Insights into coherent forward scattering of neutrinos

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Outline of the talk

- Neutrinos in supernovae
- Neutrinos in neutron star mergers.
- Matter effect: What is it?
- Neutrino self-interactions.
- Phenomenology of neutrino flavor evolution in dense astrophysical object.

Neutrino flavor evolution in supernovae

- In deep interior, neutrinos are trapped.
- As they slowly escape the core, the neutrinos change flavor as they emerge.
- The neutrino flavor evolution depends on the medium through which they travel.

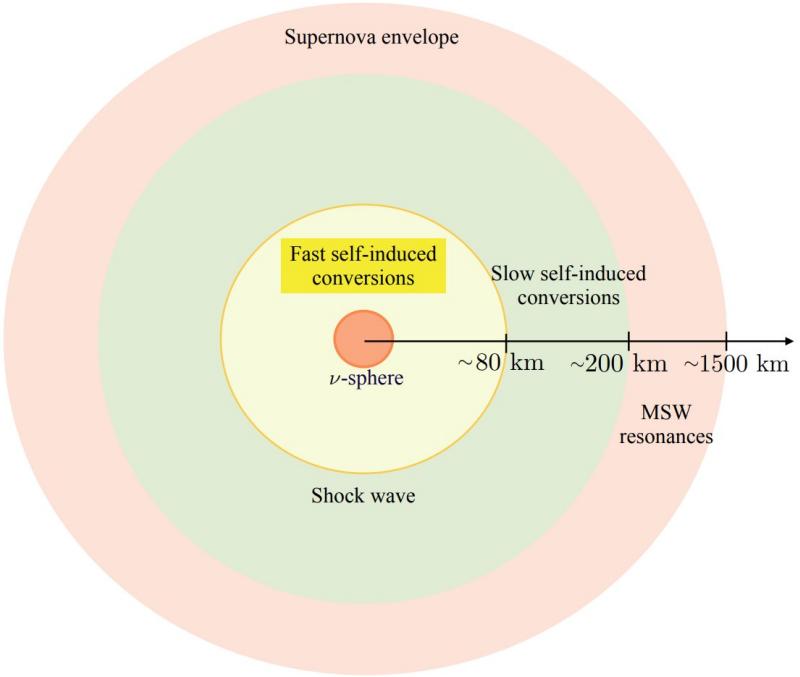

Image: Tamborra and Shalgar
ArXiv: 2011.01948

Neutrino flavor evolution in Neutron Star Mergers

- Neutron star mergers are known to be sites of r-process nucleosynthesis.
- Electron neutrinos and antineutrinos convert protons to neutrons and vice-versa affecting r-process nucleosynthesis rates.
- Understanding neutrino flavor evolution in neutron star mergers is crucial.

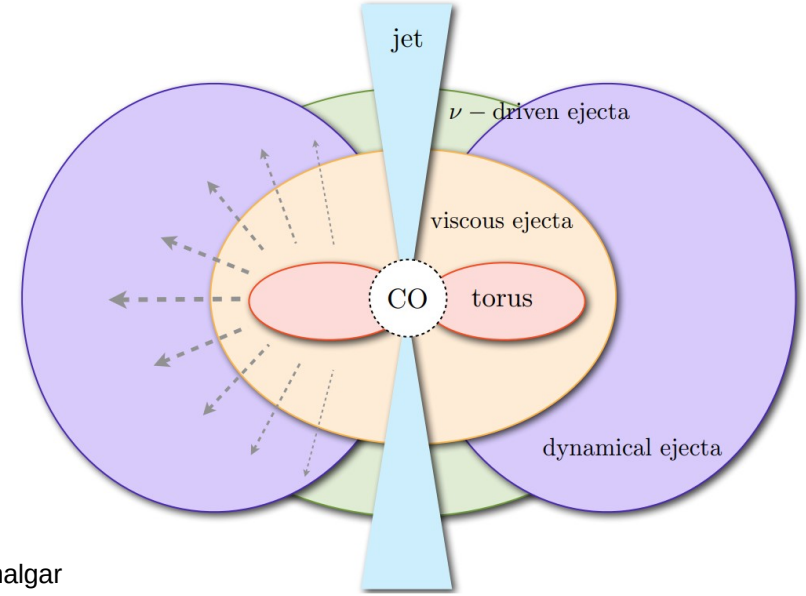

Image: Tamborra and Shalgar
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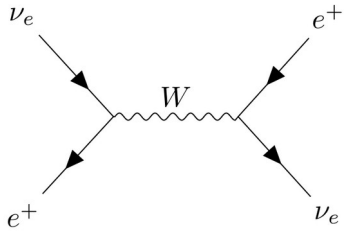
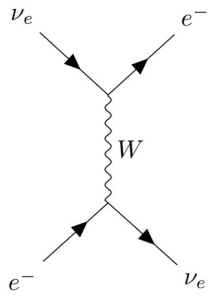
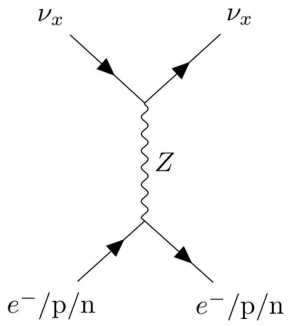
Scattering of neutrinos with matter

