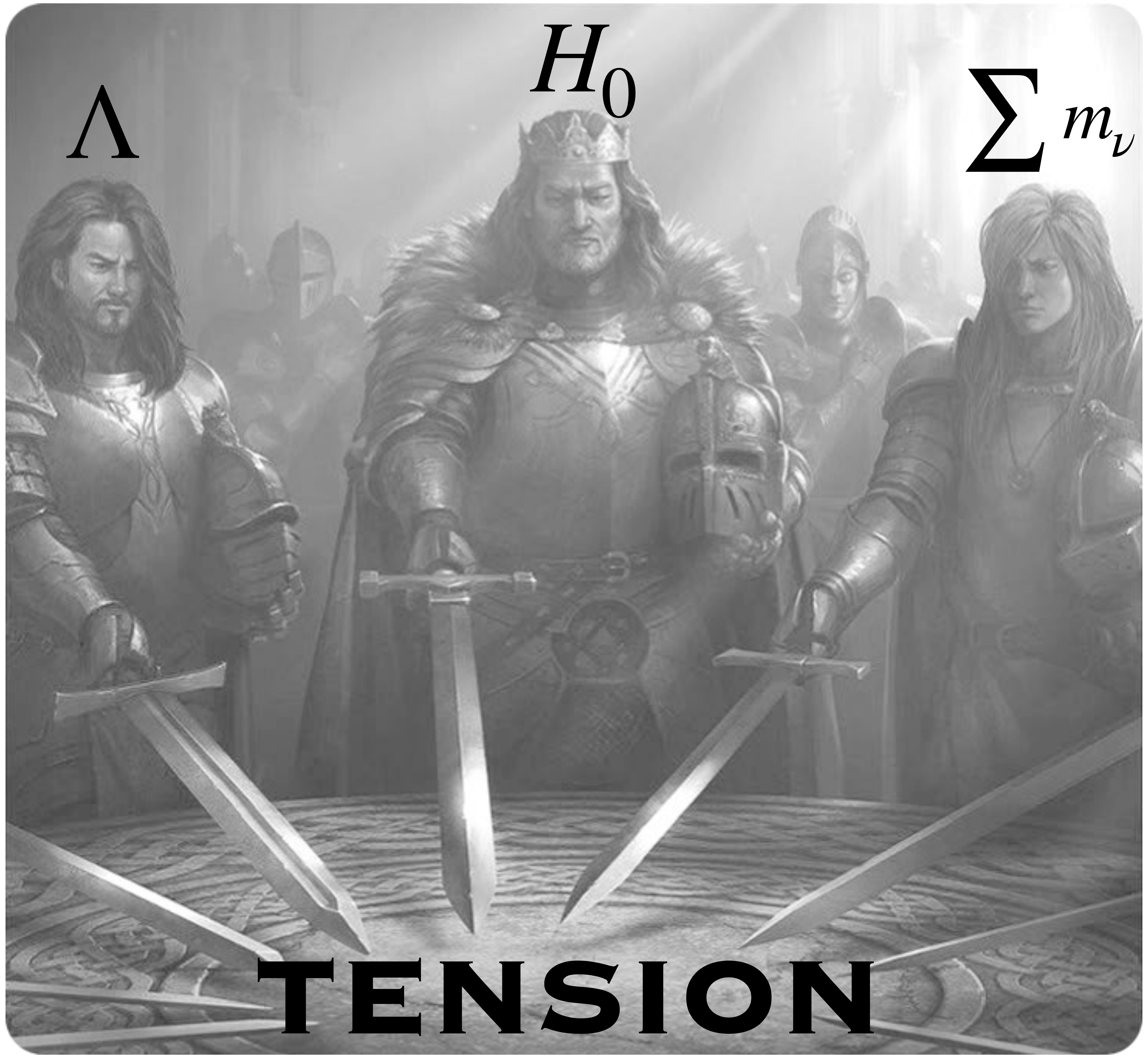
Cosmic Tensions



QUANTUM ANALOGUES WORKSHOP

Luxemburg, 16th September 2025

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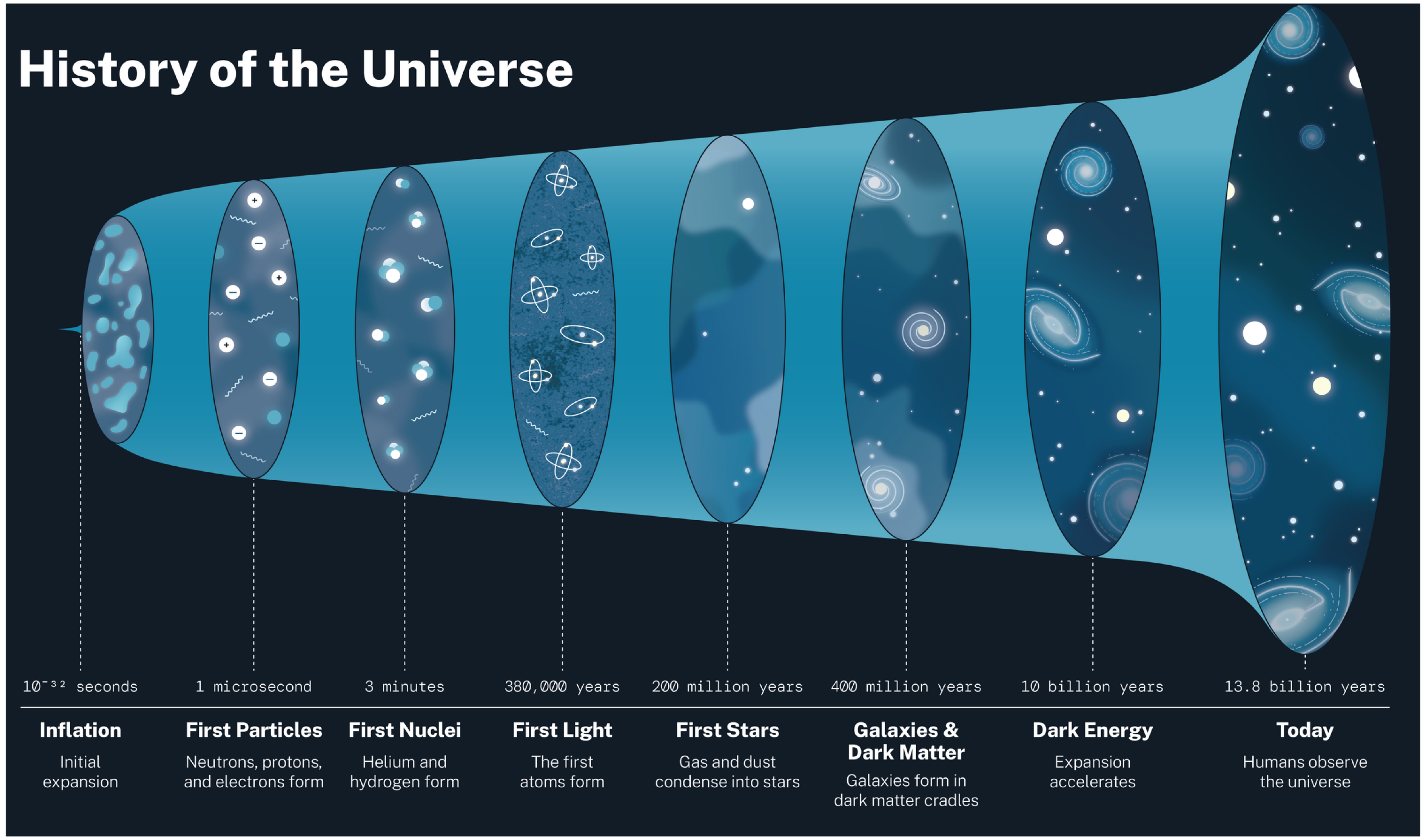
The University of Sheffield

Slides (as well as codes and notes) available at

https://github.com/williamgiare/wgcosmo

1 A Brief Introduction to ΛCDM Cosmology



Topics Covered

- Standard model of cosmology
- Cosmic Microwave Background
- Distance Measurements

ΛCDM Cosmology

General Relativity
To describe gravitational interactions

Standard Model
To describe fundamental interactions

Well understood

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

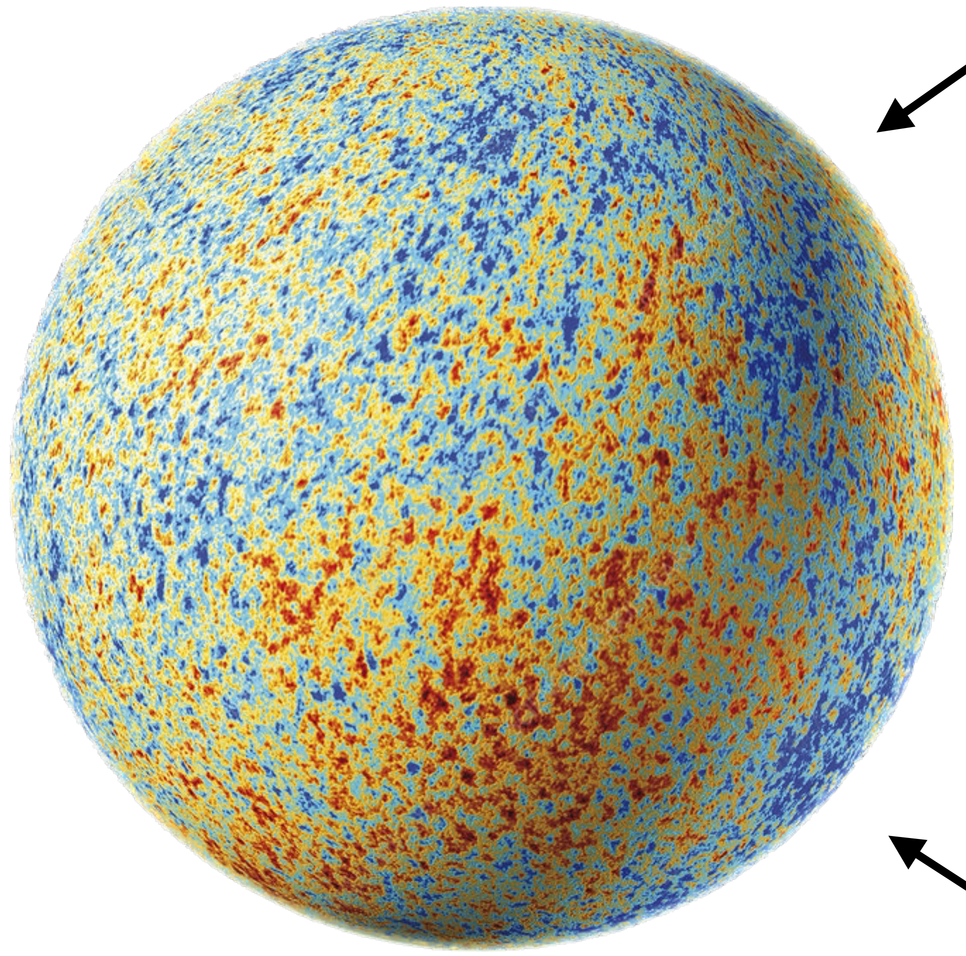
Dark Energy (cosmological constant Λ)
To explain the late-time accelerated expansion of the Universe

Not so well understood

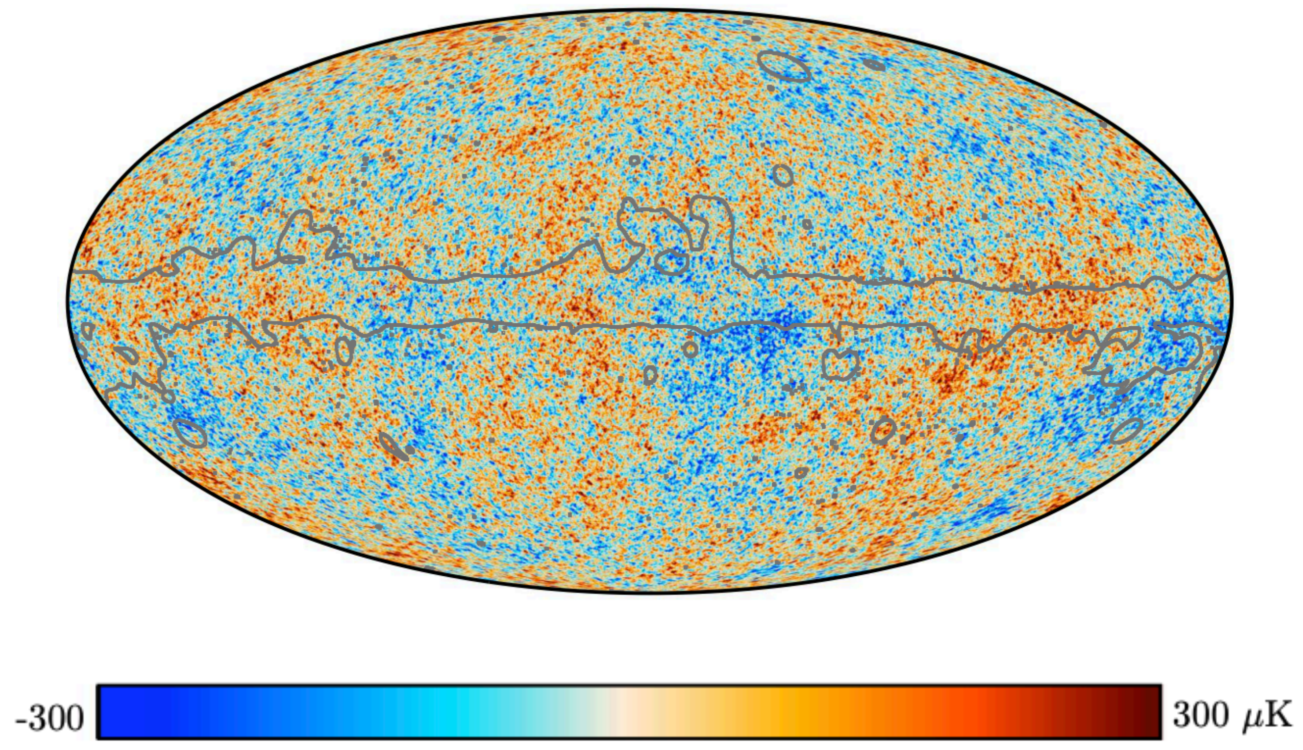
My pictorial representation of ΛCDM cosmology

Cosmic Microwave Background

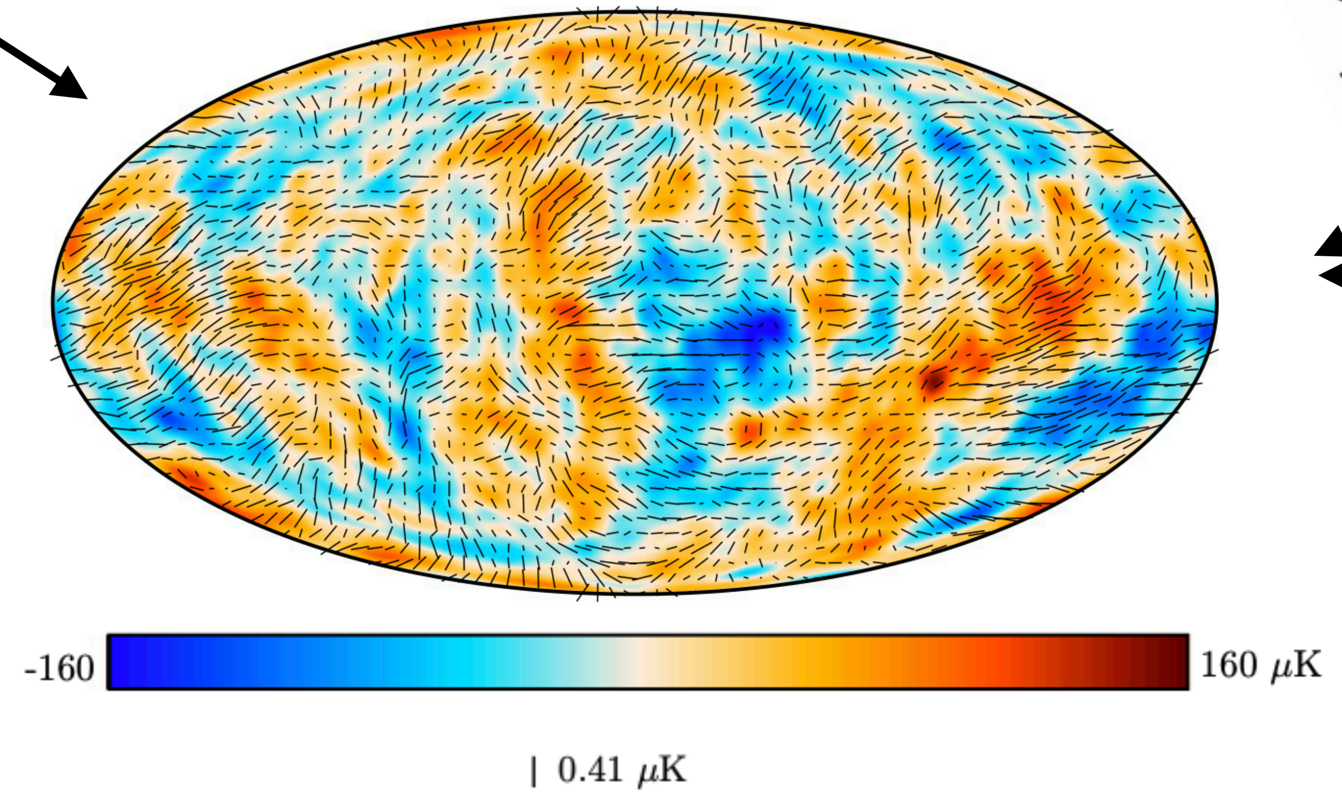
Relic Photons from the Big Bang

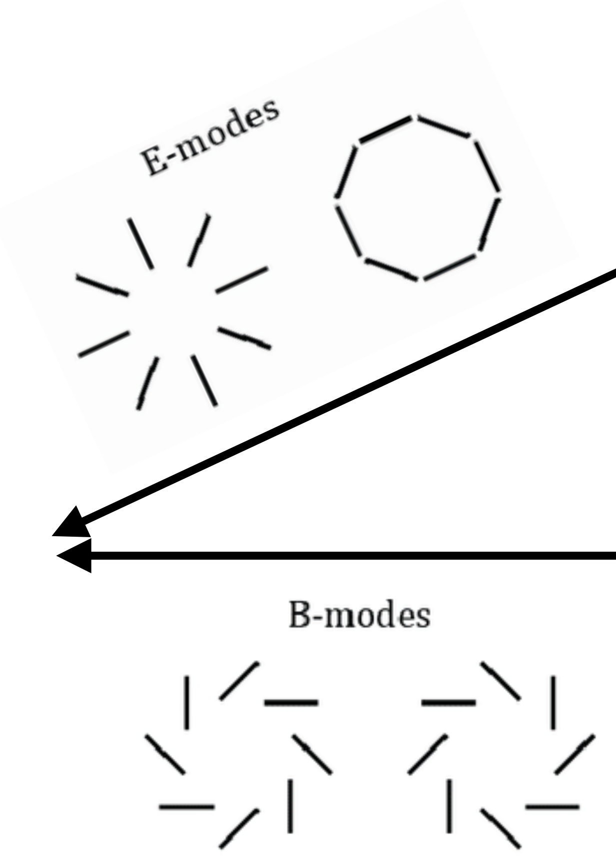


Temperature anisotropies



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**)

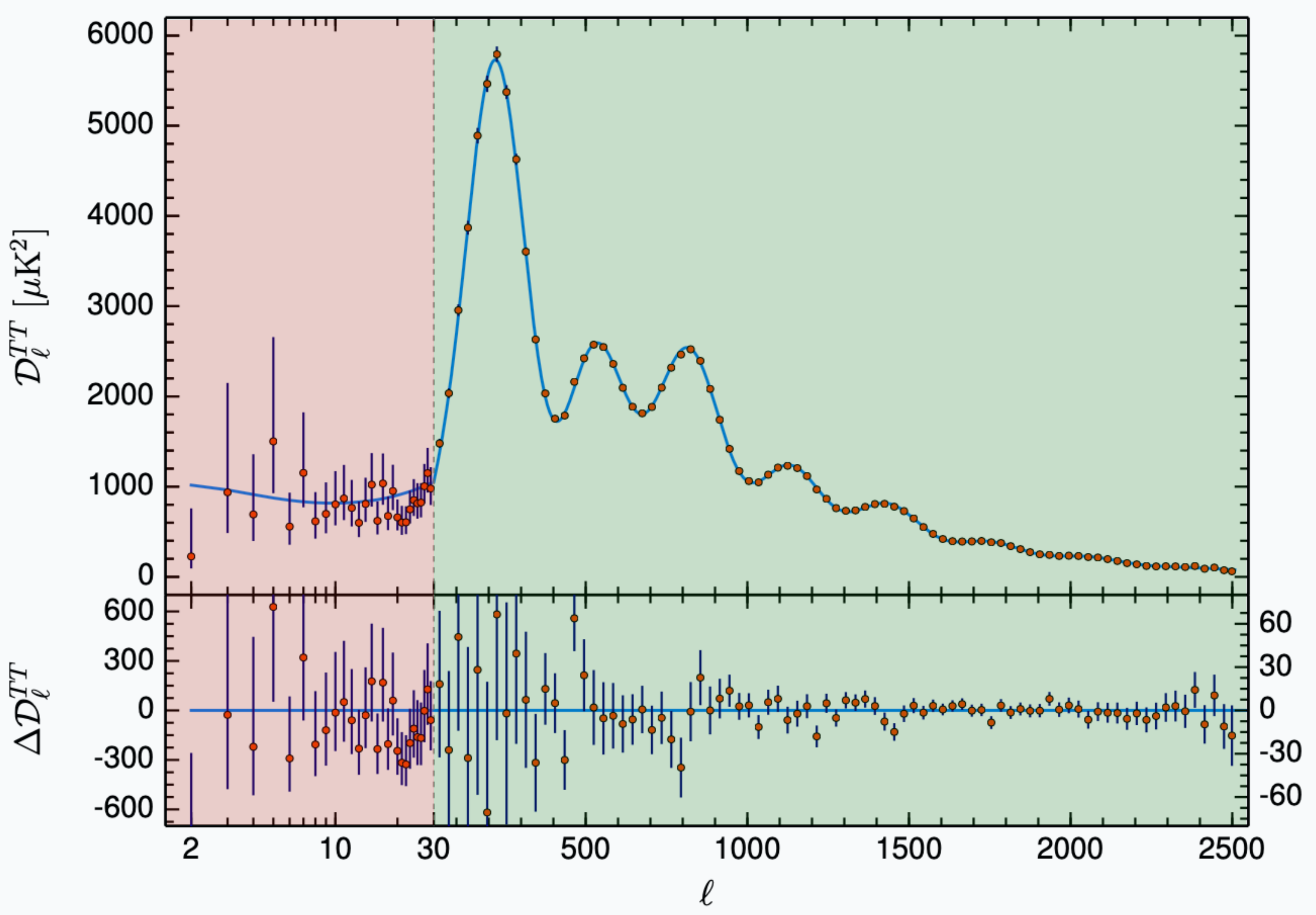
2) Temperature and E-mode cross-spectrum C_ℓ^{TE}
(**TE spectrum**)

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

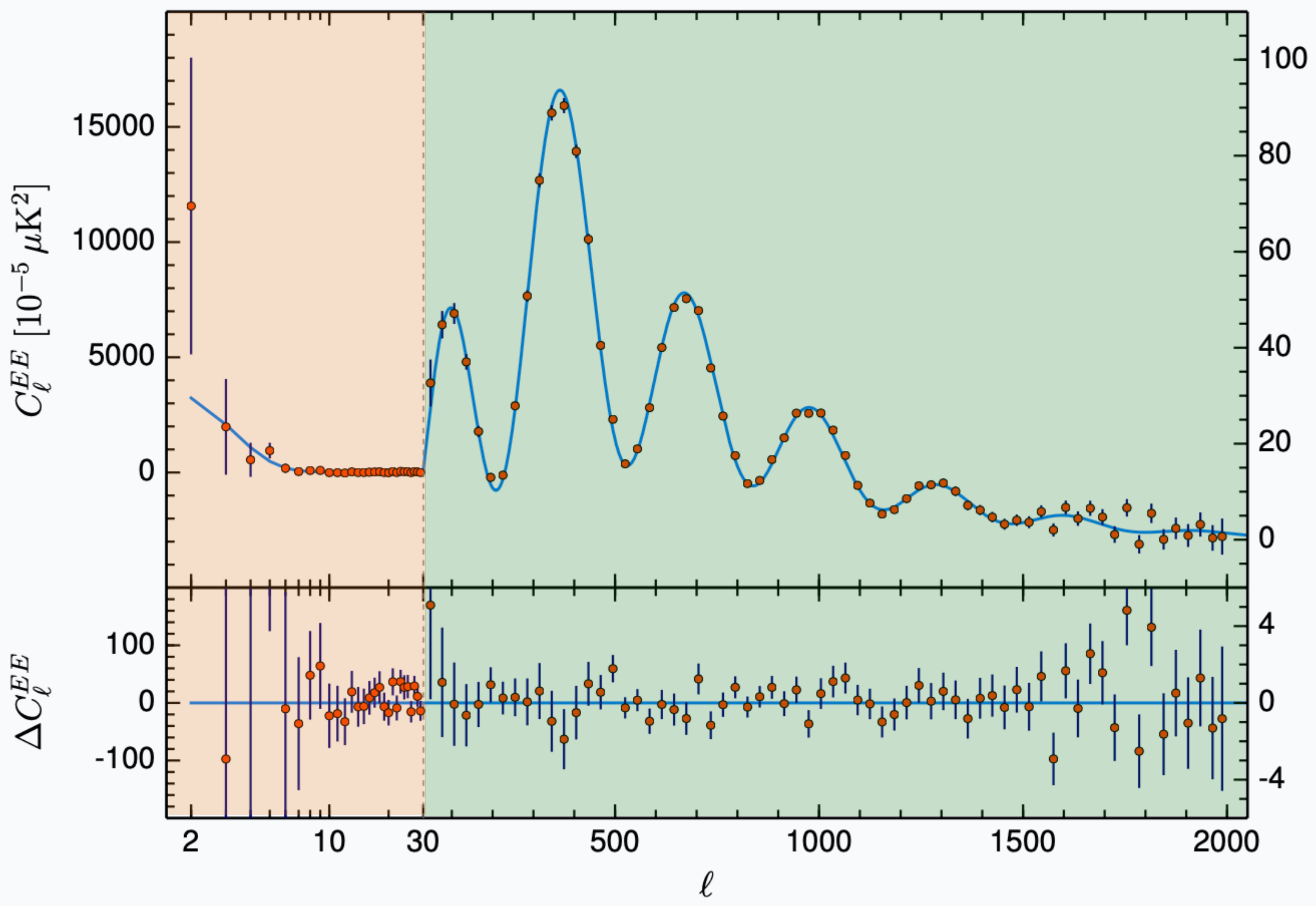
4) Angular power spectrum of B-mode polarization C_ℓ^{BB}
(**BB spectrum**)

Planck Satellite Data

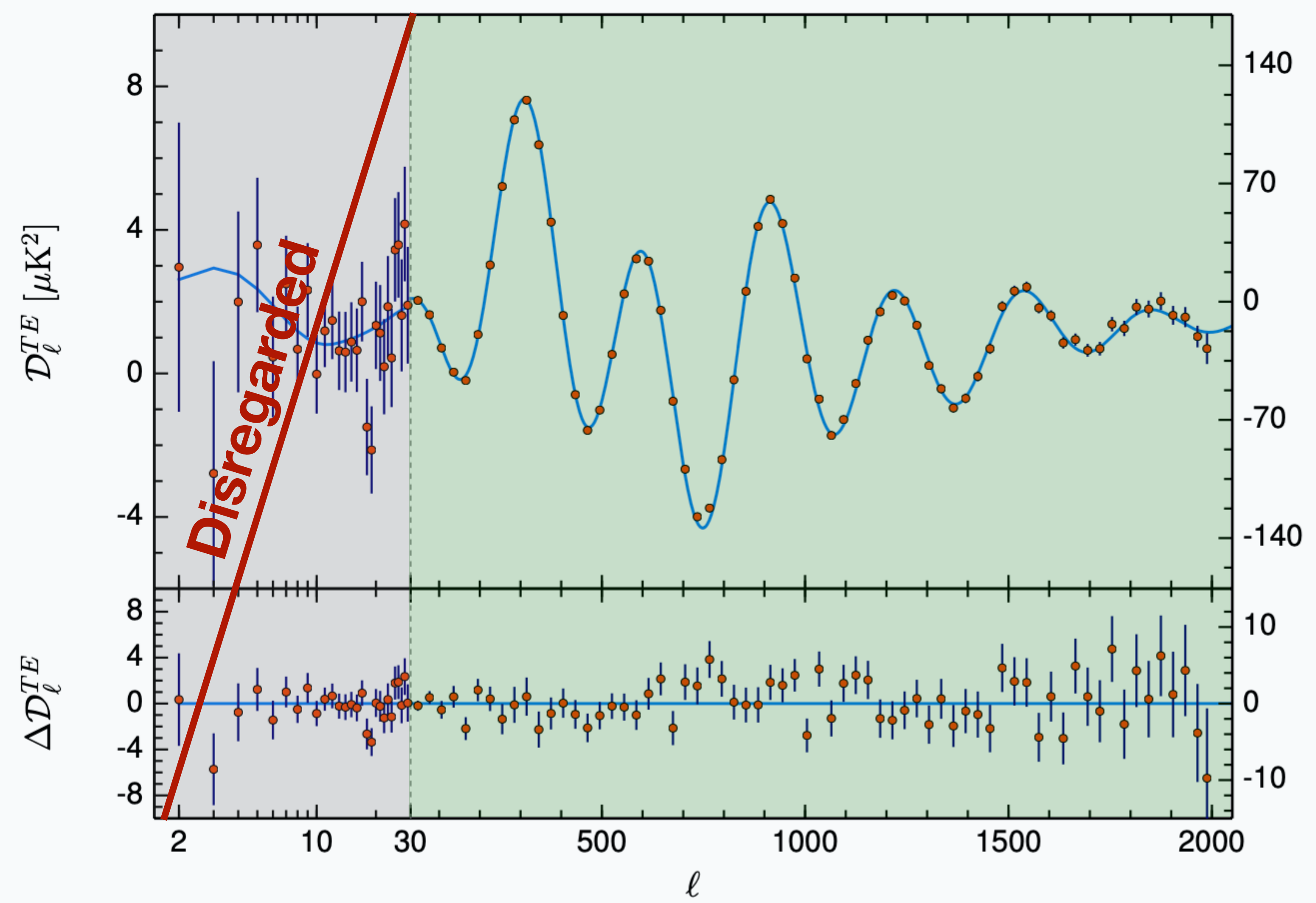
TT Spectrum



EE Spectrum



TE Cross-Spectrum



Low-multipole temperature data

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

Low-T

Low-multipole Polarization data

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

Low-E

Disregarded

Low-multipole ~~TE data~~

~~$2 \leq \ell \leq$~~ 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

Cosmic Distances

Einstein Field Equations

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

$\longleftrightarrow$

We start from the Einstein equation with a positive Cosmological Constant Λ to describe the dynamics of the Universe

Cosmic Distances

Einstein Field Equations

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$\longleftrightarrow$

We start from the Einstein equation with a positive Cosmological Constant Λ to describe the dynamics of the Universe

Fredmann Equation

$$H^2(z) = H_0^2 \left[\Omega_r \cdot (1+z)^4 + \Omega_m \cdot (1+z)^3 + \Omega_\Lambda\right]$$

$\longleftrightarrow$

Once we specify the geometry (flat FRW) and the stress energy density components (matter, radiation, etc), we know the expansion rate of the Universe $H(z) \equiv \dot{a}/a$

Cosmic Distances

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Once we specify the geometry (flat FRW) and the stress energy density components (matter, radiation, etc), we know the expansion rate of the Universe $H(z) \equiv \dot{a}/a$

Cosmic Distances

$$D_L(z) = (1+z)^2 D_A(z) \propto \int_0^z dz' H(z')^{-1}$$

Distance Duality Relation

Model Dependence here!!

