r-process nucleosynthesis in neutron star mergers

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TECHNISCHE UNIVERSITÄT DARMSTADT

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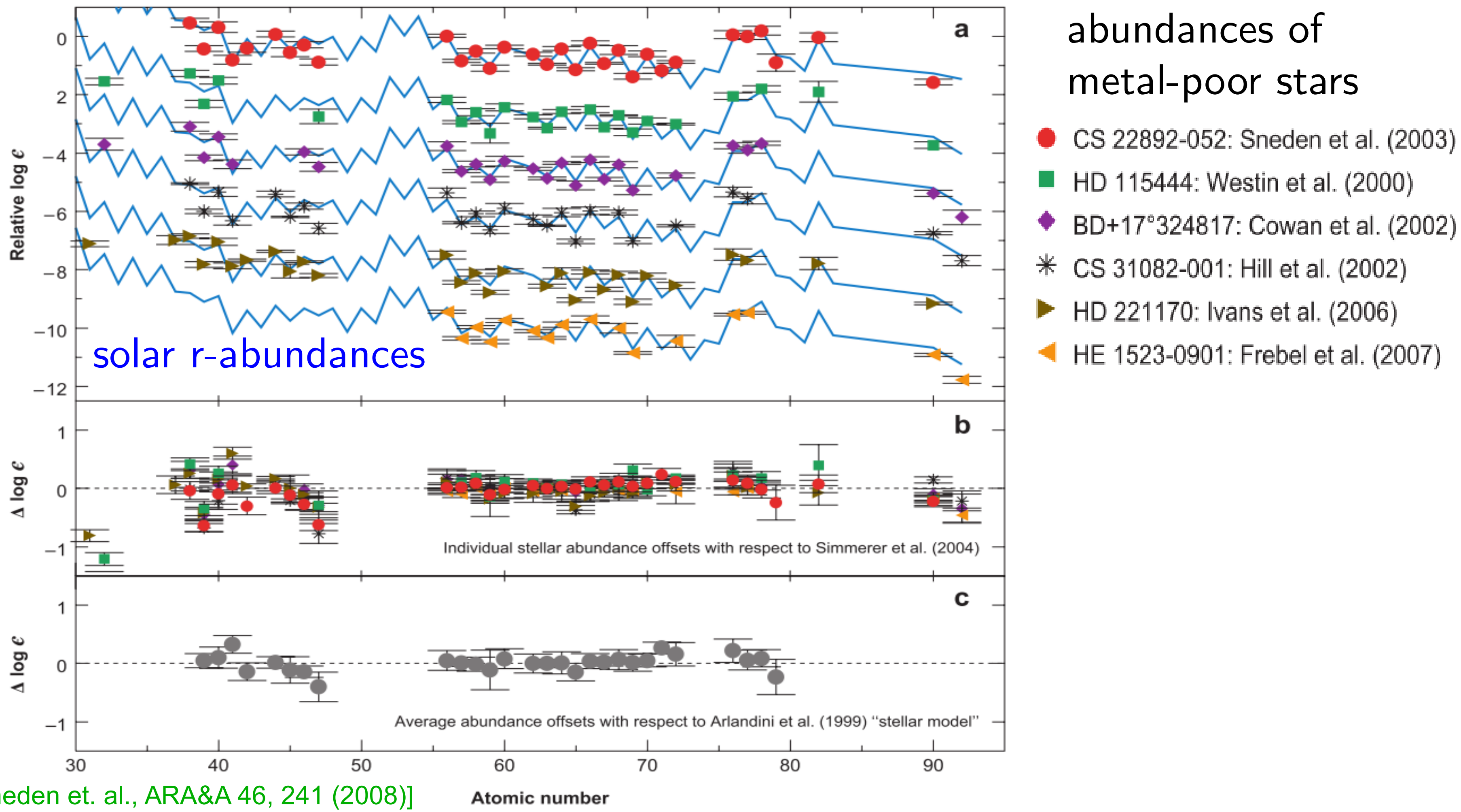
outline

- Introduction
- General feature of the r-process in NSM dynamic ejecta
- Impact of nuclear masses – abundances and lightcurve
- Summary and outlook

collaborators:
K. Langanke (GSI) G. Martínez-Pinedo (TUD & GSI) J. Mendoza-Temis (UNAM)
A. Bauswein (HITS) T. Janka (MPA, Garching)
D. Kasen (UCB) J. Barnes (UCB)
A. Arcones (TUD & GSI) B. Metzger (Columbia) R. Fernández (UCB)

observations of r-process elements

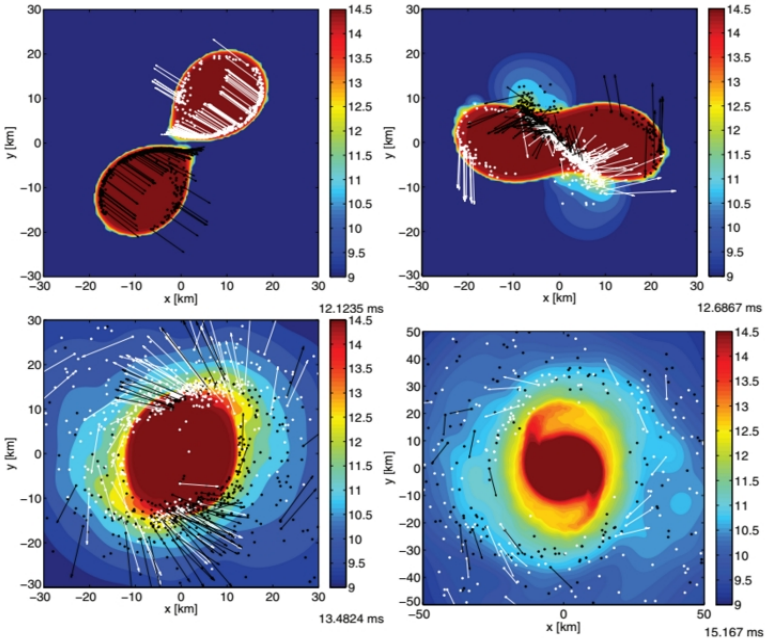


[Sneden et. al., ARA&A 46, 241 (2008)]

astrophysical sites: core-collapse supernovae or neutron star mergers?

compact object mergers

[Bauswein, Goriely, Janka, ApJ 773, 78 (2013)]



- gravitational wave

- origin of short γ-ray bursts

- r-process nucleosynthesis

- kilonova due to the radioactive decay of r-process nuclei

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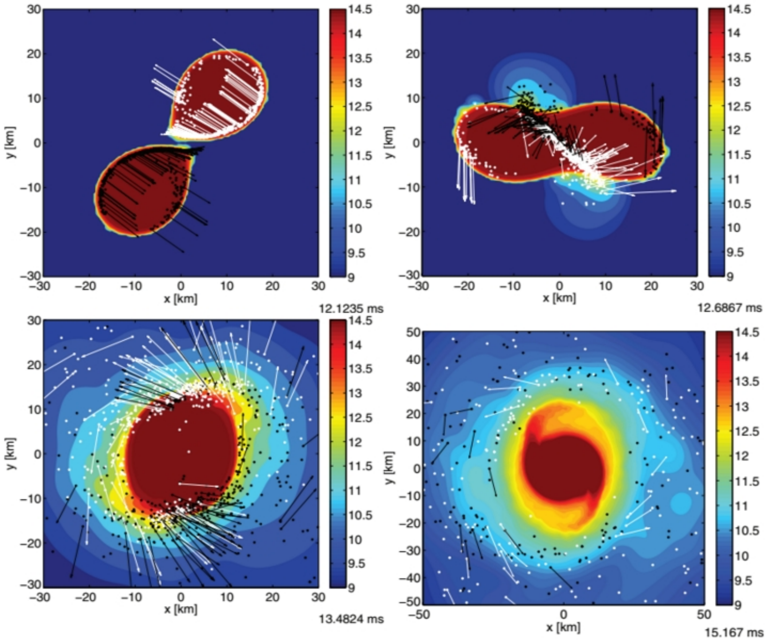
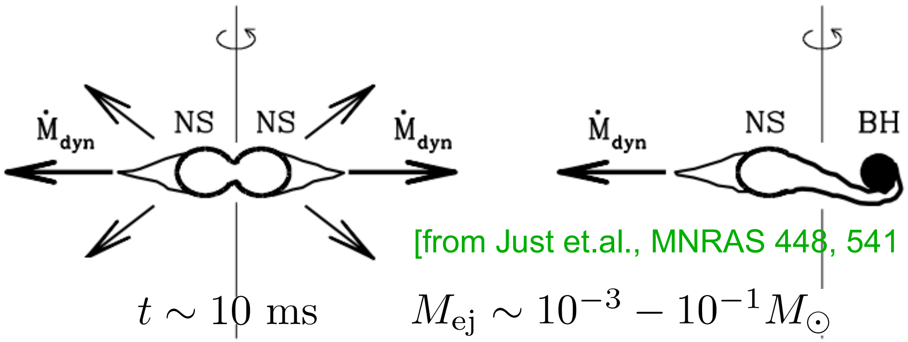


Merger phase: dynamical ejecta

(due to shock heating or tidal force)

[Bauswein+, Rosswog+, Rezzolla+, Sekiguchi+,...]



[from Just et.al., MNRAS 448, 541 (2015)]

$t \sim 10$ ms $M_{ej} \sim 10^{-3} - 10^{-1} M_{\odot}$

$\bar{s} \lesssim 10\ k_B$ $Y_e \lesssim 0.15$

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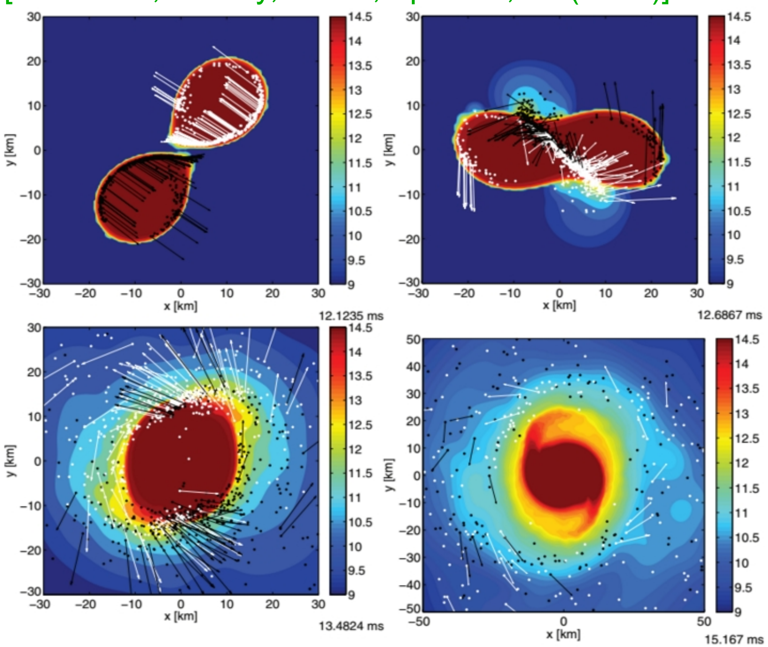

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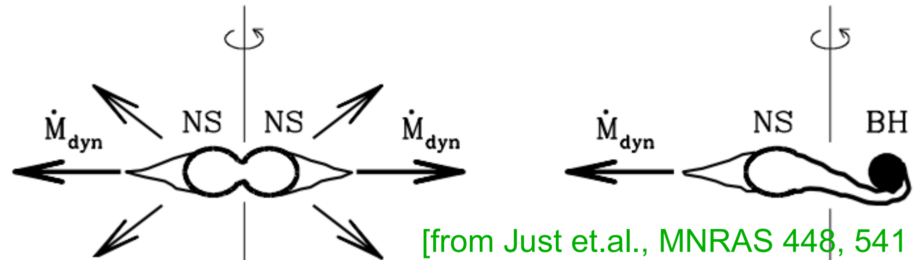

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$t \sim 10$ ms $M_{ej} \sim 10^{-3} - 10^{-1} M_\odot$

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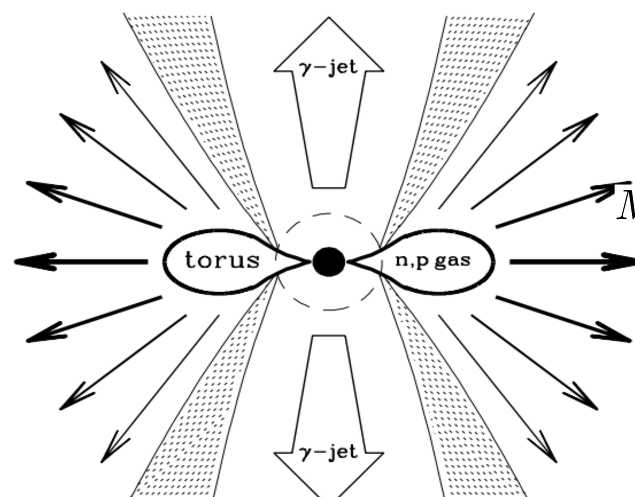
BH/HMNS-torus phase: disk ejecta

(due to viscosity, recommbination, ν-heating)

[Just+, Fernandez+, Perego+,...]



