

Cosmological implications of DESI DR2 BAO measurements in light of the latest ACT DR6 CMB data

C. Garcia-Quintero,^{1,*} H. E. Noriega,^{2,3} A. de Mattia,⁴ A. Aviles,² K. Lodha,^{5,6} D. Chebat,⁴ J. Rohlf,⁷ S. Nadathur,⁸ W. Elbers,⁹ J. Aguilar,¹⁰ S. Ahlen,⁷ O. Alves,¹¹ U. Andrade,^{12,11} S. Bailey,¹⁰ S. BenZvi,¹³ D. Bianchi,^{14,15} D. Brooks,¹⁶ E. Burtin,⁴ R. Calderon,¹⁷ A. Carnero Rosell,^{18,19} P. Carrilho,²⁰ F. J. Castander,^{21,22} E. Chaussidon,¹⁰ T. Claybaugh,¹⁰ S. Cole,⁹ A. Cuceu,^{10,*} R. de Belsunce,¹⁰ A. de la Macorra,³ N. Deiosso,²³ J. Della Costa,^{24,25} Arjun Dey,²⁵ Biprateep Dey,^{26,27} Z. Ding,²⁸ P. Doel,¹⁶ A. Font-Ribera,²⁹ J. E. Forero-Romero,^{30,31} E. Gaztañaga,^{21,8,22} H. Gil-Marín,^{32,21,33} S. Gontcho A Gontcho,¹⁰ G. Gutierrez,³⁴ J. Guy,¹⁰ C. Hahn,³⁵ H. K. Herrera-Alcantar,^{36,4} K. Honscheid,^{37,38,39} C. Howlett,⁴⁰ D. Huterer,^{41,11} M. Ishak,⁴² S. Juneau,²⁵ R. Kehoe,⁴³ D. Kirkby,⁴⁴ A. Kremin,¹⁰ O. Lahav,¹⁶ C. Lamman,¹ M. Landriau,¹⁰ L. Le Guillou,⁴⁵ A. Leauthaud,^{46,47} M. E. Levi,¹⁰ Q. Li,⁴⁸ M. Manera,^{49,29} P. Martini,^{37,50,39} W. L. Matthewson,⁵ A. Meisner,²⁵ J. Mena-Fernández,⁵¹ R. Miquel,^{52,29} J. Moustakas,⁵³ A. Muñoz-Gutiérrez,³ J. A. Newman,²⁷ G. Niz,^{54,55} E. Paillas,^{35,56} N. Palanque-Delabrouille,^{4,10} J. Pan,¹¹ W. J. Percival,^{57,58,59} F. Prada,⁶⁰ I. Pérez-Ràfols,⁶¹ M. Rashkovetskyi,¹ C. Ravoux,⁶² A. J. Ross,^{37,50,39} G. Rossi,⁶³ E. Sanchez,²³ D. Schlegel,¹⁰ M. Schubnell,^{41,11} H. Seo,⁶⁴ A. Shafieloo,^{5,6} J. Silber,¹⁰ D. Sprayberry,²⁵ G. Tarlé,¹¹ P. Taylor,³⁹ M. Vargas-Magaña,³ M. Walther,^{65,66} B. A. Weaver,²⁵ C. Yèche,⁴ P. Zarrouk,⁴⁵ Z. Zhai,⁶⁷ C. Zhao,⁶⁸ and R. Zhou¹⁰

(DESI Collaboration)

¹*Center for Astrophysics, Harvard & Smithsonian, 60 Garden Street, Cambridge, Massachusetts 02138, USA*

²*Instituto de Ciencias Físicas, Universidad Nacional Autónoma de México, Av. Universidad s/n, Cuernavaca, Morelos, C. P. 62210, México*

³*Instituto de Física, Universidad Nacional Autónoma de México, Circuito de la Investigación Científica, Ciudad Universitaria, Cd. de México C. P. 04510, México*

⁴*IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France*

⁵*Korea Astronomy and Space Science Institute, 776, Daedeokdae-ro, Yuseong-gu, Daejeon 34055, Republic of Korea*

⁶*University of Science and Technology, 217 Gajeong-ro, Yuseong-gu, Daejeon 34113, Republic of Korea*

⁷*Physics Department, Boston University, 590 Commonwealth Avenue, Boston, Massachusetts 02215, USA*

⁸*Institute of Cosmology and Gravitation, University of Portsmouth, Dennis Sciama Building, Portsmouth, PO1 3FX, United Kingdom*

⁹*Institute for Computational Cosmology, Department of Physics, Durham University, South Road, Durham DH1 3LE, United Kingdom*

¹⁰*Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, California 94720, USA*

¹¹*University of Michigan, 500 S. State Street, Ann Arbor, Michigan 48109, USA*

¹²*Leinweber Center for Theoretical Physics, University of Michigan, 450 Church Street, Ann Arbor, Michigan 48109-1040, USA*

¹³*Department of Physics and Astronomy, University of Rochester, 206 Bausch and Lomb Hall, P.O. Box 270171, Rochester, New York 14627-0171, USA*

¹⁴*Dipartimento di Fisica "Aldo Pontremoli," Università degli Studi di Milano, Via Celoria 16, I-20133 Milano, Italy*

¹⁵*INAF-Osservatorio Astronomico di Brera, Via Brera 28, 20122 Milano, Italy*

¹⁶*Department of Physics and Astronomy, University College London, Gower Street, London, WC1E 6BT, United Kingdom*

¹⁷*CEICO, Institute of Physics of the Czech Academy of Sciences, Na Slovance 1999/2, 182 21, Prague, Czech Republic*

¹⁸*Departamento de Astrofísica, Universidad de La Laguna (ULL), E-38206, La Laguna, Tenerife, Spain*

¹⁹*Instituto de Astrofísica de Canarias, C/Vía Láctea, s/n, E-38205 La Laguna, Tenerife, Spain*

²⁰*Institute for Astronomy, University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, United Kingdom*

²¹*Institut d'Estudis Espacials de Catalunya (IEEC), c/Estève Terradas 1, Edifici RDIT, Campus PMT-UPC, 08860 Castelldefels, Spain*

²²*Institute of Space Sciences, ICE-CSIC, Campus UAB, Carrer de Can Magrans s/n, 08913 Bellaterra, Barcelona, Spain*

²³*CIEMAT, Avenida Complutense 40, E-28040 Madrid, Spain*

- ²⁴Department of Astronomy, *San Diego State University*, 5500 Campanile Drive, San Diego, California 92182, USA
- ²⁵*NSF NOIRLab*, 950 N. Cherry Avenue, Tucson, Arizona 85719, USA
- ²⁶Department of Astronomy and Astrophysics, *University of Toronto*, Toronto, Ontario M5S 3H4, Canada
- ²⁷Department of Physics & Astronomy and Pittsburgh Particle Physics, Astrophysics, and Cosmology Center (PITT PACC), *University of Pittsburgh*, 3941 O'Hara Street, Pittsburgh, Pennsylvania 15260, USA
- ²⁸*University of Chinese Academy of Sciences*, Nanjing 211135, People's Republic of China
- ²⁹*Institut de Física d'Altes Energies (IFAE)*, The Barcelona Institute of Science and Technology, Edifici Cn, Campus UAB, 08193, Bellaterra (Barcelona), Spain
- ³⁰Departamento de Física, *Universidad de los Andes*, Cra. 1 No. 18A-10, Edificio Ip, CP 111711, Bogotá, Colombia
- ³¹Observatorio Astronómico, *Universidad de los Andes*, Cra. 1 No. 18A-10, Edificio H, CP 111711 Bogotá, Colombia
- ³²Departament de Física Quàntica i Astrofísica, *Universitat de Barcelona*, Martí i Franquès 1, E08028 Barcelona, Spain
- ³³*Institut de Ciències del Cosmos (ICCUB)*, *Universitat de Barcelona (UB)*, c. Martí i Franquès, 1, 08028 Barcelona, Spain
- ³⁴*Fermi National Accelerator Laboratory*, PO Box 500, Batavia, Illinois 60510, USA
- ³⁵*Steward Observatory*, *University of Arizona*, 933 N. Cherry Avenue, Tucson, Arizona 85721, USA
- ³⁶*Institut d'Astrophysique de Paris*, 98 bis boulevard Arago, 75014 Paris, France
- ³⁷Center for Cosmology and AstroParticle Physics, *The Ohio State University*, 191 West Woodruff Avenue, Columbus, Ohio 43210, USA
- ³⁸Department of Physics, *The Ohio State University*, 191 West Woodruff Avenue, Columbus, Ohio 43210, USA
- ³⁹*The Ohio State University*, Columbus, 43210 Ohio, USA
- ⁴⁰School of Mathematics and Physics, *University of Queensland*, Brisbane, Queensland 4072, Australia
- ⁴¹Department of Physics, *University of Michigan*, 450 Church Street, Ann Arbor, Michigan 48109, USA
- ⁴²Department of Physics, *The University of Texas at Dallas*, 800 W. Campbell Road, Richardson, Texas 75080, USA
- ⁴³Department of Physics, *Southern Methodist University*, 3215 Daniel Avenue, Dallas, Texas 75275, USA
- ⁴⁴Department of Physics and Astronomy, *University of California, Irvine*, California 92697, USA
- ⁴⁵*Sorbonne Université, CNRS/IN2P3, Laboratoire de Physique Nucléaire et de Hautes Energies (LPNHE)*, FR-75005 Paris, France
- ⁴⁶Department of Astronomy and Astrophysics, *UCO/Lick Observatory*, *University of California*, 1156 High Street, Santa Cruz, California 95064, USA
- ⁴⁷Department of Astronomy and Astrophysics, *University of California, Santa Cruz*, 1156 High Street, Santa Cruz, California 95065, USA
- ⁴⁸Department of Physics and Astronomy, *The University of Utah*, 115 South 1400 East, Salt Lake City, Utah 84112, USA
- ⁴⁹Departament de Física, Serra Hünter, *Universitat Autònoma de Barcelona*, 08193 Bellaterra (Barcelona), Spain
- ⁵⁰Department of Astronomy, *The Ohio State University*, 4055 McPherson Laboratory, 140 W 18th Avenue, Columbus, Ohio 43210, USA
- ⁵¹*Laboratoire de Physique Subatomique et de Cosmologie*, 53 Avenue des Martyrs, 38000 Grenoble, France
- ⁵²*Institució Catalana de Recerca i Estudis Avançats*, Passeig de Lluís Companys, 23, 08010 Barcelona, Spain
- ⁵³Department of Physics and Astronomy, *Siena College*, 515 Loudon Road, Loudonville, New York 12211, USA
- ⁵⁴Departamento de Física, DCI-Campus León, *Universidad de Guanajuato*, Loma del Bosque 103, León, Guanajuato C. P. 37150, México
- ⁵⁵*Instituto Avanzado de Cosmología A. C.*, San Marcos 11 - Atenas 202. Magdalena Contreras. Ciudad de México C. P. 10720, México
- ⁵⁶*Instituto de Estudios Astrofísicos*, Facultad de Ingeniería y Ciencias, Universidad Diego Portales, Av. Ejército Libertador 441, Santiago, Chile
- ⁵⁷Department of Physics and Astronomy, *University of Waterloo*, 200 University Ave W, Waterloo, Ontario N2L 3G1, Canada
- ⁵⁸*Perimeter Institute for Theoretical Physics*, 31 Caroline St. North, Waterloo, Ontario N2L 2Y5, Canada

⁵⁹Waterloo Centre for Astrophysics, *University of Waterloo*, 200 University Ave W,
Waterloo, Ontario N2L 3G1, Canada

⁶⁰*Instituto de Astrofísica de Andalucía (CSIC)*, Glorieta de la Astronomía, s/n, E-18008 Granada, Spain

⁶¹Departament de Física, EEBE, *Universitat Politècnica de Catalunya*,
c/Eduard Maristany 10, 08930 Barcelona, Spain

⁶²*Université Clermont-Auvergne*, CNRS, LPCA, 63000 Clermont-Ferrand, France

⁶³Department of Physics and Astronomy, *Sejong University*, 209 Neungdong-ro,
Gwangjin-gu, Seoul 05006, Republic of Korea

⁶⁴Department of Physics & Astronomy, *Ohio University*, 139 University Terrace, Athens, Ohio 45701, USA

⁶⁵*Excellence Cluster ORIGINS*, Boltzmannstrasse 2, D-85748 Garching, Germany

⁶⁶University Observatory, Faculty of Physics, *Ludwig-Maximilians-Universität*,
Scheinerstrasse 1, 81677 München, Germany

⁶⁷Department of Astronomy, School of Physics and Astronomy, *Shanghai Jiao Tong University*,
Shanghai 200240, China

⁶⁸Department of Astronomy, *Tsinghua University*, 30 Shuangqing Road,
Haidian District, Beijing, China, 100190



(Received 4 May 2025; accepted 26 June 2025; published 15 October 2025)

We report cosmological results from the Dark Energy Spectroscopic Instrument (DESI) measurements of baryon acoustic oscillations (BAO) when combined with recent data from the Atacama Cosmology Telescope (ACT). By jointly analyzing ACT and *Planck* data and applying conservative cuts to overlapping multipole ranges, we assess how different *Planck* + ACT dataset combinations affect consistency with DESI. While ACT alone exhibits a tension with DESI exceeding 3σ within the Λ CDM model, this discrepancy is reduced when ACT is analyzed in combination with *Planck*. For our baseline DESI DR2 BAO + *Planck* PR4 + ACT likelihood combination, the preference for evolving dark energy over a cosmological constant is about 3σ , increasing to over 4σ with the inclusion of type Ia supernova data. While the dark energy results remain quite consistent across various combinations of *Planck* and ACT likelihoods with those obtained by the DESI collaboration, the constraints on neutrino mass are more sensitive, ranging from $\sum m_\nu < 0.061$ eV in our baseline analysis, to $\sum m_\nu < 0.077$ eV (95% confidence level) in the CMB likelihood combination chosen by ACT when imposing the physical prior $\sum m_\nu > 0$ eV.

