# GrRproc: A graph-based method to calculate r-process abundances

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## Abstract

Understanding the origin of elements in our Universe is one of the outstanding questions in science. The astrophysical rapid neutron capture process (r-process) is believed to be responsible for creating half of the heavy isotopes up to bismuth and all of thorium and uranium in our Universe.
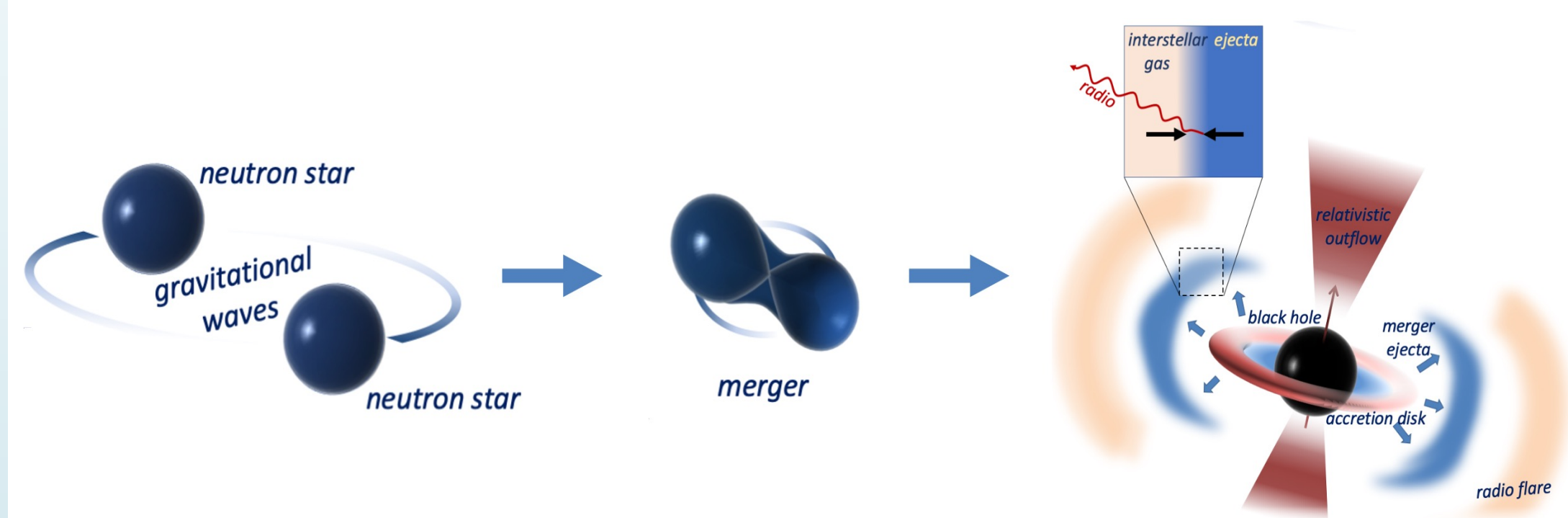
Figure 1