Charged current interaction occur between neutrinos and charged leptons of the same flavor.





Neutral current processes are flavor blind – Same for all flavors.



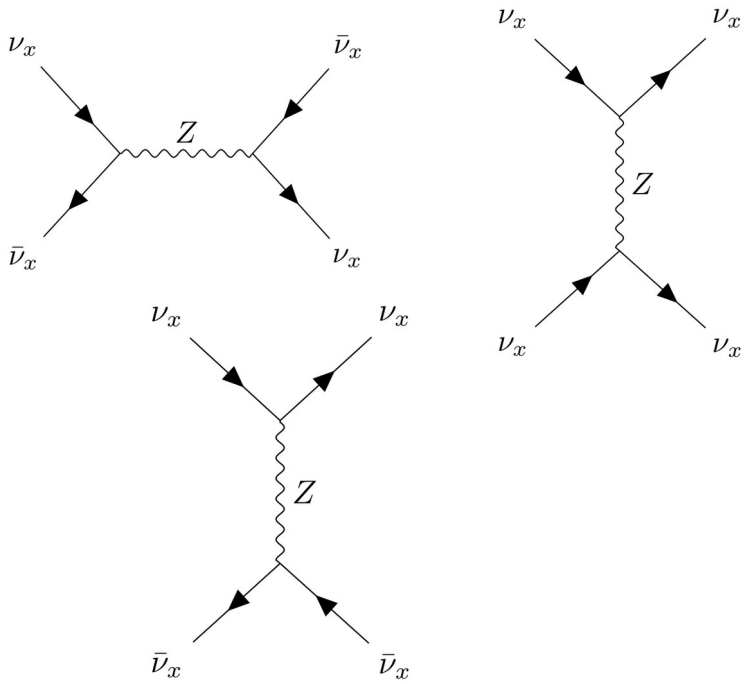
x : any flavor

p: Proton

n: Neutron

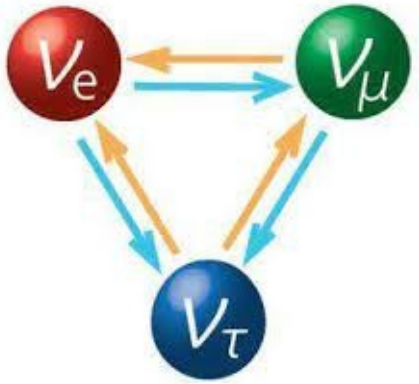
Scattering of neutrinos with other neutrinos

Neutrinos can interact with each other only via neutral current interactions.



Neutrino flavor

- Flavor is not a good quantum number.
- Neutrino created as one flavor can transform into another flavor.
- Throughout this talk we will work in the two flavor approximation. Ignore tau neutrino.



Neutrino flavor evolution

$$i\frac{\partial}{\partial t}\begin{pmatrix}\psi_e\\ \psi_\mu\end{pmatrix} = \hat{H}\begin{pmatrix}\psi_e\\ \psi_\mu\end{pmatrix}$$

Schrodinger equation for evolution of neutrino flavor in two flavor approximation

In vacuum:

$$i\frac{\partial}{\partial t}\begin{pmatrix}\psi_e\\ \psi_\mu\end{pmatrix} = \frac{\omega}{2}\begin{pmatrix}-\cos 2\theta_{\mathrm{V}} & \sin 2\theta_{\mathrm{V}}\\ \sin 2\theta_{\mathrm{V}} & \cos 2\theta_{\mathrm{V}}\end{pmatrix}\begin{pmatrix}\psi_e\\ \psi_\mu\end{pmatrix}$$

