Cosmology from the Smallest scales

Workshop on Tensions in Cosmology

Corfù - September, 11 2023

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OVERVIEW

PART 1

CONCORDANCE COSMOLOGY QUANDARIES

Part 1 in one line:

We point out some challenges of ΛCDM cosmology, including anomalies from different CMB measurements

PART 2

THREE HINTS OF NEW PHYSICS FROM THE SMALLEST SCALES

Part 2 in one line:

We provide and discuss 3 examples of emerging hints of new physics from the smallest scales

PART 3

OUTLOOKS AND CONCLUSIONS

Part 3 in one line:

We summarise the main conclusions

1 Concordance Cosmology Quandaries

Objective:

We highlight challenges of ΛCDM cosmology, including emerging **anomalies from** the most recent CMB measurements released by the **Planck satellite** and the **Atacama Cosmology Telescope (ACT)**, and **studying their *overall* consistency**.

Main References of Part 1:

- **2209.12872** — E. Di Valentino, **WG,** A. Melchiorri, J. Slik,
- **2209.14054** — E. Di Valentino, **WG,** A. Melchiorri, J. Slik,
- **2305.16919** — **WG**

My pictorial representation of ΛCDM cosmology

ΛCDM Cosmology

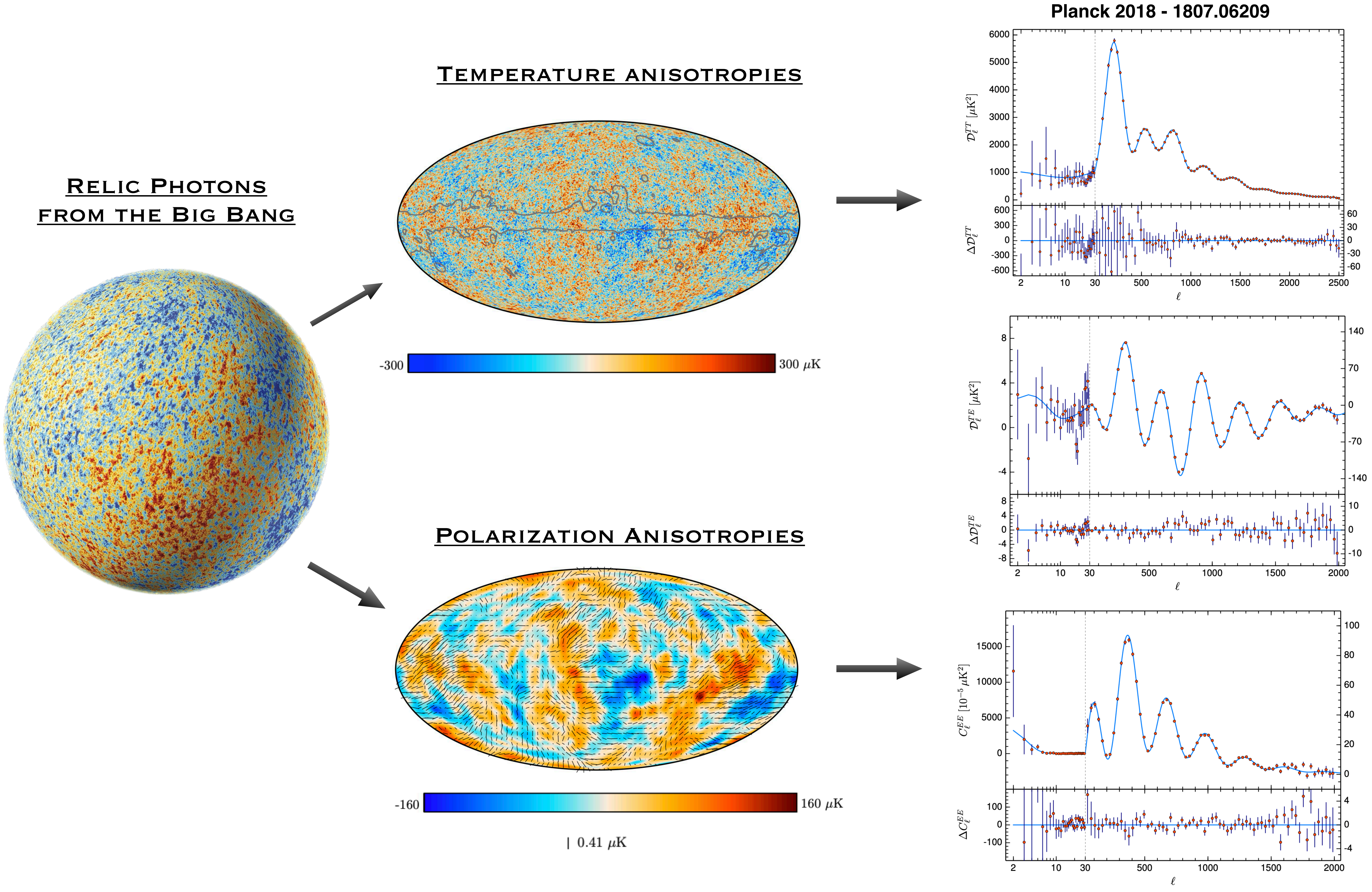
General Relativity
to describe gravitational interactions

Standard Model
To describe fundamental interactions

Inflation
to explain spatial flatness, homogeneity on large scales and inhomogeneities on small-scales.

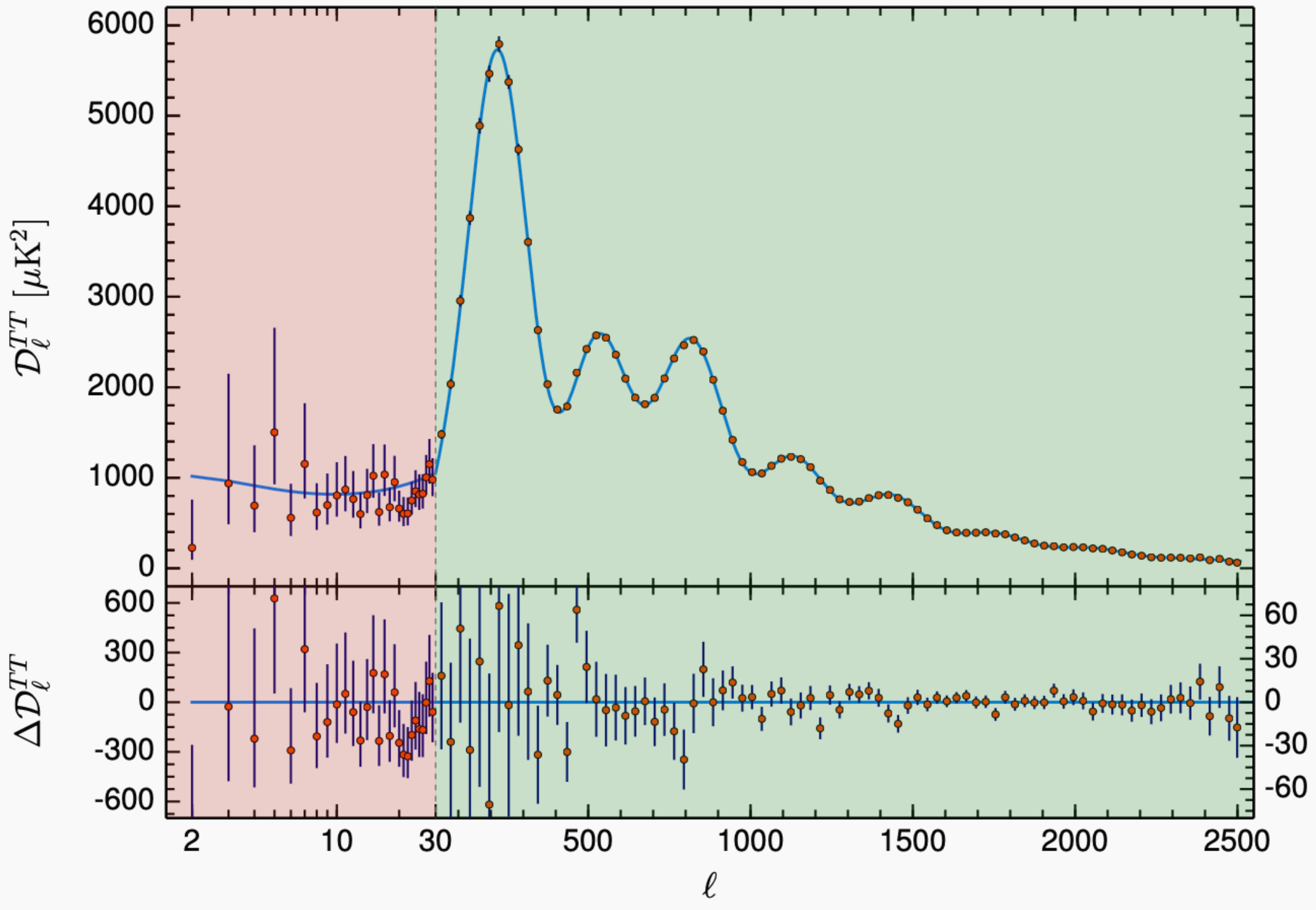
Cold Dark Matter
to Facilitate structure formation and explain the observational evidence for a missing mass in the Universe

Dark Energy (cosmological constant Λ)
to explain the late time accelerated expansion of the Universe


Planck 2018 - 1807.06209
Relic Photons
from the Big Bang
Temperature anisotropies
-300
300 μK
Polarization Anisotropies
-160
160 μK
| 0.41 μK

Planck 2018 - 1807.06209

Temperature Anisotropies

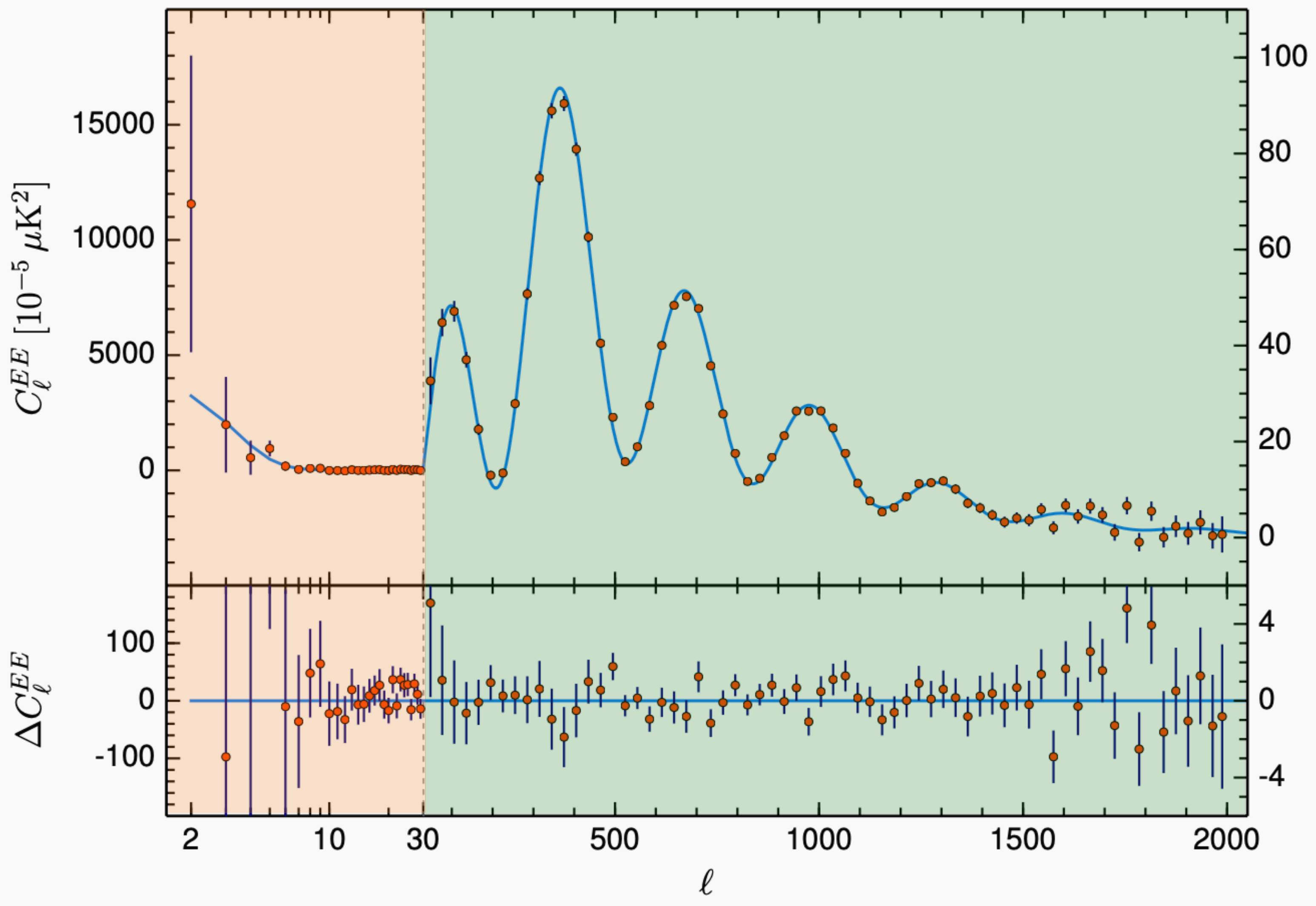


Low-multipole temperature data

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

Low-T

E-Mode Polarization

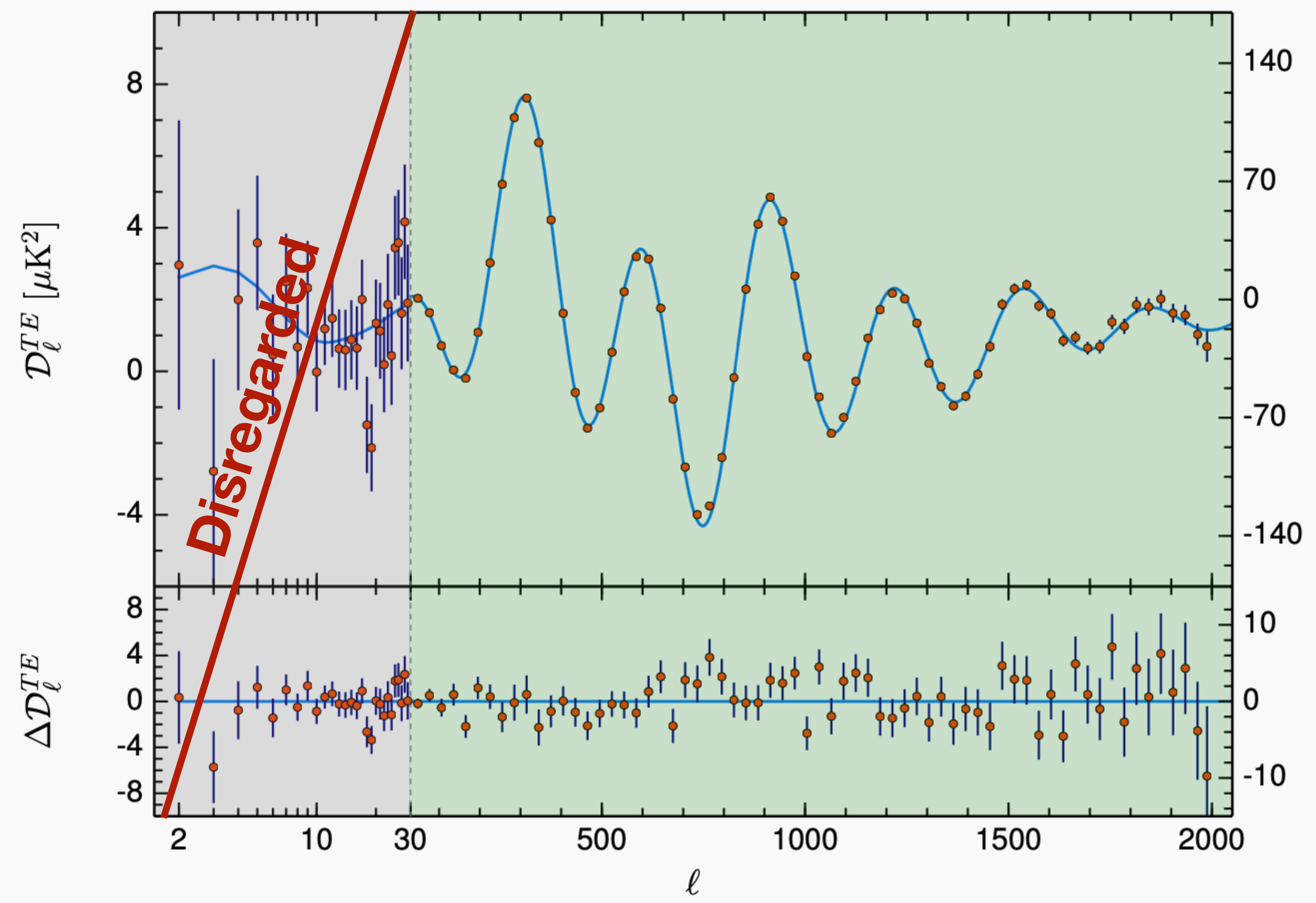


Low-multipole Polarization data

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

Low-E

TE Spectrum



Disregarded

~~**Low-multipole TE data**~~

~~$2 \leq \ell \lesssim 30$ 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

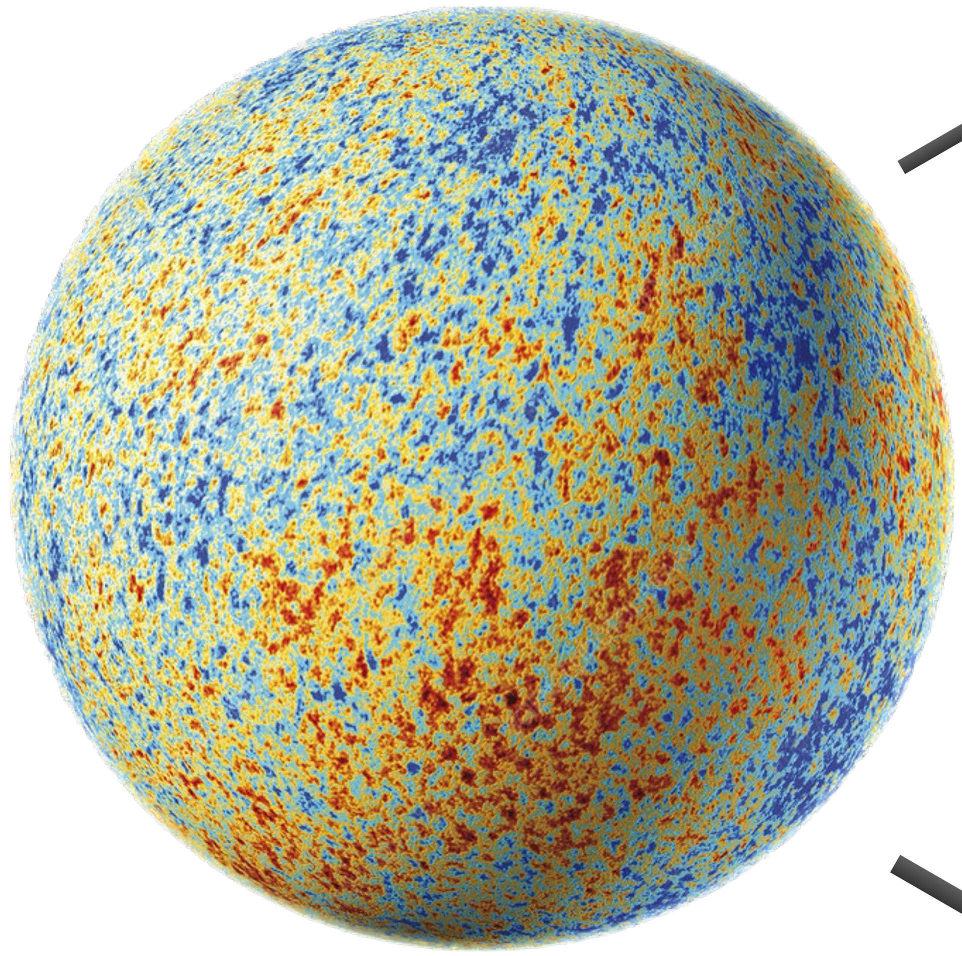
$30 < \ell \lesssim 2000$ in the EE Spectrum

High-multipole TE data

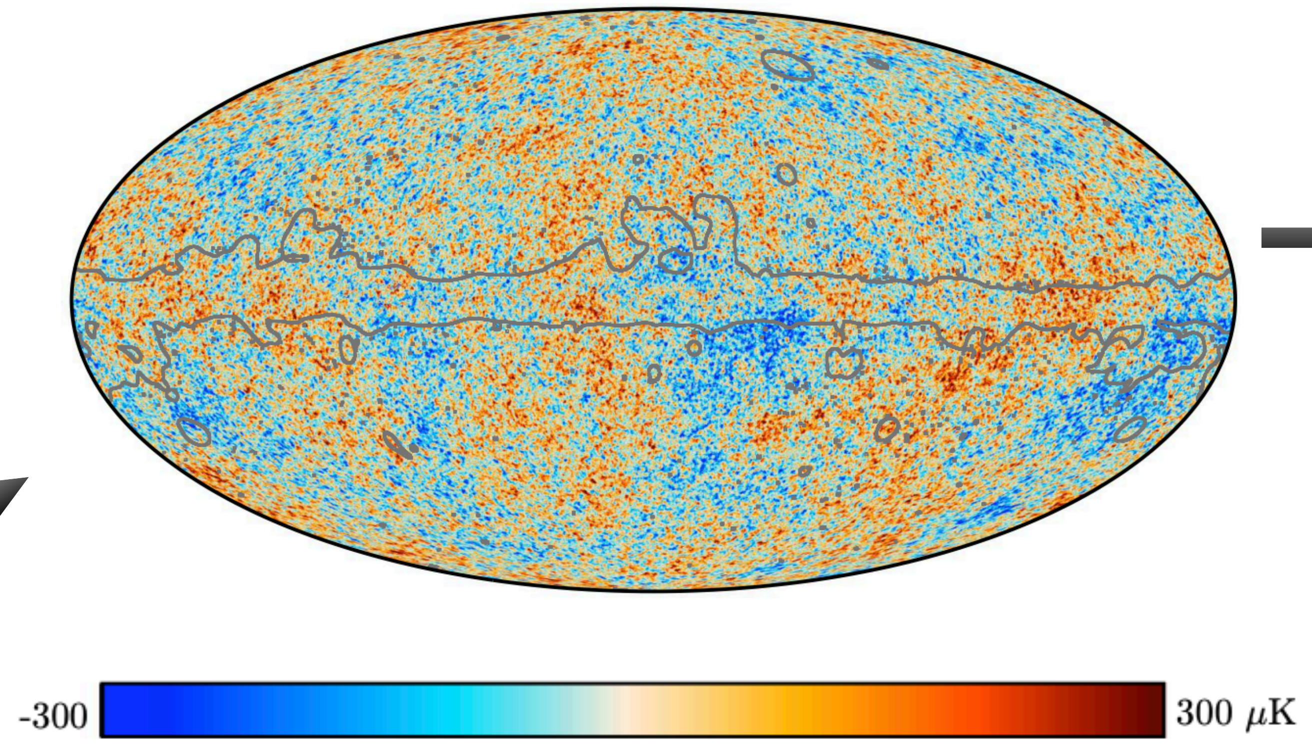
$30 < \ell \lesssim 2000$ in the TE Spectrum

TT-TE-EE

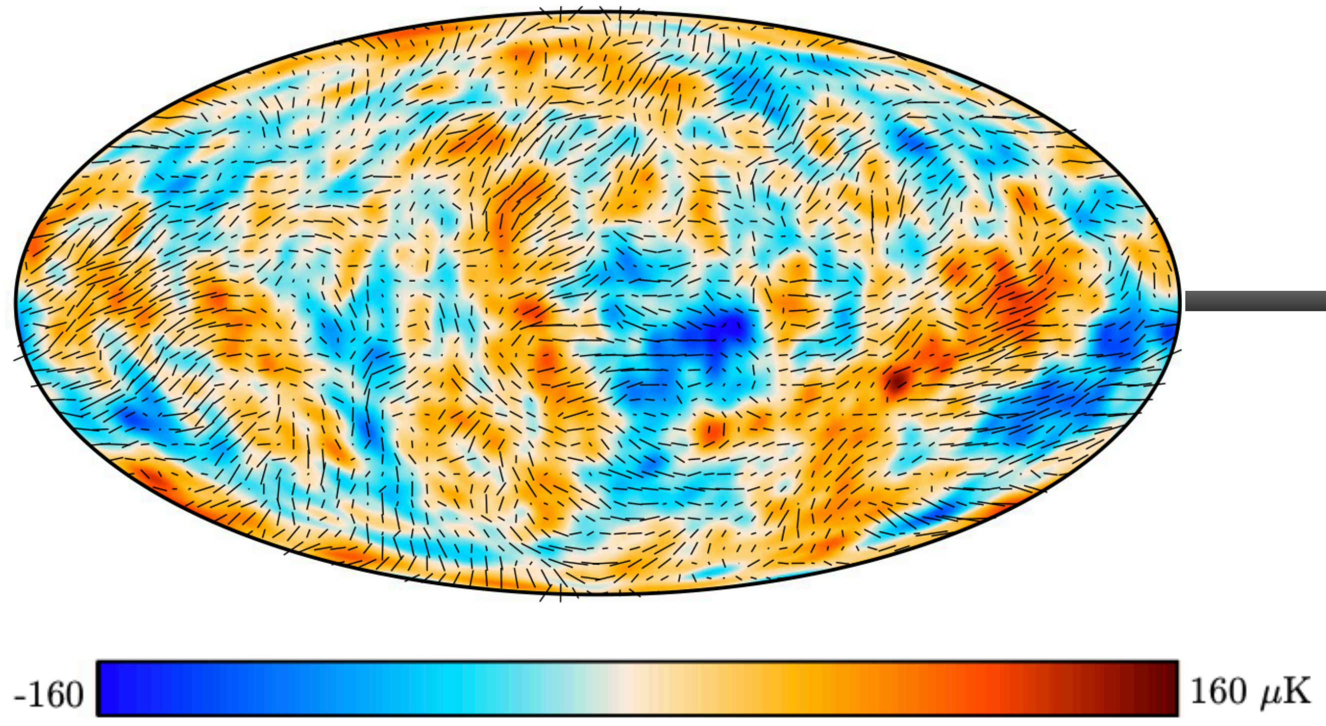
Relic Photons from the Big Bang



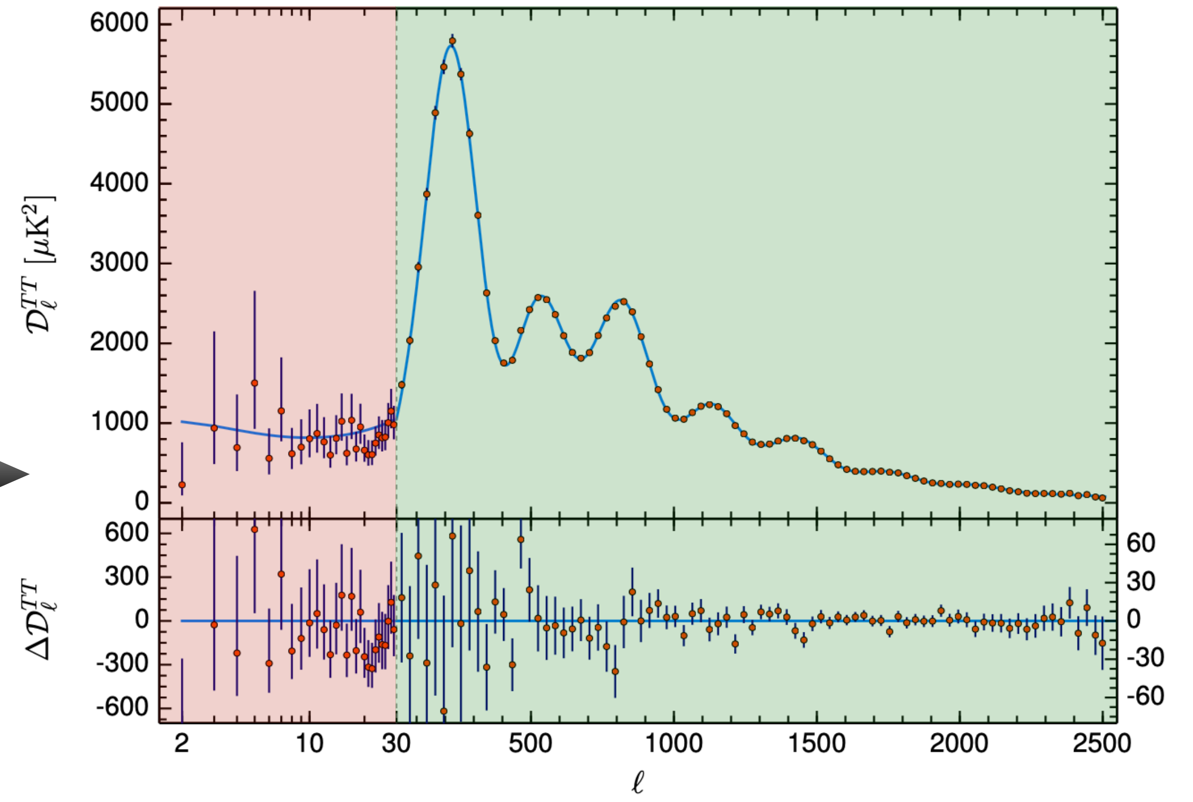
Temperature anisotropies

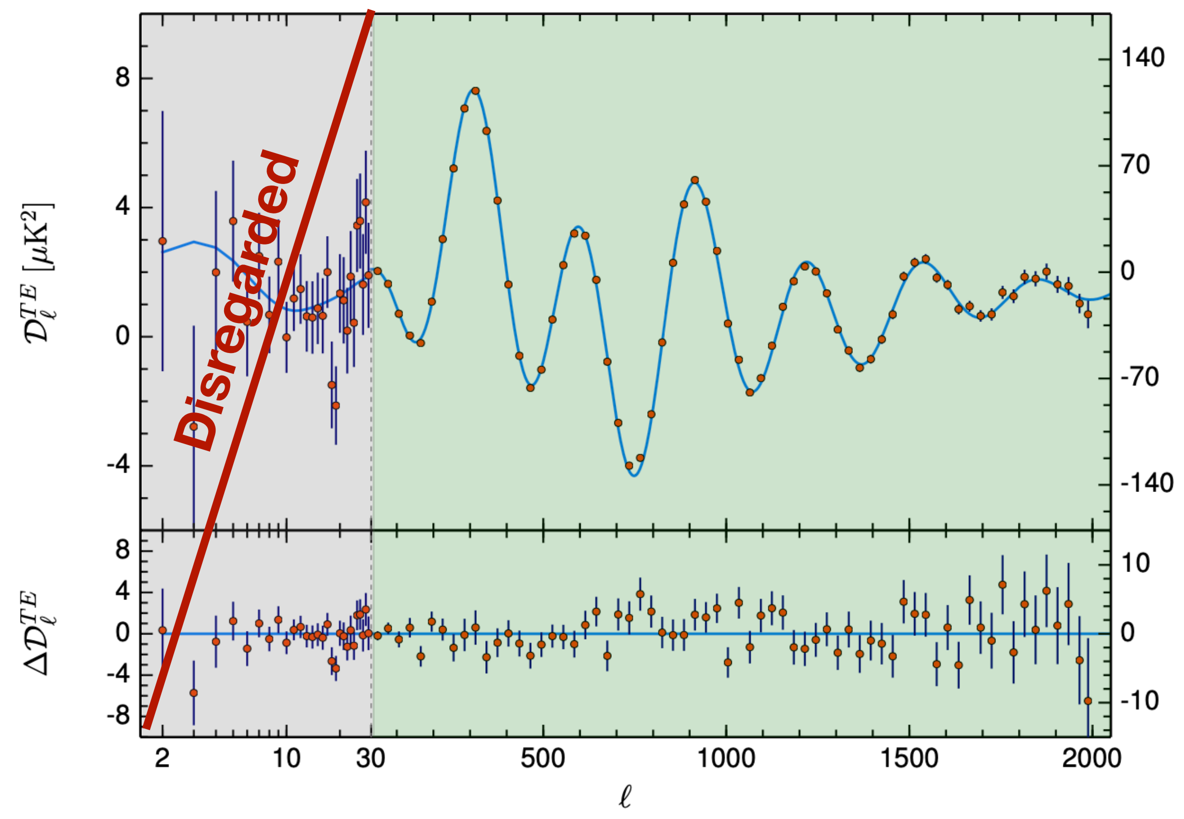


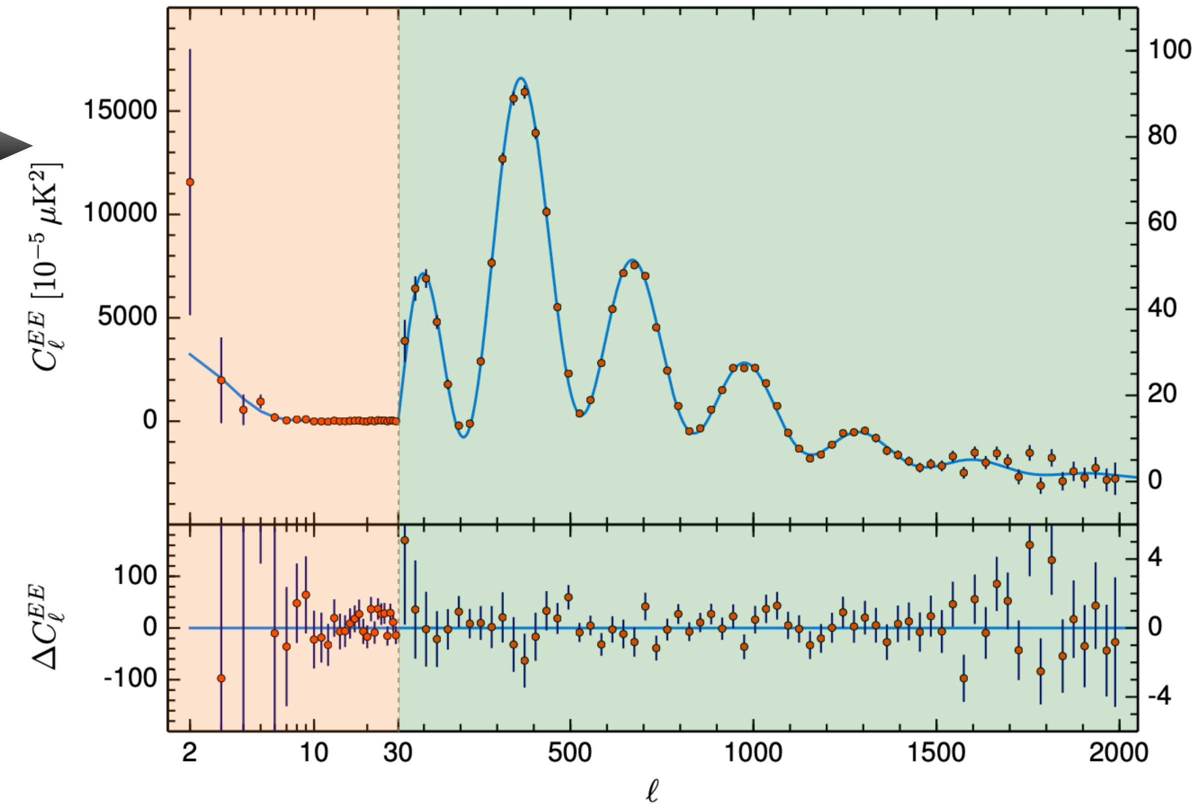
Polarization anisotropies



Planck 2018 - 1807.06209







Planck 2018 - 1807.06209

Results for
TT-TE-EE+low-T+low-E

$\Omega_b h^2$	0.02236 ± 0.00015
$\Omega_c h^2$	0.1202 ± 0.0014
$100\theta_{MC}$	1.04090 ± 0.00031
τ	$0.0544^{+0.0070}_{-0.0081}$
$\ln(10^{10} A_s)$	3.045 ± 0.016
n_s	0.9649 ± 0.0044
H_0 [km s^{-1} Mpc^{-1}] . .	67.27 ± 0.60
Ω_Λ	0.6834 ± 0.0084
Ω_m	0.3166 ± 0.0084
$\Omega_m h^2$	0.1432 ± 0.0013
$\Omega_m h^3$	0.09633 ± 0.00029
σ_8	0.8120 ± 0.0073
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$.	0.834 ± 0.016
$\sigma_8 \Omega_m^{0.25}$	0.6090 ± 0.0081
z_{re}	7.68 ± 0.79
$10^9 A_s$	$2.101^{+0.031}_{-0.034}$
$10^9 A_s e^{-2\tau}$	1.884 ± 0.012
Age [Gyr]	13.800 ± 0.024
z_*	1089.95 ± 0.27
r_* [Mpc]	144.39 ± 0.30
$100\theta_*$	1.04109 ± 0.00030
z_{drag}	1059.93 ± 0.30
r_{drag} [Mpc]	147.05 ± 0.30
k_D [Mpc^{-1}]	0.14090 ± 0.00032
z_{eq}	3407 ± 31
k_{eq} [Mpc^{-1}]	0.010398 ± 0.000094
$100\theta_{s,eq}$	0.4490 ± 0.0030

Hubble Tension

The tension between the value of the Hubble parameter as directly measured by using local distance ladder measurements of Type Ia supernova and the value inferred by CMB observations reached the level of 5σ

How do we measure H_0 for the CMB?

