# Neutrino flavor conversions in astrophysical environments

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

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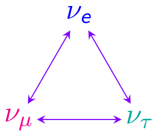



- Late 1960s Homestake experiment discovers the solar neutrino deficit.
- 1998 Super-Kamiokande finds the first strong evidences of neutrino oscillations.
- 2001 Sudbury Neutrino Observatory resolves the solar neutrino problem by proving that solar neutrinos have converted into other active flavors.

**How can we explain these conversions ?**
**What are their effects in astrophysical environments ?**

# Table of contents

# Neutrino oscillations and density matrix

- We work in a $n_f = 2$ scheme : $\nu_e$, $\nu_x$.
- Neutrinos have masses and mixing :

$$\nu_k, \text{ propagating (mass basis)} \neq \nu_\alpha, \text{ interacting (flavor basis)}$$
$$|\nu_\alpha\rangle = U\,|\nu_k\rangle, \text{ U rotation matrix}$$

- Describing their flavor evolution in the mean-field approximation : density matrix $\rho$ ($\bar{\rho}$) such that :

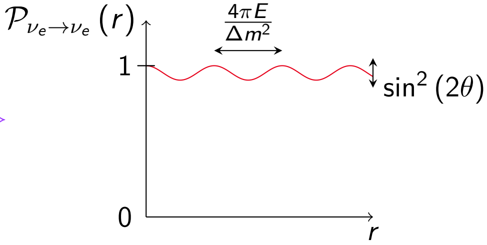
$$i\dot{\rho} = [h, \rho]$$

- Propagation of an initial $\nu_e$ (using $r = t$ in natural units)

$$\rho\,(r) = \begin{pmatrix} \mathcal{P}_{\nu_e\to\nu_e}\,(r) & \times \\ \times & \mathcal{P}_{\nu_e\to\nu_x}\,(r) \end{pmatrix}.$$

# Neutrino oscillations in vacuum

$$h_0 = U \begin{pmatrix} 0 & 0 \\ 0 & \frac{\Delta m^2}{2q} \end{pmatrix} U^\dagger \quad \Rightarrow$$



# Matter effects

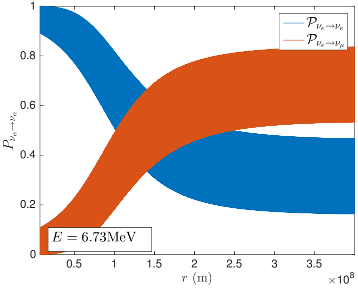
- Matter creates a new component to the Hamiltonian

$$h_{\text{mat}}(r) = \begin{pmatrix} \sqrt{2}G_F n_e(r) & 0 \\ 0 & 0 \end{pmatrix}$$

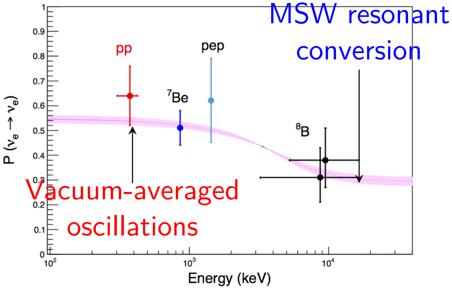
- $n_e(r)$ varies : $h^{ee} - h^{xx}$ may become null.
  $\rightarrow$ MSW resonance [ Wolfenstein 1978, Mikheev & Smirnov 1985 ].

$$\sqrt{2}G_F n_e(r) = \frac{\Delta m^2}{2q} \cos 2\theta$$

- Flavor conversion if resonance and adiabaticity.



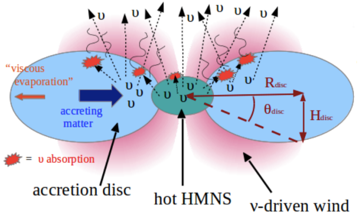

My numerical results.




Borexino measurements.

