Nuclear physics impact on kilonova light curves

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

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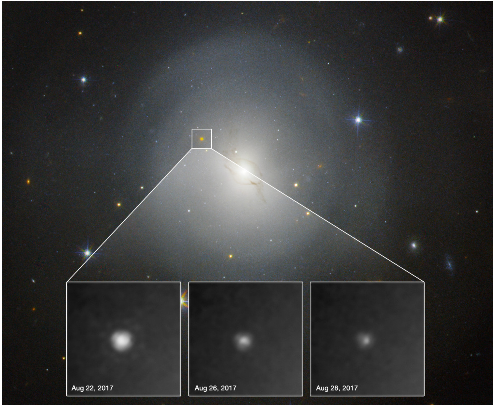
AT 2017 gfo: electromagnetic signature from r process

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

Kilonova: Electromagnetic signature of the r process

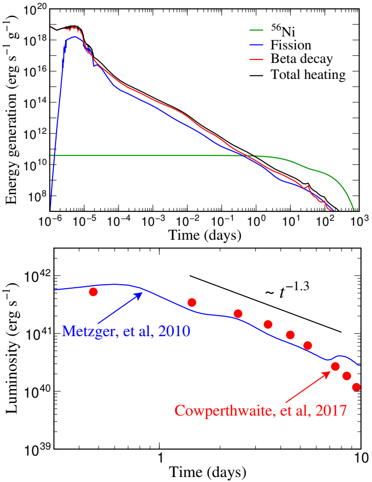
Large amount of ejecta can produce an electromagnetic transient [Li & Paczyński 1998]

Signature of r process nucleosynthesis [Metzger et al 2010]:

- Energy from radioactive decay of nuclei ($\dot{\varepsilon} \sim t^{-1.3}$)
- Thermalization of decay products [Barnes et al 2016]

Sensitive to the atomic opacity [Barnes & Kasen, 2013, Tanaka & Hotokezaka 2013]

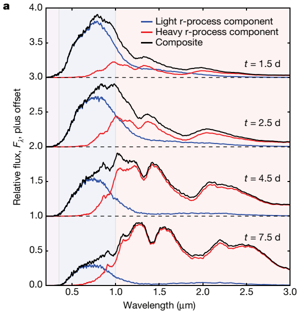
- Lanthanides/Actinides poor: Blue with peak L at $\sim$ days
- Lanthanides/Actinides rich: Red with peak L at $\sim$ weak



Metzger, *et al*, MNRAS **406**, 2650 (2010)

Two components model

Kasen et al, Nature 551, 80 (2017)

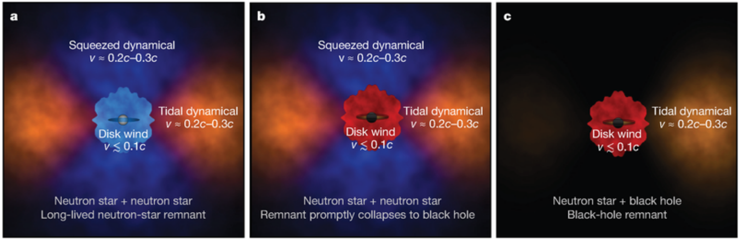


- Blue component from polar ejecta subject to strong neutrino fluxes (light r process)

$$M = 0.025\,\mathrm{M}_\odot, v = 0.3c, X_{\mathrm{lan}} = 10^{-4}$$

- Red component disk ejecta after NS collapse to a black hole (light and heavy r process)

