

Snowmass 2021 Letter of Interest: Supernova neutrinos and particle-physics opportunities

Primary topical groups:

NF08/TF11 (Theory of Neutrino Physics)
NF04 (Neutrinos From Natural Sources)

Other topical groups: TF08, TF09, CF3, CF7

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As DUNE and other neutrino observatories prepare for the next nearby core-collapse supernova, the theory community must position itself to take full advantage of the groundbreaking advances the event will enable. At stake are insights into **(1)** the flavor oscillations and fundamental properties of neutrinos, **(2)** the presence of beyond-Standard-Model (BSM) particles and couplings, and **(3)** the physics of one of the marquee targets of multi-messenger astronomy. The particle physics of neutrinos shapes and reveals the astrophysics of compact objects. The purpose of this LoI is to draw attention to the promising opportunities arising from this nexus.

(1) Neutrino oscillations and properties Nonzero neutrino mass radically changes the nature of neutrino transport in supernovae, rendering oscillation phenomenology indispensable. Recent years have witnessed rapid progress in neutrino quantum kinetics, especially with respect to collective oscillations and flavor-field instabilities [1–20]. These developments potentially have major consequences for the neutrino signal and other observables, but definitive statements require a deeper understanding of the microphysics. Major strides in this area are very likely to take place over the coming years.

Many studies have found that the flavor evolution of supernova neutrinos reflects fundamental particle properties such as the mass hierarchy (potentially resolvable through the atmospheric MSW resonance, for example), the mixing angles, and the Dirac CP phase, as reviewed in Refs. [21–26]. In-medium effects on the coherent evolution of neutrino spin/helicity may even bear imprints that depend on the absolute neutrino mass scale, on the neutrino magnetic moment, and on whether the neutrinos are Dirac or Majorana [27–30]. The sensitivity of neutrino oscillations to these properties motivates and benefits from the experimental effort led by DUNE and other collaborations.

(2) Dark-sector and other BSM physics Compact objects have a particular, privileged access to BSM scenarios that is not replicated elsewhere. Energy-loss arguments, for example, have been used to constrain (or at least make questionable) an impressive array of models in regions of parameter space that are untouched by other bounds [31–43]. Notably, these studies are all predicated on the neutrino signal detected from SN 1987A. We have every reason to expect that the model-testing legacy of supernova-neutrino astronomy will grow more prolific still.

Supernovae are especially valuable as probes of new physics involving neutrinos directly. One very active class of models consists of those with sterile neutrinos, which are variously motivated by oscillation anomalies, dark matter, baryogenesis, and the origin of neutrino mass [44–54]. More generally, the full wealth of physics opened up by the neutrino portal to the dark sector of our universe is still being uncovered. The large lepton degeneracies found in compact-object environments make them notably sensitive to processes that violate lepton number. Supernovae also provide a site to directly probe neutrino self-interactions—a crucial part of the SM that has not been tested directly in terrestrial laboratories—as well as non-standard neutrino (self-)interactions [55–62]. Other scenarios include, for instance, large neutrino magnetic moments [63–68]. A number of these ideas have been given impetus by recent experimental anomalies. In many cases, the new physics being proposed is closely linked to neutrino flavor and its evolution.

As the particle-physics community continues to think expansively about where BSM physics might be found, it is imperative that we continue to look to supernovae as unique and physically rich laboratories.

(3) Multi-messenger astronomy The next explosion of a nearby core-collapse supernova will be a watershed event in multi-messenger astronomy. Neutrinos will bring with them a wealth of information, offering a glimpse into the inner depths of the exploding star. From the signal we will learn not only about neutrinos themselves, but about the stellar progenitor, pre-collapse evolution, the explosion mechanism, composition (*e.g.*, entropy, electron fraction, neutron-to-proton ratio) and nucleosynthesis, cooling of the

proto-neutron star, the QCD phase diagram, possibly black-hole formation, and the expected diffuse supernova neutrino background [69–86]. In short, there will be significant mutual payoff for particle and supernova physics. It is in the great interest of both communities to prepare for this opportunity.

