Nuclear Reaction Networks

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RESEARCH FOR GRAND CHALLENGES

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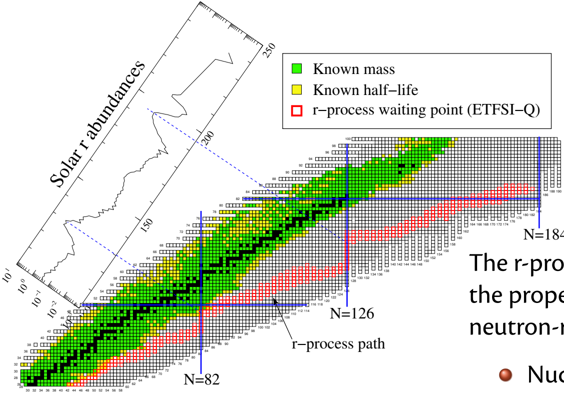
Lecture 3: Applications to the r process

R-process sites

- Any r-process site should be able to produce both the “seed” nuclei where neutrons are captured and the neutrons that drive the r-process. The main parameter describing the feasibility of a site to produce r-process nuclei is the neutron-to-seed ratio: n_n/n_{seed}.
- If the seed nuclei have mass number A_{seed} and we have n_n/n_{seed} neutrons per seed, the final mass number of the nuclei produced will be $A = A_{\text{seed}} + n_n/n_{\text{seed}}$.
- For example, taking $A_{\text{seed}} = 90$ we need $n_n/n_{\text{seed}} = 100$ if we want to produce the 3rd r-process peak ($A \sim 195$) and $n_n/n_{\text{seed}} = 150$ to produce U and Th.

Making Gold in Nature: r-process nucleosynthesis

Astrophysical environment must provide a large amount of free neutrons.
Depends on the neutron richness of the ejecta.



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

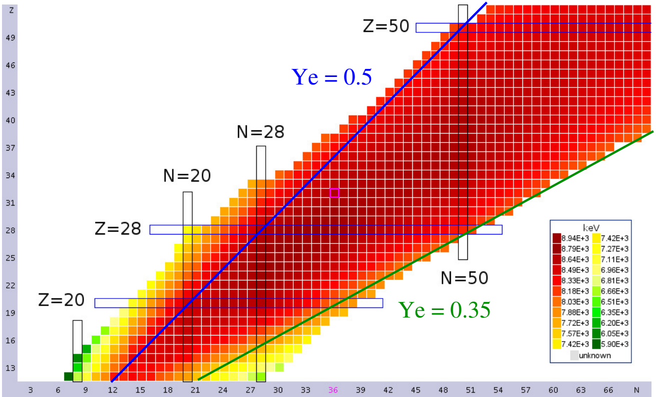
- Nuclear masses.
- Beta-decay half-lives.
- Neutron capture rates.
- Fission rates and yields.

R-process sites

In an astrophysical site there are only two possible ways to achieve large neutron-to-seeds:

1. Let us consider high temperature neutron-rich matter with high entropy that it is ejected at high velocities. As the material expands α particles will be formed. However, the build up of heavy nuclei by 3-body reactions becomes very unefficient by two reasons: 1) Too many photons per nucleon due to the high entropy, 2) Too litle time to produce heavy nuclei due to the fast expansion. It means that we will have an α-rich freeze out with a few heavy nuclei produced and many neutrons left ($Y_\alpha \approx Y_e/2$, $Y_n \approx 1 - 2Y_e$). The Big Bang is an extreme case of α-rich freeze-out. This is commonly denoted as “high entropy” r-process
2. Let us consider matter very high density matter with low entropies. Due to the high densities electrons have large fermi energies and will drive the composition very neutron rich. At some point the neutron drip line is reached and nuclei start to “drip” neutrons. This is the situation in the crust of neutron stars where densities are 10^{12-13} g cm^{-3} and $Y_e \lesssim 0.05$: $Y_n = 1 - \langle A \rangle Y_e / \langle Z \rangle$, $Y_h = Y_e / \langle Z \rangle$; $n_s = Y_n / Y_h = \langle A \rangle [\langle Z \rangle / (Y_e \langle A \rangle) - 1]$; $n_s \sim 500 - 2000$. This is commonly denoted as “low entropy” r-process.

