Snowmass2021 - Letter of Interest

CMB-S4: Probes of the Dark Universe

Thematic Areas:

■ (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:
CMB-S4 Collaboration Science Council [sc@cmb-s4.org]

Authors:
The CMB-S4 Collaboration
This Letter is adapted from the CMB-S4 Science Case, Reference Design, and Project Plan [1]
arxiv:1907.04473v1

Abstract:

The ingredients of the Universe that have not yet been directly observed, such as dark matter and dark energy, are central to some of the biggest open questions in modern physics. Observations of the cosmic microwave background (CMB) have allowed for extremely valuable insights into the nature of these mysterious dark components of the Universe. CMB-S4, a future ground-based CMB experiment, will provide extremely precise measurements of the CMB temperature and polarization anisotropies. These measurements, both on their own and in conjunction with other observations, will allow for new means by which to reveal the properties of the dark universe. The impact of these forthcoming CMB observations can be enhanced with future large scale structure surveys that can be used for cross correlation and complementary studies of cosmological perturbations and evolution. Furthermore, joint analyses of cosmological and terrestrial probes of dark matter and neutrino physics can provide a more complete picture than either in isolation.

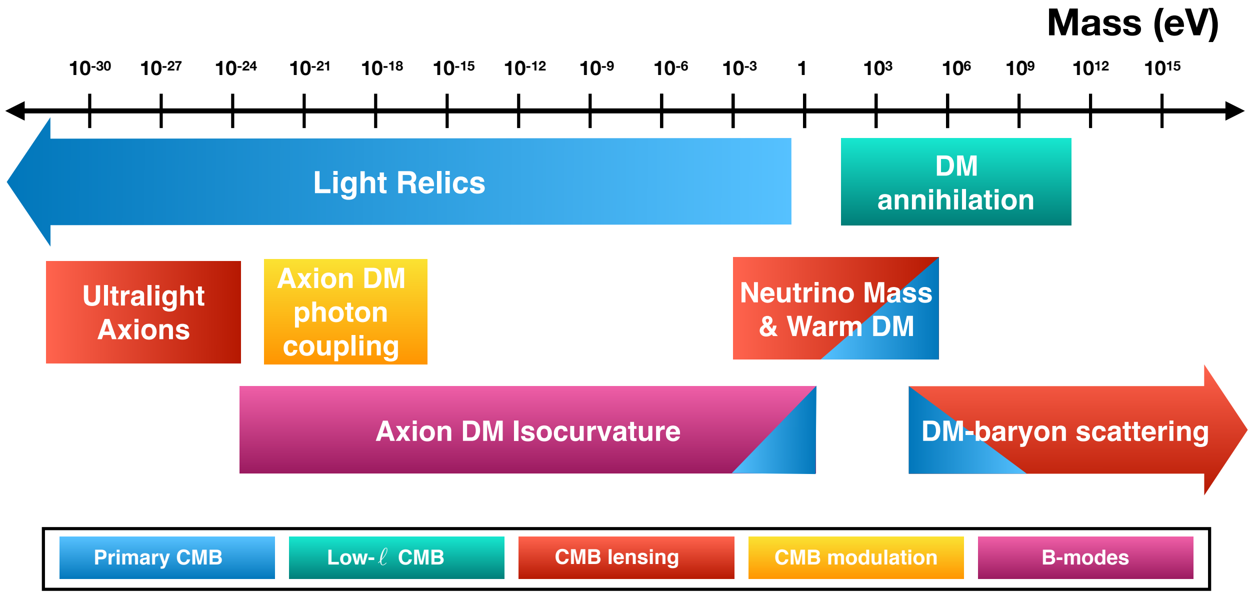

Figure 1: Schematic representation of the various ways in which measurements from CMB-S4 will be used to constrain dark sector physics across a vast range of mass scales.

CMB-S4: CMB-S4 was conceived by the community during the 2013 Snowmass physics planning activity as the path forward to realizing the enormous potential of cosmic microwave background (CMB) measurements for understanding the origin and evolution of the Universe, from the highest energies at the dawn of time through the growth of structure to the present day. CMB-S4 will probe fundamental physics and astrophysics with a millimeter-wavelength survey of unprecedented depth over a large sky area[1–3]. These measurements will represent a leap forward in the study of the CMB, which in the half century since its first discovery, has again and again transformed our understanding of the early Universe.