In the multi-messenger paradigm, neutrino physics is one piece of a larger puzzle. The better it is understood, the more effectively *non*-neutrino observations can be leveraged for insight, and vice versa. The conjunction of neutrino observatories, gravitational-wave observatories like LIGO, and photon observatories will give us unprecedented information concerning physics over a vast range of couplings—especially at the feeblest.

Although the focus here has been on supernovae, similar issues and opportunities are present in cosmology (through cosmic neutrinos and the diffuse supernova neutrino background) and neutron-star mergers. Supernovae, the early universe, and mergers collectively span disparate physical conditions and highly complementary observables. As we move forward with the Snowmass planning effort, we believe it is worth keeping these interconnections in mind.

The fundamental-physics potential of supernova neutrinos is a topic that interfaces with several areas of research: neutrino oscillations and properties, dark-sector and other BSM physics, and astronomy and cosmology, among others. With this LoI, our aim has been to accentuate some of the most active and urgent focal points. We are eager to contribute to discussions at the relevant Snowmass meetings, and we look forward to communicating the importance of this subject to the wider community.

References

- [1] J. F. Cherry, J. Carlson, A. Friedland, G. M. Fuller, and A. Vlasenko, Phys. Rev. Lett. **108**, 261104 (2012).
- [2] J. F. Cherry, J. Carlson, A. Friedland, G. M. Fuller, and A. Vlasenko, Phys. Rev. D **87**, 085037 (2013).
- [3] C. Volpe, D. Väänänen, and C. Espinoza, Phys. Rev. D **87**, 113010 (2013).
- [4] Y. Zhang and A. Burrows, Phys. Rev. D **88**, 105009 (2013).
- [5] A. Vlasenko, G. M. Fuller, and V. Cirigliano, Phys. Rev. D **89**, 105004 (2014).
- [6] B. Dasgupta and A. Mirizzi, Phys. Rev. D **92**, 125030 (2015).
- [7] L. Johns, M. Mina, V. Cirigliano, M. W. Paris, and G. M. Fuller, Phys. Rev. D **94**, 083505 (2016).
- [8] A. Malkus, G. C. McLaughlin, and R. Surman, Phys. Rev. D **93**, 045021 (2016).
- [9] R. F. Sawyer, Phys. Rev. Lett. **116**, 081101 (2016).
- [10] I. Izaguirre, G. Raffelt, and I. Tamborra, Phys. Rev. Lett. **118**, 021101 (2017).
- [11] J. Y. Tian, A. V. Patwardhan, and G. M. Fuller, Phys. Rev. D **95**, 063004 (2017).
- [12] V. Cirigliano, M. W. Paris, and S. Shalgar, Phys. Lett. B **774**, 258 (2017).
- [13] M.-R. Wu and I. Tamborra, Phys. Rev. D **95**, 103007 (2017).
- [14] S. A. Richers, G. C. McLaughlin, J. P. Kneller, and A. Vlasenko, Phys. Rev. D **99**, 123014 (2019).
- [15] F. Capozzi, B. Dasgupta, A. Mirizzi, M. Sen, and G. Sigl, Phys. Rev. Lett. **122**, 091101 (2019).
- [16] H. Nagakura, T. Morinaga, C. Kato, and S. Yamada, Astrophys. J. **886**, 139 (2019).
- [17] M. J. Cervia, A. V. Patwardhan, A. B. Balantekin, S. N. Coppersmith, and C. W. Johnson, Phys. Rev. D **100**, 083001 (2019).
- [18] J. D. Martin, C. Yi, and H. Duan, Phys. Lett. B **800**, 135088 (2020).