- **The angular size of the sound horizon (θ_s)**
- **The baryon density ($\Omega_b h^2$)**
- **The cold dark matter density ($\Omega_c h^2$)**

Model of Early Universe

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

- **The sound horizon (r_s)**
- **The Distance from the CMB ($D_A = r_s / \theta_s$)**

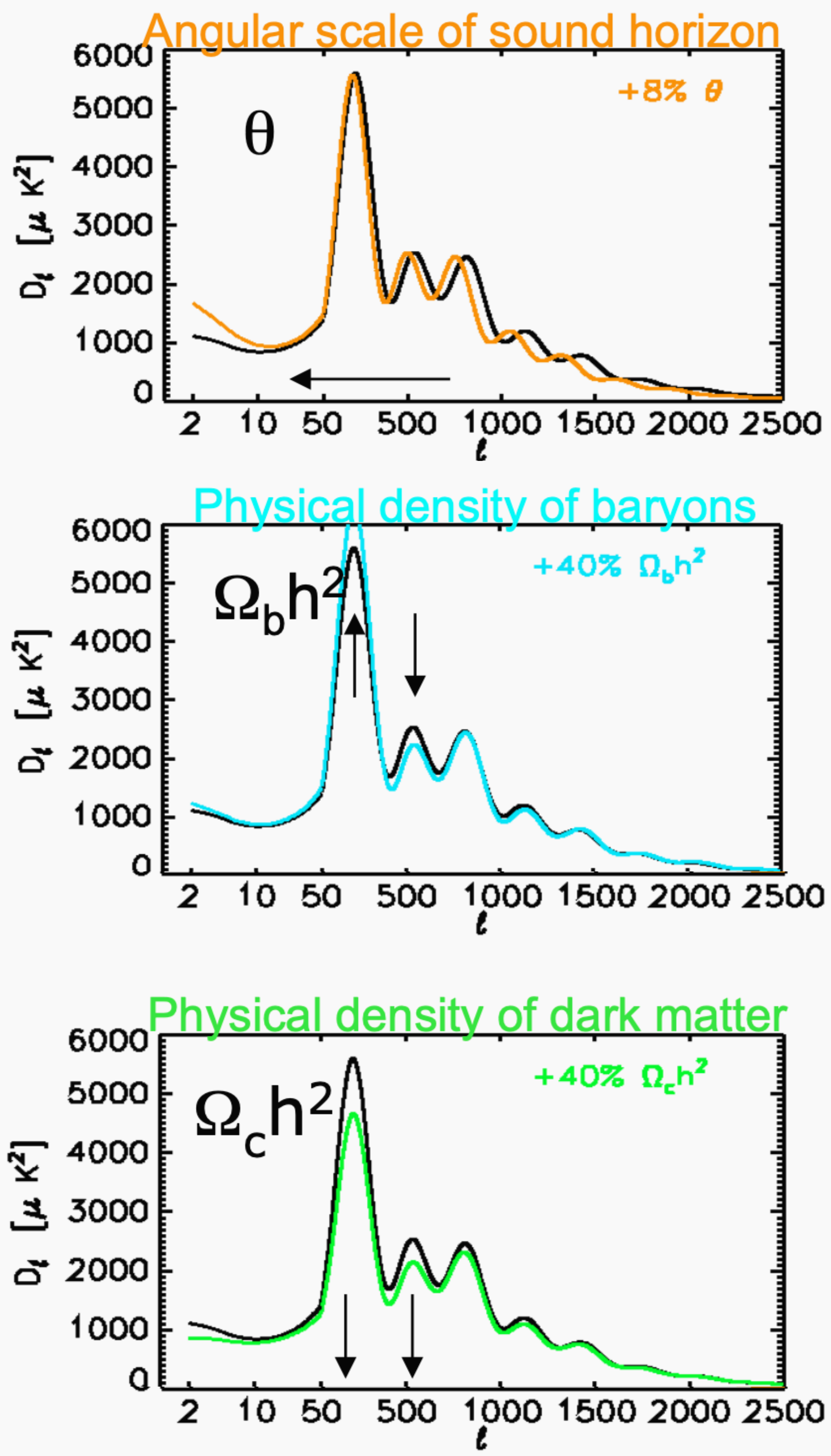
Model of Late Universe

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

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

- **The Hubble Parameter (H_0)**

S. Galli
'The H_0 debate form a CMB prospective'



CMB Anomalies

CMB observations have achieved sub-percent accuracy.

While this is a blessing, it also represents a challenge: as precision increases, any deviations or anomalies may become more statistically significant and point to tensions in our understanding of the Universe

Planck

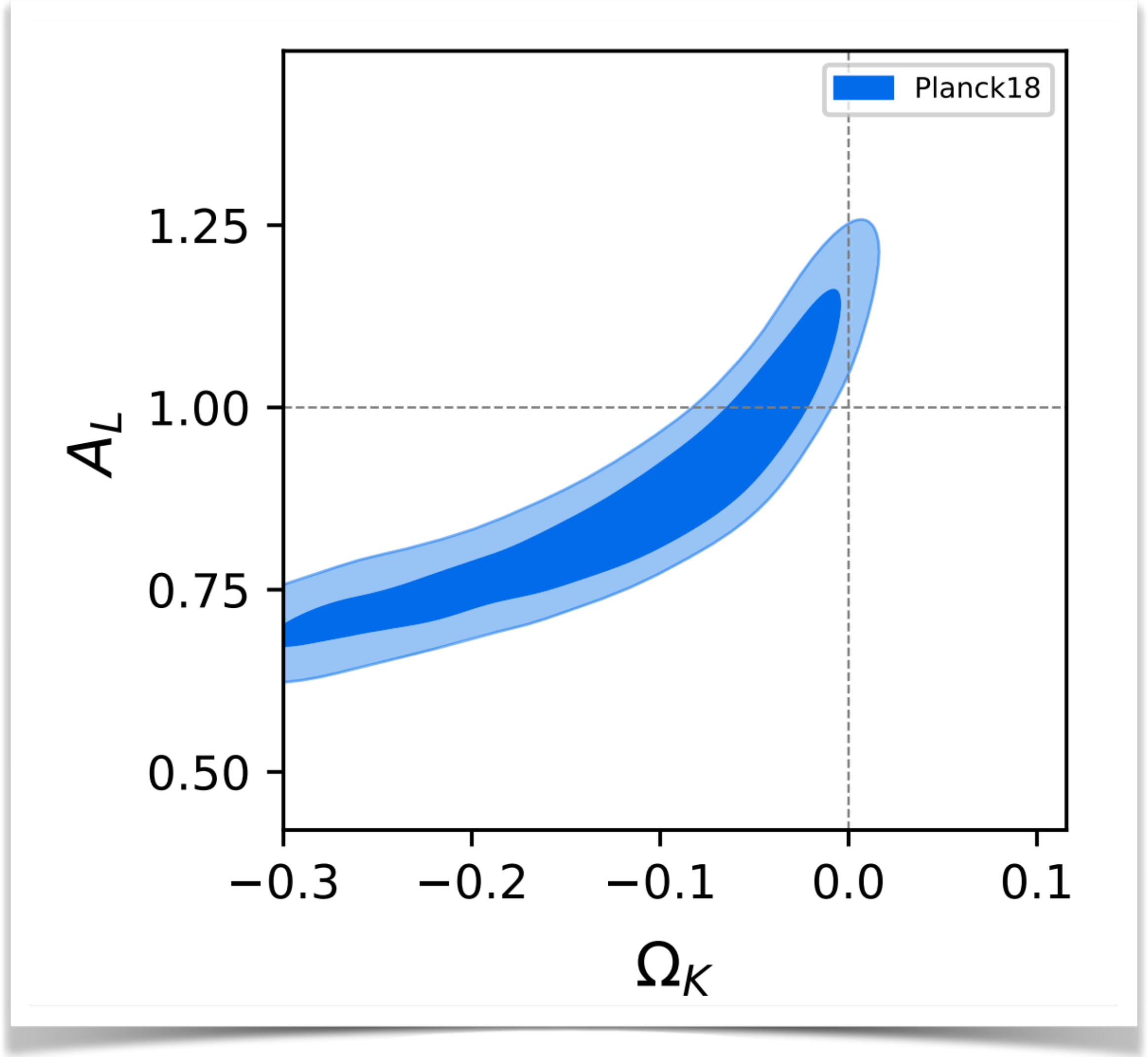
In recent years, CMB data released by the Planck Collaboration have unveiled a few mild anomalies that have become the subject of intense study and debate:

- Preference for a **higher lensing amplitude** at about 2.8 standard deviations observed in the Planck Temperature and Polarization data

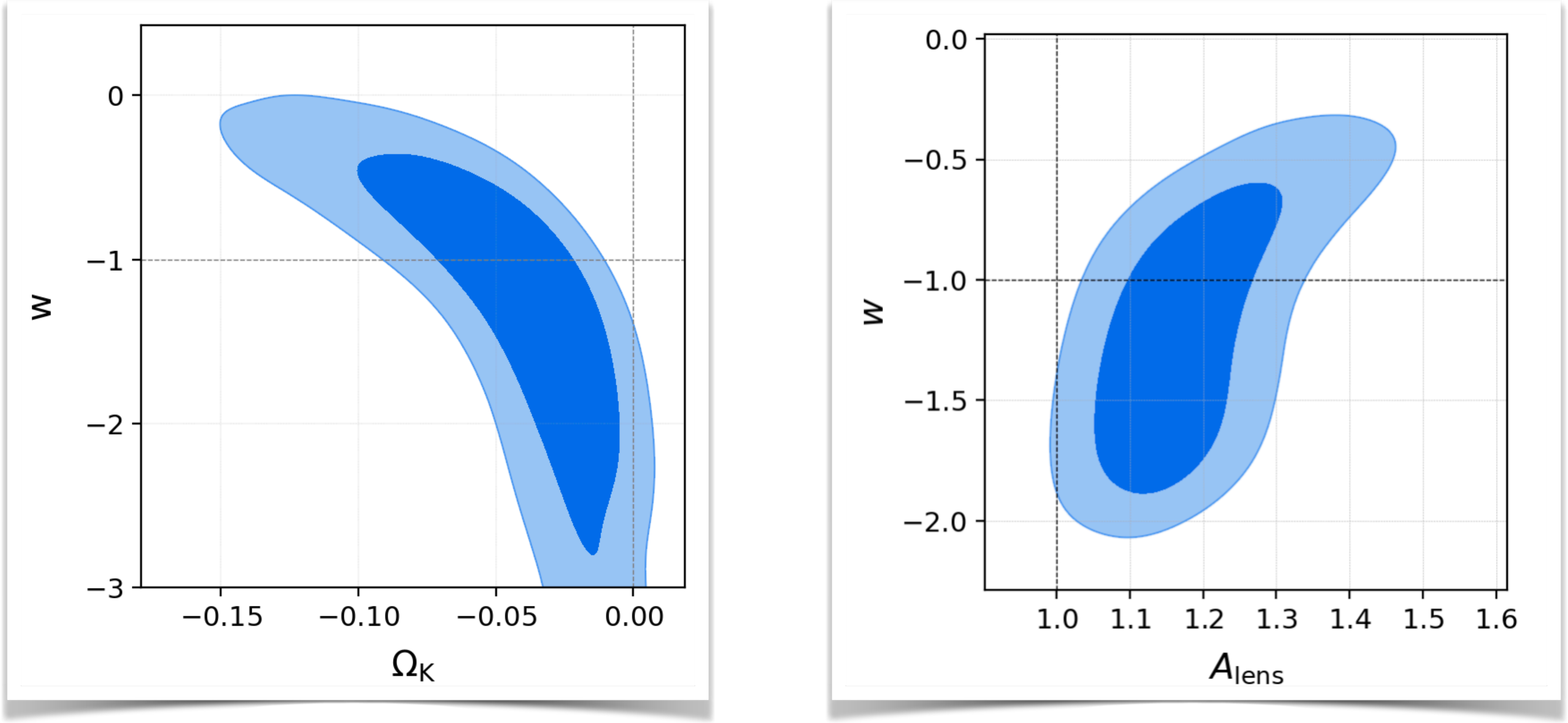
- Indication for a **closed Universe** at the level of 3.4 standard deviations in the Planck Temperature and Polarization data

- A mild preference (~95% CL) for a **phantom Dark Energy** equation of state (**w<-1**)

E. Di Valentino *et al,* - 1911.02087



L.A. Escamilla, WG, *et al,* - 2307.14802



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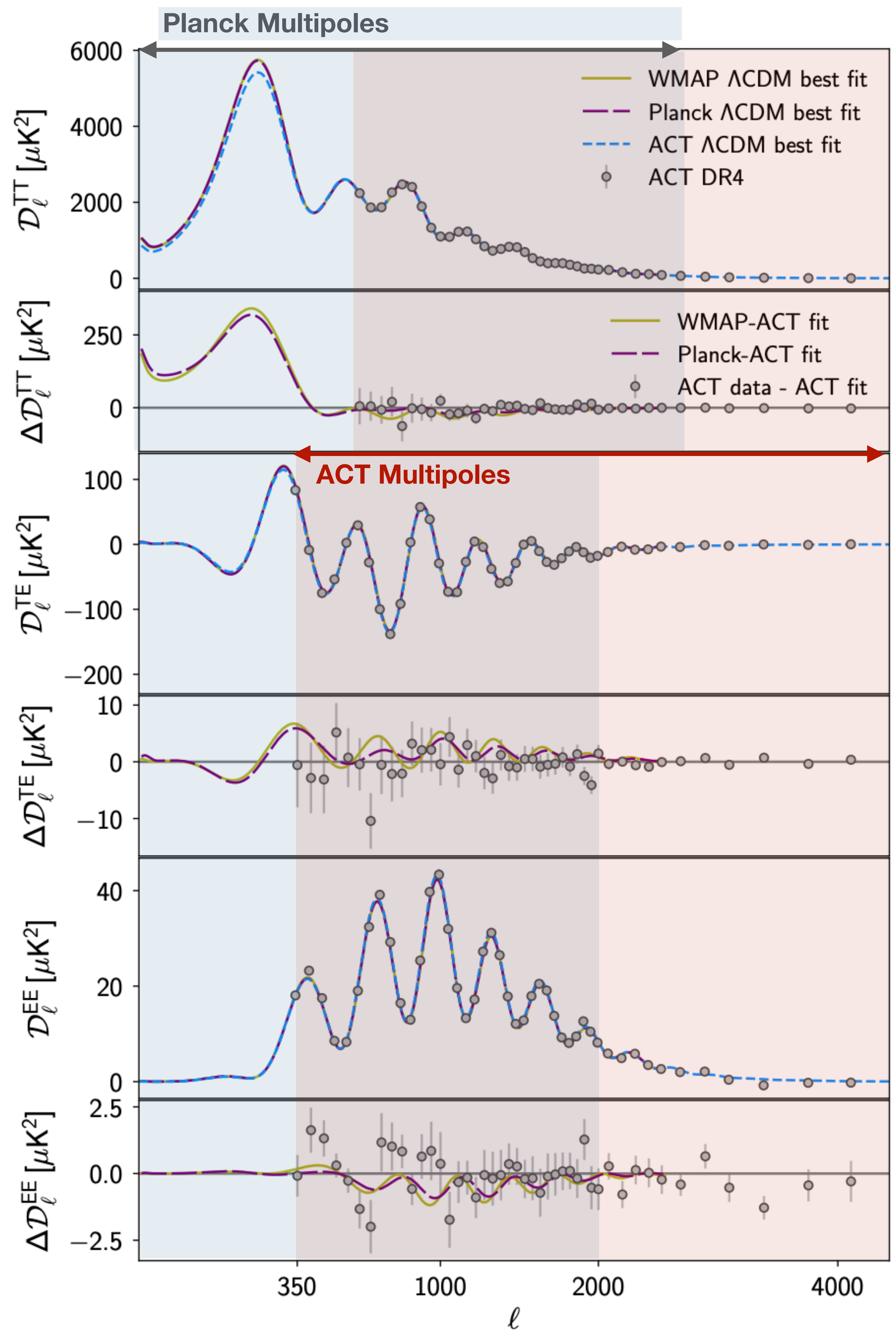
Atacama Cosmology Telescope (ACT)

Same Observables as Planck, but at smaller angular scales (higher multipoles = smaller scales)

- **High-multipole temperature data**
  $650 < \ell \lesssim 4200$ in the TT Spectrum
- **High-multipole EE Polarization data**
  $350 < \ell \lesssim 4200$ in the EE Spectrum
- **High-multipole TE data**
  $350 < \ell \lesssim 4200$ in the TE Spectrum

While ACT is not as constraining as Planck, this data reach a sensitivity on cosmological parameters comparable to Planck, allowing for precise tests of the results.

ACT-DR4 - 2007.07288



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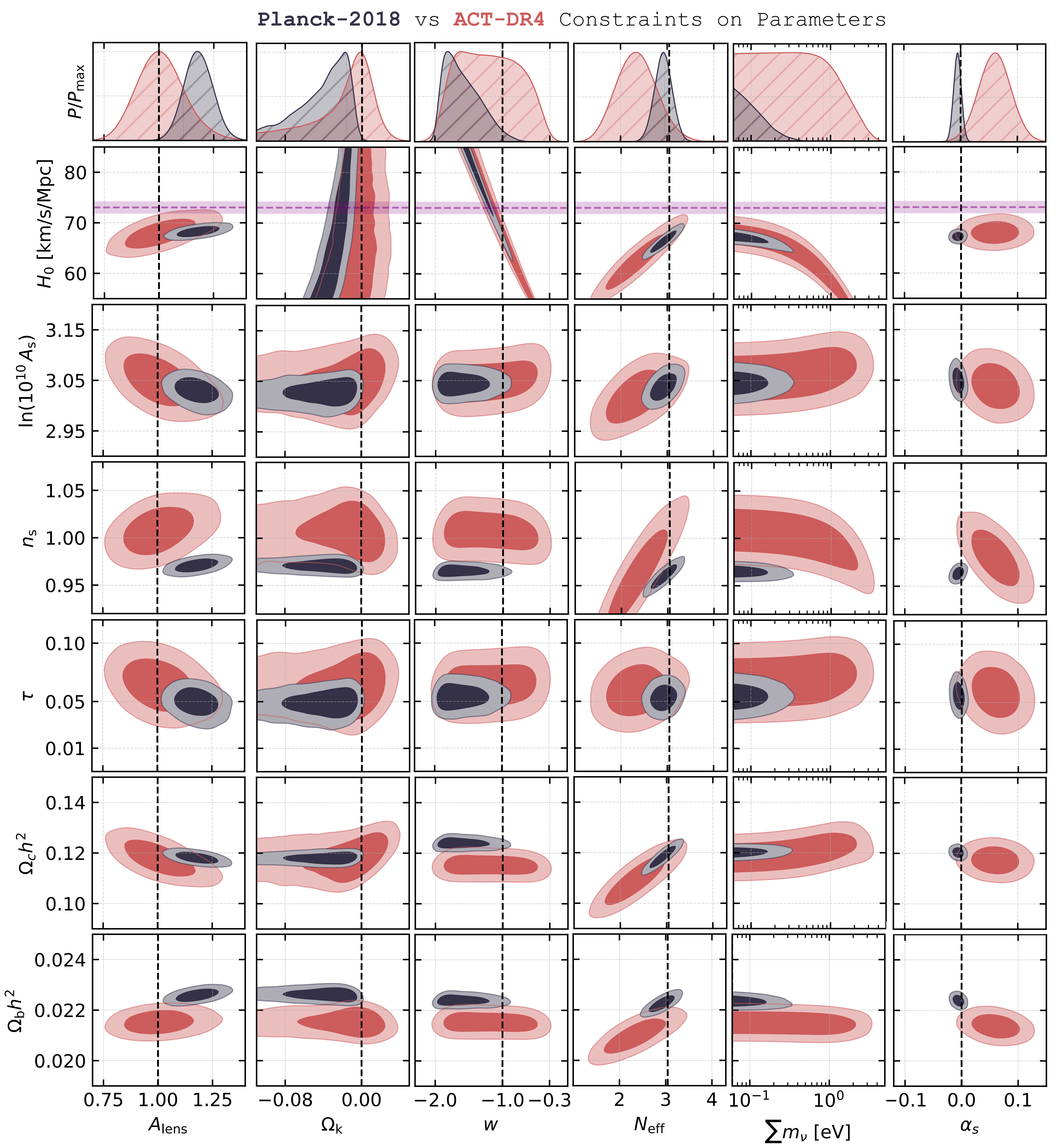
ACT data have provided full support for a spatially flat Universe and a lensing amplitude consistent with ΛCDM, showing, however other relevant deviations from the standard cosmological model:

- Preference for a unitary **spectral index** of primordial perturbations (in tension with Planck at 99.3% CL)
- A smaller **effective number of relativistic degrees of freedom** in the early Universe (in tension with the SM at ~2.5 standard deviations)
- A preference (~2.5 standard deviations) for a **positive running** of the scalar spectral index



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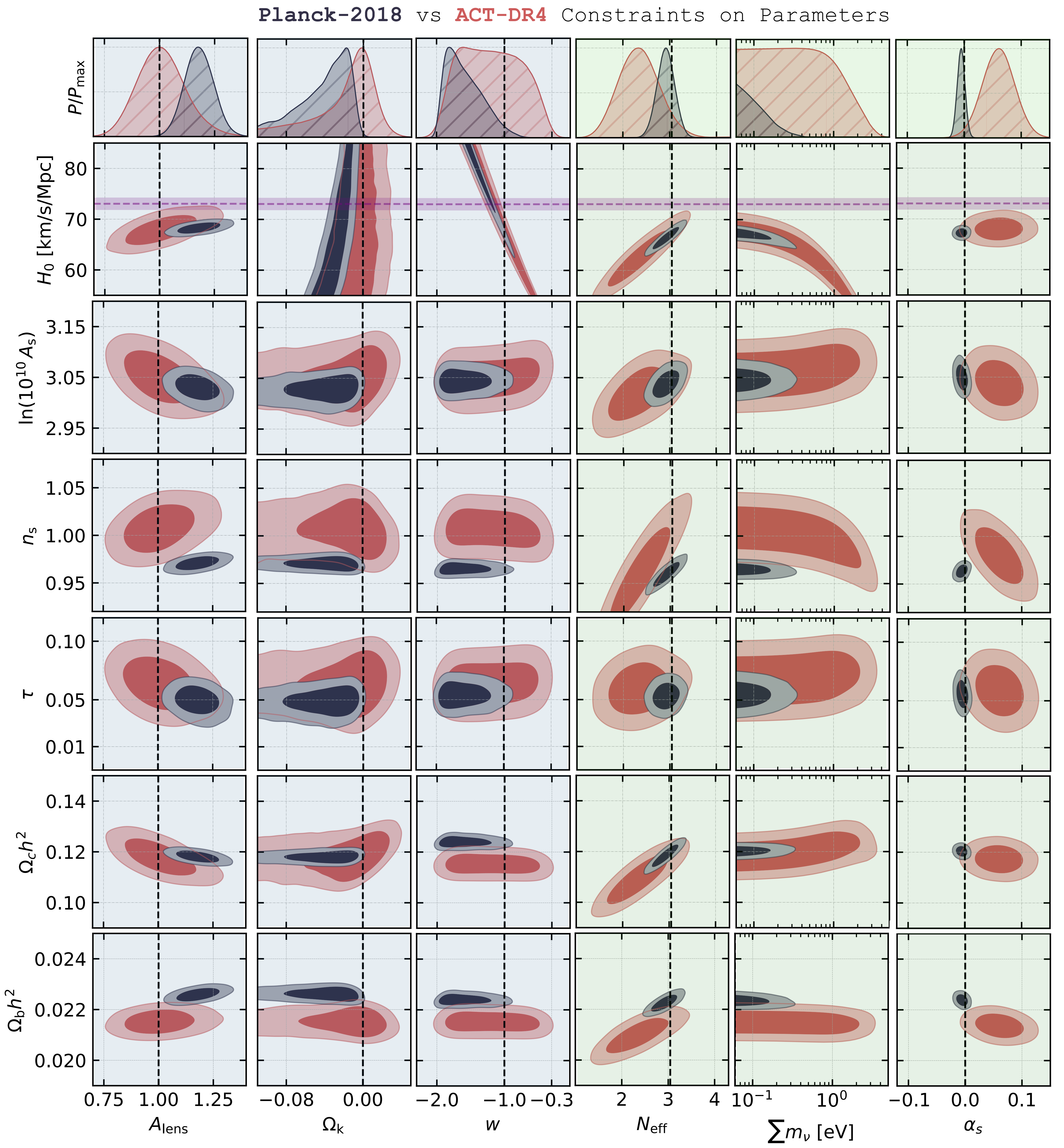
- A preference (~2.5 standard deviations) for a **positive running** of the scalar spectral index

Planck anomalies ***always*** involve parameters associated with the **local Universe** such as the lensing amplitude, the spacetime geometry, and the dark energy equation of state. **[Cleaned away by Astrophysical data!]**

ACT anomalies ***always*** involve parameters associated with the ***early Universe*** such as the baryon energy density, the spectral index, its running, and N_{eff}. **[NOT cleaned away by Astrophysical data!]**

Planck Anomalies <-> Local Universe

ACT Anomalies <-> Early Universe



Evaluating the global consistency

What makes CMB anomalies difficult to interpret ***individually*** is that different experiments often point in discordant directions, and none of the most relevant deviations can be cross-validated through independent probes.

Accurate statistical methods have been developed to quantify the ***global*** agreement between experiments under a given model of cosmology

E. Di Valentino, WG, *et al* - 2209.14054

Cosmological model	d	χ^2	p	$\log S$	Tension
ΛCDM	6	16.3	0.012	−5.17	2.51 σ
$\Lambda\mathrm{CDM} + A_{\mathrm{lens}}$	7	18.5	0.00977	−5.77	2.58 σ
$\Lambda\mathrm{CDM} + N_{\mathrm{eff}}$	7	13	0.0719	−3	1.80 σ
$\Lambda\mathrm{CDM} + \Omega_k$	7	16.5	0.0209	−4.75	2.31 σ
wCDM	7	16.8	0.0187	−4.9	2.35 σ
$\Lambda\mathrm{CDM} + \sum m_\nu$	7	20.7	0.00421	−6.86	2.86 σ
$\Lambda\mathrm{CDM} + \alpha_s$	7	20.6	0.00448	−6.78	2.84 σ

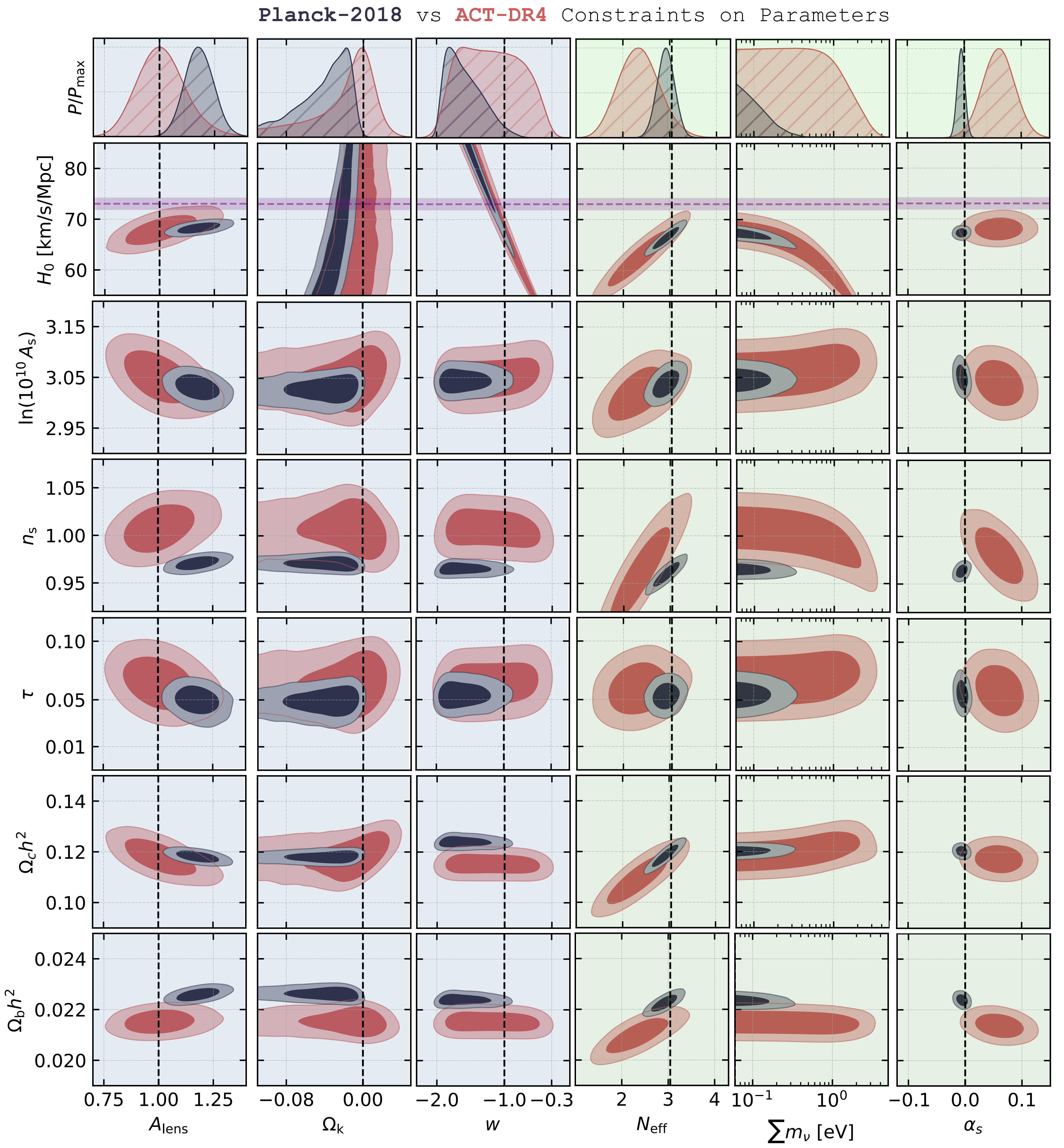
Tension between the two probes is mostly caused by a **mismatch in the early Universe**.

Rerum cognoscere causas

Acquiring a clear understanding of this difference becomes a crucial need in relation to different emerging **hints for new physics** that often call for a new paradigm shift in cosmology while relying almost entirely on the resilience of such observations.

WG - 2305.16919

Planck Anomalies <-> Local Universe | ACT Anomalies <-> Early Universe



2 Three Hints of New Physics from the smallest scales

Objective:

We discuss **3 hints of new physics** linked to the pillars of the cosmological model, **Inflation**, **Dark Matter** and **Dark Energy.** The first one shows **tensions** among CMB experiments; The second one gets support only from small-scale measurements, with **NO tension** among experiments; the third one shows **agreement** among CMB experiments.

Main References of Part 2:

- **2210.09018** — **WG,** F. Renzi, O. Mena, E. Di Valentino, A. Melchiorri
- **2305.15378** — **WG,** S. Pan, E. Di Valentino, W. Yang, J. De Haro, A. Melchiorri
- **2303.16895** — P. Brax, C. van de Bruck, E. Di Valentino, **WG**, S. Trojanowski
- **2305.01383** — P. Brax, C. van de Bruck, E. Di Valentino, **WG**, S. Trojanowski
- **2301.06097** — A. Bernui, E. Di Valentino, **WG**, S. Kumar, R. C. Nunes
- **2305.01383** — Y. Zhai, **WG,** C. van de Bruck, E. Di Valentino, O. Mena, R. C. Nunes

Tensions

No tension & No agreement

Agreement

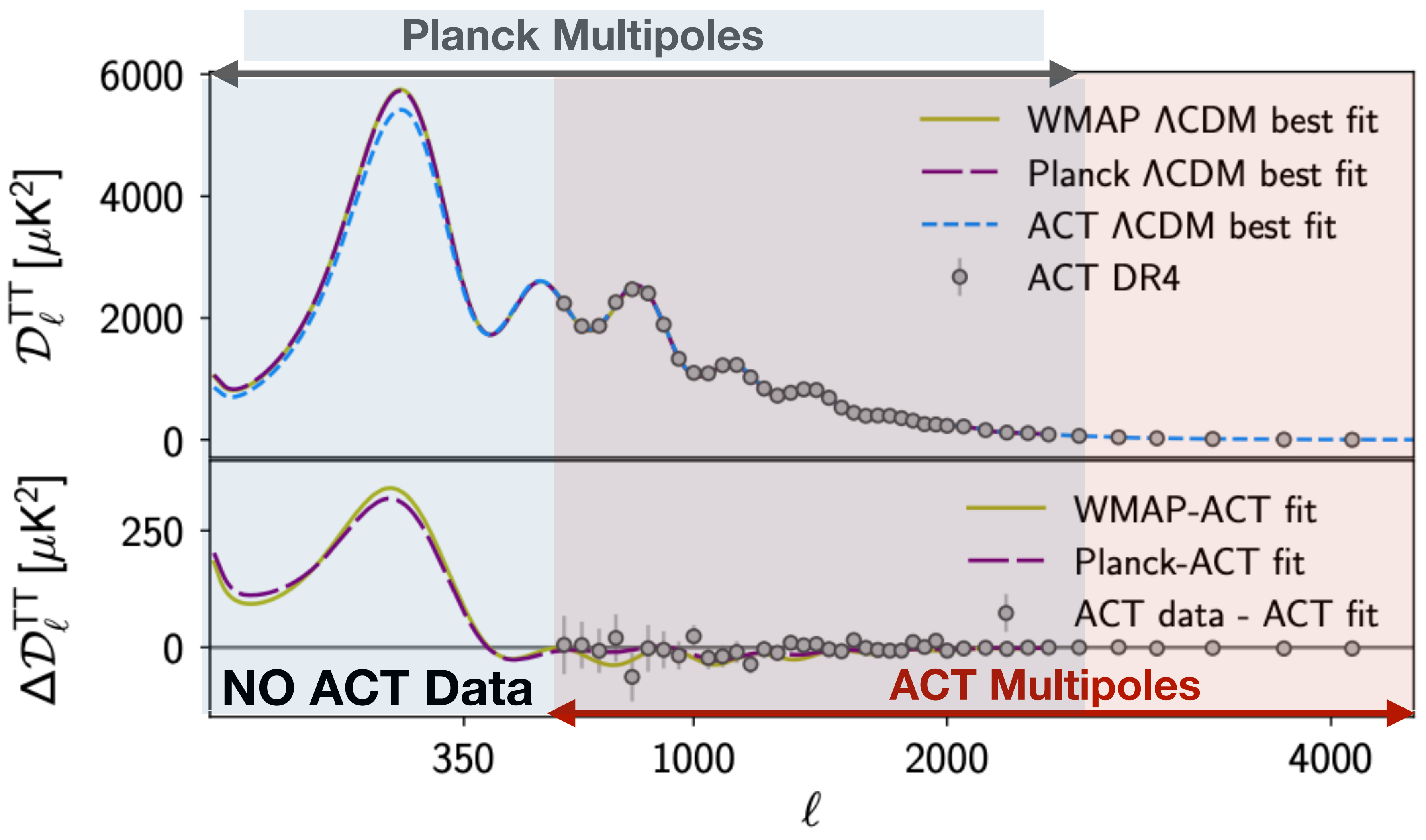
HINT 1 INFLATION

Assuming a ΛCDM cosmology, the main source of tension between ACT and Planck arises from the measurements of the **scalar spectral index** and the **baryon energy density**

If we believe these differences to emerge from limitations in the data, a logical step is to identify which (missing) part of the dataset is responsible for the discrepancy

ACT Temperature data

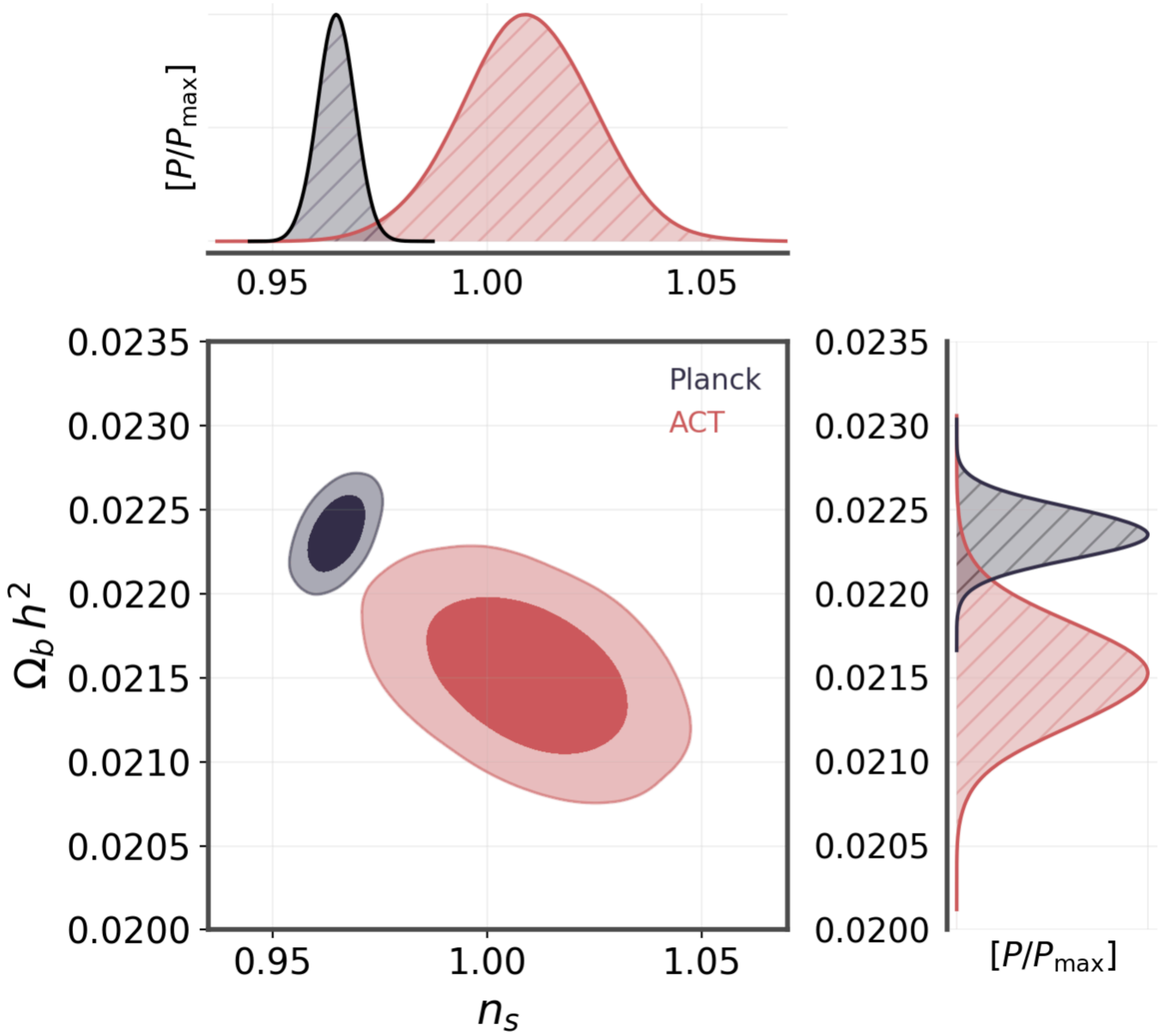
In the **absence of data around the first two acoustic peaks**, there is a strong degeneracy between $\Omega_b h^2$ and n_s as a lower value of the former can be mimicked by a larger value of the latter



ACT-DR4 - 2007.07288

Parameter	ACT	Planck
Basic:		
$100\Omega_b h^2$	2.153 ± 0.030	2.241 ± 0.015
$100\Omega_c h^2$	11.78 ± 0.38	11.97 ± 0.14
$10^4\theta_{MC}$	104.225 ± 0.071	104.094 ± 0.031
τ	0.065 ± 0.014	0.076 ± 0.013
n_s	1.008 ± 0.015	0.9668 ± 0.0044
$\ln(10^{10} A_s)$	3.050 ± 0.030	3.087 ± 0.026

