Neutrino flavor evolution in dense environments : theory and observational implications

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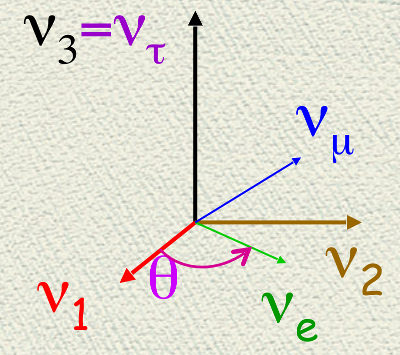
Neutrino oscillations in vacuum

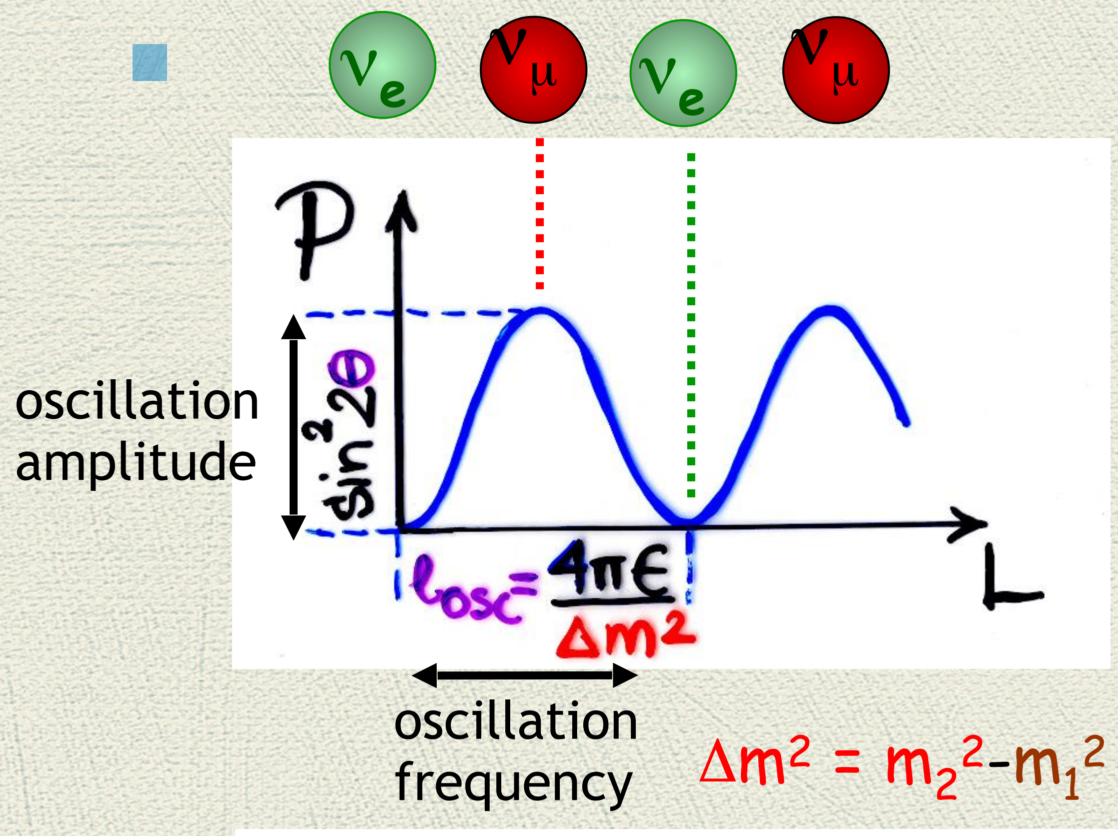
- In analogy with K_0-K_0bar oscillations, Pontecorvo (1957) makes the hypothesis that neutrinos can change flavor while propagating.



$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \qquad \Delta m^2 = m_2^2 - m_1^2$$

flavor basis

mass basis

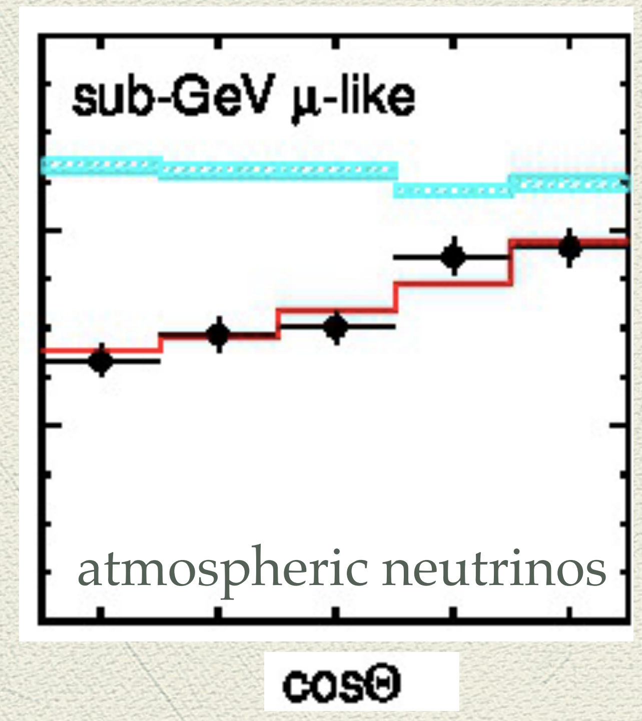
- 

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

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

probability for neutrino oscillations

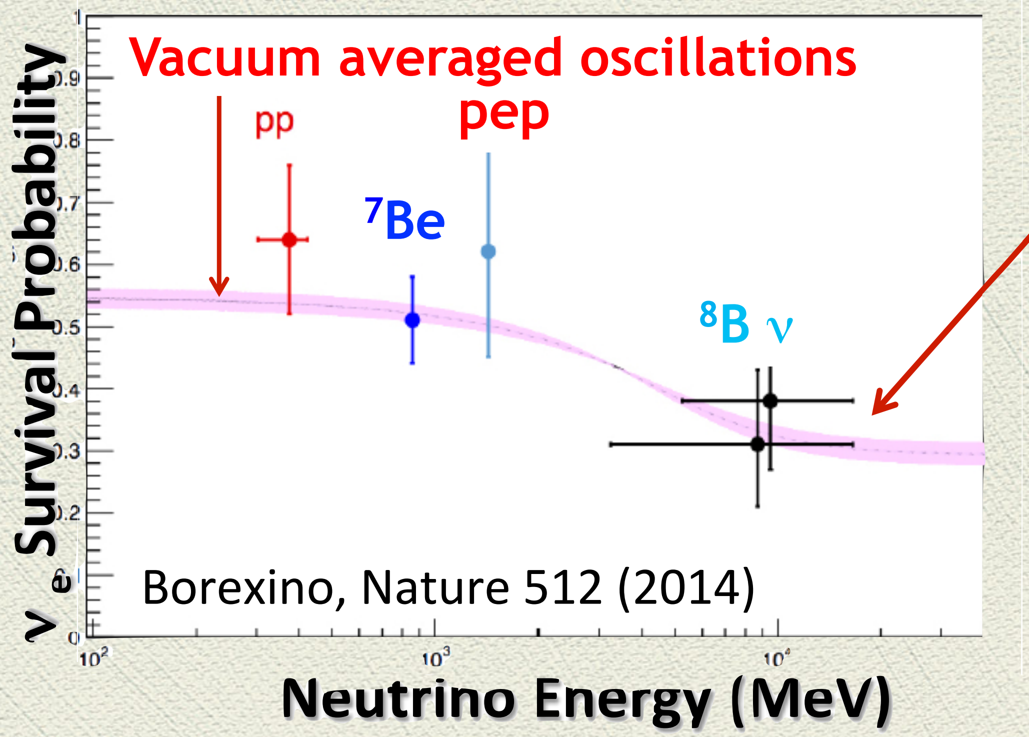
- Discovery in 1998 by Super-Kamiokande, SNO measures the total solar flux in 2001 - solar neutrino deficit problem solved.

