Snowmass2021 - Letter of Interest

Insights for Fundamental Physics and Cosmology with Light Relics

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
■ (TF9) Astro-particle physics & cosmology
■ (NF2) Sterile Neutrinos
■ (NF3) BSM

Contact Information:

Joel Meyers (Southern Methodist University) [jrmeyers@smu.edu]

Authors: (see list after the text)

Abstract:

The extremely hot and dense environment of the early Universe provides the conditions that lead to the production of the fundamental ingredients of our Universe, even those which are very weakly coupled to Standard Model states. Long-lived species produced during this phase of expansion affect the evolution of the Universe, leaving imprints in many cosmological observables. The insight offered by cosmology into light relic particles is particularly valuable, given the challenges in detecting such species by other means. The gravitational effects of any light relics can be observed through their unique imprint in the cosmic microwave background, the large-scale structure, and the primordial light element abundances, and are important in determining the initial conditions of the Universe. Future cosmological observations can be orders of magnitude more sensitive than current experiments. These observations offer a unique and broad discovery space for new physics in the dark sector and beyond. A detection of an excess light relic abundance would be a clear indication of new physics and would provide the first direct information about the hot Universe prior to neutrino decoupling. The absence of a signal places powerful constraints on dark sectors competitive with experimental and astrophysical probes.

Cosmic Neutrinos: The cosmic neutrino background provides a useful example of the physics of cosmological light relics and the insights provided by cosmological measurements of the light relic density. In the very early Universe, neutrinos were kept in thermal equilibrium with the Standard Model plasma until the temperature dropped below about 1 Mev and neutrinos decoupled from the plasma. The background of cosmic neutrinos persists today, with a temperature and number density similar to that of the cosmic microwave background (CMB). The cosmic neutrino energy density ρ_ν can be expressed in terms of the effective number of neutrino species, $N_{\rm eff} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{\rho_\nu}{\rho_\gamma}$, where ρ_γ is the energy density in photons. Detailed calculations of neutrino decoupling predict that in the Standard Model $N_{\rm eff}^{\rm SM} = 3.045$[1–3].

Cosmology is sensitive to the gravitational effects of neutrinos (and all light relics), both through their mean energy density[4–7] and their fluctuations, which propagate at the speed of light in the early universe due to the free-streaming nature of neutrinos[7–10]. A radiation fluid whose fluctuations do not exceed the sound speed of the plasma[11,12] could arise from large neutrino self-interactions[13,14], neutrino-dark sector interactions, or dark radiation self-coupling. Such a radiation fluid can be observationally distinguished from free-streaming radiation, providing a test of new physics in the neutrino and dark sectors[9,15,16].

New Light States: A measurement of the value of $N_{\rm eff}$ provides vastly more information than just the energy density in cosmic neutrinos. The parameter $N_{\rm eff}$ is a probe of any particles that have the same gravitational influence as relativistic neutrinos, which is true of any (free-streaming) radiation. Furthermore, this radiation could have been created at much earlier times when the energy densities were even higher than in the cores of stars or supernovae, shedding light on the physics at new extremes of temperature and density, and providing further insight into our early cosmic history.

New sources of (dark) radiation are well motivated by both particle physics and cosmology[17–19]. New light particles are predicted in many extensions of the Standard Model, including axions and sterile neutrinos, or can arise as a consequence of solving the hierarchy problem[17–38]. For large regions of unexplored parameter space, these light particles are thermalized in the early universe and lead to additional radiation at later times. Light species are ubiquitous in models of the late universe as well: they may form the dark matter (e.g. axions), be an essential ingredient of a more complicated dark sector as the force carrier between dark matter and the Standard Model (or itself), or provide a source of dark radiation for a dark thermal history. Furthermore, these new particles could also play a role in explaining discrepancies in the measurements of the Hubble constant H_0[39–43], the amplitude of large-scale matter fluctuations σ_8[44–47], and the properties of clustering on small scales[48,49]. Measuring the total radiation density is a broad window into all these possibilities as well as additional scenarios that we have yet to consider[50].

