

Snowmass2021 - Letter of Interest

Cosmology Intertwined III: $f\sigma_8$ and S_8

Thematic Areas: (check all that apply /■)

- (CF1) Dark Matter: Particle Like
- (CF2) Dark Matter: Wavelike
- (CF3) Dark Matter: Cosmic Probes
- (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
- (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
- (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
- (CF7) Cosmic Probes of Fundamental Physics
- (Other) [*Please specify frontier/topical group*]

Contact Information:

Eleonora Di Valentino (JBCA, University of Manchester, UK) [eleonora.divalentino@manchester.ac.uk]

Authors:

Eleonora Di Valentino (JBCA, University of Manchester, UK)
Luis A. Anchordoqui (City University of New York, USA)
Yacine Ali-Haïmoud (New York University, USA)
Luca Amendola (University of Heidelberg, Germany)
Nikki Arendse (DARK, Niels Bohr Institute, Denmark)
Marika Asgari (University of Edinburgh, UK)
Mario Ballardini (Alma Mater Studiorum Università di Bologna, Italy)
Elia Battistelli (Sapienza Università di Roma and INFN sezione di Roma, Italy)
Micol Benetti (Università degli Studi di Napoli Federico II and INFN sezione di Napoli, Italy)
Simon Birrer (Stanford University, USA)
Marco Bruni (Institute of Cosmology and Gravitation, Portsmouth, UK, and INFN Sezione di Trieste, Italy)
Erminia Calabrese (Cardiff University, UK)
David Camarena (Federal University of Espirito Santo, Brazil)
Salvatore Capozziello (Università degli Studi di Napoli Federico II, Napoli, Italy)
Angela Chen (University of Michigan, Ann Arbor, USA)
Jens Chluba (JBCA, University of Manchester, UK)
Anton Chudaykin (Institute for Nuclear Research, Russia)
Eoin Ó Colgáin (Asia Pacific Center for Theoretical Physics, Korea)
Francis-Yan Cyr-Racine (University of New Mexico, USA)
Paolo de Bernardis (Sapienza Università di Roma and INFN sezione di Roma, Italy)
Jacques Delabrouille (CNRS/IN2P3, Laboratoire APC, France & CEA/IRFU, France & USTC, China)
Jo Dunkley (Princeton University, USA)
Celia Escamilla-Rivera (ICN, Universidad Nacional Autónoma de México, Mexico)
Agnès Ferté (JPL, Caltech, Pasadena, USA)
Fabio Finelli (INAF OAS Bologna and INFN Sezione di Bologna, Italy)

Wendy Freedman (University of Chicago, Chicago IL, USA)
Noemi Frusciante (Instituto de Astrofísica e Ciências do Espaço, Lisboa, Portugal)
Elena Giusarma (Michigan Technological University, USA)
Adrià Gómez-Valent (University of Heidelberg, Germany)
Will Handley (University of Cambridge, UK)
Luke Hart (JBCA, University of Manchester, UK)
Alan Heavens (ICIC, Imperial College London, UK)
Hendrik Hildebrandt (Ruhr-University Bochum, Germany)
Daniel Holz (University of Chicago, Chicago IL, USA)
Dragan Huterer (University of Michigan, Ann Arbor, USA)
Mikhail M. Ivanov (New York University, USA)
Shahab Joudaki (University of Oxford, UK and University of Waterloo, Canada)
Marc Kamionkowski (Johns Hopkins University, Baltimore, MD, USA)
Tanvi Karwal (University of Pennsylvania, Philadelphia, USA)
Lloyd Knox (UC Davis, Davis CA, USA)
Luca Lamagna (Sapienza Università di Roma and INFN sezione di Roma, Italy)
Julien Lesgourgues (RWTH Aachen University)
Matteo Lucca (Université Libre de Bruxelles, Belgium)
Valerio Marra (Federal University of Espirito Santo, Brazil)
Silvia Masi (Sapienza Università di Roma and INFN sezione di Roma, Italy)
Sabino Matarrese (University of Padova and INFN Sezione di Padova, Italy)
Alessandro Melchiorri (Sapienza Università di Roma and INFN sezione di Roma, Italy)
Olga Mena (IFIC, CSIC-UV, Spain)
Laura Mersini-Houghton (University of North Carolina at Chapel Hill, USA)
Vivian Miranda (University of Arizona, USA)
David F. Mota (University of Oslo, Norway)
Jessica Muir (KIPAC, Stanford University, USA)
Ankan Mukherjee (Jamia Millia Islamia Central University, India)
Florian Niedermann (CP3-Origins, University of Southern Denmark)
Alessio Notari (ICCUB, Universitat de Barcelona, Spain)
Rafael C. Nunes (National Institute for Space Research, Brazil)
Francesco Pace (JBCA, University of Manchester, UK)
Antonella Palmese (Fermi National Accelerator Laboratory, USA)
Supriya Pan (Presidency University, Kolkata, India)
Daniela Paoletti (INAF OAS Bologna and INFN Sezione di Bologna, Italy)
Valeria Pettorino (AIM, CEA, CNRS, Université Paris-Saclay, Université de Paris, France)
Francesco Piacentini (Sapienza Università di Roma and INFN sezione di Roma, Italy)
Vivian Poulin (LUPM, CNRS & University of Montpellier, France)
Marco Raveri (University of Pennsylvania, Philadelphia, USA)
Adam G. Riess (Johns Hopkins University, Baltimore, USA)
Vincenzo Salzano (University of Szczecin, Poland)
Emmanuel N. Saridakis (National Observatory of Athens, Greece)
Anjan A. Sen (Jamia Millia Islamia Central University New Delhi, India)
Arman Shafieloo (Korea Astronomy and Space Science Institute (KASI), Korea)
Anowar J. Shajib (University of California, Los Angeles, USA)
Joseph Silk (IAP Sorbonne University & CNRS, France, and Johns Hopkins University, USA)
Alessandra Silvestri (Leiden University)
Martin S. Sloth (CP3-Origins, University of Southern Denmark)