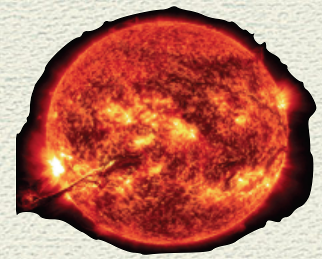


Current status

- Oscillation in vacuum well established.
  Most of the mixing parameters (angles) measured.

- Neutrinos undergo different flavor transformation mechanisms in matter.

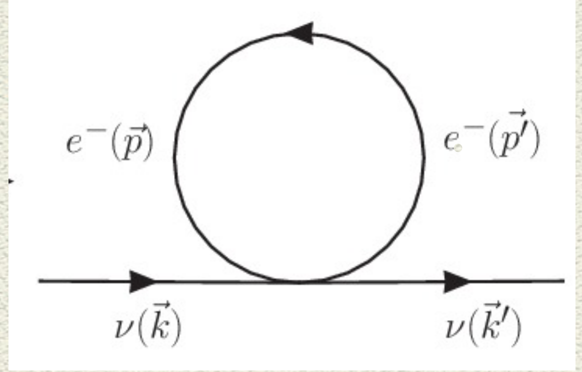




MSW solution

Mikheev-Smirnov-Wolfenstein effect

resonant adiabatic flavor conversion



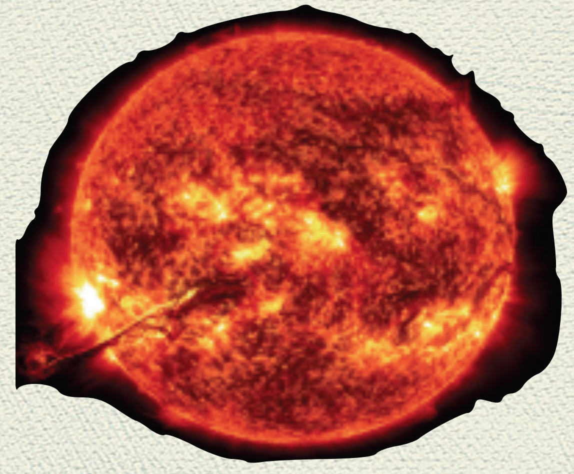
$$h_{mat} = \sqrt{2} G_F \rho_e$$

- Neutrinos undergo various flavor transformation mechanisms in matter.
  They influence the neutron richness of the material through :

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

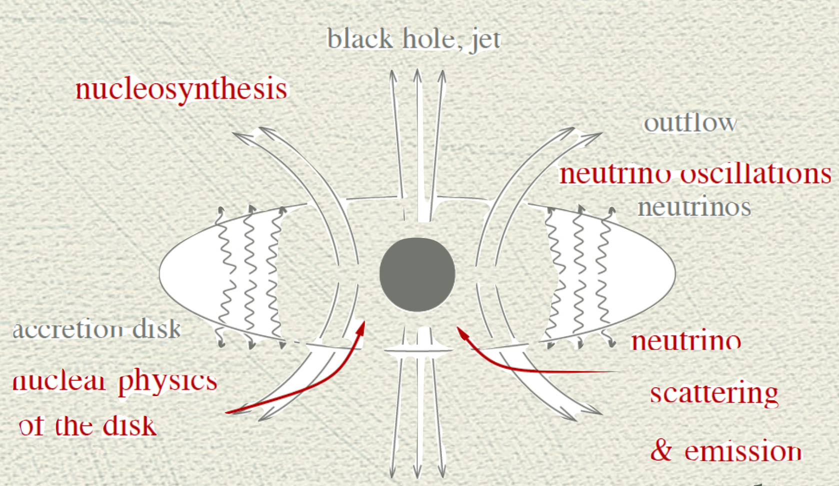
that sets the electron fraction, a key parameter for heavy elements nucleosynthesis. $Y_e = \frac{p}{p+n}$

