Neutrino astrophysics and connections with nuclear physics

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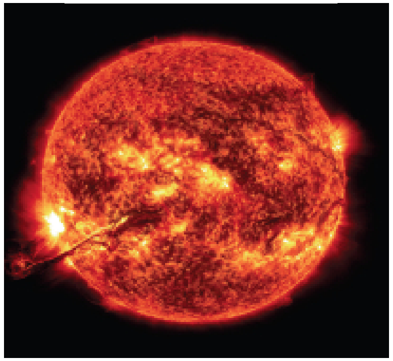
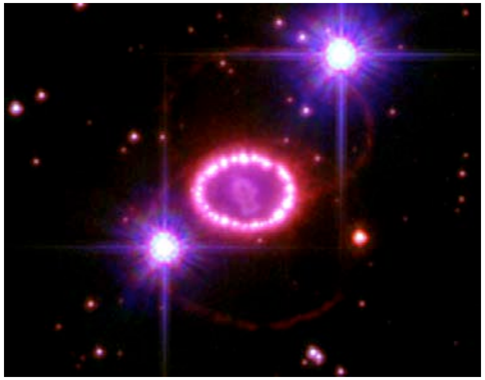
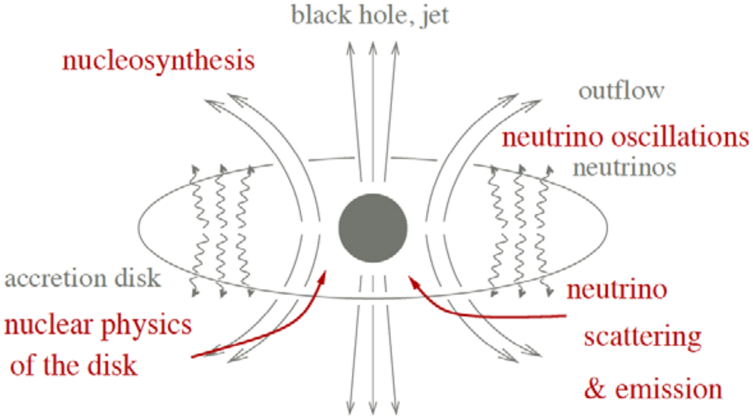
the Sun



core-collapse Supernovae

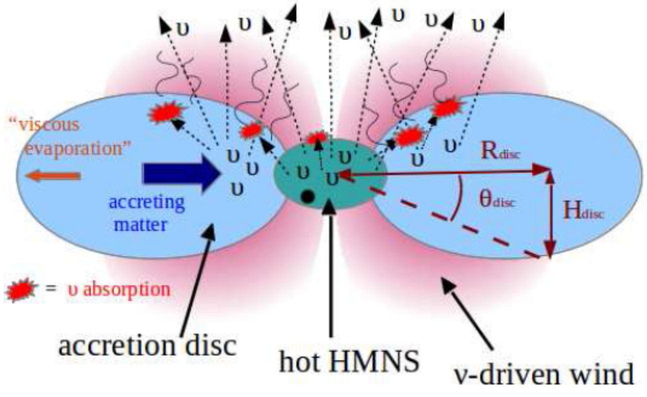


accretion disks around black holes



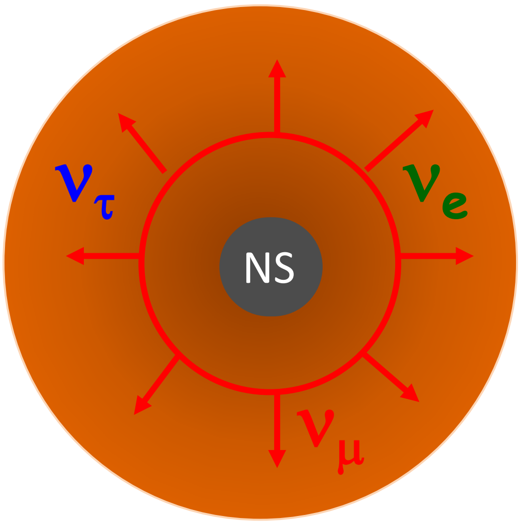
from McLaughlin

or neutron star mergers remnants



from Perego, A. 2014

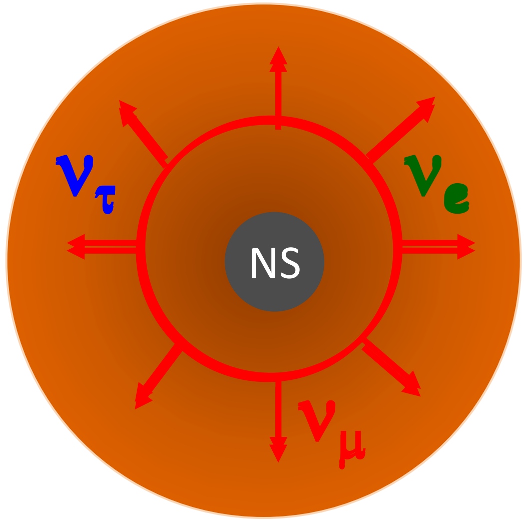
Neutrinos from gravitational core-collapse



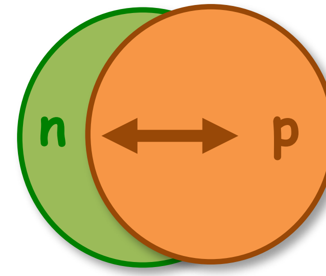
- They comprise : SN II (H in their spectra), SN I b/c (H envelop lost), Ib has He, no Si, Ic none (H and He envelop lost).
- Stars with masses :
  $6\ M_{sun} < M < 8\ M_{sun}$ **O-Ne-Mg SNe**
  $M > 8\ M_{sun}$ **Iron-core SNe**
- 99 % of the gravitational energy (10^{53} ergs) is radiated as neutrinos and anti-neutrinos of all flavours.

Neutrinos tightly linked to key astrophysics issues :

- How do massive stars explode ?
- What is the site where heavy elements are made ?



ν in stars or accretion disks

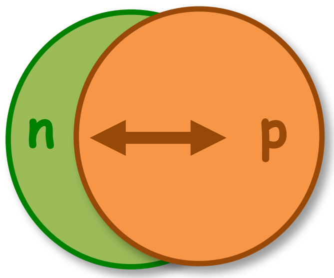


atomic nucleus

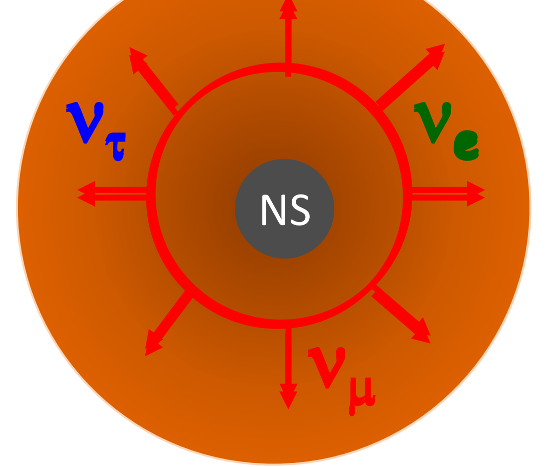
10^{57}	**N**	200
weak	**interaction**	strong
unbound	**system**	bound
$\rho_{ji} = \langle a_i^{+} a_j \rangle$ neutrinos $\overline{\rho}_{ji} = \langle b_i^{+} b_j \rangle$ anti-neutrinos	**density**	$\rho = \langle a^{+} a \rangle$ neutrons protons

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

To determine the dynamics

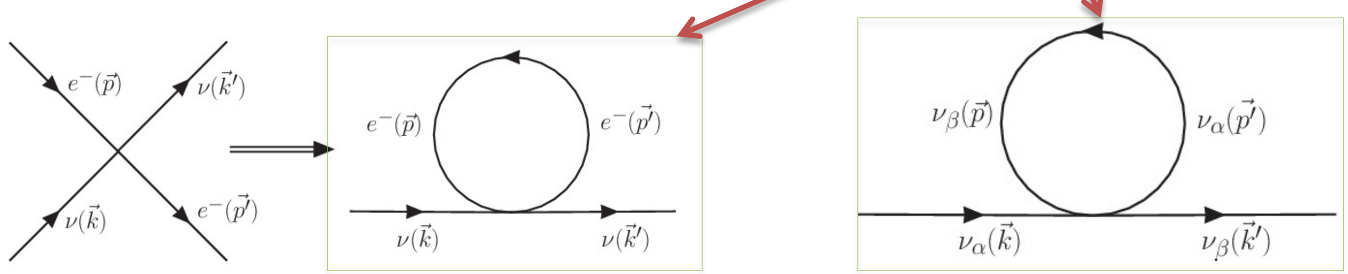


$$\rho = \langle a^{+} a \rangle$$ one-body density matrix



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

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



neutrino-matter

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

neutrino self-interactions

non-linear term

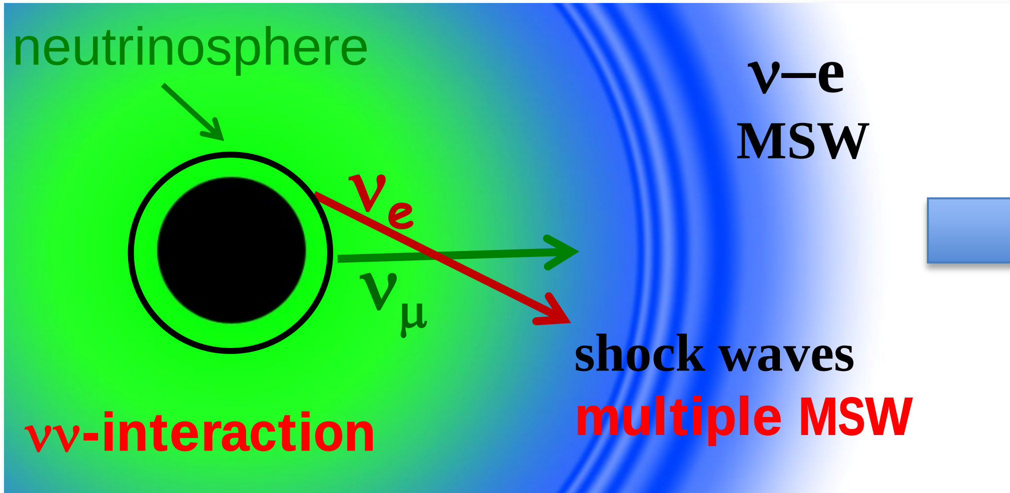
MEAN-FIELD approximation

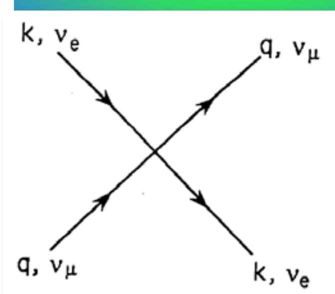
First equation of the BBGKY hierarchy and beyond

