Gravity wave and neutrino bursts from stellar collapse: A sensitive test of neutrino masses

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New methods are proposed with the goal to determine absolute neutrino masses from the simultaneous observation of the bursts of neutrinos and gravitational waves emitted during a stellar collapse. It is shown that the neutronization electron neutrino flash and the maximum amplitude of the gravitational wave signal are tightly synchronized with the bounce occurring at the end of the core collapse on a time scale better than 1 ms. The existing underground neutrino detectors (SuperKamiokande, SNO, . . .) and the gravity wave antennas soon to operate (LIGO, VIRGO, . . .) are well matched in their performance for detecting galactic supernovae and for making use of the proposed approach. Several methods are described, which apply to the different scenarios depending on neutrino mixing. Given the present knowledge on neutrino oscillations, the methods proposed are sensitive to a mass range where neutrinos would essentially be mass degenerate. The 95% C.L. upper limit which can be achieved varies from 0.75 eV/c^2 for large ν_e survival probabilities to 1.1 eV/c^2 when in practice all ν_e's convert into ν_μ's or ν_τ's. The sensitivity is nearly independent of the supernova distance.

I. INTRODUCTION

The understanding of the origin of the tiny neutrino mass scale is one of the most puzzling problems in fundamental physics. On one hand finite neutrino masses of order 1 eV/c^2 or below indicate new physics beyond the standard model, as such masses are generally induced from a large mass scale (see e.g. Ref. [1]), possibly as large as the Planck scale. On the other hand neutrino masses of order 1 eV/c^2 have cosmological implications as relic neutrinos could represent a significant part of dark matter. Recent analyses of galaxy clustering in the context of a nonzero cosmological constant tend to limit the contribution of hot dark matter (neutrinos) to masses less than 4 eV/c^2 [2]. The limit can be lowered to 2.2 eV/c^2 when the recent data on cosmic microwave background (CMB) anisotropies are included [3]. Also it is possible that ultrahigh-energy cosmic rays originate from interactions of primary neutrinos with cosmological relic neutrinos, producing so-called *Z* bursts [4,5]: if this scenario prevails, the cosmic-ray energy spectrum beyond the Greisen-Zatsepin-Kuzmin (GZK) limit [6] would be sensitive to neutrino masses in the eV/c^2 range [7].

Strong experimental evidence has been recently presented for neutrino flavor oscillations [8]. Although the complete picture is not totally clear, the most solid interpretation of the reduced solar ν_e flux on Earth (see for instance Ref. [9] for a recent analysis) and the ν_μ deficit in atmospheric production by cosmic rays as detected by underground experiments relies on mixing, where the mass eigenstates ν_i are linear combinations of the 3 neutrino flavor states. The current scenario is based on (i) $\nu_e - \nu_\mu$ oscillations with four distinct solutions, three with near-maximal mixing and $\Delta m_{12}^2 = |m_{\nu_1}^2 - m_{\nu_2}^2| \sim 10^{-10}$, $\sim 10^{-7}$ or $\sim 5 \ 10^{-5}$ eV^2/c^4 and the fourth (less favored) with small mixing and $\Delta m_{12}^2 \sim 10^{-5}$ eV^2/c^4, and (ii) $\nu_\mu - \nu_\tau$ oscillations with a unique solution characterized by maximal mixing and $\Delta m_{23}^2 \sim 3.5 \times 10^{-3}$ eV^2/c^4. Several experimental programs are under-

way in order to confirm the interpretation in terms of oscillations [8].

Even if nonzero Δm_{ij}^2 are nearly established the absolute neutrino mass scale is still unknown. Direct measurements of neutrino masses provide us only with upper limits [10]: 3 eV/c^2 for ν_e [11,12], 190 keV/c^2 for ν_μ and 18 MeV/c^2 for ν_τ. In the context of the neutrino oscillations discussed above only the ν_e mass limit is relevant. Putting together this limit and the oscillation results, two extreme scenarios for the neutrino mass spectrum can be considered: (i) a spread-out spectrum with $m_{\nu_\tau} \sim 60$ meV/c^2, $m_{\nu_\mu} \sim 3$ meV/c^2 and $m_{\nu_e} \ll 3$ meV/c^2, or (ii) a nearly degenerate spectrum with a common mass as large as 3 eV/c^2 and a splitting determined by the small Δm_{ij}^2 from the observed oscillations. While the first solution looks more natural, i.e. resembling the charged lepton and quark mass pattern, the second one is cosmologically more interesting and might also be easier to understand in the context of maximal mixing, a feature quite different from what is observed with quarks.

