The creation of the first r-process peak elements in the aftermath of neutron star merger

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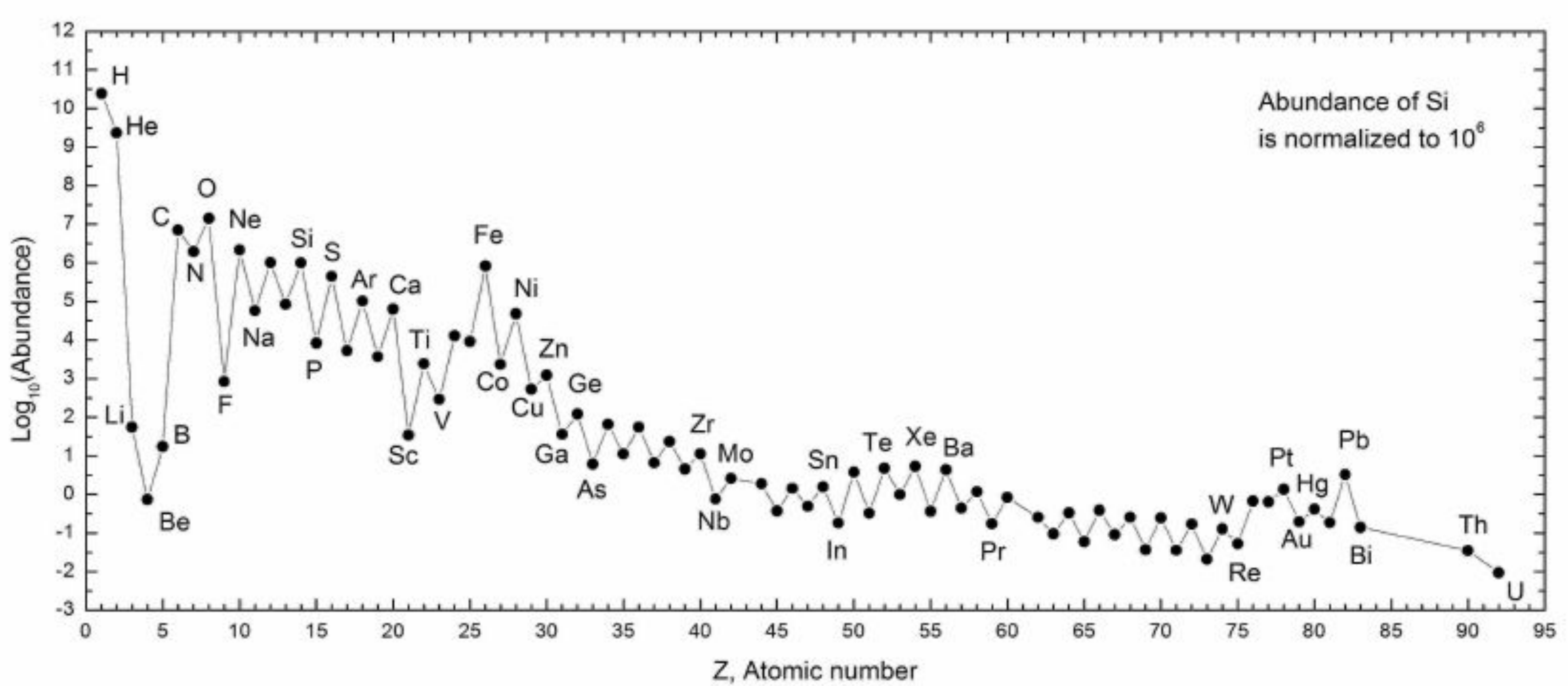
Outline

- Introduction
- Nuclear physics and the r-process
- Site(s) of the r-process
- Astrophysical conditions for the creation of the first r-process peak
- Sensitivity study on the first r-process peak
- Overview

Introduction

- Most of H and He are created shortly after the Big Bang
- Other elements up to Fe are synthesized through nuclear fusion or the interaction with cosmic rays



GSI

Introduction

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Window at Wixhausen protestant church

- Binding energy per nucleus is maximum at the region of iron-56
- High temperatures make inverse reactions comparable
- Coulomb barrier is increasing with Z making direct fusion more difficult

We need neutron capture processes to synthesize heavier elements

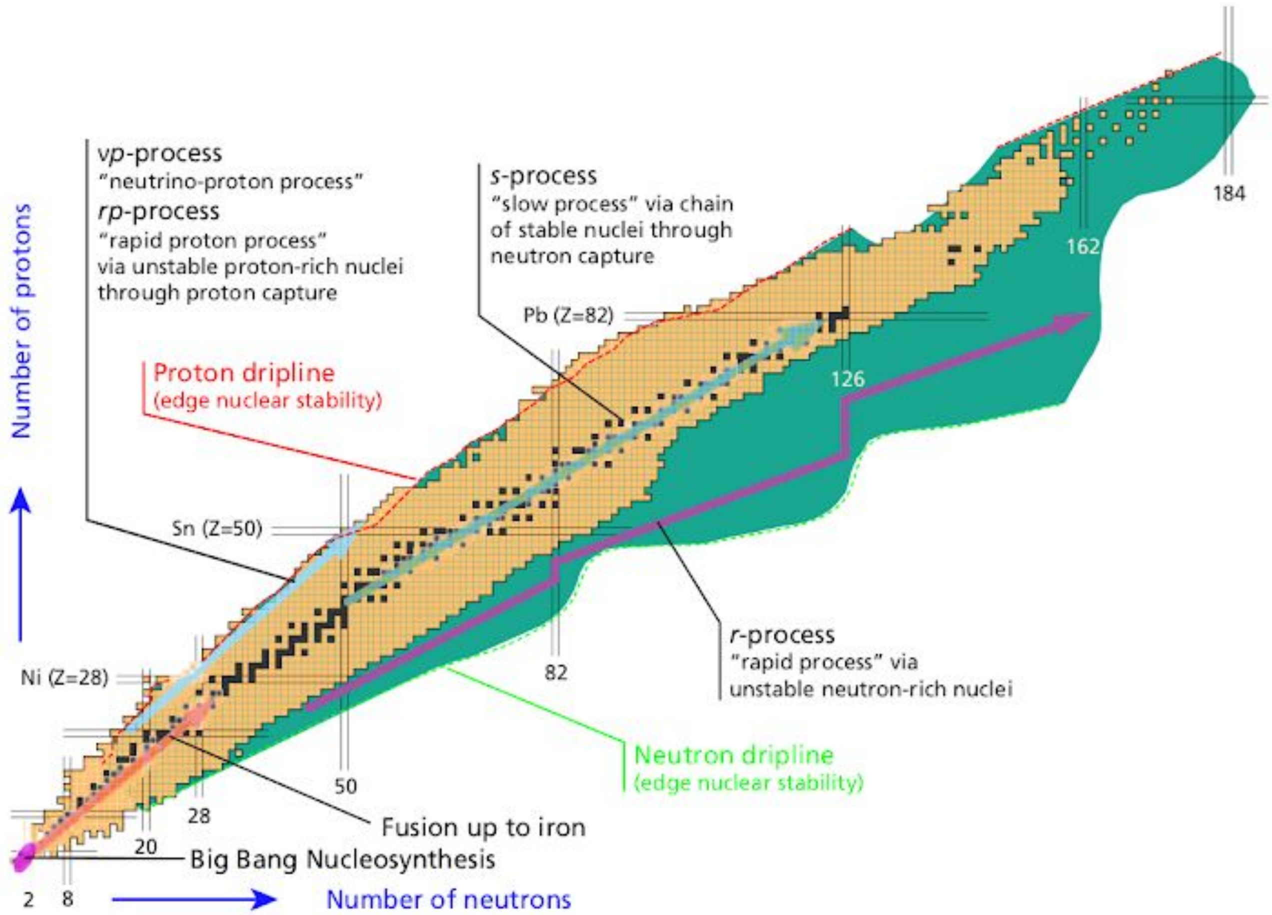
Introduction

There are two main neutron capture processes identified first at 1957 by Burbidge et al. and Cameron et al.

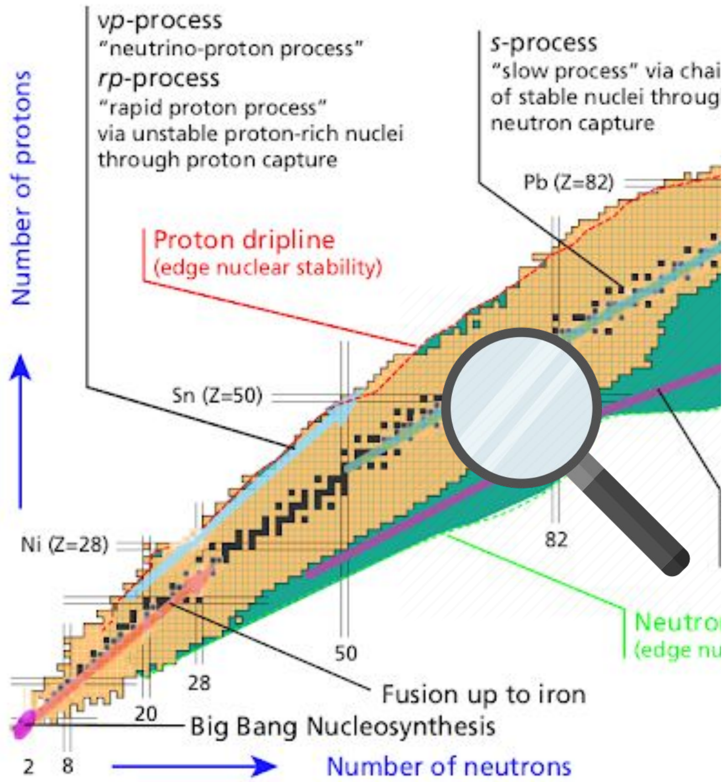
These processes where the slow (s) and rapid (r).

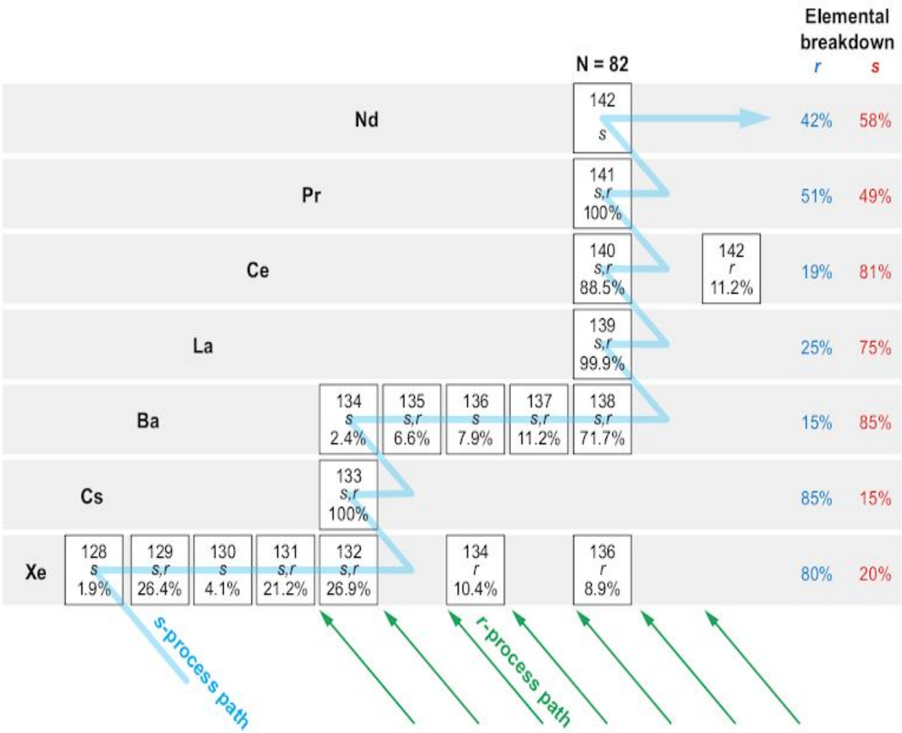
- The s-process operates in a time scale much longer than the mean time for β-decay(τ_β), i.e., $\tau_n >> \tau_\beta$.
- The r-process operates much faster such as $\tau_n << \tau_\beta$.

