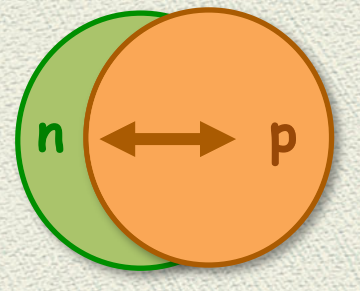
Neutrino flavor evolution
beyond the standard frameworks

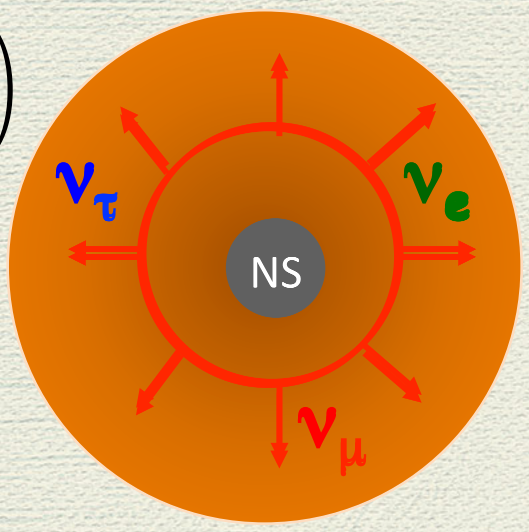
Maria Cristina Volpe
Laboratoire Astroparticule et Cosmologie (APC), Paris

Neutrino evolution equations in dense environments

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

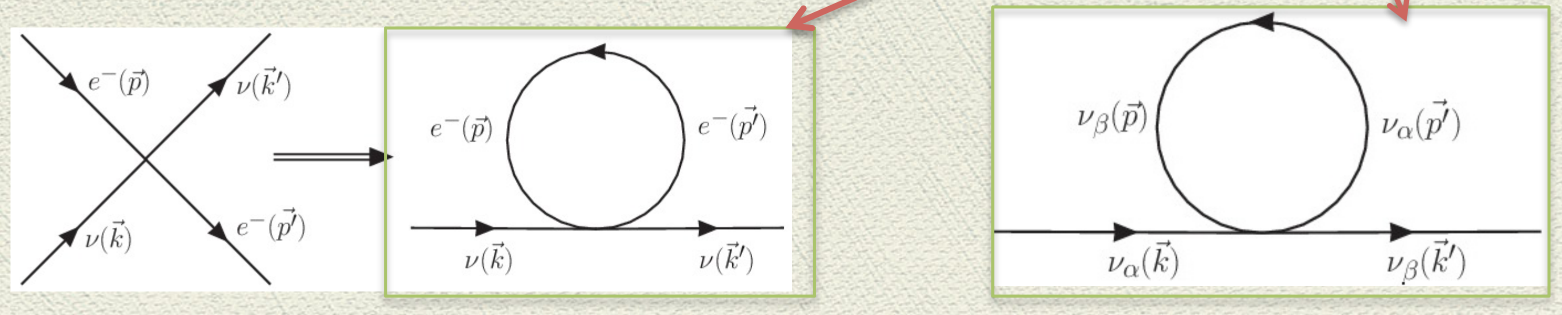


$\rho = \langle a^+ a \rangle$ one-body density matrix



BBGKY hierarchy : mean-field and beyond

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



neutrino-matter

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

neutrino self-interactions

non-linear term

MEAN-FIELD approximation

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

Volpe, Väänänen, Espinoza. PRD 87 (2013)

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

Beyond this framework : pairing correlators, helicity (spin) coherence, collisions.

Beyond usual mean-field : Helicity coherence

- Most general mean-field equations include contributions from correlators with helicity change, due to the neutrino mass.