The contribution to $N_{\rm eff}$ from any thermal light relic is easy to predict because its energy density in equilibrium is fixed by the temperature and the number of internal states (e.g. spin configurations). Under mild assumptions[51], the contribution to $\Delta N_{\rm eff}$ is determined by two numbers, the last temperature at which it was in equilibrium, T_F, and the effective number of spin degrees of freedom, g_s, according to $\Delta N_{\rm eff} = g_s\left(\frac{43/4}{g_\star(T_F)}\right)^{4/3}$. The function $g_\star(T_F)$ is the number of effective degrees of freedom (defined as the number of independent states with an additional factor of $7/8$ for fermions) present in the thermal plasma at the temperature T_F and accounts for how much the photons are heated by the annihilation of heavy states after the decoupling of the new species. The next generation of CMB observations are expected to reach a precision of $\sigma(N_{\rm eff}) = 0.03$[52–54], which would extend our reach in T_F by several orders of magnitude for a particle with spin $s > 0$ and be the first measurement sensitive to a real scalar ($s = 0$) that decouples prior to the QCD phase transition.

The impact of the coming generation of observations is illustrated in Fig. 1. The anticipated improvements in measurements of $N_{\rm eff}$ translate into orders of magnitude in sensitivity to the temperature T_F. This temperature sets the reach in probing fundamental physics. Even in the absence of a detection, future cos-

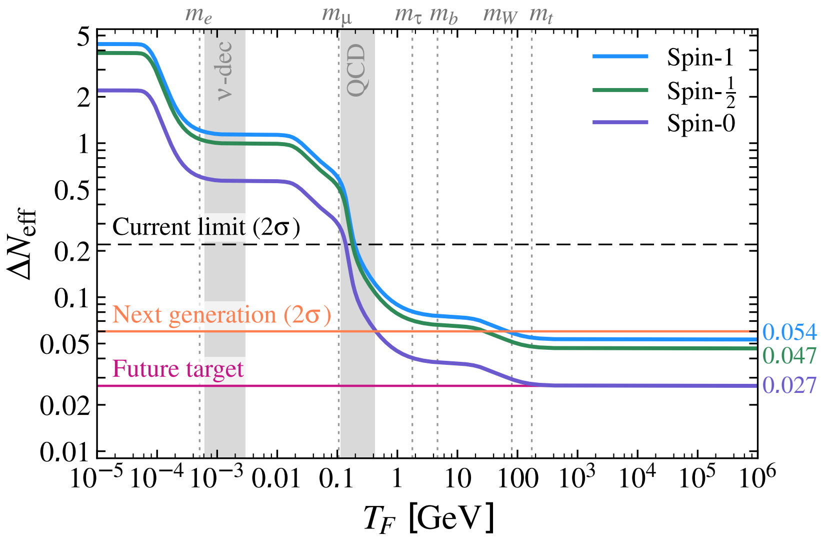

Figure 1: Contributions of a single massless particle, which decoupled at the temperature T_F from the Standard Model, to the effective number of relativistic species, $N_{\rm eff} = N_{\rm eff}^{\rm SM} + \Delta N_{\rm eff}$, with the Standard Model expectation $N_{\rm eff}^{\rm SM} = 3.045$ from neutrinos. The limit at 95% c.l. from current observations[49], and the anticipated sensitivity of next-generation CMB experiments[52–55] illustrate the power of cosmological surveys to constrain light thermal relics. The displayed values on the right are the observational thresholds for particles with different spins and arbitrarily large decoupling temperature, and provide particularly compelling targets for future observations[56–59]. Figure reproduced from Ref. 50.

mological probes would place constraints that can be orders of magnitude stronger than current probes of the same physics, including for axion-like particles[34] and dark sectors[37,38,60,61]. These contributions to $N_{\rm eff}$ asymptote to specific values of $\Delta N_{\rm eff} = 0.027, 0.047, 0.054$ for a massless (real) spin-0 scalar, spin-1/2 (Weyl) fermion and spin-1 vector boson, respectively (see Fig. 1). A cosmological probe with sensitivity to $\Delta N_{\rm eff}$ at these levels would probe physics back to the time of reheating for even a single additional species. These thresholds are within reach of some proposed CMB[56] and 21 cm experiments[57,58].

Gravitational Waves: Even without new light particles, $N_{\rm eff}$ is a probe of new physics that changes our thermal history, including processes that result in a stochastic background of gravitational waves[62–64]. Violent phase transitions and other nonlinear dynamics in the primordial universe could produce such a background, peaked at frequencies much larger than those accessible to B-mode polarization measurements of the CMB or, in many cases, direct detection experiments such as LIGO and LISA[65–69]. For particularly violent sources, the energy density in gravitational waves can be large enough to make a measurable contribution to $N_{\rm eff}$[69–71].