Light Relics: CMB-S4 will probe the fundamental physics of ingredients of our Universe that are difficult or impossible for us to observe directly. The gravitational influence of the radiation density in the present day Universe is negligible, but it played a significant role in evolution of the early Universe. Any species apart from photons that were present and relativistic prior to recombination contribute to the light relic density. The small-scale temperature and polarization power spectra of the CMB are particularly sensitive to the density of light relics.

The collective influence of the three already-known light relics (the three families of Standard Model neutrinos) has already been detected at high significance in CMB data. New light species are ubiquitous in extensions to the Standard Model of particle physics, and there is good motivation from both particle physics and cosmology to consider additional sources of radiation[4–6]. New light particles may arise in the form of axions and sterile neutrinos, or can appear as a byproduct of new symmteries that would explain the small mass of the Higgs boson[4–25]. Furthermore, light particles can thermalize in the early Universe for wide ranges of unexplored parameter space, leading to an observable level of additional radiation. Light particles may form the dark matter (e.g., axions) or part of a dark sector, they can mediate forces in the dark and visible sectors, or they can result from the decay of new heavier particles. These possibilities may also play a role in explaining the discrepancies observed in the Hubble constant H_0 measurements[26–30], the amplitude of fluctuations σ_8[31–34], and clustering on small scales[35,36]. The observational constraints on the light relic density expected from CMB-S4 are therefore expected to have broad implications for fundamental physics[37]. Joint analysis of data from CMB-S4 and a 21 cm experiment like PUMA[38,39] is exptected to provide much tighter constraints on the density of light relics than either experiment alone.

In addition to searching for new light relics, CMB-S4 will provide useful insights into neutrino physics. Neutrinos were relativistic before recombination, but at least two mass eigenstates are non-relativistic today. As a result, neturinos leave distinct imprints on the CMB and on large scale structure[40–43] that will allow for measurements of the absolute mass scale of neutrinos in the coming years[1,2,44–47]. CMB-S4 in conjuction with galaxy surveys will have the power to detect properties of neutrinos that complement those probed by terrestrial experiments that measure neutrino oscillations, study the influence of neutrino mass on beta decay, and search for neutrinoless double-beta decay.

Dark Matter: CMB measurements have great power in testing dark matter models and constraining parts of the parameter space that are inaccessible to laboratory experiments. The CMB is sensitive to the physics of dark matter throughout cosmic history independent of the local distribution. Small-scale CMB anisotropy measuements enabled by CMB-S4 will probe dark matter-baryon interactions in the early Universe[48–50]. These measurements will be sensitive to particle masses outside the detection limits of most existing direct-detection experiments. Furthermore, CMB-S4 will provide important consistency checks for small-scale-structure probes of dark matter microphysics that will be studied with upcoming galaxy surveys. A combination of CMB, large scale structure, astrophysical, and laboratory observations therefore provide a robust path forward for dark matter searches.

The exquisite sensitivity of the CMB to the depth and size of the dark matter gravitational potentials near the surface of last scattering makes it a particularly good probe of any new physics affecting the clustering of dark matter on large scales at early times. This sensitivity to dark matter density fluctuations is extended to lower redshifts via the weak gravitational lensing that CMB photons experience as they propagate to us. Similar to how tight coupling with photons inhibits the growth of baryon fluctuations until the epoch of hydrogen recombination, dark matter interacting with dark radiation at early times experiences a suppressed growth of structure due to the dark-radiation pressure opposing gravitational infall. Models where such interactions arise are diverse in their particle content[51–53], have been invoked to explain the apparent low amplitude of matter fluctuations measured by certain weak-lensing surveys[32,54,55], and naturally arise in the context of self-interacting dark matter which may address anomalies on subgalactic scales[56].

Axions and axion-like particles are well-motivated dark matter candidates[5]. The CMB, through measurements of CMB lensing, temperature, and polarization[57–59], offers the best gravitational probe of the axion dark matter density across a range of scales in the ultra-light regime. CMB-S4 will extend this range of masses and provide a complement to terrestrial axion searches, typically focused on higher masses.

