Neutrinos from Supernovae: a Review

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Abstract In this paper, we review the theoretical mechanisms for the production of neutrinos
in supernovae explosions and other astrophysical scenarios of interest. We use these elements
to consider the likelihood of observations of neutrinos from extrasolar sources. A review of
the current neutrino observatories and their sensitivities is also presented.

Key words: accretion – supernovae – neutrinos: neutrino detectors

1 INTRODUCTION

When discussing neutrino production from astrophysical sources, it is well to remember that neutrinos are
very hard to detect. Their notoriously small cross section allows them, once formed by nuclear processes,
to carry enormous energies outward from the cores of massive stars during a core collapse.

From an observational point of view, their presence and effects can be rather subtle. The typical neutrino
observatory has a mass of tens to thousands of tons and occupies a sizable piece of real estate.

One of the customary sources of neutrinos is core collapse from massive stars during a supernova
explosion. John Danziger's review of supernovae at various wavelengths (Danziger, 2005) has shown in re-
markable detail the rather varied nature of supernova light curves. For a discussion of the theory of neutrino
production, recall Gulio Auriemma's (Auriemma 2005) and Sergio Colafrancesco's (Colafrancesco 2005)
discussion of the mechanisms of neutrino formation. Nino Panagia also notes talk supernova are ubiquitous
(Panagia, 2005).

Here, I give brief consideration of some models for supernovae (both Type I and Type II), with an
emphasis on neutrino production. In addition to the production of neutrinos in core collapse supernovae,
pulsars can, under reasonable assumptions of pulsar models, produce significant neutrino fluxes. Detectable
fluxes of neutrinos can also be produced when hadrons accelerated from rapidly rotating pulsars interact
with the pulsar's supernova envelope. In addition, pulsars in binary systems can produce detectable fluxes of
neutrinos when accelerated hadrons from the pulsar interact with the accretion disk material. Finally, Rose
et al. (1984) noted that jets originating in the cores of active galaxies and propagating through the ambient
medium therein produce significant neutrino fluxes. Jets are as a possible source of neutrinos.

As a part of this paper, we will take note of a remarkable event, the beginning of observational, extraso-
lar neutrino astronomy, which occurred with the detection from SN 1987a of a neutrino pulse shortly before
the visible supernova, from SN 1987a (see Danziger 2005 for a review) in the Large Magellanic Cloud.

We will then discuss the current status of neutrino observatories. I am reminded in many ways of the
early days of γ–ray astronomy. The joke at that time was that one was lucky to be a γ-ray astronomer,
because you could know each photon personally (there weren't that many). That modest beginning has lead
to what some have called a golden age of astronomy, including γ-ray astronomy. I believe we are seeing the
beginnings of such a golden age for neutrino astronomy.

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2 TYPES OF SUPERNOVAE

As John Danziger has pointed out in his talk, there are two basic types of supernovae and of supernova progenitors.

For a Type Ia supernova, the progenitor system is a white dwarf in a close binary system with helium rich accretion from an evolved companion. The white dwarf can be very old up to 10 billion years. These supernova can occur in old (i.e., halo) populations of stars.

Type II SN have a massive, supergiant star as a progenitor. These stars are typically as young as 1 million years old. Of course, the real sky is never simple like this. John Danziger's talk has pointed out the level of controversy associated with the classification of SN 1987a.

This difficulty with classification of supernovae brings to mind Francis Bacon's rather famous quote, that "the subtlety of nature is many times greater than the subtlety of the senses and understanding (Bacon 1620)."

In part, the difficulty of classification derives from the variance in the physical conditions of the progenitor systems. Type Ia supernovae acquire their energy from nuclear fusion (helium, carbon, and oxygen to iron) in a deep gravitational potential. The progenitor star in this case is a white dwarf contained within a binary system consisting of a helium-rich companion star. While the system ends with the collapse of a white dwarf into a neutron star, the accretion rate and accreting material must vary considerably from case to case.

