Fast neutrino flavor conversions inside the neutrino sphere in the core-collapse supernovae

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M. Delfan Azari *et al.*, Phys. Rev. **D** 99, 103011

M. Delfan Azari *et al.*, (arXiv: 1910.06176)

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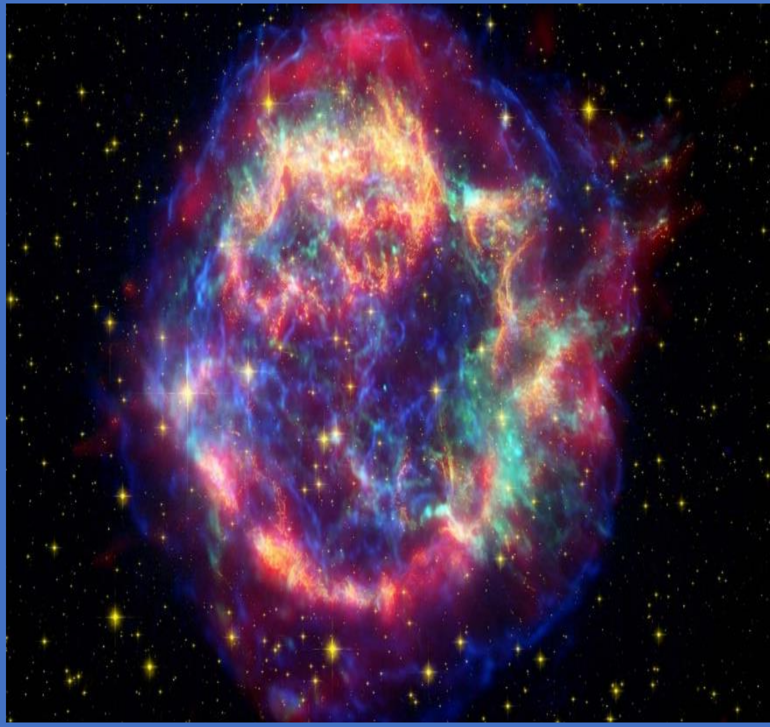
Fate of a star depends on its Mass