$$M = 0.04\,\mathrm{M}_\odot, v = 0.15c, X_{\mathrm{lan}} = 10^{-1.5}$$

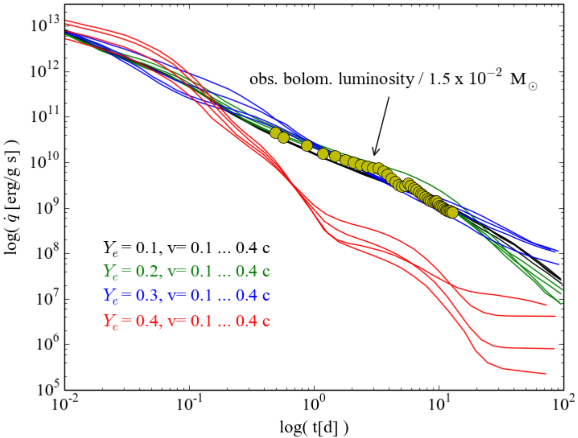


What can we learn from kilonova observations?

- 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?

Constraining Y_e of the ejecta

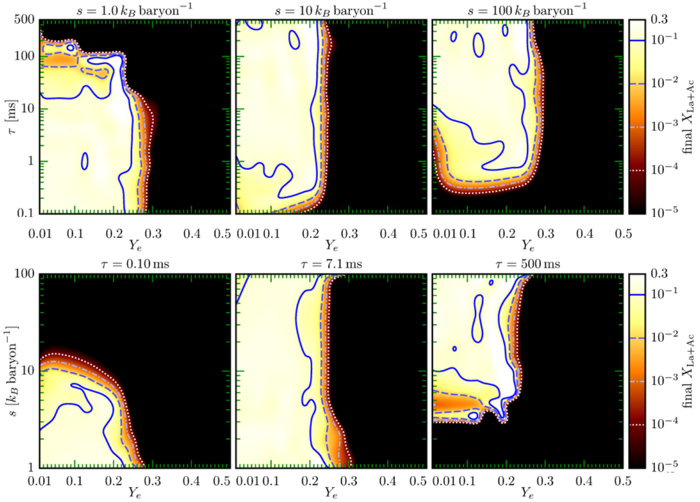
Rosswog et al, arXiv:1710.05445 [astro-ph.HE]



- Rosswog et al argue that lightcurve observations constrain $Y_e \lesssim 0.3$.
- Within current uncertainties higher Y_e components are possible but they will affect the lightcurve at early times.

Lanthanide and Actinide production

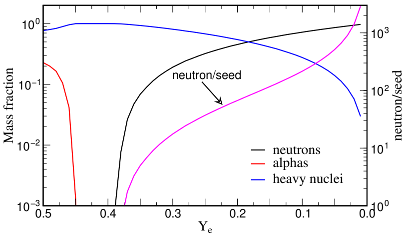
Lippuner & Roberts have shown that Lanthanides are produced for $Y_e \lesssim 0.25$ for a broad range of astrophysical conditions

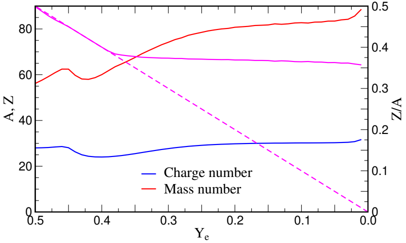


Abundances at 3 GK

The neutron-to-seed, n_s is the main parameter determining the production of heavy elements.

$$A_f = A_i + n_s$$





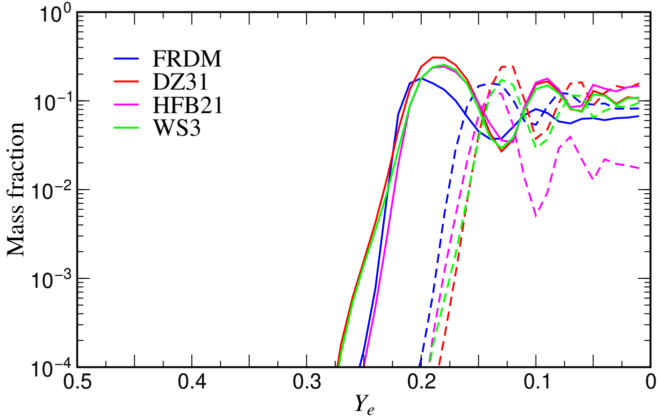
For neutron-rich moderate entropy ejecta ($s \sim 20$) ejecta we have:

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

Calculation by Bowen Jiang

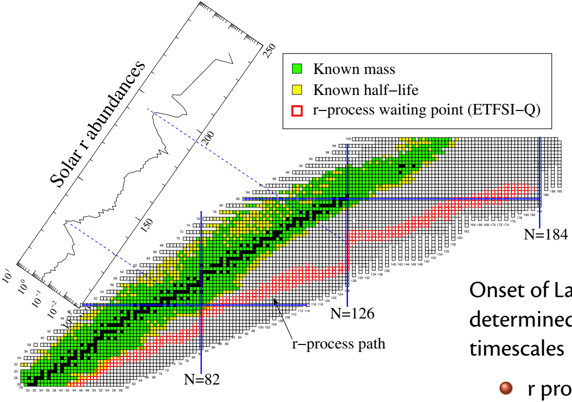
Sensitivity to nuclear masses

Despite of smooth variation with Y_e of n_s and A_i there is a sudden onset of Lanthanide and Actinide production independent of the mass model.



Lanthanide and Actinide mass fractions at 1 day.

r process nucleosynthesis



Onset of Lanthanide production is determined by competition of two timescales

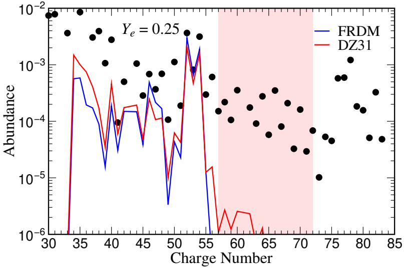
- r process duration: time necessary for using all neutrons
- beta-decay half-lives along the path up to $N = 82$: time required to produce Lanthanides.

Similar phenomena occurs at $N = 126$ for Actinides.

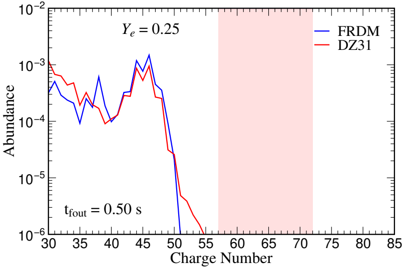
Long beta-decay half-lives around $N = 82$ determine the onset of Lanthanide production.

Evolution elemental abundances

Final abundances



Freeze-out ($n_s = 1$) abundaces



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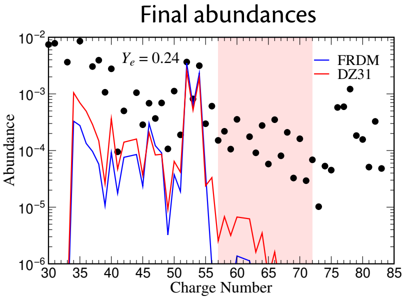

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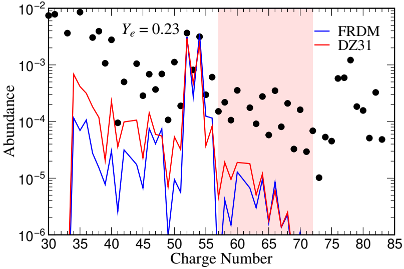

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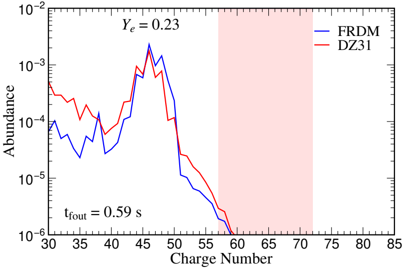

