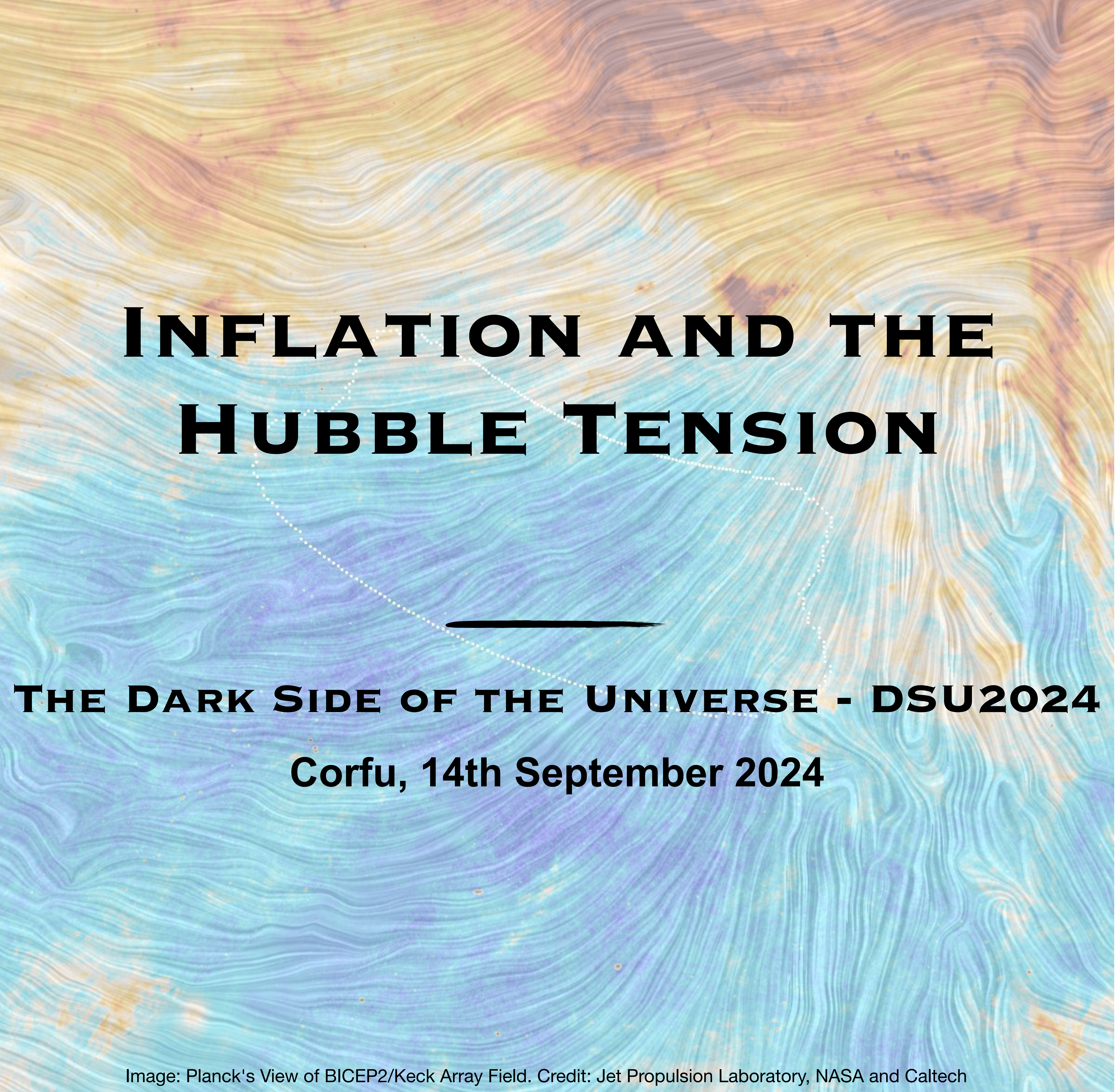

Inflation and the Hubble Tension

The Dark Side of the Universe - DSU2024

Corfu, 14th September 2024

Image: Planck's View of BICEP2/Keck Array Field. Credit: Jet Propulsion Laboratory, NASA and Caltech

William Giarè

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Research Associate in Theoretical Cosmology

The University of Sheffield
School of Mathematics & Statistics

Based on:

WG, PRD 109 (2024) 12, 12354 • arXiv: 2404.12779

Acknowledgment:

Travel expenses were partially covered by the Travel Award sponsored by the open-access journal Universe published by MDPI

Single Field Slow-Roll Inflation

We obtain inflation from a single scalar field minimally coupled to gravity

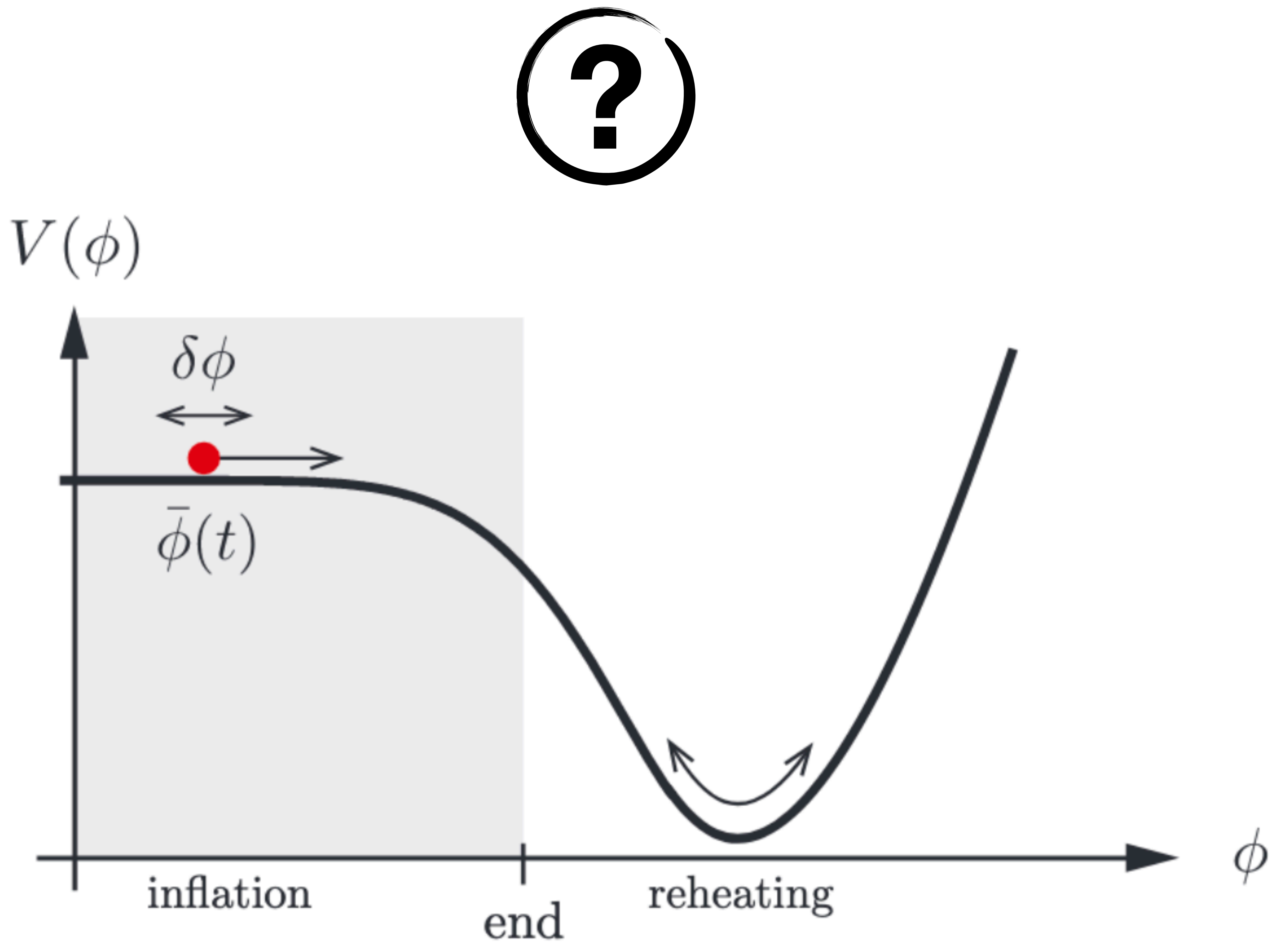
$$S = \int d^4x\sqrt{-g}\left[\frac{M_p^2}{2}R - \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right]$$

Slow-Roll Conditions

$$V(\phi) \gg \dot{\phi} \qquad \frac{V_\phi^2}{V} \ll H^2 \qquad |V_{\phi\phi}| \ll H^2$$

Slow-Roll Parameters

$$\epsilon \doteq \frac{M_{\rm pl}^2}{2}\left(\frac{V_\phi^2}{V^2}\right) \ll 1 \quad |\eta| \doteq \left|M_{\rm pl}^2\left(\frac{V_{\phi\phi}}{V}\right)\right| \ll 1$$



PRIMORDIAL PERTURBATIONS

Planck 2018

1807.06209

Primordial Scalar Modes

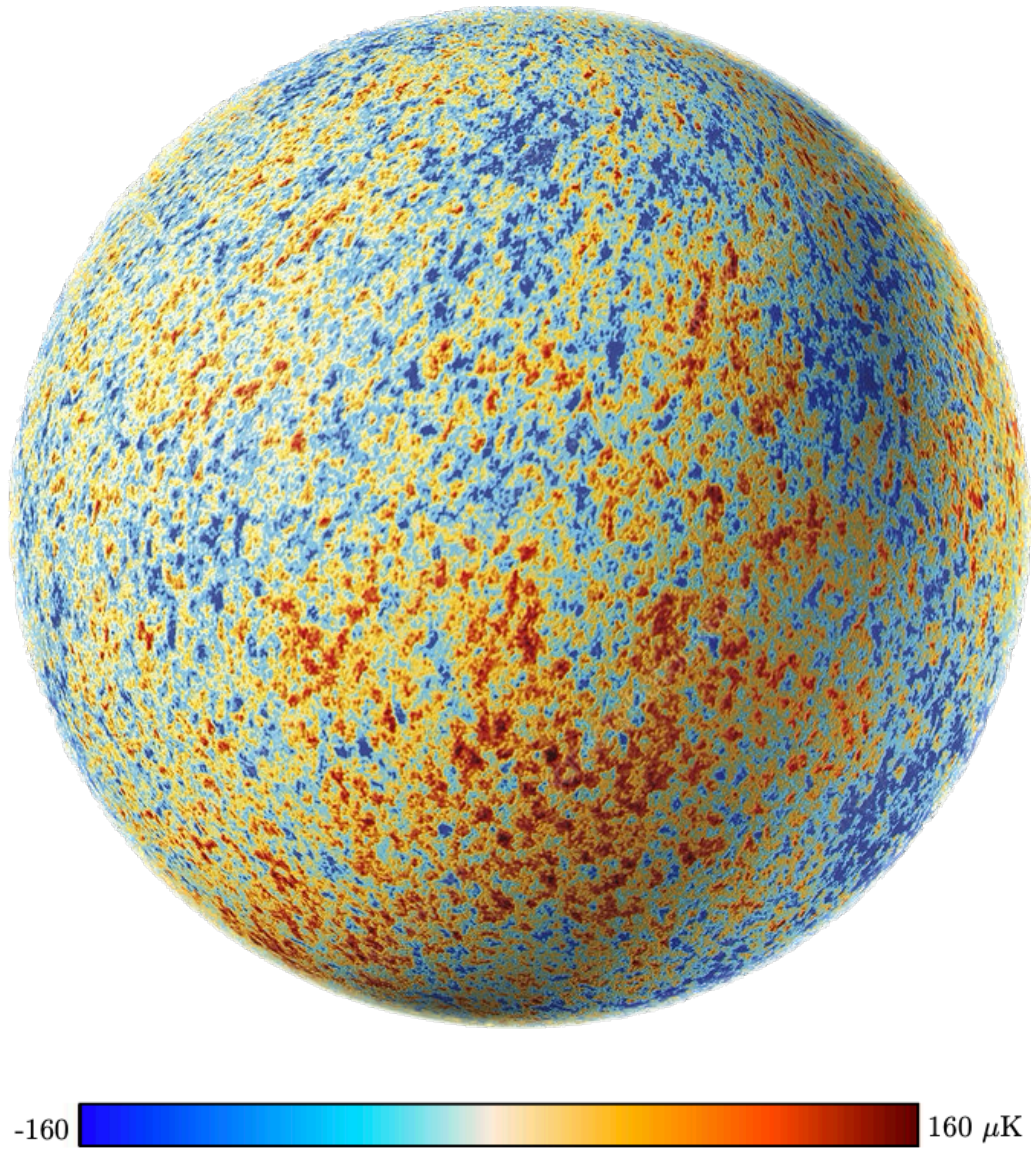
Quantum **fluctuations of the Inflaton field** can source irregularities in the **CMB**

$$\mathcal{P}_s(k) = A_s \left(\frac{k}{k_*}\right)^{n_s - 1} \qquad n_s - 1 = \left.\frac{d \ln \mathcal{P}_s}{d \ln k}\right|_{k=k_*} = 2\eta - 6\epsilon$$

Primordial Tensor Modes

Quantum **fluctuations in the metric** could source a stochastic background of **Primordial Gravitational Waves,** imprinting the **CMB**

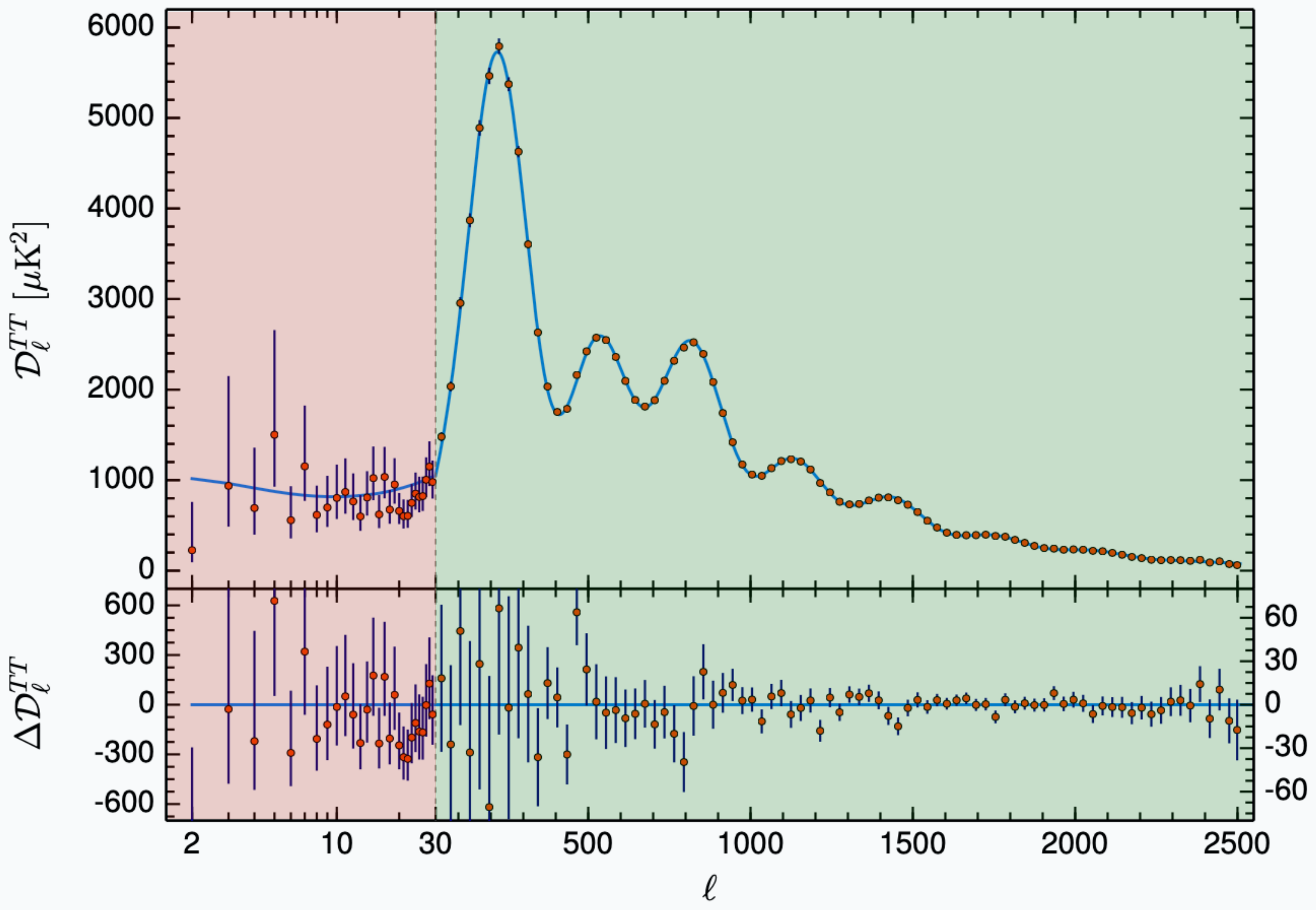
$$\mathcal{P}_T(k) = r A_s \left(\frac{k}{k_*}\right)^{n_T} \qquad n_T = \left.\frac{d \ln \mathcal{P}_T}{d \ln k}\right|_{k=k_*} = -\frac{r}{8} = -2\epsilon$$



