Nucleosynthesis of Heavy Elements: Open Questions

Uncertainties surrounding the r-process in neutron star mergers

JINA workshop: Forging conncections

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June 28, 2017

FNSNF SWISS NATIONAL SCIENCE FOUNDATION

TECHNISCHE UNIVERSITÄT DARMSTADT

HELMHOLTZ GEMEINSCHAFT

SFB 1245

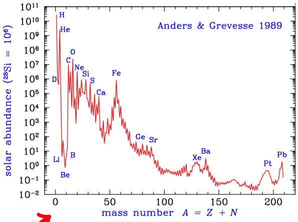
The solar abundances

s-process
AGB stars
massive stars

r-process
neutron star mergers?
MHD SNe?
ν-driven winds in CCSNe?

i-process?
AGB stars?

γ-process
CCSNe
type Ia SNe

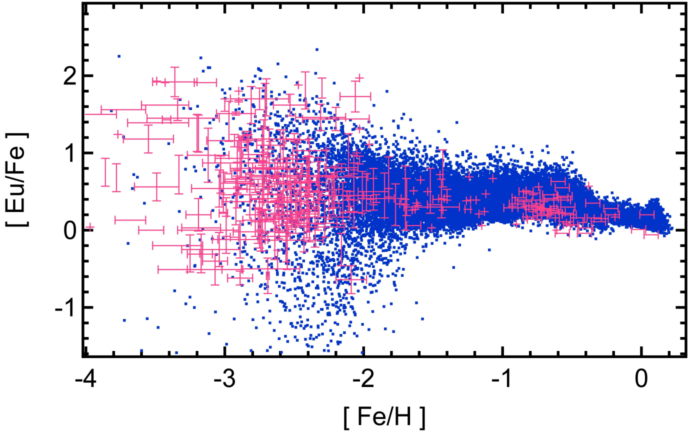


explosive nucleosynthesis
CCSNe

rp-process
X-ray (super-)bursts

νp-process
ν-driven winds in CCSNe

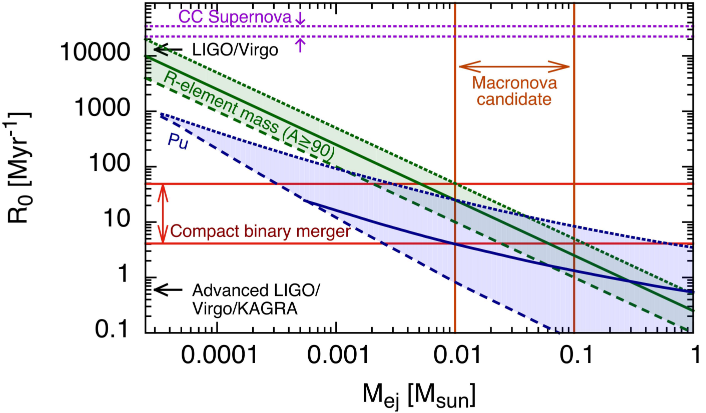
Galactic chemical evolution



Wehmeyer et al. (2015)

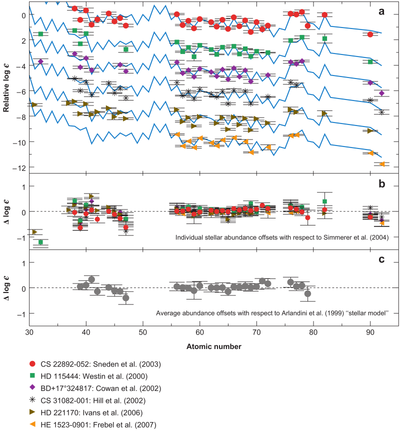
↗ Lee, Wehmeyer

Frequency and ejected mass per event



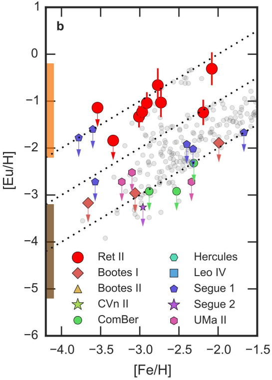
Hotokezaka et al. (2015)

Heavy element abundances in atmospheres of metal-poor stars



Sneden et al. (2008)

