Nuclear physics impact on r-process and kilonovae

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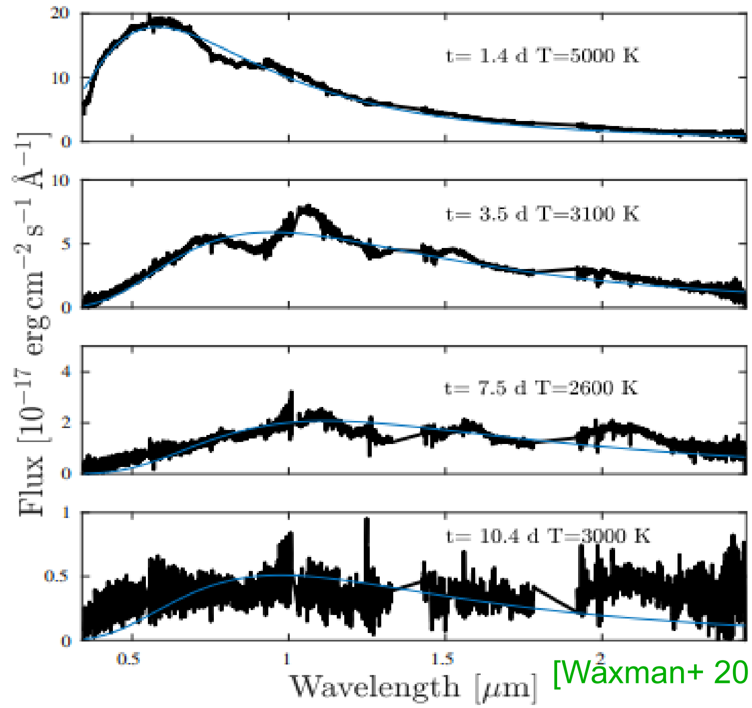
Neutron star merger and kilonova

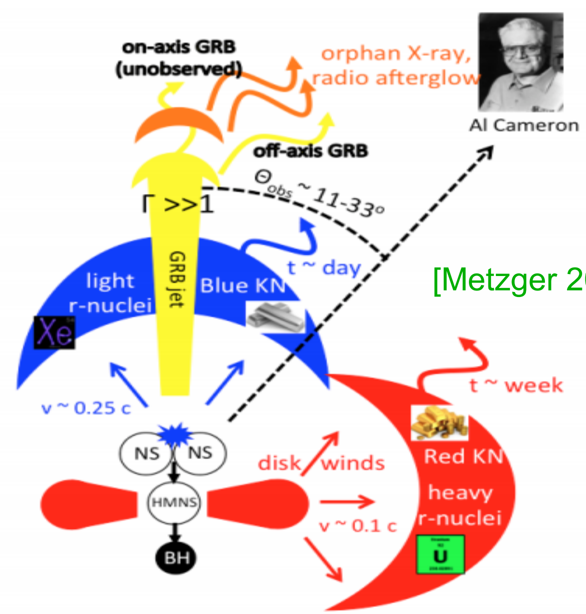
The GW170817 follow-up optical/infrared observations strongly indicate kilonova being powered by the decay of the r-process nuclei

The kilonova lightcurve/spectra modeling depends on:

- ejecta mass/velocity
- opacity
- radioactive decay energy
- particle thermalization
- ...



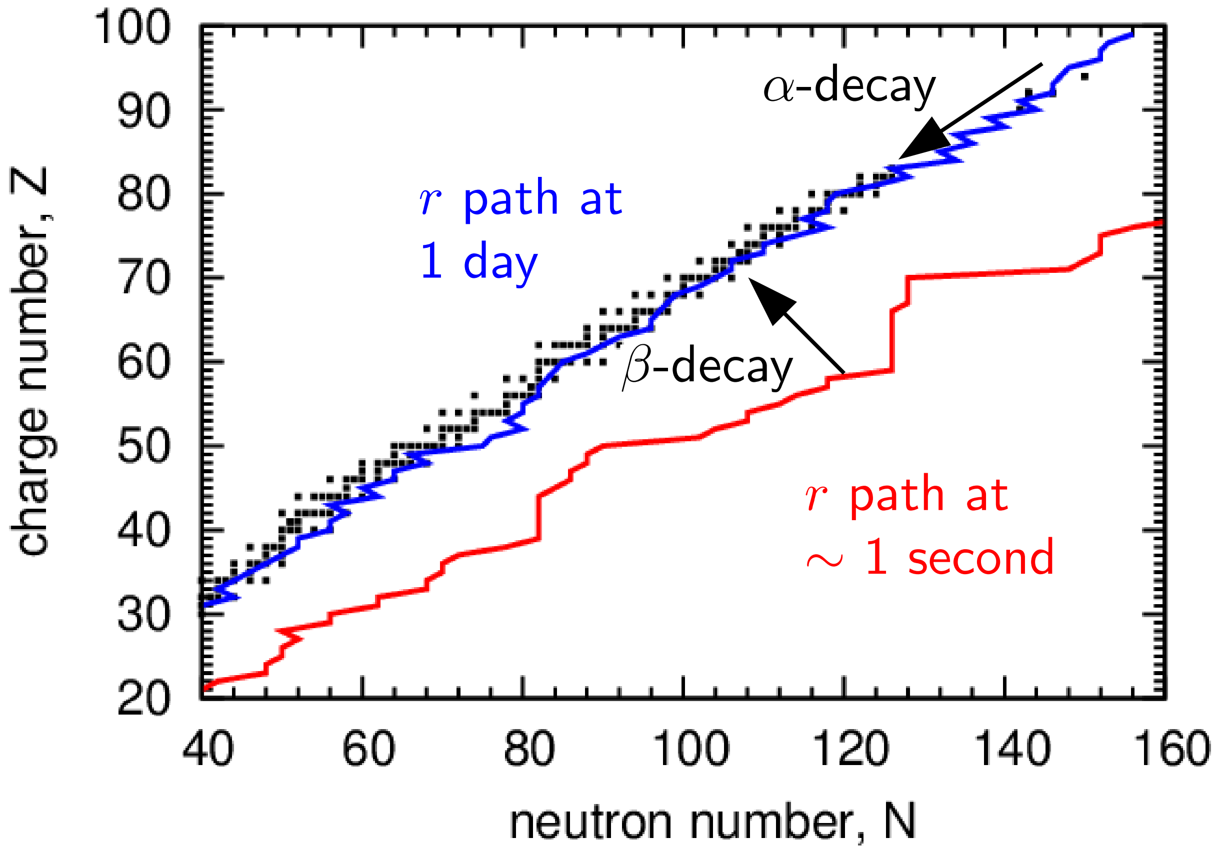
[Waxman+ 2017]



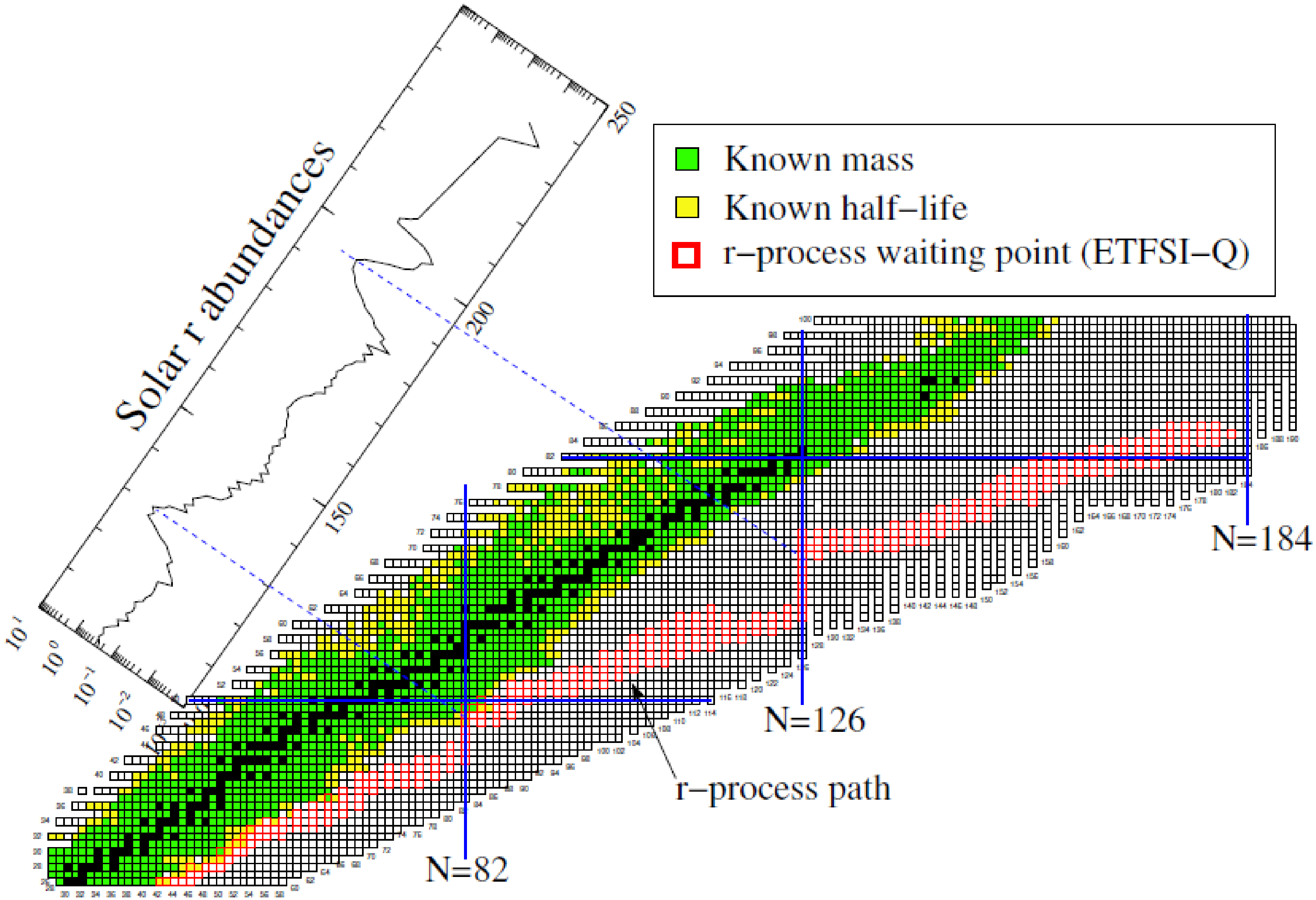
[Metzger 2017]

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.



largely rely on theoretical nuclear physics inputs...

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 $S_n \gtrsim S_n^0$

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

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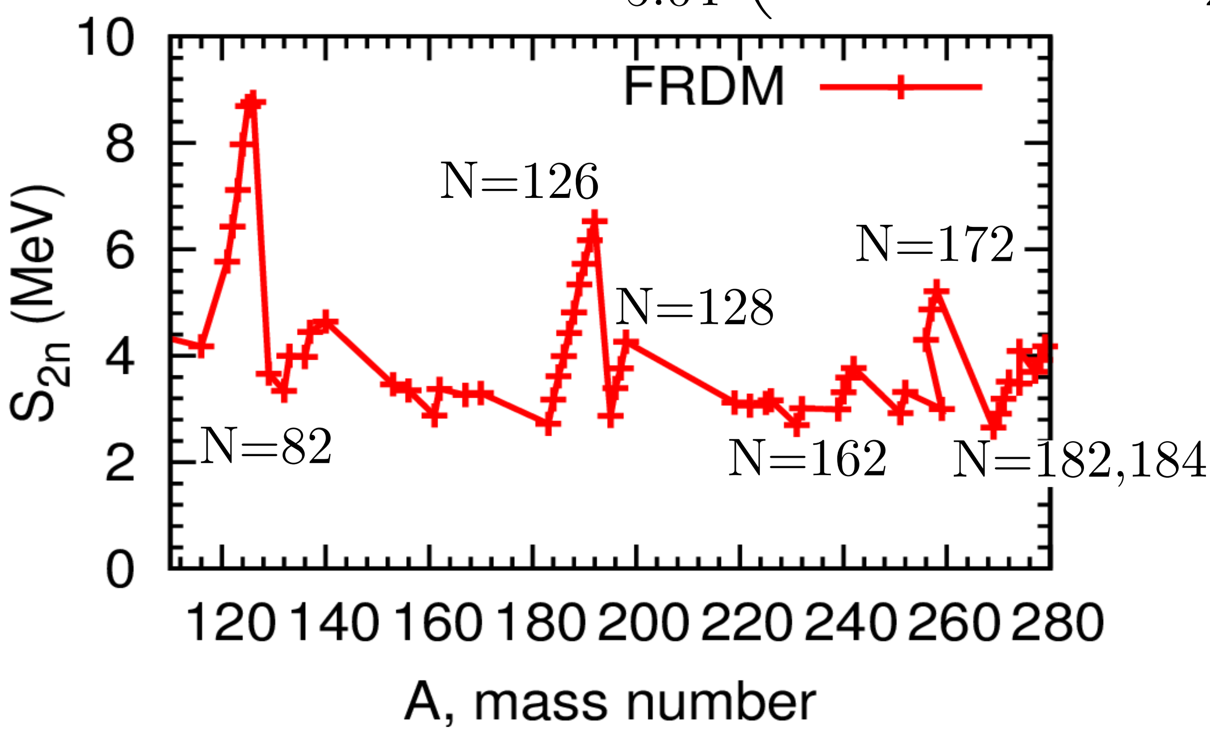


$R_{n/s} = 1$

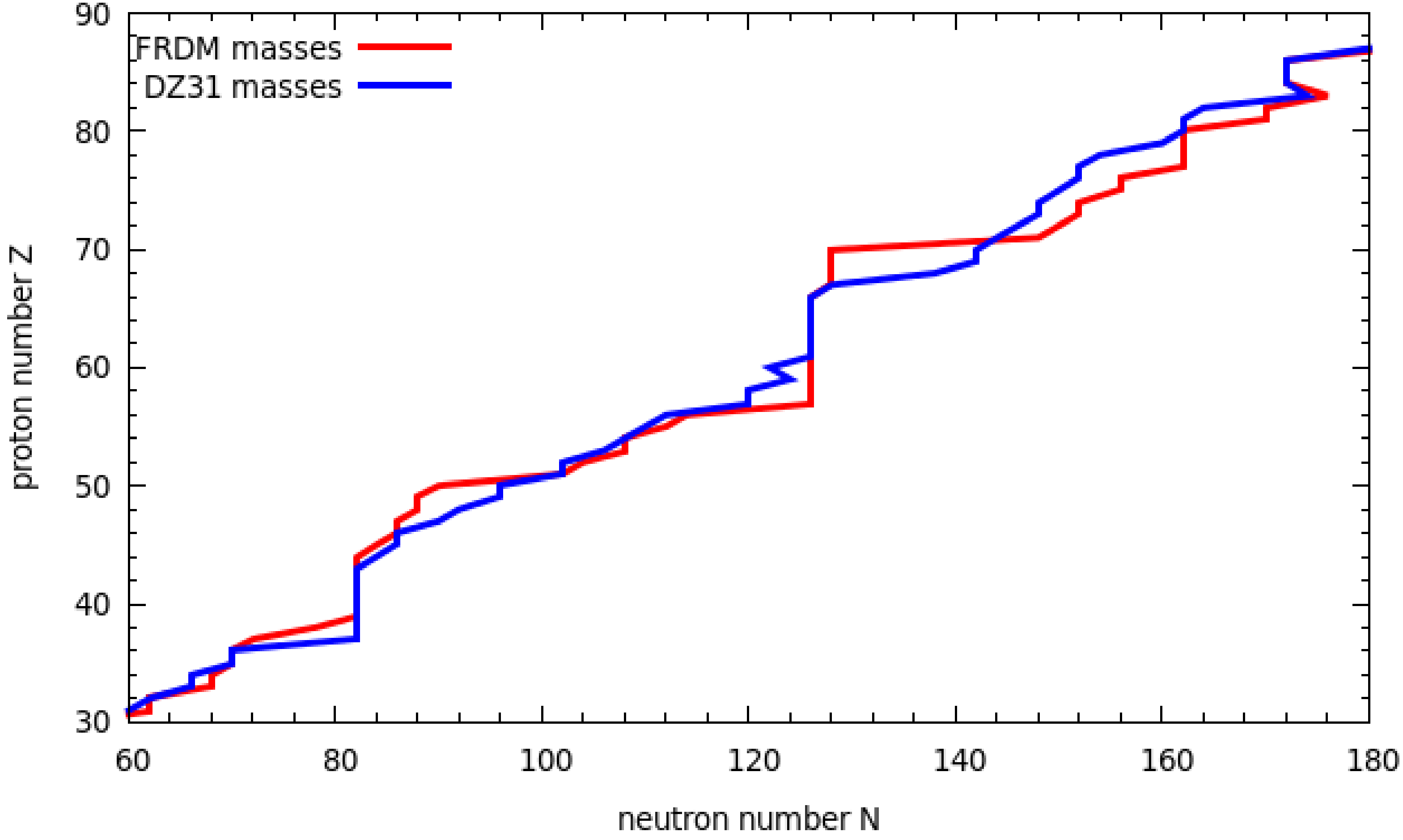
$T \approx 0.75$ GK

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

$S_n^0 \approx 1.4$ MeV

nuclear masses

nuclear mass prediction determine the r-process path and therefore the abundances

