Supernova Neutrinos

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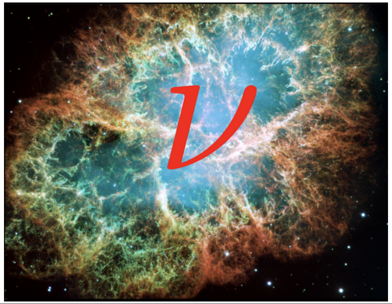
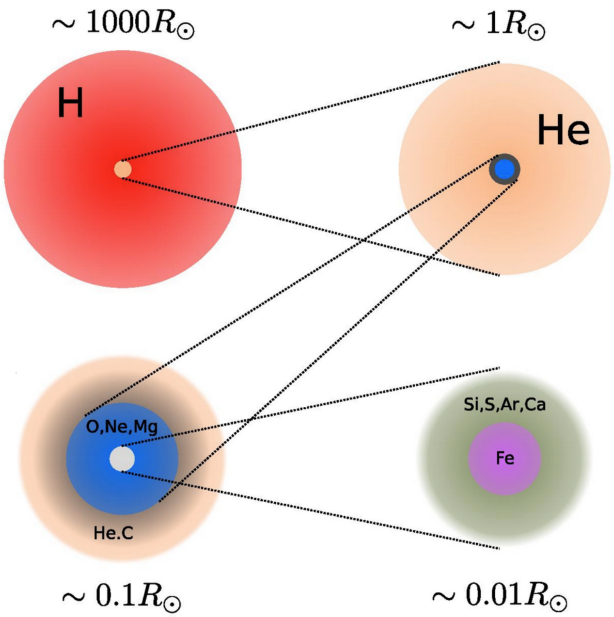


VILLUM FONDEN

Outline of the talk

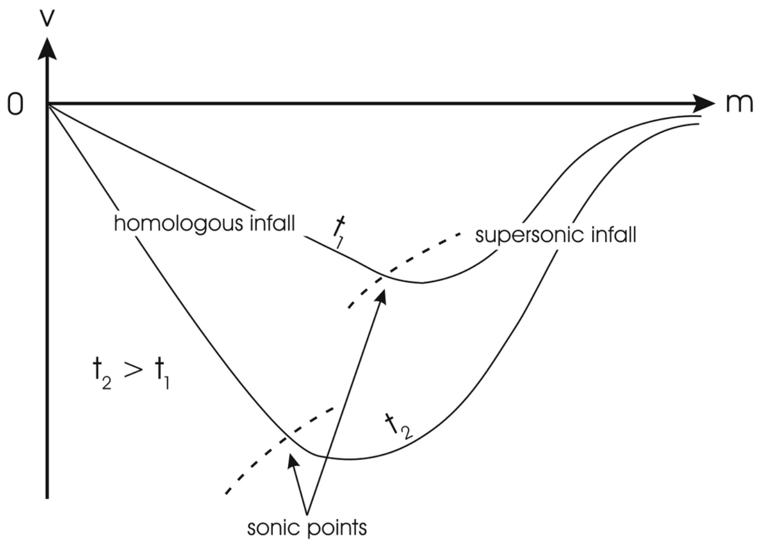
- Core-collapse supernovae
- Role of neutrinos
- R-process nucleosynthesis
- Neutrino oscillations
- Conclusion

What is a (core-collapse) supernova?



- Stars heavier than about 8 times the mass of the Sun for a onion like structure with heavier elements at the center.
- Iron is the most stable element (in terms of binding energy per nucleon)
- Energy cannot be released by fusion of Iron and heavier elements.

The collapse of the core ...

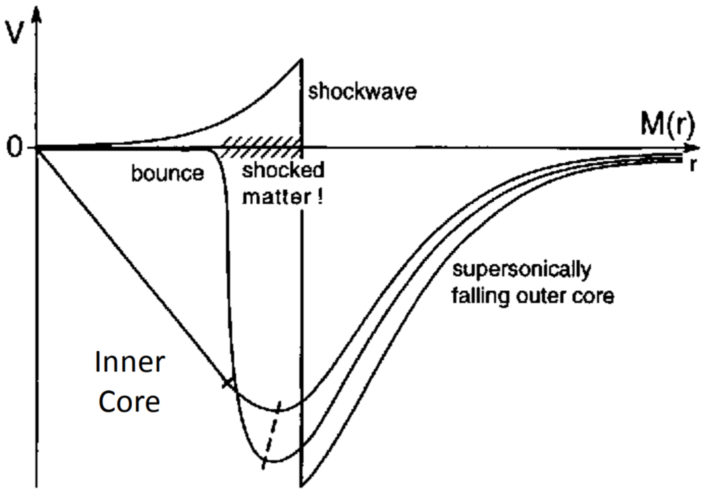


Stellar Structure and Evolution: Kippenhahn et.al. (1990)

- Inner core undergoes a "homologous" collapse, until nuclear densities are reached.

