Neutrinos from core-collapse supernovae and binary neutron star mergers

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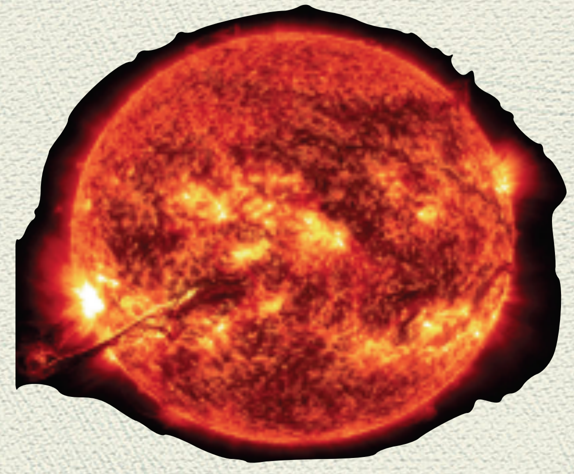
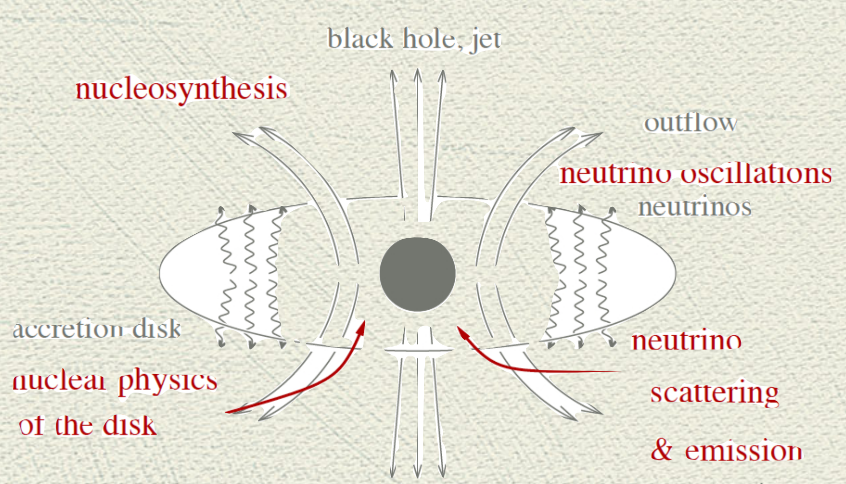
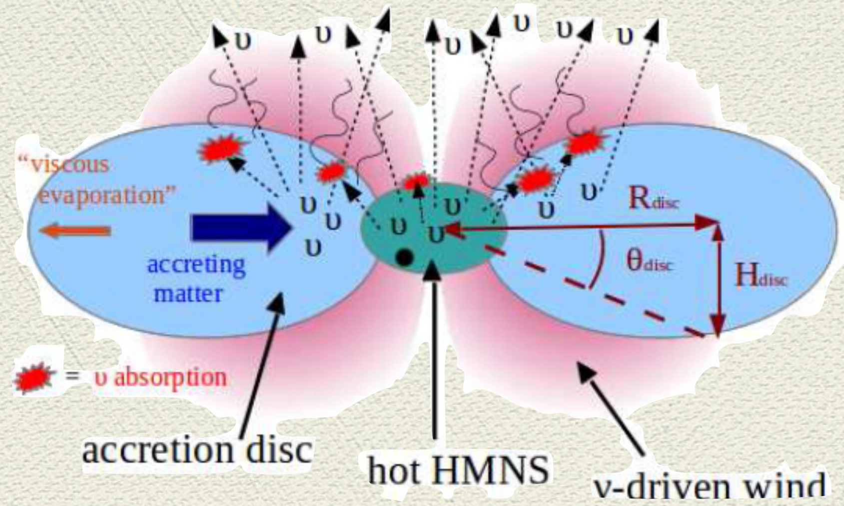


Sun

core-collapse Supernovae



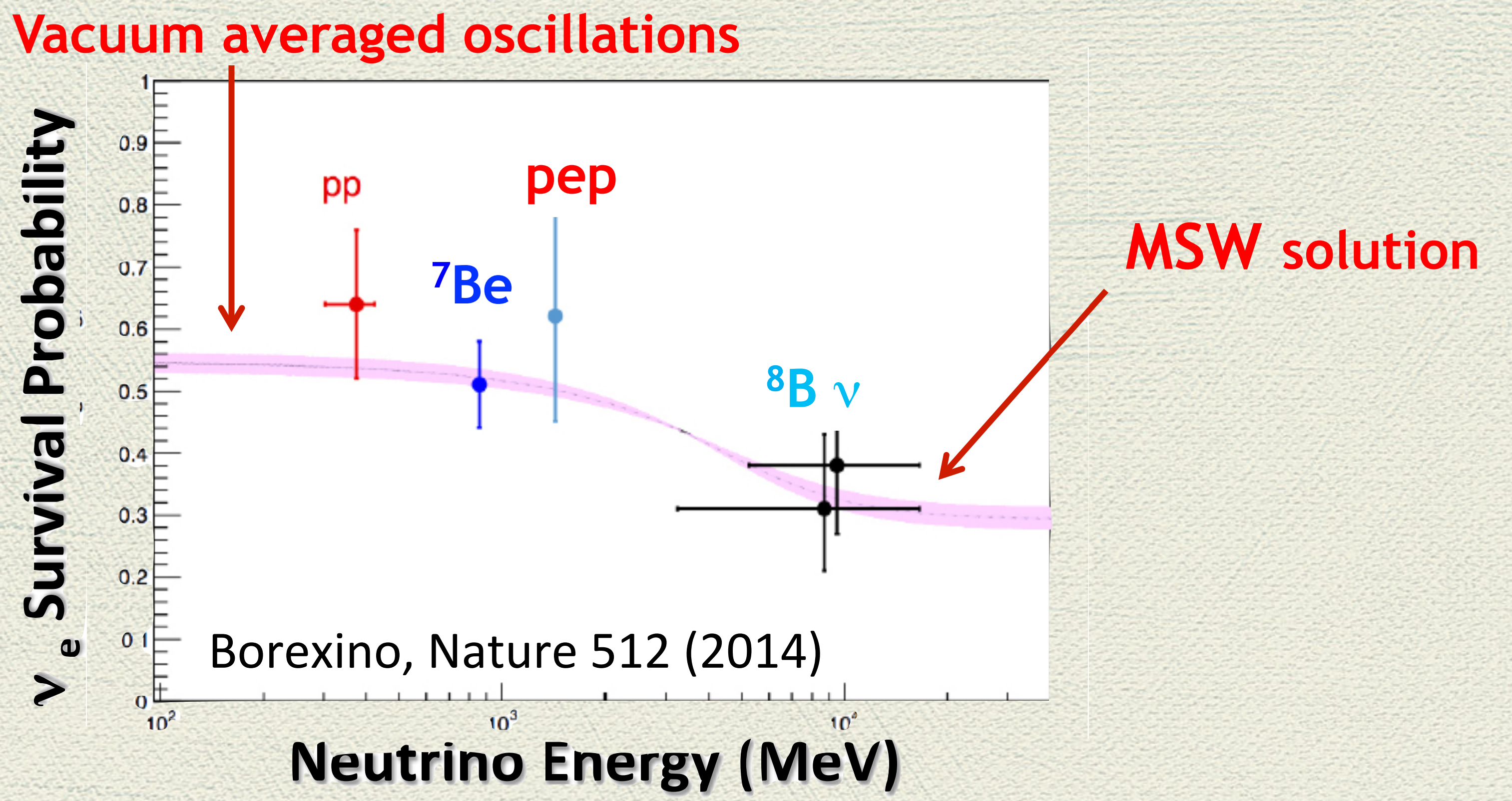
McLaughlin



Perego et al, 2014

accretion disks around black holes or neutron star mergers remnants

Solar neutrino observations



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

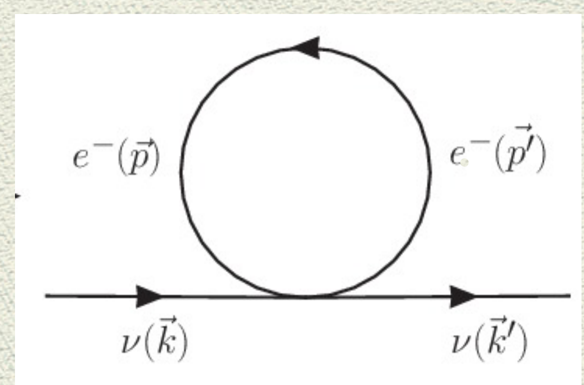
Energy production of low mass main sequence stars confirmed — pp reaction chain.

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

The Mikheev-Smirnov-Wolfenstein effect

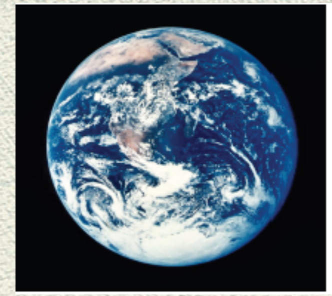
Neutrinos interact with matter and undergo resonant adiabatic flavor conversion.

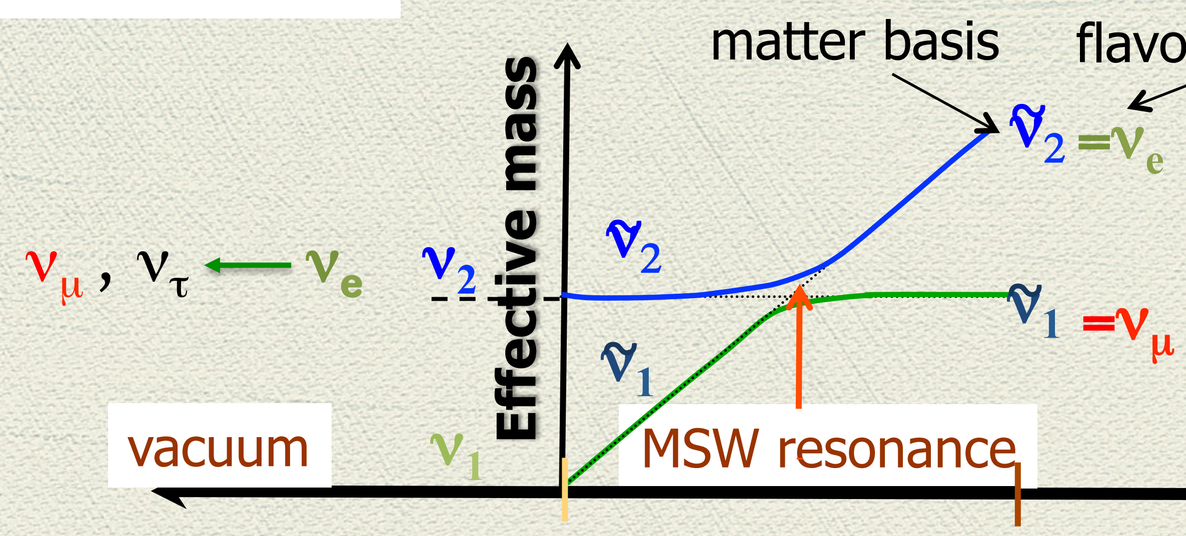
Wolfenstein PRD (1978)
Mikheev, Smirnov(1985)

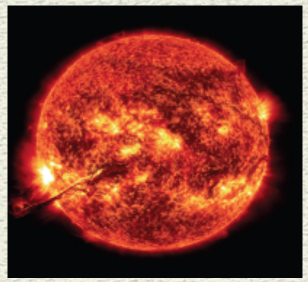


$$h_{mat} = \sqrt{2} G_F \rho_e$$

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 :

