Time-of-Flight Delay Between Oscillating Neutrinos and Gravitational Waves from Supernovae and the Neutrino Mass Problem

Herman J. Mosquera Cuesta[1,2]

Abdus Salam International Centre for Theoretical Physics, Strada Costiera 11, Miramare 34014, Trieste, Italy

[2] *Centro Brasileiro de Pesquisas Físicas, Laboratório de Cosmologia e Física Experimental de Altas Energias*

Rua Dr. Xavier Sigaud 150, CEP 22290-180 Urca, Rio de Janeiro, RJ, Brazil

[3] *Centro Latinoamericano de Física (CLAF), Avenida Wenceslau Braz 173, Botafogo, Rio de Janeiro, RJ, Brazil*

e-mail: hermanjc@cbpf.br

(April 4, 2001)

Neutrino oscillations during core bounce of a supernova collapse may induce detectable gravitational-wave bursts by the time they are trapped in the core. For large-scale distances the flavor changing neutrinos get delayed on its trip to Earth while the gravitational waves they emit do not. Since the oscillation mechanism sets up the *offset* for both emissions, this fact yields in a time-of-flight delay between both the radiations that, whenever measured, could provide an inedit estimative of the absolute scale of neutrino masses.

PACS numbers: 97.60.Gb, 14.60.Pq, 04.30.Db, 04.40.Dg

Over several decades the experimental search for the neutrino mass spectrum has revealed unsuccessful. The neutrino mass remains an elusive issue, yet, although some laboratory bounds have been put for the electron neutrino ($\nu_e \sim$ 3eV) [1,2], while for the mu neutrino ($\nu_\mu \sim$ 170keV) [3] and tau neutrino ($\nu_\tau \sim$ 18MeV) [4]. The prediction of the existence of non-zero mass neutrinos is a consequence of the violation of the lepton number, L, either directly or via loops [5]. Accidentally or not, most of the extensions of the standard model of particle physics imply a non-conservation of the lepton number L, and in this manner open pathways for the neutrinos to adquire mass. One of the main difficulties to the task of determining the neutrino masses from atmospheric neutrino experiments concerns to the ability of neutrino detectors to be sensitives to their mass differences instead of doing so to the neutrino mass itself [6]. Recently SuperKamiokande Experiment have presented compelling evidences for neutrinos having a mass [7]. Searches for weak decays may also lead to confidently stablishing whether or not neutrinos have masses [8–10]. Below we suggest a realistic and promissing procedure to achieve this goal.

In this letter is argued that a highly improved and largely accurate determination of the neutrino absolute mass-scale can be achieved by direct measurements of the delay in *time-of-flight* between the neutrinos (νs) themselves and the gravitational-wave burst generated by the asymmetric escaping flux of $\nu_{e,\bar{\mu},\bar{\tau}}$ neutrinos that changed flavor into *steriles* (ν_s) during the early core bounce of a Type-II supernova (SN) explosion, as shown in Ref. [11]. The crucial issue concerning flavor changes is that having a non-zero mass, even a very tiny one, this property will cause a massive neutrino to get the detector later than a massless one. This phenomenon should produce a strong correlation between neutrino arrival times and their energies, a fact that could directly allow to account for the relative masses [12].

It has been claimed that the best way to determine in an uniquely manner the neutrino masses is to take advantage of their interaction properties with matter. Theory shows that it is possible to measure or constrain the neutrino mass scale using the *time-of-flight* delay they exhibit when traversing some distance. In particular, Beacon, Boyd and Mezzacappa [12] have suggested that the early black hole (BH) formation in a core-collapse supernova may abruptly truncate the neutrino flux, producing a sharp cutoff that may prove useful to impose strong constraints on the *mu* and *tau* neutrino masses. Despite being quite promissing for rendering the looked for mass-spectrum, this technique exhibits at least two problems. Firstly, it does not take into consideration the role of the emission of gravitational radiation from the just formed BH in assisting to close the issue. This BH formation process naturally sets up an *offset* which could very well be used in techniques based on *time-of-flight delay* to help in constraining the neutrino mass if its gravitational waves were detected in coincidence with the neutrino bursts, as we suggest below. Secondly, it is not clear in that picture if the neutrinos will free-streaming after the BH appearance or if conversely they will diffuse convectively [13]. Moreover, the technique (motivated by theoretical works) only works in supernovae leading to BHs formation, and says nothing about those SNe events leaving neutron stars (NSs) as their remnants, the most abundant process from the observational point of view, as evidenced in pulsar catalogs. That is why we propose here an alternative procedure to settle down this neutrino mass issue.