- The outer part, which is in free-fall slams onto the inner core with supersonic speeds.

… and the bounce.



E Müller: Saas-Fee Lectures (1998)

- When the inner core reaches nuclear density the infalling outer core slams into it.
- The inner core ‘bounces back’.
- This results in a shockwave that propagates outwards.

The stalling of the shockwave ...

- The shock-wave produced by the bounce is supposed to blow up the outer envelope.

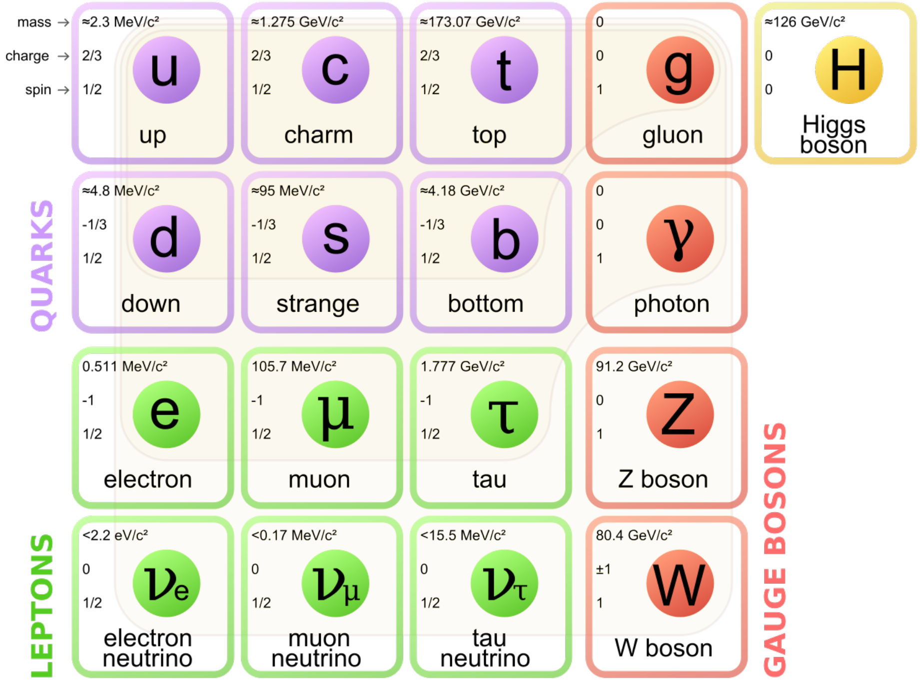
- Numerical simulations showed that the shockwave looses energy while propagating in the outer core.

- The shockwave looses energy because it dissociates Iron group nuclei.

Neutrinos to the rescue ...

- 99 percent of energy released by the supernova is in the form of elementary particles called neutrinos, which only interact via weak interactions (and gravity).

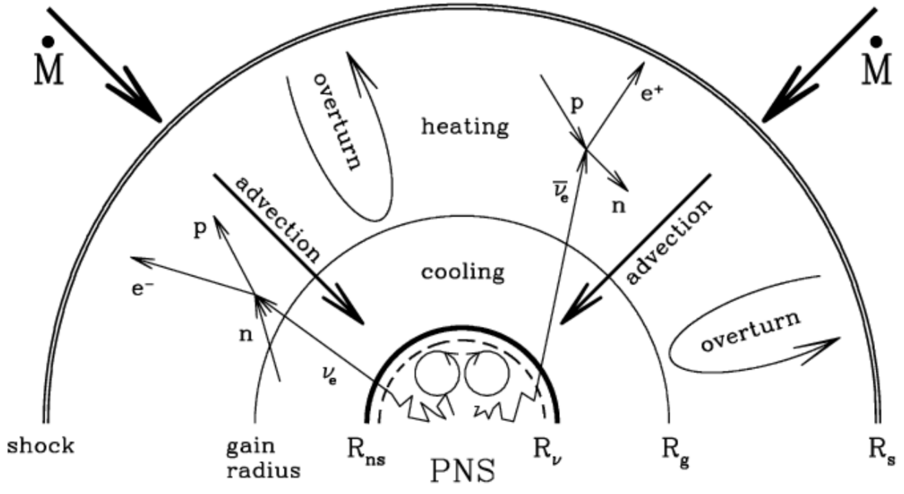
- Neutrinos come in three flavors: electron, muon, tau – and their anti-particles.



