Oscillation of high energy neutrinos in Choked GRBs

Sarira Sahu[1]
Andrés Felipe Osorio Oliveros[2,3]
Juan Carlos Sanabria[2]
[1]Instituto de Ciencias Nucleares, UNAM, Mexico City
[2]Universidad de Los Andes, Bogota, Colombia
[3]Fermi National Laboratory, Batavia, IL

It is believed that choked gamma-ray bursts (CGRBs) are the potential candidates for the production of high energy neutrinos in GeV-TeV energy range. These CGRBs out number the successful GRBs by many orders. So it is important to observe neutrinos from these cosmological objects with the presently operating neutrino telescope IceCube. We study the three flavor neutrino oscillation of these high energy neutrinos in the presupernova star environment which is responsible for the CGRB. For the presupernova star we consider three different models and calculate the neutrino oscillation probabilities, as well as neutrino flux on the surface of these star. The matter effect modifies the neutrino flux of different flavors on the surface of the star. We have also calculated the flux of these high energy neutrinos on the surface of the Earth. We found that for neutrino energies below ≤ 10 TeV the flux ratio does not amount to 1:1:1, whereas for higher energy neutrinos it does.

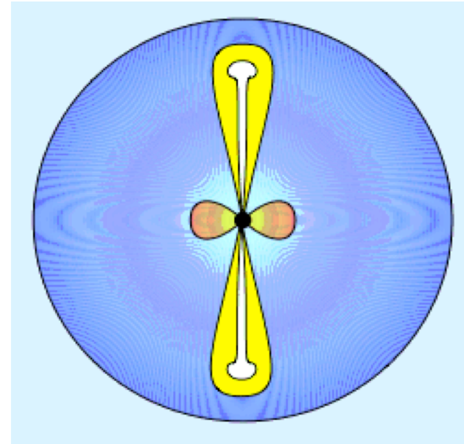
Core collapse of massive stars resulting in relativistic jets breaking through the stellar envelope for GRB production. γ-rays are produced by Synchrotron, Inverse-Compton scattering of Fermi accelerated electrons. Same shocks are also responsible for HE protons and finally HE neutrinos.

What happens when the Jet has no sufficient energy to punch through the stellar envelope ?

Observed rate of GRBs--- $\leq 10^{-3}$
A large fraction of them fail to emerge out of the envelope
⇒ may give **Orphan radio afterglow.**
Irrespective of successful or choked scenario, Fermi accelerated protons of energy $\geq 10^5$ GeV will be produced in internal shock of the jet. Also the buried jet produces thermal X-ray at ≈ 1 keV. (also through pp, pn)

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ \rightarrow n + e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu \\ p + \pi^0 \rightarrow p + \gamma + \gamma \end{cases}$$

Neutrino Oscillation in Matter:



$$|\nu_\alpha> = \sum_{i=1}^{3} U^*_{\alpha i}|\nu_i>$$

$U^*_{\alpha i}$ → 3X3 mixing matrix

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$= \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta_{cp}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{cp}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{cp}} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}s_{13}c_{12}e^{i\delta_{cp}} & -s_{23}c_{12} - s_{13}s_{12}c_{23}e^{i\delta_{cp}} & c_{23}c_{13} \end{pmatrix} (2$$

where $c_{ij} \equiv \cos\theta_{ij}$ and $s_{ij} \equiv \sin\theta_{ij}$ for $i, j = 1, 2, 3$.

Standard Oscillation Parameters are used:

$\Delta m^2_{21} = 8.0\times10^{-5}\ eV^2$, $\theta_{12}=33.8^o$, $\theta_{23}=45^o$
$\Delta m^2_{32} = 3.2\times10^{-3} eV^2$, $\theta_{13}=8.8^o$, $\delta_{CP}=0$.

