Neutrinos in Core-collapse supernova and Nucleosynthesis

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Theory Needs of Next-Decade Experiments"

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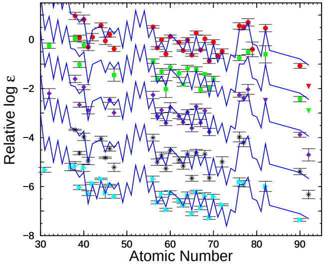
Outline

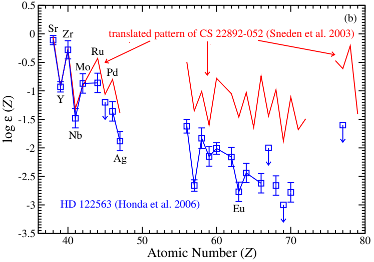
Heavy elements and metal-poor stars

Cowan & Sneden, Nature **440**, 1151 (2006)



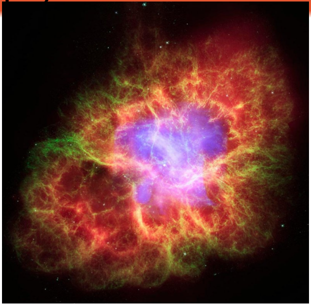
- Stars poor in heavy r-process elements but with large abundances of light r-process elements (Sr, Y, Zr)
- Production of light and heavy r-process elements is decoupled.
- Astrophysical scenario: neutrino-driven winds from core-collapse supernova

- Stars rich in heavy r-process elements ($Z > 52$) and poor in iron (r-II stars, $[\mathrm{Eu/Fe}] > 1.0$).
- Robust abundance patter for $Z > 52$, consistent with solar r-process abundance.
- These abundances seem the result of events that do not produce iron. [Qian & Wasserburg, Phys. Rept. **442**, 237 (2007)]
- Possible Astrophysical Scenario: Neutron star mergers.



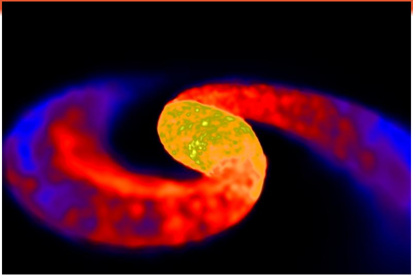
Honda *et al*, ApJ **643**, 1180 (2006)

Astrophysical sites



Core-collapse supernova

- Neutrino-winds from protoneutron stars.
- Aspherical explosions, Jets, Magnetorotational Supernova, … [Winteler *et al*, ApJ **750**, L22 (2012)]
- Neutrino-induced r-process in He layers [Banerjee *et al.*, PRL **106**, 201104 (2011)]



Neutron star mergers

- Matter ejected (~ 0.01 $M_\odot$) dynamically during merger.
- Electromagnetic emission from the decay of r-process nuclei [Kilonova, Metzger et al, MNRAS **406**, 2650 (2010)]
- Winds from accretion disks around black holes [Wanajo & Janka, ApJ **746**, 180 (2012)]

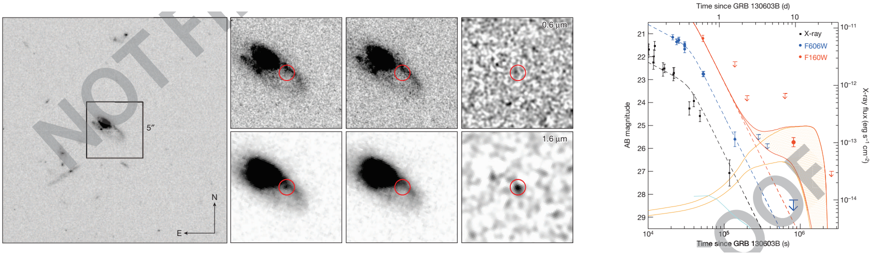
Kilonova Observation

LETTER

doi:10.1038/nature12505

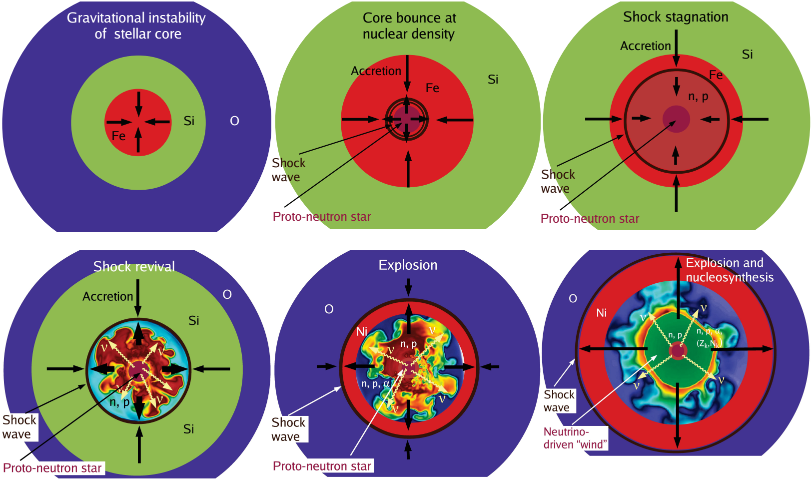
A ‘kilonova’ associated with the short-duration γ-ray burst GRB 130603B

N. R. Tanvir[1], A. J. Levan[2], A. S. Fruchter[3], J. Hjorth[4], R. A. Hounsell[3], K. Wiersema[1] & R. L. Tunnicliffe[2]



Direct observation of an r-process nucleosynthesis event?