$t \sim 100$ ms $-$ few s

$M_{ej} \sim 10^{-3} - 10^{-1} M_\odot$

$\bar{s} \sim$ 10-50 k_B

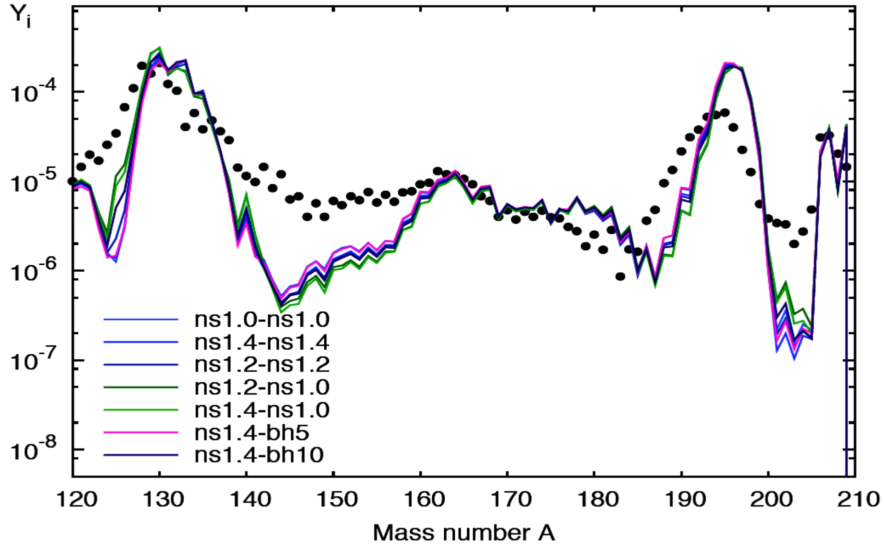
$Y_e \sim 0.1 - 0.4$

[from Just et.al., MNRAS 448, 541 (2015)]

dynamical ejecta : robust r-process

- different merging objects:

[Korobkin, Rosswog, Arcones, Winteler, MNRAS 426, 1940 (2012)]



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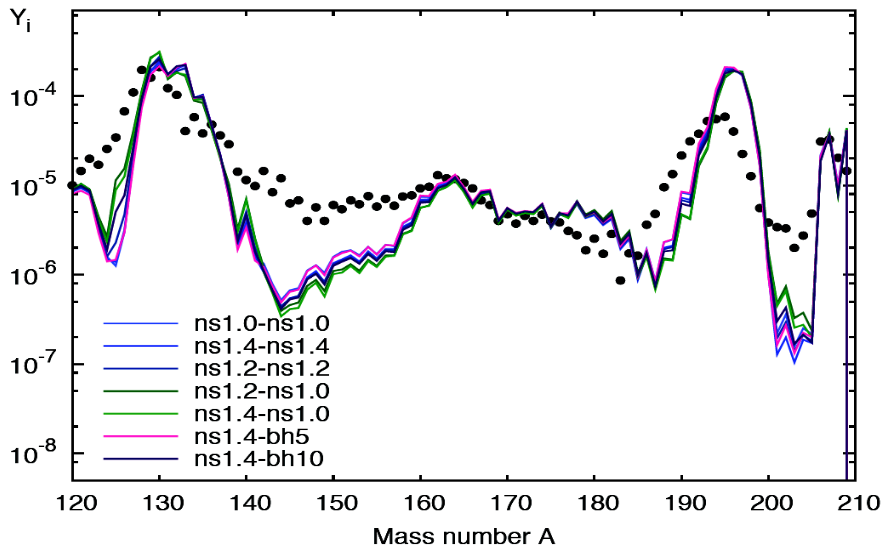
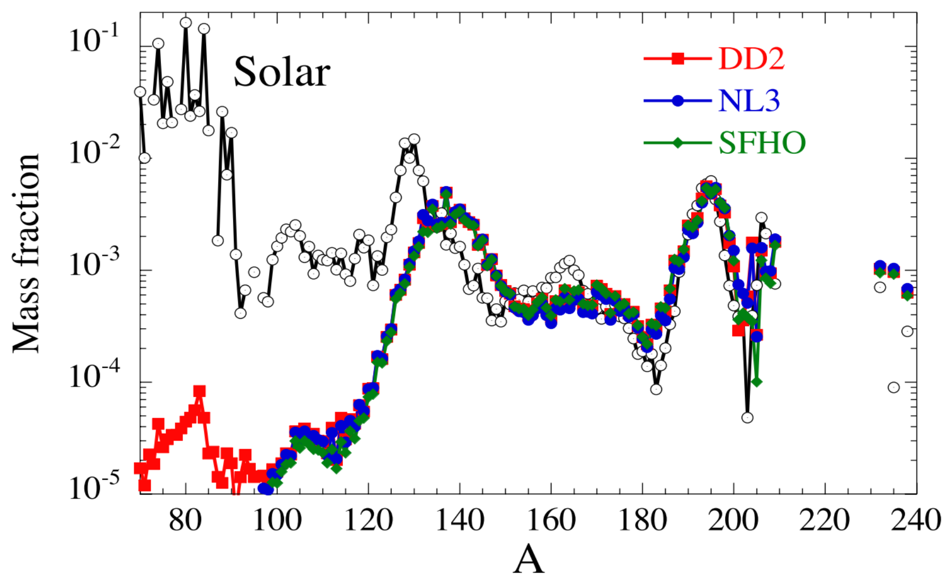


- different equations of state:

[Bauswein, Goriely, Janka, ApJ 773, 78 (2013)]



nuclear reaction network

Modelling r-process requires the knowledge of extremely neutron-rich nuclei, such as masses, β-decay half-lives, neutron capture rates, fission rates and yields.

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Experimentally measured properties/rates : NuDat & Reaclib.

Theoretical inputs :

- nuclear ground state properties: Möller+ 1995,
- β-decay: Möller+ 2003,
- α-decay: Dong & Ren 2005,
- (n, γ) and (γ, n) for $Z \leq 83$: computed with 4 mass models (FRDM, DZ31, WS3, HFB21), Mendoza-Temis+ 2015,
- (n, γ), (γ, n), and n-induced fission for $Z > 83$: Panov+ 2010,
- β-delayed & spontaneous fission: Zinner, PhD Thesis 2007 & Petermann+ 2012,
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Solve the reaction equations with the initial composition determined by NSE for a given set of $(\rho,\ T,\ Y_e)|_{T_0=6\mathrm{GK}}$, and the time profile of $\rho(t)$.

Temperature is co-evolved taking account of nuclear heating.

astrophysical variations

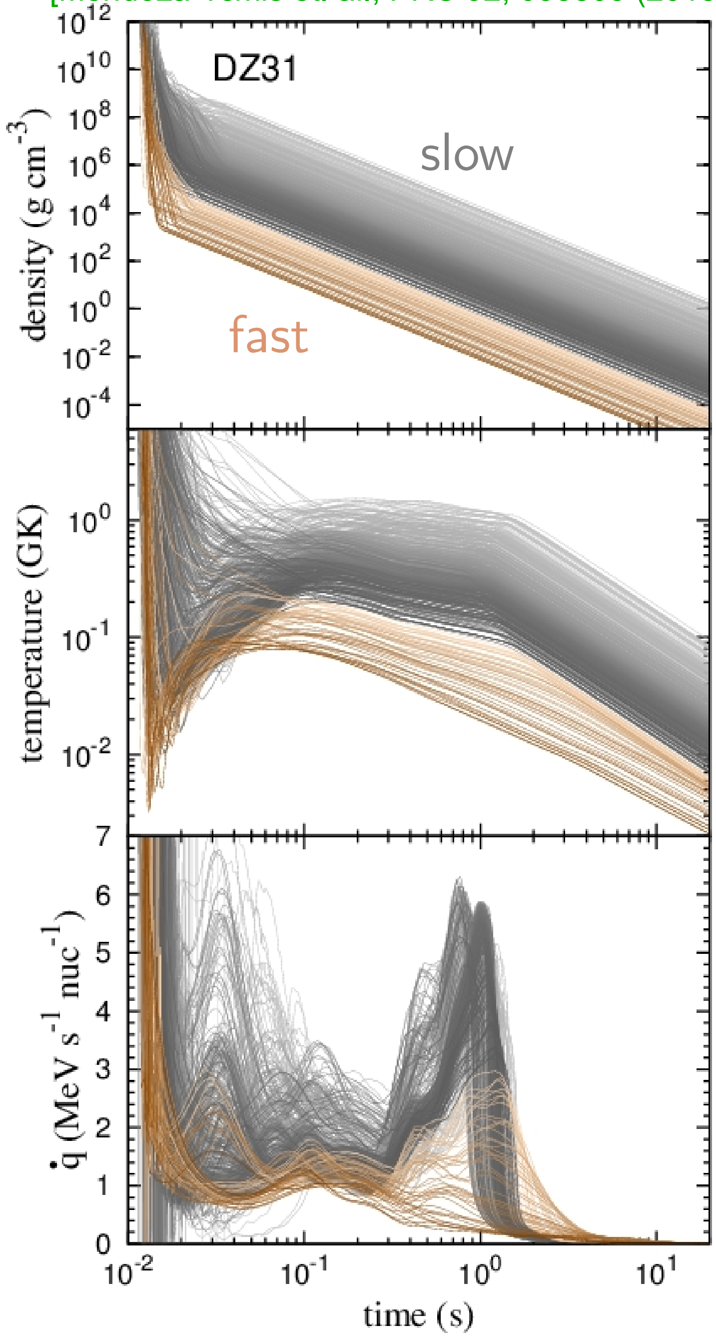
$1.35\ M_\odot - 1.35\ M_\odot$ model from Bauswein+ 2013

$M_{\rm ej} \sim 1.70 \times 10^{-3}\ M_\odot$

$0.01 < Y_{e,\rm init} < 0.06$

$400 < R_{\rm n/s,init} < 2000$

[Mendoza-Temis et. al., PRC 92, 055805 (2015)]



