Neutrino propagation in the presence of nonstandard interactions in binary neutron star mergers

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A. Chatelain, C. Volpe, Arxiv:1710.11518

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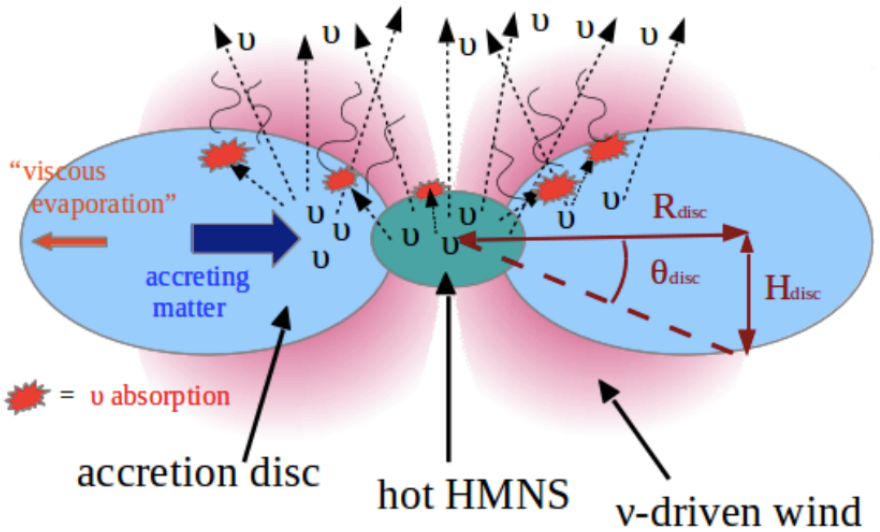
1. Framework
2. Impact of nonstandard interactions in BNS mergers
3. Conclusions and perspectives

Binary Neutron Star mergers



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

- Still little studied.
- Neutrino driven winds : good candidates for r-process nucleosynthesis.
- Gravitational waves detection : more info (GW170104 !).

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

→ How can nonstandard interactions impact neutrino flavor conversions in this environment ?

Neutrino flavor conversions in BNS : the model

- Two neutrino flavors in the mean-field approximation.
- Two evolution equations : $i\dot{\rho} = [H, \rho]$ and $i\dot{\bar{\rho}} = \left[\bar{H}, \bar{\rho}\right]$.
- ρ is the density matrix :

$$\rho(r) = \begin{pmatrix} |\nu_e|^2 & \nu_e \nu_x^* \\ \nu_e^* \nu_x & |\nu_x|^2 \end{pmatrix} = \begin{pmatrix} \mathcal{P}_{\nu_e \to \nu_e}(r) & \times \\ \times & \mathcal{P}_{\nu_e \to \nu_x}(r) \end{pmatrix}$$

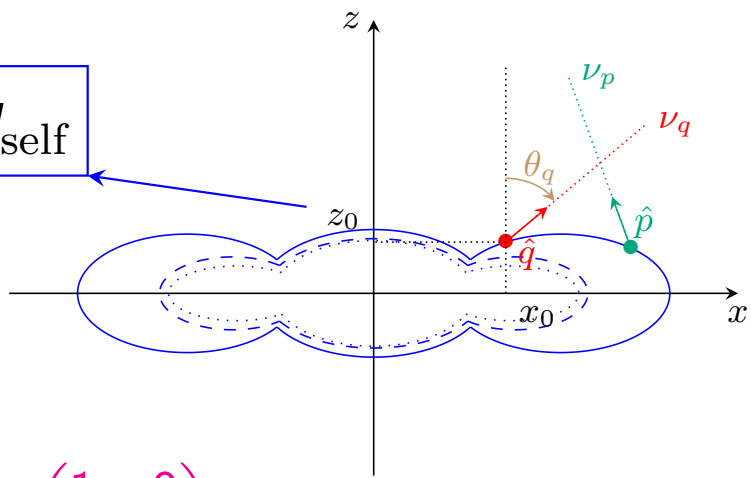
$$H = \boxed{H_{\rm vac}} + \boxed{H_{\rm mat}} + \boxed{H_{\rm self}}$$

$$H_{\rm vac} = \omega \begin{pmatrix} -c_{2\theta} & s_{2\theta} \\ s_{2\theta} & c_{2\theta} \end{pmatrix}$$

$$\underbrace{\begin{pmatrix} \nu_e \\ \nu_x \end{pmatrix}}_{\text{Flavor basis}} = \underbrace{\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}}_{\text{Mixing matrix } U} \underbrace{\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}}_{\text{Mass basis}}$$

$$H_{\rm mat} = \lambda Y_e \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$$

