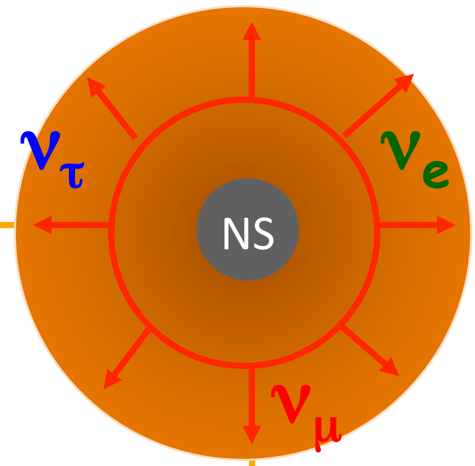


Neutrinos and Supernovae

ν

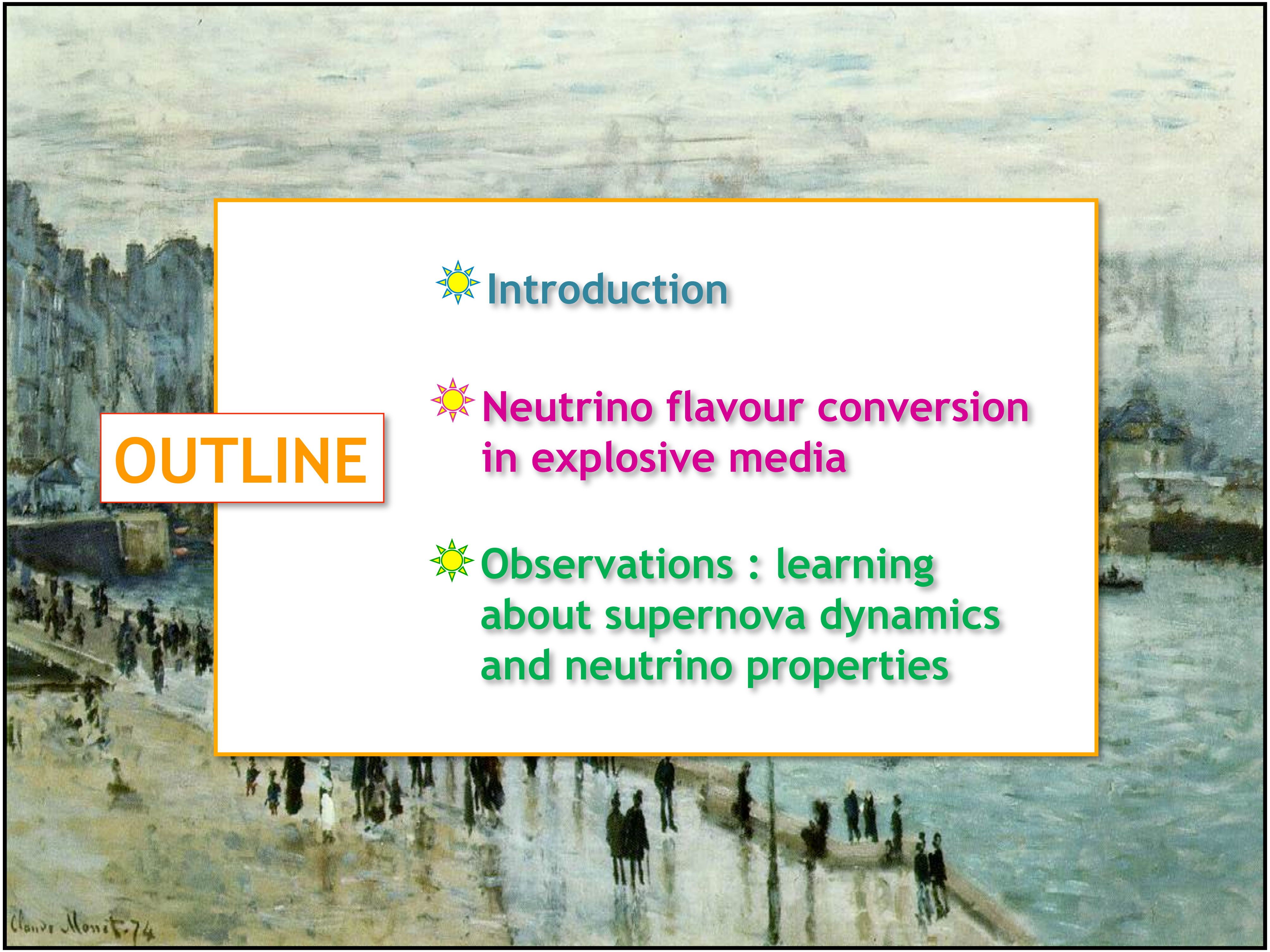
Cristina VOLPE
(Institut de Physique Nucléaire Orsay, France)

OUTLINE

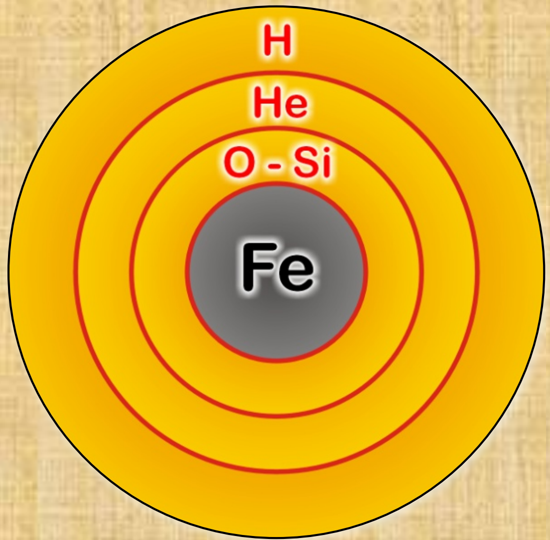
- Introduction

- Neutrino flavour conversion in explosive media

- Observations : learning about supernova dynamics and neutrino properties



Core-collapse supernovae (SN)



- Stars with masses :
  6 Msun < M < 8 Msun O-Ne-Mg SN
  M > 8 Msun Iron-core SN

- 99 % of the gravitational energy (10^{53} ergs) is radiated as neutrinos and anti-neutrinos of all flavours.

- The burst lasts about 10 seconds.

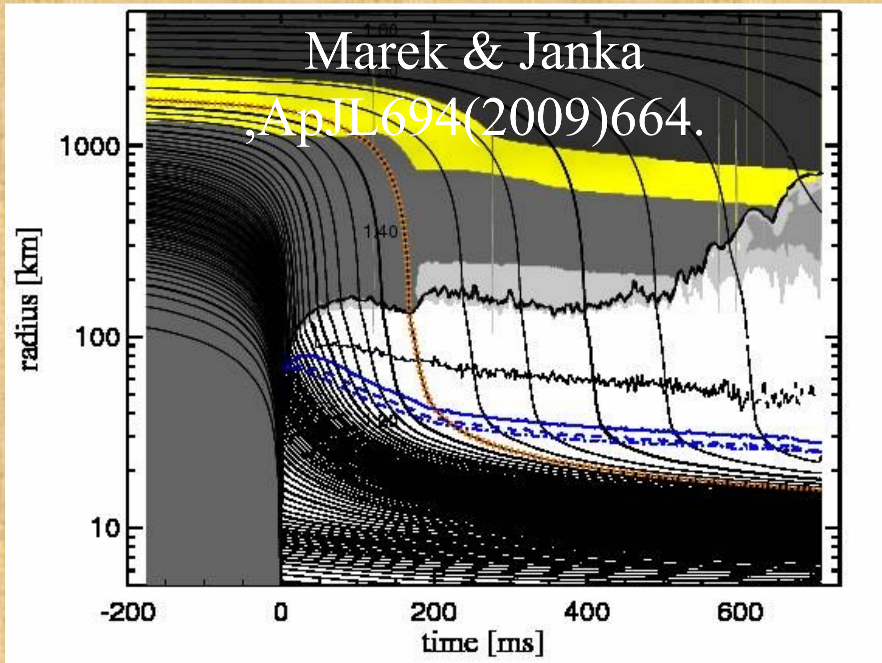
- The SN neutrino fluxes span the energy range from a few to 50 MeV (with a tail).

Why investigating SN neutrinos?

- **SN dynamics**
  - explosion mechanism not unravelled yet
  - nucleosynthesis processes (r-process, νp-process, ν-process)
  - to test SN models
- **ν properties**
  - flavour conversion phenomena in explosive environments
  - unknown neutrino properties impact SN physics, e.g. θ_{13}, mass hierarchy, sterile neutrinos, non-standard interactions, leptonic CP violation (δ), ...

Do iron-core SNe explode ?

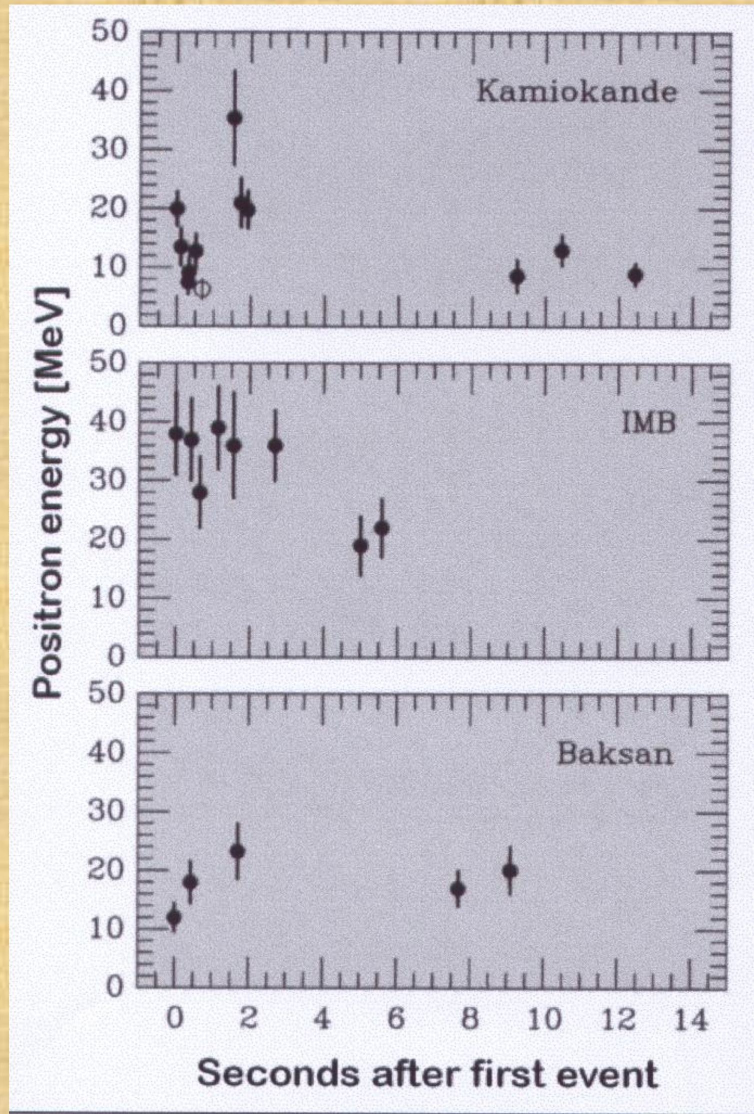
- A longstanding problem.
- In the last decade, SN simulations have become 2D-3D, include convection and realistic neutrino transport.



The explosion mechanism delineated :
a combination of convection- neutrino – hydro instability (SASI).

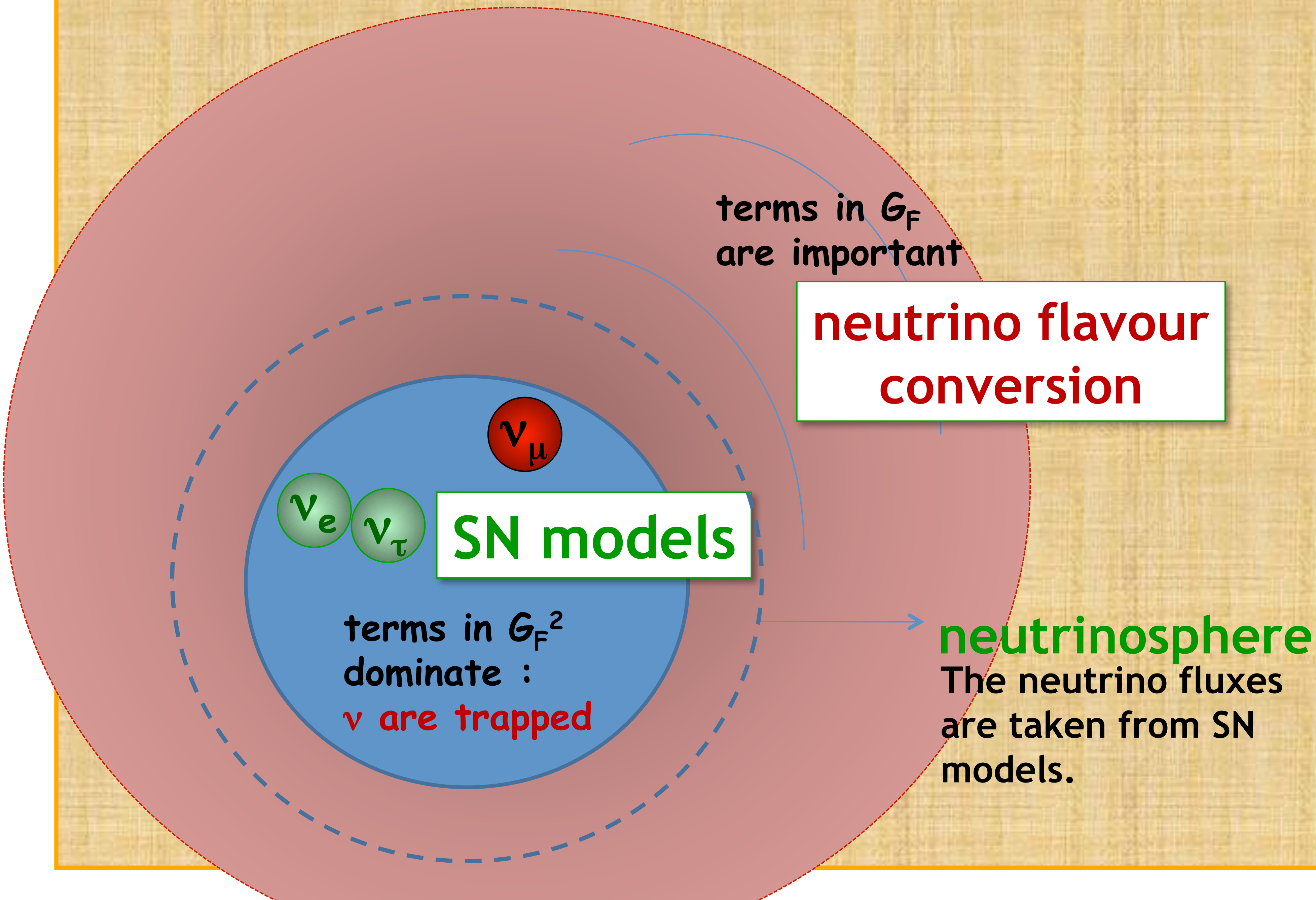
SN1987A events

SN1987A LMC (50 kpc)

