Neutrino flavor conversions in binary neutron star mergers: helicity coherence

Amélie Chatelain
Laboratoire AstroParticule et Cosmologie, Paris Diderot
"Helicity coherence in binary neutron star mergers and nonlinear feedback"

July 2017
1. Introduction

2. Helicity coherence in binary neutron star mergers

3. Conclusions
Introduction

Neutrino flavor conversions in astrophysical environments

Open questions remain, eg

- Mass hierarchy
- Absolute mass scale
- Majorana or Dirac nature

Conversions in dense astrophysical environments (SNe, compact binary objects, ...) involve $\nu$ self-interaction, more complex phenomena.
Neutrino flavor conversions: formalism

- **2 effective neutrino flavors** \((\nu_e, \nu_x)\)
- **Density matrix formalism in the mean field approximation**

\[
\rho(r) = \begin{pmatrix}
|\nu_e|^2 & \nu_e \nu_x^* \\
\nu_e^* \nu_x & |\nu_x|^2
\end{pmatrix} = \left( P_{\nu_e \rightarrow \nu_e}(r) \times P_{\nu_e \rightarrow \nu_x}(r) \right) \rightarrow \dot{\rho}_i = [H, \rho] \\
\dot{\bar{\rho}} = [\bar{H}, \bar{\rho}]
\]

\[
H = H_{\text{vac}} + H_{\text{mat}} + H_{\text{self}}
\]

\[
\bar{H} = -H_{\text{vac}} + H_{\text{mat}} + H_{\text{self}}
\]

Vacuum

\(|\nu_\alpha\rangle = U |\nu_k\rangle\)

Matter

\(\nu \quad \text{Self-interaction}\)

\(\nu_{\beta} \quad \nu_{\beta}\)

\(Z^0 \quad \nu_{\alpha} \quad \nu_{\alpha}\)
Binary Neutron Star mergers: the astrophysical context

Still little studied.

Neutrino driven winds: candidates for r-process nucleosynthesis.

Gravitational waves detection could bring more information.

$\nu_e + n \rightarrow p + e^- \quad \bar{\nu}_e + p \rightarrow n + e^+$

Set $Y_e = \frac{p}{n+p}$.

→ What about neutrino flavor conversions?
Flavor conversions in BNS: Matter Neutrino Resonance

- $L\bar{\nu}_e > L\nu_e$: possible MSW-like cancellation between matter term and $\nu$ self interaction term $\rightarrow$ Matter Neutrino Resonance.

$\nu_e$ flux at 100km vs initial flux

Could relaxing some hypothesis change these behaviors?

Figure: [Malkus, McLaughlin, Surman, PRD93, 2015]
1 Introduction

2 Helicity coherence in binary neutron star mergers

3 Conclusions
Beyond the mean field approximation: helicity coherence

\[ i\dot{\rho} = [H, \rho] \quad \quad i\dot{\bar{\rho}} = [\bar{H}, \bar{\rho}] \]

- Most general equations in the mean field approximation: first order corrections to the relativistic limit $\propto m \rightarrow$ Helicity Coherence, coupling $\nu_L \leftrightarrow \nu_R$ (Dirac) or $\nu \leftrightarrow \bar{\nu}$ (Majorana). [Volpe, Vaananen, Espinoza, PRD87, 2013] [Vlasenko, Cirigliano, Fuller, PRD89, 2014] [Serreau, Volpe, PRD90, 2014]

- First study of this term [Vlasenko, Fuller, Cirigliano, 1406.6724]: toy model with one Majorana $\nu$ flavor $\rightarrow$ significant conversions $\nu \leftrightarrow \bar{\nu}$, sustained by nonlinear feedback.

→ Can these corrections produce some effects in a more realistic scenario?
Helicity coherence in binary neutron star mergers

Extended mean field evolution equations [Serreau, Volpe, PRD90, 2014]

- Consider Majorana neutrinos, 2 flavors.

  \[ \dot{\rho} = [H, \rho] \quad \dot{\bar{\rho}} = [\bar{H}, \bar{\rho}] \]

- Generalized matrices \(2 \times 2 \rightarrow 4 \times 4\).

  \[ \rho \rightarrow \rho_G = \begin{bmatrix} \rho & \zeta \\ \zeta^\dagger & \bar{\rho}^T \end{bmatrix} \]

  - \(\rho (\bar{\rho})\) : density matrices for \(\nu (\bar{\nu})\);
  - \(\zeta\) : coupling \(\nu-\bar{\nu}\) sectors.