Introduction



Introduction





from Sneden, Cowan, and Gallino, Annu. Rev. Astrophys. **46**, 241 (2008)

Introduction

- The s-process is relatively well understood because:
  - Nuclear properties involved in s-process are easier to measure
  - The site is better constraint

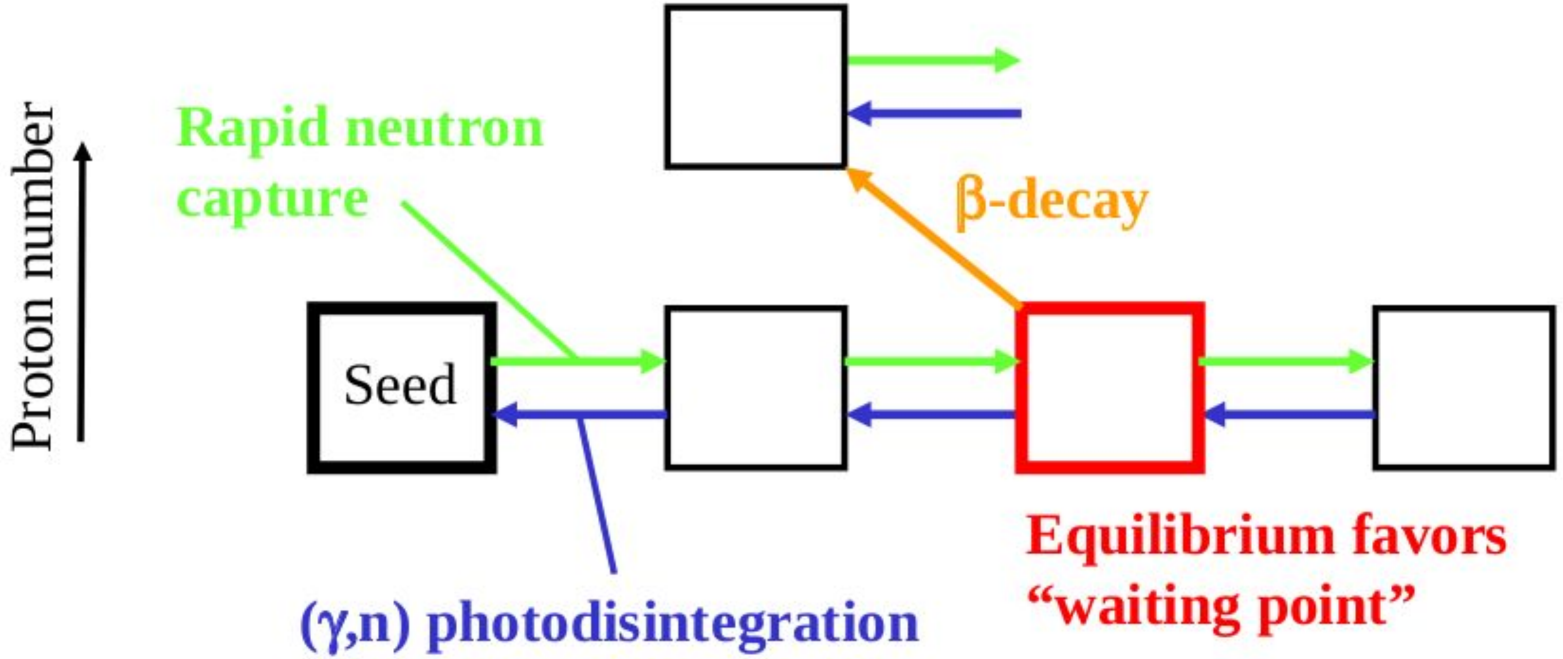
- The r-process suffer from uncertainties because:
  - Nuclear properties are difficult to measure
  - The site of r-process is still under investigation

Nuclear physics and the r-process

Since in the r-process $\tau_n << \tau_\beta$ an element will start capturing neutrons until (n, γ) $\rightleftharpoons$ (γ, n).

The equilibrium favors waiting points.

The equilibrium point depends on the neutron density and the temperature, while the abundance of the isotopes depend and the path of the r-process S_n



Nuclear physics and the r-process

To calculate the reaction rates we use the Hauser Feshbach statistical model.

- It depends in highly statistical quantities like level densities and gamma strength functions
- It is applicable only if a large amount of resonances in the region are available.

Cross section for reaction from channel a to channel b

Optical Potential

Level Densities

Gamma Strength Function

Mass Model

$$\sigma^{\mu}_{n,\gamma}(E) \propto \sum_{J^\pi}(2J+1)\frac{T^{\mu}_{n}(J^\pi)T_\gamma(J^\pi)}{T_{tot}(J^\pi)}$$

Summation over all possible states

Sum over all channels Transmission coefficients

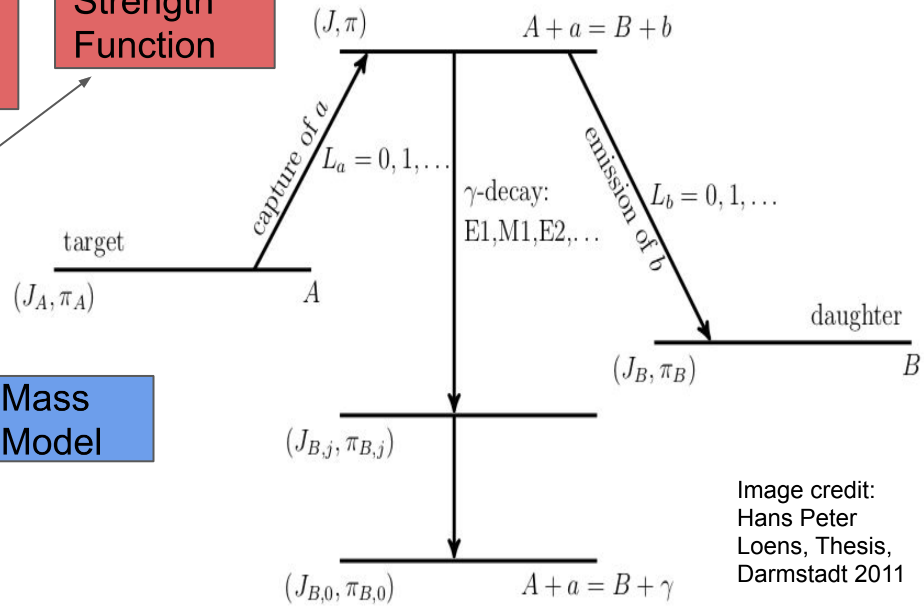


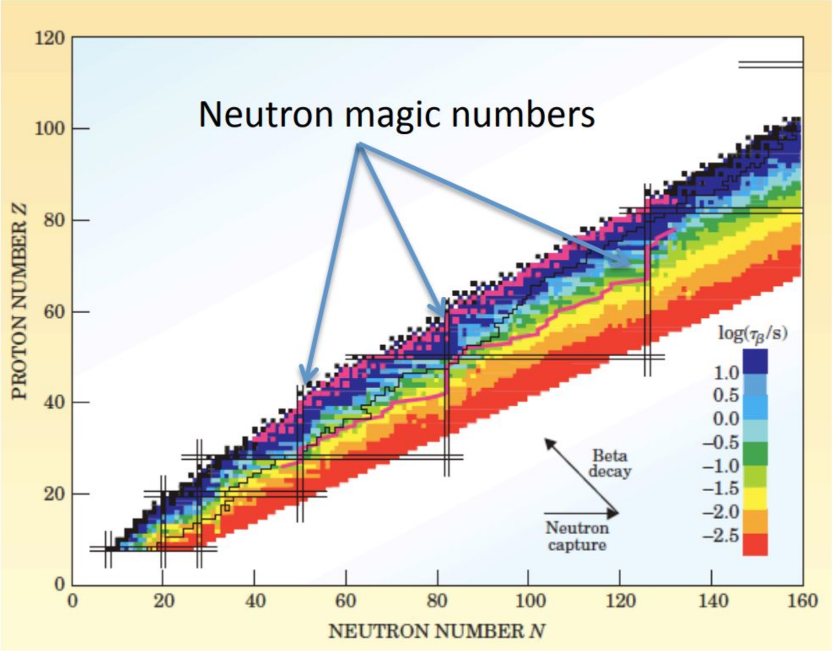
Image credit: Hans Peter Loens, Thesis, Darmstadt 2011

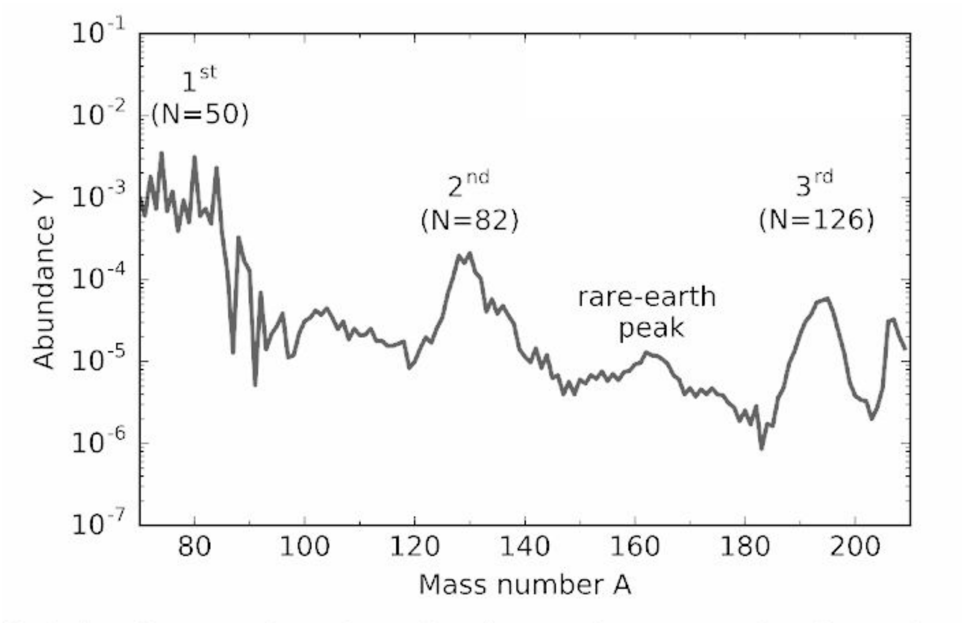
Nuclear physics and the r-process

Matter accumulates close to closed neutron shell, because:

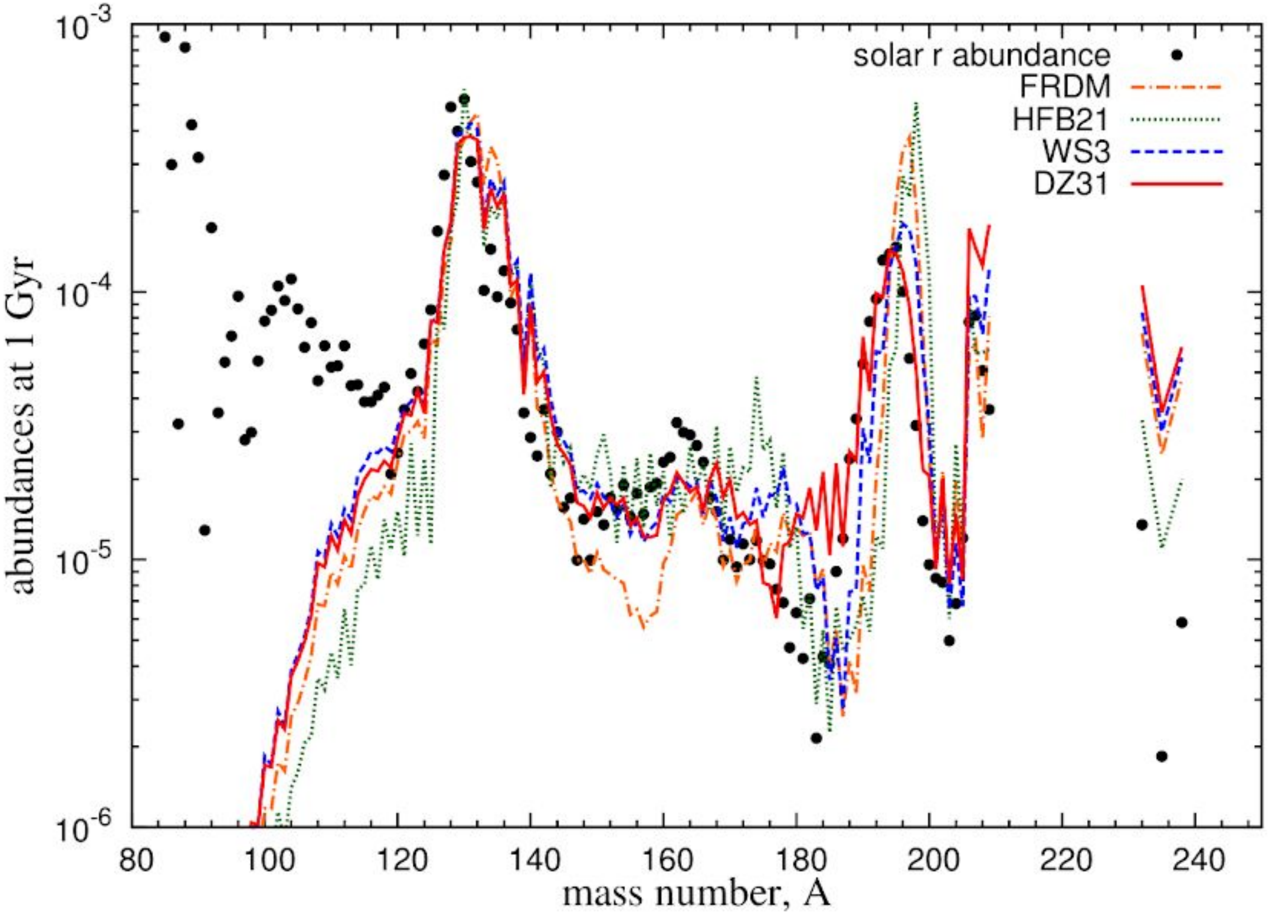
1. Neutron capture cross-sections are lower at magic shells.
2. *beta*-decay half lives are larger at magic shells