$M_{star} \gtrsim 8\ M_{sun}$

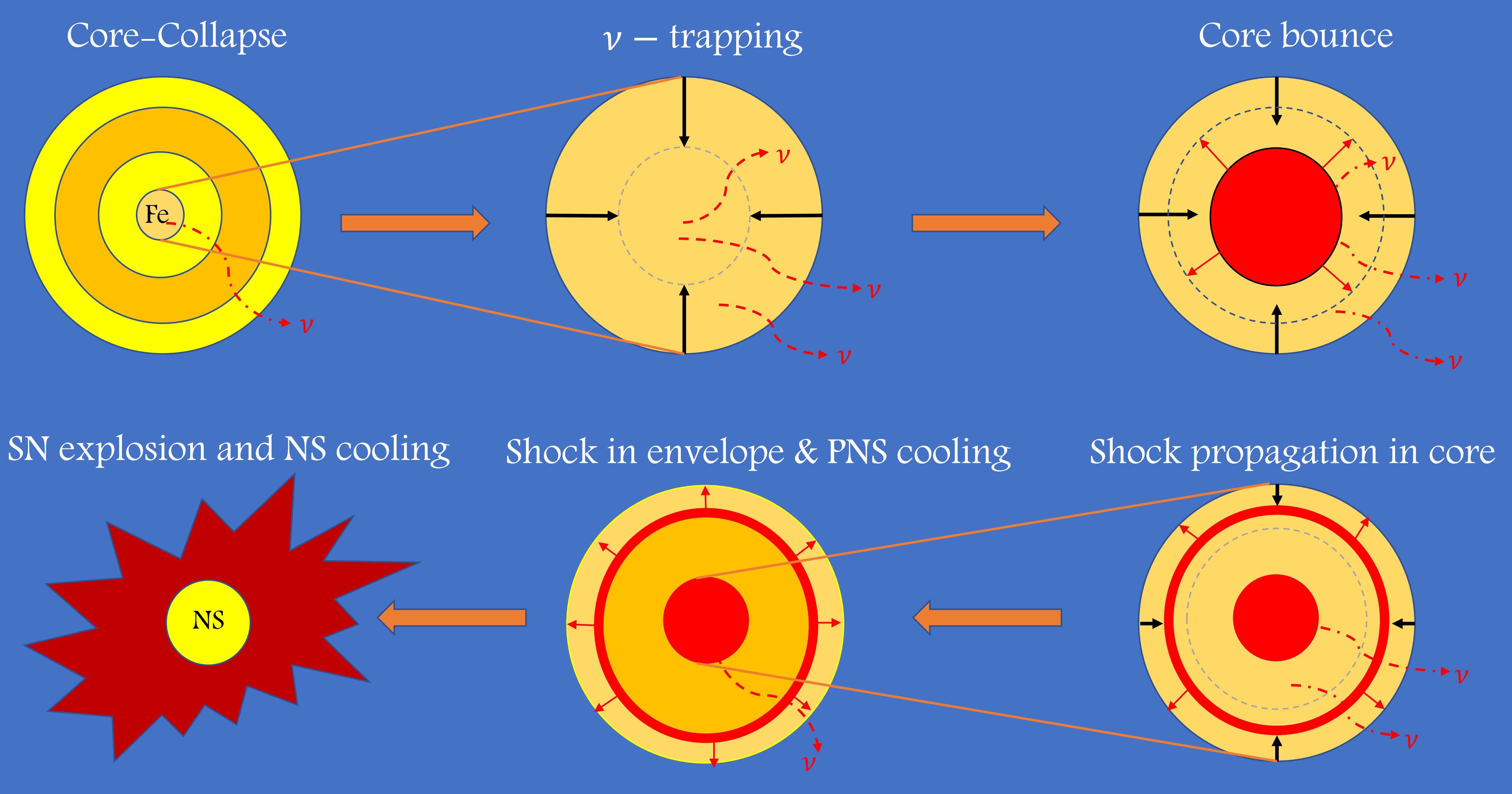
Core-Collapse

Supernovae



SN 1987A

Cassiopeia A

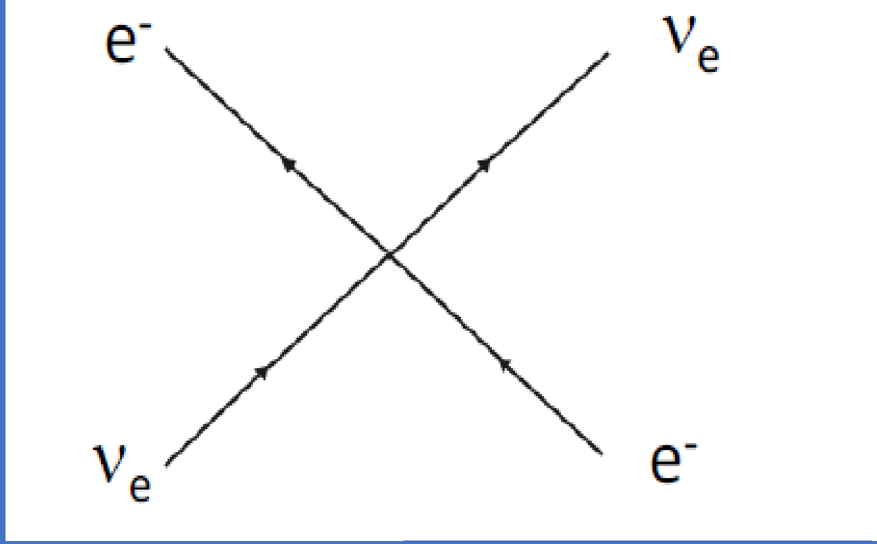


Core-Collapse
ν – trapping
Core bounce
Fe
ν
SN explosion and NS cooling
Shock in envelope & PNS cooling
Shock propagation in core
NS

Why neutrinos ?

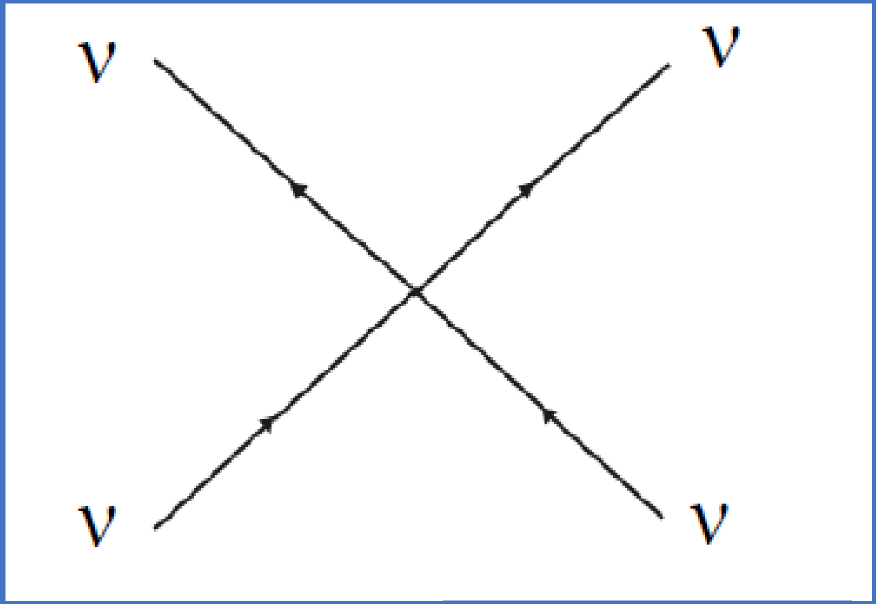
- ✓ almost all of the binding energy of NS liberated in the gravitational collapse is emitted in the form of neutrinos and the kinetic energy of matter in the supernova explosion is just 1% of this energy.

- ✓ In the $\nu -$ heating mechanism, a fraction of ν_e and $\bar{\nu}_e$ are re-absorbed by the matter between the shock front and the so-called gain radius and deposit their energy to push the stagnated shock again.



