Sensitivity of the PICO-500 Bubble Chamber to Supernova Neutrinos Through Coherent Nuclear Elastic Scattering

Scott Fallows\textsuperscript{a}, Tetiana Kozynets\textsuperscript{a,}\textsuperscript{*}, Carsten Krauss\textsuperscript{a}

\textsuperscript{a}Department of Physics, University of Alberta, Edmonton, T6G 2E1, Canada

Abstract

Ton-scale direct dark matter search experiments should be sensitive to neutrino-induced recoil events from either \textsuperscript{8}B solar neutrinos or the brief but intense flux from a core collapse supernova in the Milky Way. These low-threshold detectors are sensitive to the very low recoil energies, of order 10 keV, deposited via coherent elastic scatters between supernova neutrinos and target nuclei. Large superheated fluid detectors like PICO-500, a bubble chamber to be initially filled with an active target of 1 t or more of C\textsubscript{3}F\textsubscript{8}, should see multiple-bubble events from CE\textsubscript{NS} if the detector is live during a neutrino burst from a supernova that is nearby, shown here to be on the order of 10 kpc. This paper discusses conditions under which bubble chambers could be used as an independent measurement in the event of a supernova similar to SN 1987A, with particular sensitivity to the currently less-constrained heavy-lepton $\nu_x$ channel.

1. Introduction

At the end of their lifetime, massive stars, typically with $10 M_\odot \leq M \leq 20 M_\odot$, may undergo core collapse and explode as Type II supernovae, having most of the gravitational binding energy of their remnants radiated away in neutrinos \cite{1}. Given a sufficiently small distance to a supernova progenitor and an adequate detection sensitivity, it is possible for these neutrinos to be witnessed on Earth, as they may engage in both charged current (CC) and neutral current (NC) interactions with matter. Any such observation is highly valuable in terms of contributing to the current understanding of core collapse and neutrino physics \cite{2}. For that reason, since the detection of nearly a dozen neutrinos from SN 1987A in the Large Magellanic Cloud by the Kamiokande-II \cite{3}, Irvine-Michigan-Brookhaven (IMB) \cite{4}, and Baksan \cite{5} experiments, much effort has been put into planning and commissioning detectors capable of observing a large neutrino signal from the next supernova. Present facilities include the water Cherenkov detectors Super-Kamiokande \cite{6} and IceCube \cite{7}, the scintillator-filled KamLAND \cite{8} and Borexino \cite{9}, as well as the Pb-based HALO \cite{10}. All of these detectors are in principle sensitive to elastic scattering of heavy-lepton $\nu_x$ off electrons and NC and CC interactions of $\nu_e$ and $\bar{\nu}_e$ with neutrons and protons in target nuclei, while water Cherenkov and scintillators additionally have the inverse beta decay detection channel \cite{2}. However, the recently observed coherent elastic neutrino-nucleus scattering (CE\textsubscript{NS}) of neutrinos of all flavors \cite{11, 12}, which features large cross sections and should ideally constitute the dominant part of the neutrino signal, cannot be presently observed in the aforementioned experiments, as typical recoil energies of CE\textsubscript{NS} interaction are of keV scale and therefore fall below the energy thresholds in these detectors. Ton-scale direct dark matter search detectors, on the contrary, tend to have thresholds on the order of a few keV and may get around this limitation. The CE\textsubscript{NS} sensitivity has been projected for CLEAN \cite{13}, XMASS \cite{14}, LZ \cite{15}, and XENON1T \cite{16} scintillators, all of which have been shown to be competitive. The purpose of the present paper is to draw attention to the potential of a direct dark matter search bubble chamber to likewise detect supernova neutrinos via CE\textsubscript{NS} using the example of the funded PICO-500 experiment, both for its planned initial configuration of a 1 t C\textsubscript{3}F\textsubscript{8} target and for other similar configurations that could potentially be built and operated.

