Nuclear robustness of the r process in neutron-star mergers

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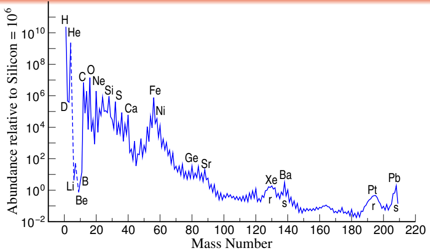
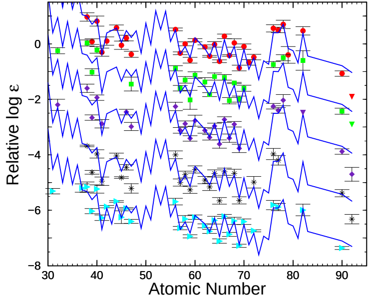
Observational signatures

- Elements heavier than iron produced by neutron capture processes: s and r process.
- r process requires an environment with large neutron to seed ratios.



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



- Stars rich in heavy r-process elements ($Z > 50$) and poor in iron (r-II stars, $[\mathrm{Eu}/\mathrm{Fe}] > 1.0$).
- Robust abundance patter for $Z > 50$, consistent with solar r-process abundance.
- Possible Astrophysical Scenario: Neutron star mergers.

Core-collapse supernova: neutrino driven winds

Neutrino interactions determine Y_e

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

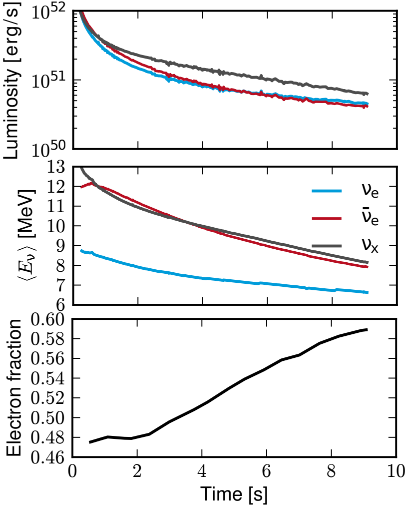
Neutron-rich ejecta:

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

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

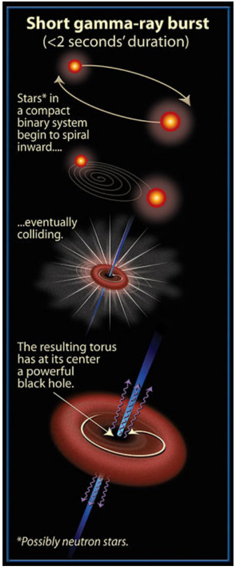
Energy difference related to symmetry energy (GMP+ 2012, Roberts+ 2012)

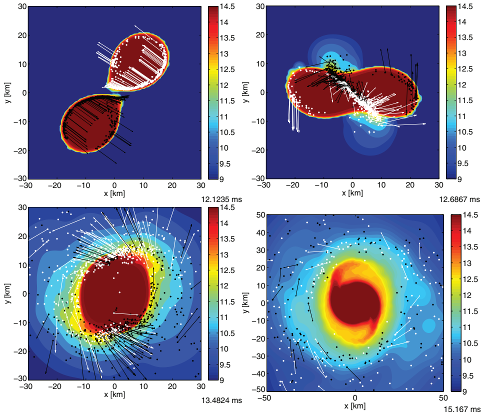
1D Boltzmann transport simulation (DD2 EoS)



no strong r process allowed (GMP+ 2013)

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

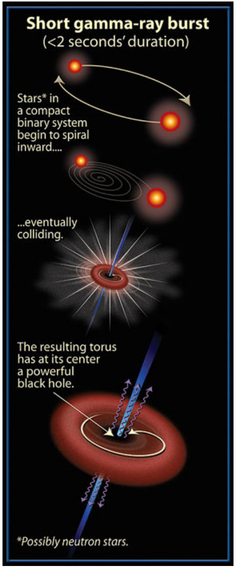


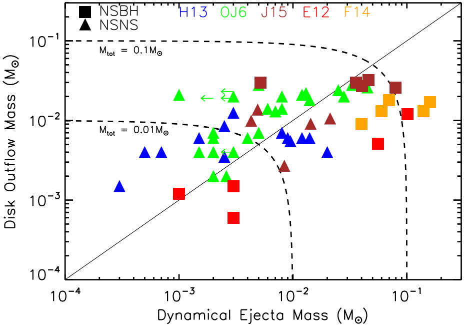


Basuswein, Goriely, Janka, ApJ 773, 78 (2013)

- Mergers are expected to eject dynamically around 0.001-0.01 $M_\odot$ of neutron rich-material ($Y_e \sim 0.01$). Impact of weak interactions is not yet fully clear.