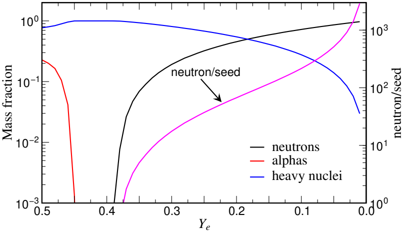
Dependence on Y_e

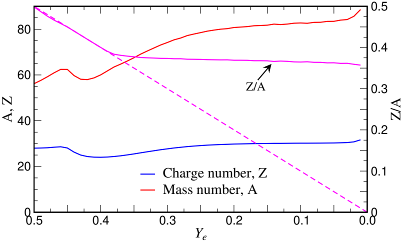


With reduced Y_e the peak of the nuclear abundance distribution moves from ^{56}Ni to heavier neutron rich nuclei. For low Y_e becomes energetically favourable to have free neutrons.

Abundances at 3 GK

Adiabatic expansions with $s = 15$





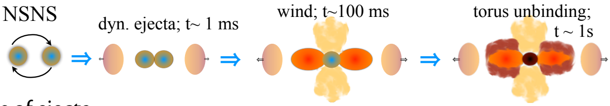
For neutron-rich moderate entropy ejecta ($s \sim 20$) ejecta we have:

$$n_s = A\left(\frac{Z}{A}\frac{1}{Y_e} - 1\right)$$

Calculation by Bowen Jiang

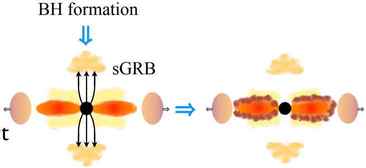
Merger channels and ejection mechanism

In mergers we deal with a variety of initial configurations (netron-star neutron-star vs neutron-star black-hole) with additional variations in the mass-ratio.

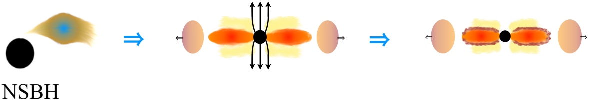


Two sources of ejecta:

- Dynamical (early times)
- Accretion disk (long term evolution)



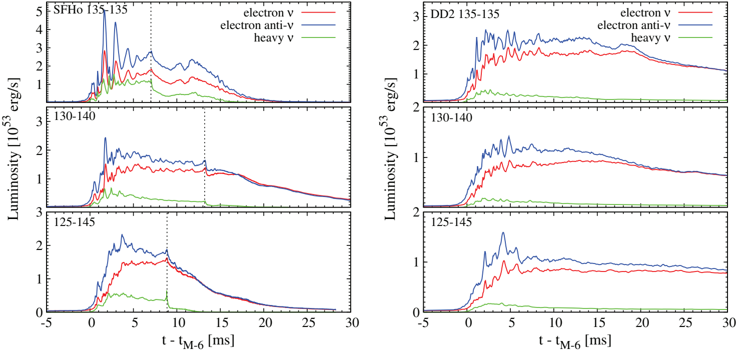
Their properties depend on the impact of neutrinos



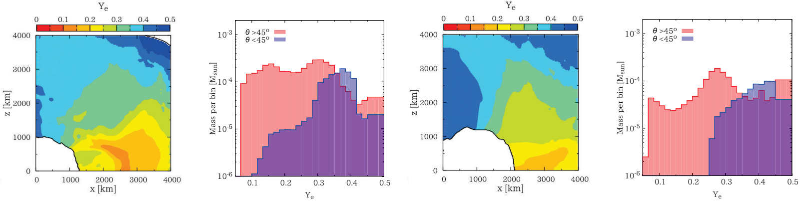
Rosswog *et al*, Class. Quantum Gravity **34**, 104001 (2017)

Impact of neutrinos on NS-NS mergers

Sekiguchi+, PRD **93**, 124046 (2016)



Shibata+, PRD **96**, 123012 (2017)



Why is Y_e modified?