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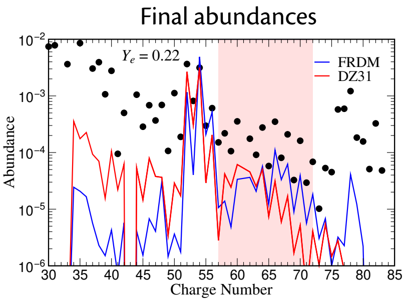

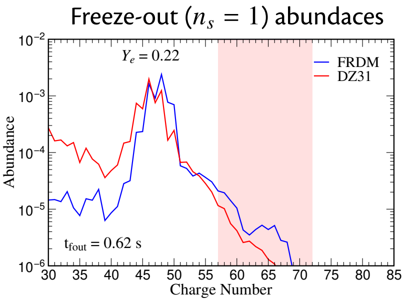

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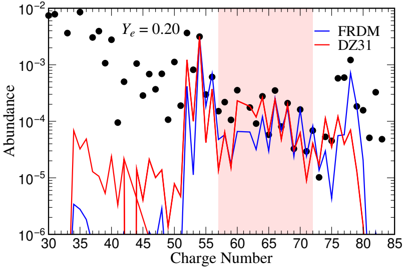

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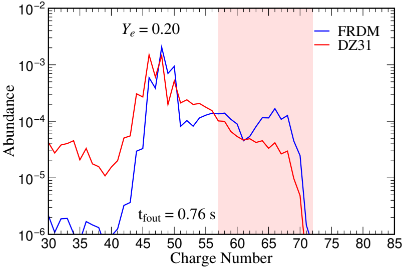
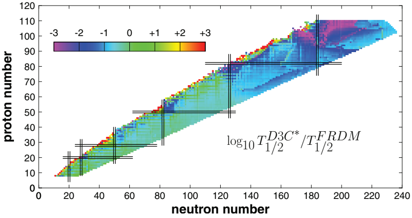
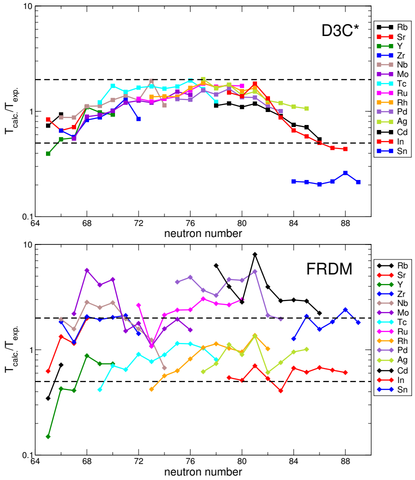


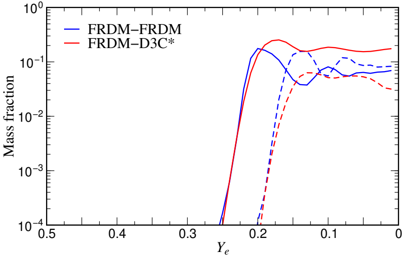
Beta-decay half-lives

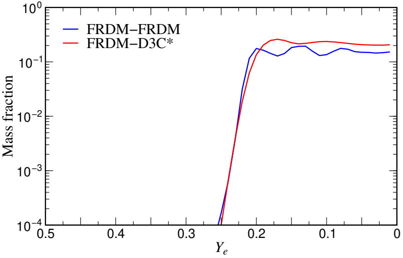
- Many of the relevant beta-decay half-lives have been recently measured at RIKEN (Lorusso *et al*, 2015)
- Theoretical advances allow for fully microscopic calculations (Marketin et al, 2016) of beta-decay half-lives predicting shorter half-lives than those traditionally used (Möller et al, 2003)





Impact of beta-decay half-lives





New half-lives increase Lanthanides and reduce Actinides. There is a net increase in the amount of Lanthanides+Actinides.

Summary

- Onset of Lanthanide production determined by a competition between r-process duration and beta-decays timescale along the path around $N = 82$.
- Identification of key nuclei is in progress.
- Similar effects expected for $N = 126$ regulating the production of Actinides.