Type II supernova are also powered by gravity (collapse of the iron-rich core of a supergiant star, and the consequent nuclear burning that results. Yet, even Fowler's thesis (i.e., that the evolution of a star is determined entirely by its initial chemical composition upon formation and its mass) allows for some considerable variance in the capstone of its evolution as a supernova (Fowler 1984).

After the explosion, the environments in the vicinity of the supernovae also vary considerably. A Type Ia SN produces a gaseous remnant very rich in Fe (see, e.g. Hillebrandt & Niemeyer 2000) and a neutron star. For a Type II SN , the explosion yields a gaseous supernova remnant, with elements heavier than iron, and a neutron star or black hole. In both cases, I hope to show that under proper circumstances, the systems can produce a great many neutrinos.

2.1 Progenitor Populations

Massive stars in the Milky Way are formed in the spiral arms of our galaxy. These stars represent a small fraction ($< 1\%$) of normal stars (e.g. Strigari 2005 for a discussion). The density of such massive stars has been estimated by a number of authors. The progenitor population is shown in Figure 1. Clearly the most likely distance for a new supernova is of order 10 kpc. Most of the estimates of detectability for neutrinos from a new supernova use this as the likely distance.

3 NEUTRINO PRODUCTION

3.1 Type II SN Neutrino Production

[56]Fe has the maximum binding energy for nucleons, which suggests that no more heat production can occur for fusion for elements heavier than iron. When the iron core reaches a mass of ~ 1.4 solar masses, gravity overcomes the Fermi repulsion, the core collapses as the electrons of iron atoms are absorbed by protons and inverse beta decay produces a prompt burst of neutrinos. The process is sketched (e.g. Keil et al. 2003) in the set of equations below.

$$
\begin{aligned}
e^- + p &\rightarrow \nu_e + n, \\
e^+ + e^- &\rightarrow \nu_e + \overline{\nu}_e, \\
e^+ + e^- &\rightarrow \nu_\mu + \overline{\nu}_\mu, \\
e^+ + e^- &\rightarrow \nu_\tau + \overline{\nu}_\tau.
\end{aligned}
\tag{1}
$$

The net result of this is a flux of neutrinos of various types that transport energy from the core as it collapses.

The flux of neutrinos is very time dependent, as shown in Figure 2 (Hix et al. 2003). The plot shows both the luminosity (in the upper plot) in units of 10^{46} Watts (or 10^{53} erg s^{-1}). The lower plot shows the energies of the neutrinos, which have energies of order 10's of MeVs.
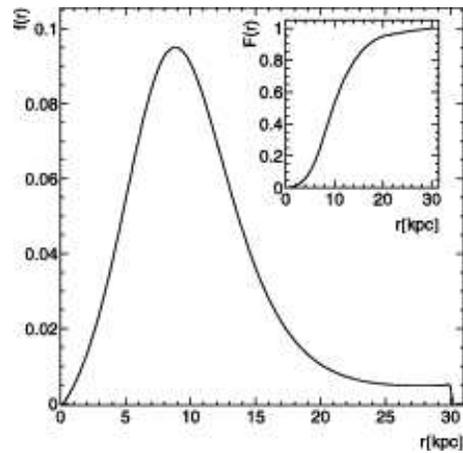
Fig. 1 Progenitor population: Estimate of the density of Type II supernova progenitor stars within the Milky Way, adapted from: J. Ahrens et al., 2002, Astroparticle Physics, 16, 345–359; K. Hirata et al., 1987, Phys. Rev. Lett. 58, 1490–1493; and J.N. Bahcall and T. Piran, 1983, Astrophys. J. 267, L77.
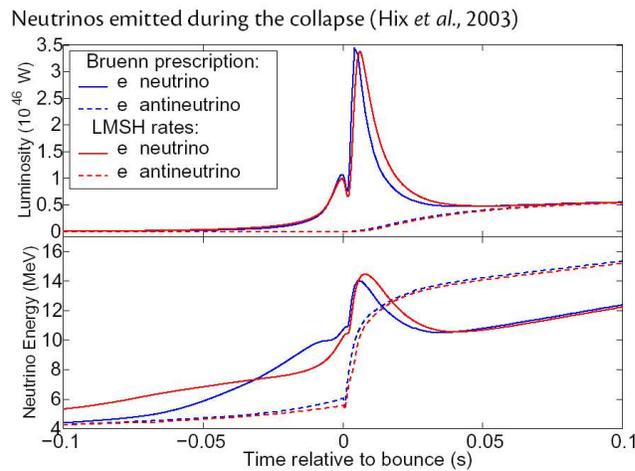

