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Prospective constraints on neutrino masses from a core-collapse supernova

John Ellis,[1,2] Hans-Thomas Janka,[3] Nikolaos E. Mavromatos,[1,2] Alexander S. Sakharov,[2,4] and Edward K. G. Sarkisyan[2,5]

[1]*Theoretical Particle Physics and Cosmology Group, Department of Physics, King's College London, Strand, London WC2R 2LS, United Kingdom*

[2]*Physics Department, CERN, CH-1211 Geneva 23, Switzerland*

[3]*Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, D-85748 Garching, Germany*

[4]*Department of Physics, Wayne State University, Detroit, Michigan 48202, USA*

[5]*Department of Physics, University of Texas at Arlington, Arlington, Texas 76019, USA*

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We discuss the prospects for improved upper limits on neutrino masses that may be provided by a core-collapse supernova explosion in our Galaxy, if it exhibits time variations in the neutrino emissions on the scale of a few milliseconds as suggested by recent two-dimensional simulations. Analyzing simulations of such neutrino emissions using the wavelet technique adopted in [J. Ellis, H.-T. Janka, N. E. Mavromatos, A. S. Sakharov, and E. K. G. Sarkisyan, Phys. Rev. D **85**, 045032 (2012)], we find that an upper limit $m_\nu \sim 0.14$ eV could be established at the 95% confidence level if the time variations in emissions were to be preserved during neutrino propagation to the Earth.

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I. INTRODUCTION

The observation of a neutrino pulse from supernova SN 1987a has provided many of the most sensitive probes of neutrino properties [1,2], notably including interesting upper limits on neutrino masses. Initial estimates yielded upper limits $m_\nu \sim \mathcal{O}(10)$ eV [3], but a recent analysis [4] has derived the stronger upper limit $m_\nu < 5.8$ eV, thanks to improved understanding of one-dimensional (spherically symmetric) neutrino emission models.

Based on a recently developed new generation of two-dimensional simulations (axially symmetric with polar grid) of core-collapse supernovae [5], we have reported recently [6] on the sensitivity to Lorentz-violating effects in neutrino propagation that could be obtained if the time variations are observed in the neutrino emissions from a future core-collapse supernova in our galaxy. It has long been appreciated that SN 1987a provides the most stringent upper limits on an energy-independent deviation of the neutrino velocity δv from that of light [7], and also strong upper limits on possible dependences $\delta v \sim E$, E^2 [8]. These limits have recently attracted increased attention, as they constrain significantly models for the OPERA report [9] of superluminal neutrino propagation [10,11]. It was also shown in [8] that these limits could be improved if another galactic supernova were to be observed.

In the present paper, we report on a study of the sensitivity to neutrino mass that would be provided if the time variations found in these two-dimensional simulations were indeed to be observed. This prospective sensitivity is very competitive with other constraints on neutrino masses, and provides additional motivation (if it is needed) for further validation of the results of two-dimensional core-collapse supernova simulations [5,12,13], particularly via the development of robust three-dimensional simulations [14,15]. Such simulations could be expected to modify the results presented here, with a tendency to reduce the observability of any time structures in the neutrino signal. We note also that we make other assumptions that are on the optimistic side, e.g., we use the signal from one radial ray, rather than a full hemisphere, we follow [5] in using a relatively soft equation of state [16], and we neglect neutrino oscillations, which are difficult to quantify with generality.

II. TWO-DIMENSIONAL SIMULATION OF A CORE-COLLAPSE SUPERNOVA

As discussed in [5], the neutrino emission during the post-bounce accretion phase in the two-dimensional simulation (unlike its one-dimensional counterpart) exhibits rapid time-variability because of anisotropic mass flows in the accretion layer around the newly formed neutron star. These flows lead to large-scale, nonradial mass motions in the layer between the protoneutron star surface and the accretion shock, creating hot spots that can produce transiently in preferred directions neutrino radiation that is more luminous and with a harder spectrum. These temporal variations in the luminosities and mean energies are expected to persist during the hundreds of milliseconds length of the accretion phase. Such variations could yield fractional changes of 10% or more in the emissions of electron neutrinos and antineutrinos during the most violent phases of core activity in two-dimensional models with no or only slow rotation [5,13]. Smaller effects are expected for muon and tau neutrinos, because lower fractions of them are produced in the outer layers of the protoneutron star where asymmetric accretion causes the largest perturbations. The fluctuating neutrino emission has been shown [5] to be detectable in the IceCube detector [17] in the case of a neutrino burst from a future Galactic supernova, with typical frequencies between several tens of

