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On neutrino properties and gravitational waves

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Multi-messenger astronomy can be a relevant tool for getting information about neutrino masses and their ordering using the measurement of the time lapses between the arrival of neutrinos and the other light messenger, e.g. the graviton, emitted in astrophysical catastrophes. We elucidate the experimental reach and challenges for planned neutrino detectors such as Hyper-Kamiokande as well as future several megaton detectors.

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1. Introduction

The fascinating discovery by the LIGO collaboration [1] has opened up a new way of exploring the Universe. Gravitational waves (GW)s carry detailed information about astrophysical catastrophes and can provide a clear reference time for multi-messenger astronomy. In particular, these events might bring insight on two of the open issues in neutrino physics, i.e. the absolute neutrino mass scale and the neutrino mass spectrum. Oscillation experiments are not sensitive to their masses, therefore information about their tiny mass comes from cosmology where an upper bound on the sum of the active neutrinos $\sum_i m_i < 0.23$ eV can be established. More recently, more stringent limits have been obtained through the Lyman alpha forest power spectrum, $\sum_i m_i < 0.12$ eV [2].

Current available neutrino oscillation data [7] are compatible with two types of neutrino mass spectra. Depending on the sign of $\Delta m^2_{31(32)}$, two types of neutrino mass spectrum are possible: normal (NO) and inverted (IO) ordering, which, if the lightest neutrino mass, m_{min}, is small compared to $\Delta m^2_{31(32)}$ leads to the Normal or Inverted Hierarchical (NH or IH) ordering. Whereas, if m_{min} is comparable to $\Delta m^2_{31(32)}$ the spectrum is referred to as Quasi-Degenerate (QD) (see, e.g., [3]). The current cosmological bounds are strongly disfavouring the degenerate regime. The detection of GWs is a crucial test of general relativity and, as already discussed in the literature (e.g. [4, 5]), it is also important to deduce other relevant physical properties. This new information can be derived when comparing, for example, their propagation velocity with those of photons and neutrinos coming both from the same astrophysical source. The observation of gravitational wave events accompanied by counterpart events, like neutrino detections, could improve our knowledge about the ordering and the masses of these tiny particles.

2. Ingredients

We closely follow the outlining and the analysis done in [6]. Let us consider a potential observation of an astrophysical catastrophe such as the merging of a neutron star binary or the core bounce of a core-collapsed supernova (SN). We denote with $T_g \equiv L/v_g$, $T_{\nu_i} \equiv L/v_{\nu_i}$ and $T_\gamma \equiv L/v_\gamma$, respectively, the time of propagation of a GW, a given neutrino mass eigenstate and photons with group velocities v_g, v_{ν_i}, and v_γ. Following the left panel in Fig. 1 a GW is emitted at the time t_g^E from a source at distance L and detected on Earth at t_g. Similarly, we have emission and detection times for photons and neutrinos. The difference of the arrival times between the GWs and neutrinos, $\tau_{obs} \equiv t_\nu - t_g$, or the GW and a photon, $\tau^\gamma_{obs} \equiv t_\gamma - t_g$, are both observables. Typically the emission times of the three signals (GW, γ and ν) do not coincide. For instance in the supernova explosion SN1987A, the neutrinos arrived approximately 2 – 3 hours before the associated photons.

Let us assume now that a neutrino is emitted at $t_\nu^E = t_g^E + \tau^\nu_{int}$ and detected at time t_ν. A relativistic mass eigenstate neutrino with mass $m_i c^2 \ll E$ ($i = 1,2,3$) propagates with a group velocity:

$$\frac{v_i}{c} = 1 - \frac{m_i^2 c^4}{2E^2} + \mathcal{O}\left(\frac{m_i^4 c^8}{8E^4}\right) , \tag{2.1}$$

where we assumed that the different species of neutrinos have been produced with a common energy value E. If a given neutrino is produced by a source at a distance L, the time-of-flight delay

