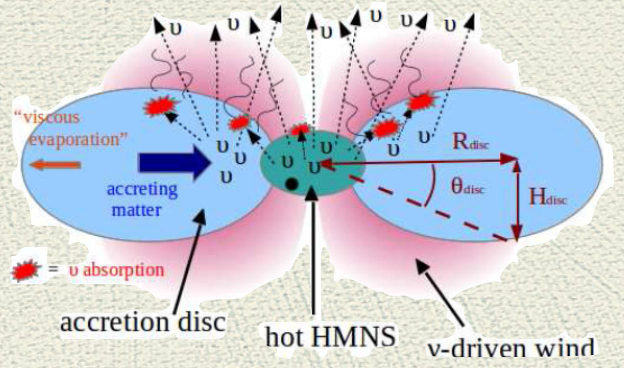
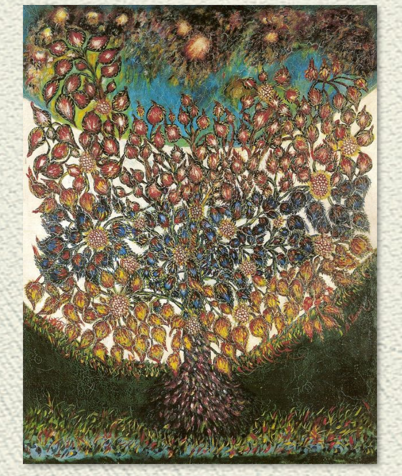
Neutrinos in dense environments :
from kilonovae to future supernova neutrino observations

Maria Cristina Volpe

Laboratoire AstroParticule et Cosmologie (APC), Paris



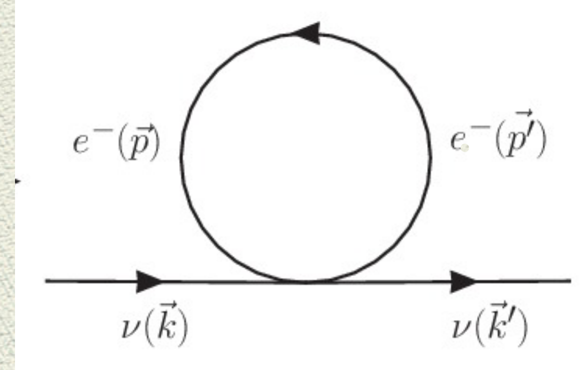


SN1987A- LMC

The Mikheev-Smirnov-Wolfenstein effect

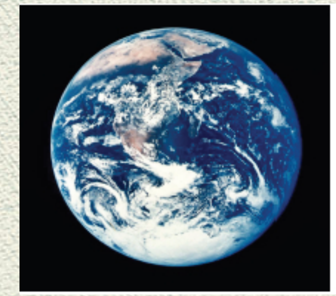
Neutrinos interact with matter and undergo resonant adiabatic flavor conversion.

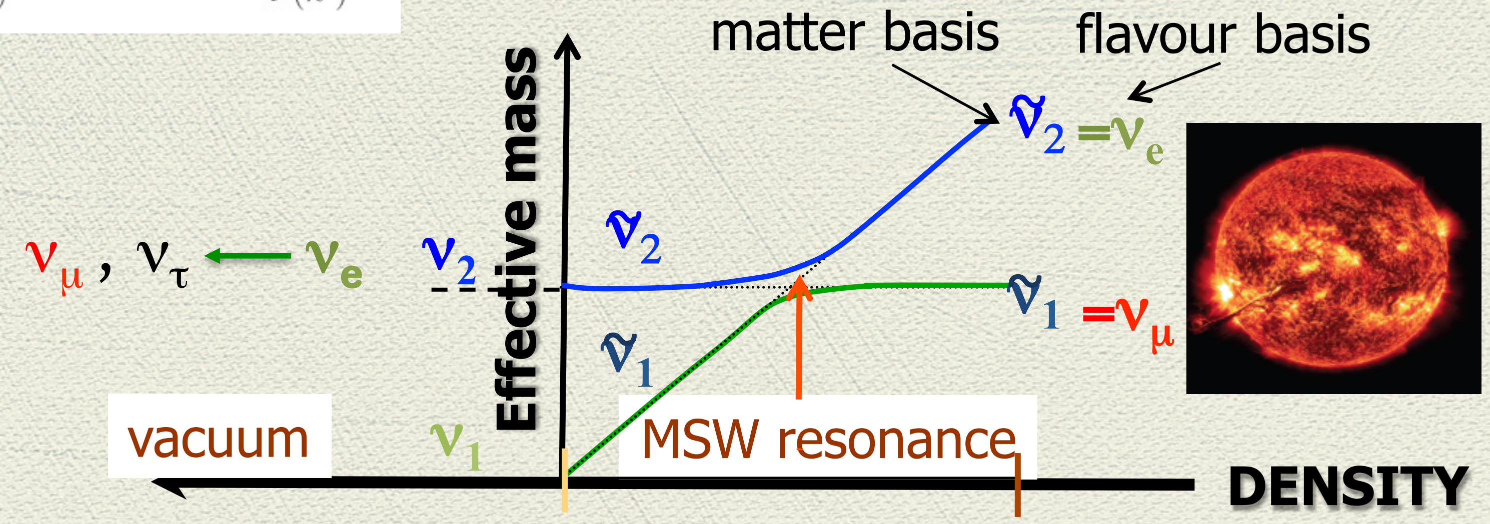
Wolfenstein PRD (1978)
Mikheev, Smirnov(1985)



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

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 : $\gamma = \dfrac{|\dot{\theta}_M|}{\Delta\tilde{m}^2/4E} << 1$

