Status of SN neutrino detectors

Walter Fulgione

IFSI-To and INFN
Torino - Italy

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Outline

• The neutrino signal
  • neutrino burst from core collapse SN
  • neutrino oscillations
  • open problems

• Core collapse neutrino detection
  • The strategy after SN1987A
  • Water Cherenkov
  • Long string Water Cherenkov
  • Scintillators
  • Liquid Ar
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  • Liquid Ar
Neutrino emission

..the shock spends energy, mostly by the photo dissociation of heavy nuclei into nucleons and stalls, before reaching the outer shells. This change in the matter composition increases the electron capture rate producing a first neutrino burst: the **shock break-out neutrino burst**: \( e^- + p \rightarrow n + \nu_e \)

The model predicts a second impulsive neutrino signal of the duration of \( \sim 500 \text{ ms} \) related to the **accretion** phase just before the explosion.

The **cooling** of the hot interior of the proto-neutron star proceeds by neutrino-pair production and diffusive loss of neutrinos of all three lepton flavors: \( e^- + e^+ \rightarrow \nu_i + \bar{\nu}_i \)
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The explosive nucleosynthesis process (r-process and vp-process) are thought to occur in this phase. They strongly depend upon the properties of the matter when the supernova was only a few seconds old, sampling directly the neutrino luminosity and temperatures.
1) As the density reaches $\rho_{\text{trap}} \sim 10^{12}$ g/cm$^3$, neutrinos interact efficiently with matter and are essentially trapped in the core. This determines duration and spectra of the $\nu$ emission (thermal spectra with average neutrino energy 10-20 MeV during some 10 seconds).

2) The proto-neutron star will liberate its binding energy radiating neutrinos of all flavors:
$$E_b = G_N M_{\text{NS}}^2 / R_{\text{NS}} \sim (1 - 4) \times 10^{53} \text{ erg}$$

3) Due to their different interaction with the stellar matter, neutrinos decouple at different stellar radii and then at different temperatures following the hierarchy:
$$T_{\nu_e} \leq T_{\nu_e} \leq T_{\nu_x}$$

with $\nu_x$ representing all non electron neutrino flavors.
neutrino oscillations

On the basis of our present knowledge of neutrino oscillation (disregarding effects due to $\nu - \bar{\nu}$ coherent interactions)...

.. In their path from the high density region where they are generated to the lower density one where they escape the star, neutrinos cross two resonance layers. 

H resonance ($\Delta m^2_{\text{atm}}, \theta_{13}$), $\rho_H \sim 10^3 - 10^4$ g/cm$^3$

L resonance ($\Delta m^2_{\text{sol}}, \theta_{\text{sol}}$), $\rho_L \sim 10 - 100$ g/cm$^3$

..mixing their energy spectra.

The temperature hierarchy at the detector will be modified depending on the values of the mixing angle $\theta_{13}$ and on the $\nu$ mass hierarchy, both unknown.

open problems

While successful in nature, in most numerical supernova models the shock stalls, so that the fate of the entire star is to produce a black hole, but no optical supernova.

Stars of 8-11 solar masses may be relatively easy to explode. These stars, however, do not eject enough mass to explain the origin of abundant heavy elements such as O, Mg, Si, S and Ca.)
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Core collapse dynamics and explosion mechanism must be stamped in the features of the neutrino signal.
• The neutrino signal
  • neutrino burst from core collapse SN
  • neutrino oscillations
  • open problems

• Core collapse neutrino detection
  • The strategy after SN1987A
  • Water Cherenkov
  • Long string Water Cherenkov
  • Scintillators
  • Liquid Ar
Core collapse neutrino detection

G.V. Domogatsky and G.T. Zatsepin,
in Proc. of the 9th ICRC, London, 1965

$\bar{\nu}_e + p \rightarrow e^+ + n$

$n + p \rightarrow d + \gamma [2.2\text{MeV}]$

Golden channel: inverse beta decay
Main difficulties

Small cross section.
For scintillators and water Cherenkov detectors and for a "1987A-like" core collapse at 10 kpc.

\[ N_{ev} \approx 0.2 \pm 0.3 \times \frac{M}{1 \text{ ton}} \times \frac{D}{10 \text{ kpc}}^{-2} \]

hundreds tons of target are required to observe the entire Galaxy.

