Nuclear uncertainties on the production of radioactive r-process nuclei

Meng-Ru Wu (Niels Bohr Institute)

Electromagnetic Signatures of r-process Nucleosynthesis in Neutron Star Binary Mergers, INT Program INT-17-2b, Seattle, USA, July 24 – August 18, 2017

Nuclear reaction network

$$\dot{Y}_i = \sum_j \mathcal{N}_j^i \lambda_j Y_j + \sum_{j,k} \mathcal{N}_{j,k}^i \rho N_{\mathrm{A}} \langle j,k \rangle Y_j Y_k + \sum_{j,k,l} \mathcal{N}_{j,k,l}^i \rho^2 N_{\mathrm{A}}^2 \langle j,k,l \rangle Y_j Y_k Y_l.$$

one-body reaction: decay, photo-disintegration, spon. & β-delayed fission...

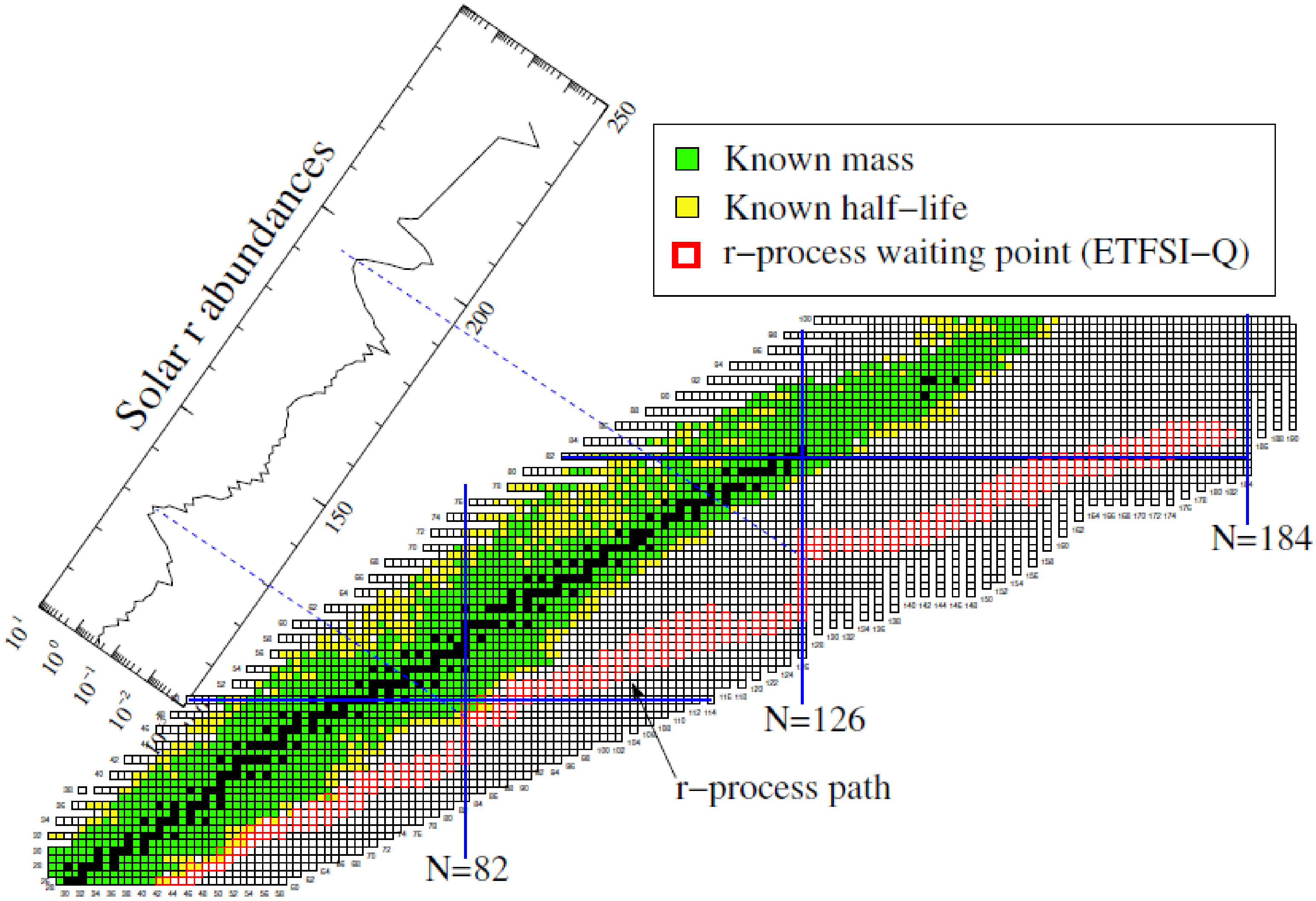
two-body reaction: neutron captures, neutron-induced fission...

three-body reaction: $\alpha\alpha n$, αnn...

temperature evolution coupled to nuclear reactions through entropy change due to nuclear energy release, assuming $pdV = 0$

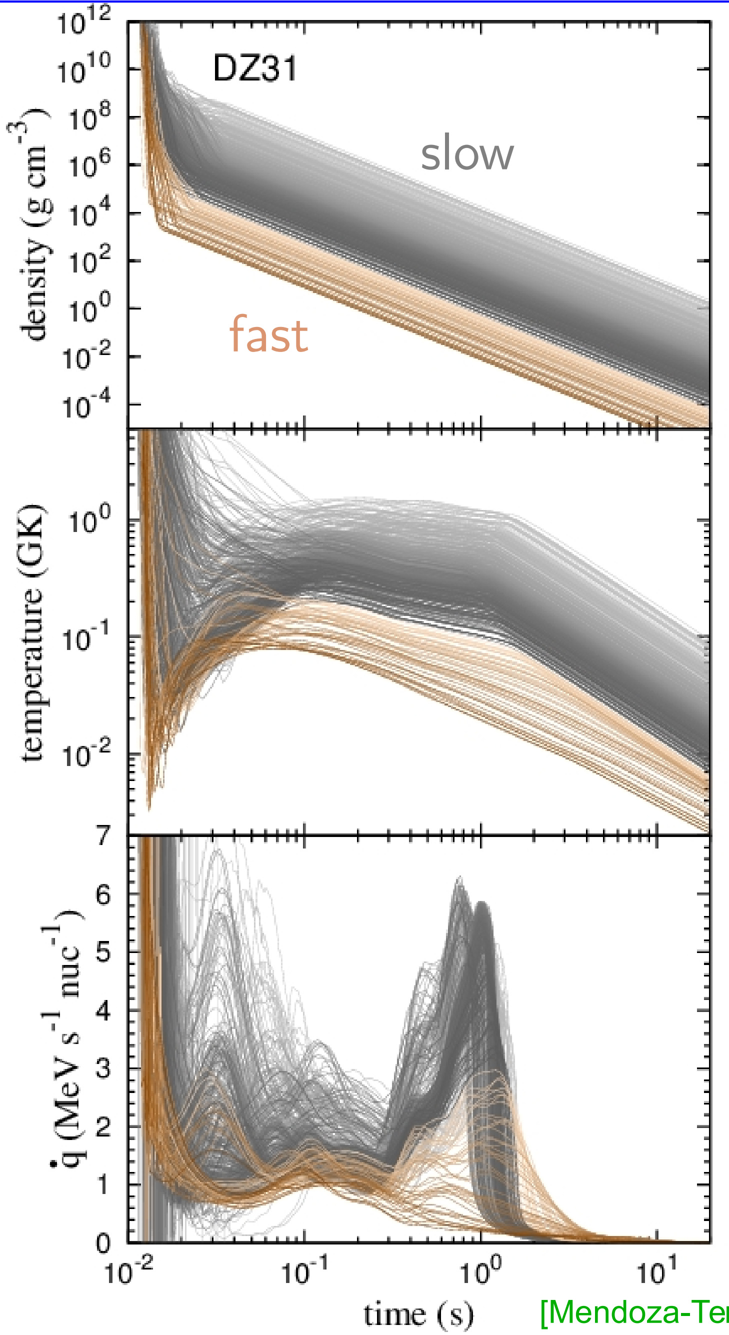
$$\frac{ds}{dt} = -\frac{1}{k_B T} \sum_i \left(m_i c^2 + \mu_i \right) \frac{dY_i}{dt}$$

The initial composition usually determined by NSE for given $\rho(0)$, $T(0)$, $Y_e(0)$. Closed equations with the supply of $\rho(t)$.



largely rely on theoretical nuclear physics inputs...

r-process heating and abaundance evolution



[Mendoza-Temis+ 2015]

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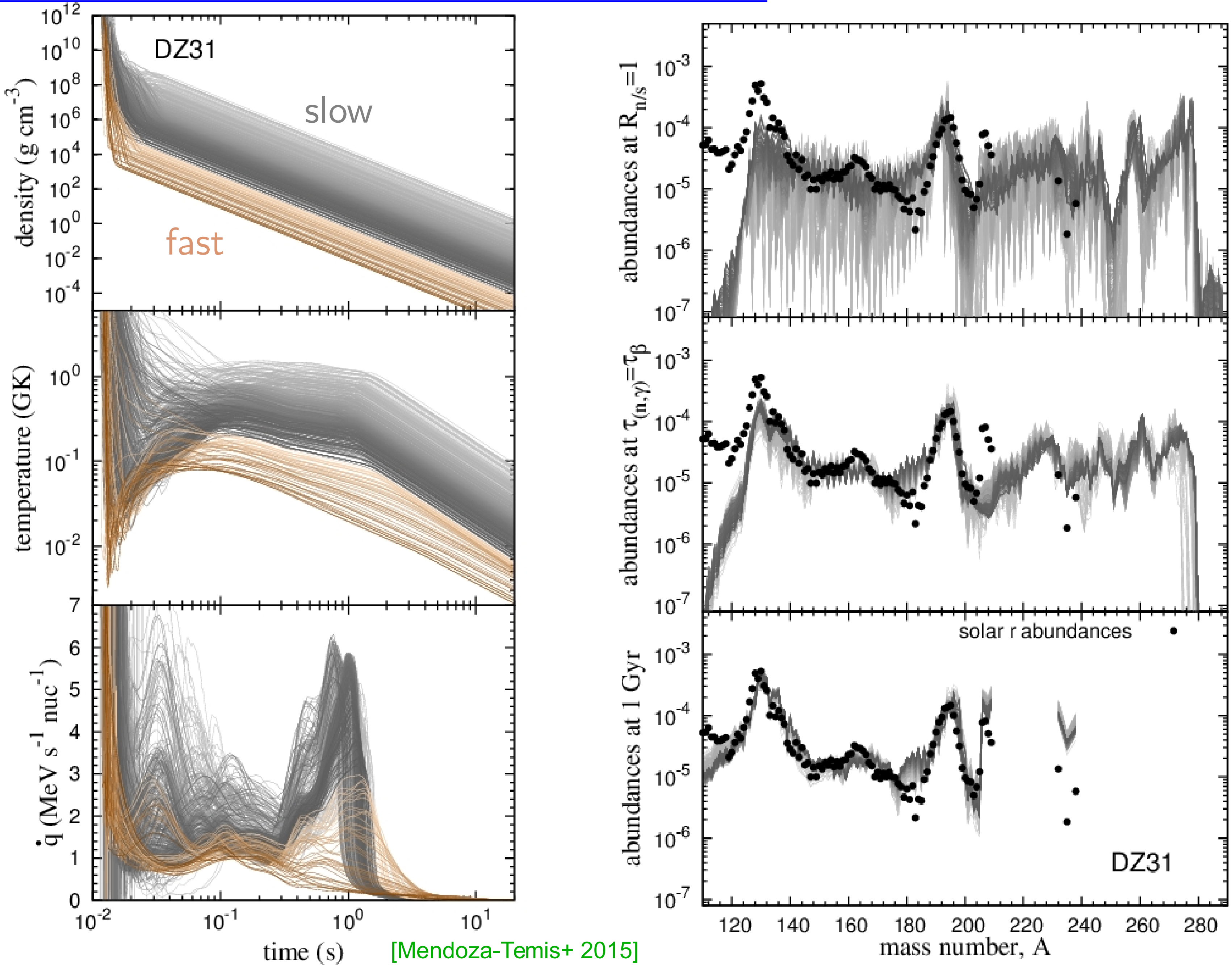
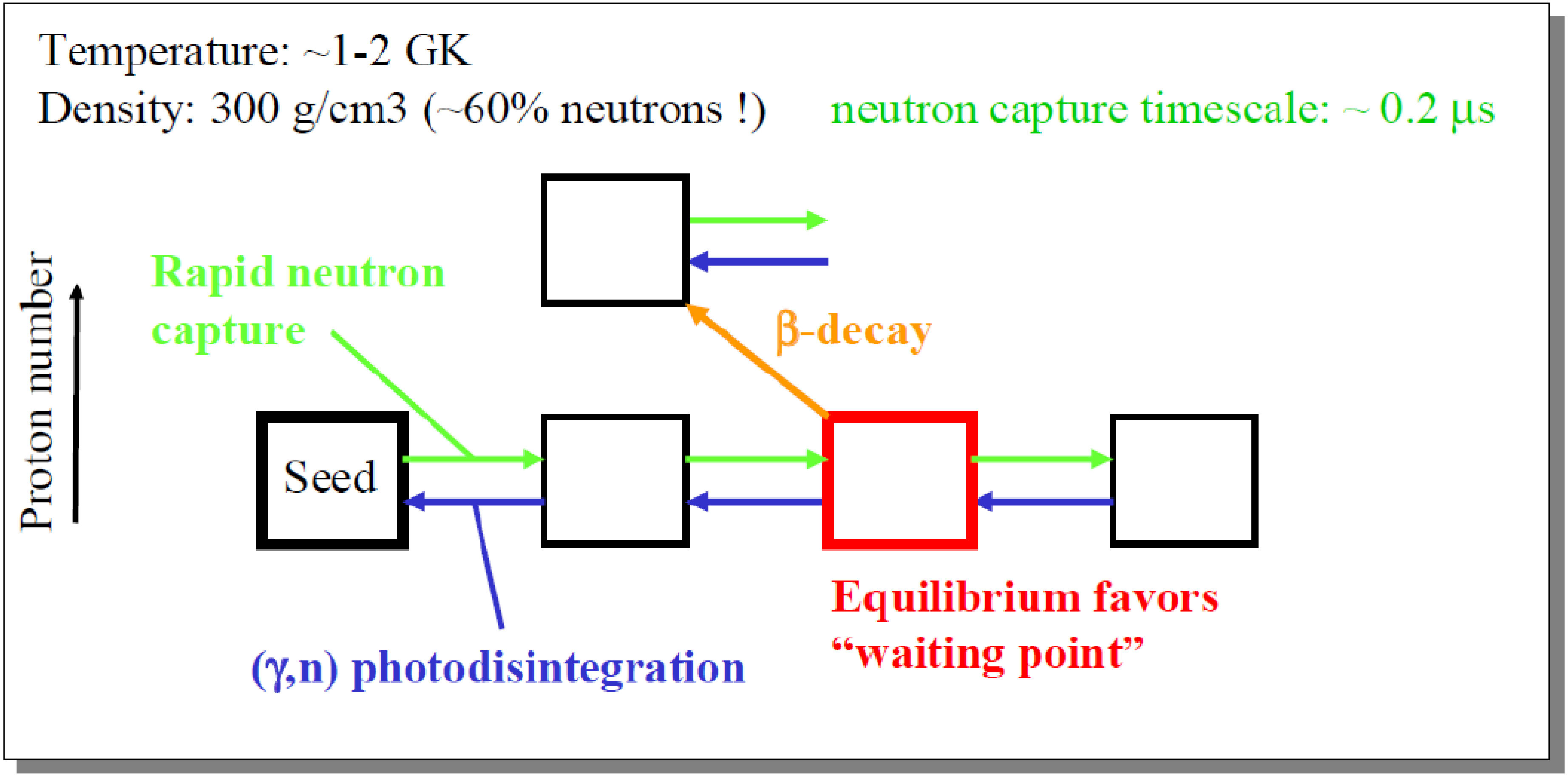


[Mendoza-Temis+ 2015]

What nuclear physics inputs are important?



quasi-equilibrium flow is usually reached during the r-process

nuclear masses

$(n,\gamma) \leftrightarrow (\gamma,n)$ equilibrium:

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

along an isotopic chain, the abundance peaks at nucleus with neutron separation energy $S_n = S_n^0$

$$S_n^0(\mathrm{MeV}) = \frac{T_9}{5.04}\left(34.075 - \log n_n + \frac{3}{2}\log T_9\right)$$