Dark Energy: CMB-S4 constraints will be among the most powerful tests of the cosmological constant—more crucially, the simultaneous sensitivity to the expansion and the growth of structure will allow us to distinguish the dark-energy paradigm from modifications to general relativity. There are many models for acceleration in the latter class, and CMB-S4 will be generically useful in constraining them. CMB-S4 will measure the growth of structure through observation of CMB lensing and the abundance and clustering of galaxy clusters. CMB-S4 will allow unprecedented measurements of velocity fields through the kinetic Sunyaev-Zel'dovich effect. These measurements can be used to distinguish dark energy from interesting models of modified gravity[60–63] and will provide complementary constraints to redshift-space distortions and weak lensing measurements, probing larger physical scales. In addition to probing the global dynamics of dark energy, CMB-S4 will also be sensitive to the imprint of new parity-violating physics within the dark-energy sector which results in cosmic birefringence[64–67]. Detection of these parity-violating correlations would have paradigm-changing implications for cosmological scale physics, and may present a unique handle to probing microphysics of dark energy. Joint analysis of CMB data along with other astronomical observations that are sensitive to expansion and growth will allow for comprehensive probes of dark energy.

References

[1] K. Abazajian, G. Addison, P. Adshead, Z. Ahmed, S. W. Allen, D. Alonso, M. Alvarez, A. Anderson, K. S. Arnold, C. Baccigalupi, K. Bailey, D. Barkats, D. Barron, P. S. Barry, J. G. Bartlett, R. Basu Thakur, N. Battaglia, E. Baxter, R. Bean, C. Bebek, A. N. Bender, B. A. Benson, E. Berger, S. Bhimani, C. A. Bischoff, L. Bleem, S. Bocquet, K. Boddy, M. Bonato, J. R. Bond, J. Borrill, F. R. Bouchet, M. L. Brown, S. Bryan, B. Burkhart, V. Buza, K. Byrum, E. Calabrese, V. Calafut, R. Caldwell, J. E. Carlstrom, J. Carron, T. Cecil, A. Challinor, C. L. Chang, Y. Chinone, H.-M. S. Cho, A. Cooray, T. M. Crawford, A. Crites, A. Cukierman, F.-Y. Cyr-Racine, T. de Haan, G. de Zotti, J. Delabrouille, M. Demarteau, M. Devlin, E. Di Valentino, M. Dobbs, S. Duff, A. Duivenvoorden, C. Dvorkin, W. Edwards, J. Eimer, J. Errard, T. Essinger-Hileman, G. Fabbian, C. Feng, S. Ferraro, J. P. Filippini, R. Flauger, B. Flaugher, A. A. Fraisse, A. Frolov, N. Galitzki, S. Galli, K. Ganga, M. Gerbino, M. Gilchriese, V. Gluscevic, D. Green, D. Grin, E. Grohs, R. Gualtieri, V. Guarino, J. E. Gudmundsson, S. Habib, G. Haller, M. Halpern, N. W. Halverson, S. Hanany, K. Harrington, M. Hasegawa, M. Hasselfield, M. Hazumi, K. Heitmann, S. Henderson, J. W. Henning, J. C. Hill, R. Hlozek, G. Holder, W. Holzapfel, J. Hubmayr, K. M. Huffenberger, M. Huffer, H. Hui, K. Irwin, B. R. Johnson, D. Johnstone, W. C. Jones, K. Karkare, N. Katayama, J. Kerby, S. Kernovsky, R. Keskitalo, T. Kisner, L. Knox, A. Kosowsky, J. Kovac, E. D. Kovetz, S. Kuhlmann, C.-l. Kuo, N. Kurita, A. Kusaka, A. Lahteenmaki, C. R. Lawrence, A. T. Lee, A. Lewis, D. Li, E. Linder, M. Loverde, A. Lowitz, M. S. Madhavacheril, A. Mantz, F. Matsuda, P. Mauskopf, J. McMahon, M. McQuinn, P. D. Meerburg, J.-B. Melin, J. Meyers, M. Millea, J. Mohr, L. Moncelsi, T. Mroczkowski, S. Mukherjee, M. Münchmeyer, D. Nagai, J. Nagy, T. Namikawa, F. Nati, T. Natoli, M. Negrello, L. Newburgh, M. D. Niemack, H. Nishino, M. Nordby, V. Novosad, P. O'Connor, G. Obied, S. Padin, S. Pandey, B. Partridge, E. Pierpaoli, L. Pogosian, C. Pryke, G. Puglisi, B. Racine, S. Raghunathan, A. Rahlin, S. Rajagopalan, M. Raveri, M. Reichanadter, C. L. Reichardt, M. Remazeilles, G. Rocha, N. A. Roe, A. Roy, J. Ruhl, M. Salatino, B. Saliwanchik, E. Schaan, A. Schillaci, M. M. Schmittfull, D. Scott, N. Sehgal, S. Shandera, C. Sheehy, B. D. Sherwin, E. Shirokoff, S. M. Simon, A. Slosar, R. Somerville, D. Spergel, S. T. Staggs, A. Stark, R. Stompor, K. T. Story, C. Stoughton, A. Suzuki, O. Tajima, G. P. Teply, K. Thompson, P. Timbie, M. Tomasi, J. I. Treu, M. Tristram, G. Tucker, C. Umiltà, A. e. van Engelen, J. D. Vieira, A. G. Vieregg, M. Vogelsberger, G. Wang, S. Watson, M. White, N. Whitehorn, E. J. Wollack, W. L. Kimmy Wu, Z. Xu, S. Yasini, J. Yeck, K. W. Yoon, E. Young, and A. Zonca, "CMB-S4 Science Case, Reference Design, and Project Plan," *arXiv e-prints* (July, 2019) arXiv:1907.04473, arXiv:1907.04473 [astro-ph.IM].