The rate of gravitational collapses in our Galaxy is 2±1 event/100 years.

The absence of a firm model.
Which does not allow a fine tuning of the \( \nu \) burst search.
new strategy

..after the detection of neutrinos from SN1987A:
new strategy

..after the detection of neutrinos from SN1987A:

neutrino detectors must be able to recognize SN explosions independently of any other signal

• The only neutrino burst detected (SN1987A) have been recognized thanks to its correlation with the electromagnetic signal.  
• We need experiments able to disentangle the $\nu$ burst in the absence of any other signal and promptly, to be used as a trigger for all others detectors (gw, em and particle detectors), allowing the study of this rare event since its first instant.

SNEWS
..after the detection of neutrinos from SN1987A:

**neutrino detectors must be able to recognize SN explosions independently of any other signal**

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**SNEWS**

The ideal experiment should have the capabilities to measure:

- \( L_{\nu_e}(t), L_{\bar{\nu}_e}(t), L_{\nu_x}(t) \);
- \( E_{\nu_e}(t), E_{\bar{\nu}_e}(t), E_{\nu_x}(t) \); and
- pointing

**Table 1. Supernova neutrino detector types and their primary capabilities.**

<table>
<thead>
<tr>
<th>Detector type</th>
<th>Material</th>
<th>Energy</th>
<th>Time</th>
<th>Point</th>
<th>Flavour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scintillator</td>
<td>C, H</td>
<td>y</td>
<td>y</td>
<td>n</td>
<td>( \bar{\nu}_e )</td>
</tr>
<tr>
<td>Water Cherenkov</td>
<td>H\textsubscript{2}O</td>
<td>y</td>
<td>y</td>
<td>y</td>
<td>( \bar{\nu}_e )</td>
</tr>
<tr>
<td>Heavy water</td>
<td>D\textsubscript{2}O</td>
<td>NC: n</td>
<td>y</td>
<td>n</td>
<td>All</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CC: y</td>
<td>y</td>
<td>y</td>
<td>( \nu_e, \bar{\nu}_e )</td>
</tr>
<tr>
<td>Long string water Cherenkov</td>
<td>H\textsubscript{2}O</td>
<td>n</td>
<td>y</td>
<td>n</td>
<td>( \bar{\nu}_e )</td>
</tr>
<tr>
<td>Liquid argon</td>
<td>Ar</td>
<td>y</td>
<td>y</td>
<td>y</td>
<td>( \nu_e )</td>
</tr>
<tr>
<td>High Z/neutron</td>
<td>Pb, Fe</td>
<td>y</td>
<td>y</td>
<td>n</td>
<td>All</td>
</tr>
<tr>
<td>Radio-chemical</td>
<td>( ^{37}\text{Cl}, ^{127}\text{I}, ^{71}\text{Ga} )</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>( \nu_e )</td>
</tr>
</tbody>
</table>
**Water Cherenkov**

