Crossings Between the Angular Distributions of Neutrinos in the Supernova Core

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Outline

- A brief overview of fast neutrino oscillations
- Electron lepton number crossings: A necessary condition for fast oscillations
- Order of magnitude estimates for the condition of ELN crossings
- Simplified formalism to determine whether ELN crossings exist in a spherical geometry
- Comments on non-spherical geometry
- Conclusions

Collective Neutrino Oscillations

- The physics of neutrino self-interaction for a long time was focused on coherent forward scattering of neutrinos in a neutrino medium

$$\nu_\alpha + \nu_\beta \rightarrow \nu_\alpha + \nu_\beta$$

- The flavor evolution of neutrino in this case is non-linear is nature because the Hamiltonian governing the flavor evolution depends on the flavor of the neutrinos in the medium
- Inspite of the challenging nature of the problem the equation of neutrino flavor evolution were solve in 'neutrino-bulb' model. (Perfectly spherical geometry and instantaneous decoupling of all neutrinos at a certain radius)

H. Duan, G. M. Fuller, J. Carlson and Y. Z. Qian, Phys. Rev. D **74**, 105014 (2006) [astro-ph/0606616].

Fast neutrino oscillations

- In the neutrino bulb-model fast pairwise conversions of neutrinos,

$$\nu_\alpha + \nu_\alpha \rightarrow \nu_\beta + \nu_\beta$$

  is not relevant and not included.
- It was argued by Sawyer that if we take into account the fact that neutrinos of different flavor decouple at different radii, then pair-wise conversions can become important.
- In the case of coherent pairwise conversions the time-scale of neutrino flavor evolution is very small
  $(\sim G_F(n_{\nu_e} - n_{\bar{\nu}_e}) \approx \mathcal{O}(10)$ cm$)$

R. F. Sawyer, Phys. Rev. Lett. **116**, no. 8, 081101 (2016) [arXiv:1509.03323 [astro-ph.HE]].

ELN crossings

- A more restrictive condition for the occurrence of fast pairwise conversions is the occurrence of electron lepton number crossings in the neutrino spectra.
  I. Izaguirre, G. Raffelt and I. Tamborra, Phys. Rev. Lett. **118**, no. 2, 021101 (2017) [arXiv:1610.01612 [hep-ph]].
  B. Dasgupta, A. Mirizzi and M. Sen, JCAP **1702**, no. 02, 019 (2017) [arXiv:1609.00528 [hep-ph]].

  S. Abbar and H. Duan, Phys. Rev. D **98**, no. 4, 043014 (2018) [arXiv:1712.07013 [hep-ph]].
- The electron lepton number has to be positive in a part of the angular range and negative in another part.

