SUPERNOVA TYPE II DYNAMICS AND NEUTRINO DETECTION

DAVID B. CLINE

University of California Los Angeles,
Department of Physics and Astronomy, Box 951447
Los Angeles, California 90095-1547 USA
dcline@physics.ucla.edu

Abstract

We review the current status of understanding of the SNII explosion process and neutrino emission from the recent conference at Marina del Rey, February 15 and 16, 2001. The effects of neutrino mixing can be very important in the SNII environment. We discuss the current status of the analysis of 1987A data for the hypothesis of the LMA solar neutrino mixing—the data seems to rule this out strongly. We then discuss the different neutrino detectors with an emphasis on the new ones or novel concepts. Finally we discuss the supernova watch programs, ICARUS, that will produce a clean ν_e signal and OMNIS.

1. Introduction

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 a cosmologically significant range. A neutrino with a mass in the higher end of this range (*i.e.*, $10 \le m_\nu \le 30$ 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. 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} → 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.

2. Progress in Supernova Dynamics

We report here on the conference held at Marina del Rey (Los Angeles, California) February 15 and 16. To start with, we review the key results from the neutrino detector of SN1987A. Figure 1a shows the expected neutrino luminosity function from Mayle and Wilson [2]. Note there is a sharp rise, narrow peak at 500ms and a long tail. In Figure 1b, we show the combined results of the neutrino detctor of 1987A—which is remarkably similar to Figure 1a. Thus it is concluded that the general features of the neutrino burst fit the simple theory well.

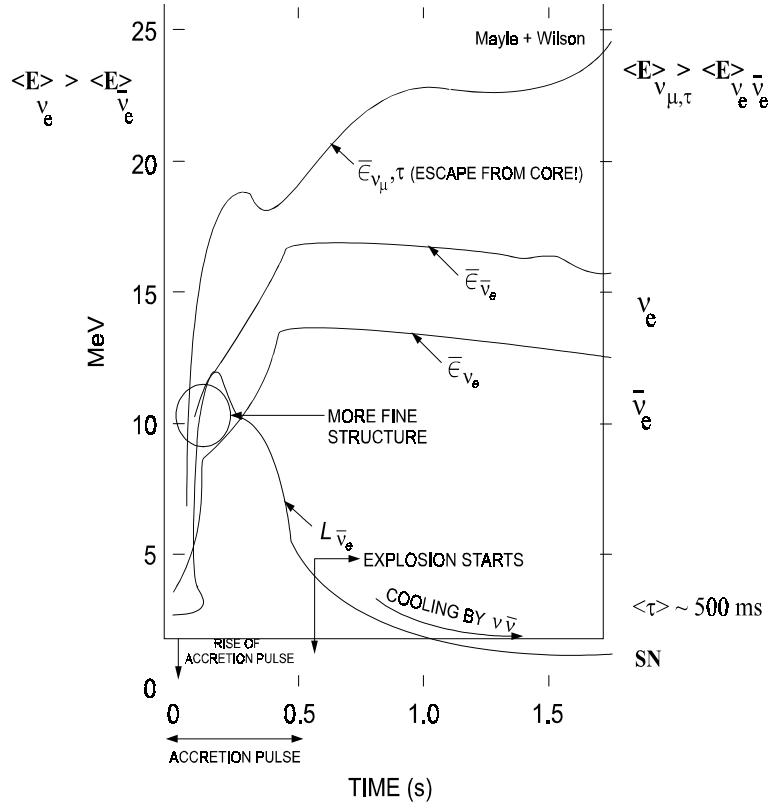


Figure 1a.

At the Marina del Rey meeting the general viewpoint of the current simulation for the stellar collapse at SN explosion can be summarized in Table 1. However, we must agree with S. Colgate's viewpoint that the neutrino heating and convection cause the explosion as illustrated in Figure 2 [3].

It is clear that detection of the neutrinos from a nearby supernova will supply a very important aspect to theses issues as well as stressed by Adam Burrows [4]. Table 2 gives the general features of the SNII neutrino signal that should be measured the next time SNII goes off locally. In the various simulations there appear to be changes in the neutrino energy spectra at or near the explosion time [2].