These close neutron shells at N=50,82,126 correspond to the abundance peaks at A≅82, 136, 190





Nuclear physics and the r-process



Nuclear physics and the r-process

At early times (days), the decay of radioactive elements produced during the r-process is going to emit energy following a power law:

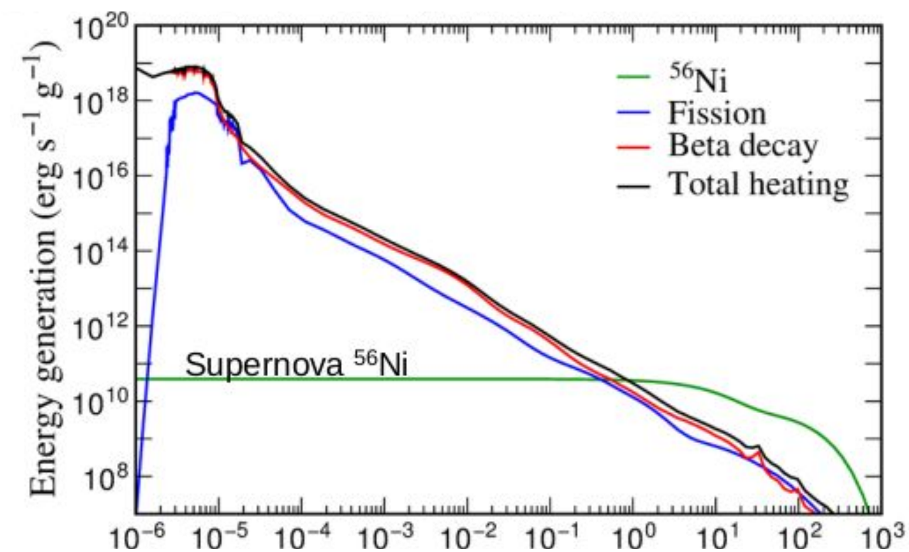
$$\dot{\varepsilon} \sim t^{-1.3}$$ (Way & Wigner 1948, Metzger et al 2010)

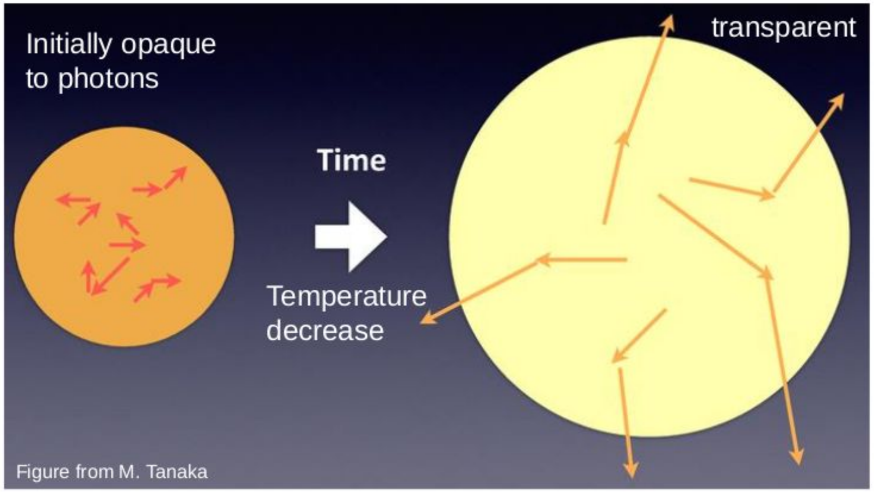
The expected electromagnetic transient depends on:

1. Energy production rate
2. Thermalization efficiency of the gas
3. Opacity of the gas

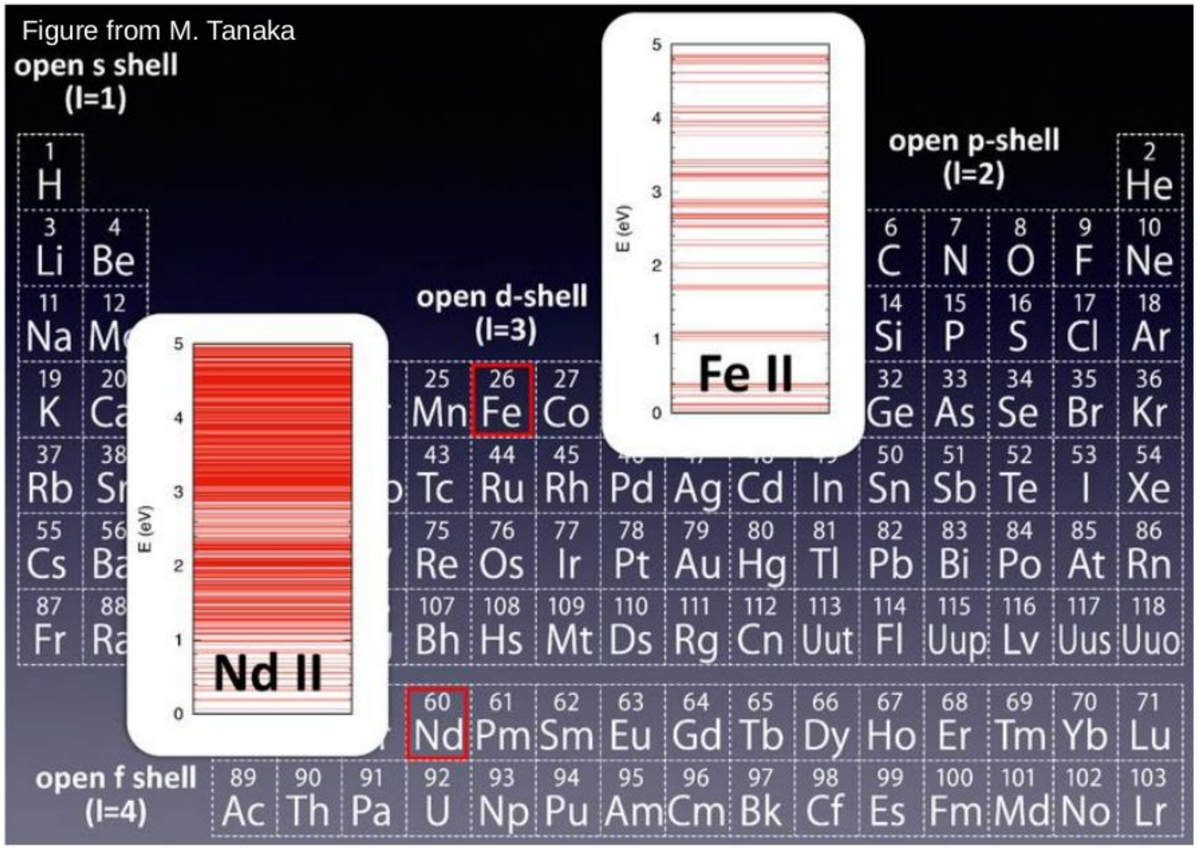
Low opacity -> hot matter, short wavelengths (blue)

High opacity -> cold mater, longer wavelengths (red)





Nuclear physics and the r-process



Large number of states of Lanthanides/Actinides leads to a high opacity

Barnes & D. Kasen, Astrophys. J. 775, 18 (2013);Tanaka & Hotokezaka, Astrophys. J. 775, 113 (2013).

Site(s) of the r-process

- r-process is a primary process

- Any r-process site must be able to produce both the “seed” nuclei where neutrons are captured and the neutrons that drive the r-process. The main parameter describing the feasibility of a site to produce r-process nuclei is the neutron-to-seed ratio: n_n/n_{seed}.

- If the seed nuclei have mass number A and we have n_n/n_{seed} neutrons per seed, the final mass number of the nuclei produced will be $A = A_{seed} + n_n/n_{seed}$.

Site(s) of the r-process

Core collapse Supernova?
Neutron star merger?
Or both?

Core-Collapse Supernova

Neutron star merger

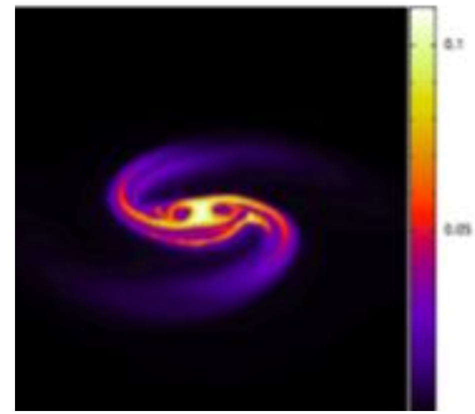
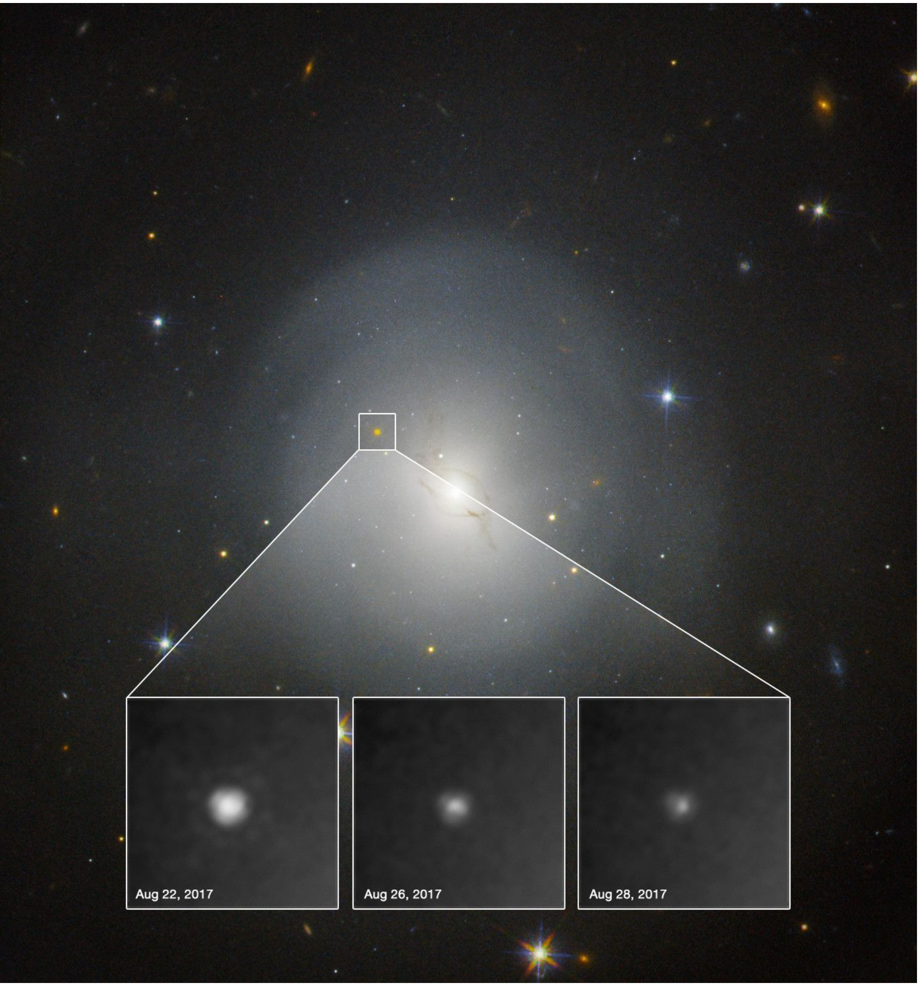


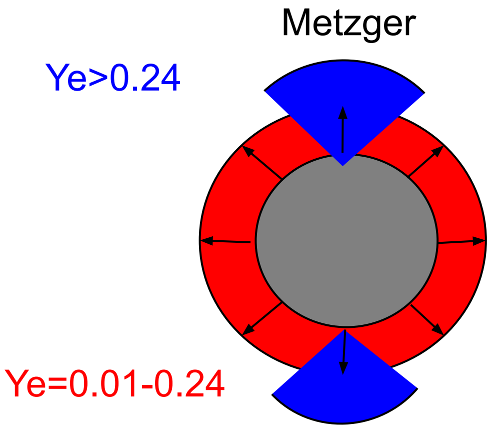
Image credits:NASA-Stephan Rosswog

Conditions (Ye,entropy)	No	Yes
Observation	No	Yes

Final abundances fine structure are independent of the astrophysical scenarios and only depend on the nuclear physics inputs

