Nucleosynthetic signatures of astrophysical r-process sites

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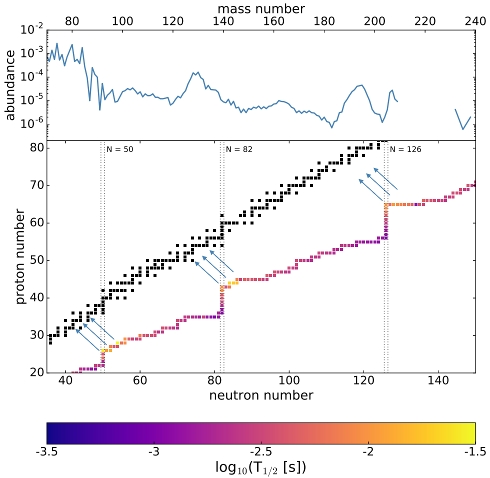
The (solar) r-process abundance pattern



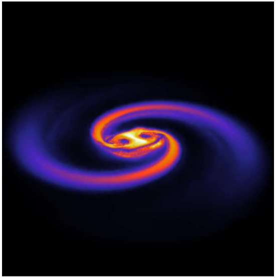
Uncertainties for r-process calculations:

- nuclear properties (e.g. masses)
  - neutron capture cross sections
  - β-decay rates
  - fission rates & fragment distribution
- hydrodyn. conditions
  - $Y_e = \frac{n_p}{n_p+n_n}$
  - entropy
  - expansion timescales

Giacomazzo, Eichler & Arcones (2018)

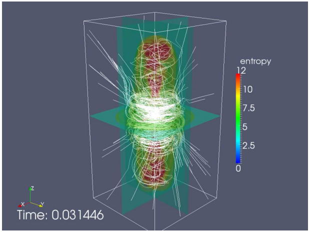
Possible sites of the r-process

Compact binary mergers



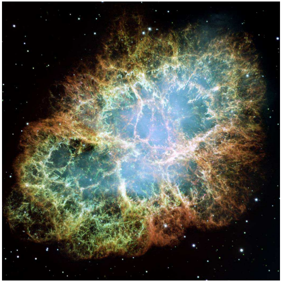
Rosswog et al. (2017)

Magneto-hydrodynamically driven (MHD) SNe



Winteler et al. (2012)

(Regular) core-collapse SNe (ν-driven wind)



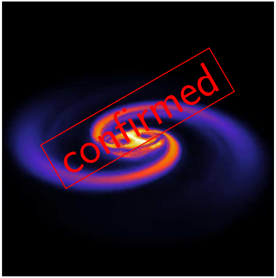
weak (limited) r-process

e.g., Arcones & Martinez-Pinedo (2011)

...and collapsars, QCD phase-transition SNe, ...!

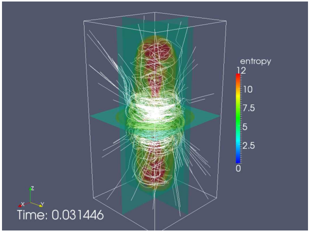
Possible sites of the r-process

Compact binary mergers



Rosswog et al. (2017)

Magneto-hydrodynamically driven (MHD) SNe



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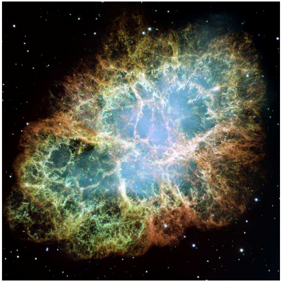

weak (limited) r-process
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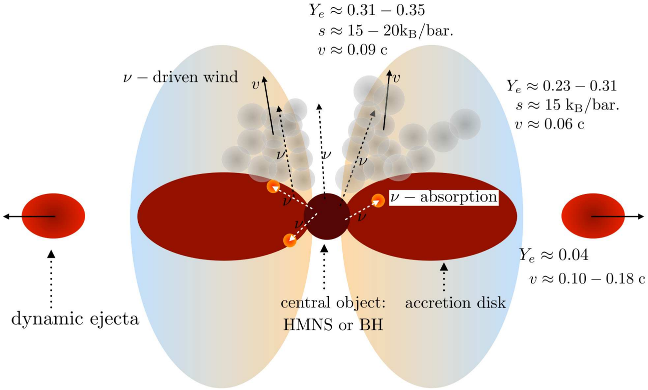
Neutron star mergers: ejecta



Rosswog (2015)