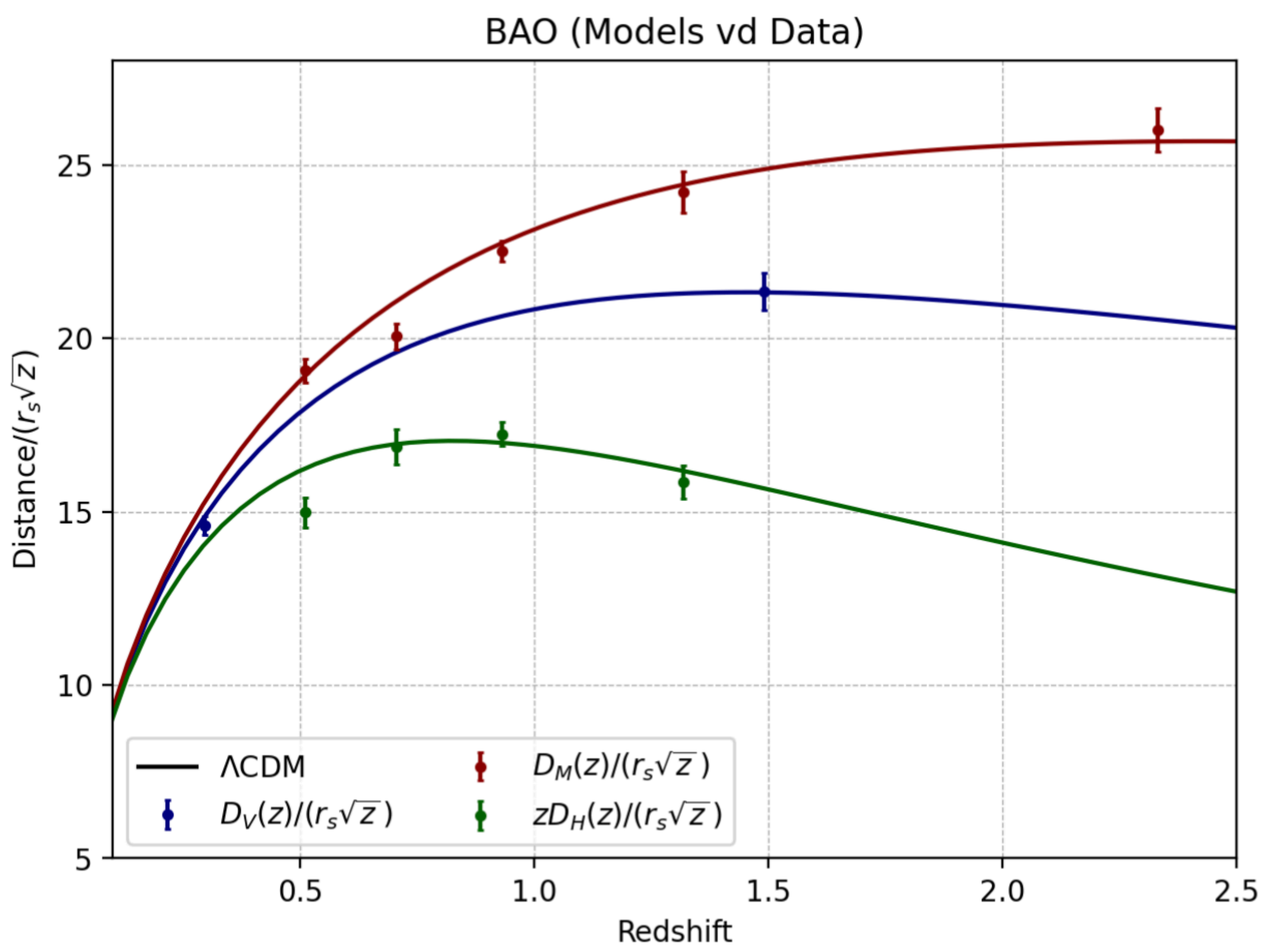
$\longleftrightarrow$

Once we know $H(z)$, we have a map between the redshift z, the Luminosity Distance $D_L(z)$ and the Angular Diameter Distance $D_A(z)$ which is a unique prediction of the cosmological model

Cosmic Distances

Baryon Acoustic Oscillations

- The **comoving angular diameter distance** $D_M(z) = D_A(z)(1+z)$, i.e., the spatial distance between two objects in the direction perpendicular to the line-of-sight;
- The **line-of-sight distance** $D_H(z) = c/H(z)$, i.e., the distance along the line-of-sight between an observer and an object;
- The **volume-averaged distance** $D_V(z) = [zD_H(z)D_M^2(z)]^{1/3}$, i.e., the quantity to which isotropic BAO measurements are sensitive.
- **Require calibration:** all the distances relative to the sound horizon at the Drag epoch



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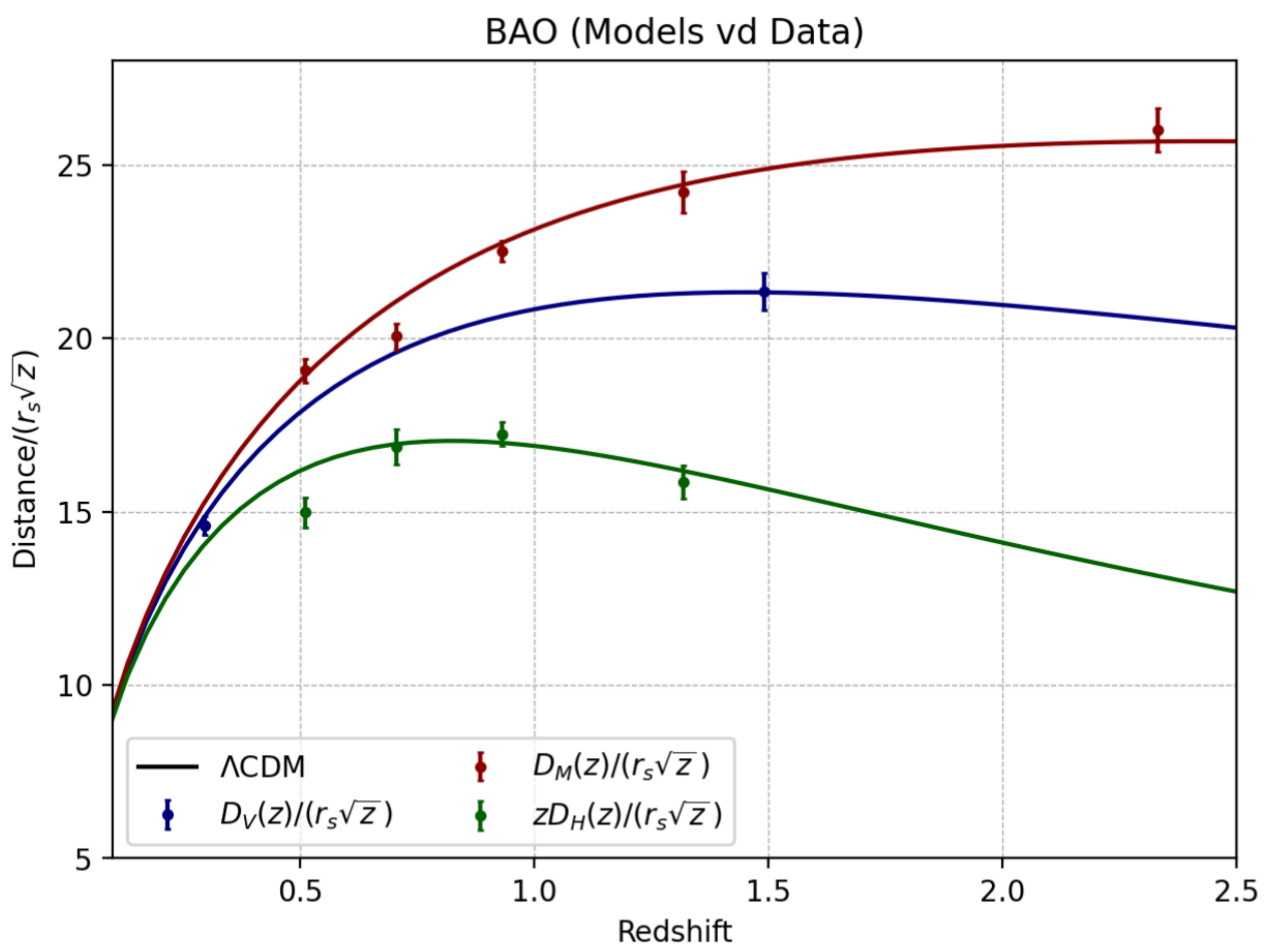
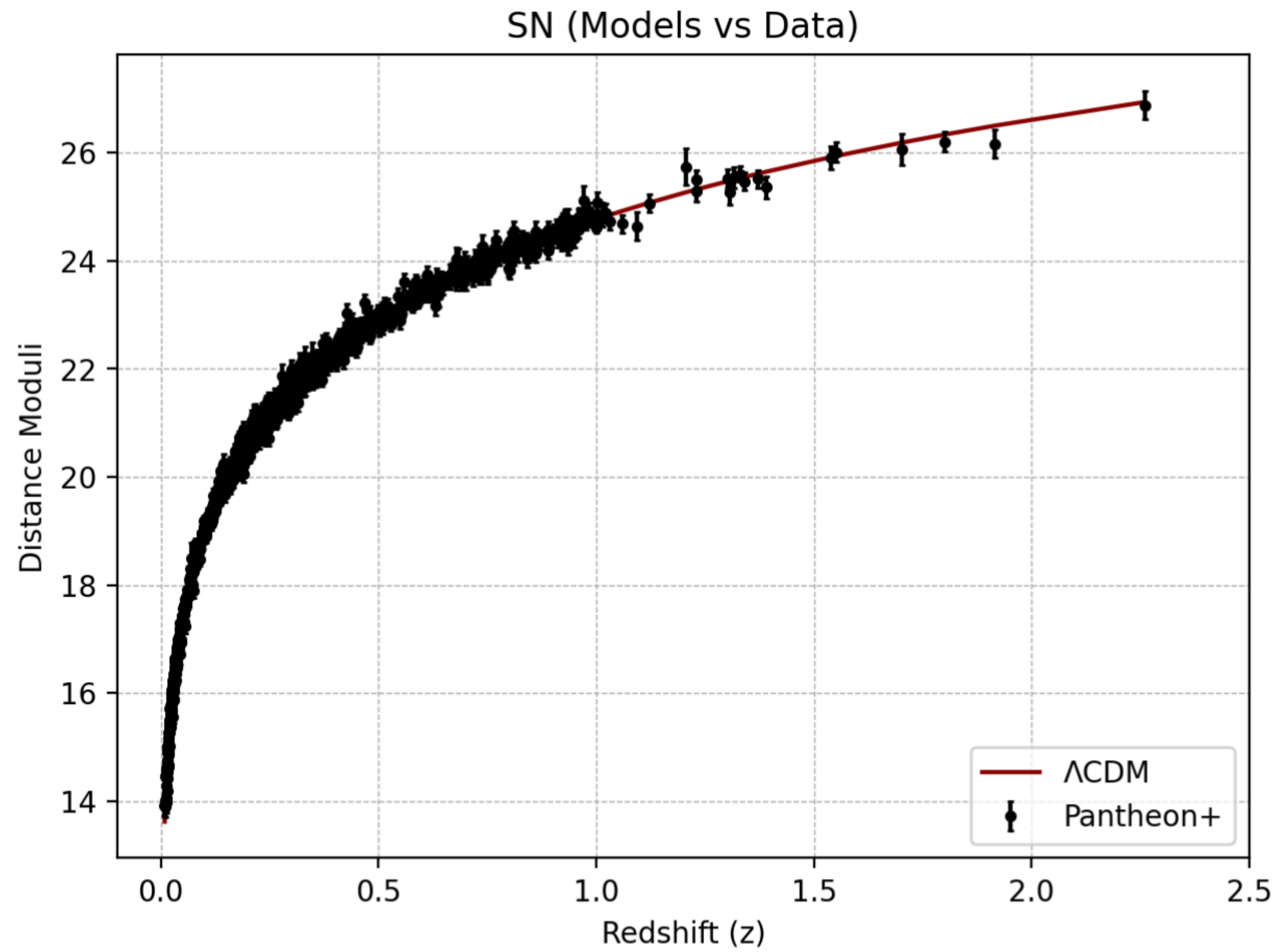
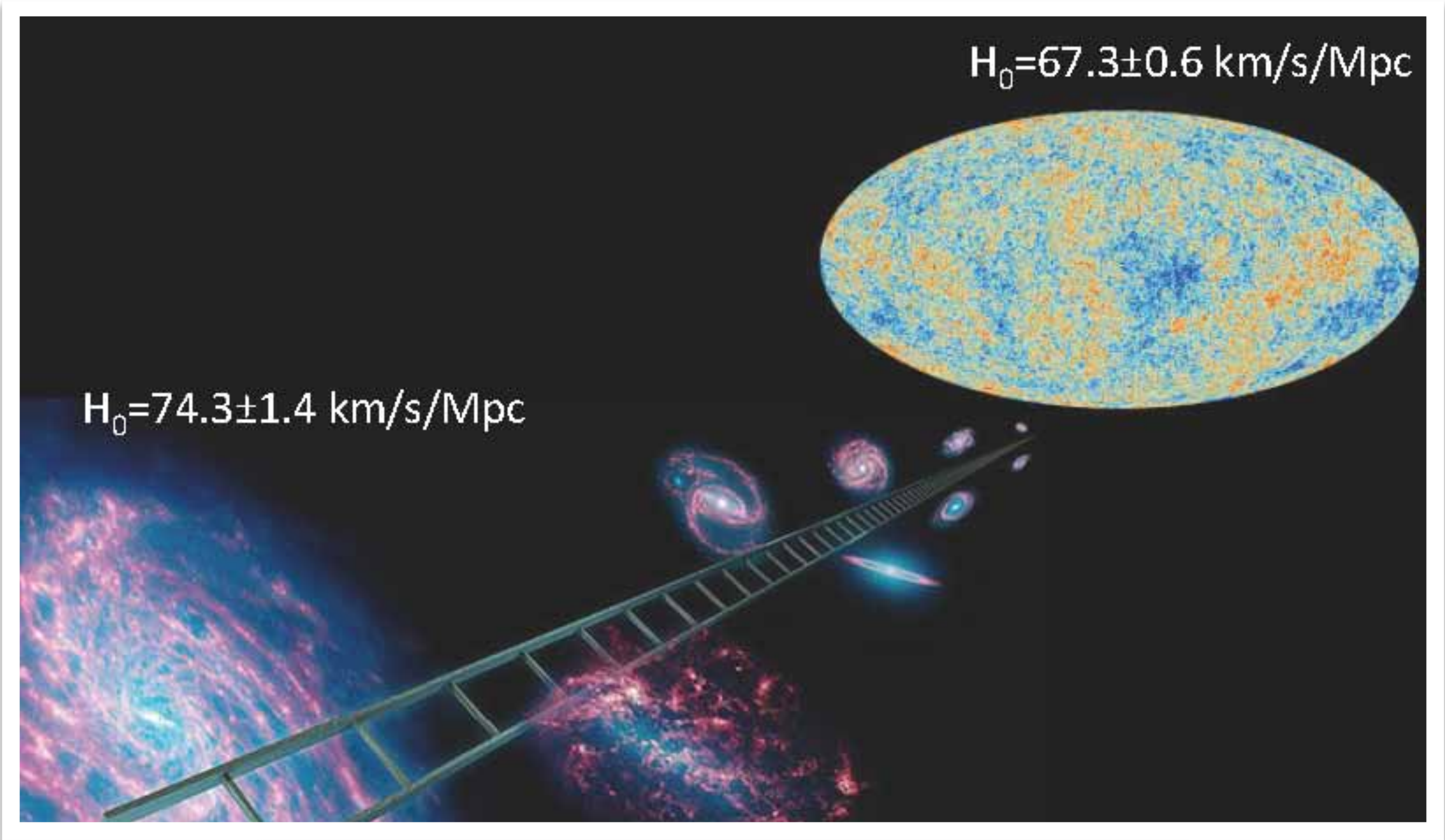


Type Ia Supernovae

- **Distance Moduli**: $\mu(z)^{\rm th} = 5\log_{10}\left(\frac{D_L(z)}{10\,\mathrm{pc}}\right) - 5$
- **Require calibration:** $\mu(z)^{\rm obs} = m(z) - M$ where $m(z)$ is the observed magnitude of SN at that given z while M is the absolute magnitude defined as the apparent magnitude at 10 parsec



2 A Brief Introduction to Cosmic Tensions



Overview of Topics Covered

- Hubble Tension
- S8 Tension
- Neutrino Mass Bounds Tension

Hubble Tension

Riess et al., arXiv:2112.04510

5σ tension in the value of the Hubble parameter H_0

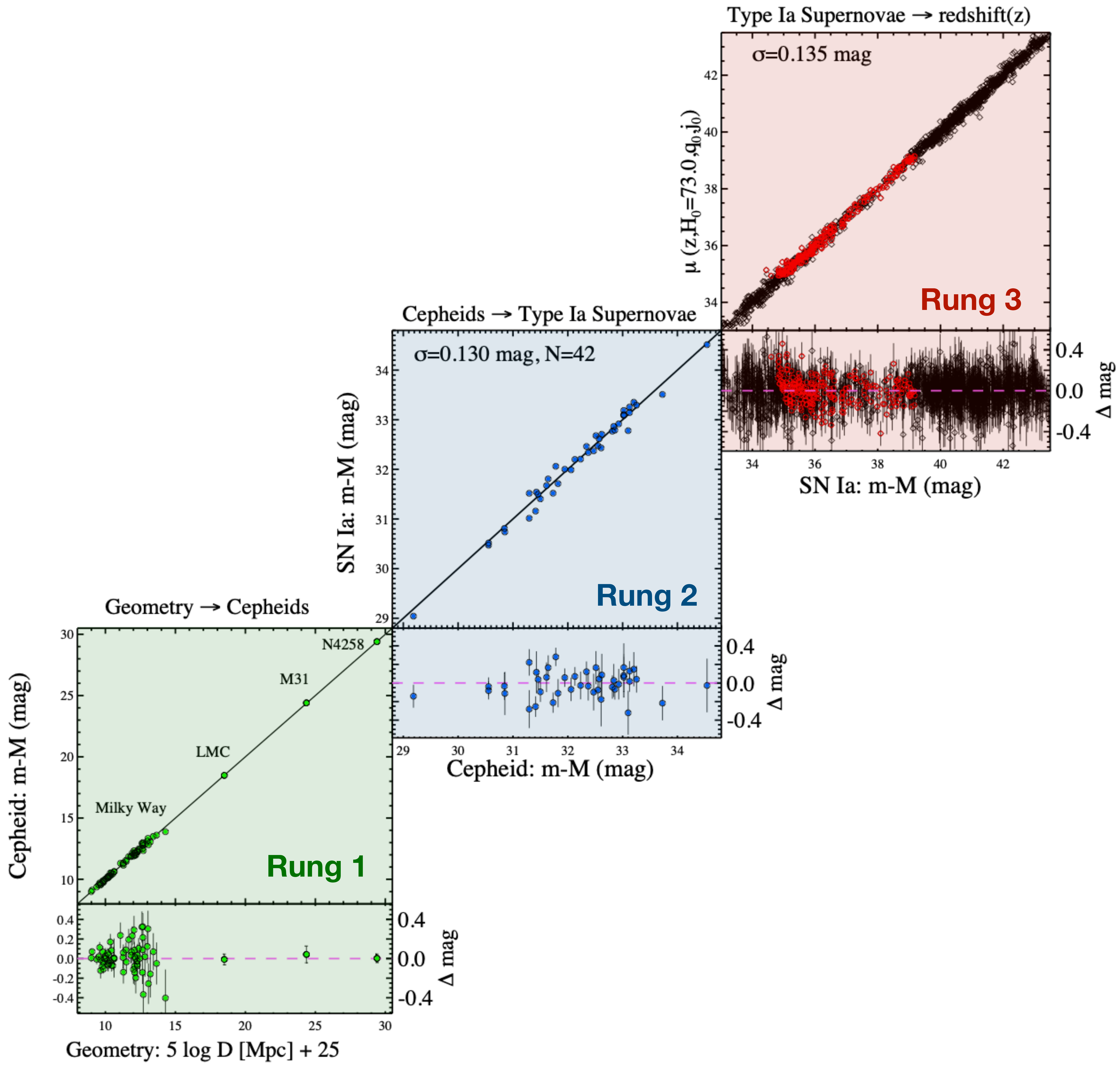
Direct Measurement

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

Model-independent, based on Type-Ia Supernovae

Distance Ladder Methodology in a Nutshell:

- **Rung 1:**
  Calibrate Cepheid luminosities using geometric anchors
  (i.e., parallax, eclipsing binaries, masers)
- **Rung 2:**
  Calibrate Type Ia supernovae in host galaxies with Cepheid distances
- **Rung 3:**
  Use calibrated supernovae Ia in the Hubble flow to measure H_0



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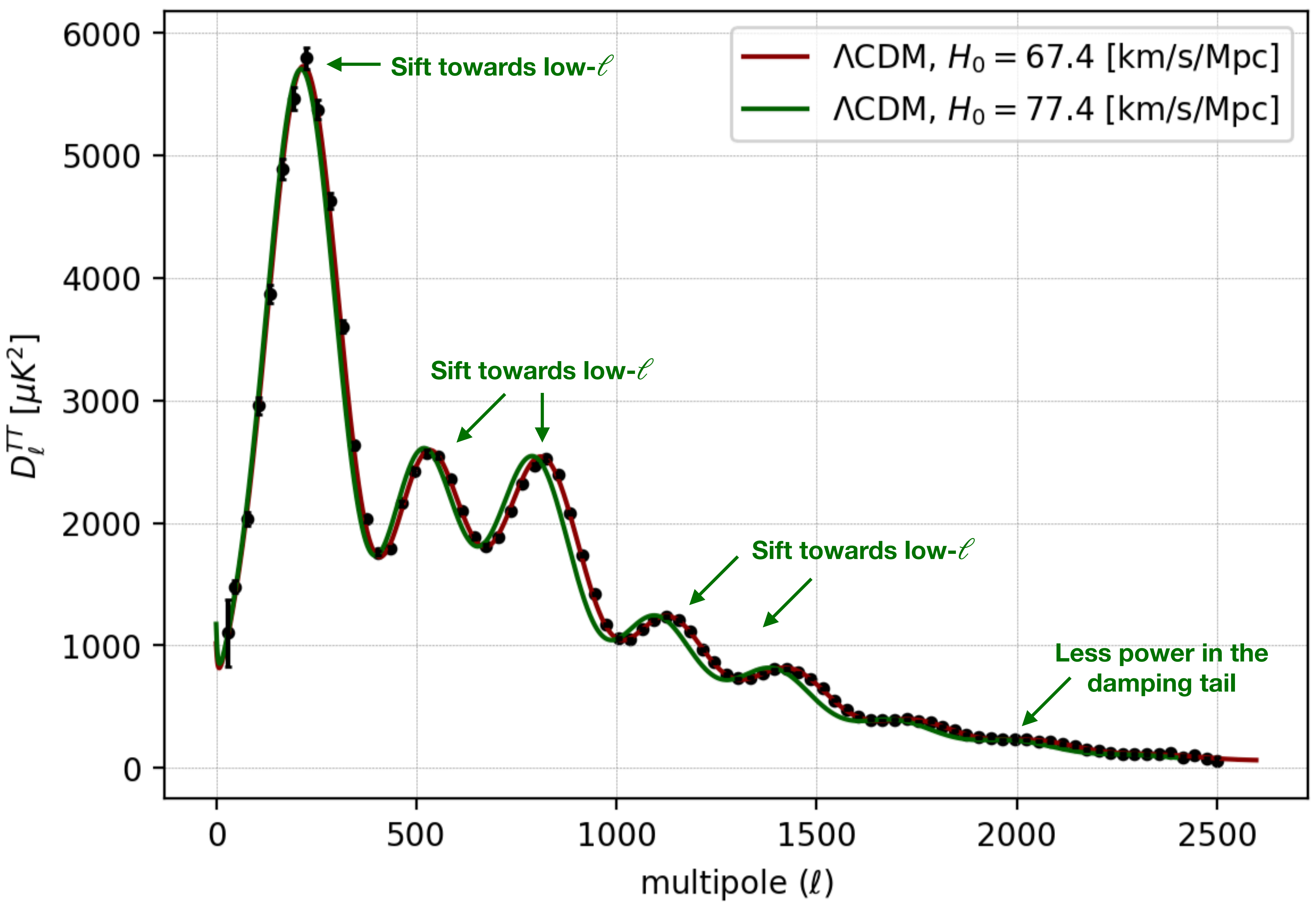
Indirect Measurement

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

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



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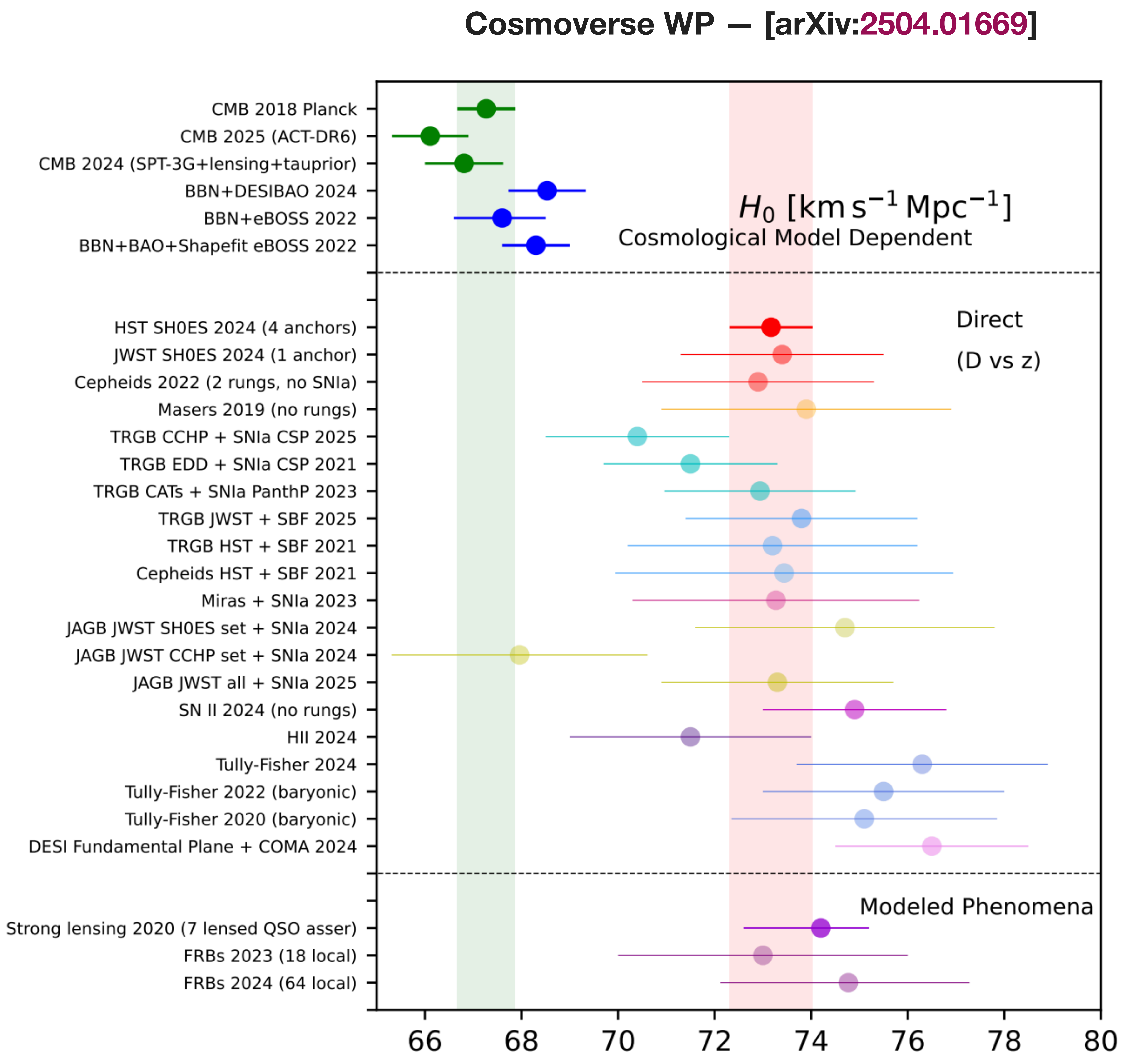
Model-dependent, inferred from CMB measurement (in ΛCDM)

Tension confirmed by many other independent probes



S_8 Tension

S_8 measures the **amplitude of density fluctuations on scales of of 8h^{-1} Mpc**

$$S_8 = \sigma_8 \cdot \sqrt{\Omega_m/0.3}$$

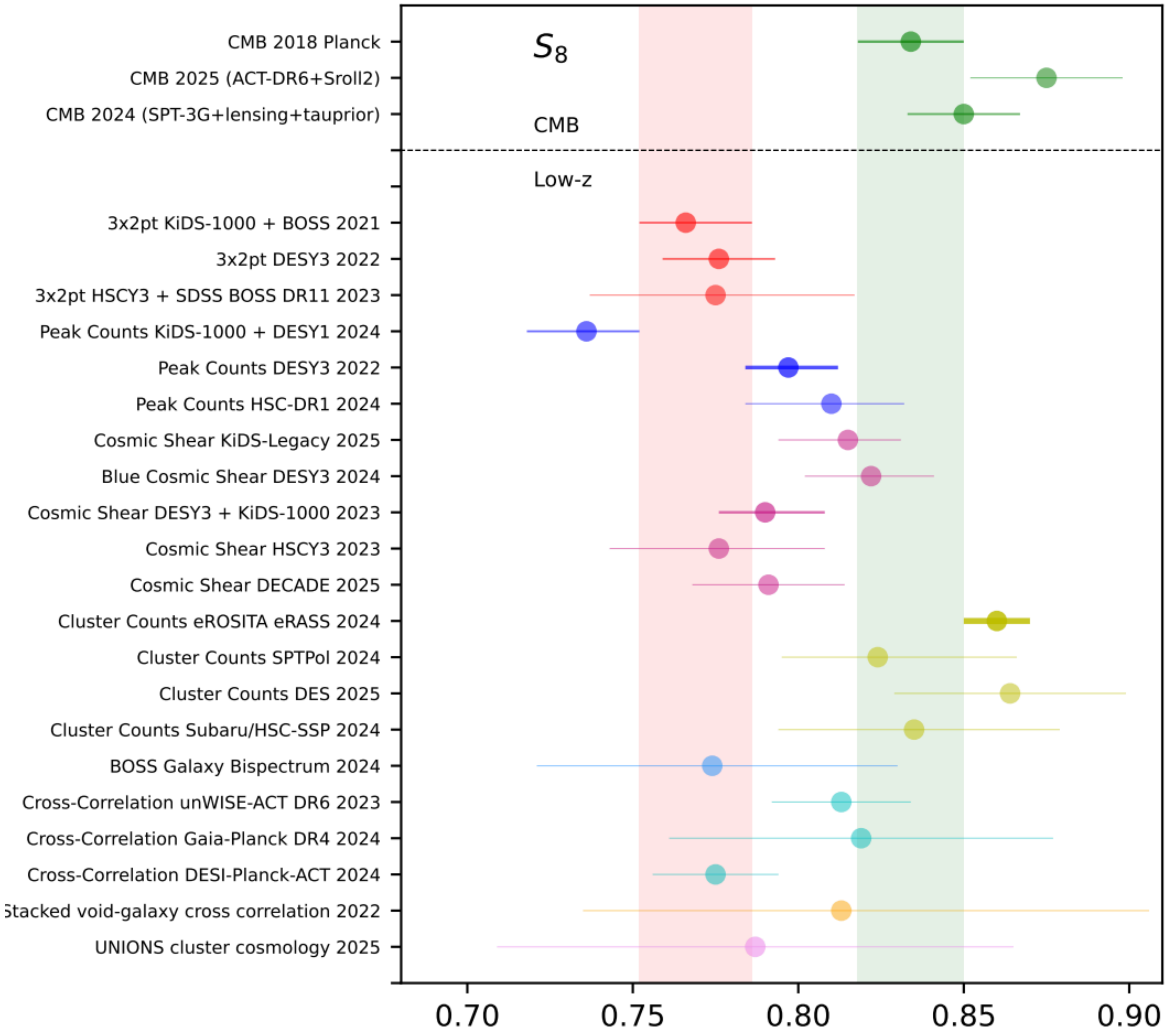
$$\sigma_R = \langle\, | \delta_R^2 | \,\rangle = \frac{1}{2\pi^2} \int dk\, k^2\, P_m(k,z)\, W^2(k,R)$$

Matter Power Spectrum

Window Function Smoothed on R h^{-1} Mpc (R=8 for σ_8)

CMB and Week Lensing estimates seem to disagree (at $2\sigma - 3.5\sigma$ level)