[2] **CMB-S4** Collaboration, K. N. Abazajian *et al.*, "CMB-S4 Science Book, First Edition," arXiv:1610.02743 [astro-ph.CO].

[3] M. H. Abitbol, Z. Ahmed, D. Barron, R. Basu Thakur, A. N. Bender, B. A. Benson, C. A. Bischoff, S. A. Bryan, J. E. Carlstrom, and C. L. Chang, "CMB-S4 Technology Book, First Edition," *arXiv e-prints* (Jun, 2017) arXiv:1706.02464, arXiv:1706.02464 [astro-ph.IM].

[4] R. Essig *et al.*, "Working Group Report: New Light Weakly Coupled Particles," in *Community Summer Study 2013: Snowmass on the Mississippi (CSS2013), Minneapolis, MN, USA, July 29-August 6, 2013*. 2013. arXiv:1311.0029 [hep-ph].

[5] D. J. E. Marsh, "Axion Cosmology," *Phys. Rept.* **643** (2016) 1–79, arXiv:1510.07633 [astro-ph.CO].

[6] J. Alexander *et al.*, "Dark Sectors 2016 Workshop: Community Report," arXiv:1608.08632 [hep-ph].

[7] K. Abazajian, G. M. Fuller, and M. Patel, "Sterile neutrino hot, warm, and cold dark matter," *Phys. Rev.* **D64** (2001) 023501, arXiv:astro-ph/0101524 [astro-ph].

[8] A. Strumia and F. Vissani, "Neutrino masses and mixings and...," arXiv:hep-ph/0606054 [hep-ph].

[9] L. Ackerman, M. R. Buckley, S. M. Carroll, and M. Kamionkowski, "Dark Matter and Dark Radiation," *Phys. Rev. D* **79** (2009) 023519, arXiv:0810.5126 [hep-ph].

[10] A. Boyarsky, O. Ruchayskiy, and M. Shaposhnikov, "The Role of sterile neutrinos in cosmology and astrophysics," *Ann. Rev. Nucl. Part. Sci.* **59** (2009) 191–214, arXiv:0901.0011 [hep-ph].

[11] A. Arvanitaki, S. Dimopoulos, S. Dubovsky, N. Kaloper, and J. March-Russell, "String Axiverse," *Phys. Rev.* **D81** (2010) 123530, arXiv:0905.4720 [hep-th].

[12] D. Cadamuro, S. Hannestad, G. Raffelt, and J. Redondo, "Cosmological bounds on sub-MeV mass axions," *JCAP* **1102** (2011) 003, arXiv:1011.3694 [hep-ph].

[13] D. E. Kaplan, G. Z. Krnjaic, K. R. Rehermann, and C. M. Wells, "Dark Atoms: Asymmetry and Direct Detection," *JCAP* **1110** (2011) 011, arXiv:1105.2073 [hep-ph].

[14] K. N. Abazajian *et al.*, "Light Sterile Neutrinos: A White Paper," arXiv:1204.5379 [hep-ph].

[15] F.-Y. Cyr-Racine and K. Sigurdson, "Cosmology of atomic dark matter," *Phys. Rev.* **D87** no. 10, (2013) 103515, arXiv:1209.5752 [astro-ph.CO].

