Neutrino Properties from Astrophysical Sources

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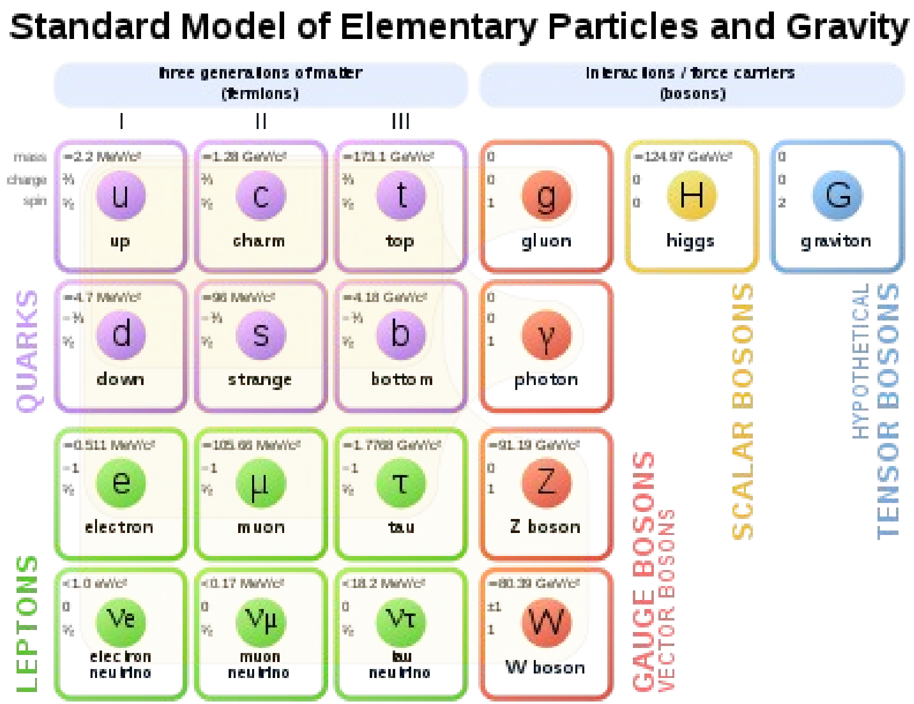
Outline of the talk

- Introduction
- Astrophysical sources
- Neutrino properties: Neutrino flavor evolution (SM and BSM)
- Neutrino properties: Neutrino interactions (SM and BSM)
- Conclusions

Neutrinos ...



- Massless in the Standard Model.
- Only particles to only interact via weak interactions (and gravity).
- In this talk: SM = SM + non-zero neutrino masses.

Properties of Neutrinos

Microscopic:

- Masses of neutrinos and their mass ordering
- Mixing angles
- CP phase
- Couplings, cross section
- Electromagnetic properties

Emergent (Macroscopic):

- Temperature (average energy)
- Pressure
- Energy density
- Flavor evolution

Pros and cons of astrophysical sources

Pros:

- Extreme energy possible
- Large number densities
- Large magnetic field possible
- Very large propagation distance
- …

Cons:

- Source may not be well-modeled
- Source itself may be unknown
- Very large propagation distance
  (Yes, it is here too)
- …

Conversions Vs Collisions

Neutrino properties via conversions (aka transformations or oscillations)

- For eg., Flavor transformation, spin-flip, BSM coupling via coherent forward scattering, existence of sterile neutrinos.

Neutrinos properties via interaction with other particles.

- Standard Model and beyond Standard Model (BSM) couplings.

Neutrino flavor evolution

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

Schrodinger equation for evolution of neutrino flavor in two flavor approximation

In vacuum:

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

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

Vacuum frequency

θ_{V}

Vacuum mixing angle

Terms proportional to identity not physical

Matter effect

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

Charge current

Neutral current

$$H = \frac{\Delta m^2}{4E}\begin{pmatrix}-\cos 2\theta & \sin 2\theta\\ \sin 2\theta & \cos 2\theta\end{pmatrix} + \begin{pmatrix}\sqrt{2}G_{\mathrm{F}}n_e - \sqrt{2}G_{\mathrm{F}}\frac{n_B}{2} & 0\\ 0 & -\sqrt{2}G_{\mathrm{F}}\frac{n_B}{2}\end{pmatrix}$$

Three flavors mixing parameters

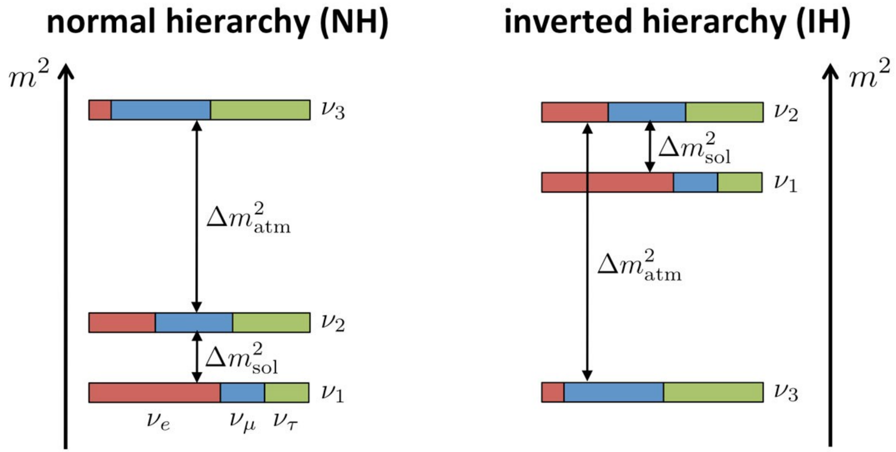
Parameter	value (Normal ordering)
θ_{12}	33.44°
θ_{23}	49.2°
θ_{13}	8.57°
$\Delta m^2_{12} (\Delta m^2_{\mathrm{sol}})$	7.42×10^{-5} eV^2
$\lvert\Delta m^2_{13}\rvert (\lvert\Delta m^2_{\mathrm{atm}}\rvert)$	2.51×10^{-3} eV^2
δ_{CP}	$(169^\circ, 246^\circ)$ $(1\ \sigma)$