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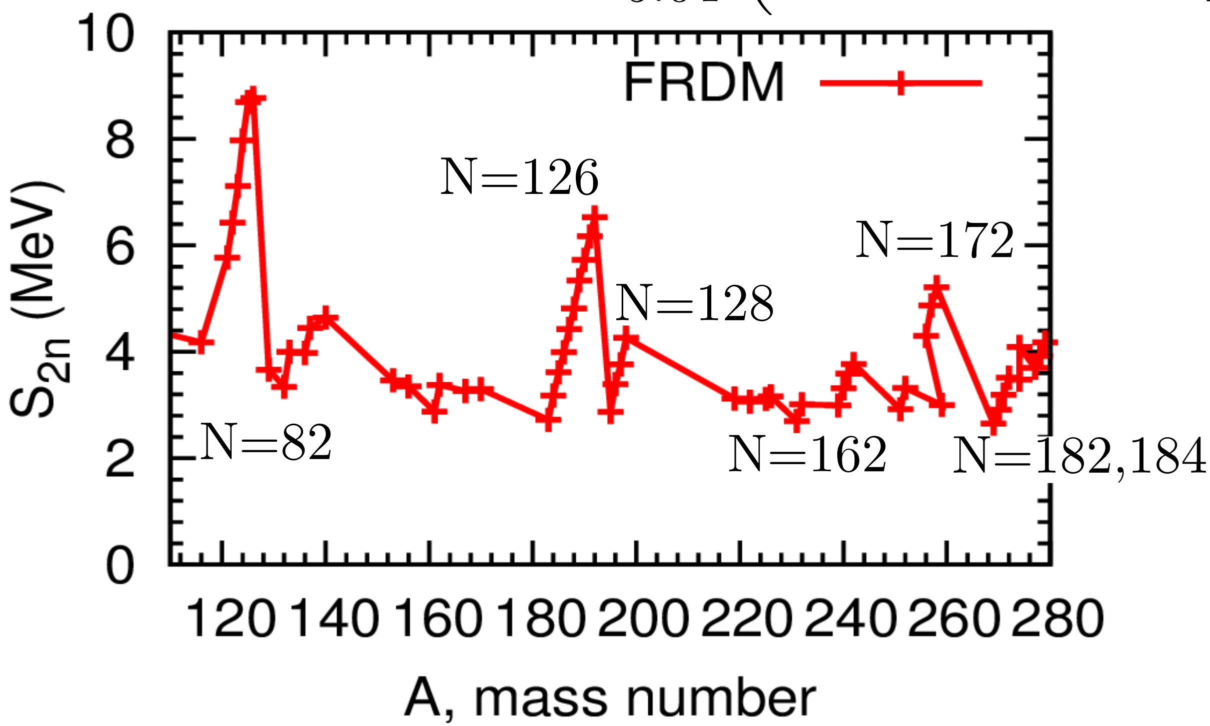

$R_{n/s} = 1$

$T \approx 0.75$ GK

$n_n \approx 3 \times 10^{24}$ cm^{-3}

$S_n^0 \approx 1.4$ MeV

$\rightarrow$ nuclear mass prediction determine the r-process path

beta decay rates

steady β flow:

$$Y(Z)\langle\lambda_\beta(Z)\rangle = Y(Z+1)\langle\lambda_\beta(Z+1)\rangle$$

$\rightarrow$ nuclei with longer β-decay halflives are more abundant

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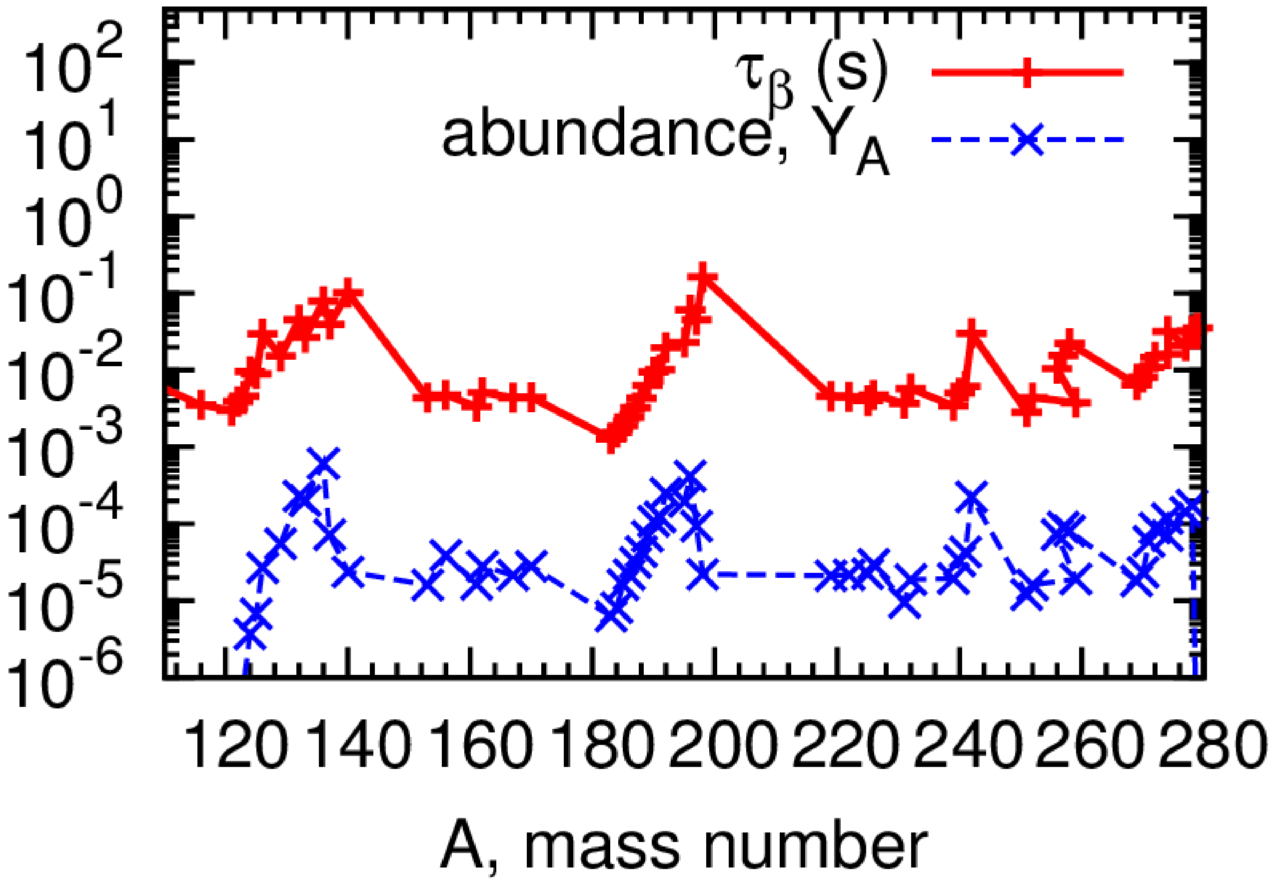

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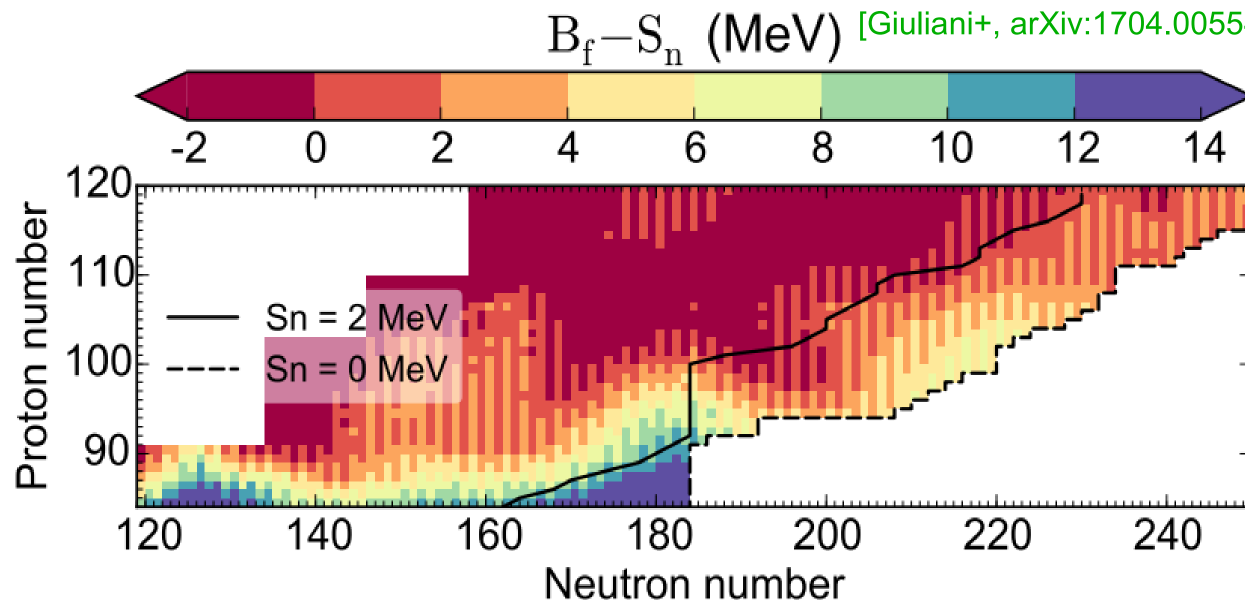
fission rates and fragment distributions

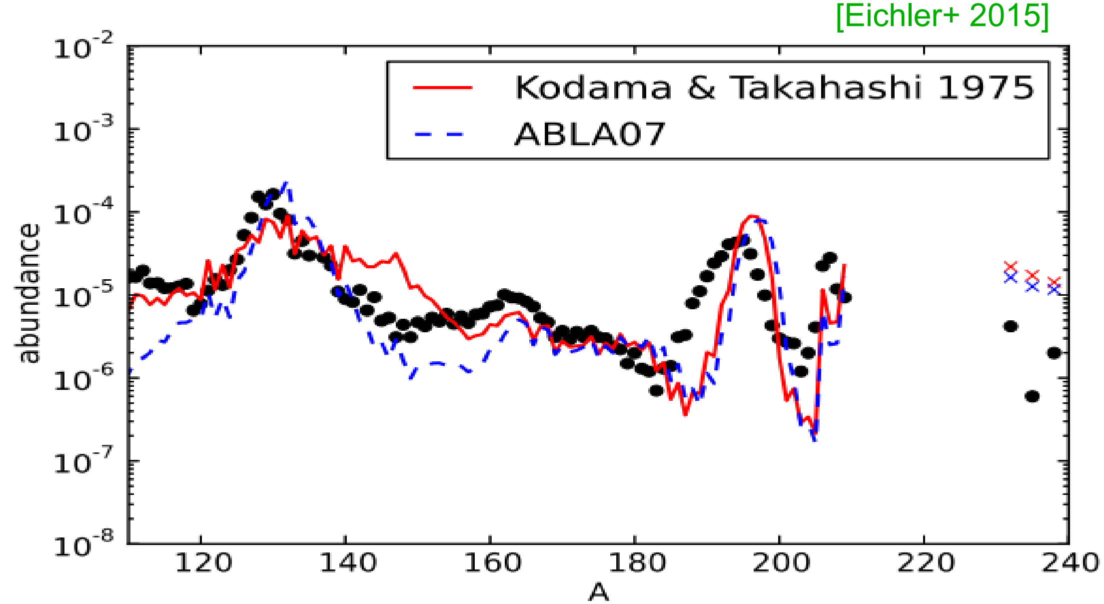
fission barrier height prediction determines where the r-process ends

[Giuliani+, arXiv:1704.00554]

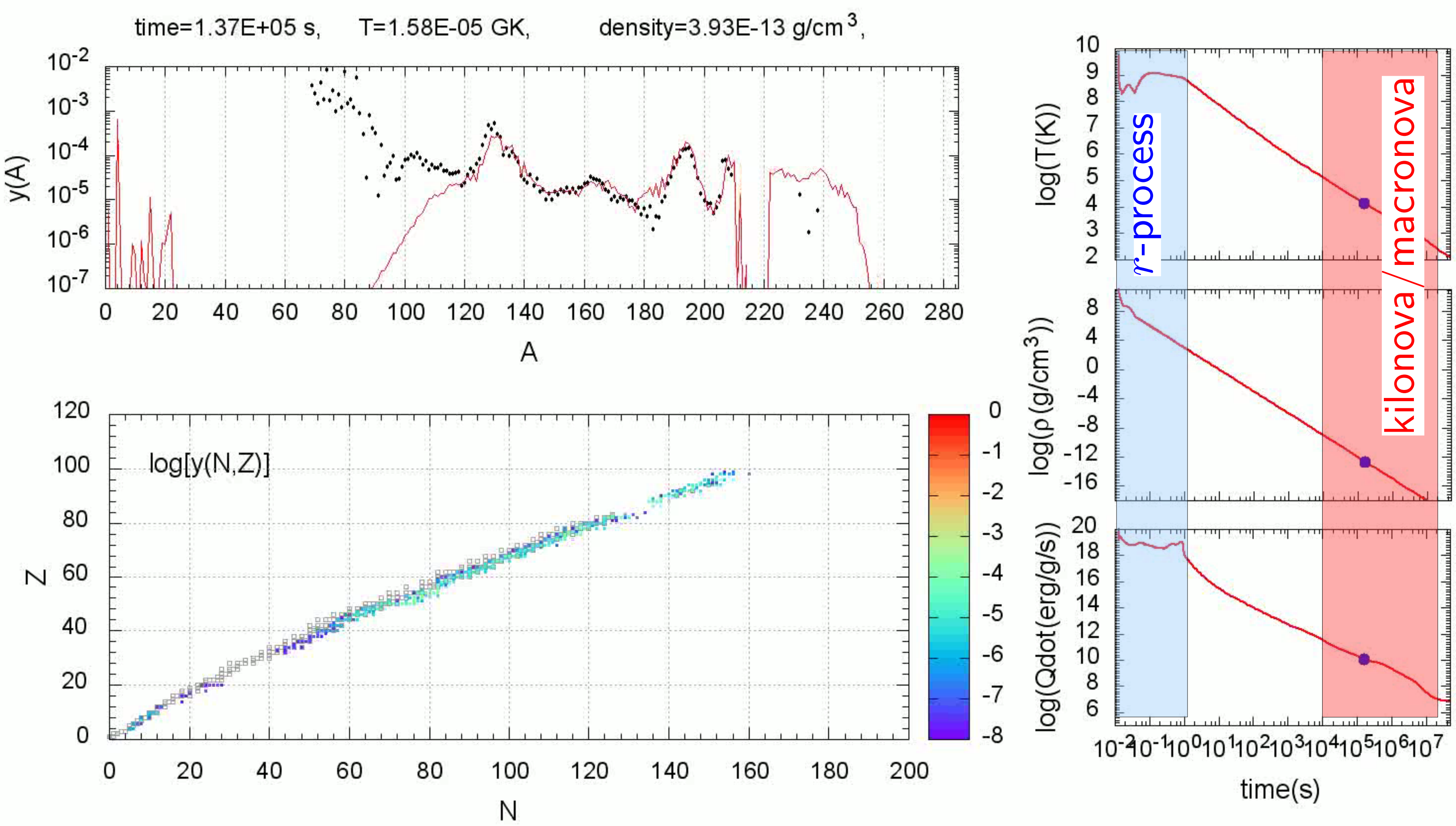


fragment distributions can shape the patterns around and above the 2nd peak

[Eichler+ 2015]



