Neutrinos and Explosive Nucleosynthesis

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Neutrinos in Cosmology, in Astro-, Particle- and Nuclear Physics

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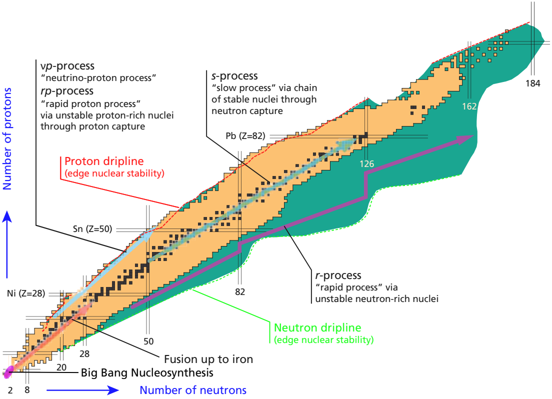
HELMHOLTZ GEMEINSCHAFT

GSI

Outline

Stellar nucleosynthesis processes

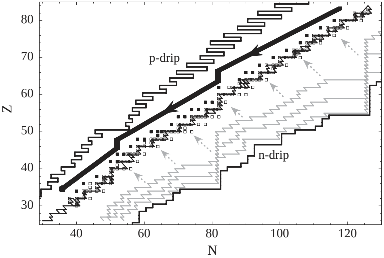
In 1957 Burbidge, Burbidge, Fowler and Hoyle and independently Cameron, suggested several nucleosynthesis processes to explain the origin of the elements.

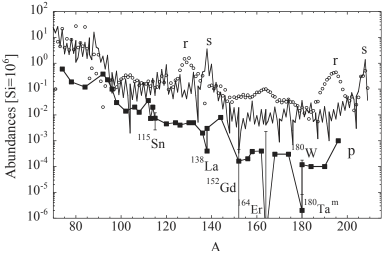


BBFH suggested that neutron deficient nuclei are produced by proton captures in an evironment with proton densities of 10^2 g cm^{-3} and $T \sim 2$–3 GK.

Nucleosynthesis beyond iron

Three processes contribute to the nucleosynthesis beyond iron: s-process, r-process and p-process (γ-process).

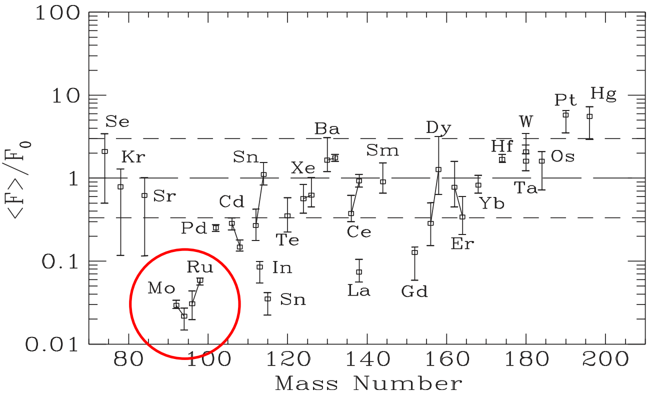




- s-process: relatively low neutron densities, $\tau_n > \tau_\beta$
- r-process: large neutron densities, $\tau_n < \tau_\beta$.
- p-process: photodissociation of s-process material.

Nucleosynthesis beyond iron

p-process fails to explain the solar abundances of ^{92,94}Mo and ^{96,98}Ru [Arnould & Goriely, Phys. Rep. **384** (2003) 1]



Can supernova proton-rich ejecta be a site for the synthesis of of ^{92,94}Mo and ^{96,98}Ru and Ru?