Volpe et al., PRD 87 (2013)

Flavor conversion in supernovae

Novel phenomena uncovered



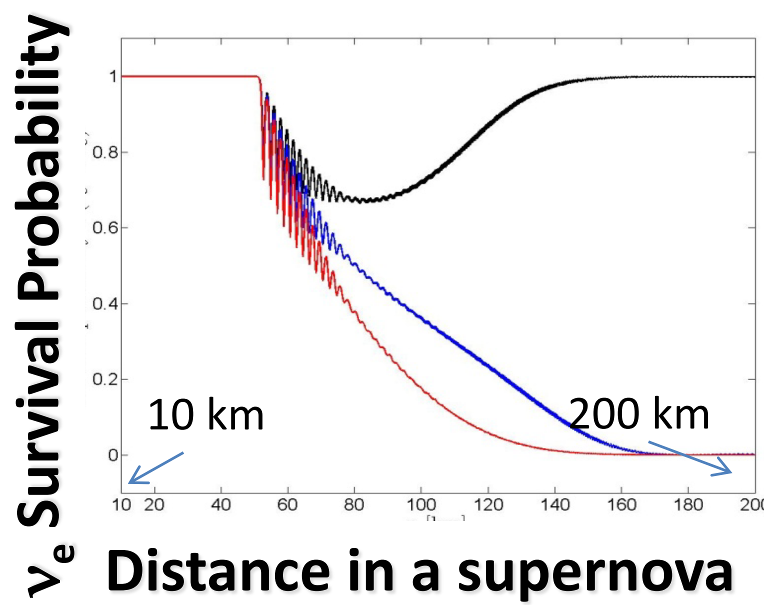


Pantaleone, PLB 1992
Sigl and Raffelt, 1993

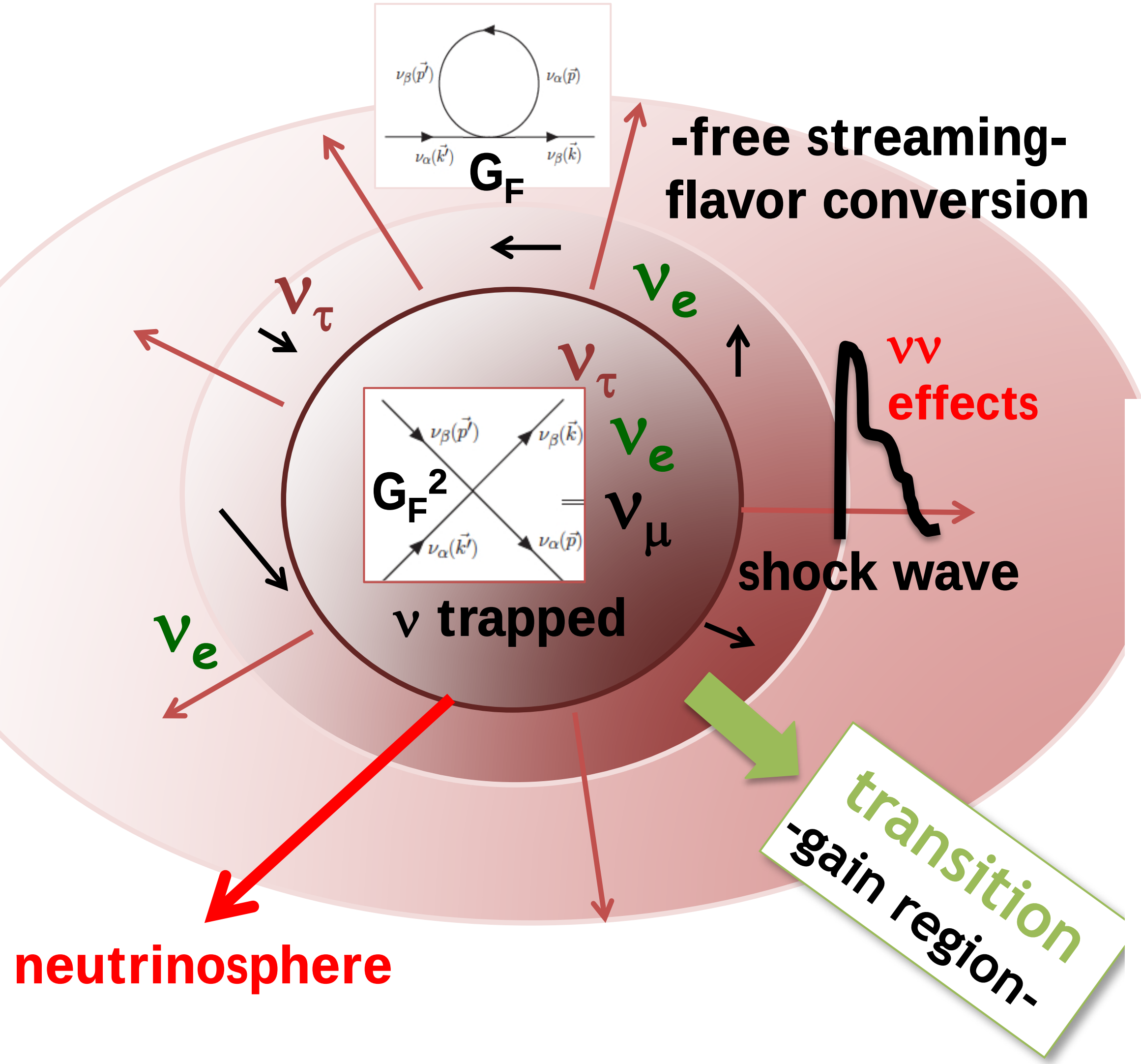
- Efficient conversion occurs close to the neutrinosphere

Models of increasing complexity studied since a decade

Duan, Fuller, Qian, Ann. Rev. 60 (2010)

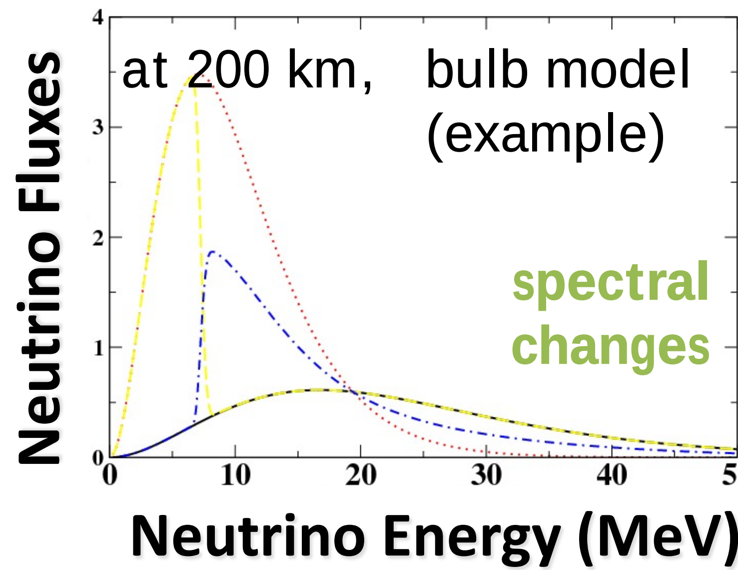


In supernovae

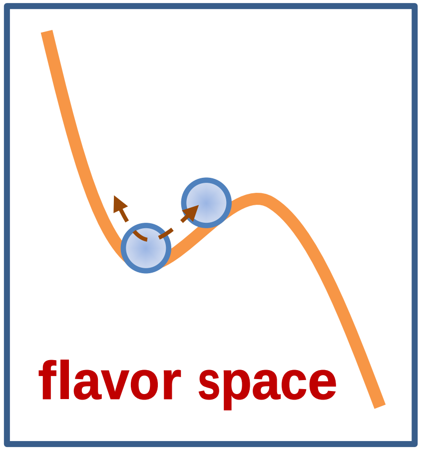


$\nu_e + n \rightarrow p + e^-$
$\bar{\nu}_e + p \rightarrow n + e^+$

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



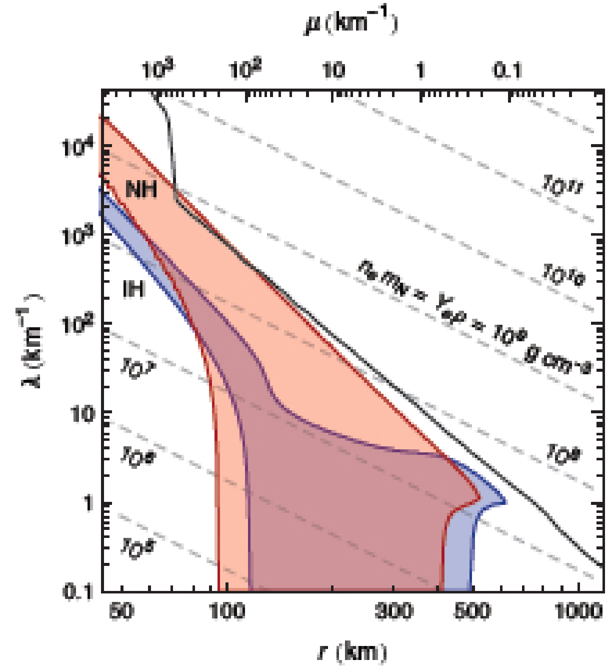
Collective neutrino modes and linearization



Small amplitude motion

Collective modes and instabilities can be studied with the linearization.

Banerjee, Dighe, Raffelt, PRD84 (2011)



Raffelt et al, PRL(2013)

Stability matrix

$$\boxed{\begin{pmatrix} A & B \\ \bar{B} & \bar{A} \end{pmatrix}} \begin{pmatrix} \rho' \\ \bar{\rho}' \end{pmatrix} = \omega \begin{pmatrix} \rho' \\ \bar{\rho}' \end{pmatrix}$$

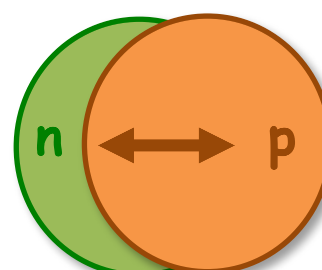
S eigenvalues :

-> real : stable collective

-> imaginary : instabilities

connection to collective modes in other many-body systems (nuclei, clusters, ...)