Hz and roughly 200 Hz [5]. Uncertainties in these predictions include the possibility of a stiffer nuclear equation of state, the neutrino transport description that is used, and (most importantly) the two-dimensional nature of the simulation.

We base our analysis here on the maximal effects to be expected within the mature two-dimensional models currently available. We therefore consider emission of electron antineutrinos from the (north) pole as predicted by the $15M_\odot$ simulation with the relatively soft equation of state of Lattimer and Swesty [16], as presented in [5], with no averaging over a wider range of latitudes. Possible flavor conversions between electron antineutrinos and other antineutrino flavors are ignored.

III. WAVELET ANALYSIS TECHNIQUE

We use a wavelet transform technique (see [18] for a review and [6] for a more detailed description of the approach used here) to analyze the neutrino time series generated by the simulated supernova explosion.

We use the Morlet wavelet, which is nonorthogonal, complex, and contains a number of oscillations sufficient to detect narrow features of the power spectrum. We recall that it consists of a plane wave modulated by a Gaussian function in a variable η:

$$\psi_0(\eta) = \pi^{-1/4} e^{i\omega_0\eta} e^{-\eta^2/2}, \tag{1}$$

where ω_0 is a dimensionless frequency. The continuous wavelet transform of a discrete sequence x_n is defined as the convolution of x_n with a scaled and translated version of $\psi_0(\eta)$:[1]

$$W_n(s) = \Sigma_{n'=0}^{N-1} x_{n'} \psi^*[(n'-n)\delta t/s]. \tag{2}$$

In our analysis, the x_n are obtained from a number of independent statistical realizations of the neutrino signal calculated in [5], as discussed in more detail in the last paragraph of Sec. 2.3 of [6]. By varying the wavelet scale s and translating along the localized time index n, one can construct a picture showing both the amplitude of any features versus the scale and how this amplitude varies with time. Although it is possible to calculate the wavelet transform using (2), it is convenient and faster to perform the calculations in Fourier space. According to the convolution theorem, the wavelet transform is the Fourier transform of the product:

$$W_n(s) = \Sigma_{k=0}^{N-1} \hat{x}_k \psi^*(s\omega_k) e^{i\omega_k n\delta t}, \tag{3}$$

where $\omega_k = +\frac{2\pi k}{N\delta t}$ and $-\frac{2\pi k}{N\delta t}$ for $k \le \frac{N}{2}$ and $k > \frac{N}{2}$, respectively. After suitable normalization [6], the expectation value of $|W_n(s)|^2$ for a white-noise process is σ^2 for all n and s. We choose discrete scales related by powers of two:

$$s_j = 2^{j\delta j} s_0, \qquad j = 0, 1, \ldots, J,$$
$$J = (1/\delta j)\log_2(N\delta t/s_0), \tag{4}$$

where s_0 is the smallest resolvable scale and J determines the largest scale. In the middle panel of Fig. 1, we use: $N = 1024$, $\delta t = 1.785 \times 10^{-4}$ s, $s_0 = 2\delta t$, $\delta j = 0.125$, and $J = 48$. In our subsequent analysis, we determine significance levels for the wavelet spectra with reference to a Gaussian white-noise background spectrum.