Astrophysical simulations

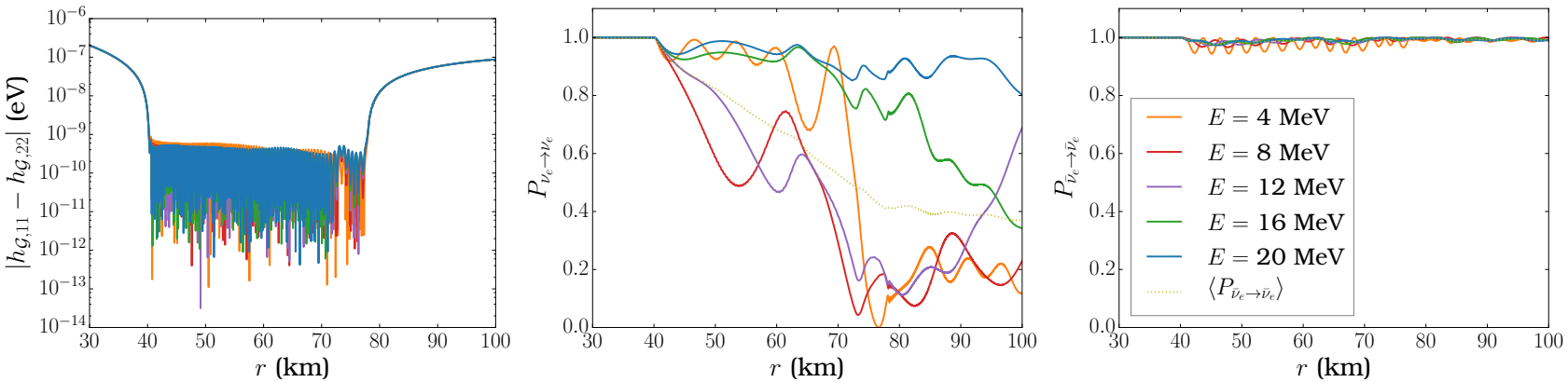


The Matter Neutrino Resonance

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

$$H_{ee} - H_{xx} = \lambda Y_e + H_{\mathrm{self},ee} - H_{\mathrm{self},xx} - 2\omega c_{2\theta} \approx 0$$

- Adiabaticity increased by nonlinear feedback.



[Malkus, Kneller, McLaughlin, Surman, PRD86,2012] [Malkus, Friedland, McLaughlin, 1403.5797] [Malkus, McLaughlin, Surman, PRD93,2016] [Vaananen, McLaughlin, PRD93, 2016] [Zhu, Perego, McLaughlin, PRD94, 2016] [Frensel, Wu, Volpe, Perego, PRD95, 2017]

Nonstandard interactions

- Matter-Neutrino NSI. Possible origin of anomalies, searched in various experiments (oscillation, scattering, ...).
- Constraints :

$$\begin{pmatrix} |\,\epsilon_{ee}\,| < 2.5 & |\,\epsilon_{e\mu}\,| < 0.21 & |\,\epsilon_{e\tau}\,| < 1.7 \\ & |\,\epsilon_{\mu\mu}\,| < 0.05 & |\,\epsilon_{\mu\tau}\,| < 0.2 \\ & & |\,\epsilon_{\tau\tau}\,| < 9.0 \end{pmatrix}$$

- New term to our Hamiltonian.

$$H_{\rm NSI} = \lambda \begin{pmatrix} \epsilon_{ee} & \epsilon_{e\tau} \\ \epsilon_{\tau e} & \epsilon_{\tau\tau} \end{pmatrix} \rightarrow \lambda \begin{pmatrix} \frac{Y_\odot - Y_e}{Y_\odot}\delta\epsilon^n & (3+Y_e)\,\epsilon_0 \\ (3+Y_e)\,\epsilon_0^* & 0 \end{pmatrix}$$

$$\boxed{|\,\delta\epsilon^n\,| \leq \mathcal{O}\,(1-10)} \qquad \boxed{|\,\epsilon_0\,| \leq \mathcal{O}\,(0.1-1)}$$

