# Challenges in neutrino (astro)physics

ν

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# OUTLINE

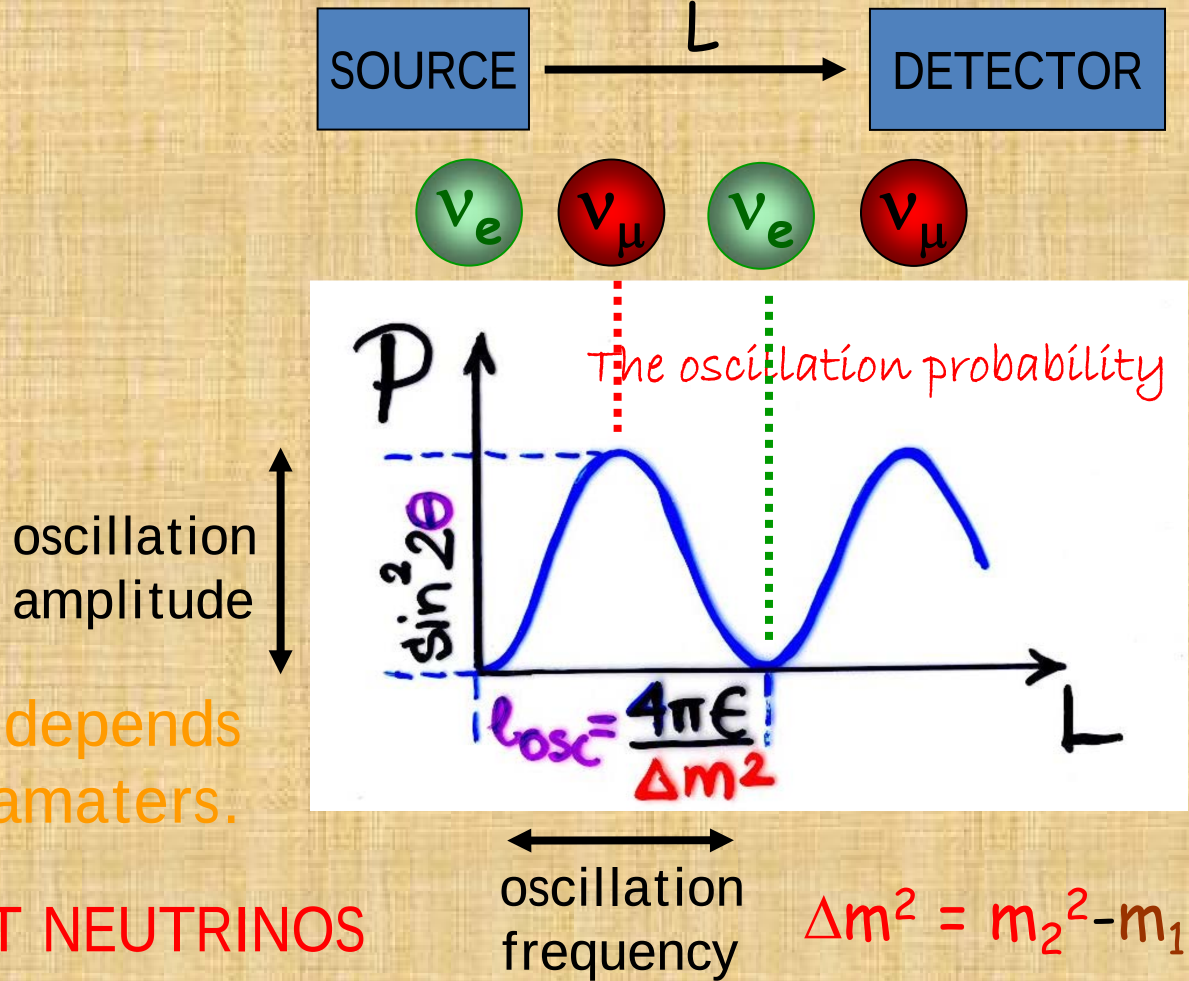
- Status and open questions
  - Recent progress on neutrino propagation in media
  - CP violation searches and astrophysics
- Conclusions

# The conjecture of neutrino oscillations

Pontecorvo, 1957

Bruno Pontecorvo
(1913 – 1993)

Neutrinos can modify their flavor while travelling.
This is the neutrino oscillation phenomenon.

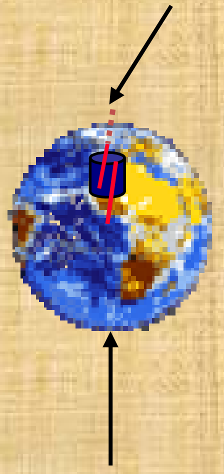



The phenomenon depends on oscillation paramaters.

IT REQUIRES THAT NEUTRINOS ARE MASSIVE.

$\Delta m^2 = m_2^2 - m_1^2$

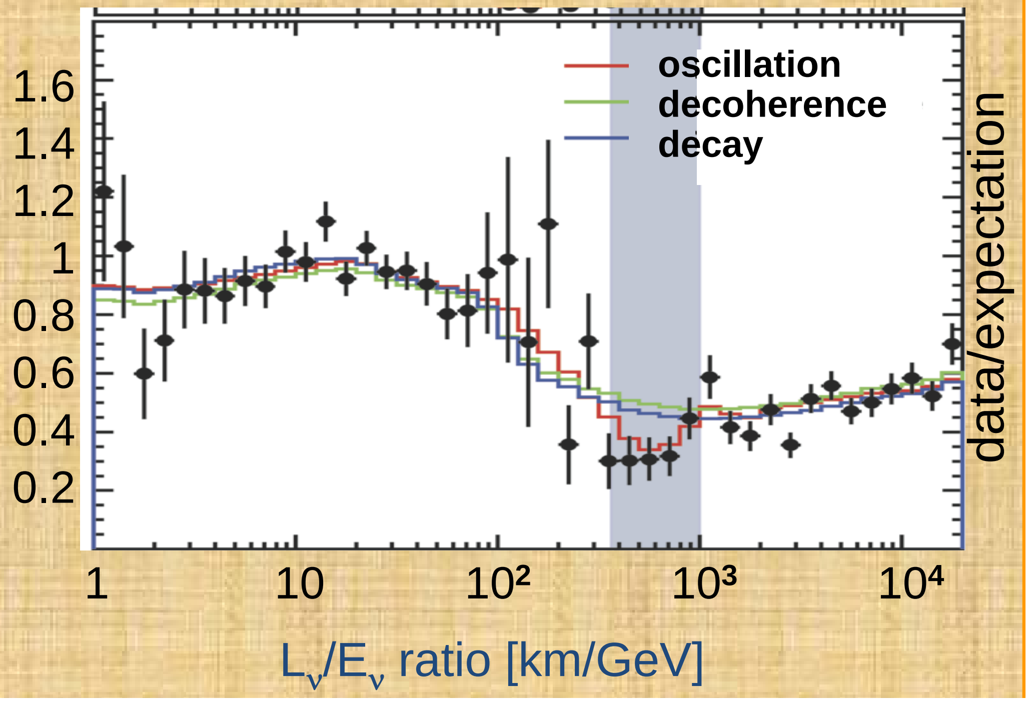
# Recent Advances in Neutrino Physics



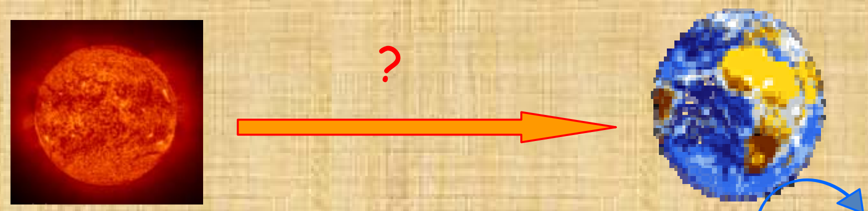
- 1998 : Super-Kamiokande discovers neutrino oscillations.
- 2000 : SNO measures the total ($\nu_e$, $\nu_\mu$, $\nu_\tau$ ) solar neutrino flux.
- 2001 : K2K confirms Super-Kamiokande result.
- 2002 : KAMLAND determines the solar solution (LMA).
- 2006 : MINOS measures precisely the atmospheric $\Delta m^2$.
- 2007 : Mini-BOONE does not confirm the LSND observation.

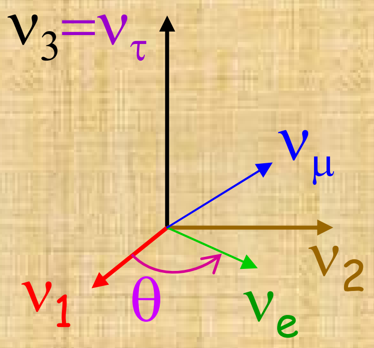
AN IMPRESSIVE PROGRESS IN THE LAST DECADE in our knowledge of its properties.

*Many puzzles have been solved with an incredible impact on various domains of physics.*



# THEORETICAL DESCRIPTION




mixing angle

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

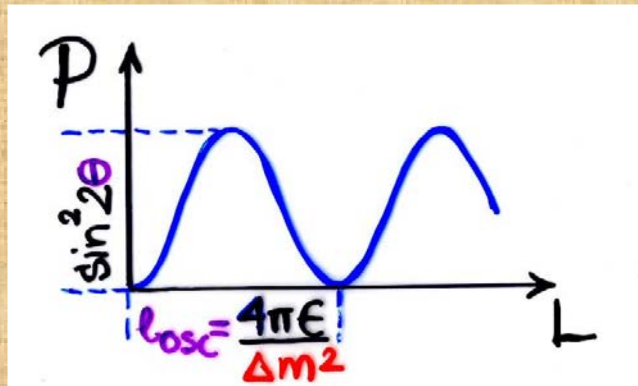
flavour basis — mass basis

$\Delta m^2 = m_2^2 - m_1^2$

- The time evolution is : $|\nu_e(t)\rangle = \cos\theta \cdot e^{-iE_1 t}|\nu_1\rangle + \sin\theta e^{-iE_2 t}|\nu_2\rangle$

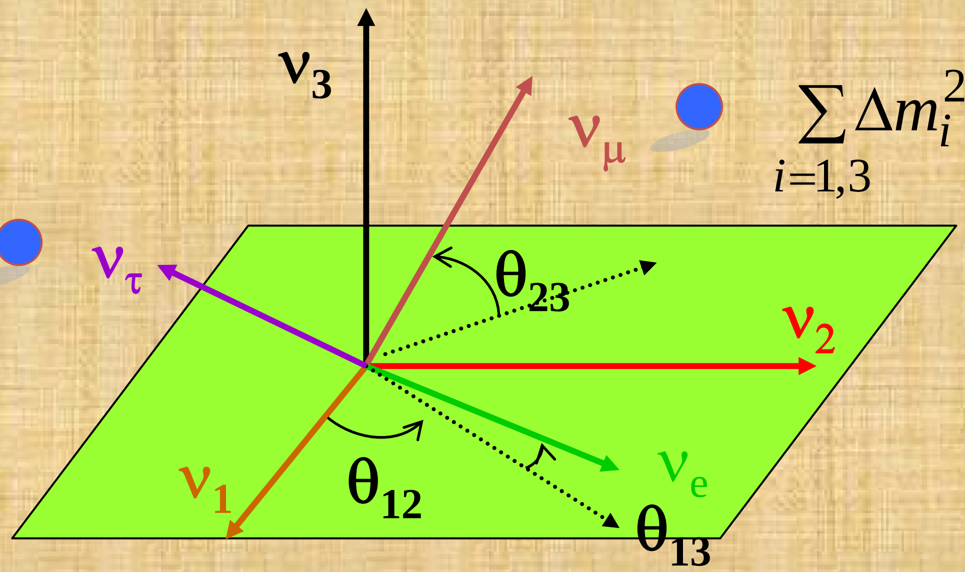
- $P(\nu_e \to \nu_\mu) = \sin^2 2\theta \sin^2\left(\frac{L}{4E}\Delta m^2\right)$

probability for neutrino oscillations



# THE 3-flavours OSCILLATION PARAMETERS

- In the case of three families, there are three mass eigenstates ($\nu_1, \nu_2, \nu_3$) and three flavour eigenstates ($\nu_e, \nu_\mu, \nu_\tau$).