Cosmoverse WP — [arXiv:2504.01669]



S_8 Tension

Angus H. Wright, et al., (kids Legacy) — [arXiv:2503.19441]

S₈ measures the **amplitude of density fluctuations on scales of of 8h^{-1} Mpc**

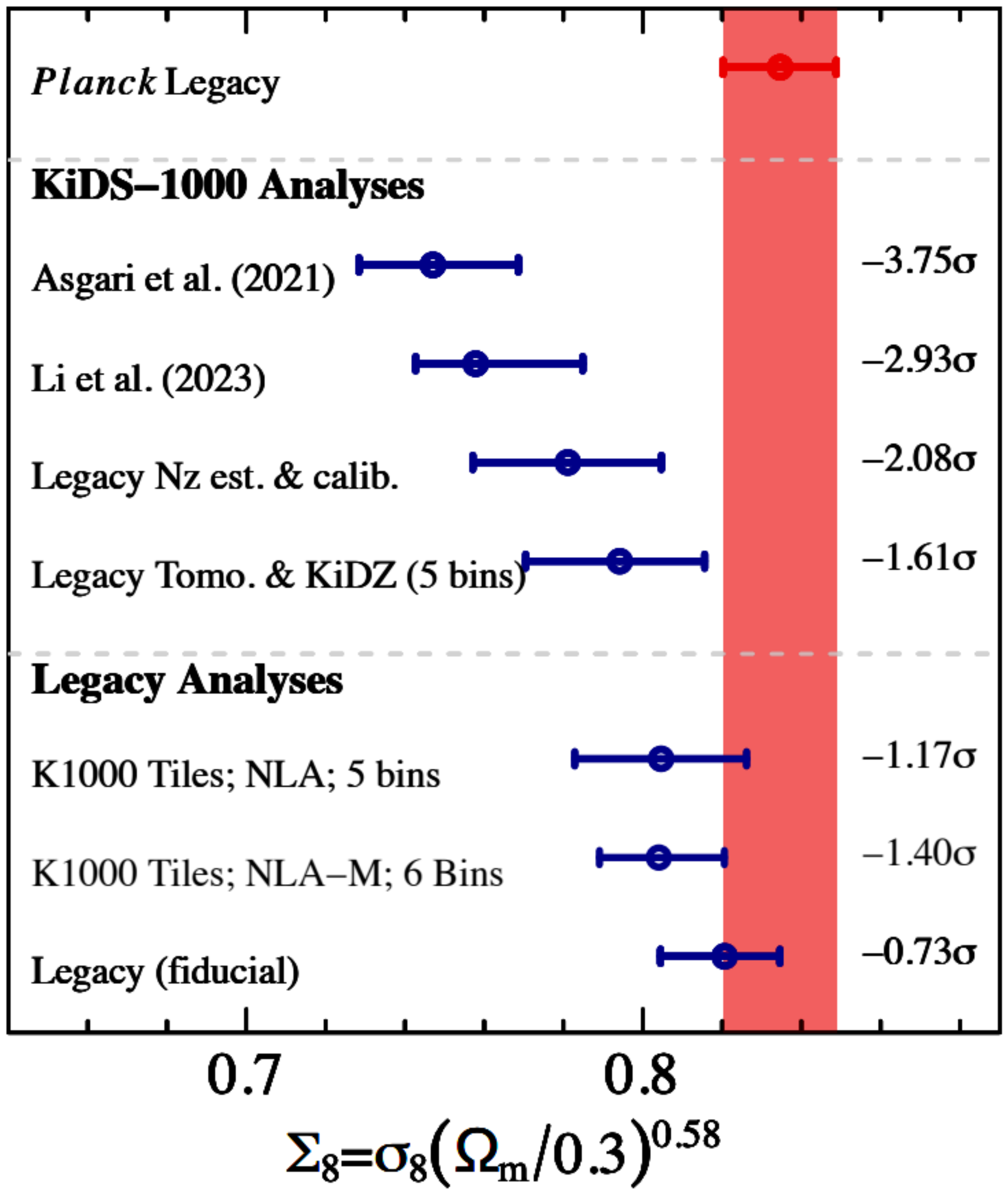
$$S_8 = \sigma_8 \cdot \sqrt{\Omega_m/0.3}$$

$$\sigma_R = \langle | \delta_R^2 | \rangle = \frac{1}{2\pi^2} \int dk\, k^2\, P_m(k,z)\, W^2(k,R)$$

Matter
Power Spectrum

Window Function
Smoothed on R h^{-1} Mpc
(R=8 for σ₈)

⚠️ **Kids Legacy Week Lensing re-analyses in line with CMB**



Neutrino Tension

Total Neutrino Mass and Ordering

Neutrino oscillations measured by terrestrial experiments indicate that at least two neutrinos are massive:

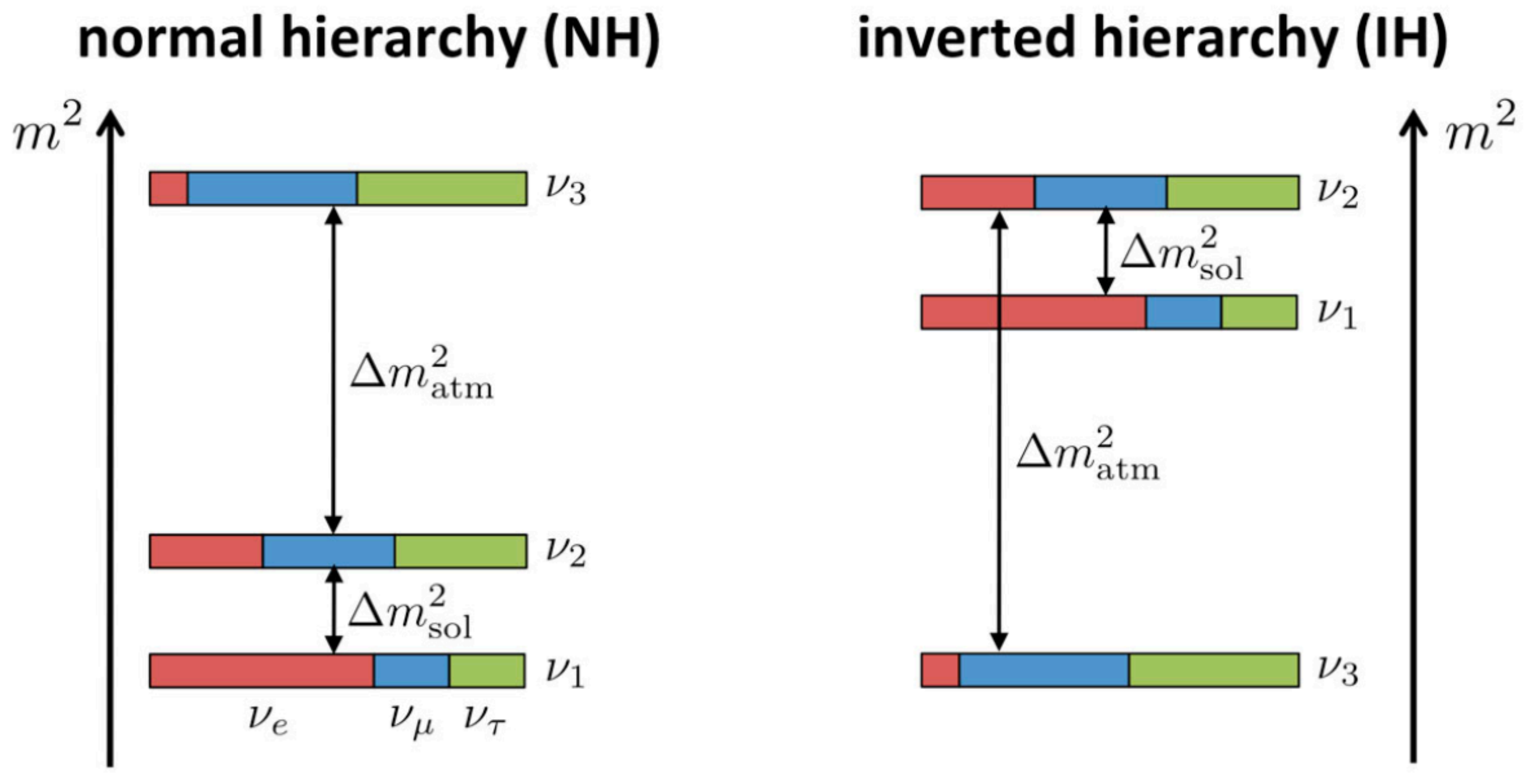
- **Atmospheric splitting**: $|\Delta m^2_{3,1}| = |m_3^2 - m_1^2| \sim 2.55 \times 10^{-3}\,\mathrm{eV}^2$
- **Solar splitting**: $\Delta m^2_{2,1} = m_2^2 - m_1^2 \sim 7.5 \times 10^{-5}\,\mathrm{eV}^2$

Since the sign of $|\Delta m^2_{3,1}|$ is unknown, two mass orderings are possible:

1) **Normal Ordering** ($m_1 < m_2 < m_3$)

2) **Inverted Ordering** ($m_3 < m_1 < m_2$)

Credit: Figure taken from S. Vagnozzi — *Weight them all!*



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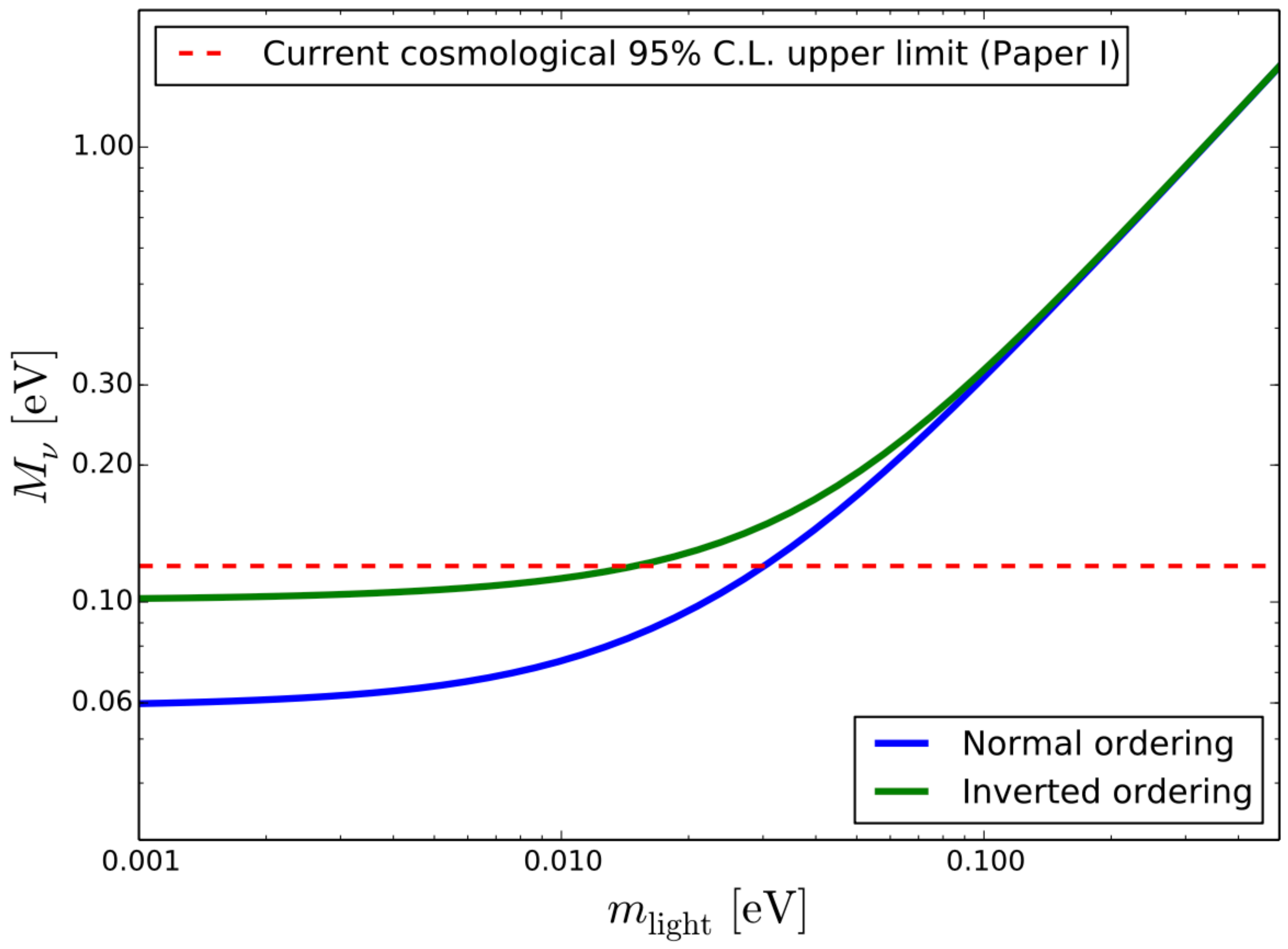
If we set the mass of the lightest neutrino to $m_{\mathrm{light}} = 0$, within the two orderings, we get a lower limit on the total mass from neutrino oscillations

1) **Normal Ordering:** $\sum m_\nu > 0.06\,\mathrm{eV}$

2) **Inverted Ordering:** $\sum m_\nu > 0.1\,\mathrm{eV}$

Credit: Figure taken from S. Vagnozzi — *Weight them all!*



Neutrino Tension

Early Universe Constraints

The total neutrino mass $\sum m_\nu$ impacts the CMB in various ways:

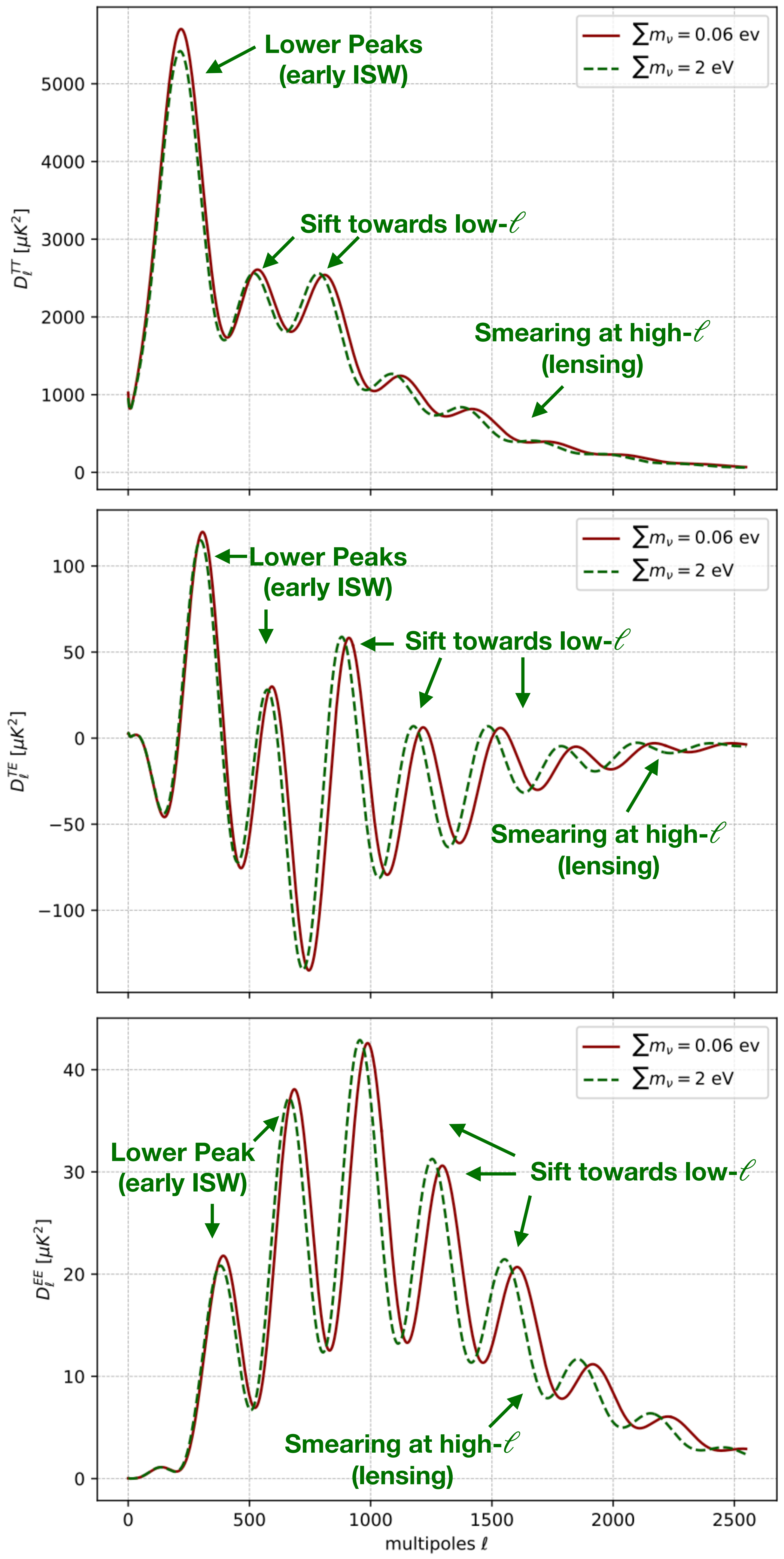
1) it **boosts the late-time non-relativistic density**, affecting the scale-angle relations on the last scattering surface and the **late ISW effects**.

2) affects the non-relativistic transition of neutrinos by changing the pressure-to-density ratio and causing metric fluctuations observable in the **early ISW effect**.

3) it **reduces weak lensing effects** on the CMB by **suppressing the matter power spectrum and CMB spectra at small scales**.

$$\sum m_\nu < 0.24\,\mathrm{eV}$$ Planck - (TT TE EE) + lensing

Planck 2018 results. VI [arXiv:1807.06209]

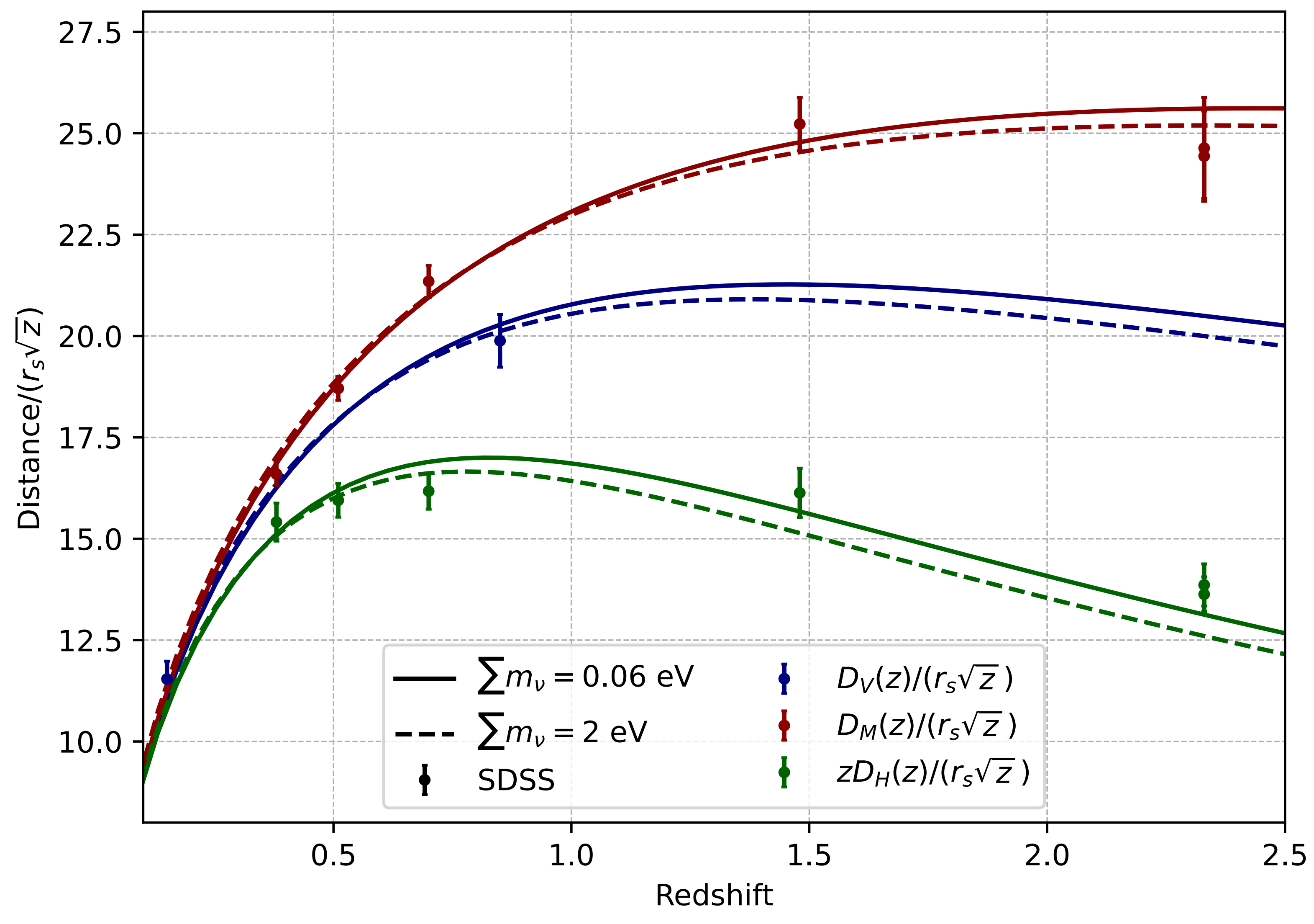


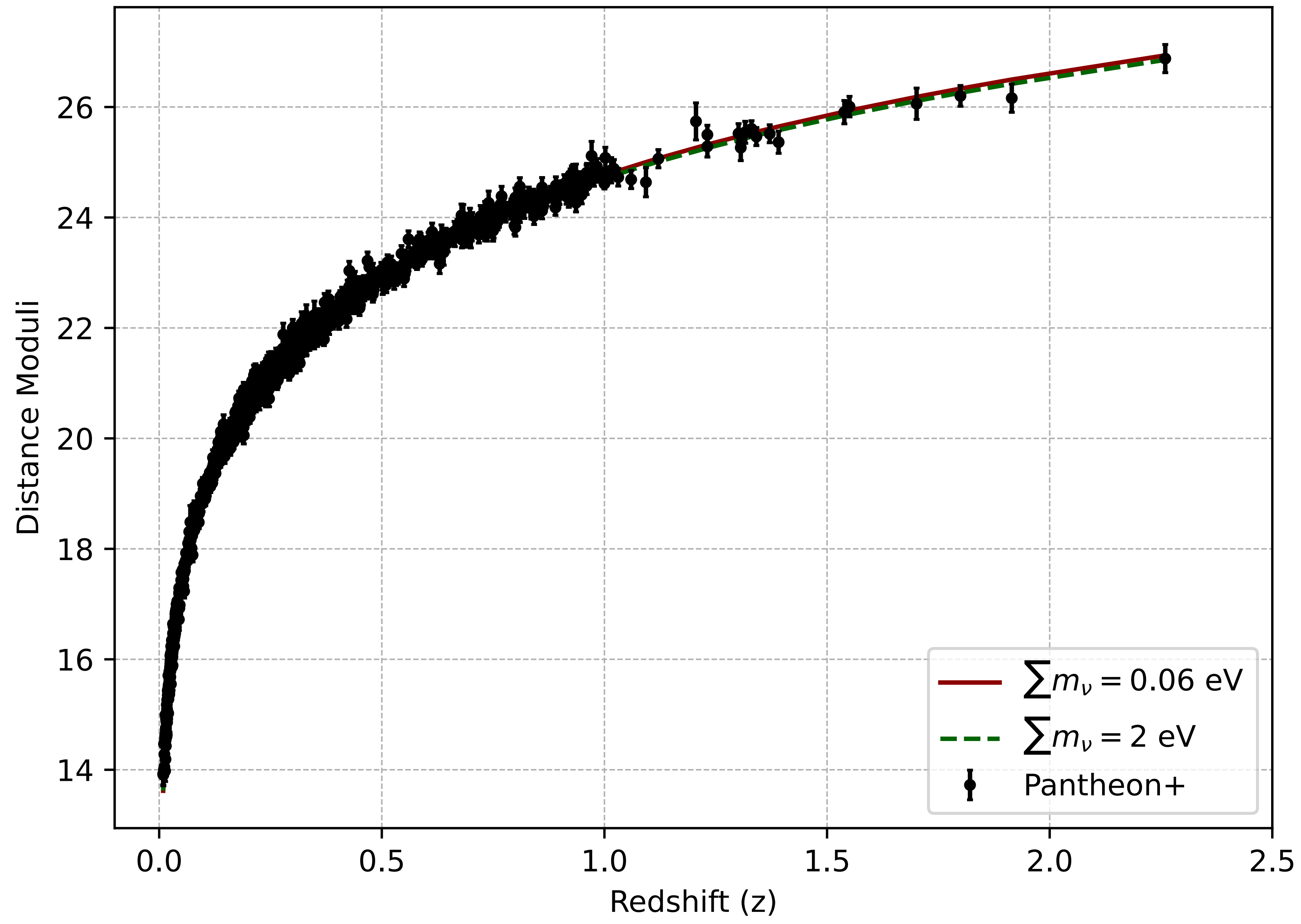
Neutrino Tension

Late Universe Constraints

How can we improve the CMB limit on Neutrinos?

1) Neutrinos will become non-relativistic particles, contributing to the matter energy density at late times. Depending on their mass, they will alter **cosmic distances**, measured by BAO and, in part, Supernovae.





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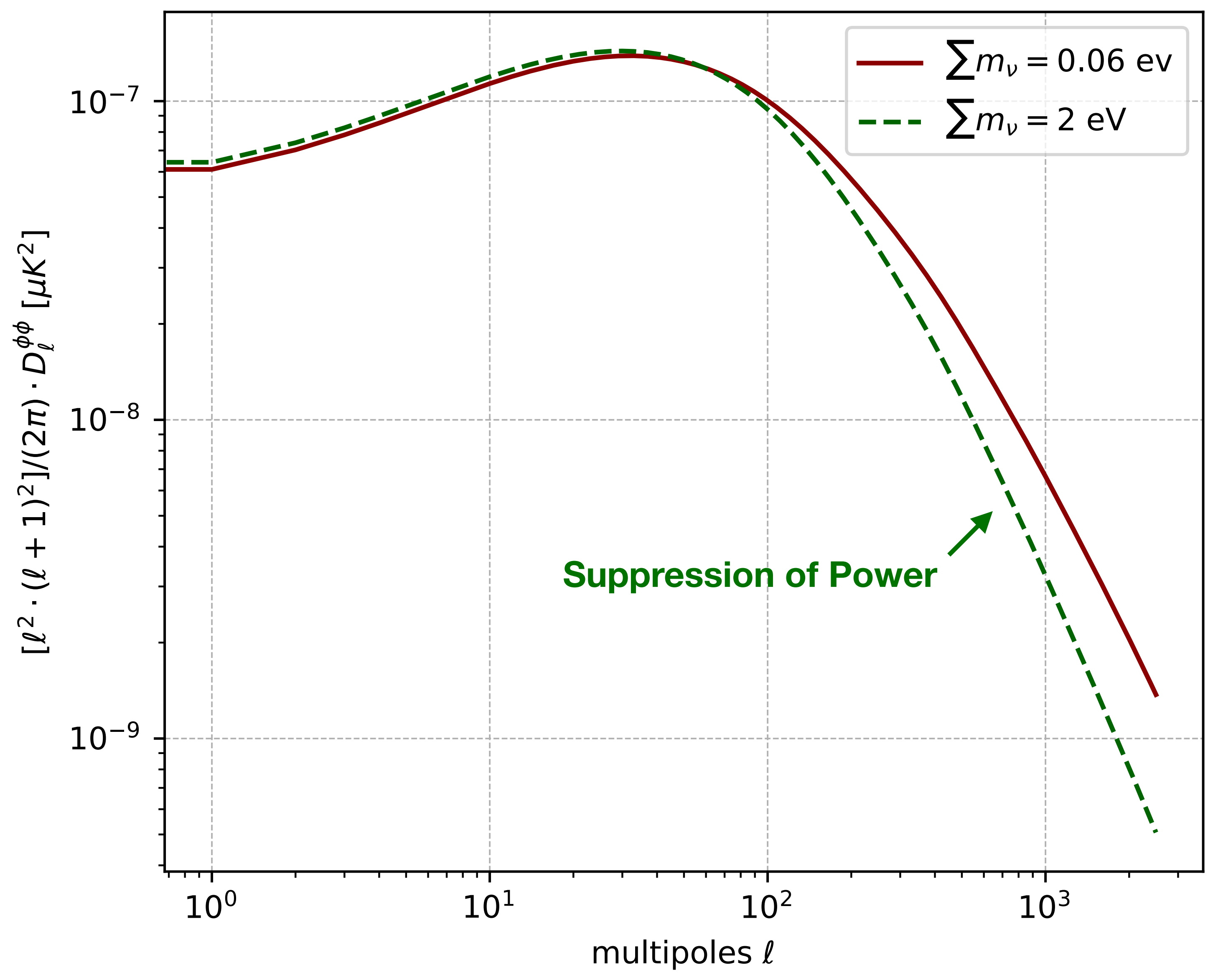
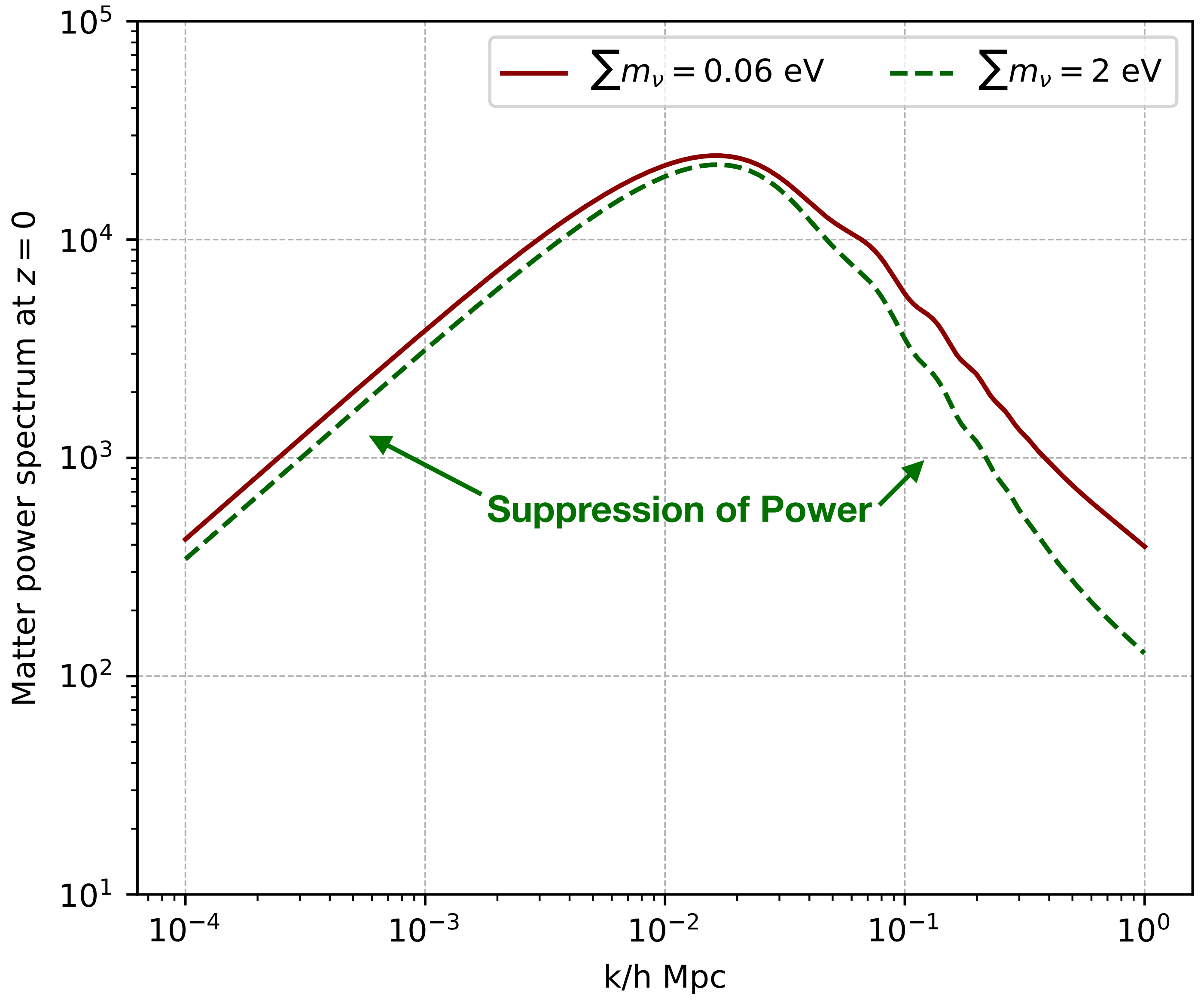
2) Neutrinos will suppress structure formation, affecting other local observables such as the matter power spectrum and weak lensing. We can examine the **large-scale structure** of the Universe.





