POSSIBLE CP-VIOLATION IN CORE-COLLAPSE SUPERNOVAE

Jerome Gava

IPN Orsay

GDR Neutrino Bordeaux, 26/10/07

ArXiv: astro-ph/0710.3112 [A.B.Balantekin, J.Gava ,C.Volpe]

Possible CP-violation in core-collapse Supernovae

Jerome Gava

IPN Orsay

GDR Neutrino Bordeaux, 26/10/07

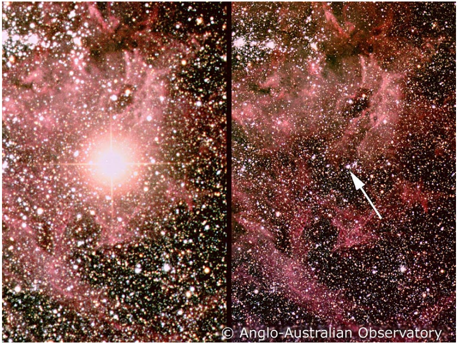
ArXiv: astro-ph/0710.3112 [A.B.Balantekin, J.Gava ,C.Volpe]

Possible CP-violation in core-collapse Supernovae

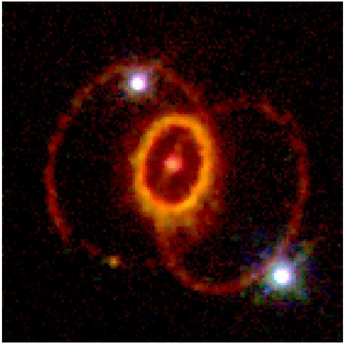
Possible CP-violation in core-collapse Supernovae

Supernovae Type II

- *Explosion at the end of the life of a* **massive** *star ($\geq 8\,\mathcal{M}_{SUN}$) due to the* **gravitational collapse** *of the iron-core into a* **hot** & **dense** *object, the* *Proto-Neutron Star (NS)*
- *99% of the energy ($\simeq 10^{53}$ ergs$\simeq 10^{59}$ MeV) is released by* **neutrinos** *and* **anti-neutrinos** *of all flavors*



(LEFT) SN1987A 10 days after.



(RIGHT) SN1987A Remnant (NS)

MAIN CURRENT PROBLEMS ON SUPERNOVAE

For the shock wave, simulations fail to explode.
The shock wave stalls at 200 Km

Core-collapse supernovae are a possible site for the nucleosynthesis of heavy elements via the r-process.

Main current problems on Supernovae

*For the shock wave, simulations fail to explode.
The shock wave stalls at 200 Km*

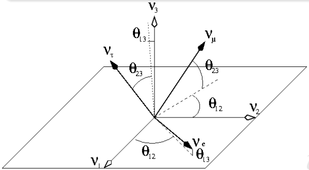
Core-collapse supernovae are a possible site for the nucleosynthesis of heavy elements via the r-process.

Neutrino masses and mixings

Properties:

-3 flavours ν_e, ν_μ, ν_τ, only weak interactions and vanishing masses in the SM.
-Neutrino oscillations = mismatch between the **flavor basis** ν_α *(diagonal charged lepton interactions) and the* **mass basis** ν_i *(diagonal mass matrices)$\Rightarrow$ transition probabilities*

$$| \nu_\alpha >= \sum_i \mathcal{U}^{\alpha i}_{MNSP} | \nu_i >$$



$\mathcal{U}_{MNS}$ contains 3 angles +1 (3) phase(s) [Dirac, Majorana].

Only 2 angles and 2 square-mass differences are measured :

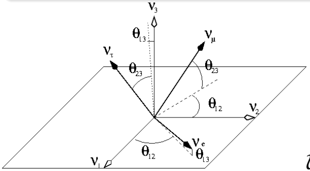
- $\Delta m^2_{12} \simeq 8 \times 10^{-5}\mathrm{eV}^2$, $\Delta m^2_{23} \simeq 2.5 \times 10^{-3}\mathrm{eV}^2 \rightarrow$ **quasi-degenerate** *or* **hierarchical**.

Neutrino masses and mixings

Properties:

-3 flavours ν_e, ν_μ, ν_τ, only weak interactions and vanishing masses in the SM.
-Neutrino oscillations = mismatch between the **flavor basis** *ν_α (diagonal charged lepton interactions) and the* **mass basis** *ν_i (diagonal mass matrices)$\Rightarrow$ transition probabilities*

$$| \nu_\alpha > = \sum_i \mathcal{U}^{\alpha i}_{MNSP} | \nu_i >$$



$\mathcal{U}_{MNS}$ contains 3 angles +1 (3) phase(s) [Dirac, Majorana].

