An “archaeological” quest for galactic supernova neutrinos

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**ABSTRACT:** We explore the possibility to observe the effects of electron neutrinos from past galactic supernovae, through a geochemical measurement of the amount of Technetium 97 produced by neutrino-induced reactions in a Molybdenum ore. The calculations we present take into account the recent advances in our knowledge of neutrino interactions, of neutrino oscillations inside a supernova, of the solar neutrino flux at Earth and of possible failed supernovae. The predicted Technetium 97 abundance is of the order of $10^7$ atoms per 10 kilotons of ore, which is close to the current geochemical experimental sensitivity. Of this, $\sim 10 - 20\%$ is from supernovae. Considering the comparable size of uncertainties, more precision in the modeling of neutrino fluxes as well as of neutrino cross sections is required for a meaningful measurement.
1. Introduction

The question of the rate of core-collapse supernovae in our galaxy is as interesting – in connection with the history of star formation, the origin of elements and climate evolution – as it is difficult.

Next to more traditional approaches – based on astronomical searches, observation of radioactive decays and historical records – an interesting combination of neutrino physics, nuclear physics and geochemistry offers a way to count past supernovae and learn about their neutrino output. The idea, first proposed in 1988 by Haxton and Johnson (HJ) [1], relies on the fact that energetic electron neutrinos can produce Technetium 97 (\(^{97}\text{Tc}\)) from natural Molybdenum (\(^{98}\text{Mo}\) and \(^{97}\text{Mo}\)) via the reactions \(^{98}\text{Mo}(\nu_e, e^- n)\(^{97}\text{Tc}\)) and the \(^{97}\text{Mo}(\nu_e, e^-)\(^{97}\text{Tc}\)). The lifetime of \(^{97}\text{Tc}\) is \(2.6 \cdot 10^6\) years, which eliminates the possibility of the \(^{97}\text{Tc}\) found on earth to be primordial. Therefore presence of \(^{97}\text{Tc}\) in a Molybdenum ore is a result of either neutrino or cosmic-ray reactions. Any excess of \(^{97}\text{Tc}\), over the expected contribution of solar neutrinos and of cosmic-rays, is an historical imprint of nearby supernova explosions that happened
before any human technology was there to study them! This suggests the possibility for an “archaeological” quest of the neutrinos from past galactic supernovae, through a geochemical measurement.

In spite of the challenges and uncertainties involved, Haxton and Johnson came to positive conclusions: the neutrino-induced production of $^{97}$Tc in Molybdenum rocks, such as the Henderson mine in Colorado, was estimated to happen at an average of $1.57 \cdot 10^{-36}$ captures per second per target atom, about 40% of the background due to solar neutrinos, and corresponding to a detectable abundance of $^{97}$Tc at the present time. It was understood that the background due to cosmic rays could, in principle, be reduced to acceptable levels by excavating deeply enough and/or measuring the $^{97}$Tc attenuation rate as a function of the excavation depth.

In 1988 the idea was ahead of its time, in a field mostly focused on the disappearing solar and atmospheric neutrinos. Therefore it remained restricted to a small community [2]. Initial experimental efforts, led by K. Wolfsberg (LANL), lacked the funds necessary to overcome technical difficulties, and were soon abandoned [3, 4, 5].

Today the field is more mature: after solving the solar and atmospheric anomalies and discovering neutrino oscillations, research has focused more on supernova neutrinos, whereas supernova models have become sufficiently predictive. A geochemical measurement of $^{97}$Tc production could constrain the galactic supernova rate (the extragalactic contribution is negligible), for a given model of neutrino spectra and luminosities from an individual supernova, without the extinction effects typical of astronomy. Notably, even dark neutrino sources – e.g., those that give no luminous signal due to rapid formation of a black hole – would be counted. The capability to trace back to ancient supernovae in our galaxy would be an unique complement to the activity of real time, large scale liquid detectors. With the masses of 0.1-1 Mt envisioned for the near future [6, 7], these detectors should see the diffuse flux of neutrinos that continuously reaches the Earth from all the supernovae of the universe and that has a substantial cosmological component (see e.g. [8]). Finally, the $^{97}$Tc data could be the only one available on electron neutrinos from supernovae! They would add complementary information compared to the $\bar{\nu}_e$ data from SN1987A [9, 10, 11]. It is fascinating that this information, so important to have a complete picture of core-collapse, is there, buried in Molybdenum rocks, only waiting to be deciphered.

In the present paper we perform detailed calculations of the expected amount of Technetium 97 produced by the neutrino-induced reactions in Molybdenum ore, due to both solar and supernova neutrinos. Our predictions are based on the best available results on the solar neutrino fluxes and on the recent developments in the study of neutrino oscillations inside the star. To estimate uncertainties, we also consider a range of values for the galactic supernova rate as well as for the neutrino fluxes at the
neutrino-sphere, in accordance with supernova modeling. The structure of the paper is as follows. In Section II and III we give generalities on the supernova galactic rate and on the solar and supernova neutrino fluxes. Section IV describes calculations of the neutrino-nucleus cross sections. The results are summarized in Section V, while conclusions are in Section VI.

2. Supernovae in our galaxy: rates and distances

The rate of core collapse supernovae (SNe) in the Milky Way is known only up to its order of magnitude. The rate $R_{sn} \simeq 0.09$ yr$^{-1}$ used by HJ, is practically excluded by the lower values measured recently (table 1). Scaling from external galaxies and gamma rays from galactic $^{26}$Al independently favor a rate of $R_{sn} \simeq 0.02$ yr$^{-1}$ as central value, and up to $R_{sn} \simeq 0.05$ yr$^{-1}$ at 3σ. These are consistent with the much more uncertain estimate from historical records of galactic SNe, which favors a higher rate. The upper limit from the non-observation of supernova neutrino bursts is rather loose, but still of interest for its being extinction-free and sensitive to possible failed supernovae, as mentioned in sec. 1.

Table 1: Estimated rate of galactic core-collapse SNe per century, from [12], with permission of the author.

| Method                              | Rate    | Authors                        | Refs. |
|-------------------------------------|---------|--------------------------------|-------|
| Scaling from external galaxies      | 2.5 ± 0.9 | van den Bergh & McClure (1994) | [13, 14] |
|                                     | 1.8 ± 1.2 | Cappellaro & Turatto (2000)    | [15, 16] |
| Gamma-rays from galactic $^{26}$Al  | 1.9 ± 1.1 | Diehl et al. (2006)            | [14]  |
| Historical galactic SNe (all types) | 5.7 ± 1.7 | Strom (1994)                   | [17]  |
|                                     | 3.9 ± 1.7 | Tammann et al. (1994)          | [18]  |
| No neutrino burst in 25 years$^a$   | < 9.2 (90% CL) | Alekseev & Alekseeva (2002)   | [19]  |

$^a$The limit of Ref. [19] is scaled to 25 years of neutrino sky coverage.