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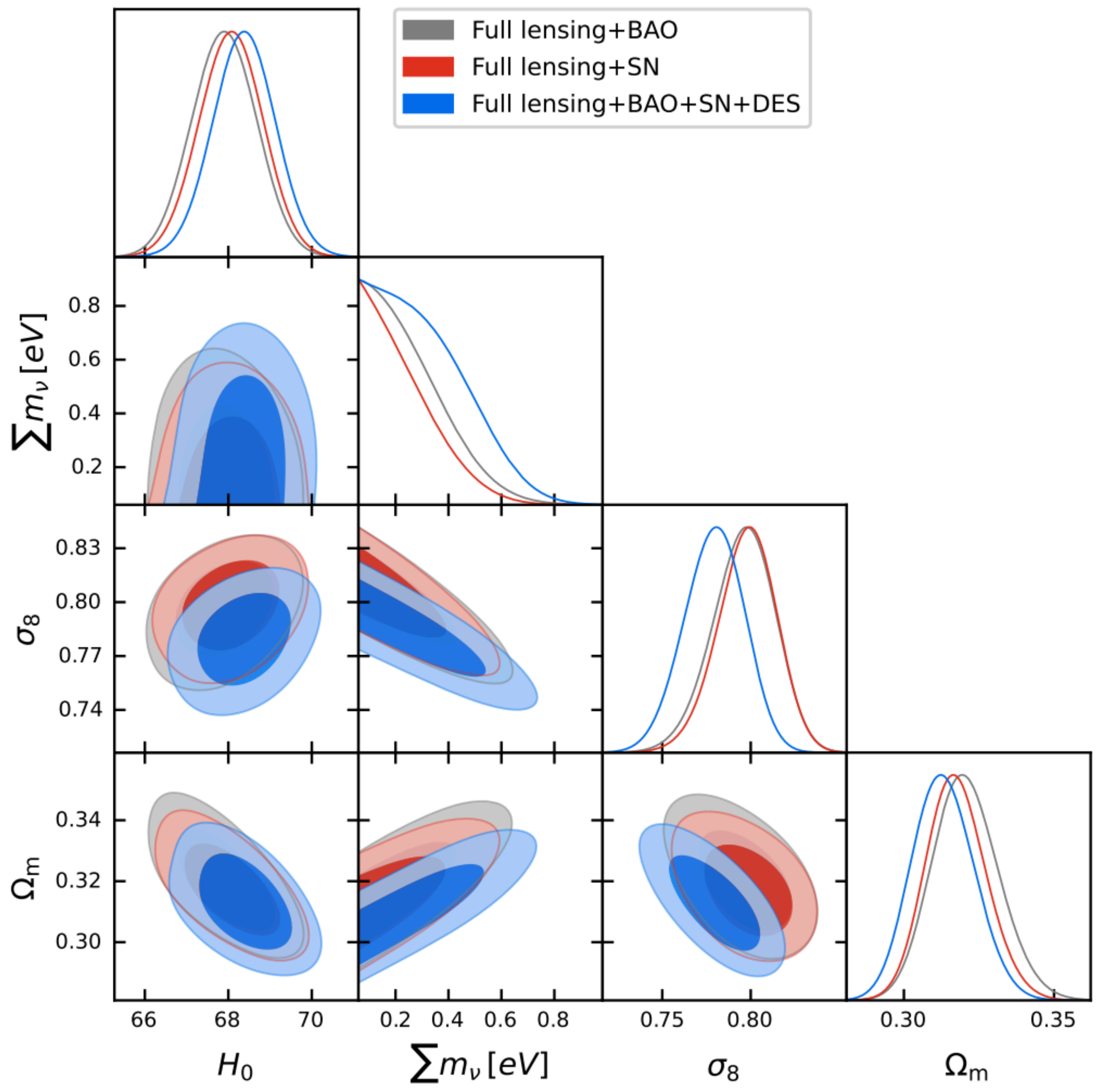
$$\sum m_\nu \lesssim 0.8\,\mathrm{eV} \quad \text{Distances+lensing}$$

WG, et al. **[arXiv:2307.14204]**



Neutrino Tension

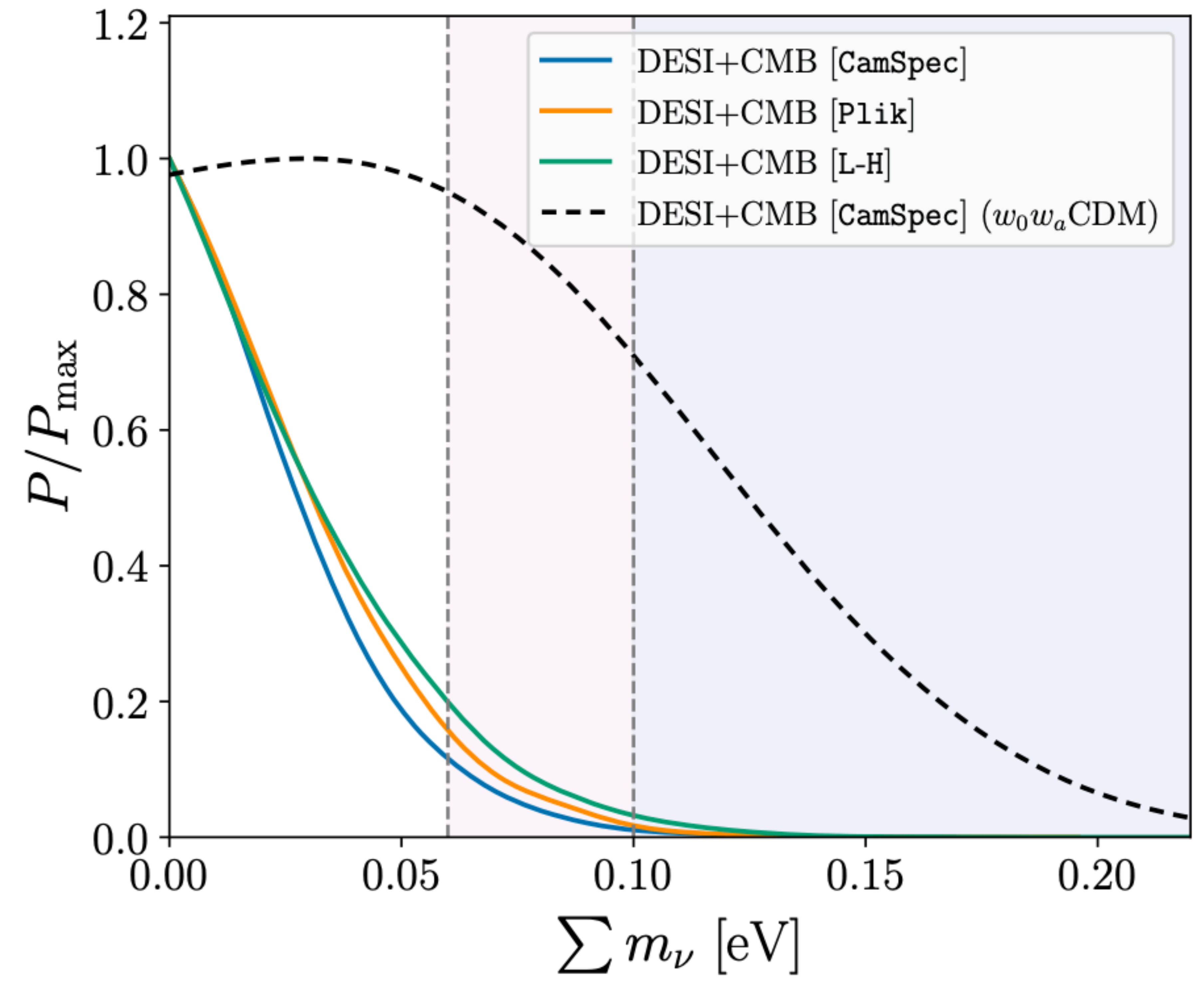
DESI DR2 Results II: Measurements of Baryon Acoustic Oscillations and Cosmological Constraints

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

The DESI collaboration

We present baryon acoustic oscillation (BAO) measurements from more than 14 million galaxies and quasars drawn from the Dark Energy Spectroscopic Instrument (DESI) Data Release 2 (DR2), based on three years of operation. For cosmology inference, these galaxy measurements are combined with DESI Lyman-α forest BAO results presented in a companion paper. The DR2 BAO results are consistent with DESI DR1 and SDSS, and their distance-redshift relationship matches those from recent compilations of supernovae (SNe) over the same redshift range. The results are well described by a flat ΛCDM model, but the parameters preferred by BAO are in mild, 2.3σ tension with those determined from the cosmic microwave background (CMB), although the DESI results are consistent with the acoustic angular scale θ_* that is well-measured by Planck. This tension is alleviated by dark energy with a time-evolving equation of state parametrized by w_0 and w_a, which provides a better fit to the data, with a favored solution in the quadrant with $w_0 > -1$ and $w_a < 0$. This solution is preferred over ΛCDM at 3.1σ for the combination of DESI BAO and CMB data. When also including SNe, the preference for a dynamical dark energy model over ΛCDM ranges from $2.8 - 4.2\sigma$ depending on which SNe sample is used. We present evidence from other data combinations which also favor the same behavior at high significance. From the combination of DESI and CMB we derive 95% upper limits on the sum of neutrino masses, finding $\sum m_\nu < 0.064$ eV assuming ΛCDM and $\sum m_\nu < 0.16$ eV in the $w_0 w_a$ model. Unless there is an unknown systematic error associated with one or more datasets, it is clear that ΛCDM is being challenged by the combination of DESI BAO with other measurements and that dynamical dark energy offers a possible solution.

DESI 2025 — [arXiv:2503.14738]



- **CMB+DESI-DR2:** $\sum m_\nu < 0.064$ **eV**
- **Oscillation Experiments NO:** $\sum m_\nu > 0.06$ **eV**
- **Oscillation Experiments IO:** $\sum m_\nu > 0.1$ **eV**

Neutrino Tension

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Neutrino cosmology after DESI: tightest mass upper limits, preference for the normal ordering, and tension with terrestrial observations

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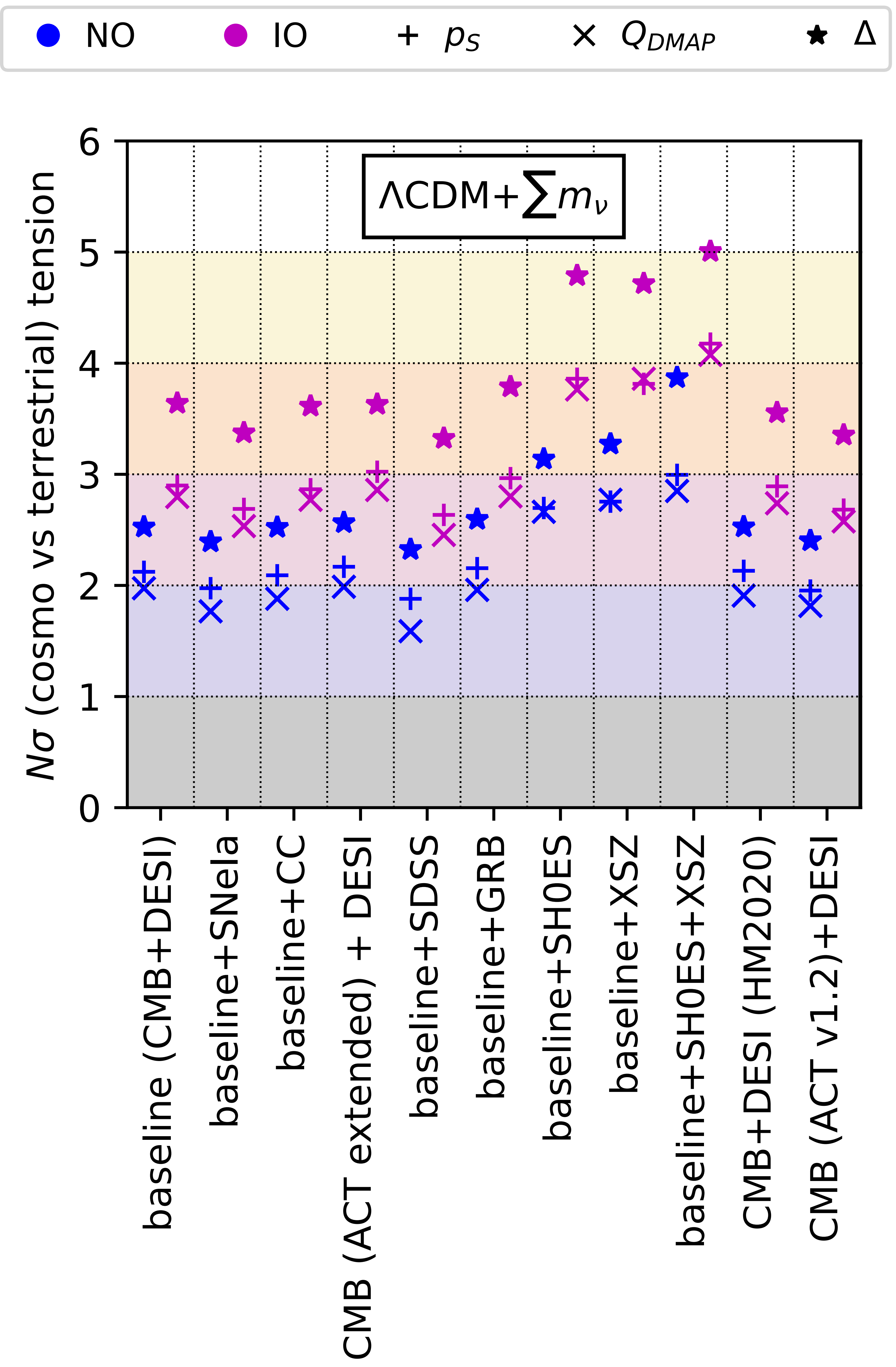
Maria Giovanna Dainotti[g,h,i,j] Eleonora Di Valentino[c] Olga Mena[k]
Davide Pedrotti[b,l] Simony Santos da Costa[b,l] and Sunny Vagnozzi[b,l]

Abstract: The recent DESI Baryon Acoustic Oscillation measurements have led to tight upper limits on the neutrino mass sum, potentially in tension with oscillation constraints requiring $\sum m_\nu \gtrsim 0.06\,\mathrm{eV}$. Under the physically motivated assumption of positive $\sum m_\nu$, we study the extent to which these limits are tightened by adding other available cosmological probes, and robustly quantify the preference for the normal mass ordering over the inverted one, as well as the tension between cosmological and terrestrial data. Combining DESI data with Cosmic Microwave Background measurements and several late-time background probes, the tightest 2σ limit we find without including a local H_0 prior is $\sum m_\nu < 0.05\,\mathrm{eV}$. This leads to a strong preference for the normal ordering, with Bayes factor relative to the inverted one of 46.5. Depending on the dataset combination and tension metric adopted, we quantify the tension between cosmological and terrestrial observations as ranging between 2.5σ and 5σ. These results are strenghtened when allowing for a time-varying dark energy component with equation of state lying in the physically motivated non-phantom regime, $w(z) \geq -1$, highlighting an interesting synergy between the nature of dark energy and laboratory probes of the mass ordering. If these tensions persist and cannot be attributed to systematics, either or both standard neutrino (particle) physics or the underlying cosmological model will have to be questioned.

Keywords: neutrino masses from cosmology, cosmological neutrinos, dark energy experiments, neutrino properties

ArXiv ePrint: 2407.18047

JCAP01(2025)153



WHAT'S THE MATTER (DENSITY)?

Although all the datasets are well described by a flat ΛCDM model:

- **DESI-2025 BAOs show a mild tension (2.3σ) with Planck.**
- **DESI-2025 BAO+Planck** leads to a **moderate shift (~1.5σ – 2σ)** in Planck's preferred parameter space, notably **favouring a larger H_0 and a lower Ω_m.**
- **DESy5-SN+Planck** favours **larger Ω_m and lower H_0.**

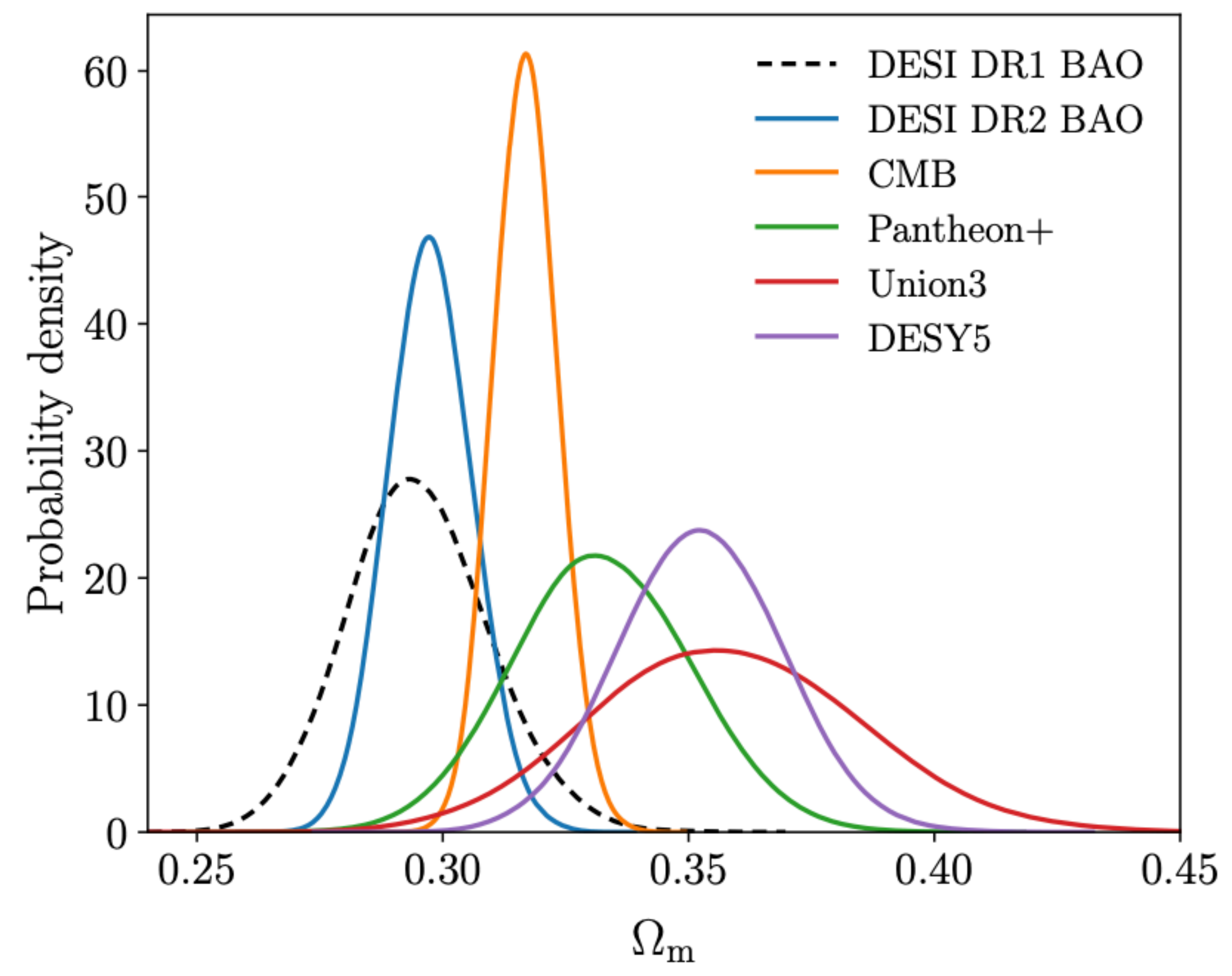
=> Planck+DESI-2025 BAO and Planck+DESy5 SN pull the parameter space in opposite directions.

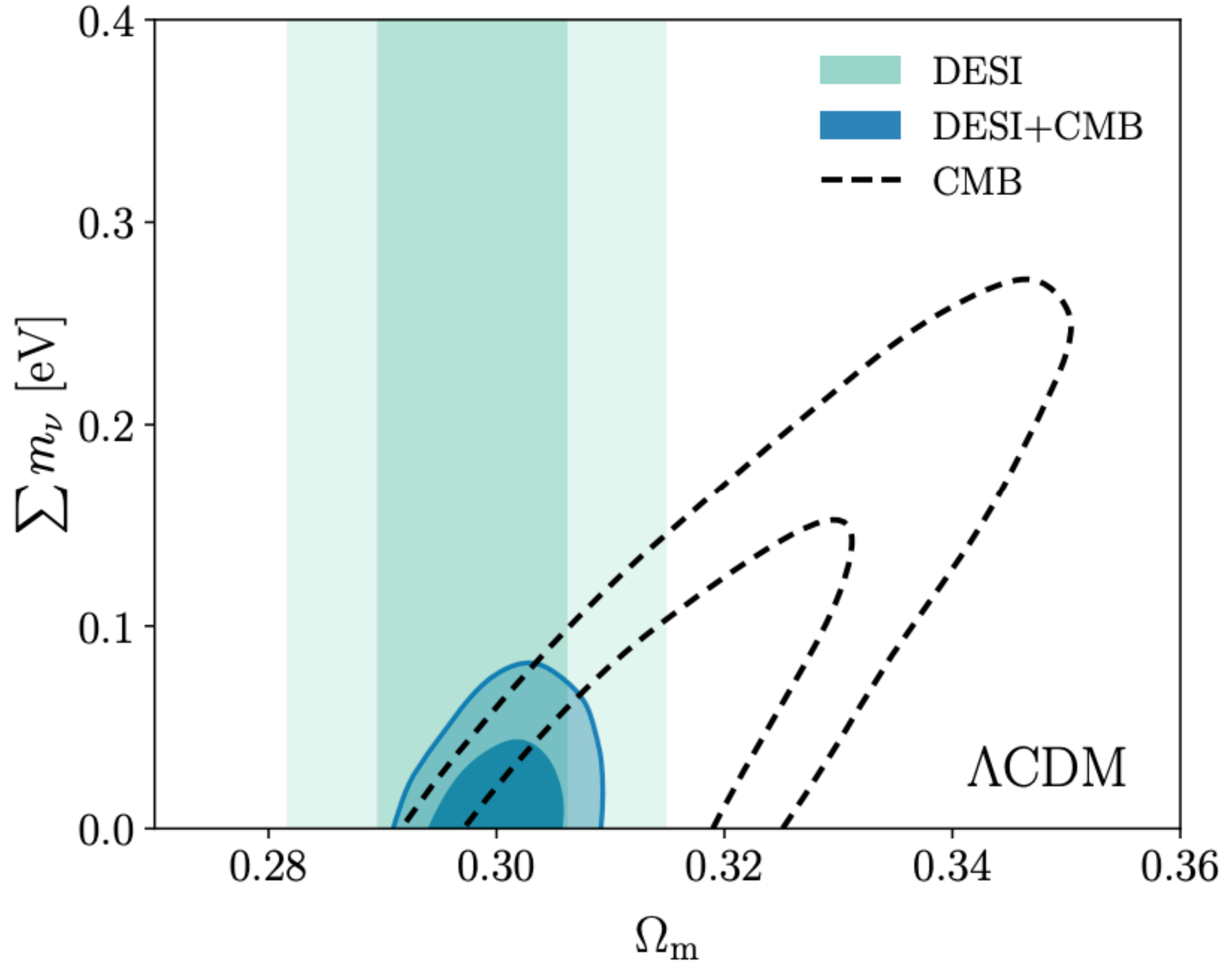
Note that the DESI-2025 BAO preference for lower values of Ω_m is largely responsible for the neutrino tension:

$$\Omega_m h^2 = \Omega_b h^2 + \Omega_c h^2 + \boxed{\Omega_\nu h^2}$$

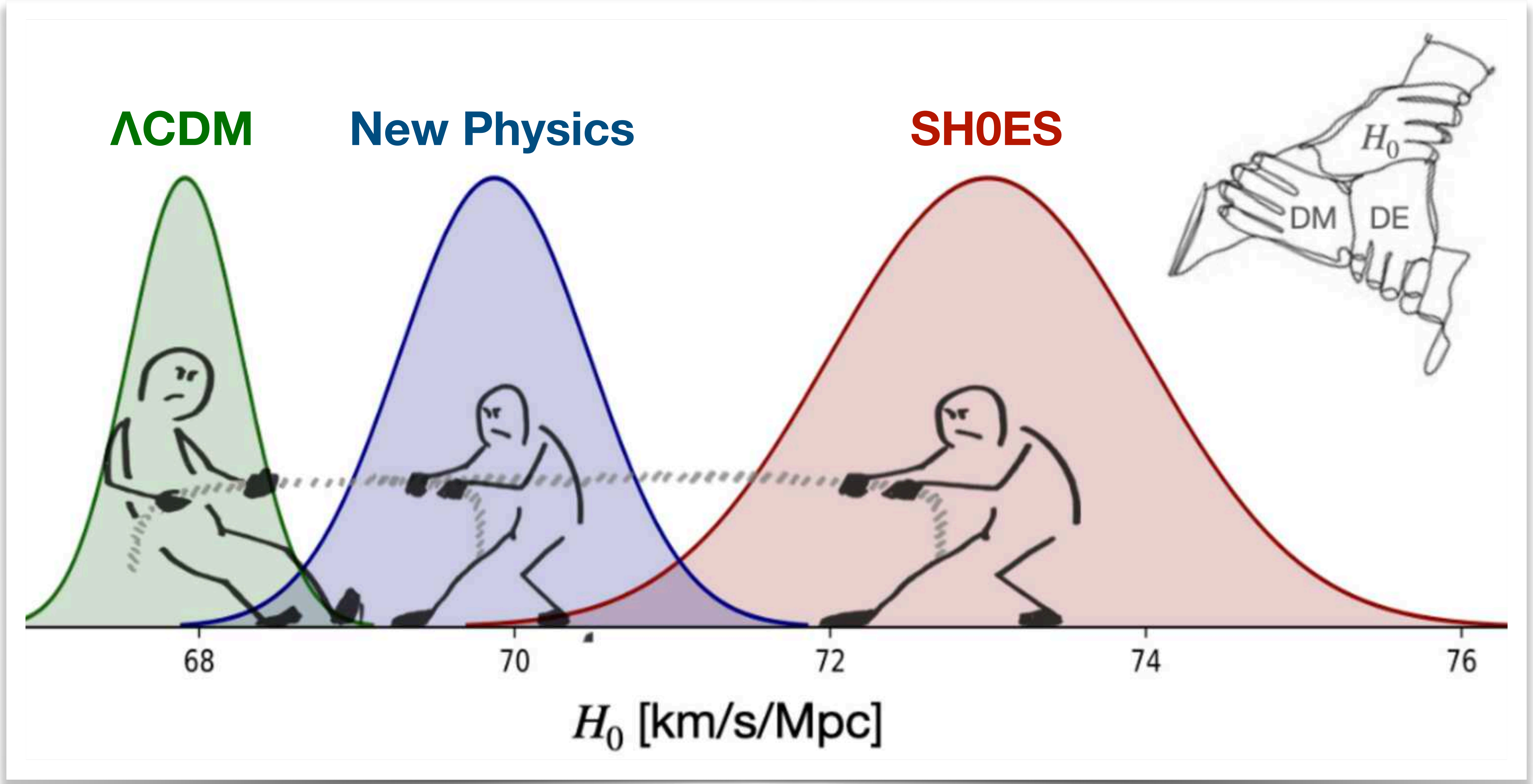
$$\boxed{\Omega_\nu h^2 \sim \frac{\sum m_\nu}{93.14\, h^2\,\mathrm{eV}}}$$

DESI 2025 — [arXiv:2503.14738]





3 | A Brief Introduction to Possible Solutions



Overview of Topics Covered

- Dynamical Dark Energy
- Interacting Dark Energy
- Early Dark Energy

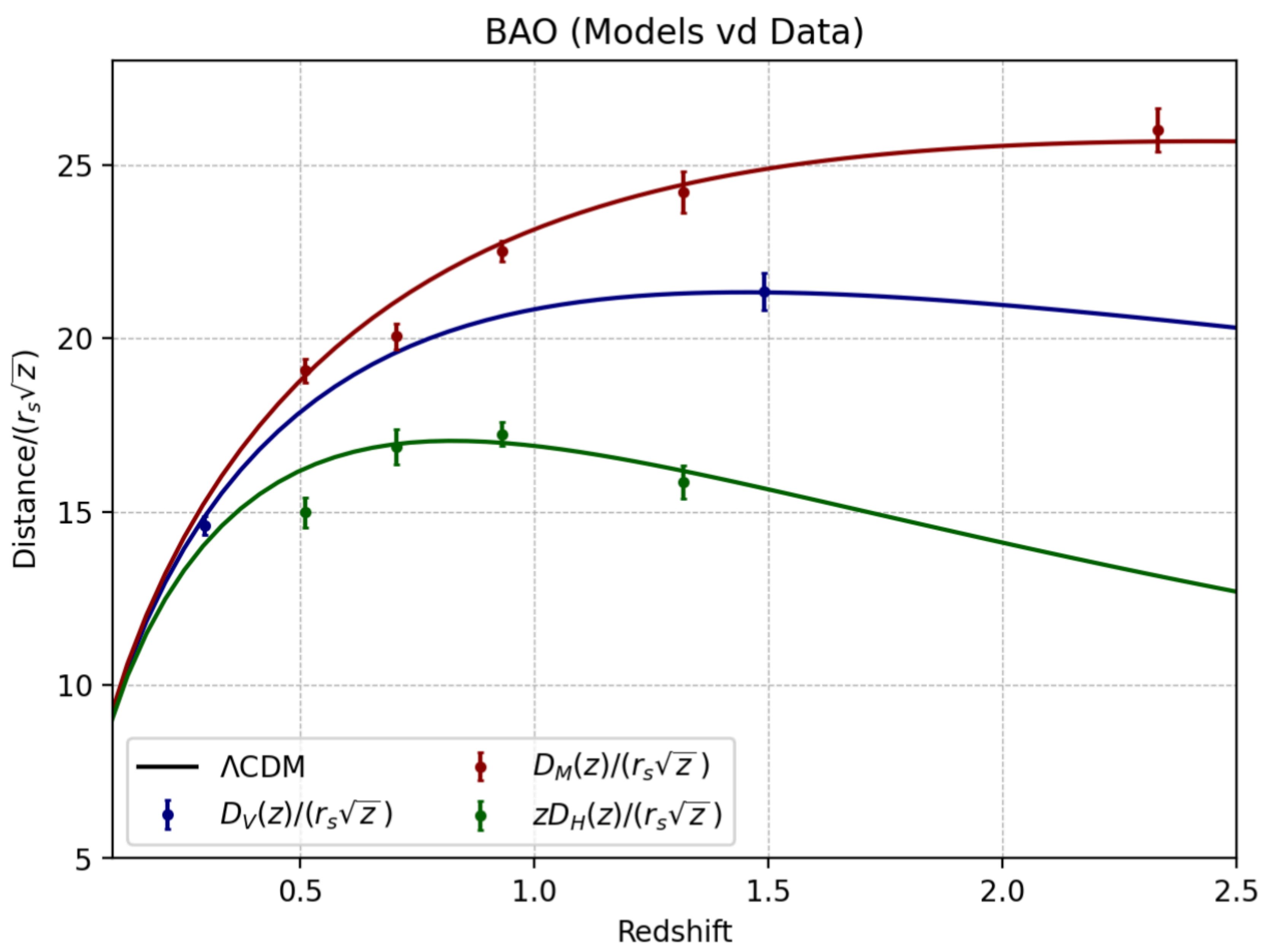
Is it Λ's fault?