Planck 2018

1807.06209

TT Spectrum

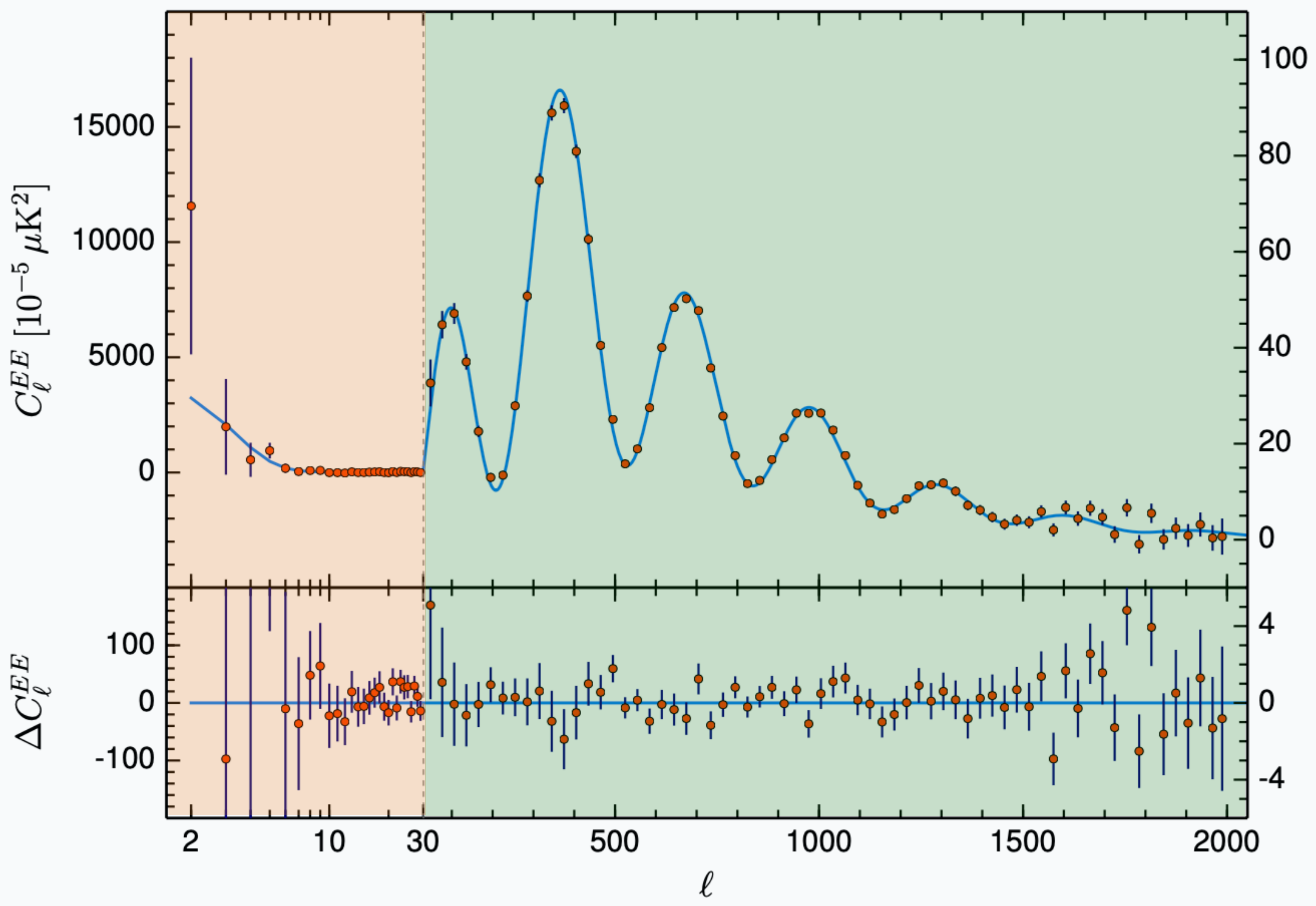


Low-multipole temperature data

$2 \le \ell \le 30$ in the TT Spectrum

Low-T

EE Spectrum

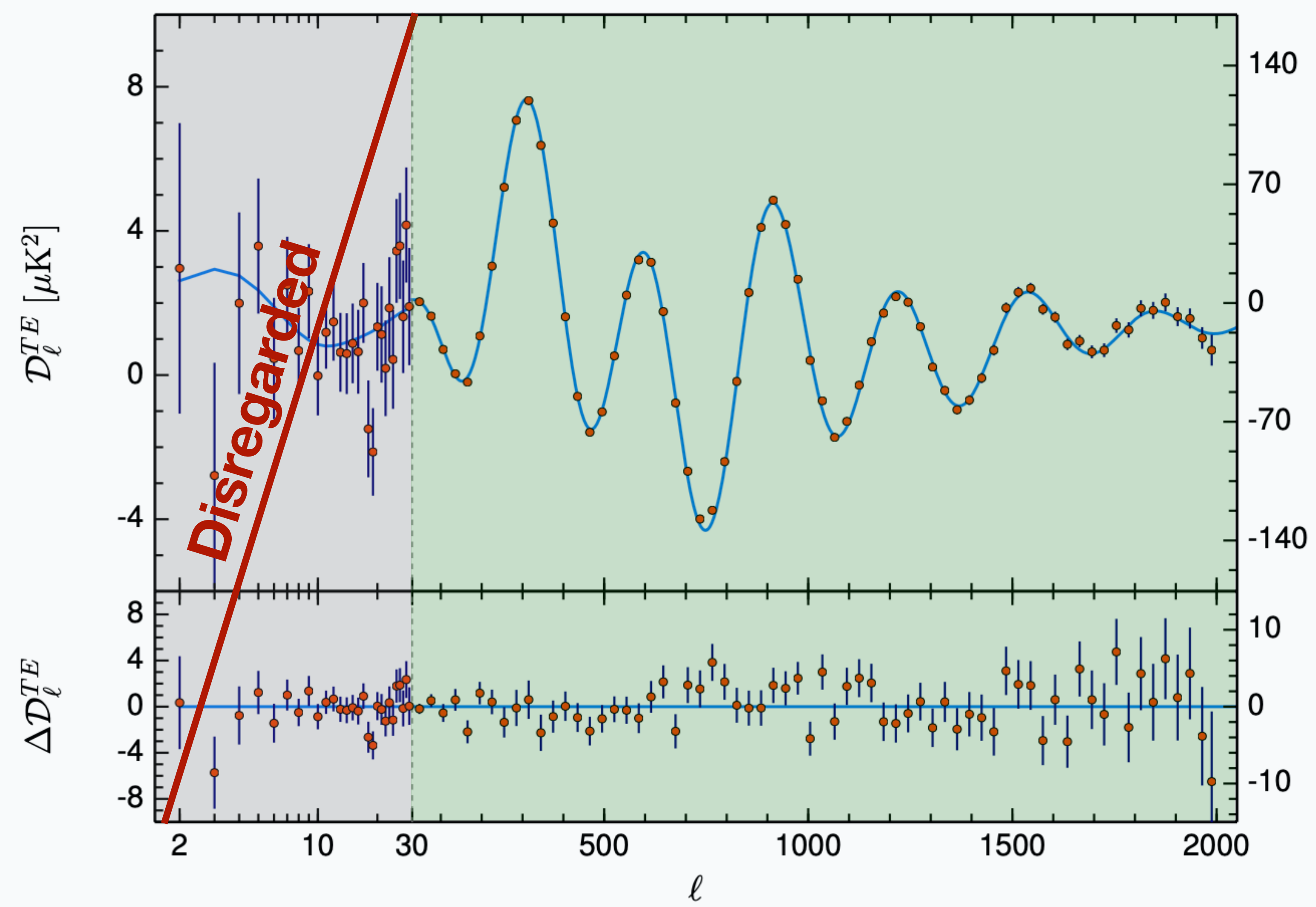


Low-multipole Polarization data

$2 \le \ell \le 30$ in the EE Spectrum

Low-E

TE Cross-Spectrum



Disregarded

Low-multipole TE data

$2 \le \ell \le 30$ in the TE Spectrum

The low-TE data show excess of variance compared to simulations at low multipoles, for reasons that are not understood

High-multipole temperature data

$30 < \ell \lesssim 2500$ in the TT Spectrum

High-multipole EE Polarization data

$30 < \ell \lesssim 2000$ in the EE Spectrum

High-multipole TE data

$30 < \ell \lesssim 2000$ in the TE Spectrum

BICEP/KEK 2018

2110.00483

Note: $\ell \propto 1/\theta \propto 1/R$

Scalar and Tensor modes contribution to CMB spectra:

TT spectrum: Scalar > Tensor at any ℓ

TE spectrum: Scalar > Tensor at any ℓ

EE spectrum: Scalar > Tensor at any ℓ

BB spectrum: Tensor > Scalar at $\ell \lesssim 100$ (i.e., at large scales)

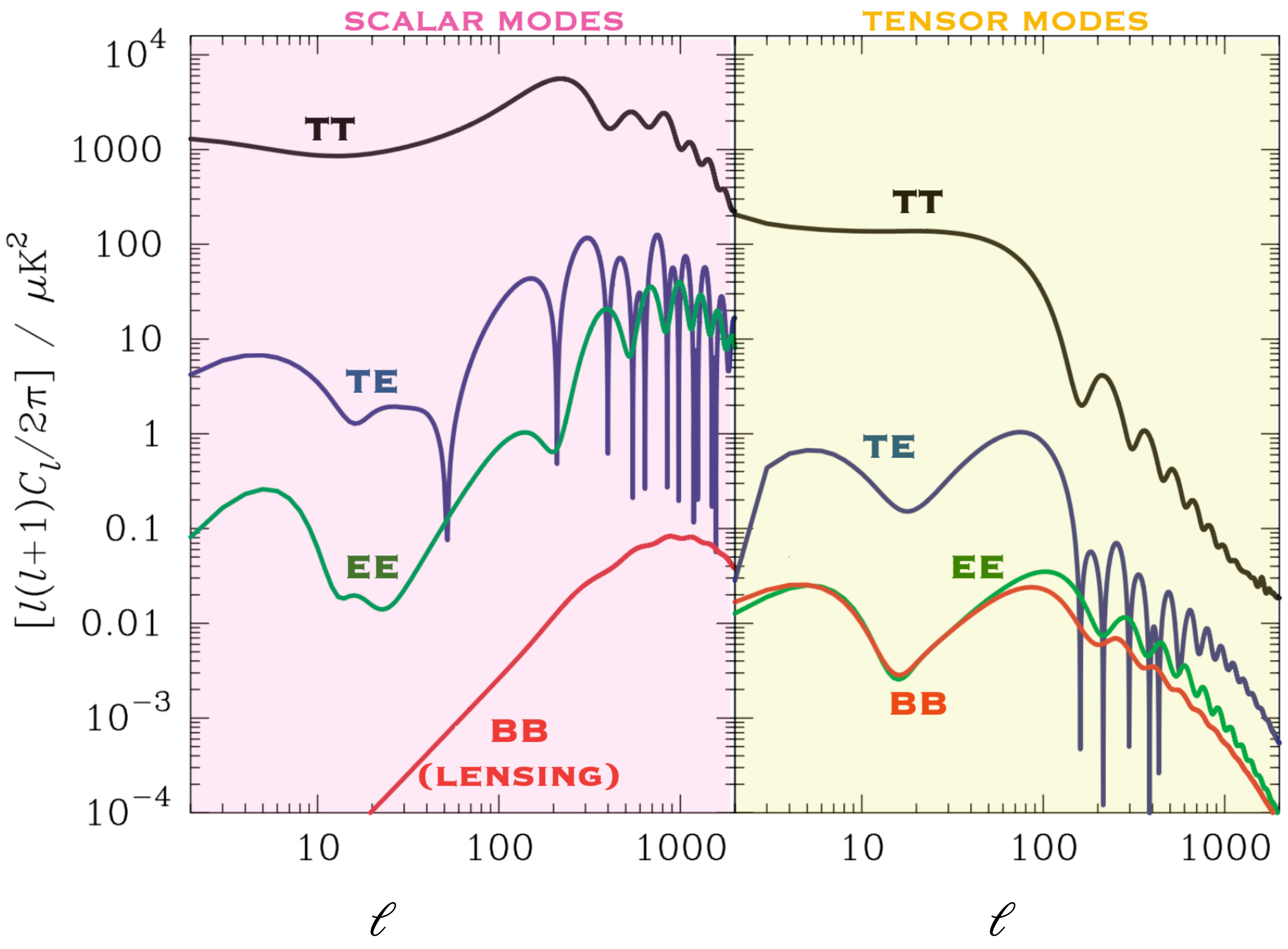


Figure inspired by Gorbunov & Rubakov
"Cosmological Perturbations and Inflationary Theory", Chapter 10
See also A. Challinor arXiv:astro-ph/0606548

B-Modes Polarization

To constrain primordial tensor modes we need large-scale B-mode polarization

Many experiments have been (and will be) collecting data

BICEP/KEK-2018 most precise data so far

BICEP/KEK 2018

2110.00483

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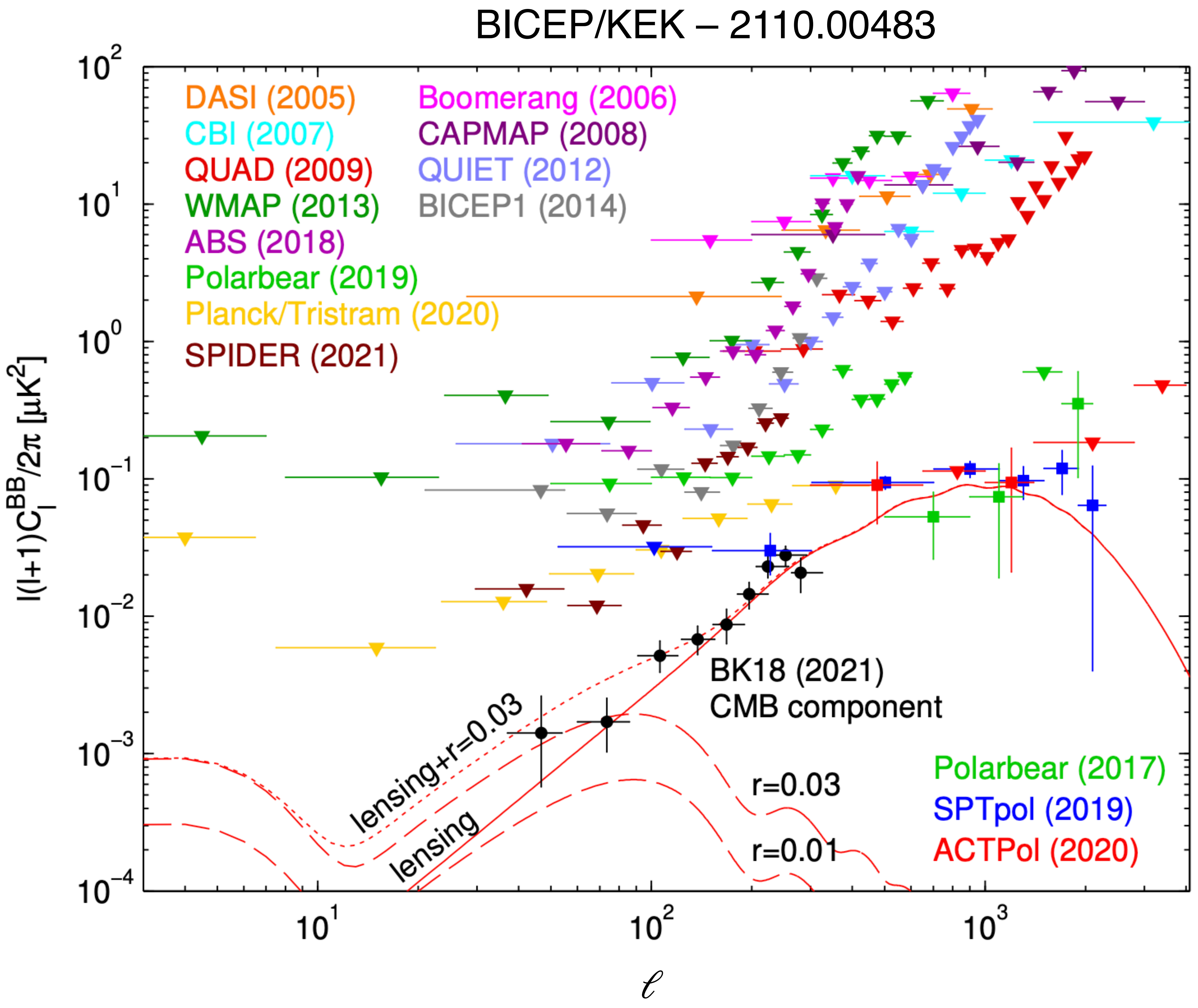


Joint Planck-BICEP/KEK Analysis

Planck 2018
1807.06209

BICEP/KEK 2018
2110.00483

Inflationary spectrum parameters:

1) $n_s \neq 1$ **at 8.5σ :** $n_s = 0.9678 \pm 0.0036$ (at 68% CL)

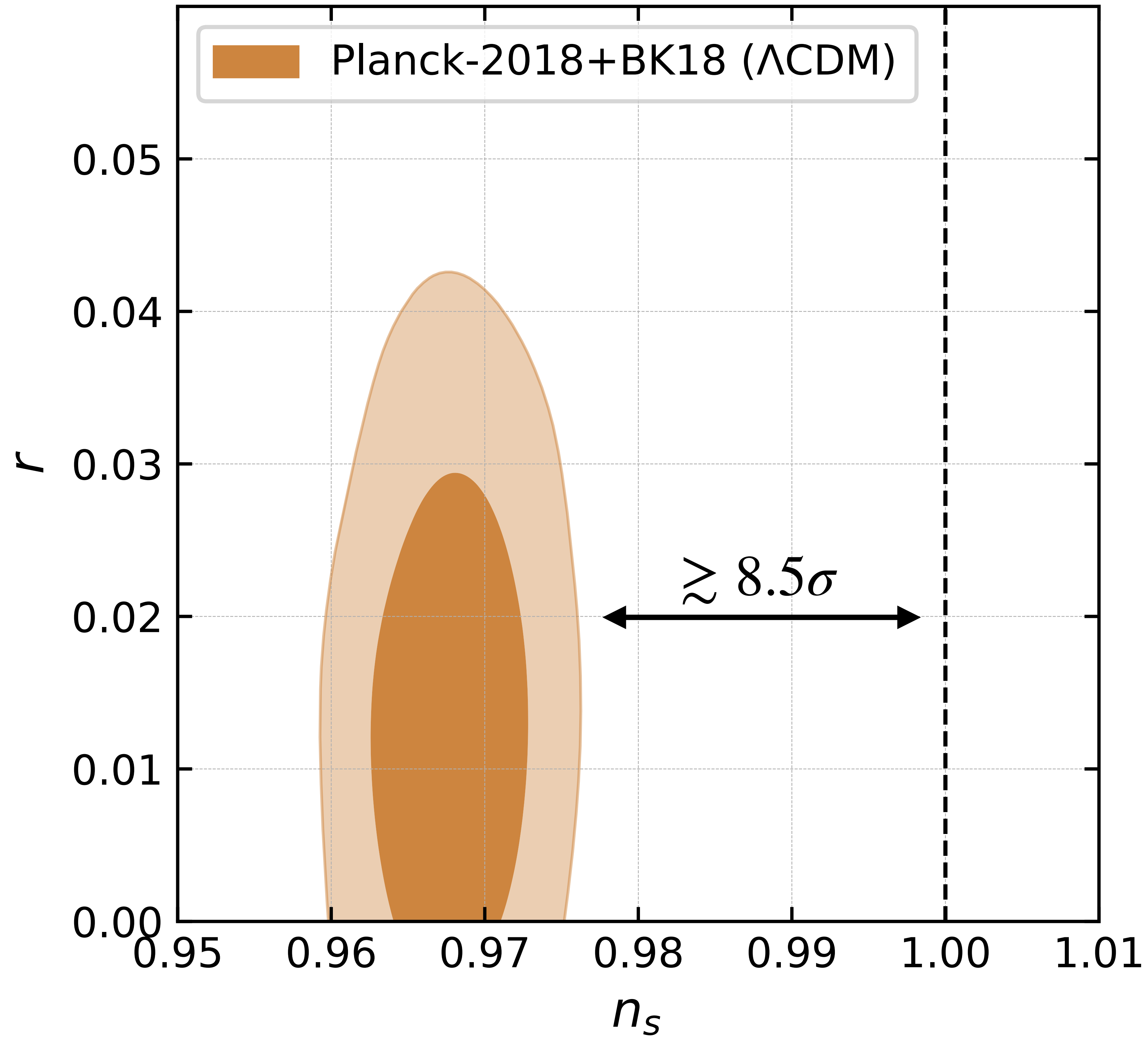
2) **No detection of tensor modes:** $r < 0.035$ (at 95%CL)

Slow-roll parameters:

1) η **measured to** $\eta = -0.0130^{+0.0024}_{-0.0029}$ (at 68% CL)

2) **upper limit** $\epsilon < 0.0022$ (at 95%CL)

