Investigating fast flavor swap of neutrinos

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Introduction

Collective neutrino oscillation, such as the fast flavor conversions (FFC), can dramatically change the neutrino radiation fields.[1]

In this study, we investigate a special collective behavior "Fast Flavor Swap" (FFS), i.e., the complete interchange between different neutrino flavors[2], based on a colliding neutrino beam model, using the numerical simulation code COSEν[3].

This FFS may play an important role in CCSNe and BNSMs.

Collective Oscillation - FFC

$$G_\nu(v_z) \equiv \frac{1}{n_{\nu_e}} \int \frac{E^2 \mathrm{d}E}{(2\pi)^2} \left[(f_{\nu_e} - \alpha\, f_{\bar{\nu}_e}) \right]$$

Electron neutrino-lepton number (ELN) angular distribution

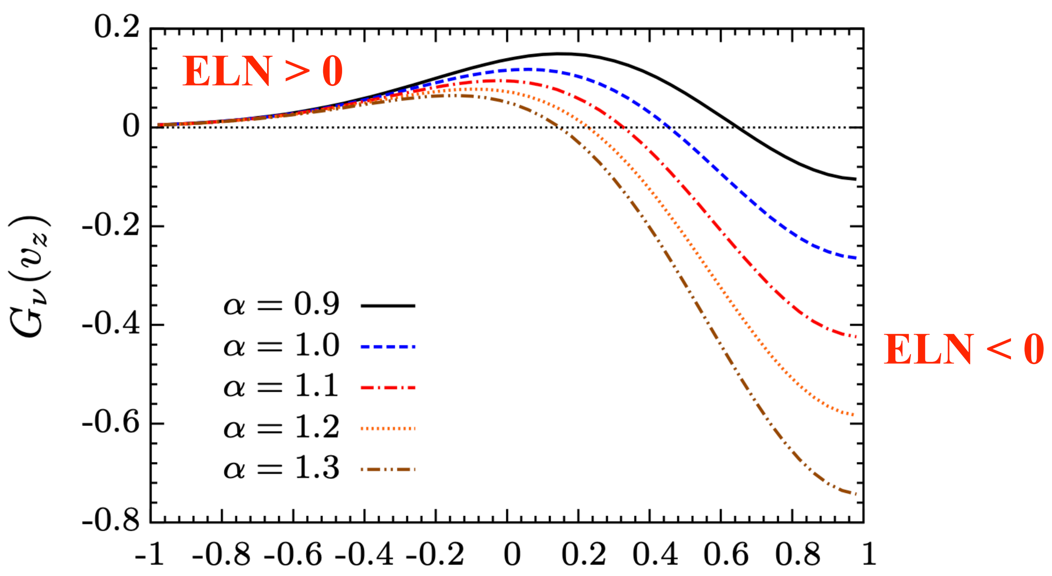
G_v has "zero-crossing"

↓

fast flavor instability (FFI)

↓

FFC happen
(Even FFS happen)
($\nu_e \bar{\nu}_e \leftrightarrow \nu_x \bar{\nu}_x$)



(Asymmetry parameter $\boldsymbol{\alpha} = \dfrac{n_{\bar{\nu}_e}}{n_{\nu_e}}$: the ration of number density)

Quantum Kinetic Equation

$$\underbrace{(\partial_t + v_z \partial_z)}_{\text{advection}} \rho(t,z,v_z) = \underbrace{-\mathrm{i}\,[H_{\nu\nu}}_{\text{Neutrino Oscillation}}, \rho(t,z,v_z)]$$

$$\varrho = \begin{bmatrix} \varrho_{ee} & \varrho_{ex} \\ \varrho_{ex}^* & \varrho_{xx} \end{bmatrix}$$

Density Matrix
(two flavor neutrino system)

$$H_{\nu\nu} = \mu \int_{-1}^{+1} \mathrm{d}v_z' (1 - v_z v_z') G_{v_z'} \rho_{v_z'}$$

Neutrino self-interaction term

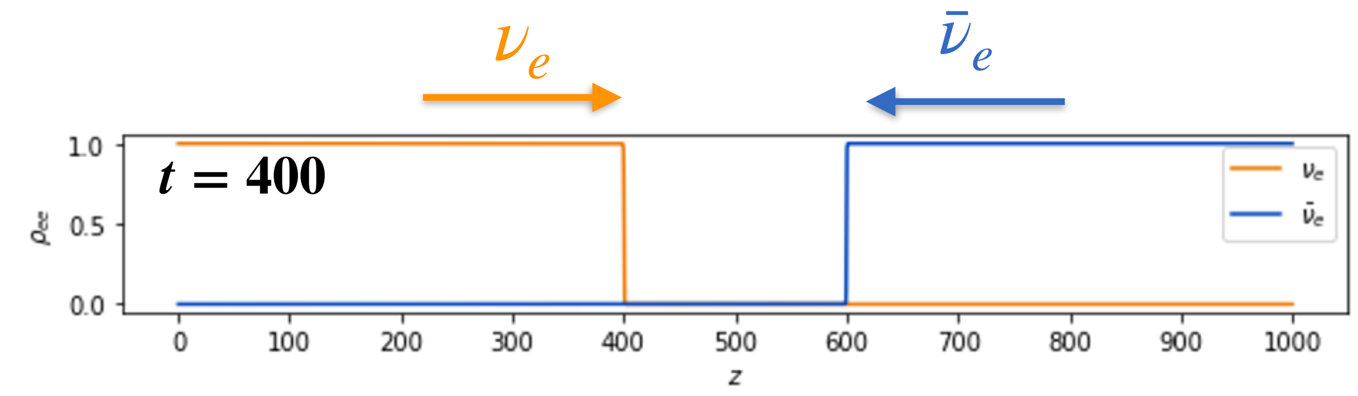
$$\mu = \sqrt{2} G_\mathrm{F} n_{\nu_e}$$

