Explosive nucleosynthesis of heavy elements

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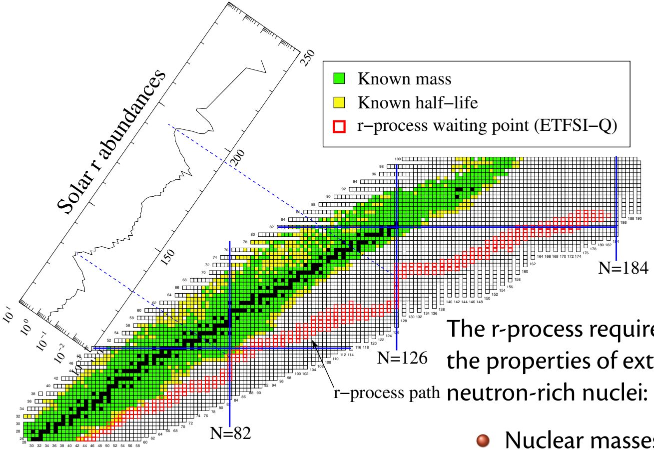
Outline

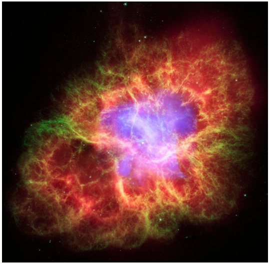
Making Gold in Nature: r-process nucleosynthesis



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

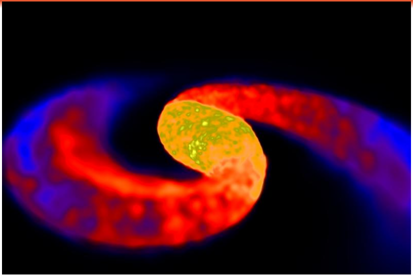
- Nuclear masses.
- Beta-decay half-lives.
- Neutron capture rates.
- Fission rates and yields.

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?

Neutrino-driven winds

Main processes:

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

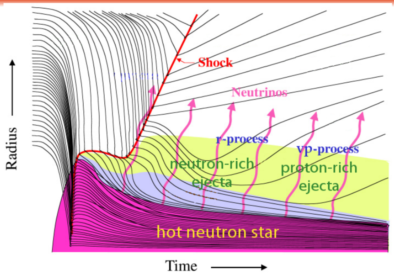
Neutrino interactions determine the proton to neutron ratio.

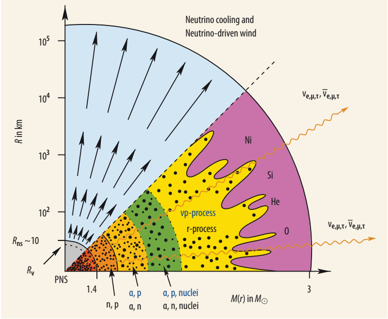
Neutron-rich ejecta:

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

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

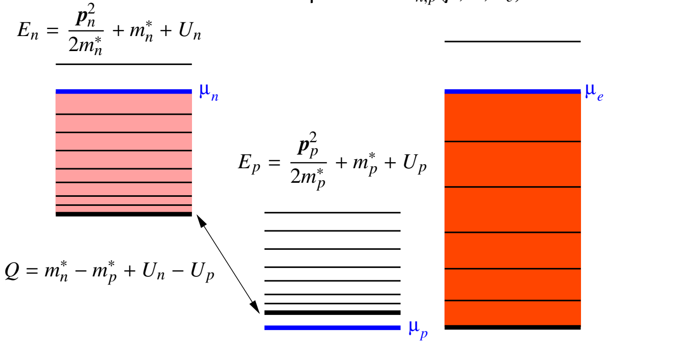
We need accurate knowledge of ν_e and $\bar{\nu}_e$ spectra





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

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

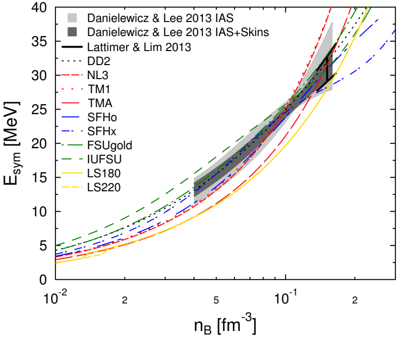
- $\bar{\nu}_e$ absorption affected by energy threshold (ΔU).

