Cosmology in Extended Parameter Space with DESI DR2 BAO: A $2\sigma+$ Detection of Non-zero Neutrino Masses with an Update on Dynamical Dark Energy and Lensing Anomaly

Shouvik Roy Choudhury[a]

[a]Institute of Astronomy and Astrophysics, Academia Sinica, No. 1, Section 4, Roosevelt Road, Taipei 106319, Taiwan

E-mail: sroy@asiaa.sinica.edu.tw

Abstract. We obtain constraints in a 12 parameter cosmological model using the recent DESI Data Release (DR) 2 Baryon Acoustic Oscillations (BAO) data, combined with Cosmic Microwave Background (CMB) power spectra (Planck Public Release (PR) 4) and lensing (Planck PR4 + Atacama Cosmology Telescope (ACT) Data Release (DR) 6) data, uncalibrated type Ia Supernovae (SNe) data from Pantheon+ and Dark Energy Survey (DES) Year 5 (DESY5) samples, and Weak Lensing (WL: DES Year 1) data. The cosmological model consists of six ΛCDM parameters, and additionally, the dynamical dark energy parameters (w_0, w_a), the sum of neutrino masses ($\sum m_\nu$), the effective number of non-photon radiation species ($N_{\rm eff}$), the scaling of the lensing amplitude ($A_{\rm lens}$), and the running of the scalar spectral index (α_s). Our major findings are the following: i) With CMB+BAO+DESY5+WL, we obtain the first $2\sigma+$ detection of a non-zero $\sum m_\nu = 0.19^{+0.15}_{-0.18}$ eV (95%). Replacing DESY5 with Pantheon+ still yields a $\sim$1.9σ detection. ii) The cosmological constant lies at the edge of the 95% contour with CMB+BAO+Pantheon+, but is excluded at $2\sigma+$ with DESY5, leaving evidence for dynamical dark energy inconclusive, contrary to claims by DESI collaboration. iii) With CMB+BAO+SNe+WL, $A_{\rm lens} = 1$ is excluded at $> 2\sigma$, while it remains consistent with unity without WL data — suggesting for the first time that the existence of lensing anomaly may depend on non-CMB datasets. iv) The Hubble tension persists at 3.6–4.2σ with CMB+BAO+SNe; WL data has minimal impact.

Contents

1 Introduction

The nature of dark energy (DE) remains one of the most pressing mysteries in modern cosmology. While the Λ-Cold Dark Matter (ΛCDM) model has been widely successful in explaining a range of low and high-redshift cosmological observations, the recent cosmological constraints from the Dark Energy Spectroscopic Instrument (DESI) collaboration [1–4] have provided tantalizing evidence for evolving dark energy, with a potential phantom crossing at a redshift of $z \simeq 0.5$ considering various popular parameterizations for the dynamical nature of dark energy [4]. Combined with the CMB and type Ia Supernovae observations, the DESI Data Release (DR) 2 measurements of the Baryon Acoustic Oscillations (BAO) presently rejects the cosmological constant at the level of 2.8, 3.8, and 4.2σ depending on the supernovae dataset used (PantheonPlus [5], Union3 [6], and Dark Energy Survey Year 5 (DESY5) Supernovae [7] respectively), while using an 8 parameter cosmological model, with the Chevallier-Polarski-Linder (CPL) parameterization [8, 9] for the equation of state (EoS) of the dynamical DE. The EoS in CPL parameterization given by $w(z) \equiv w_0 + w_a\, z/(1+z)$, where z is the redshift. The evidence for an evolving dark energy has strengthened slightly from the previous paper related to the first data release (DR1) of DESI [1]. However, contrary to the DESI DR1 BAO results, currently even the CMB+BAO dataset combination also rejects the cosmological constant at more than 2σ [3]. The significant implications of these results have sparked a substantial number of subsequent studies on dark energy [see, e.g., 10–55].

Another important result from the DESI collaboration is on the neutrino masses. CMB data combined with DESI DR2 BAO puts a stringent constraint of $\sum m_\nu < 0.0642$ eV (95%) in the ΛCDM+$\sum m_\nu$ model (assuming three degenerate neutrino masses) with no evidence for a detection of a non-zero neutrino mass sum [3, 56], which also rules out the inverted mass hierarchy of neutrinos (that requires a minimum $\sum m_\nu$ of 0.096 eV [57]) at more than 2σ. However, given that the DESI results prefer a dynamical dark energy model over ΛCDM, it is debatable how much importance should be put on the neutrino mass bounds obtained in the ΛCDM+$\sum m_\nu$ model. In a model extended with dynamical dark energy (i.e., w_0w_aCDM+$\sum m_\nu$) this bound relaxes to $\sum m_\nu < 0.129$ eV with CMB+BAO+DESY5, which still allowes for both the normal (that requires a minimum $\sum m_\nu$ of 0.057 eV [57]) and inverted hierarchies of neutrinos.[1] We note, however, that such strong bounds have

[1] For earlier bounds on $\sum m_\nu$ in the literature, see e.g., [58–64]. For more recent studies, see [10, 65–67]

attracted attention from the particle physics and cosmology community regarding the possible explanation of a lack of detection of non-zero neutrino masses and apparent possibility of the $\sum m_\nu$ posterior peak occuring at a negative neutrino mass range (i.e., $\sum m_\nu < 0$) [53, 68–70]. In ΛCDM, the DESI BAO data prefers a lower value of Ω_m than Planck (see, e.g., Fig. 10 of [3]), which leads to an apparent issue of $\omega_c + \omega_b > \omega_m$ for joint analyses with CMB and BAO datasets, as pointed out in [69, 70], and that in turn produces such strong bounds on $\sum m_\nu$ in the ΛCDM+$\sum m_\nu$ model. However, we note that the cosmological data favors an evolving dark energy instead of Λ, and in a cosmological model with evolving dark energy, the Ω_m tension does not appear [3].

In [10], using CMB data with DESI DR 1 BAO and uncalibrated supernovae measurements, in a 12-parameter cosmological model[2], we showed that the evidence for dynamical dark energy is not robust yet, since CMB+BAO+Pantheon+ still included the cosmological constant ($w_0 = -1$, $w_a = 0$) within 2σ on the 2D contour plot in the $w_0 - w_a$ plane. We also noticed that the $\sum m_\nu$ posterior probability distributions peaked in the $\sum m_\nu > 0$ region, with three dataset combinations producing a 1σ+ detection. The extended model consisted of the six standard ΛCDM parameters and the following simple extensions: the dynamical dark energy equation of state parameters (CPL: w_0 and w_a), the sum of neutrino masses ($\sum m_\nu$) and effective number of non-photon radiation species ($N_{\rm eff}$), the scaling of the lensing amplitude ($A_{\rm lens}$), and the running of the scalar spectral index (α_s). For CMB data, we used the latest Planck Public Release 4 (PR4) likelihoods (2020): HiLLiPoP and LoLLiPoP [76], and Planck PR4 lensing combined with ACT DR6 lensing likelihoods [77]. For BAO, we used DESI DR1 BAO likelihoods [1], and for supernovae, the latest uncalibrated type Ia Supernovae likelihoods: Pantheon+ [5] and DESY5 [7].