Terms proportional to identity not physical

$$\omega = \frac{\Delta m^2}{2E}$$

Vacuum frequency

θ_{V} Vacuum mixing angle

Neutrino flavor evolution

Amplitude of survival

$$\begin{aligned}\psi_e(t+\delta t) &= \psi_e(t) + i\delta t\,(H_{ee}\psi_e(t) + H_{e\mu}\psi_\mu(t)) \\ \psi_\mu(t+\delta t) &= \psi_\mu(t) + i\delta t\,(H_{\mu e}\psi_e(t) + H_{\mu\mu}\psi_\mu(t))\end{aligned}$$

$$P_{ee}(t) = |\psi_e(t)^*\psi_e(0)|^2$$

$$\hat{H} = \begin{pmatrix} H_{ee} & H_{e\mu} \\ H_{\mu e} & H_{\mu\mu} \end{pmatrix} \overset{\text{vacuum}}{=} \frac{\omega}{2}\begin{pmatrix} -\cos 2\theta_V & \sin 2\theta_V \\ \sin 2\theta_V & \cos 2\theta_V \end{pmatrix}$$

Hamiltonian of matter effect

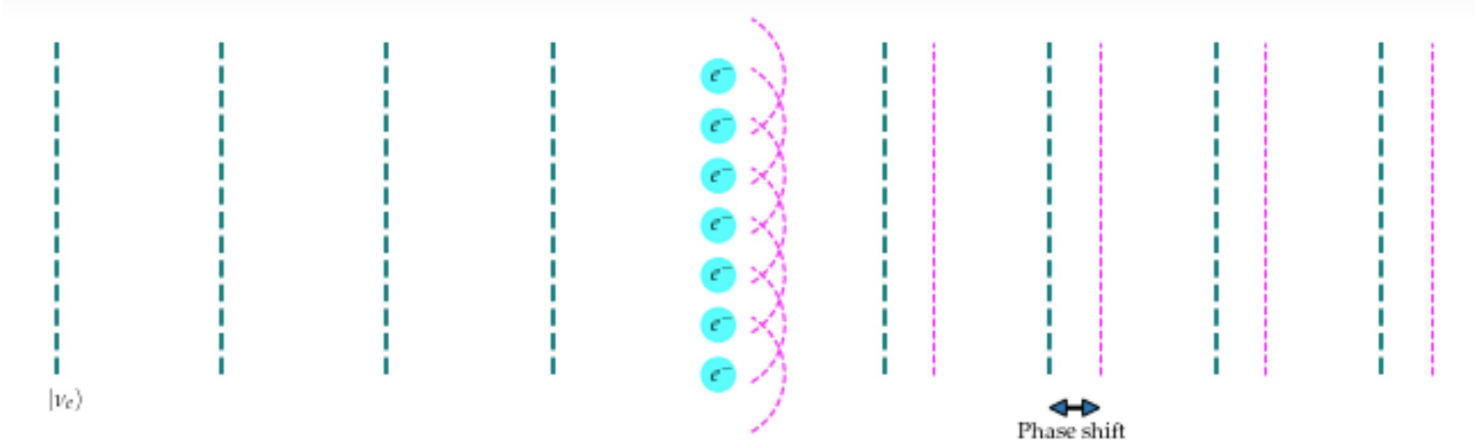
$$\hat{H} = \begin{pmatrix} H_{ee} & H_{e\mu} \\ H_{\mu e} & H_{\mu\mu} \end{pmatrix} \overset{\text{vacuum}}{=} \frac{\omega}{2} \begin{pmatrix} -\cos 2\theta_{\mathrm{V}} & \sin 2\theta_{\mathrm{V}} \\ \sin 2\theta_{\mathrm{V}} & \cos 2\theta_{\mathrm{V}} \end{pmatrix}$$

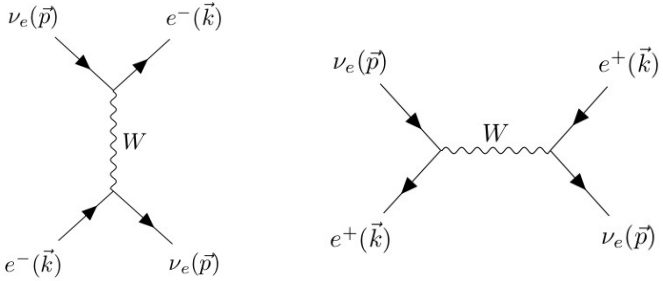
$$\xrightarrow{\text{In matter}} \frac{\omega}{2} \begin{pmatrix} -\cos 2\theta_{\mathrm{V}} & \sin 2\theta_{\mathrm{V}} \\ \sin 2\theta_{\mathrm{V}} & \cos 2\theta_{\mathrm{V}} \end{pmatrix} + \begin{pmatrix} \sqrt{2} G_{\mathrm{F}} (n_{e^-} - n_{e^+}) & 0 \\ 0 & 0 \end{pmatrix}$$

