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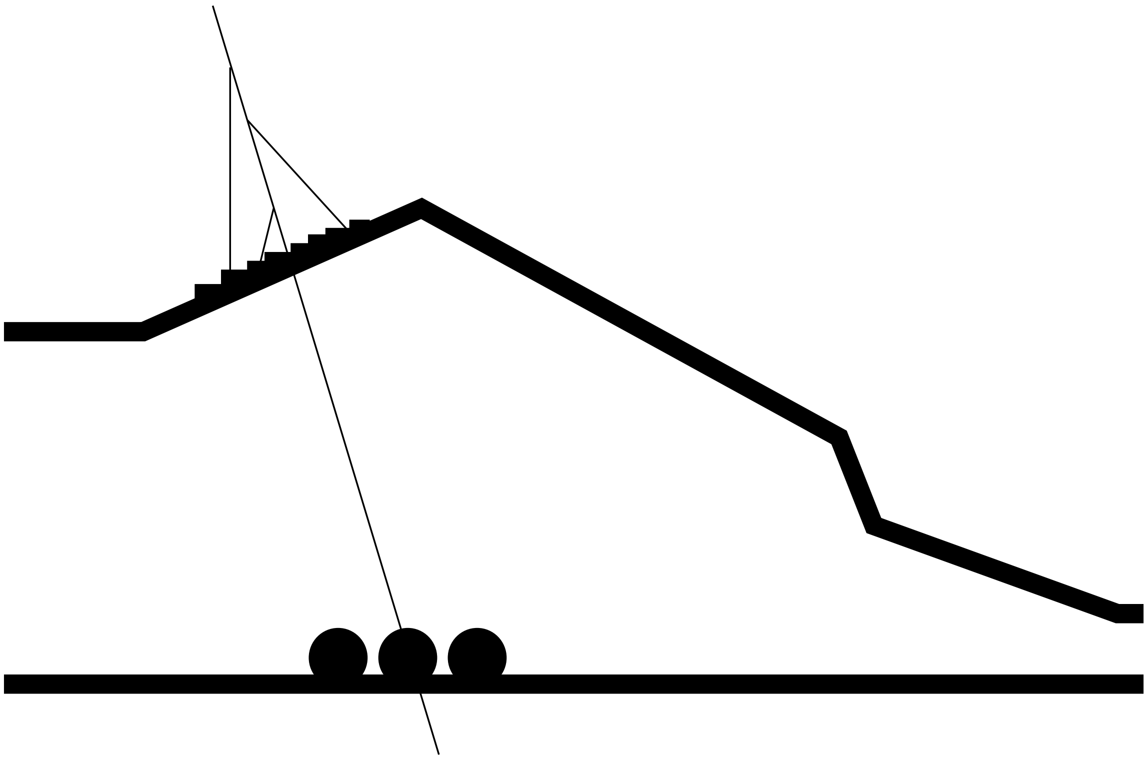
5 Maggio 1999



On the possibility of detecting the $\bar{\nu}_e$ burst from the collapse of a neutron star into a black hole

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ASTRONOMY AND ASTROPHYSICS in press

INFN - Laboratori Nazionali del Gran Sasso

Published by **SIS-Pubblicazioni**
dei Laboratori Nazionali di Frascati

INFN - Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso

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On the possibility of detecting the $\bar{\nu}_e$ burst from the collapse of a neutron star into a black hole

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Abstract

The possibility of detecting the $\bar{\nu}_e$ burst from the collapse of a neutron star into a black hole is discussed for an existing SN neutrino detector.

The expected signal has been evaluated on the basis of the model predictions on the ν emission and compared with the detector background. The experimental conditions are discussed in order to maximize the signal to noise ratio.

A fraction up to 10% (depending on the ν energy spectrum) of the stars of our Galaxy, distributed through distances which extent up to the Galactic Center, could be observed by a $1kt$ liquid scintillator detector such as the Large Volume Detector at Gran Sasso.

1 Introduction

In the frame of a possible model ([Gourgoulhon & Haensel 1993]) a sharp, low energy neutrino bounch is expected to accompany the collapse of a neutron star into a black hole.

The phenomenon can occur due to accreting material on a binary neutron star and is practically undetectable by any other process.

