

# Helicity coherence in binary neutron star mergers and nonlinear feedback

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*"Helicity coherence in binary neutron star mergers and non-linear feedback"*

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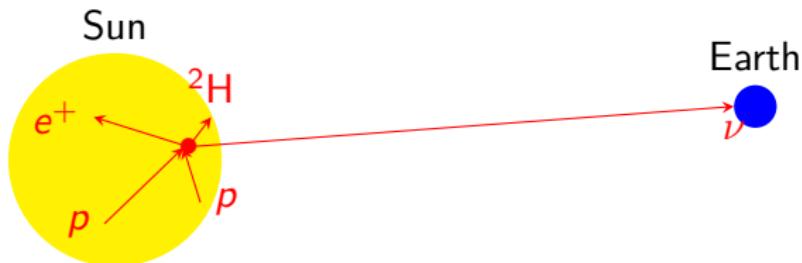
## 1 Introduction

## 2 Helicity coherence in Binary Neutron Star Mergers

- Theoretical framework
- Our model : Binary Neutron Star mergers
- Neutrino sector : Matter Neutrino Resonance
- Helicity coherence

## 3 Conclusion

# The solar neutrino problem



- Bethe, 1939  $pp$  chain reaction  $\text{H} \rightarrow {}^4\text{He}$ , producing > 99% solar energy.
- 1960s Homestake : measure  $\nu_e$  flux → deficit compared to Solar Standard Model prediction.

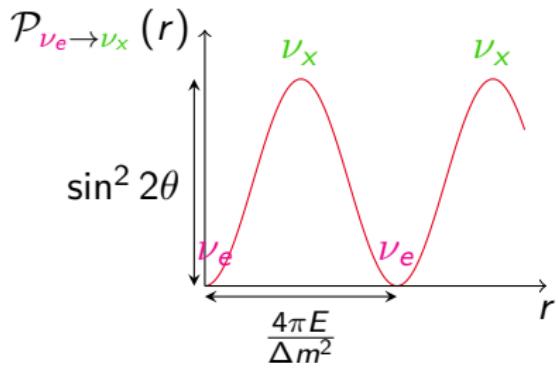
Where are these missing  $\nu_e$ s ?

# Solving this problem : $\nu$ oscillations in vacuum

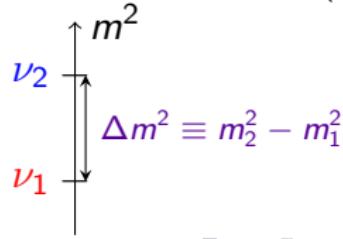
- Neutrinos are **massive** particles with **mixing**.

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

→ Interference.



$$\mathcal{P}_{\nu_e \rightarrow \nu_x}(r) = \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 r}{4E} \right)$$



# Vacuum oscillations : spin formalism

- Density matrix formalism in the mean field approximation

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

- Decompose  $\rho = \frac{1}{2} (\mathbb{1} + \vec{P} \cdot \vec{\sigma})$  :

$$\vec{P} = \text{Tr} \rho \vec{\sigma} = \begin{pmatrix} 2\Re(\rho_{12}) \\ -2\Im(\rho_{12}) \\ \rho_{11} - \rho_{22} \end{pmatrix} \rightarrow \dot{\vec{P}} = \vec{B} \times \vec{P}$$

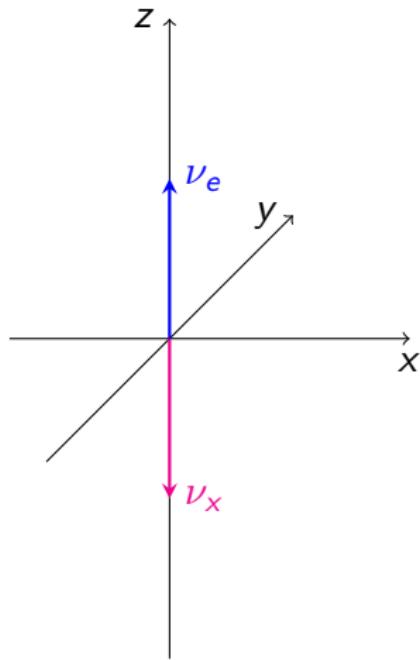
Precession equation

$$\rightarrow P_z(t) = 2\mathcal{P}_{\nu_e \rightarrow \nu_e}(t) - 1.$$

- $H = \frac{1}{2} (\text{Tr} H \mathbb{1} + \vec{B} \cdot \vec{\sigma})$ ,  $\vec{B} = \text{Tr} H \vec{\sigma}$