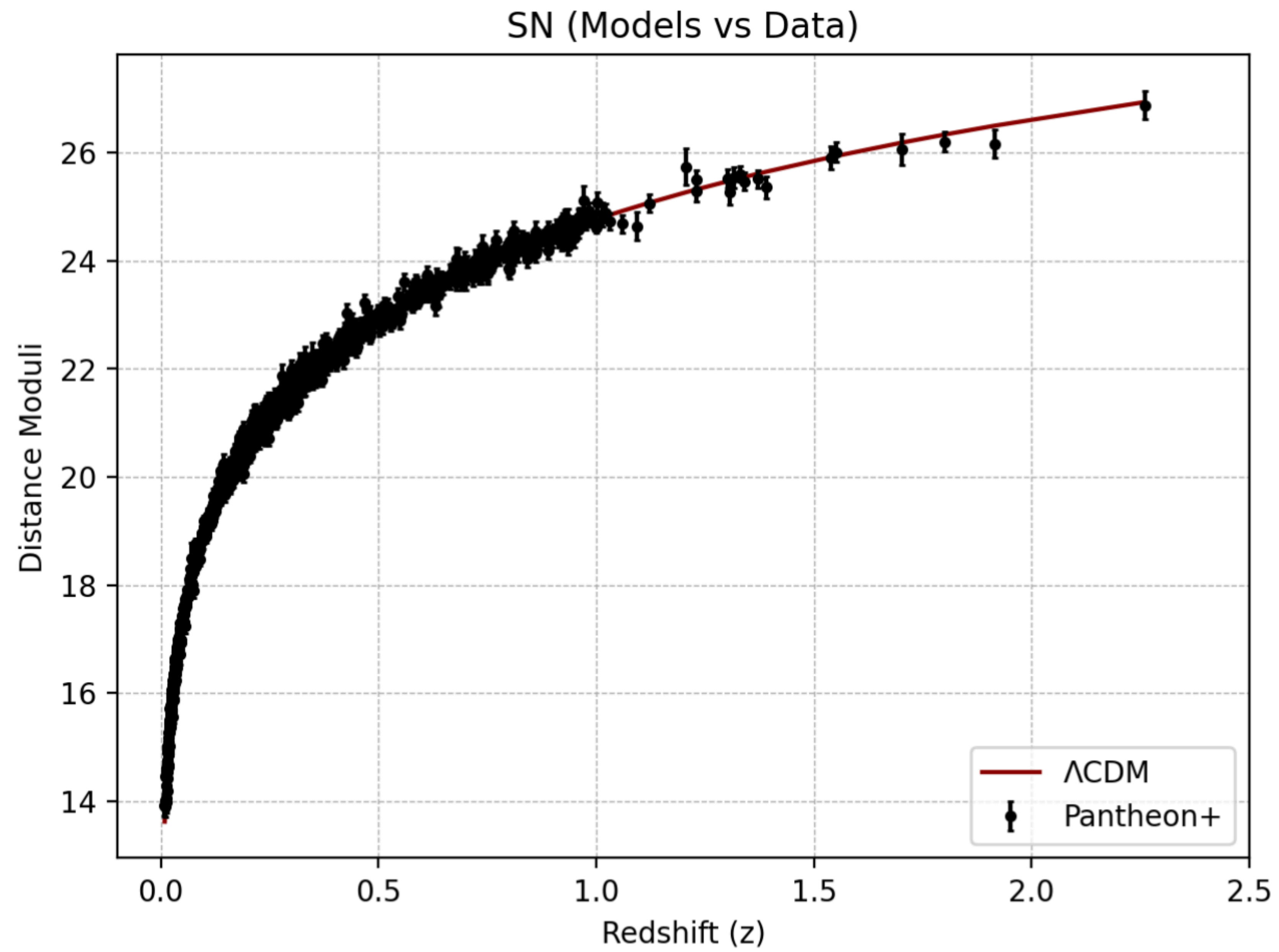
$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

Constant Component in the Einstein Tensor

Ω_Λ is a Cosmological Constant term. Assumption is not free from limitations:

- **Asymptotical cosmology:** A positive Λ implies living in an asymptotically de Sitter universe, which seems to contrast with several theories/models of quantum gravity proposing instead an asymptotically anti-de Sitter universe
- **Physical interpretation:** Based on QFT calculations, one would expect a zero-point energy density 10^{50} to 10^{120} orders of magnitude larger than what is inferred by cosmological data
- **Why Now?:** Why are we so lucky to live precisely in the cosmic epoch when such a constant component came to be dominant?





Is it Λ's fault?

$$H^2(z) \simeq H_0^2\left[\Omega_m \cdot (1+z)^3 + \Omega_\Lambda\right] \simeq H_0^2\left[\Omega_m \cdot (1+z)^3 + 1 - \Omega_m\right]$$

Constant Component in the Freedman Equation

Ω_m fixes the whole redshift dependence

Ω_Λ is a Cosmological Constant term. Assumption is not free from limitations:

- **Asymptotical cosmology:** A positive Λ implies living in an asymptotically de Sitter universe, which seems to contrast with several theories/models of quantum gravity proposing instead an asymptotically anti-de Sitter universe
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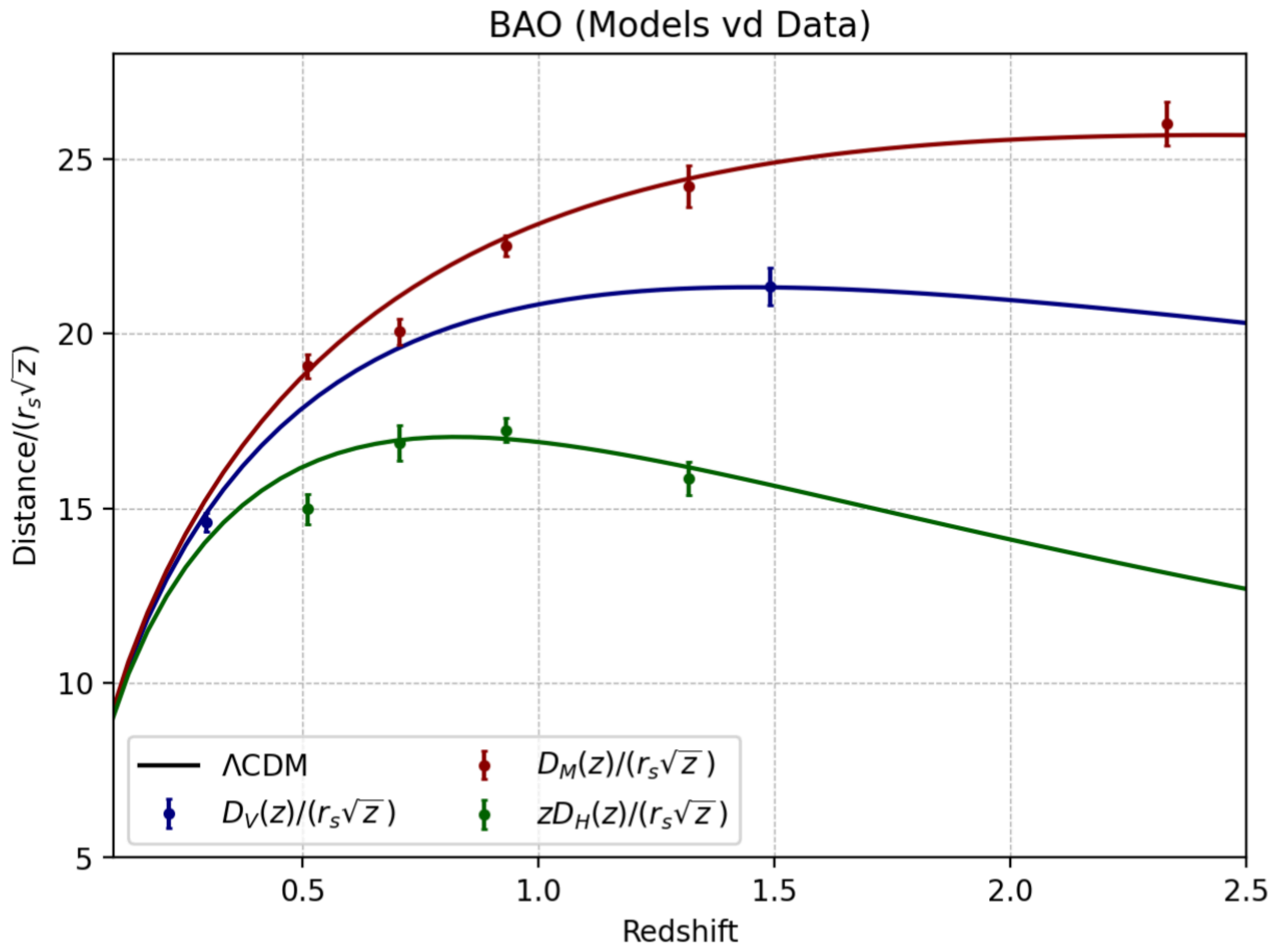
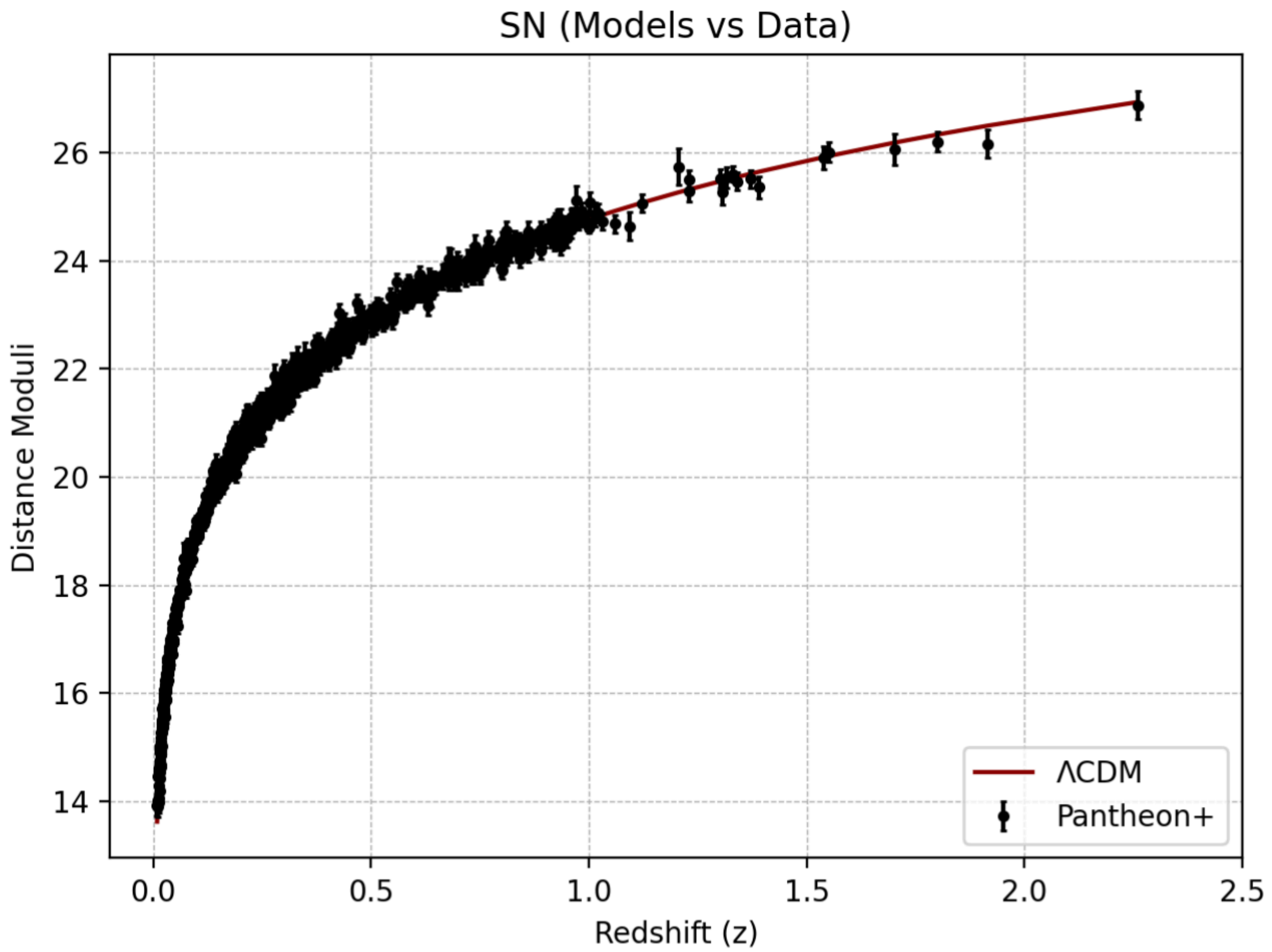
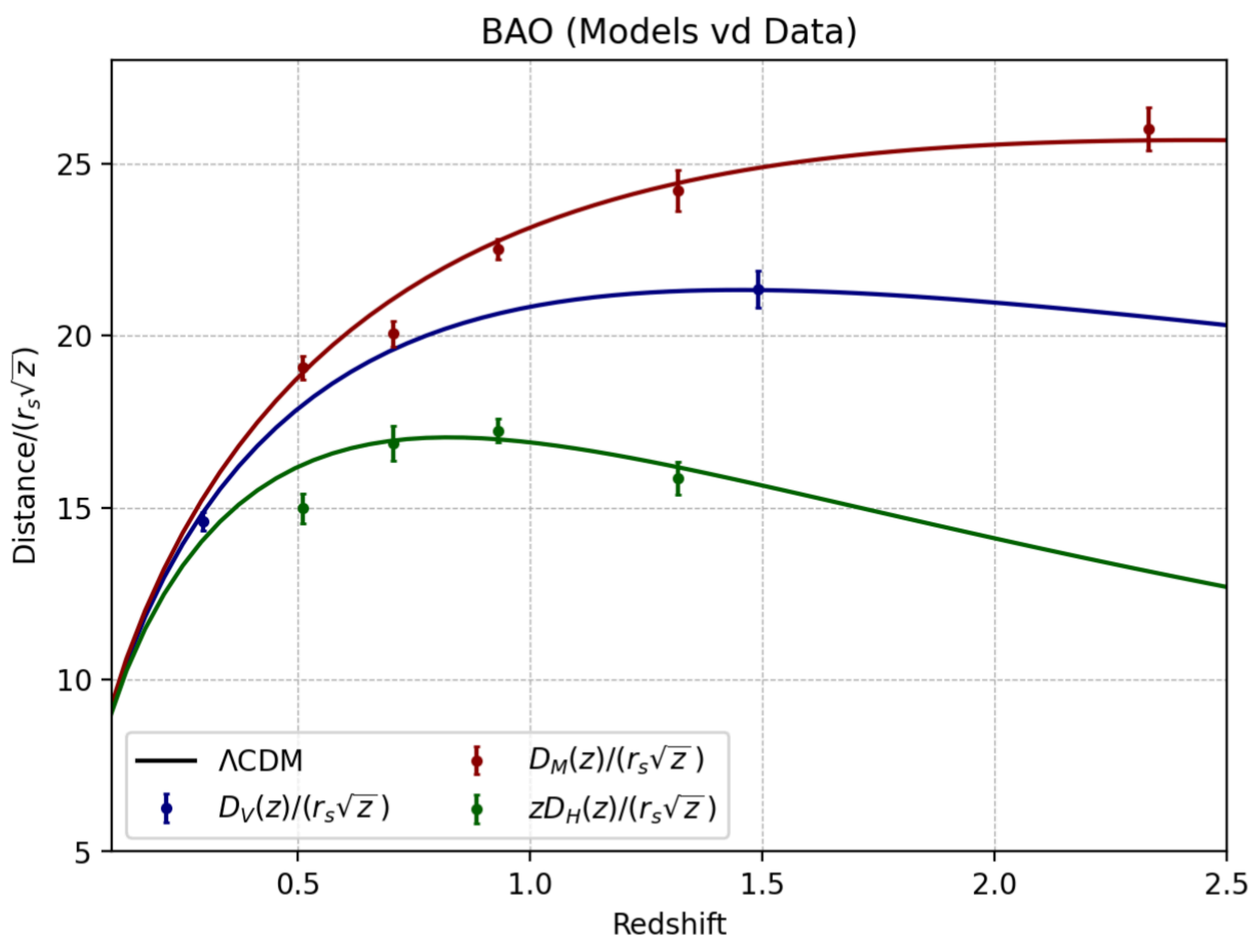


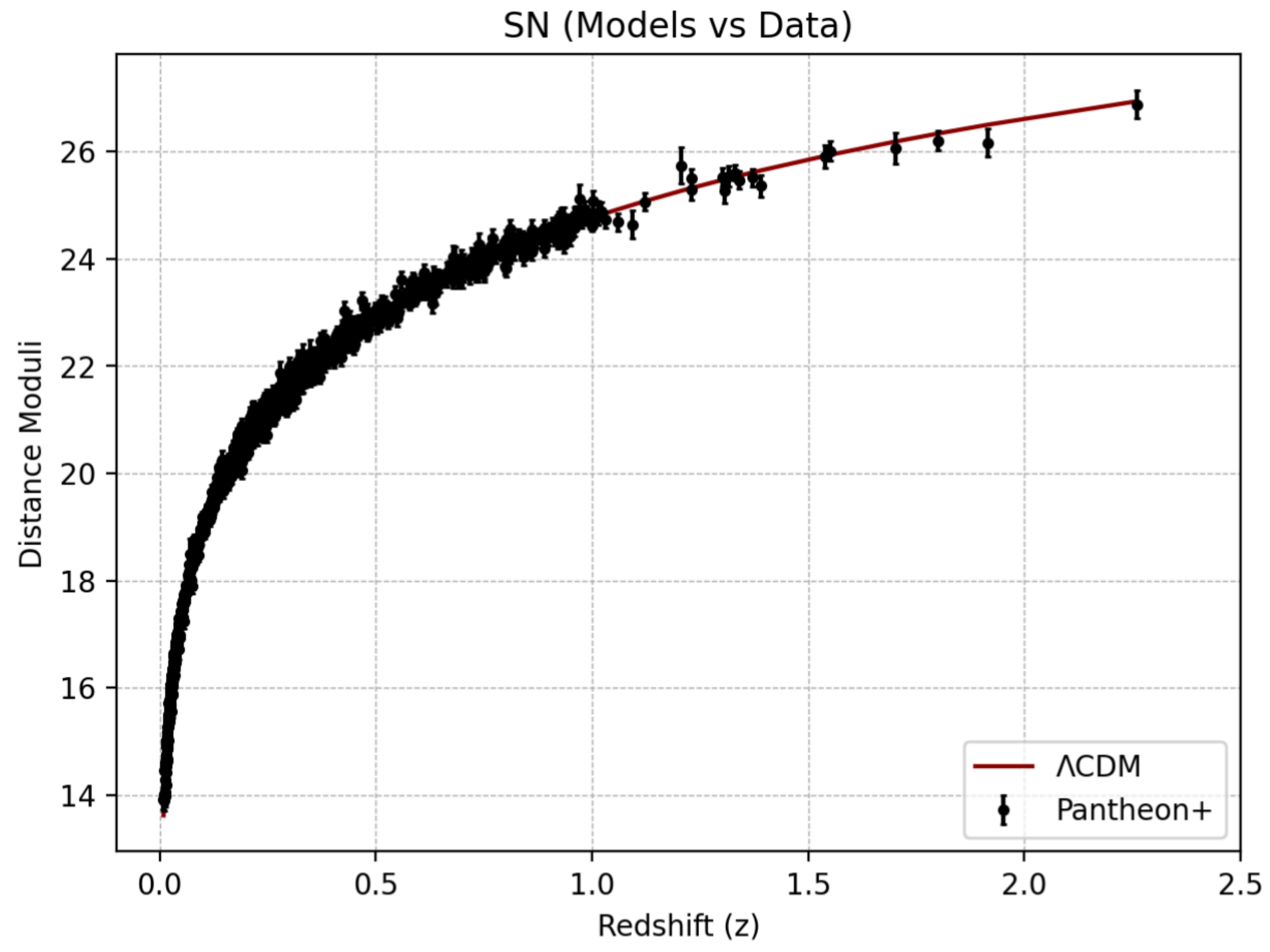


Is it Λ's fault?

$$D_L(z) = (1+z)^2 D_A(z) \propto \int_0^z dz' H(z')^{-1}$$

Distance Predictions





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Evolving Dark Energy

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

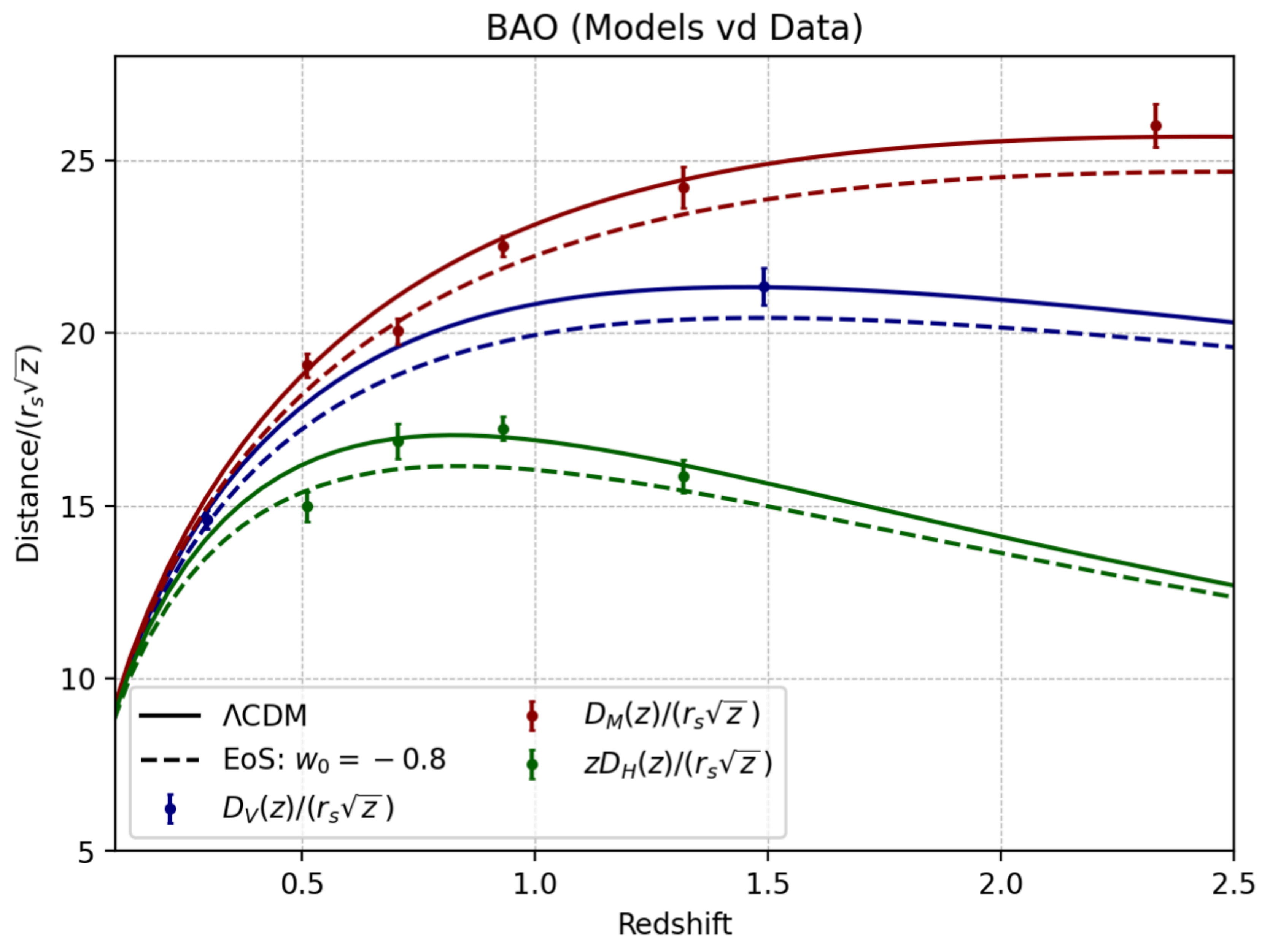
Modified Gravity?

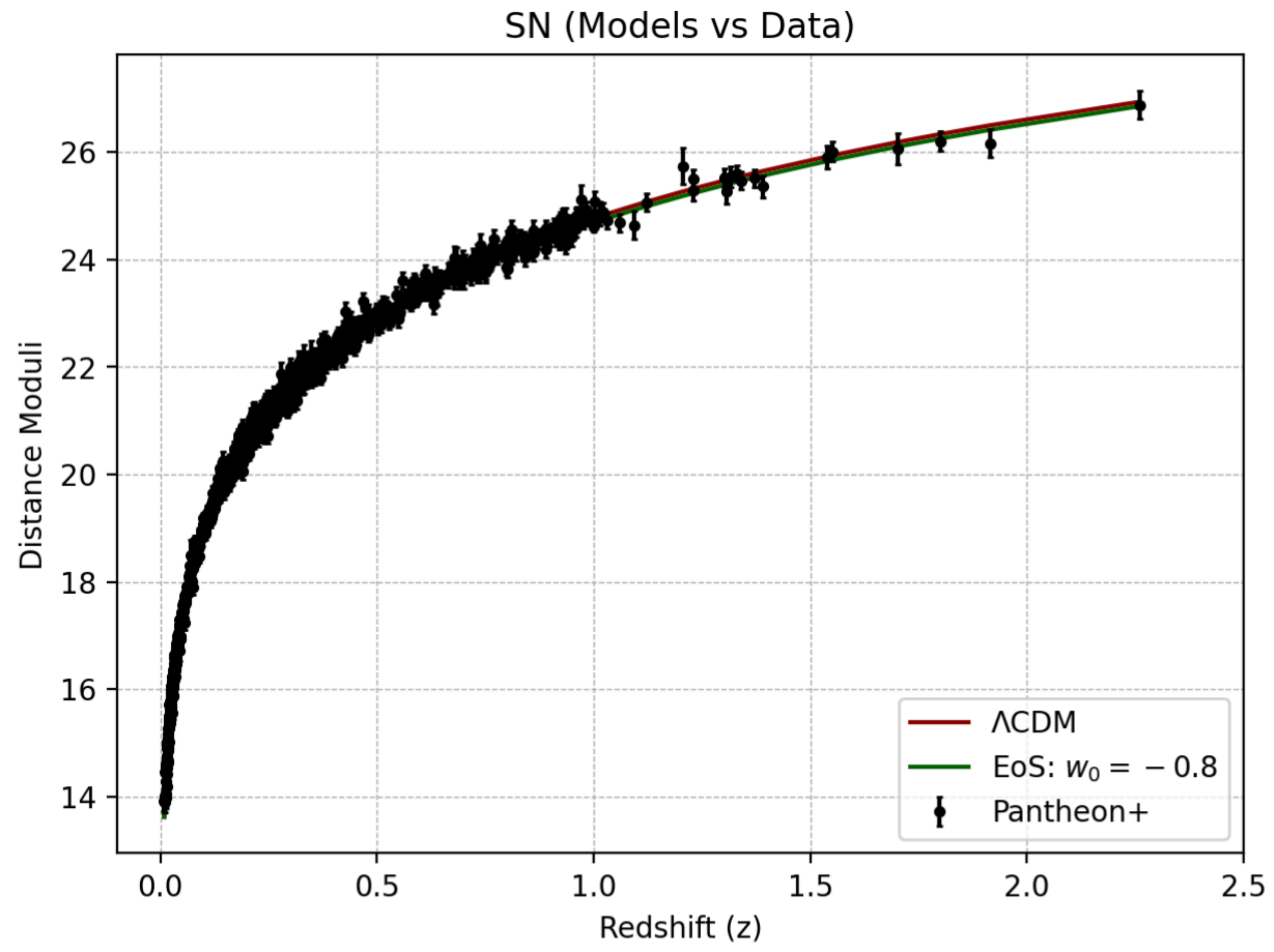
Non-standard component?
(e.g., scalar field(s), fluid(s), etc.)

$\Omega_{\mathrm{DE}}(z)$ is a generic DE component with

- **Energy density:** $\rho_{\mathrm{DE}}(z)$
- **Pressure:** $P_{\mathrm{DE}}(z)$
- **Equation of State (EoS):** $w(z) = \dfrac{P_{\mathrm{DE}}(z)}{\rho_{\mathrm{DE}}(z)}$

We get an accelerated phase of expansion if $w(z) < -1/3$





Evolving Dark Energy

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

Non-standard (dynamical?) component

$\Omega_{\rm DE}(z)$ is a generic DE component with

- **Energy density:** $\rho_{\rm DE}(z)$
- **Pressure:** $P_{\rm DE}(z)$
- **Equation of State (EoS):** $w(z) = \dfrac{P_{\rm DE}(z)}{\rho_{\rm DE}(z)}$

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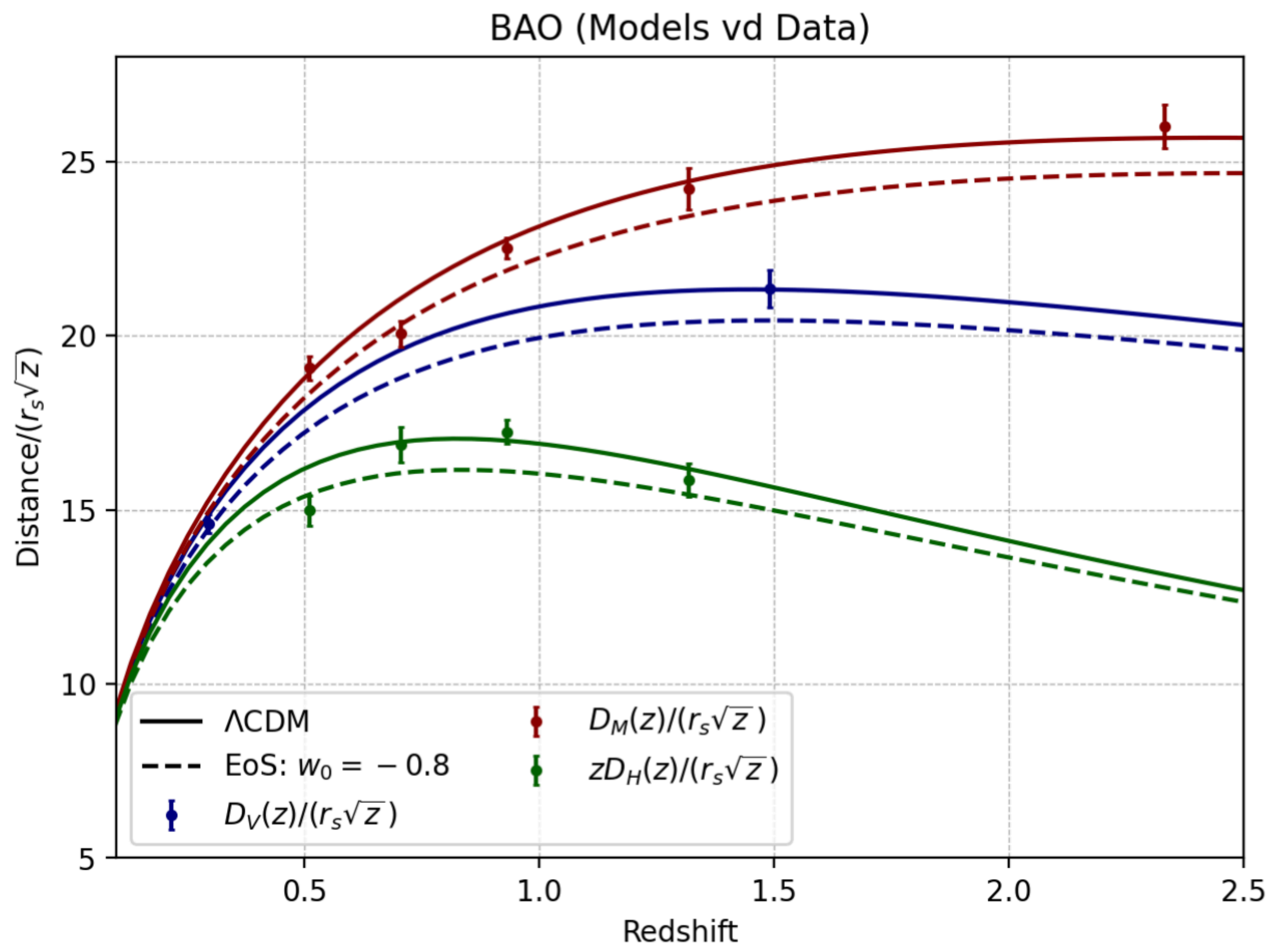

