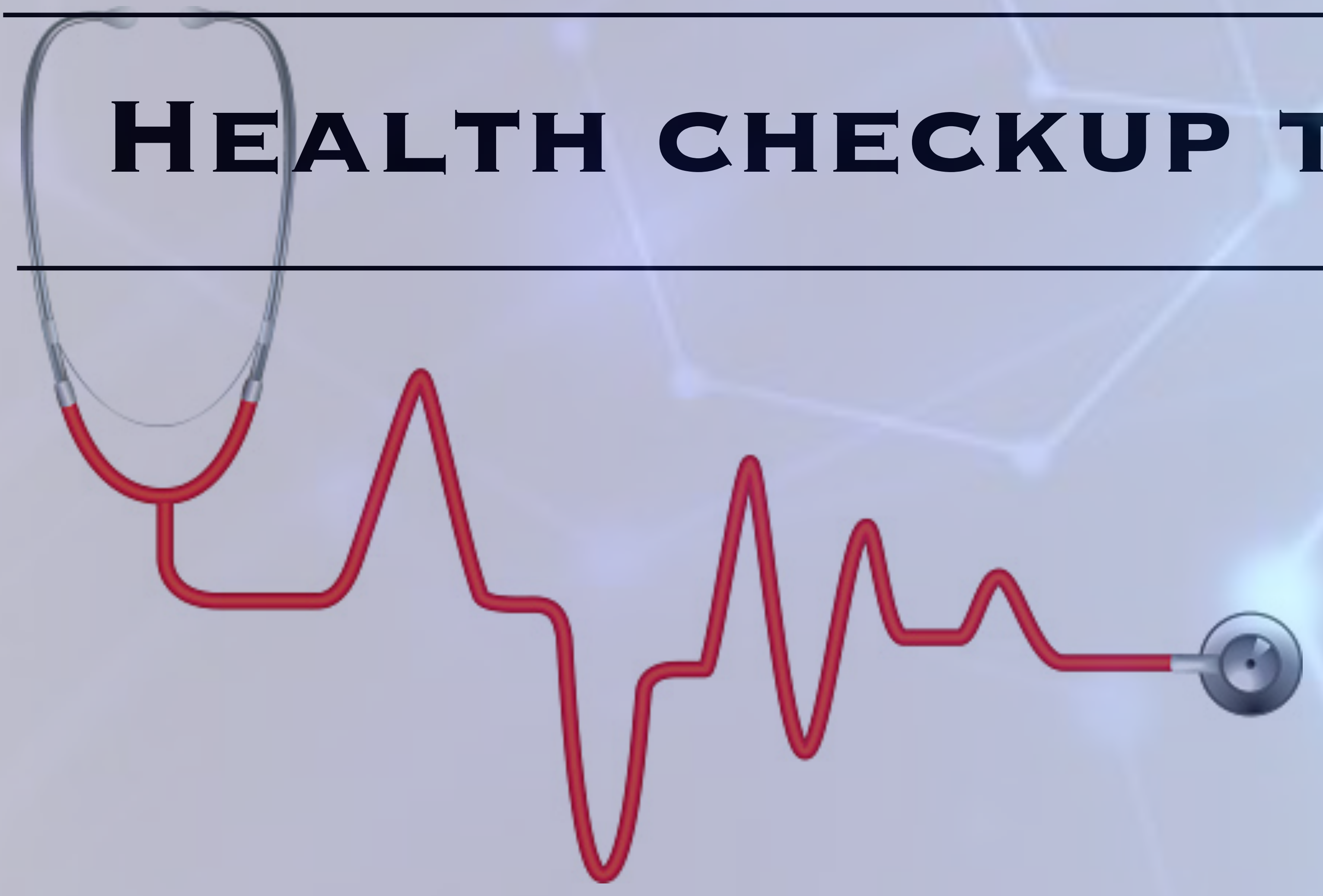
Galileo Galilei Institute for Theoretical Physics

CENTRO NAZIONALE INFN DI STUDI AVANZATI

GGI Post-Doc Day

Florence, 16 December 2022

Health checkup test of the standard cosmological model



William Giarè

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Disclaimers

1) This talk will cover only a part of my work at GGI

Papers and Topics I've been working on this year:

October

September

May

March

1. arXiv:2210.14159 [pdf, other] astro-ph.CO
Towards a reliable calculation of relic radiation from primordial gravitational waves
Authors: William Giarè, Matteo Forconi, Eleonora Di Valentino, Alessandro Melchiorri

2. arXiv:2210.09865 [pdf, other] astro-ph.CO gr-qc
Revealing the effects of curvature on the cosmological models
Authors: Weiqiang Yang, William Giarè, Supriya Pan, Eleonora Di Valentino, Alessandro Melchiorri, Joseph Silk

3. arXiv:2210.09018 [pdf, other] astro-ph.CO
Harrison-Zel'dovich spectrum gets back?
Authors: William Giarè, Fabrizio Renzi, Olga Mena, Eleonora Di Valentino, Alessandro Melchiorri

4. arXiv:2209.14054 [pdf, other] astro-ph.CO
Quantifying the global "CMB tension" between the Atacama Cosmology Telescope and the Planck satellite in extended models of cosmology
Authors: Eleonora Di Valentino, William Giarè, Alessandro Melchiorri, Joseph Silk

5. arXiv:2209.12872 [pdf, other] astro-ph.CO doi 10.1103/PhysRevD.106.103506
Health checkup test of the standard cosmological model in view of recent Cosmic Microwave Background Anisotropies experiments
Authors: Eleonora Di Valentino, William Giarè, Alessandro Melchiorri, Joseph Silk

6. arXiv:2205.07849 [pdf, other] astro-ph.CO hep-ph doi 10.1088/1475-7516/2022/09/022
Cosmological Bound on the QCD Axion Mass, Redux
Authors: Francesco D'Eramo, Eleonora Di Valentino, William Giarè, Fazlollah Hajkarim, Alessandro Melchiorri, Olga Mena, Fabrizio Renzi, Seokhoon Yun

7. arXiv:2203.06142 [pdf, other] astro-ph.CO hep-ph doi 10.1016/j.jheap.2022.04.002
Cosmology Intertwined: A Review of the Particle Physics, Astrophysics, and Cosmology Associated with the Cosmological Tensions and Anomalies
Authors: Elcio Abdalla, Guillermo Franco Abellán, Amin Aboubrahim, Adriano Agnello, Ozgur Akarsu, Yashar Akrami, George Alestas, Daniel Aloni, Luca Amendola, Luis A. Anchordoqui, Richard I. Anderson, Nikki Arendse, Marika Asgari, Mario Ballardini, Vernon Barger, Spyros Basilakos, Ronaldo C. Batista, Elia S. Battistelli, Richard Battye, Micol Benetti, David Benisty, Asher Berlin, Paolo de Bernardis, Emanuele Berti, Bohdan Bidenko , et al. (178 additional authors)

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2) this talk is set up to reach a broad audience

Some parts may sound very trivial for experts in cosmology!
(Sorry in advance!)

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SOME PARTS MAY SOUND VERY TRIVIAL FOR EXPERTS IN COSMOLOGY!
(SORRY IN ADVANCE!)

3) THE TIME-SLOT IS SHORT, I WILL SKIP TECHNICAL DETAILS

SO, DO NOT HESITATE TO ASK QUESTIONS!

)

Introduction

Lambda Cold Dark Matter (ΛCDM) Cosmology

Building Blocks

General Relativity
to describe gravitational interactions

Standard Model
To describe fundamental interactions

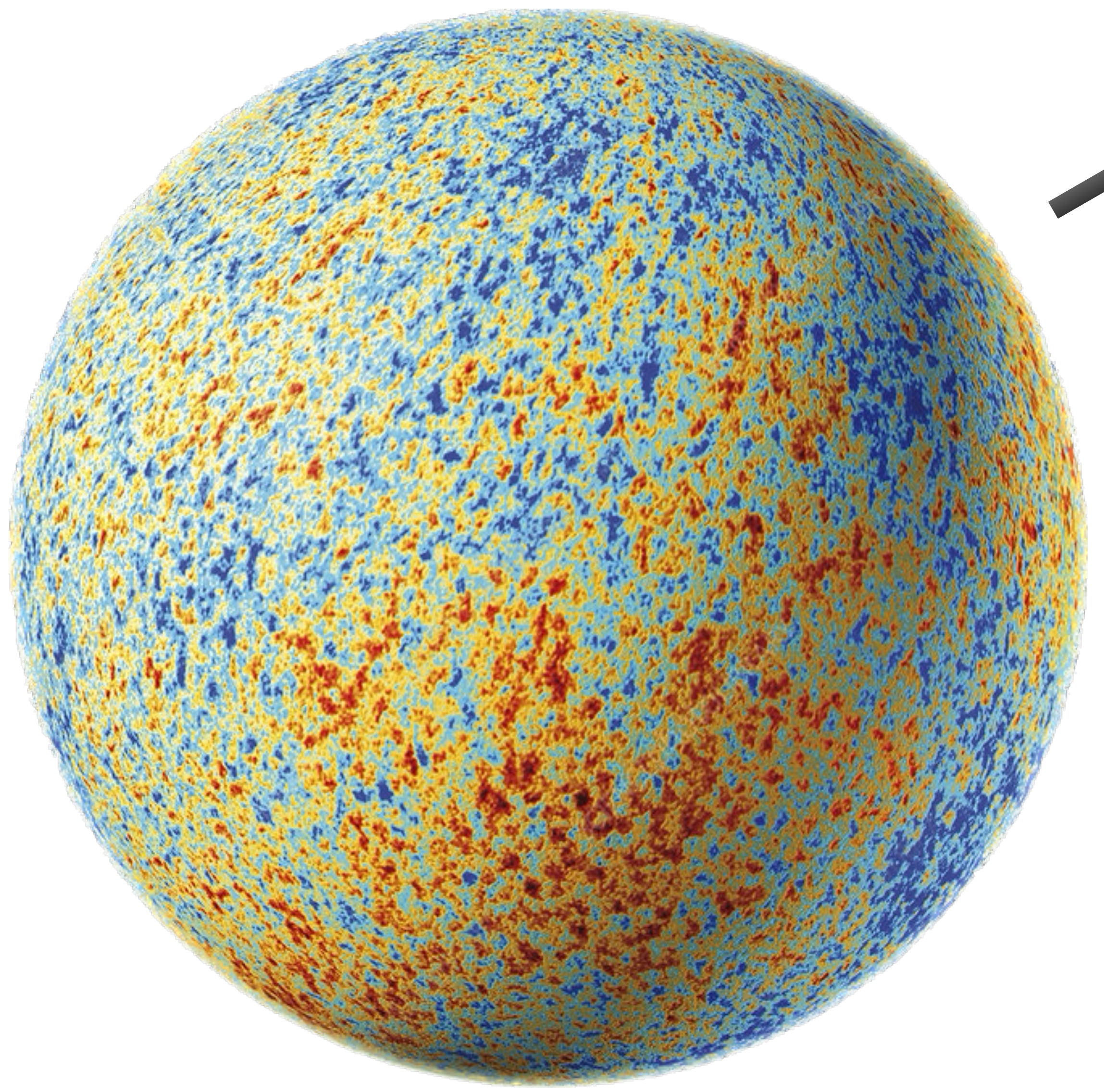
Inflation
to explain spatial flatness, homogeneity on large scales and inhomogeneities on small-scales.

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

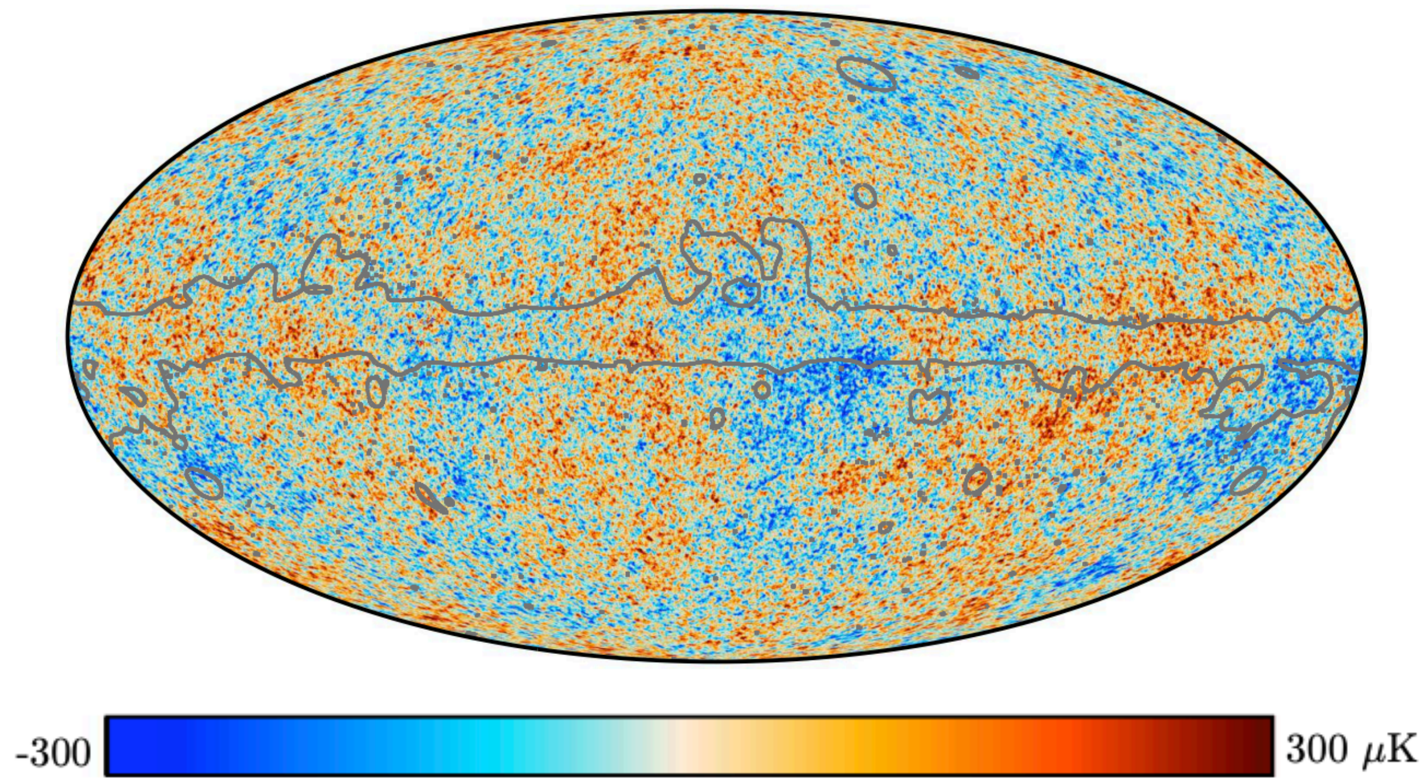
Dark Energy (cosmological constant Λ)
to explain the late time accelerated expansion of the Universe