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

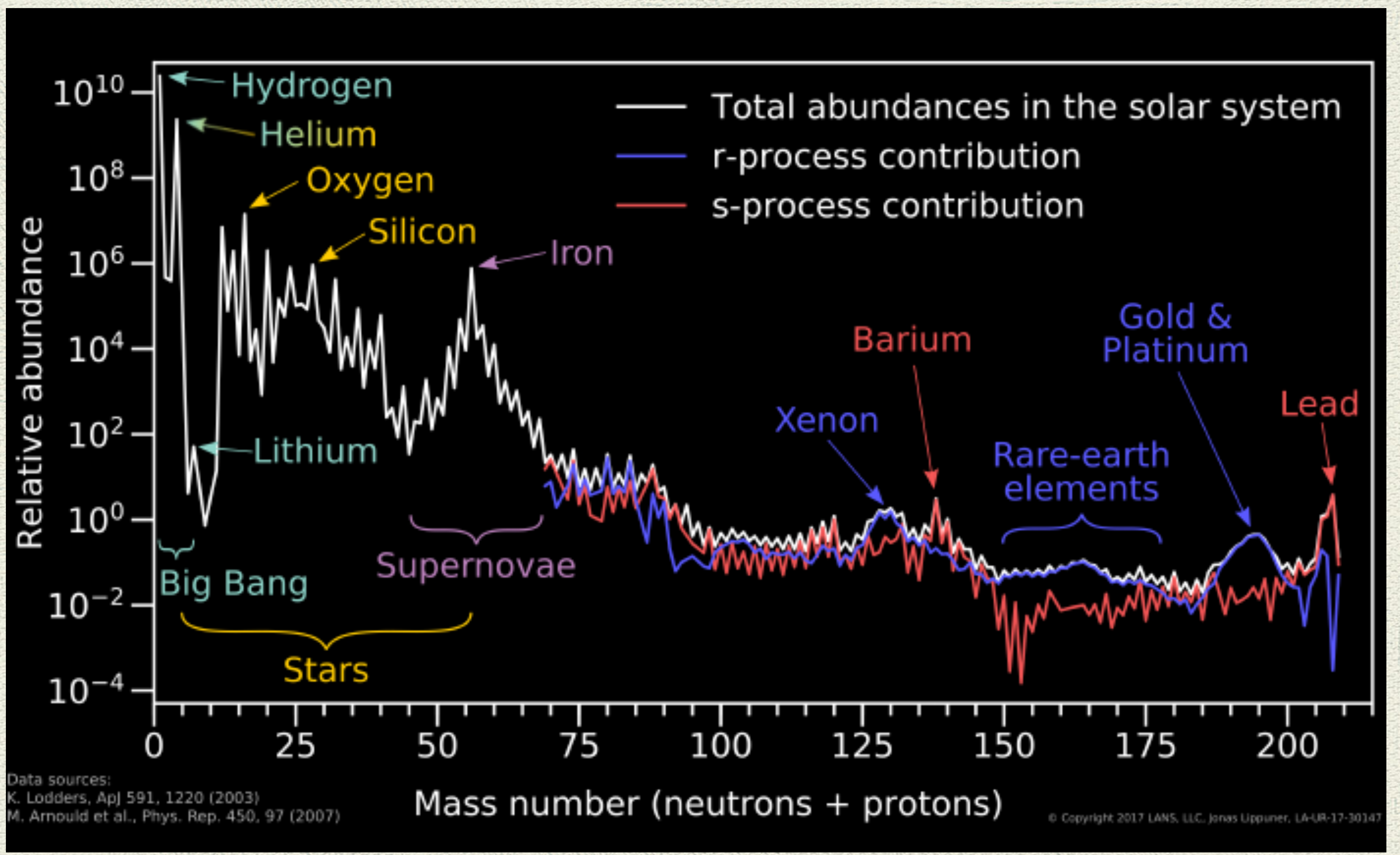
Adiabaticity : $\gamma = \frac{|\dot{\theta}_M|}{\Delta\tilde{m}^2/4E} << 1$

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

Heavy elements nucleosynthesis

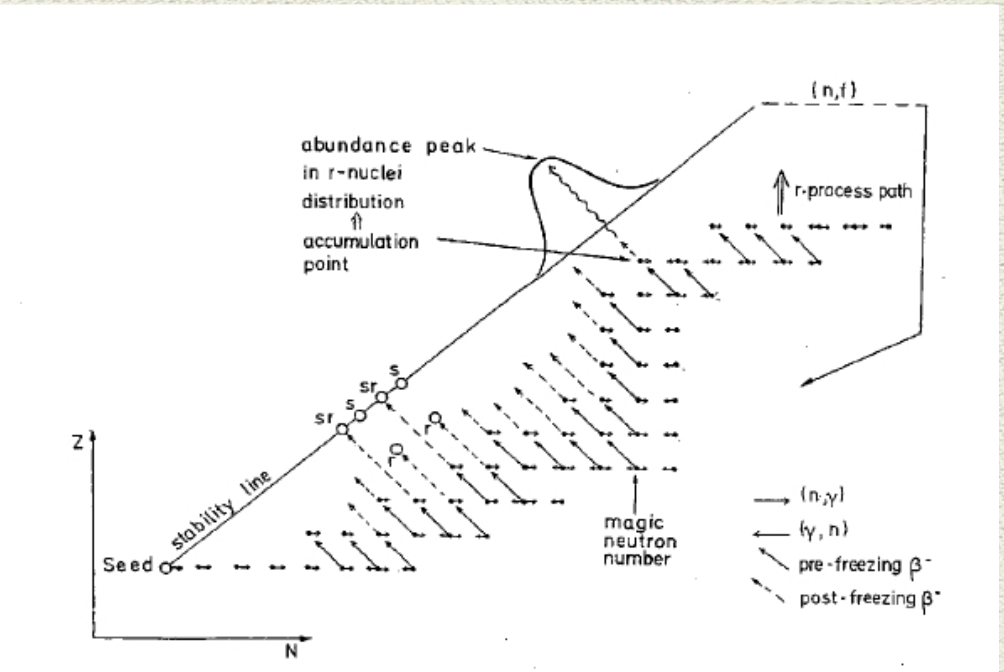
- Two main mechanisms at the origin of elements heavier than iron : s-process (s-slow) and r-process (r-rapid).

- Double peak structures at the first A=90, the second A=130 and third A=190 peaks due to both the s-process and the r-process.



The r-process sites : a longstanding question

- The r-process : neutron-capture is fast compared to half-lives of neutron-rich unstable nuclei.



The nuclear flow goes far away from the stability line producing thousands of nuclei close to the neutron drip line.

- Candidate sites : supernovae and accretion disks around compact objects - black holes and binary neutron stars. Supernovae simulations show that the astrophysical conditions are not met (not enough neutrons). Binary neutron star mergers do.

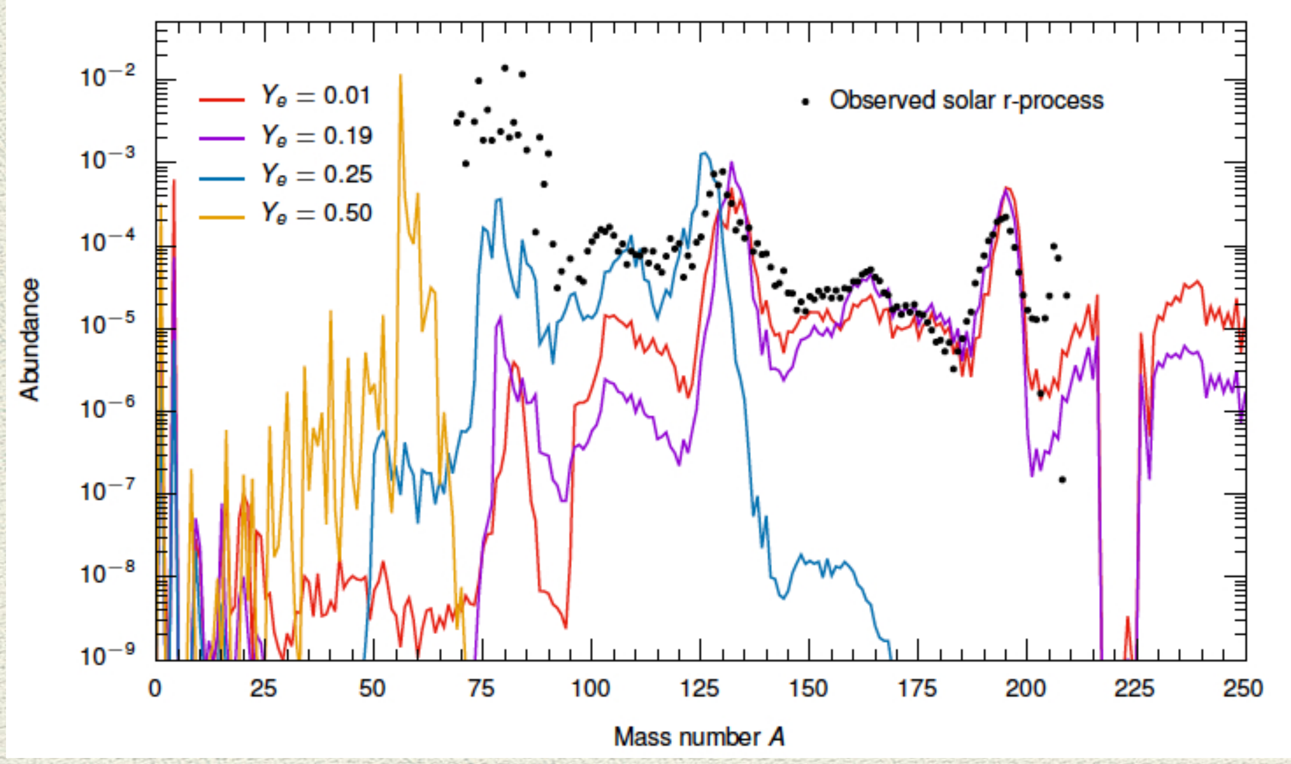
- Recent kilonova : direct evidence for r-process elements.

Neutrinos and the electron fraction

- 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 electron fraction - $Y_e = \dfrac{p}{p+n}$



Roberts 2015, arXiv :1508.03133

The electron fraction is a key parameter for the nucleosynthetic abundances.

The electron fraction and flavor transformation

- Neutrino flavor transformation influences Ye because it modifies the neutrino fluxes - spectral swappings.

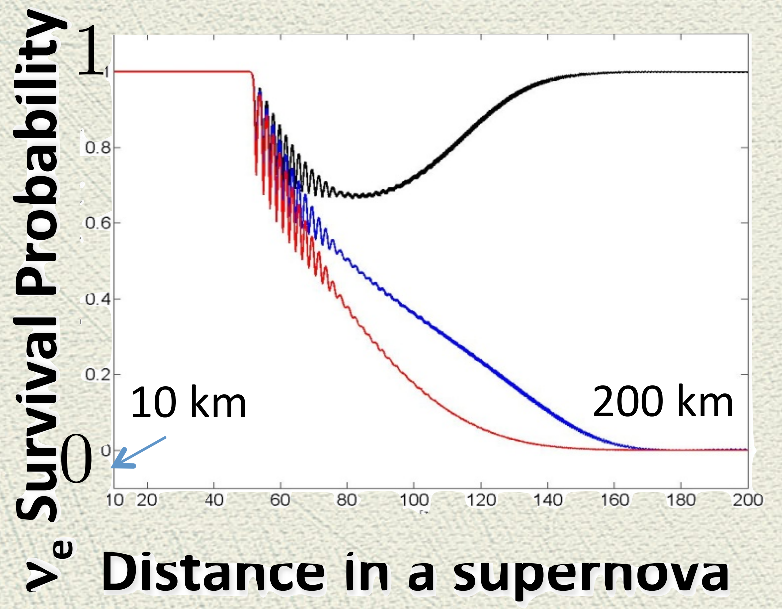
AN EXAMPLE : the neutrino fluxes during evolution

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

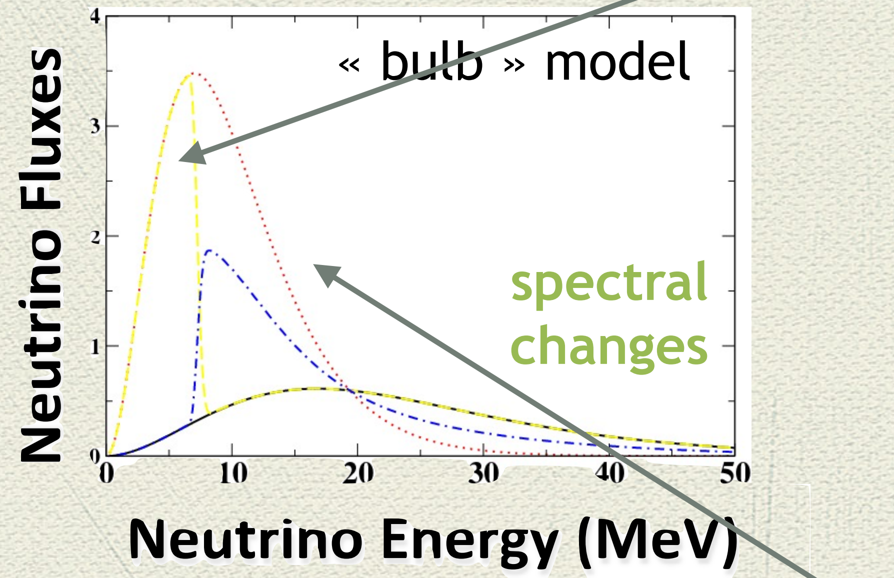
neutrino fluxes at the neutrino sphere

neutrino fluxes at 200 km from it

$\phi_0(E)$ $\phi(E)$



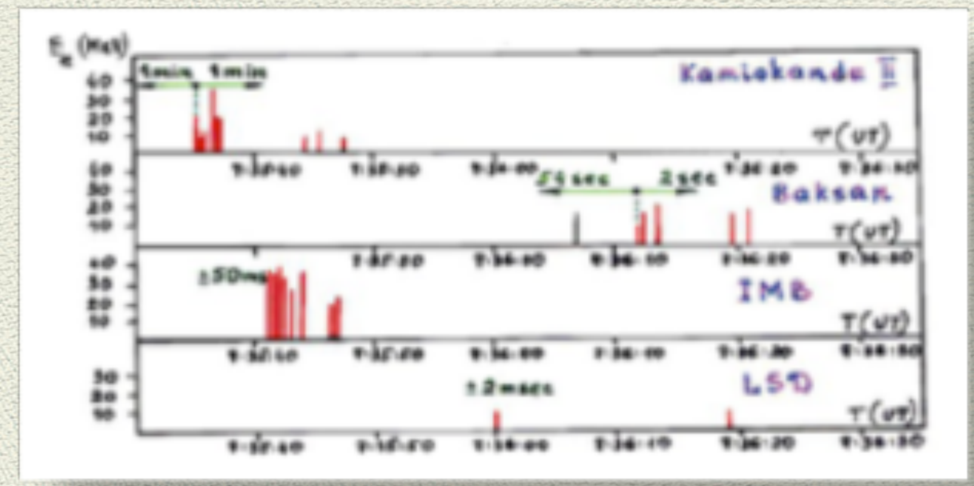
If $P(\nu_e \to \nu_e) \approx 1$ $\phi_{\nu_e}(E) = \phi^0_{\nu_e}(E)$