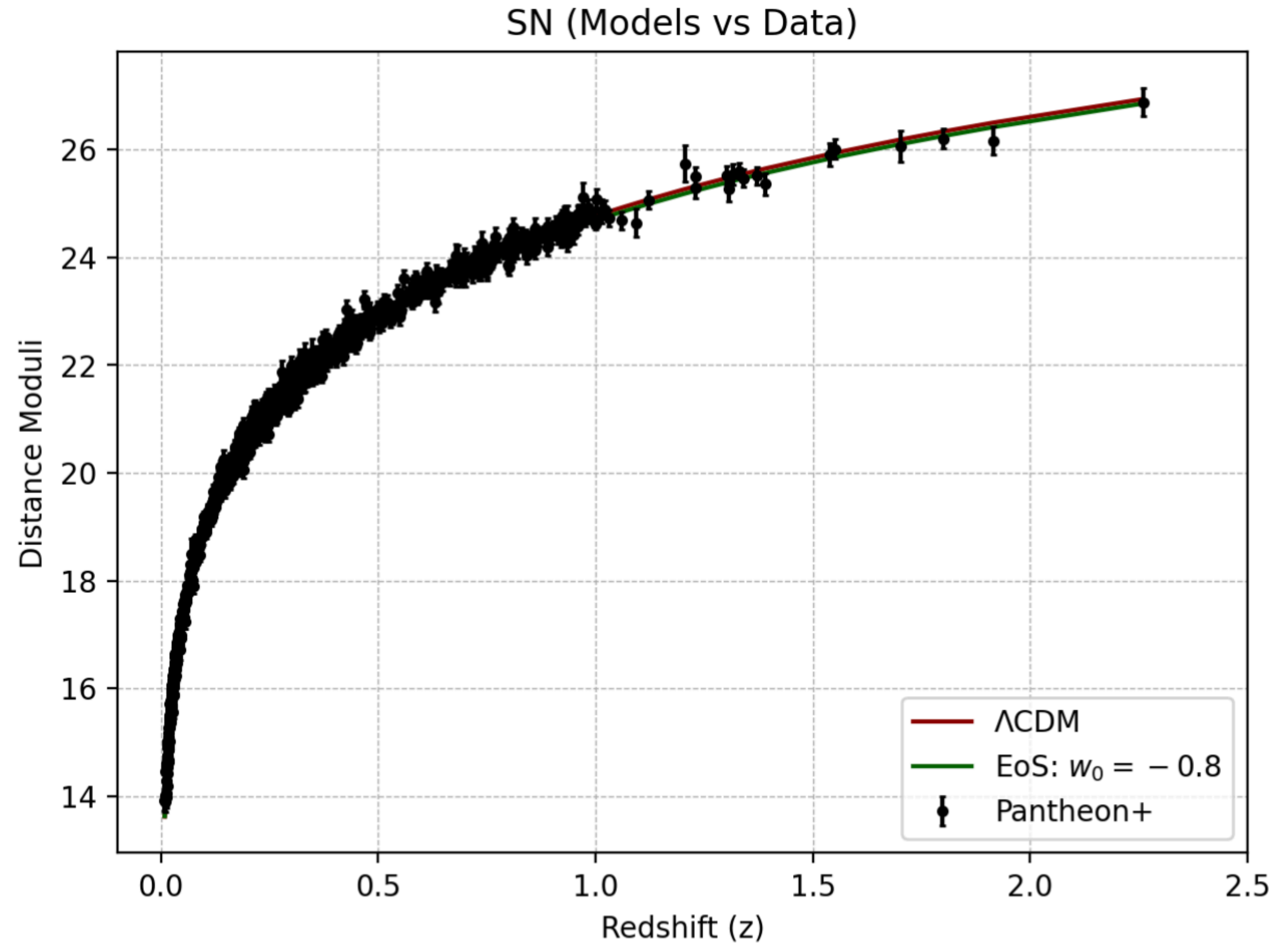

EVOLVING DARK ENERGY

$$D_L(z) = (1+z)^2 D_A(z) \propto \int_0^z dz' H(z')^{-1}$$

More freedom
in Distance Predictions

$\Omega_{\rm DE}(z)$ is a generic DE component with

- **Energy density:** $\rho_{\rm DE}(z)$
- **Pressure:** $P_{\rm DE}(z)$
- **Equation of State (EoS):** $w(z) = \dfrac{P_{\rm DE}(z)}{\rho_{\rm DE}(z)}$

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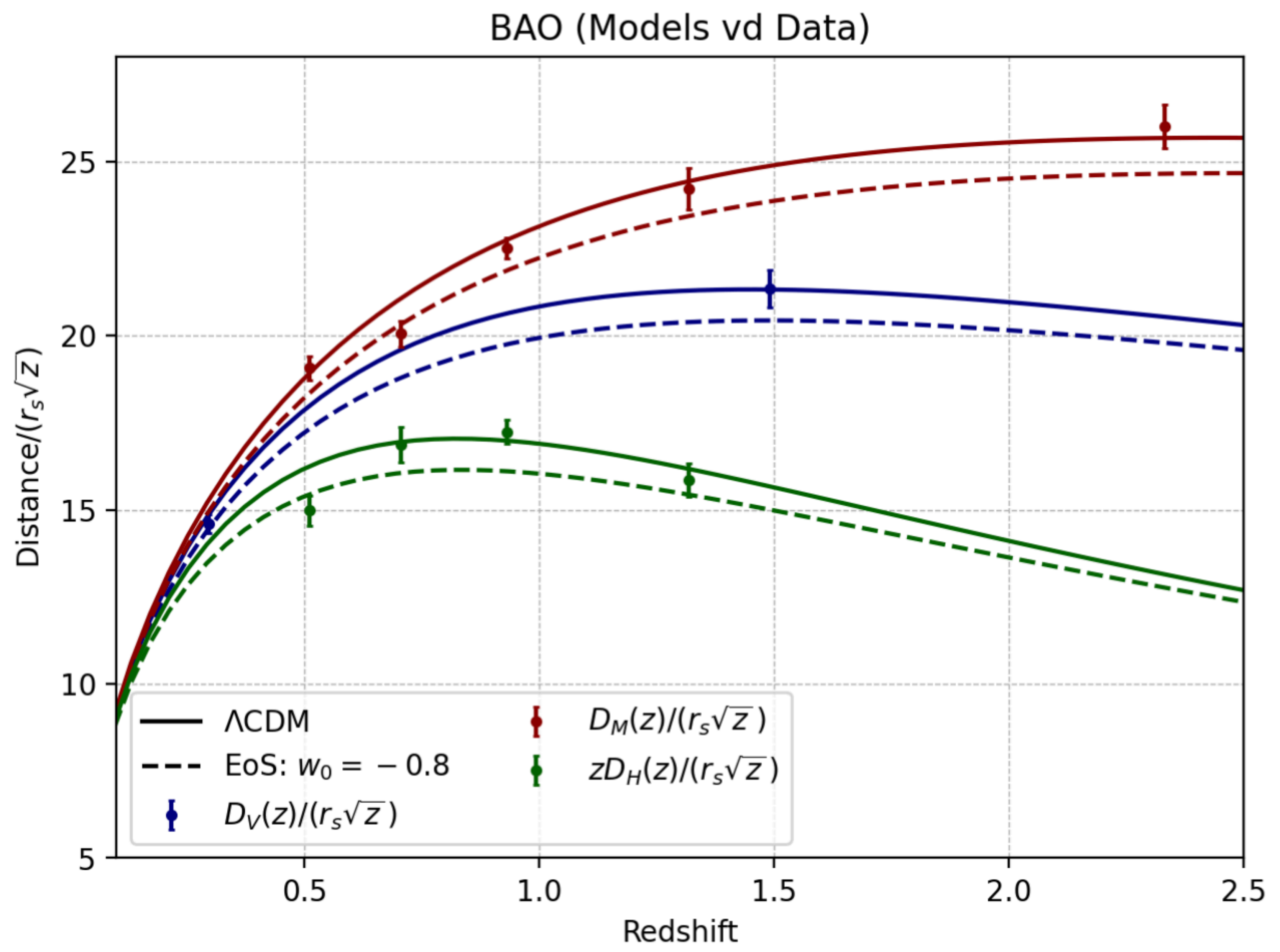
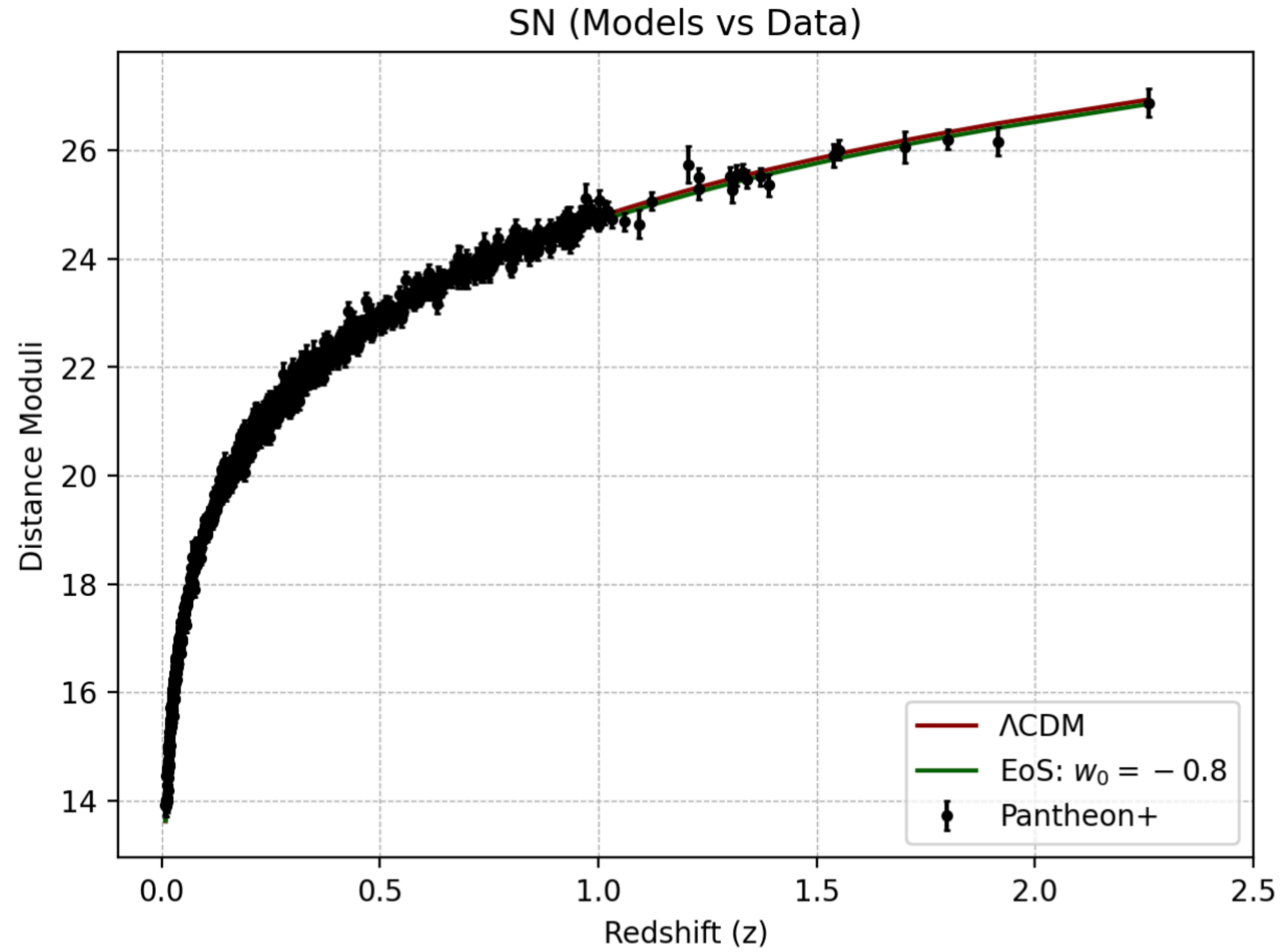




Evolving Dark Energy

DESI DR2 Results II: Measurements of Baryon Acoustic Oscillations and Cosmological Constraints

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

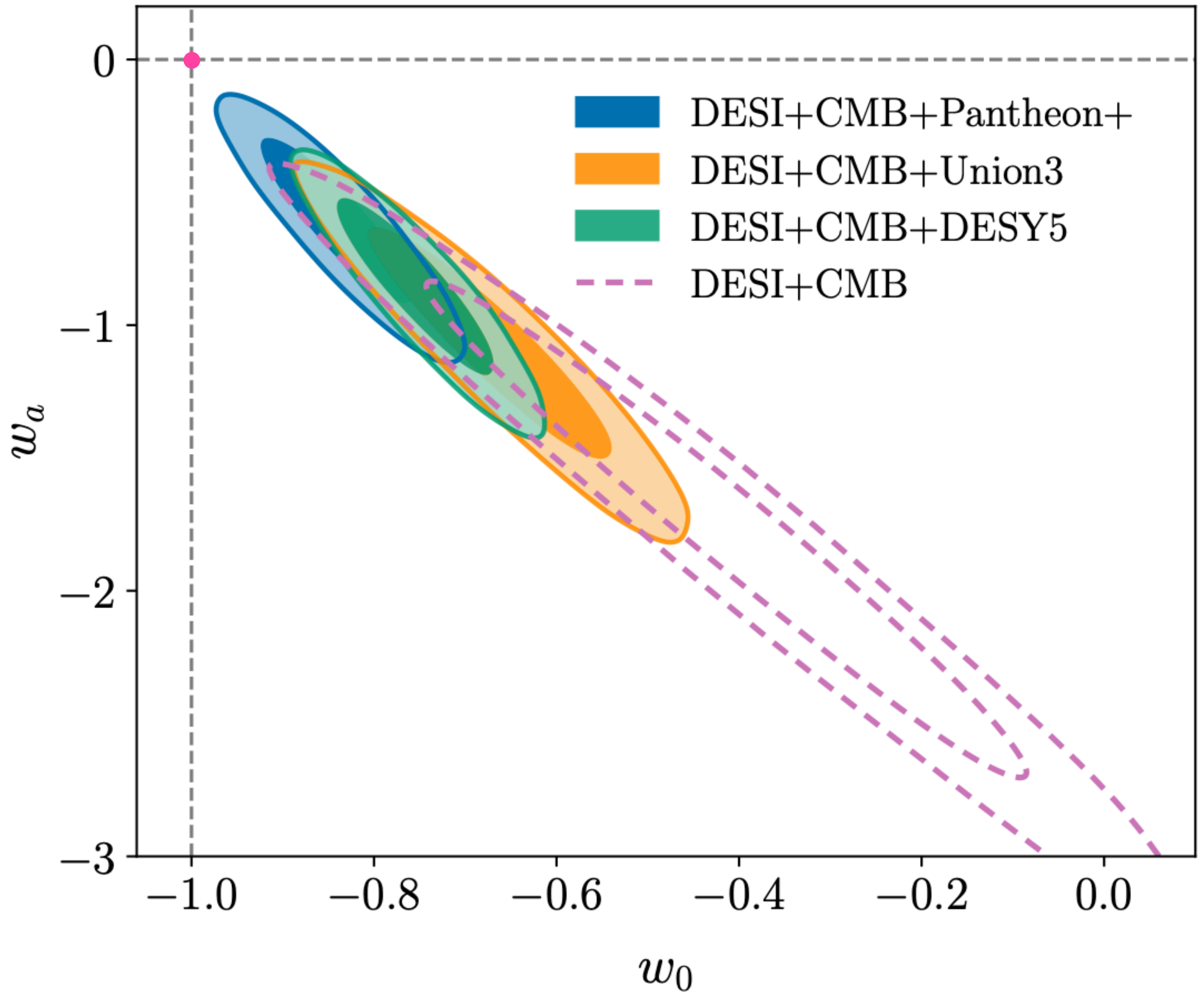
The DESI collaboration

We present baryon acoustic oscillation (BAO) measurements from more than 14 million galaxies and quasars drawn from the Dark Energy Spectroscopic Instrument (DESI) Data Release 2 (DR2), based on three years of operation. For cosmology inference, these galaxy measurements are combined with DESI Lyman-α forest BAO results presented in a companion paper. The DR2 BAO results are consistent with DESI DR1 and SDSS, and their distance-redshift relationship matches those from recent compilations of supernovae (SNe) over the same redshift range. The results are well described by a flat ΛCDM model, but the parameters preferred by BAO are in mild, 2.3σ tension with those determined from the cosmic microwave background (CMB), although the DESI results are consistent with the acoustic angular scale θ_* that is well-measured by Planck. This tension is alleviated by dark energy with a time-evolving equation of state parametrized by w_0 and w_a, which provides a better fit to the data, with a favored solution in the quadrant with $w_0 > -1$ and $w_a < 0$. This solution is preferred over ΛCDM at 3.1σ for the combination of DESI BAO and CMB data. When also including SNe, the preference for a dynamical dark energy model over ΛCDM ranges from $2.8 - 4.2\sigma$ depending on which SNe sample is used. We present evidence from other data combinations which also favor the same behavior at high significance. From the combination of DESI and CMB we derive 95% upper limits on the sum of neutrino masses, finding $\sum m_\nu < 0.064$ eV assuming ΛCDM and $\sum m_\nu < 0.16$ eV in the $w_0 w_a$ model. Unless there is an unknown systematic error associated with one or more datasets, it is clear that ΛCDM is being challenged by the combination of DESI BAO with other measurements and that dynamical dark energy offers a possible solution.

Favored at $\sim 3 - 4\sigma$ level over Λ

Chevallier-Polarski-Linder DE EoS:

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



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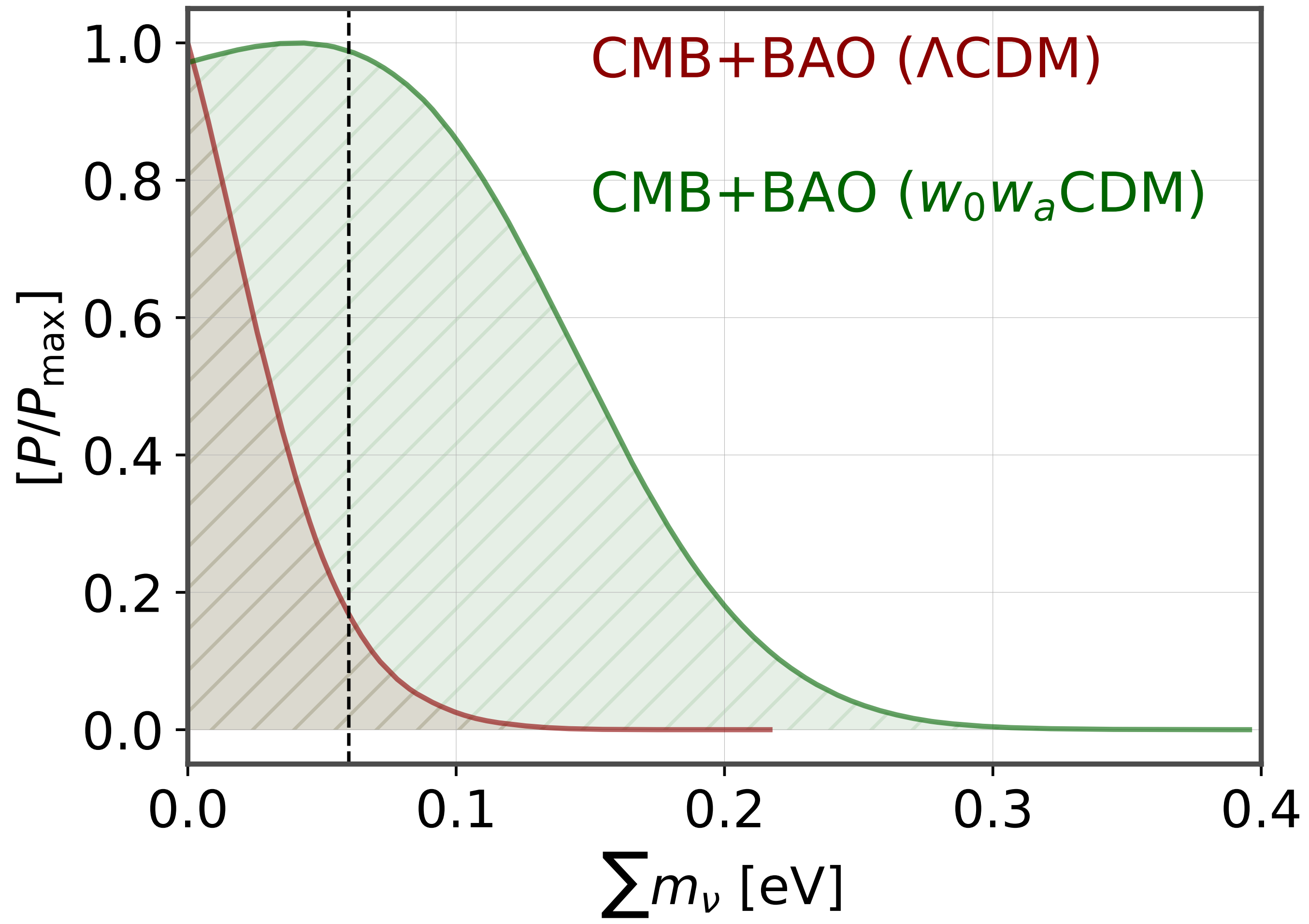
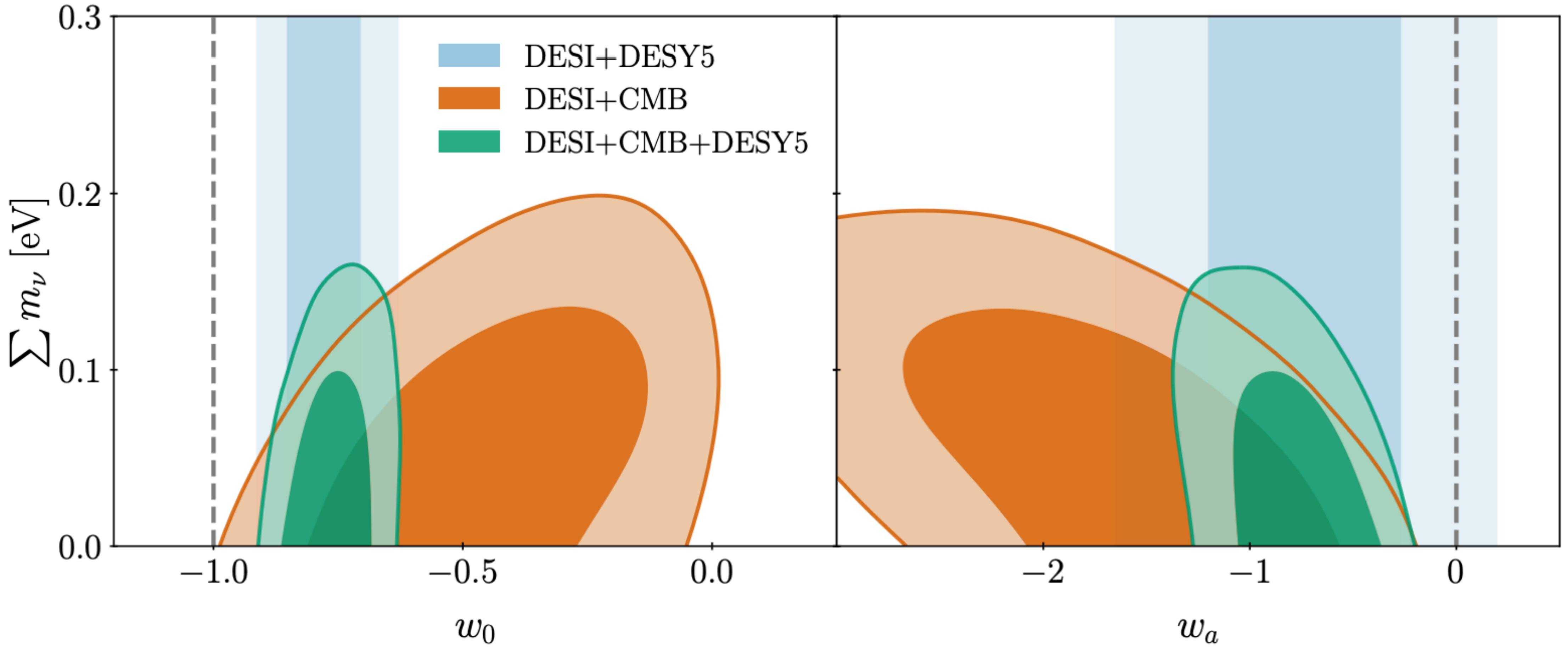
Reconcile neutrino tension: $\sum m_\nu < 0.16$ eV



DESI 2025 — [arXiv:2503.14738]



Evolving Dark Energy

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Robust preference for Dynamical Dark Energy in DESI BAO and SN measurements

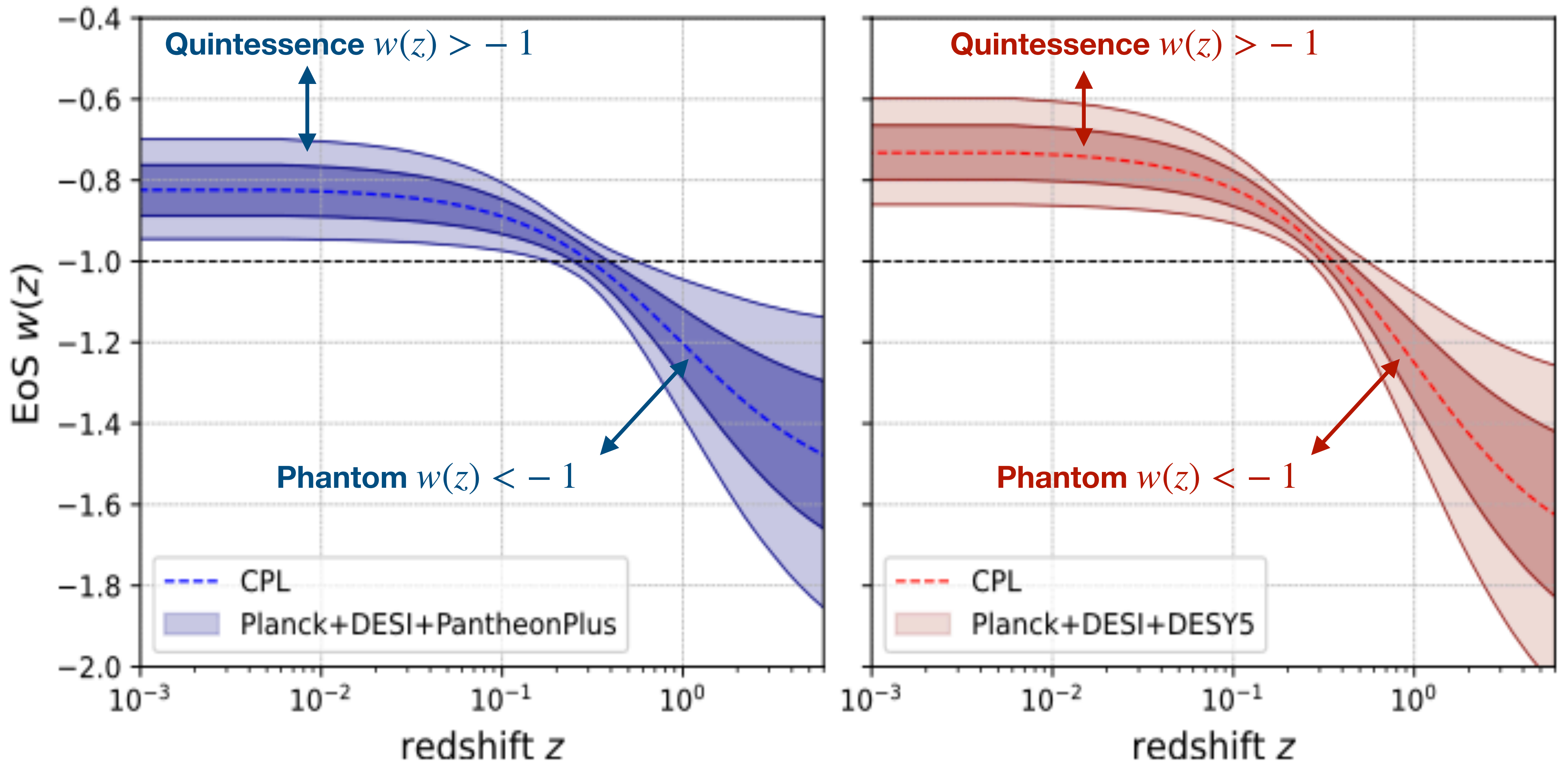
William Giarè[a,*] Mahdi Najafi,[b,c] Supriya Pan[d,e] Eleonora Di Valentino[a]
and Javad T. Firouzjaee[b,c,f]

Abstract: Recent Baryon Acoustic Oscillation (BAO) measurements released by DESI, when combined with Cosmic Microwave Background (CMB) data from Planck and two different samples of Type Ia supernovae (Pantheon-Plus and DESY5) reveal a preference for Dynamical Dark Energy (DDE) characterized by a present-day quintessence-like equation of state that crossed into the phantom regime in the past. A core *ansatz* for this result is assuming a linear Chevallier-Polarski-Linder (CPL) parameterization $w(a) = w_0 + w_a(1-a)$ to describe the evolution of the DE equation of state (EoS). In this paper, we test if and to what extent this assumption impacts the results. To prevent broadening uncertainties in cosmological parameter inference and facilitate direct comparison with the baseline CPL case, we focus on 4 alternative well-known models that, just like CPL, consist of only two free parameters: the present-day DE EoS (w_0) and a parameter quantifying its dynamical evolution (w_a). We demonstrate that the preference for DDE remains robust regardless of the parameterization: w_0 consistently remains in the quintessence regime, while w_a consistently indicates a preference for a dynamical evolution towards the phantom regime. This tendency is significantly strengthened by DESY5 SN measurements. By comparing the best-fit χ^2 obtained within each DDE model, we notice that the linear CPL parameterization is not the best-fitting case. Among the models considered, the EoS proposed by Barboza and Alcaniz consistently leads to the most significant improvement.

JCAP10(2024)035

(How) does the preference depend on CPL?