# Vacuum oscillations : Larmor precession

Flavor space

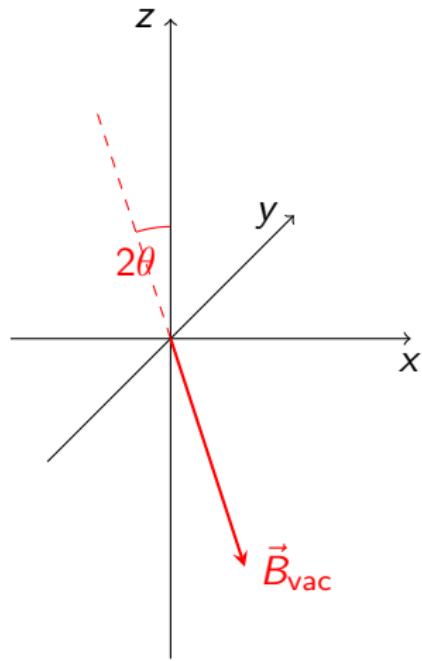


$$H_{\text{vac}}(E) = \frac{\Delta m^2}{4E} \begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix}$$

$$\Rightarrow \vec{B}_{\text{vac}}(E) = \frac{\Delta m^2}{2E} \begin{pmatrix} \sin 2\theta \\ 0 \\ -\cos 2\theta \end{pmatrix}$$

# Vacuum oscillations : Larmor precession

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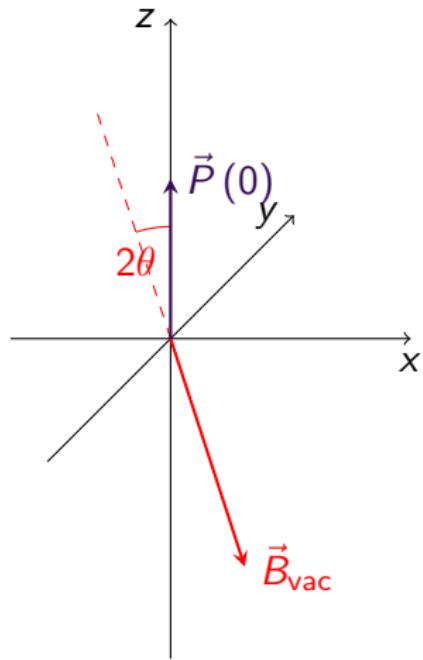


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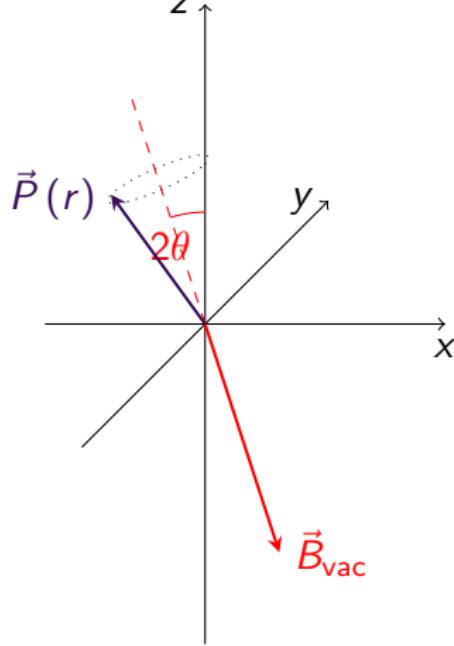