In this scenario neutrinos are produced mainly via non equilibrium weak interaction processes and their flavor could yield interesting information about the properties of matter at very high density. In fact, in such processes, β^- reactions strongly dominate over β^+ ones and $\bar{\nu}_e$ and $\bar{\nu}_\mu$ would be mainly produced.

The predicted $\bar{\nu}$ burst has the duration of a fraction of a millisecond and, due to the strong gravitational and Doppler red shift ($z \approx 1$), the average $\bar{\nu}_e$ energy at infinity is $< E_{\bar{\nu}_e} > \approx 4$ MeV.

In the most favorable case the total $\bar{\nu}_e$ energy, as measured by a distant observer, is a few times 10^{50} erg. If one includes neutrino opacity the burst luminosity and the average energy of neutrinos at infinity would be reduced.

In this paper we will evaluate the possibility to detect such a signal with an existing detector. What is needed is a massive detector, with high efficiency at low $\bar{\nu}_e$ energy and the ability to distinguish $\bar{\nu}_e$ interactions to reduce the background.

Liquid scintillator detectors, located in well shielded enviroments, are sensitive to low energy $\bar{\nu}_e$ via the capture reaction:

$$\bar{\nu}_e + p \rightarrow n + e^+ \tag{1}$$

with threshold energy: $E_{th}^{\bar{\nu}_e} \approx (m_n\text{-}m_p)+m_e \approx 1.8$ MeV and detectable energy: $E_d = T_{e^+} + 2m_e c^2 \approx E_{\bar{\nu}_e} - 0.8 MeV$ where T_{e^+} is the kinetic energy of the positron.

In addition, the signal due to the (n,p)-capture ($E_\gamma = 2.23$ MeV) can provide a good signature of the $\bar{\nu}_e$ interaction.

We detail our calculation for the LVD ν telescope ([LVD Collaboration 1992]), located in the Gran Sasso Underground Laboratory at a minimum rock coverage of $3000m$ of water equivalent, whose main purpose is the detection of ν bursts from gravitational stellar collapses. We assume $1kt$ of scintillator as in the LVD core-counters: 1.5 m^3 modules that can be operated at very low energy thresholds, with average efficiency for n-capture detection: $\epsilon_n = 60\%$.

2 Expected ν signal

In this section the number of expected $\bar{\nu}_e$ interactions from the neutron star collapse described by Gourgoulhon and Haensel (1993) is evaluated. For the total energy converted into ν we use: $E_{\bar{\nu}_e}^{\infty} = E_{\bar{\nu}_\mu}^{\infty} = 5.0 \cdot 10^{50} erg$ with an average $\bar{\nu}_e$ energy at the detector: $< E_{\bar{\nu}_e} > |_\infty \approx 4 MeV$.

For the $\bar{\nu}_e$ energy spectrum no indication is obtained from the model and in analogy with the case of gravitational stellar collapse, a Fermi Dirac neutrino specrum with non zero chemical potential has been adopted:

$$\frac{dN_\nu}{dE_\nu} = \frac{E_\nu^2}{exp(\frac{-E_\nu}{T} - \eta) + 1} \tag{2}$$

with chemical potential $\eta = \mu/T$ ranging between 0 and 4, and emission temperature T between 2 and 2.5 MeV. A red shift $\frac{\omega}{\omega_0} = \frac{1}{2}$ is then applied.

Different couples of spectral parameters T and η have been choosen in order to keep the average $\bar{\nu}_e$ energy around 4 MeV as predicted by the model. In Table 1 the set of parameters used in the calculation are summarized.

$T[MeV]$	η	$< E^{\infty}_{\bar{\nu}_e} >$	$N^{\infty}_{\bar{\nu}_e}$
2.5	0	3.9	$8.0 \cdot 10^{55}$
2.5	2	4.5	$7.0 \cdot 10^{55}$
2.0	2	3.6	$8.7 \cdot 10^{55}$
2.0	4	4.5	$7.0 \cdot 10^{55}$

Table 1: Spectral characteristics and total number of $\bar{\nu}_e$ assumed in calculations.

Electron anti-neutrinos, producing the bulk of events at these energies, interact with the detector target (C_nH_{2n+2}) mainly through reaction (1) (for cross sections see [Vogel 1984]). The detected energy spectra are shown in Fig.1.