Matter effect $r >\sim 10^3$ km

Wolfenstein PRD 17, 2369, 1978



$\nu - \nu$ self interaction $r \sim 10^2$ km

Duan et al., PRD 74, 105014, 2006

Basic Equations and Formulae

M^2: Mass-squared matrix

v^μ : (1,**v**)

Λ^μ : $\sqrt{2}G_F(n_e - n_{e^+})u^\mu$

$d\Upsilon'$ =d**v**'/4π

Equation of Motion:

$$(\partial_t + v.\nabla_r)\rho = i[\rho, H]$$

$$\rho = \frac{f\upsilon_e + f\upsilon_x}{2} + \frac{f\upsilon_e - f\upsilon_x}{2}\begin{bmatrix} S_{\mathbf{p}} & S_{\mathbf{p}} \\ S_{\mathbf{p}}^* & -S_{\mathbf{p}} \end{bmatrix}$$

$$H = \underbrace{\frac{M^2}{2E}}_{\text{Kinetic Hamiltonian}} + \underbrace{v^\mu \Lambda_\mu \frac{1}{2}\sigma_3}_{\text{Matter Hamiltonian}} + \underbrace{\sqrt{2}G_F \int \frac{E'^2 dE'}{2\pi^2} d\Upsilon' v^\mu v'_\mu \rho'}_{\text{Neutrino-Neutrino Hamiltonian}}$$

Kinetic Hamiltonian — Vacuum Oscillation

Matter Hamiltonian — MSW Oscillation

Neutrino-Neutrino Hamiltonian — Collective Oscillation

Basic Equations and Formulae

Linearized Equation of Motion:

$$i(\partial t + v.\nabla_r)S_v = v^{\mu}\left(\Lambda_{\mu} + \Phi_{\mu}\right)S_v - \int \frac{d\mathbf{v}'}{4\pi} v^{\mu} v'_{\mu}\, G_{v'} S_{v'}$$

$$G_v = \sqrt{2} G_F \int_0^{\infty} \frac{dE E^2}{2\pi^2}\left[f_{\nu_e}(E, \mathrm{v}) - f_{\overline{\nu}_e}(E, \mathrm{v})\right]$$

$$\Phi^{\mu} \equiv \frac{d\mathbf{v}}{4\pi} G_v v^{\mu}$$

Assuming the solutions in the form of ;

$$S_v(t, r) = Q_v(\Omega, K)e^{-i(\Omega t - K.r)}$$

$$v^{\mu} k_{\mu} Q_v = a^{\mu}$$

where ; $a^{\mu} \equiv -\int \frac{d\mathbf{v}'}{4\pi} v^{\mu} v'_{\mu}\, G_{v'} Q_{v'}$

$k^{\mu} = K^{\mu} - \Lambda^{\mu} - \Phi^{\mu}$ with $k^{\mu} = (\omega, \mathbf{k})$

$$\Pi^{\mu\nu}(\omega, \mathbf{k})\, a_{\nu} = 0$$

Polarization tensor $\Pi^{\mu\nu} = \eta^{\mu\nu} + \int \frac{dV}{4\pi} G_V \frac{v^{\mu} v^{\nu}}{\omega - V.k}$

$$\mathrm{D}(\omega, \mathbf{k}) \equiv \det[\Pi] = 0$$

Background Numerical Model

✓ Results of the realistic 2D simulations on the K-Supercomputer
Nagakura et al., ApJ 854, 136 (2018)

✓ For non-rotating progenitor model of M_{star}=11.2 $M_{\odot}$
Woosley et al., Reviews of Modern Physics 74, 1015 (2002)

✓ Boltzmann equation for neutrino transport being solved and special relativistic effect with a two energy grid technique. Nagakura et al., ApJS 214,16 (2014)

✓ Newtonian hydrodynamical equations & the Poisson equation for self-gravity were solved simultaneously.

Method

- ✓ Equations are written on spherical coordinates (r , θ) and three momentum space (E, θ_ν, ϕ_ν)
- ✓ Computational domains :

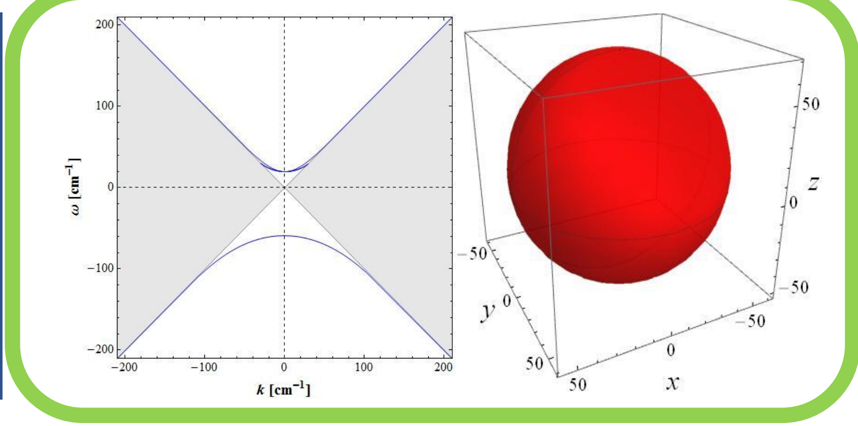
$$0 \le r \le 5000 \text{ km}$$
$$0 \le \theta \le \pi$$
$$0 \le E \le 300 \text{ MeV}$$
$$0 \le \theta_\nu \le \pi$$
$$0 \le \phi_\nu \le 2\pi$$

