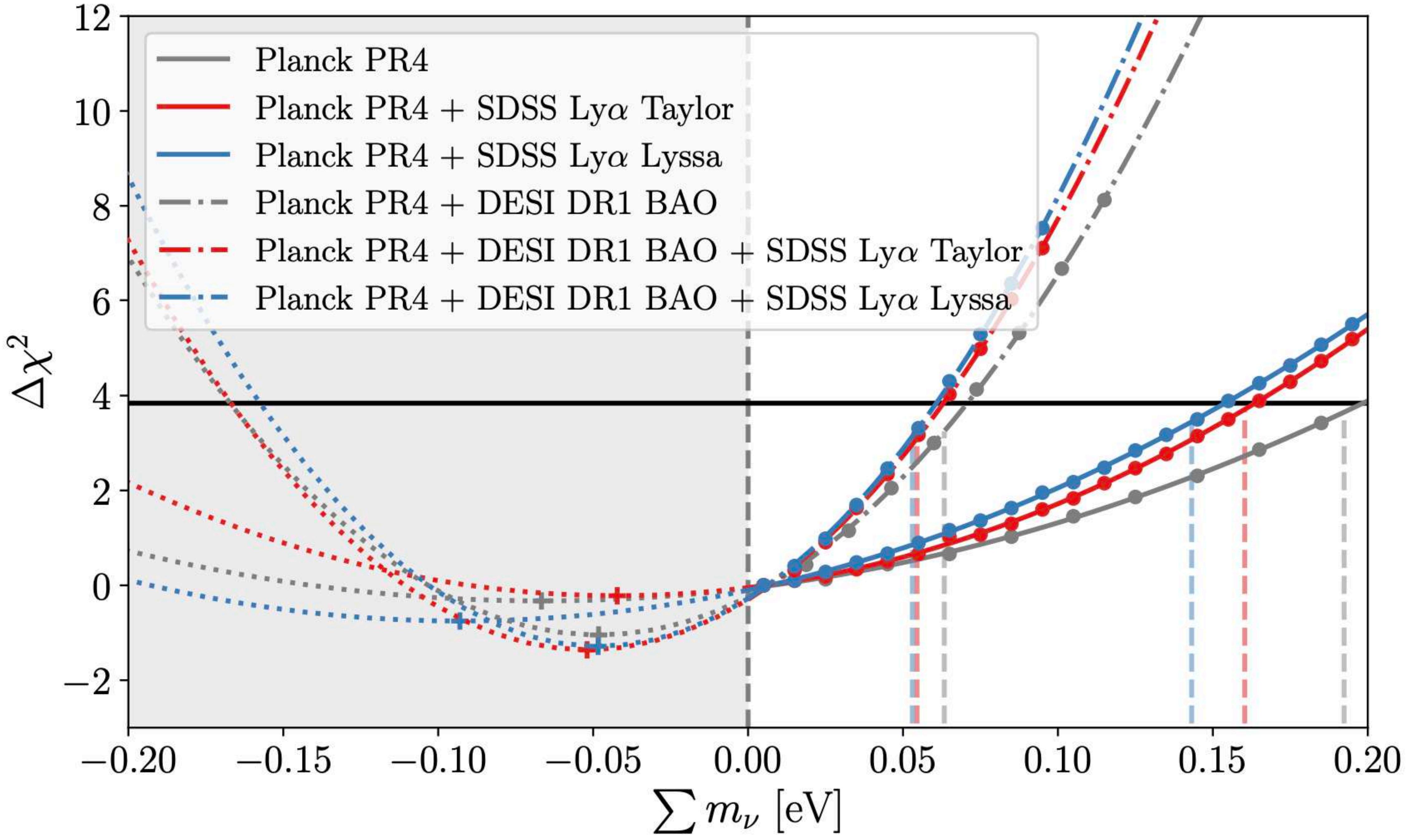
Planck intermediate results XVI, 2014



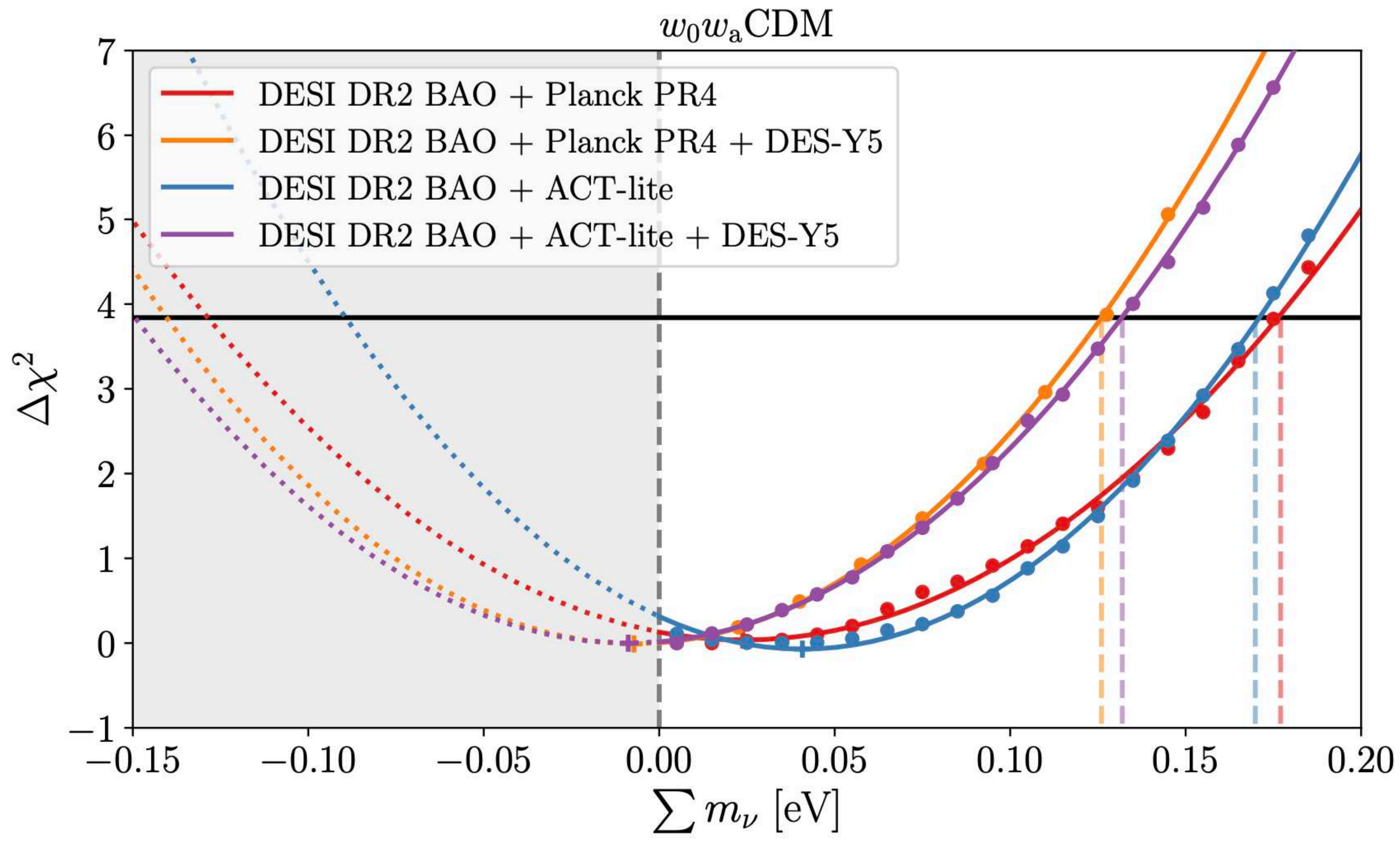
Naredo-Tuero et al 2024

Neutrino mass

Chebat et al 2025 - Cosmological neutrino mass: a frequentist overview in light of DESI



$$\Delta\chi^2\left(\sum m_\nu\right) = \chi^2\left(\sum m_\nu\right) - \chi^2\left(\sum m_\nu = 0.005\,\mathrm{eV}\right)$$



	μ_0	σ	μ_{95}
ΛCDM			
DESI DR1 BAO + Planck PR4 (no lensing)	-0.068	0.067	0.074
DESI DR1 BAO + Planck PR4	-0.048	0.054	0.063
DESI DR2 BAO + Planck PR4	-0.036	0.043	0.053
DESI DR2 BAO + ACT-lite	-0.038	0.048	0.060
DESI DR1 BAO + Planck PR3 `plik`	-0.046	0.055	0.068
DESI DR1 FS+BAO + Planck PR3 `plik`	-0.063	0.053	0.053
Planck PR4	-0.067	0.130	0.192
Planck PR4 + SDSS Lyman-α Taylor	-0.042	0.102	0.160
Planck PR4 + SDSS Lyman-α Lyssa	-0.093	0.115	0.143
Planck PR4 + SDSS Lyman-α Taylor + DESI DR1 BAO	-0.052	0.050	0.055
Planck PR4 + SDSS Lyman-α Lyssa + DESI DR1 BAO	-0.048	0.048	0.053
w_0w_aCDM			
DESI DR2 BAO + Planck PR4	0.024	0.078	0.177
DESI DR2 BAO + Planck PR4 + DES-Y5	-0.007	0.068	0.126
DESI DR2 BAO + ACT-lite	0.041	0.066	0.171
DESI DR2 BAO + ACT-lite + DES-Y5	-0.009	0.077	0.132
Ω_K + ΛCDM			
DESI DR2 BAO + Planck PR4	-0.044	0.064	0.085