# Table of contents

# Understanding neutrino oscillations in NS-NS binaries.



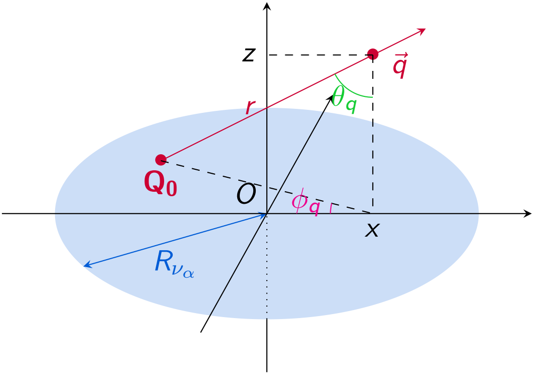

- NS-NS binaries : candidate site for r-process nucleosynthesis.
- Neutrino has a key role in neutrino-driven winds.

$$\nu_e + n \rightarrow p + e^-$$

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

$\rightarrow$ Sets the fraction $Y_e = \frac{p}{n+p}$, crucial for r-process nucleosynthesis.

- Very high neutrino luminosities $\longrightarrow$ self-interaction.
- Need to model neutrino emission : single-angle approximation.




$$h_{\text{self}}(r) = \sqrt{2} G_F \sum_\alpha \int \mathrm{d}q \left[ j_{\nu_\alpha}(q)\, G_{\nu_\alpha}(r)\, \rho_{\nu_{\underline{\alpha}}}(r,q) - j_{\bar{\nu}_\alpha}(q)\, G_{\bar{\nu}_\alpha}(r)\, \rho_{\bar{\nu}_{\underline{\alpha}}}(r,q) \right]$$

# Understanding the MNR

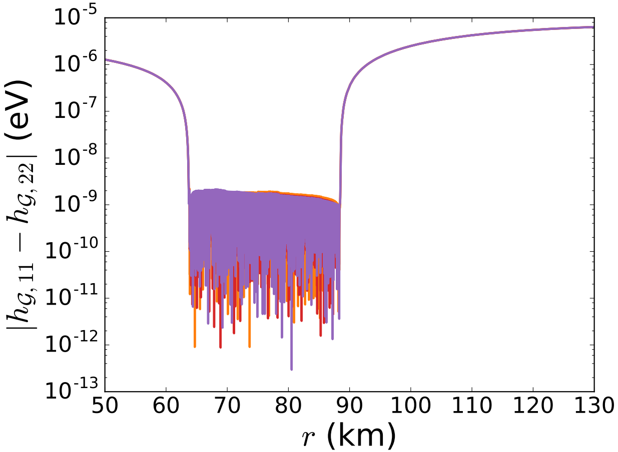
- Initially $L_{\bar{\nu}_e} > L_{\nu_e} \rightarrow h_{\text{self}}^{ee} < 0$ : new MSW-like resonant conversion

$$h^{ee} - h^{xx} = -\frac{\Delta m^2}{2q}\cos 2\theta + \sqrt{2}G_F n_B Y_e + h_{\text{self}}^{ee} - h_{\text{self}}^{xx}$$

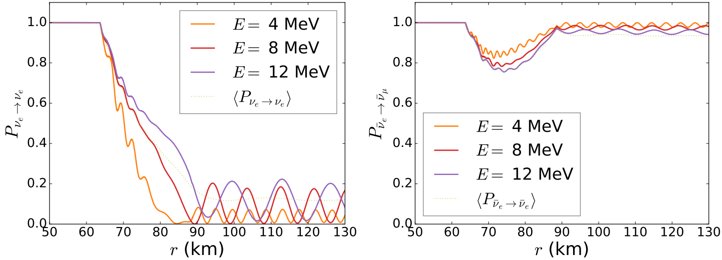
Matter-Neutrino Resonance, closer to the disk.

- Resonance maintained by a non-linear feedback involving cancellation of matter and neutrino diagonal terms of the Hamiltonian.

# Cancellation maintained over 30 km



- Modifies $\nu_e$ and $\bar{\nu_e}$ fluxes (from my two-flavor simulations).




- Releasing some hypotheses could modify these properties and the $\frac{n}{p}$.