3) Slow-roll hierarchy $1 \gg |\eta| \gg \epsilon$



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2110.00483

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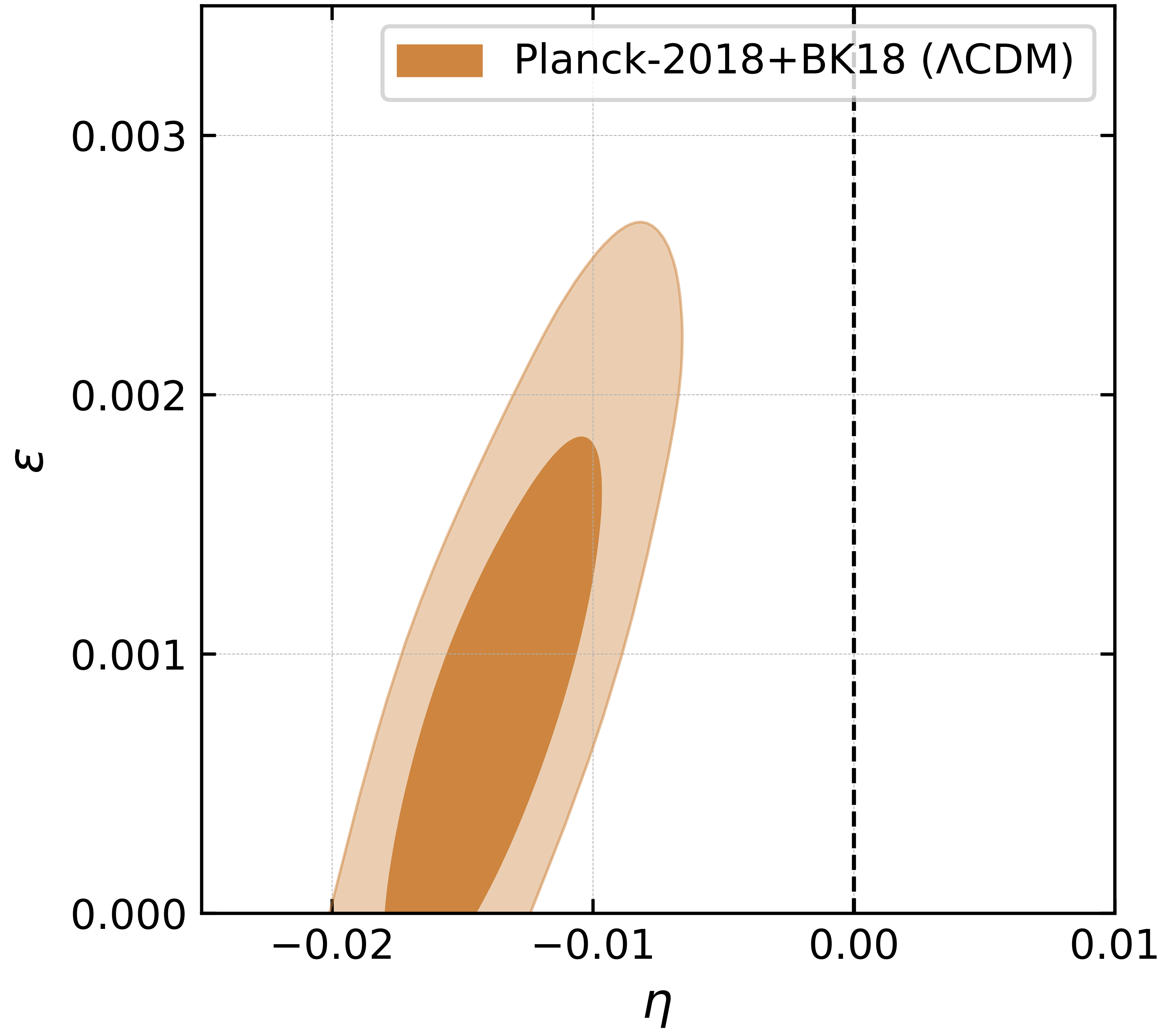

Joint Planck-BICEP/KEK Analysis

Planck 2018
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BICEP/KEK 2018
2110.00483

"All models are equal, but some models are more equal than others"

Starobinsky Inflation

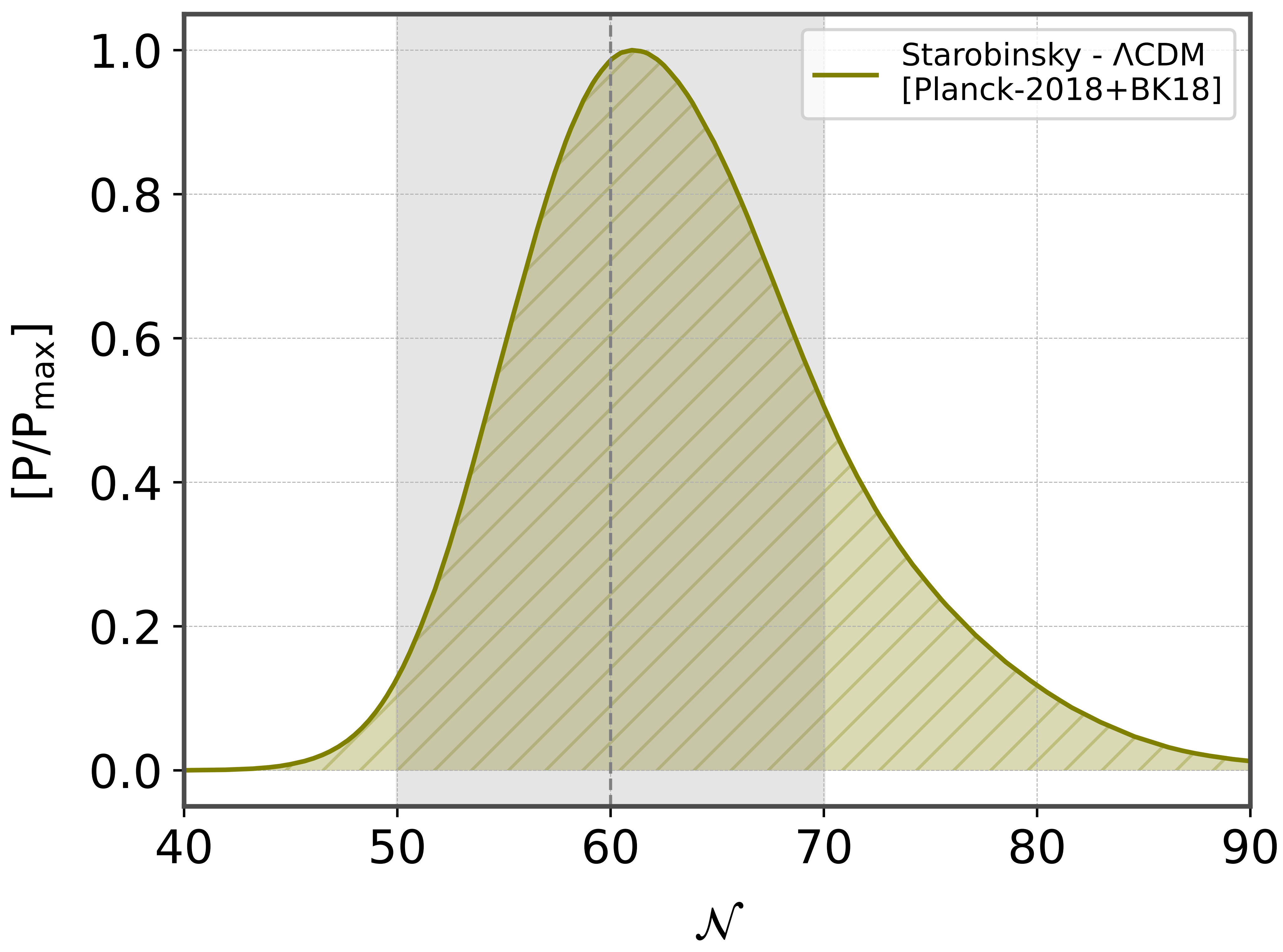
Inflation is controlled by the **squared Ricci scalar** in the effective action

$$S = \frac{1}{2M_{\rm Pl}^2}\int d^4x\sqrt{-g}\left(R + \frac{R^2}{6M^2}\right)$$

It gives ***predictions*** for n_s and r

$$n_s \simeq 1 - \frac{2}{\mathcal{N}} \qquad r \simeq \frac{12}{\mathcal{N}^2} \qquad 50 \lesssim \mathcal{N} \lesssim 70$$

Model in perfect agreement with Planck and BICEP/KECK



The Hubble Tension

5σ tension in the value of the Hubble parameter H_0

Direct Measurement

SH0ES: $H_0 = 73 \pm 1$ km/s/Mpc

Model-independent, based on Type-Ia Supernovae

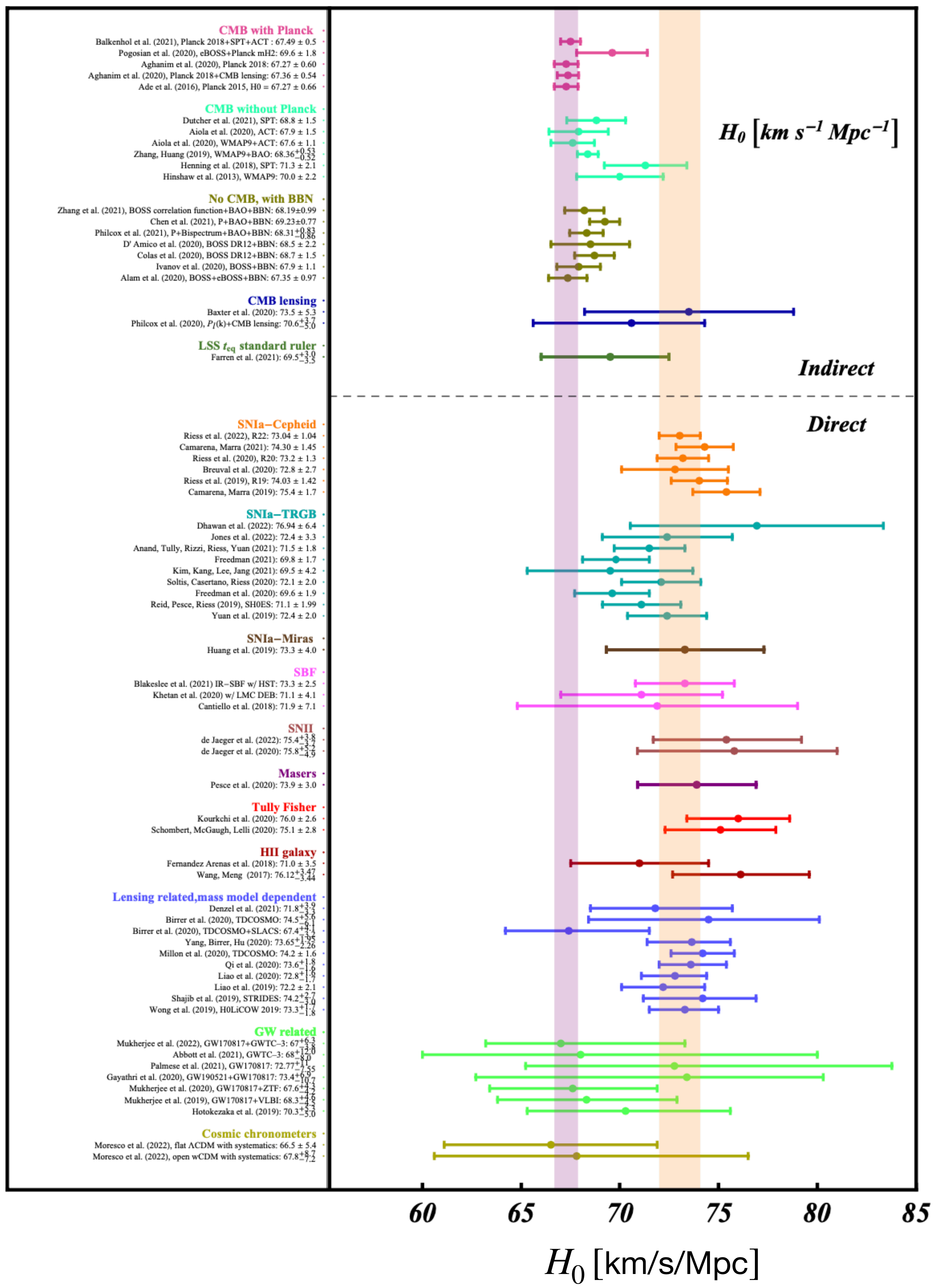
Indirect Measurement

Planck: $H_0 = 67.4 \pm 0.5$ km/s/Mpc

Model-dependent, inferred from CMB measurement (in ΛCDM)

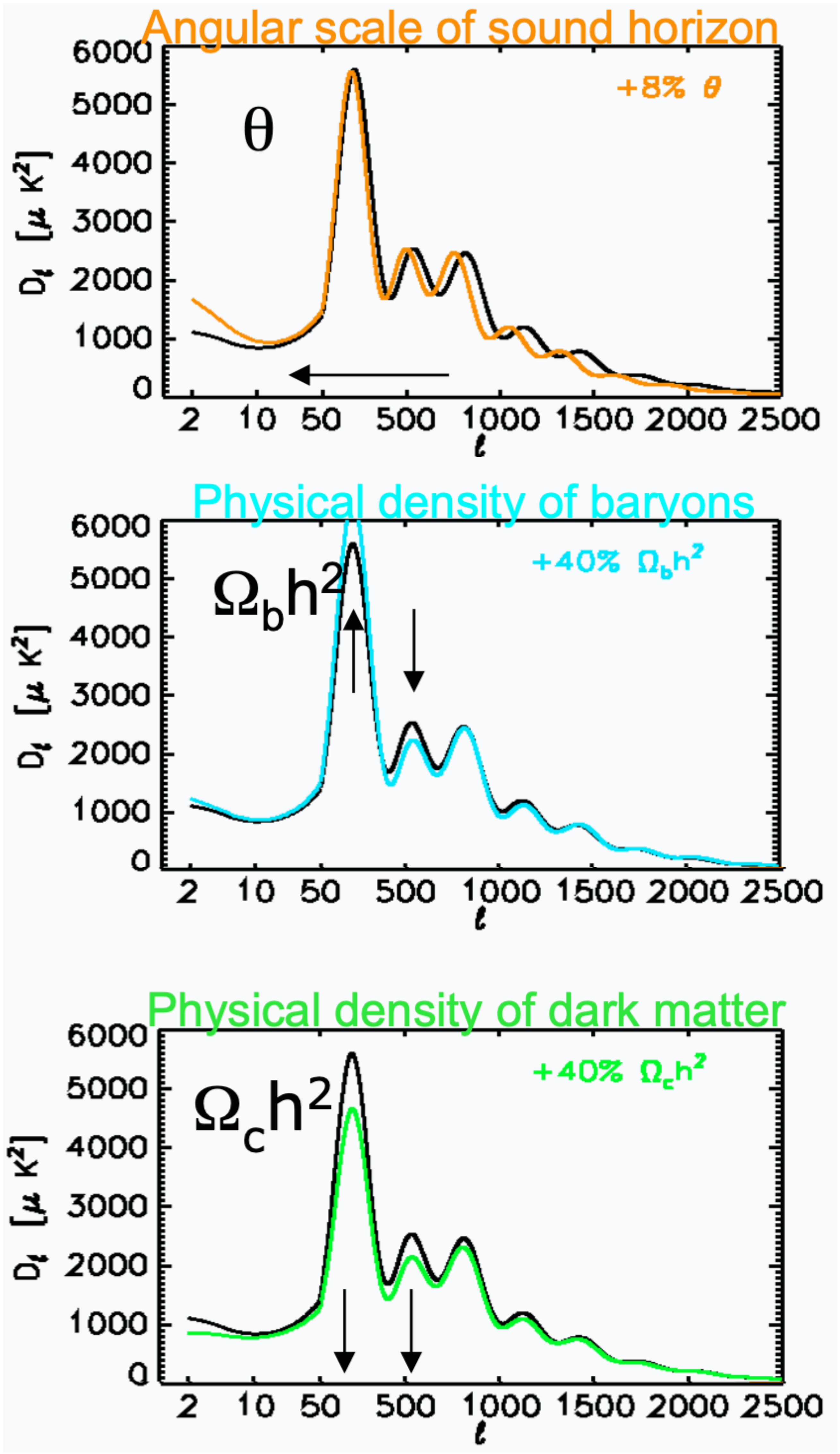
Tension confirmed by many other independent probes

Snowmass 2021 – 2203.06142



The Hubble Tension

S. Galli
"The H_0 debate from a CMB prospective"



How do we measure H_0 from the CMB?

- **Angular size of the sound horizon (θ_s)**
- **Baryon density ($\Omega_b h^2$)**
- **Cold dark matter density ($\Omega_c h^2$)**

Model of Early Universe

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

- **Sound horizon $r_s(z_*)$**
- **Angular diameter distance from the CMB, $D_A(z_*) = r_s(z_*)/\theta_s$**

Model of Late Universe

$$D_A(z_*) = \int_0^{z_*} dz \, H(z)^{-1}$$

$$H^2(z) = H_0^2 \left[\Omega_m (1+z)^3 + \Omega_{\mathrm{DE}}(z) + \ldots\right]$$

- **Hubble Parameter (H_0)**

Early Time Solutions

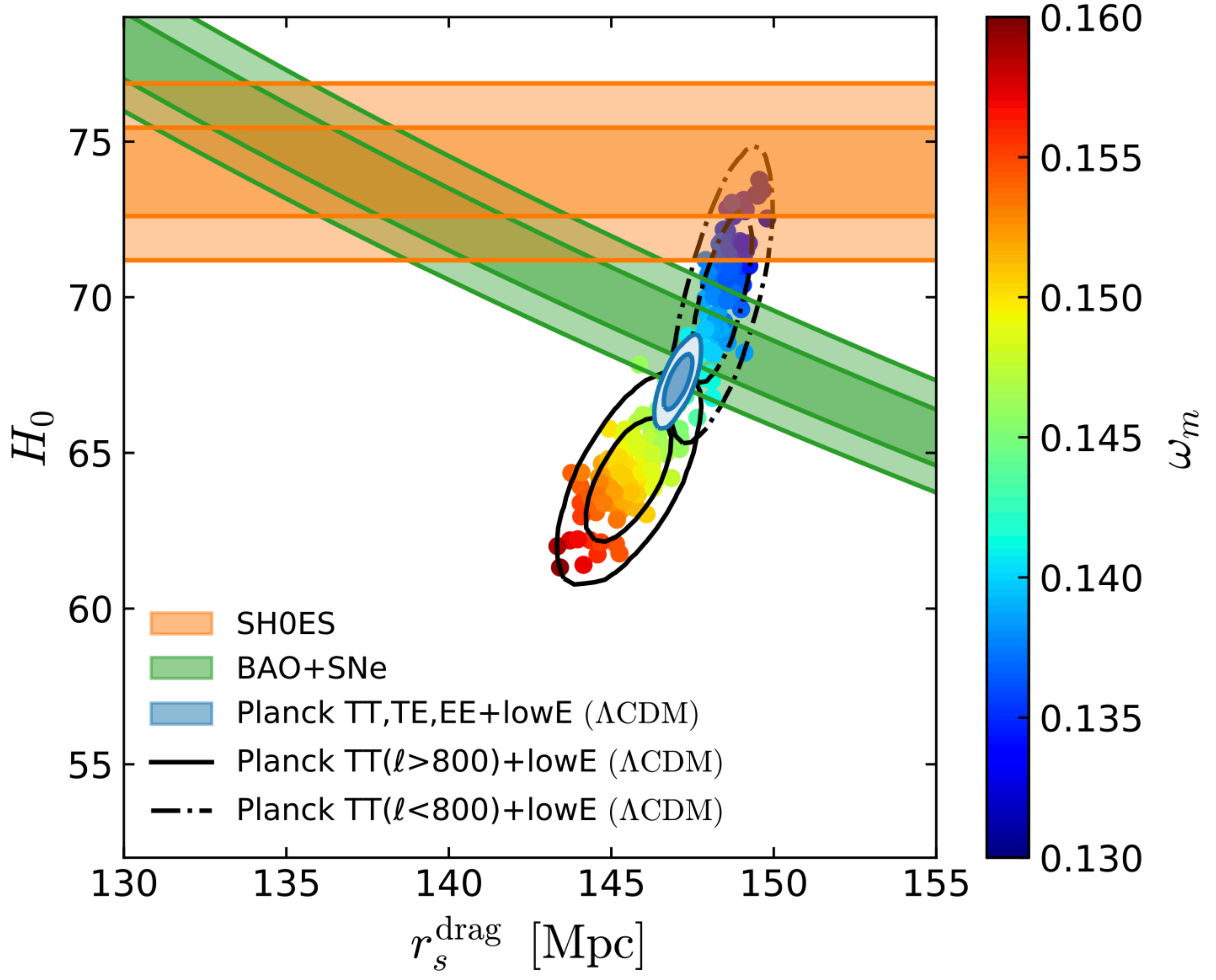
If some **New Physics reduces** $r_s(z_*)$ **,** H_0 **should increase to keep** θ_s **fixed**

$$\theta_s = \frac{r_s(z_*)}{D_A(z_*)}$$

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

$$D_A(z_*) \simeq \frac{1}{H_0} \int_0^{z_*} \frac{dz}{\left[\Omega_m (1+z)^3 + \Omega_\Lambda\right]^{1/2}}$$

Knox and Millea – 1908.03663



How can we decrease $r_s(z_*)$?