- Explored in Sun and SNe. [Friedland, Lunardini, Pena-Garay, PLB594, 2004] [Esteban-Pretel, Tomas, Valle, PR76, 2007] [Blennow, Mirizzi, Serpico, PRD78, 2008] [Stapleford, Vaananen, Kneller, McLaughlin, Shapiro, PRD94, 2016] [Sen, Dighe, 2017]

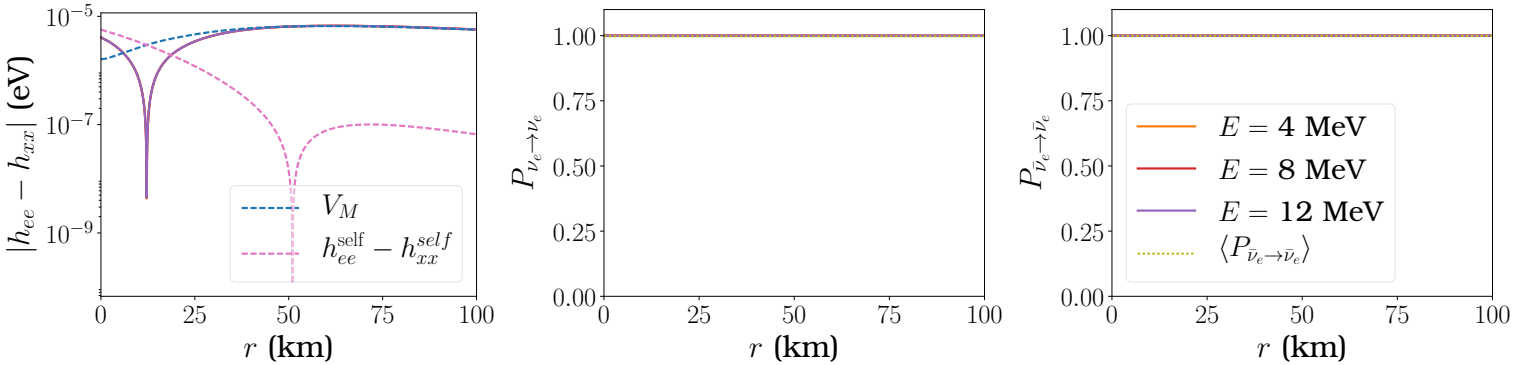
  $\hookrightarrow$ What are the effects of NSI in binary neutron star mergers ?

Matter Neutrino Resonance modified

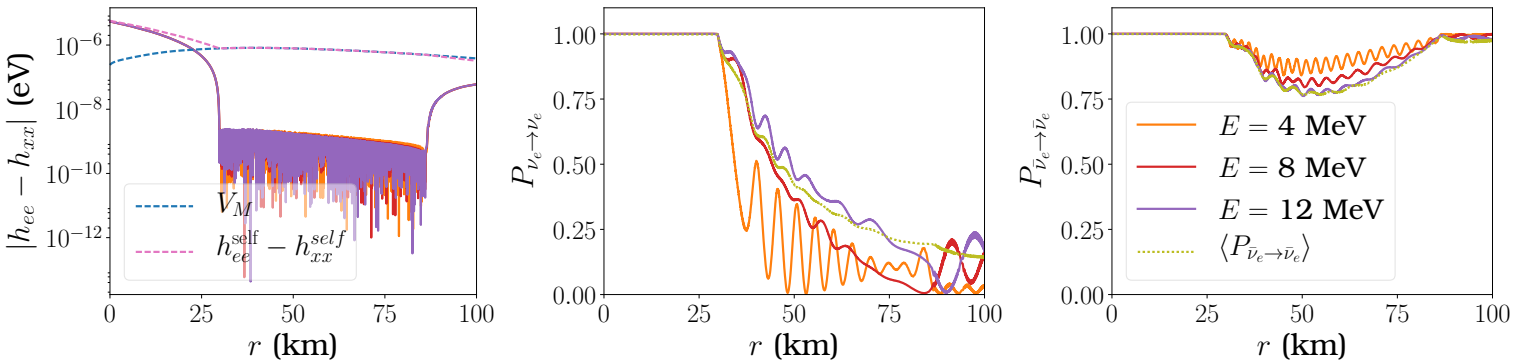
$$\underbrace{\lambda\left[Y_e + \frac{Y_\odot - Y_e}{Y_\odot}\delta\epsilon^n\right]}_{V_M} + H_{\mathrm{self},ee} - H_{\mathrm{self},xx} - 2\omega c_{2\theta} \approx 0$$

Can modify the location and adiabaticity of the MNR.

