Production of first r-process peak elements in neutron star mergers

Stylianos Nikas
Friday 26th March 2021, SFB Workshop

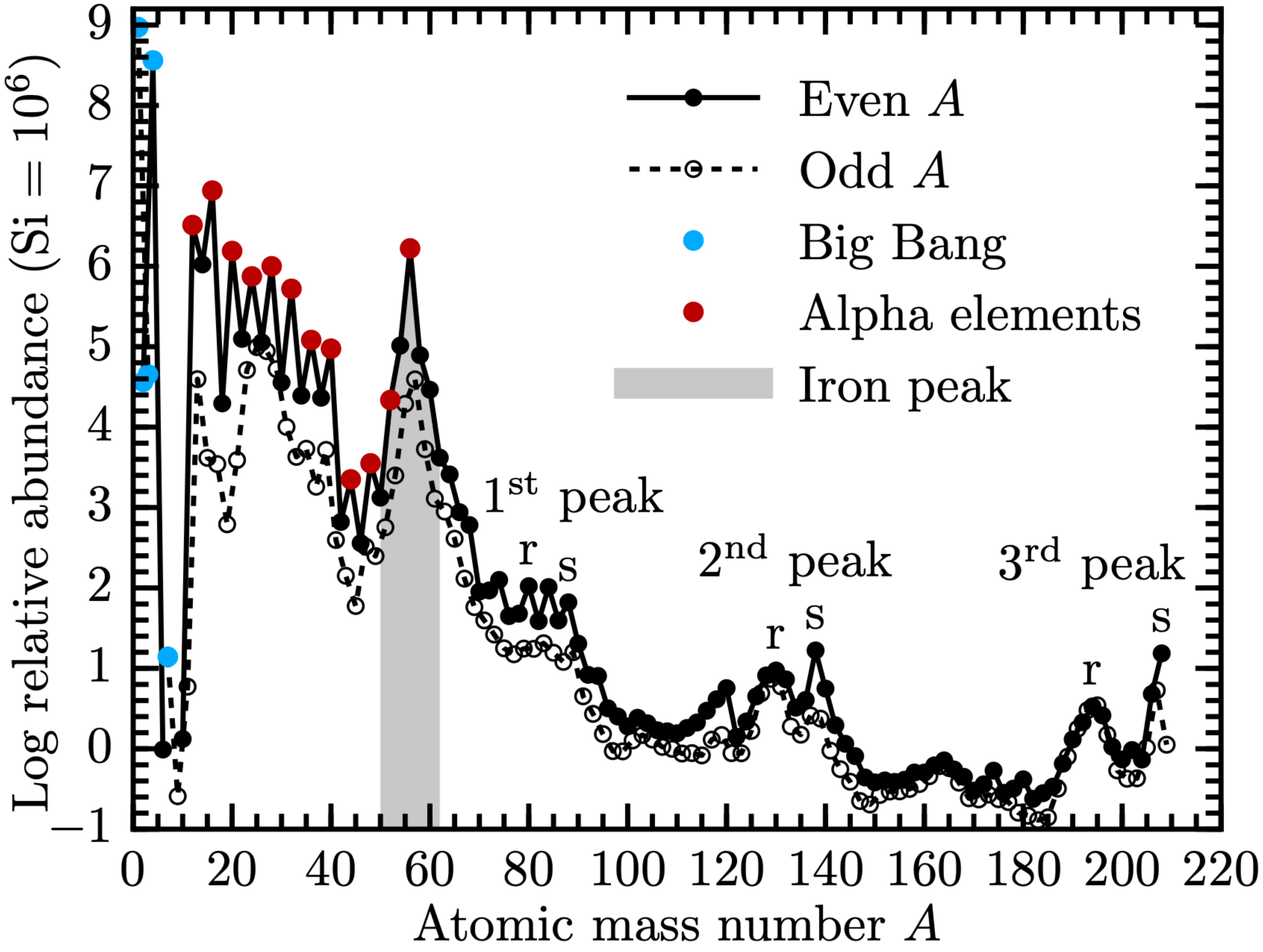
TECHNISCHE
UNIVERSITÄT
DARMSTADT

SFB 1245

GSI

ESO/L. Calçada/M. Kornmesser

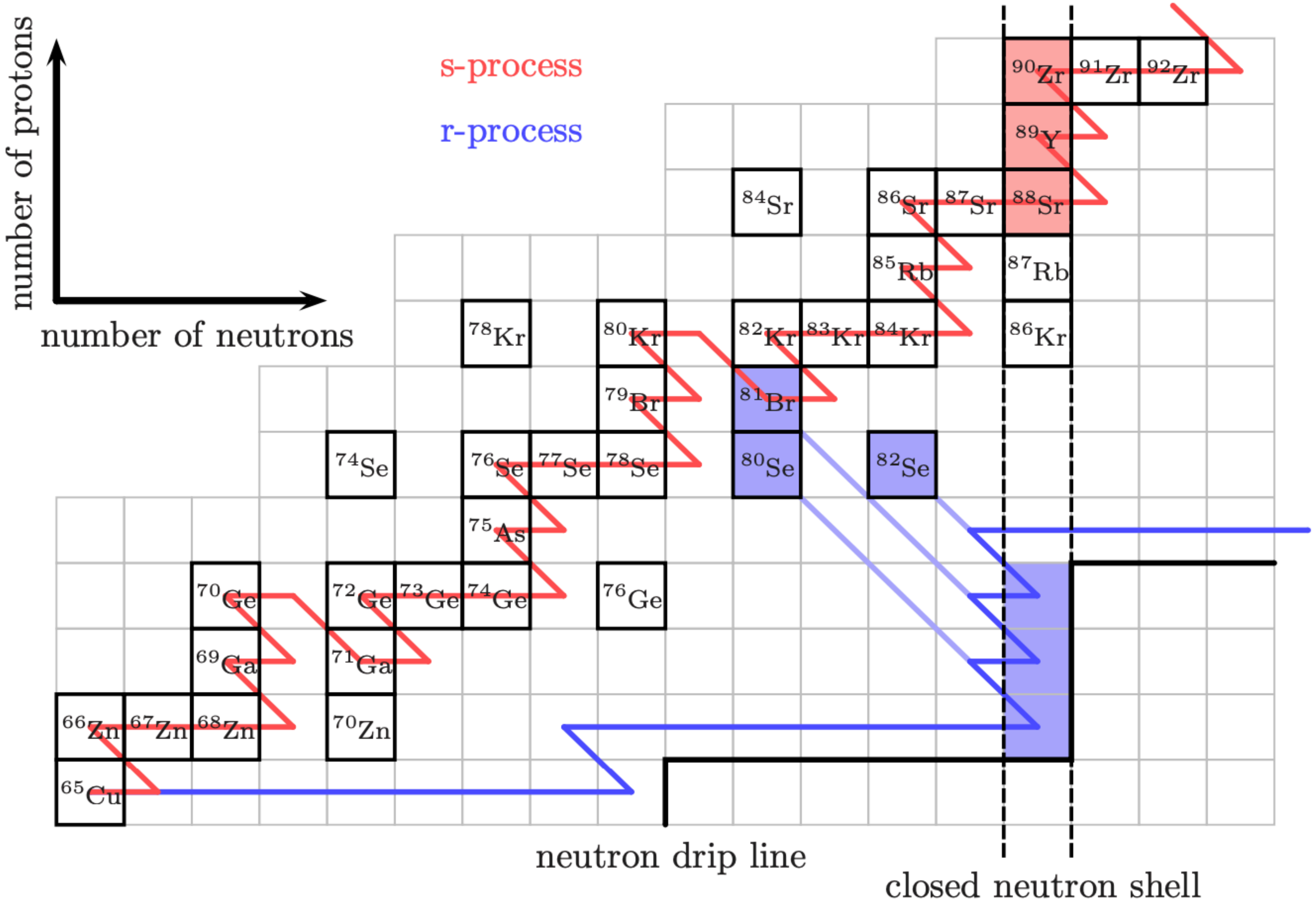
The solar system abundance pattern



J. Lippuner (2018)

- The lightest elements were created in the Big Bang and fusion in stars predominantly creates alpha elements.
- The iron peak is made in core-collapse and type Ia supernovae.
- Elements beyond the iron peak are synthesised by the slow (s) and rapid (r) neutron capture processes

Neutron capture processes



These neutron capture processes are:

- The slow (s) process

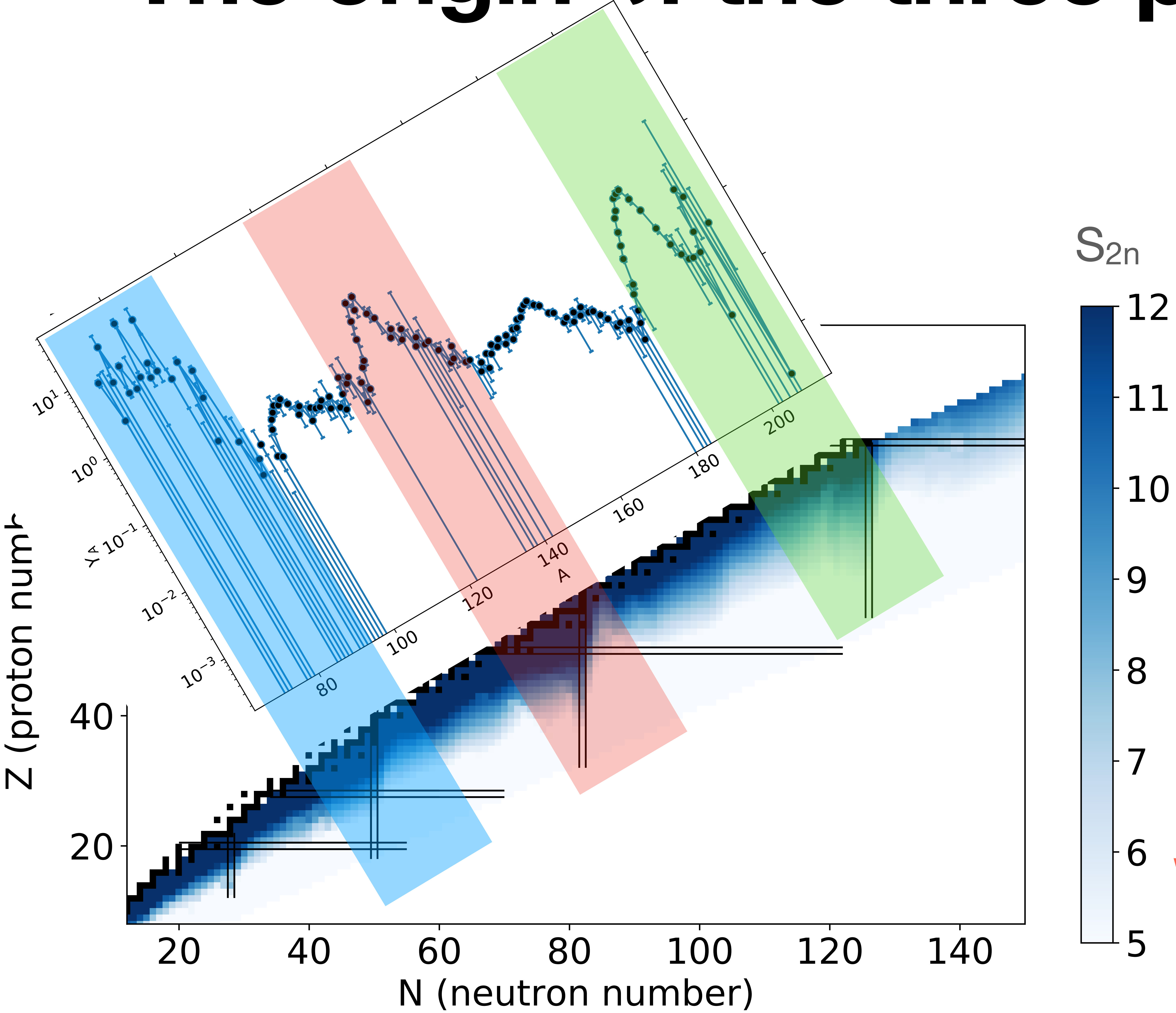
  $\tau_n >> \tau_{1/2}$ - low neutron density

- The rapid (r) process

  $\tau_n << \tau_{1/2}$ high neutron density

*Burbidge **et al.** (1957) • Cameron (1957)*

The origin of the three peak structure

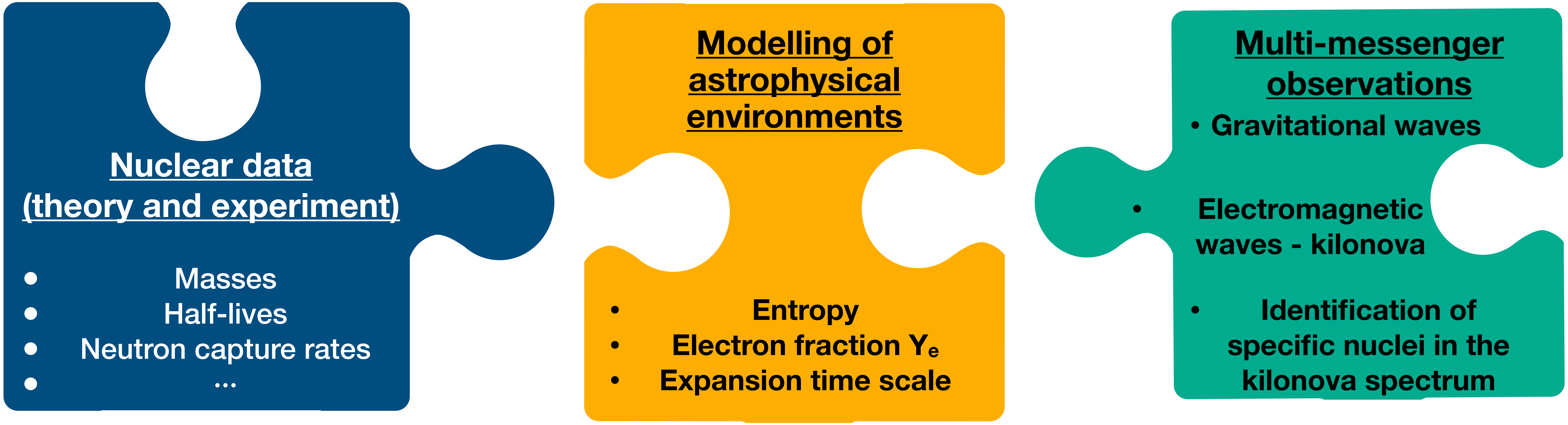


What causes these abundance peaks?

Nuclear structure!

We will focus on the creation of the first r-process peak

Modelling the r-process



<u>Nuclear data (theory and experiment)</u>

- Masses
- Half-lives
- Neutron capture rates
- …

<u>Modelling of astrophysical environments</u>

- **Entropy**
- **Electron fraction Y_e**
- **Expansion time scale**

<u>Multi-messenger observations</u>

- **Gravitational waves**
- **Electromagnetic waves - kilonova**
- **Identification of specific nuclei in the kilonova spectrum**

C J Horowitz **et al.** (2019), • JJ Cowan ***et al.*** (2019)

Modelling the r-process

Sets the structure of the abundance pattern.