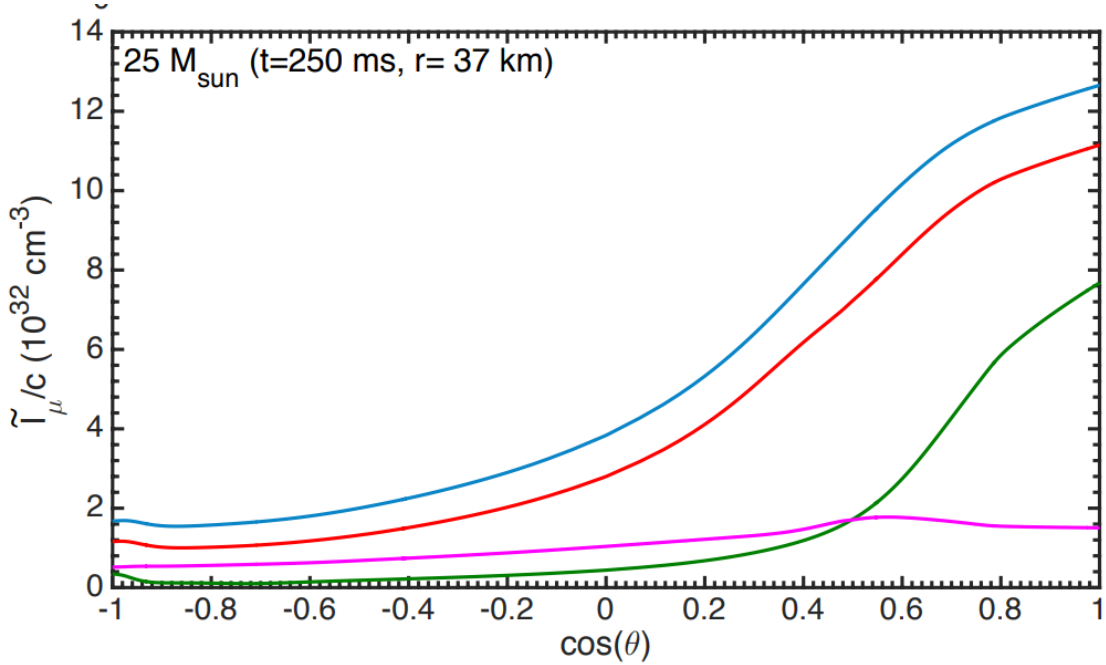
Importance of fast pairwise conversions

- Since the length scale of fast oscillations can be very small, the neutrino flavor can evolve over distances which are much smaller than the mean free path of neutrinos in inside the neutrino-sphere.
- The fast pair-wise conversions can occur even if the vacuum frequency is zero.

ELN crossings in a spherically symmetric supernova

- In a spherically symmetric supernova, the occurrence of ELN crossings or lack thereof is determined by the width of the neutrino angular distribution, and the normalization.
- Since the electron neutrinos decouple at a larger radius than electron anti-neutrinos, we expect the angular distribution of ν_e to be broader than $\bar{\nu}_e$.
- If the normalization of ν_e is much larger or smaller than $\bar{\nu}_e$, then we cannot get a ELN crossing. The normalizations have to be comparable.

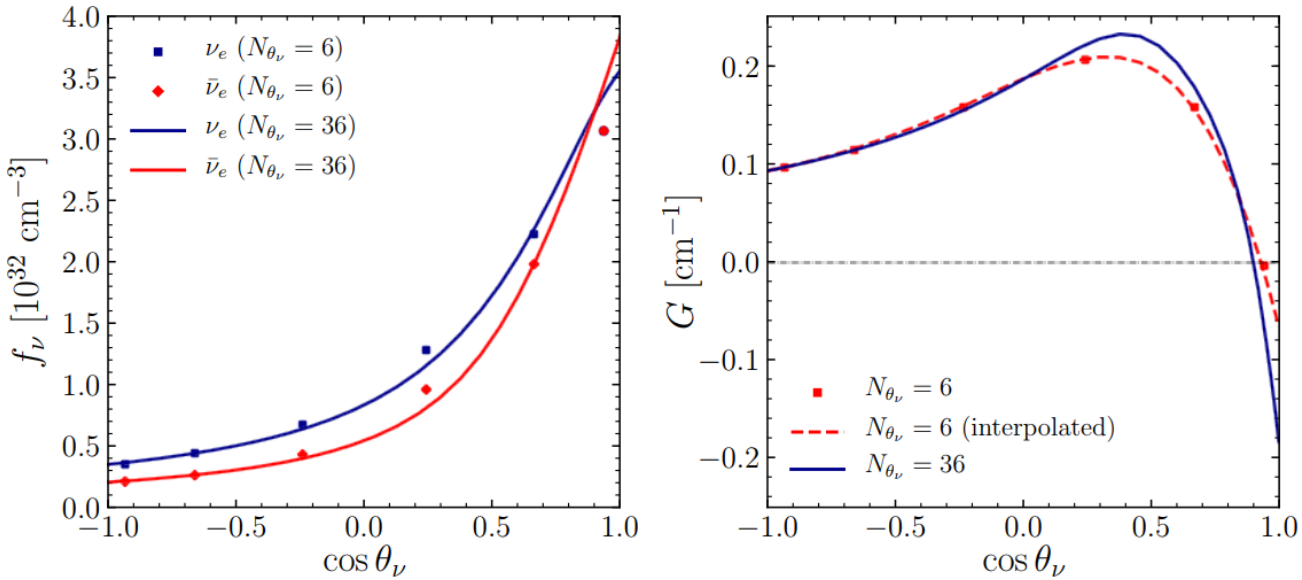
There is a consensus that there is no consensus