1) Working on the Baryon-Photon fluid sound speed $c_s(z)$ before recombination

2) Increasing the expansion rate of the Universe $H(z)$ **before recombination:**

$$H(z) = H_0 \left[\Omega_m (1+z)^3 + \Omega_r (1+z)^4\right]^{1/2}$$

Increasing radiation: $\Omega_r = \Omega_\gamma \left(1 + 0.23\, N_{\rm eff}\right)$ $\quad N_{\rm eff} \rightarrow 3.04 + \Delta N_{\rm eff}$

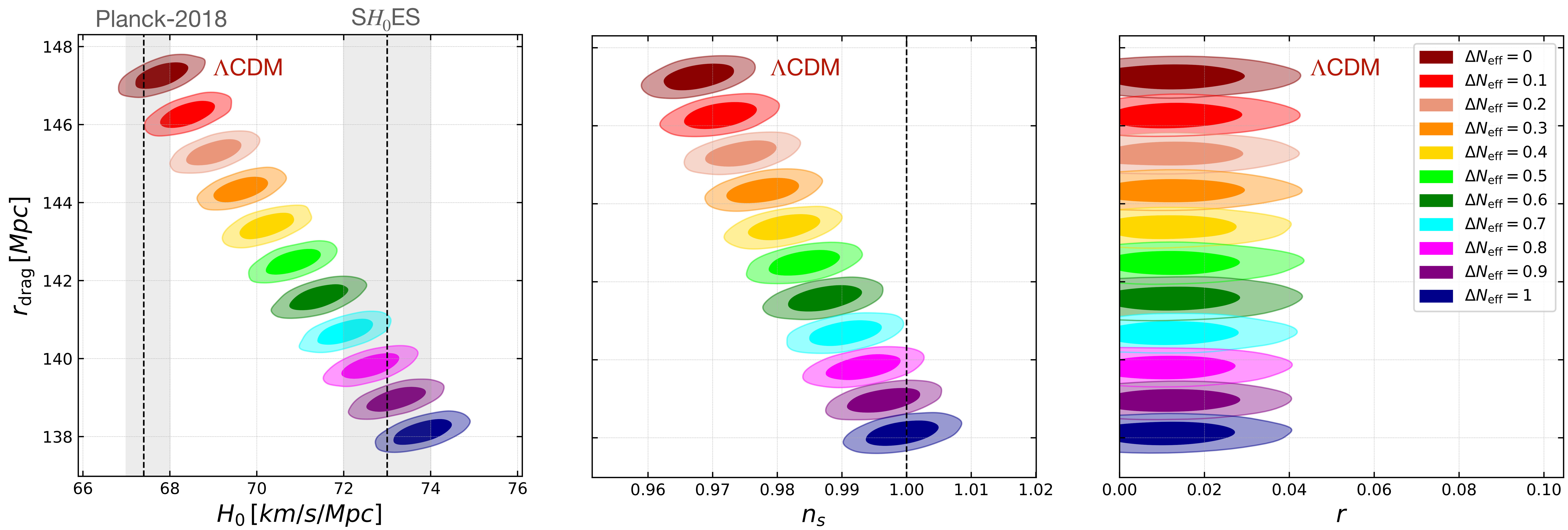
Inflation and Dark Radiation

Planck 2018
1807.06209

BICEP/KEK 2018
2110.00483

What happens increasing radiation in the early Universe?

WG — PRD 109 (2024) 12, 12354 • arXiv: 2404.12779



Reducing r_s we shift to larger H_0

Larger H_0 implies $n_s \to 1$

Constraints on r do not change

Inflation and Dark Radiation

Planck 2018
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BICEP/KEK 2018
2110.00483

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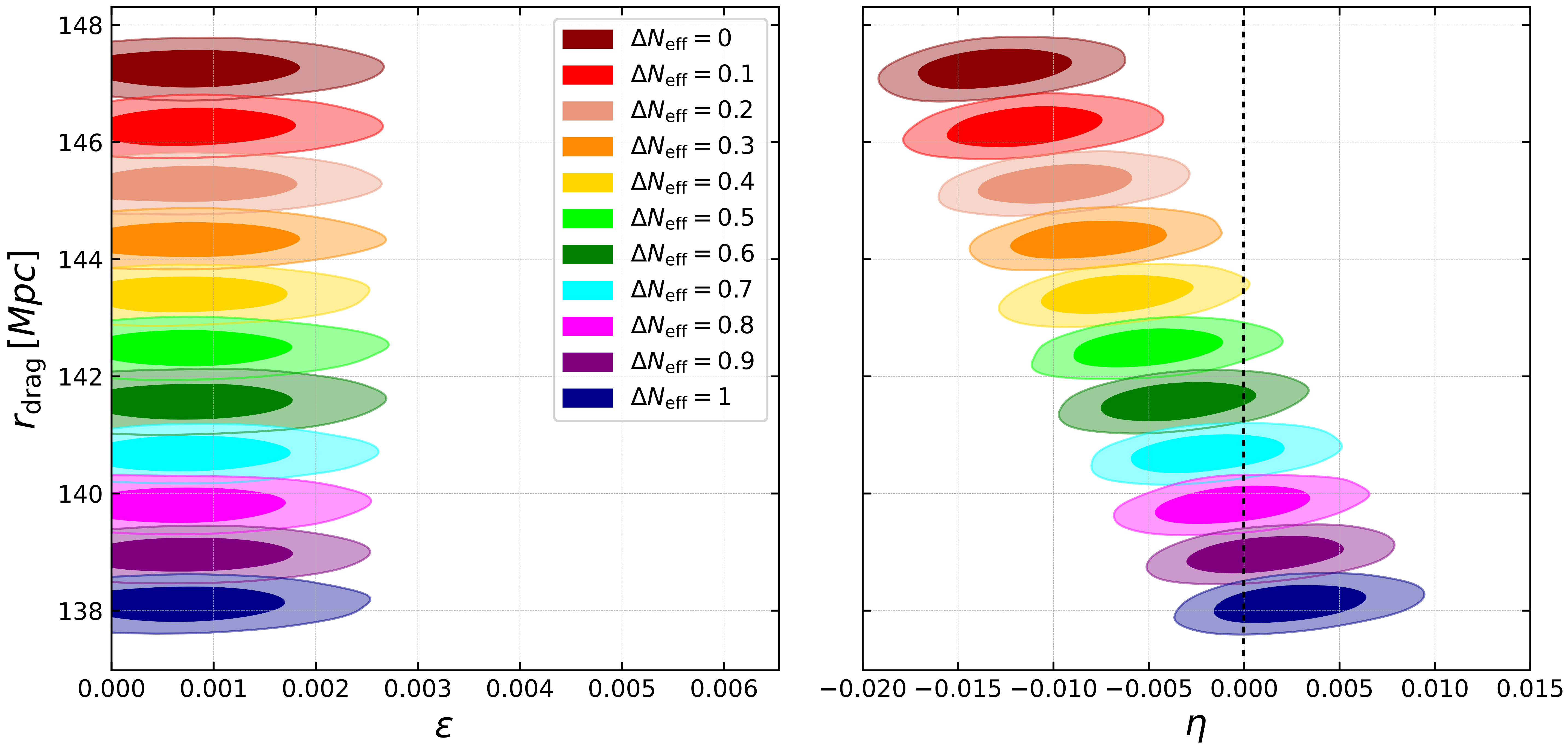

Upper bounds ϵ do not change

Constraints on η shift significantly

Inflation and Dark Radiation

Planck 2018
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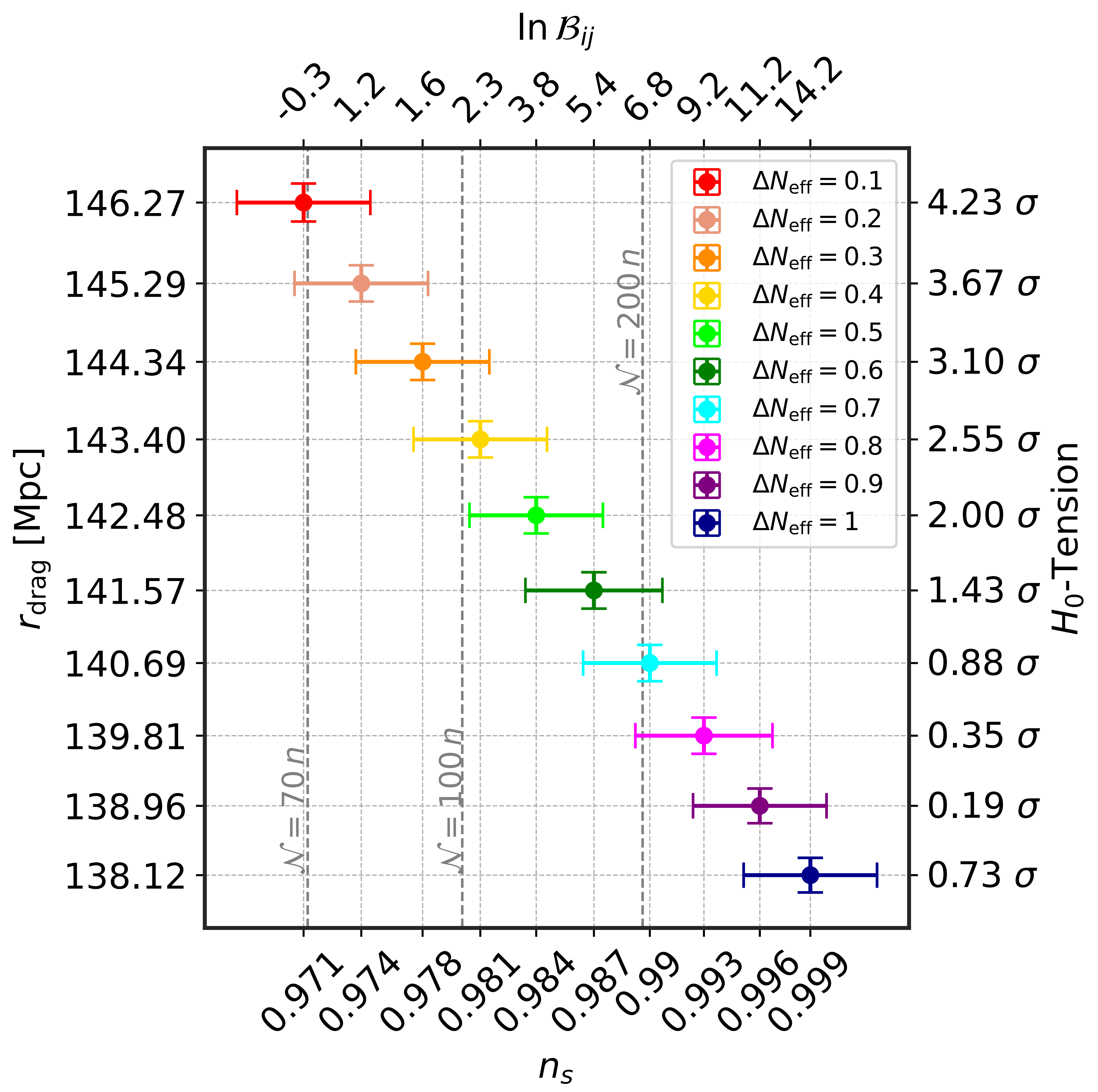


How Much Dark Radiation is allowed?

- To reduece the H0-tension to ~2σ we need $\Delta N_{\rm eff} \gtrsim 0.4$, **Srongly Disfavoured** compared to ΛCDM [1]
- Models with $0.2 \lesssim \Delta N_{\rm eff} \lesssim 0.3$ can reduce the H0-tension to ~3.5σ while being "only" **weakly disfavoured** compared to ΛCDM [1]

To what extent are constraints on inflation sensitive?

- Models with $0.2 \lesssim \Delta N_{\rm eff} \lesssim 0.3$ already require a change in perspective for Inflation: **Starobinsky-like models are no longer supported**

[1] We refer to the following scale for the strength of evidence:

$\lvert\ln B_0\rvert$	Odds	Probability	Strength of evidence
< 0.1	$\lesssim 3:1$	< 0.750	Inconclusive
1	$\sim 3:1$	0.750	Weak
2.5	$\sim 12:1$	0.923	Moderate
5	$\sim 150:1$	0.993	Strong

Inflation and Early Dark Energy

Planck 2018
1807.06209

BICEP/KEK 2018
2110.00483

Early Dark Energy

A light scalar field behaves similarly to a cosmological constant, increasing the expansion rate in the early Universe. Then it must decay faster than matter.

Effects quantified by the maximal fractional contribution to the total energy density

$$f_{\rm EDE} = \max_z \left(\frac{\rho_{\rm EDE}(z)}{\rho_c(z)} \right)$$

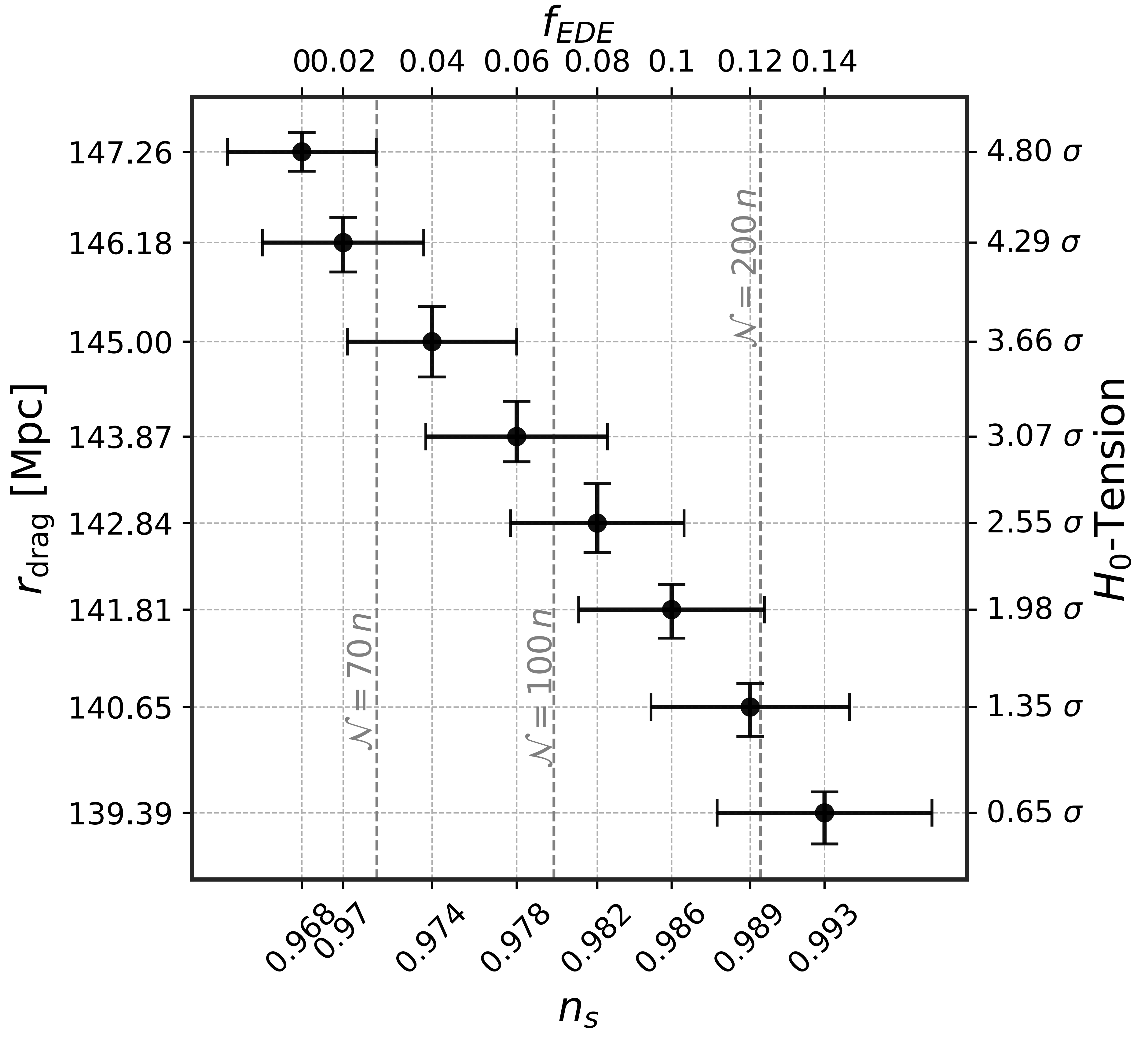
What if $f_{\rm EDE} \neq 0$?

1) $H(z)$ increases before recombination, reducing $r_{\rm drag}$ and increasing H_0

2) We move towards $n_s \to 1$

3) $0.04 \lesssim f_{\rm EDE} \lesssim 0.06$ already **not compatible with Staribinsky-like models**

WG — PRD 109 (2024) 12, 12354 • arXiv: 2404.12779



INFLATION AND EARLY DARK ENERGY

Planck 2018
1807.06209

BICEP/KEK 2018
2110.00483

WG — PRD 109 (2024) 12, 12354 • arXiv: 2404.12779

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Effects quantified by the maximal fractional contribution to the total energy density

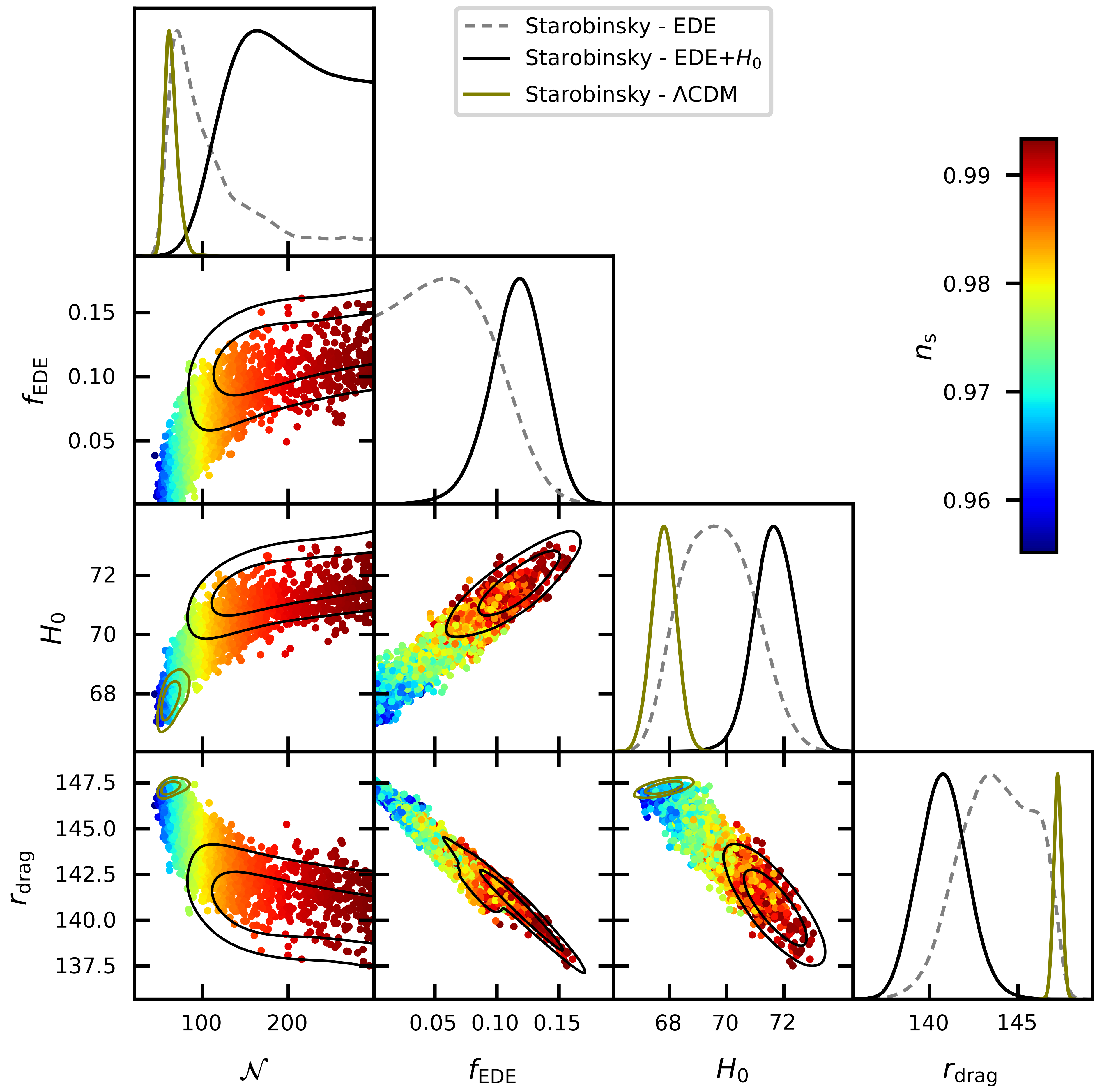
$$f_{\text{EDE}} = \max_z \left(\frac{\rho_{\text{EDE}}(z)}{\rho_c(z)} \right)$$

