Snowmass 2021 Letter of Interest:
Cosmological Neutrinos

Primary topical groups:
NF08/TF11 (Theory of Neutrino Physics)
NF04 (Neutrinos From Natural Sources)

Other topical groups:
NF01 (Neutrino Oscillations)
NF02 (Sterile Neutrinos)
NF03 (BSM)
NF05 (Neutrino properties)
CF1 (Dark Matter: Particle-like)
CF7 (Cosmic Probes of Fundamental Physics)

Primary contact information:
Evan Grohs (University of California, Berkeley) [egrohs@berkeley.edu]

Secondary contact information:
A. Baha Balantekin (University of Wisconsin, Madison) [baha@physics.wisc.edu]
George M. Fuller (University of California, San Diego) [gfuller@ucsd.edu]
Lucas Johns (University of California, Berkeley) [ljohns370@gmail.com]
Alexander Kusenko (University of California, Los Angeles) [kusenko@ucla.edu]
Amol V. Patwardhan (University of California, Berkeley) [apatwardhan2@berkeley.edu]
Manibrata Sen (University of California, Berkeley; Northwestern University) [manibrata@berkeley.edu]

Endorsers:
Kevork N. Abazajian (University of California, Irvine)
Kam Arnold (University of California, San Diego)
V. Barger (University of Wisconsin, Madison)
Darcy Barron (University of New Mexico)
Jeffrey M. Berryman (University of Kentucky; University of California, Berkeley)
Daniel Blaschke (Los Alamos National Laboratory)
Nikita Blinov (Fermi National Accelerator Laboratory)
J. Richard Bond (CITA, University of Toronto)
Alexey Boyarsky (Leiden University)
Vincenzo Cirigliano (Los Alamos National Laboratory)
Alain Coc (Université Paris–Saclay, IJCLab)
Ryan Cooke (Durham University)
Francis-Yan Cyr-Racine (University of New Mexico)
Eleonora Di Valentino (University of Manchester)
Olivier Doré, (Jet Propulsion Laboratory, California Institute of Technology)
Marco Drewes (Université catholique de Louvain)
Raphael Flauger (University of California, San Diego)
J. A. Formaggio (Laboratory for Nuclear Science, Massachusetts Institute of Technology)
Julien Froustey (Institut d'Astrophysique de Paris)
Stefano Gariazzo (CSIC-Universitat de València)
Martina Gerbino (INFN Ferrara)
Carlo Giunti (INFN Torino)
Rasmus S. L. Hansen (Niels Bohr Institute, University of Copenhagen)
Wick Haxton (University of California, Berkeley)
Toshitaka Kajino (National Astronomical Observatory of Japan)
Manoj Kaplinghat (University of California, Irvine)
Kevin J. Kelly (Fermi National Accelerator Laboratory)
Marilena Loverde (Stony Brook University)

Cecilia Lunardini (Arizona State University)
Pedro Machado (Fermi National Accelerator Laboratory)
Danny Marfatia (University of Hawaii at Manoa)
Samuel D. McDermott (Fermi National Accelerator Laboratory)
A. B. McDonald (Queen's University)
Joel Meyers (Southern Methodist University)
Silvia Pascoli (Durham University)
Saori Pastore (Washington University in St. Louis)
Georg Raffelt (Max Planck Institute for Physics, Munich)
Guenter Sigl (Institut für theoretische Physik, Universität Hamburg)
Volodymyr Takhistov (University of California, Los Angeles)
Irene Tamborra (Niels Bohr Institute, University of Copenhagen)
Water Tangarife (Loyola University Chicago)
Raymond R. Volkas (The University of Melbourne)
Liang Yang (University of California, San Diego)
Yue Zhang (Carleton University)

Overview

The physics surrounding neutrino mass and neutrino interactions presents key research opportunities in elementary particle physics, both in theory and in experiment. Paralleling the developments in those fields, advances in observational astrophysics and cosmology promise unprecedented precision in the measurement of cosmological quantities. Since those quantities in many cases are shaped by how the physics of neutrinos plays out in the cauldron of the very early universe, and its aftermath, we can expect synergistic advances in both the fundamental physics of neutrinos and in cosmology. In what follows we point out several areas ripe for future investigation.