Nuclear data (theory and experiment)

- Masses
- Half-lives
- Neutron capture rates
- …

Sets the neutron/seed ratio responsible for the heaviest elements that can be created.

Modelling of astrophysical environments

- Entropy
- Electron fraction Y_e
- Expansion time scale

Provides observations for meaningful comparisons.

Multi-messenger observations

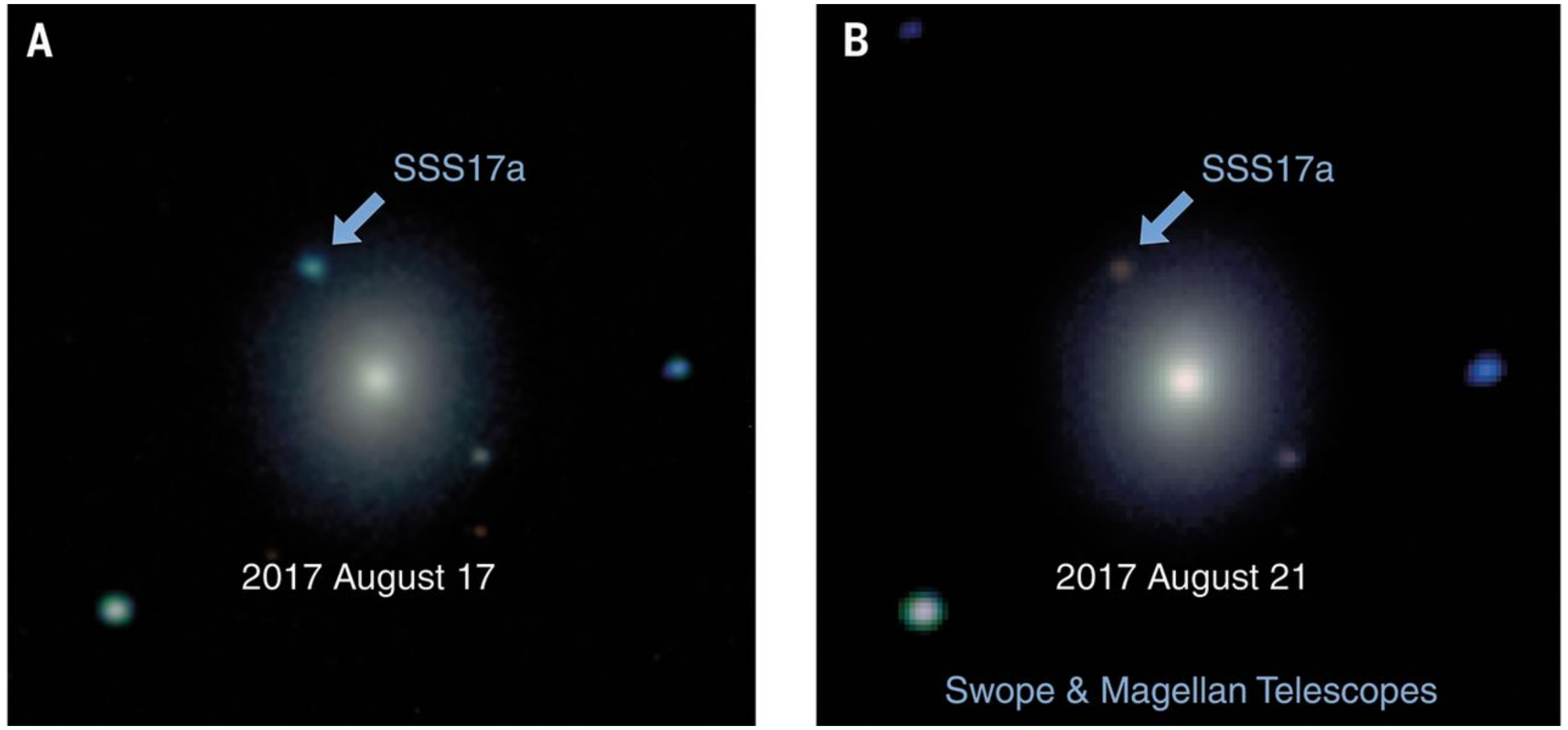
- Electromagnetic waves - kilonova
- Identification of specific nuclei in the kilonova spectrum

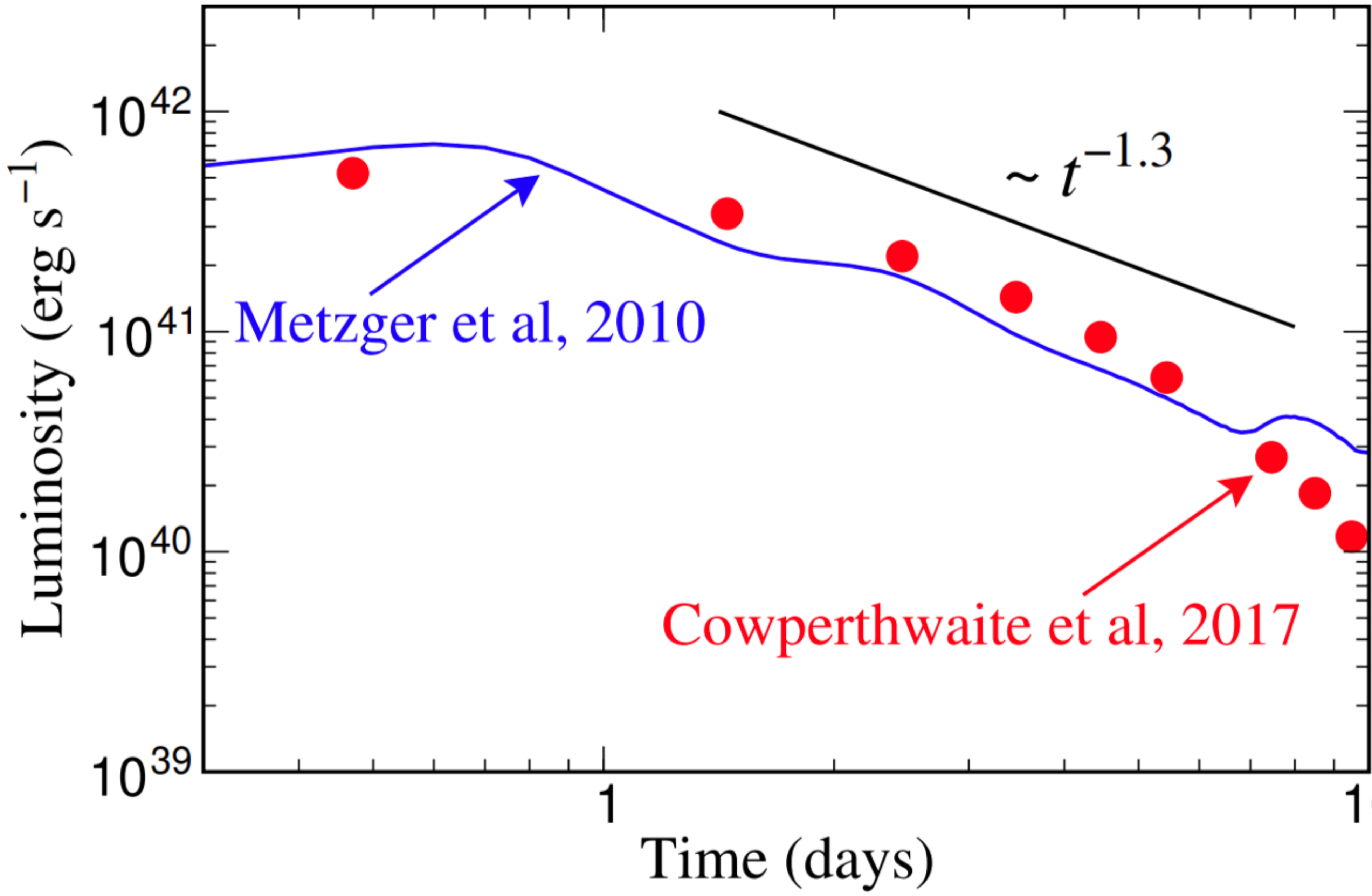
C J Horowitz **et al.** (2019), • JJ Cowan ***et al.*** (2019)

Multi-messenger observations

The observation of GW170817 followed by the AT2017gfo transient matching the predictions of kilonova

Kilonova is the strong electromagnetic radiation emission due to the radioactive decay of heavy r-process nuclei that are produced and ejected during the merger process.





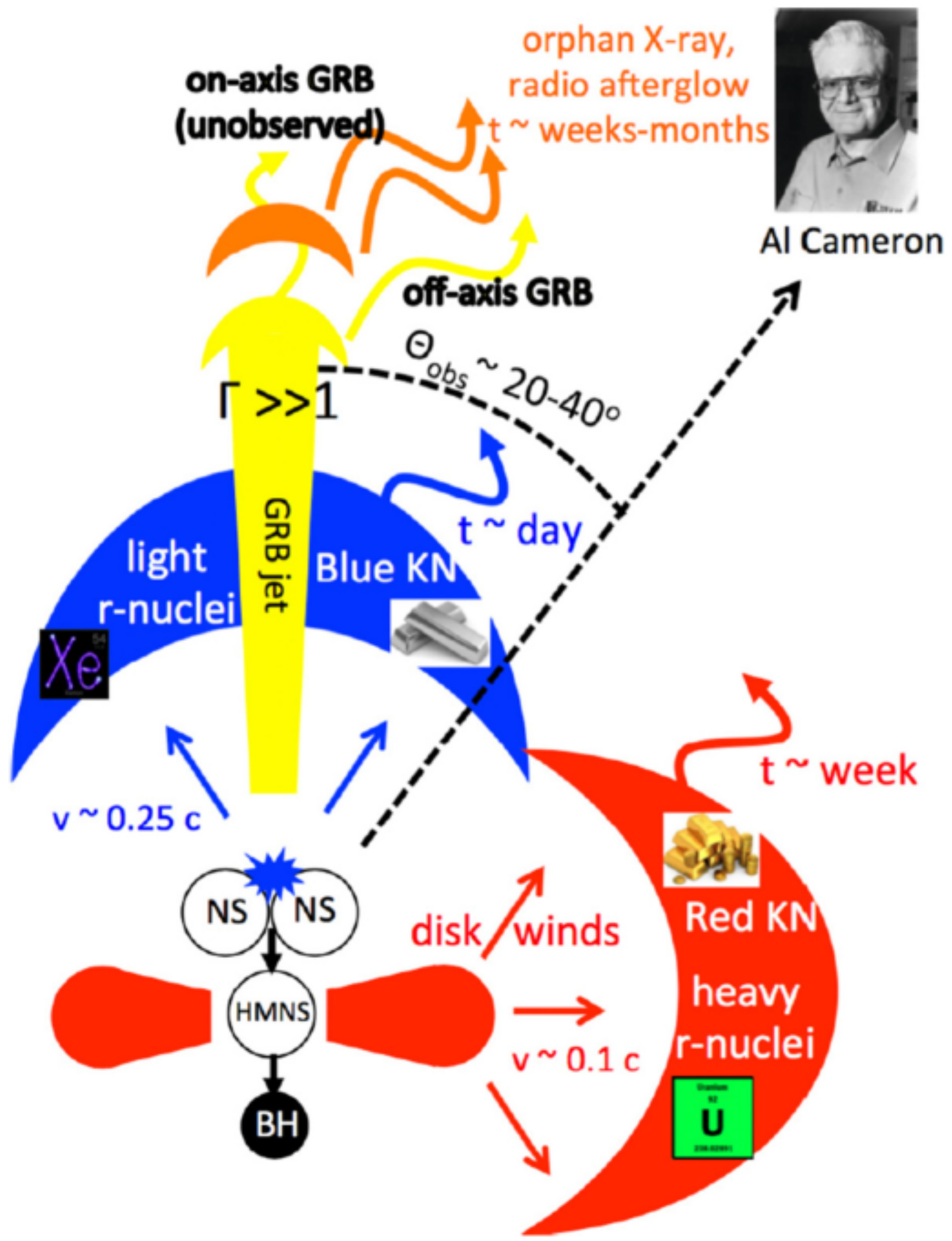
B.P. Abbott ***et al.*** (2017) · Metzger ***et al.*** (2010) +

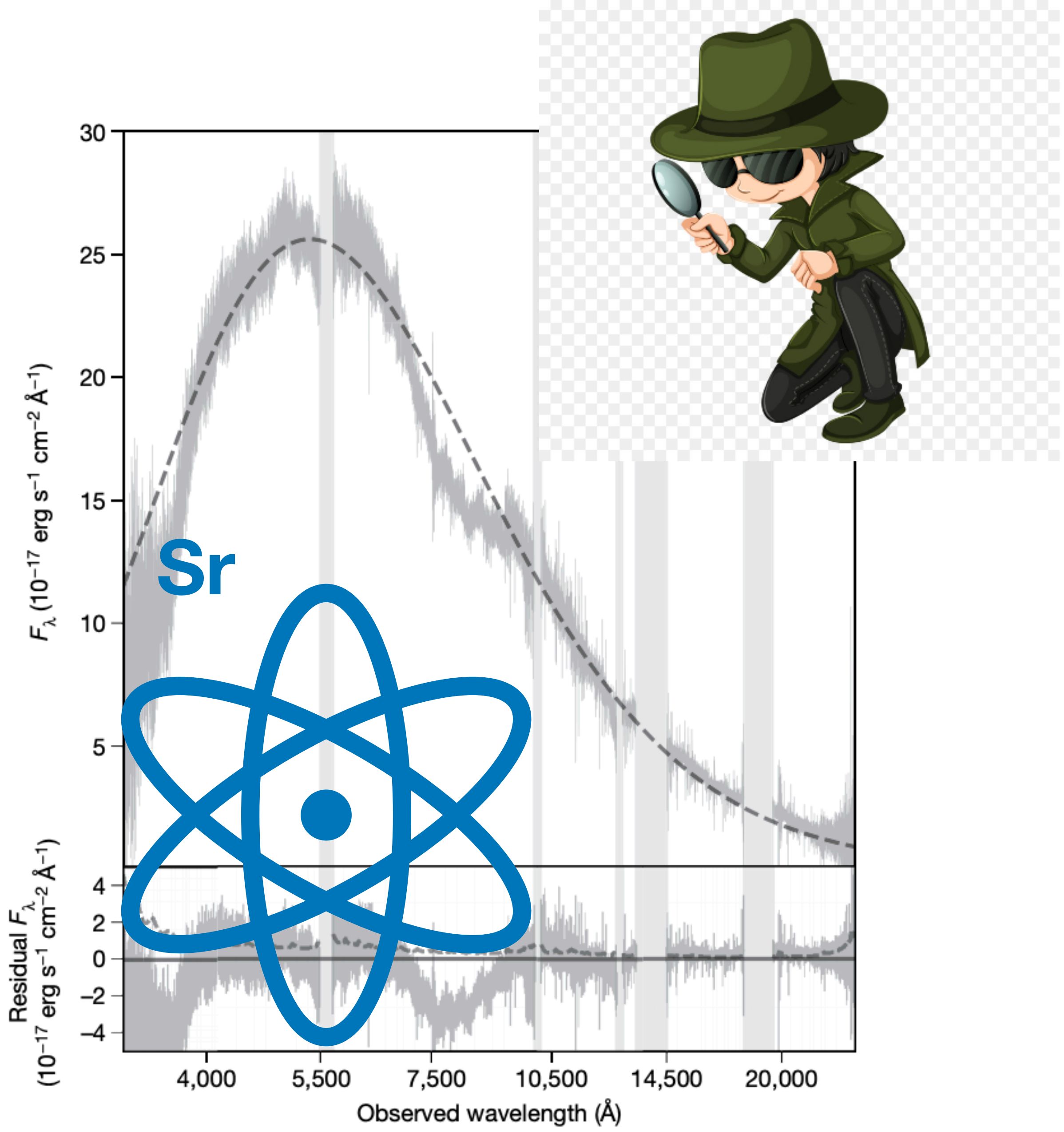
What did we learn?

