

Supernova Neutrino Detection

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Abstract

Detecting neutrinos is the key to understanding core-collapse supernovae, but this is notoriously difficult due to the small interaction cross section of neutrinos and the low frequency of supernovae in galaxies. The revolutionary implications of the detection of about 20 neutrinos from SN 1987A tell us that this quest is worthy. However, there is the sobering fact that there have been no other detections, before or since. Now, after decades of effort and patience, we have good reasons to anticipate that detecting supernova neutrinos again is within reach, in particular for the Diffuse Supernova Neutrino Background (DSNB). A first detection of the DSNB in a short time is possible if Super-Kamiokande is upgraded with the proposed modification of dissolved gadolinium to allow neutron tagging. Longer-term, a comprehensive understanding of core-collapse supernovae will require something like the possible Hyper-Kamiokande detector, eventually also with dissolved gadolinium. This systematic path towards increasing sensitivity will surely lead to further revolutionary discoveries in astrophysics.

Keywords: Supernova, neutrino, Diffuse Supernova Neutrino Background, Super-Kamiokande, Hyper-Kamiokande

1. Preface and Outline

This is the beginning of an age of precision particle astrophysics, echoing the transition to the age of precision cosmology that we entered around a decade ago.

What does precision mean? Obviously, it means that some things are measured well. More importantly, it means that multiple things are measured well, in different ways, and that we have an opportunity to compare them to each other and to theoretical expectations. The age of precision is thus really the age of synthesis, and this provides special opportunities to learn surprising new things. The progress from this synthesis in cosmology has been tremendous, and similar benefits are expected in particle astrophysics.

One of the most exciting of the several frontiers in particle astrophysics is associated with the detection of astrophysical neutrinos. So far, only the Sun and the nearby Supernova 1987A have clearly been detected.

But there are now strong reasons to believe that detections in three broad energy ranges are imminent: the MeV range (e.g., the Super-Kamiokande detector and neutrinos from core-collapse supernovae), the TeV range (e.g., the IceCube detector and neutrinos from observed gamma-ray sources), and the EeV range (e.g., the ANITA detector and neutrinos produced in the energy losses of the highest-energy cosmic rays).

Optimism has always been required in neutrino astrophysics, but now it is objectively warranted. The reasons for optimism are based on improved auxiliary data, better theoretical modeling, and vast recent or pending increases in detector sensitivity. This talk focuses on the prospects in the MeV range; please see other talks at this meeting for the prospects at higher energies.

Progress in all three energy ranges is needed to exploit the promise of neutrino astrophysics. Initially, the numbers of detected events will be small, so the measurements themselves will not be precise; however,

these measurements will be greatly leveraged by the high precision of other data and by theory. Eventually, we will have bigger detectors and large numbers of neutrinos. (Maybe someday like for gamma rays, for which the precision era is already here.)

The data from SN 1987A provide a Rosetta Stone for relating the different languages used to describe core-collapse supernovae. With this event, three important lines of inquiry were finally joined (e.g., see Ref. [1]). First, observational evidence from Astronomy: that the progenitor stars of optical Type II supernovae were shown to be massive stars, in this case a blue $\sim 20M_{\odot}$ supergiant. Second, experimental evidence from Physics: that an optical Type II supernova was shown to be preceded by a short (~ 10 s), energetic ($\sim 10^{53}$ erg) burst of low-energy (~ 10 MeV) neutrinos. Third, a long-ago-proposed unifying framework from Theory, now confirmed: that the core collapse of massive stars at the ends of their lives leads to the production of a proto-neutron star, which must be accompanied by a burst of neutrinos to balance the change in binding energy.

Now, 25 years later, where do things stand? There has been tremendous progress in astronomy on understanding the massive stars that lead to core collapses, the optical supernovae they produce, and the mapping between the different varieties of each. As an example of the latter, it has now been confirmed that the minimum progenitor mass to eventually lead to core collapse is $\sim 8M_{\odot}$, as expected from theory. And there has been tremendous progress in the theoretical work of modeling core collapses, the neutrino signals they produce, and if they lead to visible explosions. As an example of the latter, explosions are now seen in some simulations, modeling with two dimensions has nearly complete physics, and modeling in full three dimensions is beginning (see Ref. [2] and references therein).

However, there have been no new experimental detections of supernova neutrinos, and we cannot make progress on the synthesis of the above three lines of inquiry until we have new, better Rosetta Stones, ideally a well-observed Milky Way supernova combined with data from a variety of more distant supernovae.

Without new neutrino data, we will never be able to satisfactorily answer many important questions. How do core-collapse supernovae explode? How do they form neutron stars and black holes? What are the nucleosynthesis products of supernovae? What are the actions and properties of neutrinos there? What is the cosmic rate of black hole formation? Which supernova-like events make neutrinos? What else is out there that makes neutrinos?

Those are only a few examples of pressing questions. Why is neutrino detection so crucial? Fundamentally, because only neutrinos can reveal the physical conditions deep inside collapsing stars. (Neutrino emission depends on temperature and density, which are known to be large enough; gravitational wave emission requires significant deviations from spherical symmetry, which may not be present.) In many cases, detecting even small numbers of neutrinos could give decisive answers about supernovae. Finally, the next detection of supernova neutrinos will open new frontiers in the nascent field of observational neutrino astrophysics. Please see other talks at this meeting for a more complete perspective on supernova neutrinos.

In the following, I first discuss the three detection modes for supernova neutrinos, for nearby, semi-nearby, and distant sources. After explaining why the most likely next detection will come from the most distant supernovae, I focus the discussion there, on the Diffuse Supernova Neutrino Background (DSNB). In the three subsequent sections, I review the theoretical predictions, the present experimental limits, and the future prospects for the DSNB. Finally, I offer some concluding remarks, including on more general perspectives.

My remarks in these proceedings are abbreviated and simplified. Please see the posted slides of the talk for more details, as well as the papers cited there and the few that are cited below.

I use the term supernova a bit sloppily. I always mean a core-collapse, and I usually mean to include those failed explosions that don't produce an optical supernova at all, instead forming a stellar-mass black hole, but still do produce a neutrino burst.

2. Three Detection Modes for Supernova Neutrinos

There are three frontiers in the detection of supernova neutrinos, all with different advantages and challenges, but with a common goal: to provide unique insights into what happens when massive stars die, that rate at which that occurs, and the variety in the outcomes. For more details, see Ref. [3] and references therein.

- **Burst mode:** The high-statistics detection of a supernova in the Milky Way will probe all details of the neutrino emission, including the full time and flavor information. The supernova rate in our Galaxy is low, $R \sim 0.01 \text{ yr}^{-1}$, but the number of detected neutrinos per supernova is large, e.g., $N \sim 10^4$ in Super-Kamiokande. Other existing detectors will also play important roles, e.g., oil-based detectors can measure the fluxes of all

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