Snowmass2021 - Letter of Interest

[Supernova Burst and Other Low-Energy Neutrino Physics in DUNE]

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
■ (TF11) Theory of neutrino physics
□ (NF9) Artificial neutrino sources
■ (NF10) Neutrino detectors
□ (Other) Cosmic Frontier, Instrumentation Frontier, Computational Frontier

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Collaboration (optional): DUNE

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Abstract: Official DUNE LOI describing the low-energy neutrino physics sensitivity of the experiment. DUNE will have good sensitivity to a supernova burst within the Milky Way, and possibly beyond, allowing study of a wide range of astrophysics and particle physics topics. DUNE will participate in the worldwide multi-messenger astronomy effort, with unique sensitivity to the electron-neutrino component of the supernova burst. The low-energy capabilities of DUNE are not limited to supernova bursts; initial studies suggest significant sensitivity to solar neutrinos and possibly other low-energy sources of neutrinos.

The Deep Underground Neutrino Experiment (DUNE) is a next-generation, long-baseline neutrino oscillation experiment. The massive liquid argon time-projection chamber (LArTPC) far detector (FD) located at the 4850 ft level of Sanford Underground Research Facility (SURF), in Lead, South Dakota, USA, facilitates sensitivity to neutrinos with energies in the range up to about 100 MeV, such as those produced by the Sun and in core-collapse supernovae. Charged-current interactions of neutrinos from around 5 MeV to several tens of MeV create short electron tracks in liquid argon, potentially accompanied by gamma-ray and other secondary particle signatures. This Letter of Interest summarizes the conclusions presented in [1, 2] and recent studies. The DUNE collaboration anticipates that additional LOIs relevant to sensitivity to low-energy neutrinos in a DUNE-like experiment will be submitted by individuals.

Core-collapse supernovae within our own Galaxy are expected to occur once every few decades; there is a reasonable chance for one to occur during the several-decade expected lifetime of the DUNE experiment. Because these events are so rare, it is critical that experiments be prepared to capture as much data as possible when one does occur. This places stringent requirements on detector livetime, DAQ and triggering systems, and reconstruction capabilities for low-energy events. DUNE's expected energy threshold is a few MeV of deposited energy and the expected energy resolution is around 10-20% for energies in the few tens of MeV range. While the expected event rate varies significantly among models of supernova bursts, the 40-kt (fiducial) DUNE detector would be expected to observe approximately 3000 neutrinos from a supernova burst at 10 kpc. Because DUNE's far detector is a liquid-argon TPC, the dominant interaction is charged-current absorption of ν_e on ^{40}Ar: $\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$. This sensitivity to electron neutrinos, as opposed to antineutrinos, is unique to argon detectors. Subdominant ν_e charged-current and neutrino-electron elastic scattering will also contribute. Another mode of interest is neutral-current scattering on argon nuclei, which may be identified by a cascade of de-excitation gammas. DUNE will participate in worldwide multi-messenger astronomy efforts, such as SNEWS [3], and, will be able to provide pointing information to localize an observed supernova [1, 4].

In a core-collapse supernova, the neutrino signal starts with a short, sharp "neutronization" burst primarily composed of ν_e. This is followed by an "accretion" phase lasting several hundred milliseconds, and then a "cooling" phase which lasts about 10 seconds and represents the bulk of the signal, roughly equally divided among all flavors of neutrinos and antineutrinos. The flavor content and spectra of neutrinos change throughout these phases, so the supernova's evolution can be mapped out using the neutrino signal. Information about the progenitor, the collapse, the explosion, and the remnant, as well as information about neutrino properties, are contained in this signal. The flux spectrum may be parameterized by the "pinched-thermal" model. DUNE will have sensitivity to determining the parameters describing the ν_e spectrum; see Fig. 2. Other astrophysical observables include: the formation of a black hole, which would cause a sharp signal cutoff (e.g., [5–7]); shock wave effects (e.g., [8]), which would cause a time-dependent change in flavor and spectral composition as the shock wave propagates; the standing accretion shock instability (SASI) [9, 10], a "sloshing" mode predicted by three-dimensional neutrino-hydrodynamics simulations of supernova cores which would give an oscillatory flavor-dependent modulation of the flux; and turbulence effects [11, 12], which would also cause flavor-dependent spectral modification as a function of time.