Effective strength of $H_{\nu\nu}$

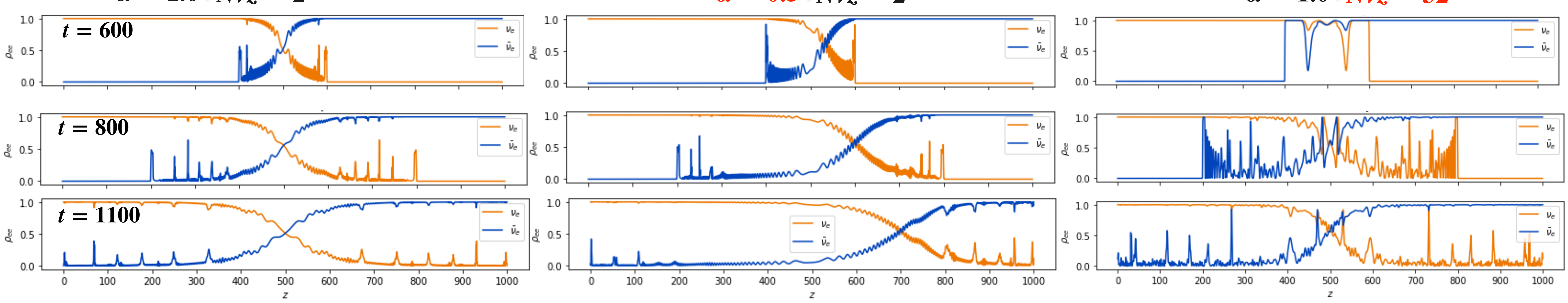
Model

In some specific geometry structure of stars, neutrino of different flavors travel in **nearly opposite directions** may happen.
In our toy-model, neutrino beams are **emitted at opposite boundaries**, and **pass each other**!

→ **Colliding neutrino-beam model**



Time evolution of ν_e & $\bar{\nu}_e$ density



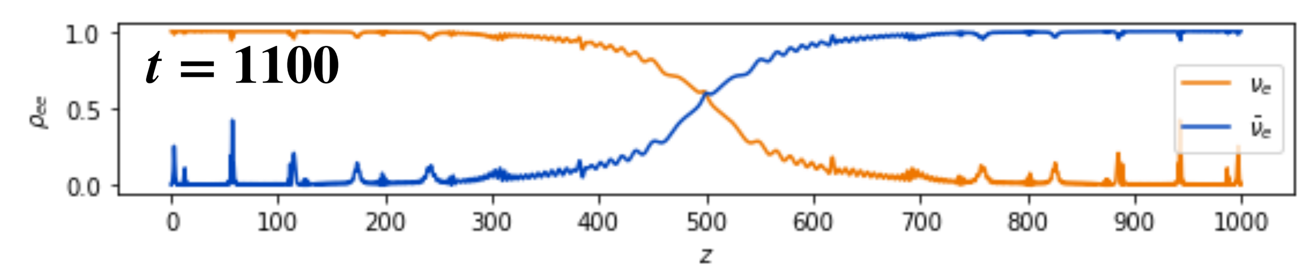
(we define $\mu \equiv 1$, then express t & z in the unit of μ^{-1})

Results: from FFC to FFS

- **FFC proceeds to flavor swap ($\rho_{ee} \sim 0$), not stopping at a flavor equilibrium state**
- **When $\alpha = 1$ (symmetric case), FFC develops at the center of the spatial domain ($z \sim 500$)**
- **When $\alpha \neq 1$, the transition layer is no longer stationary**
- **For the multiple beam case, the onset time delayed**
- **Future work:** consider only right-going baems with time-dependent α, to see if FFS will happen!

Triggered by "vacuum term"

- In previous results, we adopted **artificial perturbation**
- **In realistic system,** collective oscillation is triggered by **vacuum oscillation**
- **Choose mixing angle $\theta \sim 10^{-6}$**



FFS still happen!!!

Reference

[1]Xiong, Zewei, et al. Fast neutrino flavor conversions in a supernova: Emergence, evolution, and effects. *Physical Review D*, 2024, 109.12: 123008.
[2] Zaizen, M., & Nagakura, H. (2024). Fast neutrino-flavor swap in high-energy astrophysical environments. *Physical Review D*, *109*(8), 083031.
[3] George, Manu, et al. "COSEv: A collective oscillation simulation engine for neutrinos." *Computer Physics Communications* 283 (2023): 108588.

full Simulation Animations

https://jameswu1007.github.io/SSP2024_animations/