Fission in r-process nucleosynthesis and implications for late-time heating of the dynamical ejecta

INT workshop: Observational Signatures of r-process Nucleosynthesis in Neutron Star Mergers

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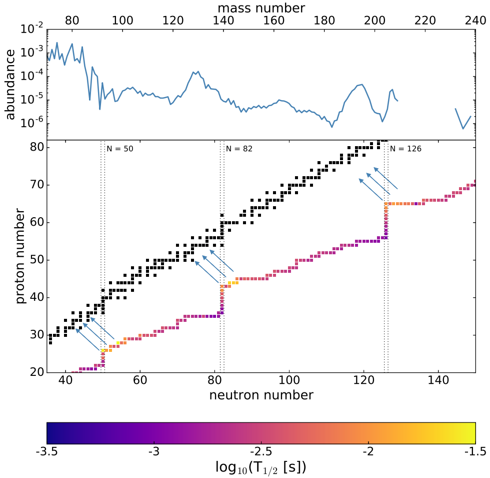
Outline

- Nuclear physics effects around the r-process freeze-out in dynamical ejecta of neutron star mergers
  - masses
  - fission
  - β-decays

- Some thoughts on late-time fission contribution to the heating rates in the dynamical ejecta

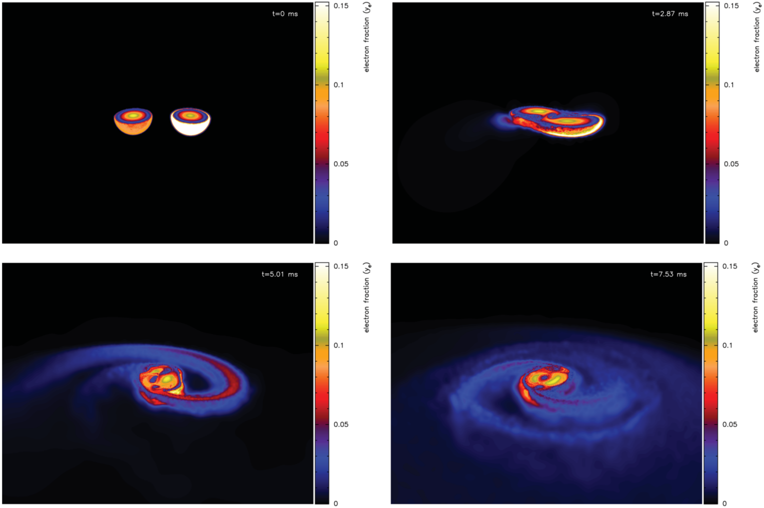
The (solar) r-process abundance pattern



Uncertainties for r-process calculations:

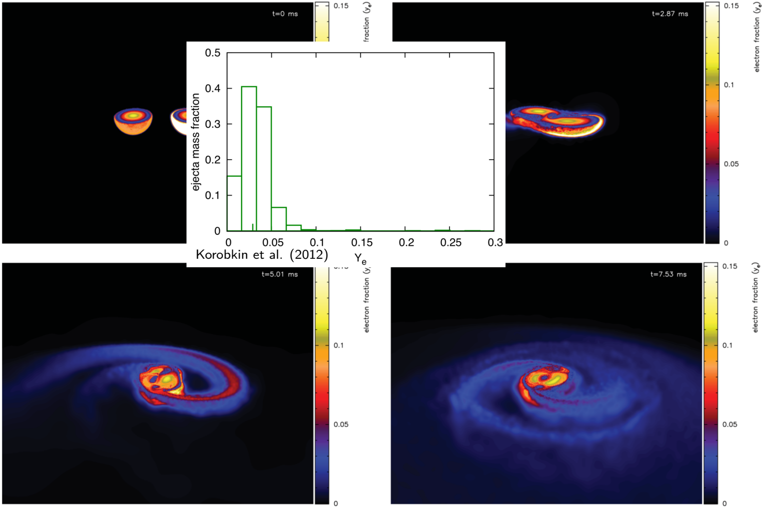
- nuclear properties
  - neutron capture cross sections
  - β-decay rates
  - fission rates & fragment distribution
- hydrodyn. conditions
  - $Y_e = \frac{n_p}{n_p+n_n}$
  - temperatures and densities
  - expansion timescales

Hydrodynamical model



Rosswog, Piran, & Nakar (2013)