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

- $\sim 10\%$ of the ejecta expands very fast $\rightarrow$ free neutrons left at the end of the r-process

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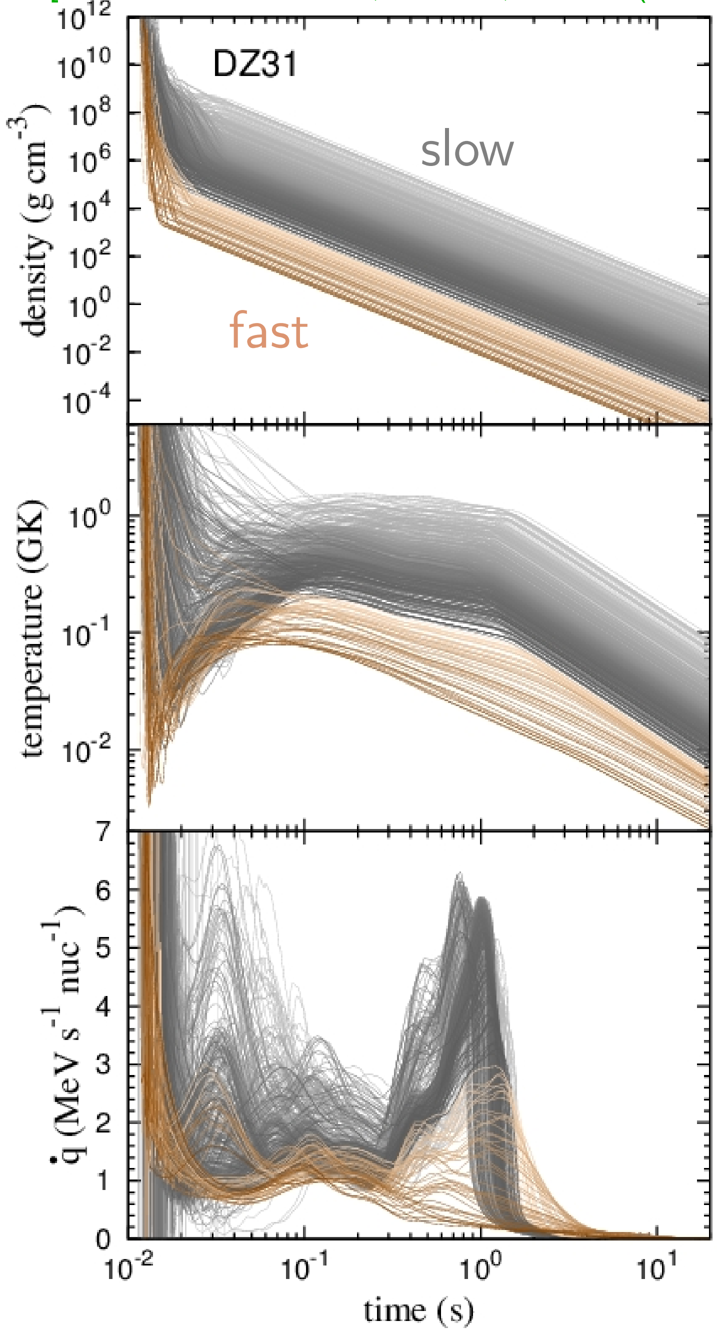

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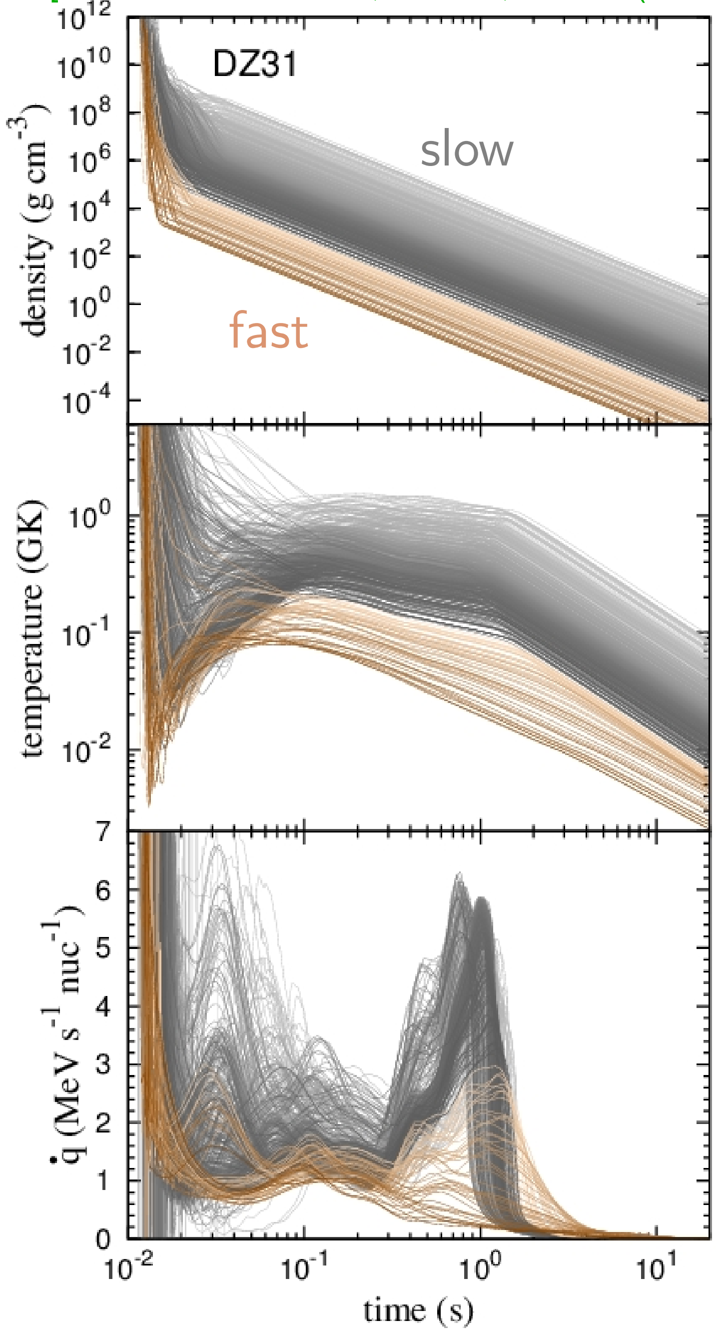
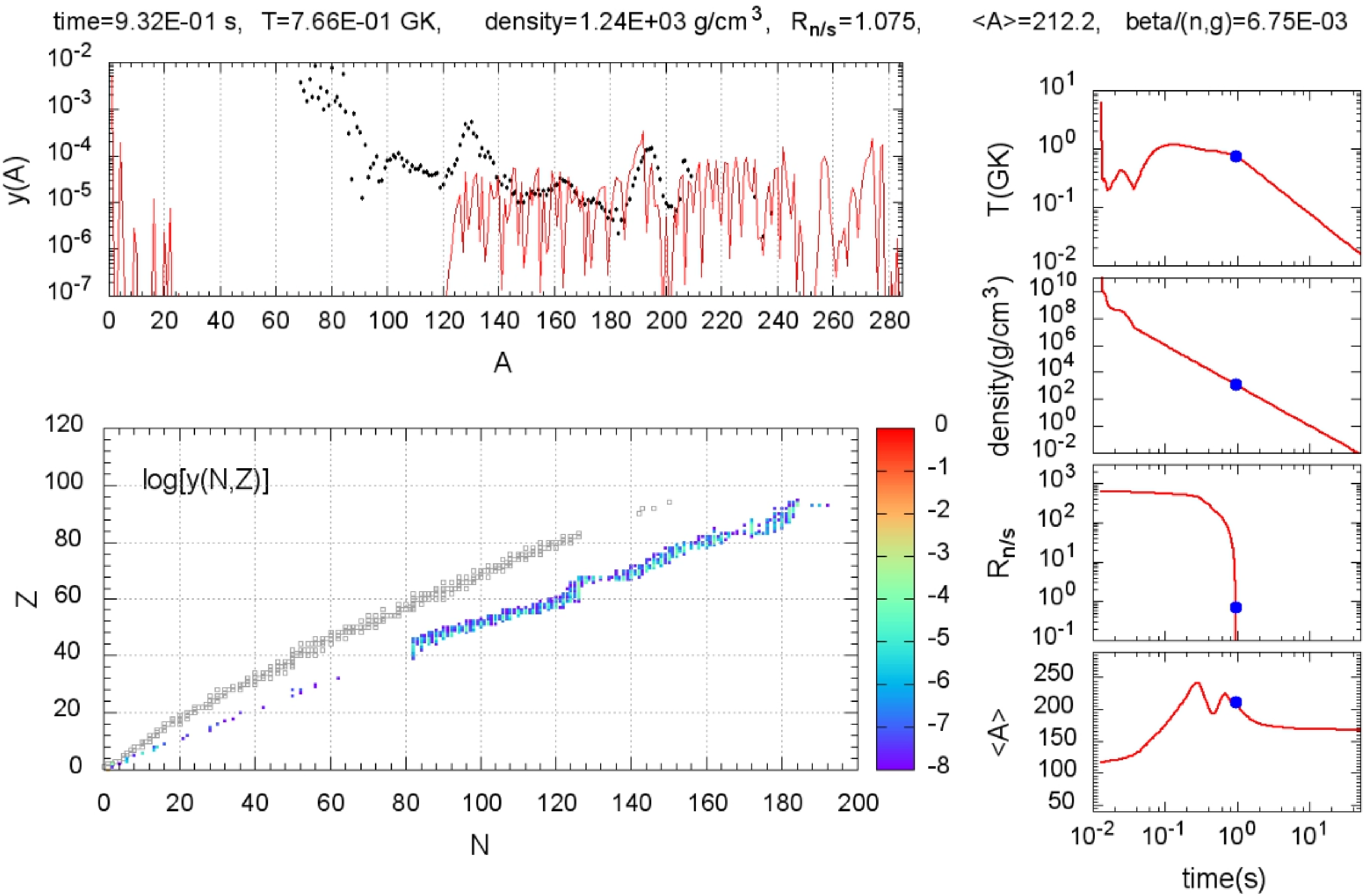
- nuclear energy production plays an important role for heating up the ejecta

[Mendoza-Temis et. al., PRC 92, 055805 (2015)]