WG *et al,* - 2210.09018



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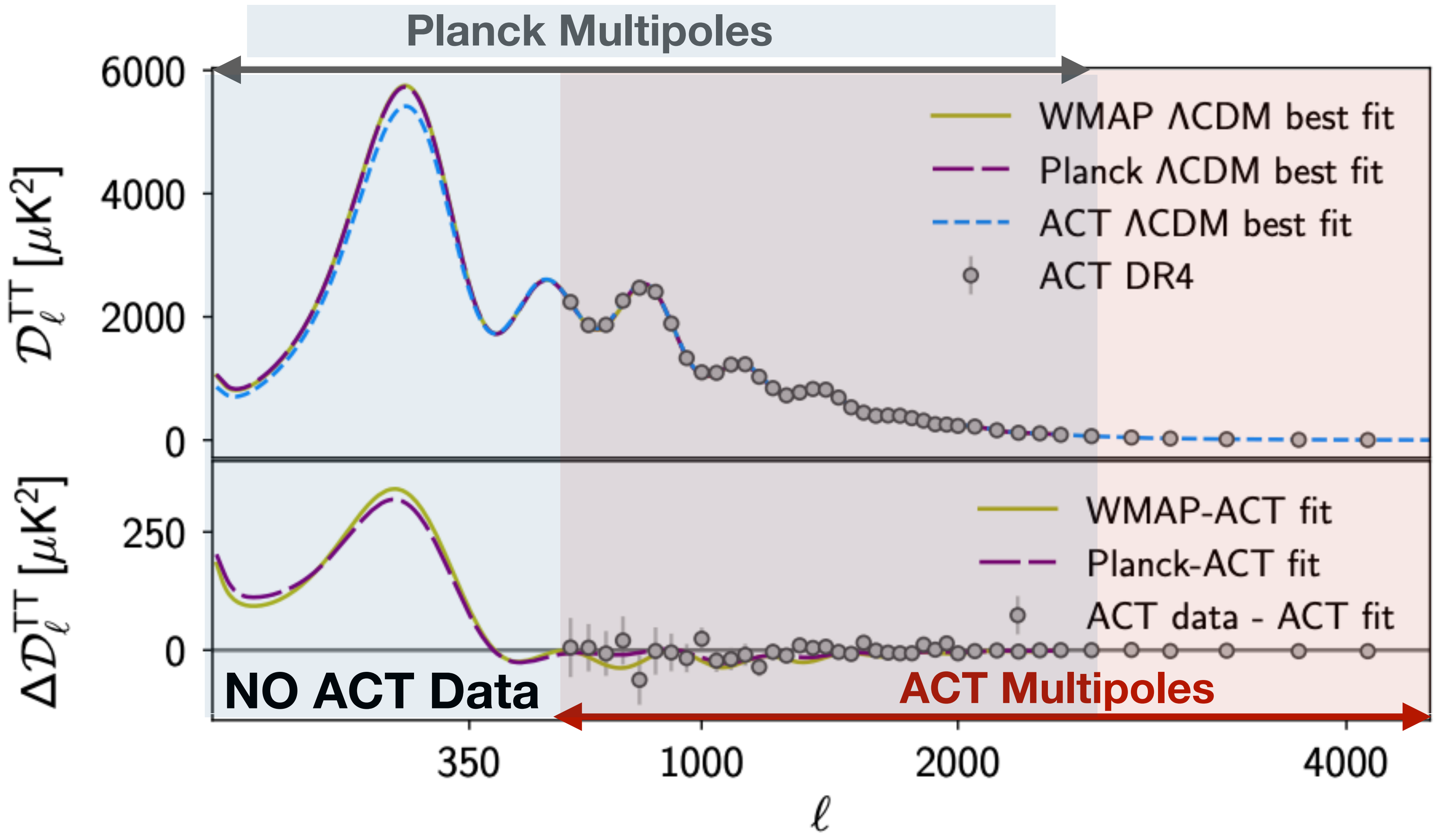

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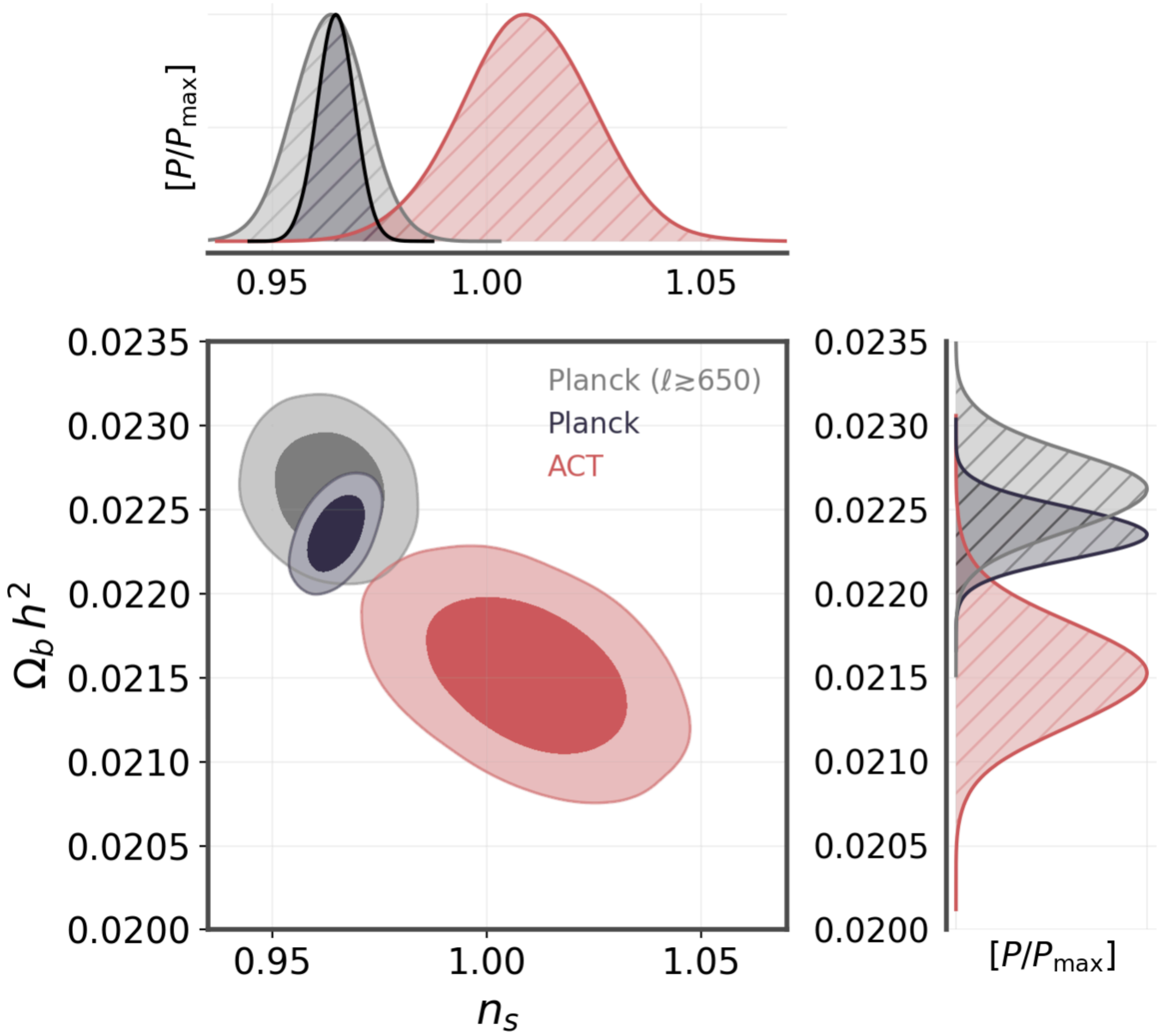

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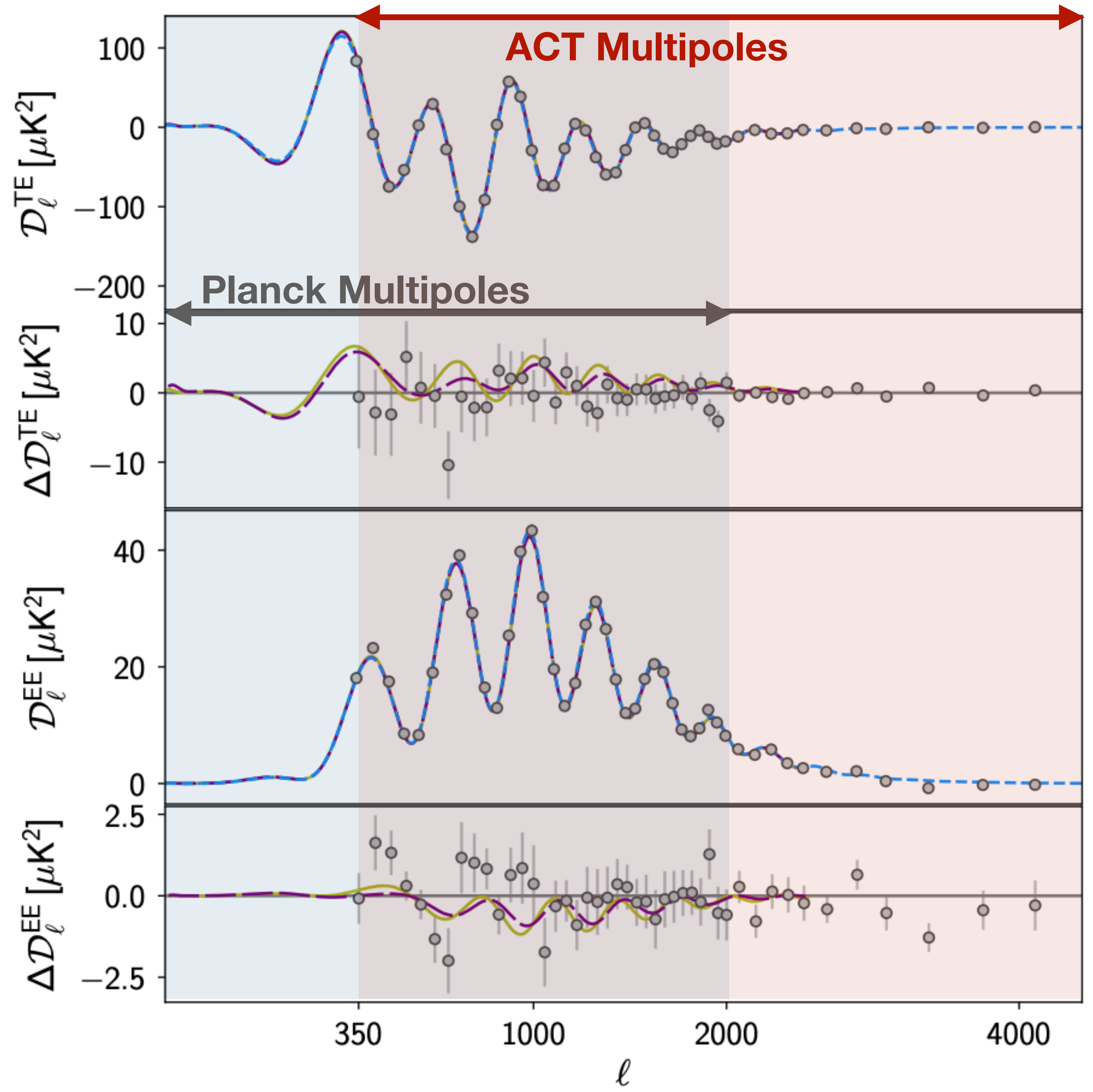
ACT Polarisation data

Is the disagreement coming from TE and/or EE ?



ACT-DR4 - 2007.07288

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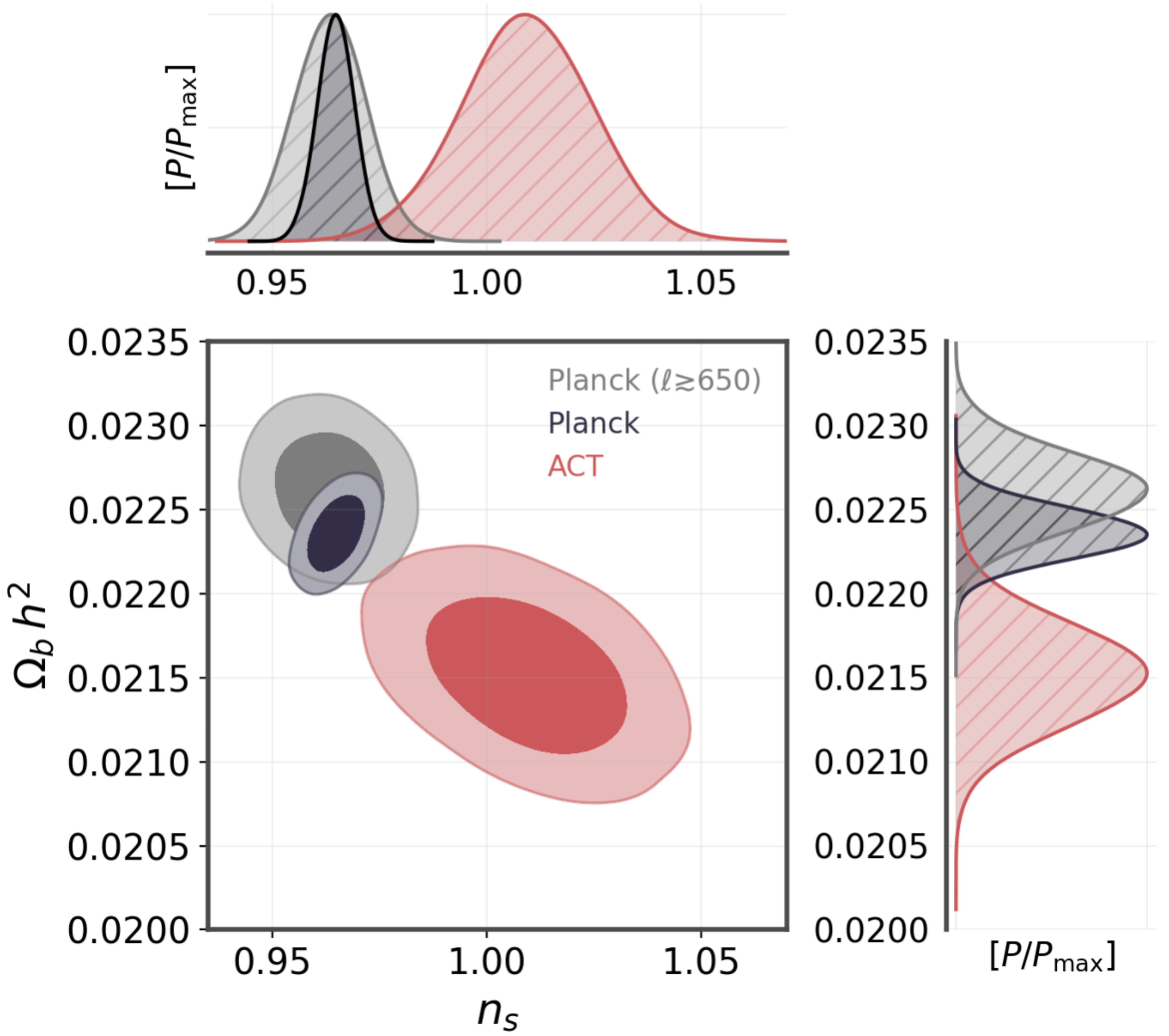

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ACT (τ = 0.0544 ± 0.0070)	1.007 ± 0.015
ACT + Planck low E	1.001 ± 0.011
ACT+BAO (DR12)	1.006 ± 0.013
ACT+BAO (DR16)	1.006 ± 0.014
ACT+DES	1.007 ± 0.013
ACT+SPT+BAO (DR16)	0.997 ± 0.013
ACT+SPT+BAO (DR12)	0.996 ± 0.012
Planck	0.9649 ± 0.0044
Planck+BAO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

ACT-DR4 - 2007.07288

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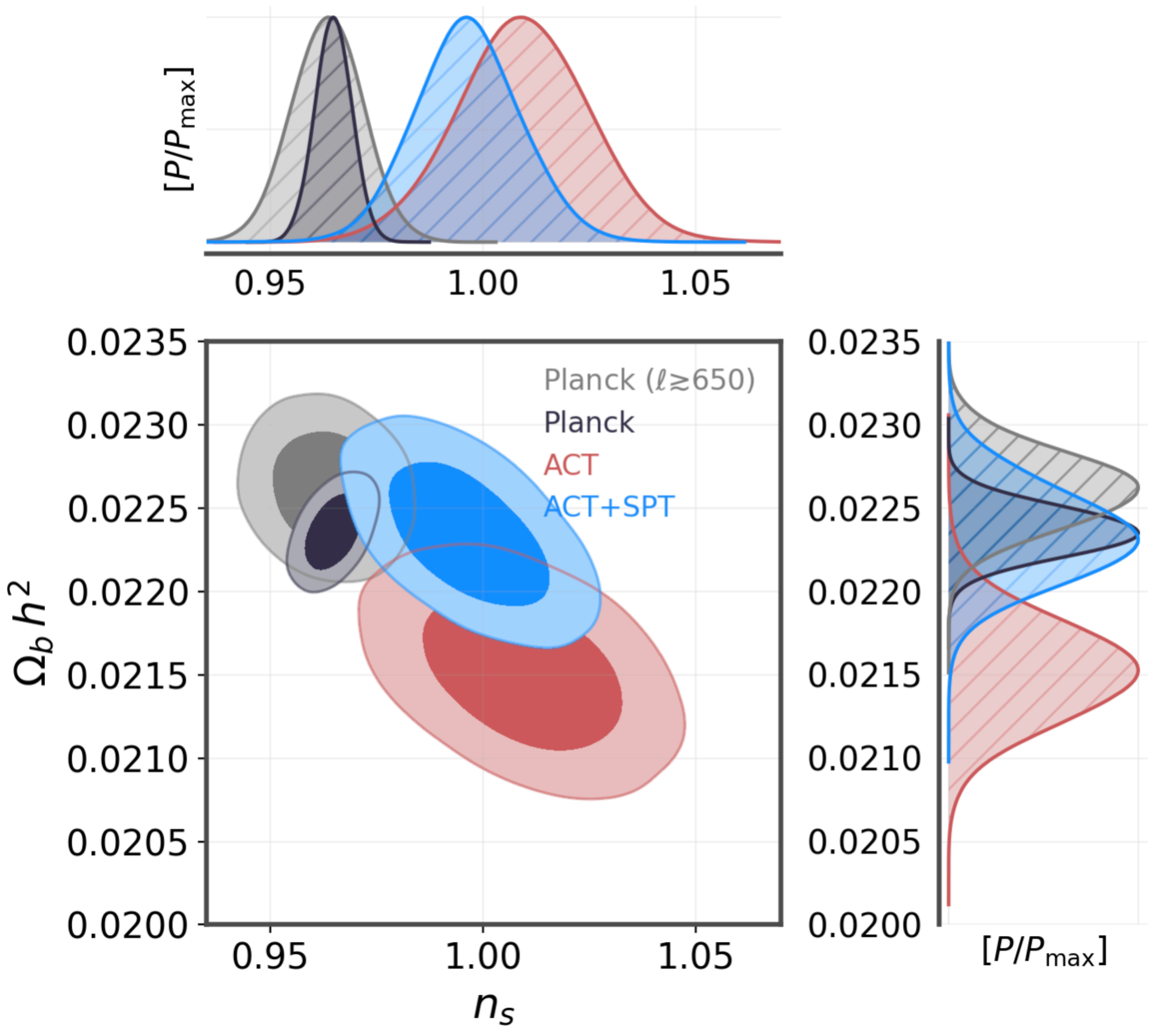

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Large scale Structure data

Including Astrophysical data does not change the conclusion

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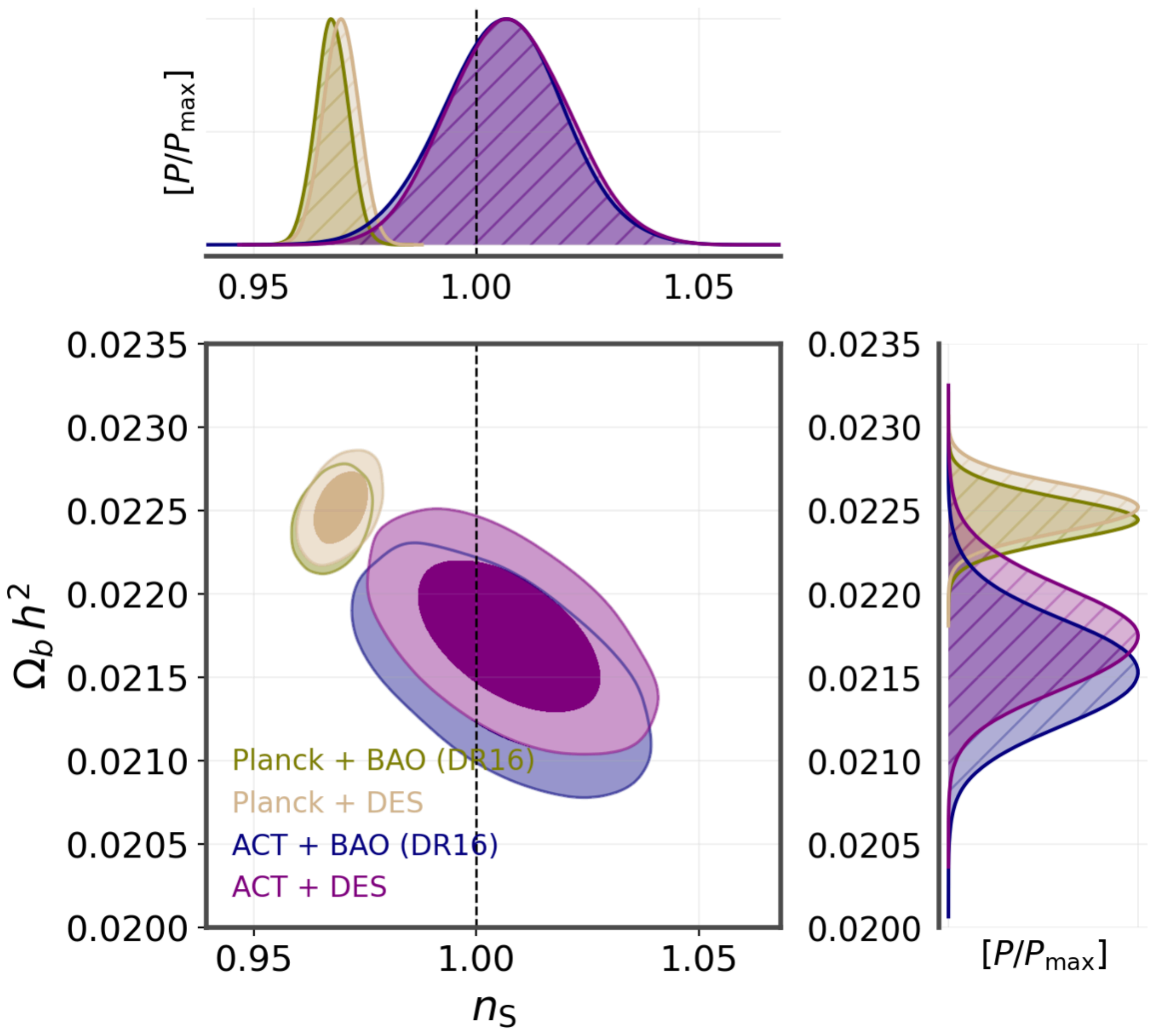

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Assuming a ΛCDM cosmology, the main source of tension between ACT and Planck arises from the measurements of the **scalar spectral index** and the **baryon energy density**

If we take data at face value, the **most typical Inflationary potentials fail to explain small-scale CMB observations**

Case Study: Starobinsky Inflation

We assume Starobinsky Inflation from the onset in the cosmological model

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

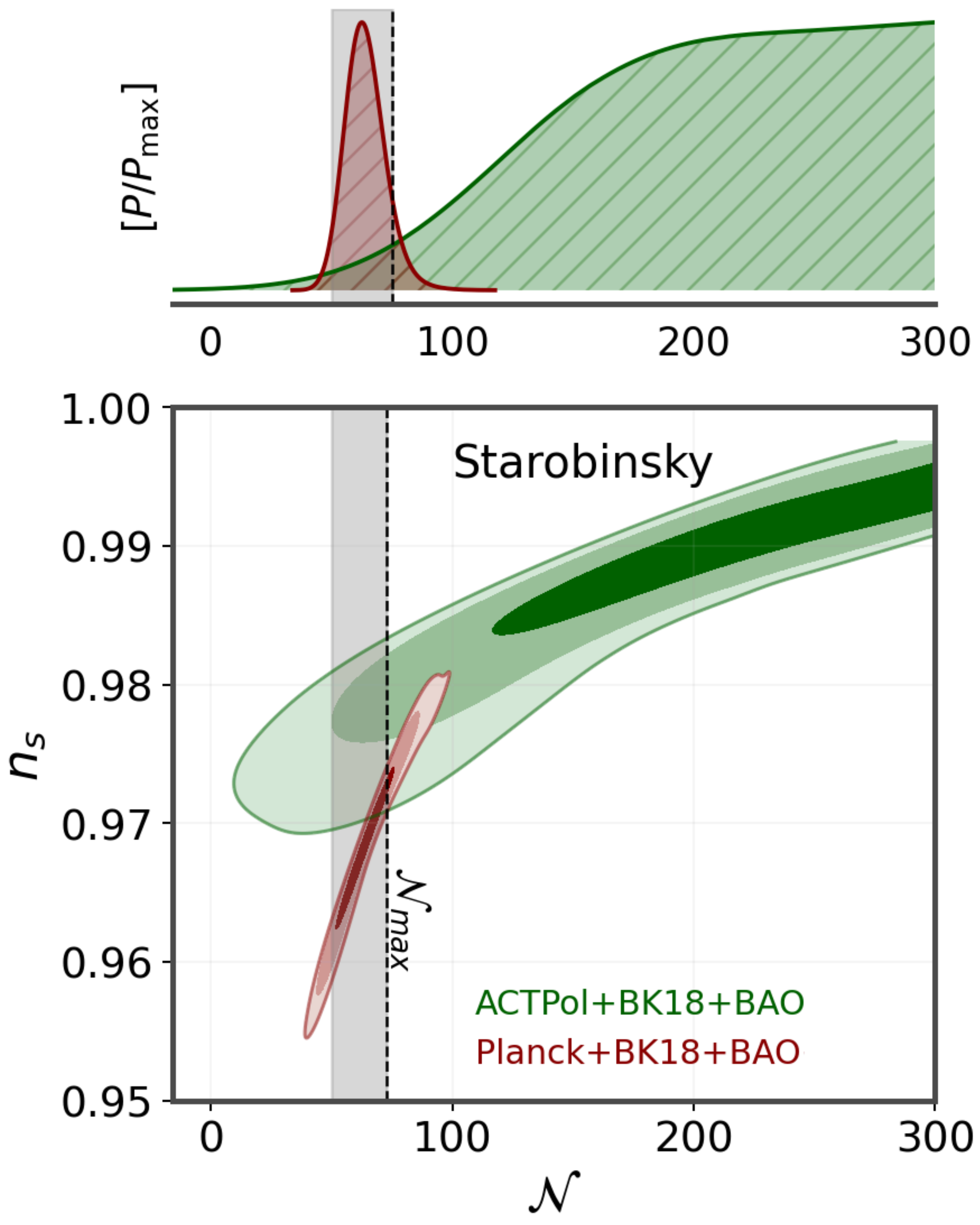
Where parameters are related to the last e-folds of expansion

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

- Starobinsky Inflation is in **perfect agreement with Planck** as well as with B-mode polarization data from the BICEP/Keck Collaboration.
- Starobinsky Inflation is **disregarded by ACT** data as the preference for a scale-invariant spectrum would require a number of last e-folds of expansion which is too large.

This dichotomy makes it **challenging to identify a group of models** that can be universally considered the preferred choice based on CMB observations

WG, *et. al.* - 2305.15378



Planck+BK18+BAO: $\mathcal{N} = 64 \pm 9$ at 68% CL

ACT+BK18+BAO: $\mathcal{N} > 100$ at 95% CL

HINT 2 Dark Matter (DM)

Neutrino-DM Interactions

Euler Equations in the Newtonian Gauge:

$$\dot{\theta}_\nu = k^2\psi + k^2\left(\frac{1}{4}\delta_\nu - \sigma_\nu\right) - \dot{\mu}\,(\theta_\nu - \theta_{\mathrm{DM}})$$

$$\dot{\theta}_{\mathrm{DM}} = k^2\psi - \mathscr{H}\theta_{\mathrm{DM}} + \frac{4}{3}\frac{\rho_\nu}{\rho_{\mathrm{DM}}}\dot{\mu}\,(\theta_\nu - \theta_{\mathrm{DM}})$$

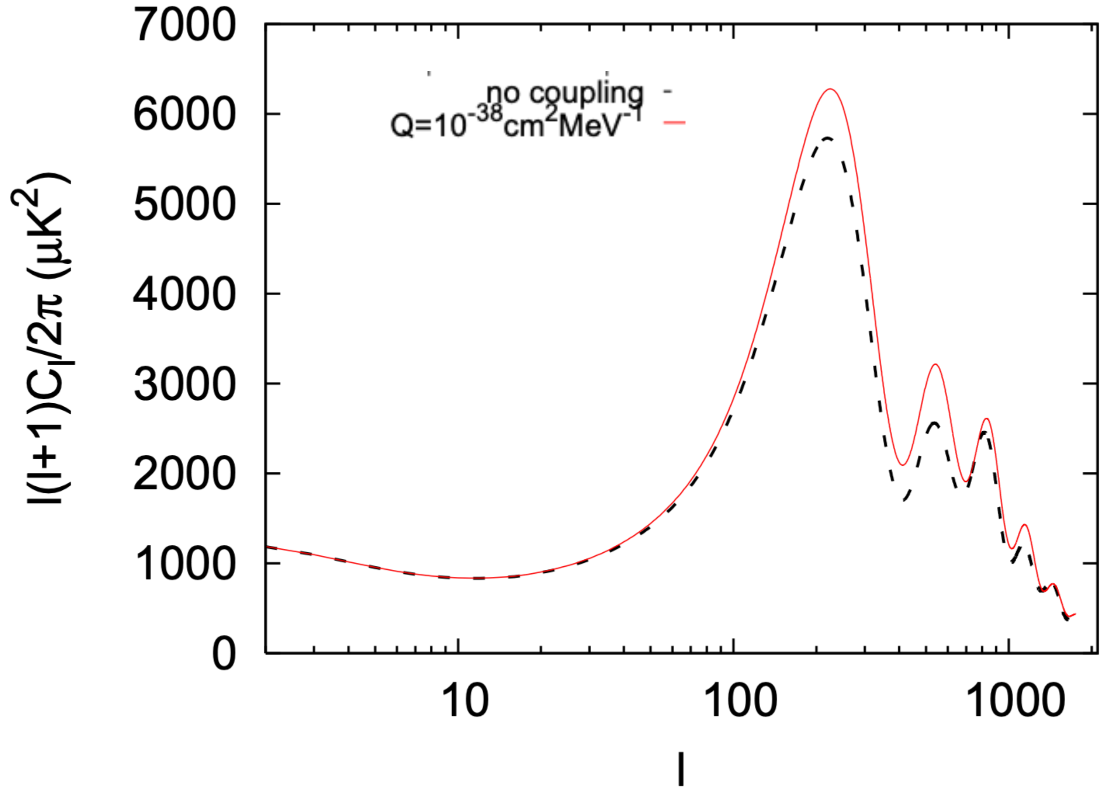
Were:

$$\dot{\mu} = a\,c\,\frac{\rho_{\mathrm{DM}}}{m_{DM}}\,\sigma_{\nu\mathrm{DM}}$$

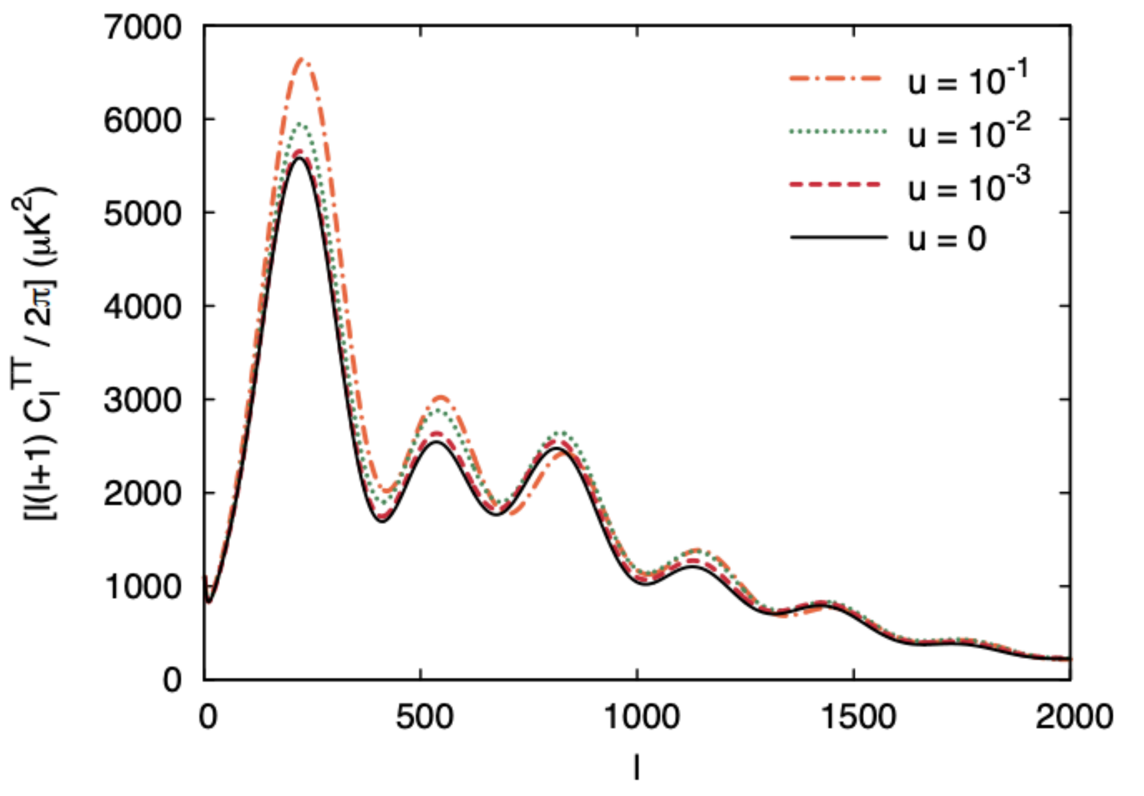
Interaction Strength

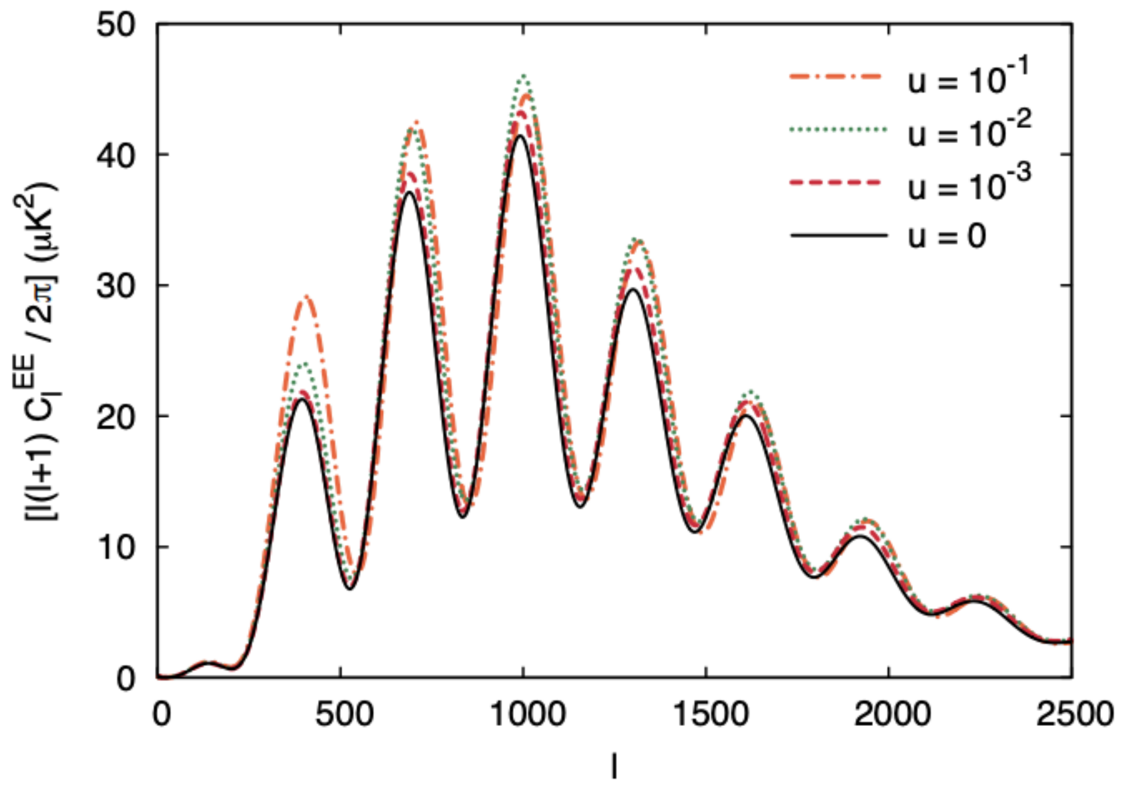
$$u_{\nu\mathrm{DM}} \doteq \left[\frac{\sigma_{\nu\mathrm{DM}}}{\sigma_{\mathrm{Th}}}\right]\left[\frac{m_{\mathrm{DM}}}{100\,\mathrm{GeV}}\right]^{-1}$$

