Neutrino flavor conversions in binary neutron star mergers : helicity coherence

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"Helicity coherence in binary neutron star mergers and nonlinear feedback"
A. Chatelain, C. Volpe, Phys.Rev.D95 (2017)

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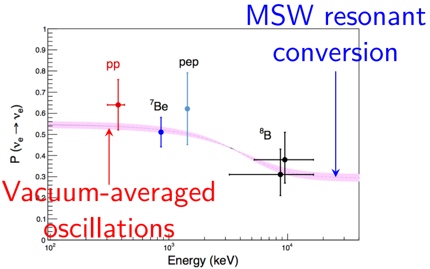
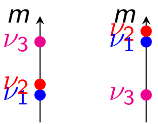
Neutrino flavor conversions in astrophysical environments



[Borexino collaboration, Nature 512, 2014]

Open questions remain, eg

- Mass hierarchy



- Absolute mass scale
- Majorana or Dirac nature

Conversions in dense astrophysical environments (SNe, compact binary objects, ...) involve ν self-interaction, more complex phenomena.

Neutrino flavor conversions : formalism

- 2 effective neutrino flavors (ν_e, ν_x)
- Density matrix formalism in the mean field approximation

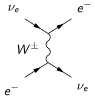
$$\rho(r) = \begin{pmatrix} |\nu_e|^2 & \nu_e \nu_x^* \\ \nu_e^* \nu_x & |\nu_x|^2 \end{pmatrix} = \begin{pmatrix} \mathcal{P}_{\nu_e \to \nu_e}(r) & \times \\ \times & \mathcal{P}_{\nu_e \to \nu_x}(r) \end{pmatrix} \to \begin{matrix} i\dot{\rho} = [H, \rho] \\ i\dot{\bar{\rho}} = [\bar{H}, \bar{\rho}] \end{matrix}$$

$$H = H_{\text{vac}} + H_{\text{mat}} + H_{\text{self}}$$

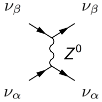
$$\bar{H} = -H_{\text{vac}} + H_{\text{mat}} + H_{\text{self}}$$

Vacuum: $|\nu_\alpha\rangle = U |\nu_k\rangle$

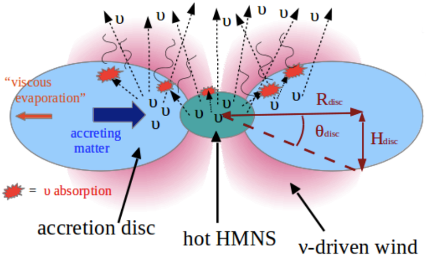
Matter



ν **Self-interaction**



Binary Neutron Star mergers : the astrophysical context



[Perego et al., Mon.Not.Roy.Astron.Soc. 443, 2014]

- Still little studied.
- Neutrino driven winds : candidates for r-process nucleosynthesis.
- Gravitational waves detection could bring more information.

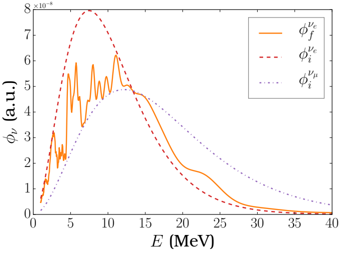
$$\left.\begin{array}{l}\nu_e + n \to p + e^- \\ \bar{\nu}_e + p \to n + e^+\end{array}\right\} \text{ Set } Y_e = \frac{p}{n+p}.$$

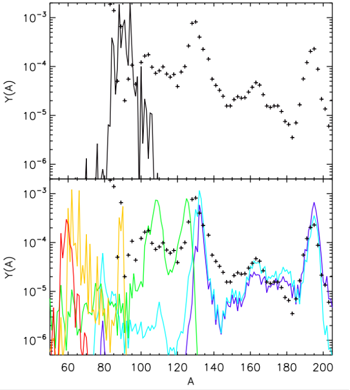
→ What about neutrino flavor conversions ?

Flavor conversions in BNS : Matter Neutrino Resonance

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

ν_e flux at 100km vs initial flux





Could relaxing some hypothesis change these behaviors ?

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

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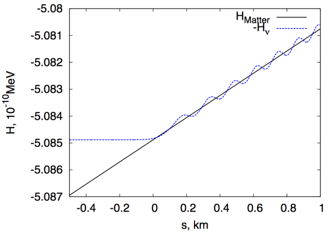
Beyond the mean field approximation : helicity coherence

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

- 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 ν flavor $\rightarrow$ significant conversions $\nu \leftrightarrow \bar{\nu}$, sustained by nonlinear feedback.