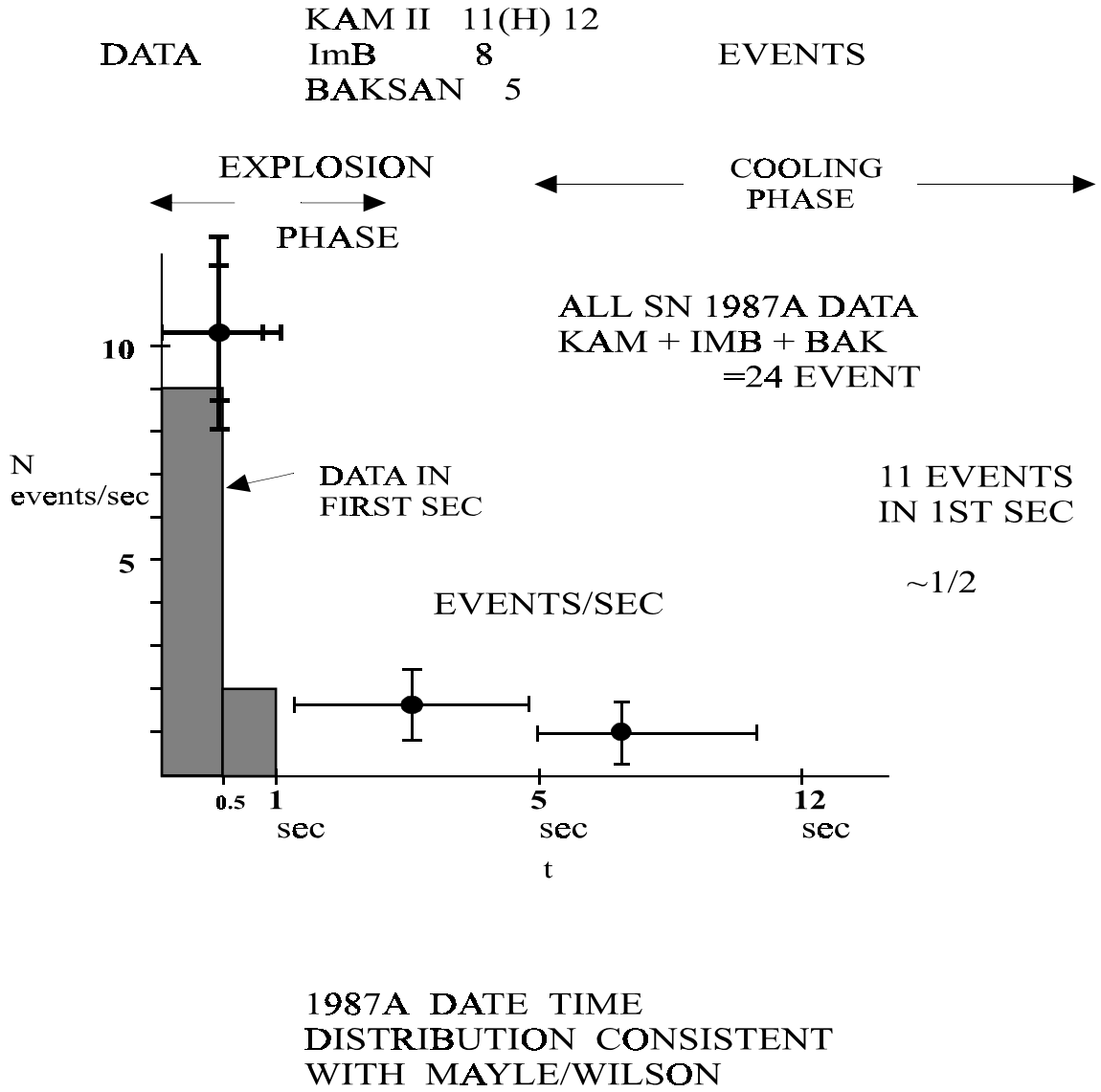


Figure 1b.

Table 1. Situation in the SNII Simulation Program

1. Some 1D calculations give explosions regularly (LLNL - J. Wilson et al). Some do not (ORNL...). The difference is not understood but could be due to the equation of State used. However, all agree that the most complete physics can be put ionto 1D calculation.

2. Some 2D calculations give explosion (A. Burrows, etc.), but the 1D modeler claims the physics in the code is marginal!

<u>Still a state of confusion as to what causes the explosion</u>

Perhaps detection of all neutrino flavor for a SNII will give the key information.

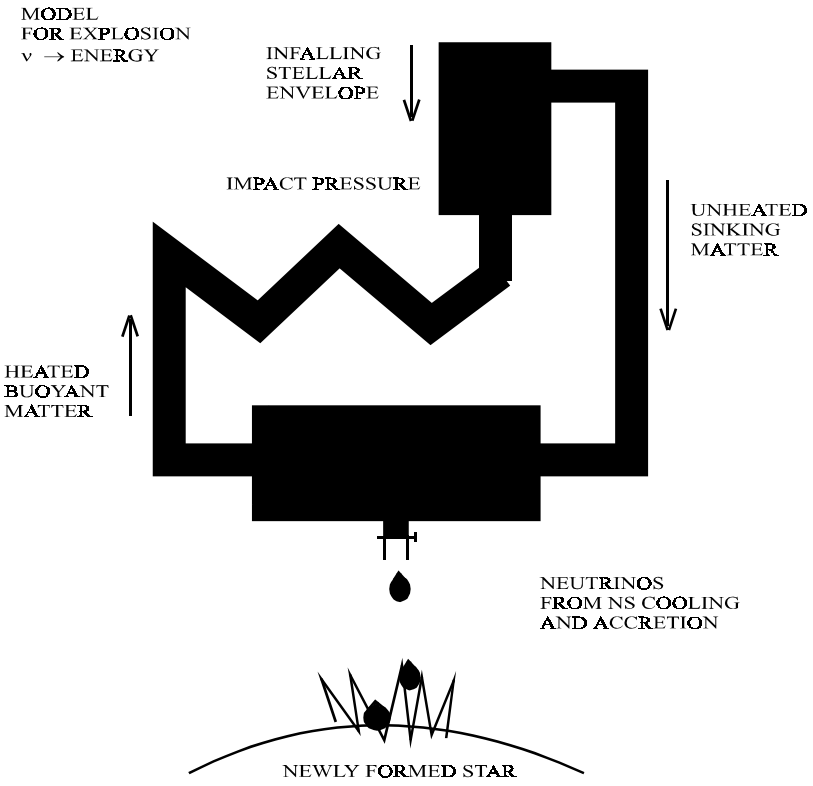


Figure 2.

Table 2. Features in Supernova Neutrino Signal (Ref. 4)

- "υ_μ" emission dominates (oscillation?) OMNIS
- *break-out flash* of υ_e´s (and sudden spectral change)
- slow (~20 ms) rise of $\overline{\upsilon}_e$ ´s (and υ_μ´s)
- *pulsations* in L_υ
- Drop the L's after "long-term" explosion due to reversal of accretion: Mechanism!
- Post break-out rise in average neutrino energy
- Long-term decay of L_υ and ε_υ (in 10's of seconds)
- Black hole formation (abrupt turn-off)
- Signatures of hydrodynamic instabilities ("convection")
- CAN DISCRIMINATE *DELAYED* EXPLOSION FROM *PROMPT*

3. Neutrino Signals From SN II Including Neutrino Mixing

SN II emit all types of neutrinos and anti-neutrinos with about the same luminosity per neutrino on anti-neutrino species. The expected energy spectrum is very different as can be seen in Fig. 3. Table 3 gives a set of options for mixing and tests [1].

