Explosive nucleosynthesis of heavy elements

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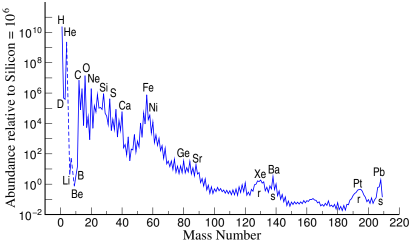
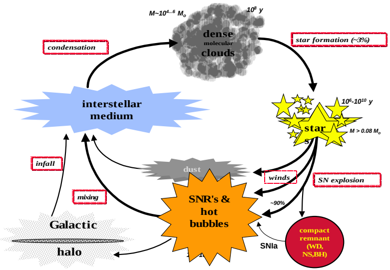
Outline

Signatures and nucleosynthesis processes

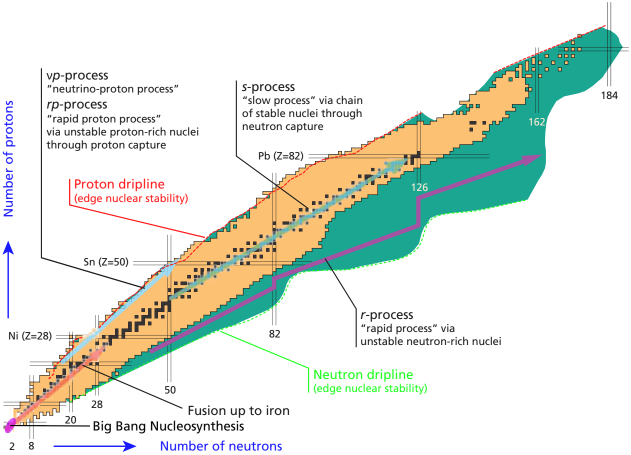
- Solar system abudances contain signatures of nuclear structure and nuclear stability.
- They are the result of different nucleosynthesis processes operating in different astrophysical environments and the chemical evolution of the galaxy.





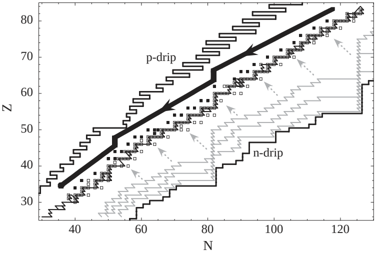
Stellar nucleosynthesis processes

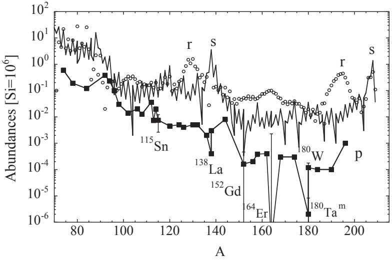
In 1957 Burbidge, Burbidge, Fowler and Hoyle and independently Cameron, suggested several nucleosynthesis processes to explain the origin of the elements.



Nucleosynthesis beyond iron (Traditional description)

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

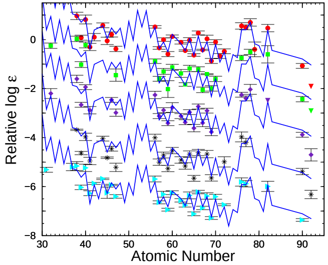




- s-process: relatively low neutron densities, $n_n = 10^{10-12}$ cm^{-3}, $\tau_n > \tau_\beta$
- r-process: large neutron densities, $n_n > 10^{20}$ cm^{-3}, $\tau_n < \tau_\beta$.
- p-process: photodissociation of s-process material.

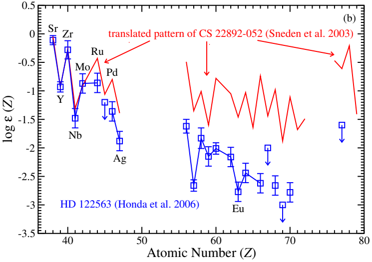
Heavy elements and metal-poor stars

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



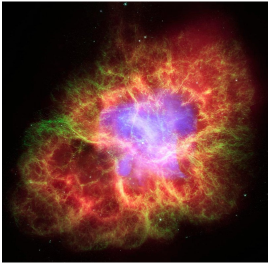
- Stars rich in heavy r-process elements ($Z > 50$) and poor in iron (r-II stars, $[\mathrm{Eu/Fe}] > 1.0$).
- Robust abundance patter for $Z > 50$, consistent with solar r-process abundance.
- These abundances seem the result of events that do not produce iron. [Qian & Wasserburg, Phys. Rept. **442**, 237 (2007)]
- Possible Astrophysical Scenario: Neutron star mergers.

