Occurrence of fast collective neutrino oscillations inside the neutrino sphere in core-collapse supernovae

MILAD DELFAN AZARI, SHOICHI YAMADA, TAIKI MORINAGA, HIROKI NAGAKURA, SHUN FURUSAWA, AKIRA HARADA, WAKANA IWAKAMI, HIROTADA OKAWA and KOHSUKE SUMIYOSHI

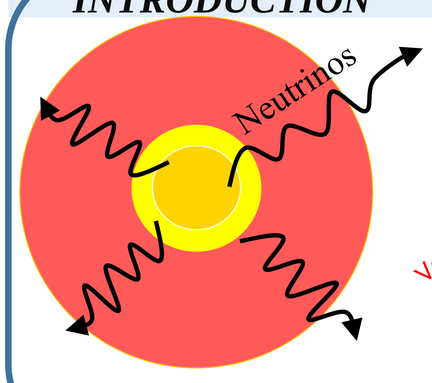
Department of Pure and Applied Physics, Graduate School of Advanced Science and Engineering, Waseda University 3-4-1, Okubo, Shinjuku, Tokyo, 169-8555 Japan

Email : milad@heap.phys.waseda.ac.jp

INTRODUCTION :

Neutrinos are densely populated deep inside the core of massive stars after their gravitational collapse to produce supernova explosions and form compact objects such as neutron stars and black holes. It has been considered that they may change their flavor identities through fast-pairwise conversions induced by mutual forward scatterings. If true, the dynamics of supernova explosions will be influenced, since the conversions may occur near the neutrino sphere. We study such possibilities based on the results of realistic simulations of CCSNe in two spatial dimensions under axisymmetry. As we have solved the Boltzmann equations for neutrino transfer in the simulation, the angular distributions of neutrinos in momentum space are available. We firstly extract some of these distributions at different points and times from the numerical data then we perform a thorough survey of the ELN crossing. Finally we apply linear analysis to asses the possibility of the conversion. We report for the first time the positive detections deep inside the core at $r \sim 16.5 - 21$ km. We find that the low values of the electron fraction Y_e produced by convective motions together with appearance of the light elements are important for ELN crossing by enhancing the chemical potential difference between proton and neutron and hence by mitigating the Fermi-degeneracy of electron-type neutrino.

INTRODUCTION



Equation of Motion:

$$(\partial_t + \mathbf{v}.\boldsymbol{\nabla}_\mathbf{r})\rho = i[\rho, H]$$

$$\rho = \frac{fv_e + fv_x}{2} + \frac{fv_e - fv_x}{2}\begin{pmatrix} s_\mathbf{p} & S_\mathbf{p} \\ S_\mathbf{p}^* & -s_\mathbf{p} \end{pmatrix},$$

Vacuum

$$H = \frac{M^2}{2E} + v^\mu \Lambda_\mu \frac{1}{2}\sigma_3 + \sqrt{2}G_F \int \frac{E'^2 dE'}{2\pi^2} d\Upsilon' v^\mu v'_\mu \rho',$$

Matter — Collective

Linearized Equation of Motion:

$$i(\partial t + \mathbf{v}.\boldsymbol{\nabla}_\mathbf{r})S_\mathbf{v} = v^\mu(\Lambda_\mu + \Phi_\mu)S_\mathbf{v} - \int d\Upsilon' v^\mu v'_\mu G_{\mathbf{v}'} S_{\mathbf{v}'}$$

For a plane wave $S_\mathbf{v}(t, r) = Q_\mathbf{v}(\Omega, K)e^{-i(\Omega t - \mathbf{K}.\mathbf{r})}$

EOM becomes: $v_\mu \Pi^{\mu\nu} a_\nu = 0$

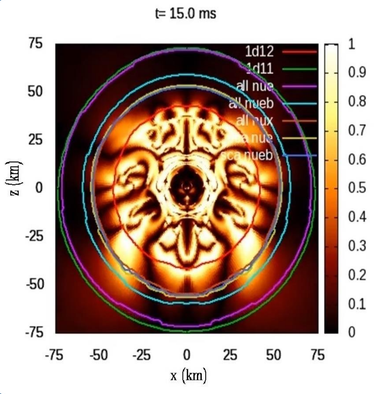
$$a_\mu = -\int \frac{d\mathbf{v}}{4\pi} v_\mu G_\mathbf{v} Q_\mathbf{v}$$

