Neutrino astrophysics

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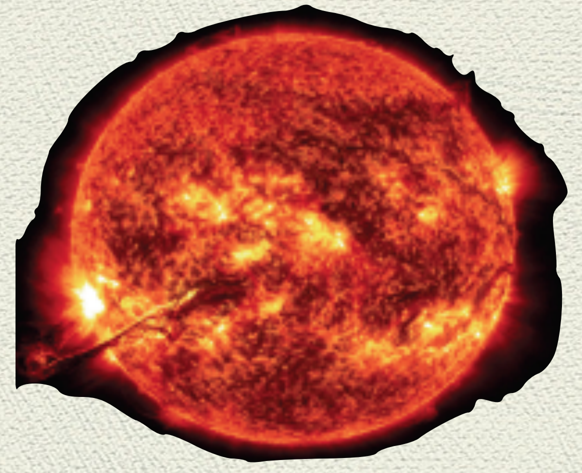
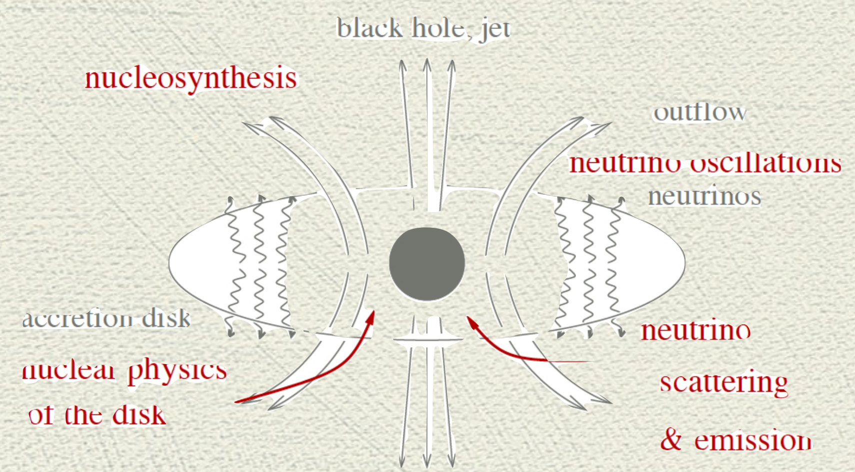
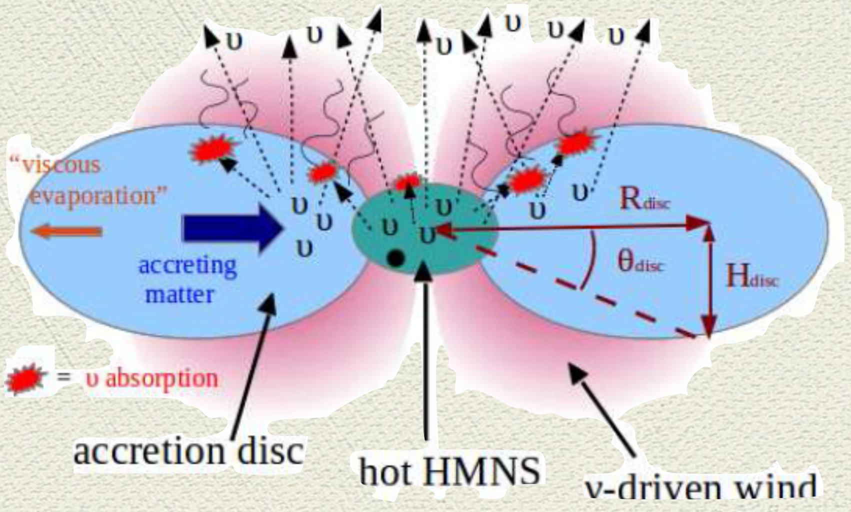


Sun

core-collapse Supernovae



McLaughlin



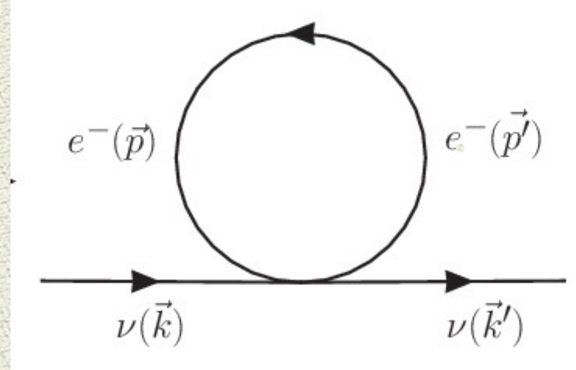
Perego et al, 2014

accretion disks around black holes or neutron star mergers remnants

Solar neutrinos

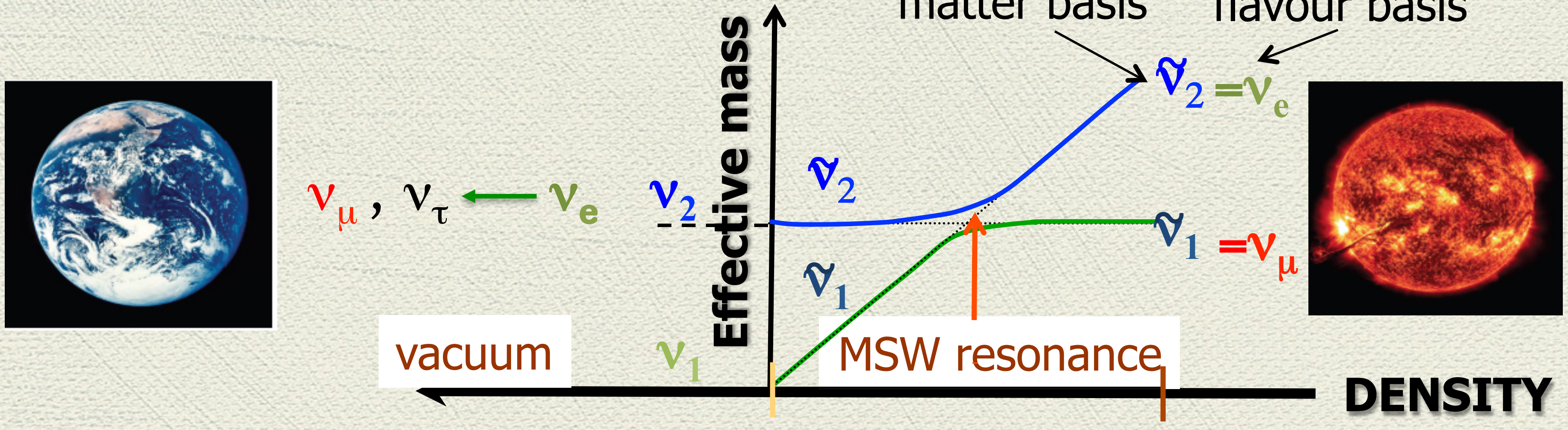
Neutrinos interact with matter and undergo resonant adiabatic flavor conversion : the Mikheev-Smirnov-Wolfenstein effect.

Wolfenstein PRD (1978)
Mikheev, Smirnov(1985)



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

mean-field approximation



$$h_\nu = \begin{pmatrix} -\Delta\tilde{m}^2/4E & -i\dot{\theta}_M \\ i\dot{\theta}_M & \Delta\tilde{m}^2/4E \end{pmatrix}$$

neutrino hamiltonian in the matter basis

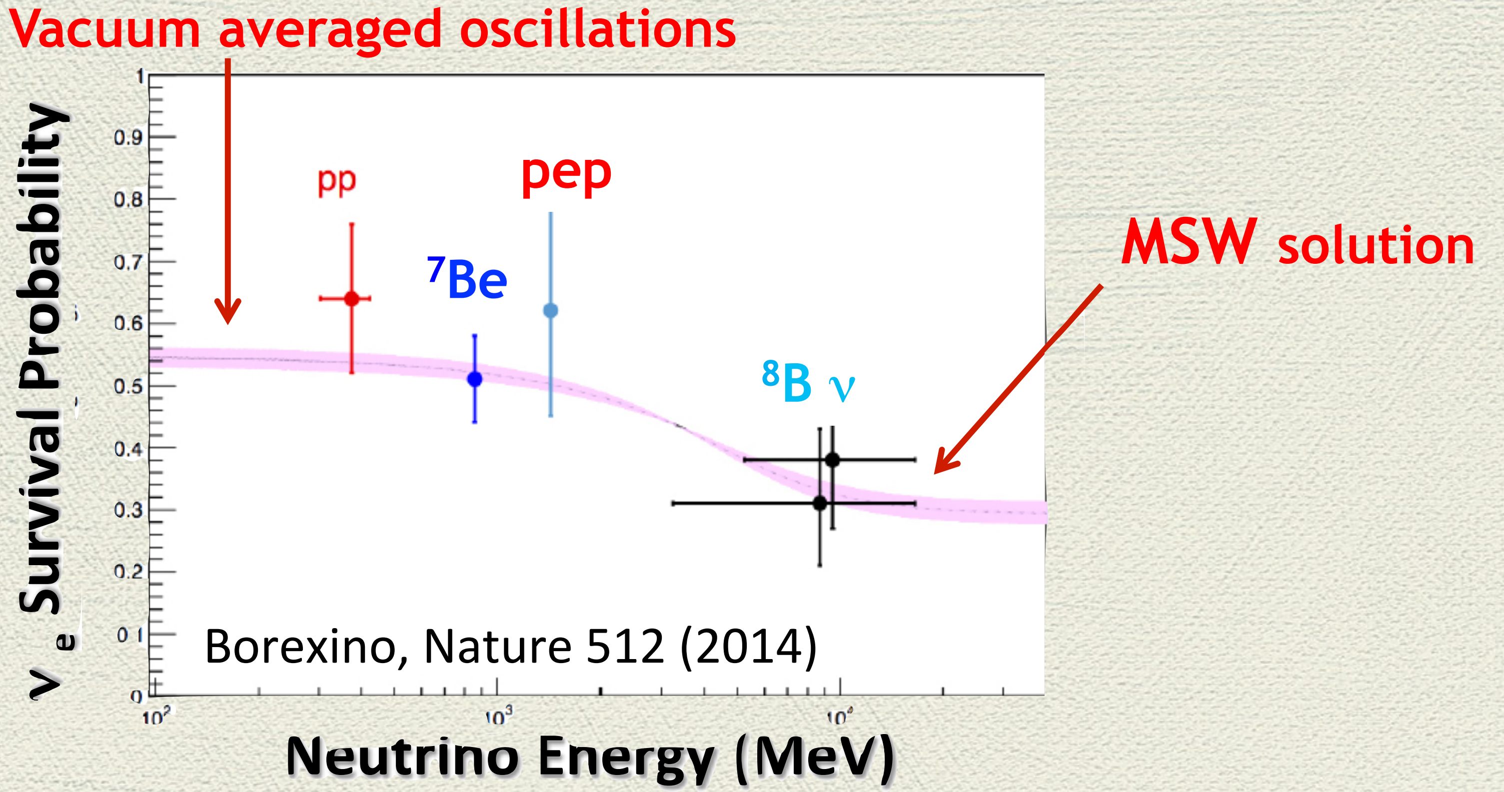
Resonance condition :