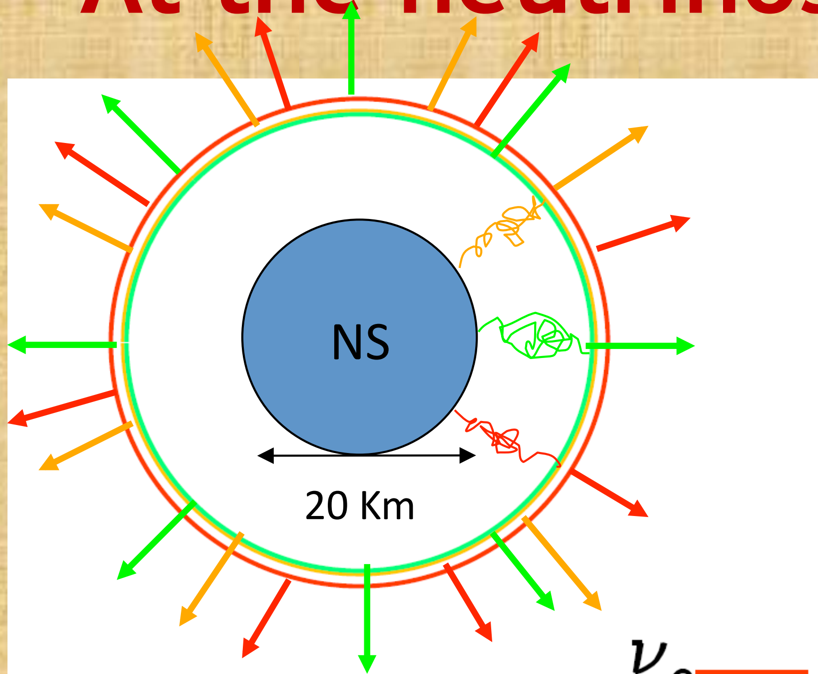


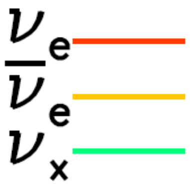
Expectations are roughly confirmed.

A comment on the models

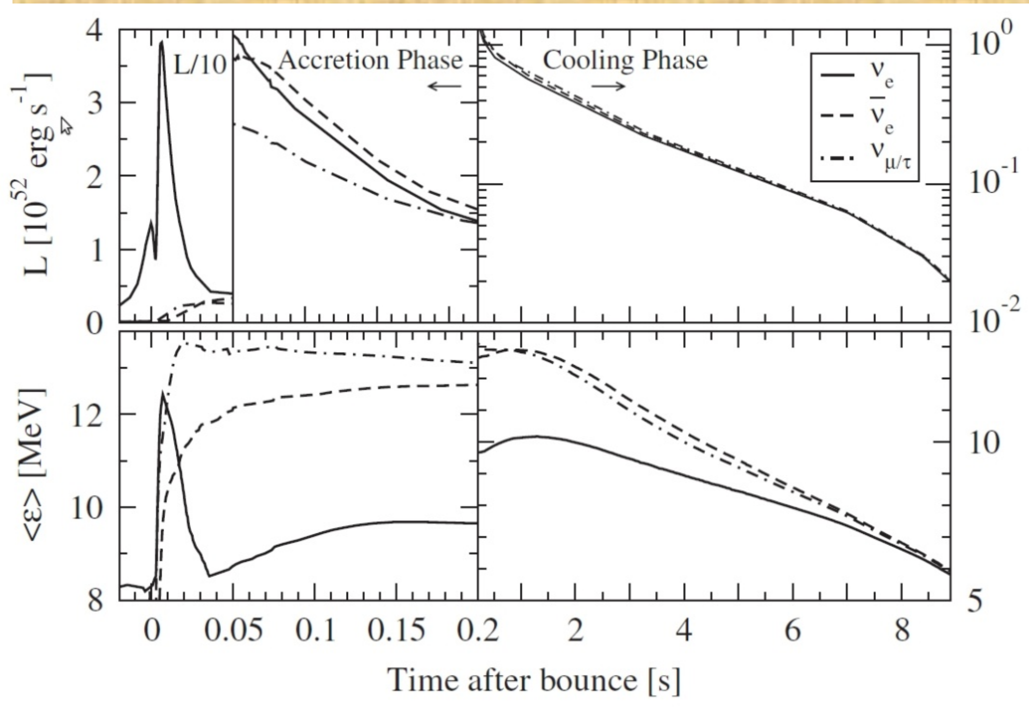


At the neutrinosphere : the ν fluxes





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



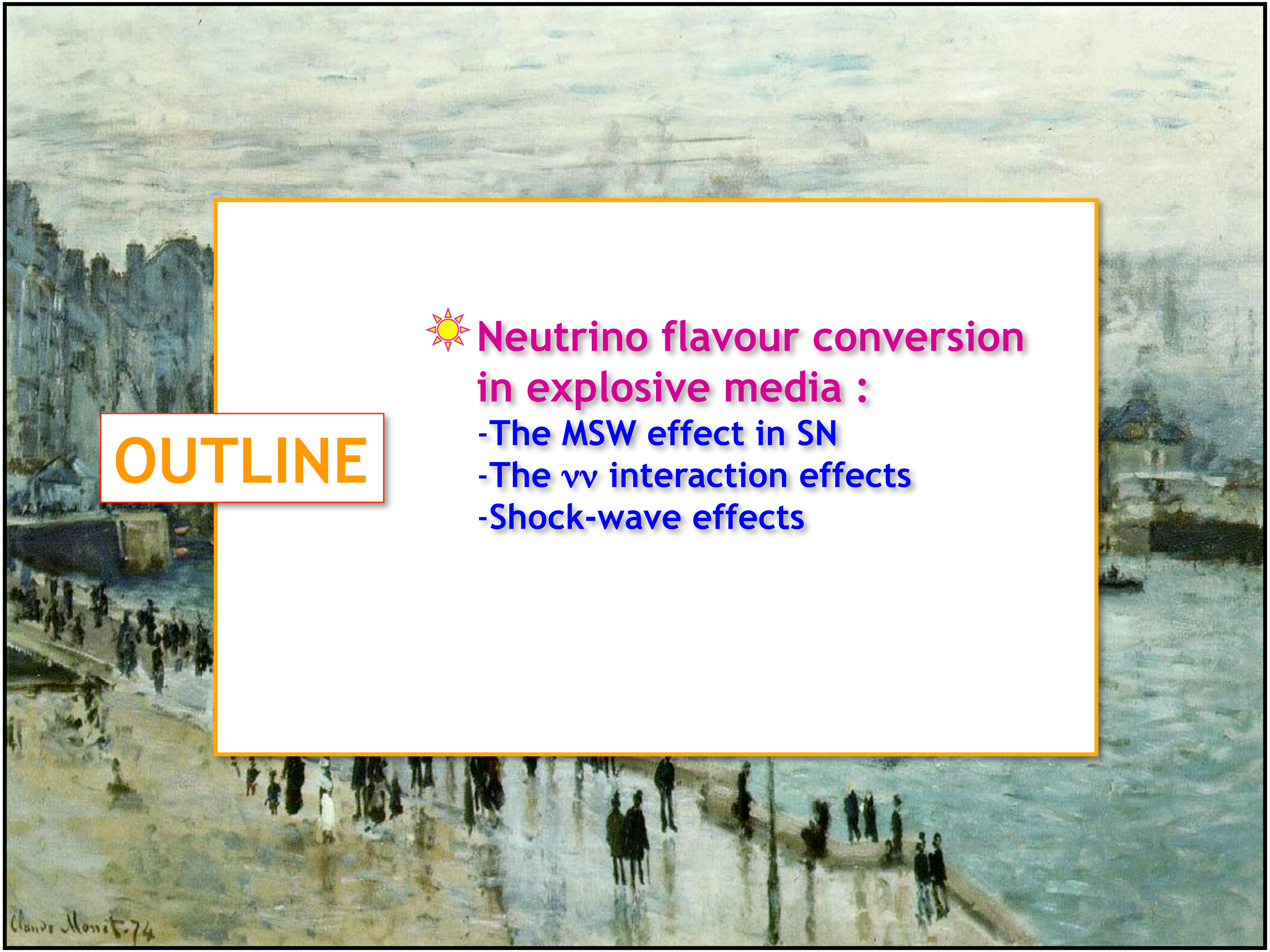
Hüdepohl *et al.* PRL104 (2010)

Different neutrino flavours have different neutrinospheres.

Muon and tau neutrinos only have NC while electron (anti)neutrinos undergo NC and CC.

$\langle E_{\nu e} \rangle < \langle E_{\bar{\nu} e} \rangle < \langle E_{\nu x} \rangle$

Neutrinos follow closely the explosion.



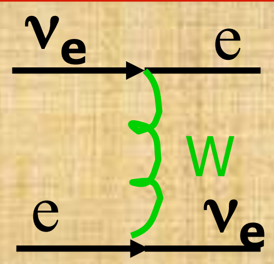
OUTLINE

☀ **Neutrino flavour conversion in explosive media :**

- The MSW effect in SN
- The $\nu\nu$ interaction effects
- Shock-wave effects

Neutrino flavour conversion in matter

The Mikheev-Smirnov-Wolfenstein (MSW) effect



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

Neutrino coupling with matter induces a <u>resonant flavour conversion</u>.

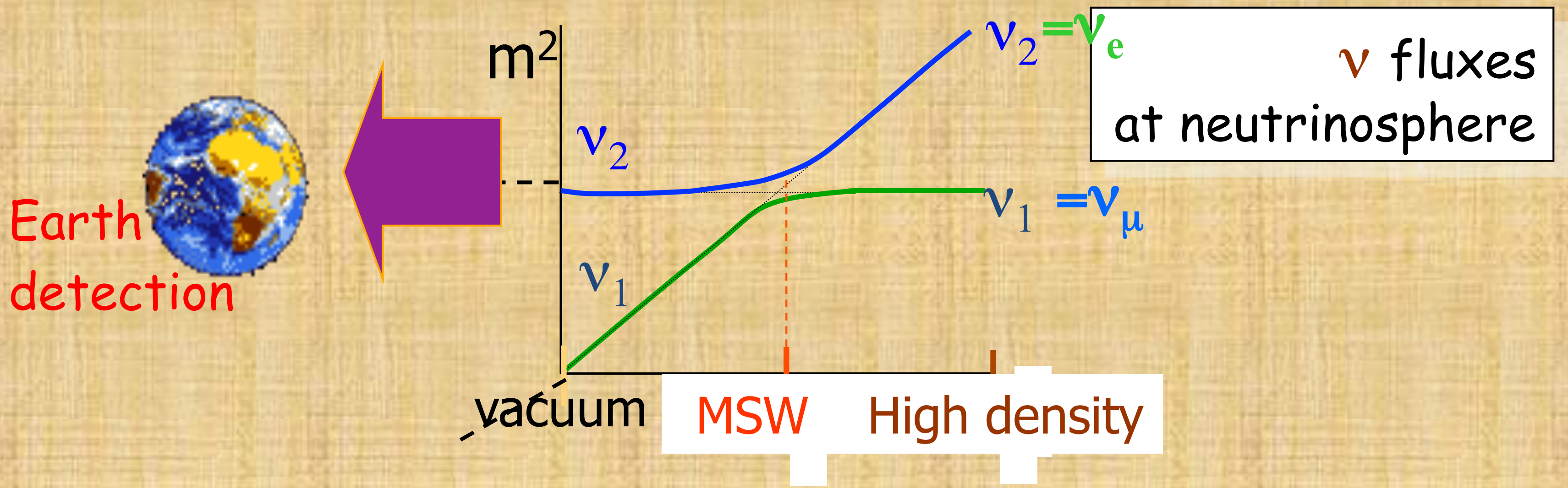
In the flavour basis, the neutrino evolution equations in matter :

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

vacuum term

matter term

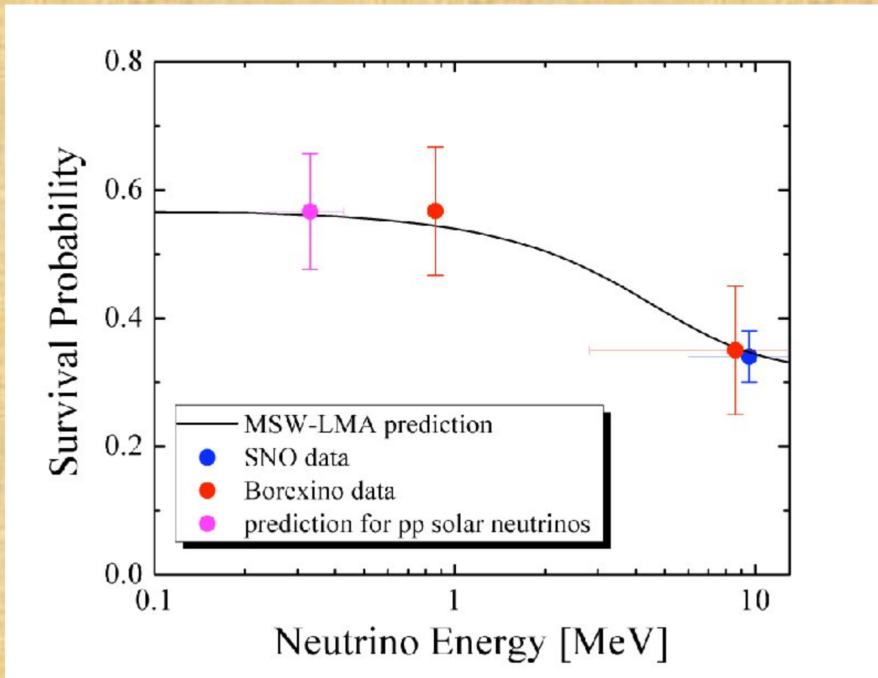
The Mikheev-Smirnov-Wolfenstein effect



Flavour conversion is efficient if :
- the resonance condition is met ;
- the evolution at resonance is adiabatic.

