r-process nucleosynthesis yields and their heating rates

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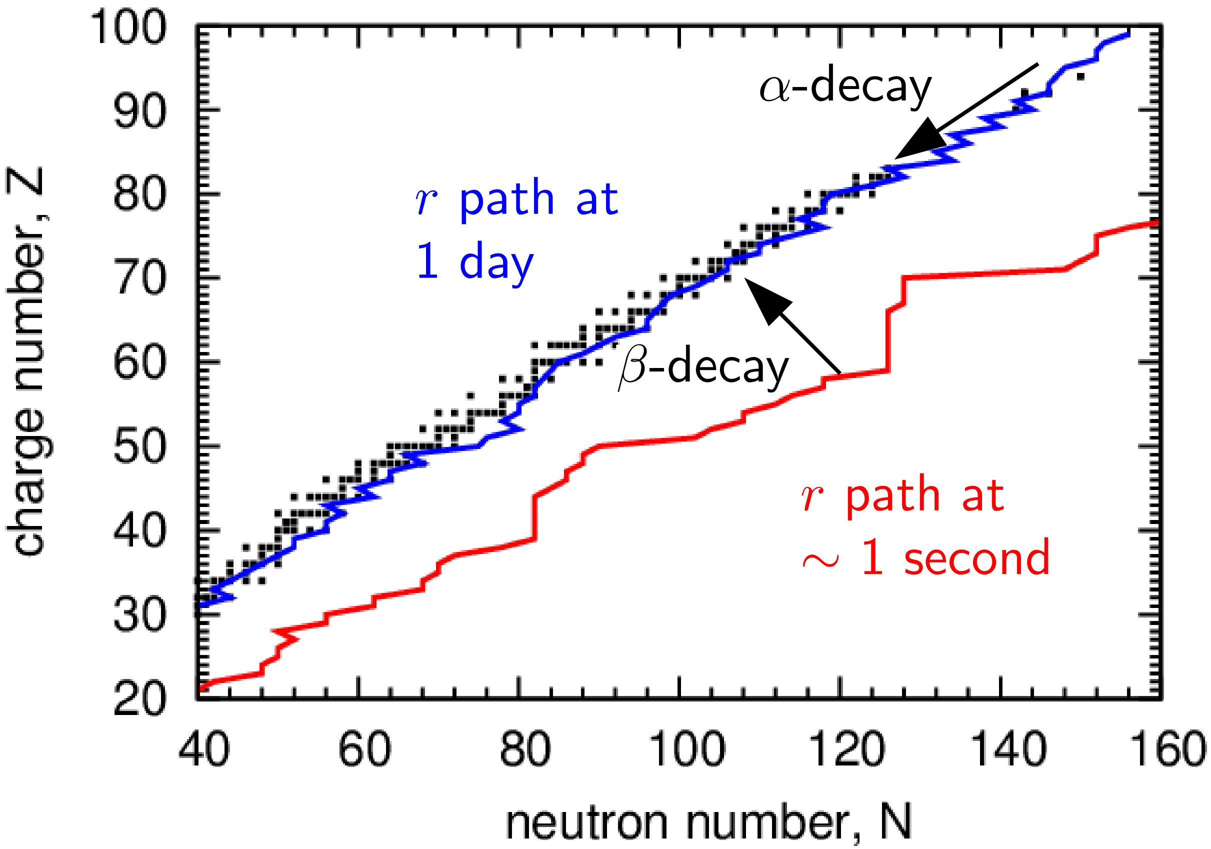
Radioactive decay of the r-process nuclei

The nuclear energy release from the radioactive decay of the r-process nuclei is the source powering the kilonovae [e.g., Arnett's law: $\mathrm{L}(\mathrm{t}_{\mathrm{peak}}) = \dot{\varepsilon}(t_{\mathrm{peak}})$]



At $\sim$ a day, the nuclear properties, e.g., the half-lives, the Q-value, are known. However, their abundances are determined by the initial astrophysical conditions and the unknown properties of the neutron-rich nuclei.

Abundances and heating rates

- Parametrized trajectories characterized by the initial Y_e, entropy s, and expansion timescale $\tau_{\rm dyn}$ at 6 GK (see e.g., Lippuner & Roberts 2016).

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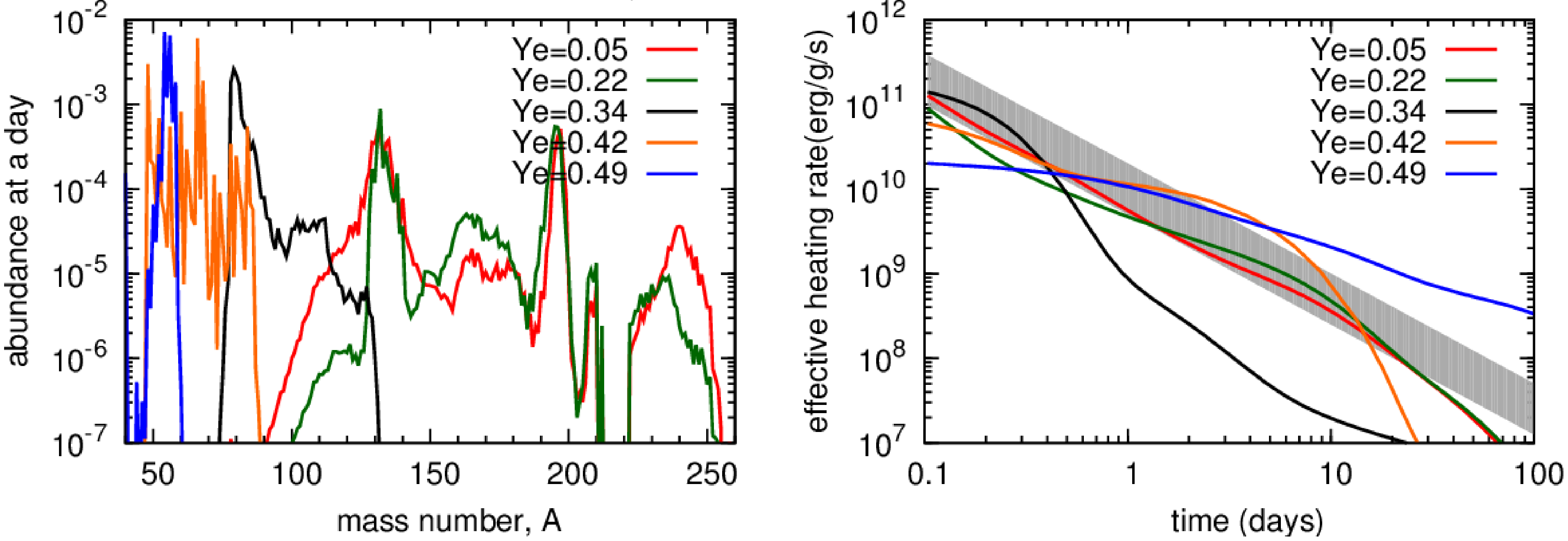

Effective heating rate $= 0.25 \times \dot{Q}_\beta + \dot{Q}_\alpha + \dot{Q}_{\rm fis}$