(1) **Neutrino Mass**: The known, standard model "active" neutrinos are very light compared to the charged leptons and quarks in their respective families. The neutrino mass-squared differences are known from neutrino flavor oscillation experiments and observations [1, 2]. The neutrino mass hierarchy and the absolute masses remain unknown. However, the hierarchy likely will be inferred experimentally (e.g., via DUNE [3]) to 5σ within 6 years, with good hints within 3 years. The "sum of the light neutrino masses," $\sum m_\nu$, is a prime target for Stage-4 CMB experiments [4], with an uncertainty that could reach $\sim 15\,\mathrm{meV}$ [5], providing an independent handle on the neutrino mass hierarchy and the neutrino collision-less damping scale [6]. A positive signal in forthcoming tonne-scale neutrino-less double beta decay experiments [7–11] would mean lepton number violation and that neutrinos are Majorana in character, the decay being enabled by either neutrino mass-mediated chirality flip [12] or by BSM physics. If the hierarchy is "normal," the mass-mediated channel might imply that the lightest neutrino mass eigenvalue is $m_1 > 10\,\mathrm{meV}$, in turn implying $\sum m_\nu > 75\,\mathrm{meV}$ which would be $\sim 15\,\mathrm{meV}$ above the $m_1 = 0$ case. Moreover, the $0\nu\beta\beta$ nuclear matrix element – which also may be altered by BSM physics – is a frontier issue even in standard model physics [13]. In any case, tension between cosmological and experimental handles on neutrino mass physics could give new insights into elementary particle physics, astrophysics, or both. KATRIN [14, 15], Project 8 [16], and similar tritium endpoint experiments may eventually provide probes of the "ν_e mass" in the $\sim 100\,\mathrm{meV}$ range. Direct detection of cosmological neutrinos would also yield measurements of the ν_e mass [17]. Charge-less neutrinos may acquire mass differently than do charged particles in the standard model Higgs paradigm [18]. That invites new, potentially testable BSM alternatives.

(2) **Flavor Physics and Additional States**: The neutrino weak interaction states, ν_e, ν_μ, ν_τ, are not coincident with the mass states, ν_1, ν_2, ν_3, enabling neutrino oscillations/flavor transformation. The three vacuum mixing angles in the PMNS transformation between these bases are measured [19]; the Dirac and (for Majorana) two Majorana CP-violating phases in this unitary transformation remain unmeasured. CP-violation will be probed in long baseline oscillation experiments [20, 21] and, to some extent, in $0\nu\beta\beta$ experiments. Any additional neutrino flavors, a feature of many neutrino mass and dark sector physics models, must have sub-weak interactions, hence they are labeled "sterile." However, their mass scales are completely unknown, with see-saw-like mass schemes suggesting large scales [22], and other schemes suggesting both large $>$ GeV, intermediate $\sim$ keV, and $\sim$ eV mass regimes [23–26]. Though their vacuum mixing with active states is constrained by experiment and astrophysical considerations [27], sterile neutrinos could be copiously produced in the early universe through lepton number-driven medium-enhanced oscillations [28] and decoherence [29] and by a variety of nonstandard neutrino interactions (NSI) [30, 31], some involving dark sector physics. For example, the $\sim$ keV mass scale sterile states make for intriguing dark matter candidates [32–34], potentially probable with next generation X-ray observatories, e.g., ATHENA and XRISM, whose energy resolution will be sufficient to resolve the virial width of X-ray lines originating from decay of a dark matter constituent. Heavier sterile states produced in the early universe may comprise relatively long lived non-thermal relics, whose decays may

generate dilution sufficient to be revealed in $N_{\rm eff}$ or BBN. Short baseline oscillation experiment (e.g., MiniBooNE [35]) and reactor neutrino [36, 37] anomalies have been interpreted as active-sterile oscillation with large mixing at the $\sim 1\,\mathrm{eV}$ mass scale. This is incompatible with cosmological bounds, resulting in an explosion of speculation about neutrino NSIs [38] and dark sector physics [39–41]. Likewise, the discordance in the Hubble parameter determinations has led to many ideas invoking the similar neutrino-sector BSM considerations [42–45].

