Fast neutrino-flavor conversion inducing flavor swap

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Abstract

Neutrino transports play important roles in the dynamics of core-collapse supernovae (CCSNe) and binary neutron-star mergers (BNSMs). On the other hand, collective neutrino oscillation from quantum kinetics dramatically changes the neutrino radiation fields. In this poster, we discuss the occurrence of flavor swap, i.e., complete interchange between different flavors, in BNSMs.

1. Collective Neutrino Oscillation

Quantum Kinetics + Neutrino transport (= beyond Boltzmann)

$$\underbrace{(\partial_t + \boldsymbol{v}\cdot\nabla)\,\rho}_{\text{Advection}} = \underbrace{-\mathrm{i}\,[\mathcal{H}_{\nu\nu}, \rho]}_{\text{Oscillation}} + \underbrace{\mathcal{S}_{\rm col}}_{\text{Collisions (neglected)}}$$

$$\rho = \begin{pmatrix} f_{ee} & f_{e\mu} & f_{e\tau} \\ f_{\mu e} & f_{\mu\mu} & f_{\mu\tau} \\ f_{\tau e} & f_{\tau\mu} & f_{\tau\tau} \end{pmatrix}$$

Density matrix (not occupation dist. $f_{\alpha\alpha}$)

$$\mathcal{H}_{\nu\nu} = \sqrt{2}G_{\rm F}\int \frac{\mathrm{d}^3q'}{(2\pi)^3}(1-\boldsymbol{p}\cdot\boldsymbol{q}')\,[\rho(q') - \bar{\rho}^*(q')]$$

Neutrino self-interaction term

Changes the neutrino radiation field.

Fast neutrino-flavor conversion (FFC) :
Zero-crossing in the ELN-XLN angular distributions triggers flavor instability, inducing flavor conversion ($\nu_e\bar{\nu}_e \leftrightarrow \nu_X\bar{\nu}_X$).

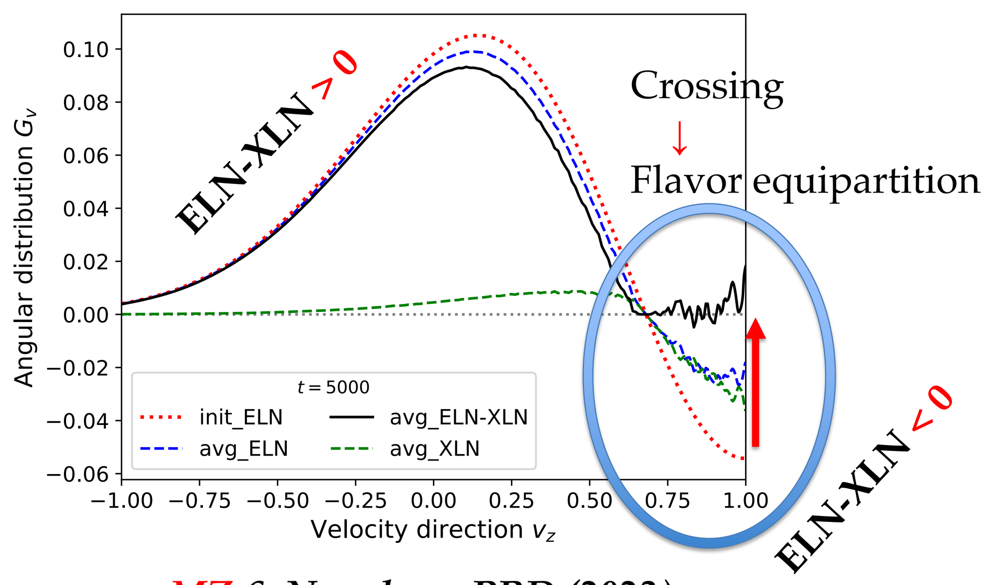
$$G_v = \int \frac{E_\nu^2 \mathrm{d}E_\nu}{2\pi^2}\,[(f_{\nu_e} - f_{\bar{\nu}_e}) - (f_{\nu_X} - f_{\bar{\nu}_X})]$$

ELN (electron neutrino-lepton number)

Left: Numerical results mimicking neutrino distributions in CCSNe.