Reticulum II



Ji et al. (2016)

↗ Frebel, Roederer, Safarzadeh

Milestones for nucleosynthesis in neutron star mergers

1974	First description of compact mergers as r-process site	Lattimer & Schramm (1974)
1994	Simulation predicts (dynamically ejected) mass loss from a binary NSM	Davies et al. (1994)
1999	First nucleosynthesis calculations from hydrodynamical trajectories	Freiburghaus et al. (1999)
2008	additional mass loss channels: disk and neutrino-driven outflows	Beloborodov (2008), Dessart et al. (2009)
now	accurate simulations to predict the behaviour of ejected matter	Rosswog et al. (2011), Bauswein et al. (2013), Wanajo et al. (2014), etc.

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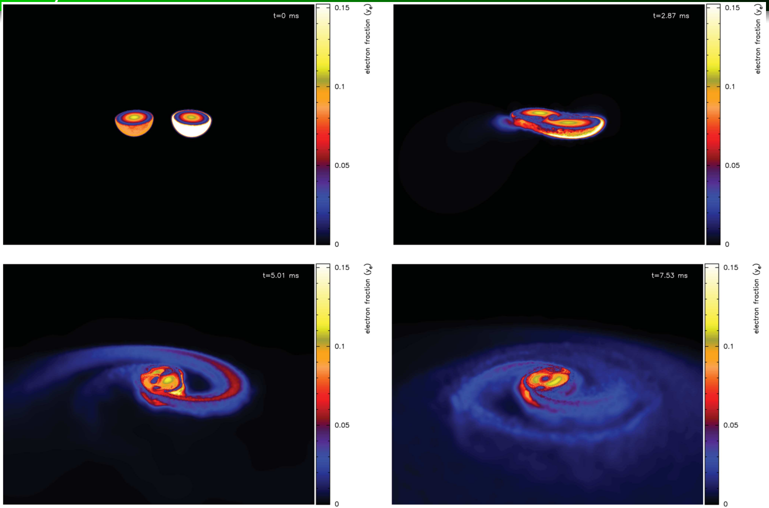
Major challenges in hydrodynamical simulations

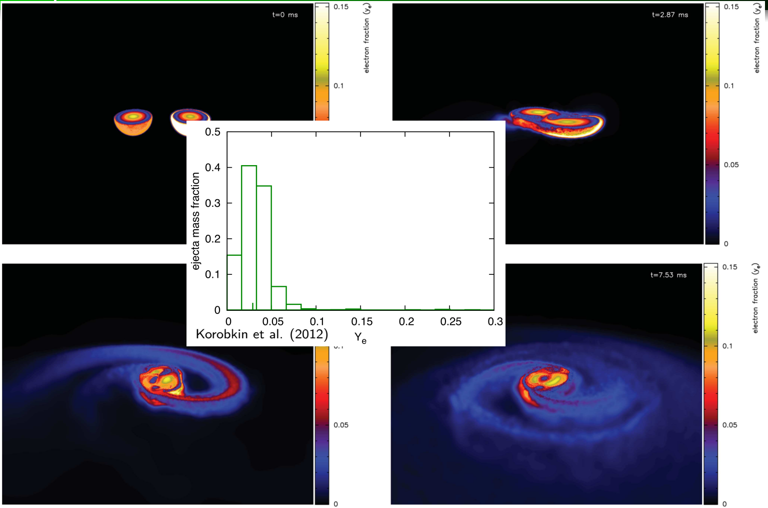
- neutrino transport
- equation of state
- general relativity

Hydrodynamical models



Rosswog, Piran, & Nakar (2013)