R-process abundances come from a combination of appropriate astrophysical conditions (Figure 1) and nuclear reactions (Figure 2) of thousands nuclei.
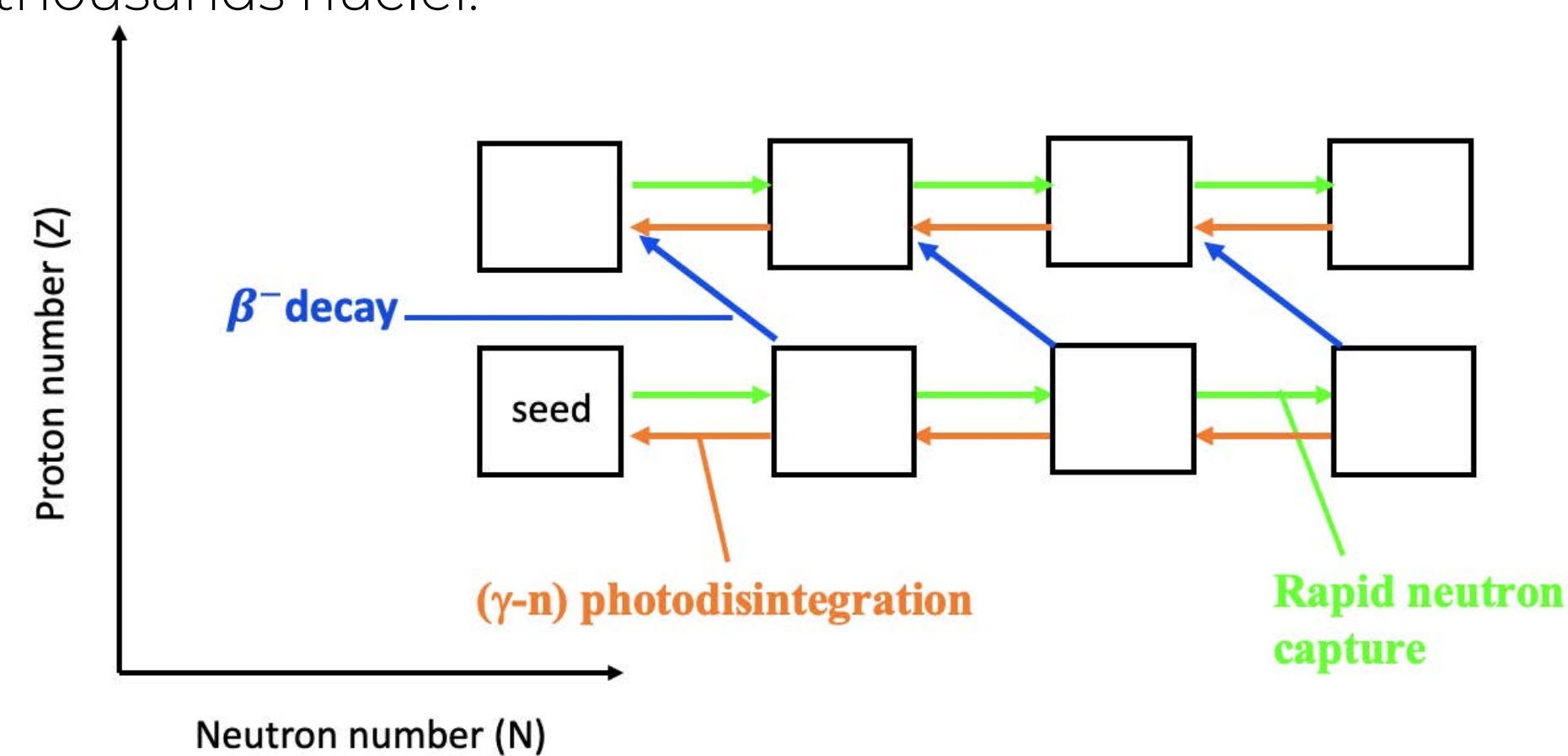


Figure 2

We introduce **GrRproc**, a novel graph-based methodology for simulating the r-process nucleosynthesis. Unlike traditional approaches, GrRproc can demonstrate the relative abundance contribution from species to species over each timestep.

## Reaction Networks

Reaction networks are collections of species and the potential reactions interlinking them. In studying the r-process, one is interested in tracing the dynamic evolution of species abundances over time.

$$\frac{dY_i}{dt} = -\sum_r \sum_{j \neq i}^n \lambda_{ij}^{(r)} Y_i + \sum_r \sum_{j \neq i}^n \lambda_{ji}^{(r)} Y_j$$

Which can be written as: $\frac{dY}{dt} = -AY$

By using Implicit differentiation: $\frac{Y(t+\Delta t) - Y(t)}{\Delta t} = -AY(t+\Delta t)$