Why this method is inedit?, and how can it in fact work? The main motivation for proposing this new procedure to constrain neutrino masses is because the *offset* for both gravitational waves and neutrino bursts is neatly set up when the oscillation take place, a new mechanism introduced by Mosquera Cuesta elsewhere [11]. In ordinary neutrino convection gravitational waves are also produced. However, it is not well-understood when exactly the wave generation process take place because the convection overturn timescale is not the unique relevant quantity driven the core dynamics [13]. If "light curves" with very high temporal resolution can be obtained during a given supernova event, thus by inspecting both of the detected signals we will be able in principle to either rule out or confirm the occurrence of the conversion phenomenon suggested in Ref. [11]. If positively evidenced, then we can accurately set its timing and get indications of when the transition took place. From those pieces of information we can derive the time-of-delay between the signals because massive neutrinos cannot travel at the speed of light, the one in Einstein's theory gravitational waves propagate. The precise timing of both the events will constrain the neutrino mass spectrum from a very novel physical mechanism. At this point, we call to the reader's attention Ref. [14] where a different speed of propagation of GWs discontinuities is presented.

The neither non-spherical, nor core-concentric deformation of the neutrino resonance surface builds up the analogous to a quadrupole distortion of a mass-energy distribution, driving the emission of a burst of gravitational waves whenever neutrino oscillations occur*. The potential generation of this new class of gravitational-wave bursts by the time the oscillating neutrinos can freely escape from the supernova core have been advanced in a previous work [11]. The characteristics of the GWs produced by an anisotropic neutrino flux can be estimated by using the general relativity quadrupole formula obtained from a post-Newtonian expansion [16–18]

$$h_{ij}^{TT}(\mathbf{X},t) = \frac{2G}{c^4 R} P_{ijkl}(\mathbf{N}) \times \int d^3x \rho \left(2v^k v^l - x^k \partial_l \Phi - x^l \partial_k \Phi\right), \qquad (1)$$

being $R = |\mathbf{X}|$, Φ, ρ and v represent the source distance, Newtonian potential, mass-density and its velocity, respectively. $P_{ijkl} \equiv (\delta_{ik} - N_i N_k)(\delta_{jl} - N_j N_l) - \frac{1}{2}(\delta_{ij} - N_i N_j)(\delta_{kl} N_k N_l)$ describes the traceless-transverse (TT) projection operator onto the plane orthogonal to the outgoing wave direction $\mathbf{N}$. Eq.(1) can be transformed into the standard quadrupole formula

$$h_{ij}^{TT}(\mathbf{X},t) = \frac{2G}{c^4 R} P_{ijkl}(\mathbf{N}) \frac{\partial^2}{\partial t^2} Q_{kl}(t - R/c), \qquad (2)$$

with $Q_{kl}(t) = \int d^3x \rho(\mathbf{x},t) \left[x_i x_j - 1/3 \delta_{ij} \mathbf{x}^2\right]$ defines the trace-free part of the *mass-quadrupole tensor* of the matter (massive neutrino fluid) distribution. Eq.(2) may be expressed in terms of the neutrino luminosity as [19,13]:

$$h_{ij}^{tt} = \frac{4G}{c^4 R} \int_{-\infty}^{t} \alpha(t') L_\nu(t') dt', \qquad (3)$$

where $\alpha(t')$ is the instantaneous quadrupole anisotropy, and $L_\nu(t)$ the total neutrinos' luminosity. We use this mass-quadrupole approximation below. Since it is the neutrino oscillation what drives the emission of gravitational radiation in this scenario, the key parameter to estimate its wave characteristic amplitude is the transition probability, which tell us about how many neutrino can actually undergo flavor conversions. The total neutrino luminosity during the conversions (Eq.(3)) can be estimate from it.