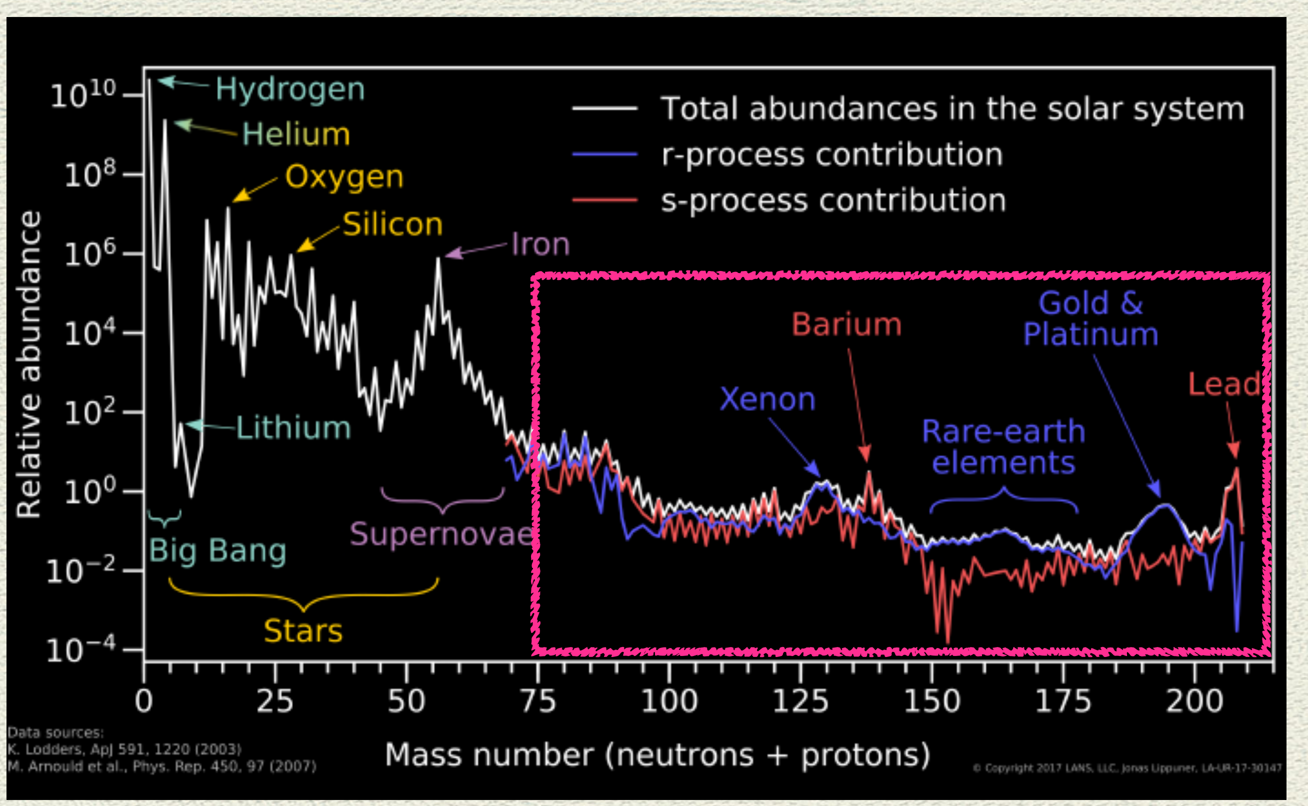
Also in supernovae, in accretion disks around compact objects, in the Earth and in the Early Universe (BBN epoch)

Nucleosynthesis : *r-process*

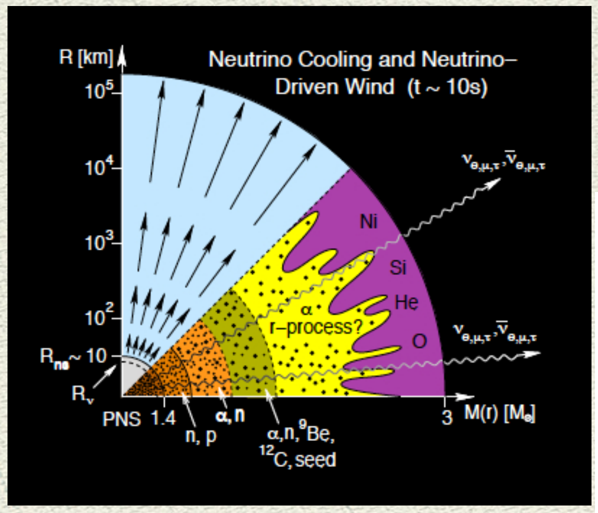
r-process
(r- stands for rapid neutron capture)
Astrophysical process where elements heavier than iron are made. It occurs on a short time scale and in a neutron-rich environment.

Longstanding open question in astrophysics :
What are the sites for the r-process ?

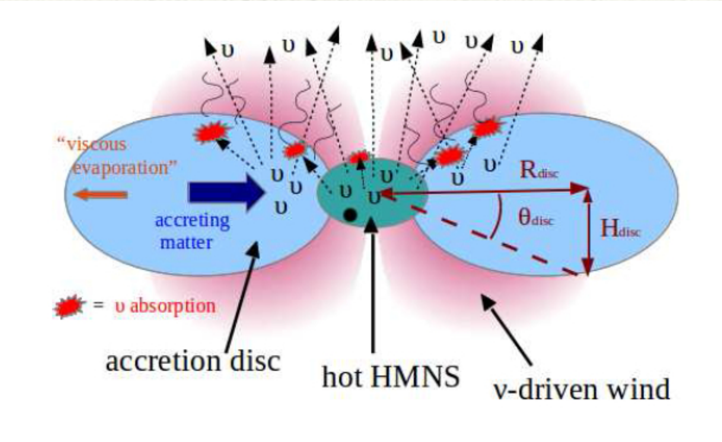
During r-process neutron capture on nuclei occurs faster than beta-decay, producing lots of neutron-rich (exotic) nuclei.



Candidate sites for r-process nucleosynthesis :
core-collapse supernovae and compact objects
- accreting disks around black holes and binary neutron star mergers (BNS).



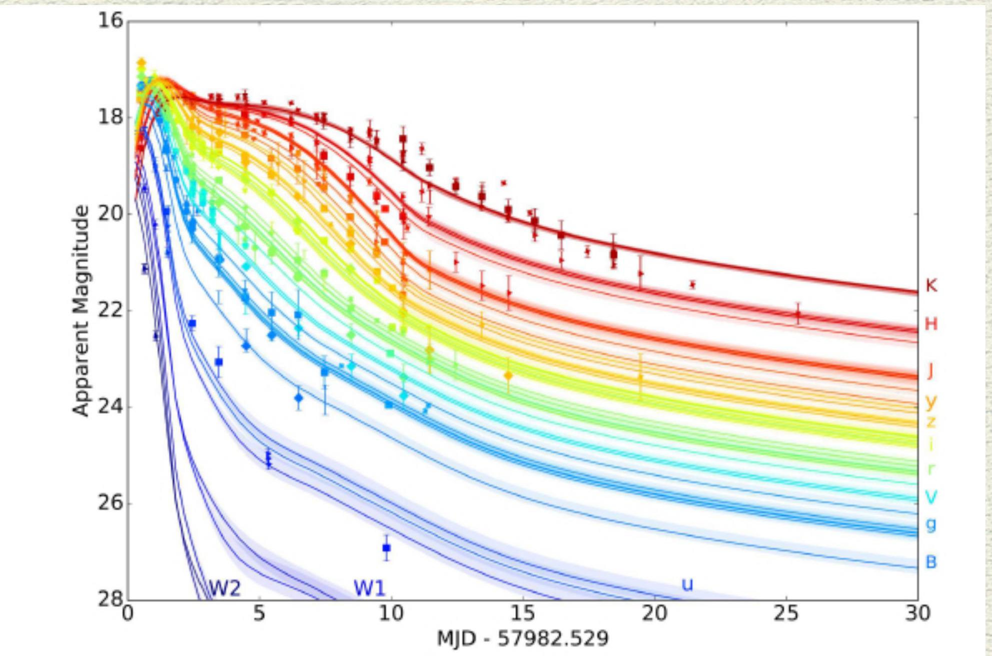
more frequent



more neutron rich

GW170817 and the kilonova

First measurement of gravitational waves from a binary neutron star merger (BNS), in coincidence with a short gamma ray burst and a kilonova.



Villar et al, Ap. Jl. (2017) 851, L21

Kilonova
Electromagnetic emission powered by the decay of radioactive elements.
Signal compatible with lanthanide free ejecta (blue component) and ejecta with lanthanides (red component).

r-process and neutrinos

r-process nucleosynthetic abundances depend on astrophysical conditions (entropy, dynamical timescales, ...), properties of neutron-rich nuclei (neutron capture rates, half-lives, masses) and neutrinos.

