Snowmass2021 - Letter of Interest

Deciphering explosion physics from the supernova neutrino signal

NF Topical Groups:

■ (NF1) Neutrino oscillations
■ (NF2) Sterile neutrinos
■ (NF3) Beyond the Standard Model
■ (NF4) Neutrinos from natural sources
■ (NF10) Neutrino detectors
■ (TF9) Astro-particle physics & cosmology
■ (TF11) Theory of neutrino physics
■ (CF7) Cosmic probes of fundamental physics

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Abstract: Core-collapse supernovae are some of the most spectacular phenomena in nature. They greatly influence the properties of the universe we live in, shaping the Galaxy and seeding it with heavy elements. Yet, their exact mechanism is not completely established and continues to fuel a lot of active research. With the advent of the large, next-generation underground neutrino detectors, the neutrino burst from the next galactic core-collapse supernova will allow us to observe the development of the explosion in real time, during the first crucial ten seconds. How to read this signal, relate it to the underlying physical processes, and how to best optimize the detector design, are a subject of much urgency. In this letter of interest, we briefly outline the relevant physics issues and relevant detector aspects. We argue that close collaboration between experimentalists and theorists is required for optimal progress.

The mechanism of core-collapse supernova explosions has been the focus of intense investigations for over six decades[1–6]. It is firmly established that the shock front, which initially forms inside the collapse core, stalls at the radius of several hundred kilometers. The puzzle is how, and under which conditions, this shock gets revived and overpowers the ram pressure of the infalling material.

In the neutrino-driven paradigm, this happens due to the energy deposited by the enormous flux of neutrinos streaming out of the collapsed core. As this deposition occurs just above the surface of the protoneutron star (PNS), in the so-called gain region[7], a complicated convective motion ensues behind the shock front. The full problem involves three-dimensional hydrodynamics and neutrino transport, giving rise to some of the most sophisticated and resource-intensive supercomputing calculations in the world[8–12]. Uncertainties in the nuclear equation of state, the role of the rotation and magnetic fields, and a possible role of new particle physics effects, all add to the complexity.

To test this picture, it is essential to obtain direct experimental information on the evolution of the density profile around the PNS during the crucial first several seconds after the onset of the explosion. Since the region of interest is shrouded by the stellar envelope, it cannot be directly observed in photons. The task thus falls on neutrinos (and also, possibly, on gravitational waves). In the era of large detectors under active development, such as DUNE and Hyper-Kamiokande, the task becomes to identify the relevant signatures in the neutrino signal and to establish a quantitative connection between them and the physical conditions inside the exploding star.

In fact, it has been known for two decades how such information might, in principle, be imprinted in the neutrino signal. The relevant effect comes from considering neutrino flavor oscillations in the envelope of the star. While the material there is transparent to neutrinos, its density- and flavor-dependent index of refraction can have a large impact on neutrino oscillations. The most familiar illustration of this phenomenon is the MSW effect[13;14], which is confirmed to operate for solar neutrinos. The transformation happens at densities such that the matter potential is comparable to the vacuum splitting between a pair of mass eigenstates (the so-called MSW resonance). The nature of the transformation is dictated by the rate with which the density changes in the resonant layer. Specifically, when the density scale height is much larger than the relevant neutrino oscillation length, the evolution is adiabatic. This is indeed what happens to solar neutrinos, owing to the smoothness of the solar density profile.

In a supernova, these transformations occur at densities of order 10^3 g/cm^3 and, again, at 10^1 g/cm^3 [15]. At the onset of the explosion of a typical iron-core-collapse supernova, such densities lie well outside of the central engine, in the stellar envelope. Until the shock front reaches these layers, the matter profile there remains that of the progenitor star. The density scale height at the relevant radius is much larger than the neutrino oscillation length and the resulting flavor transformation has the adiabatic nature, just like in the Sun.

A few seconds into the explosion, however, the situation changes in a nontrivial way. First of all, when the expanding front shock rolls through the layer with densities $\sim 10^3$ g/cm^3, the profile there becomes effectively discontinuous. Just as important, however, is the density distribution behind the moving shock front[16]. There, a low-density region is formed, known as the hot bubble[17;18]. The bubble is created by a high-entropy material that originates from the protoneutron star surface. Density features in this region, such as shocks and turbulence, can have a great impact on the evolution of neutrino flavor[18]. Indeed, if the densities in the hot bubble are lower than at the front shock, it is the hot bubble that will impact the flavor evolution first.