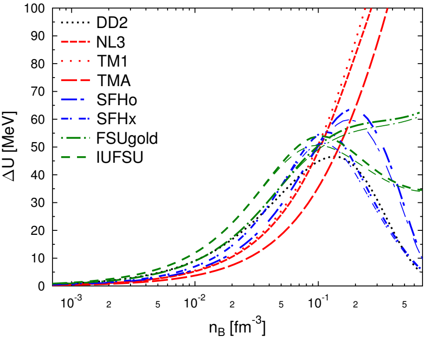
$$\chi(E_\nu) \propto (E_\nu - \Delta m^* - \Delta U)^2 \quad E_\nu > \Delta m^* + \Delta U$$

- 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)

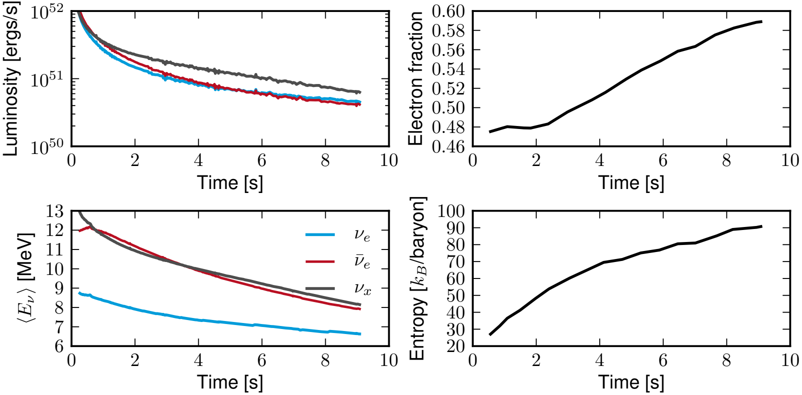




Figures from Matthias Hempel (Basel)

Impact on neutrino luminosities and Y_e evolution

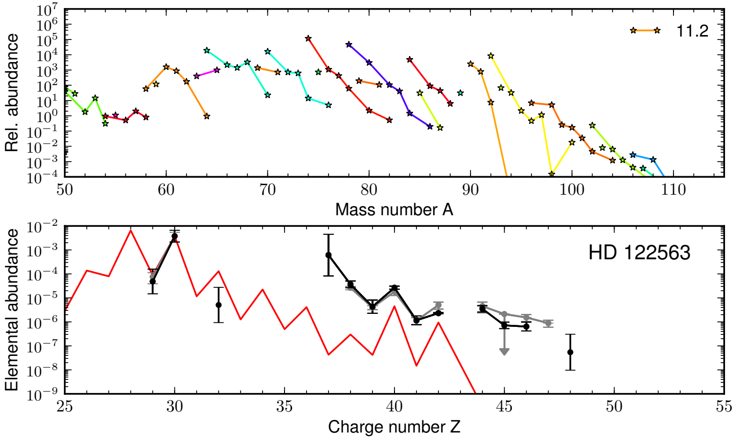
1D Boltzmann transport radiation simulations (artificially induced explosion) for a 11.2 $M_\odot$ progenitor based on the DD2 EoS (Stefan Typel and Matthias Hempel).



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

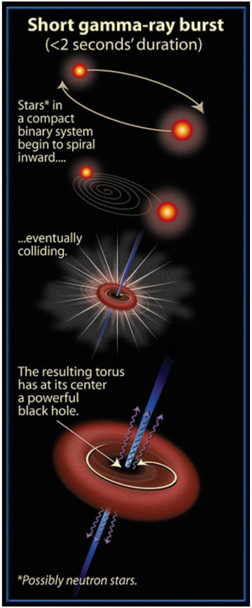
GMP, Fischer, Huther, J. Phys. G **41**, 044008 (2014).