r-process and kilonovae/marcrnovae



y: number fraction of nuclei per baryon

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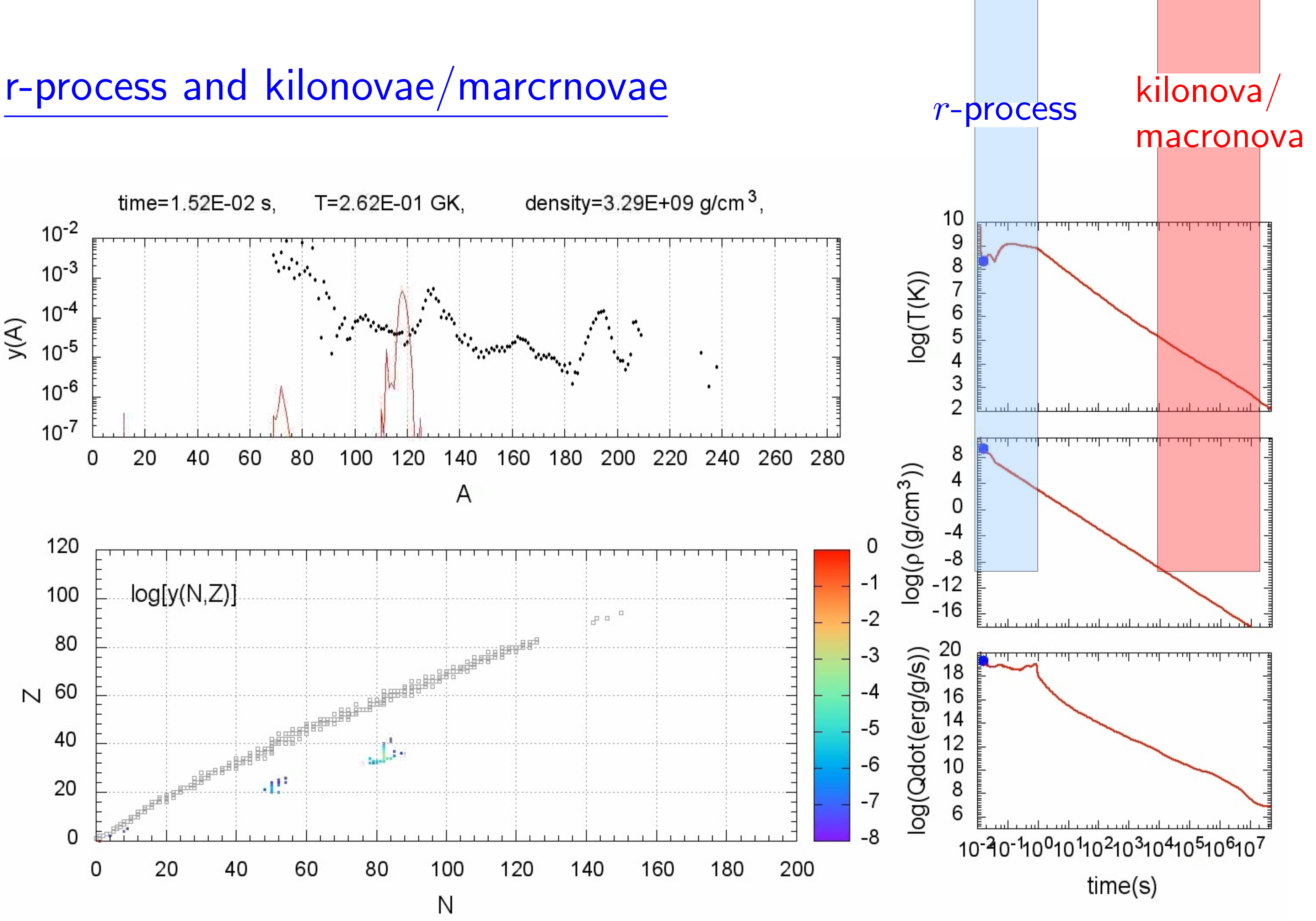


y: number fraction of nuclei per baryon

kilonovae/marcrnovae observations

[Tanvir+ Nature 500 (2013) 547, Berger+ ApJL 774 (2013) 23]

back-of-the-envelope calculations assuming lightcurve peaks at the time when

$\tau_{\rm diffusion} \sim \tau_{\rm expansion}$: [eg Metzger+ 2010]

$$t_{\rm peak} \sim \left(\frac{0.1\kappa M_{\rm ej}}{c v_{\rm ej}}\right)^{1/2}$$

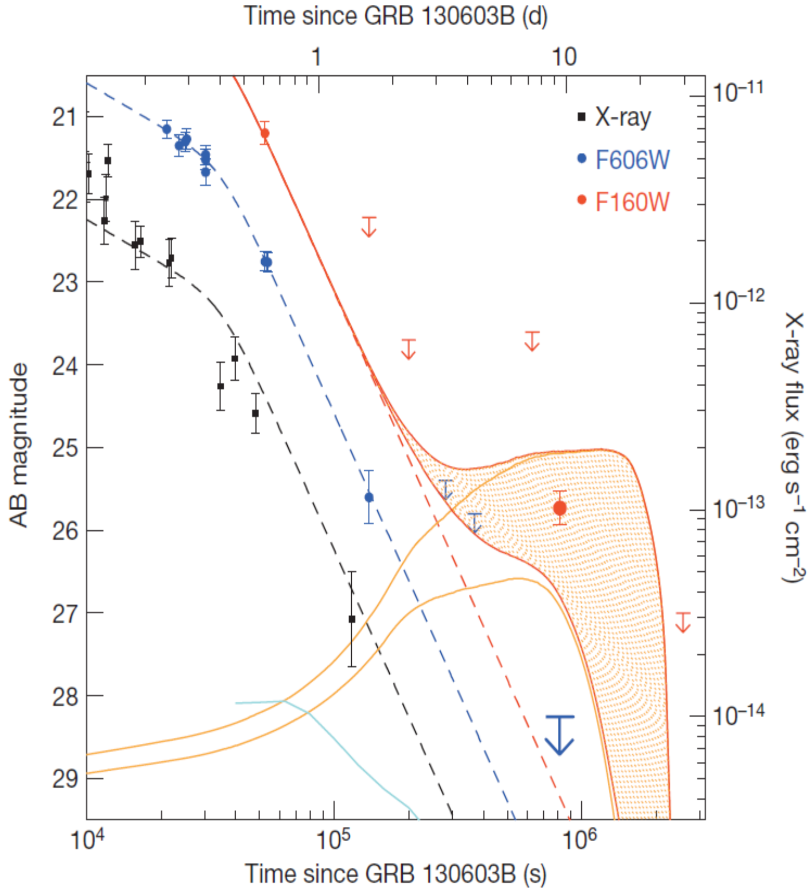
$$\sim 2.7 \text{ day} \left[\left(\frac{\kappa}{10{\rm cm}^2/{\rm g}}\right)\left(\frac{M_{\rm ej}}{0.005 M_\odot}\right)\left(\frac{0.1c}{v_{\rm ej}}\right)\right]^{1/2}$$

$$L_{\rm peak} \sim 8.1 \times 10^{40} {\rm erg/s}$$

$$\times \left[\left(\frac{f}{3\times 10^{-6}}\right)\left(\frac{10{\rm cm}^2/{\rm g}}{\kappa}\right)\left(\frac{M_{\rm ej}}{0.005 M_\odot}\right)\left(\frac{v_{\rm ej}}{0.1c}\right)\right]^{1/2}$$

$$T_{\rm peak} \sim 3 \times 10^3 {\rm K}$$

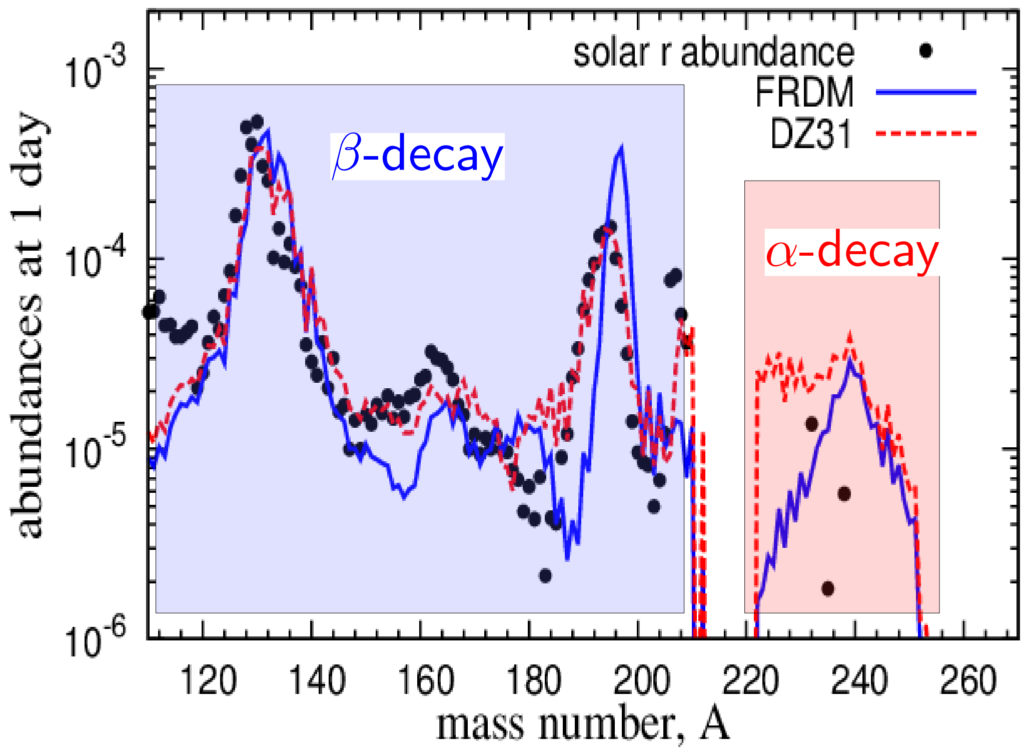
$$\times \left[\left(\frac{f}{3\times 10^{-6}}\right)^2\left(\frac{10{\rm cm}^2/{\rm g}}{\kappa}\right)^3\left(\frac{0.005 M_\odot}{M_{\rm ej}}\right)\left(\frac{0.1c}{v_{\rm ej}}\right)\right]^{1/8}$$

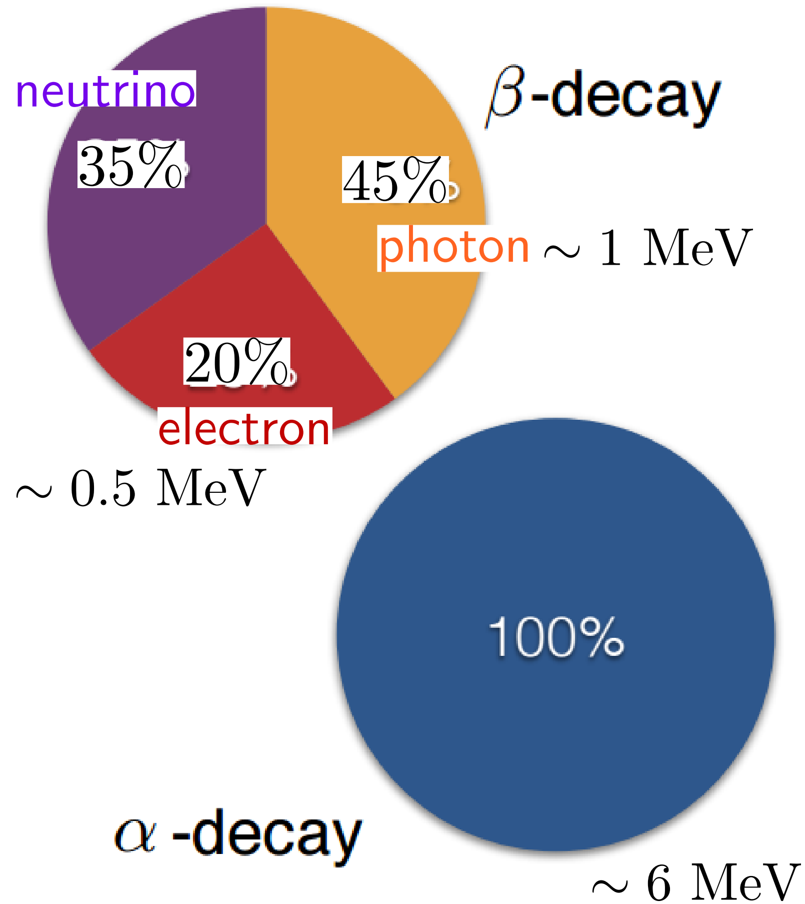


κ: opacity, f: heating efficiency

Nuclear physics impact on kilonova heating

At kilonova time, large difference for $220 \lesssim A \lesssim 240$





[Barnes+2016]

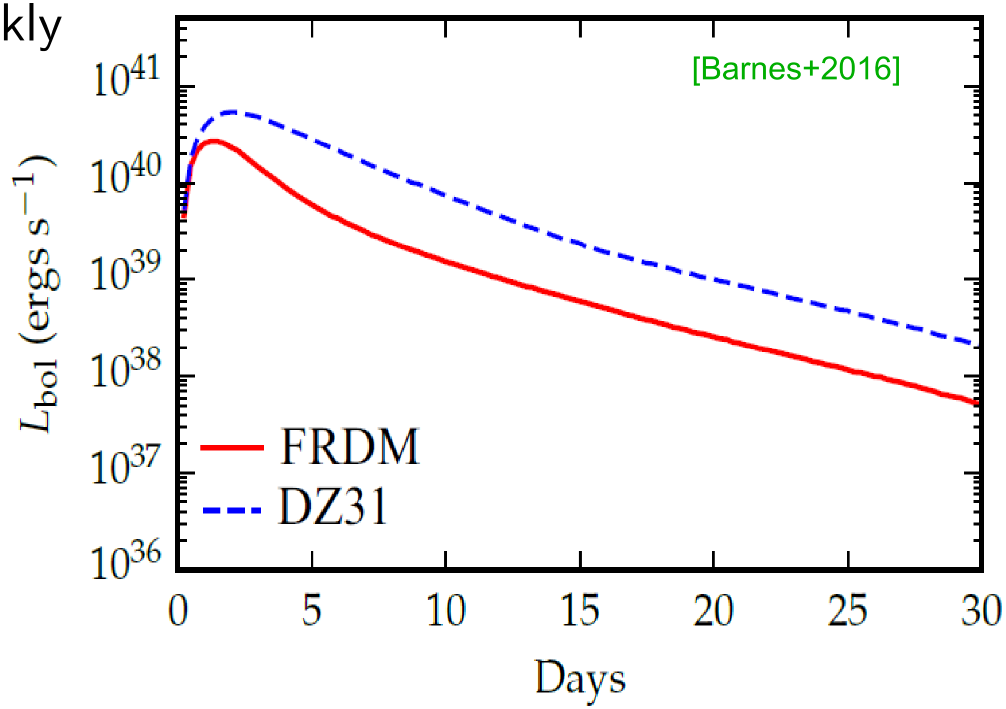
Nuclear physics impact on kilonova heating

- 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

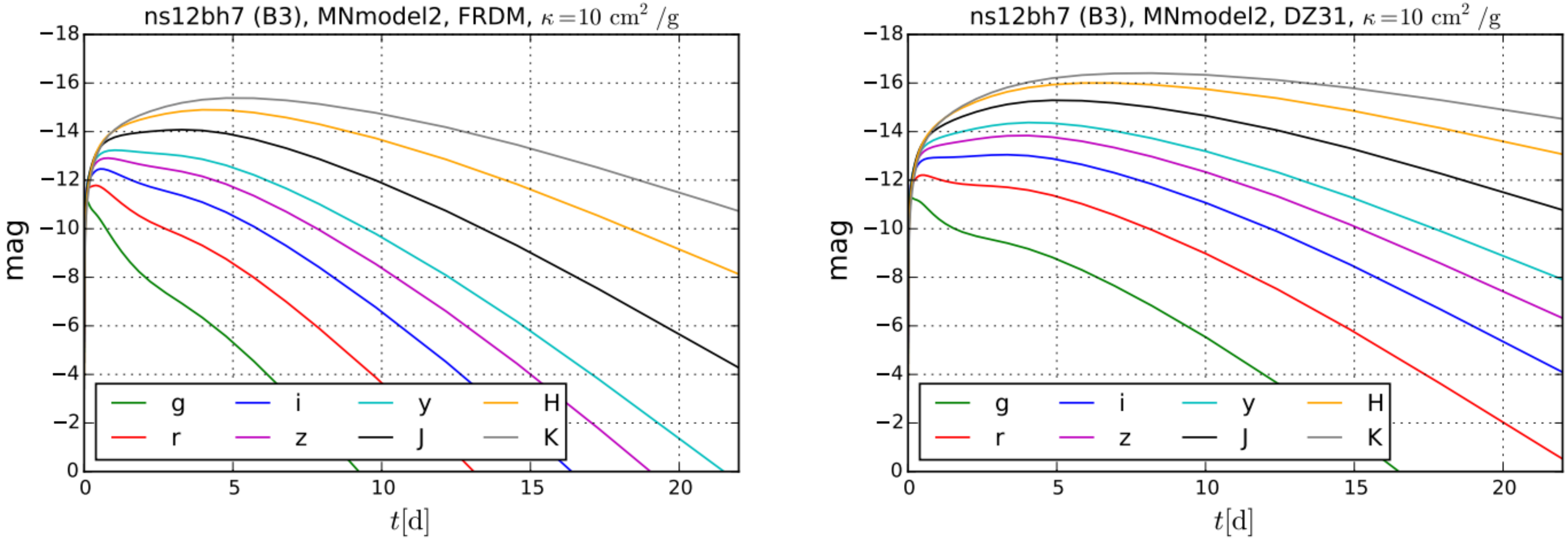
[Hotokezaka+2016, Barnes+2016]