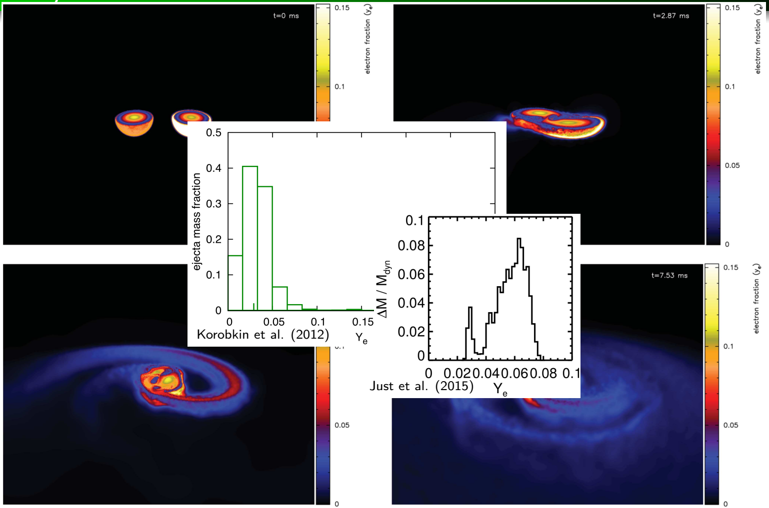
Hydrodynamical models



Korobkin et al. (2012)

Rosswog, Piran, & Nakar (2013)

Hydrodynamical models



Rosswog, Piran, & Nakar (2013)

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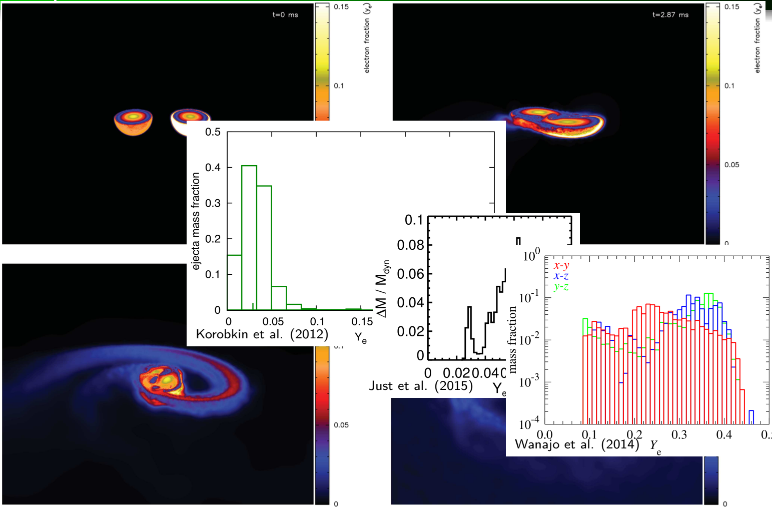
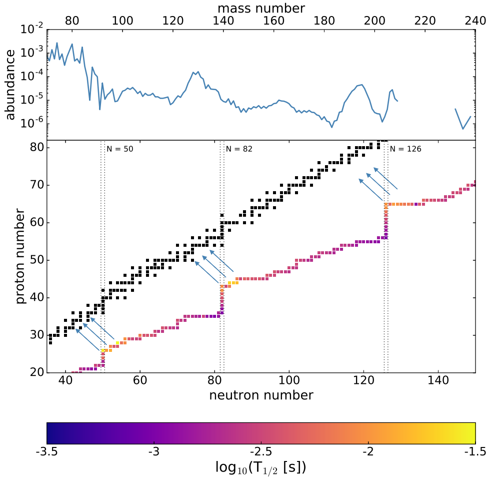


Rosswog, Piran, & Nakar (2013)

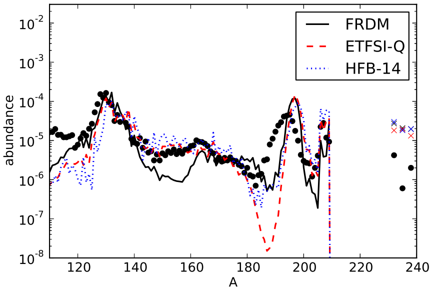
The (solar) r-process abundance pattern



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

Uncertainties: masses



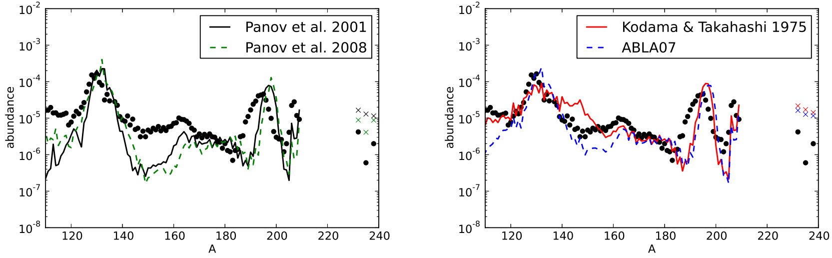
Eichler et al. (2015)