Blue $= \nu_e$, Red $= \bar{\nu}_e$. No crossing for 25 $M_\odot$ 250 millisecond after bounce from 1D simulation.

I. Tamborra, L. Huedepohl, G. Raffelt and H. T. Janka, Astrophys. J. **839**, 132 (2017) [arXiv:1702.00060 [astro-ph.HE]].

There is a consensus that there is no consensus



Some 3D simulations, ELN crossings visible in some directions.

S. Abbar, H. Duan, K. Sumiyoshi, T. Takiwaki and M. C. Volpe, arXiv:1812.06883 [astro-ph.HE].

Some 3D simulations do not find crossings.

M. D. Azari, S. Yamada, T. Morinaga, W. Iwakami, H. Okawa, H. Nagakura and K. Sumiyoshi, arXiv:1902.07467 [astro-ph.HE].

Simple formalism for ELN crossings

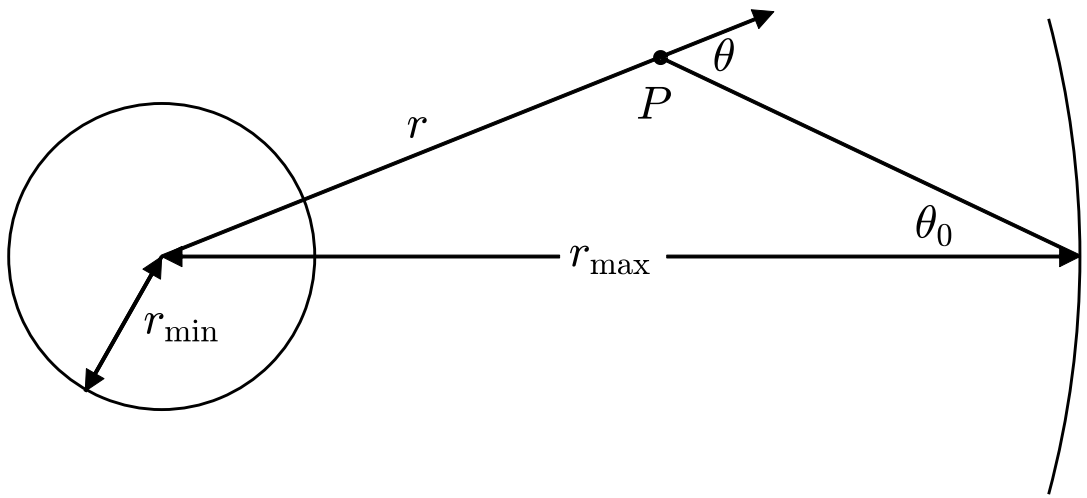
1. Spherical symmetry assumed
2. The number of neutrinos is locally conserved. The absorption and emission is thus treated as effective scatterers.
3. Each scattering is locally isotropic.
4. Energy-averaged, flavor-dependent neutrino distributions are adopted.
5. Only two neutrino flavor eigenstates are considered.