Fig. 2 Time history of neutrinos emitted during core collapse: Figure from Hix et al., 2003. See, also, Bethe, H.A., 1990, Rev. Mod. Phys., 62, 801; and H.A., Janka, H.-Th, et al., 2002, Core Collapse of Massive Stars, Ed., C.L. Fryer, Kluwer Academic Publishers, Dordrecht (astro-ph/0212314).

The various phases for a Type II SN can be illustrated in the following manner. Referring to Figure 2, the bounce time is at zero in the figure. During the *infall phase*, which is initiated by collapse of the stellar core, electron neutrinos are produced from electron capture on nuclei and free protons. A *rebound phase* occurs when an inbound shock wave rebounds after the core reaches nuclear densities as a neutron star begins to form. During the *electron-neutrino burst* phase, a hydrodynamic shock moves outward, weakens, and eventually stalls, after loosing energy (via photo-disintegrations of heavy nuclei to free nucleons). Electron-neutrinos are produced by electron captures onto hot matter behind this shock. These electron neutrinos eventually escape in a luminous burst. During the *accretion phase*, matter falling through the stalled shock is heated and eventually accumulates around the newly-formed neutron star. The accretion layer radiates high fluxes of all kinds of energetic neutrinos (see Janka 2002 for a detailed discussion).

Table 1 Expected Number of Detected ν_μ, taken from
Beall and Bednarek, 2002

	$P_{\mathrm{ms}} = 3$ $\beta = 0.1$	$P_{\mathrm{ms}} = 3$ $\beta = 0.01$	$P_{\mathrm{ms}} = 10$ $\beta = 0.1$
$p\gamma \rightarrow \nu_\mu$ (H)	320	84	16
$pp \rightarrow \nu_\mu$ (H)	3230	465	85
$p\gamma \rightarrow \nu_\mu$ (N)	59	21	4
$pp \rightarrow \nu_\mu$ (N)	912	210	39

It is worth noting that the preceding description is an outline of a rather refined theory. It will be a very good thing to test this with an appeal to data. *The most direct data available to probe the innards of a star during a supernova come from neutrinos.*

3.2 Neutrino Production from the Interaction of Pulsars with an Ambient Medium

3.2.1 Neutrino production from pulsars interacting with supernova envelopes

Neutrinos can also be emitted at early stages of the SN envelope expansion by the interaction of hadronic material with the overburden of the supernova envelope (Beall & Bednarek 2002).

Figure 3 shows the spectra of muon neutrinos and antineutrinos produced in interactions of nucleons from photo-disintegration of iron nuclei with the thermal radiation field inside the supernova envelope (upper plot) and from interactions of iron nuclei with the matter of the envelope (lower plot). The density factor, $\eta = 1$ (i.e., an unfragmented shell), and the initial periods and acceleration efficiencies are: $P_{\mathrm{ms}} = 3$ and $\beta = 0.1$ (full histograms), $P_{\mathrm{ms}} = 3$ and $\beta = 0.01$ (dashed), and $P_{\mathrm{ms}} = 10$ and $\beta = 0.1$ (dotted). For this scenario, the highest detection rates of neutrinos are expected during about 1 to 2 months after the supernova explosion from particle interaction with the matter in the envelope.
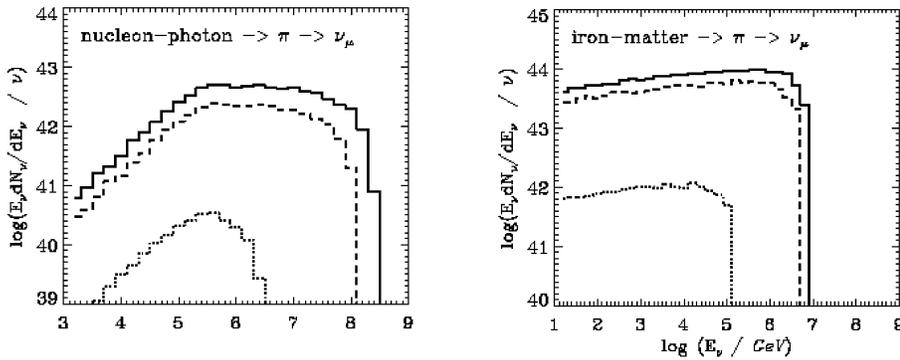

