

Learning about Supernova Neutrinos with Xenon Dark Matter Detectors

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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

spherically symmetric Garching model with explosion triggered by hand during 0.5–0.6 ms [168,169].

Figure: 1D spherically symmetric SN simulation (M=27 M_{sun}), Garching group.

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

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

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Dual-Phase Xenon Dark Matter Detectors

Are these detectors sensitive to SN neutrinos?

Neutrino-Nucleus Elastic Scattering

borators, ' some intriguing indications, and some ambi-

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tric filler material in a magnetic field. The field and tem-

Principles and applications of a neutral-current detector for neutrino physics and astronomy

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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 $(10-10)$ 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 spallationsources, reactors, supernovas, and solar and terrestrial neutrinos. A preliminary estimate of the most difficult backgrounds is attempted.

Neutrino-Nucleus Elastic Scattering

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Supernova observation via neutrino-nucleus elastic scattering in the CLEAN detector

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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 $(3.1 \times 10^{20} \text{ m})$. 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_n and ν_r from supernovae. We consider many detectors and a range of target materials from 4 He to 208 Pb. 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.

> Alternatively, it may be possible to detect #*^x* using inelastic excitations of Pb. Proposals include using lead perchlor-

See also Beacom, Farr & Vogel, PRD (2002).

Dual-Phase Xenon Detectors

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_{sun})
- Two equations of state (LS220 & Shen EoS).

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

Scattering Rates and the proportion of the property of the state yields the S1 (or prompt scintillation) signal. An electric **The interaction of a SCATTEMIO RATES** cleus through CES causes the nucleus to recoil with the nucleus to recoil with the nucleus to recoil with the n *d*²*R dE*R*dt*pb cleus through CES causes the nucleus to recoil with the nucleus through contract with the nucleus to recoil with t energy *E*R. The di↵erential scattering rate in terms of *E*^R is given by

Recoil differential rate drift field of size *O*(1) kV/cm draws the ionization electrons to the liquid-gas interface. A second electric field of energy *E*R. The di↵erential scattering rate in terms of *E*^R is given by

The neutrino transport in SN hydrodynamical simulations is solved within the weak-interaction basis for all

are propagating through the stellar envelope as well as on their way to Earth. This a↵ects the neutrino flavour distribution detected on Earth. In particular, neutrinos undergo the Mikheev-Smirnov-Wolfenstein (MSW) e↵ect [55, 56], which a↵ects the survival probability of each neutrino flavour according to the adiabaticity of the matter profile. The MSW e↵ect could be modified by turbulence or significant stochastic fluctuations in the stellar matter density (see e.g. [57–60]). In addition, neutrino– neutrino interactions are believed to be important and can aa \mathcal{A}

For our purpose, however, the details of the oscillation physics are not important. sensitive to all neutrino flavours and the total neutrino flux is conserved. Hence, the same total flux produced at

Non-standard physics may lead to situations where

 $\mathbf{7}$, $\mathbf{8}$, $\mathbf{7}$, $\mathbf{8}$, $\mathbf{8}$, $\mathbf{8}$ cles [9, 65, 66]. All of these cases a↵ect the heating of the star, implying that the total neutrino flux reaching the Earth could be di↵erent from the total neutrino flux at \mathbf{f}_eff in this paper, we will not consider \mathbf{f}_eff

the expected energy distribution [3, 4, 61].

 \sim

$$
\frac{d^2 R}{dE_{\rm R} dt_{\rm pb}} = \sum_{\nu_{\beta}} N_{\rm Xe} \int_{E_{\nu}^{\rm min}} dE_{\nu} f_{\nu_{\beta}}^0 (E_{\nu}, t_{\rm pb}) \frac{d\sigma}{dE_{\rm R}}
$$
\nCoherent elastic neutrino-nucleus cross-section

\n
$$
\frac{d\sigma}{dE_{\rm R}} = \frac{G_F^2 m_{\rm N}}{4\pi} Q_W^2 \left(1 - \frac{m_{\rm N} E_{\rm R}}{2E_{\nu}^2}\right) F^2 (E_{\rm R})
$$
\n
$$
Q_W = N - (1 - 4 \sin^2 \theta_W) Z
$$
\n
$$
F(E_{\rm R}) = \frac{3j_1(qr_n)}{qr_n} \exp\left(-\frac{(qs)^2}{2}\right)
$$

dE^R

, (5)