Implications for Starobinsky inflation

1) Perfect agreement with Planck+BICEP/KEK assuming ΛCDM

2) Can be in agreement with Planck+BICEP/KEK for negligible f_{EDE}

3) **NOT** in agreement with Planck+BICEP/KEK if EDE solves the H_0 tension



Conclusions

Widespread consensus in the cosmology community

1) **Robust constraints** on Inflation from Planck and BICEP/KEK data: $n_s = 0.9678 \pm 0.0036$ and $r < 0.035$
2) **Starobinsky Inflation leading model**

Important caveats surrounding these results

1) Any **constraint on the inflationary parameters** is intrinsically **model-dependent** (can we rely on ΛCDM?)
2) Early time solutions of the **Hubble Tension can shift Planck and BICEP/KEK-2018 results towards** $n_s \to 1$
3) ACT **small-scale CMB data** point towards $n_s \sim 1$ (**in disagreement with Planck and Starobinsky Inflation**)

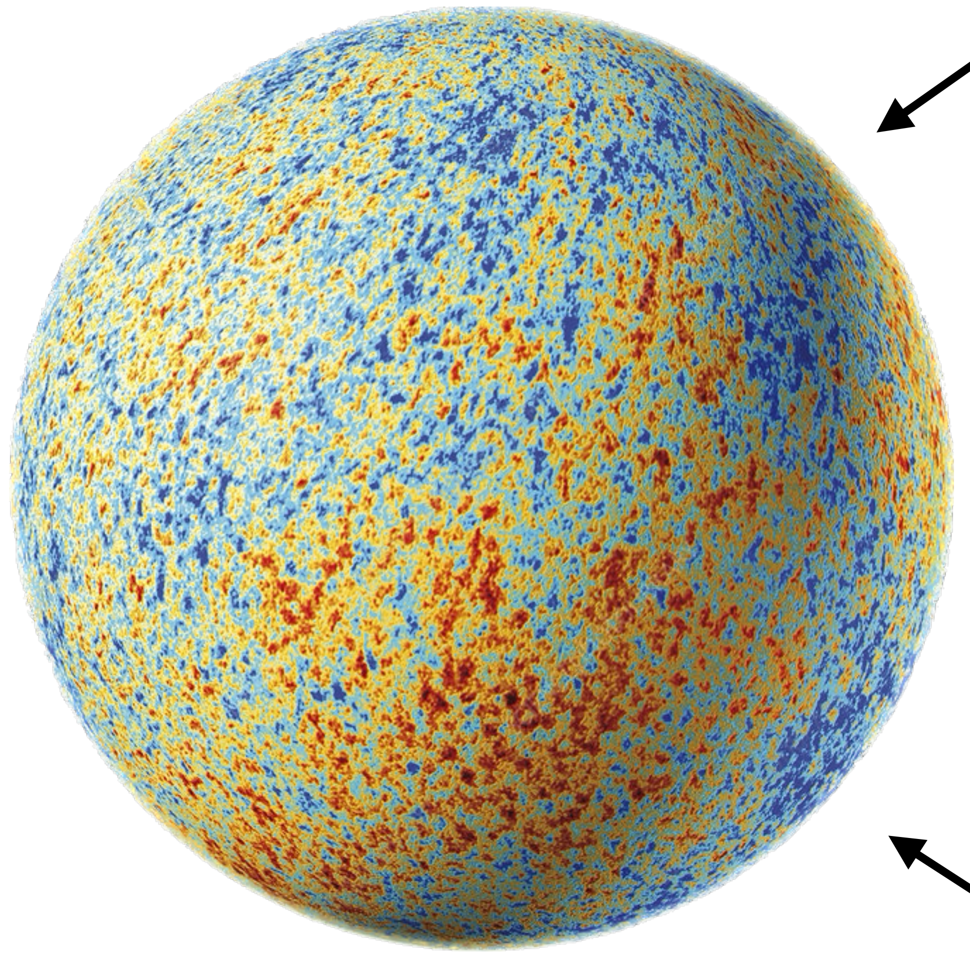
Possible implications

1) We might need to rethink inflation. Too early to say!
2) Doing model selection is premature and not completely safe without understanding the nature of the H_0 tension

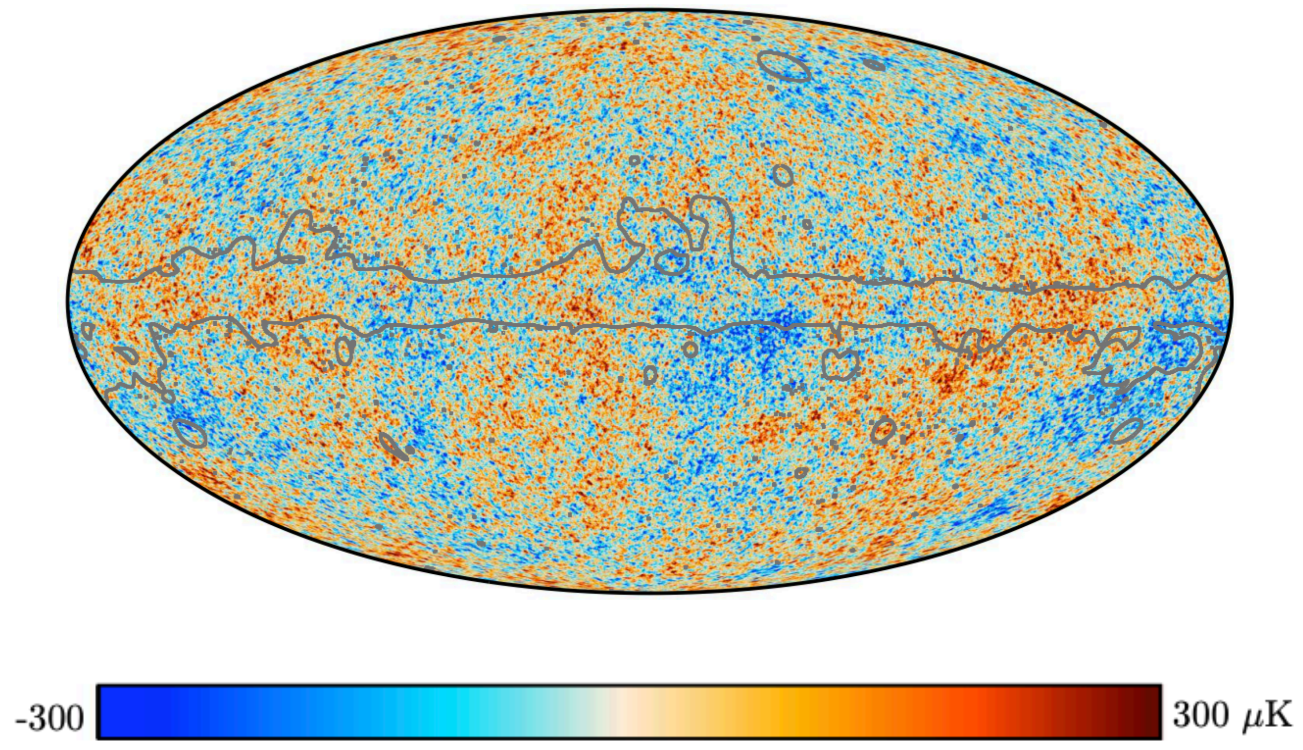
Backup Slides

Primordial Perturbations

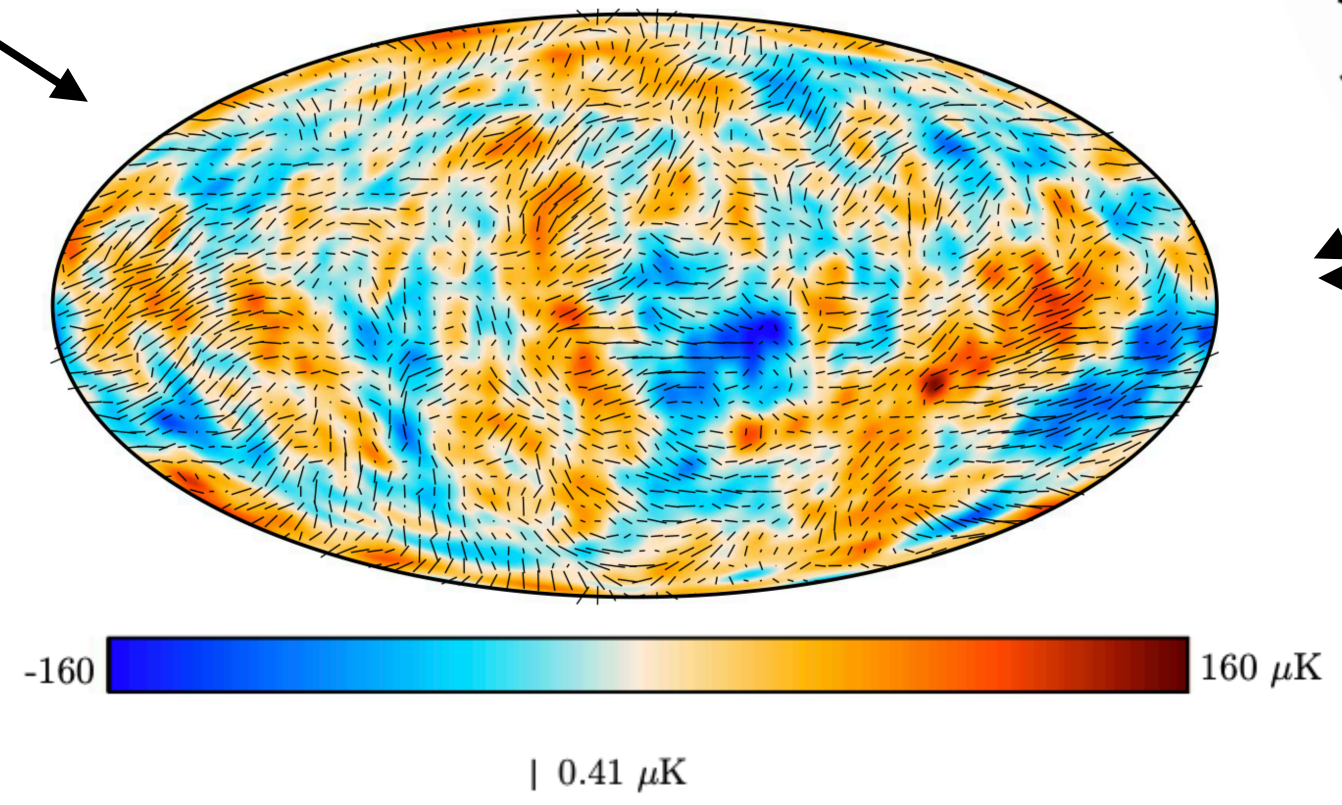
Relic Photons from the Big Bang

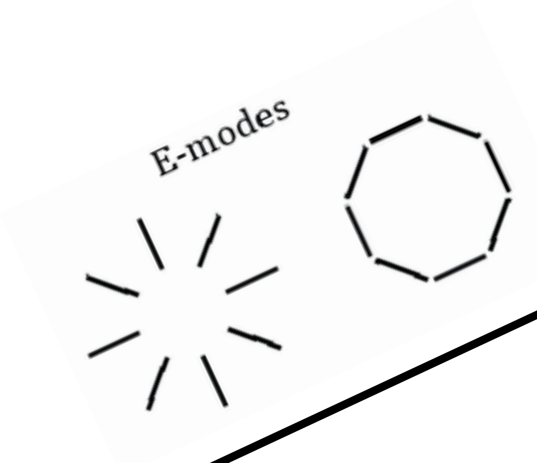


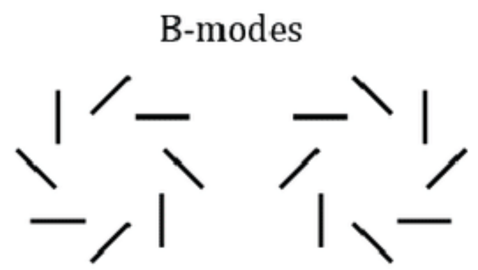
Temperature anisotropies



Polarization







We can extract 4 independent observables

(note: assuming that parity is conserved)

1) Angular power spectrum of temperature anisotropies C_ℓ^{TT}
(**TT spectrum**)

2) Temperature and E-mode cross-spectrum C_ℓ^{TE}
(**TE spectrum**)

3) Angular power spectrum of E-mode polarisation C_ℓ^{EE}
(**EE spectrum**)

4) Angular power spectrum of B-mode polarisation C_ℓ^{BB}
(**BB spectrum**)

Linking Inflation and the CMB

$$\left[C_\ell^{XY}\right]_{\text{scalar}} = \frac{2\pi}{\ell(\ell+1)} \int_0^\infty d\ln k\; T_\ell^X(k)\, T_\ell^Y(k)\, \mathscr{P}_{\rm s}(k)$$

Scalar Transfer functions

Scalar spectrum

$$\left[C_\ell^{XY}\right]_{\text{tensor}} = \frac{2\pi}{\ell(\ell+1)} \int_0^\infty d\ln k\; T_\ell^X(k)\, T_\ell^Y(k)\, \mathscr{P}_{\rm t}(k)$$

Tensor Transfer functions

Tensor spectrum

Transfer Functions:

- Scalar and Tensor transfer functions are different
- $C_\ell^{\rm tot} = \left[C_\ell\right]_{\text{scalar}} + \left[C_\ell\right]_{\text{tensor}}$
- In $\left[C_\ell^{XY}\right]_{\text{scalar}}$ we have: $X, Y = \{T, E\}$
- In $\left[C_\ell^{XY}\right]_{\text{tensor}}$ we have: $X, Y = \{T, E, B\}$
- Transfer functions are different for T, E, B

BICEP/KEK 2018

2110.00483

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Note: $\ell \propto 1/\theta \propto 1/\mathrm{R}$

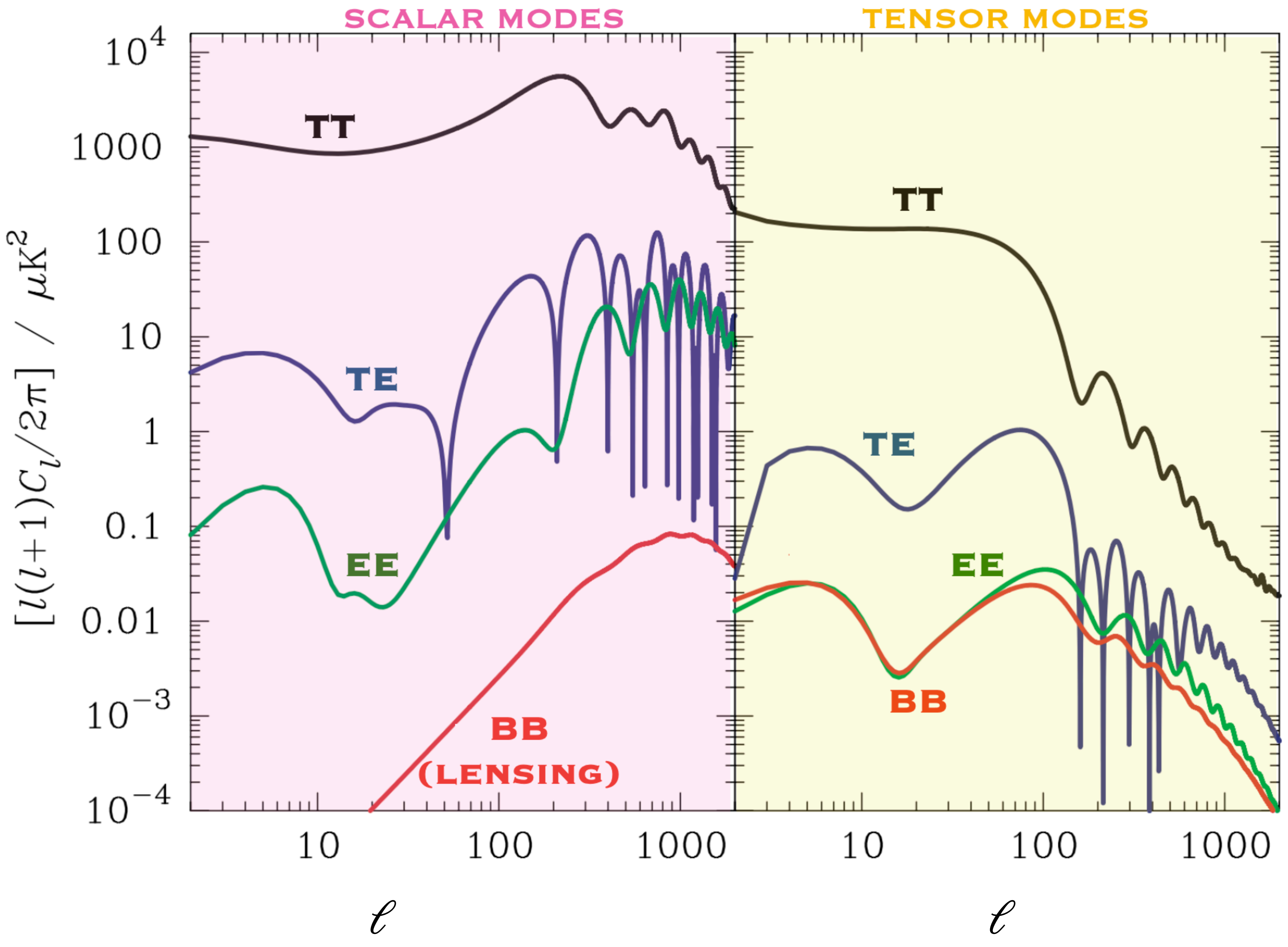

Figure inspired by Gorbunov & Rubakov "Cosmological Perturbations and Inflationary Theory", Chapter 10 See also A. Challinor arXiv:astro-ph/0606548

PLANCK 2018

1807.06209

BICEP/KEK 2018

2110.00483

Joint analysis of Planck and BICPE/KEK:

1) $n_s \neq 1$ **at 8.5σ :** $n_s = 0.9678 \pm 0.0036$ (at 68% CL)

2) **No detection of tensor modes:** $r < 0.035$ (at 95%CL)