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)

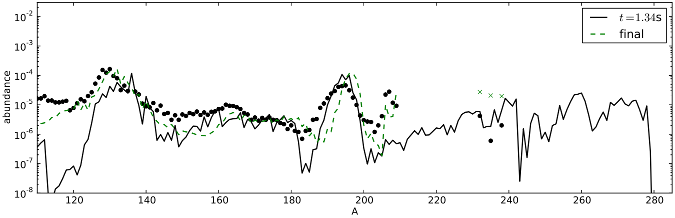
Uncertainties: fission models



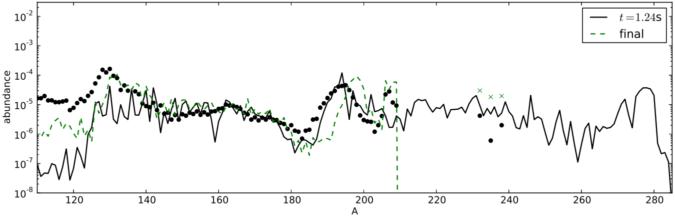
fission models determine:

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

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



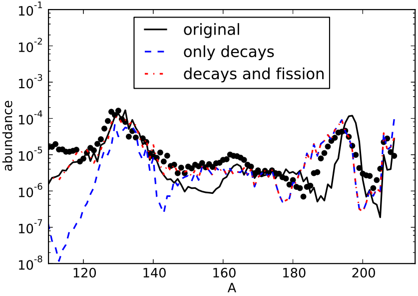
FRDM (1995)



HFB-14

What happens after the freeze-out?

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



see also Surman & Engel (2001)

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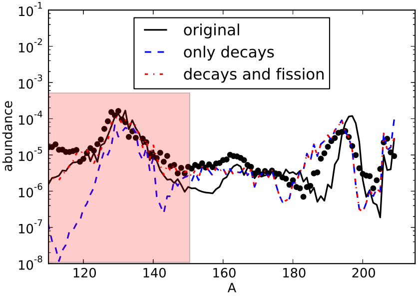

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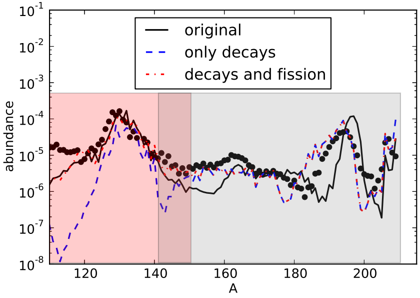

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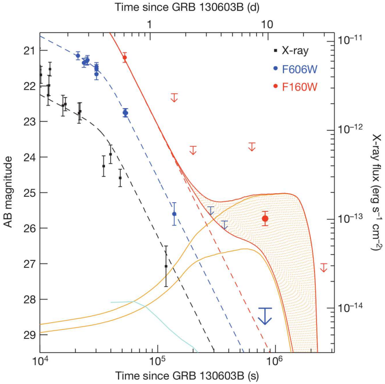
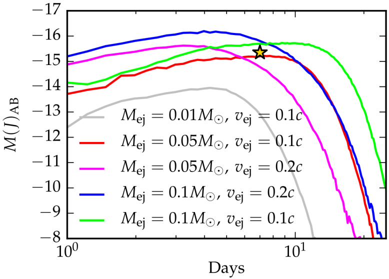
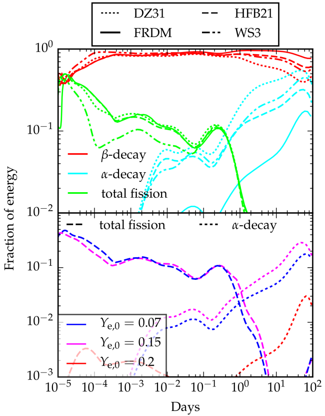


Tanvir et al. (2013)

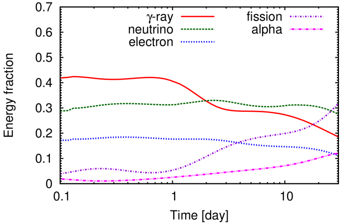


Barnes et al. (2016)