1.1. Operational Principles of Superheated Fluid Detectors

Bubble chambers use superheated fluids such as C\textsubscript{3}F\textsubscript{8} to detect elastic scatters on target nuclei. Nuclear recoils that deposit an energy above the detector’s thermodynamic threshold, as set by its operating temperature and pressure, will nucleate a bubble that grows to visible size. This visible bubble is detected by high-speed cameras that trigger a hydraulic compression of the target fluid until the pressure is high enough that the vapor condenses back into the liquid state. To reset the detector, the hydraulic system reduces the pressure, returning the target to the superheated state. Superheated fluids have a very strong intrinsic rejection of electron recoils, typically of order $10^{-10}$ or larger, which can be adjusted as required by varying the thermodynamic conditions. The resulting very low overall event rates lead to typical live-time fractions of $\sim90\%$ \cite{17, 18}.

$^*$kozynets@ualberta.ca

Preprint submitted to Elsevier

June 6, 2018
The fluoroalkane fluids used in these chambers are typically inexpensive, and the detector technology is both conceptually and mechanically simple. This makes it quite practical to scale to large target masses, relative to other dark matter direct detection technologies. If the bubble chamber technique is combined with a high-neutron-density target, the flavor-blindness of CEmNS enables such chambers to have particularly good sensitivity, relative to large water Cherenkov neutrino detectors, to the heavy-lepton component of the supernova neutrino flux.

1.2. PICO-500 and Future Chambers

PICO-500 is a ton-scale bubble chamber to be deployed underground at SNOLAB that is currently in the design and early procurement stage. This detector’s greatly increased volume will push the boundary for current low-background bubble chamber technology. The baseline design is for a target composed of 1 t of superheated C3F8, but several other target options are being explored, both for this and for future chambers. In the first operational phase of PICO-60, a bubble chamber filled with 36.8 kg of C3F8 was demonstrated to run stably [19]. An even larger chamber filled with an iodine-rich target is of continued interest. Projections of such a chamber’s sensitivity to supernova neutrinos via CEmNS are given in Section 3.1, as compared to an equal volume of C3F8 and of the liquid nobles 40Ar and 132Xe. We note that PICO-500 will not be sensitive to the CC channels accessible to classic neutrino detectors, as electronic interactions are invisible to the bubble chamber in the dark matter operational mode.

For the future PICO-500 operation, the goal is to have only a few neutron-induced multiple-bubble events per year. The observation of a multiple-bubble event, such as that expected from nearby-supernova CEmNS, is entirely orthogonal both to PICO’s single-bubble WIMP-search channel and to its simultaneous multi-bubble neutron channel. This detection would be a highly complementary signal to those seen in coincidence in other detectors.

2. Inputs to Sensitivity Projection

2.1. Supernova Neutrino Fluxes

One of the earliest models that supernova neutrino spectra were approximated with was based on a Boltzmann energy distribution at a constant temperature. For analysis of the SN 1987A data, single-temperature fits were accepted for neutrinos of all flavors, as the few events observed via absorption of electron neutrinos by protons and electron scattering of all types of neutrinos did not allow to separate them at a reasonable significance level [20]. However, a three-temperature Boltzmann distribution model has been widely employed to describe the simulated spectra of supernova neutrinos [13, 21]:

\[
\psi_j^{(B)}(E_\nu) = \frac{1}{4\pi d^2} \frac{n_j E_\nu^2}{2 \tau_j} \cdot e^{-\frac{E_\nu}{\tau_j}},
\]

where \(n_j\) denotes the number of neutrinos of flavor \(j\) \((\nu_e, \bar{\nu}_e, \nu_x\) or \(\bar{\nu}_x \equiv \{\nu_e, \bar{\nu}_e, \nu_x, \bar{\nu}_x\}\)) emitted from a supernova at a distance \(d\) from the Earth, \(\tau_j\) stands for the effective temperature specific for this flavor, and \(E_\nu\) is the neutrino energy. The result of the right-hand side expression evaluation is then the neutrino number flux density \(\psi_j^{(B)}(E_\nu)\), which has the units of inverse energy if temperature is taken in energy units.