- [19] L. Johns, H. Nagakura, G. M. Fuller, and A. Burrows, Phys. Rev. D **101**, 043009 (2020).
- [20] J. F. Cherry *et al.*, Phys. Rev. D **102**, 023022 (2020).
- [21] H. Duan and J. P. Kneller, J. Phys. G **36**, 113201 (2009).
- [22] H. Duan, G. M. Fuller, and Y.-Z. Qian, Ann. Rev. Nucl. Part. Sci. **60**, 569 (2010).
- [23] A. Mirizzi *et al.*, Riv. Nuovo Cim. **39**, 1 (2016).
- [24] S. Chakraborty, R. Hansen, I. Izaguirre, and G. Raffelt, Nucl. Phys. **B908**, 366 (2016).
- [25] S. Horiuchi and J. P. Kneller, J. Phys. G **45**, 043002 (2018).
- [26] A. B. Balantekin and B. Kayser, Ann. Rev. Nucl. Part. Sci. **68**, 313 (2018).
- [27] A. de Gouvêa and S. Shalgar, J. Cosmol. Astropart. Phys. **2012**, 027 (2012).
- [28] V. Cirigliano, G. M. Fuller, and A. Vlasenko, Phys. Lett. B **747**, 27 (2015).
- [29] P. Pustoshny and A. Studenikin, Phys. Rev. D **98**, 113009 (2018).
- [30] S. Abbar, Phys. Rev. D **101**, 103032 (2020).
- [31] G. Raffelt and D. Seckel, Phys. Rev. Lett. **60**, 1793 (1988).
- [32] C. Hanhart, J. A. Pons, D. R. Phillips, and S. Reddy, Phys. Lett. B **509**, 1 (2001).
- [33] H. K. Dreiner, J.-F. m. c. Fortin, C. Hanhart, and L. Ubaldi, Phys. Rev. D **89**, 105015 (2014).
- [34] D. Kazanas, R. N. Mohapatra, S. Nussinov, V. L. Teplitz, and Y. Zhang, Nucl. Phys. B **890**, 17 (2015).
- [35] E. Rrapaj and S. Reddy, Phys. Rev. C **94**, 045805 (2016).
- [36] C. Mahoney, A. K. Leibovich, and A. R. Zentner, Phys. Rev. D **96**, 043018 (2017).
- [37] J. H. Chang, R. Essig, and S. D. McDermott, J. High Energy Phys. **09**, 051 (2018).
- [38] A. Sung, H. Tu, and M.-R. Wu, Phys. Rev. D **99**, 121305 (2019).
- [39] W. DeRocco, P. W. Graham, D. Kasen, G. Marques-Tavares, and S. Rajendran, Phys. Rev. D **100**, 075018 (2019).
- [40] N. Bar, K. Blum, and G. D’Amico, Phys. Rev. D **101**, 123025 (2020).
- [41] D. Croon, G. Elor, R. K. Leane, and S. D. McDermott, arXiv:2006.13942 .
- [42] R. Bollig, W. DeRocco, P. W. Graham, and H.-T. Janka, Phys. Rev. Lett. **125**, 051104 (2020).
- [43] P. Carenza *et al.*, Journal of Cosmology and Astroparticle Physics **2019**, 016 (2019).
- [44] K. Abazajian, G. M. Fuller, and M. Patel, Phys. Rev. D **64**, 023501 (2001).
- [45] P. Fayet, D. Hooper, and G. Sigl, Phys. Rev. Lett. **96**, 211302 (2006).
- [46] M. L. Warren, G. J. Mathews, M. Meixner, J. Hidaka, and T. Kajino, Int. J. Mod. Phys. A **31**, 1650137 (2016).
- [47] C. A. Argüelles, V. Brdar, and J. Kopp, Phys. Rev. D **99**, 043012 (2019).
- [48] V. Syvolap, O. Ruchayskiy, and A. Boyarsky, arXiv:1909.06320 .
- [49] A. M. Suliga, I. Tamborra, and M.-R. Wu, J. Cosmol. Astropart. Phys. **2019**, 019 (2019).
- [50] Z. Xiong, M.-R. Wu, and Y.-Z. Qian, Astrophys. J. **880**, 81 (2019).

