Neutrinos in Core-collapse Supernovae: The Role of Neutrino Flavor Evolution in the Explosion Mechanism

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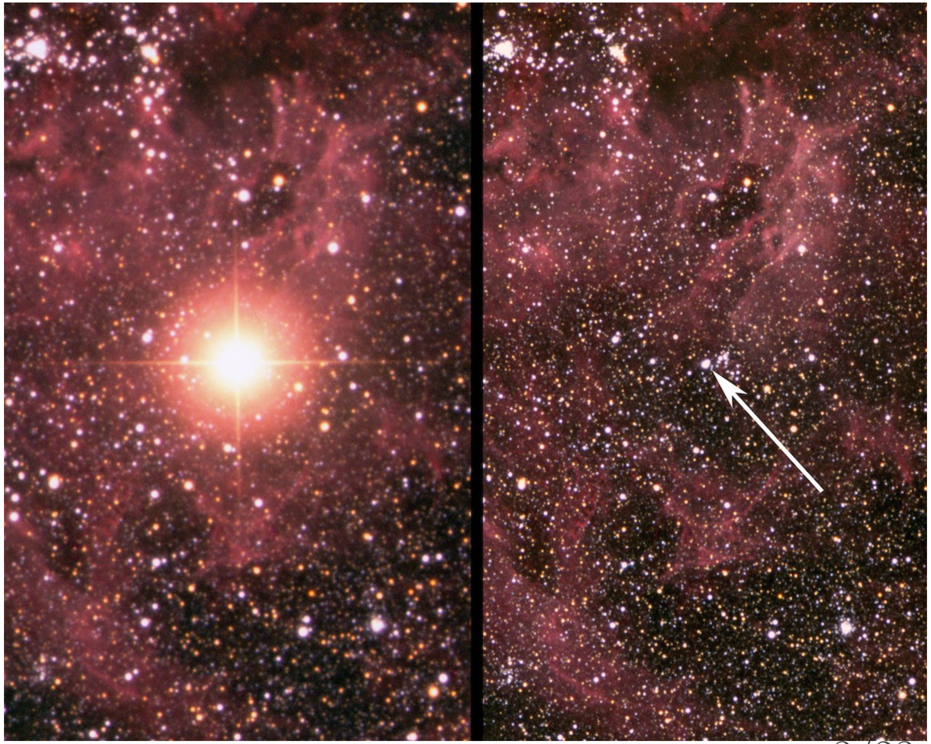
Outline