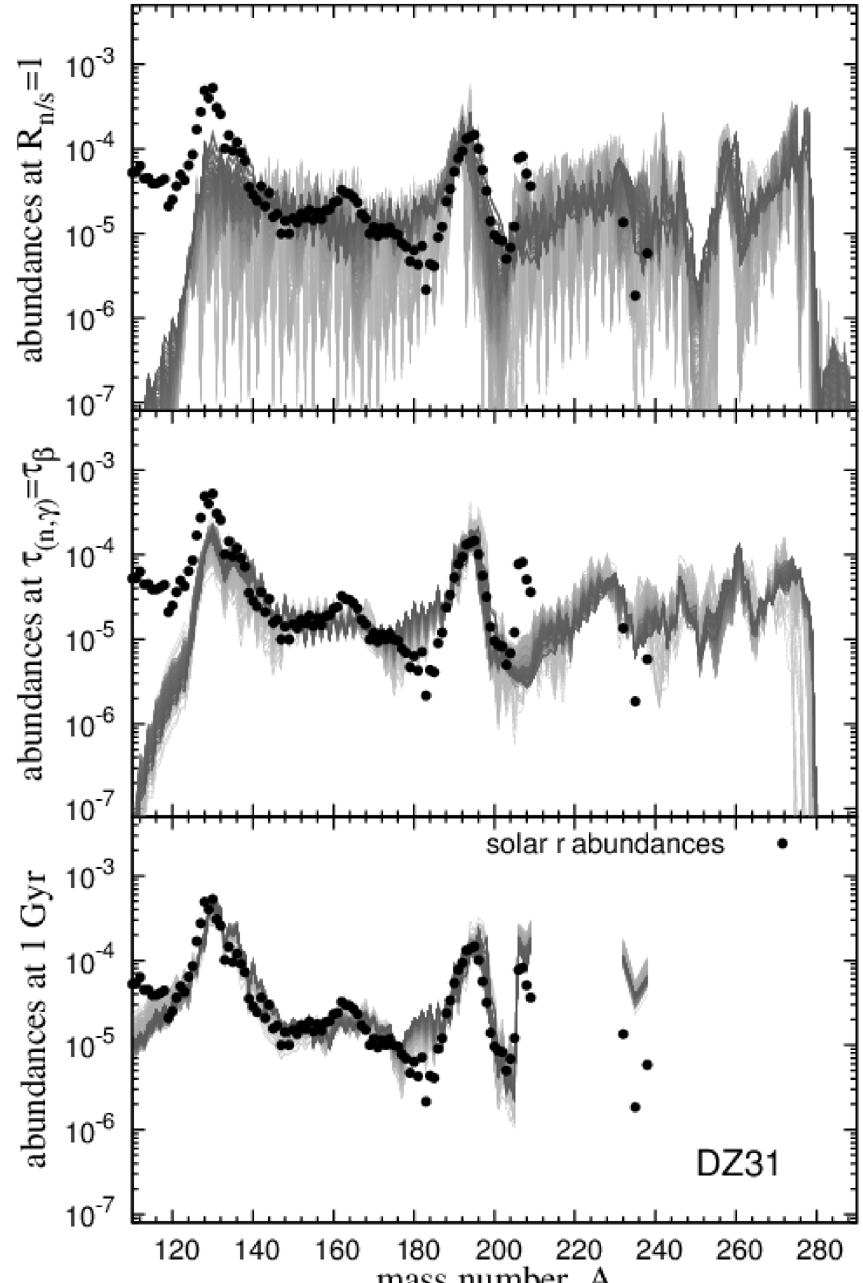
r-process of slow ejecta



abundances at different phases

- third peak ($A \sim 195$) forms during the neutron capture process.

- the position of the third peak sfifts in between the times when $R_{\mathrm{n/s}} = 1$ and $\tau_{(n,\gamma)} = \tau_\beta$.



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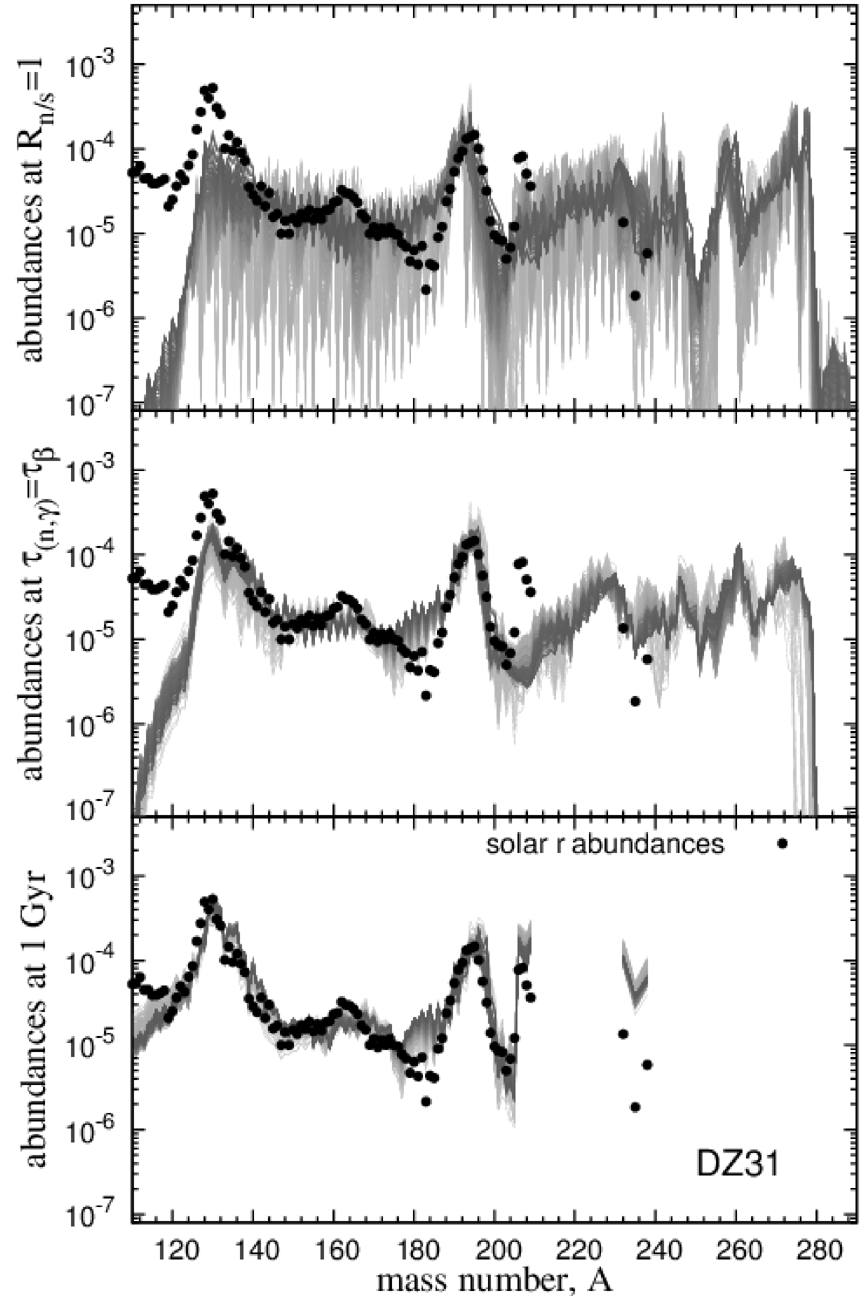
- fissioning nuclei may be dominately piled up above the third peak.

- second peak ($A \sim 130$) forms later by fission + residual neutron captures.



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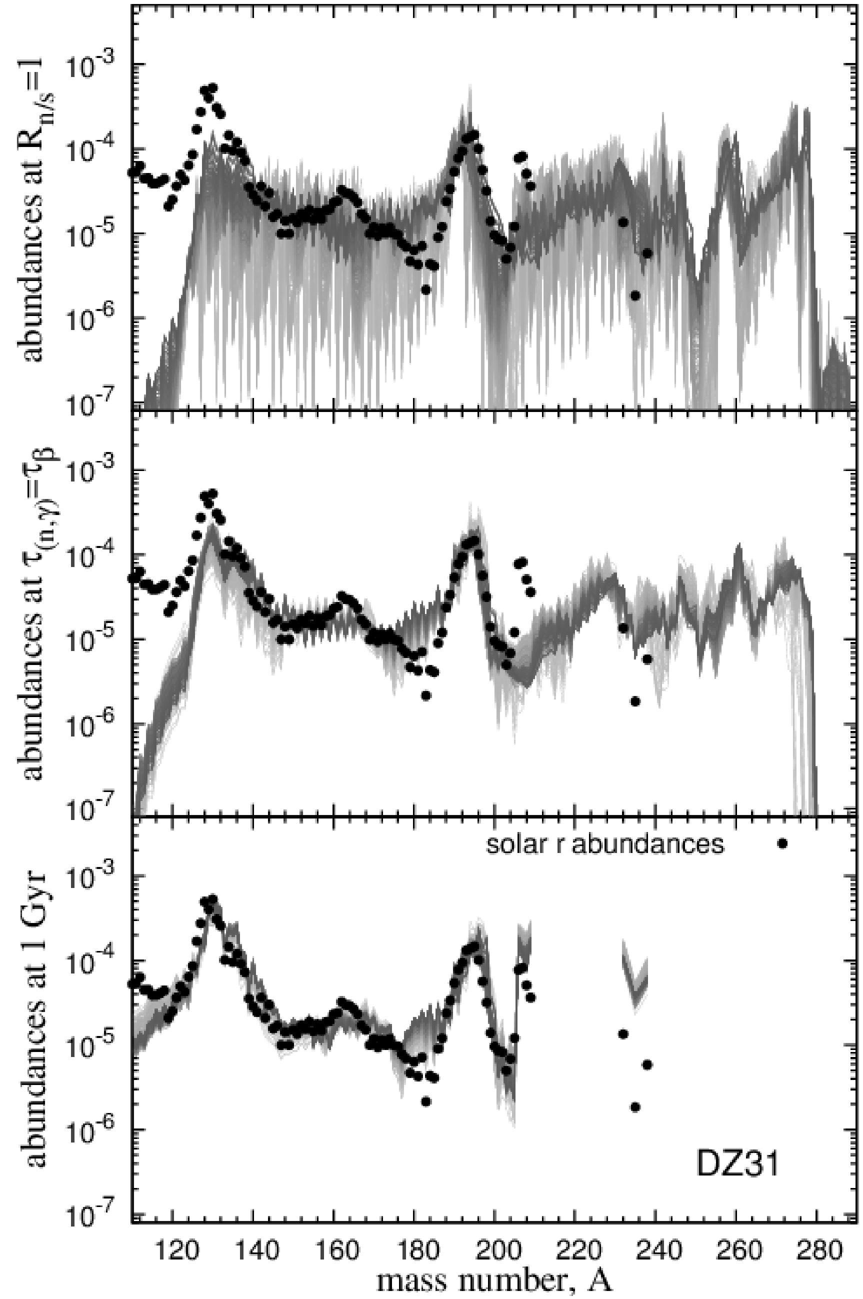


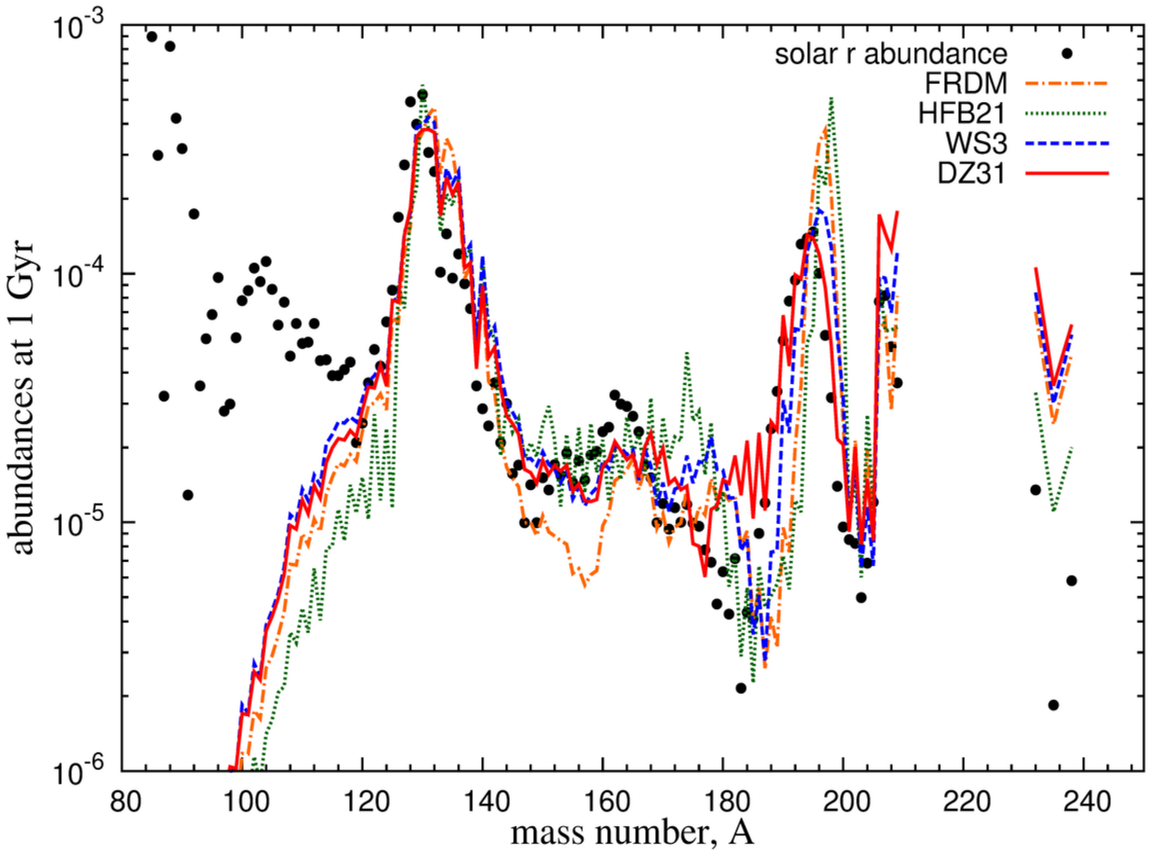
role of uncertain nuclear physics inputs?