Observables: The effect of the radiation density on the damping tail of the anisotropy power spectrum drives the constraint on $N_{\rm eff}$ from the CMB. High-resolution maps of the CMB are expected to provide a measurement of $\sigma(N_{\rm eff}) = 0.03$ in the coming decade[52–54] and future surveys such as CMB-HD are expected to reach $\sigma(N_{\rm eff}) = 0.014$[56]. Measurements of the primordial abundances of light elements can also be used to infer the relic density of neutrinos and other light species, with deuterium[72] and helium-4[73,74] currently providing the tightest constraints. These measurements are expected to provide useful complementarity with CMB measurements[75–78] but are not expected to drive improvements on $N_{\rm eff}$ constraints on their own[79]. Maps of the large-scale structure of the Universe from galaxy and weak lensing surveys can provide complementary measurements of the radiation content[55,57,80]. A future 21 cm intensity mapping experiment like PUMA[58], in conjunction with CMB-S4, could improve constraints to $\sigma(N_{\rm eff}) = 0.013$[57], providing extremely broad insight into physics beyond the Standard Model.

References

[1] G. Mangano, G. Miele, S. Pastor, T. Pinto, O. Pisanti, *et al.*, "Relic neutrino decoupling including flavor oscillations," *Nucl.Phys.* **B729** (2005) 221–234, `arXiv:hep-ph/0506164 [hep-ph]`.

[2] E. Grohs, G. M. Fuller, C. T. Kishimoto, M. W. Paris, and A. Vlasenko, "Neutrino energy transport in weak decoupling and big bang nucleosynthesis," *Phys. Rev.* **D93** no. 8, (2016) 083522, `arXiv:1512.02205 [astro-ph.CO]`.

[3] P. F. de Salas and S. Pastor, "Relic neutrino decoupling with flavour oscillations revisited," *JCAP* **1607** no. 07, (2016) 051, `arXiv:1606.06986 [hep-ph]`.

[4] P. J. E. Peebles, "Primordial Helium Abundance and the Primordial Fireball. II," *Astrophys. J.* **146** (1966) 542.

[5] D. Dicus, E. Kolb, Gleeson, Sudarshan, V. Teplitz, and M. Turner, "Primordial Nucleosynthesis Including Radiative, Coulomb, and Finite-Temperature Corrections to Weak Rates," *Phys. Rev. D* **26** (1982) 2694.

[6] Z. Hou, R. Keisler, L. Knox, M. Millea, and C. Reichardt, "How Massless Neutrinos Affect the Cosmic Microwave Background Damping Tail," *Phys. Rev.* **D87** (2013) 083008, `arXiv:1104.2333 [astro-ph.CO]`.

[7] S. Bashinsky and U. Seljak, "Neutrino perturbations in CMB anisotropy and matter clustering," *Phys. Rev.* **D69** (2004) 083002, `arXiv:astro-ph/0310198 [astro-ph]`.

[8] B. Follin, L. Knox, M. Millea, and Z. Pan, "First Detection of the Acoustic Oscillation Phase Shift Expected from the Cosmic Neutrino Background," *Phys. Rev. Lett.* **115** no. 9, (2015) 091301, `arXiv:1503.07863 [astro-ph.CO]`.

[9] D. Baumann, D. Green, J. Meyers, and B. Wallisch, "Phases of New Physics in the CMB," *JCAP* **1601** (2016) 007, `arXiv:1508.06342 [astro-ph.CO]`.

[10] D. Baumann, D. Green, and M. Zaldarriaga, "Phases of New Physics in the BAO Spectrum," *JCAP* **11** (2017) 007, `arXiv:1703.00894 [astro-ph.CO]`.

[11] N. Bell, E. Pierpaoli, and K. Sigurdson, "Cosmological Signatures of Interacting Neutrinos," *Phys. Rev. D* **73** (2006) 063523, `arXiv:astro-ph/0511410 [astro-ph]`.

[12] A. Friedland, K. Zurek, and S. Bashinsky, "Constraining Models of Neutrino Mass and Neutrino Interactions with the Planck Satellite," `arXiv:0704.3271 [astro-ph]`.

[13] F.-Y. Cyr-Racine and K. Sigurdson, "Limits on Neutrino-Neutrino Scattering in the Early Universe," *Phys. Rev.* **D90** no. 12, (2014) 123533, `arXiv:1306.1536 [astro-ph.CO]`.

[14] L. Lancaster, F.-Y. Cyr-Racine, L. Knox, and Z. Pan, "A Tale of Two Modes: Neutrino Free-Streaming in the Early Universe," *JCAP* **07** (2017) 033, `arXiv:1704.06657 [astro-ph.CO]`.

[15] C. Brust, Y. Cui, and K. Sigurdson, "Cosmological Constraints on Interacting Light Particles," *JCAP* **08** (2017) 020, `arXiv:1703.10732 [astro-ph.CO]`.