Fig. 3 Spectra of muon neutrinos and antineutrinos produced in interactions of nucleons from photo-disintegration of iron nuclei with the thermal radiation field inside the supernova envelope and from interactions of iron nuclei with the matter of the envelope, taken from Beall and Bednarek 2002.

For a supernova inside our Galaxy at a distance, $D = 10$ kpc, we obtain the expected flux of muon neutrinos produced in nucleon-photon interactions during $1 \times 10^4 - 2 \times 10^6$ s after the explosion and produced in nuclei-matter collisions during $2 \times 10^6 - 3 \times 10^7$ s after the explosion by integrating the neutrino spectra shown in Figure 2. The likelihood of detecting these neutrinos by a detector with a surface area of 1 km^2 can be obtained using the probability of neutrino detection given by Gaisser & Grillo (1987). Table 1 is taken from Beall & Bednarek (2002).

The results of our calculations, for the surface magnetic fields and initial periods of pulsars specified by the models I, II, III, and a density factor $\eta = 1$, are shown in Table 1 for the case of neutrinos arriving from directions close to the horizon, i.e. not absorbed by the Earth (H), and for neutrinos which arrive moving upward from the nadir direction and are partially absorbed (N). For absorption coefficients see Gandhi (2000).

The number of neutrinos that can be detected by a $1\,\mathrm{km}^2$ detector in the case for horizontal and nadir directions is: 1.1×10^3 (H = Horizontal) and 250 (N = Nadir), respectively, at $t = 10^4 - 10^5$ s; 2.7×10^3 and 590 at $t = 10^5 - 3 \times 10^5$ s; 7.9×10^3 and 1.7×10^3 at $t = 3 \times 10^5 - 10^6$ s; 1.2×10^4 and 2.5×10^3 at $t = 10^6 - 2 \times 10^6$ s; 1.8×10^5 and 6.4×10^4 at $t = 2 \times 10^6 - 10^7$ s; and 400 and 150 at $t = 10^7 - 3 \times 10^7$ s.

For this scenario, the highest detection rates of neutrinos are expected during about one–two months after supernova explosion from the phase of particle interaction with the matter of the envelope (Beall & Bednarek 2002).

3.2.2 Neutrinos from fast pulsars in molecular clouds

Figure 4 shows the differential spectra of muon neutrinos and antineutrinos produced in hadronic interactions of iron nuclei with the matter of a molecular cloud at the Galactic Center for the models discussed in Figure 3. The dashed curves indicate the atmospheric neutrino background, ANB (Lipari 1993) within of the source and the dotted line shows the 3 yr sensitivity of the IceCube detector (Hill 2001).
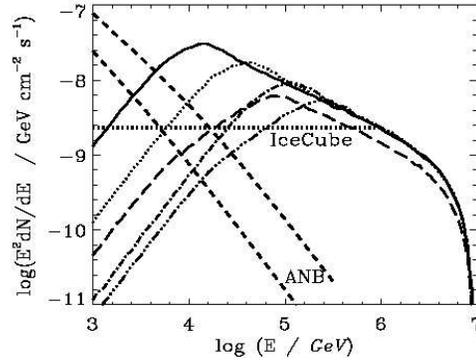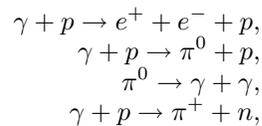

Fig. 4 Figure taken from Bednarek, W.K., 2001, MNRAS, "Production of neutrons, neutrinos and γ-rays by a very fast pulsar in the Galactic Center region."