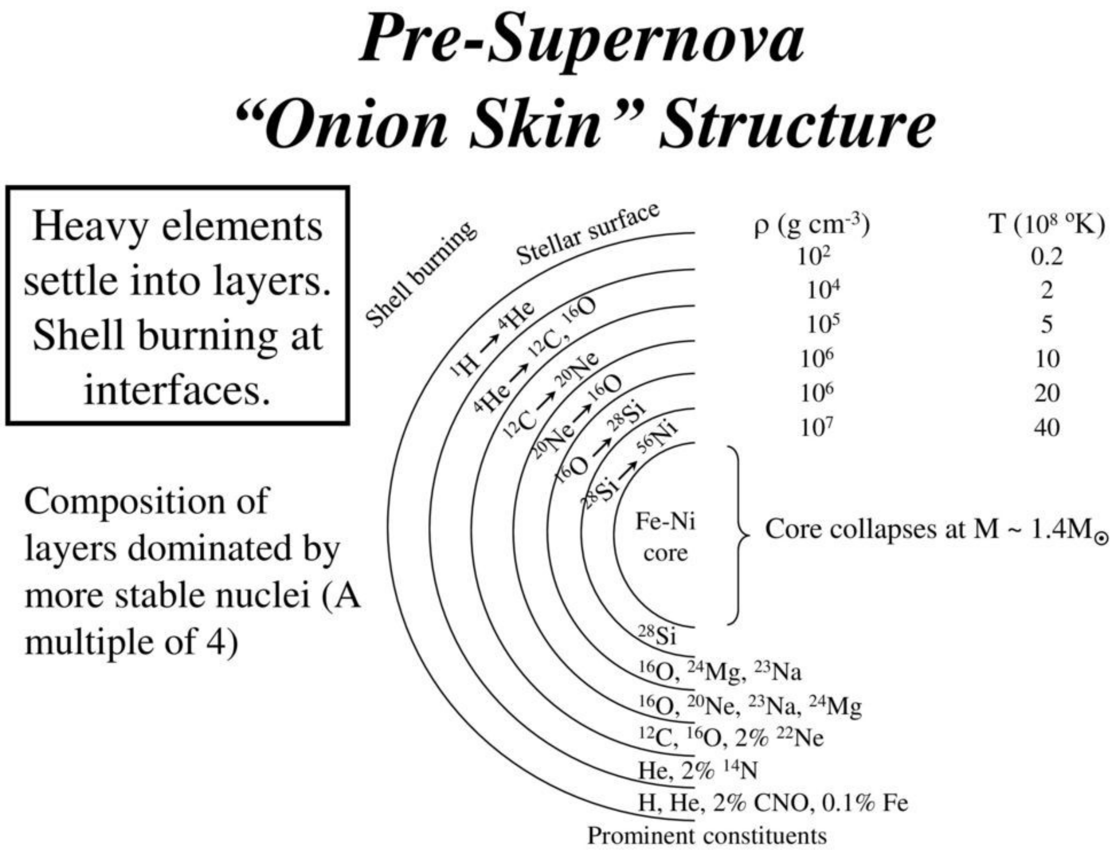
- Core-collapse supernovae.
- Role of neutrinos in core-collapse supernovae.
- Neutrino transport.
- Neutrino flavor evolution.
- Role of neutrino flavor evolution in core-collapse supernovae.

Introduction: Core-collapse Supernovae

Stars which have a mass of more than 8 solar masses die in a cataclysmic explosion called core-collapse supernovae.

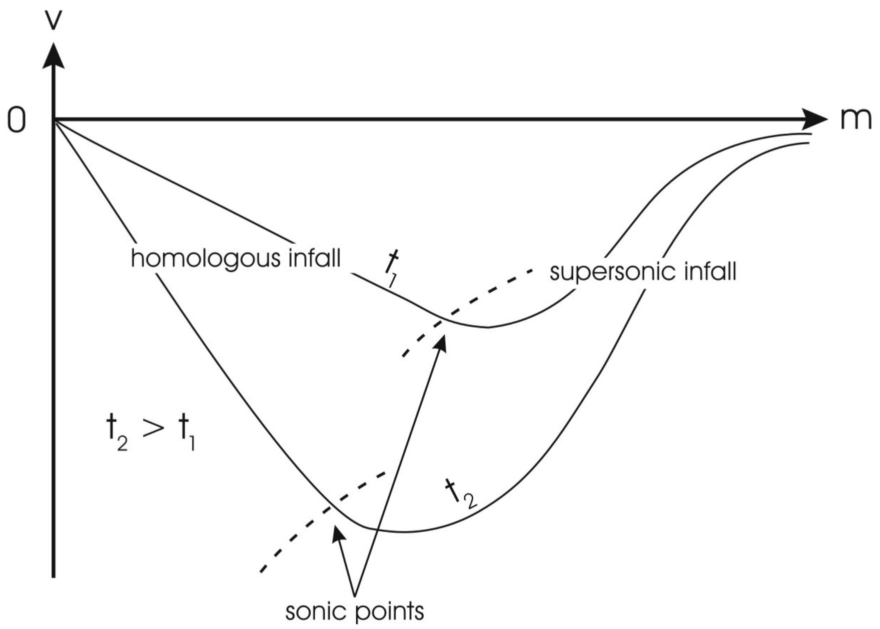


The beginning of the end ...