[16] G. Choi, C.-T. Chiang, and M. LoVerde, "Probing Decoupling in Dark Sectors with the Cosmic Microwave Background," *JCAP* **1806** no. 06, (2018) 044, `arXiv:1804.10180 [astro-ph.CO]`.

[17] 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]`.

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

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

[20] 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]`.

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

[22] 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]`.

[23] 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]`.

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

[25] 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]`.

[26] 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]`.

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

[28] 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]`.

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

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

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

[32] 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]`.

[33] 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]`.

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

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

[36] 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]`.

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

[38] 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]`.

[39] 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]`.

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

[41] 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]`.

[42] 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]`.

[43] 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]`.

[44] 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]`.

[45] 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]`.

[46] 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]`.

[47] 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]`.

[48] 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]`.

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

[50] 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]`.

[51] B. Wallisch, "Cosmological Probes of Light Relics," `arXiv:1810.02800 [astro-ph.CO]`.

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

[53] S. Hanany *et al.* (PICO Collaboration), "PICO: Probe of Inflation and Cosmic Origins," `arXiv:1902.10541 [astro-ph.IM]`.

[54] K. Abazajian *et al.*, "CMB-S4 Science Case, Reference Design, and Project Plan," `arXiv:1907.04473 [astro-ph.IM]`.

[55] D. Baumann, D. Green, and B. Wallisch, "Searching for light relics with large-scale structure," *JCAP* **1808** no. 08, (2018) 029, `arXiv:1712.08067 [astro-ph.CO]`.

[56] N. Sehgal *et al.*, "CMB-HD: An Ultra-Deep, High-Resolution Millimeter-Wave Survey Over Half the Sky," `arXiv:1906.10134 [astro-ph.CO]`.

[57] 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]`.

[58] **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]`.

[59] D. J. Schlegel *et al.*, "Astro2020 APC White Paper: The MegaMapper: a z ¿ 2 Spectroscopic Instrument for the Study of Inflation and Dark Energy," `arXiv:1907.11171 [astro-ph.IM]`.

[60] P. Adshead, Y. Cui, and J. Shelton, "Chilly Dark Sectors and Asymmetric Reheating," *JHEP* **06** (2016) 016, `arXiv:1604.02458 [hep-ph]`.

[61] D. Green and S. Rajendran, "The Cosmology of Sub-MeV Dark Matter," *JHEP* **10** (2017) 013, `arXiv:1701.08750 [hep-ph]`.

[62] L. A. Boyle and A. Buonanno, "Relating gravitational wave constraints from primordial nucleosynthesis, pulsar timing, laser interferometers, and the CMB: Implications for the early Universe," *Phys. Rev.* **D78** (2008) 043531, `arXiv:0708.2279 [astro-ph]`.

[63] A. Stewart and R. Brandenberger, "Observational Constraints on Theories with a Blue Spectrum of Tensor Modes," *JCAP* **0808** (2008) 012, `arXiv:0711.4602 [astro-ph]`.

[64] P. D. Meerburg, R. Hložek, B. Hadzhiyska, and J. Meyers, "Multiwavelength constraints on the inflationary consistency relation," *Phys. Rev.* **D91** no. 10, (2015) 103505, `arXiv:1502.00302 [astro-ph.CO]`.

[65] M. Maggiore, "Gravitational Wave Experiments and Early Universe Cosmology," *Phys. Rept.* **331** (2000) 283, `arXiv:gr-qc/9909001 [gr-qc]`.

[66] R. Easther and E. Lim, "Stochastic Gravitational Wave Production After Inflation," *JCAP* **04** (2006) 010, `arXiv:astro-ph/0601617 [astro-ph]`.

[67] J. Dufaux, A. Bergman, G. Felder, L. Kofman, and J.-P. Uzan, "Theory and Numerics of Gravitational Waves from Preheating after Inflation," *Phys. Rev. D* **76** (2007) 123517, `arXiv:0707.0875 [astro-ph]`.

[68] M. Amin, M. Hertzberg, D. Kaiser, and J. Karouby, "Nonperturbative Dynamics of Reheating After Inflation: A Review," *Int. J. Mod. Phys. D* **24** (2014) 1530003, `arXiv:1410.3808 [hep-ph]`.

[69] C. Caprini and D. Figueroa, "Cosmological Backgrounds of Gravitational Waves," *Class. Quant. Grav.* **35** (2018) 163001, `arXiv:1801.04268 [astro-ph.CO]`.