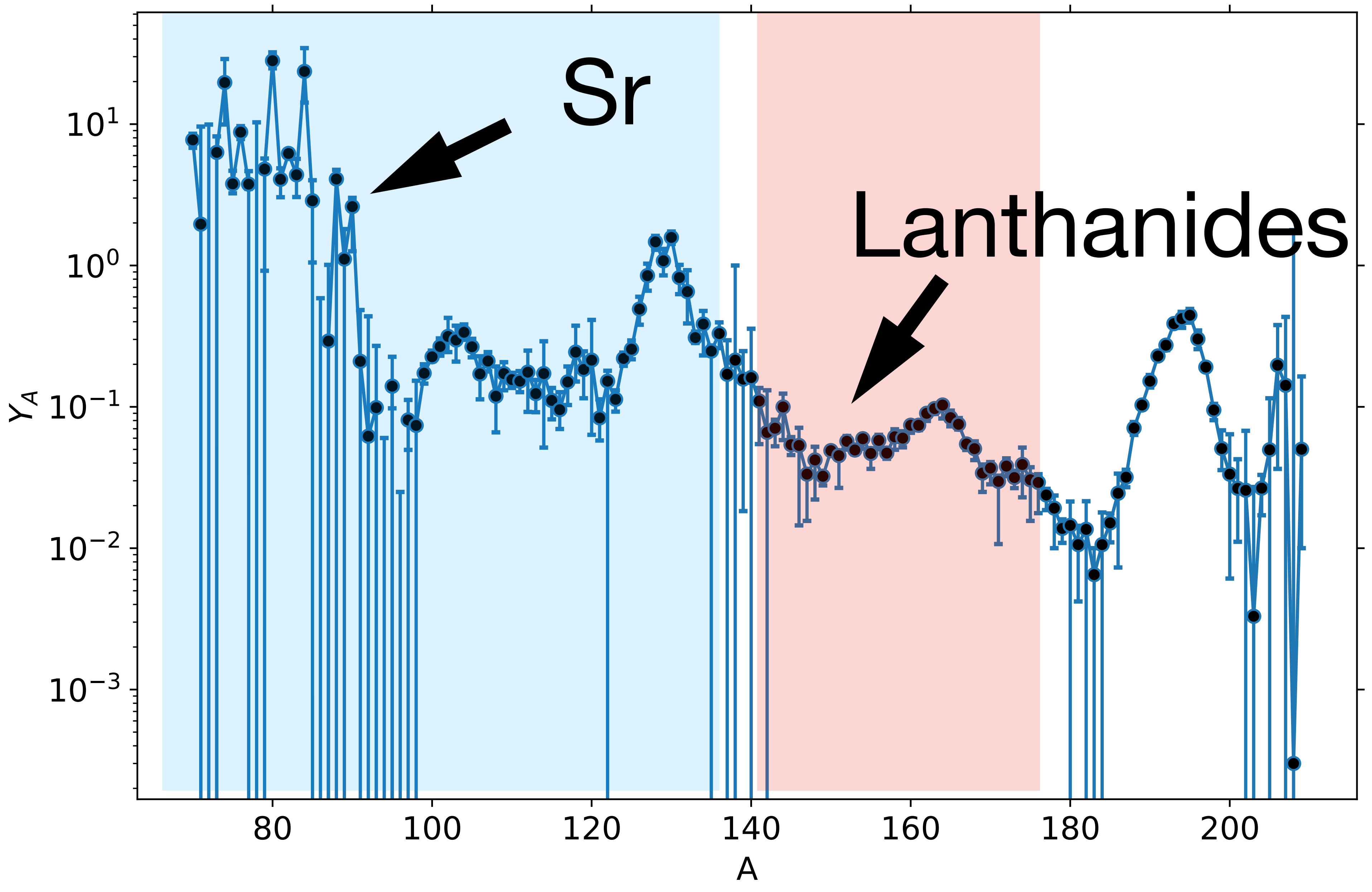
The EM transient matches the kilonova predictions.

The colour evolution of the emission signals presence at least 2 different emission channels one of which produces lanthanides free ejecta.

The presence of Sr provides direct evidence of the creation of light r-process elements.







Watson **et al.** (2020) · Metzger **et al**. (2011) · Metzger **et al**. (2019) ·

Modelling of the astrophysical environment

Three quantities are responsible for setting the neutron to seed ratio:

Entropy (S)

$$S \approx T^3/\rho$$

Electron fraction (Ye)

$$Y_e = \frac{n_e}{n_b}$$

expansion timescale (τ)

$$\rho(t) = \begin{cases} \rho_0 e^{-t/\tau} & t \leq 3\tau, \\ \rho_0 \left(\frac{3\tau}{et}\right)^3 & t \geq 3\tau \end{cases}$$

<u>Typical values in mergers polar ejecta:</u>

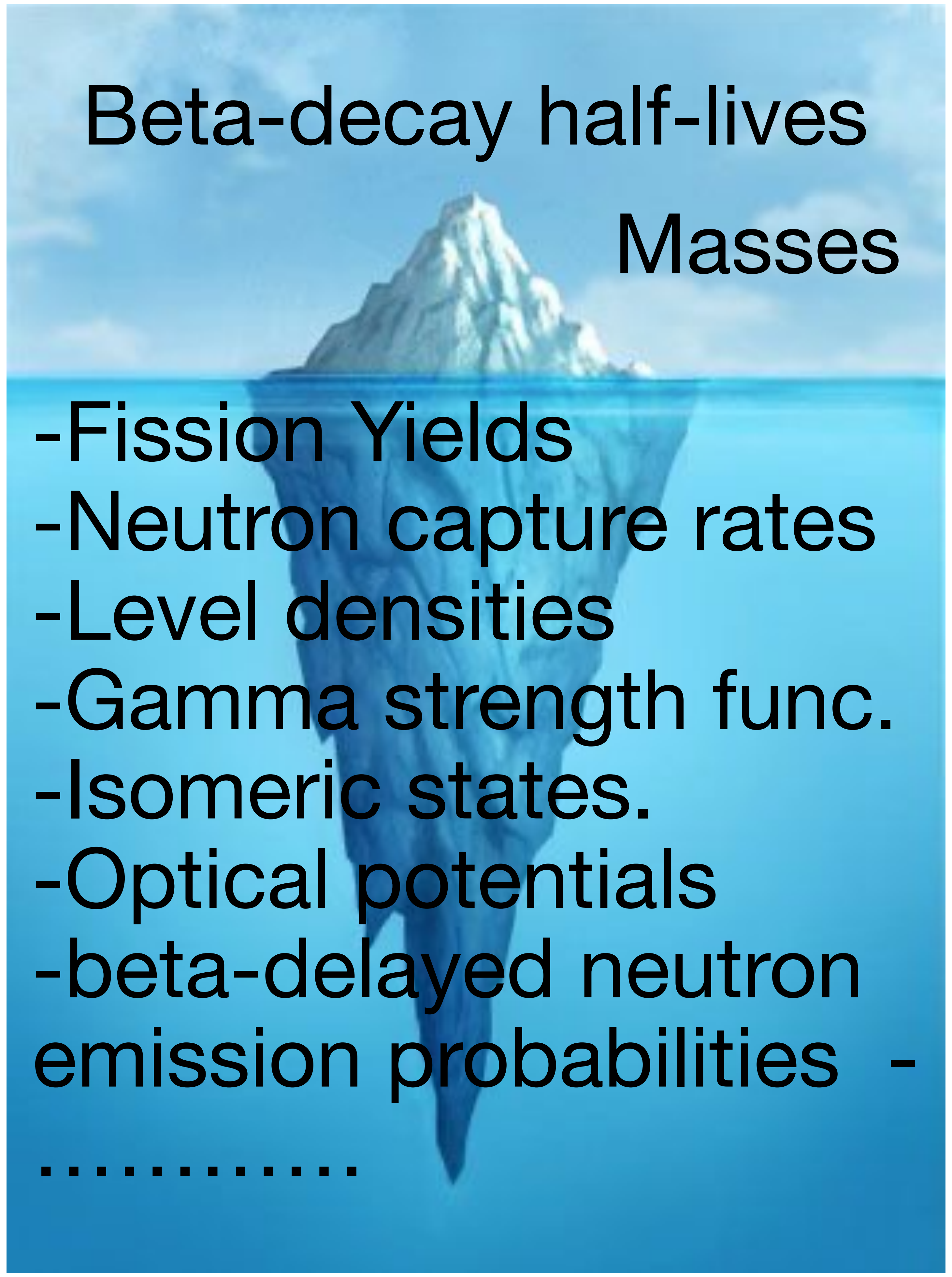
$S = 10 - 30\ k_B$/baryon

$Y_e = 0.25 - 0.50$

$\tau \sim$ ms

Kawaguchi ***et al.*** (2019) · Lippuner ***et al.*** (2015) · Pergo ***et al.*** (2019) · Bauswein ***et al.*** (2013) · Radice ***et al.*** (2018) +