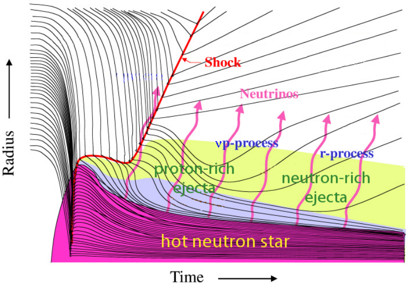
Explosive Nucleosynthesis

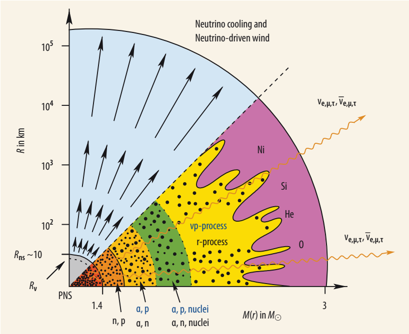
Main processes:

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

Neutrino interactions determine the proton to neutron ratio.
Proton rich ejecta
$\langle E_{\bar{\nu}_e} \rangle - \langle E_{\nu_e} \rangle < 4(m_n - m_p) \approx 5.2\,\text{MeV}$

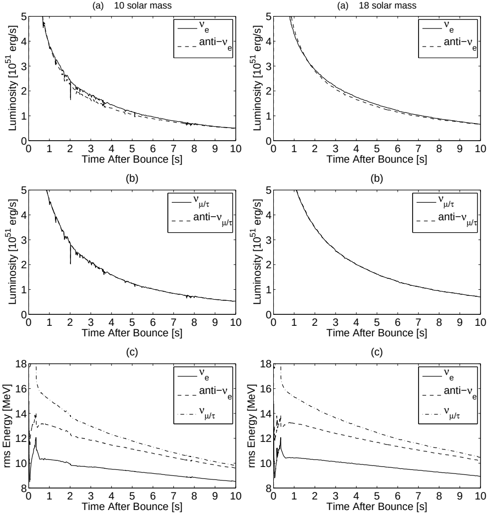
- νp-process (proton-rich ejecta).
- r-process (neutron-rich ejecta)

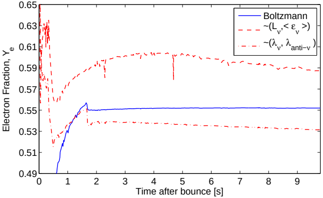




Evolution of neutrino fluxes and energies: Y_e

Fischer *et al*, arXiv:0908.1871, have performed the first Boltzmann neutrino transport study of the proto-neutron star evolution.



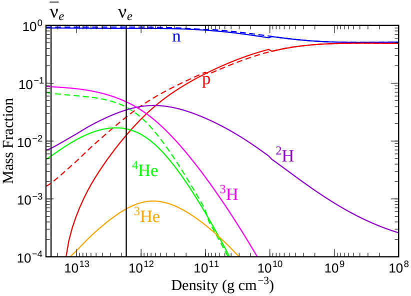


Ejecta is always proton-rich

How well is the neutrino spectrum known?

Neutrino spectrum and luminosities are determined by the neutrino interactions with matter in the protoneutron star atmosphere. Presence of light nuclei results in important changes in the average energies of the emitted neutrinos. [A. Arcones, *et al.*, PRC **78**, 015806 (2008)]

Light nuclei are more abundant than protons



Major contributors to opacity:

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

ν_e opacity is independent of EoS.
However, for $\bar{\nu}_e$:

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

instead of

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

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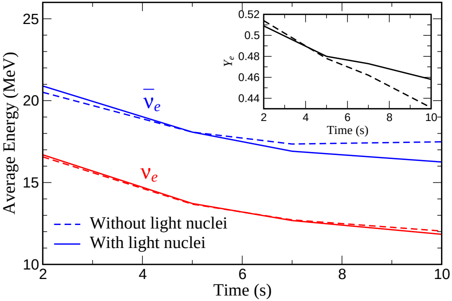
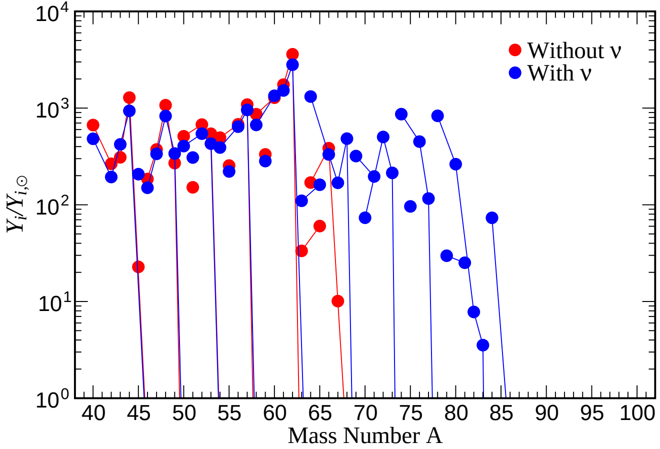
Impact in the energies of neutrinos and Y_e



Boltzmann transport calculations are necessary for an accurate estimate of the effect.

Impact neutrino interactions in proton-rich ejecta

Neutrino interactions are responsible for the production of nuclei with $A > 64$



The νp process

- Proton rich matter is ejected under the influence of neutrino interactions.
- Nuclei form (mainly $N = Z$) at distances where a substantial antineutrino flux is present.
- Antineutrino charge-current capture time and expansion time scale are similar ($\sim$ 1 s)

Neutrinos speed-up matter flow

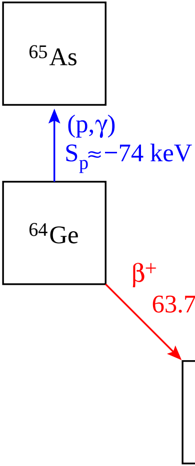
$\bar{\nu}_e + p \rightarrow e^+ + n$

$n + {}^{64}\text{Ge} \rightarrow {}^{64}\text{Ga} + p$

${}^{64}\text{Ga} + p \rightarrow {}^{65}\text{Ge} \quad \ldots$

These reactions constitute the νp-process

C. Fröhlich, *et al.*, PRL **96**, 142502 (2006)



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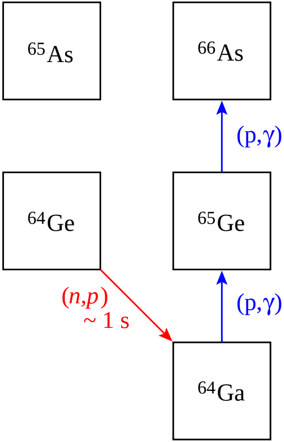
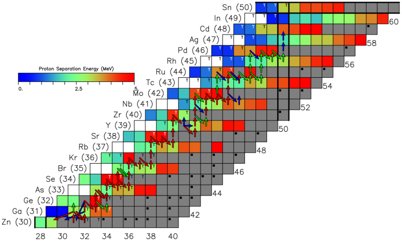
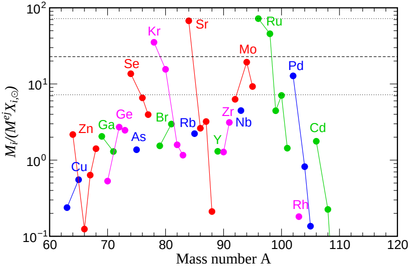


The νp process

Supernova model courtesy from H.-Th. Janka





Sensitivity to masses and astrophysical conditions.