Here we keep $R_{sn}$ as a free normalization; results for transition rates will be given for $R_{sn} \simeq 0.01$ yr$^{-1}$, as they can be easily rescaled for other values. The final results for the $^{97}$Tc abundance (table 6) refer to the more realistic $R_{sn} \simeq 0.03$ yr$^{-1}$, for easier comparison with previous literature on supernova neutrinos where this rate is commonly used.
To describe the spatial distribution of supernovae in our galaxy we use cylindric coordinates \((r, z, \theta)\) centered at the galactic center, which is at \(d_\odot \simeq 8.5\) kpc of distance from us. We assume a uniform distribution in \(\theta\) and adopt the following function for the distribution in \(r\) and \(z\):

\[
n_{cc}(r) \propto r^\xi \exp(-r/u) \times \left[ 0.79 \ e^{-(z/212\ \text{pc})^2} + 0.21 \ e^{-(z/636\ \text{pc})^2} \right], \tag{2.1}
\]

which fits observations of neutron stars with the parameters \(\xi = 4\) and \(u = 1.25\) kpc \([20, 21, 22]\), and is illustrated in more detail in ref. [23].

![Figure 1: The distribution with the distance from Earth of a Monte Carlo-generated population of \(10^5\) supernovae. The distribution in Eq. (2.1) was used, with \(\xi = 4\) and \(u = 1.25\) kpc.]

With this, we calculate the distribution of supernovae with the distance from Earth, using both numerical integration and the Monte Carlo Method (fig. 1). We find that the neutrino flux at Earth corresponds to the flux one would obtain if all the supernovae were at the effective distance \(d_{\text{eff}} = 4.26\) kpc, which we use throughout the paper.
With the alternate set of parameters given in [23] ($\xi = 2.35$, $u = 1.528$ kpc) we get a value only slightly different, $d_{\text{eff}} = 4.6$ kpc.

The Monte Carlo approach was used to investigate possible variations in the results due to one single supernova very close to the Earth, $d \lesssim 100$ pc or so. Our results agree with those in HJ on how such variations can be safely neglected: only very few ($\sim 2$ in $10^5$) events satisfy this condition, therefore the uncertainty due to the fluctuation of supernova positions in the galaxy turns out to be small compared to other uncertainties of different nature (total neutrino luminosity per supernova, etc.).

We have not investigated effects of local deviations from the spatial distribution (2.1). Nguyen and Johnson have studied this possibility [2], pointing out that a particularly high supernova rate in the Sco-Cen region of the galaxy might result in an increase of the $^{98}\text{Mo}(\nu_e,e^-n)^{97}\text{Tc}$ production rate, to a level equivalent to the whole galactic supernova neutrino production with $R_{\text{sn}} = 0.01$ yr$^{-1}$ rate. The full investigation of this possibility is beyond the scope of our paper; still one can effectively include it here as a further uncertainty in the rate $R_{\text{sn}}$, which is a free parameter for us.

3. Solar and supernova neutrino fluxes

3.1 Neutrinos from supernovae

A core collapse supernova is an extremely powerful neutrino source. It releases about $3 \cdot 10^{53}$ ergs of energy within $\sim 10$ seconds in neutrinos and antineutrinos of all flavors before the star explodes, leaving behind a neutron star or, in rare cases, a black hole.

The spectrum of the neutrinos of a given flavor $w$ at production in the star is approximately thermal, and commonly described by the form [24]:

$$F_{0w}^w = \frac{(1 + \alpha_w)^{1+\alpha_w}L_w}{\Gamma(1 + \alpha_w)E_{0w}^2} \left(\frac{E}{E_{0w}}\right)^{\alpha_w} e^{-(1+\alpha_w)E/E_{0w}},$$

with average energies $E_{0w}$ in the range of $10 - 20$ MeV and with the muon and tau species (collectively called $\nu_x$ from here on) being harder than the electron ones due to their weaker (neutral current only) coupling to matter. $L_w$ is the (time-integrated) luminosity in each flavor, $L_w \sim 5 \cdot 10^{52}$ ergs; $\alpha_w$ is a parameter describing the shape of the spectrum, $\alpha_w \simeq 2 - 5$ [24], with larger $\alpha_w$ corresponding to narrower spectrum.

For the purpose of studying the dependence of our results on the original neutrino fluxes, we choose three sets of parameters (Table 2) that are inspired by current numerical calculations [25, 24, 26] (see also [8] for a summary of those) and that can be considered as representative of natural and extreme cases. The cases of an especially
high or low $\nu_e$ flux at Earth are modeled mostly by varying the average energy and luminosity of the original $\nu_x$ flux. This is justified by the fact that this flux is responsible for at least $\sim 70\%$ of the $\nu_e$ flux in a detector, as will be clarified below.

|                  | best     | natural | worst    |
|------------------|----------|---------|----------|
| $(E_e, E_x)/\text{MeV}$ | (13,22)  | (12,18) | (10,16)  |
| $(L_e, L_x)/L_0$   | (1,2)    | (1,1)   | (1, 0.5) |
| $(\alpha_e, \alpha_x)$ | (3.5,2.5)| (3.5,2.5)| (3.5,2.5)|

Table 2: The three sets of input parameters for the neutrino fluxes used in this paper. Here $L_0 = 0.5 \cdot 10^{53}$ ergs.

As they propagate from the production point to a detection point on Earth, the neutrinos undergo flavor conversion (oscillations). Therefore, up to a geometric factor $1/4\pi d^2$, with $d$ the distance star-Earth, the flux of $\nu_e$ in a detector at Earth depends on the fluxes at production as:

$$F_e = pF^0_e + (1 - p)F^0_x,$$

(3.2)

with $p$ the $\nu_e$ survival probability. For a given density profile of the star $p$ is determined by number of physical phenomena, namely: (i) neutrino -neutrino coherent scattering, which induces complicated non-linear effects [27, 28, 29, 30, 31, 32, 33, 34, 35, 36] (ii) two MSW resonances produced by neutrino-electron scattering [37, 38, 39] and (iii) oscillations inside the Earth [38, 40, 41]. As a result $p$ is a function of the neutrino energy, the mixing angle $\theta_{13}$ and the mass hierarchy (ordering) of the neutrino mass spectrum, i.e., the sign of the mass squared splitting $\Delta m^2_{31}$ (see e.g., [38]). For the normal mass hierarchy, $\Delta m^2_{31} > 0$, $p$ varies in the interval

$$p = 0 - \sin^2 \theta_{12} \simeq 0 - 0.31$$

(3.3)

as $\sin^2 \theta_{13}$ increases in the interval $\sin^2 \theta_{13} \simeq 10^{-5} - 10^{-2}$ [38, 39]. Here $\theta_{12} \simeq 34^\circ$ is the “solar” mixing angle (see e.g. [42]). For the extreme values of $\theta_{13}$, the dependence of the survival probability on the energy is negligible in first approximation; oscillations in the Earth are also at the level of few per cent when averaged over the different arrival directions of the neutrinos [43], therefore they will be neglected here.

