# Neutrino astrophysics

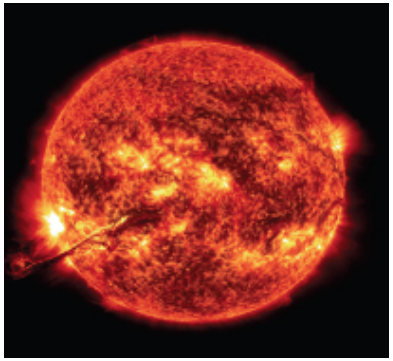
Maria Cristina VOLPE

AstroParticule et Cosmologie (APC)
Paris, FRANCE

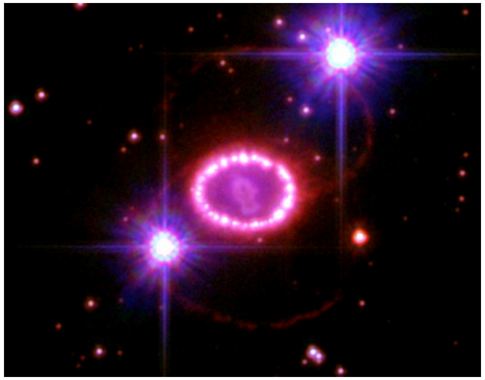
# Outline

- Introduction
- Theoretical aspects of flavor evolution, recent developments and open issues
- Observational aspects of supernova $\nu$
- Flavor evolution in binary neutron star merger (BNS) remnants
- Conclusions

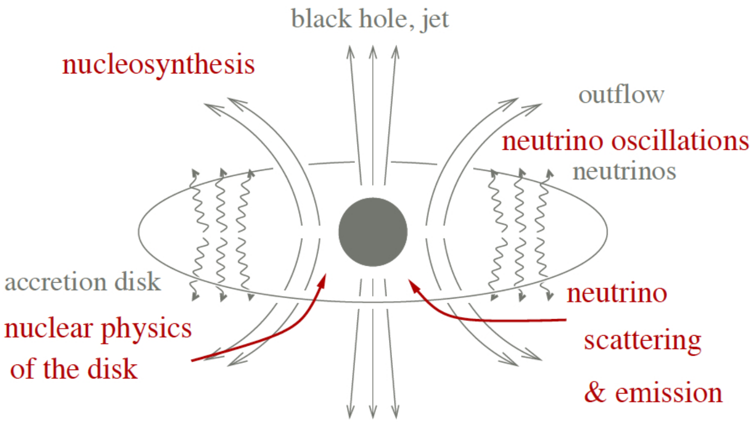
## the Sun



## core-collapse Supernovae

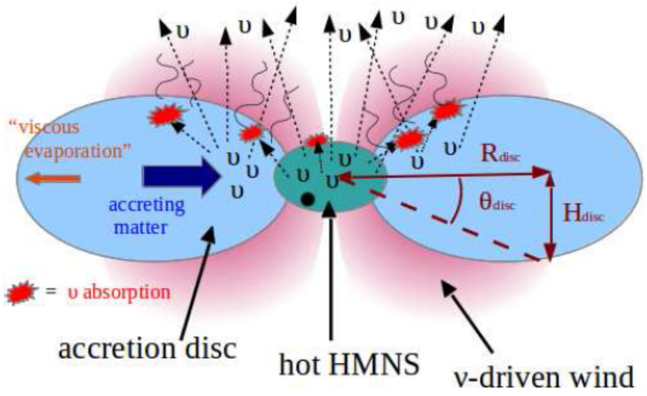


## accretion disks around black holes




from McLaughlin

## or neutron star mergers remnants

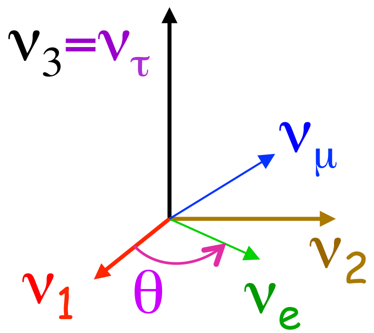



from Perego, A. 2014

# The oscillation phenomenon in vacuum

Neutrino oscillations occur if the neutrino interaction and propagation basis do not coincide, analogy with $K_0$-$\overline{K_0}$ systems.

Pontecorvo JETP 6 (1957)

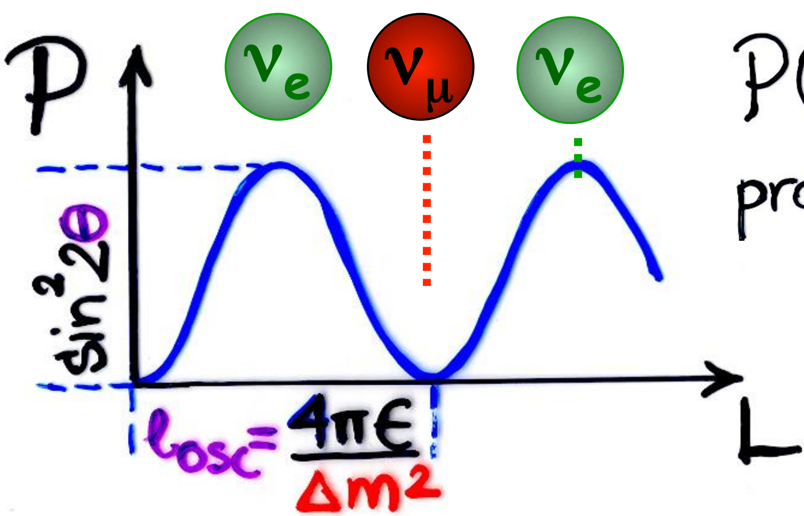



$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

flavour basis — mixing angle — mass basis

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

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

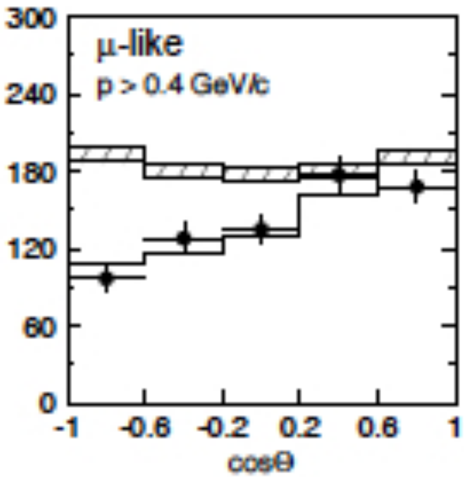



$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta \sin^2\left(\frac{L}{4E}\Delta m^2\right)$$

probability for neutrino oscillations

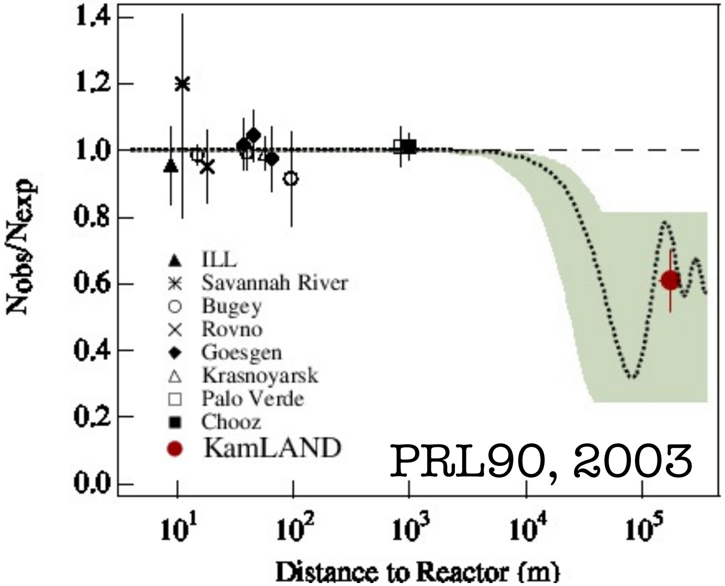
AN INTERFERENCE PHENOMENON

# The neutrino oscillation discovery


Neutrinos : elementary massive particles with non-zero mixings

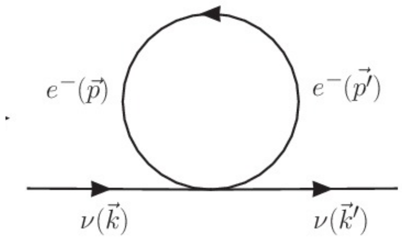

Total solar neutrino flux consistent with Standard Solar Model




Mikheev-Smirnov-Wolfenstein large-mixing-angle solution

# The Mikheev-Smirnov-Wolfenstein effect

Resonant flavour conversion due to ν-matter interactions



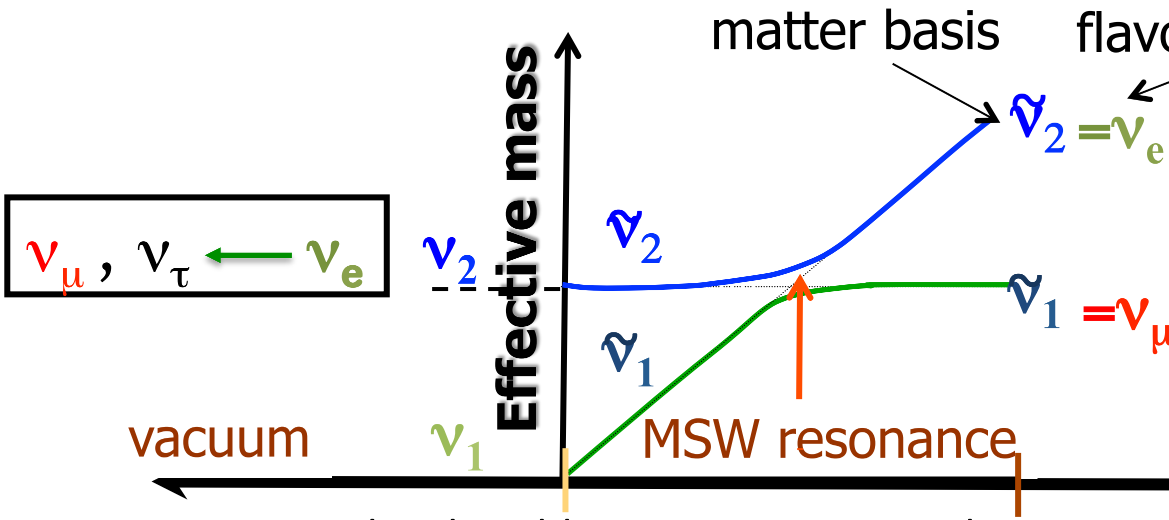

$$H_{\nu_e}(\rho_e) = \sqrt{2} G_F \, \rho_e$$

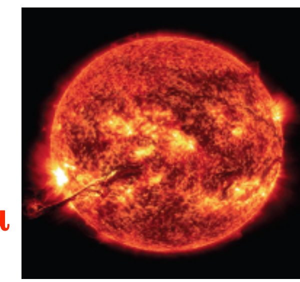
MEAN-FIELD

electron number density

Wolfenstein PRD (1978)

