Extended evolution equations and helicity coherence

Reconstructing E_b

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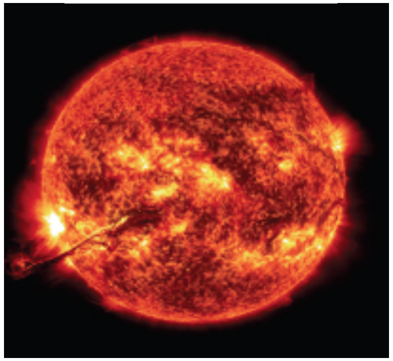
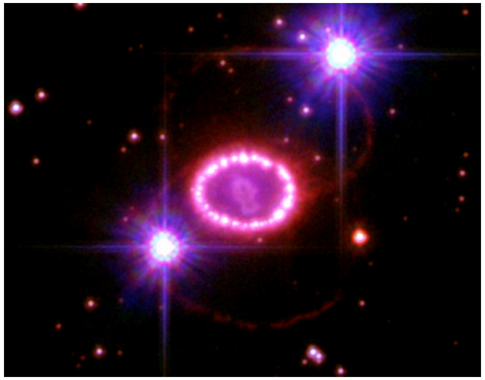
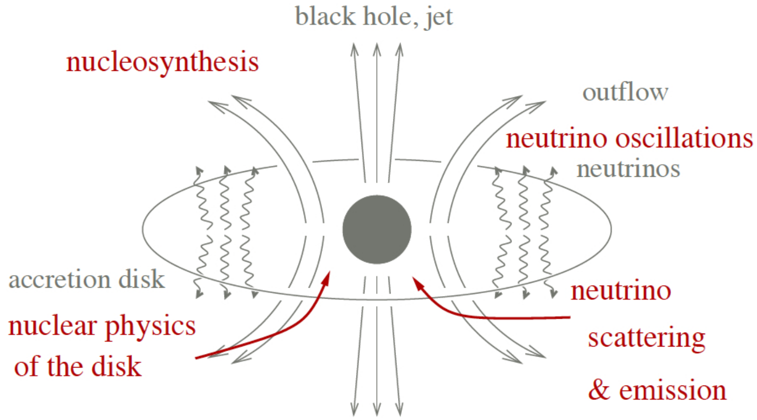
the Sun



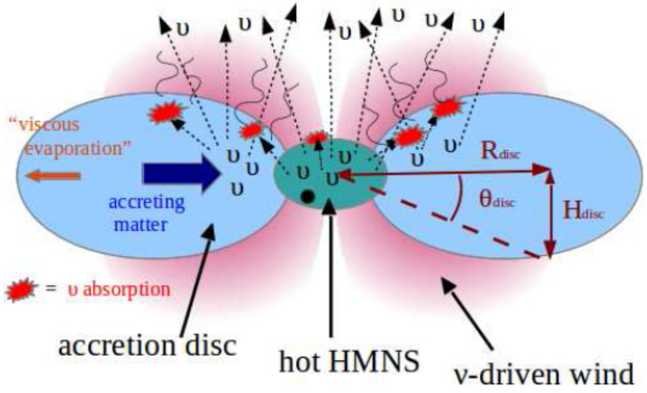
core-collapse Supernovae



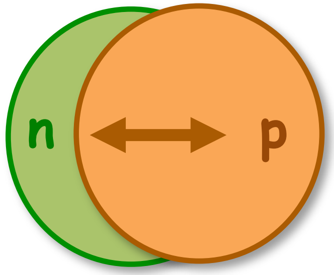
accretion disks around black holes or neutron star mergers remnants