$$H = U \mathrm{diag}(0, \Delta m^2_{12}, \Delta m^2_{13}) U^\dagger$$

$$\begin{bmatrix} c_{12} c_{13} & s_{12} c_{13} & s_{13} e^{-i\delta_{\mathrm{CP}}} \\ -s_{12} c_{23} - c_{12} s_{23} s_{13} e^{i\delta_{\mathrm{CP}}} & c_{12} c_{23} - s_{12} s_{23} s_{13} e^{i\delta_{\mathrm{CP}}} & s_{23} c_{13} \\ s_{12} s_{23} - c_{12} c_{23} s_{13} e^{i\delta_{\mathrm{CP}}} & -c_{12} s_{23} - s_{12} c_{23} s_{13} e^{i\delta_{\mathrm{CP}}} & c_{23} c_{13} \end{bmatrix}$$

The large ratio (~30) in the mass-squared differences justifies the use of two-flavor approximations in most (but not all) cases.

Neutrino mass ordering



- Matter effects necessary to see sign of mass-squared difference in two flavor approximation

- Solar mass squared difference is positive.

Neutrino mass ordering using galactic supernova

- Can neutrinos mass ordering be determined using “collective neutrinos oscillations”?

- Matter effect during the neutronization burst.

Supernova neutrinos

- 99 percent of energy released by a core-collapse supernova is in the form of neutrinos.
- Proto-neutron star is so dense that neutrinos are "trapped" in the region for about 10 seconds.
- The initial neutrino flux is mostly electron neutrinos due to electron capture.
- In later stages, thermal emission of neutrinos – Potential experienced by neutrinos due to other neutrinos important (Z-boson exchange).