Only 2 angles and 2 square-mass differences are measured :

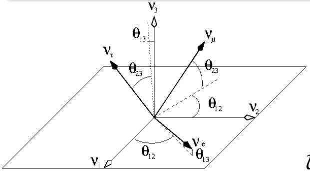
- $\Delta m^2_{12} \simeq 8 \times 10^{-5}\mathrm{eV}^2$, $\Delta m^2_{23} \simeq 2.5 \times 10^{-3}\mathrm{eV}^2 \rightarrow$ **quasi-degenerate** *or* **hierarchical**.

Neutrino masses and mixings

Properties:

-3 flavours ν_e, ν_μ, ν_τ, only weak interactions and vanishing masses in the SM.
-Neutrino oscillations = mismatch between the **flavor basis** *ν_α (diagonal charged lepton interactions) and the* **mass basis** *ν_i (diagonal mass matrices)$\Rightarrow$ transition probabilities*

$$| \nu_\alpha >= \sum_i \mathcal{U}^{\alpha i}_{MNSP} | \nu_i >$$



$\mathcal{U}_{MNS}$ contains 3 angles +1 (3) phase(s) [Dirac, Majorana].

Only 2 angles and 2 square-mass differences are measured :

- $\Delta m^2_{12} \simeq 8 \times 10^{-5}\mathrm{eV}^2$, $\Delta m^2_{23} \simeq 2.5 \times 10^{-3}\mathrm{eV}^2 \rightarrow$ **quasi-degenerate** *or* **hierarchical**.

Still Open Questions

Important parameters remain unkown

- *Value of θ_{13} ?(Double-CHOOZ, T2K)*
Currently CHOOZ gives: sin$^2(2\theta_{13}) < 0.19$
- *Value of the CP-Violation phase δ ? (e.g Super-Beam, Beta-Beam, Neutrino Factory)*
- *What is the hierarchy? Normal or Inverted?*

- *Can there be possible CP-Violation effects in core-collapse supernovae?*
- *Can we learn about CP-Violation in the lepton sector from core-collapse supernova neutrino signals?*

STILL OPEN QUESTIONS

Important parameters remain unkown

- *Value of θ_{13} ?(Double-CHOOZ, T2K)*
Currently CHOOZ gives: $sin^2(2\theta_{13}) < 0.19$
- *Value of the CP-Violation phase δ ? (e.g Super-Beam, Beta-Beam, Neutrino Factory)*
- *What is the hierarchy? Normal or Inverted?*

- *Can there be possible CP-Violation effects in core-collapse supernovae?*
- *Can we learn about CP-Violation in the lepton sector from core-collapse supernova neutrino signals?*

Still Open Questions

Important parameters remain unkown

- *Value of θ_{13} ?(Double-CHOOZ, T2K)*
Currently CHOOZ gives: $sin^2(2\theta_{13}) < 0.19$
- *Value of the CP-Violation phase δ ? (e.g Super-Beam, Beta-Beam, Neutrino Factory)*
- *What is the hierarchy? Normal or Inverted?*

- *Can there be possible CP-Violation effects in core-collapse supernovae?*
- *Can we learn about CP-Violation in the lepton sector from core-collapse supernova neutrino signals?*

Still Open Questions

Important parameters remain unkown

- *Value of θ_{13} ?(Double-CHOOZ, T2K)*
Currently CHOOZ gives: $\sin^2(2\theta_{13}) < 0.19$
- *Value of the CP-Violation phase δ ? (e.g Super-Beam, Beta-Beam, Neutrino Factory)*
- *What is the hierarchy? Normal or Inverted?*

- *Can there be possible CP-Violation effects in core-collapse supernovae?*
- *Can we learn about CP-Violation in the lepton sector from core-collapse supernova neutrino signals?*

STILL OPEN QUESTIONS

Important parameters remain unkown

- *Value of θ_{13}?(Double-CHOOZ, T2K)*
Currently CHOOZ gives: $\sin^2(2\theta_{13}) < 0.19$
- *Value of the CP-Violation phase δ ? (e.g Super-Beam, Beta-Beam, Neutrino Factory)*
- *What is the hierarchy? Normal or Inverted?*

- *Can there be possible CP-Violation effects in core-collapse supernovae?*
- *Can we learn about CP-Violation in the lepton sector from core-collapse supernova neutrino signals?*