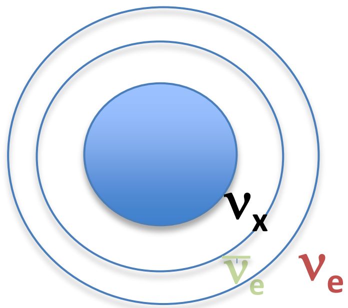
Väänänen and Volpe, PRD88 (2013)

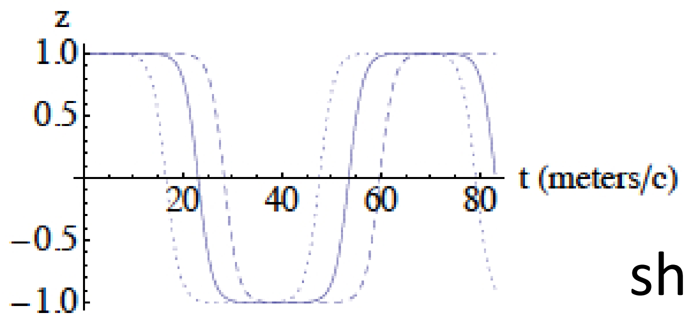


nuclear resonances

The transition region

❖ if different neutrinospheres considered



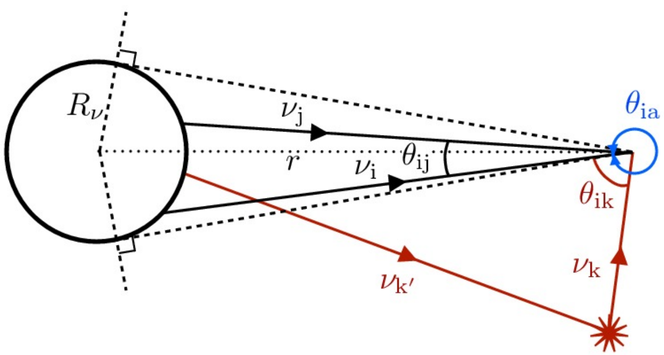


Conversion at short time scales

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

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

R – generalised density matrix
H – generalised Hamiltonian

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

R and H have helicity and flavor structure, $2N_f \times 2N_f$.

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

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

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

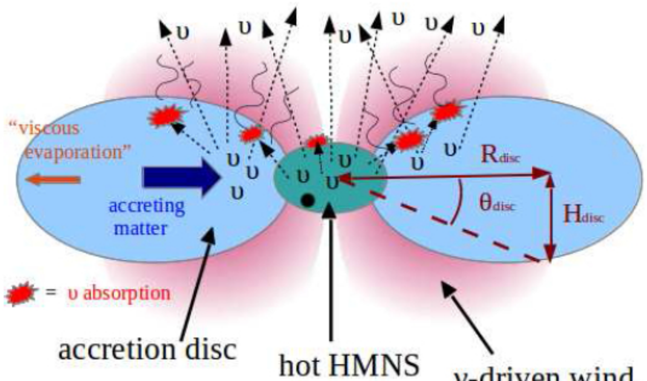
The influence of helicity coherence on flavor evolution ?

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

Vlasenko, Fuller, Cirigliano, 1406.6724

Helicity coherence (mass terms) effects

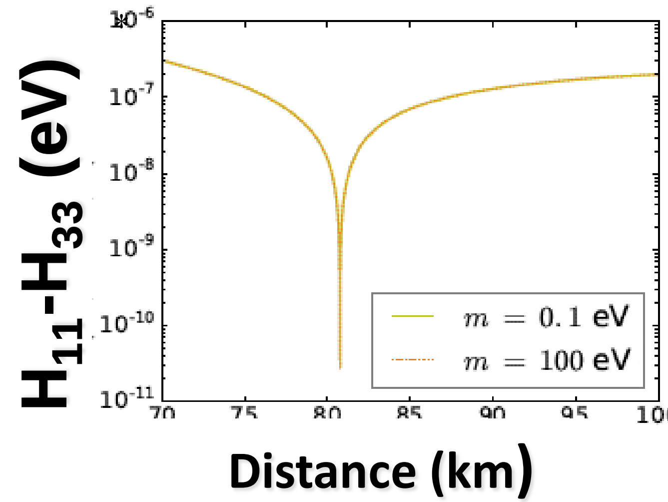
neutron star mergers remnant



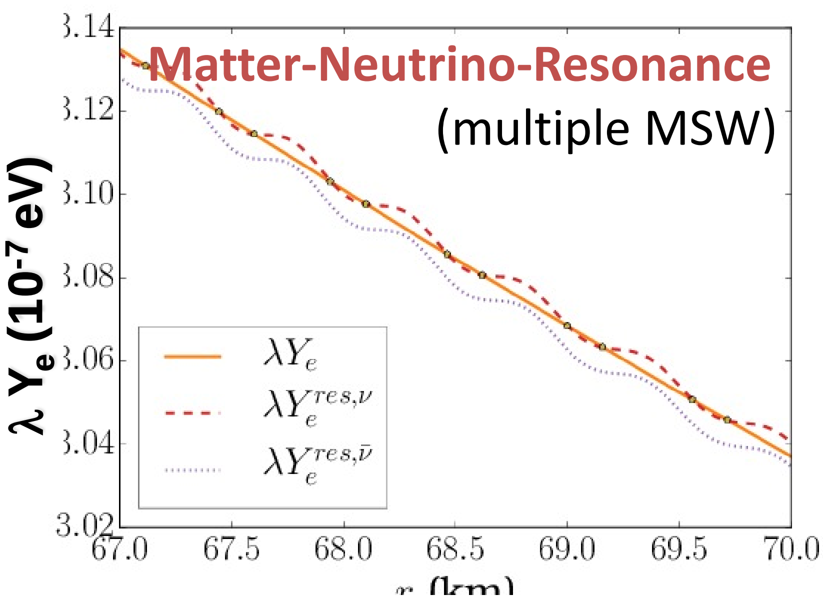
from Perego *et al.*, 2014

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

In two flavors
H is a 4 x 4 matrix.



- resonance condition fulfilled
- adiabaticity not sufficient

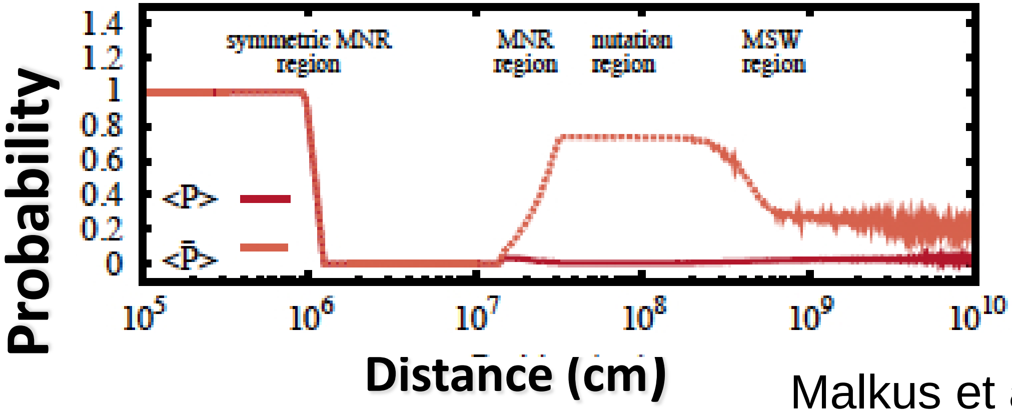


Distance (km)

Non-linear feedback does not enhance mass effects.

Chatelain,Volpe, PRD(2017) 1611.01862

Flavor phenomena and nucleosynthesis in accretion disks



Matter-Neutrino Resonance

Excess of $\bar{\nu}_e$ over ν_e

The self-interaction and matter potentials cancel.

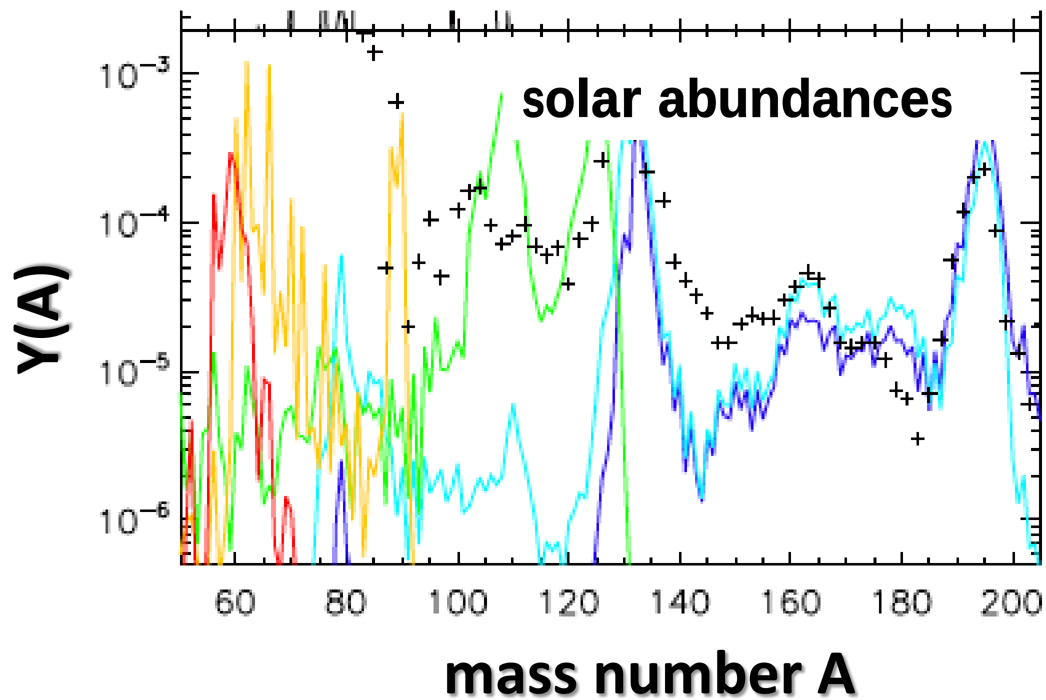
Malkus et al, PRD86 (2012), 96 (2016)

The site(s) where nucleosynthesis produces heavy elements, by rapid neutron capture searched.