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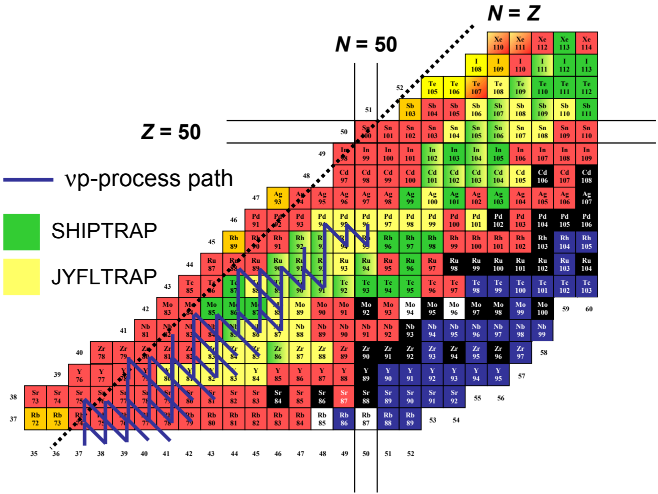
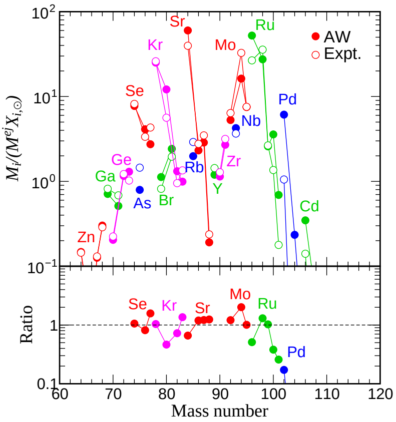
Masses measured at SHIPTRAP and JYFLTRAP



C. Weber *et al*, Phys. Rev. C **78**, 054310 (2008)

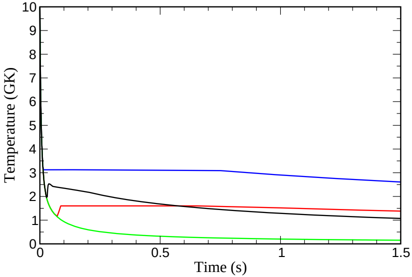
Influence new masses

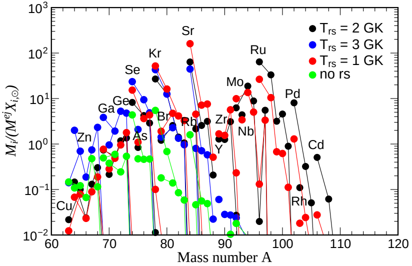


- New set of reaction rates using new experimental masses (T. Rauscher).
- New experimentar values close to Audi-Wapstra systematics. Little changes in abundances.
- No spectroscopic information is known for these nuclei. Sensitivity studies of the important reaction rates are necessary. However, νp-process seems to occur under $(p,\gamma) \rightleftarrows (\gamma,p)$ equilibrium.
- Having the nuclear physics under control allows to explore the astrophysical uncertainties. The νp-process can be used constrain the evolution of the ejected matter.

Sensitivity to temperature evolution

The νp-process nucleosynthesis is rather sensitive to the temperature evolution of the ejected matter. In particular, to the interaction with the reverse shock.



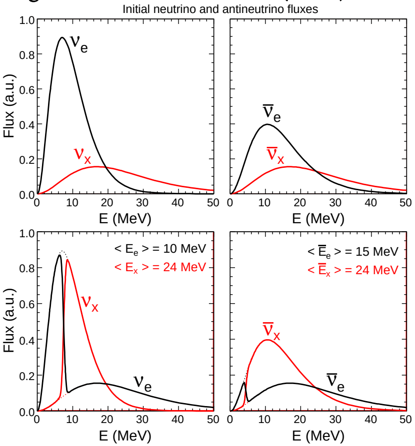


(A. Arcones & GMP, in preparation)

Collective neutrino transitions

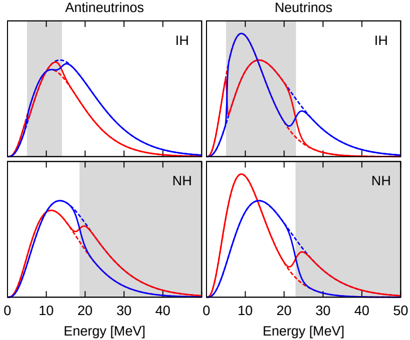
Nucleosynthesis may be sensitive to collective neutrino transitions.
Changes are sensitive to the assumed spectra of neutrinos.