Mikheev, Smirnov(1985)



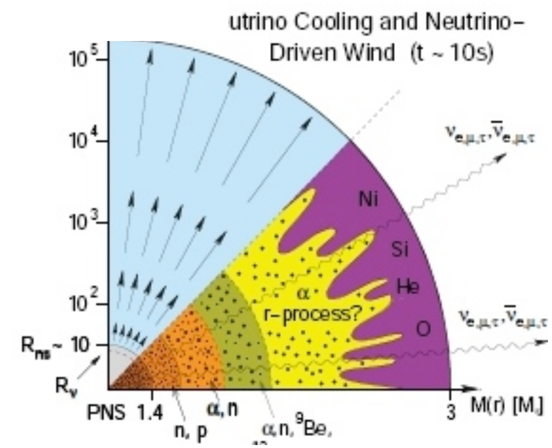



Two level problem in quantum mechanics

In the Sun : evolution through the resonance adiabatic, sign of one of the $\Delta m^2$ determined

Also in supernovae, in accretion disks around compact objects, in the Earth and in the Early Universe (BBN epoch)

# Neutrinos in dense environments



Janka 07

Linked to the key issues

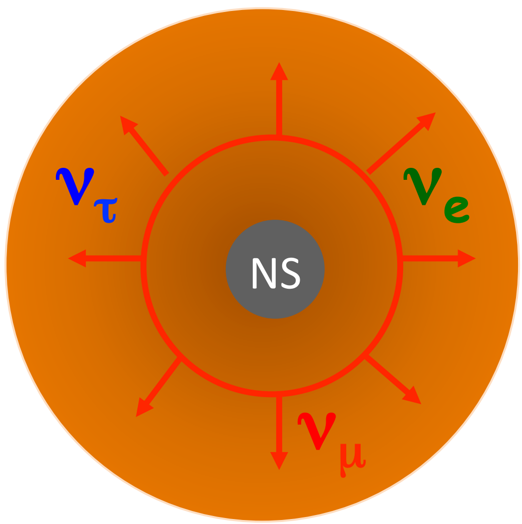
- **How do massive stars explode ?**
  Current simulations :
  multidimensional, realistic ν transport,
  convection and turbulence, hydrodynamical instabilities (SASI).

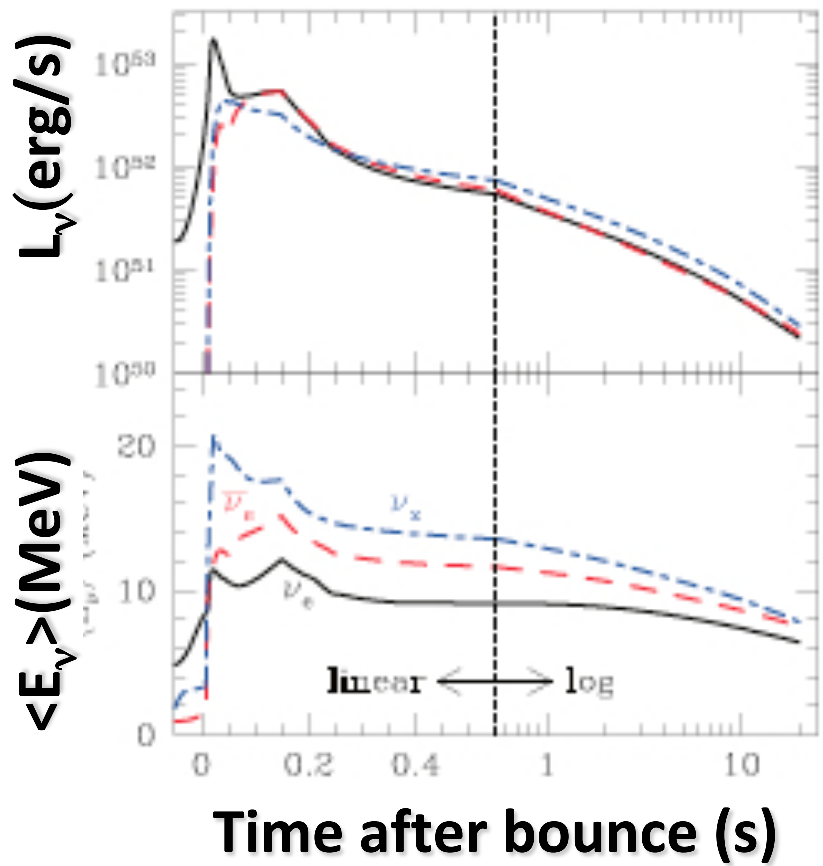
- **What are the sites where heavy elements are made ?**
  Candidate sites for heavy elements nucleosynthesis :
  supernovae, accretion disks around compact objects (BH, NS-NS, BH-NS)

see e.g. Focus issue «Nucleosynthesis and the role of neutrinos»,
J.Phys. G 41 (2014)

# Neutrinos from gravitational core-collapse

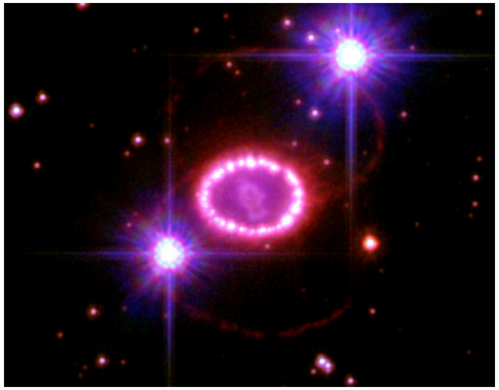
99 % of the gravitational energy ($10^{53}$ ergs) is radiated as neutrinos and anti-neutrinos of all flavours.

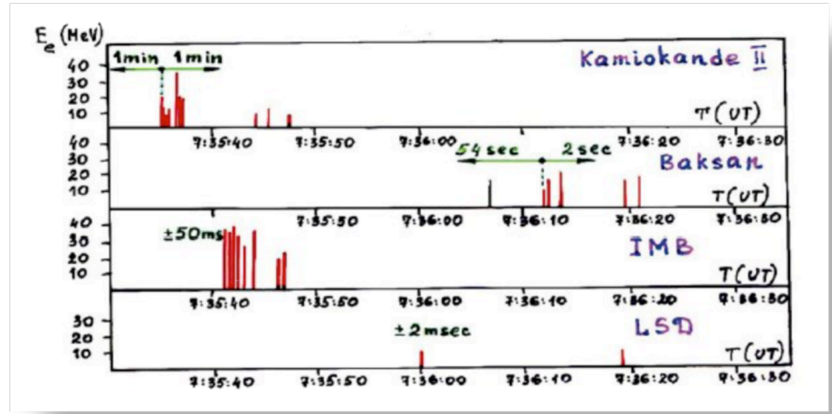



Nakazato et al, arXiv : 1210.6841

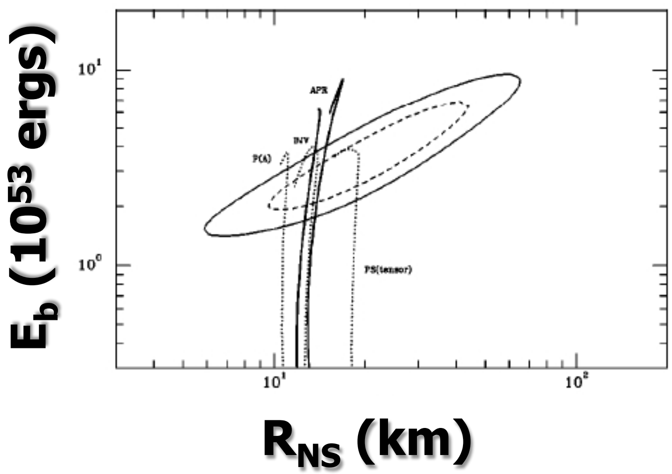
# SN1987A



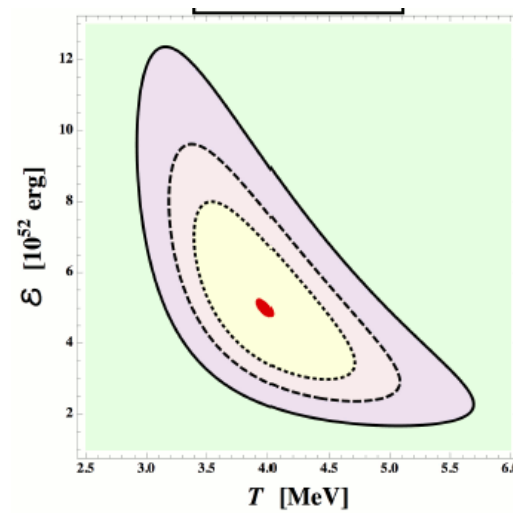



Suzuki, A. J. Conf. Phys. 120 (2008)

Sanduleak 69$^0$202, a blue super-giant in Large Magellanic Cloud, at 50 kpc, no remnant found so far. Hirata et al, PRL58(1987)




Loredo, Lamb, PRD65 (2002)