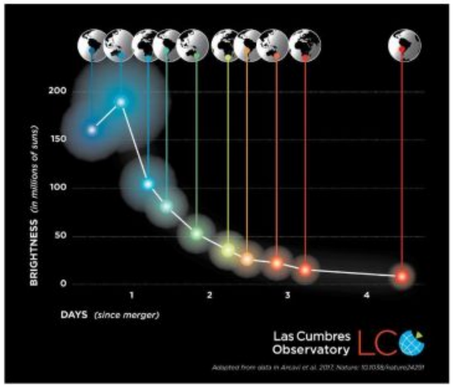
Site(s) of the r-process

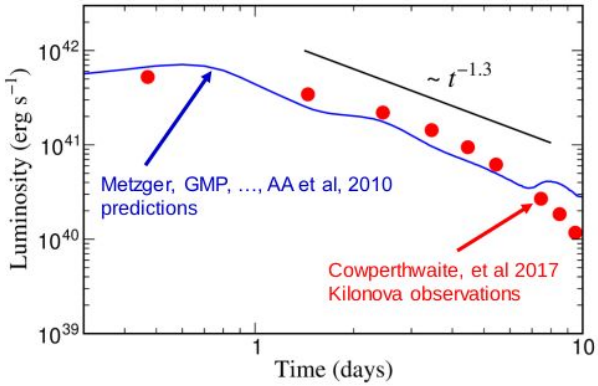


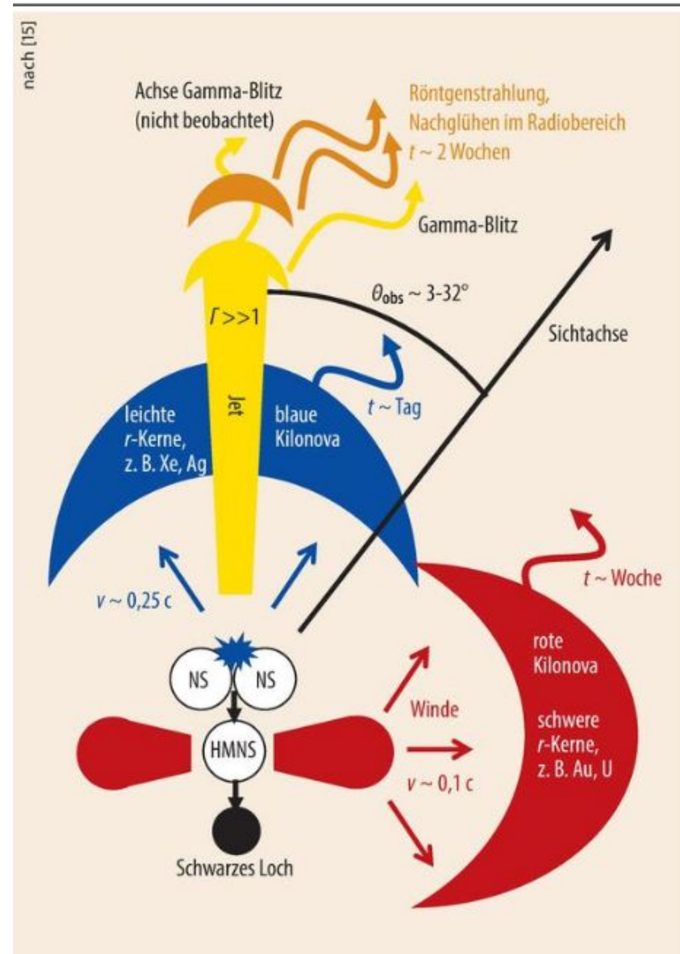


- The EM emission, from compact objects, powered by the radioactive decay of elements that were synthesized is called kilonova.
- The observation of blue light indicates lanthanide free ejecta (Y_e>0.25) in early times.
- The proportion of the lanthanides created in later times is ~10^{-2}-10^{-3} solar masses
- Sr lines in the kilonova spectra

Site(s) of the r-process







- Emission of GW
- Ejecta at polar regions subject to large neutrino fluxes production of light r-process elements
- Star collapses and neutrino emission ceases production of heavy r-process nuclei

What do we need to model the r-process?

Astrophysical conditions:

- Electron fraction Y_e
- Expansion time τ
- Entropy S

Nuclear Physics data:

- Beta decay rates
- Fission yields
- Reaction rates
  - Branching ratios
  - Nuclear masses
  - Optical potential
  - Level density
  - gSF and more…

What do we need to model the r-process?

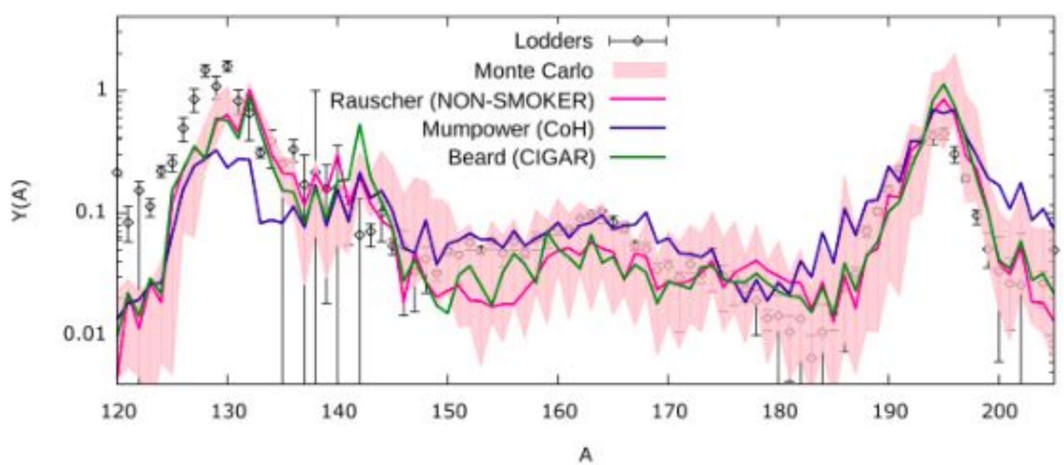
Astrophysical conditions:

- Electron fraction Y_e (Largely unconstrained due to the neutrino fluxes)
- Expansion time τ (Constraint from simulations)
- Entropy S (Simulation dependent)

Nuclear Physics data:

- Beta decay rates
- Fission yields
- Reaction rates
  - Branching ratios
  - Nuclear masses
  - Optical potential
  - Level density
  - gSF and more….

Nikas et al. (on preparation)



Astrophysical conditions for the creation of the first r-process peak

How to create the first r-process peak elements

Consistent with NSM

High temperature T with high entropy S relatively high Ye

This will lead to α-rich freeze out

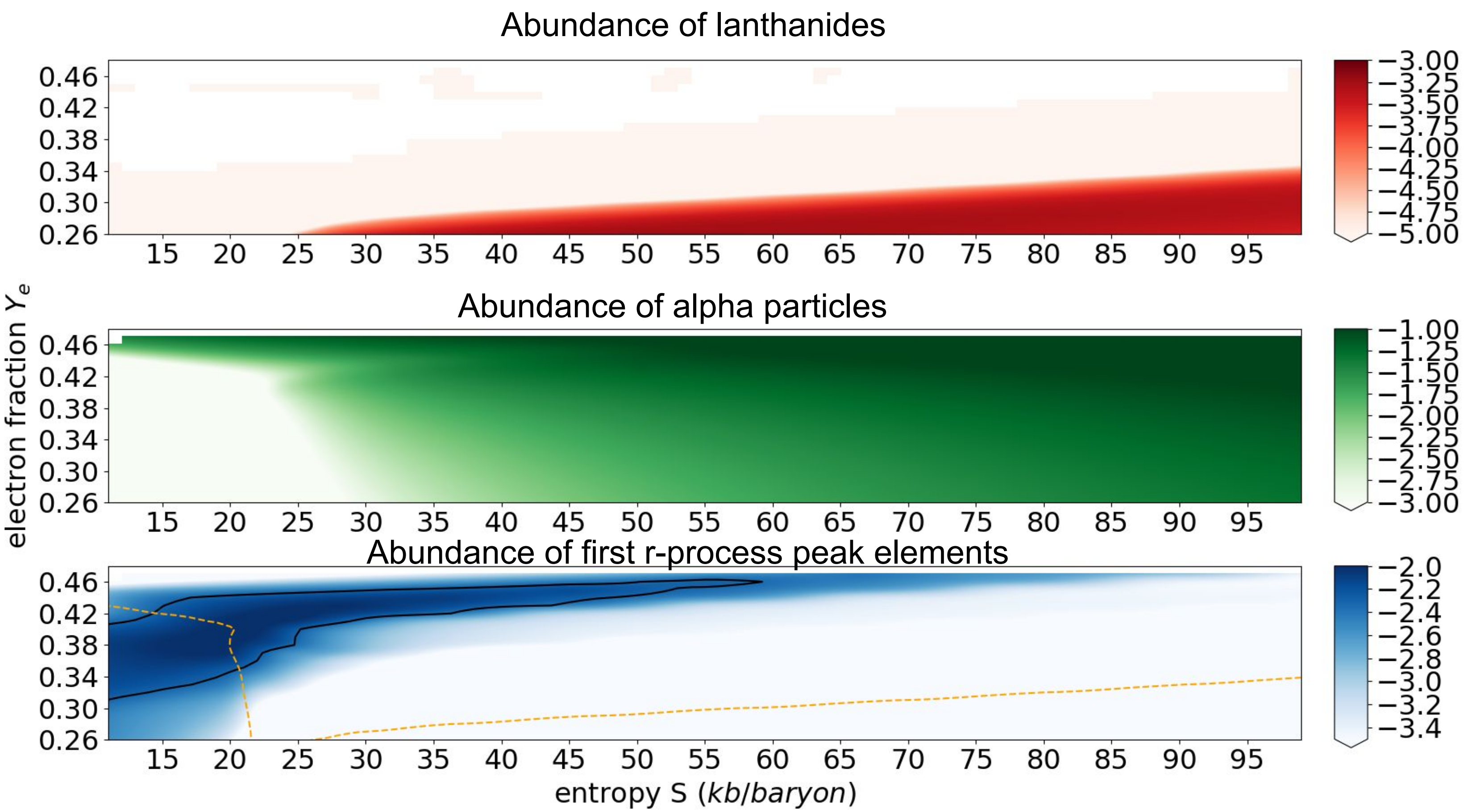
- Enhancement of “alpha-elements”
- extension of the Fe-group to higher masses (56Ni to 64Ge and for very high entropies up to A=80)

High density ρ with low entropy S and moderate Ye

This will lead to conditions where α particles at not present when r-process operates