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



- Present-day Quintessence equation of state $w(z) > -1$
- Quintessence to Phantom crossing at $z \sim 0.3 - 0.4$
- Late-time Phantom equation of state $w(z) < -1$

Evolving Dark Energy

Resilient across alternative parameterizations

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

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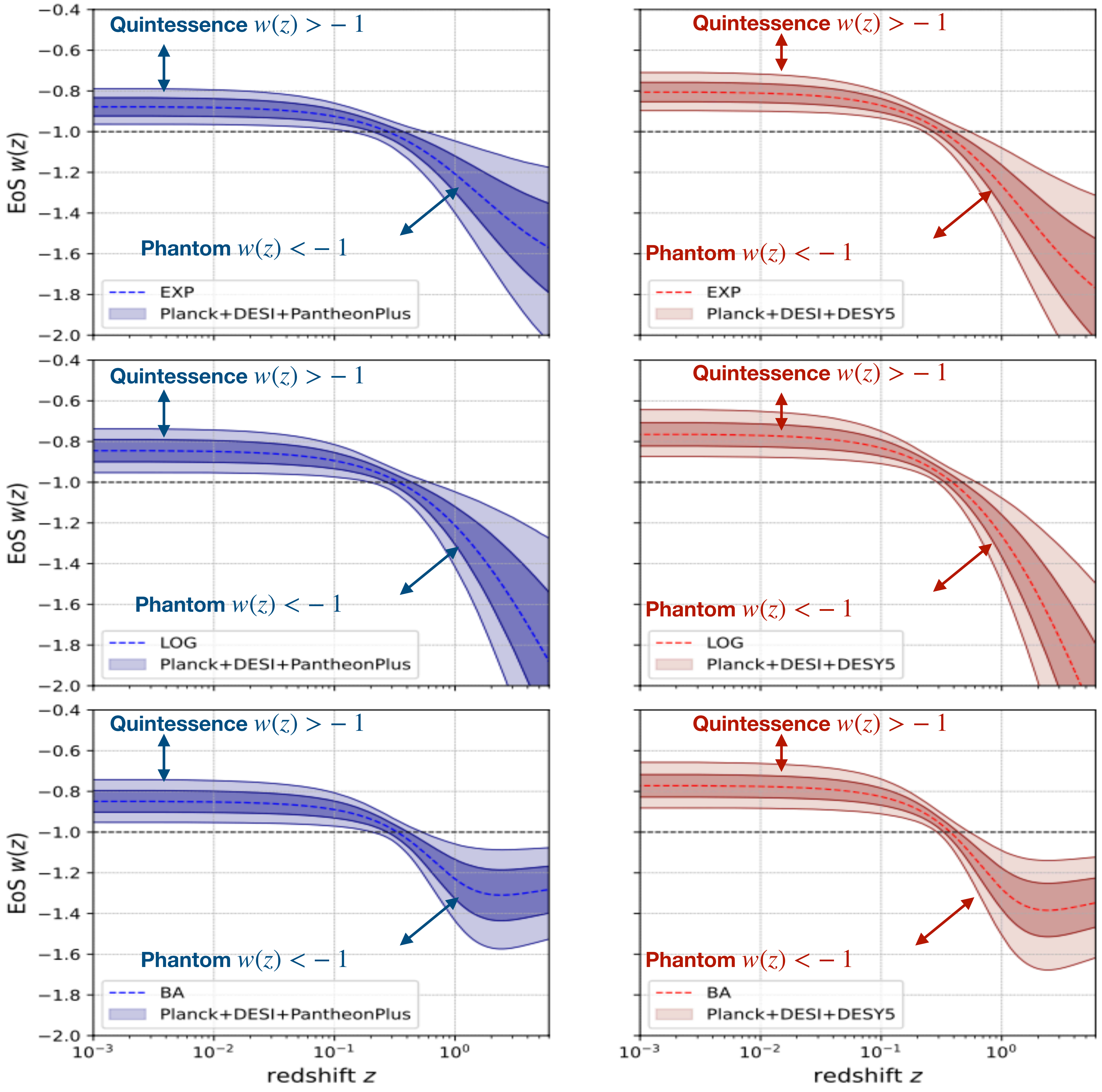

Evolving Dark Energy

Physics of the Dark Universe 48 (2025) 101906

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journal homepage: www.elsevier.com/locate/dark

Review article

An overview of what current data can (and cannot yet) say about evolving dark energy

William Giarè [a], Tariq Mahassen [a], Eleonora Di Valentino [a], Supriya Pan [b,c,*]

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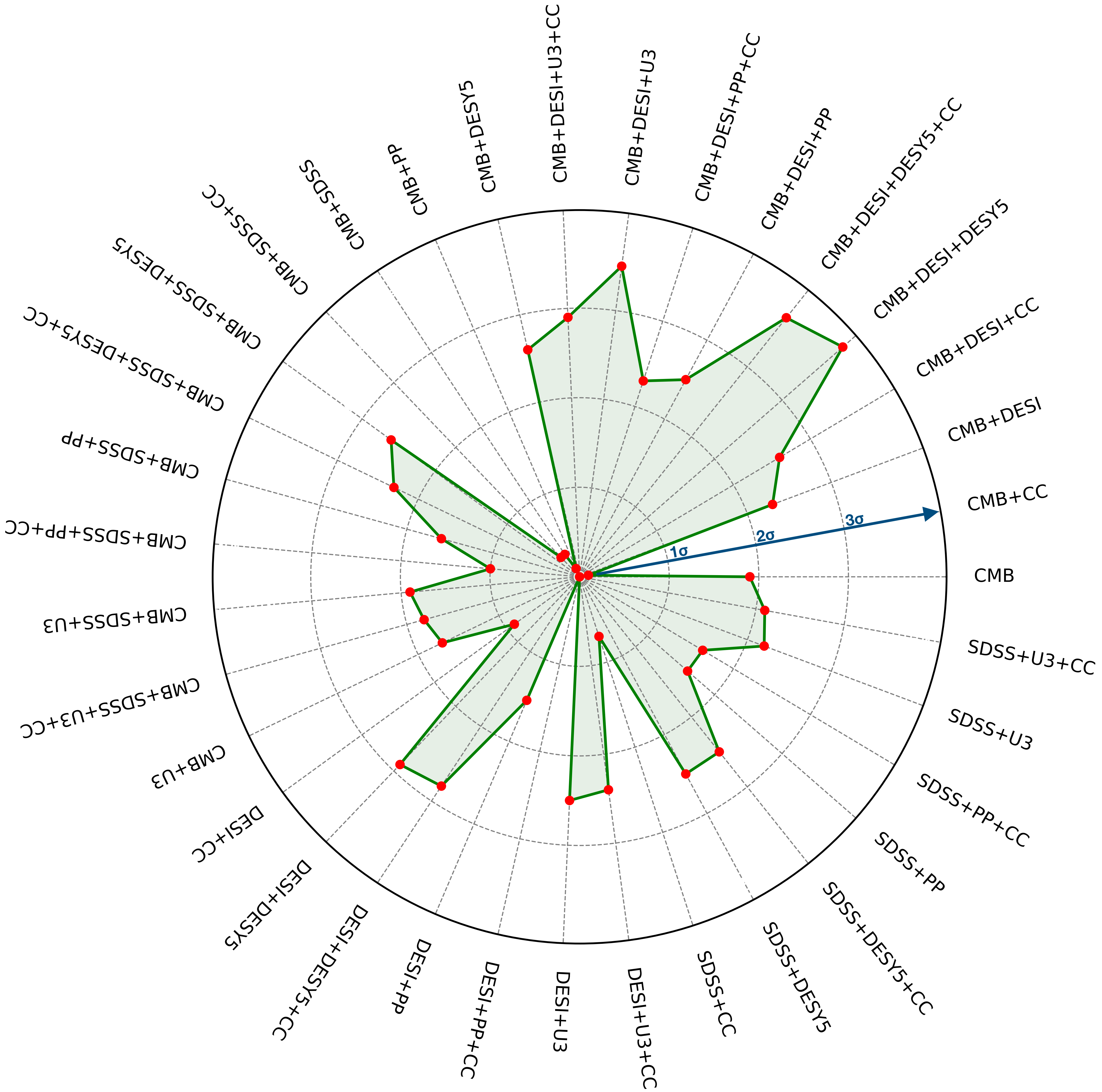
ARTICLE INFO

Keywords:
Dynamical dark energy
Cosmological parameters
Observations

ABSTRACT

Recent measurements of Baryon Acoustic Oscillations (BAO) and distance moduli from Type Ia supernovae suggest a preference for Dynamical Dark Energy (DDE) scenarios characterized by a time-varying equation of state (EoS). This focused review assesses its robustness across independent measurements and surveys. Using the Chevallier-Polarski-Linder (CPL) parametrization to describe the evolution of the DE EoS, we analyze over 35 dataset combinations, incorporating Planck Cosmic Microwave Background (CMB) anisotropies, three independent Type Ia supernova (SN) catalogs (PantheonPlus, Union3, DESY5), BAO measurements from DESI and SDSS, and expansion rate measurements $H(z)$ inferred from the relative ages of massive, passively evolving galaxies at early cosmic times known as Cosmic Chronometers (CC). This review has two main objectives: first, to evaluate the statistical significance of the DDE preference across different dataset combinations, which incorporate varying sources of information. Specifically, we consider cases where only low-redshift probes are used in different combinations, others where individual low-redshift probes are analyzed together with CMB data, and finally, scenarios where high- and low-redshift probes are included in all possible independent combinations. Second, we provide a reader-friendly synthesis of what the latest cosmological and astrophysical probes can (and cannot yet) reveal about DDE. Overall, our findings highlight that combinations that *simultaneously* include PantheonPlus SN and SDSS BAO significantly weaken the preference for DDE. However, intriguing hints supporting DDE emerge in combinations that do not include DESI-BAO measurements: SDSS-BAO combined with SN from Union3 and DESY5 (with and without CMB) support the preference for DDE.

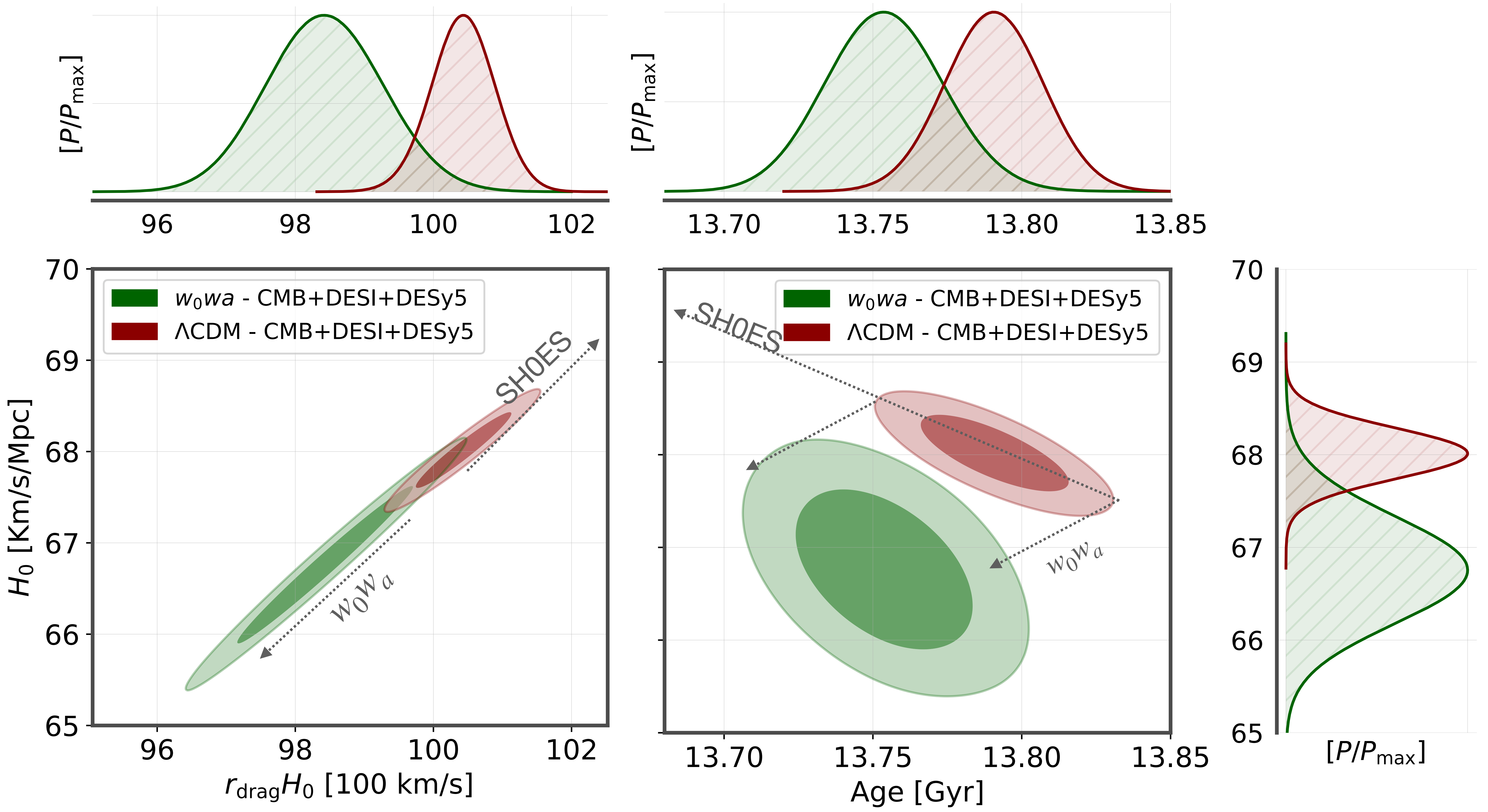
Preference supported by many Independent Probes



Evolving Dark Energy

Can Evolving Dark Energy solve the H_0 Tension?

Fails to reconcile the Hubble Tension



WG & *E. Di Valentino* [arXiv: 25xx.xxxx]

APPROACHES TO THE H_0 TENSION

How do we measure H_0 from 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

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

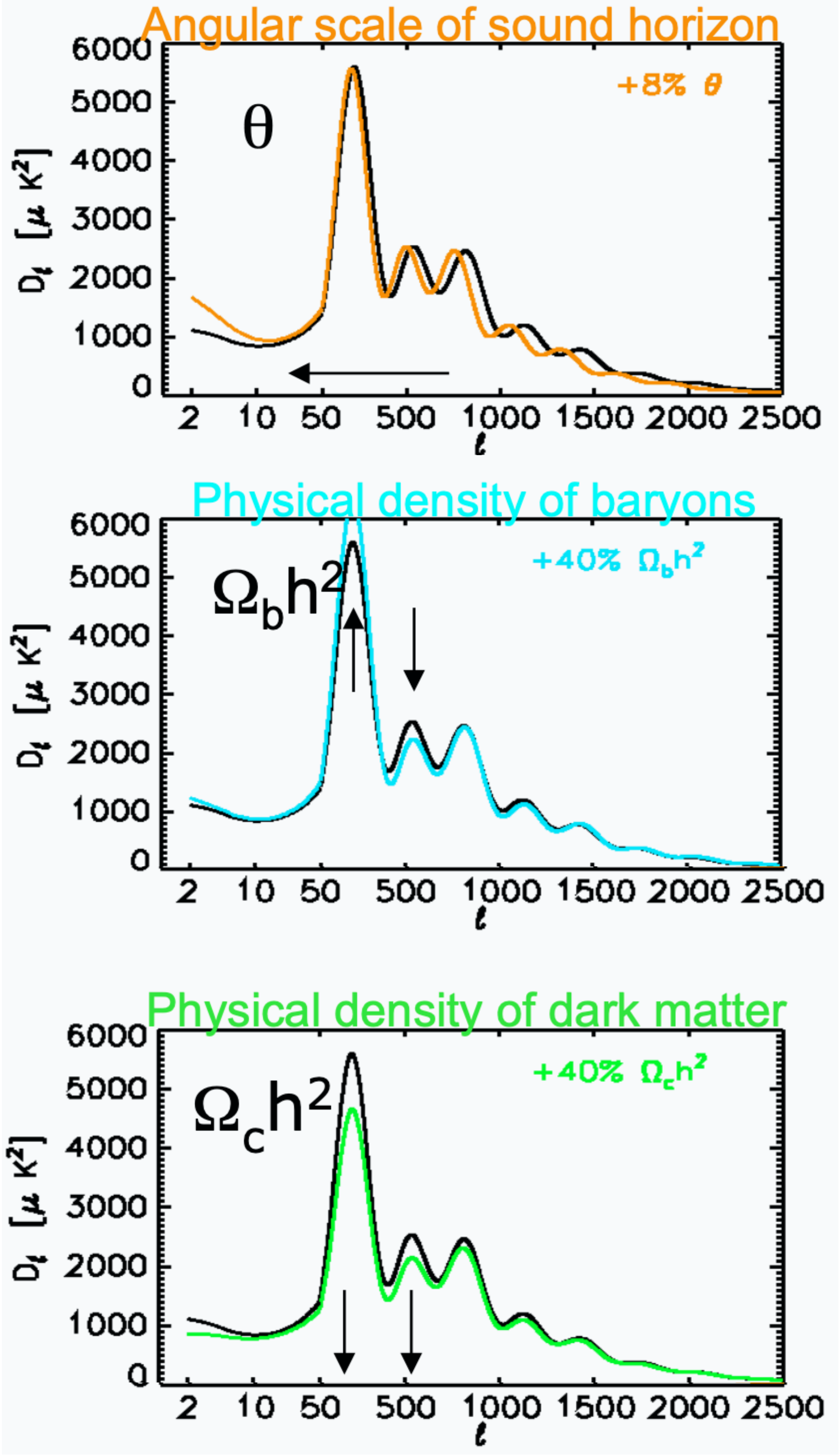
- **The sound horizon $r_s(z_*)$**
- **The angular diameter distance from the CMB, $D_A(z_*) = r_s(z_*)/\theta_s$**

Model of Late Universe

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

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

- **The Hubble Parameter (H_0)**



INTERACTING DARK ENERGY

PHYSICAL REVIEW LETTERS **133,** 251003 (2024)

Interacting Dark Energy after DESI Baryon Acoustic Oscillation Measurements

William Giarè,[1,*] Miguel A. Sabogal,[2,†] Rafael C. Nunes,[2,3,‡] and Eleonora Di Valentino[1,§]
[1]*School of Mathematics and Statistics, University of Sheffield, Hounsfield Road, Sheffield S3 7RH, United Kingdom*
[2]*Instituto de Física, Universidade Federal do Rio Grande do Sul, 91501-970 Porto Alegre RS, Brazil*
[3]*Divisão de Astrofísica, Instituto Nacional de Pesquisas Espaciais, Avenida dos Astronautas 1758, São José dos Campos, 12227-010, São Paulo, Brazil*

(Received 29 April 2024; revised 14 June 2024; accepted 19 November 2024; published 18 December 2024)

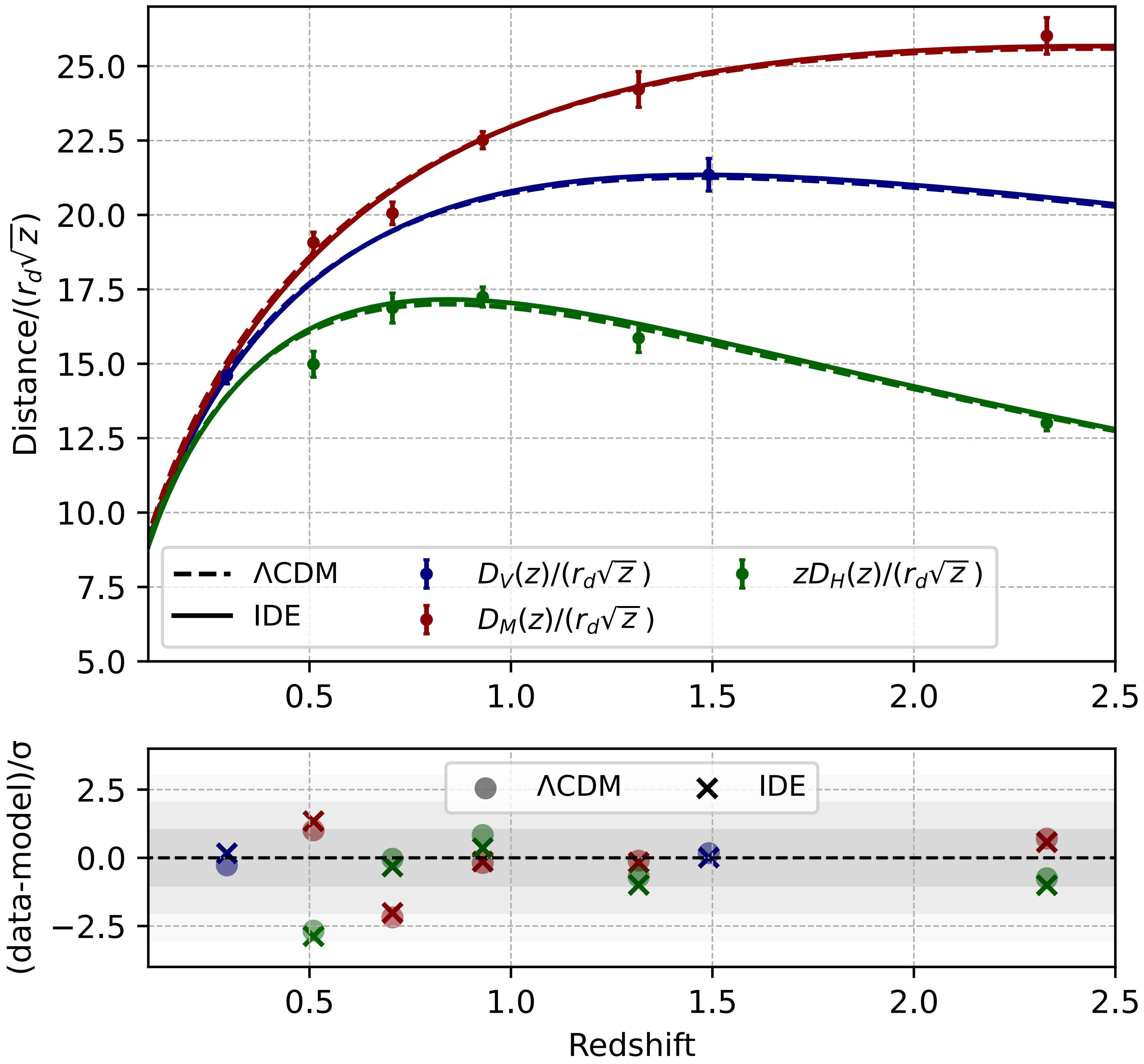
We investigate the implications of the baryon acoustic oscillations measurement released by the Dark Energy Spectroscopic Instrument for interacting dark energy (IDE) models characterized by an energy-momentum flow from dark matter to dark energy. By combining Planck-2018 and Dark Energy Spectroscopic Instrument data, we observe a preference for interactions, leading to a nonvanishing interaction rate $\xi = -0.32^{+0.18}_{-0.14}$, which results in a present-day expansion rate $H_0 = 70.8^{+1.4}_{-1.7}$ km/s/Mpc, reducing the tension with the value provided by the SH0ES Collaboration to less than $\sim 1.3\sigma$. The preference for interactions remains robust when including measurements of the expansion rate $H(z)$ obtained from the relative ages of massive, early-time, and passively evolving galaxies, as well as when considering distance moduli measurements from Type Ia supernovae sourced from the Pantheon-plus catalog using the SH0ES Cepheid host distances as calibrators. Overall, the IDE framework provides an equally good, or better, explanation of both high- and low-redshift *background* observations compared to the lambda cold dark matter model, while also yielding higher H_0 values that align more closely with the local distance ladder estimates. However, a limitation of the IDE model is that it predicts lower Ω_m and higher σ_8 values, which may not be fully consistent with large-scale structure data at the *perturbation* level.

DOI: 10.1103/PhysRevLett.133.251003

IDE introduces **energy-momentum transfer from DM to DE**

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

We focus on the interacting rate $Q = \xi \mathscr{H} \rho_{\rm DE}$



Interacting Dark Energy

PHYSICAL REVIEW LETTERS **133,** 251003 (2024)

Interacting Dark Energy after DESI Baryon Acoustic Oscillation Measurements

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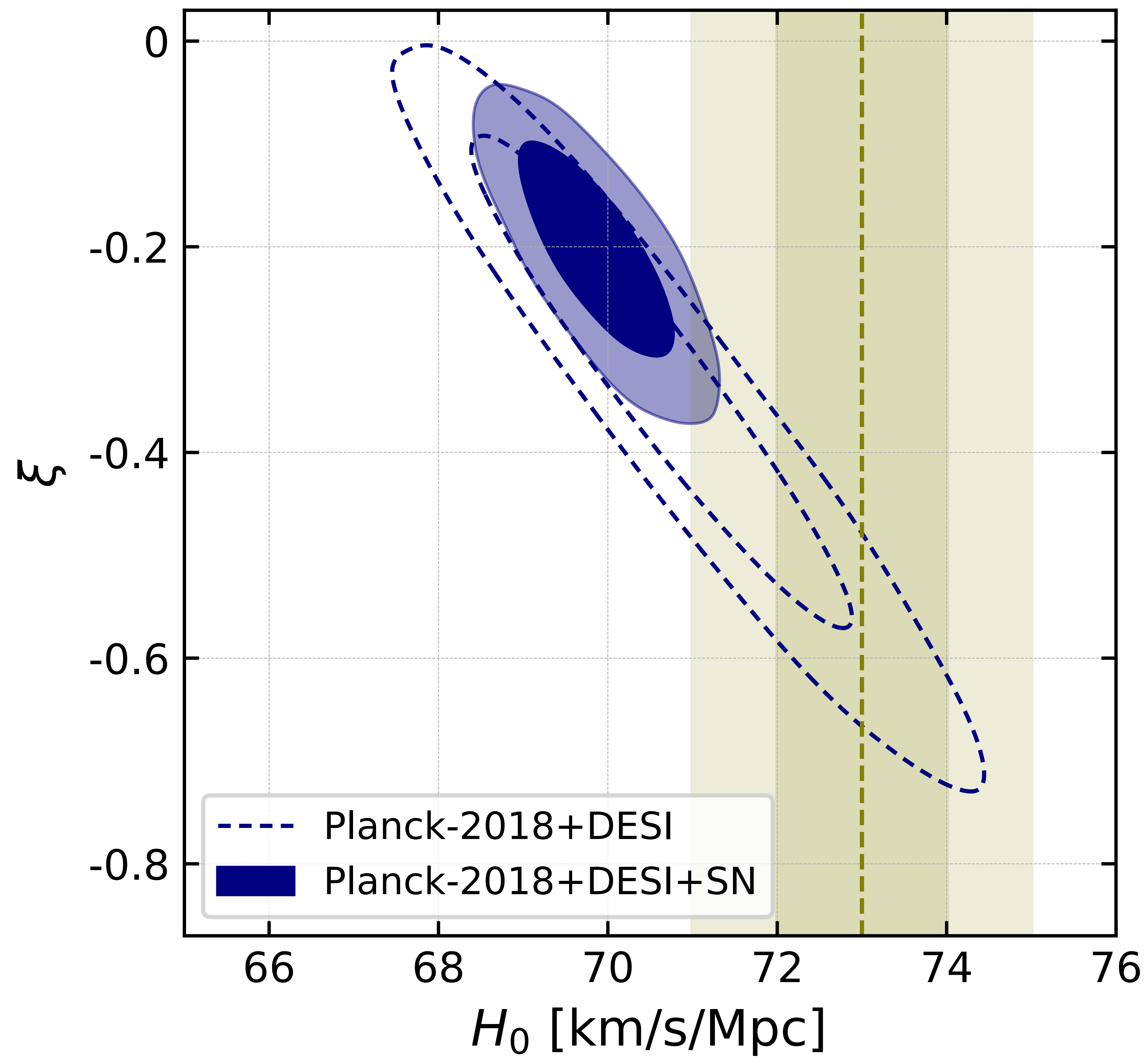

Implications of Late-Time Models

PHYSICAL REVIEW D **112,** 023515 (2025)

Implications of distance duality violation for the H_0 tension and evolving dark energy

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We investigate whether a violation of the distance duality relation (DDR) $D_L(z) = (1+z)^2 D_A(z)$ connecting the angular diameter and luminosity distances can explain the Hubble tension and alter the evidence for dynamical dark energy in recent cosmological observations. We constrain five phenomenological parametrizations of DDR violation using baryon acoustic oscillation measurements from the DESI survey calibrated with the sound horizon derived from *Planck* cosmic microwave background data and the Pantheon + Type Ia supernova (SNIa) catalog calibrated with the supernova absolute magnitude from the Supernovae H_0 for the equation of state program. We find that two toy models can resolve the tension: a constant offset in the DDR (equivalent to a shift in the calibration of the SNIa data) $D_L(z)/D_A(z) \simeq 0.925(1+z)^2$, which leaves the hint for evolving dark energy unaffected, or a change in the power-law redshift dependence of the DDR restricted to $z \lesssim 1$, $D_L(z)/D_A(z) \simeq (1+z)^{1.866}$, together with a constant phantom dark energy equation of state $w \sim -1.155$. The Bayesian evidence slightly favors the latter model. Our phenomenological approach motivates the investigation of physical models of DDR violation as a novel way to explain the Hubble tension.

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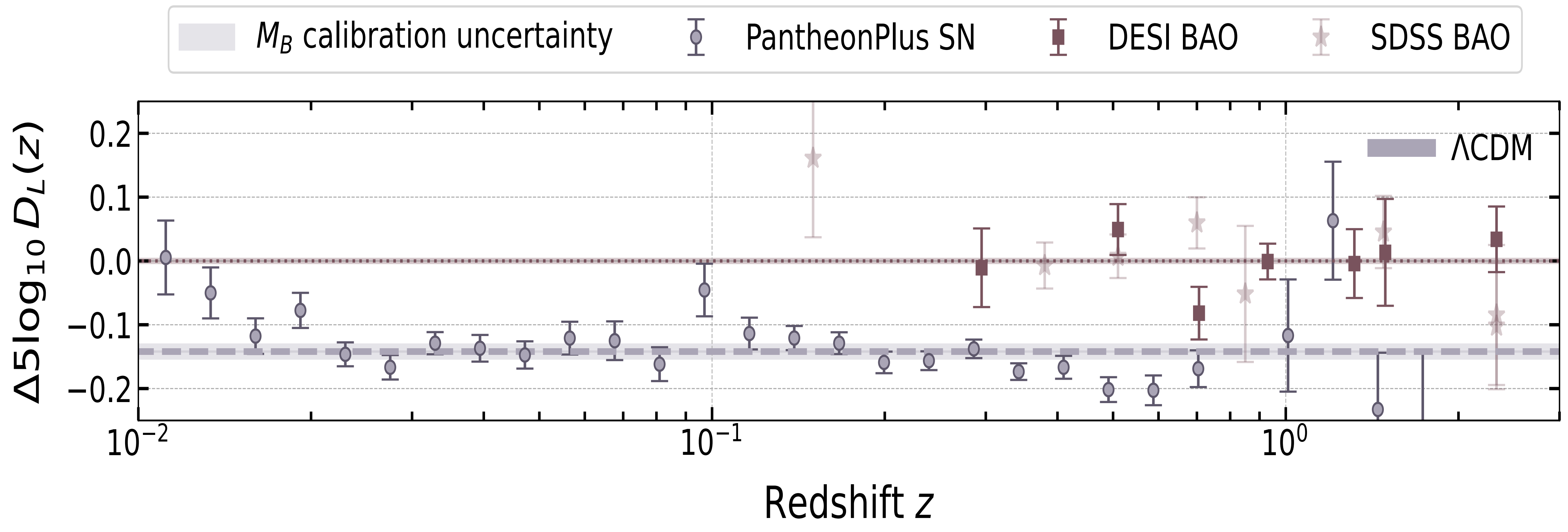
H_0 Tension or Distance Calibration Tension?