- $$\sum_{i=1,3} \Delta m_i^2 = \underbrace{m_2^2 - m_1^2}_{\Delta m_{21}^2} + \underbrace{m_3^2 - m_2^2}_{\Delta m_{32}^2} + m_1^2 - m_3^2$$

  Only two $\Delta m^2$ are independent.

- The two basis are related by a unitary matrix, called the Maki-Nakagawa-Sakata-Pontecorvo (MNSP) matrix.

$$c_{ij} = \cos\theta_{ij} \quad s_{ij} = \sin\theta_{ij}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\theta_{23}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\theta_{13}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\theta_{12}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

THE CP violating phase INTRODUCES A $\nu$-$\bar{\nu}$ ASYMMETRY.

# THE PRESENT STATUS

- To reconstruct the MNSP mixing matrix :
  3 mixing angles, 1 CP Dirac phase, 2 Majorana phases

| | | |
|---|---|---|
| $\theta_{12}$ | $sin^2 2\theta_{12} = 0.86^{+0.03}_{-0.04}$ | (SNO, Kamland) |
| $\theta_{23}$ | $sin^2 2\theta_{23} > 0.92$ | (Super-Kamiokande, K2K, MINOS, …OPERA) |
| $\boxed{\theta_{13}\ ?}$ | $\boxed{sin^2 2\theta_{13} < 0.19}$ | ( CHOOZ,..., but soon Double-CHOOZ, Daya-Bay, T2K…) |

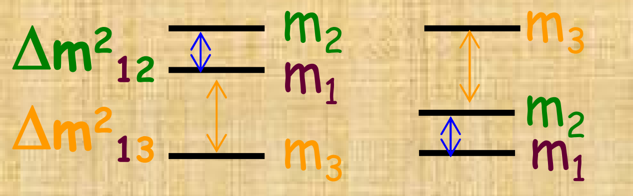
The Dirac and Majorana phases are unknown.
The Dirac phase influence neutrino oscillations, Majorana ones do not.

- To reconstruct the mass pattern:
  Experimentally only mass squared differences are known.

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

- The mass ordering (hierarchy) ?

Mass scale?




Inverted ($\Delta m^2_{13}$ <0) Normal ($\Delta m^2_{13}$>0)

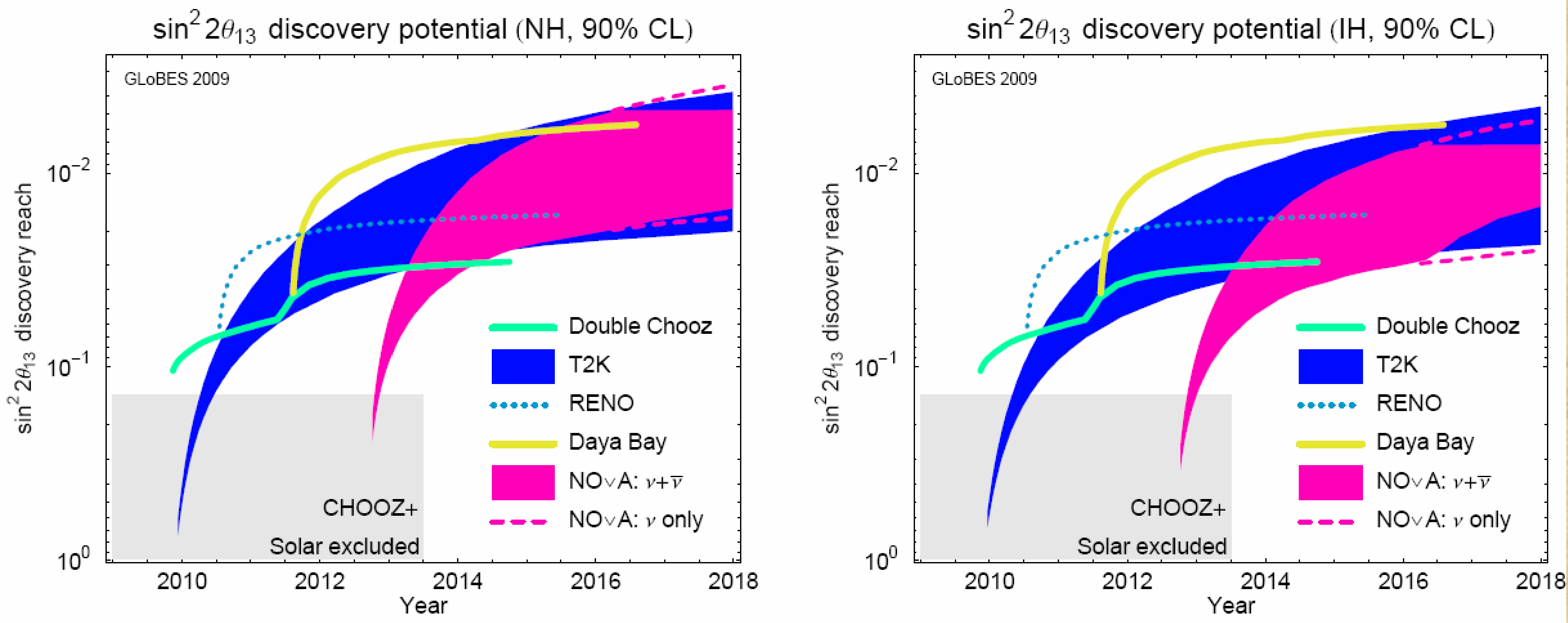
# THE key OPEN QUESTIONS

- The third mixing angle $\theta_{13}$ — Double-CHOOZ, Daya-Bay, T2K,..
- The Dirac phase — T2K, No$\nu$A, super-beams, beta-beams, neutrino factories
- The Majorana phases — from double-beta decay experiments
- The absolute mass scale — KATRIN, MARE,…
- The mass hierarchy — supernovae, beta-beams, $\nu$-factories, double-beta,…
- The neutrino nature — Gerda, Cuore, Super-Nemo,…

**A wealth of experiments are under construction or at a R&D level.**

*exciting discoveries might be close...*

# $\theta_{13}$ - expected sensitivities




P. Huber, M. Lindner, T. Schwetz, W. Winter, arXiv: 0907.1861

*Discovery potential (90% CL) for $\sin^2 2\theta_{13}$*
*from reactors and accelerators*

THE VALUE OF $\Theta_{13}$ CRUCIAL FOR FUTURE CP SEARCHES.

# Neutrino propagation in dense media

Neutrino oscillations are crucial to understand and predict neutrino evolution in several contexts :

- Neutrinos emitted from the Sun

  A wealth of solar experiments.

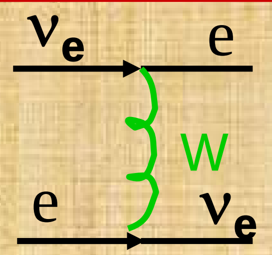
- Neutrino time and energy spectra from massive stars (core-collapse supernovae) and accretion disk-black hole (AD-BH) scenarios

  Observatories existing (ex. SK, KamLAND, LVD) or under study, as « megaton detectors »: MEMPHYS, GLACIER, LENA -- LAGUNA Design Study in FP7 -- one of the 7 ASPERA (astroparticle in Europe) priorities

- Neutrino evolution in the Early Universe

  Just before Big-Bang Nucleosynthesis

# Neutrino propagation in matter




$V(\rho) \sim G_F \rho_e$.

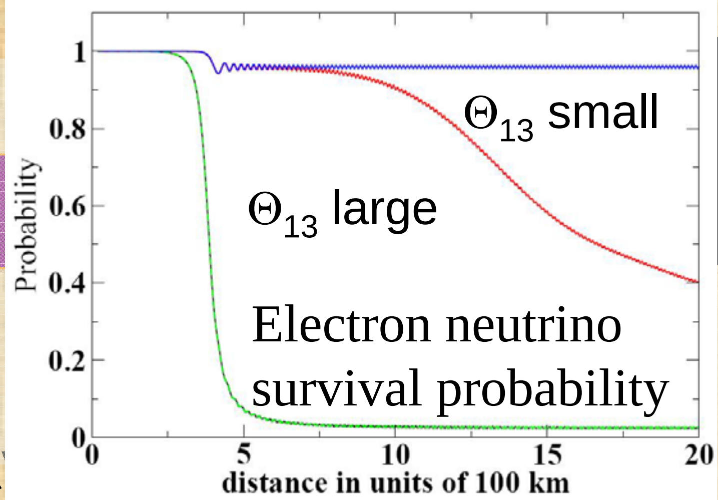
The Mikheev-Smirnov-Wolfenstein (MSW) effect ('78, '86) : neutrino coupling with matter induces a resonant flavour conversion.

The neutrino evolution equations in matter are

vacuum term matter term

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

The resonant onversion depends on the degree of adiabaticity of the MSW resonance (density profile and mixing parameters).