Astrophysical sites for neutrino flavor conversion

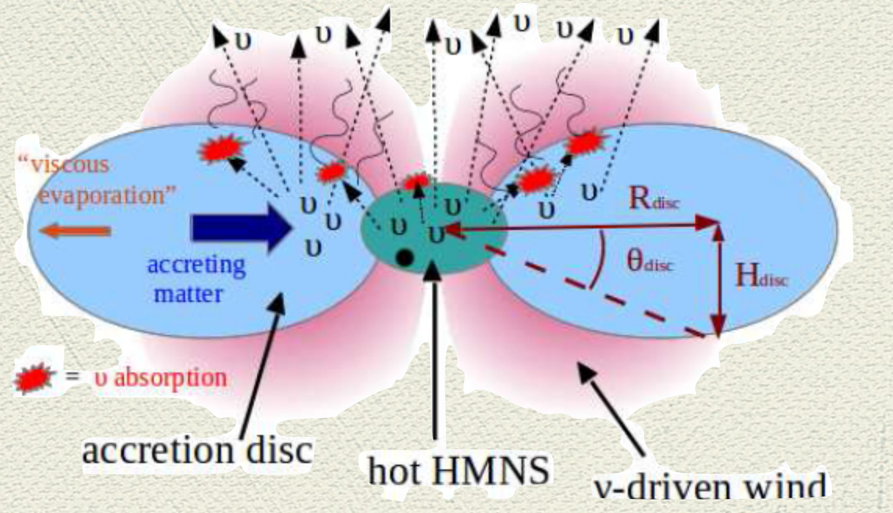


Sun

core-collapse Supernovae



McLaughlin

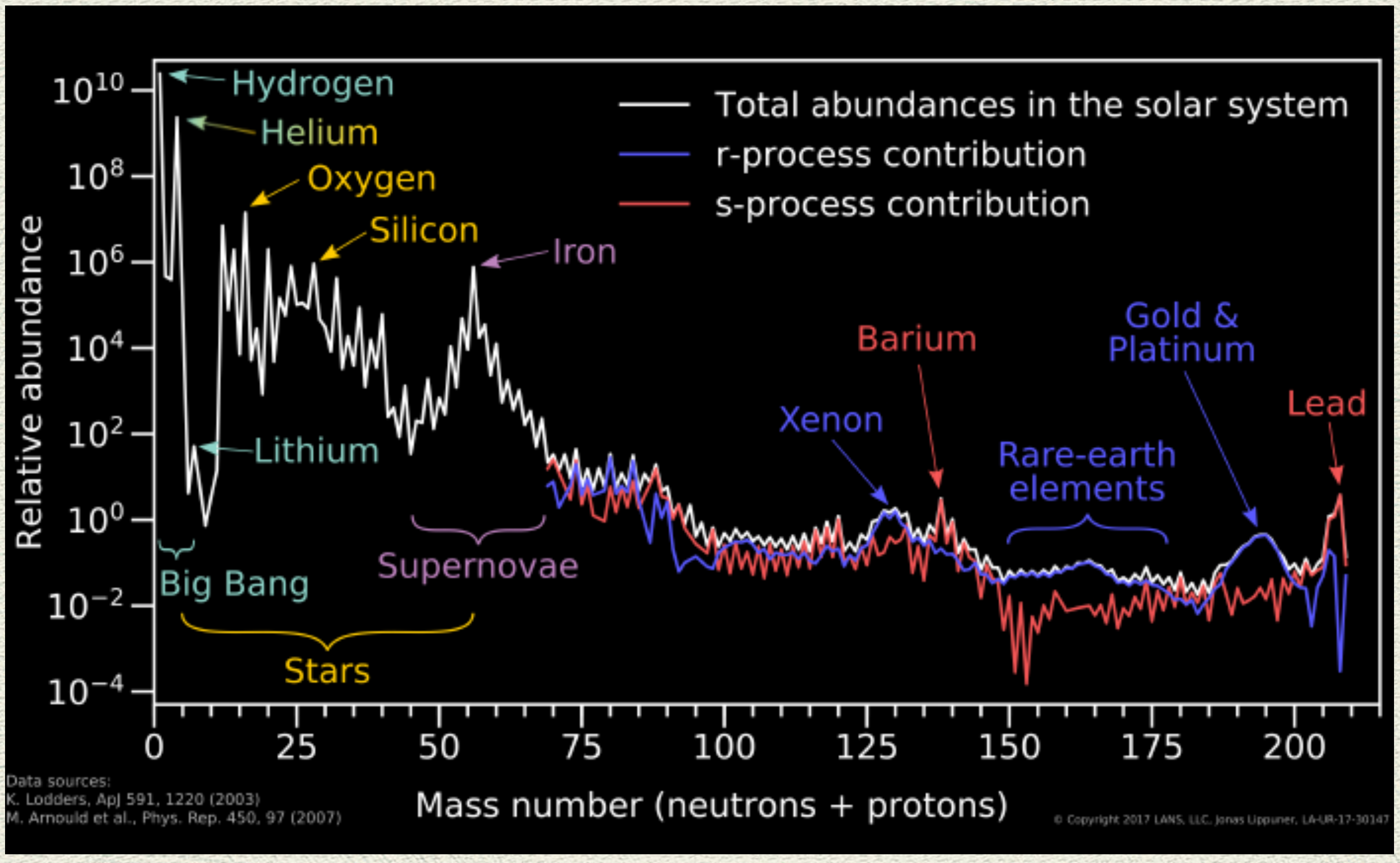


Perego et al, 2014

accretion disks around black holes

neutron star mergers remnants

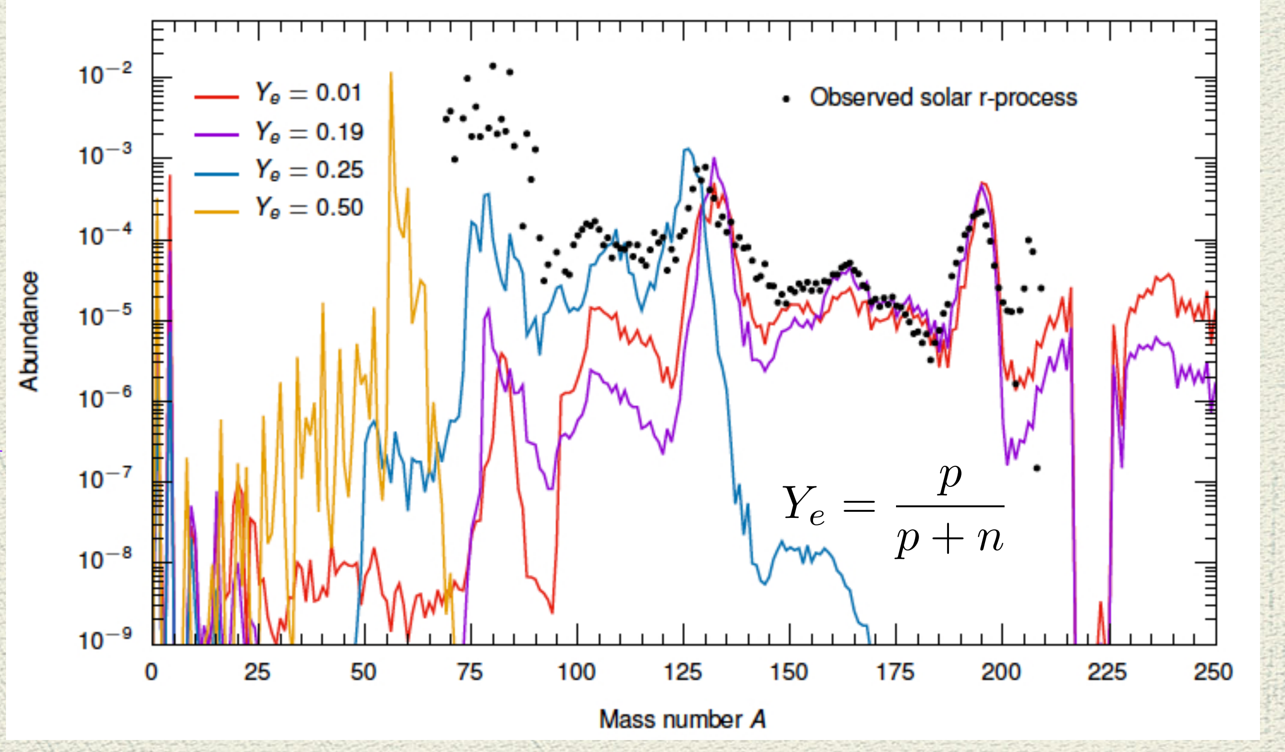
Heavy elements nucleosynthesis



- Neutron captures responsible for the synthesis of elements heavier than iron.
- Three mechanisms : s-process (s for slow), r-process (r for rapid) and p-process (p for proton).

- Strong r-process (with rare-elements and the third peak) very sensitive to the electron fraction Ye.
  1-Ye : number of available neutrons.

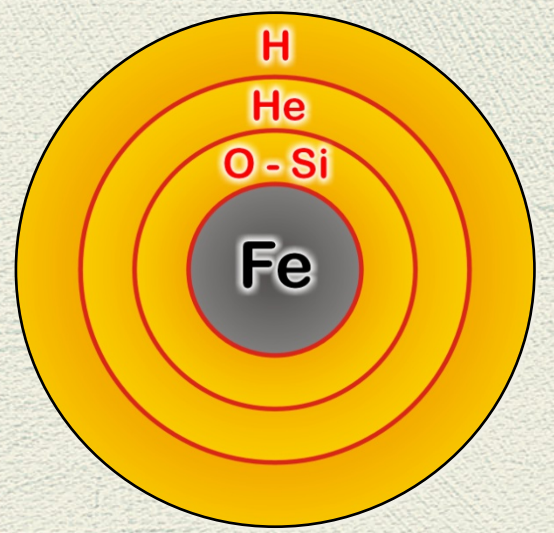
Site(s) for the r-process not (fully) unravelled yet : core-collapse supernovae and kilonovae