Formalism:

- We seek the steady state solution of,

$$\cos\theta \frac{d\rho_\theta(r)}{dr} = -\frac{1}{2}\int_{-1}^{1} \mathcal{C}^{\text{loss}} \rho_\theta(r) d\cos\theta' + \frac{1}{2}\int_{-1}^{1} \mathcal{C}^{\text{gain}} \rho_{\theta'}(r) d\cos\theta'$$

in which has the following spherical geometry



Application to supernova data

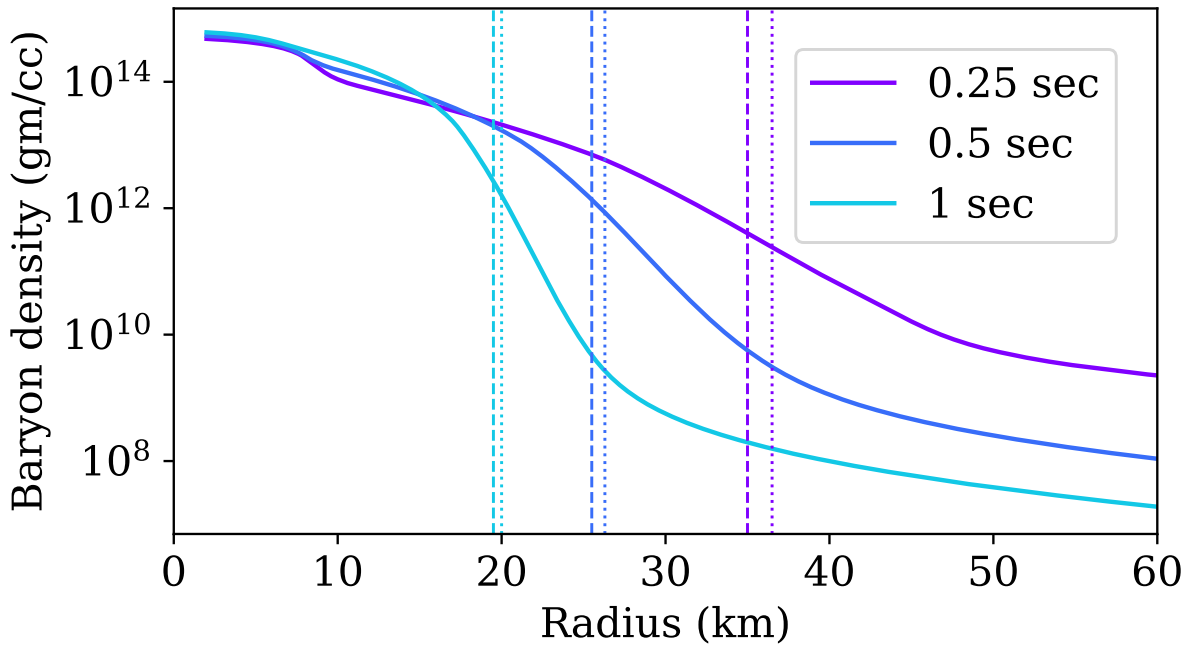


Figure: Radial baryon density profile at various time steps

Source: Garching Supernova Archive

No ELN crossing for $t = 0.25$ sec

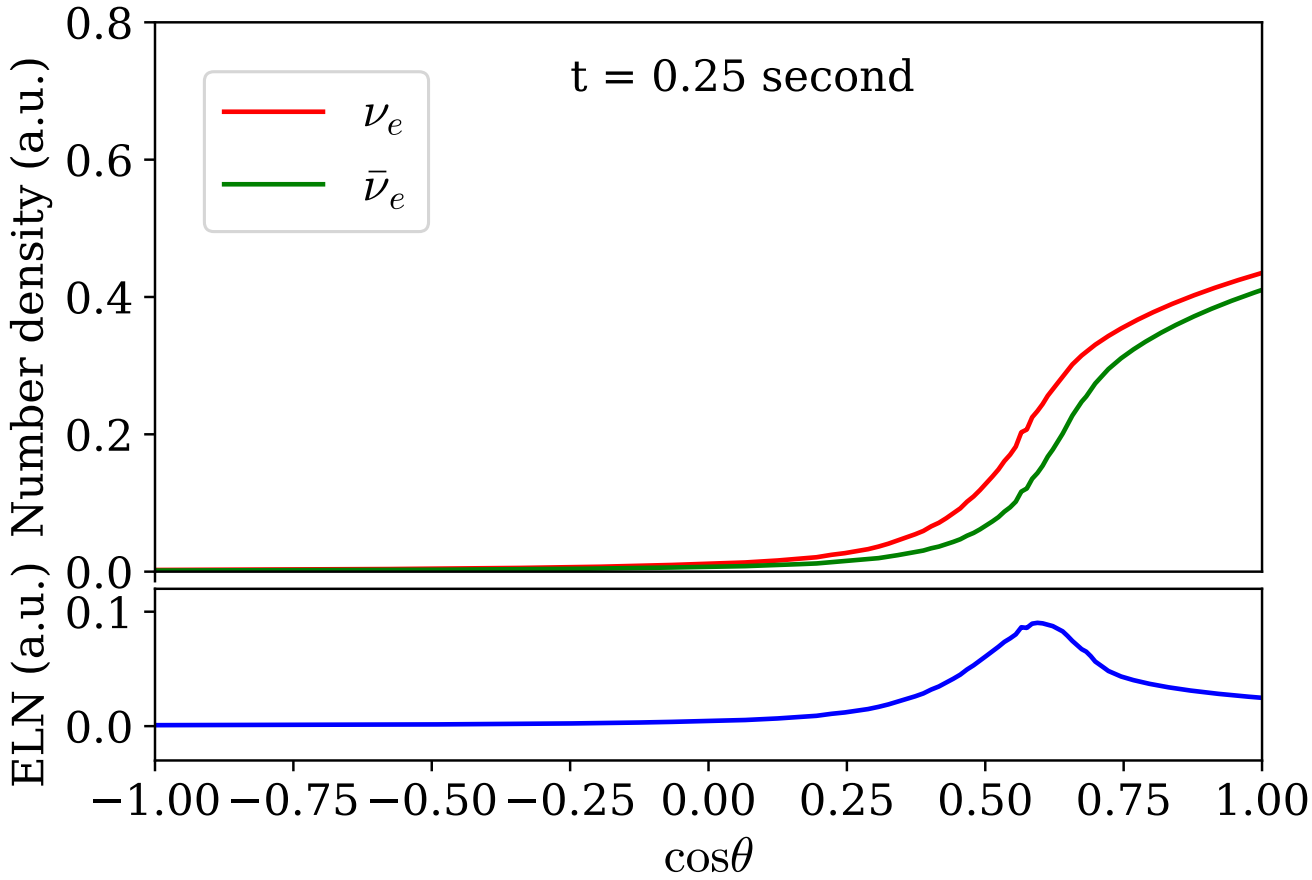


Figure: ν_e and $\bar{\nu}_e$ angular distributions.