DOI: 10.1103/d6yc-xpqb

I. INTRODUCTION

The current understanding of the expansion of the Universe has been built upon rapidly evolving observations from a variety of cosmological probes. Each cosmological dataset provides information about the Universe at different epochs. The cosmic microwave background (CMB) data provide a description of the Universe at redshift $z \approx 1090$, a mere 400,000 years after the big bang. Baryon acoustic oscillations (BAO) from galaxy surveys constrain the expansion history of the Universe at $0.1 < z < 4.2$, exploring the matter dominated era and the recent era of cosmic acceleration. type Ia supernovae (SNe Ia) data were used to discover dark energy [1,2] and constrain the expansion history at low redshifts. The combination of these cosmological probes across the evolving Universe provides

quantitative information on the temporal evolution of the dark energy density.

The most precise BAO measurements to date come from the Dark Energy Spectroscopic Instrument (DESI). DESI is installed on the Mayall Telescope at the Kitt Peak National Observatory [3–6], and uses robotically controlled fiber-optic cables [7–11] to simultaneously capture light from up to 5000 preselected galaxies and quasars across an eight-square-degree field of view. By analyzing the spectra of collected light, DESI has obtained redshift information on over 30 million extragalactic objects during the first three years of observations [12–14]. BAO measurements from more than 14 million galaxies and quasars [15,16], as well as from 820,000 Lyman- α forest spectra [17–19] have significantly contributed to current knowledge of cosmological parameters.

Recently, the DESI collaboration presented a cosmological analysis based on the latest BAO measurements from its Data Release 2 (DR2) [16]. This analysis points to discrepancies between datasets becoming more relevant within the Λ CDM model, highlighting evolving dark energy as a possible solution (or alternatively, unrecognized systematics in one or more datasets, or a rare statistical

*Contact author: cgarciaquintero@cfa.harvard.edu

Published by the American Physical Society under the terms of the *Creative Commons Attribution 4.0 International* license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.

fluctuation), and also reporting updated constraints on the neutrino mass (with an extended analysis allowing an effective neutrino mass parameter that allows negative values [20]). In particular, while the DESI DR2 BAO results are broadly consistent with the picture of the Λ CDM cosmological model, they exhibit a 2.3σ tension [16] with *Planck* CMB data (including external CMB lensing data from [21]) in the $(\Omega_m, H_0 r_d)$ 2D parameter space [14,22–26]. On the other hand, a time evolving dark energy component is favored by the joint analysis of these datasets, a scenario in which the datasets are consistent. This behavior can be deduced through either a simple CPL parametrization ($w_0 w_a$ CDM) [27,28], or other dark energy reconstruction methods [29]. Using the $w_0 w_a$ CDM parametrization, DESI BAO DR2 combined with CMB temperature and polarization anisotropies, as well as CMB lensing, shows evolving dark energy is preferred at 3.1σ . This preference ranges 2.8σ – 4.2σ when including SNe Ia data, depending on which SNe sample is used [16] (this preference is also supported by the Dark Energy Survey BAO and SNe combined analysis [30]).

Around the same time as the DESI DR2 results were published, the Atacama Cosmology Telescope (ACT) collaboration also presented their final results on the CMB power spectrum measurements and cosmological implications [31–33], based on their Data Release 6 (DR6) with five years of observations. The ACT results provide measurements on the small-scale region of the CMB spectrum, adding extra information to the damping tail of the CMB not covered by the *Planck* space-based mission. Conversely, *Planck* is able to resolve anisotropies in the temperature and polarization of the CMB maps at large scales not accessible to ACT ($\ell < 600$), making the two CMB datasets complementary to each other.

Given the mild discrepancy between DESI BAO and *Planck* CMB (including ACT DR6 CMB lensing), it becomes important to evaluate the effect of the final ACT DR6 dataset in the context of DESI BAO, whether analyzed individually or combined with *Planck*. A conservative combination of ACT and *Planck* involves considering non-overlapping multipole ranges of each CMB spectrum. While in [31] the complete ACT dataset was complemented with CMB measurements from *Planck* up to $\ell = 1000$ to provide a complete CMB picture, other combinations with different multipole cuts are of interest, notably combinations between ACT and *Planck* based on the multipole ranges where each CMB experiment is more precise. Different combinations may impact parameters such as the physical cold-dark-matter density $\Omega_c h^2$ (where h is the hubble constant normalized to $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$), which can affect the discrepancy between DESI and CMB, and impact the evidence in favor of $w_0 w_a$ CDM. While ACT alone reports a higher $\Omega_c h^2$ value compared to *Planck* [31] (a $\sim 1.5\sigma$ shift), the P-ACT combination used by the ACT collaboration measures a slightly lower $\Omega_c h^2$ with respect to *Planck*.

In addition, BAO helps break geometric degeneracies in CMB constraints on neutrino mass. DESI reported a 95% upper limit of $\sum m_\nu < 0.064 \text{ eV}$ for the sum of neutrino masses in the Λ CDM model when combined with *Planck* CMB data, that changes to $\sum m_\nu < 0.078 \text{ eV}$ with an alternative *Planck* CMB likelihood [16]. The constraints on the neutrino mass is relaxed to $\sum m_\nu < 0.16 \text{ eV}$ in a $w_0 w_a$ CDM model. These differences in the neutrino mass constraints further justify a joint DESI + ACT analysis that covers the neutrino sector.

The purpose of this work is to explore the cosmological implications of including the latest ACT power spectrum data and likelihoods within the BAO + CMB + SNe combination already analyzed by the DESI Collaboration, and assess the robustness of the conclusions made by DESI in light of the latest ACT data. We extend the analysis to different combinations of the ACT and *Planck* datasets based on other multipole cuts that can be more precise at measuring $\Omega_c h^2$ and other parameters.

In Sec. II, we describe the datasets, likelihoods, and methodology. In Sec. III, we test the consistency of DESI and CMB data within the Λ CDM model. In Sec. IV, we present the results of dark energy for different datasets, including ACT DR6 power spectra. In Sec. V, we present constraints on the neutrino masses. Finally, we present our conclusions in Sec. VI.

II. METHODOLOGY AND DATA

The purpose of this work is to explore the cosmological implications of incorporating the latest ACT power spectrum data [31] into a combined analysis with BAO, CMB, and SNe observations, as presented in [16]. We also consider the CMB data from *Planck* [34] and assess how the inclusion of ACT data affects the cosmological parameters. As reported in [31], ACT measures a higher $\Omega_c h^2$ value compared to *Planck* (a 1.5σ shift). Also, it was observed that the P-ACT combination defined in [31] favors a lower value of $\Omega_c h^2$ compared to both *Planck* (0.4σ lower) and ACT (1.9σ lower). Since the CMB measurement of $\Omega_c h^2$ is key for the DESI results as it can affect the discrepancy between DESI and CMB, the preference for $w_0 w_a$ CDM and the neutrino mass constraints, the exploration of these CMB datasets and how to combine *Planck* with ACT becomes relevant. Additionally, the results presented in [16,31] use a different version for the low- ℓ EE likelihood, which can have an impact on the neutrino mass constraints and deserves exploration.

The CMB high- ℓ power spectra from *Planck* and ACT are combined in a conservative way, without modeling a covariance between the surveys, but rather by applying simple data cuts. ACT resolves temperature anisotropies at smaller angular scales compared to *Planck*: its CMB spectra start at $\ell = 600$ – 1000 (depending on the frequency

array) [31] and extend up to $\ell = 8500$. On the other hand, *Planck* can resolve the anisotropies well on large scales, even in the low- ℓ regime ($\ell < 30$) where the distribution of the CMB spectra is non-Gaussian, while its high- ℓ spectra are measured up to $\ell = 2500$. In our analysis, we consider the official *Planck* Release 3 (PR3) [35–37], as well as *Planck* Release 4 (PR4) [38], which is a reanalysis using the NPIPE processing pipeline and CMB lensing reconstruction of NPIPE maps [39]. Throughout this work, we focus on the PR4 CamSpec high- ℓ likelihood, which provides $\sim 8\%$ – 10% tighter constraints than PR3 Plik [40] on relevant parameters for this work such as $\Omega_c h^2$ and Ω_m , when analyzing CMB alone.

We summarize the datasets used in this work in Table I and define the variations under which we combine CMB datasets. Motivated by the ACT baseline data as defined in [31], we use the ACT DR6 high- ℓ spectra with the `act_dr6_mflike` likelihood¹ in combination with the low- ℓ EE *Planck* data analyzed through the `SRoll2` likelihood code [41]² (see also [42,43] for works related to the `SRoll2` maps) but with the inclusion of CMB lensing from the combination of *Planck* NPIPE and ACT DR6 as described in [44]. We label this combination simply as ACT.³ Since the ACT data cannot fully constrain the first two CMB acoustic peaks, it is useful to complement it with data from other CMB surveys. We define an analogous combination to P-ACT as used in [31], based on a combination of ACT DR6 and PR3 (`plik_lite`),⁴ but with the addition of CMB lensing. We consider fits to the PR4 data only, matching the baseline CMB combination presented in [16]. Since *Planck* and ACT probe a common part of the CMB spectra, we test different combinations between the two by means of ℓ cuts. We consider combinations between PR4 and ACT DR6 with a baseline low- ℓ TT Commander and low- ℓ EE SimAll data from *Planck* ($\ell < 30$) [35], CMB lensing, and mixed high- ℓ information from PR4 and ACT DR6 split by a multipole cut ℓ_{TT} and a common cut $\ell_{\text{TE,EE}}$. This cut uses PR4 TT information for $\ell < \ell_{\text{TT}}$ and then ACT DR6 information for higher values of ℓ up to $\ell = 8500$. Similarly, the common TE and EE cut uses PR4 data for $\ell < \ell_{\text{TE,EE}}$ and ACT DR6 for the rest of the ℓ range up to $\ell = 8500$. We define the explicit cuts we use below.

We construct a CMB combination that can be regarded as maximal in the information included from ACT DR6, using its full CMB spectra. However, since the ACT DR6

data are highly impacted by atmospheric noise in the range $600 < \ell < 1000$ [32], we increase the *Planck* TT coverage and use $\ell_{\text{TT}} = 1000$ and $\ell_{\text{TE,EE}} = 600$, as done for P-ACT. This combination is analogous to P-ACT in this work but uses PR4 CamSpec. We label this combination as $\text{PR4}_{(1000,600)} + \text{ACT}$. We also test a combination with $\ell_{\text{TT}} = 2000$ and $\ell_{\text{TE,EE}} = 1000$ motivated by Fig. 12 in [31]. This combination corresponds approximately to the multipole range where the precision of ACT DR6 in measuring the TT spectrum across frequency channels begins to become comparable to, or slightly exceed, that of *Planck*, around $\ell \sim 2000$. Similarly, $\ell = 1000$ is a point where ACT DR6 is roughly more precise in measuring TE compared to *Planck*, while $\ell = 1000$ is also the scale at which approximately the white noise transition occurs for the ACT DR6 EE polarization data. We label this combination simply as $\text{PR4} + \text{ACT}$ and consider it as our baseline CMB combination. We note that this choice of ℓ cuts may not correspond to the configuration that minimizes cosmological parameter uncertainties, but rather should provide a fair approximation. For the latter set of cuts, we also test the effect of the `SRoll2` likelihood by defining an analogous variation where we replace the low- ℓ EE SimAll likelihood with the low- ℓ EE `SRoll2` likelihood and label this $\text{PR4}_{(\text{SRoll2})} + \text{ACT}$. Table I summarizes the CMB variations used in this paper. We discuss the effect on the parameter space for some of these combinations with respect to ACT DR6 and PR4 in Appendix A.

We use DESI DR2 BAO data (see [16] for definitions of comoving distances D_M , D_H , and D_V) containing measurements of D_V/r_d at redshifts $0.1 < z < 0.4$ for the bright galaxy sample (BGS) tracer, and measurements of D_H/r_d and D_M/r_d for the rest of the tracers, luminous red galaxies (LRGs) at $0.4 < z < 0.6$ and $0.6 < z < 0.8$, a combined tracer LRG + ELG at $0.8 < z < 1.1$ (where ELG stands for emission line galaxy), the ELG tracer at $1.1 < z < 1.6$, quasars (QSO) at $0.8 < z < 2.1$ plus the Ly α forest and the correlation with QSO positions, at $1.8 < z < 4.2$. Here, r_d represents the sound horizon at the drag epoch, when acoustic waves stall in the primordial plasma as baryons cease to feel the drag from the photons.

We also used SNe Ia data from Pantheon+ that consists of 1550 spectroscopically classified type Ia SNe [49]. Similarly, we use the Union3 sample that consists of 2087 SNe Ia and uses an alternative analysis framework based on Bayesian hierarchical modeling using Unity 1.5 [46]. We also include SNe Ia data from the DESY5 sample with 1635 photometrically classified SNe [47].

