FERMILAB
DEC 11 1996
LIBRARY

GALACTIC AND EXTRAGALACTIC SUPERNOVA NEUTRINO-BURST DETECTION*

UCLA-APH-0087-5/96

DAVID B. CLINE
Department of Physics and Astronomy, Box 951547
University of California Los Angeles
Los Angeles, California 90095-1547 USA

UCLA-APH-0087-5-96
Fermilab Library
0 1160 0045597 6

Type-II supernova explosions are of enormous importance for astrophysicists and for Life itself. We describe some of the motivation for detection of the neutrino burst from galactic and extragalactic supernovas that will provide information on how supernovas explode. In addition, we show how to measure a cosmologically interesting neutrino mass using the proposed detector at the Supernova Burst Observatory (SNBO), as well as other existing free-proton-type detectors such as Super Kamiokande. We give results of recent neutron background measurements and detector simulations for a detector at the WIPP site in New Mexico. We also indicate how an extragalactic supernova can be detected using a high-mass SNBO detector and a coincidence between LIGO, VIRGO, NEPTUNE, *etc.*, gravity-wave detectors.

1 Introduction

The issue of whether or not neutrinos have masses is important for astrophysics and cosmology. Unfortunately, experimental terrestrial probes of neutrino mass, especially the ν_μ and/or ν_τ masses, remain problematic. Astrophysical considerations may represent the best hope for determining neutrino masses and mixings. In this paper, we examine how proposed neutral-current-based, supernova neutrino-burst detectors, in conjunction with the next generation water-Čerenkov detectors, could use a galactic supernova event to either measure or place constraints on the $\nu_{\mu,\tau}$ masses in excess of 5 eV.[1,2] Such measurements would have important implications for our understanding of particle physics, cosmology, and the solar neutrino problem and would be complementary to proposed laboratory vacuum-oscillation experiments.

A light neutrino mass between 1 eV and 100 eV would be highly significant for cosmology. In fact, if a neutrino contributes a fraction Ω_ν of the closure density of the Universe, it must have a mass $m_\nu \approx 92\ \Omega_\nu\ h^2$ eV, where h is the Hubble parameter in units of 100 km s^{-1} Mpc^{-1}. Reasonable ranges for Ω_ν and h then give 1 eV to 30 eV as

---

*Presented at the International Workshop on the Identification of Dark Matter (The University of Sheffield, UK, Sept. 1996) and to be published in the Proceedings by World Scientific.

a cosmologically significant range. A neutrino with a mass in the higher end of this range (*i.e.*, $10 \leq m_\nu \leq 30$ eV) could contribute significantly to the closure density of the Universe. The cosmic background explorer (COBE) observation of anistropy in the microwave background, combined with observations at smaller scales, and the distribution of galaxy streaming velocities, have been interpreted as implying that there are two components of dark matter: hot ($\Omega_{HDM} \sim 0.3$) and cold ($\Omega_{CDM} \sim 0.6$). The hot dark matter (HDM) component could be provided by a neutrino with a mass of about 7 eV.[3-5]

Despite the cosmological and particle physics interest in massive neutrinos, there are very few terrestrial experimental means for measuring the neutrino masses. The electron neutrino mass is constrained by the tritium end-point experiments to be less than about 4 eV. It is conceivable that $\nu_{\mu,\tau}$ accelerator neutrino-oscillation experiments, such as the NOMAD and CHORUS experiments at CERN, and the COSMOS (E803) experiment at Fermilab could be used to imply a mass in the cosmologically interesting range for ν_μ or ν_τ. This would depend on there being a fairly large vacuum mixing between these neutrino flavors. Nucleosynthesis from supernovas (SNs) could possibly provide a signature for neutrinos with these masses.

In summary, the particle physics and astrophysics reasons to detect Type-II supernova (SNII) ν/ν's are:

1. To measure ν mass ($m_{\nu_\mu}, m_{\nu_\tau}$) in the ≥ few eV range by time of flight [(TOF) neutrino oscillations are not required], and to detect neutrino oscillations in the $10^{-8} \rightarrow$ 1-eV δm range using the MSW effect for the supernova;

2. To study the dynamics of supernova explosions, *e.g.*, the equation of state of hot matter and the explosion mechanism (neutrinos carry nominal information);

3. To determine the rate of SNIIs in the Galaxy (some supernovas may not produce light);

4. To direct the detection of black hole formation in real time.

Some of the human reasons to be interested in SNII explosions are:

1. They have produced many of the elements needed for life (*e.g.*, at least half of the gold on Earth),

2. They may have caused shock waves that started our solar system,
3. They may have helped form organic molecules in molecular clouds,
4. They could have (A) helped form homochirality in biomolecules and (B) caused extinctions due to excess defects in DNA.