For $\Delta m^2_{31} < 0$ the calculation of $p$ is complicated by the effects of neutrino -neutrino scattering, which could be strong few seconds after the start of the neutrino burst [44] and induce a swap of the $\nu_e$ and $\nu_x$ fluxes above a critical energy $E_c \sim 6 - 9$ MeV.
[30, 31, 32, 33, 34, 35, 36]. Still, the survival probability remains within the interval in Eq. (3.3) at all times (see e.g. [34]), so one can always define a time averaged survival probability with value in this interval.

For our purposes, it is sufficient to consider $p$ as energy independent, as $E_c$ is typically below threshold of the cross sections of interest (see sec. 4), and take the two extreme cases of total ($p = 0$) and minimal ($p = \sin^2 \theta_{12}$) flux permutation. This is adequate to show the extent of variation of the $^{97}$Tc abundance with the conversion pattern.

![Graph showing time averaged solar and supernova neutrino fluxes at Earth.](image)

**Figure 2:** Time averaged solar (leftmost curve) and supernova (lines extending to the right) $\nu_e$ fluxes at Earth, inclusive of oscillation effects. The solid curves correspond, from upper to lower, to the best, natural and worst scenarios in Table 2 and complete flavor permutation ($p = 0$, see Eqs. (3.2) and (3.3)). The dashed ones refer to the same scenarios with the minimal permutation ($p \simeq 0.31$). A rate $R_{sn} = 10^{-2}$ yr$^{-1}$ was used.

Fig. 2 shows the time averaged supernova $\nu_e$ flux at Earth:

$$F_{e,\text{earth}} = R_{sn} F_e / (4\pi d_{eff}^2).$$  \hspace{1cm} (3.4)
We have plotted the six fluxes at Earth obtained with the two extreme values of $p$ and the three scenarios in Table 2. They are averaged over time for the purpose of comparison with the solar neutrino flux\(^1\).

All that was discussed so far refers to the most common scenario of core collapse supernova, the one that leads to a successful explosion and the formation of a neutron star. Stars of mass above 25-40 $M_\odot$ ($M_\odot = 1.99 \cdot 10^{30}$ Kg being the mass of the sun), a 10 – 20% fraction of all collapse candidates, could either explode and form a black hole by fallback or collapse into a black hole directly, with no explosion (see e.g. [45] and references therein). The neutrino emission in the latter case has been studied recently [46, 47, 48, 49, 50] and found to be characterized by a much shorter burst ($O(1)$ s or less) with luminosity and average energies higher than the neutron-star forming case, especially in $\nu_e$ and $\bar{\nu}_e$. Higher and more energetic fluxes have been found [46, 47, 48, 49] for the stiffer equation of state (EoS) by Shen et al. (S) [51] compared to the softer one by Lattimer and Swesty (LS) [52].

Here we model the contribution of these failed supernovae to the time averaged supernova $\nu_e$ flux (shown in fig. 3) using the original fluxes presented in ref. [50] (fig. 5 there). Those have the character of examples, only roughly representing the possible variations that one can have with the EoS and progenitor model, for which a comprehensive study still lacks. They are characterized by the parameters $E_{0x} \simeq 24$ MeV, $L_x \simeq 0.45 \cdot 10^{53}$ ergs, $E_{0e} \simeq 20.7$ MeV, $L_e \simeq 1.4 \cdot 10^{53}$ ergs for the S EoS and by $E_{0x} \simeq 22$ MeV, $L_x \simeq 0.2 \cdot 10^{53}$ ergs, $E_{0e} \simeq 17$ MeV, $L_e \simeq 0.54 \cdot 10^{53}$ ergs for the LS one. For the spectral shapes, we checked that Eq. (3.1) is a reasonable approximation; still we chose to interpolate the numerically calculated points in [50] with a polynome of order 4 in the plane $\log(E) - \log(F_{w0})$. Results have only minor differences compared to the more conservative linear fit used in [50].

In absence of indications of the opposite, we assumed that black hole forming collapses have the same spatial distribution, Eq. (2.1), as the neutron star forming ones, and that the estimated ratio of rates for the two types of collapses, $R_{bh}/R_{sn} \sim 0.1 – 0.2$ is valid for our galaxy. We have also considered the conversion effects to be the same for the two types, Eqs. (3.2) and (3.3). While this is not the case for every value of $\theta_{13}$, it is true for the extreme values of $\theta_{13}$ and of $p$, which are of the most interest here [50]. Fig. 3 reveals that the contribution of failed supernovae is at the level of tens of per cent of the total flux at $E \sim 20 – 30$ MeV, and can exceed the flux from regular supernovae above 50-60 MeV depending on the parameters. Notice that for

\(^1\)Using a time averaged flux might be somewhat confusing, because it might suggest the idea of a flux that is continuous in time. In contrast with the solar one, the supernova neutrino flux we are considering is far from continuous: it consists of $\sim 10$ s bursts that reach the Earth a few times per century and whose effects on the $^{97}$Tc production accumulate over several millions of years.
Figure 3: The same of fig. 2 for the flux of failed supernovae, obtained using the fluxes in fig. 5 of [50]. Of the two solid curves, the upper (lower) is for the Shen (Lattimer-Swesty) EoS. The same holds for the dashed lines. We took a rate for failed collapse of $R_{bh} = 10^{-3} \text{ yr}^{-1}$.

failed supernovae the $\nu_e$ flux is smaller for total flavor permutation $p = 0$, because in this case the flux of $\nu_e$s at Earth originates from the less luminous original $\nu_x$ flux.