The effect of possible neutrino conversions inside the core of a supernova on the gravitational waves emanating from the star was considered in Ref. [11]. It was shown there that GWs may be produced by the time neutrinos undergo spin-flavor transitions within the first few milliseconds after the core collapse. The estimated GWs amplitude proved to be accurately detectable by LIGO I up to distances $R \sim 55$kpc, while GWs produced during the cooling phase (when most of the neutrinos escape by diffusion in the conventional mechanism) is nearly at the limit for detectability of LIGO for $R \sim 10$kpc [19]. Next we recast part of the discussion introduced in Ref. [11].

In order to produce an effect, neutrinos must be able to escape the core without thermalizing with the stellar material. For active neutrino species of energies ≈ 10MeV, this is not possible as long as the matter density is $\gtrsim 10^{10}\mathrm{gcm}^{-3}$. Since the production rate of neutrinos is a steeply increasing function of matter density (production rate $\propto \rho^n$, where ρ is the matter density and $n > 1$), the overwhelming majority of the neutrinos of all species produced are trapped. So the contribution to the GWs amplitude is negligible, irrespective of the neutrino conversions taking place within the active neutrino flavors.

Sterile neutrinos, on the other hand, would be able to escape the core. Though they are not directly produced inside the star, if any active neutrino species can be copiously converted into sterile neutrinos through oscillations, it may be possible to dramatically increase the number of escaping neutrinos. This effect can be significant only if these active $\leftrightarrow$ sterile transitions take place inside the neutrinospheres of the active neutrinos, i.e. at $\rho \gtrsim 10^{10}\mathrm{gcm}^{-3}$.

Although in principle the case of vacuum oscillations may appear as an interesting possibility, it was shown in

*Minakata and Smirnov [15] have noted that new effects are possible in the presence of strong gravitational fields: resonant conversion of neutrinos can also occur in sources endowed with time varying powerful gravitational fields.

Ref. [11] that pure vacuum oscillations into sterile neutrinos cannot increase the number of escaping neutrinos dramatically in the parameter range where matter effects can be neglected. Thus we focus here on conversions occurring in the very dense supernova core.

The matter effects may help in allowing more neutrinos to escape, if resonant neutrino conversions into sterile neutrinos occur inside the neutrinosphere of the active neutrinos. In the case of $\nu_e \leftrightarrow \nu_s$ oscillations, the resonance occurs if

$$\sqrt{2}G_F\left(N_e(x)-\frac{1}{2}N_n(x)\right)\equiv A(x)=\frac{\Delta m^2}{2E_\nu}\cos 2\theta. \quad (4)$$

Here $N_e(x)$ is the electron number density (given by $N_{e^-}-N_{e^+}$) while $N_n(x)$ is the neutron number density. In the case of $\nu_{\mu,\tau} \leftrightarrow \nu_s$ the N_e term is absent, while in the case of antineutrinos, the potential changes by an overall sign. Numerically, for $\nu_e \leftrightarrow \nu_s$ oscillations,

$$A(x)=7.5\times 10^2\left(\frac{\mathrm{eV}^2}{\mathrm{MeV}}\right)\left(\frac{\rho_m(x)}{10^{10}\mathrm{g/cm}^3}\right)\times\left(\frac{3Y_e}{2}-\frac{1}{2}\right) \quad (5)$$

where Y_e is the electron number fraction. For $\nu_{\mu,\tau} \leftrightarrow \nu_s$ oscillations, the last term in parenthesis is changed to $\left(\frac{Y_e}{2}-\frac{1}{2}\right)$. For all order of magnitude estimates we perform henceforth, we take the last term in the parenthesis to be of order one.

The neutrino conversions in the resonance region can be strong if the adiabaticity condition is fulfilled: the oscillation probability is $P_{as}=\cos^2\theta$, which is close to 1 in the case of small mixing angles. Moreover, after the resonance region, the newly created sterile neutrinos have very a small probability ($P_{sa}^{\mathrm{average}}=(1/2)\sin^2 2\theta$) of oscillating back to active neutrinos, which could be potentially trapped.