Analytical heating rate $= 10^{10} \times t_{\rm d}^{-1.3}$ erg/g/s

Y_e dependence

Colors: ratio between the effective heating rate and the analytical heating rate

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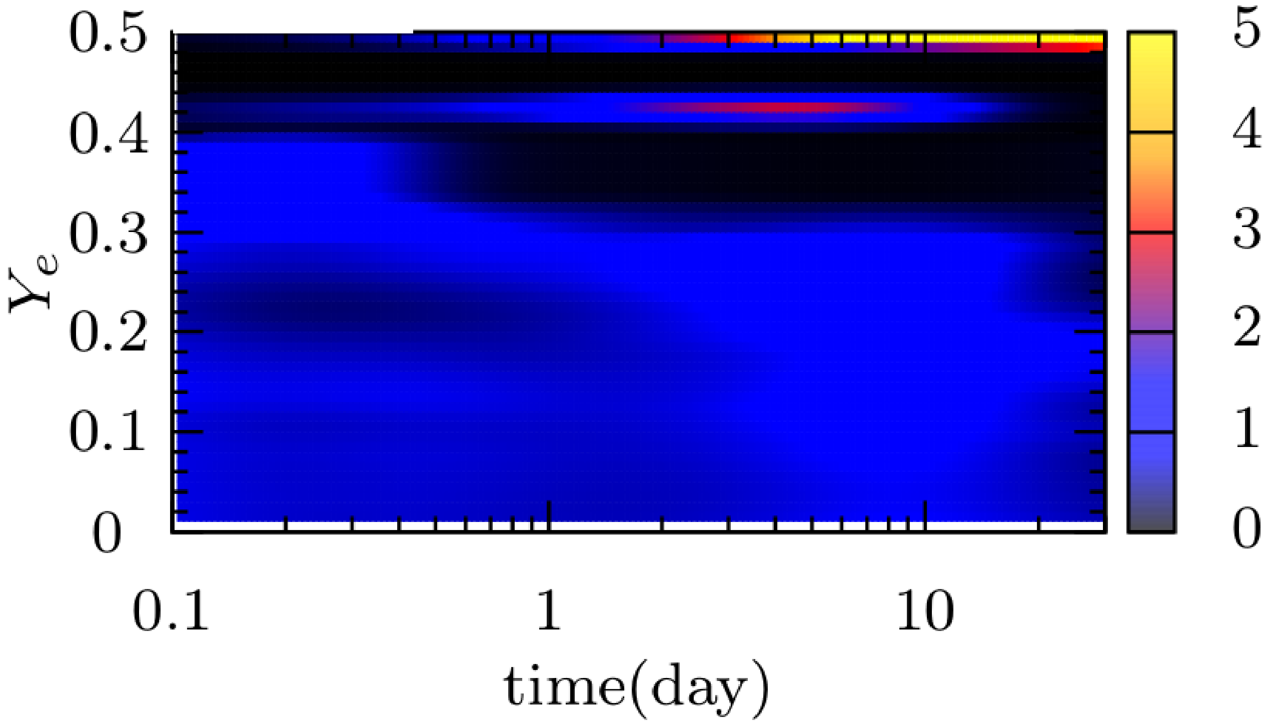
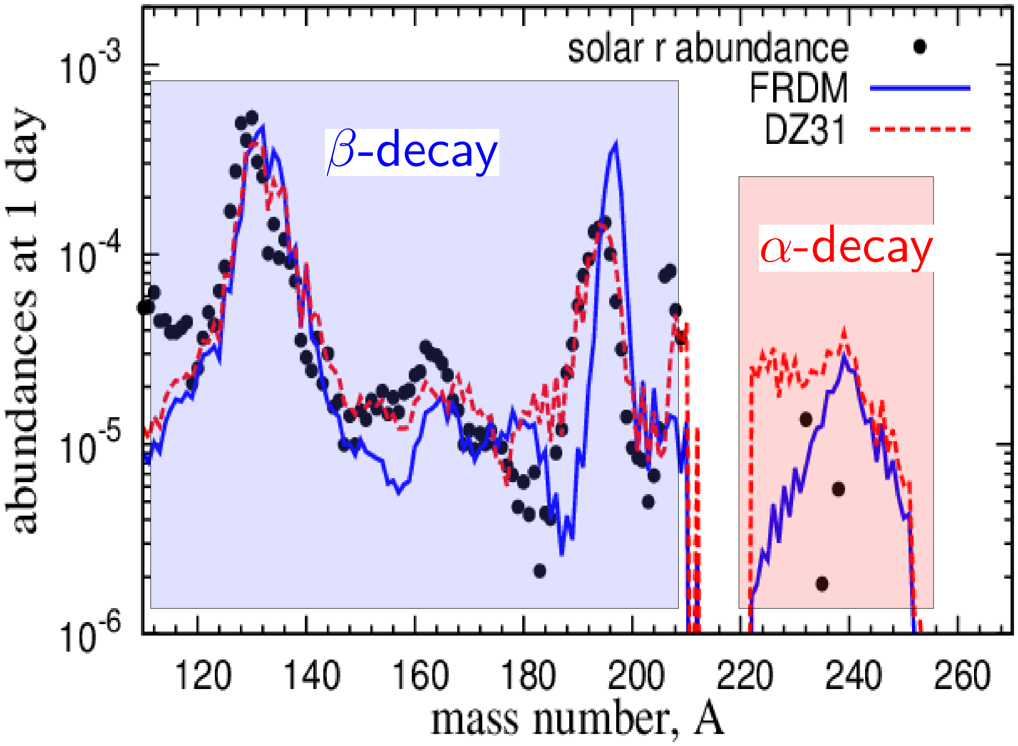
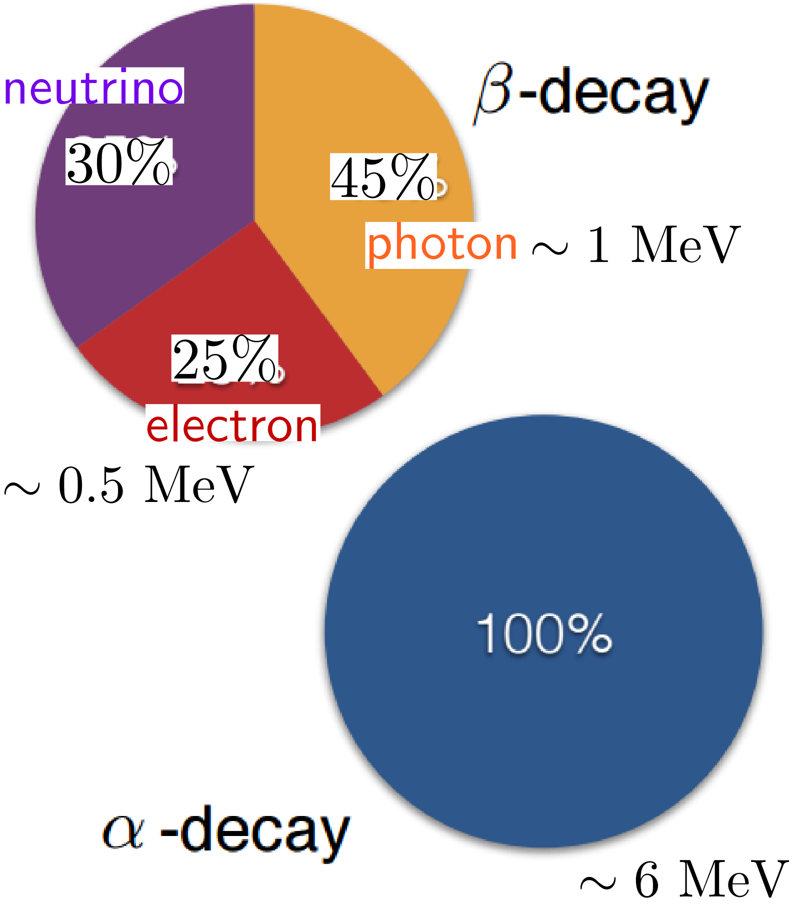


- relative little heating power for $Y_e \gtrsim 0.3$
- more or less agree with the analytical heating rate for $Y_e \lesssim 0.3$

Nuclear physics impact on kilonova heating

For ejecta with very low $Y_e \lesssim 0.1$, initially cold ($s \sim 1$ per nucleon), different nuclear mass inputs can give rise to large abundance difference for $220 \lesssim A \lesssim 240$





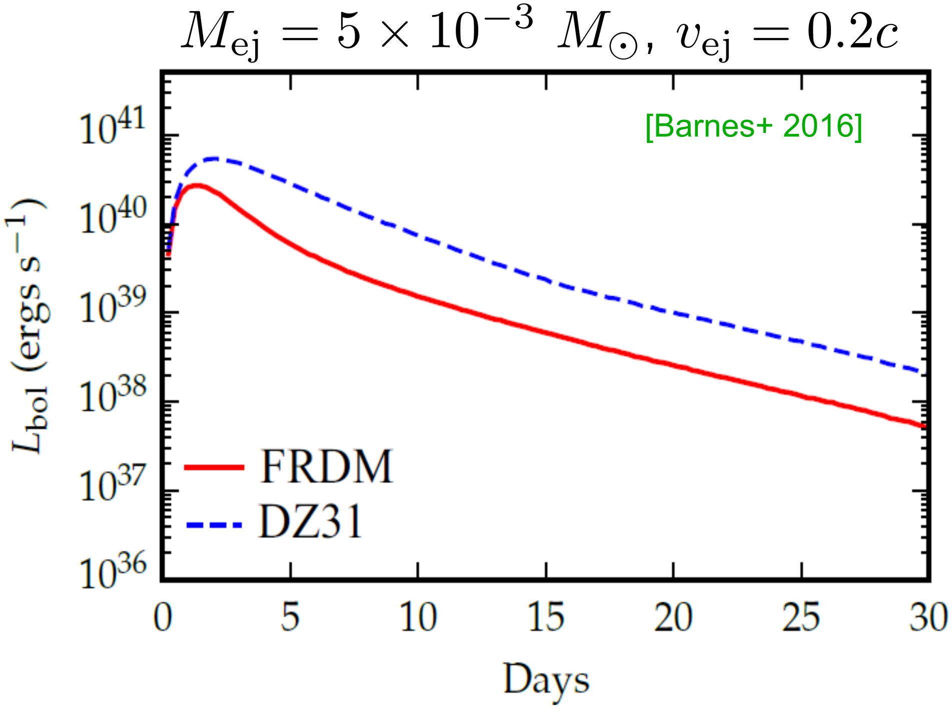
[Barnes+ 2016]

Nuclear physics impact on kilonova heating

- α decays may release similar amount of energy as β decays per second, sensitively depending on the adopted nuclear mass model

- α & β particles thermalize in a similar way while γ-ray thermalization quickly become inefficient

[Hotokezaka+2016, Barnes+2016]



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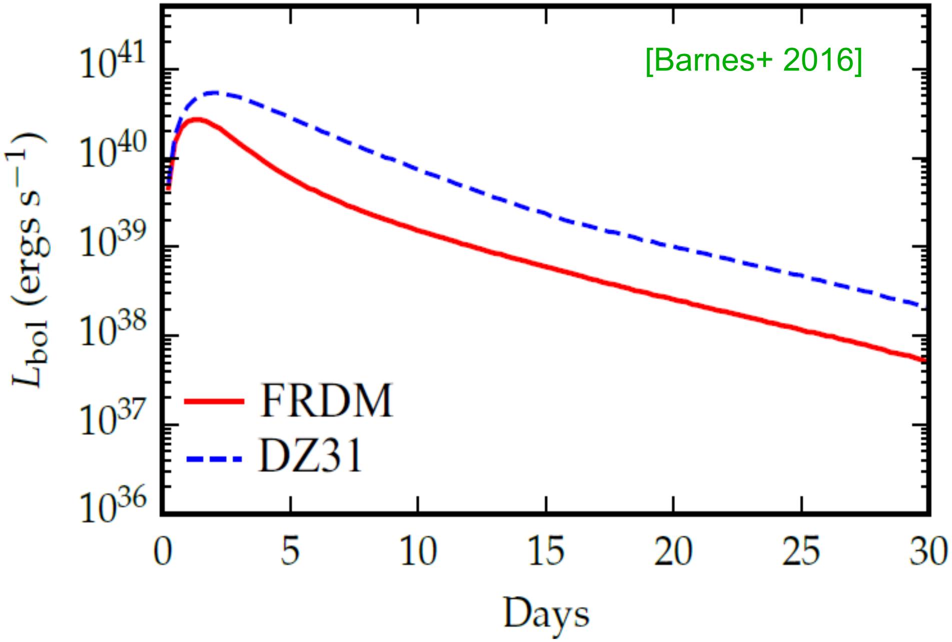
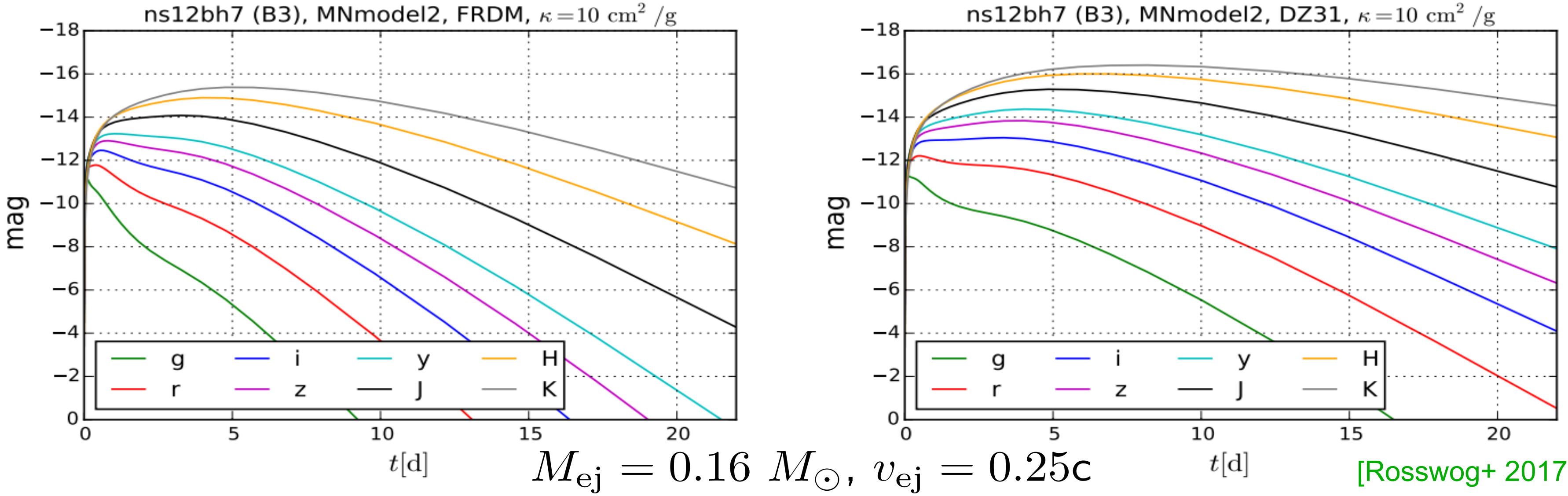
$$M_{\rm ej} = 5 \times 10^{-3}\ M_\odot,\ v_{\rm ej} = 0.2c$$