ELN crossing exists for $t = 0.5$ sec

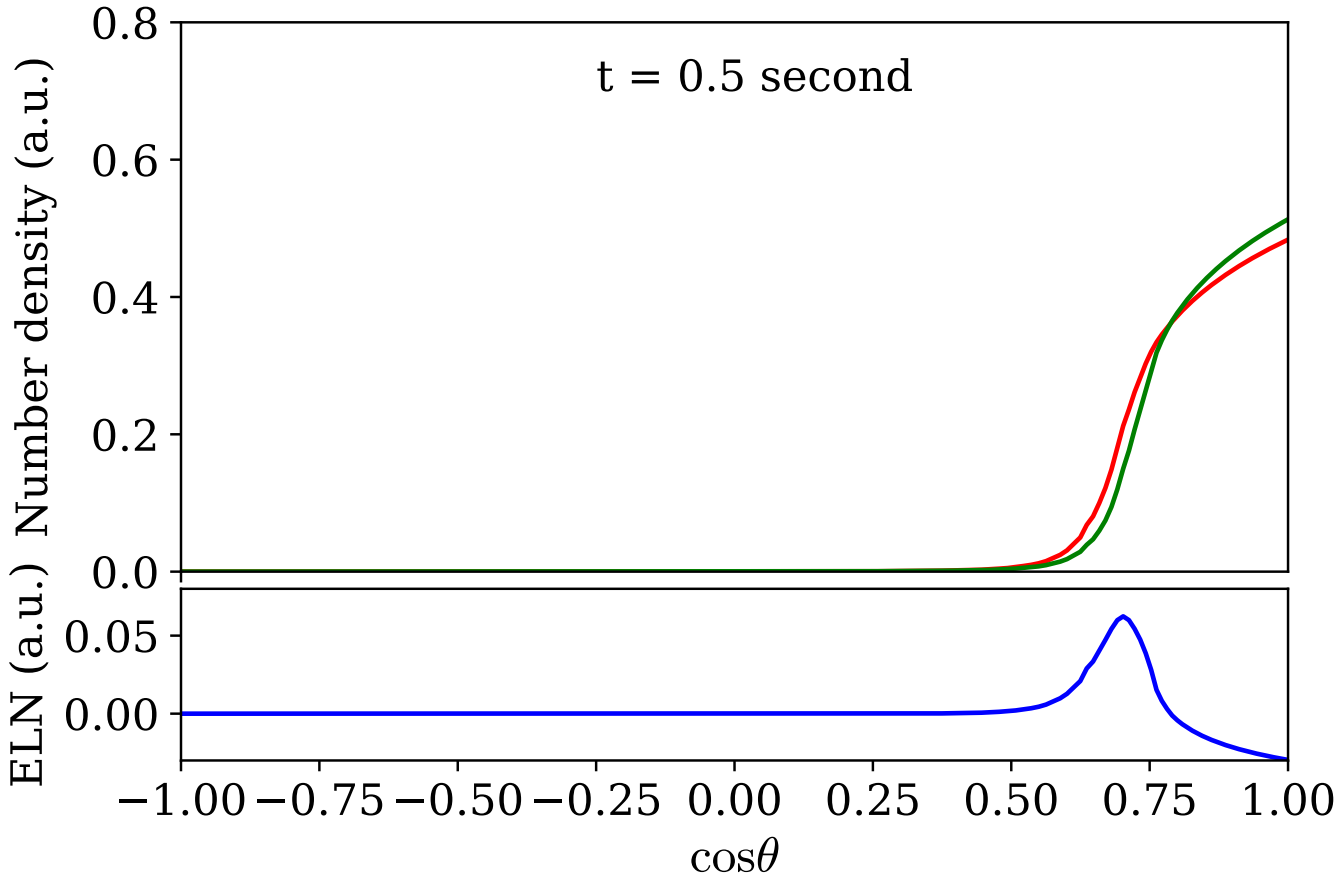


Figure: ν_e and $\bar{\nu}_e$ angular distributions.

Why do we get ELN crossings for later times?

- In order to understand why we get a crossing at later times but not earlier times, we consider a simple toy model.
- The temperature and chemical potential of neutrinos is fixed at 10 MeV, and we use to baryon density profiles,

$$\rho_{B,\mathrm{caseA}}(r) = 10^{14} \exp\left(0.25(5-r)\right) \ \mathrm{gm/cc} \ ,$$

and a second case that includes a steeply falling baryon density profile ("case B")

$$\rho_{B,\mathrm{caseB}}(r) = 10^{14} \exp\left(0.5(5-r)\right) \ \mathrm{gm/cc} \ .$$