- fission & β-decay [Eichler+ 2015,...]

- neutron capture rates (nuclear masses) [Mendoza-Temis+ 2015, Martin+ 2016,...]

variation due to nuclear mass models

different (n, γ) and (γ, n) rates for $Z \leq 83$ with four mass models



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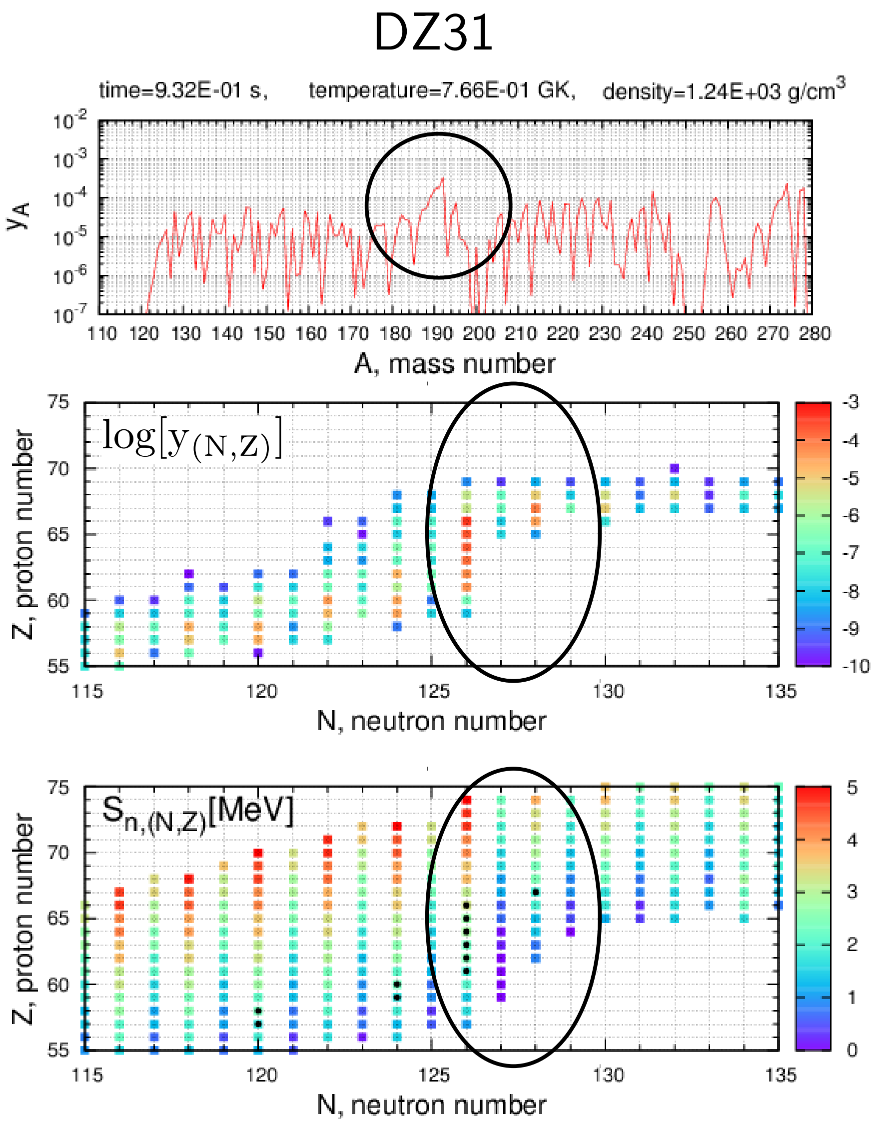
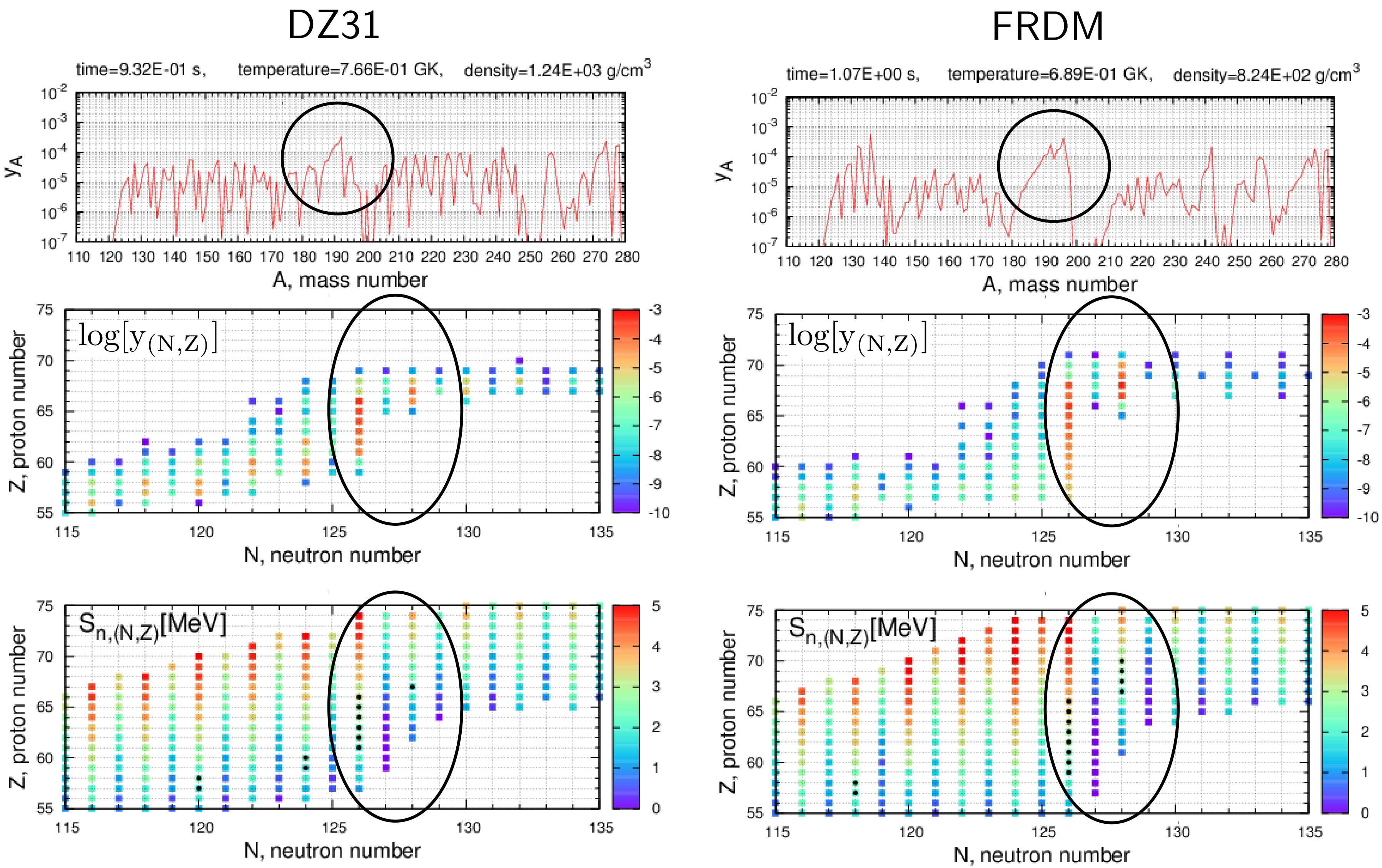


in DZ31, material piles at $(N, Z) = (126, 66)$, $A = 192$ at the time when $R_{n/s} = 1$ and later shift to $A \approx 195$

variation due to nuclear mass models



in FRDM, the large drop of neutron separation energy at N=129 leads to the pile-up of material of $(N, Z) = (128, 68)$, $A = 196$ already at the time when $R_{n/s} = 1$. Later it shifts to $A \sim 199$.

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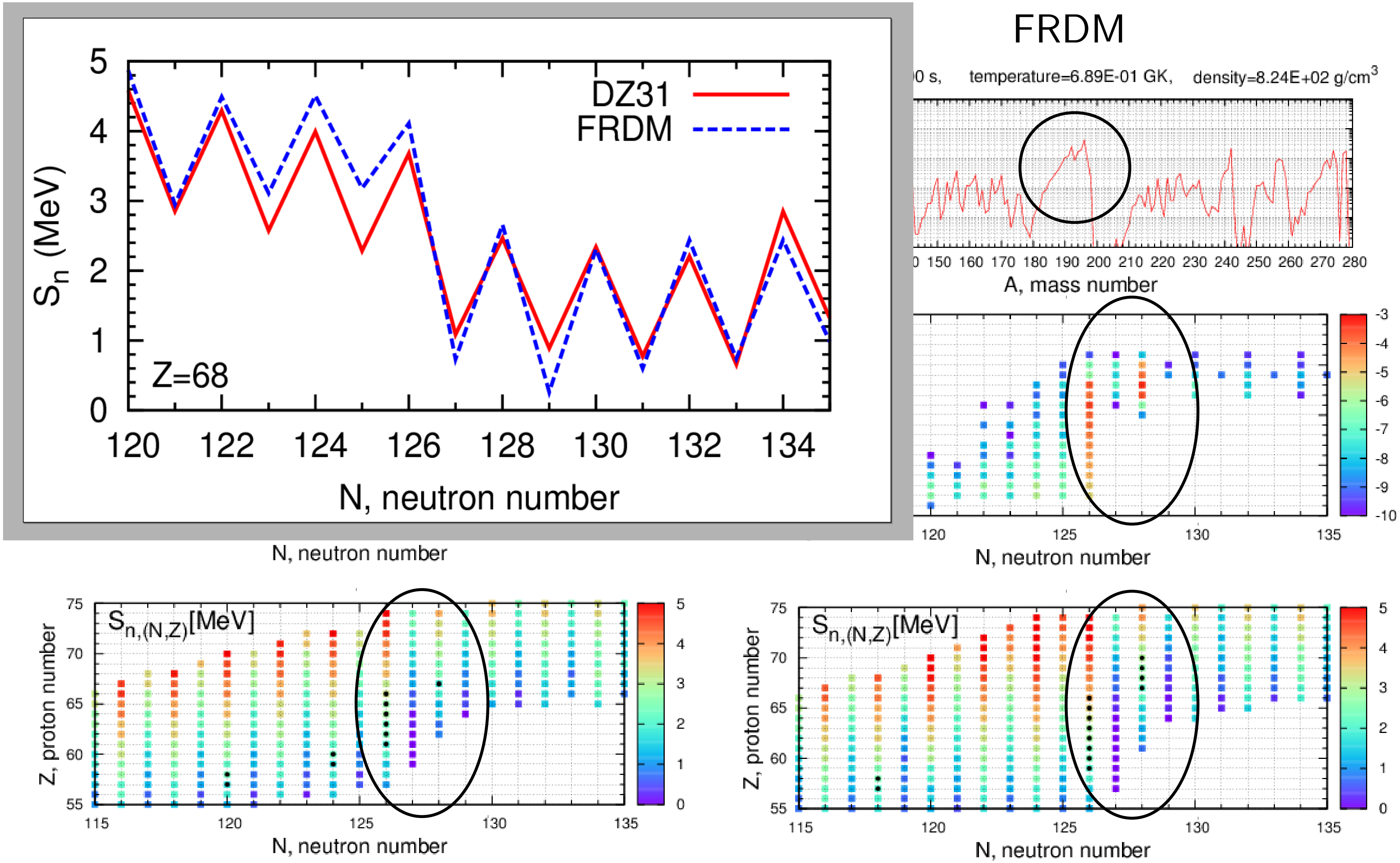