- Neutrinos determine richness of matter

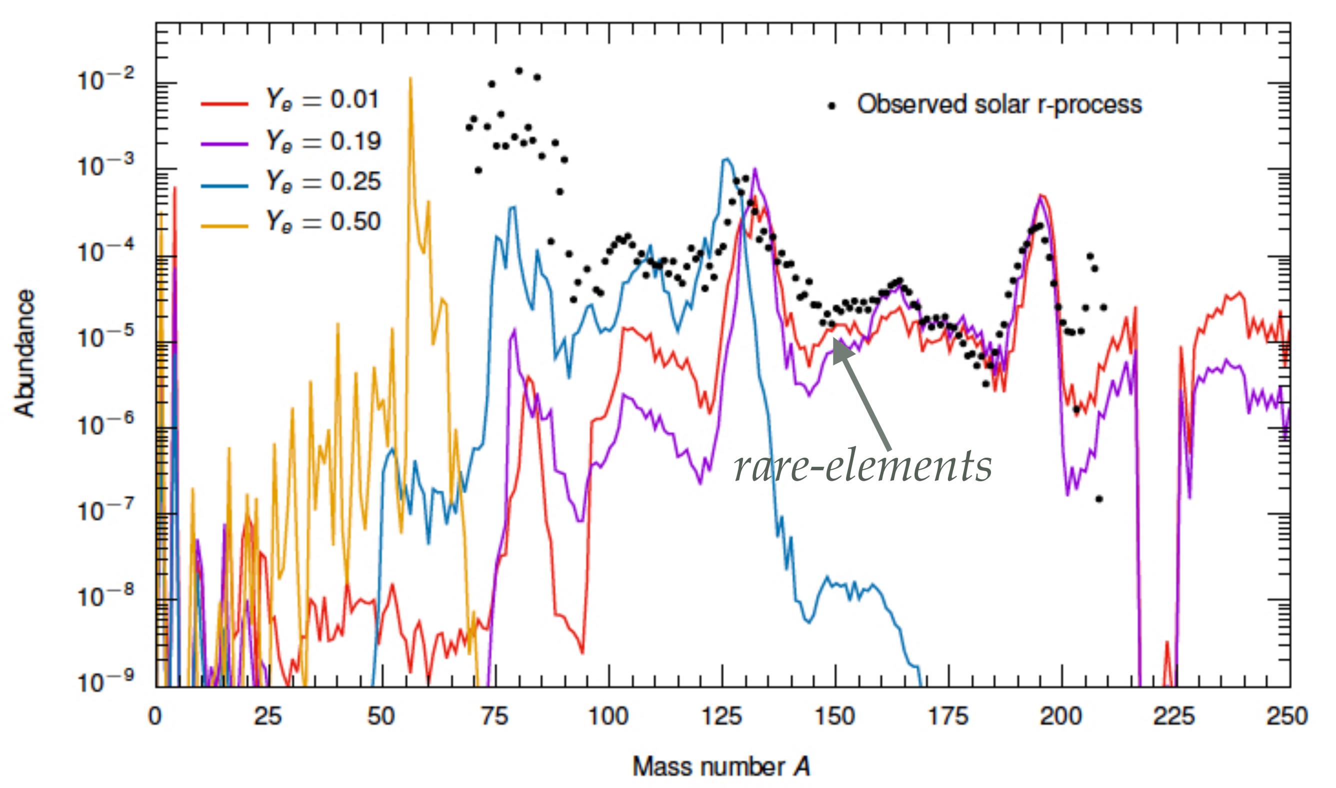
$\bar{\nu}_e + p \rightarrow n + e^+ \qquad \nu_e + n \rightarrow p + e^-$

and set the neutron-to-proton ratio, through the electron fraction **Ye**

$$\boxed{Y_e = \frac{p}{p+n} \qquad Y_n = 1 - Y_e}$$

- Rates on neutrons and protons depend on flavor evolution :

$$\frac{\lambda_{\nu_e n}}{\lambda_{\bar{\nu}_e p}} = \frac{<\sigma_{\nu_e n}>}{<\sigma_{\bar{\nu}_e p}>}$$



Ye = 0.5, no r-process elements

Ye < 0.25, rare-elements plateau and third element peak (strong r-process)

Neutrino evolution equations in flat spacetime

mean-field approximation

Samuel, PRD48 (1993); Sawyer PRD72 (2005),
Pehlivan and Balantekin, J. Phys. G 34 (2007)

linearised mean-field equations

Banerjee, Dighe, Raffelt, PRD84 (2011)
Väänänen and Volpe PRD88 (2013)

A dispersion relation approach

Izaguirre, Raffelt, Tamborra, PRL 118 (2017)

mean-field and extended mean-field

Volpe, Väänänen Espinoza, PRD87 (2013)
Serreau and Volpe PRD90 (2014)

towards the many-body solution

Birol, Pehlivan, Balantekin, Kajino, PRD98 (2018)
Cervia, Patwardhan, Balantekin, Coppersmith, Johnson, 1908.03511

quantum kinetic equations

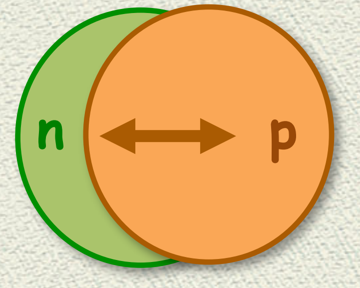
Sigl and Raffelt, Nucl. Phys. B 406 (1993)
Vlasenko, Fuller, Cirigliano, PRD89 (2014)

Numerous theoretical frameworks

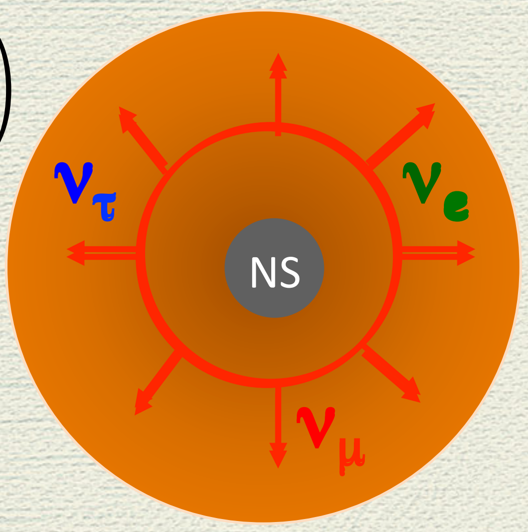
Volpe, Int. J. Mod. Phys. E24 (2015), *a review*