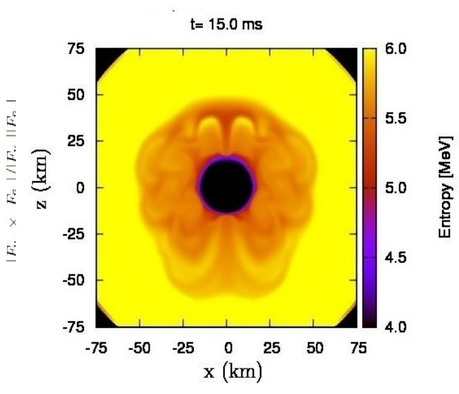
Polarization tensor $\Pi^{\mu\nu} = \eta^{\mu\nu} + \int \frac{d\mathbf{v}}{4\pi} G_\mathbf{v} \frac{v^\mu v^\nu}{\omega - \mathbf{v}.\mathbf{k}}$

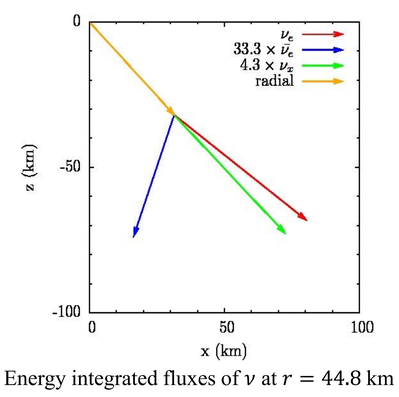
$$\det[\Pi] = 0 \quad (*)$$

NUMERICAL MODEL

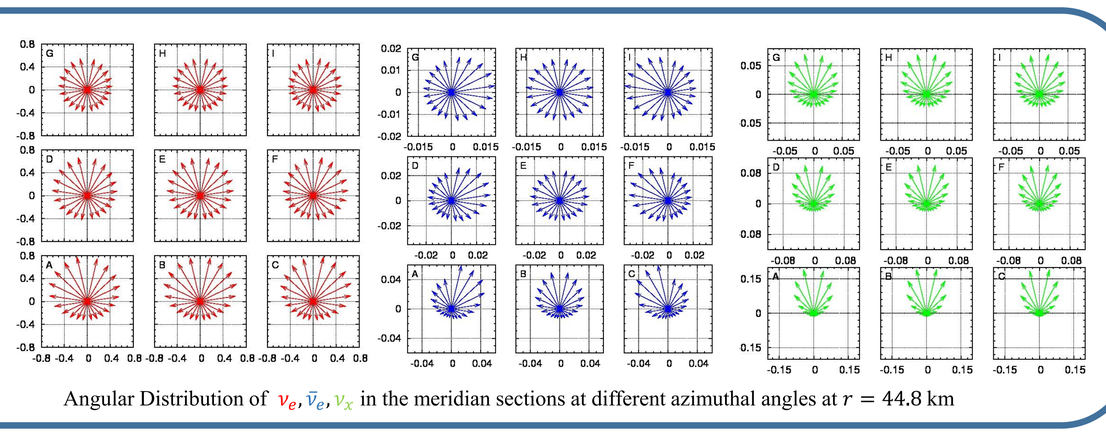
- ✓ Realistic 2D Boltzmann-neutrino-radiation-hydrodynamical simulations
- ✓ Fully self-consistent non-rotating 11.2 $M_\odot$ progenitor
- ✓ Boltzmann equations for neutrino transport has been solved by applying the discrete co-ordinate method and taking fully into account effects of special relativity with two energy grid technique.
- ✓ Newtonian hydrodynamical equations and the Poisson equation for self-gravity are solved.
- ✓ All equations are written on spherical coordinates (r, θ) under the assumption of spatial axisymmetry.