P. Serra et al. 0911.4411

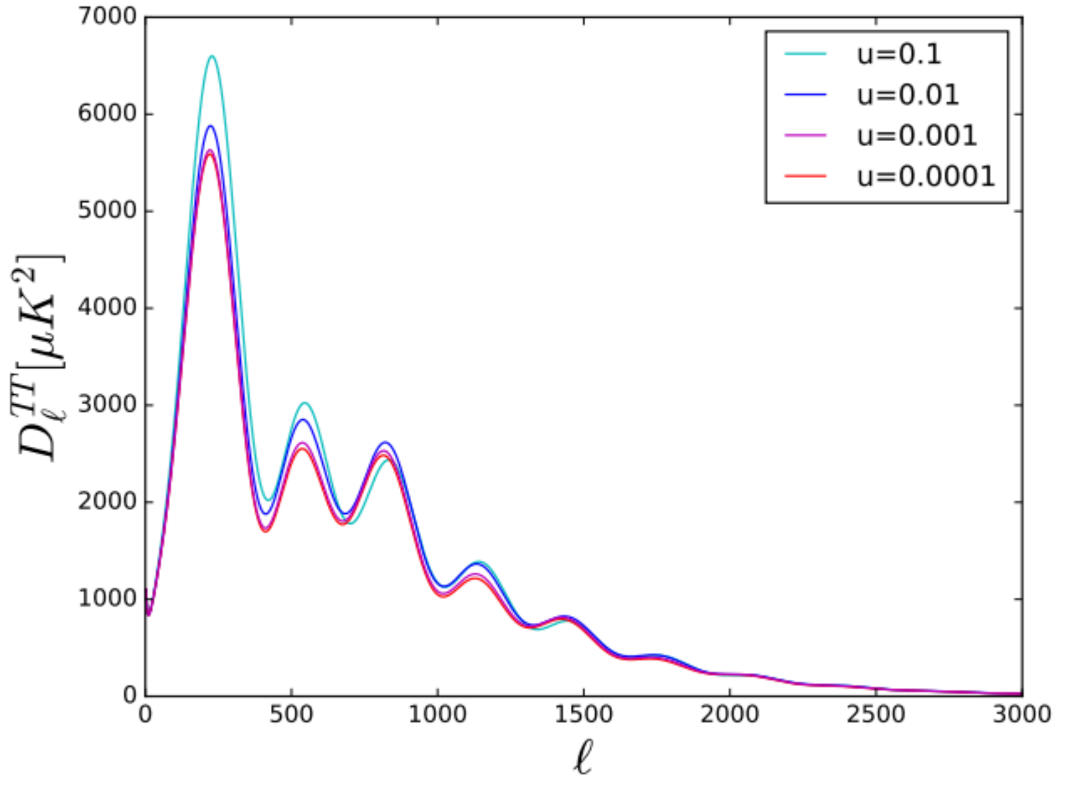


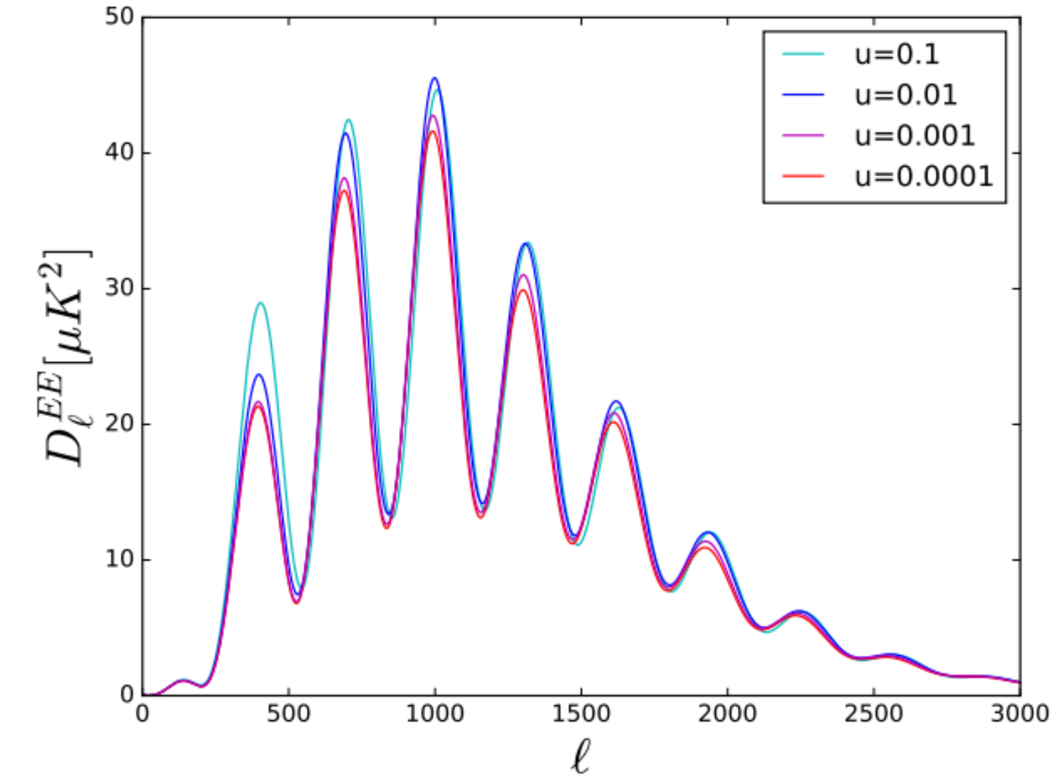
R. J. Wilkinson et al 1309.7588

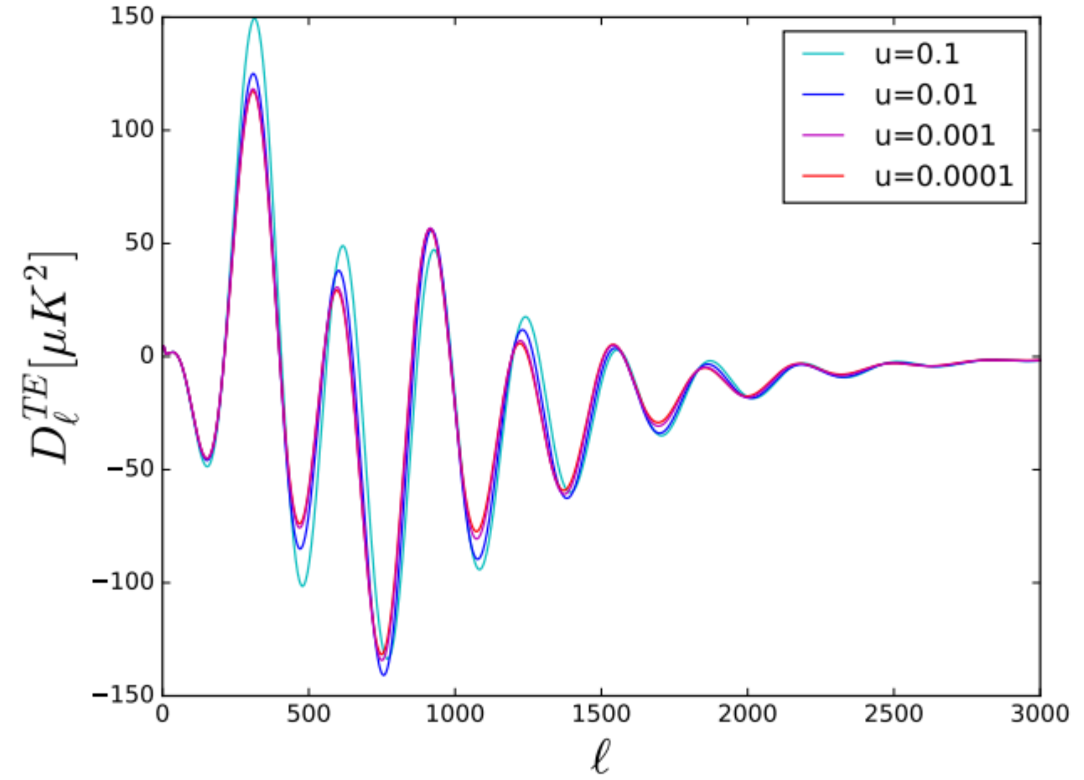




E. Di Valentino et al. 1710.02559







Work Assumptions

$\sigma_{\nu\mathrm{DM}} \sim T^0$ (i.e., $\sigma_{\nu\mathrm{DM}} \sim$ const)

$\sum m_\nu \sim 0$ (i.e., mass-less limit)

HINT 2 DARK MATTER (DM)

NEUTRINO-DM INTERACTIONS

Euler Equations in the Newtonian Gauge:

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Were:

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INTERACTION STRENGTH

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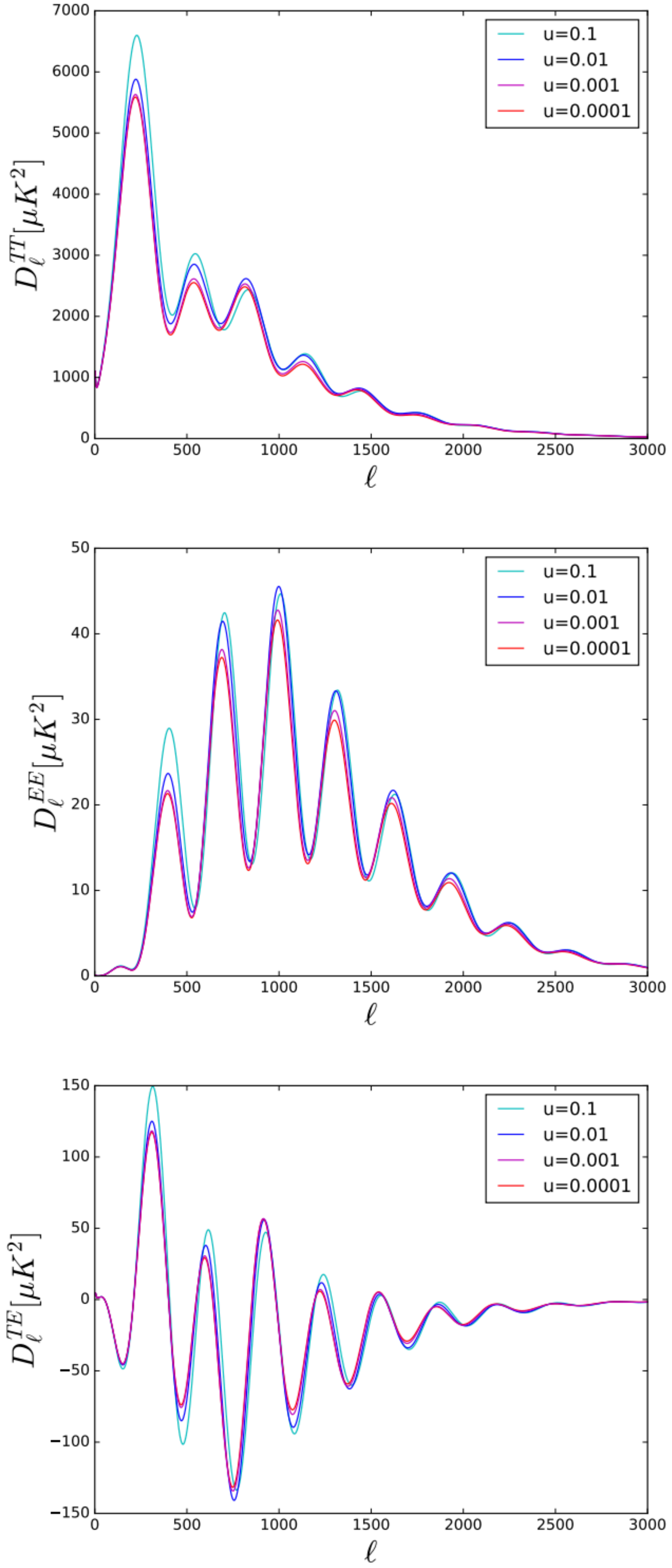

No Evidence for νDM interactions!

From **Planck** CMB temperature and polarization data, **no hints for neutrino-DM interactions** have ever been found.

Only an **upper bound** on the value of the **interaction strength** has been derived.

E. Di Valentino et al. 1710.02559

ΛCDM + u Parameter	Planck TT + lowTEB	Planck TT + lowTEB + lensing	+ $N_{\rm eff}$ Planck TT + lowTEB	+ $N_{\rm eff}$ Planck TT + lowTEB + lensing
$\Omega_b h^2$	$0.02224^{+0.00023}_{-0.00024}$	$0.02226^{+0.00027}_{-0.00026}$	$0.02232^{+0.00037}_{-0.00041}$	$0.02234^{+0.00035}_{-0.00040}$
$\Omega_c h^2$	$0.1195^{+0.0022}_{-0.0023}$	$0.1186^{+0.0021}_{-0.0022}$	$0.1205^{+0.0039}_{-0.0045}$	$0.1197^{+0.0039}_{-0.0041}$
τ	$0.079^{+0.018}_{-0.020}$	$0.070^{+0.015}_{-0.018}$	$0.083^{+0.018}_{-0.024}$	$0.074^{+0.016}_{-0.021}$
n_s	$0.9652^{+0.0066}_{-0.0065}$	$0.9667^{+0.0071}_{-0.0065}$	$0.969^{+0.015}_{-0.017}$	$0.971^{+0.014}_{-0.017}$
$ln(10^{10}A_s)$	$3.091^{+0.034}_{-0.039}$	$3.071^{+0.027}_{-0.033}$	$3.100^{+0.040}_{-0.053}$	$3.080^{+0.034}_{-0.044}$
$H_0[\mathrm{Km\,s^{-1}\,Mpc^{-1}}]$	67.5 ± 1.0	67.8 ± 1.0	$68.3^{+2.6}_{-3.2}$	$68.7^{+2.4}_{-3.0}$
σ_8	$0.825^{+0.017}_{-0.016}$	$0.814^{+0.014}_{-0.012}$	$0.830^{+0.021}_{-0.025}$	$0.819^{+0.019}_{-0.021}$
$log_{10}u_{\nu DM}$	< -4.1	< -4.0	< -4.0	< -4.0
$N_{\rm eff}$	3.046	3.046	$3.14^{+0.32}_{-0.35}$	$3.15^{+0.28}_{-0.33}$
$\Sigma m_\nu[eV]$	0.06	0.06	0.06	0.06

HINT 2 Dark Matter (DM)

Neutrino-DM Interactions

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$$\dot{\theta}_{\rm DM} = k^2\psi - \mathscr{H}\theta_{\rm DM} + \frac{\mathbf{4}}{\mathbf{3}}\frac{\boldsymbol{\rho}_\nu}{\boldsymbol{\rho}_{\mathbf{DM}}}\dot{\boldsymbol{\mu}}\,(\boldsymbol{\theta}_\nu - \boldsymbol{\theta}_{\mathbf{DM}})$$

Were:

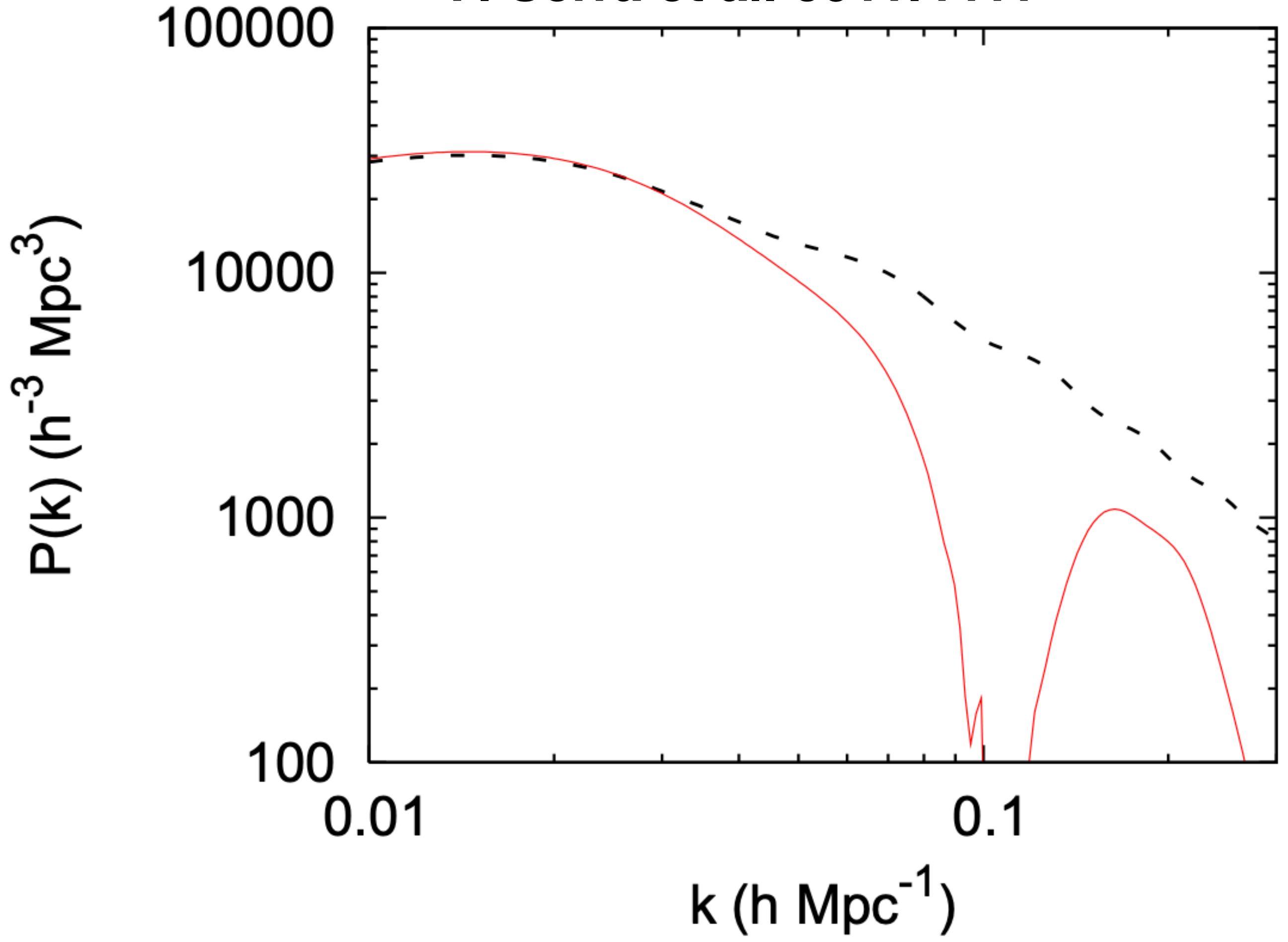
$$\dot{\mu} = a\,c\,\frac{\rho_{\rm DM}}{m_{DM}}\,\sigma_{\nu\rm DM}$$

Interaction Strength

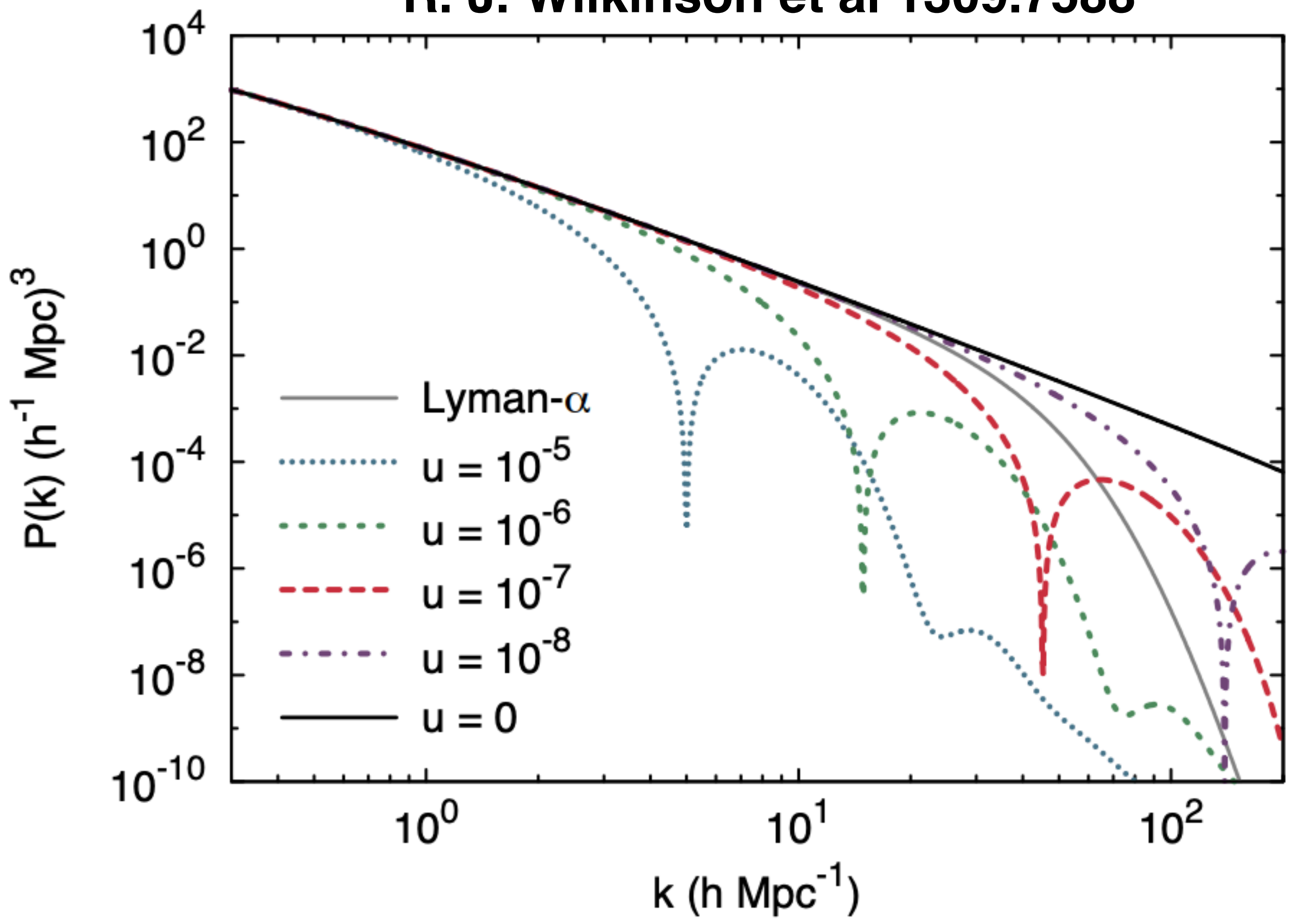
$$u_{\nu\rm DM} \doteq \left[\frac{\sigma_{\nu\rm DM}}{\sigma_{\rm Th}}\right]\left[\frac{m_{\rm DM}}{100\,{\rm GeV}}\right]^{-1}$$

Take a Look at the Matter Power Spectrum

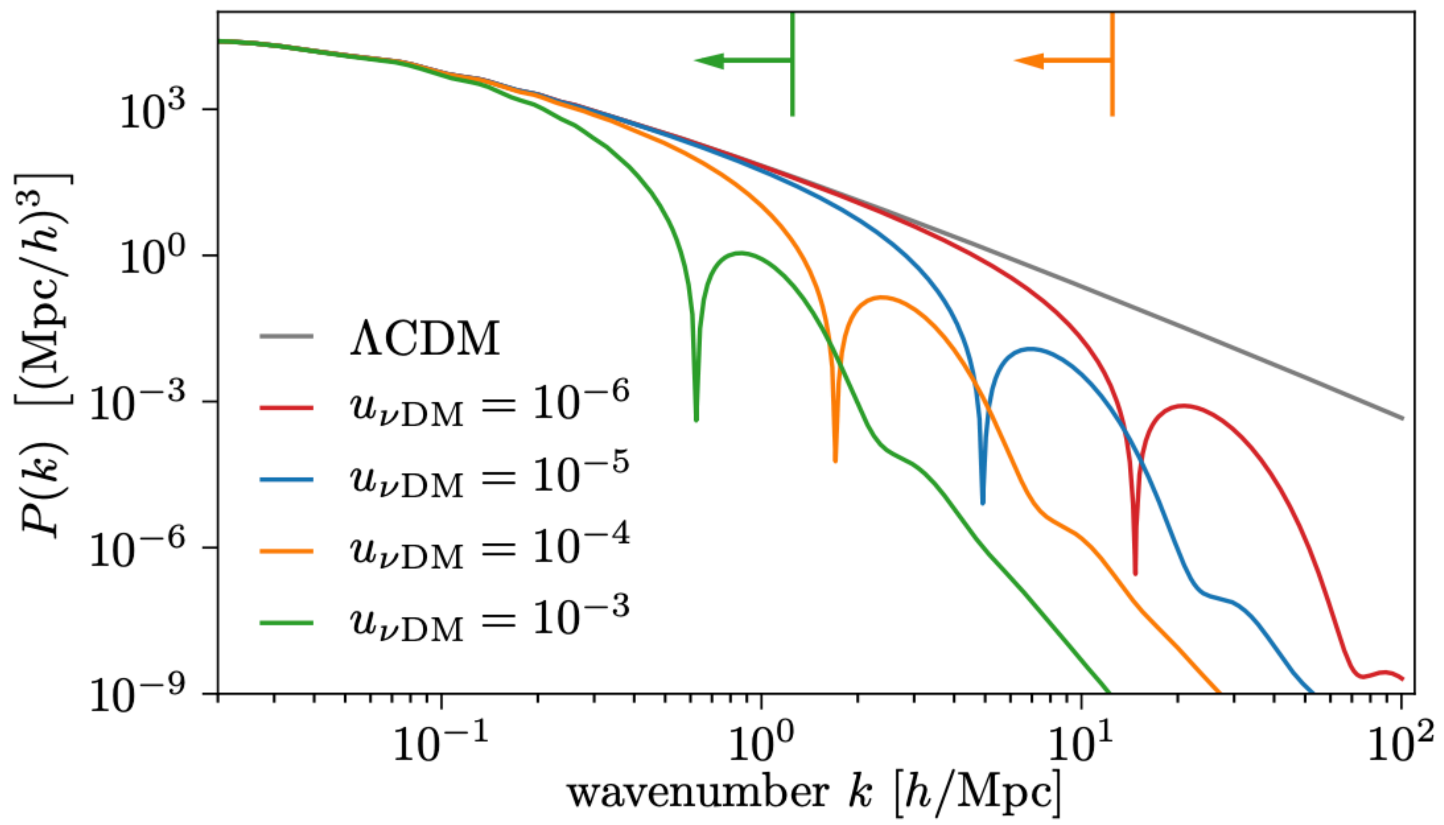
P. Serra et al. 0911.4411



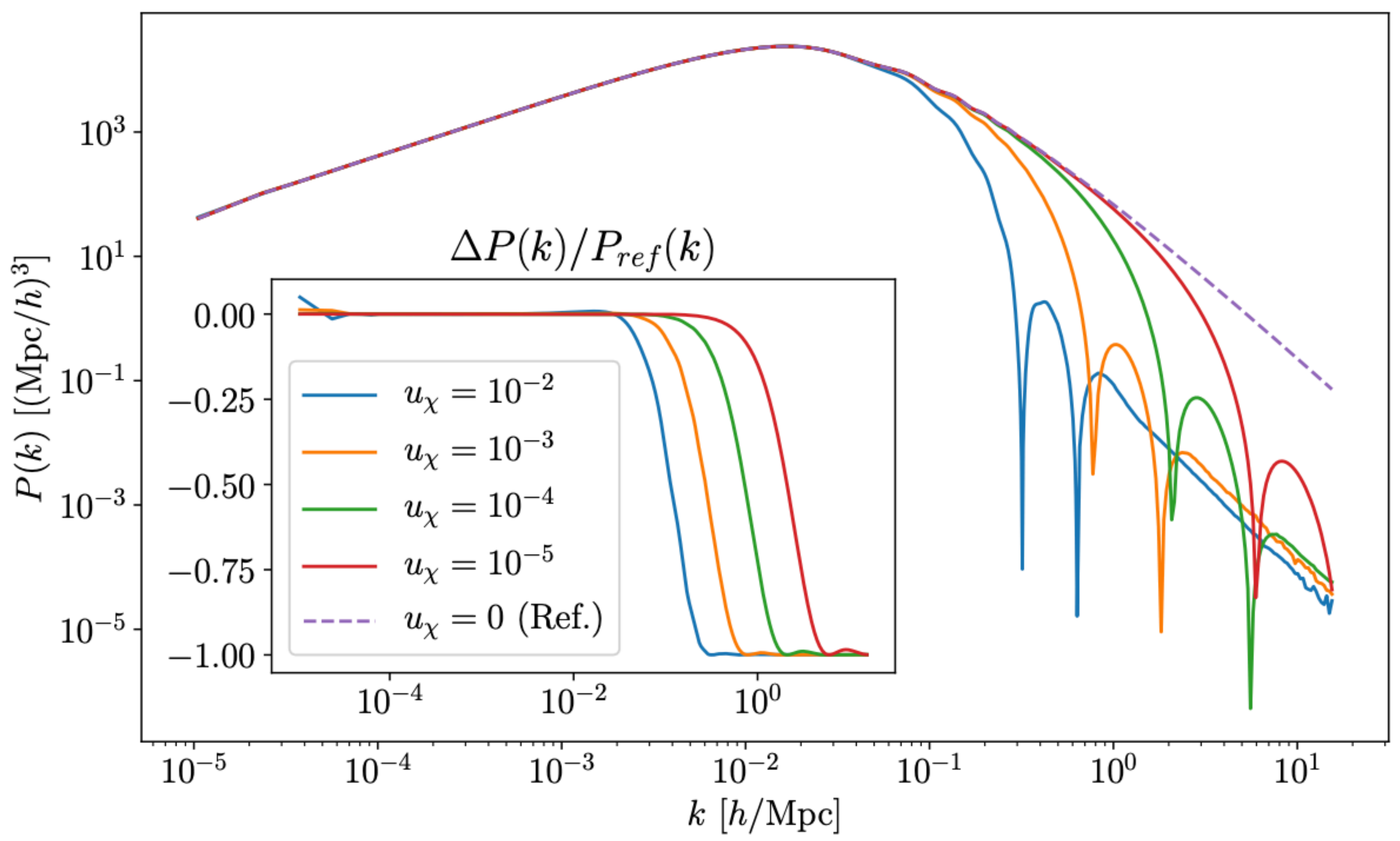
R. J. Wilkinson et al 1309.7588



J. Stadler et al. 1903.00540



M. R. Mosbech et al. 2011.0420



For Small couplings the Neutrino Damping is relevant on small scales (i.e., $k \sim 1/u^{1/2}\,[h/Mpc]$)

(See also G. Mangano, A. Melchiorri et al, 0606190)

$k \propto \ell \rightarrow$ Anything similar at high ℓ in the CMB spectra?

HINT 2 Dark Matter (DM)

The relative **effects of tiny vDM interactions** in the CMB are several **orders of magnitude larger on small scales** than on **large scales**

Brax et al. (WG) 2303.16894 and 2305.01383

Neutrino-DM Interactions

Euler Equations in the Newtonian Gauge:

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Were:

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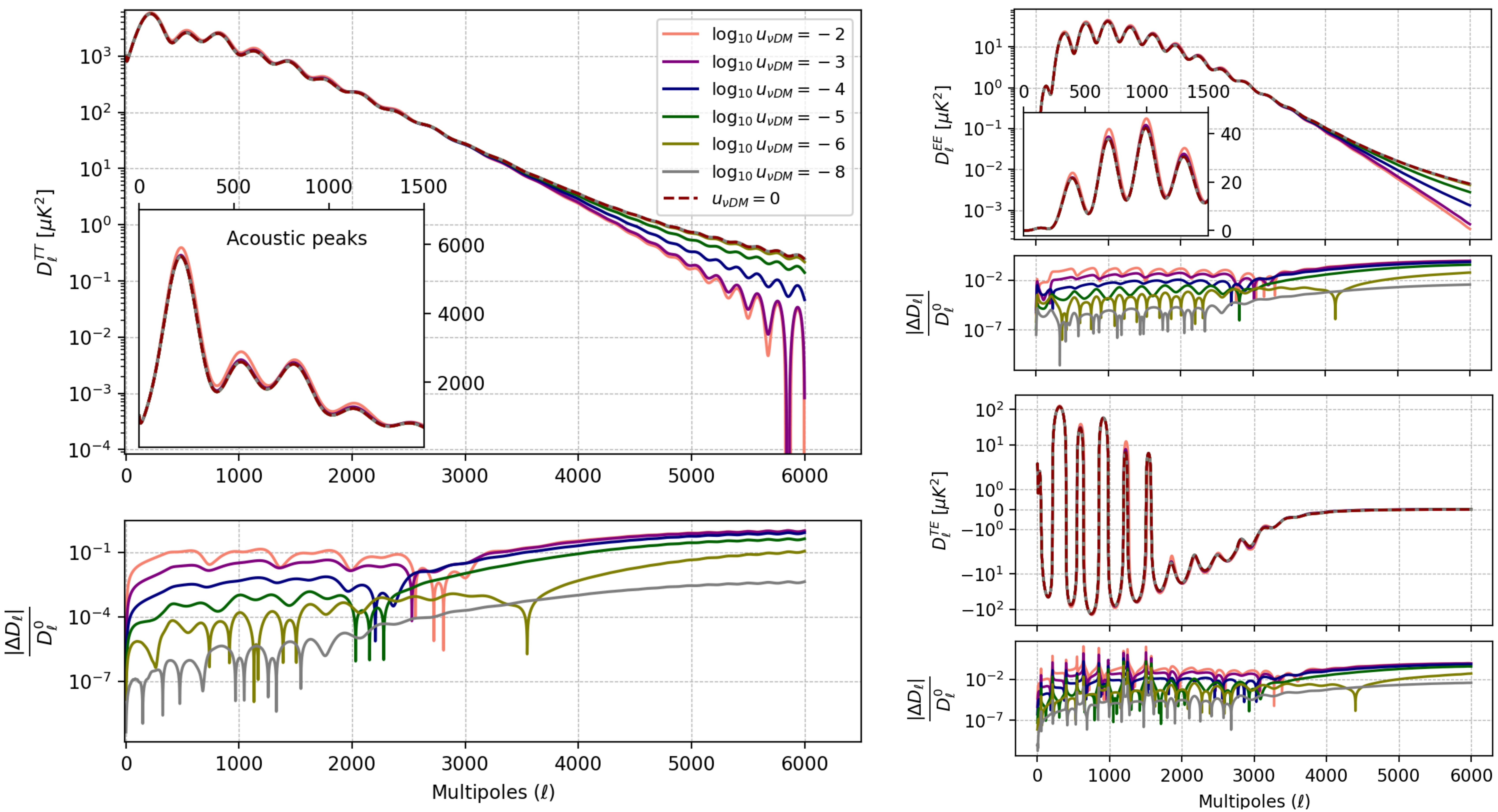

Hint 2 Dark Matter (DM)

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The relative **effects of tiny vDM interactions** in the CMB are several **orders of magnitude larger on small scales** than on **large scales**

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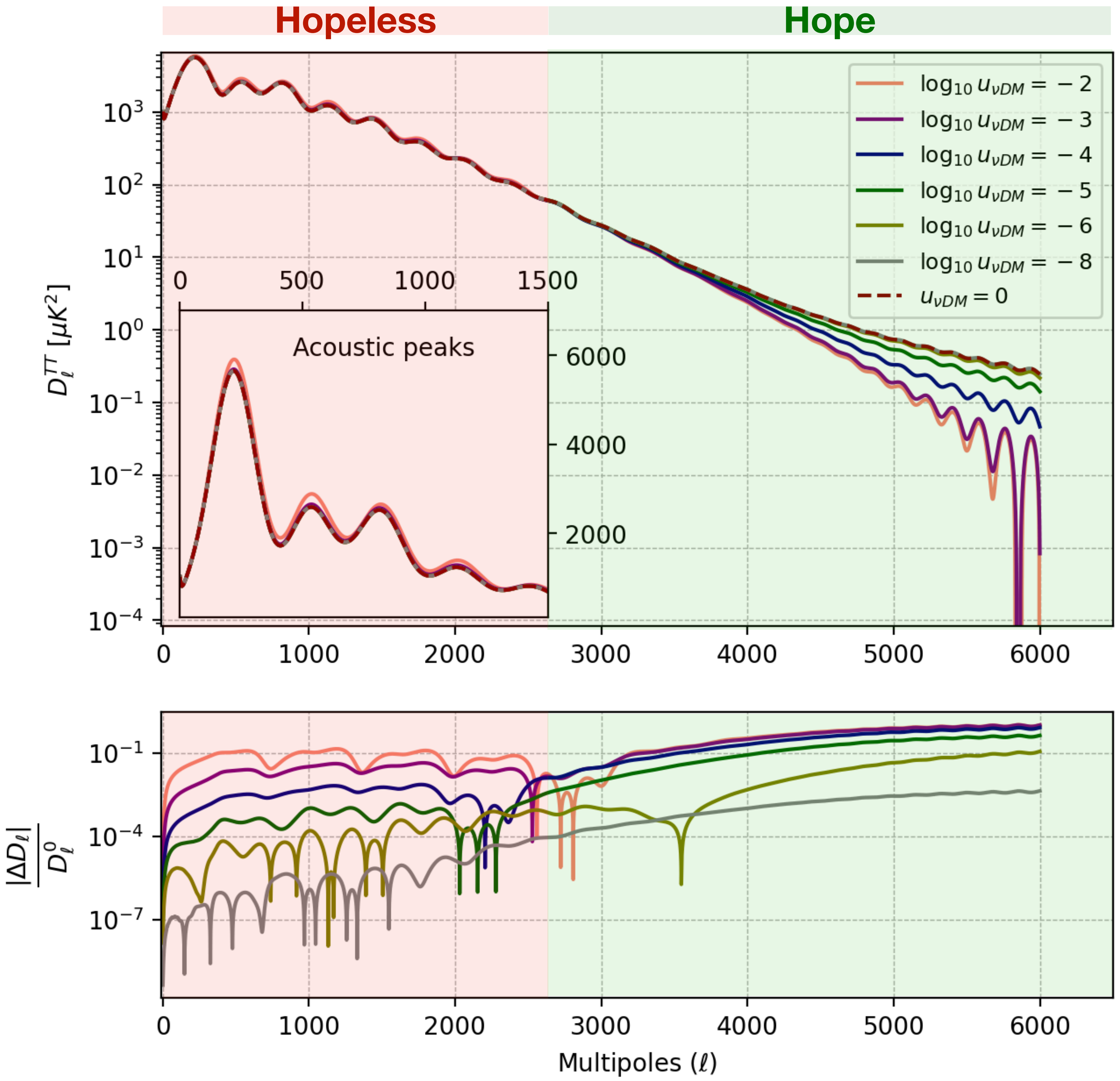

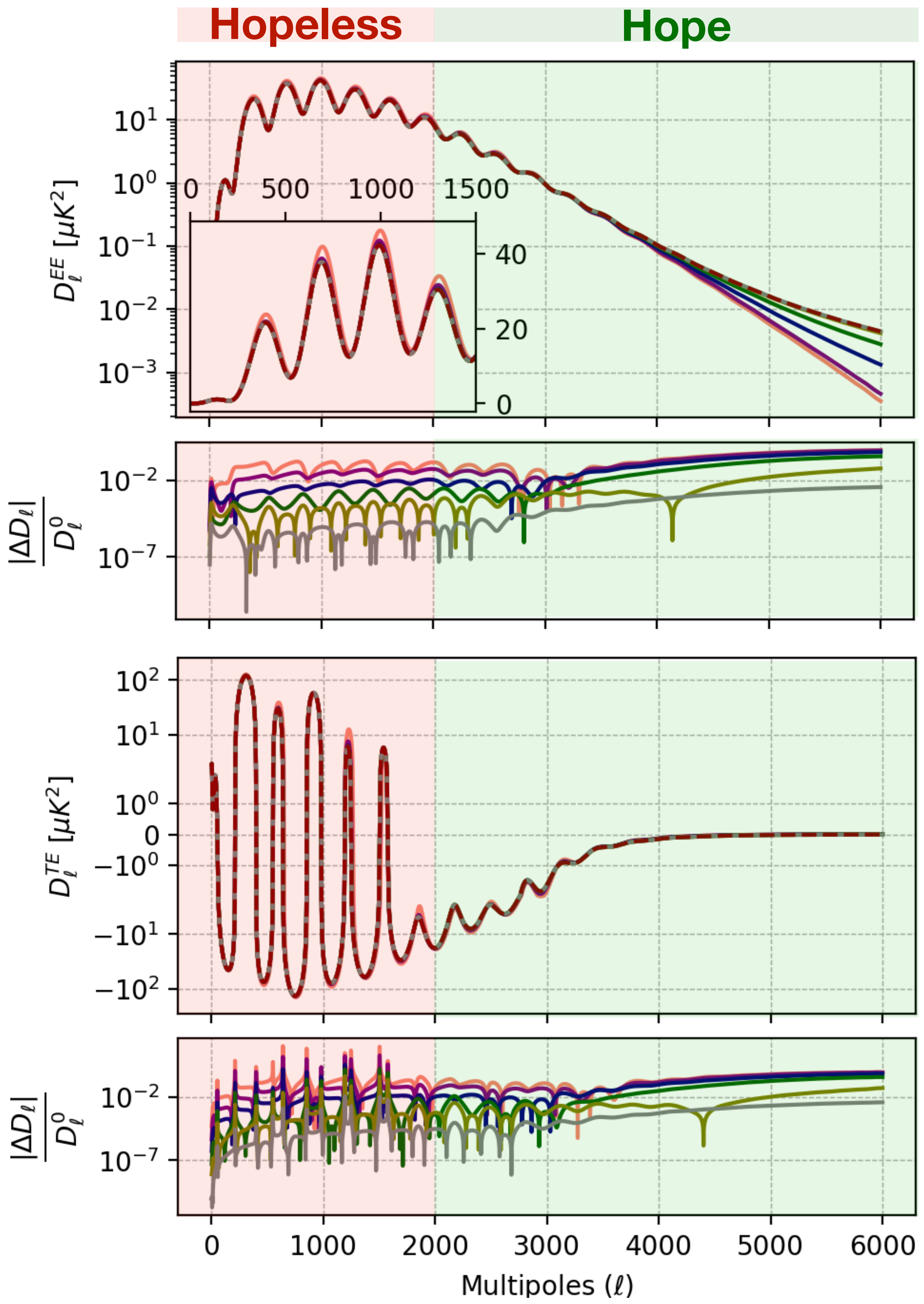

HINT 2 DARK MATTER (DM)