In the mass basis, the total Hamiltonian is

$$\mathscr{H}_m = H_m + U^{-1} V_f U$$
$$= H_m + V_m.$$

$$H_f = U H_m U^{-1}.$$

$$A = \pm\sqrt{2} G_F N_e = \pm\sqrt{2} G_F \frac{\rho}{m_N},$$

$$H_m = \begin{pmatrix} E_1 & 0 & 0 \\ 0 & E_2 & 0 \\ 0 & 0 & E_3 \end{pmatrix},$$

$$V_f = \begin{pmatrix} A & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix},$$

Flavor basis it is

$$\mathscr{H}_f = H_f + V_f.$$

$$P_{\nu_\alpha \to \nu_\beta}(L) \equiv P_{\alpha\beta}(L) = |\langle \nu_\beta | U_f(L) | \nu_\alpha \rangle|^2$$

$$= \delta_{\alpha\beta} - 4 \sum_{\substack{a=1 \\ a<b}}^{3} \sum_{b=1}^{3} P_a(L)_{\beta\alpha} P_b(L)_{\beta\alpha} \sin^2 x_{ab},$$

The total evolution operator is given by

$$U_f(L) = \prod_i^n U_f(L_i),$$

Presupernova Star Models:

- Model A

$$\rho(r) = \rho_* \times \left(\frac{R_*}{r} - 1\right)^3 \frac{\text{g}}{\text{cm}^3}.$$

This model represents a star with a radiative envelope. $\rho_* = 4.0\times10^{-6}$ g/cm. This model is valid only in the region where the Jet is produced and the star envelope i.e.

$r_j \leq r \leq R_*$

– Model B

$$\rho(r) = \rho_* \times \begin{cases} \left(\frac{R_*}{r}\right)^n & ; 10^{10.8}\,\text{cm} < r < r_b \\ \left(\frac{R_*}{r}\right)^n \frac{(r-R_*)^5}{(r_b-R_*)^5} & ; r > r_b \end{cases} \frac{\text{g}}{\text{cm}^3}. \quad (34)$$

This is a Blue Supergiant (BSG) with n=17/7

– Model C

$$\rho(r) = \rho_* \mathscr{A} \left(\frac{R_*}{r} - 1\right)^{n_{eff}} \frac{\text{g}}{\text{cm}^3}, \quad (35)$$

where the parameters of model C are given as

$$(n_{eff}, \mathscr{A}) = \begin{cases} (2.1, 20) & ; 10^{10.8}\,\text{cm} < r < 10^{11} \\ (2.5, 1.0) & ; r > 10^{11}\,\text{cm}. \end{cases}$$