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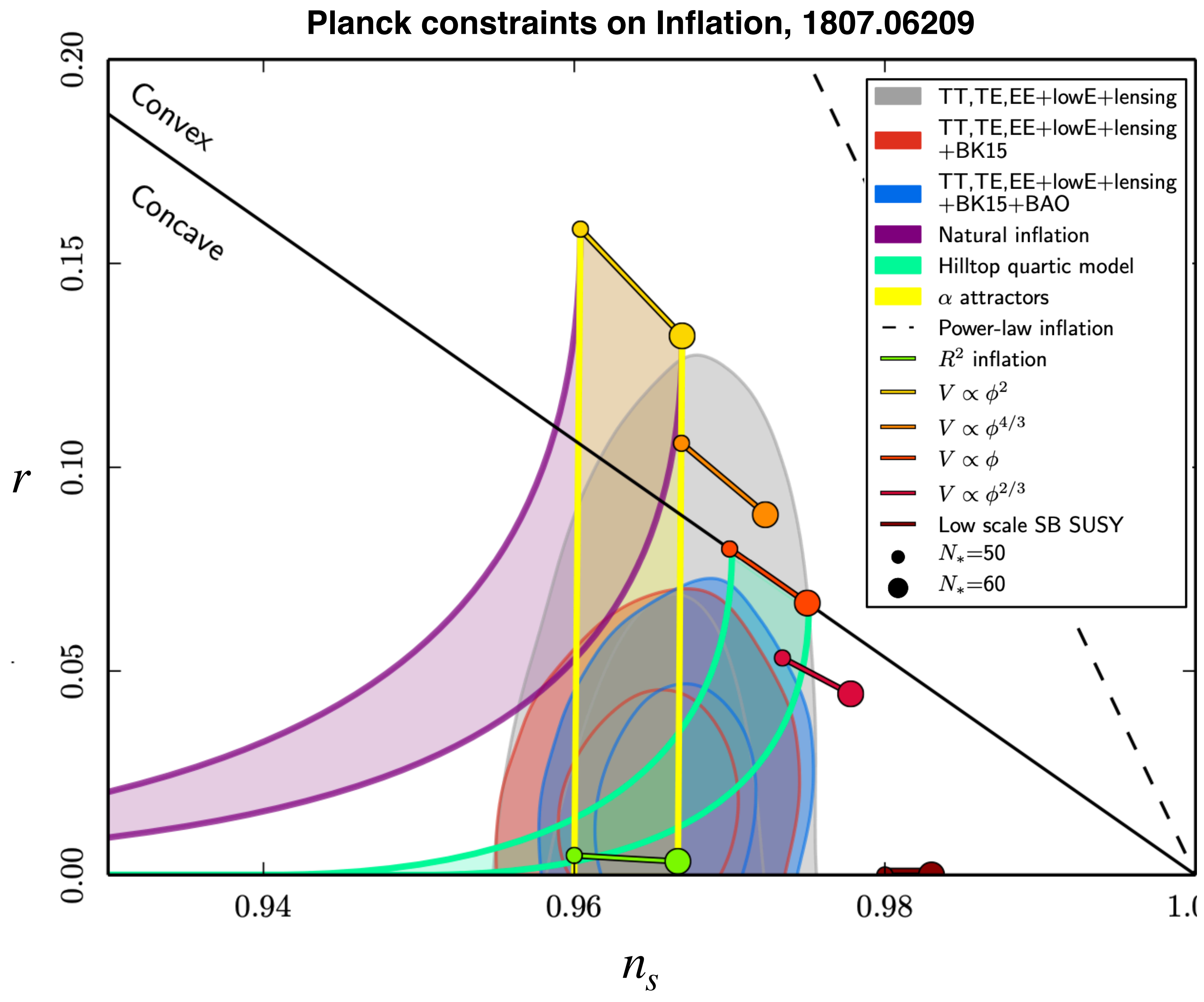
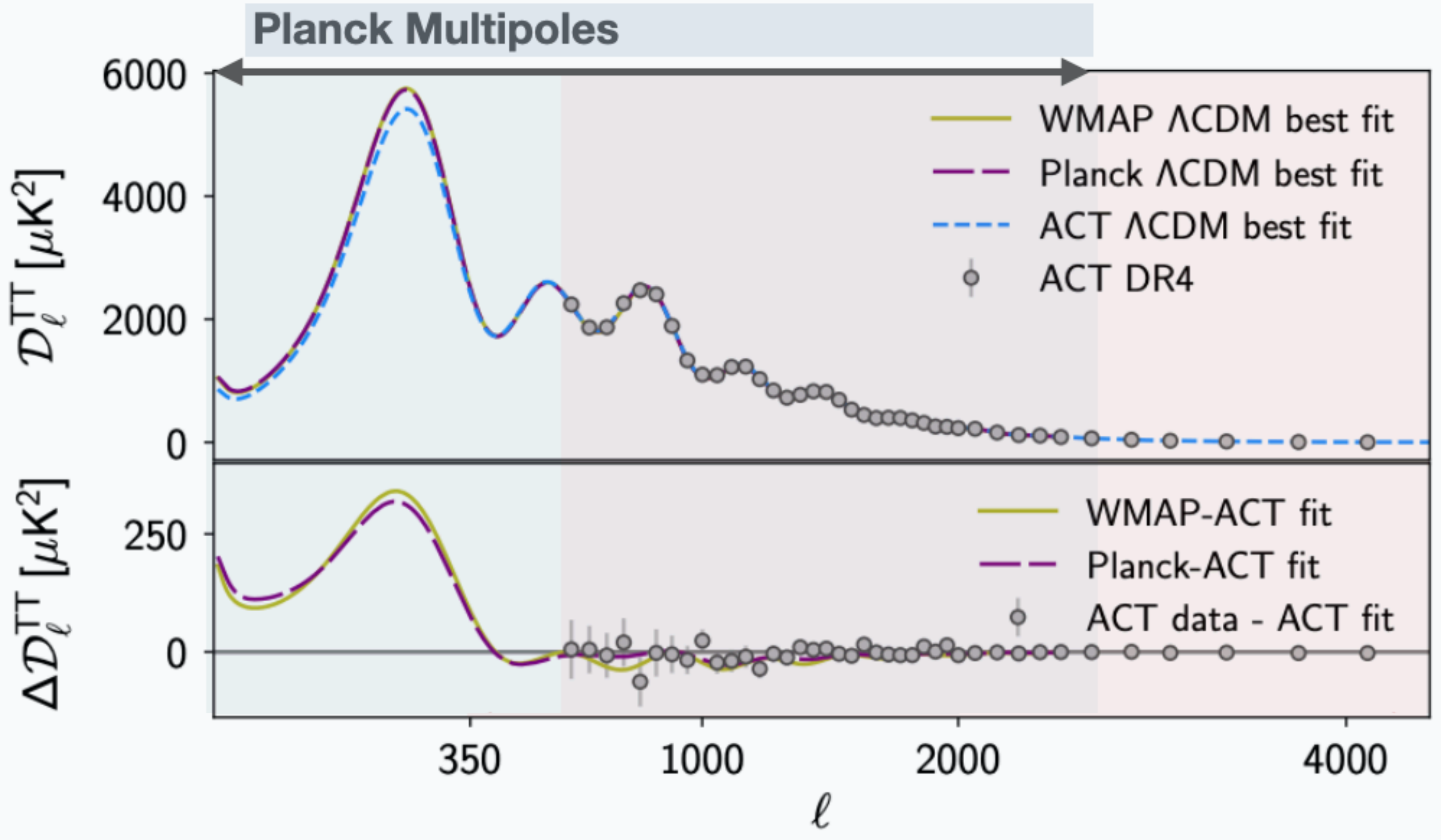


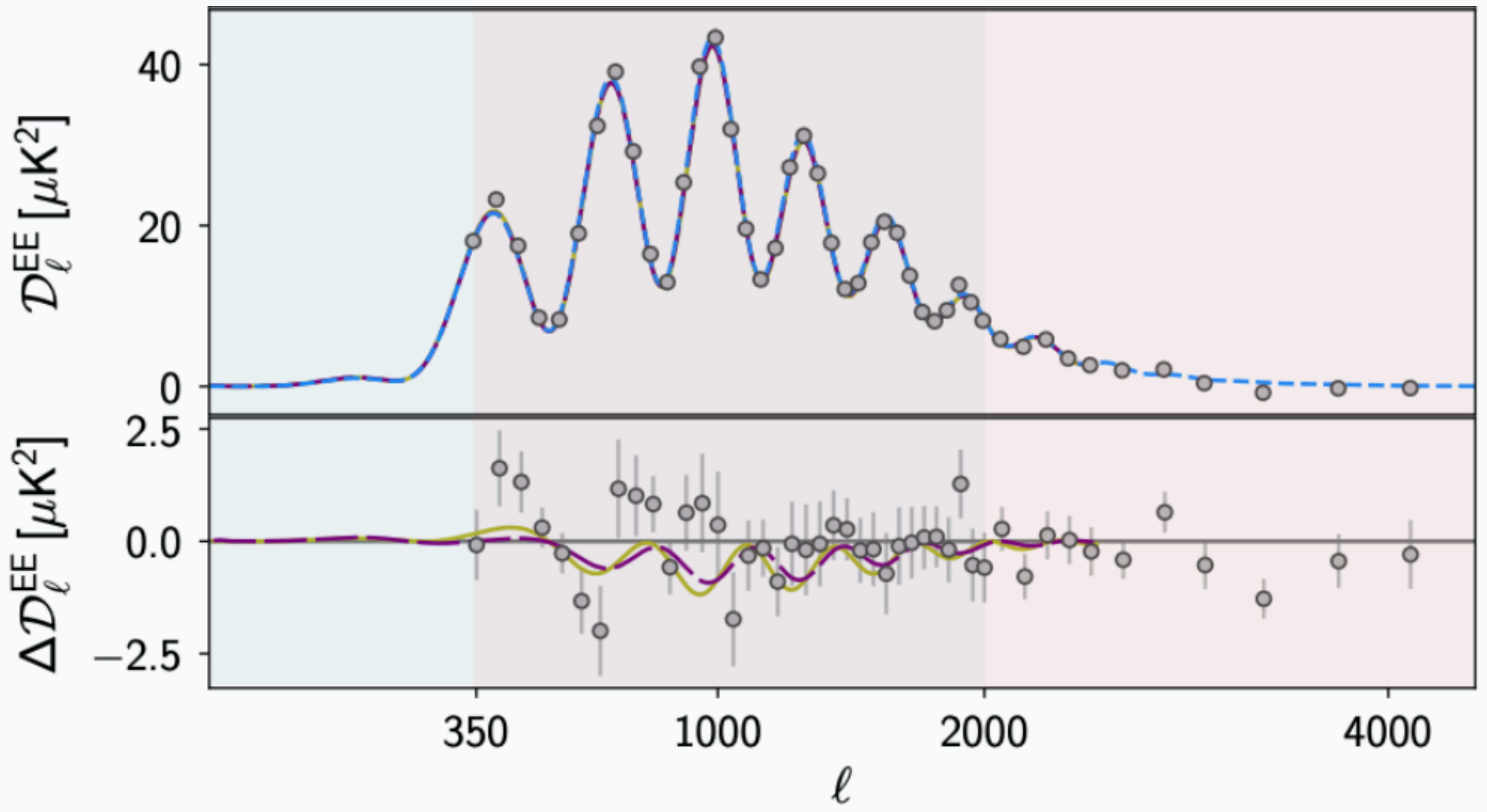
Atacama Cosmology Telescope

2007.07288

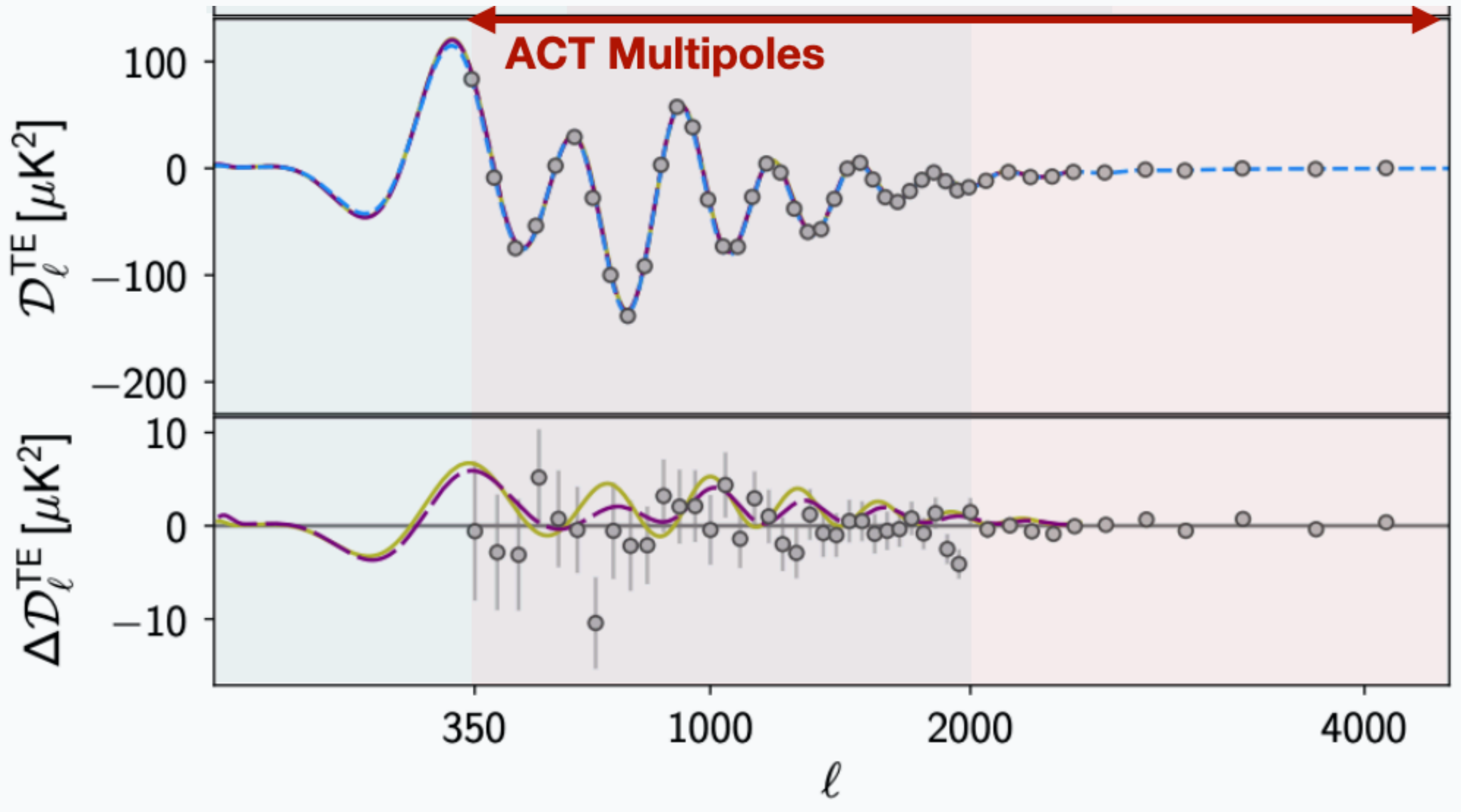
TT Spectrum



EE Spectrum



TE Cross-Spectrum



High-multipole temperature data

$600 < \ell \lesssim 4200$ in the TT Spectrum

High-multipole EE Polarization data

$350 < \ell \lesssim 4200$ in the EE Spectrum

High-multipole TE data

$350 < \ell \lesssim 42000$ in the TE Spectrum

Note:
Planck probes $\ell \in [2,2000]$

Atacama Cosmology Telescope

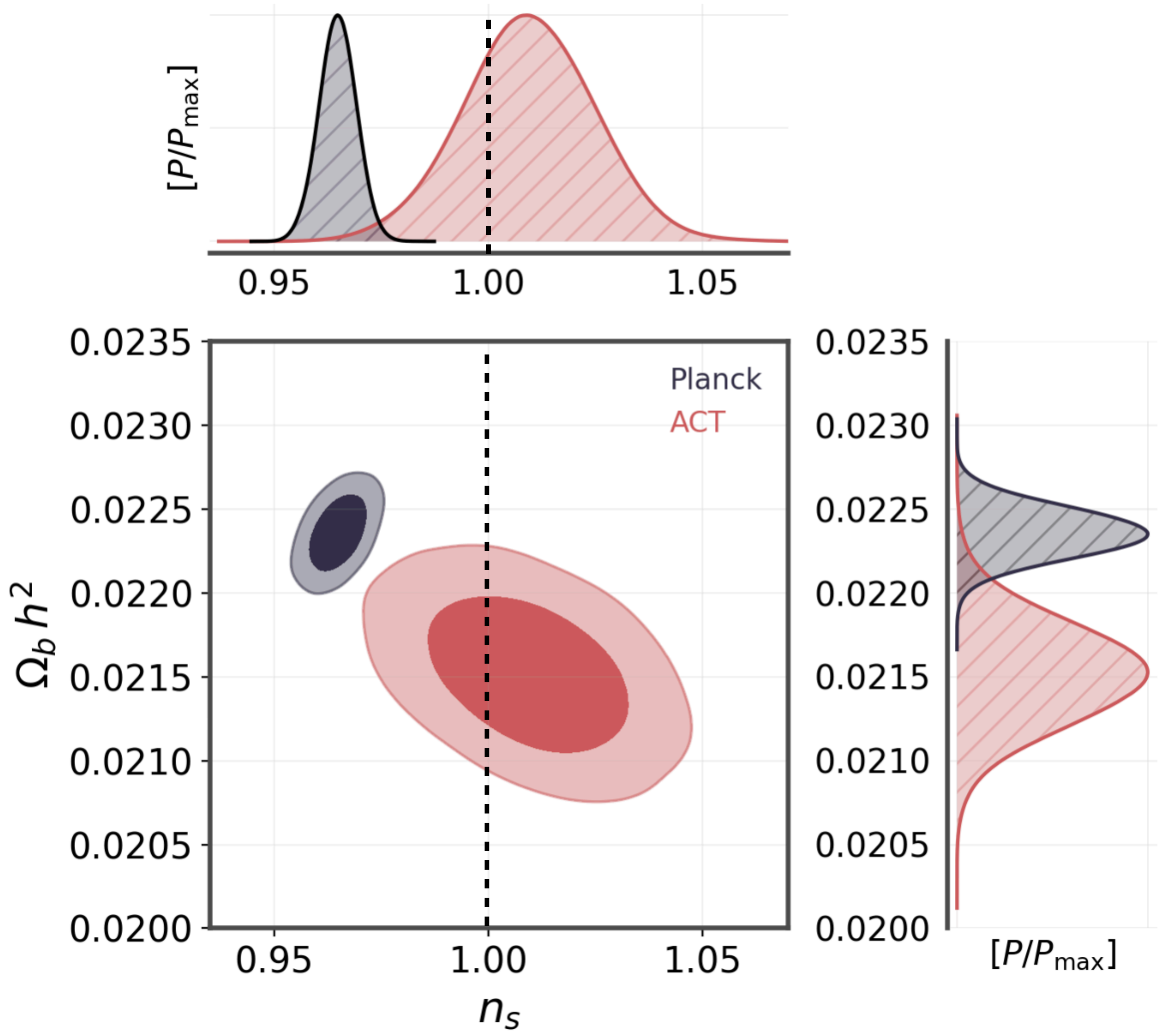
2007.07288

ACT shows a preference for $n_s \simeq 1$ (in 3σ disagreement with Planck)

Dataset	Scalar Spectral Index (n_s) ΛCDM
ACT	1.009 ± 0.015
ACT (τ = 0.0544 ± 0.0070)	1.007 ± 0.015
ACT + Planck low E	1.001 ± 0.011
ACT+BAO (DR12)	1.006 ± 0.013
ACT+BAO (DR16)	1.006 ± 0.014
ACT+DES	1.007 ± 0.013
ACT+SPT+BAO (DR16)	0.997 ± 0.013
ACT+SPT+BAO (DR12)	0.996 ± 0.012
Planck	0.9649 ± 0.0044
Planck+BAO (DR12)	0.9668 ± 0.0038
Planck+BAO (DR16)	0.9677 ± 0.0037
Planck+DES	0.9696 ± 0.0040
Planck ($2 \leq \ell \leq 650$)	0.9655 ± 0.0043
Planck ($\ell > 650$)	0.9634 ± 0.0085

WG et al. – 2210.09018

WG, *et al.* — *MNRAS* 521 (2023) • arXiv: 2210.09018



ATACAMA COSMOLOGY TELESCOPE

2007.07288

ACT shows a preference for $n_s \simeq 1$ (in 3σ disagreement with Planck)

Dataset	Scalar Spectral Index (n_s) ΛCDM
ACT	1.009 ± 0.015
ACT (τ = 0.0544 ± 0.0070)	1.007 ± 0.015
ACT + Planck low E	1.001 ± 0.011
ACT+BAO (DR12)	1.006 ± 0.013
ACT+BAO (DR16)	1.006 ± 0.014
ACT+DES	1.007 ± 0.013
ACT+SPT+BAO (DR16)	0.997 ± 0.013
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Planck	0.9649 ± 0.0044
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Planck ($2 \le \ell \le 650$)	0.9655 ± 0.0043
Planck ($\ell > 650$)	0.9634 ± 0.0085