No ELN crossing for shallow profile

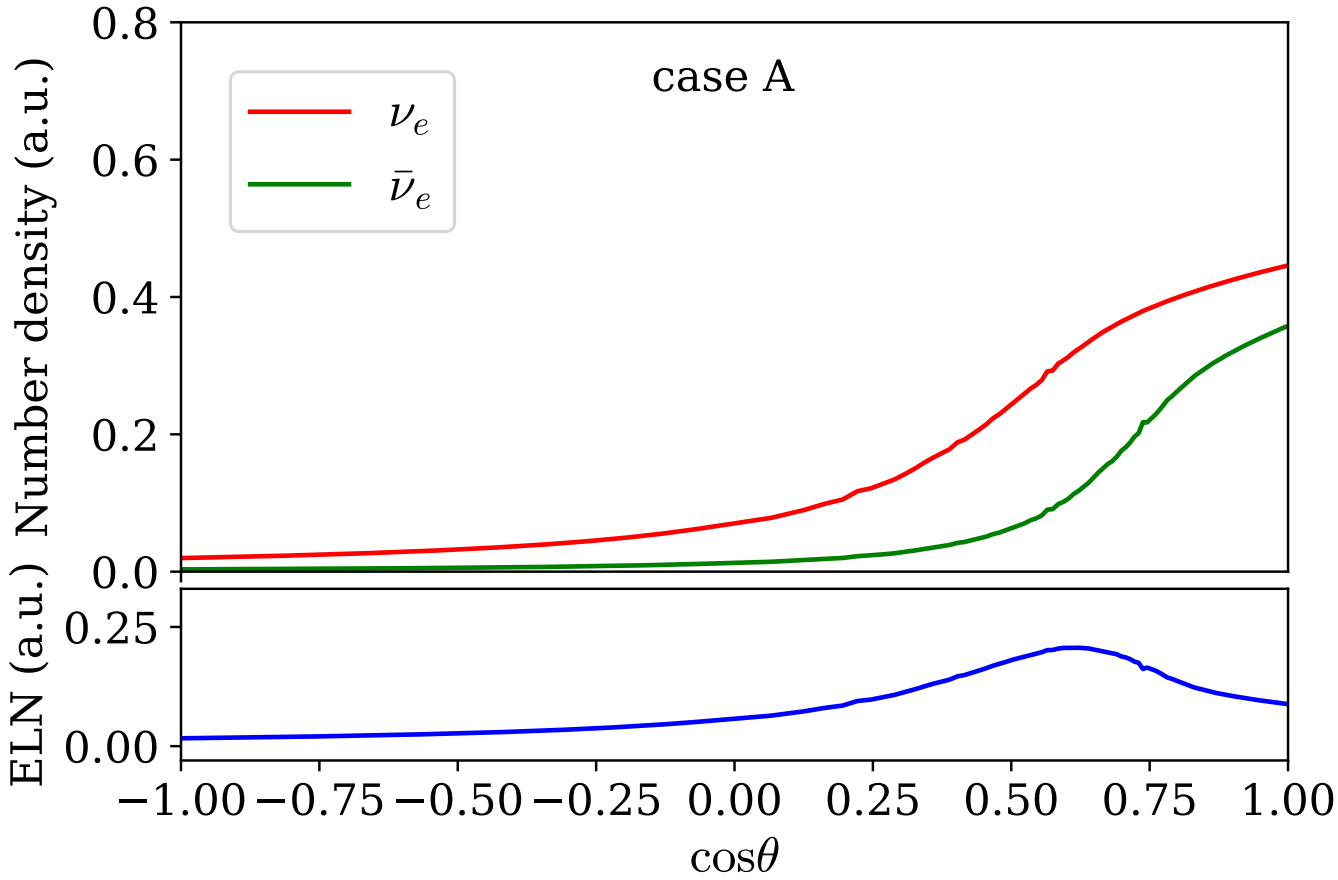


Figure: ν_e and $\bar{\nu}_e$ angular distributions.