The density profile, the neutrino energy and the mixing parameters say if the conversion is adiabatic/non-adiabatic.

Experimentally observed !



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

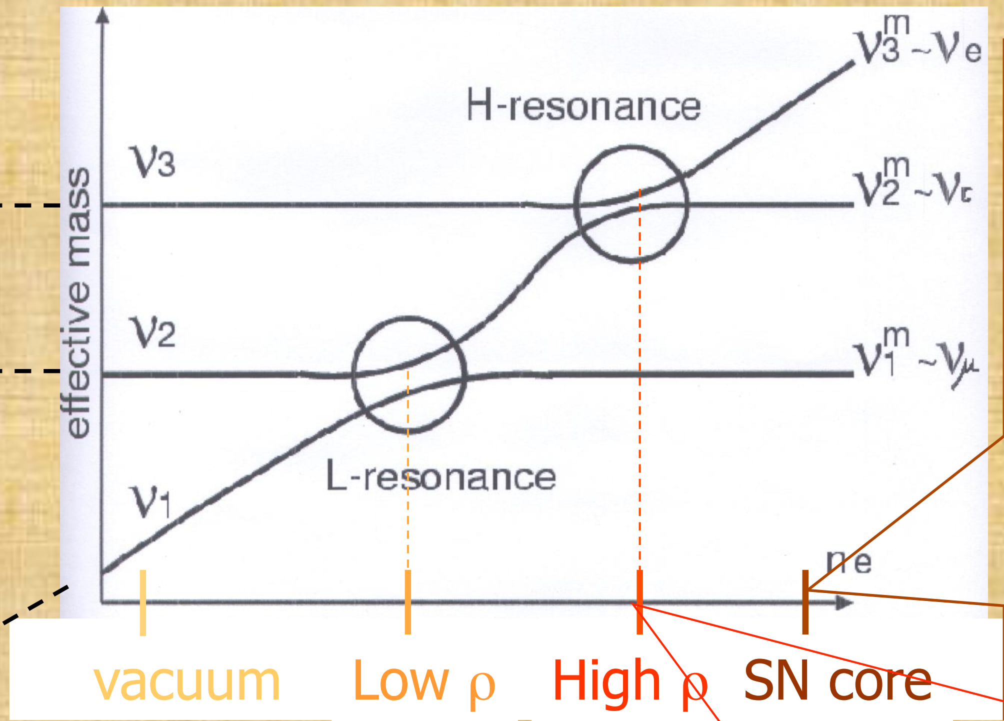
Borexino Collaboration, J. Conf. Ser. 202, 012028 (2010)

The MSW effect in supernovae

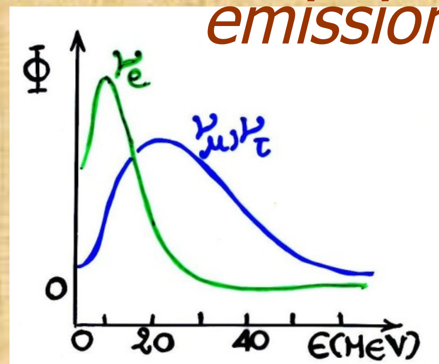
The MSW effect is encountered twice (three times) :

Dighe and Smirnov, PRD62(2000)033007

ν_e, ν_μ, ν_τ, detection on earth



ν-fluxes at emission



$\langle E_{\nu_e} \rangle < \langle E_{\nu_{\mu,\tau}} \rangle$

9–12 18-22 MeV

The hopping probability P_H :

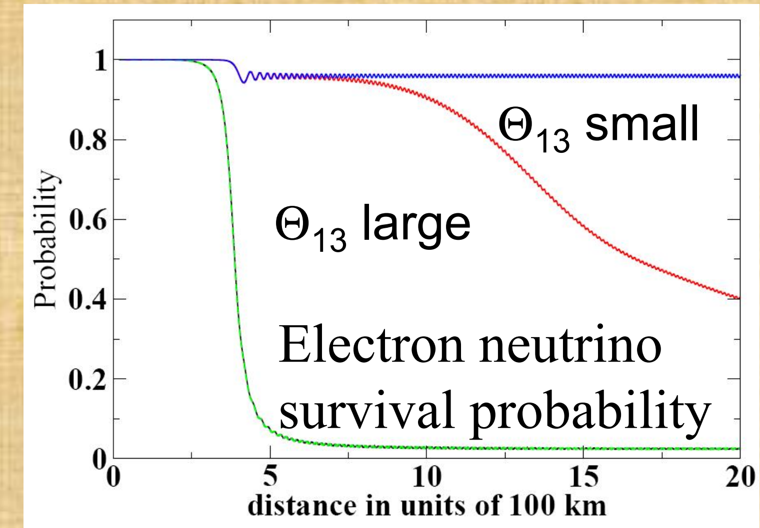
$$P_H = \exp\left[-2\pi r_H \frac{\Delta m^2}{2E} \sin^2\theta_{13} \right]$$

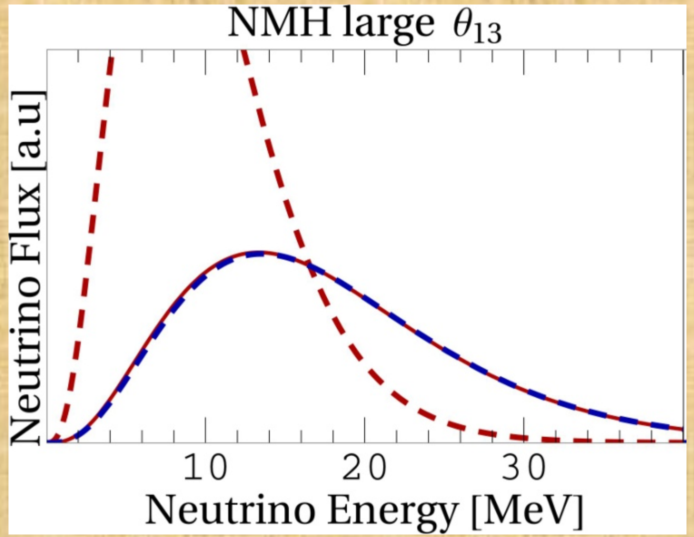
If $\sin^2 2\theta_{13} >> 10^{-3}$ $P_H = 0$ $\nu_e \longrightarrow \nu_3$

If $\sin^2 2\theta_{13} << 10^{-3}$ $P_H = 1$ $\nu_e \longrightarrow \nu_2$

THE FLAVOUR CONVERSION AT THE HIGH RESONANCE DEPENDS ON THE NEUTRINO MASS HIERARCHY AND ON θ_{13}.

A numerical example :

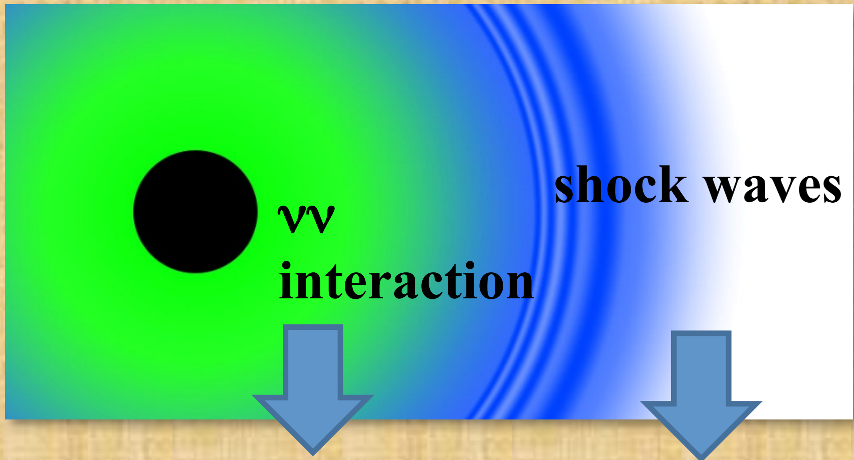


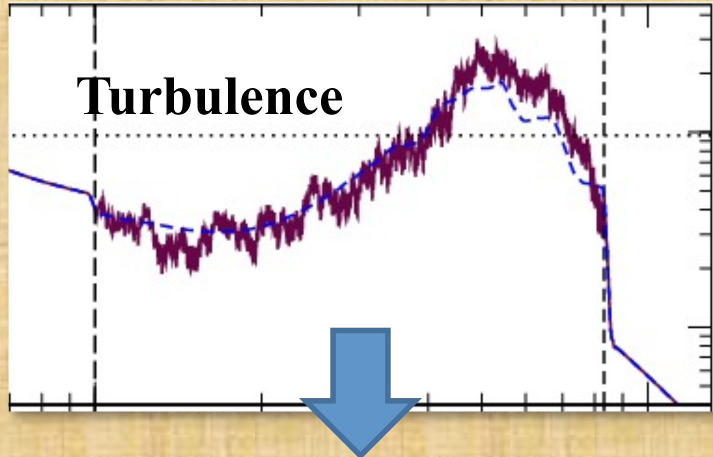


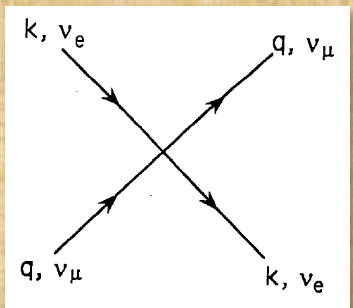
Important impact on the fluxes.

Neutrino flavour conversion in SN

The case of core-collapse supernovae turns out to be much more complex : new flavour conversion phenomena emerge.







Collective flavour conversion effects

Multiple MSW resonances

New features arise

Understanding the different facets of flavour conversion in SN :
the object of intense investigation.

νν 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), Fogli, Lisi, Mirizzi, Marrone, JCAP 2007, Raffelt and Smirnov, PRD 76 (2007), Estebal et al PRD 76 (2007), Gava and Volpe PRD(2008), Kneller, Gava, Volpe, McLaughlin (2009), Dasgupta, Dighe, Raffelt, Smirnov, PRL103(2009) , Dasgupta, Mirizzi, Tamborra, Tomas, PRD81 (2010), Fogli, Lisi, Marrone, Tamborra, JCAP0910(2009), …

…

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., S.Galais, J.Kneller, C.Volpe and J.Gava, PRD(2010), ...

Turbulence

Loreti et al, PRD 52 (1995); Balantekin et al, PRD 54 (2006), Friedland and Gruzinov, hep/0607244, Fogli et al JCAP 0606 (2006);. Kneller ,arXiv: 1004.1288, J. P. Kneller and C. Volpe, PRD (2010), arXiv: 1006.0913, …

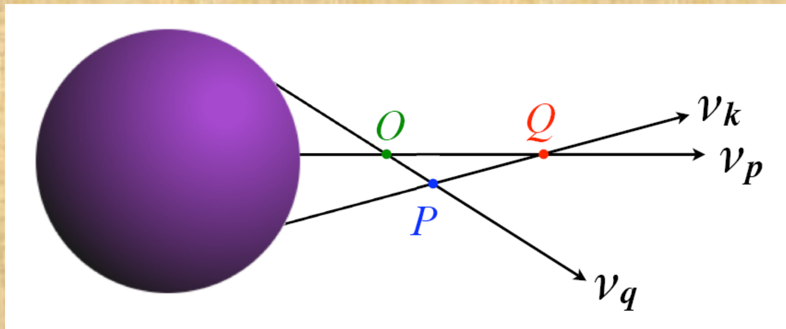
The ν–ν interaction

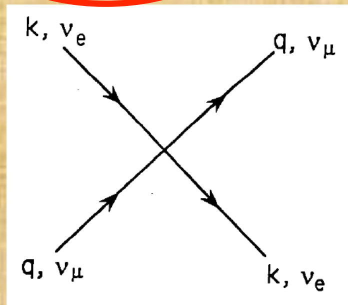
J. Pantaleone, PLB 287 (1992), Samuel,PRD 48 (1993), Sigl and Raffelt, NPB 406 (1993),

Duan,Fuller,Qian PRD74 (2006)

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

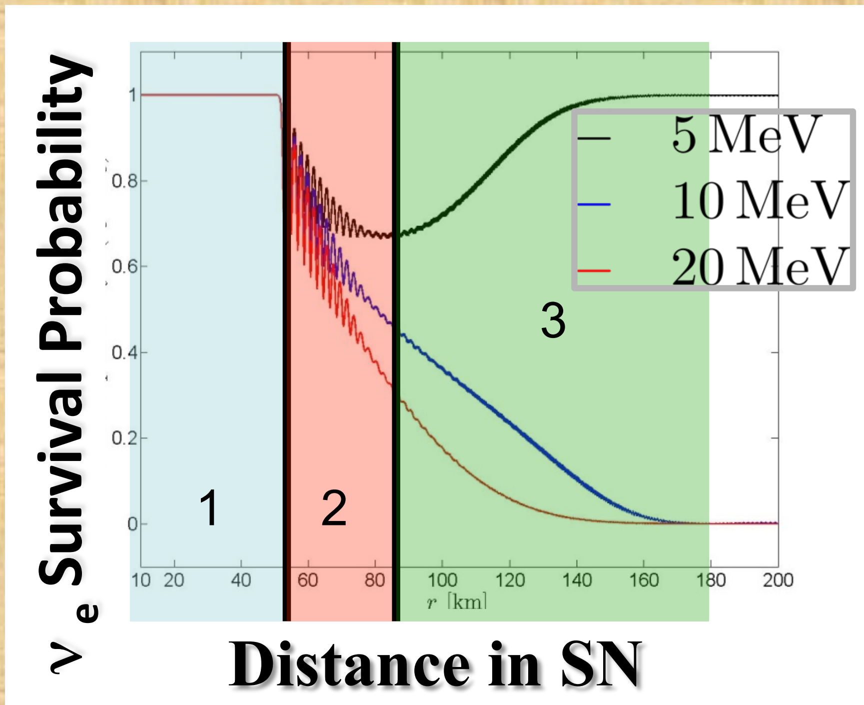
$$H = H_{vacuum} + H_{matter} + H_{\nu\nu}(\rho_\nu)$$

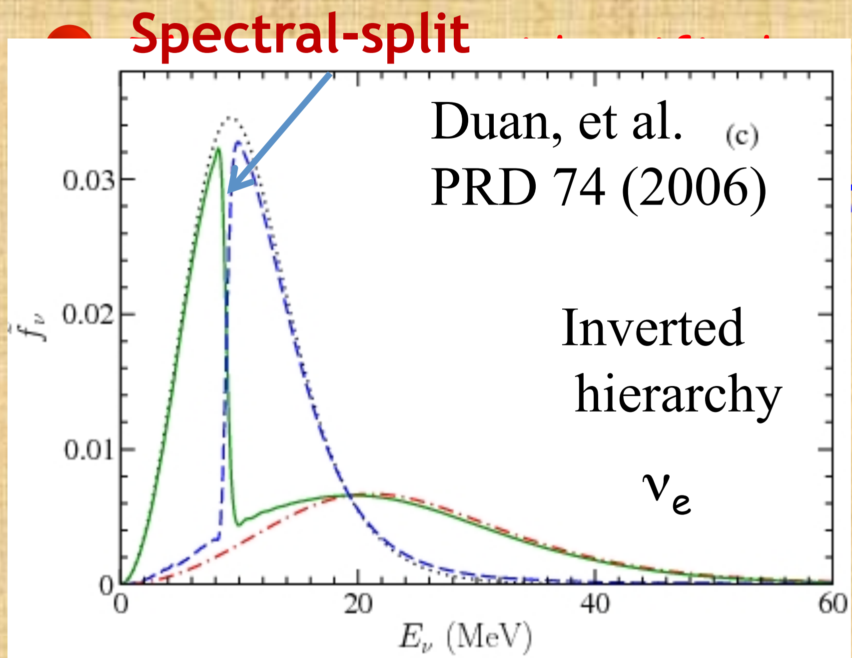




- Involved numerically : large number of coupled stiff non-linear equations.