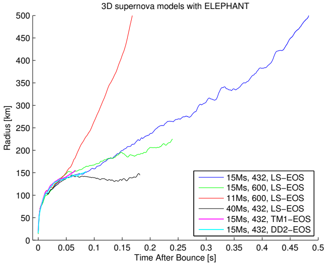
Core-collapse supernova



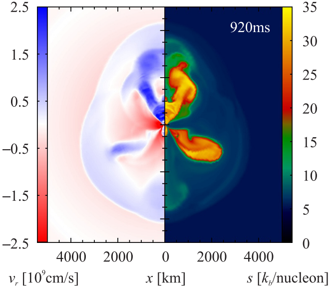
H.-Th. Janka, *et al*, PTEP 01A309 (2012)

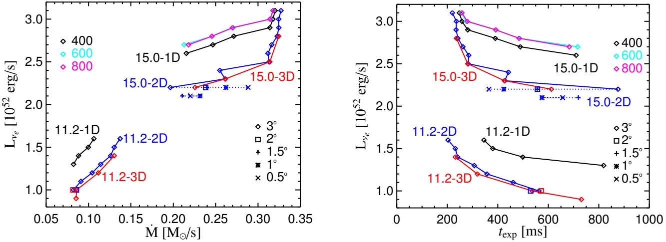
Multidimensional simulations

M. Liebendörfer *et al.* (2012)



B. Müller, H.-Th. Janka & Marek, ApJ **756**, 84 (2012)

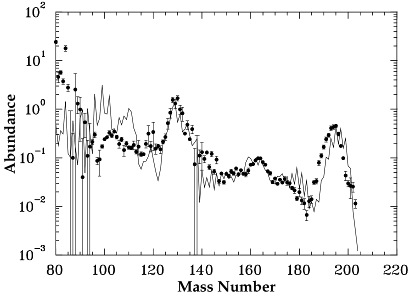


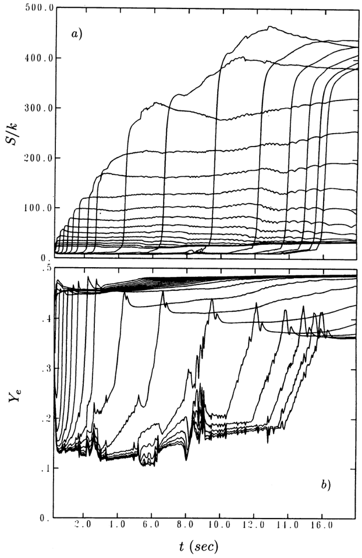


F. Hanke, A. Marek, B. Müller & H.-Th. Janka, ApJ **755**, 138 (2012)

Neutrino-driven winds and r-process

- Woosley *et al*, ApJ **433**, 229 (1994), suggested neutrino-driven winds as the r-process site.
- High entropy conditions not confirmed by any other group, Takahashi, Witti, Janka, A&A **286**, 857 (1994) …





Role of weak interactions

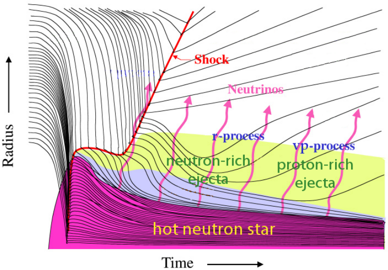
Main processes:

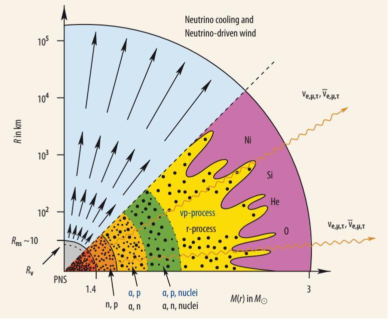
$$\nu_e + n \rightleftarrows p + e^-$$
$$\bar{\nu}_e + p \rightleftarrows n + e^+$$

Neutrino interactions determine the proton to neutron ratio.
Proton rich ejecta

$$\langle E_{\bar{\nu}_e} \rangle - \langle E_{\nu_e} \rangle < 4(m_n - m_p) \approx 5.2\,\mathrm{MeV}$$