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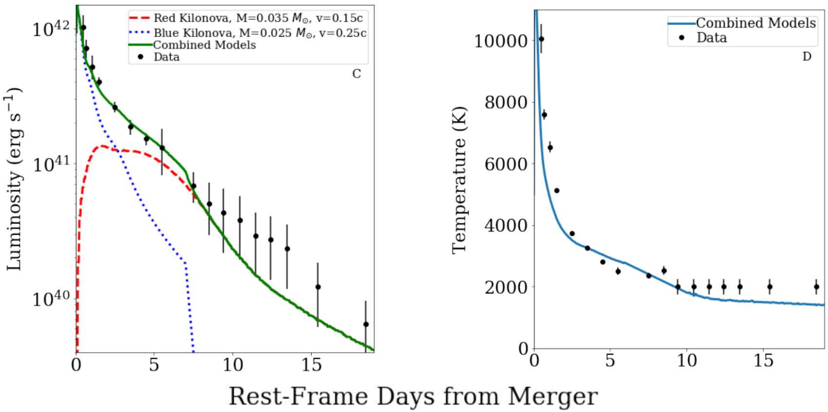
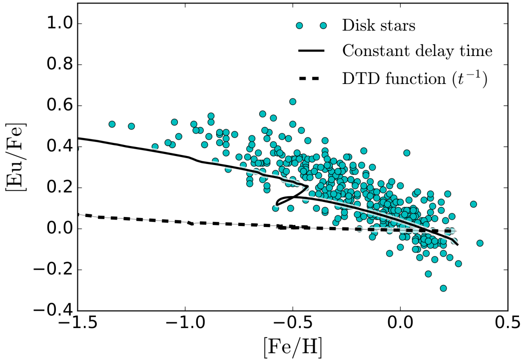


Kilpatrick et al. (2017)

Delay-time distributions of NS mergers

Delay-time distribution (DTD): probability distribution function of coalescence times for BNS systems

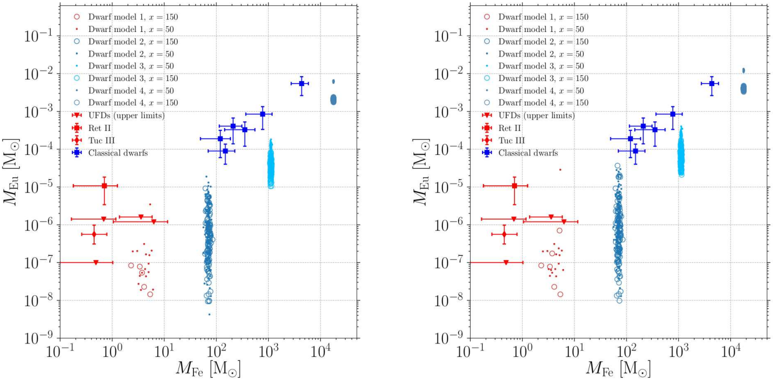
Most current models agree on a DTD that goes with t^{-1}



Côté et al. (2019)

see also Côté et al. (2017), Hotokezaka et al. (2018), Simonetti et al. (2019)

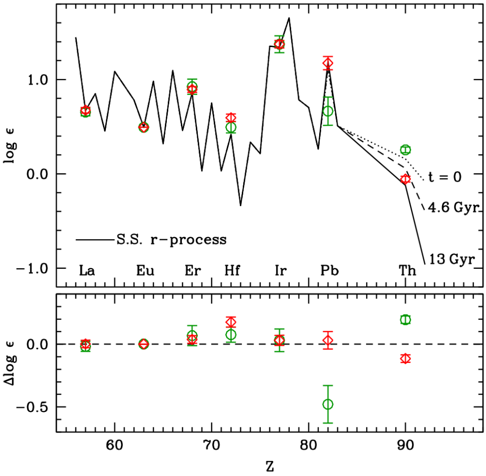
(Ultra-Faint) Dwarf Galaxies



In a shallow grav. potential well, not all the ejecta from a merger are retained, leading to low [Eu/Fe] estimates

Bonetti et al. (2019)

Actinide-boost stars

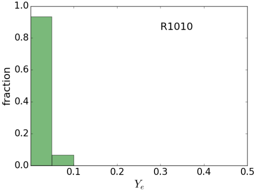


Roederer et al. (2009)

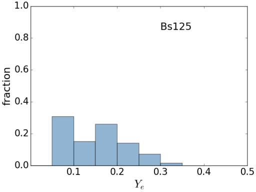
see also Schatz et al. (2002), Mashonkina et al. (2014), Ji & Frebel (2018), Holmbeck et al. (2018)

R-Process in different sites

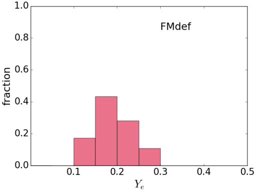
NS-NS dyn. ejecta:
Rosswog et al. (2013)