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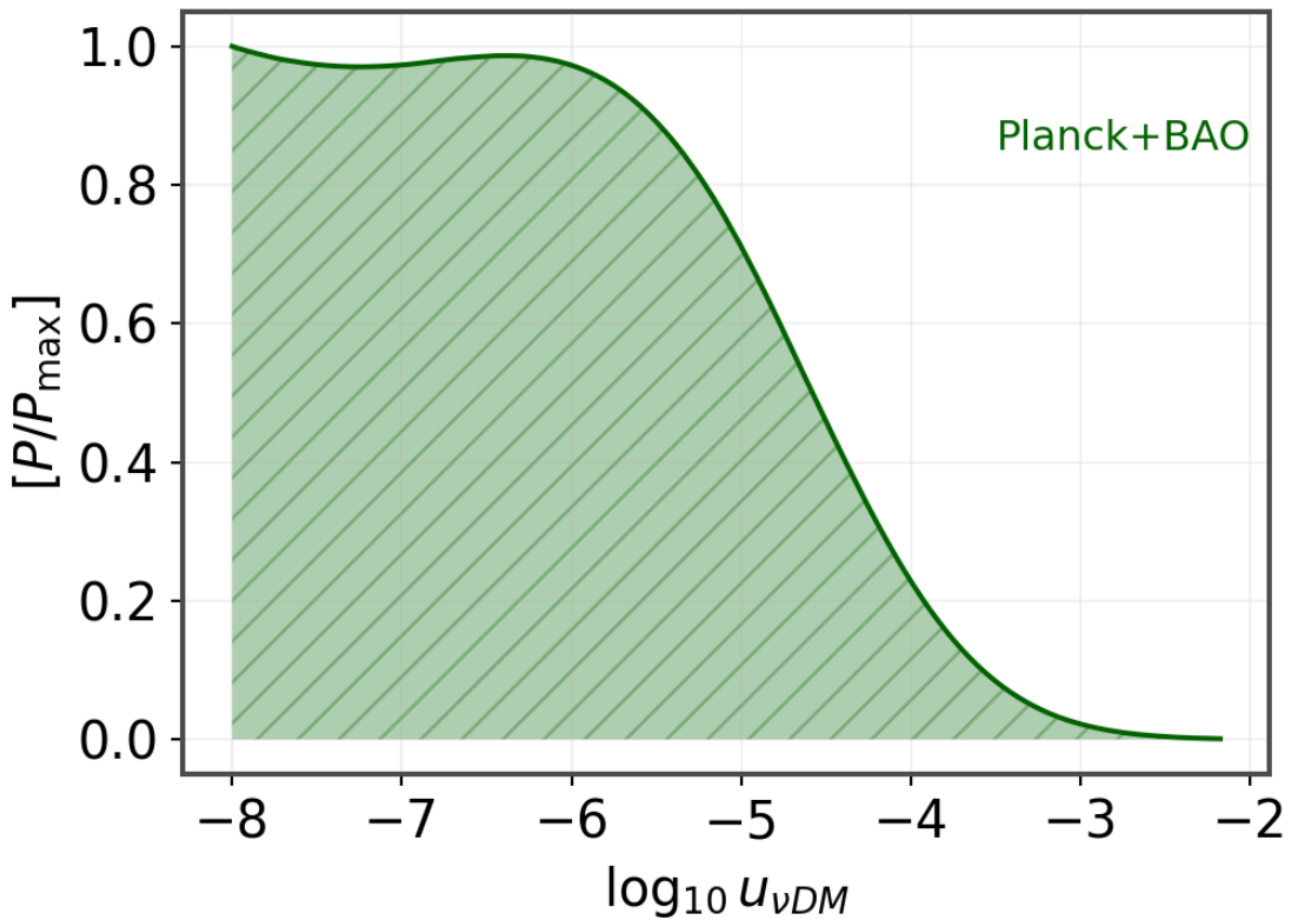
Brax et al. (WG) 2303.16894 and 2305.01383

Parameter	Planck	Planck + BAO
$\Omega_{\rm b}h^2$	0.02239 ± 0.00015	0.02239 ± 0.00013
$\Omega_{\rm c}^{\nu\rm DM}h^2$	0.1196 ± 0.0012	0.11958 ± 0.00093
$100\theta_{\rm s}$	1.04193 ± 0.00030	1.04191 ± 0.00028
$\tau_{\rm reio}$	0.0528 ± 0.0074	0.0524 ± 0.0072
$\log(10^{10}A_{\rm s})$	3.039 ± 0.014	3.038 ± 0.014
$n_{\rm s}$	0.9642 ± 0.0044	0.9642 ± 0.0038
$log_{10}u_{\nu DM}$	$< -4.42\,(< -3.95)$	$< -4.46\,(< -4.39)$
H_0	$68.03 \pm 0.55\,(68.0^{+1.1}_{-1.1})$	$68.05 \pm 0.42\,(68.05^{+0.81}_{-0.82})$
σ_8	$0.806^{+0.013}_{-0.0097}\,(0.806^{+0.024}_{-0.028})$	$0.807^{+0.011}_{-0.0084}\,(0.807^{+0.020}_{-0.021})$



HINT 2 DARK MATTER (DM)

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$$\dot{\theta}_{DM} = k^2\psi - \mathcal{H}\theta_{DM} + \frac{4}{3}\frac{\rho_\nu}{\rho_{DM}}\dot{\mu}\left(\theta_\nu - \theta_{DM}\right)$$

Were:

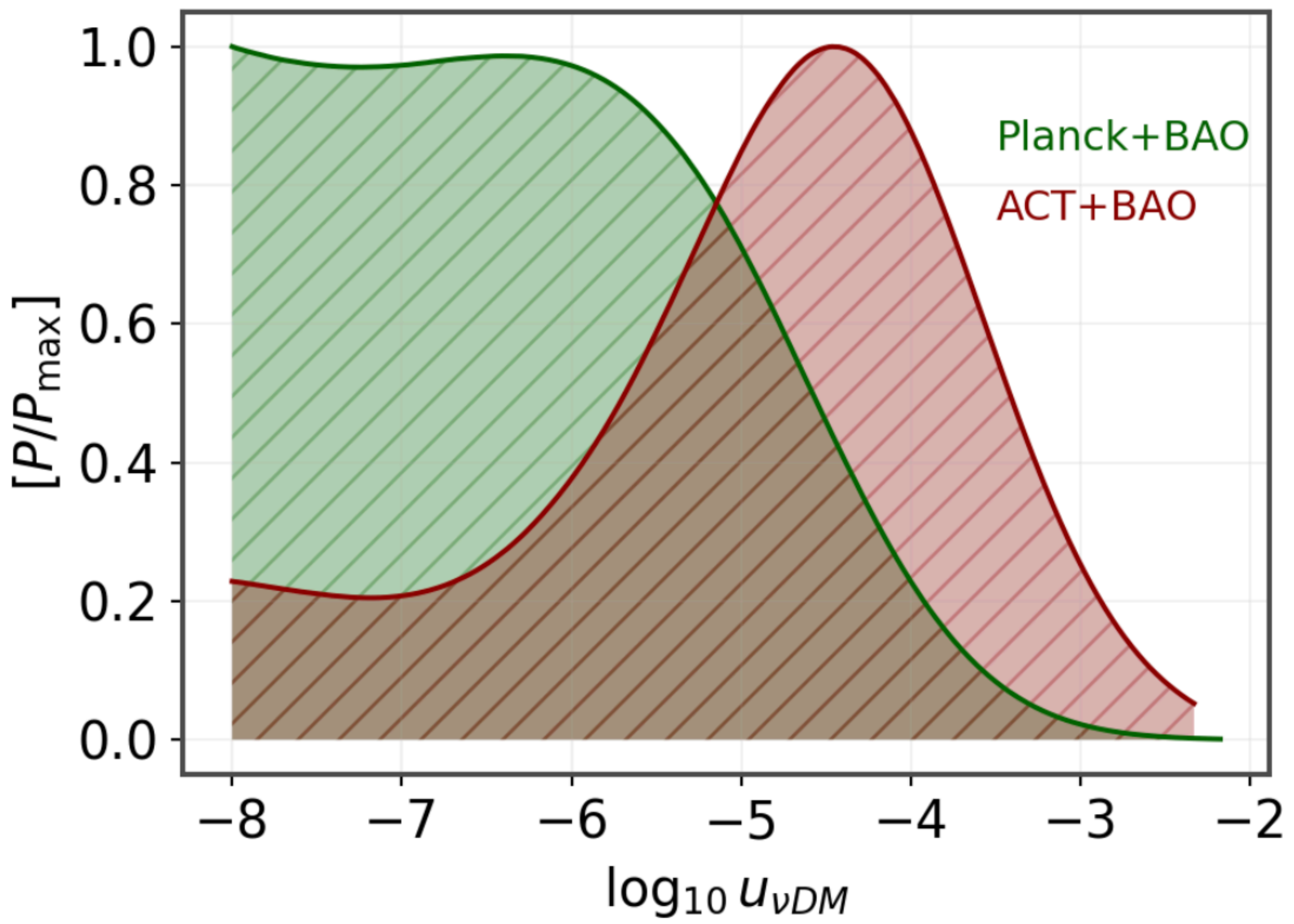
$$\dot{\mu} = a\,c\,\frac{\rho_{DM}}{m_{DM}}\sigma_{\nu DM}$$

INTERACTION STRENGTH

$$u_{\nu DM} \doteq \left[\frac{\sigma_{\nu DM}}{\sigma_{Th}}\right]\left[\frac{m_{DM}}{100\,\text{GeV}}\right]^{-1}$$

Brax et al. (WG) 2303.16894 and 2305.01383

Parameter	ACT	ACT + BAO
$\Omega_b h^2$	0.02153 ± 0.00030	0.02154 ± 0.00030
$\Omega_c^{\nu DM} h^2$	0.1185 ± 0.0039	0.1198 ± 0.0015
$100\theta_s$	1.04337 ± 0.00069	1.04321 ± 0.00063
τ_{reio}	0.064 ± 0.015	0.062 ± 0.014
$\log(10^{10} A_s)$	3.049 ± 0.030	3.047 ± 0.030
n_s	1.004 ± 0.016	1.001 ± 0.014
$log_{10} u_{\nu DM}$	$-5.08^{+1.5}_{-0.98}\,(< -3.74)$	$-4.86^{+1.5}_{-0.83}\,(< -3.70)$
H_0	$68.2 \pm 1.6\,(68.2^{+3.3}_{-3.3})$	$67.66 \pm 0.58\,(67.7^{+1.1}_{-1.2})$
σ_8	$0.823^{+0.025}_{-0.021}\,(0.823^{+0.046}_{-0.050})$	$0.821^{+0.025}_{-0.020}\,(0.821^{+0.044}_{-0.050})$



Hint 2 Dark Matter (DM)

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Were:

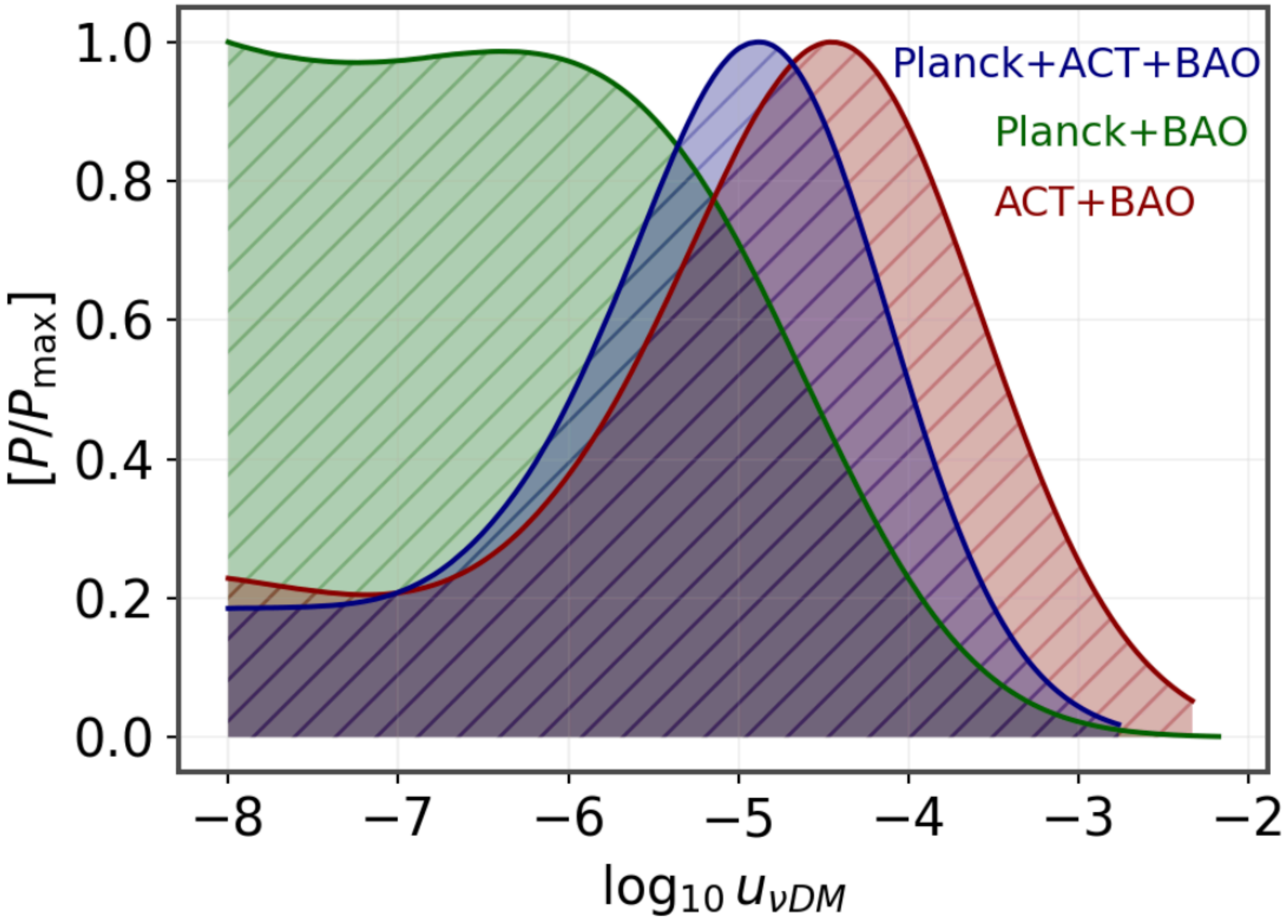
$$\dot{\mu} = a\, c\, \frac{\rho_{\mathrm{DM}}}{m_{DM}}\,\sigma_{\nu\mathrm{DM}}$$

Interaction Strength

$$u_{\nu\mathrm{DM}} \doteq \left[\frac{\sigma_{\nu\mathrm{DM}}}{\sigma_{\mathrm{Th}}}\right]\left[\frac{m_{\mathrm{DM}}}{100\,\mathrm{GeV}}\right]^{-1}$$

Brax et al. (WG) 2303.16894 and 2305.01383

Parameter	Planck + BAO	ACT + BAO	ACT + Planck + BAO
$\Omega_b h^2$	0.02239 ± 0.00013	0.02154 ± 0.00030	0.02236 ± 0.00012
$\Omega_c^{\nu\mathrm{DM}} h^2$	0.11958 ± 0.00093	0.1198 ± 0.0015	0.11975 ± 0.00097
$100\theta_s$	1.04191 ± 0.00028	1.04321 ± 0.00063	1.04206 ± 0.00026
τ_{reio}	0.0524 ± 0.0072	0.062 ± 0.014	0.0563 ± 0.0064
$\log(10^{10} A_s)$	3.038 ± 0.014	3.047 ± 0.030	3.053 ± 0.013
n_s	0.9642 ± 0.0038	1.001 ± 0.014	0.9678 ± 0.0036
$log_{10} u_{\nu DM}$	$< -4.46\ (< -4.39)$	$-4.86^{+1.5}_{-0.83}\ (< -3.70)$	$-5.20^{+1.2}_{-0.74}\ (< -4.17)$
H_0	$68.05 \pm 0.42\ (68.05^{+0.81}_{-0.82})$	$67.66 \pm 0.58\ (67.7^{+1.1}_{-1.2})$	$68.01 \pm 0.43\ (68.01^{+0.83}_{-0.85})$
σ_8	$0.807^{+0.011}_{-0.0084}\ (0.807^{+0.020}_{-0.021})$	$0.821^{+0.025}_{-0.020}\ (0.821^{+0.044}_{-0.050})$	$0.820^{+0.011}_{-0.0093}\ (0.820^{+0.021}_{-0.023})$



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Were:

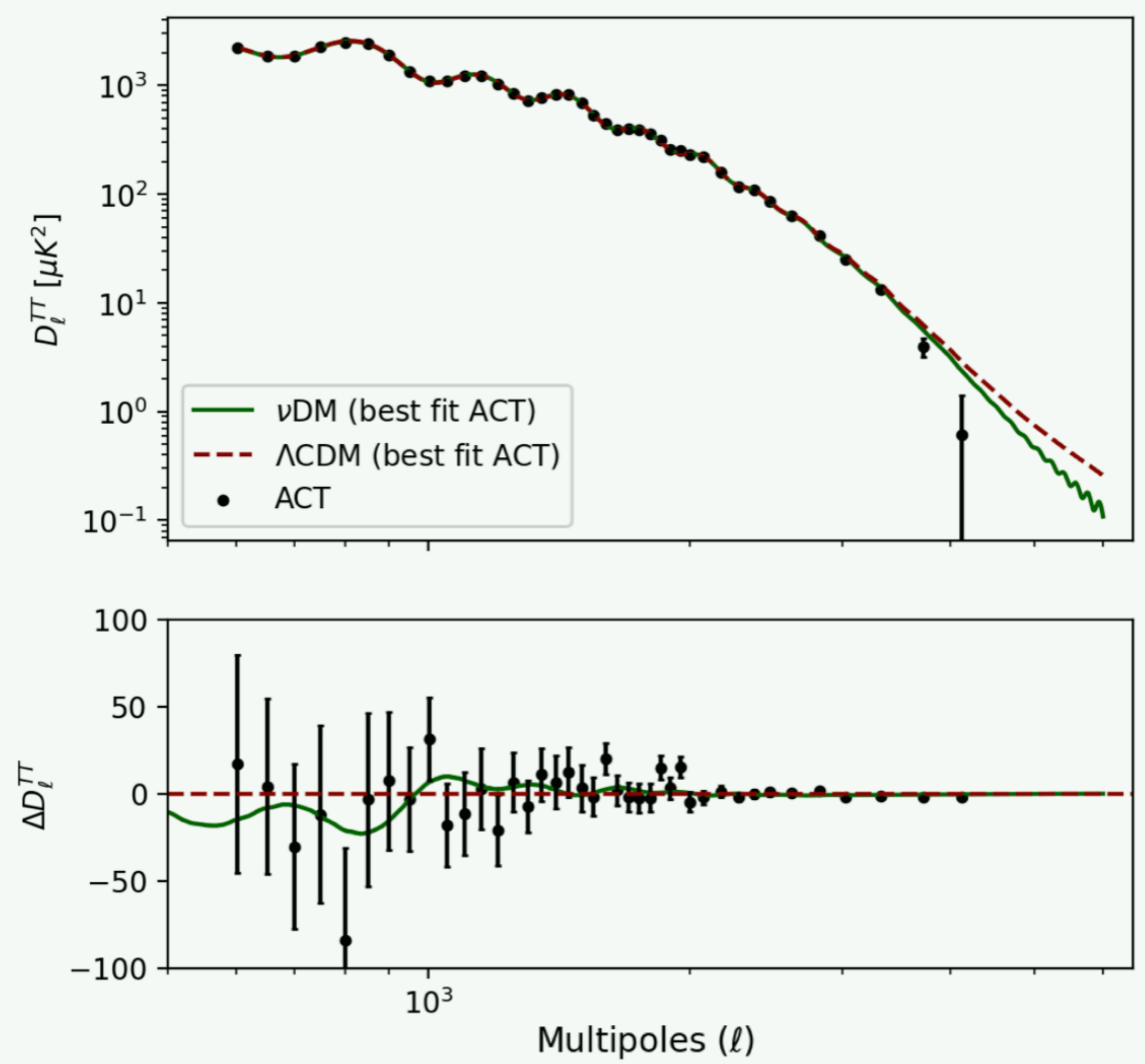
$$\dot{\mu} = a\,c\,\frac{\rho_{\rm DM}}{m_{DM}}\,\sigma_{\nu{\rm DM}}$$

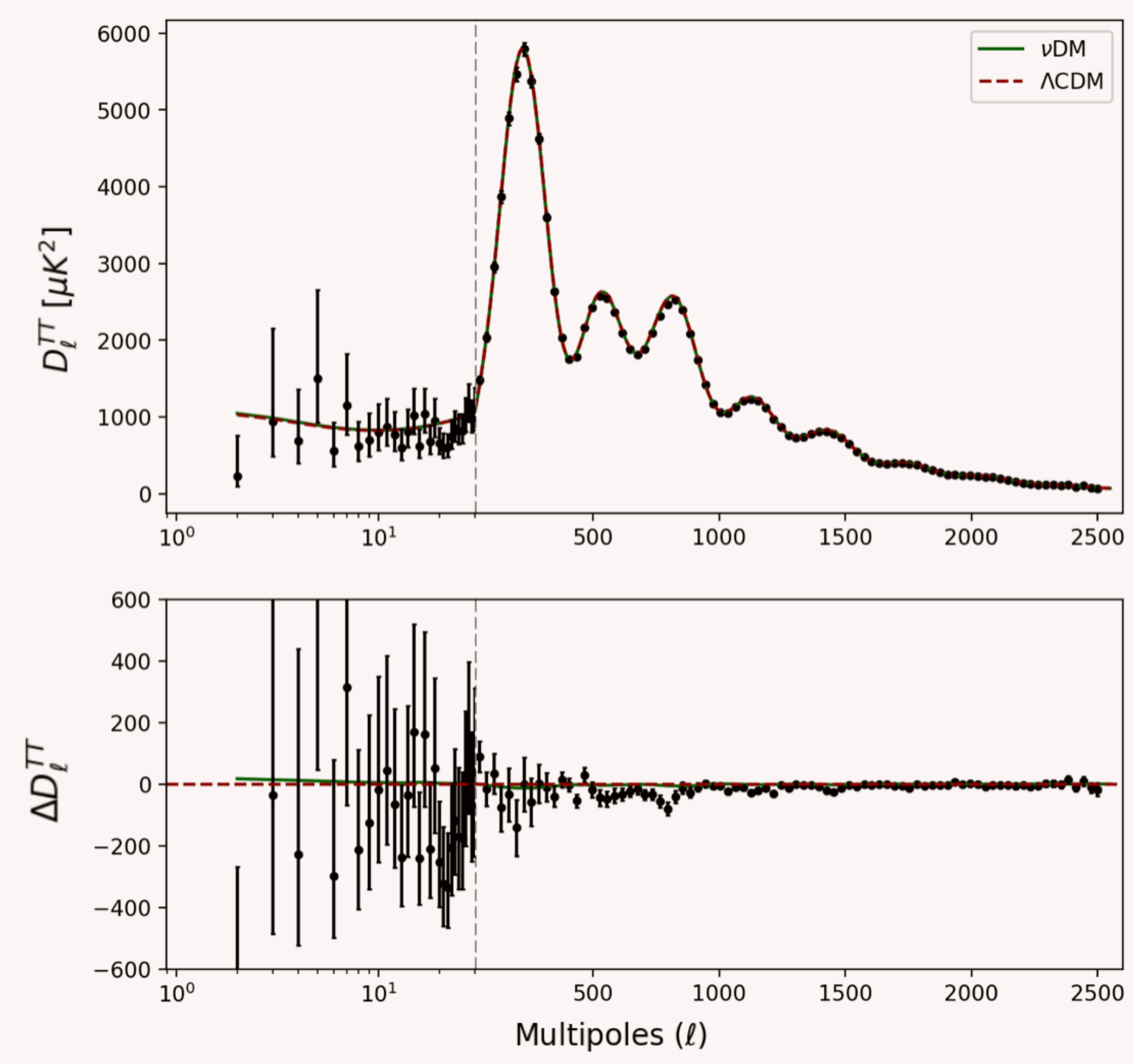
Interaction Strength

$$u_{\nu{\rm DM}} \doteq \left[\frac{\sigma_{\nu{\rm DM}}}{\sigma_{\rm Th}}\right]\left[\frac{m_{\rm DM}}{100\,{\rm GeV}}\right]^{-1}$$

Analysing the most recent **large and small-scale CMB observations** from **ACT DR-4** (alone and) in combination with **Planck 2018**, we find a **compelling indication for non-vanishing νDM interaction**

Brax et al. (WG) 2303.16894 and 2305.01383





This preference arises from an actual **improvement in the fit to the ACT high-multipole data** while leaving the fit to the **Planck data basically unchanged**

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$$\dot{\theta}_{\rm DM} = k^2\psi - \mathscr{H}\theta_{\rm DM} + \frac{4}{3}\frac{\rho_\nu}{\rho_{\rm DM}}\dot{\mu}\left(\theta_\nu - \theta_{\rm DM}\right)$$

Were:

$$\dot{\mu} = a\,c\,\frac{\rho_{\rm DM}}{m_{DM}}\,\sigma_{\nu\rm DM}$$

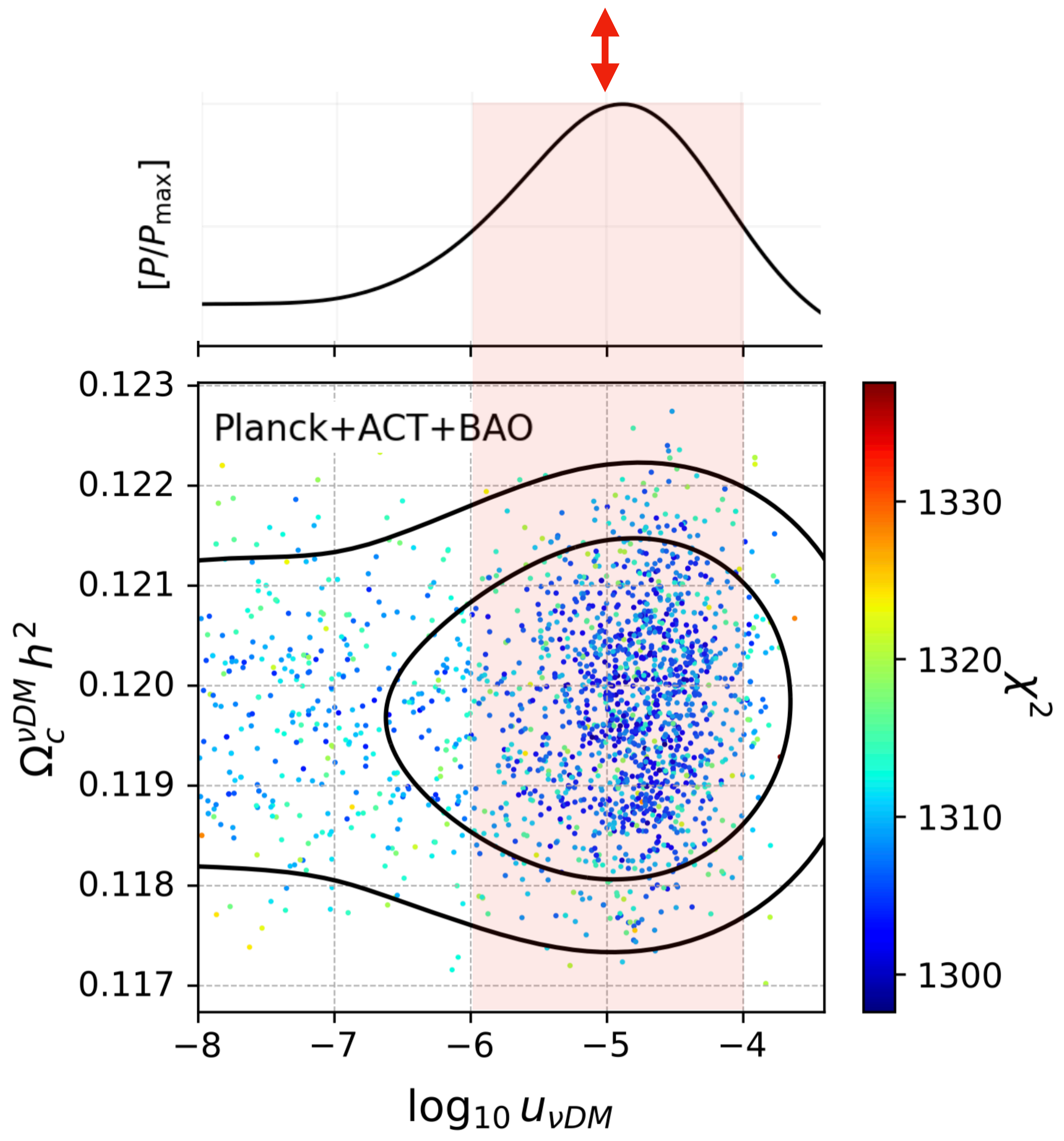
Interaction Strength

$$u_{\nu\rm DM} \doteq \left[\frac{\sigma_{\nu\rm DM}}{\sigma_{\rm Th}}\right]\left[\frac{m_{\rm DM}}{100\,\rm GeV}\right]^{-1}$$

This becomes evident through the **pronounced decrease in the chi-2 value associated with the peak** of the posterior distribution.

Brax et al. (WG) 2303.16894 and 2305.01383

Parameter	ACT + Planck + BAO
$\Omega_b h^2$	0.02236 ± 0.00012
$\Omega_c^{\nu\rm DM} h^2$	0.11975 ± 0.00097
$100\theta_s$	1.04206 ± 0.00026
$\tau_{\rm reio}$	0.0563 ± 0.0064
$\log(10^{10}A_s)$	3.053 ± 0.013
n_s	0.9678 ± 0.0036
$log_{10}u_{\nu DM}$	$-5.20^{+1.2}_{-0.74}$ (< -4.17)
H_0	68.01 ± 0.43 $(68.01^{+0.83}_{-0.85})$
σ_8	$0.820^{+0.011}_{-0.0093}$ $(0.820^{+0.021}_{-0.023})$



There is **NO tension** between ACT and Planck about this model

HINT 2 DARK MATTER (DM)

NEUTRINO-DM INTERACTIONS

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$$\dot{\theta}_{\rm DM} = k^2\psi - \mathscr{H}\theta_{\rm DM} + \frac{4}{3}\frac{\rho_\nu}{\rho_{\rm DM}}\dot{\mu}\,(\theta_\nu - \theta_{\rm DM})$$

Were:

$$\dot{\mu} = a\,c\,\frac{\rho_{\rm DM}}{m_{DM}}\,\sigma_{\nu\rm DM}$$

INTERACTION STRENGTH

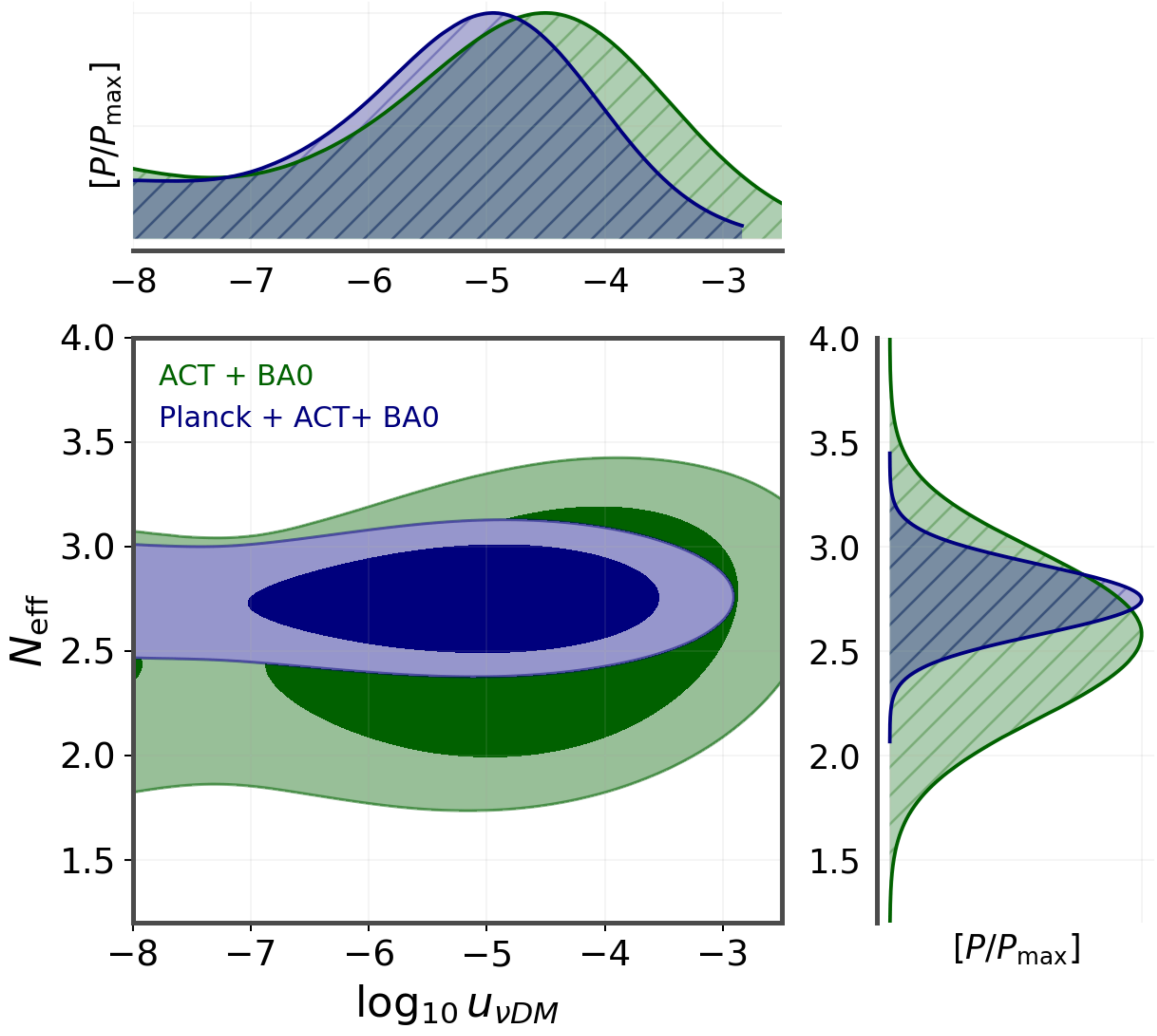
$$u_{\nu\rm DM} \doteq \left[\frac{\sigma_{\nu\rm DM}}{\sigma_{\rm Th}}\right]\left[\frac{m_{\rm DM}}{100\,\rm GeV}\right]^{-1}$$

Despite our result being just at 1σ level (reflecting the current CMB data sensitivity):

CMB+BAO: $\log_{10} u_{\nu DM} = -5.20^{+1.2}_{-0.74}$

Brax et al. (WG) 2303.16894 and 2305.01383

1) It is **stable** when the **effective number of relativistic degrees of freedom** is varied



HINT 2 DARK MATTER (DM)

NEUTRINO-DM INTERACTIONS

Euler Equations in the Newtonian Gauge:

$$\dot{\theta}_\nu = k^2\psi + k^2\left(\frac{1}{4}\delta_\nu - \sigma_\nu\right) - \dot{\mu}\left(\theta_\nu - \theta_{\rm DM}\right)$$

$$\dot{\theta}_{\rm DM} = k^2\psi - \mathcal{H}\theta_{\rm DM} + \frac{4}{3}\frac{\rho_\nu}{\rho_{\rm DM}}\dot{\mu}\left(\theta_\nu - \theta_{\rm DM}\right)$$

Were:

$$\dot{\mu} = a\,c\,\frac{\rho_{\rm DM}}{m_{DM}}\,\sigma_{\nu{\rm DM}}$$

INTERACTION STRENGTH

$$u_{\nu{\rm DM}} \doteq \left[\frac{\sigma_{\nu{\rm DM}}}{\sigma_{\rm Th}}\right]\left[\frac{m_{\rm DM}}{100\,{\rm GeV}}\right]^{-1}$$

Despite our result being just at 1σ level (reflecting the current CMB data sensitivity):

CMB+BAO: $\log_{10} u_{\nu DM} = -5.20^{+1.2}_{-0.74}$

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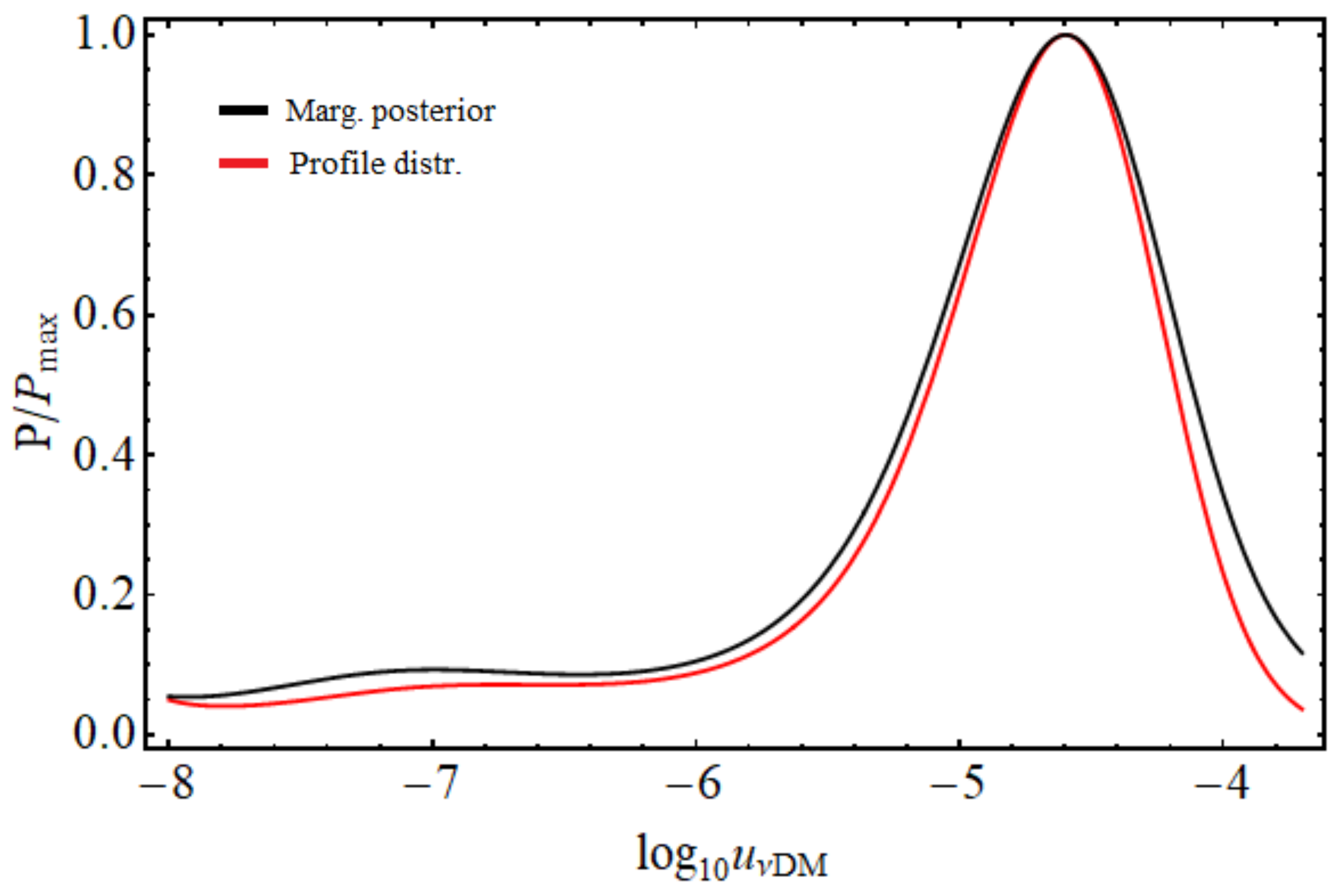
WG, A. Gomez-Valent, E. Di Valentino, … (in preparation)