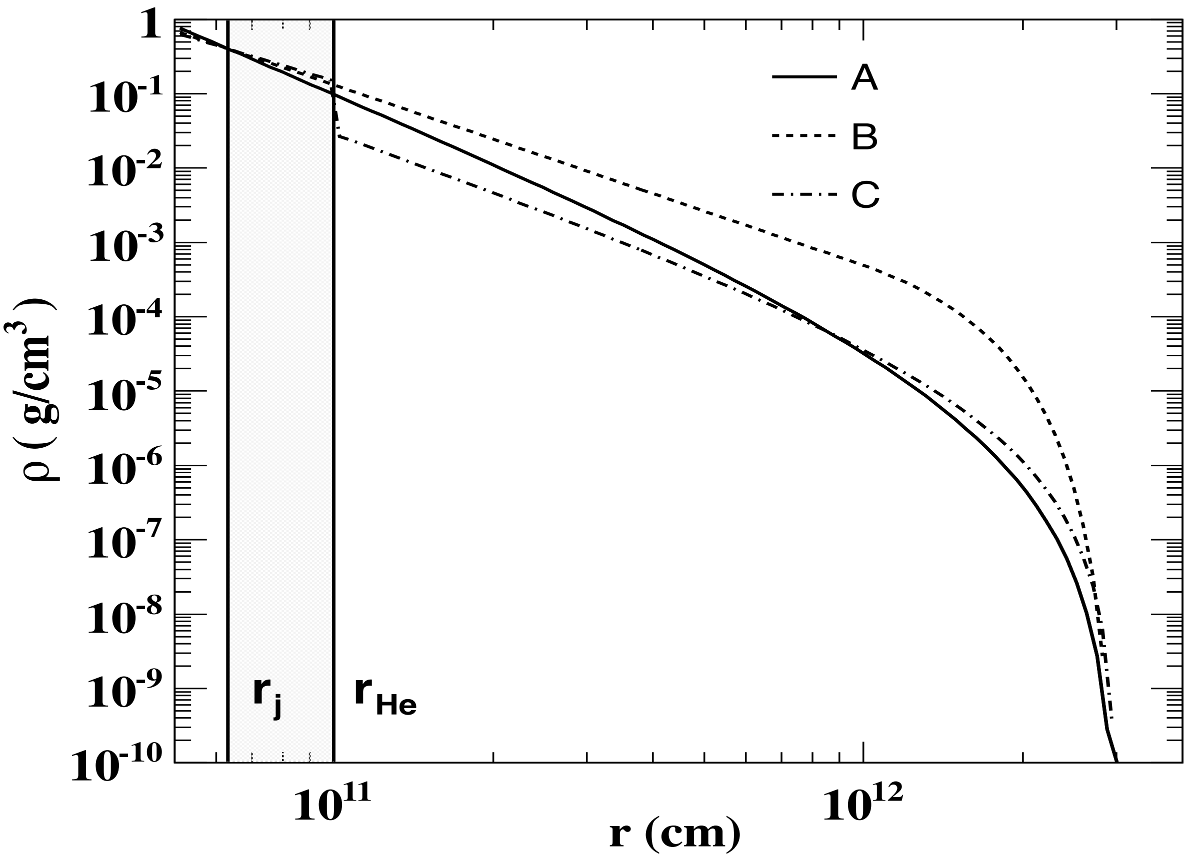