Nuclear dependency for light curves



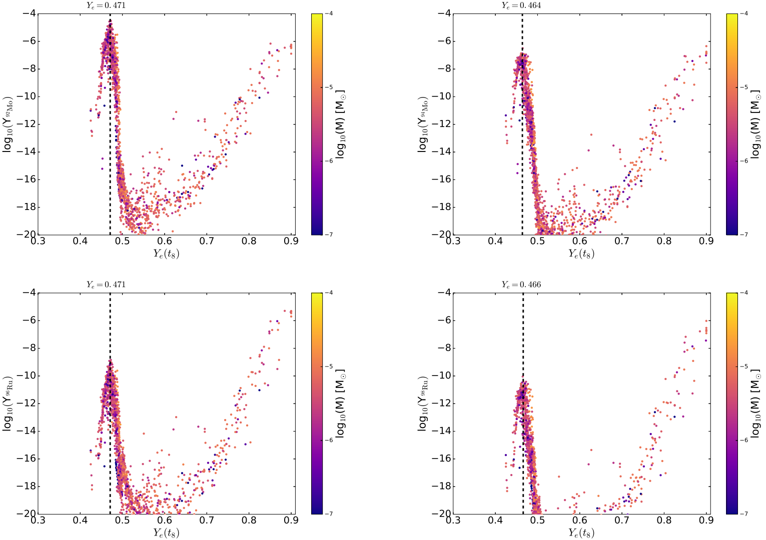
Barnes et al. (2016)



Hotokezaka et al. (2016)

see also Wollaeger et al. (2017)

Mo and Ru production in 2D CCSN ejecta (11.2 $M_\odot$)



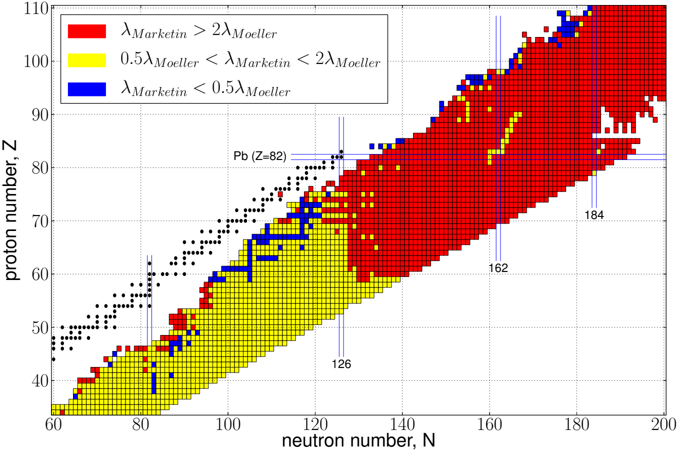
Eichler et al. (submitted)

↗ Travaglio

Summary

- Binary neutron star mergers look more and more likely to be (one of) the r-process site(s)
- Accurate hydrodynamical models have emerged only in the last few years
- However: Large uncertainties in nuclear physics and hydrodynamics
- After the freeze-out from $(n, \gamma) - (\gamma, n)$ equilibrium the features of the final abundance distribution only start to appear
  - 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
- kilonova light curve observations may present possible new diagnostics for mass models and decay rates

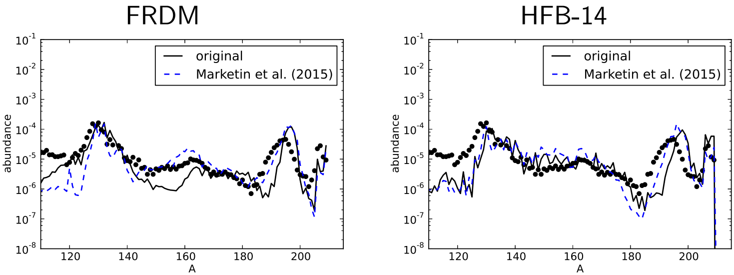
New sets of β-decay rates: D3C* (Marketin et al. 2015)



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

↗ Dillmann

The effect of β-decay rates on the final abundances



Eichler et al. (2015)