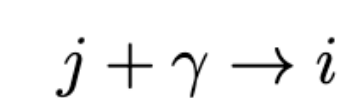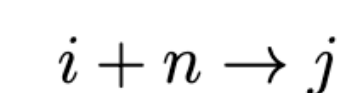Finally, we can get the abundance of species at next time step:

$$Y(t + \Delta t) = M(t, \Delta t) Y(t)$$

Where transitional matrix $M(t, \Delta t)$ stores the detailed information of the abundance flow.
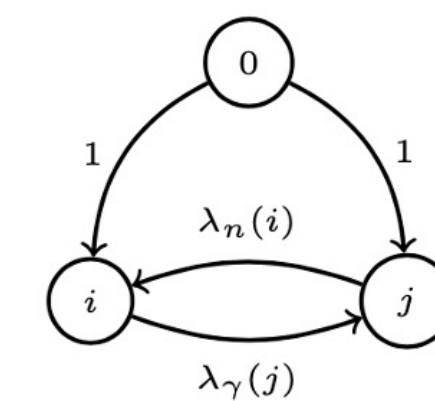
## Graph Theory

Using our graph theory, we can get the transitional matrix $M(t, \Delta t)$ with branchings (directed, acyclic graph with no indegree > 1).
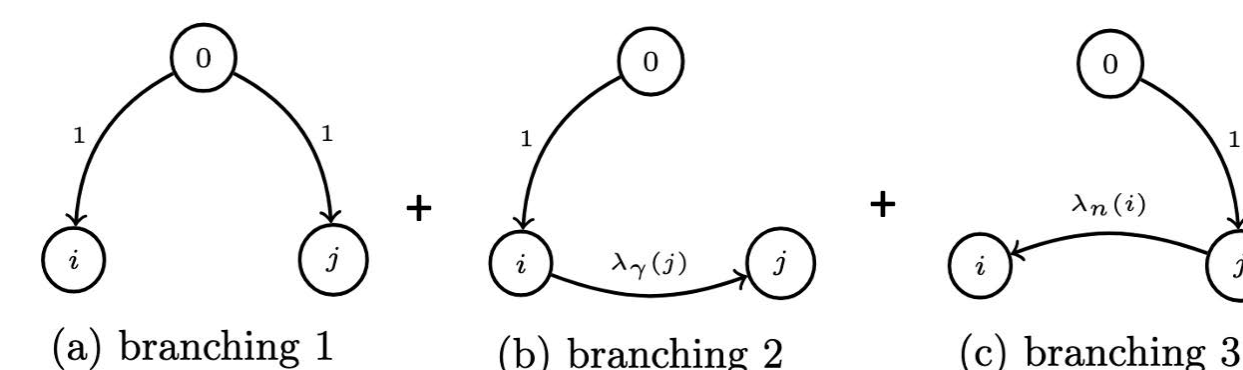
In a simple two species case:

$$i + n \rightarrow j$$
$$j + \gamma \rightarrow i$$

The corresponding graph is:



All branchings are:



(a) branching 1    (b) branching 2    (c) branching 3

$$M(t, \Delta t) = \frac{1}{1 + \lambda_n(i) + \lambda_\gamma(j)} \begin{bmatrix} 1 + \lambda_\gamma(j) & \lambda_\gamma(j) \\ \lambda_n(i) & 1 + \lambda_n(i) \end{bmatrix}$$