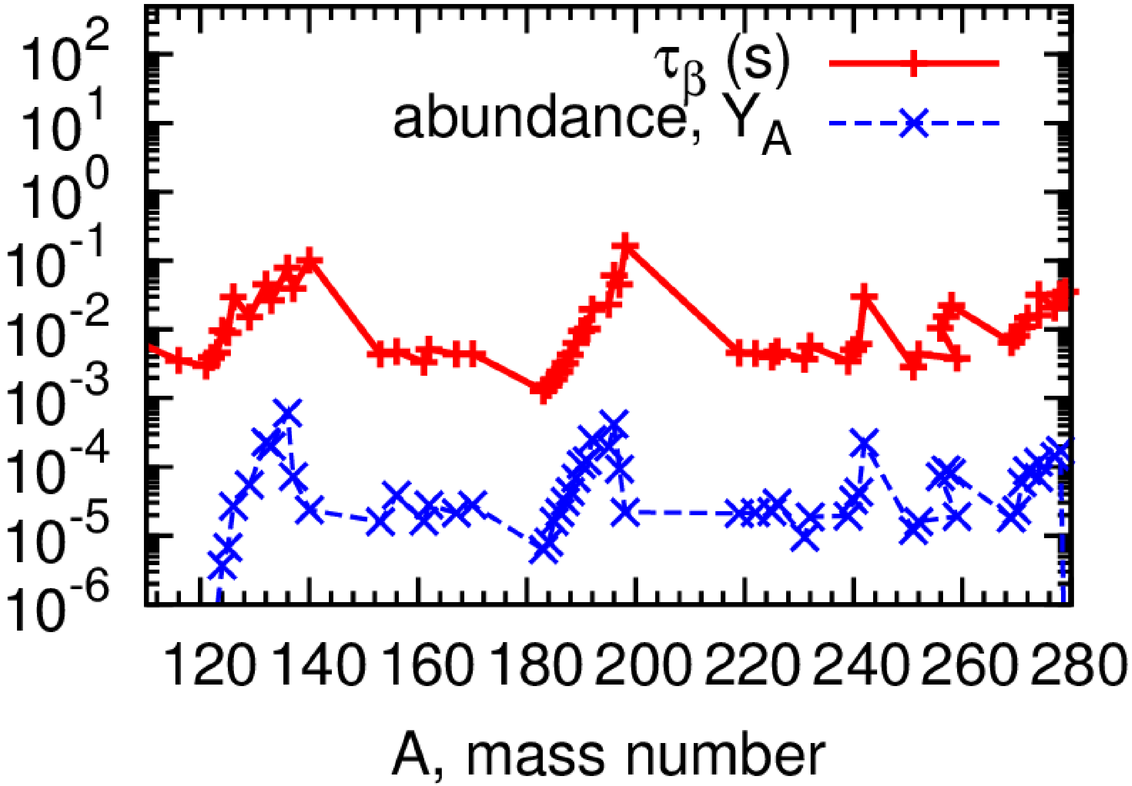


(See Martin+, Mendoza-Temis+, Mumpower+ Goriely+ and many many others)

beta decay rates

steady β flow: $Y(Z)\langle\lambda_\beta(Z)\rangle = Y(Z+1)\langle\lambda_\beta(Z+1)\rangle$

→ nuclei with longer β-decay halflives are more abundant



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

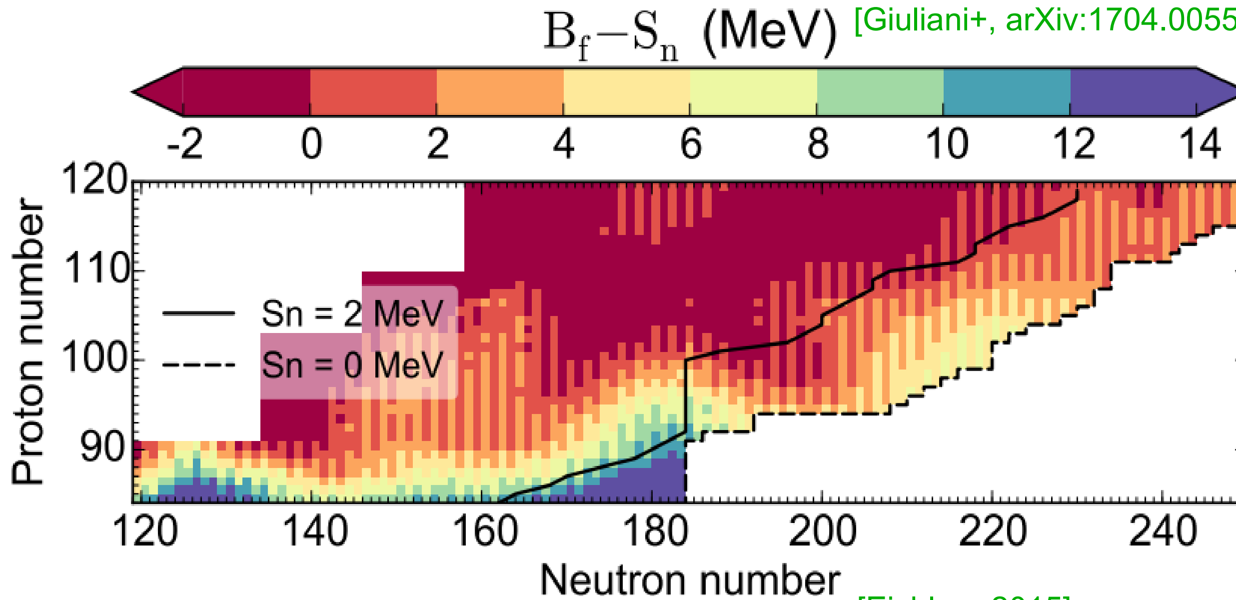
$S_n^0 \approx 1.4$ MeV

(β-decay rates also shapes the final abundance pattern and peak locations during the r-process freeze-out. E.g., Eichler+ 2015, Friedel and Tomislav's talks in the workshop and other works...)

fission rates and fragment distributions

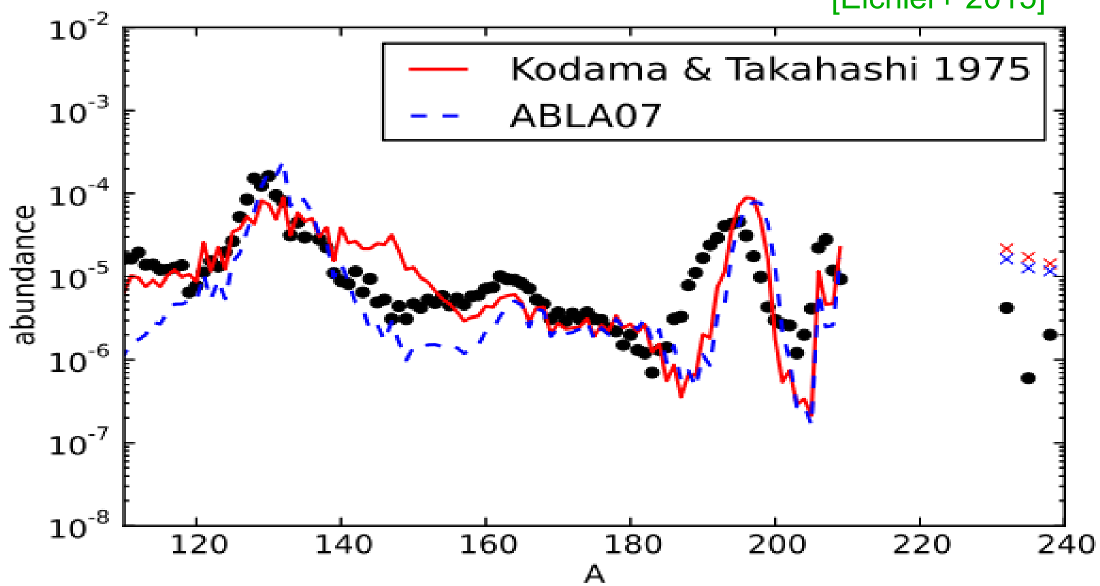
fission barrier height prediction determines where the r-process ends

[Giuliani+, arXiv:1704.00554]



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

[Eichler+ 2015]



(See also Goriely+, Mumpower+,...)

Impact of nuclear physics input on low Y_e ejecta

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

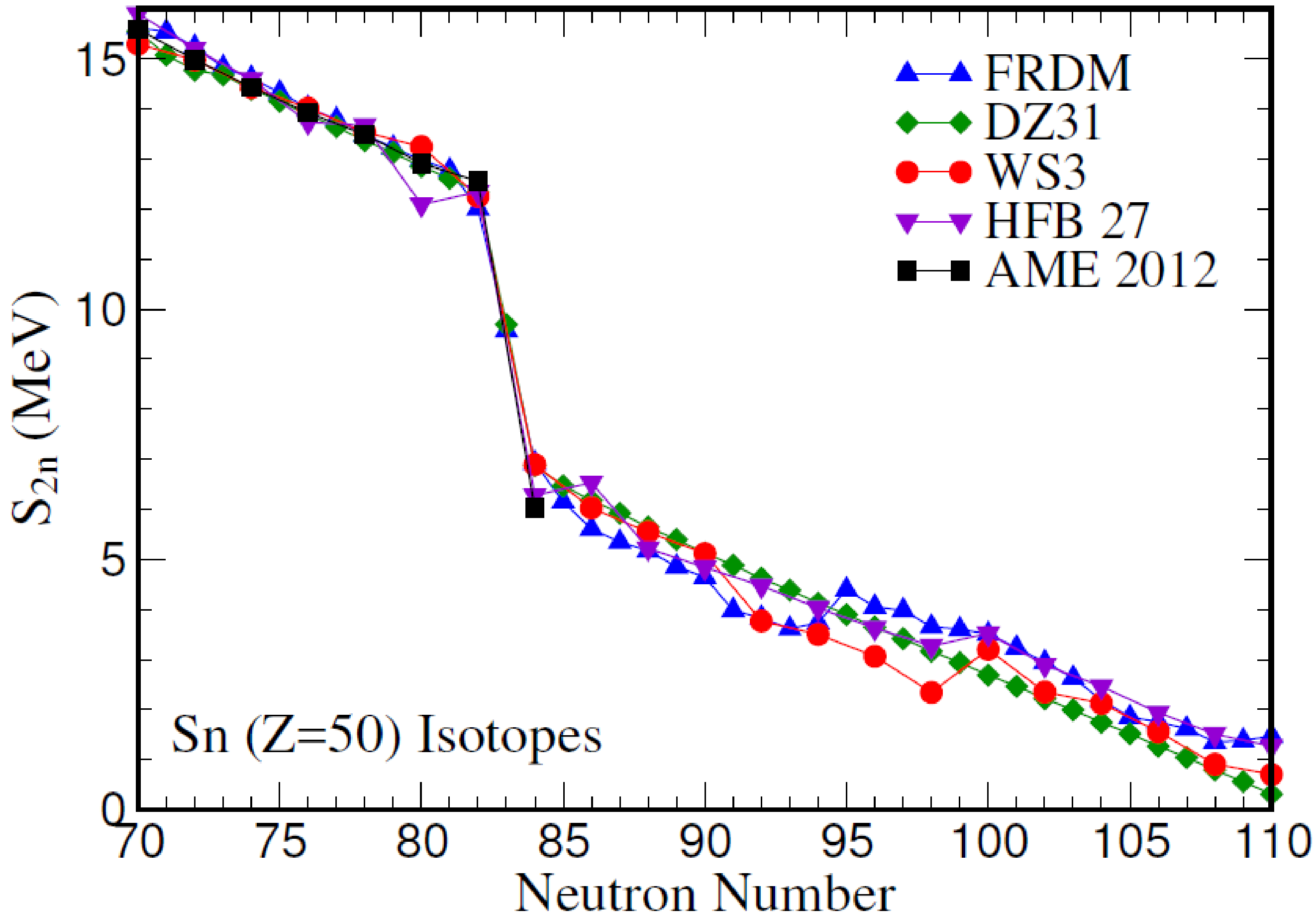
WS3: Weizsacker-Skyrme mass model, macroscopic+microscopic

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

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

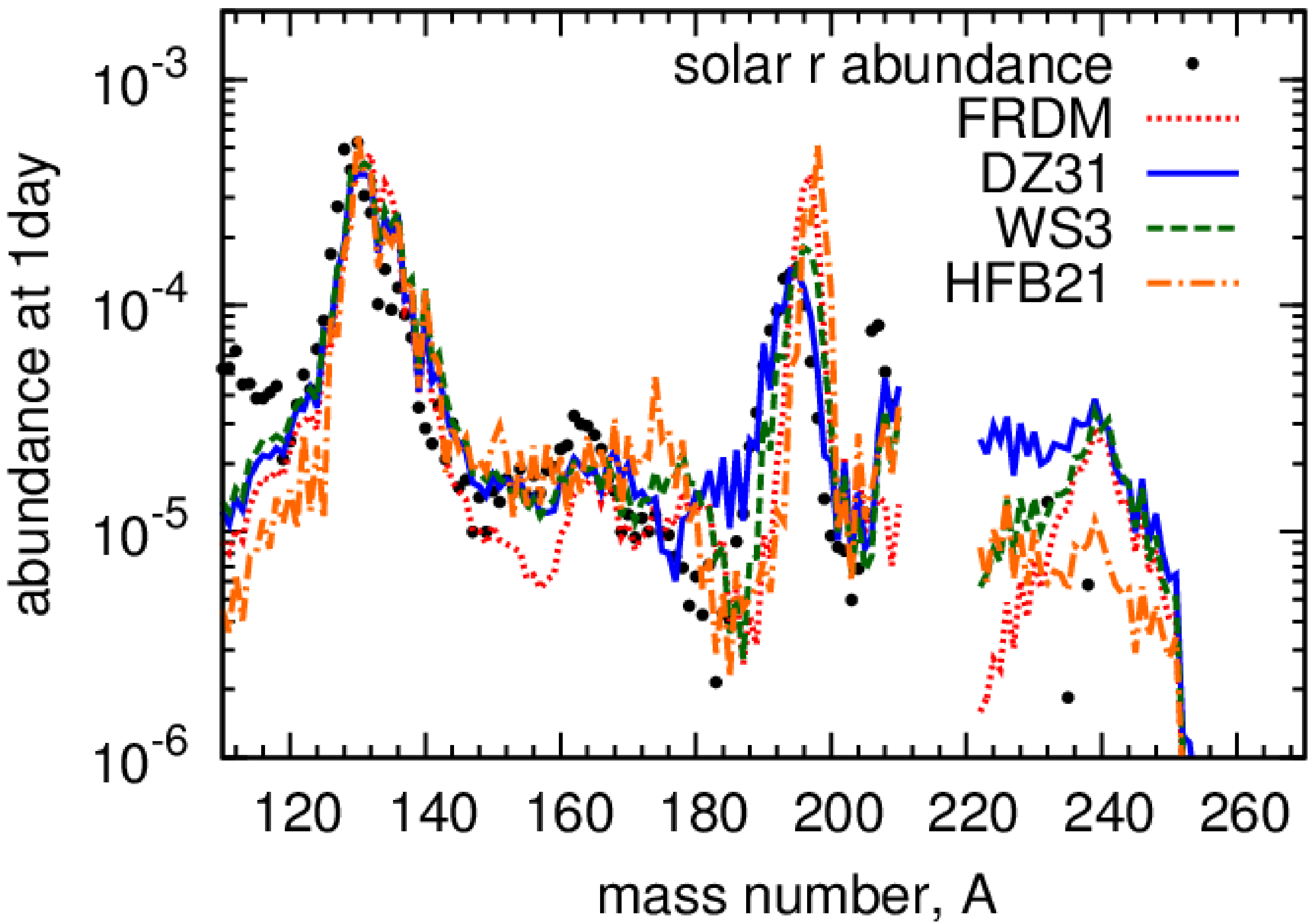
Comparison S_{2n}

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



Variations in localized regions responsible for different abundances predictions.