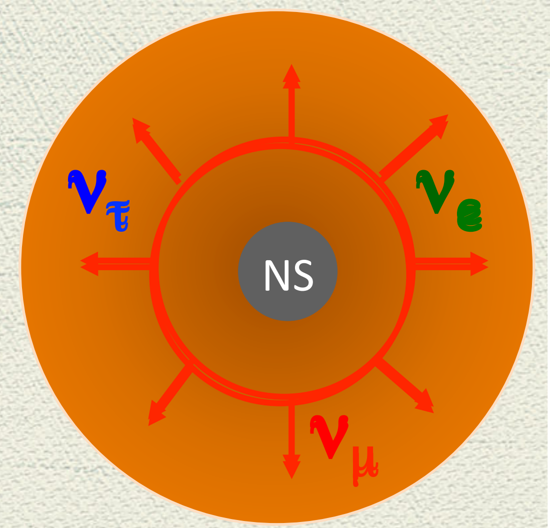


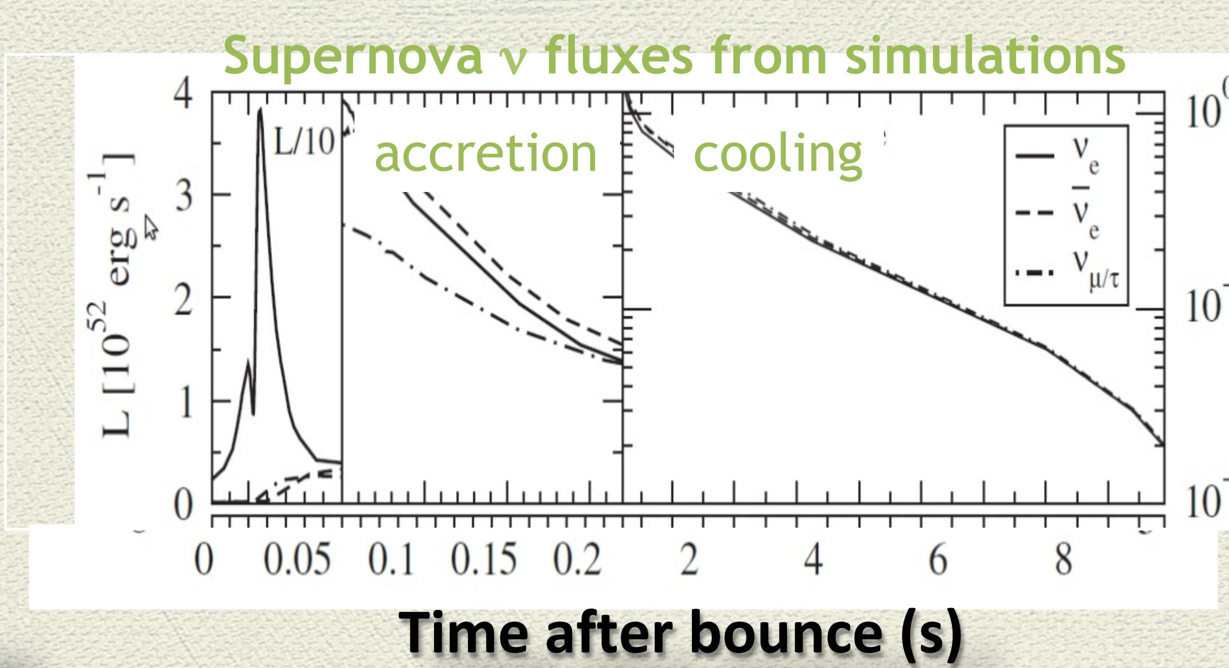
Neutrino signal from future supernovae

- Core-collapse supernovae (> 6 M_{Sun}) shine their gravitational binding energy in a 10 seconds burst of neutrinos of all flavors.
  3 10^{53} erg for a 1.4 Msun newly born neutron star - 10^{58} neutrinos in the MeV energy range

  First (and unique) observation : SN1987A.



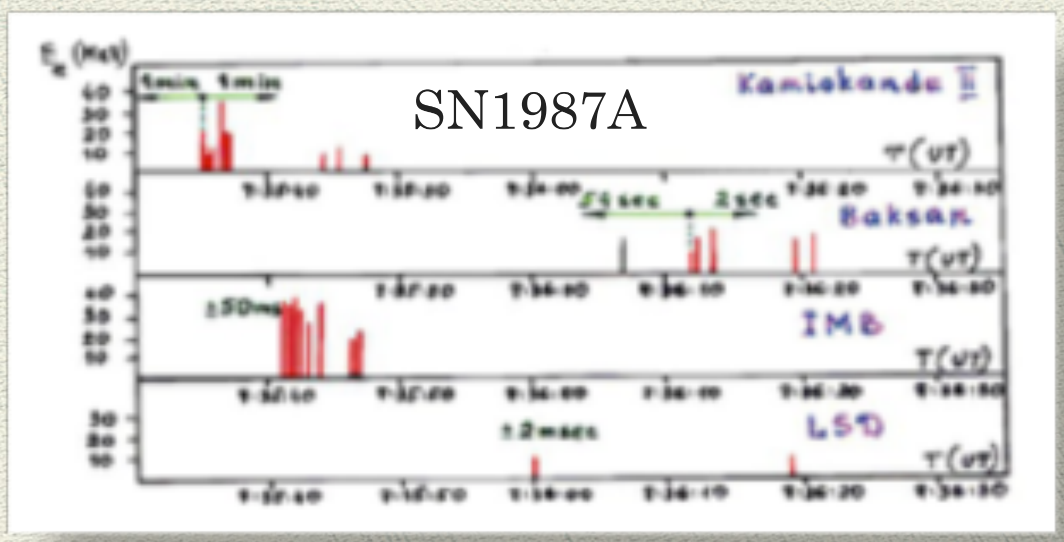




Hüdepohl *et al.* PRL 104 (2010)

Neutrino fluxes encode imprints of the explosion.

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



What can we learn from supernova observations ?

Neutrino luminosity curves and spectra bring crucial information about

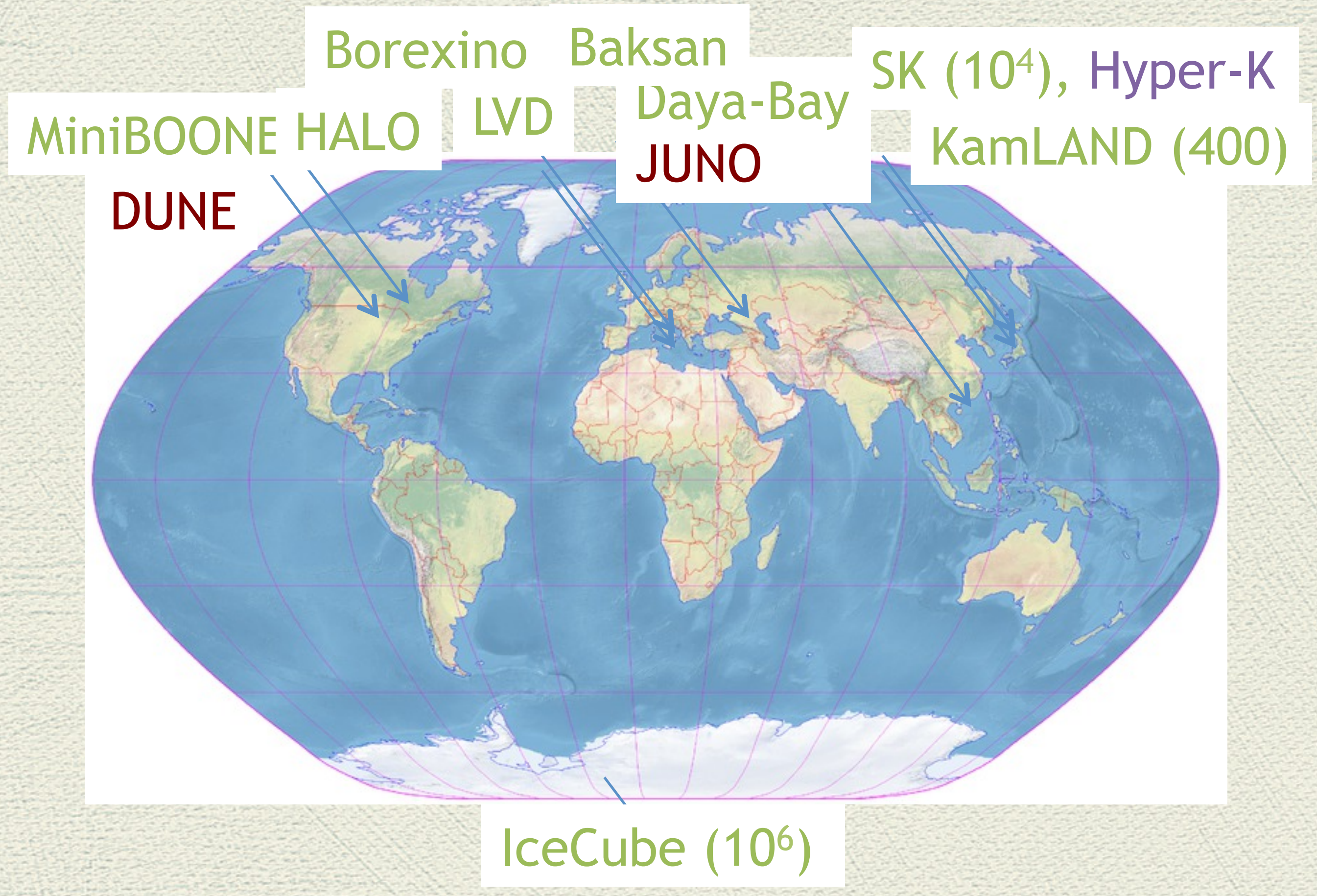
Supernovae

- SNe explosion dynamics
- Mass-Radius, binding energy of the neutron star
- SNe location
- …