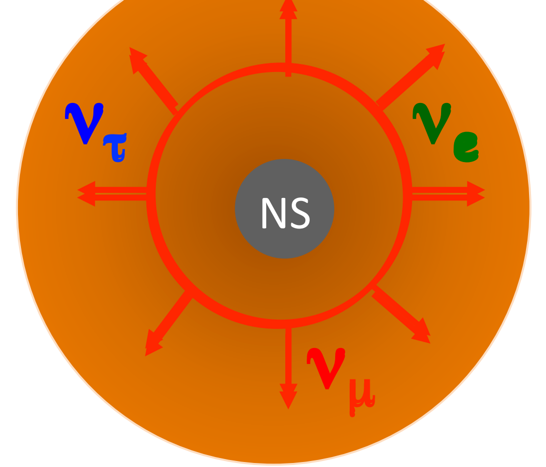
from McLaughlin



from Perego, A. 2014



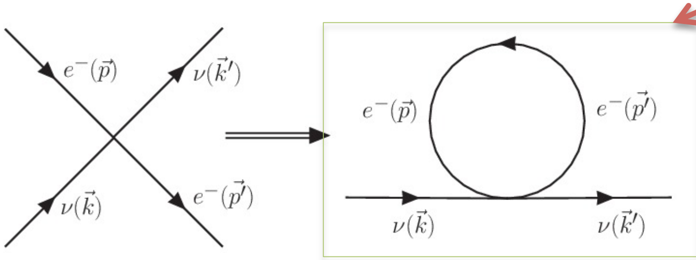
To determine the dynamics

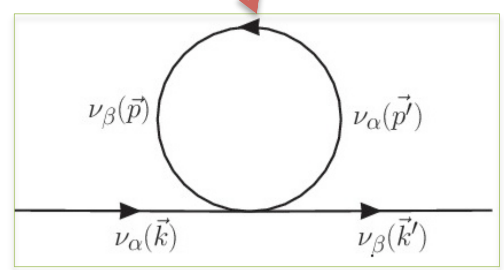


$\rho = \langle a^{+} a \rangle$ one-body density matrix

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

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





MEAN-FIELD approximation

neutrino-matter

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

neutrino self-interactions
non-linear term

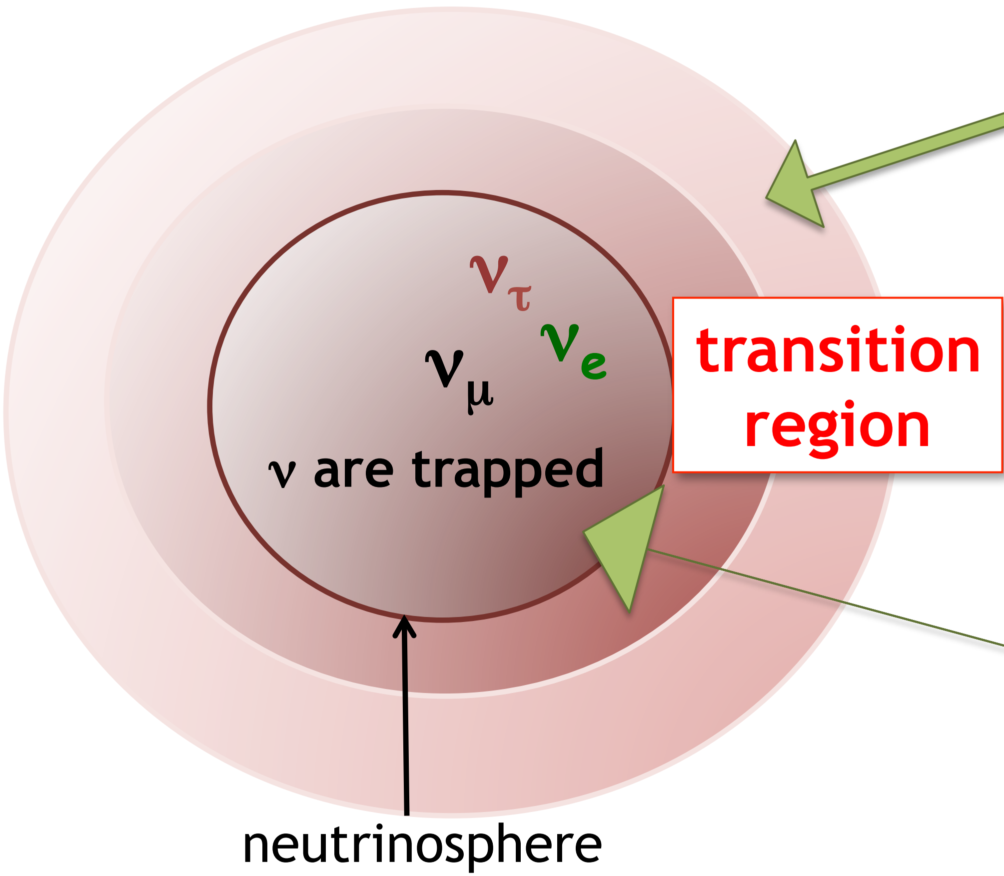
BBGKY hierarchy : first equation, and beyond mean-field

Volpe, Väänänen, Espinoza. PRD 87 (2013)

Description of ν evolution in dense environments

Several approaches used to derive evolution equations - *density matrices, effective spins, Green's functions and path integrals, BBGKY hierarchy*.

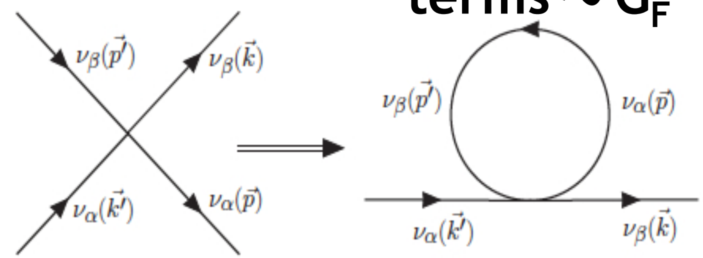
Volpe, arXiv: 1506.06222



Equation based on :