In the course of the past decade, more accurate models have been developed. The current standard is the pinched flux model, involving the “pinching parameter” \(\alpha\) and the average neutrino energy \(\langle E_\nu \rangle\) [22, 23]:

\[
\psi^{(p)}(E_\nu, \Omega) = \frac{\Omega}{4\pi d^2 \langle E_\nu \rangle} \cdot f^{(p)}(E_\nu),
\]

where

\[
f^{(p)}(E_\nu) = A \left(\frac{E_\nu}{\langle E_\nu \rangle}\right)^\alpha \exp \left[-(\alpha + 1) \frac{E_\nu}{\langle E_\nu \rangle}\right]
\]

is the normalized gamma distribution \((A = \frac{(\alpha + 1)^{\alpha+1}}{\langle E_\nu \rangle^\alpha (\alpha+1)!})\) and \(\Omega\) is the total energy emitted in neutrinos [24]. Both \(\alpha\) and \(\langle E_\nu \rangle\) are in general time-dependent, and their values can be obtained from simulations or fits to future high-resolution spectral data. With \(\alpha = 2\) at all post-bounce times, Eq. 2 reduces to Eq. 1 [25].

In this work, we will consider only the pinched flux model and examine the time evolution of the corresponding spectrum using the simulated 1D neutrino signal from the Garching Core-Collapse Supernova Archive [26], obtained for a 20\(M_\odot\) progenitor [27] leaving a neutron star of nearly 1.95\(M_\odot\) baryonic mass. This model is preferred over three-temperature Boltzmann because with \(\alpha\) held constant, as implied by Eq. 1, the latter becomes an oversimplification when energy moments evolve in time. The dependence of \(\langle E_\nu \rangle\) and \(\langle E_\nu^2 \rangle\) outputs of a 1D supernova simulation [28] on the post-bounce time \(t_{pb}\) enables us to find \(\alpha(t_{pb})\) directly from:

\[
\frac{\langle E_\nu^2 \rangle}{\langle E_\nu \rangle^2} = \frac{2 + \alpha}{1 + \alpha}
\]

In Fig. 1, we reproduce the time dependence of the \(\alpha\) parameter for different flavors (with \(\nu_x \equiv \{\nu_x, \bar{\nu}_x\}\) and \(\bar{\nu}_x \equiv \{\bar{\nu}_e, \bar{\nu}_\tau\}\), as defined in [28]). We observe that before \(t_{pb}\) reaches 1 s, \(\alpha\) changes drastically with time and stays far away from the Boltzmann-like \(\alpha = 2\) for all flavors. Higher values of this parameter for \(\nu_e\) and \(\bar{\nu}_e\) imply more severe pinching than for \(\nu_x\) and \(\bar{\nu}_x\). Nearly half of the total energy is, however, radiated within the first two seconds following the core collapse. To show this, we plot the ratio of the luminosity integrated up to \(t_{pb}\) to the total energy of nearly 4.3 \(\times 10^{53}\) ergs produced over the time scale of 16.8 s as a function of \(t_{pb}\) in Fig. 2. We note that since the explosion of the star was triggered artificially in the discussed 1D model [28], the neutrino emission properties in the accretion phase (0.2–1 s) might differ from those of the
full 3D supernova models, which do explode naturally but are not currently run over time scales longer than 0.5 s due to high computational costs. Once sufficiently long neutrino signals from 3D supernova simulations become available, neutrino emission in the accretion phase can be compared between the 1D and the 3D cases, and the results presented in the following sections can be further refined. However, as the exact time evolution of neutrino spectra is expected to differ even more across progenitor models and neutron star remnant masses than between 1D and 3D simulations, the present discussion is sufficient for a basic sensitivity projection study.