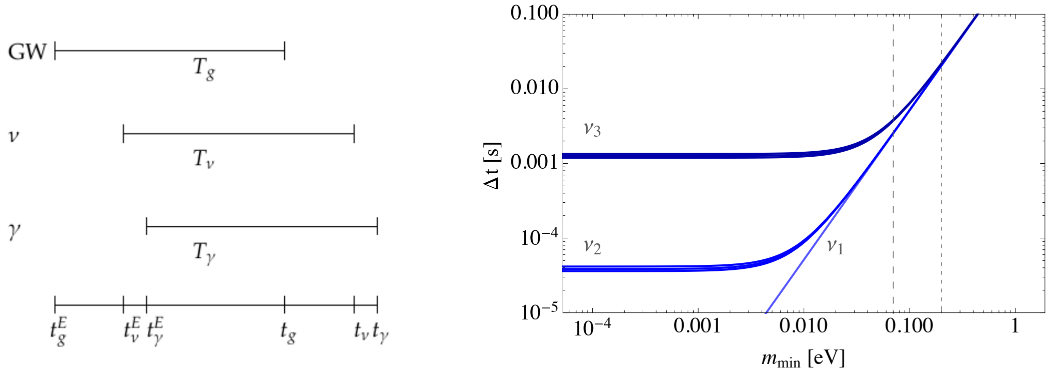

Figure 1: (Left Panel) GW, neutrino and photon propagation in time. (Right Panel) The range of Δt_i ($i = 1,2,3$), the time delay of neutrinos with respect to photons, vs the lightest of the neutrino masses, m_{min}, for a distance of 1 Mpc and 10 MeV. We show the results for NO considering a the 3σ uncertainty in oscillation parameters [7]. The dashed and dotted vertical lines correspond to the Planck limit on the sum of neutrinos masses and the perspective upper limits from the KATRIN experiment.

Δt_i with respect to a massless particle, emitted by the same source at the same time, is [1]

$$\Delta t_i \cong \frac{m_i^2 c^4}{2E^2}\frac{L}{c} = 2.57\left(\frac{m_i c^2}{\mathrm{eV}}\right)^2\left(\frac{E}{\mathrm{MeV}}\right)^{-2}\frac{L}{50\mathrm{kpc}}\; s. \tag{2.2}$$

We observe that large distances and small neutrino energies are needed in order to maximise the experimental sensitivity. For distances around 50 kpc (SN1987A) and an energy of 10 MeV, a neutrino with a mass of 70 meV would arrive $\sim 10^{-4}$ s later than a massless particle. Similar to (2.2) we express the time delay between the arrival of two neutrino mass eigenstates as:

$$\Delta t_{\nu_i \nu_j} = \Delta t_i - \Delta t_j = \frac{\Delta m_{ij}^2 c^4}{2E^2} T_0 \quad \text{with} \quad T_0 = \frac{L}{c}\,, \tag{2.3}$$

with $\Delta m_{ij}^2 = m_i^2 - m_j^2$ and to leading order in m^2c^4/E^2. We note, that in this limit the time intervals do not depend on the absolute neutrino mass scale, but solely on the square mass differences which are measured experimentally.

3. Disentangling neutrino mass ordering

Using Eq. (2.3), we can observe that if the detector uncertainty is 10^{-3} s we are able to disentangle the atmospheric (solar) squared mass differences with a signal coming from a distance larger than 0.8 (26) Mpc assuming neutrinos have an energy of about 10 MeV. This means, that for neutrinos with an average energy of 10 MeV, the delay time of the heaviest neutrino mass eigenstate with respect to the lightest is larger than 10^{-3} s independently of the absolute neutrino mass scale and hierarchy, for distances larger than ~ 0.8 Mpc. Therefore, assuming an accuracy of 10^{-3} s, the relevant sources are those at distances larger than 0.8 Mpc. With better time accuracy the distance decreases linearly. We show in the right panel in Fig. 1 the time delay (for each mass eigenstate)

[1] Here we do not take into account cosmic expansion since we consider sources at low redshift, $z \ll 0.1$. This causes an error less than 5%.

m_{min} [eV]	Δt_{ν_i} [s]	
	NO	IO
0	0	$1.23 \cdot 10^{-5}(10^{-3})$
	$3.86 \cdot 10^{-7}(10^{-5})$	$1.26 \cdot 10^{-5}(10^{-3})$
	$1.26 \cdot 10^{-5}(10^{-3})$	0
0.01	$5.14 \cdot 10^{-7}(10^{-5})$	$1.28 \cdot 10^{-5}(10^{-3})$
	$9.00 \cdot 10^{-7}(10^{-5})$	$1.32 \cdot 10^{-5}(10^{-3})$
	$1.32 \cdot 10^{-5}(10^{-3})$	$5.14 \cdot 10^{-7}(10^{-5})$

m_{min} [eV]	Δt_{ν_i} [s]	
	NO	IO
0	0	$4.91 \cdot 10^{-3}(10^{-2})$
	$1.54 \cdot 10^{-4}(10^{-3})$	$5.06 \cdot 10^{-3}(10^{-2})$
	$5.06 \cdot 10^{-3}(10^{-2})$	0
0.01	$2.06 \cdot 10^{-4}(10^{-3})$	$5.11 \cdot 10^{-3}(10^{-2})$
	$3.60 \cdot 10^{-4}(10^{-3})$	$5.27 \cdot 10^{-3}(10^{-2})$
	$5.27 \cdot 10^{-3}(10^{-2})$	$2.06 \cdot 10^{-4}(10^{-3})$

Table 1: (Left) Benchmark time lapses for ν_1, ν_2 and ν_3 respectively. We consider a distance of 10 kpc (1 Mpc) and a neutrino energy of $E = 10$ MeV. (Right) The distance is set to 1 Mpc (10 Mpc) and the neutrino energy to $E = 5$ MeV.