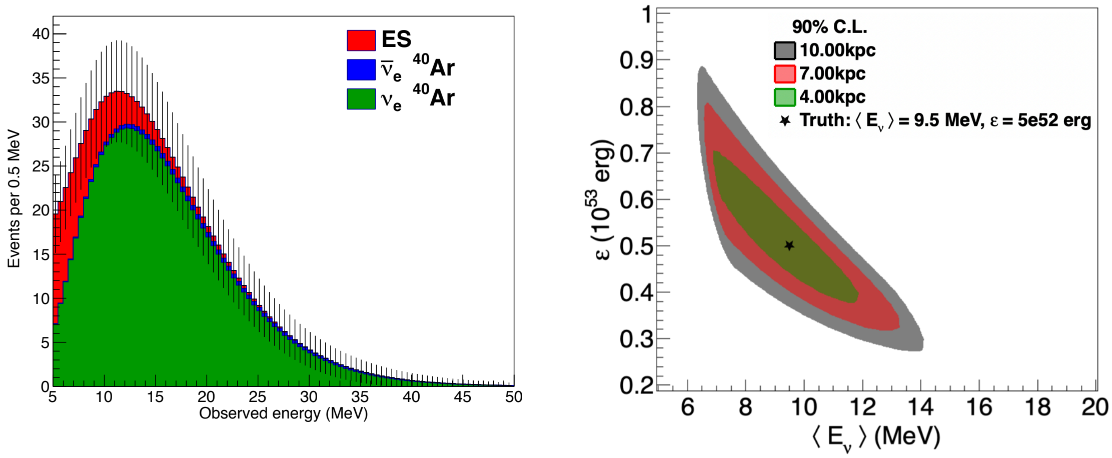

Figure 2: Left: Expected measured spectrum in DUNE as a function of observed energy, after detector response smearing and integrated over time, for the model in [13]. Event rates are computed using SNOwGLoBES [14] with a transfer matrix based on full DUNE simulation and reconstruction. Right: Sensitivity regions in $(\langle E_\nu \rangle, \varepsilon)$ space (profiled over pinching parameter α) for the ν_e spectrum for three different supernova distances. SNOwGLoBES assumes a transfer matrix made using MARLEY [15] with a 20% Gaussian resolution on detected energy, and a step efficiency function with a 5 MeV detected energy threshold.

Study of the energy balance of a supernova burst can provide constraints on new physics scenarios, the existence of which would alter the energy transport process within the explosion. The complexity of the neutrino flavor transformation probabilities is greater in a supernova burst because of the kinematics of the explosion itself and the possibility for neutrino-neutrino scattering and collective modes of oscillation. These effects will imprint on the neutrino signal and can be used to study these phenomena experimentally. The true neutrino mass ordering has a strong impact on the expected signal [16], particularly in early times including the neutronization burst. Knowledge of the mass ordering from other experiments may be used to better extract other particle and astrophysical knowledge from the observed supernova burst signal.

Neutrinos and antineutrinos from other astrophysical sources, such as solar [17] and diffuse background supernova neutrinos [18], are also potentially detectable. While detection of these sources will be challenging, particularly because of the presence of radioactive background in the detector, initial studies suggest potential for DUNE to select a sample of solar neutrinos that would allow a significant improvement in the measurement of Δm^2_{21} as well as observations of the the *hep* and ^{8}B solar neutrino flux. Development of reconstruction, calibration, and triggering/DAQ infrastructure will play an important role in enabling a broader physics program at low energies.

DUNE will have good sensitivity to a supernova burst within the Milky Way, and possibly beyond, allowing study of a wide range of astrophysics and particle physics topics. DUNE will participate in the worldwide multi-messenger astronomy effort, with unique sensitivity to the electron-neutrino component of the supernova burst.

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