[16] C. Brust, D. E. Kaplan, and M. T. Walters, "New Light Species and the CMB," *JHEP* **12** (2013) 058, arXiv:1303.5379 [hep-ph].

[17] S. Weinberg, "Goldstone Bosons as Fractional Cosmic Neutrinos," *Phys.Rev.Lett.* **110** (2013) 241301, arXiv:1305.1971 [astro-ph.CO].

[18] A. Salvio, A. Strumia, and W. Xue, "Thermal axion production," *JCAP* **1401** (2014) 011, arXiv:1310.6982 [hep-ph].

[19] M. Kawasaki, M. Yamada, and T. T. Yanagida, "Observable dark radiation from a cosmologically safe QCD axion," *Phys. Rev.* **D91** no. 12, (2015) 125018, arXiv:1504.04126 [hep-ph].

[20] P. W. Graham, D. E. Kaplan, and S. Rajendran, "Cosmological Relaxation of the Electroweak Scale," *Phys. Rev. Lett.* **115** no. 22, (2015) 221801, arXiv:1504.07551 [hep-ph].

[21] D. Baumann, D. Green, and B. Wallisch, "A New Target for Cosmic Axion Searches," arXiv:1604.08614 [astro-ph.CO].

[22] N. Arkani-Hamed, T. Cohen, R. T. D'Agnolo, A. Hook, H. D. Kim, and D. Pinner, "Nnaturalness," arXiv:1607.06821 [hep-ph].

[23] Z. Chacko, N. Craig, P. Fox, and R. Harnik, "Cosmology in Mirror Twin Higgs and Neutrino Masses," *JHEP* **07** (2017) 023, arXiv:1611.07975 [hep-ph].

[24] N. Craig, S. Koren, and T. Trott, "Cosmological Signals of a Mirror Twin Higgs," *JHEP* **05** (2017) 038, arXiv:1611.07977 [hep-ph].

[25] Z. Chacko, D. Curtin, M. Geller, and Y. Tsai, "Cosmological Signatures of a Mirror Twin Higgs," *JHEP* **09** (2018) 163, arXiv:1803.03263 [hep-ph].

[26] M. Archidiacono, E. Giusarma, S. Hannestad, and O. Mena, "Cosmic Dark Radiation and Neutrinos," *Adv. High Energy Phys.* **2013** (2013) 191047, arXiv:1307.0637 [astro-ph.CO].

[27] J. Bernal, L. Verde, and A. Riess, "The Trouble with H_0," *JCAP* **10** (2016) 019, arXiv:1607.05617 [astro-ph.CO].

[28] B. Zhang, M. Childress, T. Davis, N. Karpenka, C. Lidman, B. Schmidt, and M. Smith, "A Blinded Determination of H_0 from Low-Redshift Type Ia Supernovae, Calibrated by Cepheid Variables," *Mon. Not. Roy. Astron. Soc.* **471** (2017) 2254, arXiv:1706.07573 [astro-ph.CO].

[29] G. Addison, D. Watts, C. Bennett, M. Halpern, G. Hinshaw, and J. Weiland, "Elucidating ΛCDM: Impact of Baryon Acoustic Oscillation Measurements on the Hubble Constant Discrepancy," *Astrophys. J.* **853** (2018) 119, arXiv:1707.06547 [astro-ph.CO].

[30] K. Aylor, M. Joy, L. Knox, M. Millea, S. Raghunathan, and K. Wu, "Sounds Discordant: Classical Distance Ladder & ΛCDM-Based Determinations of the Cosmological Sound Horizon," arXiv:1811.00537 [astro-ph.CO].

[31] N. MacCrann, J. Zuntz, S. Bridle, B. Jain, and M. Becker, "Cosmic Discordance: Are Planck CMB and CFHTLenS Weak Lensing Measurements Out of Tune?," *Mon. Not. Roy. Astron. Soc.* **451** (2015) 2877, arXiv:1408.4742 [astro-ph.CO].

[32] J. Lesgourgues, G. Marques-Tavares, and M. Schmaltz, "Evidence for dark matter interactions in cosmological precision data?," *JCAP* **1602** no. 02, (2016) 037, arXiv:1507.04351 [astro-ph.CO].