Fermi constant

Number of electrons minus positrons

Coherent forward scattering of neutrinos

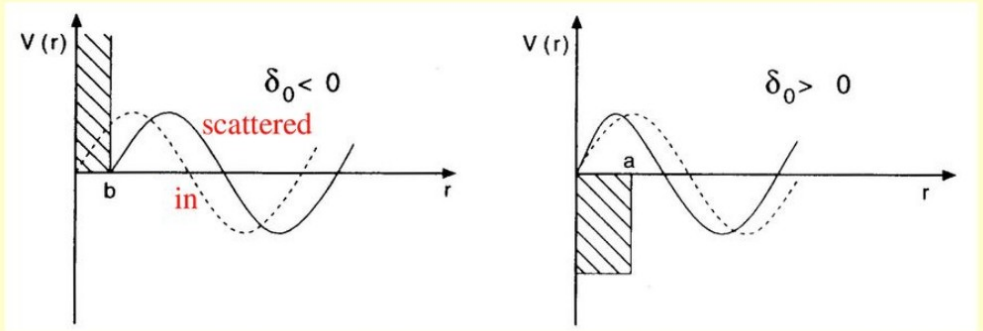




How is it different from scattering?

- Scattering: Momentum i.e., energy and direction changes due to interaction with potential
- Coherent forward scattering: Momentum is unchanged due to the potential, but the there is a phase change.
- Constructive interference in forward direction.

positive (negative) phase shift for attractive (repulsive) potential



Hamiltonian of neutrino self-interactions

Number density of neutrinos

Density matrix for neutrinos and antineutrinos

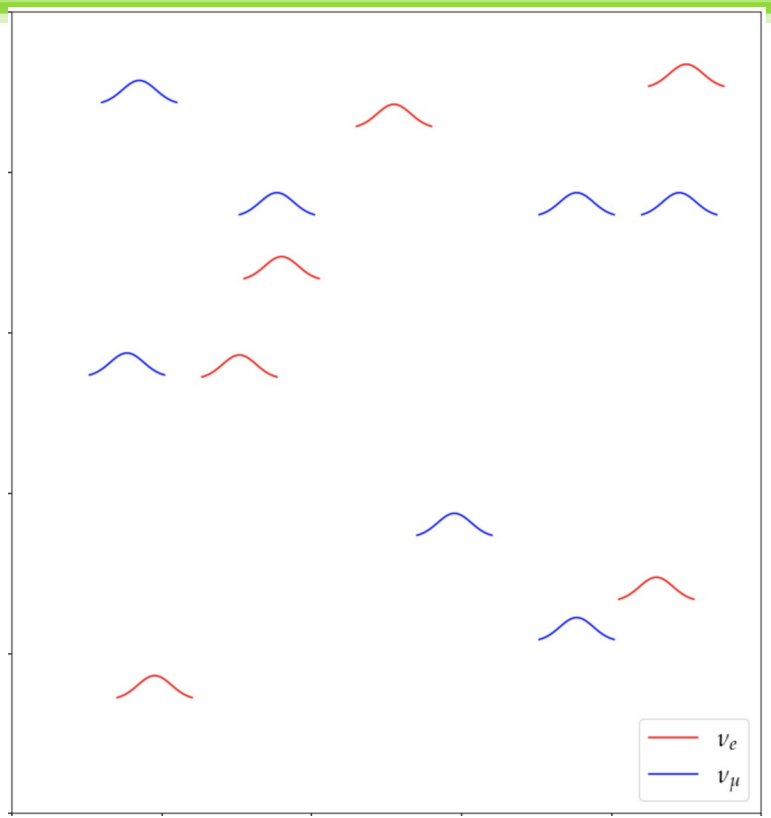
Fermi constant

$$H_{\nu\nu}(\mathbf{v}) = \sqrt{2} G_{\mathrm{F}} n_{\nu} \int (\rho(\mathbf{v}') - \bar{\rho}(\mathbf{v}'))\,(1 - \mathbf{v}\cdot\mathbf{v}')\, d\mathbf{v}'$$