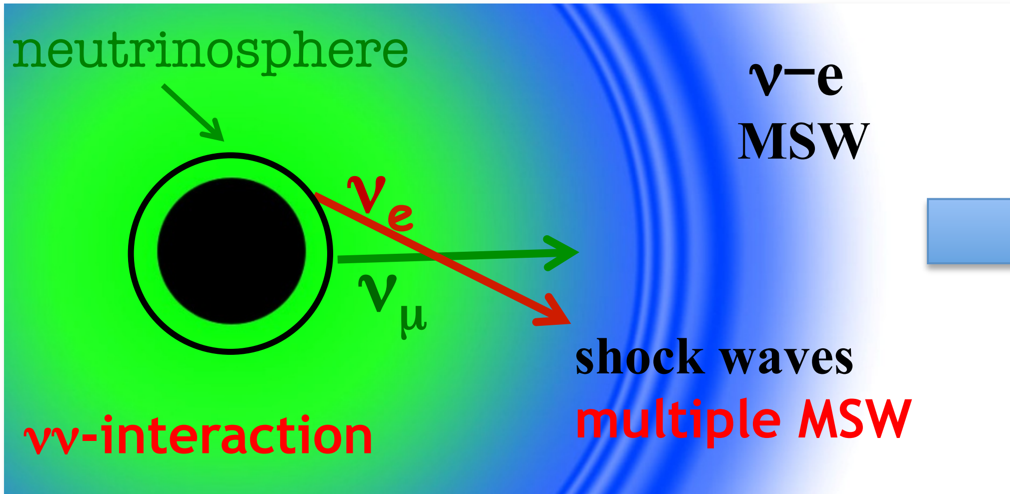


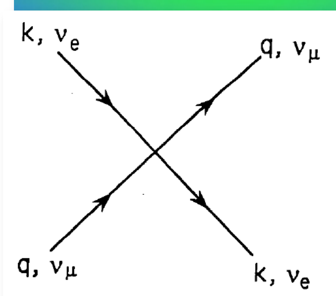

Vissani, JPG42 (2014)

SN1987A : Delayed explosion mechanism favored over the prompt one.

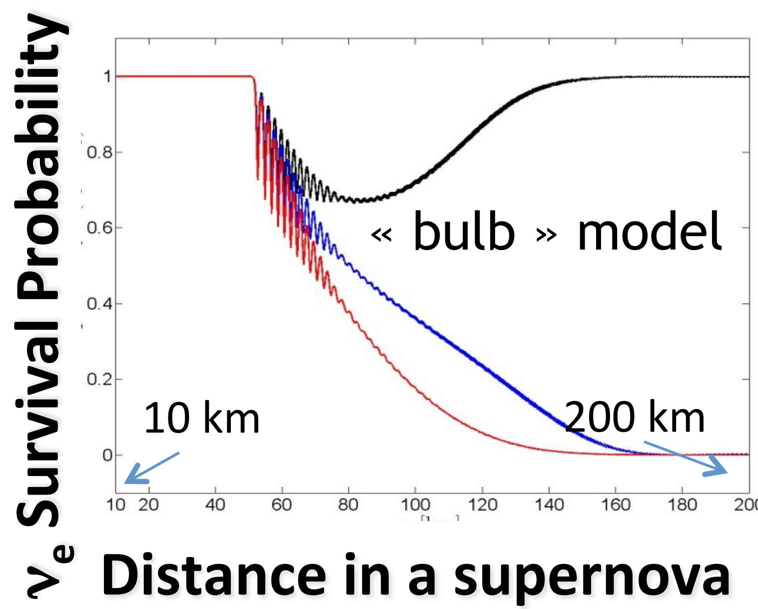
# Flavor conversion in supernovae

Novel phenomena uncovered



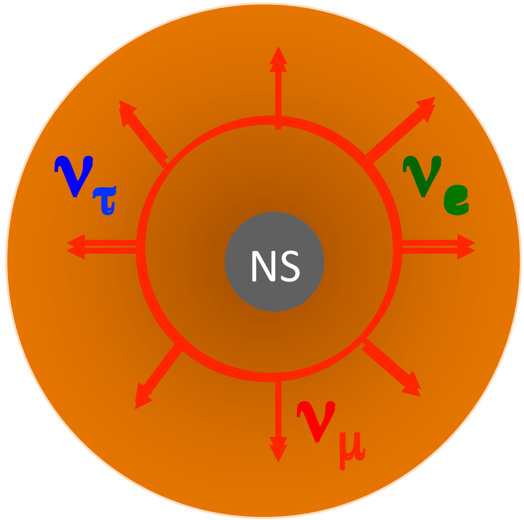

Pantaleone, PLB 1992



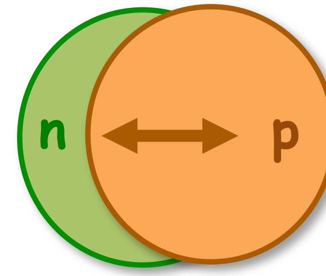

- Efficient conversion occurs close to the neutrinosphere

Models of increasing complexity studied since a decade

Duan, Fuller, Qian, Ann. Rev. 60 (2010)




$\nu$ in stars or accretion disks




atomic nucleus

| | | |
|---|---|---|
| $10^{57}$ | **N** | 200 |
| weak | **interaction** | strong |
| unbound | **system** | bound |
| $\rho_{ji} = \langle a_i^+ a_j \rangle$ neutrinos<br>$\bar{\rho}_{ji} = \langle b_i^+ b_j \rangle$ anti-neutrinos | **density** | $\rho = \langle a^+ a \rangle$ neutrons protons |

Neutrino flavor evolution in dense environments :
a many-body problem

To determine the dynamics exactly:

$\rho_1 = \langle a^+ a \rangle$ one-body density

$\rho_{12} = \langle a^+ a^+ a a \rangle$ two-body

$\rho_{123} = \langle a^+ a^+ a^+ a a a \rangle$ three-body

... N-body

# To determine the dynamics exactly:

$\rho_1 = \langle a^+ a \rangle$ one-body density

$\rho_{12} = \langle a^+ a^+ a a \rangle$ two-body

$\rho_{123} = \langle a^+ a^+ a^+ a a a \rangle$ three-body

... N-body

$$i\dot{\rho}_1 = [t_1, \rho_1] + \mathrm{Tr}_{(2)} \{[v_{12}, \rho_{12}]\}$$

$$i\dot{\rho}_{12} = [t_1 + t_2 + v_{12}, \rho_{12}] + \mathrm{Tr}_{(3)} \{[v_{13} + v_{23}, \rho_{123}]\}$$

$$\vdots$$

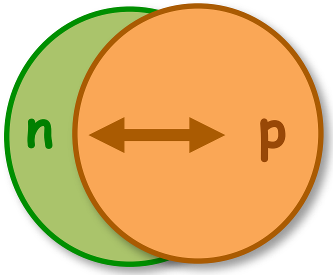
$$i\dot{\rho}_{1\cdots n} = \left[\sum_{i=1}^{n} t_i + \sum_{j>i=1}^{n} v_{ij}, \rho_{1\cdots n}\right] + \sum_{i=1}^{n} \mathrm{Tr}_{(n+1)} \left\{\left[v_{i(n+1)}, \rho_{1\cdots(n+1)}\right]\right\}$$

H = t + v

Hamiltonian

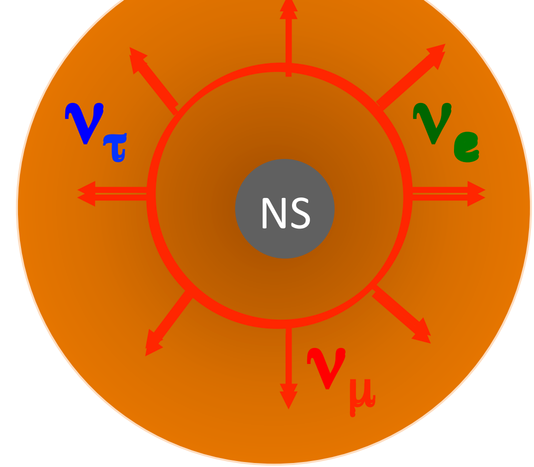
**Born-Bogoliubov-Green-Kirkwood-Yvon (BBGKY) hierarchy**

an infinite set of equations for a relativistic system



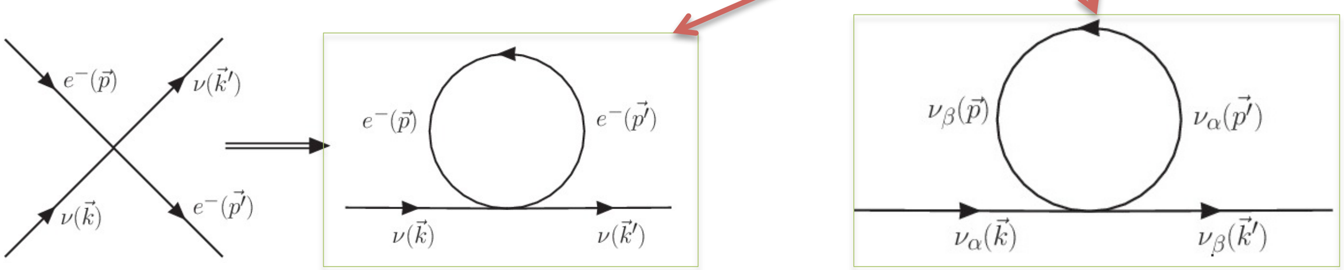

# To determine the dynamics

$\rho = \langle a^{+} a \rangle$ one-body density matrix




$$i\dot{\rho} = [h(\rho), \rho]$$

$$h(\rho) = h_0 + h_{mat} + h_{\nu\nu}(\rho)$$




neutrino-matter

$$h_{mat} = \sqrt{2} G_F \, \rho_e$$

neutrino self-interactions

non-linear term

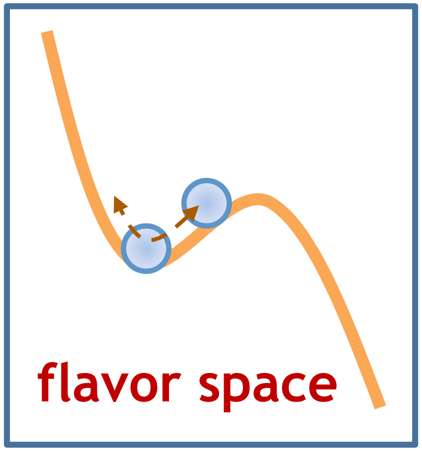
MEAN-FIELD approximation

**BBGKY hierarchy : mean-field and beyond**

Volpe, Väänänen, Espinoza. PRD 87 (2013)