HINT 2 Dark Matter (DM)

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Were:

$$\dot{\mu} = a\,c\,\frac{\rho_{\rm DM}}{m_{DM}}\,\sigma_{\nu\rm DM}$$

Interaction Strength

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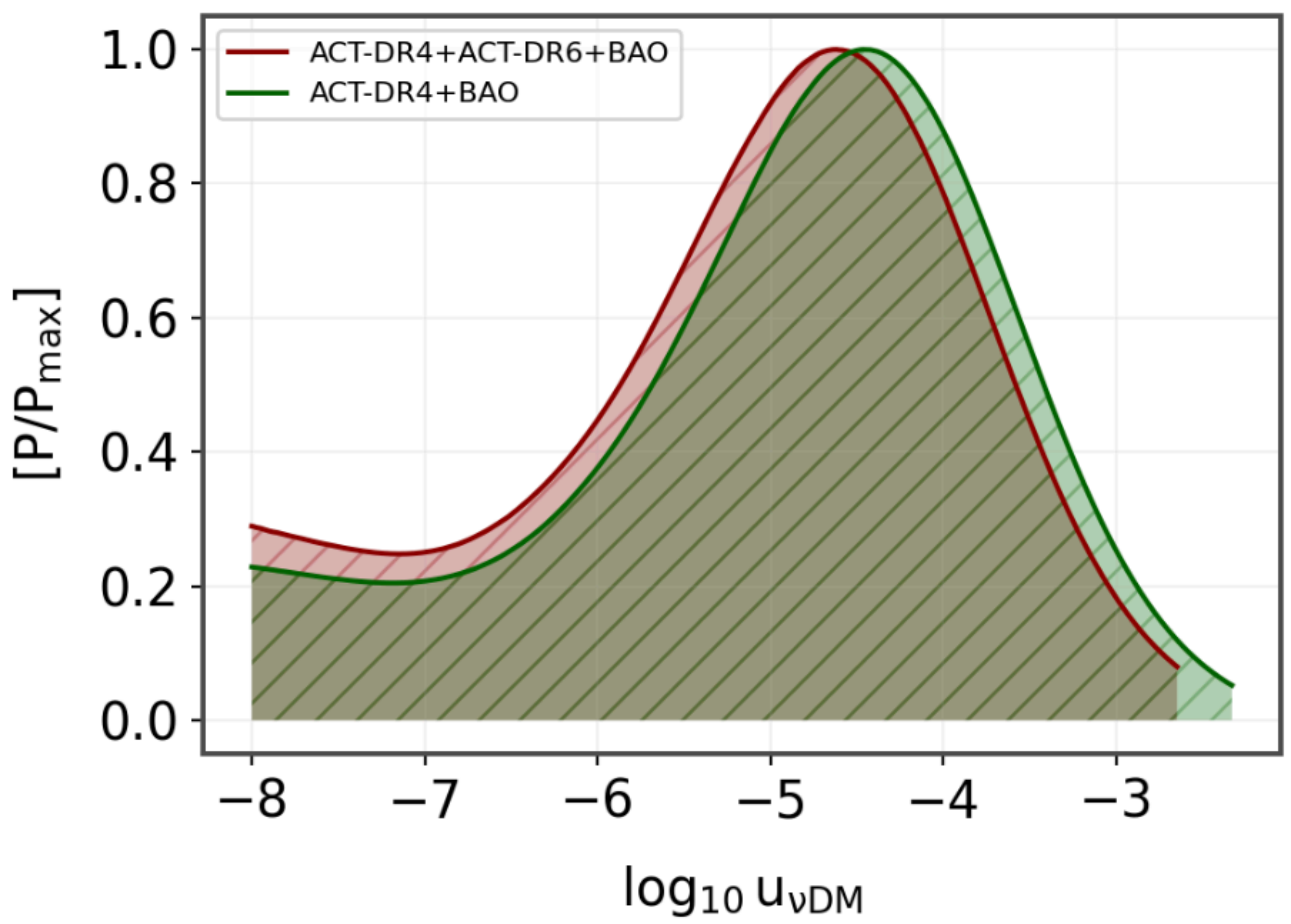

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NEUTRINO-DM INTERACTIONS

Euler Equations in the Newtonian Gauge:

$$\dot{\theta}_\nu = k^2\psi + k^2\left(\frac{1}{4}\delta_\nu - \sigma_\nu\right) - \dot{\mu}\,(\theta_\nu - \theta_{\rm DM})$$

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Were:

$$\dot{\mu} = a\,c\,\frac{\rho_{\rm DM}}{m_{DM}}\,\sigma_{\nu{\rm DM}}$$

INTERACTION STRENGTH

$$u_{\nu{\rm DM}} \doteq \left[\frac{\sigma_{\nu{\rm DM}}}{\sigma_{\rm Th}}\right]\left[\frac{m_{\rm DM}}{100\,{\rm GeV}}\right]^{-1}$$

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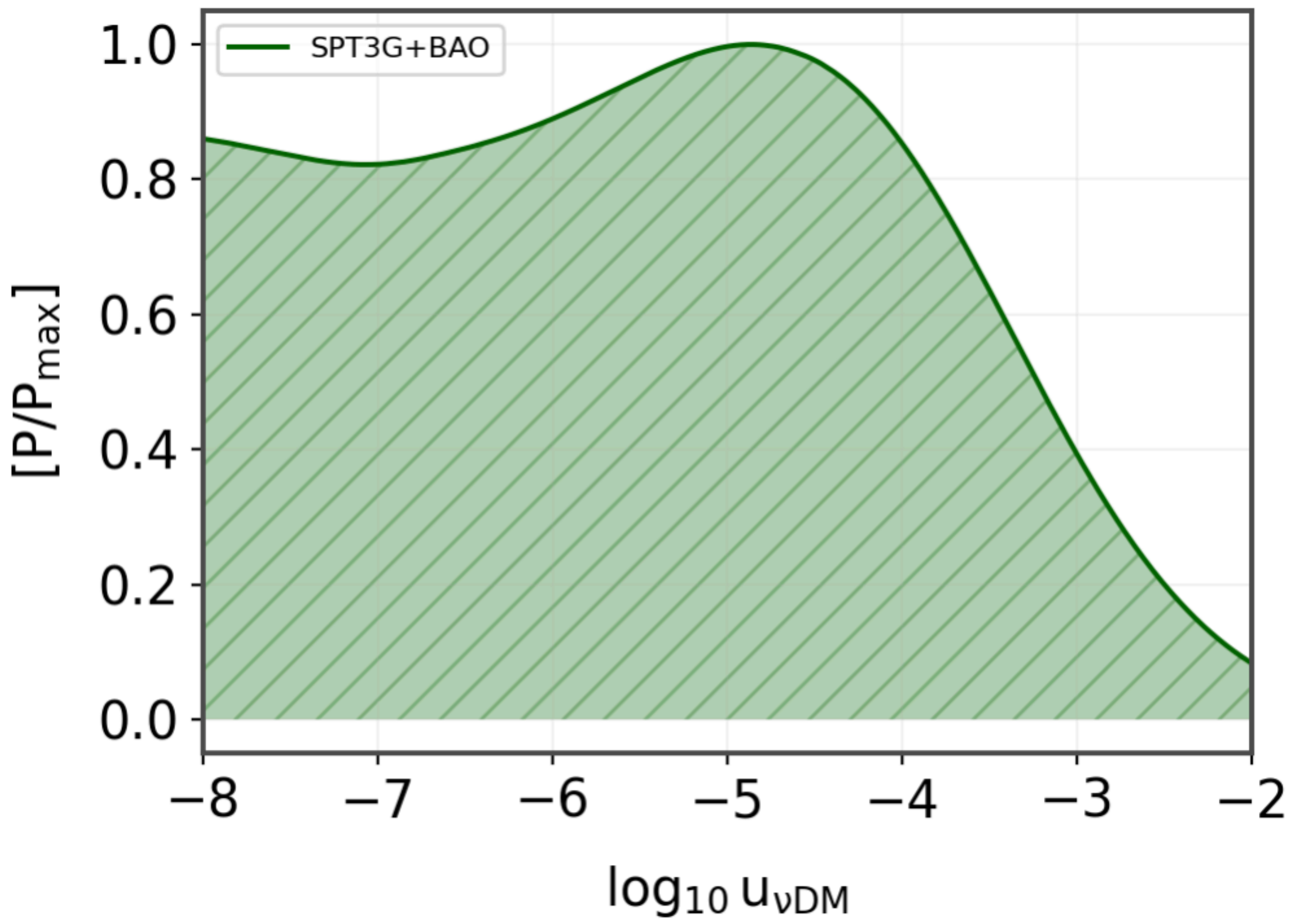
4) It is **partially supported by recent SPT temperature and Polarization Data**

WG, A. Gomez-Valent, E. Di Valentino, … (in preparation)



HINT 2 DARK MATTER (DM)

NEUTRINO-DM INTERACTIONS

Euler Equations in the Newtonian Gauge:

$$\dot{\theta}_\nu = k^2\psi + k^2\left(\frac{1}{4}\delta_\nu - \sigma_\nu\right) - \dot{\mu}\,(\theta_\nu - \theta_{DM})$$

$$\dot{\theta}_{DM} = k^2\psi - \mathscr{H}\theta_{DM} + \frac{4}{3}\frac{\rho_\nu}{\rho_{DM}}\dot{\mu}\,(\theta_\nu - \theta_{DM})$$

Were:

$$\dot{\mu} = a\,c\,\frac{\rho_{DM}}{m_{DM}}\,\sigma_{\nu DM}$$

INTERACTION STRENGTH

$$u_{\nu DM} \doteq \left[\frac{\sigma_{\nu DM}}{\sigma_{Th}}\right]\left[\frac{m_{DM}}{100\,\mathrm{GeV}}\right]^{-1}$$

Despite our result being just at 1σ level (reflecting the current CMB data sensitivity):

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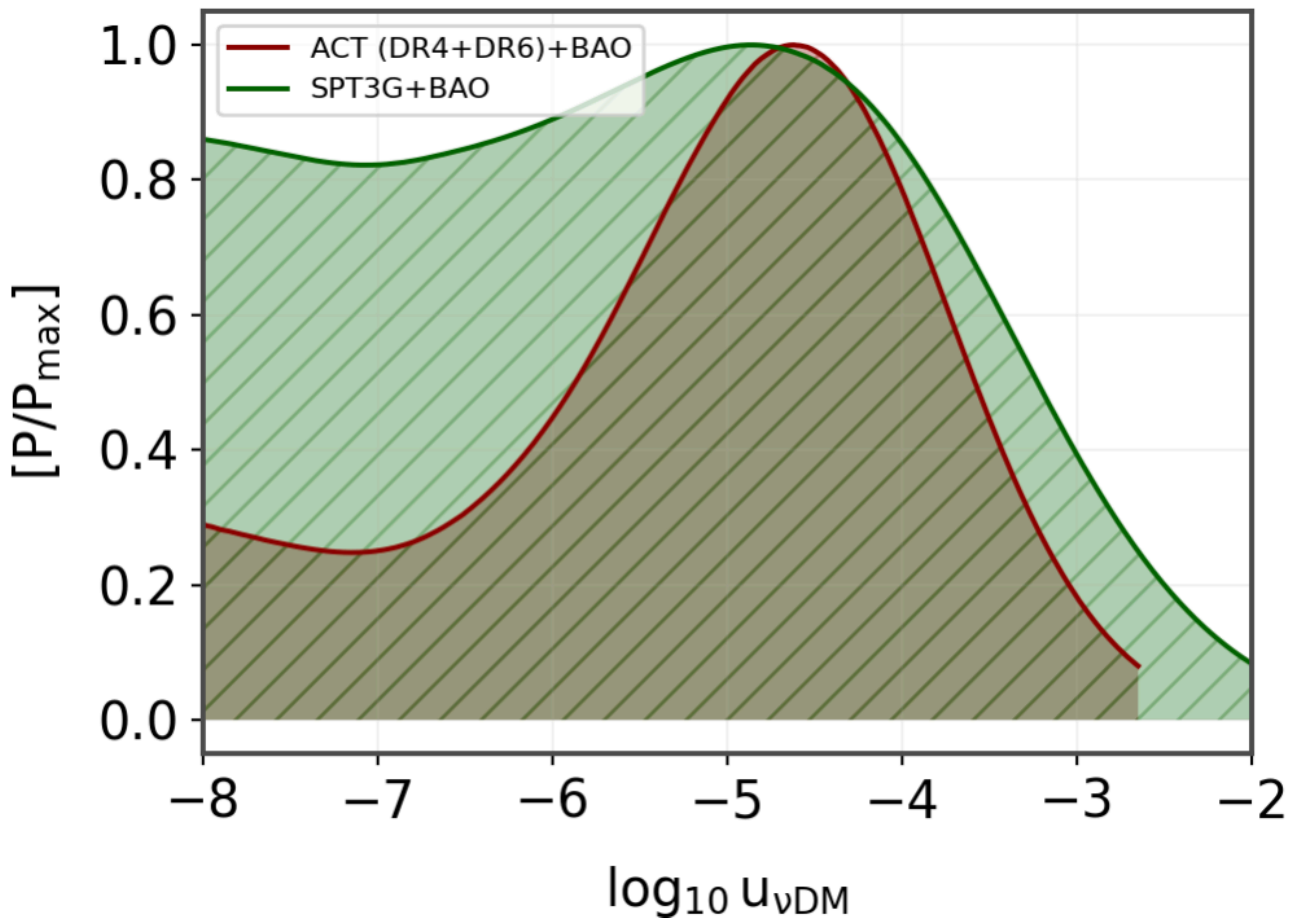

Hint 2 Dark Matter (DM)

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Were:

$$\dot{\mu} = a\,c\,\frac{\rho_{\rm DM}}{m_{DM}}\,\sigma_{\nu\rm DM}$$

Interaction Strength

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4) It is **partially supported by recent SPT temperature and Polarization Data**
5) it is supported by **an independent 3σ indication from Lyman-α data**:

Lyman-α: $\log_{10} u_{\nu DM} = -5.42^{+0.17}_{-0.08}$

D.C. Hooper and M. Lucca, 2110.04024

↓

This is something to carefully check in light of upcoming and future CMB data

HINT 3 Dark Energy (DE)

Different combinations of **Planck**, **ACT** and **WMAP** (9-year) data provide similar results, **favoring IDE** with a 95%CL significance in the majority of the cases

Interacting Dark energy

IDE introduces **energy-momentum transfer from DM to DE**, modifying their individual energy conservation equations

$$\nabla_\mu (T_{\rm DM})^\mu{}_\nu = +\frac{Q(v_{\rm DM})_\nu}{a} \qquad \nabla_\mu (T_{de})^\mu{}_\nu = -\frac{Q(v_{\rm DM})_\nu}{a}$$

We focus on an interacting model with an interacting rate:

$$Q = \xi \mathscr{H} \rho_{de}$$

DM-DE Boltzmann equations in the Synchronous gauge:

$$\dot\delta_{\rm DM} = -\theta_{\rm DM} - \frac{1}{2}\dot h + \xi \mathscr{H}\frac{\rho_{de}}{\rho_{\rm DM}}(\delta_{de} - \delta_{\rm DM}) + \xi\frac{\rho_{de}}{\rho_{\rm DM}}\left(\frac{k v_T}{3} + \frac{\dot h}{6}\right)$$

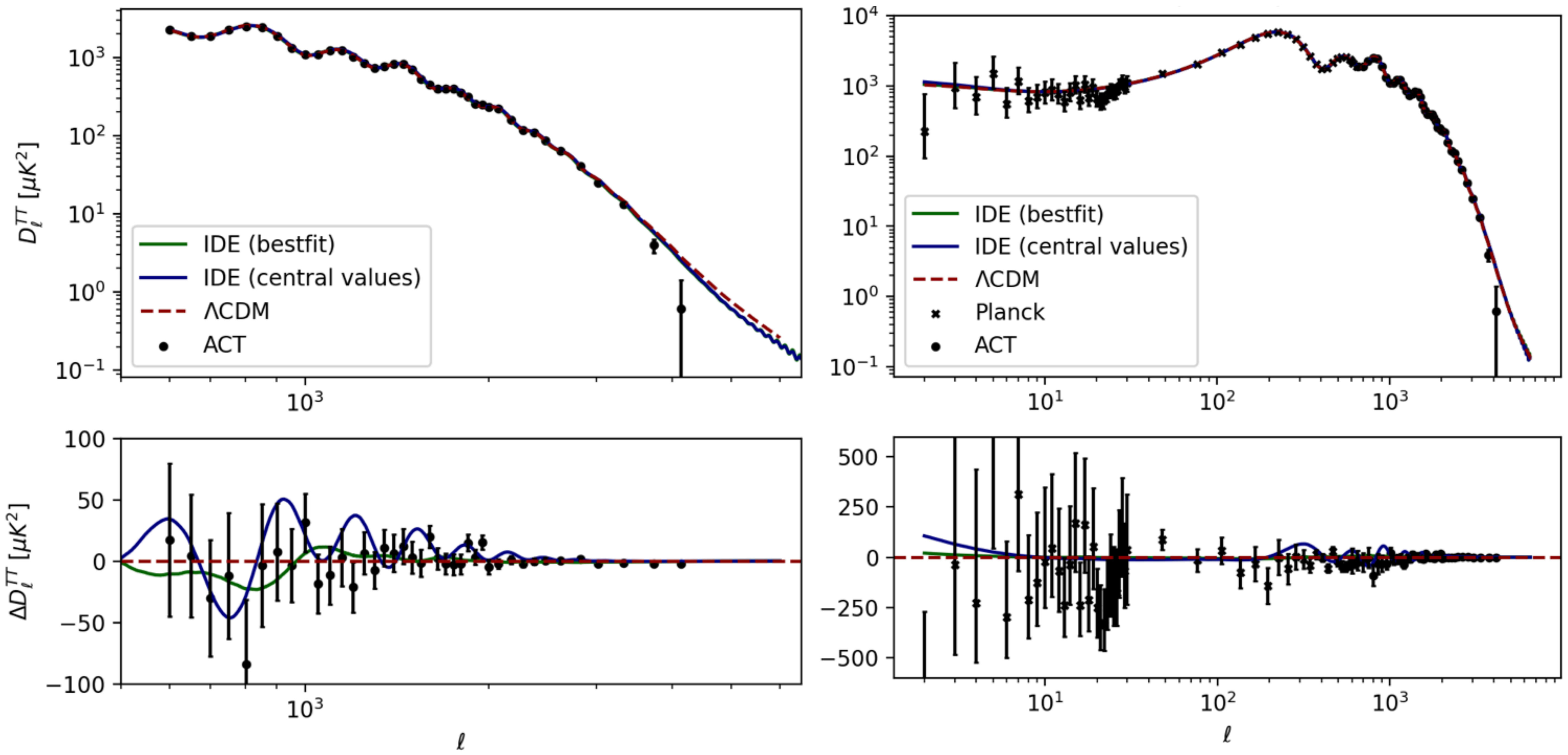
$$\dot\theta_{\rm DM} = -\mathscr{H}\theta_{\rm DM}$$

$$\dot\delta_{de} = -(1+w)\left(\theta_{de} + \frac{\dot h}{2}\right) - 3\mathscr{H}(1-w)\left[\delta_{de} + 3\mathscr{H}(1+w)\frac{\theta_{de}}{k^2}\right] + 3\mathscr{H}^2\xi(1-w)\frac{\theta_{de}}{k^2} - \xi\left(\frac{k v_T}{3} + \frac{\dot h}{6}\right)$$

$$\dot\theta_{de} = 2\mathscr{H}\theta_{de} + \frac{k^2}{1+w}\delta_{de} + 2\mathscr{H}\frac{\xi}{1+w}\theta_{de} - \xi\mathscr{H}\frac{\theta_{\rm DM}}{1+w}$$

Y. Zhai, WG *et al*, - 2303.08201

Parameter	Planck	ACT	ACT+WMAP	ACT+Planck
$\Omega_b h^2$	0.02237 ± 0.00015	0.02153 ± 0.00032	0.02238 ± 0.00020	0.02238 ± 0.00013
$\Omega_c h^2$	$0.067^{+0.042}_{-0.031}$ (< 0.115)	< 0.0754 (< 0.111)	$0.070^{+0.046}_{-0.021}$ (< 0.117)	$0.067^{+0.042}_{-0.030}$ (< 0.115)
H_0	71.6 ± 2.1	$72.6^{+3.4}_{-2.6}$	$71.3^{+2.6}_{-3.2}$	$71.4^{+2.5}_{-2.8}$
$\tau_{\rm reio}$	0.0534 ± 0.0079	0.063 ± 0.015	0.061 ± 0.014	0.0533 ± 0.0073
$\log(10^{10} A_s)$	3.042 ± 0.016	3.046 ± 0.030	3.064 ± 0.028	3.047 ± 0.014
n_s	0.9655 ± 0.0045	1.010 ± 0.016	$0.9741^{+0.0066}_{-0.0064}$	0.9699 ± 0.0038
ξ	$-0.40^{+0.23}_{-0.20}$	$-0.46^{+0.20}_{-0.28}$	$-0.38^{+0.35}_{-0.14}$	$-0.40^{+0.27}_{-0.23}$



HINT 3 DARK ENERGY (DE)

INTERACTING DARK ENERGY

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$$Q = \xi \, \mathscr{H} \, \rho_{de}$$

DM-DE Boltzmann equations in the Synchronous gauge:

$$\dot\delta_{\rm DM} = -\theta_{\rm DM} - \frac{1}{2}\dot h + \xi \mathscr{H} \frac{\rho_{de}}{\rho_{\rm DM}} (\delta_{de} - \delta_{\rm DM}) + \xi \frac{\rho_{de}}{\rho_{\rm DM}} \left(\frac{k v_T}{3} + \frac{\dot h}{6} \right)$$

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Preference for **IDE yields a value of the expansion rate H0 consistent with SH0ES**

Y. Zhai, WG *et al,* - 2303.08201

Parameter	Planck	ACT	ACT+WMAP	ACT+Planck
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$\tau_{\rm reio}$	0.0534 ± 0.0079	0.063 ± 0.015	0.061 ± 0.014	0.0533 ± 0.0073
$\log(10^{10} A_s)$	3.042 ± 0.016	3.046 ± 0.030	3.064 ± 0.028	3.047 ± 0.014
n_s	0.9655 ± 0.0045	1.010 ± 0.016	$0.9741^{+0.0066}_{-0.0064}$	0.9699 ± 0.0038
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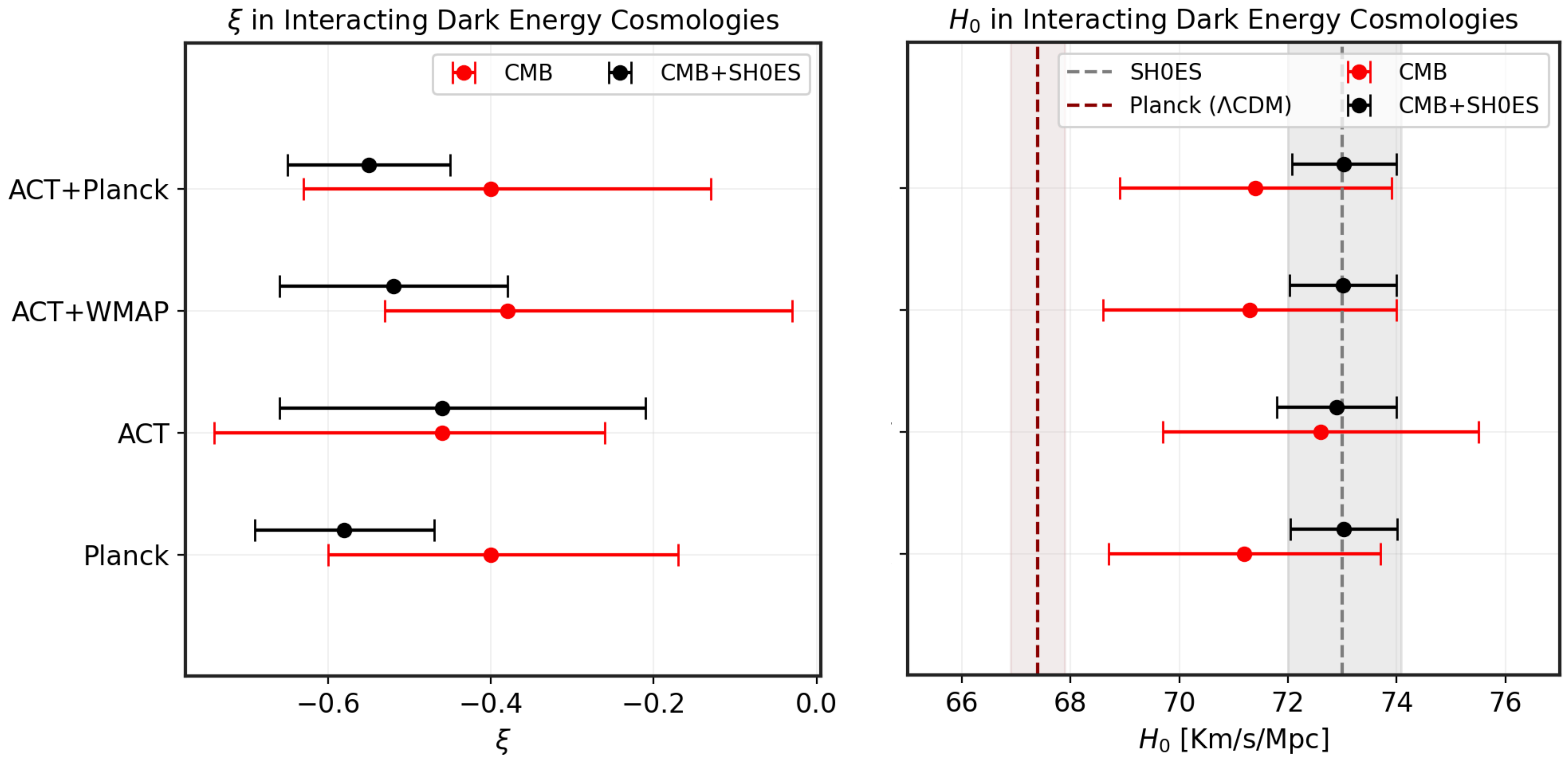

Hint 3 Dark Energy (DE)

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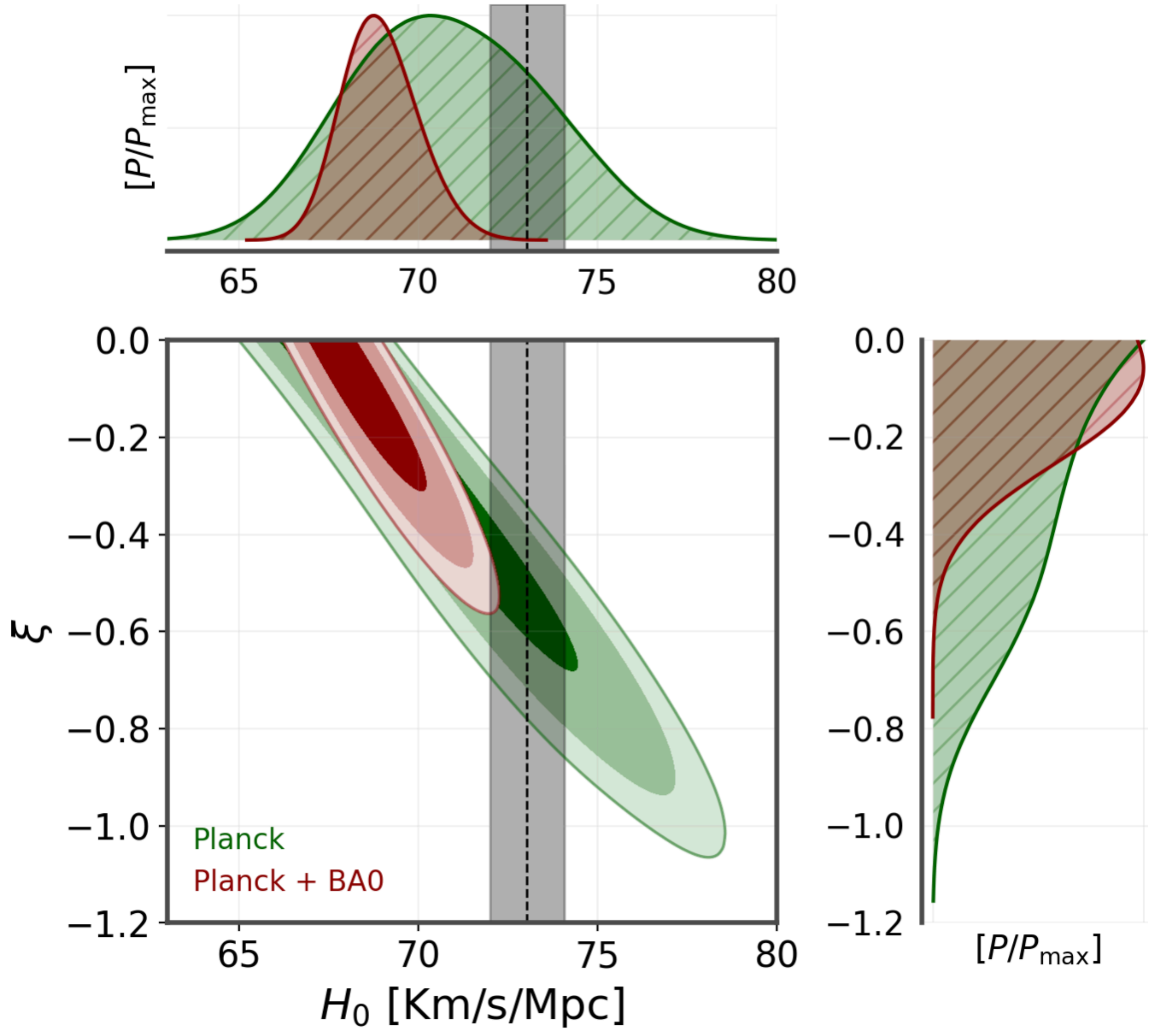
A. Bernui *et al (WG)* - 2301.06097

Parameter	CMB	CMB+BAO-3D
$10^2 \times \Omega_b h^2$	2.239 ± 0.015	2.236 ± 0.013
$\Omega_c h^2$	$0.067^{+0.042}_{-0.031}$ (< 0.115)	$0.101^{+0.016}_{-0.012}$
H_0	71.6 ± 2.1	$68.92^{+0.96}_{-1.2}$
$\tau_{\rm reio}$	0.0534 ± 0.0079	0.0544 ± 0.0079
$\log(10^{10} A_s)$	3.042 ± 0.016	3.045 ± 0.016
n_s	0.9655 ± 0.0045	0.9650 ± 0.0037
ξ	$-0.40^{+0.23}_{-0.20}$ (> -0.775)	> -0.207 (> -0.389)



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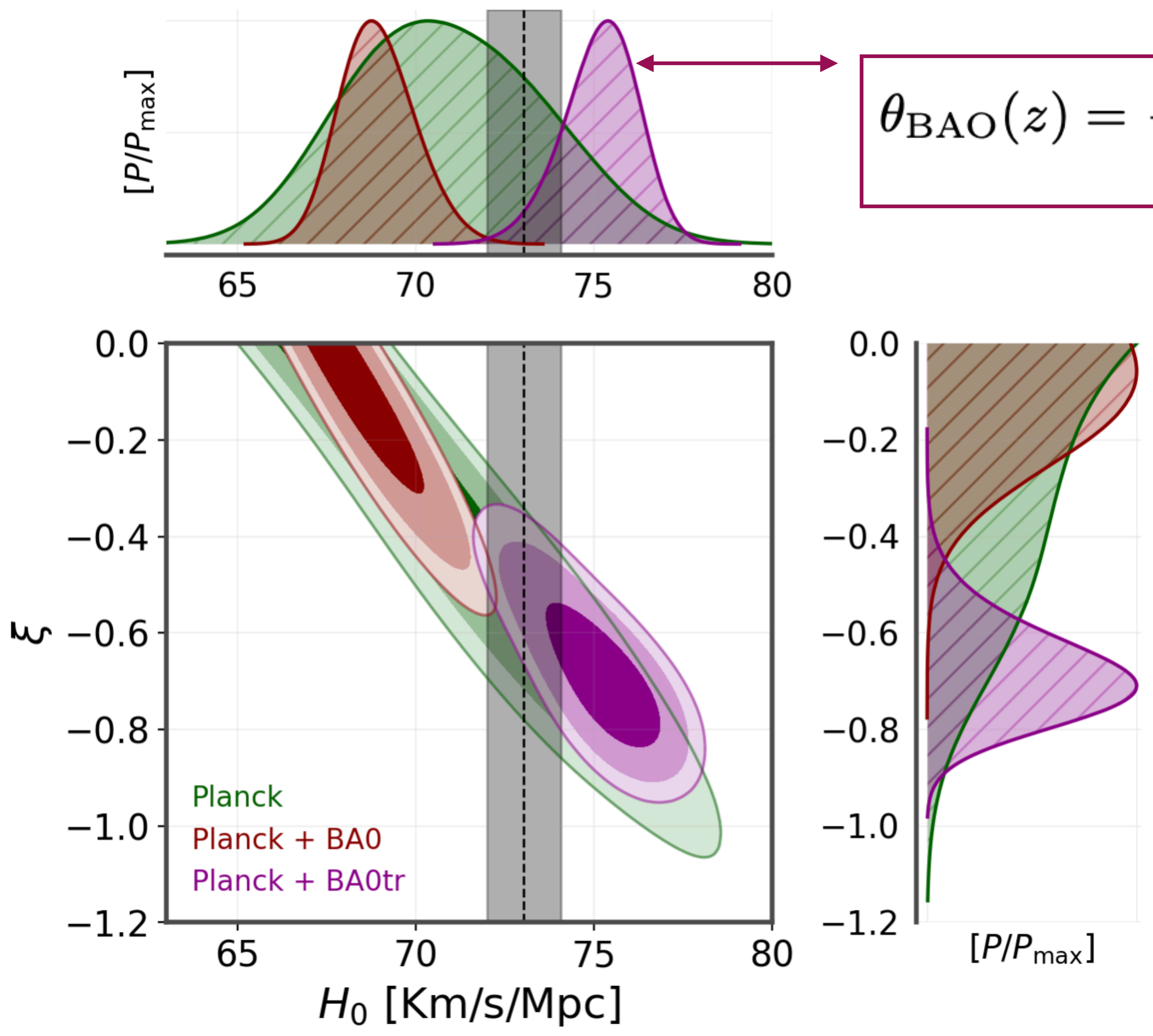
A. Bernui *et al (WG)* - 2301.06097

Parameter	CMB	CMB+BAO-3D	CMB+BAO-2D (ON)
$10^2 \times \Omega_b h^2$	2.239 ± 0.015	2.236 ± 0.013	2.248 ± 0.014
$\Omega_c h^2$	$0.067^{+0.042}_{-0.031}$ (< 0.115)	$0.101^{+0.016}_{-0.012}$	$0.022^{+0.014}_{-0.019}$
H_0	71.6 ± 2.1	$68.92^{+0.96}_{-1.2}$	$75.2^{+1.1}_{-0.96}$
$\tau_{\rm reio}$	0.0534 ± 0.0079	0.0544 ± 0.0079	0.0556 ± 0.0082
$\log(10^{10} A_s)$	3.042 ± 0.016	3.045 ± 0.016	3.044 ± 0.017
n_s	0.9655 ± 0.0045	0.9650 ± 0.0037	0.9695 ± 0.0040
ξ	$-0.40^{+0.23}_{-0.20}$ (> -0.775)	$> -0.207 (> -0.389)$	$-0.683^{+0.088}_{-0.11}$



$$\theta_{\rm BAO}(z) = \frac{r_d}{(1+z)d_A(z)}$$

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A. Bernui *et al (WG)* - 2301.06097

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ξ	$-0.40^{+0.23}_{-0.20}$ (> -0.775)	$> -0.207 (> -0.389)$	$-0.683^{+0.088}_{-0.11}$

Constraints at 68% CL on the parameters of the ΛCDM model.

Parameter	CMB	CMB+BAO-3D	CMB+BAO-2D (ON)
$10^2 \times \Omega_b h^2$	2.236 ± 0.015	2.245 ± 0.013	2.263 ± 0.014
$\Omega_c h^2$	0.1202 ± 0.0014	0.11911 ± 0.00096	0.1165 ± 0.0011
H_0	67.32 ± 0.62	67.84 ± 0.43	69.01 ± 0.51
$\tau_{\rm reio}$	0.0536 ± 0.0081	0.0590 ± 0.0070	0.0606 ± 0.0081
$\log(10^{10} A_s)$	3.043 ± 0.016	3.053 ± 0.015	3.049 ± 0.017
n_s	0.9646 ± 0.0045	0.9677 ± 0.0037	0.9742 ± 0.0038

- Using the angular BAO measurements from the Brazil National Observatory **(ON)** group in **2002.09293** we observe **differences with respect to BAO-3D, both for ΛCDM and IDE**

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WG, E. Di Valentino, … (in preparation)

A. Bernui *et al* (WG) - 2301.06097

Parameter	CMB	CMB+BAO-3D	CMB+BAO-2D (ON)	CMB+BAO-2D (M&M)
$10^2 \times \Omega_b h^2$	2.239 ± 0.015	2.236 ± 0.013	2.248 ± 0.014	2.237 ± 0.014
$\Omega_c h^2$	$0.067^{+0.042}_{-0.031}$ (< 0.115)	$0.101^{+0.016}_{-0.012}$	$0.022^{+0.014}_{-0.019}$	$0.089^{+0.019}_{-0.016}$
H_0	71.6 ± 2.1	$68.92^{+0.96}_{-1.2}$	$75.2^{+1.1}_{-0.96}$	69.9 ± 1.1
$\tau_{\rm reio}$	0.0534 ± 0.0079	0.0544 ± 0.0079	0.0556 ± 0.0082	0.0537 ± 0.0078
$\log(10^{10} A_s)$	3.042 ± 0.016	3.045 ± 0.016	3.044 ± 0.017	3.044 ± 0.016
n_s	0.9655 ± 0.0045	0.9650 ± 0.0037	0.9695 ± 0.0040	0.9657 ± 0.0039
ξ	$-0.40^{+0.23}_{-0.20}$ (> -0.775)	$> -0.207 (> -0.389)$	$-0.683^{+0.088}_{-0.11}$	$-0.26^{+0.18}_{-0.12}$ (> -0.505)

Constraints at 68% CL on the parameters of the ΛCDM model.