We should not forget that SN1987A[6] taught us a great deal about this problem.

2. Measuring the Neutrino Mass by Time of Flight

Perhaps the most straightforward and obvious nature of a massive neutrino would come from the lengthening in flight time from a distant supernova. For example, the flight time difference between ν_τ and ν_e ($\bar{\nu}_e$) in seconds is

$$\Delta t = 5.14 \times 10^{-2} R_{\mathrm{kpc}} \left[\left(\frac{m_{\nu_e}}{E_{\nu_e}} \right)^{-2} - \left(\frac{m_{\nu_x}}{E_{\nu_x}} \right)^{-2} \right] \mathrm{s} \quad ,$$

where E_{ν_x} is the neutrino energy in MeV, m_{ν_x} is in eV, and R_{kpc} is the distance to the supernova in units of 10 kpc (shown schematically in Fig. 1). A finite neutrino mass would alter the neutrino spectra in characteristic ways that could result in broadening and flattening of the observed signal.

The reactions for detecting the neutrinos are given in Table 1. Event rates for various detectors for a galactic supernova are given in Tables 2(A) and (B).[7]

Thus, neutrino masses might be obtained by comparing the observed neutrino signal with the signal expected from supernova models. Since detectors such as Super Kamiokande (SK) are relatively insensitive to ν_μ and ν_τ, they are unlikely to measure cosmologically significant neutrino masses for these flavors. One of the neutral-current-based detectors being built at present is the Sudbury Neutrino Observatory (SNO). The general features of the SNII neutrino burst are shown in Fig. 2.[1] Recent 2-dimensional (2-D) simulations suggest even more fine structure in the burst, as shown in Fig. 3.[8]

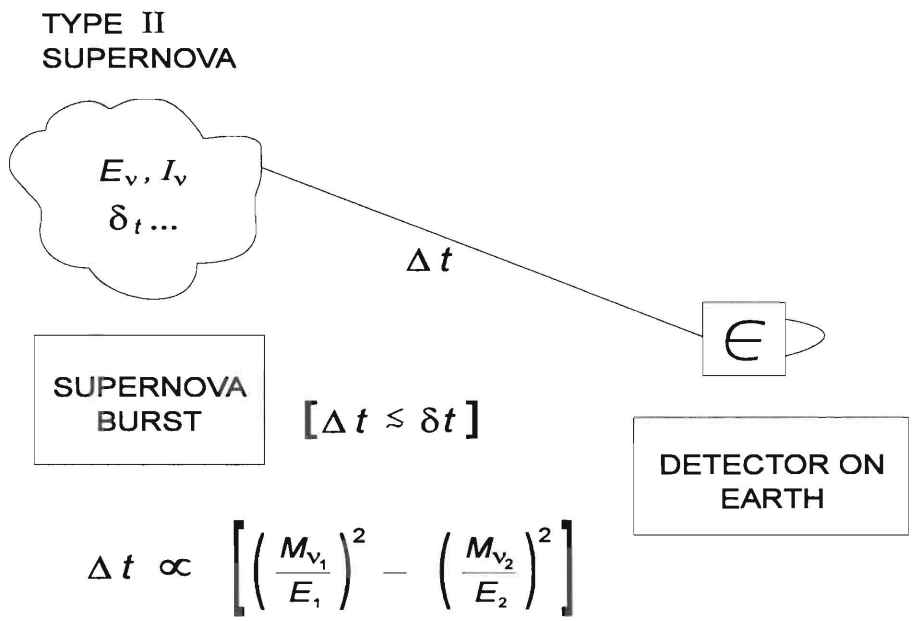

Figure 1: Schematic of method to measure neutrino mass by TOF.

Table 1. Method for detecting supernova ν's.