$$h_{\nu,11} - h_{\nu,22} \approx 0$$

Adiabaticity :

$$\gamma = \frac{\mid \dot{\theta}_M \mid}{\Delta\tilde{m}^2/4E} << 1$$

Current status of solar neutrino observations



Vacuum averaged oscillations

MSW solution

Borexino, Nature 512 (2014)

Vacuum-averaged oscillations versus MSW suppression of high energy ^{8}B neutrinos.

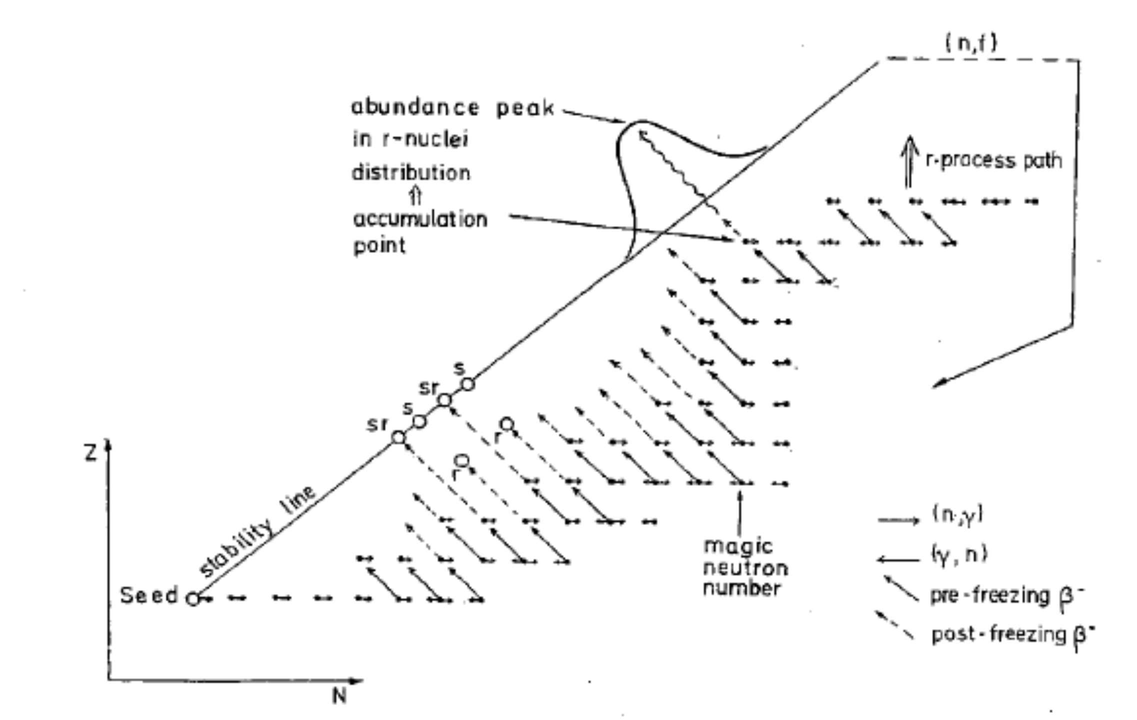
Energy production of low mass main sequence stars confirmed — pp reaction chain.

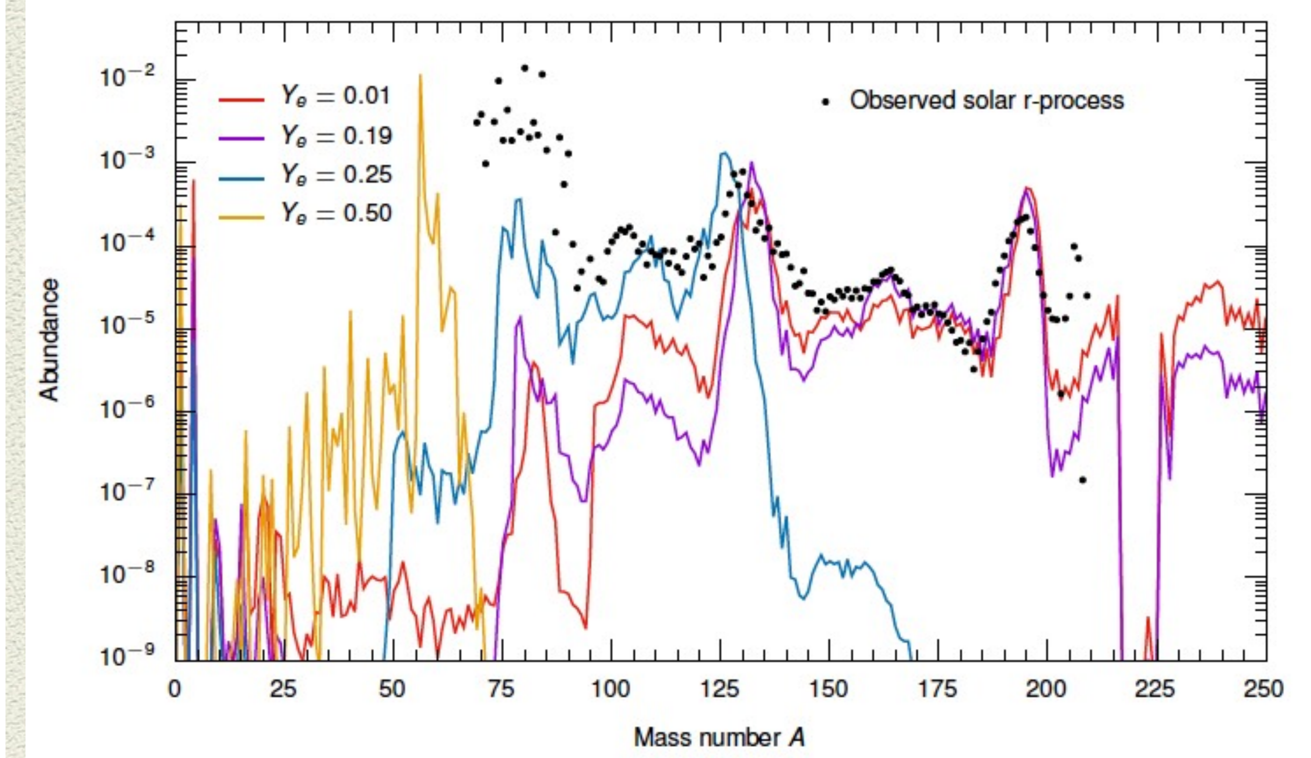
Future measurement of CNO neutrinos - main energy production in massive main sequence stars.

The site of heavy elements nucleosynthesis is still unknown

- Heavy elements (A > 90) are produced in stellar environments during a fast process in presence of a large number of neutrons (*r*-process).