Hamiltonian of neutrino self-interactions

Number density of neutrinos

Density matrix for neutrinos and antineutrinos

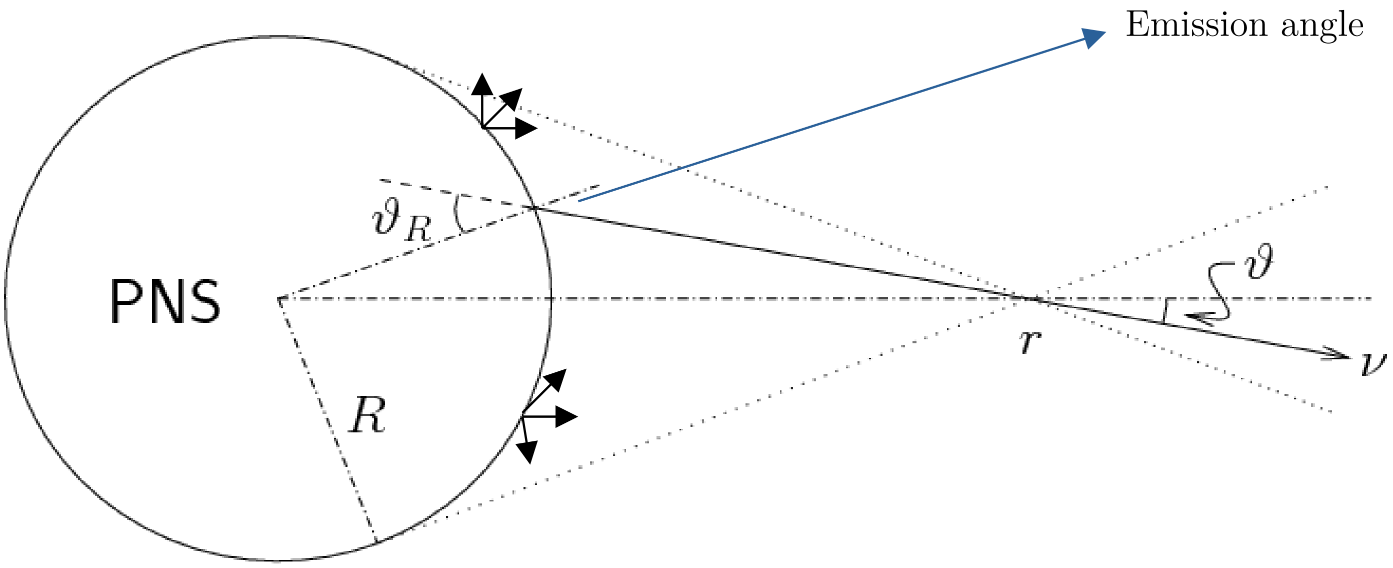
Fermi constant

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

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

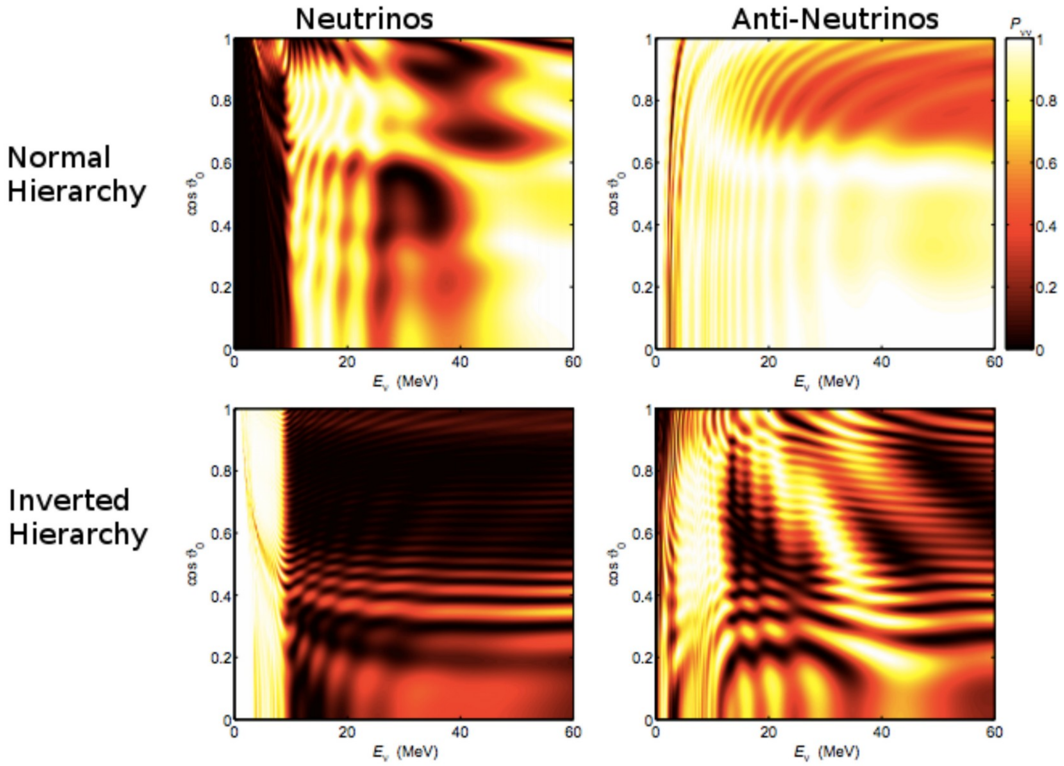
Velocity of neutrino in the medium

Neutrino-bulb model



Duan et.al. ArXiv:0606616

Collective neutrino oscillations



Duan et.al.
ArXiv:0606616

Limitations of the bulb-model

- Perfect spherical symmetry assumed. Not true (see Duan and SS arXiv:1412.7097)

- Neutrino decoupling instantaneous and happens for all flavors and for all energies at the same radius.

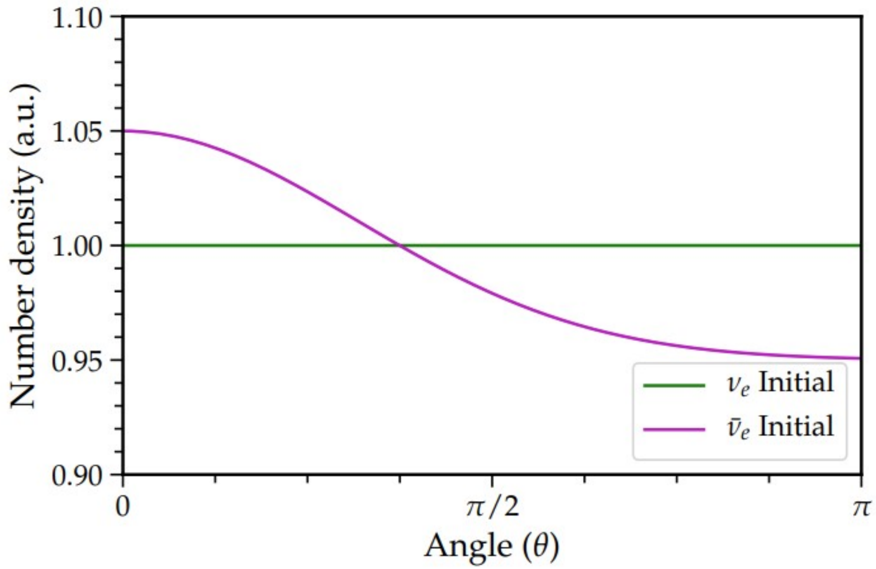
Consequence of these assumptions:

Neutrino flavor transformations start at much lower density (or equivalently at larger radius)

Flavor transformation in high density region

In the decoupling region (Standard Model Physics):

- Fast flavor transformation due to presence of electron lepton number crossing in the decoupling region. (See the talk by Ian Padilla-Gay. See also Tamborra and SS arXiv:2011.01948 & SS and Tamborra arXiv: 1904.07236)



Collective neutrino oscillations

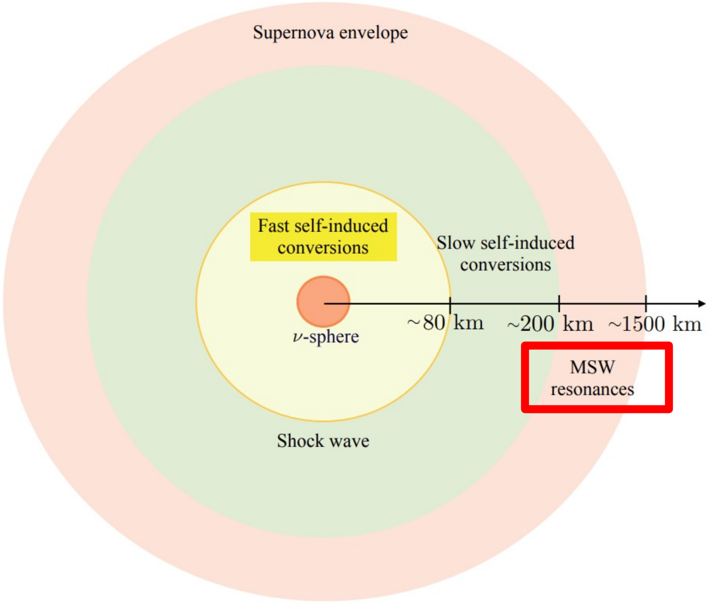
- With our current understanding of collective neutrino oscillations it is not clear whether mass ordering can be measured.

