

The Supernova Early Warning System

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Alec Habig and Kate Scholberg describe the Supernova Early Warning System (SNEWS), an international network of neutrino detectors set up to provide a fast alert to the astronomical community if the participating experiments detect the distinctive burst of neutrinos from a stellar core collapse in or near the Milky Way.

Waiting for the next supernova

Astronomers now routinely observe the photon emission from hundreds of core-collapse supernovae per year, but only once has such an event been observed using a different type of messenger. This was the celebrated SN1987A, a supernova in the Large Magellanic Cloud, just outside the Milky Way. At the time, a handful of detectors saw a few dozen neutrinos directly from the heart of the spectacular explosion. That neutrino signal confirmed the hypothesis that massive stars die when their burnt-out cores can no longer support the weight of the rest of the star¹. The violent rebound of infalling matter from the ultra-dense compact stellar remnant creates a weeks-long display of electromagnetic radiation. Neutrinos interact very weakly with matter, enabling them to take off with the vast majority of the supernova's energy within tens of seconds of the explosion. The neutrinos from the 1987 supernova emerged a few hours before the first supernova light turned on, but their traces were picked out of recorded data only after the supernova had been spotted optically.

Next time, it will be different. The world now possesses an array of much larger and more sophisticated neutrino detectors deployed in multiple locations, mostly underground. These detectors lie in wait for the next neutrino burst, continually sifting through their data streams for a supernova-like signal. The observed neutrino burst in itself will be a rich source of scientific data, illuminating questions in both astrophysics and particle physics. But, finding it quickly — perhaps hours or days before the photons beat their way out of the stellar envelope — will enable astronomers to react quickly and gather as much information as possible from a rare ringside seat. This will be possible with the SNEWS alert system.

Neutrino detectors

Although neutrinos are famously weakly interacting, they do occasionally leave observable trails in matter. However, detectors must be very large in order to capture the traces of just a few neutrinos. For a core-collapse supernova at 10 kpc — just beyond the centre of the

Milky Way — about 1,000 tonnes of detector material are required to record about 100 neutrino interactions. Furthermore, in order to record a clean signal, detectors are best located underground, allowing the rock overhead to filter out the high rate of ordinary cosmic rays that would swamp the faint neutrino traces in a surface detector.

Several neutrino detectors (FIG. 1) with sensitivity to a supernova burst are currently in operation^{2,3}. Most of these detectors have other reasons to exist: they observe neutrinos from the Sun, the atmosphere, and radioactivity of the Earth, as well as neutrinos from human-made sources such as beams and reactors. Their primary goal is to understand the mass and flavour-changing properties of neutrinos.

One of these detectors is the 32-kilotonne Super-Kamiokande at the Kamioka Observatory in Japan, a detector made of water, best known for the Nobel-prize-winning observation of neutrino oscillations. IceCube, at the South Pole, is even larger, but its widely spaced photo-detectors cannot observe individual supernova neutrino interactions — instead, they look for an overall glow of Cherenkov radiation in the ice. KamLAND, also at the Kamioka site, Borexino and Large Volume Detector (LVD) at Laboratori Nazionali del Gran Sasso in Italy, and Daya Bay, in China, use scintillation oil. They are smaller, but sensitive to lower-energy neutrinos. The Helium and Lead Observatory (HALO) at SNOLAB in Canada is made of lead, and looks for neutrino-induced neutrons popping out of the lead nuclei.

SNEWS

SNEWS⁴ is an inter-experiment network with the goal of providing a prompt alert to astronomers of the observation of a supernova neutrino burst. SNEWS has been in existence since 1998 and has been running in 'automated' mode since 2005, with the aforementioned experiments currently participating. Currently, detectors such as NOvA at Fermilab in the US, SNO+ at SNOLAB, KM3Net in the Mediterranean Sea, XENONnT at Laboratori Nazionali del Gran Sasso and Baksan in Russia are preparing to join SNEWS⁴.