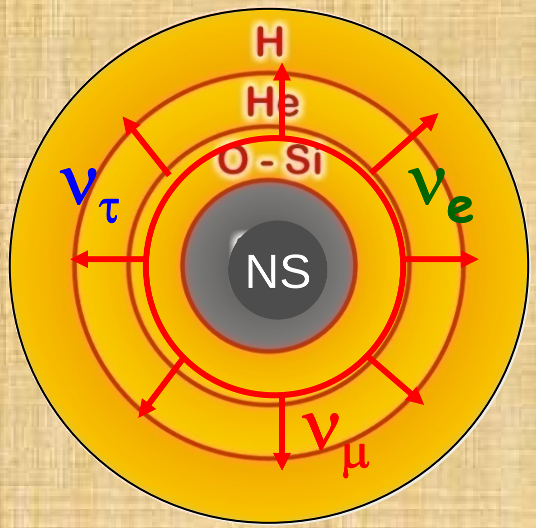



MSW resonance

$\nu$ fluxes at emission inside the star

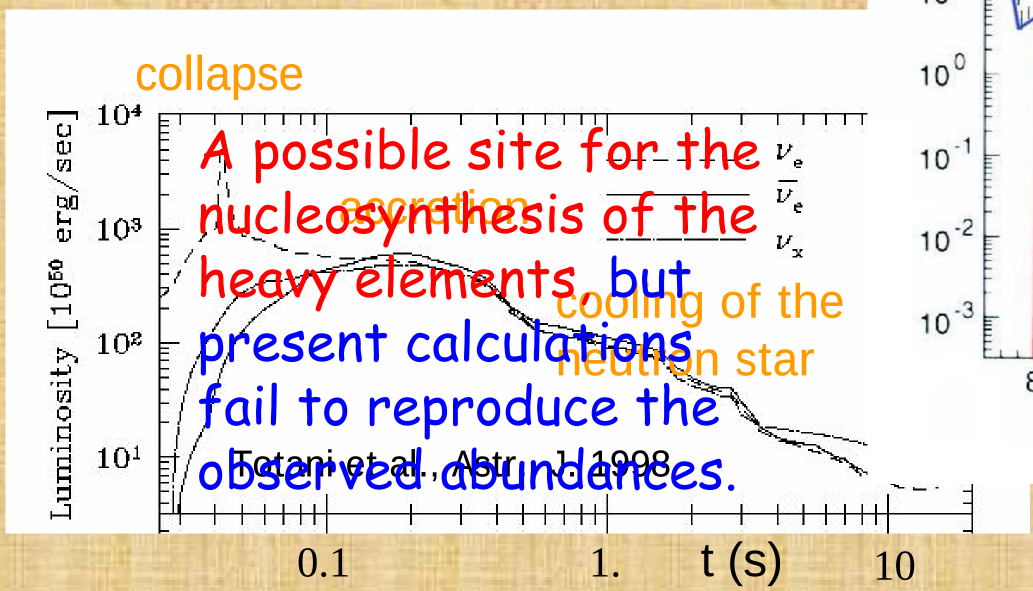
the beautiful explanation of the « solar neutrino deficit » problem !

# Core-collapse supernovae (SN)

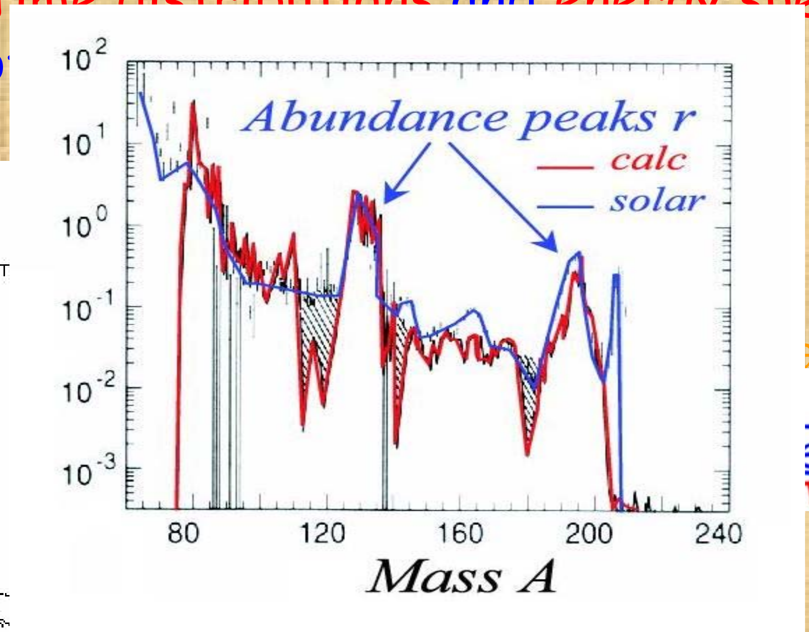


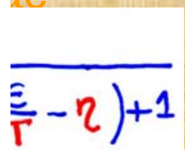

99 % of the energy is emitted as neutrinos of all flavours in a short burst of about 10 s.

Time distributions and energy spectra o…




A possible site for the nucleosynthesis of the heavy elements, but present calculations fail to reproduce the observed abundances.




$$\langle E\nu_e\rangle < \langle E\bar{\nu}_e\rangle < \langle E\nu_x\rangle$$

Neutrinos follow closely the explosion.

Hierarchy of average energies

FUTURE OBSERVATIONS IMPORTANT.

# Neutrino propagation in SN

A NEW UNDERSTANDING OF $\nu$–PROPAGATION :

- Neutrino-neutrino interaction is important :
  Collective phenomena emerge.

- Temporally evolving density profiles with shock waves have to be included :
  These engender multiple resonances and phase effects.

- Turbulence effects, studies still at its beginning.

See the review from Duan and Kneller, arXiv:0904.0974

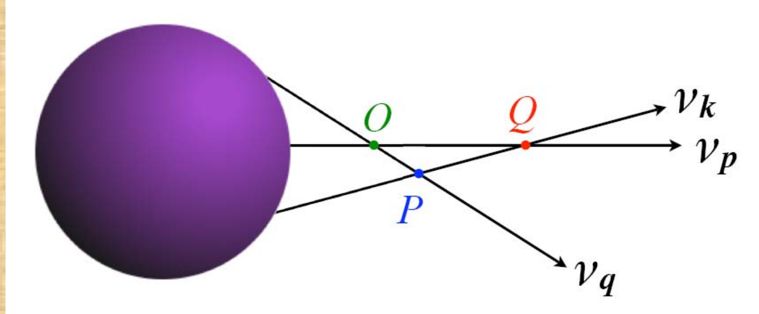
IMPRESSIVE PROGRESS IN THE LAST FEW YEARS !

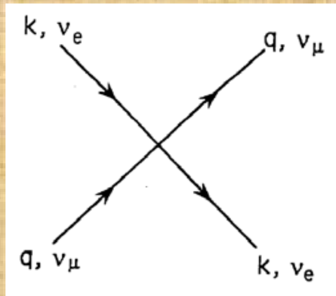
# The ν–ν interaction

J. Pantaleone, PLB 287 (1992), Samuel,PRD 48 (1993), Sigl and Raffelt NPB 406 (1993), Pastor, Raffelt, Semikoz, PRD 65 (2002), Qian and Fuller, PRD 52 (1995) , Balantekin and Yuksel, New. J. Phys. 7 (2005), Duan,Fuller,Qian PRD74 (2006), PRL 97 (2006), PRD 75, 76 (2007), PRL 2008, PRD77 (2008), Raffelt and Smirnov, PRD 76 (2007), Estebal et al PRD 76 (2007), Gava and Volpe PRD(2008), Kneller, Gava, Volpe, McLaughlin (2009)…

- Important progress since 2006 :
  the inclusion of the neutrino-neutrino interaction modifies signficantly the neutrino propagation in matter.

$$H = H_{vacuum} + H_{matter} + H_{\nu\nu}$$



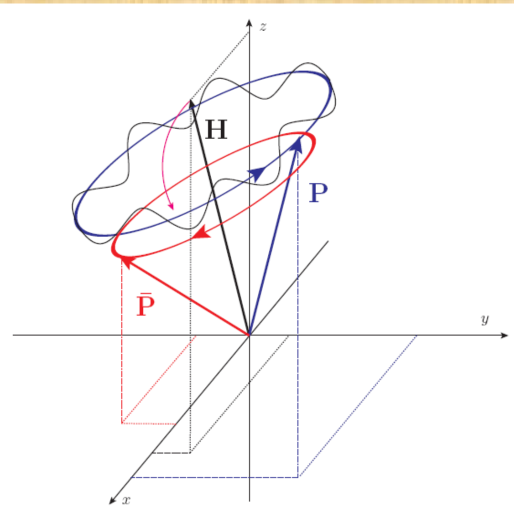




$$H_{\nu\nu} = \frac{\sqrt{2}G_F}{2\pi R_\nu^2} D(r/R_\nu) \sum_\alpha \int [\rho_{\nu_{\underline{\alpha}}}(q') L_{\nu_{\underline{\alpha}}}(q') - \rho^*_{\bar{\nu}_{\underline{\alpha}}}(q') L_{\bar{\nu}_{\underline{\alpha}}}(q')] dq'$$

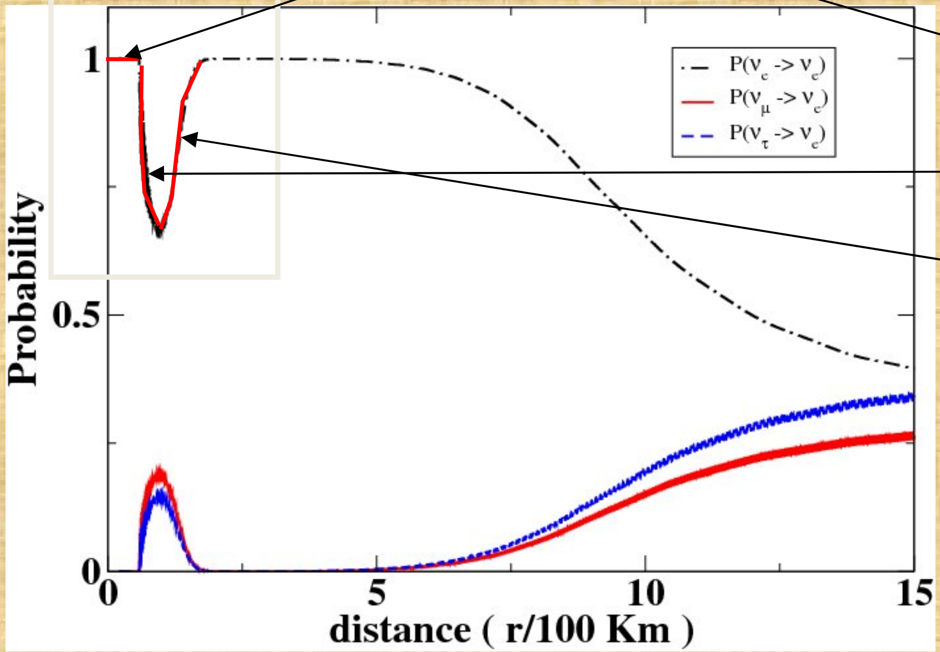
- Involved numerically :
  large number of coupled stiff non-linear equations.
  Approximations :
  single-angle (only radial propagation) vs multi-angle

# Emergence of new collective phenomena

Samuel PRD 48 (1993), Sigl and Raffelt NPB 406 (1993), Pastor, Raffelt, Semikoz, PRD 65 (2002), Duan,Fuller, Qian PRD74 (2006), PRL 97 (2006),Hannestad, Raffelt, Sigl, Wong, PRD 74 (2006), Raffelt,Smirnov, PRD 76 (2007)