In this paper, we extend the work in [10] by using the new DESI DR2 BAO data [3], while using the same CMB and supernovae (SNe) datasets. Apart from that, we also use the Dark Energy Survey Year 1 (DESY1) data on galaxy clustering and weak lensing [78][3]. Our main goals for this paper are as follows: 1) As in [10], we want to check whether the evidence for dynamical dark energy survives in a largely extended parameter space with simple extensions to the cosmological model. 2) We want to re-assess the $\sum m_\nu$ posteriors with the new DESI DR2 BAO likelihoods and the DES Year 1 results, in this extended model, to check whether we can obtain any 2σ detection of positive non-zero $\sum m_\nu$. 3) We aim to further investigate the lensing anomaly or $A_{\rm lens}$-anomaly [81] situation in the presence of weak lensing data. 4) We aim to assess the level of robustness of the Hubble tension [82, 83] in this largely extended parameter space. With the release of the DESI DR2 BAO data, we believe it is an opportune moment to revisit and update the constraints within such an extended cosmological model. The resulting constraints will undoubtedly be of significant value to both the cosmology and particle physics communities.

The structure of the paper is as follows: Section 2 outlines the analysis methodology. In Section 3, we present and discuss the results of our statistical analysis. We conclude in Section 4. A summary of the cosmological parameter constraints is provided in Table 2.

1

[2] For previous studies in such largely extended parameter spaces, see [63, 71–75].

[3] We note here that a newer data on weak lensing from DES exists (DES Year 3), but the likelihoods are released only for CosmoSIS [79] and not Cobaya [80], which we use in this paper.

2 Analysis methodology

We outline the cosmological model, parameter sampling and plotting codes, as well as the priors on parameters in Section 2.1. Section 2.2 presents a discussion on the cosmological datasets utilized in this study.

2.1 Cosmological model and parameter sampling

Here is the parameter vector for this extended model with 12 parameters :

$$\theta \equiv \left[\omega_c,\ \omega_b,\ \Theta_s^*,\ \tau,\ n_s,\ \ln(10^{10}A_s), w_{0,\mathrm{DE}}, w_{a,\mathrm{DE}}, N_{\mathrm{eff}}, \sum m_\nu, \alpha_s, A_{\mathrm{lens}}\right]. \tag{2.1}$$

The first six parameters correspond to the ΛCDM model: the present-day cold dark matter energy density, $\omega_c \equiv \Omega_c h^2$; the present-day baryon energy density, $\omega_b \equiv \Omega_b h^2$; the reionization optical depth, τ; the scalar spectral index, n_s; and the amplitude of the primordial scalar power spectrum, A_s (both evaluated at the pivot scale $k_* = 0.05\ \mathrm{Mpc}^{-1}$). Additionally, Θ_s^* represents the ratio of the sound horizon to the angular diameter distance at the time of photon decoupling.

The remaining six parameters extend the ΛCDM cosmology. For the CPL parametrization of the dark energy equation of state, we use the notation ($w_{0,\mathrm{DE}}$, $w_{a,\mathrm{DE}}$) interchangeably with (w_0, w_a). The other parameters, as outlined in the introduction, include the effective number of non-photon radiation species (N_{eff}), the sum of neutrino masses ($\sum m_\nu$), the running of the scalar spectral index (α_s), and the scaling of the lensing amplitude (A_{lens}).

We note that we adopt the degenerate hierarchy for neutrino masses, where all three neutrino masses are equal ($m_i = \sum m_\nu/3$ for $i = 1, 2, 3$), and impose a prior $\sum m_\nu \geq 0$. This choice is justified since cosmological observations primarily constrain the total neutrino mass sum through its effect on the energy density [84], and even upcoming cosmological data will remain insensitive to the small neutrino mass splittings [85]. Furthermore, forecasts indicate that assuming a degenerate hierarchy instead of the true mass hierarchy introduces only a negligible bias in the event of a detection of $\sum m_\nu$ [85]. Additionally, there is no definitive evidence favoring a particular neutrino mass hierarchy, even when combining cosmological constraints with terrestrial experiments, such as neutrino oscillation and beta decay data [86].

Since we allow for variations in the running of the scalar spectral index ($\alpha_s \equiv dn_s/d\ln k$, where k is the wave number), we assume a standard running power-law model for the primordial scalar power spectrum, expressed as

$$\ln \mathcal{P}_s(k) = \ln\, A_s + (n_s - 1)\, \ln\left(\frac{k}{k_*}\right) + \frac{\alpha_s}{2}\left[\ln\left(\frac{k}{k_*}\right)\right]^2. \tag{2.2}$$

A small value of $\log_{10}|\alpha_s| = -3.2$ naturally arises in slow-roll inflationary models [87], though certain other inflationary scenarios can yield larger values (see, e.g., [88–90]).

Parameter Sampling: For all Markov Chain Monte Carlo (MCMC) analyses in this paper, we use the cosmological inference code Cobaya [80, 91]. Theoretical cosmology calculations are performed using the Boltzmann solver CAMB [92, 93]. When incorporating the combined Planck PR4 + ACT DR6 lensing likelihood, we apply the higher precision settings recommended by ACT.

To assess chain convergence, we utilize the Gelman and Rubin statistics [94], ensuring that all chains satisfy the convergence criterion of $R-1 < 0.01$. We use GetDist [95] to derive

Parameter	Prior
$\Omega_{\mathrm{b}} h^2$	[0.005, 0.1]
$\Omega_{\mathrm{c}} h^2$	[0.001, 0.99]
τ	[0.01, 0.8]
n_s	[0.8, 1.2]
$\ln(10^{10} A_s)$	[1.61, 3.91]
Θ_s^*	[0.5, 10]
$w_{0,\mathrm{DE}}$	[-1, -0.33]
$w_{a,\mathrm{DE}}$	[-2, 2]
N_{eff}	[2, 5]
$\sum m_\nu$ (eV)	[0, 5]
α_s	[-0.1, 0.1]
A_{lens}	[0.1, 2]

Table 1. Flat priors on the main cosmological parameters constrained in this paper.

parameter constraints and generate the plots presented in this paper. Broad flat priors are imposed on the cosmological parameters, as detailed in Table 1.

2.2 Datasets

CMB: Planck Public Release (PR) 4: We utilize the most recent large-scale (low-l) and small-scale (high-l) Cosmic Microwave Background (CMB) temperature and E-mode polarization power spectra measurements from the Planck satellite. For the high-l ($30 < l < 2500$) TT, TE, and EE data, we adopt the latest HiLLiPoP likelihoods, as detailed in [76]. The low-l ($l < 30$) EE spectra are analyzed using the most recent LoLLiPoP likelihoods, also described in [76]. Both of these likelihoods are derived from the Planck Public Release (PR) 4, the latest reprocessing of data from the LFI and HFI instruments through a unified pipeline, NPIPE, which provides a slightly larger dataset, reduced noise, and improved consistency across frequency channels [96]. For the low-l TT spectra, we employ the Commander likelihood from the Planck 2018 collaboration [81]. We collectively refer to this set of likelihoods as **"Planck PR4."**

CMB lensing: Planck PR4+ACT DR6. CMB experiments also measure the power spectrum of the gravitational lensing potential, $C_l^{\phi\phi}$, through 4-point correlation functions. In our analysis, we utilize the latest NPIPE PR4 Planck CMB lensing reconstruction [97] along with the Data Release 6 (DR6) from the Atacama Cosmology Telescope (ACT) (version 1.2) [77, 98]. Following the recommendations of the ACT collaboration, we adopt the higher precision settings [77]. For conciseness, we refer to this dataset combination as **"lensing"**.