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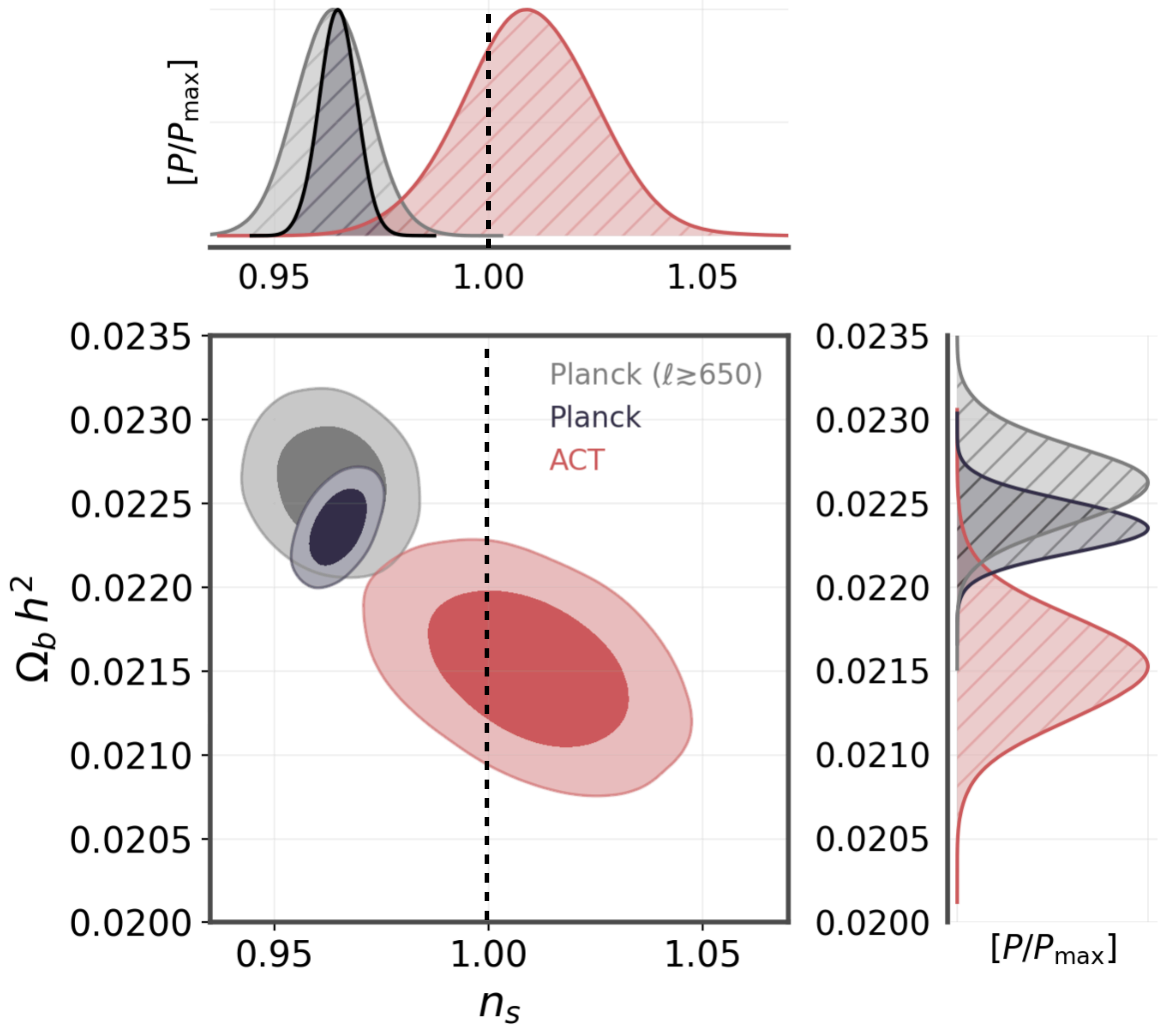

Atacama Cosmology Telescope

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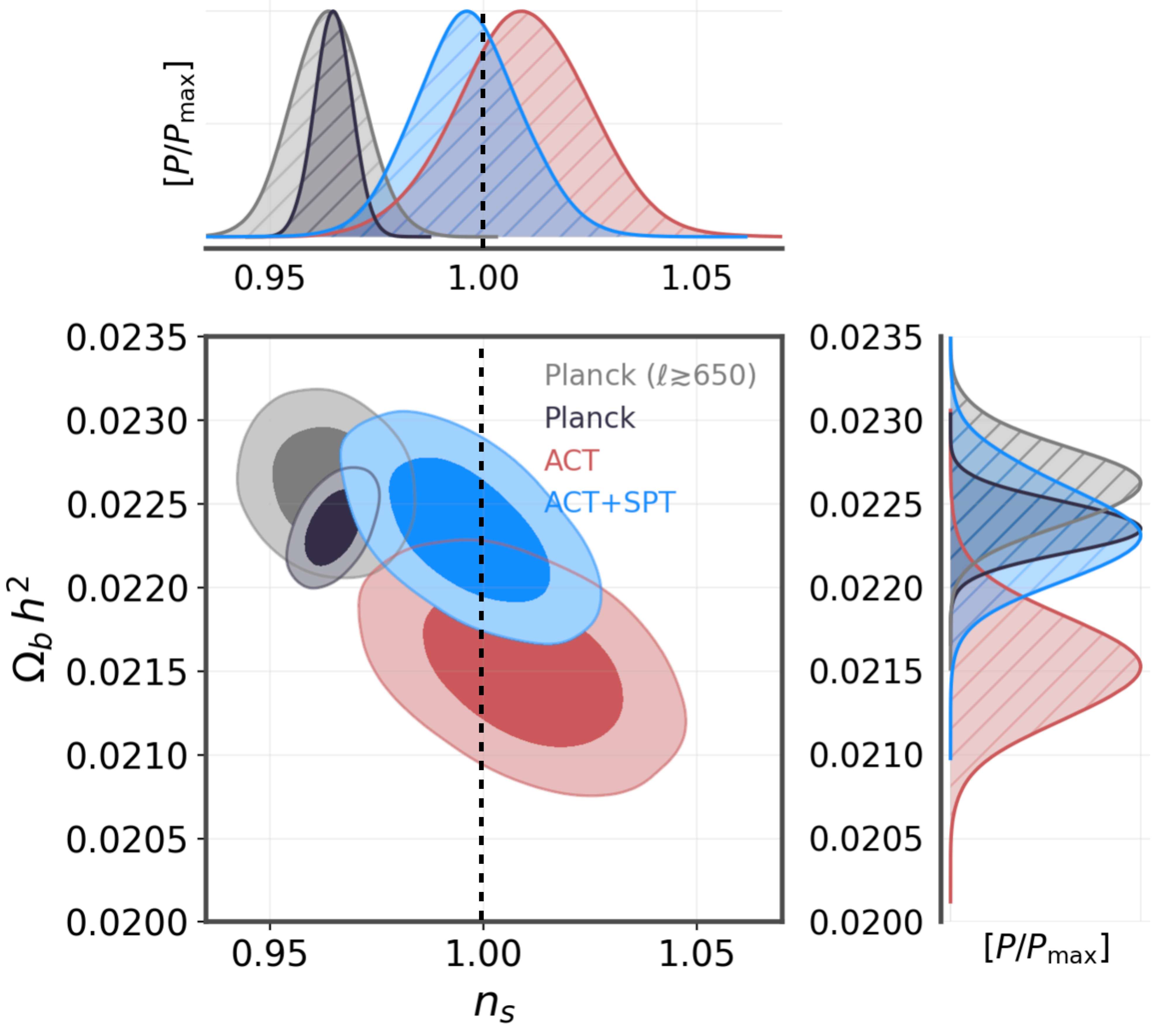
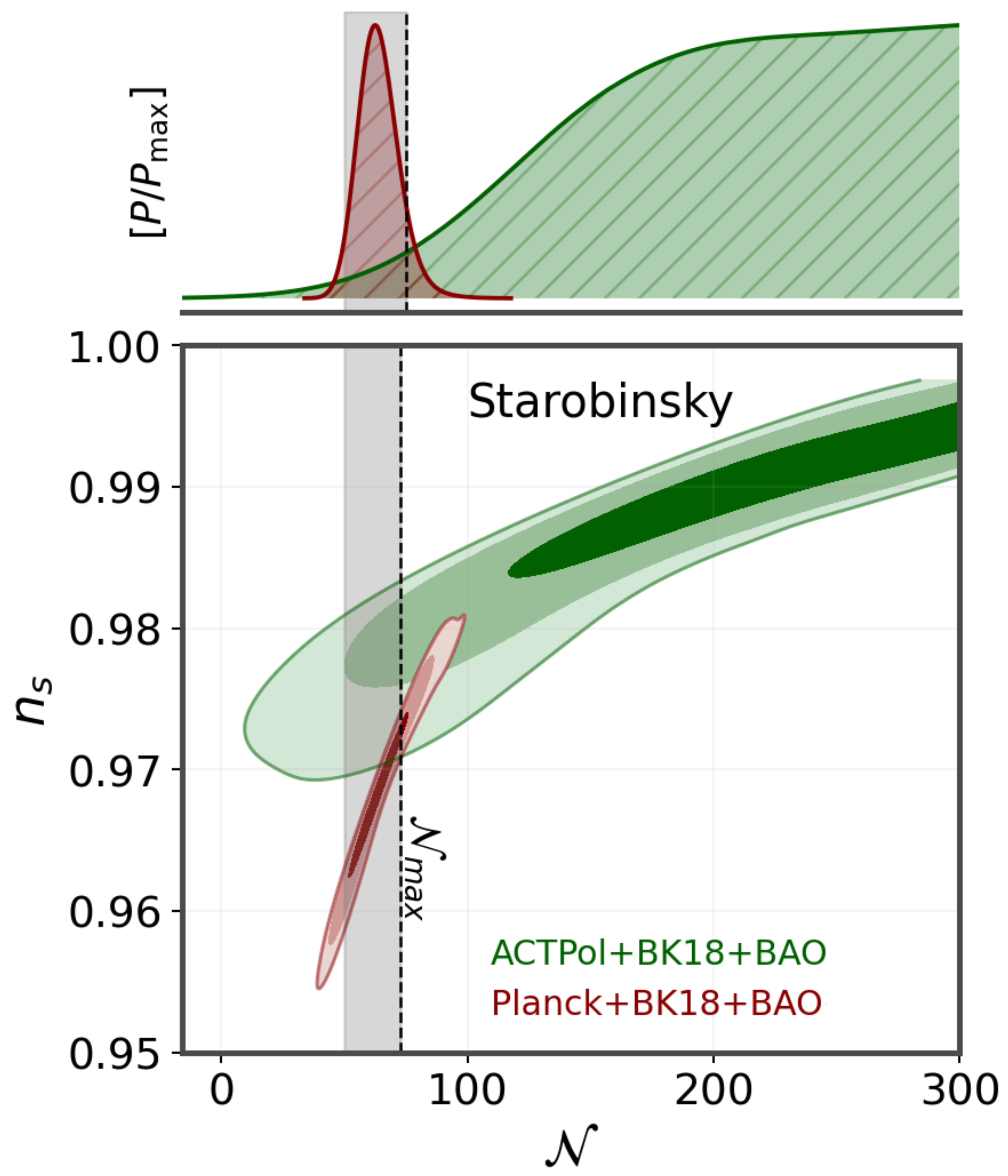


Atacama Cosmology Telescope

2007.07288

WG, *et al.* — *JCAP* 09 (2023) 019 • arXiv: 2305.15378



Implications for Starobinsky inflation:

1) Perfect **agreement with Planck+BICEP/KEK**: $\mathcal{N} = 64 \pm 9$ at 68% CL

2) Strong **disagreement with ACT+BICEP/KEK**: $\mathcal{N} > 100$ at 95% CL

Large and small scale CMB data DO NOT agree on the inflationary potential

INFLATION AND DARK RADIATION

Planck 2018
1807.06209

BICEP/KEK 2018
2110.00483

WG — PRD 109 (2024) 12, 12354 • arXiv: 2404.12779

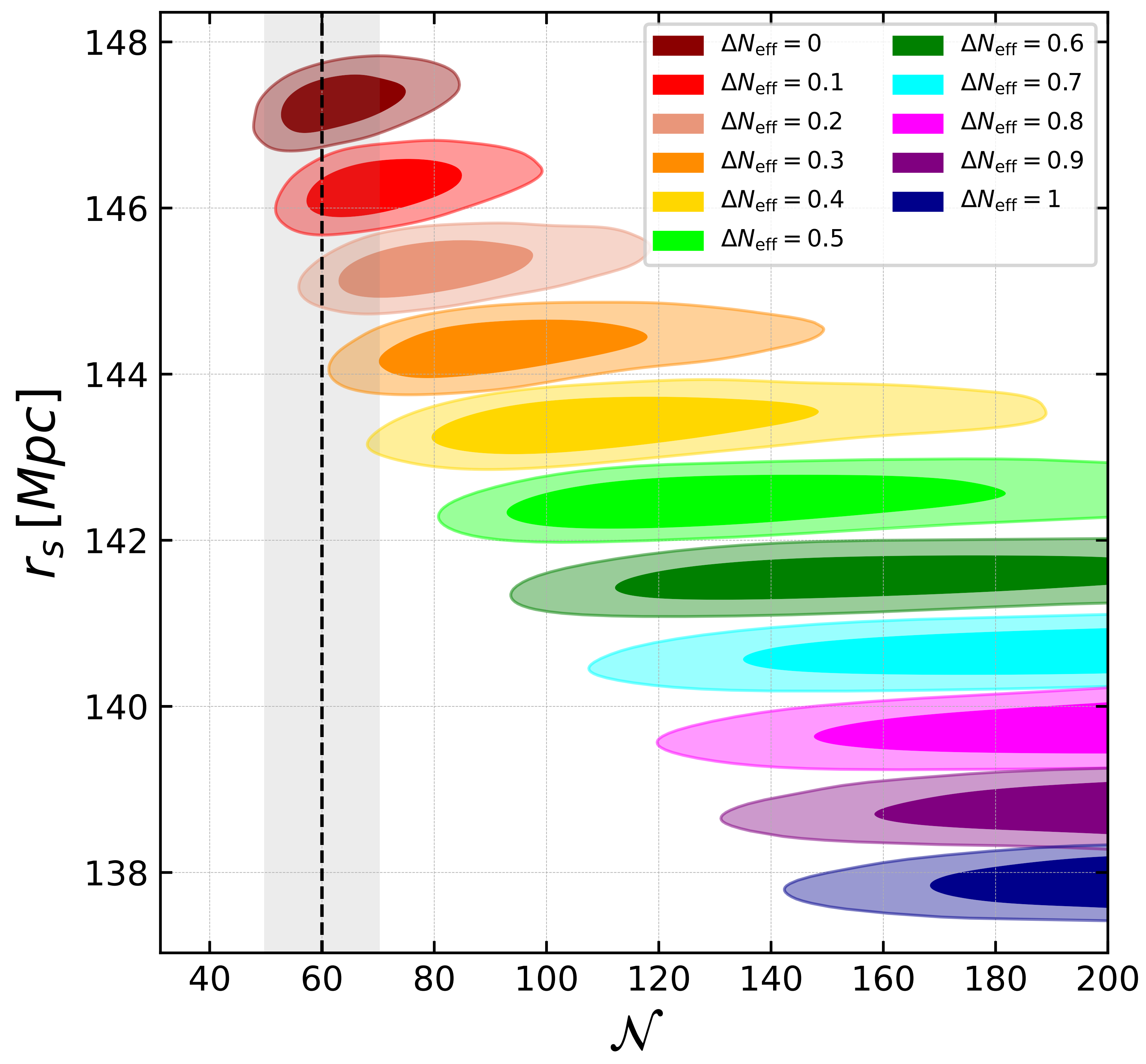
Implications for Starobinsky Inflation

1) Starobinsky inflation gives *predictions* for $n_s = 1 - 2/\mathcal{N}$ and $r = 12/\mathcal{N}^2$

2) Increasing $\Delta N_{\rm eff}$ decreases r_s and increases H_0 thereby shifting $n_s \to 1$.

3) In Starobinsky Inflation this would require $\mathcal{N} \to \infty$

4) It can be no longer supported when considering new physics

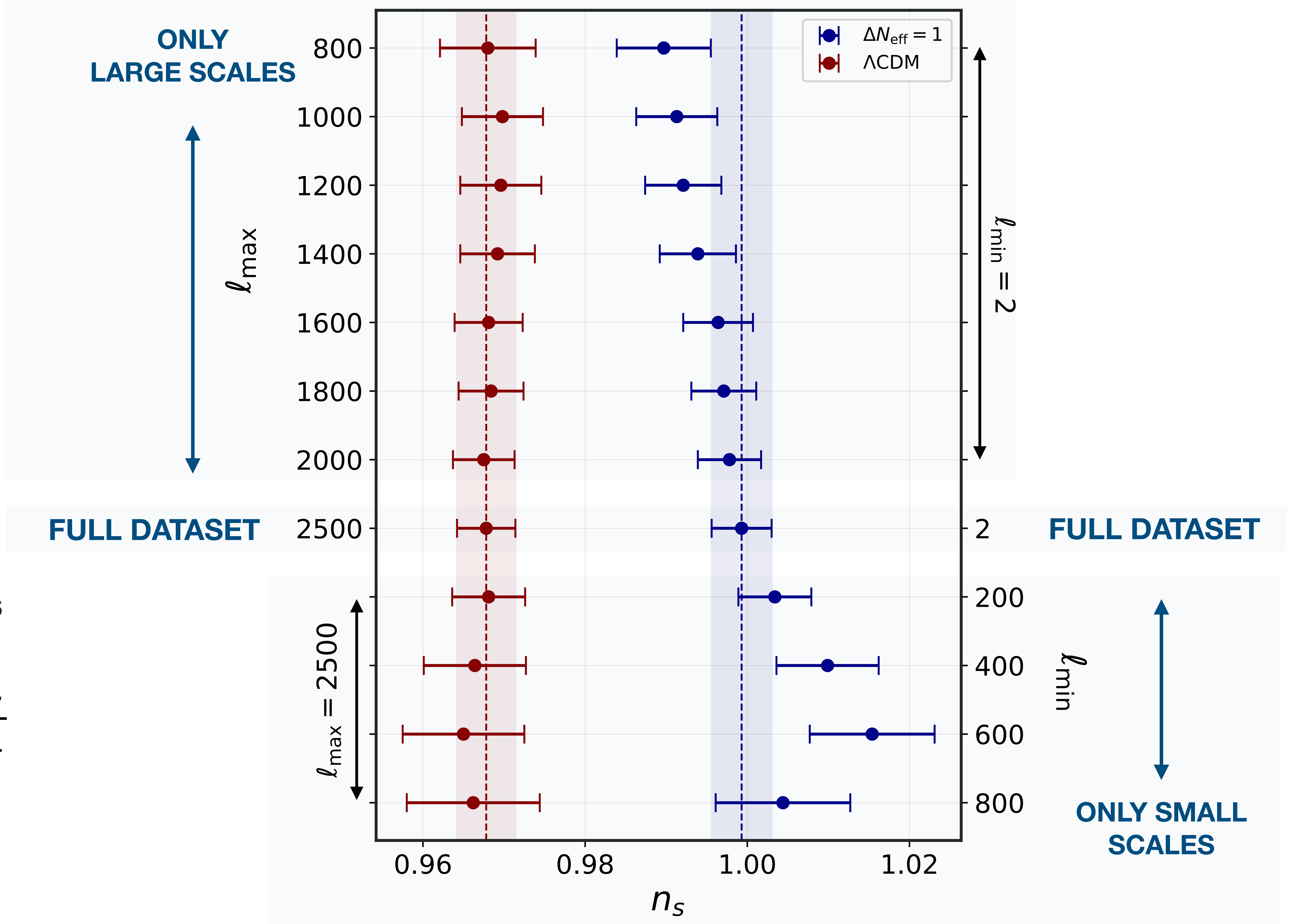


Inflation and Dark Radiation

Planck 2018
1807.06209

BICEP/KEK 2018
2110.00483

WG & Elsa M. Teixeira — in preparation



Domino effect in the CMB fit at different scales

$$\frac{\delta H_0}{H_0} \simeq -\frac{\delta D_A}{D_A} \simeq \frac{\delta k_D}{k_D} \simeq \frac{1}{2}\frac{\delta \omega_{cdm}}{\omega_{cdm}} \simeq \frac{\delta \omega_b}{\omega_b} \simeq \frac{\delta n_s}{0.4}$$

(See also Gen Ye et. al. – 2303.09729)

Inflation and Early Dark Energy

Planck 2018
1807.06209

BICEP/KEK 2018
2110.00483

Early Dark Energy

A light scalar field behaves similarly to a cosmological constant, increasing the expansion rate in the early Universe. Then it must decay faster than matter.