3.2 Solar neutrinos

Solar neutrinos are the only significant background that can not be eliminated. In the energy range of interest here, $\nu_e$s from the $^8$B and hep reactions of the fusion chain are relevant. The former component extends to 16.6 MeV energy, while hep neutrinos reach 18.8 MeV. We describe these fluxes following the Bahcall-Serenelli-Basu BS05(PO) solar model [53]. There, the $^8$B component is normalized to $\Phi_B = 5.69 \cdot 10^6 \text{ cm}^{-2}\text{s}^{-1}$, and the hep one to $\Phi_{hep} = 7.93 \cdot 10^3 \text{ cm}^{-2}\text{s}^{-1}$ (unoscillated values). The solar neutrino survival probability as a function of energy was taken as the best fit in [54] (fig. 2 of this reference), corresponding to the LMA-MSW oscillation parameters $\Delta m^2_{21} = 7.92 \cdot 10^{-5} \text{ eV}^2$ and $\sin^2 \theta_{12} = 0.314$. With these, the oscillated fluxes at Earth
are $\Phi_B^{osc} = 2.17 \cdot 10^6 \text{ cm}^{-2}\text{s}^{-1}$, and $\Phi_{hep}^{osc} = 2.81 \cdot 10^3 \text{ cm}^{-2}\text{s}^{-1}$. The total of the two, differential in energy, is shown in figs. 2 and 3.

Notice that the oscillated fluxes at Earth used here differ substantially from those used by Haxton & Johnson: $\Phi_B^{HJ} = 1.1 \cdot 10^6 \text{ cm}^{-2}\text{s}^{-1}$, and $\Phi_{hep}^{HJ} = 1.6 \cdot 10^4 \text{ cm}^{-2}\text{s}^{-1}$. This difference is a result of the two decades of progress in solar neutrino research, and is one of the major novelties of our work.

A comment on uncertainties on the solar neutrino flux is due. Errors on the measured $\Delta m_{21}^2$ and $\sin^2 \theta_{12}$ are of $\sim 3\%$ and $\sim 10\%$ (at $1\sigma$) respectively [42]; corresponding to an error of the order of $\sim 10\%$ on the solar neutrino survival probability. The solar model itself has uncertainties, e.g. those associated to using different inputs for the solar opacities [53], which are at the level of $\mathcal{O}(0.1)\%$. Here we do not include all these uncertainties explicitly, because they do not impact our conclusions significantly; moreover, we note that for our purposes the oscillated fluxes $\Phi_{hep}^{osc}$ and $\Phi_B^{osc}$ are the only relevant quantities (assuming their spectra as known). These are measurable very precisely, in principle. The SNO experiment has already measured $\Phi_B^{osc}$ (the part of the flux above its threshold of $\sim 5$ MeV) with precision of $\sim 3-5\%$ (statistical and systematic, $1\sigma$) [42], while a measurement of hep neutrinos requires to wait for the next phase of solar detectors [55]. The importance of a precise measurement of the solar neutrino fluxes in view of a possible $^{97}\text{Tc}$ experiment will be discussed briefly in sec. 5.

4. Neutrino-induced cross sections

Predictions of neutrino-nucleus cross sections in the solar and supernova energy range require a precise knowledge of the transitions to the low lying states and to the resonance region, well above the particle emission thresholds. The latter include both allowed transitions associated to the Gamow-Teller and Isobaric Analogue State - and the forbidden ones, such as the spin-dipole and higher multipoles. The particular reaction cross sections of interest are $^{98}\text{Mo}(\nu_e, e^- n)^{97}\text{Tc}$ and $^{97}\text{Mo}(\nu_e, e^-)^{97}\text{Tc}$. In this work we follow two different procedures to calculate the contribution to the cross sections coming from the Gamow-Teller and Isobaric Analogue State on one hand and the spin-dipole and higher multipoles (up to $J = 5$) on the other hand. In the first one we use the allowed approximation, which corresponds to the low momentum transfer, as done in Haxton and Johnson’s paper. For all other multipoles we use the Walecka formalism [56] for the reaction cross section without neglecting the momentum transfer, with the transition matrix elements provided by the microscopic Quasi-Particle Random-Phase Approximation (QRPA). Note that this is at variance with [1] where only the spin-dipole is included whose contribution is estimated using the Goldhaber-Teller model.
Figure 4: $^{98}\text{Mo}(\nu_e,e^-n)^{97}\text{Tc}$ reaction cross section as a function of the neutrino energy. The dashed curve presents the contribution due to the Gamow-Teller and Isobaric Analogue State transitions, evaluated within the allowed approximation using experimental data. The dotted curve shows the contribution coming from the spin-dipole and other multipoles (up to $J = 5$), calculated with the QRPA approach. The total cross section is also shown (solid line).

To evaluate the transition matrix elements of the Gamow-Teller and Isobaric Analogue State within the allowed approximation, we exploit the only measurement available, the one by J. Rapaport et al. [57], who studied $^{98}\text{Mo}(p,n)^{98}\text{Tc}$ reaction at forward angles for 120 MeV incident protons. This procedure is the same as in [1]. It is important to remind that the model-independent Fermi and Ikeda sum-rules tell us that the total strength associated to the Fermi and Gamow-Teller transitions is given by $N-Z$ and $3(N-Z)$ respectively, $N$ and $Z$ being the number of neutrons and protons of the considered nucleus. In [57] it is found that a fraction of the Gamow-Teller strength $B(\text{GT})$, i.e. $\sum B(\text{GT})=28 \pm 5$, is distributed to excite the $^{98}\text{Tc}$ states having up to 18 MeV above the ground state. Since the experimental data are cut above 18 MeV we have checked the influence of a $B(\text{GT})$ strength located at higher energy by extrapolating the experimental data with different curves (Gaussian or Lorentzian). The results (sec. 5) turn out not to be sensitive to the specific extrapolation curve chosen. On the other hand, the Fermi transitions are dominated by the Isobaric Analog State of $^{98}\text{Mo}$, located at $E = 9.656$ MeV above $^{98}\text{Tc}$ ground state. This single resonance carries all the Fermi strength $B(\text{F})$ given by the Fermi sum-rule, namely $B(\text{F}) = (N-Z) = 14$. 

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Concerning the forbidden transitions, their contribution to the cross section has been calculated using the QRPA approach. The largest contribution comes from the $1^-$ and $2^-$ transitions to $^{98}\text{Tc}$ which essentially affects the high energy part of the cross section (above 40 MeV). The total cross section we use in this work is shown in Figure 4.

The need to minimize the background from solar neutrinos motivates the choice of the process $^{98}\text{Mo}(\nu_e, e^{-}n)^{97}\text{Tc}$, where one neutron is emitted. For this reaction the threshold in energy for neutron emission is high enough (8.96 MeV) to suppress the pp solar neutrino flux completely and the $^8\text{B}$ and $^{hep}$ fluxes partially compared to the supernova contribution. We make the assumption that all the excited states of $^{98}\text{Tc}$ laying above neutron emission threshold will decay by emitting neutrons and produce $^{97}\text{Tc}$ in its ground state. Note that the $^{97}\text{Mo}+p$ threshold is by 1.1 MeV lower than $^{97}\text{Tc}+n$ one. However proton emission at low energies should be highly suppressed compared to the neutron one due to the Coulomb barrier. At higher energies the $^{97}\text{Mo}+p$ channel should become as much important as the $^{97}\text{Tc}+n$ one. Thus, at these energies, our predictions should overestimate the rate of $^{97}\text{Tc}$ production from $^{98}\text{Mo}$.