Possible CP-violation in core-collapse Supernovae

Neutrino evolution in matter with CP

For the three neutrinos we take

$$T_{23}T_{13}T_{12} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{pmatrix} \begin{pmatrix} C_{13} & 0 & S_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -S_{13}e^{i\delta} & 0 & C_{13} \end{pmatrix} \begin{pmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad (1)$$

The MSW Equation is

$$i\frac{\partial}{\partial t}\begin{pmatrix} \Psi_e \\ \tilde{\Psi}_\mu \\ \tilde{\Psi}_\tau \end{pmatrix} = \left[T_{13}T_{12} \begin{pmatrix} E_1 & 0 & 0 \\ 0 & E_2 & 0 \\ 0 & 0 & E_3 \end{pmatrix} T_{12}^\dagger T_{13}^\dagger + \begin{pmatrix} V_c & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \right] \begin{pmatrix} \Psi_e \\ \tilde{\Psi}_\mu \\ \tilde{\Psi}_\tau \end{pmatrix}. \qquad (2)$$

where we introduce the combinations:

$$\tilde{\Psi}_\mu = \cos\theta_{23}\Psi_\mu - \sin\theta_{23}\Psi_\tau \; \text{and} \; \tilde{\Psi}_\tau = \sin\theta_{23}\Psi_\mu + \cos\theta_{23}\Psi_\tau \qquad (3)$$

Neutrino evolution in matter with CP

For the three neutrinos we take

$$T_{23}T_{13}T_{12} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{pmatrix} \begin{pmatrix} C_{13} & 0 & S_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -S_{13}e^{i\delta} & 0 & C_{13} \end{pmatrix} \begin{pmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (1)$$

The MSW Equation is

$$i\frac{\partial}{\partial t}\begin{pmatrix} \Psi_e \\ \tilde{\Psi}_\mu \\ \tilde{\Psi}_\tau \end{pmatrix} = \left[T_{13}T_{12}\begin{pmatrix} E_1 & 0 & 0 \\ 0 & E_2 & 0 \\ 0 & 0 & E_3 \end{pmatrix} T_{12}^\dagger T_{13}^\dagger + \begin{pmatrix} V_c & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}\right]\begin{pmatrix} \Psi_e \\ \tilde{\Psi}_\mu \\ \tilde{\Psi}_\tau \end{pmatrix}. \quad (2)$$

where we introduce the combinations:

$$\tilde{\Psi}_\mu = \cos\theta_{23}\Psi_\mu - \sin\theta_{23}\Psi_\tau \text{ and } \tilde{\Psi}_\tau = \sin\theta_{23}\Psi_\mu + \cos\theta_{23}\Psi_\tau \quad (3)$$

Neutrino evolution in matter with CP

For the three neutrinos we take

$$T_{23}T_{13}T_{12} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{pmatrix} \begin{pmatrix} C_{13} & 0 & S_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -S_{13}e^{i\delta} & 0 & C_{13} \end{pmatrix} \begin{pmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (1)$$

The MSW Equation is

$$i\frac{\partial}{\partial t}\begin{pmatrix} \Psi_e \\ \tilde{\Psi}_\mu \\ \tilde{\Psi}_\tau \end{pmatrix} = \left[T_{13}T_{12}\begin{pmatrix} E_1 & 0 & 0 \\ 0 & E_2 & 0 \\ 0 & 0 & E_3 \end{pmatrix} T_{12}^\dagger T_{13}^\dagger + \begin{pmatrix} V_c & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \right] \begin{pmatrix} \Psi_e \\ \tilde{\Psi}_\mu \\ \tilde{\Psi}_\tau \end{pmatrix}. \quad (2)$$

where we introduce the combinations:

$$\tilde{\Psi}_\mu = \cos\theta_{23}\Psi_\mu - \sin\theta_{23}\Psi_\tau \ \textit{and}\ \tilde{\Psi}_\tau = \sin\theta_{23}\Psi_\mu + \cos\theta_{23}\Psi_\tau \quad (3)$$

Neutrino Mixing Matrices

We have

$$\tilde{H} = \begin{pmatrix} A & B & Ce^{-i\delta} \\ B & E & De^{-i\delta} \\ -Ce^{i\delta} & De^{i\delta} & F \end{pmatrix} \tag{4}$$

Using

$$S^{\dagger} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{i\delta} \end{pmatrix}. \tag{5}$$

and we obtain:

$$\tilde{H}(\delta) = S^{\dagger}\tilde{H}(\delta = 0)S \tag{6}$$

Neutrino Mixing Matrices

We have

$$\tilde{H} = \begin{pmatrix} A & B & Ce^{-i\delta} \\ B & E & De^{-i\delta} \\ -Ce^{i\delta} & De^{i\delta} & F \end{pmatrix} \tag{4}$$