The possible different models of neutrino mass is shown in Fig. 3. These different mass structures have important consequences for the MSW effect in the SN II and the search for the correct neutrino mass spectrum. It has been shown that future SN neutrino detects could resolve these different mass spectra [5],[6].

It is now clear that neutrino mixing can be very important in the supernova environment. This has been emphasized recently by Fuller et al [5] and by Dighe and Smirnov [6]. A very recent development was discussed at the Marina del Rey meeting by Sato [7] and C. Lunardini [8]. Figure 4 shows the schemata by Sato that would yield very different neutrino and neutrino spectra for future detectors to observe. This could lead to a remarkably sensitive measurement of the neutrino mixing parameters θ_{13} and θ_{23}.

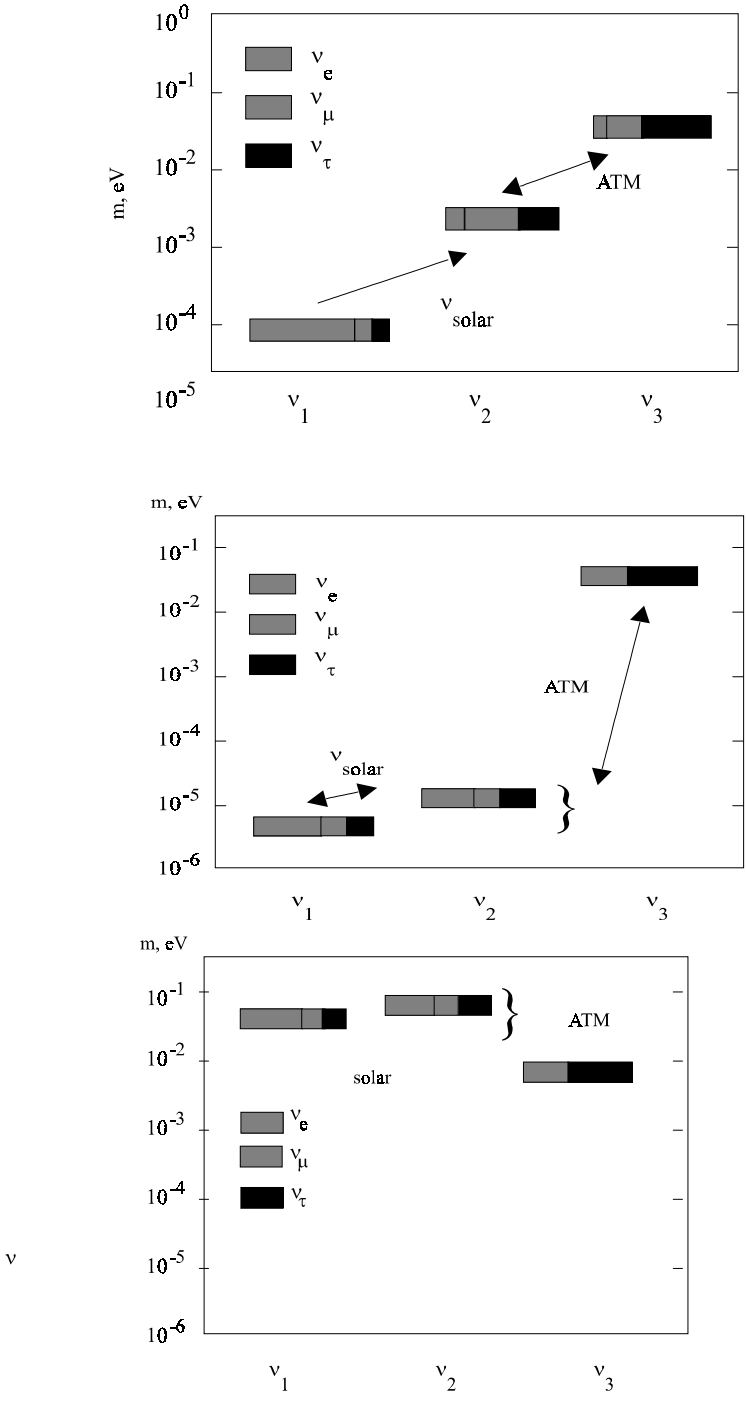
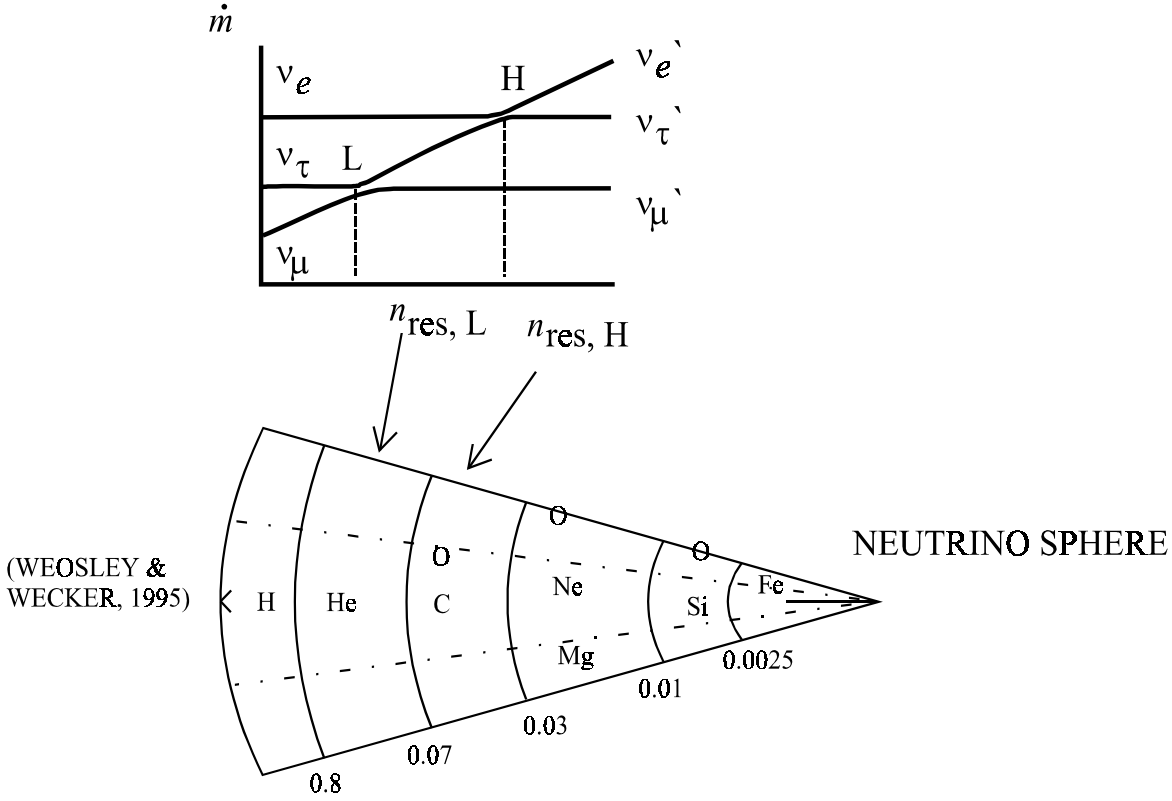