- New complications keep arising as we understand more about the phenomenology of collective neutrino oscillations.

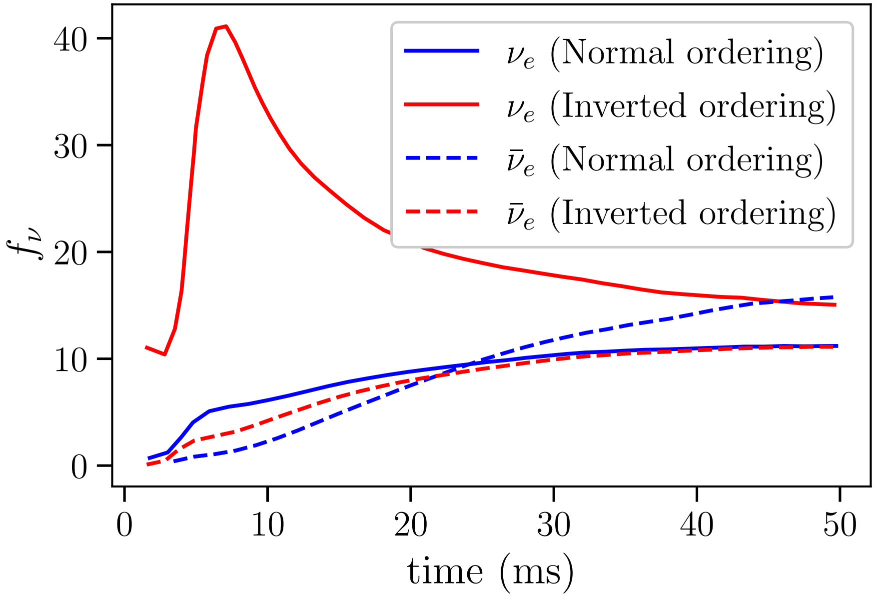
No collective oscillations during neutronization burst

- Electron lepton number approximately conserved in collective neutrino oscillations.
- Only electron neutrinos emitted in the first ~10 ms
- No collective oscillations possible

Supernova neutrinos and mass ordering



Tamborra and SS ArXiv: 2011.01948



Dighe et.al. Arxiv:hep-ph/9907423

De Gouvea et.al. ArXiv:1910.01127

Neutrino interactions

- **Neutrino-Nucleon scattering (BSM):** Additional mediator which couples to neutrinos and nucleons. Implies nucleon-nucleon and neutrino-neutrino scattering.

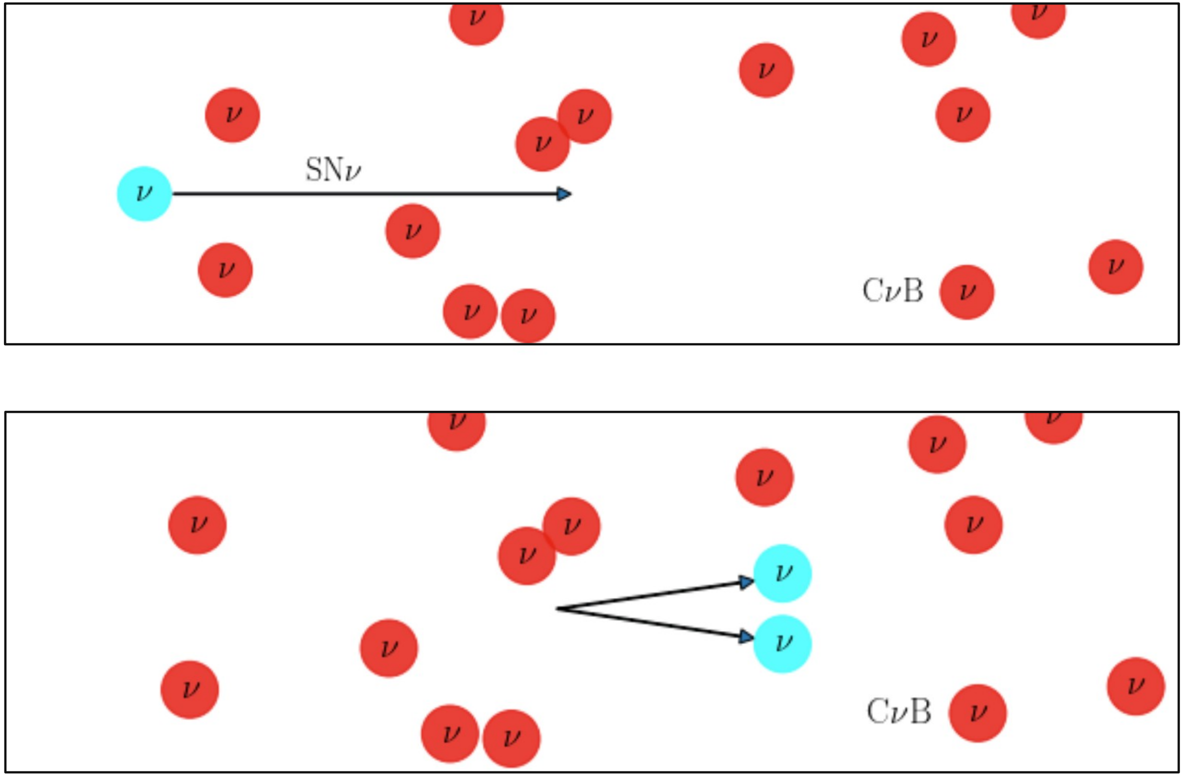
- **Neutrino-Neutrino scattering (BSM):** Laboratory constrains from emission of new mediator by final state neutrino. Are astrophysical constrains competitive?