Impact of masses on abundances

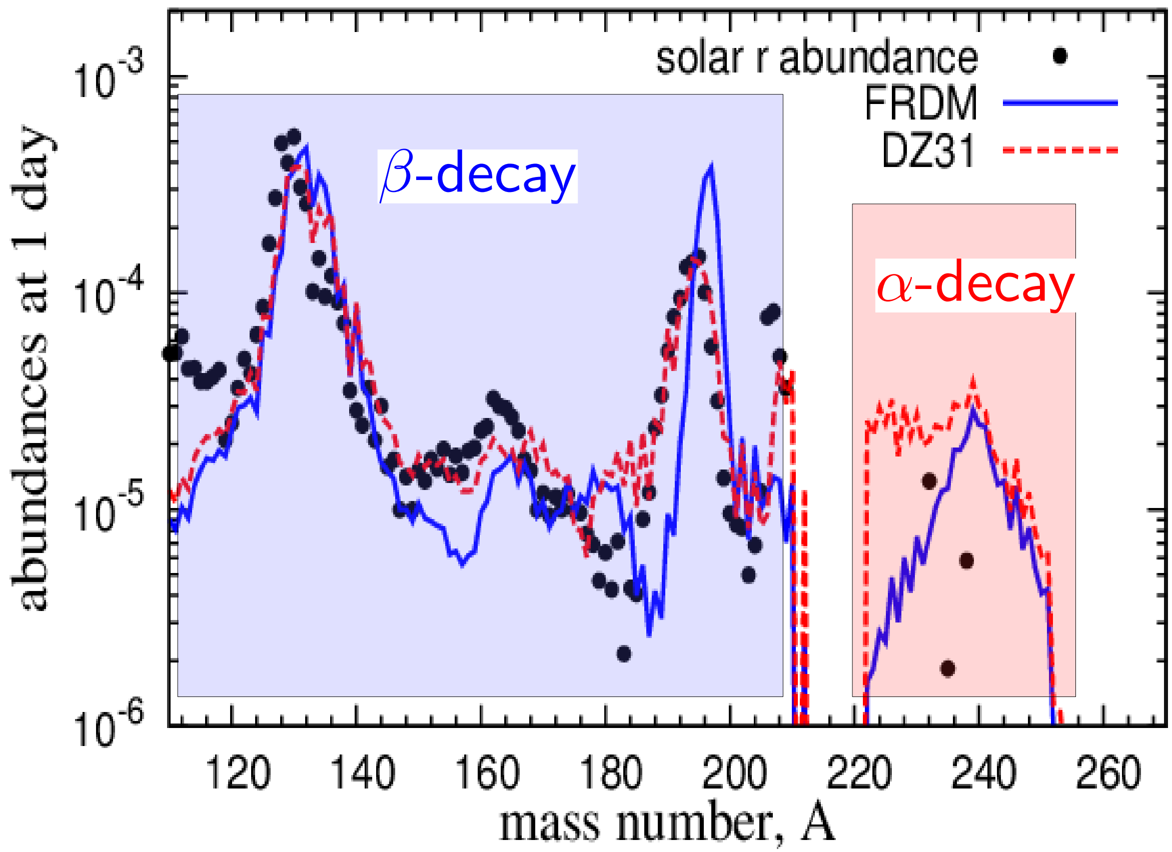


only the (n,γ) and (γ,n) for nuclei with $Z <= 83$ are changed

Impact of masses on abundances

the prediction of the trans-lead abundances can depend greatly on the adopted nuclear mass models

[Mendoza-Temis, MRW, Martinez-Pinedo+, PRC 92 (2015) 055855]



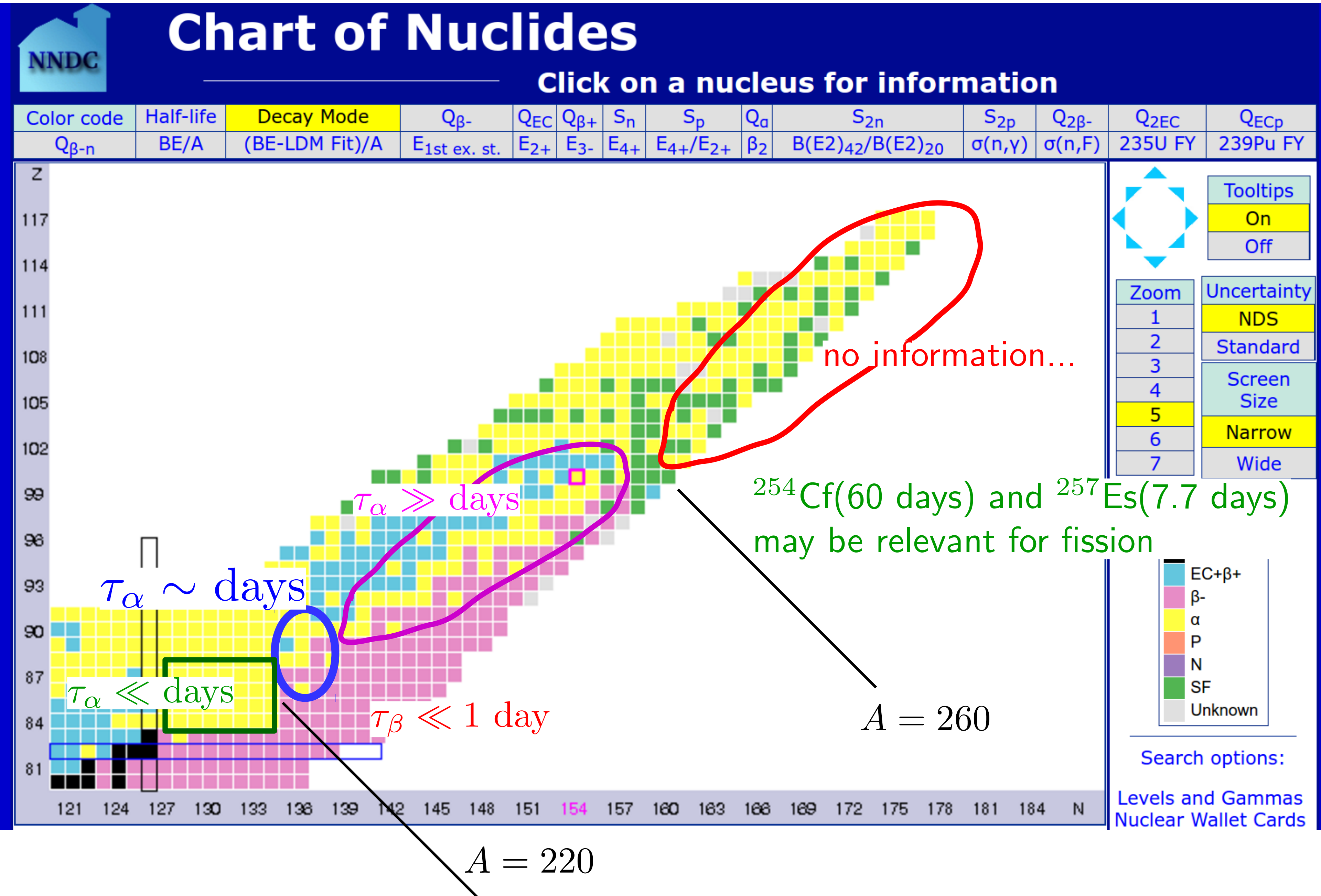
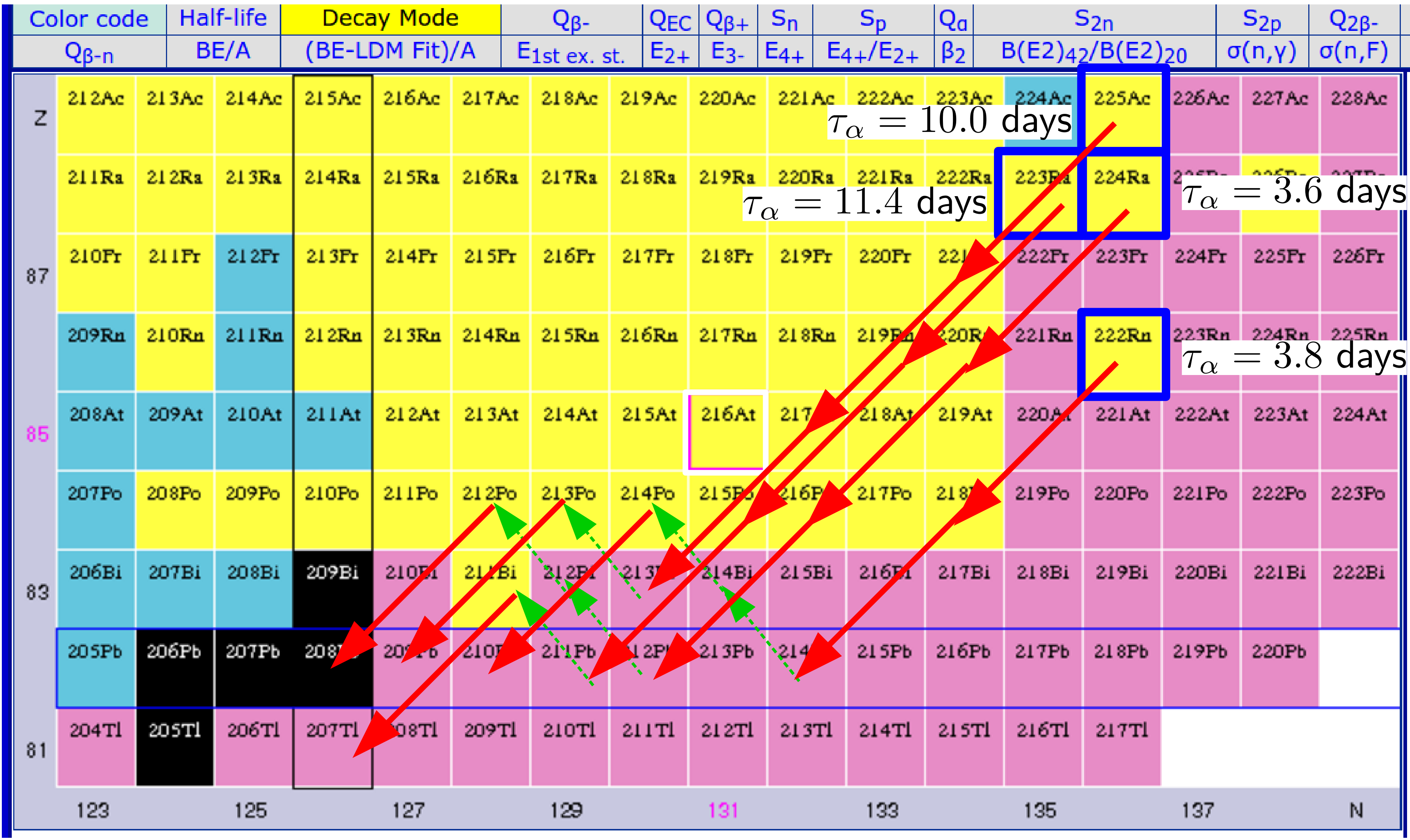


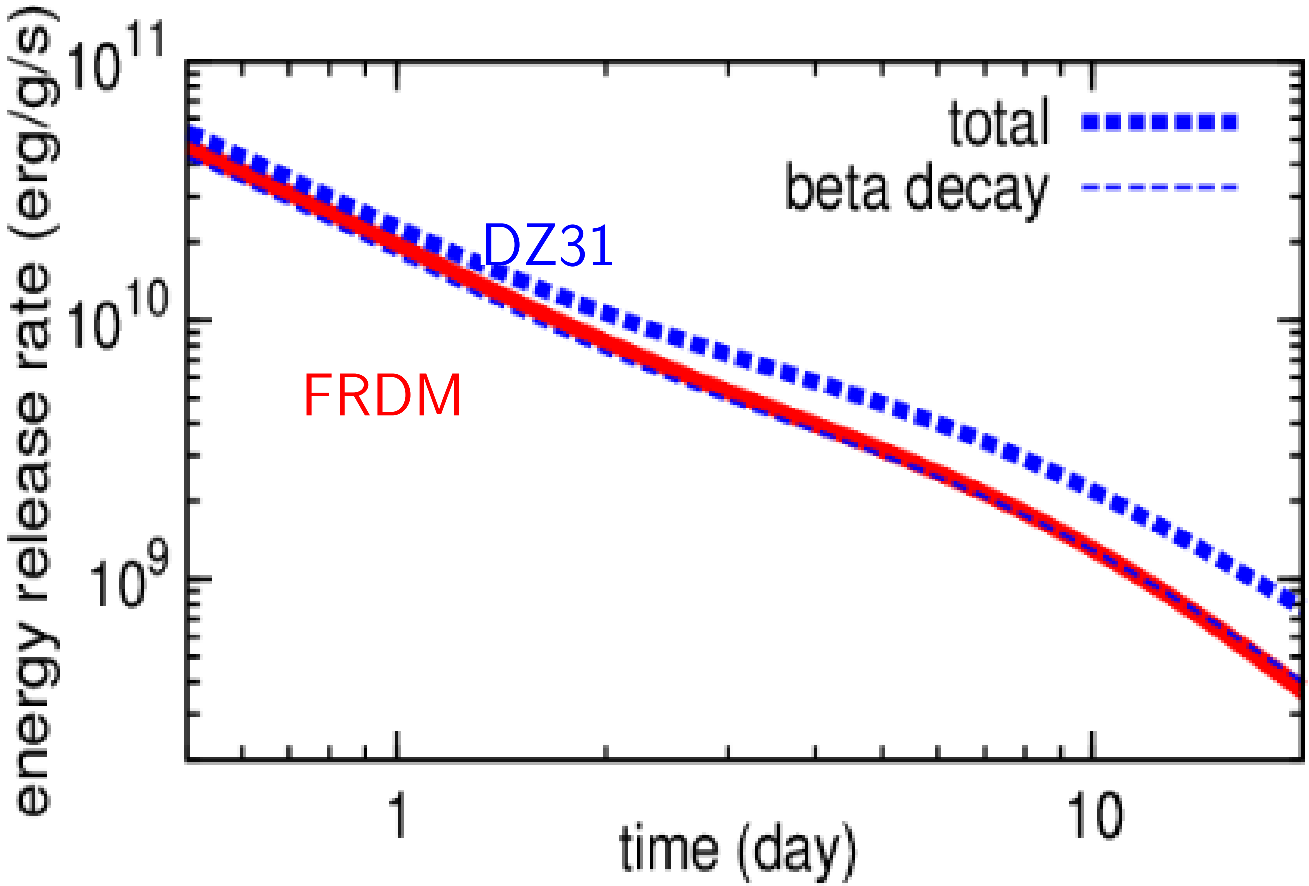
Chart of Nuclides
Click on a nucleus for information
Color code
Half-life
Decay Mode
Tooltips
On
Off
Zoom
Uncertainty
NDS
Standard
Screen Size
Narrow
Wide
EC+β+
β-
α
P
N
SF
Unknown
Search options:
Levels and Gammas
Nuclear Wallet Cards
no information...
^{254}Cf(60 days) and ^{257}Es(7.7 days) may be relevant for fission
$\tau_\alpha \gg$ days
$\tau_\alpha \sim$ days
$\tau_\alpha \ll$ days
$\tau_\beta \ll 1$ day
$A = 260$
$A = 220$

Relevant α-decays



Nuclear physics inputs and the kilonova heating rate

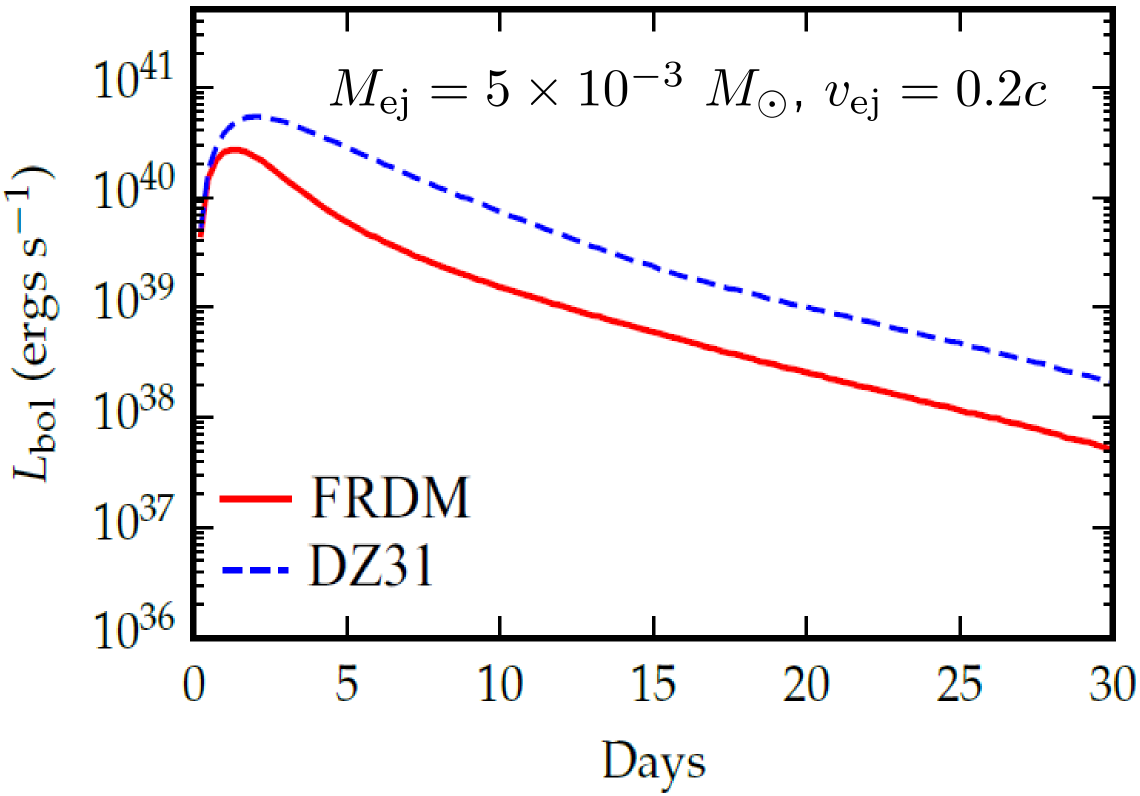
α-decays goes in "chains" at $t \gtrsim 3$ days and releases $Q_\alpha \sim 6$ MeV in each decay, compared to typical $Q_\beta \sim 1$ MeV. Therefore, it can dominate the radioactive energy release