Tristan L. Smith (Swarthmore College, Swarthmore, USA)
Carsten van de Bruck (University of Sheffield, UK)
Licia Verde (ICREA, Universidad de Barcelona, Spain)
Luca Visinelli (GRAPPA, University of Amsterdam, NL)
Benjamin D. Wandelt (IAP Sorbonne University & CNRS, France, and CCA, USA)
Weiqiang Yang (Liaoning Normal University, Dalian, China)

Abstract: The standard Λ Cold Dark Matter cosmological model provides a wonderful fit to current cosmological data, but a few tensions and anomalies became statistically significant with the latest data analyses. While these anomalies could be due to the presence of systematic errors in the experiments, they could also indicate the need for new physics beyond the standard model. In this Letter of Interest we focus on the tension of the Planck data with weak lensing measurements and redshift surveys, about the value of the matter energy density Ω_m , and the amplitude or rate of the growth of structure ($\sigma_8, f\sigma_8$). We list a few interesting models for solving this tension, and we discuss the importance of trying to fit with a single model a full array of data and not just one parameter at a time.

The S_8 tension – The standard Λ Cold Dark Matter (Λ CDM) cosmological model provides an amazing fit to current cosmological data. However, some statistically-significant tensions in cosmological parameter estimations emerged between the Planck experiment, measuring the Cosmic Microwave Background (CMB) anisotropies, and other low-redshift cosmological probes. In addition to the long standing *Hubble constant* H_0 disagreement, a tension of the Planck data with weak lensing measurements and redshift surveys has been reported, about the value of the matter energy density Ω_m , and the amplitude or rate of growth of structure (σ_8 , $f\sigma_8$). Although this tension could be due to systematic errors, it is worthwhile to investigate the possibility of new physics beyond the standard model. The tension can be visualized in the σ_8 vs Ω_m plane (see Fig. 1) and is often quantified using the $S_8 \equiv \sigma_8 \sqrt{\Omega_m/0.3}$ parameter, along the main degeneracy direction of weak lensing measurements. This can be also related to $f\sigma_8(z=0)$, measured by galaxy redshift space distortions (RSD)^{1;2}, where $f = [\Omega_m(z)]^{0.55}$ approximates the growth rate.

The mismatch between the high S_8 value estimated by Planck assuming Λ CDM (grey contour in Fig. 1), $S_8 = 0.834 \pm 0.016$ ¹, and the lower value preferred by cosmic shear measurements, it is known as the S_8 tension. This tension is above the 2σ level with KiDS-450⁴⁻⁷ ($S_8 = 0.745 \pm 0.039$) and KiDS-450+2dFLenS⁸ ($S_8 = 0.742 \pm 0.035$), with KiDS+VIKING-450 (KV450)⁹ ($S_8 = 0.737^{+0.040}_{-0.036}$), with DES^{10;11} ($S_8 = 0.783^{+0.021}_{-0.025}$), and with CFHTLenS¹²⁻¹⁴. Recently, KiDS-1000³ reported a $\sim 3\sigma$ tension ($S_8 = 0.766^{+0.020}_{-0.014}$, red contour in Fig. 1) with Planck. This is already obvious from cosmic shear alone¹⁵, but when combined with galaxy clustering, the degeneracy breaking between σ_8 and Ω_m does not change the tension level. Therefore, the combined analysis helps in pointing out that the tension, at 3.1σ in this case, is driven by σ_8 rather than Ω_m . In addition, there is the Lyman- α result¹⁶, a late time probe probing scales similar to weak lensing, completely in agreement with a lower S_8 value and in tension at $\sim 2.6\sigma$ with Planck. The tension becomes 3.2σ if we consider the combination of KV450 and DES-Y1^{17;18} or 3.4σ for BOSS+KV450¹⁹ ($S_8 = 0.728 \pm 0.026$, blue contour in Fig. 1). Preferring a higher value for the S_8 parameter there is also the measurement from the first-year data of HSC SSP²⁰, for which $S_8 = 0.804^{+0.032}_{-0.029}$ (see Fig. 2), but also KiDS-450+GAMA²¹ finding $S_8 = 0.800^{+0.029}_{-0.027}$. Finally, in agreement with a lower value $S_8 = 0.703 \pm 0.045$ there is an estimate from the BOSS Galaxy Power Spectrum²².