A delicate task is to accurately predict the $^{97}\text{Mo}(\nu_e, e^{-})^{97}\text{Tc}$ cross section, since no experimental information is available. Following ref [1] for this case we have evaluated the $^{97}\text{Mo}(\nu_e, e^{-})^{97}\text{Tc}$ cross section exploiting the sum-rule argument, namely scaling the $B(GT)$ strength from the $^{98}\text{Mo}(p, n)^{98}\text{Tc}$ measurement by the ratio $(N-Z)^{97}\text{Mo}/(N-Z)^{98}\text{Mo}$. This scaling is performed after having subtracted the near-threshold events describing the transition to the $^{98}\text{Tc}$ ground state. In fact, the $^{97}\text{Mo}(\nu_e, e^{-})^{97}\text{Tc}_{g.s.}$ transition matrix elements is negligibly small as one can check by converting the $^{97}\text{Tc}_{g.s.}$ lifetime ($\tau_{1/2} = 2.6 \cdot 10^6$ s). Concerning the Fermi strength, we consider that all the strength $B(F)=2T=13$ is associated to the Isobaric Analogue State located at 11.05 MeV excitation energy of the $^{97}\text{Tc}$ nucleus. As in the $^{98}\text{Mo}$ case, we neglect $^{97}\text{Tc}$ production above the $^{96}\text{Tc}+n$ threshold. Since again we make the assumption that 100\% of the cases a neutron is produced, this time we slightly underestimate the $^{97}\text{Tc}$ production from $^{97}\text{Mo}$, which will give in particular fewer supernovae events.

5. Results

5.1 Rates

The table in figure 5 presents our predicted $^{97}\text{Tc}$ production rates from $^{98}\text{Mo}$ and $^{97}\text{Mo}$ due to both solar and supernova neutrinos.

Let us first comment on the $^{98}\text{Mo}(\nu_e, e^{-}n)^{97}\text{Tc}$ channel. Solar neutrinos produce $^{97}\text{Tc}$ essentially via the Gamow-Teller and the Fermi transitions to excited states of $^{98}\text{Tc}$, which then decay by emitting a neutron; the contribution from forbidden tran-
### Table 1

|                  | $98\text{Mo}(\nu_\text{e},n)\,97\text{Tc}$ | $97\text{Mo}(\nu_\text{e})\,97\text{Tc}$ |
|------------------|------------------------------------------|------------------------------------------|
|                  | HJ | Allowed only | Total (allowed + forbidden) | HJ | Total (allowed + forbidden) |
| $8\text{B}$      | 3.17 | 5.07 | 5.07 | 37.4 |
| hep              | 1.0 | 0.14 | 0.14 | 0.2 |
| Total solar      | 4.17 | 5.21 | 5.21 | 31 | 37.6 |
| SN (best)        | 0.73 - 1.0 | 1.13 - 1.58 | 0.23 - 0.30 |
| SN (natural)     | 0.28 - 0.36 | 0.37 - 0.49 | 1.7 | 0.10 - 0.12 |
| SN (worst)       | 0.12 - 0.14 | 0.15 - 0.18 | 0.048 - 0.051 |
| BH (S Eos)       | 0.08 - 0.12 | 0.17 - 0.22 | 0.02 - 0.03 |
| BH (LS EoS)      | 0.03 - 0.04 | 0.06 - 0.07 | 0.08 - 0.010 |

**Figure 5:** $97\text{Tc}$ production rates ($10^{-37} \times s^{-1}$) associated to neutrinos from the sun and supernovae (where BH indicates failed, black hole-forming supernovae), in comparison with Haxton and Johnson’s (HJ) ones. Intervals for SN rates take into account the variations in the neutrino oscillation pattern (normal vs inverted mass hierarchy and small vs large $\theta_{13}$). All our results are obtained with a galactic rate $R_{sn} = 0.01$ yr$^{-1}$ ($R_{bh} = 0.001$yr$^{-1}$) for successful (failed) supernovae. They can be easily rescaled for other values of this quantity. Natural values of $R_{sn}$ are $0.02 - 0.03$ yr$^{-1}$, but the larger interval $0.01 - 0.05$ yr$^{-1}$ is allowed (table 1). HJ’s numbers refer to a supernova rate of 0.09 yr$^{-1}$.

In comparison to HJ [1], we find a higher rate of transition due to $8\text{B}$ neutrinos, result of the larger (almost double) normalization of this flux after oscillations (sec. 3). In contrary, the rate due to the $hep$ flux is an order of magnitude smaller because of the smaller initial normalization and the further reduction of the flux due to flavor conversion.

In Figure 5 we show predictions for supernova neutrinos considering a galactic supernova rate of 0.01 yr$^{-1}$ and taking into account a range of values for the supernova neutrino fluxes at the neutrino-sphere and at the surface of the supernova, due to the
unknown neutrino mixing parameters (Table 2, fig. 2). Contrary to the solar case, the rate from supernova neutrinos has an important contribution (∼30-60%) coming from the forbidden transitions since the neutrino spectra cover several tens of MeV energy range. Obviously, an increased luminosity or average neutrino energy boosts the $^{97}$Tc production rate. One can see that our predictions are typically one order of magnitude smaller than what Haxton and Johnson estimated. The difference is mostly due to a higher supernova rate, $R_{sn} = 0.09 \, \text{yr}^{-1}$ and a higher neutrino luminosity ($8 \cdot 10^{52} \, \text{ergs}$ compared to our $L_0 = 0.5 \cdot 10^{53} \, \text{ergs}$), as well as the fact that the flavor permutation of supernova neutrinos was not included by HJ. Inclusion of oscillations increases the supernova flux above $\sim 15 - 20 \, \text{MeV}$, as observed in sec. 3, and therefore lessens the gap between our results and those in [1] 2. Still, while HJ concluded that the rate of $^{98}$Mo($\nu_e, e^- n$)$^{97}$Tc reaction due to supernova neutrinos should be as much as 1.3 times the solar one, our finding is that the supernova contribution is most likely at the level of tens of per cent, but can amount to more than half the solar contribution accepting optimistic neutrino parameters and $R_{sn} \gtrsim 0.03 \, \text{yr}^{-1}$, as allowed by current estimates (table 1).