$$Y_e = \frac{p}{p+n}$$

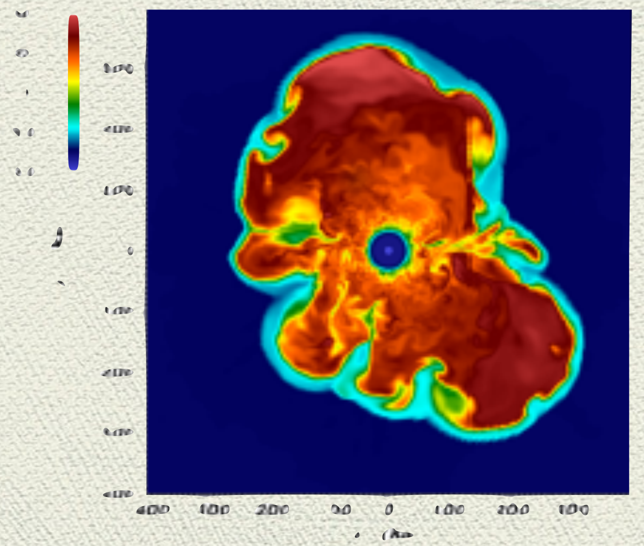




Roberts 2015, arXiv :1508.03133

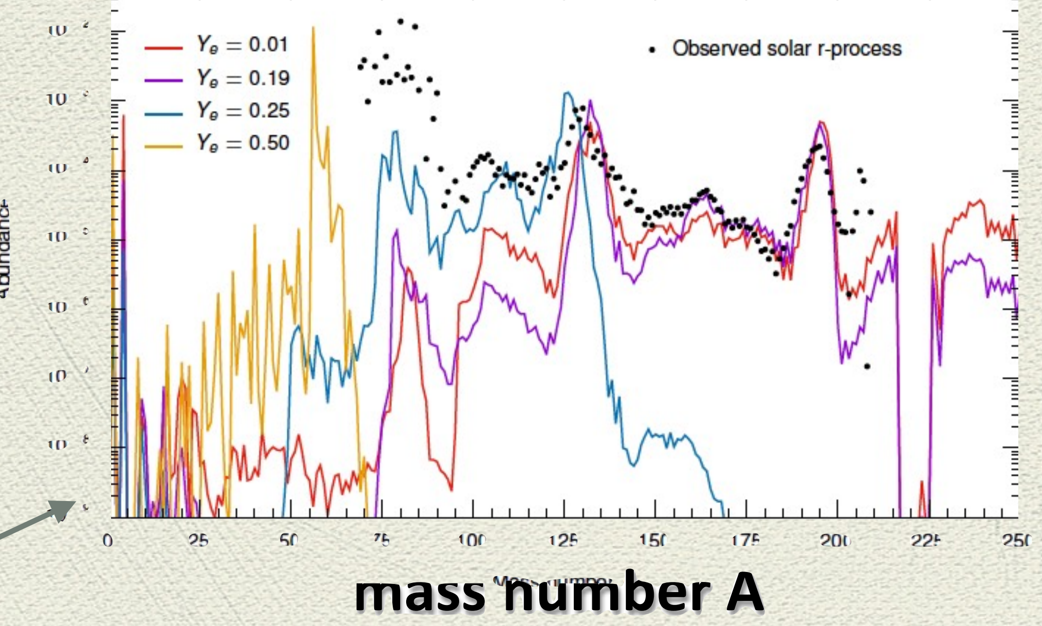
- Supernovae and accretion disks around compact objects - black holes and binary neutron stars - are candidate sites with lots of neutrinos.

Neutrinos in dense environments



Mueller et al,
arXiv: 1705.00620

Iron core-collapse supernova explosions



Heavy elements nucleosynthesis

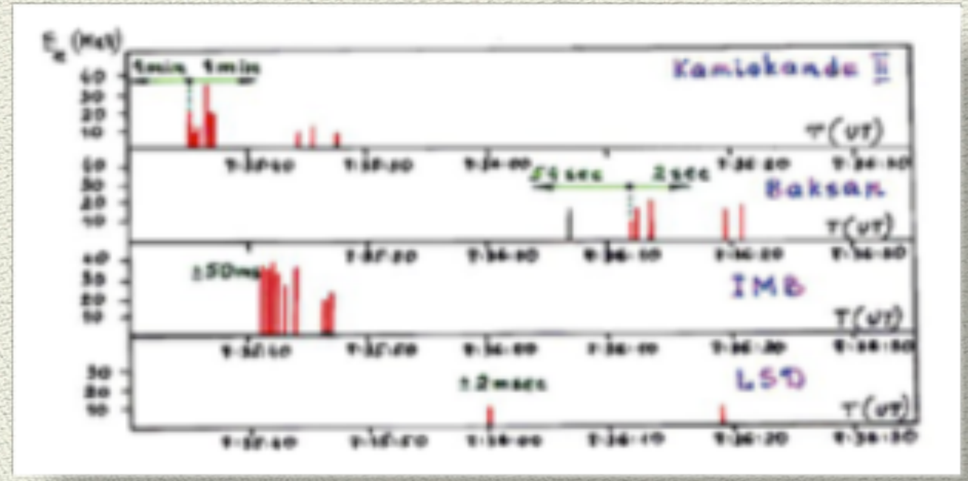
Understanding
the role of neutrinos
and flavor conversion

Predicting the neutrino fluxes for future observations :

- an (extra)galactic supernova - we expect 10^4 - 10^6 events at 10 kpc
- the diffuse supernova neutrino background - EGADS project (Super-K + Gd)

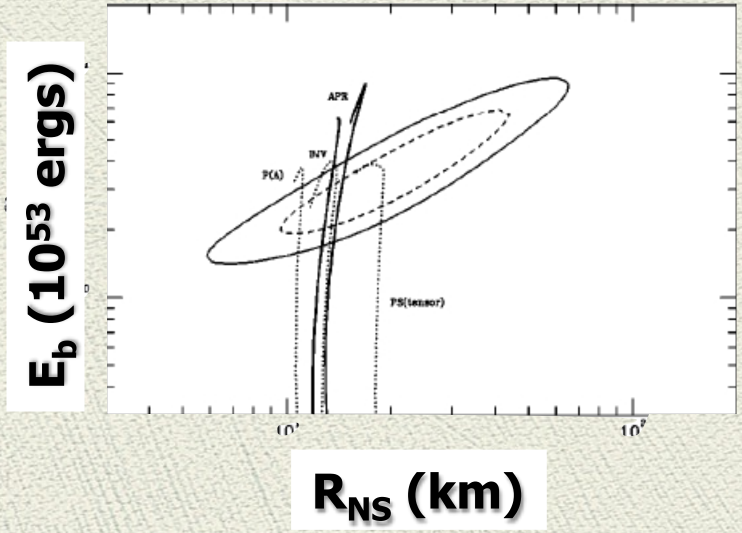
Neutrinos from core-collapse Supernovae

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

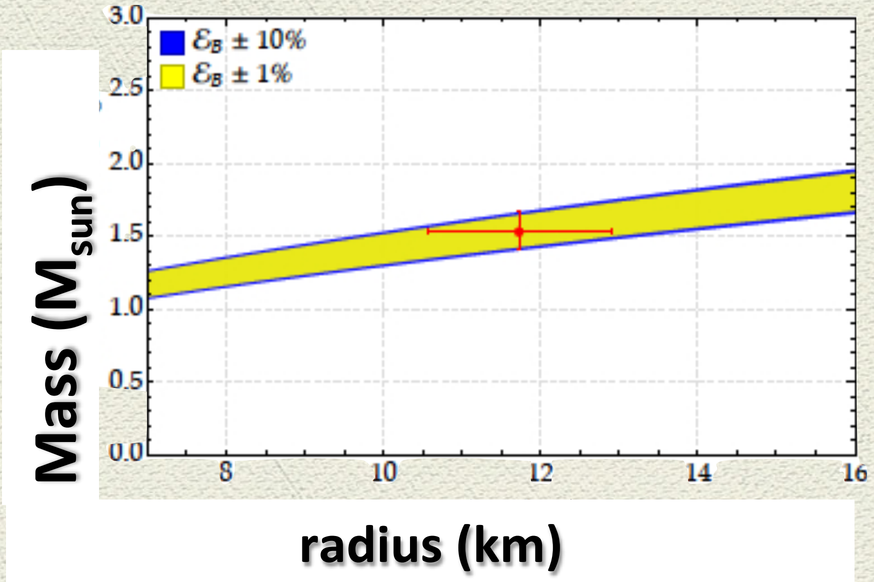


Sanduleak 69^{0}202, a blue super-giant in Large Magellanic Cloud, at 50 kpc, no remnant found so far.

SN1987A : Delayed explosion mechanism favored over the prompt one.



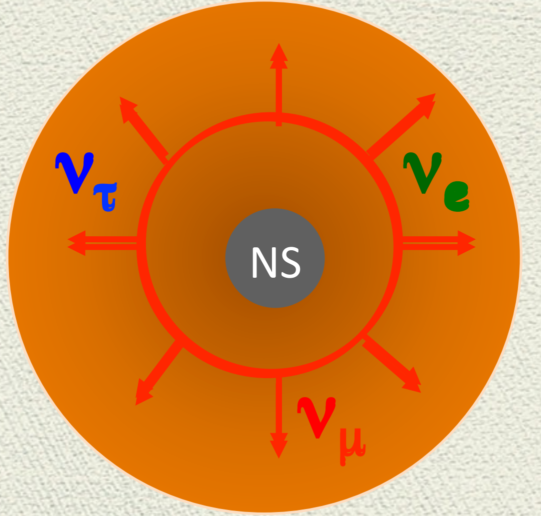
Loredo, Lamb, PRD 2002



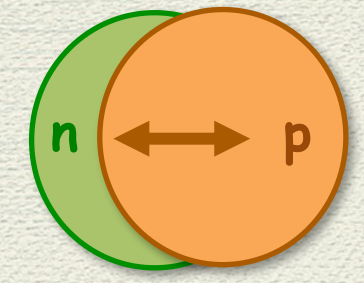
Gallo Rosso et al., JCAP1711 (2017)

Predictions for Super-K and Hyper-K in case of a supernova at 10 kpc

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



ν in stars or accretion disks



atomic nucleus

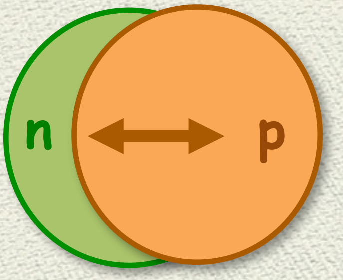
10^{57}	**N**	200
weak	**interaction**	strong
unbound	**system**	bound
$\rho_{ji} = \langle a_i^+ a_j \rangle$ neutrinos $\bar{\rho}_{ji} = \langle b_i^+ b_j \rangle$ anti-neutrinos	**density**	$\rho = \langle a^+ a \rangle$ neutrons protons