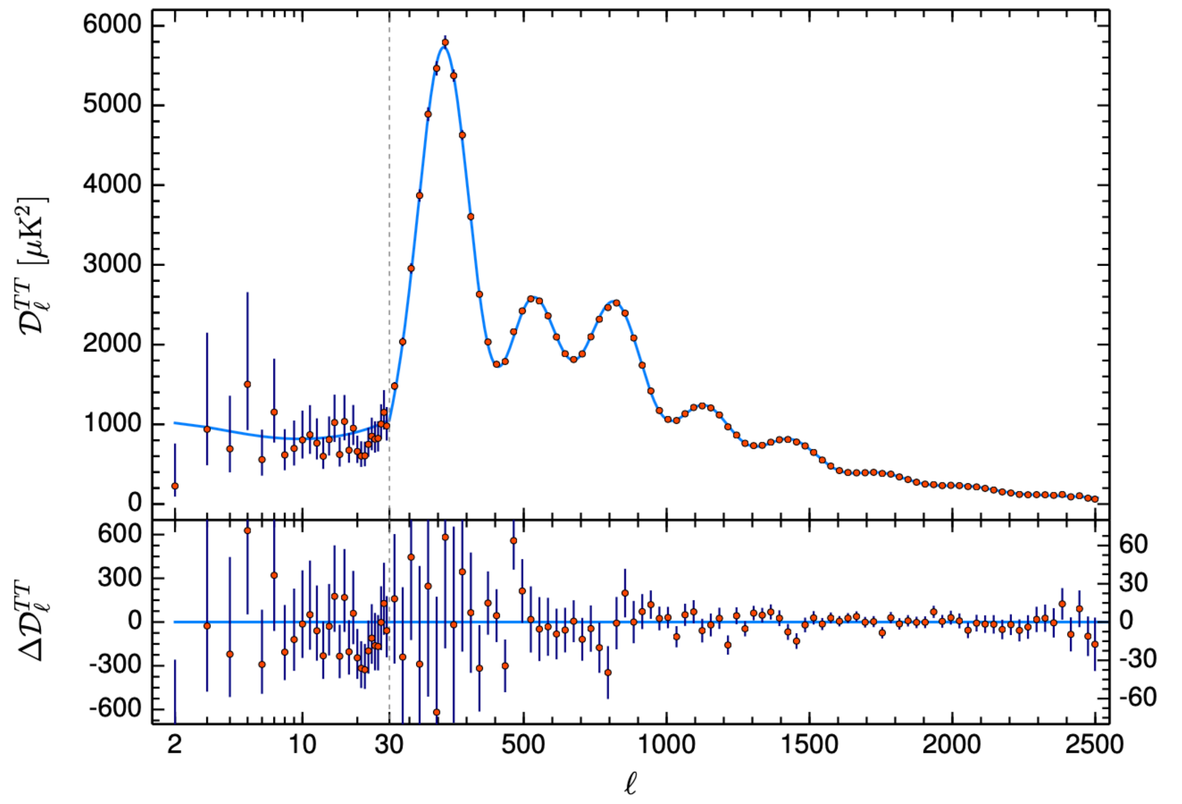
Cosmic Microwave Background Radiation

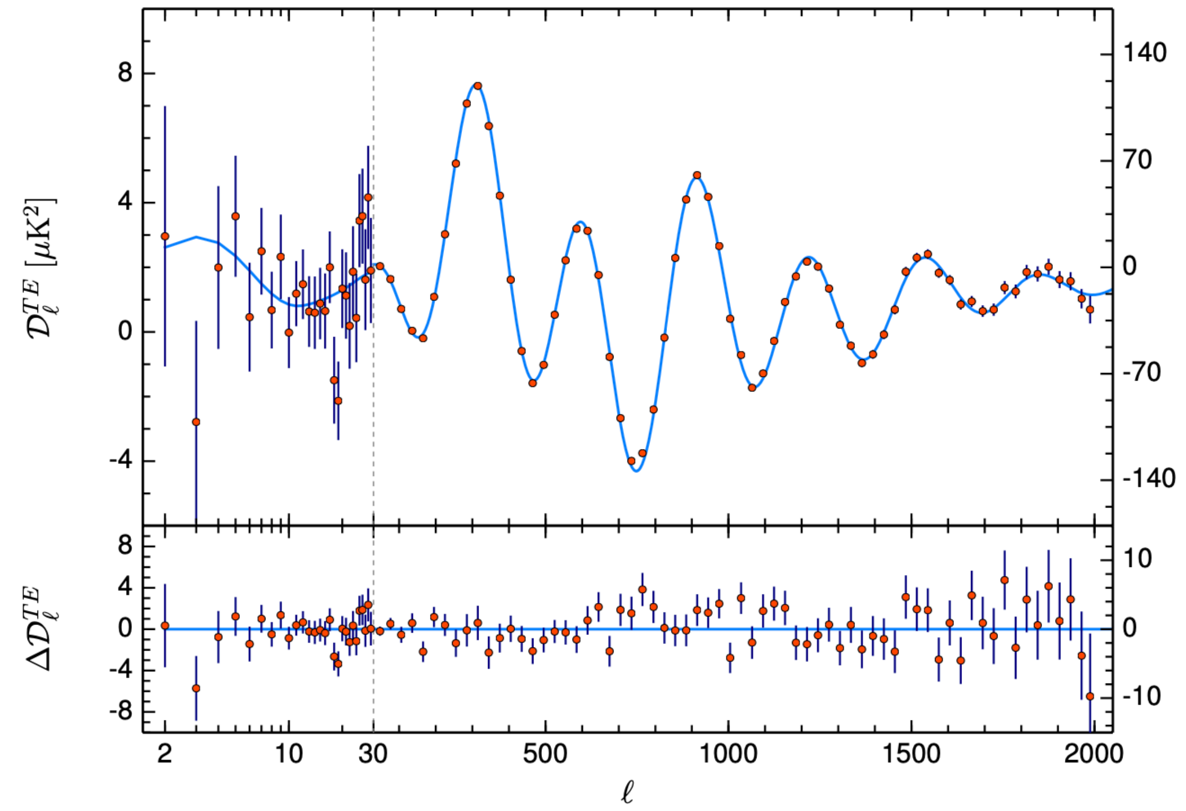
Relic Photons from the Big Bang



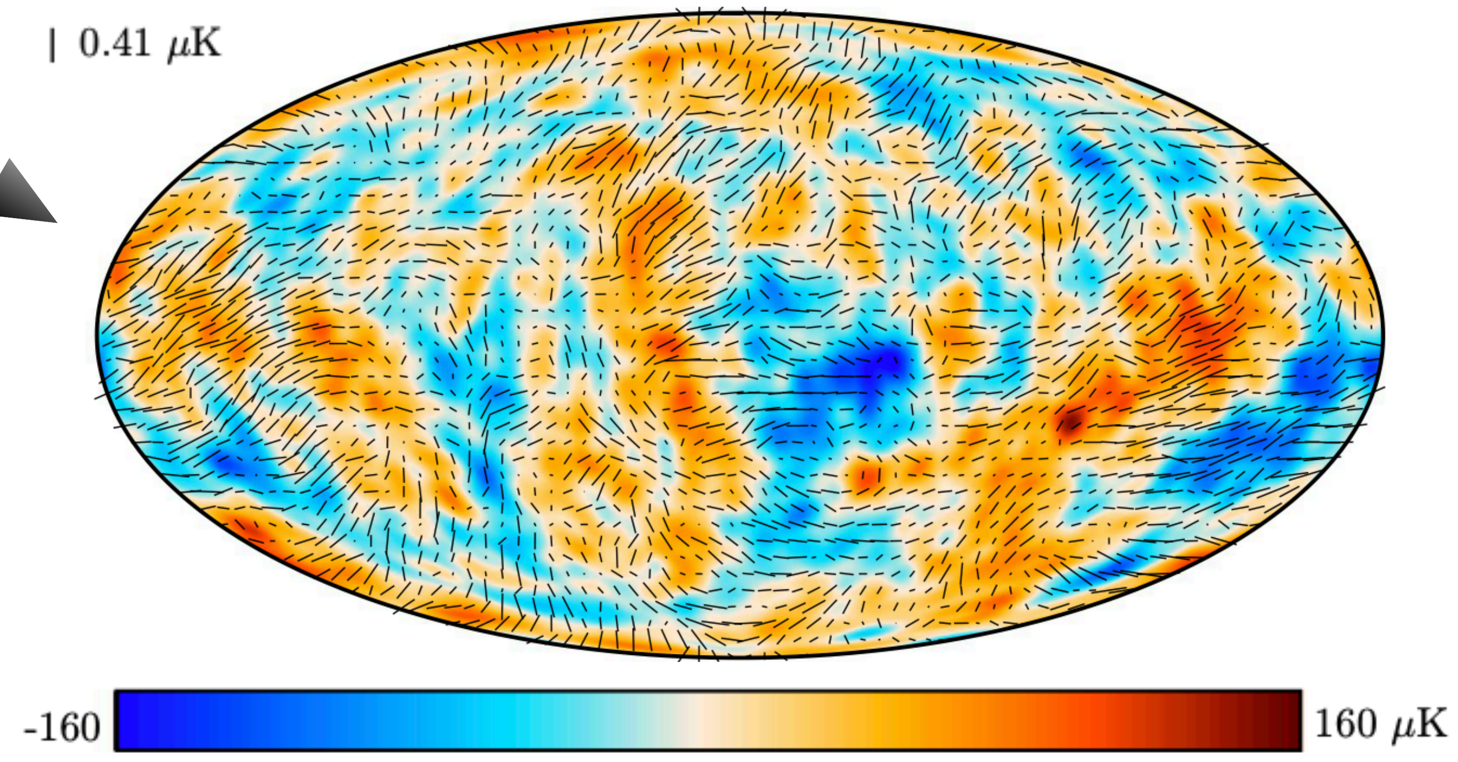
Temperature anisotropies

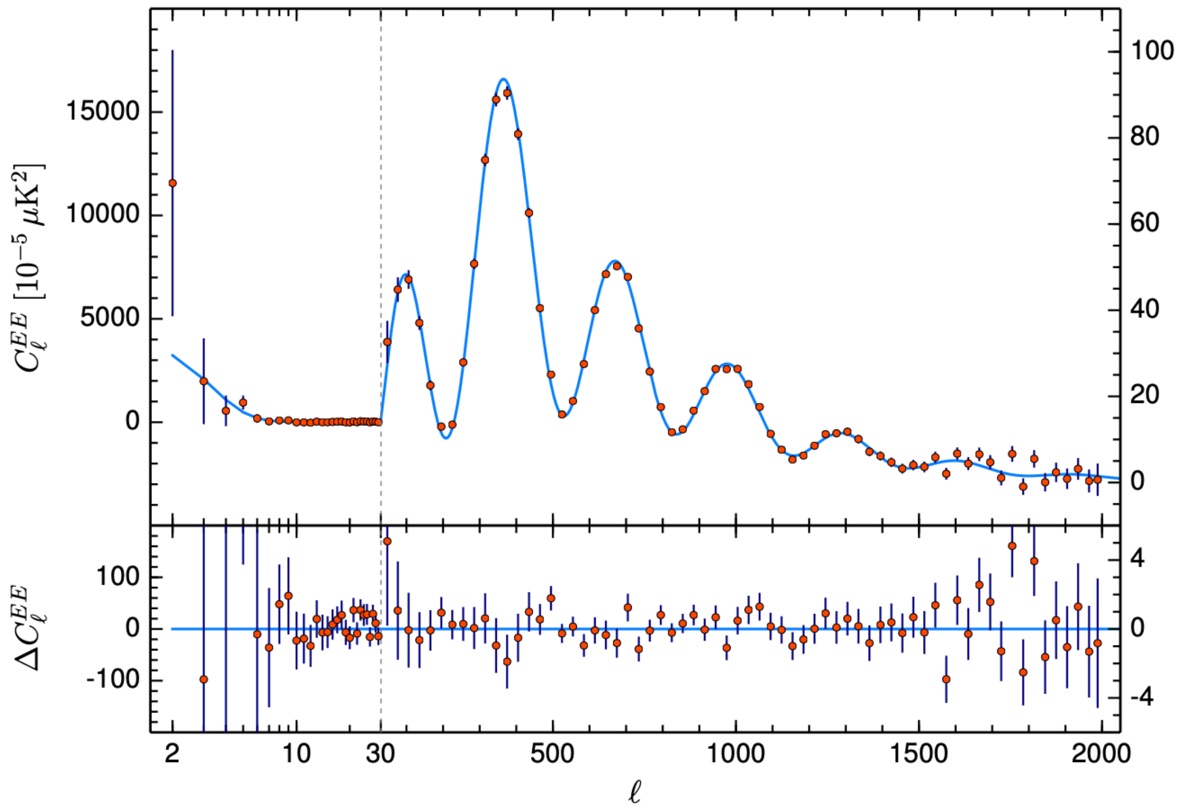






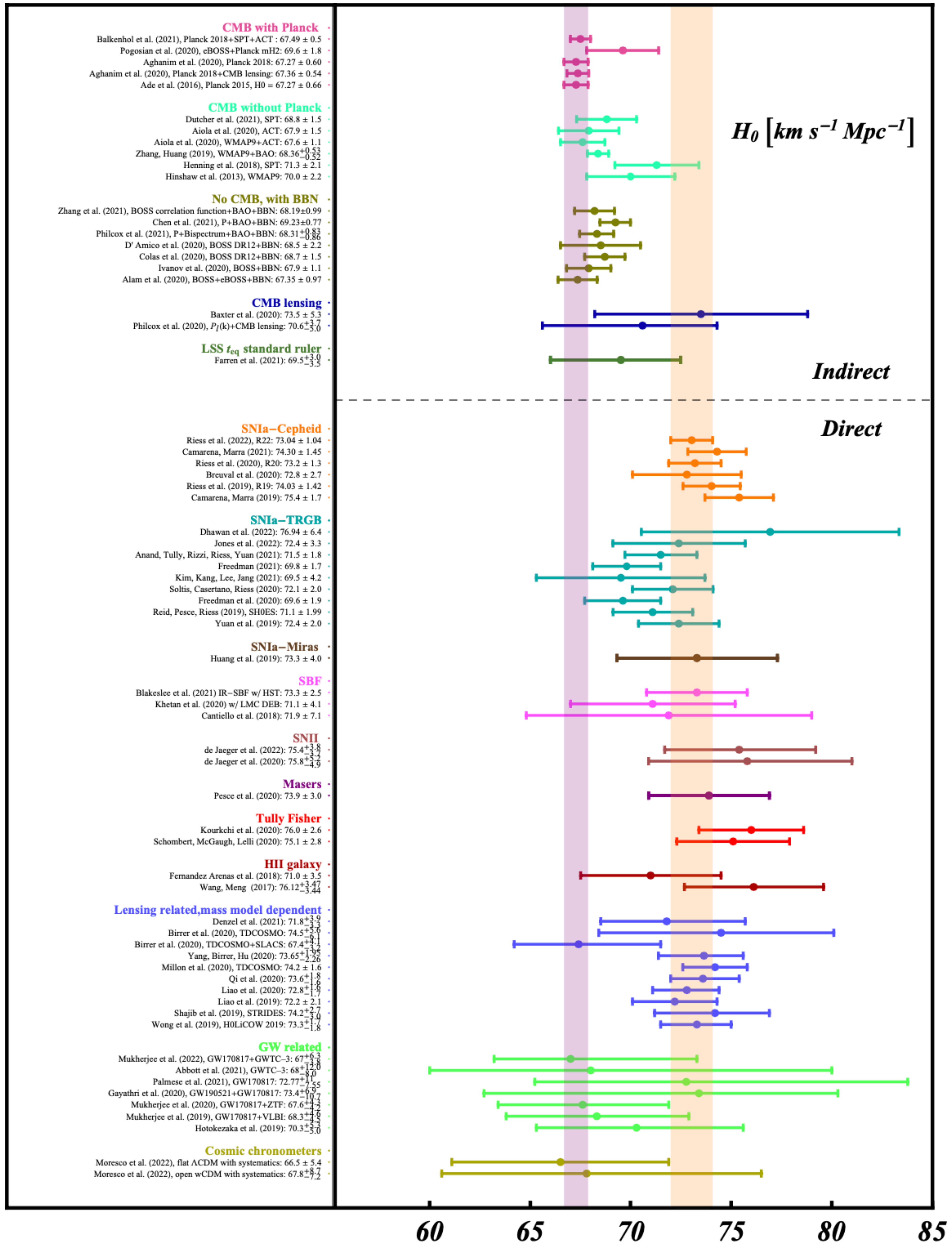
Polarization anisotropies





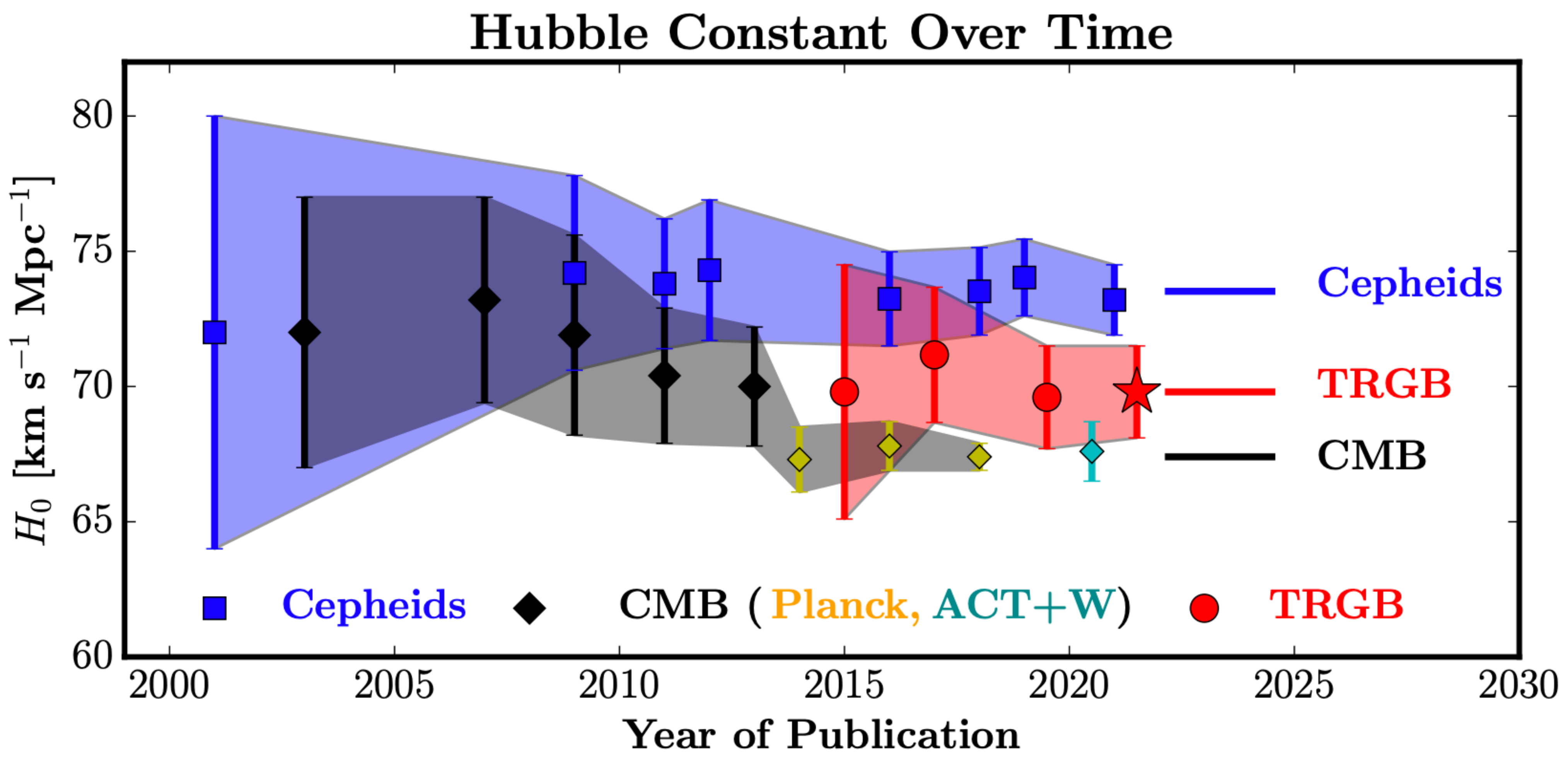
68% CL constraint on the Hubble parameter from different cosmological probes

Snowmass Collaboration, [arXiv: 2203.06142]



Tension ~~Precision~~ Cosmology

In the last years, some tensions (Hubble, S_8 ...) among high and low redshift observations are questioning the validity of this standard scenario...



... revealing either some important unaccounted-for systematics in the data (Hubble tension now at 5 sigmas) or the need for new physics beyond ΛCDM

Not only H0: Tensions and Anomalies in Cosmology

Hubble Parameter (H_0)

- Tension between CMB and local measurements

Matter clustering (Ω_m / σ_8 / S_8)

- Tension between CMB and weak leasing surveys

Lensing Amplitude (A_{lens}) and Curvature (Ω_K)

- Moderate Planck preference for higher lensing amplitude and closed Universe

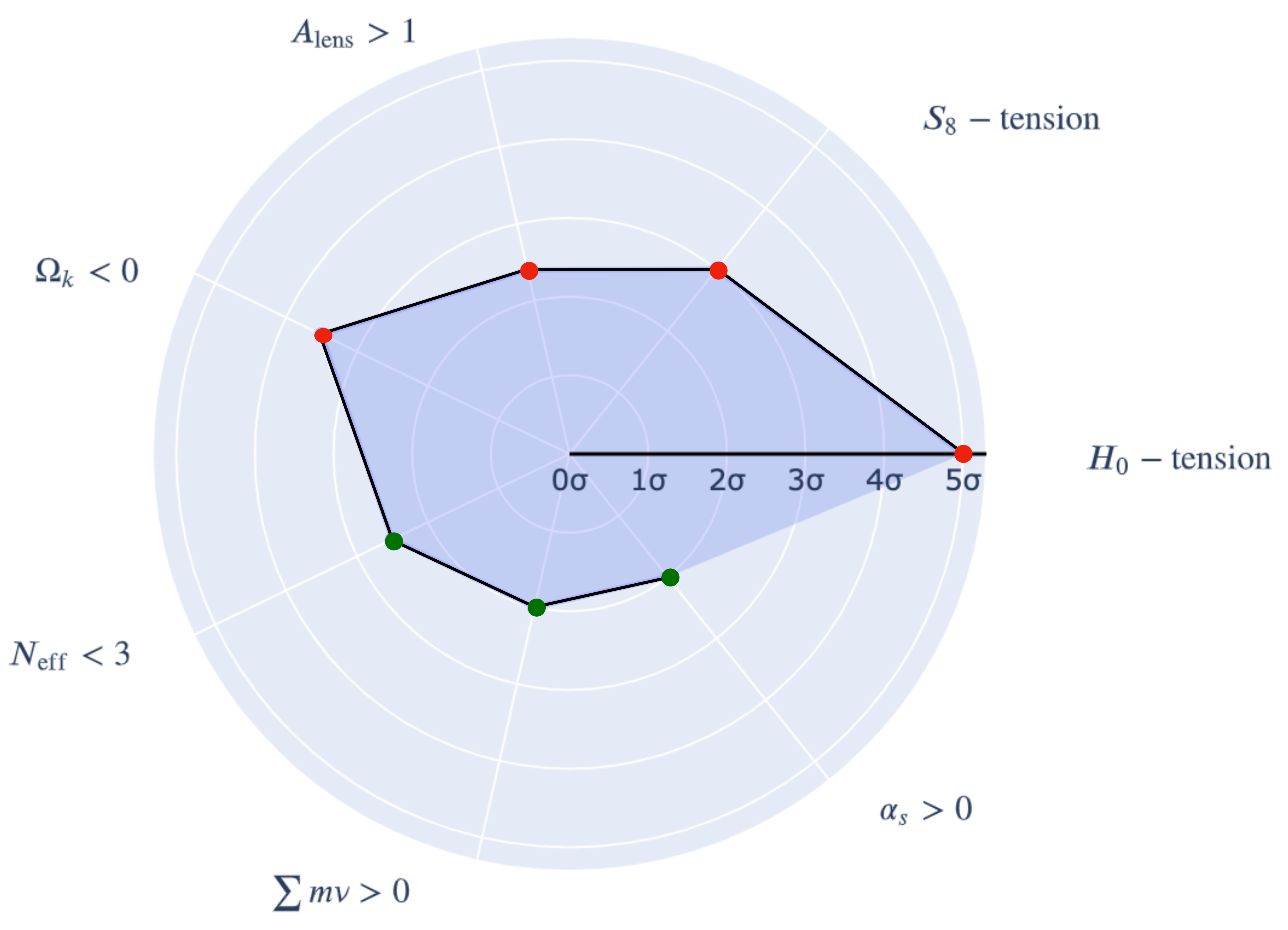
Early Universe Radiation (N_{eff})

- Mild ACT preference for the neutrino mass and $N_{eff}<3$

Running(s) of inflationary spectral index (α_s)

- Slight ACT preference for a running of the spectral index $\alpha_s > 0$

Some intriguing cosmological tensions and anomalies



Our Aim

1

Testing ΛCDM

We can relax some assumptions of ΛCDM and introduce additional parameters