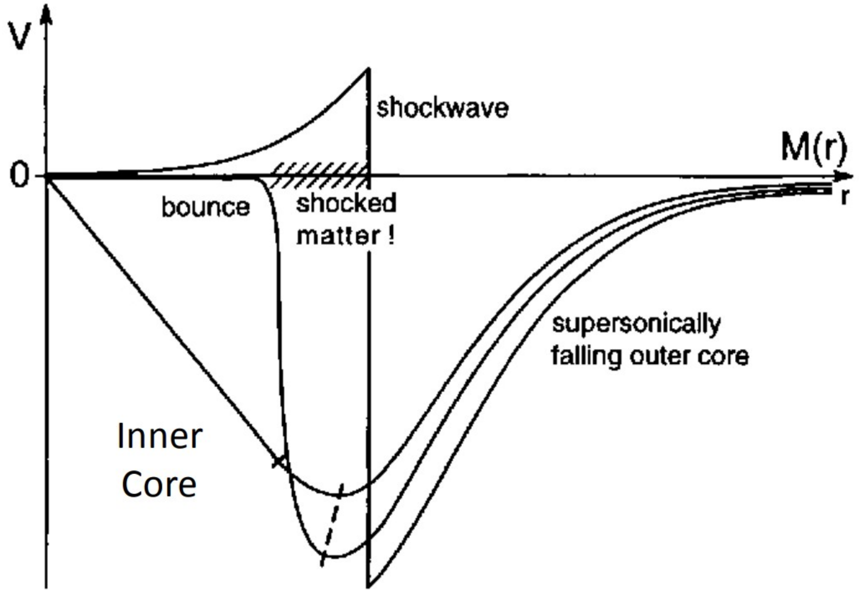
The collapse of the core ...

- The inner core-collapses under it own weight.
- The collapse of the inner core is homologous: velocity proportional to radius.
- Size of the inner core is almost independent of the progenitor.



The bounce ...

- When the inner core reaches nuclear density the infall of the inner core stops.
- The outer core “bounces” of the inner core resulting in a shock wave.

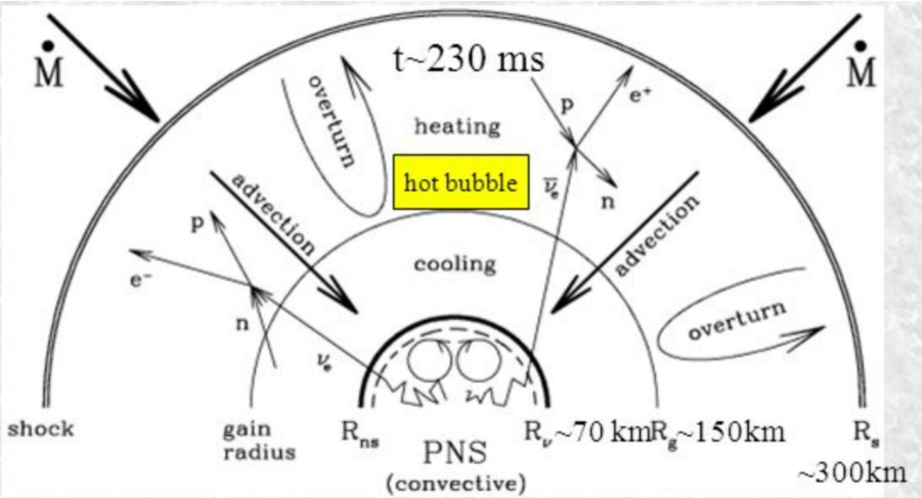


Propagation of the shock ...

- Shock is generated at the interface of the inner and outer core.
- As the shock propagates through the outer core it breaks apart Iron nuclei in the outer core loosing energy.
- Neutrinos to the rescue: They can cause the revival of the shock.

Role of neutrinos ...

- Heating: The neutrinos emitted from the interior can interact with the colder outer regions, heating the outer regions.
- Cooling: Neutrinos emitted from the inner regions of the supernova can reduce the temperature.



H.-T. Janka, K. Kifonidis, M. Rampp
Lect.Notes Phys.578:333-363,2001

Role of neutrinos ...

- 99% of the energy released in the form of neutrinos.
- The neutrino heating and cooling rates play an important role in the dynamics of supernova.
- Cooling rates are determined by beta reactions and thermal processes (Pair production, Bremsstrahlung, etc.)
- Heating rates are primarily determined by the beta reaction rates.