Since the energy threshold and the efficiency for reducing the background by using the n-capture signature are decisive, we will discuss the results for different values of such parameters.

The counter energy resolution can be expressed ([Antonioli et al. 1991]) by:

$$\frac{\sigma_E}{E} = 7\% + \frac{23\%}{\sqrt{E[MeV]}} \tag{3}$$

and the detector efficiency $\epsilon(E_d, E_{th})$, for $E_{th} \leq 10MeV$, by the gaussian integral function:

$$\epsilon(E_d, E_{th}) = \frac{A}{\sqrt{2\pi}} \int_{-\infty}^{x} e^{\frac{-y^2}{2}} dy \tag{4}$$

with: $x = \frac{(E_d - E_{th})}{\sigma_{E_{th}}}$ and $A = 1 - \frac{E_{th}}{100}$, the 50% detection efficiency being at $E_d \approx E_{th}$.

As a first step we will assume as detection efficiency of thermal neutrons $\epsilon_n = 1$ ($\epsilon_n < 1$ will be discussed in the last section).

Main results are summarized in Fig.2 where, for different spectral characteristics of the $\bar{\nu}_e$ emission, the number of expected interactions N_{ev} in the $1kt$ detector due to a collapsing neutron star at the distance of $1kpc$ is shown as a function of the detector energy threshold E_{th}.

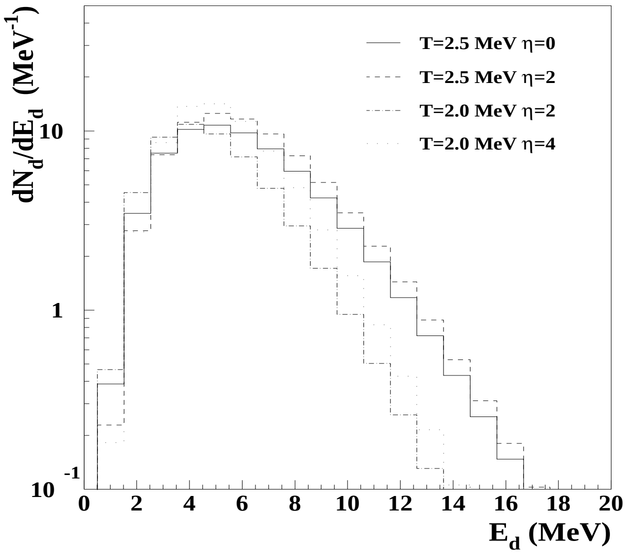

Figure 1: Detected energy spectra for different spectral parameters.

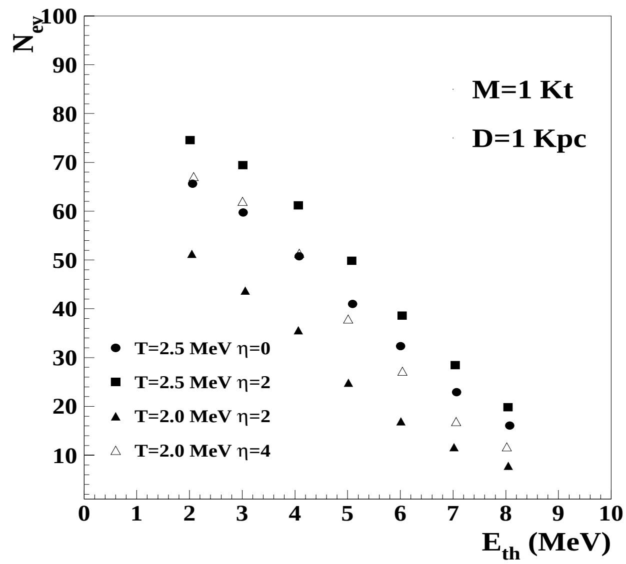

Figure 2: Number of expected events in the LVD $1kt$ core detector as a function of the threshold parameter E_{th}, for a collapsing n-star at the distance of $1Kpc$. Results for different $\bar{\nu}_e$ spectra are shown.

3 The background

In order to evaluate the background sources for the event under study, two contributions have to be taken into account:
a) correlated signals involving more then one counter; b) uncorrelated signals which, by chance, cluster in the characteristic time of the searched physical event.