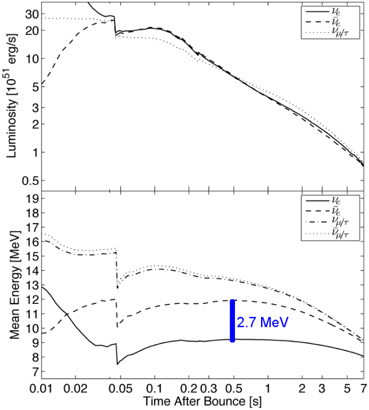
- neutron-rich ejecta: r-process
- proton-rich ejecta: νp-process





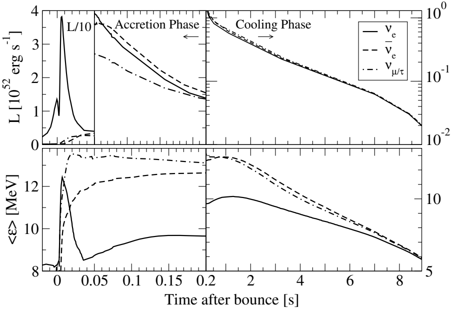
Long term evolution neutrino luminosities and average energies

Long-term radiation hydrodynamic simulations of the collapse and explosion of an 8.8 $M_\odot$ ONeMg core,



Fischer *et al*, A&A **517**, A80 (2010)

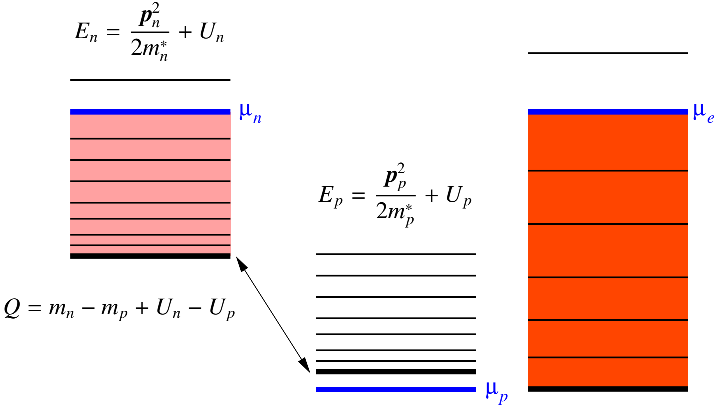
ejecta are always proton rich



Hüdepohl *et al.*, PRL **104**, 251101 (2010)

Neutrino interactions at high densities

Equations of State for core-collapse simulations treat neutrons and protons as "non-interacting" (quasi)particles that move in a mean-field potential $U_{n,p}(\rho, T, Y_e)$.



$$E_n = \frac{\boldsymbol{p}_n^2}{2m_n^*} + U_n$$

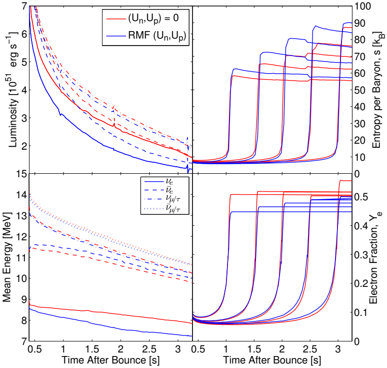
$$E_p = \frac{\boldsymbol{p}_p^2}{2m_p^*} + U_p$$

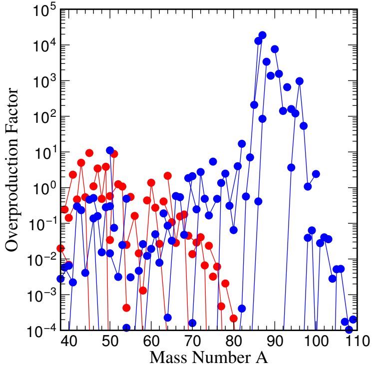
$$Q = m_n - m_p + U_n - U_p$$

- Mean-field potentials so far neglected in all simulations.
- Opacity for $\nu_e + n \to p + e^-$ increased ($\bar{\nu}_e + p \to n + e^+$ decreased).
- Energy difference between ν_e and $\bar{\nu}_e$ increased.

Impact neutrino mean energies and Y_e

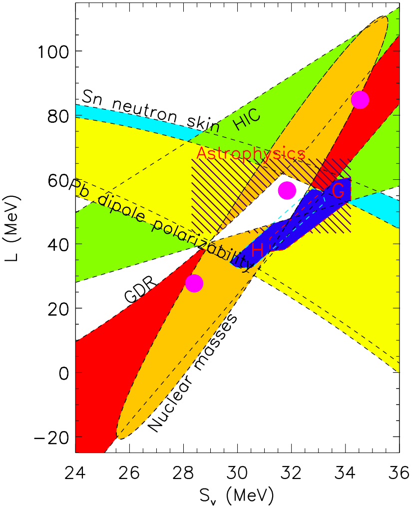
15 $M_\odot$ star simulations [GMP, Fischer, Lohs, Huther, PRL **109**, 251104 (2012)]