$$\Lambda\,\mathrm{CDM} + \sum_i \mathrm{p_i}$$

$$p_i \in \{\Omega_k\,, dn_s/d\log k\,, N_{\mathrm{eff}}\,, \sum m_\nu\,,\ \ldots\}$$

or even different parameterizations for the dark sector

$$\mathrm{X\,CDM}$$

$$\mathrm{X} \in \{\Lambda\,, \mathrm{w_0}\,, \mathrm{w_0 w_a}, \ldots\}$$

2

Testing New Physics

More precise observations will offer us the possibility to use Cosmology as a laboratory to test fundamental Physics

Extensions to GR

Modified gravity theories able to capture the underling phenomenology of the early and late time Universe.

Extensions to SM

extensions to the SM with additional species/ DM candidates

Results

Mainly Based on:

arXiv:2210.09018 [pdf, other] astro-ph.CO

Harrison-Zel'dovich spectrum gets back?

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DATA

Planck 2018 (TT TE EE)

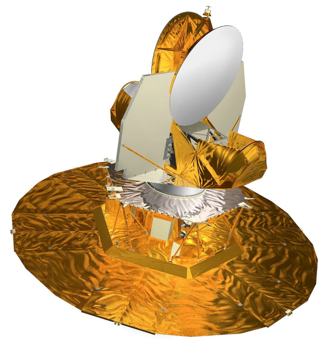
Temperature and polarization likelihood which also includes low multipole data (l < 30)

Atacama Cosmology Telescope (ACT)

DR4 likelihood for temperature and polarization spectra

South Pole Telescope (SPT)

SPT3G TE likelihood



WMAP

9-yrs observations, Always Combined with ACT or SPT

MODELS

$$\underset{X \in \{\Lambda, w\}}{X\,\mathrm{CDM}} + \sum_i p_i \in \{\Omega_k, N_{eff}, \sum m_\nu, dn_s/d\log k\}$$

Curvature (Ω_K)

We explore curved background geometries parametrized by the curvature density parameter

Inflation (α_s)

We relax we relax the assumption of scale-invariant primordial perturbations by introducing a running of the spectral index α_s

Neutrinos (M_ν) and Early Universe Radiation (N_{eff})