(3) **Weak Decoupling/BBN and CMB Probes**: The next generation Stage-4 CMB experiments promise $\mathcal{O}(1\%)$ precision in measurements of the non-photon radiation energy density [46], e.g., $N_{\rm eff}$, at photon decoupling and in the primordial helium abundance. Comparable precision in the primordial deuterium abundance can be attained with the advent of 30m-class telescopes [47–50]. These measurements, when combined with high precision simulations of the evolution of the early universe through the weak decoupling and BBN epochs [51–55], may provide new probes of many of the issues discussed above, including neutrino NSIs, dilution from non-thermal relic particle decays [56–59], inhomogeneous entropy distributions from a variety of BSM physics issues, etc. In turn, the salient issue in simulating physics (standard model and BSM) in the weak decoupling and BBN regimes is providing a complete quantum kinetic treatment of neutrino scattering [60, 61], entropy flow, and flavor transformation. These calculations, pushing the boundaries of high performance computing, will enable future cosmological observations to provide probes of subtle BSM physics, in some cases complementary to accelerator-based experiments, and in other cases unique. Enabling this probe will be facilitated by better measurements of nuclear reaction physics associated with deuterium production, e.g., $n(p,\gamma)d$ [62], and deuterium destruction, e.g., $d(p,\gamma)^3\mathrm{He}$ [63]. Disentangling signatures of BSM physics from standard model nuclear uncertainties [64–67] is an important goal. This includes resolving the beam [68] versus bottle [69] measurements of neutron lifetime (hence, the axial vector weak coupling), and the nuclear reactions that may accompany BSM physics attempts at resolving the $^7\mathrm{Li}/^7\mathrm{Be}$ problem in standard BBN [70, 71].

(4) **Neutrino Portal to Dark Matter/Dark Sector Physics**: Models for dark matter and dark sector physics may have implications for the interactions of neutrinos in the early universe [72], as well as in experimental settings [73, 74], as described above. A dark sector that broadly mimics the standard model, save for masses and couplings, is a case in point. One or more of the particles, elementary or composite, in that sector may comprise a dark matter constituent. Though gravitation is the one commonality between the standard model and dark sectors (e.g., black holes could be created in either sector) very small couplings may enable communication between the sectors. For example, dark neutrinos and dark Zs may appear in the standard model sector as sterile neutrinos and NSIs, respectively. Models along these lines have been invoked to explain short baseline neutrino oscillation anomalies [75–77], and may have significant, or subtle effects in early universe or compact object physics. Moreover, the evolution of the dark sector itself, e.g., in darkleosynthesis-like models [78, 79], etc., may figure in both dark matter and in structure formation [80–84].

In Summary: Considerations of cosmological neutrinos comprise a promising frontier in elementary particle physics, rife with opportunities in theory, experiment, and observation.

---

[1] **Super-Kamiokande** Collaboration, "Atmospheric neutrino oscillation analysis with external constraints in Super-Kamiokande I-IV," Phys. Rev. D **97**, 072001 (2018), arXiv:1710.09126 [hep-ex].

[2] **SNO** collaboration, "The Sudbury Neutrino Observatory," Nuclear Instruments and Methods in Physics Research A **449**, 172–207 (2000), arXiv:nucl-ex/9910016 [nucl-ex].

[3] **DUNE** Collaboration, "Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE) Conceptual Design Report Volume 1: The LBNF and DUNE Projects," arXiv e-prints , arXiv:1601.05471 (2016), arXiv:1601.05471 [physics.ins-det].

[4] **CMB-S4** Collaboration, J. E. Carlstrom *et al.*, "CMB-S4," in *Bulletin of the American Astronomical Society*, Vol. 51 (2019) p. 209, arXiv:1908.01062 [astro-ph.IM].

[5] **CMB-S4** Collaboration, J. E. Carlstrom *et al.*, "CMB-S4 Science Book, First Edition," ArXiv e-prints (2016), arXiv:1610.02743.

[6] Cora Dvorkin, Martina Gerbino, David Alonso, Nicholas Battaglia, Simeon Bird, Ana Diaz Rivero, Andreu Font-Ribera, George Fuller, Massimiliano Lattanzi, Marilena Loverde, Julian B. Muñoz, Blake Sherwin, Anze Slosar, and Francisco Villaescusa-Navarro, "Neutrino Mass from Cosmology: Probing Physics Beyond the Standard Model," BAAS **51**, 64 (2019), arXiv:1903.03689 [astro-ph.CO].