- 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



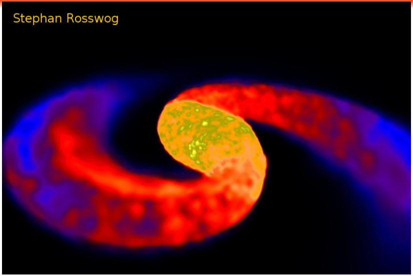
Honda *et al*, ApJ **643**, 1180 (2006)

r-process astrophysical sites



Core-collapse supernova

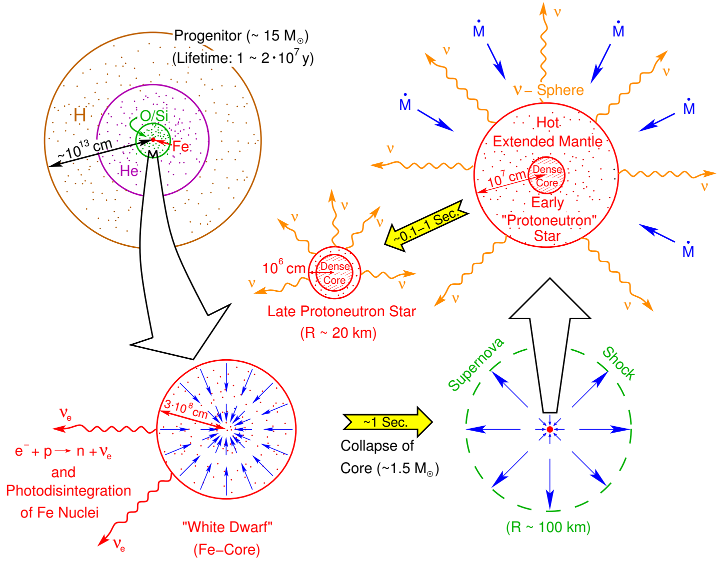
- Neutrino-winds from protoneutron stars.
- Aspherical explosions, Jets, Magnetorotational Supernova, … [Winteler *et al*, ApJ **750**, L22 (2012); Mösta *et al*, arXiv:1403.1230]



Neutron star mergers

- Matter ejected ($\sim 0.01\ M_{\odot}$) dynamically during merger.
- Electromagnetic emission from radioactive decay of r-process nuclei [KiloNova, Metzger *et al* (2010), Roberts *et al* (2011), Bauswein *et al* (2013)]
- What is the additional contribution from the accretion disk?

Collapse and Explosion



Role of weak interactions

Main processes:

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

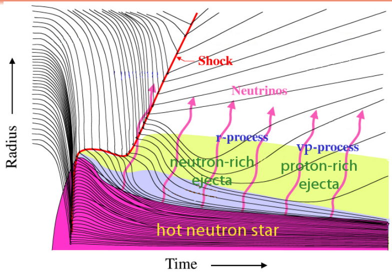
Neutrino interactions determine the proton to neutron ratio.

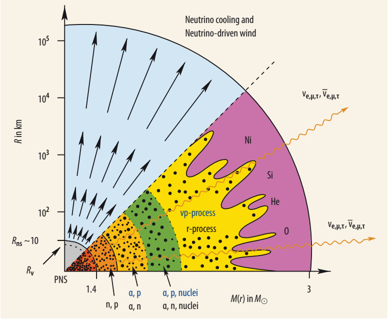
Neutron-rich ejecta:

$$\langle E_{\bar{\nu}_e} \rangle - \langle E_{\nu_e} \rangle > 4\Delta_{np} - \left[\frac{L_{\bar{\nu}_e}}{L_{\nu_e}} - 1\right]\left[\langle E_{\bar{\nu}_e} \rangle - 2\Delta_{np}\right]$$

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

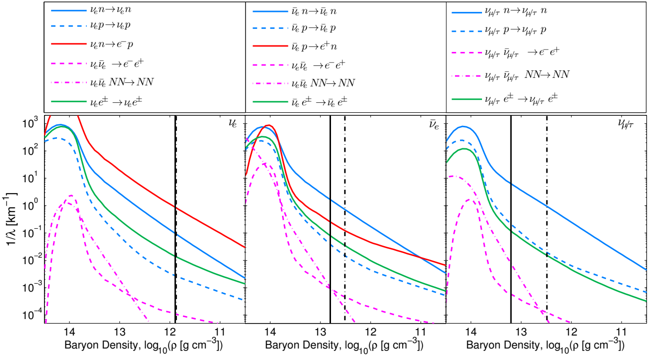
We need accurate knowledge of ν_e and $\bar{\nu}_e$ spectra





Weak rates in the decoupling region

Several process contribute to the determination of neutrino spectra.