BAO: DESI Data Release (DR) 2.We incorporate the latest measurement of the Baryon Acoustic Oscillation (BAO) signal from Data Release 2 of the Dark Energy Spectroscopic Instrument (DESI) collaboration [3] (for reference to the earlier DR1, see [1]). This dataset includes observations from the Bright Galaxy Sample (BGS, $0.1 < z < 0.4$), the Luminous Red Galaxy Sample (LRG, $0.4 < z < 0.6$ and $0.6 < z < 0.8$), the Emission Line Galaxy Sample (ELG, $1.1 < z < 1.6$), the combined LRG and ELG sample within a shared redshift range (LRG+ELG, $0.8 < z < 1.1$), the Quasar Sample (QSO, $0.8 < z < 2.1$), and the Lyman-α Forest Sample (Lyα, $1.77 < z < 4.16$). We refer to this complete dataset as **"DESI2."**

Parameter	Planck PR4 +lensing+DESI2	Planck PR4 +lensing+DESI2+PAN+	Planck PR4 +lensing+DESI2+PAN++WL	Planck PR4 +lensing+DESI2+DESY5	Planck +lensing+DESI2+DESY5+WL
$\Omega_b h^2$	0.02238 ± 0.00020	0.02246 ± 0.00019	0.02253 ± 0.00019	0.02242 ± 0.00020	0.02251 ± 0.00019
$\Omega_c h^2$	0.1190 ± 0.0028	0.1191 ± 0.0028	0.1184 ± 0.0028	0.1190 ± 0.0028	0.1184 ± 0.0028
τ	$0.0584^{+0.0061}_{-0.0068}$	0.0586 ± 0.0066	0.0579 ± 0.0065	0.0586 ± 0.0065	0.0579 ± 0.0065
n_s	0.972 ± 0.009	0.975 ± 0.009	0.978 ± 0.009	0.974 ± 0.009	0.977 ± 0.009
$\ln(10^{10} A_s)$	3.042 ± 0.016	3.043 ± 0.016	3.039 ± 0.016	3.043 ± 0.016	3.039 ± 0.016
$100\Theta_s^*$	1.04082 ± 0.00040	1.04082 ± 0.00039	1.04086 ± 0.00040	1.04083 ± 0.00039	1.04085 ± 0.00039
$\sum m_\nu$ (eV)	$0.147^{+0.064}_{-0.12}$ (1σ), < 0.302 (2σ)	< 0.242 (2σ)	0.166 ± 0.087 (1σ), < 0.313 (2σ)	< 0.261 (2σ)	0.190 ± 0.088 (1σ), $0.19^{+0.15}_{-0.18}$ (2σ)
$N_{\rm eff}$	3.10 ± 0.19	3.15 ± 0.19	3.16 ± 0.19	3.12 ± 0.19	3.15 ± 0.19
w_0	-0.46 ± 0.23	-0.864 ± 0.056	-0.859 ± 0.057	-0.775 ± 0.061	-0.768 ± 0.062
w_a	-1.61 ± 0.70	$-0.44^{+0.26}_{-0.22}$	$-0.47^{+0.27}_{-0.23}$	$-0.72^{+0.29}_{-0.24}$	$-0.76^{+0.30}_{-0.26}$
$n_{\rm run}$	-0.0031 ± 0.0074	-0.0018 ± 0.0072	0.0004 ± 0.0072	-0.0022 ± 0.0073	0.0002 ± 0.0072
$A_{\rm lens}$	$1.061^{+0.046}_{-0.54}$ (1σ)	$1.068^{+0.042}_{-0.50}$ (1σ)	1.104 ± 0.044 (1σ), $1.104^{+0.089}_{-0.084}$ (2σ)	$1.063^{+0.043}_{-0.52}$ (1σ)	1.104 ± 0.044 (1σ), $1.104^{+0.090}_{-0.085}$ (2σ)
H_0 (km/s/Mpc)	$64.0^{+2.0}_{-2.6}$	67.9 ± 1.0	67.9 ± 1.0	67.0 ± 1.0	67.1 ± 1.0
S_8	0.823 ± 0.021	$0.808^{+0.019}_{-0.016}$	0.791 ± 0.015	$0.812^{+0.019}_{-0.017}$	0.793 ± 0.016
Ω_m	0.350 ± 0.023	0.309 ± 0.006	0.309 ± 0.006	0.318 ± 0.006	0.318 ± 0.006

Table 2. Bounds on cosmological parameters in the 12 parameter extended model. Marginalized limits are given at 68% C.L. whereas upper limits are given at 95% C.L. Note that H_0, S_8, and Ω_m are derived parameters.

SNe Ia: Pantheon+.We incorporate the latest Supernovae Type-Ia (SNeIa) luminosity distance measurements from the Pantheon+ Sample [99], which consists of 1550 spectroscopically confirmed SNeIa spanning the redshift range $0.001 < z < 2.26$. For our analysis, we use the publicly available likelihood from [5], which accounts for both statistical and systematic covariance. This likelihood applies a constraint of $z > 0.01$ to mitigate the impact of peculiar velocities on the Hubble diagram. We refer to this dataset as **"PAN+"**.

SNe Ia: DES Year 5. We make use of the luminosity distance measurements from the latest supernova sample, which includes 1635 photometrically classified SNeIa in the redshift range $0.1 < z < 1.3$, publicly released by the Dark Energy Survey (DES) as part of their Year 5 data release [7]. We refer to this dataset as **"DESY5"**.

We note that PAN+ and DESY5 share some supernovae in common. To prevent double counting, these two datasets are never used simultaneously in our analysis.

Weak Lensing: DES Year 1. We include the likelihood from the combined analysis of galaxy clustering and weak gravitational lensing, using 1321 deg^2 of *griz* imaging data from the first year of the Dark Energy Survey [78]. We refer to this dataset as **"WL"**.

3 Numerical results

The main findings from our cosmological parameter estimation are summarized in Table 2 and illustrated in Figures 1–6.

We provide a brief summary of our findings related to the cosmological parameters below:

- $w_{0,\rm DE}$ and $w_{a,\rm DE}$: As shown in Figure 1, when CMB and BAO data are combined with Pantheon+, the cosmological constant scenario ($w_{0,\rm DE} = -1$, $w_{a,\rm DE} = 0$) lies at the edge of the 95% confidence contour. We also find that a region of the quintessence/non-phantom dark energy parameter space ($w(z) \geq -1$ at all redshifts) is also allowed

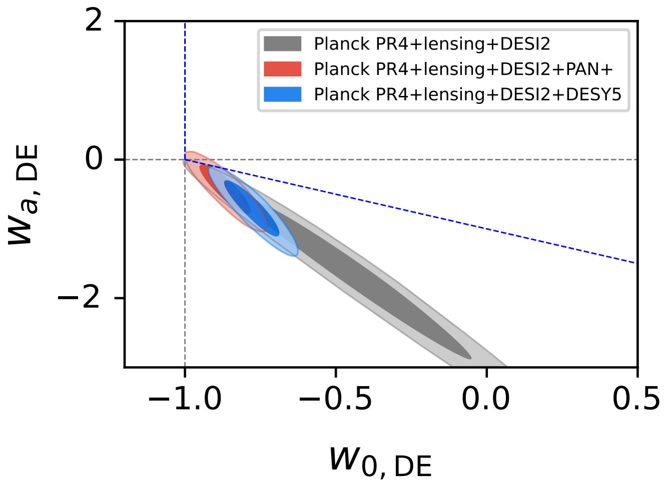

Figure 1. 68% and 95% marginalised contours in the $w_{0,\mathrm{DE}} - w_{a,\mathrm{DE}}$ plane for different data combinations. The area to the right of the vertical dashed blue line and above the slanted dashed blue line represents the parameter space corresponding to quintessence-like or non-phantom dark energy.