It is therefore very important to investigate the possibility to directly measure neutrino masses below the current ν_e mass limit. In this paper a new method is proposed[1] to determine neutrino masses by exploiting the timing between the bursts of gravitational waves (GW) and of neutrinos emitted just at the end of the collapsing phase of a supernova. This technique capitalizes on the availability of operating underground detectors which are well suited to the neutrino energy range from supernovae (SuperKamiokande [14], SNO [15], and other less sensitive detectors [16,17]) and on forthcoming GW interferometric antennas [Laser Interferomemtric Gravitational Wave Observatory (LIGO) [18], VIRGO [19], and others [20,21]] whose sensitivity to short

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[1]After this work was completed, we were made aware that the same generic idea had been proposed earlier [13]. The authors did not, however, elaborate on the practical feasibility of the method.

bursts is well matched. The combination of an astronomical baseline and millisecond timing allows one to reach the 1 eV/c^2 level for the neutrino mass and possibly better. Several variants are proposed which match the performances of the neutrino detectors and apply in different scenarios for neutrino mixing.

Many studies have already been performed on the possibility to use supernova explosions to measure or bound neutrino masses. Following the first neutrino observations from supernova SN 1987A [22,23] ν_e mass limits have been obtained around 20 eV/c^2 [24] using the time spread of the burst a few seconds long which would be sensitive to massive neutrinos. Other methods have been proposed for the next near-galactic supernova occurrence [25,26] with sensitivities reaching 3 eV/c^2 [27]. In the case where the stellar core collapses early into a black hole, the neutrino production is suddenly quenched, providing a method with an estimated mass sensitivity of 1.8 eV/c^2 [28].

II. SUPERNOVA DYNAMICS

The physics of type II stellar collapse and the subsequent radiation of gravitational waves and of neutrinos has been a subject of intense research for more than 40 years. Extensive reviews and references can be found [29,30]. Here we only recall the main model-independent features on which our approach is based.

The infalling iron core of the star produces electron neutrinos when electrons are captured by protons. The core collapse is homologous and as nuclear densities are exceeded it becomes opaque to neutrinos which are captured inside. The small nuclear compressibility brings the collapse to a halt, producing a bounce which generates a strong shock wave travelling back through the neutrinosphere, at which point the medium becomes transparent enough for the neutrinos to escape. This generates a short ν_e flash and signals the onset of the emission of all neutrino types produced thermally as $\nu\bar{\nu}$ pairs from the heat generated on the accretion surface during infall. Unlike for the ν_e burst the thermal emission is expected to last a few seconds. The main point is the strong time correlation between the bounce and the ν_e flash generated by neutronization in the low-density outer part of the core. The flash delay and its duration are controlled by the shock dynamics whose description is expected to be strongly model-dependent. However, the timescale involved is so short that it can be determined on quite general ground by hydrodynamics considerations [31–34].

The shock wave is generated deep into the core ($r \sim 10$ km) and propagates outward with a velocity $v \sim 0.1\ c$ whose precise value depends on the shock strength. The shock reaches the neutrinosphere at a radius $r_0 \sim 90$ km defined such that the neutrinos see only one absorption length of matter outside of it. The number of ν_e's rises fast and then decays exponentially. Many estimates have been given in the literature [32], the most recent ones from sophisticated hydrodynamical simulations [35]. The mean timing of the ν_e pulse with respect to the bounce turns out to be $\Delta t_{\nu_e,bounce} = (3.5 \pm 0.5)$ ms. While the above estimates of v, r_0 and subsequently $\Delta t_{\nu_e,bounce}$ depend on the properties of the
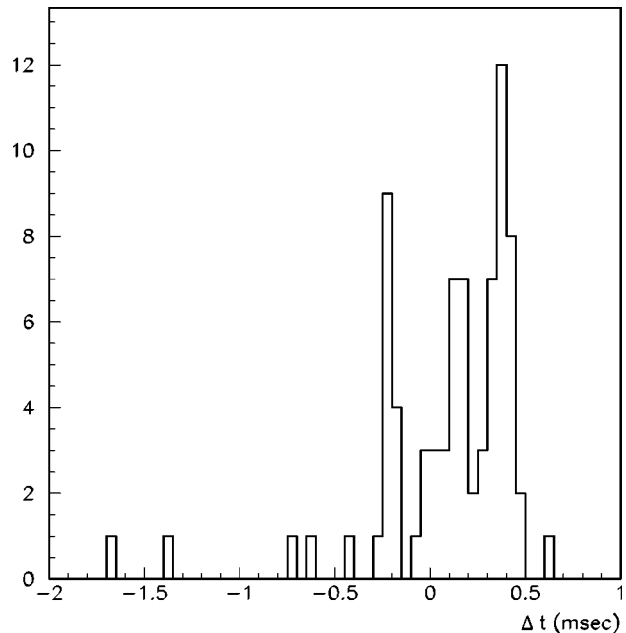

FIG. 1. Distribution of the time difference between the maximum of the GW amplitude and the core collapse bounce for the signals simulated in Ref. [34].

compressed nuclear matter, valuable information can be deduced from observables such as the mean ν_e energy in the flash [32], thus helping through simulation to constrain the range of the relevant parameters. Finally, the integrated luminosity in the ν_e flash is estimated to be $\int L_{\nu_e} dt \sim 3 \times 10^{51}$ erg, corresponding to about 1% of the total energy carried away by neutrinos in the few seconds following the initial collapse.