[33] F. Köhlinger *et al.*, "KiDS-450: The Tomographic Weak Lensing Power Spectrum and Constraints on Cosmological Parameters," *Mon. Not. Roy. Astron. Soc.* **471** (2017) 4412, arXiv:1706.02892 [astro-ph.CO].

[34] 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** (2018) 4894, arXiv:1707.06627 [astro-ph.CO].

[35] D. Weinberg, J. Bullock, F. Governato, R. Kuzio de Naray, and A. Peter, "Cold Dark Matter: Controversies on Small Scales," *Proc. Nat. Acad. Sci.* **112** (2015) 12249, arXiv:1306.0913 [astro-ph.CO].

[36] **Planck** Collaboration, Planck Collaboration VI, "Planck 2018 results. VI. Cosmological parameters," arXiv:1807.06209 [astro-ph.CO].

[37] D. Green *et al.*, "Messengers from the Early Universe: Cosmic Neutrinos and Other Light Relics," *Bull. Am. Astron. Soc.* **51** no. 7, (2019) 159, arXiv:1903.04763 [astro-ph.CO].

[38] R. Ansari *et al.* (Cosmic Visions 21 cm Collaboration), "Inflation and Early Dark Energy with a Stage II Hydrogen Intensity Mapping Experiment," arXiv:1810.09572 [astro-ph.CO].

[39] **PUMA** Collaboration, A. z. Slosar *et al.*, "Packed Ultra-wideband Mapping Array (PUMA): A Radio Telescope for Cosmology and Transients," arXiv:1907.12559 [astro-ph.IM].

[40] J. R. Bond and A. S. Szalay, "The Collisionless Damping of Density Fluctuations in an Expanding Universe," *Astrophys. J.* **274** (1983) 443–468.

[41] C.-P. Ma, "Linear power spectra in cold + hot dark matter models: Analytical approximations and applications," *Astrophys. J.* **471** (1996) 13–23, arXiv:astro-ph/9605198 [astro-ph].

[42] W. Hu and D. J. Eisenstein, "Small scale perturbations in a general MDM cosmology," *Astrophys.J.* **498** (1998) 497, arXiv:astro-ph/9710216 [astro-ph].

[43] W. Hu, D. J. Eisenstein, and M. Tegmark, "Weighing neutrinos with galaxy surveys," *Phys.Rev.Lett.* **80** (1998) 5255–5258, arXiv:astro-ph/9712057 [astro-ph].

[44] J. Aguirre *et al.* (Simons Observatory Collaboration), "The Simons Observatory: Science Goals and Forecasts," *JCAP* **02** (2019) 056, arXiv:1808.07445 [astro-ph.CO].

[45] **DESI** Collaboration, A. Aghamousa *et al.*, "The DESI Experiment Part I: Science,Targeting, and Survey Design," arXiv:1611.00036 [astro-ph.IM].

[46] L. Amendola *et al.*, "Cosmology and fundamental physics with the Euclid satellite," *Living Rev. Rel.* **21** no. 1, (2018) 2, arXiv:1606.00180 [astro-ph.CO].

[47] T. Brinckmann, D. C. Hooper, M. Archidiacono, J. Lesgourgues, and T. Sprenger, "The promising future of a robust cosmological neutrino mass measurement," *JCAP* **1901** (2019) 059, arXiv:1808.05955 [astro-ph.CO].

[48] V. Gluscevic and K. K. Boddy, "Constraints on Scattering of keV-TeV Dark Matter with Protons in the Early Universe," *Physical Review Letters* **121** no. 8, (Aug., 2018) 081301, arXiv:1712.07133.

[49] K. K. Boddy and V. Gluscevic, "First cosmological constraint on the effective theory of dark matter-proton interactions," *Phys. Rev.* **D 98** no. 8, (Oct, 2018) 083510, arXiv:1801.08609 [astro-ph.CO].

[50] W. L. Xu, C. Dvorkin, and A. Chael, "Probing sub-GeV dark matter-baryon scattering with cosmological observables," *Phys. Rev.* **D 97** no. 10, (May, 2018) 103530, arXiv:1802.06788.

[51] L. G. van den Aarssen, T. Bringmann, and C. Pfrommer, "Is dark matter with long-range interactions a solution to all small-scale problems of Λ CDM cosmology?," *Phys. Rev. Lett.* **109** (2012) 231301, arXiv:1205.5809 [astro-ph.CO].