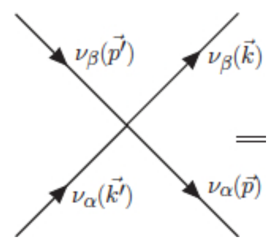
- ❑ mean-field approximation

terms ~ G_F

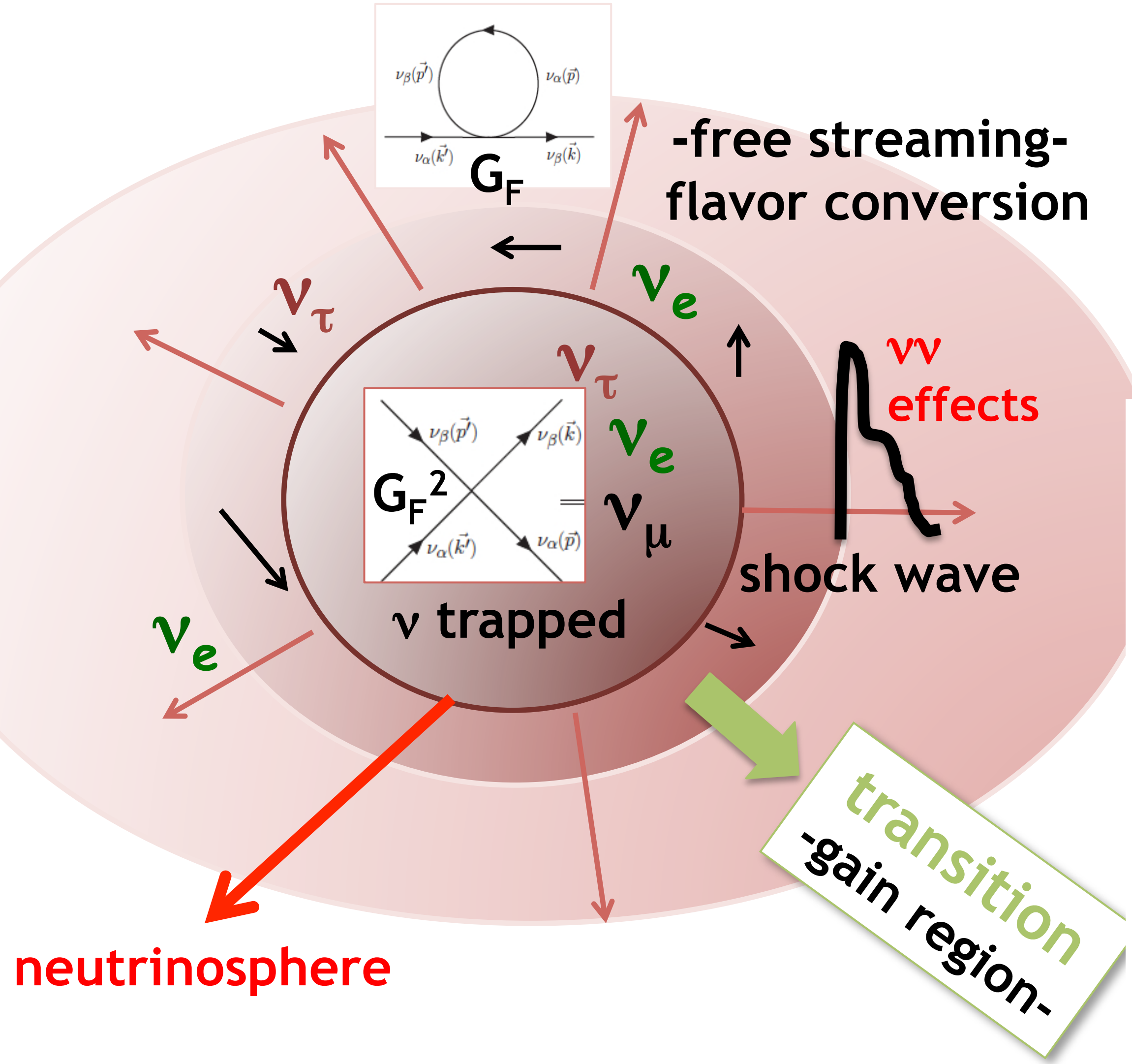


- ❑ extended mean-field
- ❑ Boltzmann equation

terms ~ G_F^2

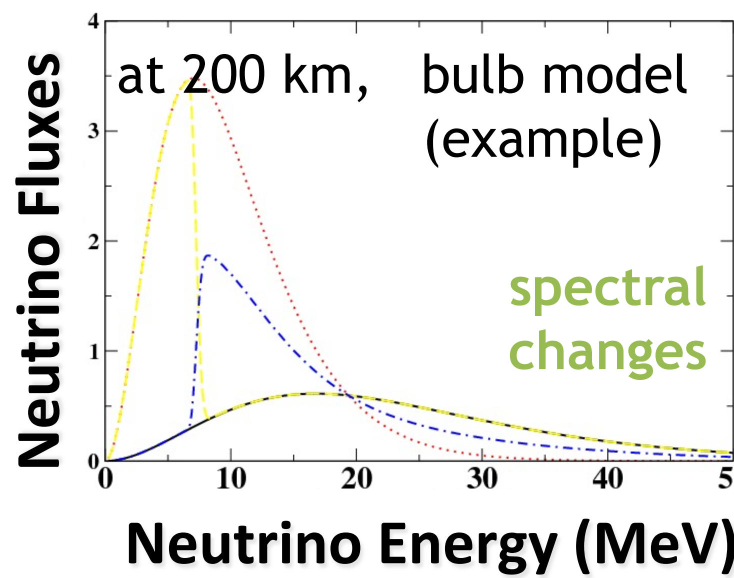


In supernovae



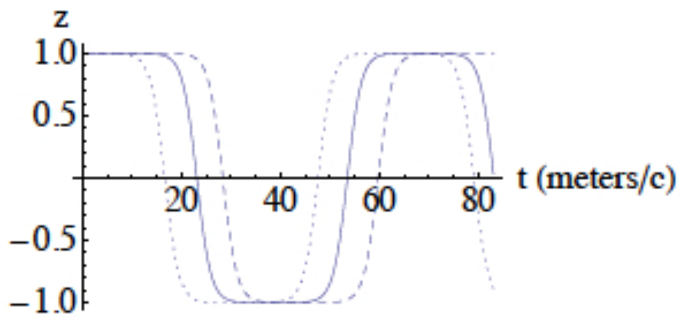
$\nu_e + n \rightarrow p + e^-$
$\bar{\nu}_e + p \rightarrow n + e^+$

Spectral changes can modify the supernova dynamics, nucleosynthesis and supernova observations



The transition region

- if different νspheres considered

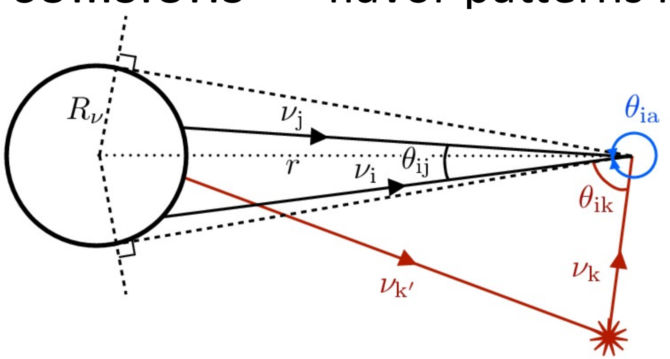


Conversion at
short time scales

Sawyer, PRL108 (2016)

- collisions -> flavor patterns modified (schematic evaluation)

Cherry et al, PRL108 (2012)



Competition between the collision and flavor timescales ?

The transition region : extended mean-field equations