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

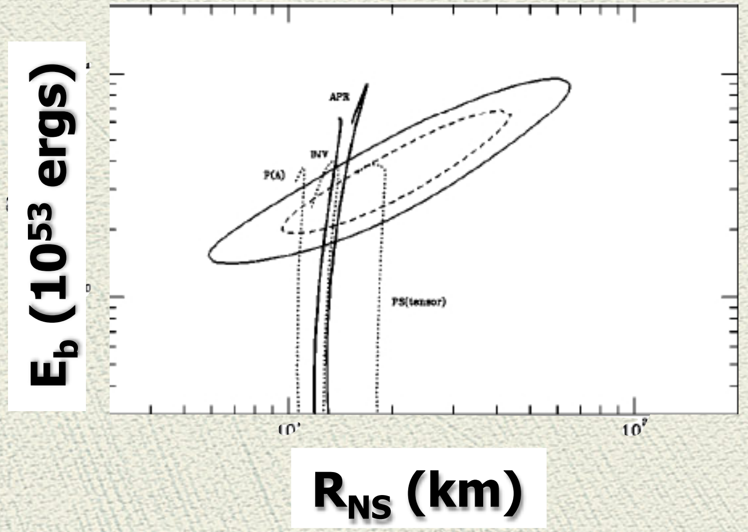
SN1987A

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

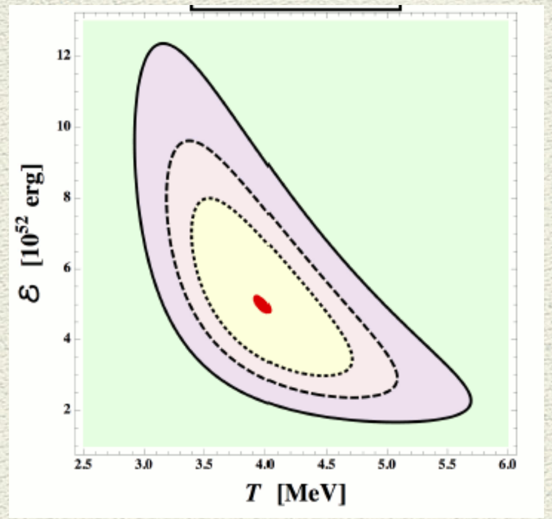


Sanduleak $69^{0}202$, a blue super-giant in Large Magellanic Cloud, at 50 kpc, no remnant found so far.

SN1987A : Delayed explosion mechanism favored over the prompt one.



Loredo, Lamb, PRD 2002



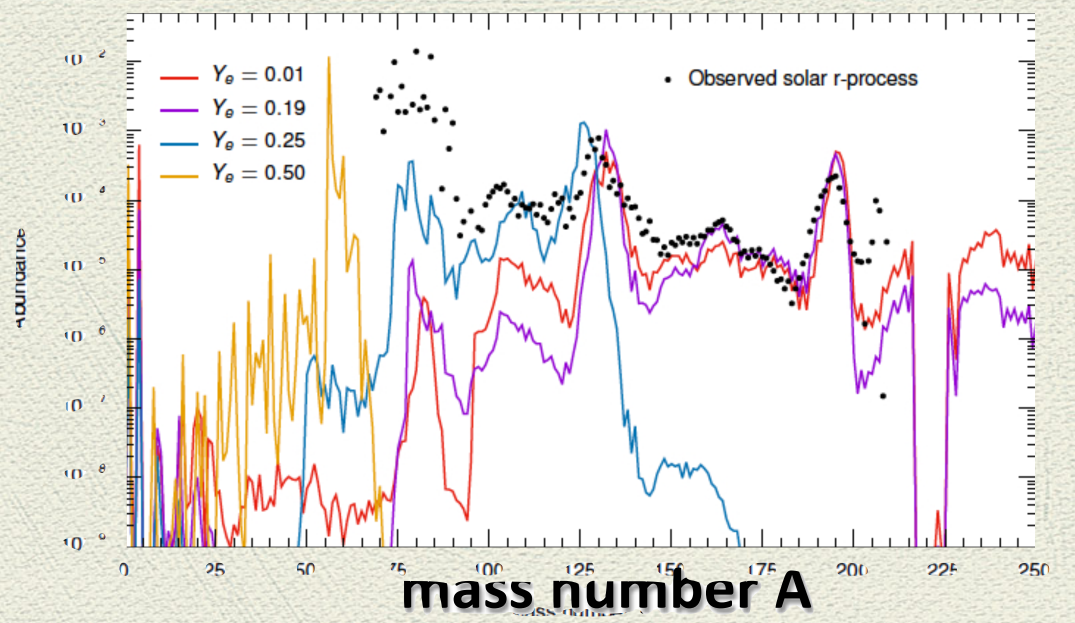
Vissani, JPG (2014)

Neutrinos from core-collapse supernovae

Predictions of the neutrino fluxes for future observations :

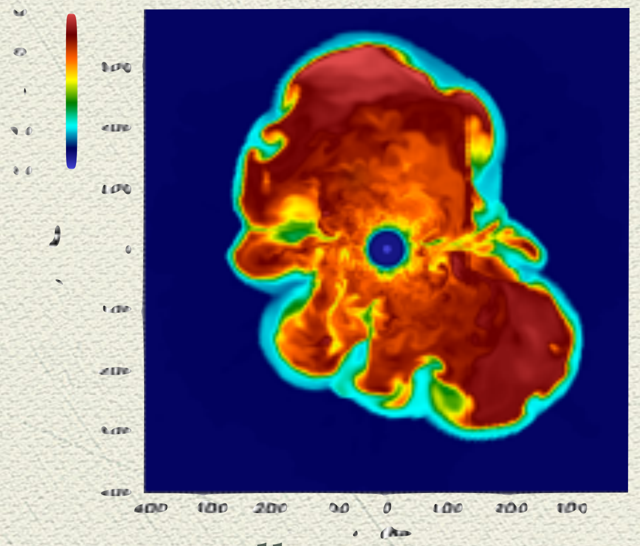
- an (extra)galactic supernova - 10^4 -10^6 events at 10 kpc
- diffuse supernova neutrino background - EGADS project (Super-K + Gd)

Understanding
the role of neutrinos
and flavor conversion



Heavy elements nucleosynthesis

Simulations complex
(multi-D, hydro-instabilities,
convection, turbulence,
realistic neutrino transport and
nuclear networks).
A comparison of 1D models :
E. O' Connor et al., arXiv :1806.04175

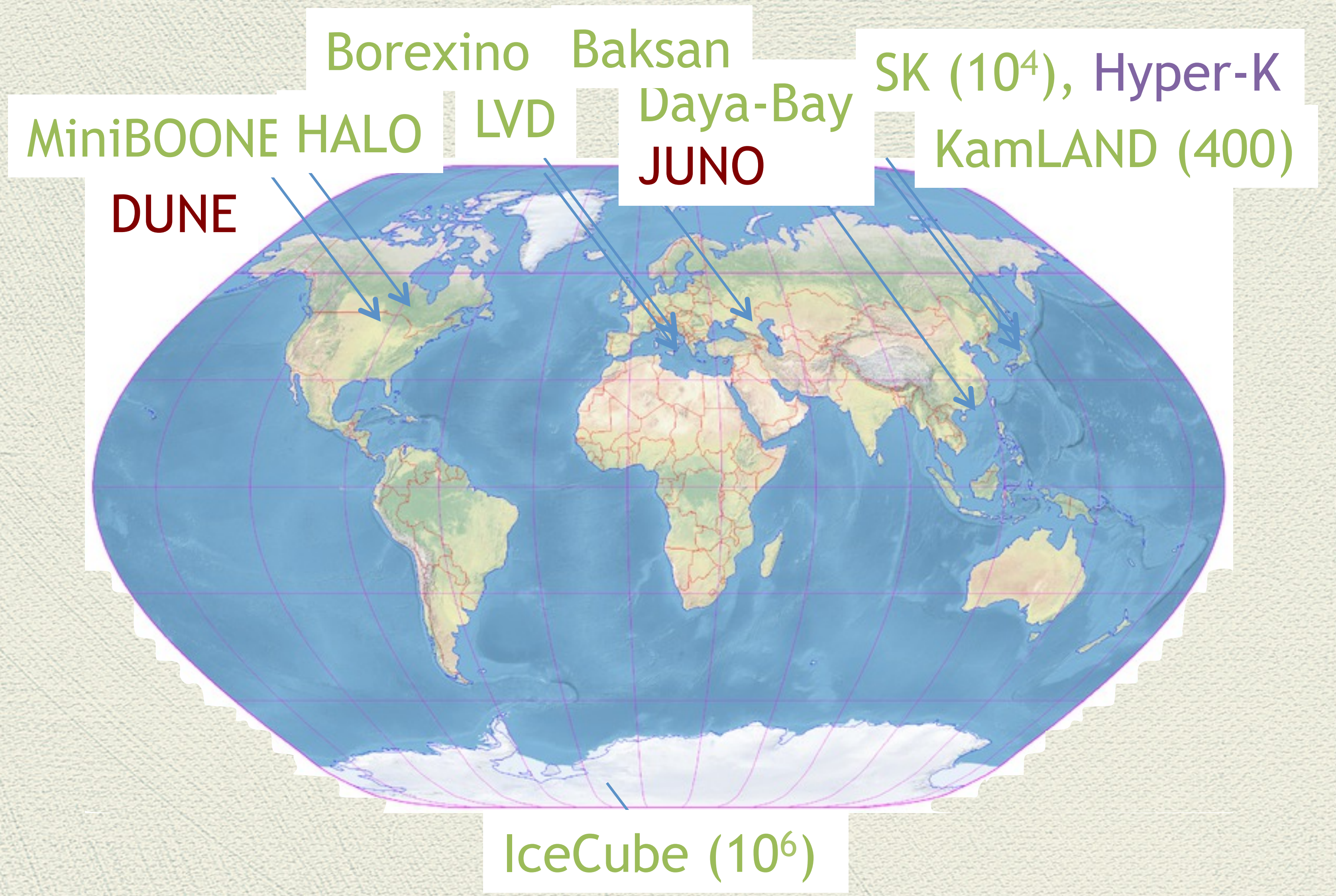


Mueller et al,
arXiv: 1705.00620

Iron core-collapse supernova explosions

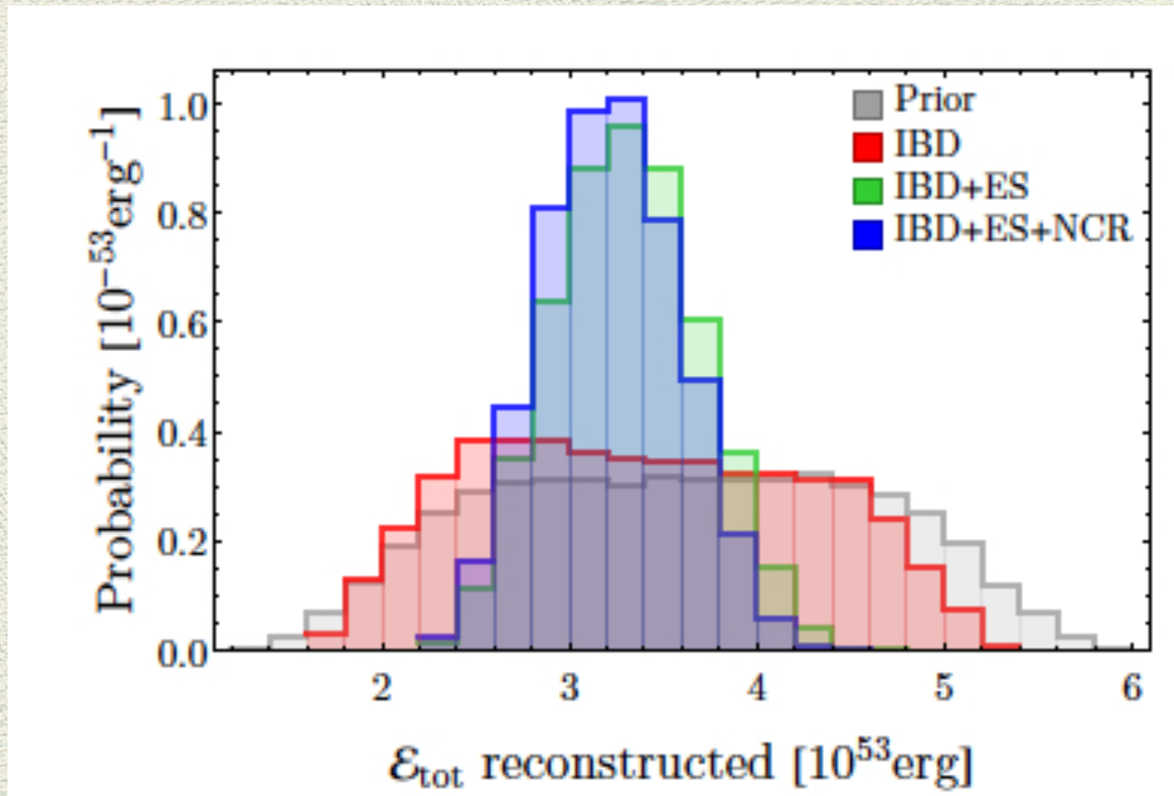
Supernova Early Warning System and SNe observations

Expected events for a supernova in our galaxy (10 kpc) up to 10^6



Detection channels : scattering on protons, electrons, nuclei.
Sentivity to all flavors, time and energy signal will be measured.