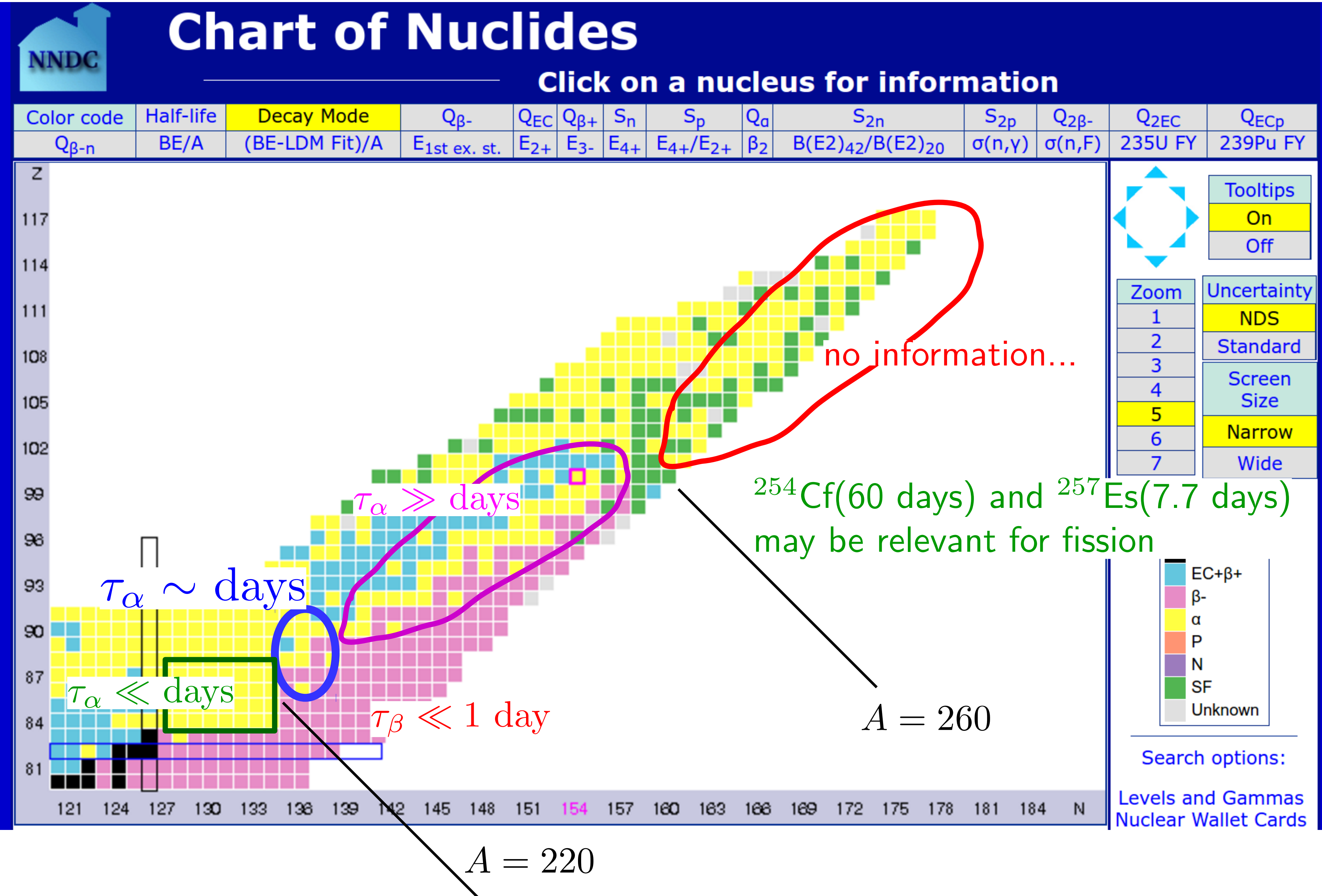
[Barnes+ 2016]



$$M_{\rm ej} = 0.16\ M_\odot,\ v_{\rm ej} = 0.25{\rm c}$$

[Rosswog+ 2017]

what heavy nuclei can be relevant for kilonova heating?



no information...

$\tau_\alpha \gg$ days

^{254}Cf(60 days) and ^{257}Es(7.7 days) may be relevant for fission

$\tau_\alpha \sim$ days

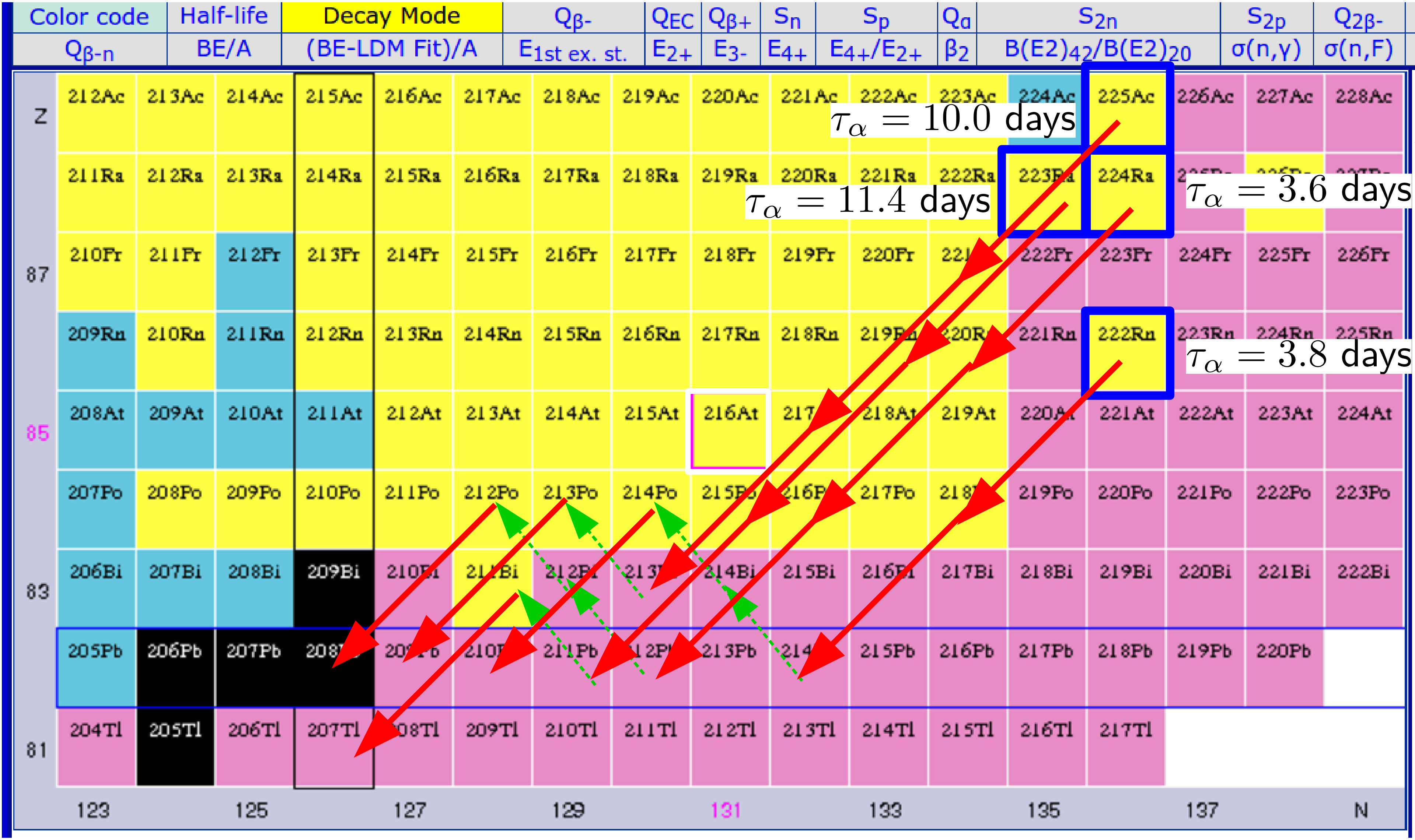
$\tau_\alpha \ll$ days

$\tau_\beta \ll 1$ day

$A = 260$

$A = 220$

α decay chains at days to weeks



Z	212Ac	213Ac	214Ac	215Ac	216Ac	217Ac	218Ac	219Ac	220Ac	221Ac	222Ac	223Ac	224Ac	225Ac	226Ac	227Ac	228Ac
	211Ra	212Ra	213Ra	214Ra	215Ra	216Ra	217Ra	218Ra	219Ra	220Ra	221Ra	222Ra	223Ra	224Ra	[illegible]	[illegible]	[illegible]
87	210Fr	211Fr	212Fr	213Fr	214Fr	215Fr	216Fr	217Fr	218Fr	219Fr	220Fr	221	222Fr	223Fr	224Fr	225Fr	226Fr
	209Rn	210Rn	211Rn	212Rn	213Rn	214Rn	215Rn	216Rn	217Rn	218Rn	219R	220R	221Rn	222Rn	223Rn	224Rn	225Rn
85	208At	209At	210At	211At	212At	213At	214At	215At	216At	217	218At	219At	220A	221At	222At	223At	224At
	207Po	208Po	209Po	210Po	211Po	212Po	213Po	214Po	215P	216P	217Po	218	219Po	220Po	221Po	222Po	223Po
83	206Bi	207Bi	208Bi	209Bi	210Bi	211Bi	212Bi	213	214Bi	215Bi	216Bi	217Bi	218Bi	219Bi	220Bi	221Bi	222Bi
	205Pb	206Pb	207Pb	208	209Pb	210	211Pb	212P	213Pb	214	215Pb	216Pb	217Pb	218Pb	219Pb	220Pb	
81	204Tl	205Tl	206Tl	207Tl	208Tl	209Tl	210Tl	211Tl	212Tl	213Tl	214Tl	215Tl	216Tl	217Tl			
	123		125		127		129		131		133		135		137		N