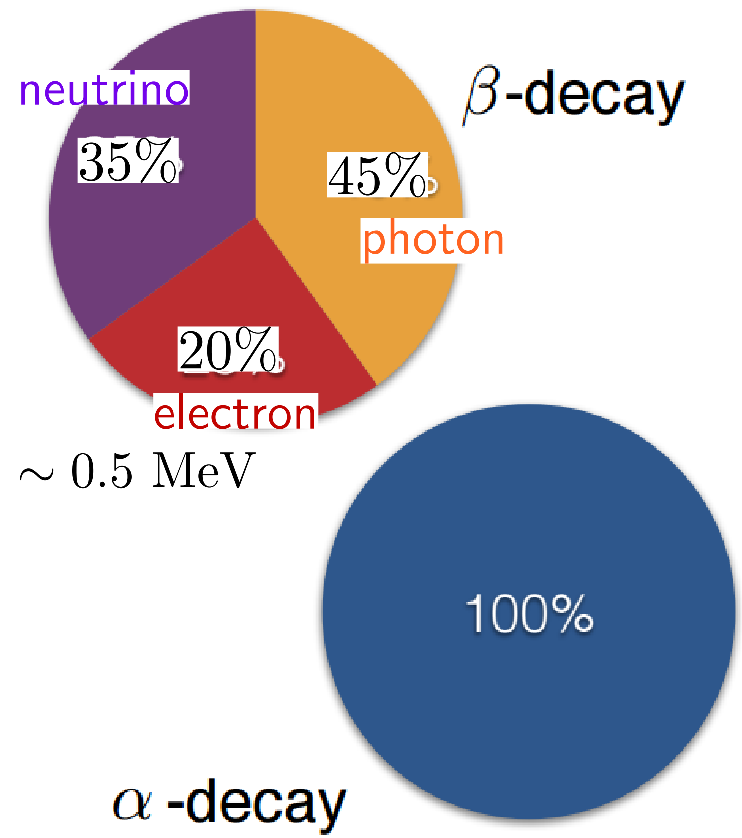


Nuclear physics inputs and the kilonova heating rate

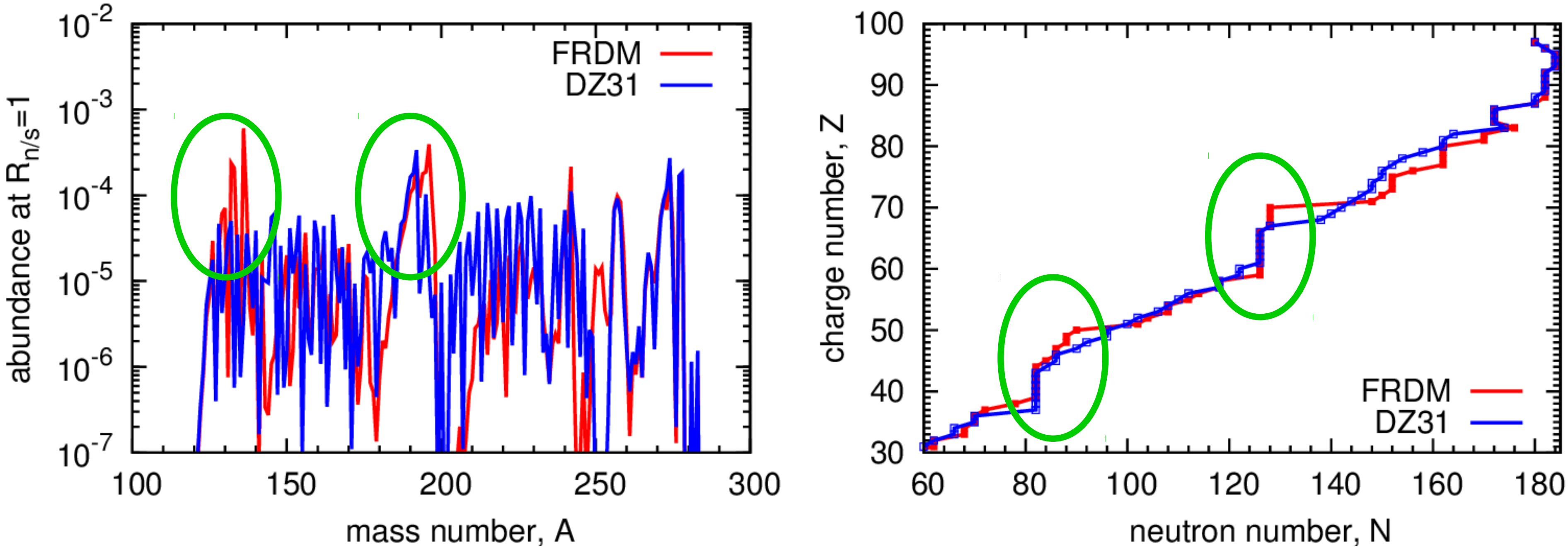
- α & β particles thermalize in a similar way while γ-ray thermalization quickly become inefficient

[Barnes, Kasen, MRW, Martinez-Pinedo, ApJ 829 (2016) 110]





Link to nuclear mass predictions

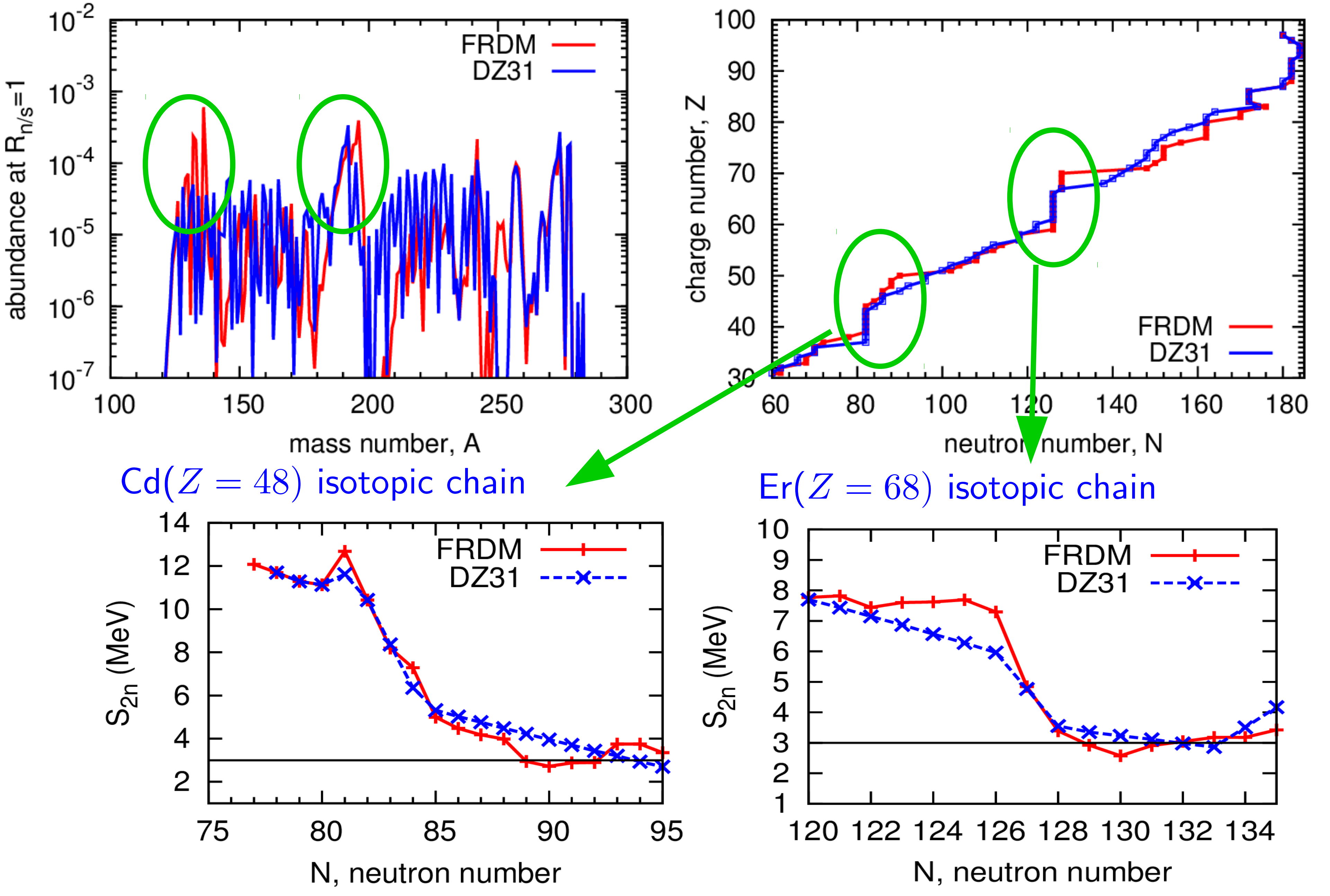


the r-process path with FRDM mass model extends to larger Z for regions slightly above the shell closure

$\rightarrow$ longer β-decay half-lives

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

Link to nuclear mass predictions



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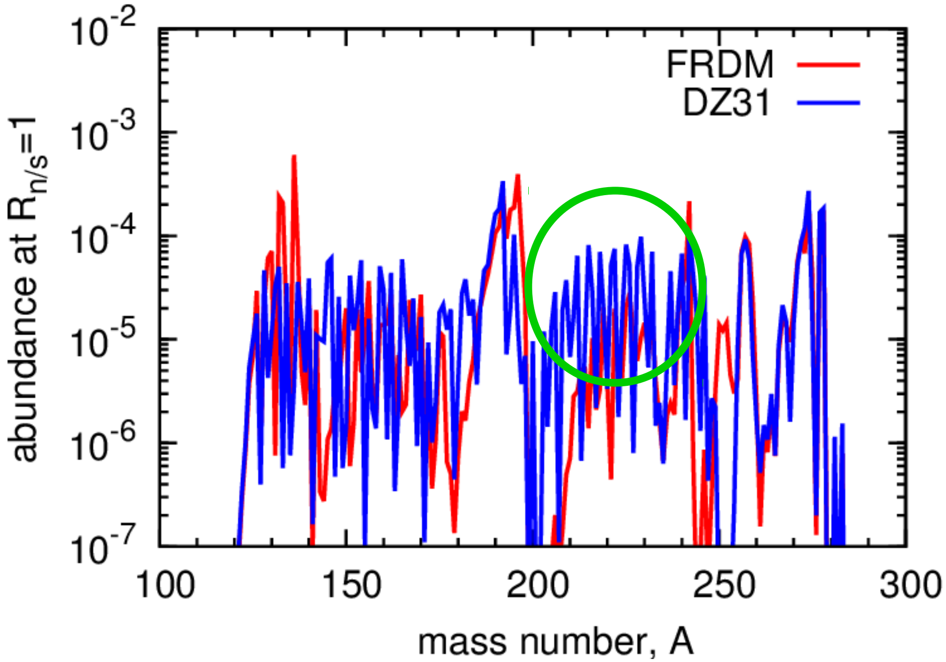
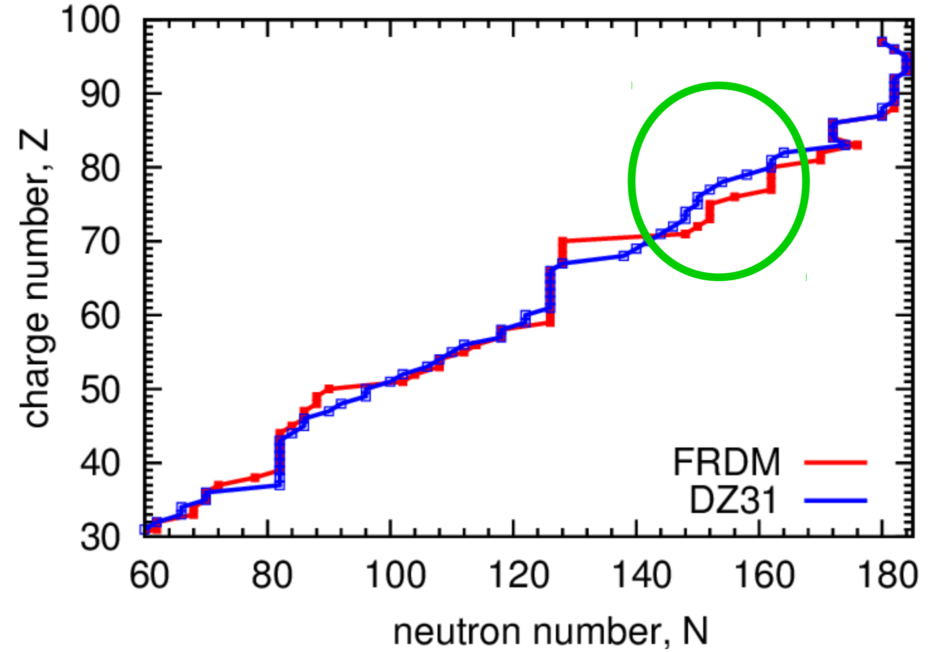


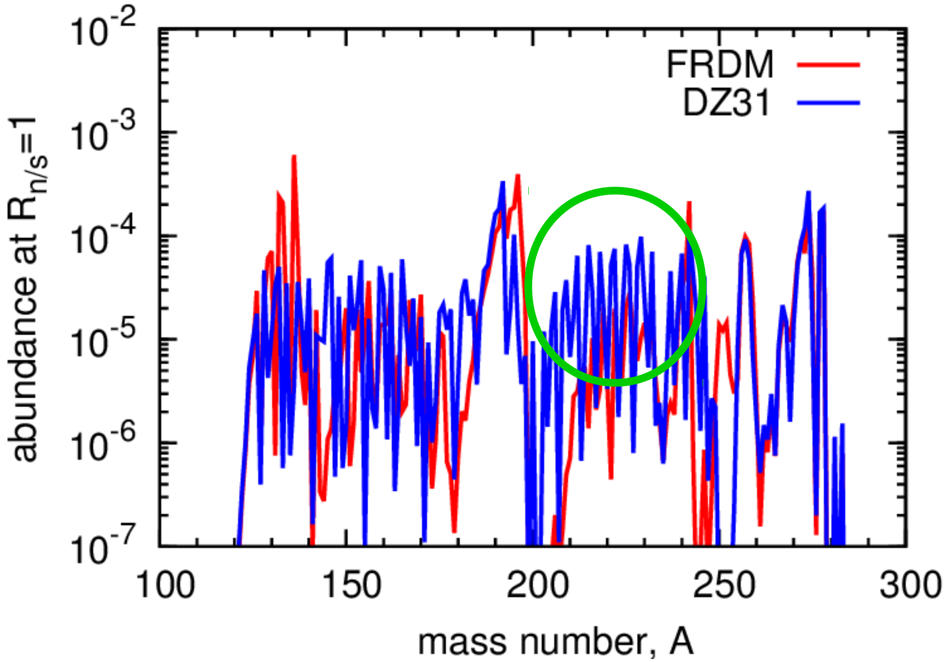


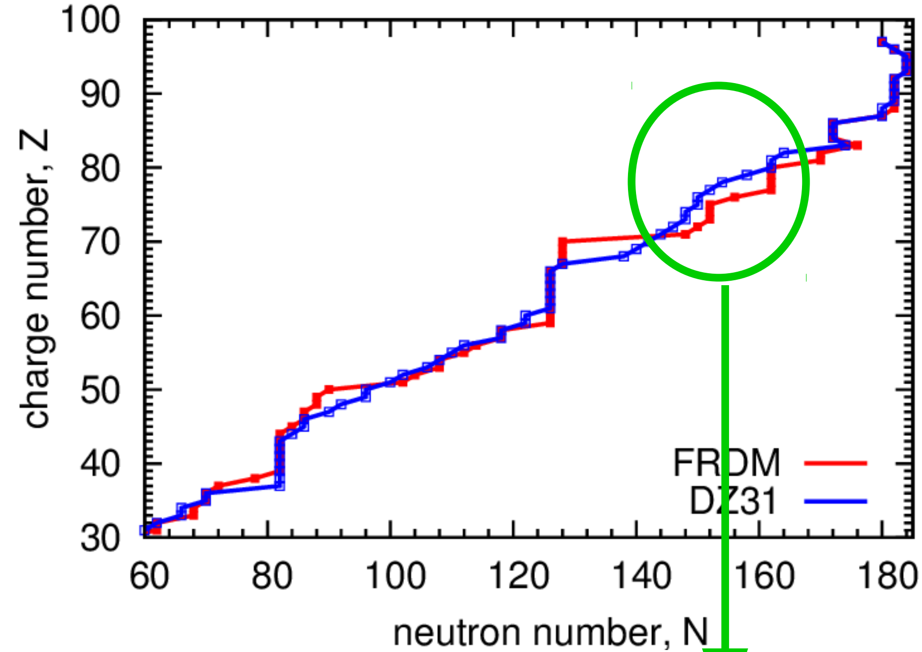
on the other hand, at the region around $A \sim 230$, the path of FRDM extends to larger N