Reconstructing gravitational binding energy



Nine-degrees of freedom likelihood.

Fluences described by a power law, MSW included, normal ordering

Combining inverse beta-decay, elastic scattering and neutral current on oxygen

	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^*	$2.5 \in [1.5, 3.5]$	$2.5 \in [1.5, 3.5]$	$2.5 \in [1.5, 3.5]$

Gravitational binding energy reconstructed with 3%, 11 % precision with Hyper-Kamiokande, Super-Kamiokande respectively.

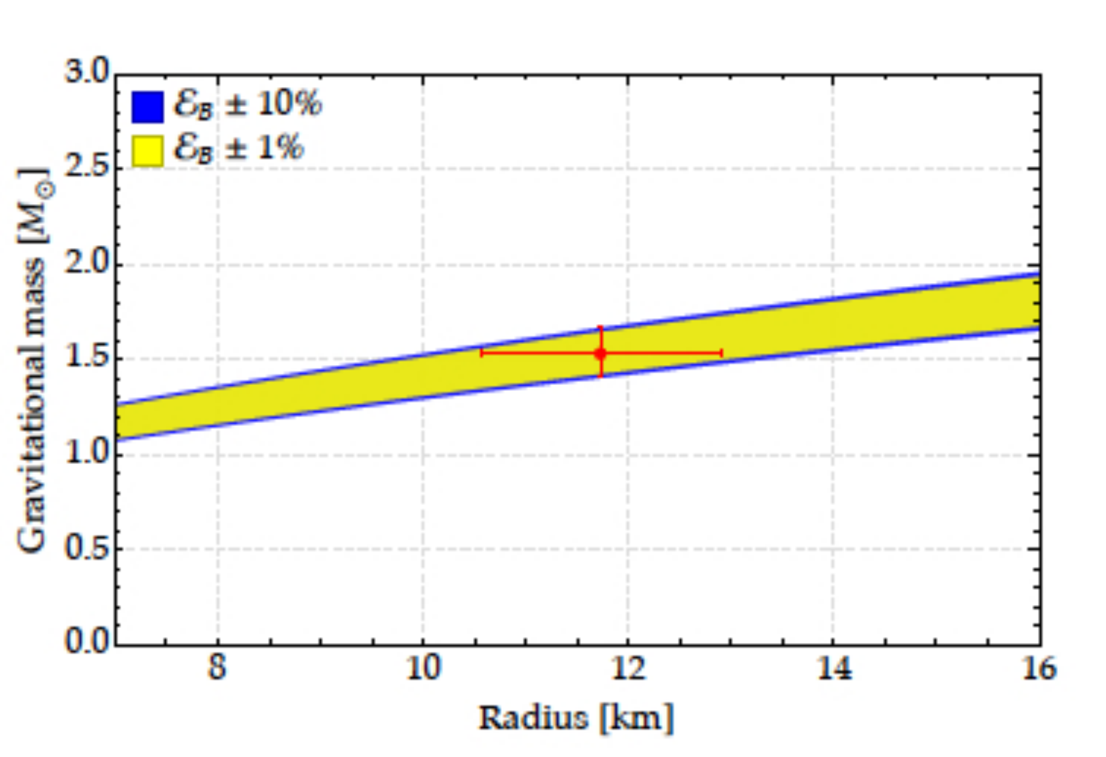
Gallo Rosso, Vissani, Volpe, JCAP1711 (2017), 1708.00760 ; 1804 (2018) arXiv:1712.05584.

Compactness and M-R of the newly born neutron star

Using the relation between the gravitational binding energy and the compactness from different equations of state

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

Lattimer & Prakash, Phys. Rep. 2007



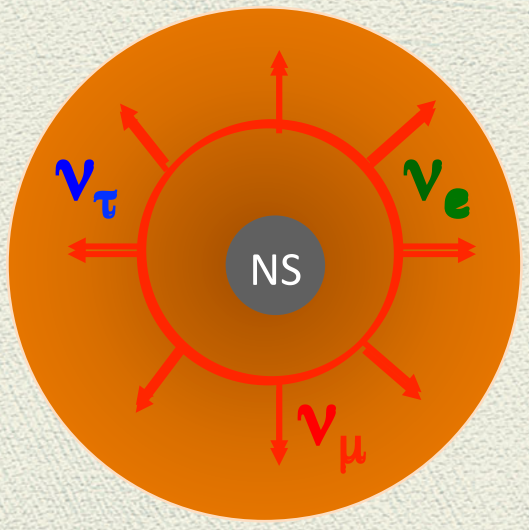
(b) Mass–Radius constraint

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

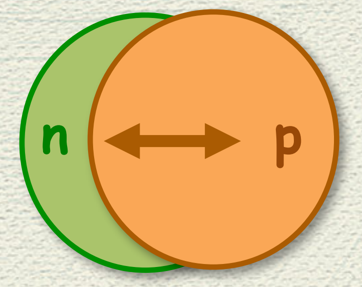
$$\text{with} \quad \epsilon = \frac{1}{4}\sqrt{\frac{\mathcal{E}_\mathrm{B} G}{0.6\,R\,c^4}}.$$

Gallo Rosso, Vissani, Volpe, JCAP1711 (2017), 1708.00760.

Neutrino flavor evolution in dense environments



ν in stars or accretion disks

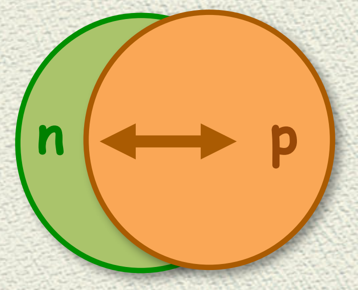


atomic nucleus

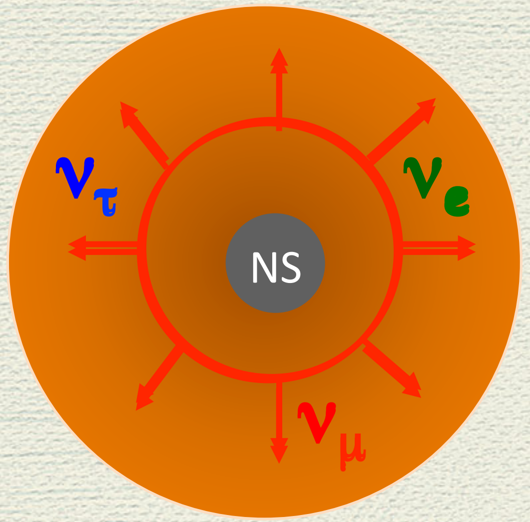
10^{57}	**N**	200
weak	**interaction**	strong
unbound	**system**	bound
$\rho_{ji} = \langle a_i^{+} a_j \rangle$ neutrinos $\bar{\rho}_{ji} = \langle b_i^{+} b_j \rangle$ anti-neutrinos	**density**	$\rho = \langle a^{+} a \rangle$ neutrons protons

A many-body problem

Neutrino evolution equations in dense environmnents



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

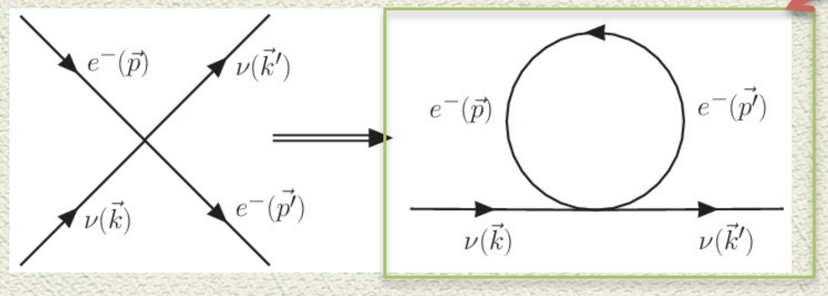


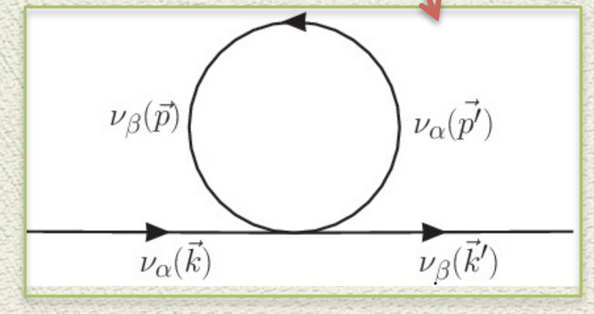
$$\rho = \begin{pmatrix} < a^\dagger_{\nu_e} a_{\nu_e} > & < a^\dagger_{\nu_\mu} a_{\nu_e} > \\ < a^\dagger_{\nu_e} a_{\nu_\mu} > & < a^\dagger_{\nu_\mu} a_{\nu_\mu} > \end{pmatrix}$$

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

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

neutrino self-interactions

non-linear term

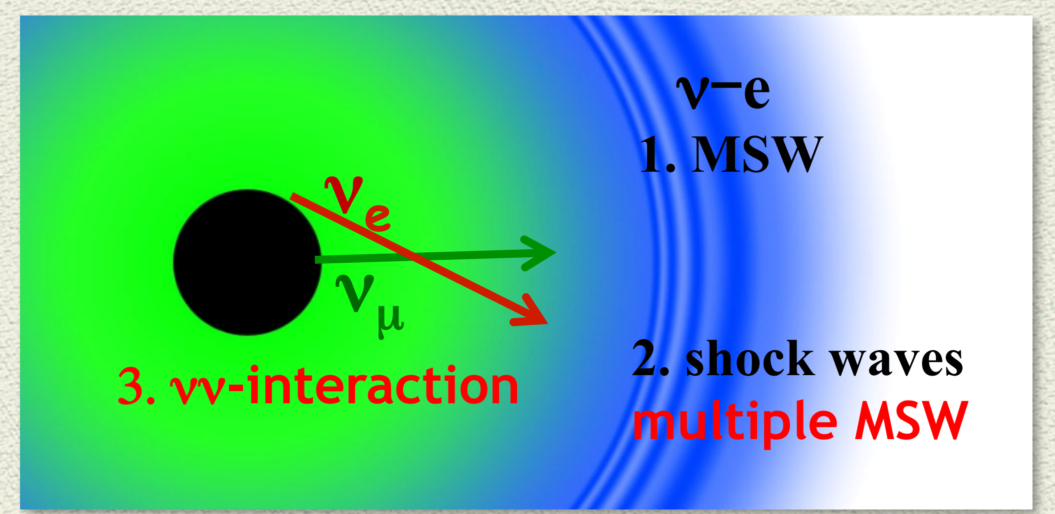
$$h_{\nu\nu} = \sqrt{2} G_F \sum_\alpha [\int (1 - \hat{q} \cdot \hat{p}) \times [\mathrm{d}n_{\nu_{\underline{\alpha}}} \rho_{\nu_{\underline{\alpha}}}(\vec{p}) - \mathrm{d}n_{\bar{\nu}_{\underline{\alpha}}} \bar{\rho}_{\bar{\nu}_{\underline{\alpha}}}(\vec{p})]],$$

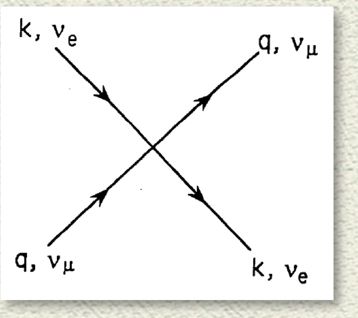
Volpe, Väänänen, Espinoza. PRD 87 (2013)

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

Extended equations derived - e.g. with corrections due to the neutrino mass.