- Normal $\bar{\nu}_e + p \rightarrow e^+ + n$
- Measurement of "neutron burst" in inexpensive medium (SNBO)

  $\nu_{\mu,\tau} + N \rightarrow \nu_{\mu,\tau} + \underset{\text{detect}}{n} + X$

- Coherent interaction in sensitive detector $\nu_x A \rightarrow \nu_x A$: requires

  $\left\{\begin{matrix} E_t < \text{keV} \\ \text{mass} > 10\ \text{ton} \end{matrix}\right\}$

Table 2(A): Supernova neutrino detection methods in the 1990s.

Reactions	$\bar{\nu}_e p \rightarrow e^+ n$	$\nu_x e \rightarrow \nu_x e$	$\nu_x N \rightarrow \nu_x N$	$\nu_z N \rightarrow \nu_z N^* \rightarrow n$
<u>Parameters</u>				
Cross section	Large (KII,SK,IMB,LVD)	Small $\sim E_\nu^2$ (ICARUS)	Large for coherent process	Large at high E_{ν_x} SNO/SNBO
Neutrino energy estimate	Yes $\sim E_e$	Partial $E_{\nu_e} \sim f(E_e)$	No	No Threshold may set E_{ν_x}
ν direction	No	Yes	No	No
Time information	Yes	Yes	Yes	Yes
Down-time speculation	≳ 10%	~ 30%	?	Could be small
Maximum detector size	2×10^5 ton (H_2O) LENA ≳ 10^4 ton liq. scint. (LVD)	~ 2×10^5 ton (H_2O) or ~ 10^3 ton Cryogenic (ICARUS)	? Kilograms No detector proposed	~ 10^5–10^7 ton of NaCℓ (SNBO) or ~ 10^3 ton D_2O (SNO)
Background	Small if e^+ and n capture detected; OK for H_2O galactic signal	Small if directionally used to reject background	?	Depends on radioactivity of material

Table 2(B): Events expected from a galactic supernova in further supernova ν detectors at 10 kpc.

Comparison of Future Supernova ν Detectors						
Process	$\bar{\nu}_e p \to e^+ n$ $\bar{\nu}_e d \to ppe^-$	$\bar{\nu}_e e \to \bar{\nu}_e e$	$\bar{\nu}_x e \to \bar{\nu}_x e$ $x = \mu,\tau$	$\nu_e N \to N^* \nu_e$ $\to n$	$\nu_x NN \to N^* n_x$ $\to n$	ν_e prompt
Detectors						
ICARUS		~ 140	25			4[a]
SNO (1.6 kT): ($D_2O + H_2O$)	~ 435 (D_2O + H_2O shield)	3	21	~ 117	~ 200	5[a] 5-20
LVD (1.8 kT): scint	~ 342					
MACRO (1 kT): scint	~ 220					
Kamiokande II (3 kT)	~ 355	~ 1				
Super Kam (40 kT): H_2O	~ 5310	~ 17				~ 5[a]
SNBO (100 kT)	100s			~ 100s	10,000	
Comments	Measure t_ν, $E_\nu \sim E_e$, No direction	t_ν E_ν estimated from E_e θ_ν measured		t_ν only No E_ν ! No θ_ν		$\Delta r \approx 10$ ms

[a]Depends on energy spectrum of prompt ν_e and detector threshold.

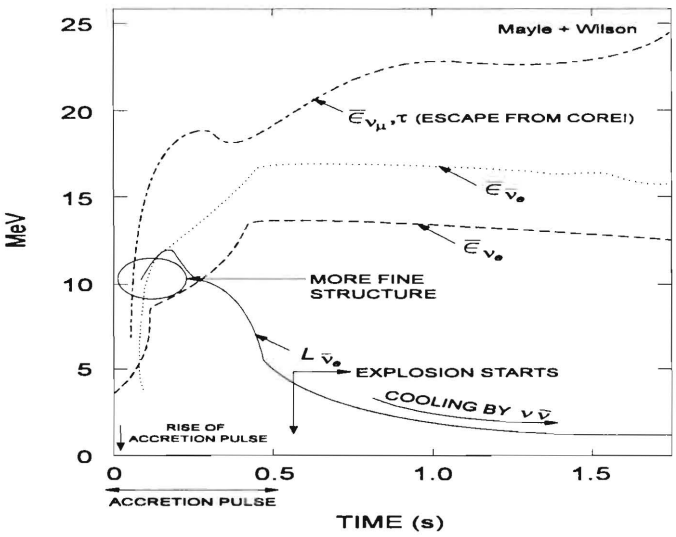

Figure 2: Schematic of the supernova ν burst properties.