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

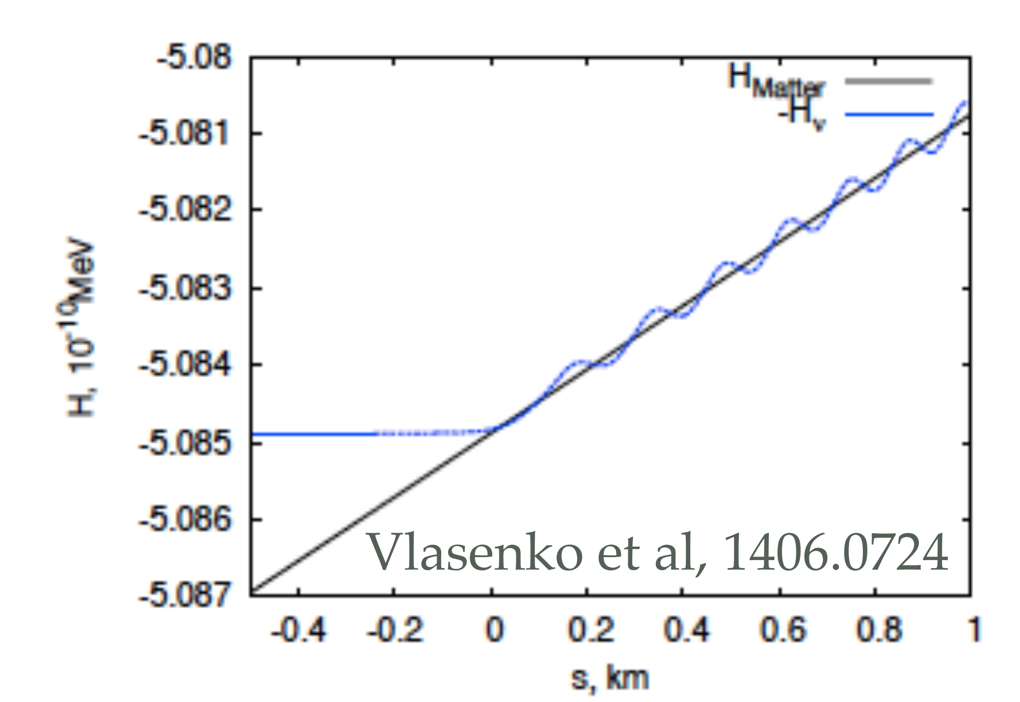
$$\mathcal{R} = \begin{pmatrix} \rho & \zeta \\ \zeta^* & \bar{\rho} \end{pmatrix} \qquad \mathcal{H} = \begin{pmatrix} h & \Phi \\ \Phi^* & \bar{h} \end{pmatrix}$$

$\mathcal{R}$ 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 $m/2E$

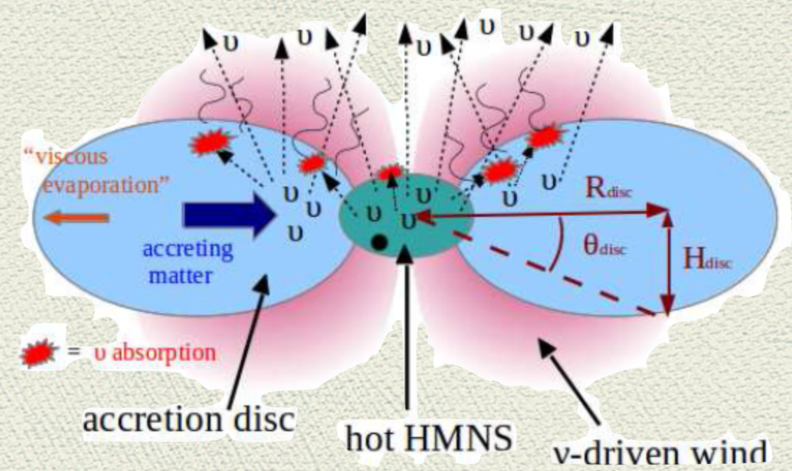
Vlasenko, Fuller, Cirigliano, PRD89 (2014)
Serreau,Volpe, PRD90 (2014)

- Toy model shown the possibility of non-linearity enhancement through non-linear feedback.



Binary neutron star merger remnants

- In binary neutron star merger remnants, an electron antineutrino excess.