$\tau_\alpha = 10.0$ days

$\tau_\alpha = 11.4$ days

$\tau_\alpha = 3.6$ days

$\tau_\alpha = 3.8$ days

production of actinides

How neutron-rich may the α-decay be important?

Initially, $Y_n^0 = 1 - Y_e$, $Y_p^0 = Y_e$

Assuming all protons are locked in seed nuclei, right before n-captures

$$R_{n/s} = \frac{Y_n}{Y_{\rm seed}} = \frac{Y_n^0 - N_{\rm seed}(Y_p^0/Z_{\rm seed})}{(Y_p^0/Z_{\rm seed})}$$

$$\langle A \rangle_{\rm final} \approx A_{\rm seed} + R_{n/s}$$

To have nuclei with $A \sim 220 - 230$ that may alpha decay at relevant time,

$$\langle A \rangle_{\rm final} \approx 190$$

With $N_{\rm seed} \approx 50$, $Z_{\rm seed} \approx 30$, it gives $Y_e = 0.16$.

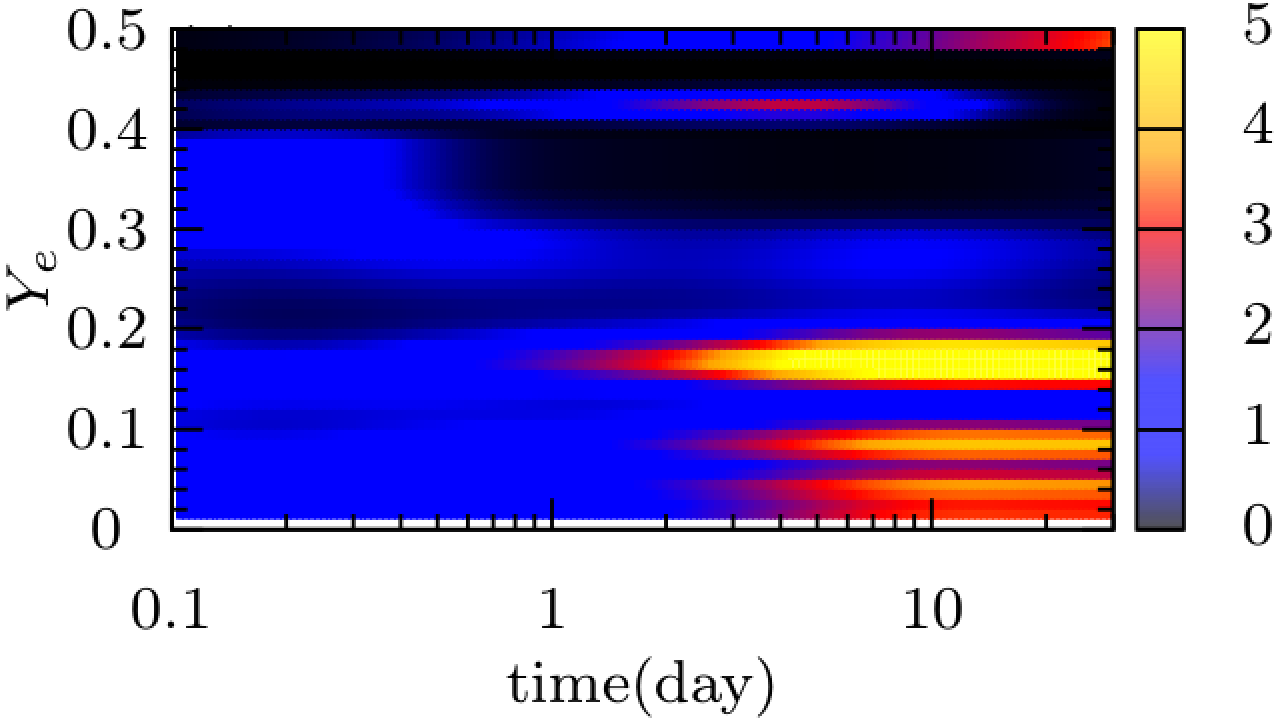
$\rightarrow$ α-heating may become dominant for ejecta with $Y_e \lesssim 0.2$

Y_e dependence with DZ31 nuclear mass model

- vary the (n, γ) and (γ, n) rates for $35 \leq Z \leq 83$ [Mendoza-Temis+ 2015]

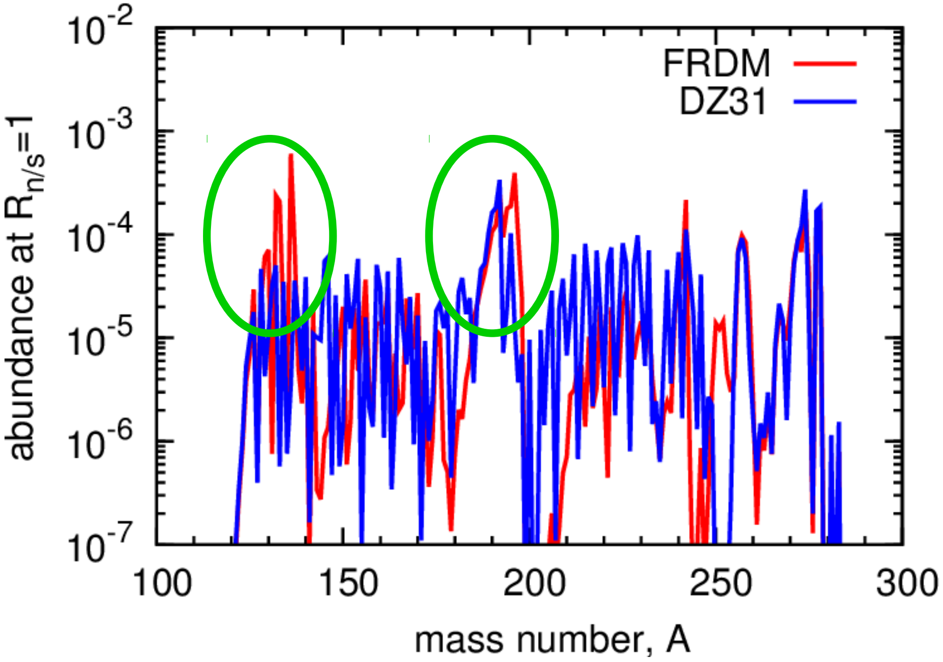
Colors: ratio between the effective heating rate and the analytical heating rate

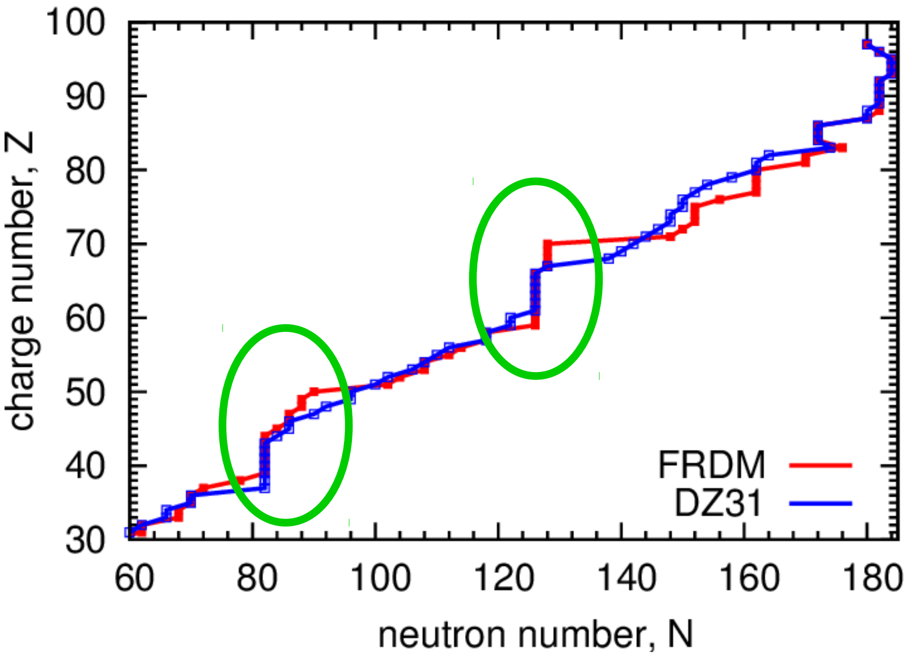
s/nucleon$= 1$, $\tau_{\rm dyn} = 1$ ms, DZ31 mass model



- the heating rate nearly unaffected for $Y_e \gtrsim 0.25$
- large enhancement due to α-decay up to $Y_e \lesssim 0.2$ for $t \gtrsim 3$ days
- the heating rate enhancement oscillates as Y_e changes