Summation of all branchings    Summation of rooted branchings

## Isotopic Abundance Calculation

We performed a calculation within a single isotopic chain, with seed nuclei Gadolinium-138 and neutrons. Under constant $T_9$ and density, the seed nuclei rapidly capture neutrons and undergo photon dissociation, ultimately achieving equilibrium.
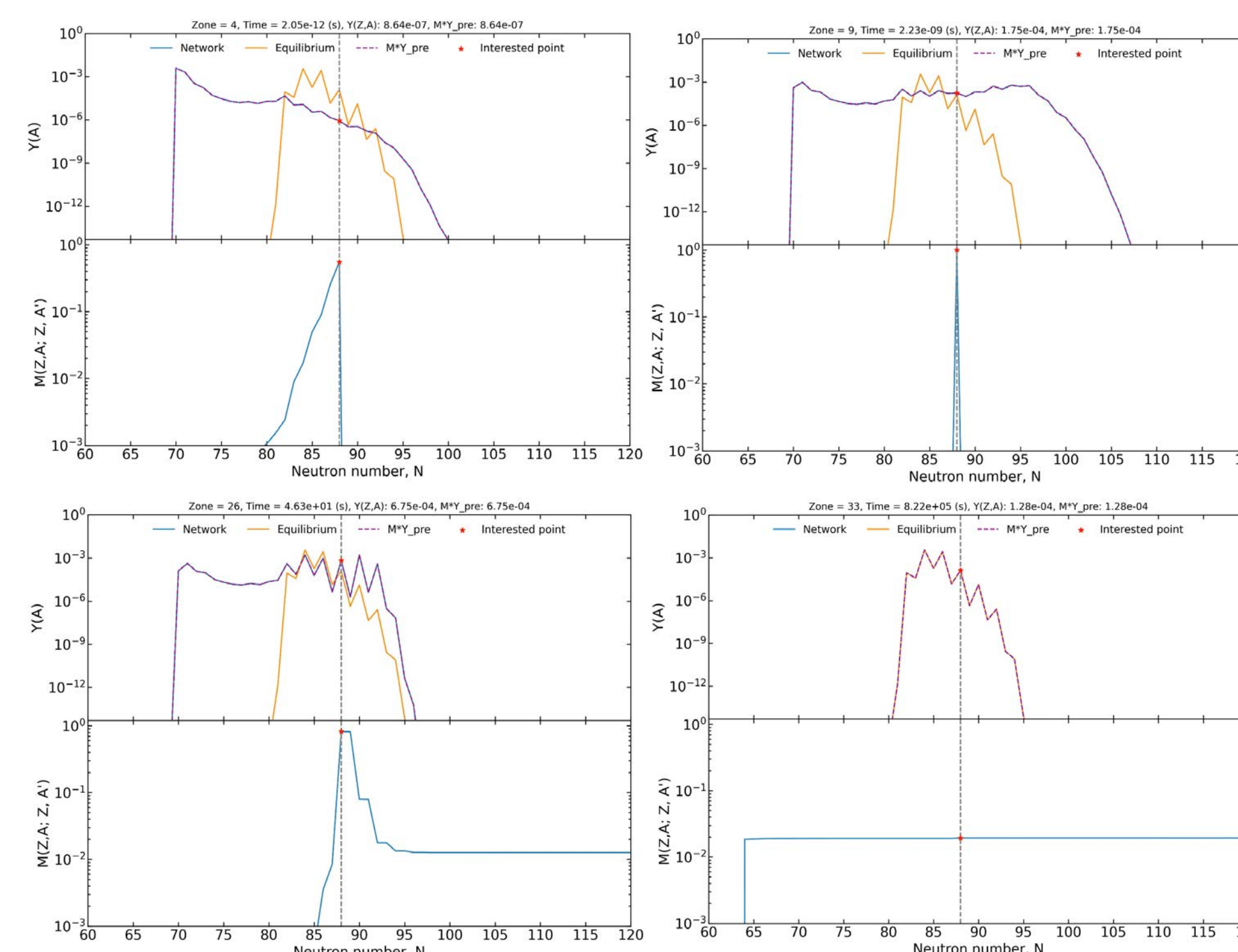


Figure 3[1]

Isotopic abundance evolution over time. The upper panel of each sub figure is the isotopic abundances calculated with different methods. While the lower panel shows the relative contribution from the neighboring nuclei to the stared nucleus.