Secret neutrino interactions

Motivations for secret neutrino interactions:

- It is possible that effects due to non-Standard interactions affect neutrino sectors more than others.
- Theoretical motivation: Why not?
- Phenomenological motivation: Neutrino sector is the least constrained from the point of view of searches of physics beyond the Standard Model.

Secret neutrino interactions: Supernova (propagation)



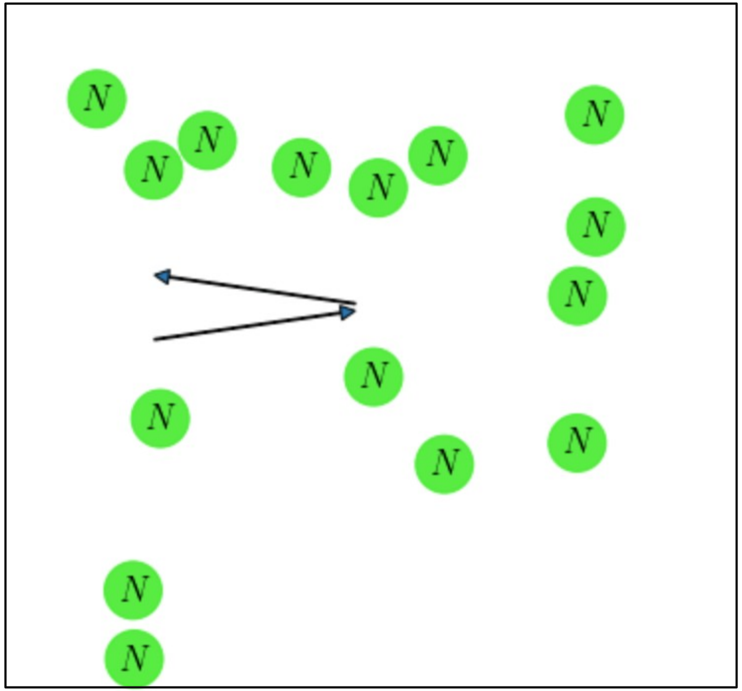
Shalgar et.al. ArXiv:1912.09115

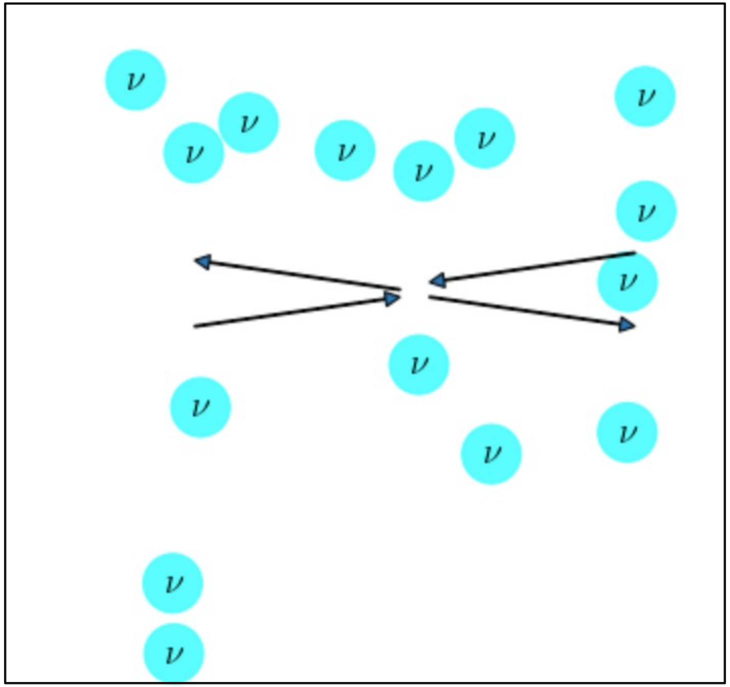
Secret neutrino interactions: within the core

- Can thermodynamic properties of neutrinos change within the core due to secret neutrino interactions?

- Can neutrino-neutrino collisions delay the escape of neutrinos from the supernova core?