- mass terms introduce helicity change: $\zeta = \langle a_+^+ a_- \rangle$

$$i\dot{\mathcal{R}}(t) = [\mathcal{H}(t), \mathcal{R}(t)] .$$

$\mathcal{R}$ – generalised density matrix
$\mathcal{H}$ – generalised Hamiltonian

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

$\mathcal{R}$ and $\mathcal{H}$ have helicity and flavor structure, $2\mathcal{N}_f \times 2\mathcal{N}_f$.

$\Phi \sim (h_{mat}^{perp} + h_{\nu\nu}^{perp}) \times m_\nu/(2E_\nu)$

Helicity coherence Φ couples ν with $\bar{\nu}$, if the medium is anisotropic.

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

The influence of helicity coherence on flavor evolution ?

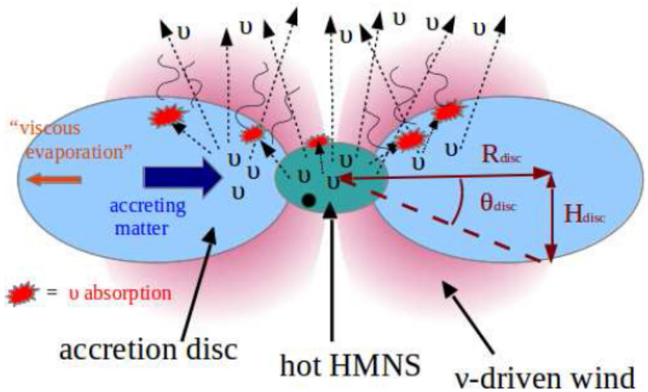
First study in a one-flavor schematic model showed it might impact neutrino flavor conversion.