$\rightarrow$ **Can these corrections produce some effects in a more realistic scenario ?**



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

- Consider Majorana neutrinos, 2 flavors.

$$\left.\begin{array}{l} i\dot{\rho} = [H, \rho] \\ i\dot{\bar{\rho}} = [\bar{H}, \bar{\rho}] \end{array}\right\} \quad i\dot{\rho}_{\mathcal{G}} = [h_{\mathcal{G}}, \rho_{\mathcal{G}}]$$

- Generalized matrices $2 \times 2 \rightarrow 4 \times 4$.

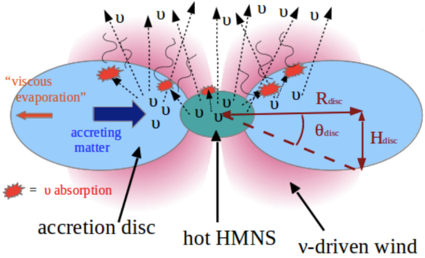
$$\rho \longrightarrow \rho_{\mathcal{G}} = \left[\begin{array}{c|c} \rho & \zeta \\ \hline \zeta^\dagger & \bar{\rho}^T \end{array}\right]$$

$$H \longrightarrow h_{\mathcal{G}} = \left[\begin{array}{c|c} H & \Phi \\ \hline \Phi^\dagger & -\bar{H}^T \end{array}\right]$$

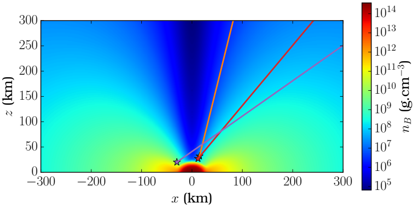
- ρ ($\bar{\rho}$) : density matrices for ν ($\bar{\nu}$);
- ζ : coupling ν-$\bar{\nu}$ sectors.
- H ($\bar{H}$) : Hamiltonian for ν ($\bar{\nu}$) ;
- Φ : **helicity coherence** coupling ν-$\bar{\nu}$ sectors, $\propto \frac{m}{E} \approx 10^{-7} - 10^{-8}$.

Our model : Binary Neutron Star mergers

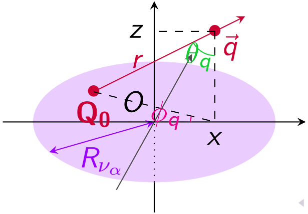
[Chatelain, Volpe, PRD95, 2017]



100ms profile



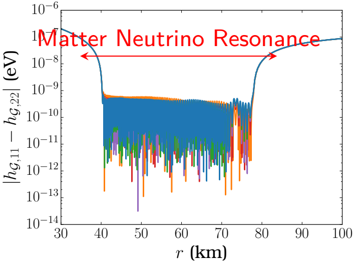
[Perego et al., Mon.Not.Roy.Astron.Soc. 443, 2014]



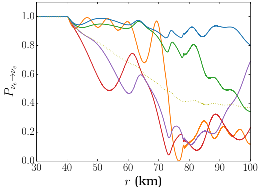
Flavor conversions in BNS without helicity coherence : Matter Neutrino Resonance

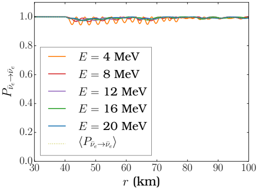
MSW effect : equality of two diagonal elements $H_{11} - H_{22} \approx 0$.

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



Nonlinear feedback : adiabaticity enhanced because of non-linearity from neutrino self-interactions.

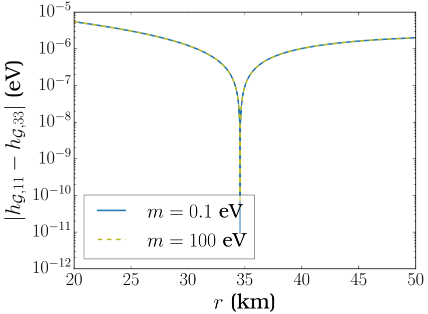




Helicity Coherence : numerical results

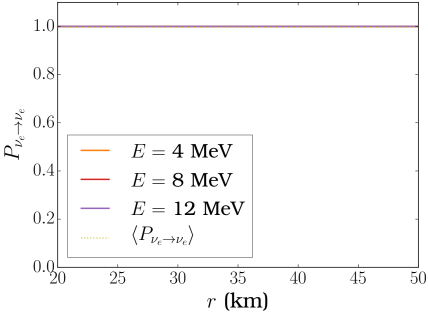
- $\frac{m}{E} \approx 10^{-8} \rightarrow$ Look for MSW-like resonance conditions that could enhance $\nu_e \leftrightarrow \bar{\nu}_e$ conversions.