Neutrinos in dense environments

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

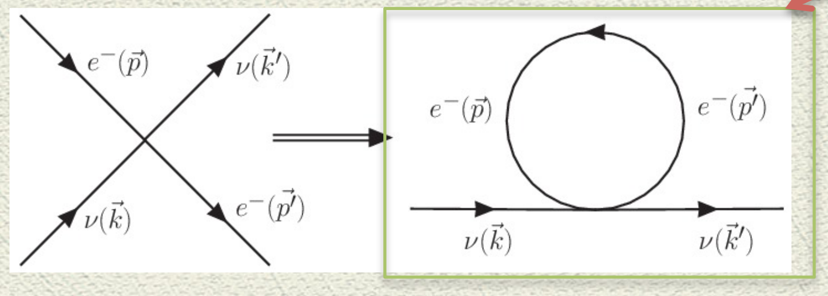


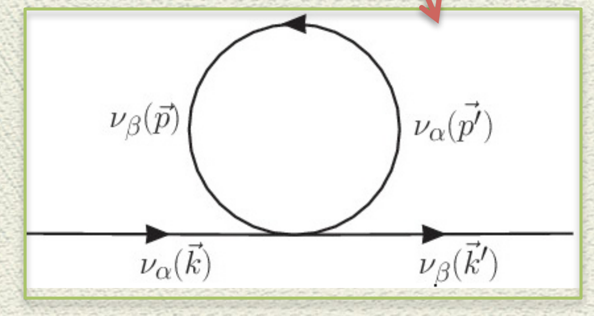
$\rho = \langle a^+ a \rangle$ one-body density matrix



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

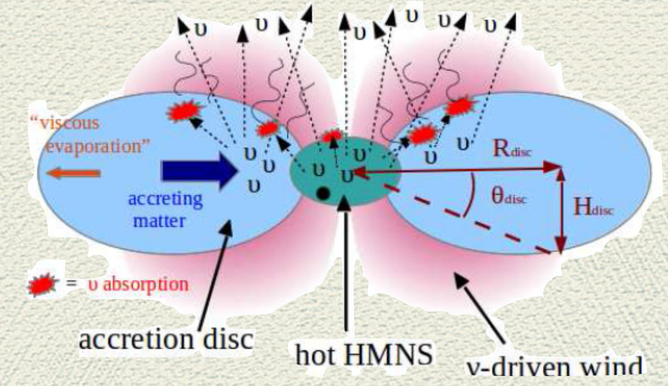
Pantaleone, PLB287 (1992)

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

Volpe, Väänänen, Espinoza. PRD 87 (2013)

Beyond usual framework : helicity coherence, collisions.

see Capozzi's talk



Matter-neutrino resonance

Matter and self-interaction potentials can cancel.

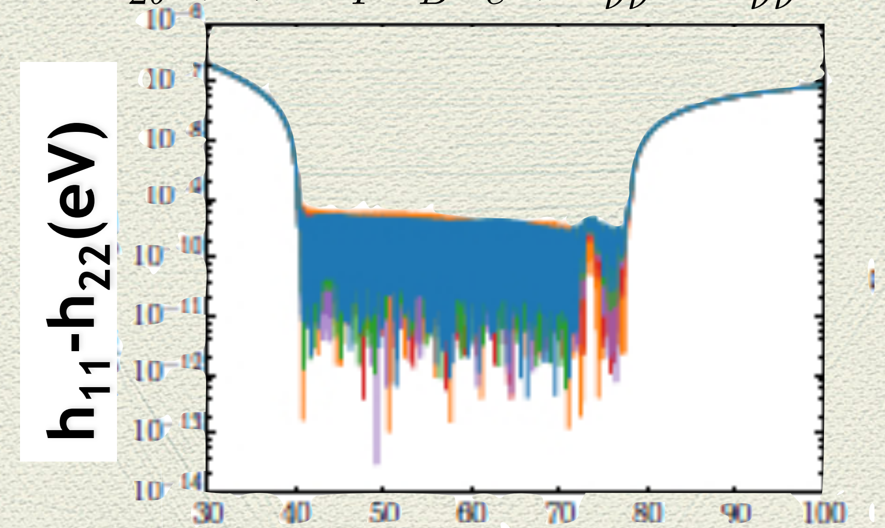
Malkus et al, PRD86 (2012), 96 (2016)

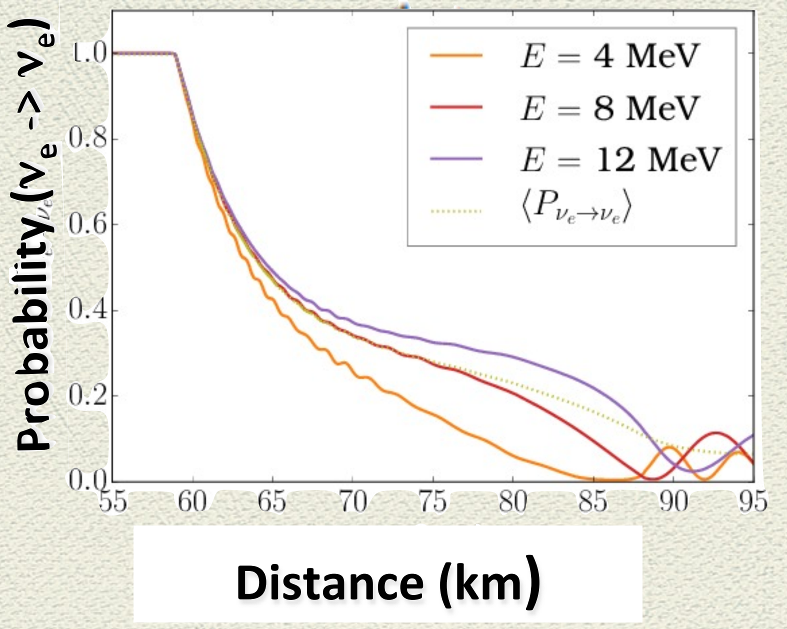
$$h_{\mathcal{G},11} - h_{\mathcal{G},22} = -2\omega c_{2\theta} + \sqrt{2} G_F n_B Y_e + h^{ee}_{\nu\nu} - h^{xx}_{\nu\nu} \simeq 0.$$

- An electron antineutrino excess.

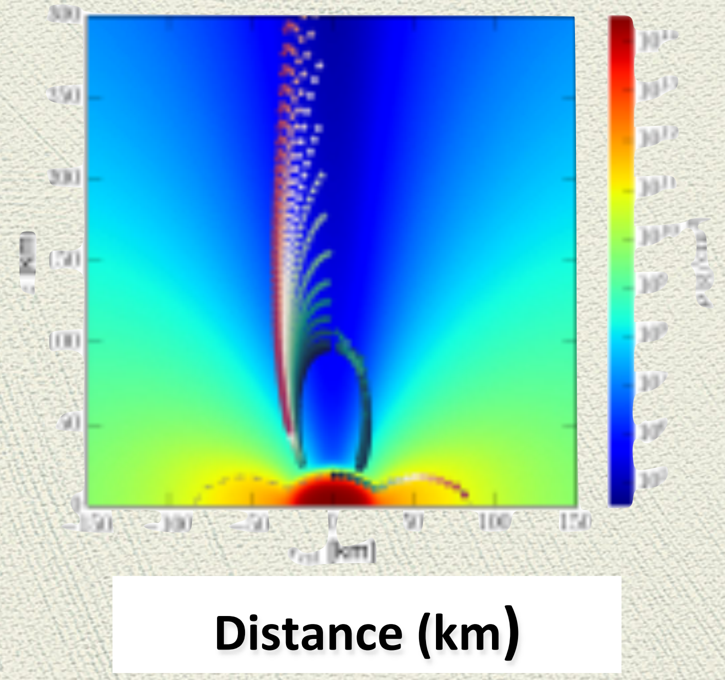
	$\langle E_\nu \rangle$	L_ν	R_ν (km)
ν_e	10.6	15	84
$\bar{\nu}_e$	15.3	30	60
ν_x	17.3	8	58
	MeV	10^{51} erg/s	

Perego et al, 2014





Chatelain, Volpe, PRD 95, 2017



Frensel et al., PRD95 (2017)

This resonance is located in the polar region, it can impact Ye and the nucleosynthetic abundances.