[7] M. Agostini *et al.*, "Results on Neutrinoless Double-β Decay of Ge76 from Phase I of the GERDA Experiment," Phys. Rev. Lett. **111**, 122503 (2013), arXiv:1307.4720 [nucl-ex].

[8] N. Abgrall *et al.*, "The large enriched germanium experiment for neutrinoless double beta decay (LEGEND)," in *American Institute of Physics Conference Series*, American Institute of Physics Conference Series, Vol. 1894 (2017) p. 020027, arXiv:1709.01980 [physics.ins-det].

[9] C. E. Aalseth *et al.*, "Search for Neutrinoless Double-β Decay in ^{76}Ge with the Majorana Demonstrator," Phys. Rev. Lett. **120**, 132502 (2018), arXiv:1710.11608 [nucl-ex].

[10] G. Anton *et al.*, "Search for Neutrinoless Double-β Decay with the Complete EXO-200 Dataset," Phys. Rev. Lett. **123**, 161802 (2019).

[11] J. B. Albert *et al.*, "Search for Neutrinoless Double-Beta Decay with the Upgraded EXO-200 Detector," Phys. Rev. Lett. **120**, 072701 (2018), arXiv:1707.08707 [hep-ex].

[12] S. Pastore, J. Carlson, V. Cirigliano, W. Dekens, E. Mereghetti, and R. B. Wiringa, "Neutrinoless double-β decay matrix elements in light nuclei," Phys. Rev. C **97**, 014606 (2018), arXiv:1710.05026 [nucl-th].

[13] Vincenzo Cirigliano, Wouter Dekens, Jordy de Vries, Michael L. Graesser, Emanuele Mereghetti, Saori Pastore, and Ubirajara van Kolck, "New Leading Contribution to Neutrinoless Double-β Decay," Phys. Rev. Lett. **120**, 202001 (2018), arXiv:1802.10097 [hep-ph].

[14] **KATRIN** Collaboration, "Improved Upper Limit on the Neutrino Mass from a Direct Kinematic Method by KATRIN," Phys. Rev. Lett. **123**, 221802 (2019), arXiv:1909.06048 [hep-ex].

[15] **KATRIN** Collaboration, "First operation of the KATRIN experiment with tritium," European Physical Journal C **80**, 264 (2020), arXiv:1909.06069 [physics.ins-det].

[16] **Project 8** Collaboration, "Single-Electron Detection and Spectroscopy via Relativistic Cyclotron Radiation," Phys. Rev. Lett. **114**, 162501 (2015), arXiv:1408.5362 [physics.ins-det].

[17] **PTOLEMY** Collaboration, "Neutrino physics with the PTOLEMY project: active neutrino properties and the light sterile case," J. Cosmology Astropart. Phys. **2019**, 047 (2019), arXiv:1902.05508 [astro-ph.CO].

[18] Csaba Csáki, Eric Kuflik, and Salvator Lombardo, "Viable twin cosmology from neutrino mixing," Phys. Rev. D **96**, 055013 (2017).

[19] Particle Data Group, "Review of Particle Physics," Progress of Theoretical and Experimental Physics **2020** (2020), 10.1093/ptep/ptaa104, 083C01, https://academic.oup.com/ptep/article-pdf/2020/8/083C01/33653179/ptaa104.pdf.

[20] **T2K** Collaboration, "First combined analysis of neutrino and antineutrino oscillations at T2K," arXiv e-prints , arXiv:1701.00432 (2017), arXiv:1701.00432 [hep-ex].

[21] **NOvA** Collaboration, "Constraints on Oscillation Parameters from ν_e Appearance and ν_μ Disappearance in NOvA," arXiv e-prints , arXiv:1703.03328 (2017), arXiv:1703.03328 [hep-ex].

[22] T. Yanagida, "Horizontal Symmetry and Masses of Neutrinos," Progress of Theoretical Physics **64**, 1103–1105 (1980).