It has been pointed out in²³ that this tension could be related to the excess of lensing measured by Planck, mimicking a larger S_8 . However, also ACT+WMAP²⁴ find a large $S_8 = 0.840 \pm 0.030$ even if it does not see a peculiar value for the lensing amplitude, while SPTpol²⁵ and the Planck CMB lensing²⁶ measurements prefer a lower value. Another possibility is the misuse of the units $h^{-1}\text{Mpc}$ in observational cosmology in²⁷. It might be worth mentioning that, while weak lensing analyses are carried out with a blinding procedure for KiDS, DES and HSC, the CMB analyses are either not blind or only partially blind.

Conjoined history problem – The H_0 disagreement is correlated to the σ_8 problem, indeed the solutions proposed to alleviate the first one, are exacerbating the CMB tension with the lower σ_8 values obtained from more direct measurements, such as galaxy clusters using the Sunyaev-Zel’dovich effect²⁸⁻³⁰, i.e. measuring the number of clusters of a certain mass M over a range of redshift.

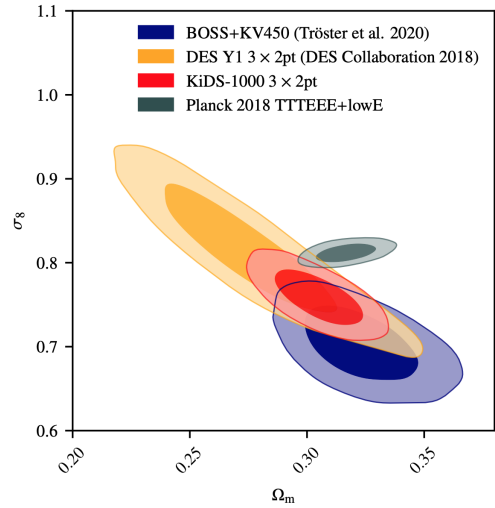


Figure 1: 68% CL and 95% CL contour plots for σ_8 and Ω_m (from Ref. ³).

¹All the bounds are reported at 68% confidence level in the text.

For example, late time transitions preferring a higher H_0 value, if they match the CMB data, prefer a lower Ω_m as well, to preserve the well measured value of $\Omega_m h^2$, known as geometric degeneracy. This effect produces a modification of distances to sources, the growth of structure, and of the sound horizon and CMB anisotropies³¹, and usually results in higher σ_8 than for Λ CDM because of an extended era of matter domination. However, also early-time dark energy solutions of the H_0 tension increase σ_8 because they need a higher primordial curvature perturbation amplitude to offset the damping effect of the unclustered component. Therefore, because of the mutual effects and correlations, it is important to perform a conjoined analysis, fitting with a single model a full array of data^{32–34}, and not just one parameter alone. At the same time, if a model solves the S_8 tension (the $z = 0$ value), the growth history at different redshift, by plotting $f\sigma_8(z)$ directly against $H(z)$, should be checked^{35;36}, because conjoint history can deviate significantly at intermediate scales. Hence, any solution to the S_8 tension should pass other cosmological tests, i.e. it should simultaneously fit the expansion and growth histories probed by Baryon Acoustic Oscillations (BAO), RSD-lensing cross correlations, galaxy power spectrum shape and void measurements³⁷.

Solutions – There are many papers investigating this tension^{23;27;38–67}, but the solutions proposed are not enough to put in agreement all the cosmological available data^{68–70}. We can distinguish the following categories:

- Axion monodromy inflation⁵⁷.
- Extended parameter spaces^{23;39–42} with $A_L > 1$ ⁷¹, i.e. using the phenomenological lensing parameter as a consistency check and determining whether it is different from unity⁷².
- Active and Sterile Neutrinos^{55;56}.
- Interacting dark energy models, where the energy flows from the dark matter to the dark energy^{43;44}.
- Decaying dark matter^{63;64;73;74}, or Cannibal dark matter⁶⁵.
- Minimally and non-minimally coupled scalar field models as possible alternatives for dark energy⁵¹.
- Modified Gravity models^{52;53;75;76}.
- Running vacuum models in which $\Lambda = \Lambda(H)$ is an affine power-law function of the Hubble rate^{45;46;77;78}.
- Quartessence, a single dark component mimicking both dark matter and dark energy⁴⁸.