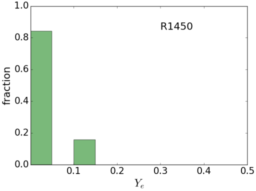
NS-NS dyn. ejecta:
Bovard et al. (2017)



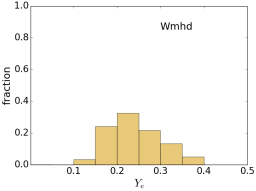
NSM disk ejecta:
Fernandez & Metzger (2013)



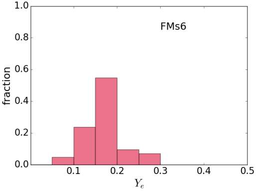
NS-BH dyn. ejecta:
Rosswog et al. (2013)



MHD SN:
Winteler et al. (2012)

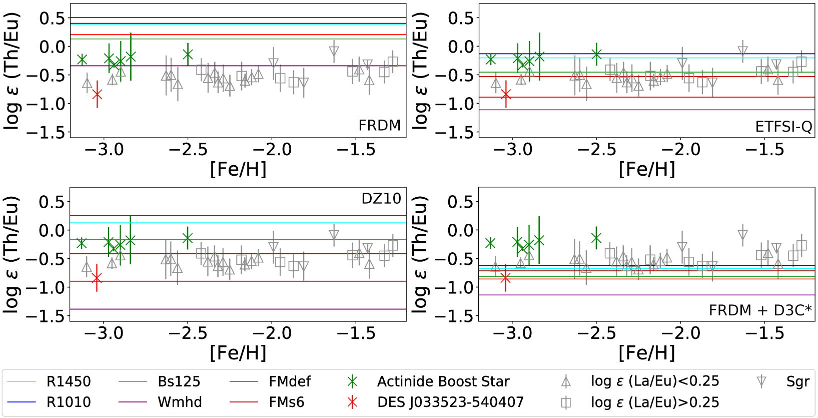


NSM disk ejecta:
Fernandez & Metzger (2013)



Y_e: "neutron-richness" of the ejecta, $Y_e = \frac{n_p}{n_n + n_p}$

Actinide abundances in observations and models

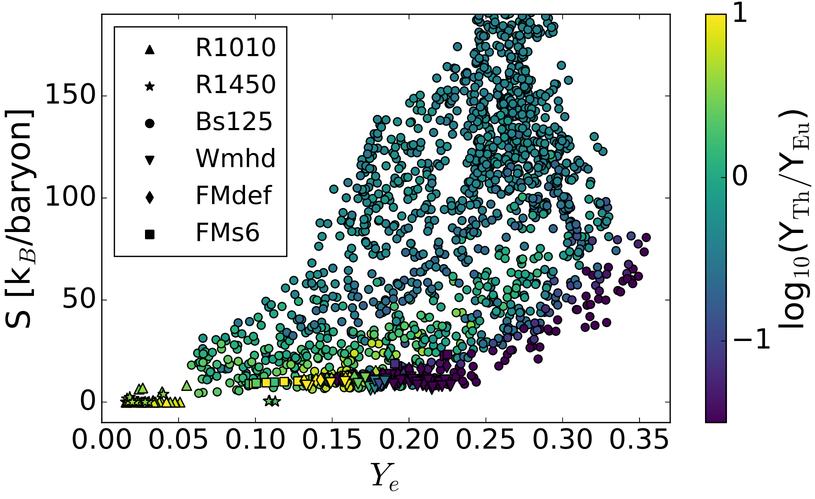


stellar data from: Roederer et al. (2009), Mashonkina et al. (2014), Holmbeck et al. (2018)
DES J033523-540407: Ji & Frebel (2018); Sgr: CJ Hansen et al. (2018)

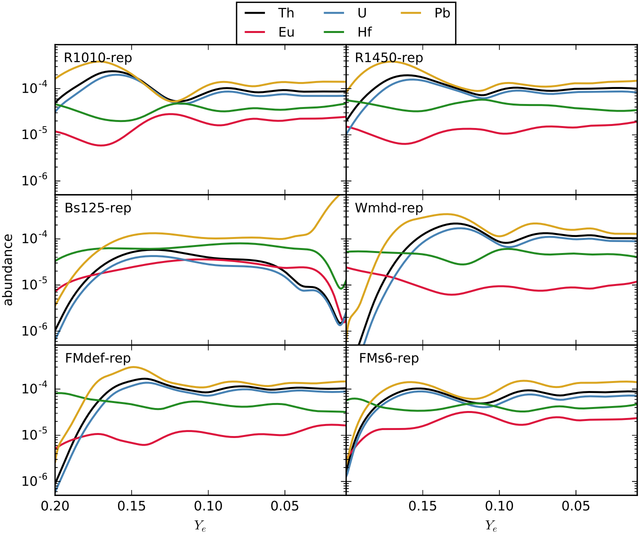
theoretical ratios 10 Gyr after event

Eichler et al. (2019)