Δt_i considering NO as function of the lightest neutrino mass, setting the neutrino energy to 10 MeV and the distance of the source to 1 Mpc. The physically relevant arrival time differences between neutrino mass eigenstates $\Delta t_{\nu_i \nu_j}$ can be readily determined from the figure. We also report in the plot the future sensitivity on the absolute neutrino mass of the β-decay experiment KATRIN which is expected to be around 0.2 eV and the constraints given by the Planck Collaboration on the sum of the light active neutrinos $\sum_i m_i \leq 0.23$ eV 95% CL. In Table 1 we produce relevant benchmark neutrino time lapses considering two different source-distances for different values of the lightest neutrino mass for 5 and 10 MeV neutrinos.

From Table 1 we observe that for the given distance and energy, the NO and IO spectra differ by having different time delay patterns. We note that for IO the delay between the two heaviest mass eigenstates is equivalent to the time lapse between the first two lighter mass eigenstates for NO.

Further information can in principle be obtained from the ratio between the amplitudes of the different neutrinos reaching the detector. Due to the large distances considered here, neutrinos will be detected incoherently with a probability $P\left(\nu_\alpha \to \nu_\beta\right) = \sum_i \left|U_{\alpha i}\right|^2 \left|U_{\beta i}\right|^2$, where α and β are flavour eigenstates. This expression holds true whenever the time arrival differences among the three mass eigenstates is smaller than the detector time resolution. However, when $\Delta t_{\nu_i \nu_j}$ is larger than the detector resolution, then each mass eigenstates ν_i can be detected independently and will interact with the detector with probability [2]

$$P\left(\nu_\alpha \to \nu_\beta\right)_i = \left|U_{\alpha i}\right|^2 \left|U_{\beta i}\right|^2 \ . \tag{3.1}$$

In [6], we construct a simplified scenario to illustrate the effect of (3.1) on a possible pattern of neutrino detection and show that, at least in principle, one can observe interesting time-patterns reflecting the neutrino ordering and mixing.

[2] We work in the regime of incoherence. Defining σ_{xP} (σ_{xD}) as the spatial width of the production (detection) neutrino wave packet, we work under the assumption that $|(v_j - v_k)L/c| \gg \max(\sigma_{xP}, \sigma_{xD})$ being v_i and v_j the two group velocities of the two wave packets of neutrino mass eigenstates ν_i and ν_j.

4. Concluding with a Preliminary Feasibility Study

In order to shed light on the proposed effect, we conclude [6] with a preliminary study of the actual experimental feasibility. Since the whole set up utilises neutrinos from distant sources, we ultimately need to estimate the number of detected neutrinos assuming a specific source at a given distance. The three vital parameters for increasing the time lapse between mass eigenstates are: the distance from the source L, the energy of the emitted neutrino, E_ν, and the absolute neutrino mass m_{min}. Although large distances increase the time lapses, the corresponding rate observed will quickly fall off. As a consequence, if the neutrino counterparts of events like GW150914 would be emitted by the source, it would be hard, if not impossible, to detect them on Earth. In [6], we use a Poisson probability distribution to compute expected the number of detected events via inverse beta decay using from a given source. These estimates show that it is possible to reach phenomenologically interesting neutrino mass differences from sources at $\sim$1 Mpc provided one can combine more than one Mton experiment. Furthermore, the time resolution in neutrino detection can, in the future, be expected to go below one millisecond. If this is the case it would allow sources as close as 100 kpc to become relevant for our analysis. In this case the neutrino flux increases by two orders of magnitude.

To conclude, we derived the theoretical and phenomenological conditions under which multi-messenger astronomy can disentangle or further constrain the neutrino mass ordering. We have also argued that it can provide salient information on the absolute neutrino masses. We added a preliminary feasibility study to substantiate and further motivate our theoretical analysis. We have seen that future experiments can be useful also in testing independently the cosmological bounds on neutrino absolute masses. However, this requires high resolution timing and a significant increase in the combined fiducial volume compared to the current Cherenkov water detectors.

Conversely one can use future results on neutrino properties to provide detailed information about astrophysical sources emitting simultaneously GWs, photons and neutrinos, and possibly lower uncertainties in the emitted multi-messenger signal from the source.

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