ELN crossing exist for steep profile

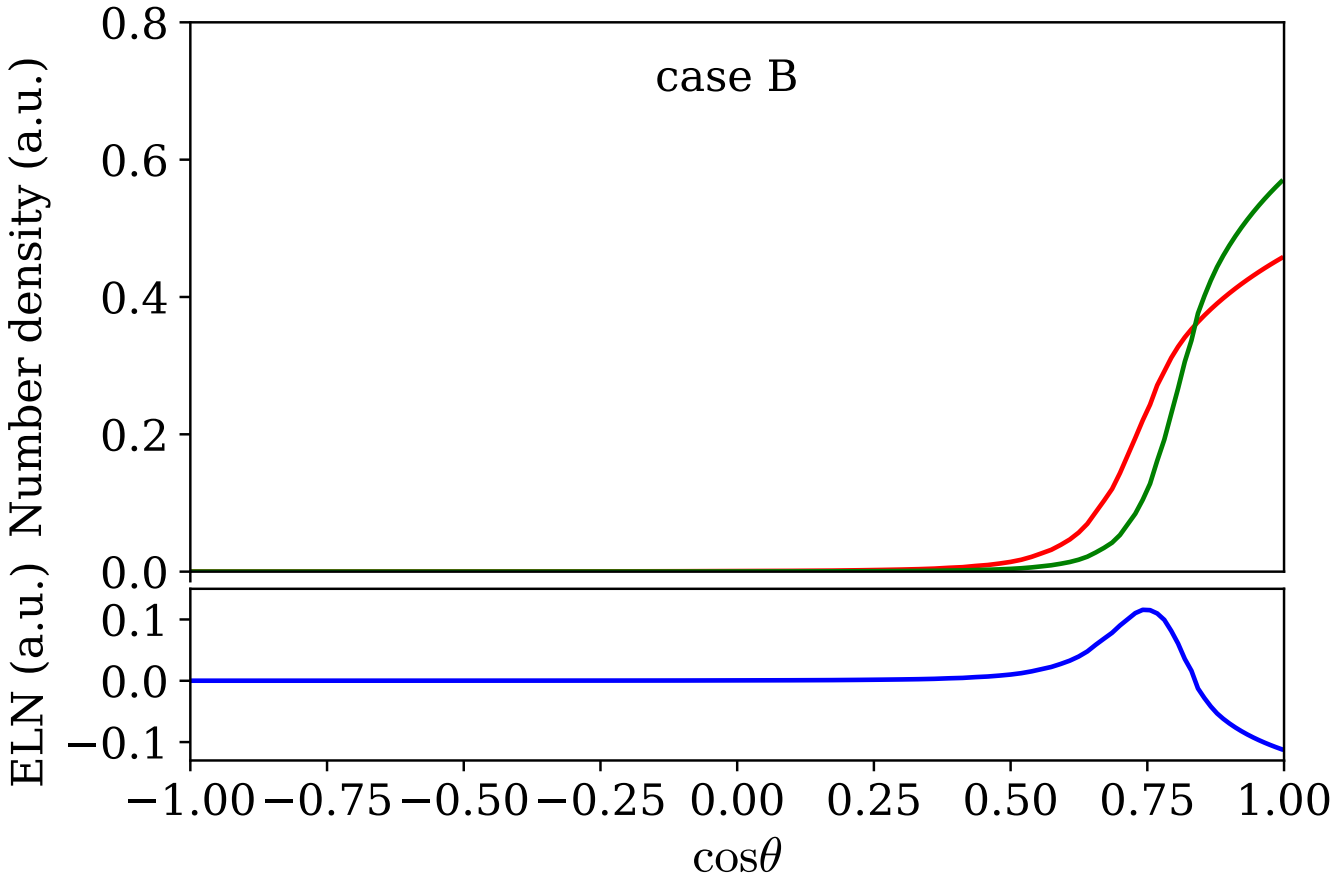


Figure: ν_e and $\bar{\nu}_e$ angular distributions.

Discussion on LESA

- Can we apply the same technique for non-spherical geometry?
- The same formalism can be repeated in (θ, ϕ) space for an observer.

Conclusions

- ELN crossing preferred in late-stages ($t \gtrsim 0.5$ sec) of superenovae.
- Why? In late-stage the baryon density profile is steep.
- Do fast oscillations affect supernova explosion mechanism?

Thank you!

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