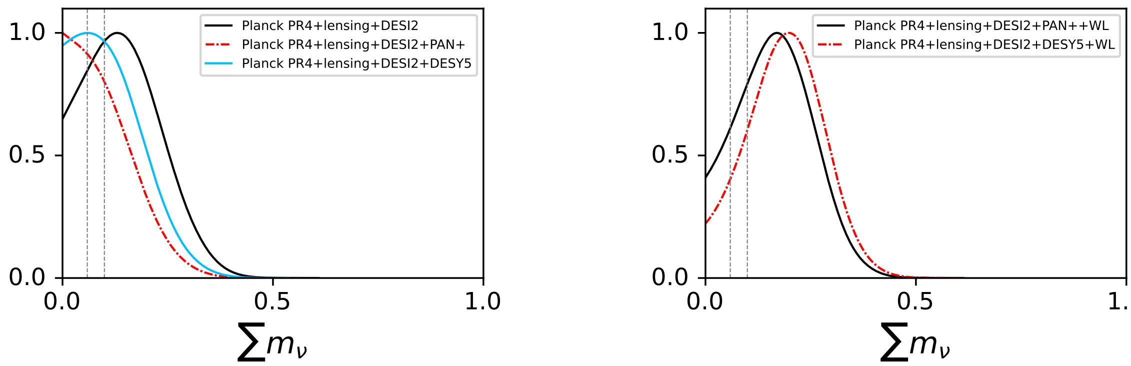

Figure 2. A comparison of the 1D marginalized posterior distributions for $\sum m_\nu$ [eV] across various data combinations. The panel in the right shows results with the DES Year 1 Weak Lensing data (WL) included. Note that in the right panel, the Planck PR4+lensing+DESI2+DESY5+WL dataset combination leads to a 2σ+ detection of non-zero $\sum m_\nu$. The two vertical black dashed lines (in both panels) indicate the minimum mass thresholds for the normal (0.057 eV) and inverted (0.096 eV) neutrino mass hierarchies, respectively.

within 2σ with Pantheon+. However, when using the DESY5 SNe Ia data, we find that the cosmological constant is excluded at more than 2σ, with a $\sim 2\sigma$ level tension also observed for non-phantom (quintessence-like) dark energy models. Therefore, we conclude that the evidence reported by the DESI BAO collaboration for a dynamical dark energy equation of state is not yet conclusive. We note that the addition of the WL data has negligible effect on the constraints on the DE equation of state parameters, and thus it does not change any conclusions regarding the same.

- $\sum m_\nu$: Figure 2 shows the 1D marginalized posterior distributions of $\sum m_\nu$ for different

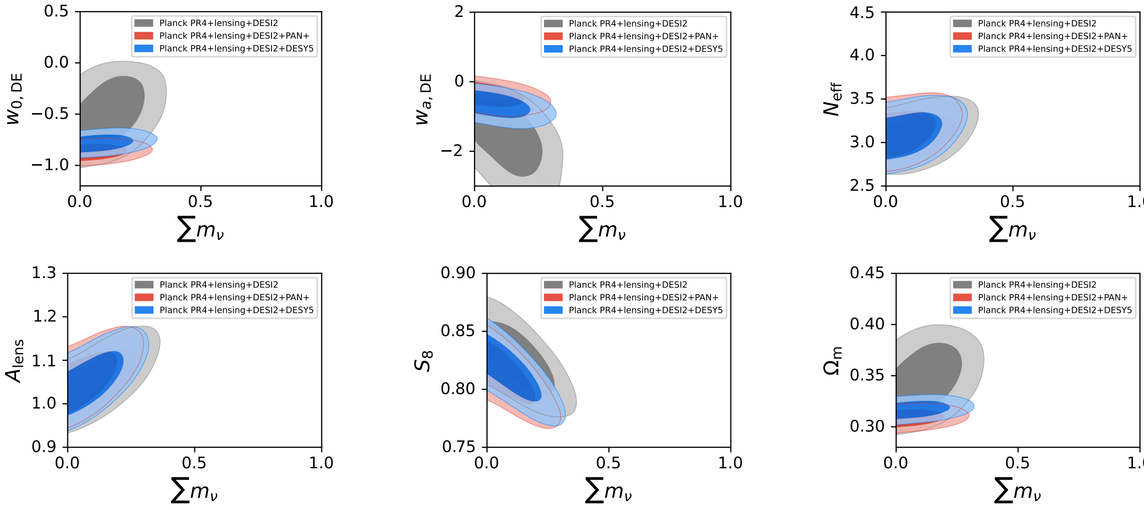

Figure 3. A comparison of the 2D correlation plots between $\sum m_\nu$ [eV] and various other parameters across various data combinations.

dataset combinations, while Figure 3 displays the 68% and 95% 2D confidence contours between $\sum m_\nu$ and several other cosmological parameters. We notice in the left panel of Figure 2, that without the WL data, there is no 2σ detection of non-zero neutrino masses, but still, we do find that the posteriors peak in the $\sum m_\nu > 0$ region for Planck PR4+lensing+DESI2 and Planck PR4+lensing+DESI2+DESY5. In fact, there is a 1σ+ detection with Planck PR4+lensing+DESI2. However, with the addition of the WL data, we find clear peaks in the $\sum m_\nu$ posteriors, with a 2.1σ detection with Planck PR4+lensing+DESI2+DESY5+WL at $\sum m_\nu = 0.19^{+0.15}_{-0.18}$ eV and a 1.9σ detection with Planck PR4+lensing+DESI2+PAN++WL. As far as we are aware, this is the first 2σ+ detection of a non-zero $\sum m_\nu$ with DESI DR2 BAO data. The detection with WL follows from the strong negative correlation between S_8 and $\sum m_\nu$, as visualized in the middle bottom panel of Figure 3. The lower S_8 values due to the WL data leads to rejection of smaller neutrino masses. We note here that the DES Year 1 WL data used in this work provides a value of $S_8 = 0.783^{+0.021}_{-0.025}$ in the ΛCDM model [78], which is only discrepant at the level of 0.95σ with the S_8 value in this 12 parameter model using CMB+BAO+PAN+ and 1.07σ with CMB+BAO+DESY5. Thus it is okay to combine the WL data with the CMB+BAO+SNe combination. Also note that if we consider a 12 parameter model with WL data alone, then the errors on S_8 will likely be larger, thereby reducing the discrepancy further. Previously in [10], we had also noted that the S_8 tension is only at the level of 1.4σ with the DES Year 3 data (see also [76]), which prefers slightly lower values of S_8 than DES Year 1 [100]. Therefore, had we used the DES Year-3 likelihoods instead, we would likely have obtained stronger evidence for a non-zero $\sum m_\nu$. It is worth noting, however, that recent results from the completed KiDS survey report slightly higher constraints on S_8, with $S_8 = 0.815^{+0.016}_{-0.021}$ within the ΛCDM framework [101]. Therefore, it remains uncertain whether a non-zero $\sum m_\nu$ detection would persist when using the KiDS dataset. However, caution is warranted, as the model favored by the DESY5 data deviates significantly from the standard ΛCDM framework, and thus, the S_8 inference from KiDS data might also differ from ΛCDM. We also observe that with the CMB+BAO+SNe combination, $\sum m_\nu$ exhibits