MNR without NSI



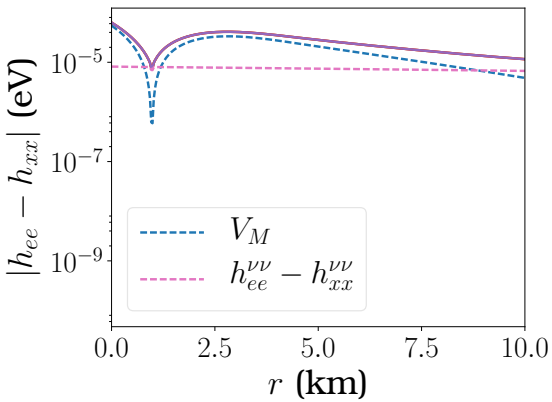
MNR with NSI

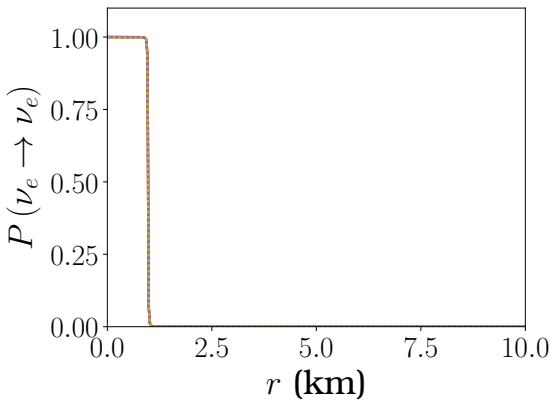


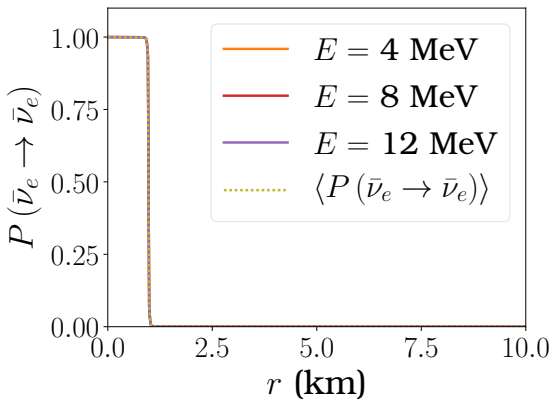
The Inner (I) resonance

$$\underbrace{\lambda\left[Y_e + \frac{Y_\odot - Y_e}{Y_\odot}\delta\epsilon^n\right]}_{V_M} \approx 2\omega c_{2\theta} - (H_{\mathrm{self},ee} - H_{\mathrm{self},xx}) \approx 0$$

- Self-interaction : no effect on location or adiabaticity of the resonance. [Esteban-Pretel, Tomas, Valle, PR76, 2007]
- Can be localized extremely close to the neutrinosphere.
- Creates similar transformations for neutrinos and antineutrinos.