– see Volpe, «Neutrino quantum kinetic equations », Int. J. Mod. Phys.E24(2015)

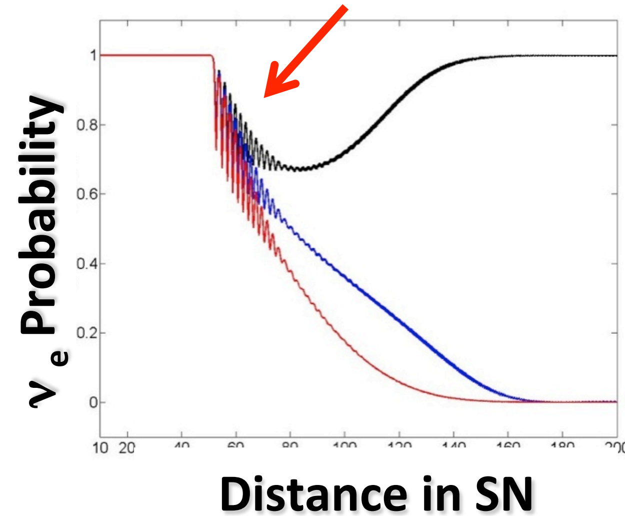
# Collective neutrino modes and linearization




**Small amplitude motion**

Collective modes and instabilities can be studied with the linearization.

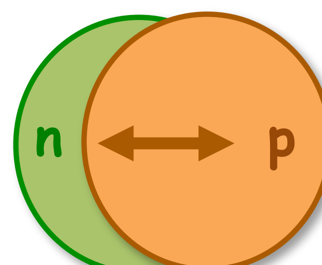
Banerjee, Dighe, Raffelt, PRD84 (2011)




Stability matrix

$$\begin{pmatrix} A & B \\ \bar{B} & \bar{A} \end{pmatrix} \begin{pmatrix} \rho' \\ \bar{\rho}' \end{pmatrix} = \omega \begin{pmatrix} \rho' \\ \bar{\rho}' \end{pmatrix}$$

S eigenvalues :
-> real : stable collective
-> imaginary : instabilities

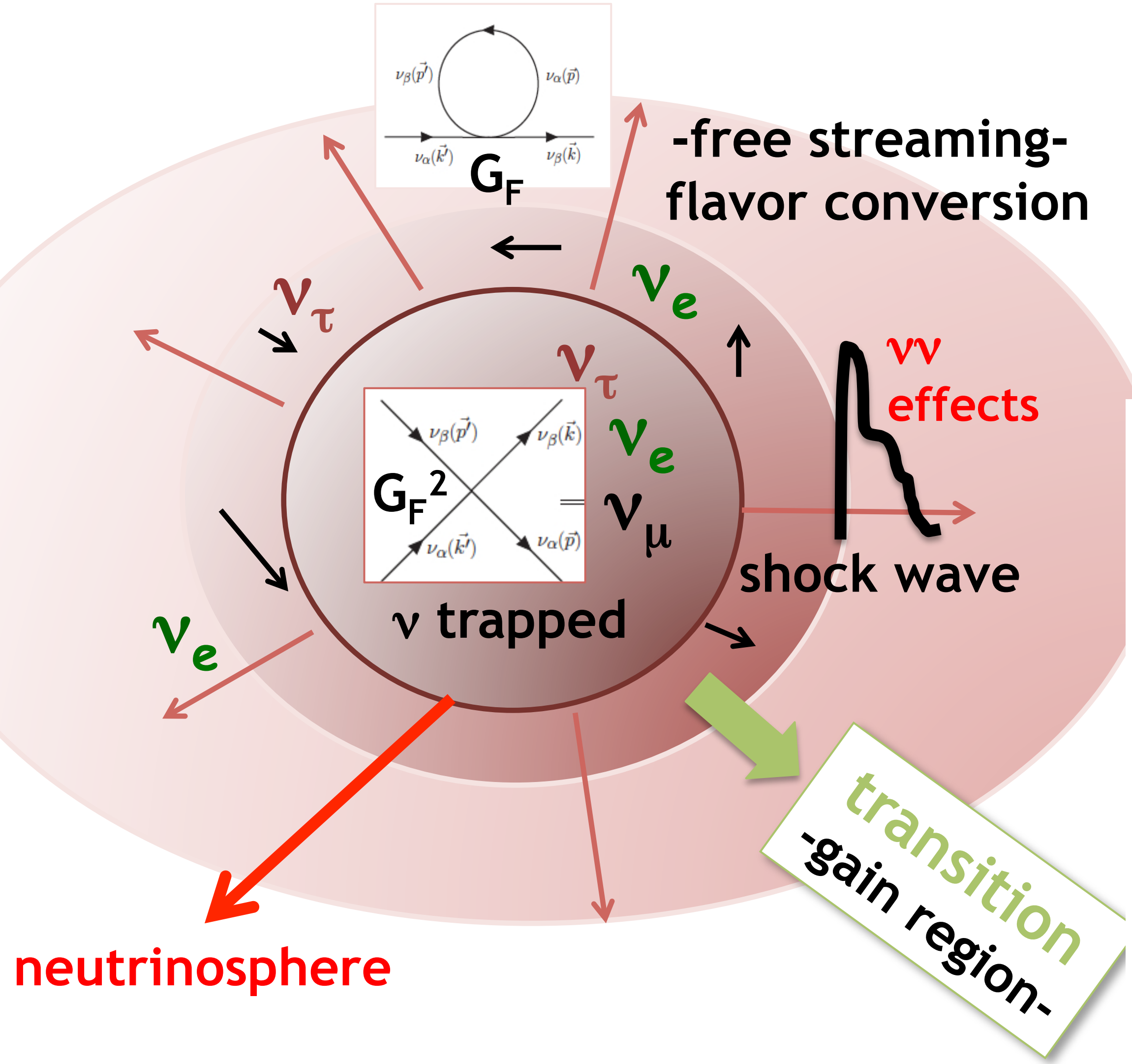


nuclear resonances

*connection to collective modes in other many-body systems (nuclei, clusters, ...)*

Väänänen and Volpe, PRD88 (2013)

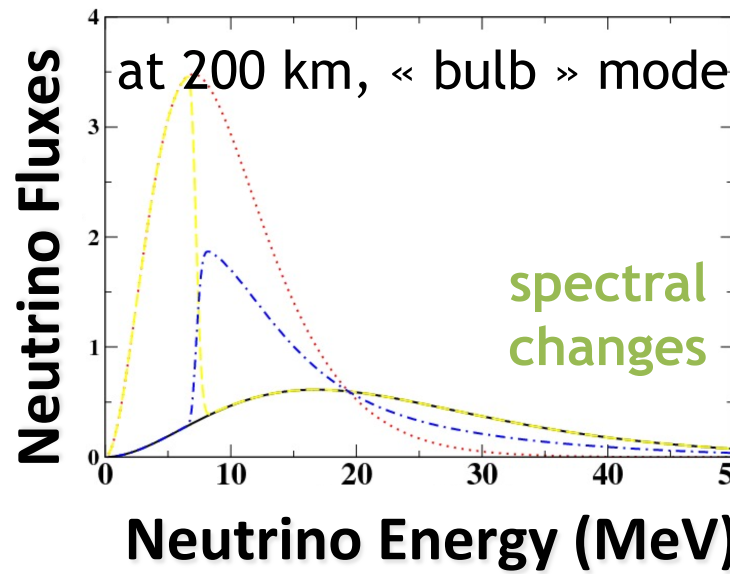
# In supernovae explosions




$\nu_e + n \rightarrow p + e^-$

$\bar{\nu}_e + p \rightarrow n + e^+$

Heating rate behind the shock could be enhanced by spectral changes of the neutrino fluxes.



# Numerous aspects investigated in a decade...

- Symmetry breaking

  New instabilities found, broken symmetries.

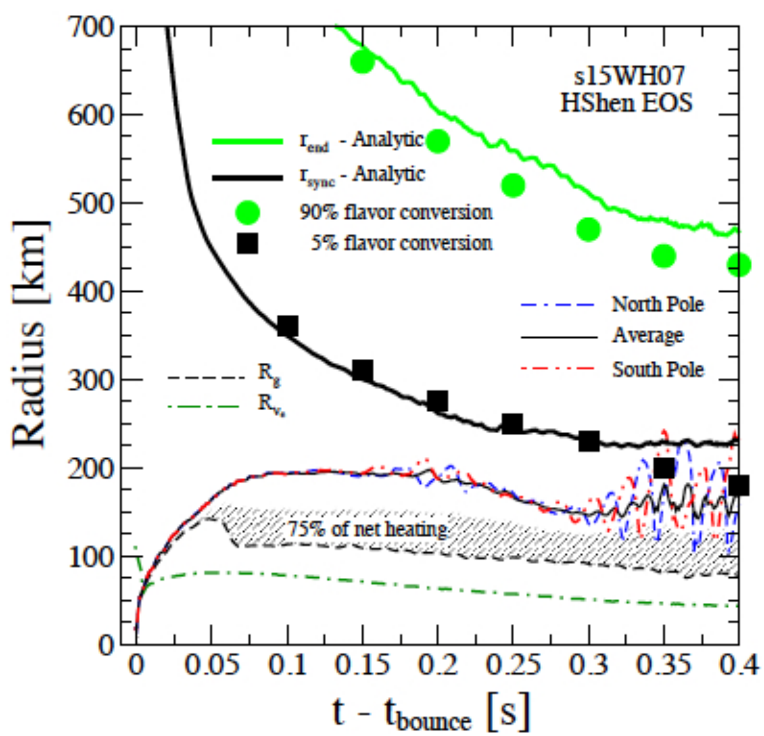
  see e.g. Raffelt, Sarixas, Seixas, PRL 111 (2013)

- Role of decoherence
- Impact on nucleosynthesis

  Balantekin and Yuksel, Journ. Phys. 2005, Duan, McLaughlin, Surman JPG 2010, Meng-Ru et al, PRD91 (2015), ...