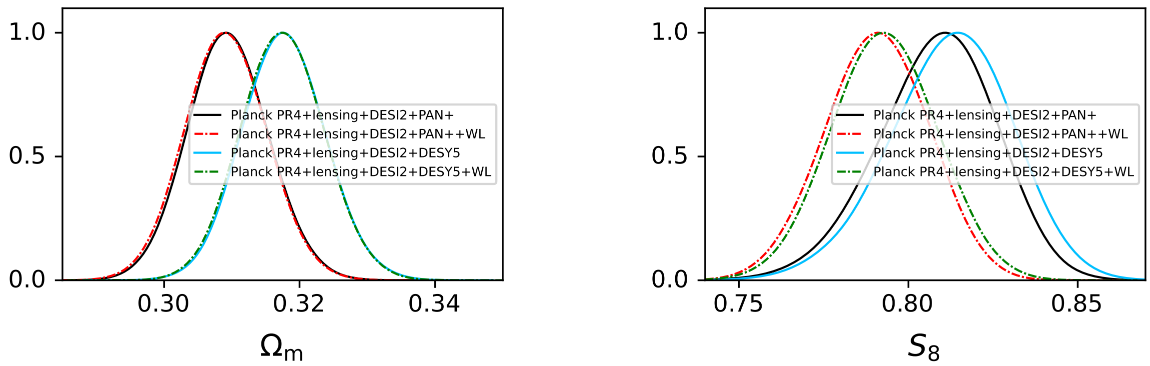

Figure 4. A comparison of the 1D marginalized posterior distributions for Ω_m and S_8 across various data combinations. Note that the Ω_m posteriors remain similar with the addition of WL data, but the S_8 values are lowered.

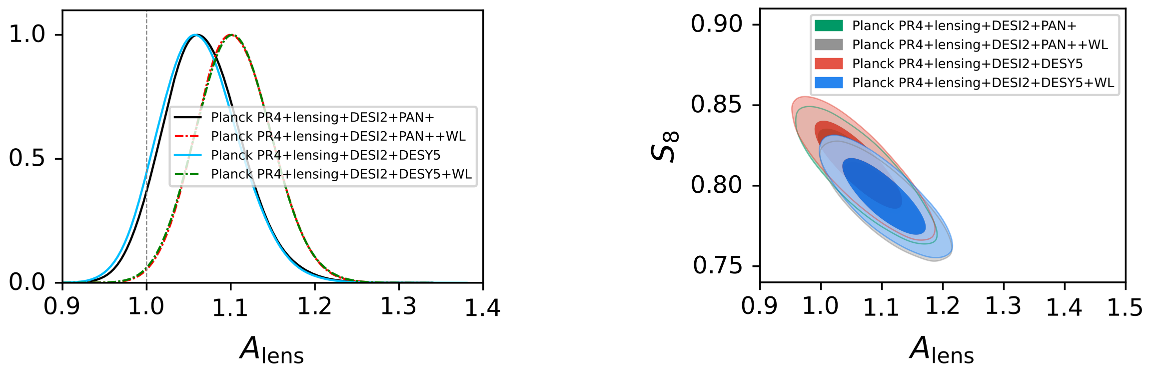

Figure 5. The left panel shows the 1D posterior distributions of $A_{\rm lens}$ for various data combinations. The right panel shows its 2D correlation plots with the S_8 parameter. We note that dataset combinations with WL included leads to a $2\sigma+$ lensing anomaly due to the strong correlation with S_8.

mild correlations with $N_{\rm eff}$, Ω_m, and w_0, while its correlations with $A_{\rm lens}$, w_a, and S_8 are notably stronger. These parameter correlations contribute to the loosening of the constraints on $\sum m_\nu$.

- Ω_m and S_8: From the 1D posterior distributions in the left panel of Figure 4, we find that while the inclusion of WL data has minimal effect on the estimation of Ω_m, the DESY5 dataset favors slightly higher values of Ω_m compared to Pantheon+. In contrast, the right panel of Figure 4 shows that, as expected, adding the WL data shifts the preferred S_8 values to lower values.

- $A_{\rm lens}$: The right panel of Figure 5 reveals a strong negative correlation between S_8 and $A_{\rm lens}$. Examining the left panel, we observe that the inclusion of WL data shifts the $A_{\rm lens}$ values to higher values—a direct consequence of this correlation. As shown in Table 2, with the addition of WL data, the inferred $A_{\rm lens}$ deviates from unity by more than 2σ. This is a significant result because, for the first time in literature, we find

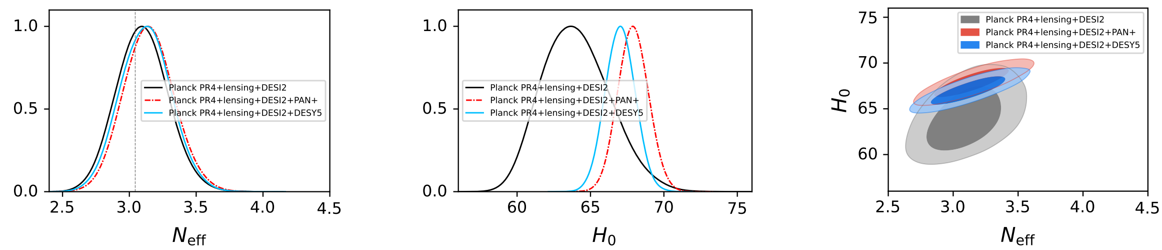

Figure 6. The left and middle panels show the 1D posterior distributions of $N_{\rm eff}$ and H_0 (km/s/Mpc) respectively, for various data combinations. The dashed vertical line in the left panel corresponds to the standard model value of $N_{\rm eff} = 3.044$. The right panel shows the 2D correlation plot between the two parameters, showing a strong correlation between them.

proof that the existence of the lensing anomaly might depend on non-CMB datasets as well, like the WL data here.

- $N_{\rm eff}$ and H_0: From the left-most panel of figure 6, we find that the obtained posteriors of $N_{\rm eff}$ are in complete agreement with the standard model value of $N_{\rm eff} = 3.044$. Whereas, from the middle panel, we notice that the H_0 values are not high enough to solve the Hubble tension. Indeed, if one uses the values of H_0 from table 2, one finds that the Hubble tension is present at the level of 3.6-4.2σ depending on the supernovae dataset used. Thus, one can consider that the Hubble tension is robust against the simple extensions to ΛCDM studied in this paper. Addition of the WL data does not change these numbers significantly. The right-most panel in Figure 6 shows the expected strong correlation between $N_{\rm eff}$ and H_0.