Neutrinos influence the neutron richness

$$\nu_e + n \rightarrow p + e^-$$

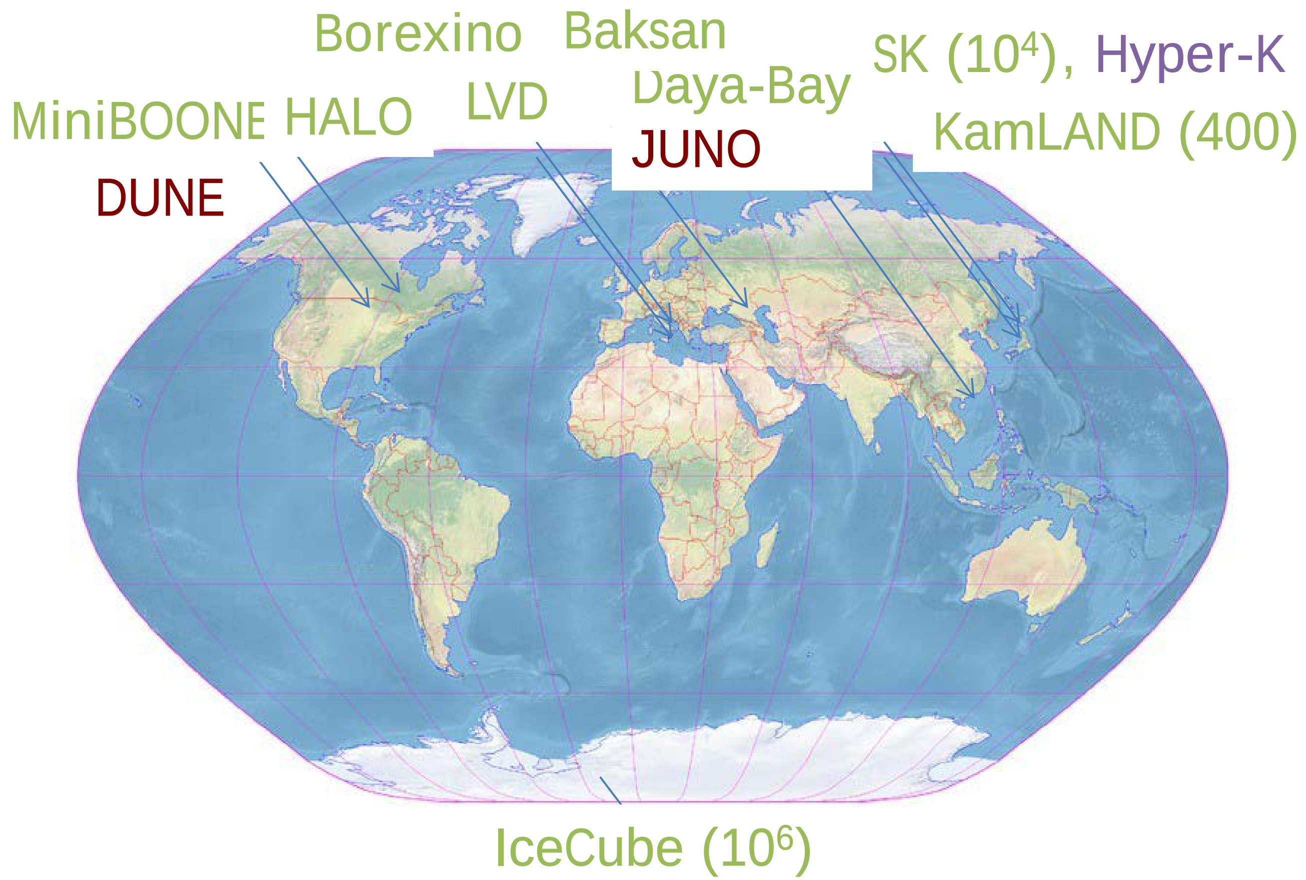
$$\bar{\nu}_e + p \rightarrow n + e^+$$



GW from BNS, as the recent observation, crucial.

Supernova Early Warning System and SNe observatories

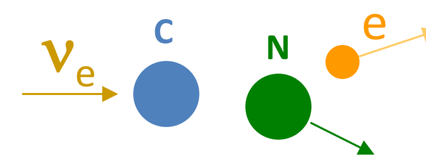
Events for a supernova explodes in our galaxy (10 kpc), up to 10^6 events

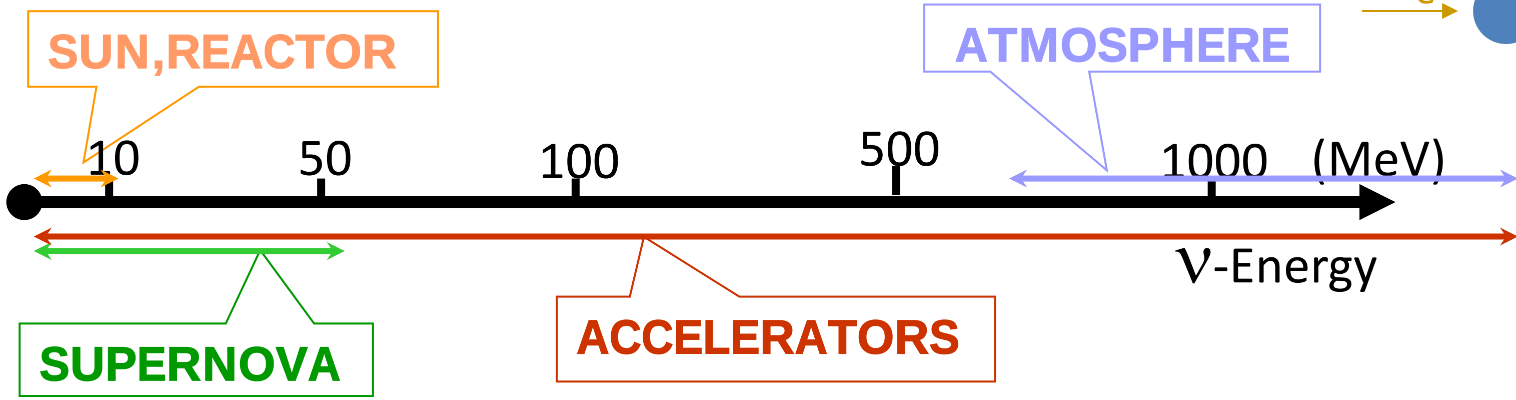


Detection channels : scattering of anti-ν_e with p, ν_e with nuclei, ν_x with *e, p*

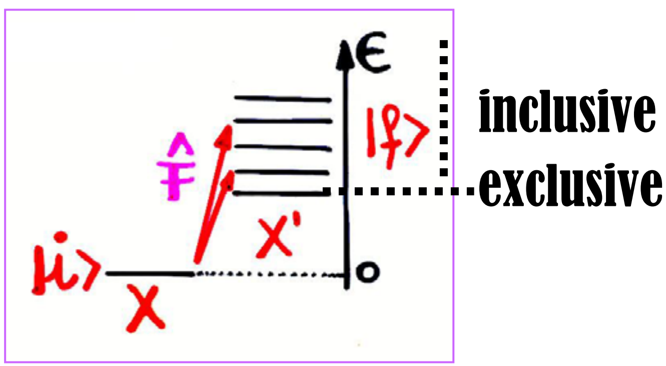
We will measure the time, energy signal from future (extra)galactic explosions.

Neutrino-nucleus cross sections





Experimental data scarce (d and ^{56}F, ^{12}C). Predictions based on various models, see eg. Brown, Hayes, Kolbe, Fuller, Haxton, Jachowitz, Kubodera, Langanke, Lazauskas, Martinez-Pinedo, McLaughlin, Vogel, Volpe,….



H_f

$$|\langle f|\sum_k j_\ell(qr_k) Y_\ell(\hat{r}_k) t_\pm(k)|i\rangle|^2$$

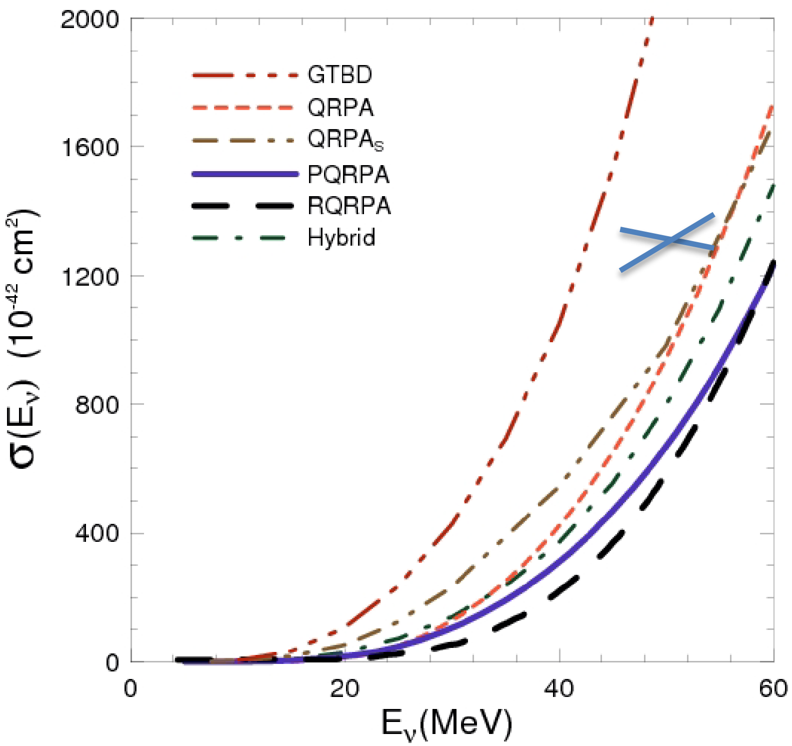
FERMI (ISOSPIN) TYPE TRANSITIONS

$$|\langle f|\sum_k j_\ell(qr_k)[Y_\ell(\hat{r}_k)\times\sigma]^{(k)} t_\pm(k)|i\rangle|^2$$

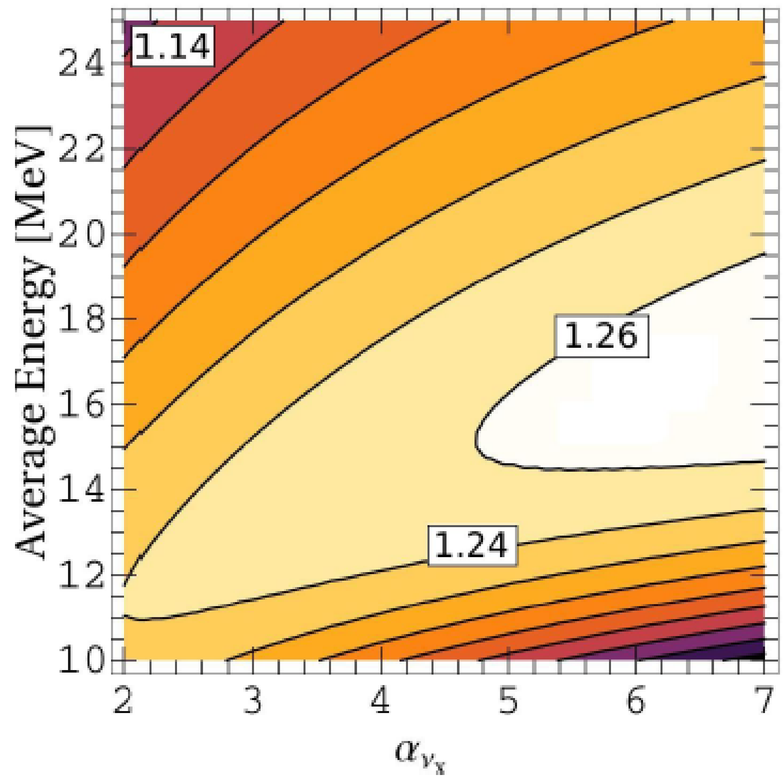
GAMOW-TELLER (SPIN-ISOSPIN) TRANSITIONS

Significant variations among the predictions….