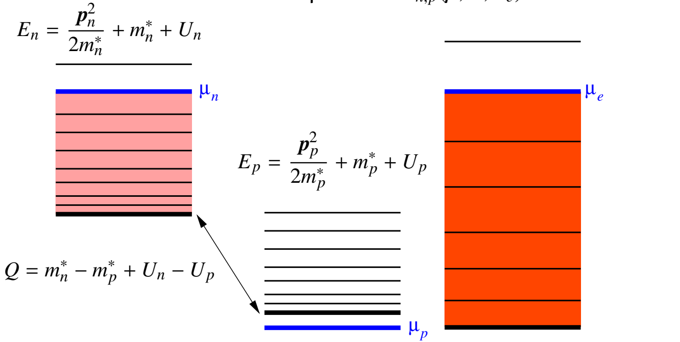


- ν_e: dominated by charged-current process: $\nu_e + n \rightleftarrows p + e^-$
- $\bar{\nu}_e$: interplay between charged-current and neutral current processes.

  $e^+ + n \to p + \bar{\nu}_e$ dominates the production.
  $\bar{\nu}_e + e^- \to \bar{\nu}'_e + e^-$ and $\bar{\nu}_e + n \to \bar{\nu}'_e + n$ fundamental for spectra formation and decoupling.

Neutrino interactions at high densities

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



- ν_e absorption opacity affected by final state electron blocking

$$\chi(E_\nu) \propto (E_\nu + \Delta m^* + \Delta U)^2 \exp\left(\frac{E_\nu + \Delta m^* + \Delta U - \mu_e}{kT}\right), \quad \Delta U = U_n - U_p$$

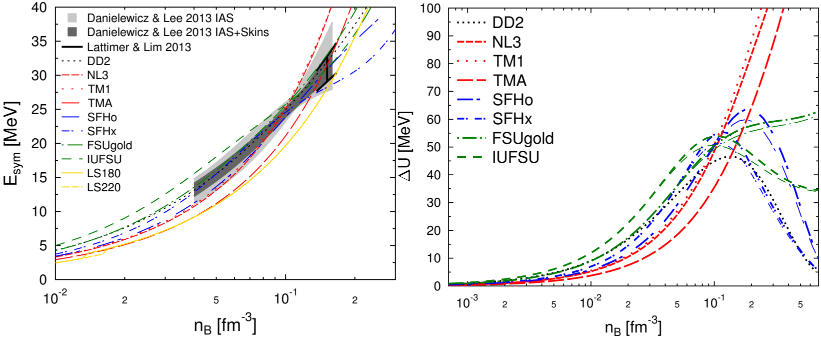
- $\bar{\nu}_e$ absorption affected by energy threshold (ΔU).

$$\chi(E_\nu) \propto (E_\nu - \Delta m^* - \Delta U)^2 \quad E_\nu > \Delta m^* + \Delta U$$

- larger symmetry energy (larger ΔU) implies: i) the larger the energy difference between ν_e and $\bar{\nu}_e$; ii) smaller electron flavor luminosities.

Constrains in the symmetry energy

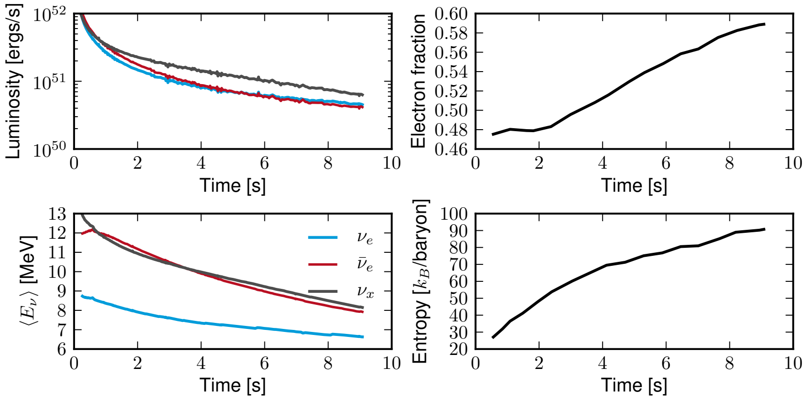
- Combination nuclear physics experiments and astronomical observations (Lattimer & Lim 2013)
- Isobaric Analog States (Danielewicz & Lee 2013)