Neutrino flavour conversion triggered by the νν-interaction





Important modifications of ν-fluxes, near the neutrinosphere

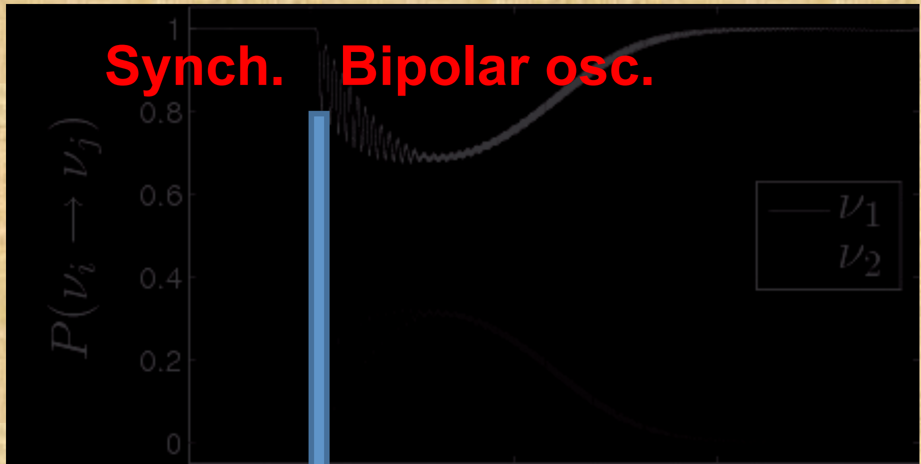
The role of the matter phase

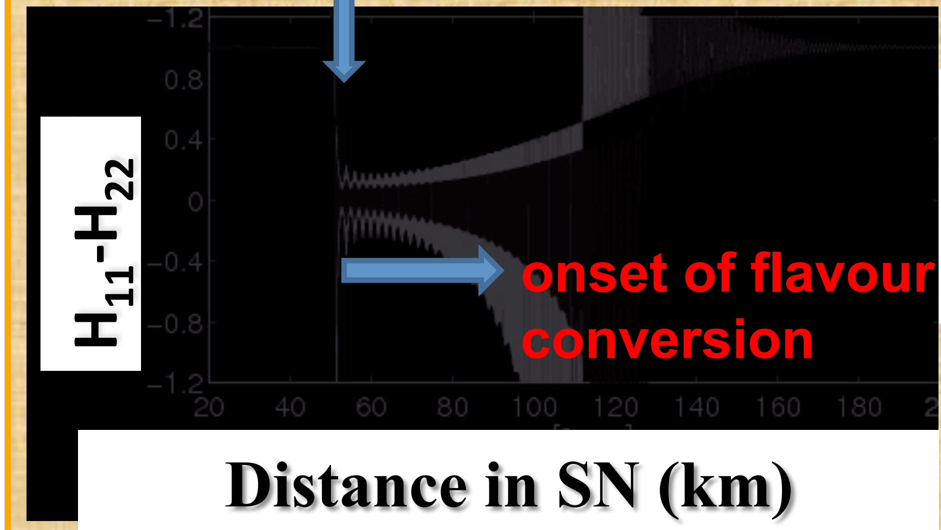
S. Galais, J. P. Kneller , C. Volpe, arXiv: 1102.1471

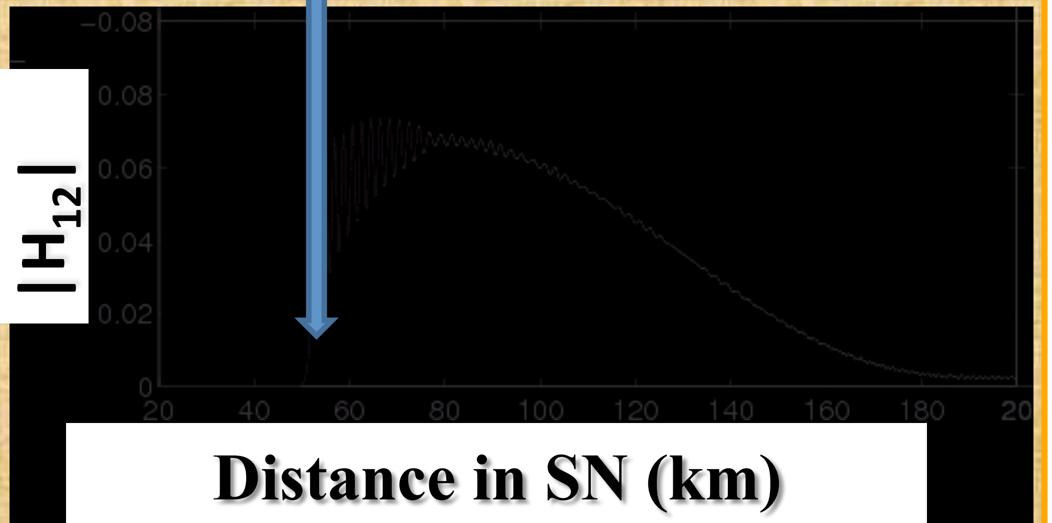
In 2ν flavors the matter Hamiltonian :

$$\tilde{H} = \begin{pmatrix} H_{11} & H_{12} \\ H^*_{12} & H_{22} \end{pmatrix}$$

The phase derivative contributes to diagonal & off-diagonal terms.



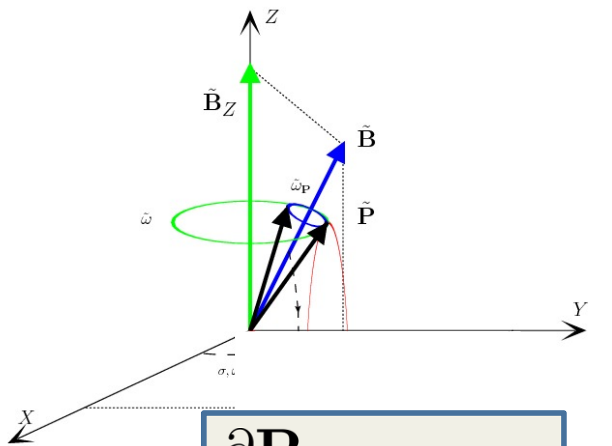




The onset of bipolar oscillations due to a rapid growth of the phase derivative.

Understanding the dynamics using the polarization vector formalism

Polarization vector formalism



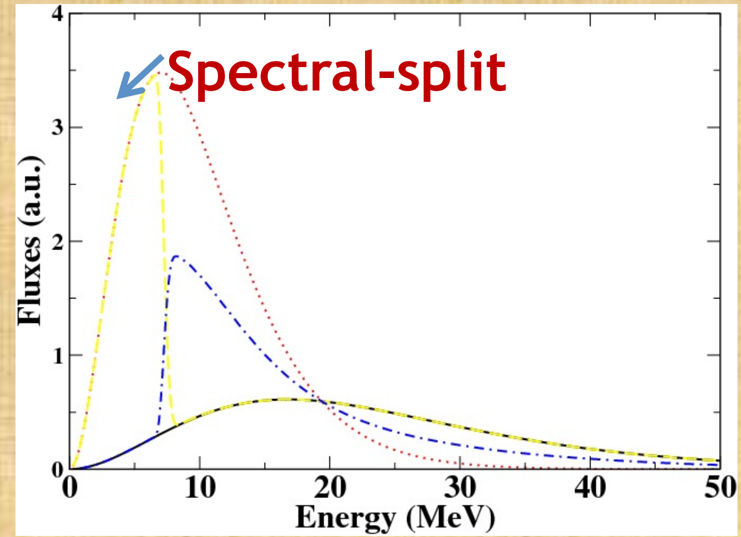
$$\frac{\partial \mathbf{P}}{\partial x} = \mathbf{B} \wedge \mathbf{P}$$

$$\mathbf{B} = \begin{pmatrix} 2\,\mathcal{R}(H_{e\mu}) \\ -2\,\mathcal{I}(H_{e\mu}) \\ H_{ee} - H_{\mu\mu} \end{pmatrix} \qquad \mathbf{P} = \begin{pmatrix} 2\,\mathcal{R}(\psi_e \psi_\mu^*) \\ -2\,\mathcal{I}(\psi_e \psi_\mu^*) \\ |\psi_e|^2 - |\psi_\mu|^2 \end{pmatrix}$$

Example : Flavor basis

The neutrino evolution with the neutrino polarization vectors : the precession of an effective spin around an effective magnetic field.

Many aspects unravelled



Open questions remain, e.g. for the spectral split phenomenon a comprehensive understanding is still missing…

-A flavour pendulum (nutation):
Duan, Fuller, Qian,PRD 74(2006)

-A gyroscopic flavour pendulum (precession and nutation):
Hannestad, Raffelt, Sigl, and Wong,
Phys. Rev. D74, 105010 (2006), 0608695.

- The spectral split as a precession solution :
Duan, Fuller, Qian, PRD76(2007)
Meng and Qian, PRD (2011)

- An adiabatic MSW like evolution in the comoving frame :
Raffelt and Smirnov PRD 76 (2007), PRL 2007

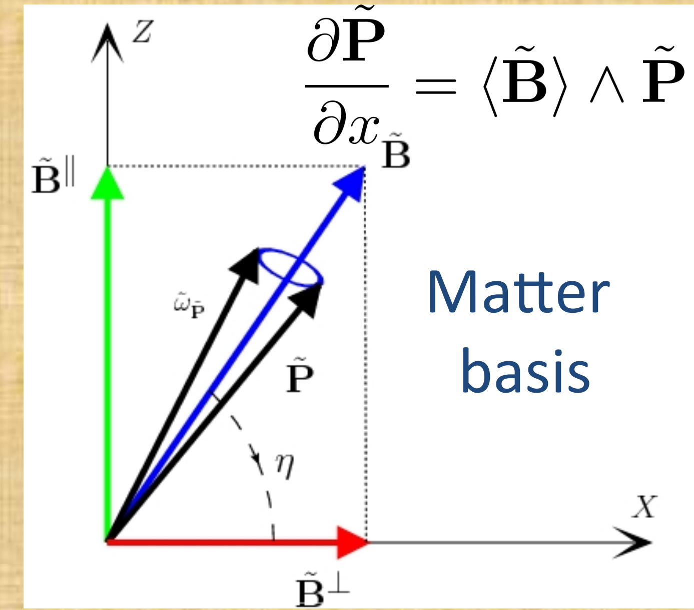
- The extention to three flavours (SU(3)) :
Dasgupta and Dighe PRD (2007)

- There can be single and multiple splits depending on the neutrino flux ratios at the neutrinosphere:
Dasgupta, Dighe, Raffelt, Smirnov, PRL103(2009)
Dasgupta, Mirizzi, Tamborra, Tomas, PRD81 (2010),
Fogli, Lisi, Marrone, Tamborra, JCAP0910(2009)

- It can be described as a system of quasi-particles :
Pehlivan, Balantekin, Kajno, Toshida, arXiv:1105.1182

The spectral split: a magnetic resonance phenomenon

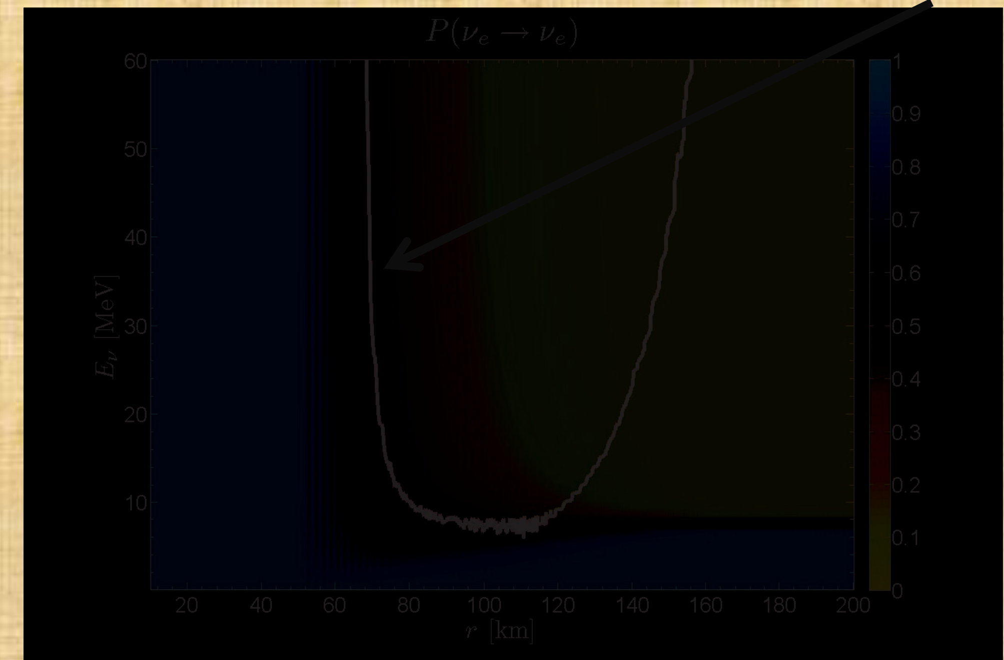
Galais and Volpe, to appear in PRD, arXiv:1103.5302 .