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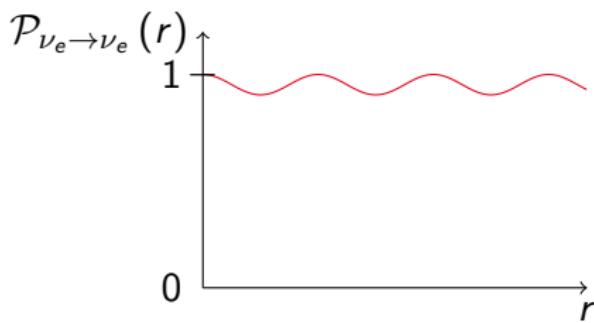
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Flavor space



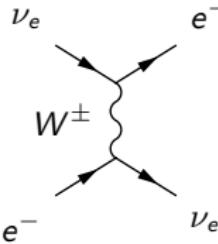
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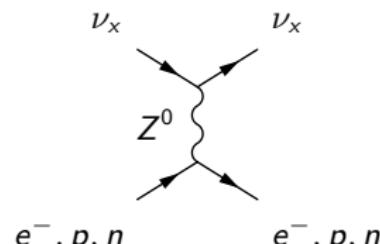


# Neutrino in the Sun : Mikheev Smirnov Wolfenstein effect

[Wolfenstein, PRD17, 1978] [Mikheev, Smirnov, Sov. J. Nucl. Phys., 1985]



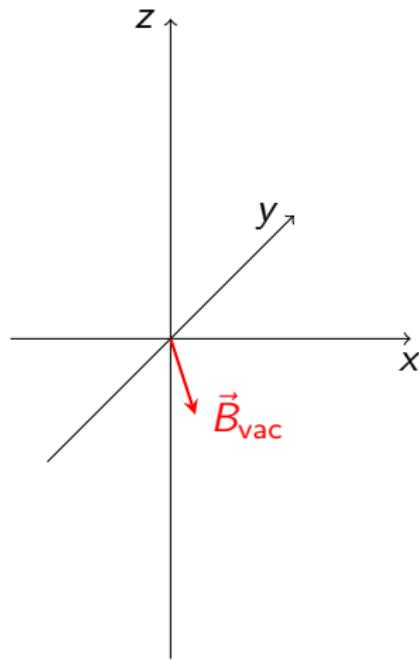
CC : Only  $\nu_e$ .



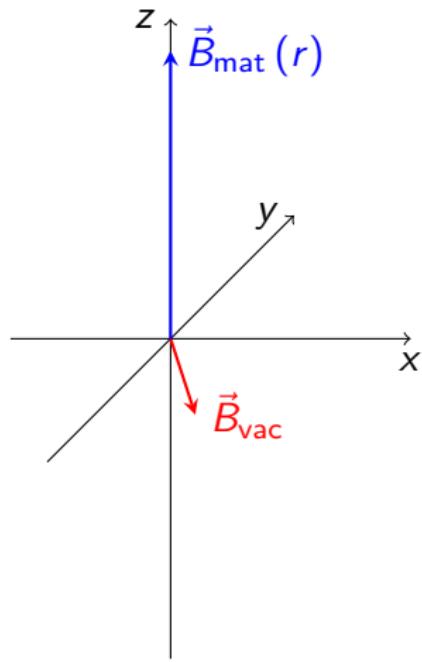
NC : flavor blind.

- $H = H_{\text{vac}} \rightarrow H = H_{\text{vac}} + H_{\text{mat}}$ , with  $H_{\text{mat}}(r) = \begin{pmatrix} \sqrt{2}G_F n_e(r) & 0 \\ 0 & 0 \end{pmatrix}$ .
- $\vec{B} = \vec{B}_{\text{vac}} \rightarrow \vec{B} = \vec{B}_{\text{vac}} + \vec{B}_{\text{mat}}$ , with  $\vec{B}_{\text{mat}}(r) = \begin{pmatrix} 0 \\ 0 \\ \sqrt{2}G_F n_e(r) \end{pmatrix}$ .