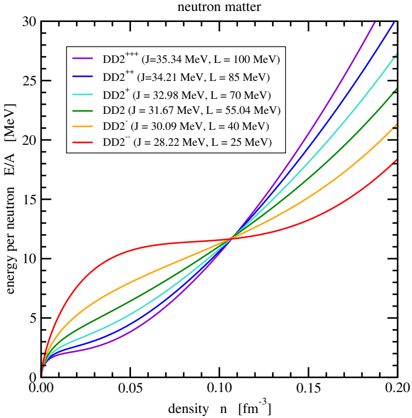


- Neutron-rich ejecta are possible in neutrino-driven winds.
- Neutron-richness sensitive to nuclear symmetry energy [see also Roberts, Reddy, & Shen, PRC **86**, 065803 (2012)]
- However the entropy are not large enough to produce elements heavier than $A \sim 120$.

Constrains on symmetry energy



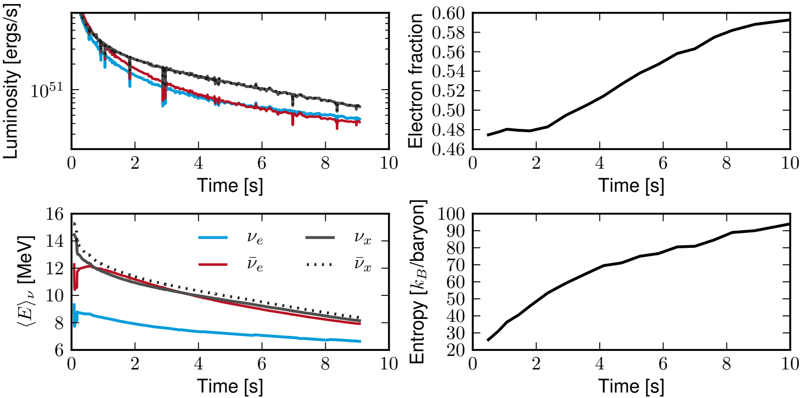
Lattimer and Lim, ApJ 771, 51 (2013)



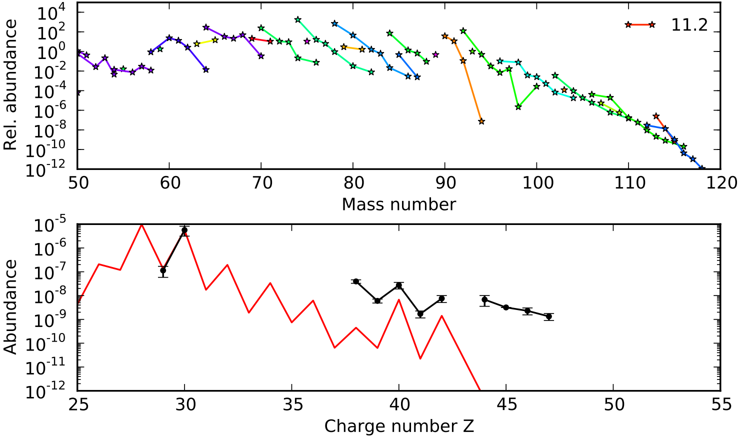
From S. Typel

Evolution EoS consistent with Symmetry energy constrains

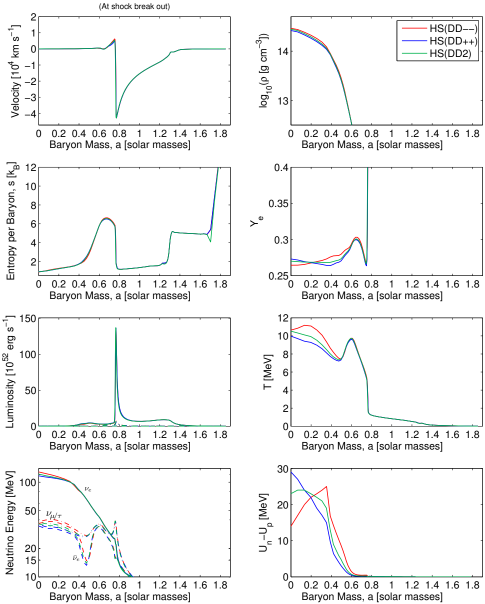
Fischer, Hempel, GMP, Typel, in preparation