We test deviations from Λ CDM, corresponding to dynamical dark energy, by means of the $w_0 w_a$ CDM parametrization based on an equation of state of dark energy given by $w(a) = w_0 + w_a(1 - a)$, with w_0 and w_a as free parameters. Finally, when performing constraints on the sum of neutrino masses, we adopt a physical prior $\sum m_\nu > 0$

¹The likelihood can be found at: https://github.com/ACTCollaboration/act_dr6_mflike/tree/main.

²The inclusion of the low- ℓ EE data helps to break degeneracies between the optical depth parameter τ and the amplitude of primordial scalar fluctuations A_s .

³Note that this would be equivalent to ACT-L, in the nomenclature used in [31].

⁴The absolute calibration parameter A_{Planck} is shared between the two CMB likelihoods.

TABLE I. Summary of the primary datasets (1-3) and CMB combinations (4-5) used in this work. For the CMB data, we also indicate the individual likelihood packages that were used in the fits.

Datasets	Description
<i>1. BAO data</i>	
DESI DR2	BAO measurements from DESI DR2 in the range $0.1 < z < 4.2$ [16,19].
<i>2. SNe Ia data</i>	
Pantheon+	A compilation of 1550 spectroscopically confirmed SNe Ia in the range $0.001 < z < 2.26$ [45].
Union3	A compilation of 2087 SNe-Ia (among which 1363 SNe Ia are common to Pantheon+) that were analyzed through an updated Bayesian framework [46].
DES5	A compilation of 1635 SNe Ia in the redshift range $0.10 < z < 1.13$ complemented by an external sample consisting of 194 SNe Ia common to Pantheon+ in the range $0.025 < z < 0.10$ [47].
<i>3. CMB standalone likelihoods (including CMB lensing)</i>	
low- ℓ TT	<i>Planck</i> 2018 PR3 low- ℓ Commander likelihood for TT in the range $2 \leq \ell < 30$ [35,36].
low- ℓ EE SimAll	<i>Planck</i> 2018 PR3 low- ℓ SimAll likelihood for EE in the range $2 \leq \ell < 30$ [35,36].
low- ℓ EE SRoll2	Alternative low- ℓ likelihood for EE based on the SRoll2 code in the range $2 \leq \ell < 30$ [41].
high- ℓ PR3	<i>Planck</i> PR3 Plik_lite likelihood for the high- ℓ CMB TT, TE, EE spectra from $\ell = 30$ up to $\ell = 2500$ [35,36].
high- ℓ PR4	<i>Planck</i> PR4 high- ℓ temperature and polarization likelihood using NPIPE maps. The high- ℓ TT, TE, EE spectra from <i>Planck</i> extends from $\ell = 30$ up to $\ell = 2500$ [40,48].
ACT DR6	Power spectra from the anisotropies in the temperature and polarization CMB maps from the 6th data release of the Atacama Cosmology Telescope. The CMB power spectra extends from $\ell = 600$ –1000 (depending on the frequency array) up to $\ell = 8500$ [31].
CMB lensing	Combination of the CMB lensing measurements from the reconstruction of the CMB lensing potential using <i>Planck</i> PR4 NPIPE maps [39], and the CMB lensing measurements from the ACT Data Release 6 (DR6), which consists of five seasons of CMB temperature and polarization observations, with 67% of sky fraction overlap with <i>Planck</i> [21,44].
<i>4. Main CMB combinations</i>	
ACT	low- ℓ EE SRoll2 + ACT DR6 + CMB lensing
P-ACT	low- ℓ TT + low- ℓ EE SRoll2 + high- ℓ PR3 ($\ell < 1000$ TT, $\ell < 600$ TE, EE) + ACT DR6 + CMB lensing
PR4 + ACT	low- ℓ TT + low- ℓ EE SimAll + high- ℓ PR4 ($\ell < 2000$ TT, $\ell < 1000$ TE, EE) + ACT DR6 ($\ell \geq 2000$ TT, $\ell \geq 1000$ TE, EE) + CMB lensing
<i>5. Additional CMB combinations studied</i>	
ACT (no CMB lensing)	low- ℓ EE SRoll2 + ACT DR6 (same as ACT base in [31])
ACT (low- ℓ TT, EE)	low- ℓ TT + low- ℓ EE SimAll + ACT DR6 + CMB lensing
PR4	low- ℓ TT + low- ℓ EE SimAll + high- ℓ PR4 + CMB lensing (same as baseline CMB in [16])
PR4 _(1000,600) + ACT	low- ℓ TT + low- ℓ EE SimAll + high- ℓ PR4 ($\ell < 1000$ TT, $\ell < 600$ TE, EE) + ACT DR6 + CMB lensing
PR4 _(SRoll2) + ACT	low- ℓ TT + low- ℓ EE SRoll2 + high- ℓ PR4 ($\ell < 2000$ TT, $\ell < 1000$ TE, EE) + ACT DR6 ($\ell \geq 2000$ TT, $\ell \geq 1000$ TE, EE) + CMB lensing

and assume three degenerate states. Throughout this work, we adopt the priors and tension metrics as described in [16].

III. CONSISTENCY OF DESI DR2 BAO AND CMB WITHIN Λ CDM

In this section, we explore the consistency between DESI BAO data and CMB across the CMB combinations described in Sec. II, assuming the Λ CDM model. In [16] it was pointed out that DESI DR2 BAO data show a discrepancy of 2.3σ with PR4. It is interesting to assess how this discrepancy stands with the latest CMB spectra from ACT, which provide precision measurements of the small-scale CMB anisotropies in temperature and

polarization, as well as tight constraints on the CMB damping tail. At the cosmological parameter level, the quantitative comparison between BAO and CMB data is performed by analyzing the 2D posteriors on the combination $H_0 r_d - \Omega_m$, which are the two cosmological parameters constrained by BAO data. The left panel of Fig. 1 shows the comparison of two CMB combinations (ACT in green, and PR4 + ACT in purple) with DESI BAO and DESY5 SNe data. We observe that the discrepancy between DESI and CMB occurs along the degeneracy direction of constant $\Omega_m h^3 = \text{const.}$ [50], roughly preserving the location of the first acoustic peak. This ensures that DESI is consistent with the acoustic angular scale θ_* predicted from CMB. In the following, we describe how

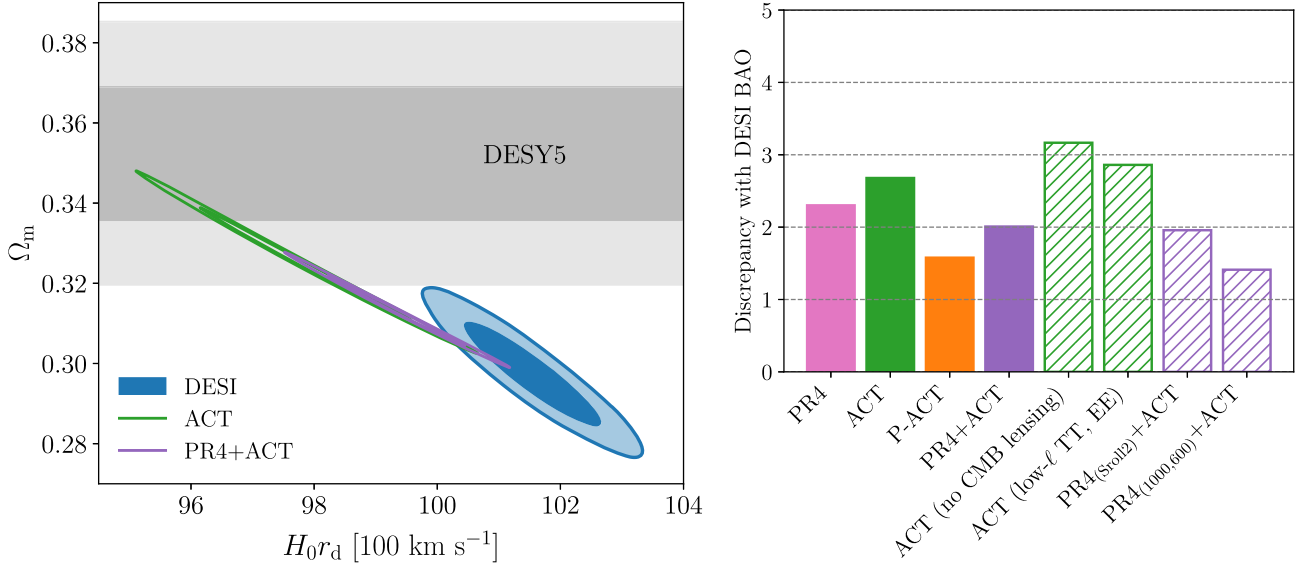


FIG. 1. Left: the 68% and 95% constraints on the $H_0 r_d$ - Ω_m 2D parameter space for DESI DR2 BAO, ACT, PR4 + ACT, and DESY5 SNe Ia, under the Λ CDM model. The combination based on ACT alone with SR0112 is shown in green, while our baseline combination PR4 + ACT is shown in purple. The ACT dataset shows a 2.7σ tension with DESI (3.2σ if CMB lensing is excluded), while the combination of PR4 + ACT shows a 2.0σ tension with DESI, once CMB lensing and low- ℓ TT data have been also included. Right: tension between DESI DR2 BAO and different CMB variations (expressed in $n\sigma$ units), in the Λ CDM model. The tension is calculated given the 2D posterior distributions of Ω_m and $H_0 r_d$. The first bars shown are PR4 (pink), ACT (green), P-ACT (orange) and PR4 + ACT (purple). The hatched bars of the corresponding color represent variations of the CMB dataset.

the consistency between CMB and DESI changes across the various CMB combinations.

The base ACT combination (without CMB lensing) shown in [31] reports high values of $\Omega_c h^2$ and $\Omega_b h^2$ and a lower H_0 with respect to *Planck*. This further pushes the ACT (no CMB lensing) data away from DESI, leading to a moderate 3.2σ tension. The inclusion of CMB lensing reduces this tension to 2.7σ . Interestingly, this is the opposite effect observed in [16], where excluding CMB lensing elongates the CMB contours reducing the discrepancy between DESI and PR4 data. The discrepancy persists even when the low- ℓ SR0112 likelihood is replaced with low- ℓ SimAll and low- ℓ TT information is included, leading to a 2.8σ discrepancy. However, the combination of P-ACT with the CMB lensing included alleviates the discrepancy leading to a 1.6σ difference with DESI. This pull of the CMB contours toward the DESI best-fit value is related to the higher values of $\Omega_b h^2$ and the spectral index n_s measured by ACT with respect to *Planck*, as well as to parameter correlations, as explained in Appendix A.

We further explore how DESI compares with a combination of PR4 and ACT. While ACT is more consistent with PR3 as compared to PR4 as pointed out in [31], here we assess the consistency between ACT and PR4 under the assumed ℓ cuts before combining them and verify that the overall discrepancy is 2.0σ or less in a six-parameter space under Λ CDM, and that individual parameters show discrepancies below this threshold. Our baseline CMB dataset labeled as PR4 + ACT shows a 14% and 23% precision

improvement in n_s and $\Omega_b h^2$ parameters, respectively, with respect to PR4 (see Fig. 7). Also, it shows only a mild discrepancy of 2.0σ with DESI (or 1.9σ for PR4(SR0112) + ACT). Applying a cut analogous to the one assumed in the P-ACT combination but using PR4, leads to a 1.4σ discrepancy with DESI, for our PR4(1000,600) + ACT combination. We also tested that removing the $600 < \ell < 1000$ TT data from *Planck* to avoid any overlaps in ℓ while still using a dataset that is “maximal” in ACT increases the discrepancy with DESI to 2.0σ .

We summarize the results in the right-hand side panel of Fig. 1 highlighting the three base CMB combinations for the rest of this work: ACT (the new CMB dataset), P-ACT (the official combination using PR3) and PR4 + ACT (our baseline combination using PR4).

Finally, the left panel of Fig. 1 also shows the SNe Ia data from DESY5 (for a more comprehensive comparison of all cosmological probes), which favors a high value of Ω_m with respect to DESI and CMB. Other SNe Ia datasets (not shown in Fig. 1), Pantheon+ and Union3, show a slightly better consistency with DESI. If we combine DESI with P-ACT, the Ω_m tension between DESI + CMB and SNe Ia ranges from 1.6σ for Pantheon+, to 2.0σ for Union3, and to 3.0σ for DESY5. The corresponding posteriors are shown in Fig. 2. We do not observe a significant change in these numbers using different CMB datasets. Overall, the combination between DESI and any CMB combination of *Planck* and ACT shows a mild to moderate discrepancy with the Ω_m measurement from SNe Ia, under Λ CDM.

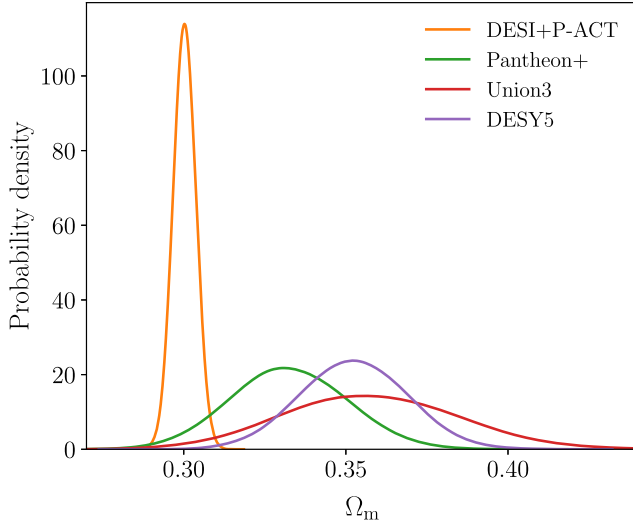


FIG. 2. 1D marginalized posterior constraints on Ω_m for the DESI + P-ACT combination compared to the various SNe Ia datasets. We combine DESI with P-ACT since the datasets are consistent under the Λ CDM model according to Fig. 1. Results using the DESI + PR4 + ACT combination are consistent with those of DESI + P-ACT.