[70] P. Adshead, J. Giblin, and Z. Weiner, "Gravitational Waves from Gauge Preheating," *Phys. Rev. D* **98** (2018) 043525, `arXiv:1805.04550 [astro-ph.CO]`.

[71] M. Amin, J. Fan, K. Lozanov, and M. Reece, "Cosmological Dynamics of Higgs Potential Fine Tuning," *Phys. Rev. D* **99** (2019) 035008, `arXiv:1802.00444 [hep-ph]`.

[72] R. J. Cooke, M. Pettini, and C. C. Steidel, "One Percent Determination of the Primordial Deuterium Abundance," *Astrophys. J.* **855** no. 2, (2018) 102, `arXiv:1710.11129 [astro-ph.CO]`.

[73] E. Aver, K. A. Olive, and E. D. Skillman, "The effects of He I λ10830 on helium abundance determinations," *JCAP* **1507** no. 07, (2015) 011, `arXiv:1503.08146 [astro-ph.CO]`.

[74] A. Peimbert, M. Peimbert, and V. Luridiana, "The Primordial Helium Abundance and the Number of Neutrino Families," *Rev. Mex. Astron. Astrofis.* **52** (2016) 419, `arXiv:1608.02062 [astro-ph.CO]`.

[75] W. Fischler and J. Meyers, "Dark Radiation Emerging After Big Bang Nucleosynthesis?," *Phys. Rev.* **D83** (2011) 063520, `arXiv:1011.3501 [astro-ph.CO]`.

[76] J. Hasenkamp, "Dark Radiation from the Axino Solution of the Gravitino Problem," *Phys. Lett. B* **707** (2012) 121, `arXiv:1107.4319 [hep-ph]`.

[77] D. Hooper, F. S. Queiroz, and N. Y. Gnedin, "Non-Thermal Dark Matter Mimicking An Additional Neutrino Species In The Early Universe," *Phys. Rev.* **D85** (2012) 063513, `arXiv:1111.6599 [astro-ph.CO]`.

[78] J. Hasenkamp and J. Kersten, "Dark Radiation from Particle Decay: Cosmological Constraints and Opportunities," *JCAP* **08** (2013) 024, `arXiv:1212.4160 [hep-ph]`.

[79] A. Laguë and J. Meyers, "Prospects and Limitations for Constraining Light Relics with Primordial Abundance Measurements," *Phys. Rev. D* **101** no. 4, (2020) 043509, `arXiv:1908.05291 [astro-ph.CO]`.

[80] D. Baumann, F. Beutler, R. Flauger, D. Green, A. Slosar, M. Vargas-Magaña, B. Wallisch, and C. Yèche, "First Constraint on the Neutrino-Induced Phase Shift in the Spectrum of Baryon Acoustic Oscillations," *Nat. Phys.* (2019) , `arXiv:1803.10741 [astro-ph.CO]`.

Additional Authors:

Kevork Abazajian (University of California, Irvine),
Zeeshan Ahmed (Kavli Institute of Particle Astrophysics and Cosmology, SLAC),
Mustafa A. Amin (Rice University),
Daniel Baumann (University of Amsterdam),
Benjamin Beringue (University of Cambridge),
J. Richard Bond (Canadian Institute for Theoretical Astrophysics, University of Toronto),
Thejs Brinckmann (C.N. Yang Institute for Theoretical Physics, Stony Brook University),
John E. Carlstrom (University of Chicago, ANL),
Anthony Challinor (University of Cambridge),
Francis-Yan Cyr-Racine (University of New Mexico),
Eleonora Di Valentino (University of Manchester, UK),
Olivier Doré (JPL),
Cora Dvorkin (Harvard University),
Simone Ferraro (LBNL),
George M. Fuller (University of California, San Diego),
Martina Gerbino (INFN Ferrara),
Daniel Green (University of California, San Diego),
Evan Grohs (University of California Berkeley),
Nikhel Gupta (School of Physics, University of Melbourne),
Gilbert Holder (University of Illinois at Urbana-Champaign),
Lloyd Knox (University of California, Davis),
Ely D. Kovetz (Ben-Gurion University, Israel),
Marilena Loverde (Stony Brook University),
P. Daniel Meerburg (University fo Groningen),
Joel Meyers (Southern Methodist University),
Suvodip Mukherjee (University of Amsterdam),
Michael D. Niemack (Cornell University),
Neelima Sehgal (Stony Brook University),
Anže Slosar (Brookhaven National Laboratory),
Benjamin Wallisch (Institute for Advanced for Advanced Study & University of California, San Diego),
Scott Watson (Syracuse University)