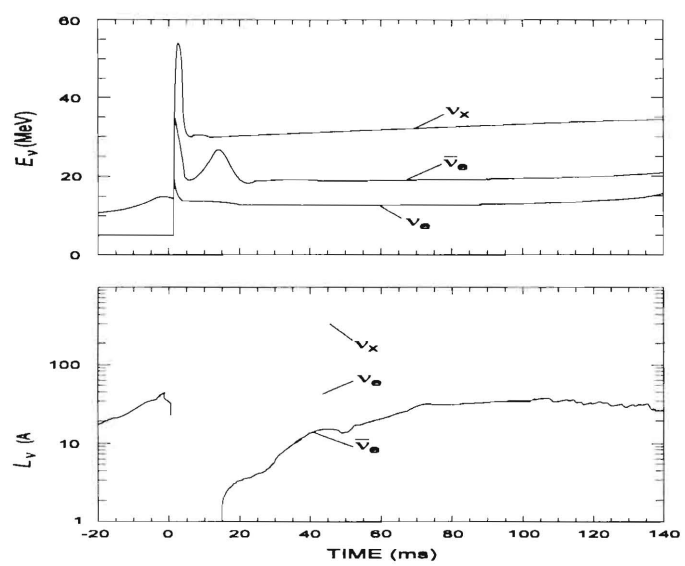

Figure 3: Possible fine structure in the supernova ν burst from recent calculations.[7]

3 The Different Types of Supernova Neutrino Detectors and Neutrino Masses

Recently there has been real progress in supernova simulations giving an explosion.[7] These calculations give interesting predictions for the neutrino spectra, as shown in Figs. 2 and 3. Detectors like the SK and SNBO may be able to detect such effects, however the SNBO detector may be of crucial importance for this study.[1] Using these various detectors, it should be possible to detect a finite neutrino mass, as shown in Fig. 4.[1] The characteristics of the detector are listed in Table 2(A), and Table 2(B) gives the expected count rates.

In this analysis, we have assumed the existence of a very massive neutral-current detector (the SNBO), which we discuss next. By using these different detectors it will be possible to measure the μ or τ neutrino masses, as shown in Fig. 4, which could determine a mass to ~ 10 eV. To go to lower mass, we need to use the possible fine structure in the burst shown in Fig. 2; we have shown that it may be possible to reach ~3eV with very large detectors in this case.[7]

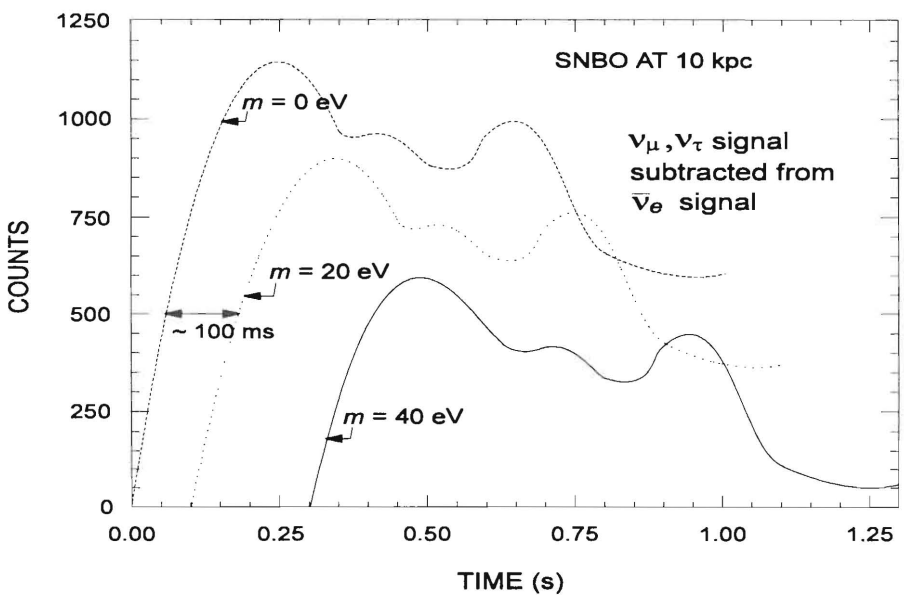

Figure 4: Difference in signals in SK and SNBO for a neutrino mass of 20 – 40 eV.