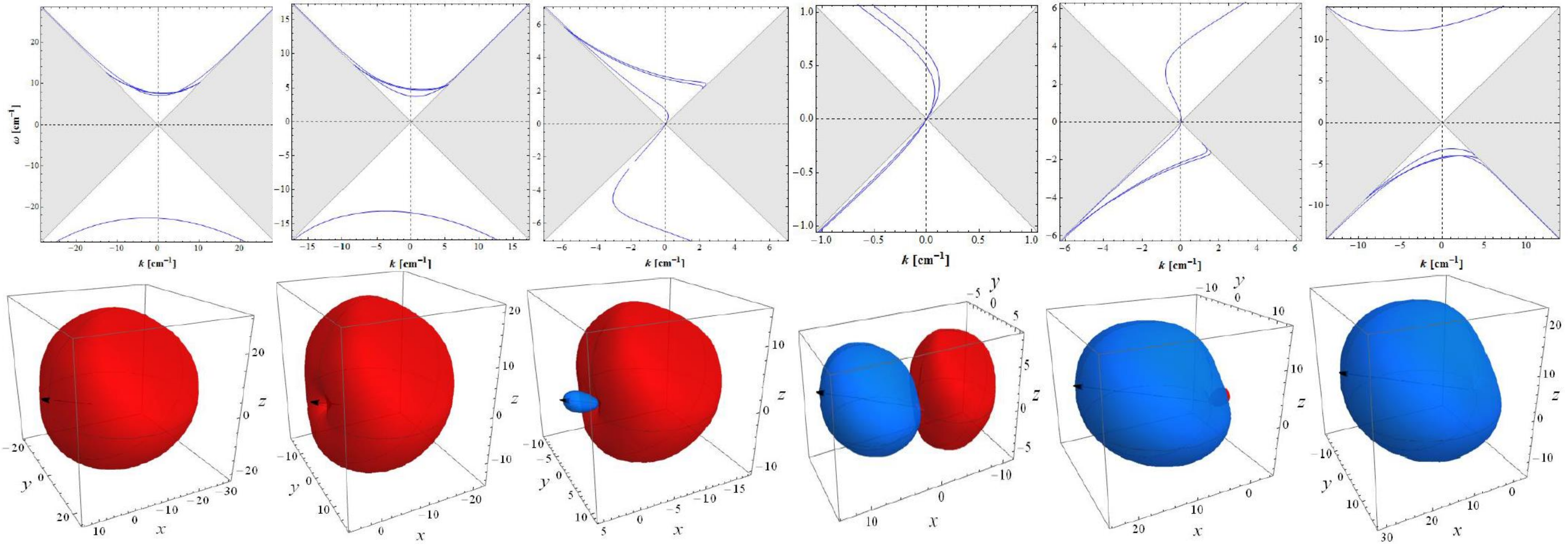
For 384 (r), 128 (θ), 20 (E), 10 (θ_ν) and 6 (ϕ_ν) mesh cells.

Results- Scaled data at

t= 15 ms $(r = 44.8 \text{ km}, \theta = 2.36 \text{ rad})$

Crossing : $\int \frac{E^2 dE}{2\pi^2}\left(f_{\bar{\nu}_e}(E,\theta_\nu,\phi_\nu) - f_{\nu_e}(E,\theta_\nu,\phi_\nu)\right) \geq 0$





$\bar{\nu}_e$ ×25 $\bar{\nu}_e$ × 31 $\bar{\nu}_e$ × 35 $\bar{\nu}_e$ × 39.5 $\bar{\nu}_e$ × 45 $\bar{\nu}_e$ × 49

New definitions

Γ= The ratio of the anti-electron neutrino and the electron neutrino

$$\Gamma = \frac{n_{\overline{\nu}_e}}{n_{\nu_e}}$$

$$n_\nu = \int \frac{d^3p}{(2\pi)^3} f_\nu \qquad d^3p = E^2 dE\ sin\theta d\theta d\phi$$

Reminder：

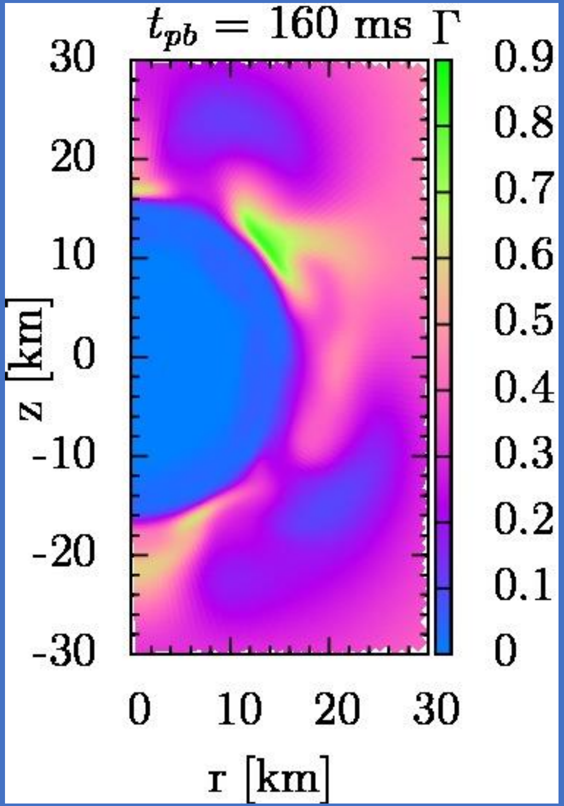
Crossing：
$$\int \frac{E^2 dE}{2\pi^2}\left(f_{\overline{\nu}_e}(E,\theta_\nu,\phi_\nu) - f_{\nu_e}(E,\theta_\nu,\phi_\nu)\right) \geq 0$$