Hydrodynamical model



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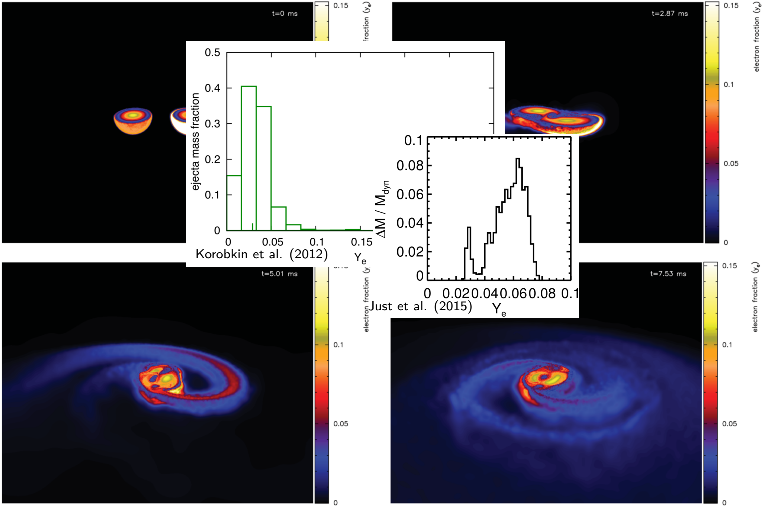
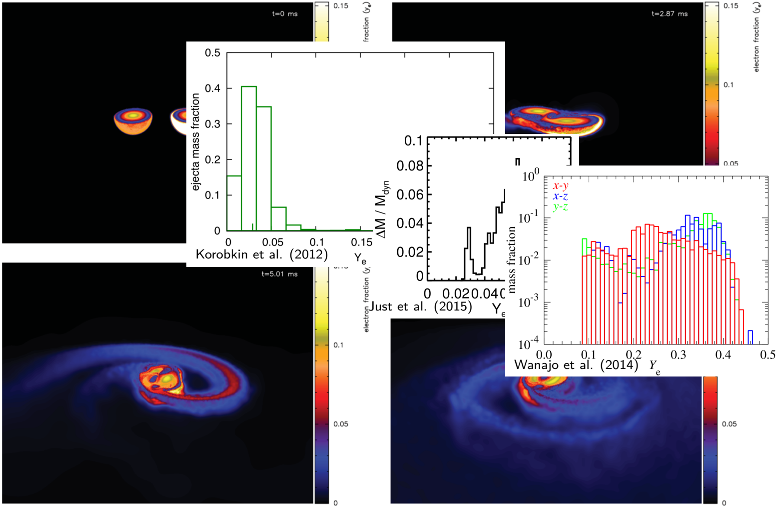


Rosswog, Piran, & Nakar (2013)

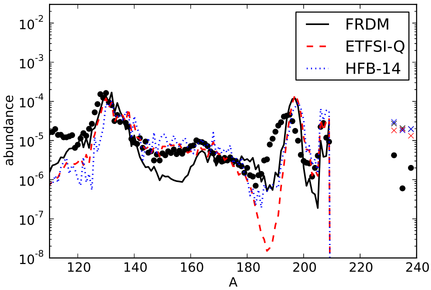
Hydrodynamical model



Rosswog, Piran, & Nakar (2013)

↗ talks by Shibata, Foucart, Just, Tchekhovskoy, Siegel, Perego, Bovard

Uncertainties: masses



Eichler et al. (2015)

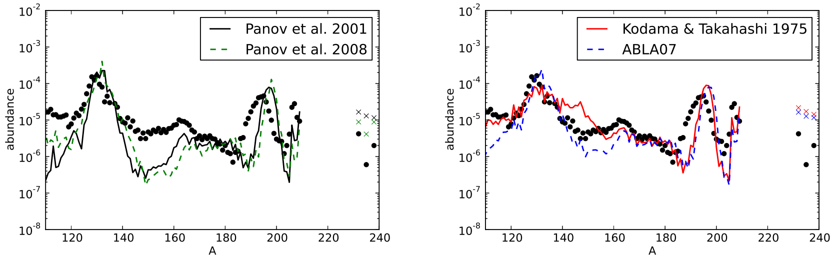
Masses determine the reaction rates, and with it

- the r-process path
- freeze-out effects
- the fission regions

see also Mendoza-Temis et al. (2015), Mumpower et al. (2015), Petermann et al. (2012)