Neutrinos to the rescue …

- Bethe and Wilson proposed that if a small fraction of this energy, which is in the form of neutrinos

- If it is deposited in the right place at the right time, the resulting hydrodynamical instability and revive the shock.



Janka, arXiv:0008432

Energy is deposited by neutrinos in the gain region.

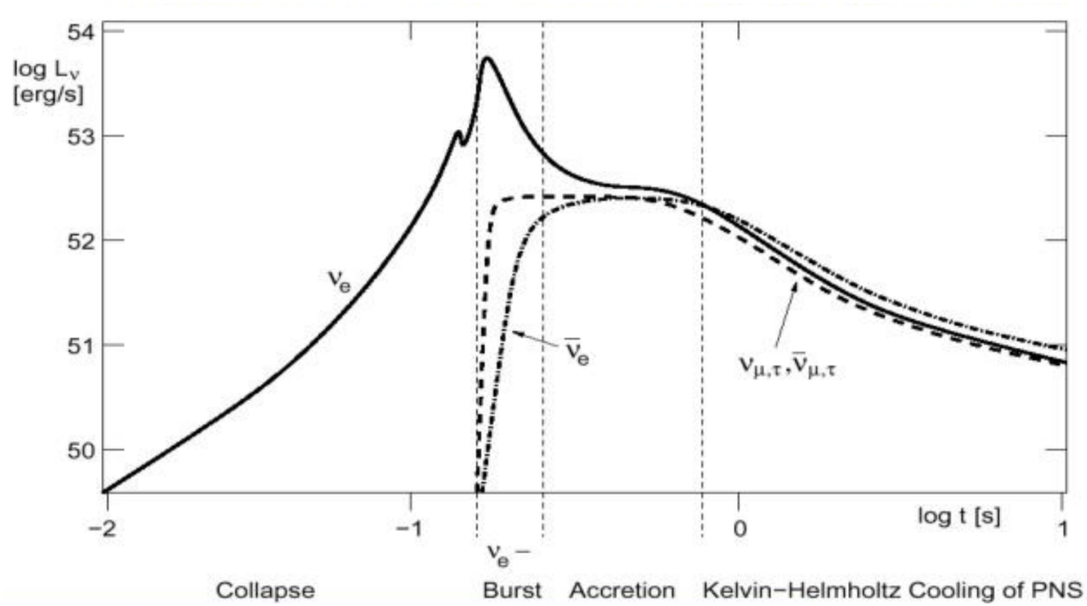
- Number of neutrinos emitted.

- Energy of the neutrinos. Because cross section of neutrinos with matter increases with energy.

- And their flavor, because …

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

Neutrino Luminosity



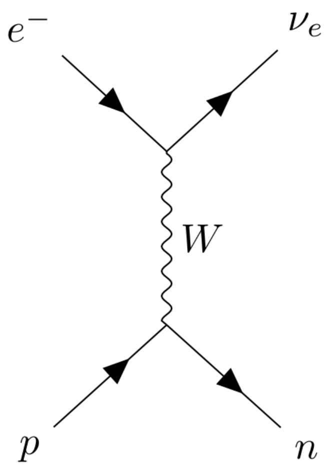
Total Luminosity of Sun = 3.8×10^{33} ergs/s

Neutrino Luminosity of Sun = 8.7×10^{31} ergs/s

Neutrino production: Neutronization burst

- In the first 10-20 milliseconds most of the neutrino emission is due to electron capture.

- This happens too early in the supernova to affect supernova dynamics.