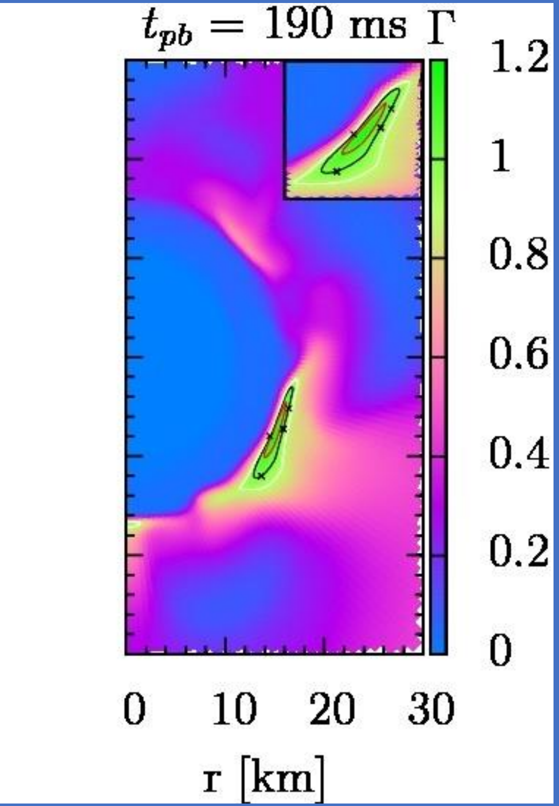
Results

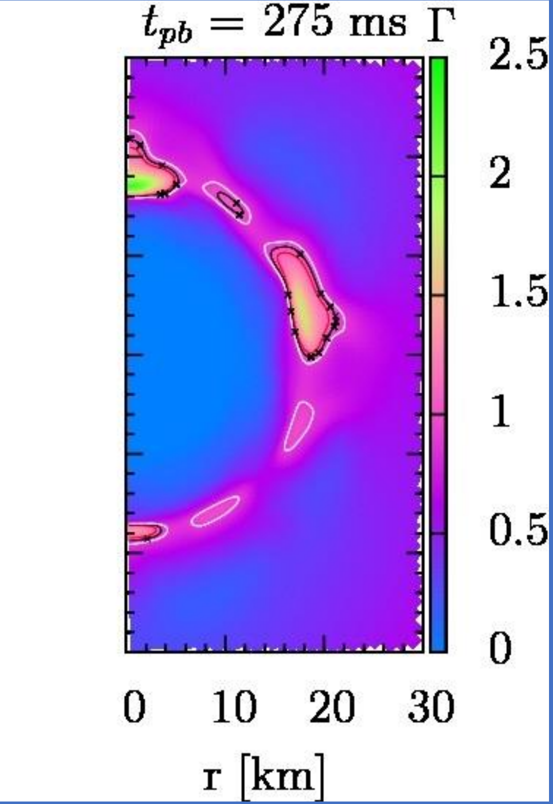
$$\Gamma = \frac{n_{\bar{\nu}_e}}{n_{\nu_e}}$$