[23] Alexander Kusenko, Fuminobu Takahashi, and Tsutomu T. Yanagida, "Dark matter from split seesaw," Physics Letters B **693**, 144–148 (2010), arXiv:1006.1731 [hep-ph].

[24] R. Adhikari *et al.*, "A White Paper on keV sterile neutrino Dark Matter," J. Cosmology Astropart. Phys. **2017**, 025 (2017), arXiv:1602.04816 [hep-ph].

[25] Enrico Bertuzzo, Sudip Jana, Pedro A. N. Machado, and Renata Zukanovich Funchal, "Neutrino masses and mixings dynamically generated by a light dark sector," Physics Letters B **791**, 210–214 (2019), arXiv:1808.02500 [hep-ph].

[26] Graciela B. Gelmini, Philip Lu, and Volodymyr Takhistov, "Cosmological dependence of non-resonantly produced sterile neutrinos," J. Cosmology Astropart. Phys. **2019**, 047 (2019), arXiv:1909.13328 [hep-ph].

[27] Alexander Kusenko, Silvia Pascoli, and Dmitry Semikoz, "Bounds on heavy sterile neutrinos revisited," Journal of High Energy Physics **2005**, 028 (2005), arXiv:hep-ph/0405198 [hep-ph].

[28] Xiangdong Shi and George M. Fuller, "New Dark Matter Candidate: Nonthermal Sterile Neutrinos," Phys. Rev. Lett. **82**, 2832–2835 (1999), arXiv:astro-ph/9810076 [astro-ph].

[29] Scott Dodelson and Lawrence M. Widrow, "Sterile-neutrinos as dark matter," Phys. Rev. Lett. **72**, 17–20 (1994), arXiv:hep-ph/9303287.

[30] André de Gouvêa, Manibrata Sen, Walter Tangarife, and Yue Zhang, "Dodelson-Widrow Mechanism in the Presence of Self-Interacting Neutrinos," Phys. Rev. Lett. **124**, 081802 (2020), arXiv:1910.04901 [hep-ph].

[31] Kevin J. Kelly, Manibrata Sen, Walter Tangarife, and Yue Zhang, "Origin of sterile neutrino dark matter via secret neutrino interactions with vector bosons," Phys. Rev. D **101**, 115031 (2020), arXiv:2005.03681 [hep-ph].

[32] Kevork Abazajian, George M. Fuller, and Mitesh Patel, "Sterile neutrino hot, warm, and cold dark matter," Phys. Rev. D **64**, 023501 (2001), arXiv:astro-ph/0101524.

[33] Alexander Kusenko, "Sterile neutrinos: The Dark side of the light fermions," Phys. Rept. **481**, 1–28 (2009), arXiv:0906.2968 [hep-ph].

[34] Graciela B. Gelmini, Philip Lu, and Volodymyr Takhistov, "Cosmological dependence of resonantly produced sterile neutrinos," J. Cosmology Astropart. Phys. **2020**, 008 (2020), arXiv:1911.03398 [hep-ph].

[35] **MiniBooNE** Collaboration, "Significant Excess of ElectronLike Events in the MiniBooNE Short-Baseline Neutrino Experiment," arXiv e-prints , arXiv:1805.12028 (2018), arXiv:1805.12028 [hep-ex].

[36] **Daya Bay** Collaboration, "Evolution of the Reactor Antineutrino Flux and Spectrum at Daya Bay," Phys. Rev. Lett. **118**, 251801 (2017), arXiv:1704.01082 [hep-ex].

[37] A. C. Hayes, Gerard Jungman, E. A. McCutchan, A. A. Sonzogni, G. T. Garvey, and X. B. Wang, "Analysis of the Daya Bay Reactor Antineutrino Flux Changes with Fuel Burnup," Phys. Rev. Lett. **120**, 022503 (2018), arXiv:1707.07728 [nucl-th].

[38] Nikita Blinov, Kevin J. Kelly, Gordan Krnjaic, and Samuel D. McDermott, "Constraining the Self-Interacting Neutrino Interpretation of the Hubble Tension," Phys. Rev. Lett. **123**, 191102 (2019), arXiv:1905.02727 [astro-ph.CO].