- “Weak r-process” with strong dependence on nuclear physics

Astrophysical conditions for the creation of the first r-process peak



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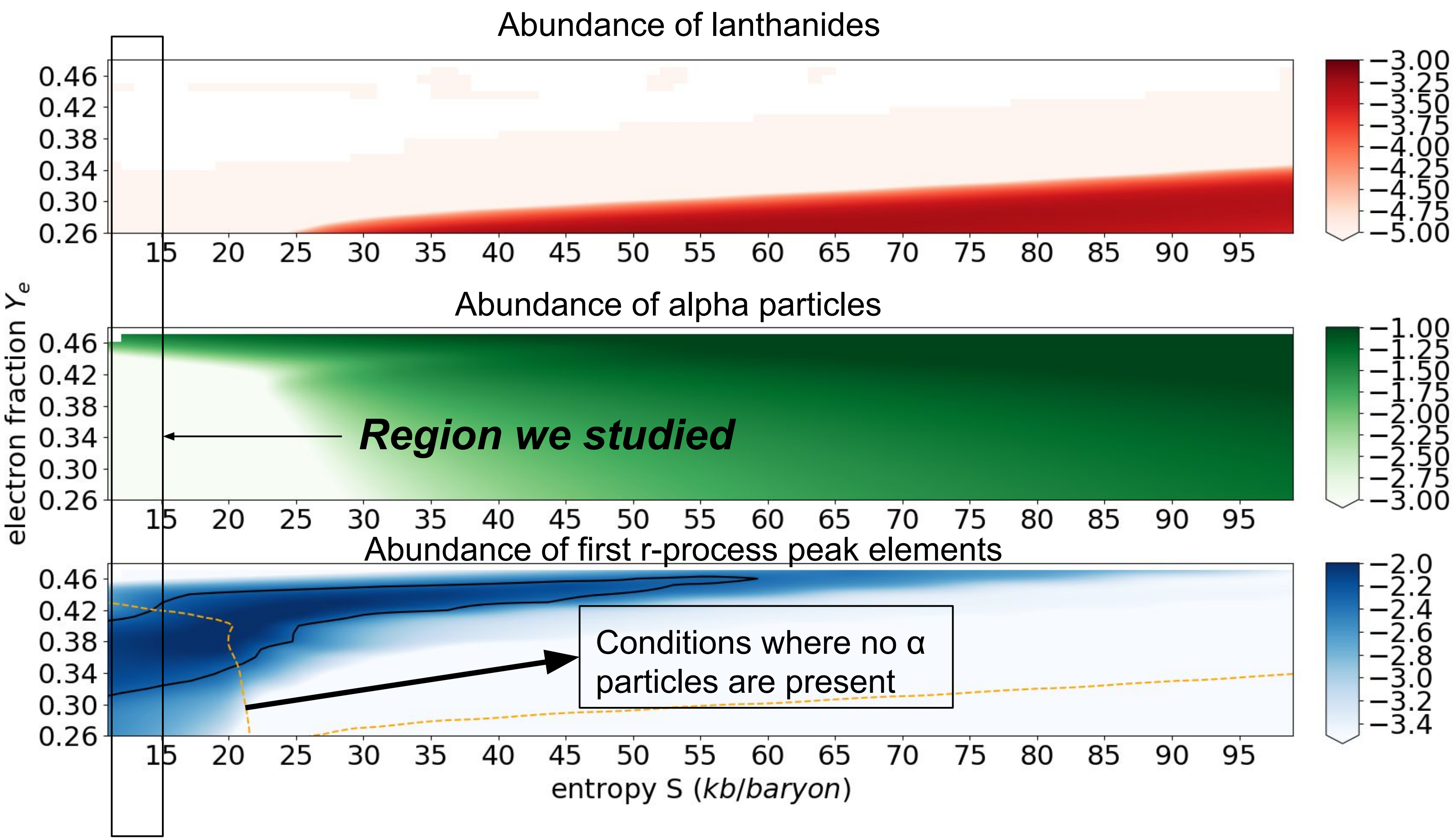
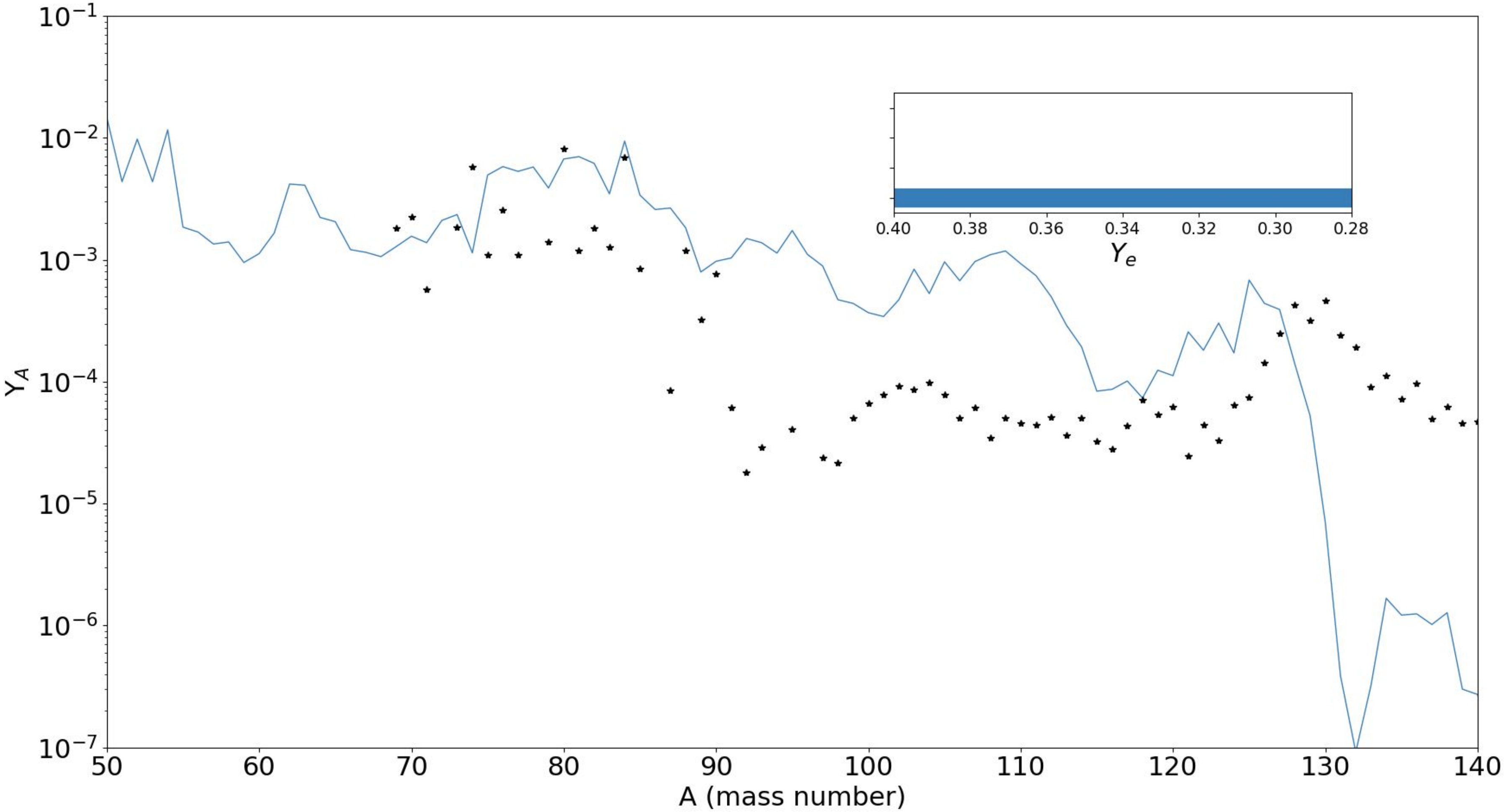


Results of the nuclear reaction network for different Y_e's



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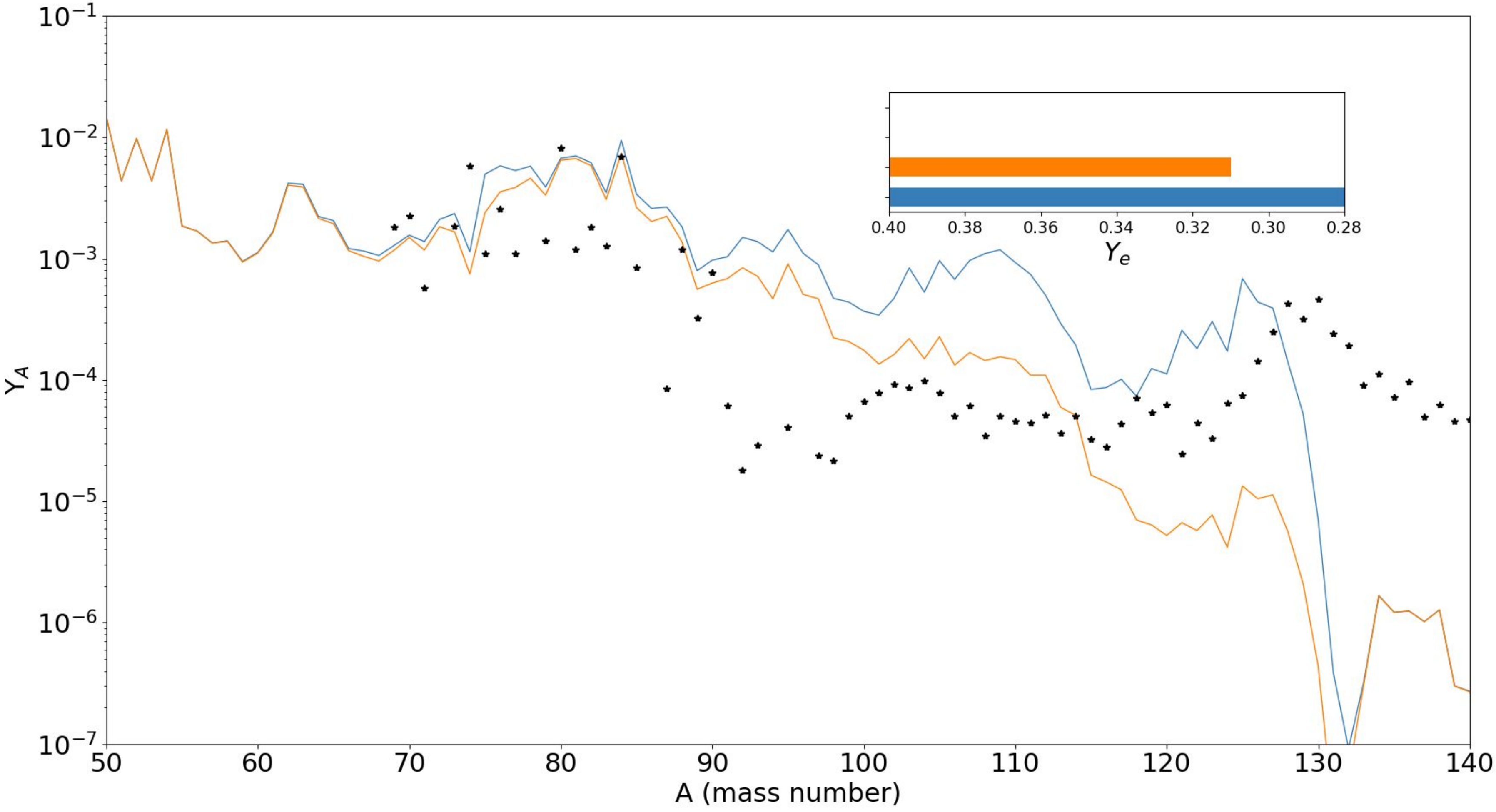

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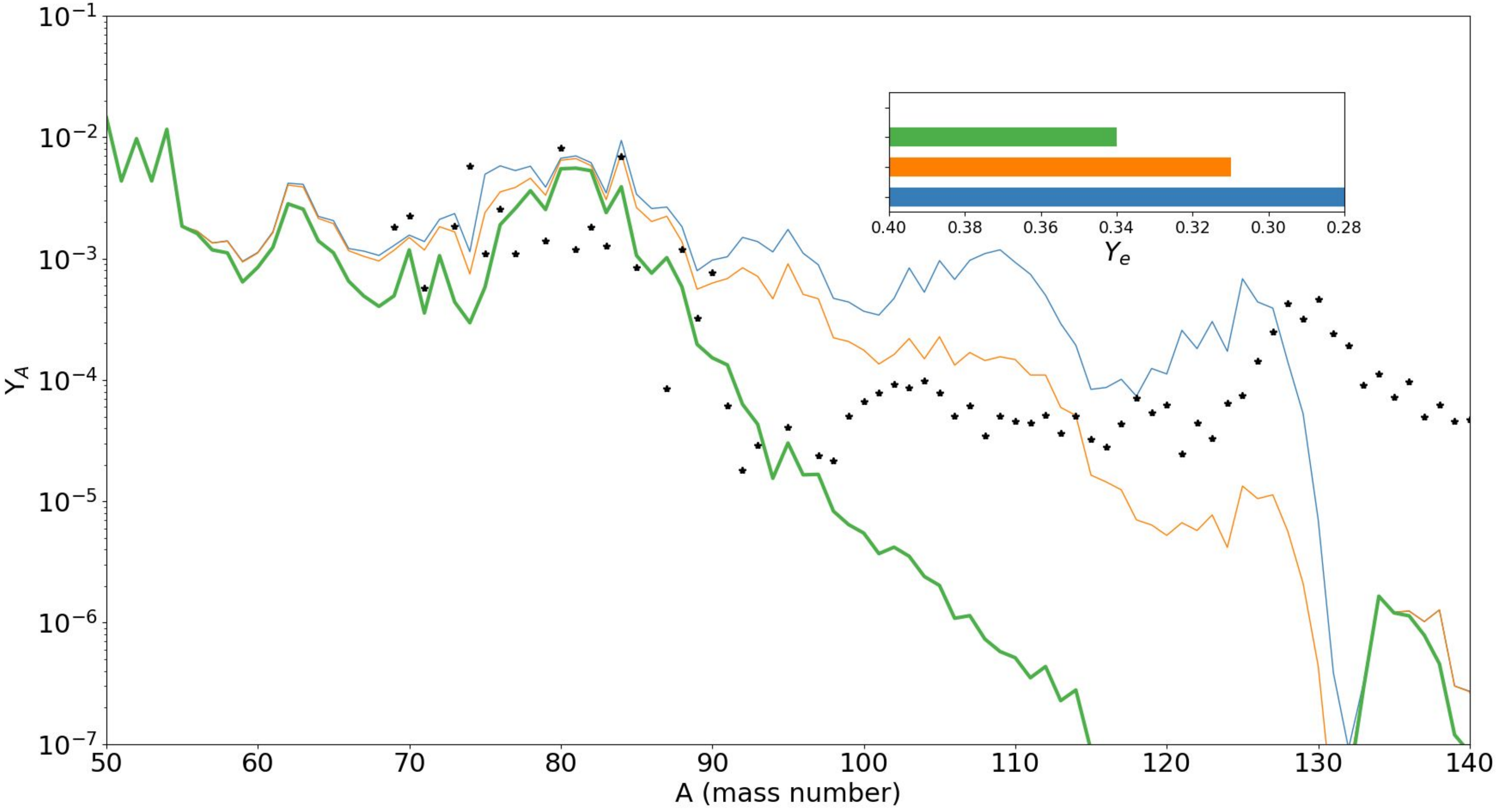