4 Conclusions

Building upon our previous work [10], in this paper, we have presented updated cosmological constraints within a 12-parameter extended cosmological model, utilizing a comprehensive combination of recent datasets. These include Baryon Acoustic Oscillations (BAO) from the DESI Data Release 2, Cosmic Microwave Background (CMB) temperature and polarization power spectra from Planck PR4, and CMB lensing data from Planck PR4+ACT DR6, uncalibrated type Ia Supernovae (SNe) from both the Pantheon+ and DES Year 5 (DESY5) surveys, and Weak Lensing (WL) measurements from the DES Year 1 survey. The parameter space extends the standard six ΛCDM parameters by including the dark energy equation of state parameters (w_0, w_a), the sum of neutrino masses ($\sum m_\nu$), the effective number of non-photon relativistic species ($N_{\rm eff}$), the lensing amplitude scaling ($A_{\rm lens}$), and the running of the scalar spectral index (α_s). Our key results are summarized as follows:

- **Neutrino Mass Detection:** Using CMB+BAO+DESY5+WL, we report the first 2σ+ preference for non-zero neutrino mass with $\sum m_\nu = 0.19^{+0.15}_{-0.18}$ eV (95%). A similar, though slightly weaker, $\sim$1.9σ signal is obtained when DESY5 is replaced with Pantheon+. Without the WL dataset, while there is no significant detection of non-zero neutrino masses, we still find that the $\sum m_\nu$ posteriors peak at the $\sum m_\nu > 0$ region for CMB+BAO and CMB+BAO+DESY5. The detection with WL data is driven by a strong negative correlation between S_8 and $\sum m_\nu$, with lower S_8 values preferring larger masses. We note that there is no significant S_8-tension between WL and CMB+BAO+SNe, thus it is okay to combine them.

- **Dynamical Dark Energy:** We find that the cosmological constant lies at the edge of the 95% confidence contour when using CMB+BAO+Pantheon+, and is excluded at more than 2σ when DESY5 is included instead of Pantheon+. This suggests that the evidence for dynamical dark energy still remains dataset-dependent and inconclusive; and less robust than recently claimed by the DESI collaboration [3]. We note that a region of the quintessence/non-phantom dark energy is also allowed by the datasets when we use Pantheon+. Addition of the WL data has negligible impact on the dynamical dark energy constraints.

- **Lensing Anomaly:** We find that $A_{\rm lens} = 1$ is excluded at over 2σ when WL data is included alongside CMB+BAO+SNe. In contrast, without WL, the results remain consistent with $A_{\rm lens} = 1$ at 2σ (albeit not at 1σ). This indicates, for the first time, that the existence of lensing anomaly might be dependent on non-CMB datasets, such as galaxy weak lensing measurements.

- **Hubble Tension:** The Hubble tension remains unresolved, with a persistent 3.6–4.2σ discrepancy between CMB+BAO+SNe and the SH0ES measurement [82], depending on the SNe dataset used. The addition of WL data does not significantly alter this tension.

Overall, our analysis emphasizes the critical importance of combining multiple cosmological probes and of testing large extensions to the standard model of cosmology to obtain a better understanding of cosmological parameters. While hints of physics beyond ΛCDM continue to appear in individual sectors—such as neutrino masses, lensing amplitude, and dark energy—their statistical significance remains sensitive to dataset combinations.

Acknowledgments

We acknowledge the use of the HPC facility at ASIAA (https://hpc.tiara.sinica.edu.tw/) where the numerical analyses were done. S.R.C. also acknowledges the support from grant Nos. AS-IA-112-M04, NSTC 112-2112-M-001-027-MY3, and I-IAA-ROY.

References

[1] DESI collaboration, *DESI 2024 VI: Cosmological Constraints from the Measurements of Baryon Acoustic Oscillations*, 2404.03002.

[2] DESI collaboration, *DESI 2024 VII: Cosmological Constraints from the Full-Shape Modeling of Clustering Measurements*, 2411.12022.

[3] DESI collaboration, *DESI DR2 Results II: Measurements of Baryon Acoustic Oscillations and Cosmological Constraints*, 2503.14738.

[4] DESI collaboration, *Extended Dark Energy analysis using DESI DR2 BAO measurements*, 2503.14743.

[5] D. Brout et al., *The Pantheon+ Analysis: Cosmological Constraints*, *Astrophys. J.* **938** (2022) 110 [2202.04077].

[6] D. Rubin et al., *Union Through UNITY: Cosmology with 2,000 SNe Using a Unified Bayesian Framework*, 2311.12098.

[7] DES collaboration, *The Dark Energy Survey: Cosmology Results With ˜1500 New High-redshift Type Ia Supernovae Using The Full 5-year Dataset*, 2401.02929.

[8] M. Chevallier and D. Polarski, *Accelerating universes with scaling dark matter*, *Int. J. Mod. Phys. D* **10** (2001) 213 [gr-qc/0009008].

[9] E.V. Linder, *Exploring the expansion history of the universe*, *Phys. Rev. Lett.* **90** (2003) 091301 [astro-ph/0208512].

[10] S. Roy Choudhury and T. Okumura, *Updated Cosmological Constraints in Extended Parameter Space with Planck PR4, DESI Baryon Acoustic Oscillations, and Supernovae: Dynamical Dark Energy, Neutrino Masses, Lensing Anomaly, and the Hubble Tension*, *Astrophys. J. Lett.* **976** (2024) L11 [2409.13022].

[11] Y. Tada and T. Terada, *Quintessential interpretation of the evolving dark energy in light of DESI observations*, *Phys. Rev. D* **109** (2024) L121305 [2404.05722].

[12] K.V. Berghaus, J.A. Kable and V. Miranda, *Quantifying Scalar Field Dynamics with DESI 2024 Y1 BAO measurements*, 2404.14341.

[13] C.-G. Park, J. de Cruz Perez and B. Ratra, *Using non-DESI data to confirm and strengthen the DESI 2024 spatially-flat w_0w_aCDM cosmological parameterization result*, 2405.00502.

[14] W. Yin, *Cosmic clues: DESI, dark energy, and the cosmological constant problem*, *JHEP* **05** (2024) 327 [2404.06444].

[15] D. Shlivko and P.J. Steinhardt, *Assessing observational constraints on dark energy*, *Phys. Lett. B* **855** (2024) 138826 [2405.03933].

[16] M. Cortês and A.R. Liddle, *Interpreting DESI's evidence for evolving dark energy*, 2404.08056.

[17] DESI collaboration, *DESI 2024: Constraints on Physics-Focused Aspects of Dark Energy using DESI DR1 BAO Data*, 2405.13588.

[18] Y. Carloni, O. Luongo and M. Muccino, *Does dark energy really revive using DESI 2024 data?*, 2404.12068.

[19] K.S. Croker, G. Tarlé, S.P. Ahlen, B.G. Cartwright, D. Farrah, N. Fernandez et al., *DESI Dark Energy Time Evolution is Recovered by Cosmologically Coupled Black Holes*, 2405.12282.

[20] P. Mukherjee and A.A. Sen, *Model-independent cosmological inference post DESI DR1 BAO measurements*, *Phys. Rev. D* **110** (2024) 123502 [2405.19178].

[21] N. Roy, *Dynamical dark energy in the light of DESI 2024 data*, 2406.00634.

[22] H. Wang and Y.-S. Piao, *Dark energy in light of recent DESI BAO and Hubble tension*, 2404.18579.

[23] I.D. Gialamas, G. Hütsi, K. Kannike, A. Racioppi, M. Raidal, M. Vasar et al., *Interpreting DESI 2024 BAO: late-time dynamical dark energy or a local effect?*, 2406.07533.

[24] L. Orchard and V.H. Cárdenas, *Probing Dark Energy Evolution Post-DESI 2024*, 2407.05579.