Figure 3. Different schemes for the Neutrino Mass spectrum adopted from Ref. 6.



RESONANCE CONDTITION: $n_e = n_{res} = \frac{1}{2\sqrt{2}G_F} \frac{\Delta m^2}{E} \cos 2\theta$

TWO RESONANCES (H at C+O shell, L at He shell)

THEN

HOW ARE ν_e , ν_μ, ν_τ COVERTED EACH OTHER?

HOW ARE THE ENERGY SPECTRA DEFORMED?

PRECEDING WORKS:

DIGHE, SMIRNOV hep-pk/9907423

Figure 4.

4. A Re-Analysis of 1987A Data

Because the ν_x spectrum is expected to be harder than the ν_e or $\bar{\nu}_e$, one signature for neutrino oscillation is to observe a hard component in the ν_e or $\bar{\nu}_e$ spectrum from the process $\nu_x \rightarrow \nu_e$ or $\bar{\nu}_x \rightarrow \bar{\nu}_e$. We can define the neutrino flux in the following way:

$$\langle \nu_e \rangle = (1 - p)\langle \nu_e \rangle_o + p\langle \nu_x \rangle_o \quad , \qquad (1)$$

$$\langle \bar{\nu}_e \rangle = (1 - \bar{p})\langle \bar{\nu}_e \rangle_o + \bar{p}\langle \bar{\nu}_x \rangle_o \quad , \qquad (2)$$

where $\langle \nu_e \rangle_o$, $\langle \bar{\nu}_e \rangle_o$, $\langle \nu_x \rangle_o$, $\langle \bar{\nu}_x \rangle_o$ denote the unmixed neutrino spectra and $p,\bar{p}$ the mixing fraction.

In vacuum, we can write $p = (1/2)\sin^2 2\theta$ and $\bar{p} = (1/2)\sin^2 2\theta$. Figure 6 shows the distorted $\bar{\nu}_e$ event spectrum for various values of $\bar{p}$. Thus, even a small mixing ($\bar{p} = 0.2$) causes an appreciable event spectrum distortion at high energy and should be readily detected in the next supernova event.

As is well known, there were 20 events recorded in SN1987A: 12 by the Kamiokande detector [9] and 8 by the IMB detector [11]. We first turn to the initial analysis of L. Krauss [11].

First we comment on the Kamiokande and IMB event populations:

1. The IMB detector had a strong bias against low energy events.
2. The mass of the IMB detector was about three times larger than the Kamiokande detector and thus was more sensitive to higher energy neutrino events that are less probable.
3. The Kamiokande detector had excellent low energy properties, as was later demonstrated by the observation of solar neutrinos.
4. Some of the pmt's for the IMB detector were not operational during the recording of SN1987A events.

Smirnov, Spergel, and Bahcall tried another analysis [12]. They fit the combined Kamiokande and IMB data with a model that allowed for $\nu_x \rightarrow \nu_e$ mixing as given by formula (2). They did not correct for the obvious differences in the Kamiokande and IMB event population (threshold, different detector, masses, possible differencesindetectionefficiency, etc.) but just added up the integral of the total event energies. They gave an exhaustive discussion of the different types of temperature distributions that may occur for the different neutrino flavors from the supernova emission. They expressed their results as a function of the mean energy of the ν_x neutrinos. Since most models gave this value to be 22 MeV or greater, we use that value in the results shown here. In Fig. 5, we have replotted the results of this analysis for the 95% confidence level reported in the paper. Note that most of the LMA and all of the vacuum oscillation (or "just so") is excluded.

One can be critical of this analysis due to the fact that no attempt was made to correct for the different experimental conditions in the Kamiokande and IMB experiments.

However, these results may well be a conservative lower limit, since corrections for the experimental differences will decrease the impact of the high energy events in IMB, as shown by the Krauss analysis.

Because of the problems of comparing the two populations of events illustrated in points 1 through 4 above, we propose that a sensible analysis should use the data set with the least bias. Based on the Kamiokande data alone, while this set has no event with an energy above 40 MeV, there is no reason why the detector would not have recorded such events had they been produced. In Fig. 6, we show the Kamiokande data and the predictions of neutrino mixing. The case $\bar{p} = 1/2$ is excluded to at least 99% confidence level. Even with a lower statistical sample, the conclusions of this analysis are as powerful as those of Smirnov, Spergel, and Bahcall [12]. We believe these results largely exclude the LMA solar neutrino solution.

Table 3.