Neutrinos

- Mass ordering (normal or inverted)
- New physics effects - sterile neutrinos, non-standard interactions, neutrino magnetic moment, …
- CP violation effects (subleading)

SN observatories and the Supernova Early Warning System (SNEWS)



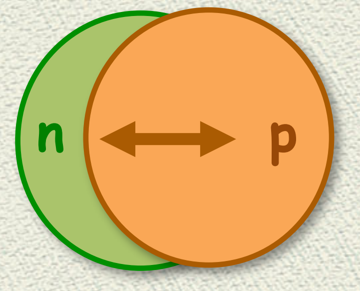
- Detection of time and energy neutrino signal
- Sensitivity to all flavors by inverse beta-decay, scattering on electrons and nuclei

- 10^4 - 10^6 events expected from a 10 kpc supernova
- Diffuse supernova neutrino background measurement upcoming - Super-KGd (Japan) (

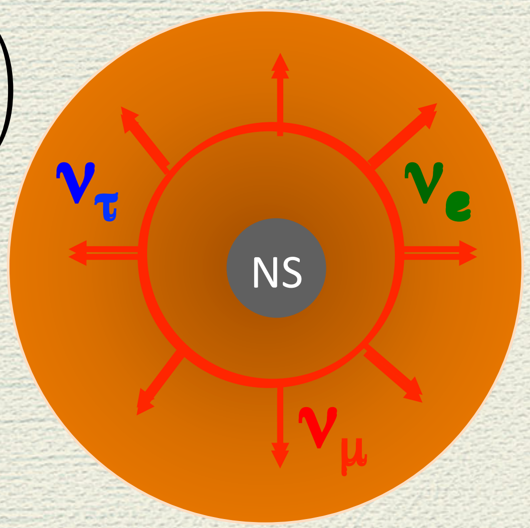
Predictions of the neutrino fluxes for future observations necessary

Neutrino evolution equations in dense environments

$$\rho = \begin{pmatrix} < a^\dagger_{\nu_e} a_{\nu_e} > & < a^\dagger_{\nu_\mu} a_{\nu_e} > \\ < a^\dagger_{\nu_e} a_{\nu_\mu} > & < a^\dagger_{\nu_\mu} a_{\nu_\mu} > \end{pmatrix}$$

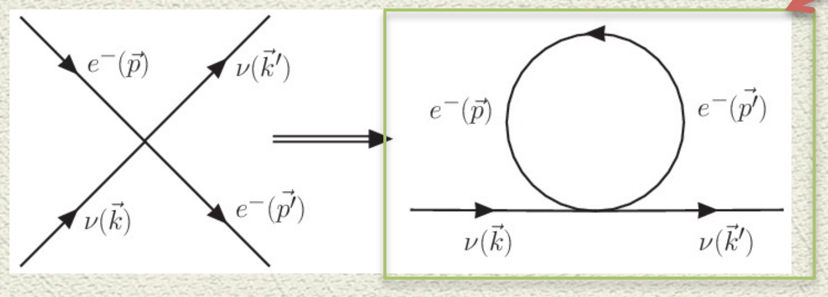


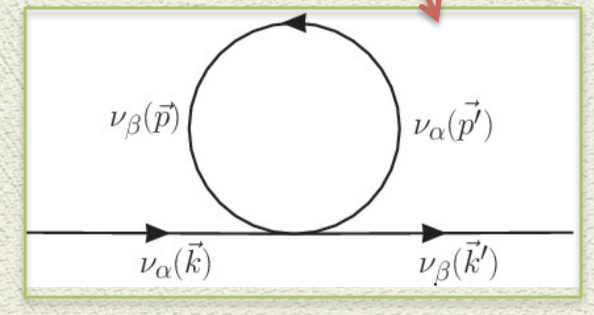
$\rho = \langle a^+ a \rangle$ one-body density matrix



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

$$i\dot{\rho} = [h(\rho), \rho] \qquad h = h_{vac} + h_{mat} + h_{\nu\nu}(\rho)$$





MEAN-FIELD approximation

neutrino-matter

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

neutrino self-interactions

non-linear term

$$h_{\nu\nu} = \sqrt{2} G_F \sum_\alpha [\int (1 - \hat{q} \cdot \hat{p}) \times [\mathrm{d}n_{\nu_{\underline{\alpha}}} \rho_{\nu_{\underline{\alpha}}}(\vec{p}) - \mathrm{d}n_{\bar{\nu}_{\underline{\alpha}}} \bar{\rho}_{\bar{\nu}_{\underline{\alpha}}}(\vec{p})]],$$

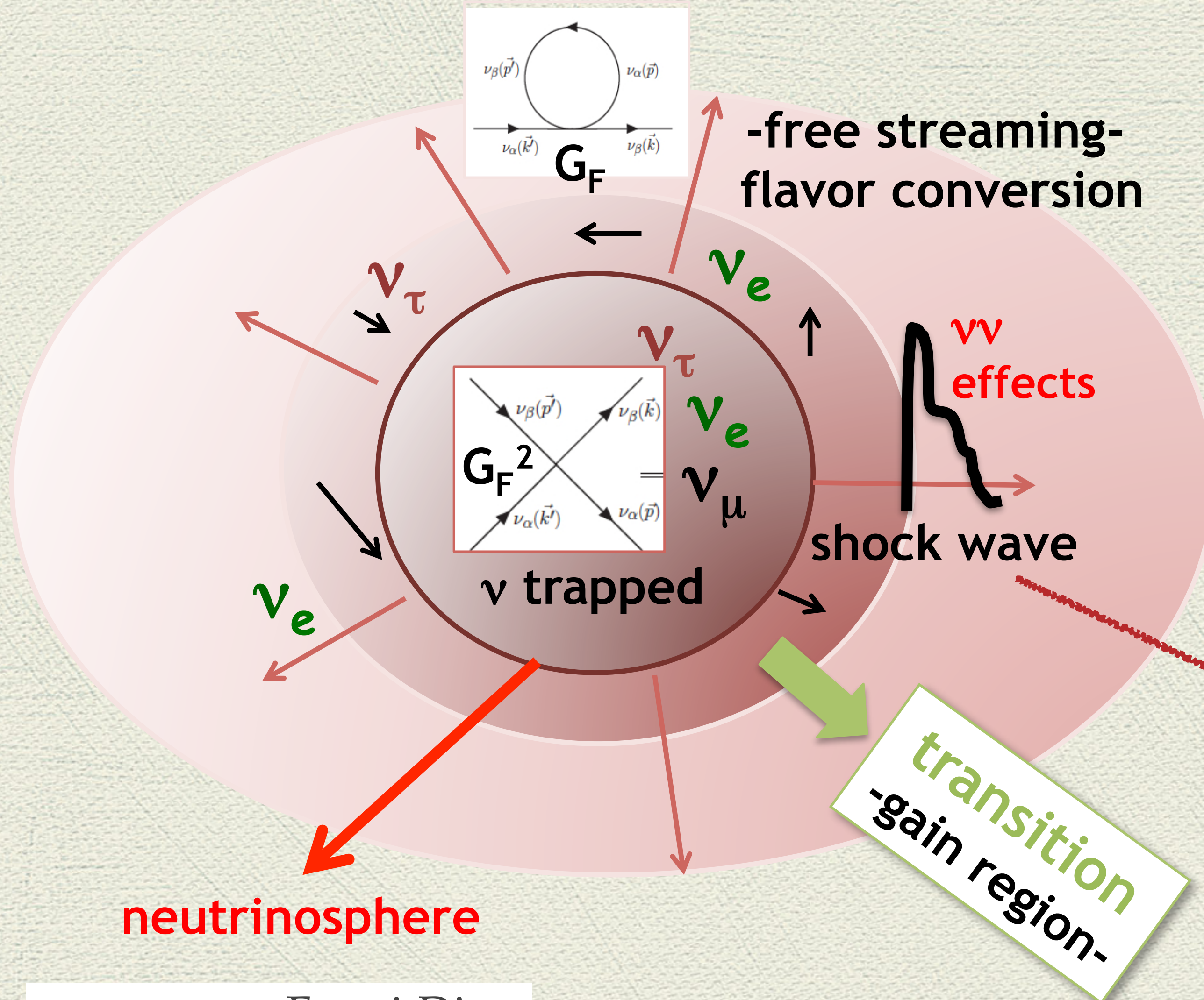
Volpe, Väänänen, Espinoza. PRD 87 (2013)