Neutrino flavor conversion in supernovae



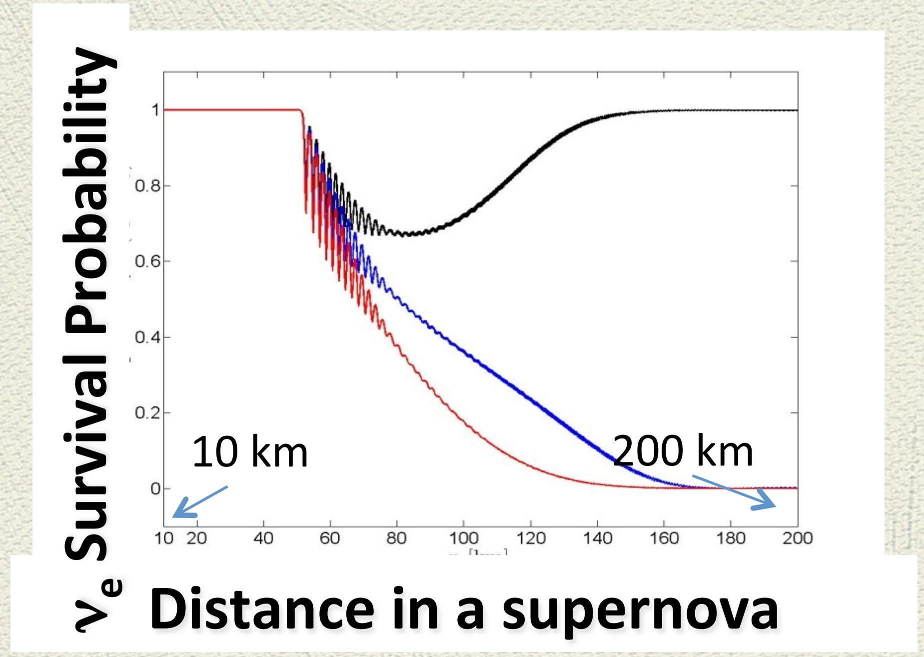


Pantaleone, PLB 1992
Sigl and Raffelt, 1993

- Efficient conversion occurs close to the neutrinosphere

Models of increasing complexity studied since a decade

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

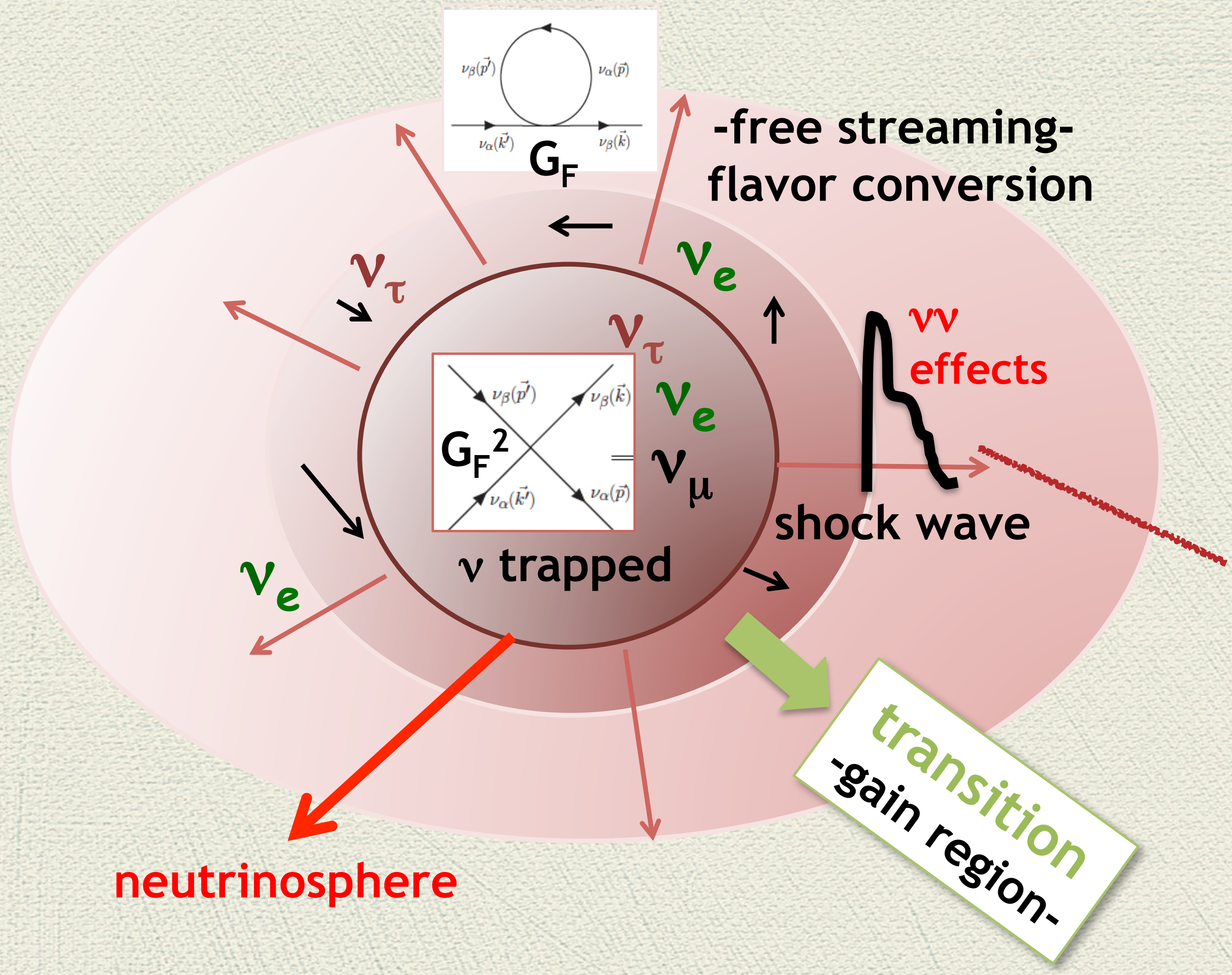


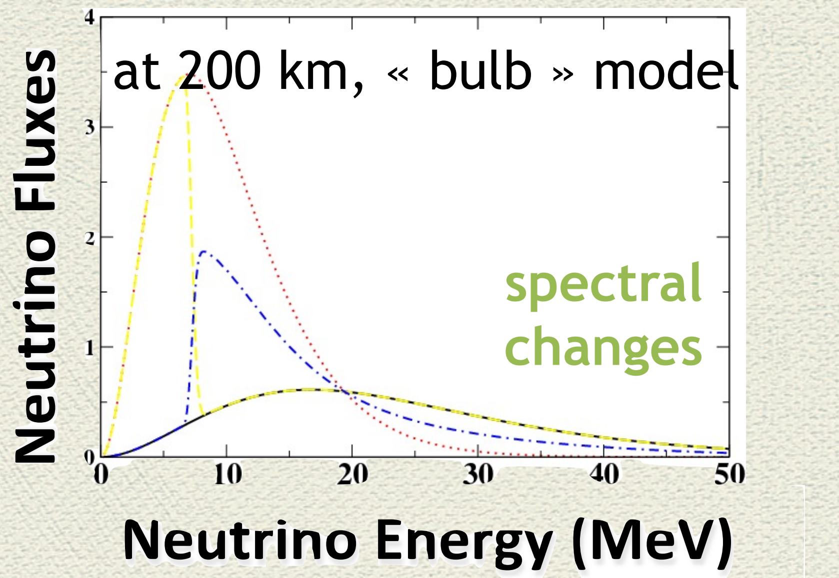
Novel conversion phenomena due to the neutrino self-interaction

Supernovae explosions and flavor conversion

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

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



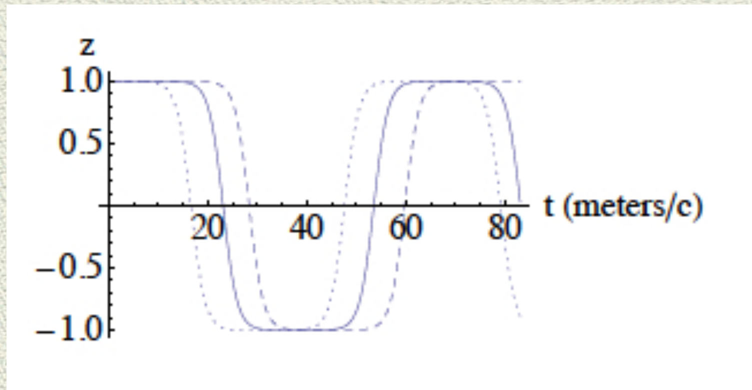


Sharp transition from the dense (Boltzmann) to the dilute (mean-field) region.

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)



- 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 $\bar{\nu}$

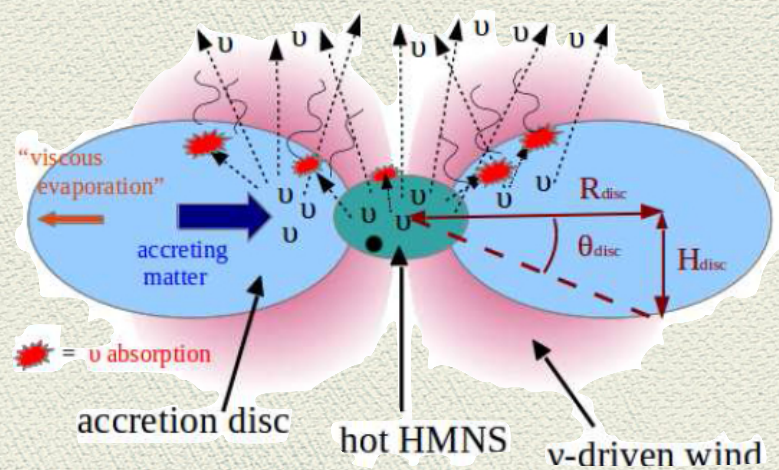
helicity (or spin) coherence

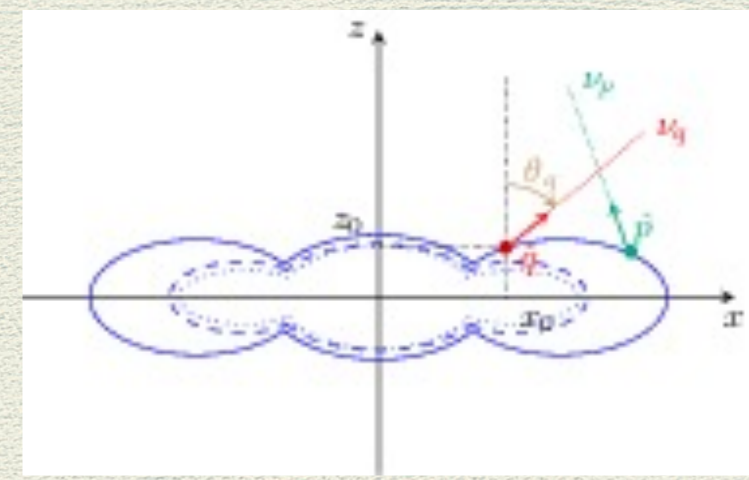
$\Phi \sim (h_{mat}^{perp} + h_{\nu\nu}^{perp})$ x $m/2E$

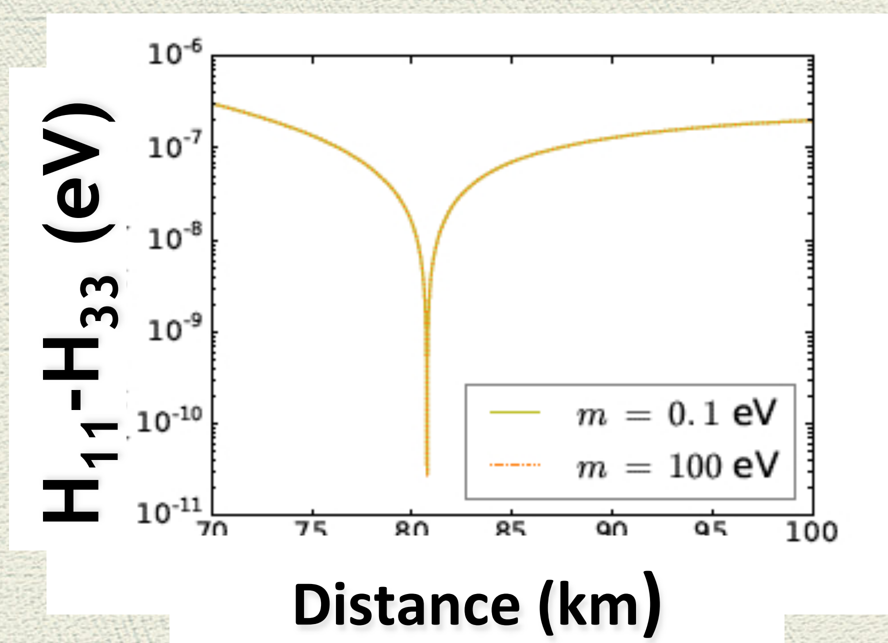
Vlasenko, Fuller, Cirigliano, PRD89 (2014)

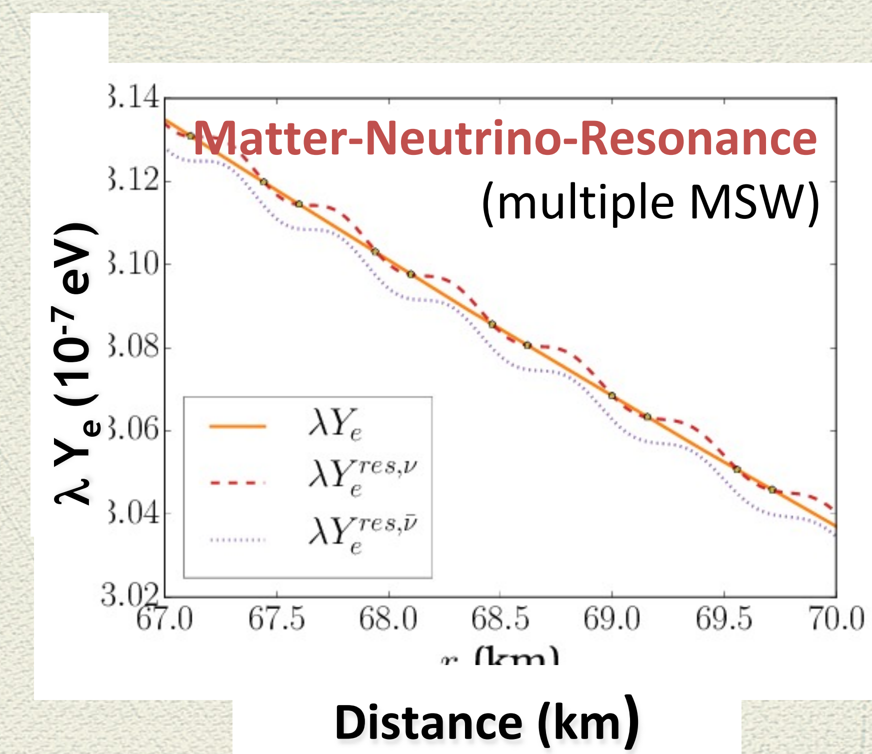
Serreau,Volpe, PRD90 (2014)

Helicity coherence









Resonance conditions fulfilled in detailed simulations but adiabaticity not enough, contrary to previous findings.