Scheme	$\nu_\odot$	ν_{atmos}	**LBL**	**SBL**	**SN ν's**	**BBN**	**SNN**
I	Yes	Yes	Yes	No	√	OK	OK
3ν mixing	$\nu_e \to \nu_{\mu,\tau}$	$\nu_\mu \to \nu_\tau$	$\nu_\mu \to \nu_\tau$	$\nu_\tau \to \nu_e$			
No LSND				$\nu_\mu \to \nu_e$		$\nu_\mu \to \nu_e$	
				τ appearance?			
II	Yes	Yes	Yes	No?	√		??
4ν mixing	$\nu_e \to \nu_s$	$\nu_\mu \to \nu\tau$	$\nu_\mu \to \nu_\tau$	$\nu_e \to \nu_\tau$	Hot	D/N	Good or bad
$\nu_\mu \to \nu_\tau$	(No extra			τ appearance?	?	ν_e-spectrum	??
(Doublet)	N.C. signal)			$\nu_e \to \nu_\tau$?	Maybe!	?	
$\nu_\odot \to \nu_s$				$\nu_e \to \nu_\mu$?	Maybe!		
LSND							
III	Yes	Yes	Yes	No	√	?	r-process
4ν mixing	$\nu_e \to \nu_\mu$	$\nu_\mu \to \nu s$	$\nu_\mu \to \nu_s$	$m_{\nu\tau}$			constraint
$\nu_\mu \to \nu_s$				$\nu_\mu \to \nu_\tau$?		T of F	
Doublet					?		
No LSND							

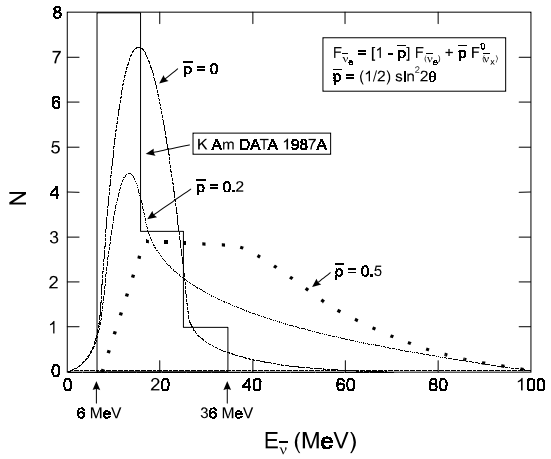


Figure 5. Limits from SN1987A (from Ref. 12).

Tests for new physics in neutrino science using different methods. LBL - long baseline beam; SBL - short baseline beam; SN υ - supernova II neutrinos; BBN - Big Bang nucleosynthesis; SNN - supernova nuclear synthesis.

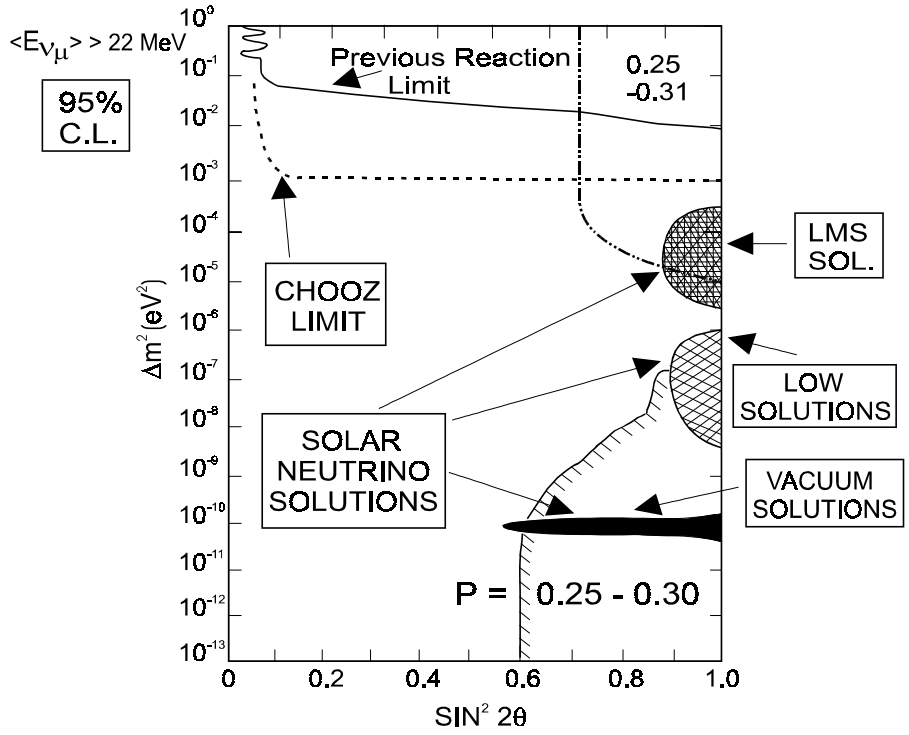


Figure 6. Comparison of the Kamiokande data with the neutrino oscillation (D. B. Cline, "Is the LMA solar-neutrino solution ruled out by SN1987A data?", Astro-Ph/0010339).

5. SUPERNOVA NEUTRINO DETECTOR AND EXPECTED RATES

In this section we discuss three new detectors as well as existing ones:

1. SNO
2. ICARUS (600T →4,800T)
3. OMNIS

The first detector has just turned on, the 600T ICARUS detector is being turned on and the OMNIS detector is being designed.

The methods that can be used to detect in real time supernova neutrinos υ_μ, υ_τ are given in Table 4. To detect $\bar{\upsilon}_e$ neutrinos the best process is

$$\bar{\upsilon} + p \rightarrow e^+ + n$$

which can be used by any detector with a hydrogen component such as H_20 or liquid scintillator. The detection of υ_e and υ_x is much more difficult. One new detector SNO can detect υ_e and υ_x interacting. The espected rates for these processes is given in Table 5 which was presented at the meeting by Reda Tafirout. This is an impressive table and shows the details in these calculations by the SNO group.

