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Supernova Neutrino Detection

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Abstract

This talk will briefly survey the capabilities of current detectors sensitive to supernova neutrino bursts. It will then cover recent progess in development of supernova neutrino detection techniques as well as prospects for specific future experiments.

Keywords: supernova, supernova neutrinos, neutrino detectors

1. Introduction

Supernovae are highly energetic phenomenon, and they release 99% of their energy in neutrino radiation, producing an enormous, but transient flux of neutrinos with energies near 10 MeV [1–3]. Observing the supernova neutrino signal would enable a wide range of opportunities, both in astrophysics and in particle physics. Supernova neutrinos decouple from the star and escape early in the collapse provide a unique observation of the inner workings of a supernova. They also provide opportunities to study neutrino oscillations in a unique environment. For example, this is perhaps the only environment where neutrino-neutrino interactions have a measurable effect [4, 5]

Nearby supernovae are rare events, so as much information as possible must be gathered energy, flavor, and time structure of the burst. A hypothetical ideal supernova detector would have to meet many requirements.

- Our hypothetical detector would need to be large, with each ktonne of mass giving an additional ~ 100 events for a supernova in the center of the galaxy.

- It would have a low energy threshold, down to a few MeV so the full energy spectrum can be observed and so as many events as possible can be collected.

- Good angular resolution would allow the detector to point back to the supernova, providing crucial early warning to photon observatories.

- Good timing resolution is required to measure the time structure of the neutrino signal, a key observable for distinguishing between supernova burst models.

- A low background rate is required is required so that every event during the burst comes from the supernova, which usually means an underground location.

- The detector would be sensitive to all three 'flavor' components of the burst (ν_e, $\bar{\nu}_e$, ν_x).

- Finally, supernovae are rare, so our detector should have high up-time and longevity and not miss it.

Generally, all these requirements cannot be met by a single detector – particular the sensitivity to all flavor components. So, multiple detectors are needed. These detectors also usually have 'day jobs' since supernova events are so infrequent.

Supernova neutrinos can be observed via a number of different reactions. The most common method for observing supernova neutrinos is via inverse beta decay (IBD). This process has a well-understood cross section and a relatively high rate, but it provides no information

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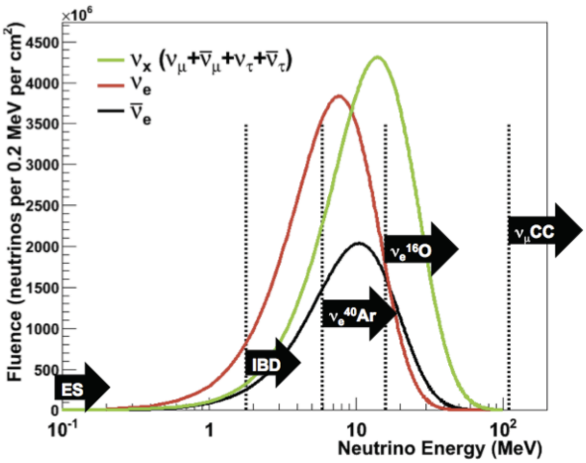

Figure 1: The supernova neutrino spectrum with the threshold for various interactions overlaid.

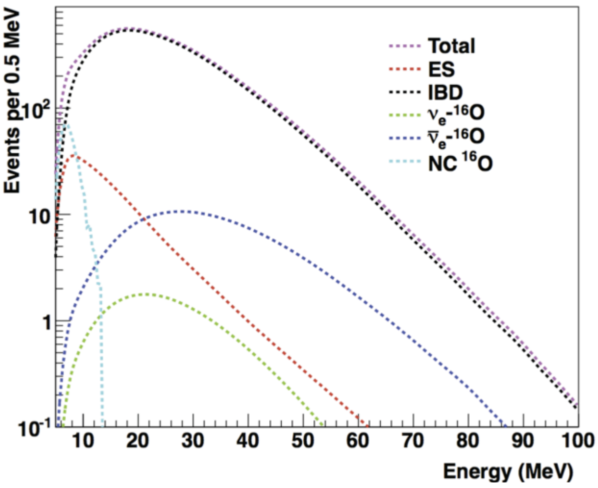

Figure 2: The event rate in a water Cherenkov detector for various interaction modes, from [8].

for pointing back to the source. The neutrinos can also be observed through the elastic scattering (both CC and NC) off of electrons, which has a low rate but provides useful pointing information form the outgoing electron direction [6], or in principle via NC elastic scatting off of the proton [7]. Finally, the neutrinos can be observed through their CC and NC interactions with nuclear targets. These interactions can be observed a number of ways, looking for outgoing $e^{\pm}$'s, neutrons, photons, or even nuclear recoils. These different processes also have different threshold energies, shown in fig. 1. Notice that the threshold for CC μ production is above the supernova spectrum, meaning the only way to observe the ν_μ component of the flux is by observing neutral current interactions.

