Possible CP-violation effects in core-collapse supernovae

A. B. Balantekin, J. Gava, C. Volpe, PLB662, 396 (2008), arXiv:0710.3112

J. Gava & C. Volpe, submitted to PRD, arXiv:0807.3418

Jérôme Gava
IPN Orsay

The experimental results on the oscillation parameters

$$U = T_{23}S^{\dagger}T^{0}_{13}ST_{12} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{T_{23}} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \boxed{e^{i\delta}} \end{pmatrix}}_{S^{\dagger}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}}_{T^{0}_{13}} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \boxed{e^{-i\delta}} \end{pmatrix}}_{S} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{T_{12}}$$

In three flavours

Maki-Nakagawa-Sakata-Pontecorvo Matrix

3 mixing angles

θ_{12} $sin^2 2\theta_{12} = 0.86^{+0.03}_{-0.04}$ (SNO, Kamland)

θ_{23} $sin^2 2\theta_{23} > 0.92$ (Super-Kamiokande)

θ_{13} ? $sin^2 2\theta_{13} < 0.19$ (CHOOZ, but soon Double-CHOOZ, T2K…)

3 masses (but experimentally only mass square differences)…

$\Delta m^2_{32} = m^2_3 - m^2_2 = 1.9 \text{ to } 3.0 \times 10^{-3} eV^2$ $\Delta m^2_{21} = m^2_2 - m^2_1 = 8.0^{+0.4}_{-0.3} \times 10^{-5} eV^2$

An important open issue

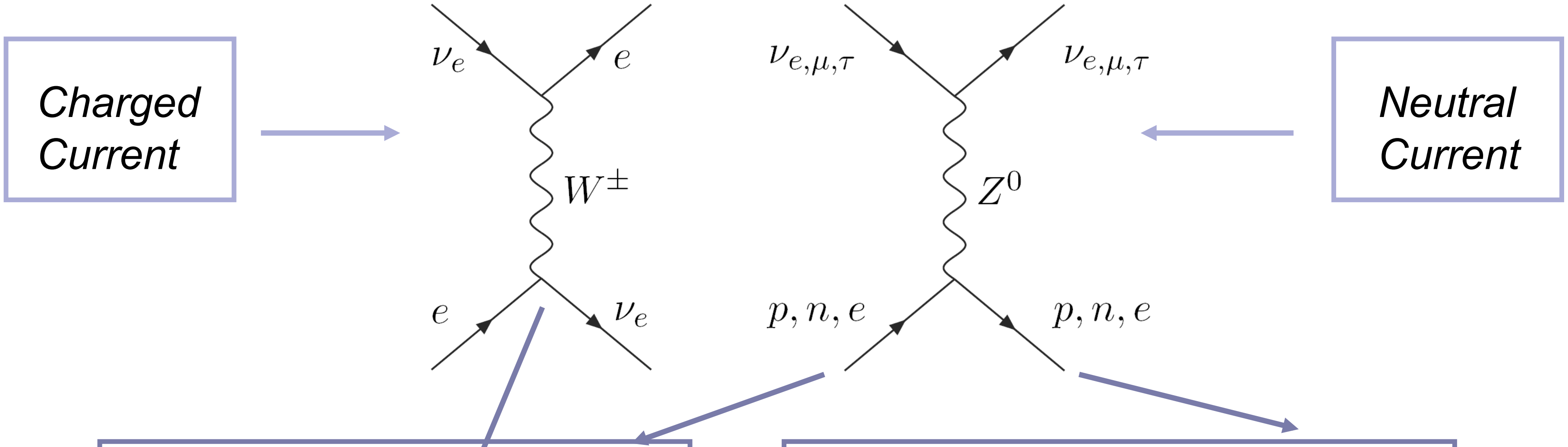
…and 1 CP violating phase

$\delta = ?$ (Super-Beams, Beta-Beams, Neutrino Factory)

Can we learn about δ with supernovae?

Neutrino oscillations in matter

With matter neutrinos interact in two ways:



Charged Current

Neutral Current

$$V_e = \sqrt{2}\, G_F \left(N_e - \frac{N_n}{2} \right)$$

$$V_\mu = V_\tau = \sqrt{2}\, G_F \left(-\frac{N_n}{2} \right)$$

Possibility of resonance of neutrino oscillation in matter called Mikheev-Smirnov-Wolfenstein (MSW) effect.

This effect explains the neutrino solar deficit problem.

CP-violation effects in presence of matter

E. Akhmedov, C.Lunardini & A.Smirnov, Nucl.Phys.B643:339-366,2002.

A. B. Balantekin, J. Gava, C. Volpe, PLB662, 396 (2008), arXiv:0710.3112

The neutrino evolution equation is

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

Vacuum term

Matter term

with

$$\tilde{\Psi}_\mu = \cos\theta_{23}\Psi_\mu - \sin\theta_{23}\Psi_\tau \;\; and \;\; \tilde{\Psi}_\tau = \sin\theta_{23}\Psi_\mu + \cos\theta_{23}\Psi_\tau$$

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

factorizes out easily and gives:

CP-violation effects in presence of matter

$$\boxed{\tilde{H}(\delta) = S^\dagger \tilde{H}(\delta = 0) S} \Longleftrightarrow \boxed{\tilde{U}(\delta) = S^\dagger \tilde{U}(\delta = 0) S}$$

Evolution operator in the T_{23} basis

This leads to the two following relations:

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

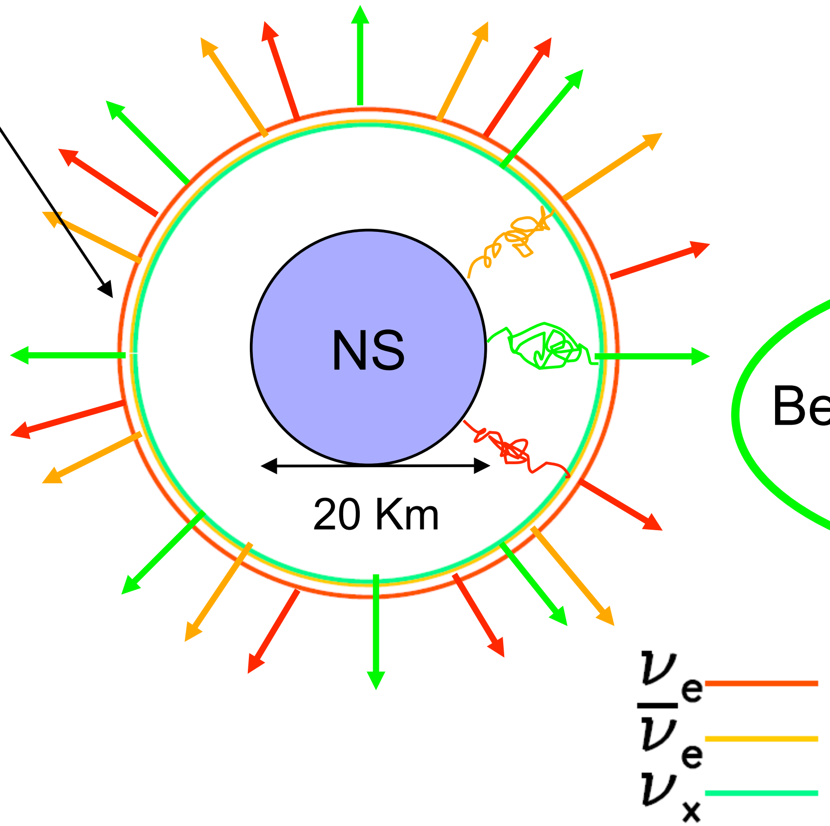
The electron neutrino survival probability does not depend on δ.

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

Valid for any density profile.

In the supernova : the fluxes emitted at the neutrinosphere

The **neutrinosphere** is where the neutrinos finally decouple from matter and are emitted.