Table 4. Detection of υ_μ and υ_τ from Supernova Neutrinos in Real Time

Two possibilities:

a) $\upsilon_x + e^- \rightarrow \upsilon_x + e^-$

- Rate low because $\sigma_{\upsilon_x e}$ Small
- Background from $\upsilon_e e \rightarrow \upsilon_e e$

b) $\upsilon_x + N \rightarrow \upsilon_x + \acute{N}$ ‘

- N = D, C, O, NaCl, Pb, Fe....

$$N' \rightarrow n + X \left\langle \begin{array}{l} \text{SNO} \\ \text{SNO/OMNIS} \end{array} \right.$$

$$N' \rightarrow \gamma + X \left\langle \begin{array}{l} \text{Super K} \\ \text{LVD/ICARUS} \end{array} \right.$$

☐ Signal depends on υ_μ,υ_μ energy spectrum

Table 5. Supernova Detection Simulation for the SNO Detector (Ref. 1)

Simulation ingredients:

1. SNO energy threshold set to ~2 MeV

2. Use detected particle counts from 100 supernova bursts (in the case of the NCDs, expect ε=45% [NCD] + 12% [O_2O]

Number of Particles from 10 kpc supernova:

Neutrino reaction	**Type**	**SNO counts [ε = 100%]**	**SNO Counts [Monte Carlo]**
$\overline{\upsilon}_e + p_{H_20} \rightarrow n + e^+$ CC		356	331
$\overline{\upsilon}_e + p_{D_20} \rightarrow n + e^+$ CC		0.2	
$\overline{\upsilon}_e + p_{AV} \rightarrow n + e^+$		CC	5
$\overline{\upsilon}_e + d \rightarrow p + p + e^-$ CC		83	72
$\overline{\upsilon}_e + d \rightarrow n + n + e^+$ CC		53 [kB] 32 [O_2O] 138 [salt] 90 [NCD]	
$\upsilon_e + {}^{16}O \rightarrow + e\,{}^{16}F + e^-$	CC	1	
$\overline{\upsilon}_e + {}^{16}O \rightarrow + e\,{}^{16}F + e^+$	CC	3	
$\overline{\upsilon}_e + d \rightarrow \upsilon_e + p + n$	NC	36 12 [O_2O] 30 [salt] 20 [NCD]	
$\overline{\upsilon}_e + d \rightarrow \overline{\upsilon}_e + p + n$	NC	36 12 [O_2O] 32 [salt] 21 [NCD]	
" υ_μ " + $+ d \rightarrow \upsilon_\mu + p + n$	NC	192 60 [O_2O] 164 [salt] 110 [NCD]	
" υ_μ " $+ {}^{16}O \rightarrow (n, \gamma, n + \gamma)$	NC	7	
$\upsilon_e + e^- \rightarrow + \upsilon_e + e^-$	ES	26	20
$\overline{\upsilon}_e + e^- \rightarrow \overline{\upsilon}_e + e^-$	ES	9	8
" υ_μ " $+ e^- \rightarrow$ " υ_μ " $+ e^-$	ES	12	9
Total SNO SN counts:		917 606 [[D_2O] 804 [salt] 681 [NCD]	

TABLE 6: YIELDS OF SUPERNOVA NEUTRINO DETECTORS

Detect\or	Target Material	Fiducial Mass (Ton)	Target Element	Yield (υ_e)	Yield ($\bar{\upsilon}_e$)	Yield (υ_μ υ_τ $\bar{\upsilon}_\mu$ $\bar{\upsilon}_\tau$)
Super K	H_2O	**32000**	**p, e, O**	**180**	**8300**	**50**
LVD	CH_2	**1200**	**p, e, C**	**14**	**540**	**30**
SNO	H_2O	**1600**	**p, e, O**	**16**	**520**	**6**
SNO	D_2O	**1000**	**d, e, O**	**190**	**180**	**300**
ICARUS	**Argon**	**600T -> 4800T**	**^{40}Ar**	**400 to ~1600 full mixing**		
OMNIS	***Fe***	**8000**	***Fe***	**20***	**20***	**1200***
OMNIS	***Pb***	**2000**	***Pb***			
no osc.				**110****	**40****	**860****
υ_μ υ_e **osc.**				4420**	**40****	**640****

* Assumes same efficiency as in Smith 1997

** Assumes a single neutron detection efficiency of 0.6

Another new detector that is just starting is the ICARUS liquid argon tracking detector – UCLA is a charter member of this collaboration (the talk was given by Botella [14]). The full ICARUS detector is shown in Figure 7.