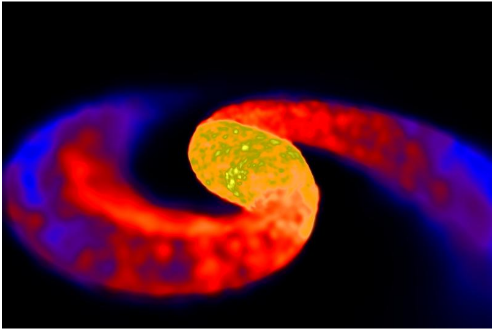
Nucleosynthesis



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



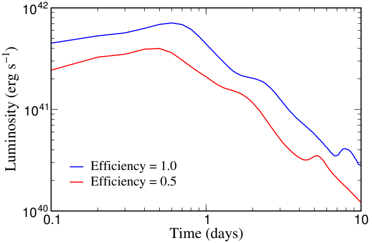


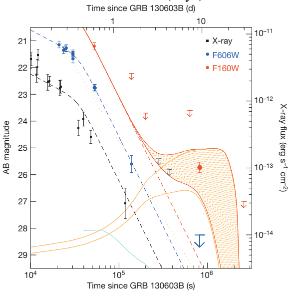
- Mergers are expected to eject around $0.01\ M_\odot$ of very neutron rich-material ($Y_e \sim 0.01$). A similar amount of less neutron-rich material ($Y_e \sim 0.1$–0.2) is expected from the accretion disk.
- They are also promising sources of gravitational waves.
- Observational signatures of the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

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.
- Light curve reaches peak brightness at times of 1 day. Typical luminosities 1000 times those of a Nova. Sensitive to photon opacities (Kasen *et al*, 2013)
- Probably observed in GRB 130603B

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

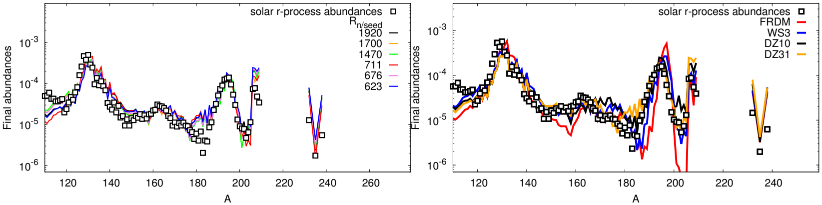




Tanvir et al, Nature **500**, 457 (2013)

Nucleosynthesis in dynamical ejecta

Joel Mendoza-Temis (PhD Thesis)



- Important role of fission yields and nuclear masses to reproduce solar abundance pattern.

Delayed outflows Black-Hole accretion disks

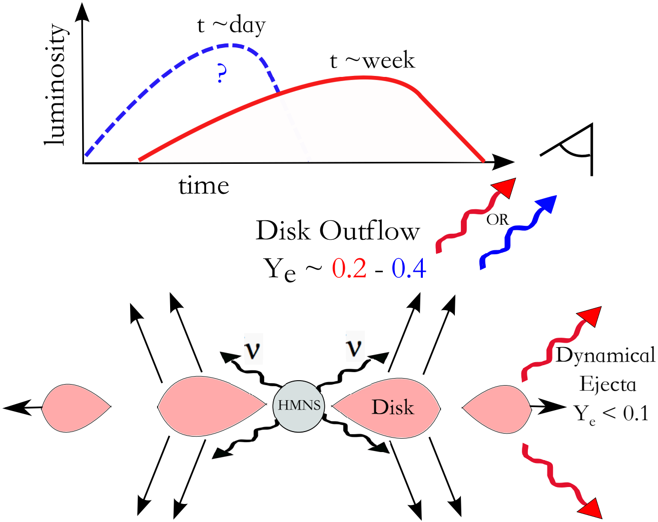
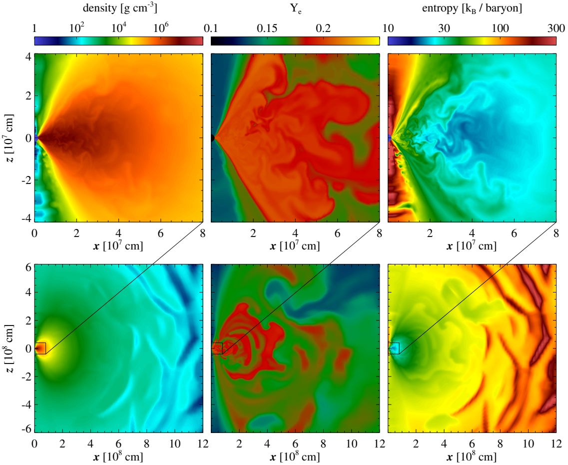


Figure from Metzger & Fernández, arXiv:1402.4803 [astro-ph.HE]