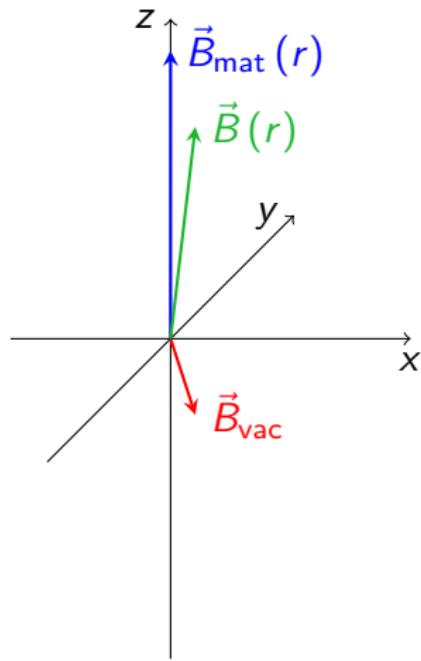
## Flavor space



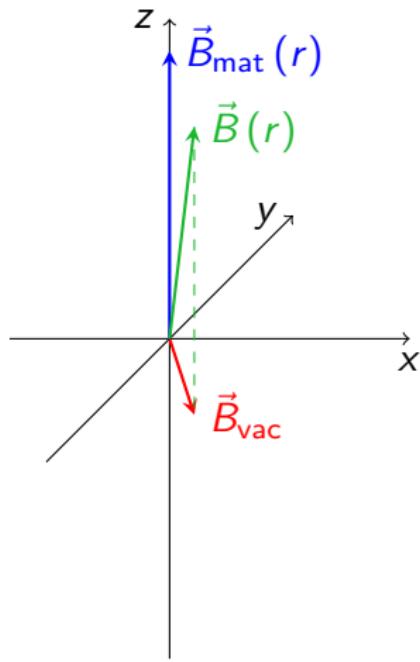
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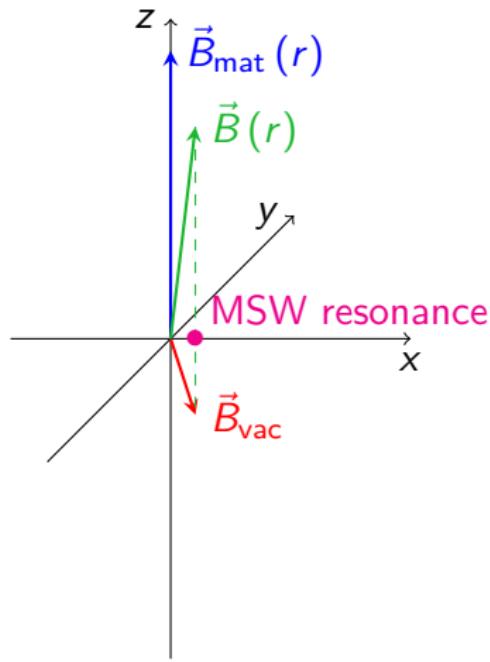


## Flavor space



# MSW Resonance

Flavor space

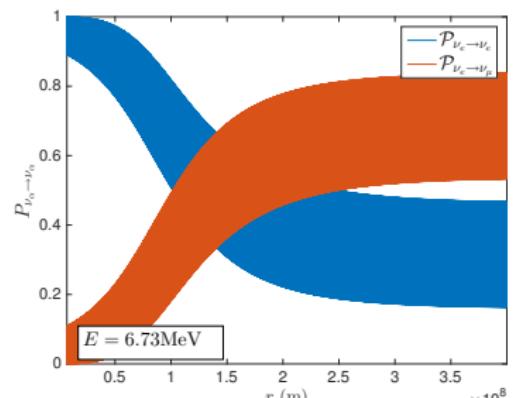


Resonance condition :