- Impact on the supernova dynamics

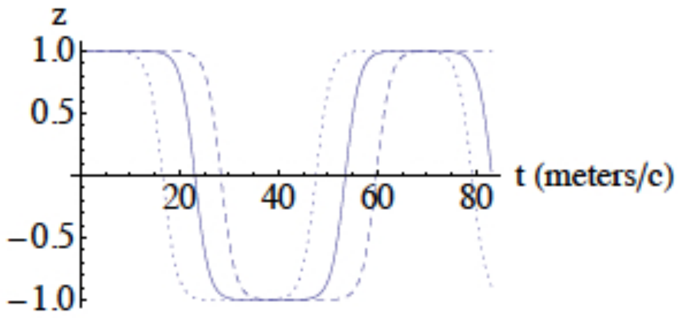
  *see the talk by H. Sasaki*




Dasgupta et al.PRD 2012

# Improved description of the transition region

- if different neutrinospheres considered

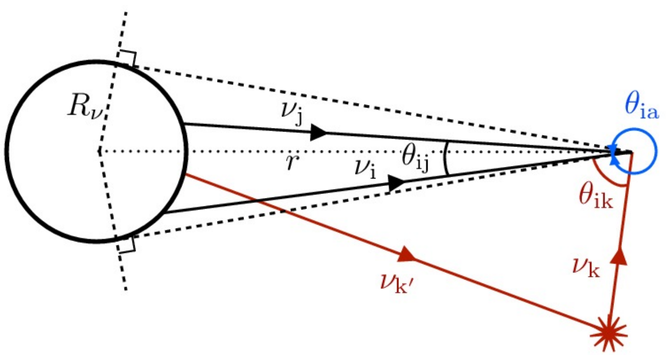



Conversion at short time scales

Sawyer, PRL108 (2016)

- collisions -> flavor patterns modified (schematic evaluation)

Cherry et al, PRL108 (2012),




*Competition between the collision and flavor timescales ?*

# Improved description of the transition region

- mass terms contributions – corrections at the mean-field level

$\zeta = \langle a_+^+ a_- \rangle$ correlators with helicity change

$\mathcal{R} = \begin{pmatrix} \rho & \zeta \\ \zeta^* & \bar{\rho} \end{pmatrix}$ $\quad \mathcal{H} = \begin{pmatrix} h & \Phi \\ \Phi^* & \bar{h} \end{pmatrix}$

$\mathcal{R}$ and $\mathcal{H}$ have helicity and flavor structure ($2\mathcal{N}_f$ x $2\mathcal{N}_f$).

$\Phi$ couples $\nu$ with $\bar{\nu}$

helicity (or spin) coherence

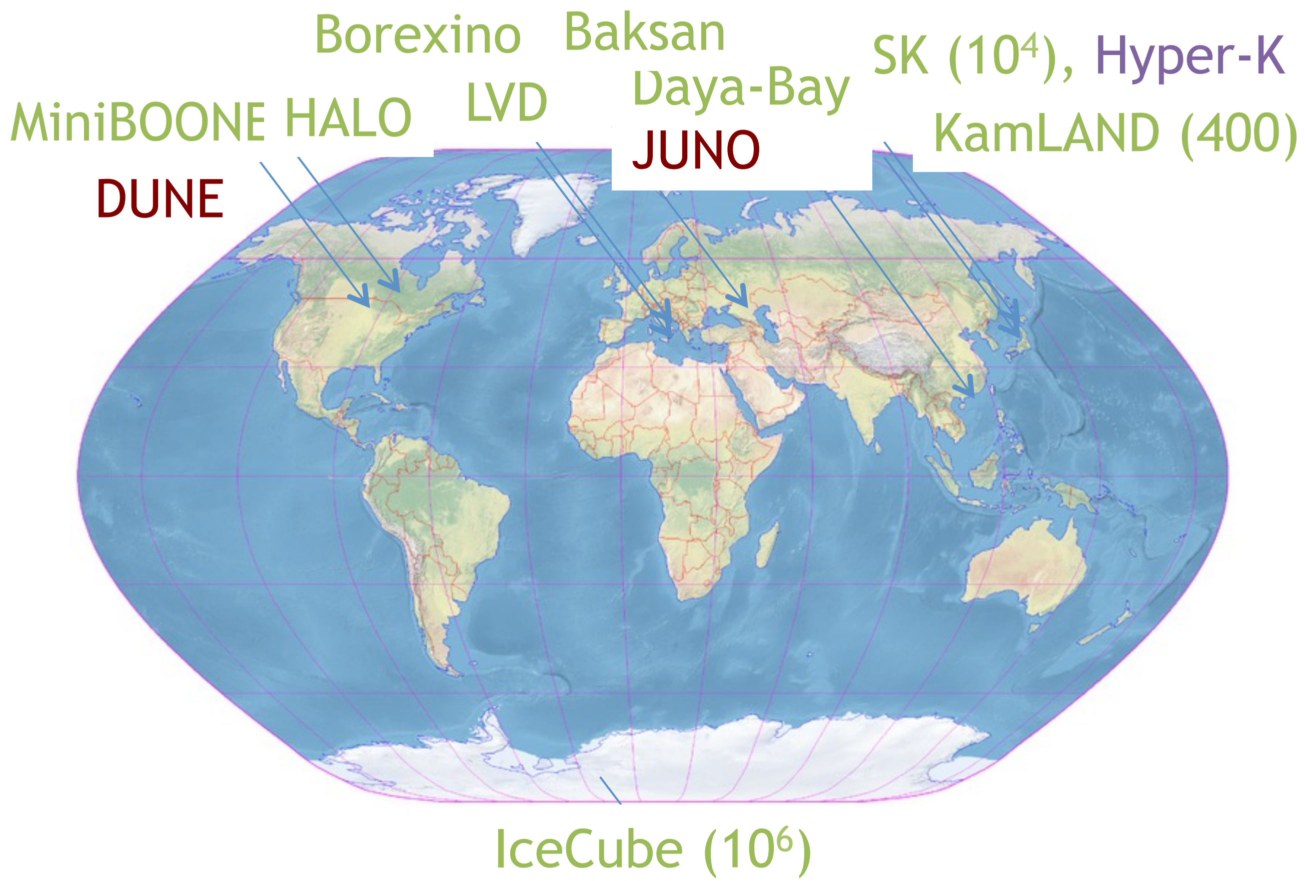
$\Phi \sim (h_{mat}^{perp} + h_{\nu\nu}^{perp})$ x $m/2E$

Vlasenko, Fuller, Cirigliano, PRD89 (2014)
Serreau,Volpe, PRD90 (2014)

*First calculation in a toy model has shown significant impact.*

# Supernova Early Warning System and SNe observatories

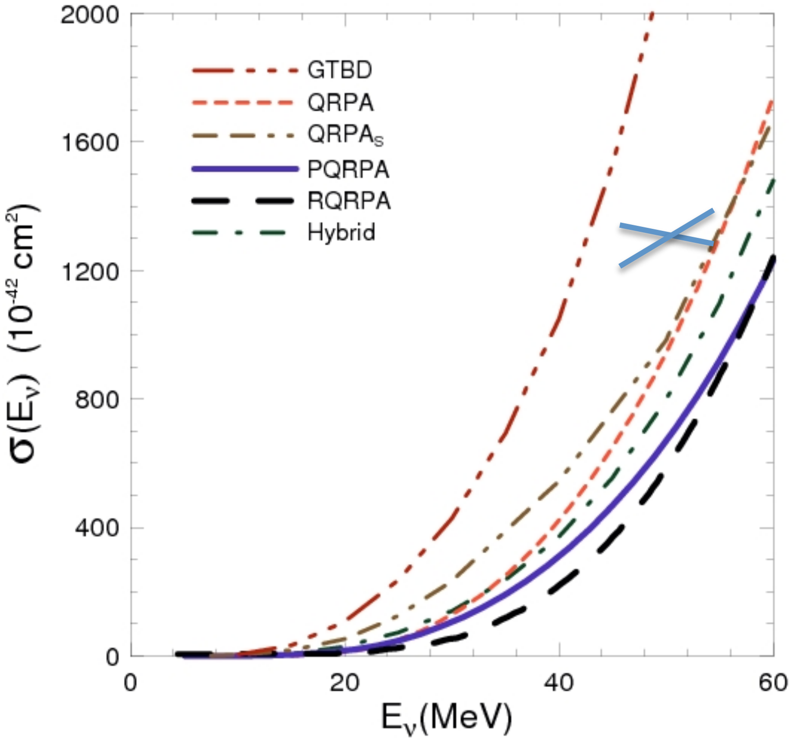
Events for a supernova explodes in our galaxy (10 kpc), up to $10^6$ events



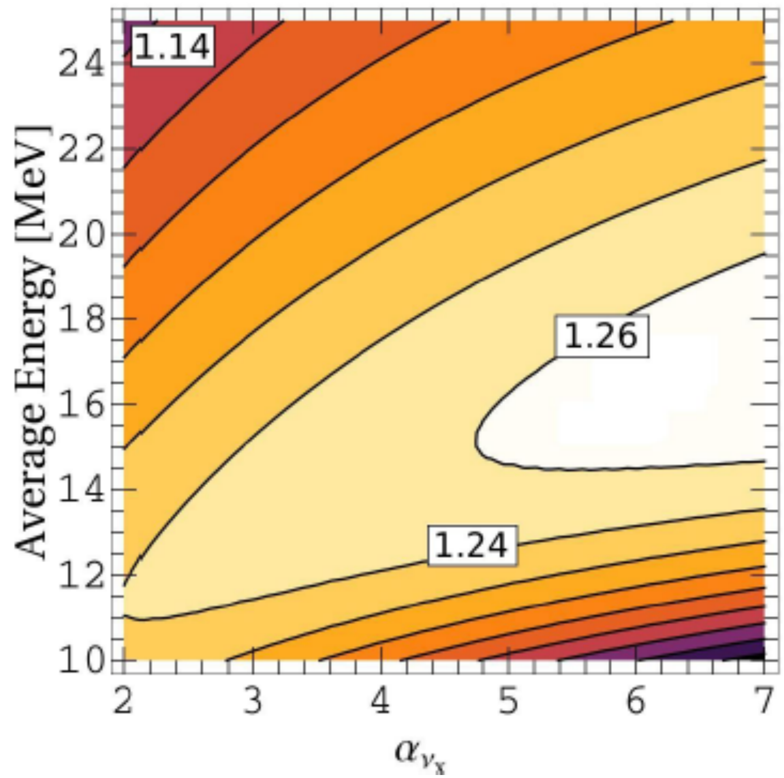

Detection channels : scattering of anti-$\nu_e$ with p, $\nu_e$ with nuclei, $\nu_x$ with *e, p*

We will measure the time, energy signal from future (extra)galactic explosions.