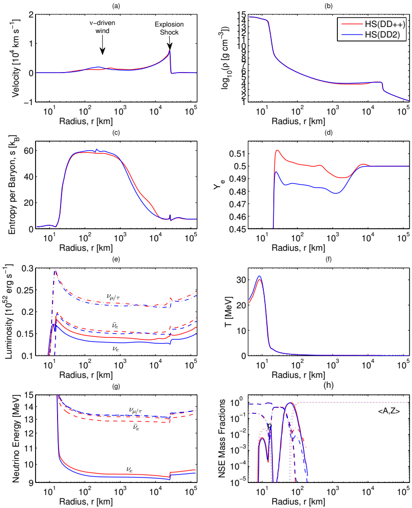
Nucleosynthesis



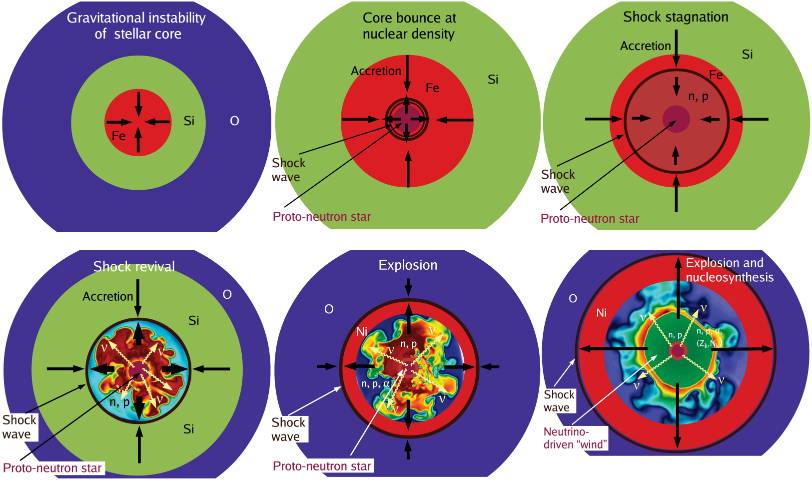
Sensitivity to symmetry energy



Sensitivity to symmetry energy



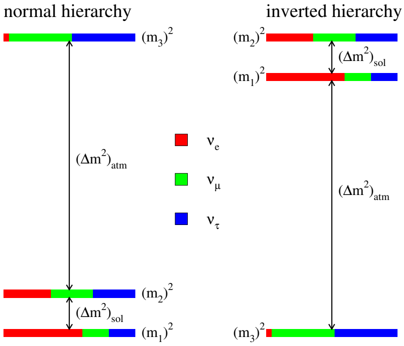
Core-collapse supernova



H.-Th. Janka, *et al*, PTEP 01A309 (2012)

Three-flavor neutrino parameters

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}c_{13}&0&s_{13}e^{-i\delta}\\0&1&0\\-s_{13}e^{i\delta}&0&c_{13}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}e^{i\lambda_2}&0\\-s_{12}&c_{12}e^{i\lambda_2}&0\\0&0&e^{i\lambda_3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}=\begin{pmatrix}U_{e1}&U_{e2}&U_{e3}\\U_{\mu1}&U_{\mu2}&U_{\mu3}\\U_{\tau1}&U_{\tau2}&U_{\tau3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



$$\Delta m^2_{\text{sol}} = \Delta m^2_{21} = (7.50 \pm 0.20)\times 10^{-5}\ \text{eV}^2$$
$$\Delta m^2_{\text{atm}} = \Delta m^2_{32} = (2.43 \pm 0.13)\times 10^{-3}\ \text{eV}^2$$
$$\theta_{12} = 34.4^\circ \pm 1.3^\circ$$
$$\theta_{23} = 45^\circ \pm 4^\circ$$
$$\theta_{13} = 8.8^\circ \pm 0.8^\circ$$

At least two massive neutrinos: $m_2 > 8.7\times 10^{-3}$ eV (Normal hierarchy)
$m_1 > 0.05$ eV (Inverted hierarchy)

Tritium decay $m_\beta = \left(\sum_k |U_{ek}|^2 m_k^2\right)^{1/2} < 2$ eV

Vacuum Oscillations

As $\Delta m^2_{21} \ll \Delta m^2_{32}$ the 3-flavor oscillation problem can be reduced to a two-flavor problem. In this case the probability that a ν_e of energy E is observed as ν_e after traveling a distance L is:

$$P(\nu_e \to \nu_e) = 1 - \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

For solar neutrinos ($E_{\nu_e} \sim 10\,\mathrm{MeV}$) the oscillation length becomes:

$$\lambda_{\mathrm{osc}} = \frac{4\pi E}{\Delta m^2_{21}} \approx 300\,\mathrm{km}$$

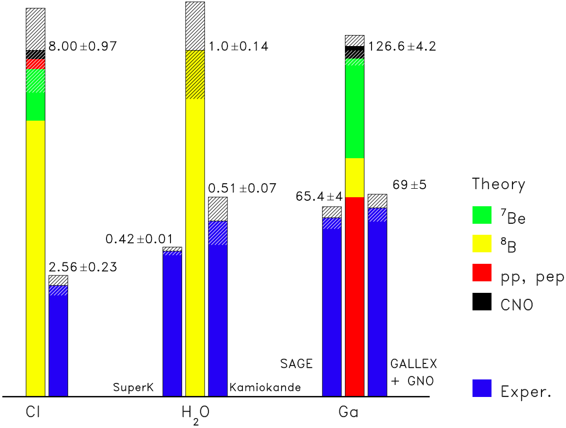
As the distance Sun-Earth and the radius of Earth are much larger than the oscillation length we can average the oscillation probability to get:

$$P(\nu_e \to \nu_e) = 1 - \frac{1}{2}\sin^2(2\theta) \approx 0.57$$

around 40% (independently of energy) of Solar neutrinos should oscillate to other flavors.