In order that the resonance condition is satisfied, we require

$$10^4\mathrm{eV}^2 \lesssim \Delta m^2\cos 2\theta\left(\frac{10\mathrm{MeV}}{E_\nu}\right)\lesssim 10^8\mathrm{eV}^2, \quad (6)$$

while the adiabaticity condition is satisfied for

$$\frac{\Delta m^2\sin^2 2\theta}{2E_\nu\cos 2\theta}\left(\frac{1}{\rho}\frac{\mathrm{d}\rho}{\mathrm{d}x}\right)^{-1}_{x=x_{\mathrm{res}}}\gg 1, \quad (7)$$

where x_{res} is the position of the resonance layer. Inside the core the mean free path is defined as

$$\left(\frac{1}{\rho}\frac{\mathrm{d}\rho}{\mathrm{d}x}\right)^{-1}_{x=x_{\mathrm{res}}}\equiv l_\nu=\frac{\pi(E_\nu/[\mathrm{MeV}])}{2.54(\Delta m^2/[\mathrm{eV}]^2)}\sim 1\ \mathrm{km}, \quad (8)$$

where we have assumed energies $E_\nu \sim afew$ MeV, typical of a supernova core[†]. Therefore the adiabaticity condition is satisfied if

$$\Delta m^2\frac{\sin^2 2\theta}{\cos 2\theta}\gg 10^{-3}\mathrm{eV}^2\left(\frac{E_\nu}{10\mathrm{MeV}}\right), \quad (9)$$

which is easily satisfied by $\Delta m^2 \gtrsim 10^4\mathrm{eV}^2$ as long as $\sin^2 2\theta \gg 10^{-7}$.

Thus, we find that a substantial fraction of neutrinos may get converted to sterile neutrinos and escape the core of the star, if the mass of the sterile neutrinos is such that [11]

$$10^4\mathrm{eV}^2 \lesssim \Delta m^2_{as} \lesssim 10^8\mathrm{eV}^2. \quad (10)$$

The mass difference of this magnitude cannot solve the observed solar and atmospheric neutrino problem, but the possibility of three active neutrinos explaining these anomalies and a heavy sterile neutrino of mass $m_s \sim$ keV still stays open. This fact was stressed earlier. The fraction of neutrinos that have the chance to escape over the first few milliseconds is, however, small. It was shown in Ref. [11] that at most a 10% of the total ν-flux can escape as sterile neutrinos. Nonetheless, an enhancement of the escape may also be obtained in the case of $\nu_e \leftrightarrow \nu_a$ oscillations (ν_a is a linear combination of ν_μ and ν_τ) if the resonance layer is placed between the ν_a-neutrinosphere and the ν_e-neutrinosphere. A similar hypothesis has been raised, in a completely different context, by Kusenko and Segré [20], in order to explain the observed peculiar velocities of pulsars. In their paper they made use of hypothetical strong magnetic fields inside the proto-neutron star to deform the resonance surface and create an asymmetric neutrino flux and hence "kick" the supernova core.

Oscillations between active and sterile neutrinos have been studied in the supernova in the past. In particular, $\nu_e \leftrightarrow \nu_s$ oscillations have been raised as a possibility which would allow the effective production of heavy nuclei in the "neutrino wind" [21]. These scenarios, however, require the resonant surface to be located well outside the ν_e-neutrinosphere. Also, there are limits on the $\nu_e \leftrightarrow \nu_s$ conversion rate inside the supernova core from the detected electron neutrino flux from SN1987A [22,23]. According to [22,23], the time spread and the number of detected ν_e events constrain $\nu_e \leftrightarrow \nu_s$ oscillations with

$$10^6 \le \Delta m^2 \le 10^8\mathrm{eV}^2 \text{ for } 10^{-3}\le \sin^2 2\theta \le 10^{-7}. \quad (11)$$

[†]This distance scale is shorter than the radius of a canonical neutron star, $\sim 10\ km$. As a result, in the case of oscillations among the active neutrinos, they can convert forward and reverse back several times once a radial distance from the proto-neutron star edge equivalent to one mean free path is reached, where they can freely get away from the core without being trapped.