Tree level

$$L_{\nu_\mu} = L_{\nu_\tau}$$

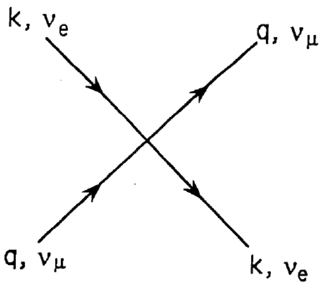
But…

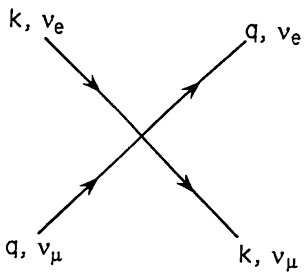
1-loop correction,
Beyond Standard Model

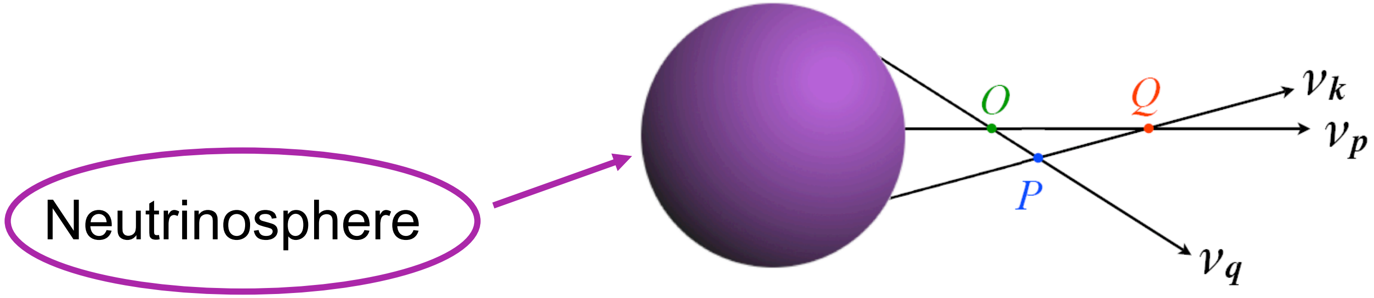
$$L_{\nu_\mu} \neq L_{\nu_\tau}$$

The neutrino-neutrino interaction

One has to take into account the neutrino-neutrino interactions:







More complicated because non-linear problem.

New physics compared to the MSW effect

CP-violation effects and ν-ν interaction

J. Gava & C. Volpe, submitted to PRD, arXiv:0807.3418

We showed analytically that :

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

when $L_{\nu_\mu} = L_{\nu_\tau}$

$$P(\nu_e \to \nu_e, \delta \neq 0) = P(\nu_e \to \nu_e, \delta = 0)$$

$$P(\nu_\mu \to \nu_e, \delta \neq 0) + P(\nu_\tau \to \nu_e, \delta \neq 0) = P(\nu_\mu \to \nu_e, \delta = 0) + P(\nu_\tau \to \nu_e, \delta = 0)$$

Still valid even with the ν−ν interactions.

CP-violation effects on the neutrino fluxes in supernovae?

The electron neutrino flux in the supernova is

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

In the standard model, at the tree level, at the neutrinosphere:

$$\boxed{L_{\nu_\mu} = L_{\nu_\tau}}$$

↓

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

AT TREE LEVEL $\phi\nu_e$ DOES NOT DEPEND ON δ WITH ν−ν INTERACTION.

Can we still have CP-violation effects in supernovae?

1°) Yes, in the Standard Model one has to take into account one loop corrections for the neutrino interaction with matter.

2°) Beyond the Standard Model : Flavor Changing Neutral Currents, etc…

$L_{\nu_\mu} \neq L_{\nu_\tau}$ at the neutrinosphere

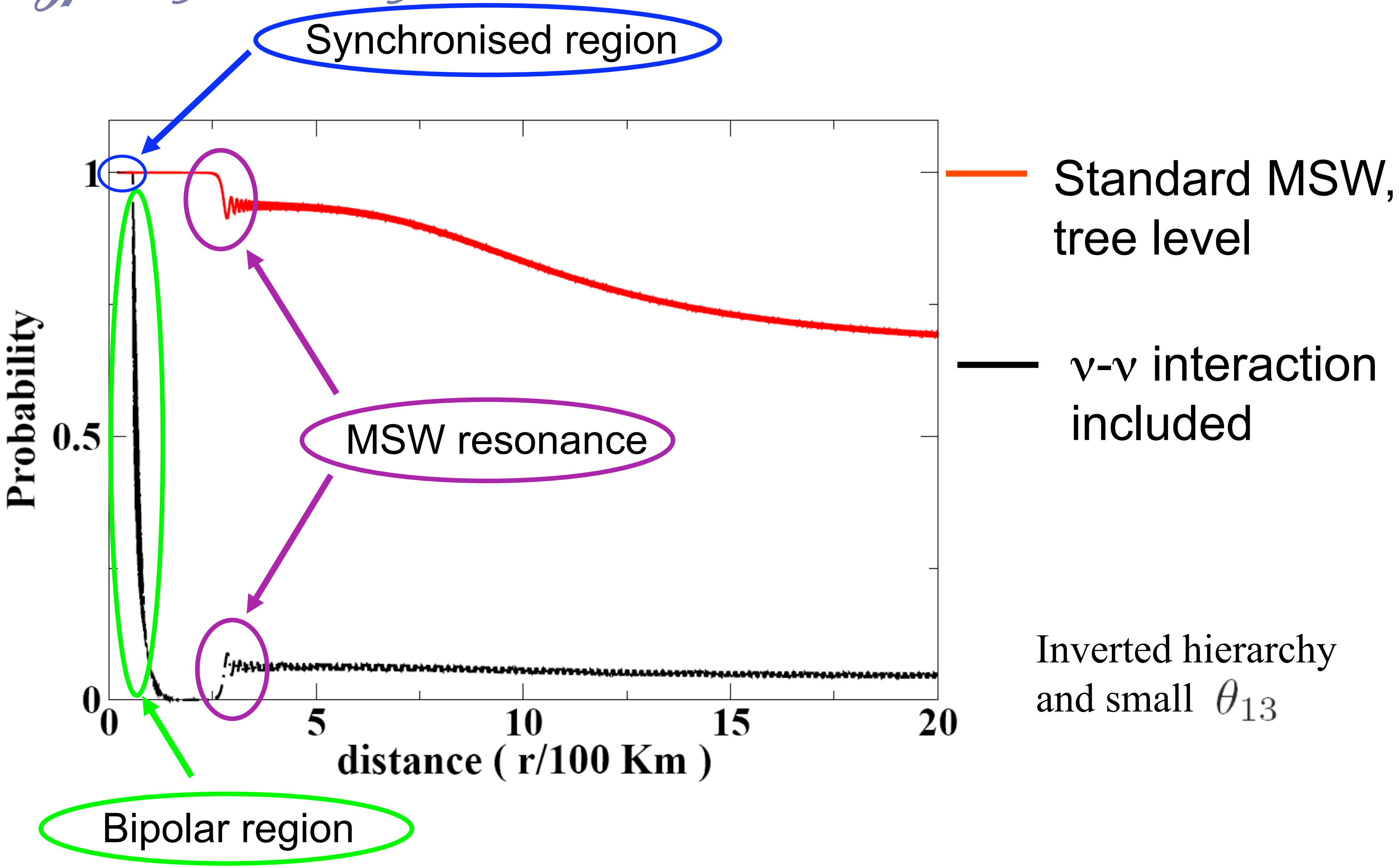
THERE CAN BE CP-VIOLATION EFFECTS IN SUPERNOVAE.

Numerical results

with $\nu-\nu$ interaction

- On probabilities and on the fluxes inside the supernova
- In a detector on Earth
- On nucleosynthesis (r-process)

Typical features of ν-ν interaction on $P(\overline{\nu_e} \to \overline{\nu_e})$