[39] Peter Ballett, Silvia Pascoli, and Mark Ross-Lonergan, "U(1)' mediated decays of heavy sterile neutrinos in MiniBooNE," Phys. Rev. D **99**, 071701 (2019), arXiv:1808.02915 [hep-ph].

[40] Jeremy Sakstein and Mark Trodden, "Early Dark Energy from Massive Neutrinos as a Natural Resolution of the Hubble

Tension," Phys. Rev. Lett. **124**, 161301 (2020), arXiv:1911.11760 [astro-ph.CO].

[41] Asli Abdullahi, Matheus Hostert, and Silvia Pascoli, "A Dark Seesaw Solution to Low Energy Anomalies: MiniBooNE, the muon $(g-2)$, and BaBar," (2020), arXiv:2007.11813 [hep-ph].

[42] S. H. Suyu, T. Treu, R. D. Blandford, W. L. Freedman, S. Hilbert, C. Blake, J. Braatz, F. Courbin, J. Dunkley, L. Greenhill, E. Humphreys, S. Jha, R. Kirshner, K. Y. Lo, L. Macri, B. F. Madore, P. J. Marshall, G. Meylan, J. Mould, B. Reid, M. Reid, A. Riess, D. Schlegel, V. Scowcroft, and L. Verde, "The Hubble constant and new discoveries in cosmology," arXiv e-prints , arXiv:1202.4459 (2012), arXiv:1202.4459 [astro-ph.CO].

[43] Suresh Kumar, Rafael C. Nunes, and Santosh Kumar Yadav, "Dark sector interaction: a remedy of the tensions between CMB and LSS data," European Physical Journal C **79**, 576 (2019), arXiv:1903.04865 [astro-ph.CO].

[44] Graciela B. Gelmini, Alexander Kusenko, and Volodymyr Takhistov, "Hints of Sterile Neutrinos in Recent Measurements of the Hubble Parameter," arXiv e-prints , arXiv:1906.10136 (2019), arXiv:1906.10136 [astro-ph.CO].

[45] Christina D. Kreisch, Francis-Yan Cyr-Racine, and Olivier Doré, "Neutrino puzzle: Anomalies, interactions, and cosmological tensions," Phys. Rev. D **101**, 123505 (2020), arXiv:1902.00534 [astro-ph.CO].

[46] Daniel Green, Mustafa A. Amin, Joel Meyers, Benjamin Wallisch *et al.*, "Messengers from the Early Universe: Cosmic Neutrinos and Other Light Relics," BAAS **51**, 159 (2019), arXiv:1903.04763 [astro-ph.CO].

[47] I. Hook (ed.), *The science case for the European Extremely Large Telescope : the next step in mankind's quest for the Universe.* (Cambridge, UK: OPTICON and Garching bei Muenchen, Germany: European Southern Observatory (ESO), 2005).

[48] David Silva, Paul Hickson, Charles Steidel, and Michael Bolte, *TMT Detailed Science Case: 2007*, Tech. Rep. (2007) http://www.tmt.org.

[49] P. McCarthy and R. A. Bernstein, "Giant Magellan Telescope: Status and Opportunities for Scientific Synergy," in *Thirty Meter Telescope Science Forum* (2014) p. 61.

[50] R. J. Cooke, M. Pettini, and C. C. Steidel, "One Percent Determination of the Primordial Deuterium Abundance," ApJ **855**, 102 (2018), arXiv:1710.11129.

[51] A. D. Dolgov and M. Fukugita, "Nonequilibrium effect of the neutrino distribution on primordial helium synthesis," Phys. Rev. D **46**, 5378–5382 (1992).

[52] A. D. Dolgov, S. H. Hansen, and D. V. Semikoz, "Non-equilibrium corrections to the spectra of massless neutrinos in the early universe," Nuclear Physics B **503**, 426–444 (1997), hep-ph/9703315.

[53] G. Mangano, G. Miele, S. Pastor, T. Pinto, O. Pisanti, and P. D. Serpico, "Relic neutrino decoupling including flavour oscillations," Nuclear Physics B **729**, 221–234 (2005), hep-ph/0506164.

[54] 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. D **93**, 083522 (2016), arXiv:1512.02205.