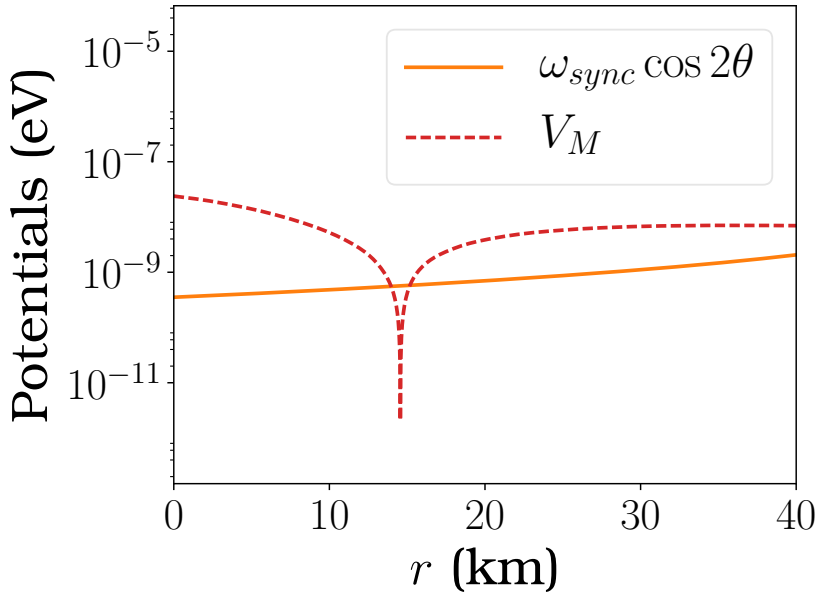


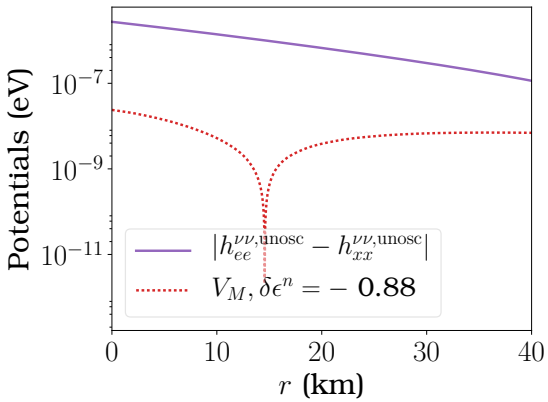


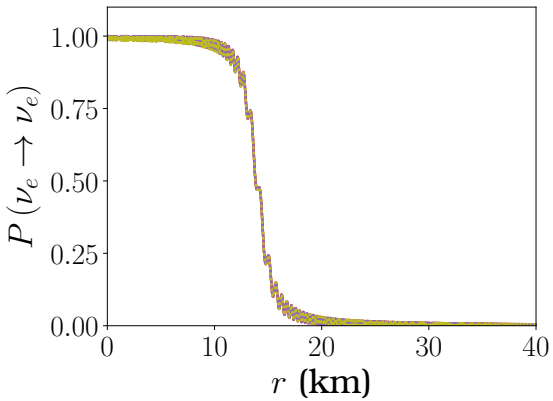
I-resonance as synchronized-MSW

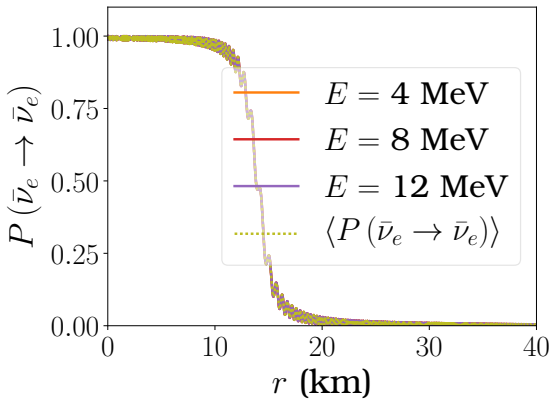
$$\omega_{\rm sync} c_{2\theta} = V_M, \ \omega_{\rm sync} \propto \frac{1}{\mu}$$

I-resonance : can be found in the presence of a strong self-interaction potential, as a **synchronized** MSW resonance.