↗ talks by Wu, McLaughlin

Uncertainties: fission models

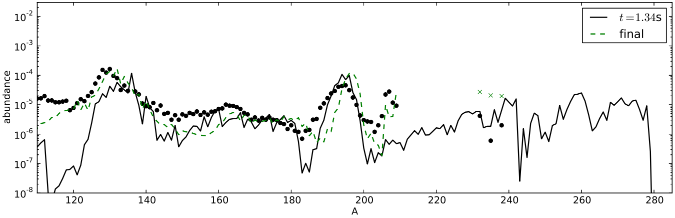


fission models determine:

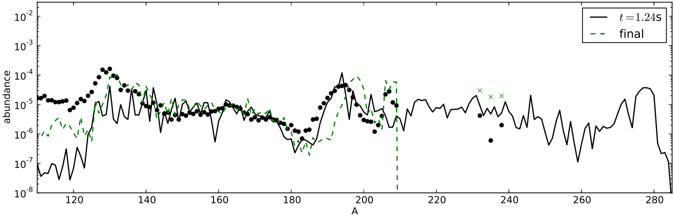
- the formation of the 2^{nd} peak
- fragments up to $A \approx 160$
- freeze-out effects

see also Goriely et al. (2013), Goriely (2015), Shibagaki et al. (2016)

Freeze-out effects



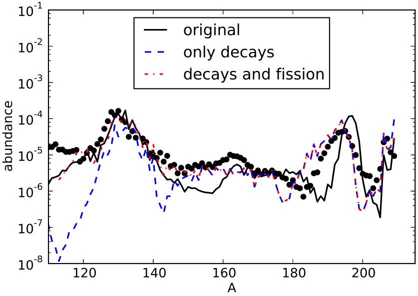
FRDM (1995)



HFB-14

What happens after the freeze-out?

reaction type	$\bar{\mathrm{A}} \uparrow$?
β-decays	×
α-decays	×
fission	×
(n,γ)	✓



see also Surman & Engel (2001)

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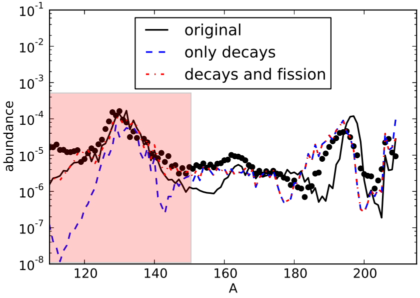

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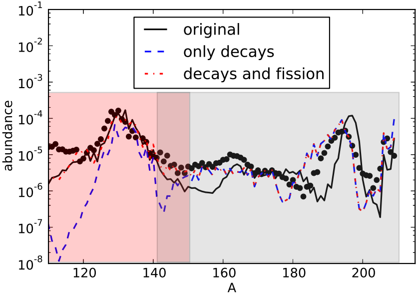
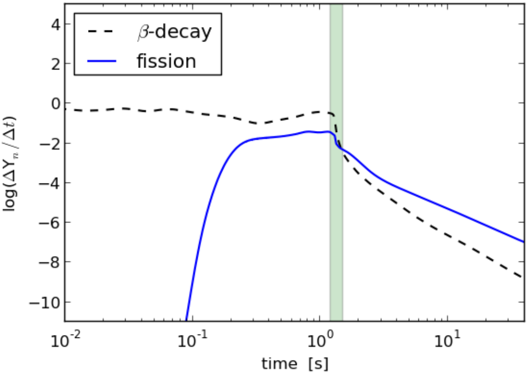
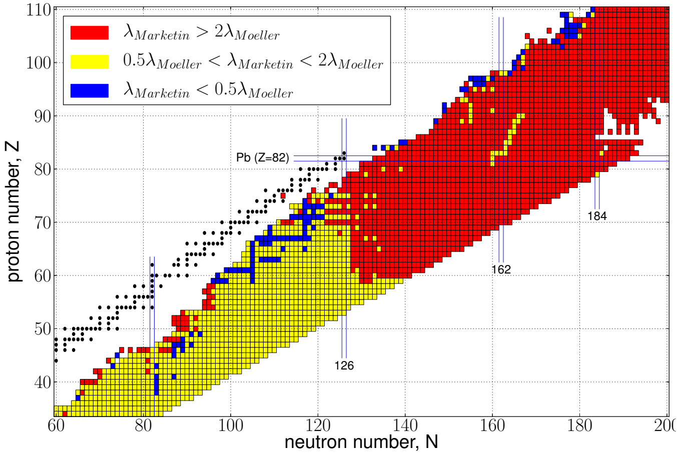


see also Surman & Engel (2001)