Actinide and lanthanide production under different conditions

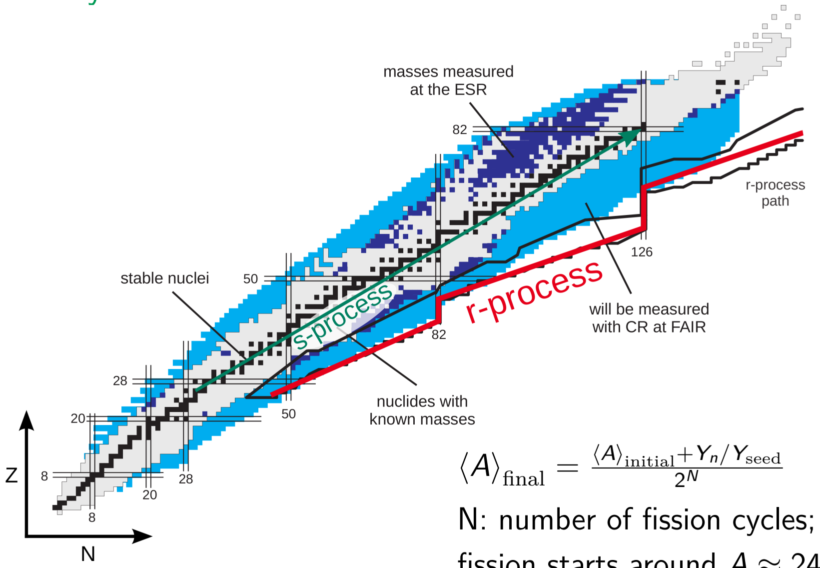


Impact of Y_e on actinide and lanthanide production



Eichler et al. (2019); see also Lippuner & Roberts (2015), Wu et al. (2017), Holmbeck et al. (2019a)

Fission cycles



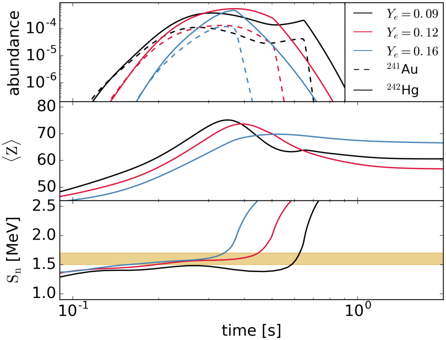
$$\langle A \rangle_{\mathrm{final}} = \frac{\langle A \rangle_{\mathrm{initial}} + Y_n/Y_{\mathrm{seed}}}{2^N}$$

N: number of fission cycles;

fission starts around $A \approx 240$

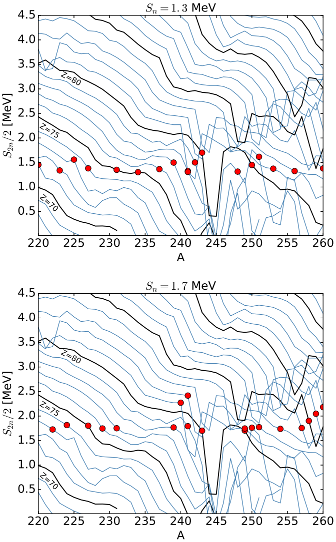
Origin of the variations in Th, U, and Eu

- R1010-rep (NS-NS merger) trajectory + FRDM
- $Y_e = 0.09, 0.16$: Maxima in Th abundance
  $Y_e = 0.12$: Minimum
- relatively long-lived isotopes ^{241}Au & ^{242}Hg are "precursor nuclei" for Th and U isotopes
- Top and middle panel show the effect of fission cycles on actinide abundances and overall composition
- Additional effect in the R1010-rep case due to the r-process path around freeze-out



Eichler et al. (2019)

Precursor nuclei of ^{232}Th on the r-process path

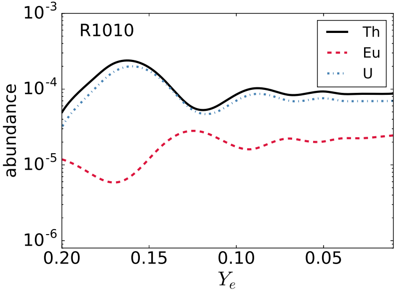


Eichler et al. (2019)