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



Nuclear physics impact on kilonova heating

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



[Rosswog+ 2017]

Nuclear physics impact on kilonova heating

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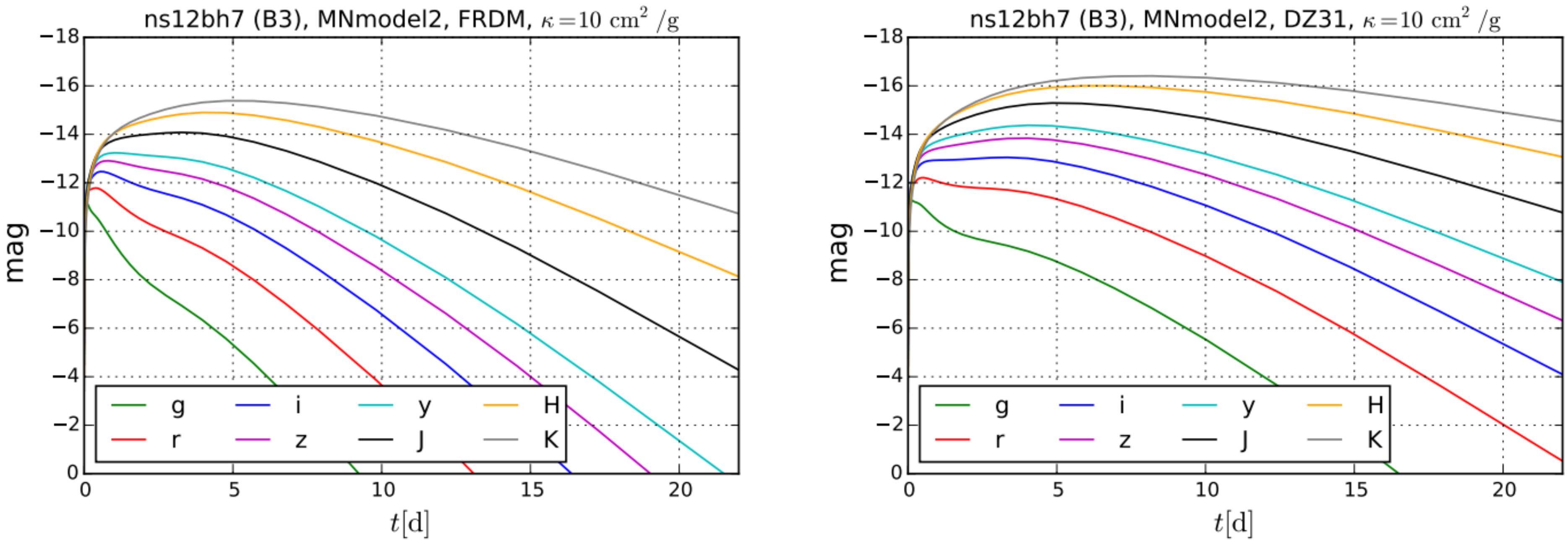
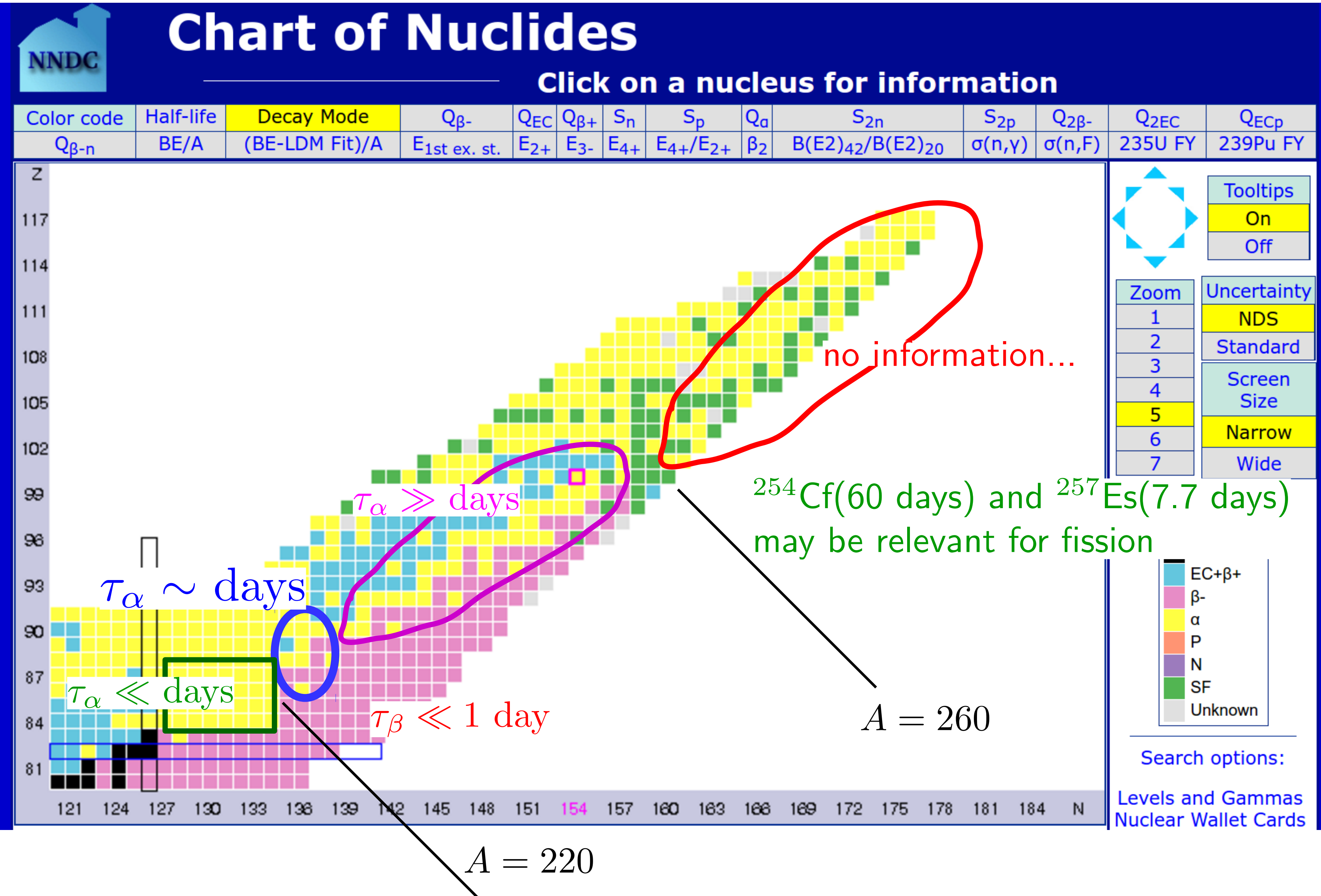


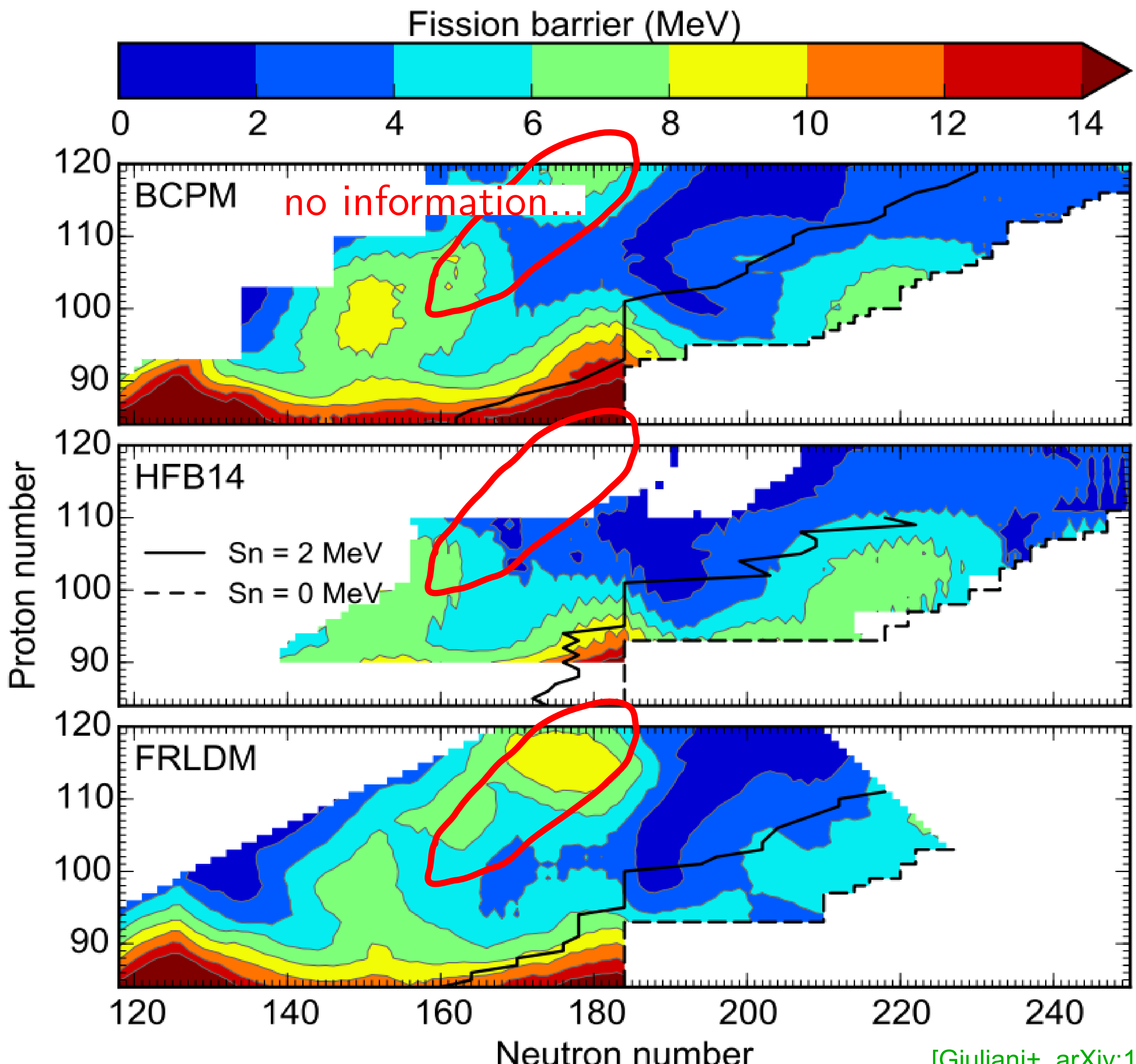
[Rosswog+ 2017]

- fission release $\sim O(100)$ MeV and their fragments can be thermalized more efficiently.

Can they contribute?

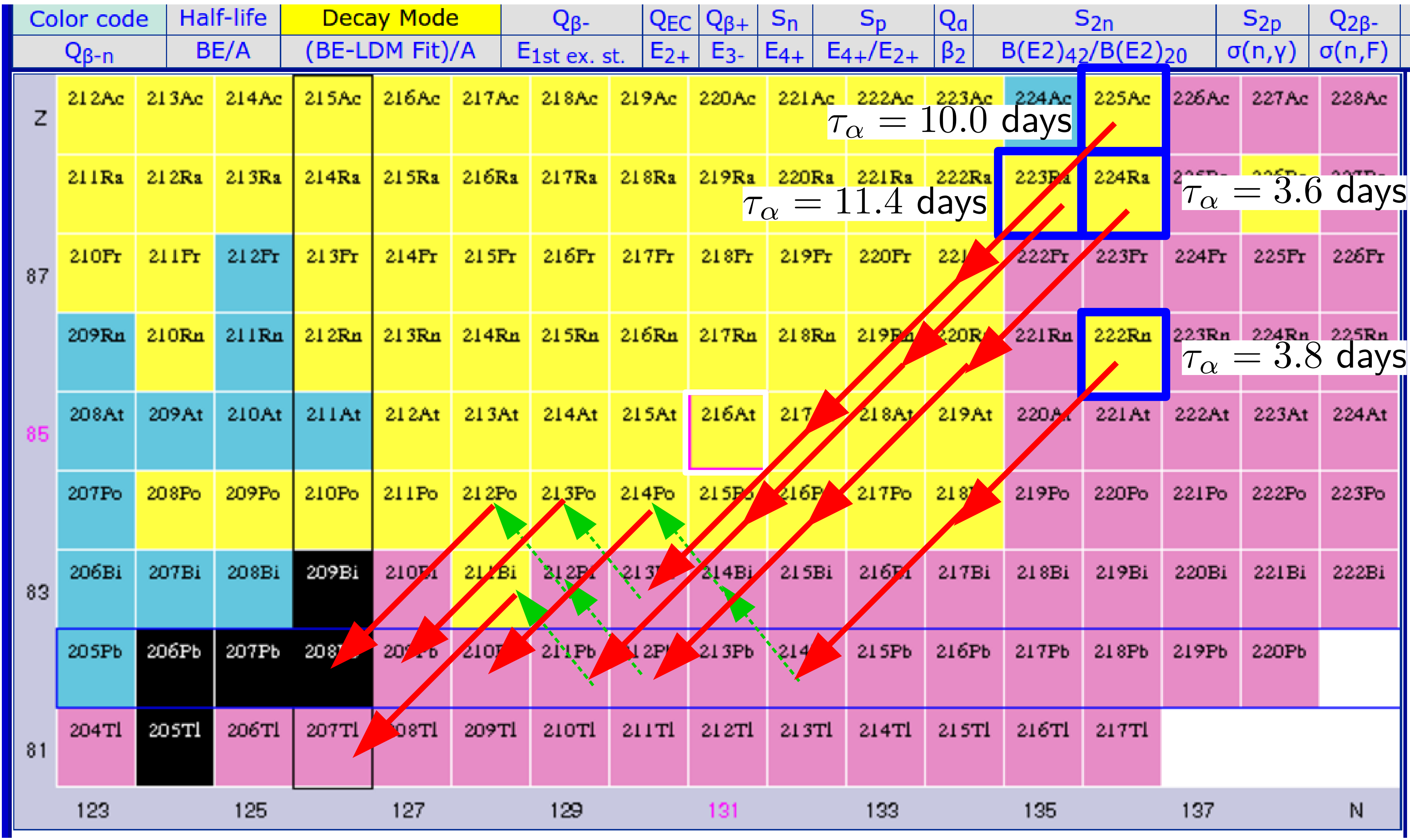
what heavy nuclei can be relevant for kilonova heating?