Y_e is mainly determined by the competition between

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

The evolution of Y_e is given by:

$$\frac{dY_e}{dt} = \lambda_{\nu_e n} Y_n - \lambda_{\bar{\nu}_e p} Y_p = \lambda_{\nu_e n} - (\lambda_{\nu_e n} + \lambda_{\bar{\nu}_e p}) Y_e,$$

using $Y_e = Y_p$ and $Y_n = 1 - Y_n$. If matter is exposed long time enough to neutrino fluxes it will reach an equilibrium given by:

$$Y_e^{\mathrm{eq}} = \frac{\lambda_{\nu_e n}}{\lambda_{\nu_e n} + \lambda_{\bar{\nu}_e p}}.$$

We need to estimate the neutrino absorption rates.

neutrino absorption rates on nucleons

If we assume that the produced electron (positron) is extremelly relativistic ($E_e = p_e c$) the cross section for (anti)neutrino absorption is:

$$\sigma(E_\nu) = \sigma_0 (E_\nu \pm \Delta)^2$$

plus sign for neutrinos and minus sign for antineutrinos, $\Delta = m_n c^2 - m_p c^2 = 1.2933$ MeV, and

$$\sigma_0 = \frac{(1 + 3g_A^2) G_F^2 V_{ud}^2}{\pi \hbar^4 c^4} = 9.33(4) \times 10^{-44}\ \mathrm{cm}^2\ \mathrm{MeV}^{-2}$$

For the absorption rate we need to integrate over the neutrino spectrum and multiply by the neutrino flux ($L_\nu/(4\pi r^2 \langle E_\nu \rangle)$) obtaining:

$$\lambda_{\nu_e n} = \frac{L_{\nu_e}}{4\pi r^2} \sigma_0 \left(\varepsilon_{\nu_e} + 2\Delta + \frac{\Delta^2}{\langle E_{\nu_e} \rangle} \right)$$

$$\lambda_{\bar{\nu}_e p} = \frac{L_{\bar{\nu}_e}}{4\pi r^2} \sigma_0 \left(\varepsilon_{\bar{\nu}_e} - 2\Delta + \frac{\Delta^2}{\langle E_{\bar{\nu}_e} \rangle} \right)$$

with $\varepsilon_\nu = \langle E_\nu^2 \rangle / \langle E_\nu \rangle$.

Equilibrium Y_e

The equilibrium Y_e^{eq} can be expressed as:

$$Y_e^{\mathrm{eq}} = \left[1 + \frac{L_{\bar{\nu}_e}}{L_{\nu_e}} \frac{\varepsilon_{\bar{\nu}_e} - 2\Delta + \Delta^2/\langle E_{\bar{\nu}_e}\rangle}{\varepsilon_{\nu_e} + 2\Delta + \Delta^2/\langle E_{\nu_e}\rangle}\right]^{-1}$$

In order to achieve $Y_e < 0.5$ we need:

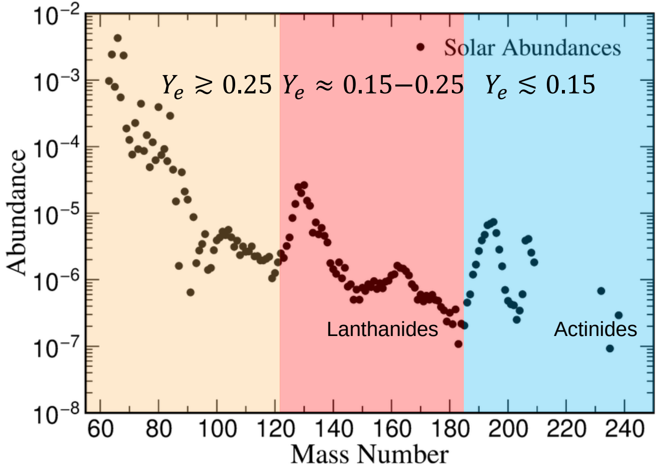
$$Y_e^{\mathrm{eq}} = \frac{\lambda_{\nu_e n}}{\lambda_{\nu_e n} + \lambda_{\bar{\nu}_e p}} < 1/2 \Rightarrow \lambda_{\bar{\nu}_e p} > \lambda_{\nu_e n}$$