Concerning the former effect we have to consider:
1 - signals associated to atmospheric muons:
secondaries produced by atmospheric μ's, which elude the anticoincidence detectors, could hit different counters imitating a $\bar{\nu}_e$ burst;
2 - signals associated to atmospheric neutrinos:
c.c. interactions of atmospheric ν_e and $\bar{\nu}_e$ with C nuclei produce two detectable signals due to prompt and delayed β reactions with an average delay of a couple of milliseconds which have a finite probability to hit two different scintillator counters;
3 - signals associated to natural radioactivity:
from the spontaneous fission of the ^{238}U impurities present in the detector materials, gammas and neutrons can be produced to simulate a cluster of $\bar{\nu}_e$ signals.

Such sources of noise can be identified by the peculiar topology, the signals belonging to the cluster being distributed along a straight line or concentrated around a vertex, hardly exceeding a multiplicity $m = 2$.

Direct experimental data on the rate of clusters of different multiplicities with large volume detectors have been reported by the Mont Blanc ([Aglietta et al. 1992]) and LVD ([LVD Collaboration 1993, 1995, 1997]) collaborations, in the search for ν bursts from SN gravitational collapses (which essentially differ from the events under discussion in the time duration: $\Delta t = 1 \div 10 sec$). It has been shown that for any time interval, down to multiplicities $m = 3$ ([Aglietta et al. 1992]), the rate of clusters follows the one expected on the basis of Poissonian statistics.

Therefore, for multiplicity $m \geq 3$, the only surviving source of background is given by the clustering of uncorrelated background signals due to fluctuations in their time distribution. We will analyze the probability of such events in more detail.

The background energy spectrum in a deep underground detector, with energy resolution which does not allow to distinguish single emission lines, after muon rejection, can be conservatively approximated by:

$$\frac{dN_{bk}}{dE_d} = C \cdot E_d^{-5.8} [events \cdot t^{-1} \cdot s^{-1} \cdot MeV^{-1}] \tag{5}$$

in the energy range up to $\approx$ 10 MeV.
The detector shielding sets the value of the constant C which can be obtained by solving Eq.(6):

$$N_{bk}(\geq E_{th}) = C \int_0^\infty \frac{dN}{dE_d} \cdot \epsilon(E_d, E_{th}) dE \tag{6}$$

In the LVD core counters the trigger rate for $E_{th} = 1.5 MeV$ is ([LVD Collaboration 1992]): $N_{bk}(\geq 1.5 MeV) \approx 33 counts \cdot s^{-1} \cdot t^{-1}$, giving $C = 6.3$. This reproduces fairly well the background counting rate of the LVD counters.

The rate of background clusters of at least m pulses in time intervals of duration Δt is:

$$f(m) = R \cdot [1 - \sum_{k=0}^{m-2} \frac{exp(-R\Delta t) \cdot (R\Delta t)^k}{k!}] \quad (7)$$

where $R = N_{bk}(\geq E_{th})$ is the total background counting rate for detector threshold E_{th} given by Eq.(6). We will refer to it from now on as imitation frequency $f_{im}(m)$.

The requirement for each pulse to be followed by a delayed signal in the same counter, as signature of occurring inverse β reaction, reduces the counting rate R by a factor $q = 1 - exp(-R_n \Delta t_n)$ where R_n is the background rate of a single counter at the characteristic energy of $n - capture$ and Δt_n is ≈ 3 times the average capture time.

For the case of LVD core at present: $< R_n >$=40 $counts \cdot s^{-1}$ and $\Delta t_n = 6 \cdot 10^{-4} s$ therefore $q = 2.4 \cdot 10^{-2}$.

For a maximum cluster duration $\Delta t = 1ms$ the imitation frequency $(events \cdot year^{-1})$ is shown in Fig.3 for $1kt$ target mass and different energy thresholds as a function of the cluster multiplicity m.