Vlasenko, Fuller, Cirigliano, 1406.6724

Helicity coherence in binary neutron star mergers (BNS)

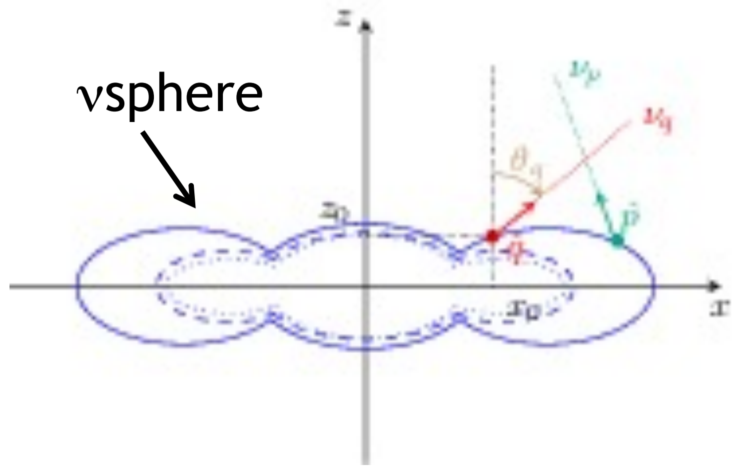
Chatelain, Volpe, PRD (2017), arXiv: 1611.01862

Investigated the role of helicity coherence along a large set of trajectories (x_0, z_0, θ_q).



from Perego *et al.*, 2014

neutron star mergers remnant



Inputs - electron fraction Y_e, baryon number density n_B, ν fluxes and νsphere radii – from detailed simulations.

	$\langle E_\nu \rangle$	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	

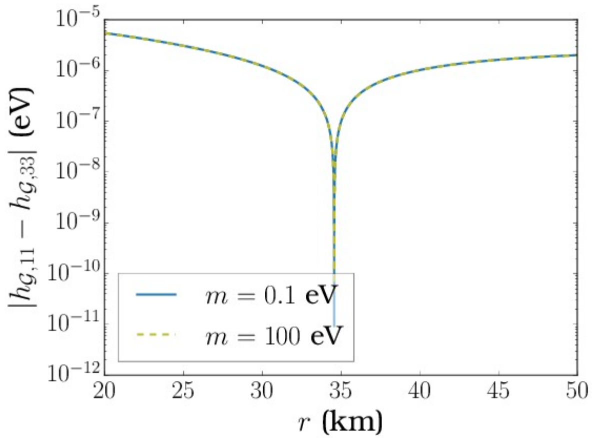
Flavor evolution in presence of helicity coherence

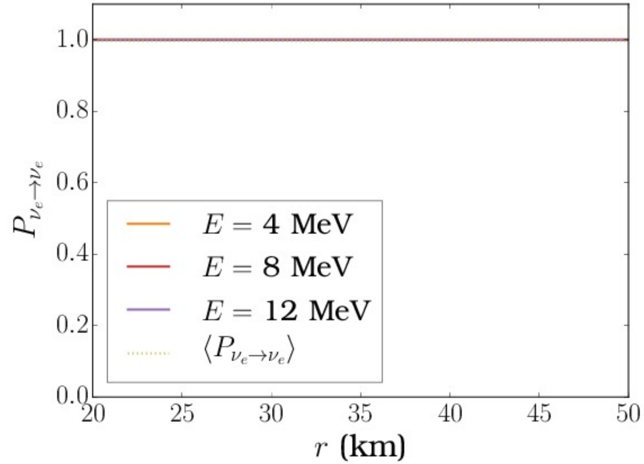
For Majorana neutrinos, the 2ν Hamiltonian $\mathcal{H} = \begin{pmatrix} h & \Phi \\ \Phi^* & \bar{h} \end{pmatrix}$

Resonance (MSW-like) conditions :

- Helicity Coherence

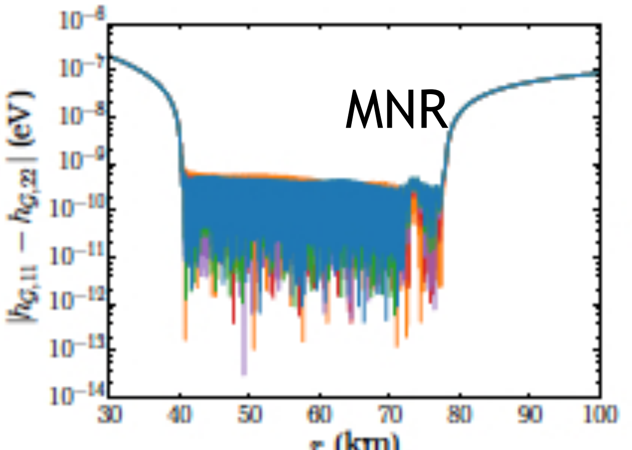
$$h_{\mathcal{G},11} - h_{\mathcal{G},33} = \sqrt{2} G_F n_B (3Y_e - 1) + 2h^{ee}_{\nu\nu} \simeq 0,$$