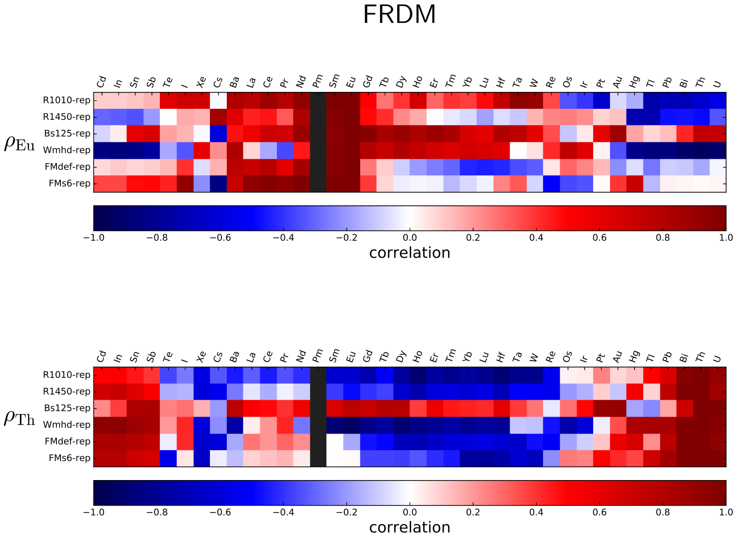
Elemental correlations with Eu and Th

If the r-process compositions in actinide-boost stars is from the same site as "regular" r-enhanced stars:

- production of some elements is enhanced under the same conditions as Th (Th-like; $\rho_{\mathrm{Th}}(\mathrm{U}) \approx +1$)
- production of some other elements is suppressed (Eu-like; $\rho_{\mathrm{Eu}}(\mathrm{U}) \approx -1$)



Elemental correlations with Eu and Th



Eichler et al. (2019)

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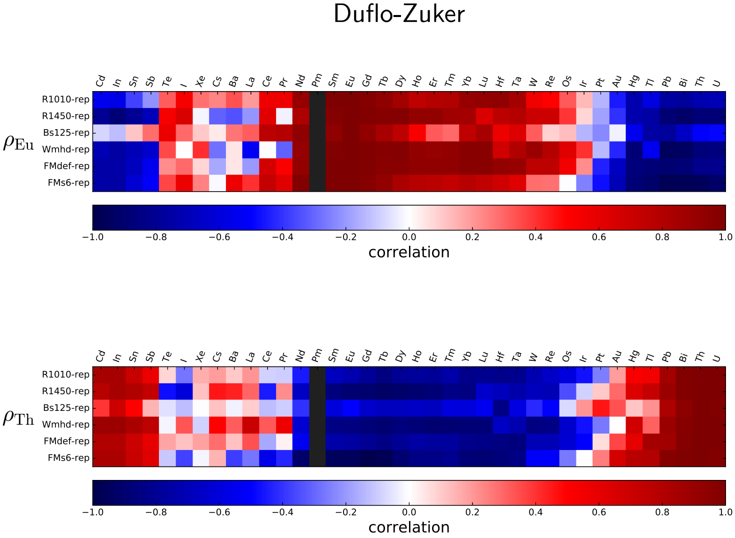
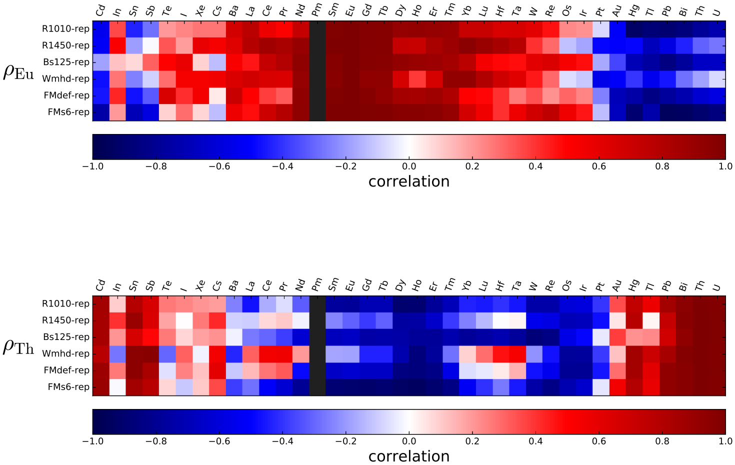


Eichler et al. (2019)