**Super-Kamiokande**

Fig. 6.—Probability of detecting supernovae assuming a specific supernova model at SK. Full (100\%) detection probability is retained out to around 100 kpc.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{\nu}_e + p \rightarrow n + e^+$</td>
<td>(88%/89%), (1)</td>
</tr>
<tr>
<td>$\nu_e + e^- \rightarrow \nu_e + e^-$</td>
<td>(1.5%/1.5%), (2)</td>
</tr>
<tr>
<td>$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$</td>
<td>(&lt;1%/&lt;1%), (3)</td>
</tr>
<tr>
<td>$\nu_x + e^- \rightarrow \nu_x + e^-$</td>
<td>(1%/1%), (4)</td>
</tr>
<tr>
<td>$\nu_e + ^{16}O \rightarrow e^- + ^{16}F$</td>
<td>(2.5%/&lt;1%), (5)</td>
</tr>
<tr>
<td>$\bar{\nu}_e + ^{16}O \rightarrow e^+ + ^{16}N$</td>
<td>(1.5%/1%), (6)</td>
</tr>
<tr>
<td>$\nu_x + ^{16}O \rightarrow \nu_x + O^<em>/N^</em> + \gamma$</td>
<td>(5%/6%), (7)</td>
</tr>
</tbody>
</table>

**SEARCH FOR SUPERNOVA NEUTRINO BURSTS AT SUPER-KAMIOKANDE**

Super-K: Time variation measurement by $\bar{\nu}_e + p$

Assuming a supernova at 10kpc.

$\bar{\nu}_e p \rightarrow e^+ n$ events give direct energy information ($E_e = E_\nu - 1.3\text{MeV}$).

**Time variation of event rate**

**Time variation of mean energy**

Enough statistics to discuss model predictions
Pointing

Super-K: $\nu$+e scattering events

SN at 10kpc

Direction of supernova can be determined with an accuracy of $\sim$5 degree.

Spectrum of $\nu$+e events can be statistically extracted using the direction to supernova.

Neutrino flux and spectrum from Livermore simulation
Super-K: Neutronization burst \((e^- + p \rightarrow n + \nu_e)\)

SN at 10kpc

Neutrino flux and spectrum from Livermore simulation

Event rate of \(\bar{\nu}_e + p\) events

Event rate of neutronization burst (forward peaked \(\nu + e^-\) scattering events)

- No oscillation
- Normal \(P_H = 1\) or Inverted hierarchy
- Normal hierarchy \(P_H = 0\)

\(P_H\): crossing probability at H resonance (\(P_H = 0\): adiabatic)

Number of events from neutronization burst is 0.9~6 events for SN@10kpc.
\(\bar{\nu}_e p\) events during this 10msec is about 8 - 30 events.

N.H. +adiamatic case: neutronization=0.9ev., \(\bar{\nu}_e p = 14\) ev.(1.4 for SN direction).
- The detection comes from increase in background counts across the entire array.
- Principal detection channel is IBD. The observable signal is totally dominated by events where a $e^+$ shower yields a single photoelectron hit in a single DOM.
- Effective volume, $V_{\text{eff}}$, approximate a sphere around each module of 5 m radius.

- Currently, with ~ 3500 deep ice modules (59/86 strings) detector mass ~ 2 Mton. (Full IceCube ~ 5000 modules detector mass ~ 3 Mton)

$$V_{\text{eff}} \propto N_\gamma \cdot A \cdot \Lambda_{\text{abs}} \propto E_{e^+} \cdot A \cdot \Lambda_{\text{abs}} \propto E_\nu^3 \cdot A \cdot \Lambda_{\text{abs}}$$

- Neutrino effective volume is proportional to:
  - $E_\nu^3$: 2 powers from $\sigma$ 1 power from $e^+/e^-$ track length;
  - $\Lambda$ the optical pathlength in the ice that depends on depth (each module may be treated independently);
  - $A$, the photocathode area of the OM.

- Thus, detection is sensitive to neutrino energy spectra - or, stated another way, effective volumes are all dependent on SN models / oscillations, & c.
Disadvantages
➡ you have no pointing or energy reconstruction.

Advantages
➡ enormous volume provides high-statistics measurement.

Time binning can be made fine: the hardware limit being 1.6ms

➡ Signal from 1987A SN at galactic center would produce 475000 excess counts in ~10 sec window on a background of $12 \times 10^6$ counts from noise - $S/N \sim 150$ in full IceCube;
Scintillators - modular
LVD is an array of 840 counters 1.5 $m^3$ each, total target: 1000 ton of $C_nH_{2n+2}$, 900 ton of Fe divided in three independent, identical "towers".