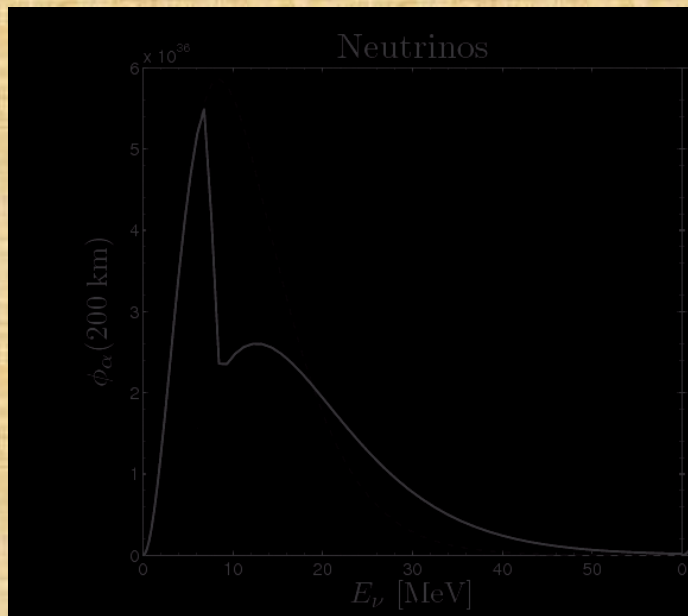


The magnetic resonance phenomenon is the spin inversion occurring when the frequency of the magnetic field in the plane is close to the spin precession frequency around Bz.

The magnetic resonance condition :

$\omega - \omega_0 = 0 \qquad (\omega - \omega_0)/\, \omega_1 << 1$





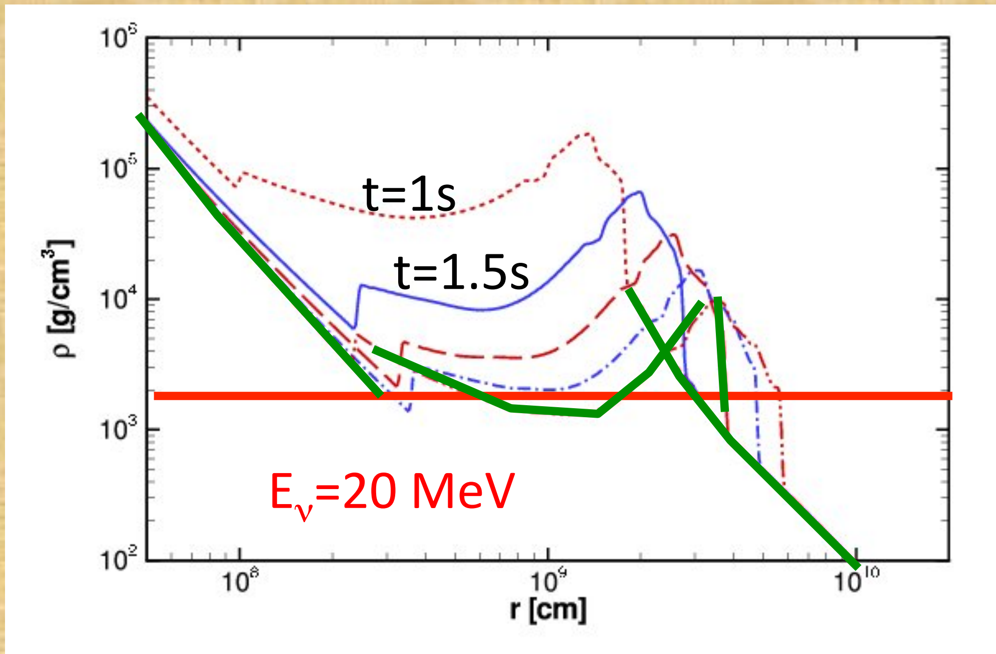
THE MAGNETIC RESONANCE CONDITION IS FULFILLED.

The shock wave effects

Neutrino evolution for a density profile including shoch waves

Schirato and Fuller (2002), arXiv : 0205390.

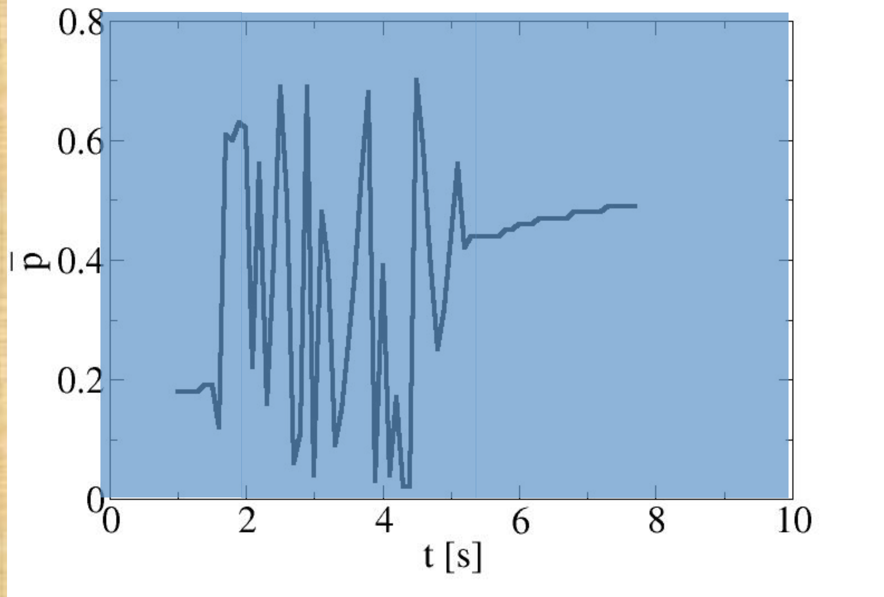
1. Before the shock (adiabatic ν propagation).
2. The shock arrives (non-adiabatic prop.).
3. Phase effects appear.
4. Post-shock propagation.



J. P. Kneller, G. C. McLaughlin, J. Brockman, PRD 77, 045023 (2008).

B. Dasgupta and A. Dighe, Phys. Rev. 75, 093002 (2007), 0510219.

inverted hierarchy, large θ_{13}



S. Galais et al., PRD 81 (2010) 053002, arXiv :0906.5294.

MULTIPLE RESONANCES AND PHASE EFFECTS APPEAR.

CP violation effects in astrophysics and cosmology (BBN epoch)

- **Solar neutrinos**

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

- **Core-collapse 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, PRD 80,053002 (2009) arXiv:0904.3823.

- **Cosmological neutrinos**

  J. Gava, C. Volpe, Nucl. Phys. B (2010), arXiv:1002.0981 .

CP violation and core-collapse SN

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.

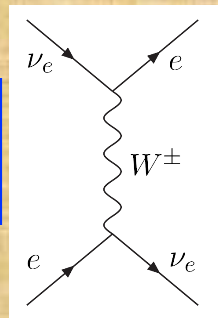
- **We have demonstrated under which conditions there can be CP violating effects in supernovae. Here the main steps :**

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

The neutrino evolution equations in matter are

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

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 effect in 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:

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

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

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 no CP effects, however …

Effects from the Dirac phase in SN

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

The ν propagation Hamiltonian does not factorize any more !

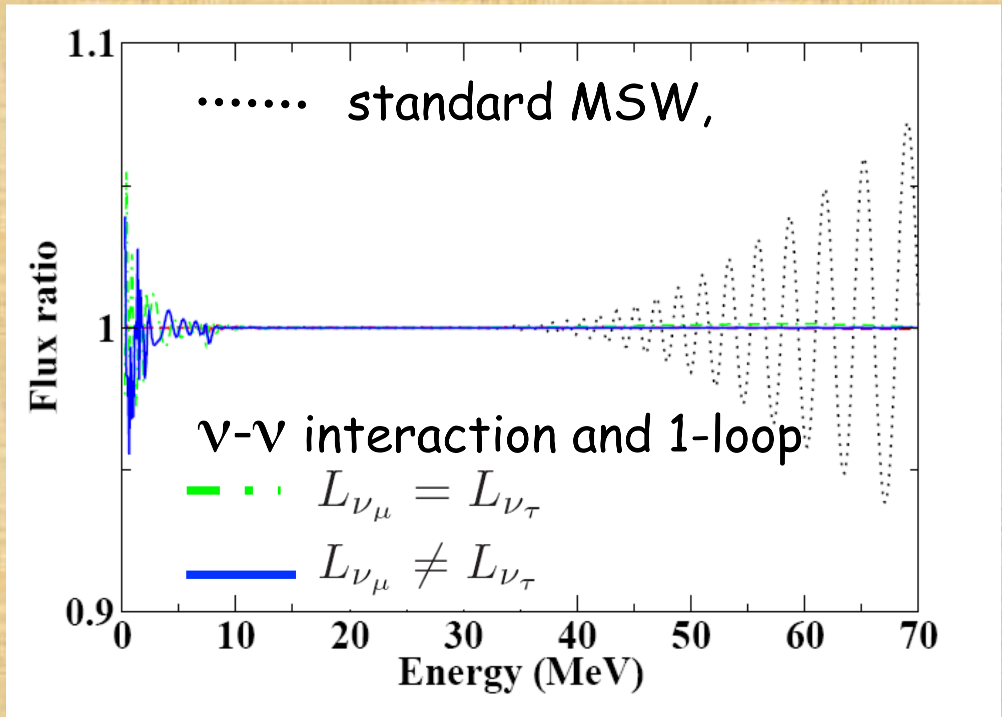
$L_{\nu_\mu} \neq L_{\nu_\tau}$ at the neutrinosphere

<u>In the Standard Model</u> loop corrections for the ν interaction with matter should be included.

<u>Beyond the Standard Model</u> might introduce differences in the ν_μ and ν_τ interaction wiht matter (Flavor Changing Neutral Currents, ...).

THERE CAN BE CP-VIOLATION EFFECTS IN SUPERNOVAE.

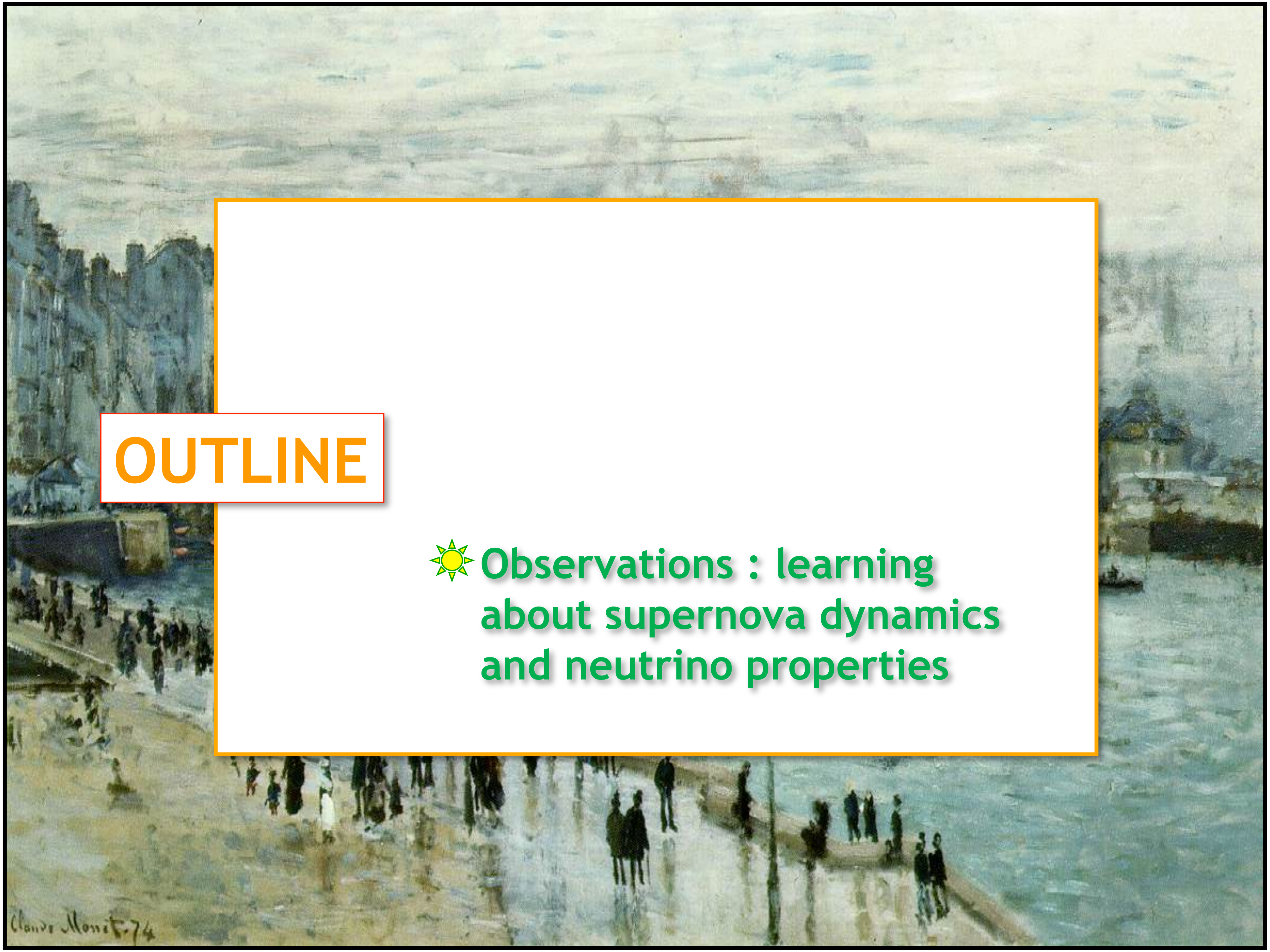
Numerical results



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

EFFECTS OF 5% ON THE ELECTRON NEUTRINO FLUXES.