Using

$$S^{\dagger} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{i\delta} \end{pmatrix}. \tag{5}$$

and we obtain:

$$\tilde{H}(\delta) = S^{\dagger}\tilde{H}(\delta = 0)S \tag{6}$$

Neutrino Mixing Matrices

We have

$$\tilde{H} = \begin{pmatrix} A & B & Ce^{-i\delta} \\ B & E & De^{-i\delta} \\ -Ce^{i\delta} & De^{i\delta} & F \end{pmatrix} \tag{4}$$

Using

$$S^{\dagger} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{i\delta} \end{pmatrix}. \tag{5}$$

and we obtain:

$$\tilde{H}(\delta) = S^{\dagger}\tilde{H}(\delta = 0)S \tag{6}$$

Neutrino Mixing Matrices

Defining

$$\mathcal{U}_0 = S\hat{U}, \tag{7}$$

and using the corresponding evolution equation

$$i\hbar \frac{d\hat{U}}{dt} = \tilde{H}\hat{U}, \tag{8}$$

we obtain:

$$\hat{U}(\delta) = S^{\dagger}\hat{U}_0 S. \tag{9}$$

Neutrino Mixing Matrices

Defining

$$\mathcal{U}_0 = S\hat{U}, \tag{7}$$

and using the corresponding evolution equation

$$i\hbar \frac{d\hat{U}}{dt} = \tilde{H}\hat{U}, \tag{8}$$

we obtain:

$$\hat{U}(\delta) = S^\dagger \hat{U}_0 S. \tag{9}$$

Neutrino Mixing Matrices

Defining

$$\mathcal{U}_0 = S\hat{U}, \tag{7}$$

and using the corresponding evolution equation

$$i\hbar \frac{d\hat{U}}{dt} = \tilde{H}\hat{U}, \tag{8}$$

we obtain:

$$\hat{U}(\delta) = S^\dagger \hat{U}_0 S. \tag{9}$$

Neutrino Mixing Matrices

It is now possible to relate oscillations probabilities for the two cases δ*=0 and* $\delta \neq 0$*. We define the amplitude for the process* $\nu_x \rightarrow \nu_y$ *to be* A_{xy} *when* $\delta \neq 0$ *and to be* A^0_{xy} *when* $\delta = 0$*.*

The previous equation can be rewritten as:

$$\begin{pmatrix} A_{ee} & A_{\tilde{\mu}e} & A_{\tau e} \\ A_{e\tilde{\mu}} & A_{\tilde{\mu}\tilde{\mu}} & A_{\tilde{\tau}\tilde{\mu}} \\ A_{e\tilde{\tau}} & A_{\tilde{\mu}\tilde{\tau}} & A_{\tilde{\tau}\tilde{\tau}} \end{pmatrix} = \begin{pmatrix} B_{ee} & B_{\tilde{\mu}e} & B_{\tau e}e^{-i\delta} \\ B_{e\tilde{\mu}} & B_{\tilde{\mu}\tilde{\mu}} & B_{\tilde{\tau}\tilde{\mu}}e^{-i\delta} \\ B_{e\tilde{\tau}}e^{i\delta} & B_{\tilde{\mu}\tilde{\tau}}e^{i\delta} & B_{\tilde{\tau}\tilde{\tau}} \end{pmatrix} \quad (10)$$

By equalizing this expression terms by terms and using

$$\tilde{\Psi}_\mu = \cos\theta_{23}\Psi_\mu - \sin\theta_{23}\Psi_\tau \text{ and } \tilde{\Psi}_\tau = \sin\theta_{23}\Psi_\mu + \cos\theta_{23}\Psi_\tau \quad (11)$$

Neutrino Mixing Matrices

It is now possible to relate oscillations probabilities for the two cases δ=0 and $\delta \neq 0$. We define the amplitude for the process $\nu_x \rightarrow \nu_y$ to be A_{xy} when $\delta \neq 0$ and to be A^0_{xy} when $\delta = 0$.

so that

$$P(\nu_x \rightarrow \nu_y, \delta \neq 0) = |A_{xy}|^2. \quad (12)$$

and

$$P(\nu_x \rightarrow \nu_y, \delta = 0) = |A^0_{xy}|^2. \quad (13)$$

Using equation (9), we obtain a system of those terms which finally yield:

Neutrino Mixing Matrices

It is now possible to relate oscillations probabilities for the two cases δ=0 and $\delta \neq 0$. We define the amplitude for the process $\nu_x \to \nu_y$ to be A_{xy} when $\delta \neq 0$ and to be A^0_{xy} when $\delta = 0$.

so that

$$P(\nu_x \to \nu_y, \delta \neq 0) = |A_{xy}|^2. \tag{12}$$

and

$$P(\nu_x \to \nu_y, \delta = 0) = |A^0_{xy}|^2. \tag{13}$$

Using equation (9), we obtain a system of those terms which finally yield:

Neutrino Mixing Matrices

It is now possible to relate oscillations probabilities for the two cases δ=0 and $\delta \neq 0$. We define the amplitude for the process $\nu_x \longrightarrow \nu_y$ to be A_{xy} when $\delta \neq 0$ and to be A^0_{xy} when $\delta = 0$.

so that

$$P(\nu_x \longrightarrow \nu_y, \delta \neq 0) = |A_{xy}|^2. \tag{12}$$

and

$$P(\nu_x \longrightarrow \nu_y, \delta = 0) = |A^0_{xy}|^2. \tag{13}$$

Using equation (9), we obtain a system of those terms which finally yield:

Analytic results

$$P(\nu_e \rightarrow \nu_e, \delta \neq 0) = P(\nu_e \rightarrow \nu_e, \delta = 0) \tag{14}$$

This result is valid for any density profile.

and we also obtain

$$P(\nu_\mu \rightarrow \nu_e, \delta \neq 0) + P(\nu_\tau \rightarrow \nu_e, \delta \neq 0) = P(\nu_\mu \rightarrow \nu_e, \delta = 0) + P(\nu_\tau \rightarrow \nu_e, \delta = 0). \tag{15}$$

which is also valid for any density profile.

Analytic results

$$P(\nu_e \to \nu_e, \delta \neq 0) = P(\nu_e \to \nu_e, \delta = 0) \tag{14}$$

This result is valid for any density profile.

and we also obtain

$$P(\nu_\mu \to \nu_e, \delta \neq 0) + P(\nu_\tau \to \nu_e, \delta \neq 0) = P(\nu_\mu \to \nu_e, \delta = 0) + P(\nu_\tau \to \nu_e, \delta = 0). \tag{15}$$

which is also valid for any density profile.

Possible CP-violation in core-collapse Supernovae

Neutrino Fluxes

$$\phi_{\nu_e}(\delta) = L_{\nu_e} P(\nu_e \to \nu_e) + L_{\nu_\mu} P(\nu_\mu \to \nu_e) + L_{\nu_\tau} P(\nu_\tau \to \nu_e)$$

with

$$L_{\nu_i}(r, E_\nu) = \frac{L^0_{\nu_i}}{4\pi r^2 (kT)^3 \langle E_\nu \rangle F_2(\eta)} \frac{E_\nu^2}{1+\exp{(E_\nu / T_\nu - \eta)}}$$

where we take a Fermi-Dirac distribution for neutrinos at the neutrino sphere.

As in the Standard Model, we have $L^0_{\nu_\mu} = L^0_{\nu_\tau}$ and $T_{\nu_\mu} = T_{\nu_\tau}$

$$\phi_{\nu_e}(\delta) = L_{\nu_e} P(\nu_e \to \nu_e) + L_{\nu_\mu} (P(\nu_\mu \to \nu_e) + P(\nu_\tau \to \nu_e))$$

Thus, the ν_e flux does not depend on δ. Neither, the $\bar{\nu}_e$ flux.

No CP-violation effects will be observable measuring ϕ_{ν_e} and $\phi_{\bar{\nu}_e}$ in a detector.

Neutrino Fluxes

$$\phi_{\nu_e}(\delta) = L_{\nu_e} P(\nu_e \to \nu_e) + L_{\nu_\mu} P(\nu_\mu \to \nu_e) + L_{\nu_\tau} P(\nu_\tau \to \nu_e)$$

with

$$L_{\nu_i}(r, E_\nu) = \frac{L^0_{\nu_i}}{4\pi r^2 (kT)^3 \langle E_\nu \rangle F_2(\eta)} \frac{E^2_\nu}{1+\exp(E_\nu / T_\nu - \eta)}$$

where we take a Fermi-Dirac distribution for neutrinos at the neutrino sphere.
As in the Standard Model, we have $L^0_{\nu_\mu} = L^0_{\nu_\tau}$ and $T_{\nu_\mu} = T_{\nu_\tau}$

$$\phi_{\nu_e}(\delta) = L_{\nu_e} P(\nu_e \to \nu_e) + L_{\nu_\mu} (P(\nu_\mu \to \nu_e) + P(\nu_\tau \to \nu_e))$$

Thus, the ν_e flux does not depend on δ. Neither, the $\bar{\nu}_e$ flux.