FRDM v.s. DZ31



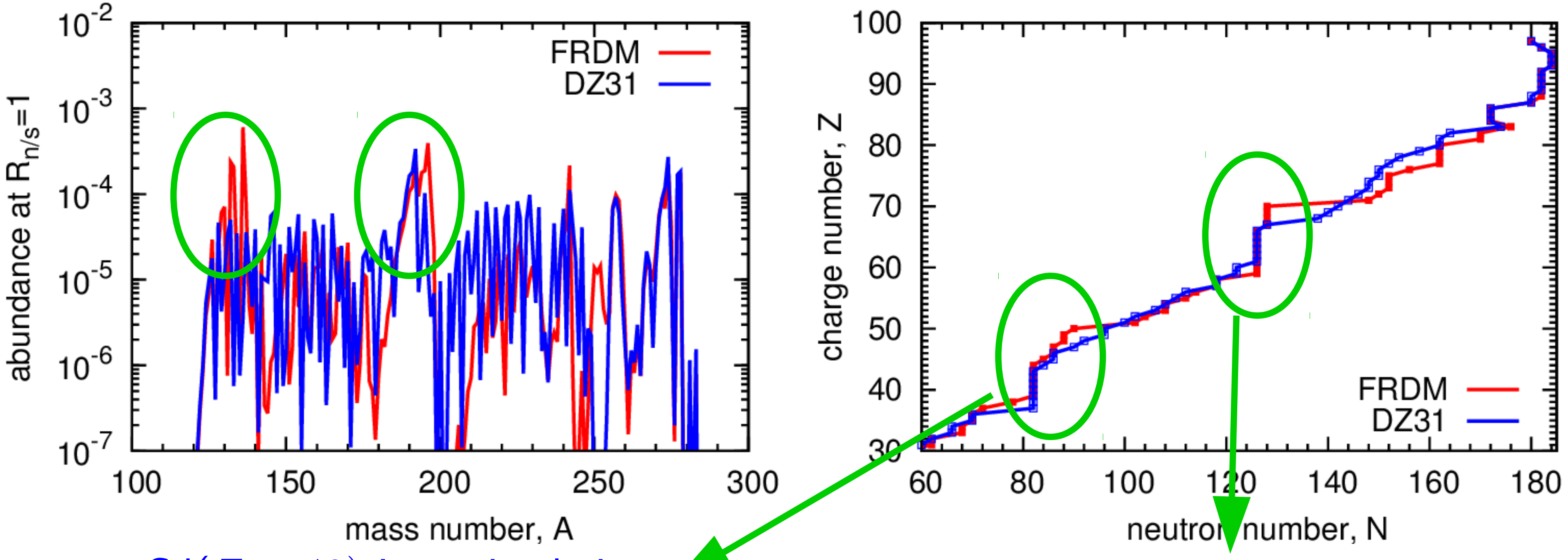


the r-process path with FRDM mass model extends to larger Z for regions slightly above the shell closure

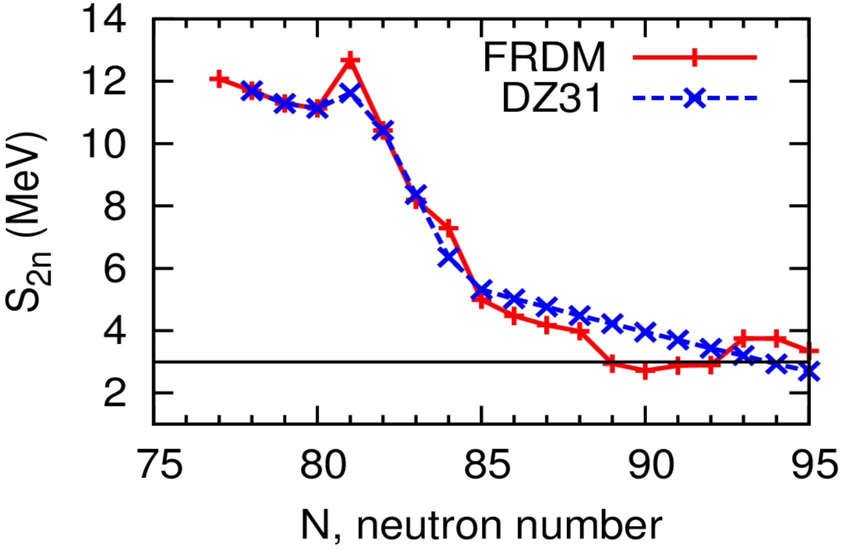
$\rightarrow$ longer β-decay half-lives

$\rightarrow$ larger abundances at peaks and smaller abundances in-between the peaks

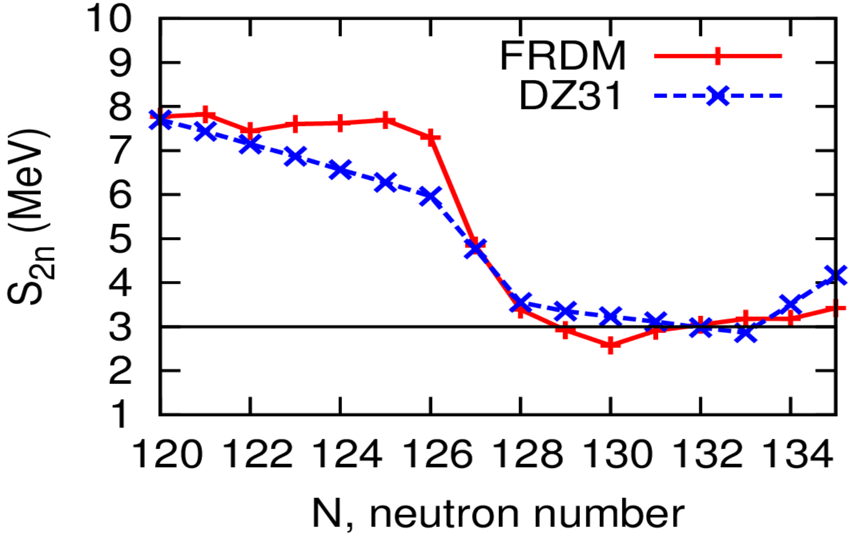
FRDM v.s. DZ31



Cd$(Z = 48)$ isotopic chain



Er$(Z = 68)$ isotopic chain



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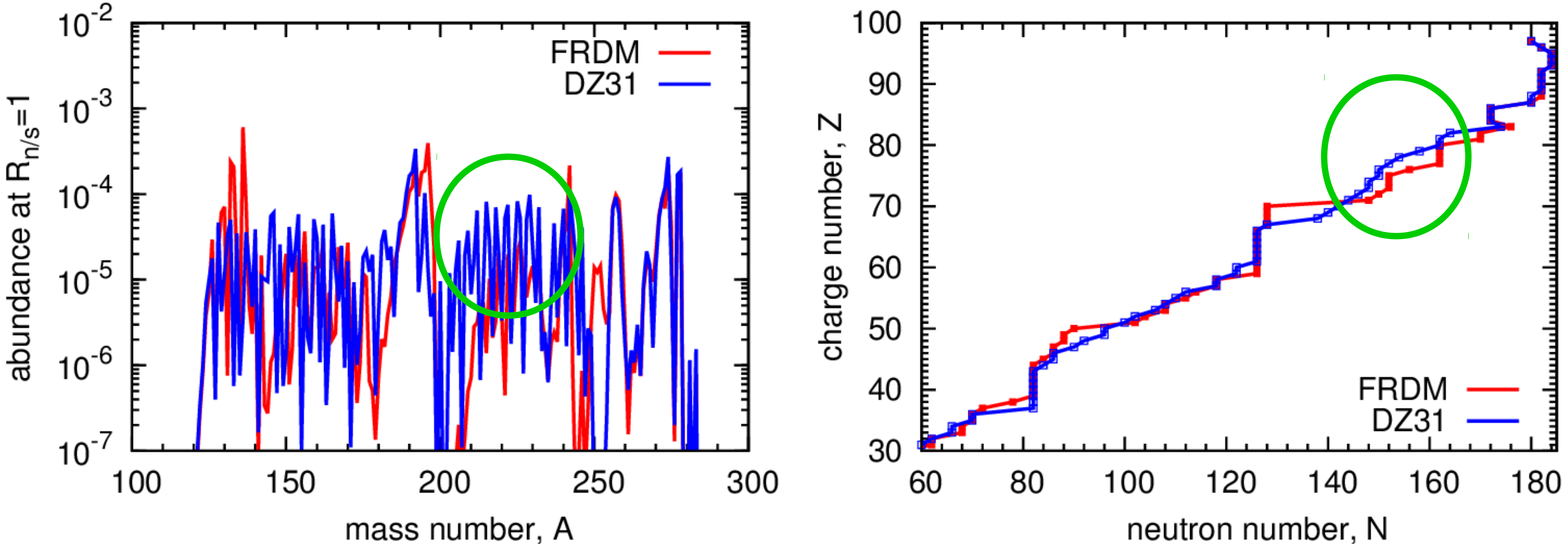
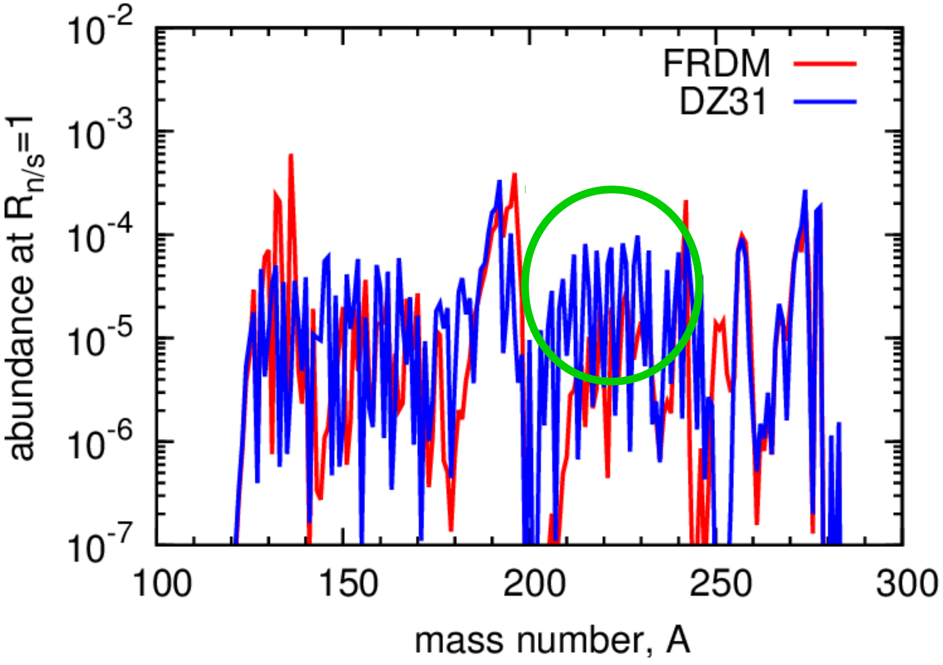