# Neutrino-nucleus cross sections




Bertulani, Samana, 0802.1553




Vaananen, Volpe, JCAP 1011 (2011)

Several projects have been proposed over the years... ORLAND at SNS (2000), low energy beta-beam (Volpe, J. Phys. G30, 2003), ν at JPARC (H.Ejiri, 2003).

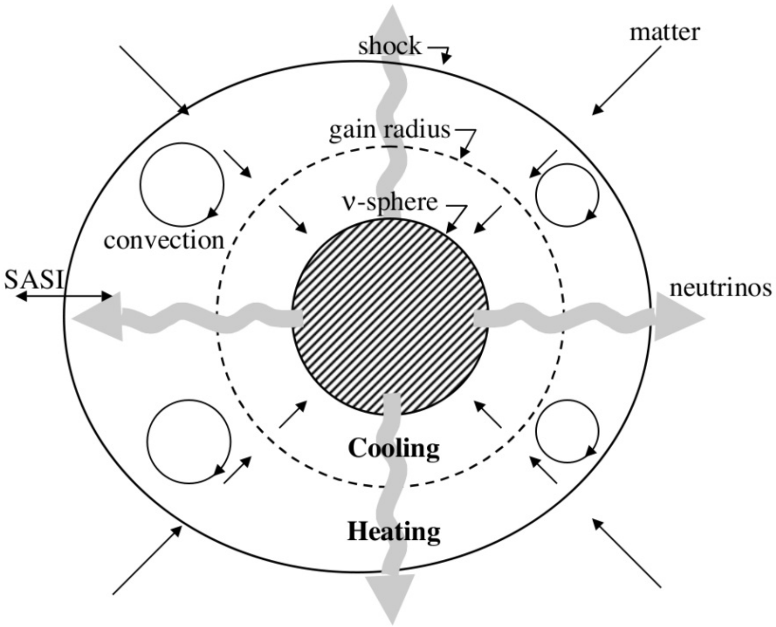
**Measurements on ν-nucleus cross sections planned at SNS by the COHERENT collaboration ! (Pb, O, Ar, Fe)**

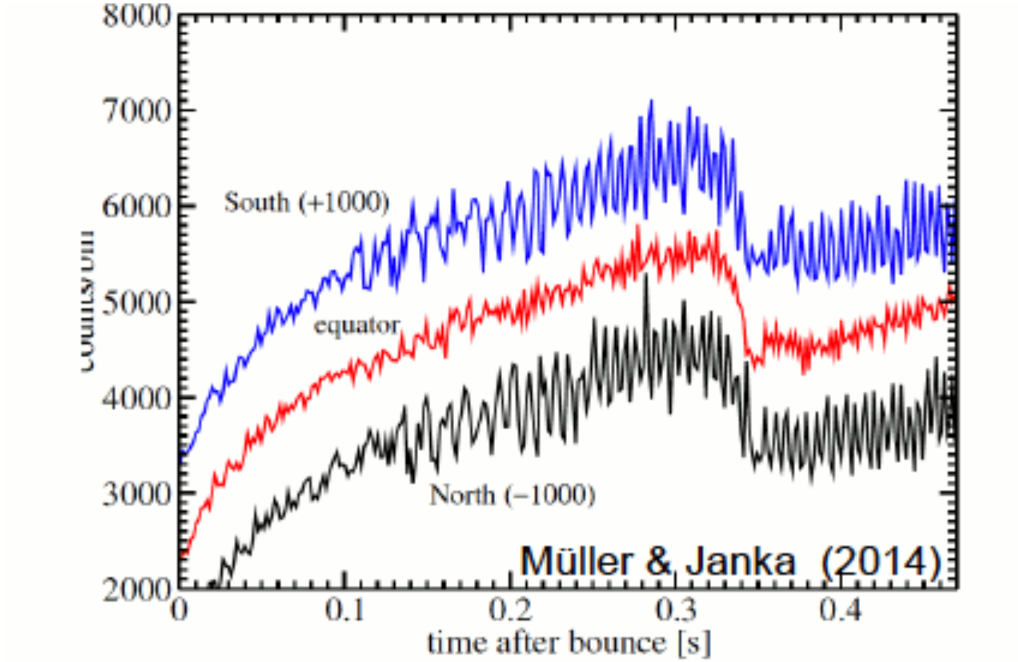
**Sensitivity to the quenching of $g_A$, also of forbidden transitions**

# The explosion mechanism and the neutrino signal

Now : Two-dimensional simulations agree for a set supernova progenitors,from three groups, accord with SN1987A explosion energy. Three-dimensional running, hints for explosions.

A. Mezzacappa's talk to «8th TPC Symposium », Paris




Time supernova neutrino signals encode the SASI signature (ICECUBE).

# Gravitational binding energy of the newly formed neutron star

*How well can we reconstruct the gravitational binding energy in a galactic explosion ?*

Most of the analysis make assumptions – ex. equipartition hypothesis, or pinching parameter fixed.

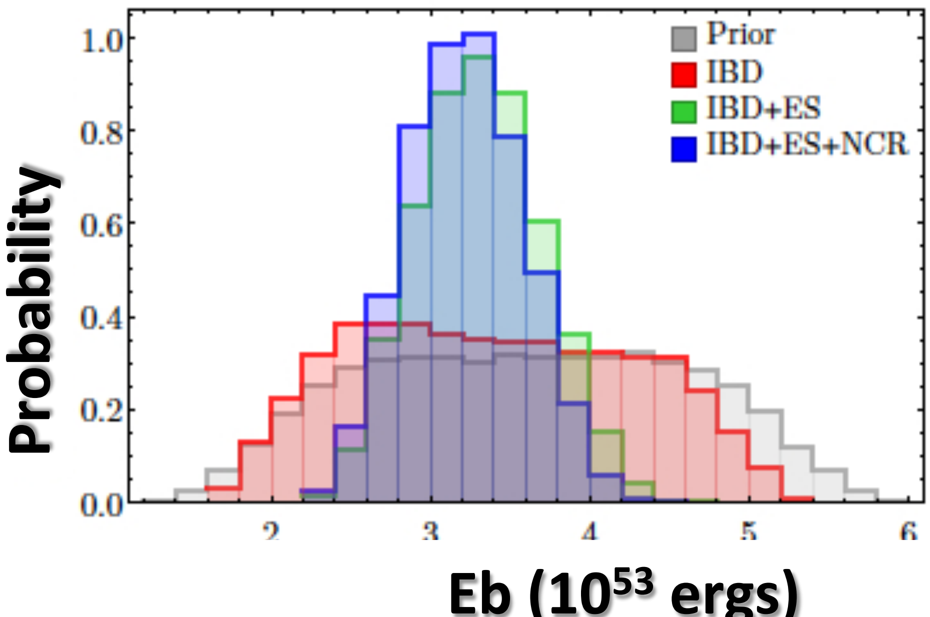
An et al. J. Phys. G43 (2016), Lu, Li, Zhou, PRD94 (2016) 023006, ...

Minakata et al, arXiv:0802.1489, only inverse beta-decay in Hyper-Kamiokande. Conclusions not optimistic...

# Reconstructing the gravitational binding energy of the neutron star

Gallo Rosso, Vissani, Volpe, JCAP1711 (2017)
Gallo Rosso, Vissani, Volpe, arXiv:1712.05584

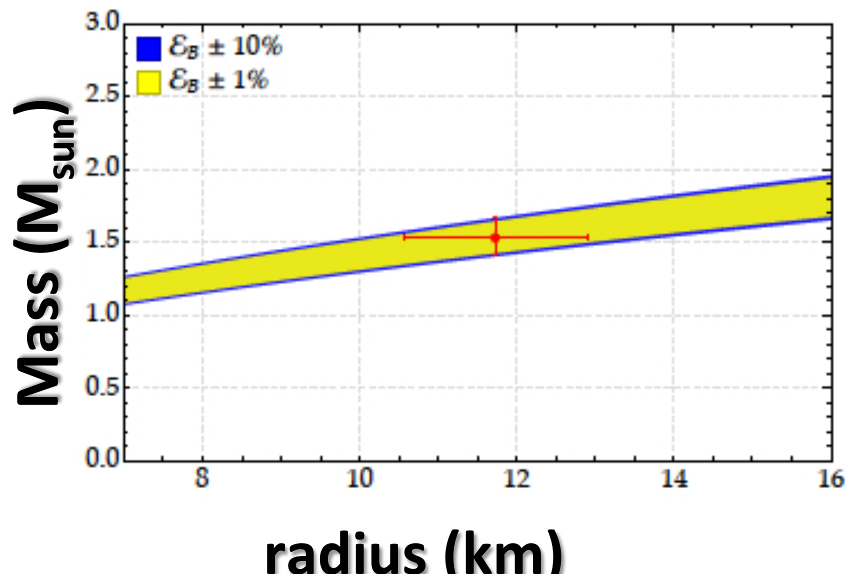
For a galactic supernova at 10 kpc.