IV. DARK ENERGY CONSTRAINTS

We proceed to explore how the constraints on dark energy as presented in [16] depend on the ACT results. We parametrize deviations from the cosmological constant using the w_0w_a CDM [27,28] dark energy equation of state given by $w(a) = w_0 + (1 - a)w_a$. As demonstrated in [16], w_0w_a CDM provides enough flexibility to jointly fit current BAO, CMB, and SNe Ia data while preserving consistency between the datasets; thus, we combine all three datasets into our analysis for w_0w_a CDM constraints.

The combination of DESI DR2 BAO with ACT, P-ACT and PR4 + ACT are shown in the w_0, w_a plane in the left-hand-side panel of Fig. 3. We observe that DESI + ACT pulls the constraints away from the $(w_0, w_a) = (-1, 0)$ limit, leading to a 2.9σ preference in favor of w_0w_a CDM. Interestingly, ACT provides a CMB dataset that is well fit by $A_{\text{Lens}} \approx 1$, where the parameter A_{Lens} can lead to an artificial smoothing of the CMB peaks [51]. Thus, it does not suffer from the so-called lensing anomaly. For DESI + P-ACT, the preference for a departure from Λ CDM diminishes to 2.4σ . On the other hand, the combination DESI + PR4 + ACT shows a 3.0σ preference in favor of w_0w_a CDM. For this combination, the errors on w_0 and w_a remain unchanged compared to P-ACT. Since the PR4 + ACT combination roughly chooses a sweet spot between *Planck* and ACT that provides more precise error bars on CMB parameters, we include more data from *Planck* compared to the P-ACT combination.

The difference between the evidence in favor of w_0w_a CDM when DESI is combined with ACT versus that when DESI is combined with P-ACT or PR4 + ACT can be

linked to the difference in the measured $\Omega_c h^2$ in the Λ CDM model by these respective CMB datasets. For example, a high CMB measurement of $\Omega_c h^2$ in Λ CDM would lead to a high Ω_m and a low $H_0 r_d$ with respect to DESI, pulling the contours away from $w_0 = -1$ and $w_a = 0$ in a w_0w_a CDM model. In contrast, a lower measurement of $\Omega_c h^2$ with respect to, e.g., PR4, would lead to more consistent results with DESI. This is also related to the importance of jointly matching physical density parameters like $\Omega_c h^2$ from the CMB with BAO, given the consistency of BAO with the CMB-predicted acoustic scale θ_* and that most of the significance in favor of w_0w_a CDM comes from CMB priors on $(\theta_*, \Omega_b h^2, \Omega_{bc} h^2)$, as discussed in [16]. As shown in Appendix A, ACT alone shows a high value of $\Omega_c h^2$ with respect to PR4, although with larger error bars. On the other hand, P-ACT shows the opposite behavior measuring a lower $\Omega_c h^2$ compared to PR4, while in PR4 + ACT the $\Omega_c h^2$ measurement is still lower than the PR4 prediction but the constraint is 19% tighter than P-ACT. In terms of the ACT data, it was reported that there is a strong dependency on the inferred values of $\Omega_c h^2$ and H_0 given the polarization efficiency calibration choices [31], which may impact the determination of these parameters.

The right-hand-side panel of Fig. 3 shows the constraints for DESI + DESY5 in combination with the three CMB baseline datasets. We can see that once the background cosmology is set by BAO and SNe Ia data, the effect of assuming a different CMB variation leads to only minor changes. As summarized in Fig. 4, we find that the significance in favor of w_0w_a CDM ranges from 2.5σ to 4.2σ , depending on the SNe Ia dataset used, while the assumed CMB variation has little impact on it. Table II summarizes the results on the effective difference on the χ^2_{MAP} , the corresponding significance in the frequentist representation, and the results for the deviance information criterion analysis, as presented in [29]. Once SNe Ia is included, the combination providing the mildest tension with Λ CDM is DESI + P-ACT + Pantheon+, with a 2.5σ significance in favor of w_0w_a CDM. However, replacing Pantheon+ with Union3 and DESY5 increases the significance in favor of w_0w_a CDM to 3.5σ and 4.0σ , respectively. The results from our baseline CMB variations provide compatible results, with tensions ranging between 2.8σ (using Pantheon+) up to 4.2σ (using DESY5). For reference, we also test the PR4_(1000,600) + ACT combination, which is more consistent with DESI than the PR4 + ACT dataset in Λ CDM. We find that DESI + PR4_(1000,600) + ACT shows a 2.7σ preference for w_0w_a CDM. Similarly, this preference ranges 2.6σ – 4.1σ when adding SNe Ia data, depending on the SNe sample. We also test the effect of using an alternative low- ℓ EE likelihood, replacing SRoll2 with SimAll in the ACT combination, and find that changing the low- ℓ polarization likelihood has little impact in the significance in favor of w_0w_a CDM. This highlights the robustness of the results presented in [16], after

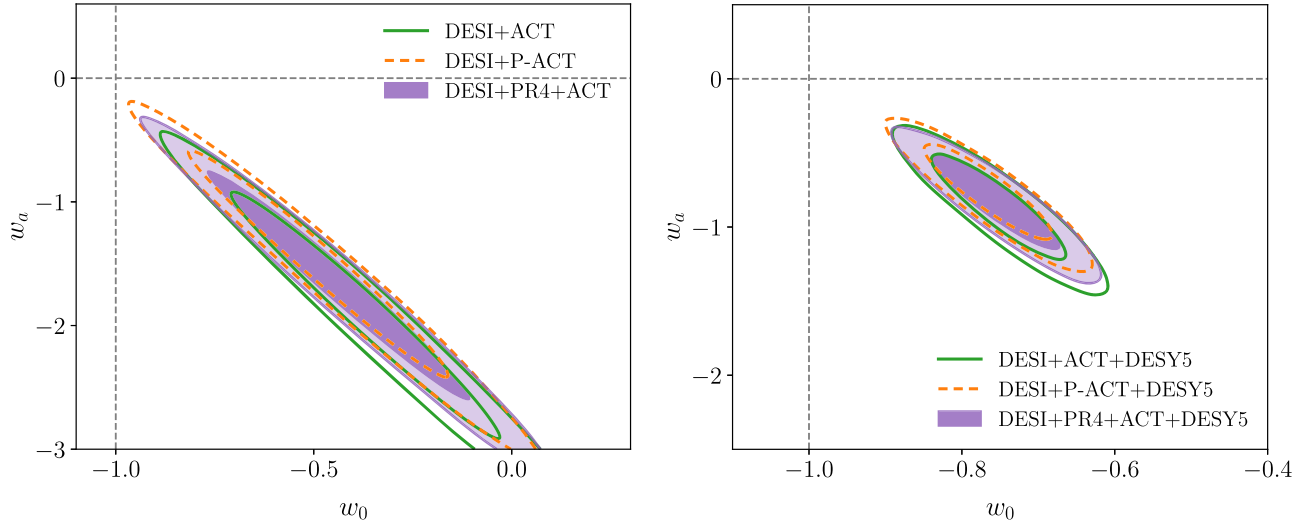


FIG. 3. Left: the 68% and 95% confidence contours in the w_0 - w_a plane using DESI DR2 BAO data in combination with CMB data. The blue contour describes the results from the combination DESI + ACT, while the unfilled orange contour shows DESI in combination with the P-ACT dataset described in [31]. The combination between DESI and our baseline CMB dataset with mixed multipole cuts in both *Planck* PR4 and ACT is shown in the unfilled green contour. The intersection of the two straight dashed gray lines represents the Λ CDM model. Right: similar to the left panel but now including DESY5 data but using a different ranges for w_0 and w_a .

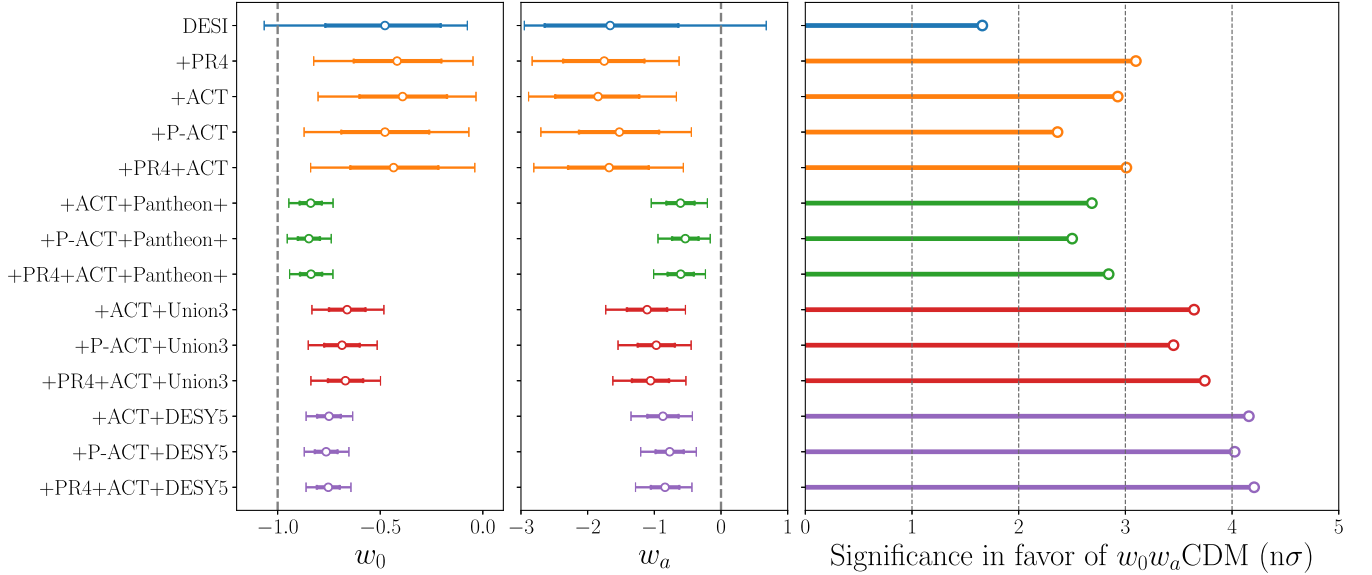


FIG. 4. 1D constraints on w_0 (left panel) and w_a (middle panel), highlighting the robustness of the results against variations in the CMB dataset chosen for the analysis. In the left and central panels, the thick bars represent the 68% errors while the thin bars correspond to the 95% errors. The vertical black dashed lines represent the Λ CDM value for w_0 and w_a . The right panel shows the corresponding significance in favor of the $w_0w_a\Lambda$ CDM model.

including newer CMB datasets based on ACT or combinations of it with *Planck*.

Finally, we summarize the results from the parameter constraints in Table III for Λ CDM and $w_0w_a\Lambda$ CDM,⁵ as well

⁵While this paper was under final review, [52] presented constraints on $w_0w_a\Lambda$ CDM from DESI + P-ACT and DESI + P-ACT + Pantheon+. We find consistent results with theirs.

as models with varying neutrino mass as discussed in the following section.

V. NEUTRINO MASS CONSTRAINTS

Despite the fact that BAO data alone cannot constrain the total neutrino mass, $\sum m_\nu$, determining Ω_m and H_0r_d from low redshifts significantly enhances the CMB sensitivity to

TABLE II. Table summarizing the results on the difference in the effective χ^2_{MAP} value for the best-fit w_0w_a CDM model relative to the best Λ CDM model with $w_0 = -1$, $w_a = 0$, and its corresponding significance level in a frequentist representation. The last column shows the results for the deviance information criteria, $\Delta(\text{DIC}) = \text{DIC}_{w_0w_a\text{CDM}} - \text{DIC}_{\Lambda\text{CDM}}$.

Datasets	$\Delta\chi^2_{\text{MAP}}$	Significance	$\Delta(\text{DIC})$
DESI + ACT	-11.4	2.9σ	-7.8
DESI + ACT + Pantheon+	-9.9	2.7σ	-6.3
DESI + ACT + Union3	-16.4	3.6σ	-13.0
DESI + ACT + DESY5	-20.7	4.2σ	-16.8
DESI + P-ACT	-8.0	2.4σ	-5.4
DESI + P-ACT + Pantheon+	-8.8	2.5σ	-4.5
DESI + P-ACT + Union3	-15.0	3.5σ	-10.9
DESI + P-ACT + DESY5	-19.5	4.0σ	-15.2
DESI + PR4 + ACT	-11.9	3.0σ	-7.8
DESI + PR4 + ACT + Pantheon+	-10.8	2.8σ	-6.5
DESI + PR4 + ACT + Union3	-17.2	3.7σ	-13.8
DESI + PR4 + ACT + DESY5	-21.1	4.2σ	-17.2

$\sum m_\nu$ via the neutrino-induced shift in the angular diameter distance to last scattering. CMB photons are sensitive to the neutrino mass through lensing, since neutrinos suppress the growth of structures below their free-streaming scale. Low- ℓ E-mode polarization of the CMB also plays an important indirect role in constraining neutrino masses by breaking the degeneracy between the optical depth to reionization and the amplitude of primordial scalar fluctuations measured from high- ℓ multipoles. This in turn gives a more accurate estimation of the lensing potential, which is suppressed on small scales by massive neutrinos. Therefore, the upper limits on $\sum m_\nu$ obtained from the combination of DESI and CMB depend on both the BAO constraining power and the choice of the CMB likelihood, as different likelihoods slightly vary in the amount of lensing power they infer from the lensed TT, TE, and EE spectra at both low- and high- ℓ .