The effect of failed supernovae on the $^{98}$Mo($\nu_e, e^- n$)$^{97}$Tc rate is significant. While certainly small compared to the solar rate, for the S EoS this contribution can easily reach $\sim 50\%$ of the one from successful supernovae, and can be even of the same size for the largest fraction of failed versus successful supernovae, $R_{bh}/R_{sn} \sim 0.2$. For the LS EoS the effect is more modest, but still at the level of $\sim 10 - 30\%$ of the total supernova contribution. We notice that, due to the more energetic neutrino fluxes, the rate from failed supernovae is very sensitive to the forbidden states, and nearly doubles when these are included in the cross section calculation.

The $^{97}$Tc production via the $^{97}$Mo($\nu_e, e^- n$)$^{97}$Tc channel constitutes a very different case, also illustrated in fig. 5. For this process the reaction threshold is only 320 keV, and therefore a large fraction of the solar $^{8}$B and hep neutrino fluxes contribute to it. Moreover at 9.8 MeV the $^{97}$Mo($\nu_e, e^- n$)$^{96}$Tc channel opens and starts dominating over the $^{97}$Tc production, further suppressing the supernova contribution to this channel. For these reasons the $^{97}$Tc production from $^{97}$Mo is largely dominated by solar neutrinos, primarily due to the GT transitions, with the supernova-induced production being only a few per cent of the total. The effect of the $^{97}$Mo($\nu_e, e^- n$)$^{97}$Tc channel is mostly to dilute the supernova signal due to scattering on $^{98}$Mo into a larger background and make a measurement more challenging.

2If we make the same assumptions as in [1] we get the same solar background (with differences up to 8%) and a supernova rate about 17% lower. This is probably due to the different procedure followed in the present work as far as the forbidden transitions are concerned.
5.2 Abundances of $^{97}$Tc in Molybdenum rocks

In order to estimate the feasibility of a geochemical experiment one should translate the calculated rates into the number of $^{97}$Tc atoms in a sample of rock, which is the experimentally measurable quantity. We calculated this for 10 kt mass of Molybdenum ore, considering that it contains about 49 t of MoS$_2$ [1], and assuming that its Mo content follows the natural isotopic abundances (i.e., 24.13% for $^{98}$Mo and 9.55% for $^{97}$Mo).

|                      | $^{98}$Mo($\nu_e,e^{-}\mathrm{n}$)$^{97}$Tc | $^{97}$Mo($\nu_e,e^{-}$)$^{97}$Tc | Total | HJ, total |
|----------------------|---------------------------------------------|----------------------------------|-------|-----------|
| Solar only           | 2.7                                         | 7.8                              | 10.6  | 8.0*      |
| Solar + 100% SN      | 3.5                                         | 7.9                              | 11.4  | 11.2      |
| Solar + 90% SN + 10% BH (S EoS) | 3.7                                         | 7.9                              | 11.6  | 11.2      |

* $^8$B only. See [1] for details.

Figure 6: Numbers of $^{97}$Tc atoms ($10^6$ unit) expected in 10 kt of rock from the two different processes of interest. Totals are given too, as well as the results for the capture rates of Haxton and Johnson (HJ) for comparison. Our results refer to a supernova rate of 0.03 yr$^{-1}$ and parameters in the “natural” scenario (Table 2) for successful supernovae (SN). Results in the last row refer to a scenario with a 10% failed supernovae (BH) with neutrino emission as in the S model of ref. [50] (see fig. 3). In all cases we have considered complete flavor permutation ($p = 0$), which gives the largest $^{97}$Tc production rates for successful SNe.

Results are presented in fig. 6. It appears that in 10 kt of Molybdenum ore that
is completely shielded from cosmic rays, there should be \( \simeq 1.1 \cdot 10^7 \) atoms of \(^{97}\text{Tc}\), of which about 10% from supernovae, for natural parameters of supernova neutrino emission and \( R_{sn} = 3 \cdot 10^{-2} \text{ yr}^{-1} \). This contribution can be larger by up to a factor of 3 if the best scenario of supernova neutrino spectra and luminosities (table 2) is realized. The effect of failed supernovae is a few per cent of the total abundance. We note how our calculated abundance is very close to that of Haxton and Johnson: this similarity is completely accidental, since our input quantities are very different and we find a substantially higher solar contribution, balanced by a lower supernova one.

Let us now discuss the significance of our result in view of an experiment. The first question is if the neutrino-induced \(^{97}\text{Tc}\) is at detectable level. The answer is affirmative: already at the time of HJ the best instruments were quoted [1] to have sensitivity down to about \( 5 \cdot 10^6 \) atoms for a pure Tc sample. A modern experiment would employ essentially the same methods, with a sensitivity slightly improved (a factor of two or so) by a number of technological updates [58]. Therefore we come to the same conclusion as HJ: at the price of setting up an industrial-scale extraction project, capable to process about 10 kt of rock at large depth\(^3\), an experiment should be feasible. Such experiment should be arranged in such a way to avoid the “roast memory” problem that was fatal to the original experimental attempt in 1988 [5]. While potentially laborious, this is not difficult conceptually.

Once established that a detection is possible, a key question is if the supernova neutrino contribution can be unambiguously identified. Our study makes it clear that this contribution is comparable to the several uncertainties involved in the problem. Indeed, already the GT strength distribution obtained from \(^{98}\text{Mo}(p, n)^{98}\text{Tc}\) measurement has more than 17% uncertainty, whereas the \(^{97}\text{Mo}(\nu, e^-)^{97}\text{Tc}\) cross section estimate along with branching ratios into the decay channels is purely phenomenological. One should also consider the \( \sim 5 - 10\% \) error on the oscillated \(^{8}\text{B}\) solar neutrino flux, and the still unmeasured hep flux.

Therefore, we conclude that a measurement of the \(^{97}\text{Tc}\) abundance in deep Molybdenum ore would be an interesting complement to studies of the solar neutrino flux, but would provide only loose upper limits on the supernova flux, perhaps at the level of the constraint from neutrino detectors on the supernova rate (table 1). Two major experimental steps should be achieved in the near future to render the geochemical quest for galactic supernova neutrinos attractive: i) an increase in precision in the measured \(^{8}\text{B}\) solar neutrino flux and a new precise measurement of the hep flux; ii) a precise measurement of the transition matrix elements for the Gamow-Teller as well as the forbidden multipoles contributing to the \(^{97}\text{Mo}(p, n)^{97}\text{Tc}\) and \(^{98}\text{Mo}(p, n)^{98}\text{Tc}\) react-

\(^3\)We stress that the use of industrial-scale equipment and large scale excavations – while exceeding the typical scale of geophysics projects – are common in the field of neutrino astrophysics.
tions, along with the branching ratio relevant to $^{97}$Tc production. This can be obtained from future charge-exchange measurements for example at KVI or RIKEN. A direct measurement of the neutrino induced cross sections could also be performed at future low energy neutrino facilities exploiting conventional sources, such as at $\nu$SNS, or at a low energy beta-beam facility [59, 60, 61].