3.2.3 Neutrino production from close binaries

Nagataki (2002) has also noted the possibility that material shed from a rapidly rotating neutron star n a close binary system can interact with the neutron star's companion to produce a significant neutrino flux. At a distance of 10 kpc, the event rate in a $1\,\mathrm{km}^2$ detector from high-energy neutrinos (such as ICECUBE, ANTARES and NESTOR) will be 2.7×10^4 events yr^{-1}. Zhang et al. (2003) have used the scenario of photomeson production from magnetars to calculate neutrino production from those sources.

3.2.4 Neutrinos from jets in AGN and supernovae

Ultrarelativistic protons will interact with sufficiently energetic photons emitted by the ambient medium or produced by the inverse Compton process. These interactions and their subsequent decays are as follows:

$$\gamma + p \rightarrow e^+ + e^- + p,$$
$$\gamma + p \rightarrow \pi^0 + p,$$
$$\pi^0 \rightarrow \gamma + \gamma,$$
$$\gamma + p \rightarrow \pi^+ + n,$$

$$\pi^+ \to \mu^+ + \nu_\mu^*,$$
$$\mu^+ \to e^+ + \nu_e + \nu_\mu^*. \tag{2}$$

Note that the cross section for the first reaction above is $\sim Z^2 \alpha \sigma_T$, where α is the fine structure constant, Z is the ion mass, and σ_T is the Thompson cross section. The presence of α particles and other ions is therefore significant even at cosmic abundances. The threshold for π-meson production is of order 100 s of MeV.

π-mesons are also produced by the interactions via

$$p + p \to p + p + \pi^0,$$
$$p + p \to n + p + \pi^+, \tag{3}$$

with a somewhat higher threshold energy (see e.g. Rose et al. 1987).

It should be noted that recent association of γ-ray bursts and distant supernovae, as presented by Hurley (Hurley 2005) and Valle (Valle 2005), suggest the intriguing possibility of supernova jets whose constituent particles can interact with the ambient medium of the supernova. *If these jets have a hadronic component, they could produce a significant time dependent neutrino flux*.

4 NEUTRINO PRODUCTION (OBSERVED)

During the collapse of a star, about 10^{57} neutrinos are produced. For SN 1987a, the progenitor star was Sandulaek -890 202 in the Large Magellanic Cloud. The mass of the star has been estimated at 15-18 solar masses. The optical observation occurred on 24 February 1987 (see Danziger, 2005, for a discussion).

4.1 The beginning of Extrasolar, Observational Neutrino Astronomy

Figure 5 shows observations of SN 1987a from Kamiokande and IMB neutrino observations at February 23 7:35 UTC. Approximately three hours before the visible light from SN 1987A reached the Earth, a burst of neutrinos was observed at three separate neutrino observatories (Kamiokande II, IBM, and Baksan). At 7:35am UT, Kamiokande II detected 12 neutrinos, IMB 8 neutrinos and Baksan 5 neutrinos, in a burst lasting less than 13 s.
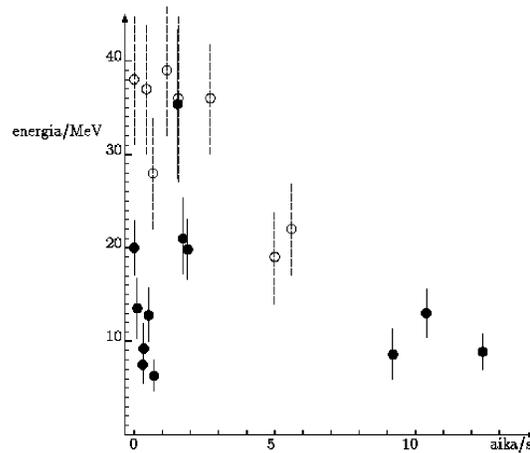