[52] F.-Y. Cyr-Racine, R. de Putter, A. Raccanelli, and K. Sigurdson, "Constraints on Large-Scale Dark Acoustic Oscillations from Cosmology," *Phys. Rev. D* **89** no. 6, (2014) 063517, arXiv:1310.3278 [astro-ph.CO].

[53] M. A. Buen-Abad, G. Marques-Tavares, and M. Schmaltz, "Non-Abelian dark matter and dark radiation," *Phys. Rev.* **D92** no. 2, (2015) 023531, arXiv:1505.03542 [hep-ph].

[54] Z. Chacko, Y. Cui, S. Hong, T. Okui, and Y. Tsai, "Partially Acoustic Dark Matter, Interacting Dark Radiation, and Large Scale Structure," *JHEP* **12** (2016) 108, arXiv:1609.03569 [astro-ph.CO].

[55] M. A. Buen-Abad, M. Schmaltz, J. Lesgourgues, and T. Brinckmann, "Interacting Dark Sector and Precision Cosmology," *JCAP* **1801** no. 01, (2018) 008, arXiv:1708.09406 [astro-ph.CO].

[56] J. S. Bullock and M. Boylan-Kolchin, "Small-Scale Challenges to the ΛCDM Paradigm," *Ann. Rev. Astron. Astrophys.* **55** (2017) 343–387, arXiv:1707.04256 [astro-ph.CO].

[57] R. Hložek, D. Grin, D. J. E. Marsh, and P. G. Ferreira, "A search for ultralight axions using precision cosmological data," *Phys. Rev.* **D91** no. 10, (2015) 103512, arXiv:1410.2896 [astro-ph.CO].

[58] R. Hložek, D. J. E. Marsh, D. Grin, R. Allison, J. Dunkley, and E. Calabrese, "Future CMB tests of dark matter: ultra-light axions and massive neutrinos," arXiv:1607.08208 [astro-ph.CO].

[59] R. Hložek, D. J. E. Marsh, and D. Grin, "Using the Full Power of the Cosmic Microwave Background to Probe Axion Dark Matter," *Mon. Not. Roy. Astron. Soc.* **476** no. 3, (2018) 3063–3085, arXiv:1708.05681 [astro-ph.CO].

[60] S. Bhattacharya and A. Kosowsky, "Dark Energy Constraints from Galaxy Cluster Peculiar Velocities," *Phys. Rev.* **D77** (2008) 083004, arXiv:0712.0034 [astro-ph].

[61] A. Kosowsky and S. Bhattacharya, "A Future Test of Gravitation Using Galaxy Cluster Velocities," *Phys. Rev.* **D80** (2009) 062003, arXiv:0907.4202 [astro-ph.CO].

[62] E.-M. Mueller, F. de Bernardis, R. Bean, and M. D. Niemack, "Constraints on gravity and dark energy from the pairwise kinematic Sunyaev-Zeldovich effect," *Astrophys. J.* **808** no. 1, (2015) 47, arXiv:1408.6248 [astro-ph.CO].

[63] E.-M. Mueller, F. de Bernardis, R. Bean, and M. D. Niemack, "Constraints on massive neutrinos from the pairwise kinematic Sunyaev-Zel'dovich effect," *Phys. Rev.* **D92** no. 6, (2015) 063501, arXiv:1412.0592 [astro-ph.CO].

[64] S. M. Carroll, "Quintessence and the rest of the world," *Phys. Rev. Lett.* **81** (1998) 3067–3070, arXiv:astro-ph/9806099 [astro-ph].

[65] M. Kamionkowski, "How to De-Rotate the Cosmic Microwave Background Polarization," *Phys. Rev. Lett.* **102** (2009) 111302, arXiv:0810.1286 [astro-ph].

[66] V. Gluscevic, M. Kamionkowski, and A. Cooray, "De-Rotation of the Cosmic Microwave Background Polarization: Full-Sky Formalism," *Phys. Rev.* **D80** (2009) 023510, arXiv:0905.1687 [astro-ph.CO].

[67] V. Gluscevic, D. Hanson, M. Kamionkowski, and C. M. Hirata, "First CMB Constraints on Direction-Dependent Cosmological Birefringence from WMAP-7," *Phys. Rev.* **D86** (2012) 103529, arXiv:1206.5546 [astro-ph.CO].