Elemental correlations with Eu and Th

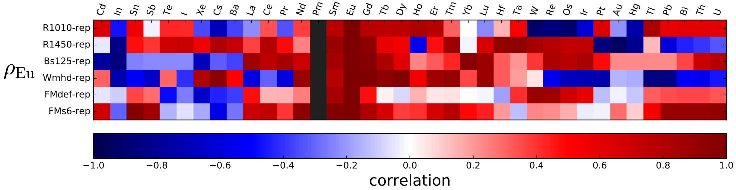
ETFSI-Q

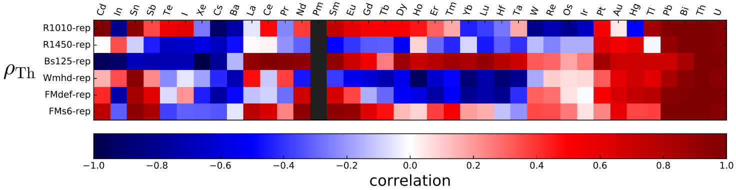


Eichler et al. (2019)

Elemental correlations with Eu and Th

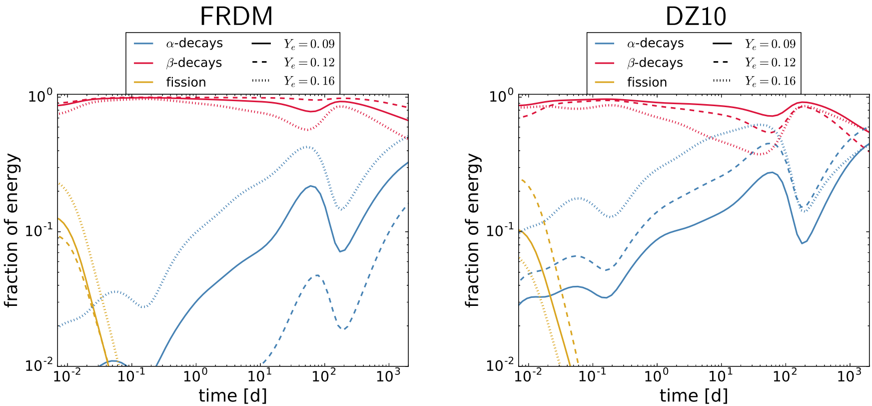
FRDM + D3C*





Eichler et al. (2019)

Late-time heating (kilonovae)

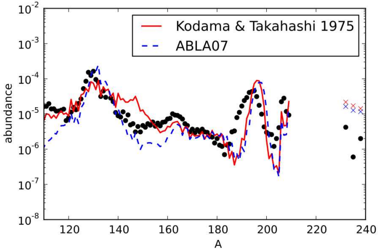


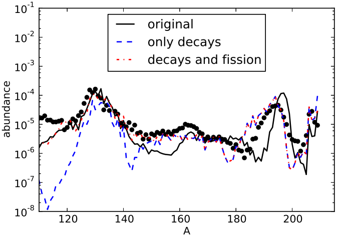
peak in α-decays around 50 d: $^{225}Ac \rightarrow {}^{209}Bi$

no peak in fission from ^{254}Cf (contrary to Zhu et al., 2018)

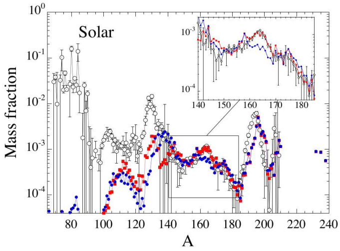
see also Barnes et al. (2016), Hotokezaka et al. (2016), Wollaeger et al. (2017), Wanajo (2018)...

The Effect of Fission

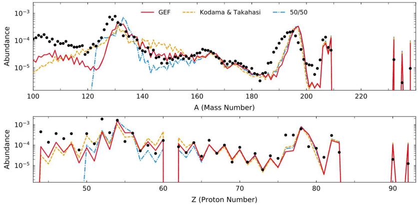




Eichler et al. (2015)



Goriely et al. (2013)

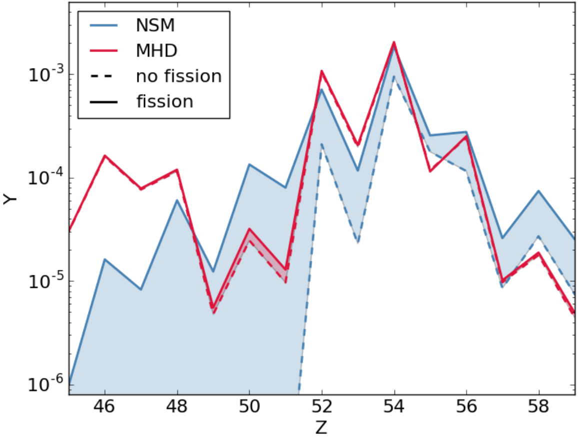


Vassh et al. (2019)