4 The Proposed Supernova Burst Observatory (SNBO)

The major problem of supernova detection is the uncertain period of time between such processes in this Galaxy. In addition, complimentary detectors should be active when the supernova goes off in order to gain the maximum amount of information possible about the explosion process and neutrino properties. In Table 3, we list some of the requirements of such an ideal supernova observatory.

Lacking an ideal observatory, a group of us have been studying a very large detector, SNBO.[1] Table 3 gives some of the guidelines for this detector,[9] and Fig. 5 gives additional detailed simulation results in the development of the SNBO detector.[10] We have located a possible site for the observatory near Carlsbad, NM, which is the WIPP site (shown in Fig. 6). We have studied the radioactive background at this site (measured by the OSU–UCLA group) and find it acceptable for a galactic supernova detector. We find less than one neutron per hour detected in a 6-ft BF_3 counter. This leads to the expectation that the background for a galactic supernova is much smaller than the signal at this site.

Table 3: The supernova burst observatory (SNBO) concept.

Scheme for a very large neutral-current detector:

- A neutral current detector (*i.e.*, $\nu_x + T \rightarrow \nu_x + T'$), with $T' \rightarrow$ neutron (detected) that tags neutrino flavor and detects galactic or extragalactic supernovas in real time,
- Adequate event rate to measure M_{ν_x} (*i.e.*, detector mass),
- A long baseline to detect a given M_{ν_x}.

The SNBO group has studied these requirements and concluded that:

- Detection of $M_{\nu_x} \geq 3$–30 eV can be carried out using galactic supernova and a massive neutral-current detector ($M_{\mathrm{SNBO}} > 10^4$ tons) with inexpensive neutron detection,
- Detection of $1 < M_{\nu_x} \geq 3$ eV will require extragalactic SNII detection and $M_{\mathrm{SNBO}} > 10^7$ tons.

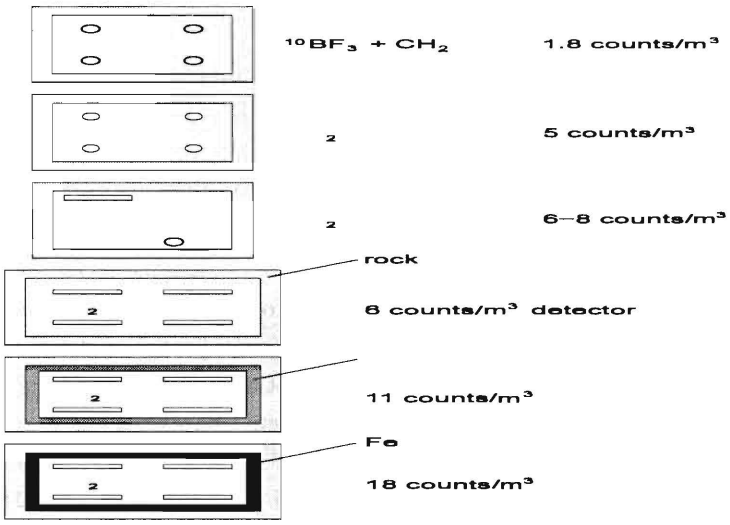

Figure 5: Simulation of various possible configurations of SNBO and different neutron detectors.[10]