Hamiltonian for neutrino with velocity $\mathbf{v}$

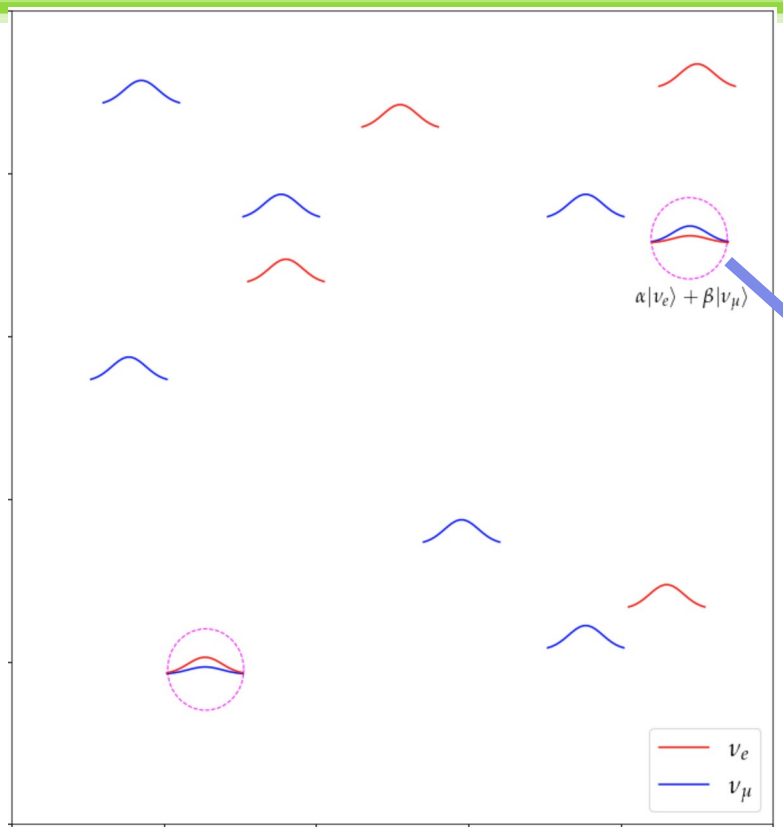
Velocity of neutrino in the medium

What is a density matrix?



$$\rho = \begin{pmatrix} \rho_{ee} & 0 \\ 0 & \rho_{\mu\mu} \end{pmatrix}$$

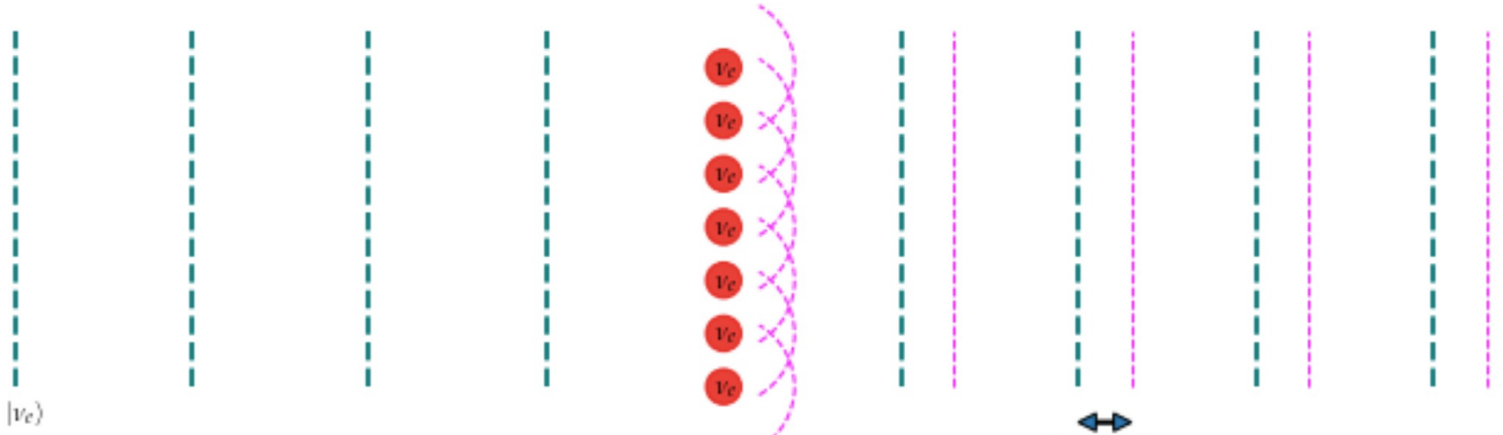
What is a density matrix?