Future – In the near future, we expect percent measurements of the expansion and growth history over a large range of experiments, i.e. using maps of the Universe obtained by the Euclid satellite, measuring the peculiar motions of galaxies using Type Ia supernovae from LSST^{79;80}, considering RSD with DESI and 4MOST, or using voids³⁷. An important role will be played by the SKA telescopes performing BAO surveys and measuring weak gravitational lensing using 21 cm intensity mapping^{81–83}. Additional upcoming 21 cm neutral hydrogen experiments measuring the expansion history will be CHIME and HIRAX. Finally, line-intensity mapping of emission from star-forming galaxies can be used to measure the BAO reaching percent-level constraints^{84;85} with the SPHEREx satellite or the ground-based COMAP instrument. All of these efforts will either reveal a systematic cause or harden the tension to strong statistical significance informing the theories mentioned above and guiding any extension/overhaul of the standard model.

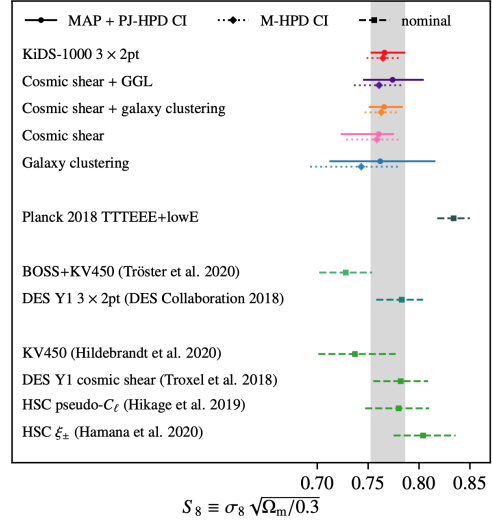


Figure 2: Whisker plot showing the 68% error bars on S_8 (from Ref. 3).

References

- [1] Z. Li, Y. Jing, P. Zhang, and D. Cheng, “Measurement of Redshift-Space Power Spectrum for BOSS galaxies and the Growth Rate at redshift 0.57,” *Astrophys. J.* **833** no. 2, (2016) 287, [arXiv:1609.03697 \[astro-ph.CO\]](#).
- [2] H. Gil-Marín, W. J. Percival, L. Verde, J. R. Brownstein, C.-H. Chuang, F.-S. Kitaura, S. A. Rodríguez-Torres, and M. D. Olmstead, “The clustering of galaxies in the SDSS-III Baryon Oscillation Spectroscopic Survey: RSD measurement from the power spectrum and bispectrum of the DR12 BOSS galaxies,” *Mon. Not. Roy. Astron. Soc.* **465** no. 2, (2017) 1757–1788, [arXiv:1606.00439 \[astro-ph.CO\]](#).
- [3] C. Heymans *et al.*, “KiDS-1000 Cosmology: Multi-probe weak gravitational lensing and spectroscopic galaxy clustering constraints,” 7, 2020. [arXiv:2007.15632 \[astro-ph.CO\]](#).
- [4] K. Kuijken *et al.*, “Gravitational Lensing Analysis of the Kilo Degree Survey,” *Mon. Not. Roy. Astron. Soc.* **454** no. 4, (2015) 3500–3532, [arXiv:1507.00738 \[astro-ph.CO\]](#).
- [5] H. Hildebrandt *et al.*, “KiDS-450: Cosmological parameter constraints from tomographic weak gravitational lensing,” *Mon. Not. Roy. Astron. Soc.* **465** (2017) 1454, [arXiv:1606.05338 \[astro-ph.CO\]](#).
- [6] I. Fenech Conti, R. Herbonnet, H. Hoekstra, J. Merten, L. Miller, and M. Viola, “Calibration of weak-lensing shear in the Kilo-Degree Survey,” *Mon. Not. Roy. Astron. Soc.* **467** no. 2, (2017) 1627–1651, [arXiv:1606.05337 \[astro-ph.CO\]](#).
- [7] S. Joudaki *et al.*, “KiDS-450: Testing extensions to the standard cosmological model,” *Mon. Not. Roy. Astron. Soc.* **471** no. 2, (2017) 1259–1279, [arXiv:1610.04606 \[astro-ph.CO\]](#).
- [8] S. Joudaki *et al.*, “KiDS-450 + 2dFLenS: Cosmological parameter constraints from weak gravitational lensing tomography and overlapping redshift-space galaxy clustering,” *Mon. Not. Roy. Astron. Soc.* **474** no. 4, (2018) 4894–4924, [arXiv:1707.06627 \[astro-ph.CO\]](#).
- [9] H. Hildebrandt *et al.*, “KiDS+VIKING-450: Cosmic shear tomography with optical and infrared data,” *Astron. Astrophys.* **633** (2020) A69, [arXiv:1812.06076 \[astro-ph.CO\]](#).
- [10] DES Collaboration, T. M. C. Abbott *et al.*, “Dark Energy Survey year 1 results: Cosmological constraints from galaxy clustering and weak lensing,” *Phys. Rev.* **D98** no. 4, (2018) 043526, [arXiv:1708.01530 \[astro-ph.CO\]](#).
- [11] DES Collaboration, M. A. Troxel *et al.*, “Dark Energy Survey Year 1 results: Cosmological constraints from cosmic shear,” *Phys. Rev.* **D98** no. 4, (2018) 043528, [arXiv:1708.01538 \[astro-ph.CO\]](#).
- [12] C. Heymans *et al.*, “CFHTLenS: The Canada-France-Hawaii Telescope Lensing Survey,” *Mon. Not. Roy. Astron. Soc.* **427** (2012) 146, [arXiv:1210.0032 \[astro-ph.CO\]](#).
- [13] T. Erben *et al.*, “CFHTLenS: The Canada-France-Hawaii Telescope Lensing Survey - Imaging Data and Catalogue Products,” *Mon. Not. Roy. Astron. Soc.* **433** (2013) 2545, [arXiv:1210.8156 \[astro-ph.CO\]](#).

