

# Supernova Neutrinos at the DUNE Experiment

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**Abstract.** The Deep Underground Neutrino Experiment (DUNE) experiment, a 40-kton underground liquid argon time-projection-chamber detector, will have unique sensitivity to the electron flavor component of a core-collapse supernova neutrino burst. We present the expected capabilities of DUNE for measurements of neutrinos in the few-tens-of-MeV range relevant for supernova detection and its corresponding sensitivity to both neutrino physics and supernova astrophysics. Recent progress and some outstanding issues are highlighted.

## 1. Introduction

Core-collapse supernovae (SNe) are massive (birth mass  $> 8M_{\odot}$ ) stars that gravitationally collapse to form either a neutron star or black hole [1, 2]. After the initial stellar collapse is halted by neutron degeneracy pressure, the outer layers of the star rebound off the core and produce an outgoing hydrodynamic shock [3, 2, 4]. At this time electron capture on disassociated nuclei produces a short ( $\sim 10$  ms) burst dominated by electron neutrinos ( $\nu_e$ ) (the *neutronization* or *breakout* burst) [2, 4]. The effect is to sap and ultimately stall the shock at around 200 km from the proto-neutron star (the remnant of the stellar core). In the subsequent *accretion* phase (lasting  $\sim 100$  ms) material continues to fall onto the star, where it is reheated and emits neutrinos of all flavors. At some point, the shock may reignite, leading to a supernova (SN) explosion and a third phase, some 10 seconds long [2, 3], in which the protoneutron star (the remnant of the stellar core that will become a neutron star or black hole) cools through further neutrino emission. In some cases re-ignition of the shock does not occur; in this case once sufficient material accretes onto the core it evolves into a black hole. The neutrino flux in the latter cases would be characterized by a hardening spectrum and a sharp cutoff [2].

Neutrinos provide a uniquely informative window into the early development of the supernova, since they begin to escape long before the system becomes transparent to electromagnetic radiation. Moreover, over 99% of the gravitational binding energy of the star is ultimately carried away by neutrinos produced in the stellar core, an energy budget orders of magnitude greater than that of the visible explosion [2, 4]. Finally, as neutrinos stream away from the core their flavor oscillation behavior is dominated first by coherent neutrino-neutrino scattering (“collective oscillations”) and then by interactions with the stellar medium (MSW effect), with vacuum oscillations taking over once they leave the supernova environment and propagate to Earth [5, 6, 7, 8]. These oscillations in the presence of high neutrino and matter densities imprint non-thermal features on the flavor-separated supernova neutrino energy spectra, some of which are dependent on the neutrino mass hierarchy [7]. For instance collective oscillations can permute the original  $\nu_e$  and  $\nu_x$  spectra above some critical energy (swaps), leading to  $\nu_e$  fluxes



peaked at higher energies and/or discontinuities in the  $\nu_e$  spectrum at a swap boundary (splits). Shock instabilities and turbulence effects can also produce a flavor-dependent modulation of the neutrino flux [2, 9, 10, 8]. A high-statistics measurement of flavor-separated spectra (both as a function of time and integrated over the entire supernova) could allow us to access and disentangle this intriguingly coupled astrophysics and particle physics.