$\rightarrow$ shorter β-decay half-lives

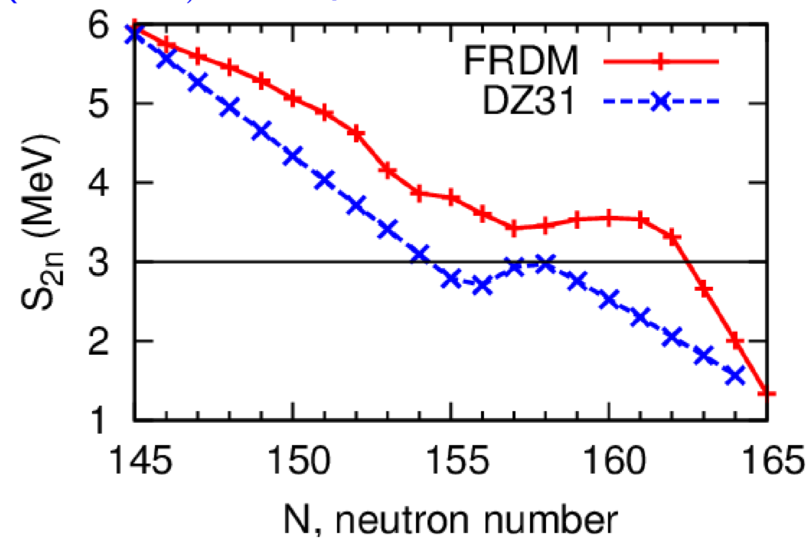
$\rightarrow$ smaller abundances

Link to nuclear mass predictions





Pt($Z = 78$) isotopic chain



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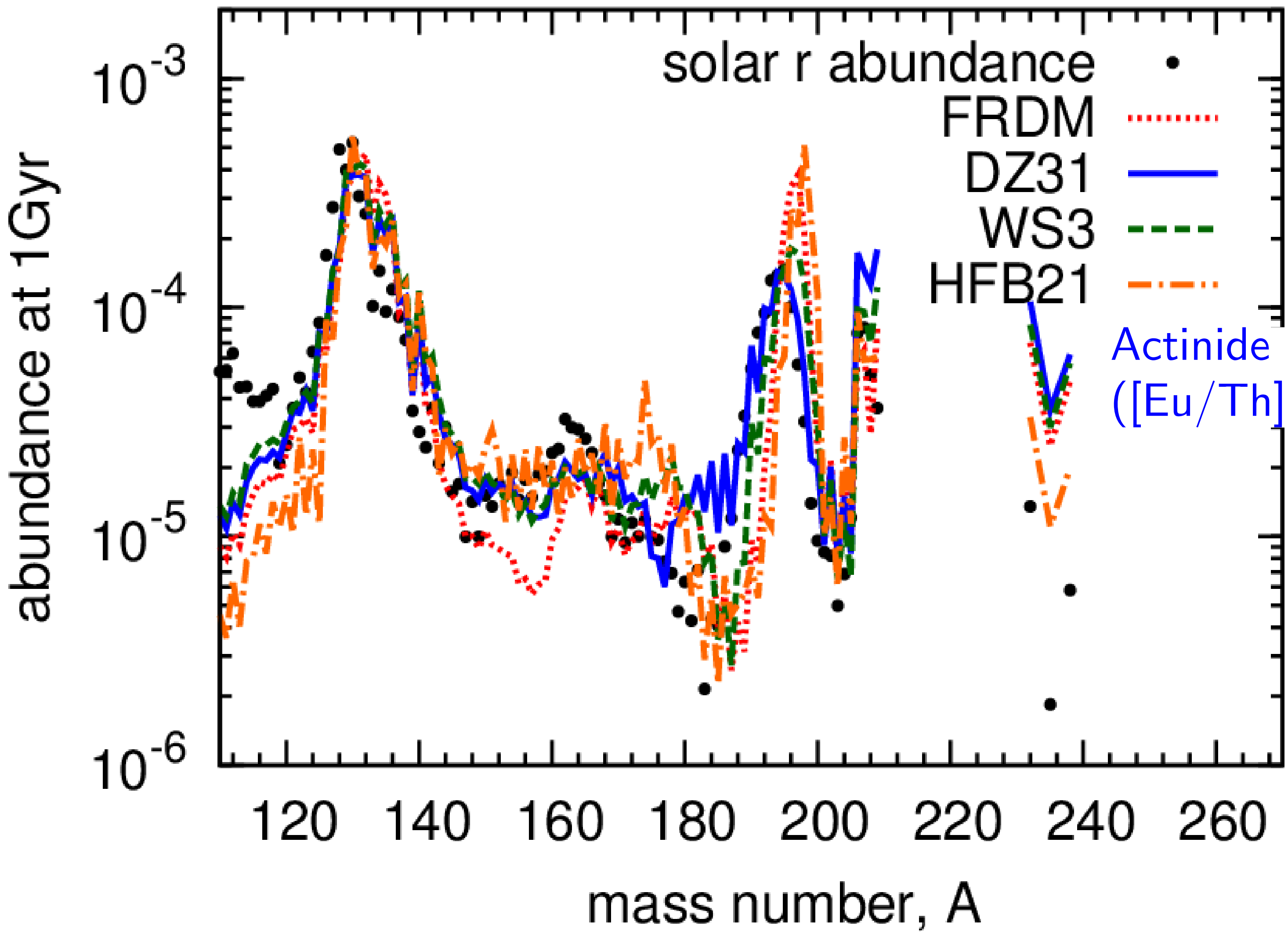
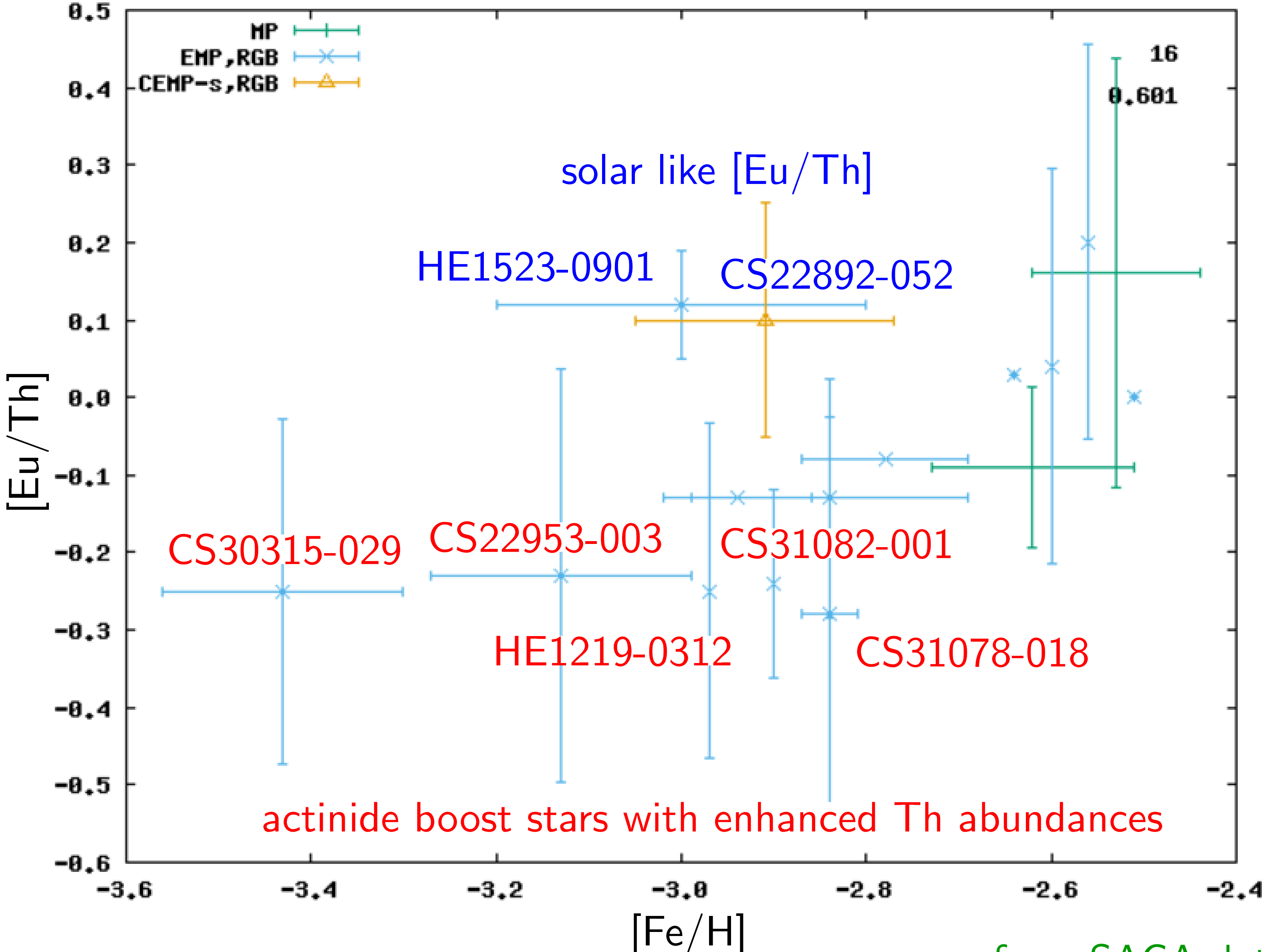
“Final” abundances and metal-poor stars



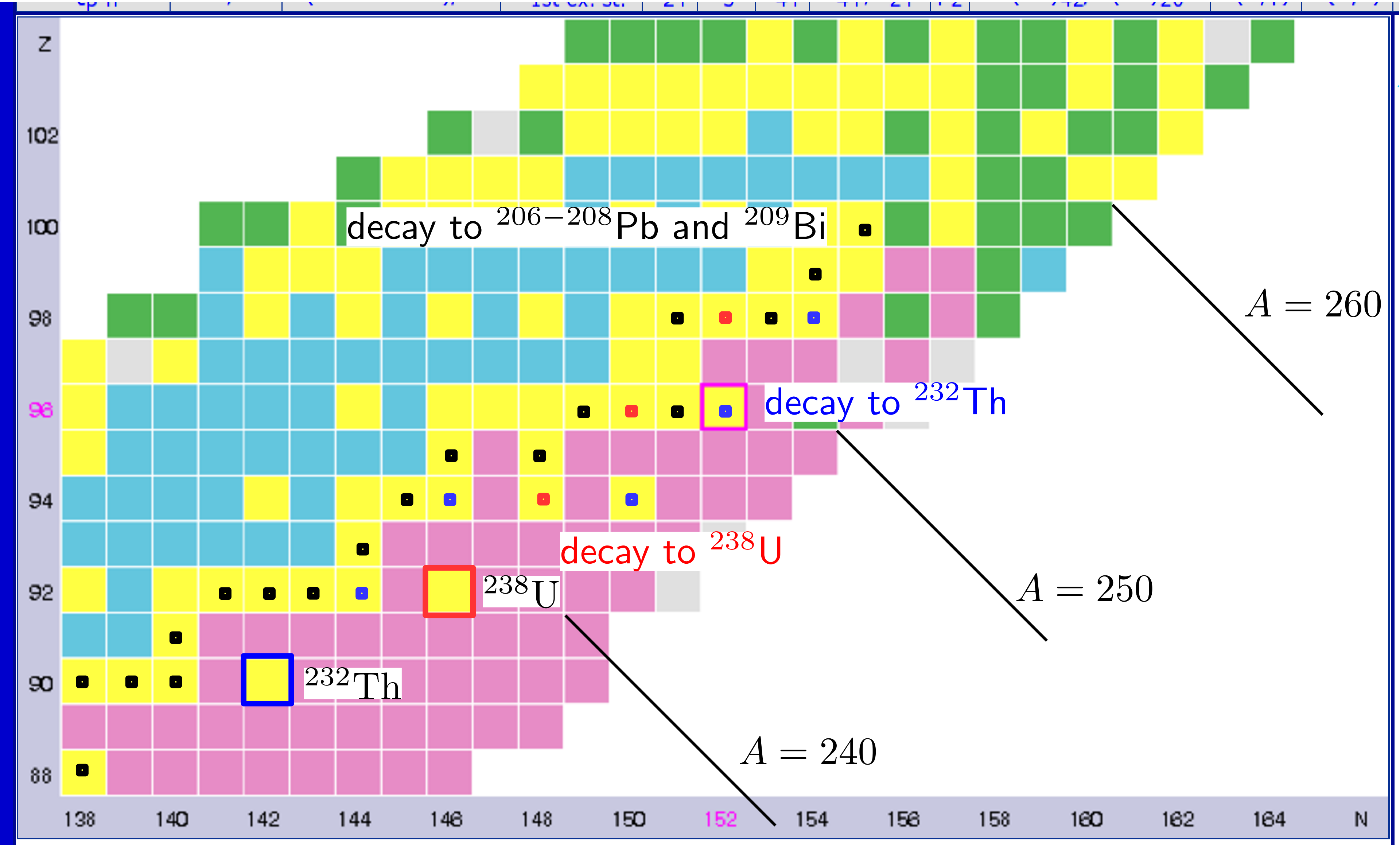
Actinide boosted!
([Eu/Th]≈ -0.3 at 13Gyr)

Actinide abundances in Metal-poor stars



from SAGA database

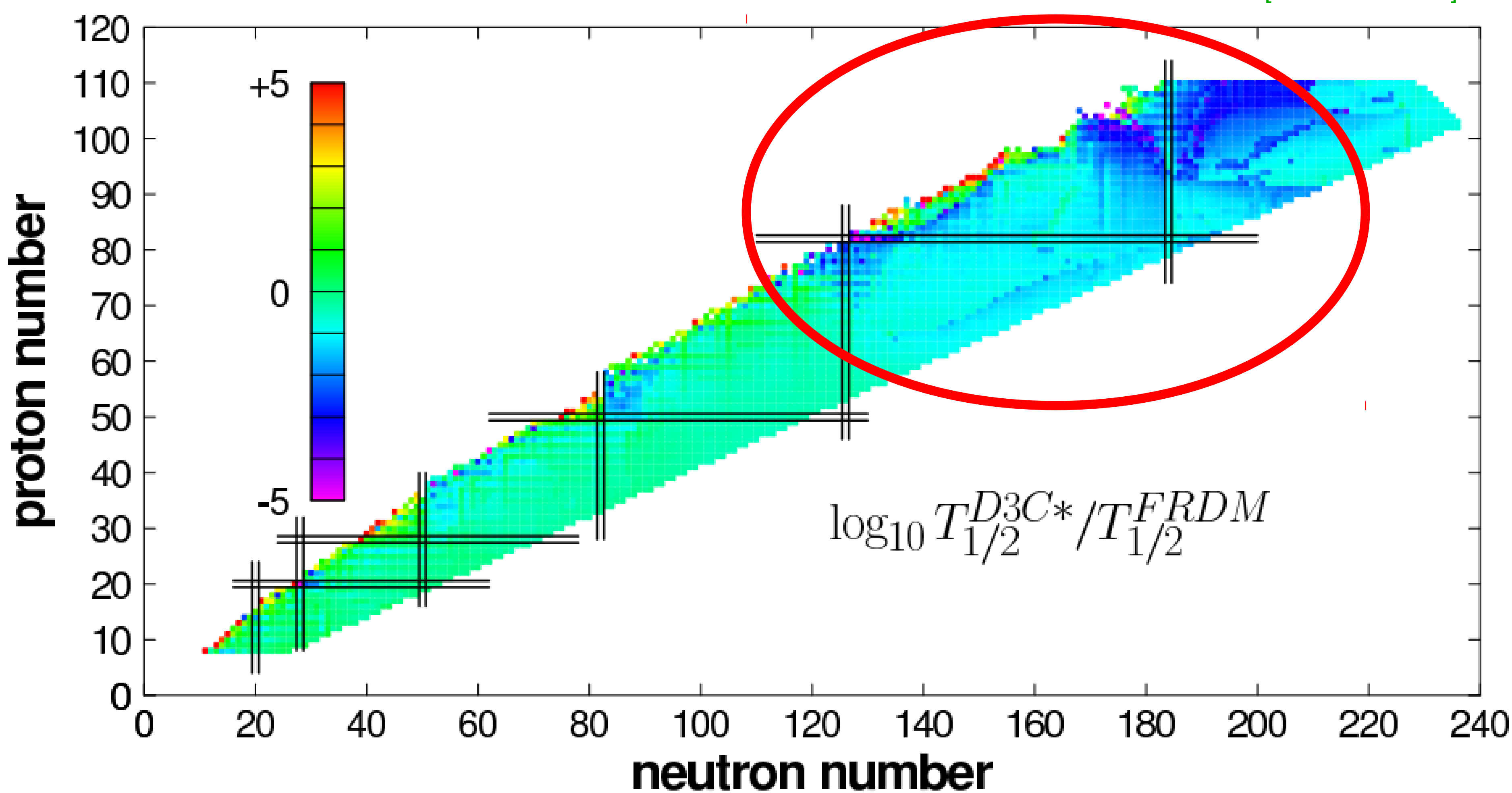
measurement of lead abundance can be useful to infer the actinide production



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

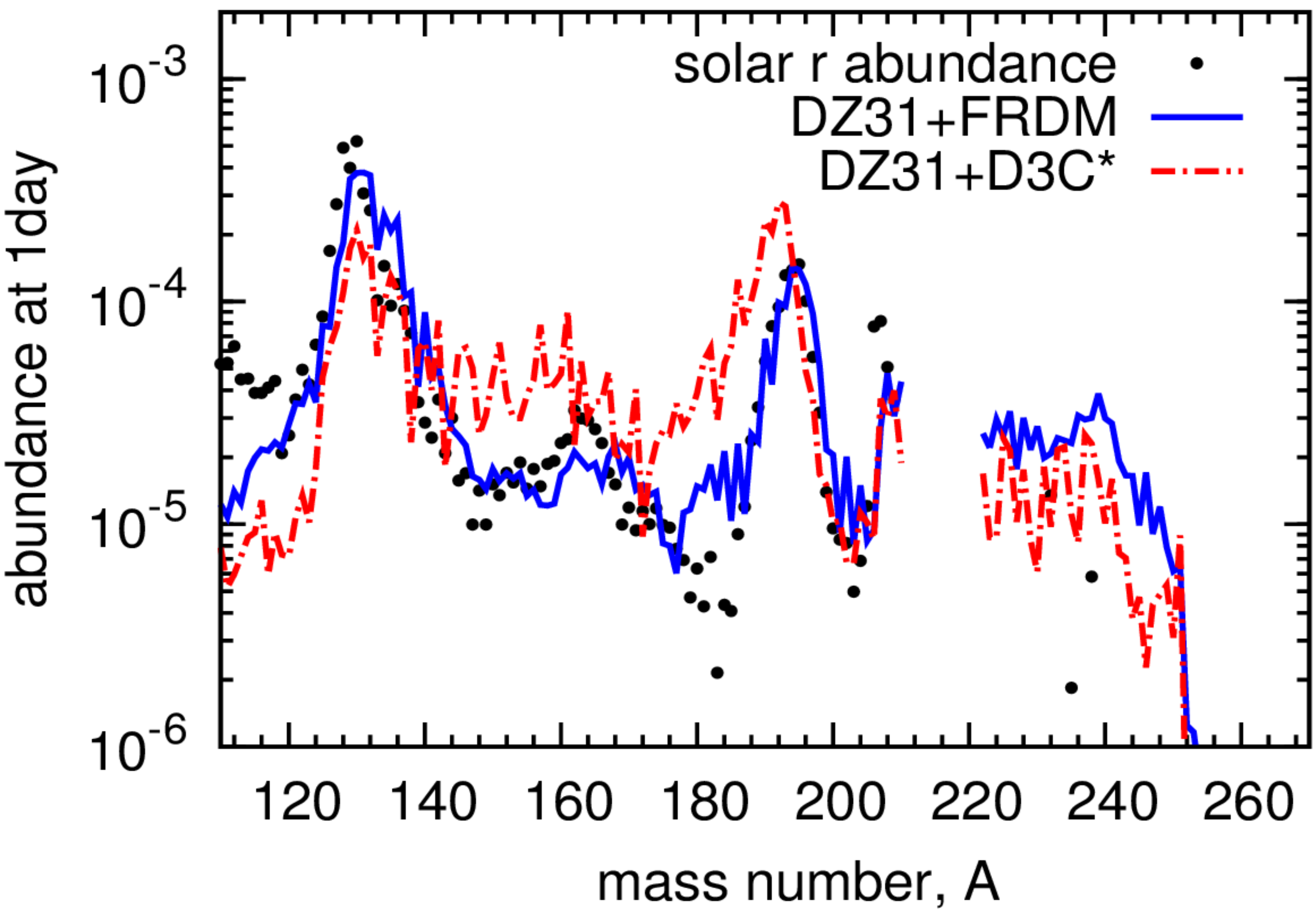
Impact of β-decay rates

[Marketin+ 2015]