The inferred constraints on $\sum m_\nu$ from BAO + CMB depend on the underlying cosmological model. In the following, we focus on the Λ CDM and w_0w_a CDM models with free total neutrino mass, assuming three degenerate mass eigenstates. We also adopt a minimal physical prior, $\sum m_\nu > 0$ eV, noting that scenarios allowing for a negative effective neutrino mass have recently gained interest [20,53–55].

Recently, the ACT collaboration set an upper bound on the total neutrino mass of $\sum m_\nu < 0.082$ eV at 95% confidence level (CL) under Λ CDM [33], based on the combination of DESI DR1 BAO measurements and what we refer to as P-ACT. Using the updated DESI DR2 BAO data, this limit tightens to $\sum m_\nu < 0.077$ eV at 95% CL, representing about a 6% reduction in the upper bound due to the improved BAO measurements in DESI DR2 with respect to DR1. This constraint is, however, about 20%

weaker than the baseline bound recently reported by the DESI collaboration, $\sum m_\nu < 0.064$ eV at 95% CL [16], which combines DESI DR2 BAO with *Planck* PR4. The difference between the P-ACT and PR4 combinations primarily arises from the treatment of low- ℓ EE and high- ℓ TT likelihoods, including specific choices of cuts.

However, we stress that these results, along with those presented below, are influenced by the prior $\sum m_\nu > 0$ eV. This dependence has been discussed in [16], and more thoroughly in [20], that employed a profile likelihood analysis to quantify the impact of the prior and further investigated the implications of effective neutrino negative masses [55]. A similar profile likelihood analysis is presented in Appendix B.

Figure 5 illustrates how the constraints on the neutrino mass are influenced by the main CMB combinations—ACT, P-ACT, and PR4 + ACT—when combined with DESI DR2 BAO. For comparison, we include the baseline results from [16] in magenta. For the PR4 + ACT combination, we observe that by cutting the PR4 likelihood at the multipoles $\ell = 2000$ in TT and $\ell = 1000$ in TEEE, and merging with ACT data starting from these multipole cuts, tightens the upper bound to $\sum m_\nu < 0.061$ eV at 95% CL (solid purple line) for Λ CDM. This results in a reduction of approximately 5% compared to the baseline results from [16], providing the tightest constraints on the total neutrino mass to date, derived exclusively from BAO and CMB datasets. Notice that similar bounds under Λ CDM have been recently obtained in [56] using a joint CMB lensing dataset from the latest three CMB experiments.

The difference in constraining power between PR4 + ACT and the baseline results from [16] stems not only from the inclusion of ACT data, but also from the specific choice of the ℓ -range where *Planck* is cut and ACT is added. In the PR4 + ACT combination, we select the region of the spectrum where the ACT signal roughly exhibits lower uncertainty compared to *Planck* across most frequency spectra (see Fig. 12 of [31]), leading to tighter neutrino mass constraints. Alternatively, the DESI + PR4_(1000,600) + ACT combination leads to a 95% bound of $\sum m_\nu < 0.072$ eV. This loosening in the constraints of $\sum m_\nu$ comes from the higher consistency between the Ω_m values of DESI and PR4_(1000,600) + ACT, compared to that of PR4 + ACT.

Additionally, Fig. 5 includes the constraints from the joint DESI + ACT analysis, which, despite covering a smaller portion of the CMB power spectrum, yields an upper bound of $\sum m_\nu < 0.073$ eV (95% CL), similar to those obtained with other CMB likelihood combinations.

In the w_0w_a CDM scenario, the combination of DESI DR2 BAO and the main CMB datasets (without SNe) yields marginalized 1D posterior distributions that peak at positive values of $\sum m_\nu$, consistent with the findings of [16]. This behavior is found across all main CMB dataset combinations. To avoid overcrowding, Fig. 6 shows

TABLE III. Summary table of key cosmological parameter constraints from DESI DR2 BAO (labeled simply as DESI) in combination with external datasets for the Λ CDM and extended models. We report the mean value and the 68% confidence for all parameters, except for the total neutrino mass, for which the 95% upper limit is quoted.

Model/Dataset	Ω_m	H_0 [km s ⁻¹ Mpc ⁻¹]	$\sum m_\nu$ [eV]	w_0	w_a
ΛCDM					
DESI + ACT	0.3003 ± 0.0039	68.48 ± 0.29	—	—	—
DESI + P-ACT	0.3003 ± 0.0035	68.43 ± 0.27	—	—	—
DESI + PR4 + ACT	0.3019 ± 0.0035	68.28 ± 0.26	—	—	—
$w_0 w_a$CDM					
DESI + ACT	$0.355^{+0.022}_{-0.020}$	$63.6^{+1.6}_{-2.0}$	—	$-0.39^{+0.23}_{-0.19}$	-1.84 ± 0.59
DESI + ACT + Pantheon+	0.3108 ± 0.0057	67.72 ± 0.60	—	-0.839 ± 0.055	$-0.61^{+0.22}_{-0.20}$
DESI + ACT + Union3	0.3274 ± 0.0088	66.09 ± 0.85	—	-0.661 ± 0.089	$-1.11^{+0.32}_{-0.28}$
DESI + ACT + DESY5	0.3188 ± 0.0058	66.94 ± 0.57	—	-0.750 ± 0.058	$-0.87^{+0.25}_{-0.22}$
DESI + P-ACT	$0.347^{+0.020}_{-0.023}$	64.1 ± 1.9	—	-0.48 ± 0.21	$-1.52^{+0.64}_{-0.56}$
DESI + P-ACT + Pantheon+	0.3098 ± 0.0056	67.62 ± 0.60	—	-0.848 ± 0.054	$-0.54^{+0.21}_{-0.18}$
DESI + P-ACT + Union3	0.3251 ± 0.0085	66.08 ± 0.84	—	-0.686 ± 0.086	$-0.97^{+0.30}_{-0.26}$
DESI + P-ACT + DESY5	0.3175 ± 0.0055	66.85 ± 0.56	—	-0.764 ± 0.056	$-0.77^{+0.22}_{-0.20}$
DESI + PR4 + ACT	0.350 ± 0.021	$63.8^{+1.8}_{-2.0}$	—	-0.43 ± 0.21	-1.68 ± 0.58
DESI + PR4 + ACT + Pantheon+	0.3107 ± 0.0056	67.59 ± 0.59	—	-0.837 ± 0.054	$-0.60^{+0.21}_{-0.19}$
DESI + PR4 + ACT + Union3	0.3265 ± 0.0085	66.00 ± 0.84	—	-0.670 ± 0.086	$-1.06^{+0.29}_{-0.26}$
DESI + PR4 + ACT + DESY5	0.3182 ± 0.0055	66.83 ± 0.56	—	-0.753 ± 0.056	$-0.84^{+0.23}_{-0.20}$
ΛCDM + $\sum m_\nu$					
DESI + ACT	0.2992 ± 0.0039	68.63 ± 0.31	< 0.0733	—	—
DESI + P-ACT	0.2987 ± 0.0037	68.61 ± 0.29	< 0.0768	—	—
DESI + PR4 + ACT	0.2999 ± 0.0036	68.50 ± 0.28	< 0.0606	—	—
$w_0 w_a$CDM + $\sum m_\nu$					
DESI + ACT	$0.355^{+0.024}_{-0.020}$	$63.7^{+1.6}_{-2.2}$	< 0.170	$-0.39^{+0.25}_{-0.19}$	$-1.85^{+0.61}_{-0.75}$
DESI + ACT + Pantheon+	0.3105 ± 0.0058	67.72 ± 0.60	< 0.124	-0.843 ± 0.056	$-0.57^{+0.24}_{-0.21}$
DESI + ACT + Union3	0.3273 ± 0.0090	66.10 ± 0.85	< 0.147	-0.665 ± 0.092	$-1.09^{+0.36}_{-0.30}$
DESI + ACT + DESY5	0.3186 ± 0.0058	66.95 ± 0.57	< 0.136	-0.753 ± 0.059	$-0.85^{+0.26}_{-0.23}$
DESI + P-ACT	0.349 ± 0.022	$63.9^{+1.8}_{-2.1}$	< 0.186	-0.45 ± 0.22	$-1.62^{+0.73}_{-0.65}$
DESI + P-ACT + Pantheon+	0.3095 ± 0.0057	67.64 ± 0.60	< 0.131	-0.852 ± 0.055	$-0.51^{+0.23}_{-0.19}$
DESI + P-ACT + Union3	0.3253 ± 0.0089	66.08 ± 0.85	< 0.155	-0.687 ± 0.090	$-0.97^{+0.34}_{-0.28}$
DESI + P-ACT + DESY5	0.3173 ± 0.0058	66.87 ± 0.56	< 0.149	-0.766 ± 0.058	$-0.76^{+0.26}_{-0.21}$
DESI + PR4 + ACT	0.350 ± 0.022	$63.9^{+1.8}_{-2.1}$	< 0.152	-0.44 ± 0.21	-1.66 ± 0.62
DESI + PR4 + ACT + Pantheon+	0.3099 ± 0.0057	67.64 ± 0.60	< 0.108	-0.846 ± 0.054	$-0.55^{+0.22}_{-0.19}$
DESI + PR4 + ACT + Union3	0.3259 ± 0.0087	66.05 ± 0.84	< 0.128	-0.678 ± 0.088	$-1.01^{+0.32}_{-0.27}$
DESI + PR4 + ACT + DESY5	0.3177 ± 0.0057	66.86 ± 0.57	< 0.122	-0.761 ± 0.057	$-0.79^{+0.25}_{-0.21}$

only the posteriors for PR4_(SR0112) + ACT (dashed black) and PR4 + ACT (solid black), the latter being the only DESI + CMB combination whose posterior peaks at zero. This case also provides the most stringent constraint on the neutrino mass within $w_0 w_a$ CDM, with $\sum m_\nu < 0.15$ eV (95% CL).

Although the DESI + CMB results are largely consistent with positive neutrino masses, they also exhibit a preference for higher values of Ω_m (see Table III), which are “stabilized” when including information from SNe Ia datasets. In that case, all posteriors peak at $\sum m_\nu = 0$,

and they would reach a maximum at negative $\sum m_\nu$ values if extrapolated.⁶ This behavior is illustrated in Fig. 6 for DESY5 and also holds when considering either Pantheon+ or Union3. These findings are consistent with those reported in [16,26], and we explore them in more detail using the profile likelihood analysis in Appendix B.

Finally, we highlight the impact of the $\ell < 30$ multipoles polarization data. In particular, we find that across all

⁶This feature has motivated interest in exploring the implications of negative effective neutrino masses [20,53–55].

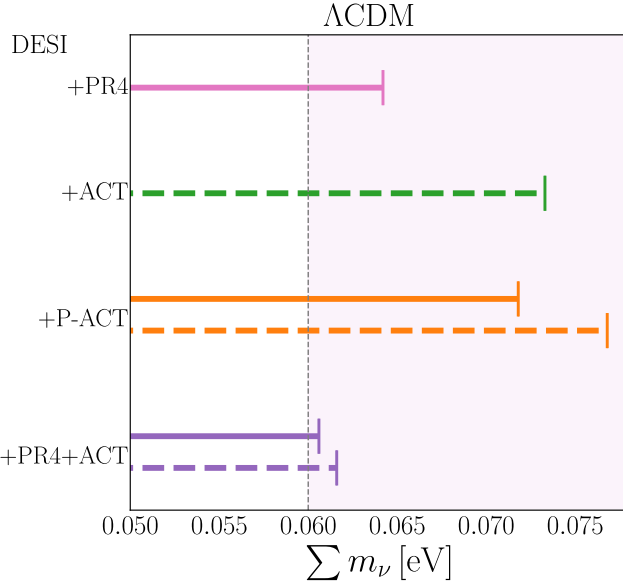


FIG. 5. Whisker plots showing the 95% confidence constraints on $\sum m_\nu$ from the combination of DESI DR2 BAO with various CMB likelihoods under the ΛCDM model. Dashed lines correspond to constraints obtained using the low- ℓ EE SRo112 likelihood, while solid lines use low- ℓ EE SimAll likelihood in each corresponding combination. The vertical dashed line and shaded region indicate the minimal sum of neutrino masses for the normal ($\sum m_\nu > 0.06$ eV) mass ordering.