The fast core collapse and the resulting bounce are expected to produce radiation of gravitational waves. Many hydrodynamical simulations assuming specific core models have been performed [38]. It is observed that the details of the produced waveform are highly model-dependent. In particular the rotation of the inner core is found to be an important factor as centrifugal forces tend to delay the collapse or even sometimes prevent it altogether. At any rate a strong correlation in time is expected between the core bounce and the maximum of gravitational radiation. This effect has been studied with specific collapse models. For example we used the library of 78 typical waveforms which has been produced in simulations [39], varying rotation and equation-of-state parameters within reasonable ranges. Despite a strong variability in the signal shape, the location of the maximum wave amplitude is tightly correlated to the bounce as shown in Fig. 1. In fact the signals with "abnormal" delays are most of the time characterized by a relatively smaller amplitude and are therefore less likely to be detected in the first place by the GW interferometers.

Thus our method is based on the strong time correlation between the ν_e flash and the peak of gravitational radiation in the event of a type II supernova.

III. NEUTRINO DETECTION

Detection of the ν_e flash is possible with already operating experiments. The most sensitive ones are SuperKamio-

kande [14] and SNO [15] which are both large volume water Cherenkov detectors.

SuperKamiokande can detect ν_e's, as well as all neutrino types, through elastic scattering on electrons

$$\nu_i e^- \rightarrow \nu_i e^-. \tag{1}$$

While this process has the advantage of being directional—essentially all events are concentrated in a cone $\cos\theta > 0.8$, where θ is the angle between the source direction and the electron recoil—it suffers from the fact that information on the incident neutrino energy E_ν is lost, the electron energy spectrum being uniformly distributed between 0 and E_ν. Thermal neutrinos such as $\bar\nu_e$'s can be detected through the charged-current process

$$\bar\nu_e p \rightarrow e^+ n. \tag{2}$$

This reaction is essentially isotropic, therefore carrying no information on the source direction, but it allows a direct measurement of $E_\nu = E_e + E_{th}$, with the threshold energy $E_{th} \simeq 1.77$ MeV.

As a heavy water Cherenkov detector, SNO has unique capabilities for detecting ν_e's and $\bar\nu_e$'s by means of the charged current processes on deuterons

$$\nu_e d \rightarrow e^- p\, p, \tag{3}$$

$$\bar\nu_e d \rightarrow e^+ n\, n, \tag{4}$$

and all neutrino types through the neutral-current reaction

$$\nu_i d \rightarrow \nu_i p\, n. \tag{5}$$

All reactions are isotropic, with energy measurement for the charged current processes, with $E_{th} \simeq 1.44$ MeV for ν_e and 4.03 MeV for $\bar\nu_e$. The neutral-current processes are detected using neutron capture by ^{35}Cl in dissolved salt, leading to an 8.6 MeV γ ray. While all the reactions discussed so far have excellent timing, of the order of a few tens of ns, the situation is not as good for the neutral-current ones where the detection timing is limited by neutron diffusion, inducing an exponentially distributed delay with a time constant of ~ 4 ms [15].

The event rates are large enough for galactic supernovae. Relevant cross sections and their energy dependence can be found in Ref. [34]. Using the luminosity given above for a supernova exploding 10 kpc away, the expected numbers are 15 for the ν_e flash and 5300 for thermal $\bar\nu_e$'s through processes (1) and (2) respectively, in SuperKamiokande. Similarly, 13 events are expected for the ν_e flash through process (3) in SNO. All these rates scale as L^{-2}, where L is the supernova distance.

IV. EFFECT OF NEUTRINO MIXING

The propagation of neutrinos from the star to the detectors can be affected by flavor oscillations. Starting with the observation of neutrinos from SN 1987A this question has been studied by many authors, considering both vacuum and matter-enhanced oscillations [40]. For our purpose it is im-
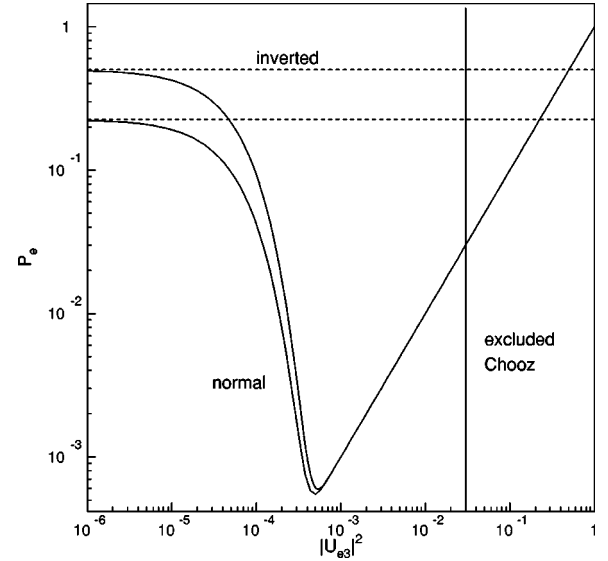