Neutrino production: Thermal processes

- In later stages (after 10-20 milliseconds), neutrinos are produced by thermal processes.
- Neutrinos of all flavors are emitted with luminosities that are of the same order of magnitude.
- All non-electron flavored neutrinos have identical spectrum.

Thermal processes:

- Bremsstrahlung:

$$N + e \rightarrow N + e + \nu + \bar{\nu}$$

- Photoneutrino:

$$\gamma + e \rightarrow e + \nu + \bar{\nu}$$

- Plasmon decay:

$$\gamma^* \rightarrow \nu + \bar{\nu}$$

- ... and others.

Energy of neutrinos

- The density in the core is so large that neutrinos are not free-streaming. They are “trapped”.
- The average energy of the neutrinos is determined by the temperature of the medium. <E>~10 MeV.
- At larger radii (~O(10) km) the density is low enough for neutrinos to start free streaming.

Energy of neutrinos

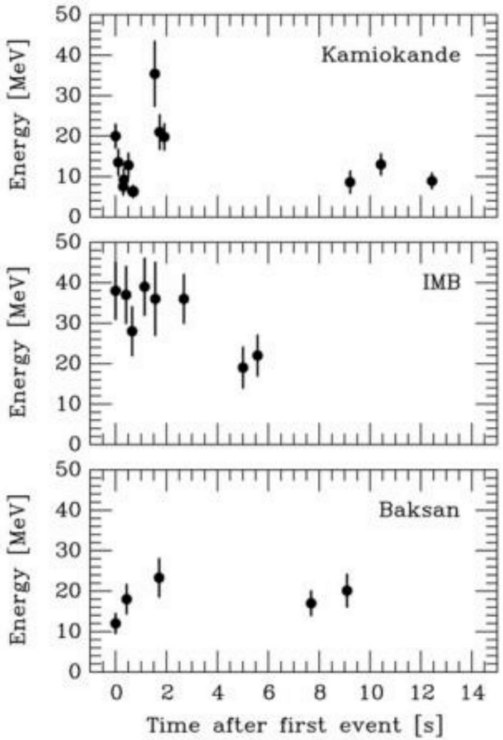
- The average energy is determined by the temperature at the radius where decoupling occurs.
- Non-electron neutrinos interact the least and they escape at a smaller radius, and hence have a larger average energy.
- Electron neutrinos have the lowest average energy.

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

Evidence for neutrino emission by supernovae ...

- On 23rd February, 1987 25 neutrinos were detected within a span of 13 seconds.

- This was due to a core-collapse supernova that exploded in the Large Magellanic Cloud (a satellite galaxy of ours).