- Neutrino flavour conversion in matter can now be described through total polarization vectors in flavour space (also density matrix or amplitudes).
- Three regimes are identified :



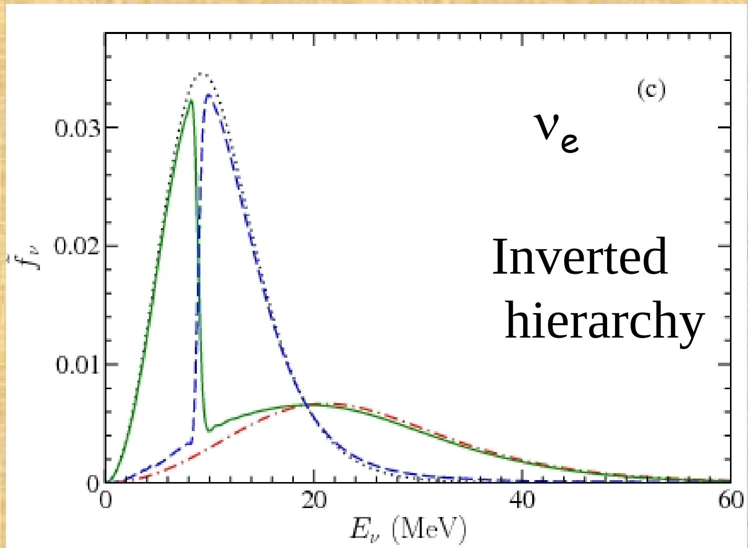

1. Synchronized region (conversion frozen).
2. Bipolar oscillations.
3. Spectral split.

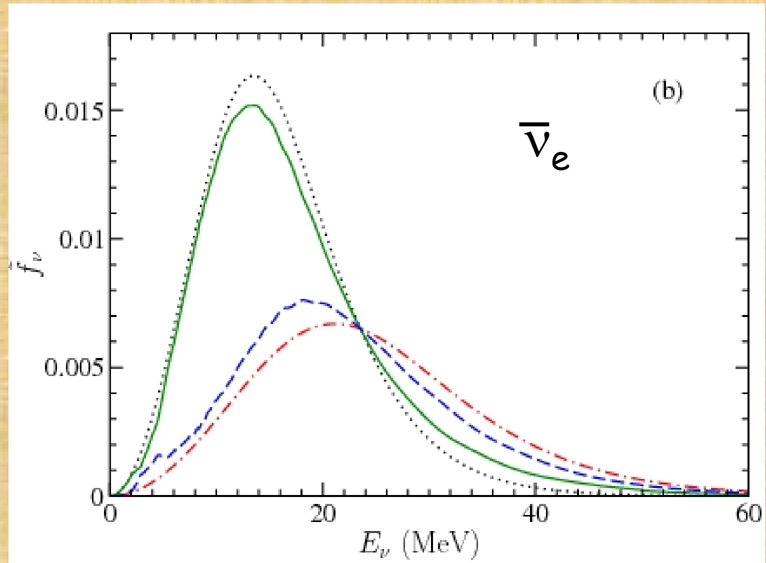
Inverted hierarchy.

$E_\nu$ = 5 MeV

J. Gava, C. Volpe, Phys.Rev.D78,(2008), 0807.3418.

# Important phenomenological implications

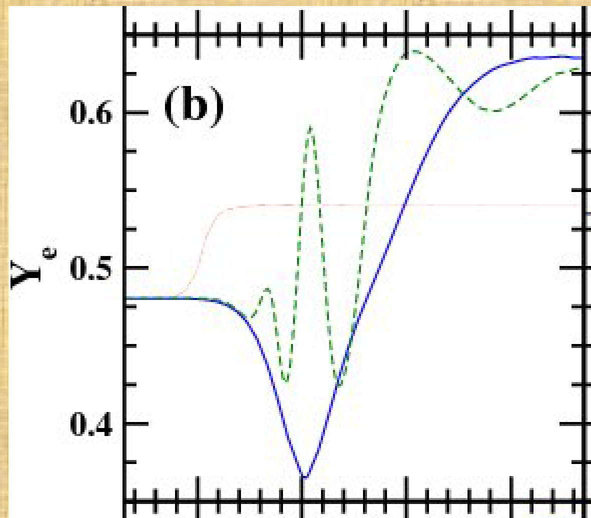



Duan, Fuller, Carlson, Qian, PRD 74 (2006)

Neutrino fluxes can be crucially modified compared to the MSW scenario.

- There can be both indirect effects in the star, e.g. on the r-process nucleosynthesis, and direct effects in a signal on Earth.




Yuksel and Balantekin, New J.Phys.7, 51(2005).

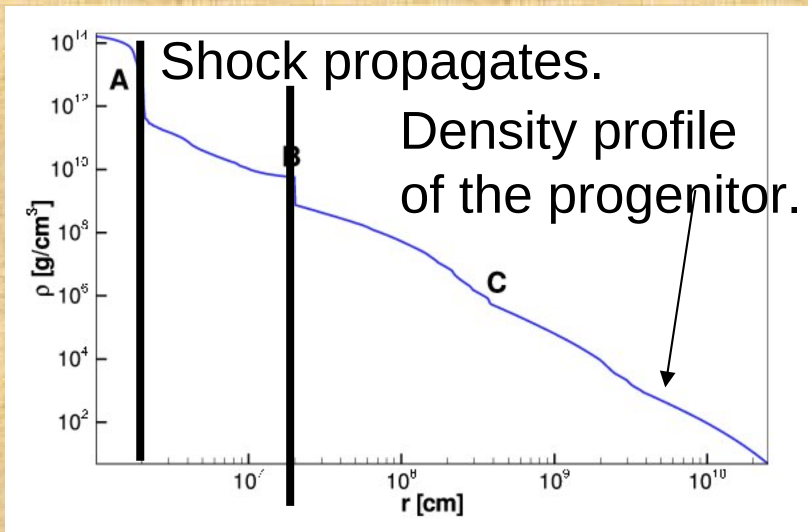
THE FLUXES CAN BE SIGNIFICANTLY MODIFIED.

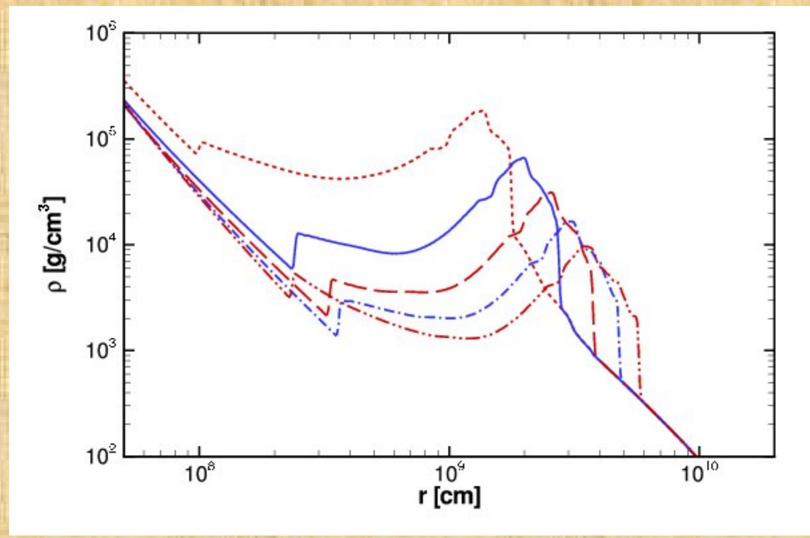
# The importance of shock waves

R. C. Schirato and G. M. Fuller (2002), arXiv : 0205390.

C. Lunardini and A. Y. Smirnov, JCAP 0306, 009 (2003), 0302033, K. Takahashi, K. Sato, H. E. Dalhed, and J. R. Wilson, Astropart. Phys. 20, 189 (2003), 0212195, G. L. Fogli, E. Lisi, A. Mirizzi, and D. Montanino, Phys. Rev. 68, 033005 (2003), 0304056., R. Tomas, M. Kachelrieß, G. Raffelt, A. Dighe, H.-T. Janka, and L. Scheck, JCAP 0409, 015 (2004), 0407132., G. L. Fogli, E. Lisi, A. Mirizzi, and D. Montanino, JCAP 4, 2 (2005), 0412046., S. Choubey, N. P. Harries, and G. G. Ross, Phys. Rev. D74, 053010 (2006), 0605255., B. Dasgupta and A. Dighe, Phys. Rev. 75, 093002 (2007), 0510219., S. Choubey, N. P. Harries, and G. G. Ross, Phys. Rev. 76, 073013 (2007), 0703092., J. P. Kneller, G. C. McLaughlin, and J. Brockman, Phys. Rev. 77, 045023 (2008), 0705.3835.,J. P. Kneller and G. C. McLaughlin, Phys. Rev. 73, 056003 (2006), 0509356...

Proto-neutron star.