FIG. 2. The electron survival probability from a stellar collapse to Earth in the large mixing-angle MSW scenario for solar neutrinos as a function of the matrix element $|U_{e3}|^2$. The solid curves correspond to the "normal" mass hierarchy, while the dashed ones stand for the "inverted" hierarchy. In each case the upper (lower) curve is computed with $\sin^2 2\theta_\odot = 1.0\ (0.7)$. The calculations follow the analysis given in Ref. [36]. The area corresponding to $|U_{e3}|^2 > 3 \times 10^{-2}$ is excluded by the CHOOZ experiment [38].

portant on one hand to estimate the ν_e survival probability, P_e, affecting the total rate for charged-current processes and consequently the statistical power of the measurement. On the other hand if P_e gets too small the neutronization flash will arrive on Earth mostly as ν_μ's or ν_τ's which can only be detected by neutral-current reactions. The SNO detector is well suited to this purpose, with however a worsening of the timing resolution due to fluctuations in the neutron capture, as discussed above.

A comprehensive treatment of oscillations for neutrinos born in a stellar collapse has been recently presented [41] and we follow here this analysis. The Mikheyev-Smirnov-Wolfenstein (MSW) resonances [42] play a crucial role while the neutrinos propagate in the matter of slowly decreasing density. The effect on ν_e's is in general important, but depends crucially on the solar neutrino oscillation solution and whether the neutrino mass hierarchy is "normal" (the mass eigenstates ν_1, ν_2 and ν_3 have increasing masses) or "inverted" (the ν_1 mass state, mostly connected to the ν_e flavor state, is the heaviest). We remark that if the mass states are spread out, as for the other fermions, it is more natural to expect the "normal" hierarchy, while for a quasi-degenerate spectrum both scenarios are equally plausible. It turns out that the value of P_e depends in a strong way on the mixing matrix element U_{e3} between ν_e and ν_3 states, the other relevant elements being fixed by unitarity and the solar mixing angle. The only known experimental constraint on U_{e3} comes from the CHOOZ reactor oscillation experiment [43], yielding $|U_{e3}|^2 < 3 \times 10^{-2}$.

Figure 2 shows the situation for the large mixing-angle ($\theta_\odot$) MSW solution, with $\sin^2 2\theta_\odot = 0.7 - 1.0$, which seems

to be favored by experimental data [8]. In this case the ν_e peak is still preserved with a survival probability between 0.2 and 0.5, except for values of $|U_{e3}|^2 > 10^{-5}$ in the normal hierarchy scenario. The small mixing-angle MSW and the vacuum oscillation solutions yield different behaviors with P_e values ranging from 0.8 to negligible. In the following we shall use a value $P_e = 0.5$ as representative of situations where the ν_e flash content is well preserved, and also consider the case where the ν_e rate becomes too small rendering $\nu_{\mu,\tau}$ detection mandatory. In this way all possibilities are covered. It should be remarked that, contrary to the ν_e case, the rate of $\bar{\nu}_e$'s remains essentially unaltered, to the extent that thermal production should result in approximately equal numbers of neutrino pairs of each flavor.

V. RELATIVE TIMING

We are now in position to discuss the relative timing of the neutrino and gravitational wave bursts. Both emission times have been seen to be closely related to the bounce time in the core collapse.

Travel times to Earth depend on neutrino and graviton masses. Very constraining bounds exist on the graviton mass m_G: in particular, precise studies of planet orbits in the solar system [44] yield a lower limit for the graviton Compton wavelength $\lambda_G = h/m_G c$ of 3×10^{12} km, much larger than the value 6×10^9 km that would produce a time delay equal to that of a 1 eV/c^2 neutrino. So we do not need to worry about nonzero graviton mass for our problem and we consider in the following that GW propagate at the speed of light c.

Neutrinos with a mass m_ν will arrive at the detectors with a propagation time delay Δt_{prop} given by

$$\Delta t_{prop} = \frac{L}{2\,c}\left(\frac{m_\nu c^2}{E_\nu}\right)^2 \tag{6}$$

$$\simeq 5.15 \text{ ms}\left(\frac{L}{10 \text{ kpc}}\right)\left(\frac{m_\nu c^2}{1 \text{ eV}}\right)^2\left(\frac{10 \text{ MeV}}{E_\nu}\right)^2. \tag{7}$$

To this time should be added any time difference at the source and another propagation delay because the neutrino and gravitational wave detectors are not located at the same site. The latter can only be derived when the source direction is known which can be achieved if the bursts are registered in coincidence by several detectors using triangulation. Of course the most precise determination is expected to come from optical telescopes, typically a few days later, when the supernova explosion finally occurs. Finally it is assumed that the distance L will be derived from the optical measurements but it should also be pointed out that a reasonable estimate of the distance can be deduced from the absolute event rate in the neutrino detectors. Indeed the total energy release in the collapse is directly related to the mass of the iron core which can be reasonably estimated with an uncertainty of typically 40% [29] leading to a 20% accurate measurement of the distance.