Neutrino-nucleus cross sections



Bertulani, Samana, 0802.1553



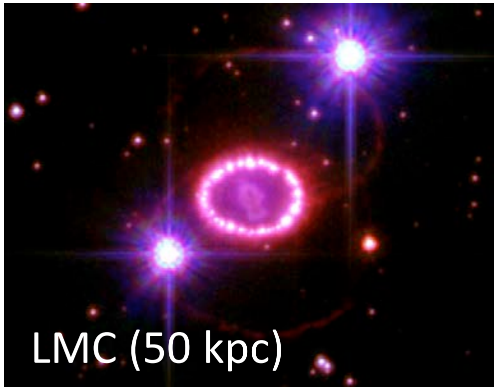
Vaananen, Volpe, JCAP 1011 (2011)

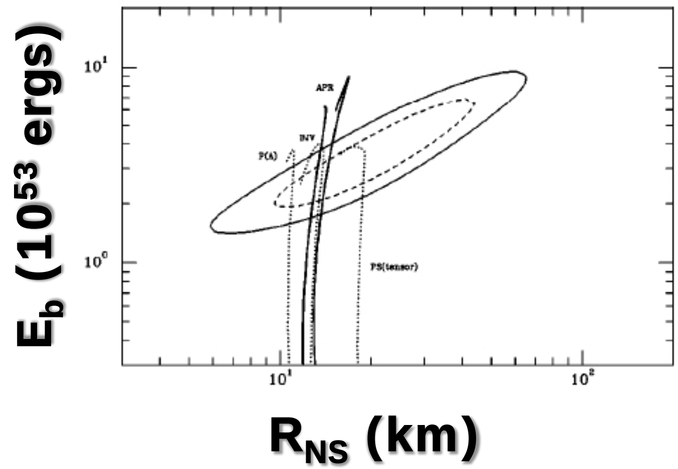
Several projects have been proposed over the years... ORLAND at SNS (2000), low energy beta-beam (2003), ν at JPARC (Ejiri, 2003)

Measurements on ν-nucleus cross sections planned at SNS by the INCOHERENT collaboration ! (Pb, O, Ar, Fe)

Sensitivity to the quenching of g_A

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 – see e.g. Vissani, J. Phys. G42 (2015).

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

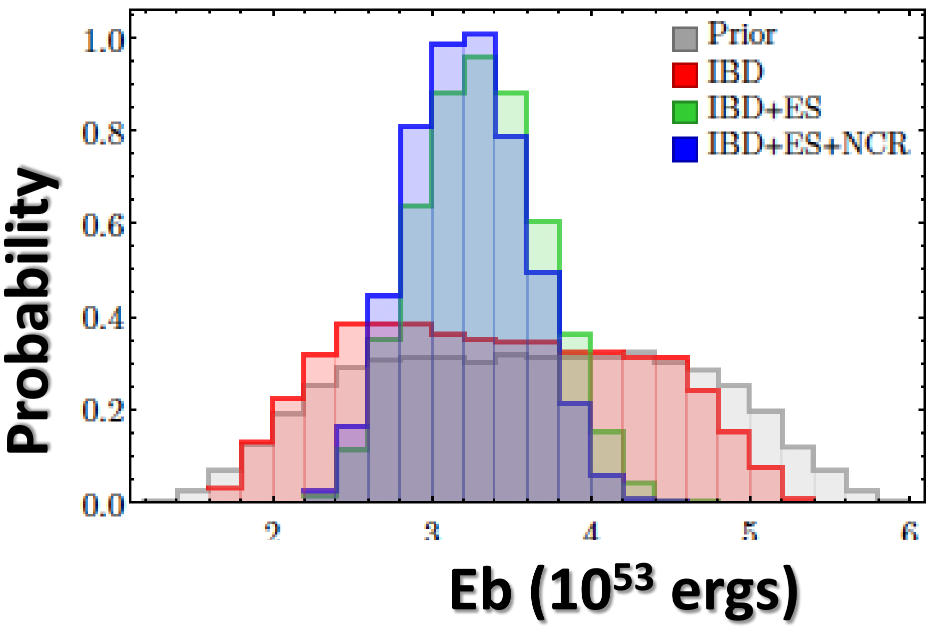
Most of the analysis make assumptions – ex. equipartition hypothesis, or pinching parameter fixed.

An et al. J. Phys. G43 (2016),
Lu, Li, Zhou, PRD94 (2016) 023006,
Minakata et al, arXiv:0802.1489, …

constructing the gravitational binding energy of the neutron sta

Gallo Rosso, Vissani, Volpe, arXiv:1708.00760

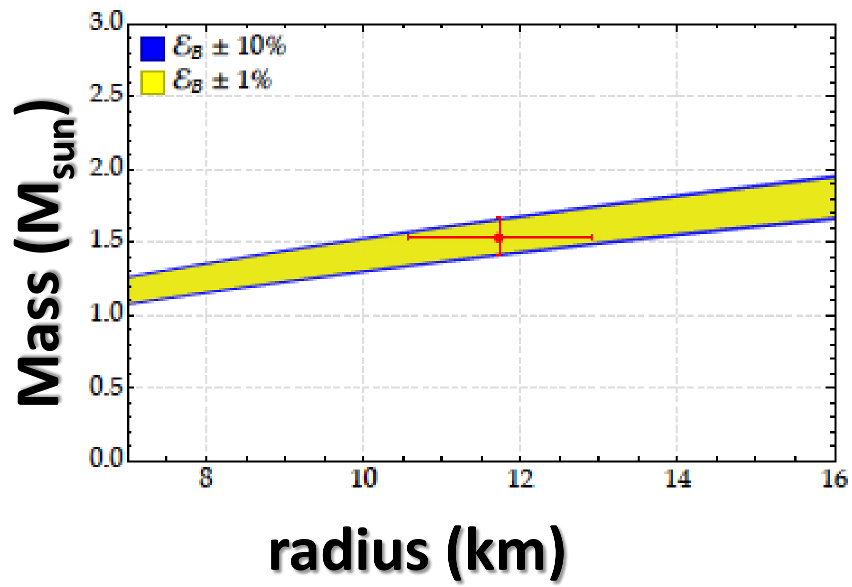
For a galactic supernova at 10 kpc. Signal in Super-Kamiokande.



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.Rep. 2007



- ✓ Likelihood without any priors
- ✓ Fluence : a power-law, MSW, NH
- ✓ Combined IBD, elastic scattering and NC on oxygen

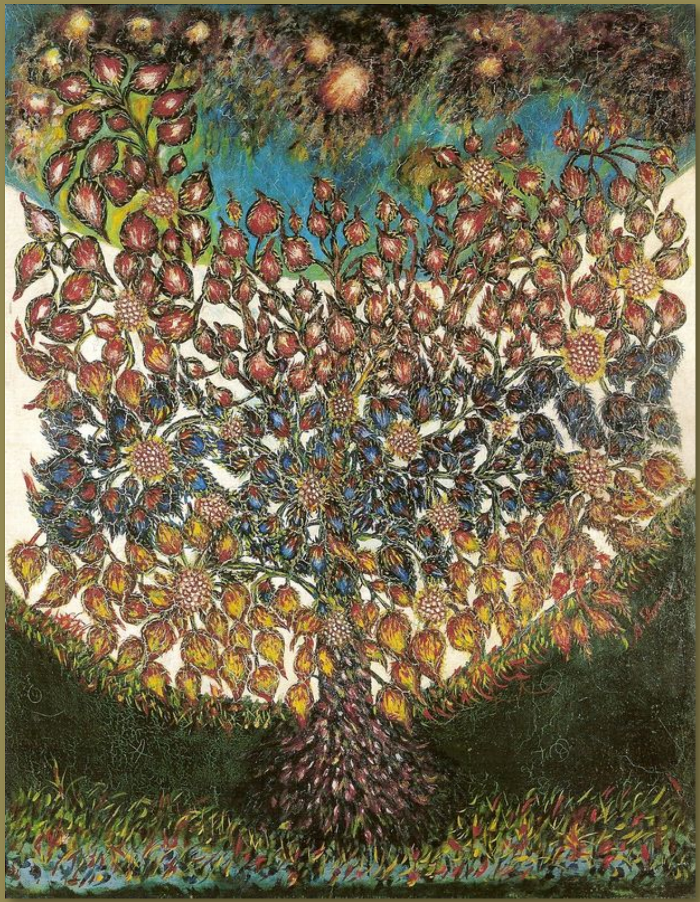
E_b reconstructed with 11% accuracy.

Conclusions and perspectives

- Neutrino flavor evolution is a many-body problem. Short scale modes seem to occur… A lot understood but the final impact on the fluxes needs to be assessed.