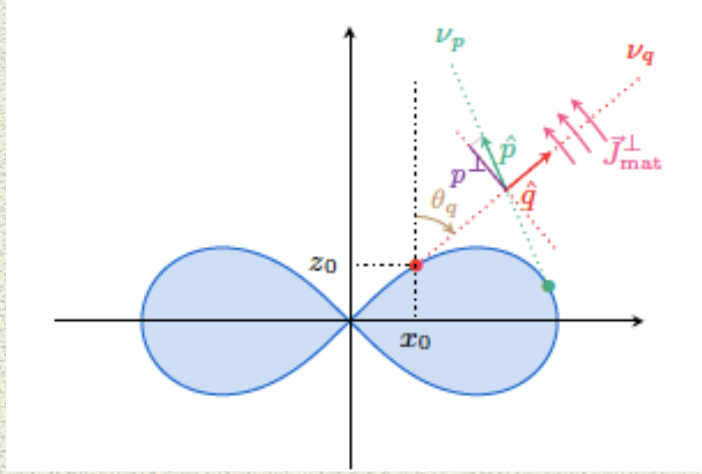


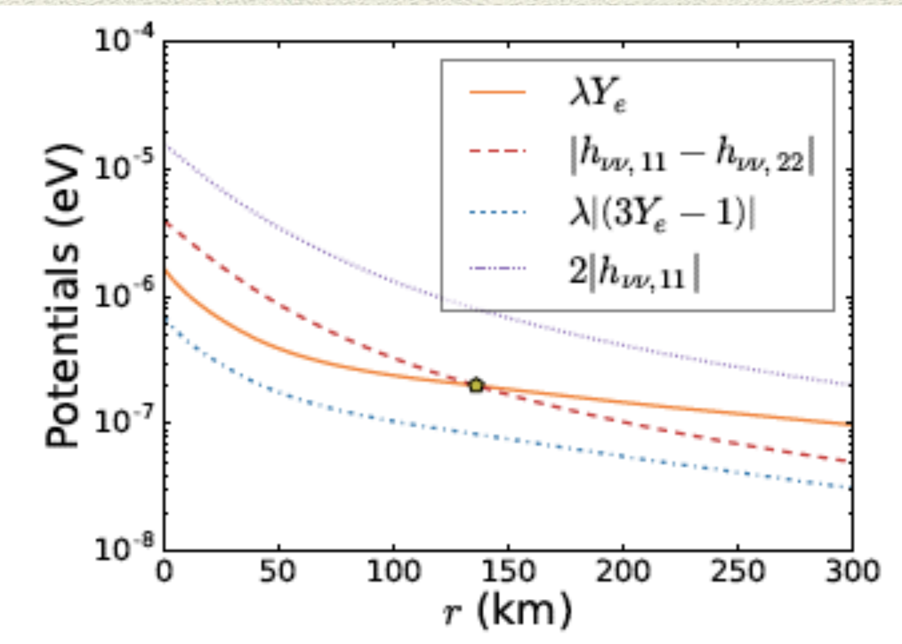
Perego et al, 2014

	$\langle E_\nu \rangle$	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	

- Matter and self-interaction potentials can cancel : Matter-Neutrino Resonance.