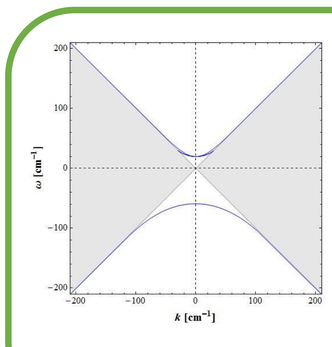


Energy integrated fluxes of ν at $r = 44.8$ km

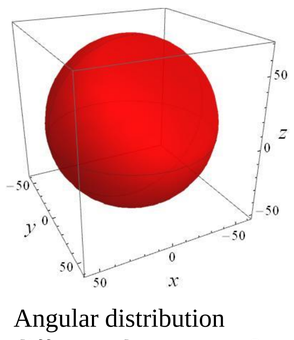


Angular Distribution of $\nu_e, \bar{\nu}_e, \nu_x$ in the meridian sections at different azimuthal angles at $r = 44.8$ km

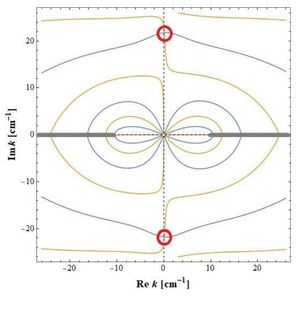
RESULTS (based on original data):



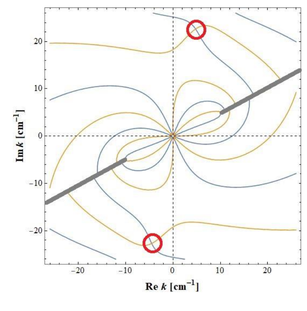
Dispersion Relation



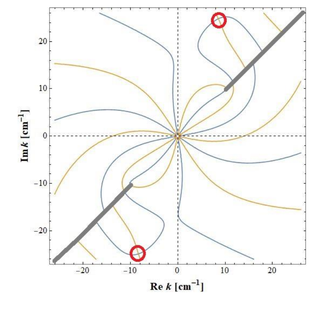
Angular distribution difference between ν_e & $\bar{\nu}_e$



$\omega = 10$



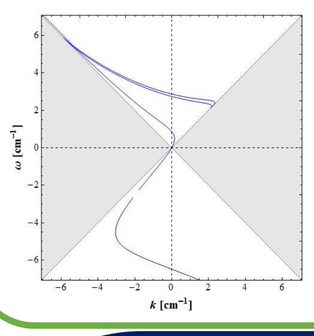
$\omega = 10 + i\ 50$

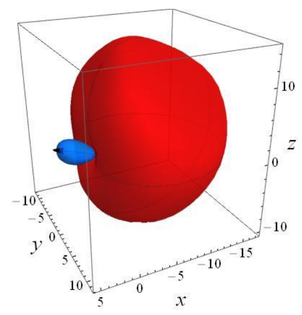


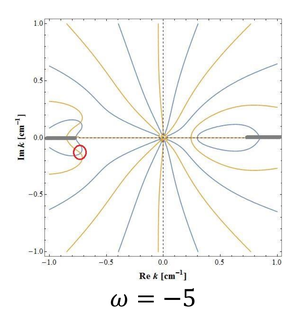
$\omega = 10 + i\ 100$

- ✓ We choose a real value of ω (ω = 10 cm^{-1}) inside the gap region in the dispersion relation plot and look for a complex-k solution. We gradually increase the imaginary part of ω (Im ω) and see whether the solutions cross on real k-axis or not.
- ✓ Red Circles indicate the solutions of equation (*) and gray lines are the zone of avoidance. Blue lines correspond to when Re [det[Π]] = 0 and orange lines correspond to Im [det[Π]] = 0.
- ✓ There is no complex-k roots crossing on real k-axis in this case which means no sign of instability.