Conditions for MSW resonances not met. Conclusions also stand for supernova neutrinos.

Chatelain, Volpe, PRD 95 (2017)

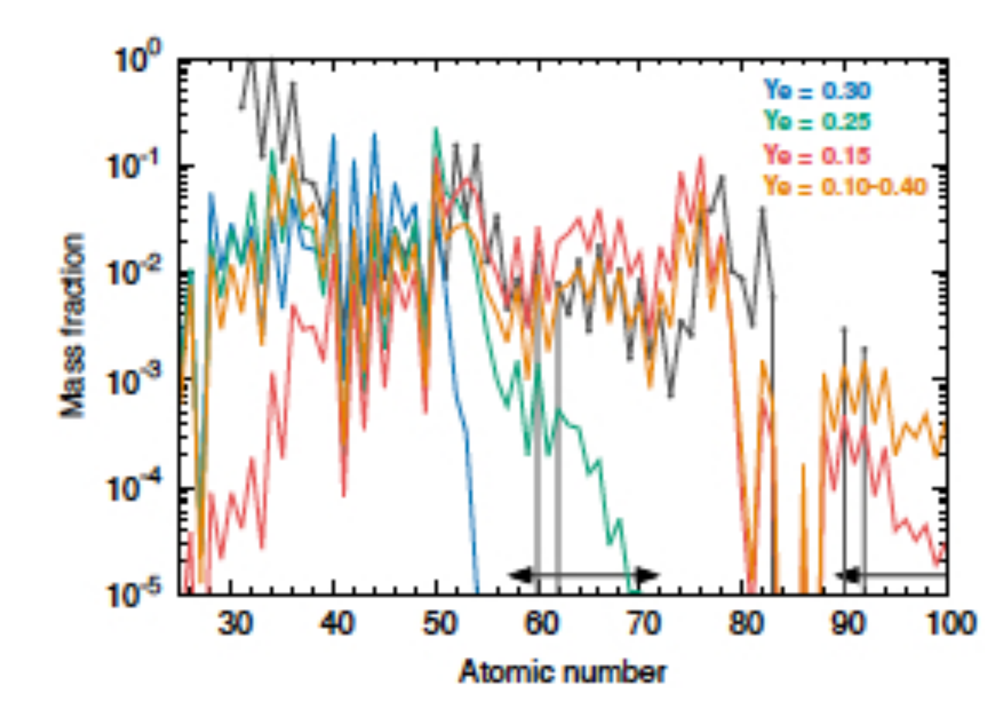
GW170817 and the kilonova

- 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 : a red and a blue components, 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.

- Observations and comparisons with mergers models : dynamical ejecta (merging phase) with Ye < 0.25, ejecta from neutrino-driven winds (post-merger phase) with Ye > 0.25.



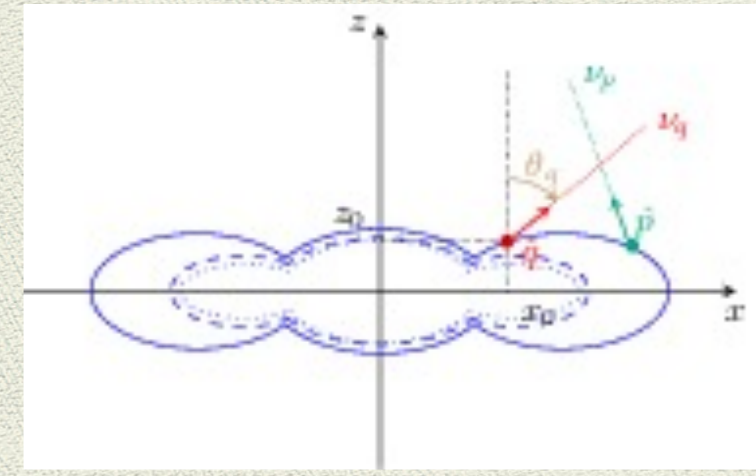
Tanaka et al, 1710.05850

Flavor evolution in ν-driven winds in BNS mergers?

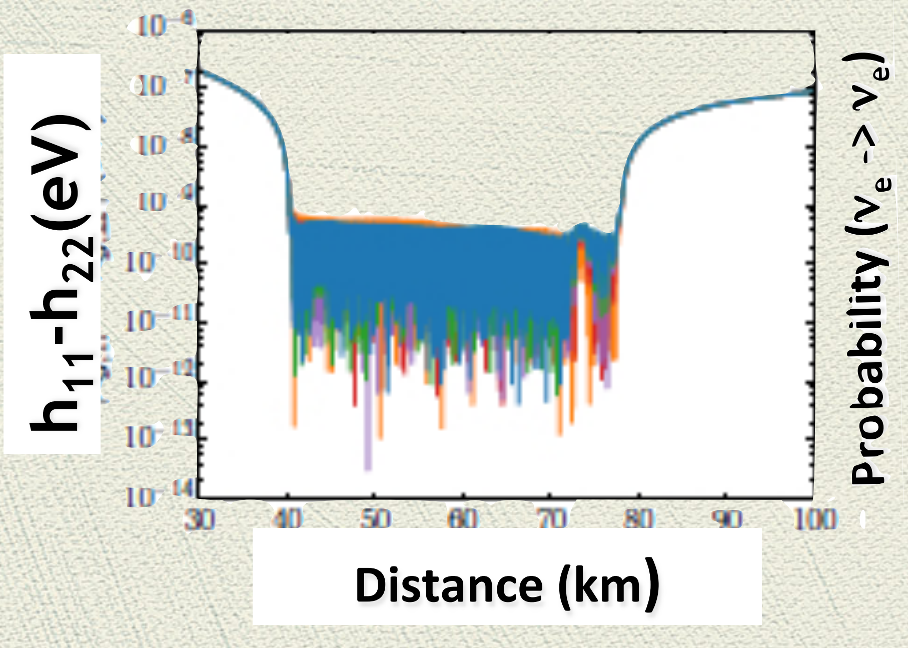
Matter-neutrino resonance

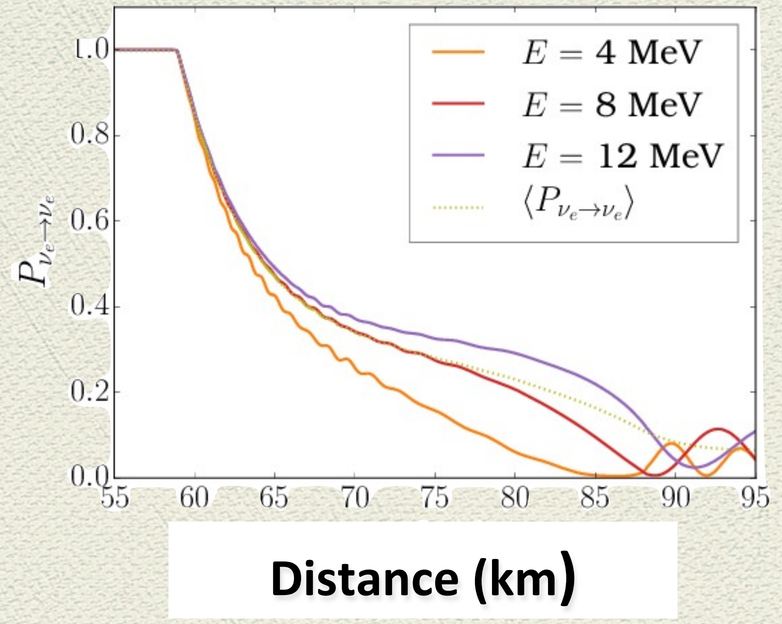
Contrary to supernovae, there is an electron antineutrino excess. It can produce a cancellation of the matter and self-interaction potentials. This is known as the Matter-Neutrino Resonance.

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



	$\langle E_\nu \rangle$	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	





Chatelain, Volpe, PRD 95 (2017), 1611.01862

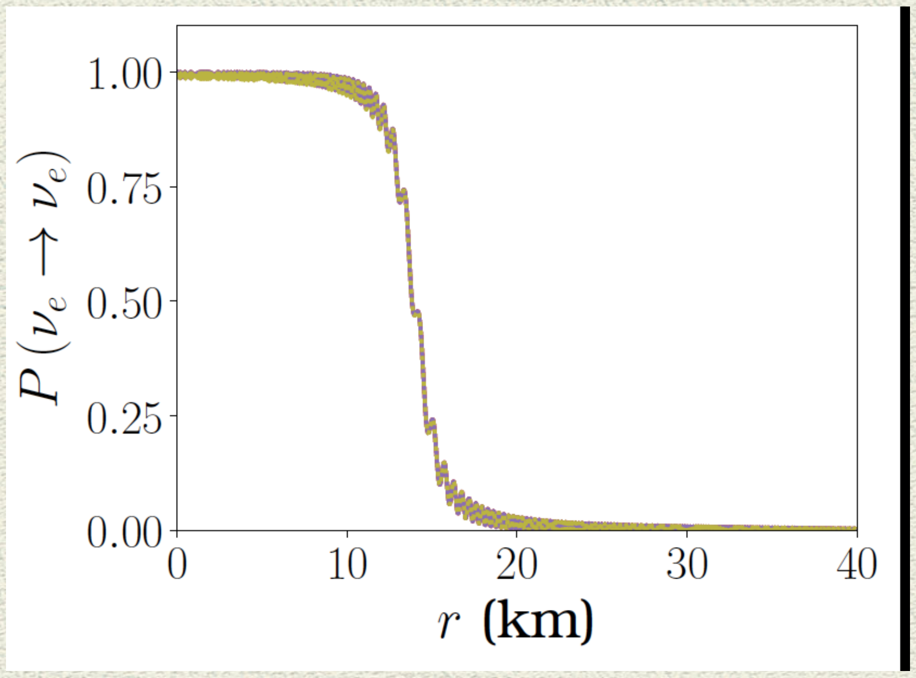
Flavor modified for electron neutrinos (and anti-neutrinos).

Flavor evolution and non-standard interactions

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

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

The I-resonance is due to a cancellation between the standard and non-standard matter terms.



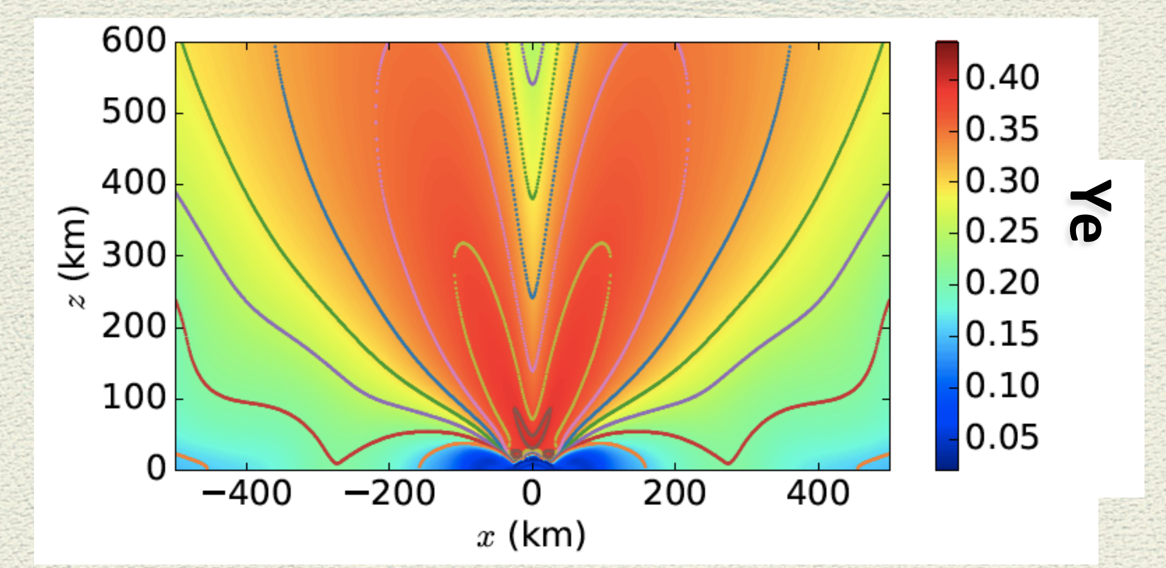
It can be seen also as a synchronized MSW resonance, where all effective spins in flavor space undergo the resonance coherently.