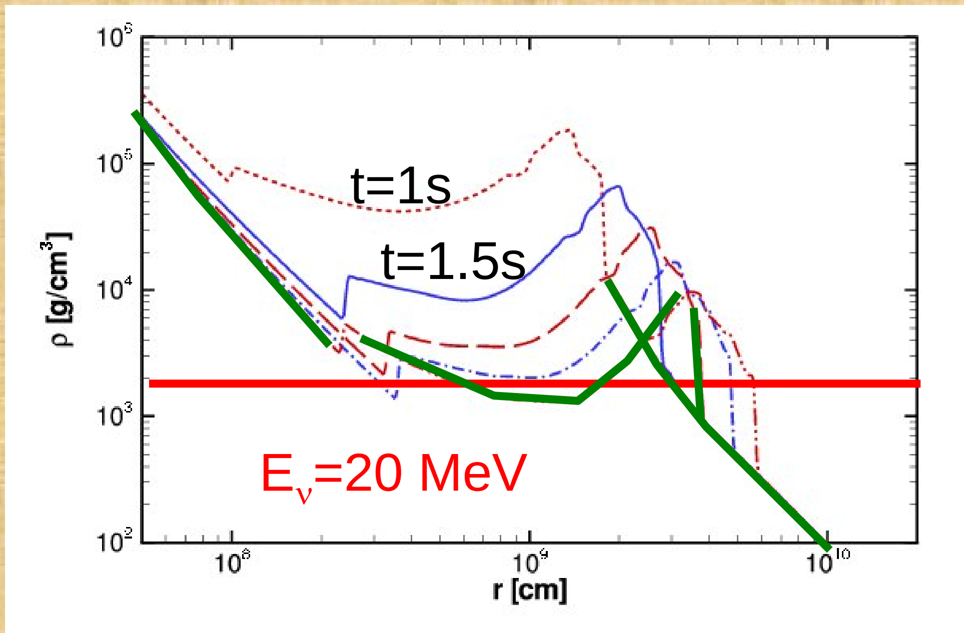



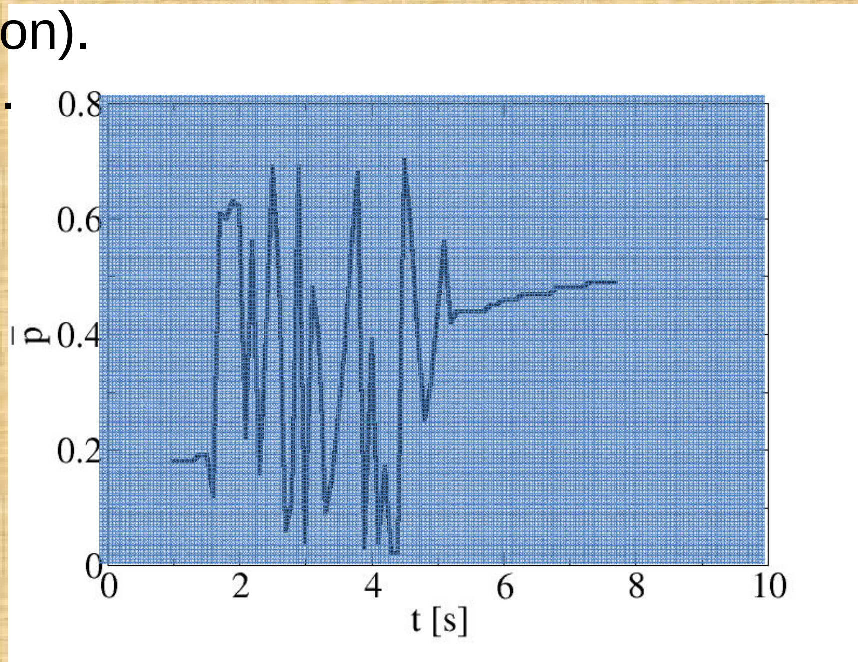

J. P. Kneller, G. C. McLaughlin, and J. Brockman, Phys. Rev. 77,045023 (20

# The shock wave effects

Evolution of the density profile with time in the MSW region.

1. Before the shock (adiabatic $\nu$ propagation).
2. The shock arrives (non-adiabatic prop.).
3. Phase effects appear.
4. Post-shock propagation.



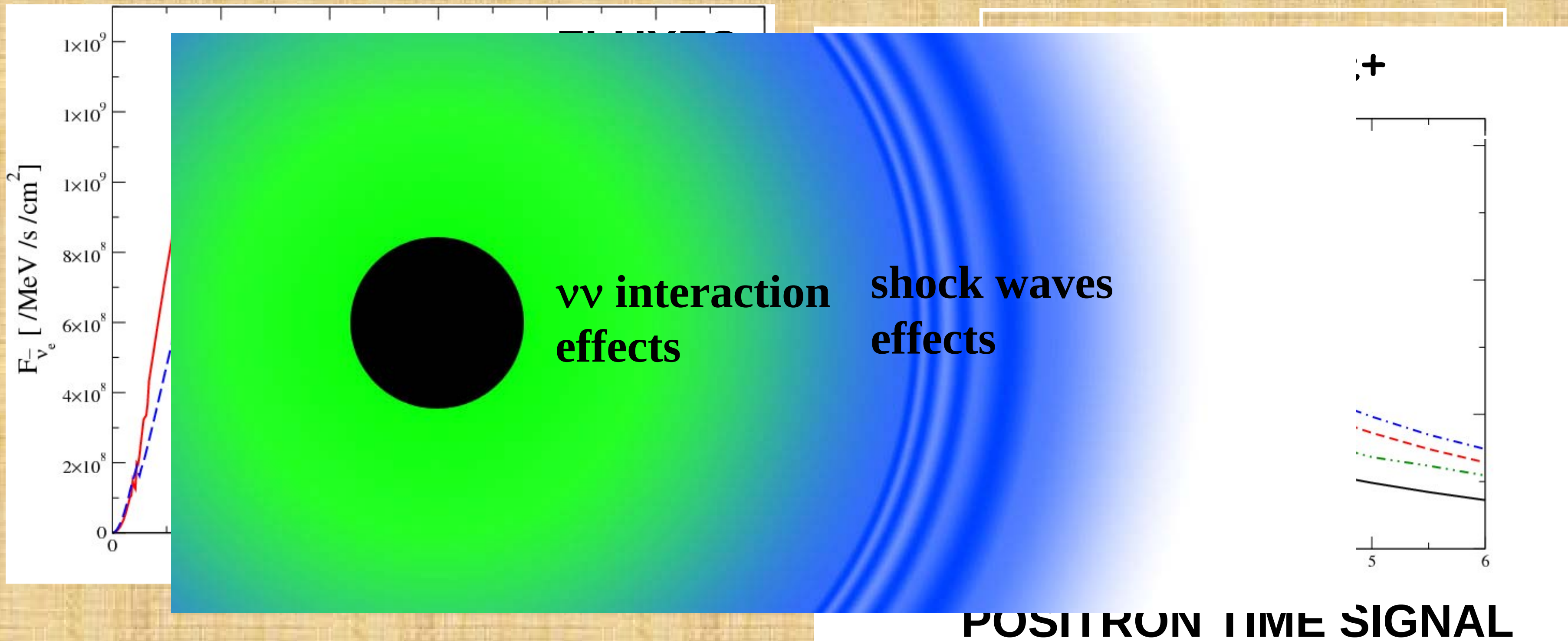




MULTIPLE RESONANCES AND PHASE EFFECTS APPEAR.

# Putting νν and shock waves together...

First calculation including the ν–ν interaction and shock wave effects.

Gava, Kneller, Volpe, McLaughlin, Phys. Rev. Lett. 103 (2009), arXiv:0902.0317

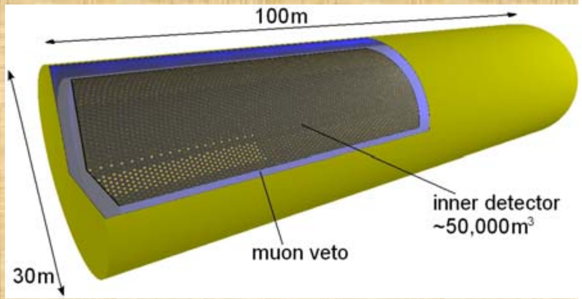


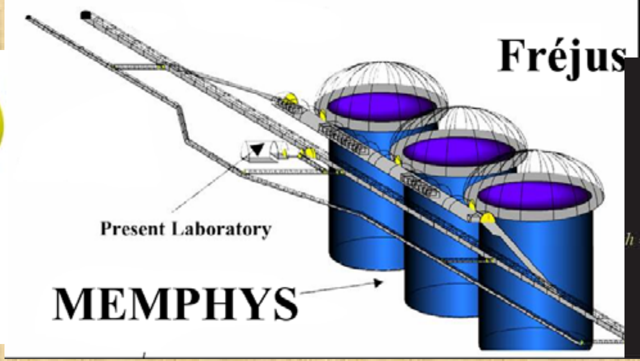

The dip (bump) can be seen at 3.5 (1) sigma in Super-Kamiokande if a supernova at 10 kpc explodes..

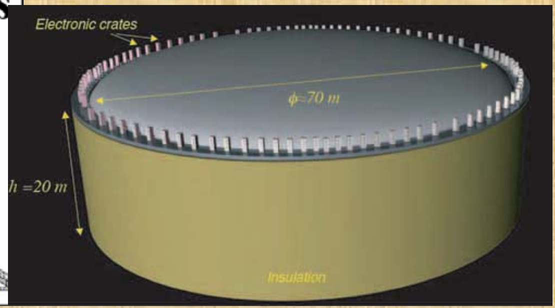
A SIGNATURE IN THE POSITRON TIME SIGNAL IF $\sin^2 2\theta_{13} > 10^{-5}$ OR $\sin 2\theta_{13} < 10^{-5}$

# Future SN observations

Several detectors are running (ex. Borexino, Kamland, Super-K,…) .
Large-size detectors are under study (LAGUNA DS, FP7, 2008-2010).



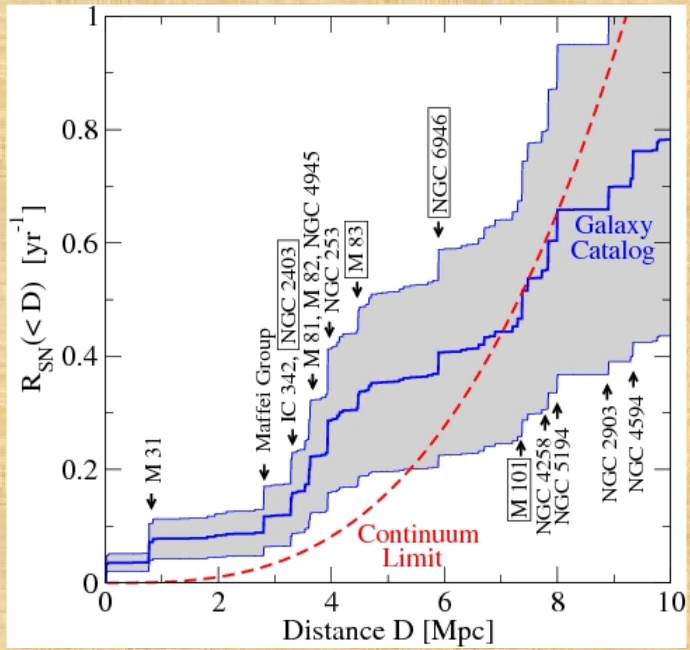




## Future strategy

I. To measure the neutrino luminosity curve from a future (extra)galactic explosion (ex. $10^5$ events in MEMPHYS).

II. To measure the diffuse supernova neutrino background (sensitive to the star formation rate as well).




Ando,Beacom,Yuksel PRL95 (2005)

**A remark on $\nu_e$ detection:** $\nu$–nucleus measurements necessary to determine the supernovae observatories's response