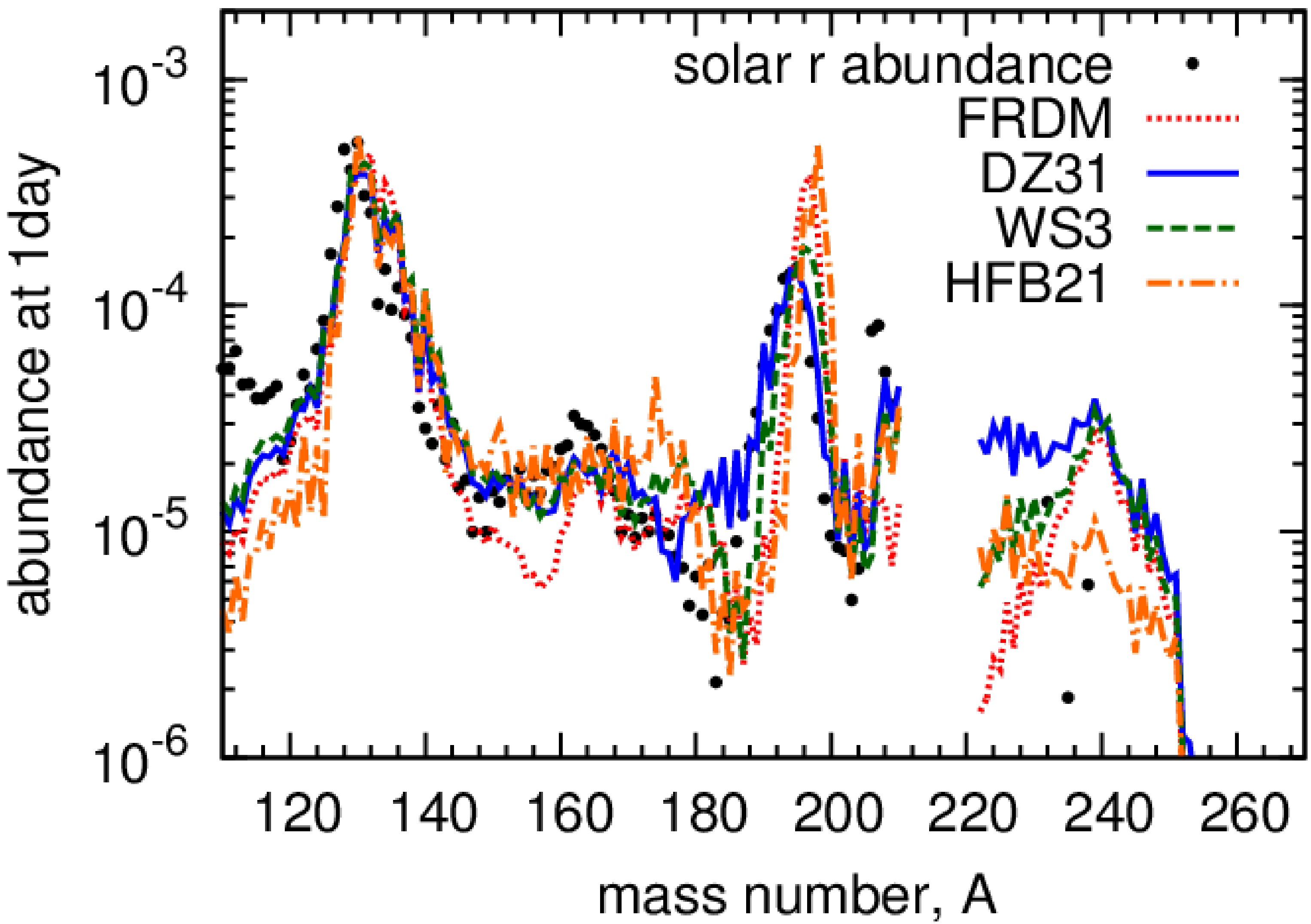


[Giuliani+, arXiv:1704.00554]

α decay chains at days to weeks



Impact of masses on abundances



only the (n, γ) and (γ, n) for nuclei with $Z <= 83$ are changed

Nuclear mass models

[Mendoza-Temis, PhD Thesis]

Table 2.2: RMSD in MeV, for the fits and predictions for different mass models.

MODEL	fit	prediction	full set	
FRDM	0.655	0.765	0.666	[Moeller+ 1995]
HFB21	0.576	0.646	0.584	[Goriely+ 2010]
WS3	0.336	0.424	0.345	[Liu+ 2011]
DZ10	0.551	0.880	0.588	[Duflo+ 1995]
DZ31	0.363	0.665	0.400	

fit: 2149 nuclei from AME03 or 1845 nuclei from AME95

prediction: 219 nuclei from AME12

FRDM: Finite Range Droplet Model, macroscopic+microscopic

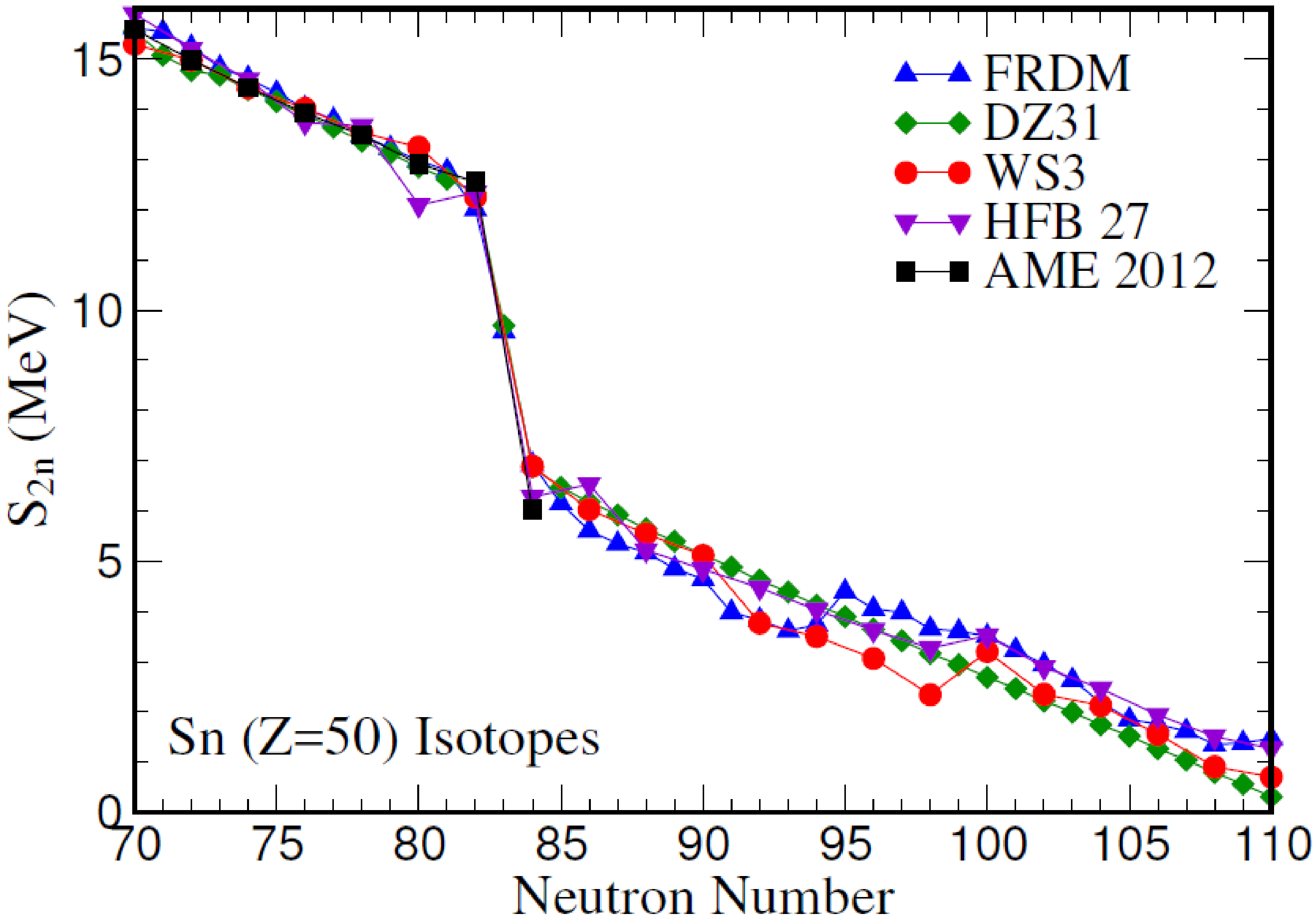
WS3: Weizsacker-Skyrme mass model, macroscopic+microscopic

DZ10/31: Duflo-Zuker mass formula, shell model inspired, macroscopic+microscopic

HFB21: mean-field model with Hatree-Fock-Bogoliubov approximation, microscopic

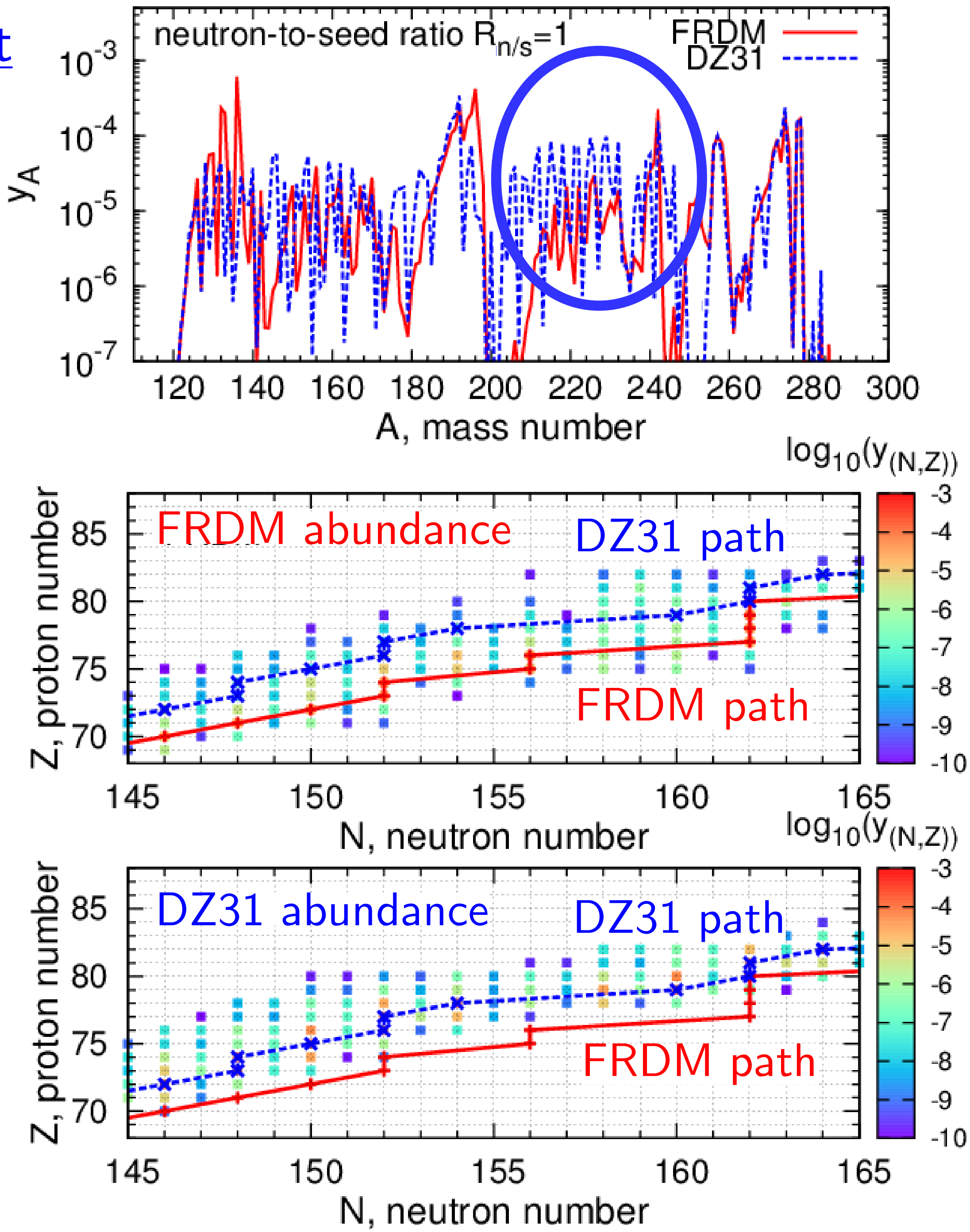
Comparison S_{2n}

Very similar predictions for Q-values (relevant quantity). slide from Gabriel

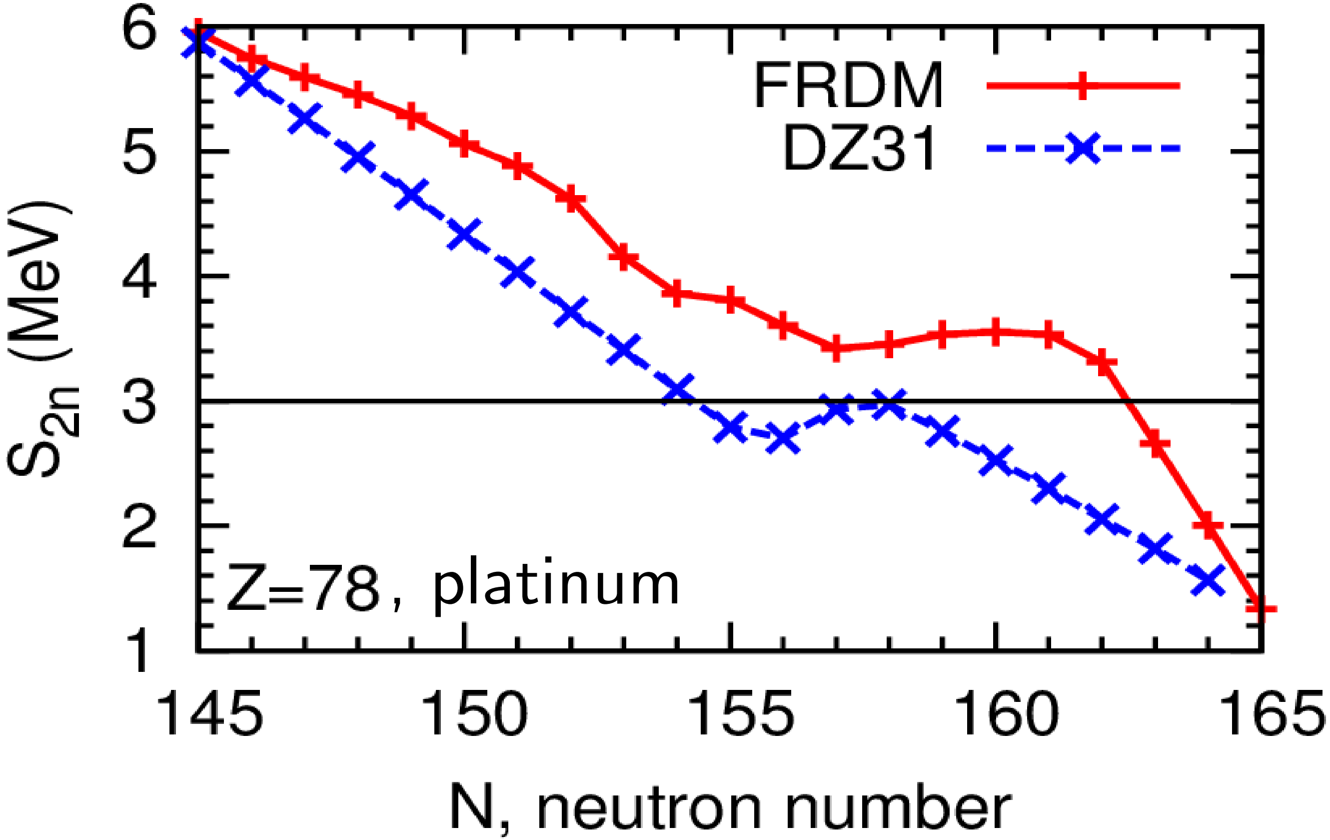


Variations in localized regions responsible for different abundances predictions.

abundance before freeze-out



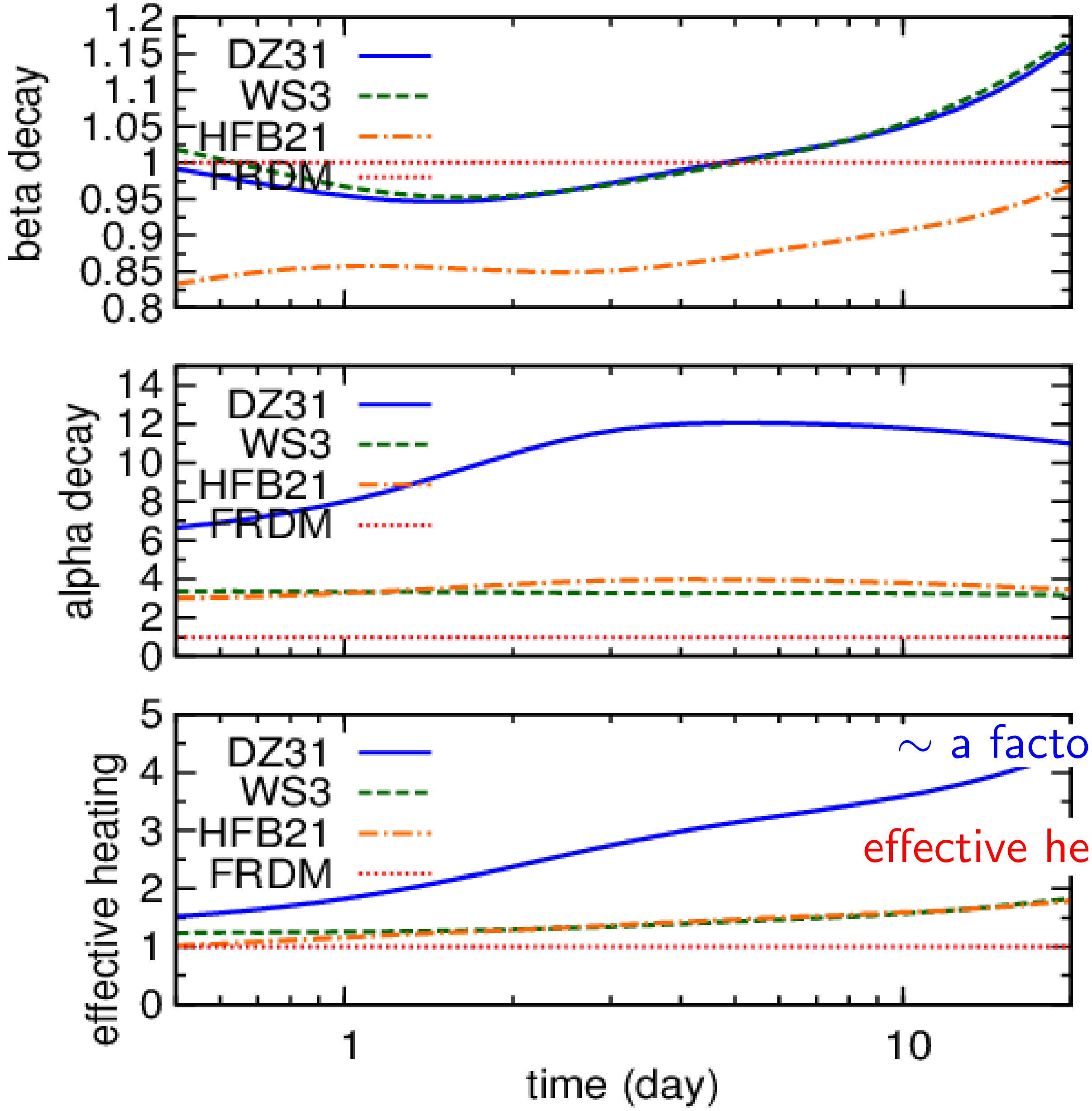
$R_{n/s} \approx 1 \quad T \approx 0.75$ GK $\quad n_n \approx 3 \times 10^{24}\ \mathrm{cm}^{-3} \quad S^0_{2n} \approx 2.8\ \mathrm{MeV}$



around the region of shape change of nuclei?

