Learning about Supernova Neutrinos with Xenon Dark Matter Detectors

Irene Tamborra
Niels Bohr Institute, University of Copenhagen

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• Neutrinos from core-collapse supernovae.
• Dual phase xenon detectors.
• SN neutrino signal in a dual-phase xenon detector. What can we learn?
• Conclusions.

Based on work in collaboration with R. Lang, C. McCabe, S. Reichard and M. Selvi (arXiv: 1606.09243).
General Features of Neutrino Signal

![Graph of neutrino signal](image)

Figure: 1D spherically symmetric SN simulation (M=27 M\(_{\odot}\)), Garching group.

- **ν\(_e\) Burst**
  - Large \(\nu_e\) luminosity peak

- **Accretion**
  - Large fluxes.
  - Large \(\nu_e - \bar{\nu}_e\) flux difference.

- **Cooling**
  - Smaller fluxes.
  - Small \(\nu_e - \bar{\nu}_e\) flux difference.

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Detectors Sensitive to SN Neutrinos

Expected number of events for a SN at 10 kpc and dominant flavor sensitivity in parenthesis.

Recent review papers: Scholberg (2012), Mirizzi, Tamborra, Janka, Scholberg et al. (2016).
Next Generation Large Scale Detectors

- Cherenkov telescopes ($\nu_e$)
  - Hyper-Kamiokande ($10^5$)
  - IceCube-Gen2
  - PINGU ($10^6$)

- Liquid Argon detectors ($\nu_e$)
  - DUNE (3000)

- Scintillation detectors ($\nu_x$)
  - RENO-50 (5400)
  - JUNO (6000)

- Dark Matter Detectors ($\nu_{e,x}, \nu_{\ell,x}$)
  - e.g., DARWIN (700)

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Dual-Phase Xenon Dark Matter Detectors

XENON1T (2 tons). Commissioning.

XENONnT & LZ (7 tons). In design.

DARWIN (40 tons). Early plans.

Are these detectors sensitive to SN neutrinos?
Principles and applications of a neutral-current detector
for neutrino physics and astronomy

A. Drukier and L. Stodolsky

Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik,
Munich, Federal Republic of Germany

(Received 21 November 1983)

We study detection of MeV-range neutrinos through elastic scattering on nuclei and identification of the recoil energy. The very large value of the neutral-current cross section due to coherence indicates a detector would be relatively light and suggests the possibility of a true “neutrino observatory.” The recoil energy which must be detected is very small (10–100 eV), however. We examine a realization in terms of the superconducting-grain idea, which appears, in principle, to be feasible through extension and extrapolation of currently known techniques. Such a detector could permit determination of the neutrino energy spectrum and should be insensitive to neutrino oscillations since it detects all neutrino types. Various applications and tests are discussed, including spallation sources, reactors, supernovae, and solar and terrestrial neutrinos. A preliminary estimate of the most difficult backgrounds is attempted.
Supernova observation via neutrino-nucleus elastic scattering in the CLEAN detector

C. J. Horowitz*
Nuclear Theory Center and Department of Physics, Indiana University, Bloomington, Indiana 47405, USA

K. J. Coakley
National Institute of Standards and Technology, Boulder, Colorado 80305, USA

D. N. McKinsey
Physics Department, Princeton University, Princeton, New Jersey 08544, USA

(Received 5 February 2003; published 28 July 2003)

Development of large mass detectors for low-energy neutrinos and dark matter may allow supernova detection via neutrino-nucleus elastic scattering. An elastic-scattering detector could observe a few, or more, events per ton for a galactic supernova at 10 kpc (3.3 × 10^20 m). This large yield, a factor of at least 20 greater than that for existing light-water detectors, arises because of the very large coherent cross section and the sensitivity to all flavors of neutrinos and antineutrinos. An elastic-scattering detector can provide important information on the flux and spectrum of ν_e and ν_x from supernovae. We consider many detectors and a range of target materials from 4He to 208Pb. Monte Carlo simulations of low-energy backgrounds are presented for the liquid-neon-based Cryogenic Low Energy Astrophysics with Noble gases detector. The simulated background is much smaller than the expected signal from a galactic supernova.

See also Beacom, Farr & Vogel, PRD (2002).
Dual-Phase Xenon Detectors

S1 = Prompt scintillation light (in LXe).
S2 = Ionization charge signal converted to scintillation signal (in GXe).

Recoil energy from a WIMP particle: \( E_R \sim 2.4 \text{ keV} \left( \frac{m_{DM}}{5 \text{ GeV}} \right)^2 \)
Recoil energy from a SN neutrino: \( E_R \sim 2.4 \text{ keV} \left( \frac{E_\nu}{12 \text{ MeV}} \right)^2 \)

Comparable recoil energies.