Effects quantified by the maximal fractional contribution to the total energy density

$$f_{\rm EDE} = \max_z \left(\frac{\rho_{\rm EDE}(z)}{\rho_c(z)} \right)$$

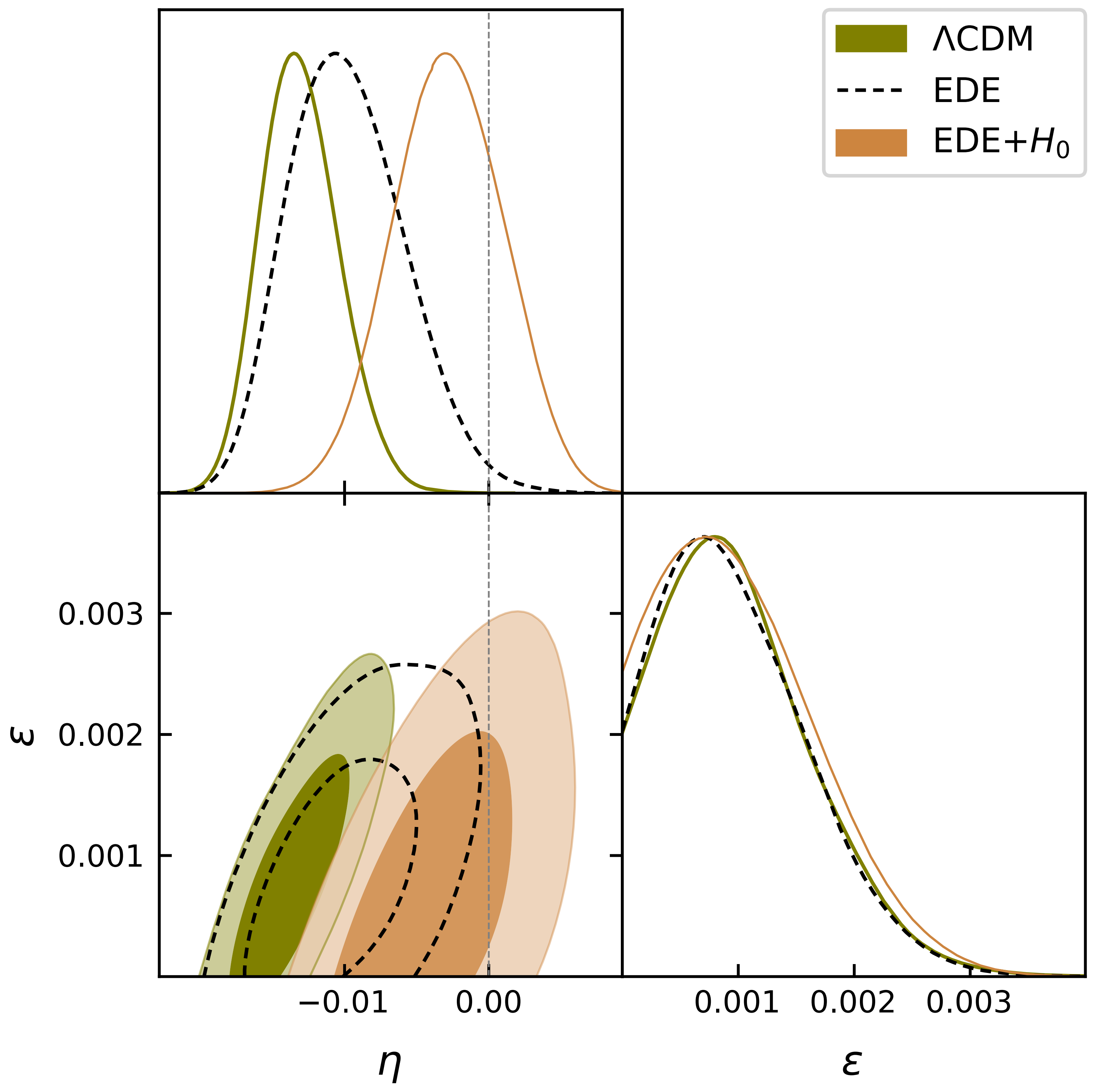
Implications for slow-roll parameters

1) $|\eta| \gg \epsilon$ assuming ΛCDM

2) $|\eta| \gtrsim \epsilon$ for negligible $f_{\rm EDE}$

3) $|\eta| \sim \epsilon$ if EDE solves the H_0 tension

WG — PRD 109 (2024) 12, 12354 • arXiv: 2404.12779



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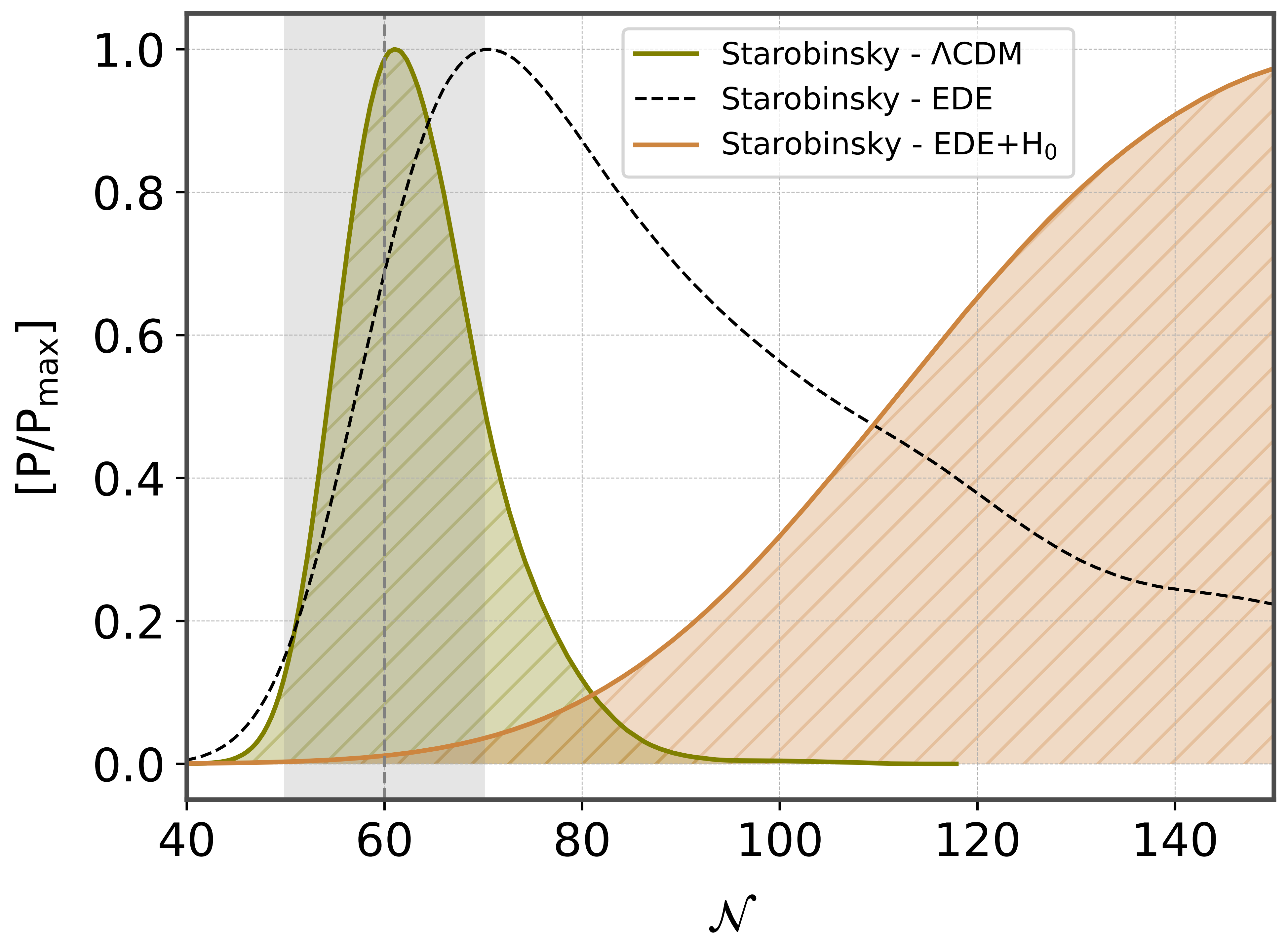
Implications for Starobinsky inflation

1) Perfect agreement with Planck+BICEP/KEK assuming ΛCDM

2) Can be in agreement with Planck+BICEP/KEK for negligible f_{EDE}

3) **NOT** in agreement with Planck+BICEP/KEK if EDE solves the H_0 tension

WG — PRD 109 (2024) 12, 12354 • arXiv: 2404.12779



Inflation and Early Dark Energy

Planck 2018
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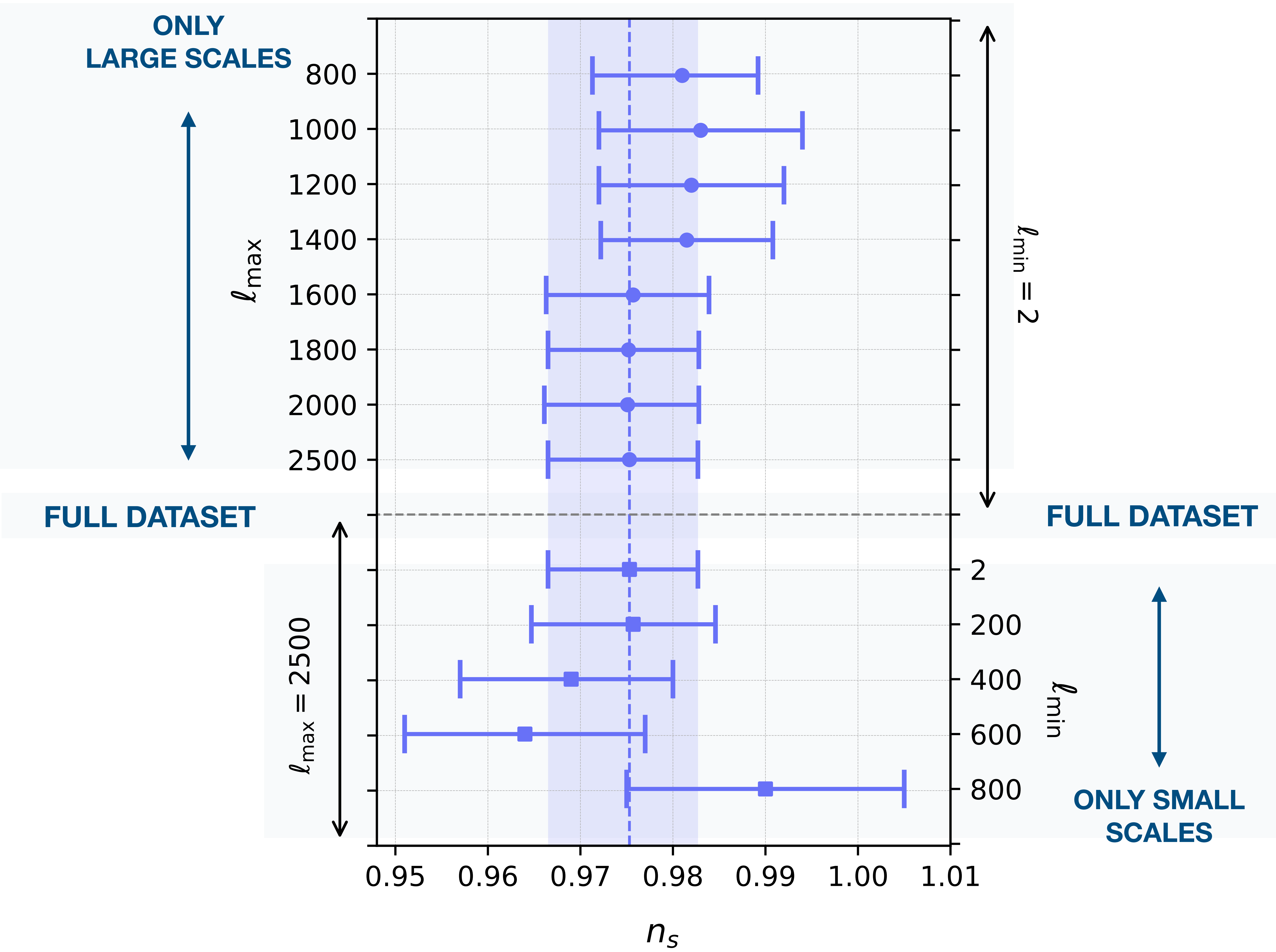
WG & Elsa M. Teixeira — in preparation



Inflation and Early Dark Energy

Atacama Cosmology Telescope

2007.07288

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Hints of New Physics in small-scale CMB data?

1) ACT small-scale CMB data give $n_s \sim 1$

2) ACT small-scale CMB data give $f_{\rm EDE} \neq 0$

3) Assuming new physics, both large and small CMB data prefer larger n_s

Parameter	EDE ($n=3$) Best-Fit	EDE ($n=3$) Marg.
$\log(10^{10}A_s)$	3.083	3.067 ± 0.034
n_s	1.064	$0.987^{+0.027}_{-0.047}$
$100\theta_s$	1.04279	1.04247 ± 0.00079
$\Omega_b h^2$	0.02214	$0.02141^{+0.00044}_{-0.00065}$
$\Omega_c h^2$	0.1425	$0.1307^{+0.0054}_{-0.0120}$
$\tau_{\rm reio}$	0.061	0.065 ± 0.015
y_p	0.9951	1.0037 ± 0.0070
$f_{\rm EDE}$	0.241	$0.142^{+0.039}_{-0.072}$
$\log_{10}(z_c)$	3.72	< 3.70
θ_i	2.97	> 0.24
H_0 [km/s/Mpc]	77.6	$74.5^{+2.5}_{-4.4}$
Ω_m	0.274	$0.276^{+0.020}_{-0.023}$
σ_8	0.883	$0.831^{+0.027}_{-0.043}$
S_8	0.844	0.796 ± 0.049
$\log_{10}(f/\text{eV})$	26.65	$27.17^{+0.34}_{-0.55}$
$\log_{10}(m/\text{eV})$	-26.90	$-27.52^{+0.26}_{-0.72}$

Colin Hill et. al. (ACT) – 2109.04451

Inflation and Late Time Solutions

Planck 2018
1807.06209

BICEP/KEK 2018
2110.00483

WG — PRD 109 (2024) 12, 12354 • arXiv: 2404.12779

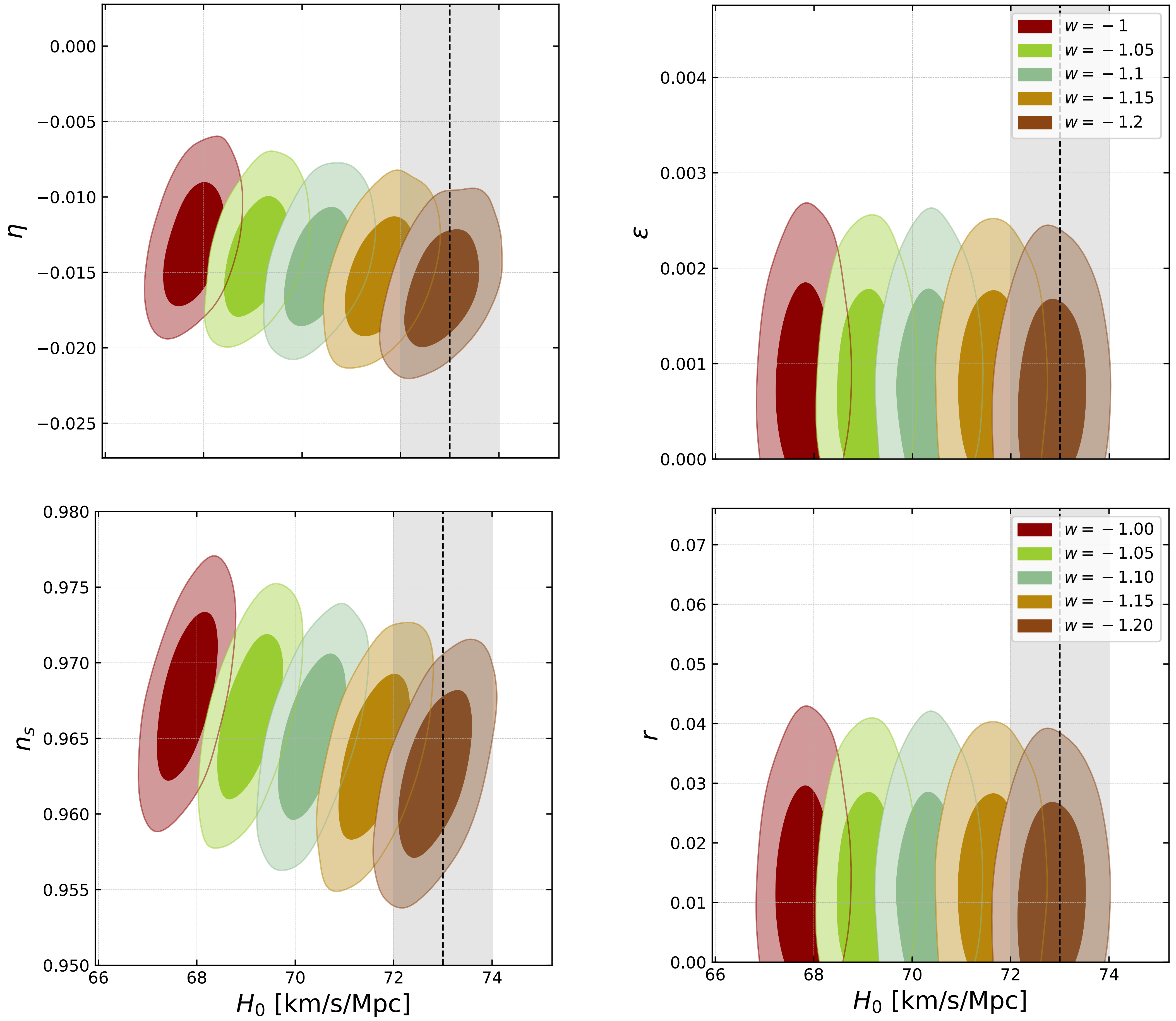
Late Time Solutions in a Nutshell

If some **New Physics** **decreases the late-time expansion rate** while leaving $r_s(z_*)$ fixed, H_0 **should increase to keep θ_s fixed**

$$\theta_s = \frac{r_s(z_{\rm CMB})}{D_A(z_{\rm CMB})}$$

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

$$D_A(z_*) = \frac{1}{H_0} \int_0^{z_*} \frac{dz}{\left[\Omega_m (1+z)^3 + \Omega_{\rm DE} (1+z)^{3(1+w)}\right]^{1/2}}$$



How?

A naive way to decrease the late-time expansion rate would be to consider a phantom Dark Energy equation of state $w < -1$

$$H(z) \simeq H_0 \left[\Omega_m (1+z)^3 + \Omega_{\rm de} (1+z)^{3(1+w)}\right]^{1/2}$$