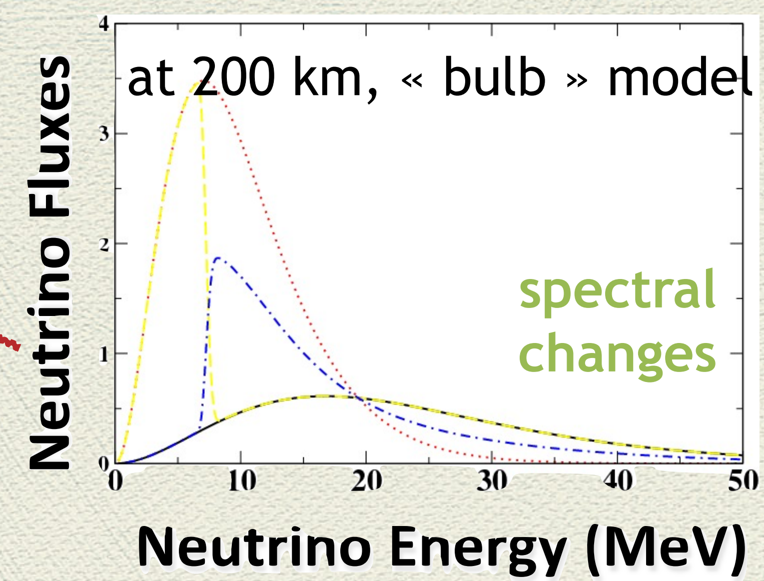
Volpe, «Neutrino quantum kinetic equations », Int. J. Mod. Phys.E24(2015)

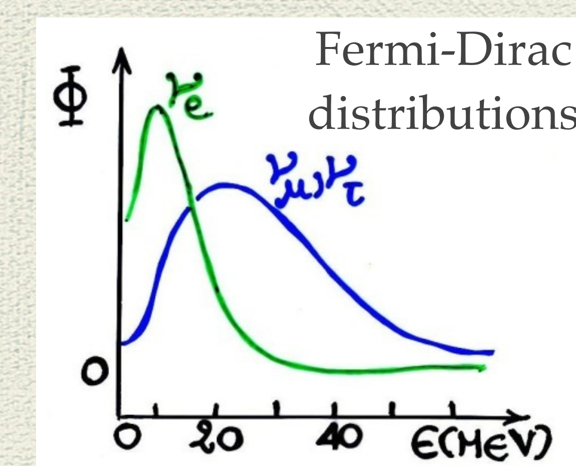
Supernovae explosions and flavor evolution

- The heating rate, behind the shock, could be enhanced by spectral changes of the neutrino fluxes.

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





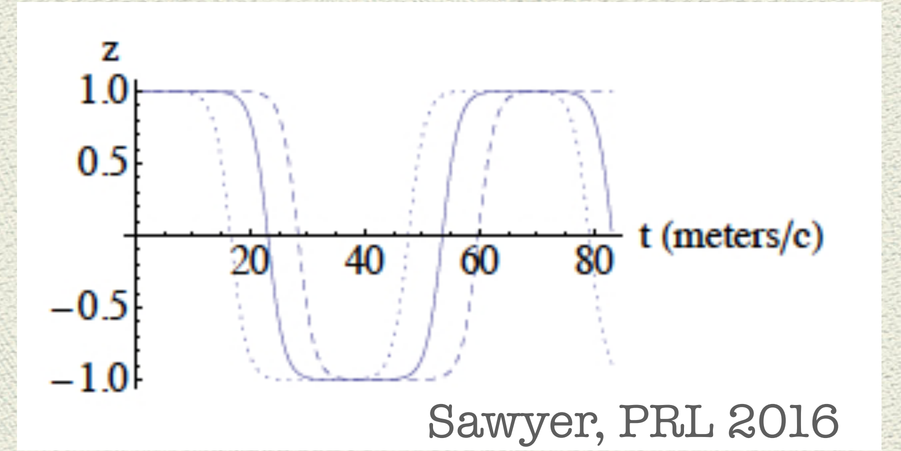


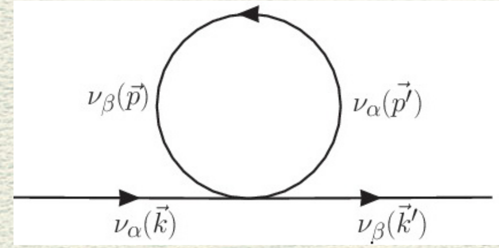
$$< E_{\nu_e} ><< E_{\bar{\nu}_e} ><< E_{\nu_{\mu,\tau}} >$$

Flavor evolution produces *spectral modifications*, compared to thermal distributions at the neutrinosphere (where they start free streaming).

«Fast» modes

- Neutrino self-interactions can produce fast conversions, on very short distance scales.





They require the presence of an electron anti-neutrino excess over the neutrino one at the neutrinosphere.

Toy models and 1-D simulations studied so far.

- <u>Open issues recently debated :</u>

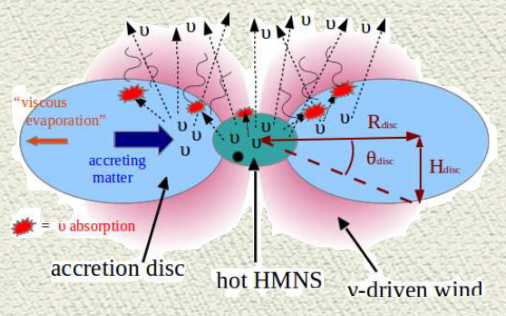
Do «fast» modes produce flavor equilibration ?

Do they influence the supernova dynamics (they occur behind the shock region) ?

Do they take place in multi-dimensional supernova simulations ?

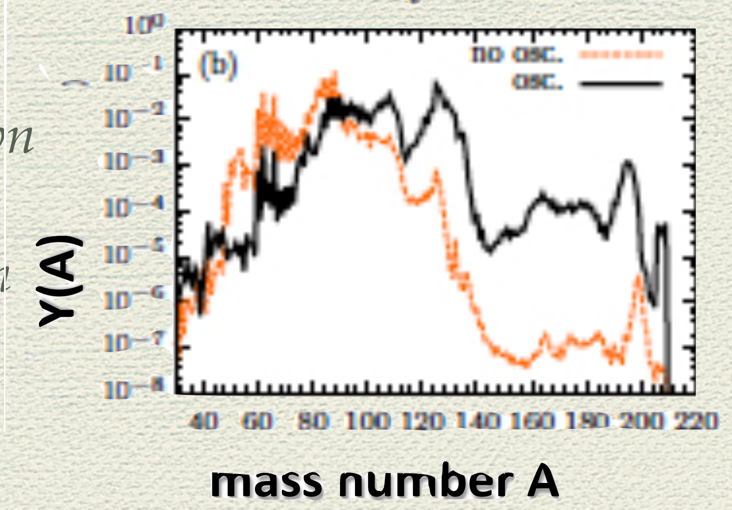
Do « fast » flavor conversion modes produce flavor equilibration ?