Chatelain, Volpe, PRD98 (2018)

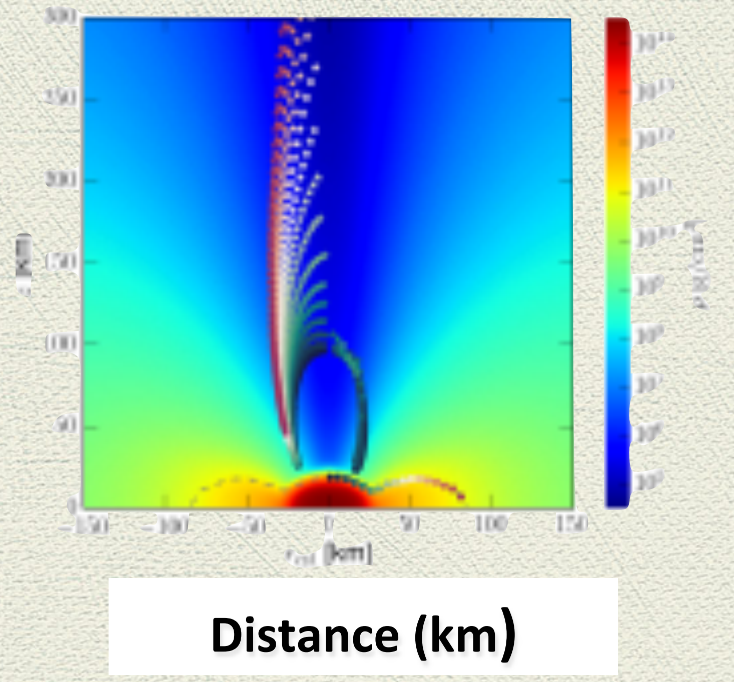
I-resonance produces flavor modification nearby the neutrino sphere.

Nucleosynthesis in neutrino driven winds and kilonovae

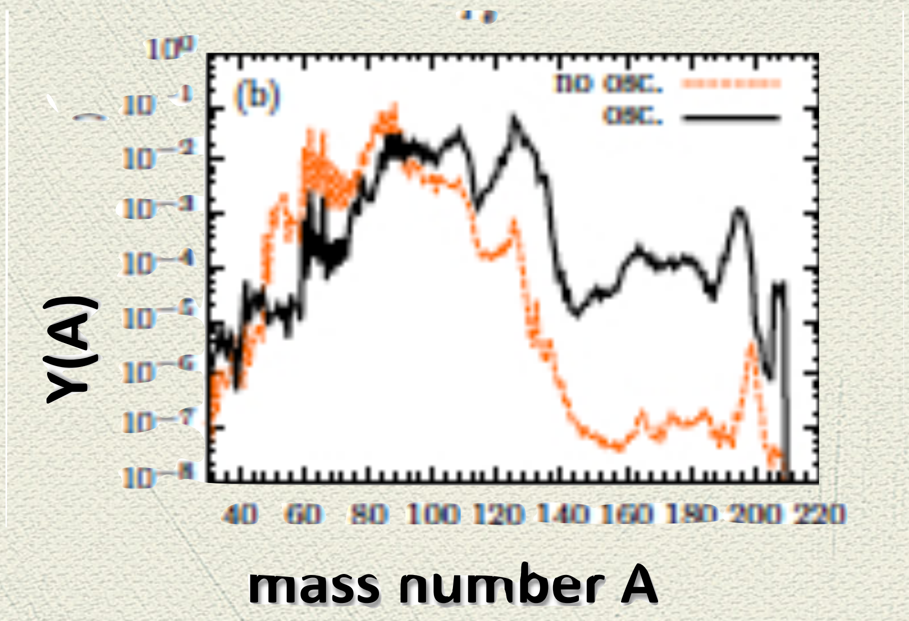
Neutrinos influence the neutron richness and determine Ye in neutrino driven winds.



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



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



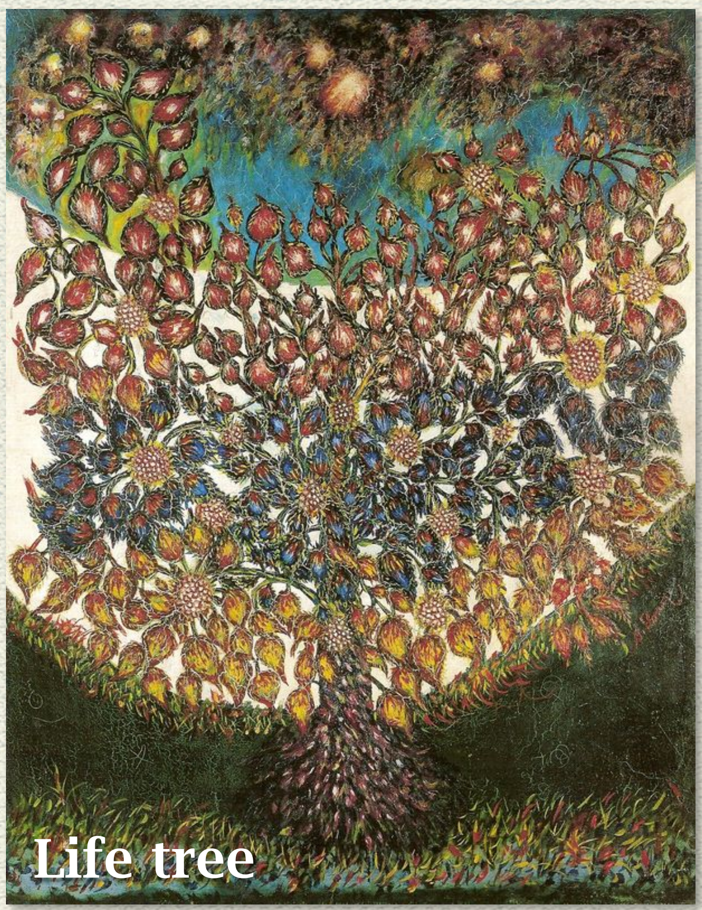
« Fast » modes, Wu et al., PRD96 (2017)

Perspectives

- Intense activity to unravel the conditions and nature of flavor conversion mechanisms. MSW-like resonances, multiple MSW, synchronized MSW, but also magnetic resonance like phenomena. Investigations necessary for future observations and maybe supernova dynamics.

- More work needed to fully assess, i.e. the role of decoherence, the influence of gravity nearby compact objects, the role of symmetry breaking, the impact of « fast » modes and of collisions.

- Neutrino flavor conversion can influence Ye and r-process nucleosynthesis. Full multi-angle and non-linear simulations needed, in relation with kilonova observations.

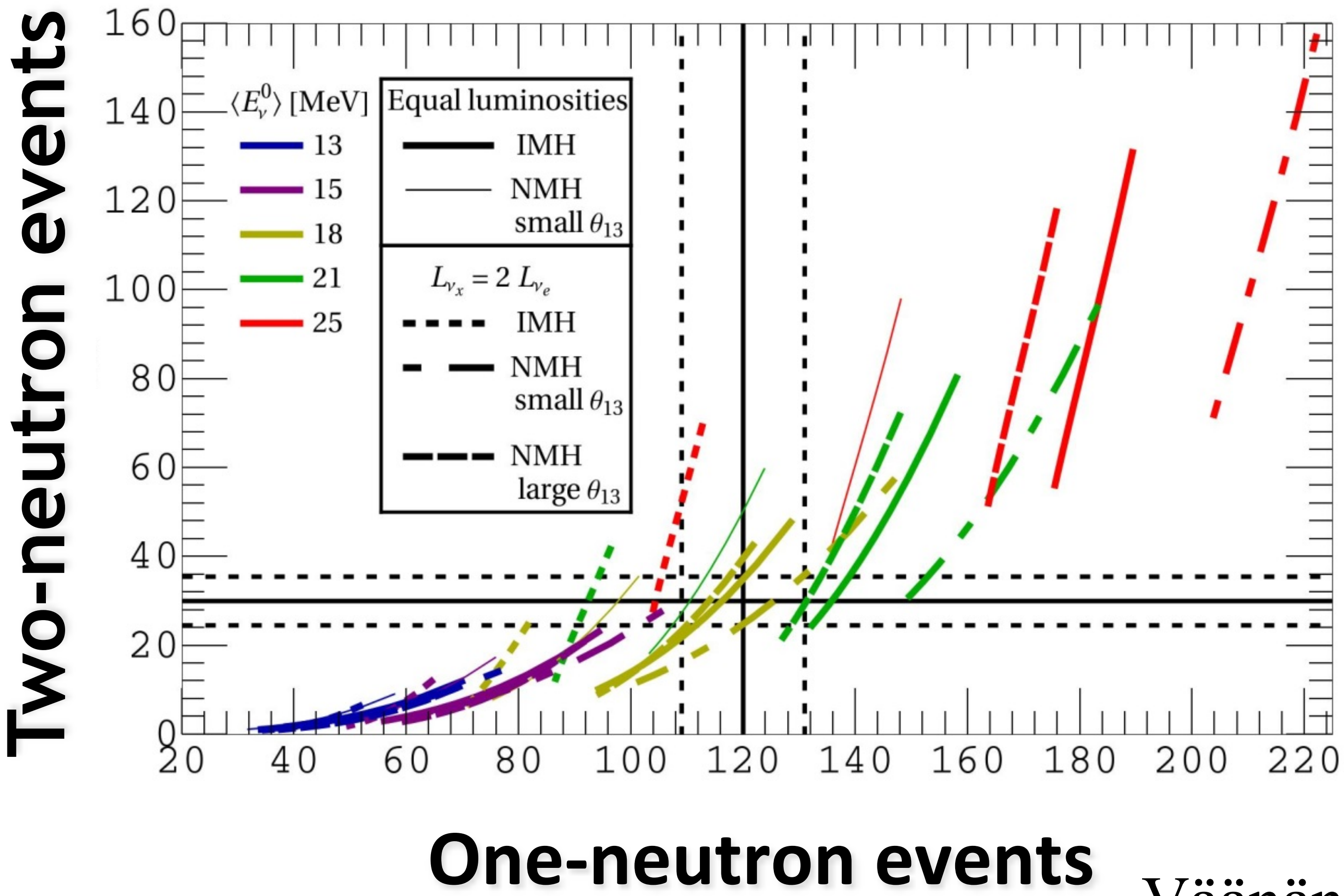


Life tree

Seraphine de Senlis

Supernovae neutrino spectra

(CC+NC) events in HALO-2 (1 kton lead) for a SN at 10 kpc



$$\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Bi} + \mathrm{n} + \mathrm{e}^-$$

$$\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Bi} + 2\mathrm{n} + \mathrm{e}^-$$

$$\nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Bi} + \mathrm{n}$$

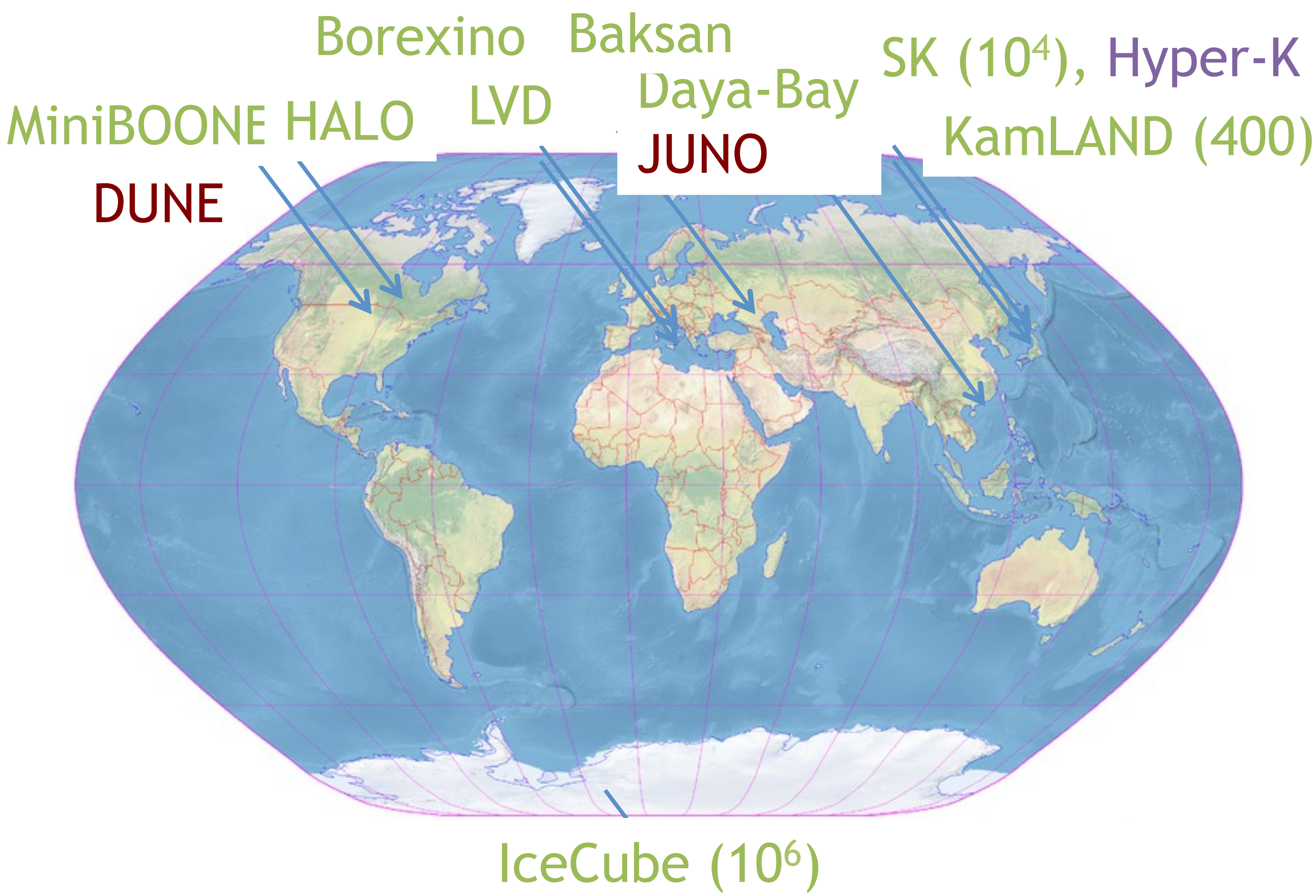
$$\nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Bi} + 2\mathrm{n}$$

Väänänen, Volpe, JCAP 1110 (2011)

Different energy thresholds should help pinning down the pinching parameter.