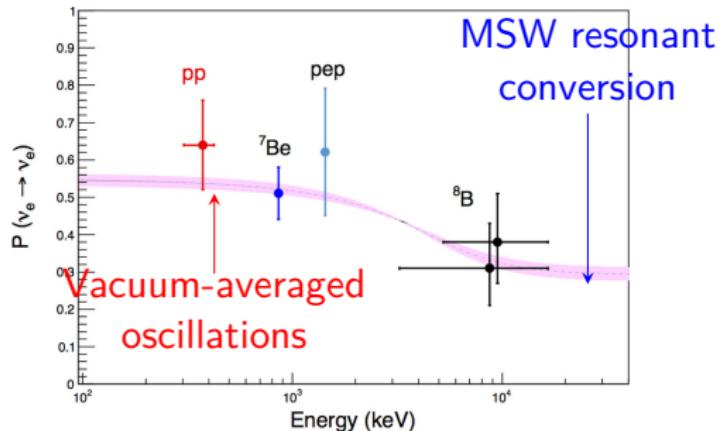
$$B_z \approx 0 \Leftrightarrow H_{11} - H_{22} \approx 0$$

$$\sqrt{2} G_F n_e(r_{\text{res}}) = \frac{\Delta m^2}{2E} \cos 2\theta$$

If adiabatic : conversions.



# Solar problem solved !



[Borexino collaboration, Nature 512, 2014]

Open questions remain, eg

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

Conversions in other astrophysical environments : Supernovae, Hypermassive Stars, Neutron Star (NS) - NS or NS-BH mergers ...

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

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

- Most general equations in the mean field approximation : first order corrections to the relativistic limit  $\propto m \rightarrow$  Helicity Coherence.

[Volpe, Vaananen, Espinoza, PRD87, 2013]

[Vlasenko, Cirigliano, Fuller, PRD89, 2014]

[Serreau, Volpe, PRD90, 2014]

- First study of this term in a toy model with only one neutrino flavor  
[Vlasenko, Fuller, Cirigliano, 2014] : significant conversions  $\nu \leftrightarrow \bar{\nu}$ .

→ Can these corrections produce some effects in a more realistic scenario ?

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# Theoretical framework

- Consider Majorana neutrinos.
- Corrections to the relativistic limit : matrices  $2 \times 2 \rightarrow 4 \times 4$ .

$$\rho \rightarrow \rho_{\mathcal{G}} = \left( \begin{array}{c|c} \rho & \zeta \\ \hline \zeta^\dagger & \bar{\rho}^T \end{array} \right)$$

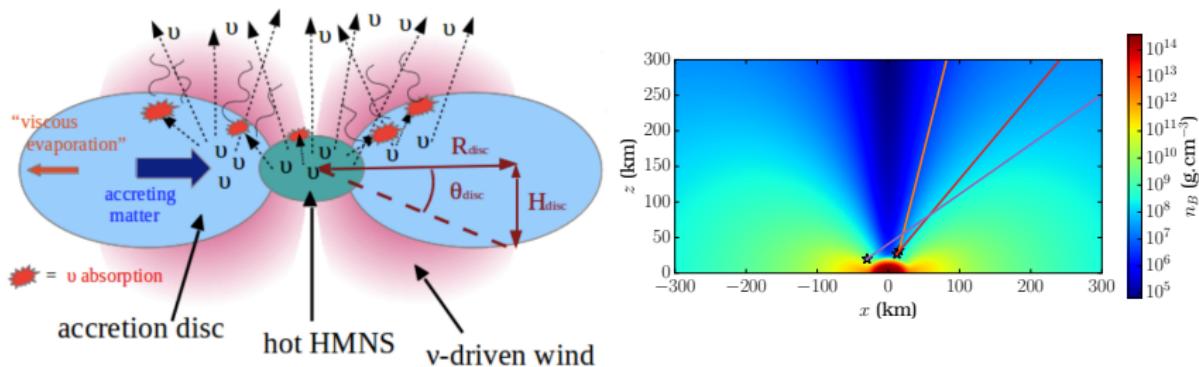
- $\rho (\bar{\rho})$  : density matrices for  $\nu (\bar{\nu})$ ;
- $\zeta$  : coupling  $\nu$ - $\bar{\nu}$  sectors.