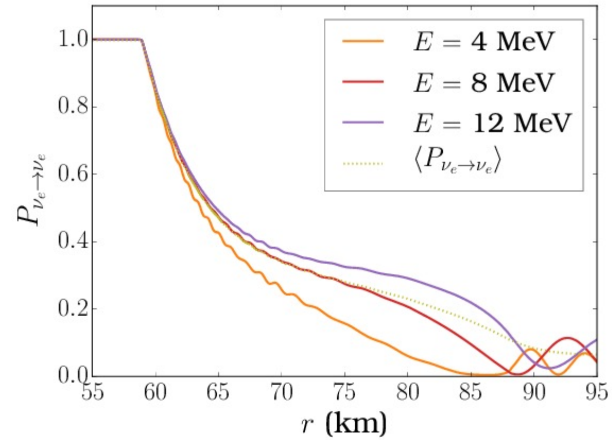




- Matter-Neutrino Resonance

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

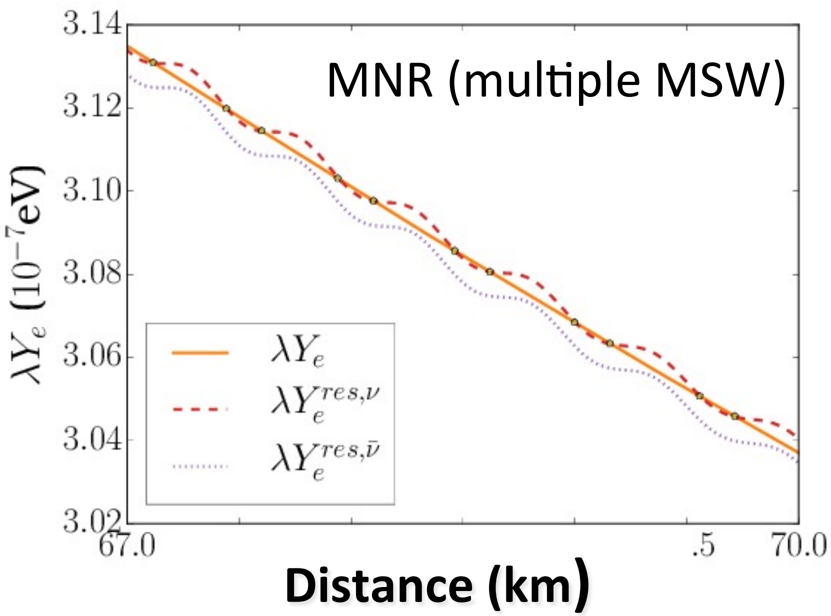




Resonance conditions met, adiabaticity not enough

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

Helicity coherence, MNR and non-linear feedback



Example of the Matter Neutrino Resonance :

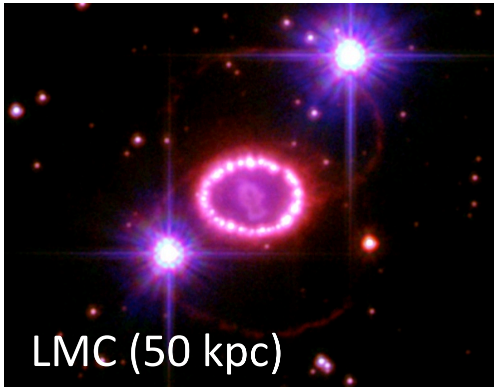
$$\lambda Y_e \simeq -(h^{ee}_{\nu\nu} - h^{xx}_{\nu\nu}) + \frac{\Delta m^2}{2p}\cos 2\theta$$

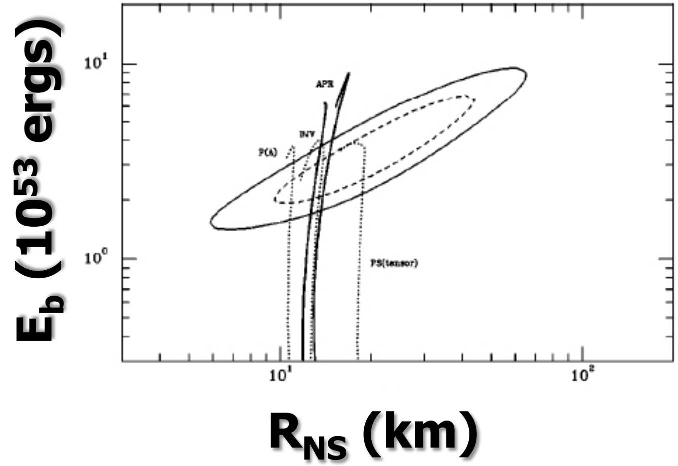
Matching between the ν self-interaction and the matter potential produced by non-linear feedback

A perturbative analysis of the conditions to have multiple MSW resonances on a short distance scale shows the matching is not possible for helicity coherence because of the radial dependence of the geometrical factor. Also true in supernovae, unless specific matter profiles are taken.

Non-linear feedback does not produce multiple MSW for helicity coherence.