The time-integrated pinched fluxes for different flavors are shown in Fig. 3, where $\nu_x$ now represents the sum of all heavy-lepton neutrino contributions. The integral runs up to 16.8 s (full duration of the neutrino signal from [26]).

Predictions of the cumulative number of bubbles expected from a full post-bounce signal impose relatively few clear constraints on the practical design of the experiment. One variable potentially impacting detector operations is a measure of the optimal time to maintain the target in the superheated state after the initial trigger event occurs. The goal is to capture as many scatter events as possible and yet recompress quickly enough to keep the detector’s live fraction high. Therefore we are interested in the total scatter yield as a function of post-bounce time, which we will denote as $I$ for the remainder of this section for brevity. To evaluate such time-dependent yields, we make use of the discrete set of $L_i(t_i)$ values from the Garching group simulation of the neutrino signal, where $L_i$ is the neutrino luminosity in the units of ergs per second, and employ the trapezoidal rule to integrate the luminosity within each $[t_i, t_{i+1}]$ bin:

$$\Delta I(t_i) \equiv \int_{t_i}^{t_{i+1}} L(t) dt \approx \frac{1}{2} \left( L_i + L_{i+1} \right) \times \left( t_{i+1} - t_i \right), \quad (5)$$

where we define $\Delta I(t_i)$ to be the energy emitted in neutrinos in $\Delta t_i$ between $t_i$ and $t_{i+1}$ for a certain neutrino flavor. The total energy normalizes the pinched flux within this bin:

$$\Delta \psi_i^{(p)} = \frac{\Delta I(t_i)}{4\pi d^2 \langle E_{\nu_i} \rangle} \cdot f_i^{(p)}(E_{\nu_i}). \quad (6)$$

By numerically integrating the resulting flux rates, $\Delta \psi_i^{(p)}$, over time, we obtain the full time dependence of the neutrino spectrum. To finally calculate the expected event rate for both time-integrated and time-dependent scenarios, it now only remains to introduce the $E_{\nu}$-dependence of the CE/NS cross sections (see Section 2.2). Section 3.1 and Section 3.2 present these estimates for PICO-500 filled
with $^{12}$C as the proposed target liquid, as well as other liquids that could potentially fill the same chamber volume in the future.

2.2. Elastic Scattering Cross Sections

Following [29], we define the differential cross section of coherent elastic scattering as a function of neutrino energy $E_\nu$ and recoil energy $T$:

$$\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi} M \cdot \left[ (Q_W^V)^2 \left( 1 - \frac{MT}{2E_\nu^2} \right) + (Q_W^A)^2 \left( 1 + \frac{MT}{2E_\nu^2} \right) \right] \cdot F(Q^2)^2. \quad (7)$$

In Eq. 7, $G_F \approx 1.166 \text{ GeV}^{-2}$ is the Fermi coupling constant; $M = AM_N \approx (N + Z) \cdot 931.5 \text{ MeV}$ is the mass of the target nucleus, with $N$ representing the number of neutrons, and $Z$ that of protons; and $F(Q^2)$ is the Helm-type ground-state elastic form factor [29]:

$$F(Q^2) = \frac{3j_1(QR_0)}{QR_0} \exp \left[ -\frac{1}{2} (Qs)^2 \right], \quad (8)$$

where momentum transfer $Q$ is related to the recoil energy $T$ via $Q = \sqrt{2MT}$ and $j_1$ is the first-order spherical Bessel function. The constant $R_0$ in Eq. 8 is uniquely defined for a target nucleus with a given atomic mass $A$: $R_0 = \sqrt{R^2 - 5s^2}$, where $R = 1.24A^{1/3}$ fm is the effective nuclear radius and $s \approx 0.5$ fm is the nuclear skin thickness.