Parameter	CMB	CMB+BAO-3D	CMB+BAO-2D (ON)	CMB+BAO-2D (M&M)
$10^2 \times \Omega_b h^2$	2.236 ± 0.015	2.245 ± 0.013	2.263 ± 0.014	2.246 ± 0.014
$\Omega_c h^2$	0.1202 ± 0.0014	0.11911 ± 0.00096	0.1165 ± 0.0011	0.11877 ± 0.00097
H_0	67.32 ± 0.62	67.84 ± 0.43	69.01 ± 0.51	67.96 ± 0.44
$\tau_{\rm reio}$	0.0536 ± 0.0081	0.0590 ± 0.0070	0.0606 ± 0.0081	0.0567 ± 0.0080
$\log(10^{10} A_s)$	3.043 ± 0.016	3.053 ± 0.015	3.049 ± 0.017	3.047 ± 0.016
n_s	0.9646 ± 0.0045	0.9677 ± 0.0037	0.9742 ± 0.0038	0.9688 ± 0.0037

- Using the angular BAO measurements from the Brazil National Observatory **(ON)** group in **2002.09293** we observe **differences with respect to BAO-3D, both for ΛCDM and IDE**
- Using the angular BAO measurements from the latest BOSS and eBOSS measurements from **Menote & Marra, 2112.10000 (M&M)**, we get the **same results for ΛCDM** while we observe **differences for IDE**

HINT 3 DARK ENERGY (DE)

WG, E. Di Valentino, … (in preparation, preliminary results)

INTERACTING DARK ENERGY

IDE introduces **energy-momentum transfer from DM to DE**, modifying their individual energy conservation equations

$$\nabla_\mu (T_{\rm DM})^\mu{}_\nu = + \frac{Q(v_{\rm DM})_\nu}{a} \qquad \nabla_\mu (T_{de})^\mu{}_\nu = - \frac{Q(v_{\rm DM})_\nu}{a}$$

We focus on an interacting model with an interacting rate:

$$Q = \xi \, \mathcal{H} \, \rho_{de}$$

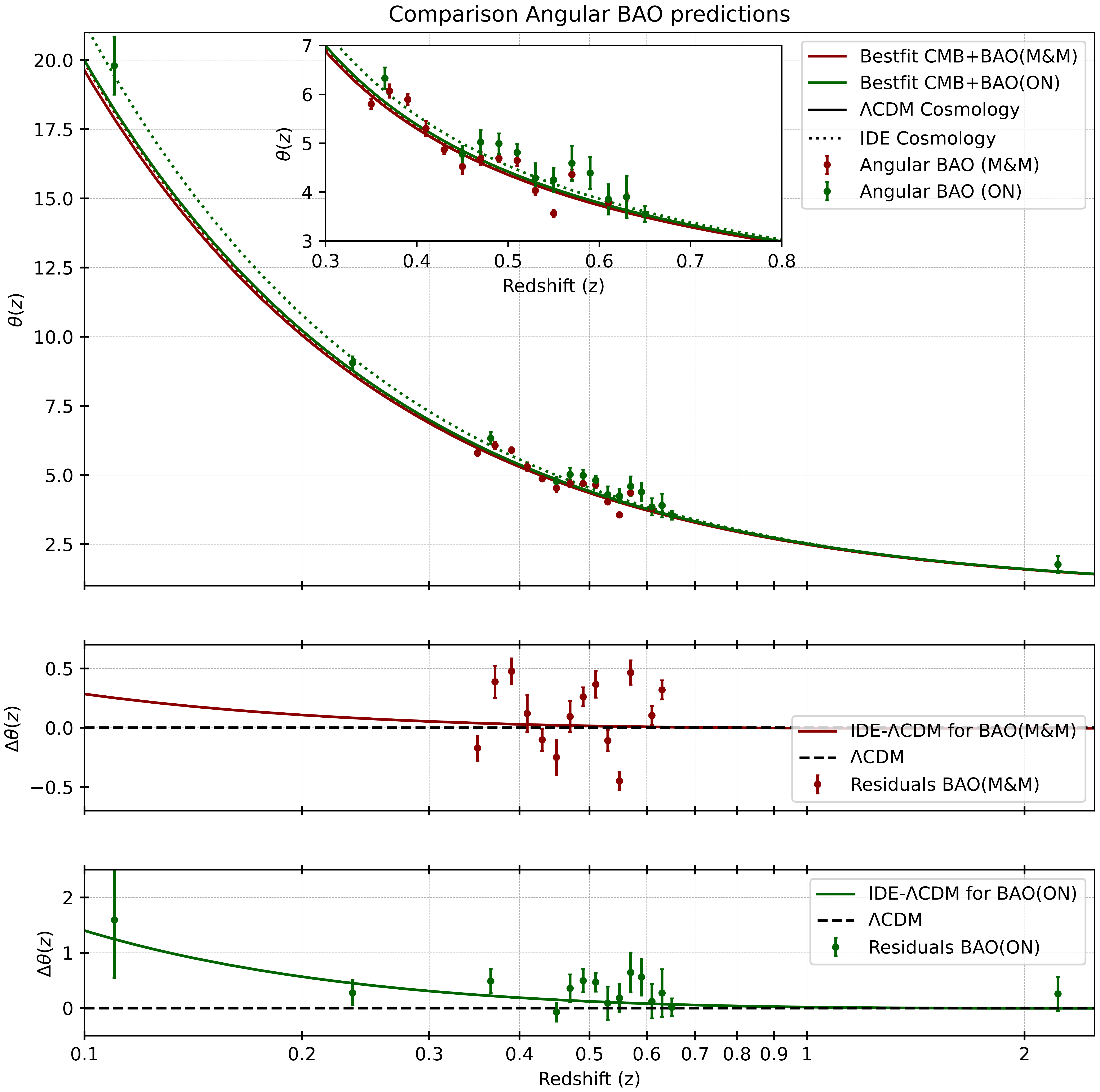
DM-DE Boltzmann equations in the Synchronous gauge:

$$\dot{\delta}_{\rm DM} = -\theta_{\rm DM} - \frac{1}{2}\dot{h} + \boldsymbol{\xi \mathcal{H} \frac{\rho_{de}}{\rho_{\rm DM}}(\delta_{de} - \delta_{\rm DM}) + \xi \frac{\rho_{de}}{\rho_{\rm DM}} \left(\frac{k v_T}{3} + \frac{\dot{h}}{6} \right)}$$

$$\dot{\theta}_{\rm DM} = -\mathcal{H}\theta_{\rm DM}$$

$$\dot{\delta}_{de} = -(1+w)\left(\theta_{de} + \frac{\dot{h}}{2}\right) - 3\mathcal{H}(1-w)\left[\delta_{de} + 3\mathcal{H}(1+w)\frac{\theta_{de}}{k^2}\right] \boldsymbol{+ 3\mathcal{H}^2\xi(1-w)\frac{\theta_{de}}{k^2} - \xi\left(\frac{k v_T}{3} + \frac{\dot{h}}{6}\right)}$$

$$\dot{\theta}_{de} = 2\mathcal{H}\theta_{de} + \frac{k^2}{1+w}\delta_{de} \boldsymbol{+ 2\mathcal{H}\frac{\xi}{1+w}\theta_{de} - \xi\mathcal{H}\frac{\theta_{\rm DM}}{1+w}}$$



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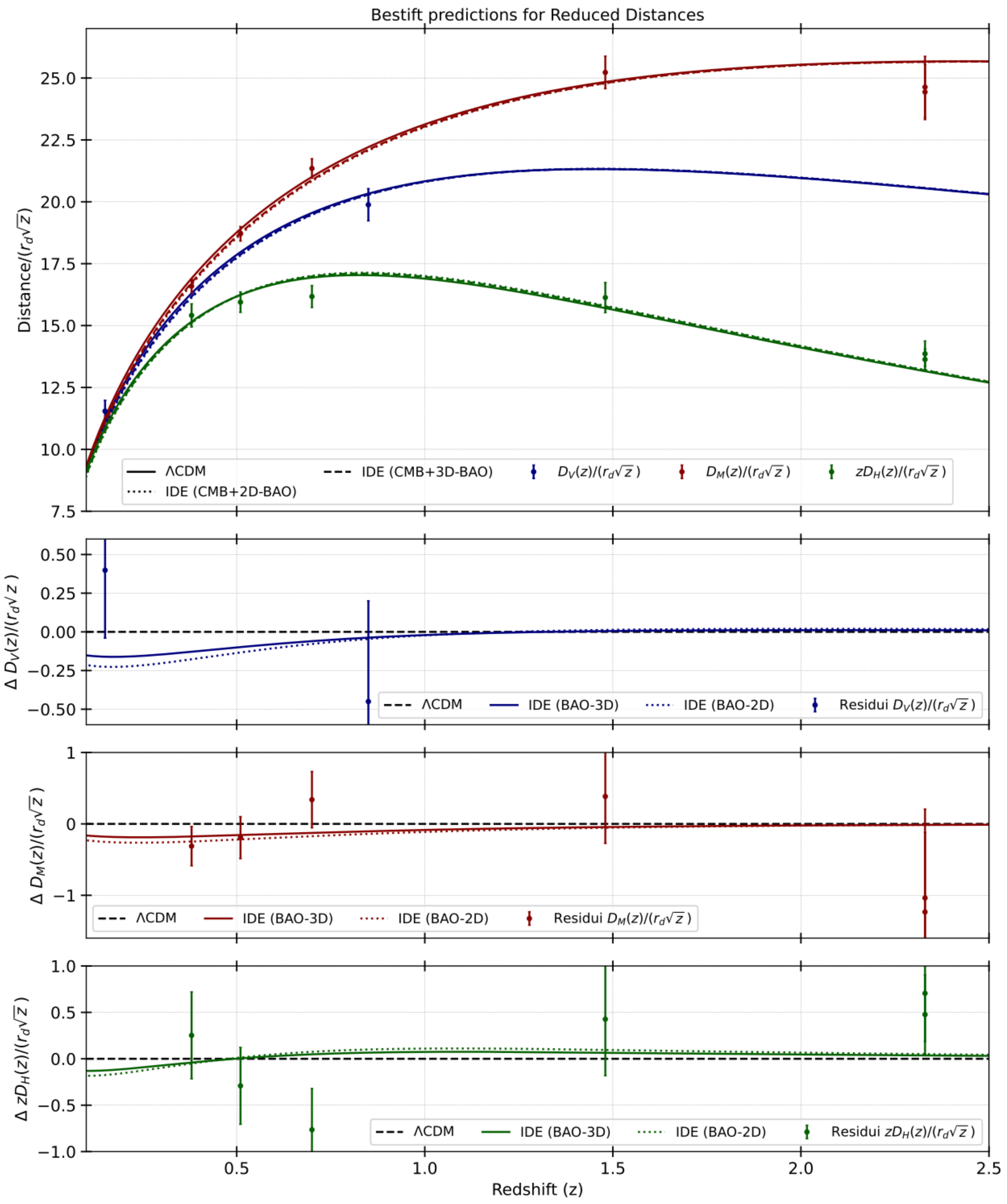
$$\dot\theta_{de} = 2\mathscr{H}\theta_{de} + \frac{k^2}{1+w}\delta_{de} + 2\mathscr{H}\frac{\xi}{1+w}\theta_{de} - \xi\mathscr{H}\frac{\theta_{\rm DM}}{1+w}$$

WG, E. Di Valentino, … (in preparation, preliminary results)



3 Outlooks and Conclusions

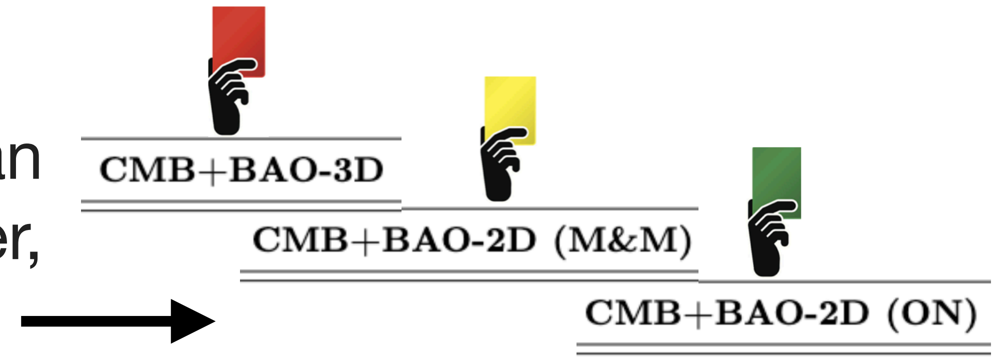
Planck and **ACT** show differences responsible for global tension between the two experiments that can be quantified at the Gaussian equivalent level of ~2.5 standard deviations (mainly caused by a mismatch in the early universe).

These differences may or may not play a significant role when testing new physics beyond ΛCDM:

- **Hint 1 — Inflation**
  Leaving aside observational systematics and taking data at face value, we encounter two **conflicting outcomes for inflationary theories**: Planck is in agreement with the most typical (Starobinsky-like) models, while the same models fail to explain the ACT data.

- **Hint 2 — Dark Matter**
  Small-scale CMB measurements can be crucial in the study of several physical models, such as **scatter-like interactions between DM and neutrinos**. The effects of such interactions may be too small to be detected on the large scales probed by Planck (from which we obtain no evidence for DM-neutrino interactions) while leaving a larger imprint on small scales probed by **ACT** (from which we obtain a 68% CL **indication for interactions, that is not in tension with Planck**).

- **Hint 3 — Dark Energy**
  All currently available CMB data are in **agreement about Interacting Dark Energy,** showing a 95% CL preference for an exchange of energy-momentum between DM and DE of around 40%. This can help alleviate the Hubble tension. However, whether this model can account for baryon acoustic oscillation (BAO) distance measurements is still a subject of debate.



Overall, independent CMB data probing different angular scales offer valuable avenues both for exploring new physics and testing our current understanding of the Universe.

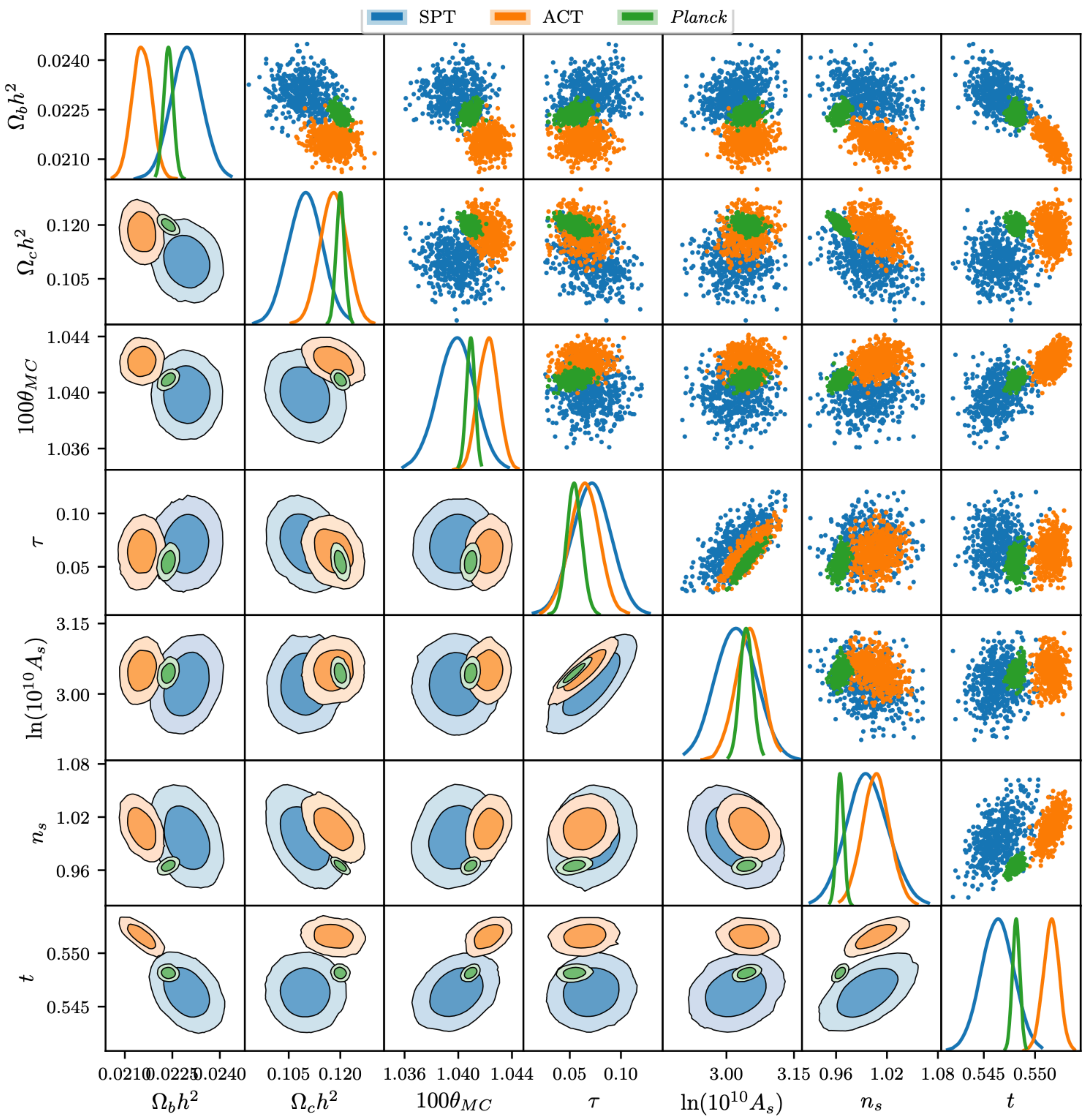
Thank You!

4i Backup Slides

Imaginary 4th Part with (cutout) supplementary material

Global Consistency of CMB experiments

W. Handley and P. Lemos, - 2007.08496



What makes CMB anomalies difficult to interpret ***individually*** is that different experiments often point in discordant directions, and none of the most relevant deviations can be cross-validated through independent probes.

Accurate statistical methods have been developed to quantify the ***global*** agreement between experiments under a given model of cosmology

$$\log S = \frac{d}{2} - \frac{\chi^2}{2} \qquad \chi^2 = \left(\mu_A - \mu_B\right)^{\mathrm{T}} \left(\Sigma_A + \Sigma_B\right)^{-1} \left(\mu_A - \mu_B\right)$$

$$\sigma(p) = \sqrt{2}\,\mathrm{erfc}^{-1}(1-p) \qquad p = \int_{\chi^2}^{\infty} \frac{x^{d/2-1} e^{-x/2}}{2^{d/2}\Gamma(d/2)} dx$$

W. Handley and P. Lemos, - 2007.08496

Dataset combination	χ^2	p	tension	$\log S$
ACT vs *Planck*	17.2	0.86%	2.63σ	-5.60
ACT vs SPT	15.4	1.77%	2.37σ	-4.68
Planck vs SPT	9.1	16.82%	1.38σ	-1.55
ACT vs *Planck*+SPT	18.4	0.52%	2.79σ	-6.22

Implications for the Hubble Tension

Late Time Solutions

Given the sound horizon and the distance from the CMB we can try to change the late-time (i.e., post recombination) expansion to get a different H_0:

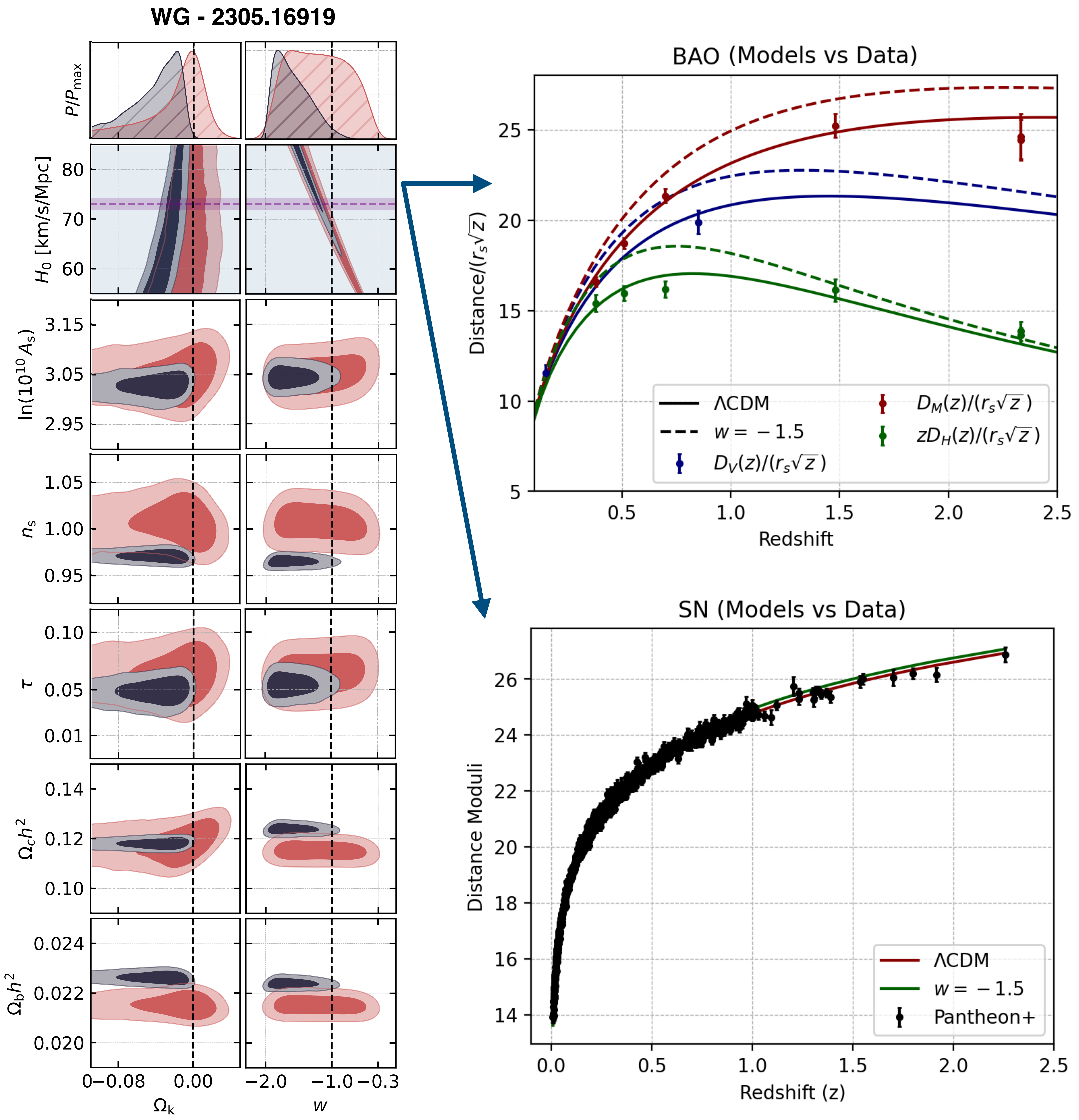
$$D_A(z_{CMB}) = \int_0^{z_{CMB}} dz\, H(z)^{-1}$$

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

One might expect these solutions to be preferred by data, given the significant room left by the CMB observations for new physics at late-times.

Instead when including local probes there is **very little room to accommodate new physics at late-times.**

In any case, it is **unlikely that the tension between ACT and Planck will have a significant impact** on these solutions since these experiments primarily disagree at early times.



Implications for the Hubble Tension

Early Time Solutions

Considering **new physics in early Universe** to change the physical size of the sound horizon

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

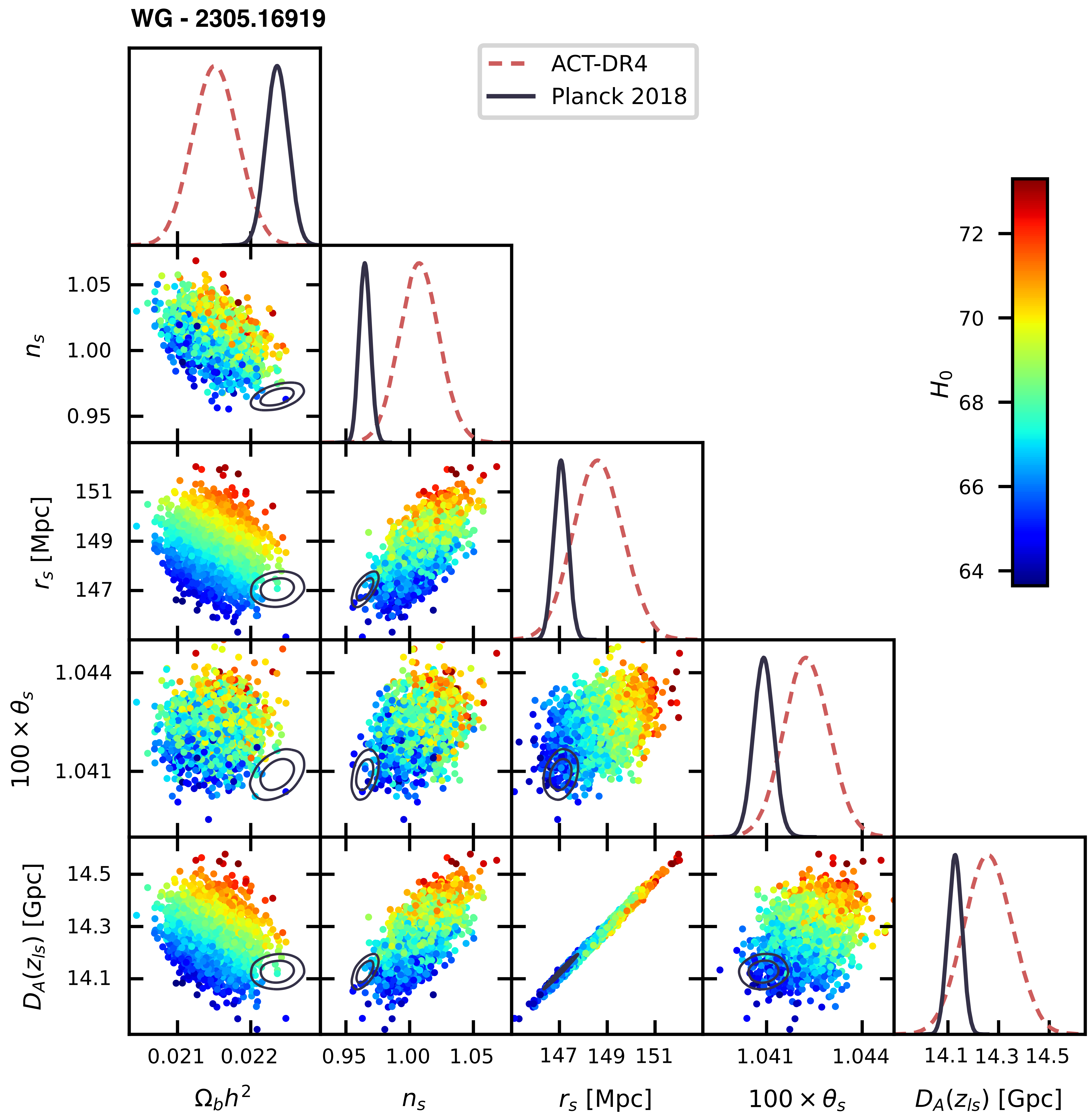
Many indications of this kind of new early-time physics arise when combining multiple CMB measurements (such as Planck and ACT), without finding clear cross-validation when these experiments are considered separately

ACT allows for greater flexibility in accommodating higher values of the sound horizon.

Planck peaks where ACT prefers very low values of H_0.

Increasing H_0 requires moving towards the region of the parameter space where the disagreement becomes more significant.

The spectral index and the Hubble constant (and the sound horizon) are all positively correlated: increasing H_0 naturally pushes n_s towards higher values



Implications for the Hubble Tension

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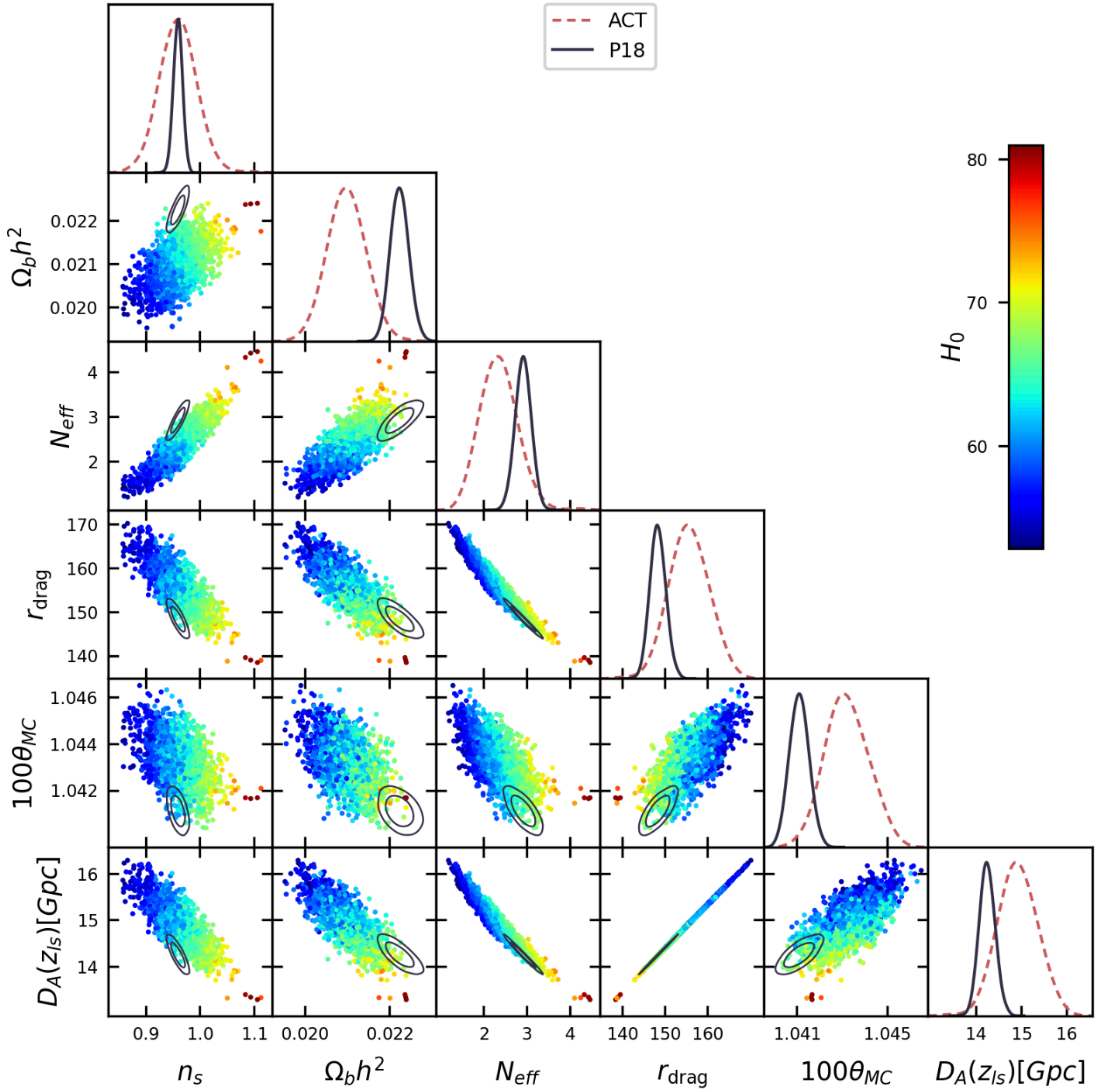
WG - 2305.16919



Implications for the Hubble Tension

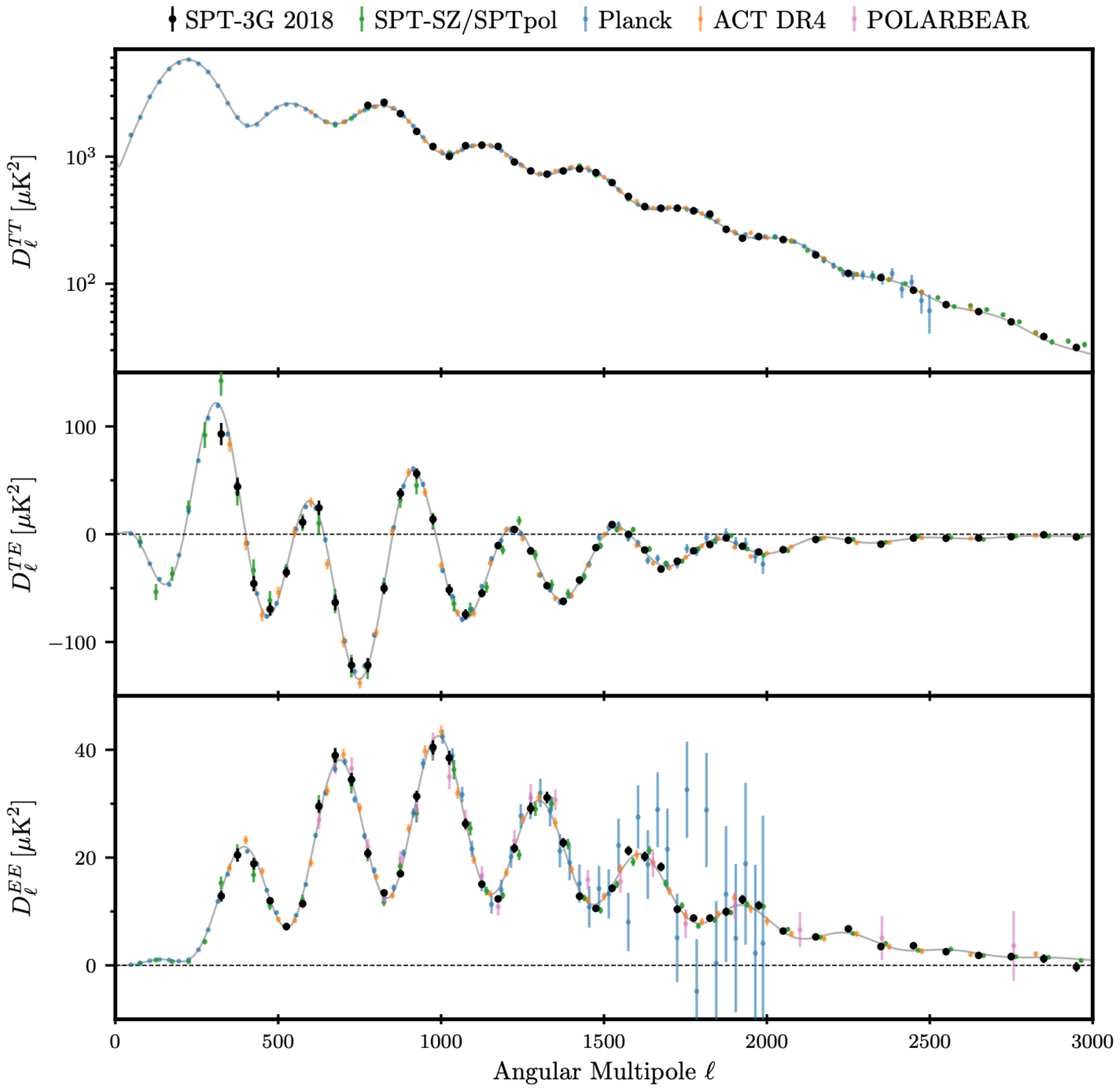
Possible solutions to H_0	ACT	PLANCK
Early Universe **New physics at early times?**	Deviations from ΛCDM, in tension with Planck ↓ Hints for new physics	Agreement with ΛCDM ↓ No clear evidence for new physics
Late Universe **New physics at late times?**	Agreement with ΛCDM ↓ Little room when local probes are considered	Deviations from ΛCDM (**erased** by local probes) ↓ Little room when local probes are considered

Hint 1 INFLATION

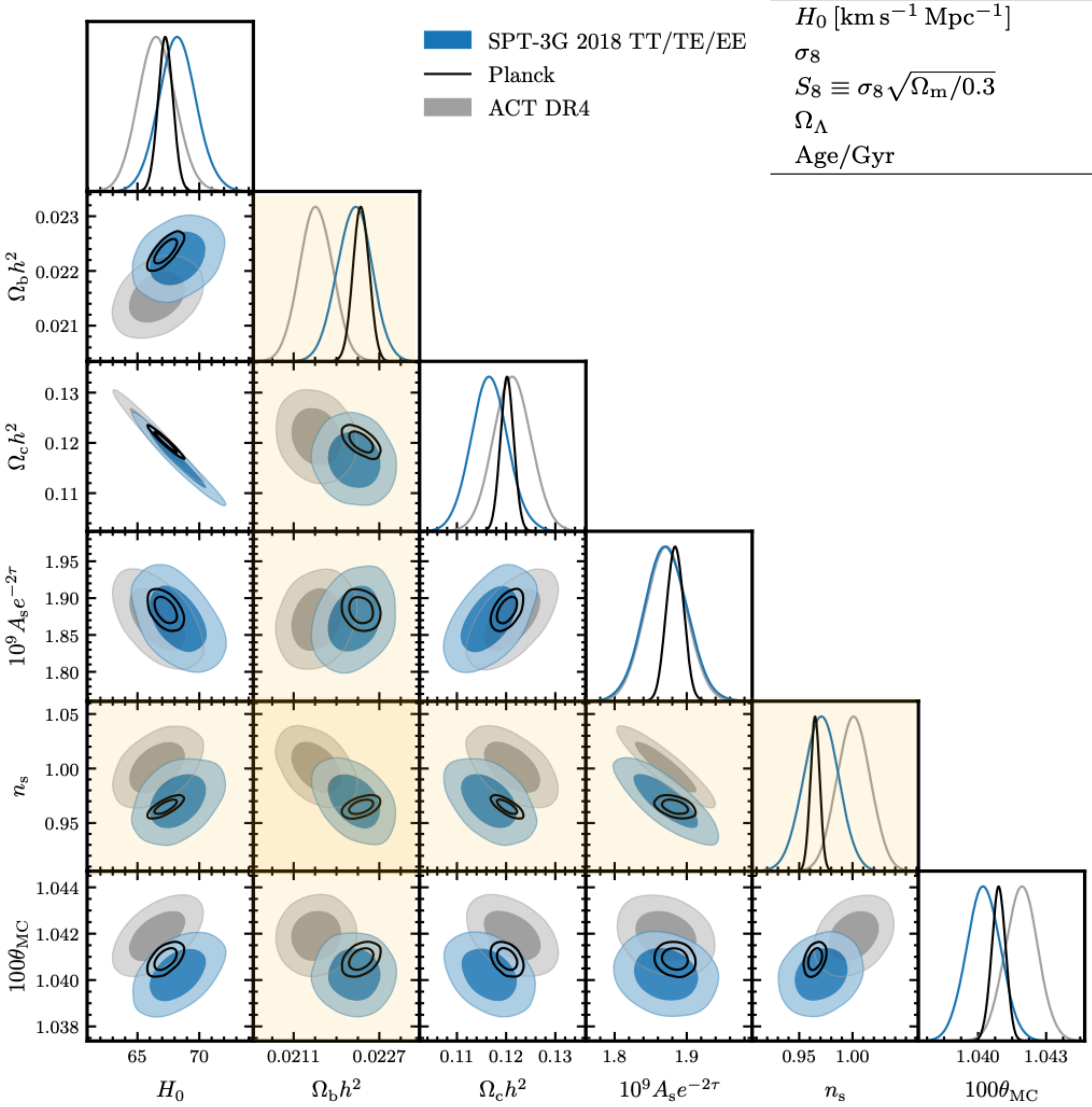
Assuming a ΛCDM cosmology, the main source of tension between ACT and Planck arises from the measurements of the **scalar spectral index** and the **baryon energy density**

If we believe these differences to emerge from limitations in the data, a logical step is to identify which (missing) part of the dataset is responsible for the discrepancy

South Pole Telescope (SPT)



	SPT-3G 2018
$\Omega_b h^2$	0.02224 ± 0.00032
$\Omega_c h^2$	0.1166 ± 0.0038
$100\theta_{MC}$	1.04025 ± 0.00074
$10^9 A_s e^{-2\tau}$	1.871 ± 0.030
n_s	0.970 ± 0.016
H_0 [km s^{-1} Mpc^{-1}]	68.3 ± 1.5
σ_8	0.797 ± 0.015
$S_8 \equiv \sigma_8 \sqrt{\Omega_m/0.3}$	0.797 ± 0.042
Ω_Λ	0.700 ± 0.021
Age/Gyr	13.815 ± 0.047



HINT 1 INFLATION

Assuming a ΛCDM cosmology, the main source of tension between ACT and Planck arises from the measurements of the **scalar spectral index** and the **baryon energy density**

If we take data at face value, the **most typical Inflationary potential fails to explain small-scale CMB observations**

Case Study: Starobinsky Inflation

We assume Starobinsky Inflation from the onset in the cosmological model

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

Where parameters are related to the last e-folds of expansion

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

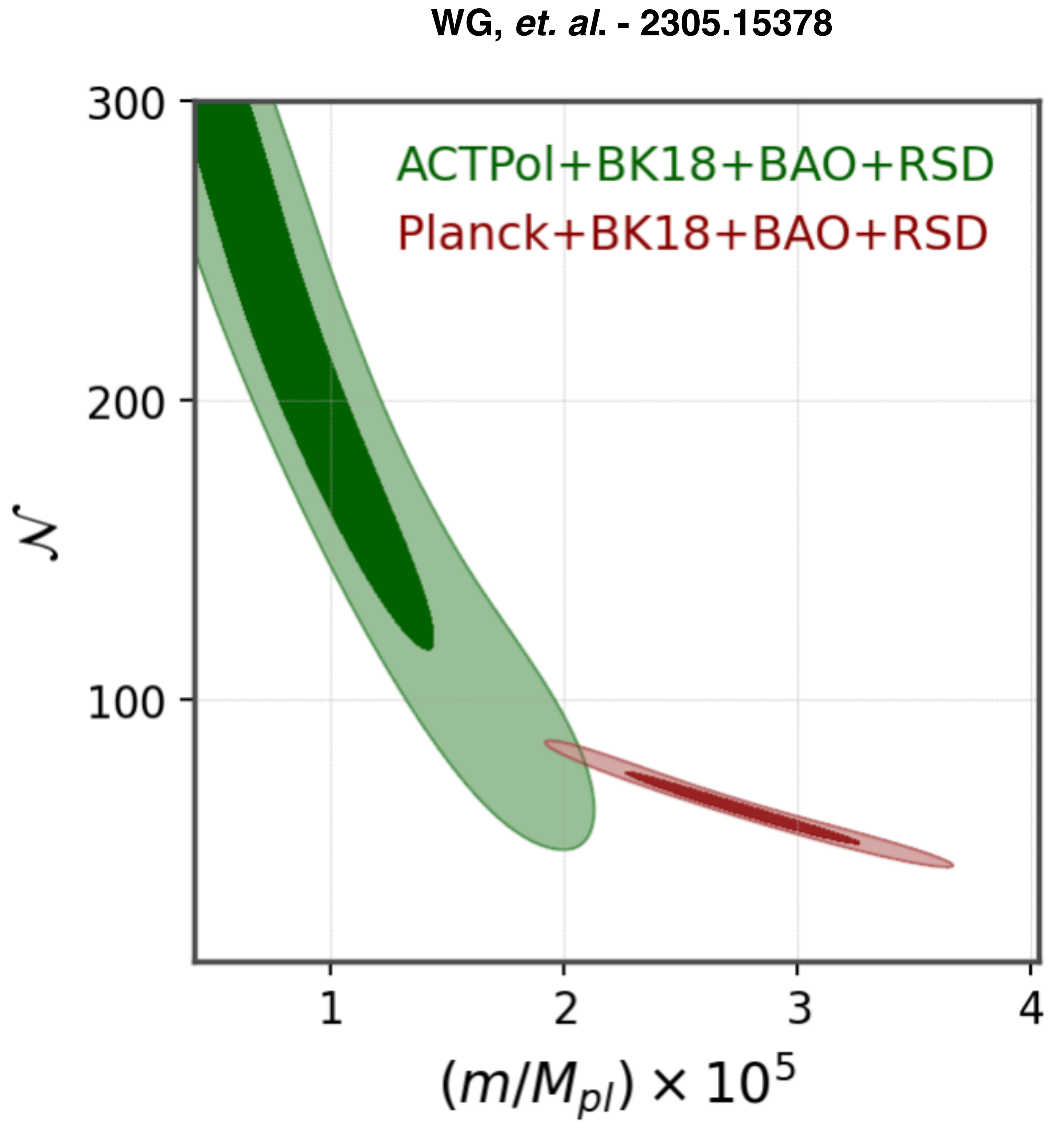
The layer of uncertainty extends beyond the model and influences the implications for fundamental physics: any predictions for *m* may reveal the energy scale of deviations from General Relativity:

Planck+BK18+BAO

$$\left(\frac{m}{M_{\rm pl}}\right) = \left(2.76 \pm 0.32\right)\times 10^{-5}$$

ACT+BK18+BAO

$$\left(\frac{m}{M_{\rm pl}}\right) = \left(0.98^{+0.29}_{-0.47}\right)\times 10^{-5}$$



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Assuming a ΛCDM cosmology, the main source of tension between ACT and Planck arises from the measurements of the **scalar spectral index** and the **baryon energy density**

If we take data at face value, the **most typical Inflationary potential fails to explain small-scale CMB observations**

What About More Complicated Models?