Synchronised region

MSW resonance

Bipolar region

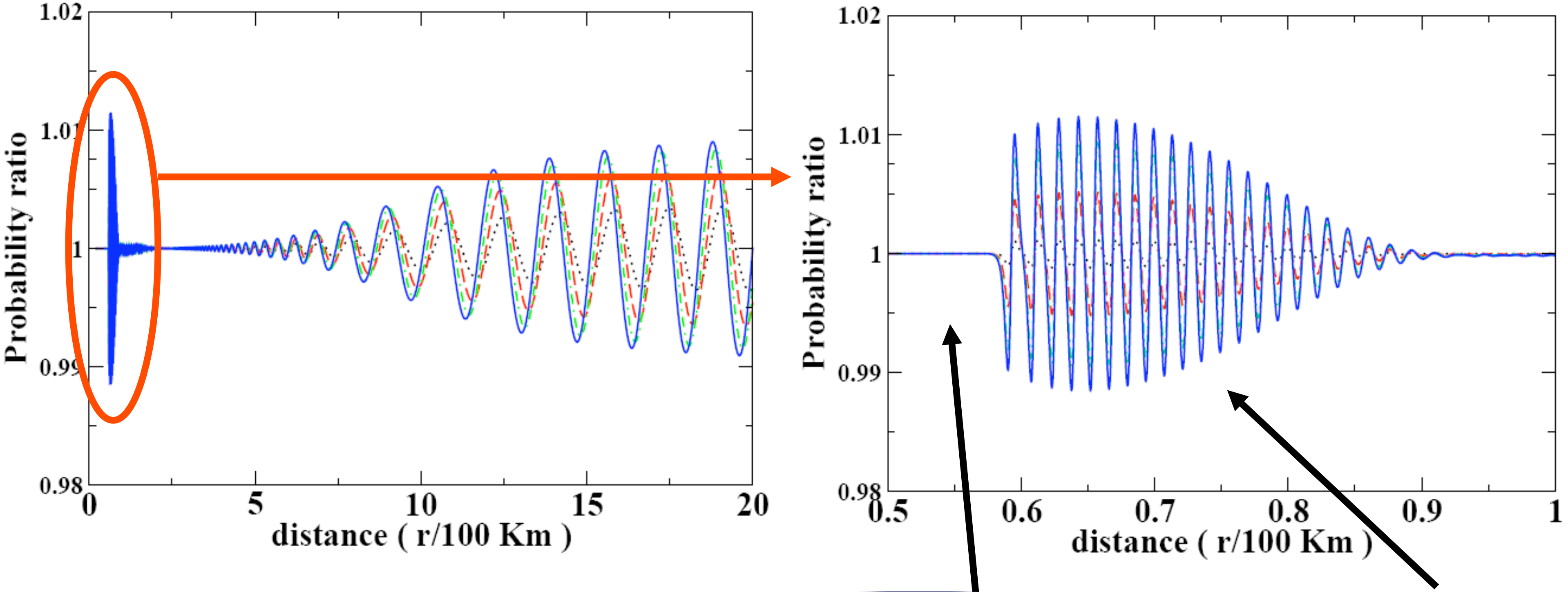
Standard MSW, tree level

ν-ν interaction included

Inverted hierarchy and small θ_{13}

CP-violation effects on $P(\nu_e \to \nu_e)$

For various value of δ.



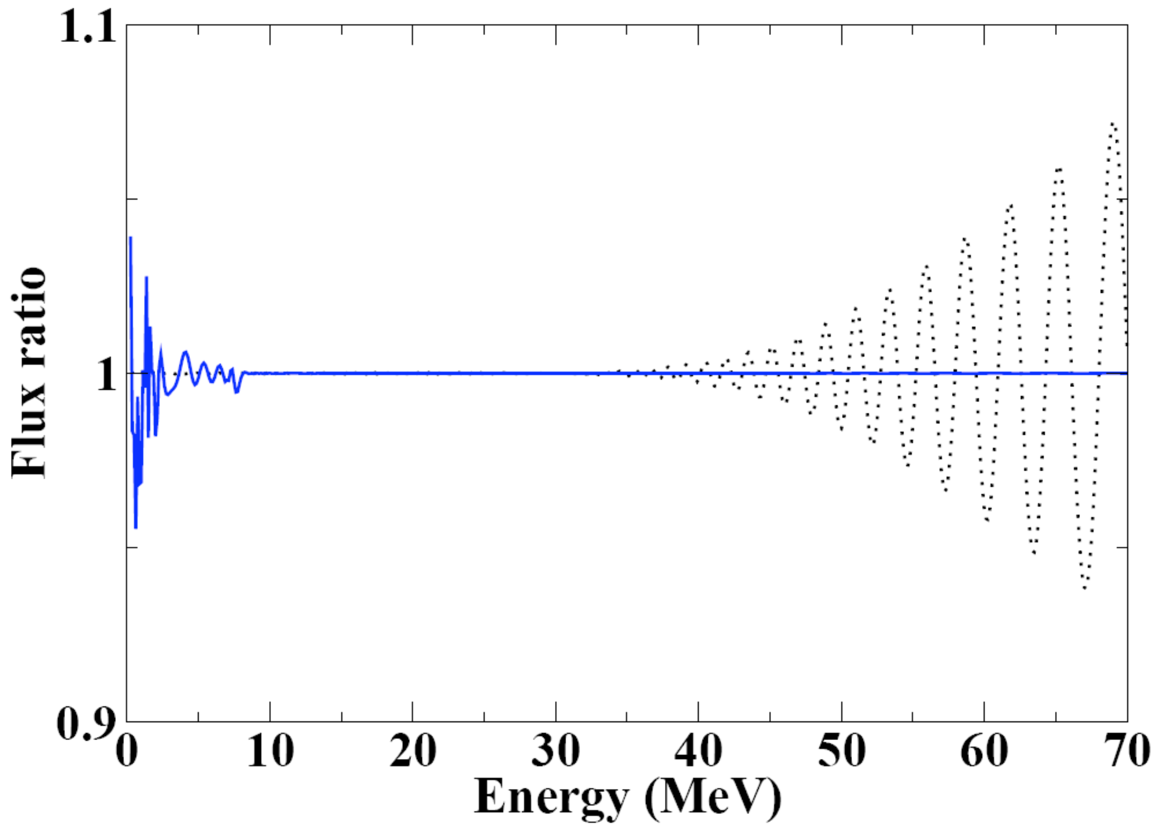
Synchronised region

Bipolar region

Inverted hierarchy and small θ_{13}

The probability depends on δ! because of one-loop corrections.

CP-violation effects on ϕ_{ν_e} *inside the supernova*



………… Standard MSW, tree level

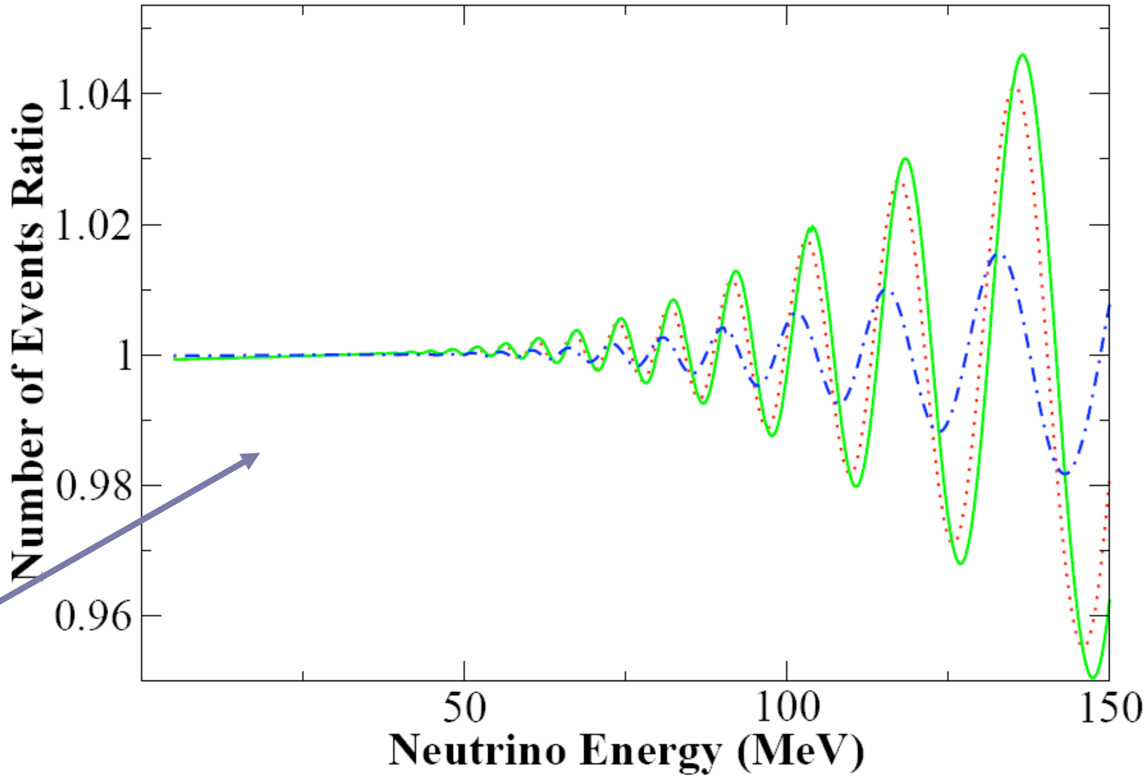
ν-ν interaction and 1-loop $L_{\nu_\mu} \neq L_{\nu_\tau}$

Most realistic case !

EFFECTS OF 5% ON THE ELECTRON NEUTRINO FLUXES.

Effects on a signal in an observatory on Earth

Number of events associated to $\bar{\nu}_e + p \rightarrow n + e^+$
from a supernova explosion at 10 kpc
in Super-Kamiokande



N(δ=180°)/N(δ=0°)

N(δ =135°) / N(δ=0°)

N(δ =45°) / N(δ=0°)

Without ν-ν interaction

EFFECTS ARE GROWING WITH δ AND WITH THE ENERGY.

SAME EFFECTS IN MEGATON DETECTOR.