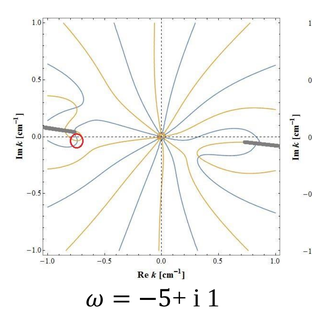
RESULTS (based on scaled data):



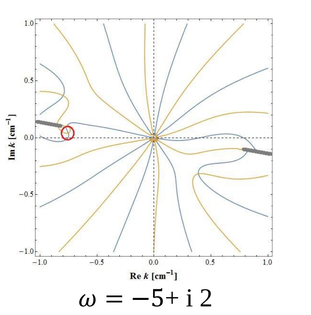




$\omega = -5$



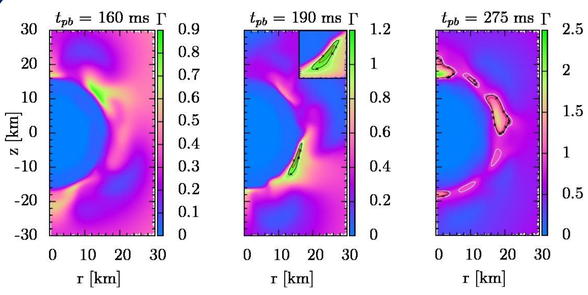
$\omega = -5 + i\ 1$



$\omega = -5 + i\ 2$

- ✓ Analysis for when the crossing occurs for the first time ($\bar{\nu}_e \times 35$)
- ✓ We choose a real value of ω (ω = -5 cm^{-1}) near the curve on in the dispersion relation plot and look for a complex-k solution. We gradually increase the imaginary part of ω (Im ω) and see whether the solutions cross on real k-axis or not.
- ✓ There is crossing on real k-axis means instability is expected here.

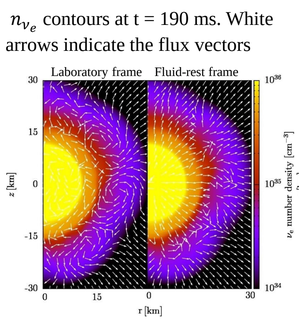
RESULTS OF THE SURVEY:



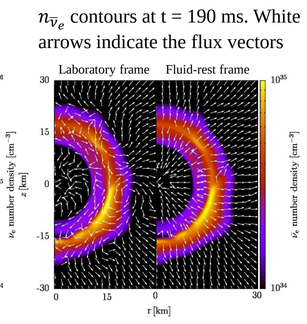
- ✓ Contour plots of the ratio of the number density of $\bar{\nu}_e$, $n_{\bar{\nu}_e} = \int \frac{d^3p}{(2\pi)^3} f_{\bar{\nu}_e}$ to that of ν_e, $n_{\nu_e} = \int \frac{d^3p}{(2\pi)^3} f_{\nu_e}$:

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

- ✓ We find that Γ becomes close to the unity at t = 160 ms but it becomes more than the unity at t = 190 and 275 ms.
- ✓ Crossing occurs when Γ = 1. White, black and red contour lines correspond to Γ = 0.9, 1.0 and 1.1, respectively. The crosses show the points of ELN crossings.

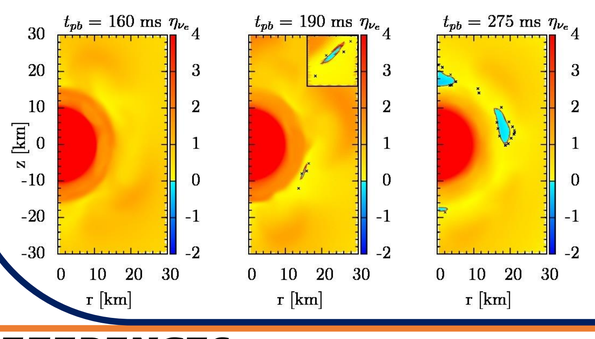


n_{ν_e} contours at t = 190 ms. White arrows indicate the flux vectors



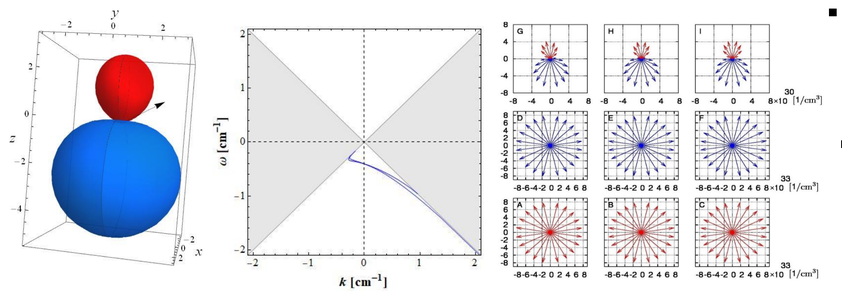
$n_{\bar{\nu}_e}$ contours at t = 190 ms. White arrows indicate the flux vectors