- [14] S. Joudaki *et al.*, “CFHTLenS revisited: assessing concordance with Planck including astrophysical systematics,” *Mon. Not. Roy. Astron. Soc.* **465** no. 2, (2017) 2033–2052, [arXiv:1601.05786 \[astro-ph.CO\]](#).
- [15] KiDS Collaboration, M. Asgari *et al.*, “KiDS-1000 Cosmology: Cosmic shear constraints and comparison between two point statistics,” 7, 2020. [arXiv:2007.15633 \[astro-ph.CO\]](#).
- [16] N. Palanque-Delabrouille, C. Yèche, N. Schöneberg, J. Lesgourgues, M. Walther, S. Chabanier, and E. Armengaud, “Hints, neutrino bounds and WDM constraints from SDSS DR14 Lyman- α and Planck full-survey data,” *JCAP* **04** (2020) 038, [arXiv:1911.09073 \[astro-ph.CO\]](#).
- [17] S. Joudaki *et al.*, “KiDS+VIKING-450 and DES-Y1 combined: Cosmology with cosmic shear,” *Astron. Astrophys.* **638** (2020) L1, [arXiv:1906.09262 \[astro-ph.CO\]](#).
- [18] M. Asgari *et al.*, “KiDS+VIKING-450 and DES-Y1 combined: Mitigating baryon feedback uncertainty with COSEBIs,” *Astron. Astrophys.* **634** (2020) A127, [arXiv:1910.05336 \[astro-ph.CO\]](#).
- [19] T. Tröster *et al.*, “Cosmology from large-scale structure: Constraining Λ CDM with BOSS,” *Astron. Astrophys.* **633** (2020) L10, [arXiv:1909.11006 \[astro-ph.CO\]](#).
- [20] T. Hamana *et al.*, “Cosmological constraints from cosmic shear two-point correlation functions with HSC survey first-year data,” *Publ. Astron. Soc. Jap.* **72** no. 1, (2020) Publications of the Astronomical Society of Japan, Volume 72, Issue 1, February 2020, 16, <https://doi.org/10.1093/pasj/psz138>, [arXiv:1906.06041 \[astro-ph.CO\]](#).
- [21] E. van Uitert *et al.*, “KiDS+GAMA: cosmology constraints from a joint analysis of cosmic shear, galaxy–galaxy lensing, and angular clustering,” *Mon. Not. Roy. Astron. Soc.* **476** no. 4, (2018) 4662–4689, [arXiv:1706.05004 \[astro-ph.CO\]](#).
- [22] M. M. Ivanov, M. Simonović, and M. Zaldarriaga, “Cosmological Parameters from the BOSS Galaxy Power Spectrum,” *JCAP* **05** (2020) 042, [arXiv:1909.05277 \[astro-ph.CO\]](#).
- [23] E. Di Valentino and S. Bridle, “Exploring the Tension between Current Cosmic Microwave Background and Cosmic Shear Data,” *Symmetry* **10** no. 11, (2018) 585.
- [24] ACT Collaboration, S. Aiola *et al.*, “The Atacama Cosmology Telescope: DR4 Maps and Cosmological Parameters,” [arXiv:2007.07288 \[astro-ph.CO\]](#).
- [25] SPT Collaboration, J. Henning *et al.*, “Measurements of the Temperature and E-Mode Polarization of the CMB from 500 Square Degrees of SPTpol Data,” *Astrophys. J.* **852** no. 2, (2018) 97, [arXiv:1707.09353 \[astro-ph.CO\]](#).
- [26] Planck Collaboration, P. Ade *et al.*, “Planck 2015 results. XV. Gravitational lensing,” *Astron. Astrophys.* **594** (2016) A15, [arXiv:1502.01591 \[astro-ph.CO\]](#).
- [27] A. G. Sanchez, “Let us bury the prehistoric h : arguments against using h^{-1} Mpc units in observational cosmology,” [arXiv:2002.07829 \[astro-ph.CO\]](#).
- [28] Planck Collaboration, P. Ade *et al.*, “Planck 2015 results. XXVII. The Second Planck Catalogue of Sunyaev-Zeldovich Sources,” *Astron. Astrophys.* **594** (2016) A27, [arXiv:1502.01598 \[astro-ph.CO\]](#).