Main purpose of LVD is detecting neutrinos from core collapse SN in our Galaxy.

\[
\overline{\nu}_e + p \rightarrow e^+ + n \\
(n,p) \rightarrow d + \gamma
\]
\[
\nu_e + ^{12}C \rightarrow ^{12}N + e^- \\
\overline{\nu}_e + ^{12}C \rightarrow ^{12}B + e^+ \\
\nu_i + ^{12}C \rightarrow \nu_i + ^{12}C + \gamma
\]
\[
\nu_e + ^{56}Fe \rightarrow ^{56}Co + e^- \\
\overline{\nu}_e + ^{56}Fe \rightarrow ^{56}Mn + e^+ \\
\nu_i + Fe \rightarrow \nu_i + Fe + \gamma
\]
The detector sensitivity has been evaluated assuming the signal from SN1987A as a standard candle:

- total emitted energy $E_b = 2.4 \times 10^{53} \text{ erg}$;
- average $\bar{\nu}_e$ energy = 14 MeV
- $T_{\nu_X} / T_{\bar{\nu}_e} = 1.1$


**STAND ALONE**

(<1 fake event/100 years)

\[
E_{\text{cut}} = 7 \text{ MeV} \quad \text{green}
\]

\[
E_{\text{cut}} = 10 \text{ MeV} \quad \text{blue}
\]


**SNEWS**

(<1 fake event/month)

\[
E_{\text{cut}} = 7 \text{ MeV} \quad \text{green}
\]

\[
E_{\text{cut}} = 10 \text{ MeV} \quad \text{blue}
\]

The ν observatory reached its final configuration at the end of 2000.

..because of its modularity, LVD can be serviced during data taking.

In case of failures, the telescope automatically remove the not properly working region and reconfigures itself at lower mass.

The effect is to adjust dynamically the LVD active mass, $M_{\text{act}}$.
April 6th 2009

LVD monitoring task

Trigger rate

muon rate
SEARCH FOR $\nu$ BURSTS

<table>
<thead>
<tr>
<th>Run</th>
<th>Start</th>
<th>End</th>
<th>Time (days)</th>
<th>Uptime (%)</th>
<th>Mass (t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>June 6$^{th}$ 1992</td>
<td>May 31$^{st}$ 1993</td>
<td>285</td>
<td>60</td>
<td>310</td>
</tr>
<tr>
<td>2</td>
<td>Aug.4$^{th}$ 1993</td>
<td>Mar.11$^{th}$ 1995</td>
<td>397</td>
<td>74</td>
<td>390</td>
</tr>
<tr>
<td>3</td>
<td>Mar.11$^{th}$ 1995</td>
<td>Apr.30$^{th}$ 1997</td>
<td>627</td>
<td>90</td>
<td>400</td>
</tr>
<tr>
<td>4</td>
<td>Apr.30$^{th}$ 1997</td>
<td>Mar.15$^{th}$ 1999</td>
<td>685</td>
<td>94</td>
<td>415</td>
</tr>
<tr>
<td>5</td>
<td>Mar.16$^{th}$ 1999</td>
<td>Dec.11$^{th}$ 2000</td>
<td>592</td>
<td>95</td>
<td>580</td>
</tr>
<tr>
<td>6</td>
<td>Dec.12$^{th}$ 2000</td>
<td>Mar.24$^{th}$ 2003</td>
<td>821</td>
<td>98</td>
<td>842</td>
</tr>
<tr>
<td>7</td>
<td>Mar.25$^{th}$ 2003</td>
<td>Feb.4$^{th}$ 2005</td>
<td>666</td>
<td>&gt;99</td>
<td>881</td>
</tr>
<tr>
<td>8</td>
<td>Feb.4$^{th}$ 2005</td>
<td>May 31$^{st}$ 2007</td>
<td>846</td>
<td>&gt;99</td>
<td>936</td>
</tr>
<tr>
<td>9</td>
<td>May 31$^{st}$ 2007</td>
<td>Apr.30$^{th}$ 2009</td>
<td>699</td>
<td>&gt;99</td>
<td>967</td>
</tr>
<tr>
<td>$\Sigma$</td>
<td>June 6$^{th}$ 1992</td>
<td>Apr.30$^{th}$ 2009</td>
<td>5618</td>
<td>94</td>
<td></td>
</tr>
</tbody>
</table>