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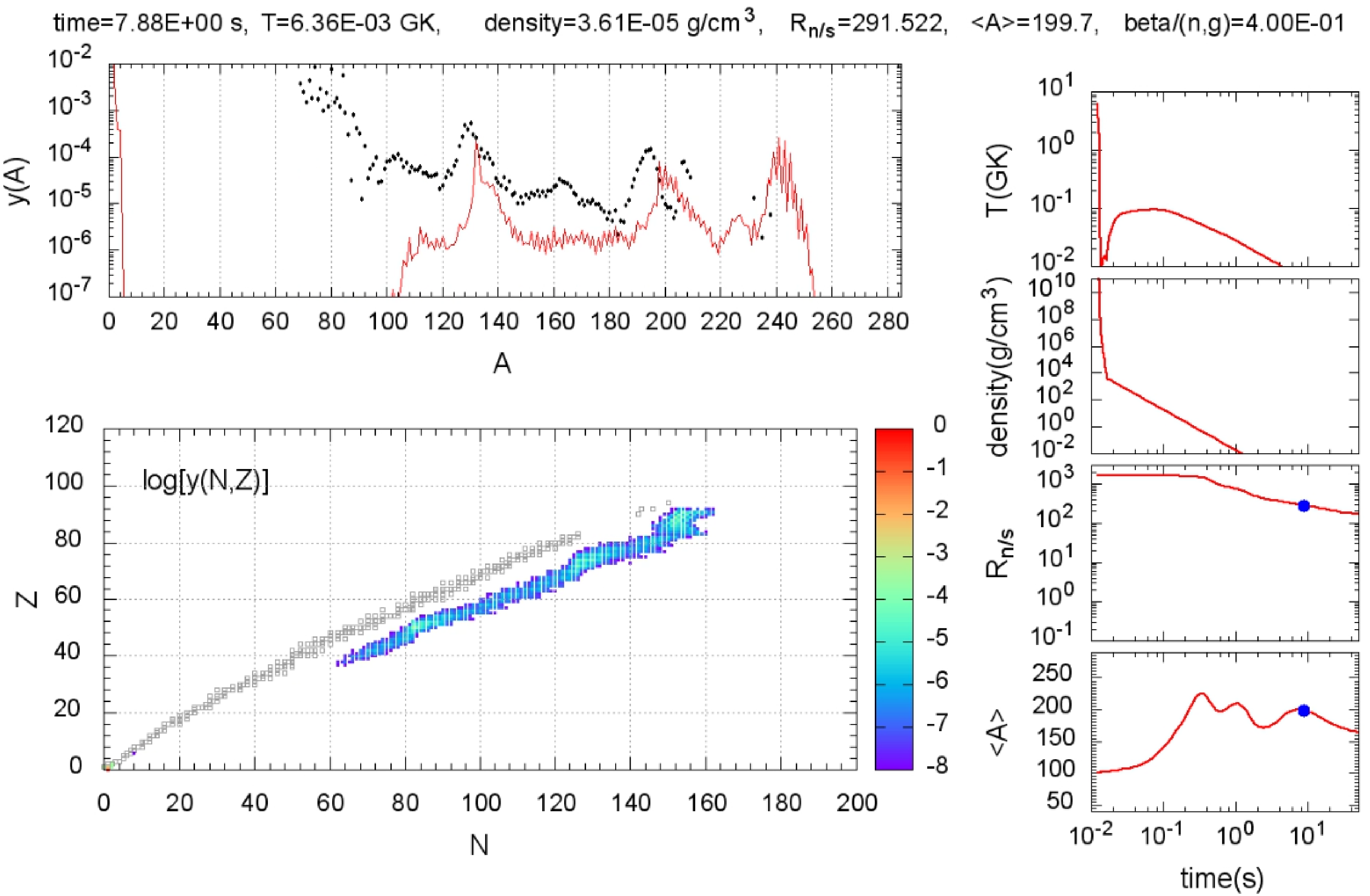
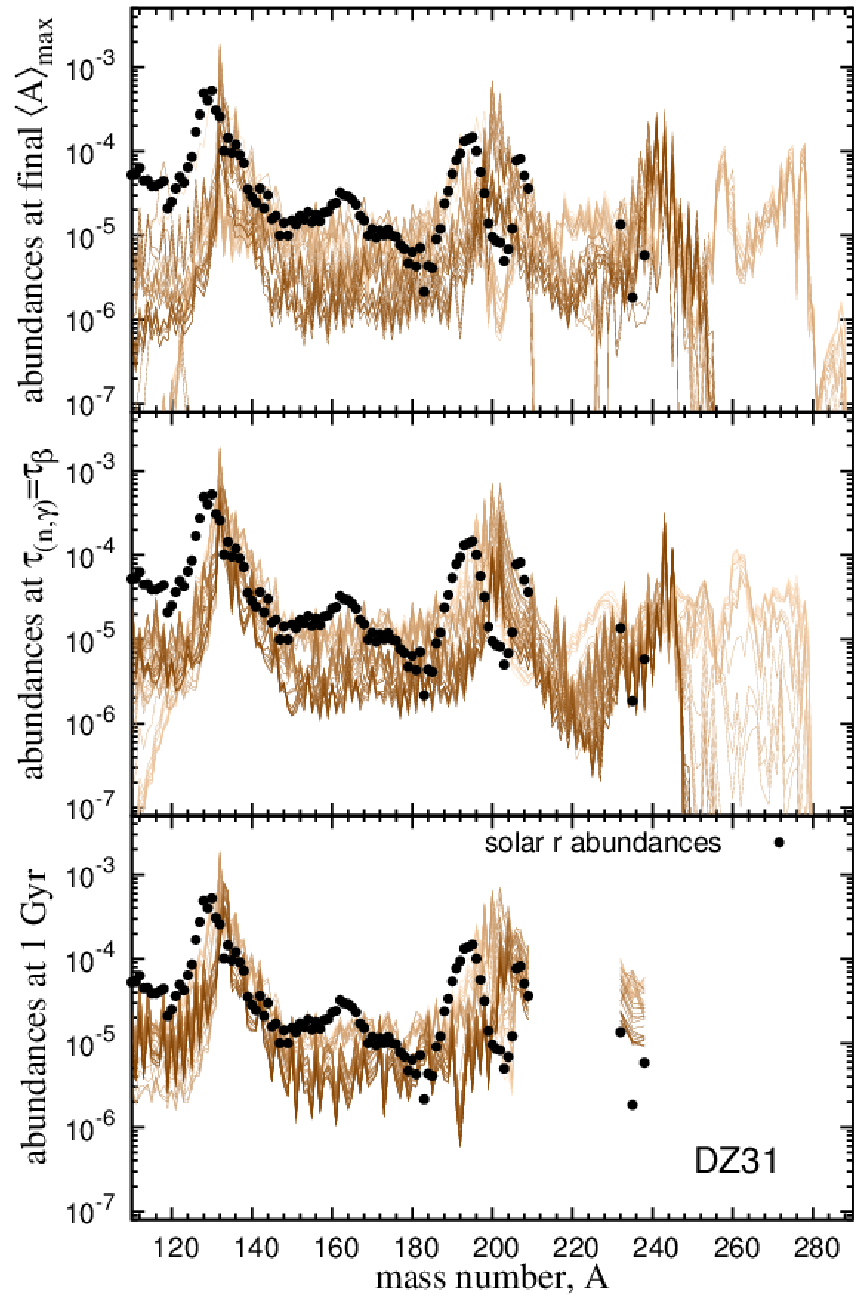
r-process of fast ejecta



abundances at different phases

- slower n-capture rates $\rightarrow$ peaks at larger $A \sim 132$ and $A \sim 200$



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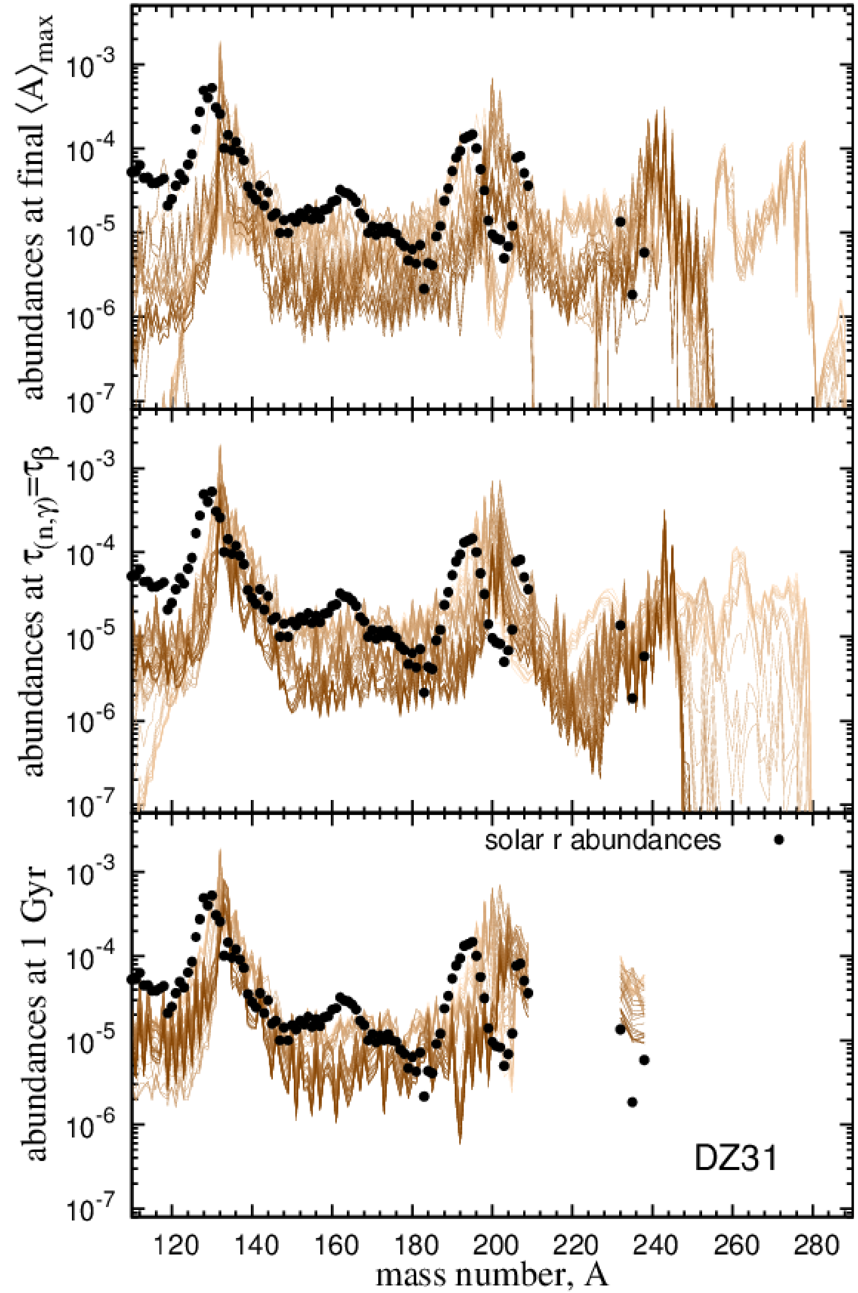
- slower n-capture rates → peaks at larger $A \sim 132$ and $A \sim 200$