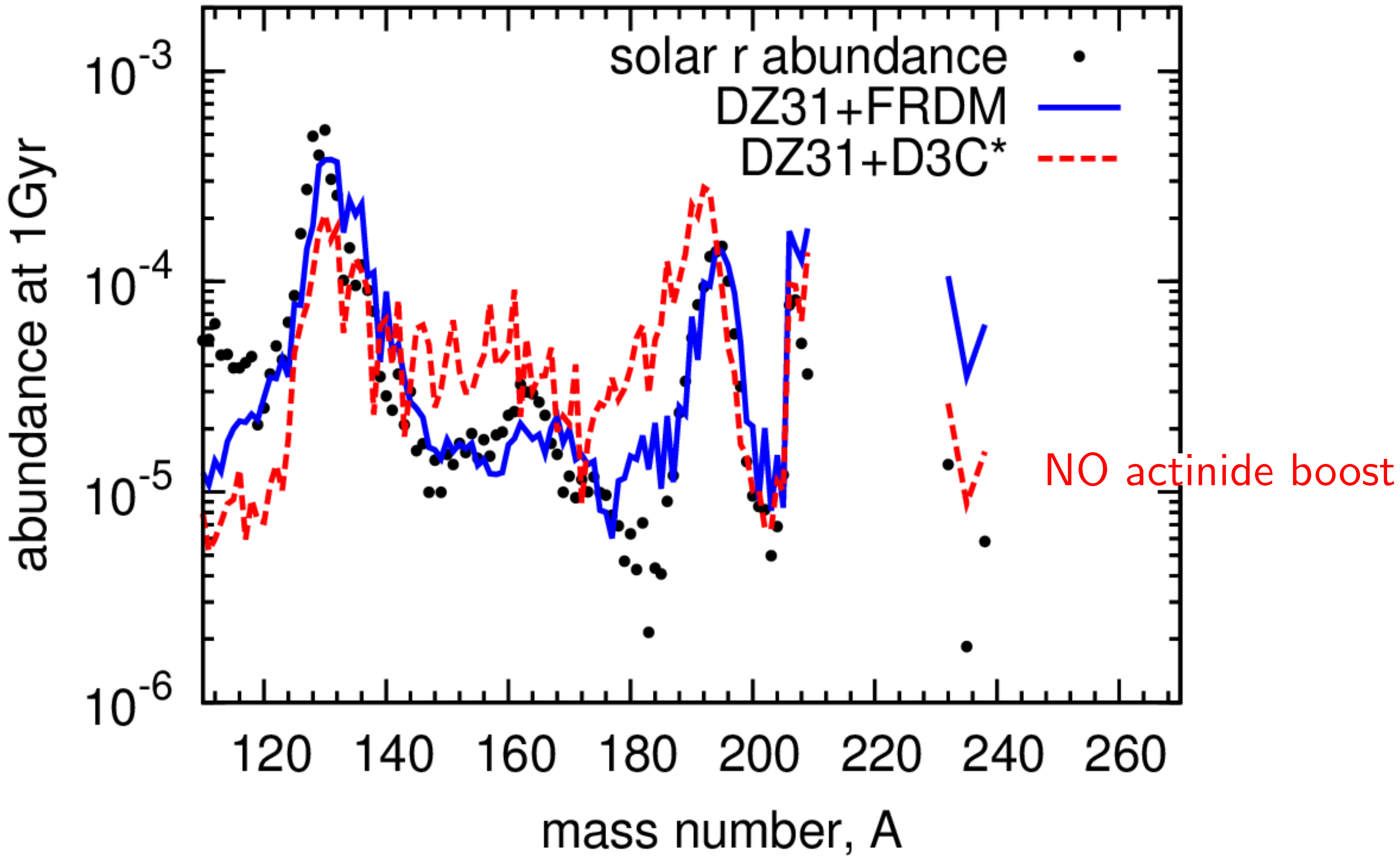
D3C* model predicts shorter τ_β for heavier nuclei

Impact of β-decay on abundances



impact on radioactive heating rates is on the level of $\sim 30\%$, due to the different relative height in peaks

Impact of β-decay on abundances



if actinides-boost production is originated from low Y_e ejecta from mergers, one may be able to link the abundances to the half-lives for the translead neutron-rich nuclei?

Neutron-decay powered pre-cursor?

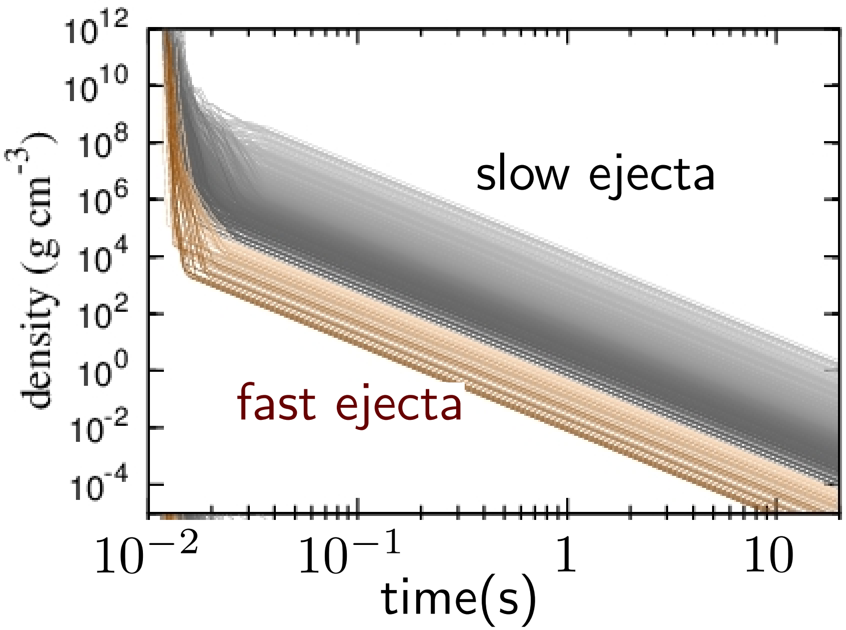
- for $\sim 90\%$ of the ejecta, neutrons are used out during the r-process time scale ~ 1 second ($\tau_{(n,\gamma)} \lesssim \tau_{\mathrm{dyn}}$)
$\rightarrow$ normal r-process

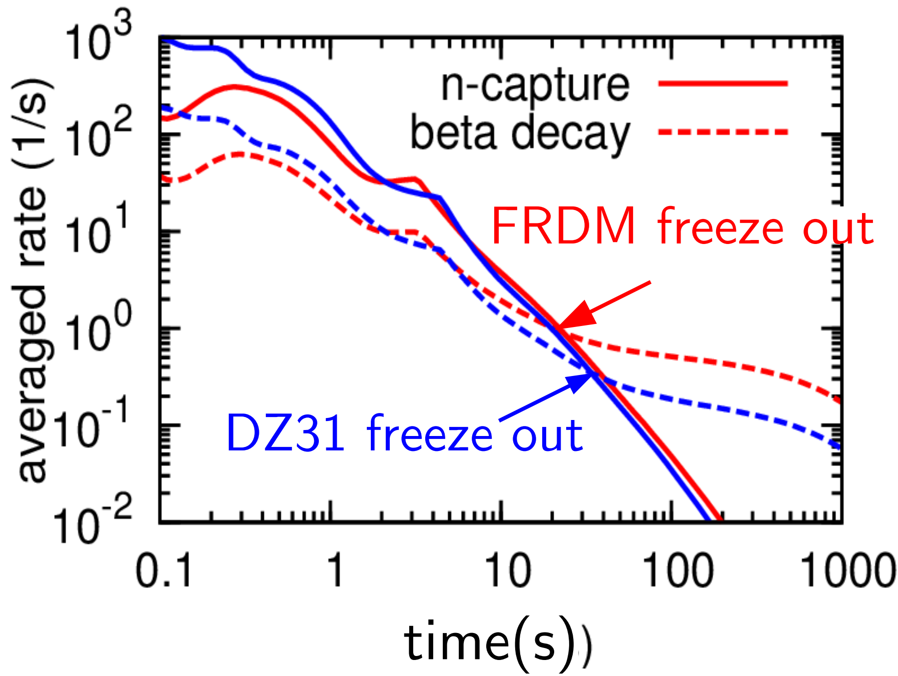
- $\sim 10\%$ of the ejecta expands very fast so that free neutrons left at the end of the r-process ("not-so-rapid" r-process)
$\rightarrow$ kilonova pre-cursor?

[Metzger+2015, Goriely+ 2015]

- unused amount of neutrons depends on the mass model again:
$\sim 40\%$ with FRDM and
$\sim 20\%$ with DZ31 at $t \approx 20$ s

[Mendoza-Temis+, PRC 92, 055805 (2015)]





We know mergers should produce lots of high Y_e material...

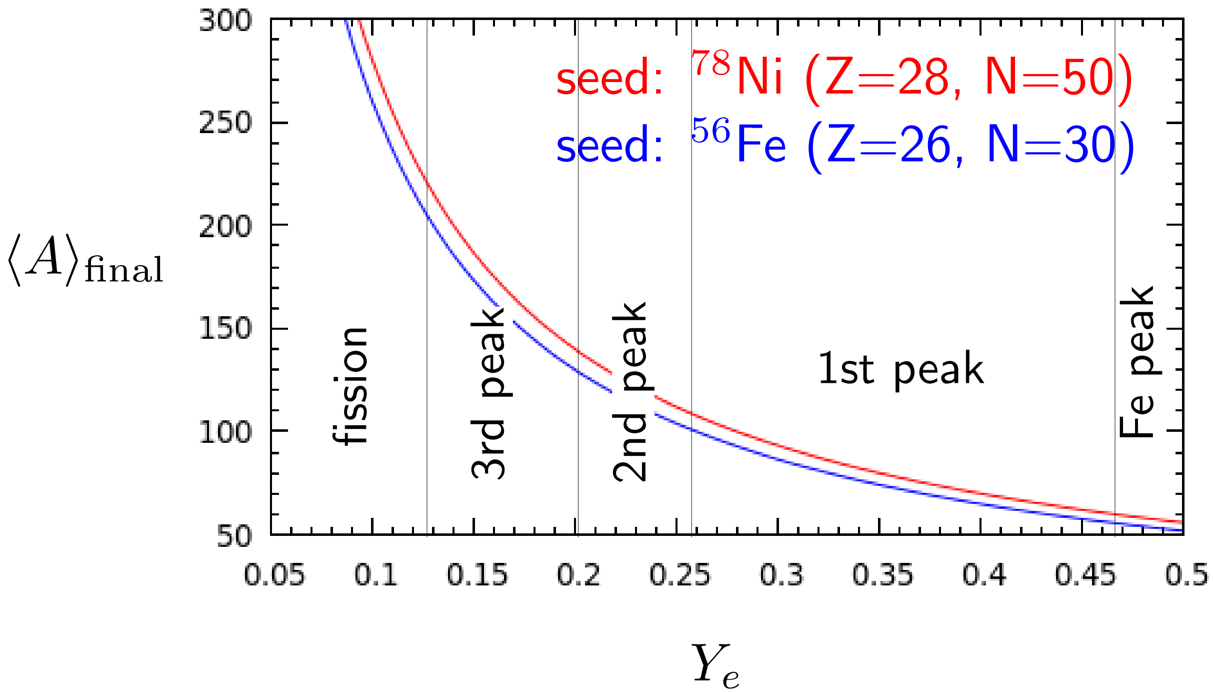
"Typical" condition of merger ejecta:

$Y_e \sim [0.01, 0.5]$, $s \sim [0-40]$ k_B/nulceon, $\tau_{\rm dyn} \sim [1, 100]$ ms

The final nucleosynthesis outcome is mostly sensitive to the initial Y_e of the ejecta

$$R_{n/s} = \frac{Y_n}{Y_{\rm seed}} = \frac{(1-Y_e) - N_{\rm seed}(Y_e/Z_{\rm seed})}{(Y_e/Z_{\rm seed})}$$

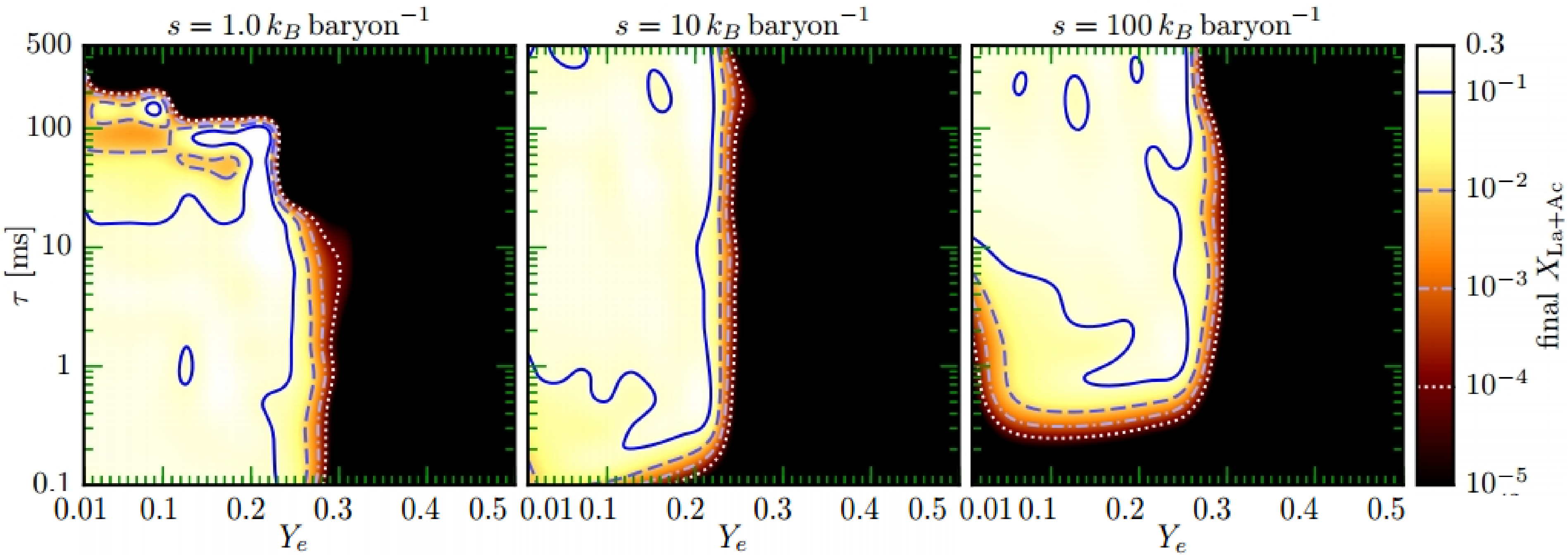
$$\langle A\rangle_{\rm final} \approx A_{\rm seed} + R_{n/s}$$



Opacity source: lanthanides and actinides

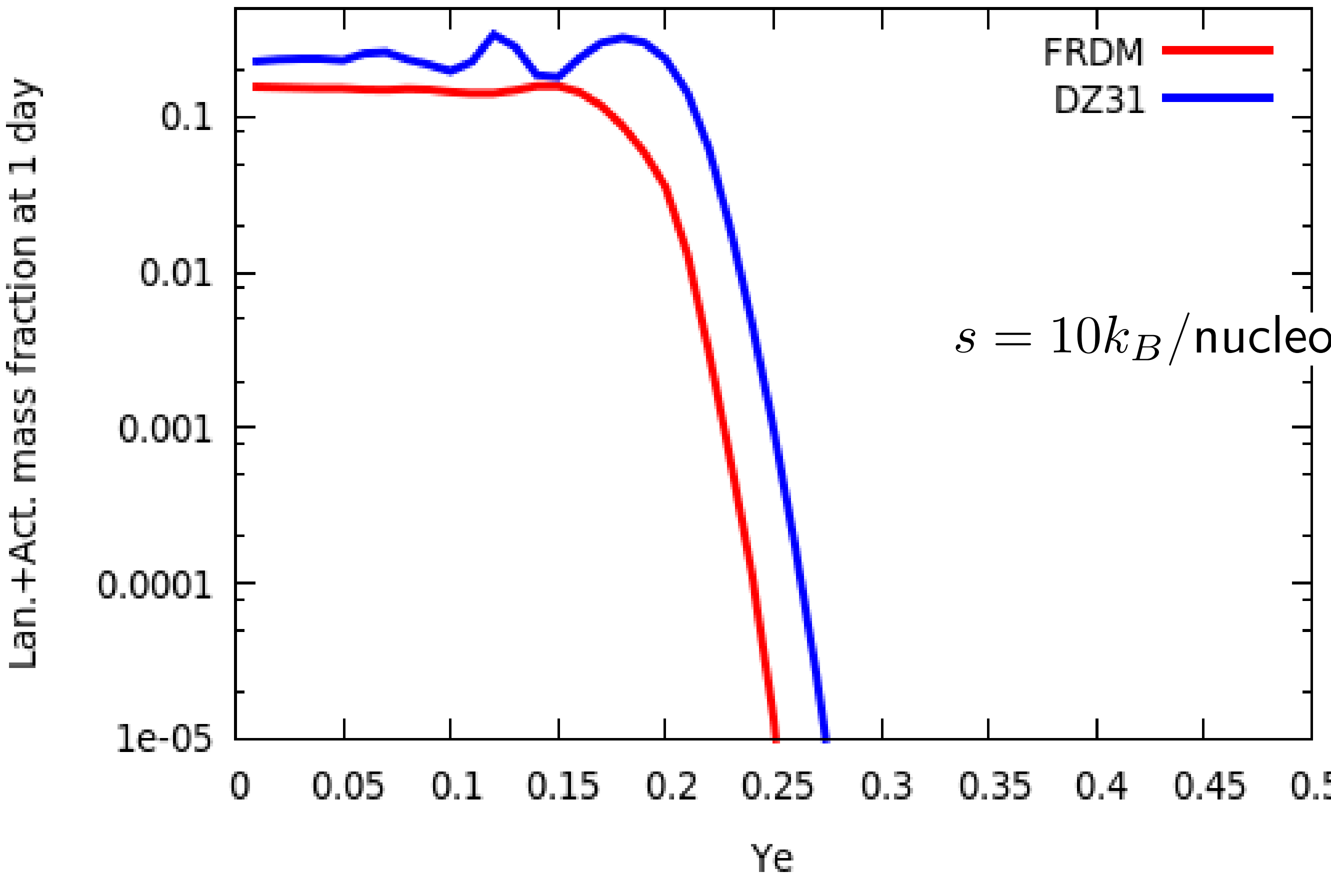
The lanthanide turnover at $Y_e \approx 0.25$