The other expressions appearing in Eq. 7 are the vector and axial-vector nuclear charges, $Q_W^V$ and $Q_W^A$, such that:

$$Q_W^V = N - (1 - 4\sin^2\theta_W) \cdot Z, \quad (9)$$

with the weak mixing angle $\sin^2\theta_W \approx 0.2386$ at momentum transfer $Q \leq 100 \text{ MeV}$ [30, 31], and

$$Q_W^A = g_p^A(Z_+ - Z_-) + g_n^A(N_+ - N_-), \quad (10)$$

where $g_p^A/g_n^A$ are the effective axial-vector coupling constants for neutral current neutrino-proton/neutron interactions, and $Z_+/N_+$ are the numbers of spin up (+) and down (−) protons/neutrons. In spin-zero nuclei, such as $^{12}\text{C}$, $^{40}\text{Ar}$, and $^{132}\text{Xe}$, both terms in Eq. 10 are equal to 0, and we end up with $Q_W^A(12\text{C}, 40\text{Ar}, 132\text{Xe}) = 0$. For nuclei that carry a non-zero spin, such as $^{19}\text{F}$ and $^{127}\text{I}$, it is typically the case that $Q_W^A/Q_W^V \sim \frac{1}{A}$ [29], which lets us safely neglect the axial-vector term for $^{127}\text{I}$ but not for $^{19}\text{F}$. Therefore, we write for fluorine nucleus:

$$Q_W^A(19\text{F}) = g_p^A \approx 1.09, \quad (11)$$

where we made use of the medium-suppressed neutrino-proton axial-vector coupling constant [32].

For each $E_\nu$ in a discrete set $\{E_{\nu,0}, E_{\nu,1}, ..., E_{\nu,n}\}$ with $E_{\nu,0} \equiv E_{\text{min}} = 1 \text{ MeV}$, $E_{\nu,n} \equiv E_{\text{max}} = 100 \text{ MeV}$, and a constant step of 0.5 MeV, we integrated the right-hand side in Eq. 7 numerically with respect to $T$ from $T_{\text{min}}$, standing for the detection threshold, to $T_{\text{max}} = \frac{2E_\nu^2}{M + 2E_\nu}$, representing the maximum recoil energy at a given neutrino energy $E_\nu$, to get full cross section $\sigma(E_\nu)$ [33]. Fig. 4a shows these recoil energy integrated cross sections plotted against $E_\nu$ for $C$ and $F$ nuclei in $^{12}$C$^{19}$F$^{132}$I assuming a threshold of 2 keV, while Fig. 4b presents the same for C, F, and I in CF$^3$I and Ar at a 10 keV threshold.

Figure 4: Recoil energy integrated cross sections of coherent elastic neutrino scattering from C, F, I, Ar, and Xe nuclei plotted against neutrino energy $E_\nu$. 

(a) $\sigma(E_\nu)$ for $\nu$ scattering off C and F in $^{12}$C$^{19}$F$^{132}$I, with $T_{\text{min}} = 2$ keV

(b) $\sigma(E_\nu)$ for $\nu$ scattering off C, F, and I in CF$^3$I, with $T_{\text{min}} = 10$ keV

(c) $\sigma(E_\nu)$ for $\nu$ scattering off $^{40}$Ar and $^{132}$Xe, with $T_{\text{min}} = 10$ keV
3. Results

3.1. Time-Integrated Scattering Rates

From the recoil energy integrated cross section $\sigma(E_\nu)$ and the functional form of the neutrino flux density, we can evaluate the total number of scatters off $N$ target nuclei in the whole range of possible recoil energies as:

$$Y = N \times \int_{E_{\nu,\text{min}}}^{E_{\nu,\text{max}}} \sigma(E_\nu) \psi(p)(E_\nu) dE_\nu$$

(12)

Table 1 lists the results of applying Eq. 12 to the case of Helm-type form factor (Eq. 8) and the pinched flux density model (Eq. 2) for neutrinos in the range 1–100 MeV emitted from a supernova at 10 kpc, with different target liquids and detection thresholds considered for PICO-500. We show how the total number of scatters with recoil energies above the detection threshold $T_{\text{min}}$ varies with the value of $T_{\text{min}}$ in Fig. 5 for the total neutrino flux integrated until $t_{\text{pb}} = 16.8$ s.