No CP-violation effects will be observable measuring ϕ_{ν_e} and $\phi_{\bar{\nu}_e}$ in a detector.

Neutrino Fluxes

$$\phi_{\nu_e}(\delta) = L_{\nu_e} P(\nu_e \to \nu_e) + L_{\nu_\mu} P(\nu_\mu \to \nu_e) + L_{\nu_\tau} P(\nu_\tau \to \nu_e)$$

with

$$L_{\nu_i}(r, E_\nu) = \frac{L^0_{\nu_i}}{4\pi r^2 (kT)^3 \langle E_\nu \rangle F_2(\eta)} \frac{E^2_\nu}{1+\exp\left(E_\nu / T_\nu - \eta\right)}$$

where we take a Fermi-Dirac distribution for neutrinos at the neutrino sphere.
As in the Standard Model, we have $L^0_{\nu_\mu} = L^0_{\nu_\tau}$ and $T_{\nu_\mu} = T_{\nu_\tau}$

$$\phi_{\nu_e}(\delta) = L_{\nu_e} P(\nu_e \to \nu_e) + L_{\nu_\mu} (P(\nu_\mu \to \nu_e) + P(\nu_\tau \to \nu_e))$$

Thus, the ν_e flux does not depend on δ. Neither, the $\bar{\nu}_e$ flux.

No CP-violation effects will be observable measuring ϕ_{ν_e} and $\phi_{\bar{\nu}_e}$ in a detector.

Electron Fraction In Supernovae

Dominant reactions that control the neutron-to-proton ratio:

$$\nu_e + \mathrm{n} \rightleftharpoons \mathrm{p} + e^-$$
$$\bar{\nu}_e + \mathrm{p} \rightleftharpoons \mathrm{n} + e^+$$

We introduce the total proton loss rate neutron loss rate:

$$\lambda_p = \lambda_{\bar{\nu}_e} + \lambda_{e^-}$$
$$\lambda_n = \lambda_{\nu_e} + \lambda_{e^+}.$$

The electron fraction is:

$$Y_e = (n_{e^-} - n_{e^+})/(n_n + n_p)$$

Electron Fraction In Supernovae

Dominant reactions that control the neutron-to-proton ratio:

$$\nu_e + \mathrm{n} \rightleftharpoons \mathrm{p} + e^-$$
$$\bar{\nu}_e + \mathrm{p} \rightleftharpoons \mathrm{n} + e^+$$

We introduce the total proton loss rate neutron loss rate:

$$\lambda_p = \lambda_{\bar{\nu}_e} + \lambda_{e^-}$$
$$\lambda_n = \lambda_{\nu_e} + \lambda_{e^+}.$$

The electron fraction is:

$$Y_e = (n_{e^-} - n_{e^+})/(n_n + n_p)$$

Electron fraction in supernovae

Since electron and positron capture rates are very small, one can write the equilibrium value of the electron fraction :

$$Y_e^{(0)} = \frac{1}{1+\lambda_p/\lambda_n}$$

The capture rates on n, p are given by

$$\lambda_{n,p} = \int \sigma_{\nu_e n, \bar{\nu}_e p}(E_\nu)\phi_{\nu_e, \bar{\nu}_e}(E_\nu)dE_\nu$$

$\sigma_{\nu_e n, \bar{\nu}_e p}$ being the reaction cross sections for the corresponding processes above.

Thus, we obtain that Ye does not depend on δ.

Electron fraction in supernovae

Since electron and positron capture rates are very small, one can write the equilibrium value of the electron fraction :

$$Y_e^{(0)} = \frac{1}{1+\lambda_p/\lambda_n}$$

The capture rates on n, p are given by

$$\lambda_{n,p} = \int \sigma_{\nu_e n, \bar{\nu}_e p}(E_\nu)\phi_{\nu_e, \bar{\nu_e}}(E_\nu)dE_\nu$$

$\sigma_{\nu_e n, \bar{\nu}_e p}$ being the reaction cross sections for the corresponding processes above.

Thus, we obtain that Ye does not depend on δ.