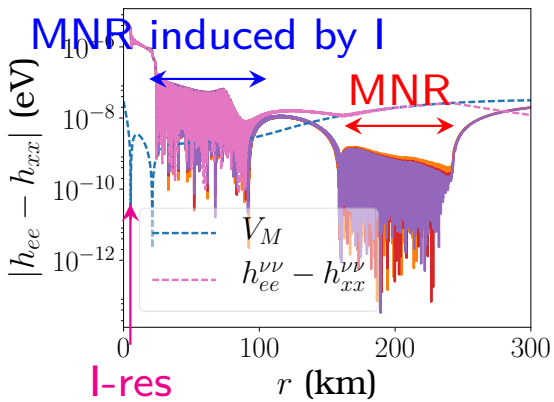


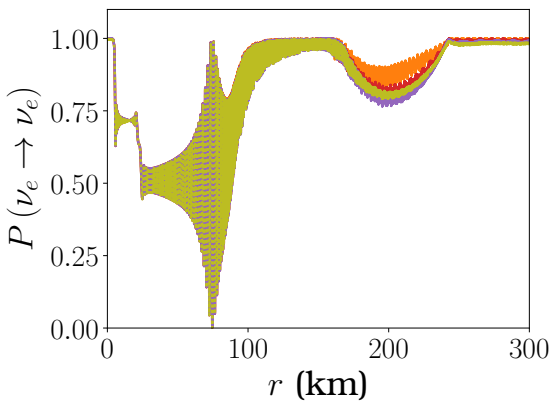


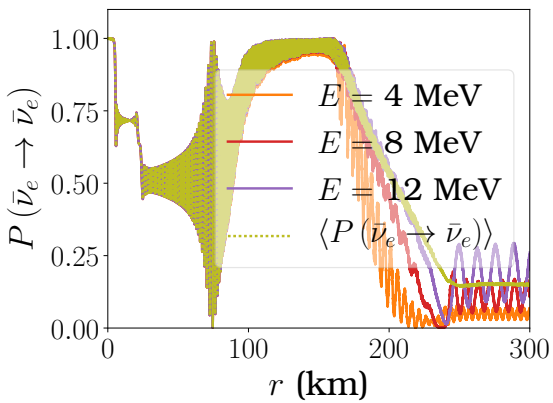
Combination Matter Neutrino and Inner resonances

Presence of Inner resonance : modify the flavor content.

- Can trigger the Matter Neutrino Resonance.
- Can encounter multiple resonances, with different patterns.







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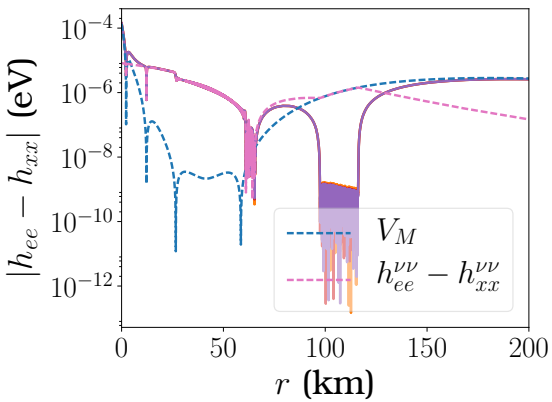
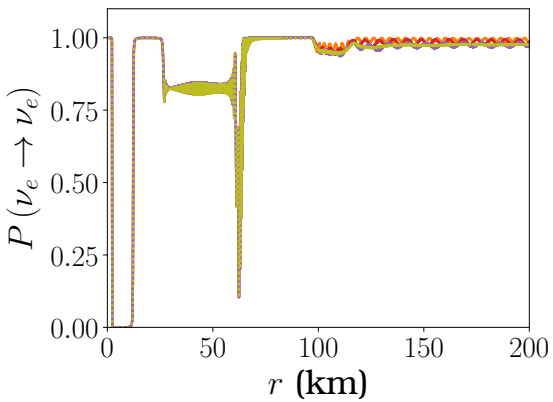
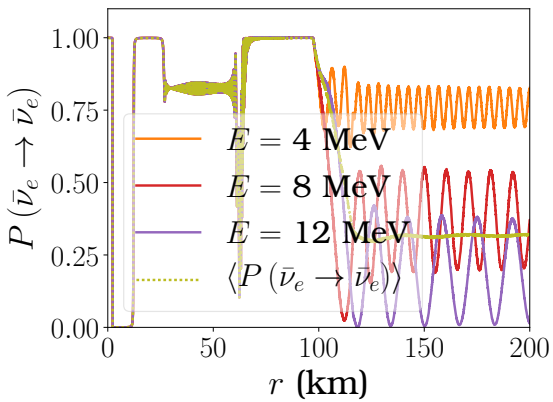