  \[ H \rightarrow h_G = \begin{bmatrix} H & \Phi \\ \Phi^\dagger & -\bar{H}^T \end{bmatrix} \]

  - \(H (\bar{H})\) : Hamiltonian for \(\nu (\bar{\nu})\);
  - \(\Phi\) : **helicity coherence** coupling \(\nu-\bar{\nu}\) sectors, \(\propto \frac{m}{E} \approx 10^{-7} - 10^{-8}\).
Our model: Binary Neutron Star mergers

[Chatelain, Volpe, PRD95, 2017]

100ms profile

Flavor conversions in BNS without helicity coherence: Matter Neutrino Resonance

**MSW effect**: equality of two diagonal elements $H_{11} - H_{22} \approx 0$.

$$H = \begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix}$$

**Nonlinear feedback**: adiabaticity enhanced because of non-linearity from neutrino self-interactions.
Helicity coherence in binary neutron star mergers

Helicity Coherence: numerical results

- $\frac{m}{E} \approx 10^{-8} \rightarrow$ Look for MSW-like resonance conditions that could enhance $\nu_e \leftrightarrow \bar{\nu}_e$ conversions.

$$h_G = \begin{bmatrix} \Phi & H \\ \Phi^\dagger & -\bar{H}^T \end{bmatrix}$$

- We find no nonlinear feedback: extremely narrow resonance.
- Artificially taking $m = 100$ eV: no difference.
Run around the resonance: no conversions, contrary to what was found in first study of this term with toy model in one flavor [Vlasenko, Fuller, Cirigliano, 2014] with $m = 1$ eV.
Why does nonlinear feedback occur?

How we analyzed it:

- Nonlinear feedback ↔ matching between matter and neutrino self-interaction derivatives.
- First order perturbation analysis of the resonance conditions.

**Matter Neutrino Resonance**

**Helicity Coherence**

- Yo-yo effect between geometry and flavor conversions.
- Multiple MSW-like resonances.
- No yo-yo effect.
- Matching possible only for very peculiar matter profiles.
Multiple MSW-like resonances conditions

- Explains how the nonlinear feedback mechanism, that enhances adiabaticity, can be set up.
- One flavor toy model [Vlasenko, Fuller, Cirigliano, 2014] : matter profile artificially smooth to enable the matching and the nonlinear feedback.

**No effects in binary neutron star mergers or in SNe. True for Dirac neutrinos.**
Table of contents

1 Introduction

2 Helicity coherence in binary neutron star mergers

3 Conclusions
• **Helicity coherence**: no effects appear due to non-relativistic corrections in a detailed astrophysical environment.
  - Answered debated question about corrections beyond usual description in the mean-field approximation.
  - Deeper insight on nonlinear feedback mechanism and matter neutrino resonance.

• **Neutrino flavor conversions in BNS mergers**: lots of on-going investigations (eg, nonstandard interactions [Chatelain, Volpe, arXiv:2017:xxxx], ...)

Thank you!
Conclusions

Conclusions and perspectives

- **Helicity coherence**: no effects appear due to non-relativistic corrections in a detailed astrophysical environment.
  - Answered debated question about corrections beyond usual description in the mean-field approximation.
  - Deeper insight on nonlinear feedback mechanism and matter neutrino resonance.

- **Neutrino flavor conversions in BNS mergers**: lots of on-going investigations (eg, nonstandard interactions [Chatelain, Volpe, arXiv:2017:xxxx], ...)

Thank you!
Backup slides
Scattering surfaces for 4.62, 10.63, 16.22, 24.65, 56.96 MeV.
Uncertainties

\[
\frac{L_{\bar{\nu}_e}}{\langle E_{\bar{\nu}_e} \rangle} / \left( \frac{L_{\nu_e}}{\langle E_{\nu_e} \rangle} \right)
\]

---

Perego et al. (2014) [Newt., TM1, adv. spectral leak.]
Ruffert et al. (1997) [Newt., LS, gray leak.]
Dessart et al. (2009) [Newt., MGFLD, HMNS+disk, Shen]
Rosswog et al. (2013) [Newt., Shen, gray leak.]
Foucart et al. (2015) [GR, LS220, gray GR leak.]
Foucart et al. (2015) [GR, DD2, gray GR leak.]
Foucart et al. (2015) [GR, SFHo, gray GR leak.]
Foucart et al. (2015) [GR, LS220, gray GR M1]