More stringent constraints come from arguing that if there were too many "escaping neutrinos," the supernova explosion itself would not take place [23]. Such bounds are, however, model dependent. One should keep in mind that the mechanism through which the explosion takes place is, in fact, not well established. On the other hand, it is very likely that, if the results of [23] are indeed correct, there is no hope of achieving $P_{\rm as}$ larger than 10%.

Thence, with this small parcel, the neutrino luminosity during the oscillation timescale ($\Delta t_{osc} \equiv \lambda_{osc}/V_\nu$, where $V_\nu \sim 2\times 10^9 {\rm cms}^{-1}$ [13]) reads:

$$L_\nu \equiv \frac{\Delta E_{\nu_a \longrightarrow \nu_s}}{\Delta t_{osc}} \sim \frac{3\times 10^{52}{\rm erg}}{1\times 10^{-4}{\rm s}} = 3\times 10^{56}{\rm ergs}^{-1}, \quad (12)$$

while during the early postbounce it gets: $L_\nu \equiv 3\times 10^{55}{\rm ergs}^{-1}$. Hence, the GWs luminosity, L_{GW}, as a function of the neutrino luminosity can be obtained by relating the GWs flux to the GWs amplitude defined by Eq.(3), to obtain:

$$\frac{c^3}{16\pi G}|\dot{h}|^2 = \frac{1}{4\pi R^2} L_{GW} \longleftrightarrow h = \frac{2G}{c^4 R}\left[\Delta t L_\nu \alpha\right]. \quad (13)$$

This yields the gravitational waves luminosity

$$L_{GW} = 3.0\times 10^{50}\frac{\rm erg}{\rm s}\left[\frac{L_\nu}{3\times 10^{55}\frac{\rm erg}{s}}\right]^2 \left(\frac{\alpha}{10^{-3}}\right)^2, \quad (14)$$

where $5\times 10^{-3} \leq \alpha \leq 5\times 10^{-4}$ [13]. It turns out that the GWs energy radiated in the process:

$$\Delta E_{GW} \sim L_{GW}\times T_{dyn} = 3\times 10^{47}{\rm ergs}, \quad (15)$$

nearly matches the one sterile neutrinos carry away from the proto-neutron star (recall that they have very small, but non-null probability $P_{sa} \sim \sin^2 2\theta$ of reconversion into actives again)

$$E_\nu = 10^{57}|_{\nu_s} \times 10^4{\rm eV}|_{\nu_s}[\frac{10^{-33}{\rm gc}^2}{\rm eV}] \sim 2\times 10^{-6}{\rm M}_\odot {\rm c}^2. \quad (16)$$

The quoted GWs energy is $\sim 10^5$ larger than current estimates from the fluid motion of the proto-neutron star constituents [24,13].

With the assumption that the neutrino oscillation process lasts at least for the timescale of the core bounce after collapse, $\Delta t_{CB} \sim 1$ ms, the GWs amplitude produced by the non-spherical outgoing front of the s-neutrinosphere may be estimated using Eq.(3) [24,11,13]

$$h_\nu^{TT} \sim 2.6\times 10^{-21}\left(\frac{55\ {\rm kpc}}{R}\right)\left[\frac{\alpha}{10^{-1}}\right] \times \left(\frac{L_\nu}{10^{55}\ {\rm ergs}^{-1}}\right)\left[\frac{\Delta T}{1\ {\rm ms}}\right], \quad (17)$$

while its equivalent characteristic (normalized) amplitude reads:

$$h_c \sim 8.2\times 10^{-23}{\rm Hz}^{-1/2}, \quad (18)$$

for a SN occurring at a distance of the Large Magellanic Cloud $R \sim 55$kpc. It was assumed that about 10% of the total neutrinos released in the SN may oscillate $\nu_{\bar{\tau},\bar{\mu}} \longleftrightarrow \nu_s$, carrying an effective (instantaneous) power $L_\nu = 3\times 10^{55}$ ergs^{-1}, i. e., $\sim 3\times 10^{52}$erg emitted during $\Delta t_{CB} \sim 1$ms [19,24]. The GWs pulse may appear similar to a delta Dirac function centred around 1kHz (the event frequency f_{gw}) superimposed onto the overall waveform numerically obtained in Ref. [24]. An event such as this is in the sensitivity bandwidth of LIGO, VIRGO and the resonant-mass TIGAs. Moreover, for galactic sources ($R \sim 10$kpc) those GWs bursts should be observed to have stronger characteristic strains.