90% C.L. Upper Limit to gravitational stellar collapses in the Galaxy is 0.15 /year
The old trigger system (pre ~2008) had a SN trigger, the normal threshold was $E_{\text{thr}} \sim 0.9\text{MeV}$.

After purifying the detector (i.e. removing radioactive isotopes) the trigger threshold is now $E_{\text{thr}} \sim 0.35\text{ MeV}$ and the SN trigger is not longer used.

An algorithm, similar to the old SN trigger, runs online to notify shift personnel of a possible SN event.

---

**KamLAND**

<table>
<thead>
<tr>
<th>Reaction</th>
<th># Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{\nu}_e + p \rightarrow e^+ + n$</td>
<td>~300</td>
</tr>
<tr>
<td>$\nu_x + p \rightarrow \nu_x + p$ (for 0.2MeV thr)</td>
<td>~270</td>
</tr>
<tr>
<td>$\nu_x + ^{12}\text{C} \rightarrow \nu_x + ^{12}\text{C}(15.11\text{MeV})$</td>
<td>~60</td>
</tr>
</tbody>
</table>

Assuming 1KT and “Standard Supernova”

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Scintillators - single volume

Thanks to Patrick Decowski

Walter.Fulgione@gmail.com
Thanks to:
A.Chavarria, A.Ianni and A.Razeto
The golden channel gives the temperature of the $\bar{\nu}_e$ (at the detector).

The $\nu_x + p$ channel can give the temperature of $\nu_x$ (at the neutrinosphere), other N.C. detection channels cannot break the degeneracy:

$$N \sim E_{tot} \frac{\langle \sigma \rangle}{T}$$

Borexino on-line

The system consists of the acquisition of individual pulses in the energy region of the neutron capture... Noise cuts are made on the pulses based on the position and stability of the baseline.

Basically, a list of candidate pulses is considered a supernova signal if it has six or more pulses where the time between subsequent pulses is less than 10 s and the time difference between first and last pulse is > 2 ms (to avoid cosmogenic neutrons).

...with this settings, the system is able to trigger on only 6 neutron captures, which corresponds to ≈ 1/10 of the expected signal from a “typical” galactic supernova and therefore, even a supernova considerably weaker or further away can potentially be detected.

55 clusters with m=4 during a 34 days test
SNO studied $\nu_e$ through:

$$\nu_e + d \rightarrow e^- + p + p$$

ICARUS T600 is going to start data taking during 2009:

$$\nu_e + {}^{40}\text{Ar} \rightarrow {}^{40}\text{K} + e^-$$

n.c.: $\nu_x + p \rightarrow \nu_x + p$  Borexino

c.c.: $\nu_e + {}^{40}\text{Ar} \rightarrow {}^{40}\text{K} + e^-$  Icarus

c.c.: $\bar{\nu}_e + p \rightarrow e^+ + n$  LVD
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$$\nu_e + ^{40}\text{Ar} \rightarrow ^{40}\text{K} + e^-$$

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c.c.: $\nu_e + ^{40}\text{Ar} \rightarrow ^{40}\text{K} + e^-$  Icarus

c.c.: $\bar{\nu}_e + p \rightarrow e^+ + n$  LVD

The number of expected events in 600 tons of Ar is not so big, nevertheless nobody knows the distance of the next galactic SN.
Thank you