Red dotted：Initial
Black one：Final

FFC proceeds to eliminate a crossing, i.e., ELN = XLN.
= Establish a stability.

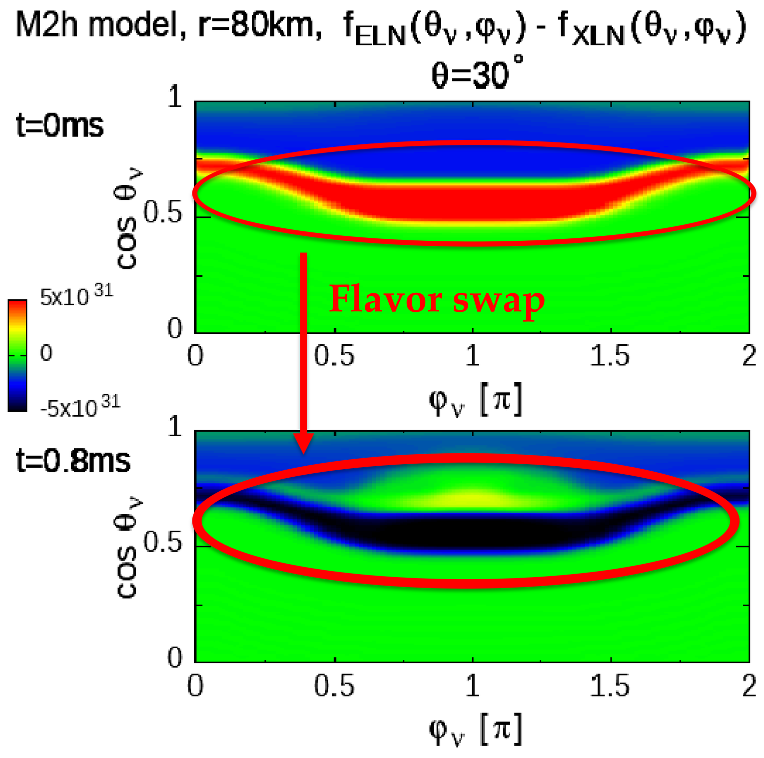


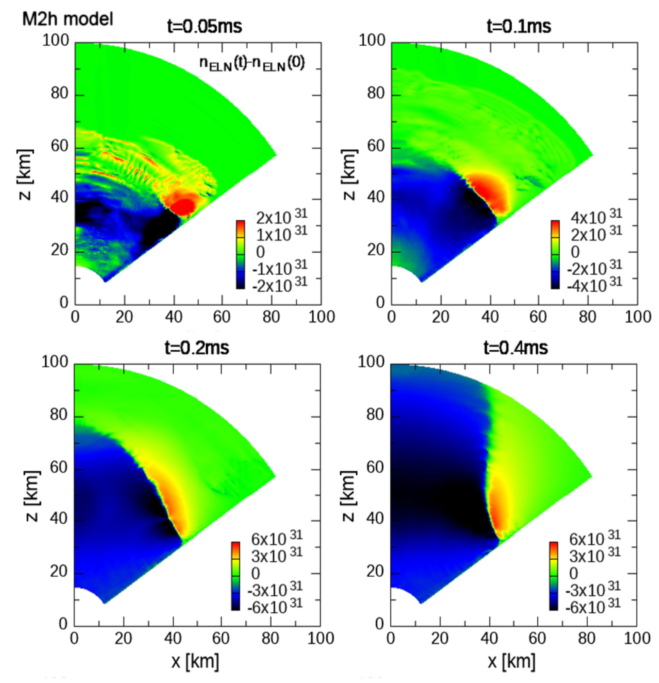
MZ & Nagakura PRD (2023)

2. Motivation & Method

2-D numerical results mimicking BNSMs.
→ Observe a flavor swap (ELN ⇄ XLN)
+ Dynamics of transition layer (EXZS) to swap.