The existence of the neutrino-driven outflow at the late stages of the explosion is investigated in the seminal 1986 work by Duncan, Shapiro and Wasserman[19] and has been elaborated on in[20–23]. It has been studied in the context of the r-process nucleosynthesis by a number of authors since[20–24].

So far, all this is well known. Some of the key quantitative questions, however, remain open to this day. Addressing them will allow one to relate specific physical conditions in the explosion to the relevant neutrino signatures, remain open.

- Neutrino oscillations in the supernova are significantly more complex than was understood back in 2004. In particular, we now know that collective flavor evolution can significantly impact the neutrino flavor survival probabilities. While the full problem is still being investigated, one would like to include their effects, at least in the baseline scenario of spherically symmetric, multi-angle calculations.
- In the existing literature, parts of the density profile are described by a set of independent, adjustable parameters[21;22]. This, in particular, includes the location and properties of the front shock as well as the so-called termination shock at the end of the neutrino-driven wind, which is seen in some numerical simulations. Prelim-

inary considerations indicate that it is the reverse shock that can leave the most prominent neutrino signature; however, a systematic treatment of the problem is presently lacking.

- The role of the turbulent density fluctuations in the flavor evolution of supernova neutrinos. While a general theoretical description of the effect of Kolmogorov turbulence exists[25], an analysis of the specific physical conditions in the hot bubble is still lacking.
- A detailed simulation of the detection effects, including radiological backgrounds, cross section uncertainties, and the effects of detector performance. Even though the charge and light collection systems in current designs of underground, massive liquid-argon time-projection chambers (LArTPCs)[26;27] are primarily targeted to GeV signatures of neutrino oscillation measurements, they are also capable of detecting supernova neutrinos. In fact, the known challenges for detecting and reconstructing MeV signatures which supernova neutrinos leave currently drive the development of many aspects of the data acquisition and light collection systems. Much R&D work remains to be done on this front.

The oscillation dynamics in dense neutrino gases remains a focus of numerous active investigations[28–30]. It is clear that the self-refraction of neutrinos can lead to large flavor permutations[30]. The complete understanding of this physics, however, is not yet available. In recent years, a lot of effort was dedicated to investigations of various effects that are brought about by the complicated geometry of the problem. Among them are the azimuthal instabilities[31] and fast oscillations[32], as well as the effect of the scattering halo during the first second of the explosion[33;34]. All these instabilities are present in the linear analysis, but the full treatment of the nonlinear evolution in the actual geometry of the problem is at present beyond the abilities of even the most advanced supercomputers. The theoretical possibilities range from complete flavor decoherence to a set of sharp spectral splits[35;36]. What one would like is a baseline prediction in a model that can be rigorously treated beginning to end and such a model for the moment is multiangle calculation in spherical symmetry.

It should also be noted that the focus on the intricacies of collective effects should not come at the expense of many other physical effects that play out in the supernova. These effects also require urgent attention in the context of modeling neutrino signals in modern terrestrial detectors. This particularly means understanding in detail the features of the density profile, their evolution, and their dependence on the physical conditions in the explosion. Neutrino signal must be predicted for its entire duration, or at least for 10-15 second.

The predictions then have to be combined with realistic detection simulations and incorporate cross-section uncertainties, detector thresholds and performance, and known radiological backgrounds.

For instance, in massive, underground LArTPCs[26;27], one of the known backgrounds is due to neutron captures on ^{40}Ar. This reaction releases a total of 6.1 MeV in several gamma rays[37], which Compton scatter leaving small charge blips. The neutrons, most less than a few MeV, are dominantly produced by (α, n) interactions in the rock following U/Th-chain decays[38–40]; muon-induced neutrons are relatively negligible[41]. Once neutrons enter the detector, they fill the volume, due to their small cross section on argon. The rate for these neutrons is presently estimated to be 1 per 100 m^3 per second. Another background is beta-decays of ^{42}K, which is created in the chain of decays of ^{42}Ar. The energy release is in the range of several MeV and the rate is 10 per m^3 per second. Finally, at sub-MeV energy one has to contend with ^{39}Ar decay, at the rate of 10^3 per m^3 per second. As supernova neutrinos leave MeV-scale electrons and photons in the detector, it is indispensable to properly reconstruct the three-dimensional position and energy deposits of such particles and thereby discriminate them from backgrounds.

A tight collaborative effort between theorists and experimentalists is necessary to fully address the issues described above and create an end-to-end predictions for the next-generation neutrino detectors.

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