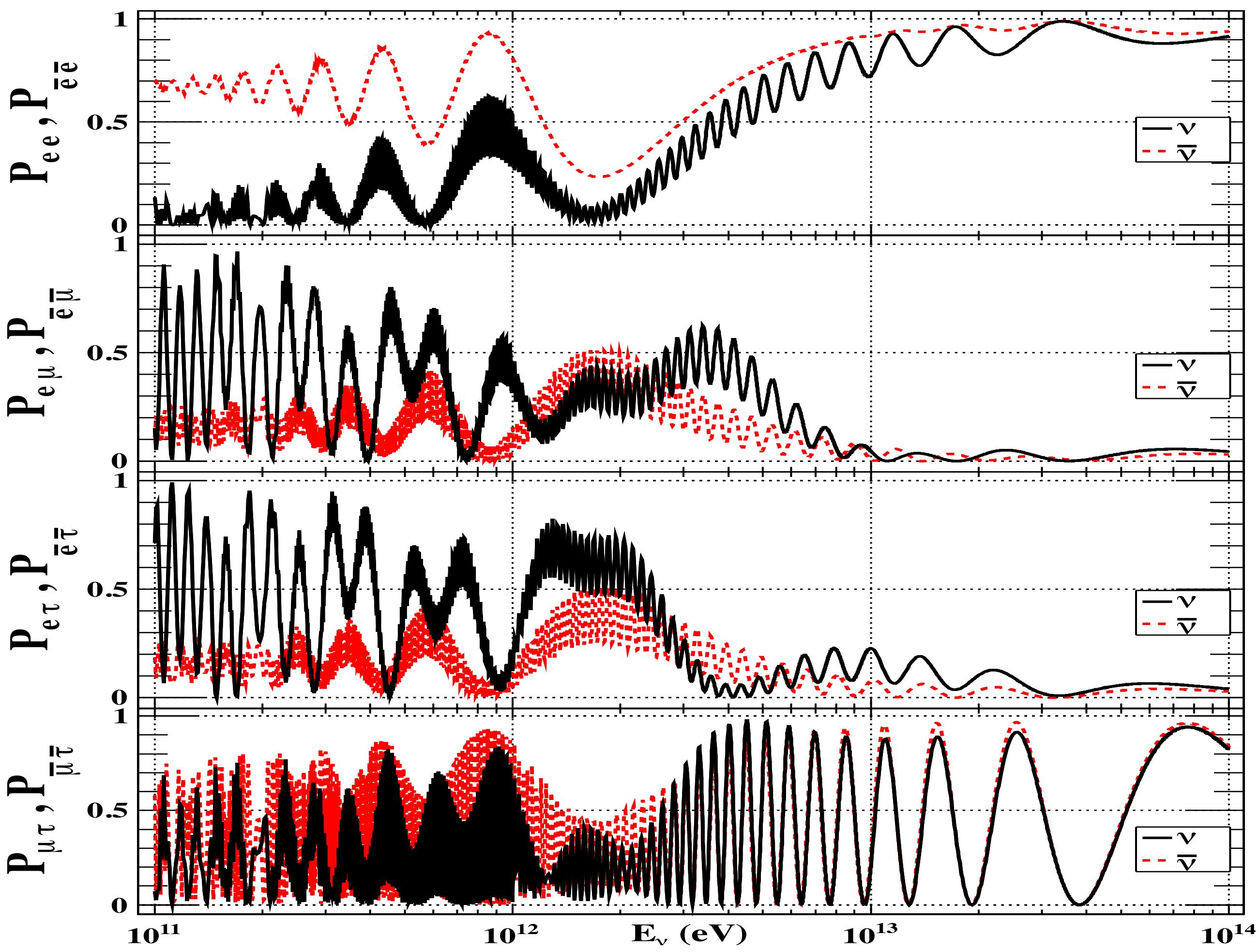