This can be translated to a condition on the average energies:

$$\varepsilon_{\bar{\nu}_e} - \varepsilon_{\nu_e} > 4\Delta - \left[\frac{L_{\bar{\nu}_e}}{L_{\nu_e}} - 1\right][\varepsilon_{\bar{\nu}_e} - 2\Delta]$$

Dependence nucleosynthesis on Y_e

Nucleosynthesis depends on neutron richness of ejecta

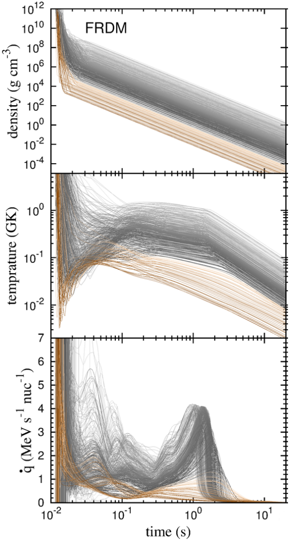


The relevant nuclear physics depends on the particular conditions.

Nucleosynthesis low Y_e ejecta

- r-process stars once electron fermi energy drops below ~ 10 MeV to allow for beta-decays ($\rho \sim 10^{11}$ g cm^{-3}).
- Important role of nuclear energy production (mainly beta decay).
- Energy production increases temperature to values that allow for an $(n, \gamma) \rightleftarrows (\gamma, n)$ equilibrium for most of the trajectories.
- Systematic uncertainties due to variations of astrophysical conditions and nuclear input

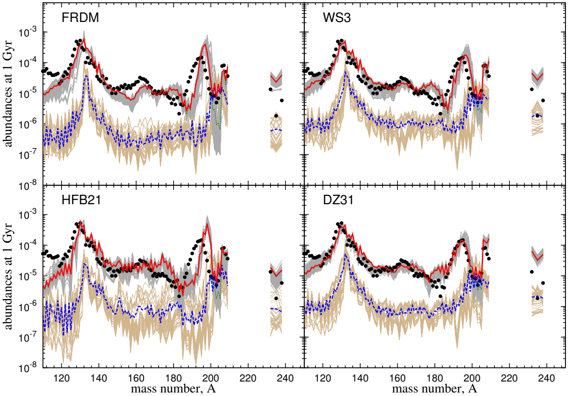
528 trajectories



Mendoza-Temis, Wu, Langanke, GMP, Bauswein, Janka, PRC **92**, 055805 (2015)

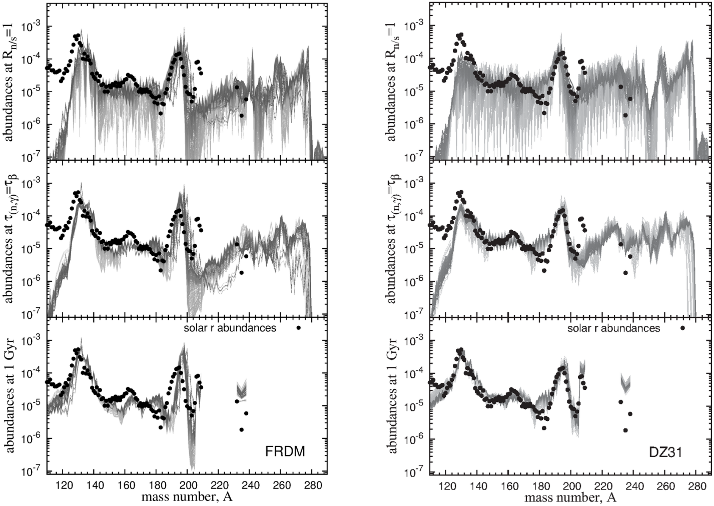
Final abundances different mass models

Mendoza-Temis, Wu, Langanke, GMP, Bauswein, Janka, PRC **92**, 055805 (2015)



- Robustness astrophysical conditions, strong sensitivity to nuclear physics
- Second peak ($A \sim 130$) sensitive to fission yields.
- Third peak ($A \sim 195$) sensitive to masses (neutron captures) and beta-decay half-lives.