# Table of contents

- Corrections coming from the mass (apart from the vacuum Hamiltonian $\propto \Delta m^2$) in the usual mean-field equations : see

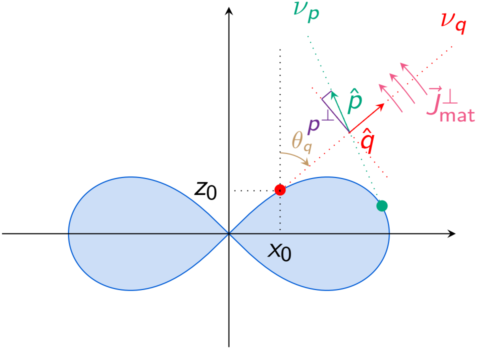
  [Volpe, Vaananen, Espinoza, 2013]
  [Vlasenko, Cirigliano, Fuller, 2013]
  [Serreau, Volpe, 2014]

- First study of this term in a toy model with only one neutrino flavor : [Vlasenko, Fuller, Cirigliano, 2014]. Conversions $\nu \leftrightarrow \bar{\nu}$ appearing because of a non-linear feedback.

$\rightarrow$ Are there any effects in a more realistic scenario ?

# Our model for studying helicity coherence effects

- Two neutrino flavors.
- Binary Neutron Star mergers environment.



# Helicity coherence

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

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

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

- $\rho$ ($\bar{\rho}$) : density matrices for $\nu$ ($\bar{\nu}$);
- $\zeta$ : coupling $\nu$-$\bar{\nu}$ sectors.
- $h$ ($\bar{h}$) : Hamiltonian for $\nu$ ($\bar{\nu}$) - include new terms $\propto \frac{m}{E}$;
- $\Phi$ : coupling $\nu$-$\bar{\nu}$ sectors, $\propto \frac{m}{q}$, involving currents $\perp \vec{q}$.

- $i\dot{\rho_{\mathcal{G}}} = [h_{\mathcal{G}}, \rho_{\mathcal{G}}]$ holds for the generalized matrices.

# The results : new resonance conditions

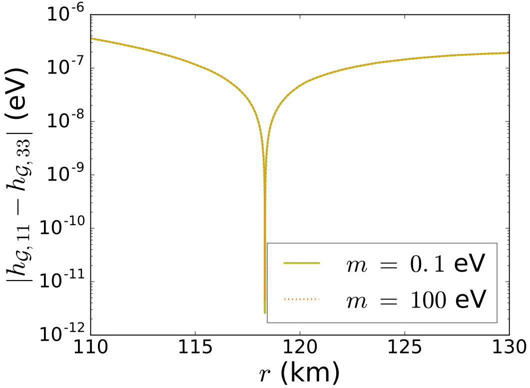
- Look for MSW-like conditions $h_{\mathcal{G},ii} - h_{\mathcal{G},jj} \simeq 0$.
- $\nu$ ($\bar{\nu}$) sector : MNR possible.
- Four new resonance conditions between $\nu$, $\bar{\nu}$. One interesting in our environment

$$h_{\mathcal{G},11} - h_{\mathcal{G},33} = \sqrt{2} G_F n_B (3Y_e - 1) + 2h^{ee}_{\nu\nu} \simeq 0$$

- Fulfillment similar to the MNR, creates transitions $\nu_e \leftrightarrow \bar{\nu}_e$, driven by $\phi^{ee} \propto \frac{m}{q} \approx 10^{-7} - 10^{-8}$.

## Numerical results

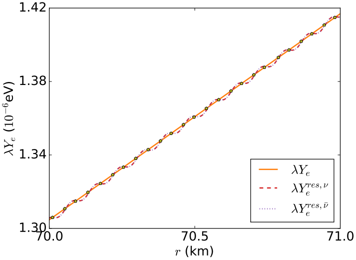
- Helicity coherence resonance present.




- ... however, no non-linear feedback and resonance too narrow : the probabilities are unchanged.

# Analysis on multiple resonances and non-linear feedback

- Non-linear feedback ↔ matching between matter and self-interaction.
- Linear analysis of the resonance conditions :
  - One flavor toy model : the matter profile is taken to be artificially smooth to enable the matching.
  - MNR : yo-yo effect between geometrical factors and conversions → multiple resonances.




  - Helicity-coherence : no such effect.
- Matching here : possible for very peculiar conditions.

# Table of contents

# Conclusion

- Neutrino oscillations : an important impact in high-energy physics, astrophysics and cosmology.
- In NS-NS binaries, neutrino conversions (MNR) could be essential in neutrino-driven wind nucleosynthesis.
- Helicity coherence : very similar to the MNR. No effective conversions in binaries neutron star merger since conditions for multiple resonances are difficult to meet.
- Open issues remain : eg, the role of inhomogeneities, effects appearing with multi-angle simulations.

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Thank you !