Observations neutrinos Sun

W. C. Haxton, R. G. Hamish Robertson & A. Serenelli, arXiv:1208.5723 [astro-ph.SR]



- Different detectors are sensitive to different neutrino energies
- Oscillation probability depends on neutrino energy

Matter effects

As neutrinos travel through the Sun they scatter mainly with electrons. ν_e have a much larger cross section that $\nu_{\mu,\tau}$. The evolution is governed by a combination of matter and vacuum hamiltonians (Mikheyev & Smirnov 1985, 1986; Wolfenstein 1978):

$$\boldsymbol{H} = \boldsymbol{H}_{\rm vac} + \boldsymbol{H}_{\rm matter}$$

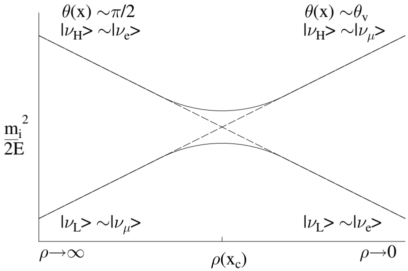
with $\boldsymbol{H}_{\rm matter}$ in the flavor basis:

$$\boldsymbol{H}_{\rm matter} = \begin{pmatrix} \sqrt{2}G_F n_e & 0 \\ 0 & 0 \end{pmatrix}, \quad n_e \equiv \text{Electron number density}$$

The neutrino “effective” mass and mixing angle depends on the local value of the electron density.

MSW mechanism

W. C. Haxton, R. G. Hamish Robertson & A. Serenelli, arXiv:1208.5723 [astro-ph.SR]



The density at the resonance is:

$$\rho_r = \frac{m_u \Delta m_{21}^2 \cos 2\theta}{2\sqrt{2} G_F E}$$

that has to be smaller than the sun core density: $\rho_{\text{core}} \approx 160 \text{ g cm}^{-3}$. Hence, only neutrinos with:

$$E \gtrsim \frac{m_u \Delta m_{21}^2 \cos 2\theta}{2\sqrt{2} G_F \rho_{\text{core}}} \approx 1.5 \text{ MeV}$$

will be affected by the MSW mechanism.

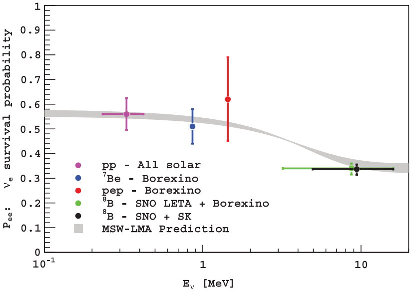
Solar Neutrinos and MSW mechanism

- Neutrinos with $E \gtrsim 1.5$ MeV will be affected by the MSW mechanism:

$$P(\nu_e \rightarrow \nu_e) = \frac{1}{2} - \frac{1}{2}\cos(2\theta) \approx 0.32$$

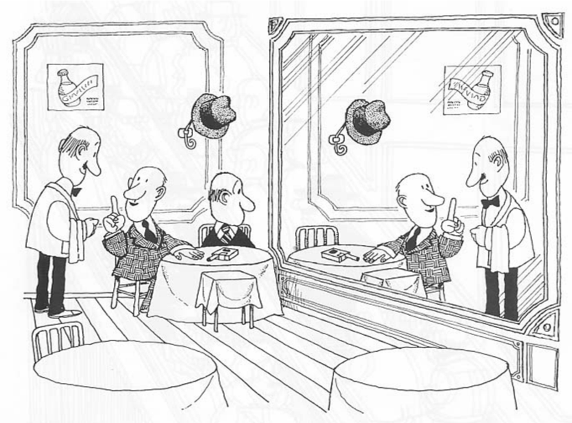
- Neutrinos with $E \lesssim 1.5$ MeV will follow vacuum oscillations

$$P(\nu_e \rightarrow \nu_e) = 1 - \frac{1}{2}\sin^2(2\theta) \approx 0.57$$



Bellini *et al*, Phys. Rev. Lett **108**, 051302 (2012)

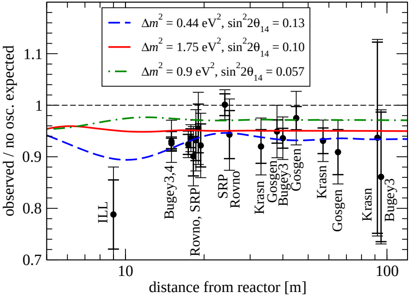
What about sterile neutrinos?