- [29] **Planck** Collaboration, P. Ade *et al.*, “Planck 2015 results. XXIV. Cosmology from Sunyaev-Zeldovich cluster counts,” *Astron. Astrophys.* **594** (2016) A24, [arXiv:1502.01597](#) [[astro-ph.CO](#)].
- [30] **SPT** Collaboration, T. de Haan *et al.*, “Cosmological Constraints from Galaxy Clusters in the 2500 square-degree SPT-SZ Survey,” *Astrophys. J.* **832** no. 1, (2016) 95, [arXiv:1603.06522](#) [[astro-ph.CO](#)].
- [31] N. Arendse *et al.*, “Cosmic dissonance: new physics or systematics behind a short sound horizon?,” *Astron. Astrophys.* **639** (2020) A57, [arXiv:1909.07986](#) [[astro-ph.CO](#)].
- [32] J. C. Hill, E. McDonough, M. W. Toomey, and S. Alexander, “Early Dark Energy Does Not Restore Cosmological Concordance,” [arXiv:2003.07355](#) [[astro-ph.CO](#)].
- [33] G. Benevento, W. Hu, and M. Raveri, “Can Late Dark Energy Transitions Raise the Hubble constant?,” [arXiv:2002.11707](#) [[astro-ph.CO](#)].
- [34] L. Knox and M. Millea, “The Hubble Hunter’s Guide,” [arXiv:1908.03663](#) [[astro-ph.CO](#)].
- [35] E. V. Linder, “Cosmic Growth and Expansion Conjoined,” *Astropart. Phys.* **86** (2017) 41–45, [arXiv:1610.05321](#) [[astro-ph.CO](#)].
- [36] E. Di Valentino, E. V. Linder, and A. Melchiorri, “ H_0 Ex Machina: Vacuum Metamorphosis and Beyond H_0 ,” [arXiv:2006.16291](#) [[astro-ph.CO](#)].
- [37] N. Hamaus, A. Pisani, J.-A. Choi, G. Lavaux, B. D. Wandelt, and J. Wellera, “Precision cosmology with voids in the final BOSS data,” [arXiv:2007.07895](#) [[astro-ph.CO](#)].
- [38] **DES** Collaboration, M. Troxel *et al.*, “Survey geometry and the internal consistency of recent cosmic shear measurements,” *Mon. Not. Roy. Astron. Soc.* **479** no. 4, (2018) 4998–5004, [arXiv:1804.10663](#) [[astro-ph.CO](#)].
- [39] E. Di Valentino, A. Melchiorri, and J. Silk, “Beyond six parameters: extending Λ CDM,” *Phys. Rev.* **D92** no. 12, (2015) 121302, [arXiv:1507.06646](#) [[astro-ph.CO](#)].
- [40] E. Di Valentino, A. Melchiorri, and J. Silk, “Reconciling Planck with the local value of H_0 in extended parameter space,” *Phys. Lett.* **B761** (2016) 242–246, [arXiv:1606.00634](#) [[astro-ph.CO](#)].
- [41] E. Di Valentino, A. Melchiorri, E. V. Linder, and J. Silk, “Constraining Dark Energy Dynamics in Extended Parameter Space,” *Phys. Rev.* **D96** no. 2, (2017) 023523, [arXiv:1704.00762](#) [[astro-ph.CO](#)].
- [42] E. Di Valentino, A. Melchiorri, and J. Silk, “Cosmological constraints in extended parameter space from the Planck 2018 Legacy release,” [arXiv:1908.01391](#) [[astro-ph.CO](#)].
- [43] E. Di Valentino, A. Melchiorri, O. Mena, and S. Vagnozzi, “Interacting dark energy after the latest Planck, DES, and H_0 measurements: an excellent solution to the H_0 and cosmic shear tensions,” [arXiv:1908.04281](#) [[astro-ph.CO](#)].
- [44] E. Di Valentino, A. Melchiorri, O. Mena, and S. Vagnozzi, “Non-minimal dark sector physics and cosmological tensions,” [arXiv:1910.09853](#) [[astro-ph.CO](#)].