Possible CP-violation in core-collapse Supernovae

Flux Ratios as a function of the distance from the Neutron Star Surface(NSS)

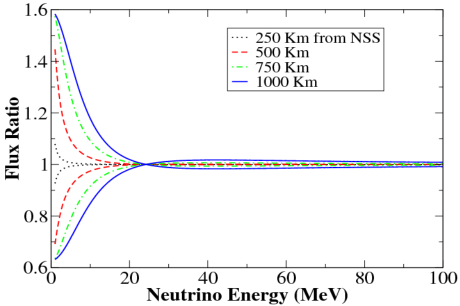


Figure: Upper curves for $\bar{\nu}_\tau$, lower curves for $\bar{\nu}_\mu$

ν_μ *Flux Ratios*

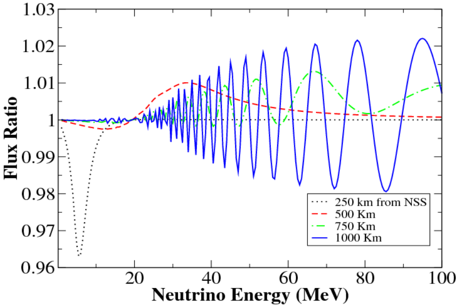


Figure: For different distances from the Neutron Star Surface

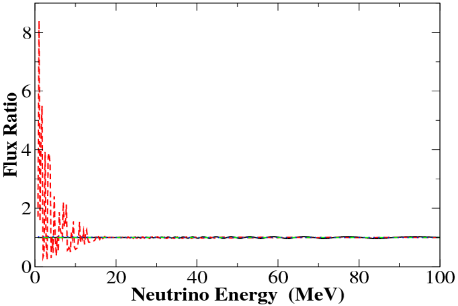


Figure: For different hierarchies (N/I) and θ_{13} (L/S)

Comparison of ν_e fluxes at 1000 Km from NSS

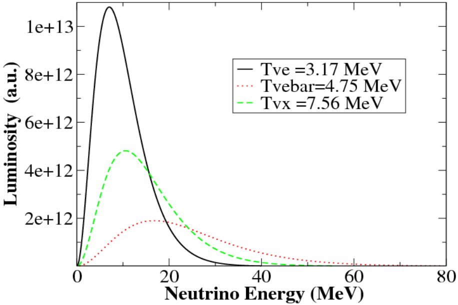


Figure: Without Oscillations

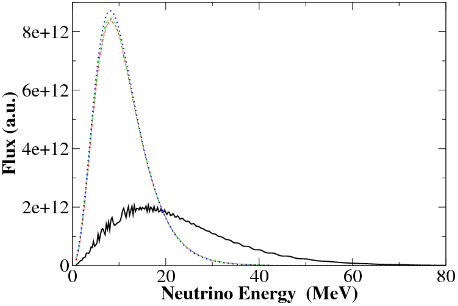


Figure: For different hierarchies and θ_{13} with $T_{\nu_\tau} - T_{\nu_\mu} = 1 MeV$

Comparison of ν_e fluxes at 1000 Km from NSS

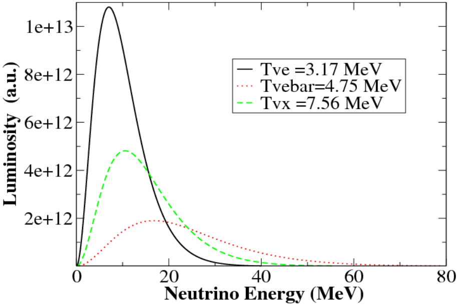


Figure: Without Oscillations

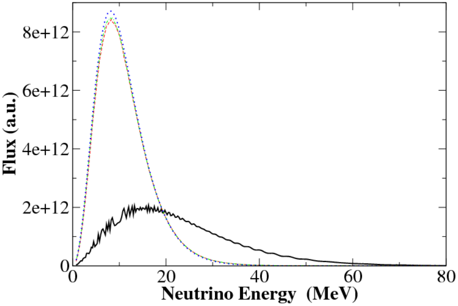


Figure: For different hierarchies and θ_{13} with $T_{\nu_\tau} - T_{\nu_\mu} = 1 MeV$

ν_e flux ratios for different hierarchies and θ_{13} with $L_{\nu_\tau} \neq L_{\nu_\mu}$