Fig. 5 Detected neutrinos: Solid lines: Kamiokande II; Dashed lines: IMB (Irvine-Michigan-Brookhaven); Baksan data unavailable The horizontal axis is time in seconds and the vertical axis is energy in MeV. Solid lines: Kamiokande II; Dashed lines: IMB (Irvine-Michigan-Brookhaven); Baksan data unavailable The horizontal axis is time in seconds and the vertical axis is energy in MeV.

4.2 Properties of Supernova 1987a

The estimates of the energetics of the explosion from the observations of SN 1987a worth noting here. The energy emitted in antineutrinos was $(3 - 6) \times 10^{53}$ erg, and the energy emitted in all neutrinos was $2 \pm 1 \times 10^{53}$ erg. The kinetic energy is $(1.4 \pm 0.1) \times 10^{51}$ erg The duration of the neutrino pulse = 13 s. As Danziger (2005) has noted, the mass of the progenitor star is estimated to be from $10 - 13 M_\odot$.

These data represent the first extrasolar observation of neutrinos. The data for the SN 1987a neutrino are not inconsistent with the standard model for type II supernovae.

5 IMPLICATIONS OF THE OBSERVATIONS OF SN 1987A FOR NEUTRINO PROPERTIES AND SUPERNOVA MODELS

It is worth noting, however, that the data are very sparse (a total of 24 neutrinos, including those not plotted that are from the Baksan detector. A more statistically significant SN neutrino light curve can place limits on the fundamental physics of stellar collapse. This argues greatly for the operation of neutrino detectors consistently over a long time to look for supernovae within the galaxy.

Janka (2002) and Raffelt (2002) and the references cited therein provide good accounts of what neutrino detection can tell us about the interior of a star during core collapse.

A comparison of the neutrino arrival time vs. the arrival time of the optical flash could set limits on neutrino mass, provided that modelling of the supernova explosion can be sufficiently precise to relate an optical flash to the core collapse.

A comparison of the calculated neutrino flux vs. the data will also be helpful in confirming our understanding of the structure of the supernova core.

6 A LOOK AT CURRENT NEUTRINO OBSERVATORIES

The number of neutrino detectors in operation, under construction, or planned is remarkable. Detectors (planned or extant) capable of detecting neutrinos from supernovae are given in Figure 6, along with the number of expected neutrino events for various detectors for a galactic supernova at a distance of 10 kpc.

The data in Figure 6 represent deep sea detectors like DUMAND, NEMO (planned site SE of Capo Passero, Sicily), AMANDA, and NESTOR (planned site of Pylos, Greece), as well as deep ice detectors like ANTARES and IceCube (planned at the ANTARES site). In addition, underground detectors like those at Gran Sasso and the Sudbury detector use various working media (sometimes designed for solar neutrino work). Fargion (2005) has also suggested a detector using Cerenkov air showers at this conference.

7 CONCLUSIONS

Several concluding remarks seem in order.

The SN 1987a neutrino data are not inconsistent with the standard model for type II supernovae. These models consist of an infalling phase initiated by the collapse of the stellar core; a rebound shock wave that reflects off the core as it reaches nuclear densities; and a hydrodynamic shock that moves outward, weakens, and eventually stalls. Electron-neutrinos (produced by electron captures in the hot matter behind the shock) eventually escape in a luminous outburst. An accretion phase follows, wherein matter falling through the stalled shock accumulates around the newly-formed neutron star and produces more neutrinos.

Other scenarios involving the interaction of the formed pulsar with its surroundings are also plausible, as is the interaction of a hadronic jet produced in the supernova with its overburden of material.

The rate of type II SN in the Milky Way ought to equal the rate of the formation of massive stars. This suggests that it is plausible to see a type II supernova "anytime".

