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Neutrino Frontier: White Paper on Neutrino Self-Interactions

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Self-interacting Neutrinos.— The study of self-interacting neutrinos beyond the Standard Model (BSM) has developed significantly over the last few years, motivated by a range of theoretical and experimental questions. In this contribution, we seek to compile a white paper on the topic to serve as a common reference of previous work and to highlight the interplay of models and of experimental and observational probes that make use of or constrain neutrino self-interactions. Previously, neutrino self-interactions have been considered as a subset of the non-standard neutrino interactions (NSI) framework, where they are parametrized via higher-dimensional operators. The NSI framework has been explored in great detail in the context of neutrino scattering and oscillations; see, e.g., Refs. [1, 2] for reviews of NSI. However, while useful in many scenarios, the NSI framework is not appropriate for all phenomena; notably, when the ultraviolet (UV) completion of neutrino self-interaction models is necessary. Such theoretically consistent models enable the combination of diverse experiments and observables to probe neutrino self-interactions.

Below we describe the primary motivations for neutrino self-interactions and highlight the physical systems in which they may play an important role.

Neutrino Mass Generation and UV Completion.— Neutrino self-interactions can arise in the context of neutrino mass generation. These extensions of the SM can feature new electroweak-charged states or SM-singlet fields only [3–7]. In models with spontaneously broken lepton number a characteristic pseudo-Nambu-Goldstone (pNGB) boson often emerges that can mediate BSM neutrino self-interactions. The pNGB nature of this boson guarantees that this particle can be naturally light, allowing BSM self-interactions to have a strength that far exceeds that of SM electroweak interactions. Such a scenario is a particularly useful benchmark since it can realize a vast range of self-interaction strengths.

Connections to Dark Matter.— Self-interacting neutrinos may shed light on the nature of dark matter. Refs. [8, 9] explored a mechanism by which the mediator of such self-interactions is the (very light) dark matter. Ref. [10] considered a number of thermal dark matter scenarios in which the same mediator that causes neutrino self-interactions connects neutrinos and dark matter. Lastly, Refs. [11, 12] found that sterile neutrino dark matter, a long-studied dark matter candidate (see Ref. [13] for a review), can be populated in the early universe via these new self-interaction mechanisms.

The Hubble Tension.— The tension between high- and low-redshift measurements of the Hubble constant H_0 has led to a wide range of theoretical proposals to alleviate this discrepancy. One of the most successful attempts at doing this makes use of neutrino self-interactions that delay the onset of neutrinos free-streaming until the Cosmic Microwave Background (CMB) epoch, modifying the inference of H_0 from the CMB data. Ref. [14] found that certain combinations of cosmological data prefer strong neutrino self-interactions (parametrized by an effective four-Fermi interaction with strength $\sim 10^9 G_F$) while eliminating the tension. Following up on this result, Refs. [6, 15] explored the complementarity of laboratory and cosmological constraints on this approach, highlighting the difficulties of implementing such a strong self-interaction in UV-complete models. A workaround for these constraints was proposed in Ref. [7]. Future CMB observations will provide further evidence or exclude this possibility [16].

Laboratory Searches.— When new neutrino self-interactions are proposed in a UV-complete fashion, new mediators are involved. These mediators can be searched for in a variety of contexts: meson decays [10, 17–19], charged lepton decays [17, 20], vector/Higgs boson decays [12, 18–20], in neutrino scattering experiments [10, 19], and at collider experiments [21]. These experimental results have important implications for the cosmological relevance of neutrino self-interactions [15].

Astrophysical Searches.— Neutrinos emitted by Galactic and extragalactic astrophysical sources provide tests of BSM neutrino self-interactions that are complementary to laboratory-based searches. Their probing power stems primarily from their very long baselines, of tens of kpc for Galactic neutrinos and of Mpc–Gpc for extragalactic neutrinos. While propagating across these vast distances, astrophysical neutrinos may have a significant chance of scattering off the background of low-energy relic neutrinos, even if the neutrino-neutrino coupling strength is feeble. The scattering may affect the energy spectrum, flavor composition, and arrival times of the astrophysical neutrinos in characteristic and potentially detectable ways. Notably, if the neutrino self-interaction is resonant, it may introduce dips in the astrophysical neutrino energy spectrum around the resonance energy, and a pile-up of neutrinos at lower energies. Previous works have studied the effects of BSM self-interactions on neutrinos from core-collapse supernovae (SNe) and on high-energy extragalactic astrophysical neutrinos. Neutrinos from core-collapse supernovae, with energies of up to a few tens of MeV, are sensitive to neutrino self-interactions via mediators with keV-scale masses, if they occur during propagation [22–25], to MeV-scale masses, if they occur in the SN core and affect the explosion mechanism [25] and flavor conversions in the core [24]. High-energy extragalactic neutrinos, with energies of TeV–PeV, are sensitive to MeV-scale mediator masses [26–33]. In either case, the effects of BSM self-interactions may be detectable in the flux of neutrinos from a single astrophysical source, or in the diffuse flux from a population of sources. Studying the effect of BSM self-interactions on astrophysical neutrinos today is timely, in preparation for the imminent detection of the next Galactic core-collapse SN, the discovery of the diffuse supernova neutrino background, the detection of more TeV–PeV neutrinos, and the discovery of EeV cosmogenic neutrinos in existing and envisioned neutrino telescopes.

Bounds from Cosmology.— The cosmological results of Refs. [14, 34] and Ref. [35] can be used to constrain BSM neutrino self-interactions [36]. These interactions lead to shifts in the position and amplitude of the CMB peaks that are constrained by data to be close to the standard cosmological predictions (neglecting the H_0 tension described above). Additionally, neutrino interactions with dark matter can leave an imprint on the CMB and large scale structure, and therefore can be likewise constrained using cosmological data [37–45]. Neutrino self-interactions can also have large impacts on the early universe around the time of Big-Bang nucleosynthesis, so precision measurements of the light element abundances can serve as powerful probes on these models [46].

Given the span of regimes in which self-interacting neutrinos may have an impact, and the fast development of research in this field, we feel that a comprehensive, coherent white paper will draw focus from the broader neutrino physics community onto this topic. Additionally, such a white paper will act as a consistent resource of this research to date, allowing interested parties to begin their own studies on the topic.

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