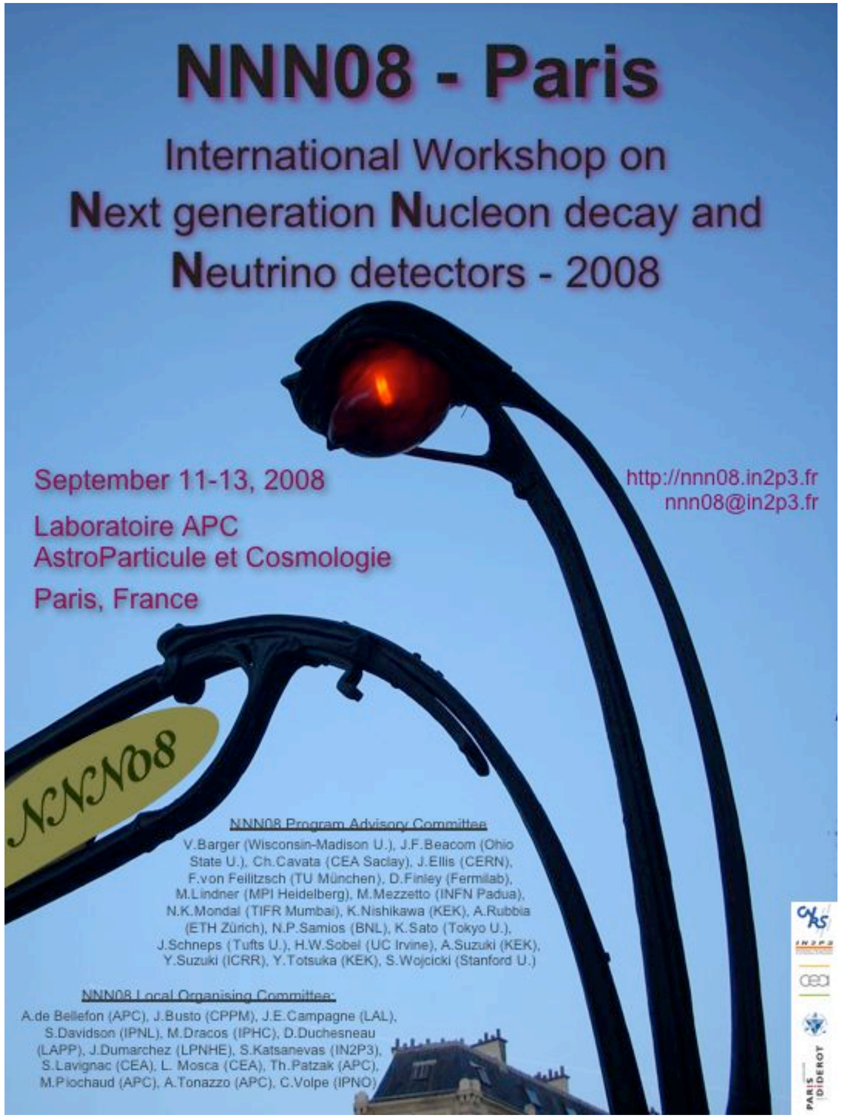
Conclusions

AT THE TREE LEVEL IN THE STANDARD MODEL:

- No effect of the CP-violating phase on $\phi\nu_e$ and on the nucleosynthesis, with and without $\nu-\nu$ interaction.

BEYOND THE TREE LEVEL AND/OR THE STANDARD MODEL:

- There are CP-violating effects because the ν_μ and ν_τ fluxes differ at the neutrinosphere.
- 5-10% effects on $\phi\nu_e$ and $\phi\bar{\nu}_e$ might be present in the supernova.
- A few percent effects on the number of events as a function of the energy on Earth, less if the neutrino-neutrino interaction is included.



NNN08 - Paris

International Workshop on
Next generation **N**ucleon decay and
Neutrino detectors - 2008

September 11-13, 2008

Laboratoire APC
AstroParticule et Cosmologie

Paris, France

http://nnn08.in2p3.fr
nnn08@in2p3.fr

NNN08 Program Advisory Committee

V.Barger (Wisconsin-Madison U.), J.F.Beacom (Ohio State U.), Ch.Cavata (CEA Saclay), J.Ellis (CERN), F.von Feilitzsch (TU München), D.Finley (Fermilab), M.Lindner (MPI Heidelberg), M.Mezzetto (INFN Padua), N.K.Mondal (TIFR Mumbai), K.Nishikawa (KEK), A.Rubbia (ETH Zürich), N.P.Samios (BNL), K.Sato (Tokyo U.), J.Schneps (Tufts U.), H.W.Sobel (UC Irvine), A.Suzuki (KEK), Y.Suzuki (ICRR), Y.Totsuka (KEK), S.Wojcicki (Stanford U.)

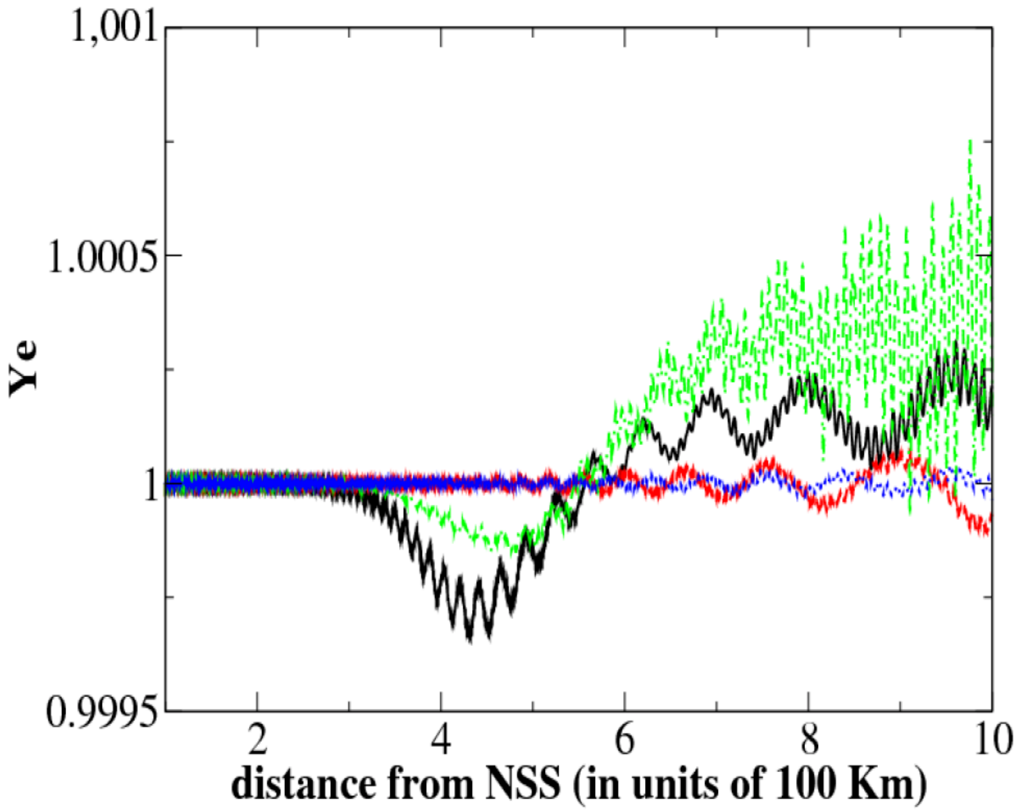
NNN08 Local Organising Committee:

A.de Bellefon (APC), J.Busto (CPPM), J.E.Campagne (LAL), S.Davidson (IPNL), M.Dracos (IPHC), D.Duchesneau (LAPP), J.Dumarchez (LPNHE), S.Katsanevas (IN2P3), S.Lavignac (CEA), L. Mosca (CEA), Th.Patzak (APC), M.Piochaud (APC), A.Tonazzo (APC), C.Volpe (IPNO)

Thank You

Possible effects on nucleosynthesis (r-process)

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



Introduction : what is a core-collapse supernova?

