Matter–Neutrino Resonance in Binary Neutron Star Merger Outflows

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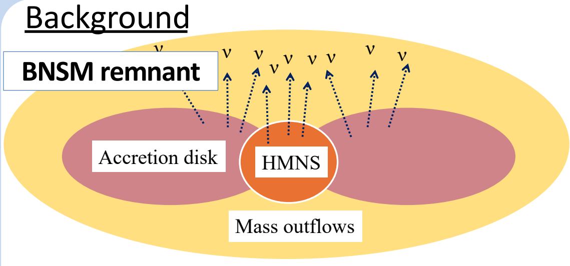
Abstract

Binary neutron star merger outflows contain intense neutrino fluxes that regulate the electron fraction and can affect r-process nucleosynthesis and kilonova emission. In antineutrino-dominated regions, cancellation between the matter and neutrino self-interaction potentials can trigger matter–neutrino resonance (MNR). We study multi-angle MNR in a stationary two-flavor spherical-bulb model and compare matter profiles with, $\lambda \propto r^{-3}$ and $\lambda \propto r^{-5}$, to study how the density gradient affects the resonance evolution. The $\lambda \propto r^{-3}$ profile produces substantial, angle-dependent flavor conversion, whereas the $\lambda \propto r^{-5}$ profile, gives much weaker conversion. Comparison with an MSW-like no-backreaction evolution shows that self-consistent flavor feedback is essential, supporting MNR as a nonlinear adiabatic conversion mechanism.

Background



$\bar{\nu}_e + p \leftrightarrow e^+ + n$ $\qquad$ $\nu_e + n \leftrightarrow e^- + p$

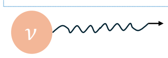
Modify the electron fraction Y_e

Affect **r-process nucleosynthesis** and **kilonova** emission.

Neutrino flavor can change during propagation. The evolution is governed by the Quantum kinetic equation:

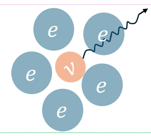
$$(\partial_t + \mathbf{v}\cdot\nabla)\rho = -i[H,\rho]$$

Vacuum Oscillation — Flavor mixing due to neutrino masses.



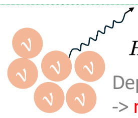
$$H_{\rm vac} = U\frac{M^2}{2E_\nu}U^\dagger$$

Matter effect (MSW) — Coherent scattering with electrons.



$$H_{\rm mat} = \sqrt{2}G_F \mathrm{diag}(n_l - \bar{n}_l)$$

Collective Oscillation — Neutrino-neutrino forward scattering.



$$H_{\nu\nu} = \mu\int d\mathbf{v}'(\rho' - \bar{\rho}')(1-\mathbf{v}\cdot\mathbf{v}')$$

Depends on the neutrino flavor states -> nonlinear feedback.

$\Big\} H$

Hot, neutron-rich BNSM remnants can generate an antineutrino-dominated neutrino field through:

$$n + e^+ \to p + \bar{\nu}_e \;\Rightarrow\; n_{\bar{\nu}_e} > n_{\nu_e}$$

$$H_{\nu\nu} = \mu\int d\mathbf{v}'(\rho' - \bar{\rho}')(1-\mathbf{v}\cdot\mathbf{v}') < 0$$

The self-interaction potential can oppose the positive matter potential.

If $\quad H_{{\rm mat},ee} \sim |H_{\nu\nu,ee} - H_{\nu\nu,xx}|$

then $\quad |H_{ex}| \gg |H_{ee} - H_{xx}|$

The remaining off-diagonal mixing can then drive large flavor conversion.

⇨ Flavor conversion↑

Matter-neutrino resonance

Motivation

- Single-angle MNR is relatively well studied, whereas multi-angle calculations show qualitatively different, angle-dependent flavor evolution.
- The physical origin of these multi-angle features remains unclear. We aim to clarify how **angular trajectories, the matter-density profile, and nonlinear flavor feedback** control MNR evolution.

Methods

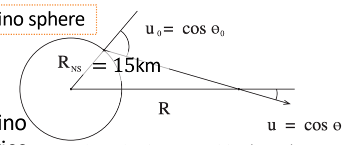
Steady state:

$$u\frac{d\rho(r,u)}{dr} = -i[H(r,u),\rho(r,u)]$$

$$u\frac{d\bar{\rho}(r,u)}{dr} = -i[\bar{H}(r,u),\bar{\rho}(r,u)]$$

ν_e and ν_e are emitted from a neutrino sphere along different angular trajectories. We assume collisionless, two-flavor, and single-energy neutrino transport, and solve the full nonlinear quantum kinetic equation.