Cross points at r = 16.5 ~ 18.1km

Cross points at r = 16.1 ~ 21.4km

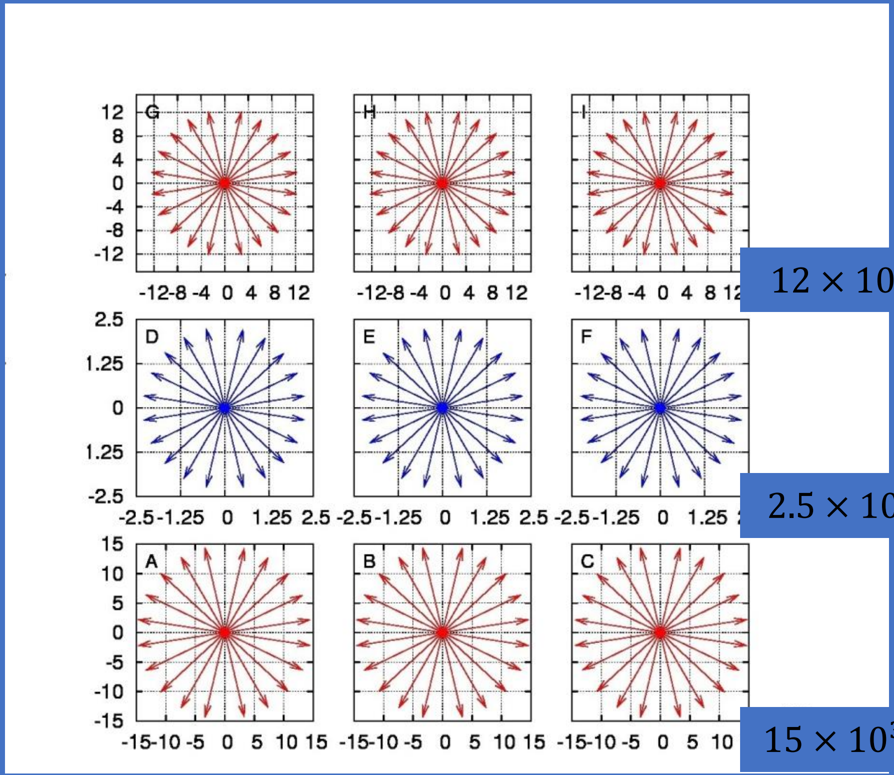






+ represents the crossing points

t= 160 ms



$12 \times 10^{34}\, 1/\mathrm{cm}^3$

$2.5 \times 10^{33}\, 1/\mathrm{cm}^3$

$15 \times 10^{34}\, 1/\mathrm{cm}^3$

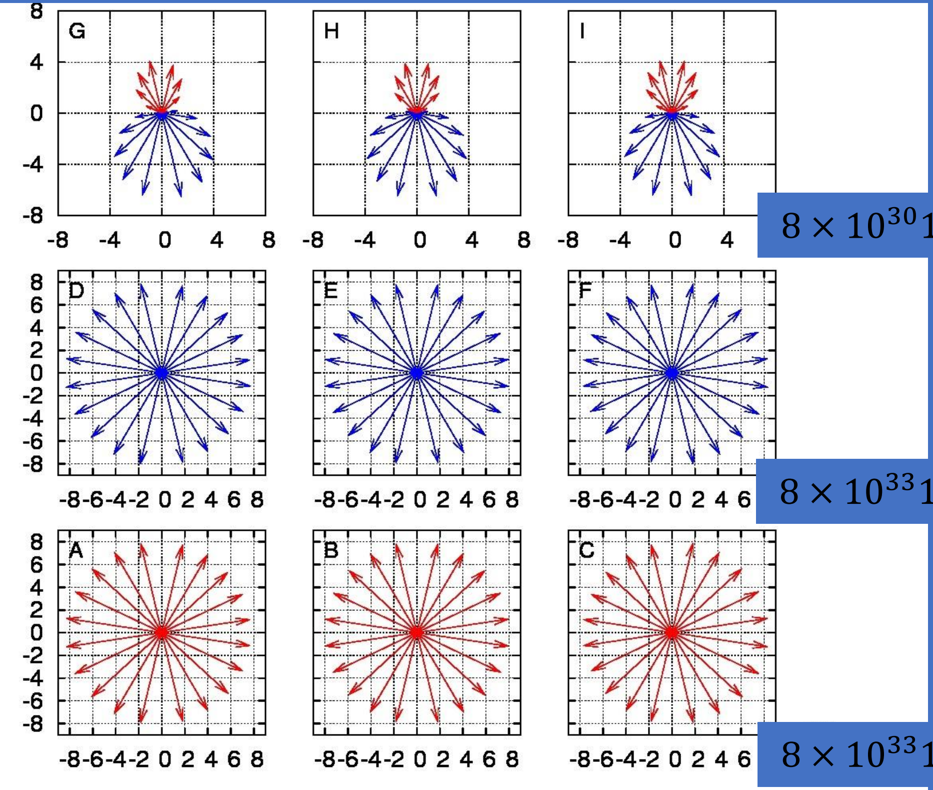
$r = 16.5$ km
$\theta = 2.1$ rad

Difference

$\bar{\nu}_e$

ν_e

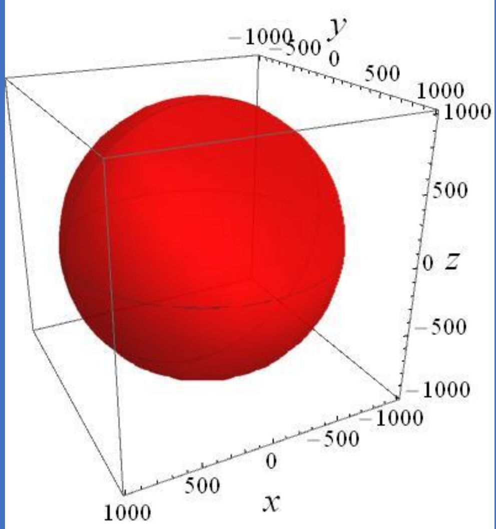
t= 190 ms