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





Wu, Fernández, GMP, Metzger, arXiv:1607.05290

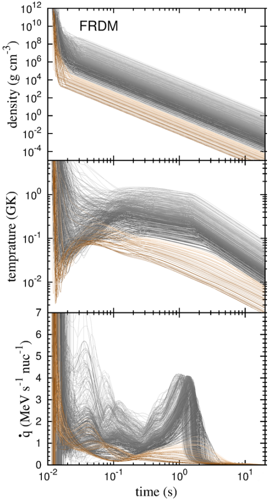
- A similar amount of material less neutron rich $Y_e \gtrsim 0.2$ is expected to be ejected from the disk. Conditions and ejection mechanism depend on central object (neutron star or black hole).
- Both dynamical and disk ejecta may contribute to radioactive electromagnetic transient (kilonova).

r process in dynamical ejecta

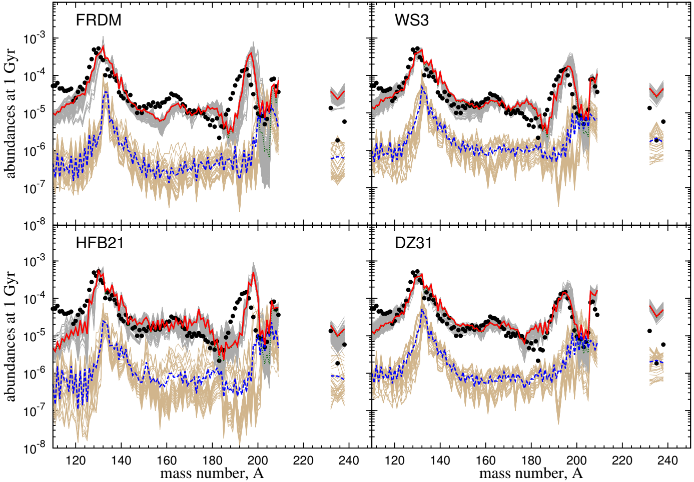
- r-process stars once electron fermi energy drops below ~ 10 MeV to allow for beta-decays ($\rho \sim 10^{11}$ g cm^{-3}).
- Important role of nuclear energy production (mainly beta decay).
- Energy production increases temperature to values that allow for an $(n,\gamma) \rightleftarrows (\gamma,n)$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

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

528 trajectories

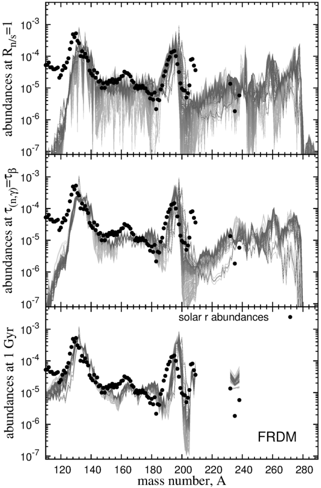


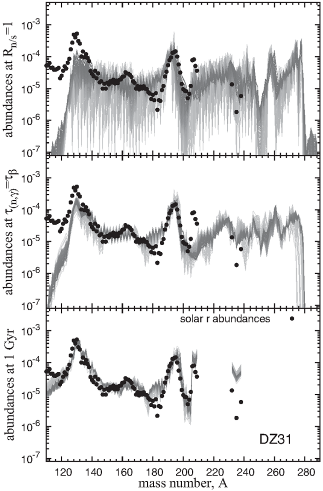
Final abundances different mass models



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

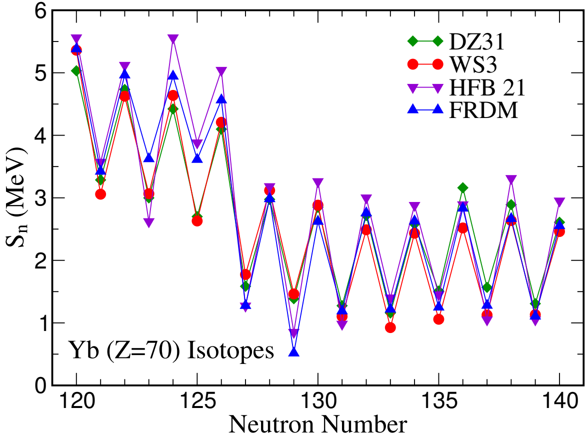
Temporal evolution (selected phases)





Fission (rates and yields) is fundamental to determine the final r-process abundances.