Fission signatures

2nd peak dependences:

- fission fragment distribution in low-Y_e environments
- mass model (S_n) otherwise



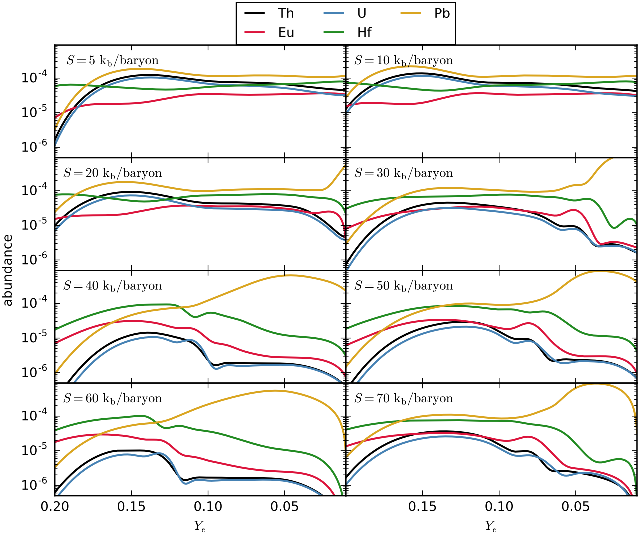
Côté et al. (2019)

R-Process properties in MHD SNe and NSMs

	MHD SNe	Mergers w/ wind	Mergers w/o wind
Zn $\propto$ Eu (early Galaxy)	yes	maybe	no
fission signature	no	yes	yes
first peak	yes	yes	no
2nd peak	yes	yes (fission)	yes (fission)
rare earth	yes	yes (fission)	yes (fission)
3rd peak	yes	yes	yes
actinides	maybe	yes	yes
act. boost	maybe	maybe	maybe
robustness betw. 2nd & 3rd peak	no	maybe	maybe

for similar table with respect to GCE see Côté et al. (2019)

Impact of the entropy on actinide (and lanthanide) production



R-process path in (n,γ)-(γ,n) equilibrium

detailed balance:

$$\lambda_{\gamma,n}(Z,A+1) = \frac{2G(Z,A)}{G(Z,A+1)} \left(\frac{A}{A+1}\right)^{3/2} \left(\frac{m_u kT}{2\pi\hbar^2}\right)^{3/2} \langle\sigma v\rangle_{n,\gamma}(Z,A) \exp[-S_n(Z,A+1)/kT]$$

$$\frac{Y(Z,A+1)}{Y(Z,A)} = \frac{\langle\sigma v\rangle_{n,\gamma}(Z,A)}{\lambda_{\gamma,n}(Z,A+1)} n_n = \frac{G(Z,A+1)}{2G(Z,A)} \left(\frac{A+1}{A}\right)^{3/2} \left(\frac{2\pi\hbar^2}{m_u kT}\right)^{3/2} n_n \exp[S_n(Z,A+1)/kT]$$

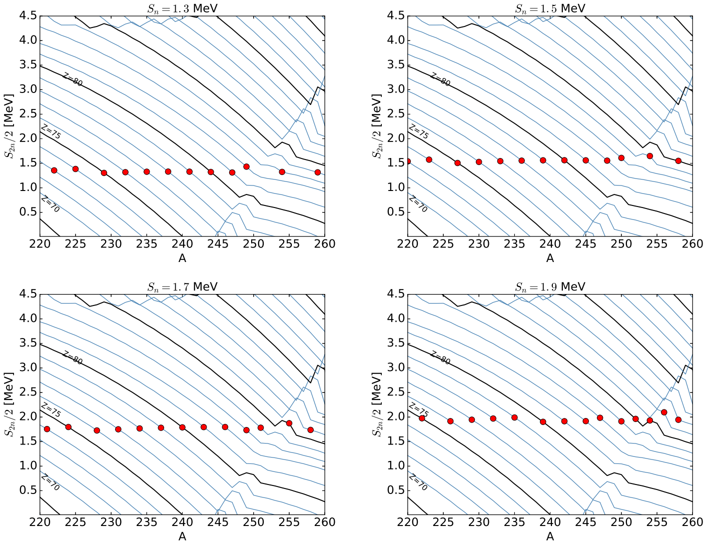
along any given isotopic chain, the isotope (Z,A) with maximum abundance can be estimated via