These time-integrated values give insight into the sensitivity of the detector that could be achieved if its dead time was negligible during the supernova burst. For the reasons given in Section 2.1, a time-dependent treatment of the total yield is preferable to optimize the detector operation; this discussion follows in Section 3.2.

4. Discussion

As per Table 1, our expectation for the number of scatters observable from CEngNS of supernova neutrinos in PICO-500, whose current design includes a ~725 L volume of C3F8, implies that such a detection is possible even at large thresholds. Indeed, for $T_{\text{min}} = 10$ keV, we would be able to confirm 2 CEngNS events if a supernova happened at a distance 10 kpc from the Earth and the detector was kept live for the whole neutrino signal duration. The latter scenario is far from realistic given the operational principles of bubble chambers, and yet the fact that thresholds as low as 2 keV can be reached for C3F8, CF3I, 40Ar, and 132Xe in Table 2.

From Fig. 6, we readily see that 1 t of C3F8 with 2 keV detection threshold turns out to give the highest yield among the investigated bubble chamber options at all post-bounce times. To quantify this statement, we provide the estimates of the time required to accumulate 1, 2, and 3 bubbles for each of C3F8, CF3I, 40Ar, and 132Xe in Table 2.
Table 1: Simulated total numbers of scatters that could be observed in 725 L of superheated C$_3$F$_8$, CF$_3$I, $^{40}$Ar, and $^{132}$Xe liquids at different detection thresholds for a supernova at $d = 10$ kpc, integrated over 16.8 seconds assuming the pinched flux model (Eq. 2) for 1D neutrino signal data [26]. For C$_3$F$_8$, the same results apply to the case of a 25 t chamber and a 50 kpc distance to a supernova. The values for thresholds currently deemed inaccessible are shown in gray.

| Target      | $T > 0.5$ keV | $T > 2$ keV | $T > 5$ keV | $T > 10$ keV | $T > 15$ keV | $T > 20$ keV |
|-------------|---------------|-------------|-------------|--------------|--------------|--------------|
| C$_3$F$_8$ [1 t] | 4.2           | 3.8         | 3.1         | 2.4          | 1.8          | 1.5          |
| CF$_3$I [1.2 t] | 22.5          | 12.5        | 5.2         | 2.0          | 1.1          | 0.7          |
| LAr [1.1 t]   | 10.5          | 8.4         | 5.7         | 3.3          | 2.1          | 1.4          |
| LXe [2.2 t]   | 62.1          | 31.9        | 11.1        | 2.7          | 0.8          | 0.3          |

Table 2: Time since the supernova burst which is required to expect $k$ bubbles in C$_3$F$_8$ and other potential liquids for PICO-500 detector, with a minimum achievable detection threshold assumed for each liquid (see Table 1).

| $k$  | $t(C_3F_8, k)$ [s] | $t(CF_3I, k)$ [s] | $t({}^{40}Ar, k)$ [s] | $t({}^{132}Xe, k)$ [s] |
|------|--------------------|--------------------|-----------------------|-----------------------|
| 1    | 0.5                | 1.0                | 0.5                   | 0.6                   |
| 2    | 1.7                | 12.0               | 1.8                   | 2.4                   |
| 3    | 4.5                | N/A                | 6.0                   | N/A                   |

neutrinos from the same progenitor in a PICO-500-sized detector: in particular, we expect to detect only about 2 events above 10 keV in 1.2 t of CF$_3$I and 3 events in 1.1 t of LAr and 2.2 t of LXe above the same threshold, with the event rates integrated over 16.8 s. The second CE$\nu$NS-caused bubble might, however, be seen in LAr just after 1.3 s after the first one, which makes it the next most suitable liquid for the purpose of supernova neutrino detection in a chamber of this kind. All of the targets considered in this study will serve their CE$\nu$NS detection purpose even better in case of a more closely located supernova progenitor; for example, the explosion of Betelgeuse at about 222 pc [34] would give nearly 2,000 times higher rates in 1 t of C$_3$F$_8$ than those presented in Table 1.

