Supernova Neutrino Detection at a Future Underground Facility

Kate Scholberg*
Massachusetts Institute of Technology

A core collapse supernova in our Galaxy would produce an enormous burst of neutrinos visible in detectors around the world. Here I examine what can be learned from the neutrino signal, and consider the capabilities of the next generation of detectors which may be sited at a national underground facility.

1. The Neutrino Signal

When the core of a massive star at the end of its life collapses, less than 1% of the gravitational binding energy of the neutron star is released in the form of optically visible radiation and kinetic energy of the expanding remnant. The remainder of the binding energy is radiated in neutrinos, of which ~1% will be electron neutrinos from an initial "breakout" burst and the remaining 99% will be neutrinos from the later cooling reactions, roughly equally distributed among flavors. Average neutrino energies are expected to be about 12 MeV for ν_e, 15 MeV for $\bar{\nu}_e$, and 18 MeV for all other flavors. The neutrinos are emitted over a total timescale of tens of seconds, with about half emitted during the first 1–2 seconds [1].

2. Physics Motivations

Neutrino Physics: A core collapse event provides a powerful and distant natural source of neutrinos, allowing the study of neutrino properties. For instance, absolute neutrino mass can be measured, exploiting the time of flight delays over the long distance from the supernova: one can look for an energy-dependent time spread in the observed events, or a flavor-dependent delay. For instance, the next supernova may well give us mass limits for ν_μ and ν_τ which are orders of magnitude better than laboratory limits. A supernova that continues its collapse to a black hole could be particularly interesting: in this case, the sharp (~ sub-millisecond) cutoff in neutrino luminosity, which should be nearly simultaneous for all flavors, provides a clean $t = 0$ for a time of flight delay measurement; such a signal could yield $\bar{\nu}_e$ mass limits in the few eV range, rivaling laboratory ones. In addition, for proposed detectors such as OMNIS, the relative NC and $\bar{\nu}_e$ time delay could give sensitivity to absolute $\nu_{\mu,\tau}$ masses as low as 6 eV (see, for example,[3] and references therein). In addition, neutrino oscillations with matter effects can be studied, as the ν flavors may partially "swap spectra" under certain conditions in the proto-neutron star core. The effects of neutrino flavor transformation in the core of the star may manifest themselves as an anomalously hot ν_e spectrum; recent results from Super-Kamiokande and SNO favor this scenario. And more information can be extracted for a supernova signal: the neutrino data from SN1987A set limits on neutrino lifetime, charge, number of neutrino families, neutrino magnetic moment, axions, and even extra dimensions.

Core Collapse Physics: The time structure, energy spectrum and flavor composition of the neutrino burst would yield information on astrophysical stellar collapse processes, even for "silent" collapses, i.e. those occurring without strong electromagnetic fireworks or in regions of the Galaxy obscured by dust. Better understanding of core collapse physics will allow one to tighten assumptions which can lead to stronger interpretations of the data for neutrino physics.

Early Alert: Because neutrinos emerge from the collapsed star's envelope hours before the electromagnetic radiation, neutrino observation can provide an *early alert* that could allow as-

*schol@mit.edu

tronomers a chance to make unprecedented observations of the very early turn-on of the supernova light curve. Such observations are exceedingly rare for extra-galactic supernovae. The SNEWS (SuperNova Early Warning System) is designed to provide an early warning for current and future detectors [4].

3. Supernova Neutrino Detectors

What is needed for a supernova neutrino detector? Primarily, one needs a **very large active mass**. A back-of-the-envelope calculation yields a few hundred inverse beta decay $\bar{\nu}_e$ events per kton of target mass for materials such as water and hydrocarbons, so ~kton masses or greater are needed, and the larger, the better.