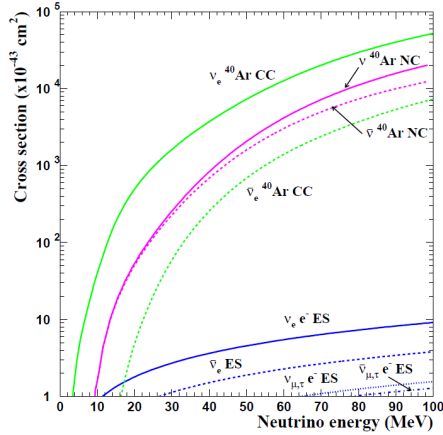
## 2. The DUNE Experiment

The Deep Underground Neutrino Experiment (DUNE) is a future dual-site, dual-detector long-baseline neutrino experiment that will make use of the Long Baseline Neutrino Facility under construction at Fermilab [11, 12]. The first, or “near” detector will be sited at Fermilab, close to the origin of the neutrino beam. The second, or “far” detector will be placed deep underground ( $\sim 4850$  ft) at the Sanford Underground Research Facility, 1300 km away from Fermilab. The Far Detector will consist of four liquid argon (LAr) time projection chamber (TPC) modules, each comprising 10-ktons of fiducial mass [11, 12]. The TPCs, which detect ionization charge from the neutrino interaction, provide good energy resolution, three-dimensional track reconstruction, particle identification derived from the energy loss along the track, and excellent spatial resolution. However the TPCs alone cannot pinpoint the location of an interaction within the charge drift region [11, 12, 9]. This limitation can be overcome using a complementary photodetection system designed to capture the 128 nm scintillation light produced by charged-particle interactions in LAr. Roughly 25% of the produced light is emitted early, with a time constant of 6 ns (prompt light), with the remainder arriving within 1.6  $\mu$ s [9]. Detection of the prompt light can be used to obtain microsecond or better timing accuracy (resulting in a few mm position resolution along the drift direction) as well as improved energy resolution.

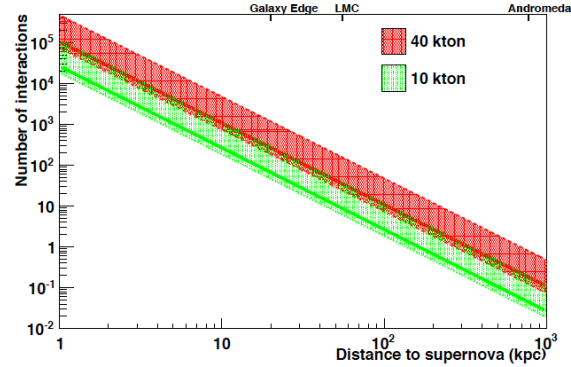
In addition to the single-phase reference design, in which all processes from charge generation to charge collection take place in liquid argon and the readout electronics are at cryogenic temperatures, a dual-phase design—where the signal is transferred to gaseous Ar and the readout electronics are warm—is also under consideration [12]. The precise design of the photodetection system varies between the single and dual-phase systems. Two large-scale prototypes, one single-phase and one dual-phase, will be deployed at CERN in 2018 and a 20-kton version of the far detector is expected to be ready for beam in 2026.

Within the broad range of physics covered by DUNE/LBNF program, the program has identified three main priorities: precision measurements of the parameters governing  $\nu_\mu \rightarrow \nu_e$  and  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  oscillations (including neutrino mass ordering and the CP-violating phase), nucleon decay searches, and the detection and measurement of the electronic neutrino flux from any Galactic core-collapse supernova occurring within the lifetime of the DUNE experiment [9]. The latter two priorities do not require a neutrino beam. Instead, they rely on the capabilities of the Far Detector and take advantage of any gap between the commissioning of the far detector and the delivery of the first neutrino beam.

There are four detection channels in LAr that are relevant for low energy (few MeV to few tens of MeV) supernova neutrinos. Two are flavor-specific charged-current interactions with respective thresholds of 1.5 and 7.48 MeV:  $\nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^*$  and  $\bar{\nu}_e + {}^{40}\text{Ar} \rightarrow e^+ + {}^{40}\text{Cl}^*$ . Then there are two flavor-agnostic channels: a neutral-current interaction with a 1.46 MeV threshold ( $\nu + {}^{40}\text{Ar} \rightarrow \nu + {}^{40}\text{Ar}^*$ ) and elastic scattering off of atomic electrons ( $\nu + e^- \rightarrow \nu + e^-$ ). Fig 1 shows the cross sections of these processes as a function of the neutrino energy [5]. Due to a combination of cross-section and reconstruction efficiency the charged-current  $\nu_e$  channel is the workhorse channel for supernova neutrino detection in DUNE, and gives DUNE a unique sensitivity to the  $\nu_e$  component of a supernova neutrino burst. The rare elastic scattering events are useful for localizing the burst origin [13]. Elastic scattering events would be distinguished by the absence of photons arising from the de-excitation of K, Cl, or Ar, and it may also be possible to use these de-excitation photons to distinguish the other three detection channels.