Taken together, these conclusions bring additional value to the C$_3$F$_8$-filled PICO-500, planned as a direct dark matter search detector. They also boost the general scientific motivation behind future design and commissioning of larger-scale detectors, as the latter would be efficient in detecting neutrinos from much more distant supernovae.

5. Acknowledgements

We thank Robert Bollig for generating the neutrino signal data, as well as Hans-Thomas Janka and Tobias Melsom for making it available via Garching Core-Collapse Supernova Archive [26] and participating in the related discussion; Kate Scholberg and Louis Strigari for giving helpful comments on the manuscript and suggesting further directions; Irene Tamborra and Shayne Reichard for facilitating the cross-checks of our results with those projected for xenon-filled chambers [16]; and Benjamin Broerman for independent local verification of the time-integrated projections for the PICO-500 event rates. The work of TK is funded by the Undergraduate Research Initiative (URI) Stipend at the University of Alberta. We also wish to acknowledge the support of the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Canada Foundation for Innovation (CFI) for funding.

References

[1] J. Bahcall, Neutrino Astrophysics, Cambridge University Press, 1989.
[2] K. Scholberg, Supernova Neutrino Detection, Annual Review of Nuclear and Particle Science 62 (1) (2012) 81–103, arXiv: 1205.6003. doi:10.1146/annurev-nucl-102711-095006.
[3] K. Hirata et al., Observation of a neutrino burst from the supernova SN1987A, Phys. Rev. Lett. 58 (1987) 1490–1493. doi:10.1103/PhysRevLett.58.1490.
[4] R. M. Bionta et al., Observation of a neutrino burst in coincidence with supernova 1987A in the Large Magellanic Cloud, Phys. Rev. Lett. 58 (1987) 1494–1496. doi:10.1103/PhysRevLett.58.1494.
[5] E. N. Alekseev, L. N. Alekseeva, V. I. Volchenko, I. V. Krivosheina, Possible detection of a neutrino signal on February 23, 1987 with the Baksan underground scintillation telescope of the Nuclear Research Institute of the Soviet Academy of Sciences, JETP Letters 45 (1987) 461–464.
[6] M. Beda et al., Search for supernova neutrino bursts at Super-Kamiokande, ApJ 669 (1) (2007) 519. URL http://stacks.iop.org/0004-637X/669/i=1/a=519.
[7] R. Abbasi et al., IceCube sensitivity for low-energy neutrinos from nearby supernovae, A&A 535 (2011) A109. doi:10.1051/0004-6361/201117810.
[8] KamLAND Collaboration, First results from KamLAND: Evidence for reactor anti-neutrino disappearance, Phys. Rev. Lett. 90 (2) (2003) hep-ex/0212021. doi:10.1103/PhysRevLett.90.021802.
[9] L. Cadonati, F. P. Calaprice, M. C. Chen, Supernova neutrino detection in Borexino, Astroparticle Physics 16 (4) (2002) 361–372. doi:10.1016/S0927-6505(01)00129-3.
[10] C. A. Duba, F. Duncan, J. Farine, A. Habig, A. Hime, R. G. H. Robertson, K. Scholberg, T. Shantz, C. J. Virtue, J. F. Wilkerson, S. Yen, HALO – the helium and lead observatory for supernova neutrinos, J. Phys.: Conf. Ser. 136 (4) (2008) 042077. doi:10.1088/1742-6596/136/4/042077.
[11] D. Akimov et al., Observation of coherent elastic neutrino-nucleus scattering, Science (2017) eaao9900 doi:10.1126/science.aao0990.
[12] J. Barranco, O. G. Miranda, T. I. Rashba, Probing new physics with coherent neutrino scattering off nuclei, J. High Energy Phys. 2005 (12) (2005) 021. doi:10.1088/1126-6708/2005/12/021.