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

- $H (\bar{H})$  : Hamiltonian for  $\nu (\bar{\nu})$  ;
- $\Phi$  : coupling  $\nu$ - $\bar{\nu}$  sectors,  $\propto \frac{m}{E} \approx 10^{-8}$

- $i\dot{\rho}_{\mathcal{G}} = [h_{\mathcal{G}}, \rho_{\mathcal{G}}]$  holds for the generalized matrices.
- $\Phi \rightarrow 0$  :  $i\dot{\rho} = [H, \rho]$  and  $i\dot{\bar{\rho}} = [\bar{H}, \bar{\rho}]$ .

# Neutrino propagation in Binary Neutron Star mergers



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

- $\nu$ -driven winds : strong candidates for **r-process** nucleosynthesis.

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

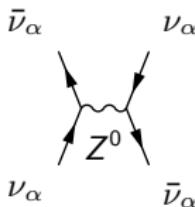
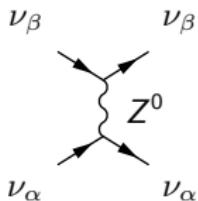
- Conversions → swap  $\stackrel{\leftrightarrow}{\nu}_e$ ,  $\stackrel{\leftrightarrow}{\nu}_x$  fluxes.

→ It is crucial to understand flavor conversions.

# $\nu$ sector, no $\nu \leftrightarrow \bar{\nu}$ coupling : self-interaction

- Very high neutrino luminosities : self-interaction.

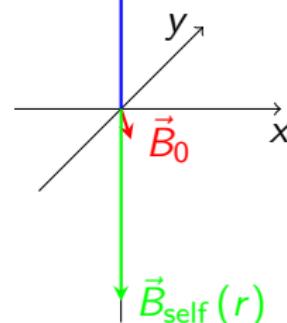
→ Introduce non-linearity !



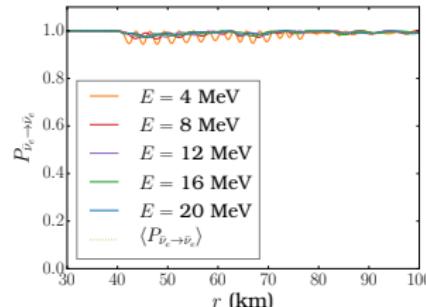
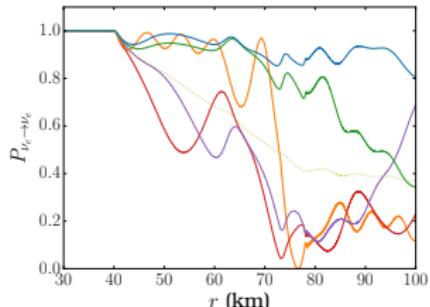
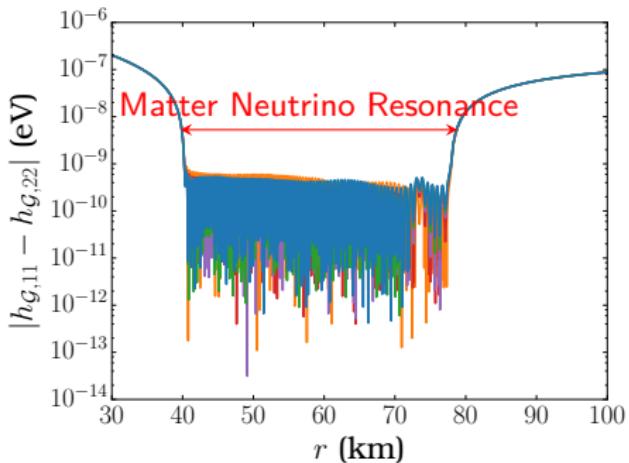
Flavor space

$$\vec{B}_{\text{mat}}(r)$$

- $\vec{B} = \vec{B}_{\text{vac}} + \vec{B}_{\text{mat}} + \vec{B}_{\text{self}}$
  - $L_{\bar{\nu}_e} > L_{\nu_e}$  :  $B_z^{\text{self}} < 0 \rightarrow$  possible cancellation  
 $B_z = H_{11} - H_{22} \approx 0$ .
- Matter Neutrino Resonance.
- Can be maintained over long distances because of a nonlinear feedback : conversions.