, (7)

ⁿ =

where the sum is over all six neutrino flavours, *N*Xe ' ⁴*.*60⇥10²⁷ is the number of xenon nuclei per tonne of liq-

where *q*² = 2*m*N*E*^R is the squared momentum transfer, *s* = 0*.*9 fm is the nuclear skin thickness, *r*²

integrated over [0*,* 7] s. As evident in all of this figure's panels, the event rate is larger for the 27 M SN progenitors, while there is a smaller dividend to the there is a smaller dividend to the there is a smaller dividend to

¹*.*23*A*¹*/*³ ⁰*.*60 fm, *^a* = 0*.*52 fm, *^A* is the atomic number of xenon, and *j*1(*qrn*) is the spherical Bessel function.

not the total flux is not conserved. The observed seemed in the observed S1 and S2 signals for the observed of the observed S1 and S2 signals **for the seemed S1** and S2 signals $\frac{1}{2}$ sterile sterile neutrinos in $\frac{1}{2}$ $\overline{\mathsf{D}}$ ifferential rate as a function of the measured S1 and S2 signals μ nction of the measured S1 and S2 signals ³⇡2*a*² ⁵*s*² is the nuclear radius parameter, *^c* ⁼ ¹*.*23*A*1*/*³ ⁰*.*60 fm, *^a* = 0*.*52 fm, *^A* is the atomic number

$$
\frac{d^2R}{d\text{S}1d\text{S}2} = \int dt_{\text{pb}} dE_{\text{R}} \,\text{pdf}\left(\text{S}1,\text{S}2|E_{\text{R}}\right) \frac{d^2R}{dE_{\text{R}}dt_{\text{pb}}}.
$$

of the SN neutrino signal, expressed in terms of the post-signal, expressed in terms of the post-signal, α

Recoil Spectra

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.

Observable Signals The symbol conservable showed starting the most likely threshold in the most likely threshold values discussion in sections IV and VI for details). An S2-only

inant electronic recoil backgrounds and the expected nuclear recoil signal, based on the ratio S2/S1 at a given $v_{\rm{1}}$ and $v_{\rm{2}}$ signals allow for S1 and S2 signals allow for S1 and S2 signals allow for S2 signals allow for a 3D reconstruction of the interaction vertex, based on the time di↵erence between the S1 and S2 signal events and the PMT hit pattern. The latter means that events can be selected from the central region of the detector, where the background rate is lowest. In these canonical dark matter searches, which utilize data collected over *O*(100) days, the S1 threshold is typically 2 PE or 35 PE, while the S2 threshold is typically \sim

For SN neutrinos though, the *O*(10) s burst of the signal requires less stringent discrimination capabilities to reduce the background signal. Although the requirement of detecting both an S_1 and an S_2 of reducing the background rate, it also significantly reduces the signal rate, especially for processes such as SN neutrino scattering where the nuclear recoil energy is small \mathcal{P}_1 , for example, for S any value of S_1 (including no S1 signal), the number of S_1 SN neutrino events for the 27 M SN progenitor with the LS220 EoS is 17.6 events/tonne. However, when additionally requiring an S1 signal with S1th = 2 PE, the number of events drops to only 7.2 events/tonne. Requiring both an S_1 and an S_2 signal therefore signal therefore signal therefore signal therefore signal the reduces the rate of CE⌫NS compared to an S2-only anal-

We now show that for a SN burst, the background rate is small enough that an S2-only analysis does not require

S2 background rate is small compared to signal.

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

Signal: 1-2.5 events/tonne/s. ne/s .

What Could We Learn?

Detection Significance

Neutrino Light Curve

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: X $\overline{}$ $\begin{bmatrix} 1 & 1 \end{bmatrix}$ parametrization for tir

ity between xenon detectors and traditional neutrino experiments should, therefore, allow for tests of oscillation

Up to this point, we have extracted information using the event rate integrated over the S2 range for a given threshold S2th. However, xenon detectors are also able to accurately measure the S2 value of an individual event. $F_{\rm eff}$ time, we investigate extracted from this spectral information. In particular, in this subsection, we demonstrate that xenon detectors can reconstruct the all-flavour neutrino di↵erential flux as \mathbf{r} function of the energy and, in the next subsection, the next subsection, that the total SN energy emitted into all flavours of neutrinos