Supernovae and observations





Loredo, Lamb, PRD 2002

SN1987A : Bayesian analysis of the energies and arrival times of the events.

Delayed explosion mechanism favored over the prompt one.

many analysis since....

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

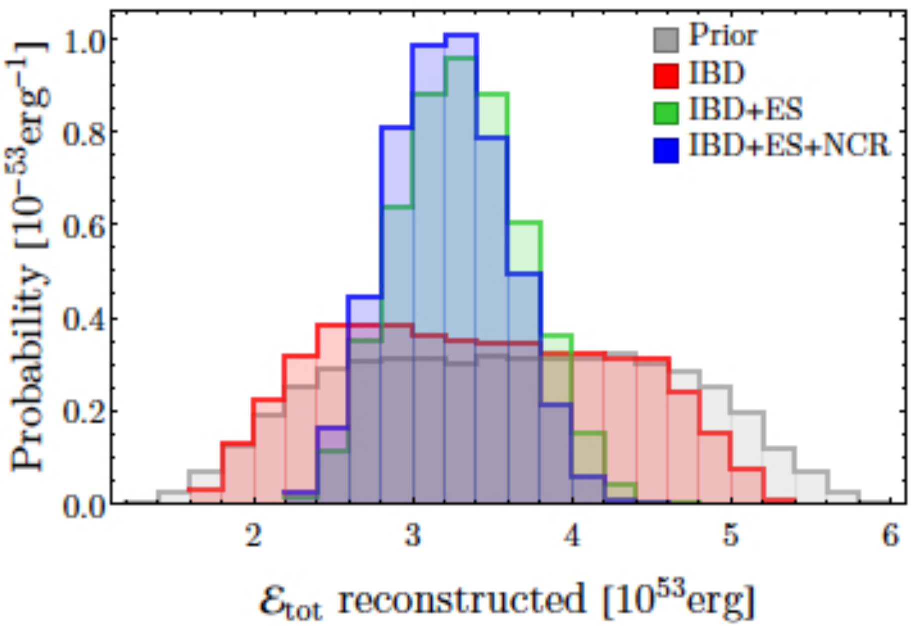
Most of the analysis make assumptions - ex. equipartition Hypothesis, or pinching parameter fixed.

exception : Minakata et al, arXiv:0802.1489

Reconstrucing the gravitational binding energy

Gallo Rosso, Vissani, Volpe, arXiv:1708.00760

For a galactic supernova at 10 kpc. Signal in Super-Kamiokande.



Likelihood without any priors (9 free parameters)

Fluence described by a power-law, MSW included, NH

Combined IBD, elastic scattering (100% tagging efficiency on IBD and ES for E_{thr} = 5 MeV) and NC on oxygen ($E\gamma$ 5−7 MeV)

	ν_e	$\bar{\nu}_e$	ν_x
$\mathcal{E}_i^*$ $[10^{53}$ erg$]$	$0.5 \in [0.2, 1]$	$0.5 \in [0.2, 1]$	$0.5 \in [0.2, 1]$
$\langle E_i^* \rangle$ [MeV]	$9.5 \in [5, 30]$	$12 \in [5, 30]$	$15.6 \in [5, 30]$
α_i^*	$2.5 \in [1.5, 3.5]$	$2.5 \in [1.5, 3.5]$	$2.5 \in [1.5, 3.5]$

True parameters used in the analysis and parameters range In the analysis

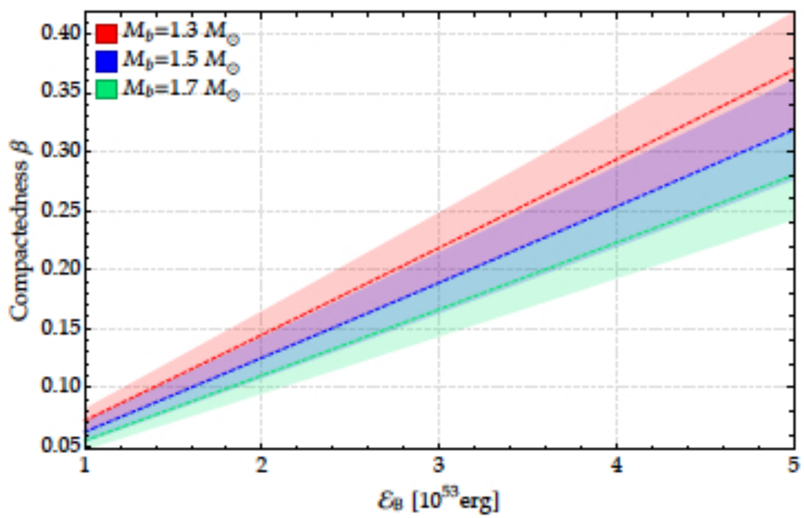
E_b reconstructed with 11% accuracy.