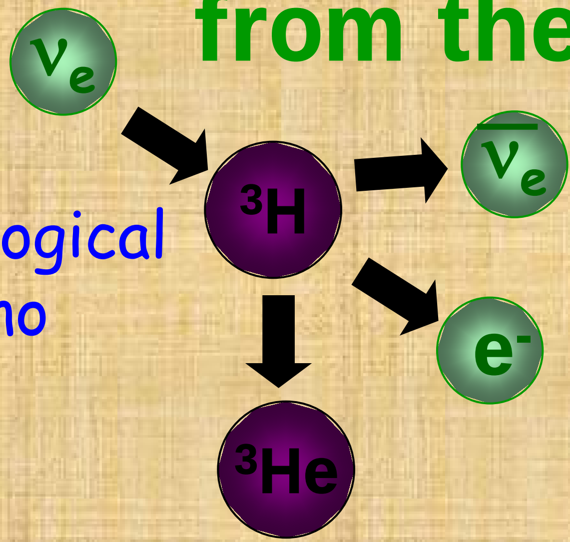
- Nuclear spin-isospin and isospin response from future measurements of neutrino-nucleus interactions at SNS. New work for theorists.

- Neutrinos from supernovae will bring crucial information for understanding the supernova explosion mechanism, on ν and the star properties, such as its compactness (M-R).



Life tree

The *dream* of detecting neutrinos from the early Universe



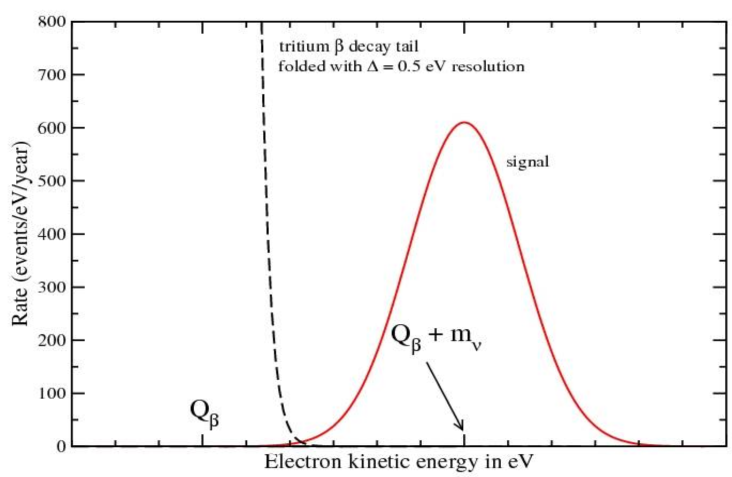
cosmological neutrino

Weinberg, Phys. Rev. 1962

USING RADIOACTIVE NUCLEI ?

The neutrino capture on a radioactive nucleus is a process with no threshold.

The cross section is enhanced : today at least one neutrino is non-relativistic.



Lazauskas,Vogel,Volpe J.Phys.G 2008

Cocco, Mangano, Messina, JCAP 2007

Example : 100 grams of tritium
10 events/year.

Background of electrons from the tritium beta-decay : a serious problem...

To determine the dynamics exactly:

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

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

To determine the dynamics exactly:

$\rho_1 = \langle a^+ a \rangle$ $\rho_{12} = \langle a^+ a^+ aa \rangle$ $\rho_{123} = \langle a^+ a^+ a^+ aaa \rangle$ ...

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

$$i\dot{\rho}_1 = [t_1, \rho_1] + \mathrm{Tr}_{(2)} \{[v_{12}, \rho_{12}]\}$$

$$i\dot{\rho}_{12} = [t_1 + t_2 + v_{12}, \rho_{12}] + \mathrm{Tr}_{(3)} \{[v_{13} + v_{23}, \rho_{123}]\}$$

$$\vdots$$

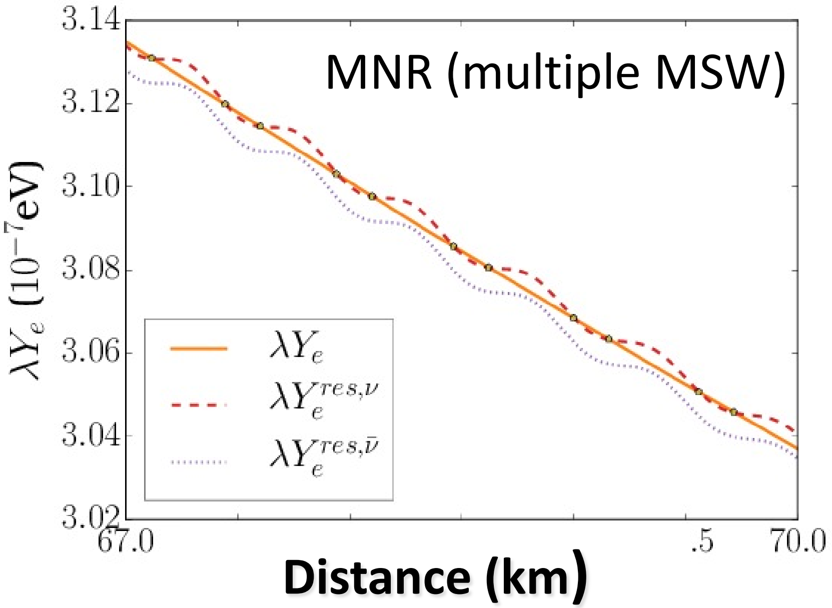
$$i\dot{\rho}_{1\cdots n} = \left[\sum_{i=1}^{n} t_i + \sum_{j>i=1}^{n} v_{ij}, \rho_{1\cdots n}\right] + \sum_{i=1}^{n} \mathrm{Tr}_{(n+1)} \left\{\left[v_{i(n+1)}, \rho_{1\cdots(n+1)}\right]\right\}$$

H = t + v
Hamiltonian

Born-Bogoliubov-Green-Kirkwood-Yvon (BBGKY) hierarchy

an infinite set of equations for a relativistic system

Helicity coherence, MNR and non-linear feedback



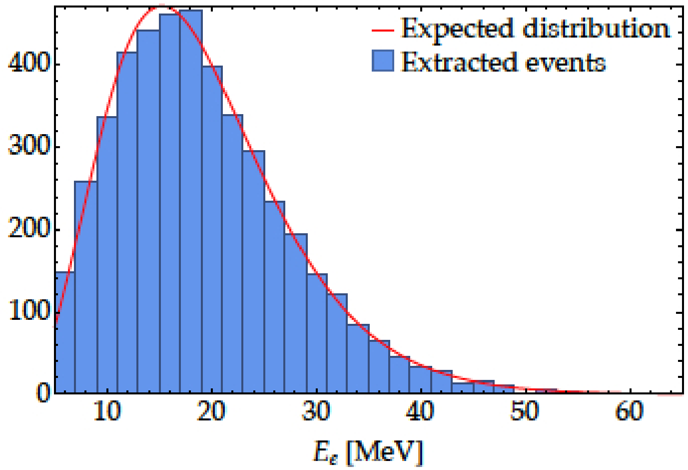
Example of the Matter Neutrino Resonance :

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

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.

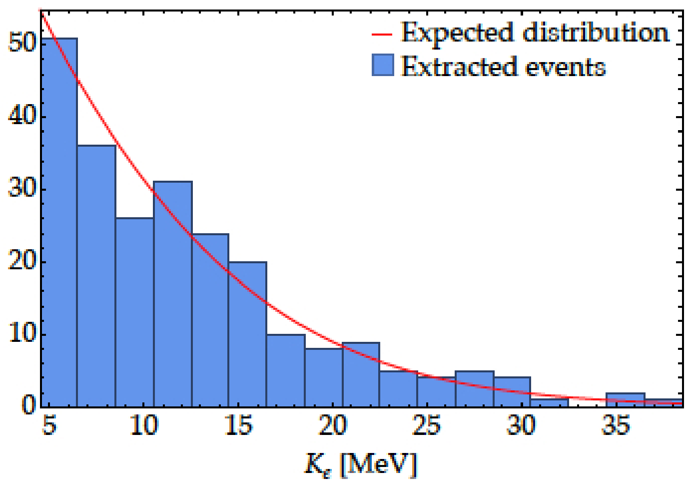
Non-linear feedback does not produce multiple MSW for helicity coherence.



(a) IBD in Super-Kamiokande

$$\mathcal{L}_j\,(\text{param.}) \propto \prod_{i=1}^{N_{\text{bin}}} \frac{\nu_i^{n_i}}{n_i} e^{-\nu_i} \quad \text{with } j = \text{IBD, ES},$$

$$\mathcal{L}_{\text{NCR}}\,(\text{param.}) = \left(2\pi \mathrm{N}_{\text{NCR}} 2\pi\sigma_\kappa^2\right)^{-1/2} \exp\left[-\frac{(n_{\text{NCR}} - \mathrm{N}_{\text{NCR}})^2}{2\mathrm{N}_{\text{NCR}}} - \frac{(\kappa-1)^2}{2\sigma_\kappa^2}\right].$$

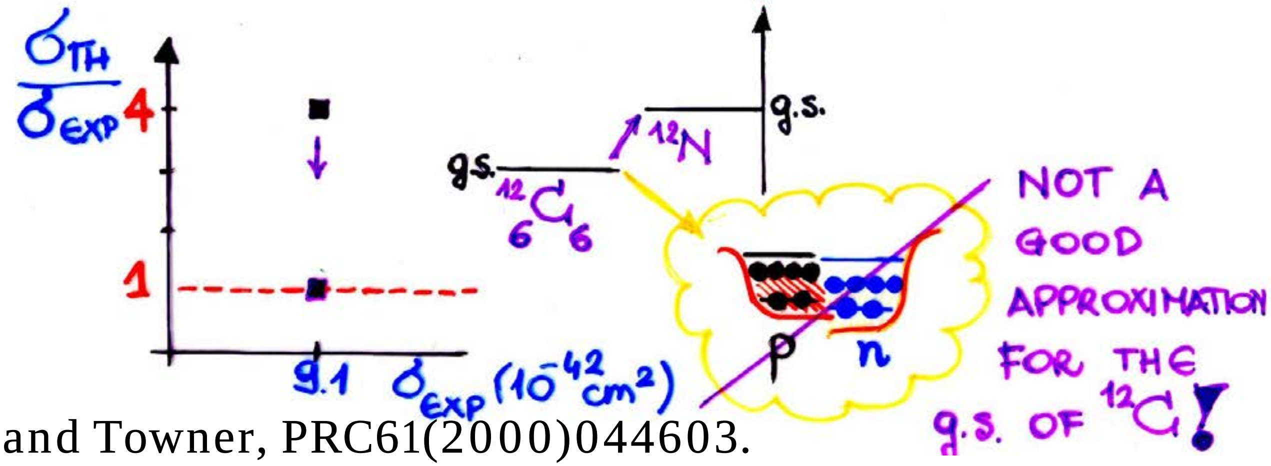


(c) ES in Super-Kamiokande

	Super-Kamiokande				
	ν_e	$\bar{\nu}_e$	ν_x	sum	n_j
IBD	—	2900	1672	4572	4565
ES	14.7	24.7	187	226	237
NCR	12	345	204	561	554
OS sig.	0.53	2.04	43.0	45.5	
IBD bkg.	—	324	77.8	401	
ES bkg.	11.0	19.2	83.3	114	

An example

Reactions of <u>neutrinos on carbon</u> (important for <u>the LSND and KARMEN experiment</u>) have been the <u>object of intensive studies</u> to understand the origin of a <u>discrepancies</u> between experiment and theory <u>by a factor of 2-4</u>.