Figures from Matthias Hempel (Basel)

Impact on neutrino luminosities and Y_e evolution

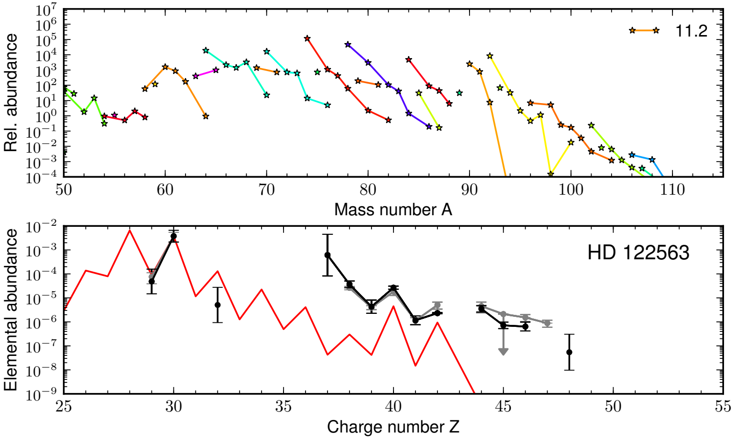
1D Boltzmann transport radiation simulations (artificially induced explosion) for a 11.2 $M_\odot$ progenitor based on the DD2 EoS (Stefan Typel and Matthias Hempel).



Y_e is moderately neutron-rich at early times and later becomes proton-rich.

GMP, Fischer, Huther, J. Phys. G **41**, 044008 (2014).

Nucleosynthesis



- Elements between Zn and Mo, including ^{92}Mo, are produced
- Mainly neutron-deficient isotopes are produced
- No elements heavier than Mo ($Z = 42$) are produced.

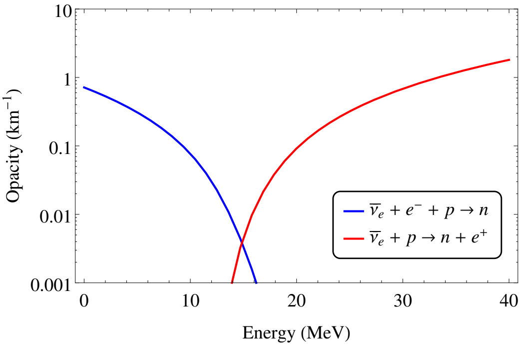
Neutron decay

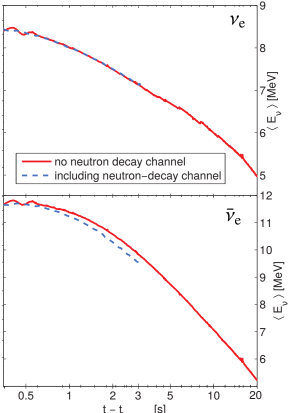
The neutron-proton energy difference in the medium could be of the order of several 10s MeV. Neutron decay is an important source of low energy neutrinos.

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

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

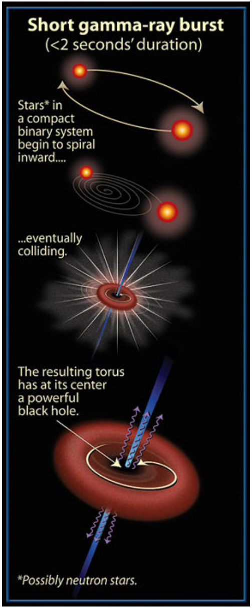
This is part of the direct URCA process in neutron stars [Lattimer *et al*, (1991)]