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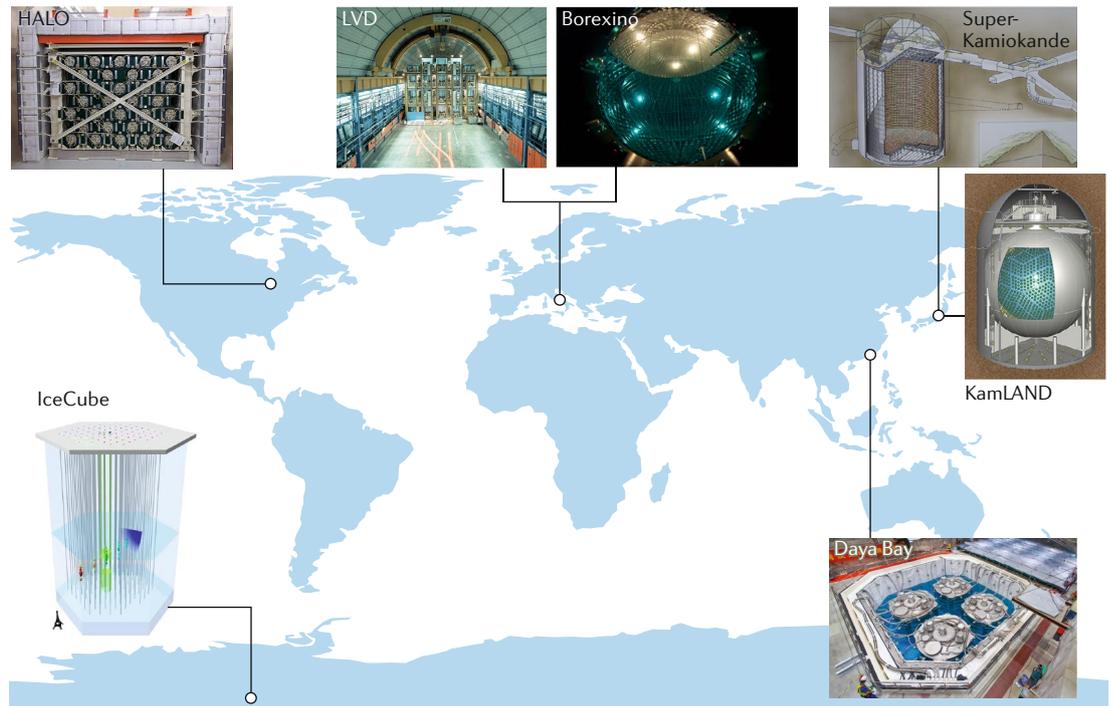


Fig. 1 | **The detectors in the Supernova Early Warning System (SNEWS) network and their locations around the world.** LVD is the Large Volume Detector, HALO refers to Helium and Lead Observatory and KamLAND is the acronym for Kamioka Liquid Scintillator Antineutrino Detector. Images courtesy of HALO; INFN LNGS–LVD Collaboration; the Borexino Collaboration; Kamioka Observatory, ICRR (Institute for Cosmic Ray Research), The University of Tokyo; the KamLAND Collaboration; IceCube Collaboration. Daya Bay image © 2010 The Regents of the University of California, through the Lawrence Berkeley National Laboratory.

Although any one detector might see a fake, random burst from mundane background, that is unlikely to happen at the same time in multiple experiments. Therefore, requiring a coincidence of signals will allow a high-confidence automated alert to be sent out well before the supernova photons reach the Earth. The network currently operates in a simple and robust way: experiments send a datagram to a central computer with a UTC time stamp of any burst they have found. If the SNEWS computer finds a coincidence within 10 s, it sends out an automated alert to a mailing list. SNEWS will also forward individual experiment information that is provided to the network. There have been no alerts so far, and no known Milky Way core collapses since SNEWS has been online.

Pointing information from neutrinos is clearly of value to astronomers, who want to know where to look for the supernova fireworks. Even if there are no fireworks, directional information from neutrinos could help locate a star that simply vanishes because its core collapses into a black hole instead of a neutron star. In such cases, the explosion might fizzle, but there would still be a bright neutrino burst. However, neutrinos do not provide very precise pointing. The most accurate pointing method makes use of the scattering of neutrinos on electrons. Some detectors, such as Super-Kamiokande, can see the direction of the kicked electron, and can gain some information about the origin of the neutrino burst on the sky. However, neutrinos only rarely scatter on electrons, and the technique with

the current detector is good to only about a 5° radius on the sky for a supernova at 10 kpc.

Another possible method is to make use of the neutrino arrival times at the various detectors around the world to ‘triangulate’ their origin on the sky.

Future prospects

SNEWS 2.0, the next generation, will implement triangulation, in combination with any intrinsic pointing information that becomes available. Pre-supernova neutrino capabilities are also in the works. During the very final stages of stellar burning, there is an expected uptick in neutrino flux and energy⁵. Such pre-supernova neutrinos could be observable for progenitors within a few kpc, hours or days before the collapse, which would provide the opportunity for a true early warning of a core collapse. In the next few decades, larger, even more capable detectors — Jiangmen Underground Neutrino Observatory (JUNO) in China, Deep Underground Neutrino Experiment (DUNE) at Fermilab and Hyper-Kamiokande at the Kamioka Observatory — will further enhance worldwide sensitivity.

Neutrinos are not the only prompt messengers of core collapse. Gravitational waves travel at the speed of light, and an asymmetrical core collapse and rebound may produce a strain signal in gravitational wave interferometers. The next nearby core collapse could result in a simultaneous observation of gravitational waves and neutrinos.

Unfortunately, one can expect only about one core collapse close enough for the neutrino and gravitational wave signal to be detected (in the Milky Way and vicinity) every few decades. This low rate has a psychological impact on the neutrino and astronomical communities: some feel that the low probability of such an event in the next few years makes it a less interesting target to prepare for. However, we feel that the rarity of the event means that it is crucial to prepare to catch every last bit of data when one eventually occurs. The mission of SNEWS is to boost the chances of scooping up lavish riches when the next star blows up.

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Competing interests

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