Fit to numerous EOS for NS

$$\frac{\mathcal{E}_B}{Mc^2} \approx \frac{(0.60 \pm 0.05)\,\beta}{1-\beta/2}, \quad \beta = \frac{GM}{Rc^2},$$

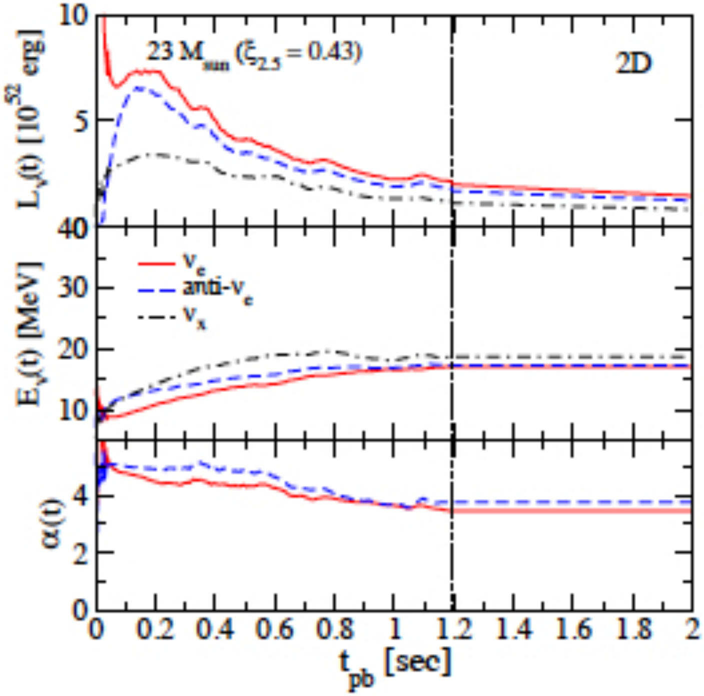
From Lattimer, Prakash,




- ✓ Likelihood without any ansatz
- ✓ Fluence : a power-law, MSW, NH
- ✓ Combined inverse beta-decay, elastic scattering and neutral current on oxygen

$E_b$ reconstructed with 11% accuracy in Super-Kamiokande
3% in Hyper-Kamiokande

# The diffuse supernova neutrino background




Horiuchi et al, 1709.06567

The integrated ν neutrino flux from supernovae at different redshifts :

$$F_\alpha(E_\nu) = \int dz \left| \frac{dt}{dz} \right| (1+z) R_{SN}(z) \frac{dN_\alpha(E'_\nu)}{dE'_\nu},$$

$$E'_\nu = (1+z)E_\nu,$$

Upper limits on DSNB fluxes :

1.4-1.9 anti-$n_e$ /cm$^2$/s

73-154 $n_e$/cm$^2$/s

Lunardini and Peres, JCAP (2008)

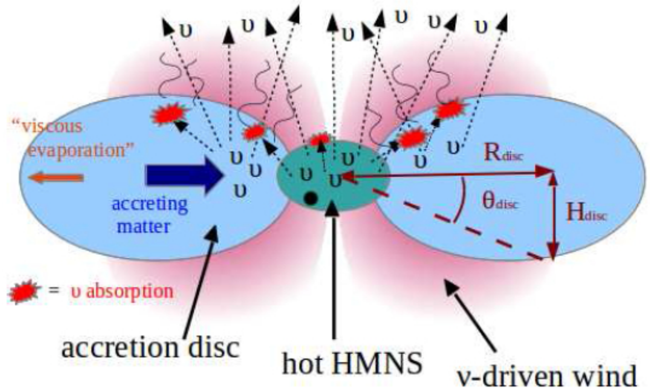
| | Events (10 y) | window | | detector |
|---|---|---|---|---|
| $\bar{\nu}_e$ | 90 | 9-25 MeV | 50 kton | scintillator |
| $\bar{\nu}_e$ | 300 | 19-30 MeV | 440 kton | Hyper-K |
| $\nu_e$ | 30 | 17-41 MeV | 50 kton | liquid argon |

Galais et al PRD 81(2010)

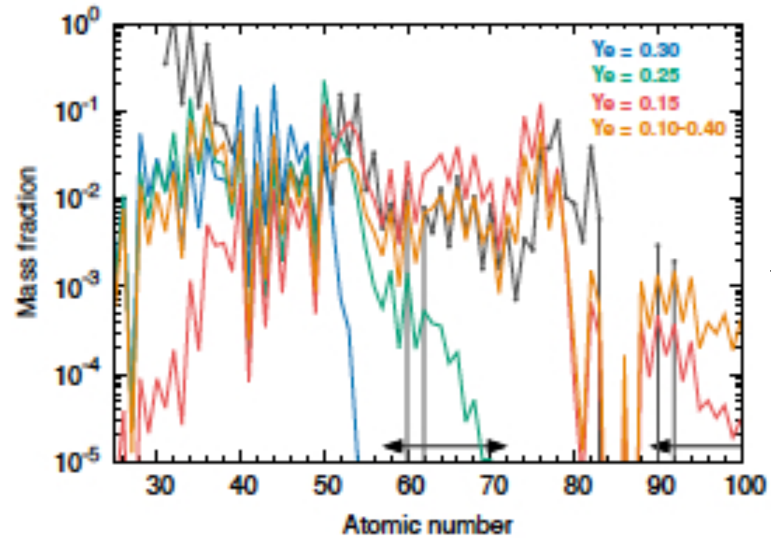
EGADS -Super-Kamiokande with Gd

DSNB discovery in the coming years

# Flavor evolution in accretion disks around compact objects and kilonova observations



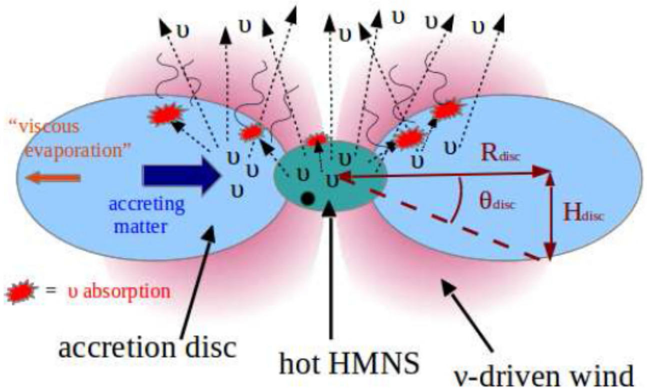

from Perego *et al.*, 2014




Tanaka et al, 1710.05850

# Helicity coherence (mass terms) effects

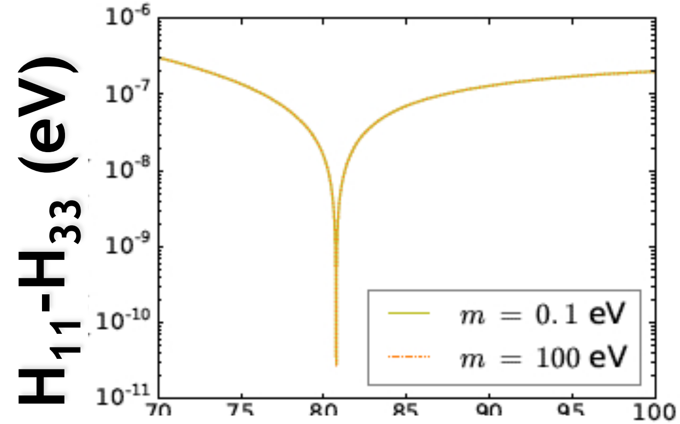
## neutron star mergers remnant




from Perego *et al.*, 2014

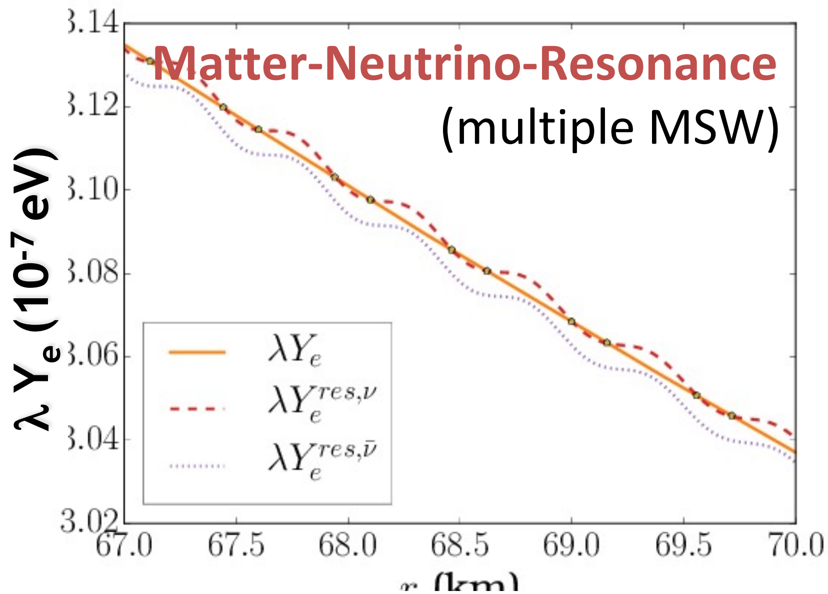
$$\mathcal{H} = \begin{pmatrix} h & \Phi \\ \Phi^* & \bar{h} \end{pmatrix}$$

In two flavors $\mathcal{H}$ is a 4 x 4 matrix.




**Distance (km)**

- resonance condition fulfilled
- adiabaticity not sufficient



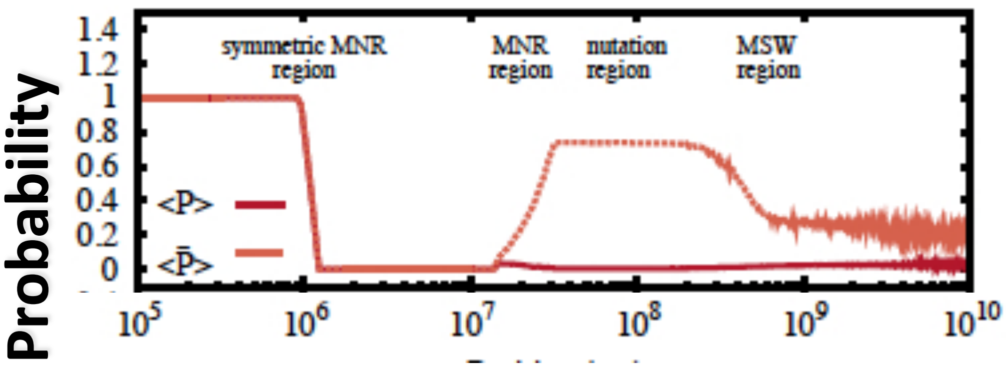

**Distance (km)**

Non-linear feedback does not enhance mass effects.

