Snowmass2021 - Letter of Interest

Astrophysical neutrinos and dark matter experiments

NF Topical Groups: (check all that apply ☐/■)

☐ (NF1) Neutrino oscillations
☐ (NF2) Sterile neutrinos
■ (NF3) Beyond the Standard Model
■ (NF4) Neutrinos from natural sources
☐ (NF5) Neutrino properties
☐ (NF6) Neutrino cross sections
☐ (NF7) Applications
☐ (NF8) Theory of neutrino physics
☐ (NF9) Artificial neutrino sources
☐ (NF10) Neutrino detectors
■ (Other) Cosmic Frontier 01: Dark Matter: Particle Like
■ (Other) Cosmic Frontier 07: Cosmic Probes of Fundamental Physics
■ (Other) Theory Frontier 09: Astro-particle physics and cosmology
■ (Other) Theory Frontier 11: Theory of Neutrino Physics

Contact Information:
Shunsaku Horiuchi (Virginia Tech) [horiuchi@vt.edu]
Louis Strigari (Texas AM University) [strigari@tamu.edu]

Authors: Julien Billard (IPNL/CNRS), James Dent (Sam Houston State University), Bhaskar Dutta (Texas AM University), Shunsaku Horiuchi (Virginia Tech), Rafael F. Lang (Purdue University), Jayden Newstead (University of Melbourne), Louis Strigari (Texas AM University), Volodymyr Takhistov (University of California, Los Angeles)

Abstract: (maximum 200 words) As experimental searches for dark matter improve in sensitivity, new challenges will arise in attempts to extract a possible signal. For direct dark matter searches in the coming decade, an important challenge and opportunity will be backgrounds caused by astrophysical neutrinos. Arriving from the Sun, atmosphere, and supernovae, these neutrinos coherently scatter on instrumented nuclei and mimic a signal from dark matter over a broad range of dark matter masses. Efforts toward understanding their spectra are necessary to properly identify their signatures in future dark matter detectors and deliver improved sensitivity to dark matter. In this LOI, we summarize the present status of relevant sources of neutrinos and describe areas where progress is needed. Additionally, we highlight promising theoretical and experimental developments which will strengthen the reach of future dark matter searches.

Astrophysical neutrinos at dark matter experiments:

To deliver improved sensitivity to dark matter, future generations of direct dark matter experiments will necessitate an understanding of new backgrounds and associated new techniques for their reduction[1]. For experiments to be deployed in the coming decades, a major new source of background (and, conversely opportunities) will arise from astrophysical neutrinos.

Direct detection experiments have delivered remarkable progress in sensitivity by both increasing detector volume and operating in the limit of extremely low backgrounds. Future direct dark matter detectors will reach the sensitivity to detect MeV–GeV neutrinos from the Sun, supernovae, and Earth's atmosphere. These neutrinos mimic a dark matter signal by coherent elastic neutrino-nucleus scattering on instrumented nuclei[2;3]. Collectively, they are often called the "neutrino floor" although it is more permeable than a real floor. Already, present direct dark matter detectors such as XENON1T[4] are on the verge of reaching the neutrino floor, with upcoming experiments such as LZ[5] and XENONnT[6] being expected to make first measurements. Furthermore, the height of the neutrino floor scales directly with the size of the systematic uncertainty which is mostly coming from neutrino fluxes. Finally, the signals of astrophysical neutrinos and their signatures will open a broader probe of DM and BSM physics[7]. All of these create both a need to better model these backgrounds, as well as opportunities to probe novel regions of theory parameter space.

While the relevant astrophysical neutrinos are historically well-known, there remains significant uncertainties in regions that overlap with dark matter signals. The primary questions therefore are: *what are the future progress in characterizing astrophysical neutrino fluxes, and given these improvements what can we learn about the nature of the dark matter and BSM physics using signals below* the present bounds from direct detection experiments? Below, we summarize these and highlight areas for progress.

Solar neutrinos:

Solar neutrinos dominate the neutrino floor over dark matter masses of 10 GeV and below. Over the last decades, there have been enormous theoretical and observational progress in understanding the Sun[8]. The Standard Solar Model has been established as the fundamental theoretical tool to model the solar interior, and is able to predict various components of the solar neutrino flux, much of which have been confirmed by direct measurements by neutrino detectors. However, the detection of the CNO neutrino flux by Borexino in 2020[9] highlights continued progress in major ways. Direct dark matter detectors will also detect solar neutrinos through standard neutrino-electron scattering. On the theory side, the Standard Solar Model has in the recent decade not been able to accommodate new measurements of photospheric heavy element abundances in the Sun's atmosphere[10] and helioseismology measurements, creating a new solar "metallicity" problem[11–14]. The theoretical uncertainty of solar neutrinos predicted by the Standard Solar Model varies depending on the channel. For example, the dominant component arising directly from the pp-channel, $pp \rightarrow^2 \mathrm{H}e^+\nu_e$, is predicted with percent uncertainty, but more uncertain are the neutrino fluxes from heavier isotopes, e.g., the 7Be, 8B, and CNO channels, with of order tens of percent uncertainty; and the solar metallicity problem exacerbates the uncertainty for the nuclei neutrino fluxes[15;16]. Theoretical progress in modeling Solar neutrinos, and connections with novel data sets to test the different solutions to the solar metallicity problem, will be crucial for understanding direct dark matter search backgrounds at low dark matter masses.