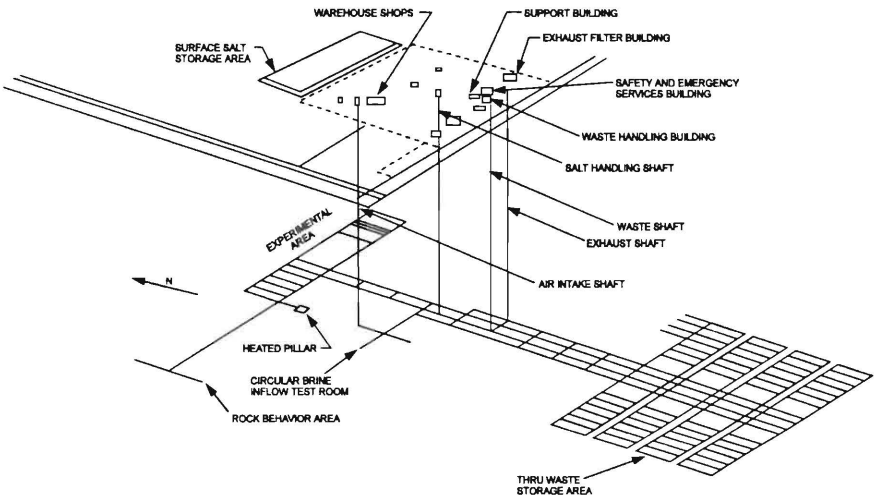

Figure 6: Isometric view of the surface and underground, looking toward the northeast, of the Wipp site near Carlsbad, NM.

In Fig. 7 (A) and (B), we show possible structures for the SNBO detector at the WIPP site for either BF_3 or scintillation detectors.[11]

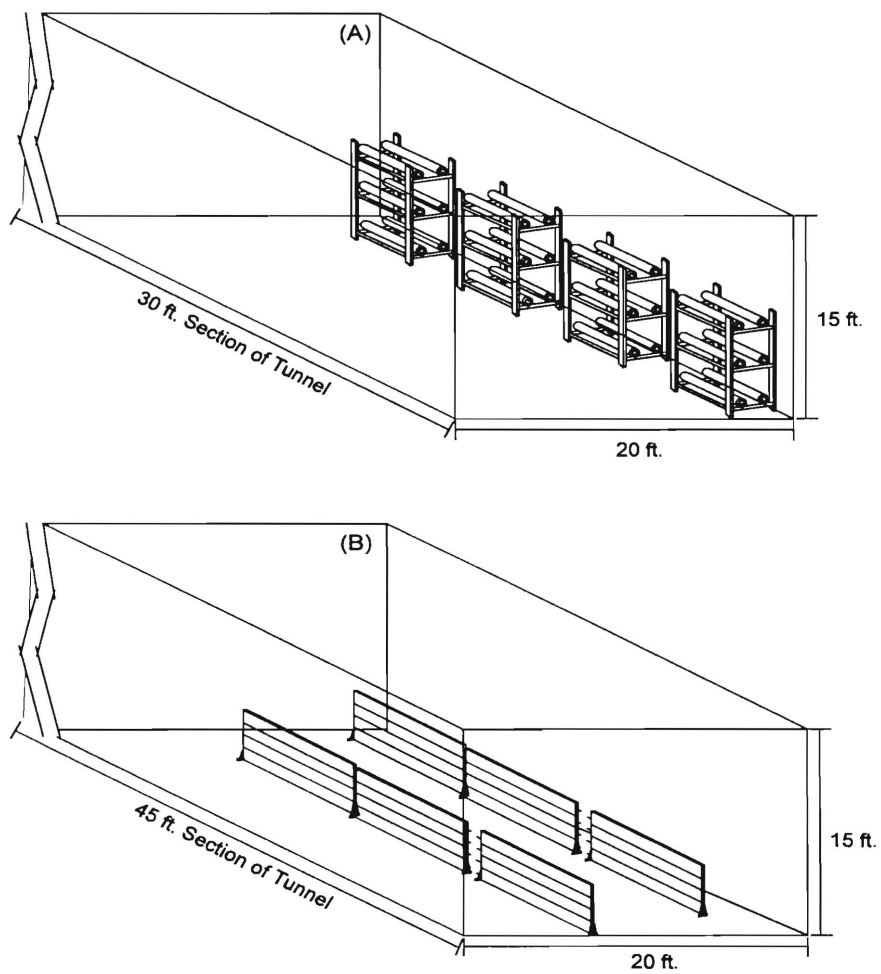

Figure 7: Schematic of SNBO at the Wipp site using (A) BF_3 and (B) 0.2%-Gd-loaded scintillator neutron detectors.

5 Recent Studies for SNBO and Real-Time Detection

With a detector like SNBO, where 10^4 counts would be recorded, it will be possible to detect the supernova within 100 ms of its start and to alert the World Wide Web to "Supernova in Progress." There are other interesting sources of neutrino bursts, as given in Table 4, that might be studied with SNBO.