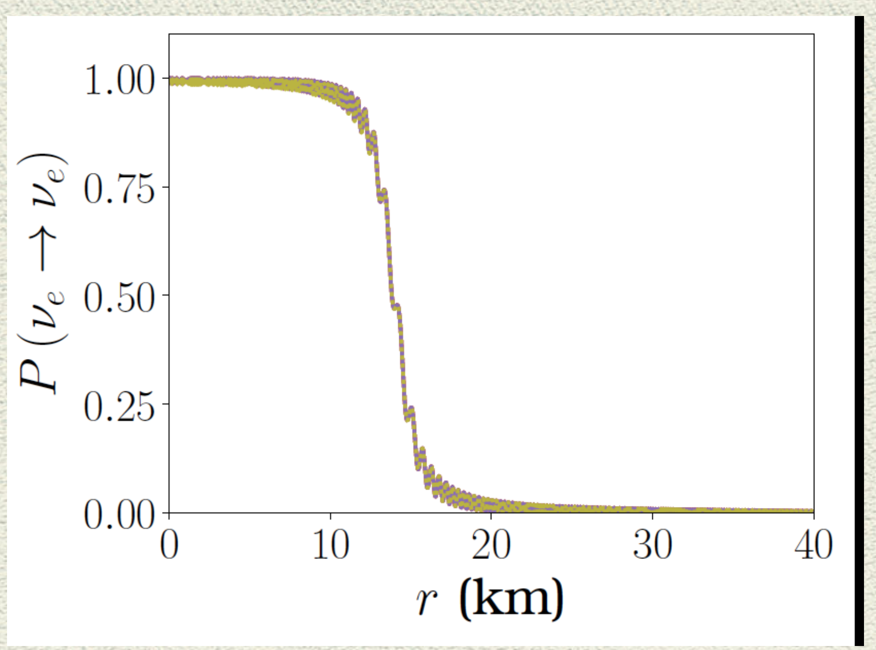
Non-standard interactions and flavor evolution

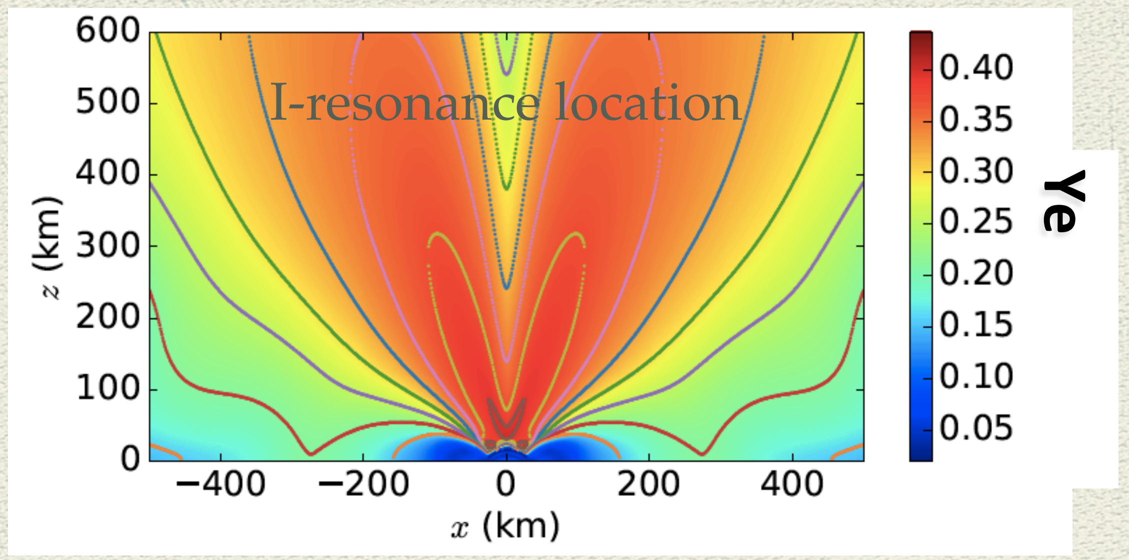
- I-resonance : MSW like resonance due to a cancellation between standard and non-standard matter terms.

$$\left(\begin{array}{ccc} |\epsilon_{ee}| < 2.5 & & |\epsilon_{e\tau}| < 1.7 \\ & & |\epsilon_{\tau\tau}| < 9.0 \end{array} \right). \qquad h_{\rm NSI} = \lambda \left(\begin{array}{cc} (\frac{Y_\odot - Y_e}{Y_\odot})\delta\epsilon^n & (3+Y_e)\epsilon_0 \\ (3+Y_e)\epsilon_0^* & 0 \end{array} \right).$$

Esteban-Pretel, A. *et al*. Phys.Rev. D81 (2010), Stapleford et al., Phys.Rev. D94 (2016)

- The I-resonance can occur also in presence of neutrino self-interactions, as a synchronized MSW.



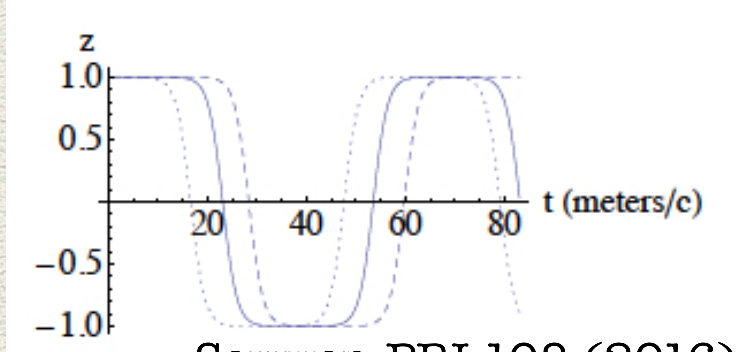


Chatelain, Volpe, PRD98 (2018)

«*Fast*» modes

- Flavor conversion occurs on a short distance scale, if the neutrino angular distributions at the neutrino sphere are better described.