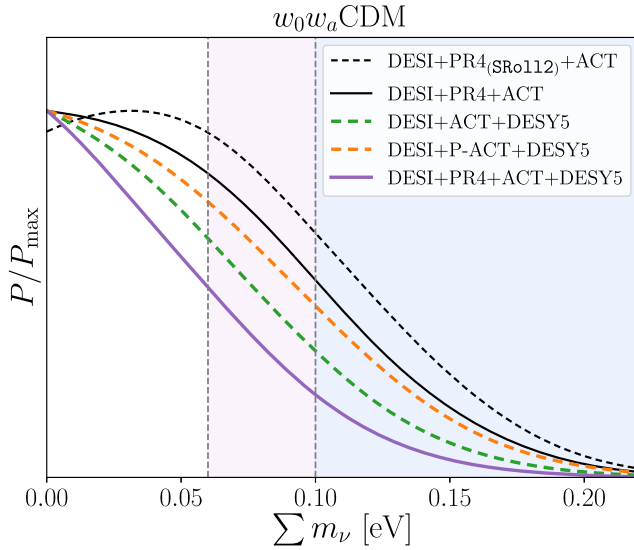


FIG. 6. 1D marginalized posterior constraints on $\sum m_\nu$ from various dataset combinations within the $w_0w_a\text{CDM}$ model. The black curves show results from combining DESI DR2 BAO with PR4 + ACT. We also present posteriors obtained using DESI DR2 BAO with the main CMB combinations, all combined with DESY5. Dashed curves correspond to datasets that include the low- ℓ EE SRo112 likelihood, while solid curves instead use the low- ℓ EE SimAll likelihood. The vertical dashed lines and shaded regions indicate the minimum sum of neutrino masses allowed for the normal ($\sum m_\nu > 0.06$ eV) and inverted ($\sum m_\nu > 0.10$ eV) mass orderings.

analyses, replacing the baseline low- ℓ SimAll likelihood with the SRo112 likelihood shifts the posterior peak toward higher values, as illustrated in Fig. 6. This is due to the higher value of τ inferred by SRo112. This shift apparently loosens the neutrino mass constraints by up to 7%, in both the ΛCDM and $w_0w_a\text{CDM}$ models.

VI. CONCLUSIONS

In this paper, we reanalyze the cosmological results on the evidence for evolving dark energy and neutrino mass constraints of the official DESI DR2 BAO analysis presented in [16] by incorporating the latest ACT DR6 CMB data. The ACT DR6 data predict higher values for the physical densities of both baryons $\Omega_b h^2$ and cold dark matter $\Omega_c h^2$, compared to *Planck*. Within the ΛCDM model, this results in a discrepancy with DESI at a level exceeding 3σ , which is larger than the 2.0σ discrepancy observed with *Planck* PR4 (without CMB lensing). Since the ACT DR6 data cover a wide range of multipoles, partially sharing angular scales with *Planck* (in the range $600 \leq \ell \leq 2500$), we combine these two CMB datasets using multipole cuts to avoid overlap. Along with ACT, we focus on two other CMB data combinations, namely, P-ACT (based on PR3, matching the combination presented in [31]), and PR4 + ACT (our baseline CMB dataset). The PR4 + ACT combination, based on PR4, uses cuts in the common multipole range between PR4 and ACT that lead to tighter constraints, showing a precision improvement of 14% in n_s and 23% in $\Omega_b h^2$ with respect to PR4, and a 5% precision improvement in the $\Omega_c h^2$ constraint over other combinations with a different ℓ -cut scheme such as PR4_(1000,600) + ACT.

We explore the evidence for evolving dark energy under these three CMB datasets using ACT DR6 and find that DESI + ACT shows a 2.9σ evidence in favor of the $w_0w_a\text{CDM}$ model. This evidence is reduced to 2.4σ when using DESI + P-ACT. This is due to the pull from P-ACT toward lower values of $\Omega_c h^2$, compared to those from ACT and *Planck* individually, in the ΛCDM model. The combination DESI + PR4 + ACT, which provides tighter constraints on cosmological parameters, leads to a 3.0σ significance in favor of $w_0w_a\text{CDM}$. We also test the inclusion of the three SNe Ia datasets, namely Pantheon+, Union3 and DESY5, and find that variations in the CMB dataset leads to at most 0.3σ differences and that the evidence for evolving dark energy can go up to 4.0σ . Therefore, we conclude that the results presented in [16] are robust in light of the new ACT CMB data.

We also present updated constraints in the neutrino mass bounds from cosmology and find that, in ΛCDM and assuming a physical prior $\sum m_\nu > 0$ eV, DESI + ACT yields a neutrino mass constraint of $\sum m_\nu < 0.073$ eV (95% CL). Our baseline CMB dataset, PR4 + ACT, imposes an upper bound of $\sum m_\nu < 0.061$ eV (95% CL) when combined with DESI. This represents a 5% reduction

in the error compared to the neutrino mass constraints in [16], for the DESI + CMB baseline combination. Extending the background to an evolving dark energy component parametrized by w_0 and w_a gives an upper mass limit of $\sum m_\nu < 0.17$ eV and $\sum m_\nu < 0.15$ eV at 95% CL, for DESI + ACT and DESI + PR4 + ACT, respectively. Consistent with [16], we find that combining DESI BAO with CMB data yields a preference for positive neutrino masses. However, this preference vanishes when SNe data are included in the analysis. Finally, we find that the use of the low- ℓ EE SRoll2 likelihood can relax the constraints on neutrino mass compared to the low- ℓ EE SimAll likelihood by up to 7%. This is due to a shift of the best-fit $\sum m_\nu$ toward larger values, related to a preference for a higher optical depth τ when using the low- ℓ EE SRoll2 likelihood.

Overall, we find the results presented in [16] to be robust under the inclusion of the ACT data for the CMB combinations tested in this work. A joint treatment of *Planck* and ACT DR6 covariance could eventually coalesce to a consolidated CMB dataset.

ACKNOWLEDGMENTS

We thank Martin White for useful comments on the manuscript while serving as internal reviewer. C. G. Q. acknowledges the support provided by NASA through the NASA Hubble Fellowship Grant No. HST-HF2-51554.001-A awarded by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., for NASA, under contract NAS5-26555. H. N. and A. A. acknowledge support by SECIHTI Grant No. CBF2023-2024-162 and PAPIIT IA101825. H. N. acknowledges support by PAPIIT-IN101124. J. R. acknowledges funding from U.S. Department of Energy Grant No. DE-SC0016021. S. N. acknowledges support from an STFC Ernest Rutherford Fellowship, grant reference No. ST/T005009/2. W. E. acknowledges STFC Consolidated Grant No. ST/X001075/1 and support from the European Research Council (ERC) Advanced Investigator grant DMIDAS (No. GA 786910). M. I. acknowledges that this material is based upon work supported in part by the Department of Energy, Office of Science, under Award No. DESC0022184 and also in part by the U.S. National Science Foundation under Grant No. AST2327245. This material is based upon work supported by the U.S. Department of Energy (DOE), Office of Science, Office of High-Energy Physics, under Contract No. DE-AC02-05CH11231, and by the National Energy Research Scientific Computing Center, a DOE Office of Science User Facility under the same contract. Additional support for DESI was provided by the U.S. National Science Foundation (NSF), Division of Astronomical Sciences under Contract No. AST-0950945 to the NSF National Optical-Infrared Astronomy Research

Laboratory; the Science and Technology Facilities Council of the United Kingdom; the Gordon and Betty Moore Foundation; the Heising-Simons Foundation; the French Alternative Energies and Atomic Energy Commission (CEA); the National Council of Humanities, Science and Technology of Mexico (CONAHCYT); the Ministry of Science and Innovation of Spain (MICINN), and by the DESI Member Institutions: [57]. The authors are honored to be permitted to conduct scientific research on I'oligam Du'ag (Kitt Peak), a mountain with particular significance to the Tohono O'odham Nation. C. G. Q. and A. C. are NASA Einstein Fellows.

DATA AVAILABILITY

The data and code to reproduce the figures are available at [58], as part of DESI's Data Management Plan.

APPENDIX A: COMBINING *PLANCK* AND ACT

We describe how the CMB variations used in this work affect the cosmological parameters within Λ CDM, under the different multipole cuts used to combine *Planck* and ACT DR6. Figure 7 shows the four parameters $\Omega_{bc}h^2$, $\Omega_b h^2$, Ω_m , and n_s , under ACT, PR4 and several CMB combinations. Here, the parameter $\Omega_{bc}h^2$ controls several elements in early physics such as the epoch of matter-radiation equality and the acoustic scale of the CMB peaks, while $\Omega_b h^2$ affects the baryon-to-photon density ratio. Also, the low-redshift data from background probes is affected by Ω_m , and n_s characterizes the scale dependence of the primordial power spectrum of scalar perturbations. Additionally, Fig. 7 also shows the 1D posterior for $\Omega_c h^2$ which is a key parameter for the deviations from $(w_0, w_a) = (1, 0)$ in $w_0 w_a$ CDM when combining DESI with CMB.

The ACT data favor higher $\Omega_{bc}h^2$ and $\Omega_b h^2$ values compared to PR4, leading to a small r_d . The higher value of $\Omega_c h^2$ measured from ACT with respect to PR4 also leads to ACT alone being less consistent with DESI. An interesting feature is the correlation observed between $\Omega_b h^2$ and n_s when measured with ACT and PR4 [59]. *Planck*, constraining large scales, measures a positive correlation, while ACT, on small scales, measures a negative correlation, making the two surveys highly complementary. This difference in the correlation of $\Omega_b h^2$ and n_s between the two CMB experiments, along with the fact that the measured values of n_s and particularly $\Omega_b h^2$ from ACT are higher than the *Planck* prediction, control the behavior of the joint constraints in the higher parameter space.

As defined in Sec. II, the PR4 + ACT combination combines PR4 and ACT such that we do not have any overlapping multipole regions and that we can get more constraining power by using each survey in the regime where its uncertainties are lower. Figure 7 shows how PR4 + ACT provides a tight constraint that falls between ACT and PR4 following the degeneracy direction of PR4.

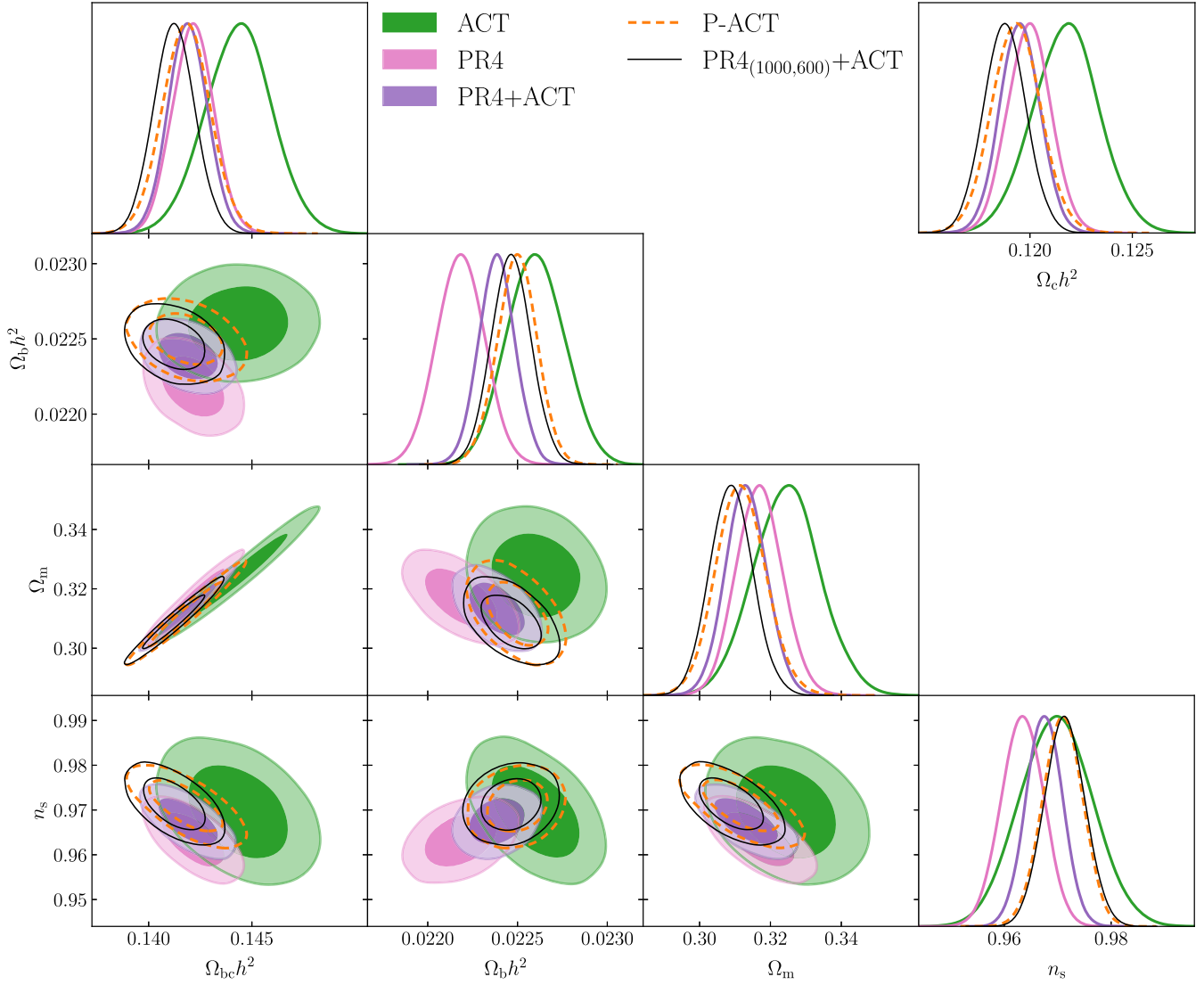


FIG. 7. The 68% and 95% confidence contours for the parameters $\Omega_{bc}h^2$, $\Omega_b h^2$, Ω_m , and n_s using various CMB datasets. The green contours show the ACT data described in [31] with CMB lensing, while the pink contours correspond to the baseline CMB dataset used in [16]. The baseline CMB dataset of this work is shown in purple, and the P-ACT and $\text{PR4}_{(1000,600)} + \text{ACT}$ results are shown in orange and black unfilled contours, respectively. The $\Omega_b h^2$ - n_s panel shows the positive correlation between these parameters as measured by PR4, opposite to the negative correlation measured by ACT (see [59]). The corresponding 1D posterior distributions on $\Omega_c h^2$ are shown in the upper right corner.