 $E_{\rm eff}$

that it is the time-integrated di↵erential flux summed

⌫ (*E*⌫*, t*pb), defined in

$$
A_T \xi_T \left(\frac{E_\nu}{\langle E_T \rangle}\right)^{\alpha_T} \exp\left(\frac{-(1+\alpha_T)E_\nu}{\langle E_T \rangle}\right) \text{ with } \alpha_T = 2.3
$$
\n
$$
\frac{1}{\sum_{i=1}^{n} 10} \exp\left(\frac{-(1+\alpha_T)E_\nu}{\langle E_T \rangle}\right) \exp\left(\frac{27 \text{ M}_{\text{Sun}}, \text{L} \text{S} 220 \text{ EoS}}{0.1 \le t_{\text{pb}} \le 1.0 \text{ [s]}}\right)
$$
\n
$$
= \frac{1}{\sum_{i=1}^{n} 10} \exp\left(\frac{27 \text{ M}_{\text{Sun}}, \text{L} \text{S} 220 \text{ EoS}}{0.1 \le t_{\text{pb}} \le 1.0 \text{ [s]}}\right)
$$
\n
$$
= \frac{1}{\sum_{i=1}^{n} 10} \exp\left(\frac{1}{\sum_{i=1}^{n} 10} \exp\left(\frac{1}{\sum_{i=1}^{n} 10} \pi\right)}{\sum_{i=1}^{n} 10} \exp\left(\frac{1}{\sum_{i=1}^{n} 10} \pi\right)} \exp\left(\frac{1}{\sum_{i=1}^{n} 10} \pi\right)
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$$
= \frac{1}{\sum_{i=1}^{n} 10} \exp\left(\frac{1}{\
$$

Excellent reconstruction of neutrino properties with DARWIN. Good prospects for XENON1T. $|E\rangle$

plifying assumption motivated by the observation from the observation from σ

approximated by a Fermi-Dirac distribution with zero

Supernova Explosion Energy

F. Comparison with dedicated neutrino detectors

We briefly compare the expected number of events of the forthcoming $\mathcal{L}_{\mathcal{A}}$ $\tau_{\rm eff}$ and $\tau_{\rm eff}$ for also Table 1 of $\tau_{\rm eff}$ overview). For a SN burst at 10 kpc, XENON1T and $X_{\rm eff}$ is a sure approximately 35 and 120 a events in total. This is approximately one order of magnitude less than DUNE, which is expected to measure approximately *^O*(10³) events mostly in the ⌫*^e* channel with α 40 tonne liquid argon detector (see Fig. 5.5 of $[23]$ In the ¯⌫*^e* channel, a larger event rates are expected from IceCube which should see approximately 10⁶ events (see $\mathcal{F}_{\mathcal{F}}$ of $\mathcal{F}_{\mathcal{F}}$ of $\mathcal{F}_{\mathcal{F}}$ of $\mathcal{F}_{\mathcal{F}}$ is expected to the set measure approximately 105 \pm 105 \pm and JUNO which should detect about 6000 events (see Figs. 4-7 of [20]). The proposed DARWIN direct detection dark matter detector, with 40 tonnes of liquid xenon, will measure approximately 700 events for all six flavours, and is thus starting to be competitive in terms of the event rate with these dedicated neutrino detectors. Of course, the quoted numbers depend on di↵erent assumptions for the adopted SN model and therefore have to be viewed only as rough estimations of the expected number of t

For what concerns the reconstruction of the SN neutrino light curve, IceCube, Hyper-Kamiokande and

proximately 330 events during the first second and 370

$$
E_{\rm tot} = \sum_{\nu_{\beta}} \int_{0s}^{7s} dt_{\rm pb} L_{\nu_{\beta}}(t_{\rm pb}) = 4\pi d^2 A_T \langle E_T \rangle
$$

Excellent reconstruction of energy emitted into neutrinos with DARWIN. Good for XENON1T. α energy emitted mo neutrinos with DARWIN. Good for λ JUNO will all measure many more events [*O*(10⁴ $\overline{ON11}$.

region covers the true value in approximately 68% of the

Summary of Physics Reach

For a SN at 10 kpc from Earth:

Table: Courtesy of C. McCabe. — 25 Amsterdam — 25

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.