Measuring cosmological distances requires **calibration**

BAO measure $\propto D_A(z)/r_d \longrightarrow$ **Planck** $r_d = 147.09 \pm 0.26$ Mpc

SN measure $\propto 5\log_{10} D_L(z) + M_b \longrightarrow$ **SH0ES** $M_b = -19.253 \pm 0.027$ mag

Assuming $D_L(z) = (1+z)^2 D_A(z)$



- Hubble tension partially recast as **distance tension** (**NOT always ~5σ**)
- Late time physics ***cannot solve* the Distance tension** (r_d and M_b unaffected)
- Late time solution ***cannot <u>fully</u> solve* the H_0 tension** (unless we break the DDR)
- Late time solution **can still help a lot with the H_0 tension**

Approaches to the H_0 Tension

How do we measure H_0 from 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

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

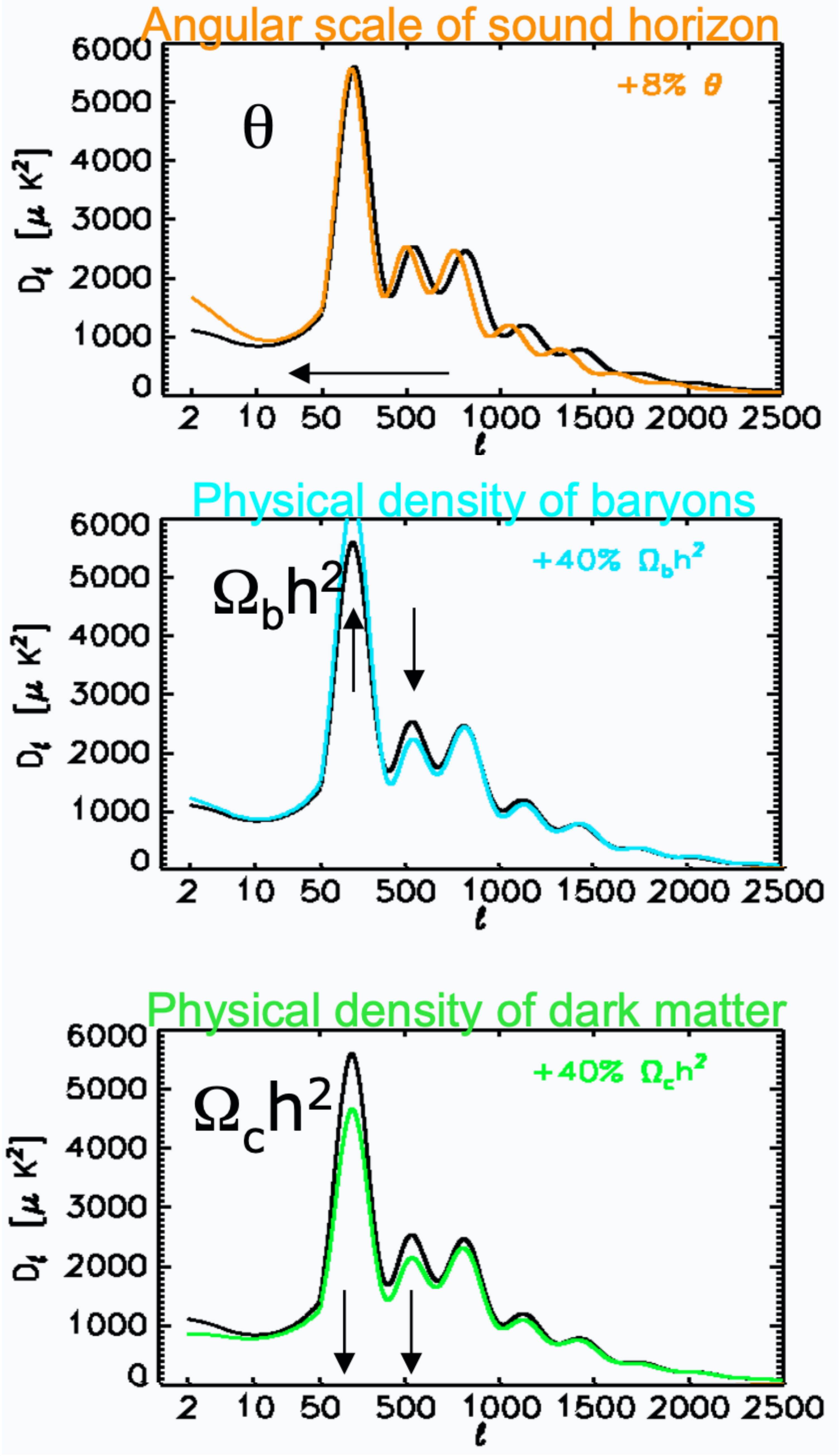
- **The sound horizon $r_s(z_*)$**
- **The angular diameter distance from the CMB, $D_A(z_*) = r_s(z_*)/\theta_s$**

Model of Late Universe

$$D_A(z_*) = \int_{0}^{z_*} dz \, H(z)^{-1}$$

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

- **The Hubble Parameter (H_0)**



Early Time Solutions

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

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

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

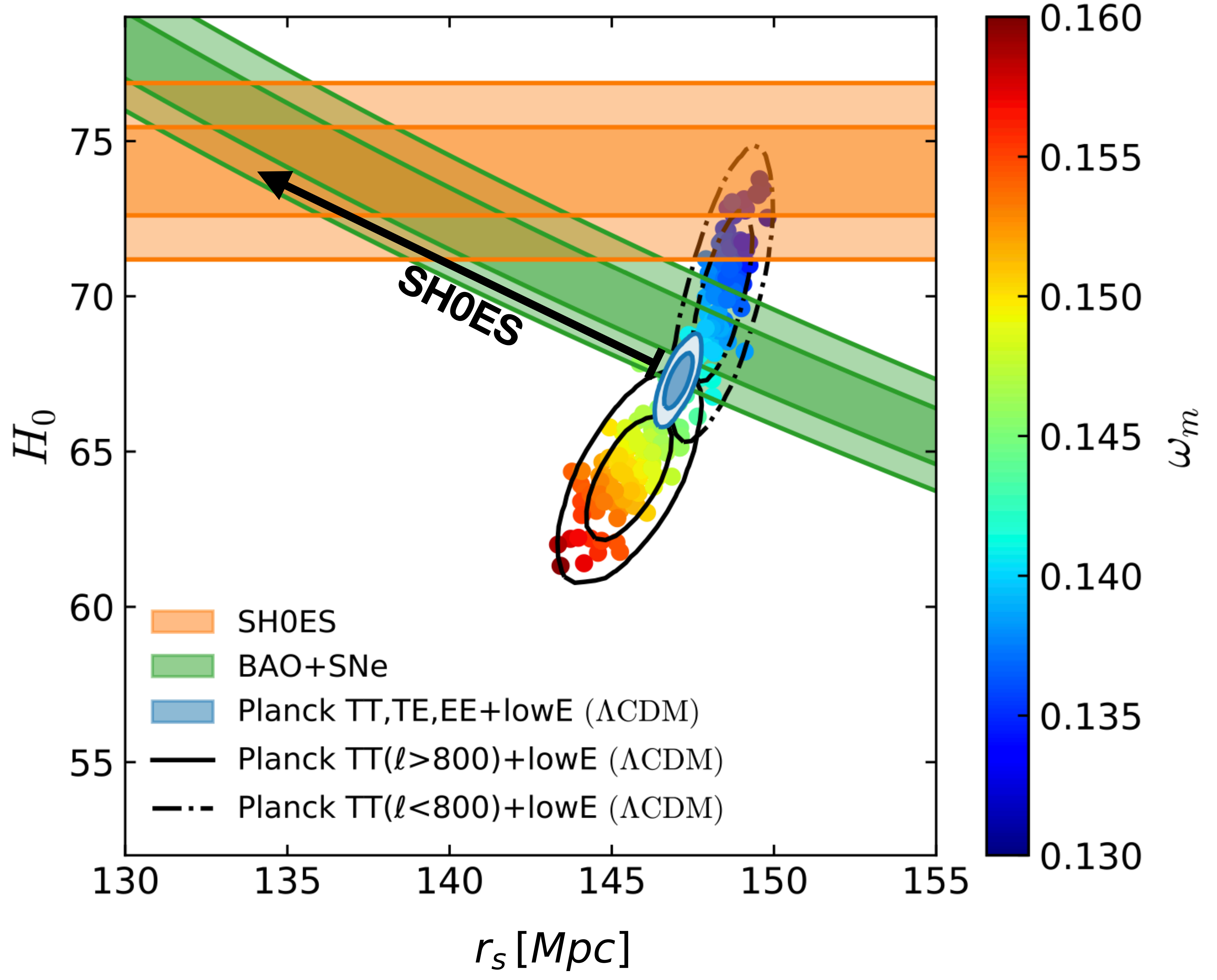
$$D_A(z_*) = \int_0^{z_*} \frac{dz}{H(z)} \simeq \frac{1}{H_0} \int_0^{z_*} \frac{dz}{\left[\Omega_m (1+z)^3 + \Omega_\Lambda\right]^{1/2}}$$

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

1) Changing the sound speed $c_s(z)$ of the Baryon-Photon fluid prior recombination

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

Knox and Millea – 1908.03663



Early Dark Energy

EDE introduces a **DE phase in the Early Universe**, quantified by

$$f_{\mathrm{EDE}} = \max_{z} \left(\frac{\rho_{\mathrm{EDE}}(z)}{\rho_c(z)} \right)$$

i.e., the maximal fractional contribution to the total energy density

Impact of ACT DR6 and DESI DR2 for Early Dark Energy and the Hubble tension

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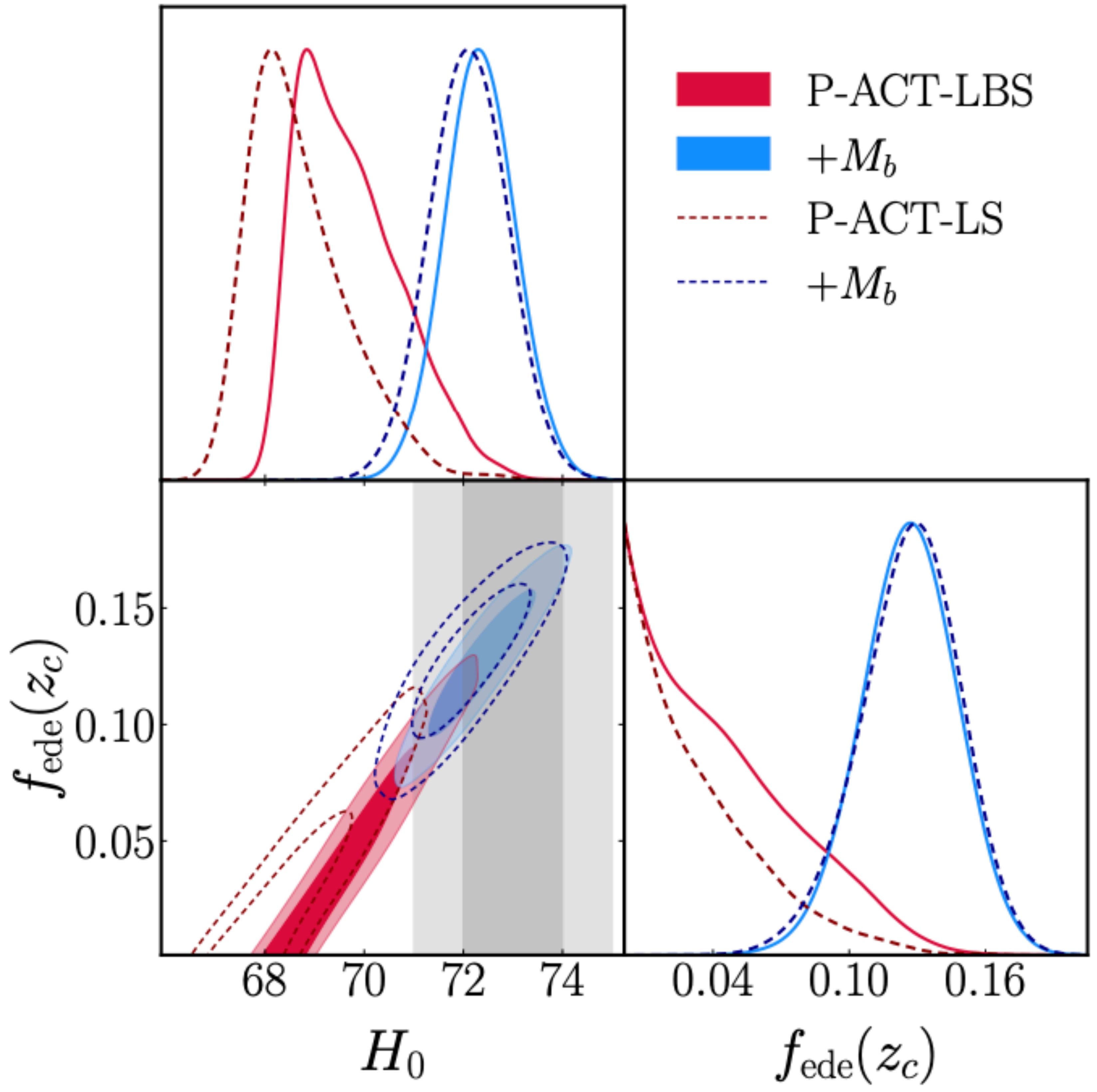
The data release six of the Atacama Cosmology Telescope (ACT DR6) and the second data release from the Dark Energy Spectroscopic Instrument (DESI DR2) recently became available. In light of these data, we update constraints on the Early Dark Energy (EDE) resolution to the Hubble tension. While ACT DR6 does not favor EDE over the core cosmological model ΛCDM, it allows for a significantly larger maximum contribution of EDE, f_{EDE}, in the pre-recombination era than the latest analysis of *Planck* NPIPE despite increased precision at small angular scales. Moreover, EDE rises the value of $H_0 r_s$, improving consistency between CMB and DESI DR2 data. We find a residual tension with SH0ES of $\sim 2\sigma$ for the combination of *Planck* at $\ell < 1000$ + ACT DR6 + lensing + Pantheon-plus + DESI DR2, a significant decrease from 3.7σ for analyses that use NPIPE and SDSS BAO data. A profile likelihood analysis reveals significant prior-volume effects in Bayesian analyses which do not include SH0ES, with confidence intervals of $f_{\mathrm{EDE}} = 0.09 \pm 0.03$ and $H_0 = 71.0 \pm 1.1$ km/s/Mpc. When including DESI data, the EDE model with $H_0 = 73$ km/s/Mpc provides a better fit than the ΛCDM model with $H_0 = 68.4$ km/s/Mpc. The inclusion of SH0ES data rises the preference well above 5σ, with $\Delta\chi^2 = -35.4$. Our work demonstrates that after ACT DR6 and DESI DR2, EDE remains a potential resolution to the Hubble tension.



A (Future) Conclusive Test

PHYSICAL REVIEW LETTERS **135,** 071003 (2025)

Model-Independent Test of Prerecombination New Physics: Measuring the Sound Horizon with Gravitational Wave Standard Sirens and the Baryon Acoustic Oscillation Angular Scale

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In a broad class of cosmological models where spacetime is described by a pseudo-Riemannian manifold, photons propagate along null geodesics, and their number is conserved, upcoming gravitational wave (GW) observations can be combined with measurements of the baryon acoustic oscillation (BAO) angular scale to provide model-independent estimates of the sound horizon at the baryon drag epoch. By focusing on the accuracy expected from forthcoming surveys such as the Laser Interferometer Space Antenna GW standard sirens and dark energy spectroscopic instrument (DESI) or Euclid angular BAO measurements, we forecast a relative precision of $\sigma_{r_d}/r_d \sim 1.5\%$ within the redshift range $z \lesssim 1$. This approach will offer a unique model-independent measure of a fundamental scale characterizing the early universe, which is competitive with model-dependent values inferred within specific theoretical frameworks. These measurements can serve as a consistency test for ΛCDM, potentially clarifying the nature of the Hubble tension and confirming or ruling out new physics prior to recombination with a statistical significance of ∼4σ.

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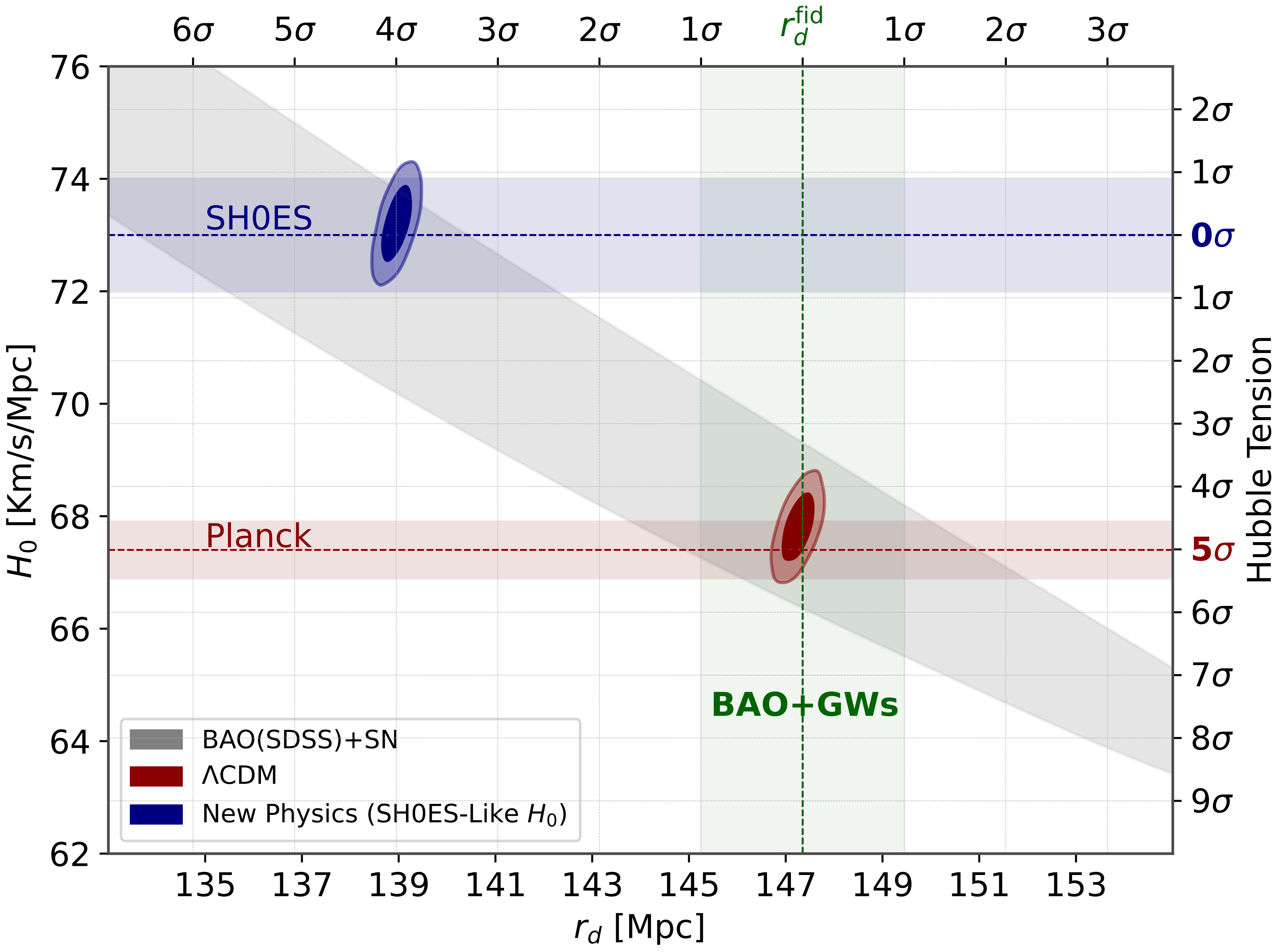
Can we measure r_d without assuming any model or calibration?



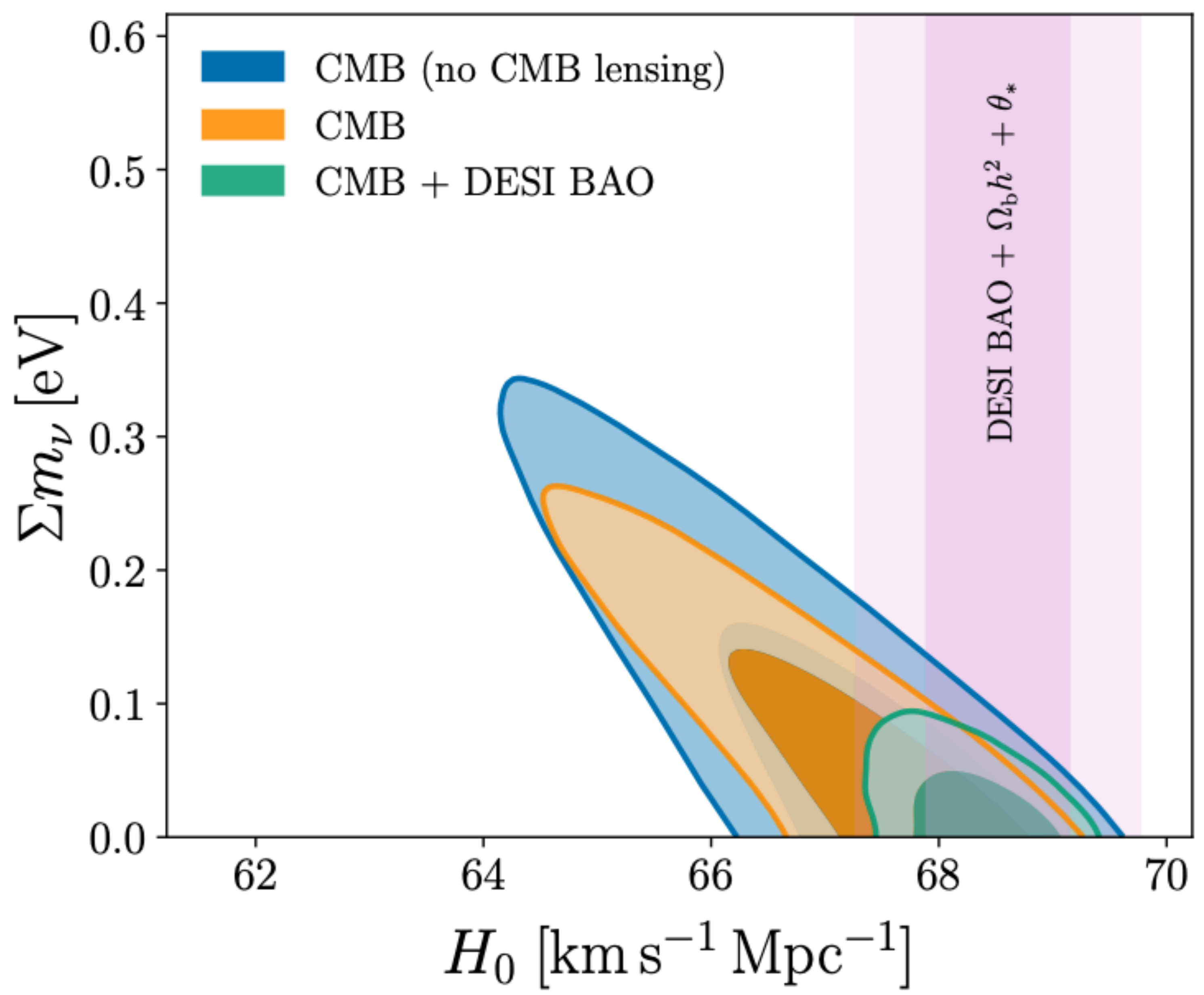
- **GW** standard sirens will measure $D_L^{\rm GW}(z)$
- **BAO** can measure $\theta_{\rm BAO}(z) \equiv \dfrac{r_{\rm d}}{(1+z)D_{\rm A}(z)} = \dfrac{(1+z)r_{\rm d}}{D_{\rm L}(z)}$ (Assuming DDR)
- **BAO+GWs** will measure $r_{\rm d} = \dfrac{\theta_{\rm BAO}\left(z_{\rm BAO}\right) D_{\rm L}^{\rm GW}\left(z_{\rm BAO}\right)}{1+z_{\rm BAO}}$

Hubble Tension, Neutrinos and S_8

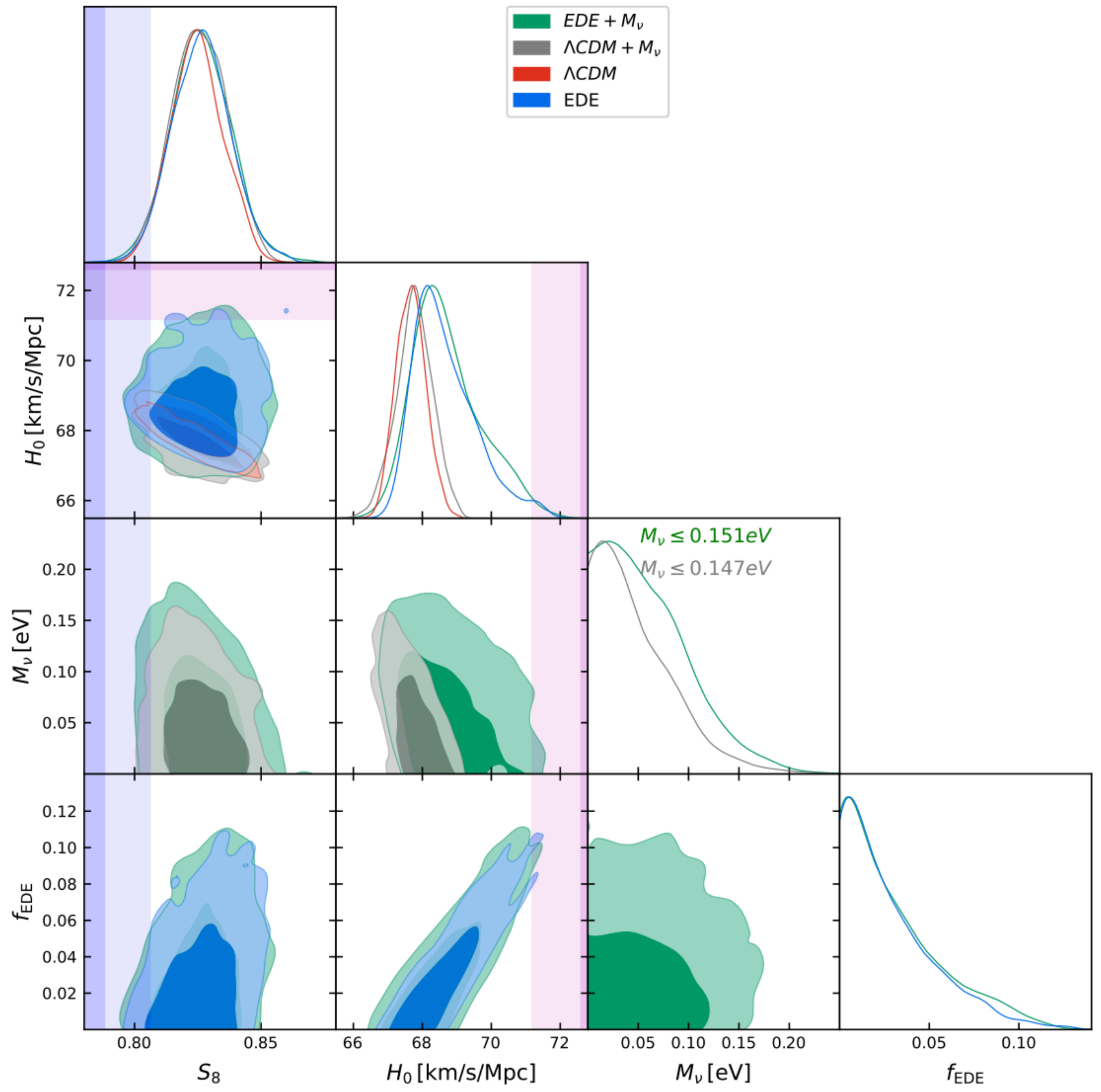
Fail to reconcile the Neutrino Tension

Fail to reconcile the S_8 Discrepancy

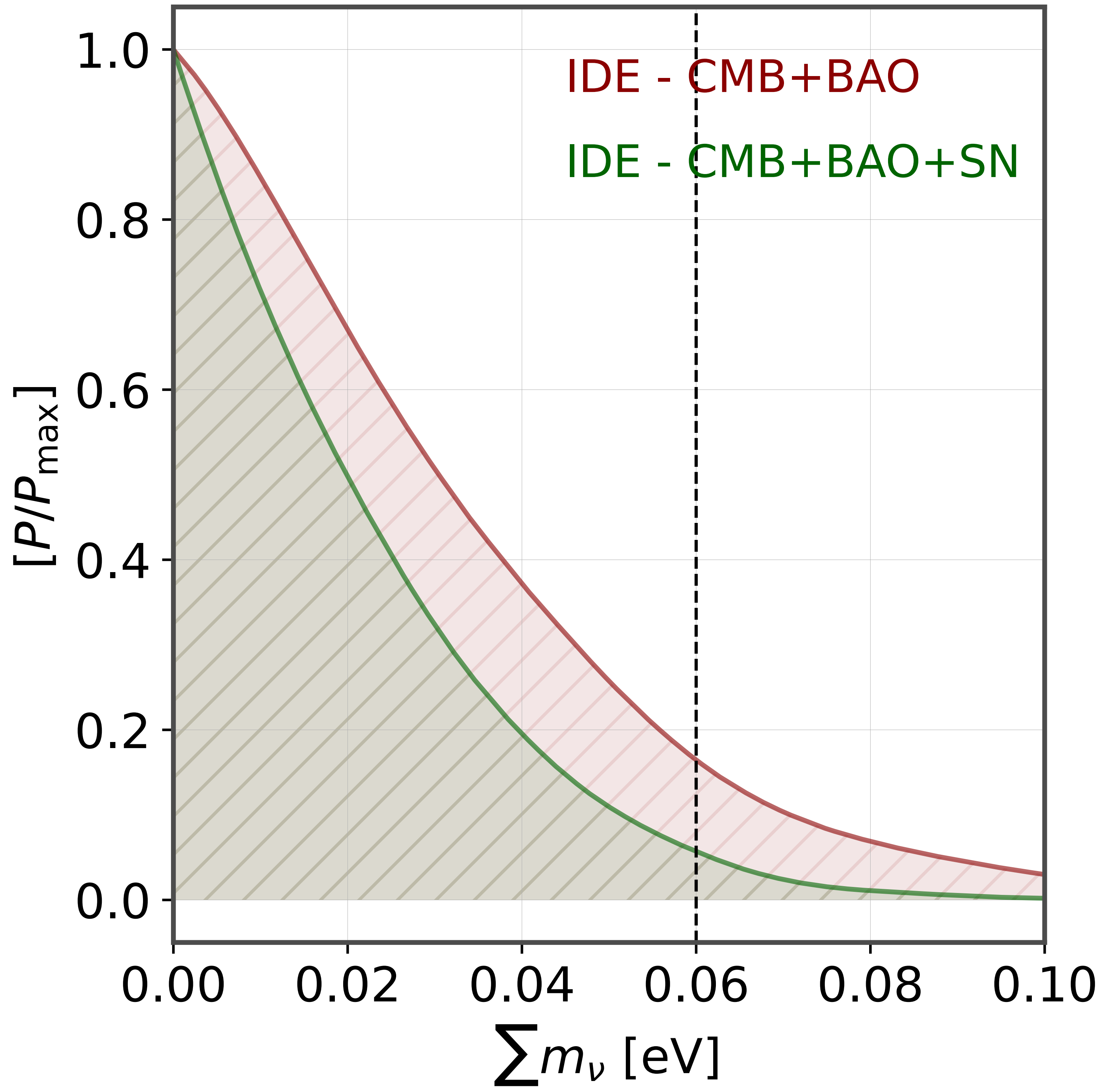
Strong anti-correlation between H_0 and $\sum m_\nu$ → **Models that can increase H_0 typically drag $\sum m_\nu$ towards smaller values**



DESI 2025 — [arXiv:2503.14738]

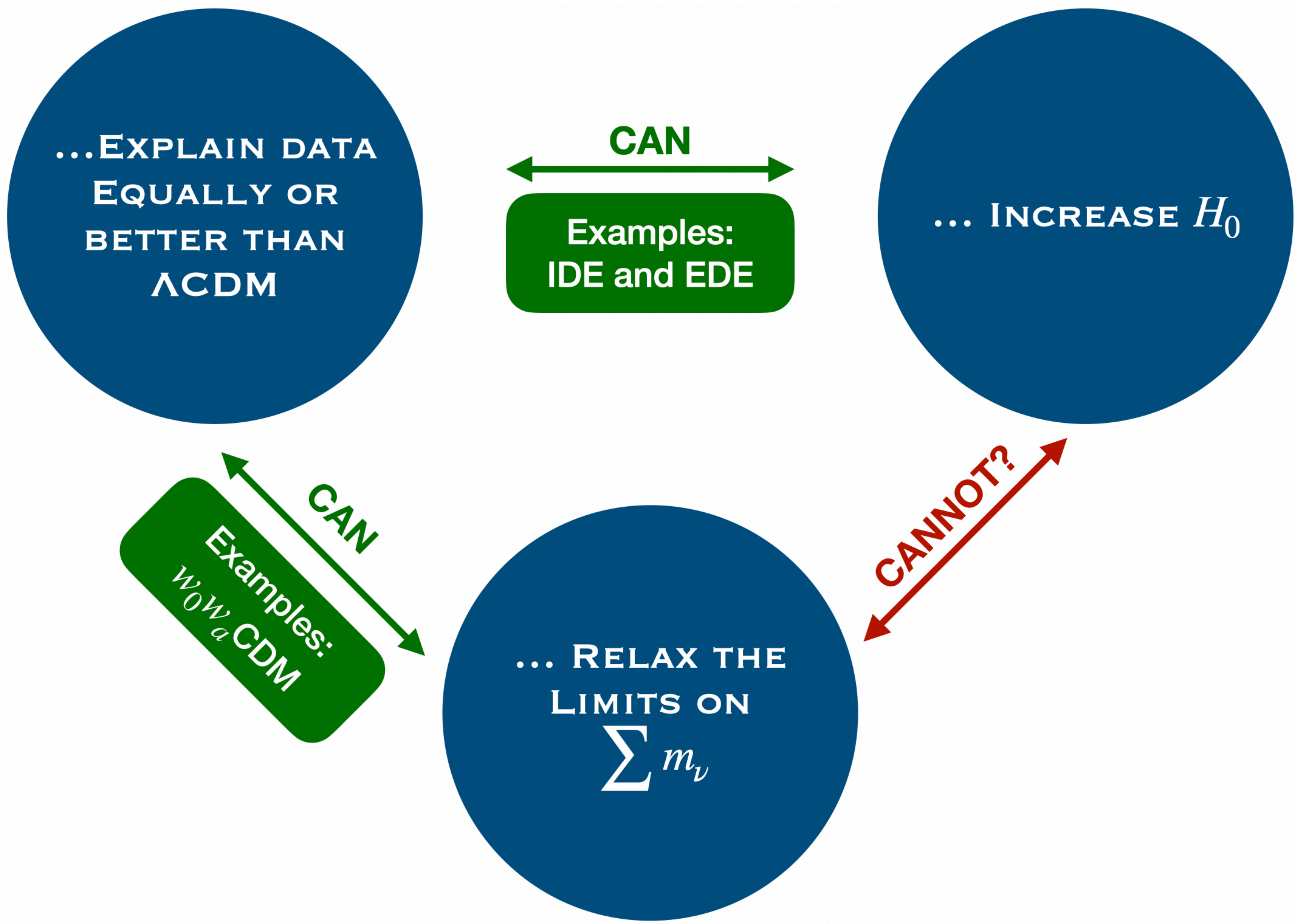


Reeves, *et al.* — [arXiv:2207.01501]



WG & *E. Di Valentino* [arXiv: 250x.xxxx]

So, We Found Models That Can…



Much remains to be understood…

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Thank You for your attention!