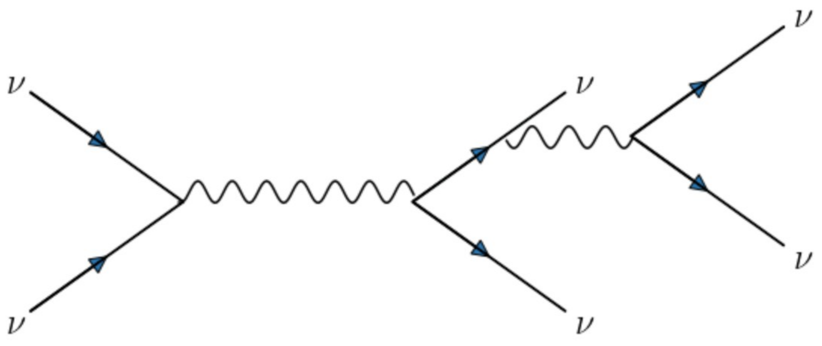
Conservation of momentum: No delay



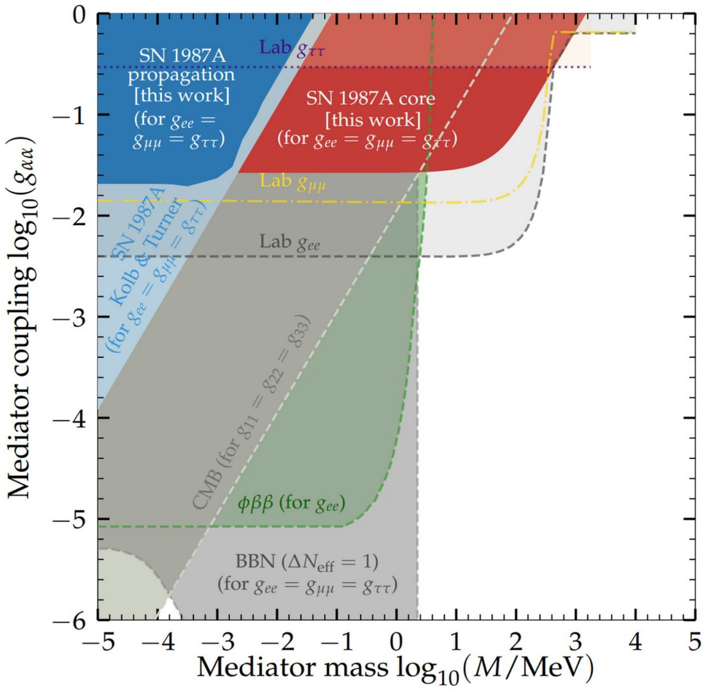


Shalgar et.al. ArXiv:1912.09115

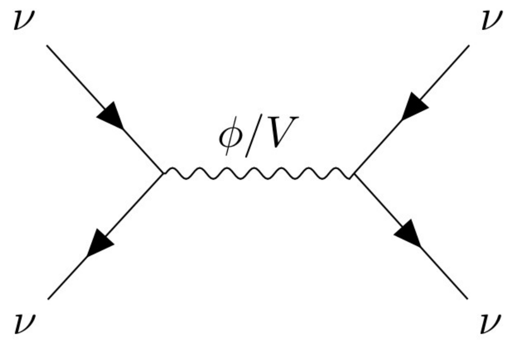
Secret neutrino interactions: 2 to 4 cross section

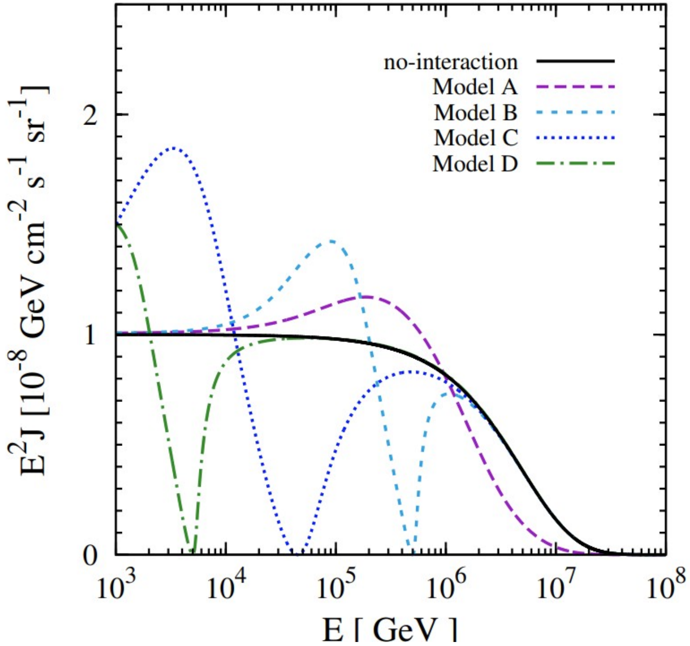


Shalgar et.al. ArXiv: 1912.09115



Secret neutrino interactions and high energy neutrinos





Ng et.al. ArXiv:1404.2288

See also Bustamante et.al ArXiv:2001.04994

Much more ...

- Sterile neutrinos (Suliga et.al. ArXiv:2004.11389)
- Non-Standard interactions (matter effect) (Barranco et. al. ArXiv:0711.0698)
- Tests of lepton number violation
- Electromagnetic properties of neutrinos (magnetic moments)
- Neutrino lifetime (decaying neutrinos) (Berryman et.al. ArXiv:1411.0308)
- Mass-varying neutrinos (Fardon et.al. astro-ph/0309800)

Conclusions

- Astrophysical systems are complementary to laboratory experiments for the study of neutrino properties.
- We have long way to go before we can use collective oscillations to study neutrino properties.
- Physics beyond the Standard Model is least constrained in the neutrino sector.

Backup slides

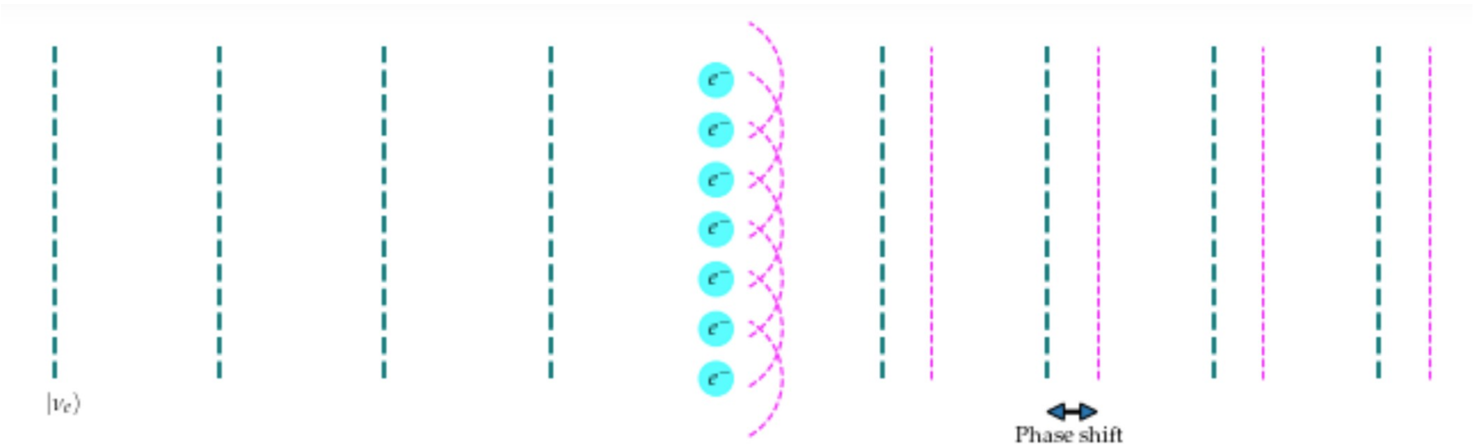
Neutrino oscillations: What is it? (Backup)