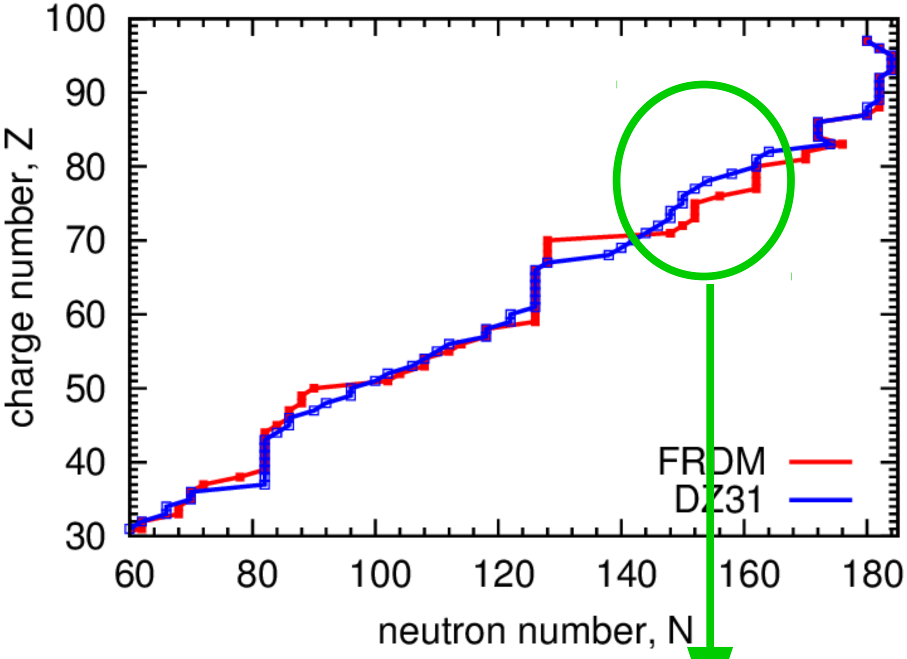
on the other hand, at the region around $A \sim 230$, the path of FRDM extends to larger N

$\rightarrow$ shorter β-decay half-lives

$\rightarrow$ smaller abundances

FRDM v.s. DZ31





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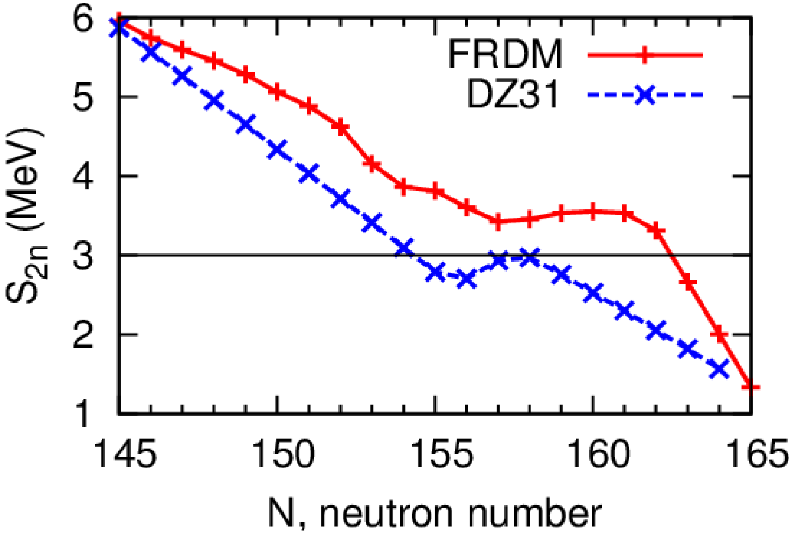
→ smaller abundances

Pt$(Z = 78)$ isotopic chain



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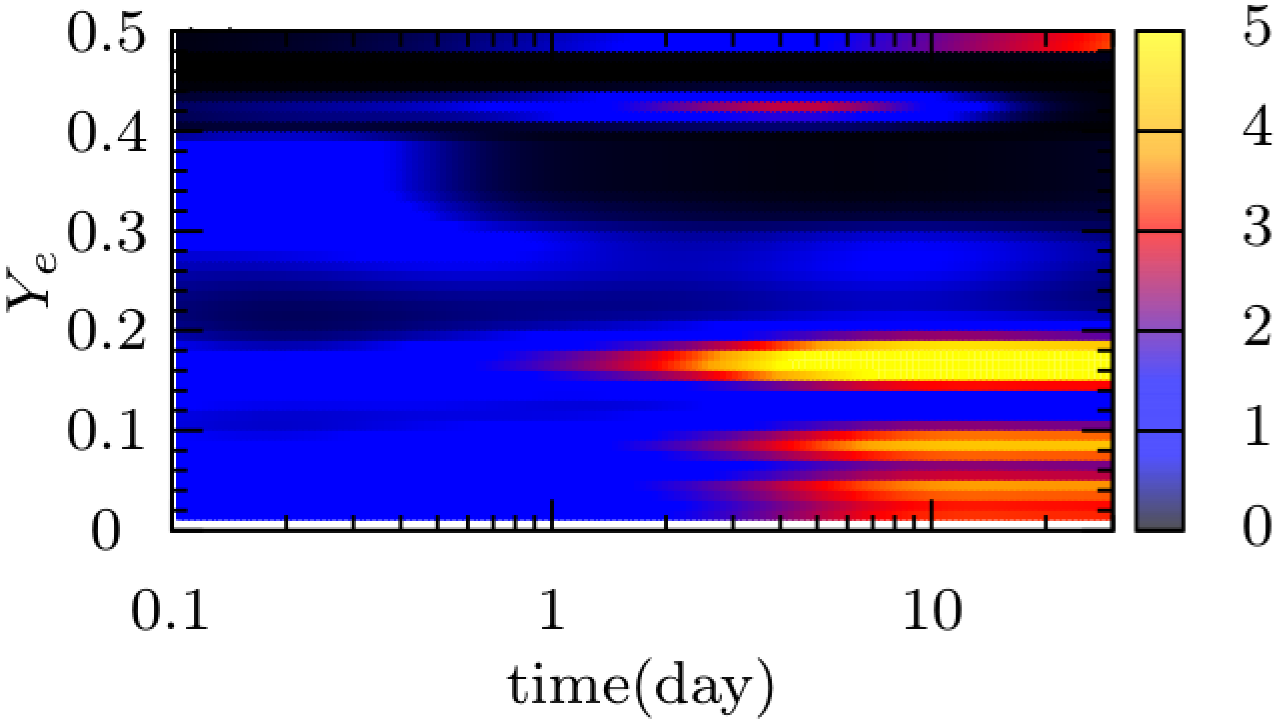