Neutrino transport ...

The Boltzmann equation:

$$\left(\frac{\partial f(\vec{p},\vec{x},t)}{\partial t} + \vec{v}\cdot\nabla f(\vec{p},\vec{x},t)\right) = \mathcal{C}^{\text{emit}} - \mathcal{C}^{\text{absorb}} f(\vec{p},\vec{x},t) + \mathcal{C}^{\text{scatter}} f(\vec{p} \leftrightarrow \vec{p}', \vec{x}, t)$$

Notice, it is a 7-dimensional equation. Not possible to solve in general.

Neutrino transport (Spherical Symmetry)

- Neutrinos are isotropically distributed with respect to the radial direction at small radii (trapped).
- At larger radii the neutrinos start escaping (peaked in the radial direction).

Neutrino transport (Flavor dependence)

- Electron neutrinos decouple at larger radius: Hence lowest energy.
- Heating rate of neutrinos goes like the cube of energy.

Neutrino flavor evolution ...

- Terminology: “Neutrino flavor evolution” – another more accurate term used to describe neutrino oscillations.
- Neutrinos created as one flavor eigenstate can be detected as another neutrino flavor eigenstate – flavor evolves.
- Neutrino flavor evolution can be modified when passing through a medium.

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**

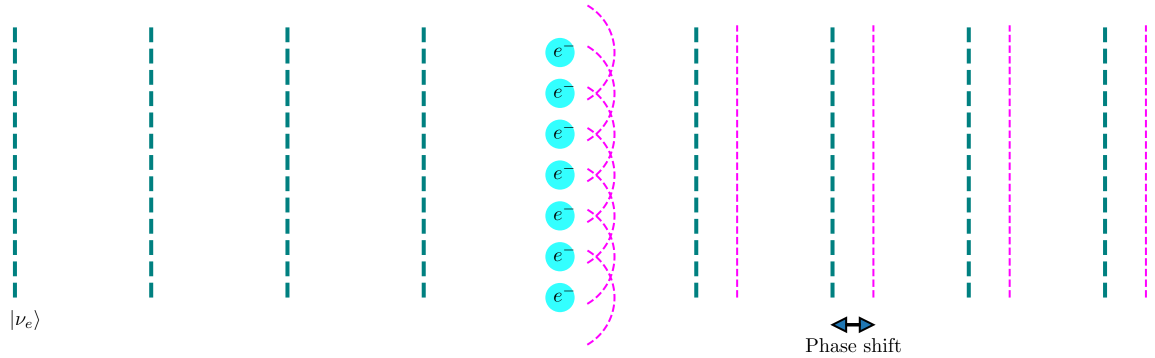
$$\omega = \frac{\Delta m^2}{2E}$$

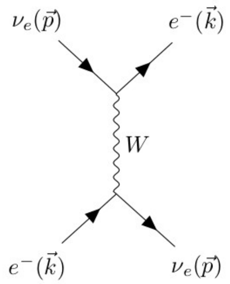
Vacuum frequency

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

θ_V Vacuum mixing angle

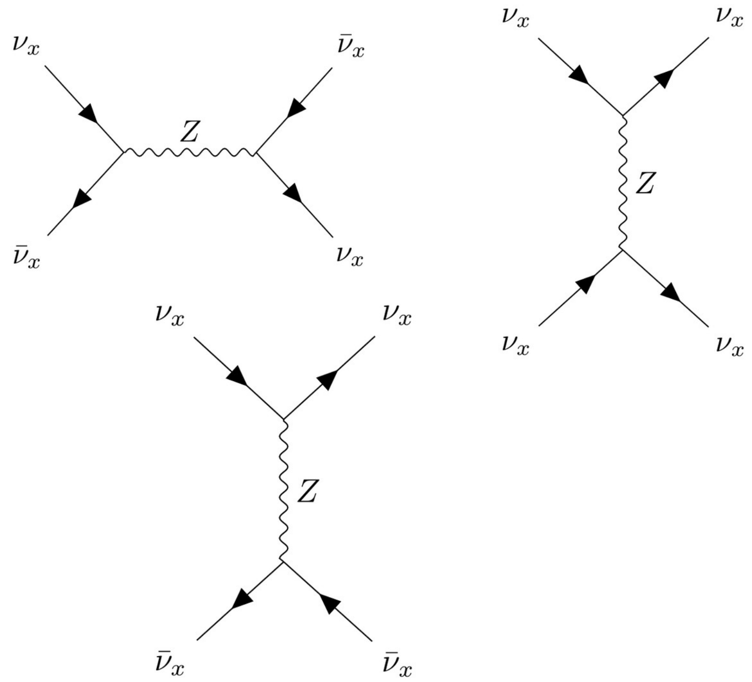
Coherent forward scattering.





