

# Collective neutrino-flavor oscillations and application to supernova nucleosynthesis

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There are still poorly known non-linear effects caused by coherent scatterings of self-interacting neutrinos emitted from the proto-neutron star in core-collapse supernovae. One of these effects manifests itself in flavor space as collective neutrino-flavor oscillation, which results in a dramatic change in energy spectra of neutrinos. This could affect the explosive nucleosynthesis such as r-process and  $\nu$ - and rp-processes in neutron-rich and proton-rich environments, respectively. We study the neutrino flavor change due to collective oscillations in the 3 flavor and multi-angle calculations and estimate the electron mole fraction  $Y_e$  that is relevant for explosive nucleosynthesis. The results are compared with those calculated by assuming a single-angle approximation which ignores the angular dependence in density matrices of neutrinos. We then find that in multi-angle case, the onset of the collective oscillation delays compared with single-angle case and that the oscillation effects in  $Y_e$  evolution are negligible. These results of numerical simulation suggest that the single-angle approximation is not necessarily a good approximation and that one has to carry out multi-angle calculations in order to obtain numerically reliable and physically realistic result of collective neutrino-flavor oscillations.

**KEYWORDS:** neutrino oscillations, supernovae, nucleosynthesis

## 1. Introduction

Neutrino flavor oscillations are expected to play an important role in several astrophysical sites such as the early universe, the core-collapse supernovae, and the neutron star mergers. Among them, the flavor oscillations of energetic neutrinos emitted from core-collapse supernovae are of particular interest because these could affect the explosive nucleosynthesis such as r-process or the neutrino-process of several specific isotopes like  ${}^7\text{Li}$ ,  ${}^{11}\text{B}$ ,  ${}^{92}\text{Nb}$ ,  ${}^{138}\text{La}$  and  ${}^{180}\text{Ta}$ .

In core-collapse supernovae, after bounce, enormous intensity of energetic neutrinos are emitted from the proto-neutron star, and around 100 km from the center, there are non-linear effects caused by coherent scatterings of self-interacting neutrinos [1], and all species of neutrinos oscillate coherently independent of their momenta. These phenomena are called collective oscillations [2]. Collective oscillations occur at the inner most core and energy spectra of electron type neutrinos change dramatically [2]. Electron fraction  $Y_e$  is also affected by these effects, so it seems that these non-linear effects will play the significant roles in supernova nucleosynthesis.