To determine the dynamics

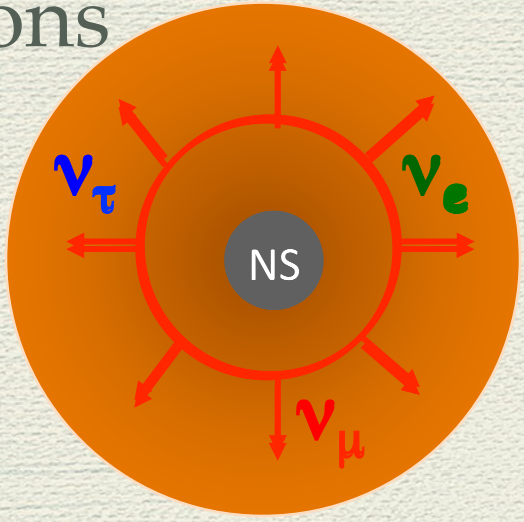
$\rho_1 = \left\langle a^+ a \right\rangle$ $\rho_{12} = \left\langle a^+ a^+ a a \right\rangle$ $\rho_{123} = \left\langle a^+ a^+ a^+ a a a \right\rangle$ …

one-body density two-body three-body N-body

The neutrino evolution equations



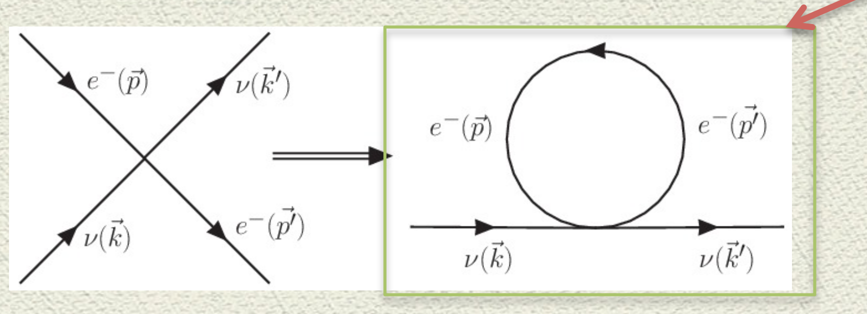
$\rho = \langle a^{+} a \rangle$ one-body density matrix

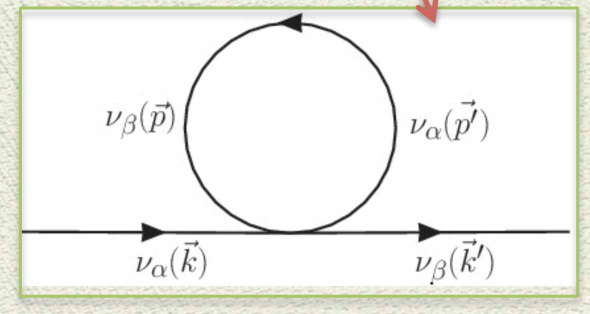


$$\rho = \begin{pmatrix} < a^\dagger_{\nu_e} a_{\nu_e} > & < a^\dagger_{\nu_\mu} a_{\nu_e} > \\ < a^\dagger_{\nu_e} a_{\nu_\mu} > & < a^\dagger_{\nu_\mu} a_{\nu_\mu} > \end{pmatrix}$$

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

neutrino self-interactions

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

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)

Novel conversion phenomena in dense media due to the neutrino self-interaction

Nucleosynthesis and neutrinos

- Neutrinos 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 neutron-to-proton ratio or electron fraction - $Y_e = \frac{p}{p+n}$

- **Neutrino flavor evolution influences Ye because flavor modification produces spectral swapping(s).**

AN EXAMPLE

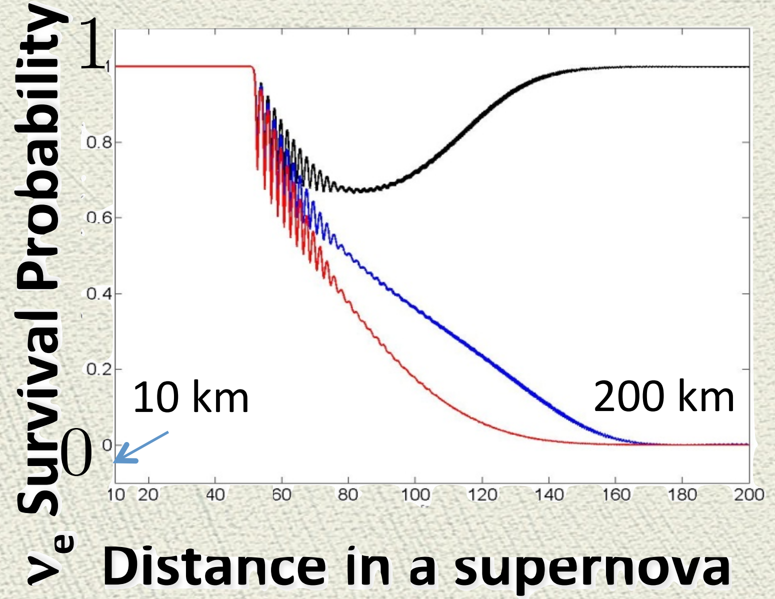
$$\phi_{\nu_e}(E) = P(\nu_e \rightarrow \nu_e)\phi^0_{\nu_e}(E) + [1 - P(\nu_e \rightarrow \nu_e)]\phi^0_{\nu_x}(E)$$