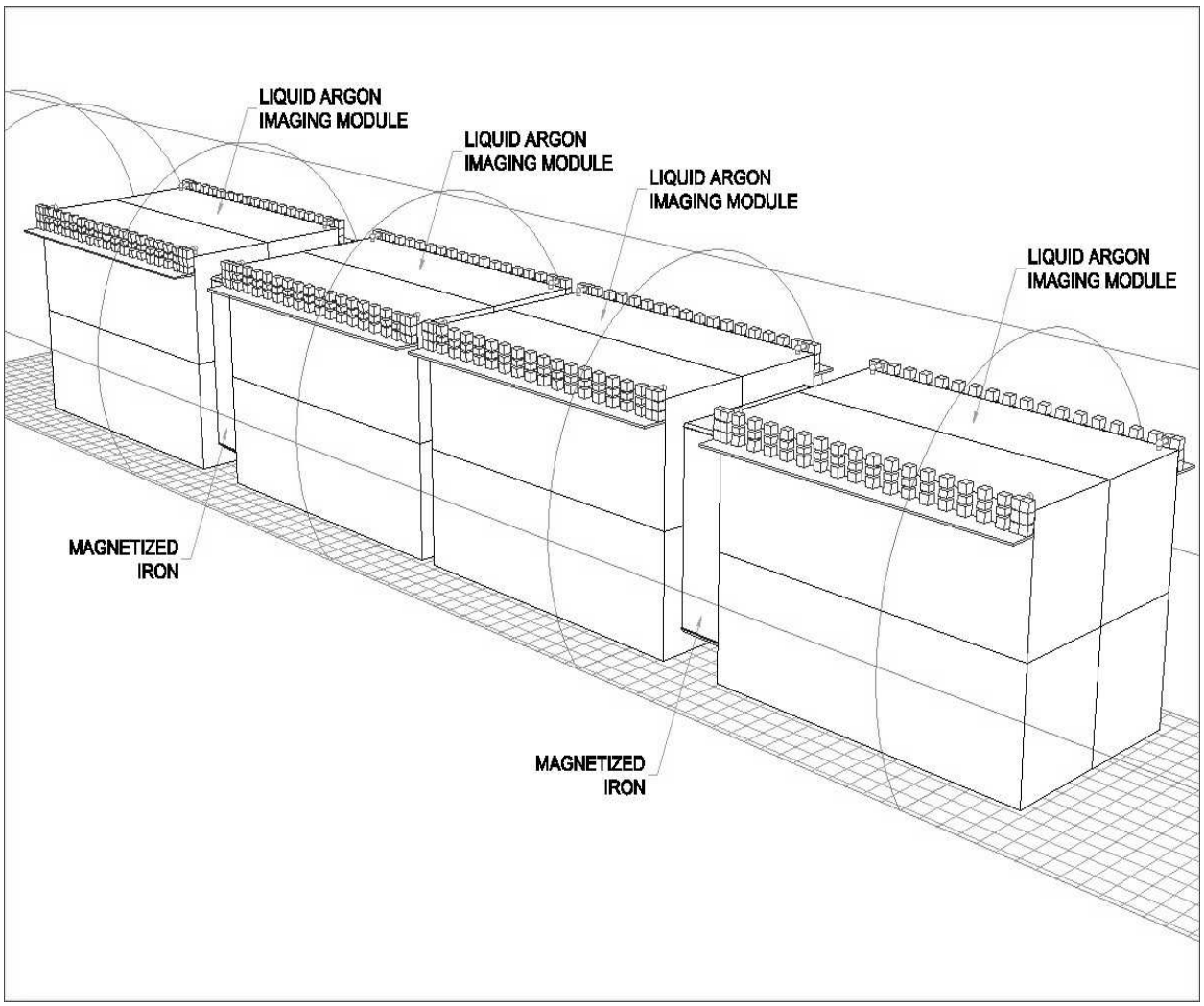


Figure 7. Schematic of the full 5000-ton ICARUS detector at Hall B at the LNGS (Ref. 14).

The ICARUS detector would provide a very clean υ_e signal since $\bar{\upsilon}_e$ interactions will be suppressed. The reactor is [14]

$$\upsilon_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-$$

with the *K decaying into several MeV photons that can be detected by Compton scattering. The expected rate for ICARUS and other detectors is given in Table 6. Note the large increase in rate for neutrino oscillations.

A very novel detector is being designed by UCLA, OSU, UCSD, LANL, University of Texas, and the LLNL group called OMNIS, and is shown schematically in Figure 8 for the Carlsbad Underground National Laboratory. This detector was just conceived by D. Cline and G. Fuller (see Ref. 15).

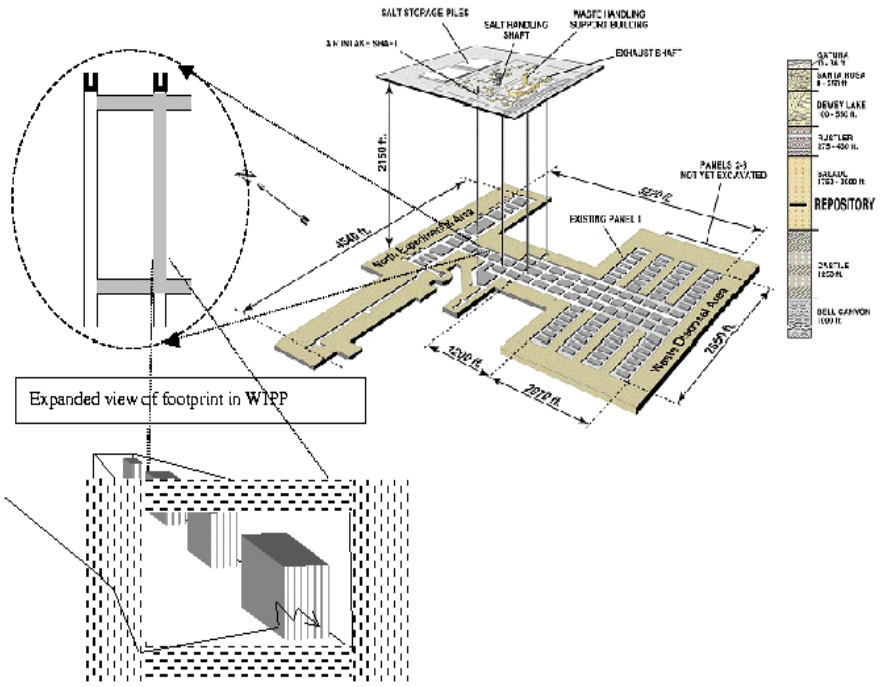


Figure 8. Schematic layout for OMNIS in a CUNL tunnel with a neutron detected.

The concept of this detector is to observe neutrons from the reactors

$$\upsilon_x + Pb \rightarrow X + \upsilon_x \quad \begin{matrix} \hookrightarrow 1n \\ \hookrightarrow 2n \end{matrix}$$

The $2n$ yield is very sensitive to neutrino oscillations as shown in Ref. 16. Their rates are given in Table 6.