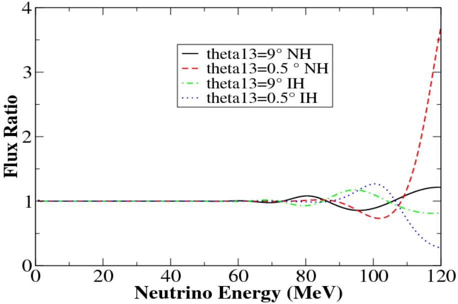


Figure: At 200 Km from NSS

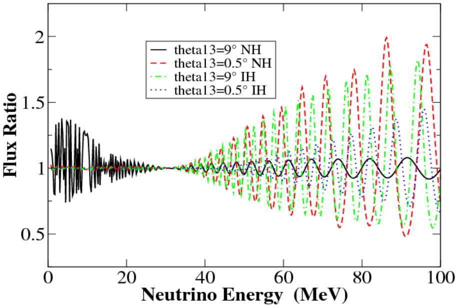


Figure: At 1000 Km from NSS

Electron Fraction and Ratios of Electron Fraction for different hierachies and θ_{13}

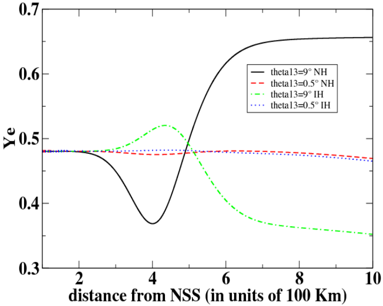


Figure: Ye for $\delta = 0°$

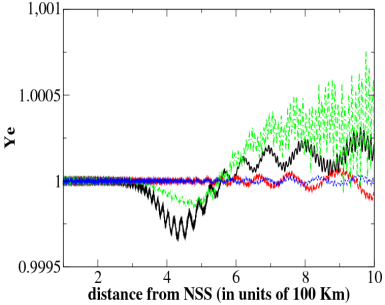


Figure: Ye Ratio: $\frac{Ye(\delta=180°)}{Ye(\delta=0°)}$

Possible CP-violation in core-collapse Supernovae

Main Results

On the probabilities

For any matter density profile : *No CP-violation effects on* $P(\nu_e \rightarrow \nu_e)$
Main analytical result valid $P(\nu_\mu \rightarrow \nu_e, \delta \neq 0) + P(\nu_\tau \rightarrow \nu_e, \delta \neq 0) = P(\nu_\mu \rightarrow \nu_e, \delta = 0) + P(\nu_\tau \rightarrow \nu_e, \delta = 0)$.

On ν_e and $\bar{\nu}_e$ fluxes and on the electron fraction

- ϕ_{ν_e} and $\phi_{\bar{\nu}_e}$ and Ye *do not* depend on δ.
No CP-violation effects will be observable by measuring ϕ_{ν_e}, $\phi_{\bar{\nu}_e}$ *in an observatory.*

Main Results

On the probabilities

For any matter density profile : No CP-violation effects on $P(\nu_e \rightarrow \nu_e)$
Main analytical result valid $P(\nu_\mu \rightarrow \nu_e, \delta \neq 0) + P(\nu_\tau \rightarrow \nu_e, \delta \neq 0) = P(\nu_\mu \rightarrow \nu_e, \delta = 0) + P(\nu_\tau \rightarrow \nu_e, \delta = 0)$.

On ν_e and $\bar{\nu}_e$ fluxes and on the electron fraction

- ϕ_{ν_e} *and* $\phi_{\bar{\nu}_e}$ *and Ye do not depend on* δ.

No CP-violation effects will be observable by measuring ϕ_{ν_e}, $\phi_{\bar{\nu}_e}$ in an observatory.

On ν_μ, $\bar{\nu}_\mu$, ν_τ and $\bar{\nu}_\tau$ fluxes

Effects up to 60% for $\bar{\nu}_\mu$ and $\bar{\nu}_\tau$ fluxes and up to 4% for ν_μ and ν_τ fluxes. Such effects will not be observable since they interact via neutral-current only.

But with different fluxes for ν_μ and ν_τ at the neutrino sphere:

Important effects on ϕ_{ν_e} and $\phi_{\bar{\nu}_e}$ fluxes appear if one takes different vmu and vtau uminosities at the neutrino sphere.In this case cp-violation effects could be observable in supernova observatories(LENA, GLACIER, MEMPHYS).

On ν_μ, $\bar{\nu}_\mu$, ν_τ and $\bar{\nu}_\tau$ fluxes

Effects up to 60% for $\bar{\nu}_\mu$ and $\bar{\nu}_\tau$ fluxes and up to 4% for ν_μ and ν_τ fluxes. Such effects will not be observable since they interact via neutral-current only.

But with different fluxes for ν_μ and ν_τ at the neutrino sphere:

Important effects on ϕ_{ν_e} and $\phi_{\bar{\nu}_e}$ fluxes appear if one takes different vmu and vtau uminosities at the neutrino sphere.In this case cp-violation effects could be observable in supernova observatories(LENA, GLACIER, MEMPHYS).