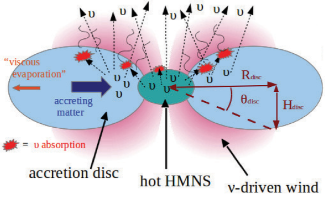
Temporal evolution (selected phases)



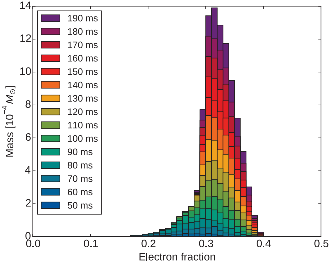
Fission is fundamental to determine the final r-process abundances.

Nucleosynthesis before BH formation

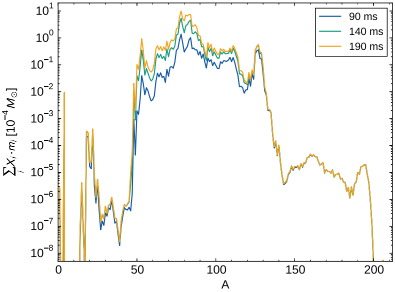
An Hypermassive neutron star produces large neutrino fluxes that drive the composition to moderate neutron rich ejecta.



Perego, *et al*, MNRAS 443, 3134 (2014)



Martin, *et al*, ApJ 813, 2 (2015)

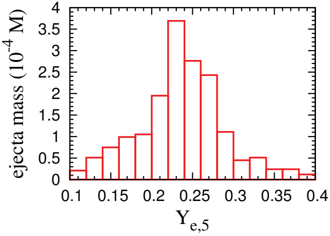


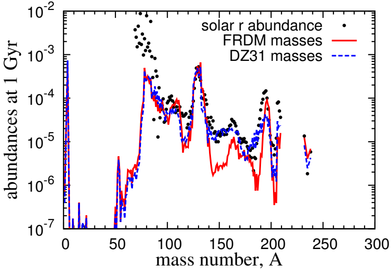
Only nuclei with $A < 120$ are produced (no lanthanides, blue kilonova).

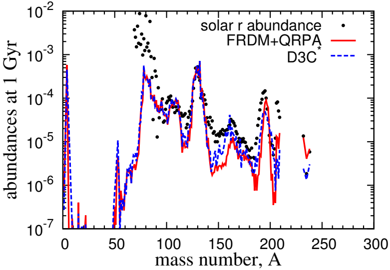
See also Lippuner et al, MNRAS **472**, 904 (2017)

Nucleosynthesis after BH formation

- Accretion disk around BH ejects relatively neutron-rich matter [Fernández, Metzger, MNRAS 435, 502 (2013)]
- Produces all r-process nuclides (Lanthanide/Actinide rich ejecta) [Wu *et al*, MNRAS 463, 2323 (2016)]



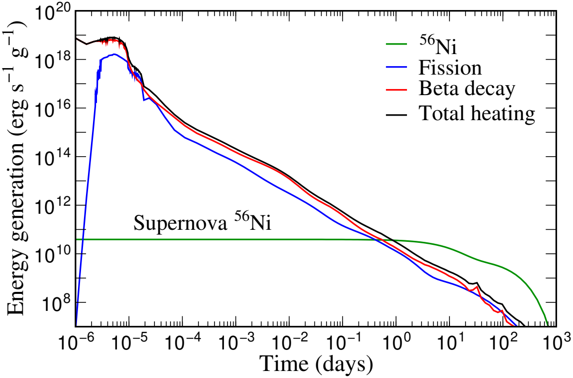




See also Just et al, MNRAS 448, 541 (2015), Siegel and Metzger PRL 119, 231102 (2017)