2. Supernova Neutrino Detectors

In reality, no single detector meets all the criteria of an ideal supernova detector. Particularly challenging is designing a detector with sensitivity to all three flavors simultaneously. However, a number of existing and planned detectors have sensitivity to different parts of the supernova flux.

2.1. Water Cherenkov

Water Cherenkov detectors look for the characteristic rings produced by Cherenkov radiation as particles moving faster than the speed of light in water slow down. These detectors are primarily sensitive to inverse beta decay induced by $\bar{\nu}_e$'s, but also see a sub-dominant but important sample of $\nu_e - e$ elastic scattering events which carry directional information to allow pointing back at the supernova, as shown in fig. 2.

The Super-Kamiokande experiment [9] in Japan is an example of this type of detector with a fiducial volume of 22.5 ktonnes. It would see 5k-10k events from a supernova 10 kpc away. It recently installed a new "SN recorder" which can handle the high event rate of a burst, allowing for a lower energy threshold and improved sensitivity. The 560 ktonne (fiducial) Hyper-Kamiokande experiment [10] is being designed as a successor to SK. It is planned to have only half the photocoverage of SK, but will still have good sensitivity to SN events. Its increased size will allow it to see supernovae from beyond our own galaxy (a supernova in Andromeda might produce 25 events in HK, while in SK it would produce only 1). It is also possible to add Gadolinium to a water Cherenkov detector, allowing both the positron and the neutron to be identified efficiently after IBD interactions [11].

The Ice Cube detector [12, 13] at the South Pole is also a water Cherenkov detector, but it would observe a somewhat different supernova signal. The widely spaced phototubes of this detector, designed for high-energy neutrino astronomy, has a multi-GeV threshold, well above the supernova energy spectrum. However, the enormous flux of $\bar{\nu}_e$ events produced in the supernova would create a large coincident increase in the singles rate on every PMT, with each PMT observing an effective mass of 700 tons. The high event rate would allow for a precise measurement of the time structure of a supernova burst out to at least 20 kpc.

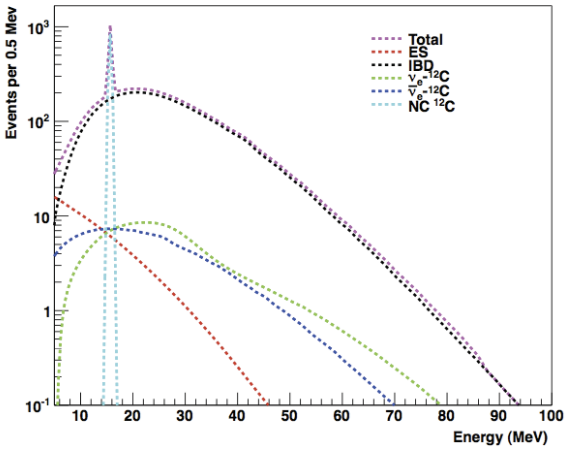

Figure 3: The event rate in a liquid scintillator detector for various interaction modes, from [8].

2.2. Scintillator

Scintillator detectors detect neutrinos by observing the chemical scintillation light produced when charged particles through them. They are also primarily sensitive to inverse beta decays with the free protons in the mineral oil solvent holding the scintillator, but can also observe a the monoenergetic de-excitation photon from NC interactions with ^{12}C which is induced by all flavors. This NC peak can be seen clearly in the event rate plot in fig. 3.

There are a number of running and soon to be running scintillator detectors with masses between 300 and 1000 tonnes. They include Borexino [14] and LVD [15] in Italy, KamLAND [16] in Japan, SNO+ [17] in Canada, NOνA [18] in the USA, and Baksan [19] in Russia. These detectors would observe between 10's and 100's of events within our galaxy and are not sensitive outside it. However, several large proposed detectors would have extraglactic sensitivity: JUNO [20] in China, RENO-50 [21] in South Korea, and LENA [22] in Europe.