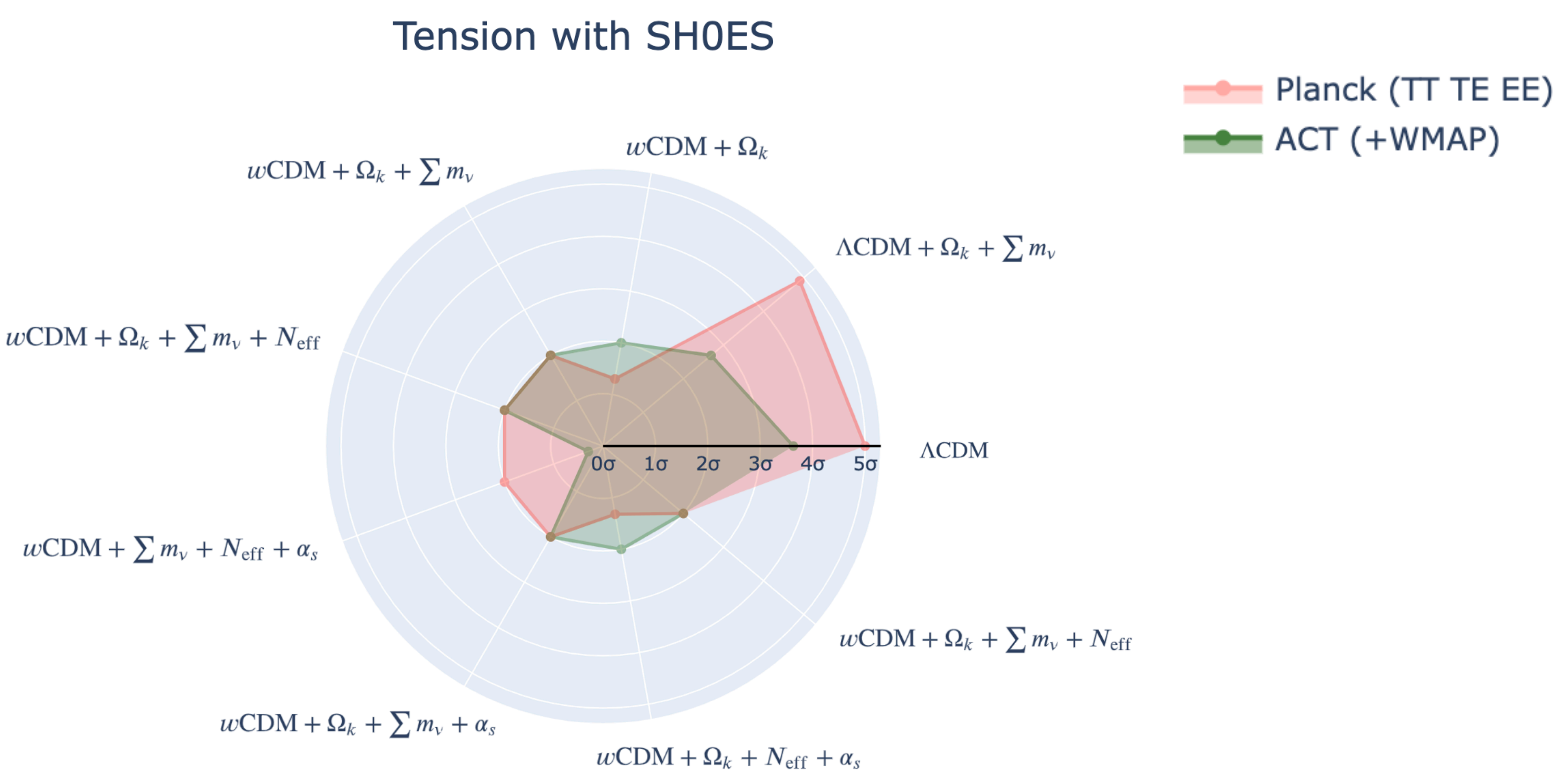
we consider neutrinos as massive particles, as robustly indicated by oscillation experiments

we change the amount of radiation in the early Universe by the effective number of relativistic particles

Dark Energy (w)

We relax the assumption $w = w_\Lambda \equiv -1$ for Dark Energy equation of statE

Expansion Rate



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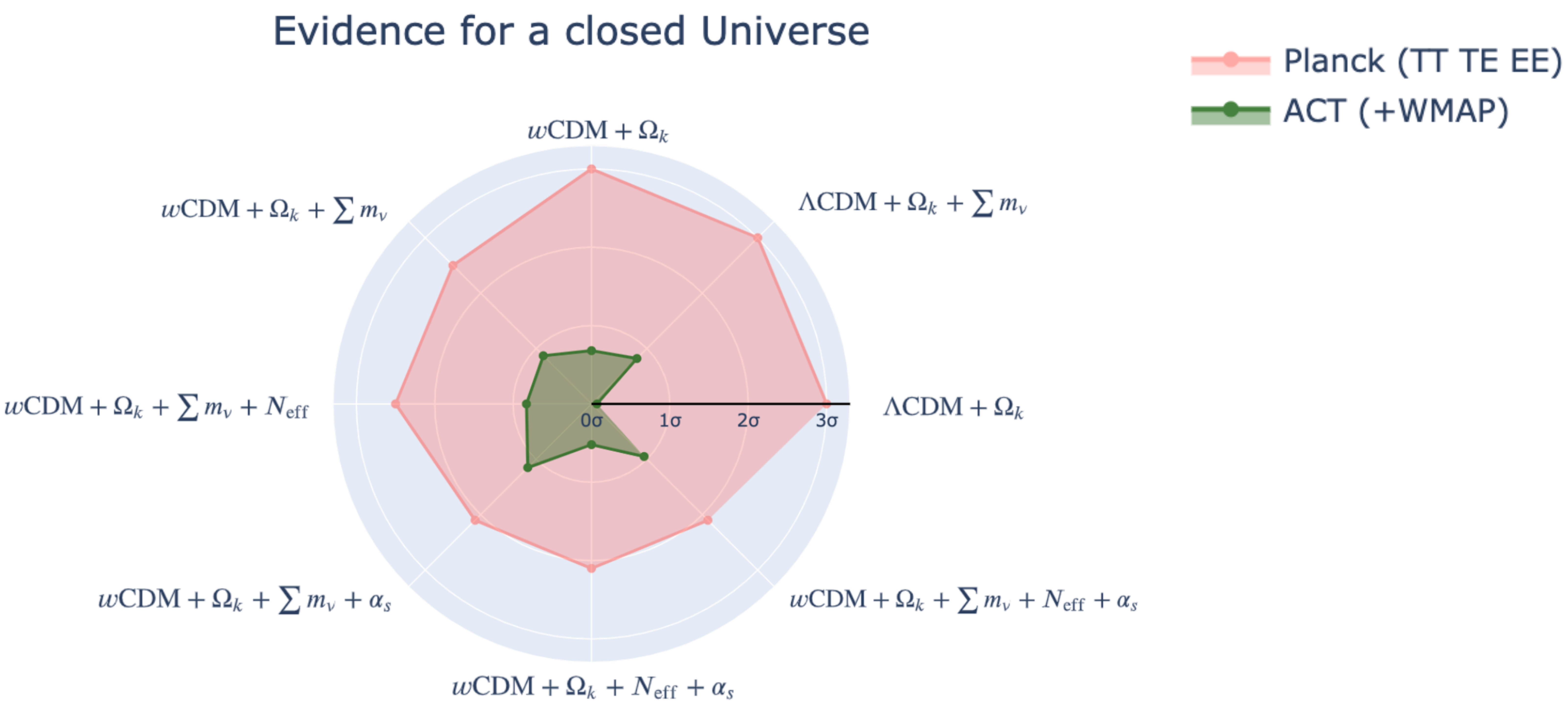
Spatial Geometry



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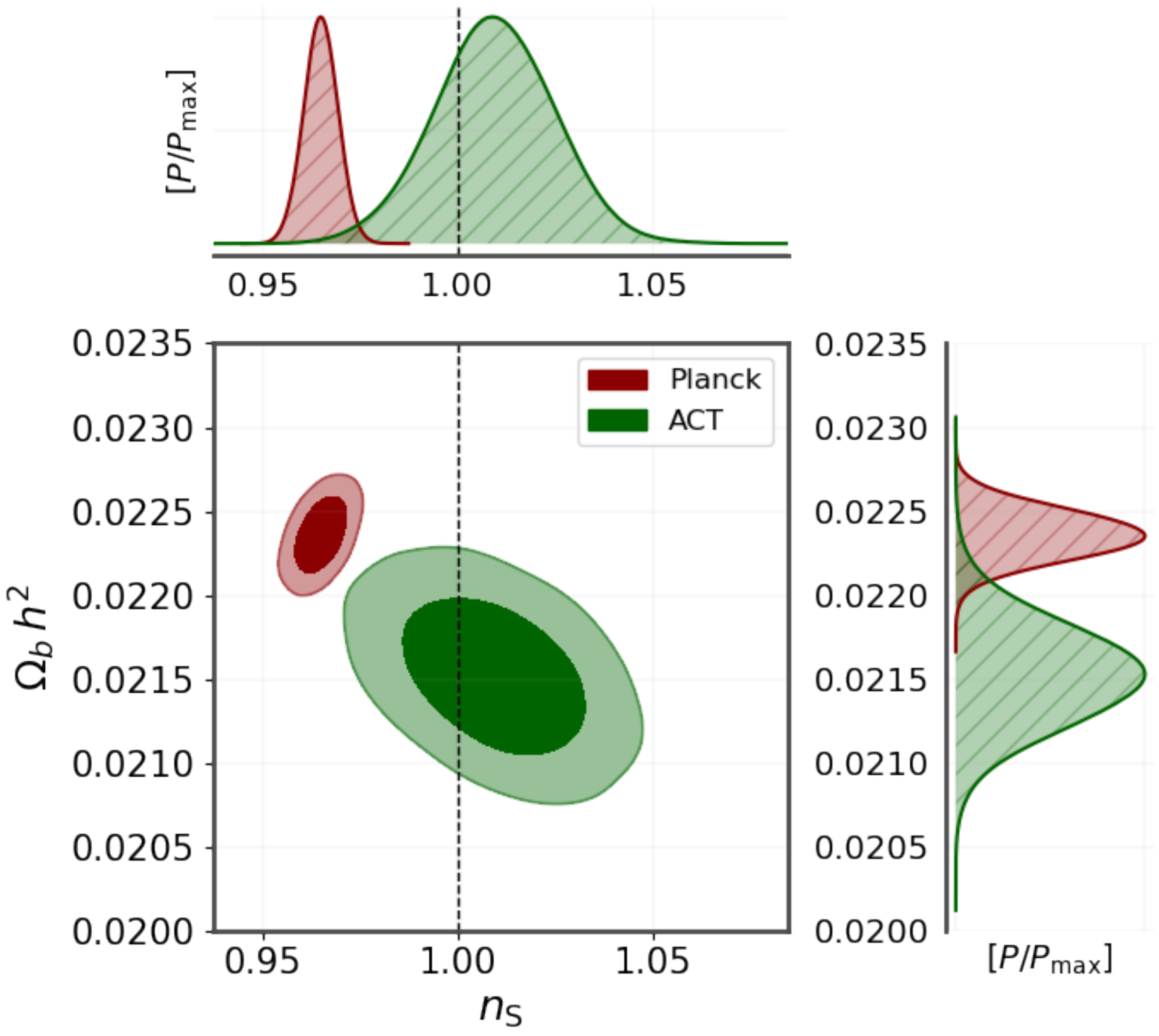