The role of $N \sim 130$

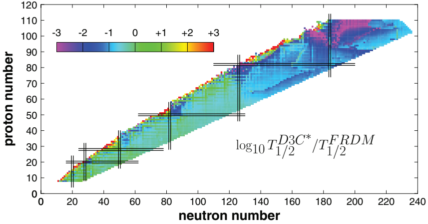


Both FRDM and HFB models predict a sudden drop in neutron separation energies approaching $N \sim 130$ for $Z \sim 70$ (shape coexistence region).

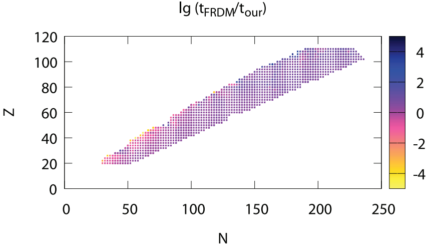
Global beta-decay calculations

- Beta-decay rates determine the speed of matter flow from light to heavy nuclei.
- r-process path determined by neutron separation energies
- nuclei with largest impact are those with larger instantaneous half-lives.
- Despite tremendous progress at RIB facilities (RIBF at RIKEN) most of the half-lives are based on theoretical calculations.
- Two microscopic calculations (GT+FF) have become available:
  - Covariant density functional theory + QRPA (Marketin+ 2016)
  - Skyrme finite-amplitude method (Mustonen & Engel 2016)

Marketin, Huther, GMP, PRC **93**, 025805 (2016)

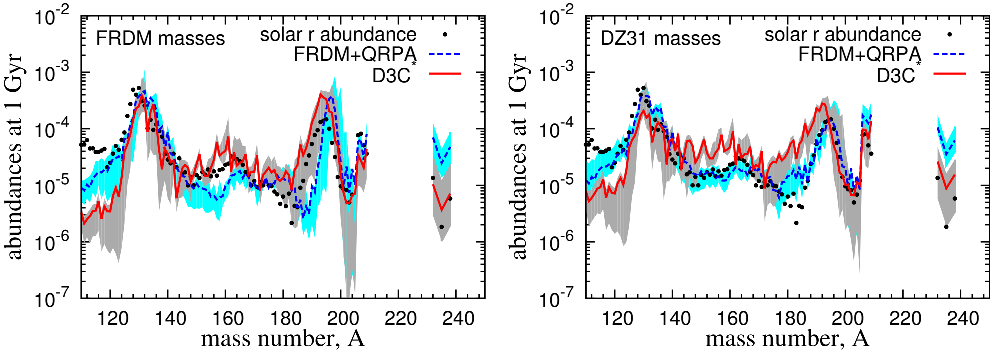


Mustonen & Engel, PRC **93**, 014304 (2016)



Impact on r-process abundances

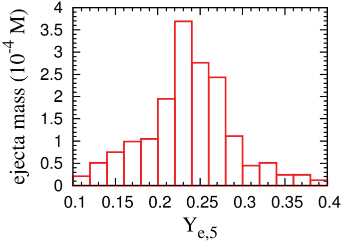
Shorter half-lives for $Z \gtrsim 80$ have a strong impact on the position of $A \sim 195$ (Eichler+ 2015).

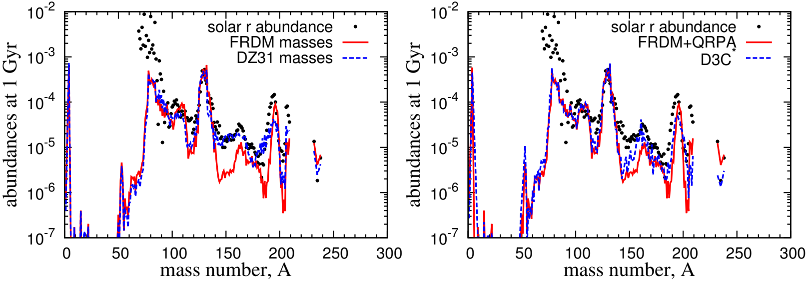


They also affect the robustness of the distribution and the shape of the 2nd peak (Wu+, in preparation)

r process on disk ejecta

- Black hole disk accretion model from R. Fernández.
- Production of all r process nuclides in all disk models considered.