Nuclear Data

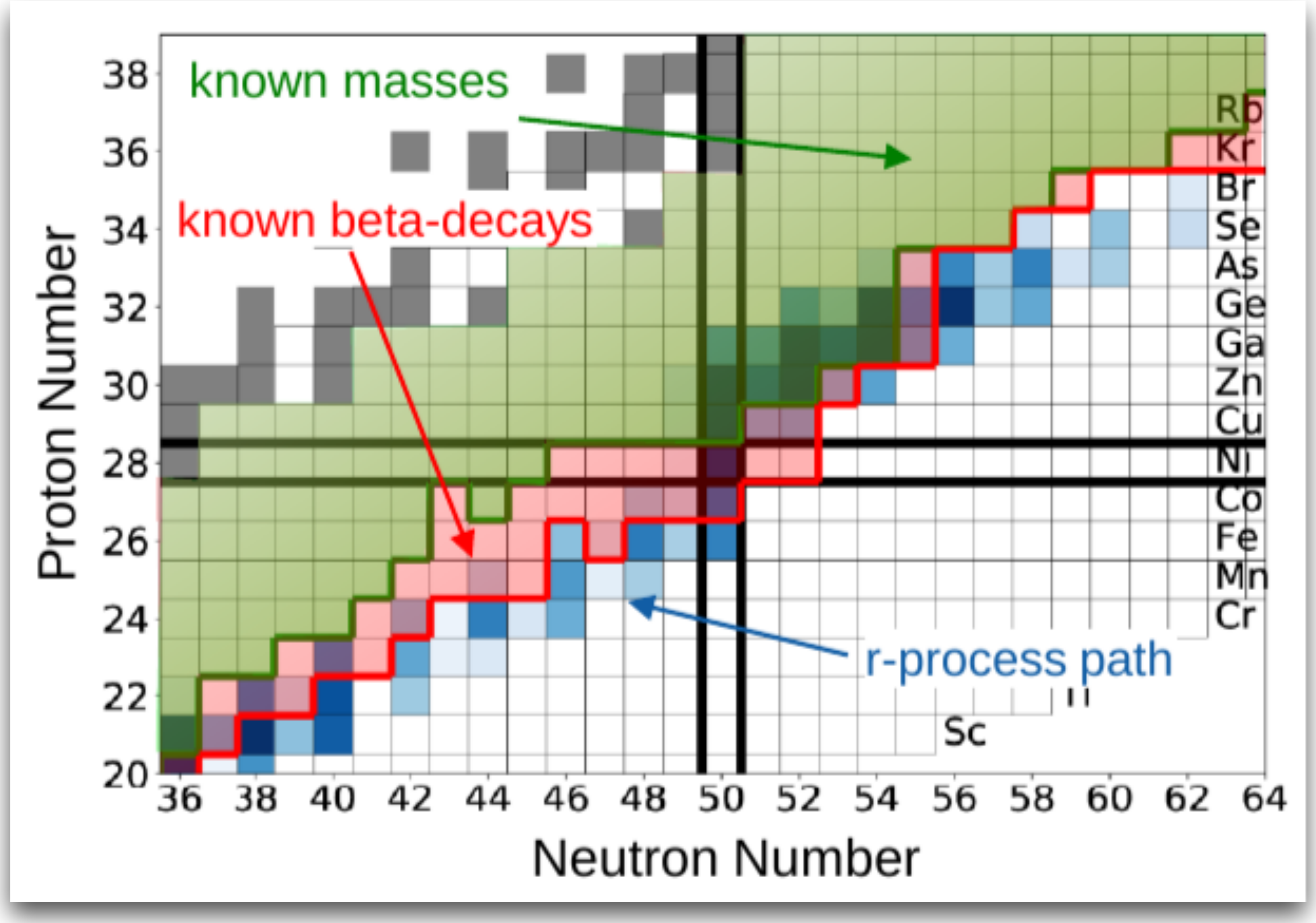


Beta-decay half-lives

Masses

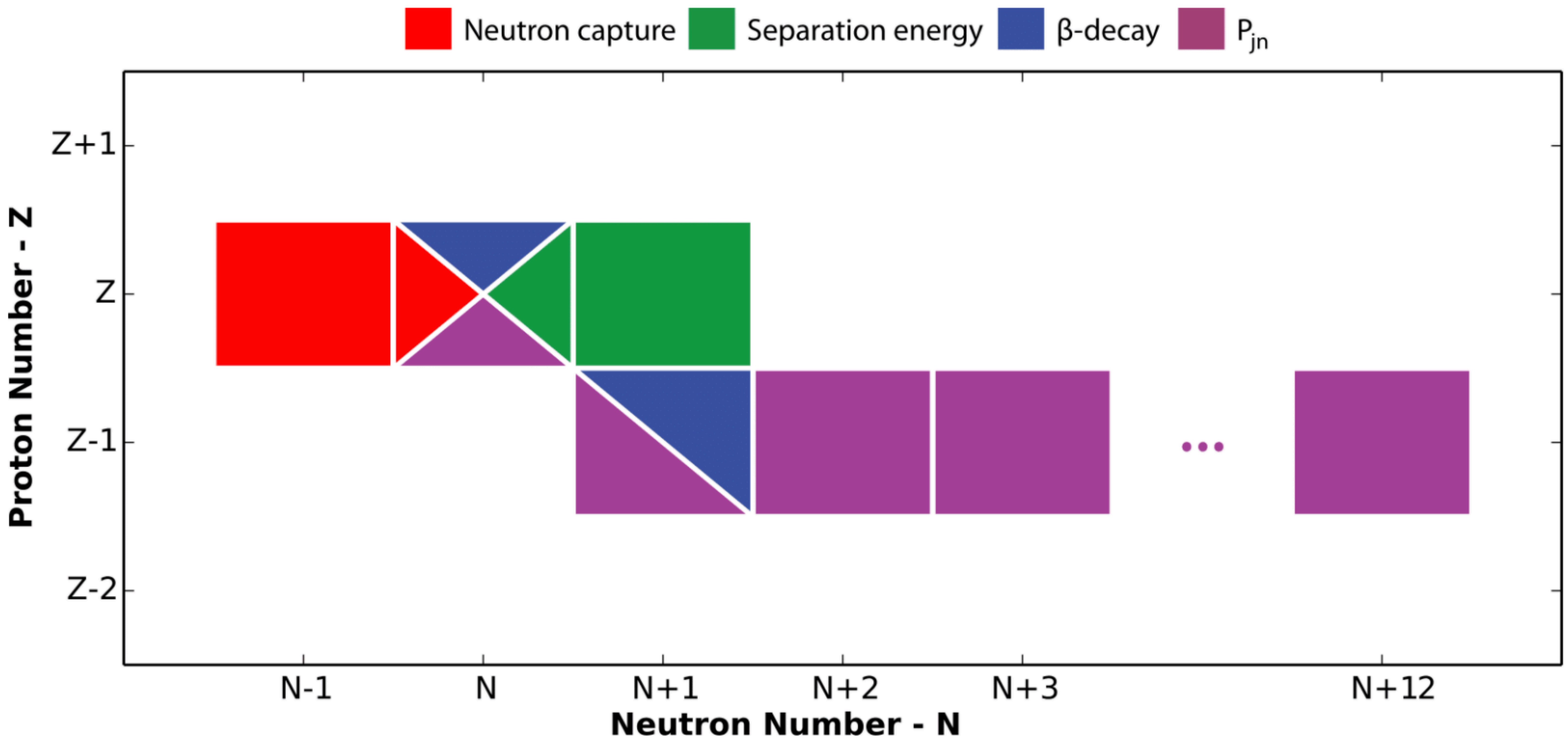
- -Fission Yields
- -Neutron capture rates
- -Level densities
- -Gamma strength func.
- -Isomeric states.
- -Optical potentials
- -beta-delayed neutron emission probabilities -

…………



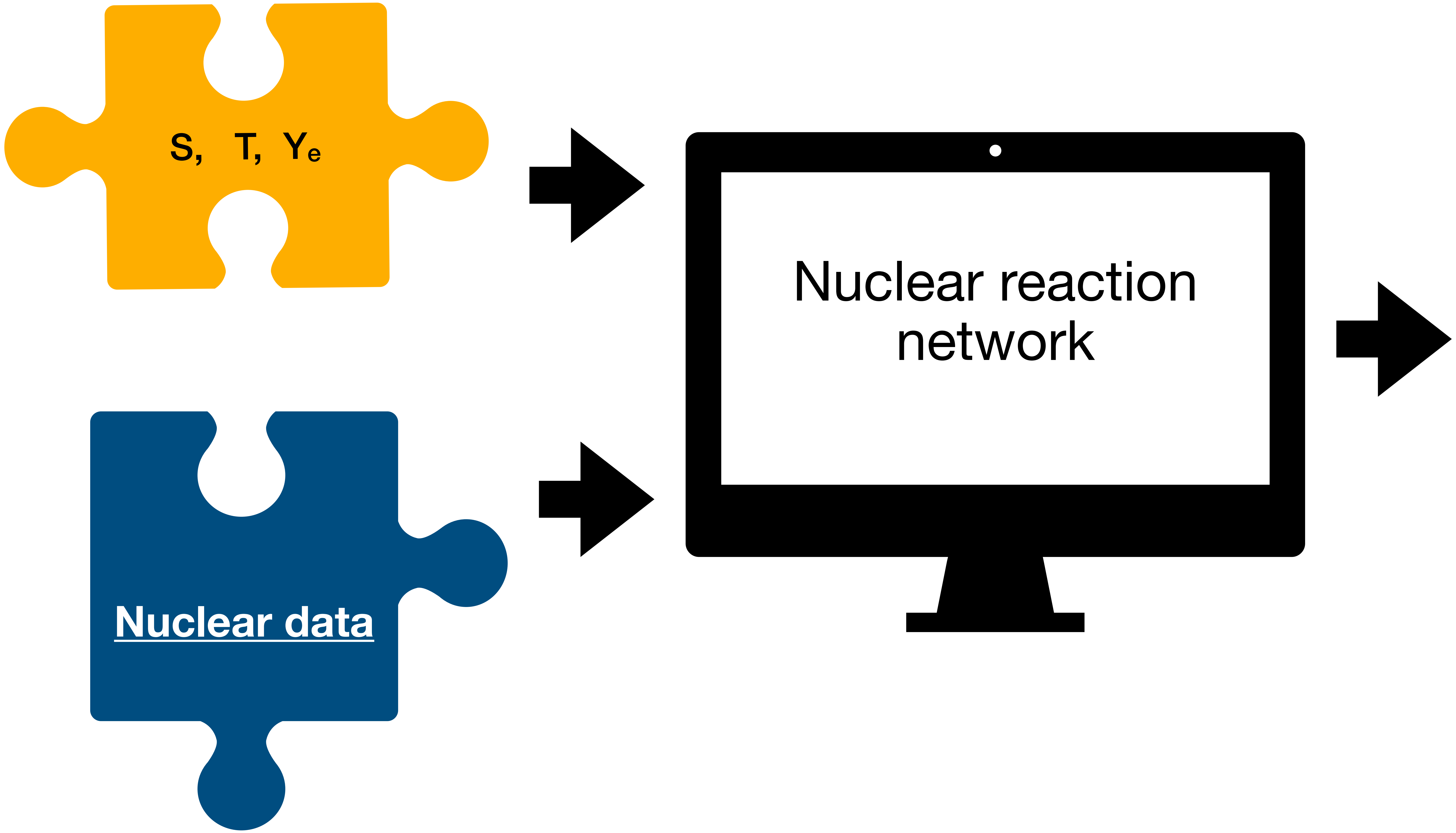
Moller *et al* (2015) · Audi *et al.* (2017) · Huang *et al.* (2017) · Wang *et al.* (2017) · Nikas *et al.* (2019) · Nikas *et al.* (2020) (preprint) · Mumpower *et al.* (2015) · Reiter *et al.* 2020 +

Why nuclear masses are so important?



Mumpower ***et al.*** (2015)