It is interesting to consider the precision which can be obtained on the quantity of interest, Δt_{prop}, hence on m_ν.

The observed time difference between the ν_e flash and the maximum of the gravitational waveform is

$$\Delta t_{\nu,GW} = \Delta t_{prop} + \Delta t_{\nu_e,bounce} - \Delta t_{GWpeak,bounce} \tag{8}$$

with obvious notations. We examine in turn the two model-dependent terms to Eq. (8) already discussed earlier and the two contributions to the experimental error on $\Delta t_{\nu,GW}$:

$\Delta t_{GWpeak,bounce}$ is expected to be very small. The value (0.1 ± 0.4) ms is obtained from the library of waveforms produced in Ref. [39] as shown in Fig. 1. The various entries correspond to different sets of parameters used in the simulation. The initial angular momentum and the compressibility of the supernuclear matter are important input variables in this respect. The time range obtained thus represents a realistic coverage of the core collapse parameters.

$\Delta t_{\nu_e,bounce}$ is discussed above with the estimate (3.5 ± 0.5) ms, where the error reflects the uncertainties in the shock wave propagation.

the measurement of the GW timing depends on the signal-to-noise ratio ρ in the detector, itself a function of the detection algorithm used to filter out the signal corresponding to the GW burst. Previous studies of robust filters [45,46] provide a timing uncertainty [47] given by $\delta t_{GW}^{peak} \sim 1.45\tau/\rho$, where τ is the rms width of the main GW peak. For the signals simulated in Ref. [39] $\tau \sim 1$ ms and the mean value of ρ is very close to 10 for supernovae located at 10 kpc, yielding a GW timing uncertainty of 0.15 ms.

the determination of the mean timing of the ν_e flash depends on the event statistics N_ν and the flash width σ_{flash} through $\delta t_\nu^{peak} = \sigma_{flash}/\sqrt{N_\nu}$, scaling as L. This translates into an uncertainty on m_ν^2 independent of the supernova distance L, as $\delta m_\nu^2 \propto \delta t/L$. Simulations [35] indicate that $\sigma_{flash} \sim (2.3 \pm 0.3)$ ms.

The total timing uncertainty can therefore be cast into two components: one of statistical nature, dominated by δt_ν^{peak}, and the other originating from systematic sources, estimated from above to be 0.65 ms. It may be possible to reduce this systematic uncertainty with the observation of an actual supernova event, since additional measurements such as the neutrino energy spectrum and the shape of the GW waveform can provide constraints on the core collapse phenomenology within the framework of existing simulation codes.

VI. DIFFERENT METHODS AND RESULTS

Several methods taking into account the time correlation between GW and neutrino bursts can be envisaged, depending on the neutrino detector type and the ν_e survival probability.
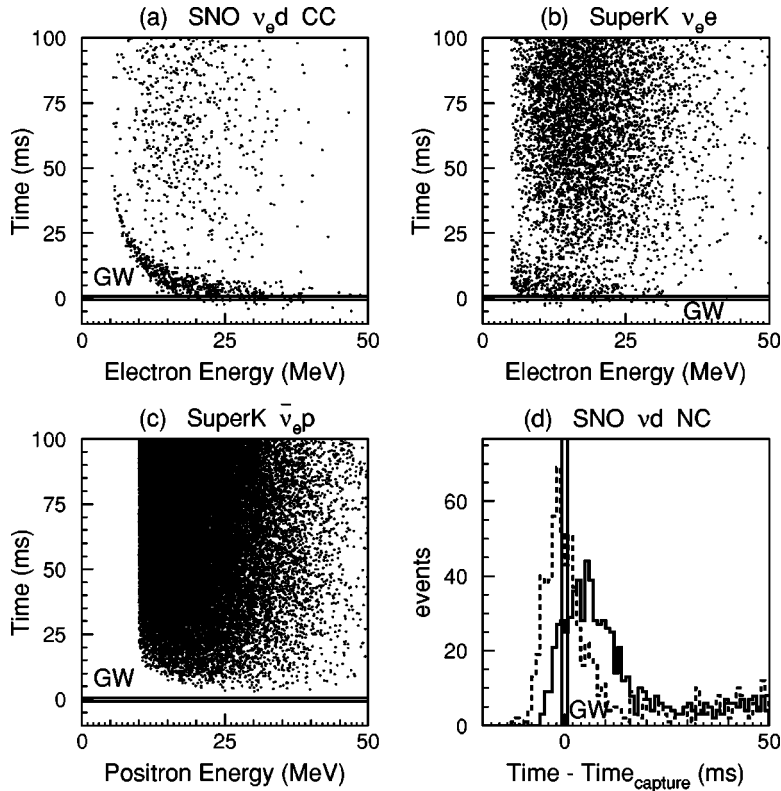
FIG. 3. Illustration of the four proposed methods with simulated data in neutrino detectors. Each situation corresponds to a supernova collapse at 10 kpc assuming a neutrino mass of 2 eV/c^2. The expected statistics is scaled up by a factor of 100 in order to better visualize the distributions. In the first three cases events are displayed as function of electron (positron) energy and arrival time (defined such that zero-mass neutrinos arrive at $t=0$, as defined by the GW timing): (a) method (1) using the $\nu_e d$ process in SNO, including background from thermal ν_e's and $\bar{\nu}_e$'s; (b) method (2) based on $\nu_e e$ elastic scattering in SuperKamiokande, with background from the $\bar{\nu}_e p$ process reduced by cuts; (c) method (3) using the $\bar{\nu}_e p$ reaction in SuperKamiokande. Finally in (d) the time distribution of neutral-current events is shown in SNO where the neutrino timing has been shifted by the average time for neutron capture (the dashed histogram corresponds to a zero-mass neutrino). In all four plots the double line labeled GW indicates the $\pm 1\sigma$ gravitational wave timing.