6. Conclusions

In this paper we have investigated the possibility to observe the integrated supernova galactic neutrino contribution by measuring the $^{97}$Tc produced by electron neutrinos in a Molybdenum ore, as first proposed in [1]. With this aim realistic estimates – reflecting the state of the art in the neutrino physics and of galactic supernovae neutrino fluxes – have been performed. For our calculations we have used experimental information on the Gamow-Teller and Fermi distributions of the $^{98}$Mo($\nu_e, e^-)$ $^{98}$Tc reaction, combined with QRPA predictions for the forbidden contributions.

We have found that the relative production of $^{97}$Tc from supernova neutrinos is about 0.1 of the solar background, which is much smaller than what was evaluated in the pioneering study [1]. For a geochemical measurement to become attractive, a better knowledge of the solar neutrino spectrum and of the $^{98}$Mo($\nu_e, e^-)$ $^{98}$Tc and $^{98}$Mo($\nu_e, e^- n$) $^{97}$Tc cross sections are necessary. An improved experimental sensitivity is desirable to reduce the quantity of rock to be processed. Future precise charge-exchange measurements at high energies and forward angles and/or neutrino-nucleus measurements for the $^{97}$Mo and $^{98}$Mo isotopes will definitely be very helpful.

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References

[1] W. C. Haxton and C. W. Johnson, *Geochemical integrations of the neutrino fluxes from stellar collapses*, Nature **333** (1988) 325–329.

[2] V. T. Nguyen and C. W. Johnson, *Time-integrated supernova neutrino flux from a nearby cluster*, Astropart. Phys. **27** (2007) 233–237 [astro-ph/0508267].

[3] W. C. Haxton, private communication.
[4] M.W. Brown, *Clues of Stellar Explosions Found Deep in Mine, Scientists Say*, the New York Times, May 26, 1988; available at http://query.nytimes.com/.

[5] *Moly-technetium used to track elusive neutrinos - Focus: Advanced Materials*, American Metal Market, Sept 11, 1991.

[6] V. Barger et. al., *Report of the US long baseline neutrino experiment study*, 0705.4396.

[7] D. Autiero et. al., *Large underground, liquid based detectors for astro- particle physics in Europe: scientific case and prospects*, JCAP 0711 (2007) 011 [0705.0116].

[8] S. Ando and K. Sato, *Relic neutrino background from cosmological supernovae*, New J. Phys. 6 (2004) 170 [astro-ph/0410061].

[9] KAMIOKANDE-II Collaboration, K. Hirata et. al., *Observation of a neutrino burst from the supernova sn987a*, Phys. Rev. Lett. 58 (1987) 1490–1493.

[10] R. M. Bionta et. al., *Observation of a neutrino burst in coincidence with supernova sn987a in the large magellanic cloud*, Phys. Rev. Lett. 58 (1987) 1494.

[11] E. N. Alekseev, L. N. Alekseeva, I. V. Krivosheina and V. I. Volchenko, *Detection Of The Neutrino Signal From Sn1987a In The Lmc Using The Inr Baksan Underground Scintillation Telescope*, Phys. Lett. B 205 (1988) 209.

[12] G. G. Raffelt, *Supernova neutrino observations: What can we learn?*, astro-ph/0701677.

[13] S. van den Bergh and R. D. McClure, *Rediscussion of extragalactic supernova rates derived from Evans’s 1980-1988 observations*, Astrophys. J., 425, 1994, 205.

[14] R. Diehl et. al., *Radioactive 26Al and massive stars in the Galaxy*, Nature 439 (2006) 45–47 [astro-ph/0601015].

[15] E. Cappellaro, R. Evans and M. Turatto, *A new determination of supernova rates and a comparison with indicators for galactic star formation*, Astron. Astrophys. 351 (1999) 459 [astro-ph/9904225].

[16] E. Cappellaro and M. Turatto, *Supernova types and rates*, arXiv:astro-ph/0012455.

[17] R. G. Strom, *Guest stars, sample completeness and the local supernova rate*, Astron. Astrophys., 288, L1, 1994.

[18] G. A. Tammann, W. Loeffler and A. Schroder, *The Galactic supernova rate*, Astrophys. J. Suppl. 92 (1994) 487–493.
[19] E. N. Alekseev and L. N. Alekseeva, *Twenty Years of Galactic Observations in Searching for Bursts of Collapse Neutrinos with the Baksan Underground Scintillation Telescope*, J. Exp. Theor. Phys. **95** (2002) 5–10 [astro-ph/0212499].

[20] I. Yusifov and I. Kucuk, *Revisiting the radial distribution of pulsars in the galaxy*, Astron. Astrophys. **422** (2004) 545–553 [astro-ph/0405559].

[21] K. M. Ferriere, *The Interstellar Environment of our Galaxy*, Rev. Mod. Phys. **73** (2001) 1031–1066 [astro-ph/0106359].

[22] D. R. Lorimer, *The Galactic population and birth rate of radio pulsars*, astro-ph/0308801.

[23] A. Mirizzi, G. G. Raffelt and P. D. Serpico, *Earth matter effects in supernova neutrinos: Optimal detector locations*, JCAP **0605** (2006) 012 [astro-ph/0604300].

[24] M. T. Keil, G. G. Raffelt and H.-T. Janka, *Monte carlo study of supernova neutrino spectra formation*, Astrophys. J. **590** (2003) 971–991 [astro-ph/0208035].

[25] T. Totani, K. Sato, H. E. Dalhed and J. R. Wilson, *Future detection of supernova neutrino burst and explosion mechanism*, Astrophys. J. **496** (1998) 216–225 [astro-ph/9710203].

[26] T. A. Thompson, A. Burrows and P. A. Pinto, *Shock breakout in core-collapse supernovae and its neutrino signature*, Astrophys. J. **592** (2003) 434 [astro-ph/0211194].

[27] S. Samuel, *Neutrino oscillations in dense neutrino gases*, Phys. Rev. **D48** (1993) 1462–1477.

[28] S. Pastor, G. G. Raffelt and D. V. Semikoz, *Physics of synchronized neutrino oscillations caused by self-interactions*, Phys. Rev. **D65** (2002) 053011 [hep-ph/0109035].