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

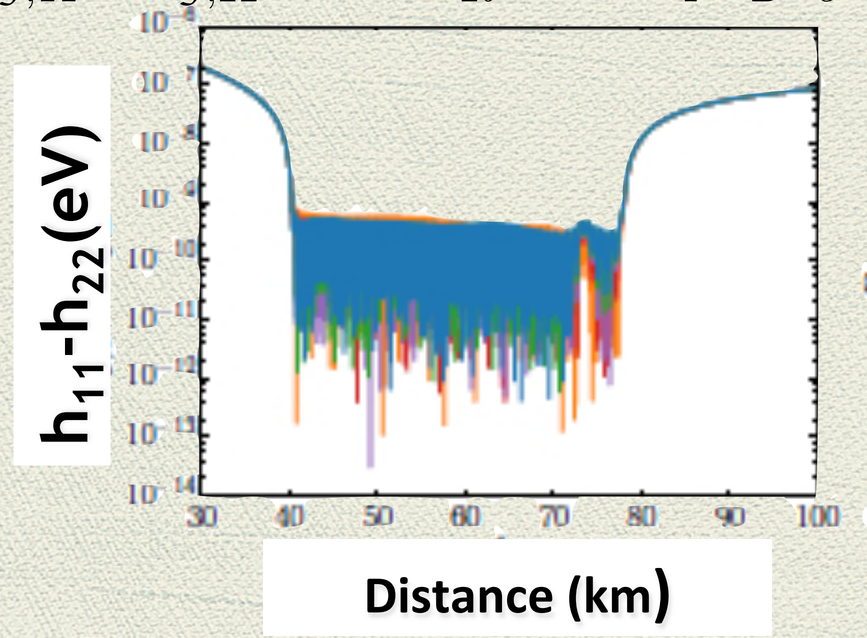


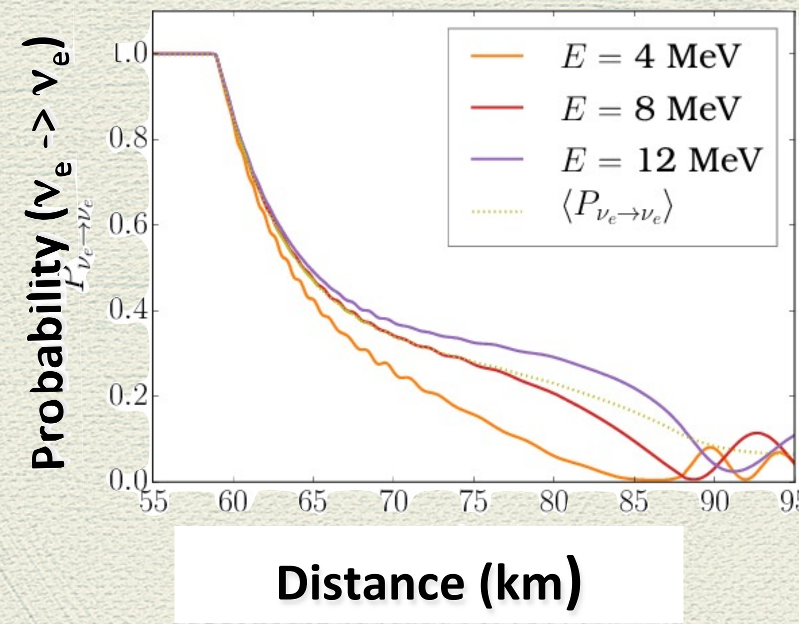


Chatelain, Volpe, PRD 95, 2017

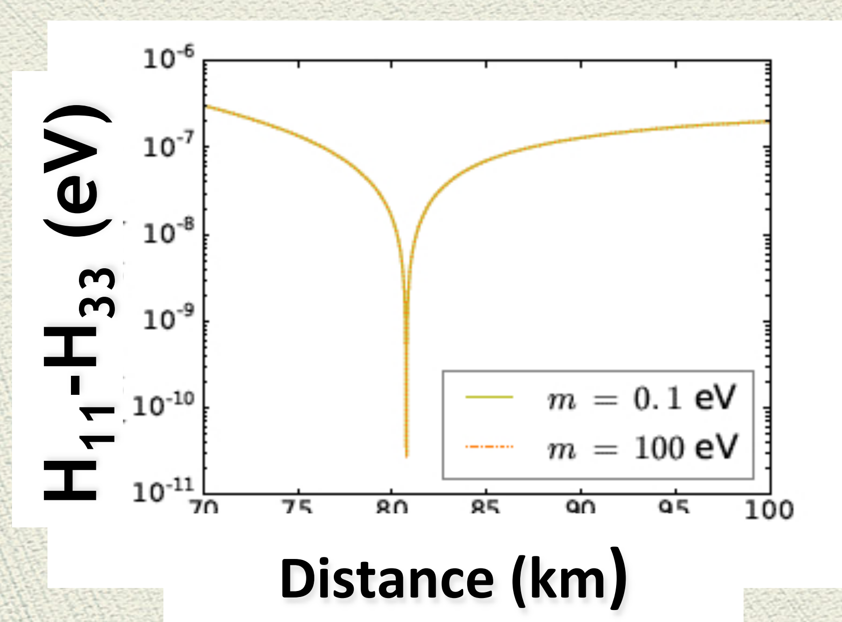
Matter neutrino resonance and helicity coherence

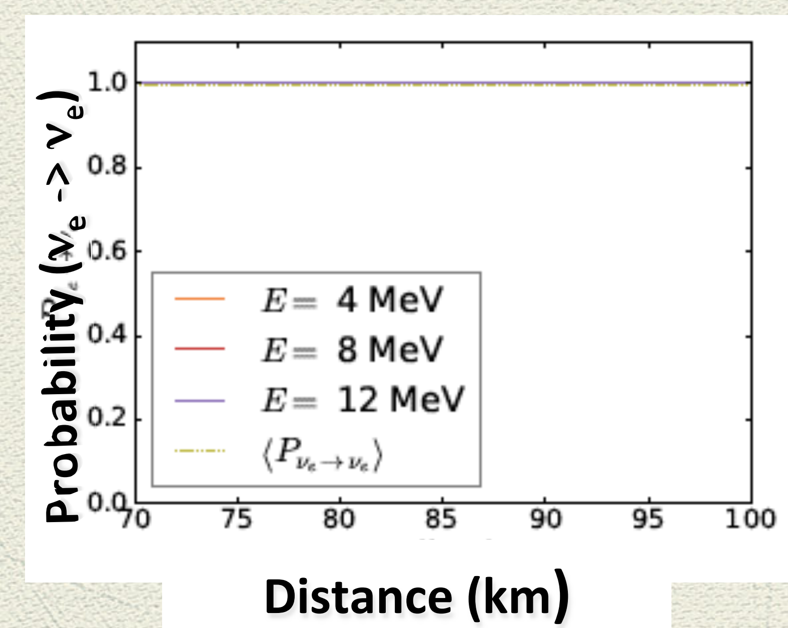
- Evolution for the matter-neutrino resonance (mostly) adiabatic.
  $$h_{\mathcal{G},11} - h_{\mathcal{G},22} = -2\omega c_{2\theta} + \sqrt{2} G_F n_B Y_e + h^{ee}_{\nu\nu} - h^{xx}_{\nu\nu} \simeq 0.$$





- Two flavors : 4 conditions possible. Resonance conditions for helicity coherence similar to the matter-neutrino resonance.
  $$h_{\mathcal{G},11} - h_{\mathcal{G},33} = \sqrt{2} G_F n_B (3Y_e - 1) + 2h^{ee}_{\nu\nu} \simeq 0$$