Energy production from r-process ejecta

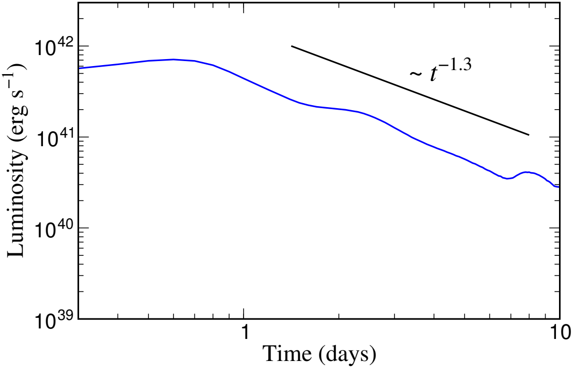
The decay of r process products produces energy following a power law $\varepsilon \sim t^{-1.3}$. Many nuclei decaying at the same time heating up the ejecta



We expect an electromagnetic transient with properties depending on:

- Energy production rate
- Efficiency energy is absorbed by gas (thermalization efficiency)
- Opacity gas (depends on composition, presence of lanthanides/actinides)

Kilonova: Electromagnetic signature of the r process



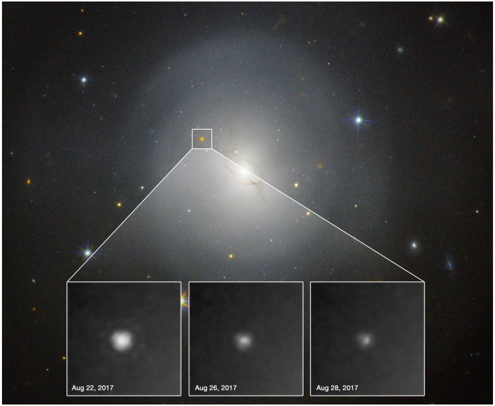
Luminosity equivalent to 1000 novas (kilonova) in timescales of days.

Depends on amount of ejected material, velocity and composition (opacity)

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

AT 2017 gfo: electromagnetic signature from r process

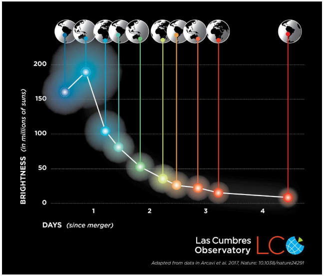
In-situ signature of r process nucleosynthesis

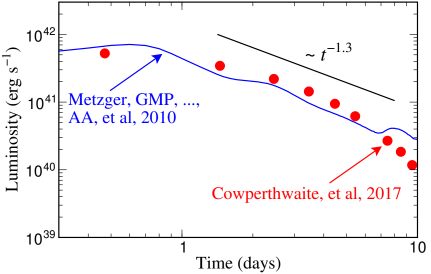


NASA and ESA. N. Tanvir (U. Leicester), A. Levan (U. Warwick), and A. Fruchter and O. Fox (STScI)

- Novel fastly evolving transitent
- Signature of statistical decay of fresly synthesized r process nuclei

AT 2017 gfo: interpretation

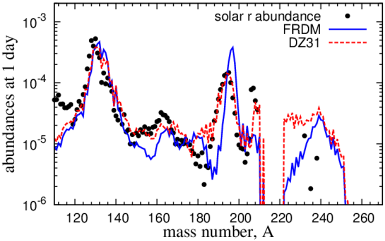


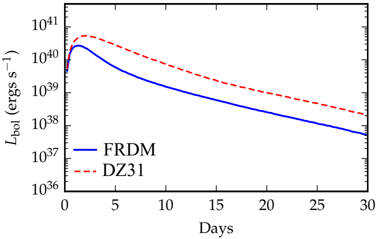


- Time evolution determined by the radioactive decay of r-process nuclei
- Two components:
  - blue dominated by light elements ($Z < 50$)
  - Red due to presence of Lanthanides ($Z = 57$–71) and/or Actinides ($Z = 89$–103)
- Likely source of heavy elements including Gold, Platinum and Uranium

Nuclear physics impact on light curve

Provided sufficiently neutron rich matter is ejected $Y_e \lesssim 0.15$ (merger neutron star black hole) a robust r process takes place