The detectors currently under development and planned can provide interesting upper limits or detections of neutrino emission from hadronic jets in galactic sources or in blazars.

The current situation should remind us of the early days of X-ray and γ-ray astronomy, when only a few photons were available for study. That beginning has led to this "Golden Age". Neutrino astronomy has the potential to be on such a path. We need consistent operation (and funding!) of all available detectors.

Experiment	location	type	direction?	spectrum?	threshold energy	Expected events	Starting year
DUMAND	Pacific - off Hawaii	water Cerenkov	no	no	0.664 MeV	planned only	planned, early 1970s
Gallex	Gran Sasso	radiochemical	no	no	0.233 MeV	1	1990-1997
GNO	Gran Sasso	radiochemical	no	no	0.233 MeV	1	1998+
Kamiokande	Japan	water Cerenkov	no	no	5 MeV	250	1985-1996
SuperKamiokande	Japan	water Cerenkov	yes	yes	5 MeV	4400	1996+
SNO	Canada	Cerenkov +	yes	yes	5 MeV	800	1999+
Borexino	Gran Sasso	liquid scintillator	no	yes	0.25 MeV	100	2005+
LVD	Gran Sasso	liquid scintillator	no	yes	5- 7 MeV	400	1991+
Macro	Gran Sasso	liquid scintillator streamer tube	no	yes	7 MeV	150	1989+
ICARUS	Gran Sasso	liquid argon			5	10-100	2005+
AMANDA	South Pole	ice Cerenkov	at GeVs	at GeVs	0.5 MeV	~100	1995+
IceCube	South Pole	ice Cerenkov	at GeVs	at GeVs	0.5 MeV	~1000	planning stages 2012+
SAGE	BNO (Baksan Neutrino Observatory)	radiochemical	no	no	0.233 MeV	1	1990+
BaksanUST	BNO	liquid scintillator			8 MeV	50	1980+
BDUNT(Baikal)	Lake Baikal	water Cerenkov	no	no	MeV range	?	1980+
LSND	Los Alamos	liquid scintillator	no	no	5 MeV	70	1993+
MiniBooNE	FermiLab	liquid scintillator	no	no	MeV range	190	2002+
Iodine	Homestake	radiochemical			0.664 MeV	25	1970+
ANTARES	Mediterranean	water Cerenkov	0.2°		MeV range	?	2008+
NEMO	Mediterranean SE of Capo Passero	water Cerenkov	?		MeV range	?	initial stages
NESTOR	Mediterranean off of Pylos, Greece	water Cerenkov	?		MeV range	?	planning stages

Fig. 6 Detectors Planned or extant capable of detecting neutrinos from supernovae. This table shows the number of expected neutrino events for various detectors for a galactic supernova at a distance of 10 kpc. Data for the observatories are taken from Riccobene et al. (2001) for the NEMO project; Sharp, et al. 2002 for MiniBooNE; Feser et al., 2003, and Neunhoffer et al. for AMANDA; Ackermann, et al. 2004, for AMANDA-II; Thompson (2005) for NEMO; and Shapiro (2005) for DUMAND.

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DISCUSSION

Giuseppina Fabbiano: Can you comment on the 3 hour delay between the neutrino burst from 1987a and the light detection?

Jim Beall: It is likely that the difference between the neutrino event and optical flash is due to the time it takes for the shock generated by the core collapse to reach the surface.

Kevin Hurley: We may not be able to detect them individually, but by co-adding many bursts, it may be possible. The AMANDA group has been doing this for several years now.

Jim Beall: I agree completely that this is a good idea and a good suggestion.

Daniele Fargion: A remark: The time delay betwen the anti-neutrino burst and the gravitational wave may test neutrino mass. In our galaxy (Fargion, 1981 -N. Cimento), it is difficult, but from ANDROMEDA (Fargion 2002) it will be possible with UNO detector + LIGO + VIRGO.

Jim Beall: I agree that the detection would prove interesting, first in terms of the neutrino correlation with gravity waves, but also for the gravity wave detection, alone.