[29] A. B. Balantekin and H. Yuksel, *Neutrino mixing and nucleosynthesis in core-collapse supernovae*, New J. Phys. **7** (2005) 51 [astro-ph/0411159].

[30] H. Duan, G. M. Fuller and Y.-Z. Qian, *Collective Neutrino Flavor Transformation In Supernovae*, Phys. Rev. **D74** (2006) 123004 [astro-ph/0511275].

[31] S. Hannestad, G. G. Raffelt, G. Sigl and Y. Y. Y. Wong, *Self-induced conversion in dense neutrino gases: Pendulum in flavour space*, Phys. Rev. **D74** (2006) 105010 [astro-ph/0608695].

[32] G. L. Fogli, E. Lisi, A. Marrone and A. Mirizzi, *Collective neutrino flavor transitions in supernovae and the role of trajectory averaging*, JCAP **0712** (2007) 010 [0707.1998].
[33] G. G. Raffelt and A. Y. Smirnov, *Adiabaticity and spectral splits in collective neutrino transformations*, Phys. Rev. D76 (2007) 125008 [0709.4641].

[34] B. Dasgupta and A. Dighe, *Collective three-flavor oscillations of supernova neutrinos*, Phys. Rev. D77 (2008) 113002 [0712.3798].

[35] A. Esteban-Pretel, S. Pastor, R. Tomas, G. G. Raffelt and G. Sigl, *Mu-tau neutrino refraction and collective three-flavor transformations in supernovae*, Phys. Rev. D77 (2008) 065024 [0712.1137].

[36] J. Gava and C. Volpe, *Collective neutrinos oscillation in matter and CP- violation*, Phys. Rev. D78 (2008) 083007 [0807.3418].

[37] S. P. Mikheev and A. Y. Smirnov, *Neutrino oscillations in a variable-density medium and ν− bursts due to the gravitational collapse of stars*, Sov. Phys. JETP 64 (1986) 4–7 [arXiv:0706.0454 [hep-ph]].

[38] A. S. Dighe and A. Y. Smirnov, *Identifying the neutrino mass spectrum from the neutrino burst from a supernova*, Phys. Rev. D62 (2000) 033007 [hep-ph/9907423].

[39] C. Lunardini and A. Y. Smirnov, *Probing the neutrino mass hierarchy and the 13-mixing with supernovae*, JCAP 0306 (2003) 009 [hep-ph/0302033].

[40] C. Lunardini, *Supernova neutrinos: Earth matter effects and neutrino mass spectrum*, Prepared for NO-VE International Workshop on Neutrino Oscillations in Venice, Venice, Italy, 24-26 Jul 2001.

[41] B. Dasgupta, A. Dighe and A. Mirizzi, *Identifying neutrino mass hierarchy at extremely small theta(13) through Earth matter effects in a supernova signal*, Phys. Rev. Lett. 101 (2008) 171801 [0802.1481].

[42] SNO Collaboration, B. Aharmim et. al., *An Independent Measurement of the Total Active 8B Solar Neutrino Flux Using an Array of 3He Proportional Counters at the Sudbury Neutrino Observatory*, Phys. Rev. Lett. 101 (2008) 111301 [0806.0989].

[43] C. Lunardini, *The diffuse supernova neutrino flux, star formation rate and SN1987A*, Astropart. Phys. 26 (2006) 190–201 [astro-ph/0509233].

[44] A. Esteban-Pretel et. al., *Role of dense matter in collective supernova neutrino transformations*, 0807.0659.

[45] S. E. Woosley, A. Heger and T. A. Weaver, *The evolution and explosion of massive stars*, Rev. Mod. Phys. 74 (2002) 1015–1071.
[46] K. Sumiyoshi, S. Yamada, H. Suzuki and S. Chiba, *Neutrino signals from the formation of black hole: A probe of equation of state of dense matter*, Phys. Rev. Lett. 97 (2006) 091101 [astro-ph/0608509].

[47] K. Sumiyoshi, S. Yamada and H. Suzuki, *Dynamics and neutrino signal of black hole formation in non-rotating failed supernovae. I. EOS dependence*, 0706.3762.

[48] T. Fischer, M. Liebendorfer and A. Mezzacappa, *The neutrino signal from protoneutron star accretion and black hole formation*, 0809.5129.

[49] K. Sumiyoshi, S. Yamada and H. Suzuki, *Dynamics and neutrino signal of black hole formation in non-rotating failed supernovae. II. progenitor dependence*, 0808.0384.

[50] K. Nakazato, K. Sumiyoshi, H. Suzuki and S. Yamada, *Oscillation and Future Detection of Failed Supernova Neutrinos from Black Hole Forming Collapse*, Phys. Rev. D78 (2008) 083014 [0810.3734].

[51] H. Shen, H. Toki, K. Oyamatsu and K. Sumiyoshi, *Relativistic equation of state of nuclear matter for supernova and neutron star*, Nucl. Phys. A, 637, 1998, 435.

[52] J. M. Lattimer and F. D. Swesty, *A generalized equation of state for hot, dense matter*, Nucl. Phys. A.

[53] J. N. Bahcall, A. M. Serenelli and S. Basu, *New solar opacities, abundances, helioseismology, and neutrino fluxes*, Astrophys. J. 621 (2005) L85–L88 [astro-ph/0412440].

[54] G. L. Fogli, E. Lisi, A. Marrone, D. Montanino and A. Palazzo, *Probing non-standard decoherence effects with solar and KamLAND neutrinos*, Phys. Rev. D76 (2007) 033006 [0704.2568].

[55] R.G. Hamish Robertson, talk at “Neutrino 2008”, Christchurch, New Zealand, 2008. Available at http://www2.phys.canterbury.ac.nz/~jaa53/.

[56] J.D. Walecka, *Muon Physics*, ed. V.M. Hughes and C.S Wu (Academis, New York, 1975).

[57] J. Rapaport et al., *Solar-Neutrino Detection: Experimental Determination of Gamow-Teller Strengths via the 98Mo and 115In (p, n) Reactions*, Phys. Rev. Lett. 54 (1985) 2325.

[58] A. Anbar (Arizona State University), private communication.

[59] C. Volpe, *What about a beta beam facility for low energy neutrinos?*, J. Phys. G30 (2004) L1–L6 [hep-ph/0303222].
[60] R. Lazauskas and C. Volpe, *Neutrino beams as a probe of the nuclear isospin and spin-isospin excitations*, Nucl. Phys. **A792** (2007) 219–228 [0704.2724].

[61] C. Volpe, *Topical review on 'beta-beams*', J. Phys. **G34** (2007) R1–R44 [hep-ph/0605033].