Spherical bulb model:



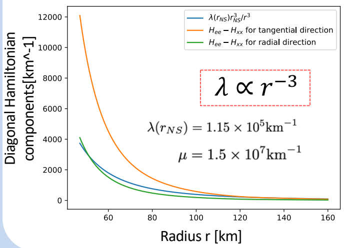
Vlasenko & McLaughlin (2018)

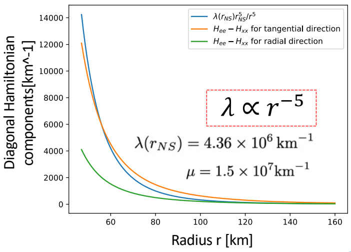
Geometrical factor:

$$u(r,u_0) = \sqrt{1 - \frac{r_{NS}^2}{r^2}(1-u_0^2)} \qquad u_0 \in [0,1]$$

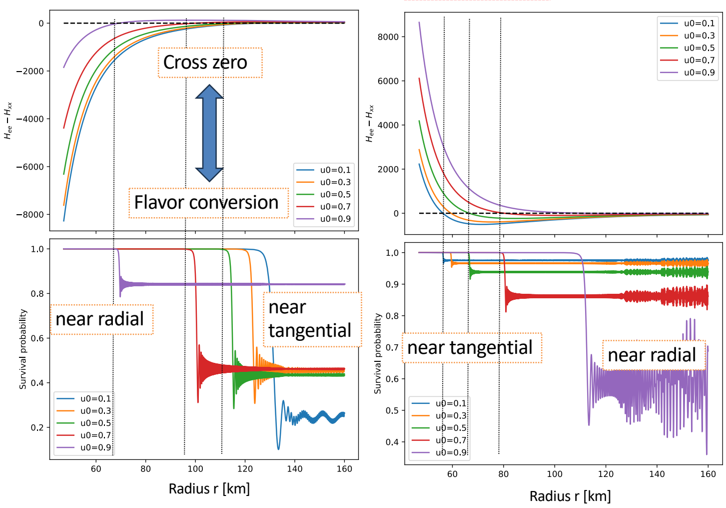
To examine the effect of the matter-density gradient, we compare two profiles for the matter term.

$$\lambda = \lambda(r_{NS})\frac{r_{NS}^n}{r^n}$$





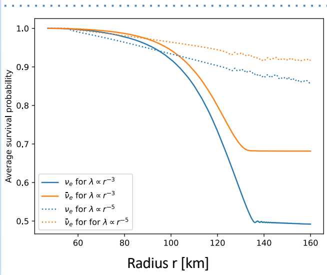
Results



Flavor conversion begins near each mode's zero crossing. **Different angular modes resonate at different radii and reach different final flavor contents.**

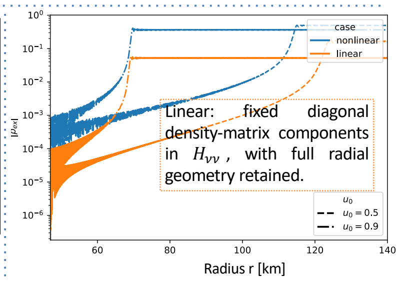
Their ordering reverses between the two matter profiles: near-radial modes cross zero and convert first for $\lambda \propto r^{-3}$, whereas near-tangential modes cross first for $\lambda \propto r^{-5}$.

The matter-profile gradient affects the conversion: For $\lambda \propto r^{-5}$, most angular modes undergo only weak conversion.



ν_e and ν_e saturate at different points.

Flavor conversion for $\lambda \propto r^{-5}$ case is much weaker.



The linear case follows the same qualitative trend, supporting an MSW-like adiabatic picture, while the deviations reflect nonlinear flavor feedback.

Summary

- Matter–neutrino potential cancellation drive large flavor conversion.
- Different angular modes resonate at different radii and reach different final flavor contents.
- Comparison with a no-backreaction MSW-like evolution indicates that MNR is a nonlinear adiabatic process.

Future work

We will examine the possible role of flavor instability and seek a predictive description of the angle-dependent saturation mechanism.