We are developing a theoretical sampler to study generic multifield models of inflation where a number of scalar fields are minimally coupled to gravity and live in a field space with a non-trivial metric

$$S = \int d^4x\sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}R - \frac{1}{2}\mathcal{G}_{IJ}g^{\mu\nu}\partial_\mu\phi^I\partial_\nu\phi^J - V(\phi^K)\right]$$

Our algorithm consists of three main parts:

- We solve the field equations through the entire inflationary period, deriving predictions for observable quantities

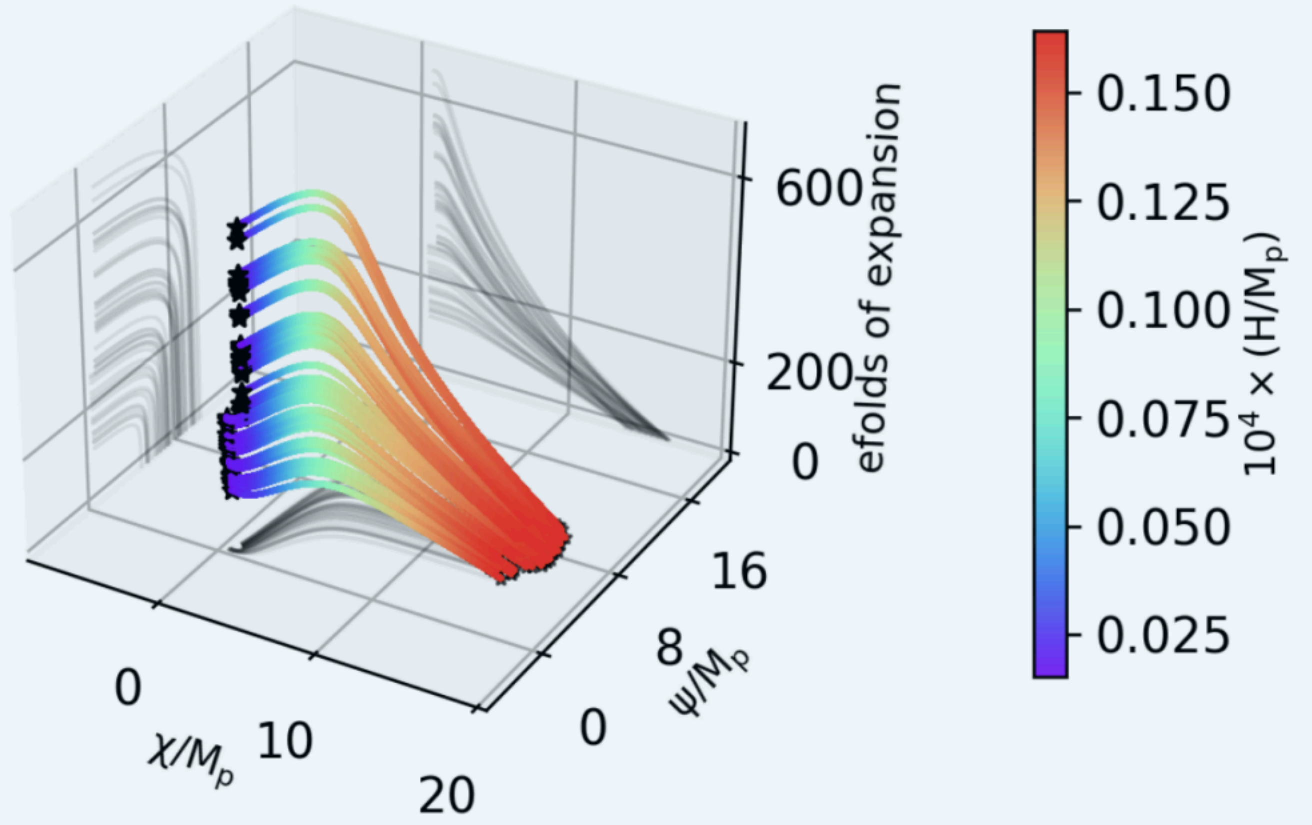
- We interface our algorithm with Boltzmann integrator codes to compute the subsequent full cosmology, including the CMB angular power spectra

- We explore a large volume of the parameter space and identify a sub-region where theoretical predictions agree with observations

ADVERTISEMENT

Tracking the Multifield Dynamics with Cosmological Data: A Monte Carlo approach

William Giarè,[1,*] Mariaveronica De Angelis,[1,†] Carsten van de Bruck,[1,‡] and Eleonora Di Valentino[1,§]
[1] *Consortium for Fundamental Physics, School of Mathematics and Statistics, University of Sheffield, Hounsfield Road, Sheffield S3 7RH, United Kingdom*
(Dated: June 22, 2023)



Got Interested? Take a look!

WG, M. De Angelis, *et. al.* - 2306.12414

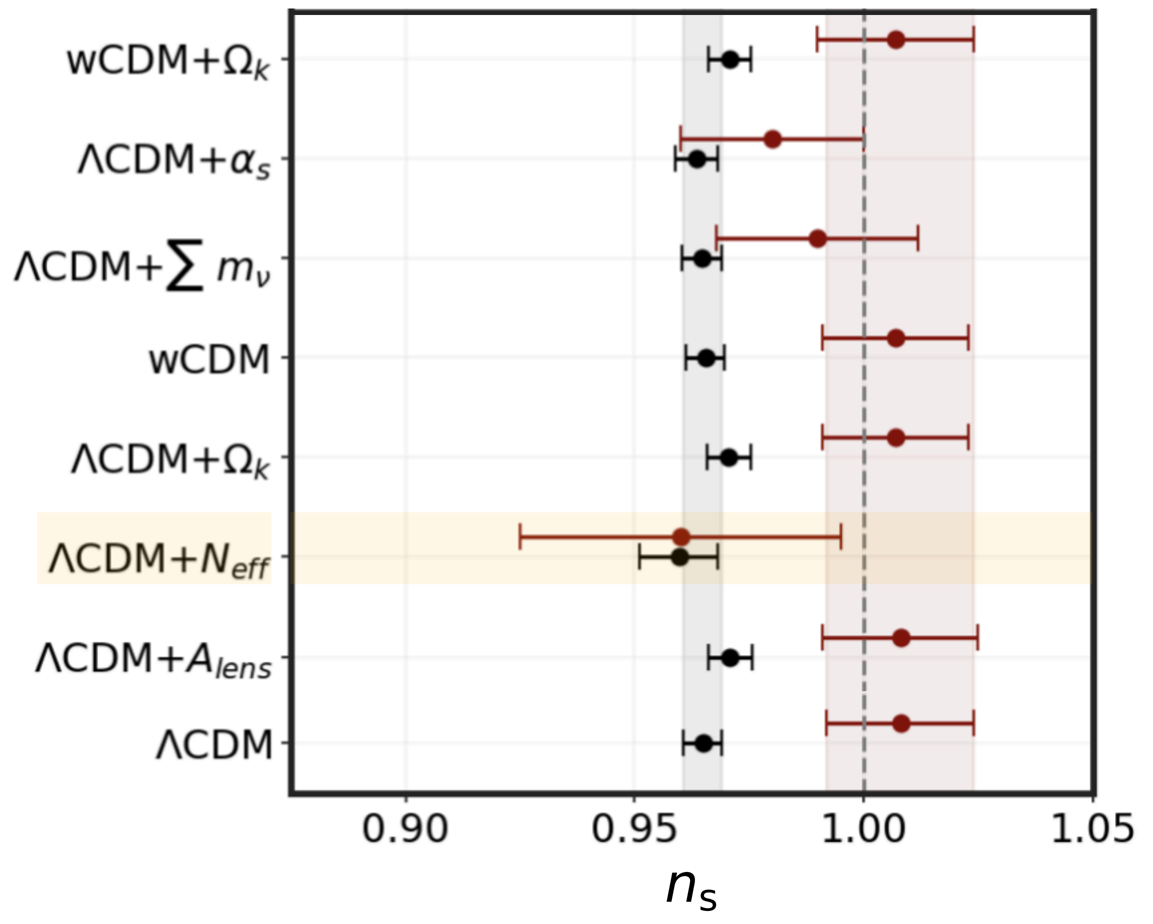
HiNT 1 INFLATION

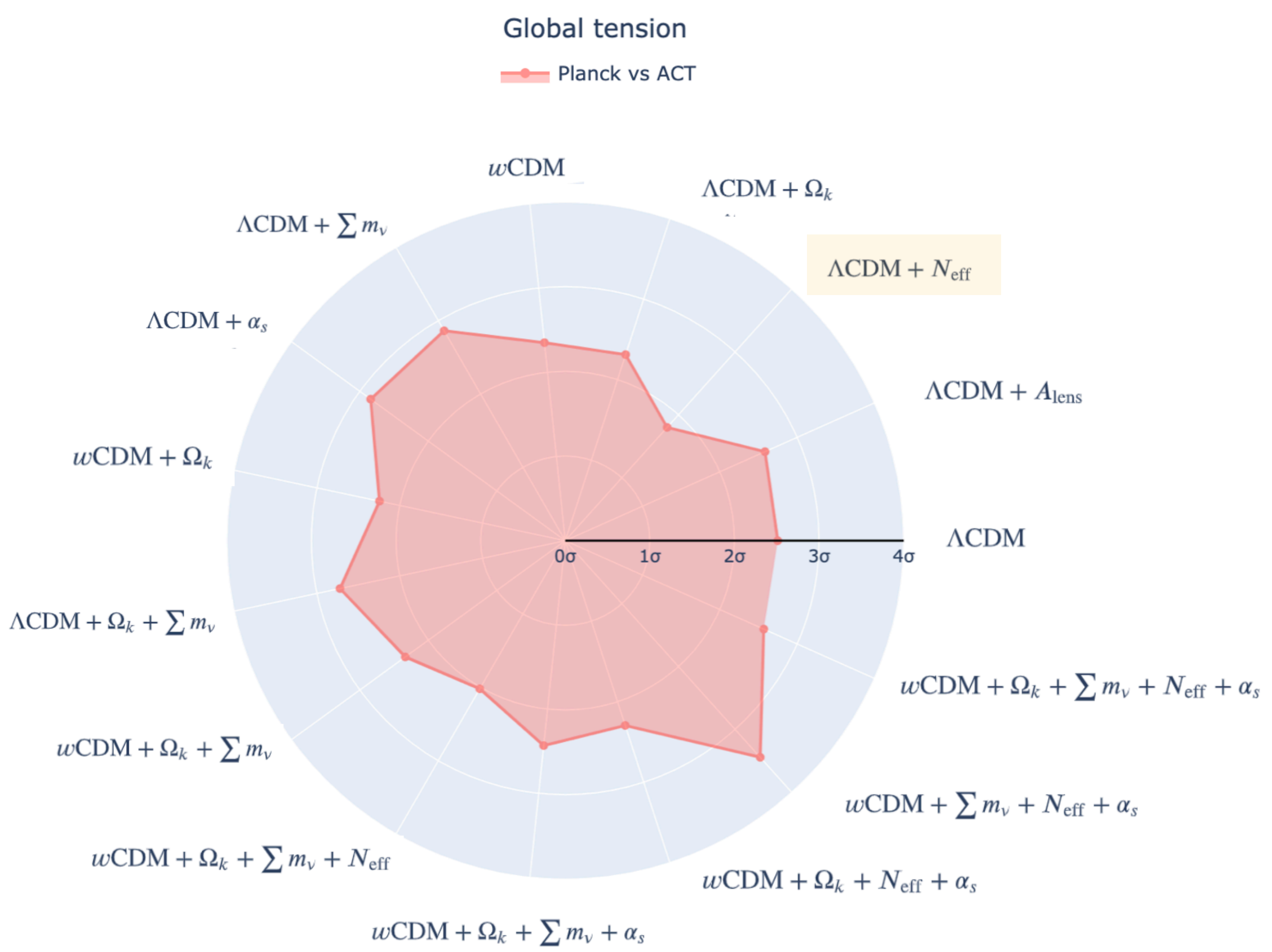
Assuming a ΛCDM cosmology, the main source of tension between ACT and Planck arises from the measurements of the **scalar spectral index** and the **baryon energy density**

A Potential solution able to restore the agreement would be considering models with significant less amount of relativistic degrees of freedom in the Early Universe

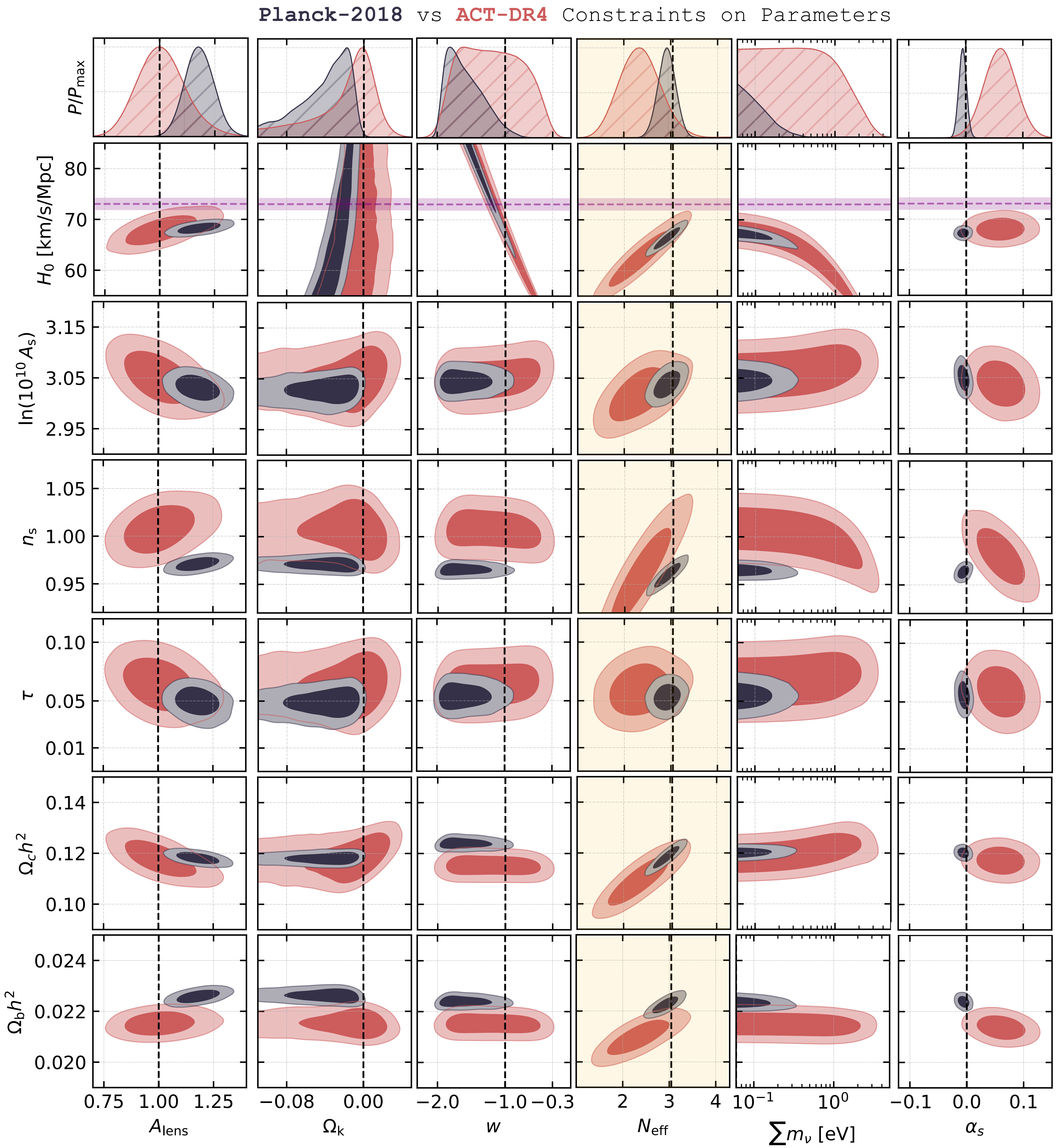
E. Di Valentino, WG, *et al* - 2209.14054

Cosmological model	d	χ^2	p	$\log S$	Tension
ΛCDM + $A_{\rm lens}$	7	18.5	0.00977	−5.77	2.58 σ
ΛCDM + Ω_k	7	16.5	0.0209	−4.75	2.31 σ
wCDM	7	16.8	0.0187	−4.9	2.35 σ
ΛCDM + $N_{\rm eff}$	7	13	0.0719	−3	1.80 σ
ΛCDM + $\sum m_\nu$	7	20.7	0.00421	−6.86	2.86 σ
ΛCDM + α_s	7	20.6	0.00448	−6.78	2.84 σ





WG - 2305.16919



Hint 2 Dark Matter (DM)

Take a Look at the Matter Power Spectrum

Neutrino-DM Interactions

Euler Equations in the Newtonian Gauge:

$$\dot{\theta}_\nu = k^2\psi + k^2\left(\frac{1}{4}\delta_\nu - \sigma_\nu\right) - \dot{\boldsymbol{\mu}}\left(\boldsymbol{\theta_\nu} - \boldsymbol{\theta_{\mathrm{DM}}}\right)$$

$$\dot{\theta}_{\mathrm{DM}} = k^2\psi - \mathscr{H}\theta_{\mathrm{DM}} + \frac{\mathbf{4}}{\mathbf{3}}\frac{\boldsymbol{\rho_\nu}}{\boldsymbol{\rho_{\mathrm{DM}}}}\dot{\boldsymbol{\mu}}\left(\boldsymbol{\theta_\nu} - \boldsymbol{\theta_{\mathrm{DM}}}\right)$$

Were:

$$\dot{\mu} = a\,c\,\frac{\rho_{\mathrm{DM}}}{m_{DM}}\,\sigma_{\nu\mathrm{DM}}$$

Interaction Strength

$$u_{\nu\mathrm{DM}} \doteq \left[\frac{\sigma_{\nu\mathrm{DM}}}{\sigma_{\mathrm{Th}}}\right]\left[\frac{m_{\mathrm{DM}}}{100\,\mathrm{GeV}}\right]^{-1}$$

G. Mangano, A. Melchiorri et al, 0606190

considered. The effect of the dark-matter–neutrino interaction can be seen on small scales in the matter power spectrum. Larger couplings will correspond

$$k \sim 0.2 \times 10^{-5}\left(\frac{10^{-22}\mathrm{cm}^2\ \mathrm{MeV}^{-1}}{Q_0}\right)^{1/2} h\,\mathrm{Mpc}^{-1}.$$

=

For Small couplings the Neutrino Damping is relevant on small scales (i.e., high k)

$k \propto \ell \rightarrow$ Anything similar at high ℓ in the CMB spectra?

HINT 2 DARK MATTER (DM)

NEUTRINO-DM INTERACTIONS

Euler Equations in the Newtonian Gauge:

$$\dot{\theta}_\nu = k^2\psi + k^2\left(\frac{1}{4}\delta_\nu - \sigma_\nu\right) - \dot{\mu}\left(\theta_\nu - \theta_{\rm DM}\right)$$

$$\dot{\theta}_{\rm DM} = k^2\psi - \mathcal{H}\theta_{\rm DM} + \frac{4}{3}\frac{\rho_\nu}{\rho_{\rm DM}}\dot{\mu}\left(\theta_\nu - \theta_{\rm DM}\right)$$

Were:

$$\dot{\mu} = a\,c\,\frac{\rho_{\rm DM}}{m_{DM}}\,\sigma_{\nu{\rm DM}}$$

INTERACTION STRENGTH

$$u_{\nu{\rm DM}} \doteq \left[\frac{\sigma_{\nu{\rm DM}}}{\sigma_{\rm Th}}\right]\left[\frac{m_{\rm DM}}{100\,{\rm GeV}}\right]^{-1}$$

Results for Temperature dependent cross-section

(with and without the effective number of relativistic degrees of freedom)

Brax et al. (WG) 2303.16894 and 2305.01383

$\sigma_{\nu{\rm DM}} \sim T^2$ (without $N_{\rm eff}$)

Parameter	Planck	Planck + BAO	ACT	ACT + BAO	ACT + Planck + BAO
$\Omega_{\rm b}h^2$	0.02239 ± 0.00015	0.02239 ± 0.00014	0.02151 ± 0.00032	0.02148 ± 0.00030	0.02235 ± 0.00012
$\Omega_{\rm c}^{\nu{\rm DM}}h^2$	0.1195 ± 0.0012	0.11950 ± 0.00094	0.1173 ± 0.0039	0.1196 ± 0.0015	0.11973 ± 0.00097
$100\theta_{\rm s}$	1.04189 ± 0.00029	1.04188 ± 0.00029	1.04342 ± 0.00072	1.04321 ± 0.00064	1.04202 ± 0.00027
$\tau_{\rm reio}$	0.0535 ± 0.0076	0.0529 ± 0.0070	0.063 ± 0.015	0.058 ± 0.013	0.0553 ± 0.0065
$\log(10^{10}A_{\rm s})$	3.041 ± 0.015	3.040 ± 0.014	3.046 ± 0.031	3.040 ± 0.029	3.051 ± 0.013
$n_{\rm s}$	0.9654 ± 0.0042	0.9654 ± 0.0036	1.007 ± 0.016	1.002 ± 0.013	0.9678 ± 0.0035
$log_{10}u_{\nu DM}$	$< -15.4\,(< -14.1)$	$< -15.35\,(< -14.3)$	$-15.2^{+1.8}_{-1.1}\,(< -13.9)$	$-15.3^{+1.8}_{-1.1}\,(< -13.9)$	$-14.9^{+1.5}_{-0.63}(< -14.3)$
H_0	$68.06 \pm 0.55\,(68.1^{+1.1}_{-1.1})$	$68.06 \pm 0.42\,(68.06^{+0.82}_{-0.86})$	$68.6 \pm 1.6\,(68.6^{+3.3}_{-3.1})$	$67.68 \pm 0.58\,(67.7^{+1.1}_{-1.1})$	67.99 ± 0.42
σ_8	$0.8212 \pm 0.0062\,(0.821^{+0.012}_{-0.012})$	$0.8206 \pm 0.0059\,(0.821^{+0.011}_{-0.011})$	$0.834 \pm 0.017\,(0.834^{+0.032}_{-0.034})$	$0.838 \pm 0.012\,(0.838^{+0.023}_{-0.023})$	0.8269 ± 0.0061

Brax et al. (WG) 2303.16894 and 2305.01383

$\sigma_{\nu{\rm DM}} \sim T^2$ (with $N_{\rm eff}$)

Parameter	Planck	Planck + BAO	ACT	ACT + BAO	ACT + Planck + BAO
$\Omega_{\rm b}h^2$	0.02228 ± 0.00022	0.02230 ± 0.00019	0.02109 ± 0.00045	0.02106 ± 0.00038	0.02210 ± 0.00017
$\Omega_{\rm c}^{\nu{\rm DM}}h^2$	0.1177 ± 0.0030	0.1176 ± 0.0029	0.1105 ± 0.0065	0.1086 ± 0.0058	0.1147 ± 0.0024
$100\theta_{\rm s}$	1.04219 ± 0.00051	1.04219 ± 0.00050	1.0445 ± 0.0012	1.0448 ± 0.0011	1.04279 ± 0.00043
$\tau_{\rm reio}$	0.0518 ± 0.0074	0.0526 ± 0.0071	0.060 ± 0.015	0.061 ± 0.013	0.0547 ± 0.0067
$\log(10^{10}A_{\rm s})$	3.033 ± 0.017	3.034 ± 0.016	3.023 ± 0.037	3.020 ± 0.030	3.035 ± 0.016
$n_{\rm s}$	0.9601 ± 0.0085	0.9612 ± 0.0070	0.969 ± 0.033	0.969 ± 0.023	0.9568 ± 0.0066
$N_{\rm eff}$	$2.91 \pm 0.19\,(2.91^{+0.38}_{-0.37})$	$2.93 \pm 0.17\,(2.93^{+0.33}_{-0.35})$	$2.49 \pm 0.44\,(2.49^{+0.87}_{-0.83})$	$2.43 \pm 0.33\,(2.43^{+0.69}_{-0.67})$	$2.73 \pm 0.14\,(2.73^{+0.30}_{-0.30})$
$log_{10}u_{\nu DM}$	$< -15.4\,(< -14.1)$	$< -15.35\,(< -14.0)$	$-15.2^{+1.7}_{-1.2}\,(< -13.8)$	$-15.3^{+1.6}_{-1.3}\,(< -13.8)$	$-15.1^{+1.7}_{-0.90}\,(< -13.8)$
H_0	$67.2 \pm 1.4\,(67.2^{+2.8}_{-2.7})$	$67.3 \pm 1.1\,(67.3^{+2.1}_{-2.2})$	$64.3 \pm 3.6\,(64.3^{+7.0}_{-7.0})$	$64.4 \pm 1.9\,(64.4^{+3.9}_{-3.6})$	$66.1 \pm 1.0\,(66.1^{+2.1}_{-2.0})$
σ_8	$0.815 \pm 0.010\,(0.815^{+0.020}_{-0.020})$	$0.8151 \pm 0.0097\,(0.815^{+0.018}_{-0.019})$	$0.810 \pm 0.025\,(0.810^{+0.050}_{-0.047})$	$0.804 \pm 0.021\,(0.804^{+0.042}_{-0.040})$	$0.8116 \pm 0.0094\,(0.812^{+0.019}_{-0.018})$

Hint 2 Dark Matter (DM)

Neutrino-DM Interactions

Euler Equations in the Newtonian Gauge:

$$\dot{\theta}_\nu = k^2\psi + k^2\left(\frac{1}{4}\delta_\nu - \sigma_\nu\right) - \dot{\boldsymbol{\mu}}\left(\boldsymbol{\theta}_\nu - \boldsymbol{\theta}_{\mathbf{DM}}\right)$$

$$\dot{\theta}_{\mathrm{DM}} = k^2\psi - \mathscr{H}\theta_{\mathrm{DM}} + \frac{\mathbf{4}}{\mathbf{3}}\frac{\boldsymbol{\rho}_\nu}{\boldsymbol{\rho}_{\mathbf{DM}}}\dot{\boldsymbol{\mu}}\left(\boldsymbol{\theta}_\nu - \boldsymbol{\theta}_{\mathbf{DM}}\right)$$

Were:

$$\dot{\mu} = a\,c\,\frac{\rho_{\mathrm{DM}}}{m_{DM}}\,\sigma_{\nu\mathrm{DM}}$$

Interaction Strength

$$u_{\nu\mathrm{DM}} \doteq \left[\frac{\sigma_{\nu\mathrm{DM}}}{\sigma_{\mathrm{Th}}}\right]\left[\frac{m_{\mathrm{DM}}}{100\,\mathrm{GeV}}\right]^{-1}$$

Sterile Neutrino Portal to νDM interactions (and constraints from other HEP processes)

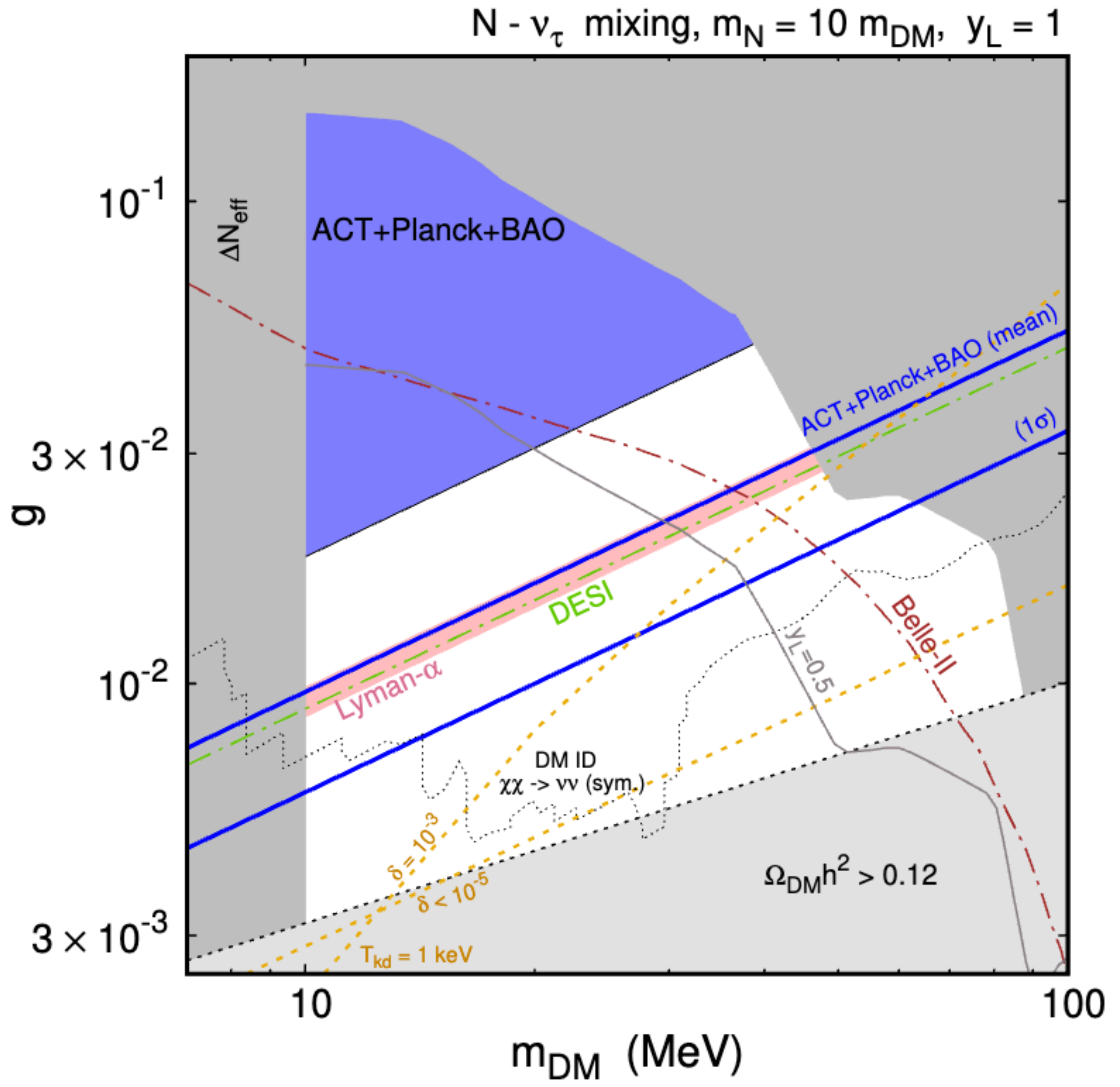


Figure 7: The parameter space of the neutrino portal DM model shown in the (m_{DM}, g) plane. One assumes $m_N = 10\ m_{\mathrm{DM}}$, $y_L = 1$ and the mass-degenerate scenario with $m_{\mathrm{DM}} \equiv m_\chi \simeq m_\phi$. ACT+Planck+BAO exclusion bounds are shown as a blue-shaded region, while the relevant average value of the $\log_{10} u_{\nu DM}$ parameter obtained in the fitting, and its 1σ deviation below the mean are illustrated with solid blue lines. Constraints on sterile-active neutrino mixing, the effective number of relativistic degrees of freedom ΔN_{eff}, and χ DM relic density are shown as grey-shaded regions. For comparison, we also present such bounds derived for a lower value of the Yukawa parameter $y_L = 0.5$ as indicated with a gray solid line. Lyman-α best-fit region is shown with red-shaded color [82]. The νDM kinetic decoupling occurs at $T_{kd} \simeq 1$ keV for $\delta = 10^{-3}$ and 10^{-8} along orange dotted lines, where $\delta = (m_\phi - m_\chi)/m_\chi$. DM indirect detection constraint on present-day annihilations of the symmetric χ DM component is shown with a black dotted line. This bound is avoided in the asymmetric DM regime. Future expected sensitivity of the Belle-II [83] and DESI [21] experiments are shown with red and light-green dash-dotted lines, respectively.

HINT 3 Dark Energy (DE)

Interacting Dark energy

IDE introduce **energy-momentum transfer from DM to DE** by modifying their individual energy conservation equations

$$\nabla_\mu T^{\mu}_{c\,\nu} = +\frac{Q(v_c)_\nu}{a} \qquad \nabla_\mu T^{\mu}_{x\,\nu} = -\frac{Q(v_c)_\nu}{a}$$

We focus on an interacting model with an interacting rate:

$$Q = \xi \mathscr{H} \rho_{de}$$

DM-DE Boltzmann equations in the Synchronous gauge:

$$\dot{\delta}_c = -\theta_c - \frac{1}{2}\dot{h} + \xi \mathscr{H} \frac{\rho_{de}}{\rho_c}(\delta_{de} - \delta_c) + \xi \frac{\rho_{de}}{\rho_c}\left(\frac{k v_T}{3} + \frac{\dot{h}}{6}\right)$$

$$\dot{\theta}_c = -\mathscr{H}\theta_c$$

$$\dot{\delta}_{de} = -(1+w)\left(\theta_{de} + \frac{\dot{h}}{2}\right) - 3\mathscr{H}(1-w)\left[\delta_{de} + 3\mathscr{H}(1+w)\frac{\theta_{de}}{k^2}\right] + 3\mathscr{H}^2\xi(1-w)\frac{\theta_{de}}{k^2} - \xi\left(\frac{k v_T}{3} + \frac{\dot{h}}{6}\right)$$

$$\dot{\theta}_{de} = 2\mathscr{H}\theta_{de} + \frac{k^2}{1+w}\delta_{de} + 2\mathscr{H}\frac{\xi}{1+w}\theta_{de} - \xi\mathscr{H}\frac{\theta_c}{1+w}$$

3D-BAO	2D-BAO
A fiducial cosmology is needed to obtain $D_V(z)$, which contains mixed measures of $H \& D_A$. To obtain H or D_A from D_V one needs extra data.	No fiducial model hypothesis; $D_A(z)$ is directly measured, with r_s as a parameter.
One has to assume a geometry, i.e. a value for Ω_k, when choosing the fiducial cosmology	One does not assume a geometry (k)
One has to deal with effects, like RSD	Less affected by systematics (no RSD, for example)
Errors are small (fiducial cosmology is used)	Errors are large
One needs a passive cosmic tracer (i.e., cosmic objects that do not evolve in the large 3D volume in analysis). In practice, only few measurements of $\{D_V(z_i)\}$ are expected.	Any cosmological tracer can be used; then one can measure $D_A(z_i)$ in many as desired redshifts bins z_i using diverse cosmic tracers.
At the end of the day, the set of $\{D_V\}$ data, or $\{H\}$, or $\{D_A\}$, are tested for consistency with the fiducial cosmology assumed, i.e., ΛCDM.	At the end of the day, the function $D_A = D_A(z)$ can be used to determine the best parameters of any cosmological model.