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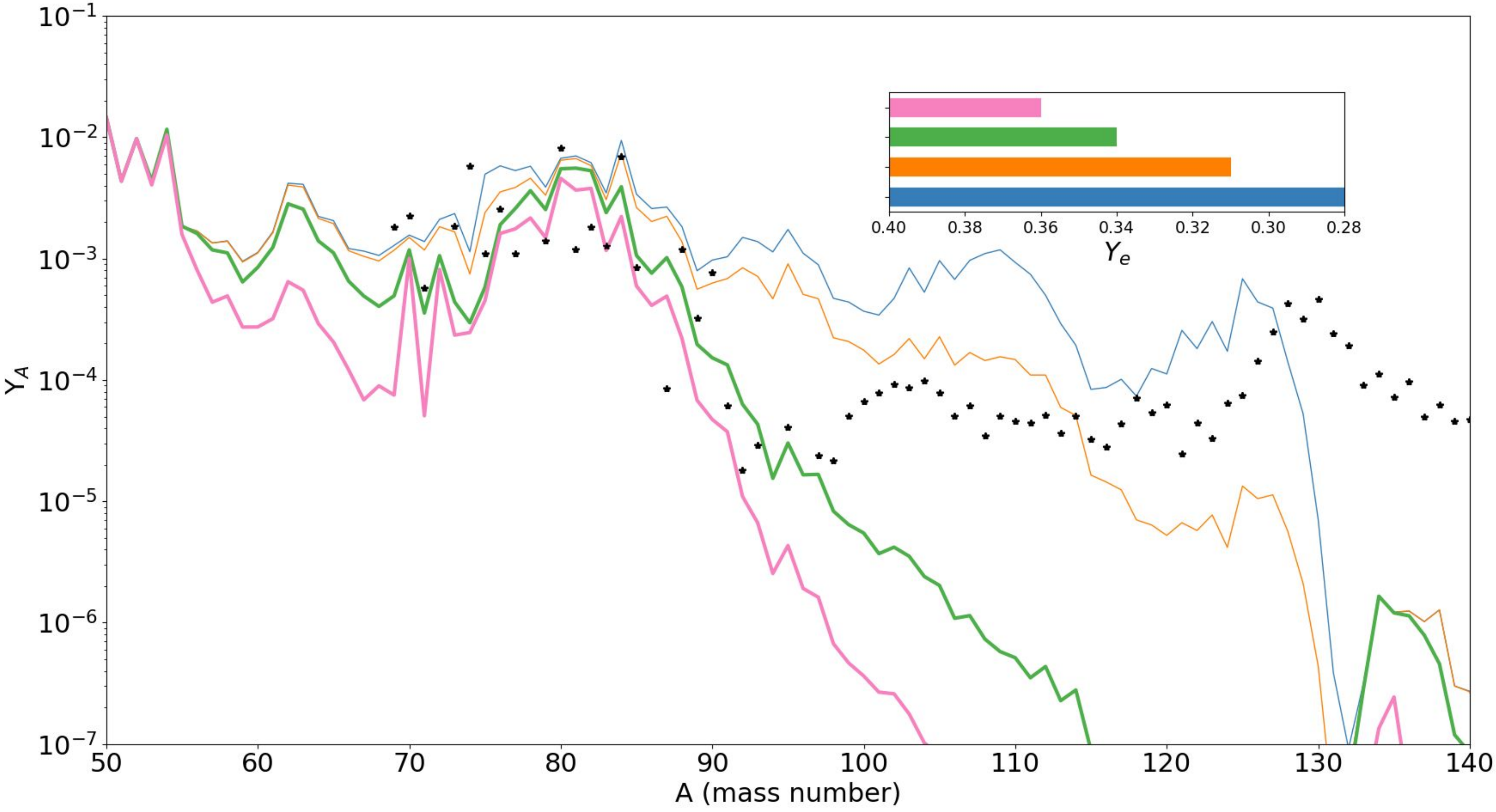

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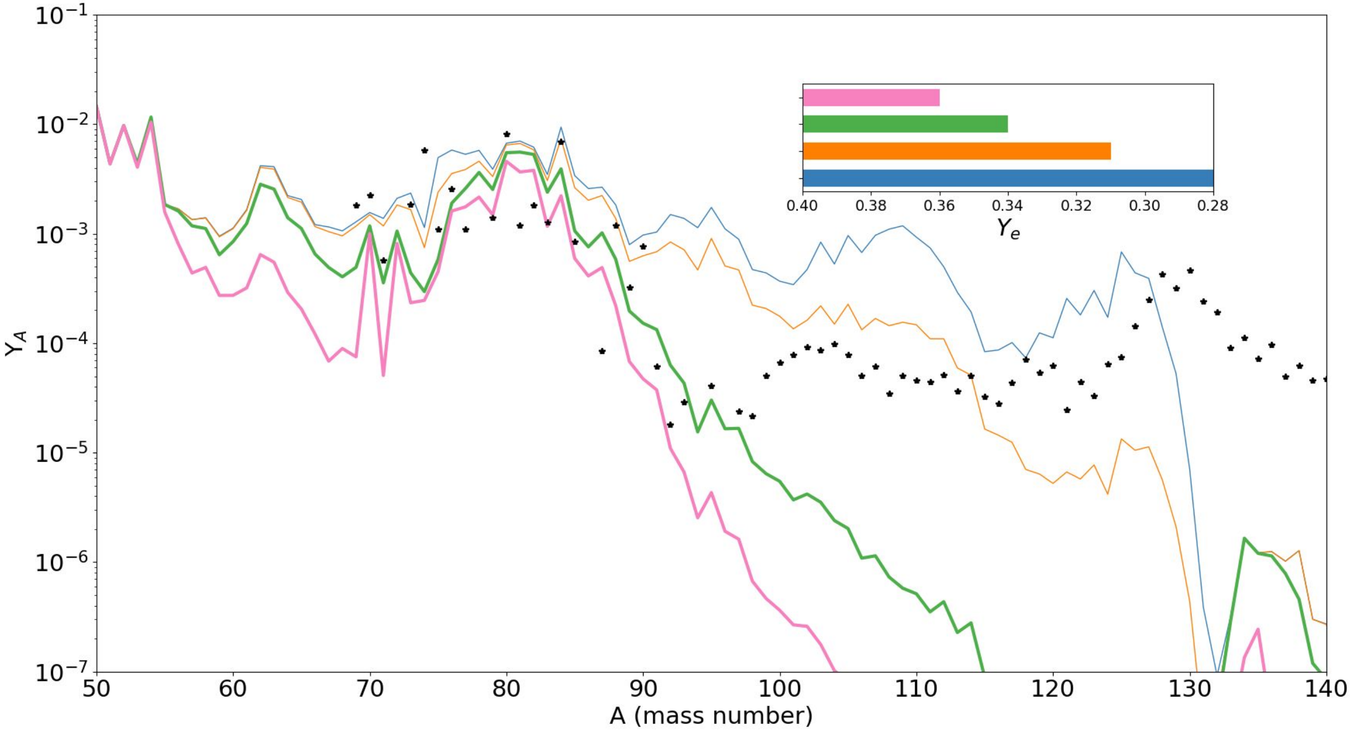
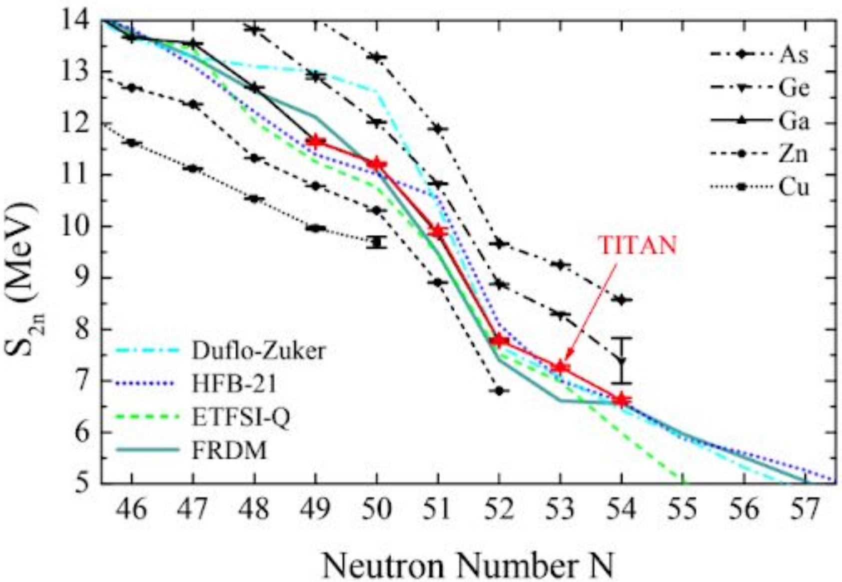


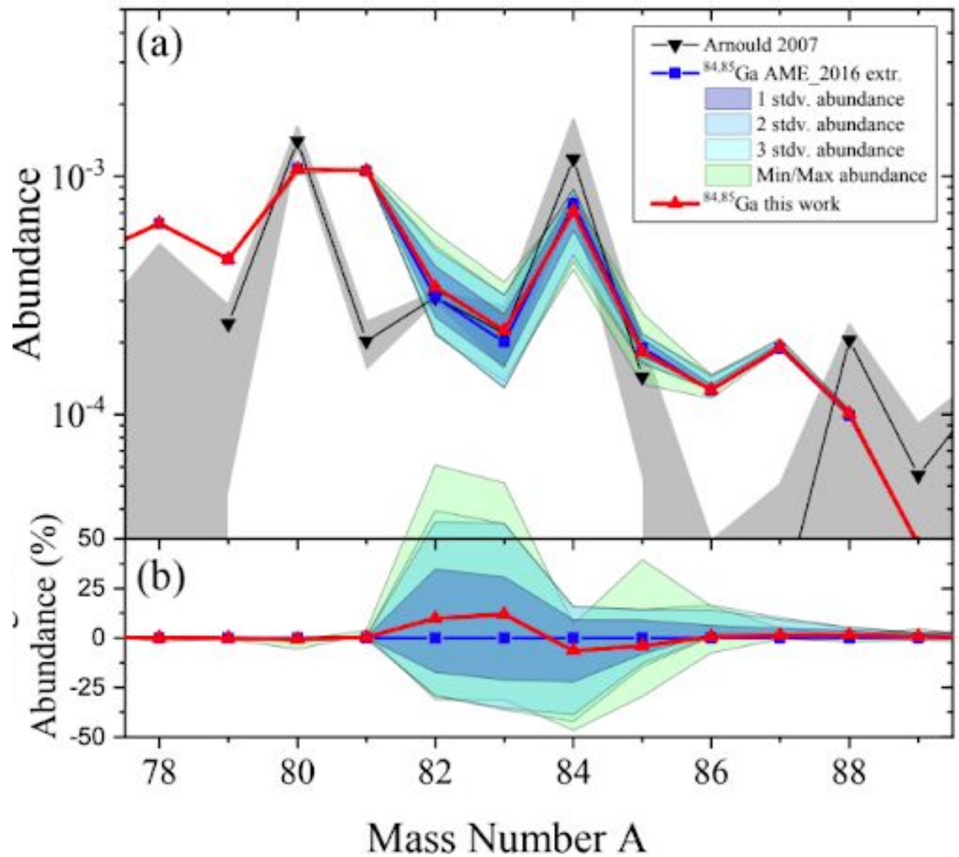
- We can recreate the first r-process peak only in a small Y_e range centered around ~0.37 assuming flat distribution accompanied by a peak at A~62 (Ni) , and a broad range of peaks at A=50-54 (Ti,Cr)

Study on Ga isotopes

Mass Measurements of Neutron-Rich Gallium Isotopes Refine Production of Nuclei of the First r-Process Abundance Peak in Neutron Star Merger Calculation

M.P. Reiter,[1,2,*] S. Ayet San Andrés,[1,3,†] J. Lippuner,[4,5,6] S. Nikas,[3,7] C. Andreoiu,[8] C. Babcock,[2] Barquest,[2] J. Bollig,[2,9] T. Brunner,[2,10] T. Dickel,[1,3] J. Dilling,[2,11] I. Dillmann,[2,12] E. Dunling,[2,1] G. Gwinner,[14] L. Graham,[2] C. Hornung,[1] R. Klawitter,[2,15] B. Kootte,[2,14] A.A. Kwiatkowski,[2,1] Y. Lan,[2,11] D. Lascar,[2,16] K.G. Leach,[17] E. Leistenschneider,[2,11] G. Martínez-Pinedo,[3,7] J.E. McKay,[2,12] S.F. Paul,[2,9] W.R. Plaß,[1,3] L. Roberts,[18] H. Schatz,[6,18,19] C. Scheidenberger,[1,3] A. Sieverding,[3,7,20] R. Steinbrügge,[2,‡] R. Thompson,[21] M.E. Wieser,[21] C. Will,[1] and D. Welch[18]