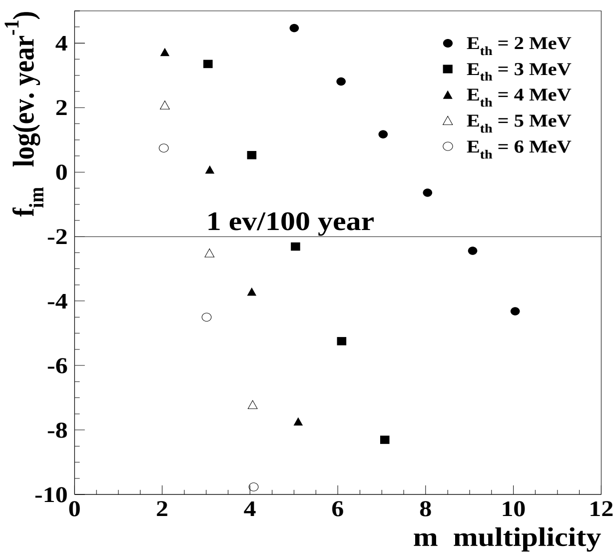

Figure 3: Imitation frequency as a function of the cluster multiplicity for different energy thresholds E_{th} and $\Delta t = 1ms$.

For energy threshold $E_{th} = 2MeV$, a cluster multiplicity $m \geq 9$ is necessary in order to have an imitation frequency lower than one event every 100 years. For $E_{th} = 3MeV$ ($4MeV$) such minimum multiplicity will be $m \geq 5$ ($m \geq 4$), in the conservative hypothesis of $\Delta t = 1ms$. We will refer to such minimum multiplicity, which is function of the the rate R, as m_{th}.

4 Discussion

The number of expected events $N_{ev}^{1kpc}(T, \eta, E_{th})$ has been calculated for different $\bar{\nu}_e$ spectra (characterized by T and η) to be compared with the minimum cluster multiplicity (m_{th}) necessary to extract the signal from the background fluctuations at the level of $f_{im} \leq 1 \cdot 10^{-2} year^{-1}$.

Such values, for each selected energy threshold, set the sensitivity of the experiment which can be written in term of maximum observable distance as:

$$D^{max}(T, \eta, E_{th}) = \sqrt{\frac{N_{ev}^{1Kpc}}{m_{th}}[Kpc]} \tag{8}$$

as shown in Fig.4.

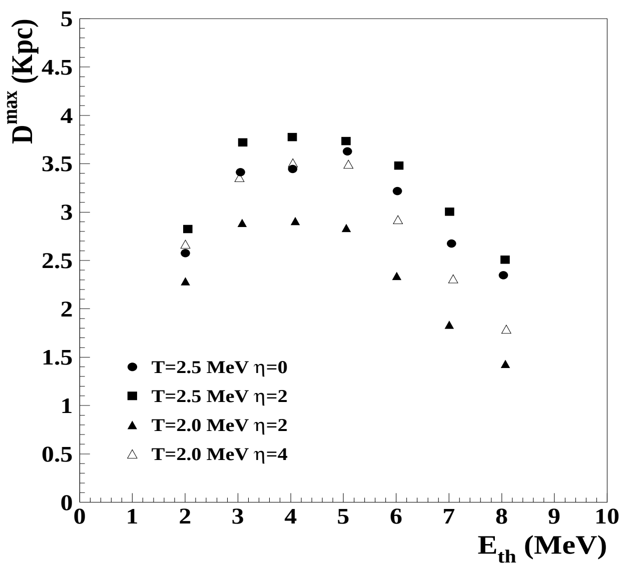

Figure 4: Maximum observable distance as a function of detector energy threshold.

The maximum detector sensitivity is achieved for $E_{th} = 4 \div 5 MeV$, which corresponds to a minimum cluster multiplicity $m_{th} = 4 \div 3$. The total trigger rate at these energies thresholds (6), is acceptable for a detector in continuous data taking[1].

By taking into account the fluctuations of the number of expected events, the sensitivity of the experiment can be expressed in terms of the fraction of stars of our Galaxy under observation $F(D)$. This fraction is:

$$F(D) = \int_D \frac{dS(D)}{dD} \cdot P_{m_{th}}(\frac{N_{ev}^{1kpc}}{D^2})dD \tag{9}$$

[1]It is assumed that the detector energy threshold for the delayed signals from neutron capture is independent from the trigger threshold and low enough to detect the $2.2 MeV$ gamma signal.

where: $\frac{dS(D)}{dD}$ is the distribution of stars in the galactic disk at a distance D from the Sun ([Bahcall & Soneira 1980]), and $P_{m_{th}}(\frac{N_{ev}^{1kpc}}{D^2})$ is the Poisson probability to detect at least m_{th} events, the average expected value being $\frac{N_{ev}^{1kpc}}{D^2}$.