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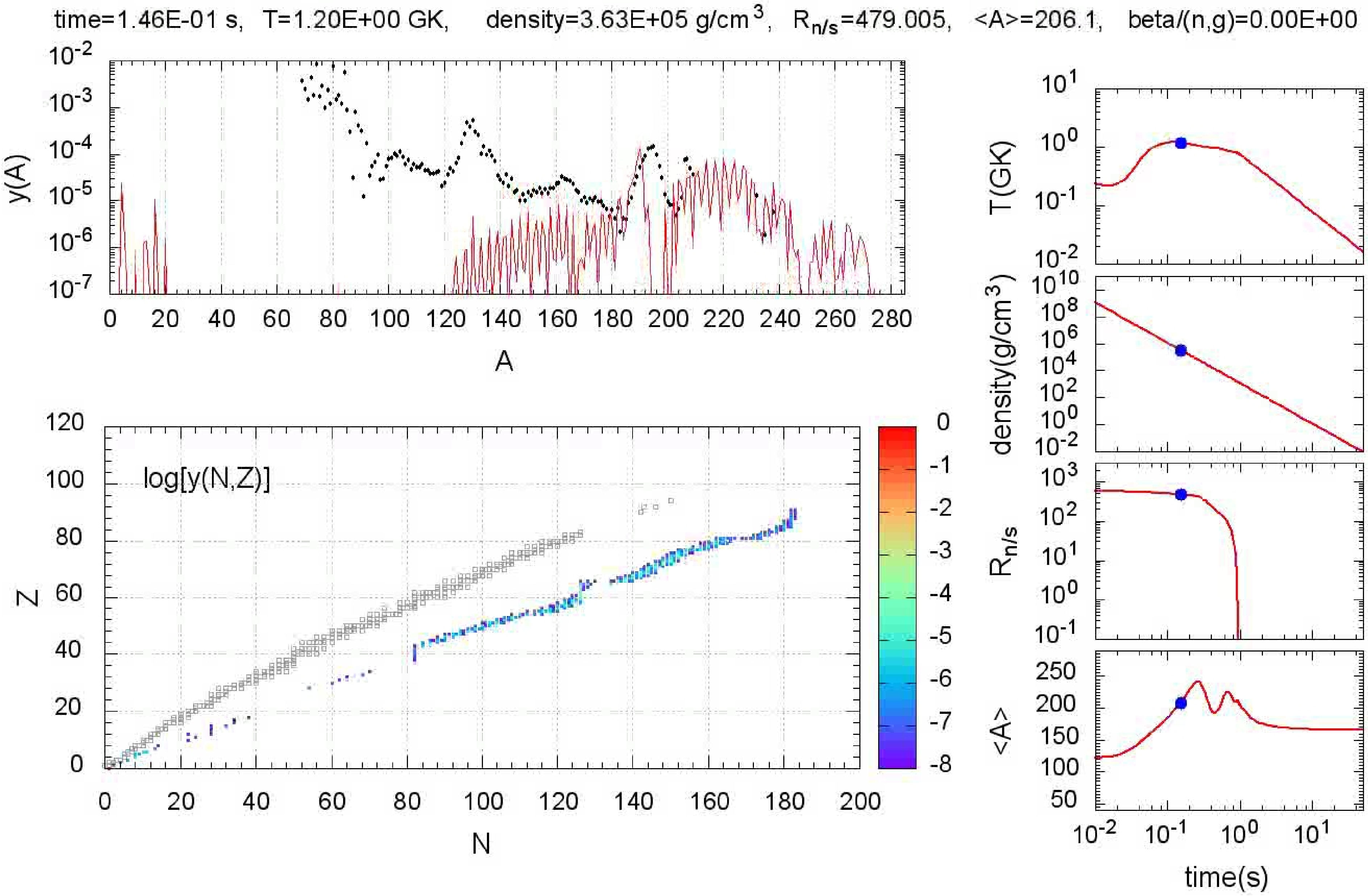
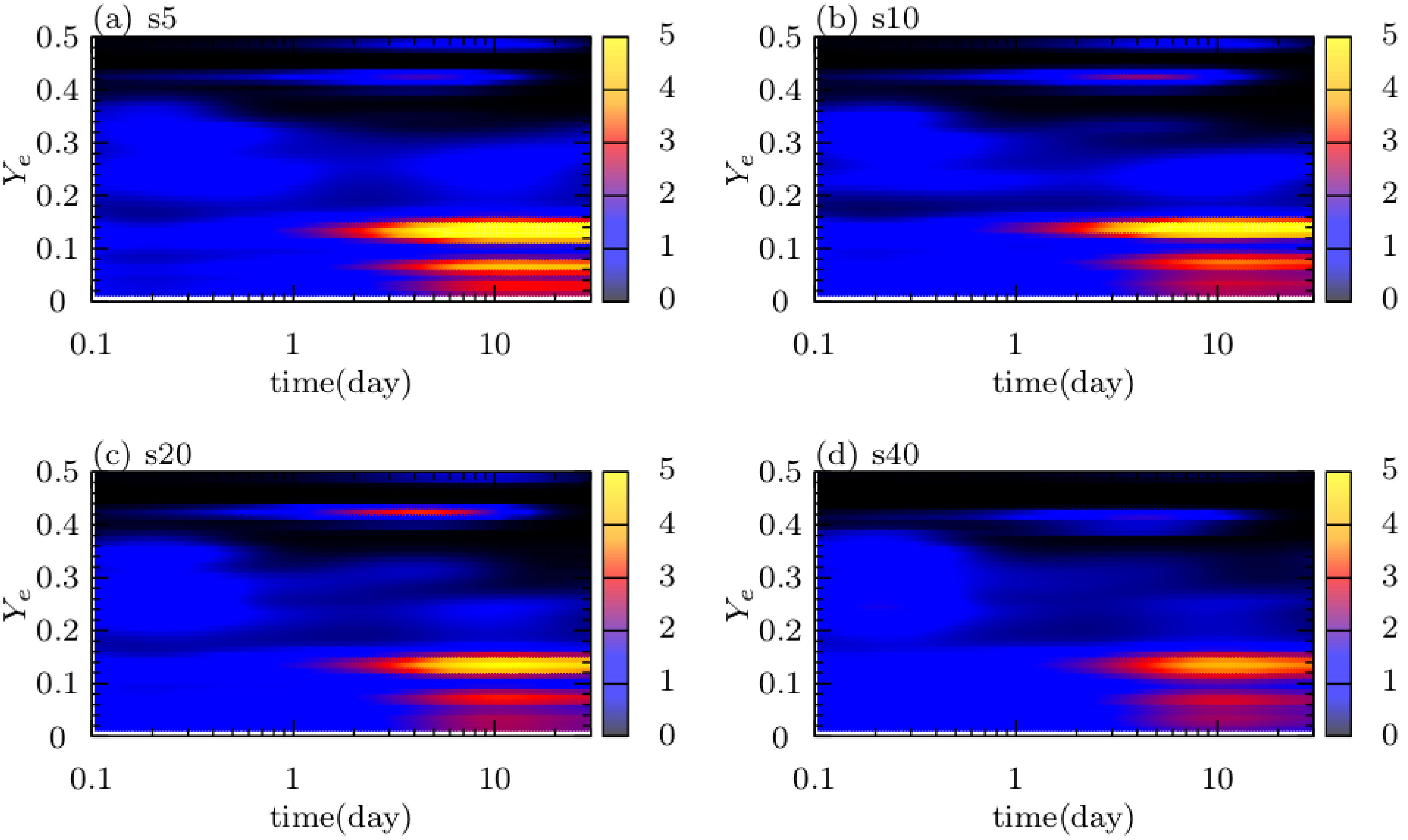


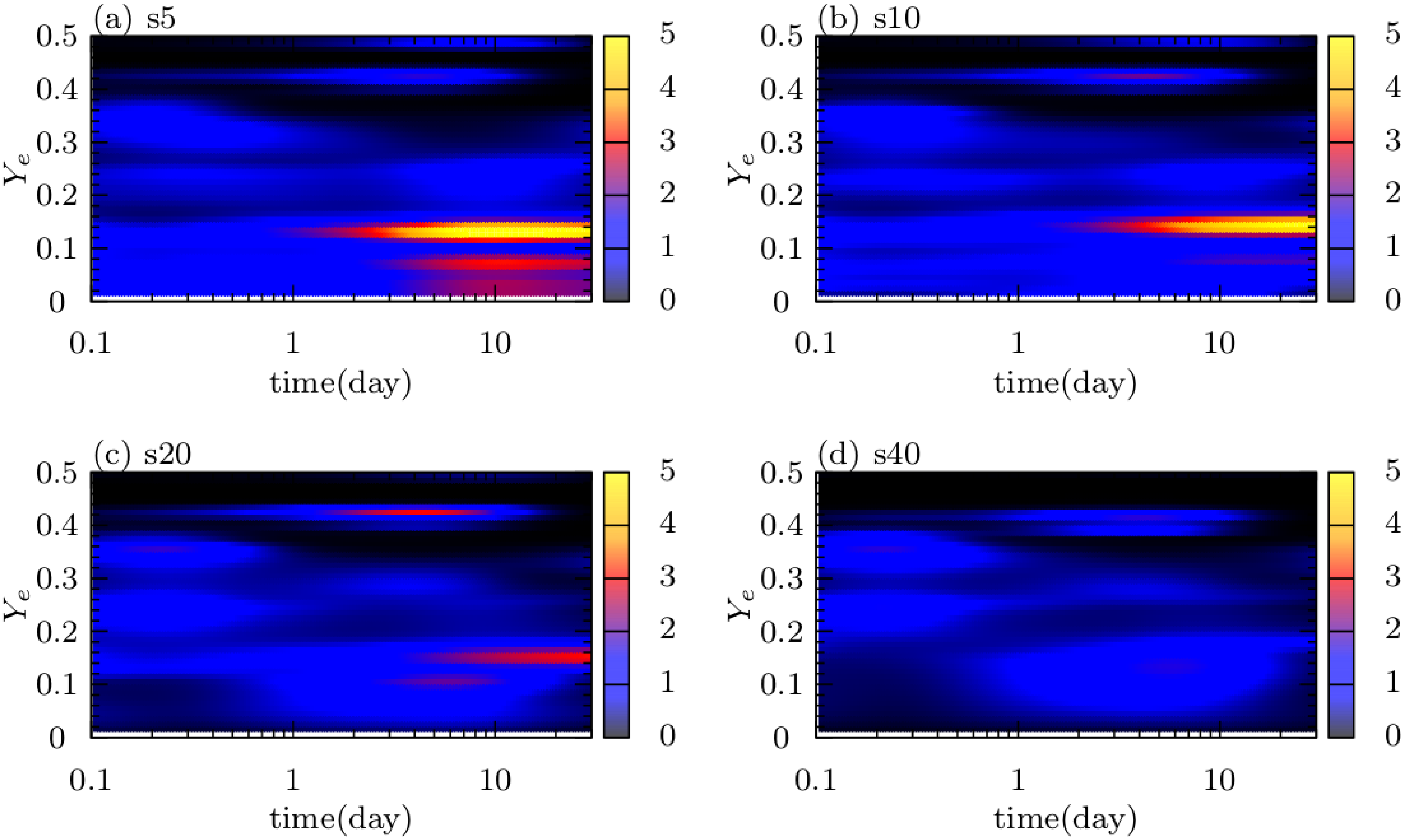
Y_e dependence with DZ31 nuclear mass model