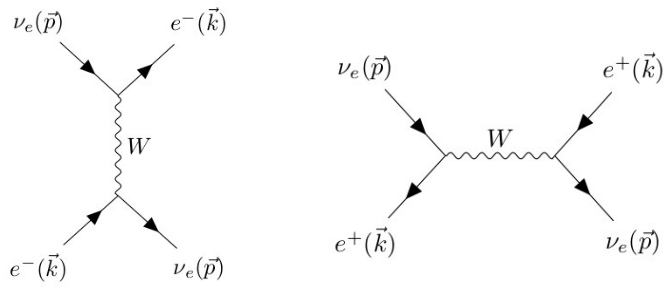
- Flavor oscillations is like the phenomenon of beats.

$$\lambda_{\text{de Broglie}} = \frac{\hbar c}{E} \approx \frac{197 \text{ MeV-fm}}{\sim 10 \text{ MeV}} \approx 20 \text{ fm}$$

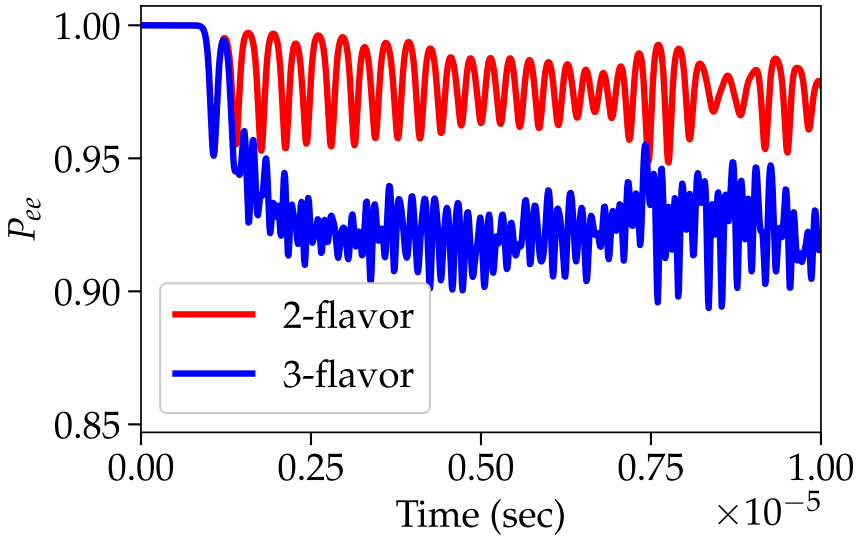
Beats or flavor oscillations occur over length of order kilometers due to the small difference in the dispersion relation for different neutrinos.

Coherent forward scattering of neutrinos (Backup)





Two Vs Three flavors (Backup)



- Justification for 2 flavor approximations: solar mass-squared difference 30 times lower than atmospheric mass-squared difference.
- Why should that be a justification for fast flavor evolution? It is not.

See also Capozzi et.al. ArXiv: 2005.14204 and Shalgar et.al. ArXiv: 2103.12743

Non-Standard Matter effect (Backup)

$$H_{\text{mat+NSI}} = \sqrt{2}G_{\text{F}}n_e \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{\mu e} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{\tau e} & \epsilon_{\tau\mu} & \epsilon_{\tau\tau} \end{pmatrix} \qquad \epsilon_{ij} \lesssim 0.1$$