- [45] A. Gómez-Valent and J. Solà Peracaula, “Density perturbations for running vacuum: a successful approach to structure formation and to the σ_8 -tension,” *Mon. Not. Roy. Astron. Soc.* **478** no. 1, (2018) 126–145, [arXiv:1801.08501 \[astro-ph.CO\]](#).
- [46] A. Gomez-Valent and J. Sola, “Relaxing the σ_8 -tension through running vacuum in the Universe,” *EPL* **120** no. 3, (2017) 39001, [arXiv:1711.00692 \[astro-ph.CO\]](#).
- [47] G. Lambiase, S. Mohanty, A. Narang, and P. Parashari, “Testing dark energy models in the light of σ_8 tension,” *Eur. Phys. J. C* **79** no. 2, (2019) 141, [arXiv:1804.07154 \[astro-ph.CO\]](#).
- [48] S. Camera, M. Martinelli, and D. Bertacca, “Does quartessence ease cosmic tensions?,” *Phys. Dark Univ.* **23** (2019) 100247, [arXiv:1704.06277 \[astro-ph.CO\]](#).
- [49] E. Di Valentino and F. R. Bouchet, “A comment on power-law inflation with a dark radiation component,” *JCAP* **10** (2016) 011, [arXiv:1609.00328 \[astro-ph.CO\]](#).
- [50] R. Burenin, “Measurements of the Matter Density Perturbation Amplitude from Cosmological Data,” *Astron. Lett.* **44** no. 11, (2018) 653–663, [arXiv:1806.03261 \[astro-ph.CO\]](#).
- [51] Z. Davari, V. Marra, and M. Malekjani, “Cosmological constraints on minimally and non-minimally coupled scalar field models,” *Mon. Not. Roy. Astron. Soc.* **491** no. 2, (2020) 1920–1933, [arXiv:1911.00209 \[gr-qc\]](#).
- [52] **Planck** Collaboration, P. A. R. Ade *et al.*, “Planck 2015 results. XIV. Dark energy and modified gravity,” *Astron. Astrophys.* **594** (2016) A14, [arXiv:1502.01590 \[astro-ph.CO\]](#).
- [53] E. Di Valentino, A. Melchiorri, and J. Silk, “Cosmological hints of modified gravity?,” *Phys. Rev. D* **93** no. 2, (2016) 023513, [arXiv:1509.07501 \[astro-ph.CO\]](#).
- [54] C.-A. Lin and M. Kilbinger, “Quantifying systematics from the shear inversion on weak-lensing peak counts,” *Astron. Astrophys.* **614** (2018) A36, [arXiv:1704.00258 \[astro-ph.CO\]](#).
- [55] R. A. Battye and A. Moss, “Evidence for Massive Neutrinos from Cosmic Microwave Background and Lensing Observations,” *Phys. Rev. Lett.* **112** no. 5, (2014) 051303, [arXiv:1308.5870 \[astro-ph.CO\]](#).
- [56] H. Böhringer and G. Chon, “Constraints on neutrino masses from the study of the nearby large-scale structure and galaxy cluster counts,” *Mod. Phys. Lett. A* **31** no. 21, (2016) 1640008, [arXiv:1610.02855 \[astro-ph.CO\]](#).
- [57] P. D. Meerburg, “Alleviating the tension at low ℓ through axion monodromy,” *Phys. Rev. D* **90** no. 6, (2014) 063529, [arXiv:1406.3243 \[astro-ph.CO\]](#).
- [58] M. M. Ivanov, E. McDonough, J. C. Hill, M. Simonović, M. W. Toomey, S. Alexander, and M. Zaldarriaga, “Constraining Early Dark Energy with Large-Scale Structure,” [arXiv:2006.11235 \[astro-ph.CO\]](#).
- [59] A. Klypin, V. Poulin, F. Prada, J. Primack, M. Kamionkowski, V. Avila-Reese, A. Rodriguez-Puebla, P. Behroozi, D. Hellinger, and T. L. Smith, “Clustering and Halo Abundances in Early Dark Energy Cosmological Models,” [arXiv:2006.14910 \[astro-ph.CO\]](#).
- [60] E. Di Valentino, C. Bøehm, E. Hivon, and F. R. Bouchet, “Reducing the H_0 and σ_8 tensions with Dark Matter-neutrino interactions,” *Phys. Rev. D* **97** no. 4, (2018) 043513, [arXiv:1710.02559 \[astro-ph.CO\]](#).