- different entropy, for $\tau_{\mathrm{dyn}} = 10$ ms

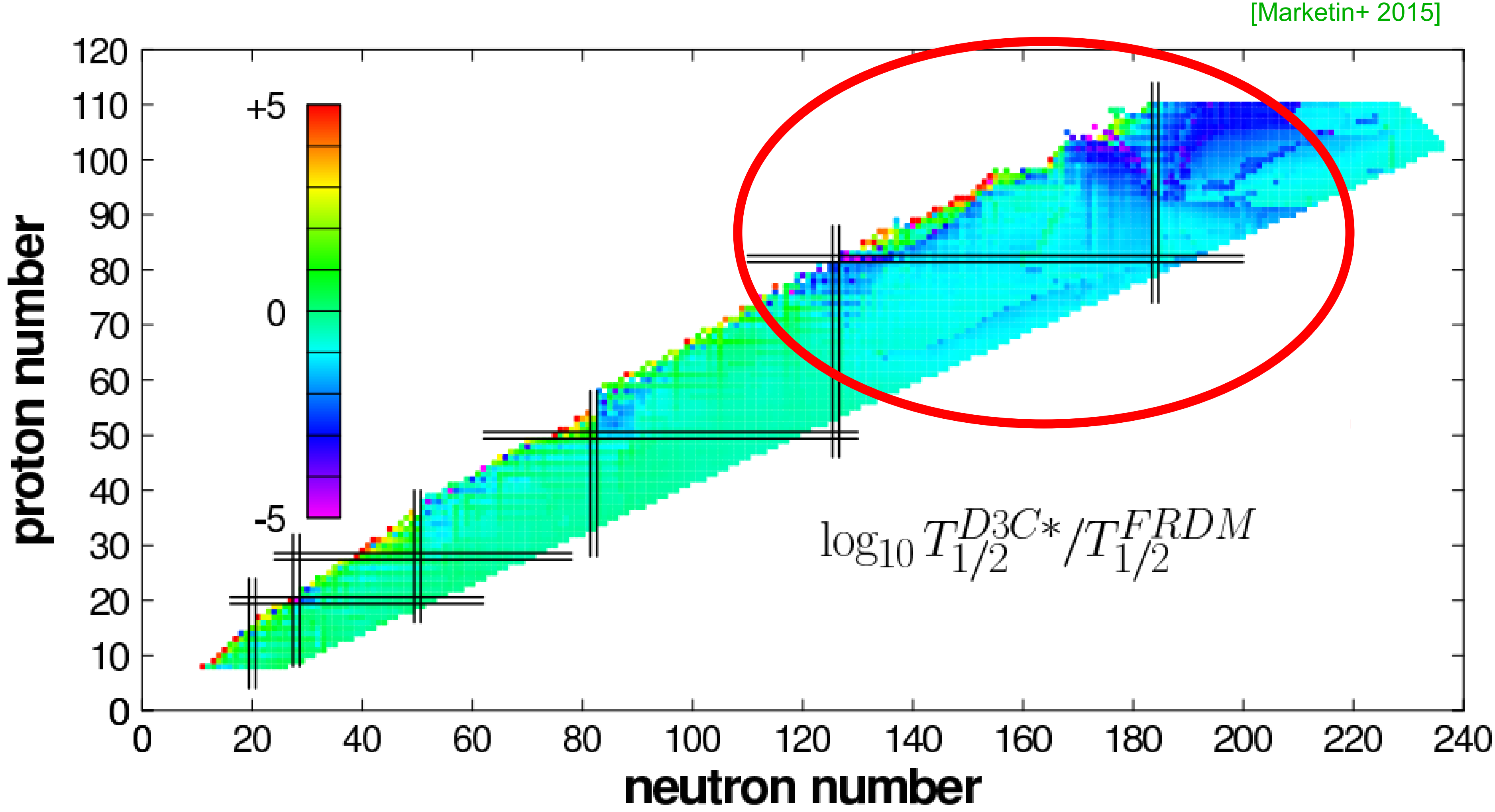


Y_e dependence with DZ31 nuclear mass model

- different entropy, for $\tau_{\mathrm{dyn}} = 1$ ms



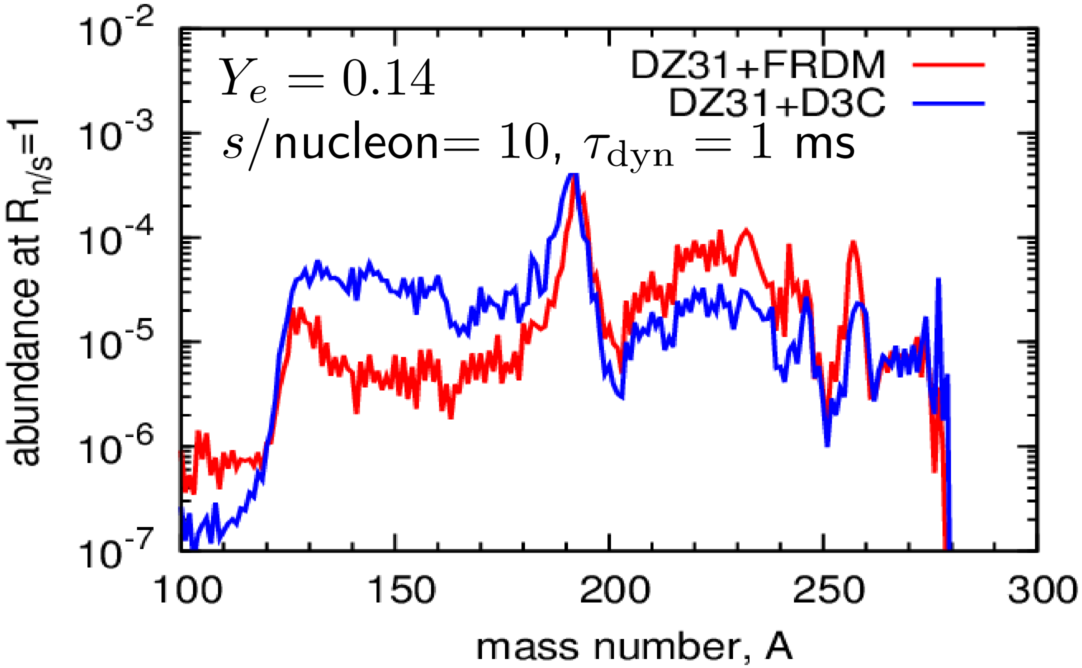
Impact of β-decay rates



D3C* model predicts shorter τ_β for heavier nuclei

Impact of β-decay rates

- more lanthanides and less actinides with D3C* β-decay half-lives



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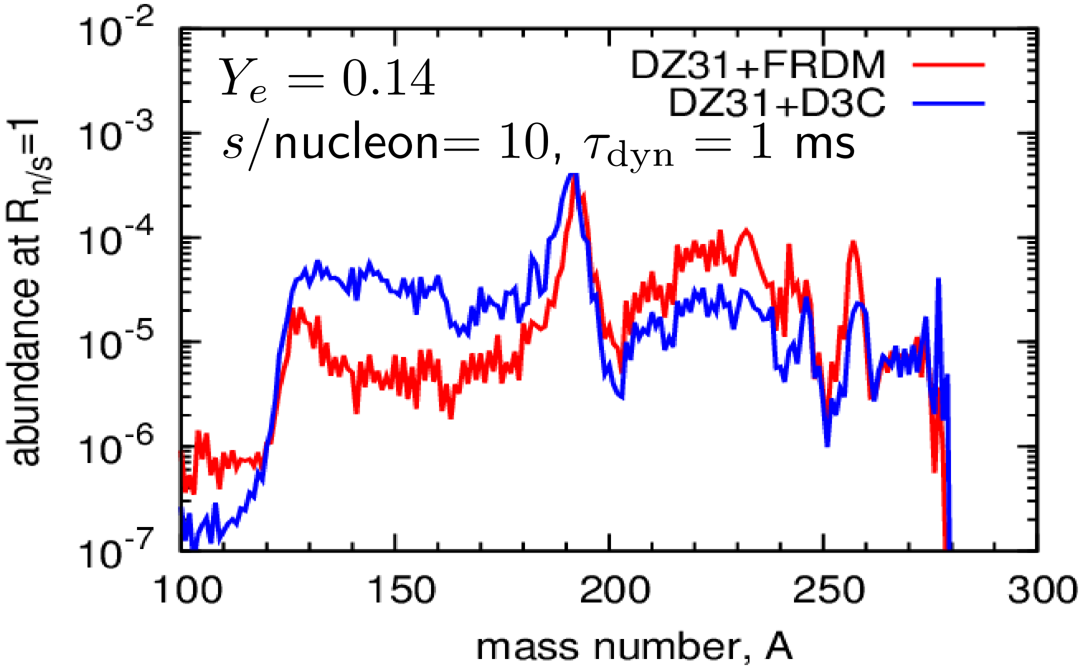

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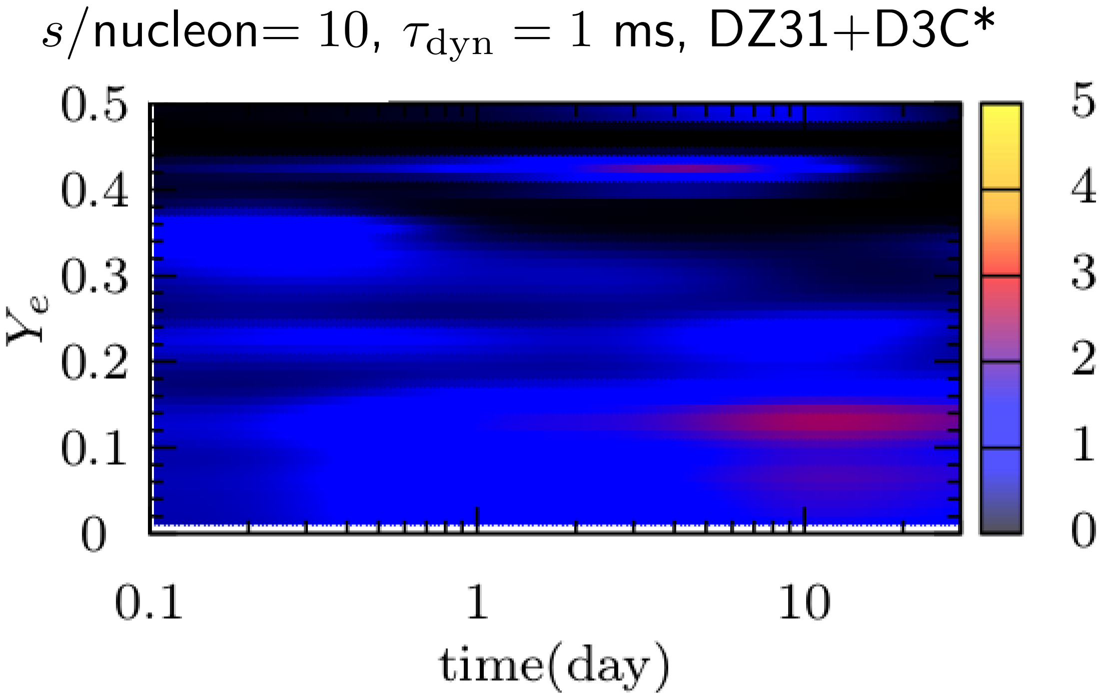

- less energy release due to the α-decay

Summary

- The radioactive energy release duing the kilonova time is insensitive to the nuclear physics inputs for $Y_e \gtrsim 0.25$.
- The nuclear heating rate can be sensitive to the composition, e.g., for ejecta with $Y_e \gtrsim 0.3$, the radioactive energy release is significantly smaller when compared to $Y_e \lesssim 0.3$.
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- For $Y_e \lesssim 0.2$, the theoretical inputs of the radioactive heating rates are subject to the uncertain nuclear physics properties of neutron-rich nuclei and can vary by a factor of ~ 5–10.

– more systematic sensitivity study is needed to better quantify the uncertainty
– how to reduce the uncertainty?
– how much does the composition-dependent heating rates affect the predicted kilonova lightcurves?