Late-time neutron release



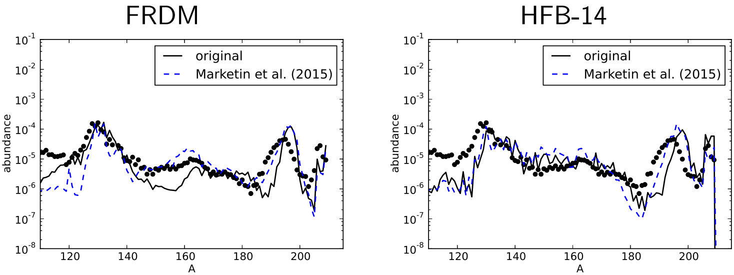
Different β-decay rates: D3C* (Marketin et al. 2015)



see also Caballero-Folch et al. (2016), Domingo-Pardo et al. (2013,2016), Kurtukian-Nieto et al. (2014), Lorusso et al (2015)

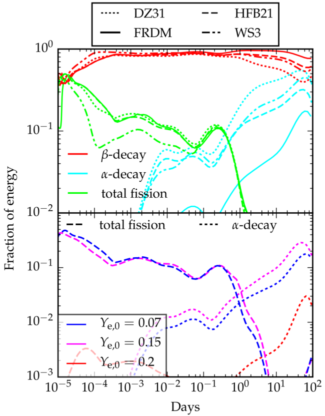
↗ talk by Marketin

The effect of β-decay rates on the final abundances

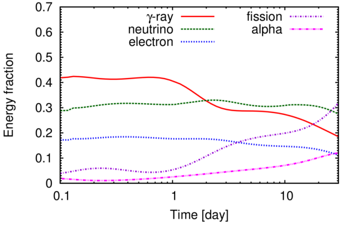


Eichler et al. (2015)

Late-time heating from radioactive decays



Barnes et al. (2016)



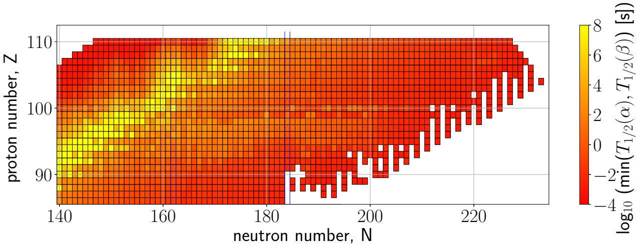
Hotokezaka et al. (2016)

see also Metzger (2014), Lippuner & Roberts (2015), Fernandez & Metzger (2016), Rosswog et al. (2017), Wollaeger et al. (2017)

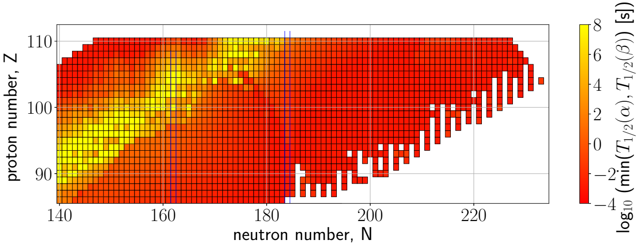
↗ talks by Korobkin, Tanaka, Hotokezaka, Piran, Wu

Survival timescales of heavy nuclei

Möller et al. (2003):

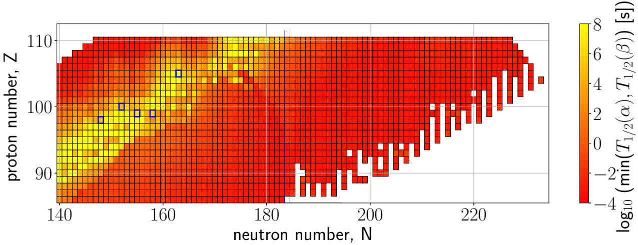


Marketin et al. (2015):



Fission powering kilonova/macronova light curves

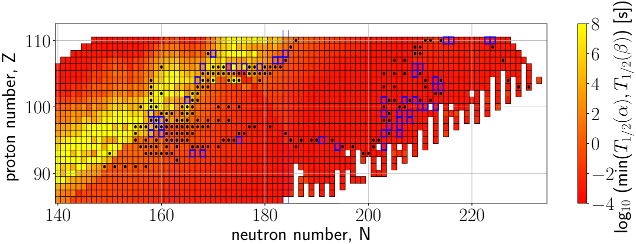
experimentally known SF rates with $1\ \mathrm{d} < \mathrm{T}_{1/2} < 2$ weeks