[13] C. J. Horowitz, K. J. Coakley, D. N. McKinsey, Supernova observation via neutrino-nucleus elastic scattering in the CLEAN detector, Physical Review D 68 (2), arXiv: astro-ph/0302071.

[14] K. Abe, et al., Detectability of galactic supernova neutrinos coherently scattered on xenon nuclei in XMASS, Astroparticle Physics 89 (2017) 51–56. doi:10.1016/j.astropartphys.2017.01.006.

[15] D. Khaitan, Supernova neutrino detection in LZ, J. Inst. 13 (02) (2018) C02024. doi:10.1088/1748-0221/13/02/C02024.

[16] R. F. Lang, C. McCabe, S. Reichard, M. Selvi, I. Tamborra, Supernova neutrino physics with xenon dark matter detectors: A timely perspective, Phys. Rev. D 94 (10) (2016) 103009. doi:10.1103/PhysRevD.94.103009.

[17] C. Amole, et al., Improved dark matter search results from PICO-2L Run 2, Phys. Rev. D 93 (2016) 061101. doi:10.1103/PhysRevD.93.061101.

[18] C. Amole, et al., Dark matter search results from the PICO-60 CF$_3$I bubble chamber, Phys. Rev. Lett. 118 (2017) 251301. doi:10.1016/j.astropartphys.2017.05.009.

[19] M. T. Keil, G. G. Raffelt, H.-T. Janka, Monte Carlo study of supernova neutrino spectra formation, ApJ 590 (2) (2003) 971. doi:10.1086/375130.

[20] I. Tamborra, B. Müller, L. Hüdepohl, H.-T. Janka, G. Raffelt, High-resolution supernova neutrino spectra represented by a simple fit, Phys. Rev. D 86 (12) (2012) 125031. doi:10.1103/PhysRevD.86.125031.

[21] J. Migenda, Detecting fast time variations in the supernova neutrino flux with Hyper-Kamiokande. ArXiv: 1609.04286.

[22] G. M. Harper, A. Brown, E. F. Guinan, E. O’Gorman, A. M. S. Richards, P. Kervella, L. Decin, An updated 2017 astrometric solution for Betelgeuse, The Astronomical Journal 154 (1) 11.

[23] G. Raffelt, D. Seckel, Self-consistent approach to neutral-current processes in supernova cores, Phys. Rev. D 52 (4) (1995) 1780–1799. doi:10.1103/PhysRevD.52.1780.

[24] D. K. Papoulias, T. S. Kosmas, COHERENT constraints to conventional and exotic neutrino physics, arXiv:1711.09773 [hep-ph].

[25] S. E. Woosley, A. Heger, Nucleosynthesis and remnants in massive stars of solar metallicity, Physics Reports 442 (1) (2007) 269–283. doi:10.1016/j.physrep.2007.02.009.

[26] A. Mirizzi, et al., Supernova neutrinos: Production, oscillations and detection, La Rivista del Nuovo Cimento 39 (2015) 1–112. doi:10.1393/ncr/i2016-10120-8.

[27] L. E. Strigari, Neutrino coherent scattering rates at direct dark matter detectors, New Journal of Physics 11 (10) (2009) 105011, arXiv:0903.3630. doi:10.1088/1367-2630/11/10/105011.

[28] G. M. Harper, A. Brown, E. F. Guinan, E. O’Gorman, A. M. S. Richards, P. Kervella, L. Decin, An updated 2017 astrometric solution for Betelgeuse, The Astronomical Journal 154 (1) 11.