A. Method 1: ν_e detection in SNO

Method 1 relies on the detection of the ν_e flash in SNO through reaction (3) providing good timing and energy information. This approach is the best when the ν_e survival probability is large enough (the precise value depends on the supernova distance). In this case the ν_e peak is well separated from the thermal distribution and its timing should be easily determined given enough events, i.e. for distances up to 13 kpc.

We have performed simulations of supernova detections over a range of distances, using $P_e=0.5$, the characteristics of the SNO detector [15] and the estimate of timing accuracies given in the preceding section. An electron detection threshold of 5 MeV has been conservatively assumed: whereas the present threshold used by SNO for solar neutrinos is only 6.75 MeV [36], the large instantaneous rate of a supernova would allow one to lower the analysis threshold essentially down to the hardware value of 2 MeV [37]. Neutrino energies are generated according to a Fermi-Dirac distribution with a characteristic temperature of 3.5 MeV. The 2-dimensional distribution of relative arrival time and neutrino energy is displayed in Fig. 3 for the distance $L=10$ kpc and a neutrino mass of 2 eV/c^2, but with a statistics enlarged by a factor of 100 in order to better visualize the problem. The neutronization peak is spread out with energy in a band which deviates from $t=0$ (the time delay between gravity waves and zero-mass neutrinos has been subtracted out for clarity) in the lowest energy range. Although the assumed neutrino temperature corresponds to a mean produced energy of 11 MeV, the observed average energy of the detected events is raised to 20 MeV because of the strong energy dependence of the cross section. A log

likelihood fit of the event population in the neutronization band yields the observed mass.

It is clear from the plot that, for small distances and consequently large neutrino rates, SNO can determine the mass by itself if statistics is sufficient to derive from the fit both the mass and the "zero-mass" arrival time. This is indeed the case since the Fermi-Dirac energy distribution of the neutrino energy is wide enough to sample situations sensitive (low energy) or not (high energy) to the mass, while the situation is reversed for the determination of the prompt arrival time. However the approach without independent timing information deteriorates rapidly with increasing distances as statistics at higher neutrino energies becomes insufficient to pin down the zero-mass time. One therefore expects GW timing to become increasingly helpful.

This expectation is verified by the results of 2-dimensional maximum likelihood fits to data of many simulated experiments, as shown in Fig. 4: the total uncertainty δm_ν^2 (corresponding to a 1σ spread) is found to be about 0.5–0.6 eV^2/c^4, essentially independent of the distance up to 13 kpc when statistics runs out, as expected. At this stage we have not tried to model the exact shape of the sensitivity curve around 13 kpc: the likelihood fits were performed requiring a minimum of 3 events in the neutronization band—a value achieved 73% of the time at 13 kpc, but decreasing to 55(27)% at 15(17) kpc. If no GW timing information is available the accuracy steadily deteriorates with the distance, reaching 1.5 eV^2/c^4 at 10 kpc and running out of events for a joint determination of both neutrino mass and zero-mass arrival time.
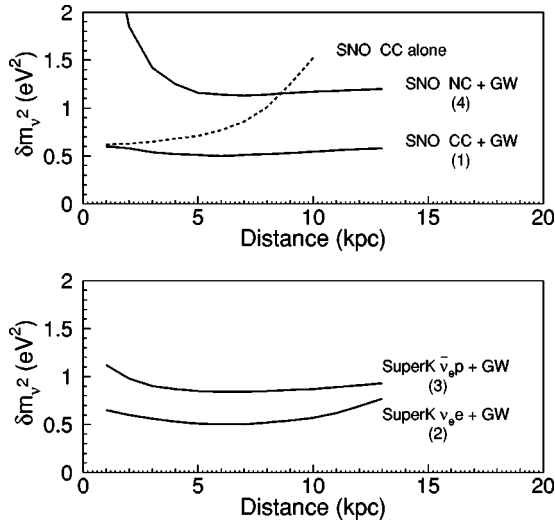
FIG. 4. The estimated sensitivity δm_ν^2 of methods 1 to 4 with the SNO (a) and SuperK (b) detectors, for stellar collapses as function of distance. Results for methods 1,2 (respectively 4) are given for $P_e = 0.5$ (respectively $P_e \sim 0$), while method 3 applies independently of P_e.