HALO, LENA, GLACIER, MEMPHYS

$^{208}Pb$ $^{12}C$ $^{40}Ar$ $^{16}O$

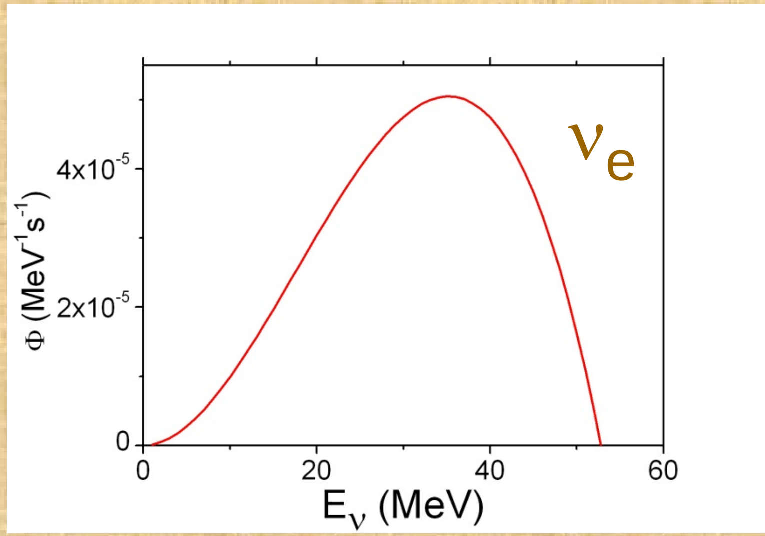
# POSSIBLE FUTURE INTENSE ν SOURCES

## CONVENTIONAL SOURCES

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

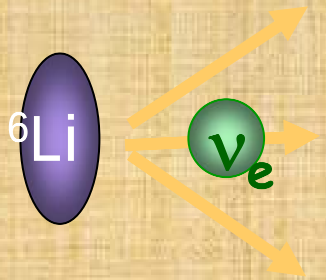
$$\mu^+ \longrightarrow e + \bar{\nu}_\mu + \nu_e$$

**Possible future sites :**
**ESS ?, JPARC, SPL**

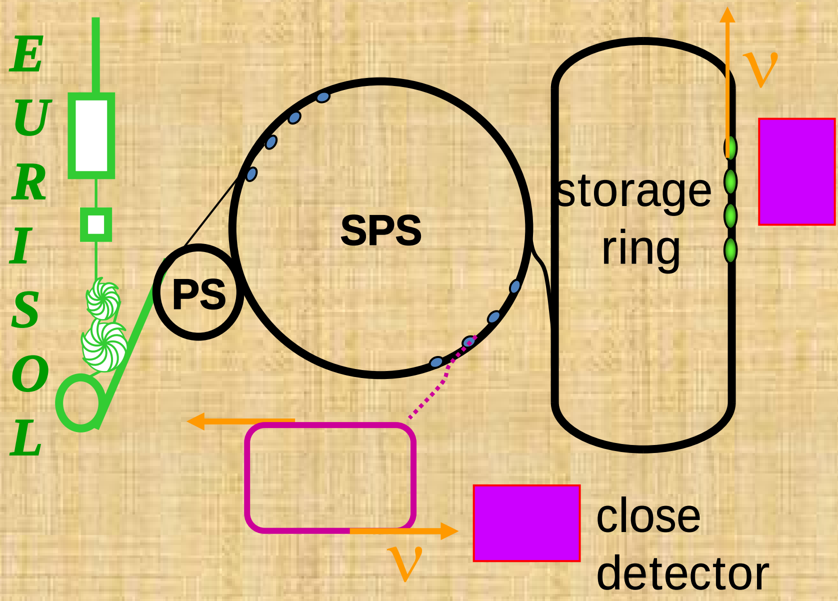



## Low energy BETA-BEAMS

C.Volpe, J Phys G 30 (2004) L1.




**Studied within EURISOL DS (FP6)**

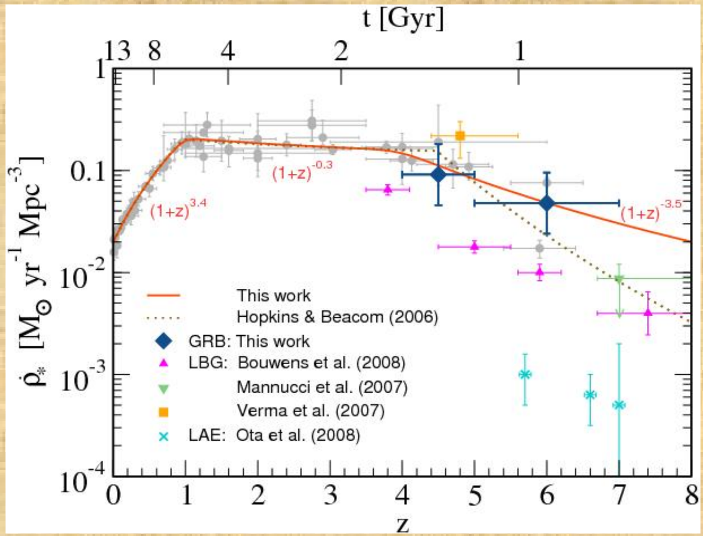


# The supernova neutrino background

Present limits :

1.08 $\bar{\nu}_e$ $cm^{-2}s^{-1}$ from SK ($E_{\nu e}$ > 19.3 MeV) Malek et al, PRL 90 (2003) & 2009

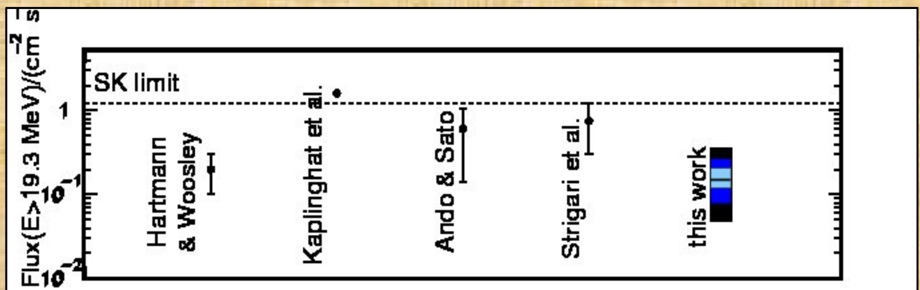
6.8 $10^3$ $\nu_e$ $cm^{-2}$ $s^{-1}$ from LSD (25 < $E_{\nu e}$ < 50 MeV) Aglietta et al. A Phys 1 (1992)




Yuksel, et al Astrophys. J.683, L5(2008).

**The star formation rate**

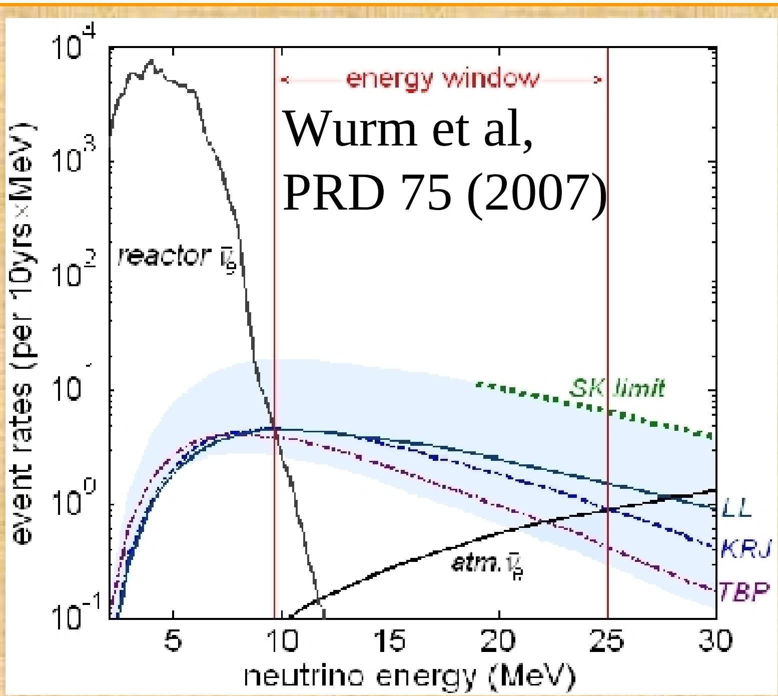
The star formation rate is nowadays constrained by various observations. Uncertanties remains, especially at small redshifts (a factor of 2 at z = 0).



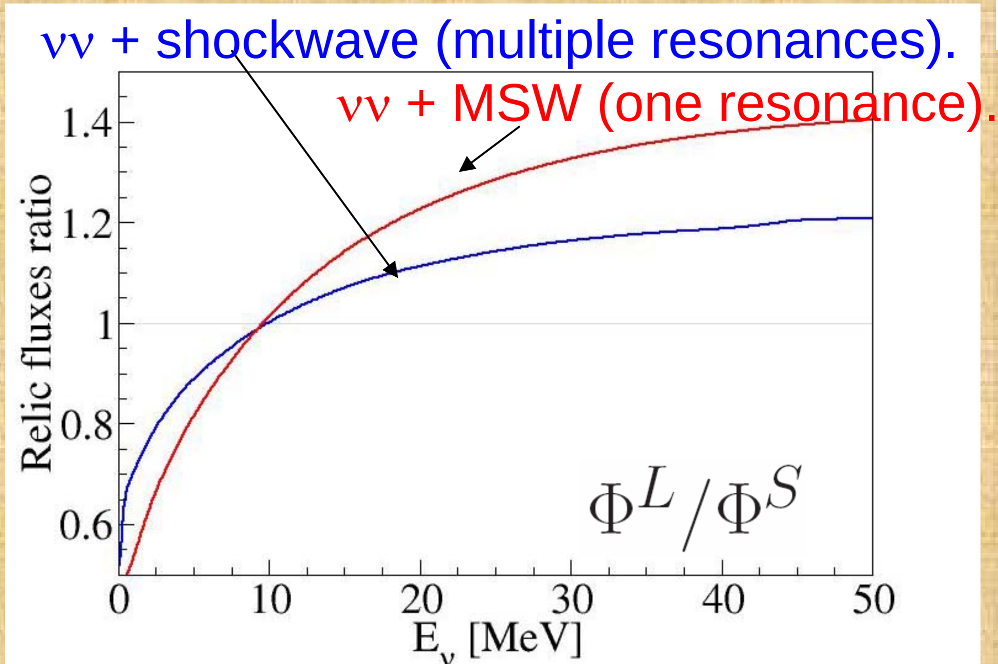

C. Lunardini, Astr. Phys., 26, 190 (2006)

Theoretical predictions on the relic neutrino fluxes are very close to the present upper limit.

There is an energy window free from backgrounds, where neutrinos from past supernovae can be discovered either with advanced technologies or with large size observatories.




**Shockwave impact:**




- ~ 10-20% effect from
- numerical caculations.
- loss of sensitivity

to the with νν interaction)

THE SHOCK WAVE HAS A SIGNIFICANT IMPACT ON THE DSNB.

S.Galais, J.Kneller, C.Volpe and J.Gava, to appear in PRD, arxiv:0906.5294

# DSNB event rates in ν-observatories

after 10 years

Water Cerenkov (440 kton) and scintillator (50 kton) detectors

| Inverted Hierarchy: with νν | | | |
|---|---|---|---|
| $N_{events}$ | Detection window | L | S |
| $\bar{\nu}_e$ | 19.3-30 MeV | **343** | **392** |
| $\bar{\nu}_e$ | 9.3-25 MeV | **91** | **91** |

Argon detectors (100 kton).

| Normal Hierarchy | | | |
|---|---|---|---|
| $N_{events}$ | Detection window | L | S |
| $\nu_e$ | 17.5-41.5 MeV | **66** | **58** |
| $\nu_e$ | 4.5-41.5 MeV | **106** | **96** |

S.Galais, J.Kneller, C.Volpe and J.Gava, to appear in PRD, arxiv:0906.5294

# CP violation searches and astrophysics

- **Solar neutrinos**

H.Minakata and S. Watanabe, Phys. Lett. B 468, 256 (1999).