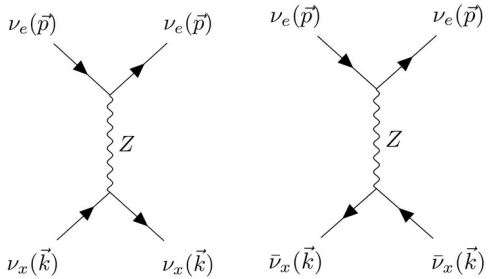


See page 38 of Non-relativistic quantum mechanics by Landau and Lifshitz.

$$\rho = \begin{pmatrix} \rho_{ee} & \rho_{e\mu} \\ \rho^*_{\mu e} & \rho_{\mu\mu} \end{pmatrix}$$

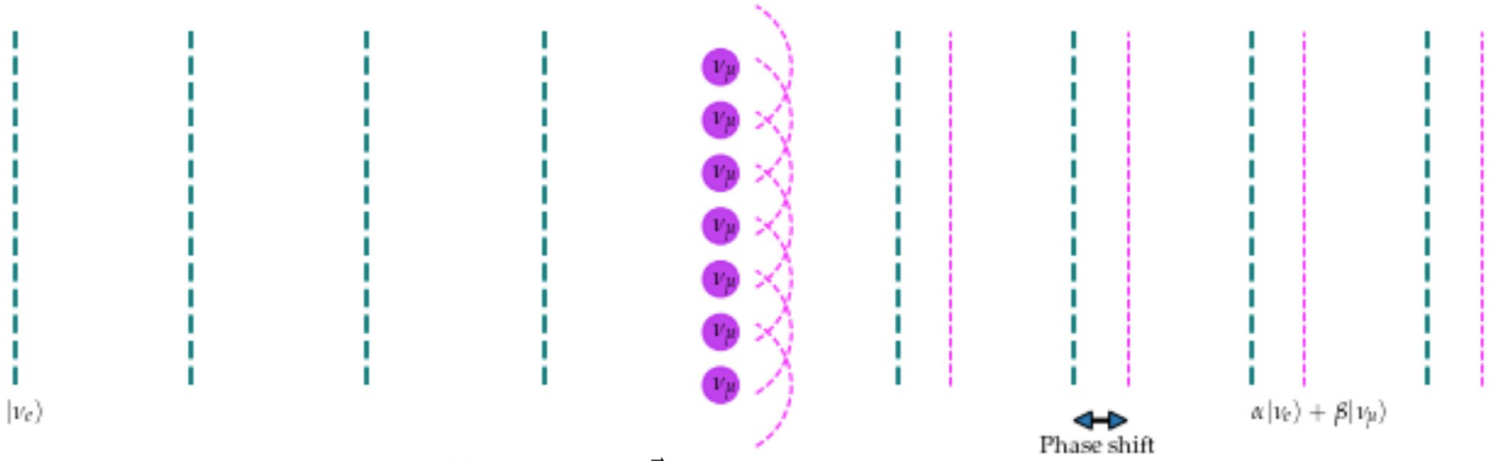
Diagonal terms of neutrino self-interactions

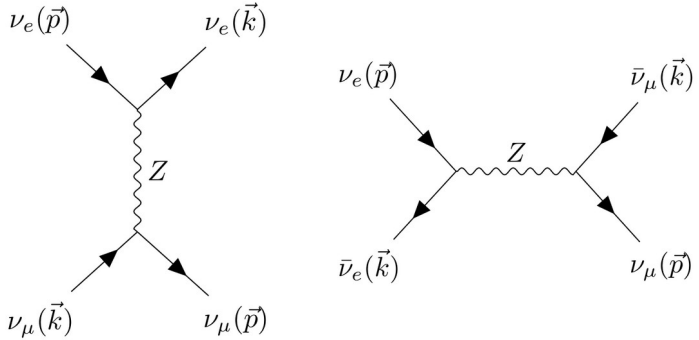




… and more diagrams like these.