Because of low background, all Xe instrumented volume can be used for SN neutrinos.
Supernova Neutrino Inputs

Four 1D simulations to gauge astrophysical uncertainty of the expected signal:
- Two progenitor masses ($11$ & $27 M_{\text{Sun}}$)
- Two equations of state (LS220 & Shen EoS).

Figure: 1D spherically symmetric SN simulations, Garching group.
Scattering Rates

Recoil differential rate

\[
\frac{d^2 R}{dE_{R}d\theta_{ph}} = \sum_{\nu} N_{Xe} \int_{E_{\nu}^{\text{min}}}^{E_{\nu}} dE_{\nu} f_{\nu} \sigma(E_{\nu}, \theta_{ph}) \frac{d\sigma}{dE_{R}}
\]

\[E_{\nu}^{\text{min}} \approx \sqrt{m_{N}E_{R}/2}\]

Coherent elastic neutrino-nucleus cross-section

\[
\frac{d\sigma}{dE_{R}} = \frac{G_{F}^{2}m_{N}^{2}q_{W}^{2}}{4\pi} \left(1 - \frac{m_{N}E_{R}}{2E_{R}}\right) F^{2}(E_{R})
\]

\[Q_{W} = 3N - (1 - 4\sin^{2}\theta_{W})Z\]

\[F(E_{R}) = \frac{3\nu_{s}(q_{r})}{q_{r}} \exp \left(-\frac{(q_{r})^{2}}{2}\right)\]

Differential rate as a function of the measured $S_{1}$ and $S_{2}$ signals

\[
\frac{d^2 R}{dS_{1}dS_{2}} = \int d\theta_{ph} dE_{R} \text{pdf} \langle S_{1}, S_{2} | E_{R} \rangle \frac{d^2 R}{dE_{R}d\theta_{ph}}.
\]
Different progenitors are distinguishable. Neutrino light-curve is reconstructable.
Observable Signals

The measured signal is the one in the S1 and S2 channels rather than the recoil spectrum.

An S2-only search is optimal for SN neutrinos. By combining S1&S2, event rate is ~ 2-3 times lower.
S2 background rate is small compared to signal.

**Background** (XENON10, XENON 100): $O(10^{-2})$ events/tonne/s.

**Signal:** 1-2.5 events/tonne/s.
What Could We Learn?
DARWIN will be sensitive to a SN burst up to the Small Magellanic Cloud.
DARWIN will be able to clearly reconstruct the neutrino light-curve and to differentiate among phases of neutrino signal. Partial sensitivity with XENONnT/LZ.

Excellent timing resolution: $\mathcal{O}(100)\mu s$. 
Neutrino Spectral Information

Ansatz on flux parametrization for time-integrated flux:

$$A_T \xi_T \left( \frac{E_\nu}{\langle E_T \rangle} \right)^{\alpha_T} \exp \left( -\frac{(1 + \alpha_T)E_\nu}{\langle E_T \rangle} \right) \text{ with } \alpha_T = 2.3$$

Excellent reconstruction of neutrino properties with DARWIN. Good prospects for XENON1T.
Excellent reconstruction of energy emitted into neutrinos with DARWIN. Good for XENON1T.
### Summary of Physics Reach

For a SN at 10 kpc from Earth:

<table>
<thead>
<tr>
<th></th>
<th>High significance discovery</th>
<th>Light curve reconstruction</th>
<th>Total nu-energy reconstruction</th>
<th>Nu-spectrum reconstruction</th>
</tr>
</thead>
<tbody>
<tr>
<td>XENON1T (2t)</td>
<td>✓</td>
<td>X</td>
<td>∼</td>
<td>∼</td>
</tr>
<tr>
<td>XENONnT/LZ (7t)</td>
<td>✓</td>
<td>~ X</td>
<td>~ ✓</td>
<td>~ ✓</td>
</tr>
<tr>
<td>DARWIN (40t)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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Table: Courtesy of C. McCabe.
Conclusions

• First self-consistent modeling of the SN neutrino signal in dual-phase Xe detectors.

• SN neutrinos will be detectable through proportional scintillation signal (S2) with low-energy threshold and negligible background.

• Features in the neutrino light curve can be discriminated with next-generation Xe detectors.

• Neutrino emission properties can be reconstructed.

• Xenon detectors sensitive to all neutrino flavors. Complementary information wrt to dedicated flavor-sensitive detectors.
Thank you for your attention!