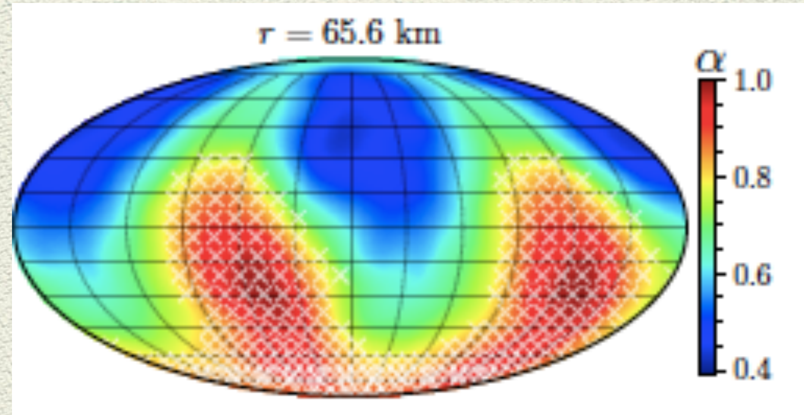
  Fast modes can potentially impact supernovae explosions, a longstanding open issue.



Sawyer, PRL108 (2016)

- First evidence for the occurrence of fast modes in 3-dimensional supernova simulations and also within the proto-neutron star.

  t= 200 ms snapshot
  Mollweide projection for
  the nue-to-antinue flux ratio



Crosses indicate fast modes

Abbar, et al, PRDD100 (2019), arXiv :1812.06883
Abbar, et al, to be submitted

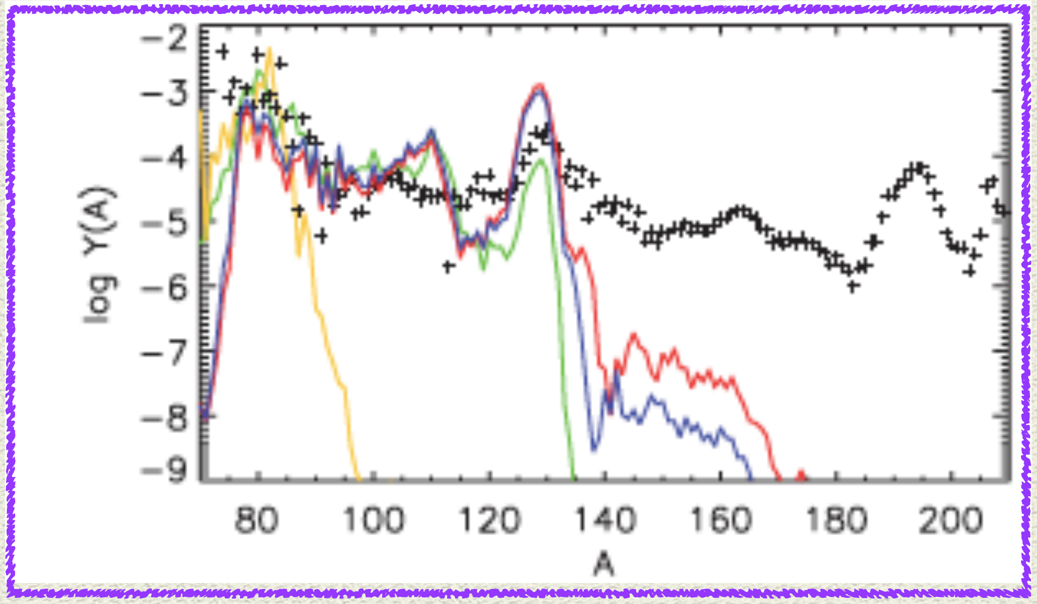
- Fast modes do not seem to produce flavor equilibration of the neutrino spectra.

Abbar, Volpe, PLB790 (2019),arXiv:1811.04215

Gravitational effects on neutrinos in dense environments

The inclusion of trajectory bending on neutrino propagation and energy redshifts can impact the neutrino spectra and r-process nucleosynthetic outcomes.

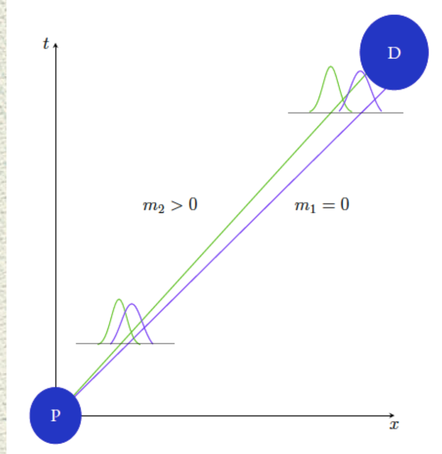
An example for an accretion-disk black hole model with Schwarzschild and Kerr metrics (no flavor transformation included).



Caballero, McLaughlin and Surman,Astr. Journ. 745 (2012).

Neutrino decoherence by wave packet propagation

- Neutrino mass eigenstates wave packets (WP) can loose coherence during propagation. In flat spacetime, the neutrino coherence length L_{coh} quantifies the distance at which coherence is lost.

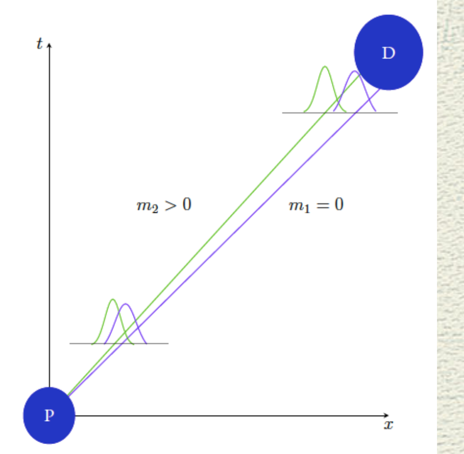


$$L = L_{coh} \quad \Delta x = \sigma_x$$

σ_x- WP width

see e.g. Giunti, Found. Phys. Lett. 17 (2004);
Kersten and Smirnov, Eur. Phys. J. C76 (2016) ;
Akhmedov, Kopp, Lindner, JCAP 1709 (2017)

Wave packet decoherence in flat spacetime



- The coordinate-space wave function is

$$\psi_j(t,\vec{x}) = \int_{\vec{p}} e^{i\vec{p}\cdot\vec{x}}\psi_j(t,\vec{p}) \qquad \int_{\vec{p}} \equiv \int \frac{d^3p}{(2\pi)^3}$$

whose Fourier components evolve according to

$$\psi_j(t,\vec{p}) = f_{\vec{p}_j}(\vec{p})e^{-iE_j(\vec{p}))t}$$

with $f_{\vec{p}_j}(\vec{p})$ the momentum distribution functions centered in $\vec{p}_j$, describing the wave-packet associated to the **j-th** mass eigenstate.

- The one-body density matrix is $\rho_{jk}(t,\vec{x}) = U^*_{\alpha j}U_{\alpha k}\psi_j(t,\vec{x})\psi^*_k(t,\vec{x})$.