neutrino fluxes at the neutrino sphere

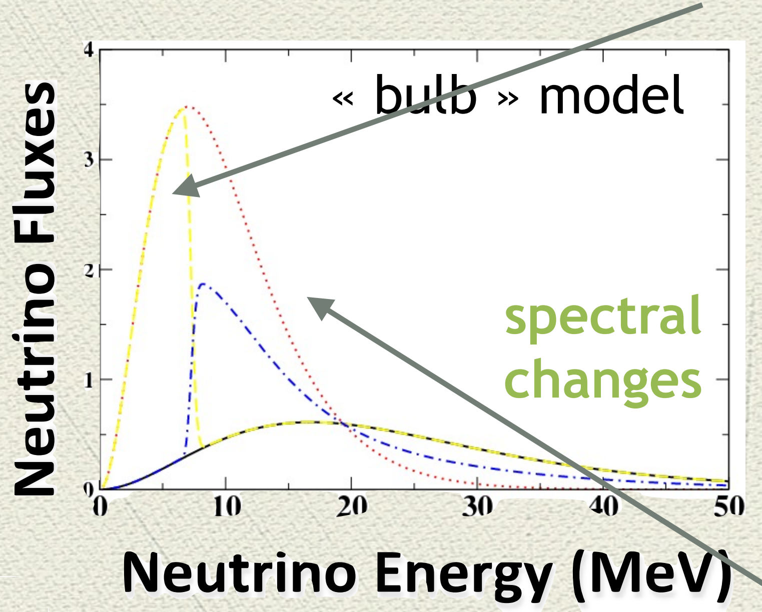
neutrino fluxes at 200 km from it

$\phi_0(E)$

$\phi(E)$



If $P(\nu_e \rightarrow \nu_e) \approx 1$ $\phi_{\nu_e}(E) = \phi^0_{\nu_e}(E)$

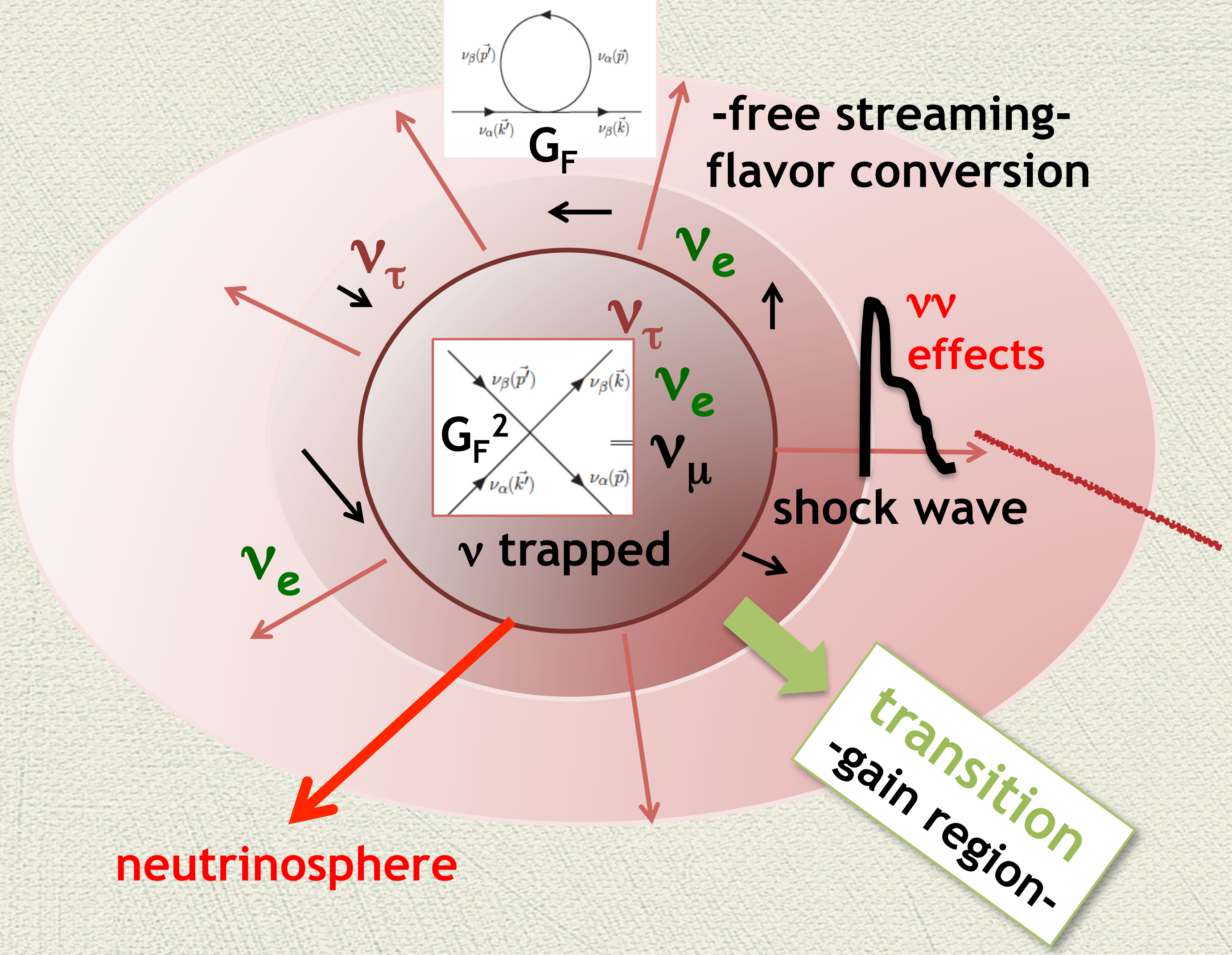


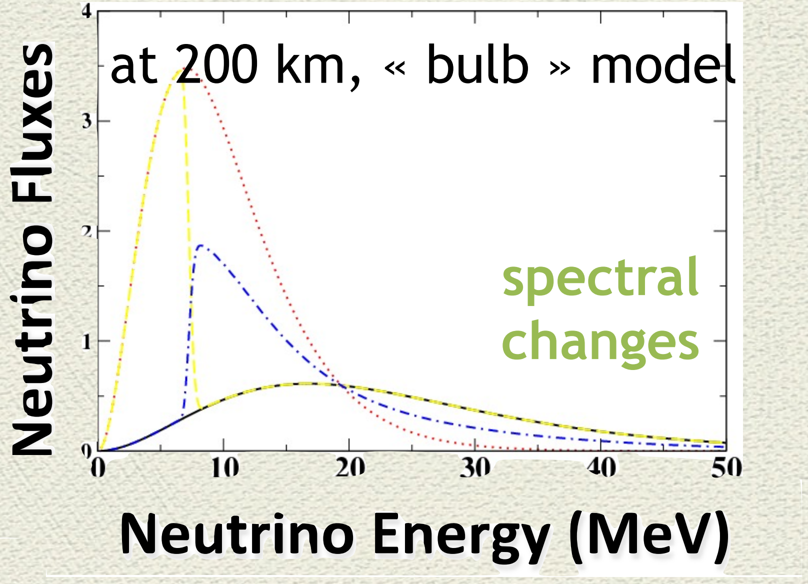
If $P(\nu_e \rightarrow \nu_e) \approx 0$ $\phi_{\nu_e}(E) = \phi^0_{\nu_x}(E)$

Supernovae explosions and flavor evolution

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

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

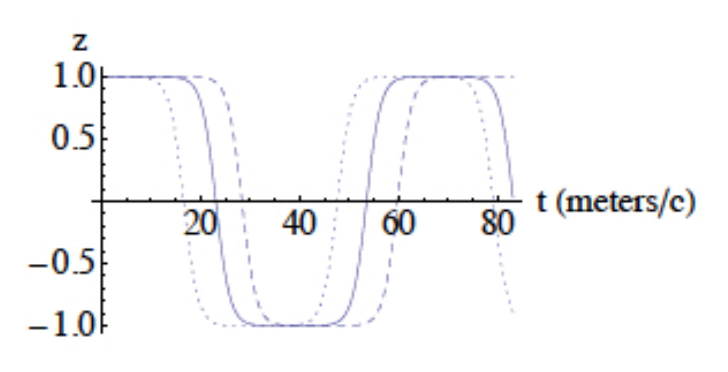




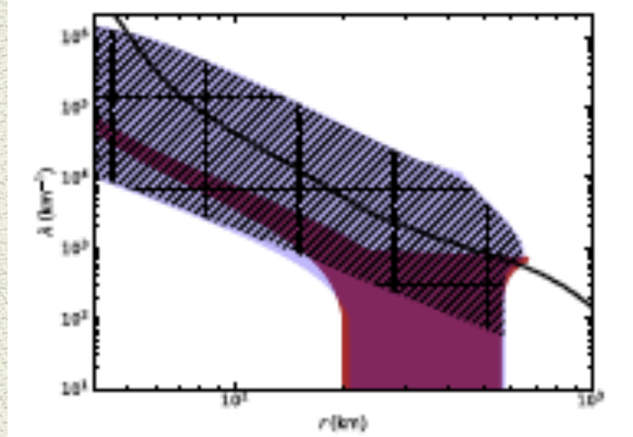
Sharp transition from the dense (Boltzmann) to the dilute (mean-field) region.

Improved description of the « transition » region

- Appearance of « fast » conversion modes on short distance scales, if emission at the neutrino-sphere is anisotropic.



Sawyer, PRL108 (2016)



Abbar, Duan, arXiv:1712.07013

- Corrections to the evolution equations from correlators with helicity change, due to neutrino mass.

$$\zeta = \left\langle a_+^+ a_- \right\rangle$$

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

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

Φ couples ν 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)

A first calculation has shown helicity coherence could modify flavor evolution significantly.

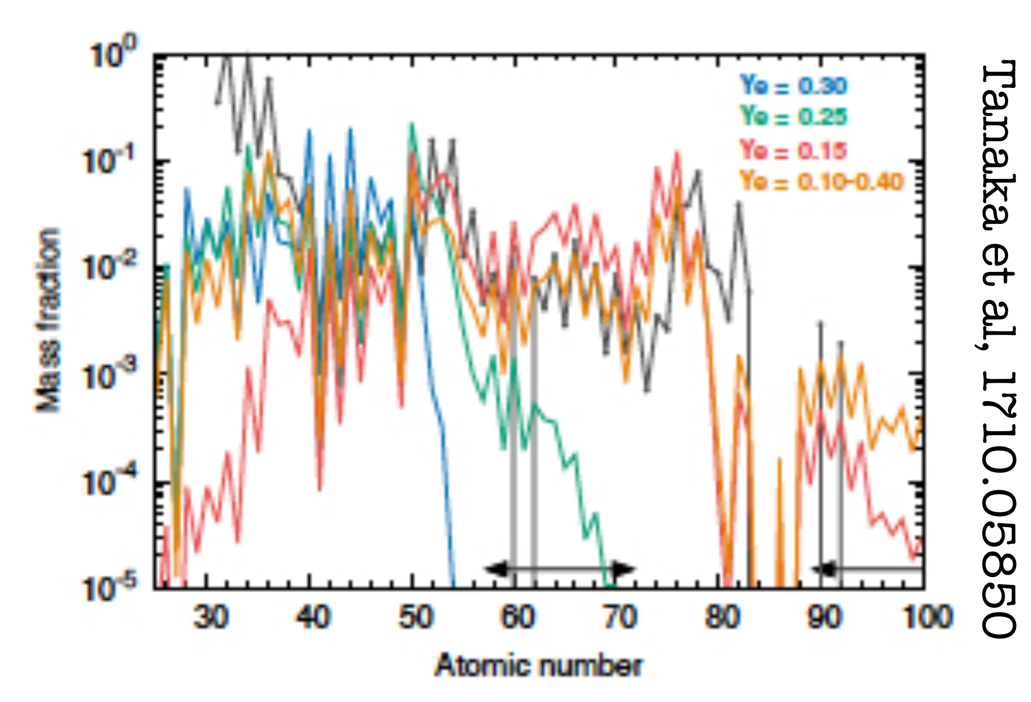
GW170817 and the kilonova observations

- The recent observation of gravitational waves from binary neutron star mergers, in coincidence with a short gamma-ray-burst and a kilonova.

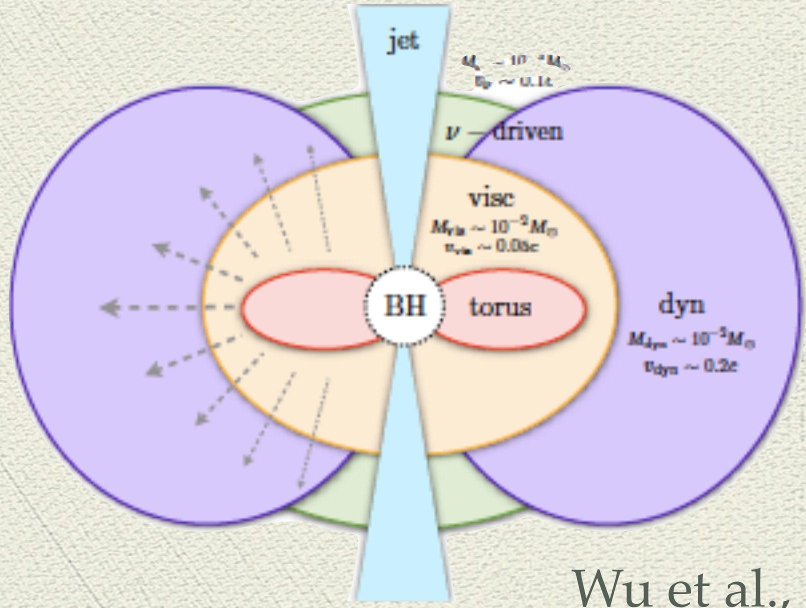
- The electromagnetic signal covering has a red and a blue components that indicate the presence of r-process elements and in particular lanthanides in the ejecta.