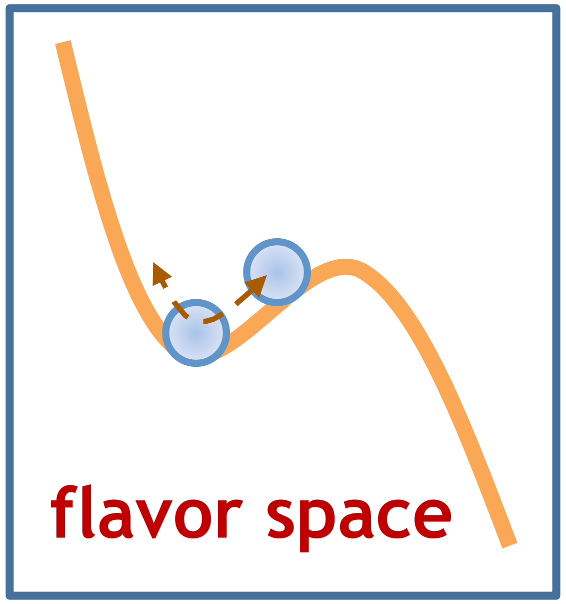
Supernova Early Warning System and SNe observatories

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



Different detection channels (time, energy, flavor):
scattering of anti-ν_e with p, ν_e with nuclei, ν_x with *e, p*

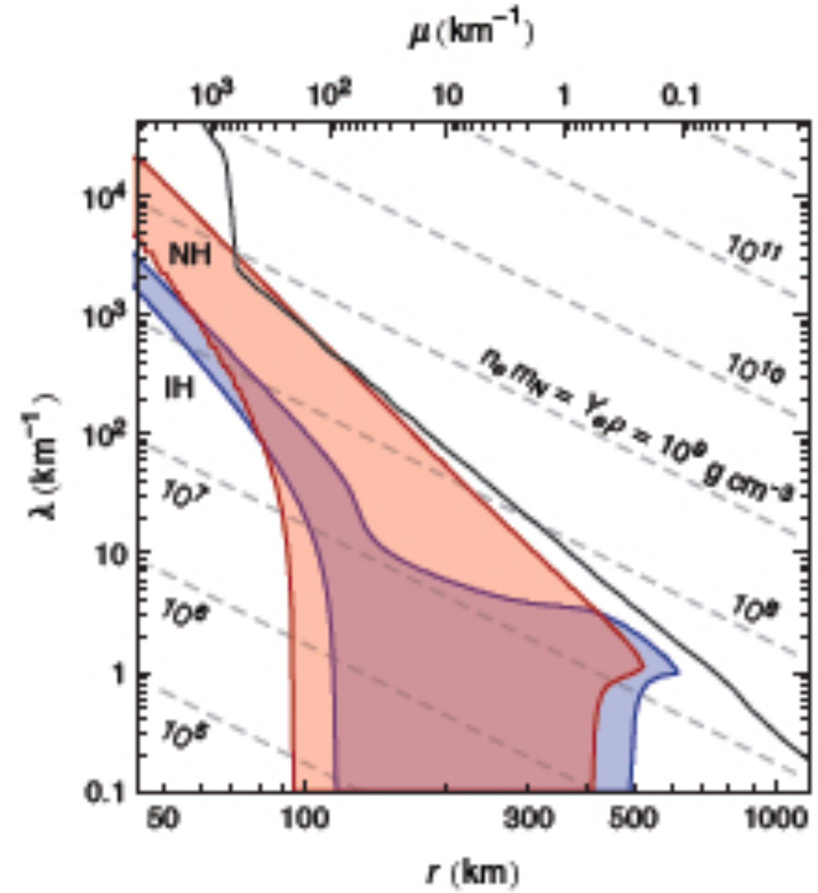
Collective neutrino modes and linearization



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

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

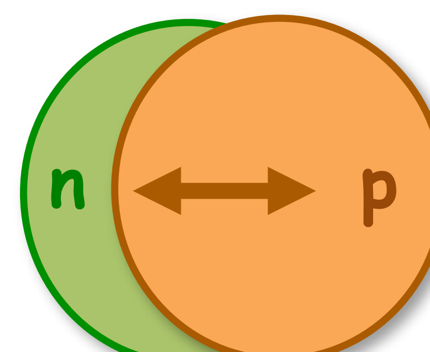
S eigenvalues :

-> real : stable collective

-> imaginary : instabilities

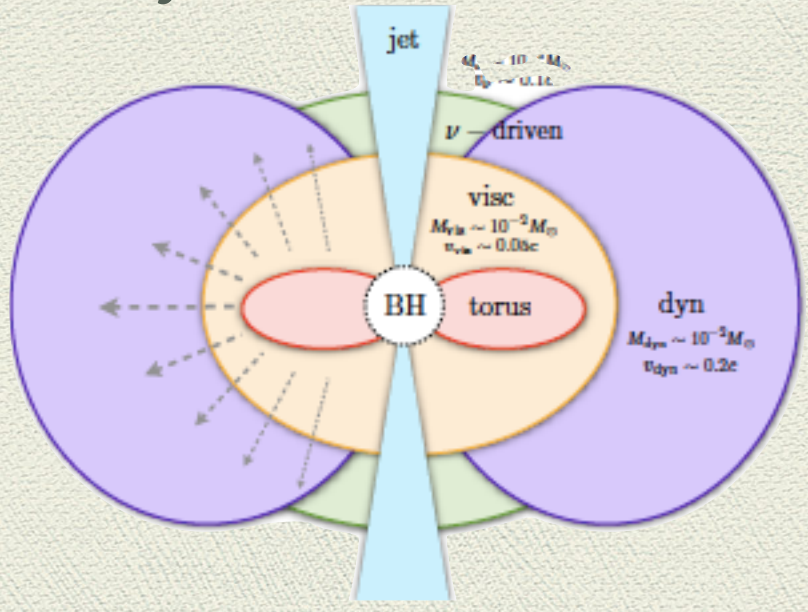
connection to collective modes in other many-body systems (nuclei, clusters, ...)

Väänänen and Volpe, PRD88 (2013)

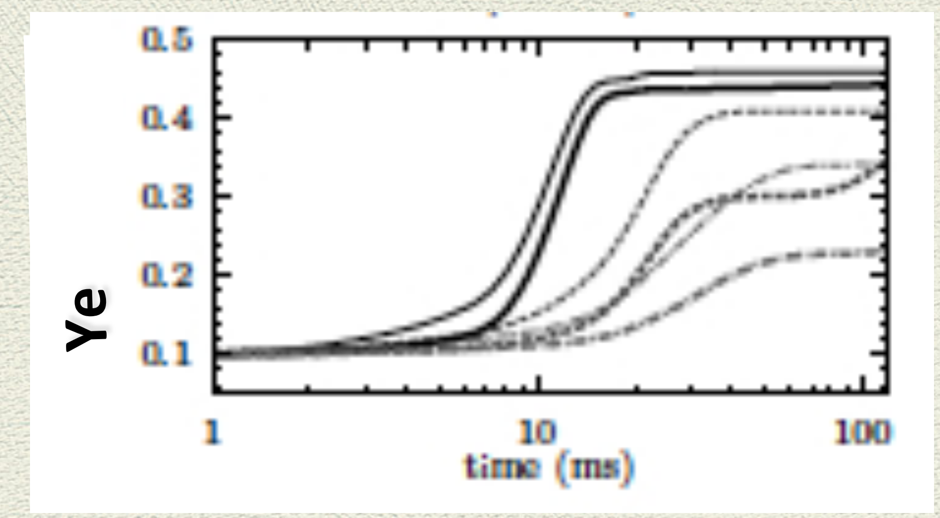


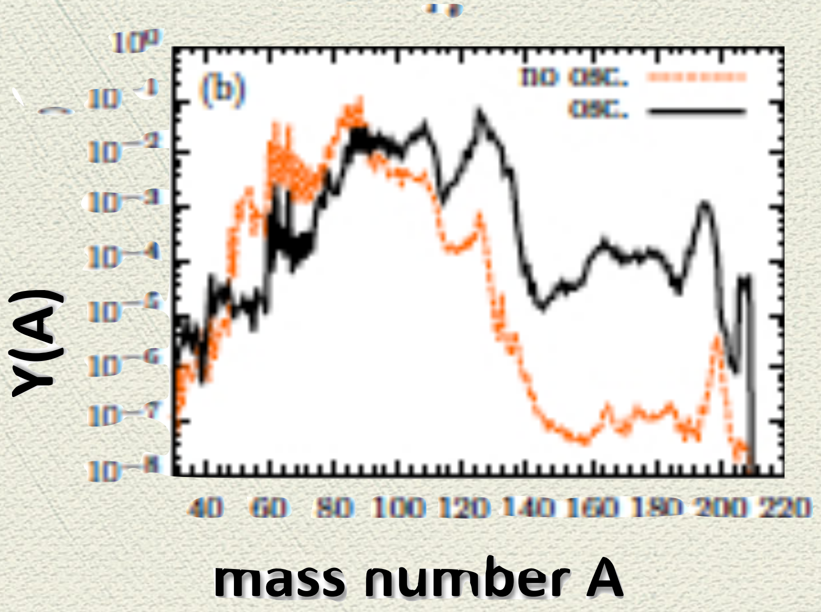
nuclear resonances

Nucleosynthesis in neutrino-driven winds and fast modes



« Fast modes » might bring an equilibration of the neutrino fluxes. An example of the impact on nucleosynthesis, in a schematic model.





Wu et al., PRD96 (2017)

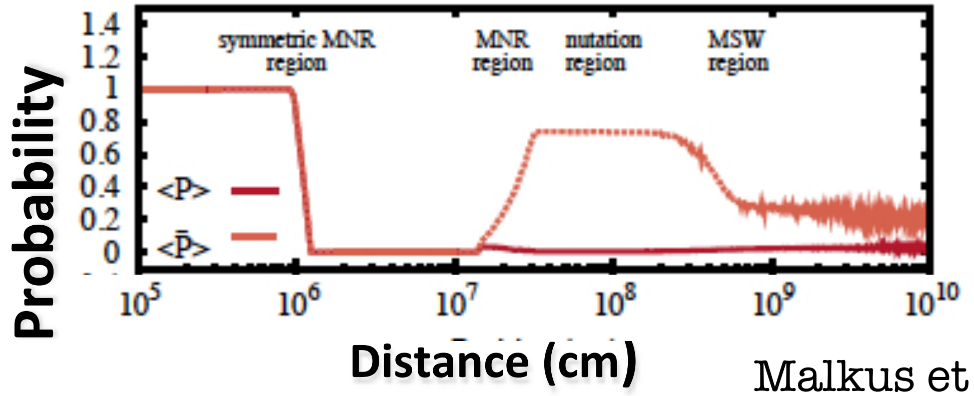
Flavor evolution here tends to decrease Ye and favors a strong r-process.

To determine the neutrino dynamics

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

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

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.

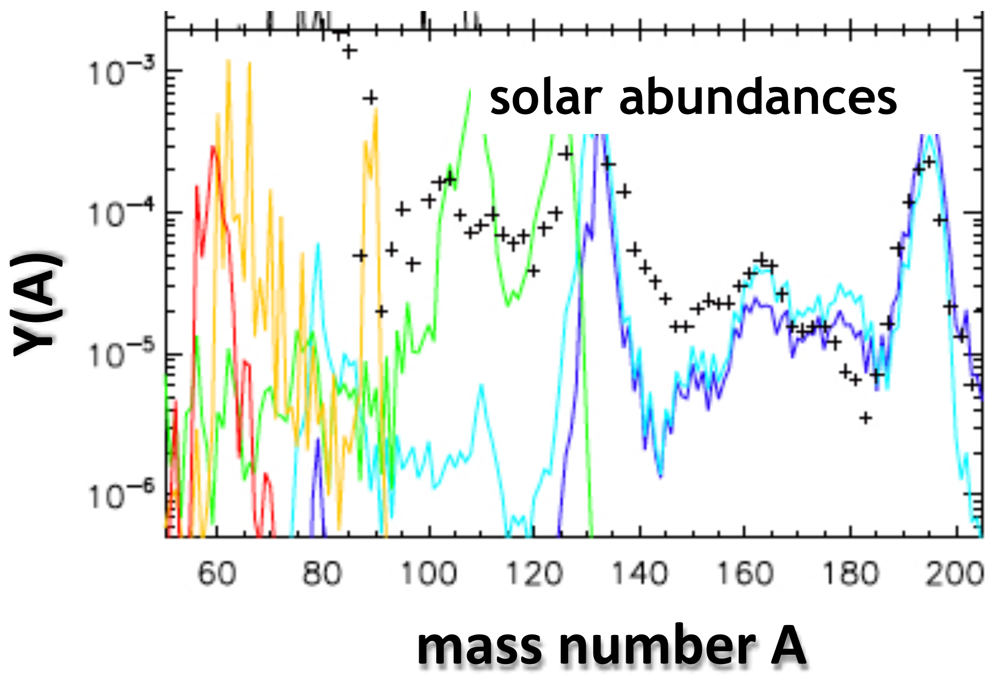
Malkus et al, PRD86 (2012), 96 (2016)

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.