- *Many speculations in the literature that the neutrino fluxes would equilibrate, i.e. become degenerate. From the point of view of observations and of simulations, this possibility would greatly simplify the problem of neutrino flavor evolution.*

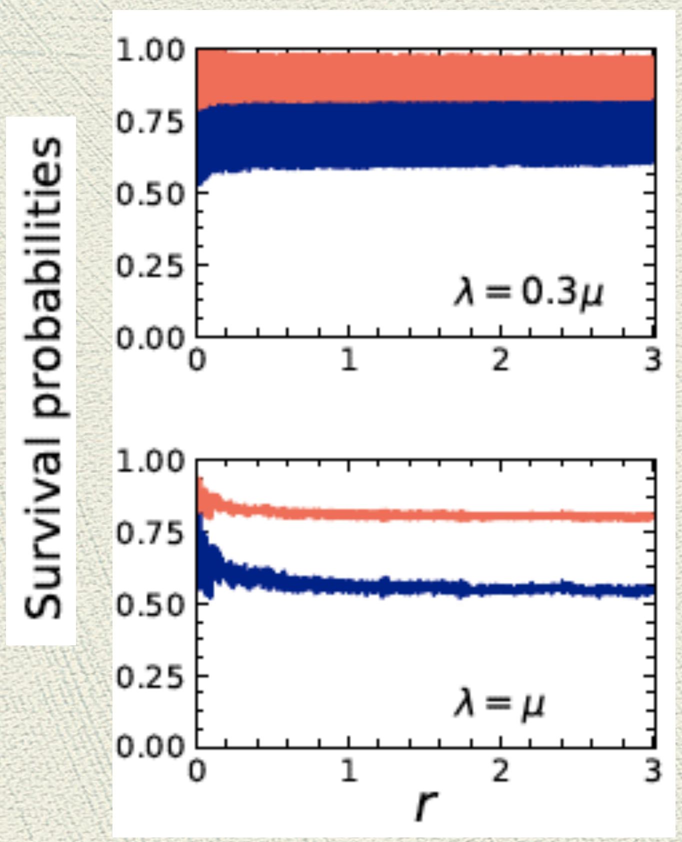


For example, it has been shown that it could produce a strong r-process in a neutrino-driven wind in a kilonova.

Wu et al., PRD96 (2017)



«Fast » modes do not produce flavor equilibration



Flavor conversion at short distance scale occurs due to neutrino self-interactions.

The survival probabilities almost never go to 0.5.

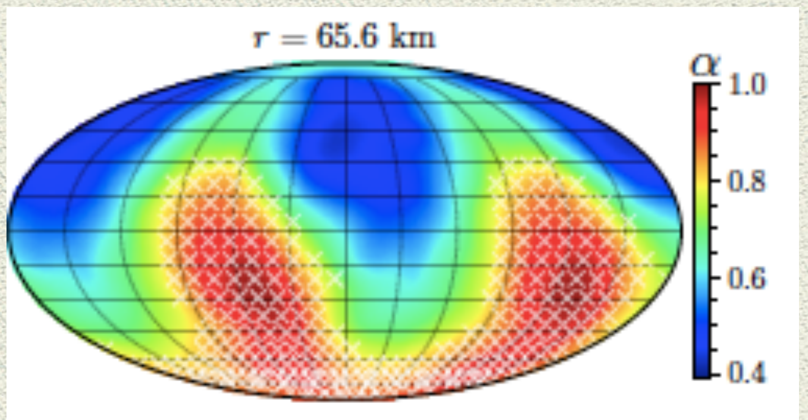
We have refuted this conjecture based on a schematic model.

Abbar, Volpe, Phys.Lett. B790 (2019)
arXiv :1812.06883

Do « fast » modes occur in multi-D supernova simulations ?

- Toy models studied so far.
  A study based on 1-D simulations did not find evidence for such modes.

« Fast » neutrino conversion modes in core-collapse supernovae



t= 200 ms snapshot

Mollweide projection for
the nue-to-antinue flux ratio

Crosses indicate occurrence
of fast modes - linearized analysis

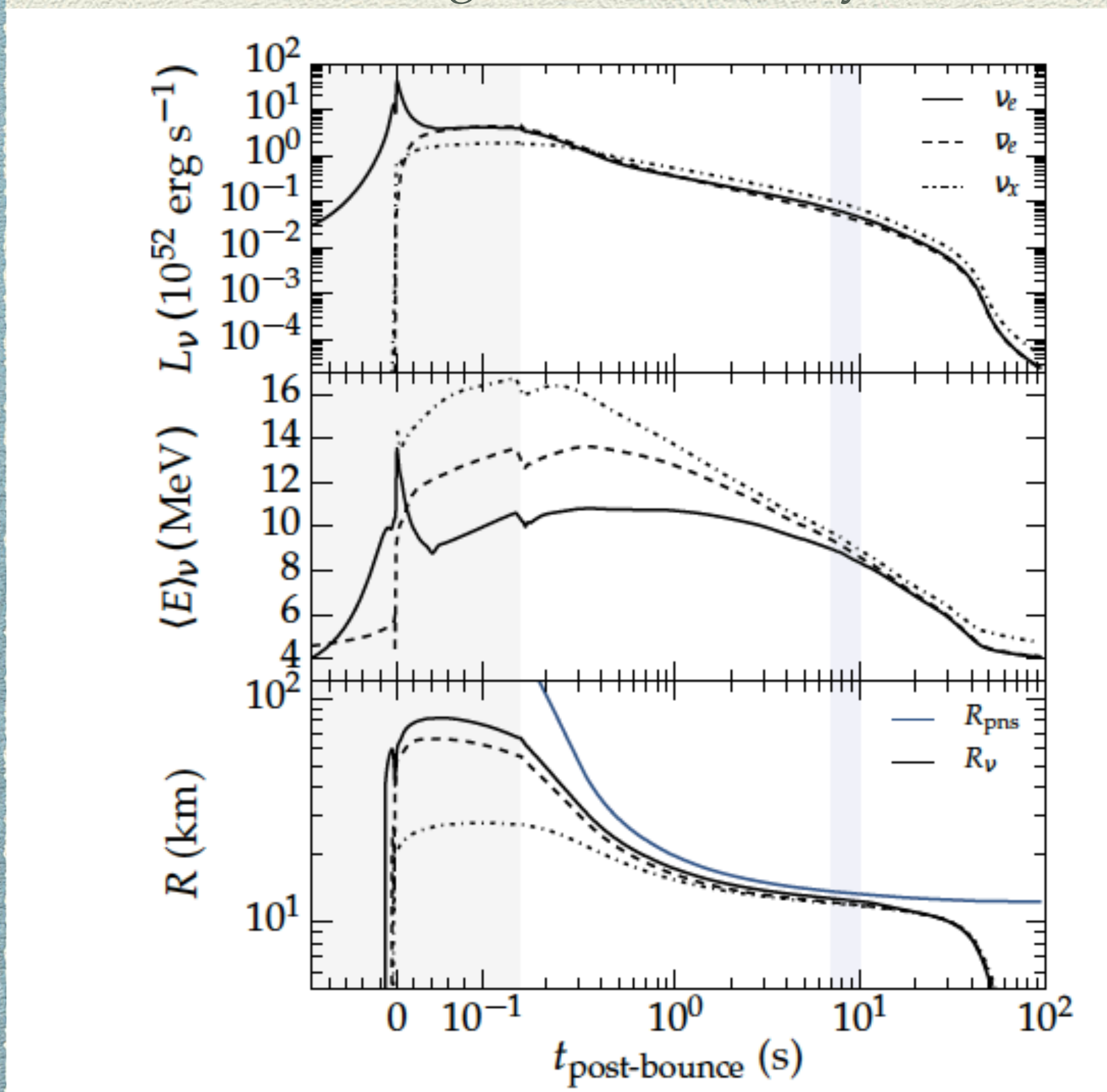
First evidence for the occurrence of neutrino flavor conversion, in 2- and 3-dimensional supernova simulations (within the neutrino sphere).

Found in 11.2 and 27 Msun progenitors and various snapshots after core-collapse. The potential impact on the shock dynamics still unknown.