The time scale over which a gravitational collapse occurs is tens of seconds, and the highest rate occurs in the first second: therefore the neutrino signal rate for a galactic center collapse will be at least 10–100 Hz. An underground location where the cosmic ray background is greatly reduced is desirable, as is a low ambient radioactivity background. However these requirements tend to be less stringent than requirements for other experiments for e.g. solar neutrino or double beta decay detection, since signal/background is relatively high during the ν burst. Nearly all of the supernova signal is expected to be over 5 MeV, making radioactive background even less of a concern than depth.

Another critical ability for doing physics with the neutrino signal is **flavor sensitivity**. As noted above, measurement of the flavor and energy composition of the signal as a function of time will yield information on core collapse physics, neutrino mass and flavor transformations. Therefore, both charged current (CC) and neutral current (NC) sensitivity and the ability to tag interaction types is essential for the next generation of detectors. **Sensitivity to ν_e** is particularly desirable, to observe the signature of the core flavor transformation expected from currently favored mixing scenarios. Continuing in this theme, the ability to measure **relative and absolute timing** of the neutrino events is important. **Good energy resolution** and **low energy threshold**, preferably down to a few MeV, is also needed. Finally, the **ability to point** back to where the neutrinos come from is desirable. Detectors exploiting the elastic scattering reaction for neutrino detection, for which information about the direction of the incoming neutrino is retained by the scattered electron, have the best hope of reconstructing the neutrino source direction [2].

Another important question is: how often is a Galactic supernova likely to occur? Estimates vary widely, but are typically in the range of about one per 30 years. This is often enough to have a reasonable hope of observing one during the next five or ten years, but rare enough to mean that we must take special care not to miss anything, if one occurs. It also means that supernova neutrino detectors should be designed with long-term running in mind.

An overview of the current and near-future generation of supernova neutrino detectors is described in reference [5]. For the more distant future, a number of new detectors with supernova neutrino detection capabilities have been proposed, some of which could be sited at a new National Underground Laboratory facility. Some of these detectors are dedicated to the purpose of supernova neutrino detection; others have different primary physics goals but also have supernova neutrino capabilities, or could be adapted to have them. For all of these detectors, the signal/background will be high during a supernova burst. Depth issues may affect an individual detector's early alert capabilities; for instance muon-induced spallation events could compromise a lead-based detector's automated alert capability. Backgrounds do have a greater effect on early alert capabilities than on ultimate physics capabilities; see Fig. 1. However some of these backgrounds (such as spallation) do have characteristics which can distinguish them from a true supernova signal, and it should be possible to suppress them, in principle even for an automated alert. Therefore, greater depth, while desirable, is not a critical issue for siting supernova neutrino detectors.

Lead-based detectors are primarily sensitive to the high energy component of the supernova neutrino flux. Proposed detectors of this type include OMNIS and LAND. Lead is a particularly promising material, with both CC and NC sensitivity. The CC reaction $\nu_e +^{208}\mathrm{Pb} \rightarrow^{208}\mathrm{Bi}^* + \mathrm{e}^-$, can be observed via either one or two neutron emission channels of $^{208}Bi^*$. The NC reaction $\nu_\mathrm{x} +^{208}\mathrm{Pb} \rightarrow^{208}\mathrm{Pb}^* + \nu_\mathrm{x}$ is observable via 2n, 1n and γ emission channels. The relative rates of these processes is highly dependent to the ν_e energy. Lead in the form of lead perchlorate has unique capabilities. The water-based solution is a good n moderator, and Cl can capture neutrons