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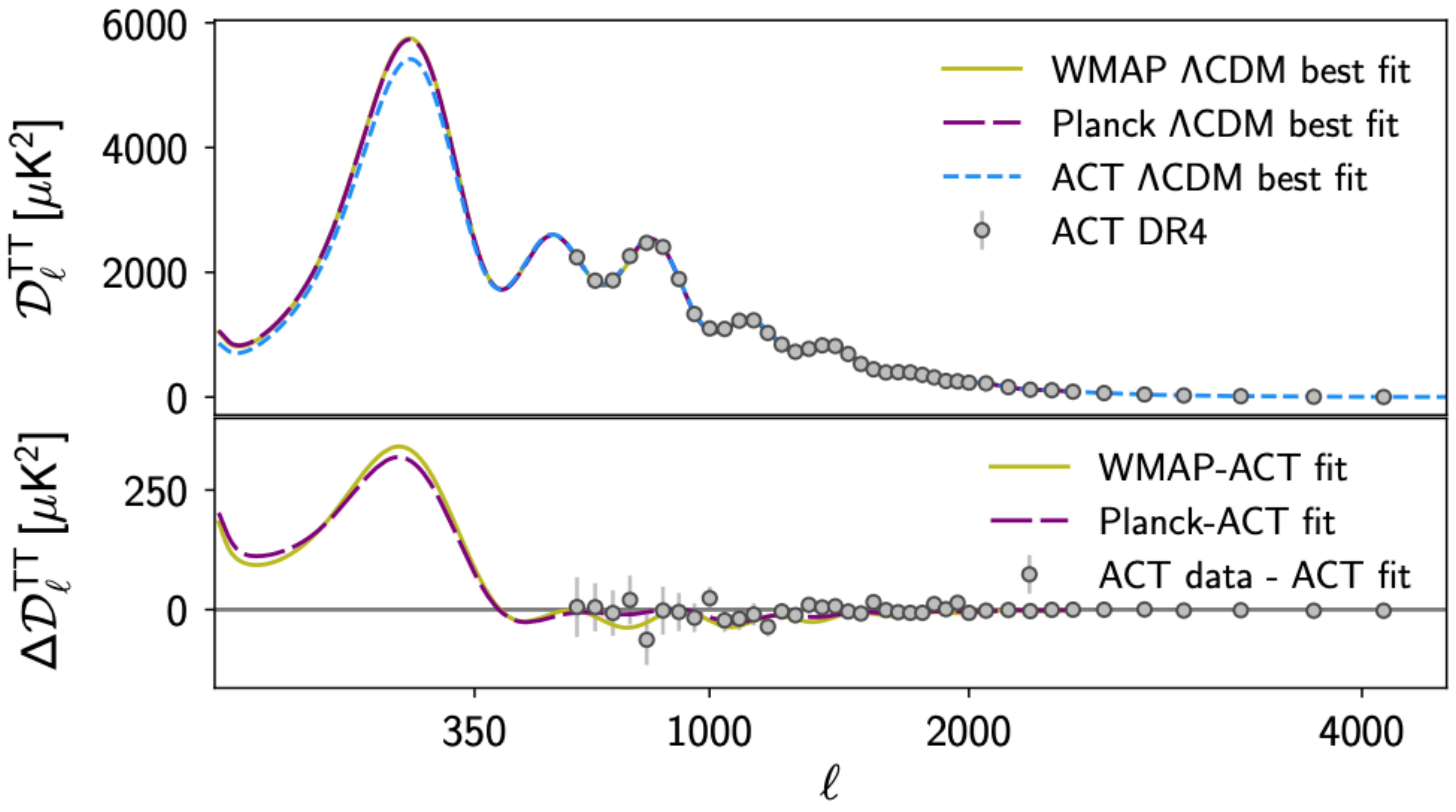
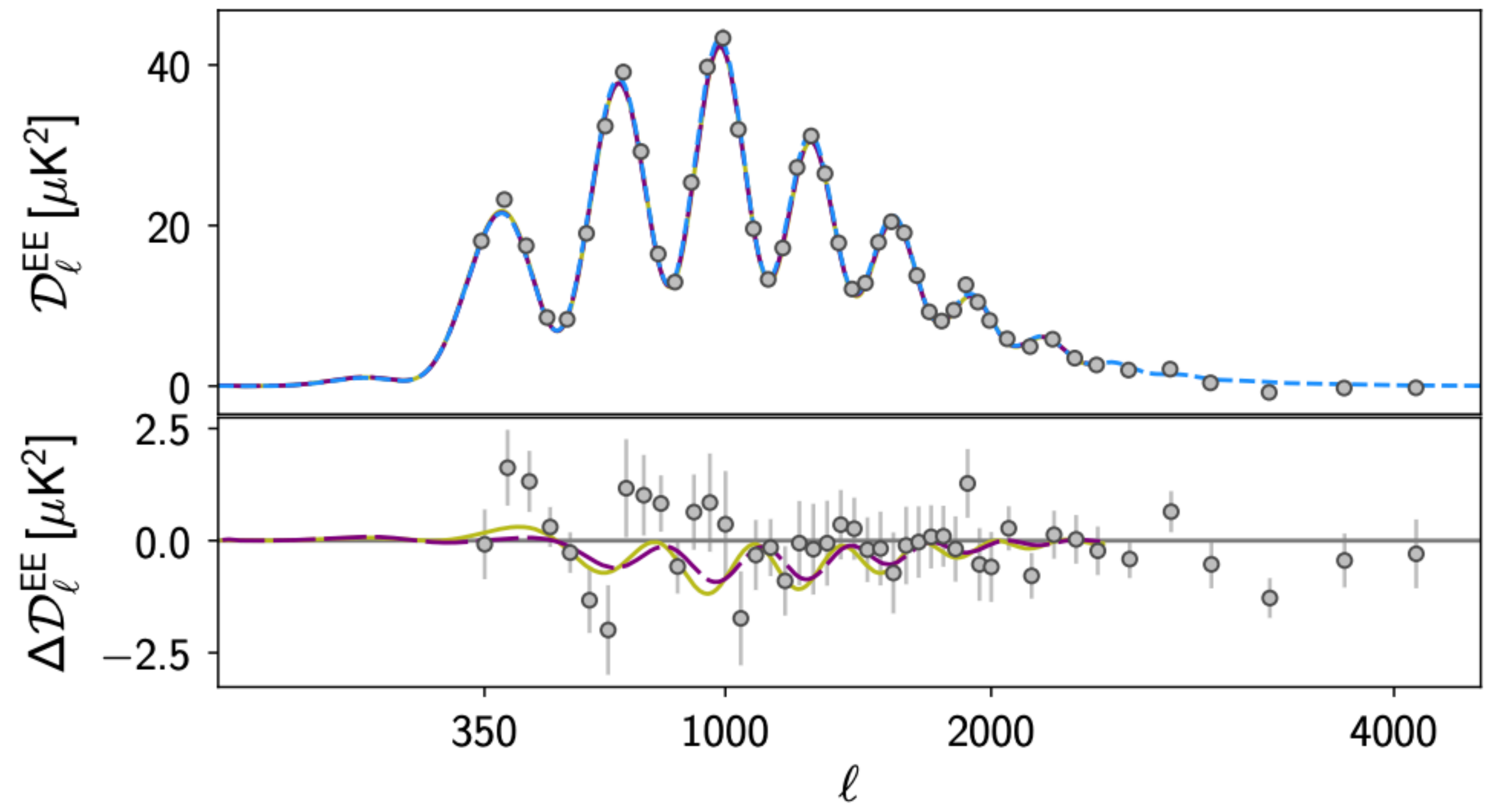
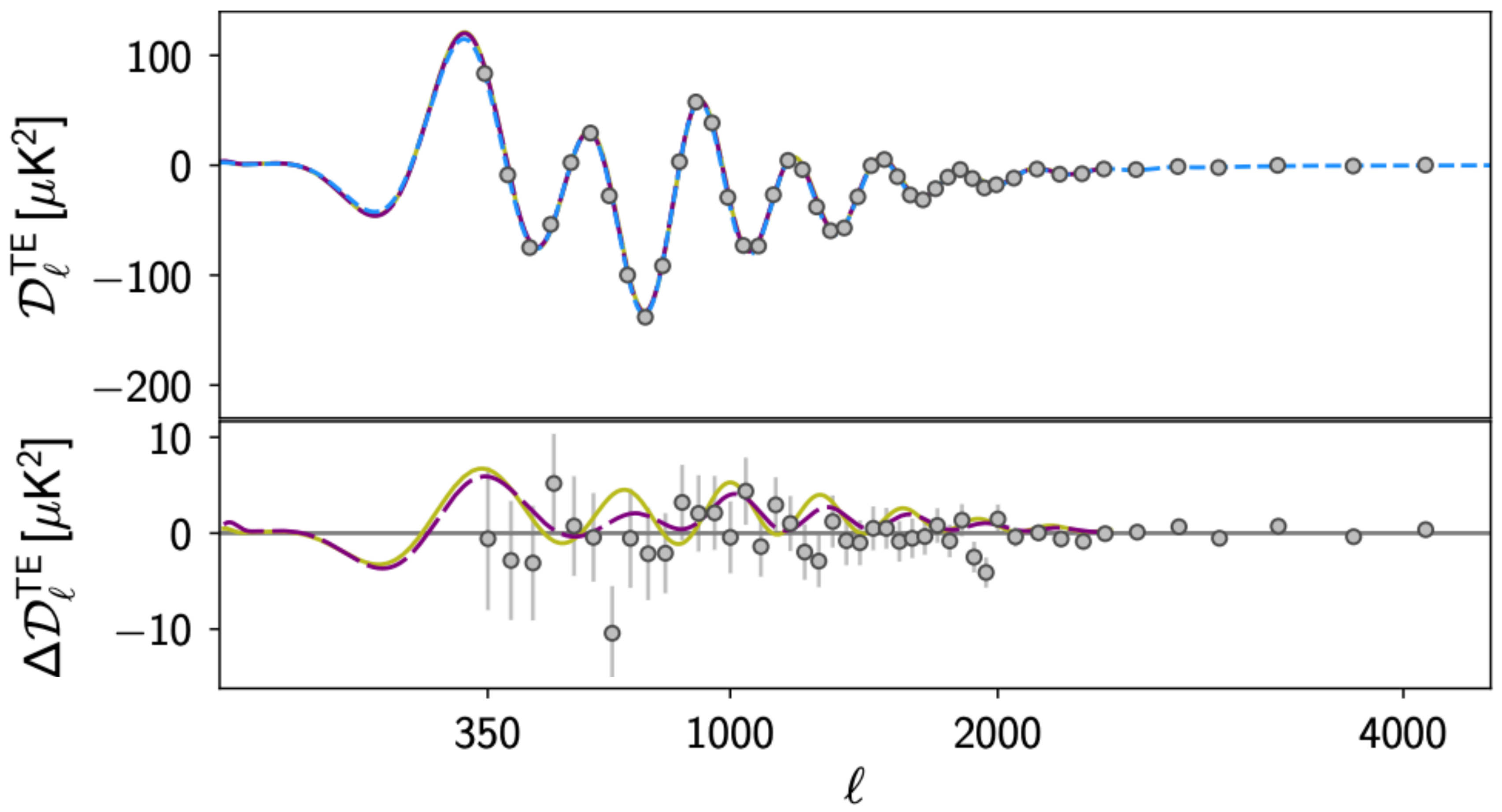
Inflation

Source: arxiv:2007.07288







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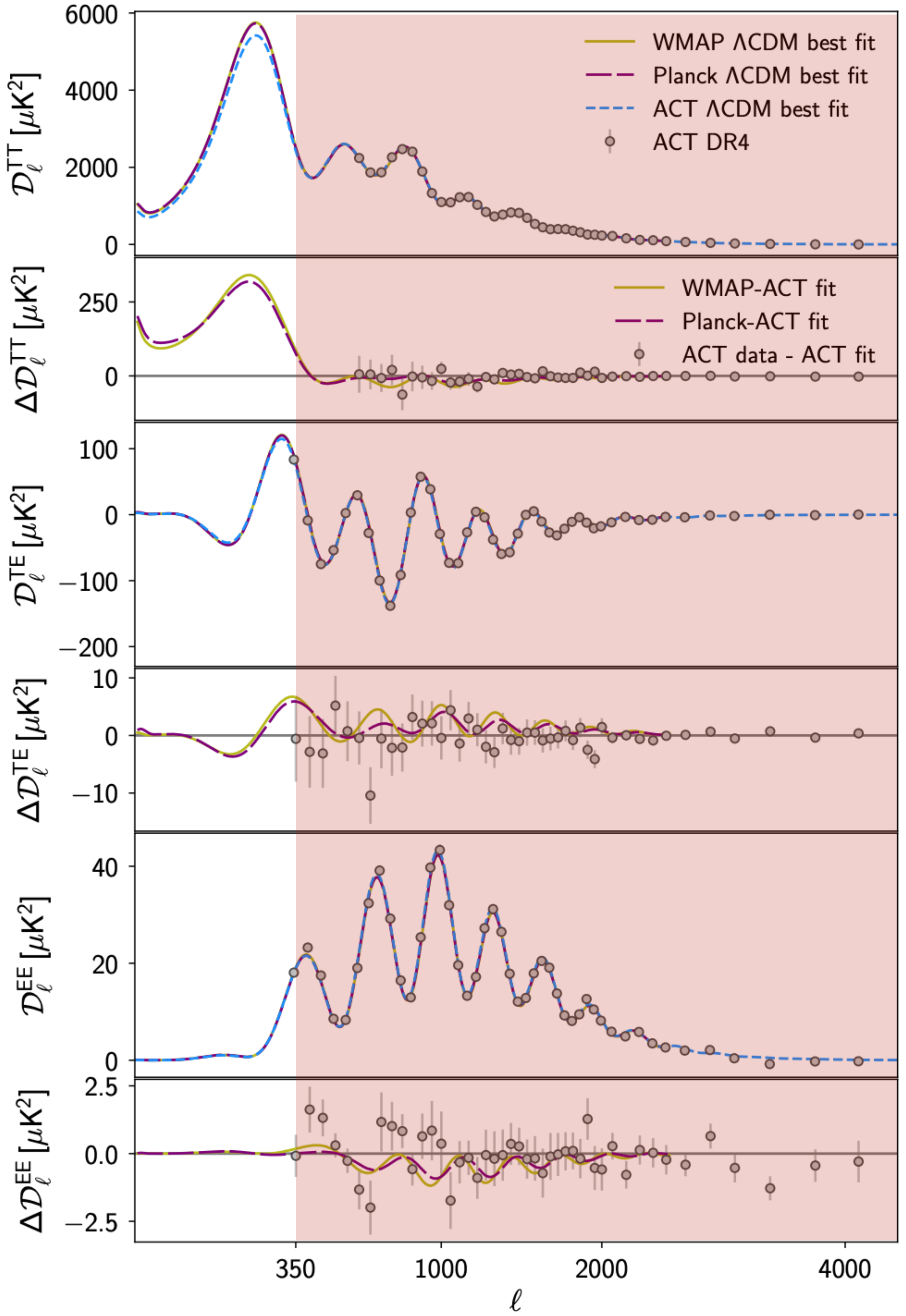
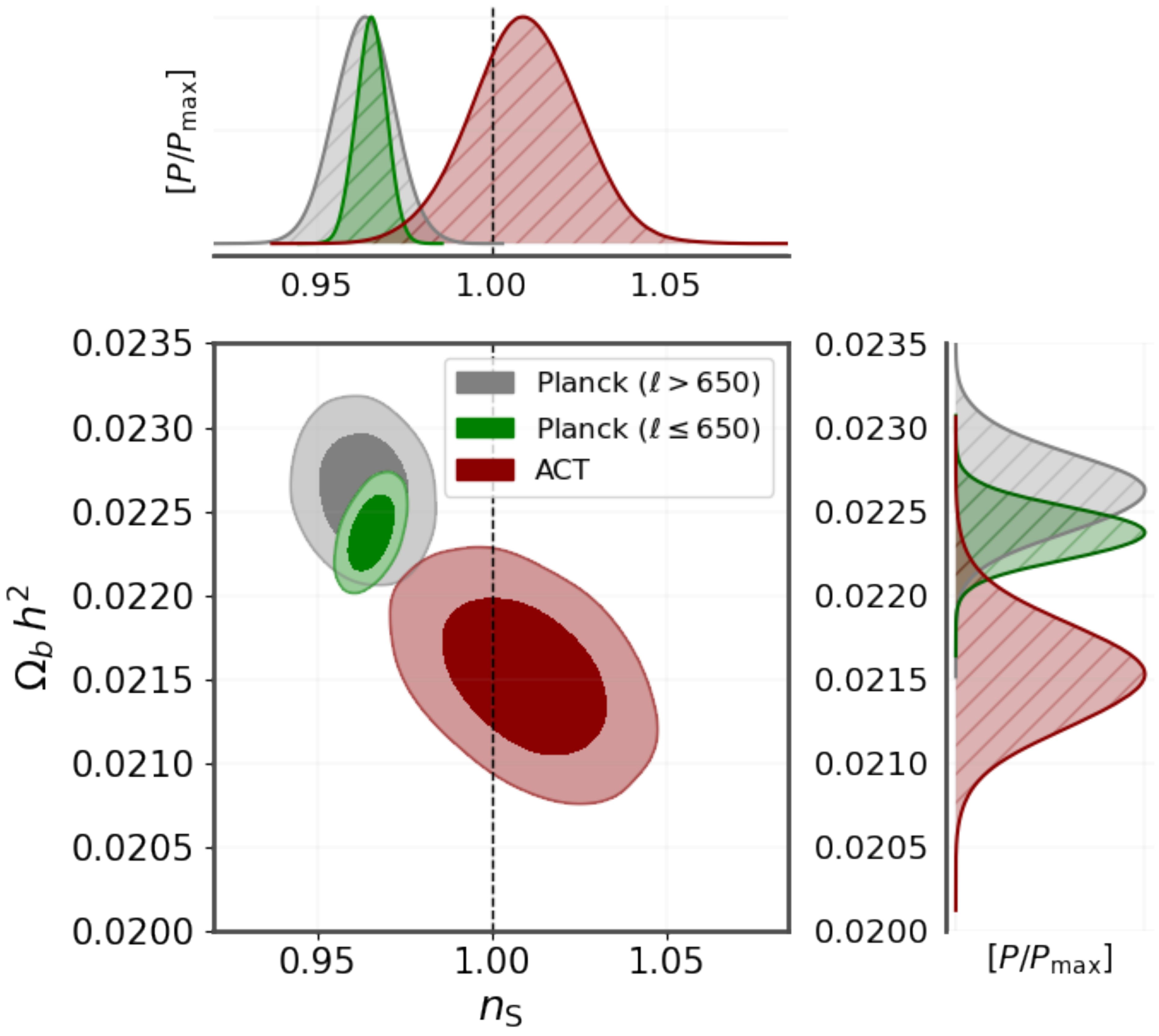
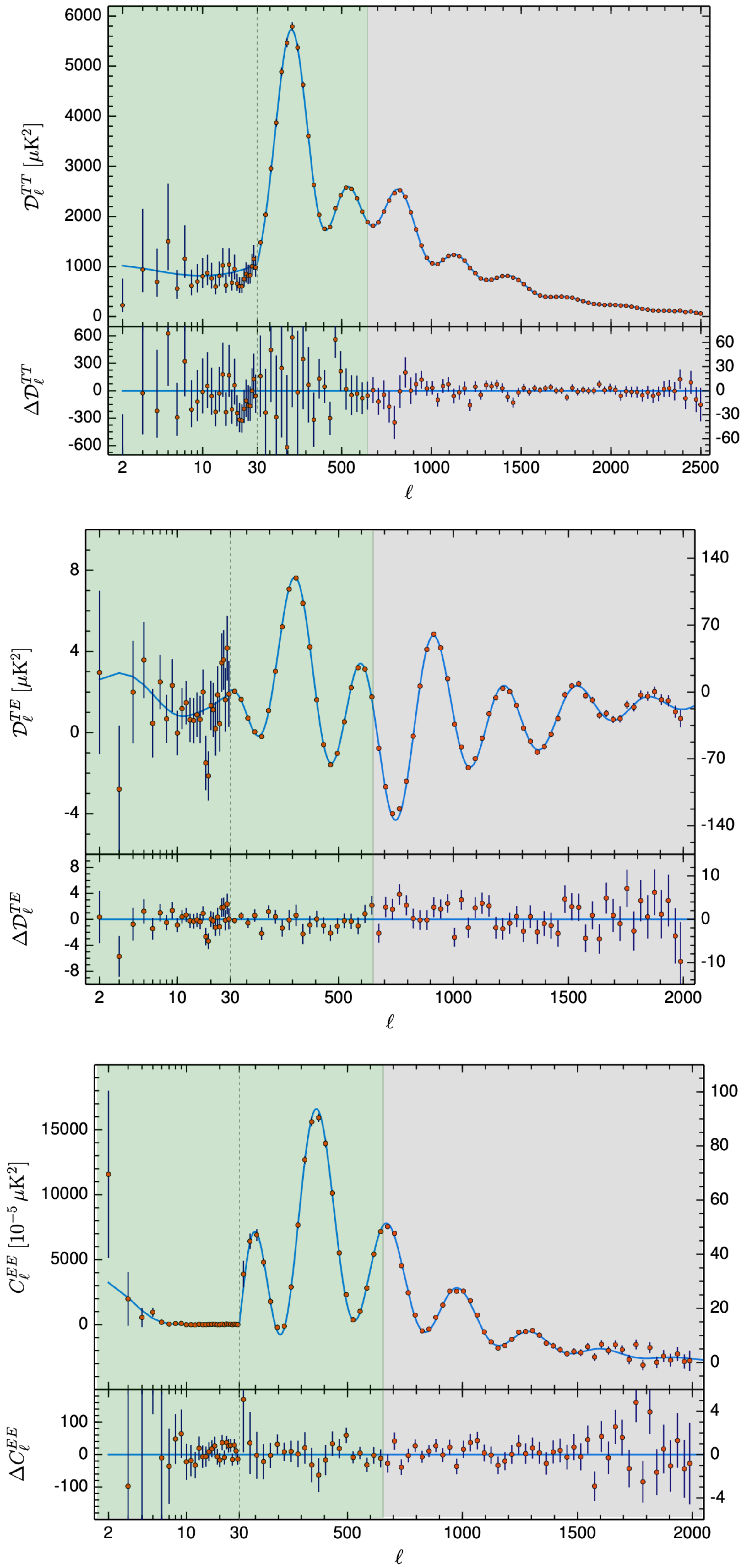
Inflation