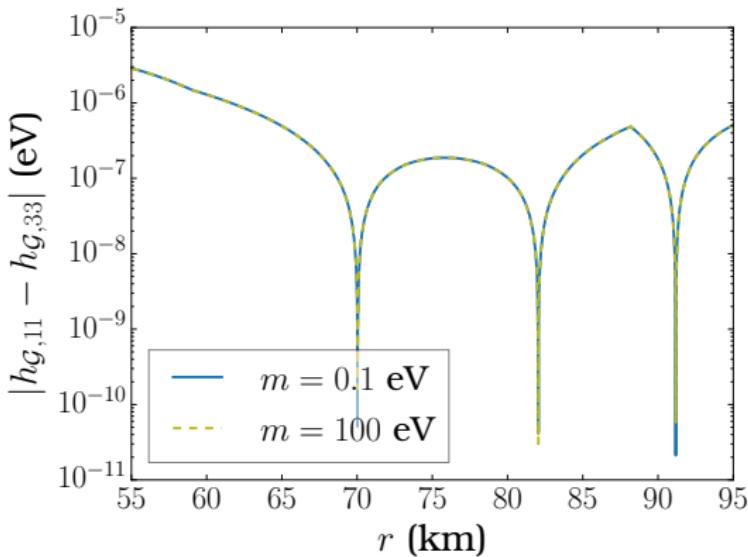


$\nu$  sector, no  $\nu \leftrightarrow \bar{\nu}$  coupling : Matter Neutrino Resonance



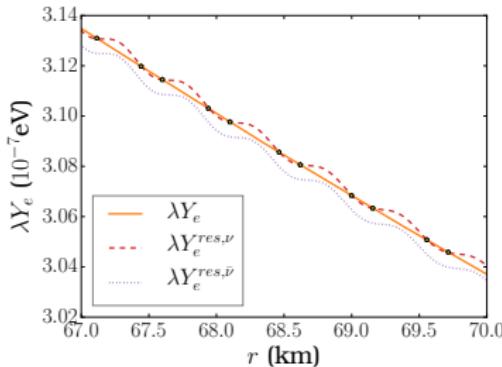
# Helicity coherence : analytical and numerical results

- $\frac{m}{E} \approx 10^{-8}$  → Look for MSW-like resonance conditions that could enhance  $\nu_e \leftrightarrow \bar{\nu}_e$  conversions, ie  $h_{G,11} - h_{G,33} \approx 0$ .
- Exist, but too narrow and no nonlinear feedback → no conversions.



# Analysis on multiple resonances and nonlinear feedback

- Nonlinear feedback  $\leftrightarrow$  matching between matter and self-interaction.
- Perturbation analysis of the resonance conditions :
  - MNR : yo-yo effect between geometry and conversions  $\rightarrow$  multiple resonances.



- **Helicity coherence** : no such effect. Matching here : possible for very peculiar conditions. **True in other environments.**
- One flavor toy model [Vlasenko, Fuller, Cirigliano, 2014] : matter profile artificially smooth to enable the matching and the nonlinear feedback.

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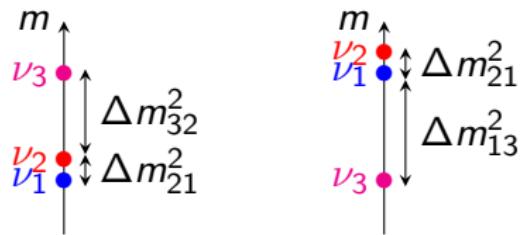
# Conclusion

- Neutrino flavor conversions in astrophysical environments : lots of on-going investigations, in particular for BNS.
  - **Helicity coherence** in BNS mergers :
    - Non-relativistic corrections → coupling  $\nu \leftrightarrow \bar{\nu}$ ,  $\propto \frac{m}{E} = \mathcal{O}(10^{-8})$ .
    - Resonances **possible** in realistic astrophysical environments ...
    - ... but **too narrow** to enable  $\nu \leftrightarrow \bar{\nu}$  conversions.
    - Analytical results : no widening due to non-linear feedback.
- **No effects appear from non-relativistic corrections in a detailed astrophysical environment.**
- Open questions : role of collisions.