- Assuming Gaussian wave packets

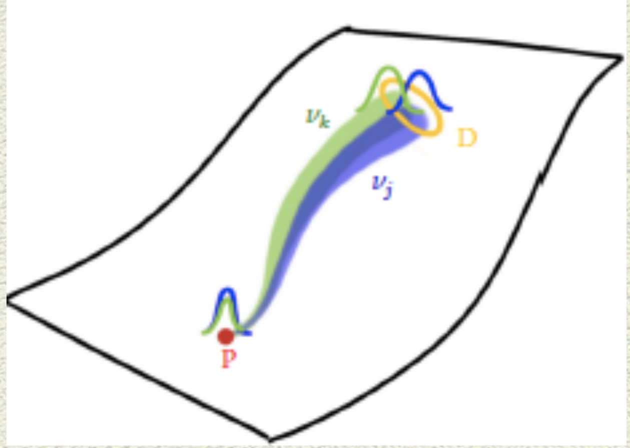
$$\rho_{jk}(t,\vec{x}) = N^{\alpha}_{jk}\int_{\vec{p},\vec{q}} \exp\left[-i\left[E_j(\vec{p}) - E_k(\vec{p})\right]t\right\} \exp\left[i(\vec{p}-\vec{q})\vec{x} - \frac{(\vec{p}-\vec{p}_j)^2}{4\sigma_p^2} - \frac{(\vec{q}-\vec{p}_k)^2}{4\sigma_p^2}\right],$$

- In order to calculate the coherence length, we expand the energies around the peak momenta $E_j(\vec{p}) = E_j + (\vec{p}-\vec{p}_j)\vec{v}_j + \mathcal{O}\left[(\vec{p}-\vec{p}_j)^2\right]$.

- By performing Gaussian integrals one gets $\rho_{jk}(\vec{x}) = A^{\alpha}_{jk}\ \rho^{osc}_{jk}(\vec{x})\ \rho^{damp}_{jk}(\vec{x})$

$$\rho^{damp}_{jk}(\vec{x}) = \exp\left[-\frac{(\vec{v}_j-\vec{v}_k)^2x^2}{4\sigma_x^2(v_j^2+v_k^2)}\right] \qquad L^{jk}_{\rm coh} = \frac{4\sqrt{2}E^2}{\left|\Delta m^2_{jk}\right|}\sigma_x$$

Wave packet decoherence in curved spacetime



- A neutrino flavor state produced in a spacetime point P

  $$|\nu_\alpha(P)\rangle = U^*_{\alpha j}|\nu_j(P)\rangle$$

  evolves to a « detection » point D

  $$|\nu_j(P, D_j)\rangle = e^{-i\phi_j(P,D_j)}|\nu_j(P)\rangle,$$

  with the covariant form of the quantum mechanical phase

  $$\phi_j(P, D_j) = \int_P^{D_j} p_\mu^{(j)} \mathrm{d}x^\mu \qquad p_\mu^{(j)} = m_j g_{\mu\nu}\frac{\mathrm{d}x^\nu}{\mathrm{d}s}$$

- For a stationary gravitational field from a compact object with spherical symmetry

  $$\mathrm{d}s^2 = -B(r)\mathrm{d}t^2 + \frac{1}{B(r)}\mathrm{d}r^2 + r^2\mathrm{d}\theta^2 + r^2\sin^2\theta d\varphi^2 \quad \text{with} \quad B(r) = 1 - \frac{r_s}{r} \qquad r_s = 2M$$

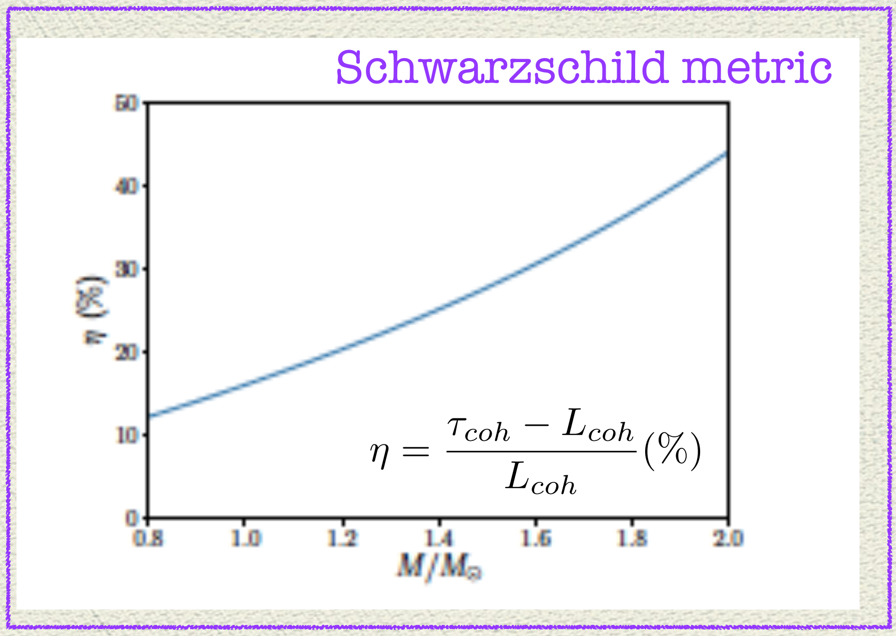
- By performing Gaussian integrals

  $$\rho_{jk}(r_P, r_D) = A^\alpha_{jk}\ \rho^{osc}_{jk}(r_P, r_D)\ \rho^{damp}_{jk}(r_P, r_D)$$

  $$\rho^{damp}_{jk}(r_P, r_D) = \exp\left[-\frac{\Delta m^4_{jk} r^2_{PD}}{32\sigma_x^2 E^4}\right],$$

  $$r^{coh}_{PD} = \frac{4\sqrt{2}\sigma_x E^2}{\Delta m^2_{jk}}$$

  $$\tau_{coh} = \sqrt{B(r^{coh}_D)}\left[r^{coh}_{PD} + r_s \ln\left(1 + \frac{r^{coh}_{PD}}{r_P - r_s}\right)\right]$$



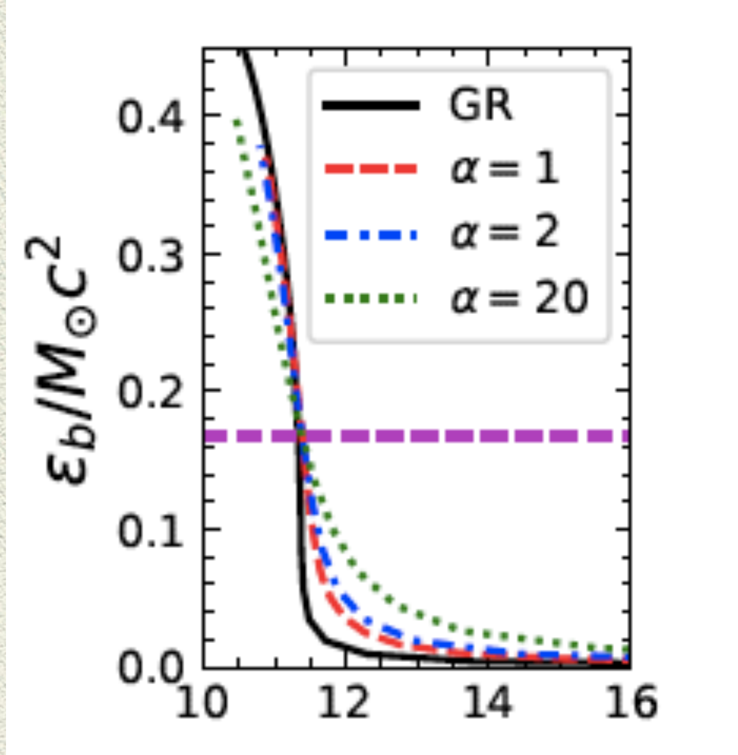
$E = 11\ MeV\ r_P = 10\ km\ \sigma_x = 4 \times 10^{-12} cm$

Chatelain and Volpe, to appear in Physics Letters B, arXiv:1906.12152

Late time neutrino signal and the binding energy-radius relation

The late time neutrino signal can be approximated by a black-body emission.
Cooling model of Reddy and Roberts used as reference.