**Figure 1.** Neutrino cross-sections relevant to supernova detection with a LAr TPC. From [5].



**Figure 2.** Estimated number of total supernova neutrino interactions in DUNE vs. distance to the supernova, for 40-kton (red band) and 10-kton (green band). The extent of the bands is determined using a wide range of supernova models based on the Garching parameterization. Solid lines represented the integrated flux from the model described in [3]. The vertical bars delimit the range of distances where a supernova is most likely to occur. Adapted from [9].

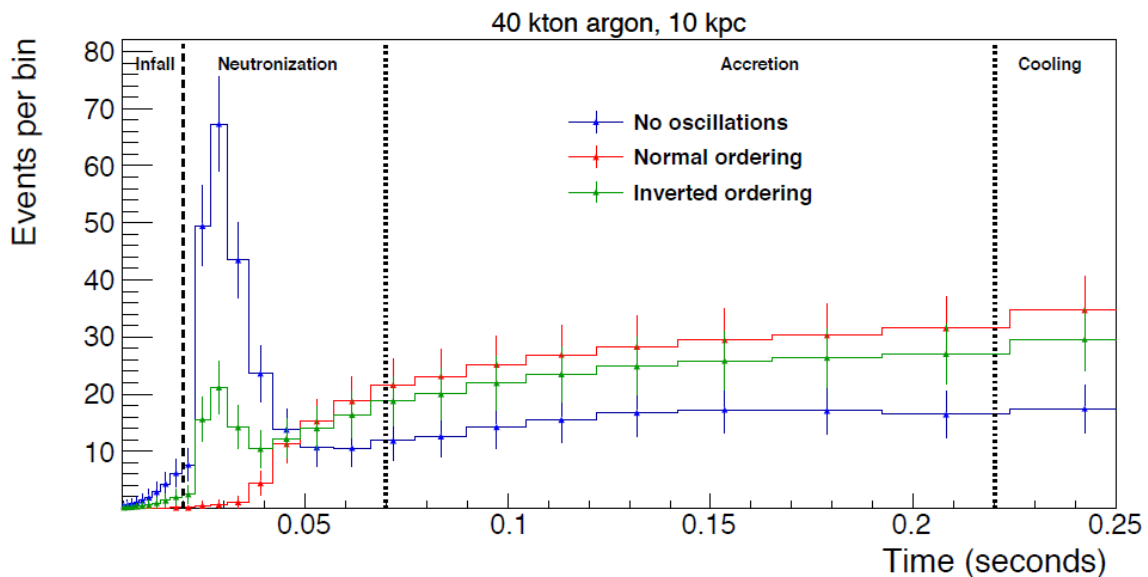
### 3. Neutrino astrophysics with DUNE

We only expect a few (1-3) supernovae per century within our Galaxy (i.e within  $\sim 10 - 15$  kpc of Earth) [9]. Stellar distributions and star formation rates tell us that the probability of a supernova is roughly constant and maximal between  $\sim 5 - 15$  kpc [14]. Figure 2 shows two estimates of the total supernova neutrino interactions in both a 10-kton far detector module and the full 40-kton Far Detector. The observed supernova neutrino flux scales with both the detector mass and the inverse square of the supernova distance [9]. The precise flux is notably model-dependent.