- [51] M. Lei, N. Steinberg, and J. D. Wells, J. High Energy Phys. **2020**, 179 (2020).
- [52] L. Mastrototaro, A. Mirizzi, P. D. Serpico, and A. Esmaili, J. Cosmol. Astropart. Phys. **2020**, 010 (2020).
- [53] A. M. Suliga, I. Tamborra, and M.-R. Wu, J. Cosmol. Astropart. Phys **2020**, 018 (2020).
- [54] J. Tang, T. Wang, and M.-R. Wu, arXiv:2005.09168 .
- [55] C. J. Stapleford, D. J. Väänänen, J. P. Kneller, G. C. McLaughlin, and B. T. Shapiro, Phys. Rev. D **94**, 093007 (2016).
- [56] A. Das, A. Dighe, and M. Sen, J. Cosmol. Astropart. Phys. **05**, 051 (2017).
- [57] K. Murase and I. M. Shoemaker, Phys. Rev. Lett. **123**, 241102 (2019).
- [58] S.-F. Ge and S. J. Parke, Phys. Rev. Lett. **122**, 211801 (2019).
- [59] S. Shalgar, I. Tamborra, and M. Bustamante, arXiv:1912.09115 .
- [60] A. de Gouvêa, I. Martinez-Soler, and M. Sen, Phys. Rev. D **101**, 043013 (2020).
- [61] K. S. Babu, G. Chauhan, and P. S. B. Dev, Phys. Rev. D **101**, 095029 (2020).
- [62] C. Creque-Sarbinowski, J. Hyde, and M. Kamionkowski, arXiv:2005.05332 .
- [63] R. Barbieri and R. N. Mohapatra, Phys. Rev. Lett. **61**, 27 (1988).
- [64] J. M. Lattimer and J. Cooperstein, Phys. Rev. Lett. **61**, 23 (1988).
- [65] Y. Pehlivan, A. B. Balantekin, and T. Kajino, Phys. Rev. D **90**, 065011 (2014).
- [66] C. Giunti and A. Studenikin, Rev. Mod. Phys. **87**, 531 (2015).
- [67] G. Magill, R. Plestid, M. Pospelov, and Y.-D. Tsai, Phys. Rev. D **98**, 115015 (2018).
- [68] V. Brdar, A. Greljo, J. Kopp, and T. Opferkuch, arXiv:2007.15563 .
- [69] I. Sagert *et al.*, Phys. Rev. Lett. **102**, 081101 (2009).
- [70] E. O'Connor and C. D. Ott, Astrophys. J. **762**, 126 (2012).
- [71] S. M. Adams, C. S. Kochanek, J. F. Beacom, M. R. Vagins, and K. Z. Stanek, Astrophys. J. **778**, 164 (2013).
- [72] B. Müller and H.-T. Janka, Astrophys. J. **788**, 82 (2014).
- [73] I. Tamborra, G. Raffelt, F. Hanke, H.-T. Janka, and B. Müller, Phys. Rev. D **90**, 045032 (2014).
- [74] M.-R. Wu, Y.-Z. Qian, G. Martínez-Pinedo, T. Fischer, and L. Huther, Phys. Rev. D **91**, 065016 (2015).
- [75] S. W. Bruenn *et al.*, Astrophys. J. **818**, 123 (2016).
- [76] K. Nakamura *et al.*, Mon. Not. R. Astron. Soc. **461**, 3296 (2016).
- [77] K. Møller, A. M. Suliga, I. Tamborra, and P. B. Denton, J. Cosmol. Astropart. Phys. **2018**, 066 (2018).
- [78] H. Nagakura, A. Burrows, D. Vartanyan, and D. Radice, arXiv:2007.05000 .
- [79] B. Müller, Ann. Rev. Nucl. Part. Sci. **69**, 253 (2019).
- [80] Z. Lin, C. Lunardini, M. Zanolin, K. Kotake, and C. Richardson, Phys. Rev. D **101**, 123028 (2020).
- [81] S. W. Li, L. F. Roberts, and J. F. Beacom, arXiv:2008.04340 .

- [82] M. L. Warren, S. M. Couch, E. P. O'Connor, and V. Morozova, *Astrophys. J.* **898**, 139 (2020).
- [83] N. Raj, V. Takhistov, and S. J. Witte, *Phys. Rev. D* **101**, 043008 (2020).
- [84] S.-F. Ge *et al.*, [arXiv:2008.03924](#) .
- [85] B. Abi *et al.*, [arXiv:2008.06647](#) .
- [86] L. Walk, I. Tamborra, H.-T. Janka, A. Summa, and D. Kresse, *Phys. Rev. D* **101**, 123013 (2020).