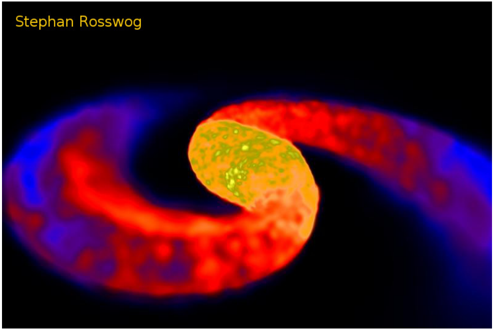




Fischer, Lohs, GMP, Qian, in preparation

Neutron star mergers: Short gamma-ray bursts and r-process

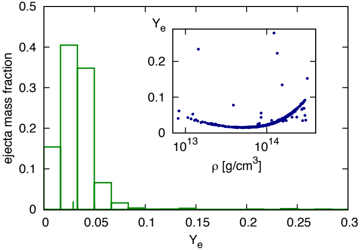


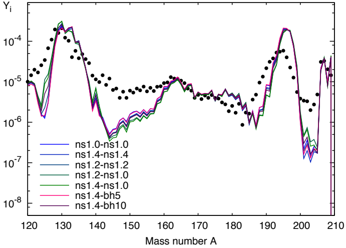


- Mergers are expected to eject around $0.01\ M_\odot$ of very neutron rich-material ($Y_e \sim 0.01$). A similar amount of less neutron-rich material ($Y_e \sim 0.1$–0.2) is expected from the accretion disk.
- They are also promising sources of gravitational waves.
- Observational signatures of the r-process?

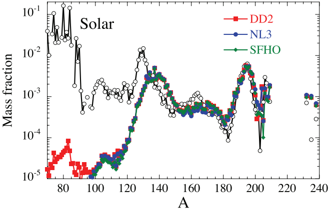
Neutron-star mergers: Astrophysically robust

Korobkin, Rosswog, Arcones, & Winteler, MNRAS **426**, 1940 (2012)



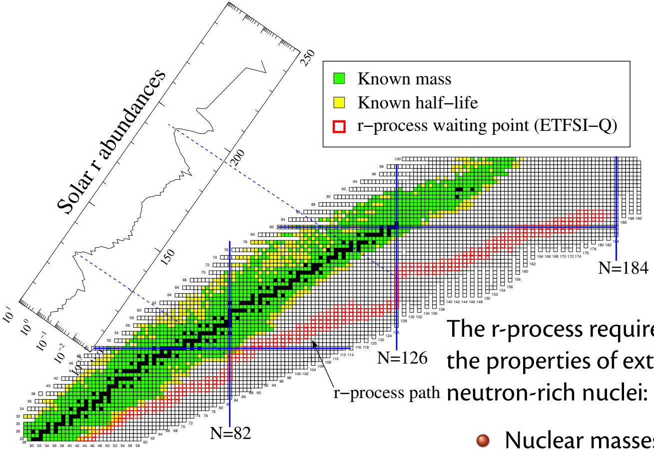


Robust to variations of the equation of state



Bauswein, Goriely, Janka, ApJ **773**, 78 (2013)

Making Gold in Nature: r-process nucleosynthesis



The r-process requires the knowledge of the properties of extremely neutron-rich nuclei:

- Nuclear masses.
- Beta-decay half-lives.
- Neutron capture rates.
- Fission rates and yields.

General features r-process

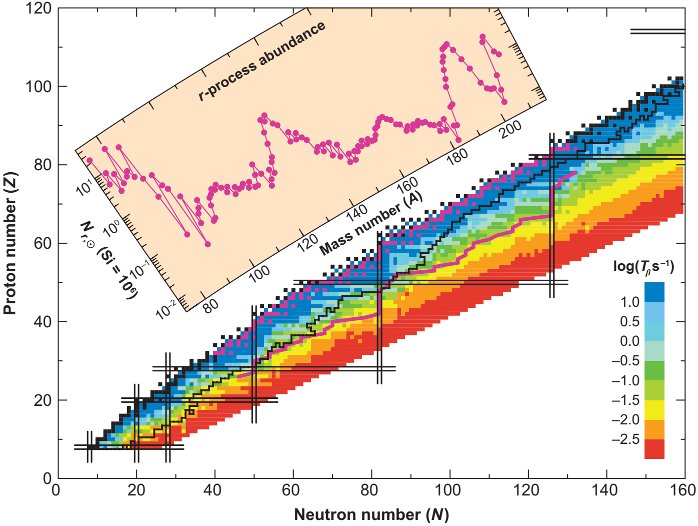
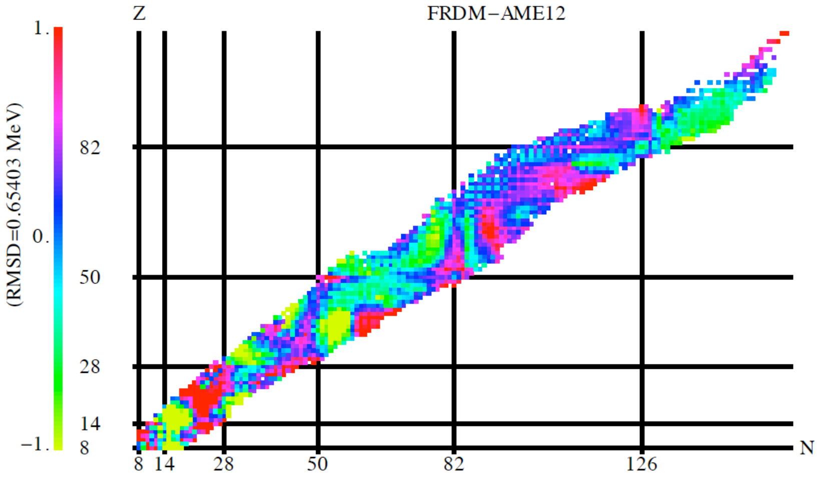