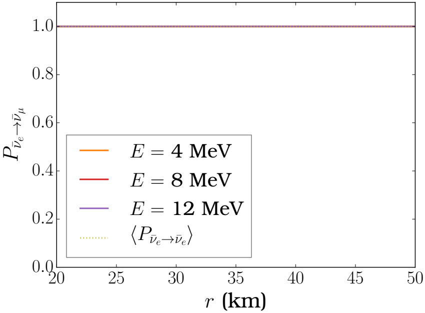
$$h_{\mathcal{G}} = \left[\begin{array}{c|c} H & \Phi \\ \hline \Phi^\dagger & -\bar{H}^T \end{array} \right]$$



- We find no nonlinear feedback : extremely narrow resonance.
- Artificially taking $m = 100$ eV : no difference.

Helicity Coherence : numerical results





$\hookrightarrow$ Run around the resonance : no conversions,

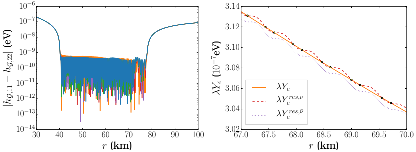
contrary to what was found in first study of this term with toy model in one flavor [Vlasenko, Fuller, Cirigliano, 2014] with $m = 1$ eV.

Why does nonlinear feedback occur ?

How we analyzed it :

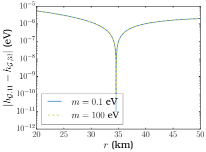
- Nonlinear feedback ↔ matching between matter and neutrino self-interaction derivatives.
- First order perturbation analysis of the resonance conditions.

Matter Neutrino Resonance



- Yo-yo effect between geometry and flavor conversions.
- Multiple MSW-like resonances.

Helicity Coherence



- 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.

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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], ...)

Conclusions and perspectives

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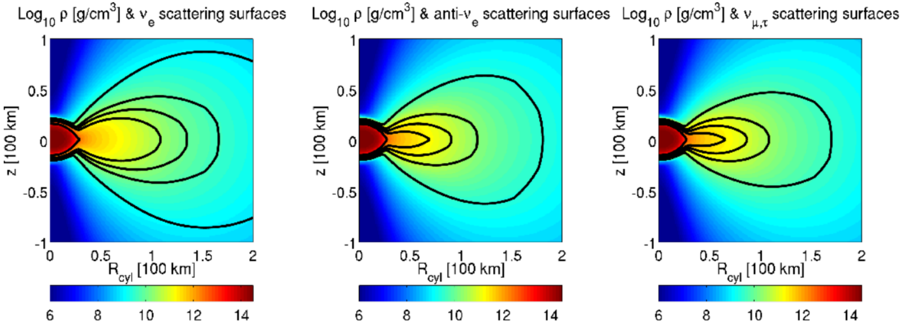
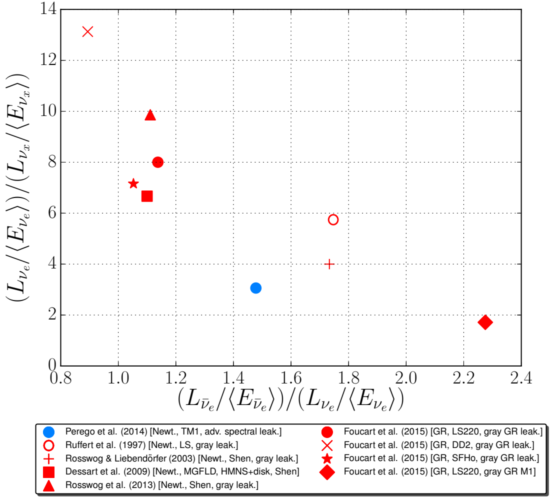
Thank you !

Backup slides

Neutrinospheres



Scattering surfaces for 4.62, 10.63, 16.22, 24.65, 56.96 MeV.


14
12
10
8
6
4
2
0
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
$(L_{\nu_e}/\langle E_{\nu_e}\rangle)/(L_{\nu_x}/\langle E_{\nu_x}\rangle)$
$(L_{\bar{\nu}_e}/\langle E_{\bar{\nu}_e}\rangle)/(L_{\nu_e}/\langle E_{\nu_e}\rangle)$
Perego et al. (2014) [Newt., TM1, adv. spectral leak.]
Ruffert et al. (1997) [Newt., LS, gray leak.]
Rosswog & Liebendörfer (2003) [Newt., Shen, 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]