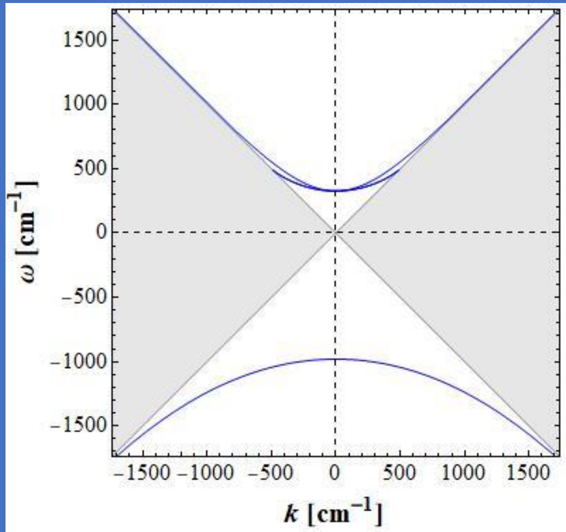


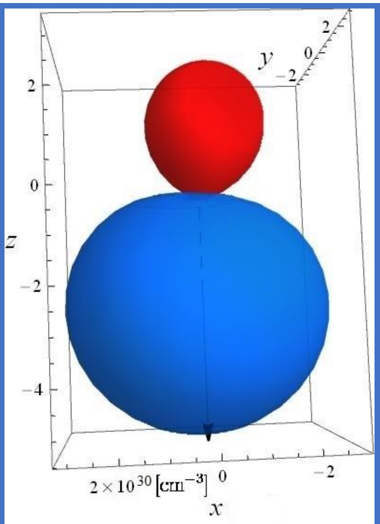
$8 \times 10^{30}\, 1/\mathrm{cm}^3$

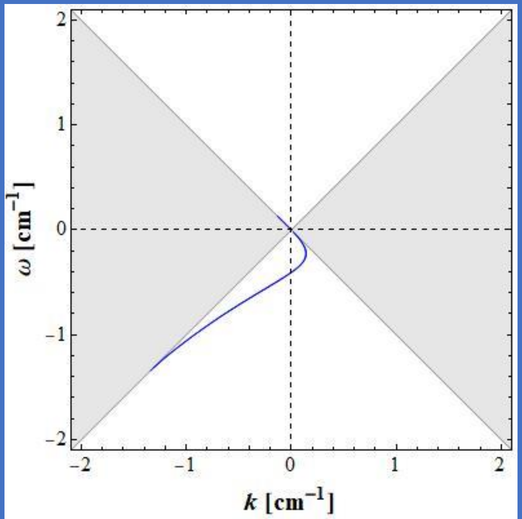
$8 \times 10^{33}\, 1/\mathrm{cm}^3$

$8 \times 10^{33}\, 1/\mathrm{cm}^3$



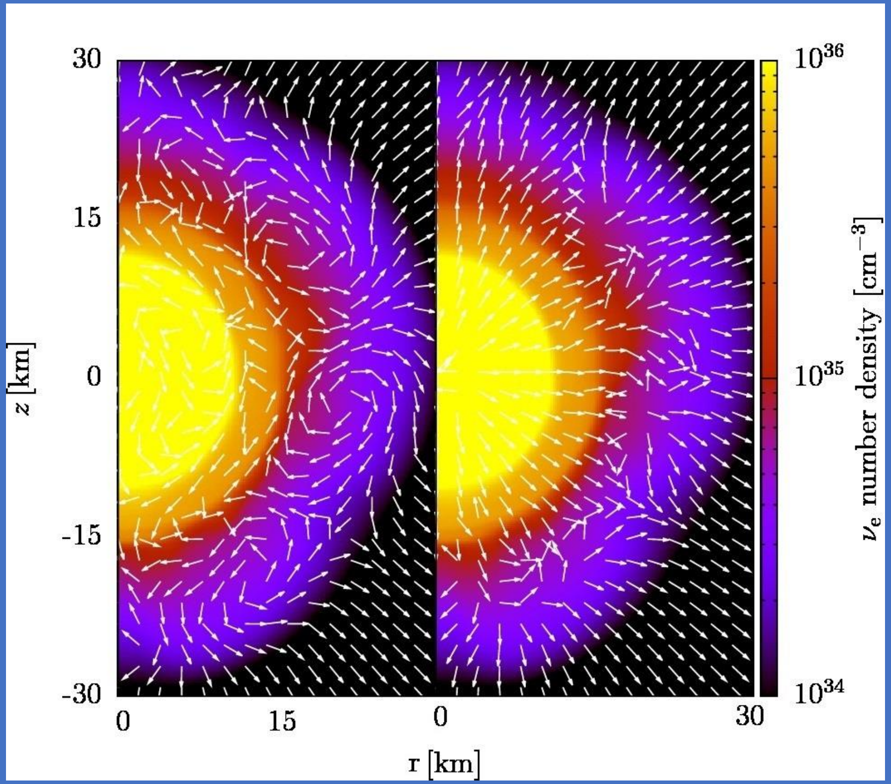


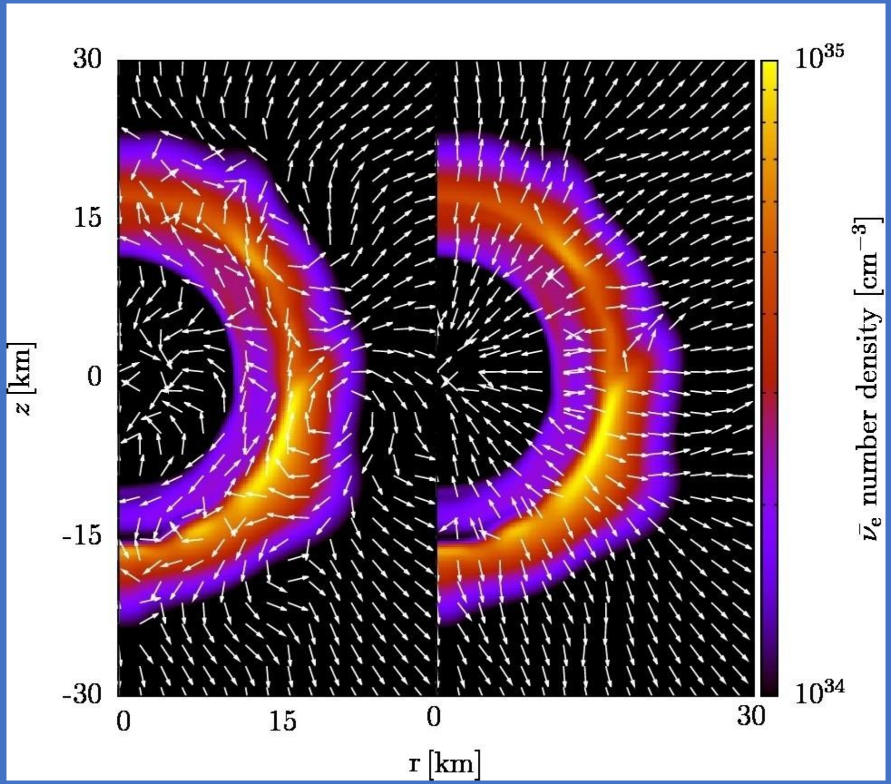




Results

$$n_\nu = \int \frac{d^3p}{(2\pi)^3} f_\nu \qquad d^3p = E^2 dE\ sin\theta d\theta d\phi$$