$$\frac{Y(Z,A+1)}{Y(Z,A)} = 1$$

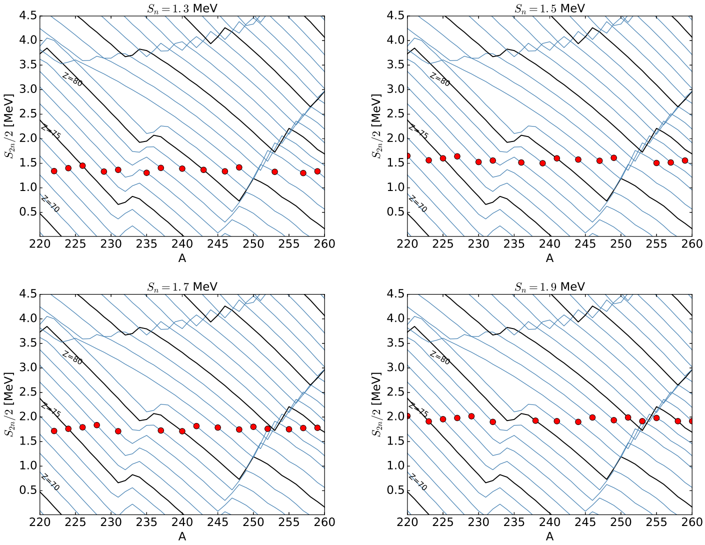
$$S_n(Z,A+1) = -kT \ln\left[\frac{G(Z,A+1)}{2G(Z,A)} \left(\frac{A+1}{A}\right)^{3/2} \left(\frac{2\pi\hbar^2}{m_u kT}\right)^{3/2} n_n\right]$$

e.g., Thielemann et al. (2017)

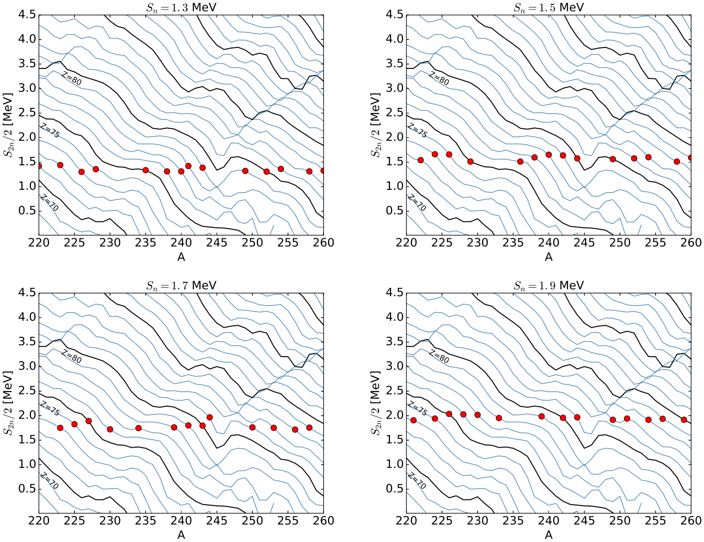
Duflo–Zuker 10 parameters



Duflo–Zuker 28 parameters



FRDM 2012



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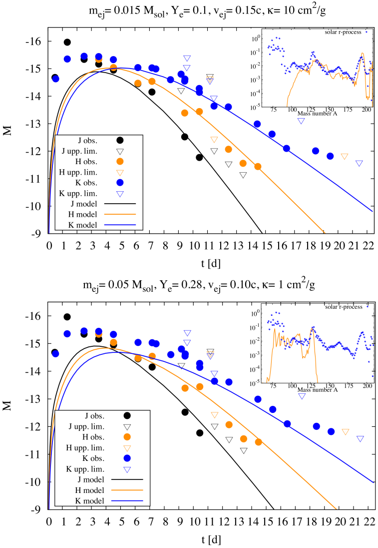
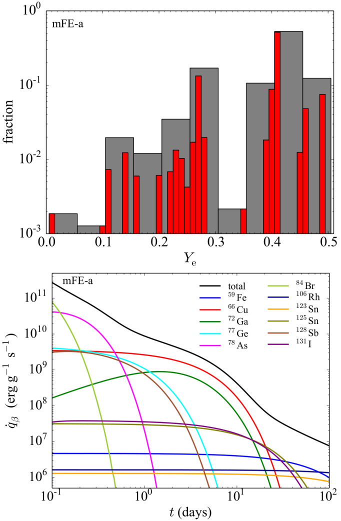


Rosswog et al. (2018)

dominant heating from ^{66}Ni $\rightarrow^{66}$Cu $\rightarrow^{66}$Zn and ^{72}Zn $\rightarrow^{72}$Ga $\rightarrow^{72}$Ge?



Wanajo (2018)