Atmospheric neutrinos:

Atmospheric neutrinos are produced through cosmic-ray collisions in the Earth's atmosphere. While this has been extremely well studied and measured, the most relevant neutrinos for dark matter detectors are those below $\sim$ 100 MeV (which produce nuclear recoils in the energy range of tens of keV). This low-energy regime has unique systematic uncertainties which complicate modeling[17;18]. For example, $\sim$ 100 MeV atmospheric neutrinos are produced by primary cosmic rays of 1–100 GeV energies, which are strongly modulated by Solar activity. In addition, cosmic rays at these energies are strongly influenced by the Earth's geomagnetic field. These introduce non-trivial temporal and spatial dependence in the atmospheric neutrino flux. Extensions of existing atmospheric neutrino models to reach sub 100 MeV energies is ongoing[19], and measurements exist by low-background searches by, e.g., Super-Kamiokande[20]. Further studies would be needed for dark matter sensitivities over a large range of dark matter mass above several tens of GeV.

Supernova neutrinos:

Massive stars end their evolution in a catastrophic core collapse, emitting a burst of $\sim 10^{58}$ neutrinos of all flavors at energies of order 10 MeV, and in many cases causing a luminous optical supernova explosion. For dark matter searches, a neutrino burst from a single supernova can be easily removed by its temporal transient nature. However, the diffuse flux of neutrinos from all stellar collapses occurring in the Universe (the Diffuse Supernova Neutrino Background, or DSNB[21;22]) cannot. Of the three major astrophysical sources contributing to the neutrino floor, supernova neutrinos remain the most data starved. Although the basic picture of a stellar core collapse was confirmed by the detection of ~ 20 neutrinos from SN1987A, there remains significant uncertainties in our understanding of supernovae and predictions of the DSNB.

Studies of the supernova neutrino emission require a numerical treatment to combine the effects of gravity, nuclear, particle, and astrophysical processes. In the past decade, simulations have made a significant transformation: whereas most early simulations could not successfully recreate a supernova explosion, recent simulations employing multi-spatial dimensions are routinely able to achieve explosions. Nevertheless, the neutrino emission still has significant uncertainties arising from, e.g., the equation of state of hot dense matter, hydrodynamic instabilities and turbulence, stellar evolution and progenitor dependence, stellar properties (such as rotation, magnetic fields), and neutrino properties in particular oscillations in dense matter, just to name a few. These are the focus of ongoing simulation efforts[23;24]. A supernova in the Milky Way galaxy will also yield a treasure trove of data to test our understanding of supernovae and neutrinos[25]. Direct dark matter detectors will contribute broadly, from supernova neutrino detection[26] to pre-supernova detection[27]. In particular, they will play a uniquely important role in probing the flavor content of supernova neutrinos, since they have a clean flavor-blind detection channel which will complement the mostly ν_e and anti-ν_e channels at neutrino experiments[26].

The DSNB is the convolution of the occurrence rate of stellar collapses as a function of distance and the neutrino emission from each stellar collapse. The DSNB therefore has sources of uncertainty in addition to those contributing to supernova neutrino emission, e.g., related to the true rate of supernova occurrences[28] and the fraction of supernovae forming black holes[29]. At present, the theoretical uncertainty on the DSNB flux is approximately at the level of $\sim 40\%$, but the next decade is expected to lead to big improvements. Large-field transient surveys such as ASAS-SN and ZTF are ongoing, and new surveys such as LSST are poised to discover more than an order of magnitude more supernovae, providing a more complete survey of supernovae[30]. Searches dedicated to stellar collapse directly to black holes[31] are also ongoing[32]. Insights obtained from simulations as well as insights from a potential nearby supernova neutrino signal will also clearly improve the DSNB predictions. And perhaps most importantly, the Super-Kamiokande detector will complete its gadolinium upgrade[33] to mitigate major backgrounds for DSNB search. This will transform DSNB search from the current background-limited one[20] to a future signal-limited one.

BSM physics:

Improved understanding of astrophysical neutrinos mentioned above also open avenues to test a variety of BSM physics. Already, reports of excess at XENON1T in 2020 may have connections to neutrino magnetic moment[34]. Studies of BSM physics impacts on the generation of neutrinos (i.e., source physics), on the survival/oscillation of neutrinos (i.e., propagation physics), and appearance of neutrinos (i.e., detection), have been performed. Due to flavor transformations as neutrinos emerge from the solar interior, a future detection of the 8B component of the solar neutrino flux will provide a new probe of non-standard neutrino interactions[35;36]. Similarly, non-standard interactions may alter the predicted flux of atmospheric neutrinos, which may be detected by future multi-ton scale xenon or argon detectors[37;38].

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