- Lanthanides elements are extremely sensitive to the electron fraction Ye. If Ye > 0.25 lanthanides are not synthesized. Neutrinos drive Ye to large values of Ye.

- Observations and comparisons with binary neutron star mergers models tell us that there are dynamical ejecta from the early merging phase, with Ye < 0.25, and ejecta from neutrino-driven winds in the late time post-merger phase with Ye > 0.25.



Tanaka et al, 1710.05850



Wu et al., 2017

Flavor evolution in ν-driven winds?

Helicity coherence in binary neutron star merger remnants

Chatelain, Volpe, PRD 95 (2017), 1611.01862

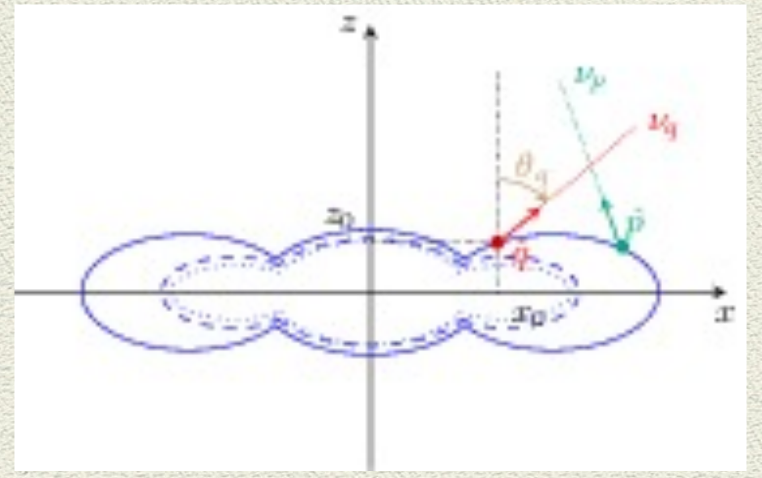
Investigated the role of correlators with helicity change in an extended mean-field description.

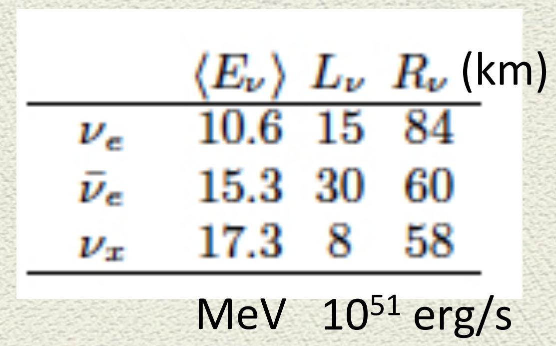
Solved the evolution equations with

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

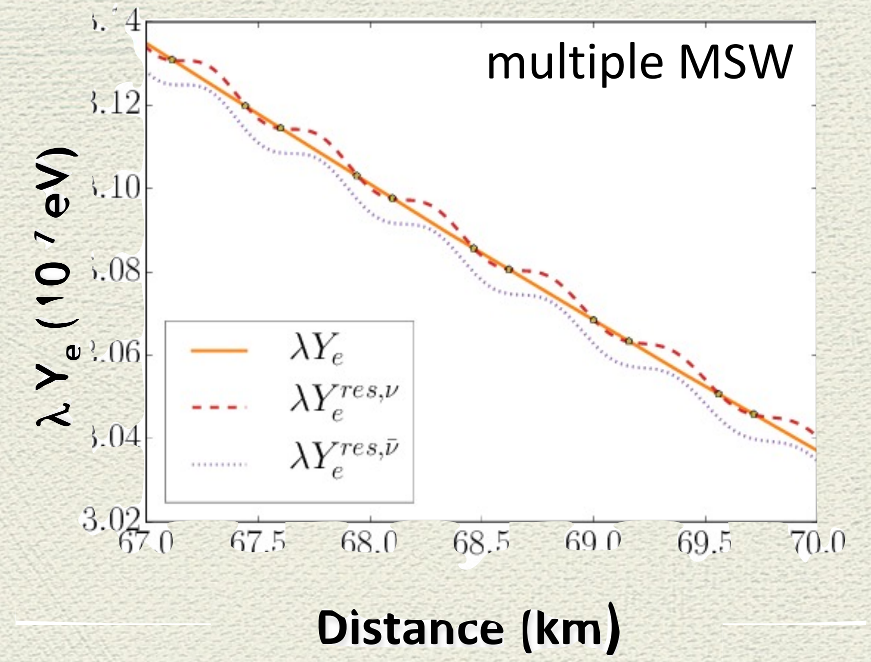
In two flavors
$\mathcal{H}$ is a 4 x 4 matrix.

Φ couples ν with $\bar{\nu}$
helicity coherence
$\Phi \sim (h_{mat}^{perp} + h_{\nu\nu}^{perp})$ x $m/2E$

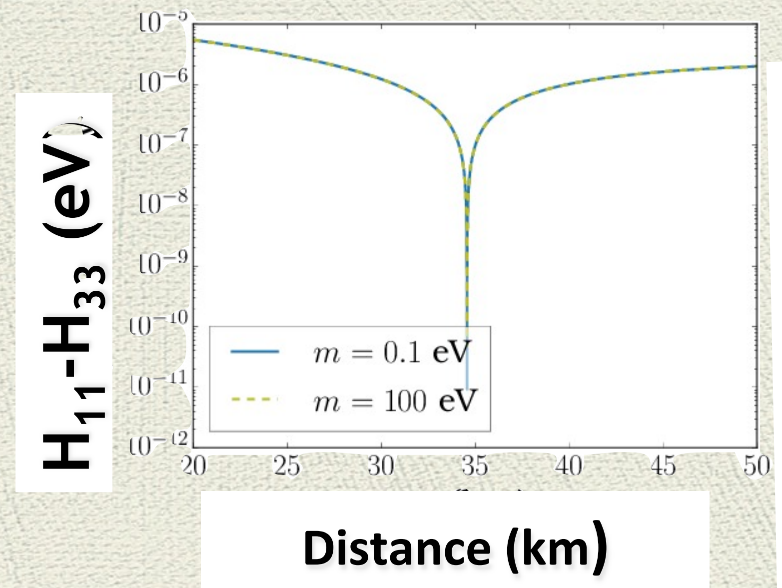


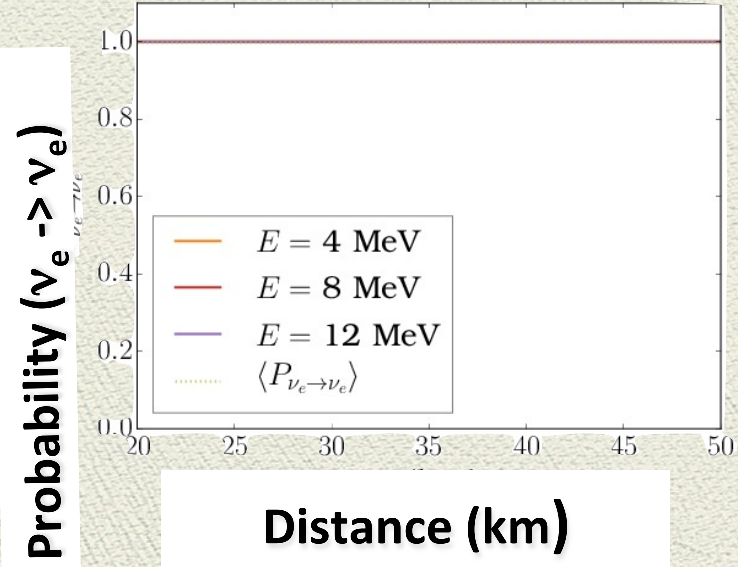


	$\langle E_\nu \rangle$	L_ν	R_ν (km)
ν_e	10.6	15	84
$\bar{\nu}_e$	15.3	30	60
ν_x	17.3	8	58
	MeV	10^{51} erg/s	



multiple MSW



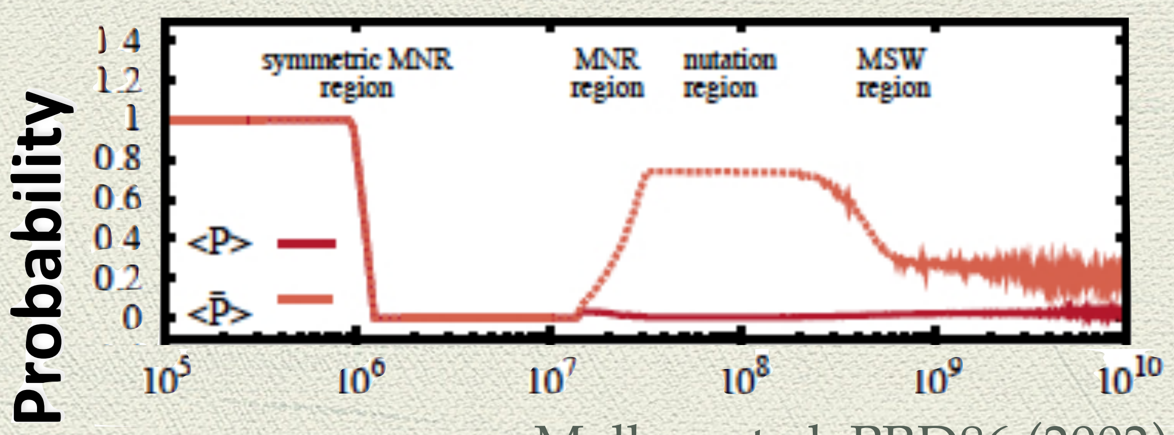


Resonance condition fulfilled but adiabaticity not enough to modify the flavor content.