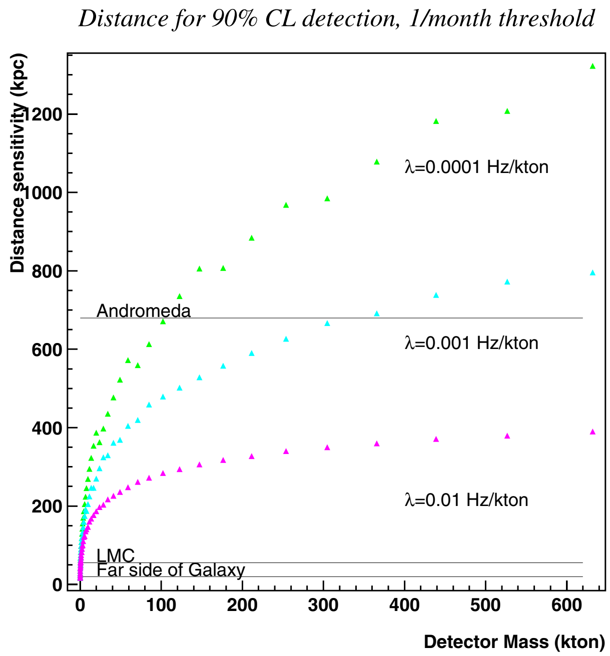

Figure 1: Early alert distance sensitivity for a supernova neutrino detector as a function of active mass, where the burst multiplicity threshold for detection is such that the accidental burst fluctuation rate is one per month.

to de-excite via an 8.6 MeV sum of γ-rays. Finally, since it is transparent, it can function as a Cherenkov radiator, and could conceivably provide a measurement of the ν_e energy spectrum. The current design of OMNIS comprises 2 kton of lead-slab detectors and 0.5 kton of lead perchlorate detectors which, for a supernova at the center of the Galaxy, should produce about 3500 events. OMNIS will also detect several hundred neutral current events, so will have good sensitivity to the ν_μs, and ν_τ components of the supernova ν flux.

A large **water Cherenkov detector** such as UNO will have excellent supernova neutrino detection capabilities. For the UNO baseline design, with 600 tons of water, $\sim$ 130,000 inverse beta decay $\bar{\nu}_e$ events are expected for a Galactic center collapse, as well as 4500 each of elastic scatters and NC ^{16}O events. A few dozen events are expected from Andromeda. Pointing to less than one degree will be possible from the thousands of elastic scattering events expected.

Liquid argon detectors have sensitivity to ν_e from supernovae via $\nu_e + {}^{40}\mathrm{Ar} \rightarrow {}^{40}\mathrm{K}^* + e^-$. A liquid argon drift chamber can detect the primary electron track as well as the secondary tracks from the ^{40}K* de-excitation, with approximately a 5 MeV threshold. Elastic scattering events are also visible. The proposed LANNDD (Liquid Argon Neutrino and Nucleon Decay Detector), with 70000 tons of liquid argon in a single chamber, could observe a signal of thousands of events from Galactic supernova. Liquid argon detectors may also have unprecedented sensitivity to relic supernova neutrinos, which have yet to be detected, because other detectors have irreducible backgrounds.

Other possibilities for future supernova neutrino detection at an underground laboratory include quasi-real-time radiochemical detectors, such as the proposed Homestake Hybrid Detector, which would have sensitivity to ν_e flavor, and possibly iron-based long baseline neutrino oscillation detectors, which could conceivably function as supernova ν-induced neutron detectors.

4. Summary

The next generation of supernova neutrino detectors which may be sited at an underground laboratory includes dedicated neutrino detectors, such as OMNIS, a lead-based detector with excellent NC sensitivity and ν_e spectral capabilities. Proposed detectors with other primary purposes, such as UNO, LANNDD, and the Homestake Hybrid Detector, would also be valuable supernova neutrino detectors. In particular UNO's signal would exceed 100,000 events for a Galactic center collapse.

References

[1] A. Burrows *et al.* Blah. *Phys. Rev. D*, 45:3361, 1992.
[2] J. Beacom and P. Vogel. Blah. *Phys. Rev. D*, 60:033007, 1999.
[3] J. Beacom *et al.* Blah. *Phys. Rev. D*, 64:073011, 2001.
[4] K. Scholberg. Blah. *Proceedings of the 3rd Amaldi Conference on Gravitational Waves*, 91, 1999.
[5] K. Scholberg. Blah. *Nucl.Phys.Proc.Suppl.*, 91:331, 2000.