- *Explosion at the end of the life of a massive star (> 8 Ms) due to the gravitational collapse of the iron core into a proto-neutron star.*
- *99 % of the energy is released by neutrinos and anti-neutrinos of all flavors (about 10^{53} ergs for about 10 seconds).*

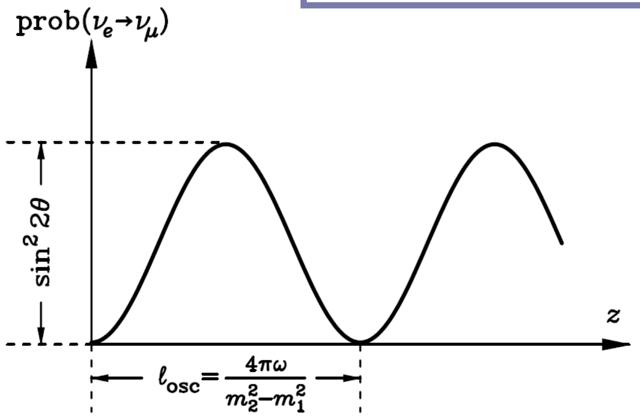
SN1987A, before (on the left) and after (on the right)

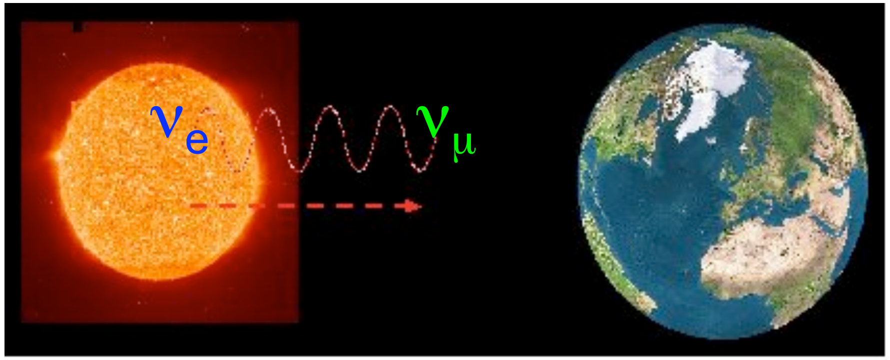
Expanding remnants of SN1987A in the large Magellanic Cloud

Neutrino oscillations in vacuum

In two flavours the oscillation probability is:

$$\boxed{P(\nu_e \rightarrow \nu_\mu;\, t) = \sin^2 2\theta_0 \, \sin^2\left(\frac{\Delta m^2}{4E} t\right)}$$





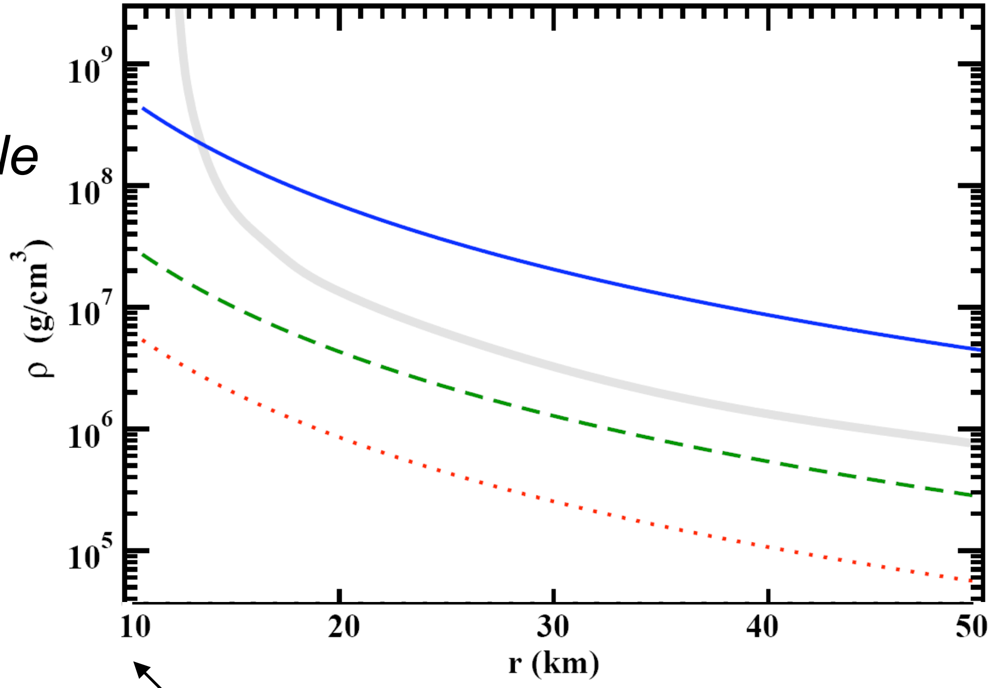
There are two oscillation parameters θ_0 and $\Delta m^2 = m_2^2 - m_1^2$.

Supernova model : the density profile

We chose the following density profile

$$\rho_B = \frac{7.5 \times 10^7}{(r/10Km)^3} g.cm^{-3}$$

Which corresponds to $t_{PB} \approx 4\ \mathrm{s}$



Neutron star surface

CP-violation effects and nu-nu interaction

J. Gava & C. Volpe, submitted to PRD, arXiv:0807.3418

We start from the Liouville-Von Neumann equation:

$$i\; i\frac{d\sum_{\nu_\alpha} L_{\nu_\alpha} S\tilde{\rho}_{\nu_{\underline{\alpha}}}(\delta)S^\dagger}{dt} = [T^0_{13}T_{12}H_{vac}T^\dagger_{12}T^0_{13}{}^\dagger + H_m + S\tilde{H}_{\nu\nu}(\delta)S^\dagger, \sum_{\nu_\alpha} L_{\nu_\alpha} S\tilde{\rho}_{\nu_{\underline{\alpha}}}(\delta)S^\dagger]$$

$$\sum_{\nu_\alpha} L_{\nu_{\underline{\alpha}}} S\tilde{\rho}_{\nu_{\underline{\alpha}}}(\mathbf{q},\delta,t=0)S^\dagger = \begin{pmatrix} L_{\nu_{\underline{e}}} & 0 & 0 \\ 0 & c^2_{23}L_{\nu_{\underline{\mu}}} + s^2_{23}L_{\nu_{\underline{\tau}}} & c_{23}s_{23}e^{-i\delta}\boxed{(L_{\nu_{\underline{\mu}}} - L_{\nu_{\underline{\tau}}})} \\ 0 & c_{23}s_{23}e^{i\delta}\boxed{(L_{\nu_{\underline{\mu}}} - L_{\nu_{\underline{\tau}}})} & s^2_{23}L_{\nu_{\underline{\mu}}} + c^2_{23}L_{\nu_{\underline{\tau}}} \end{pmatrix}$$

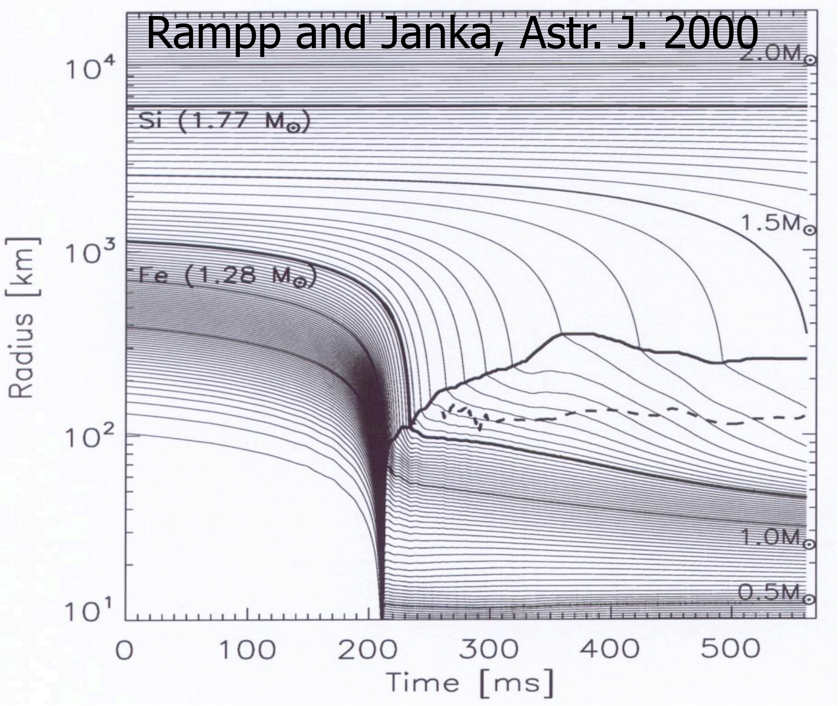
If $L_{\nu_\mu} = L_{\nu_\tau}$, by recurrence