[Lippuner & Roberts, 2015]



- not very sensitive to the initial entropy and the expansion timescale

Opacity source: lanthanides and actinides



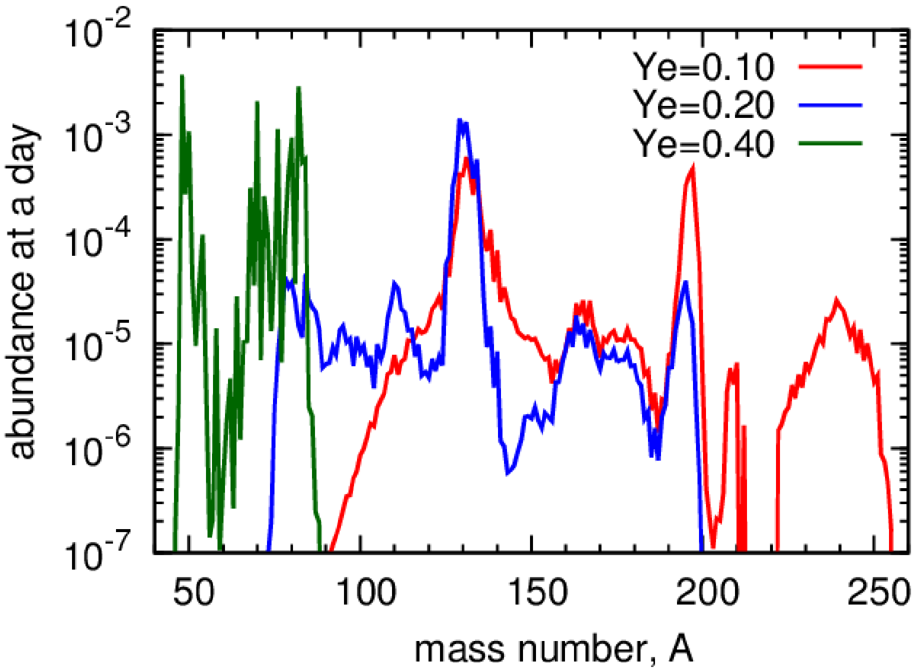
$s = 10k_B/$nucleon, $\tau = 10$ ms

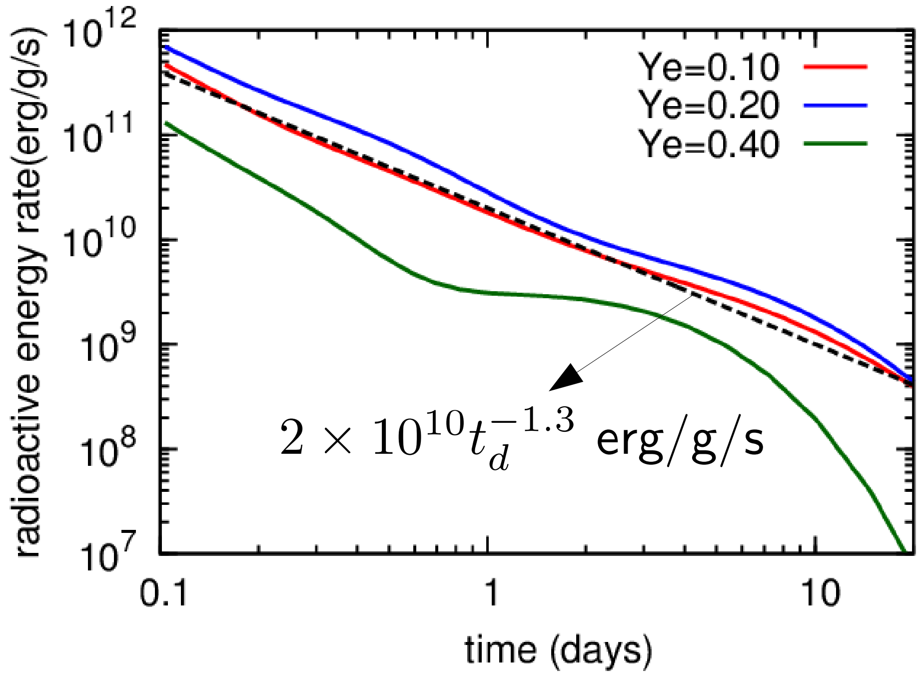
a relatively weak dependence of the lanthanide turnover on nuclear mass model inputs ($\sim 0.02 - 0.03$)

Radioactive decay of the r-process nuclei

[Metzger+2010, Korobkin+ 2011, Hotokezaka+ 2016]

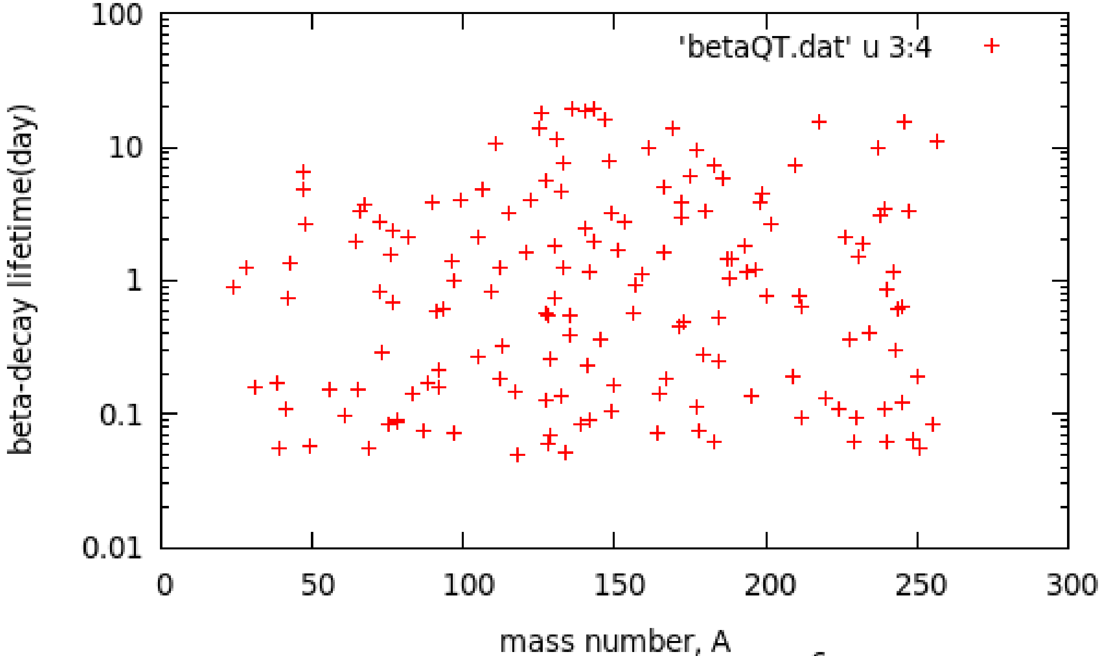
When the radioactive decay is governed by β-decay of a broad range of nuclei, the energy release rate can be approximated by a power law with an index ~ -1.3

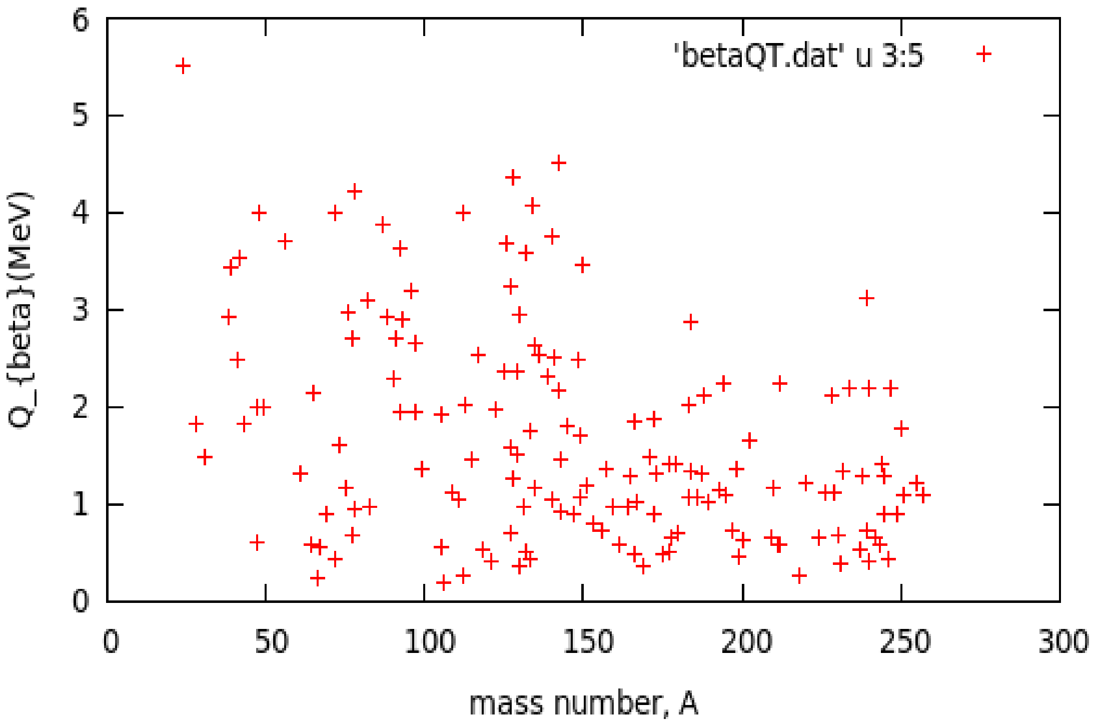




(see also Wanajo+2014, Tanaka+2017, ...)

(parametrized trajectory with entropy $s = 10$ per nucleon and dynamical time scale $\tau = 10$ ms, c.f. Lippuner & Roberts 2016)

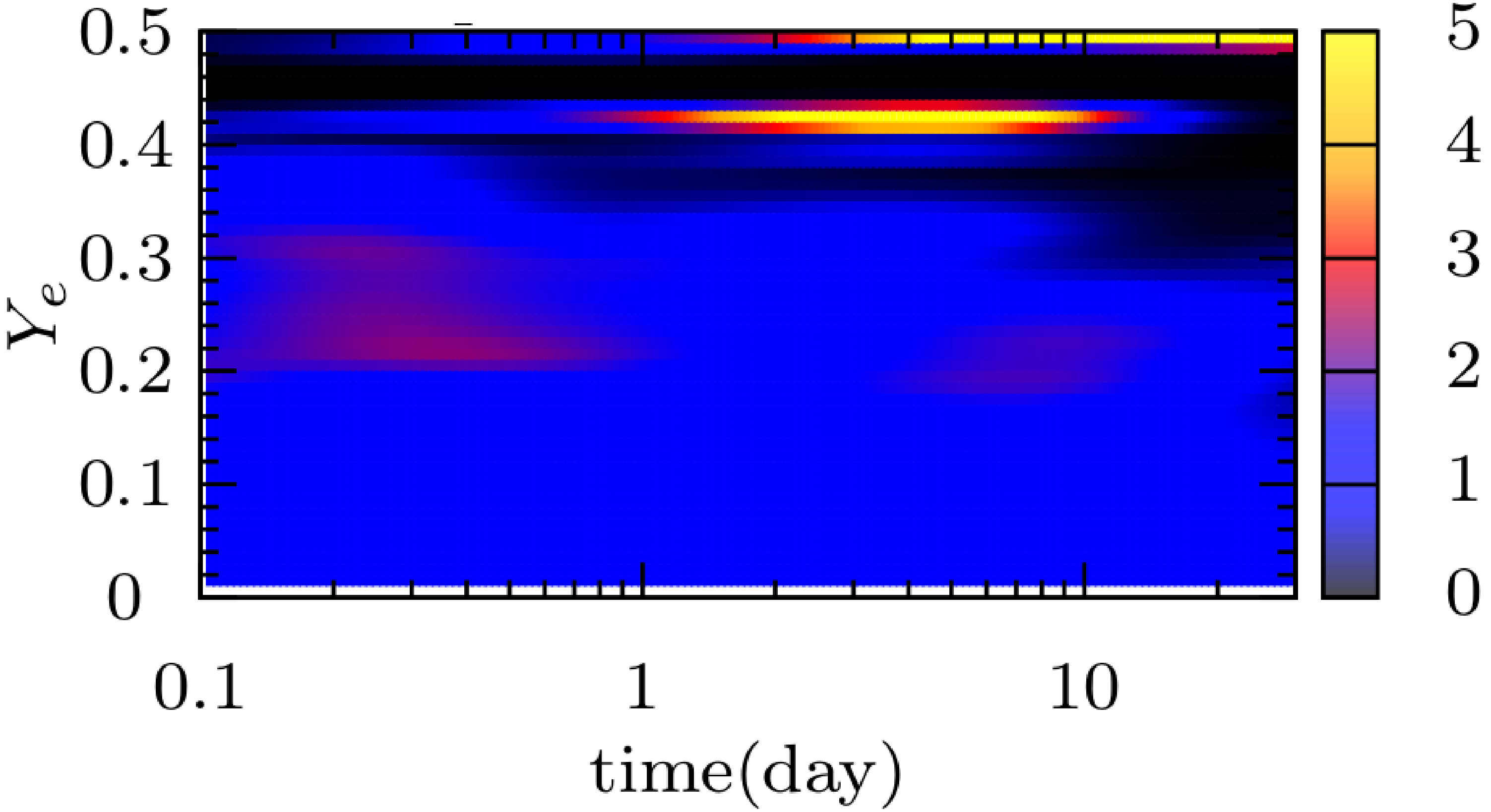

'betaQT.dat' u 3:4
beta-decay lifetime(day)
100
10
1
0.1
0.01
0
50
100
150
200
250
300
mass number, A


'betaQT.dat' u 3:5
Q_{beta}(MeV)
6
5
4
3
2
1
0
0
50
100
150
200
250
300
mass number, A

- parametrized trajectories to broadly examine the impact of both the composition and nuclear physics on the radioactive heating (c.f. Lippuner Roberts 2016)

FRDM mass model, $s = 10$, $\tau = 10$ ms, $T_0 = 8$ GK

colors: energy release relative to $2 \times 10^{10} t_d^{-1.3}$ erg/g/s

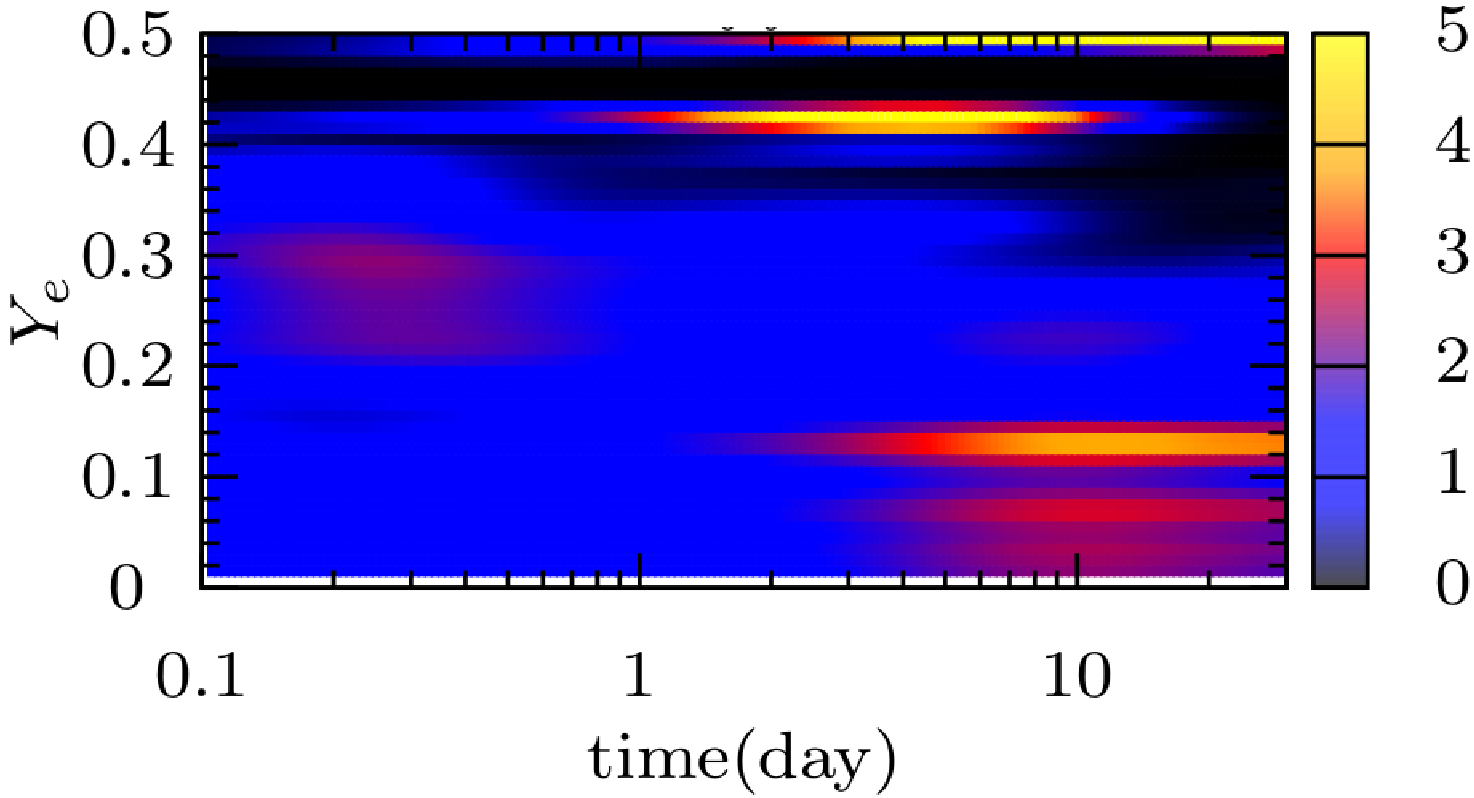


- the radioactive heating for $Y_e \gtrsim 0.35$ is suppressed, except for i) $Y_e \approx 0.42$ (Ni66 production) ii) $Y_e \approx 0.5$ (Ni56 production)