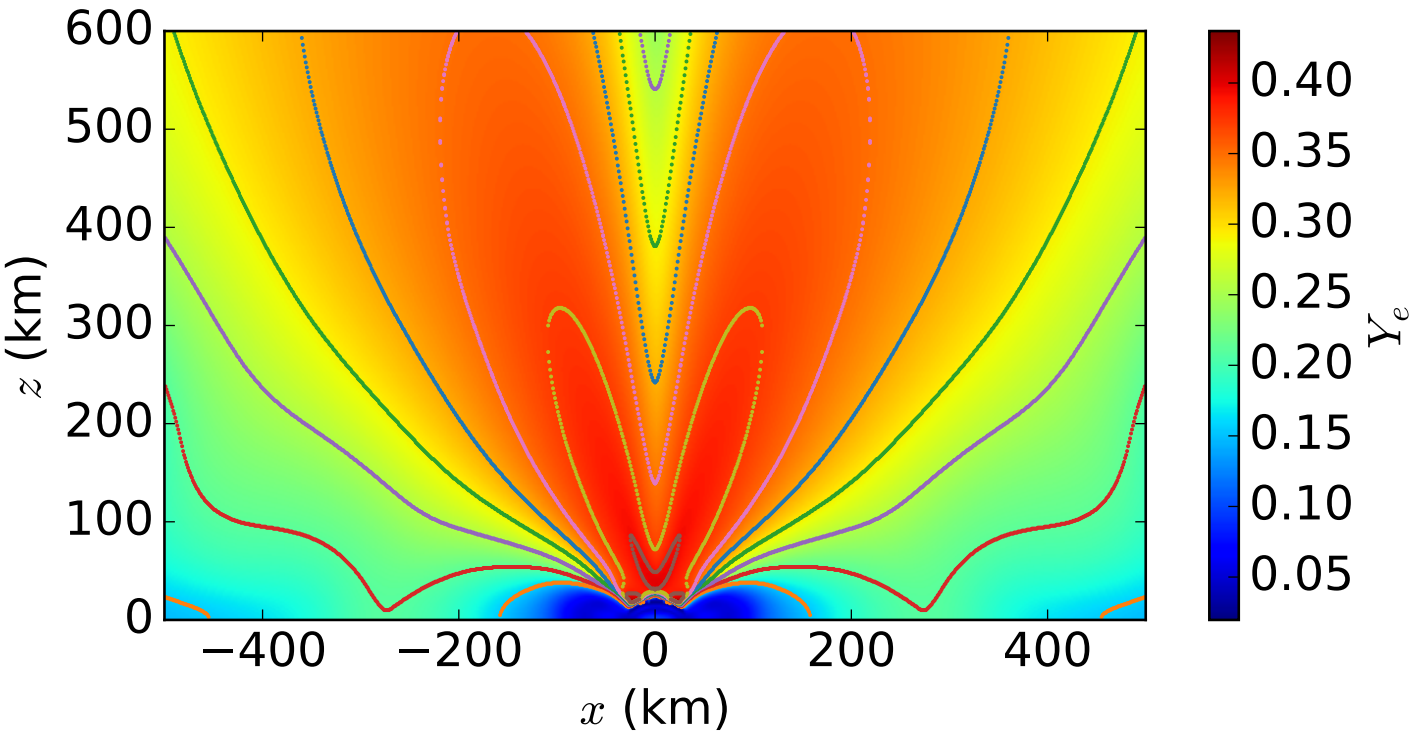




Impact on nucleosynthesis : evolution of Y_e

$$V_M = \lambda \left[Y_e + \frac{Y_\odot - Y_e}{Y_\odot} \delta\epsilon^n \right] \approx 0$$

Plot : I resonance condition for $\delta\epsilon^n \in [-0.9, -0.2]$.



I-resonances can be found for a large range of NSI parameters.

Conclusions and perspectives

- Neutrino flavor conversions in BNS mergers : lots of on-going investigations.
- **Nonstandard Interactions** : have a significant impact on flavor conversions.
  - Can shift the usual Matter Neutrino Resonance.
  - Can create an Inner resonance very close to the neutrinosphere, which can also be synchronized.
  - Can create combination and different patterns of the two resonances.
  - Could have an impact on the electron fraction and on nucleosynthesis ! *"Neutrino propagation in the presence of nonstandard interactions in binary neutron star mergers", Chatelain, Volpe, Arxiv:1710.11518*

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Thank you !