B. Method 2: ν_e detection in SuperKamiokande

Method 2 applies under the same conditions as for *method 1* with SNO, but this time using ν_e elastic scattering on electrons in the SuperKamiokande detector. Given the relative masses of the detectors and the relevant cross sections, it turns out that the statistics is similar in both cases. An apparent disadvantage of this method is that neutrino energy information is strongly reduced. However the loss of information on the neutrino mass is not large as time delays are preserved and a 2-dimensional likelihood fit still captures the essential features of the experimental distribution for most of the distance range. Background from reaction (2) must be suppressed: a rejection factor of 10 is achieved through a cut, $\cos \theta > 0.8$, where θ is the angle between the electron and the supernova directions. The latter is assumed to be known from optical observations later on.

Using an electron detection threshold of 5 MeV, likelihood fits of simulated data such as shown in Fig. 3 are performed, yielding the sensitivity curve in Fig. 4 with GW timing. As expected the value for δm_ν^2 is similar to that obtained in *method 1*, ~ 0.5–0.7 eV$^2/c^4$. As observed in *method 1*, it is still possible to fit the distribution without an a priori knowledge of the absolute timing provided by GW detection, but the sensitivity is strongly reduced in this case.

C. Method 3: $\bar{\nu}_e$ detection

Method 3 relies on the onset of $\bar{\nu}_e$ thermal production, detected essentially through the more copious reaction (2) used by essentially all neutrino experiments. For a supernova at 10 kpc the expected rates are 5300, 400, 135, and 133, in SuperKamiokande, SNO, LVD, and MACRO, respectively. Contrary to the neutronization flash the time distribution of the thermal $\bar{\nu}_e$'s is more model-dependent. With a characteristic risetime is ~ 50 ms, the shape of the spectrum on the time scale of 1–10 ms is hard to control theoretically, but the

onset is closely related to the timing of the neutronization flash [32,34]. This feature is supported by extensive simulation work [35].

The advantages of this method is the availability of the neutrino energy measurement and the fact that the rate is essentially insensitive to neutrino oscillations. A cut on the positron angle with respect to the supernova direction, $\cos \theta < 0.8$, has to be applied in order to remove the few forward-peaked electron events from elastic scattering with a signal loss of only 10%. The positron energy threshold has to be raised to 10 MeV in order to avoid the background of γ-rays from nuclear de-excitation induced by the neutral-current neutrino processes [48]. This method can be implemented without GW information [27], but the sensitivity is greatly enhanced by GW timing. A simulated distribution is given in Fig. 3(c) and likelihood fits yield the precision shown in Fig. 4, with typically $\delta m_\nu^2 \sim 0.9$ eV$^2/c^4$.

Although all other methods are limited to a supernova distance of 13 kpc because of neutrino statistics, *method 3* does not suffer from this limitation. The rate expected in SuperKamiokande would still be sufficient up to ~ 100 kpc, however the sensitivity of present GW detectors is such that one can hardly consider detections beyond our galaxy [45–47].

D. Method 4: $\nu_{\mu,\tau}$ detection in SNO

Finally, *method 4* needs to be used if neutrino oscillations turn the ν_e's in the neutronization peak into $\nu_{\mu,\tau}$'s. Again SNO is the only neutrino experiment able to exploit this possibility. The situation is however much less favorable than in *method 1*, as (i) the neutral-current cross sections are a factor 2.5 smaller than their charged-current counterparts in the 10–40 MeV range, (ii) the neutrino energy information is lost, and (iii) timing is degraded by the fluctuations in the neutron capture. In this case absolute timing from GW detection is crucial whatever the supernova distance. The fact that no energy information is available means a greater dependence on the model for the shape of the neutronization peak. There is also some uncertainty on the mean capture time, but it can be experimentally calibrated using reaction (4) which provides signals from both the prompt positron and the delayed neutron capture with good statistics.