Energy release and effective heating

Relative to FRDM



$\sim$ a factor of 3-6 at ~ 10 days

effective heating $\sim \dot{Q}_\alpha + 0.2\dot{Q}_\beta$

revelant for all mergers?

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

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

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

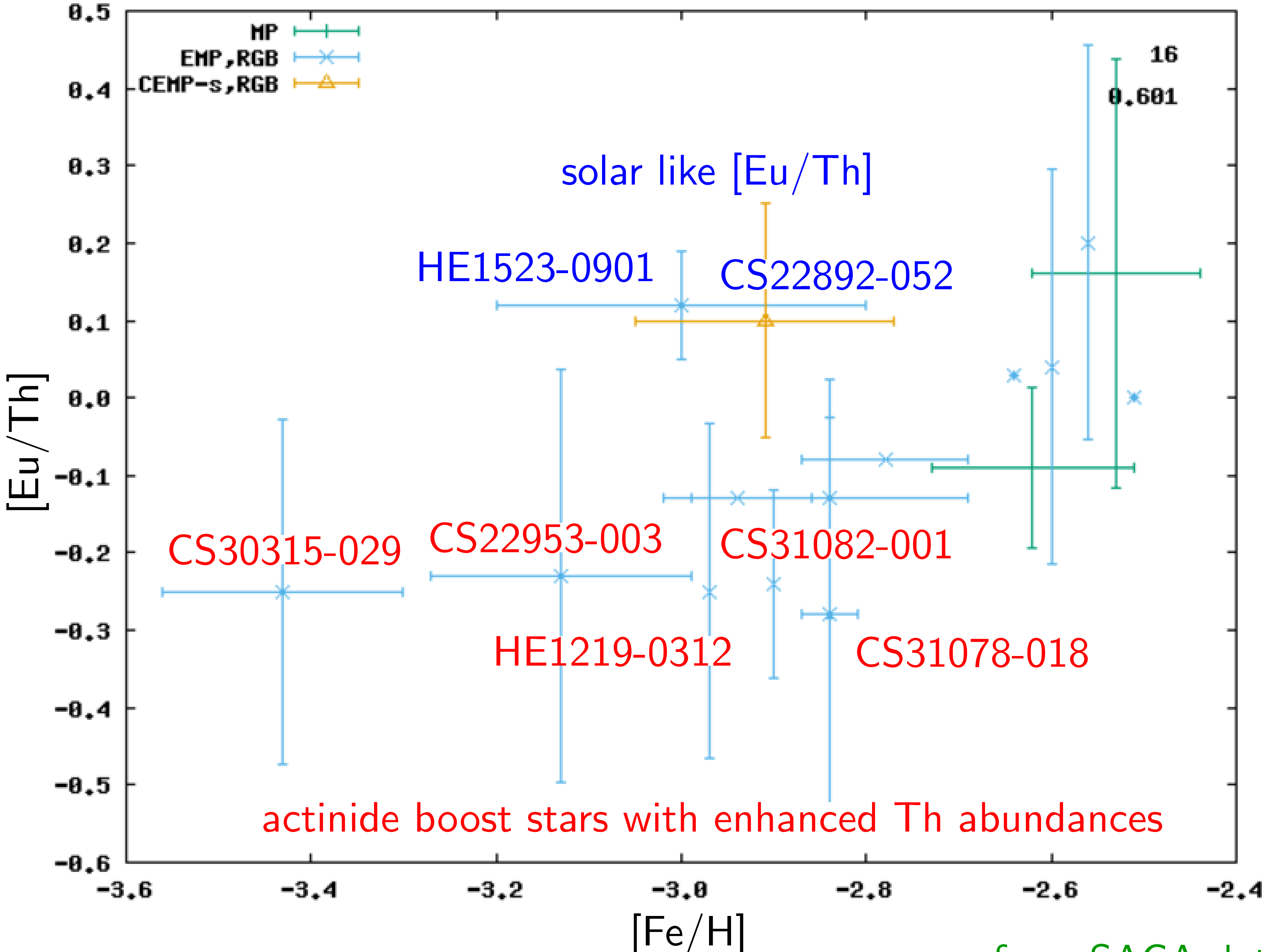
To have nuclei with $A \sim 220 - 230$ that may alpha decay at relevant time,

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

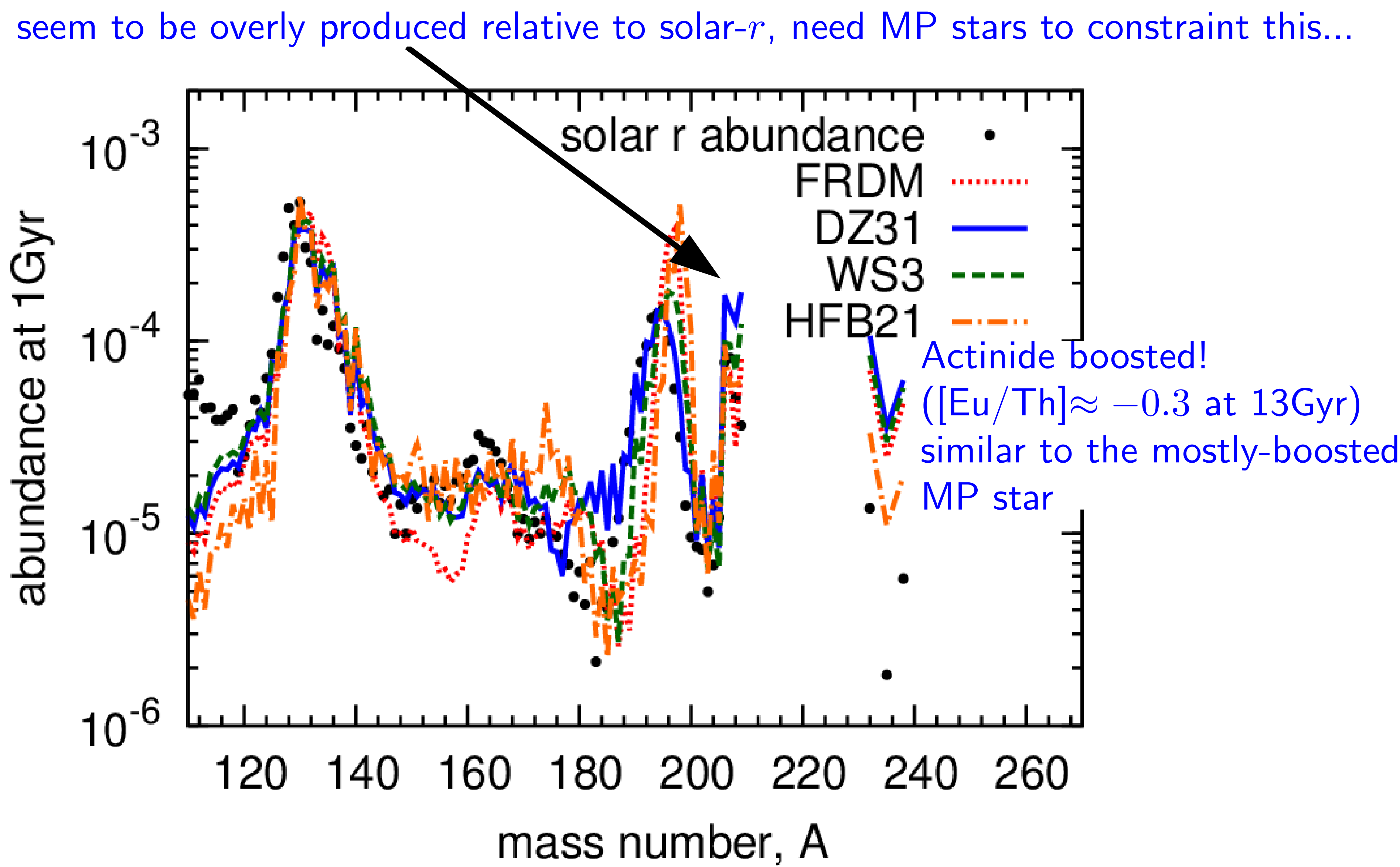
With $N_{\rm seed} \approx 50$, $Z_{\rm seed} \approx 30$, it gives $Y_e \lesssim 0.16$.

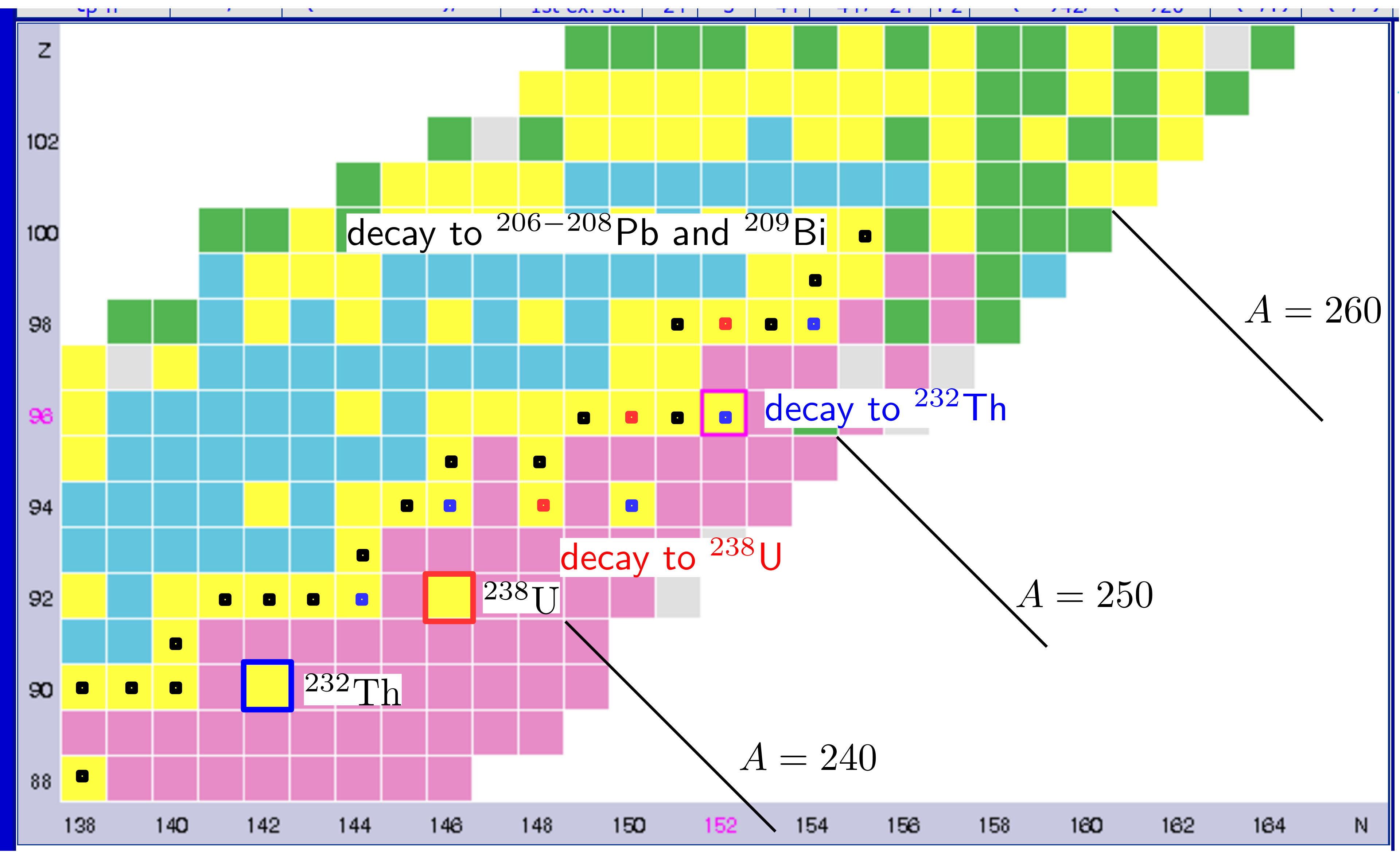
α-heating may become dominant for ejecta with $Y_e \lesssim 0.15$, smaller enhancement in disk outflow or if neutrinos increase Y_e of dynamical ejecta substantially

Actinide abundances in Metal-poor stars



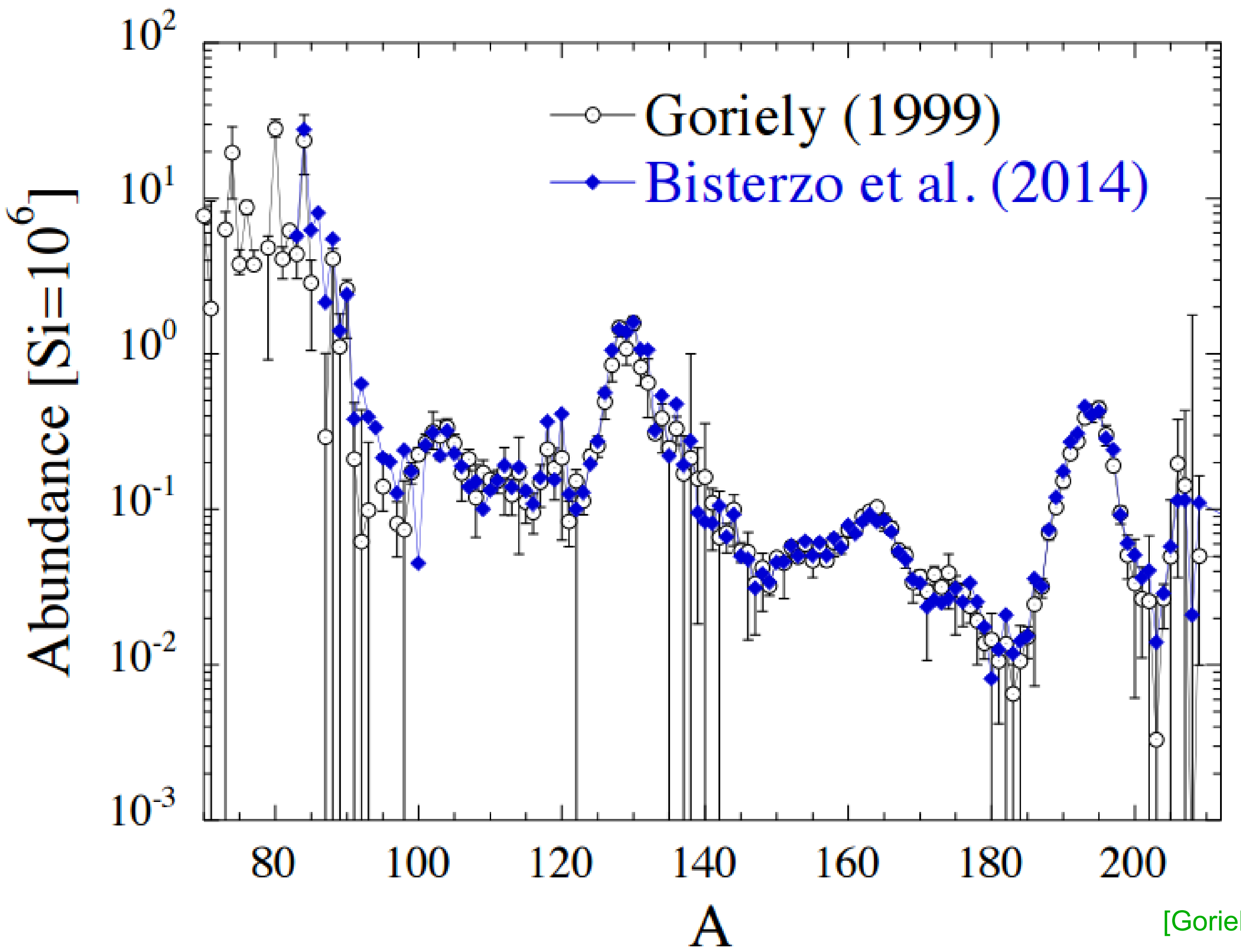
from SAGA database


seem to be overly produced relative to solar-r, need MP stars to constraint this...
solar r abundance
FRDM
DZ31
WS3
HFB21
Actinide boosted!
([Eu/Th]≈ -0.3 at 13Gyr)
similar to the mostly-boosted
MP star
abundance at 1Gyr
10^{-3}
10^{-4}
10^{-5}
10^{-6}
120
140
160
180
200
220
240
260
mass number, A