Fig. Density profiles of the presupernova star (a blue supergiant) of models A, B and C with a radius $\mathbf{R}_* = 3x10^{12}$ cm. In these models, the high energy neutrinos are produced at a radius $\mathbf{r}_j = 10^{10.8}$ cm. The Helium envelope extends up to r_{He} 10^{11} cm.

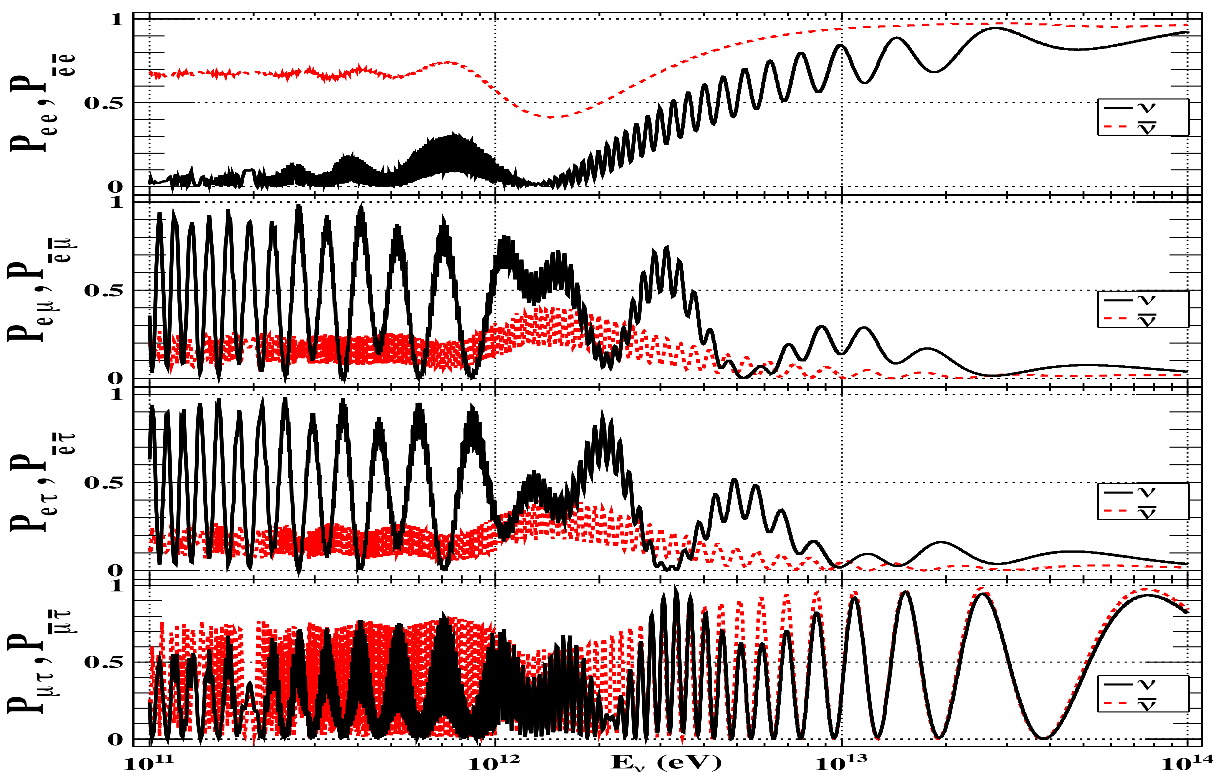
Results:

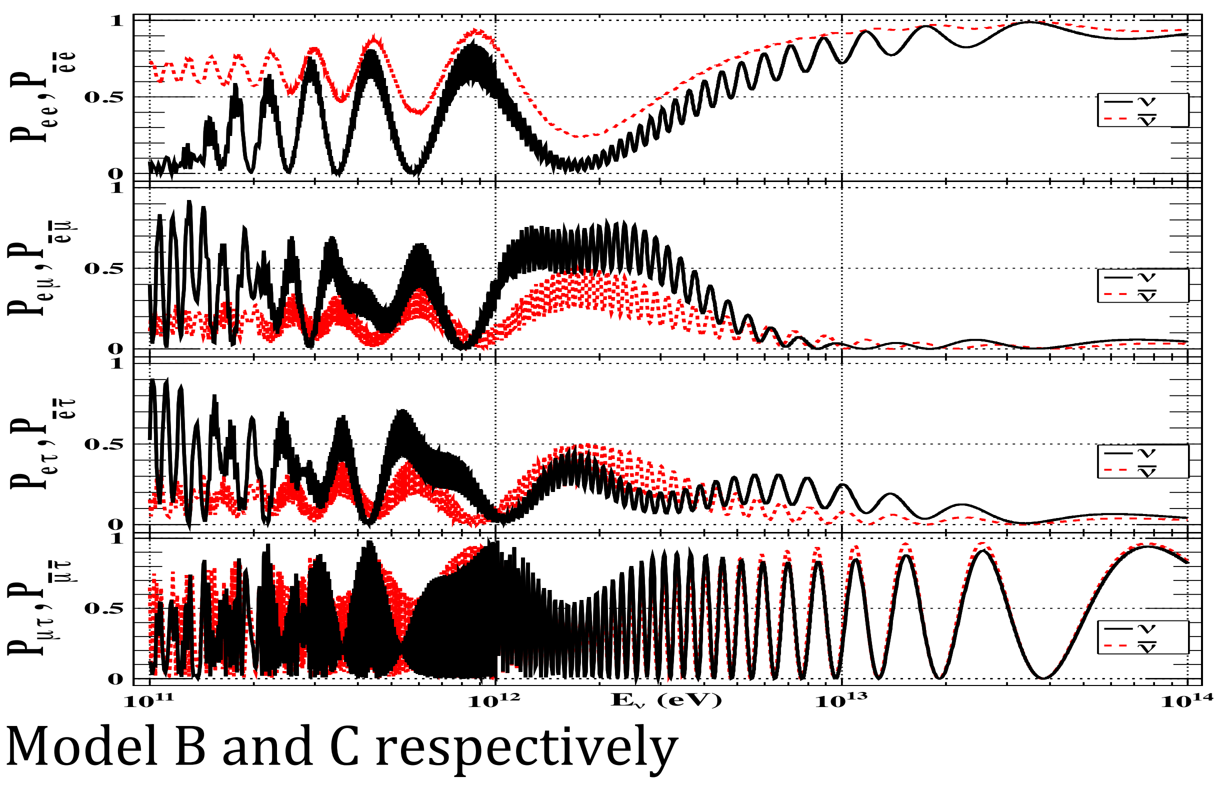
The flux observed at a distance L is

$$\Phi_{\nu_\alpha} = \sum_\beta \Phi^0_{\nu_\beta} P_{\alpha\beta},\ \alpha, \beta = e, \mu, \tau.$$