Further investigations are needed to assess the impact on observations, likely to be small…

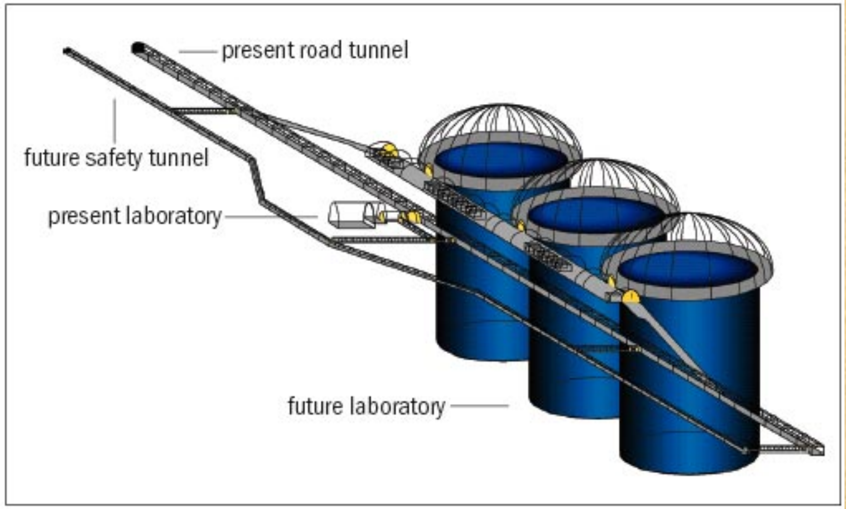


OUTLINE

- Observations : learning about supernova dynamics and neutrino properties

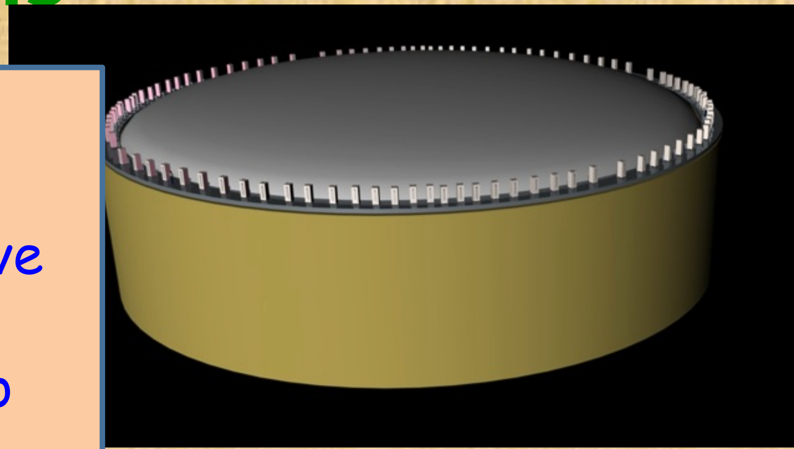
Observations

A SN neutrino signal



THE DSNB

We want to observe the diffuse supernova neutrino background
- Gd-doping and Megaton detectors .



Nucleosynthesis

Neutrinos play a key role in various nucleosynthesis processes, in particular the r-process or the neutrino process.

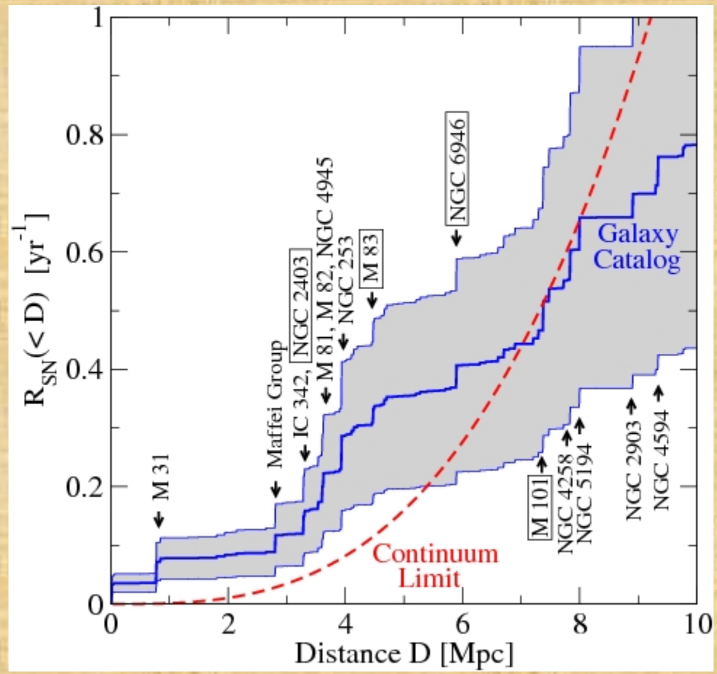
Different observations complementary.

Future SN observations

Several detectors are running (ex. Borexino, Kamland, Super-K,…) .
Large-size detectors are under study : LAGUNA DS, FP7, 2008-2010 and LAGUNA LBNO, 2011-2013).

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

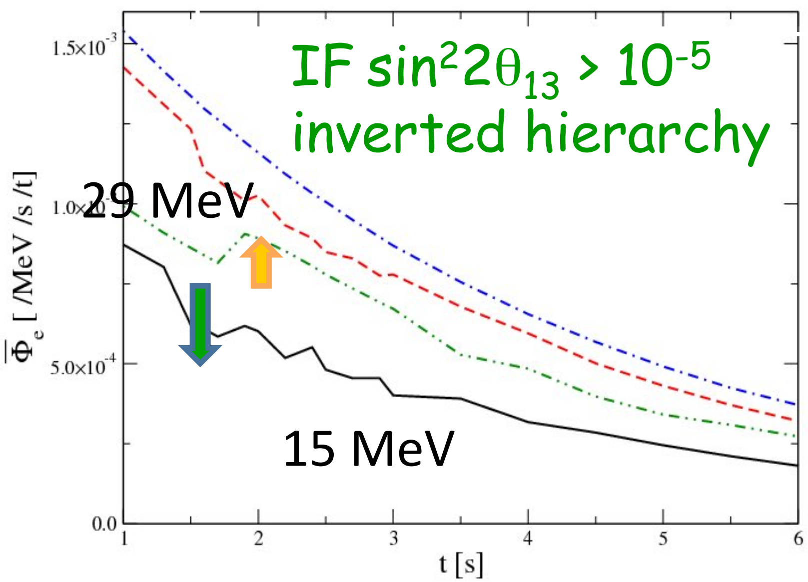
II. To measure the diffuse supernova neutrino background (sensitive to the star formation rate as well).



Ando,Beacom,Yuksel PRL95 (2005)

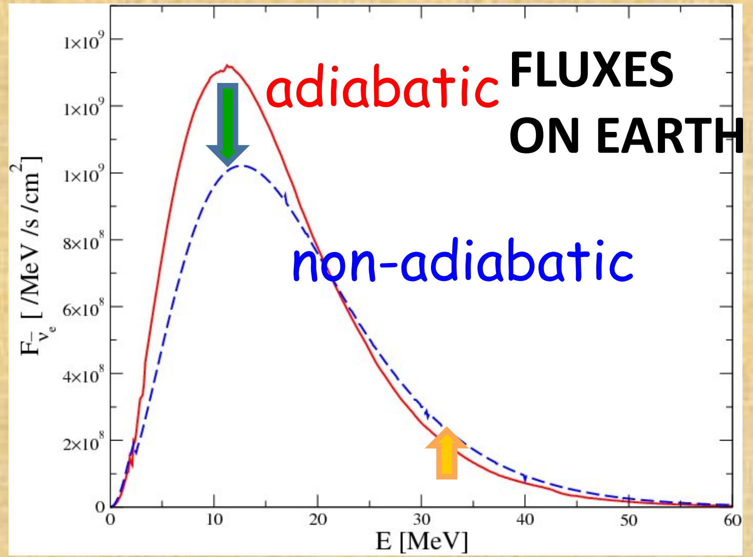
An imprint of the shock on the time signal, depending on ν-properties

$\bar{\nu}_e + p \longrightarrow n + e+$



POSITRON TIME SIGNAL

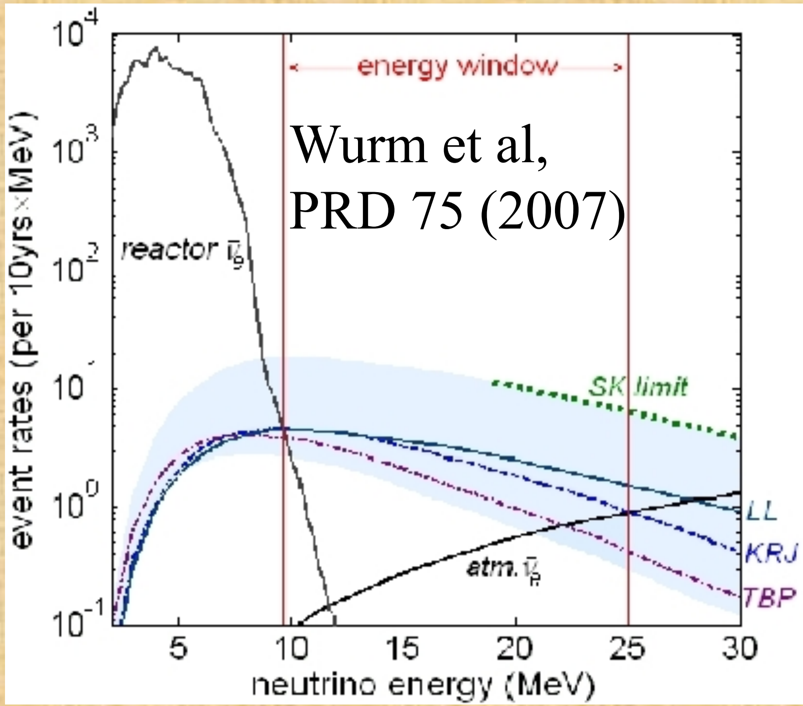
First calculation including the ν-ν interaction and shock wave effects.



Gava, Kneller, Volpe, McLaughlin, PRL 103 (2009), arXiv:0902.0317

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

DSNB event rates in ν-observatories



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Argon detectors (100 kton).

after 10 years

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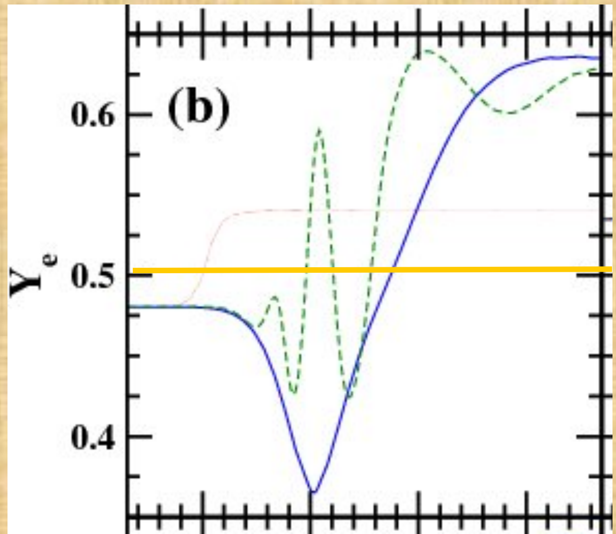
N_{events}	Detection window	L	S
ν_e	17.5-41.5 MeV	**66**	**58**
ν_e	4.5-41.5 MeV	**106**	**96**

S. Galais, J. Kneller, C. Volpe, J. Gava, PRD 81(2010) 053002, arXiv :0906.5294.

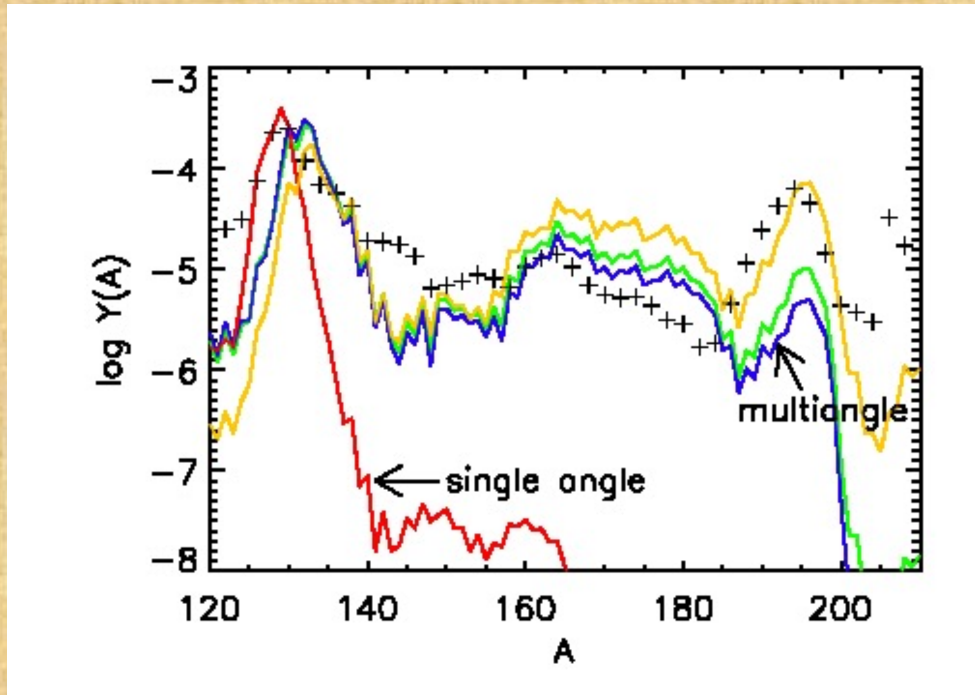
Impact on nucleosynthesis of the $\nu\nu$ int.

Effect on the neutron/proton ratio



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

Chakraborty, Choubey,
Goswami, Kar, JCAP 1006,
007 (2010), arXiv:0911.1218.