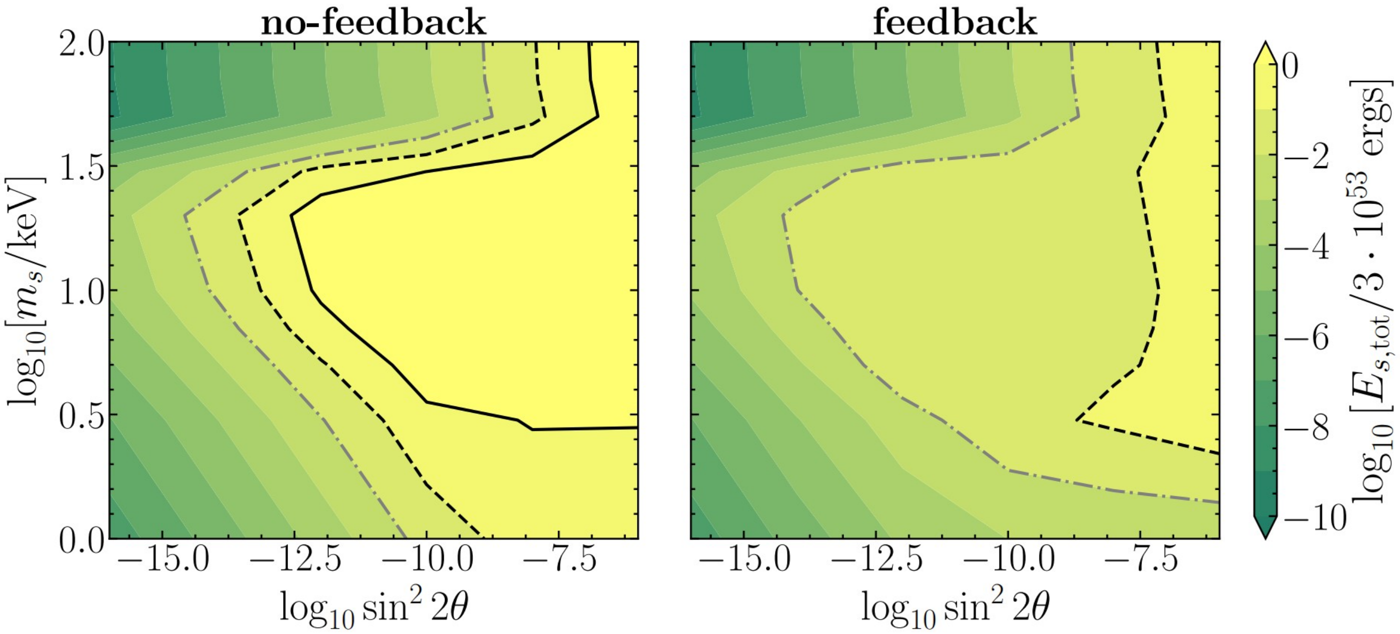
See for eg. Barranco et. al. ArXiv:0711.0698

Sterile neutrinos and energy transfer (Backup)

- Sterile neutrinos can take away energy from the core of a supernova cooling it much faster.

- If sterile neutrinos are reconverted back to active neutrinos in the "gain region" then sterile neutrinos can help in explosion.

Limits on sterile neutrinos (Backup)



Suliga et.al. ArXiv:2004.11389

Neutrino interactions (Backup)

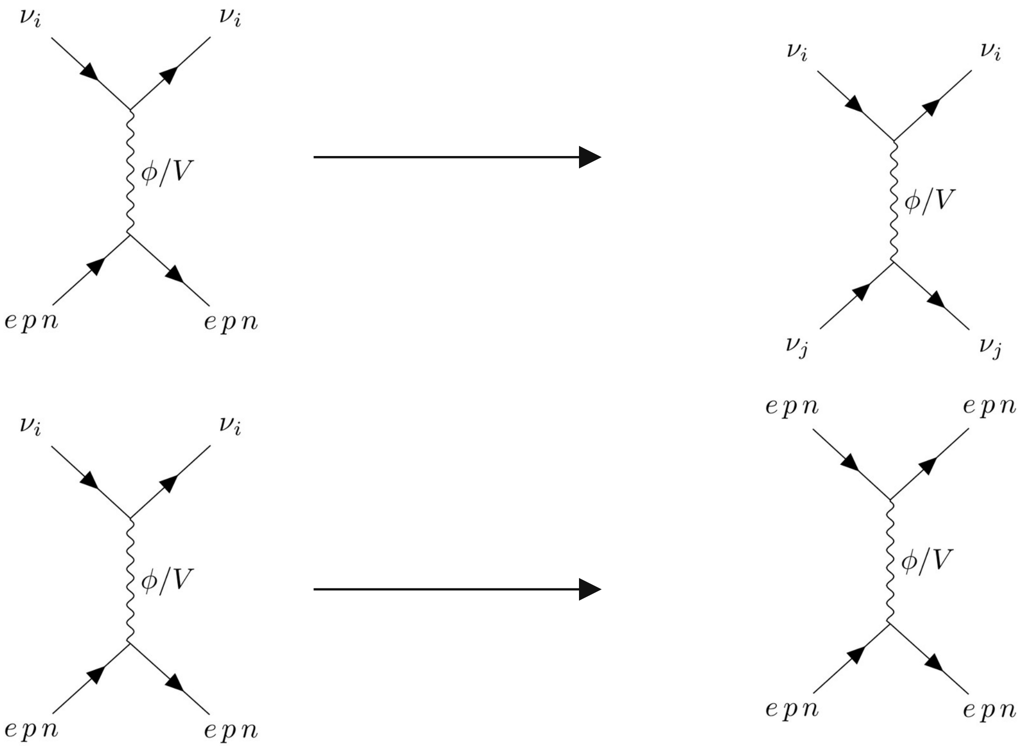
Neutrino-Nucleon scattering:

- Additional mediator which couples to neutrinos and nucleons

Implies at least one of the following:

- **Nucleon-Nucleon scattering**
- **Neutrino-Neutrino scattering**

Non-Standard Interactions (Backup)



Sterile Neutrinos

- Could there exist neutrinos that do not participate in weak interactions?
- Could be dark matter candidates
- Sterile neutrinos, if they exist can play a vital role in energy transport.
- Are primarily produced due to neutrino mixing.

Non-Standard Interactions

- Non-Standard interactions between nucleons can affect nuclear fusion reactions rates. (See Suliga, SS, and Fuller arXiv: 2012.11620)

- Non-Standard interactions cannot be seen in isolation. All the consequences of a non-Standard interaction has to be taken into account.

Neutrino oscillations: What is it?

- Weak Hamiltonian does not commute with propagation Hamiltonian.

$$[H_{\text{prop}}, H_{\text{weak}}] \neq 0$$

- This implies that the two Hamiltonians do not have simultaneous eigenstates.

$$|\nu_\alpha\rangle = U_{\alpha i}|\nu_i\rangle$$

$|\nu_\alpha\rangle$ Flavor eigenstates

$|\nu_i\rangle$ Propagation eigenstates