IV. PROSPECTIVE LIMIT ON THE NEUTRINO MASS

We display in the top panel of Fig. 1 the neutrino time series found in [5], summing over all the produced neutrino energies. It has structures on time scales below a hundredth of a second that lie beyond the fluctuations expected from a ''featureless'' white-noise spectrum. The middle panel of Fig. 1 shows the normalized wavelet power spectrum, $|W_n(s)|^2/\sigma^2$, for the time series of the neutrino emission shown in the top panel [6]. The colors represent the significance of the feature compared to a white-noise spectrum, as measured by the number of σ relative to white noise. Structures in the time series are visible on time scales down to $\sim 2 \times 10^{-3}$ s, several of which have significance well above the 95% C.L. for a white-noise spectrum (indicated by red contours). Those with time scales between 2 ms and 3 ms can be seen in the bottom panel of Fig. 1. We focus on these, rather than structures on longer time scales, aiming at the best possible time resolution.[2]

We investigate here how these structures would be smeared out by the effect of a neutrino mass on its velocity v_ν:

$$v_\nu/c = 1 - (E/m_\nu)^2. \tag{5}$$

The neutrino data collected from a supernova explosion will consist of a list of individual neutrino events with measured energies E_i and arrival times t_i, whereas the results of the simulation in [5] are presented as a set of energy fluxes within time periods of durations $\simeq$ 3–5 ms. Each of these fluxes may be treated as a black-body spectrum with a specified mean energy. We assign statistically to each neutrino in the simulation a specific time of emission and energy, based on the mean and total energy of the flux in each time period. In order to estimate the sensitivity to the neutrino mass, we make 25 statistically independent realizations of the neutrino emission, make a wavelet transform of each implementation, and analyze statistically their sensitivities to m_ν.

Our prospective upper limit on m_ν is calculated by requiring that the fine-scale time structures in the wavelet power spectrum do not disappear below the 95% C.L. of significance for a signal above the white-noise power

[1]The subscript 0 on ψ has been dropped, in order to indicate that ψ has also been normalized (see later).

[2]See, however, the caveats in [6].