This constraint means higher $\Omega_b h^2$ and n_s values compared to PR4, with the central values of these parameters landing between the PR4 and ACT constraints. The effect on the rest of the parameters can be understood from the correlations with these parameters. For example, we observe that for PR4 high values of $\Omega_b h^2$ and n_s correspond to low values of $\Omega_{bc} h^2$, as observed in Fig. 7. A similar effect occurs for Ω_m and $\Omega_c h^2$, leading to joint constraints in $\text{PR4} + \text{ACT}$ to measure lower values of Ω_m and $\Omega_c h^2$ compared to PR4. Furthermore, the fact that *Planck* and ACT individually prefer a higher value of Ω_m compared to any of their joint combinations (either P-ACT or $\text{PR4} + \text{ACT}$) becomes relevant for the tensions shown in

Fig. 1, leading to better consistency with DESI when combining *Planck* and ACT. Thus, the inferred values on these parameters play a key role in the consistency with the DESI data and therefore can affect the evidence for evolving dark energy.

Figure 7 also shows the comparison between $\text{PR4} + \text{ACT}$ and the results from P-ACT and $\text{PR4}_{(1000,600)} + \text{ACT}$. We observe that the datasets are consistent with each other, with the combinations using PR4 showing slightly tighter constraints. The precision improvement on the $\Omega_c h^2$ measurement of $\text{PR4} + \text{ACT}$ is 19% with respect to P-ACT, coming primarily from adopting PR4 instead of PR3 and secondarily due to our

multipole cuts. In fact, the PR4 + ACT is 5% more precise in $\Omega_c h^2$ than PR4_(1000,600) + ACT, coming exclusively from our choice of the ℓ cuts. Finally, the combinations P-ACT and PR4_(1000,600) + ACT contain more information from ACT than in the case of PR4 + ACT. This implies that both P-ACT and PR4_(1000,600) + ACT measure higher values of $\Omega_b h^2$ with respect to PR4 + ACT, therefore leading to lower values of $\Omega_{bc} h^2$, Ω_m and $\Omega_c h^2$.

APPENDIX B: FREQUENTIST ANALYSIS FOR NEUTRINO MASS CONSTRAINTS

When constraining the neutrino mass in Sec. V, we have seen that the posteriors tend to peak at $\sum m_\nu = 0$, which is an indication that the physical prior $\sum m_\nu > 0$ impacts our constraints. To further investigate this behavior, we perform a profile likelihood analysis for the combination of DESI DR2 BAO and ACT data⁷ in the Λ CDM and $w_0 w_a$ CDM models, and explore how these constraints are affected by the inclusion of SNe data.

We follow the same methodology as in [20], where the profile likelihood is evaluated for several fixed values of $\sum m_\nu$, while maximizing the likelihood $\mathcal{L}$ (or equivalently minimizing $\chi^2 = -2 \log \mathcal{L}$) with respect to all other cosmological and nuisance parameters. As in that work, we perform a numerical minimization of the log-likelihood using the Minuit algorithm [60], via its Python interface, iminuit [61]. The resulting profiles, shown in Fig. 8, closely follow a parabolic fit parametrized by the minimum μ_0 and its scale σ . The latter can be interpreted as the constraining power of the corresponding data combination. The minima μ_0 , the scale σ , and the 95% CL are summarized in Table IV.

The profile likelihood results are in good agreement with the Bayesian findings. In both approaches, the combination of DESI DR2 BAO and CMB data in the $w_0 w_a$ CDM model yields a peak in the positive neutrino mass region—either in the profile likelihood or in the posterior. The inclusion of SNe data primarily shifts the profile toward lower values, reaching the boundary of the physical region, while the scale σ is only moderately affected. Consequently, the tightening of the estimated upper limit is mainly driven by this shift rather than by a substantial change in the uncertainty scale.

Figure 8 shows that for the Λ CDM model, combining DESI DR2 BAO with either ACT-lite or PR4 leads to a profile likelihood minimum that lies outside the physical region, consistent with the Bayesian results presented in Sec. V. The minima from both CMB combinations remain

⁷For computational efficiency, we use the ACT-lite likelihood, a compressed version of the multifrequency likelihood (MFLike) provided by the ACT team [31]. Differences with MFLike are expected to be negligible, given that the inferred cosmological parameters agree to within 0.1σ , as shown in Appendix F of [31].

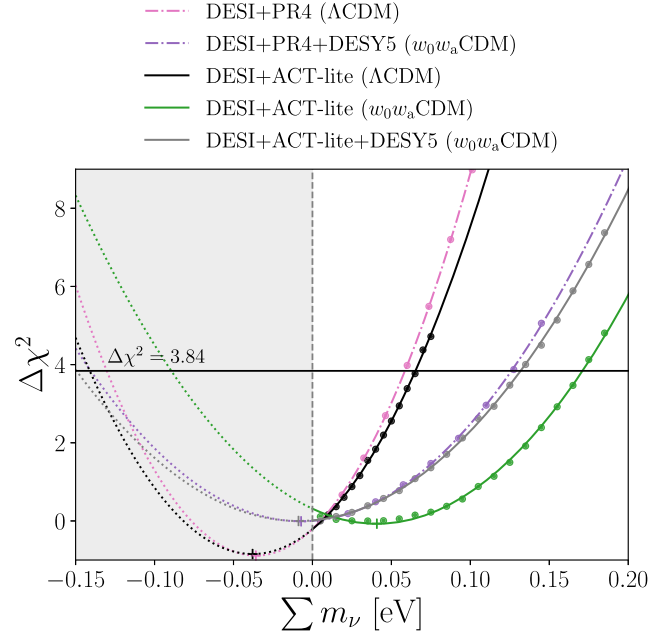


FIG. 8. Profile likelihoods for $\sum m_\nu$ from different combinations of datasets and cosmological models. The green curve corresponds to the combination of DESI DR2 BAO and ACT-lite in the $w_0 w_a$ CDM model, while the gray curve additionally includes SNe data from DESY5. For completeness, the combination DESI DR2 BAO + PR4 + DESY5 is shown in purple. The inclusion of SNe information shifts the profile back into the negative $\sum m_\nu$ region, in agreement with the Bayesian results presented in Sec. V. For comparison, we also show Λ CDM profiles using ACT-lite (black) and PR4 (pink), both with minima lying in the unphysical (negative) region.

almost unaffected, with the only difference being that ACT-lite exhibits weaker constraining power, as also observed in the Bayesian analysis. This latter behavior is also seen in the $w_0 w_a$ CDM model.

Finally, one can compare the upper bounds on $\sum m_\nu$ derived from both Bayesian and frequentist analyses. In Λ CDM, the profile likelihood leads to a smaller bound than the Bayesian method by up to 0.013 eV, while in

TABLE IV. Profile likelihood parameters for various dataset combinations and cosmological models. We report the minimum μ_0 , the scale σ , and the 95% CL computed using the Feldman-Cousins prescription [62].

Model/Dataset	μ_0 [eV]	σ [eV]	95% CL [eV]
DESI + PR4 (Λ CDM)	-0.036	0.043	< 0.053
DESI + ACT-lite (Λ CDM)	-0.038	0.048	< 0.060
DESI + ACT-lite ($w_0 w_a$ CDM)	0.041	0.066	< 0.170
DESI + PR4 + DESY5 ($w_0 w_a$ CDM)	-0.007	0.068	< 0.126
DESI + ACT-lite + DESY5 ($w_0 w_a$ CDM)	-0.009	0.072	< 0.132

w_0w_a CDM, they become very consistent, differing by up to 0.001 eV at most. This difference can be attributed to the position of the profiles and posteriors with regard to the $\sum m_\nu > 0$ eV bound. In the w_0w_a CDM model, the profiles

have minima close to or greater than zero, which brings the situation closer to a regular, uninterrupted Gaussian distribution where Bayesian and frequentist frameworks are expected to coincide.

-
- [1] A. G. Riess, A. V. Filippenko, P. Challis, A. Clocchiatti, A. Diercks, P. M. Garnavich, R. L. Gilliland, C. J. Hogan, S. Jha, R. P. Kirshner, B. Leibundgut, M. M. Phillips, D. Reiss, B. P. Schmidt, R. A. Schommer *et al.*, *Astron. J.* **116**, 1009 (1998).
- [2] S. Perlmutter, G. Aldering, G. Goldhaber, R. A. Knop, P. Nugent, P. G. Castro, S. Deustua, S. Fabbro, A. Goobar, D. E. Groom, I. M. Hook, A. G. Kim, M. Y. Kim, J. C. Lee, N. J. Nunes *et al.*, *Astrophys. J.* **517**, 565 (1999).
- [3] M. Levi, C. Bebek, T. Beers, R. Blum, R. Cahn, D. Eisenstein, B. Flaugher, K. Honscheid, R. Kron, O. Lahav, P. McDonald, N. Roe, D. Schlegel, and representing the DESI Collaboration, [arXiv:1308.0847](https://arxiv.org/abs/1308.0847).
- [4] A. Aghamousa, J. Aguilar, S. Ahlen, S. Alam, L. E. Allen, C. Allende Prieto, J. Annis, S. Bailey, C. Balland, O. Ballester, C. Baltay, L. Beaufore, C. Bebek, T. C. Beers *et al.* (DESI Collaboration), [arXiv:1611.00036](https://arxiv.org/abs/1611.00036).
- [5] A. Aghamousa, J. Aguilar, S. Ahlen, S. Alam, L. E. Allen, C. Allende Prieto, J. Annis, S. Bailey, C. Balland, O. Ballester, C. Baltay, L. Beaufore, C. Bebek, T. C. Beers *et al.* (DESI Collaboration), [arXiv:1611.00037](https://arxiv.org/abs/1611.00037).
- [6] B. Abareschi, J. Aguilar, S. Ahlen, S. Alam, D. M. Alexander, R. Alfarsy, L. Allen, C. Allende Prieto, O. Alves, J. Ameel, E. Armengaud, J. Asorey, A. Aviles, S. Bailey *et al.* (DESI Collaboration), *Astron. J.* **164**, 207 (2022).
- [7] J. H. Silber, P. Fagrelus, K. Fanning, M. Schubnell, J. N. Aguilar, S. Ahlen, J. Ameel, O. Ballester, C. Baltay, C. Bebek, D. Benton Beard, R. Besuner, L. Cardiel-Sas, R. Casas, F. J. Castander *et al.*, *Astron. J.* **165**, 9 (2023).
- [8] C. Poppett, L. Tyas, J. Aguilar, C. Bebek, D. Bramall, T. Claybaugh, J. Edelstein, P. Fagrelus, H. Heetderks, P. Jelinsky, S. Jelinsky, R. Lafever, A. Lambert, M. Lampton, M. E. Levi *et al.*, *Astron. J.* **168**, 245 (2024).
- [9] T. N. Miller, P. Doel, G. Gutierrez, R. Besuner, D. Brooks, G. Gallo, H. Heetderks, P. Jelinsky, S. M. Kent, M. Lampton, M. E. Levi, M. Liang, A. Meisner, M. J. Sholl, J. H. Silber *et al.*, *Astron. J.* **168**, 95 (2024).
- [10] J. Guy, S. Bailey, A. Kremin, S. Alam, D. M. Alexander, C. Allende Prieto, S. BenZvi, A. S. Bolton, D. Brooks, E. Chaussidon, A. P. Cooper, K. Dawson, A. de la Macorra, A. Dey, B. Dey *et al.*, *Astron. J.* **165**, 144 (2023).
- [11] E. F. Schlafly, D. Kirkby, D. J. Schlegel, A. D. Myers, A. Raichoor, K. Dawson, J. Aguilar, C. Allende Prieto, S. Bailey, S. BenZvi, J. Bermejo-Climent, D. Brooks, A. de la Macorra, A. Dey, P. Doel *et al.*, *Astron. J.* **166**, 259 (2023).
- [12] A. G. Adame, J. Aguilar, S. Ahlen, S. Alam, G. Aldering, D. M. Alexander, R. Alfarsy, C. Allende Prieto, M. Alvarez, O. Alves, A. Anand, F. Andrade-Oliveira, E. Armengaud, J. Asorey *et al.* (DESI Collaboration), *Astron. J.* **167**, 62 (2024).
- [13] A. G. Adame, J. Aguilar, S. Ahlen, S. Alam, G. Aldering, D. M. Alexander, R. Alfarsy, C. Allende Prieto, M. Alvarez, O. Alves, A. Anand, F. Andrade-Oliveira, E. Armengaud, J. Asorey *et al.* (DESI Collaboration), *Astron. J.* **168**, 58 (2024).
- [14] M. Abdul-Karim, A. G. Adame, D. Aguado, J. Aguilar, S. Ahlen, S. Alam, G. Aldering, D. M. Alexander, R. Alfarsy, L. Allen, C. Allende Prieto, O. Alves, A. Anand, U. Andrade *et al.* (DESI Collaboration), [arXiv:2503.14745](https://arxiv.org/abs/2503.14745).
- [15] U. Andrade, E. Paillas, J. Mena-Fernández, Q. Li, A. J. Ross, S. Nadathur, M. Rashkovetskyi, A. Pérez-Fernández, H. Seo, N. Sanders, O. Alves, X. Chen, N. Deiosso, M. Abdul-Karim, S. Ahlen *et al.*, [arXiv:2503.14742](https://arxiv.org/abs/2503.14742).
- [16] M. Abdul-Karim, J. Aguilar, S. Ahlen, S. Alam, L. Allen, C. Allende Prieto, O. Alves, A. Anand, U. Andrade, E. Armengaud, A. Aviles, S. Bailey, C. Baltay, P. Bansal *et al.* (DESI Collaboration), [arXiv:2503.14738](https://arxiv.org/abs/2503.14738).
- [17] L. Casas, H. K. Herrera-Alcantar, J. Chaves-Montero, A. Cuceu, A. Font-Ribera, M. Lokken, M. Abdul-Karim, C. Ramírez-Pérez, J. Aguilar, S. Ahlen, U. Andrade, E. Armengaud, A. Aviles, S. Bailey, S. BenZvi *et al.*, [arXiv:2503.14741](https://arxiv.org/abs/2503.14741).
- [18] A. Brodzeller, M. Wolfson, D. M. Santos, M. Ho, T. Tan, M. M. Pieri, A. Cuceu, M. Abdul-Karim, J. Aguilar, S. Ahlen, A. Anand, U. Andrade, E. Armengaud, A. Aviles, S. Bailey *et al.*, [arXiv:2503.14740](https://arxiv.org/abs/2503.14740).
- [19] M. Abdul-Karim, J. Aguilar, S. Ahlen, C. Allende Prieto, O. Alves, A. Anand, U. Andrade, E. Armengaud, A. Aviles, S. Bailey, A. Bault, S. BenZvi, D. Bianchi, C. Blake *et al.* (DESI Collaboration), [arXiv:2503.14739](https://arxiv.org/abs/2503.14739).
- [20] W. Elbers, A. Aviles, H. E. Noriega, D. Chebat, A. Menegas, C. S. Frenk, C. Garcia-Quintero, D. Gonzalez, M. Ishak, O. Lahav, K. Naidoo, G. Niz, C. Yèche, M. Abdul-Karim, S. Ahlen *et al.*, [arXiv:2503.14744](https://arxiv.org/abs/2503.14744).
- [21] F. J. Qu, B. D. Sherwin, M. S. Madhavacheril, D. Han, K. T. Crowley, I. Abril-Cabezas, P. A. R. Ade, S. Aiola, T. Alford, M. Amiri, S. Amodeo, R. An, Z. Atkins, J. E. Austermann, N. Battaglia, and others, *Astrophys. J.* **962**, 112 (2024).
- [22] A. G. Adame, J. Aguilar, S. Ahlen, S. Alam, D. M. Alexander, M. Alvarez, O. Alves, A. Anand, U. Andrade, E. Armengaud, S. Avila, A. Aviles, H. Awan, S. Bailey *et al.* (DESI Collaboration), [arXiv:2411.12020](https://arxiv.org/abs/2411.12020).
- [23] A. G. Adame, J. Aguilar, S. Ahlen, S. Alam, D. M. Alexander, M. Alvarez, O. Alves, A. Anand, U. Andrade, E. Armengaud, S. Avila, A. Aviles, H. Awan, S. Bailey *et al.* (DESI Collaboration), *J. Cosmol. Astropart. Phys.* **04** (2025) 012.