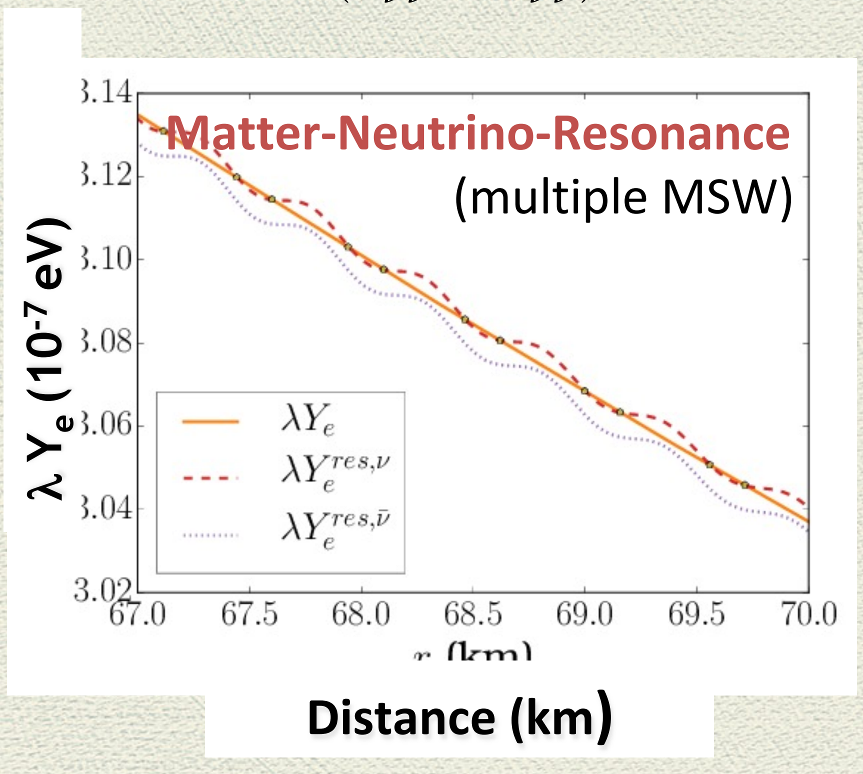


Helicity coherence and non-linear feedback

- Performed detailed investigation on numerous trajectories, based on detailed simulations of binary neutron star merger remnants. Both Dirac and Majorana neutrinos studied.
  Non-linear feedback not sufficient for adiabatic evolution.

$$\lambda Y_e \simeq -(h_{\nu\nu}^{ee} - h_{\nu\nu}^{xx}) + 2\omega c_{2\theta}$$

$$n_B(3Y_e - 1) \simeq -\frac{2}{\sqrt{2}G_F} h_{\nu\nu}^{ee}.$$



Perturbative analysis shows matching conditions between matter and self-interaction terms require peculiar matter densities.

Results hold for core-collapse supernovae.

Chatelain, Volpe, PRD 95, (2017)

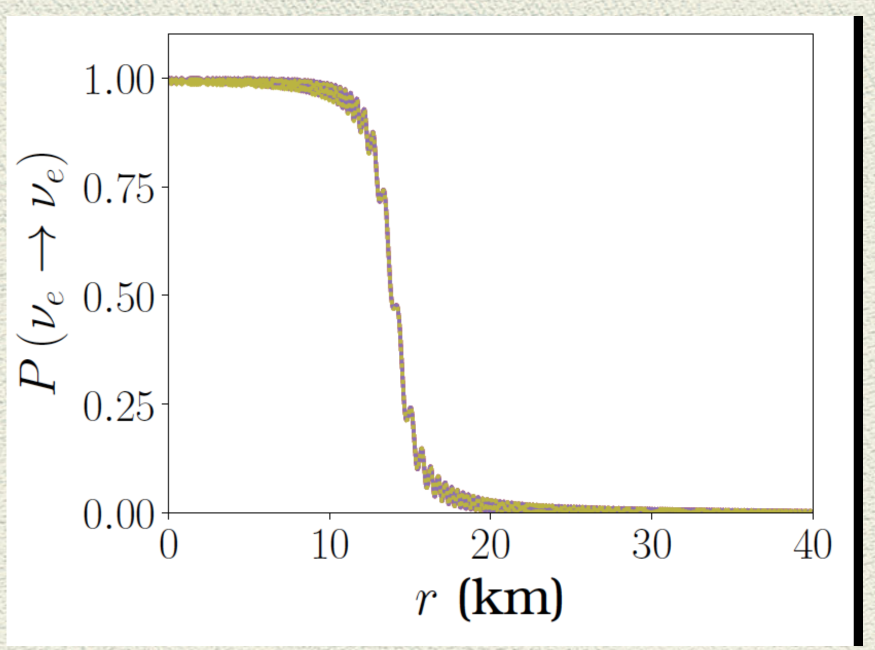
Non-standard interactions and flavor evolution