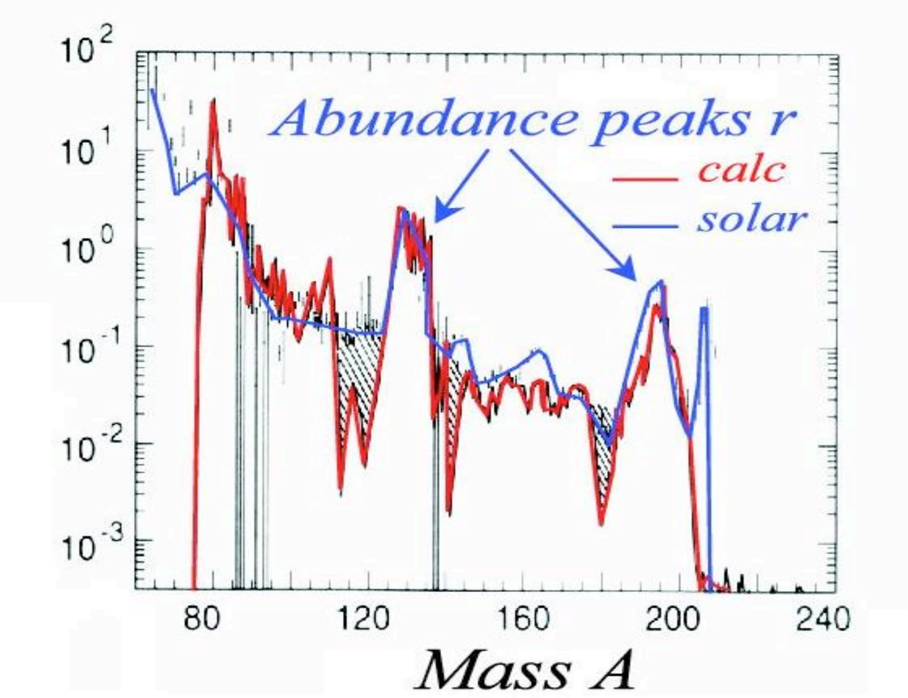
$$\boxed{\sum_{\nu_\alpha} L_{\nu_\alpha} S\tilde{\rho}_{\nu_{\underline{\alpha}}}(\mathbf{q},\delta)S^\dagger = \sum_{\nu_\alpha} L_{\nu_\alpha} \tilde{\rho}_{\nu_{\underline{\alpha}}}(\mathbf{q},\delta=0)}$$

$$\boxed{\tilde{H}_{\nu\nu}(\delta) = S\tilde{H}_{\nu\nu}(\delta=0)S^\dagger}$$

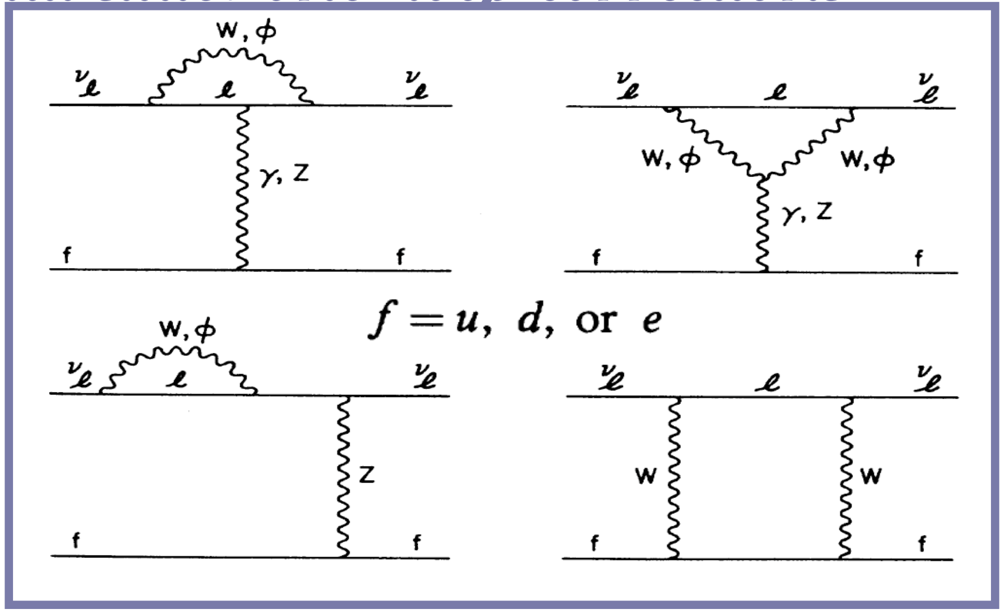
Introduction : Still open questions…

- *Numerical simulations fail to explode: the shockwave stalls at 200 Km.*
- *Core-collapse supernovae are a possible site for the nucleosynthesis of heavy-elements via the r-process.*


Rampp and Janka, Astr. J. 2000



Additional slide: one-loop corrections



$$Y_\tau^{\rm eff} = \frac{3\sqrt{2}\,G_{\rm F} m_\tau^2}{(2\pi)^2}\left[\ln\left(\frac{m_W^2}{m_\tau^2}\right) - 1 + \frac{Y_n}{3}\right] = 2.7\times 10^{-5}$$

The new evolution equation is now :

$$i\frac{\partial}{\partial t}\begin{pmatrix}\Psi_e\\ \Psi_\mu\\ \Psi_\tau\end{pmatrix} = \left[T_{23}T_{13}T_{12}\begin{pmatrix}E_1 & 0 & 0\\ 0 & E_2 & 0\\ 0 & 0 & E_3\end{pmatrix}T_{12}^\dagger T_{13}^\dagger T_{23}^\dagger + \begin{pmatrix}V_c & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & V_{\mu\tau}\end{pmatrix}\right]\begin{pmatrix}\Psi_e\\ \Psi_\mu\\ \Psi_\tau\end{pmatrix}$$

Additional slides: neutrino-neutrino interactions and the one loop order correction to matter interaction

$$i\frac{\partial}{\partial t}\begin{pmatrix}\Psi_e\\ \Psi_\mu\\ \Psi_\tau\end{pmatrix} = \Bigg[T_{23}T_{13}T_{12}\underbrace{\begin{pmatrix}E_1 & 0 & 0\\ 0 & E_2 & 0\\ 0 & 0 & E_3\end{pmatrix}}_{\text{Vacuum oscillations}} T_{12}^{\dagger}T_{13}^{\dagger}T_{23}^{\dagger} + \underbrace{\begin{pmatrix}V_c & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & V_{\mu\tau}\end{pmatrix}}_{\text{Matter interactions}}$$

$$\underbrace{\begin{pmatrix}H_{\nu_e\nu_e} & H_{\nu_e\nu_\mu} & H_{\nu_e\nu_\tau}\\ H_{\nu_\mu\nu_e} & H_{\nu_\mu\nu_\mu} & H_{\nu_\mu\nu_\tau}\\ H_{\nu_\tau\nu_e} & H_{\nu_\tau\nu_\mu} & H_{\nu_\tau\nu_\tau}\end{pmatrix}}_{\text{Neutrino-neutrino interactions}} \Bigg] \begin{pmatrix}\Psi_e\\ \Psi_\mu\\ \Psi_\tau\end{pmatrix}$$

Propagation of neutrinos in matter with the CP-violating phase

Finally we obtain :

$$\boxed{\hat{U}(\delta) = S^{\dagger}\hat{U}_0 S}$$

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

A_{xy} *amplitude for the process* $\nu_x \rightarrow \nu_y$ *when* $\delta \neq 0$

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

B_{xy} *amplitude for the process* $\nu_x \rightarrow \nu_y$ *when* $\delta = 0$

$$P(\nu_x \rightarrow \nu_y, \delta = 0) = |B_{xy}|^2$$

Neutrino oscillations in vacuum

3 masses (but experimentally only mass square differences)…

$$\Delta m^2_{32} = m^2_3 - m^2_2 = 1.9 \text{ to } 3.0 \times 10^{-3} eV^2$$

$$\Delta m^2_{21} = m^2_2 - m^2_1 = 8.0^{+0.4}_{-0.3} \times 10^{-5} eV^2$$

where the relation between them is:

$$\boxed{\Delta m^2_{12} + \Delta m^2_{23} + \Delta m^2_{31} = 0} \quad \text{with} \quad \boxed{|\Delta m^2_{21}| \ll |\Delta m^2_{31}| \simeq |\Delta m^2_{32}|}$$

which imply two possible hierarchies…

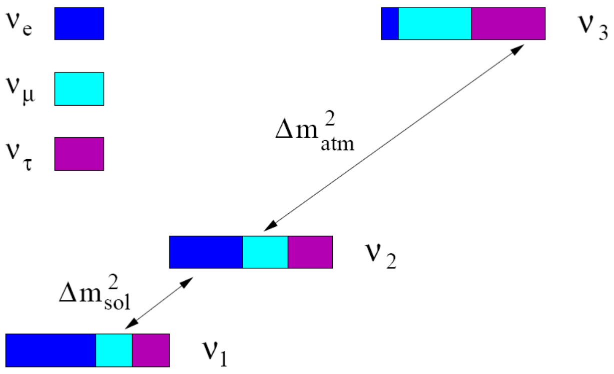


Figure 1. Normal mass hierarchy

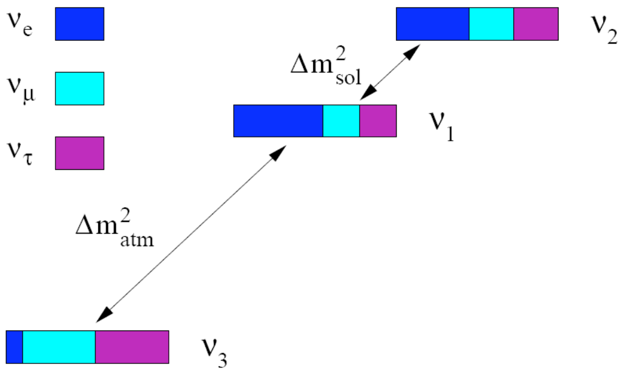


Figure 2. Inverted mass hierarchy

Neutrino oscillations in matter

In 2 flavours:

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta_0 + \sqrt{2}\,G_F N_e & \frac{\Delta m^2}{4E}\sin 2\theta_0 \\ \frac{\Delta m^2}{4E}\sin 2\theta_0 & \frac{\Delta m^2}{4E}\cos 2\theta_0 \end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

In the matter basis

$$\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix} cos\theta_m & sin\theta_m \\ -sin\theta_m & cos\theta_m \end{pmatrix}\begin{pmatrix}\nu_A\\ \nu_B\end{pmatrix}$$

Matter mixing angle

Matter basis

we obtain:

$$P(\nu_e \to \nu_\mu;\ L) = \sin^2 2\theta\ \sin^2\left(\pi\frac{L}{l_m}\right)$$

This is the same formula as in vacuum but…

Neutrino oscillations in matter

…The amplitude and the oscillation length depend on matter density

$$l_m = \frac{2\pi}{\quad} = \frac{2\pi}{\quad}$$

$${}^2\, 2\theta_0$$

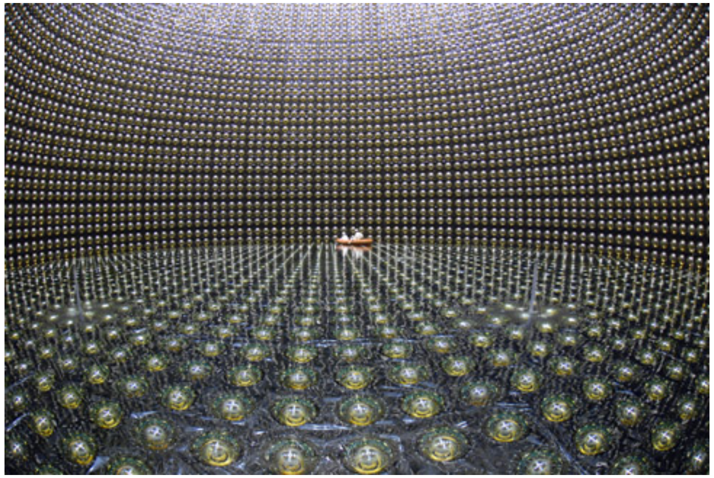
$$\sin^2 2\theta = \frac{\left(\frac{\Delta m^2}{2E}\right)^2 \sin^2 2\theta_0}{\left(\frac{\Delta m^2}{2E}\cos 2\theta_0 - \sqrt{2}\, G_F\, N_e\right)^2 + \left(\frac{\Delta m^2}{2E}\right)^2 \sin^2 2\theta_0}$$

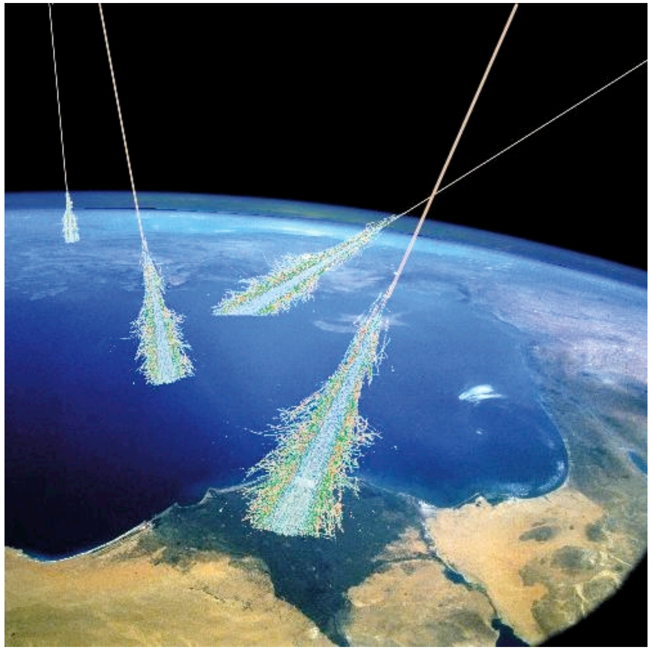
There can be a resonance for

$$\boxed{\sqrt{2}\, G_F\, N_e = \frac{\Delta m^2}{2E} \cos 2\theta_0}$$

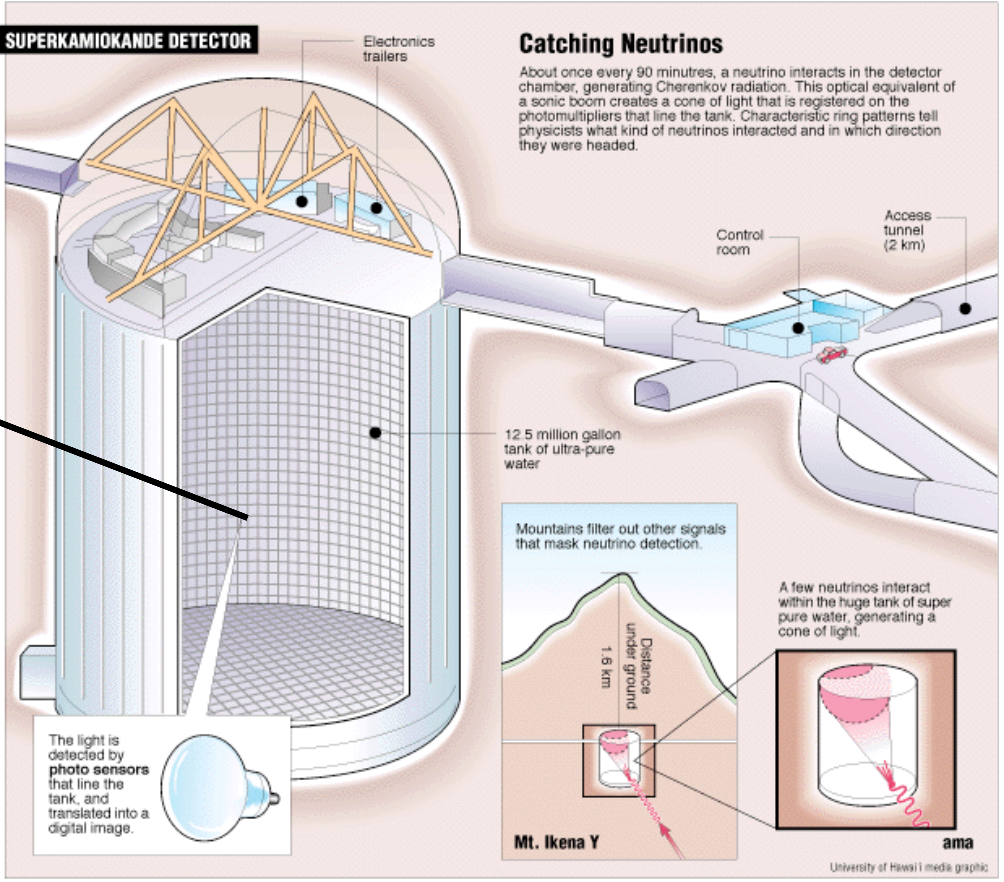
This is the Mikheev-Smirnov-Wolfenstein (MSW) effect.

Introduction: the neutrino oscillation discovery





Super-Kamiokande



Catching Neutrinos

About once every 90 minutres, a neutrino interacts in the detector chamber, generating Cherenkov radiation. This optical equivalent of a sonic boom creates a cone of light that is registered on the photomultipliers that line the tank. Characteristic ring patterns tell physicists what kind of neutrinos interacted and in which direction they were headed.

Mountains filter out other signals that mask neutrino detection.