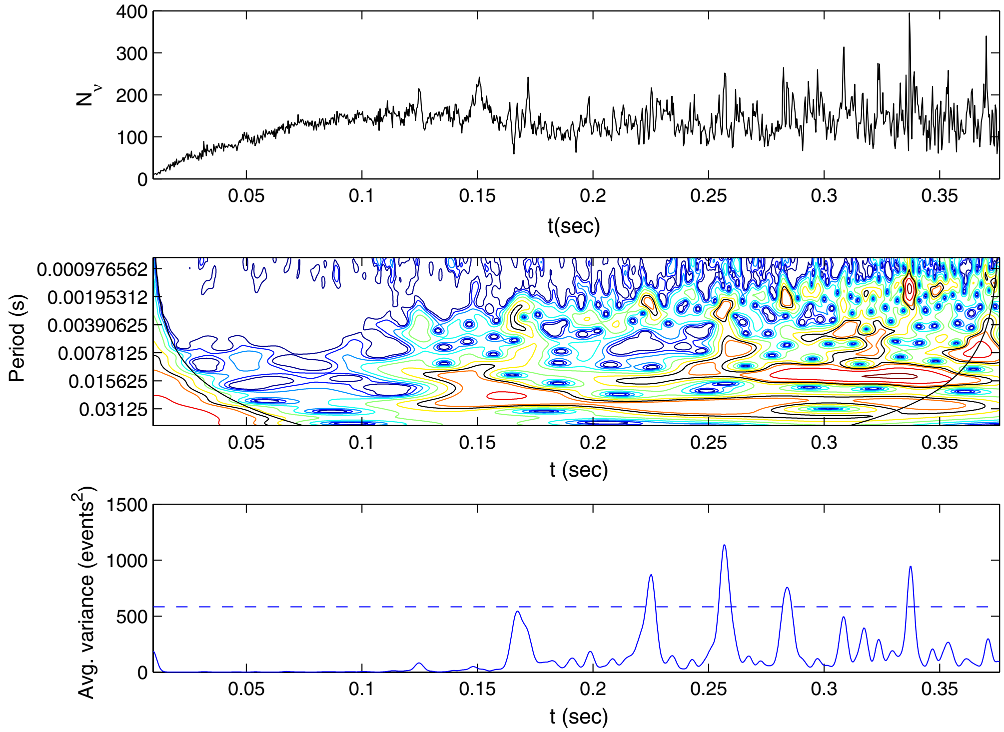

FIG. 1 (color online). *Top panel:* The time series of the neutrino emission from the two-dimensional simulation of a core-collapse supernova found in [5]. The time profile is sampled in 1024 (2^{10}) bins. *Middle panel*: The local wavelet power spectrum of the neutrino emission time series, obtained using the Morlet wavelet function (1) normalized by $1/\sigma^2$ [6]. The vertical axis is the Fourier period (in seconds), and the horizontal axis is the time of the neutrino emission. The red contours enclose regions that differ from white noise at greater than the 95% C.L. The cone of influence, where edge effects become important, is indicated by the concave solid lines at the edges of the support of the signal. *Bottom panel*: The average power in the 0.002–0.003 s band. The dashed line shows the 95% C.L. significance.

spectrum. Specifically, we apply to each neutrino event an energy-dependent time shift

$$\Delta t = \tau_m / E^2, \tag{6}$$

where

$$\tau_m = L m_\nu^2 / c. \tag{7}$$

We then vary $\tau_m(m_\nu)$ and follow the evolution of the signal in the neutrino time series. If there were a nontrivial energy-dependent mass effect during propagation from the supernova, it could be compensated by choosing the "correct" value of the time shift τ_m, in which case the original time structure at the source is recovered. On the other hand, dispersion at the source itself could not, in general, be compensated by any choice of τ_l. Quantitatively, the time structure of the supernova signal is recovered by maximizing the fraction of the scale-averaged power spectrum above the 95% C.L. line. In order to calculate a lower limit on τ_m in any specific model, we examine the fine-scale time structures that appear above the 95% C.L. in the bottom panel of Fig. 1 and determine the value of the time-shift parameter (7) at which the signal above the 95% C.L. disappears.

Figure 2 displays the result of one simulation of the effect of such an energy-dependent refractive index, sampled in 21 bins corresponding to different time shifts τ_m. The vertical axis of the lower plot shows the strength of the emissions in the structures with time scales between 2 and 3 ms, applying an energy-dependent time shift $\tau_m = 0.019\ \mathrm{s} \cdot \mathrm{MeV}^2$. Looking at the structures that occur between 0.22 and 0.34 s after the start, we see that their significant parts [those above the 95% fluctuation level for white-noise background (as seen in Fig. 1)] disappear for time delays $\tau_m = 0.019\ \mathrm{s} \cdot \mathrm{MeV}^2$ and above, corresponding to $m_\nu > 0.14$ eV if a supernova distance L of 10 kpc is assumed. This sensitivity is one-and-a-half orders of magnitude more sensitive than that found in [4], namely, $m_\nu < 5.8$ eV, based on a one-dimensional simulation of a core-collapse supernova that did not exhibit the small time-scale structures seen in Fig. 1.

We have repeated this exercise with 25 different statistical realizations of the neutrino emission, calculating in each case the amount Σ of the total signal above 95% C.L. for different values of τ_m sampled in 21 bins. The results of these 25 realizations can be fit quite well by a Gaussian distribution, as seen in Fig. 3, which displays our results for the structures with time scales between 2 and 3 ms that