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



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

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

Determination of the neutron star radius with neutrinos alone difficult.

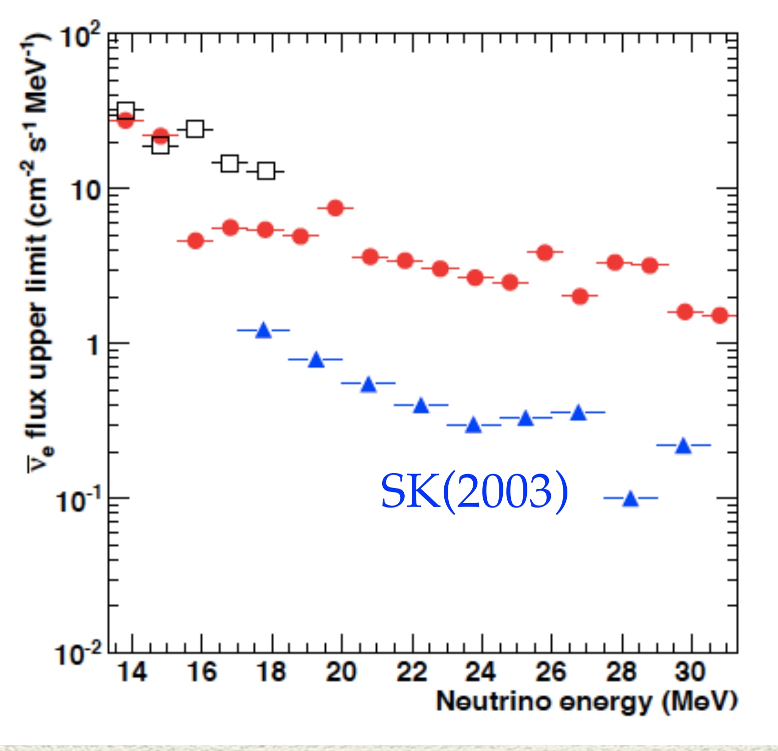
Gallo Rosso, Abbar, Vissani, Volpe, JCAP 1812 (2018).

Diffuse Supernova Neutrino Background measurement

- The relic neutrino flux depends on core-collapse supernova fluxes, the supernova rate (related to the star formation rate), integrated over redshift :

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

$E'_\nu = (1+z)E_\nu,$ neutrino redshifted energy (only the tails of the neutrino spectra matter) *z = 0,1,2*



Zhang et al., Astr. Phys. 60 (2015)

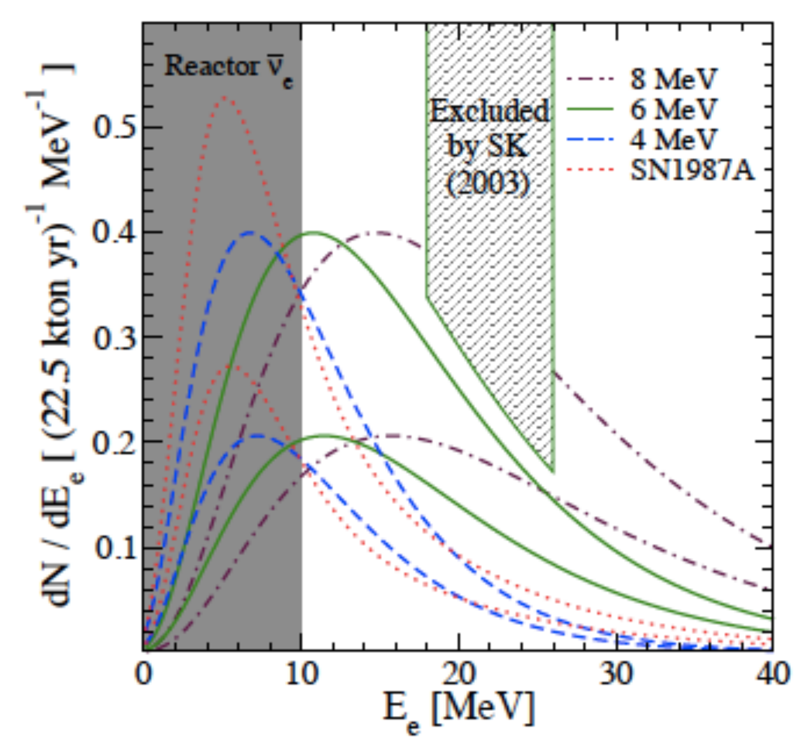
Super-Kamiokande with Gd
- neutron tagging (reduced backgrounds)

Beacom, Vagins, PRL 93 (2004)

from EGADS to **SuperK-VI+Gd (2019/20)**

Hyper-K (258 ktons) - several hundreds

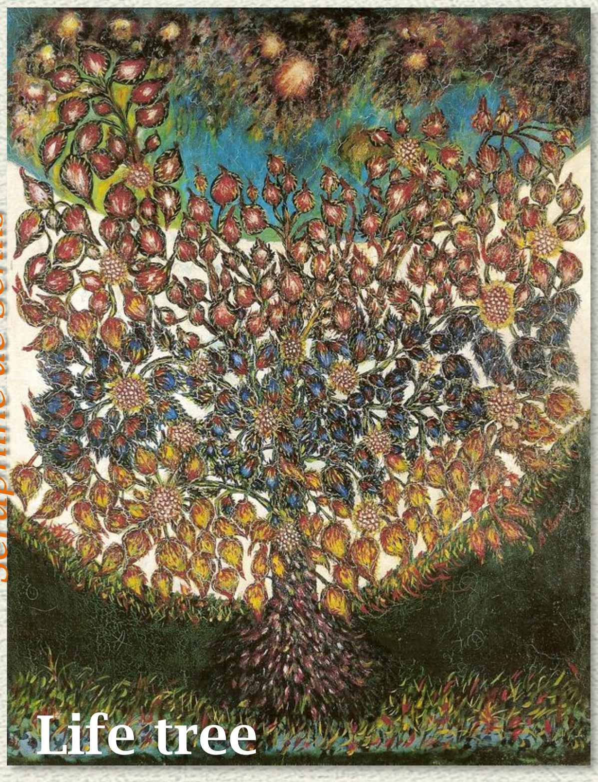
Crucial measurement of the R_{SN} and the (average) neutrino fluxes



Beacom, Ann. Rev. 60 (2010)

Conclusions et Prospectives

- Neutrinos and neutrino flavor evolution in dense environments important for r-process and the supernova dynamics. Future observation of a galactic supernova and diffuse supernova neutrino bakcgrounds.



Seraphine de Senlis

- *Theoretical description :* linearised equations, extended mean-field, many-body effects, …

  Novel *flavor mechanisms* unravelled, *fast* modes, …

- Among open issues : influence of gravity nearby compact objects, impact of of collisions, …
  For r-process, self-consistent calculations needed.