Provided the gravitational radiation effectively travels at the speed of light, the GWs burst produced via the MSW effect or by the neutrino spin-flavor conversion outburst will arrival to the GWs observatories earlier than the massive νs will do to neutrino telescopes (the analogous delay in time a massive ν had compared with a massless one emanating from a radiative decay channel). Assuming that is the case, then the time lag is given by [25,26,5]

$$\Delta T_{GW\leftrightarrow\nu} = 1.545\ {\rm s}\left(\frac{R}{55\ {\rm kpc}}\right) \times \left(\frac{m_\nu^2}{100\ {\rm eV}^2}\right)\left(\frac{100\ {\rm MeV}^2}{E_\nu^2}\right), \quad (19)$$

for a supernova event occurring in the Large Magellanic Cloud, with neutrino mass $m_\nu = 10$eV and energy $E_\nu = 10$MeV. Although several approximations are implicit in deriving Eq.(19), it proves useful to impose more stronger limits on the neutrino properties than alternative techniques can do. Since the supernova will somehow be seen (γ-rays, x-rays, visible, infra-red, radio), its position on the sky and distance R may be estimated quite accurately, including the redsift of its host galaxy, if far from the Milky Way. Further, the Universal Time of arrival of the GWs burst to three or more gravitational radiation interferometric or TIGAs detectors will be established with $\sim \mu$s of time resolution [27], while the neutrino energy and arrival to the ν telecospes will be highly precisely known by using well-stablished detection techniques [28,29,12]. It turns out that the left-hand-side of Eq.(19), the neutrino time-of-flight delay $\Delta T_{GW\leftrightarrow\nu}$, will be set up. With these quantities an accurate estimate of the neutrino mass eigenstate will readily be done, or stringent constraints given off by means not explored earlier. For a 10 kpc distance, to the galactic center; for instance, the resulting time delay should approximate: $\Delta T_{GW\longleftrightarrow\nu_s} = 0.258$ s, for a τ neutrino mass $m_{\nu\tau} \leq 24(\frac{\rm MeV}{c^2})$ and energy $E_\nu \sim 10$MeV. This time interval can straightforward be measured, as shown in Table I.

TABLE I. Time delay between GWs and ν-bursts in our flavor conversion mechanism. Estimates given here are for the neutrino mass and energy discussed in the text.

ΔT_ν^{GW} [s]	SN Distance
0.258	10kpc
1.545	55kpc
61.8	2.2Mpc
155.0	5.5Mpc

To summarise, the detection of this time-of-flight delay between neutrinos and gravitational-wave bursts they generate when the oscillation ensue will turn into more stringent constraints on the absolute mass eigenstate spectrum of neutrinos via an inedit technique. As we can see, Eq.(19) leads to a direct estimate of the neutrino mass, while it is implicit in Eq.(17) the amplitude of the GWs signal to be detected may lead to an inference pf the neutrino mass-difference. As has been remarkedly noticed, knowing with sufficient accuracy the neutrino absolute mass-scale would turn out into a key test of the physics beyond the standard model of fundamental interactions. Many properties endowed by neutrinos may directly be strongly constrained through the observations we are suggesting here: neutrino masses, magnetic moment, lifetime, etc. may receive tight lower bounds. In this mechanism, neutrinos and the gravitational waves they emit whereas conversions occur have the *same offset.* This clean way of timing may turn (viable) new and more interesting tests of the Equivalence Principle (weak, strong) to be performed through measurements of the time delay because both radiations can move freely from regions where for sure strong gravitational fields are at action: the neutrinosphere.

Moreover, the detection of the GWs itself in coincidence with the ν-flash may render useful to clarify their velocity of propagation. An open problem in gravitation theories [30,31]. Whether the gravitational waves do really run at the speed of light has been recently reviewed by Novello, De Lorenci and de Freitas [14]. They claimed, based on a new field theory of gravity, that gravitational waves propagates in a light-cone which is narrower than that of the light [14]. Therefore, the confirmation or refutation of a prediction such as this, among other also important ones, is a potential by-product of the technique here introduced.

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