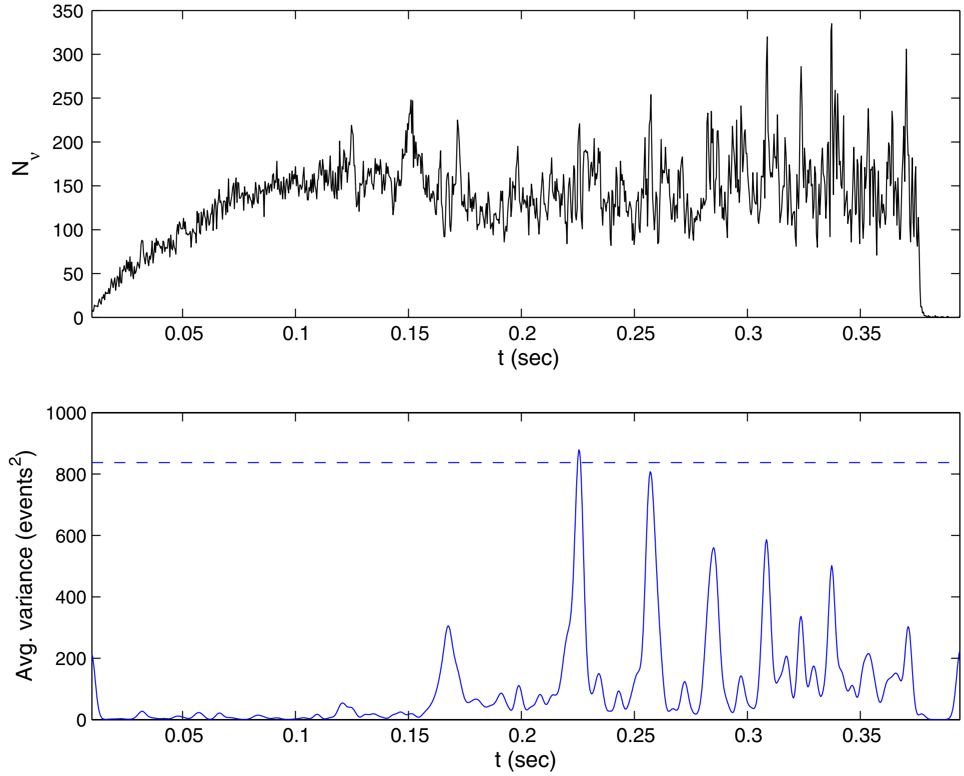

FIG. 2 (color online). *Upper panel*: The time series of the neutrino emission from the two-dimensional simulation of a core-collapse supernova after applying an energy-dependent time shift $\tau_m = 0.019\ \mathrm{s}\cdot\mathrm{MeV}^2$. *Lower panel*: The strengths of the time-scale structures of the power spectrum averaged between 2 and 3 ms disappear below the 95% C.L. of significance after applying this time shift.

occur between 0.22 and 0.34 s after the start. The position of the maximum, which defines the value of τ that maximizes the time structures in the signal and is expected to be zero, is indeed consistent with zero to within a precision of $0.001\ \mathrm{s}\cdot\mathrm{MeV}^2$, while the structures are washed out at

$$\tau_m = 0.019\ \mathrm{s}\cdot\mathrm{MeV}^2. \tag{8}$$

Hence, if significant time structures of the type found in the two-dimensional simulation [5] were to be seen in IceCube or a water Čerenkov low-energy detector in neutrino data from a core-collapse supernova at a distance of 10 kpc, one could conclude that

$$m_\nu < 0.14\ \mathrm{eV}. \tag{9}$$

On the other hand, if no such structures were seen, this could mean either that the structure was washed out by the effect of neutrino propagation with $m_\nu \gtrsim 0.14$ eV (which is still consistent with the cosmological limit $m_\nu < 0.23$ eV [19]), or that the structure found in [5,13] is not valid.

The first possibility could be probed by performing a series of analyses of the above type in several different bands of the power spectrum.[3] In practice, in the presence of an apparently structureless original signal, one would average systematically over all possible bands with a relatively small step of granularity, defined by the precision of