Off-diagonal terms of the Hamiltonian





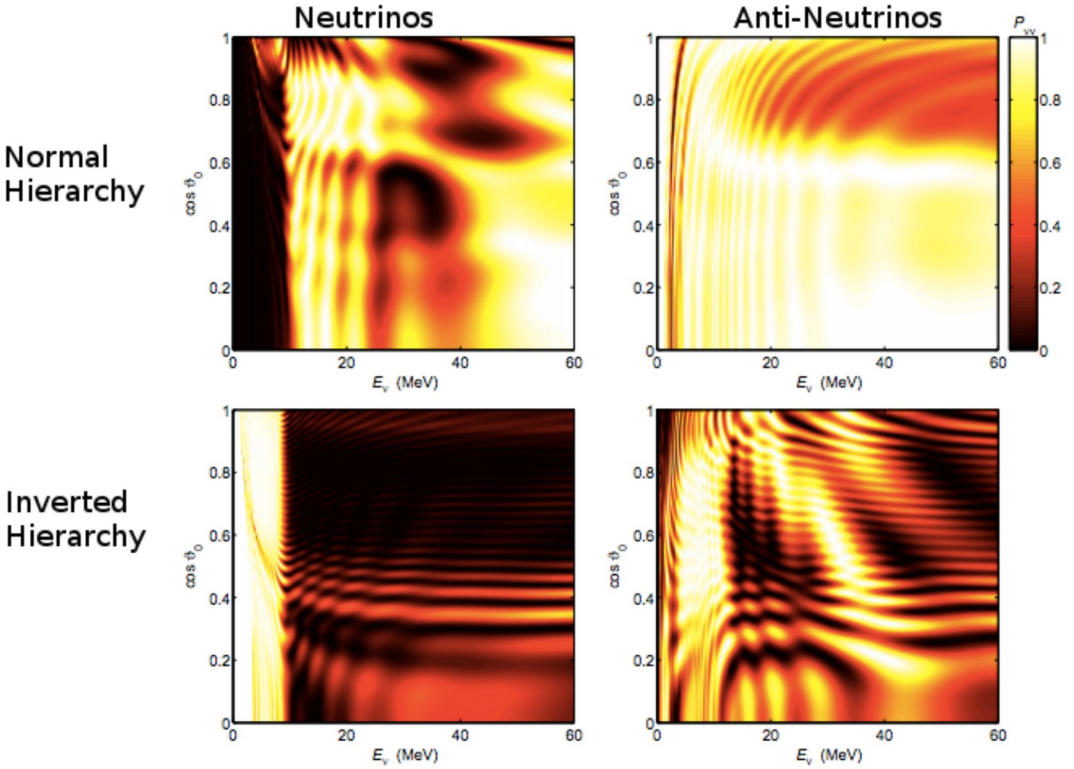
Velocity dependence of the weak interactions

$$H_{\nu\nu} \propto \langle \nu_x(\vec{p})|\gamma^\sigma|\nu_x(\vec{p})\rangle\langle \nu_x(\vec{p'})|\gamma_\sigma|\nu_x(\vec{p'})\rangle$$

$$\langle \nu_x(\vec{p})|\gamma^\sigma|\nu_x(\vec{p})\rangle \propto p^\sigma$$
$$\langle \nu_x(\vec{p'})|\gamma_\sigma|\nu_x(\vec{p'})\rangle \propto p'_\sigma$$

Dimensional argument implies $H_{\nu\nu} \propto p^\sigma p'_\sigma \to \sqrt{2}G_{\rm F} n_\nu (1 - \vec{v}\cdot\vec{v'})$

Phenomenological consequence of self-interactions



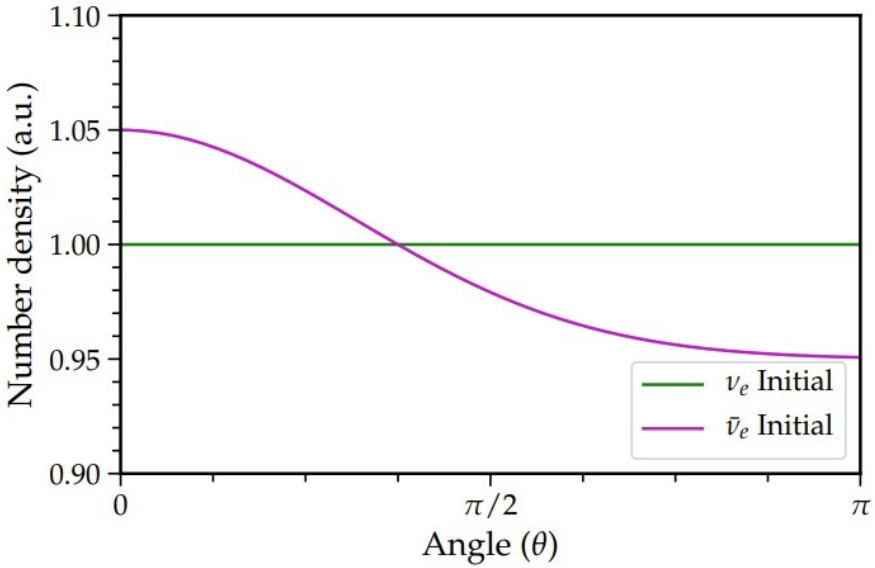
Slow oscillations: Can occur when magnitude of self-interaction potential comparable to the vacuum frequency.