Supernova 1987A

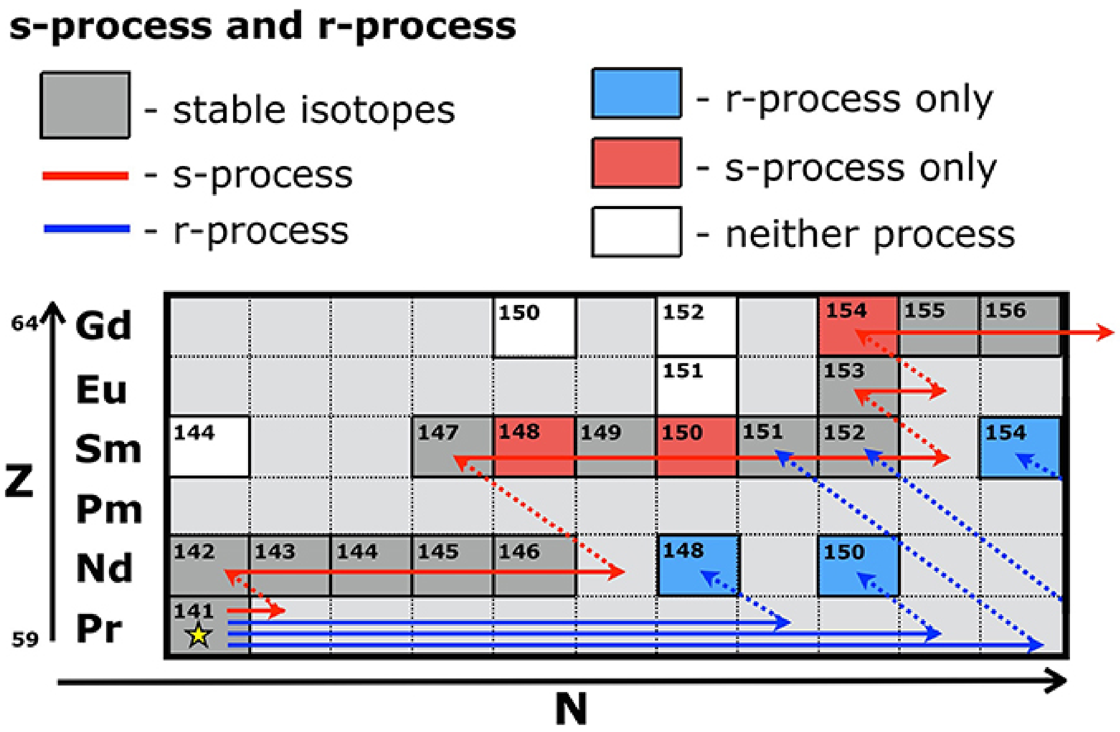
R-process nucleosynthesis

- Elements heavier than Iron can only be produced in cataclysmic events like supernovae or neutron star mergers.

- Some elements like Gold, Platinum, Silver etc., can only be produced by r-process nucleosynthesis.

- Neutrinos affect the r-process nucleosynthesis.

R-process nucleosynthesis



Role of neutrinos ...

- R-process nucleosynthesis requires neutron rich environments.

- Neutron abundance in a medium is affected by neutrinos.

- The ratio of electron neutrinos to electron anti-neutrinos, and their energies affect the following reaction rates:

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

Neutrino Oscillations.

- Neutrino flavor is not conserved. A neutrino emitted as one flavor can be change flavor as it travels. Commonly known as neutrino oscillations.

- Neutrinos experience refraction (coherent forward scattering) due to matter and other neutrinos present in the medium.

- The effect of refraction due to other neutrinos makes the neutrino flavor evolution non-linear.

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:

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

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

θ_{V} Vacuum mixing angle

Terms proportional to identity not physical

Neutrino flavor evolution

Amplitude of survival

$$\psi_e(t+\delta t) = \psi_e(t) + i\delta t\left(H_{ee}\psi_e(t) + H_{e\mu}\psi_\mu(t)\right)$$
$$\psi_\mu(t+\delta t) = \psi_\mu(t) + i\delta t\left(H_{\mu e}\psi_e(t) + H_{\mu\mu}\psi_\mu(t)\right)$$

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

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

Hamiltonian of matter effect

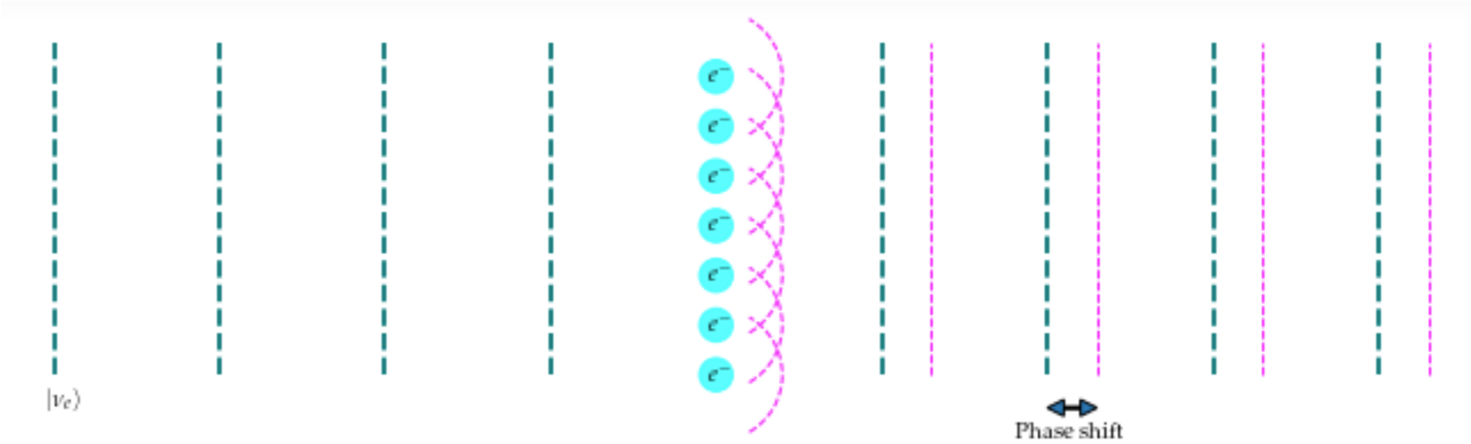
$$\hat{H} = \begin{pmatrix} H_{ee} & H_{e\mu} \\ H_{\mu e} & H_{\mu\mu} \end{pmatrix} \overset{\text{vacuum}}{=} \frac{\omega}{2}\begin{pmatrix} -\cos 2\theta_{\mathrm{V}} & \sin 2\theta_{\mathrm{V}} \\ \sin 2\theta_{\mathrm{V}} & \cos 2\theta_{\mathrm{V}} \end{pmatrix}$$