- [61] M. A. Buen-Abad, G. Marques-Tavares, and M. Schmaltz, “Non-Abelian dark matter and dark radiation,” *Phys. Rev. D* **92** no. 2, (2015) 023531, [arXiv:1505.03542 \[hep-ph\]](#).
- [62] D. Wang, “Can $f(R)$ gravity relieve H_0 and σ_8 tensions?,” [arXiv:2008.03966 \[astro-ph.CO\]](#).
- [63] A. Chudaykin, D. Gorbunov, and I. Tkachev, “Dark matter component decaying after recombination: Sensitivity to baryon acoustic oscillation and redshift space distortion probes,” *Phys. Rev. D* **97** no. 8, (2018) 083508, [arXiv:1711.06738 \[astro-ph.CO\]](#).
- [64] G. F. Abellan, R. Murgia, V. Poulin, and J. Lavalle, “Hints for decaying dark matter from S_8 measurements,” [arXiv:2008.09615 \[astro-ph.CO\]](#).
- [65] S. Heimersheim, N. Schöneberg, D. C. Hooper, and J. Lesgourgues, “Cannibalism hinders growth: Cannibal Dark Matter and the S_8 tension,” [arXiv:2008.08486 \[astro-ph.CO\]](#).
- [66] K. Jedamzik and L. Pogosian, “Relieving the Hubble tension with primordial magnetic fields,” [arXiv:2004.09487 \[astro-ph.CO\]](#).
- [67] K. Dutta, A. Roy, Ruchika, A. A. Sen, and M. Sheikh-Jabbari, “Cosmology with low-redshift observations: No signal for new physics,” *Phys. Rev. D* **100** no. 10, (2019) 103501, [arXiv:1908.07267 \[astro-ph.CO\]](#).
- [68] E. Di Valentino *et al.*, “Cosmology Intertwined I: Perspectives for the Next Decade,” [arXiv:2008.11283 \[astro-ph.CO\]](#).
- [69] E. Di Valentino *et al.*, “Cosmology Intertwined II: The Hubble Constant Tension,” [arXiv:2008.11284 \[astro-ph.CO\]](#).
- [70] E. Di Valentino *et al.*, “Cosmology Intertwined IV: The Age of the Universe and its Curvature,” [arXiv:2008.11286 \[astro-ph.CO\]](#).
- [71] E. Calabrese, A. Slosar, A. Melchiorri, G. F. Smoot, and O. Zahn, “Cosmic Microwave Weak lensing data as a test for the dark universe,” *Phys. Rev. D* **77** (2008) 123531, [arXiv:0803.2309 \[astro-ph\]](#).
- [72] **Planck** Collaboration, N. Aghanim *et al.*, “Planck 2018 results. VI. Cosmological parameters,” [arXiv:1807.06209 \[astro-ph.CO\]](#).
- [73] Z. Berezhiani, A. Dolgov, and I. Tkachev, “Reconciling Planck results with low redshift astronomical measurements,” *Phys. Rev. D* **92** no. 6, (2015) 061303, [arXiv:1505.03644 \[astro-ph.CO\]](#).
- [74] L. A. Anchordoqui, V. Barger, H. Goldberg, X. Huang, D. Marfatia, L. H. M. da Silva, and T. J. Weiler, “IceCube neutrinos, decaying dark matter, and the Hubble constant,” *Phys. Rev. D* **92** no. 6, (2015) 061301, [arXiv:1506.08788 \[hep-ph\]](#). [Erratum: *Phys.Rev.D* 94, 069901 (2016)].
- [75] J. Solà Peracaula, A. Gomez-Valent, J. de Cruz Pérez, and C. Moreno-Pulido, “Brans–Dicke Gravity with a Cosmological Constant Smooths Out Λ CDM Tensions,” *Astrophys. J. Lett.* **886** no. 1, (2019) L6, [arXiv:1909.02554 \[astro-ph.CO\]](#).
- [76] J. Sola, A. Gomez-Valent, J. d. C. Perez, and C. Moreno-Pulido, “Brans-Dicke cosmology with a Λ -term: a possible solution to Λ CDM tensions,” [arXiv:2006.04273 \[astro-ph.CO\]](#).

- [77] J. Sola, A. Gomez-Valent, and J. de Cruz Pérez, “Hints of dynamical vacuum energy in the expanding Universe,” *Astrophys. J. Lett.* **811** (2015) L14, [arXiv:1506.05793 \[gr-qc\]](#).
- [78] J. Solà, A. Gómez-Valent, and J. de Cruz Pérez, “Vacuum dynamics in the Universe versus a rigid $\Lambda = \text{const}$,” *Int. J. Mod. Phys. A* **32** no. 19-20, (2017) 1730014, [arXiv:1709.07451 \[astro-ph.CO\]](#).
- [79] C. Howlett, A. S. G. Robotham, C. D. P. Lagos, and A. G. Kim, “Measuring the growth rate of structure with Type IA Supernovae from LSST,” *Astrophys. J.* **847** no. 2, (2017) 128, [arXiv:1708.08236 \[astro-ph.CO\]](#).
- [80] D. Scolnic *et al.*, “The Next Generation of Cosmological Measurements with Type Ia Supernovae,” [arXiv:1903.05128 \[astro-ph.CO\]](#).
- [81] A. Poursidou and R. B. Metcalf, “Gravitational lensing of cosmological 21 cm emission,” *Mon. Not. Roy. Astron. Soc.* **448** (2015) 2368–2383, [arXiv:1410.2533 \[astro-ph.CO\]](#).
- [82] M. G. Santos *et al.*, “Cosmology from a SKA HI intensity mapping survey,” *PoS AASKA14* (2015) 019, [arXiv:1501.03989 \[astro-ph.CO\]](#).
- [83] P. Bull, S. Camera, A. Raccanelli, C. Blake, P. G. Ferreira, M. G. Santos, and D. J. Schwarz, “Measuring baryon acoustic oscillations with future SKA surveys,” 1, 2015. [arXiv:1501.04088 \[astro-ph.CO\]](#).
- [84] K. S. Karkare and S. Bird, “Constraining the Expansion History and Early Dark Energy with Line Intensity Mapping,” *Phys. Rev. D* **98** no. 4, (2018) 043529, [arXiv:1806.09625 \[astro-ph.CO\]](#).
- [85] J. L. Bernal, P. C. Breysse, and E. D. Kovetz, “Cosmic Expansion History from Line-Intensity Mapping,” *Phys. Rev. Lett.* **123** no. 25, (2019) 251301, [arXiv:1907.10065 \[astro-ph.CO\]](#).