The real issue in supernova ν detection is the long time needed to operate the detector between supernova explosions in the Galaxy, longer than most underground detectors have operated. One possibility is to build a large enough detector to be able to "see" extragalactic supernovas. Figure 8 shows the possible rate with distance from our galaxy as given by E. Becklin.[9] A 10^7 ton detector may observe a supernova each year, and this must be the long-term goal of the SNBO prototype study!

Table 4: Other possible observations with an SNBO.

- ν bursts from the sites of GRBs,
- ν bursts from cosmic strings,
- Neutron showers from high-energy neutrino interactions in the rock of the detector,
- ν bursts from "quiet" supernovas (no light).

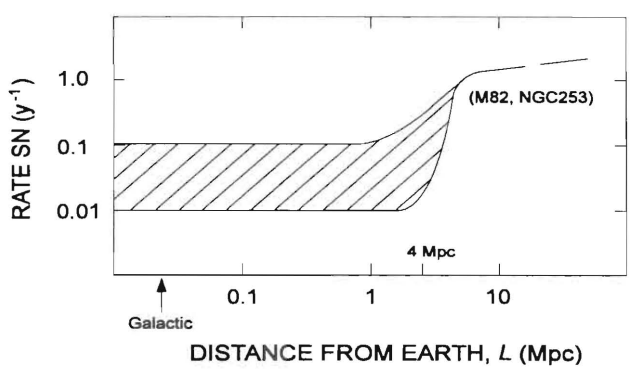

Figure 8:

Estimated rate for supernova explosions as a function of the distance from earth.[9]

In Table 5, we give a possible example of how an extragalactic SN might be detected coincidently with a gravity wave detector. While this is a long shot, the observation in real time of SNII explosions is one of the most fascinating of all adventures in science and must be attempted.

Table 5: How it may be possible to detect an extragalactic supernova burst.

- Distance: 3 Mpc to starburst galaxies to supernova using SNBO (~1/y according to E. Becklin's estimate;[9]
- Event rate: 100 events assumed;
- Scale from RAL Monte Carlo simulation[10]
  Detector: 50 m^3 → 100 events for d = 100 kpc; need ~ 5×10^5 m^3 for d = 3 Mpc;
- Background: Current measurements at the WIPP site:
  Neutron background = 1.3×10^{-4} m^{-1} s^{-1} for BF_3 detector;
- Assume same background rate for 5×10^5 m^3 detector cross section $(1/5 \times 1/5)$ m^2;
  need: 1.2×10^7 m of detector,
  1.5×10^3 counts/s,
  Fluctuations = $\sqrt{N}$ ~ 40 counts/s,
  $S/\sqrt{N}$ ~ 50/40 ~ 1;
- To raise $S/\sqrt{N}$, put SNBO in coincidence with NEPTUNE, LIGO, VIRGO, *etc.*, gravity-wave detectors.

Acknowledgements

I wish to thank members of the SNBO group and, in particular, D. Boyd, G. Fuller, P. Smith, D. Sanders, and J. Wilson for their assistance.

References

1. D. B. Cline, G. M. Fuller, W. P. Hong, B. Meyer, and J. Wilson, *Phys. Rev.* **D50**, 720 (1994).
2. Presentations to the Snowmass workshop were made by members of the SNO, Super Kamiokande, AMANDA, SNBO, and KARMAN groups and are to be published in the proceedings (World Scientific, Singapore, 1996).
3. G. F. Smooth et al., *Astrophys. J. Lett.* **396**, L1 (1992).
4. R. K. Schaefer and Q. Shafi, *Nature* **359**, 199 (1992).
5. J. R. Bond, G. E. Efstathiou, and J. Silk, *Phys. Rev. Lett.* **45**,1980-1983 (1980).
6. K. Hirata et al., *Phys. Rev. Lett.* **58** (1987) 1490; also see R. M. Bionta *et al.*, *Phys. Rev. Lett.* **58**, 1494 (1987).
7. The SNBO Group - Internal Reports, University of California Los Angeles (1993-1995).
8. M. Herant, et al., *Astrophys. J.* **435**, 339 (1994); also A. Burrows (U. AZ-Tucson), private communication (1995).
9. E. Becklin (UCLA), private communication, 1995; also see *Trends in Astroparticle Physics*, eds. D. Cline and R. Peccei (World Scientific, Singapore, 1992).
10. The simulation was carried out by Peter Smith of RAL.
11. These studies have been caried out by David Sanders of UCLA.

NAME		
TURKOT	2543	J43