- **UHE neutrinos**

Walter Winter, Phys. Rev. D 74, 033015 (2006).

- **Supernova neutrinos**

***E***. Akhmedov, C.Lunardini & A.Smirnov, Nucl.Phys.B643 (2002) 339.

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

J. Gava, C. Volpe, Phys. Rev. D78, 083007(2008), arXiv:0807.3418.

J Kneller and G.C. McLaughlin, arXiv:0904.3823.

# CP violation and core-collapse SN

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

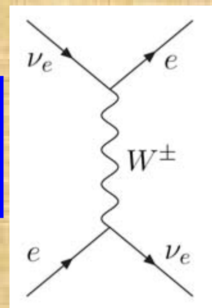
- **We have demonstrated under which conditions there can be CP violating effects in supernovae. Here the main steps :**

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

The neutrino evolution equations in matter are

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

vacuum term matterterm




with

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

the T23 basis

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

factorizes out easily and gives:

# CP violation and core-collapse SN

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

Evolution operator in the $T_{23}$ basis

This leads to the two following relations:

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

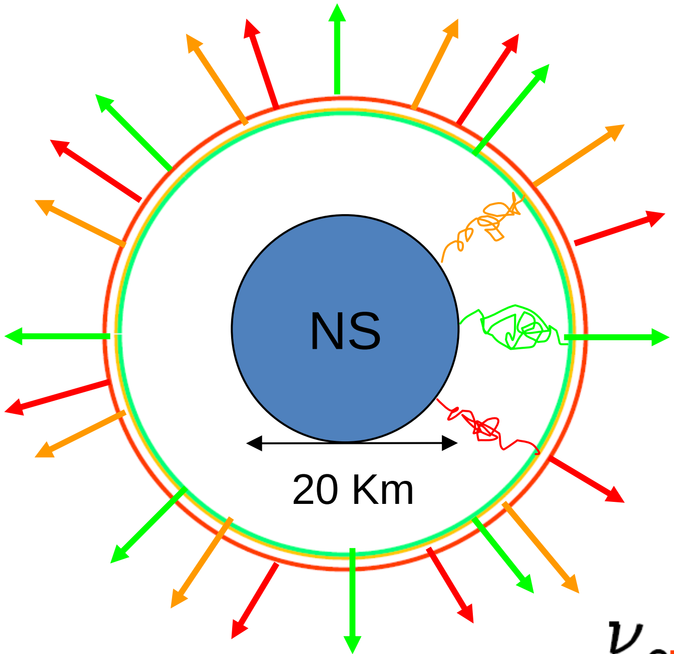
The electron neutrino survival probability does not depend on δ.

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

Exact relations, valid for any density profile.

**We have demonstrated that these relations also hold when the ν–ν interaction is included.**

J. Gava, C. Volpe, Phys. Rev. D78, 083007(2008), arXiv:0807.3418.




The **neutrinosphere** is where neutrinos finally decouple from matter.

$\nu_e$

$\bar{\nu}_e$

$\nu_x$

Tree level

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

***L*** $\boldsymbol{\nu}$- neutrino fluxes at the neutrinosphere (Fermi-Dirac or power law )

The electron neutrino flux in the SN:

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

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

AT TREE LEVEL THE $\nu$e-FLUXES DO NOT DEPEND ON THE CP PHASE

# Conditions for CP effects in SN

In the Standard Model loop corrections for the **ν** interaction with matter should be included.

Beyond the Standard Model might introduce differences in the $\nu_\mu$ and $\nu_\tau$ interaction wiht matter (Flavor Changing Neutral Currents, …).

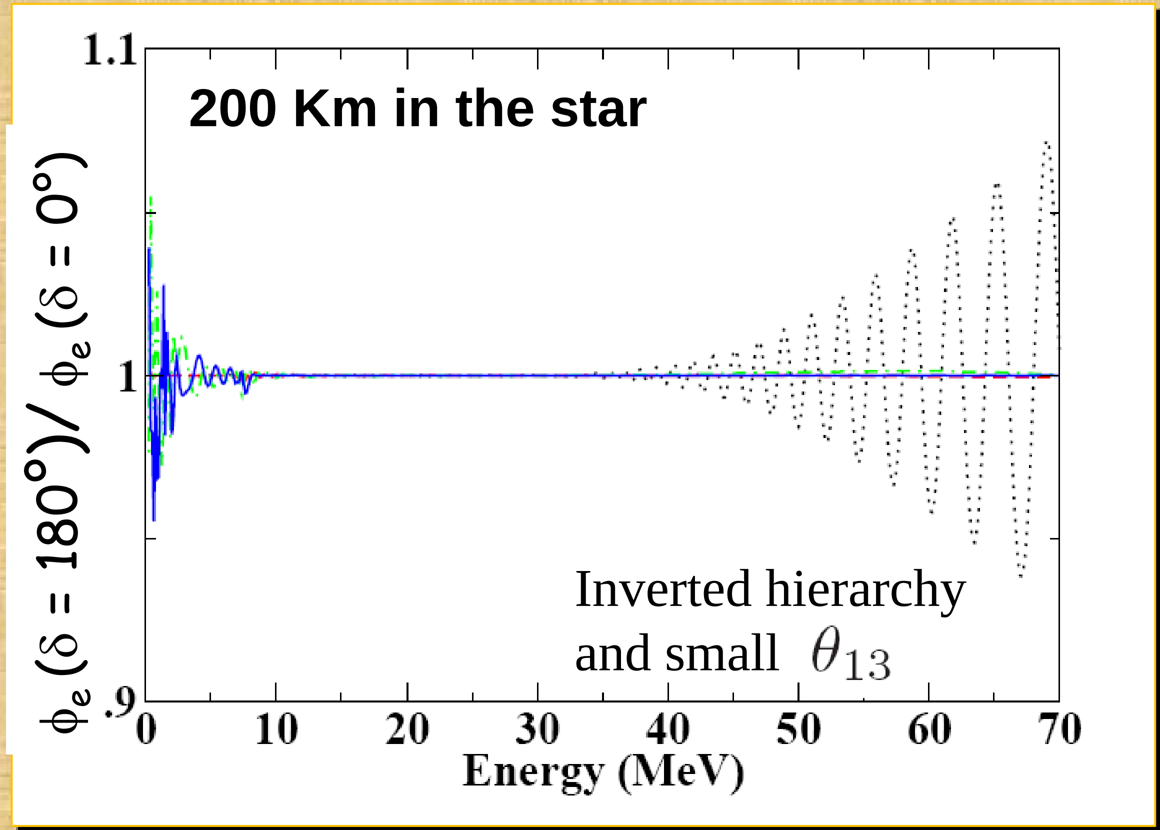
$L_{\nu_\mu} \neq L_{\nu_\tau}$ at the neutrinosphere

AND also

$\tilde{H}(\delta) \neq S^\dagger \tilde{H}(\delta = 0) S$ The ν propagation Hamiltonian does not factorize any more !

**THERE CAN BE CP-VIOLATION EFFECTS IN SUPERNOVAE.**

# Numerical results : effects on the flux ratios




................Standard MSW
tree level

More realistic case !

ν-ν interaction and 1-loop

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

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

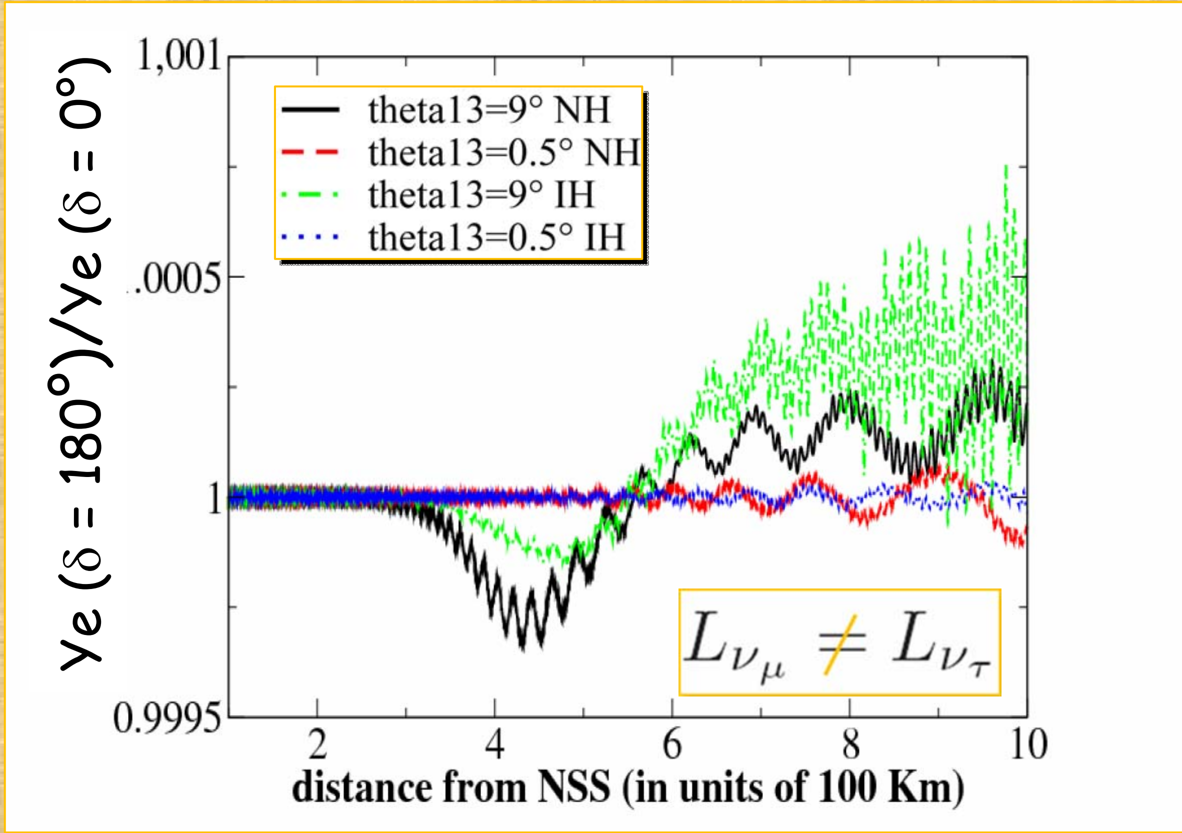
J. Gava, C. Volpe, Phys. Rev. D78, 083007(2008), arXiv:0807.3418.

EFFECTS OF 5-10 % ON THE ELECTRON NEUTRINO FLUXES
in the SUPERNOVA.