$F(D)$ is shown in Fig.5 for different spectral types and experimental conditions.

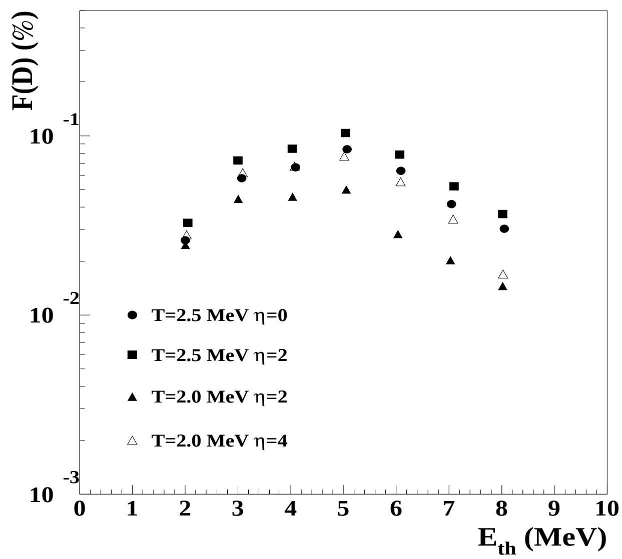

Figure 5: Fraction of stars of the Galaxy $F(D)$ which can be monitored by LVD $1Kt$ core operated at different conditions.

We can conclude that the fluctuations of the number of observed events makes $E_{th} = 5MeV$, corresponding to $m_{th} = 3$, the most favourable detector condition which allows to observe almost 10% of the stars in the Galaxy (but $E_{th}^{(1)} = 4$ MeV or $E_{th}^{(2)} = 3$ MeV, corresponding to $m_{th}^{(1)} = 4$ or $m_{th}^{(2)} = 5$ imply reductions not exceeding $20 \div 30\%$).

Finally we have to discuss the effects of neutron capture efficiency $\epsilon_n < 1$. As we have seen it acts as a factor on the number of expected events N_{ev}^{1kpc}: it means, from (8), that the maximum observable distance will be:

$$D_{\epsilon}^{max} = \sqrt{\frac{\epsilon_n \cdot N_{ev}^{1kpc}}{m_{th}}} = \sqrt{\epsilon_n} \cdot D^{max} \tag{10}$$

For $\epsilon_n = 0.6$, as at present for the LVD core, we have reductions of factors ≈ 1.3 for the maximum observable distance and 1.8 for the fraction of stars under observation.

In case of a detector unable to observe the n-capture, the signal from a n-star collapse will consist of a cluster of single pulses (without $\bar{\nu}_e$ signature) with the multiplicity shown in Fig.2. The background rate will not be attenuated by the factor q, that means, e.g. in the LVD core, a counting rate increase of a factor ≈ 40. In order to keep the maximum collapse imitation rate to 1 event every 100 years, the minimum cluster multiplicity becomes $\approx 3 \cdot m_{th}$ which corresponds to a reduction of D^{max} of $\approx \sqrt{3}$.

5 Conclusion

The sensitivity of the present generation of SN neutrino detectors to the $\bar{\nu}_e$ burst emitted by the collapse of a neutron star into a black hole has been evaluated.

The model ([Gourgoulhon & Haensel 1993]) is based on non equilibrium processes of ν emission in the core of the neutron star in which $\bar{\nu}_e$ and $\bar{\nu}_\mu$ dominate. Although the effective luminosity in nature could be lower than used here ($E^{\infty}_{\bar{\nu}_e} = E^{\infty}_{\bar{\nu}_\mu} = 5.0 \cdot 10^{50} erg$) the method is worthwhile to be developed, since the phenomenon should not be detectable via the electromagnetic radiation.

Massive detectors with high efficiency at low $\bar{\nu}_e$ energies and with the capability to distinguish $\bar{\nu}_e$ interactions seem the most suitable to observe the phenomenon.

A fraction up to 10% (depending on the parameters of the $\bar{\nu}_e$ spectra)of the stars of our Galaxy can be monitored with existing detectors.

6 Acknowledgements

Interesting comments of C.Castagnoli are gratefully acknowledged. One of us (G.N.) remembers a stimulating discussion with S.Bonazzola.

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