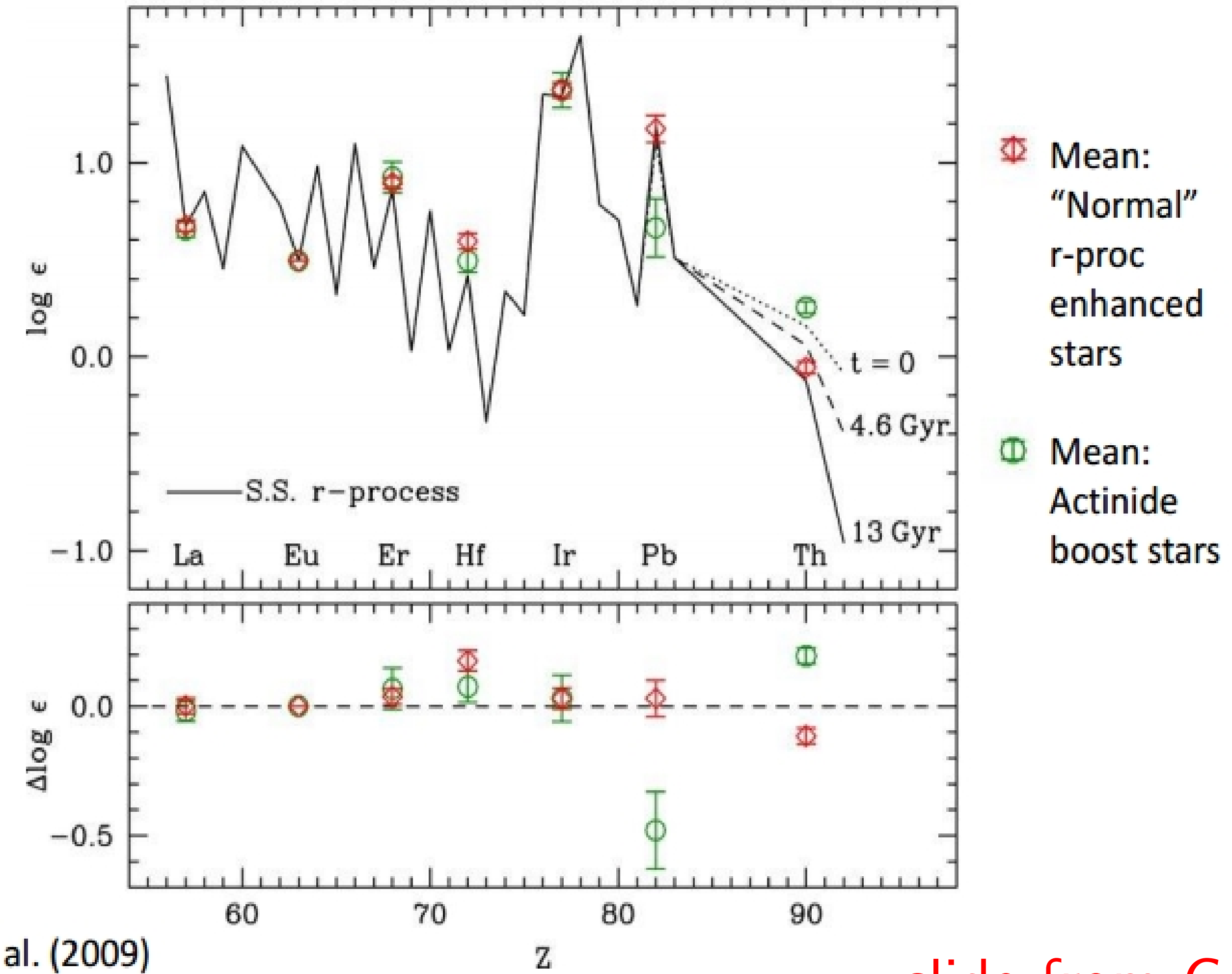
$\tau(^{232}\text{Th}) \approx 14\text{Gyr}$ $\tau(^{238}\text{U}) \approx 4.5\text{Gyr}$

Uncertainty in solar r-abundances



[Goriely+ 2016]

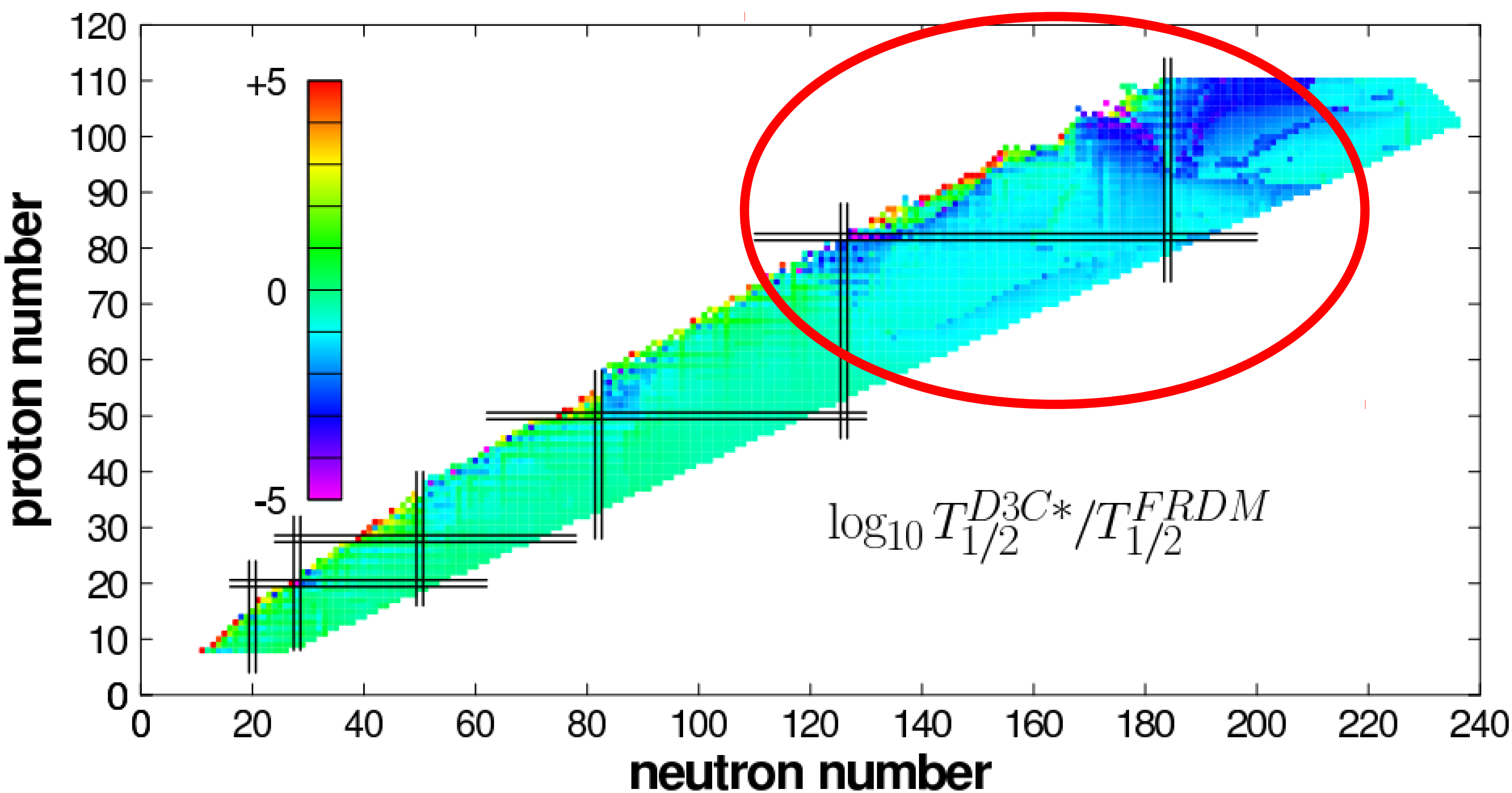
Actinide Boost



Roederer et al. (2009)

slide from C. Sakari

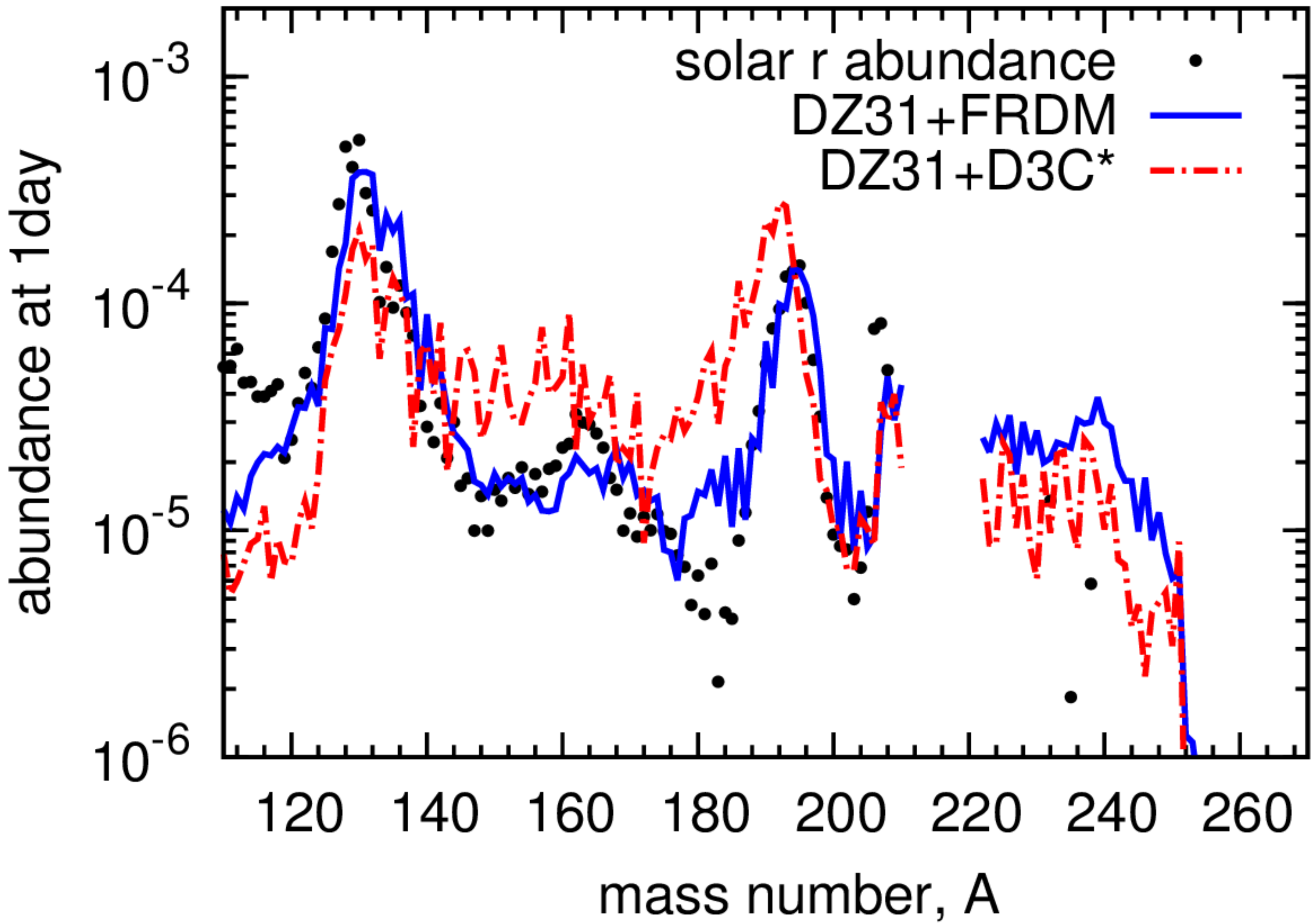
β-decay models



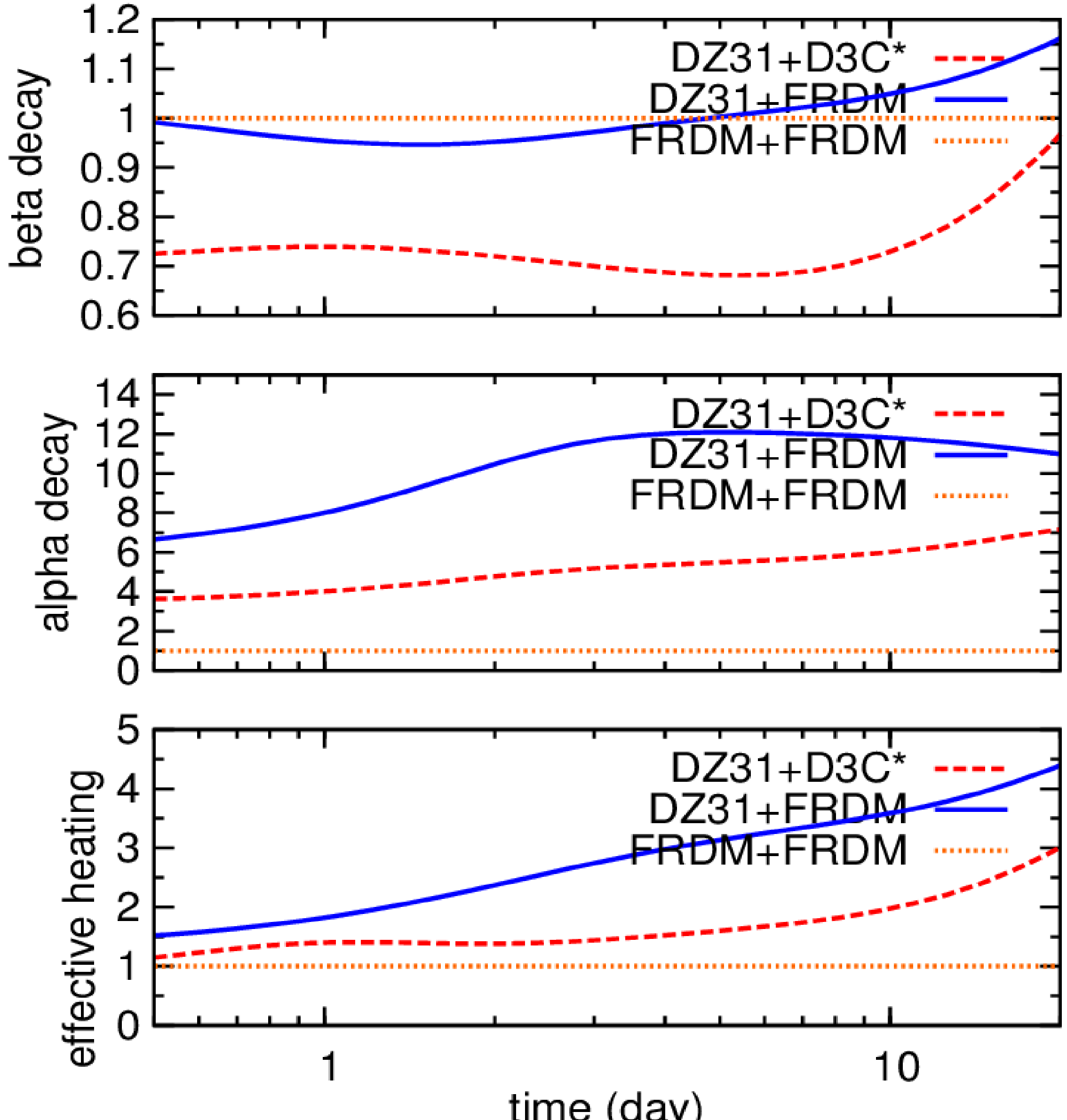
D3C* model predicts shorter τ_β for heavier nuclei