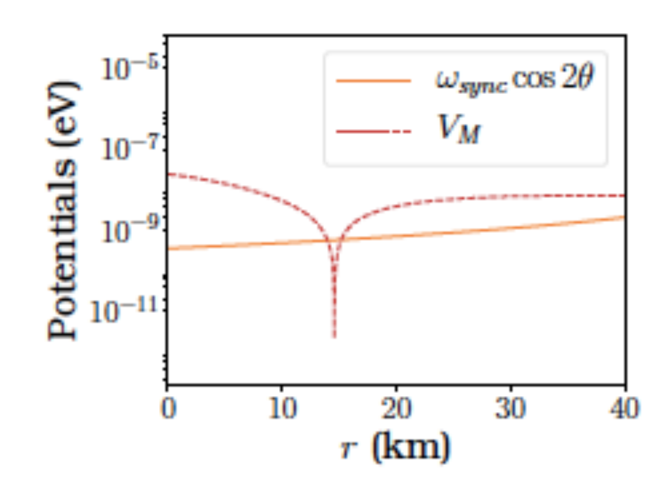
- I-resonance : MSW like resonance due to a cancellation between standard and non-standard matter terms.

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

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.





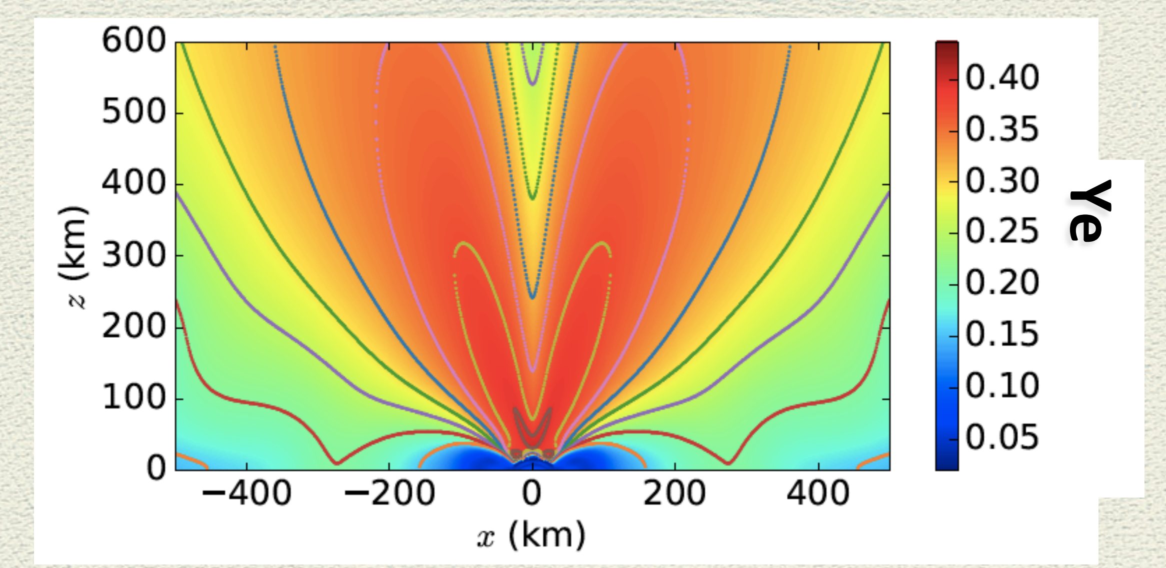
It can be seen also as a synchronized MSW resonance, where all effective spins in flavor space undergo the resonance coherently.

Chatelain, Volpe, PRD98 (2018)

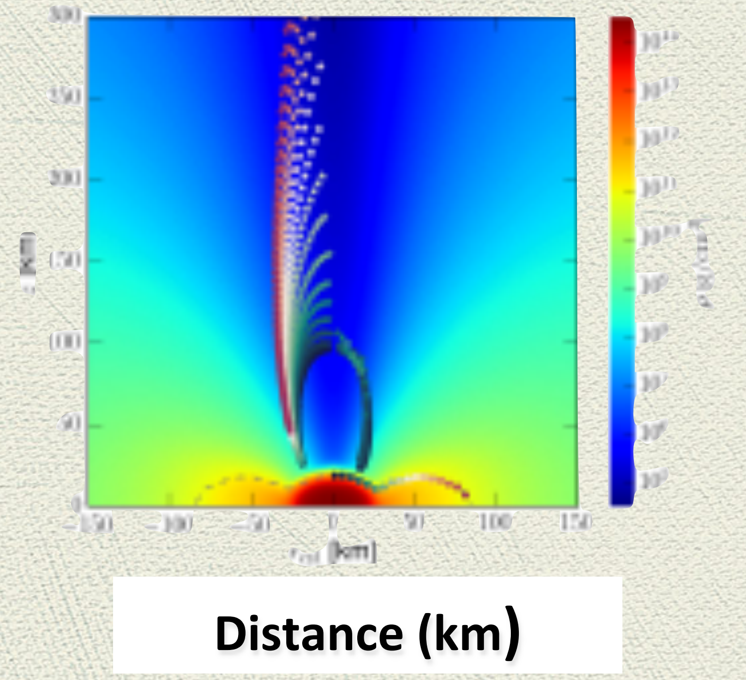
Flavor evolution, nucleosynthesis and kilonovae

Neutrinos influence the neutron richness and determine Ye in neutrino driven winds.