- [24] A. G. Adame, J. Aguilar, S. Ahlen, S. Alam, D. M. Alexander, M. Alvarez, O. Alves, A. Anand, U. Andrade, E. Armengaud, S. Avila, A. Aviles, H. Awan, S. Bailey *et al.* (DESI Collaboration), *J. Cosmol. Astropart. Phys.* **01** (2025) 124.
- [25] A. G. Adame, J. Aguilar, S. Ahlen, S. Alam, D. M. Alexander, M. Alvarez, O. Alves, A. Anand, U. Andrade, E. Armengaud, S. Avila, A. Aviles, H. Awan, B. Bahr-Kalus *et al.* (DESI Collaboration), *J. Cosmol. Astropart. Phys.* **02** (2025) 021.
- [26] A. G. Adame, J. Aguilar, S. Ahlen, S. Alam, D. M. Alexander, C. Allende Prieto, M. Alvarez, O. Alves, A. Anand, U. Andrade, E. Armengaud, S. Avila, A. Aviles, H. Awan *et al.* (DESI Collaboration), [arXiv:2411.12022](https://arxiv.org/abs/2411.12022).
- [27] M. Chevallier and D. Polarski, *Int. J. Mod. Phys. D* **10**, 213 (2001).
- [28] E. V. Linder, *Phys. Rev. Lett.* **90**, 091301 (2003).
- [29] K. Lodha, R. Calderon, W. L. Matthewson, A. Shafieloo, M. Ishak, J. Pan, C. Garcia-Quintero, D. Huterer, G. Valogiannis, L. A. Ureña-López, N. V. Kamble, D. Parkinson, A. G. Kim, G. B. Zhao, J. L. Cervantes-Cota *et al.*, [arXiv:2503.14743](https://arxiv.org/abs/2503.14743).
- [30] T. M. C. Abbott, M. Acevedo, M. Adamow, M. Aguena, A. Alarcon, S. Allam, O. Alves, F. Andrade-Oliveira, J. Annis, P. Armstrong, S. Avila, D. Bacon, K. Bechtol, J. Blazek *et al.* (DES Collaboration), [arXiv:2503.06712](https://arxiv.org/abs/2503.06712).
- [31] T. Louis, A. La Posta, Z. Atkins, H. T. Jense, I. Abril-Cabezas, G. E. Addison, P. A. R. Ade, S. Aiola, T. Alford, D. Alonso, M. Amiri, R. An, J. E. Austermann, E. Barbavara, N. Battaglia *et al.*, [arXiv:2503.14452](https://arxiv.org/abs/2503.14452).
- [32] S. Naess, Y. Guan, A. J. Duivenvoorden, M. Hasselfield, Y. Wang, I. Abril-Cabezas, G. E. Addison, P. A. R. Ade, S. Aiola, T. Alford, D. Alonso, M. Amiri, R. An, Z. Atkins, J. E. Austermann *et al.*, [arXiv:2503.14451](https://arxiv.org/abs/2503.14451).
- [33] E. Calabrese *et al.* (ACT Collaboration), [arXiv:2503.14454](https://arxiv.org/abs/2503.14454).
- [34] N. Aghanim, Y. Akrami, F. Arroja, M. Ashdown, J. Aumont, C. Baccigalupi, M. Ballardini, A. J. Banday, R. B. Barreiro, N. Bartolo, S. Basak, R. Battye, K. Benabed, J. P. Bernard *et al.* (Planck Collaboration), *Astron. Astrophys.* **641**, A1 (2020).
- [35] N. Aghanim, Y. Akrami, M. Ashdown, J. Aumont, C. Baccigalupi, M. Ballardini, A. J. Banday, R. B. Barreiro, N. Bartolo, S. Basak, K. Benabed, J. P. Bernard, M. Bersanelli, P. Bielewicz *et al.* (Planck Collaboration), *Astron. Astrophys.* **641**, A5 (2020).
- [36] N. Aghanim, Y. Akrami, M. Ashdown, J. Aumont, C. Baccigalupi, M. Ballardini, A. J. Banday, R. B. Barreiro, N. Bartolo, S. Basak, R. Battye, K. Benabed, J. P. Bernard, M. Bersanelli *et al.* (Planck Collaboration), *Astron. Astrophys.* **641**, A6 (2020).
- [37] N. Aghanim, Y. Akrami, M. Ashdown, J. Aumont, C. Baccigalupi, M. Ballardini, A. J. Banday, R. B. Barreiro, N. Bartolo, S. Basak, K. Benabed, J. P. Bernard, M. Bersanelli, P. Bielewicz *et al.* (Planck Collaboration), *Astron. Astrophys.* **641**, A8 (2020).
- [38] Y. Akrami, K. J. Andersen, M. Ashdown, C. Baccigalupi, M. Ballardini, A. J. Banday, R. B. Barreiro, N. Bartolo, S. Basak, K. Benabed, J. P. Bernard, M. Bersanelli, P. Bielewicz, J. R. Bond *et al.* (Planck Collaboration), *Astron. Astrophys.* **643**, A42 (2020).
- [39] J. Carron, M. Mirmelstein, and A. Lewis, *J. Cosmol. Astropart. Phys.* **09** (2022) 039.
- [40] E. Rosenberg, S. Gratton, and G. Efstathiou, *Mon. Not. R. Astron. Soc.* **517**, 4620 (2022).
- [41] L. Pagano, J. M. Delouis, S. Mottet, J. L. Puget, and L. Vibert, *Astron. Astrophys.* **635**, A99 (2020).
- [42] J. M. Delouis, L. Pagano, S. Mottet, J. L. Puget, and L. Vibert, *Astron. Astrophys.* **629**, A38 (2019).
- [43] R. de Belsunce, S. Gratton, W. Coulton, and G. Efstathiou, *Mon. Not. R. Astron. Soc.* **507**, 1072 (2021).
- [44] M. S. Madhavacheril, F. J. Qu, B. D. Sherwin, N. MacCrann, Y. Li, I. Abril-Cabezas, P. A. R. Ade, S. Aiola, T. Alford, M. Amiri, S. Amodeo, R. An, Z. Atkins, J. E. Austermann, N. Battaglia *et al.*, *Astrophys. J.* **962**, 113 (2024).
- [45] D. Scolnic, D. Brout, A. Carr, A. G. Riess, T. M. Davis, A. Dwomoh, D. O. Jones, N. Ali, P. Charvu, R. Chen, E. R. Peterson, B. Popovic, B. M. Rose, C. M. Wood, P. J. Brown *et al.*, *Astrophys. J.* **938**, 113 (2022).
- [46] D. Rubin, G. Aldering, M. Betoule, A. Fruchter, X. Huang, A. G. Kim, C. Lidman, E. Linder, S. Perlmutter, P. Ruiz-Lapuente, and N. Suzuki, [arXiv:2311.12098](https://arxiv.org/abs/2311.12098).
- [47] T. M. C. Abbott, M. Acevedo, M. Aguena, A. Alarcon, S. Allam, O. Alves, A. Amon, F. Andrade-Oliveira, J. Annis, P. Armstrong, J. Asorey, S. Avila, D. Bacon, B. A. Bassett *et al.* (DES Collaboration), *Astrophys. J. Lett.* **973**, L14 (2024).
- [48] G. Efstathiou and S. Gratton, *Open J. Astrophys.* **4**, 8 (2021).
- [49] D. Brout, D. Scolnic, B. Popovic, A. G. Riess, A. Carr, J. Zuntz, R. Kessler, T. M. Davis, S. Hinton, D. Jones, W. D. Kenworthy, E. R. Peterson, K. Said, G. Taylor, N. Ali *et al.*, *Astrophys. J.* **938**, 110 (2022).
- [50] W. J. Percival, W. Sutherland, J. A. Peacock, C. M. Baugh, J. Bland-Hawthorn, T. Bridges, R. Cannon, S. Cole, M. Colless, C. Collins, W. Couch, G. Dalton, R. De Propris, S. P. Driver, G. Efstathiou *et al.*, *Mon. Not. R. Astron. Soc.* **337**, 1068 (2002).
- [51] E. Calabrese *et al.*, *Phys. Rev. D* **77**, 123531 (2008).
- [52] S. Hamidreza Mirpoorian, K. Jedamzik, and L. Pogorian, [arXiv:2504.15274](https://arxiv.org/abs/2504.15274).
- [53] D. Green and J. Meyers, *Phys. Rev. D* **111**, 083507 (2025).
- [54] N. Craig, D. Green, J. Meyers, and S. Rajendran, *J. High Energy Phys.* **09** (2024) 097.
- [55] W. Elbers, C. S. Frenk, A. Jenkins, B. Li, and S. Pascoli, *Phys. Rev. D* **111**, 063534 (2025).
- [56] F. J. Qu, F. Ge, W. L. Kimmy Wu, I. Abril-Cabezas, M. S. Madhavacheril, M. Millea, E. Anderes, A. J. Anderson, B. Ansarinejad, M. Archipley, Z. Atkins, L. Balkenhol, N. Battaglia, K. Benabed, A. N. Bender *et al.*, [arXiv:2504.20038](https://arxiv.org/abs/2504.20038).
- [57] <https://www.desi.lbl.gov/collaborating-institutions>.
- [58] [10.5281/zenodo.17262475](https://zenodo.org/record/17262475).
- [59] S. Aiola, E. Calabrese, L. Maurin, S. Naess, B. L. Schmitt, M. H. Abitbol, G. E. Addison, P. A. R. Ade, D. Alonso, M. Amiri, S. Amodeo, E. Angile, J. E. Austermann, T. Baidon, N. Battaglia *et al.*, *J. Cosmol. Astropart. Phys.* **12** (2020) 047.
- [60] F. James and M. Roos, *Comput. Phys. Commun.* **10**, 343 (1975).
- [61] H. Dembinski *et al.*, [10.5281/zenodo.3949207](https://zenodo.org/record/3949207) (2020).
- [62] G. J. Feldman and R. D. Cousins, *Phys. Rev. D* **57**, 3873 (1998).