For active-sterile neutrino oscillations $\Delta m^2_{as} \sim 1$ eV and the resonances appear at densities relevant for supernova physics [Nunokawa, Peltoniemi, Rossi & Valle, PRD **56**, 1704 (1997)]

Evidence for sterile neutrinos

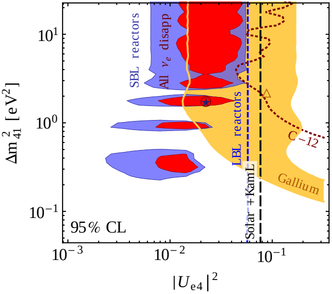
Short baseline reactor neutrino oscillation experiments show a dissappearance of neutrinos at distances 10–100 m (Reactor anomaly).



Gallium solar neutrino experiments have been tested with radioactive ^{51}Cr or ^{37}Ar sources resulting in a deficit with respect to theoretically expected value (Gallium anomaly)

$\theta_{14} \approx 9^\circ$

Kopp, Machado, Maltoni, Schwertz, JHEP05 (2013) 050



MSW mechanism

For the case of active (electron neutrinos)-sterille neutrinos. The ν_e-ν_e entry of the hamiltonian matrix is:

$$H^{ee}_{\text{matter}} = \sqrt{2}G_F n_b(c^e_v Y_e + c^p_v Y_p + c^n_v Y_n) = 3\sqrt{2}G_F n_b\left(Y_e - \frac{1}{3}\right)$$

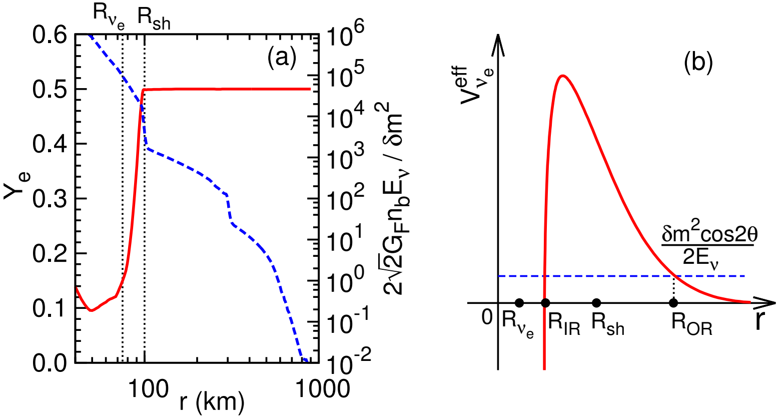
And the MSW resonance for neutrinos will appear when:

$$\frac{\Delta m^2}{2E_\nu}\cos 2\theta = \frac{3\sqrt{2}}{2}G_F n_b\left(Y_e - \frac{1}{3}\right) = V^{\text{eff}}_{\nu_e} \Rightarrow Y_e = \frac{1}{3} + \epsilon$$

and for antineutrinos:

$$\frac{\Delta m^2}{2E_\nu}\cos 2\theta = -\frac{3\sqrt{2}}{2}G_F n_b\left(Y_e - \frac{1}{3}\right) = V^{\text{eff}}_{\bar{\nu}_e} \Rightarrow Y_e = \frac{1}{3} - \epsilon$$

Supernova profiles



Neutrino conversion at the resonance

- For neutrinos we have:

$$\nu_L = \nu_e, \nu_H = \nu_s \text{ (Before res.)}, \quad \nu_L = \nu_s, \nu_H = \nu_e \text{ (After res.)}$$

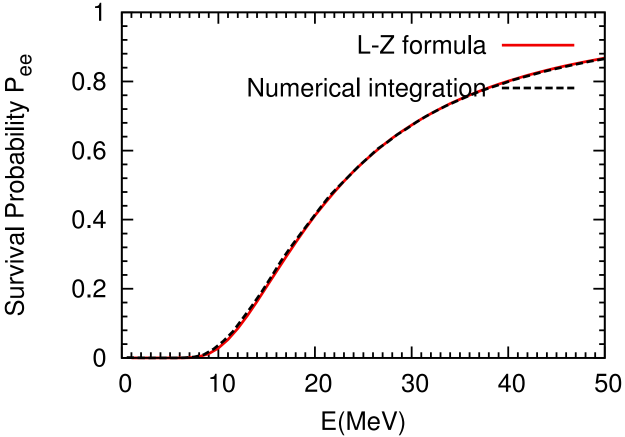
- For antineutrinos we have:

$$\bar{\nu}_L = \bar{\nu}_s, \bar{\nu}_H = \bar{\nu}_e \text{ (Before res.)}, \quad \bar{\nu}_L = \bar{\nu}_e, \bar{\nu}_H = \bar{\nu}_s \text{ (After res.)}$$

Both ν_e and $\bar{\nu}_e$ can be converted to sterile neutrinos as they cross the resonance at $Y_e \approx 1/3$.