Chatelain,Volpe, PRD(2017) 1611.01862

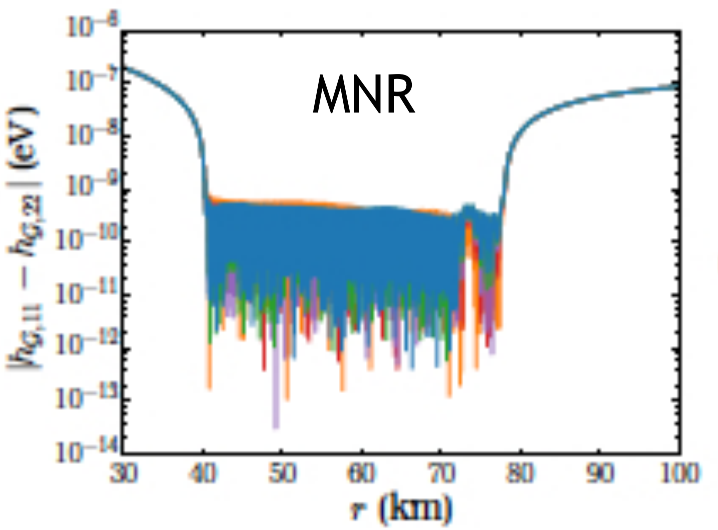
contrary to the findings in Vlasenko, Fuller, Cirigliano, 1406.6724

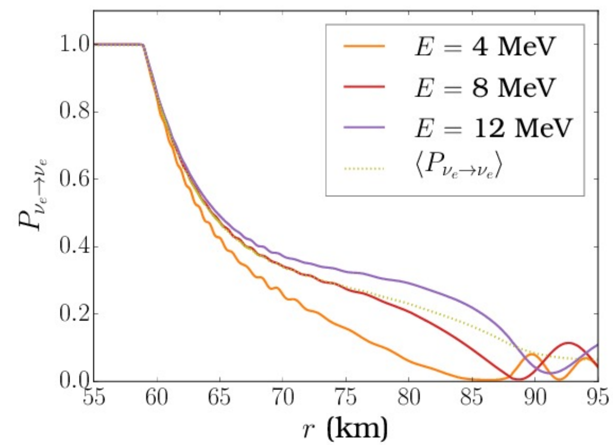
# Flavor phenomena in accretion disks around compact objects




Excess of $\bar{\nu}_e$ over $\nu_e$
The self-interaction and matter potentials cancel.

Malkus et al, PRD86 (2012)




Chatelain,Volpe, PRD(2017)
1611.01862

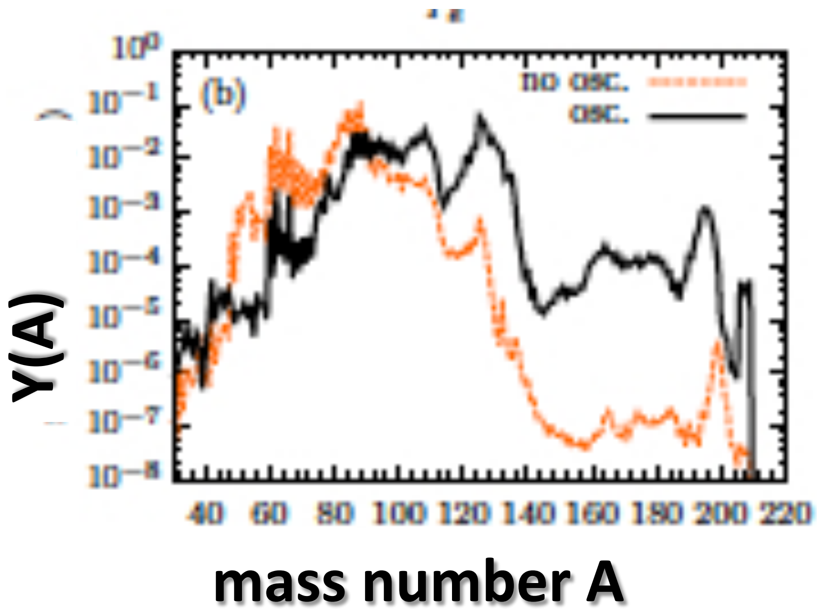
**Resonance conditions met, adiabatic evolution,**
**Ye can be modified by flavor evolution**

# Nucleosynthesis in neutrino-driven winds and kilonovae

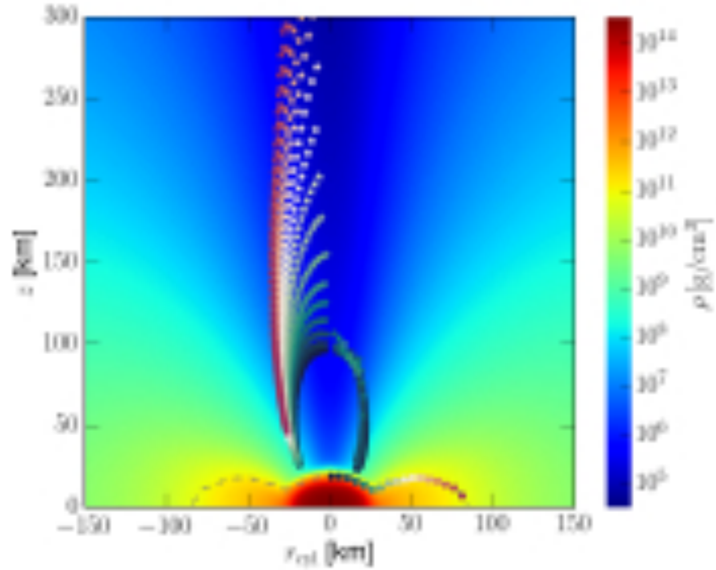
Neutrinos influence the neutron richness and determine Ye

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

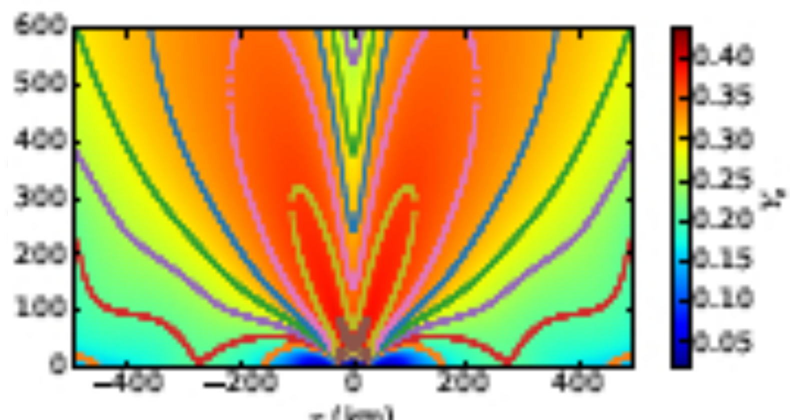
**Flavor evolution can impact Ye.**




Wu et al., PRD96(2017)



Frensel et al., PRD95(2017)




Chatelain and Volpe, PRD98 (2018)

Kilonova observations - assess the role of flavor evolution on Ye and nucleosynthesis in neutrino-driven winds

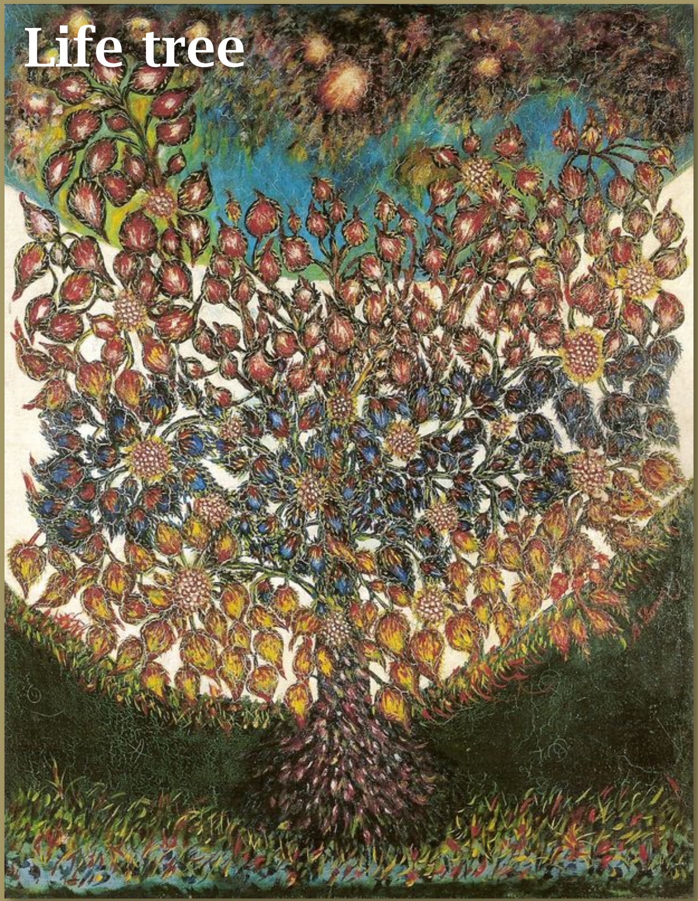
# Conclusions and perspectives

- Neutrino flavor evolution in dense astrophysical environments is a complex problem that still needs to be fully understood.

- Fast modes bring equilibration of the spectra on short distance scales. They could influence the supernova dynamics. These and other phenomena could impact nucleosynthesis in neutrino-driven winds in kilonovae.

- The total gravitational binding energy will be precisely reconstructed for a galactic supernova and also the neutrino spectra, if effects from the flavor modification simple enough (MSW or fast modes).

# Life tree



*Seraphine de Senlis*