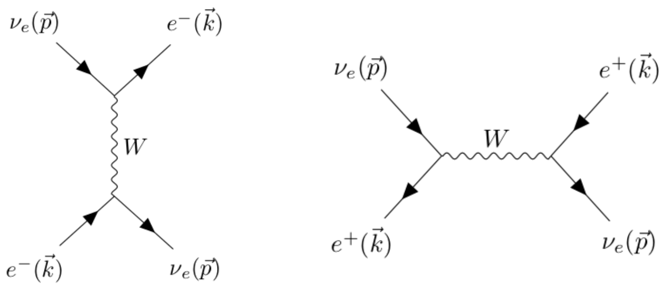
$$\xrightarrow{\text{In matter}} \frac{\omega}{2}\begin{pmatrix} -\cos 2\theta_{\mathrm{V}} & \sin 2\theta_{\mathrm{V}} \\ \sin 2\theta_{\mathrm{V}} & \cos 2\theta_{\mathrm{V}} \end{pmatrix} + \begin{pmatrix} \sqrt{2}G_{\mathrm{F}}(n_{e^-} - n_{e^+}) & 0 \\ 0 & 0 \end{pmatrix}$$

Fermi constant

Number of electrons minus positrons

Coherent forward scattering of neutrinos





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

Collective neutrinos oscillations ...

- In the interior of core-collapse supernova neutrino density is large and the refraction of neutrinos due to other neutrinos becomes important.

- In the presence of these neutrino self-interactions (due to exchange of Z-bosons), the neutrino flavor evolution of neutrinos with different momenta is correlated. This is call collective neutrino oscillations.

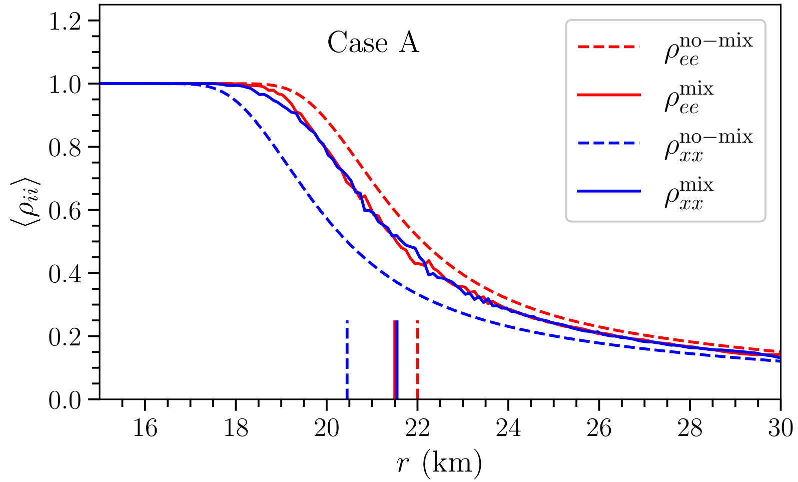
- Collective neutrino oscillations can happen in very dense regions and affect the dynamics of core-collapse supernovae.

Collective neutrino oscillations.

- Due to collective neutrino oscillations the radius at which various flavors decouple can change.

- This in turn can affect their average energy.

- This is not included in hydrodynamical simulations of supernovae.



Shalgar and Tamborra, arXiv:2206.00676

Conclusions

- Neutrinos play a major role in our understanding of core-collapse supernovae.
- The large number density of neutrinos is the dense environment of supernovae can lead to flavor evolution that can affect the dynamics of supernovae.
- Supernova neutrinos can also be a probe for us to understand supernovae.