[55] Jack J. Bennett, Gilles Buldgen, Marco Drewes, and Yvonne Y. Y. Wong, "Towards a precision calculation of the effective number of neutrinos N_{eff} in the Standard Model: the QED equation of state," J. Cosmology Astropart. Phys. **2020**, 003 (2020), arXiv:1911.04504 [hep-ph].

[56] G. M. Fuller, C. T. Kishimoto, and A. Kusenko, "Heavy sterile neutrinos, entropy and relativistic energy production, and the relic neutrino background," ArXiv e-prints (2011), arXiv:1110.6479 [astro-ph.CO].

[57] Oleg Ruchayskiy and Artem Ivashko, "Restrictions on the lifetime of sterile neutrinos from primordial nucleosynthesis," J. Cosmology Astropart. Phys. **2012**, 014 (2012), arXiv:1202.2841 [hep-ph].

[58] Graciela B. Gelmini, Philip Lu, and Volodymyr Takhistov, "Visible sterile neutrinos as the earliest relic probes of cosmology," Physics Letters B **800**, 135113 (2020), arXiv:1909.04168 [hep-ph].

[59] Alexey Boyarsky, Maksym Ovchynnikov, Oleg Ruchayskiy, and Vsevolod Syvolap, "Improved BBN constraints on Heavy Neutral Leptons," arXiv e-prints , arXiv:2008.00749 (2020), arXiv:2008.00749 [hep-ph].

[60] P. F. de Salas and S. Pastor, "Relic neutrino decoupling with flavour oscillations revisited," J. Cosmology Astropart. Phys. **7**, 051 (2016), arXiv:1606.06986 [hep-ph].

[61] Julien Froustey, Cyril Pitrou, and Maria Cristina Volpe, "Neutrino decoupling including flavour oscillations and primordial nucleosynthesis," arXiv e-prints , arXiv:2008.01074 (2020), arXiv:2008.01074 [hep-ph].

[62] Silas R. Beane, Emmanuel Chang, William Detmold, Kostas Orginos, Assumpta Parreño, Martin J. Savage, Brian C. Tiburzi, and Nplqcd Collaboration, "Ab initio Calculation of the n p $\to$ d γ Radiative Capture Process," Phys. Rev. Lett. **115**, 132001 (2015), arXiv:1505.02422 [hep-lat].

[63] L. E. Marcucci, G. Mangano, A. Kievsky, and M. Viviani, "Implication of the Proton-Deuteron Radiative Capture for Big Bang Nucleosynthesis," Physical Review Letters **116**, 102501 (2016), arXiv:1510.07877 [nucl-th].

[64] L. M. Krauss and P. Romanelli, "Big bang nucleosynthesis - Predictions and uncertainties," ApJ **358**, 47–59 (1990).

[65] G. Fiorentini, E. Lisi, S. Sarkar, and F. L. Villante, "Quantifying uncertainties in primordial nucleosynthesis without Monte Carlo simulations," Phys. Rev. D **58**, 063506 (1998), astro-ph/9803177.

[66] G.M. Hale, "Covariances from light-element r-matrix analyses," Nuclear Data Sheets **109**, 2812 – 2816 (2008), special Issue on Workshop on Neutron Cross Section Covariances June 24-28, 2008, Port Jefferson, New York, USA.

[67] C. Iliadis, K. S. Anderson, A. Coc, F. X. Timmes, and S. Starrfield, "Bayesian Estimation of Thermonuclear Reaction Rates," ApJ **831**, 107 (2016), arXiv:1608.05853 [astro-ph.SR].

[68] A. T. Yue, M. S. Dewey, D. M. Gilliam, G. L. Greene, A. B. Laptev, J. S. Nico, W. M. Snow, and F. E. Wietfeldt, "Improved Determination of the Neutron Lifetime," Phys. Rev. Lett. **111**, 222501 (2013), arXiv:1309.2623 [nucl-ex].

[69] R. W. Pattie, N. B. Callahan, C. Cude-Woods *et al.*, "Measurement of the neutron lifetime using a magneto-gravitational trap and in situ detection," Science **360**, 627–632 (2018), arXiv:1707.01817 [nucl-ex].