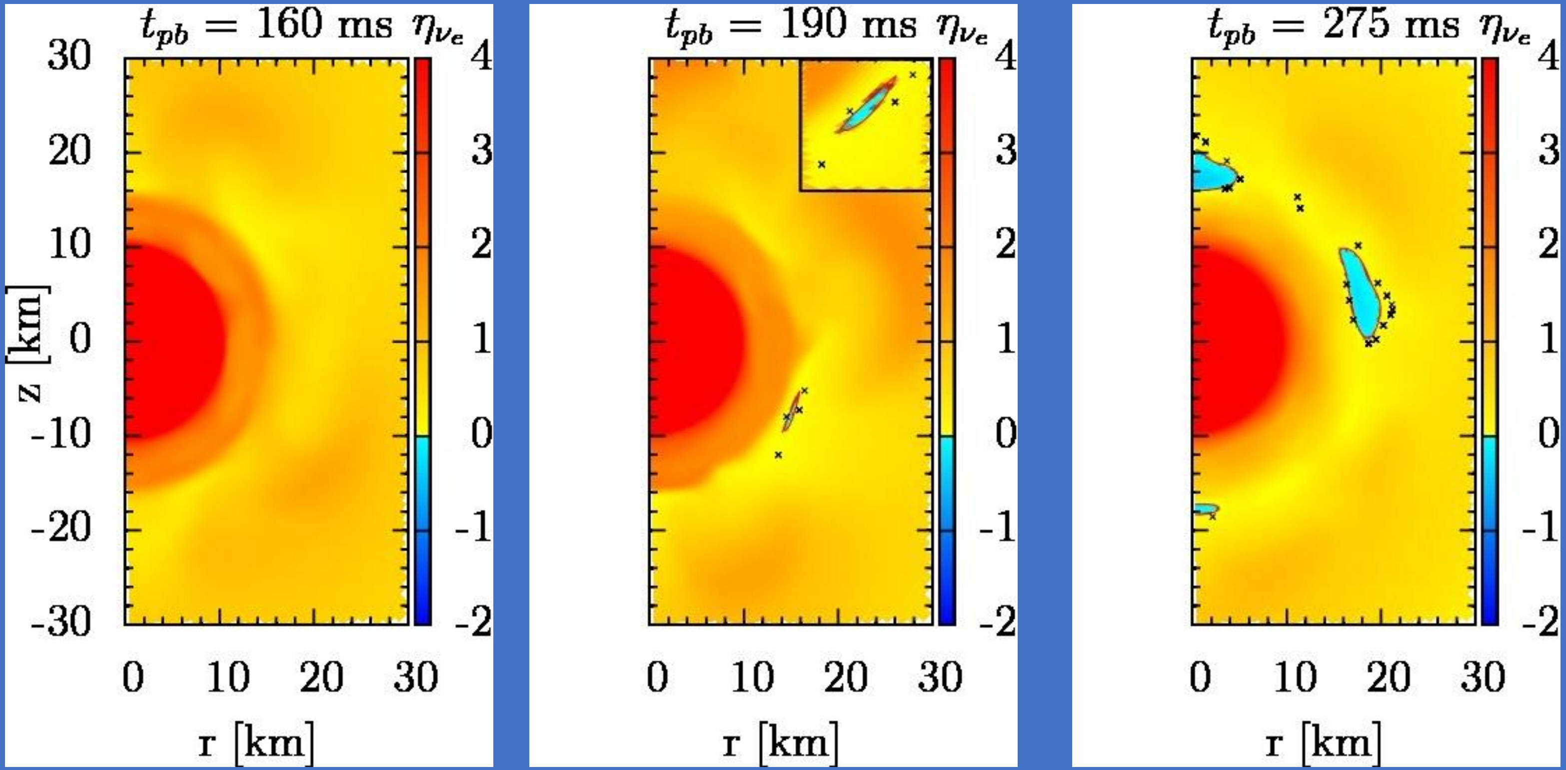
Laboratory frame | Fluid-rest frame | Laboratory frame | Fluid-rest frame

✓ $\bar{\nu}_e$ is suppressed in r < 10 km.

✓ $\bar{\nu}_e$ is more abundant at r ~ 15 km.

Results

$$\eta_{\nu_e} = \frac{\mu_{\nu_e}}{T} = \frac{(\mu_e + \mu_p) - \mu_n}{T}$$



r = 16.5 km
$\theta = 2.1$ rad
$\rho = 2.408 \times 10^{13}$ g/cm^3
$Y_e = 0.13$
$T = 20.4$ MeV
$\mu_e = 56.9$ MeV
$\mu_p = 848$ MeV
$\mu_n = 903$ MeV

+ represents the crossing points

Summary and future works

- ✓ The possible oscillation conditions in different radii and time steps has been studied.
- ✓ A systematic survey for all radii based on the angular distributions difference between the electron-neutrinos and anti-electron type neutrinos.
- ✓ It is shown that the first crossing occurs at t ~ 190 ms and the crossings occur when electron-neutrinos and anti-electron neutrinos ratio (Γ) is equal to 1.
- ✓ As recently some data for the 3D simulations from my colleagues is available, the similar investigations might be a point of interest.
- ✓ This method might be applicable to other astrophysical objects such as NS-mergers disks, etc. We plan to investigate the conversion possibilities in these objects in near future.