Neutrino-Neutrino Interactions

- Neutrinos can interact with each other only via neutral current interactions (mediated by Z-boson).



Self-Interactions:

Density matrix for neutrinos and antineutrinos

Number density of neutrinos

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 flavor evolution ...

- The nonlinearity of the Hamiltonian leads to neutrino flavor evolution that is collective in nature – the flavor evolution of different momentum modes is correlated.
- The collective flavor evolution can occur with very small time scale associated with it – fast flavor evolution, or relative large associated time scale – slow flavor evolution.

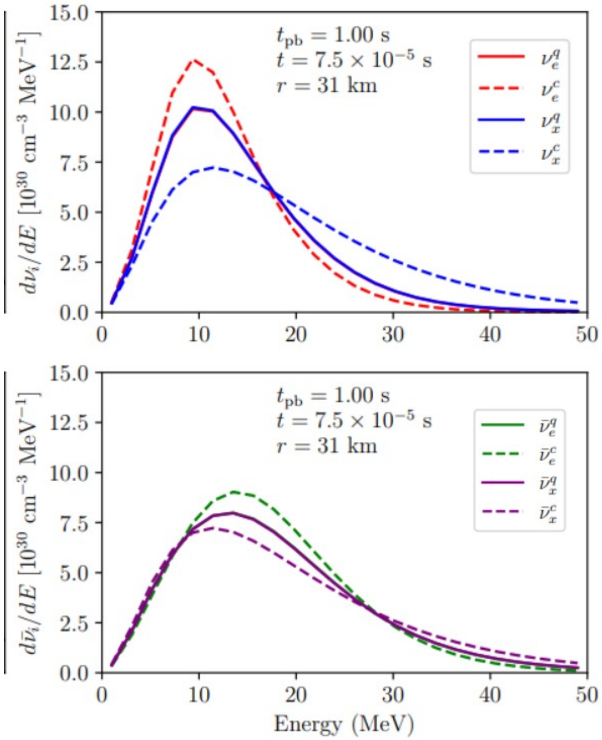
Fast flavor evolution ...

- Requires the presence of the Electron-Lepton-Number (ELN) crossing.
- Flavor evolution can exist even if ELN crossing is absent but then it is "slow".

Effects of flavor evolution in supernova …

- Flavor evolution results in a more prominent tail for electron type neutrinos.
- More electron type neutrinos at high energy tail implies more efficient heating.
- No BSM required!!!

Shalgar et.al. ArXiv: 2406.09504



Effects of flavor evolution in supernova ...

- The increased beta reactions that cause heating also change the electron fraction (change proton to neutrons and vice-versa).
- The electron fraction is an important quantity in determining the yields of heavy elements (r-process).

Future ...

- Need for a self-consistent core-collapse supernova simulations that includes neutrino flavor evolution.
- This is not only important for understanding supernova dynamics but also for understanding the synthesis of heavy elements in supernova (see Mariam's talk tomorrow).

Summary

- Neutrinos play an important role in cooling and heating.
- Heating can be enhanced by neutrino flavor conversions.
- Electron fraction and hence synthesis of heavy elements can also be affected by neutrino flavor evolution.
- Need to include neutrino flavor evolution consistently in hydrodynamical simulations of supernovae.