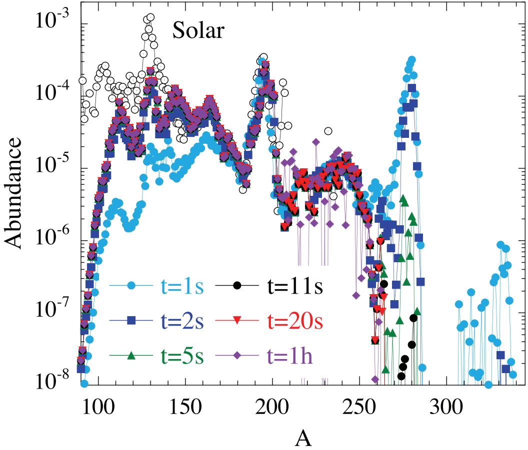


Wu, Fernández, GMP, Metzger, MNRAS in press, arXiv:1607.05290

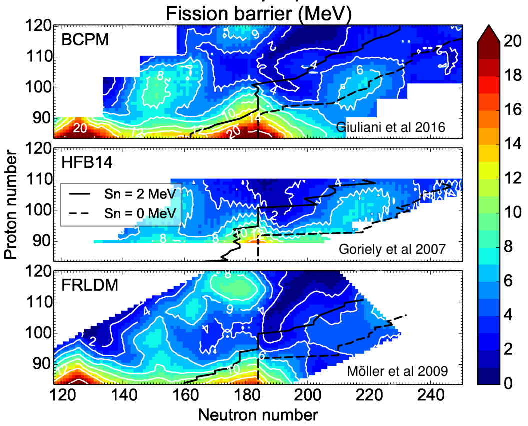
Fission barriers

The impact of different fission barriers and yields has not been sufficiently explored.

Goriely & GMP 2015

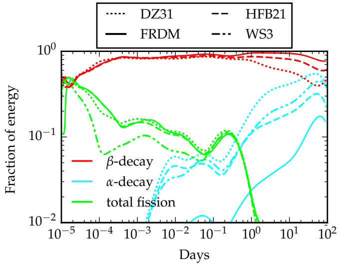


Giuliali, GMP, Robledo, in preparation

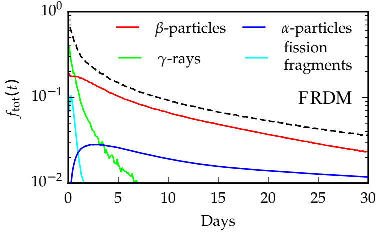


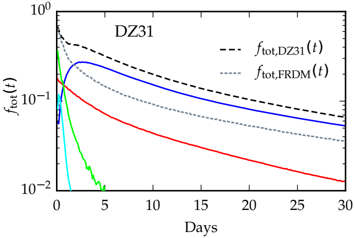
Electromagnetic transient (Kilonova)

- Radioactive decay ejected material responsible for an electromagnetic transitent: kilonova (likely observed in GRB 130603B)
- Kinolova models must address:
  - Total amount of radioactive energy released ($\dot{q} \sim t^{-\alpha}, \alpha = 1.1\text{–}1.4$)
  - Dominating decay channels at different phases
  - Efficiency of decay products thermalization



- Important differences abudances α-decaying nuclei between Pb and U.

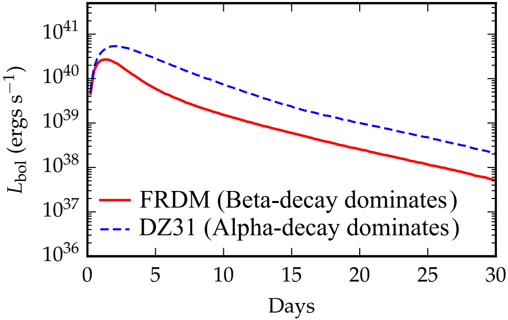




Barnes, Kasen, Wu, GMP, ApJ in press, arXiv:1605.07218

Kilonova light curve

Light curve contains nuclear physics signatures.



Ratio of luminosities at peak value and at late times can be used to constrain the amount of nuclei between Pb and U produced by the r process.

Summary

- Neutron star mergers most likely constitute the main r process site. Two type of ejecta: dynamical and disk ejecta.
- Dynamical ejecta of neutron star mergers produce a robust r-process abundance pattern mainly determined by the fission yields of superheavy nuclei. Role of weak interactions on Y_e needs to be clarified.
- Ejecta from black hole accretion disks produce all r-process nuclides in all models considered.
- Having identified the r process site we can address the role of nuclear physics in determining the abundances.
- Nuclear physics is also fundamental for accurate predictions of kilonova light curves.