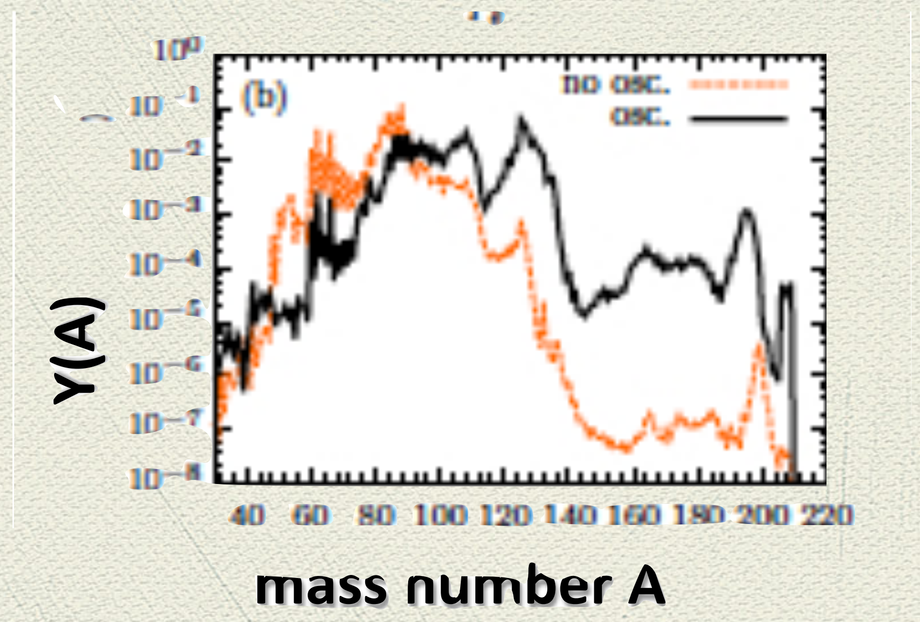
The impact on r-process nucleosynthesis in neutrino-driven winds in kilonovae needs to be assessed.



I-resonance location
Chatelain, Volpe, PRD98 (2018)



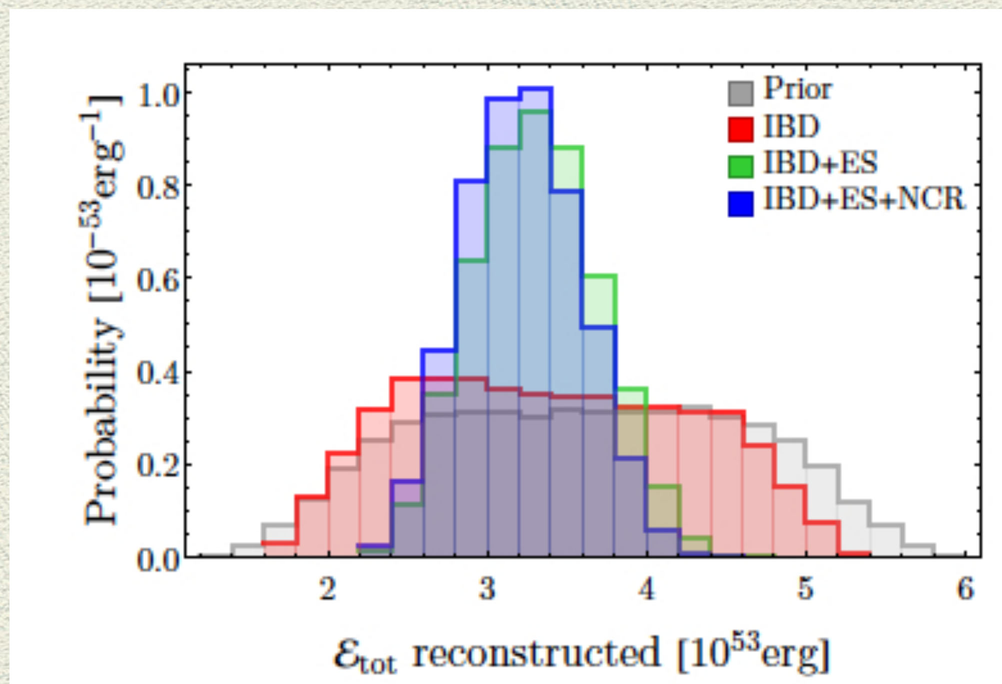
Matter-Neutrino resonance location
Frensel et al., PRD95 (2017)