2.3. Liquid Argon TPCs

Liquid Argon time projection chambers use a very different detection technology. In these detectors, the charged particles produced in an interaction with an Ar atom will ionize the liquid argon as they travel. A strong electric field will then drift these freed electrons towards planes of wires which will observe the electrons both as they pass by and as they are collected on the final anode plane. Because the active volume is entirely made up of atomic Ar, there are no free protons on which inverse beta decay can occur. Consequently, the ν_e CC interaction in the dominant one (see fig. 4, making it an interesting complement to the other two detection technologies.

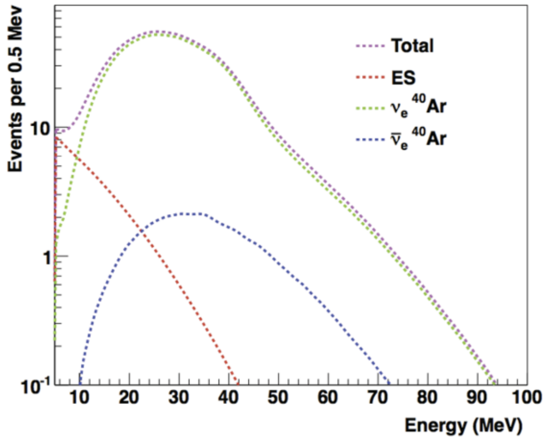

Figure 4: The event rate in a liquid argon TPC detector for various interaction modes, from [8].

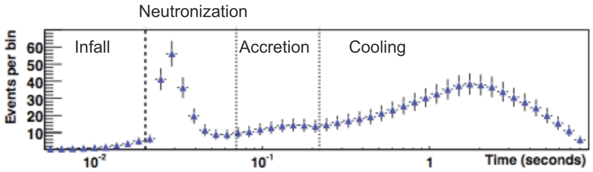

Figure 5: The time distribution of neutrino events from a core-collapse supernova, as observed in the LBNE experiment [23].

Being sensitive to the ν_e flavor component has a second important benefit. Many supernova models include a large burst of ν_e flavor neutrinos lasting only a faction of a second right when 'neutronization' occurs in the core of the star. Observing this burst would give key insights into the underlying mechanisms of the core collapse. Despite the long drift times in liquid argon detectors, simulations show that they have good enough time resolution to observe this burst, as shown in fig. 5.

Several liquid argon detectors are about to come online, and even larger ones are planned for the future. The ICARUS detector [24] in Italy just finished its run and may continue to take more data in the future after upgrades have been made. The MicroBooNE detector in the USA will begin data taking soon. In the future the LBNE project [23] in the USA will provide extragalactic sensitivity to SN bursts.

2.4. Other Detectors

There are other possible detectors that do not fit into the broad categories of large neutrino detectors. The HALO experiment [25] at SNOLAB is a specialized supernova detector, using lead targets and ^{3}He proportional counters to detect the neutrons produced in those interactions [26, 27] It is sensitive to supernovae out to more than 10 kpc. Another promising design allows for the observation of NC coherent scattering of neutrinos off of the target nuclei in a cryogenic detectors [28]. These experiments can have very high yields per mass due to their low thresholds and sensitivity to all neutrino flavors.

3. SNEWS

The high energy density of a core collapse supernova means the photons will remain trapped long after the weakly interacting neutrinos (and gravitational waves) have escaped. The neutrino signal will thus arrive hours or even days prior to the electromagnetic radiation, and thus could provide a crucial early warning to astronomers around the world. In order to facilitate this early warning, the Supernova Early Warning System (SNEWS) [29] was created. When a running neutrino experiment sees a possible supernova, an alert is sent to a coincidence server at BNL. If multiple detectors send an alert with a 10 second window, an automated alert is sent out to the astronomical community, including amateur astronomers, allowing time to prepare. The multi-experiment coincidence suppresses possible false alerts.

The system has been running smoothly for 10 years with no false alarms, and includes LVD, Borexino, Ice Cube, HALO, KamLAND, Super-Kamiokande, and soon Daya Bay.

4. Conclusion

A single core collapse supernova will provide a wealth of information, both astrophysical and about the properties of the neutrino itself. To extract all of that information, we need to observe the full flavor, energy, and time structure of the neutrino signal. Seeing all the flavors is generally not possible with a single detector, but can be done by multiple detectors observing the supernova simultaneously. The current generation of detectors are sensitive to any supernovae occurring within our galaxy. The next generation of even larger detectors will start to cover our neighboring galaxies and provide richer flavor sensitivity. When that supernova occurs, the SNEWS network will send the alert to the astronomical community so we can learn all we can from these rare events.

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