Figure 3 shows a projection of of the total (all-flavor,  $\nu_e$ -dominated) supernova neutrino flux vs time that would be measured by DUNE during the first  $\sim 25$  ms after core bounce, assuming a supernova at a distance of 10 kpc. The theoretical model used is from the Garching group [9]. Three scenarios are shown, a reference model in which neutrino oscillations are not considered (blue) and two models for which neutrino oscillations, with matter effects, are included. The later two models assume normal neutrino mass hierarchy (red) and inverted mass hierarchy (green) respectively. For a nearby supernova, a LAr TPC such as DUNE not only provides unique information about the early development of the supernova, but is strongly sensitive to the different neutrino mixing scenarios and mass hierarchies. However, it should be emphasized that the value of this measurement is not limited only to the neutronization burst period. Neutrino oscillation effects and information about the supernova dynamics, are imprinted in the light curve and energy spectra throughout the accretion and cooling phases as well.

#### 3.1. Technical requirements and challenges

In order to carry out a successful detection and study of a Galactic supernova neutrino burst, DUNE must measure neutrinos in the energy range between 5 and 100 MeV [9]. The Far



**Figure 3.** Simulated DUNE all-flavor ( $\nu_e$ -dominated) supernova neutrino “light curve” during the first  $\sim 25$  ms after core bounce, a supernova at a distance of 10 kpc. The theoretical model used is from the Garching group [15, 3]. Curves are shown for the cases of no oscillations (blue) and neutrino oscillations for normal (red) and inverted (green) neutrino mass hierarchies.

Detector must be able to recognize (trigger) and react appropriately to a supernova neutrino burst. Signal-to-noise must also be sufficiently high for supernovae in the nominal distance range of 5-15 kpc that triggering with a reasonable fake rate is possible and both the neutrino light curve and spectrum can be well-measured. This requires situating the Far Detector at sufficient depth to attenuate cosmic-ray-induced backgrounds and finding ways to reject backgrounds from radiological events that fake low-energy neutrino interactions[9]. The decay of the  $^{39}\text{Ar}$  component of natural Argon, for instance, mimics the light from low-energy neutrino interactions such 10 MeV SN neutrinos. In this case rejection criteria based on the distribution of hits within the detector shows some promise in rejecting  $^{39}\text{Ar}$  interactions while maintaining signal efficiency. Any tuning of the signal-to-noise must take into account uncertainties in the predictions for both the radiological background and signal rates. In addition to theoretical model uncertainties that affect supernova neutrino rate predictions, accurate modeling of charged-current interactions in liquid argon presents a challenge. Many cross-sections are poorly known, which means that theoretical calculations of the cross-sections must be relied upon. In other cases where the cross-sections have been measured, there are known mismatches between the theoretical prediction and the experimental result [16, 17].

Finally, as much of the unusual neutrino flavor physics of the early supernova is encoded in the time-resolved and time-integrated energy spectra, DUNE’s energy resolution at these energies must allow us to resolve spectral splits and other features. The minimum energy resolution required has been identified as 10% [9]. Loss of resolution, bias, and distortion of the spectrum due to missing energy is therefore a critical concern. Factors affecting the resolution and bias include final-state neutrons, which can wander far from the original interaction vertex, as well as failure to detect de-excitation photons.

#### 4. Summary

The supernova neutrino burst program remains a key science goal (and a design driver) for DUNE. The time, flavor, and energy structure of the neutrino flux from a nearby Galactic supernova provides insight into both the astrophysical dynamics and neutrino physics. Among other features, a Galactic supernova burst is a unique laboratory for testing models of neutrino flavor transformations in a region of high neutrino and matter density and can also be used to make an independent measurement of the neutrino mass hierarchy. The electron neutrino component of the supernova burst carries critical information, particularly about the earliest period of the burst. As a LAr TPC the DUNE Far Detector offers unique access to the  $\nu_e$  component. However, triggering on and reconstructing the low-energy supernova neutrino interactions down to 5 MeV, with adequate energy resolution, also poses unique technical challenges that are still under study.

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