Nagakura PRD (2023)

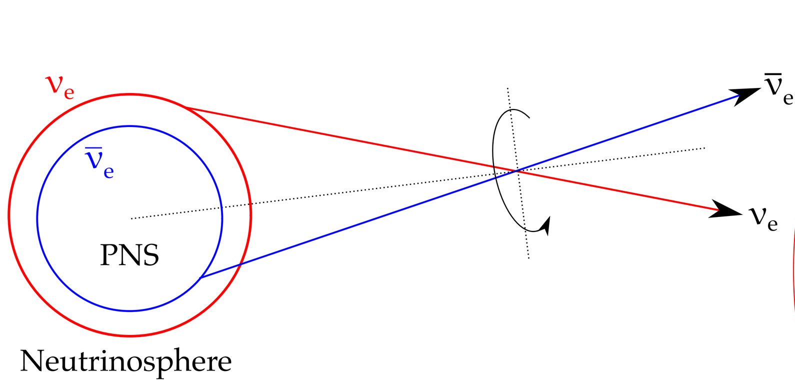


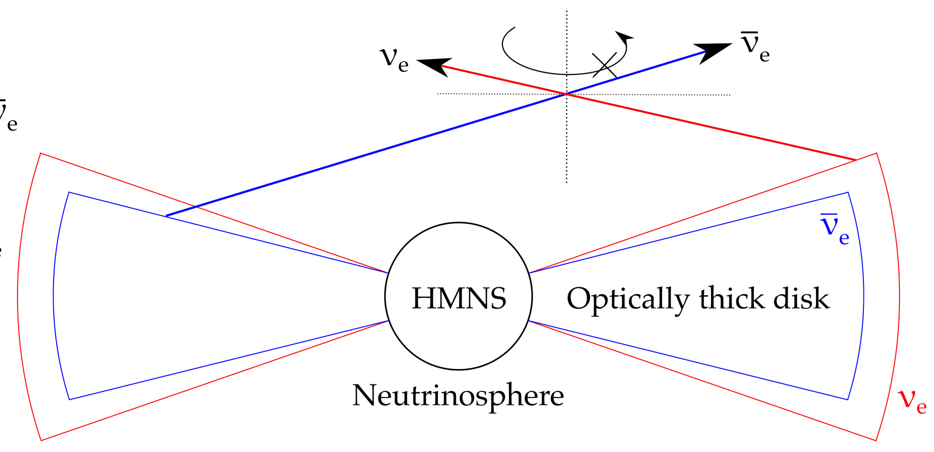


FFC proceeds to swap, not stopping at a flavor equilibrium.
Difference between BNSM and CCSN in distribution structure is critical.
Angular crossings associated with head-on collisions can emerge in BNSMs due to non-axial symmetry in momentum space.
→ "**Colliding neutrino-beam model**"

ν_e → ← $\bar{\nu}_e$

Neutrino beams (ν_e and $\bar{\nu}_e$) emitted at opposite boundaries collide each other.





3. Results for colliding neutrino-beam model

Fig. 1.