# Numerical results : effects on Ye

The electron fraction is a key parameter for the r-process nucleosynthesis :

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

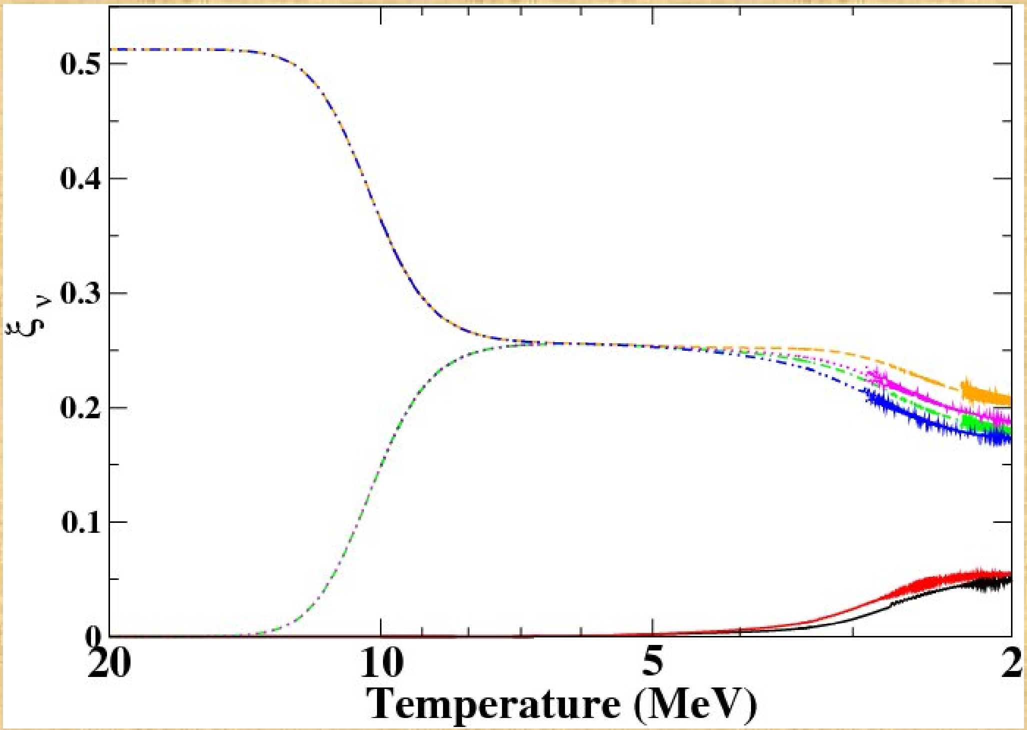



A. B. Balantekin, J. Gava, C. Volpe, PLB662, 396 (2008), arXiv:0710.3112

VERY SMALL EFFECTS ON THE ELECTRON FRACTION.

# CP effects on the neutrino degeneracy parameter at the BBN epoch ?

We have possible CP effects on the neutrino degeneracy parameters (or neutrino asymmetry) that can impact the He4 fraction at the time of Big-Bang nucleosynthesis.




J. Gava, C. Volpe, to be submitted.

EFFECTS UP TO 1% on $\xi_e$, **a few $10^{-3}$ on the He4 abundance.**

# Conclusions and Perspectives

- Neutrino physics is entering a crucial phase where experiments will bring new results to key open issues.

- Our understanding of neutrino propagation in media is undergoing major developments. Calculations have become demanding.

# Conclusions and Perspectives

A lot of theoretical and phenomenological work still needs to be done to come to an established framework and to be able to disentangle information from future observations.

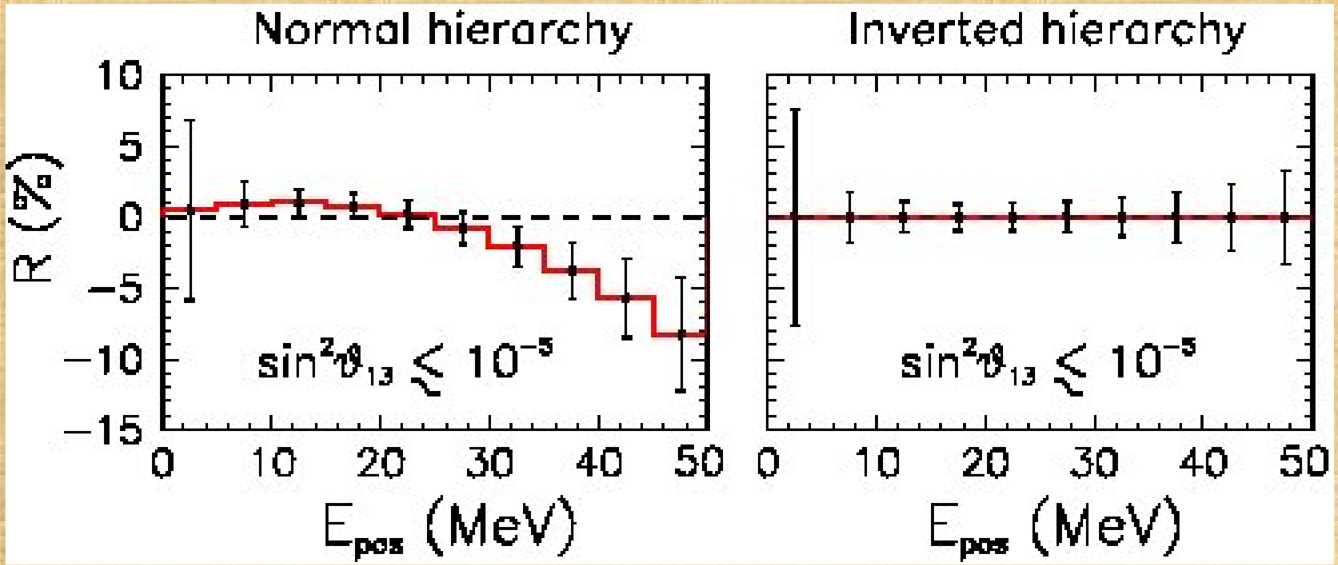
We have set the basis for the exploration of CP violating effects in media.
Further work is needed to study the possible impact e.g. on the r-process and in other Environments, such as the Early Universe.

Stay tuned ...


Danke.
Thank you!
Grazie.
Merci.

# Determining the mass hierarchy

Using two megaton detectors, one shadowed by the Earth, the other unshadowed one can identify the mass hierarchy.




Dasgupta, Dighe, Mirizzi, Phys. Rev. Lett. 101 (2008) 1718001, arXiv : 0208.1481

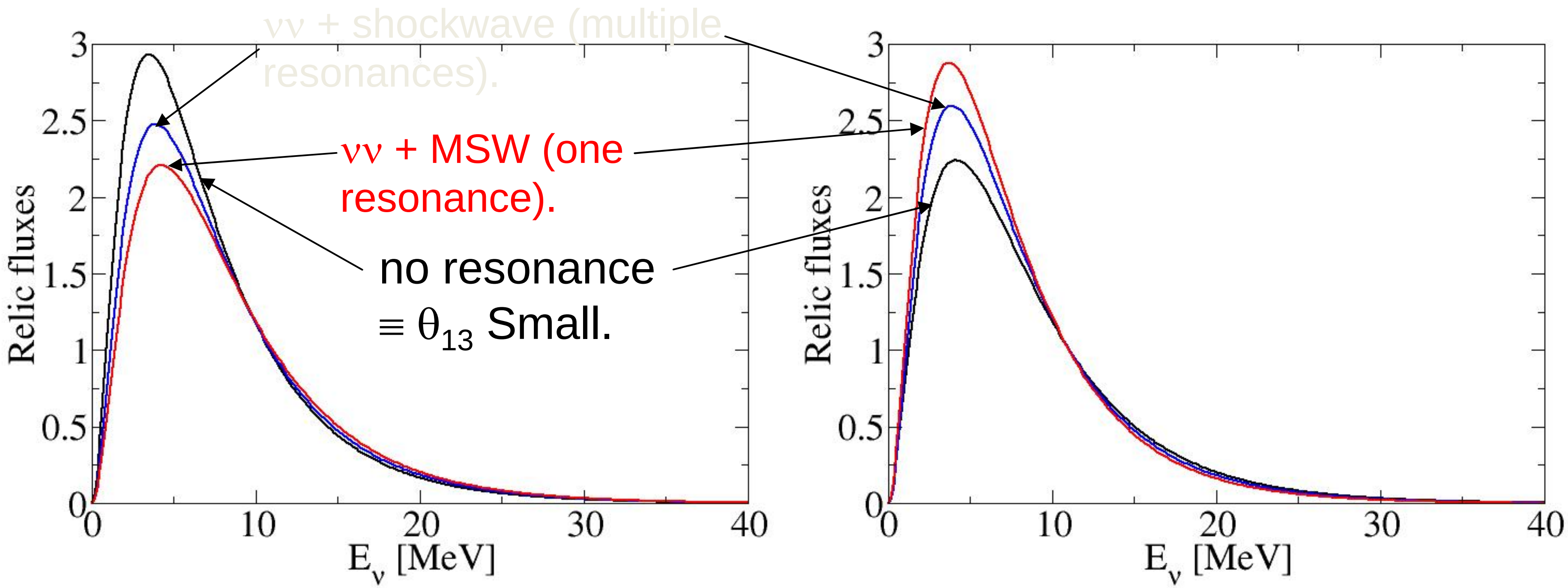
# RESULTS: relic electron (anti-)neutrino fluxes

For $\theta_{13}$ we take: $\theta_{13} = 5.73\text{x}10^{-3}\,°$ (Small).
$\theta_{13} = 0.573°$ (Large).

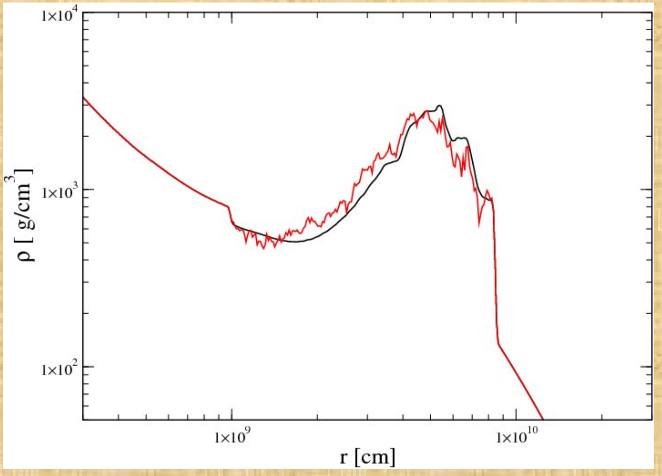
results for $\theta_{13}$ large are valid for the range: $\sin^2 2\theta_{13} \in [0.19, 10^{-5}]$

**Normal Hierarchy** for $\nu_e$.

**Inverted Hierarchy** for $\bar{\nu}_e$.



# Turbulence effects...




S.Galais, J.Kneller, C.Volpe and J.Gava,arxiv:0906.5294