- distinct $A \approx 132$ peak due to the long β-decay lifetime of $^{132}\mathrm{Sn}$

- sub-dominant role of fission and larger variations among trajectories



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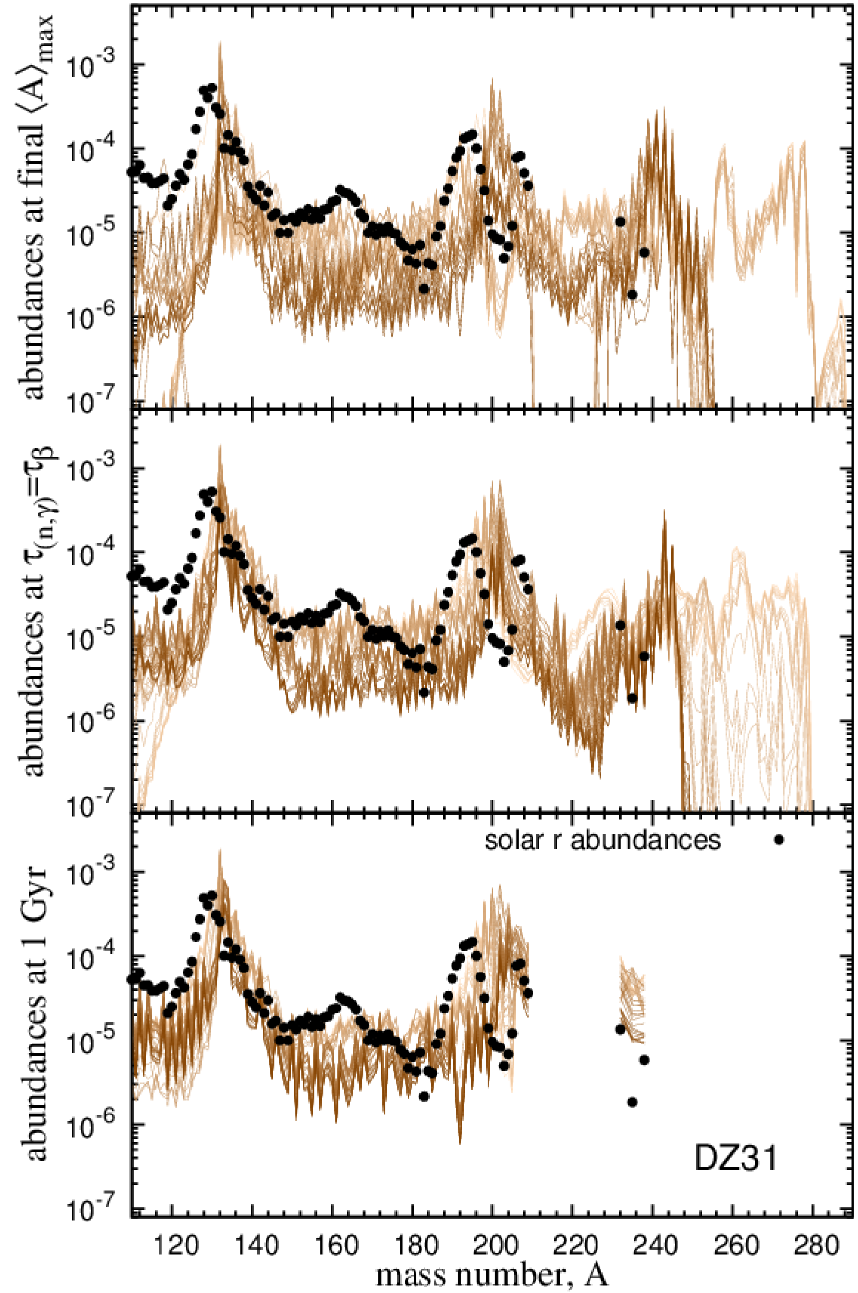
- unused amount of neutrons depends on the mass model:
$\sim 40\%$ with FRDM and
$\sim 20\%$ with DZ31 at $t \approx 20$ s



kilonova: electromagnetic signature of r-process

simple theoretical estimates assuming lightcurve peaks at the time when $\tau_{\rm diffusion} \sim \tau_{\rm expansion}$: [e.g., Metzger+ 2010]

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

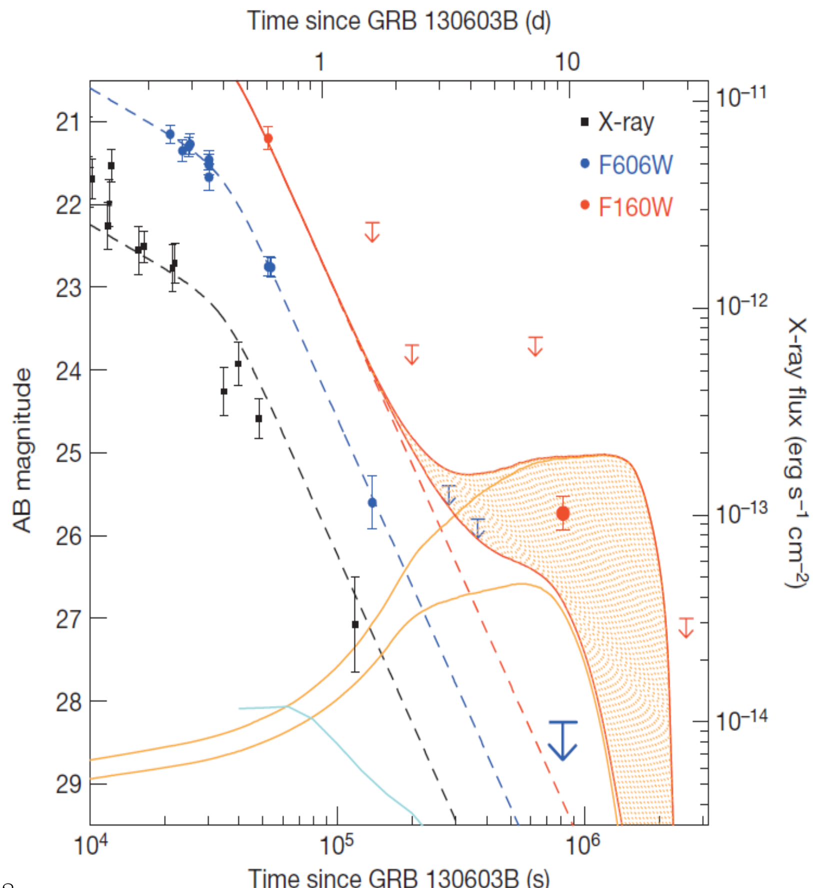
$$\sim 2.7 \text{ day} \left[\left(\frac{\kappa}{10{\rm cm}^2/{\rm g}}\right)\left(\frac{M_{\rm ej}}{0.005 M_\odot}\right)\left(\frac{0.1c}{v_{\rm ej}}\right)\right]^{1/2}$$

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

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

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

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



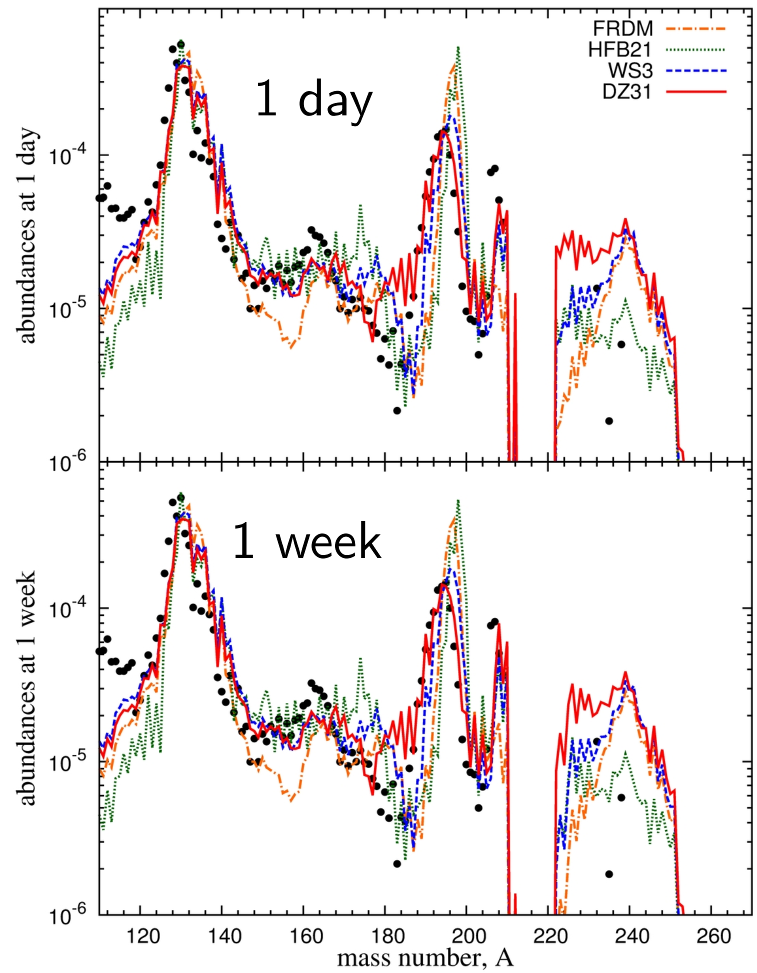
[Tanvir et. al., Nature 500, 547 (2013)]

composition relevant for kilonova

- composition affects the thermalization of photons, electrons, α, and fission fragments