- parametrized trajectories to broadly examine the impact of both the composition and nuclear physics on the radioactive heating (c.f. Lippuner Roberts 2016)

DZ31 mass model, $s = 10$, $\tau = 10$ ms, $T_0 = 8$ GK

colors: energy release relative to $2 \times 10^{10} t_d^{-1.3}$ erg/g/s

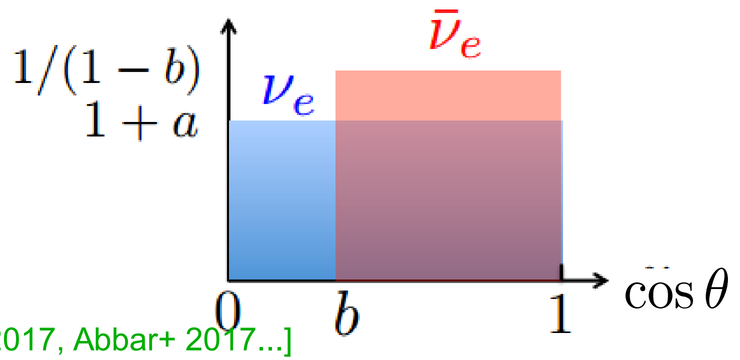


- α-heating may become dominant for ejecta with $Y_e \lesssim 0.15$

Neutrino flavor conversion in merger remnant

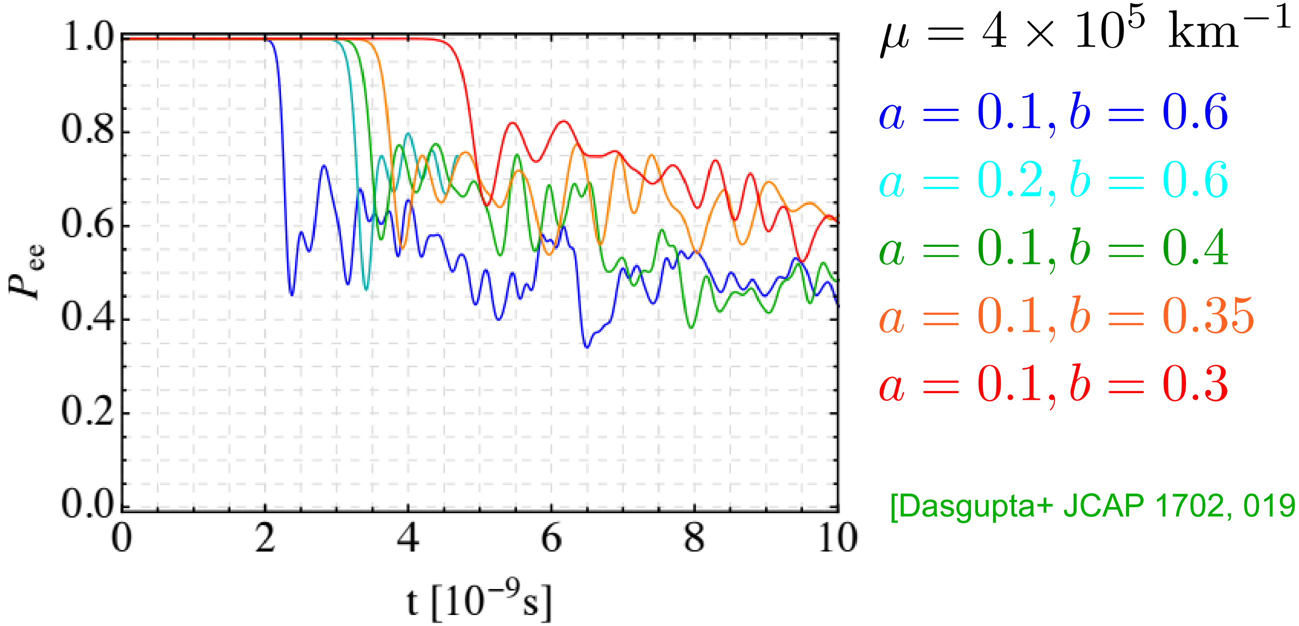
Neutrino oscillations in neutrino-dense environment

"fast" conversion can happen extremely close to the ν surfaces, provided that local angular distribution of neutrino lepton number has a "crossing" (more $\bar{\nu}_e$ than ν_e in some solid angle range, while more ν_e than $\bar{\nu}_e$ otherwise)



[Sawyer+ 2005, 2009, 2016, Izaguirre+ 2016-17, Dasgupta+ 2016, MRW+ 2017, Abbar+ 2017...]

$\rightarrow$ flavor instability of time scale $\tau \lesssim \mu^{-1} = (\sqrt{2}G_F n_\nu)^{-1}$, which implies an oscillation length scale of $\sim$ centimeters

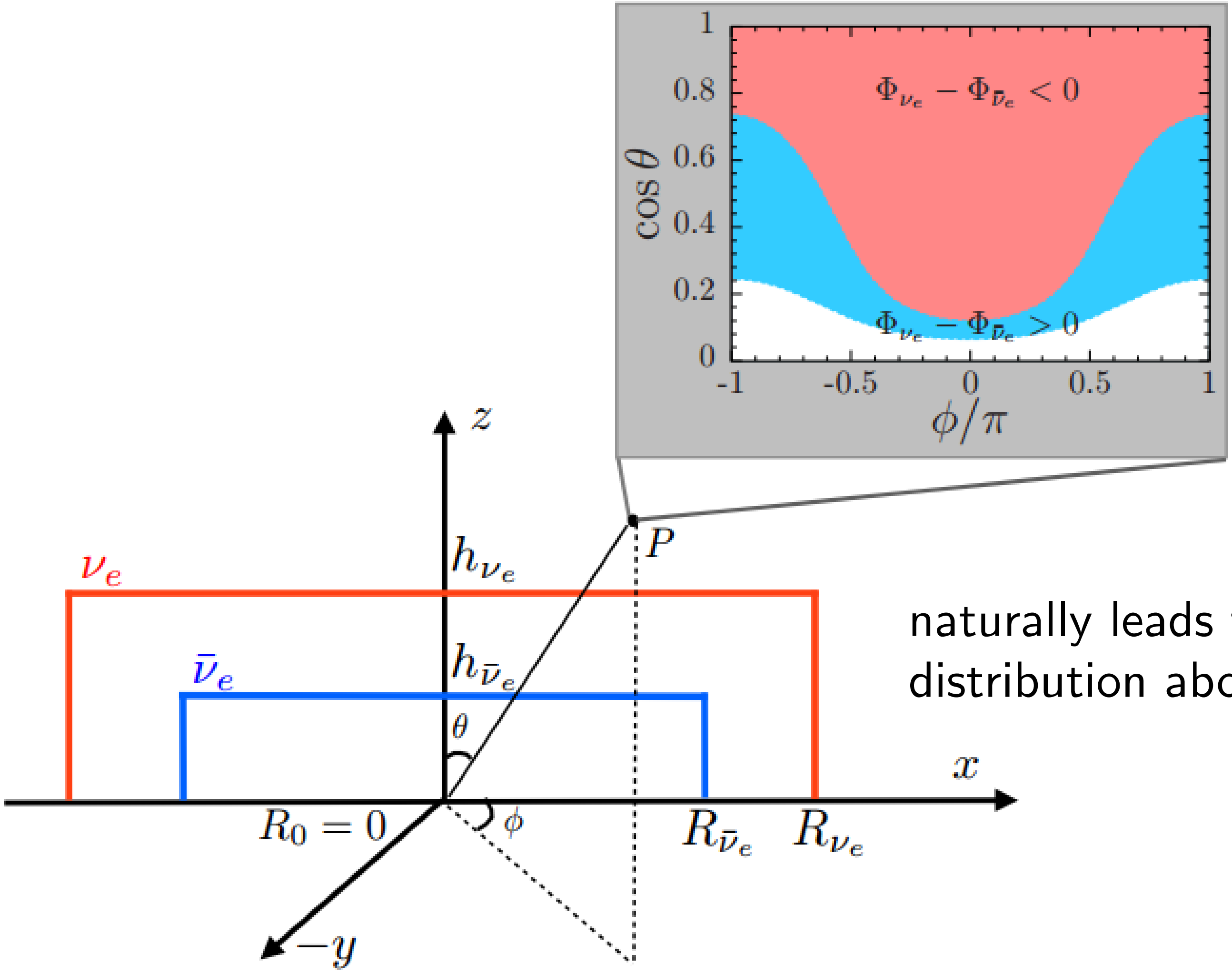


[Dasgupta+ JCAP 1702, 019 (2017]

Fast ν oscillations in merger remnants – parametrized model

Why is this particularly revelant for merger remnants?

Because they protonize, i.e., more $\bar{\nu}_e$ emission than ν_e [Foucart+, Perego+, Janka+,...]



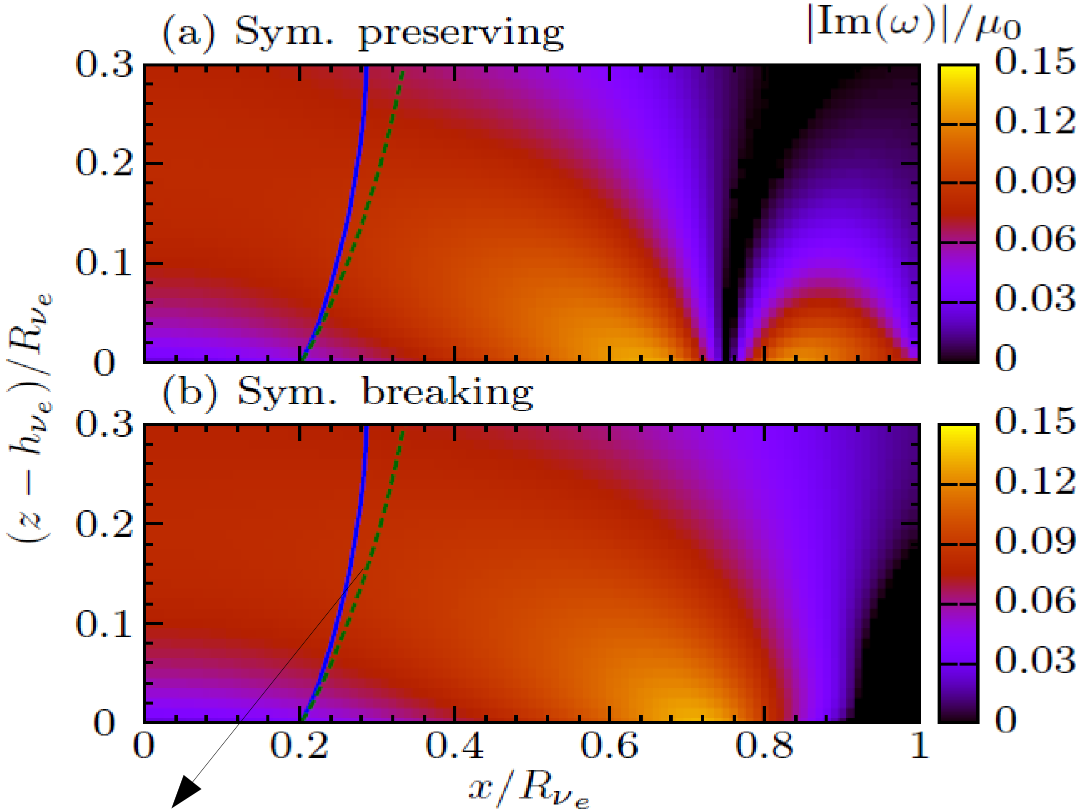
naturally leads to crossing in angular distribution above the merger remnant

[MRW & Tamborra, PRD 95, 103007, 2017]

Fast ν oscillations in merger remnants – parametrized model

$$L_{n,\bar{\nu}_e}/L_{n,\nu_e} = 1.35,\ R_{\bar{\nu}_e} = 0.75 R_{\nu_e},\ h_{\nu_e}/R_{\nu_e} = h_{\bar{\nu}_e}/R_{\bar{\nu}_e} = 0.25,\ \vec{k} = 0.$$

[MRW & Tamborra, PRD 95, 103007, 2017]



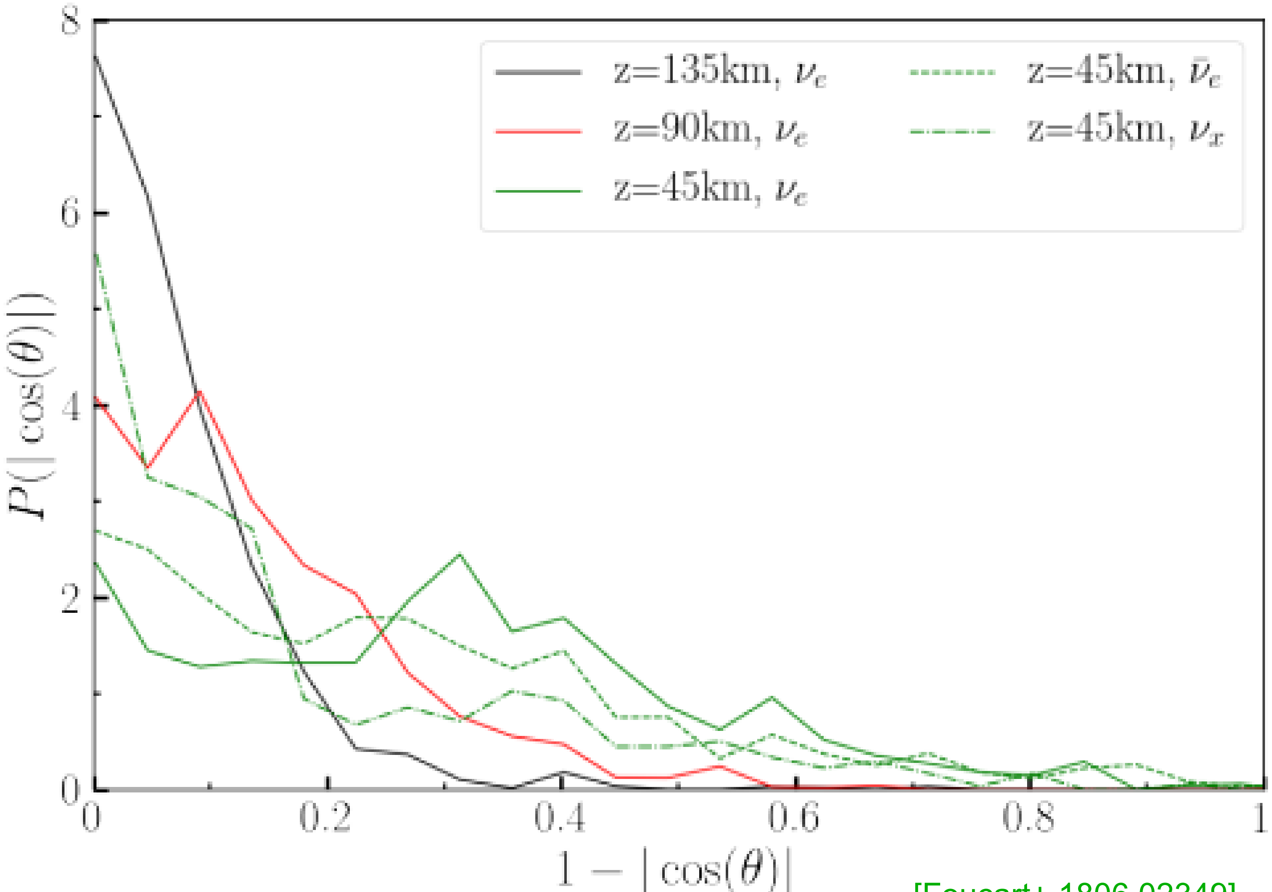
Im(ω): growth rate of flavor mixing in the linear regime

$$\mu_0 \approx 4.25\ \mathrm{cm}^{-1} \times \left(\frac{L_{\nu_e}}{10^{53}\mathrm{erg/s}}\right)\left(\frac{10\mathrm{MeV}}{\langle E_{\nu_e}\rangle}\right)\left(\frac{100\mathrm{km}}{R_{\nu_e}}\right)^2$$

fast flavor conversion condition exists everywhere above the remnant, with any reasonable parameters

Matter-neutrino resonances [Malkus+, Zhu+, Frenzel+, MRW+,...]

- Flavor equilpartition can affect dramatically the nucleosynthesis outcome in ν-driven wind from a BH-disk system [MRW, Tamborra, Just, Janka, 2017] angular distribution above the merger remnant from MC neutrino transport simulation



[Foucart+ 1806.02349]