Figure from Peter Möller.

Global mass models vs experiment

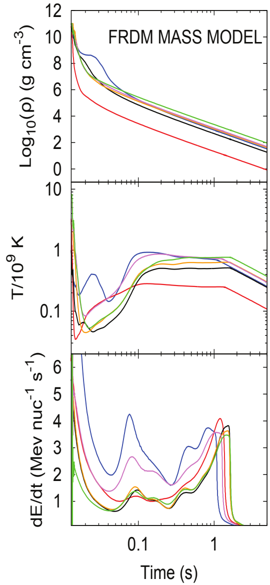


Similar behaviour for all mass models.
Problems in reproducing masses in transitional regions.

General features evolution in mergers

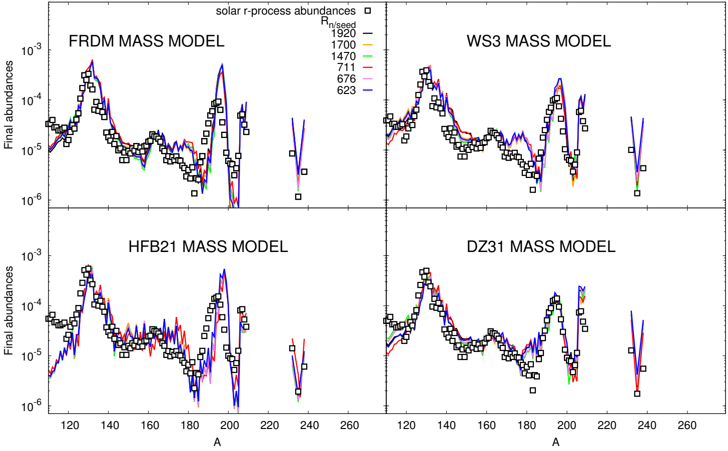
- r-process stars once electron fermi energy drops below $\sim$ 10 MeV to allow for beta-decays ($\rho \sim 10^{11}$ g cm^{-3}).
- Important role of nuclear energy production.
- Increases temperature to values that allow for an $(n,\gamma) \rightleftarrows (\gamma,n)$ equilibrium.
- r-process operates at moderate high entropies, $s \sim 50$–100 k/nuc.

Trajectories from simmulation A. Bauswein and H.-T. Janka.