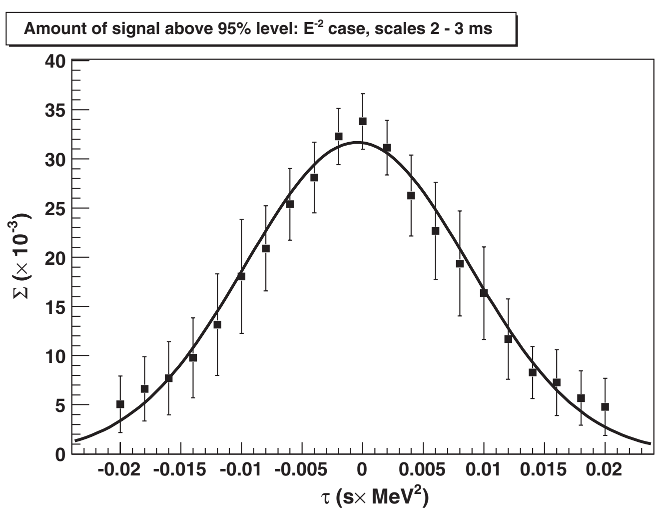

FIG. 3. A Gaussian fit to the amount Σ of the short time-scale signal above the 95% C.L., calculated for 21 values of the shift parameters τ_m. Each point is obtained as the average over 25 realizations of the time-energy assignments of individual neutrinos.

[3]We recall that, in order to obtain the greatest sensitivity, the averaging in Fig. 1 was performed in the ~2–3 ms band where the shortest time-varying structures appear above the 95% C.L. However, there are structures at other scales, e.g., in the ~7–15 ms band.

the analysis, while changing τ_m so as to maximize the amount of the signal above the 95% C.L. for the averaged power in every band included in the scan. As soon as a value of τ_m is found with a significant fraction of the signal above the 95% C.L. line at $\tau_m \gtrsim 0.019\ \mathrm{s} \cdot \mathrm{MeV}^2$, one could claim evidence for a nonzero neutrino mass. On the other hand, if such a scanning analysis delivered a negative result, inferring a lower limit on m_ν would require strong independent confirmation of the structures found in [5,13], in particular, by full three-dimensional simulations.

We note that the possibility of a time advance is also considered in Fig. 3. This would correspond to a neutrino with $m_\nu^2 < 0$, i.e., a tachyon. As pointed out, e.g., in [10], the time advance reported by OPERA [9] could not be associated with tachyonic neutrinos because, e.g., this would require an unacceptable time advance $\sim 4y$ for neutrinos from supernova SN1987a.[4] Conversely, SN 1987a provides the strongest available lower limit on negative m_ν^2. Correspondingly, observation of the short time structures suggested by [5] would establish a much stronger limit on the possible tachyonic nature of the neutrino: $m_\nu^2 > -0.02\ \mathrm{eV}^2$, which would also be significantly stronger than the bound $m_\nu^2 > -0.11\ \mathrm{eV}^2$ recently derived by combining neutrino constraints from big-bang nucleosynthesis and the cosmic microwave background [20].

V. CONCLUSIONS AND PROSPECTS

We have shown that the existence of structures with short time scales in the neutrino emission from a core-collapse supernova, as suggested by two-dimensional simulations [5,13], would open up new prospects for probing neutrino masses. The sensitivity (9) extends up to one-and-a-half orders of magnitude beyond the sensitivity provided by previous analyses based on one-dimensional supernova simulations [4]. This sensitivity is comparable to the ~ 0.2 eV obtainable with the KATRIN experiment [21], and to the potential sensitivity to m_ν provided by large-scale structure surveys in combination with measurements of the cosmic microwave background radiation [19].

If such short time structures were not to be seen in emissions from a future core-collapse supernova, many checks would be necessary before one could conceivably claim observation of a nonzero neutrino mass. In particular, it would be necessary to validate the structures predicted by the two-dimensional core-collapse supernova simulation on which this analysis is based, specifically in full three-dimensional simulations [14,15]. It would also be necessary to test the influence of some of the other special or simplifying assumptions made here, e.g., the use of the signal from one radial ray [5], the use of a relatively soft equation of state [16], and the neglect of neutrino oscillations. On the other hand, convergent indications from supernova observations, KATRIN [21], and astrophysical observations [22] would substantiate and consolidate any determination of neutrino mass in the range 0.1 to 0.2 eV.

[4]There is a more fundamental problem with Lorentz-invariant tachyonic neutrinos, namely, that there are no nontrivial finite-dimensional unitary representations of the Lorentz group for $m^2 < 0$ that could correspond to spin-1/2 fermions. However, here we restrict ourselves to phenomenological constraints on tachyonic neutrinos.

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