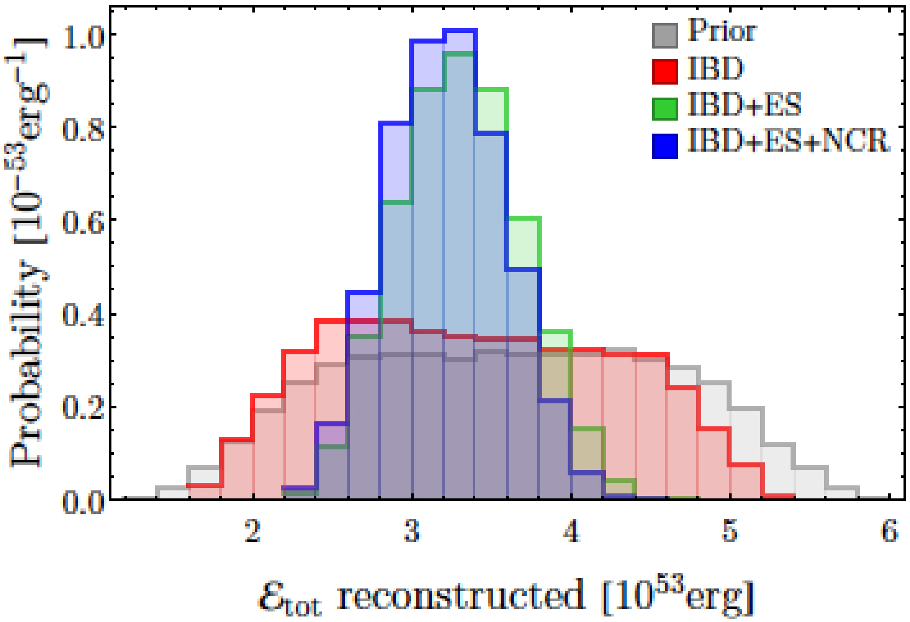
Hayes and Towner, PRC61(2000)044603.
Volpe et al. PRC62(2000)015501.

Having accurate theoretical values of the ν-nucleus reaction cross sections is a challenging task.

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

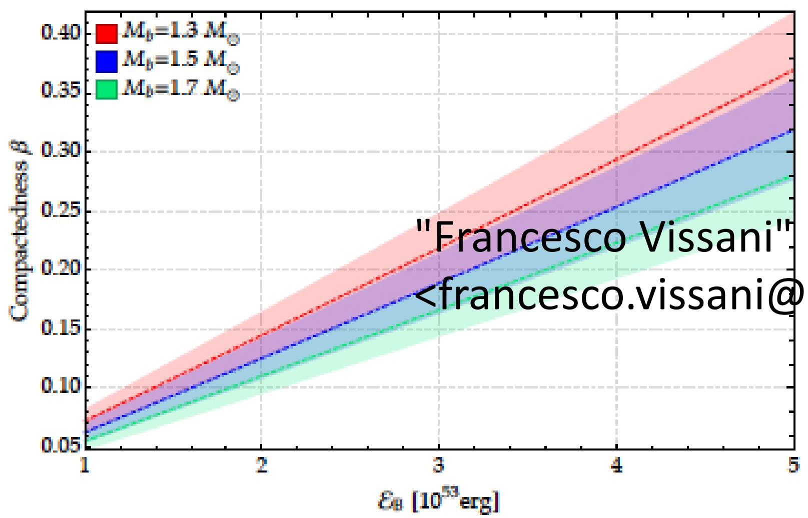
E_b reconstructed with 11% accuracy.

Compactness and M-R of the newly born neutron star

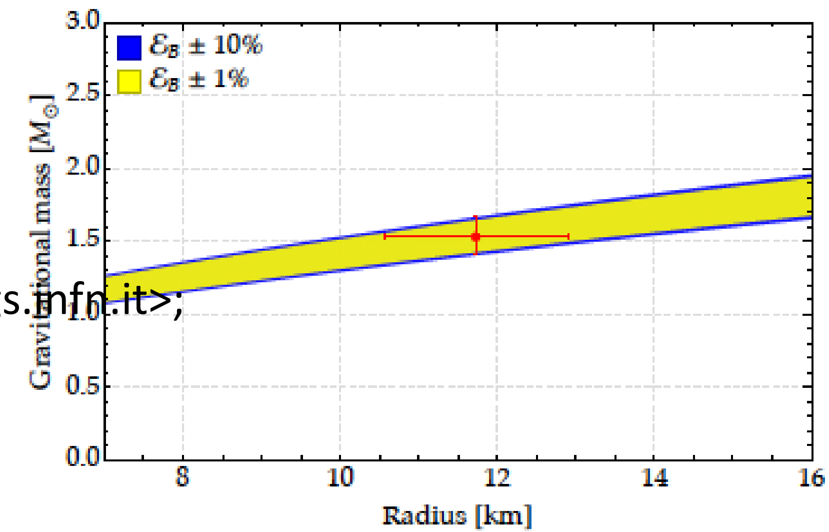
$$\frac{\mathcal{E}_{\rm B}}{Mc^2} \approx \frac{(0.60 \pm 0.05)\,\beta}{1-\beta/2}, \qquad \beta = \frac{GM}{Rc^2},$$

Lattimer & Prakash,
Phys. Rep. 2007

fit to numerous EOS for NS



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



(b) Mass–Radius constraint

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

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

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

Flavor evolution in presence of helicity coherence

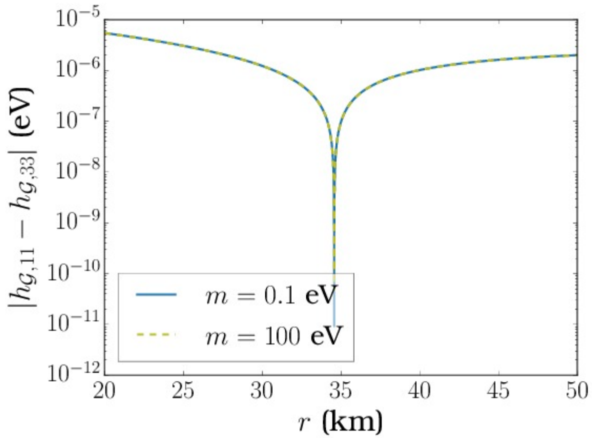
For Majorana neutrinos, the 2ν Hamiltonian

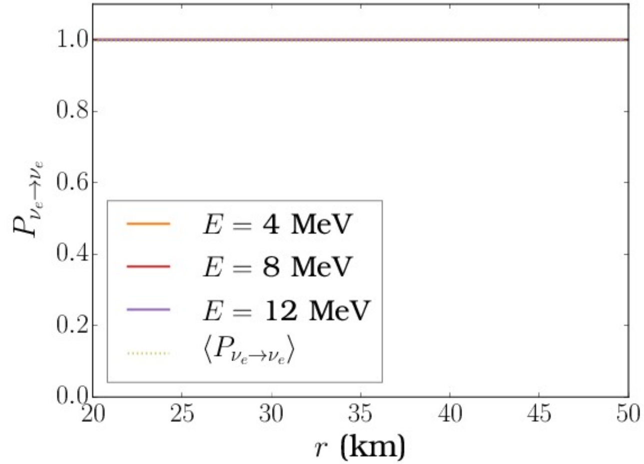
$$H = \begin{pmatrix} h & \Phi \\ \Phi^* & \bar{h} \end{pmatrix}$$

Resonance (MSW-like) conditions :

- Helicity Coherence

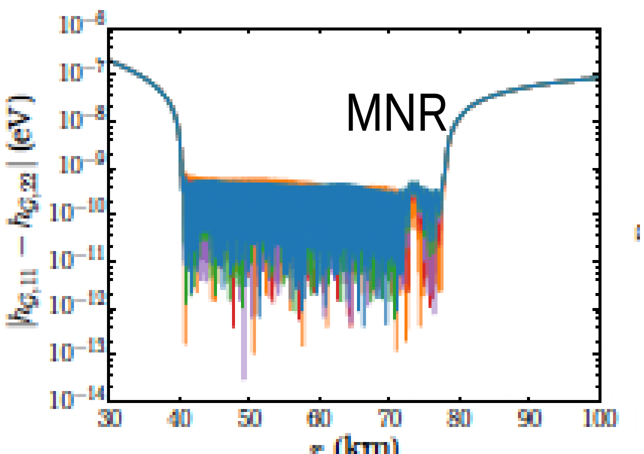
$$h_{\mathcal{G},11} - h_{\mathcal{G},33} = \sqrt{2} G_F n_B (3Y_e - 1) + 2h^{ee}_{\nu\nu} \simeq 0,$$