Phenomenological spontaneous fission rates

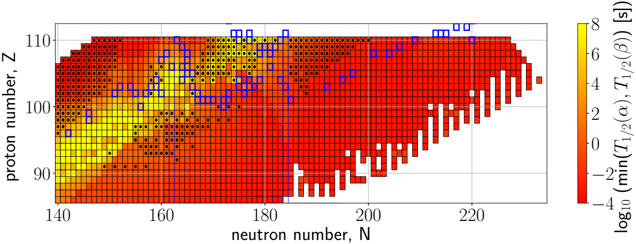
Petermann et al. (2012)

$$\log(T_{1/2})[s] = 8.08 B_f - 24.05$$



Zagrebaev et al. (2011)

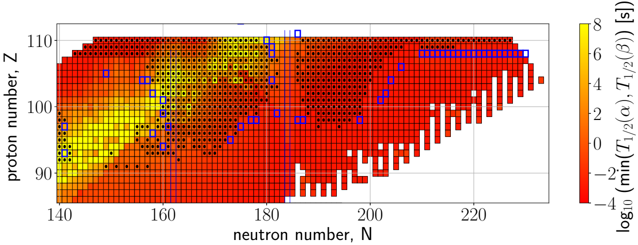
$$\log(T_{1/2})[s] = 1146.4 - 75.3\,\frac{Z^2}{A} + 1.638\left(\frac{Z^2}{A}\right)^2 - 0.012\left(\frac{Z^2}{A}\right)^3 + (7.24 - 0.095\frac{Z^2}{A})B_f + C(Z, A)$$



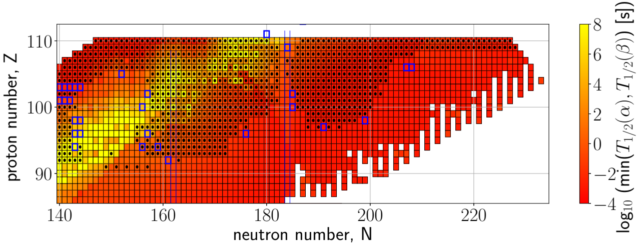
Phenomenological spontaneous fission rates

Based on ETFSI barriers (sets from I. Panov)

$\log(T_{1/2})[s] = 7.77 B_f - 33.3$

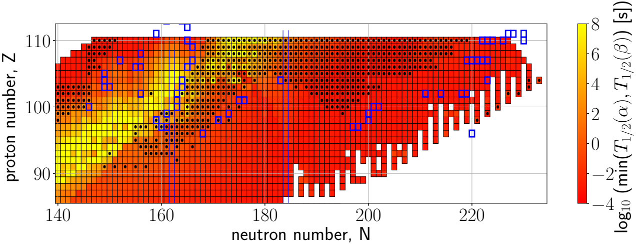


$\log(T_{1/2})[s] = 10.145 B_f - 50.127$



Spontaneous fission rates

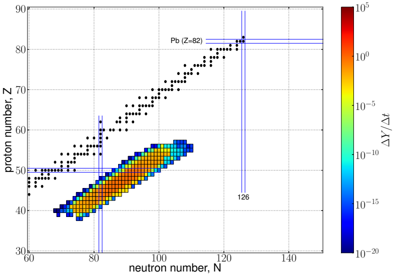
Based on BCPM EDF (Giuliani et al. 2017)



Could the distribution of fission fragments also affect the β-decay heating rate?

Snapshots at $t \approx 1.3$ s

FRDM



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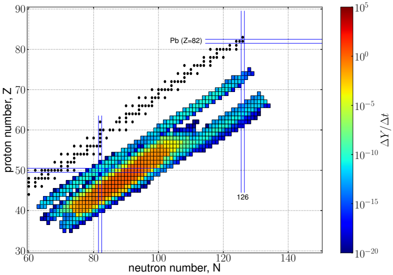

cf. Shibagaki et al. (2016)

Summary

For dynamic ejecta with low Y_e:

- shape of the r-process abundance pattern only emerges after the freeze-out from $(n,\gamma)-(\gamma,n)$ equilibrium
  - the 2^{nd} peak is filled by fission fragments
  - the rare earth peak and the 3^{rd} peak can be shifted by late neutron captures
    this can partially be prevented if the responsible neutrons are produced and recycled earlier during the $(n,\gamma)-(\gamma,n)$ equilibrium

late-time heating-rate contribution from fission questionable, since nuclei with $1\mathrm{d} < \mathrm{T}^{\mathrm{SF}}_{1/2} < 2\ \mathrm{weeks}$ are very hard to reach
$\rightarrow$ mass models with different fission barrier predictions could produce different results