Finally, there is a supernova watch system that was discussed by Mark Vagins and Kate Scholberg that is shown in Figure 9 (Ref. 17)

I wish to thank George Fuller for co-chairing the Marina del Rey meeting and Milla Baldo Ceolin for a splendid Venice meeting. I also want to thank D. L. MacLaughlan-Dumes for the splendid help at the Marina del Rey meeting.

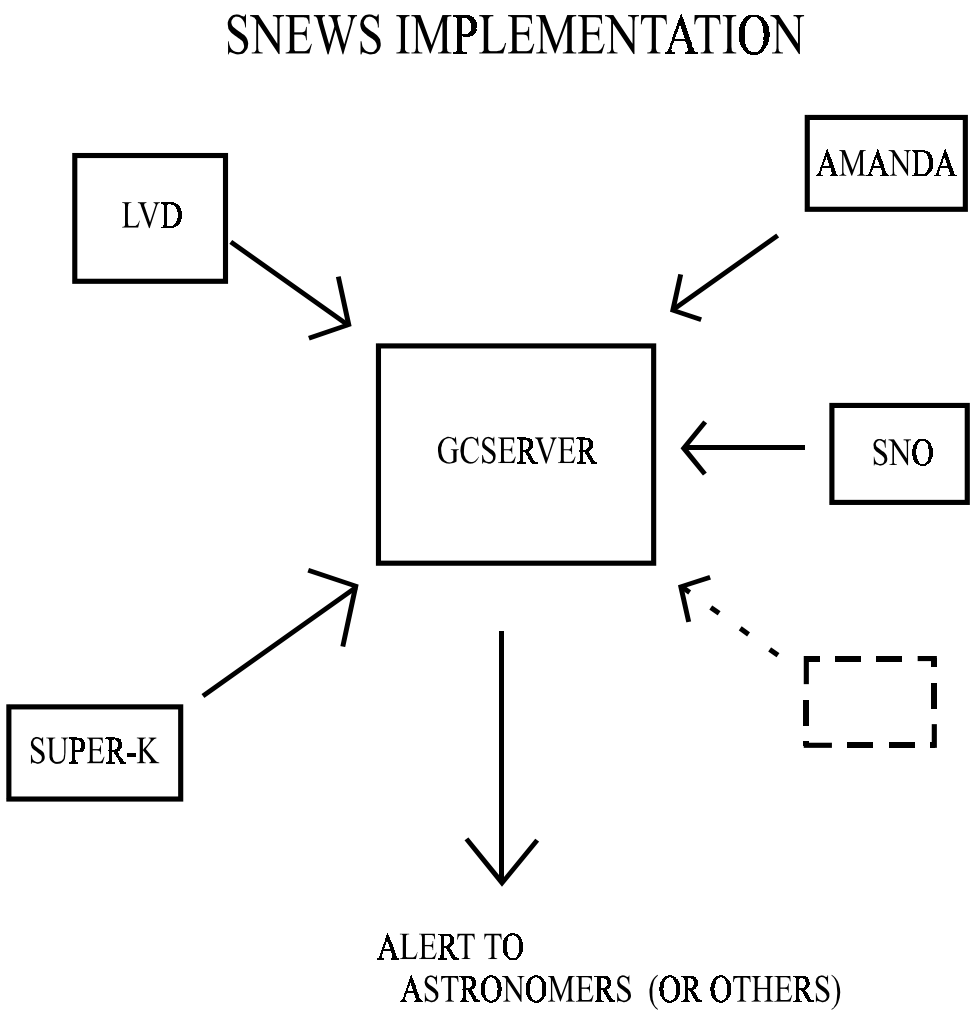

SNEWS IMPLEMENTATION
LVD
AMANDA
GCSERVER
SNO
SUPER-K
ALERT TO
ASTRONOMERS (OR OTHERS)

Figure 9.

REFERENCES

1. The various results can be found at the website:

   http://axpd24.pd.infn.it/conference2001/bollettino1.html.

   For a recent discussion see Cline, D. B., "Search for Relic Neutrinos and Supernova Bursts", in *Proceedings, Eighth Intl. Wkshp. on Neutrino Telescopes* (Venice, Feb. 23-26, 1999), ed. M. Baldo Ceolin, 1999, Col. II, pp. 309-320.

2. R. Mayle, J. R. Wilson, and D. B. Schramm, Astrophys. J. **318** (1987), 288.

3. S. Colgate, Ref. 1.

4. A. Burrows, Ref. 1.

5. G. M. Fuller, W. C. Haxton, and G. C. McLaughlin, Phys. Rev. D. **59** (1999) 085005 (and Refs. therein).

6. A. Dighe and A. Yu Smirnov, Phys. Rev. D. **62**, 033007.

7. K. Sato, Ref. 1.

8. C. Lunardini, Ref. 1.

9. Kamiokande Collaboration, K. S. Hirata et al., Phys. Rev. Lett. **58** (1987) 1490.

10. IMB Collaboration, R. M. Bionata et al., ibid. 1494.

11. M. Krauss, Nature (London) **329** (1987) 689.

12. A Yu. Smirnov, D. N. Spergel, and J. N. Bahcall, Phys. Rev. D.

13. R. Tafirout, Ref. 1.

14. A. Botella, ICARUS Collaboration, *"ICARUS-II. A Second-Generation Proton Decay Experiment and Neutrino Observatory at the Gran Sasso Laboratory"*, Proposal Vol. I & II, LNGS-94/99, 1994. ICARUS Collaboration, *"A first 600 ton ICARUS Detector Installed at the Gran Sasso Laboratory"*, Addendum to proposal, LNGS-95/10 (1995).

15. D. B. Cline, G. M. Fuller, W. P. Hong, B. Meyer, and J Wilson, Phys. Rev. D50, **720** (1994).

16. G. M. Fuller, W. C. Haxton, and G. C. McLaughlin, Phys. Rev. D. **59** (1999) 085005 (and Refs. therein).

17. See M. Vagins, K. Scholberg talk, Ref. 1.