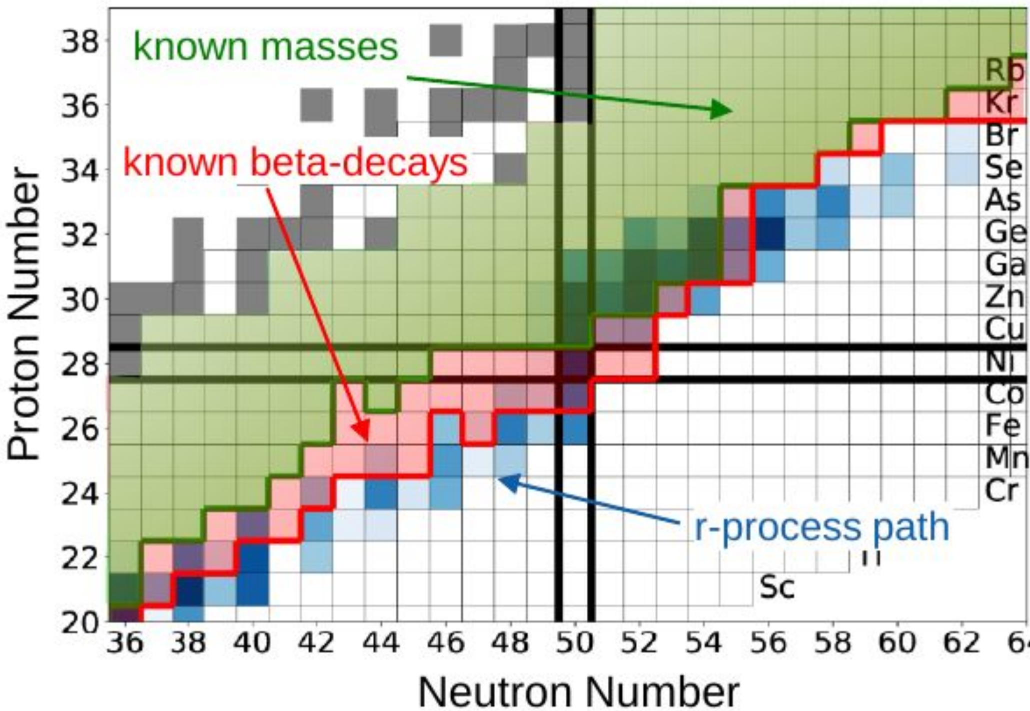




Extending the Ga study

We explore the impact of nuclear masses and beta decays to the first r-process peak for:

- $0.34 < Y_e < 0.41$
- $S = 10 - 15\ k_b$ / baryon
- $\tau = 7$ ms



We use:

Masses:

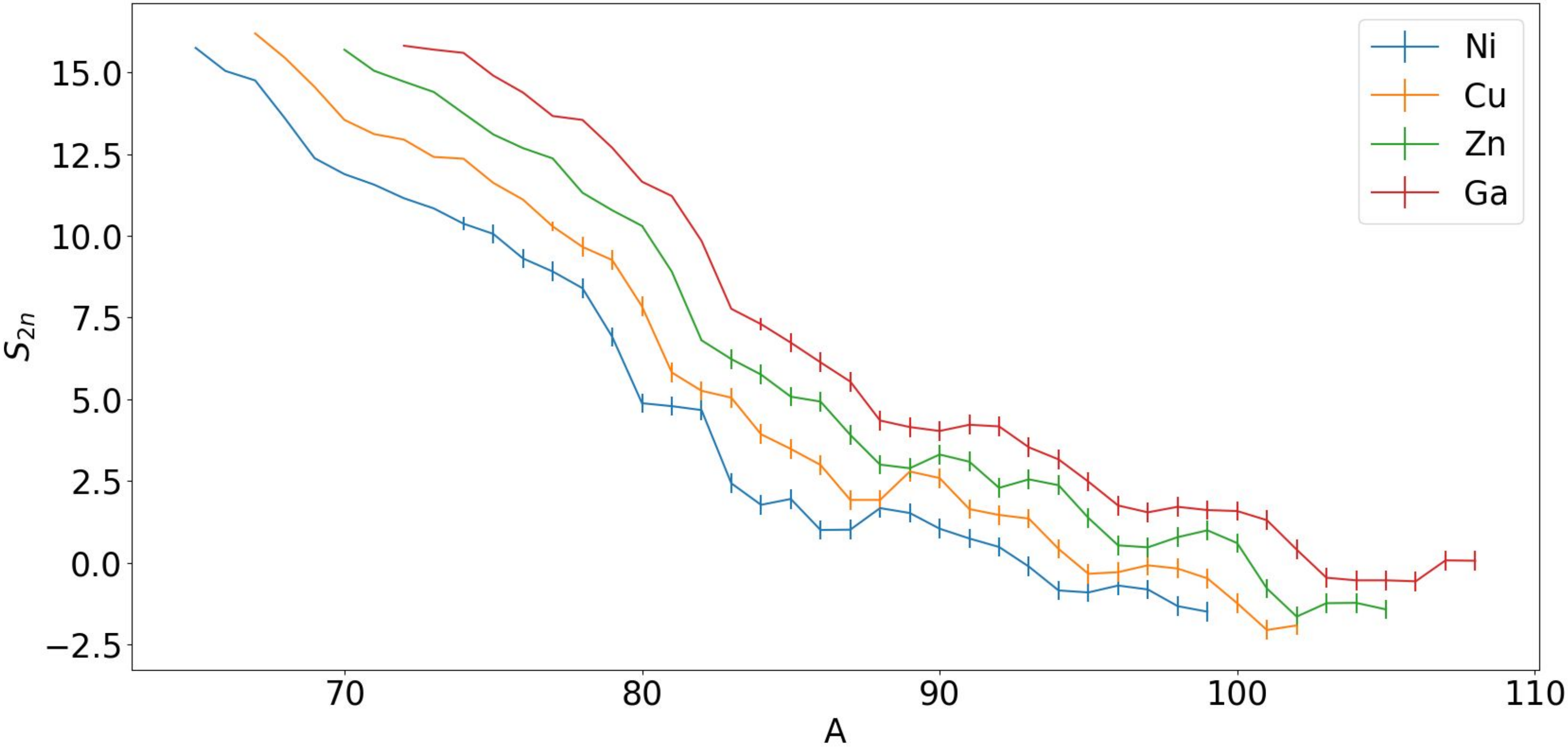
AME16+ nuclear masses
FRDM12 within 300 keV error bars
*FRDM rms (M)~0.65 MeV

beta decay rates and branching:

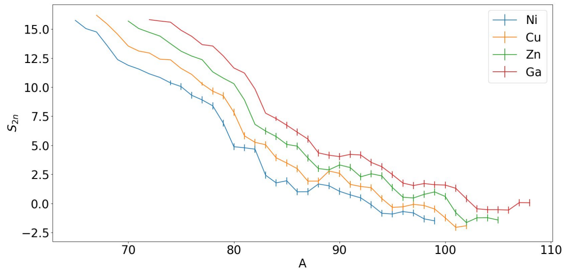
NUBASE16
FRDM12 and Marketin beta decay rates

Uncertainties: from S_{2n} to reaction rates

S_{2n} for the isotopic chains of Ni-Ga. The uncertainty for each point is labelled with vertical lines. Most of measured masses have uncertainties of few keV



Uncertainties: from S_{2n} to reaction rates

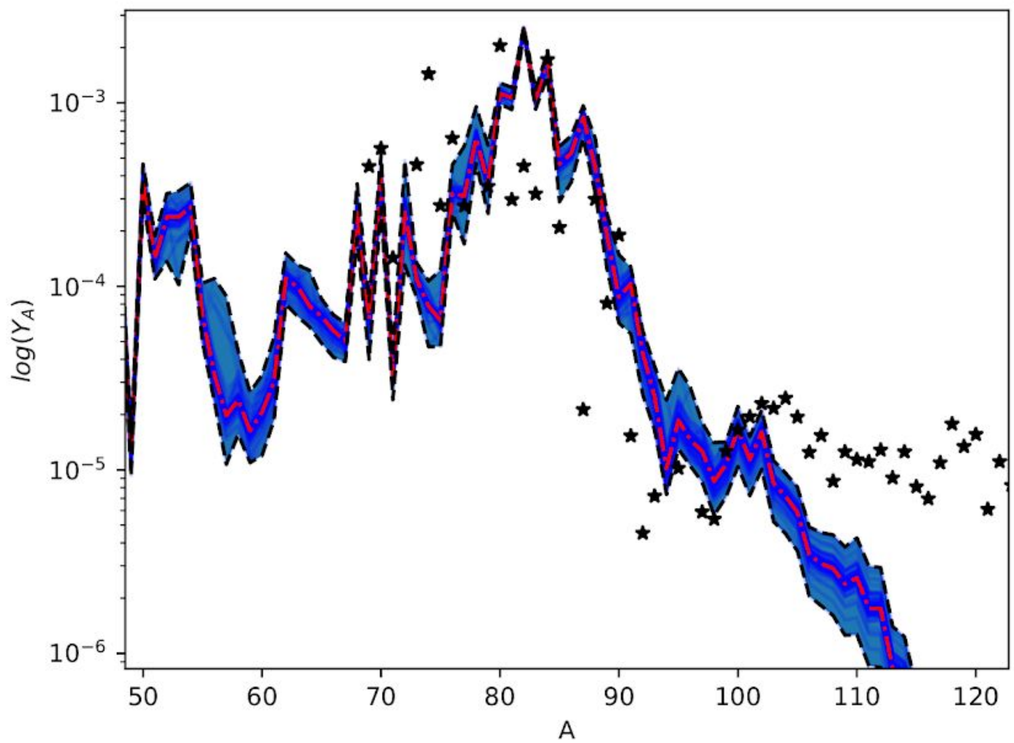


- Small changes in masses can lead to changes of RR of 1 order of magnitude or more

We use a single modified mass at a time to map the effect of RR to the calculation of abundances

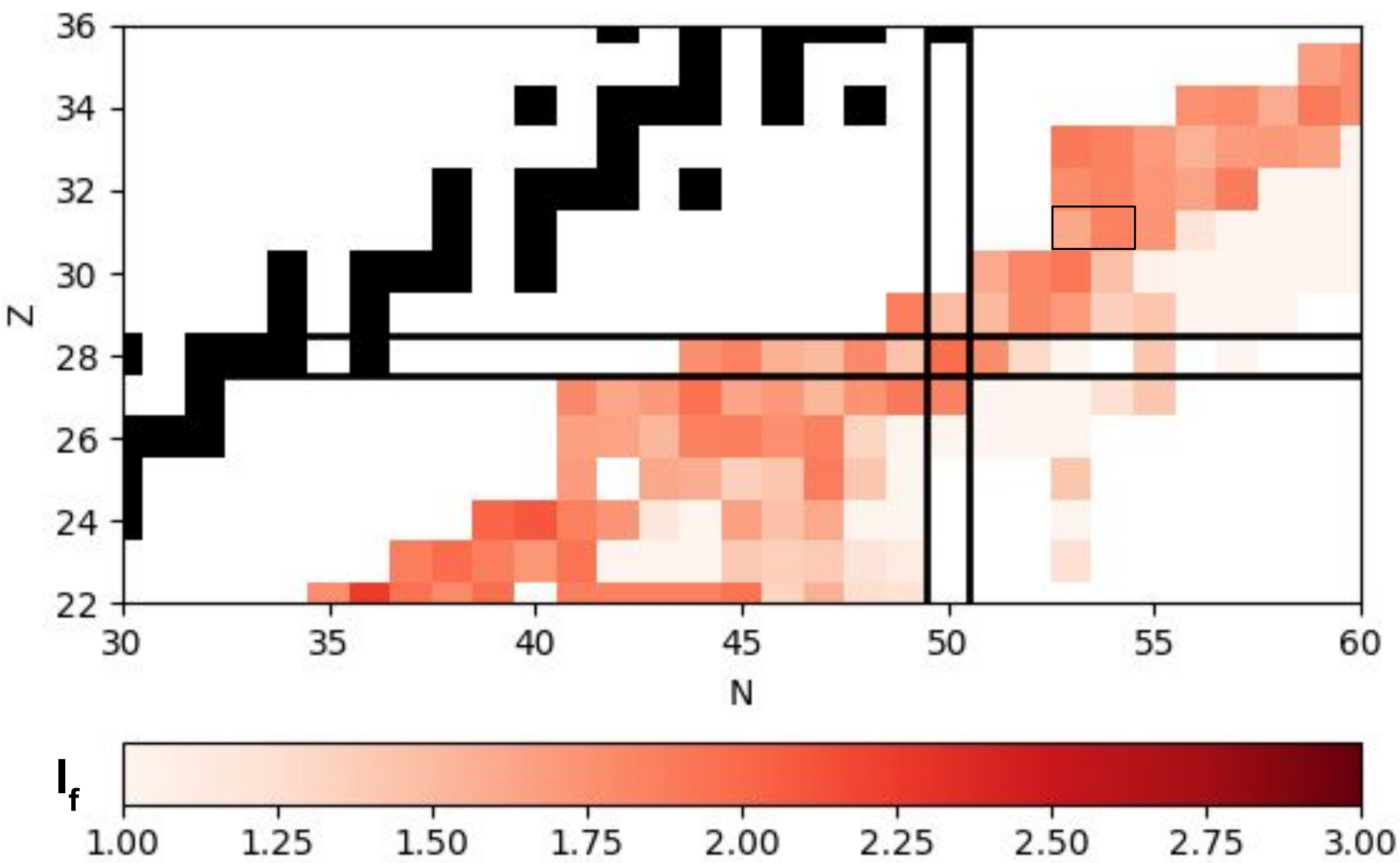
From reaction rates to abundances

If we assign to each calculation a factor according to how much the abundance pattern is changed we can simplify this plot and find the masses affecting the calculation the most