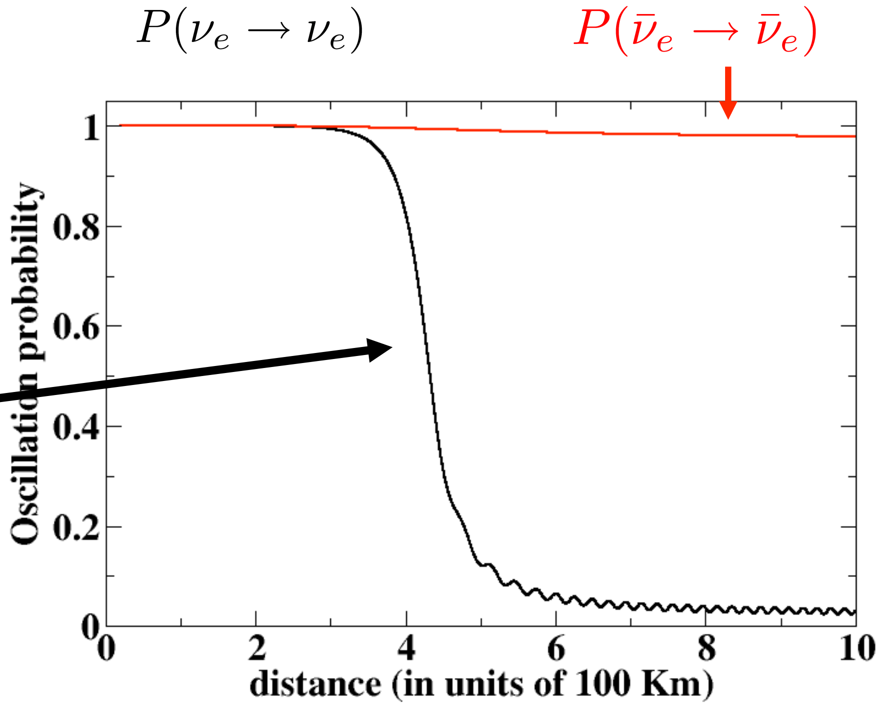
A few neutrinos interact within the huge tank of super pure water, generating a cone of light.

The light is detected by **photo sensors** that line the tank, and translated into a digital image.

In 1998, people discovered that neutrinos are oscillating!!!

Neutrino oscillations in matter

Example of the evolution of survival probabilities going through a MSW resonance.



As we can see

$$\Delta P_{ee} = P(\nu_e \to \nu_e) - P(\bar{\nu}_e \to \bar{\nu}_e) \neq 0$$

Is this true CP-violation? NO!

This is called « fake CP-violation » only due to matter asymmetry with CP. We're looking at the pure CP-violating phase δ which is present only for a three flavour system.

Propagation of neutrinos in matter with the CP-violating phase

Solar neutrinos and leptonic CP violation.

H.Minakata & S. Watanabe, Phys.Lett.B468:256-260,1999.

Supernova neutrinos: Difference of muon-neutrino - tau-neutrino fluxes and conversion effects.

E. Akhmedov, C.Lunardini & A.Smirnov, Nucl.Phys.B643:339-366,2002.

How astrophysical neutrino sources could be used for early measurements of neutrino mass hierarchy and leptonic CP phase?

Walter Winter, Phys.Rev.D74:033015,2006.

Electron fraction in Supernovae

Dominant reactions that control the proton to neutron ratio.

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

We introduce the total proton loss rate

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

The electron fraction is $$\boxed{Y_e = (n_{e^-} - n_{e^+})/(n_n + n_p)}$$

Neutrino oscillations in vacuum

- *Neutrinos have a mass!*

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Flavour basis

Rotation Matrix

Mass basis

- *In vacuum, neutrinos evolve in the mass basis:*

$$i\frac{\partial}{\partial t}\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = \begin{pmatrix} \frac{m_1^2}{2E} & 0 \\ 0 & \frac{m_2^2}{2E} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Electron fraction in Supernovae

The equilibrium value of the electron fraction is:

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

The capture rate on p and n are given by:

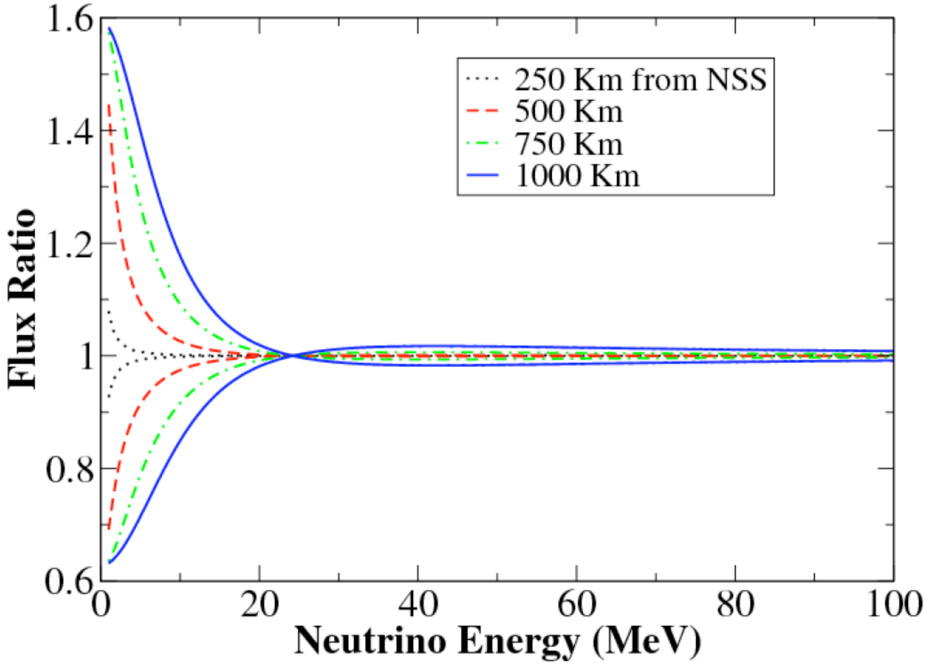
$$\boxed{\lambda_{n,p} = \int \sigma_{\nu_e n, \bar{\nu}_e p}(E_\nu)\phi_{\nu_e, \bar{\nu_e}}(E_\nu)dE_\nu}$$

Cross section of the previous reactions

Fluxes which do not depend on δ

Thus, the electron fraction Ye does not depend on δ.

Numerical results:

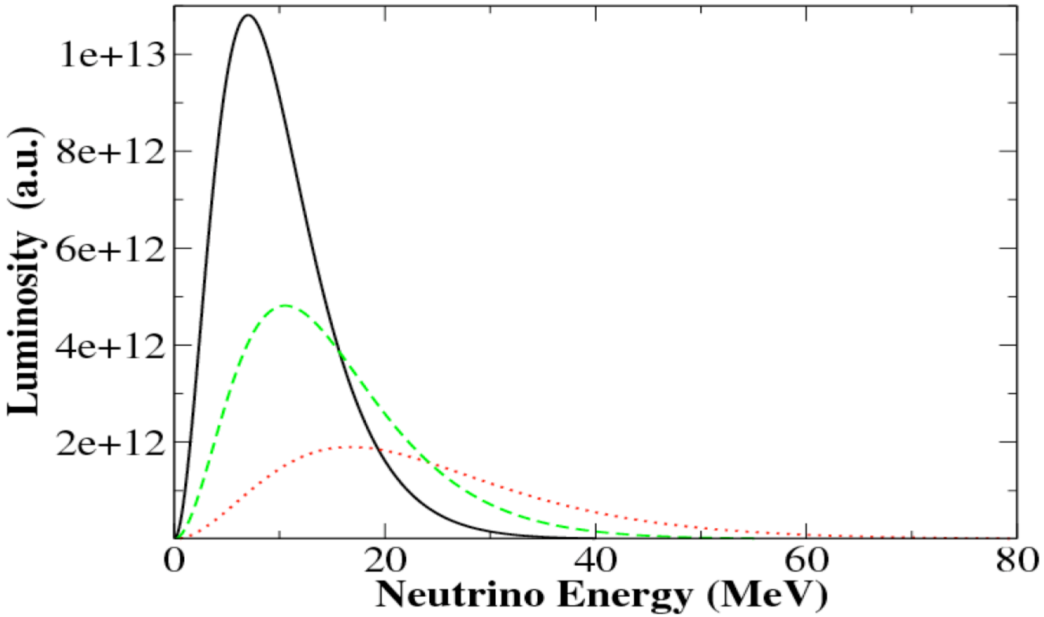


Upper curves for $\bar{\nu}_\tau$, lower curves for $\bar{\nu}_\mu$

Effects up to 60% in the supernova!

In the supernova : the fluxes emitted at the neutrinosphere

We take a Fermi-Dirac distribution for the initial luminosity:



The average energy of the different neutrino species follow the hierarchy

$$\boxed{\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x, \bar{\nu}_x} \rangle}$$