Abbar, Duan, Sumiyoshi, Takiwaki, Volpe,
arXiv :1812.06883

Observations from future core-collapse supernova neutrinos

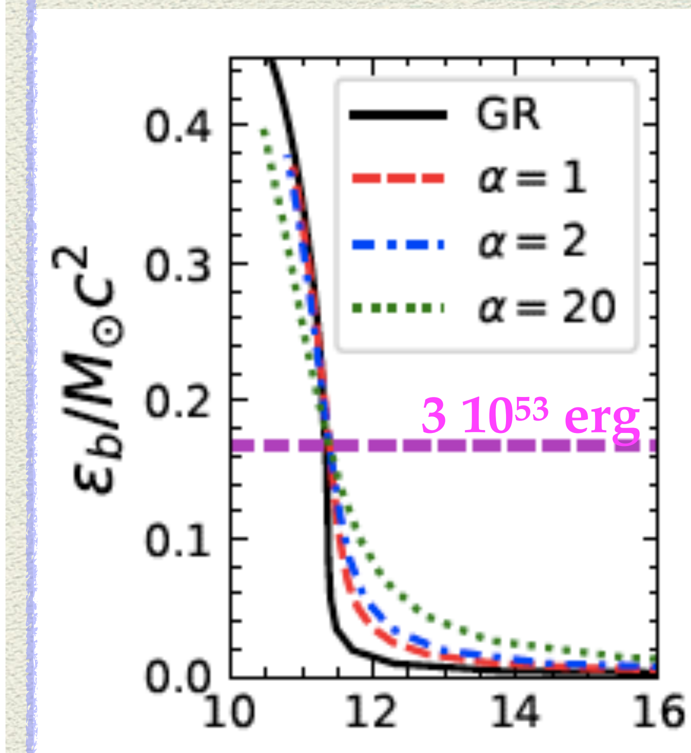
Reference : Cooling model of Reddy & Roberts.



Neutron star cooling neutrino signal :
Gravitational binding energy-star radius relation

The late time neutrino signal can be approximated as black-body emission :

$$L = 4\pi\sigma_{BB}\phi R^2 k_B^4 T^4,$$



	α−PRIOR+			
	Mean [km]	SD [km]	Acc [%]	
	23.8 (22.2)	20.5 (17.9)	86.1 (80.8)	ν_e
	9.2 (9.9)	2.4 (1.2)	25.6 (12.2)	$\bar{\nu}_e$
	13.9 (13.0)	3.4 (1.8)	24.5 (13.7)	ν_x

Eb-R relation depends on the neutron star equation of state and potentially EGR (f(R)).

Neutron star radius reconstruction with neutrinos difficult.

Gallo Rosso, Abbar, Vissani, Volpe, JCAP 1812 (2018).

Conclusions and perspectives

- Neutrino flavor evolution in dense environments is a complex many-body problem. Novel flavor conversion mechanisms being unravelled.

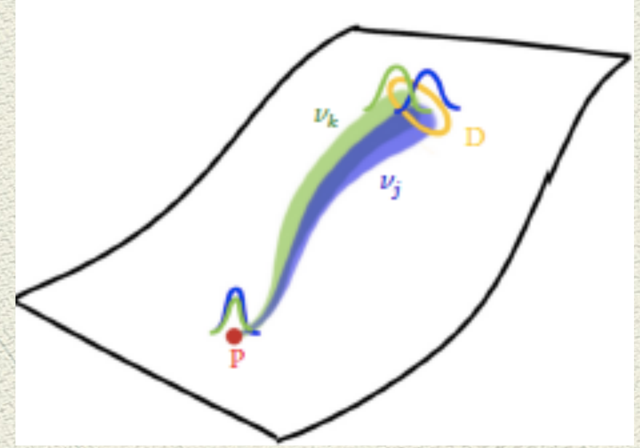
  Flavor mechanisms produce spectral modifications and can influence the shock dynamics, heavy elements nucleosynthesis (kilonovae) and future observations.

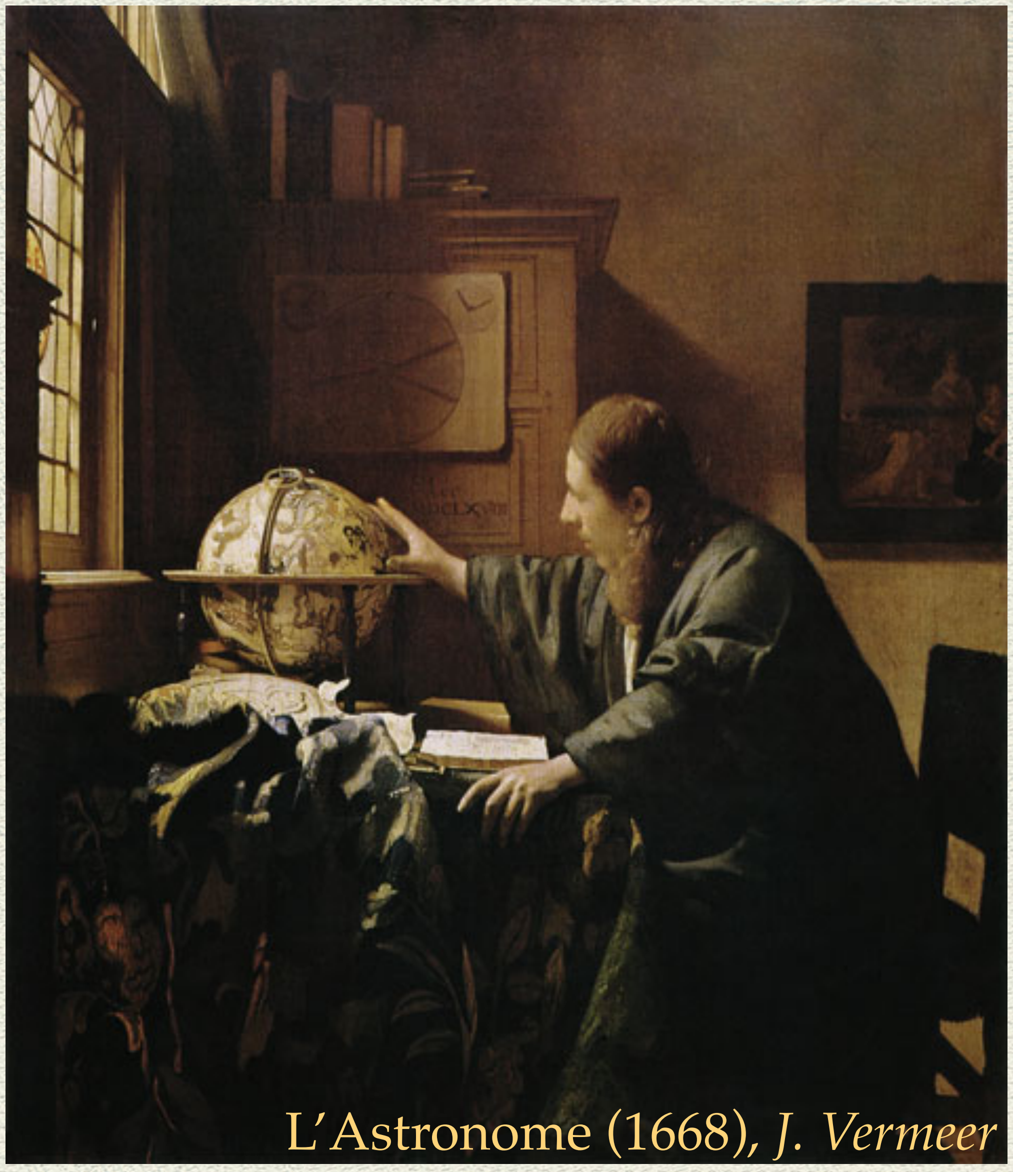
- «Fast» modes are attracting a lot of interest : *they occur in multi-D simulations and do not bring flavor equilibration*. Their impact on the shock and heavy elements nucleosynthesis to be assessed.

- Reconstructing the neutron star radius from the late time neutrino signal complex. Eb-R sensitive to neutron star equation of state, little to extended theories of gravity.

  Future supernova neutrino observations can tell us about the newly born neutron star properties and on star formation rates. Upcoming measurement of the diffuse supernova neutrino background.

- Effects of strong gravitational fields on flavor evolution needs further investigations.





L'Astronome (1668), *J. Vermeer*