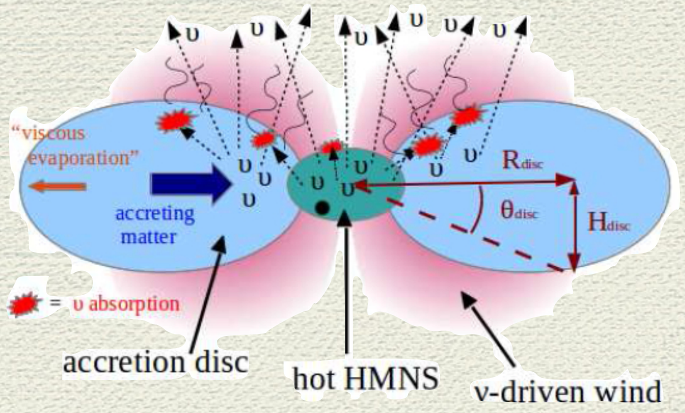
contrary to the findings in Vlasenko, Fuller, Cirigliano, 1406.6724

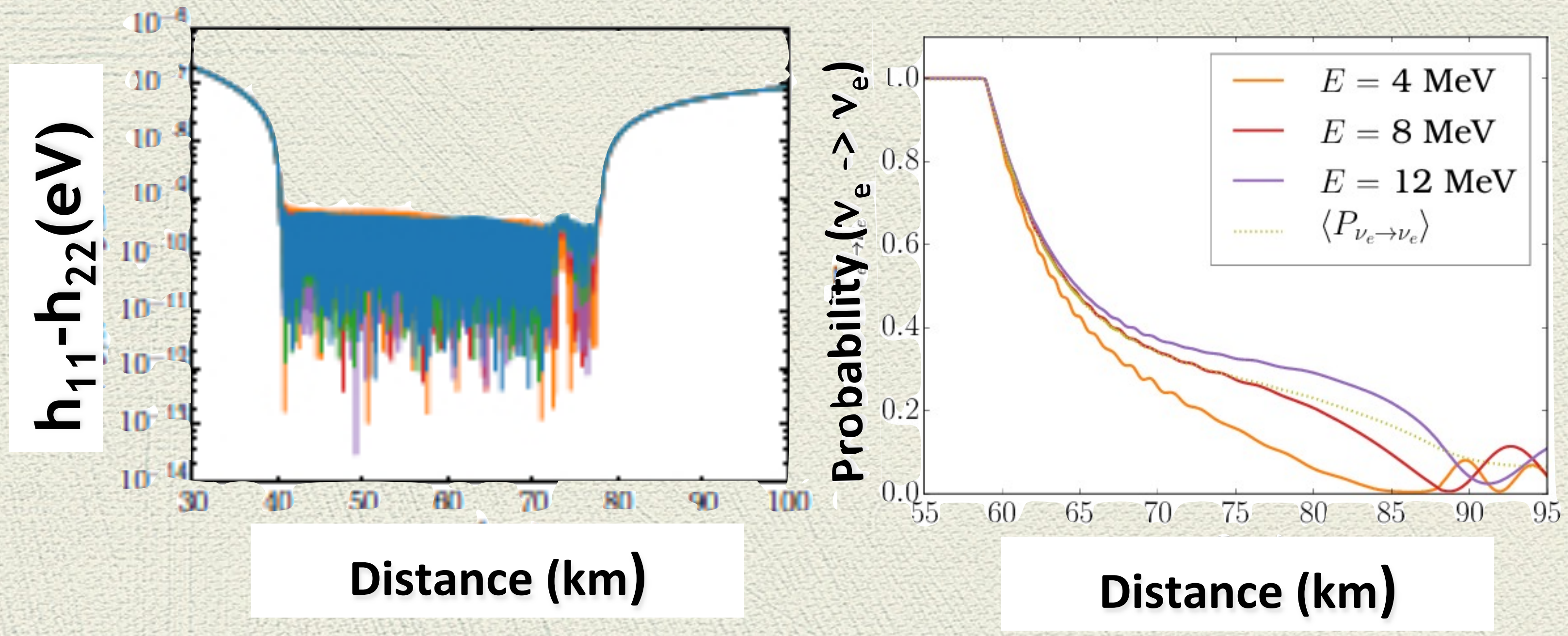
Matter-neutrino resonance in binary neutron star mergers

In binary neutron star mergers, the electron antineutrino excess can produce a cancellation of the matter and self-interaction potentials. This is known as the Matter-Neutrino Resonance.

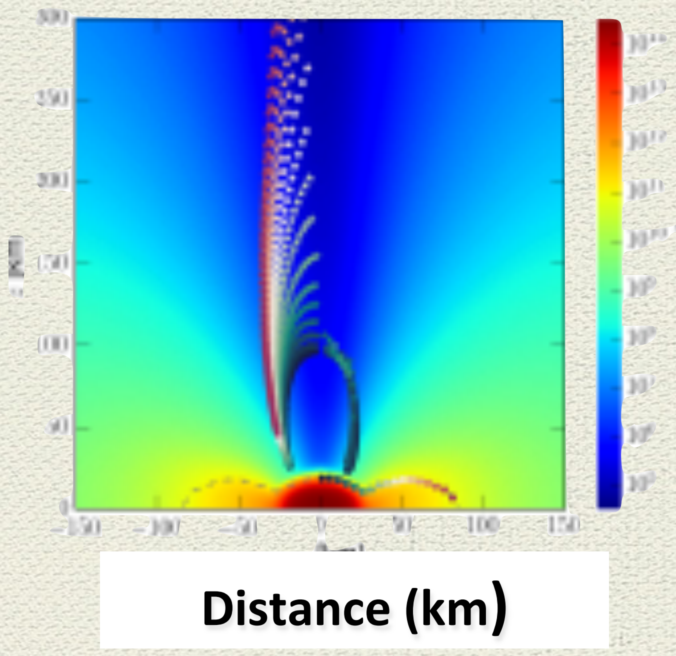


Malkus et al, PRD86 (2002)





Chatelain, Volpe, PRD 95 (2017), 1611.01862



Frensel et al., PRD95 (2017)

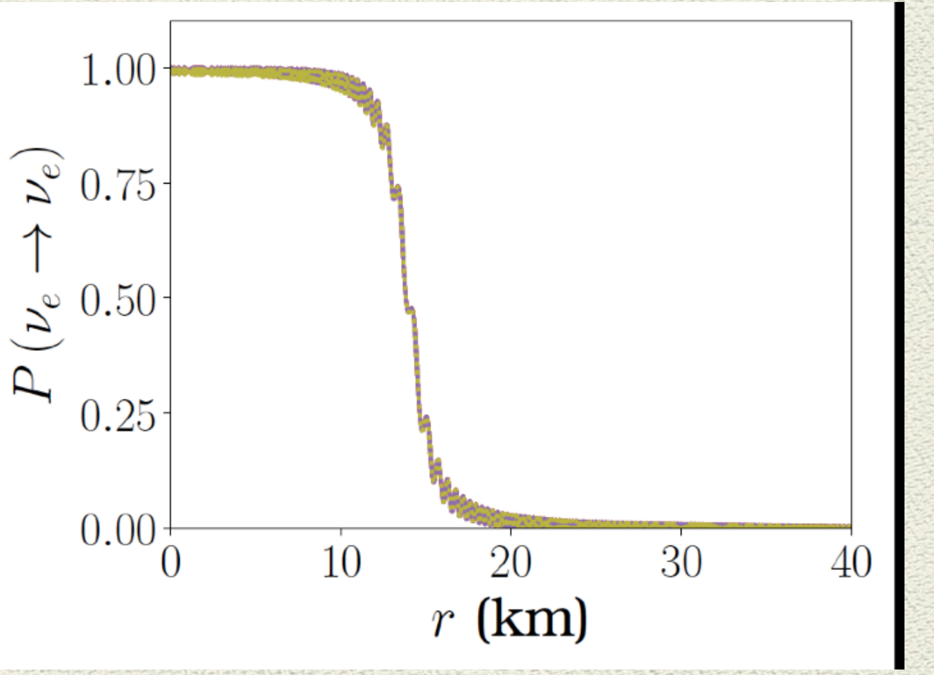
Resonance condition fulfilled, adiabatic evolution, flavor modified for electron neutrinos and anti-neutrinos. MNR resonances occur in the polar region.