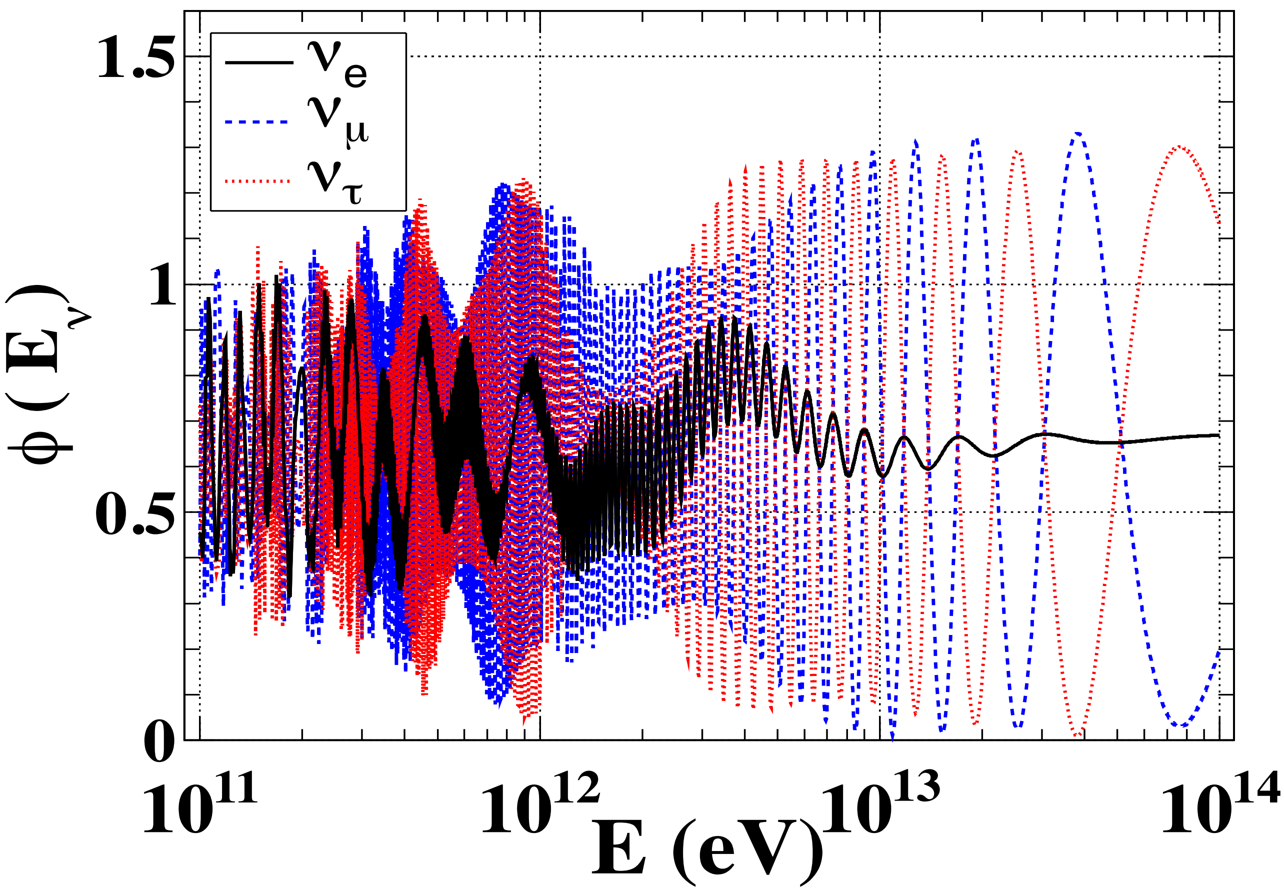


Model-A oscillation probabilities (neutrino –black, anti-neutrino—red)

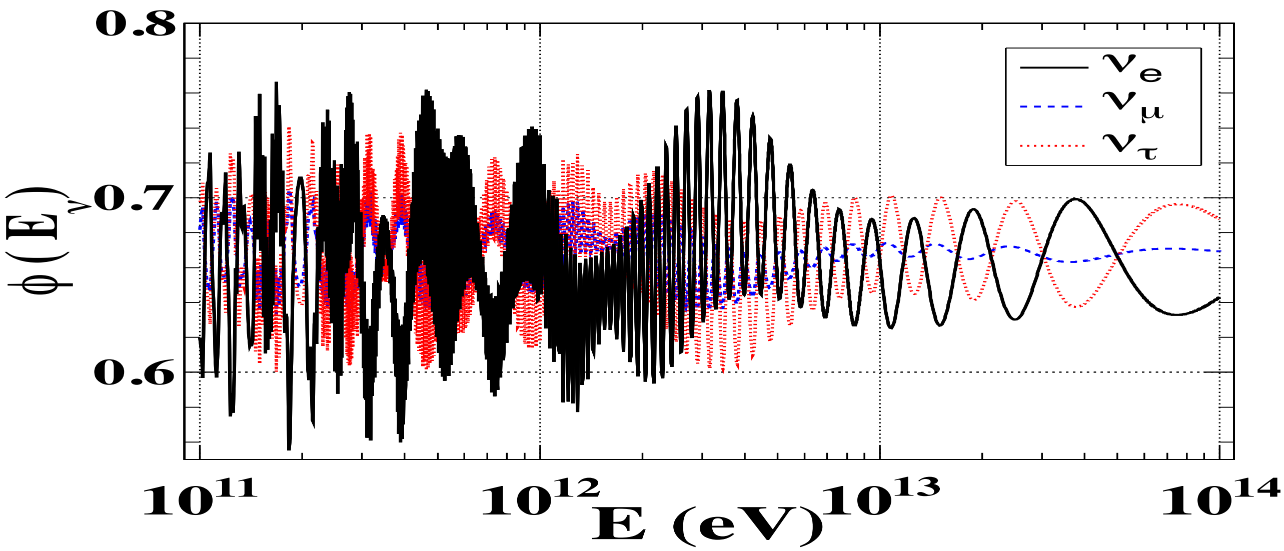




Model B and C respectively



Total flux on the surface of the star



On Surface of the Earth

Conclusions:

We observed that neutrino oscillation within the presupernova star depends on the neutrino energy and alter their flux on the surface of the star. We also calculated the flux on the earth after they travelled the intergalactic medium (vacuum oscillation) and observed that for $E\nu \leq 10$ TeV fluxes are different but above this energy the flux ratio is close to 1:1:1.

Possible detection of neutrinos by IceCube with $E\nu \leq 10$ TeV can be important as the flux changes. It might shed more light on the type of progenitors and production mechanism of high energy neutrinos.

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