[25] W. Giarè, M. Najafi, S. Pan, E. Di Valentino and J.T. Firouzjaee, *Robust Preference for Dynamical Dark Energy in DESI BAO and SN Measurements*, 2407.16689.

[26] B.R. Dinda and R. Maartens, *Model-agnostic assessment of dark energy after DESI DR1 BAO*, 2407.17252.

[27] J.-Q. Jiang, D. Pedrotti, S.S. da Costa and S. Vagnozzi, *Non-parametric late-time expansion history reconstruction and implications for the Hubble tension in light of DESI*, 2408.02365.

[28] J.a. Rebouças, D.H.F. de Souza, K. Zhong, V. Miranda and R. Rosenfeld, *Investigating Late-Time Dark Energy and Massive Neutrinos in Light of DESI Y1 BAO*, 2408.14628.

[29] S. Bhattacharya, G. Borghetto, A. Malhotra, S. Parameswaran, G. Tasinato and I. Zavala, *Cosmological constraints on curved quintessence*, *JCAP* **09** (2024) 073 [2405.17396].

[30] Y.-H. Pang, X. Zhang and Q.-G. Huang, *Constraints on Redshift-Binned Dark Energy using DESI BAO Data*, 2408.14787.

[31] O.F. Ramadan, J. Sakstein and D. Rubin, *DESI constraints on exponential quintessence*, *Phys. Rev. D* **110** (2024) L041303 [2405.18747].

[32] W.J. Wolf, C. García-García, D.J. Bartlett and P.G. Ferreira, *Scant evidence for thawing quintessence*, 2408.17318.

[33] G. Efstathiou, *Evolving Dark Energy or Supernovae Systematics?*, 2408.07175.

[34] D.A. Kessler, L.A. Escamilla, S. Pan and E. Di Valentino, *One-parameter dynamical dark energy: Hints for oscillations*, 2504.00776.

[35] S. Gao, Q. Gao, Y. Gong and X. Lu, *Null tests with Gaussian Process*, 2503.15943.

[36] G. Borghetto, A. Malhotra, G. Tasinato and I. Zavala, *Bounded Dark Energy*, 2503.11628.

[37] W.J. Wolf, C. García-García and P.G. Ferreira, *Robustness of Dark Energy Phenomenology Across Different Parameterizations*, 2502.04929.

[38] L. Huang, R.-G. Cai and S.-J. Wang, *The DESI 2024 hint for dynamical dark energy is biased by low-redshift supernovae*, 2502.04212.

[39] Z.-Y. Peng and Y.-S. Piao, *Dark energy and lensing anomaly in Planck CMB data*, 2502.04641.

[40] M. Tsedrik et al., *Interacting dark energy constraints from the full-shape analyses of BOSS DR12 and DES Year 3 measurements*, 2502.03390.

[41] A. Reeves, A. Nicola and A. Refregier, *Tuning the cosmic instrument: robust cosmology through combined probes*, 2502.01722.

[42] Y. Yang, Q. Wang, C. Li, P. Yuan, X. Ren, E.N. Saridakis et al., *Gaussian-process reconstructions and model building of quintom dark energy from latest cosmological observations*, 2501.18336.

[43] C.-G. Park and B. Ratra, *Is excess smoothing of Planck CMB ansiotropy data partially responsible for evidence for dark energy dynamics in other $w(z)$CDM parametrizations?*, 2501.03480.

[44] S.D. Odintsov, D. Sáez-Chillón Gómez and G.S. Sharov, *Modified gravity/dynamical dark energy vs ΛCDM: is the game over?*, *Eur. Phys. J. C* **85** (2025) 298 [2412.09409].

[45] J. Shim, T. Okumura and A. Taruya, *Squeezing Full-Shape Dynamical Dark Energy Constraints with Galaxy Alignments*, 2412.08150.

[46] Q. Gao, Z. Peng, S. Gao and Y. Gong, *On the Evidence of Dynamical Dark Energy*, *Universe* **11** (2025) 10 [2411.16046].

[47] G. Payeur, E. McDonough and R. Brandenberger, *Do Observations Prefer Thawing Quintessence?*, 2411.13637.

[48] G. Ye, *Bridge the Cosmological Tensions with Thawing Gravity*, 2411.11743.

[49] O. Luongo and M. Muccino, *Dark energy reconstructions combining baryonic acoustic oscillation data with galaxy clusters and intermediate-redshift catalogs*, *Astron. Astrophys.* **693** (2025) A187 [2411.04901].

[50] W.J. Wolf, P.G. Ferreira and C. García-García, *Matching current observational constraints with nonminimally coupled dark energy*, *Phys. Rev. D* **111** (2025) L041303 [2409.17019].

[51] W. Giarè, *Dynamical Dark Energy Beyond Planck? Constraints from multiple CMB probes, DESI BAO and Type-Ia Supernovae*, 2409.17074.

[52] A. Chakraborty, P.K. Chanda, S. Das and K. Dutta, *DESI results: Hint towards coupled dark matter and dark energy*, 2503.10806.

[53] W. Elbers, C.S. Frenk, A. Jenkins, B. Li and S. Pascoli, *Negative neutrino masses as a mirage of dark energy*, *Phys. Rev. D* **111** (2025) 063534 [2407.10965].

[54] W. Giarè, T. Mahassen, E. Di Valentino and S. Pan, *An overview of what current data can (and cannot yet) say about evolving dark energy*, *Phys. Dark Univ.* **48** (2025) 101906 [2502.10264].

[55] W.J. Wolf and J. Read, *Navigating permanent underdetermination in dark energy and inflationary cosmology*, 2501.13521.

[56] DESI collaboration, *Constraints on Neutrino Physics from DESI DR2 BAO and DR1 Full Shape*, 2503.14744.

[57] I. Esteban, M.C. Gonzalez-Garcia, M. Maltoni, I. Martinez-Soler, J.a.P. Pinheiro and T. Schwetz, *NuFit-6.0: updated global analysis of three-flavor neutrino oscillations*, *JHEP* **12** (2024) 216 [2410.05380].

[58] S. Roy Choudhury and S. Choubey, *Updated Bounds on Sum of Neutrino Masses in Various Cosmological Scenarios*, *JCAP* **09** (2018) 017 [1806.10832].

[59] S. Roy Choudhury and S. Hannestad, *Updated results on neutrino mass and mass hierarchy from cosmology with Planck 2018 likelihoods*, *JCAP* **07** (2020) 037 [1907.12598].

[60] I. Tanseri, S. Hagstotz, S. Vagnozzi, E. Giusarma and K. Freese, *Updated neutrino mass constraints from galaxy clustering and CMB lensing-galaxy cross-correlation measurements*, *JHEAp* **36** (2022) 1 [2207.01913].

[61] S. Vagnozzi, E. Giusarma, O. Mena, K. Freese, M. Gerbino, S. Ho et al., *Unveiling ν secrets with cosmological data: neutrino masses and mass hierarchy*, *Phys. Rev. D* **96** (2017) 123503 [1701.08172].

[62] S. Vagnozzi, S. Dhawan, M. Gerbino, K. Freese, A. Goobar and O. Mena, *Constraints on the sum of the neutrino masses in dynamical dark energy models with $w(z) \geq -1$ are tighter than those obtained in ΛCDM*, *Phys. Rev. D* **98** (2018) 083501 [1801.08553].