ACT





Planck



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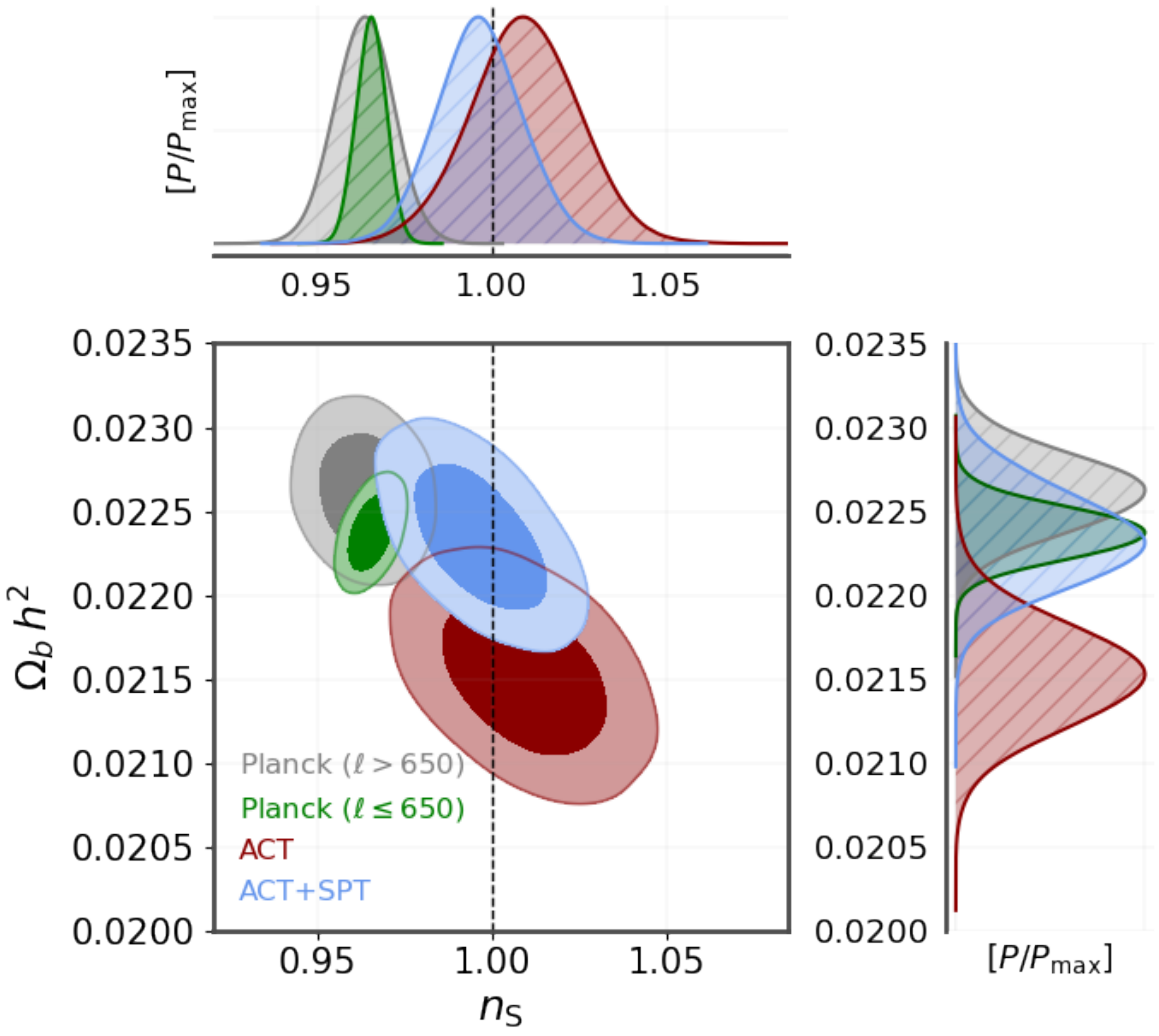

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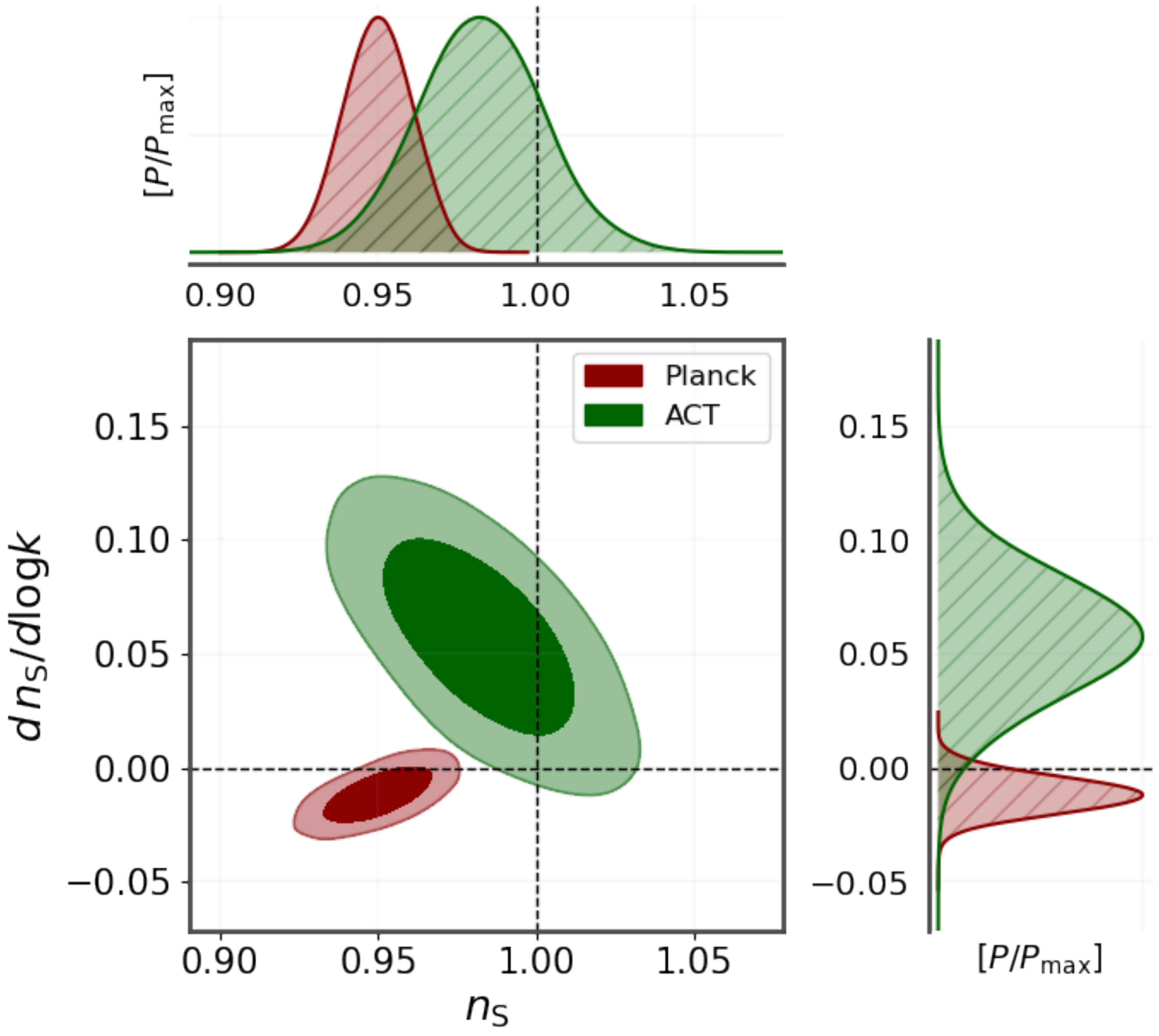

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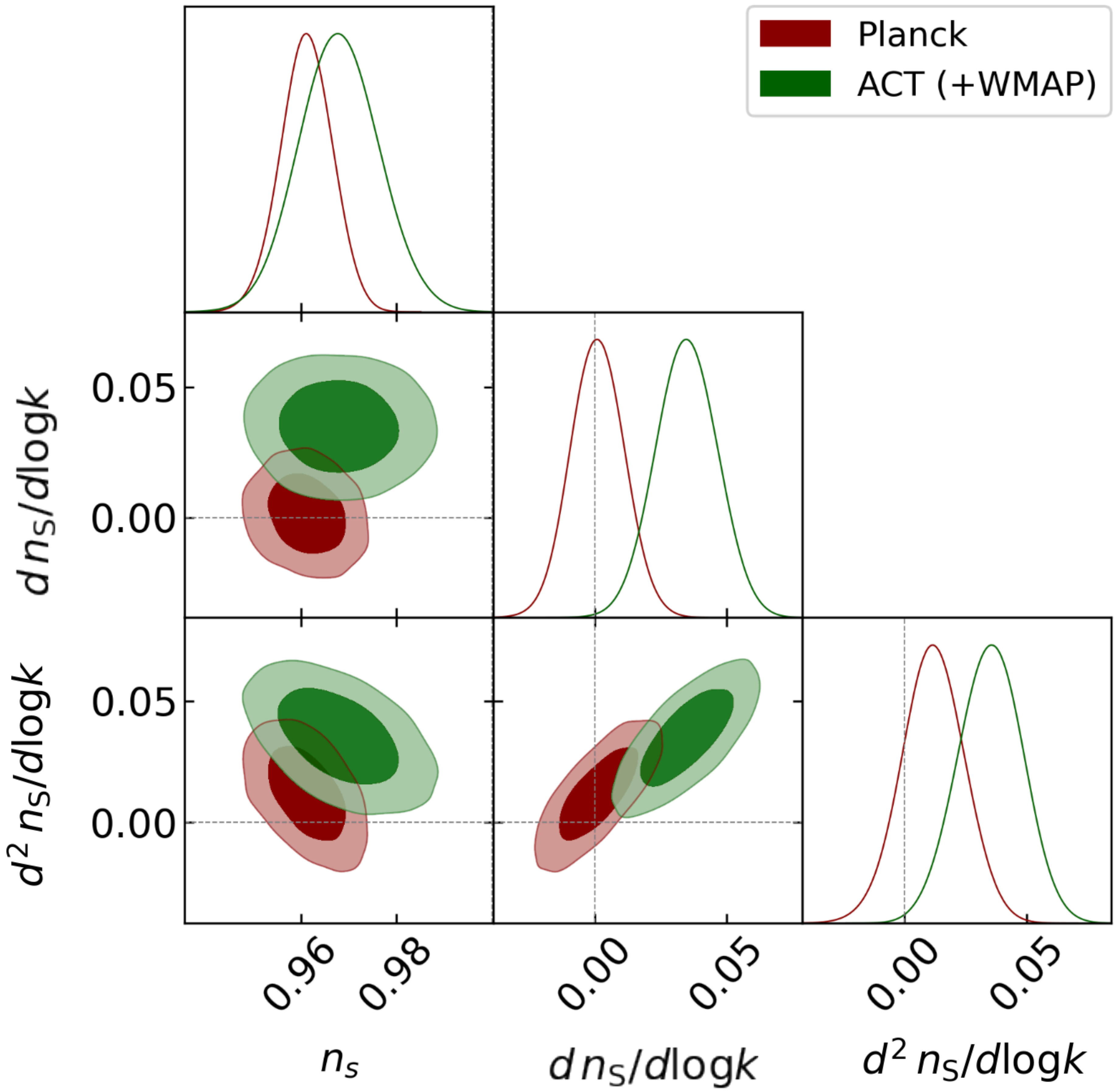