$\rightarrow$ less trans-lead and trans-uranium production

Impact of β-decay on abundances



Energy release and effective heating



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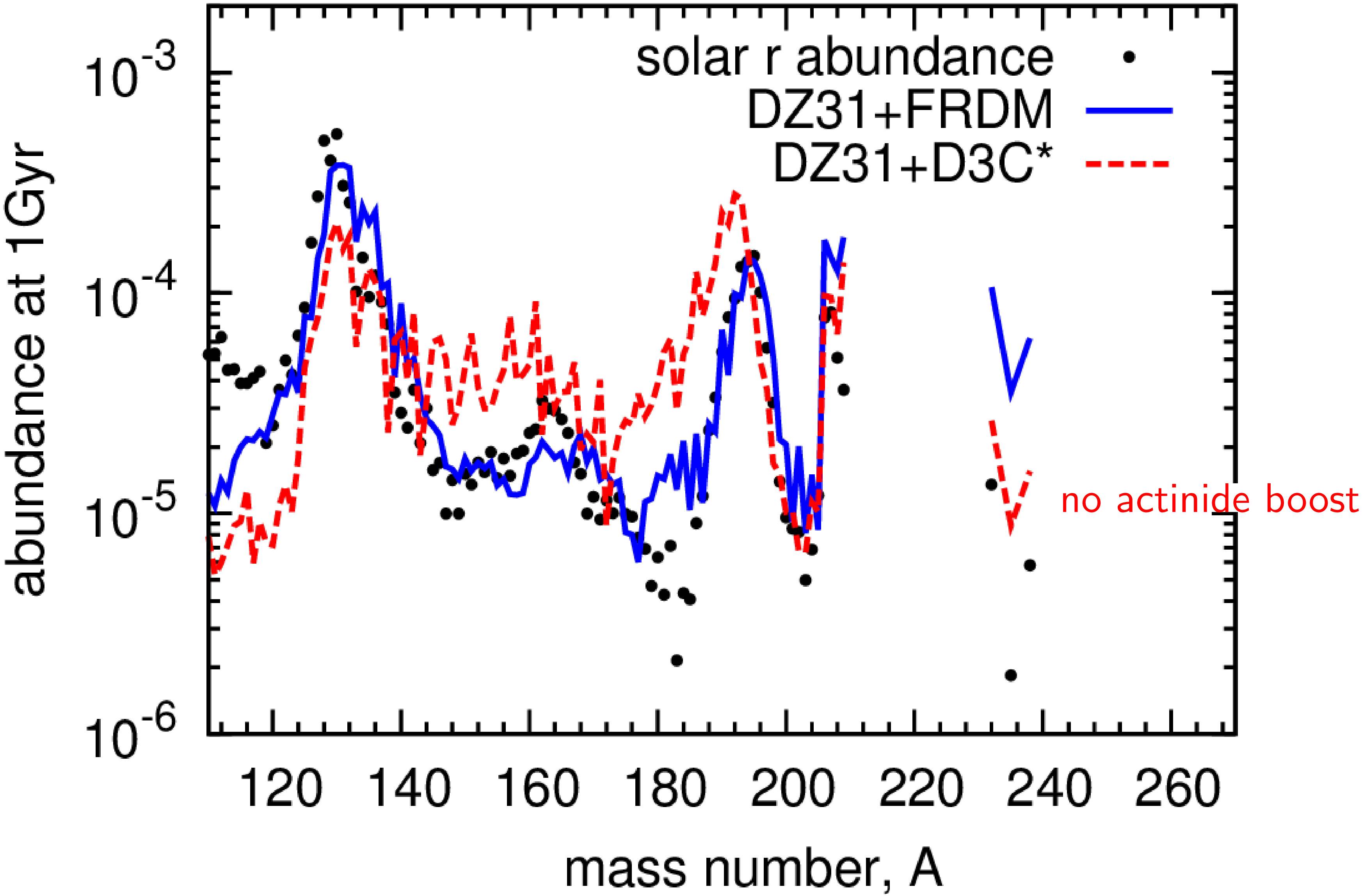
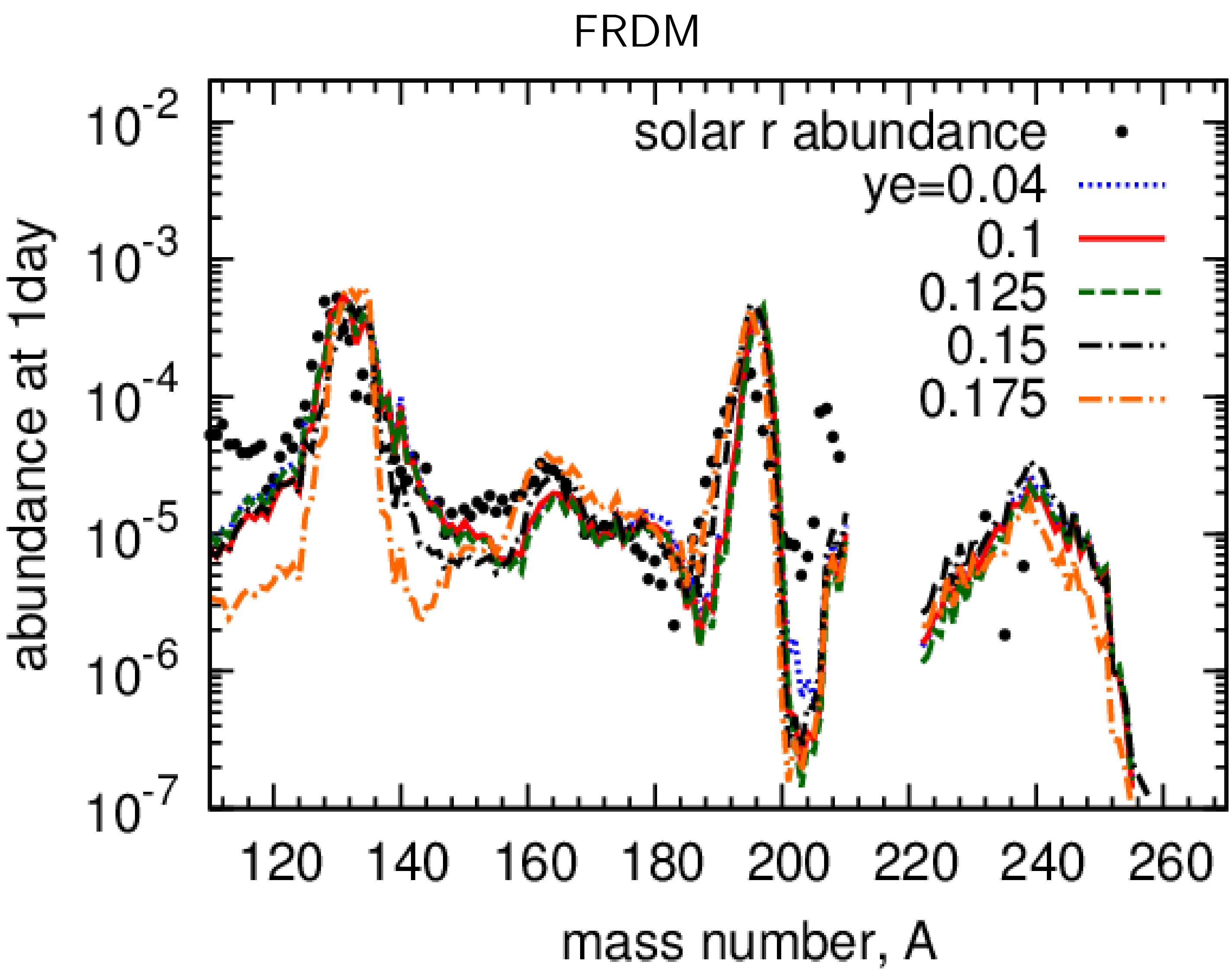


Y_e dependence



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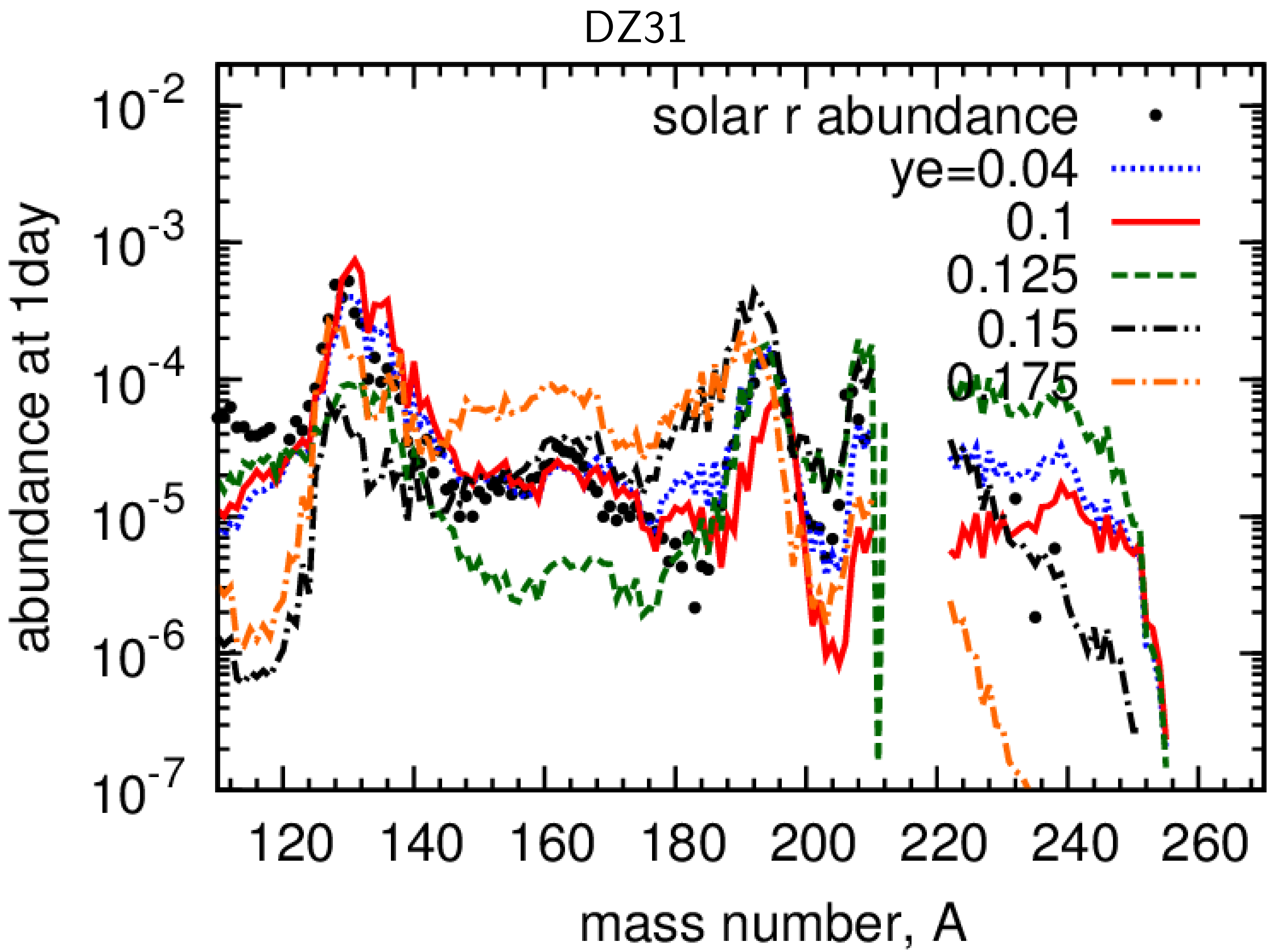
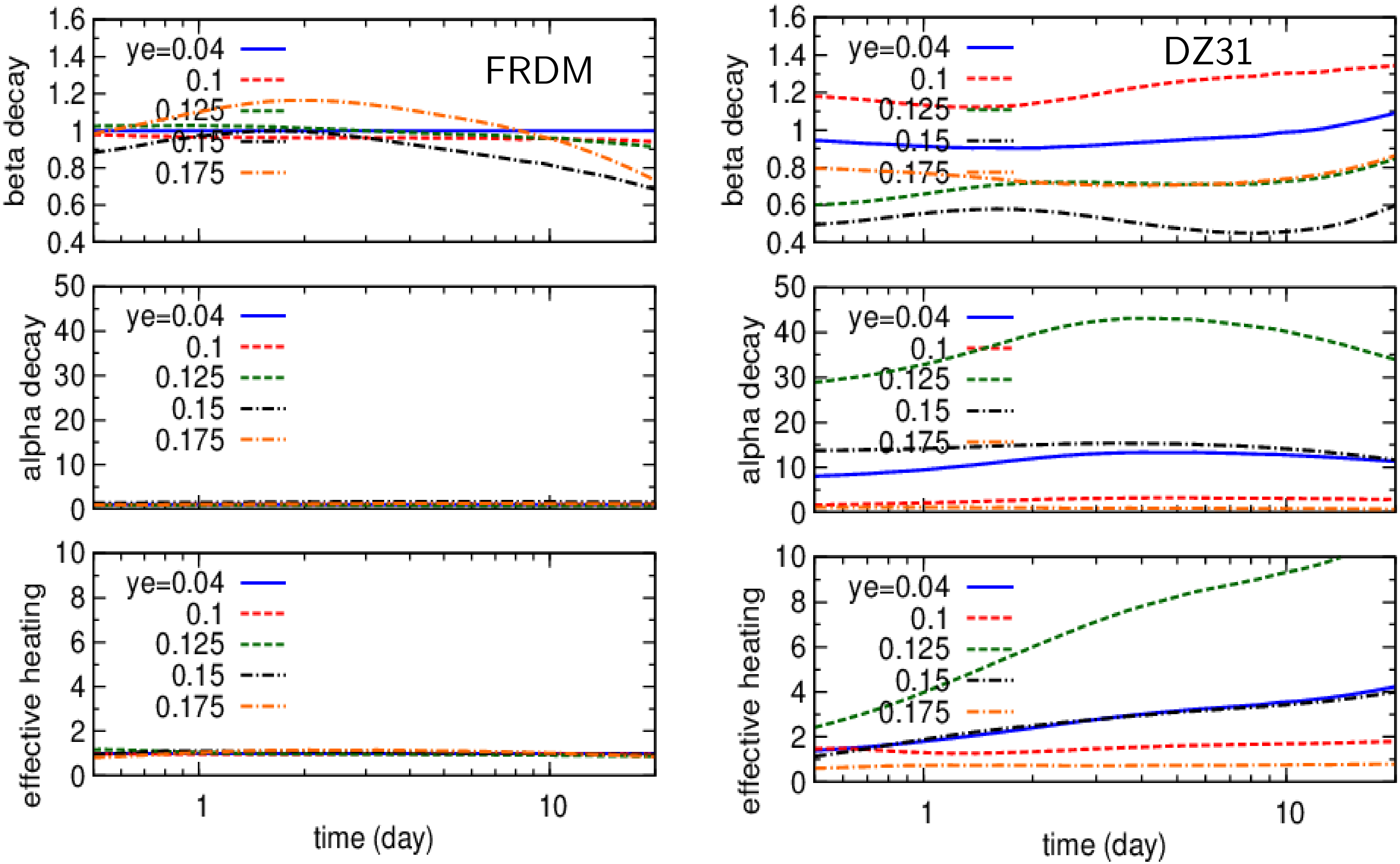


Y_e dependence

Relative to FRDM with $Y_e = 0.04$



Summary

- There is a factor of $\lesssim 10$ uncertainty exists in kilonova heating rate due to both nuclear physics inputs and Y_e.
- Maybe future metal-poor star observation can help constrain/reduce this uncertainty.