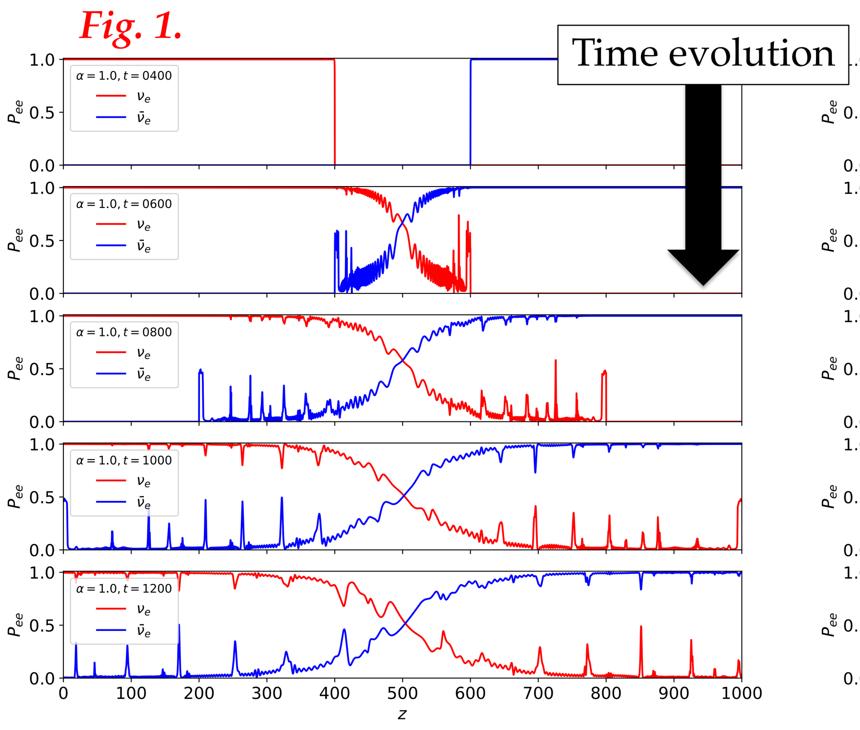
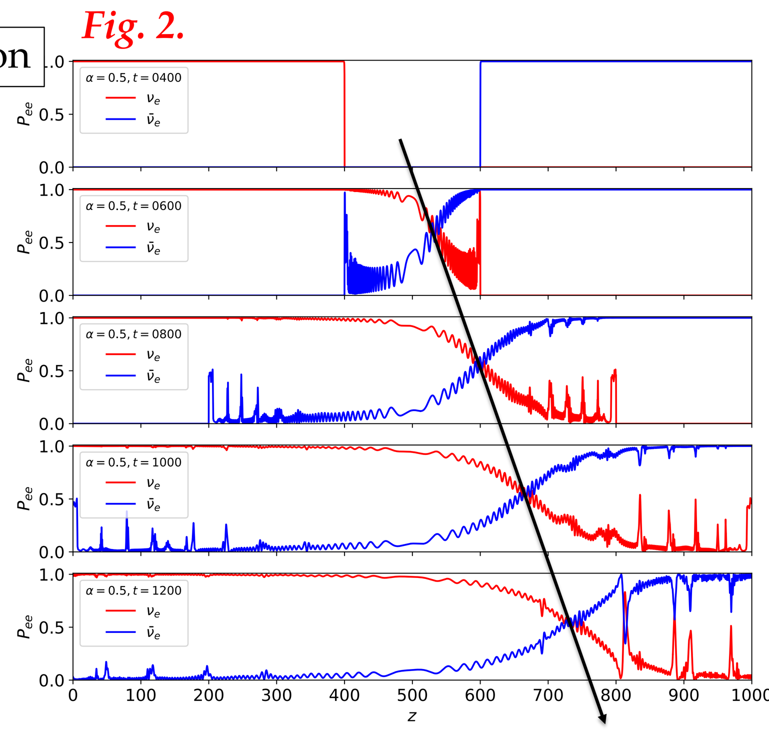