Compactness and M-R of the newly born neutron star

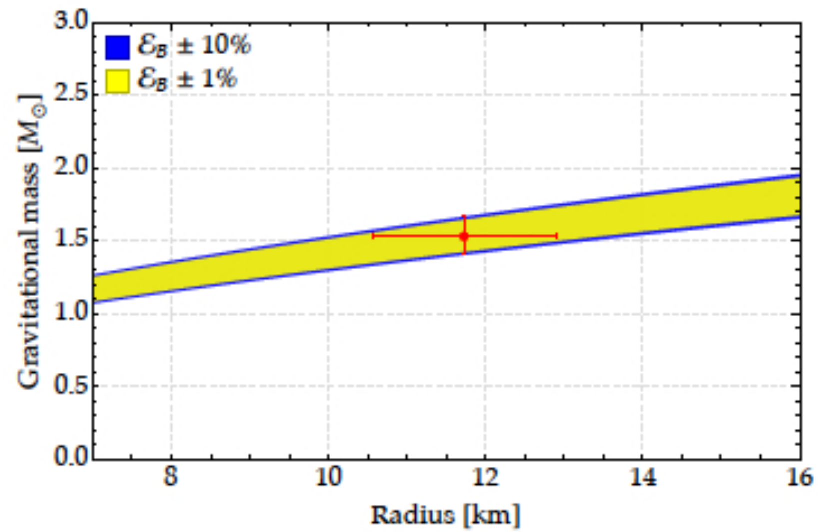
$$\frac{\mathcal{E}_\mathrm{B}}{Mc^2} \approx \frac{(0.60 \pm 0.05)\,\beta}{1-\beta/2}, \qquad \beta = \frac{GM}{Rc^2},$$

Lattimer & Prakash, Phys. Rep. 2007

fit to numerous EOS for NS



(a) Compactness–$\mathcal{E}_\mathrm{B}$ constraint



(b) Mass–Radius constraint

$$\beta = \frac{\mathcal{E}_\mathrm{B}}{0.6\,M_b c^2 - 0.1\,\mathcal{E}_\mathrm{B}}.$$

$$M = \sqrt{\frac{\mathcal{E}_\mathrm{B} R}{0.6\,G}}\left[\sqrt{1+\epsilon^2} - \epsilon\right]$$

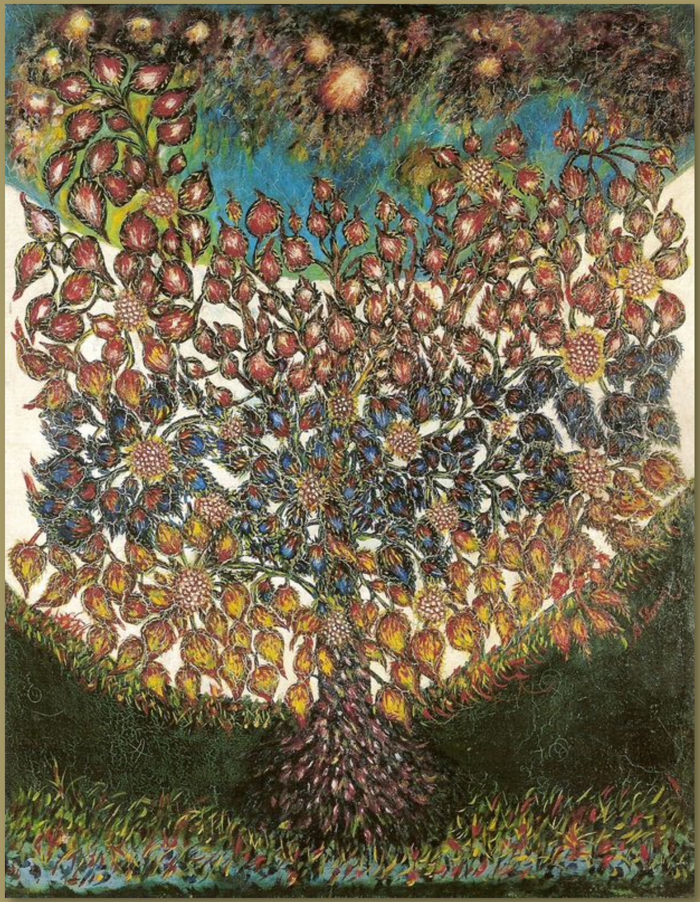
$$\text{with} \quad \epsilon = \frac{1}{4}\sqrt{\frac{\mathcal{E}_\mathrm{B} G}{0.6\,R c^4}}.$$

Conclusions and perspectives

- **The transition region needs better description.** Competition between collisions and flavor evolution.

- **Helicity coherence due to neutrino mass terms :** resonance conditions met in detailed simulations but adiabaticity not enhanced by non-linear feedback. Flavor evolution in BNS still little explored.

- Reconstructing the gravitational binding energy of the newly born neutron star : a ten to a few percent precision achievable from combined analysis <u>without priors</u> from a galactic supernova neutrino signal.



Life tree