Survival probability

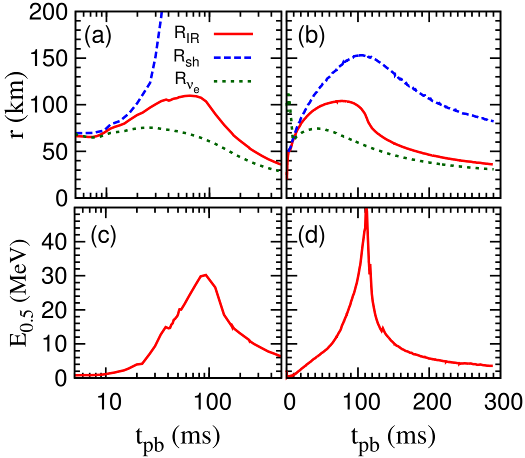
M.-R. Wu, T. Fischer, GMP, Y.-Z. Qian, arXiv:1305.2382 [astro-ph.HE]



We define $E_{0.5}$ as the energy for which the probability is 0.5. Neutrinos with lower energies are converted to sterile neutrinos

Evolution resonance radius and $E_{0.5}$

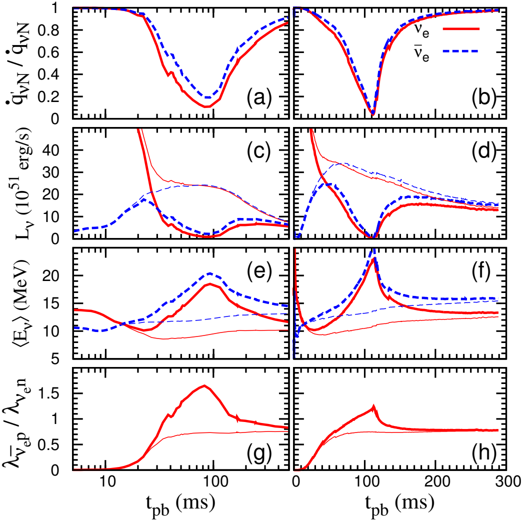
M.-R. Wu, T. Fischer, GMP, Y.-Z. Qian, arXiv:1305.2382 [astro-ph.HE]



8.8 $M_\odot$ (left) 11.0 $M_\odot$ (right)

Consequences

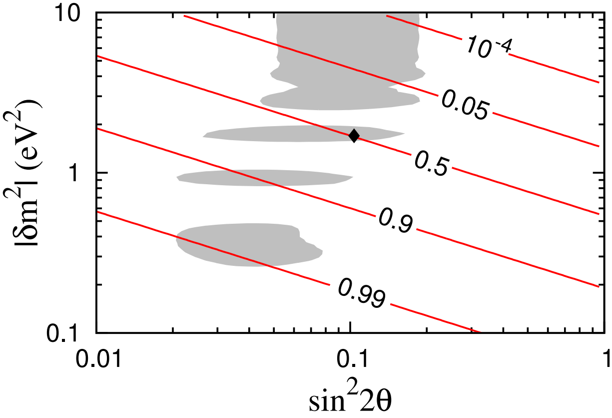
M.-R. Wu, T. Fischer, GMP, Y.-Z. Qian, arXiv:1305.2382 [astro-ph.HE]



8.8 $M_\odot$ (left) 11.0 $M_\odot$ (right)

Dependence mixing angle and δm^2

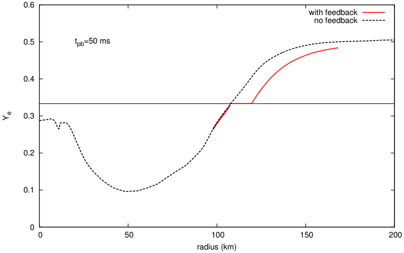
Countours of ratios of heating rates (M.-R. Wu, T. Fischer, GMP, Y.-Z. Qian, arXiv:1305.2382 [astro-ph.HE])

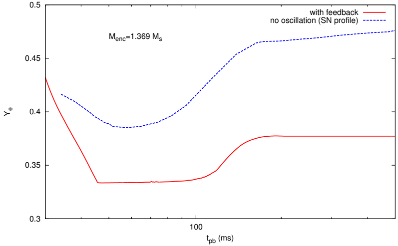


Supernova can help to constrain the mixing parameters

Feedback oscillations in Y_e

M.-R. Wu, T. Fischer, GMP, Y.-Z. Qian, in preparation





Summary

- If confirmed, the recent observation of a "kilonova" associated to GRB130603B will demonstrate that neutron star mergers are a site for the production of heavy ($A \gtrsim 120$) r-process elements.
- Neutrino-winds from core collapse supernova are expected to contribute to the production of elements lighter than $A \lesssim 120$.
- The nucleosynthesis is rather sensitive to neutrino interactions at subnuclear densities and to the symmetry energy.
- There is evidence for the existence of sterile neutrinos with masses in the eV range. If confirmed, active-sterile oscillations due to the MSW mechanism will occur in the region between neutrinosphere and supernova shock.
- The oscillations will affect supernova dynamics (reducing heating rates) and nucleosynthesis (affecting the Y_e profile of matter).
- It is necessary to include a self-consistent treatment of oscillations in supernova simulations. They will help to constrain the allowed oscillation parameter space.