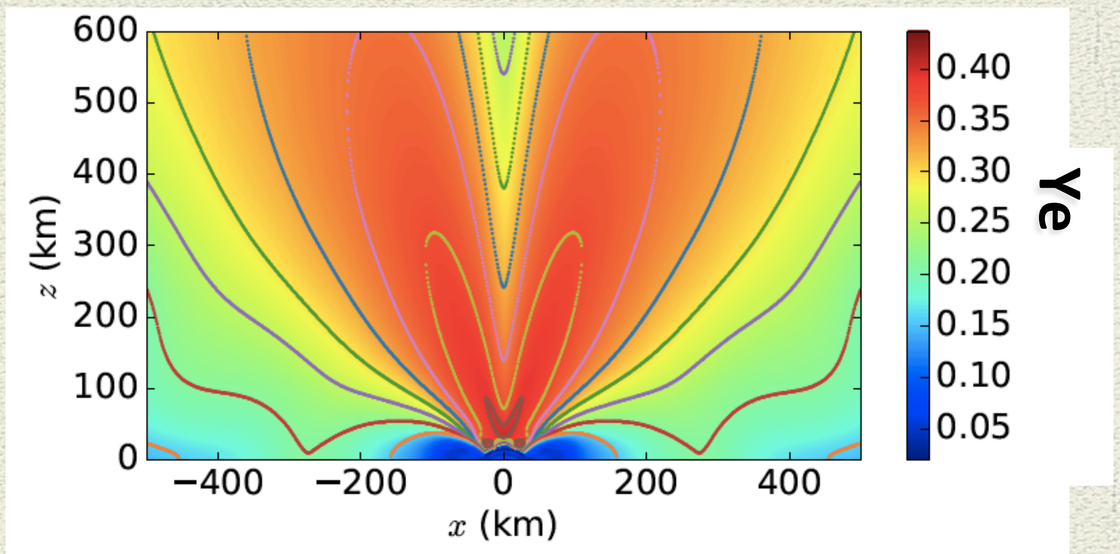
Flavor evolution and non-standard interactions

$$\begin{pmatrix} |\epsilon_{ee}| < 2.5 & |\epsilon_{e\tau}| < 1.7 \\ & |\epsilon_{\tau\tau}| < 9.0 \end{pmatrix}.$$

$$h_{\rm NSI} = \lambda \begin{pmatrix} (\frac{Y_\odot - Y_e}{Y_\odot})\delta\epsilon^n & (3+Y_e)\epsilon_0 \\ (3+Y_e)\epsilon_0^* & 0 \end{pmatrix}.$$

The I-resonance is due to a cancellation between the standard and non-standard matter terms.
It can be seen also as a synchronized MSW resonance, where all effective spins in flavor space undergo the resonance coherently.

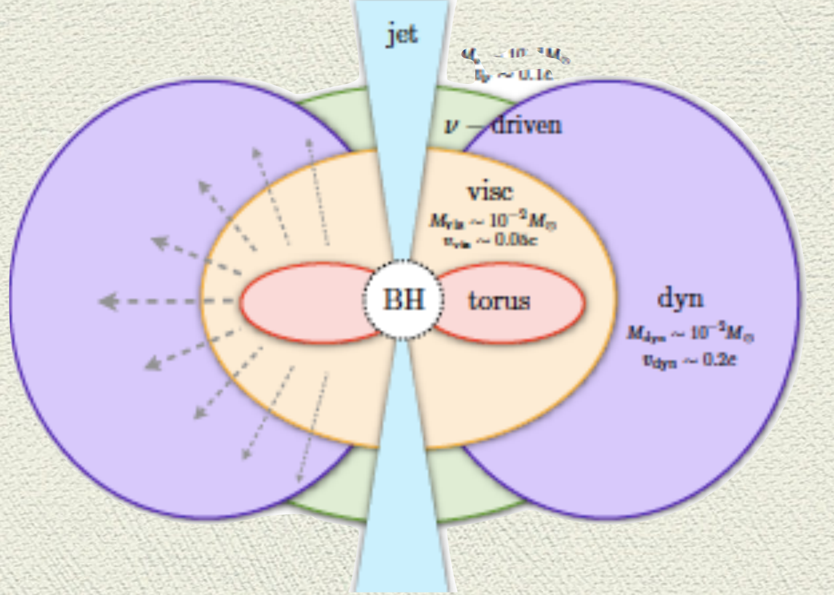




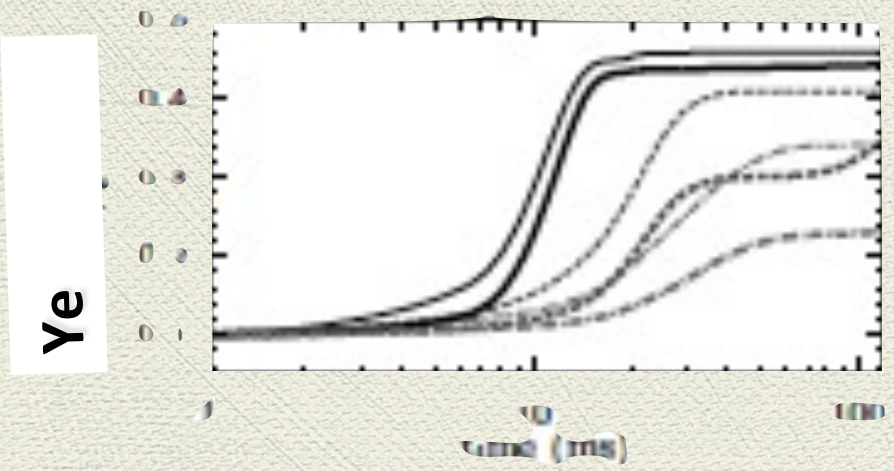
Chatelain, Volpe, PRD98 (2018)

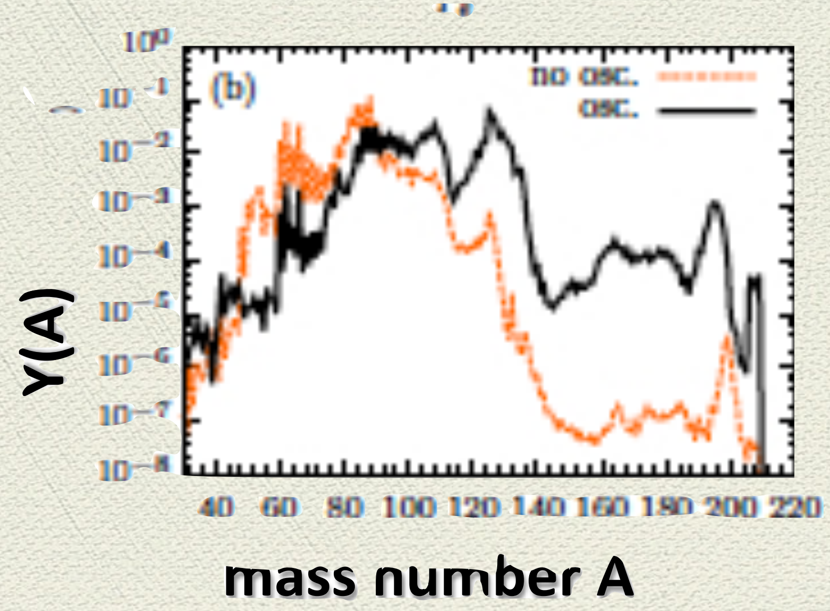
The I-resonance produces flavor modification nearby the neutrino sphere.

Nucleosynthesis in neutrino-driven winds and kilonovae



« Fast modes » might bring an equilibration of the neutrino fluxes. Here an example of the impact on nucleosynthesis, in a schematic calculation of the flavor evolution.





Wu et al., PRD96 (2017)

Flavor evolution here tends to decrease Ye and favor a strong r-process.

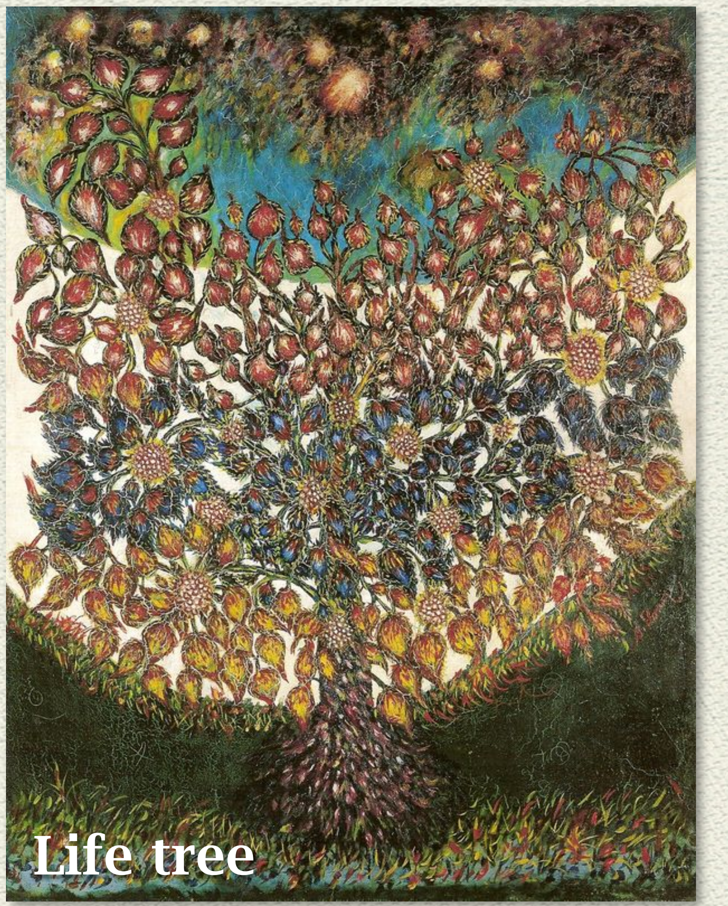
Conclusions

- Neutrino propagating in dense media modify their flavor in intriguing ways, because of neutrino self-interactions (but also shock waves, turbulence, …)

- Intense activity to unravel the conditions for the occurrence of these modes and their nature. Fast modes on short time scales as well as other collective modes can modify the shock dynamics and determine the neutron-to-proton ratio.

- Neutrino flavor conversion in binary neutron star mergers can influence r-process nucleosynthesis in neutrino-driven winds. To definitely assess its influence is important to understand their contribution in the ejecta of kilonovae and the associated electromagnetic signal.

- Many open issues remain, including the role of decoherence, the influence of gravity nearby compact objects, the role of symmetry breaking, the impact of « fast » modes and of collisions, …


Life tree

Seraphine de Senlis