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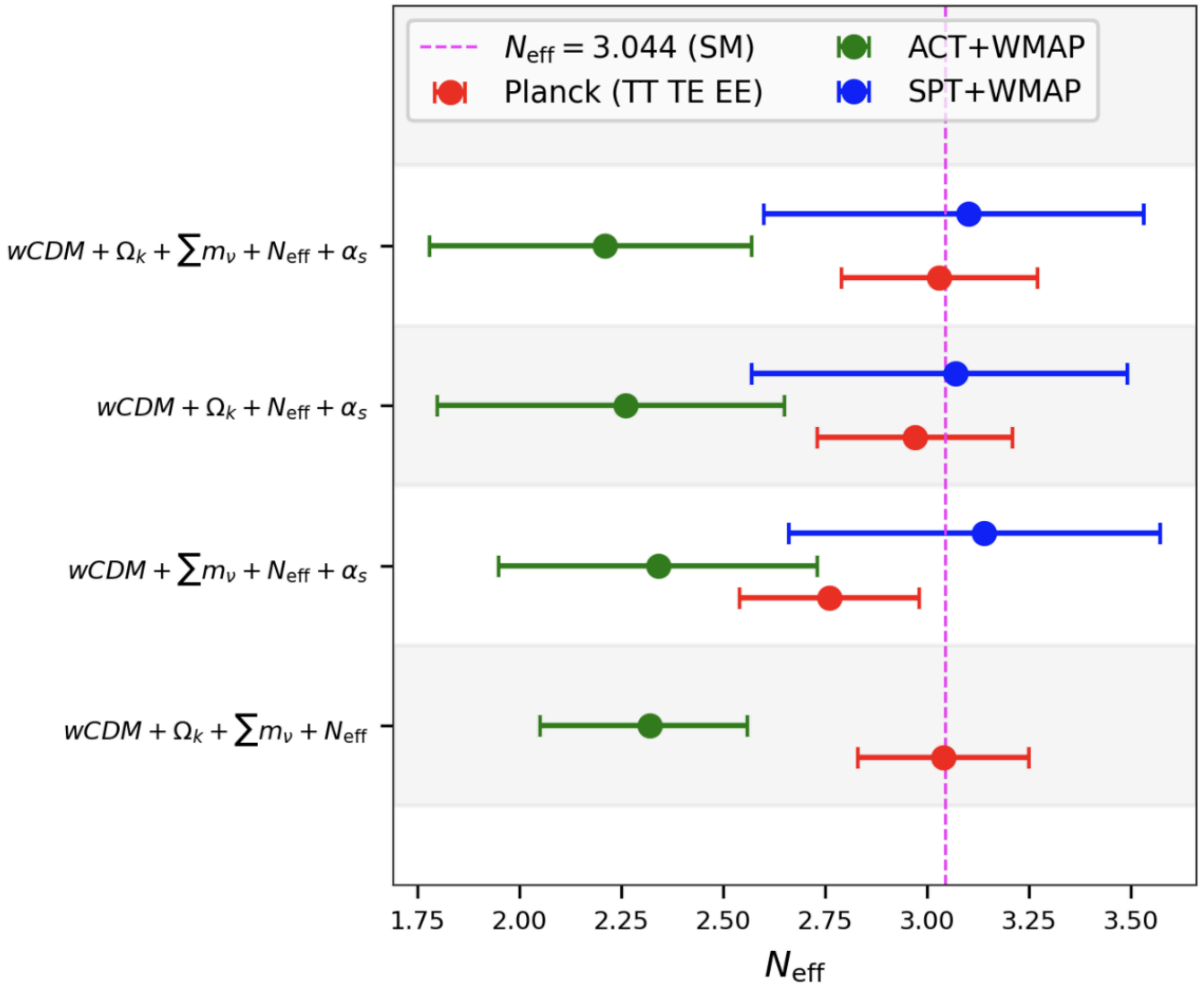
Radiation Energy-Density



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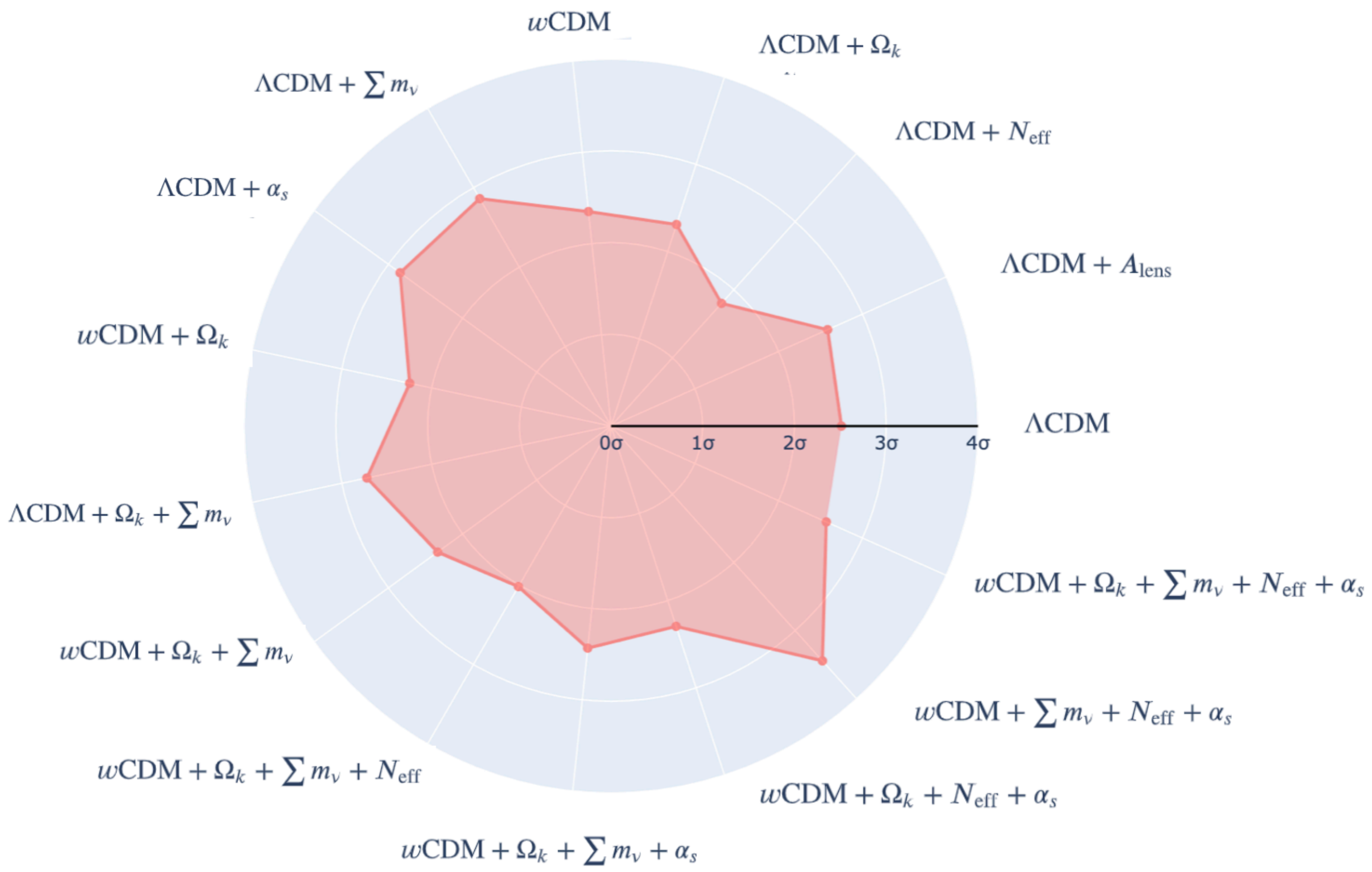
Quantifying the global "CMB" tension between ACT and Planck



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Take-away summary

The situation is quite intriguing and not completely clear

- Planck data show a preference for a closed universe, ACT and SPT (+WMAP) don't
- ACT is in 3 sigma tension with Planck about the value of the spectral index of inflationary perturbations
- ACT (+ WMAP) gives a 3 sigma indication for a ruining of the spectral index while Planck doesn't
- ACT (+ WMAP) data prefer less radiation w.r.t. the SM, Planck and SPT (+WMAP) are in agreement with $N_{eff} = 3.04$
- ACT gives a 3 Sigma preference for Early Dark Energy while Planck doesn't

CMB experiments are in moderate disagreement

- ACT and PLANCK are in tension at 2.6 standard deviation within the standard cosmological model
- This tension is not reduced in extended model of cosmology

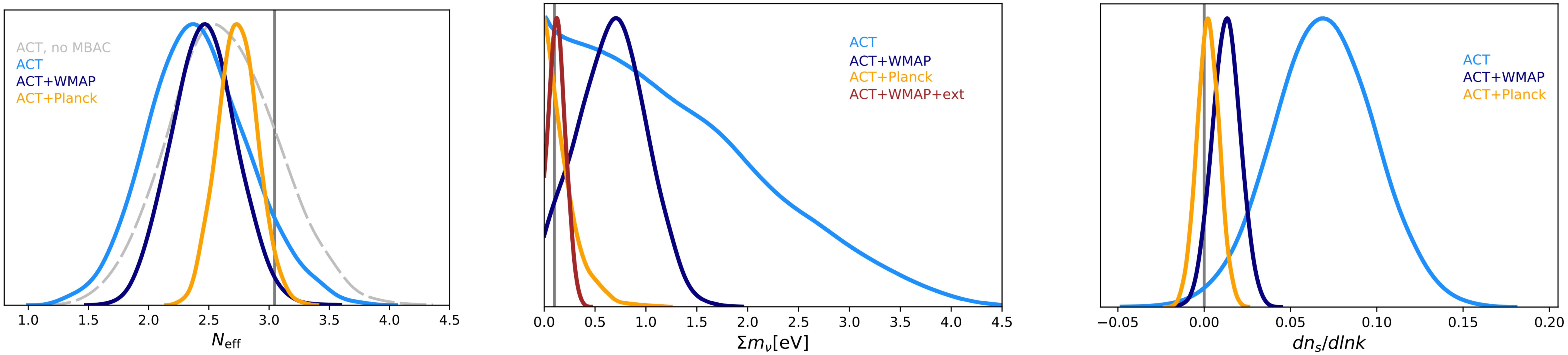
Observational systematics or new physics beyond ΛCDM?

Our analysis is not conclusive, but it reveals intriguing hints that need further investigations.
Precise CMB measurements form next-gen experiments may help

Thank you for the attention

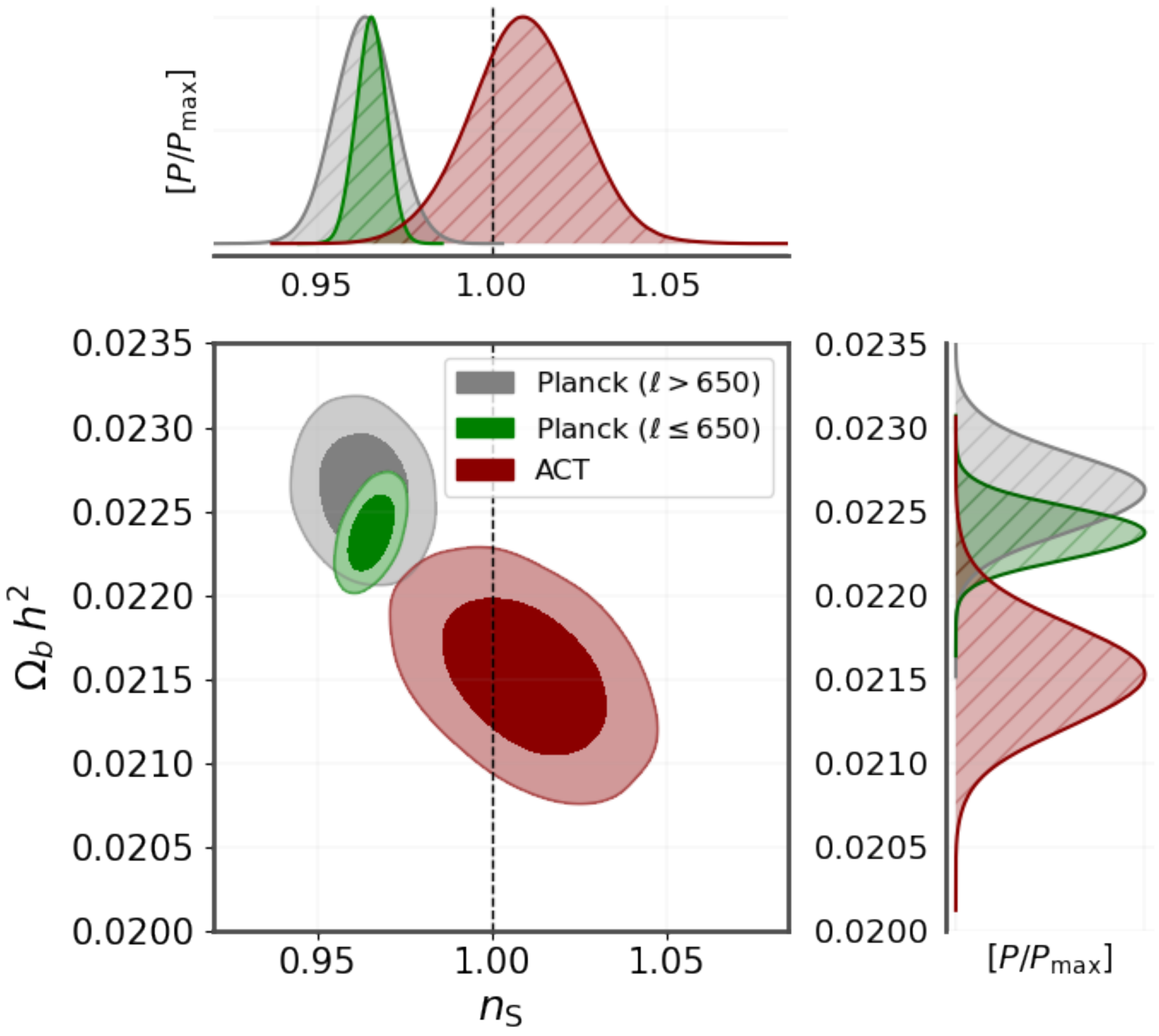
Backup Slides

ACT Anomalies in ΛCDM



Simone Aiola *et al* JCAP12(2020)047

Inflation



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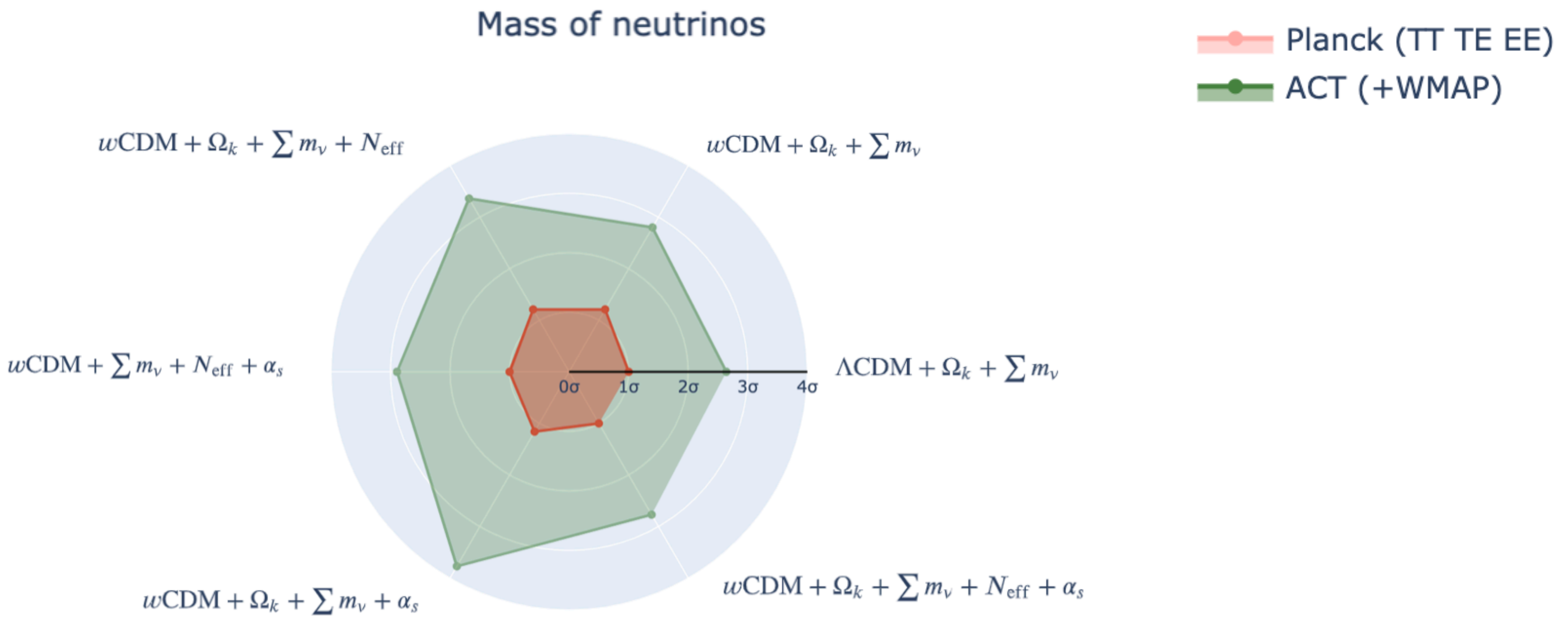
Neutrinos