Addressing the challenges for data analysis

Prior volume effects, weight volume effects, …

Many different ways to deal with them:

- More/better data
- Physical priors or prior/model reparametrization
- Parameter reparametrization (eg EFT of LSS: $b_n = \{b_1, b_2, b_{s^2}, b_{3\text{nl}}\} \longrightarrow \{b_1\sigma_8, b_2\sigma_8^2, b_{s^2}\sigma_8^2, b_{3\text{nl}}\sigma_8^3\}$)
- Profile likelihood
- Hybrid Bayesian/frequentist methods
- Approximate method to analytically marginalise over a large number of nuisance parameters (Hadzhyiska et al 2023)
- Informed prior to reduce volume effects (Marco Bonici +++, Guachalla et al 2024, Reeves et al 2025)
- Other computational methods
  - Hamiltonian Monte-Carlo approaches
- Combining data

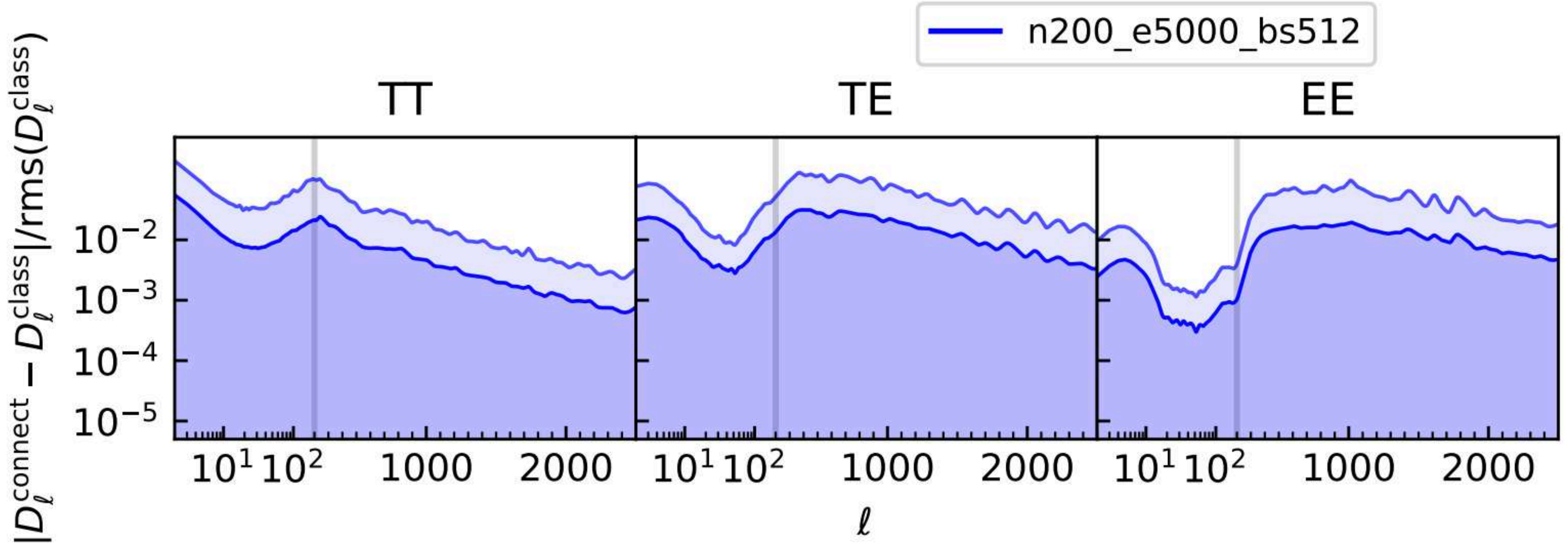
* Work in progress

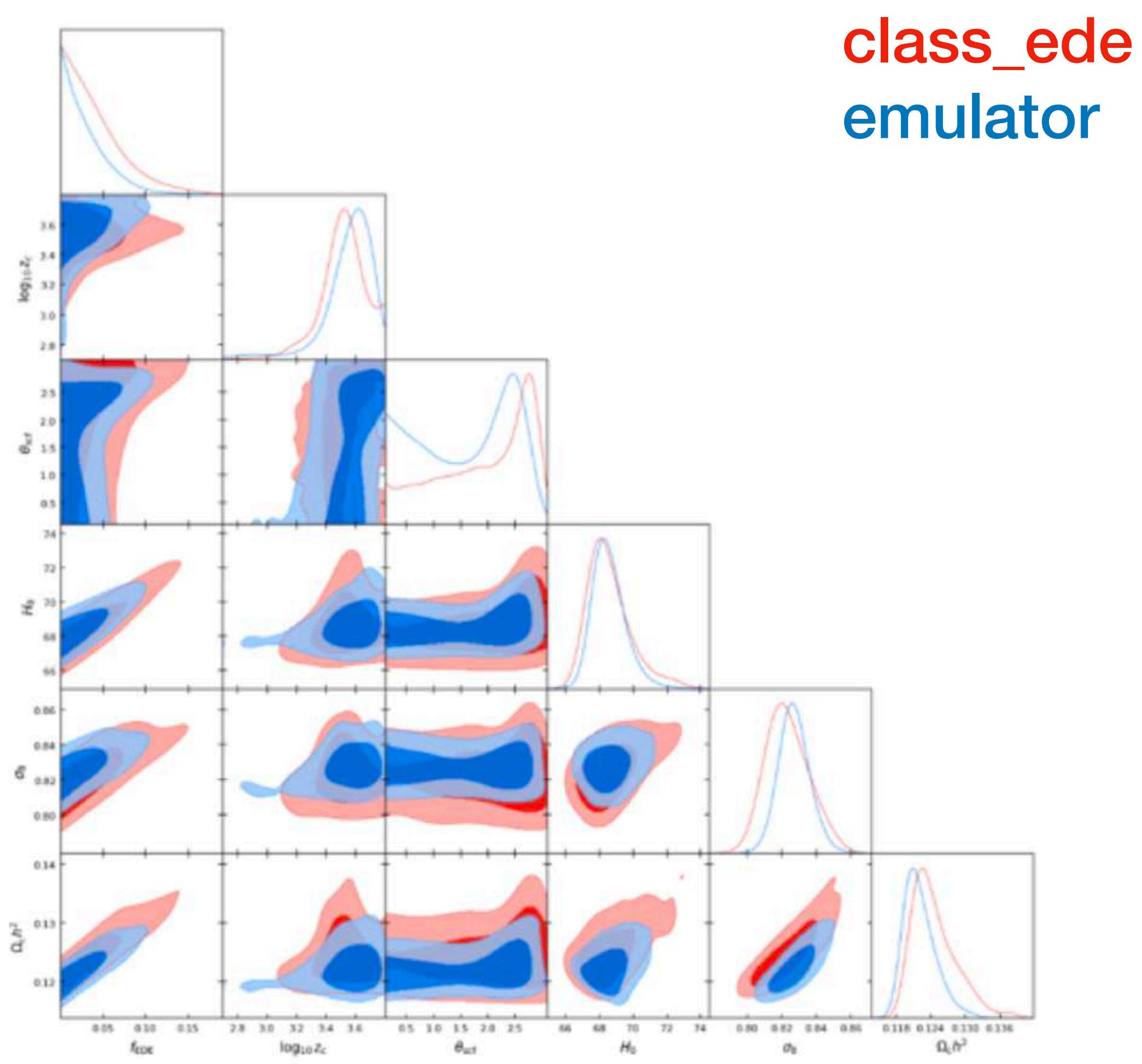
Including inside collaborations, e.g. Euclid, LiteBIRD

But let's pay attention and deal with them!!

Relevant to study the extent to which an analysis is affected by those effects!

Emulator for early dark energy



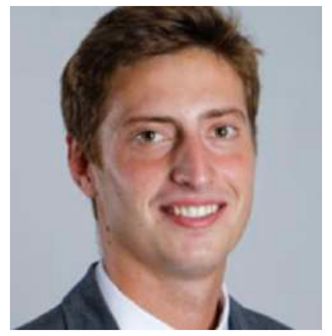


<u>Linear predictions:</u>

Boltzmann codes: axionCAMB, ClassEDE

Slow!! 1 - 3 min per spectrum

Parameter inference → very hard!



(Work in progress) <u>EDE emu</u>

*Theofile Laurent (2025 ILANCE student), **EF**, and Andreas Nygaard, 2604.XXXX*

- Based on emulator CONNECT, it accelerates theoretical prediction.
- Optimizes MCMC and PL computations
- Publicly available (soon)

STATISTICAL THINKING

Statistics: Are you Bayesian or Frequentist?

The fastest way to diagnose your statistical alignment

~~Bayesian vs Frequentist~~ Bayesian & Frequentist & ML & …

Statistical methods are available to us to use. Each statistical method should be used in the appropriate situation.

No right or wrong, no better or worse, no preference.

Not use blindly

Arman Shafieloo: "Many statistical tools not used properly [→ or interpreted] in cosmology"

Systematics dominated era?

Careful to avoid misinterpretations or "fake" new discoveries!

Higher quality data → effects of systematic more important

Particularly serious for Stage IV experiments or cosmological tensions!

Prior/marginalization effects

Inflation in the number of nuisance parameters or beyond LCDM parameters that enter the statistical analysis leading to possible marginalization or prior volume effects in standard MCMC analysis

Complementary statistical methods necessary for current and future parameter inference analysis - profile likelihood

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…


Thank you!