« Fast » modes, Wu et al., PRD96 (2017)
(assuming flavor equilibration though)
see S. Abbar's talk

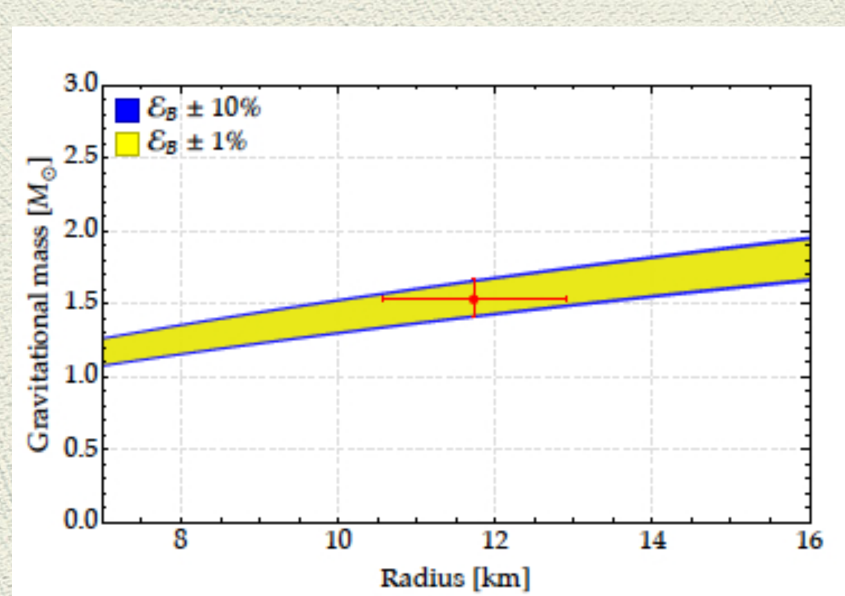
Reconstructing the gravitational binding energy of the newly formed neutron star

Likelihood analysis for a neutrino signal from a galactic supernova.



Combining inverse beta-decay, elastic scattering (and neutral current) allows to reconstruct the gravitational binding energy at a few percent accuracy - 11% in Super-Kamiokande, 3% in Hyper-Kamiokande.

see *A. Gallo Rosso's talk*



(b) Mass–Radius constraint

Fit to numerous EOS for NS

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

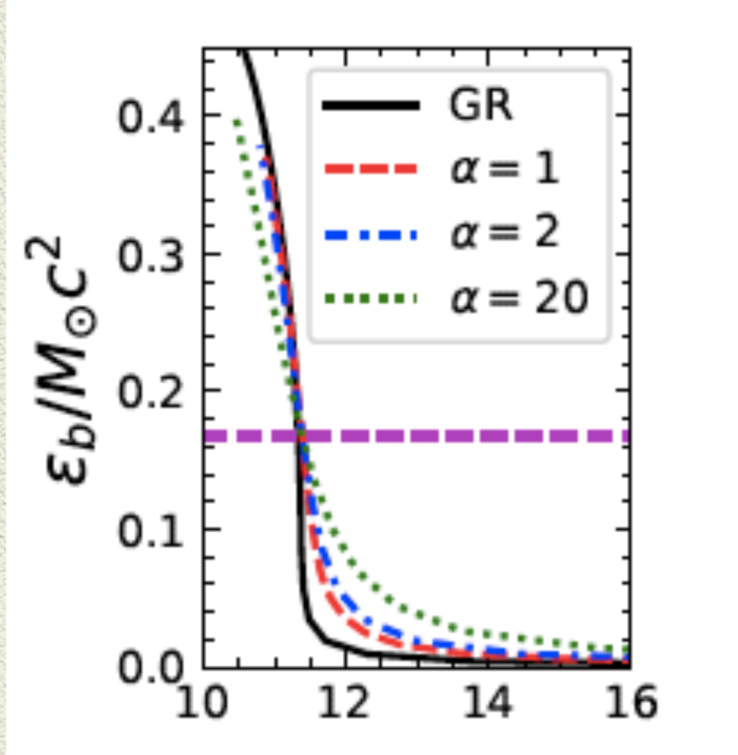
Lattimer, Prakash, Phys.Rept. 442 (2007)

Gallo Rosso, Vissani, Volpe, JCAP 1711 (2017)

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).

Conclusions and perspectives

- Helicity coherence does not produce significant flavor modification in dense environments (binary neutron star mergers and core-collapse supernovae).

  A perturbative argument shows that non-linear feedback does not enhance adiabaticity, while for other resonances (matter-neutrino resonance) it does.

- Non-standard interactions can produce the I-resonance also in presence of neutrino self-interactions.

  The effect of neutrino flavor evolution in neutrino driven winds in kilonovae still needs 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 extended theories of gravity.

  Constraints on the pinching of the neutrino fluencies can be obtained by implementing reasonable values for the neutron star radii.