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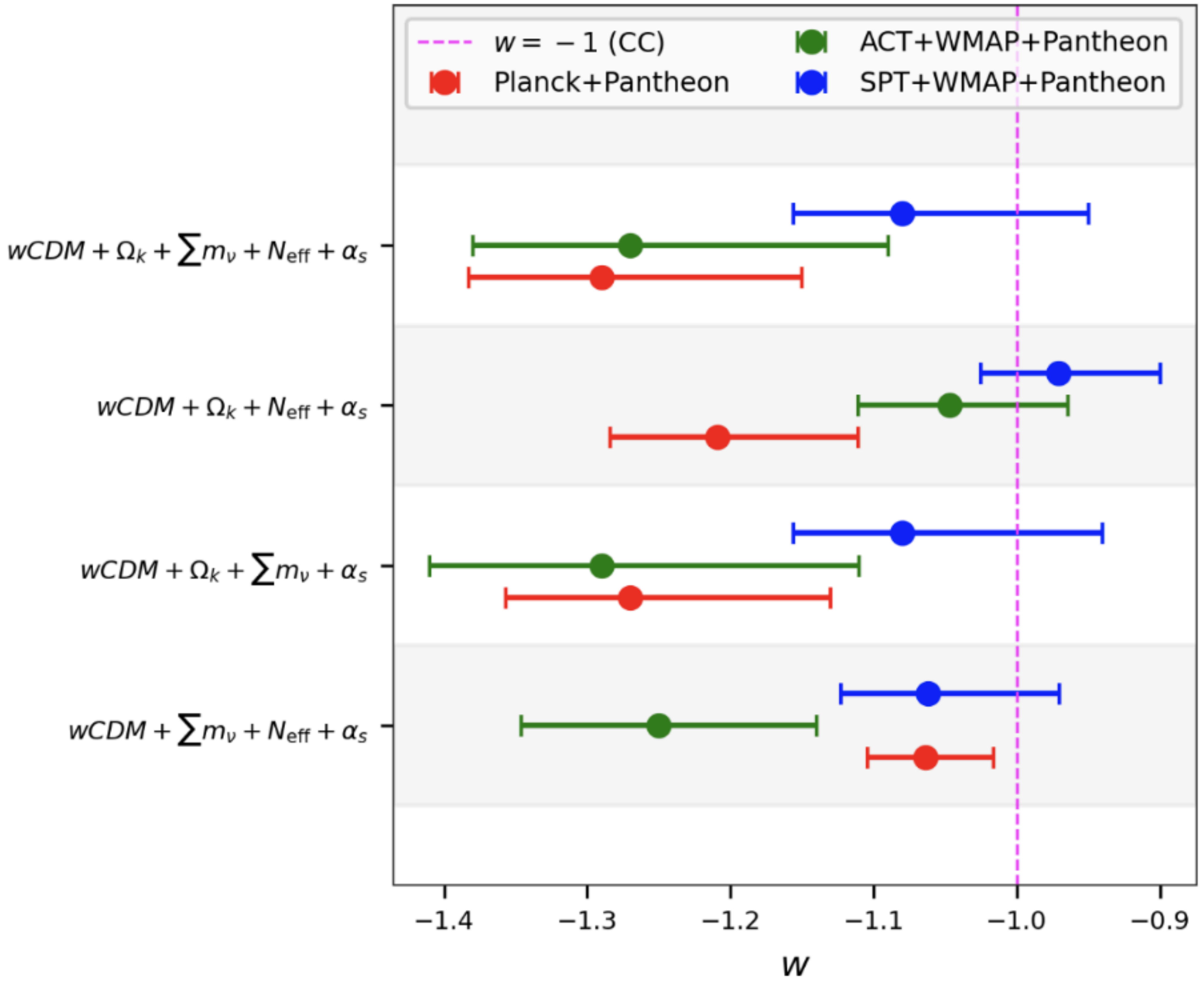
Dark Energy



Dark Energy EOS (w)

- The different CMB data poorly constrain the Dark Energy Equation of state in extended parameter-spaces and, because of the large error-bars, the results are typically consistent with a cosmological constant
- Combining the CMB data with BAO measurements the constraints usually shrink around w=−1
- considering Pantheon in combination with the CMB data, from Planck and ACT we observe a mild preference for phantom Dark Energy (w < −1) at a statistical level ranging between 1.5σ and 2.5σ

More details in:

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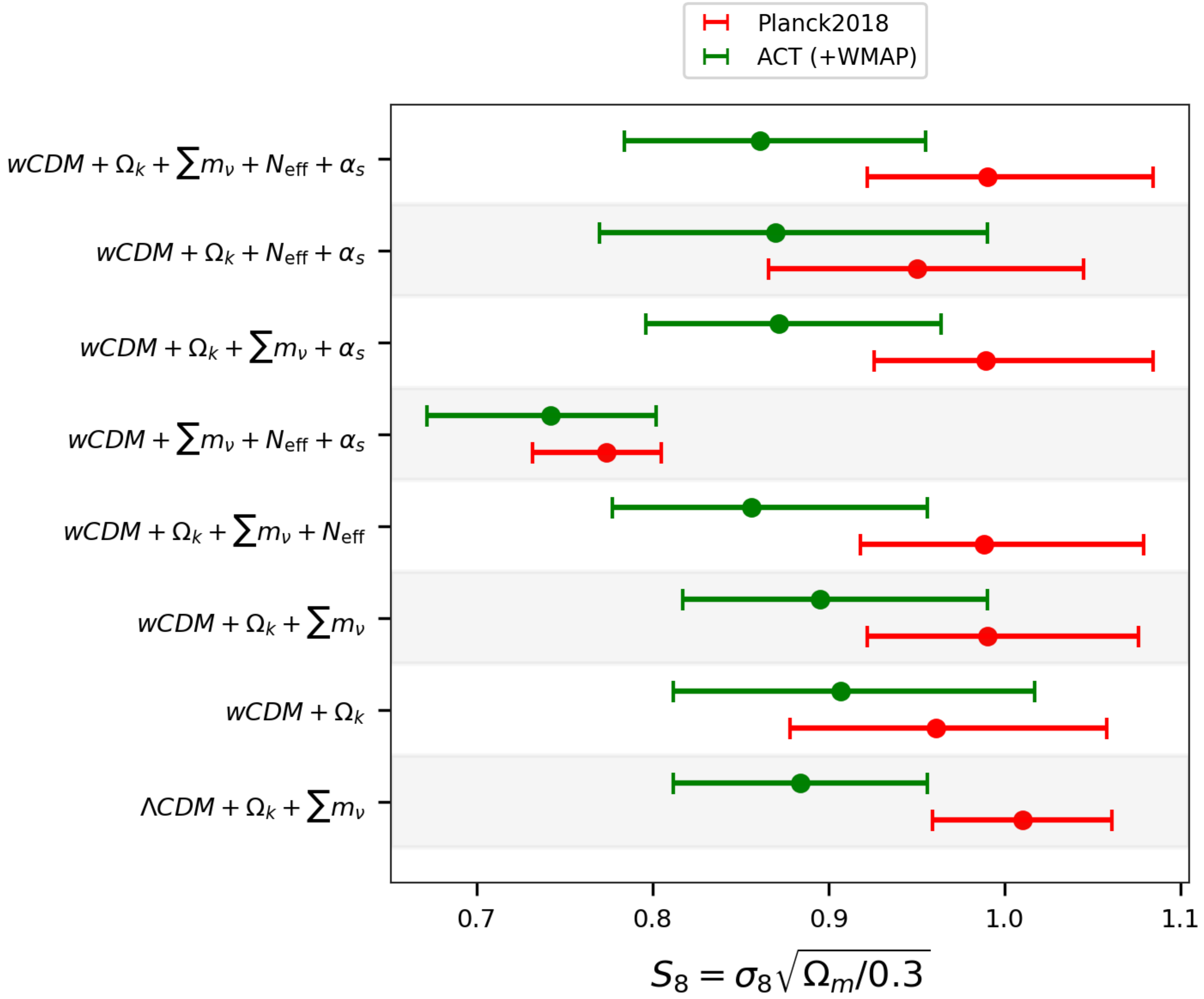
Matter Clustering parameters

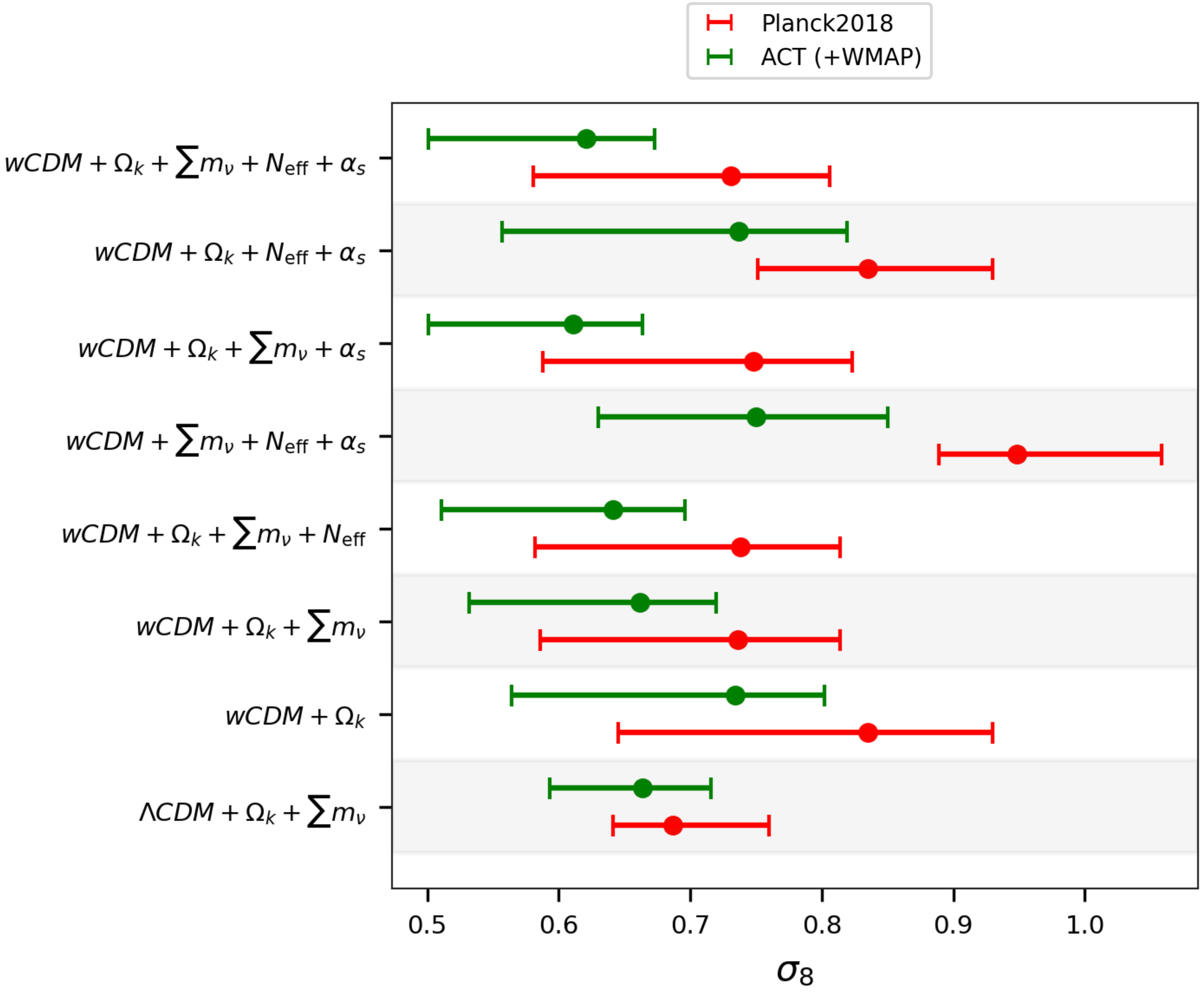


Matter clustering (S_8)

- The Planck data show a systematic preference for $S_8 \gtrsim 0.9$, in disagreement with cosmic shear surveys

- This preference is only partially supported by the Atacama Cosmology Telescope and South Pole Telescope data that, for many models, suggest instead $S_8 \sim 0.7 - 0.8$, in line with cosmic shear measurements.

Matter Clustering parameters



Matter density (Ω_m and σ_8)

However different values of S_8 often recast discordant behaviors for the parameter σ_8 and the matter density Ω_m

- Ω_m is very badly constrained in extended cosmologies and we observe a shift towards higher values from all the CMB data.

- This shift is usually compensated by a preference for smaller σ_8 in ACT and SPT, but not in Planck.

- Including BAO and Pantheon measurements, we instead recover familiar values $\Omega_m \sim 0.3$ and thus smaller S_8