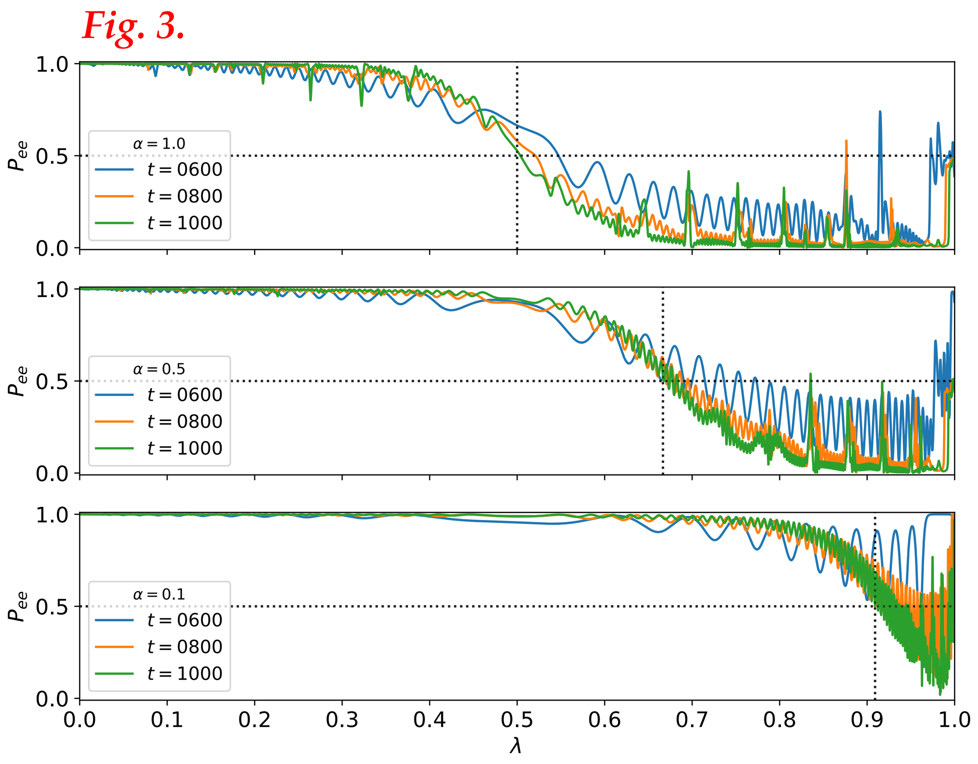
Fig. 2.



Vertical：Survival prob. of ν_e
$P_{ee} = 0$ corresponds to swap
1/2 to equipartition.
Horizontal：Spatial coordinate
Scaled by self-interaction O(cm)
Fig.1：α=1　(symmetry in ν_e and $\bar{\nu}_e$)
Fig.2：α=0.5 ($\bar{\nu}_e$ is a half of ν_e)

Fig.3：Scaled by the width between heads of neutrino beams (λ-space).
From top to bottom, α = 1, 0.5, and 0.1

Fig. 3.



1. FFC develops at the center of the spatial domain (z~500) when both beams collide and lead to fast flavor instability.
   - Flavor conversions do not stop at equilibrium state (P_{ee} ~ 0.5), but rather, achieve flavor swap (P_{ee} ~ 0).
   - This is because fresh $\bar{\nu}_e$ continues to be **supplied** from the opposite boundary.
2. In the case with $\alpha \neq 1$, the transition layer is no longer stationary but moves toward the positive z-direction with time.
   - To satisfy pair-wise flavor conversion $\nu_e\bar{\nu}_e \leftrightarrow \nu_X\bar{\nu}_X$.
3. Transition layer is time-independent in the λ-coordinate, which normalizes the z-axis by the width between the head of beams.
   - The geometry $\lambda = 1/(1+\alpha)$ and velocity $v = c(1-\alpha)/(1+\alpha)$ of transition layer are determined to satisfy the conservation of the total ν_e and $\bar{\nu}_e$ passing through (undergoing swap).

4. Summary

Neutrinos are intensively emitted from BNSMs, but the flavor population dramatically changes due to collective neutrino oscillation induced by their self-interactions. Particularly, FFC can achieve complete flavor swap unlike the case of CCSNe. This phenomenon is the most extreme case of flavor conversion and suggests that it would affect a significant change in the electron fraction of ejecta and subsequently r-process nucleosynthesis and kilonova because the population of electron-type neutrinos are significantly modified.