Fogli, *et al*, PRD **78**, 097301 (2008)



Inverted hierarchy.

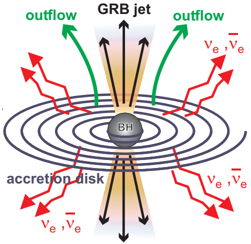
Dasgupta *et al*, PRL **103**, 051105 (2009)

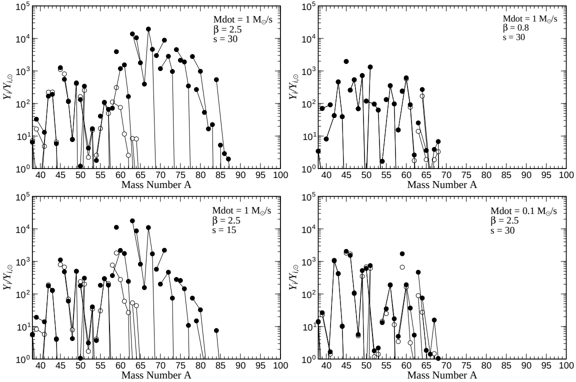


Collective neutrino transformation may provide a way to convert proton-rich ejecta into neutron-rich ejecta.

The νp-process in black hole accretions disks

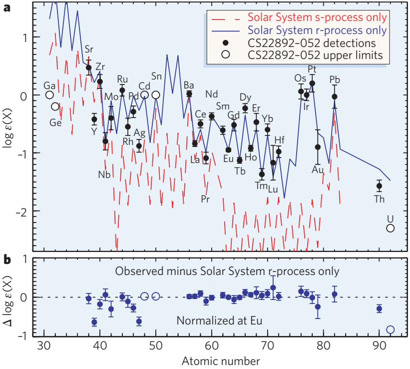
L. Kizivat, GMP, K. Langanke, R. Surman, G. McLaughlin





r-process and metal-poor stars

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

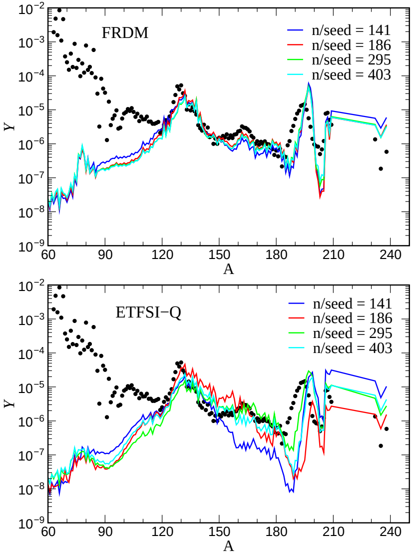


Several stars show robust r-process for $Z > 56$.

- Nucleosynthesis Signatures of few (single?) events.
- Abundances $Z > 56$ consistent with solar r-process abundance. $Z < 56$ are underproduced with respect solar abundances.
- At least two different astrophysical sites are necessary to explain solar r-process abundances.

What is the origin of the robust r-process?
Can fission cycling provide a robust r-process?

Robust r-process: fission cycling



- Depending on the mass model used fission cycling can provide a robust abundance pattern.
- FRDM: 'robust' abundance pattern as observed in metal-poor stars.
- ETFSI-Q: abundance pattern strongly depends on the astrophysical conditions.

Summary

- Nucleosynthesis in supernova ejecta is very sensitive to the emitted neutrino fluxes and spectra and possibly to oscillation phenomena.
- Supernova simulations show the existence of proton-rich ejecta that constitute the site of a novel nucleosynthesis process: The νp-process.
- The νp-process may explain the solar abundances of light p-nuclei (^{92,94}Mo, ^{96,98}Ru).
- r-process nucleosynthesis requires the knowledge of the properties of extremely neutron-rich nuclei. Future experimental facilities (FAIR) will reduce the nuclear uncertainties and greatly constrain the astrophysical models.