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- Neutrino flavor conversions in astrophysical environments : lots of on-going investigations, in particular for BNS.
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    - Analytical results : no widening due to non-linear feedback.
- **No effects appear from non-relativistic corrections in a detailed astrophysical environment.**
- Open questions : role of collisions.

Thank you !



- $\mathcal{P}_{\nu_e \rightarrow \nu_x}(r) = \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 r}{4E} \right)$  doesn't depend on sign ( $\Delta m^2$ ).
- MSW resonance condition :  $\frac{\Delta m^2}{2E} \cos 2\theta = \sqrt{2} G_F n_e(r) \rightarrow$  determine the sign of  $\Delta m_{21}^2$ .
- The sign of  $\Delta m_{32}^2$  or  $\Delta m_{13}^2$  still remains unknown.

# Effects of the MNR on nucleosynthesis

Neutrinosphere

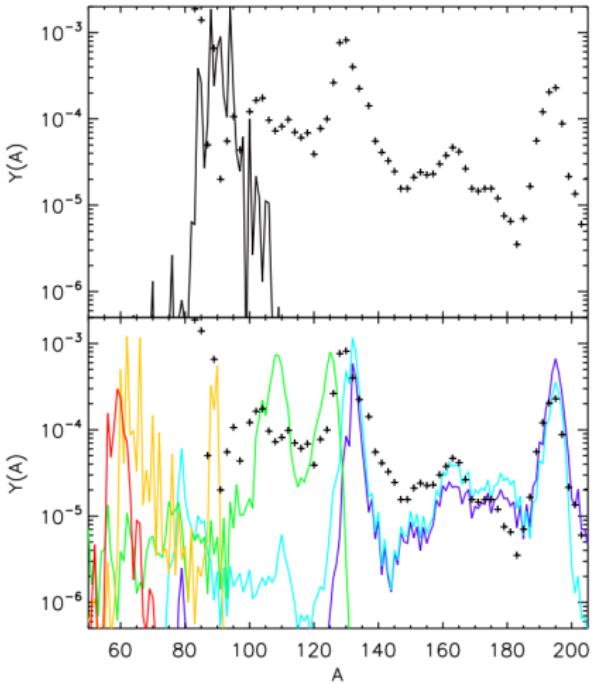
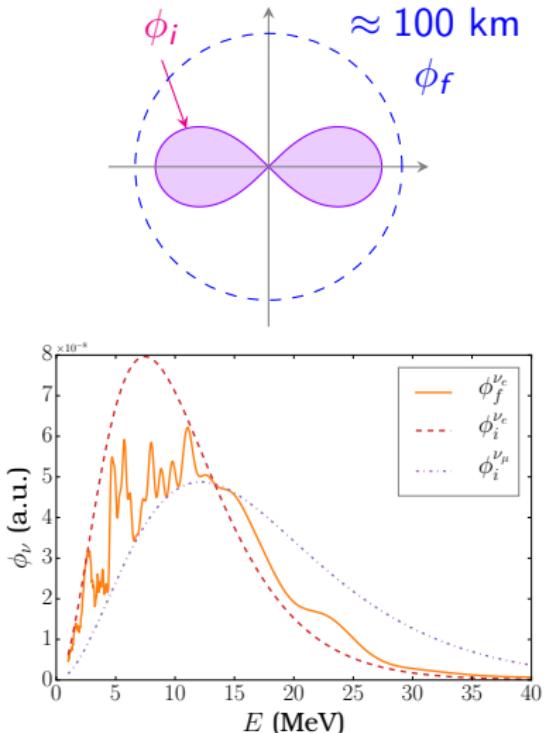


Figure: [Malkus, McLaughlin, Surman, PRD93, 2015]