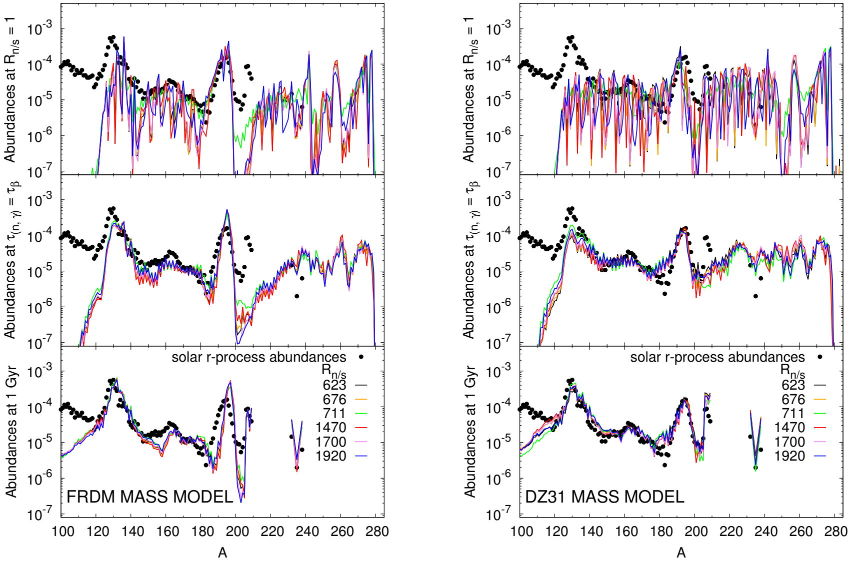
Final abundances different mass models

neutron captures computed consistently for each mass model.

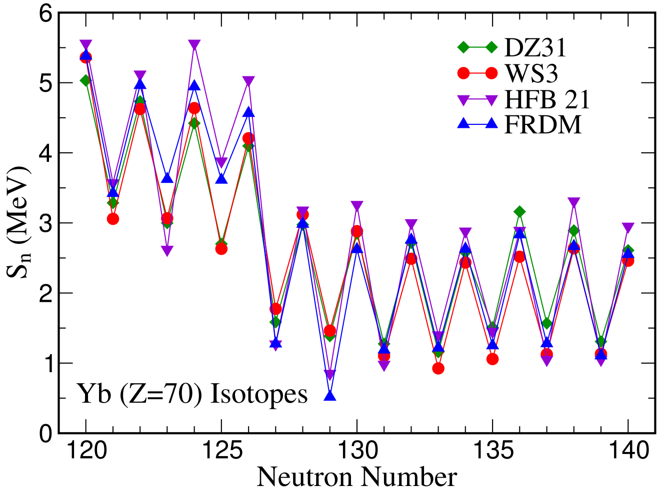


J. Mendoza-Temis, G. Martinez-Pinedo, K. Langanke, A. Bauswein, H.-Th. Janka, arXiv:1409.6135 [astro-ph.HE]

Temporal evolution (selected phases)



The role of $N \sim 130$



Both FRDM and HFB models predict a sudden drop in neutron separation energies approaching $N \sim 130$ for $Z \sim 70$.

Delayed outflows Black-Hole accretion disks

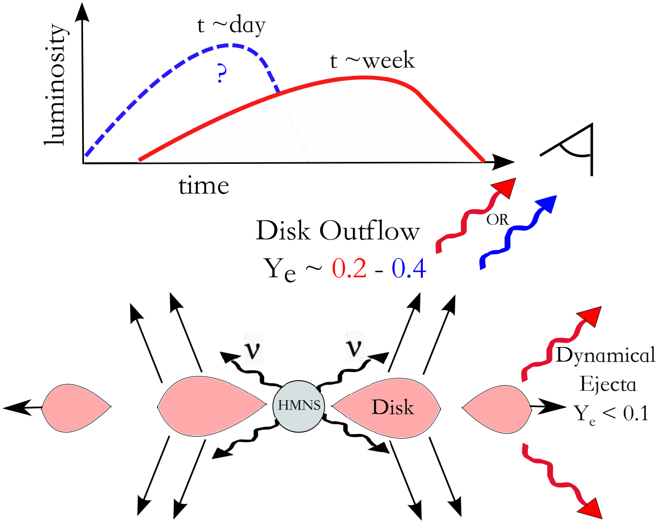
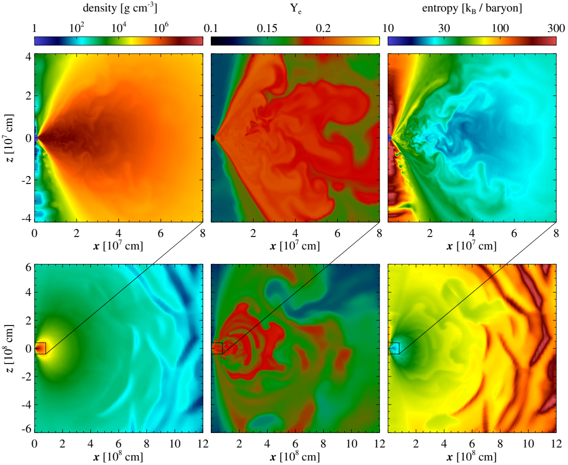