- lanthanides and actinides dominate the photon opacity

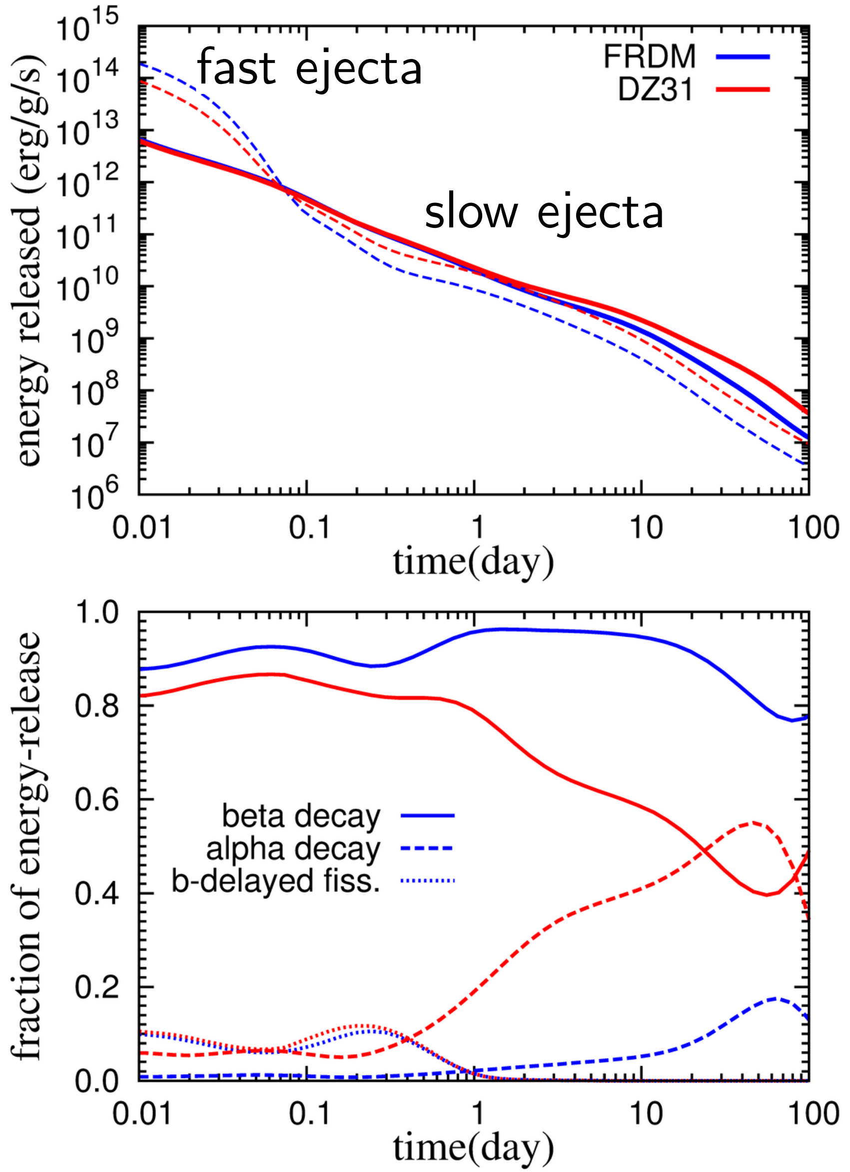
- radioactive β-decays from the peaks while the α-decays from $A \sim 230$



kilonova heating rates

- slow ejecta dominate the energy production during the kilonova time scale of days.

- fast ejecta may give rise to a precursor powered by neutron decays at $\sim$ hours due to its lower density. [Metzger et.al., MNRAS 446, 1115 (2015)]



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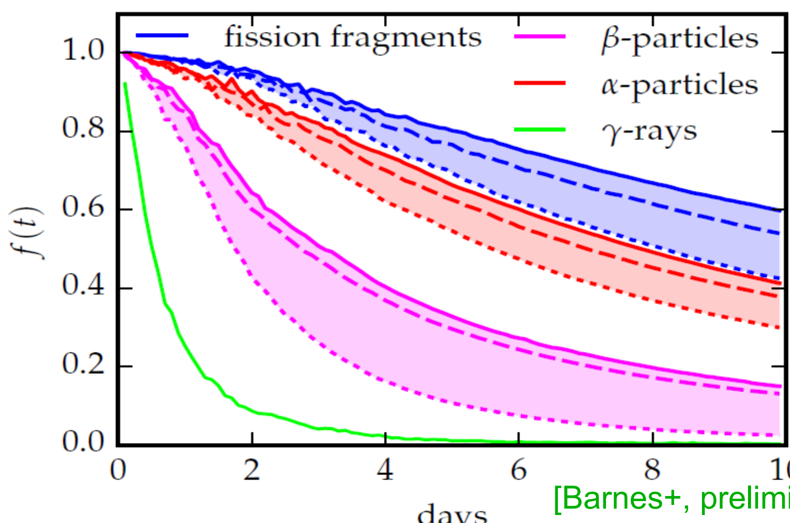
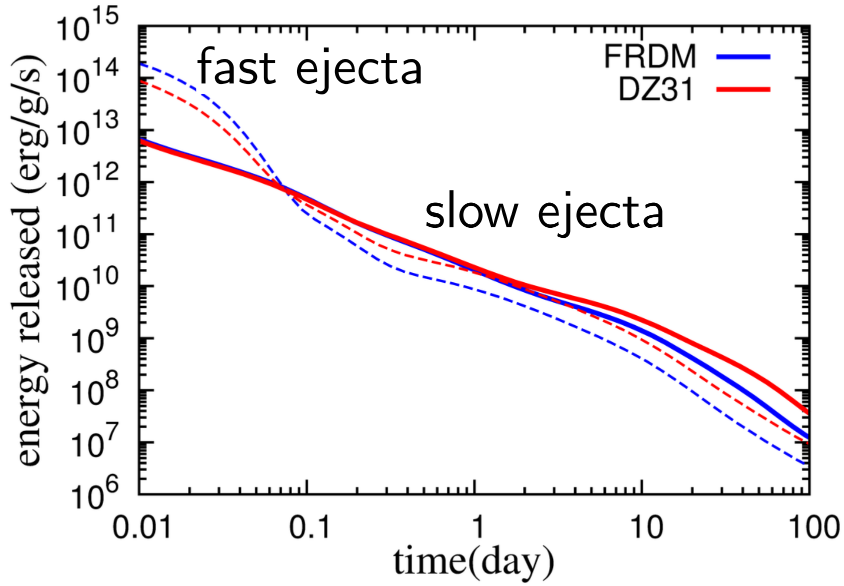
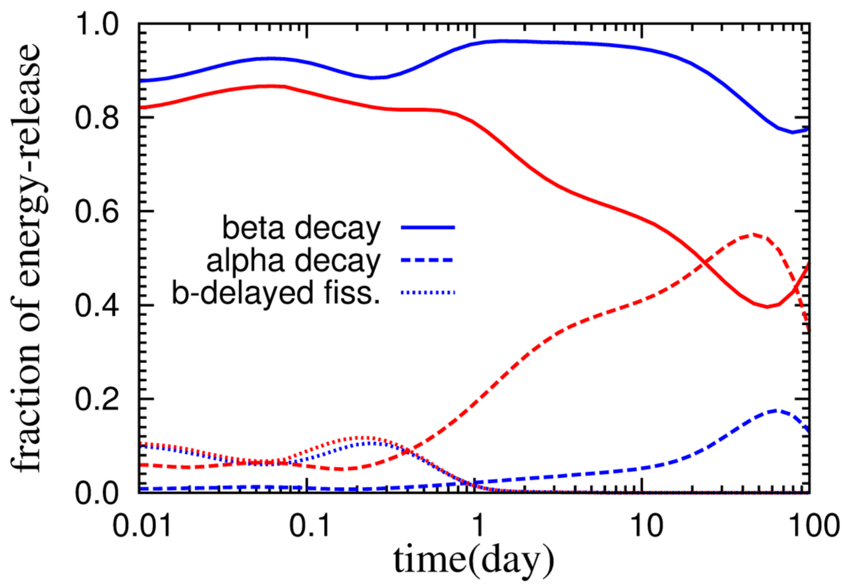
- lightcurve predicted with different nuclear inputs may differ significantly, due to different thermalization efficiency of decay/fission products.



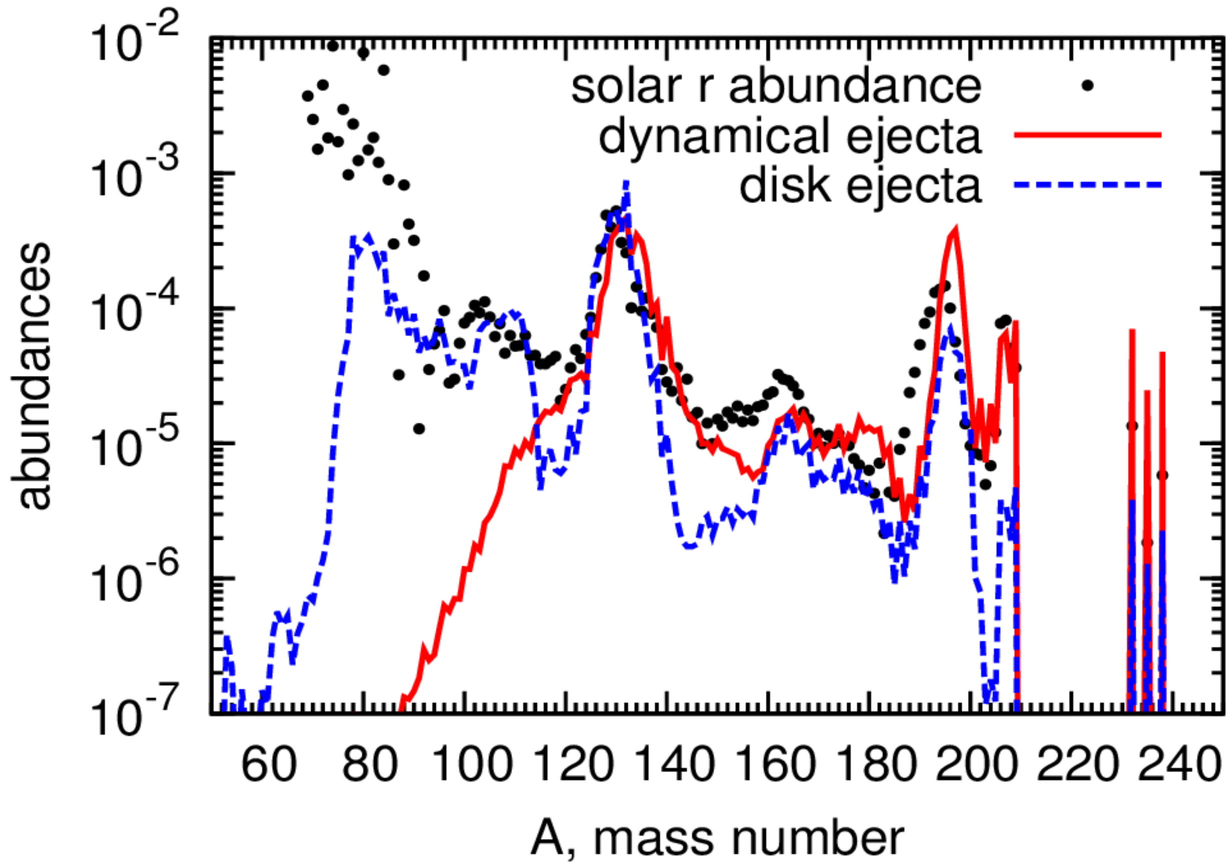
[Barnes+, preliminary]





disk ejecta

Disk model from R. Fernández+, $M_{\rm BH} = 3\ M_\odot$, $M_{\rm disk} = 0.03\ M_\odot$



viscously-driven disk ejecta may supplement the dynamical ejecta

(also see works of Just+ 2015, Martin+ 2015)

summary and outlook

- Neutron star mergers may be the astrophysical site for the robust r abundances due to the very neutron-rich ejecta.
- Nuclear physics inputs are essential in shaping the final abundance pattern. e.g., a) the position and height of the peaks are sensitive to nuclear mass model. b) 2nd peak is sensitive to the fission fragment distributions.
- The radioactive decays of the r-process products may power a kilonova. A precursor due to the neutron decays may also be obtained from very fast expanding material.
- Modeling the kilonova lightcurve again requires a good knowledge of nuclear physics
- Disk ejecta may also contribute significantly.

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- model dependence of disk ejecta?
- role of neutrinos (and oscillations)?
- consistent/improvement treatment of nuclear physics?