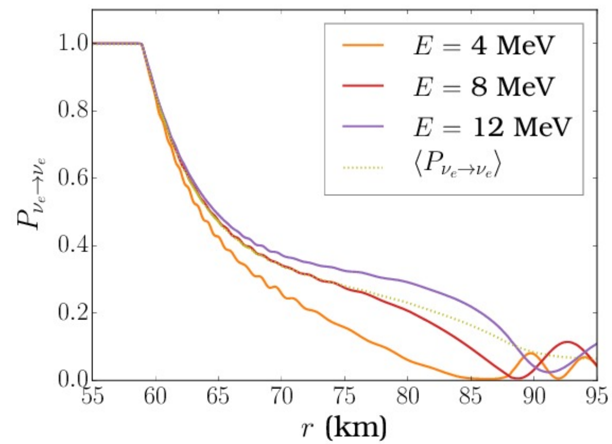




- Matter-Neutrino Resonance

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



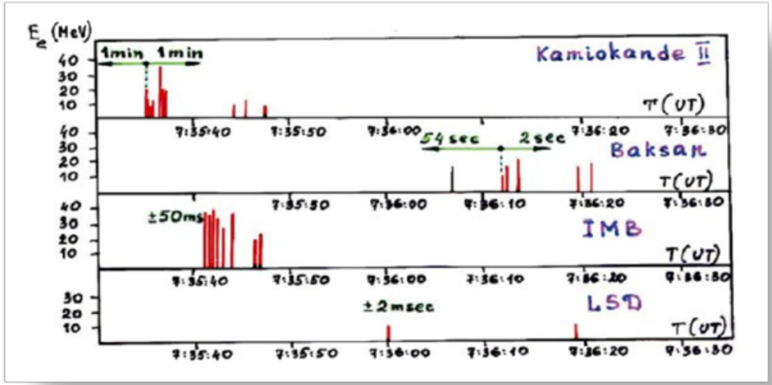


Resonance conditions met, adiabaticity not enough

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

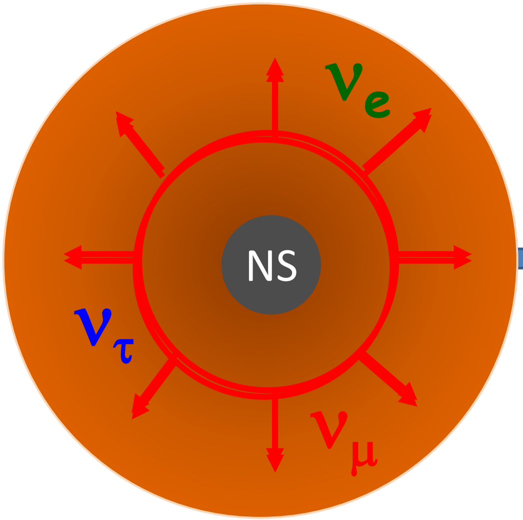
Supernova neutrinos

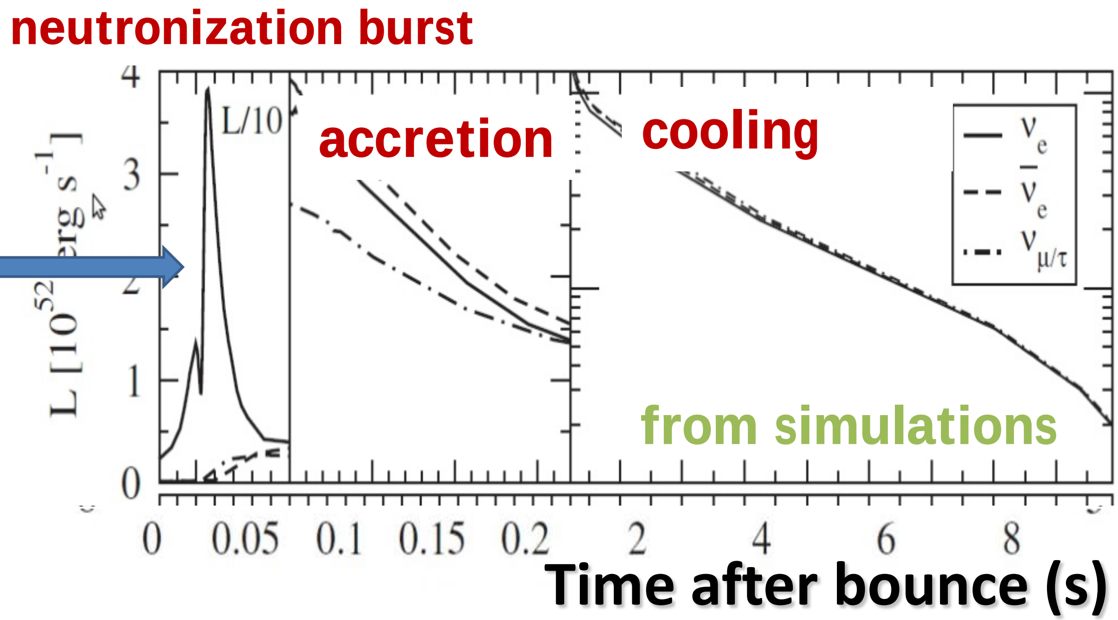
10^{57} ν of about 10 MeV in 10 s from the gravitational collapse of massive stars ($M > 8\ M_{sun}$).



Suzuki, J. of Phys. conf. (2008)
Vissani, JPG (2014)

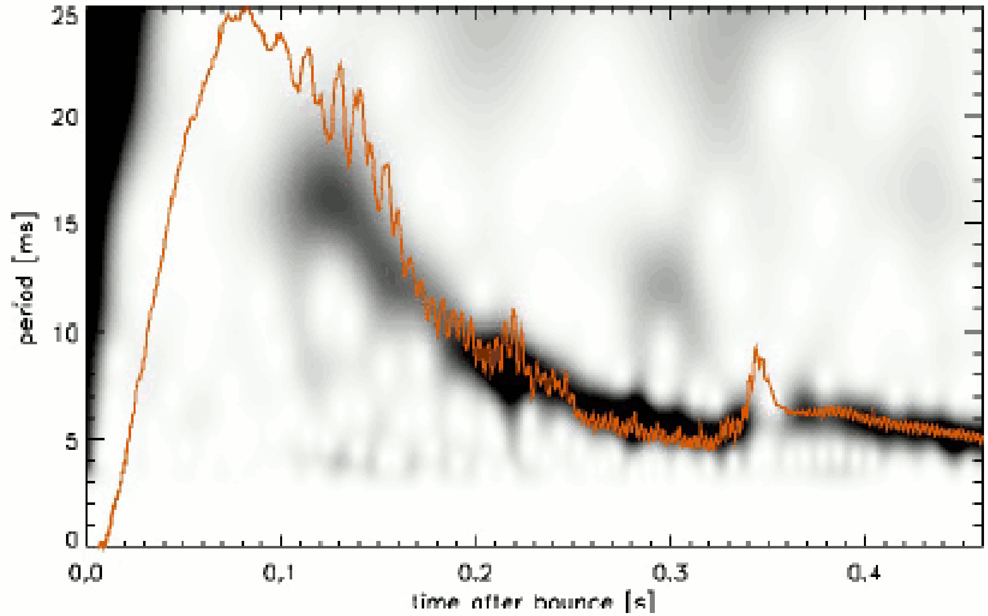
SN1987A events



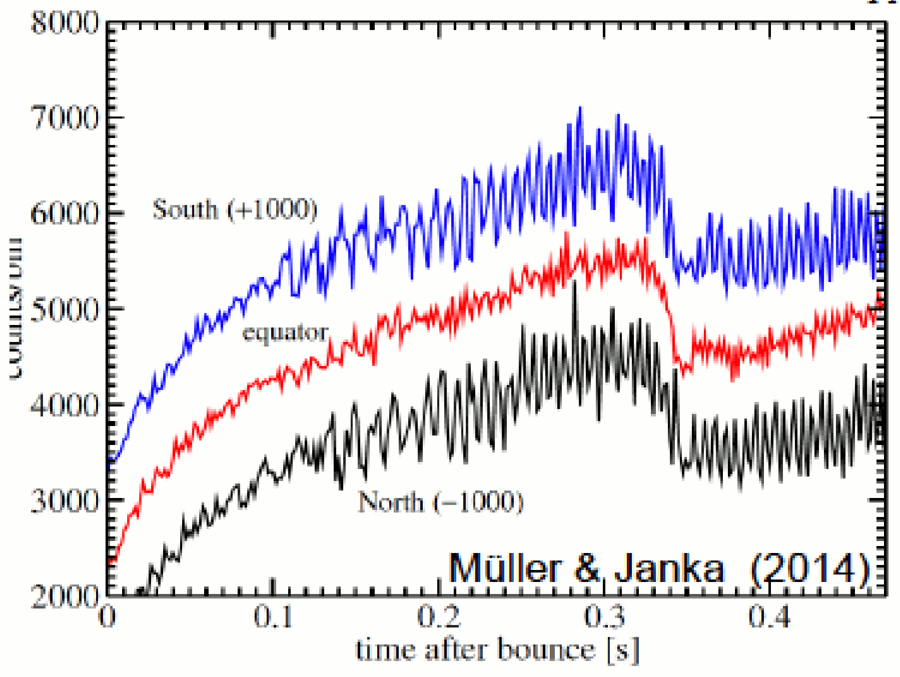


Hüdepohl *et al.* PRL 104 (2010)

sensitive probe of the supernova dynamics

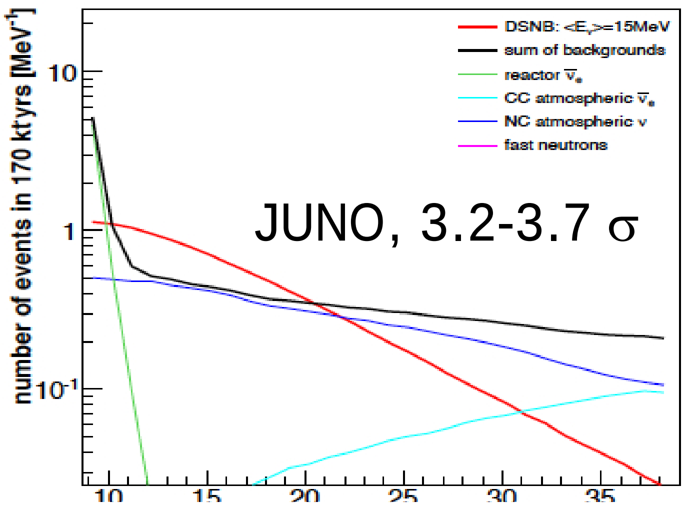


$$\text{period} \approx 19\,\text{ms}\,(r_{\text{shock}}/100\text{km})^{3/2} \ln \frac{r_{shock}}{r_{PNS}}$$



The diffuse supernova neutrino background

An et al. J. Phys.G (2016)



Prompt event energy (MeV)

The integrated ν neutrino flux from supernovae at different redshifts :

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

$$E'_\nu = (1+z)E_\nu,$$

Upper limits on DSNB fluxes :

1.4-1.9 anti-n_e /cm^2/s

73-154 n_e/cm^2/s

Lunardini and Peres, JCAP (2008)

	Events (10 y)	window	detector	
$\bar{\nu}_e$	90	9-25 MeV	50 kton	scintillator
$\bar{\nu}_e$	300	19-30 MeV	440 kton	Hyper-K
ν_e	30	17-41 MeV	50 kton	liquid argon

Galais et al PRD 81(2010)

EGADS - Super-Kamiokande with Gd.

Upcoming projects have the discovery potential.