- ❖ Instead of the ratio, now we show the plots of the number density itself in both laboratory and fluid-rest frame.
- ❖ $\bar{\nu}_e$ is suppressed in r < 10 km due to the strong Fermi-degeneracy of ν_e in this region.
- ❖ ν_e & $\bar{\nu}_e$ are flowing in the opposite directions in the regions we found crossings .

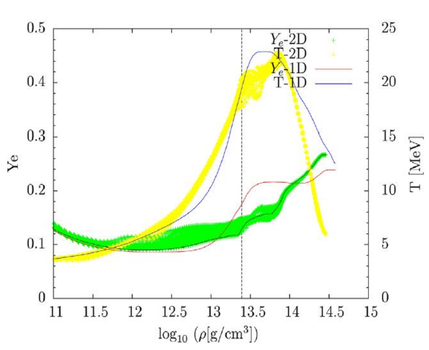


- ➢ Contour plots of $\eta_{\nu_e} = \frac{\mu_{\nu_e}}{T}$ at different times.
- ➢ Blue regions indicate the places, where η_{ν_e} is slightly smaller than 0 and the contour line indicates the points, at which η_{ν_e} = 0. The crosses show the points of ELN crossings.
- ➢ The electron hence is strongly degenerate here.

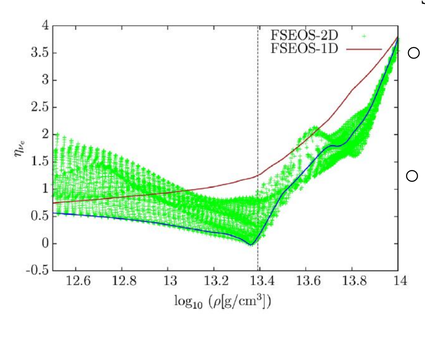
$r = 16.5$ km, $\theta = 2.1$ rad, $\rho = 2.408 \times 10^{13} g/cm^3$
$Y_e = 0.13$, $T = 20.4$ MeV, $\mu_e = 56.9$ MeV,
$\mu_p = 848$ MeV, $\mu_n = 903$ MeV



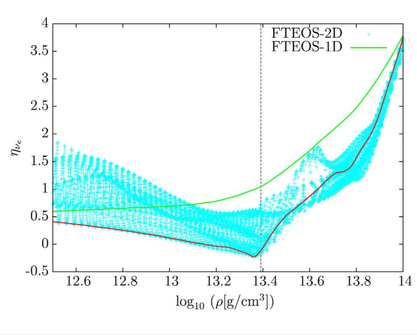
- ▪ Angular distributions of ν_e and $\bar{\nu}_e$ in the meridian sections at different azimuthal angels at r = 16.5 km at 190 ms.
- ▪ The top row panels imply the dominance of ν_e and $\bar{\nu}_e$ in each direction.
- ▪ The dispersion relation looks like the scaled data in the previous section.



- ○ Radial profile of T and Y_e as a function of density for 1D and 2D.
- ○ The values of Y_e in 1D is larger than the band of 2D around the region of our concern (black dashed line).
- ○ The protoneutron star (PNS) convection facilitates the deleptonization of PNS.



- ○ Radial profile of the degeneracy parameter of ν_e (η_{ν_e}) as a function of density for 1D and 2D for two different EOS.
- ○ It is seen that the degeneracy parameter (η_{ν_e}) is not resolved ($\eta_{\nu_e} \sim 1$) in 1D although it is lowered substantially in the region of concern ($r \sim 16.5$ km and $\rho \sim 2.4 \times 10^{13}$ g/cm^3) unlike 2D.



- ○ The ratio Γ never comes close to unity in 1D, implying no chance for ELN crossing.
- ○ The appearance of light elements, which take in most of the free protons, and lower values Y_e produced by the convective motion of matter. This seems to depend on EOS rather weakly and may occur always.

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