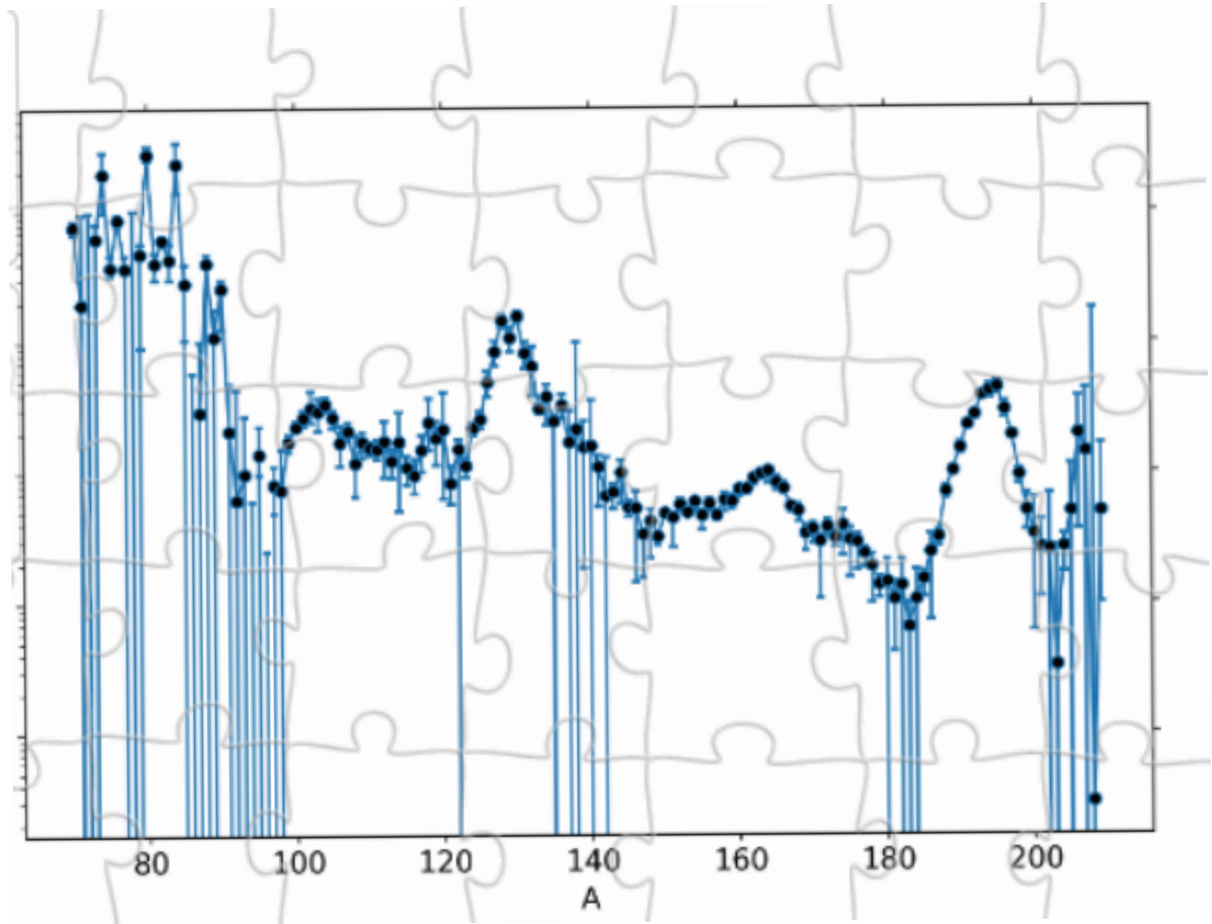
Nuclear Network calculations



S, T, Y_e

Nuclear data

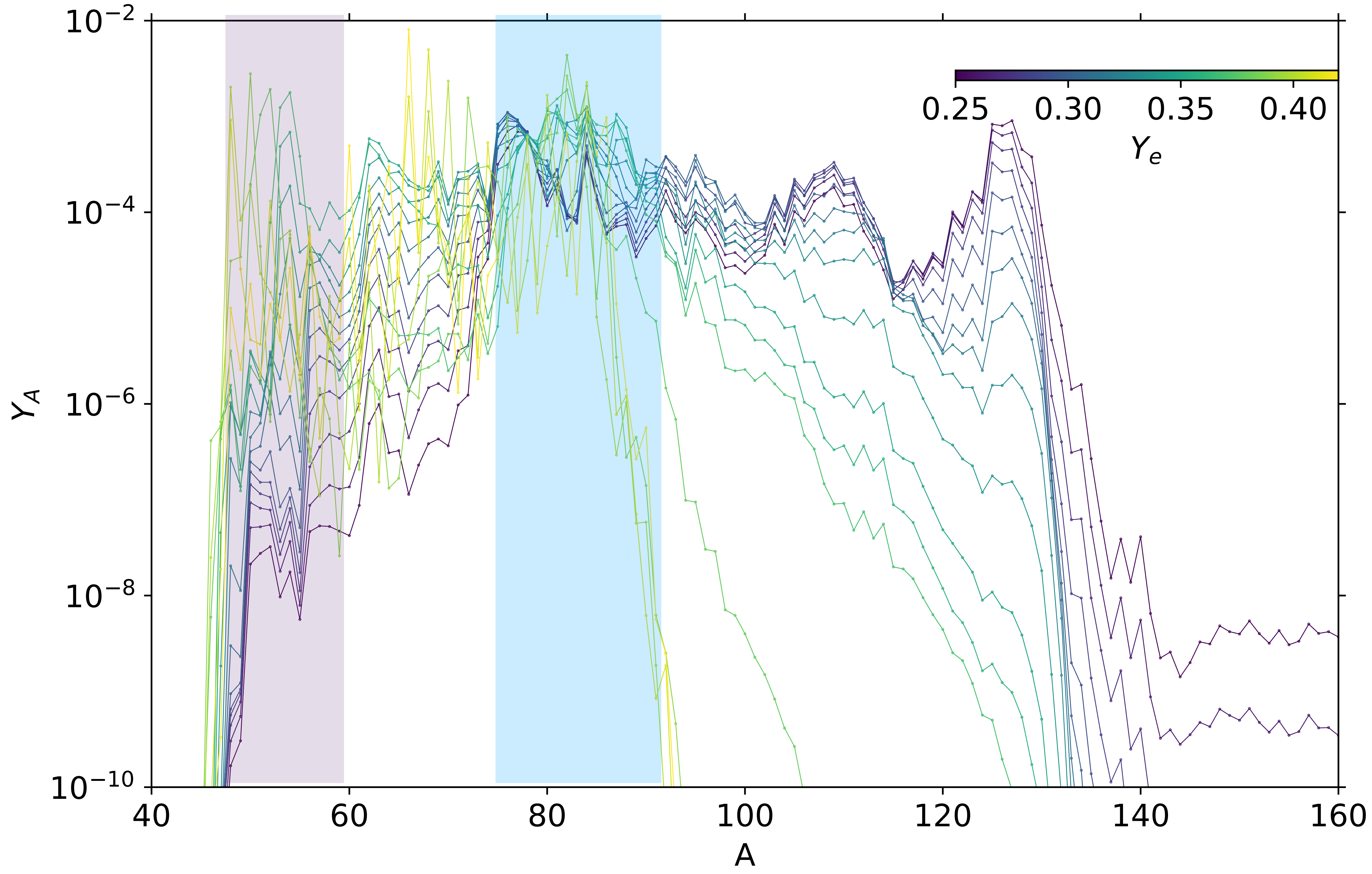
Nuclear reaction network



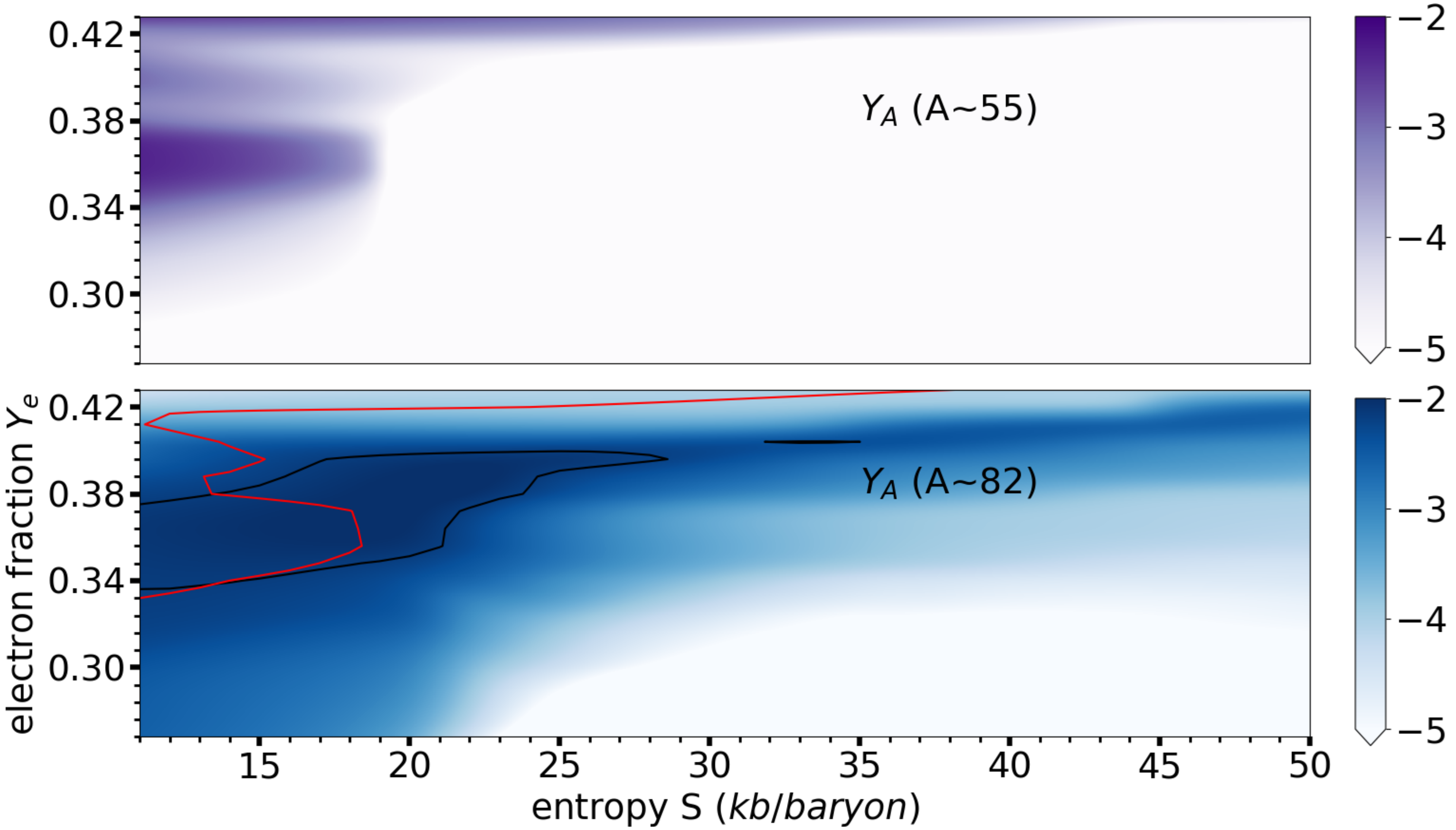
Exploring the astrophysical conditions

In the explored conditions first r-process peak is created together with a peak at A~55 for a short Ye and S range such that:

$0.33 < Ye < 0.39$ and $S < 18\ k_B/\text{baryon}$



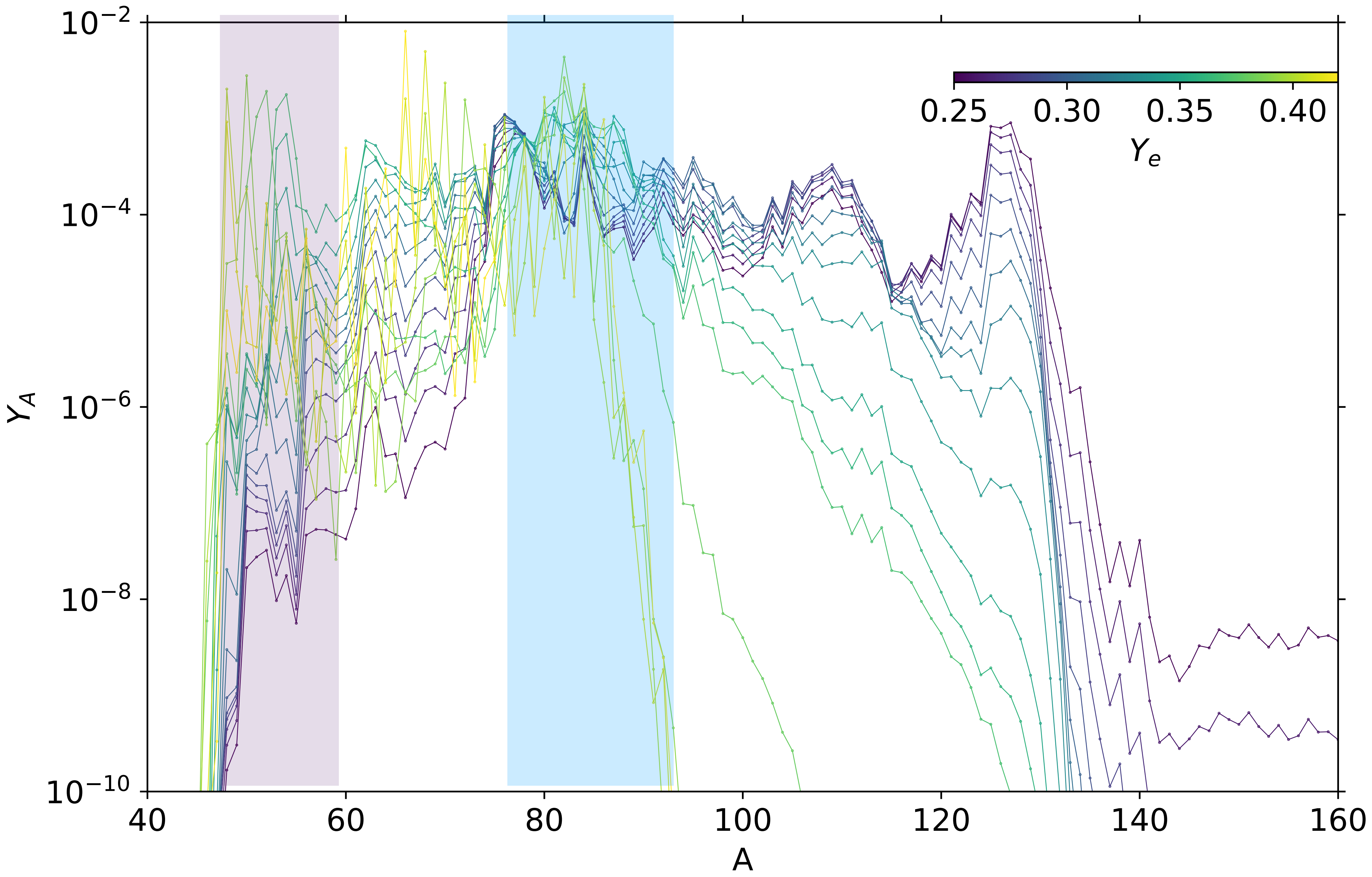
Nikas (2020) thesis work



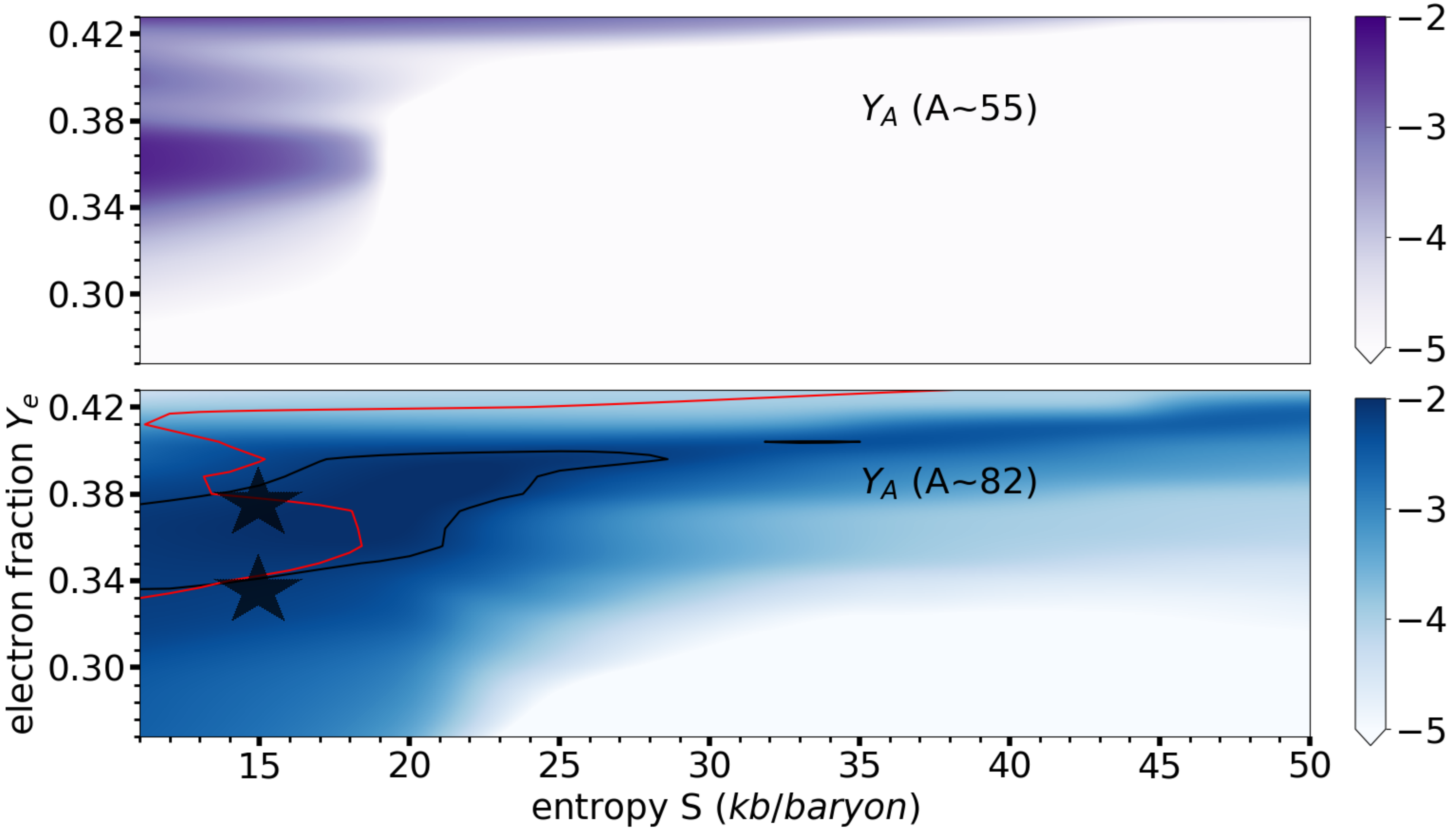
Exploring the astrophysical conditions

In the explored conditions first r-process peak is created together with a peak at A~55 for a short Ye and S range such that:

0.33 < Ye < 0.39 and S < 18 k$_B$/baryon

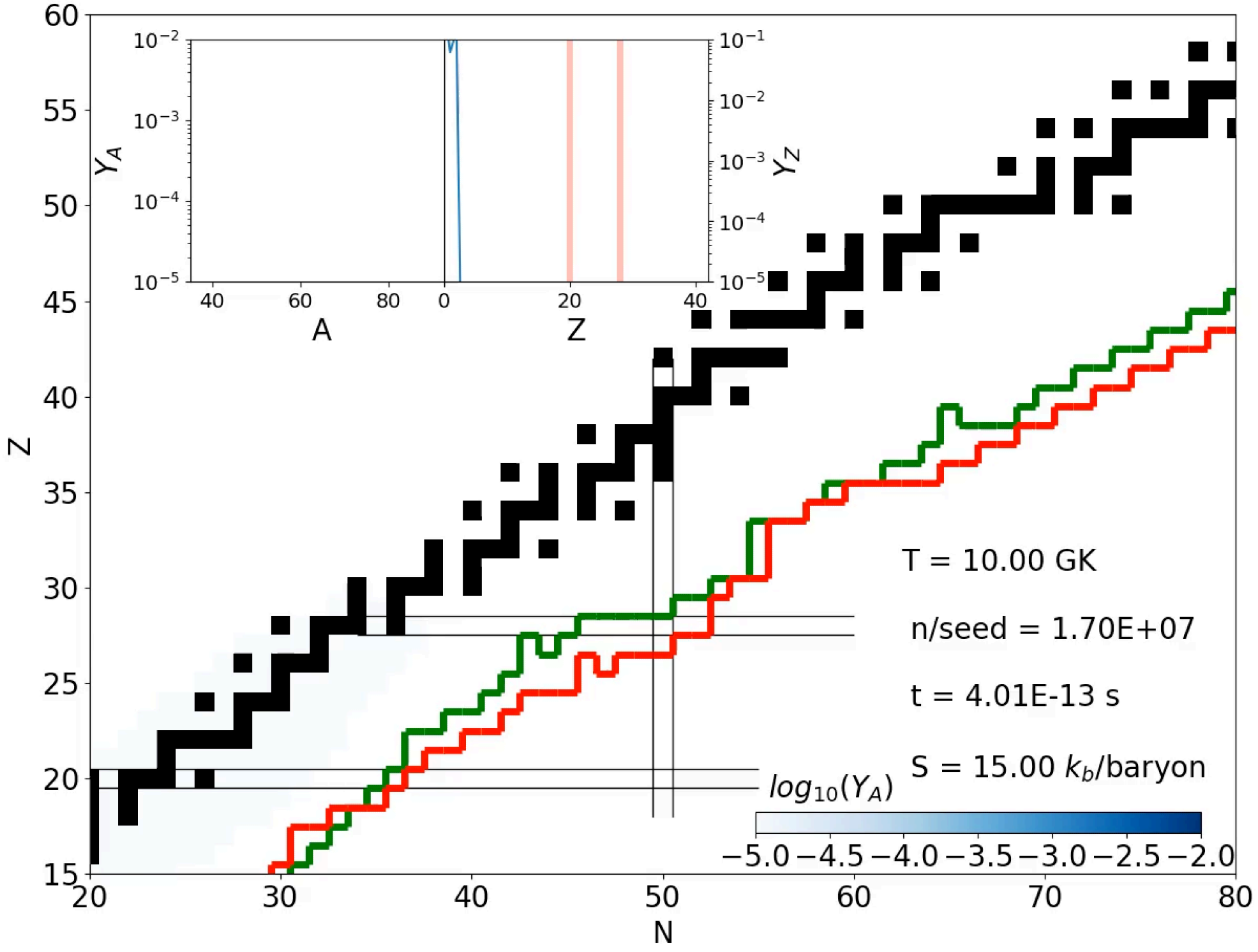


Nikas (2020) thesis work

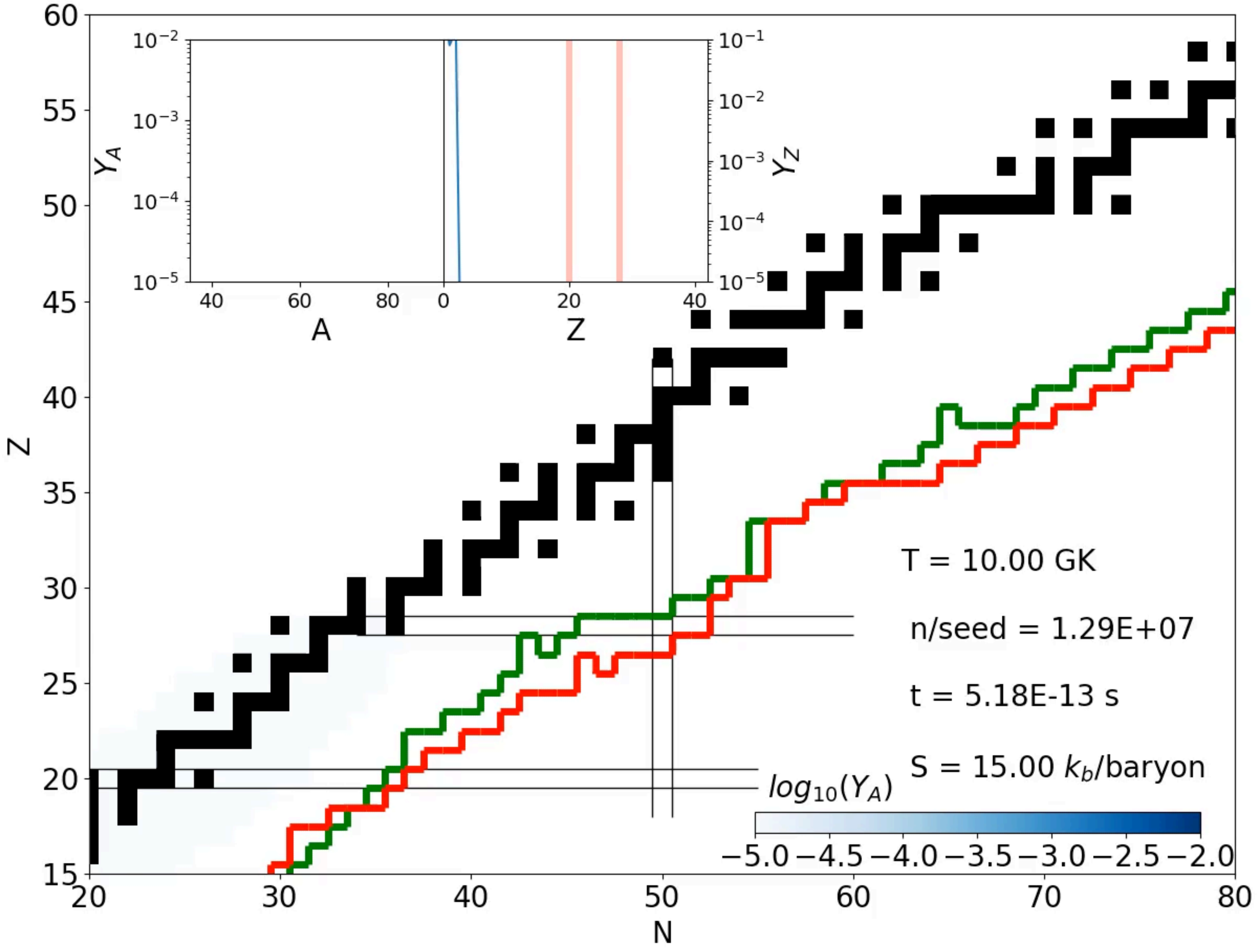


Origin of the A~55 peak

Y_e=0.34



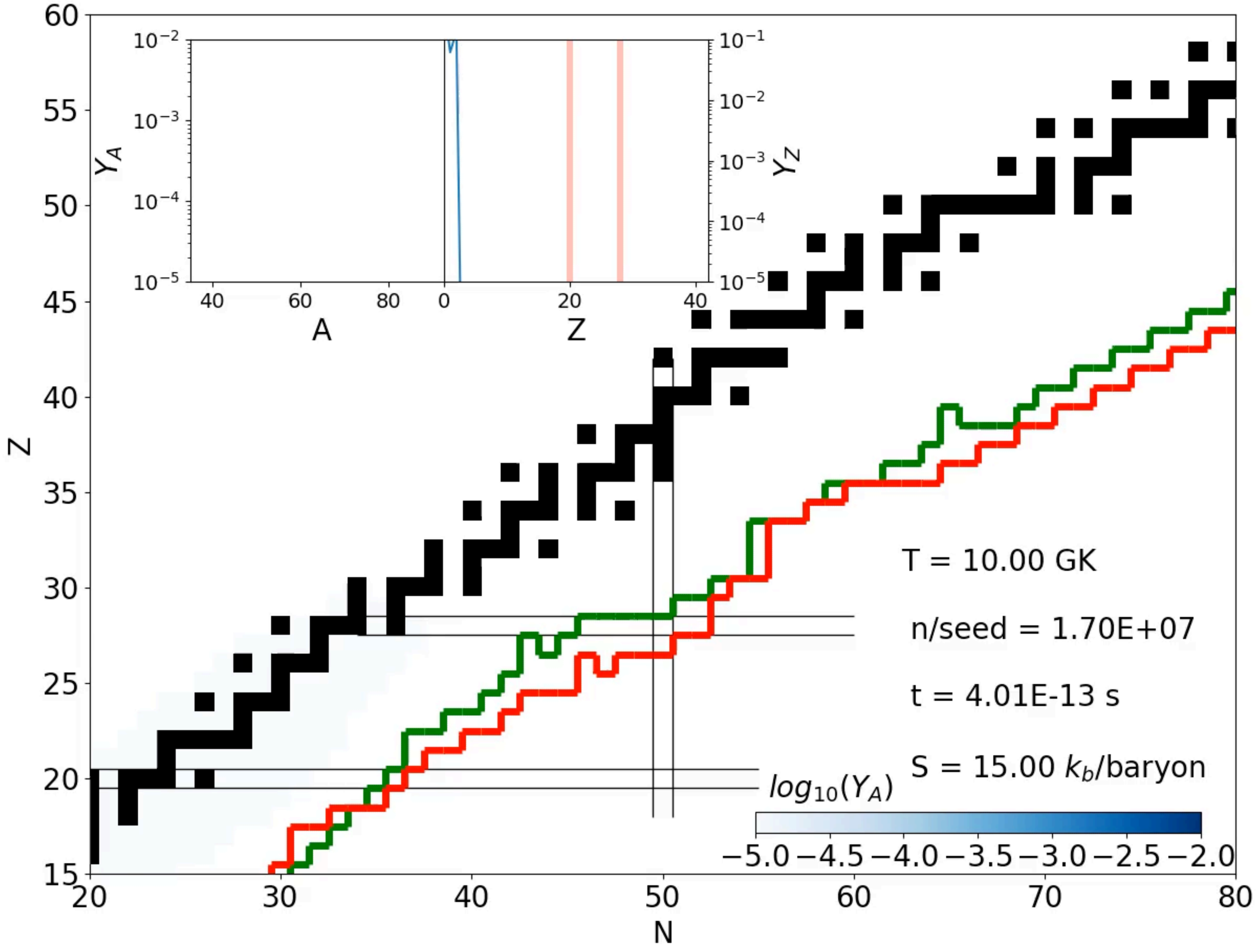
Y_e=0.38



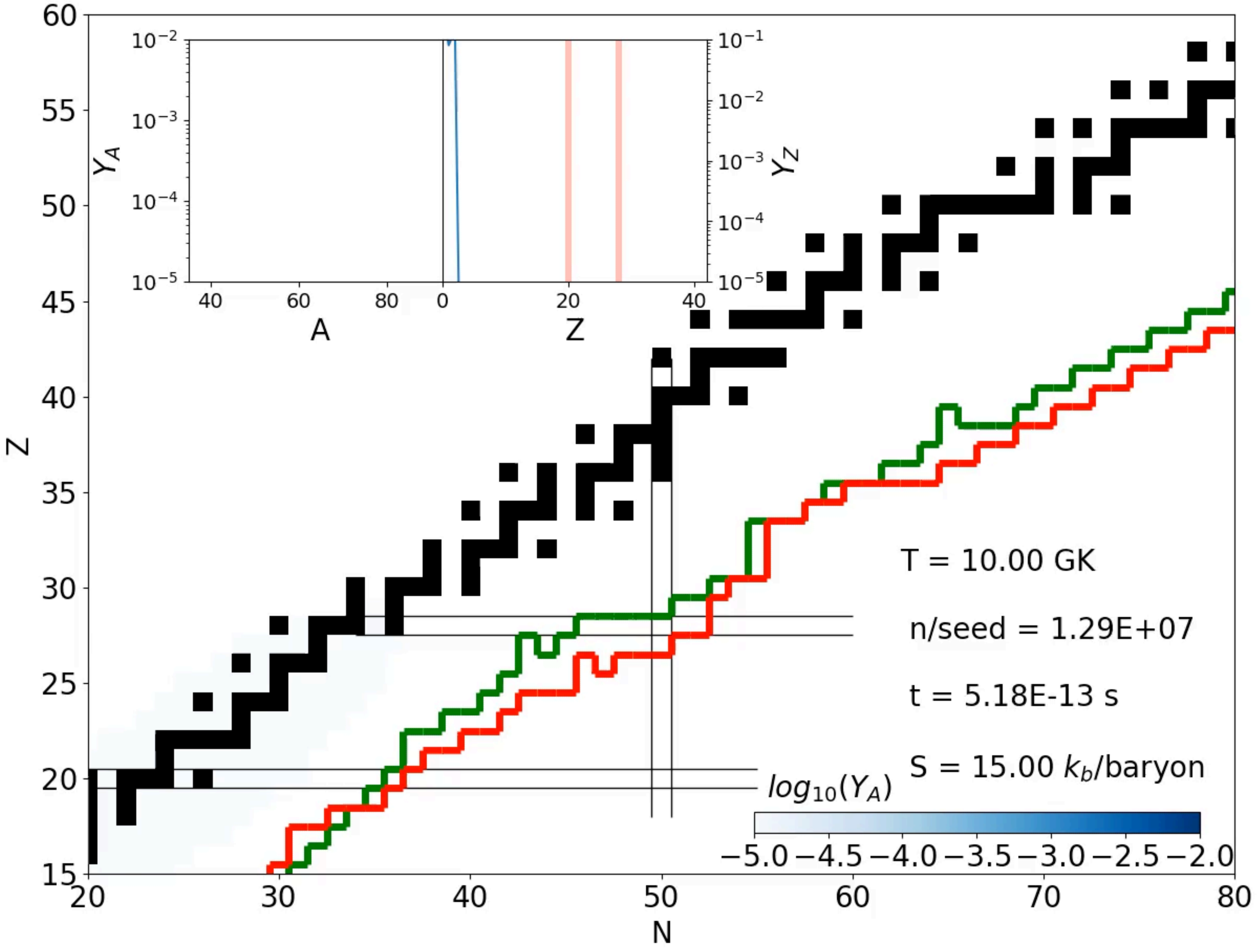
Nikas (2020) thesis work

Origin of the A~55 peak

Y_e=0.34



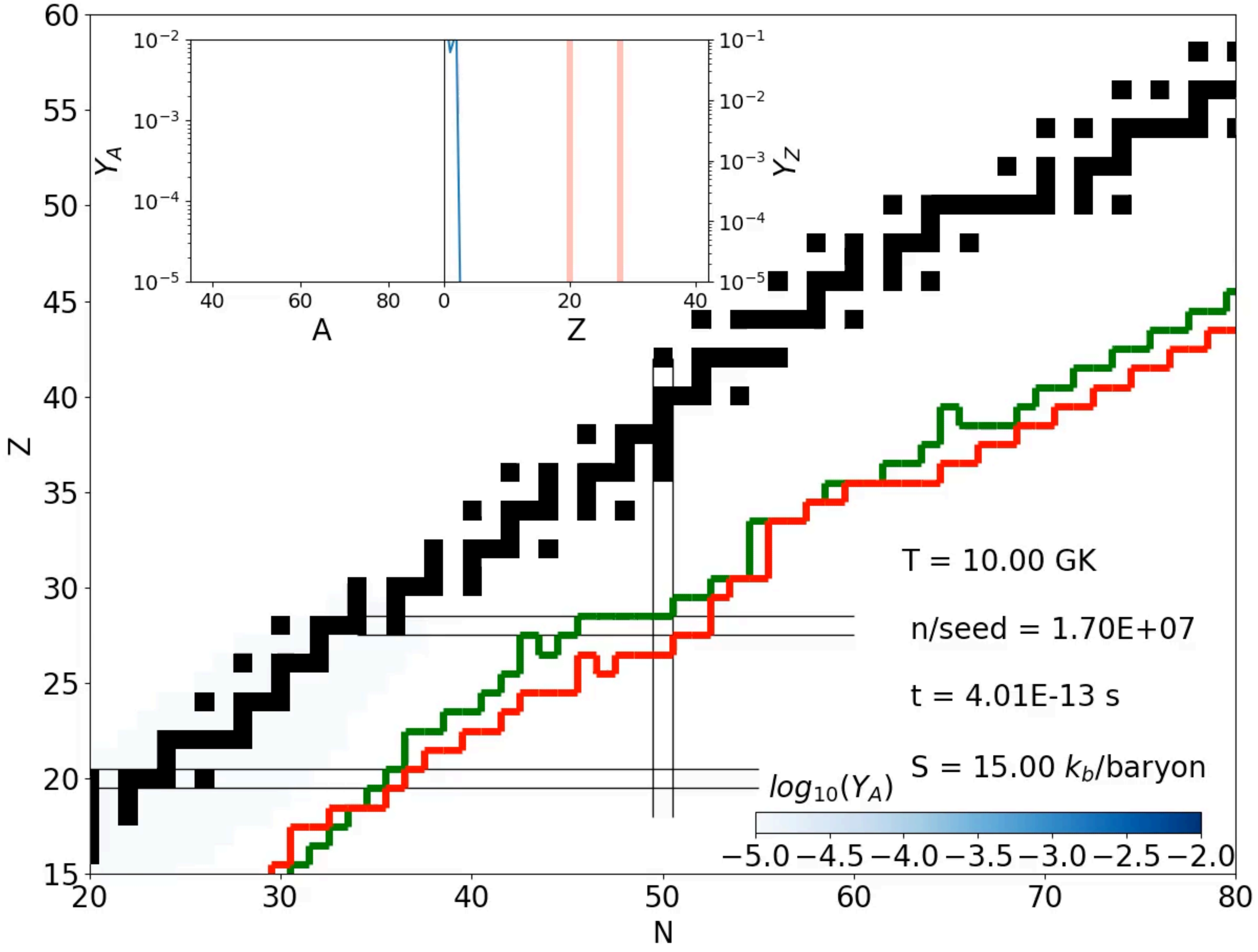
Y_e=0.38



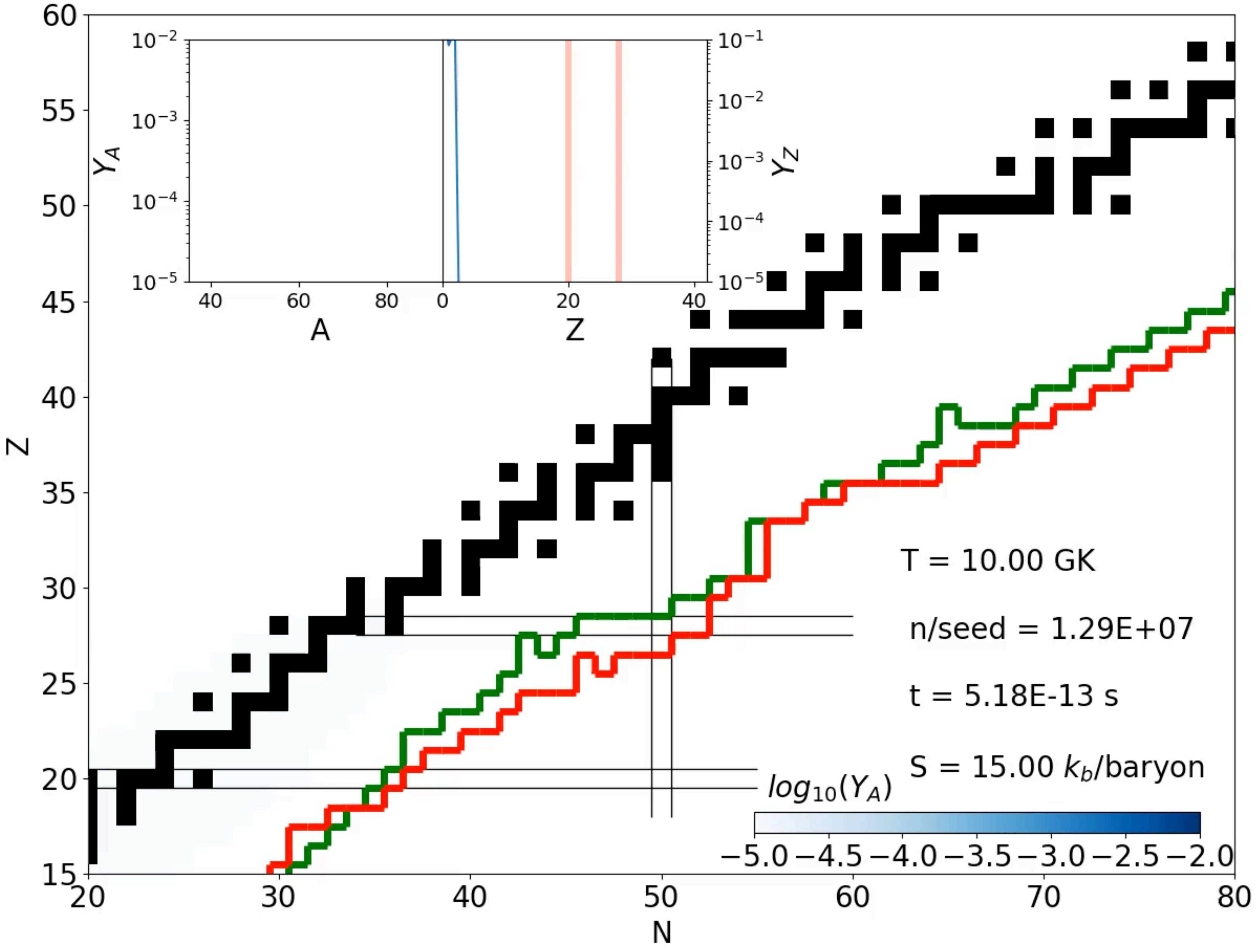
Nikas (2020) thesis work

Origin of the A~55 peak

Y_e=0.34



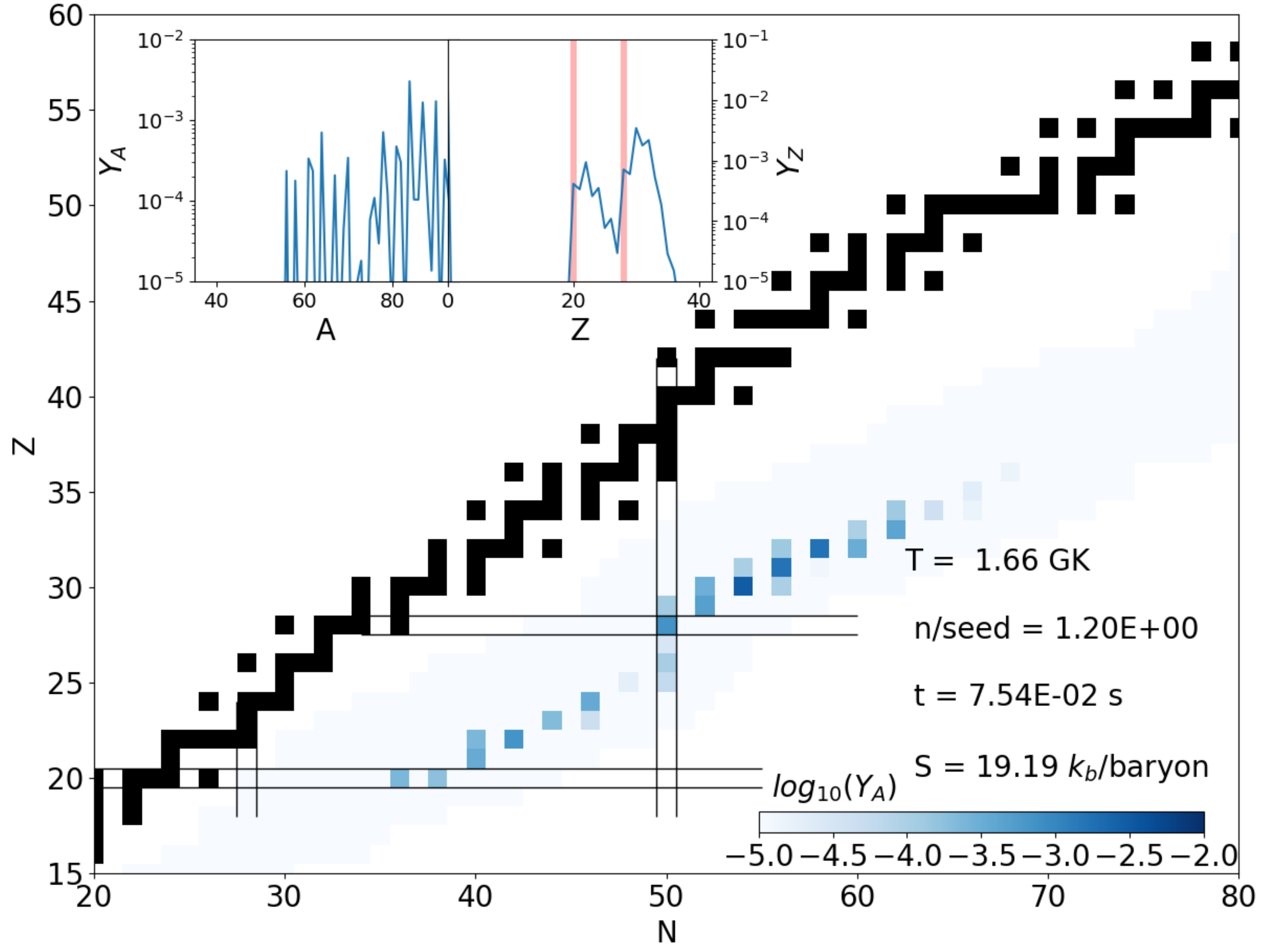
Y_e=0.38



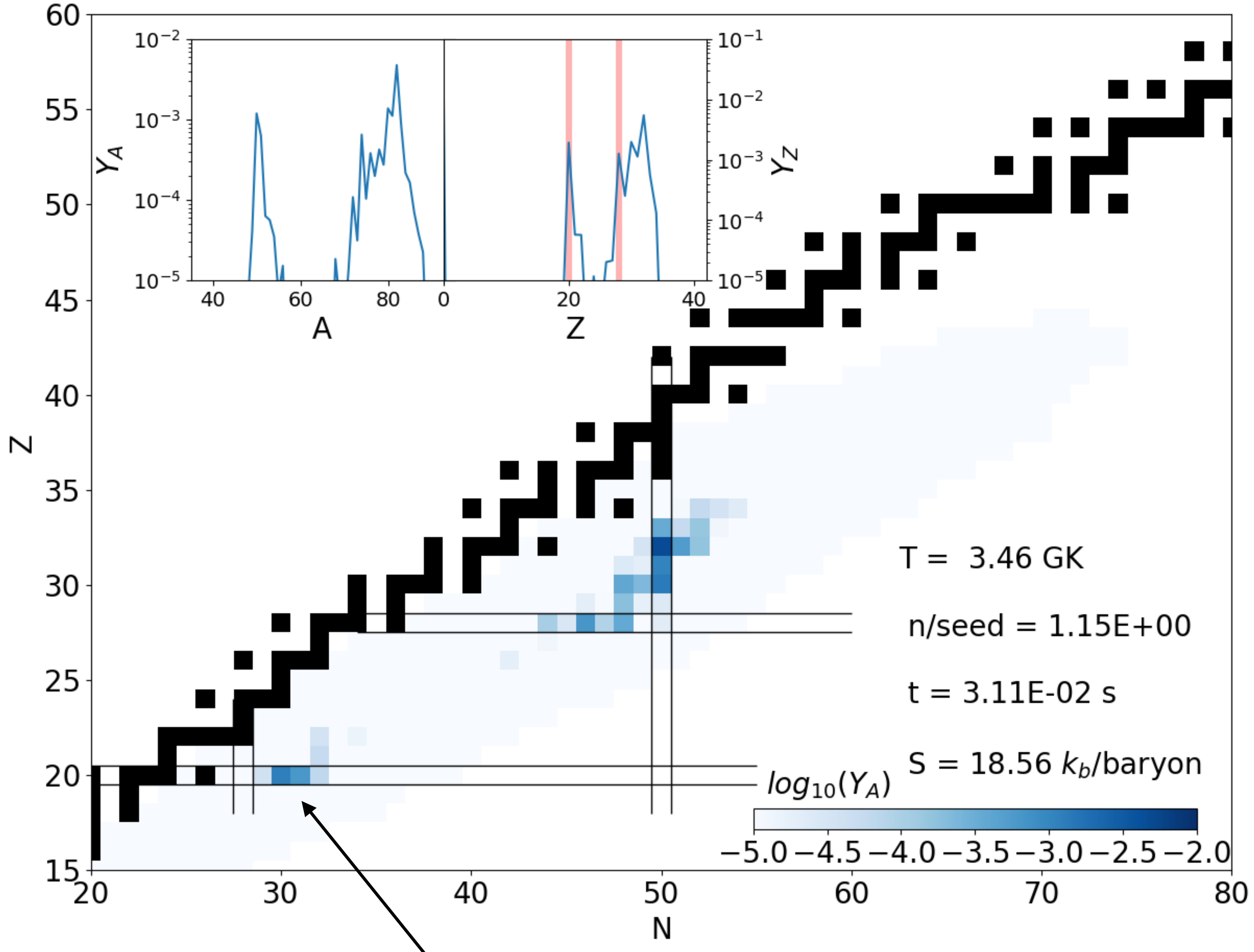
Nikas (2020) thesis work

Origin of the A~55 peak

Y_e=0.34



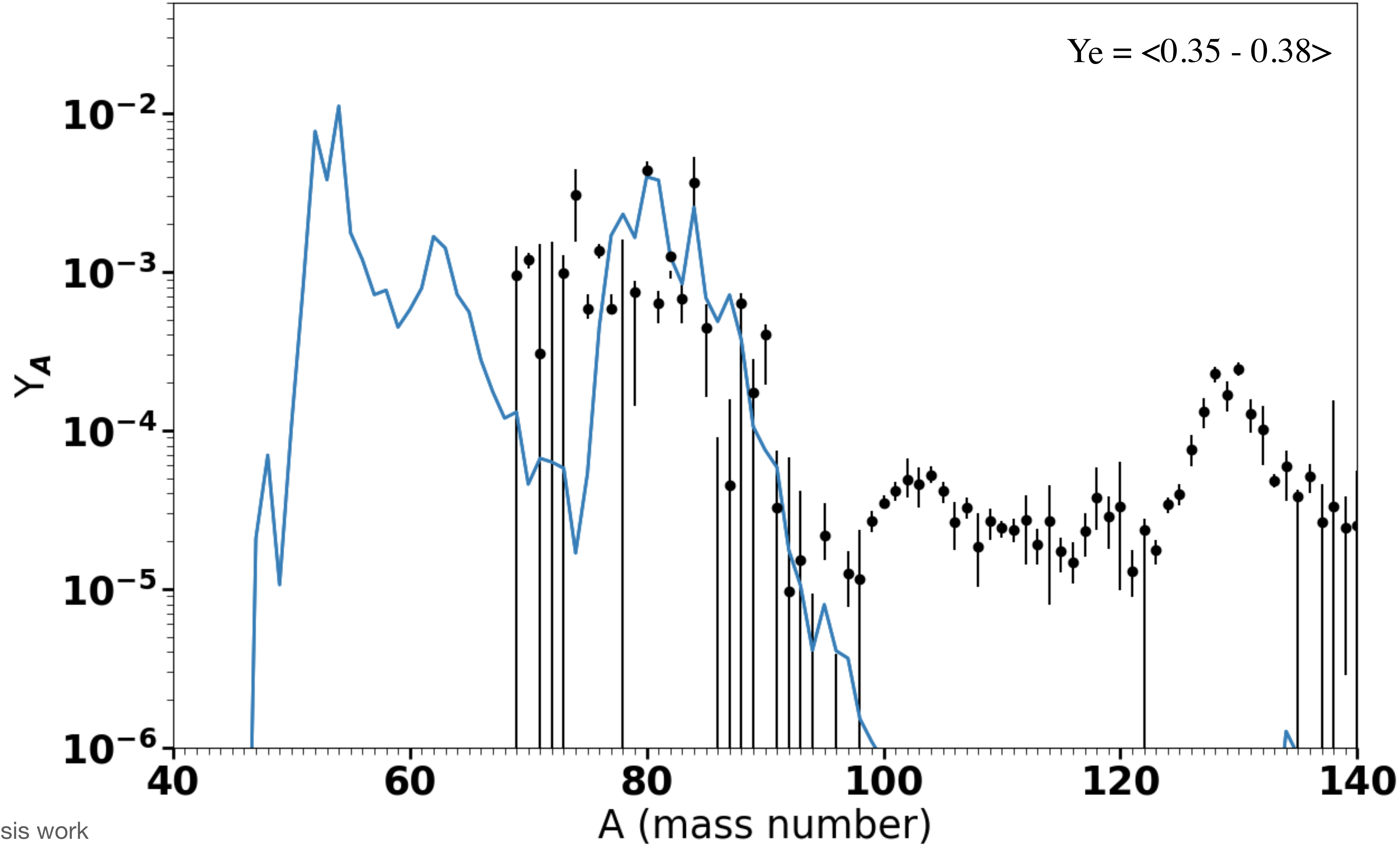
Y_e=0.38



^{52}Ca sub-shell closure

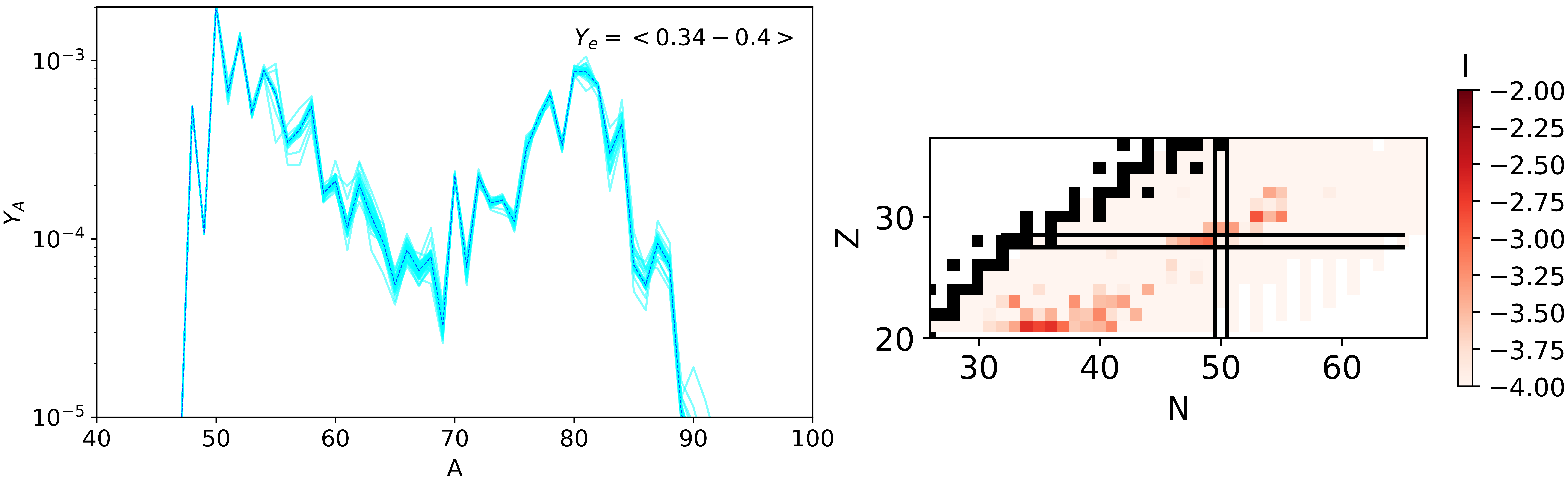