Duan, Friedland, McLaughlin, Surman
JPG 38,035201 (2010)

ν_e **detection : ν–nucleus cross sections necessary to determine the supernovae observatories's responses**

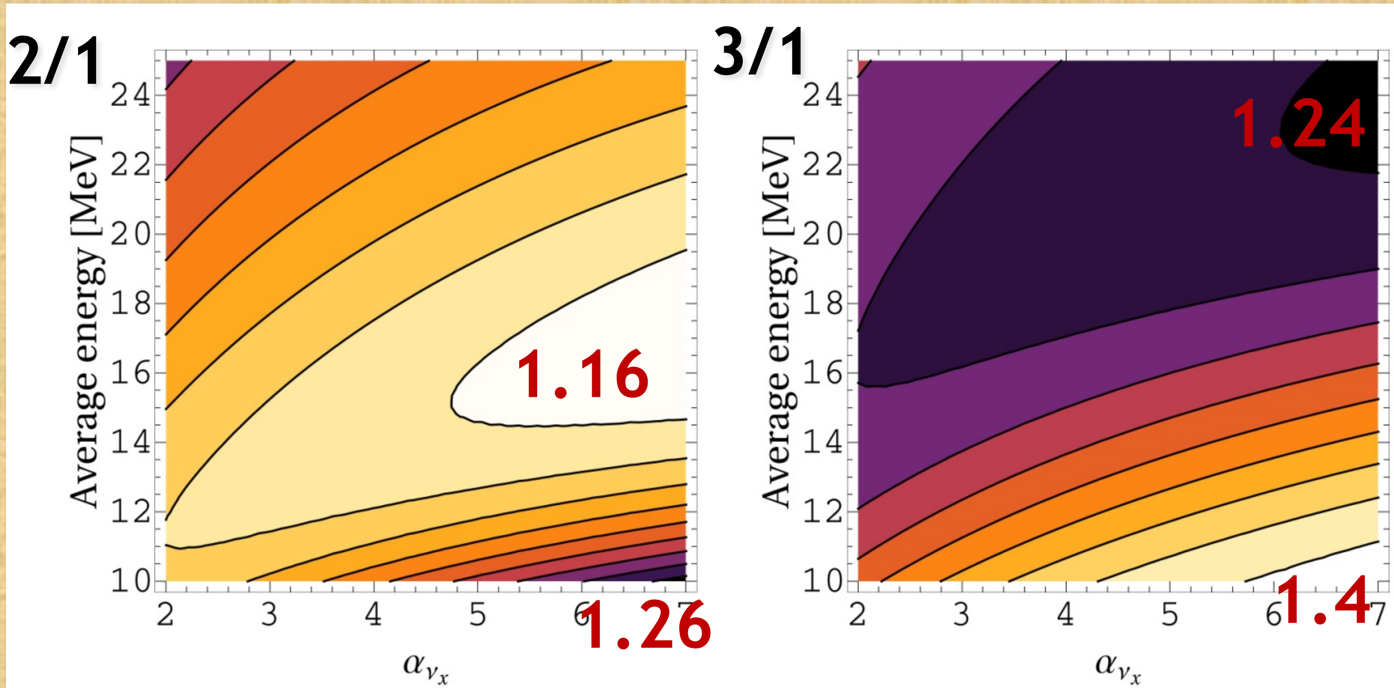
HALO, LENA, GLACIER, MEMPHYS

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

Low energy neutrino-nucleus cross section uncertainties

AN EXAMPLE

Ratio of flux-averaged cross sections



Neutrino-lead calculations used for the comparison:

1- J.Engel, et al. PRD 67, 013005 (2003) RPA

2- E. Kolbe *et al*., PRC 63, 025802 (2001) CRPA

3- N. Paar (priv. communication) relativistic RPA

Neutrino-nucleus cross section measurements welcome…

also useful for double-beta decay (ga, forbidden,…)

POSSIBLE FUTURE INTENSE ν SOURCES

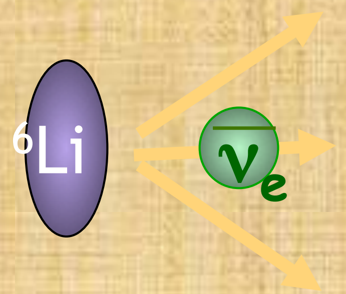
at SPALLATION SOURCES

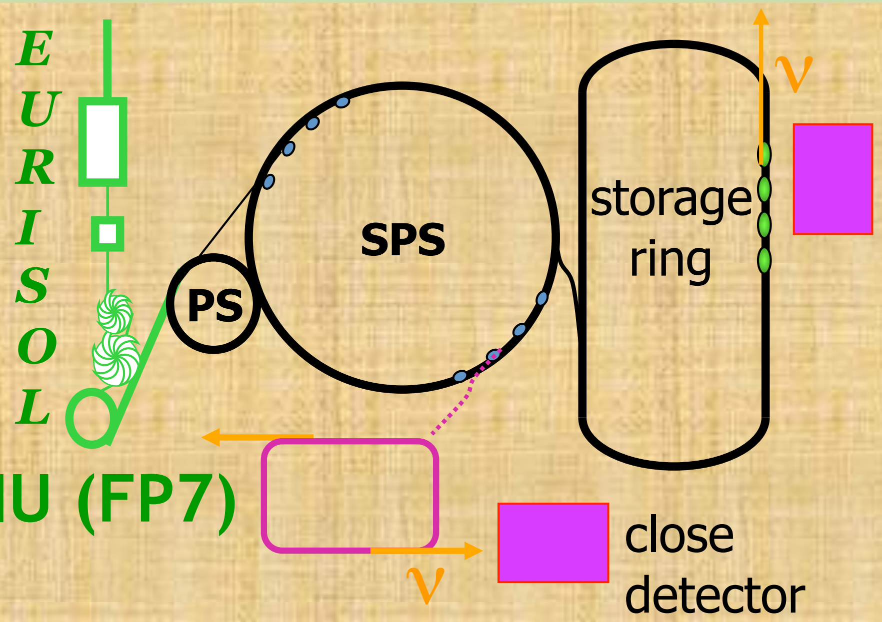
$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \longrightarrow e + \bar{\nu}_\mu + \nu_e$$

Future facilities : SNS, ESS, JSNS, SPL

Low energy BETA-BEAMS C.Volpe, J Phys G 30 (2004) L1.

A proposal to establish a facility for the production of intense and pure low energy neutrino beams in the 100 MeV energy range.





Beta-beam feasibility
EURISOL DS (FP6), EURONU (FP7)

For the next (extra)galactic supernova explosion

and the DSNB discovery

It is very important to have a network of detectors....

- **sensitive** to both **electron anti-neutrinos and** **<u>electron neutrinos</u>**. besides to neutral current.
- **with** very **different energy thresholds,** in particular for the ν_e : argon-based (5 MeV), lead-based (10, 20 MeV), scintillators and Cherenkov (about 20 MeV).
- with good **time resolution or time and energy resolution**.
- **at least one large size** (megaton) detector.

Conclusions and Perspectives

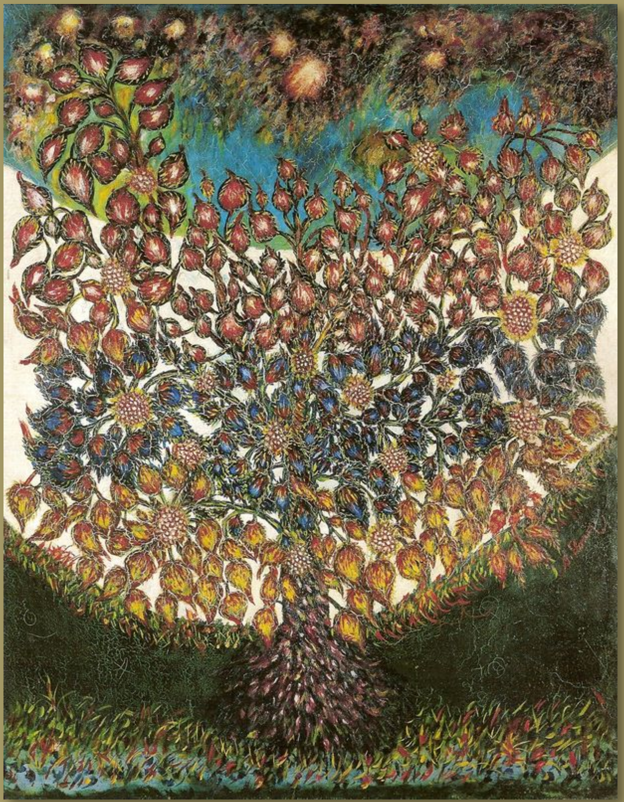
Supernova explosion on the way…
Neutrino flavour conversion processes
in such explosive media has really
increased in complexity.

The SN neutrino fluxes encode
information on ν–properties
and supernova dynamics :
A lot to learn from future observations !

Danke.

Gracias

Thank you



Grazie

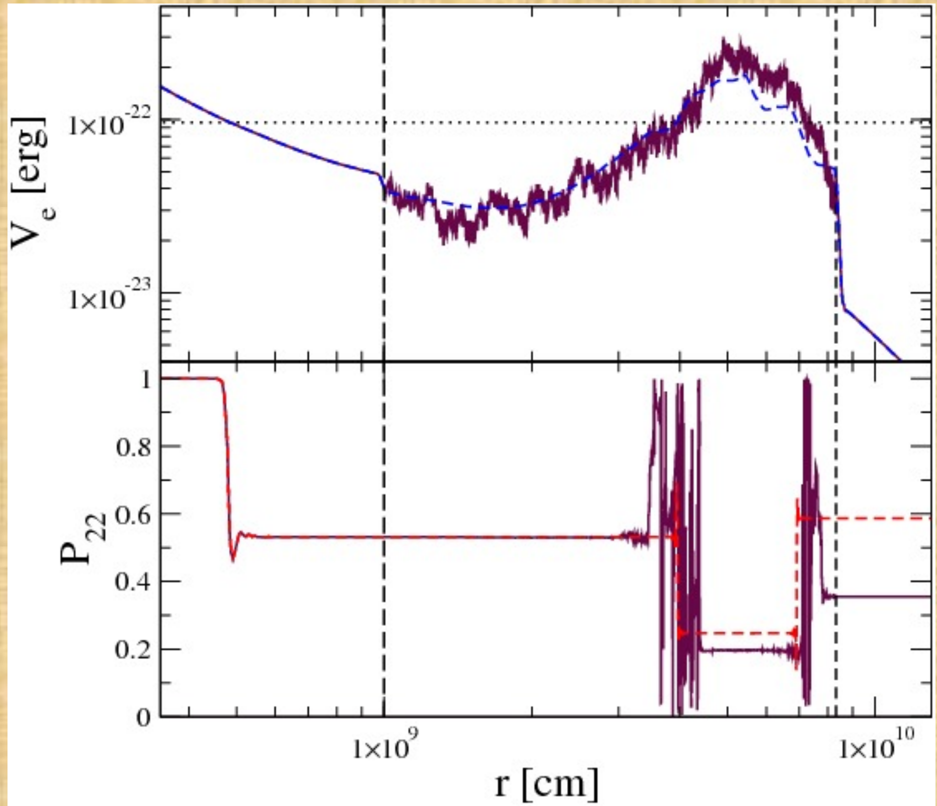
Life tree

Merci

Turbulence effects

Loreti et al, PRD 52 (1995); Balantekin et al, PRD 54 (1006); Friedland and Gruzinov, hep/0607244, Fogli et al JCAP 0606 (2006);. Kneller arXiv: 1004.1288.

Calculation of instantations of the neutrino amplitudes- not of average probabilities - in presence of shock waves and turbulence.



NEUTRINOS CAN COMPLETELY MIX («depolarize »).

TRANSITION FROM shock-wave to turbulence dominated regime, as the fluctuation amplitude increases.

Kneller and Volpe, PRD (2010) , arXiv: 1006.0913 .

The HALO project

80 tonnes of Pb, HALO-2: 1kt

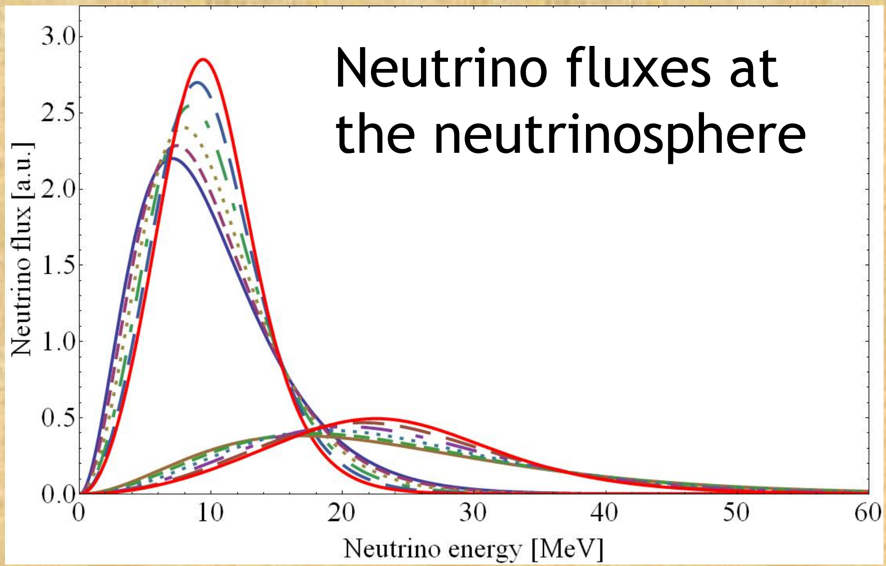
$$\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Bi} + \mathrm{n} + \mathrm{e}^-$$

$$\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Bi} + 2\mathrm{n} + \mathrm{e}^-$$

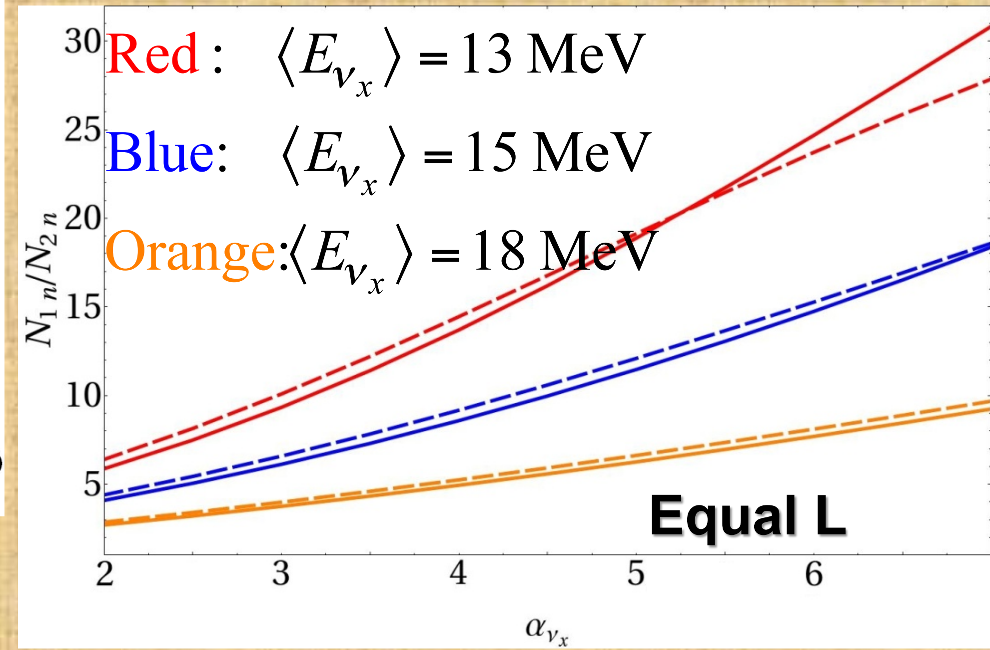
$$\nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Bi} + \mathrm{n}$$

$$\nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Bi} + 2\mathrm{n}$$

Information on the fluxes at the neutrinosphere can be extracted : a test of SN simulations



C. Volpe et, D. Vaananen to appear.



Important to have different energy thresholds.