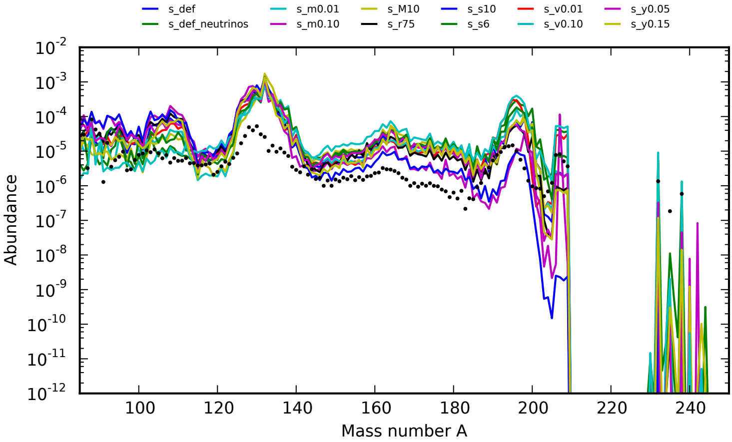
Delayed outflows Black-Hole accretion disks

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



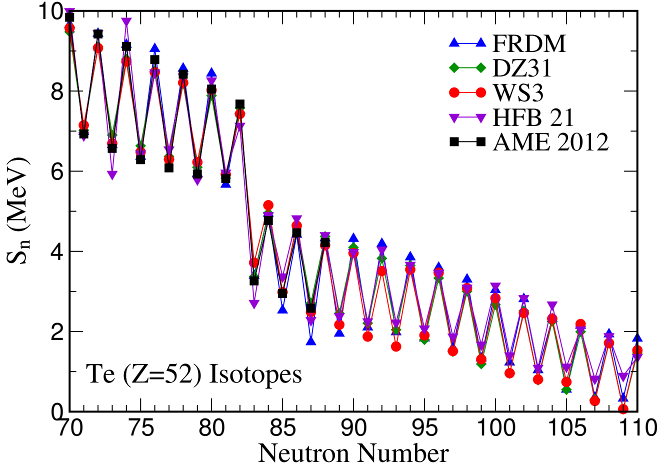
Long-lived hypermassive neutron star explored in:
Metzger & Fernández, arXiv:1402.4803 [astro-ph.HE]
Perego *et al.*, arXiv:1405.6730 [astro-ph.HE]

Nucleosynthesis in accretion disks outflows



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

Role $N \sim 90$ nuclei (Te isotopes)

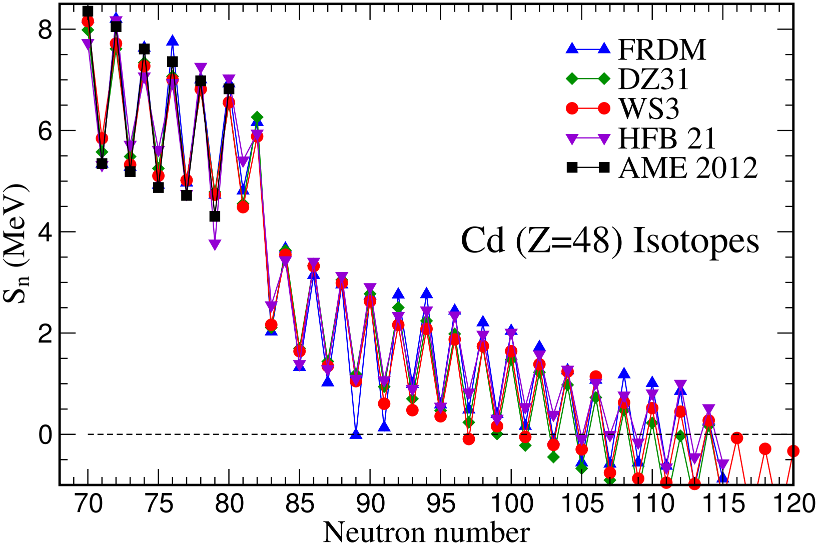


Experimental masses:

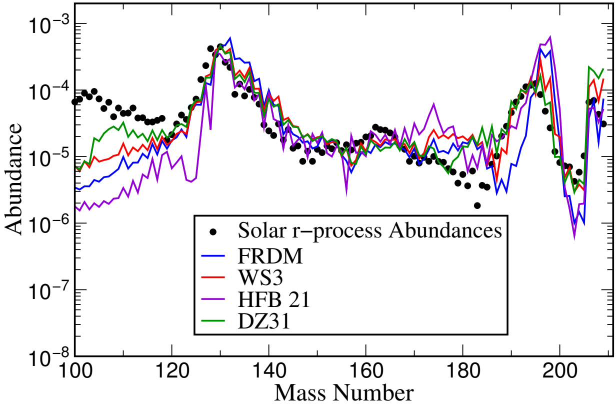
Hakala *et al*, PRL **109**, 032501 (2012) (JYFLTRAP)

Van Schelt, *et al*, PRC **85**, 045805 (2012) (Canadian penning trap)

Role $N \sim 90$ nuclei (Cd isotopes)



Impact r-process abundances (NS Mergers)

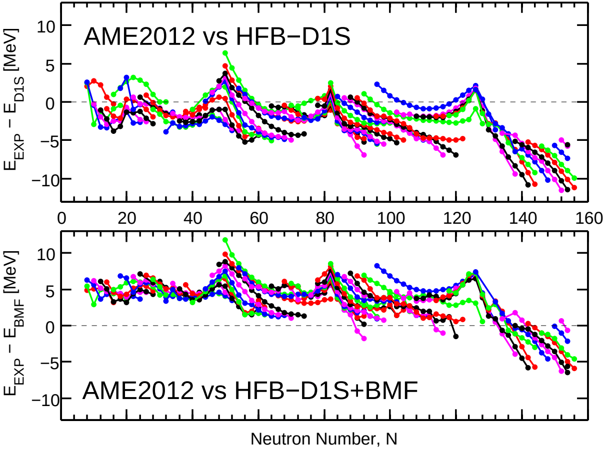


- Masses around $N = 90$ determine the mass flow from second to third r-process peaks.

Joel Mendoza-Temis (PhD)

Beyond mean field calculations of nuclear masses

First systematic study of nuclear masses including beyond mean field effects.

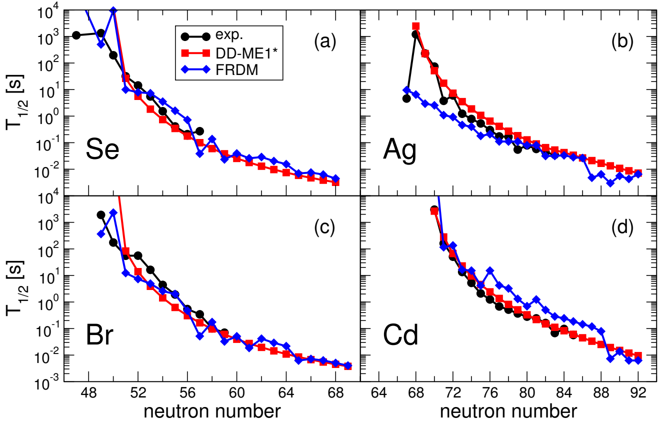


T. R. Rodríguez, A. Arzhanov, and GMP in preparation

Approaches to half-lives for r-process nuclei

- All r-process calculations are based on Möller *et al* half-lives
- Inconsistent treatment of first-forbidden transitions (based on Gross theory)
- Tendency to overestimate half-lives. Strong odd-even effects not present in data.
- There are local ($N = 50, 82, 126$) Shell-Model calculations that predict an important role of forbidden transitions [Zhi *et al.*, PRC **87**, 025803 (2013)]
- New Global calculations of beta-decay half-lives based on Covariant Density Functional Theory (Tomislav Marketin). Include consistently both Gamow-Teller and Forbidden transition.
- All nuclei treated as spherical, spherical QRPA.

Comparison for several isotopic chains



T. Marketin, GMP, in preparation

Summary

- Neutrino-winds simulations based on an EoS that is consistent with constrains on the symmetry energy produce elements between Zn and Mo, including $^{92}\mathrm{Mo}$. No heavier elements are produced.
- Neutron star mergers produce a robust abundance pattern. The combination of dynamical and disk outflow ejecta can account for the whole of solar system r-process abundances.
- The collectivity of nuclei with $Z \lesssim 50$ and $N \sim 90$ has a strong impact in nuclear masses. It regulates the flow of material from second to third peak and impacts the r-process abundances.
- A new set of global calculations of beta-decay half-lives for r-process nuclei that includes Gamow-Teller and first forbidden transitions is available.