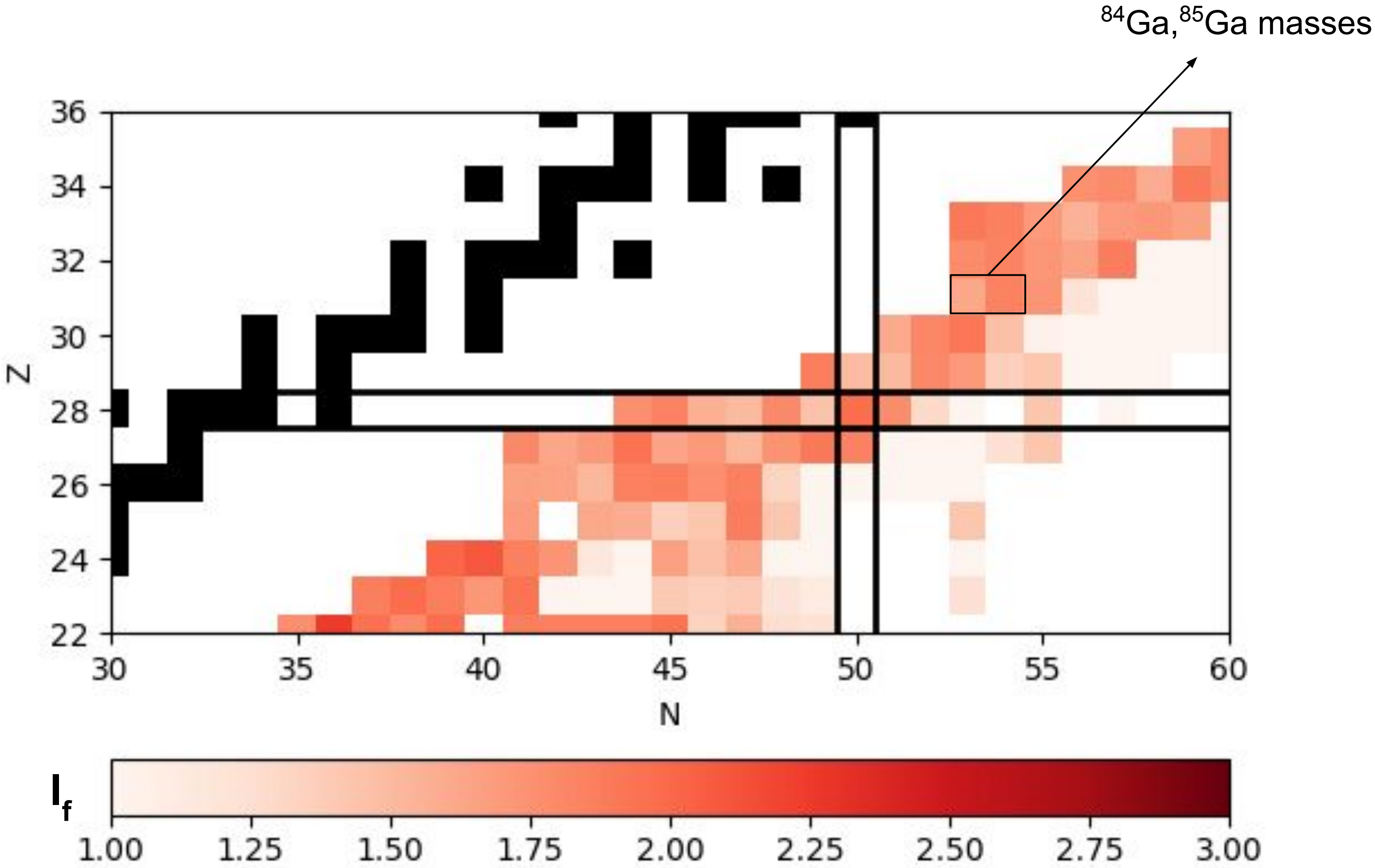


$$I_f = \sum_{A=1} \frac{\sqrt{(Y_A - Y_{A0})^2}}{0.5(Y_A + Y_{A0})}$$

Sensitivity to variations of masses



Sensitivity to variations of masses



Role of beta decays and branching ratios

Ga85

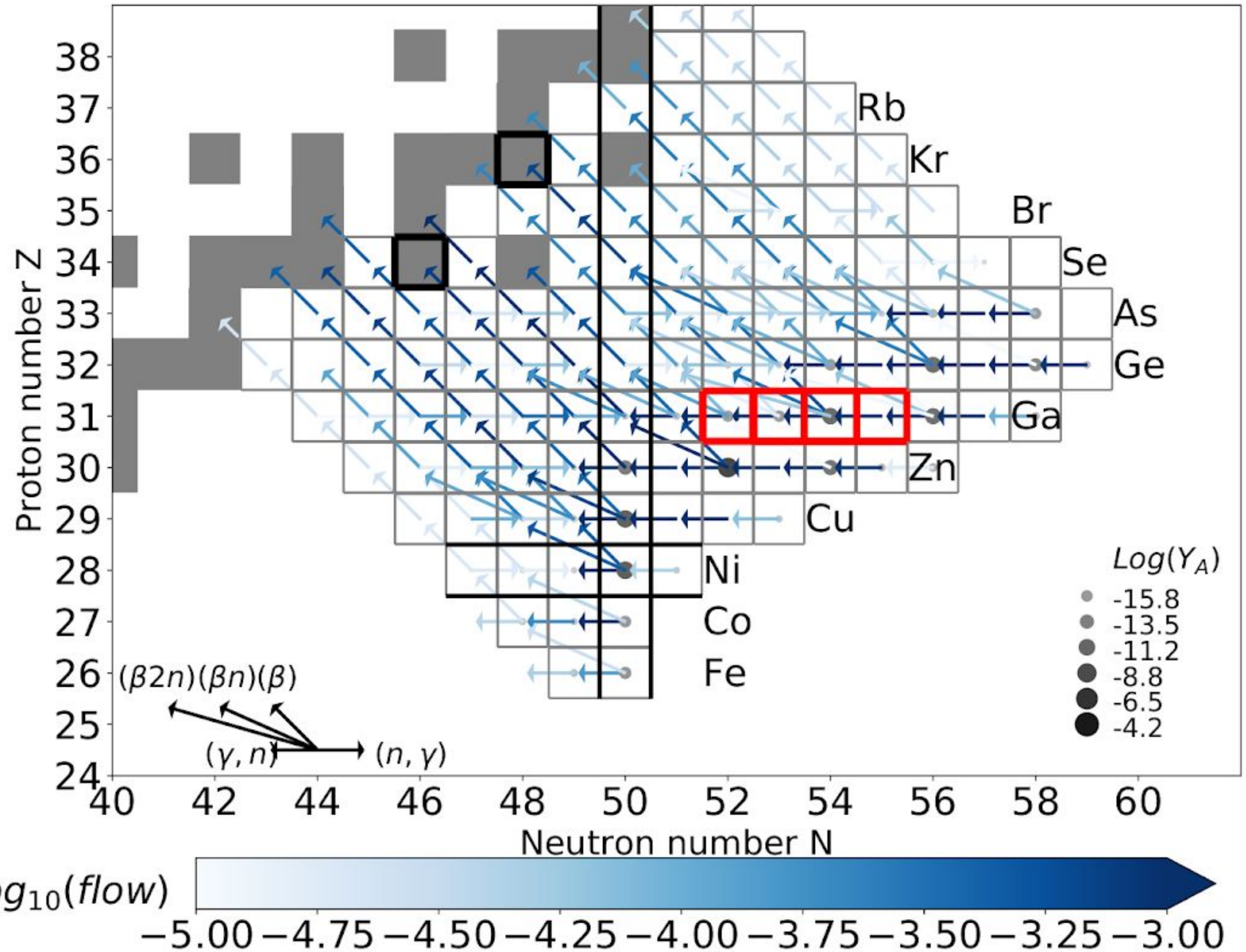
b=59#
bn=35#
b2n=6#

Zn82*

b=30%
bn=70%
b2n=0#

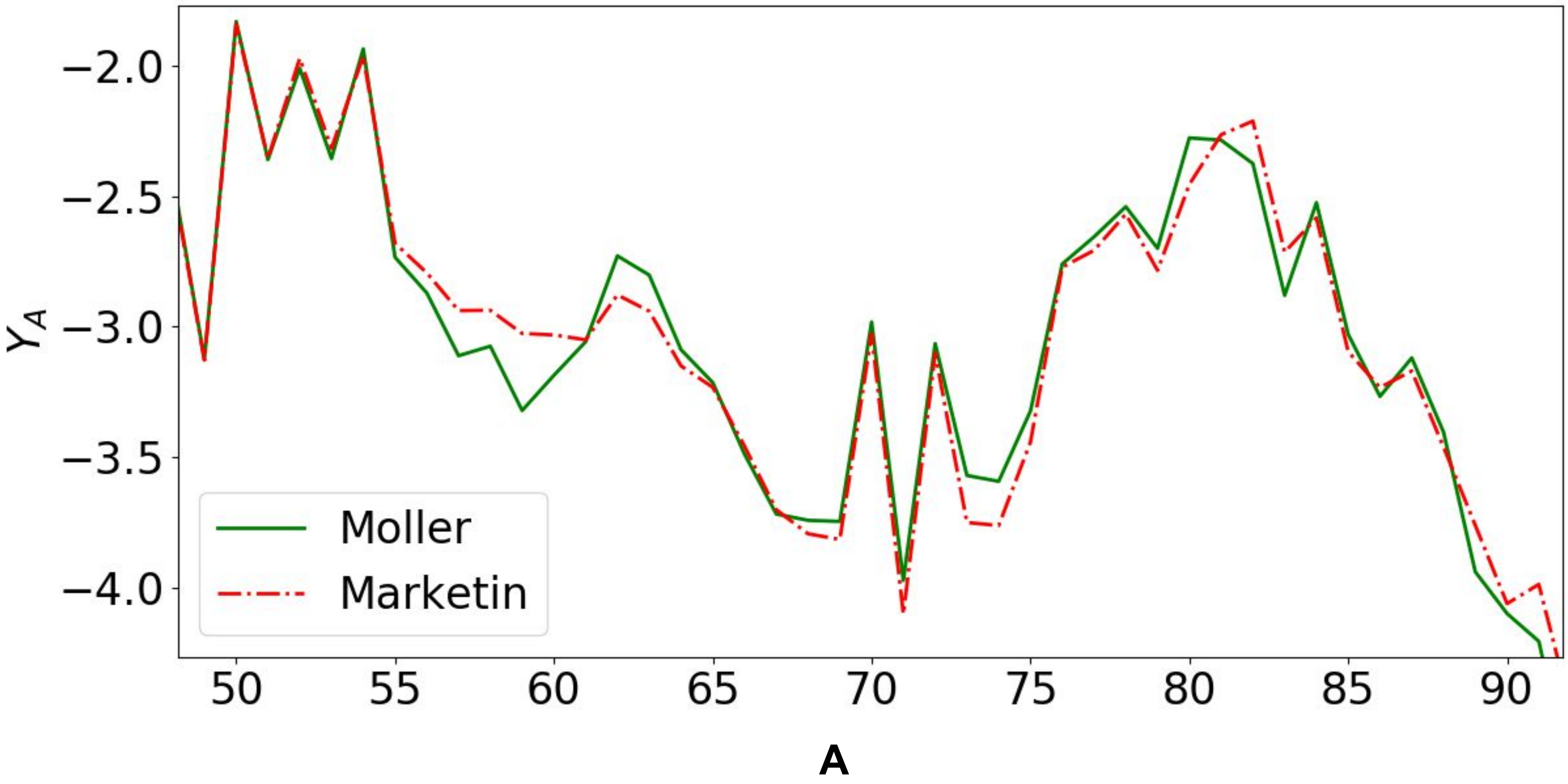
Ge88

b=?
bn=?
b2n=?



*inconsistencies in the literature (228(10) ms, 2012 178(2.5) ms 2014, 155(20) ms 2016)

Effect of using different theoretical models for beta decays



Summary

- We were able to identify a Y_e range consistent with observations of blue kilonova (AT2017gfo) that recreate the broad first r-process peak for low entropy conditions.
- We observed the effect of varying specific masses to the calculation of reaction rates.
- We used the calculated reaction rates to calculate abundance patterns and identify masses important for the formation of the 1^{st} peak
- We identified beta decay rates and branching ratios are very important for the formation of the distinct peaks in this region