H. Duan, G. M. Fuller, J. Carlson and Y. Z. Qian, [astro-ph/0608050].

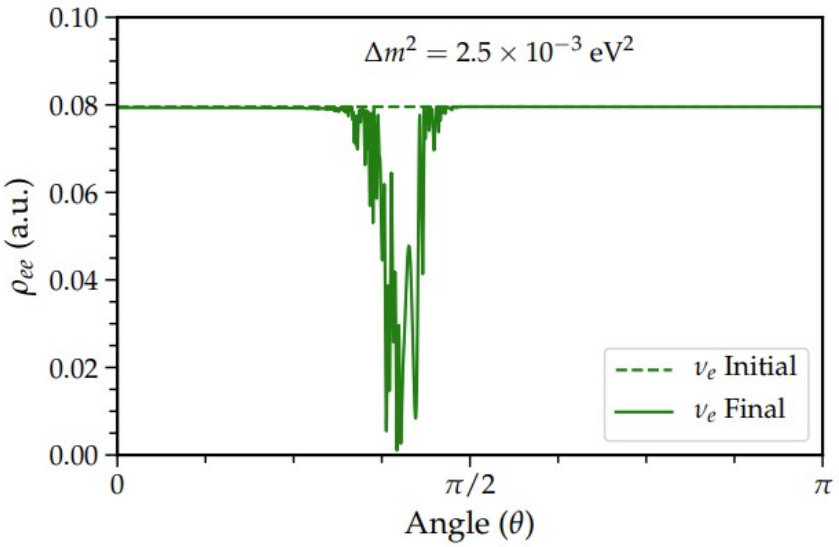
Fast flavor evolution

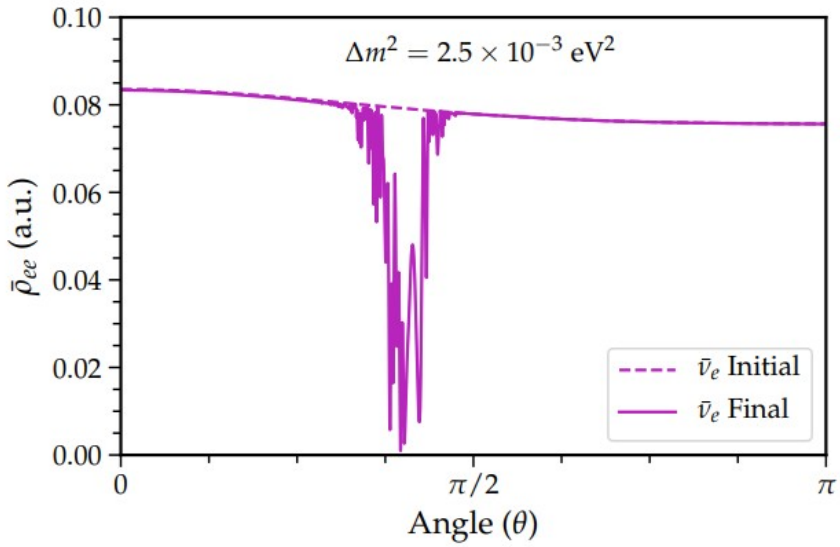
- Electron lepton number crossing essential for fast flavor evolution.
- No upper limit on the number density of neutrinos.

For a review see Tamborra and Shalgar
ArXiv: 2011.01948



Fast flavor evolution

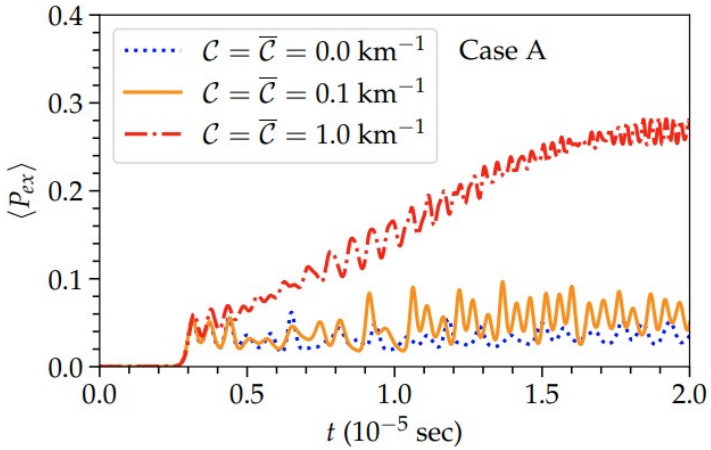




Shalgar and Tamborra, arXiv: 2007.07926

Effect of collisions

- The nonlinear evolution can lead to counterintuitive results.
- Direction changing collision term can lead to enhancement of flavor conversion, for example.



Shalgar and Tamborra, arXiv: 2011.00004

Conclusions

- Coherent forward scattering of neutrinos can significantly modify neutrino flavor evolution.
- The phenomenology of neutrino flavor evolution can become very rich due coherent forward scattering.
- There are several quantum mechanical aspects of neutrino flavor evolution are not well understood.