Nikas (2020) thesis work

Abundances for a uniform Y_e distribution



Nikas (2020) thesis work

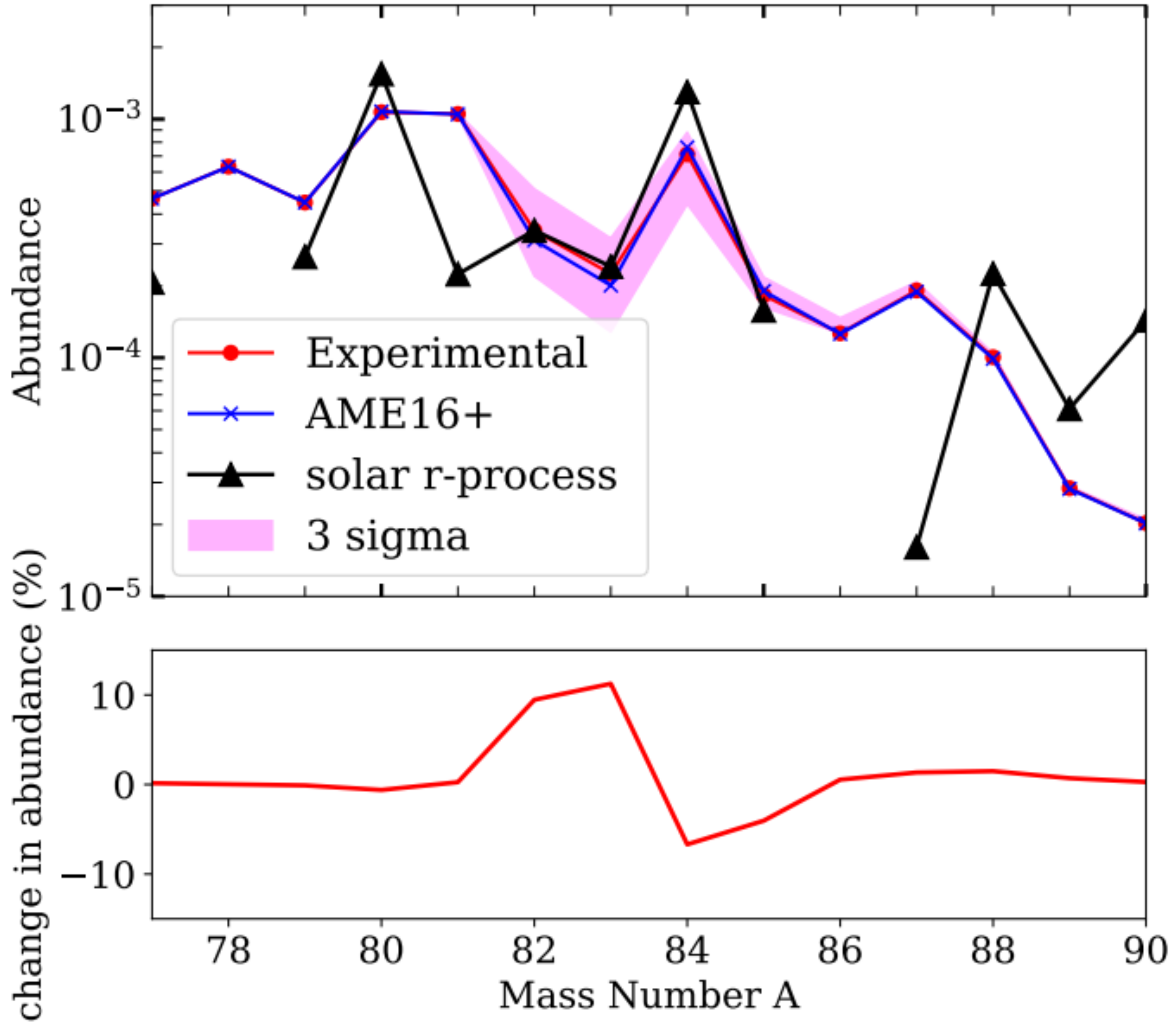
Sensitivity to nuclear masses

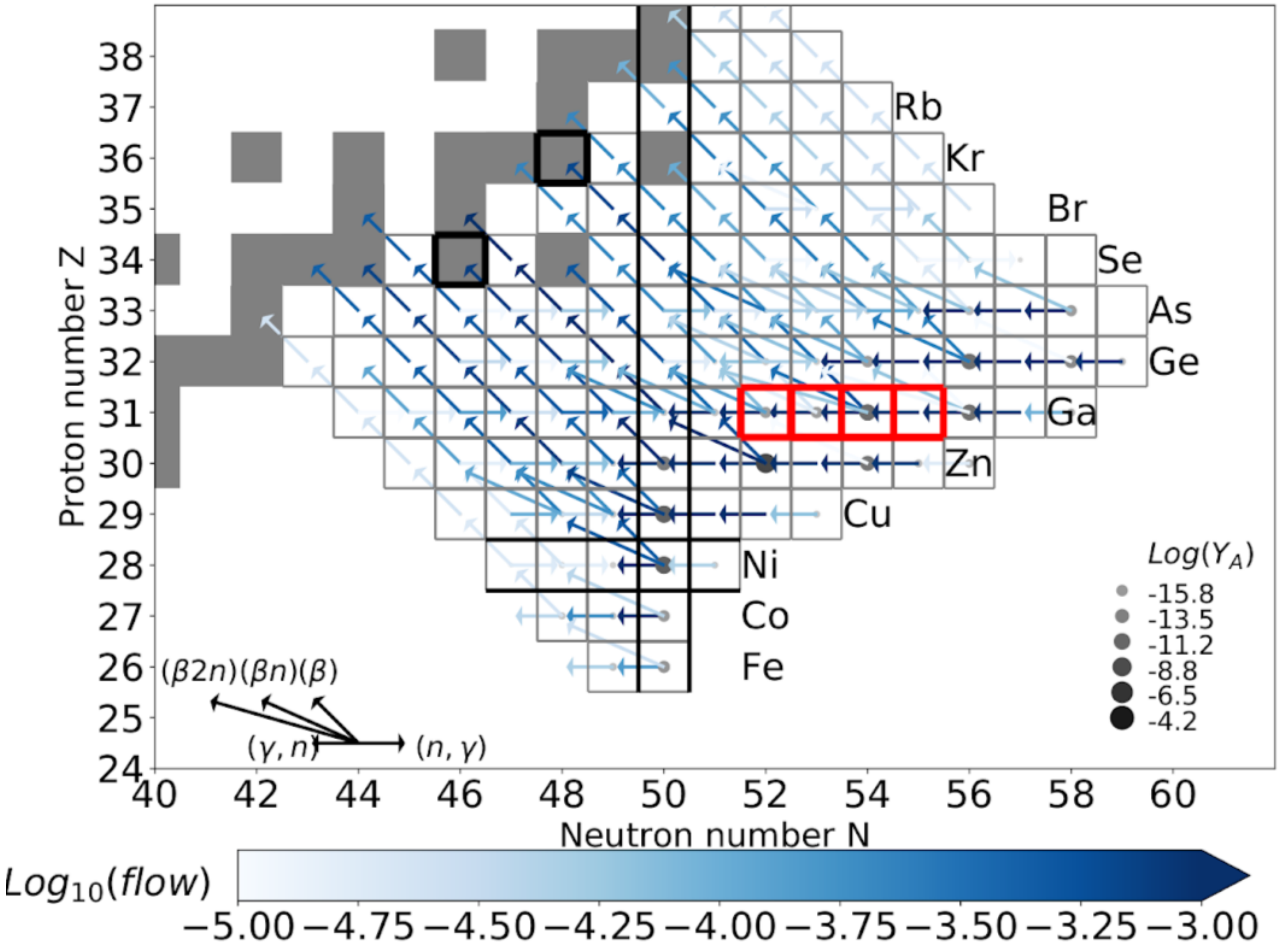


Nikas (2020) thesis work

The case of Ga

Species	$t_{1/2}$	Mass Excess $_{\text{Titan}}$ (keV)	Mass Excess $_{\text{AME16+}}$ (keV)	Difference (keV)
^{84}Ga	85	-44,094 (25)	-44,090 (200)#	4 (202)
^{85}Ga	92	-39,744 (32)	-39,850 (300)#	-106 (302)



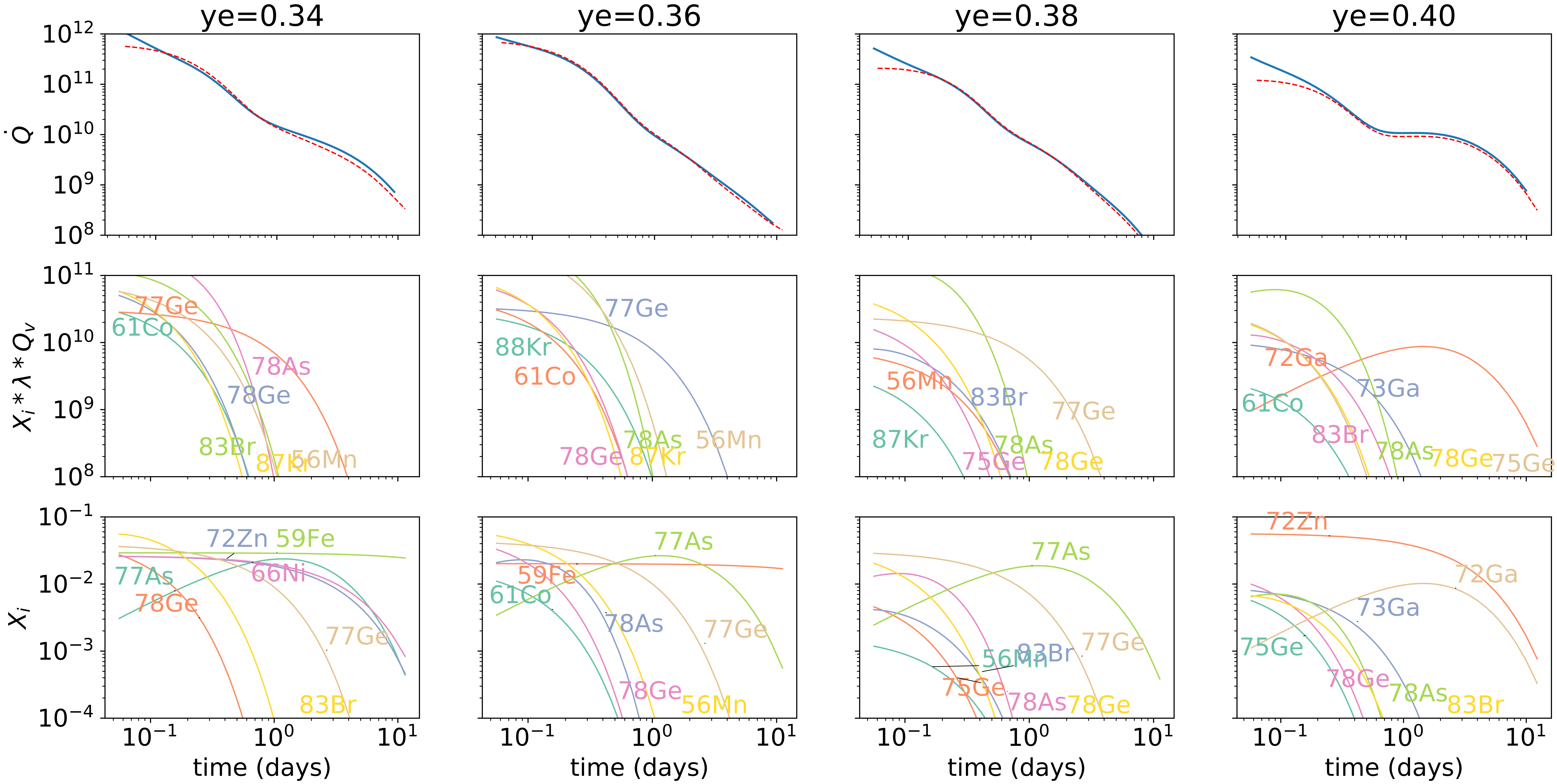


Nikas ***et al.*** (2019) · Reiter ***et al.*** (2020)

Heating - connection to the kilonova

Initial (first 10 days) heating depends only on:

^{78}As, ^{61}Co, ^{75,77,78}Ge, ^{88,87}Kr, ^{56}Mn, ^{72,73}Ga, and ^{83}Br



Nikas (2020) thesis work

Summary

The recent observation of blue kilonova established the creation of light r-process elements in the aftermath of neutron star mergers

We explored a set of astrophysical conditions realized in binary neutron star mergers and determined that it is possible to creates parts of the first r-process peak in such a scenario

We presented a sensitivity study for the most important masses affecting the creation of the abundance pattern under such conditions.

We listed the nuclei responsible for the heating production powering the kilonova

Acknowledgments

I would like to thank my collaborators G. Martínez Pinedo, K. Langanke, A. Sieverding, MP. Reiter, M. Ru Wu, and all the GSI Theory group.

Finally I would like to acknowledge support from:

SFB 1245