[63] S. Roy Choudhury and A. Naskar, *Strong Bounds on Sum of Neutrino Masses in a 12 Parameter Extended Scenario with Non-Phantom Dynamical Dark Energy ($w(z) \geq -1$) with CPL parameterization*, *Eur. Phys. J. C* **79** (2019) 262 [1807.02860].

[64] E. Di Valentino, S. Gariazzo and O. Mena, *Most constraining cosmological neutrino mass bounds*, *Phys. Rev. D* **104** (2021) 083504 [2106.15267].

[65] L. Herold and M. Kamionkowski, *Revisiting the impact of neutrino mass hierarchies on neutrino mass constraints in light of recent DESI data*, *Phys. Rev. D* **111** (2025) 083518 [2412.03546].

[66] T. Bertólez-Martínez, I. Esteban, R. Hajjar, O. Mena and J. Salvado, *Origin of cosmological neutrino mass bounds: background versus perturbations*, 2411.14524.

[67] D. Wang, O. Mena, E. Di Valentino and S. Gariazzo, *Scale and redshift dependent limits on cosmic neutrino properties*, 2503.18745.

[68] N. Craig, D. Green, J. Meyers and S. Rajendran, *No νs is Good News*, *JHEP* **09** (2024) 097 [2405.00836].

[69] G.P. Lynch and L. Knox, *What's the matter with Σm_ν?*, 2503.14470.

[70] M. Loverde and Z.J. Weiner, *Massive neutrinos and cosmic composition*, *JCAP* **12** (2024) 048 [2410.00090].

[71] E. Di Valentino, A. Melchiorri and J. Silk, *Beyond six parameters: extending ΛCDM*, *Phys. Rev. D* **92** (2015) 121302 [1507.06646].

[72] E. Di Valentino, A. Melchiorri and J. Silk, *Reconciling Planck with the local value of H_0 in extended parameter space*, *Phys. Lett. B* **761** (2016) 242 [1606.00634].

[73] E. Di Valentino, A. Melchiorri, E.V. Linder and J. Silk, *Constraining Dark Energy Dynamics in Extended Parameter Space*, *Phys. Rev. D* **96** (2017) 023523 [1704.00762].

[74] V. Poulin, K.K. Boddy, S. Bird and M. Kamionkowski, *Implications of an extended dark energy cosmology with massive neutrinos for cosmological tensions*, *Phys. Rev. D* **97** (2018) 123504 [1803.02474].

[75] E. Di Valentino, A. Melchiorri and J. Silk, *Cosmological constraints in extended parameter space from the Planck 2018 Legacy release*, *JCAP* **01** (2020) 013 [1908.01391].

[76] M. Tristram et al., *Cosmological parameters derived from the final Planck data release (PR4)*, *Astron. Astrophys.* **682** (2024) A37 [2309.10034].

[77] ACT collaboration, *The Atacama Cosmology Telescope: DR6 Gravitational Lensing Map and Cosmological Parameters*, *Astrophys. J.* **962** (2024) 113 [2304.05203].

[78] DES collaboration, *Dark Energy Survey year 1 results: Cosmological constraints from galaxy clustering and weak lensing*, *Phys. Rev. D* **98** (2018) 043526 [1708.01530].

[79] J. Zuntz, M. Paterno, E. Jennings, D. Rudd, A. Manzotti, S. Dodelson et al., *CosmoSIS: modular cosmological parameter estimation*, *Astron. Comput.* **12** (2015) 45 [1409.3409].

[80] J. Torrado and A. Lewis, *Cobaya: Code for Bayesian Analysis of hierarchical physical models*, *JCAP* **05** (2021) 057 [2005.05290].

[81] Planck collaboration, *Planck 2018 results. VI. Cosmological parameters*, *Astron. Astrophys.* **641** (2020) A6 [1807.06209].

[82] A.G. Riess et al., *A Comprehensive Measurement of the Local Value of the Hubble Constant with 1 km/s/Mpc Uncertainty from the Hubble Space Telescope and the SH0ES Team*, *Astrophys. J. Lett.* **934** (2022) L7 [2112.04510].

[83] L. Knox and M. Millea, *Hubble constant hunter's guide*, *Phys. Rev. D* **101** (2020) 043533 [1908.03663].

[84] J. Lesgourgues and S. Pastor, *Neutrino mass from Cosmology*, *Adv. High Energy Phys.* **2012** (2012) 608515 [1212.6154].

[85] M. Archidiacono, S. Hannestad and J. Lesgourgues, *What will it take to measure individual neutrino mass states using cosmology?*, *JCAP* **09** (2020) 021 [2003.03354].

[86] S. Gariazzo et al., *Neutrino mass and mass ordering: no conclusive evidence for normal ordering*, *JCAP* **10** (2022) 010 [2205.02195].

[87] J. Garcia-Bellido and D. Roest, *Large-N running of the spectral index of inflation*, *Phys. Rev. D* **89** (2014) 103527 [1402.2059].

[88] R. Easther and H. Peiris, *Implications of a Running Spectral Index for Slow Roll Inflation*, *JCAP* **09** (2006) 010 [astro-ph/0604214].

[89] K. Kohri and T. Matsuda, *Ambiguity in running spectral index with an extra light field during inflation*, *JCAP* **02** (2015) 019 [1405.6769].

[90] D.J.H. Chung, G. Shiu and M. Trodden, *Running of the scalar spectral index from inflationary models*, *Phys. Rev. D* **68** (2003) 063501 [astro-ph/0305193].

[91] J. Torrado and A. Lewis, "Cobaya: Bayesian analysis in cosmology." Astrophysics Source Code Library, record ascl:1910.019, Oct., 2019.

[92] A. Lewis, A. Challinor and A. Lasenby, *Efficient computation of CMB anisotropies in closed FRW models*, Astrophys. J. **538** (2000) 473 [astro-ph/9911177].

[93] C. Howlett, A. Lewis, A. Hall and A. Challinor, *CMB power spectrum parameter degeneracies in the era of precision cosmology*, JCAP **04** (2012) 027 [1201.3654].

[94] S.P. Brooks and A. Gelman, *General methods for monitoring convergence of iterative simulations*, Journal of Computational and Graphical Statistics **7** (1998) 434.

[95] A. Lewis, *GetDist: a Python package for analysing Monte Carlo samples*, 1910.13970.

[96] Planck collaboration, *Planck intermediate results. LVII. Joint Planck LFI and HFI data processing*, Astron. Astrophys. **643** (2020) A42 [2007.04997].

[97] J. Carron, M. Mirmelstein and A. Lewis, *CMB lensing from Planck PR4 maps*, JCAP **09** (2022) 039 [2206.07773].

[98] ACT collaboration, *The Atacama Cosmology Telescope: Mitigating the Impact of Extragalactic Foregrounds for the DR6 Cosmic Microwave Background Lensing Analysis*, Astrophys. J. **966** (2024) 138 [2304.05196].

[99] D. Scolnic et al., *The Pantheon+ Analysis: The Full Data Set and Light-curve Release*, Astrophys. J. **938** (2022) 113 [2112.03863].

[100] DES collaboration, *Dark Energy Survey Year 3 results: Cosmological constraints from galaxy clustering and weak lensing*, Phys. Rev. D **105** (2022) 023520 [2105.13549].

[101] A.H. Wright et al., *KiDS-Legacy: Cosmological constraints from cosmic shear with the complete Kilo-Degree Survey*, 2503.19441.