Diffuse Supernova Neutrino Background & other related topics

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1. Neutrino mixing

The lepton mixing matrix,

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\tau 2} & U_{\mu 3} \\ U_{\mu 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\rm CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\rm CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \tag{1.1}$$

relates neutrino flavour and mass eigenstates. Here, we have parametrised it in terms of three rotations, and we have adopted the notation $c_{ij} \equiv \cos\theta_{ij}$ and $s_{ij} \equiv \sin\theta_{ij}$, where θ_{ij} are the so-called mixing angles. In addition, the parametrisation includes a phase, $\delta_{\rm CP}$ which, when different from 0 or π, accounts for CP violation in the neutrino sector. [1] If CP symmetry is not conserved in the neutrino sector, then the oscillation probabilities $P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$.

The values of the oscillation parameters are obtained through fits to experimental data. I personally use the results from Table III, *de Salas et al.* [1]. There are two other international groups performing similar analyses [2, 3]. The differences between them are negligible for what we are doing.

2. Loss of coherence in neutrino propagation

Neutrino oscillations are an interference effect. They occur only if different neutrino mass eigenstates evolve coherently (i.e. their relative phases are well-defined and evolve smoothly with time) and if the detector is unable to distinguish the different mass eigenstates. The latter condition is met since neutrino detection is based on weak process – well-defined in the flavour basis. However, the former does not always apply.

Neutrino oscillations are pedagogically addressed using plane-wave solutions. Nonetheless, for understanding coherence, it is useful to consider neutrinos as a superposition of wave packets – one for each

[1] Note that two additional phases are needed in the case of Majorana neutrinos. However, those do not manifest in neutrino oscillations or flavour conversions.

mass eigenstate. After production, because of the different masses and momenta, neutrinos propagate with different group velocities. If the distances travelled are large enough – and the momenta are small enough –, the wave packets corresponding to each mass eigenstate will eventually separate in space and time. At that point, coherence is lost. Then, what arrives to a detector is an incoherent sum of mass eigenstate. In solar, supernova neutrinos, and also for the diffuse supernova neutrino background, the distance travelled by neutrinos is much larger than the so-called *coherence length* – distance over which coherence is kept.

Then, for a given initial flux of neutrinos of flavour α, $\Phi^0_{\nu_\alpha}$, what gets to Earth – aside from the scaling with distance, d^{-2} – is a flux of mass eigenstates such that

$$(\Phi_{\nu_1},\, \Phi_{\nu_2},\, \Phi_{\nu_3})_\oplus = (|U_{\alpha 1}|^2\Phi^0_{\nu_1},\, |U_{\alpha 2}|^2\Phi^0_{\nu_2},\, |U_{\alpha 3}|^2\Phi^0_{\nu_3})\,, \tag{2.1}$$

and analogously for antineutrinos. Notice that the unitarity of the lepton mixing matrix, i.e. $\sum_i |U_{\alpha i}|^2 = 1$, ensures that the total number of neutrinos is conserved.

Neutrinos are detected as flavour eigenstates via weak interactions. Thus, to consider the detectable flux of neutrinos (or antineutrinos) of a given flavour β, one needs to rotate back to the flavour basis, namely

$$\begin{aligned}\Phi_{\nu_\beta,\odot} &= |U_{\beta 1}|^2\Phi_{\nu_1,\odot} + |U_{\beta 2}|^2\Phi_{\nu_2,\odot} + |U_{\beta 3}|^2\Phi_{\nu_3,\odot} \\ &= \left(|U_{\beta 1}|^2|U_{\alpha 1}|^2 + |U_{\beta 2}|^2|U_{\alpha 2}|^2 + |U_{\beta 3}|^2|U_{\alpha 3}|^2\right)\Phi^0_{\nu_\alpha}\ .\end{aligned} \tag{2.2}$$

3. Introduction to neutrino decay – text in progress

Neutrino oscillations prove that at least two of the three neutrino species are massive. Whatever the mechanism originating neutrino masses is, one can prove that it would also induce neutrino radiative decays, i.e. neutrino decay to a photon and another neutrino of opposite chirality. However, depending on the neutrino-mass mechanism, the lifetime of neutrinos could actually be larger than the age of the universe, making them effectively stable – or not! Other extensions of the Standard Model of particle physics also lead to unstable neutrinos.

From a phenomenological point of view, the simplest classification is in terms of the detectability of the decay products. When the particles of the final state escape detection, we talk about *invisible* decay. Conversely, if the decay products can interact with a detector, we refer to the scenario as *visible* decay.

This classification is not ideal from a model building perspective. For instance, a very same model could have two different decay branches, one of them being visible and the other one being invisible. Another example is a decay channel such that the decay products have energies such that they would be 'invisible' to some of the detectors but 'visible' to others. However, since systematically testing every theoretical model predicting neutrino decay is unfeasible, this phenomenological constraints come in handy.

Then, the decay with of a given neutrino mass eigenstate, Γ_j would be the sum of the invisible and visible decay widths, namely,

$$\Gamma_j = \Gamma_{j,\text{visible}} + \Gamma_{j,\text{invisible}}\,, \tag{3.1}$$

where the decay width is just the inverse of the neutrino lifetime – which can also be decomposed in visible and invisible contributions.

Another classification often found in the litterature is *radiative* – when there is a photon in the final state – and *non-radiative* decays.

A final comment is needed regarding the classification in 2-body vs 3-body decays. Generally, if the new particle content – for instance pseudoscalar particle ϕ like the Majoron – is very light or massless, they decay $\nu_i \rightarrow \bar{\nu}_j + \phi$ is kinematically allowed as long as $m_i - m_j > m_\phi$. However, for heavier particles, such a decay is not possible. Nonetheless, these new pseudoscalar would mediate the decay $\nu_i \rightarrow \bar{\nu}_j + \phi(\text{virtual}) \rightarrow \bar{\nu}_j + \nu_k + \bar{\nu}_k$.

References

[1] P. F. de Salas, D. V. Forero, S. Gariazzo, P. Martínez-Miravé, O. Mena, C. A. Ternes, M. Tórtola, and J. W. F. Valle. 2020 global reassessment of the neutrino oscillation picture. *JHEP*, 02:071, 2021.

[2] Ivan Esteban, M. C. Gonzalez-Garcia, Michele Maltoni, Thomas Schwetz, and Albert Zhou. The fate of hints: updated global analysis of three-flavor neutrino oscillations. *JHEP*, 09:178, 2020.

[3] Francesco Capozzi, Eleonora Di Valentino, Eligio Lisi, Antonio Marrone, Alessandro Melchiorri, and Antonio Palazzo. Unfinished fabric of the three neutrino paradigm. *Phys. Rev. D*, 104(8):083031, 2021.