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Collective neutrino flavor conversion: Recent developments

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Abstract

Neutrino flavor evolution in core-collapse supernovae, neutron-star mergers, or the early universe is dominated by neutrino–neutrino refraction, often spawning "self-induced flavor conversion," i.e., shuffling of flavor among momentum modes. This effect is driven by collective run-away modes of the coupled "flavor oscillators" and can spontaneously break the initial symmetries such as axial symmetry, homogeneity, isotropy, and even stationarity. Moreover, the growth rates of unstable modes can be of the order of the neutrino–neutrino interaction energy instead of the much smaller vacuum oscillation frequency: self-induced flavor conversion does not always require neutrino masses. We illustrate these newly found phenomena in terms of simple toy models. What happens in realistic astrophysical settings is up to speculation at present.

1. Introduction

Neutrino dispersion in matter strongly modifies the flavor evolution caused by their masses and mixing parameters [1–3]. Moreover, in dense astrophysical environments, notably in core-

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collapse supernovae, merging neutron stars, or the early universe, neutrinos themselves provide a large refractive effect. Flavor evolution implies that the "background medium" also evolves, i.e., neutrino flavor evolution feeds back unto itself [4,5] and, among other effects, can produce collective run-away modes in flavor space. One consequence is "self-induced flavor conversion," meaning that some modes of the neutrino mean field swap flavor with other modes [6–12]. To lowest order, neutrino–neutrino interactions are flavor blind [13], so collective effects alone do not change the global flavor content of the ensemble. Yet the reshuffling among modes can effectively engender flavor equilibration. The simplest example is a gas of equal densities of ν_e and $\bar{\nu}_e$ that would turn to an equal ν–$\bar{\nu}$ mixture of all flavors, yet the overall flavor lepton numbers remain zero from beginning to end [14].

The neutrino mean field is described by flavor matrices $\varrho(t,\mathbf{r},\mathbf{p})$ with elements of the type $\langle a_i^\dagger a_j\rangle$ in terms of creation and annihilation operators with flavor index i. The diagonal elements are occupation numbers, the off-diagonal ones represent flavor correlations. The seven-dimensional phase space $(t,\mathbf{r},\mathbf{p})$ is not tractable and was always reduced by symmetry assumptions. For supernova neutrinos, one has usually assumed stationary solutions which depend only on radial distance and, in momentum space, on energy and zenith angle, reducing the problem to three dimensions. The emission region was often modeled as a "neutrino bulb," meaning an emitting surface ("neutrino sphere"), where neutrinos of all flavors emerge with a blackbody-inspired zenith-angle distribution. Such models lead to sharp spectral features ("spectral splits") caused by flavor swaps between different parts of the spectrum [15–18]. Being triggered by an instability which is sensitive to the neutrino mass ordering, these effects seemed to offer an opportunity to learn about the latter even for a very small Θ_{13} mixing angle [19].

Meanwhile the situation has changed on several fronts. The mixing angle Θ_{13} has been measured and is not very small, so the mass ordering will be experimentally accessible. Moreover, our ideas about the flavor evolution of supernova neutrinos had to be revised because it has dawned on us that the earlier symmetry assumptions had constrained the solutions in unphysical ways. Even within the bulb model of neutrino emission, axial symmetry [20–24], homogeneity [25–29], and stationarity [30,31] can be spontaneously broken, completely changing the stability conditions. It has been speculated that self-induced flavor conversion may commence in the decoupling region, much deeper than the usual "onset radius," and that flavor equilibration could be a generic outcome instead of ordered spectral swaps.

Moreover, in a more realistic emission model, ν_e, $\bar{\nu}_e$ and the other species have different zenith-angle distributions. Surprisingly, self-induced flavor conversion can then be "fast" in the sense that the evolution speed is of the order of the neutrino–neutrino interaction energy $\mu = \sqrt{2}G_{\rm F}n_\nu$ instead of the much smaller vacuum oscillation frequency $\omega = \Delta m^2/2E$ [9,32,33]. While this phenomenon had been noted a long time ago [9], its significance had eluded much of the community. Fast flavor conversion does not depend on neutrino masses,[1] except perhaps for providing initial disturbances to seed the run-away modes.[2] This counter-intuitive behavior owes to the character of self-induced flavor conversion as an instability and to its nature of flavor shuffling among modes which globally conserves flavor number.

[1] The Physics Nobel Prize 2015 was awarded "for the discovery of neutrino oscillations, which shows that neutrinos have mass." Ironically, self-induced flavor conversion does not always depend on neutrino masses, although this connection exists, of course, in the context of vacuum oscillations and standard MSW conversion.

[2] One may speculate that initial disturbances could be provided even by quantum fluctuations of our classical mean-field quantities. However, since neutrinos are known to mix and to have small masses, in practice ordinary neutrino flavor oscillations are guaranteed to provide disturbances even on the mean-field level.