The role of the matter phase (derivative)

S. Galais, J. P. Kneller , C. Volpe, a

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since the
hamilton
off-diago

In 2ν flavors the U matrix in matter :

$$\tilde{U} = \begin{pmatrix} 1 & 0 \\ 0 & e^{\imath\tilde{\beta}} \end{pmatrix} \begin{pmatrix} \cos\tilde{\theta} & \sin\tilde{\theta} \\ -\sin\tilde{\theta} & \cos\tilde{\theta} \end{pmatrix}$$

matter phase

matter angle

The ν evolution equation

$$\imath\frac{\partial\tilde{\psi}}{\partial x} = \tilde{H}\ \tilde{\psi} = \left(\tilde{K} - \imath\tilde{U}^{\dagger}\frac{\partial\tilde{U}}{\partial x}\right)\tilde{\psi}$$

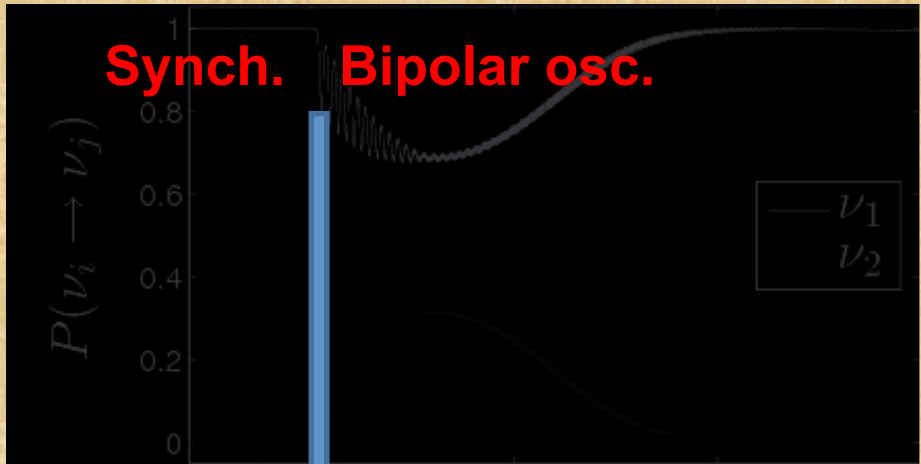
It involves the derivative of the matter phase.

$$\tilde{H} = \begin{pmatrix} H_{11} & H_{12} \\ H^{*}_{12} & H_{22} \end{pmatrix}$$

The phase derivative contributes to diagonal & off-diagonal terms.

The matter basis point of view : the phase derivative role

S. Galais, J. P. Kneller , C. Volpe, arXiv: 1102.1471



In 2ν flavors the matter Hamiltonian :

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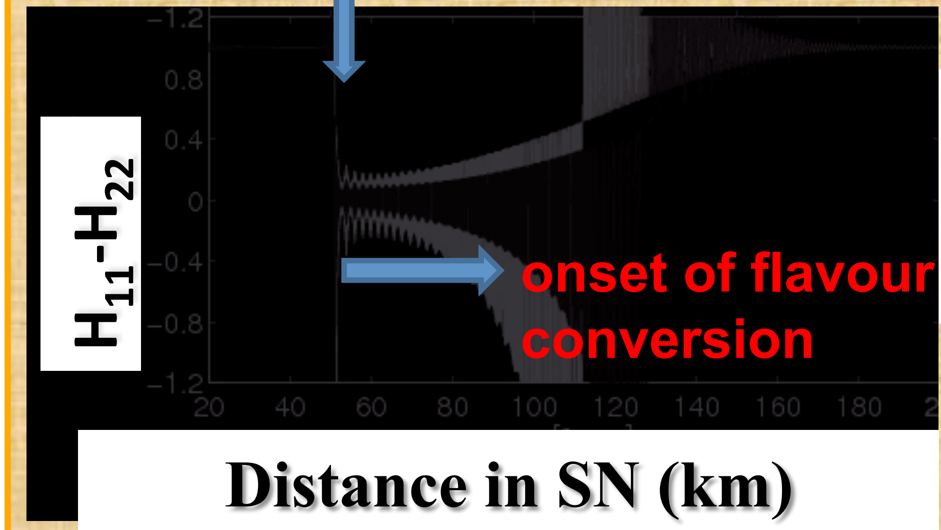
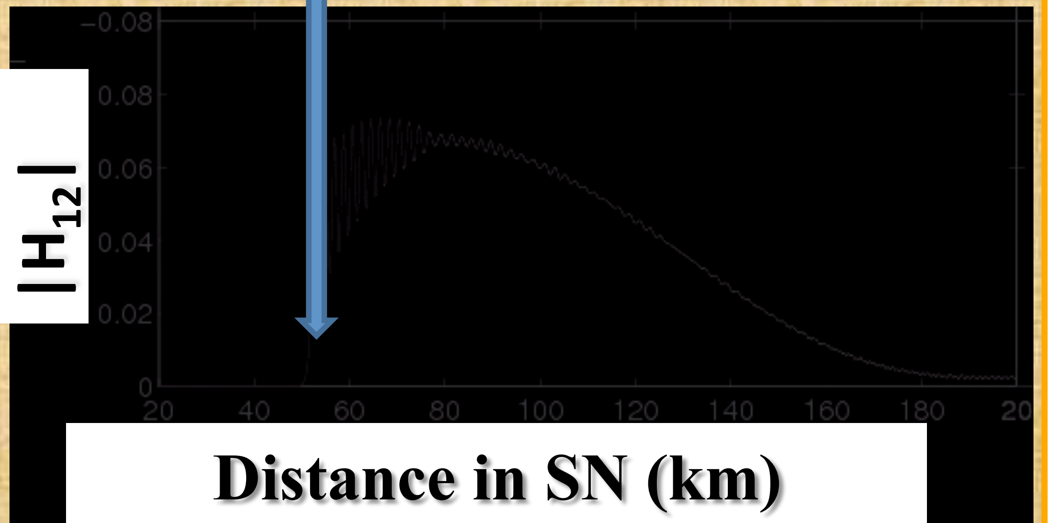




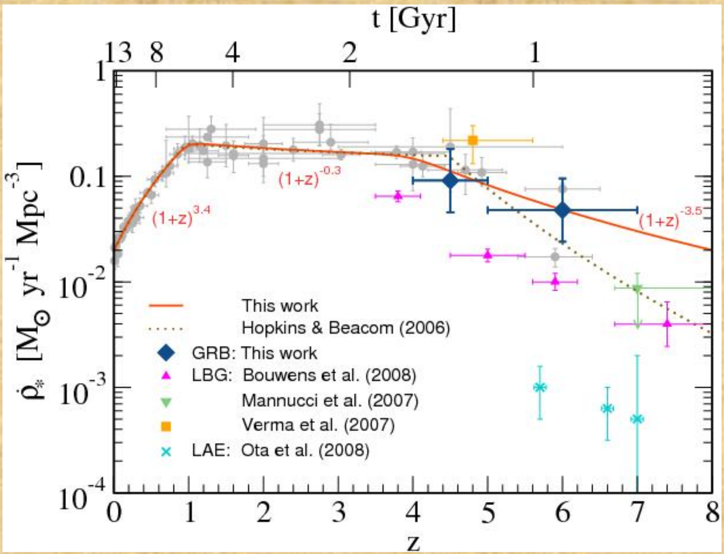
The onset of bipolar oscillations due to a rapid growth of the phase derivative.

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

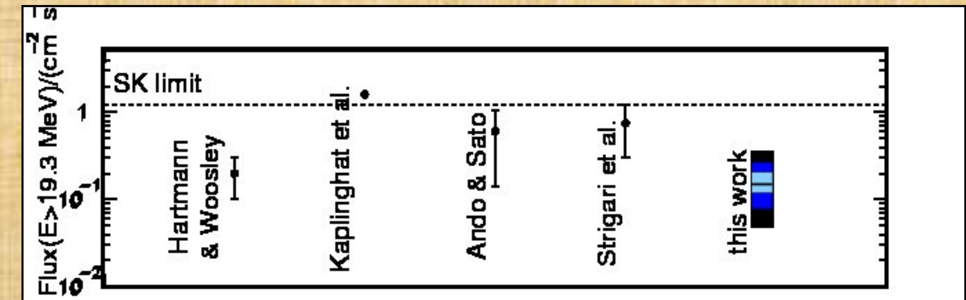
6.8 10^3 ν_e cm^{-2} s^{-1} from LSD (25 < $E_{\nu e}$ < 50 MeV) Aglietta et al. A Phys 1 (1992)



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).

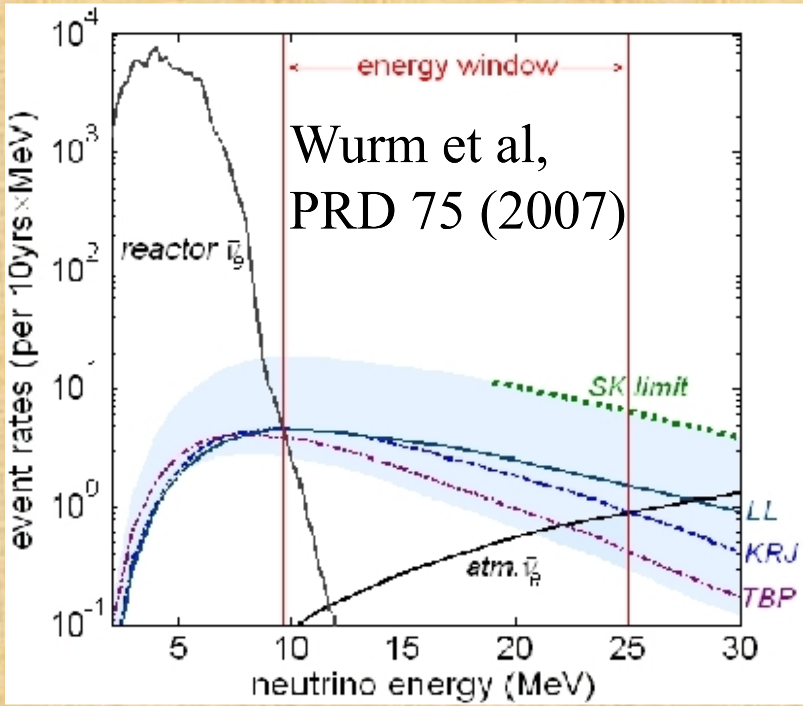
Yuksel, et al Astrophys. J.683, L5(2008).



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

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

DSNB event rates in ν-observatories



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Argon detectors (100 kton).

after 10 years

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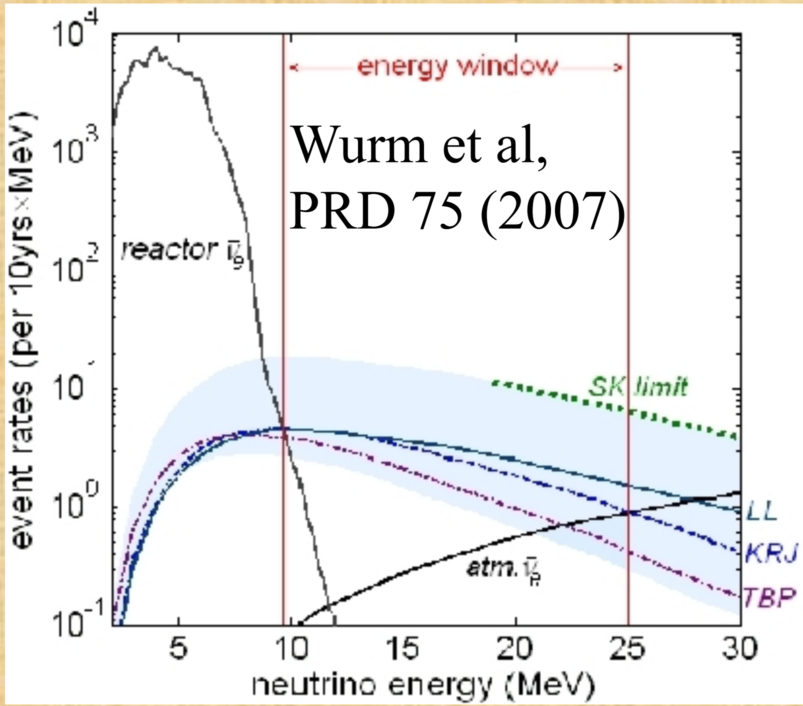

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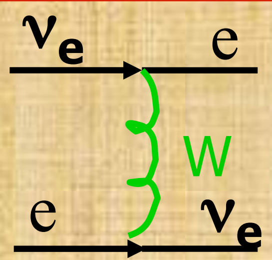
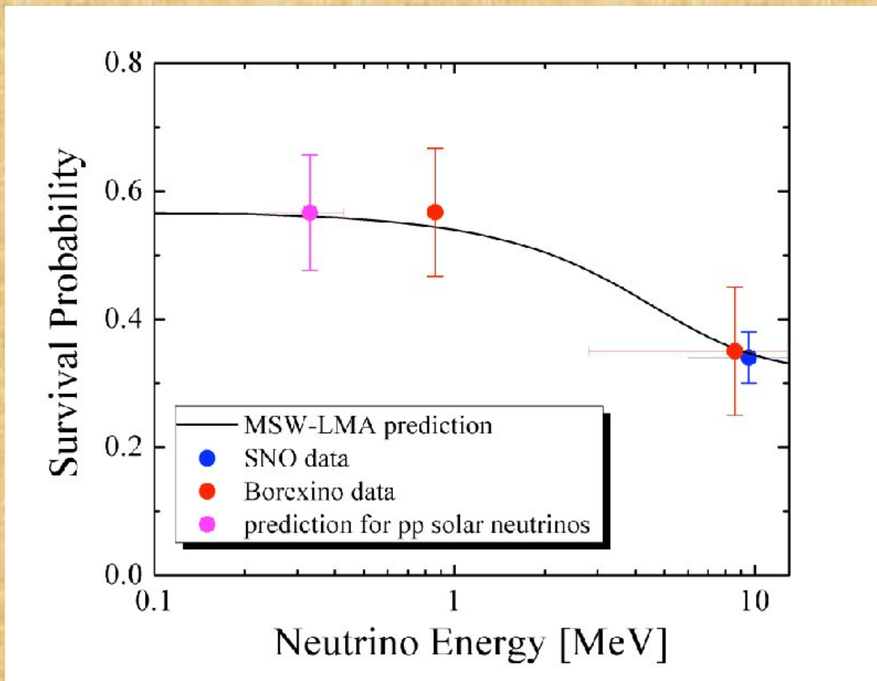
The Mikheev-Smirnov-Wolfenstein effect



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

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



The flavour conversion depends on the adiabaticity of the propagation at the resonance (density profile and mixing parameters).

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

Borexino Collaboration, J. Conf. Ser. 202, 012028 (2010)