Examples of simulated time distributions are given in Fig. 3(d). Assuming full ν_e-to-$\nu_{\mu,\tau}$ conversion, the estimated uncertainty of this method is found to be $\delta m_\nu^2 \sim 1.2$ eV$^2/c^4$ from a fit of the neutrino time distribution with respect to the GW signal. The sensitivity, shown in Fig. 4, is strongly degraded at small distances where the systematic uncertainty on the relative timing dominates over the statistical error of neutrino timing. As expected this method is less sensitive than *method 1*, but it is the only choice left if the ν_e survival probability is too small.

The sensitivities expected with the different methods are summarized in Table I for the two scenarios of large ($P_e = 0.5$) and of negligible ν_e survival probabilities. They depend rather weakly on the supernova distance and they are given at 10 kpc. Since the neutrino statistics are uncorrelated between the different methods, the overall sensitivity

TABLE I. Total uncertainties δm_ν^2 (eV^2/c^4) expected in the four proposed methods under two scenarios for neutrino oscillations. The values are quoted for a supernova at 10 kpc, but they are weakly dependent on the distance. See details in the text.

Method	$P_e = 0.5$	$P_e \sim 0$
1	0.55	-
2	0.57	-
3	0.87	0.87
4	1.63	1.15
combined	0.35	0.69

using all four approaches can be correspondingly improved to $\delta m_{\nu_e}^2 \sim 0.35$ eV^2/c^4 for $P_e = 0.5$ and ~ 0.7 eV^2/c^4 for $P_e \sim 0$. In case the experiments do not see any deviation from nonzero mass 95% C.L. upper limits of 0.75 and 1.1 eV/c^2 will be derived on the degenerate neutrino mass in the two scenarios, respectively.

VII. CONCLUSIONS AND PROSPECTS

The next type-II supernova explosion in the Galaxy is expected to provide extremely valuable information on neutrino masses. New methods, based on the availability of massive neutrino detectors and the near operation of new large interferometric gravity-wave antennas, have been proposed. They rely on the time coincidence between neutrino and gravitational wave detections. Different experimental approaches have to be considered depending on the capabilities of the various neutrino detectors and on the overall effect of oscillations between the three neutrino flavors.

The most sensitive method is based on the detection by SNO and SuperKamiokande of prompt electron neutrinos from the neutronization peak which is tightly correlated in time with the bounce terminating the stellar core collapse, itself corresponding to the maximum gravity wave activity. If the ν_e survival probability is large, this method yields a ν_e mass sensitivity for each detector almost independent of the supernova distance up to 13 kpc, measured by $\delta m_\nu^2 \sim 0.60$ eV^2/c^4. The combination of the results from SNO and SuperKamiokande would directly exclude a ν_e mass of 0.75 eV/c^2 at 95% C.L. if no significant mass effect were found. This value is a factor of 4 smaller than current limits from end-point tritium experiments. If the mass were indeed 2 eV/c^2 the expected effect would correspond to a 11 σ deviation from zero mass and the mass would be measured with a precision of 4.5%. A 1 eV/c^2 ν_e mass would still be seen at the 3 σ level and determined with a precision of 17%. Two specific methods are proposed if neutrino conversions in the outer star mantle disfavors ν_e detection. One still uses the neutronization peak and neutral-current detection in SNO, while the other is based on the measurement of the onset of thermal $\bar\nu_e$ production in SuperKamiokande. When combined they still provide a sensitivity of $\delta m_\nu^2 \sim 0.7$ eV^2/c^4 and a 95% C.L. upper limit of 1.1 eV. Finally it is interesting to note that these results follow from time differences accurately measured at a level of $\sim 10^{-15}$ of the total time of flight.

The approach can be extrapolated to the next generation of neutrino and gravitational wave detectors. A valuable goal would be to bridge the gap between the reachable mass value with present detectors (0.7 eV/c^2) and the upper range provided by neutrino oscillations in the least-degenerate neutrino mass scenario (0.06 eV/c^2). This requires a factor of 100 increase in the neutrino detector masses (HyperKamiokande?), which would be matched to the factor of 10 improvement in sensitivity considered for GW antennas on the time scale of 6–7 years [49]. Such a desirable situation would have a number of advantages: (i) the precision on the neutrino timing for a supernova detection would be improved by a factor of 10, (ii) distances up to 150 kpc could be reached with the proposed methods with a corresponding gain in the supernova rate (however modest, i.e., 20%), and (iii) the large statistics that would be available for a galactic event would permit a much better understanding of the collapse and bounce dynamics, hence offering the possibility to better control the systematic timing uncertainty from the models. This last aspect is very important because the precision on the relative GW-neutrino timing at the source must be improved from the current estimate of 0.65 ms to a value of 0.1 ms, in order to match the improved experimental timing accuracy. While this cannot be proven at the moment, it is reasonable to consider further significant progress in the simulation codes, when incorporating the constraints from precise measurements of the GW amplitude and the neutrino pulse shape as a function of time, supplemented with a determination of the neutrino energy distributions.

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