[70] Richard H. Cyburt, Brian D. Fields, Keith A. Olive, and Tsung-Han Yeh, "Big bang nucleosynthesis: Present status,"

Reviews of Modern Physics **88**, 015004 (2016), arXiv:1505.01076 [astro-ph.CO].

[71] Alain Coc and Elisabeth Vangioni, "Primordial nucleosynthesis," International Journal of Modern Physics E **26**, 1741002 (2017), arXiv:1707.01004 [astro-ph.CO].

[72] Brian Batell, Tao Han, David McKeen, and Barmak Shams Es Haghi, "Thermal dark matter through the Dirac neutrino portal," Phys. Rev. D **97**, 075016 (2018), arXiv:1709.07001 [hep-ph].

[73] Luis A. Anchordoqui, Vernon Barger, Haim Goldberg, Xing Huang, Danny Marfatia, Luiz H. M. da Silva, and Thomas J. Weiler, "IceCube neutrinos, decaying dark matter, and the Hubble constant," Phys. Rev. D **92**, 061301 (2015), arXiv:1506.08788 [hep-ph].

[74] C. A. Argüelles *et al.*, "White Paper on New Opportunities at the Next-Generation Neutrino Experiments (Part 1: BSM Neutrino Physics and Dark Matter)," arXiv e-prints , arXiv:1907.08311 (2019), arXiv:1907.08311 [hep-ph].

[75] Enrico Bertuzzo, Sudip Jana, Pedro A. N. Machado, and Renata Zukanovich Funchal, "Dark Neutrino Portal to Explain MiniBooNE Excess," Phys. Rev. Lett. **121**, 241801 (2018), arXiv:1807.09877 [hep-ph].

[76] Carlos A. Argüelles, Matheus Hostert, and Yu-Dai Tsai, "Testing New Physics Explanations of the MiniBooNE Anomaly at Neutrino Scattering Experiments," Phys. Rev. Lett. **123**, 261801 (2019), arXiv:1812.08768 [hep-ph].

[77] Alakabha Datta, Saeed Kamali, and Danny Marfatia, "Dark sector origin of the KOTO and MiniBooNE anomalies," Physics Letters B **807**, 135579 (2020), arXiv:2005.08920 [hep-ph].

[78] Gordan Krnjaic and Kris Sigurdson, "Big bang darkleosynthesis," Physics Letters B **751**, 464–468 (2015), arXiv:1406.1171 [hep-ph].

[79] Graham D. Kribs and Ethan T. Neil, "Review of strongly-coupled composite dark matter models and lattice simulations," International Journal of Modern Physics A **31**, 1643004-764 (2016), arXiv:1604.04627 [hep-ph].

[80] Diego Blas, Mathias Garny, Thomas Konstandin, and Julien Lesgourgues, "Structure formation with massive neutrinos: going beyond linear theory," J. Cosmology Astropart. Phys. **2014**, 039 (2014), arXiv:1408.2995 [astro-ph.CO].

[81] Francisco Villaescusa-Navarro, Philip Bull, and Matteo Viel, "Weighing Neutrinos with Cosmic Neutral Hydrogen," ApJ **814**, 146 (2015), arXiv:1507.05102 [astro-ph.CO].

[82] Hao-Ran Yu, J. D. Emberson, Derek Inman, Tong-Jie Zhang, Ue-Li Pen, Joachim Harnois-Déraps, Shuo Yuan, Huan-Yu Teng, Hong-Ming Zhu, Xuelei Chen, Zhi-Zhong Xing, Yunfei Du, Lilun Zhang, Yutong Lu, and Xiangke Liao, "Differential neutrino condensation onto cosmic structure," Nature Astronomy **1**, 0143 (2017), arXiv:1609.08968 [astro-ph.CO].

[83] Simeon Bird, Yacine Ali-Haïmoud, Yu Feng, and Jia Liu, "An efficient and accurate hybrid method for simulating non-linear neutrino structure," MNRAS **481**, 1486–1500 (2018), arXiv:1803.09854 [astro-ph.CO].

[84] Arka Banerjee, Devon Powell, Tom Abel, and Francisco Villaescusa-Navarro, "Reducing noise in cosmological N-body simulations with neutrinos," J. Cosmology Astropart. Phys. **2018**, 028 (2018), arXiv:1801.03906 [astro-ph.CO].