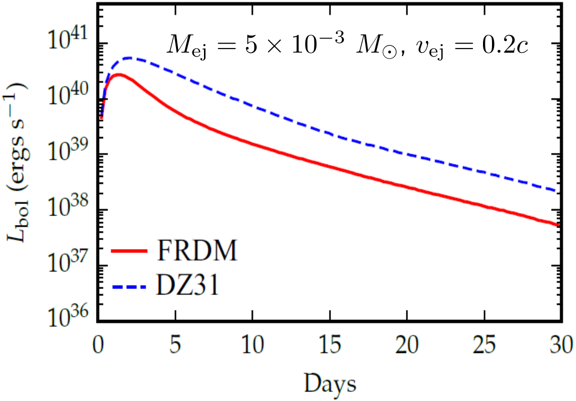
Luminosity is sensitive to abundances of long-lived actinides that release energy by alpha-decay.

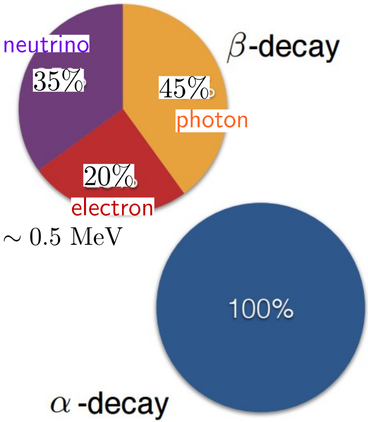
Mendoza-Temis, Wu, Langanke, GMP, Bauswein, Janka, PRC **92**, 055805 (2015)
Barnes, Kasen, Wu, GMP, ApJ **829**, 110 (2016); Rosswog et al, CQG **34**, 104001 (2017)

Nuclear physics inputs and the kilonova heating rate

- α & β particles thermalize in a similar way while γ-ray thermalization quickly become inefficient

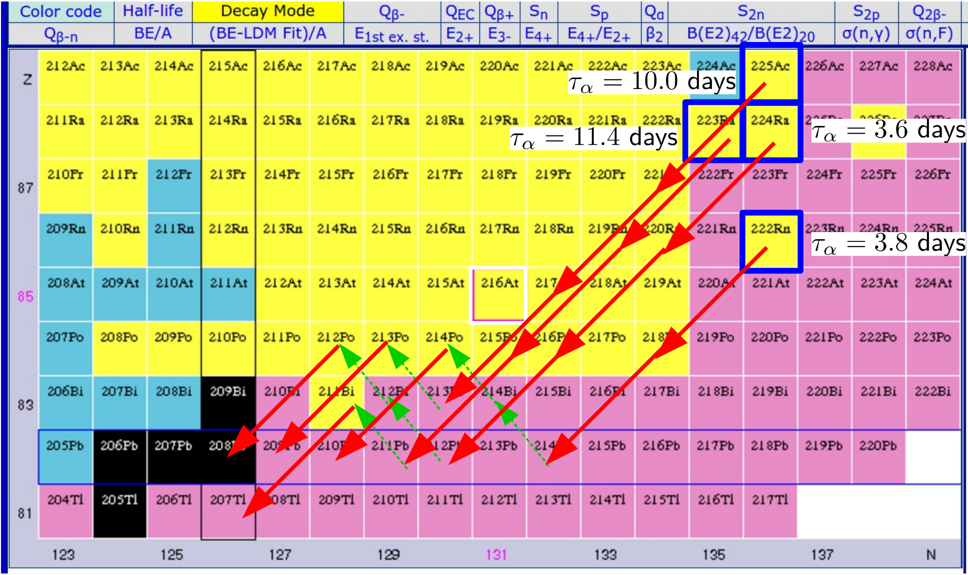
[Barnes, Kasen, MRW, Martinez-Pinedo, ApJ 829 (2016) 110]





Produces substantially larger energy than beta-decay for similar half-live. Followed by a chain of several alpha decays

Relevant α-decays



Open questions

- Kilonova observations have already been used to constrain the dynamics and morphology of the ejecta.
- So far we have indirect evidence of the r process production. Can we find evidence of the production of particular elements?
- Can we at least constrain the nucleosynthesis relevant properties of the ejecta, e.g. Y_e?
- What are the astrophysical and nuclear physics conditions relevant for the production of Lanthanides and Actinides?
- ...

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