Figure from Metzger & Fernández, arXiv:1402.4803 [astro-ph.HE]

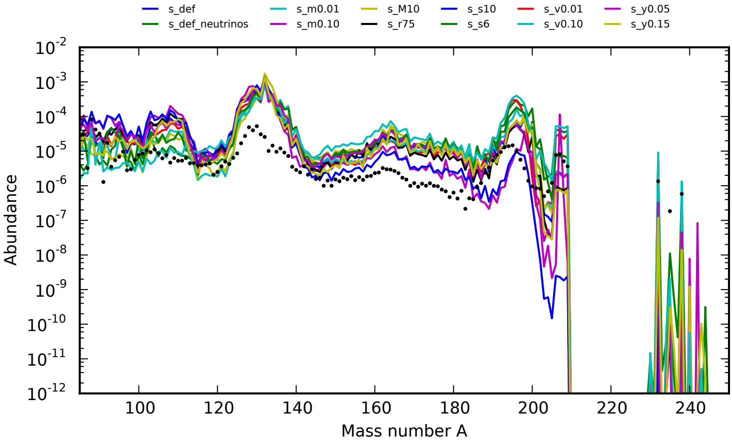
Delayed outflows Black-Hole accretion disks

R. Fernández and B. D. Metzger, MNRAS **435**, 502 (2013)



Long-lived hypermassive neutron star explored in:
Metzger & Fernández, arXiv:1402.4803 [astro-ph.HE]
Perego *et al.*, arXiv:1405.6730 [astro-ph.HE]

Nucleosynthesis in accretion disks outflows

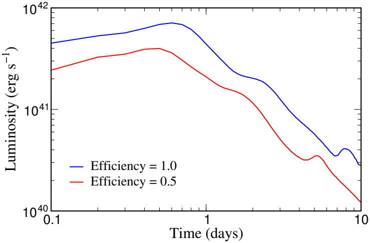


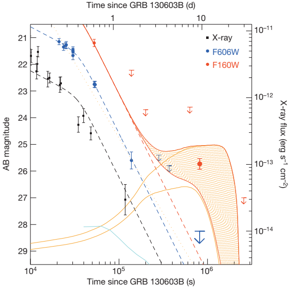
Fernández, Huther, Arcones, GMP, Metzger, in preparation.

Radioactive heating and light curve

- The r-process heating at late times goes like $t^{-1.3}$. Similar to nuclear waste decay in terrestrial reactors.
- Independent of the ejecta composition.
- Independent of the nuclear mass model.
- Typical luminosities 1000 times those of a Nova. Important contribution to photon opacities from Lanthanides (Kasen *et al*, 2013).
- Probably observed in GRB 130603B.

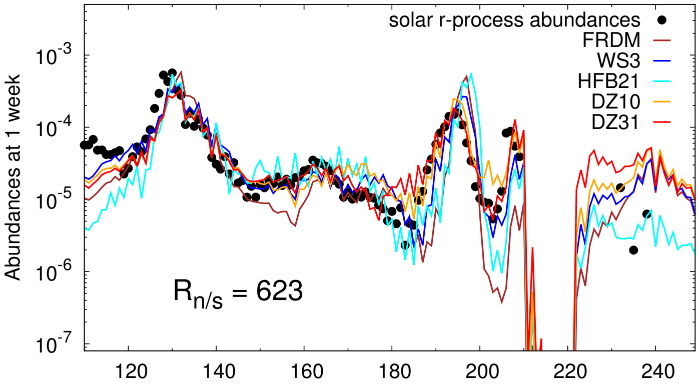
Metzger, GMP, Darbha, Quataert, Arcones *et al*, MNRAS **406**, 2650 (2010)





Tanvir et al, Nature **500**, 457 (2013)

What about the actinides?



Actinides can be an important opacity source at timescales of weeks.

Summary

- Neutrino-winds simulations based on an EoS that is consistent with constrains on the symmetry energy produce elements between Zn and Mo, including ^{92}Mo. No heavier elements are produced.
- The major opacity uncertainties relevant to nucleosynthesis are related to the interaction of $\bar{\nu}_e$ with matter.
- Neutron star mergers produce a robust r-process abundance pattern.
- Radioactive decay of r-process ejecta produces an electromagnetic transient. Observed in GRB 130603B
- The combination of dynamical and disk outflow ejecta can account for the whole of solar system r-process abundances.