## Full R-process Abundance Calculation

We can use our GrRproc to perform a comprehensive r-process calculation involving all nuclear reactions within the chart of nuclei.
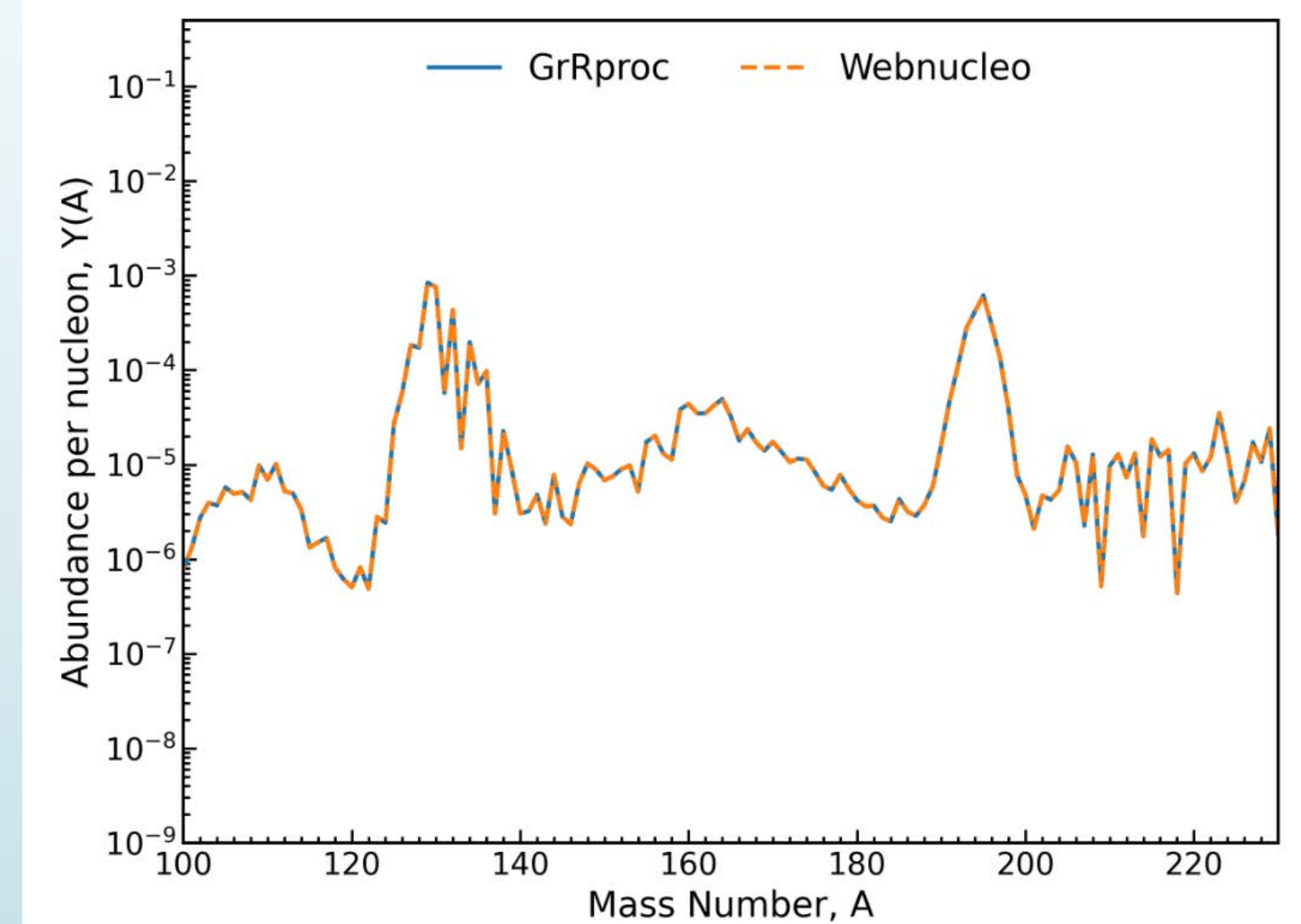


Figure 4[1]

Simulated r-process abundance pattern with two different approaches. GrRproc is implemented in python, which uses roughly the same amount of running time as using webnucleo in C++.

## Conclusions and Discussion

1. We developed a graph-based approach to compute the astrophysical r-process nucleosynthesis.

2. This method not only computes the abundance changes over each timestep, but also enables us to exam the detailed abundance flows and the relative abundance contributions from neighboring nuclei to the interested species.

3. This method allows for the meticulous examination of the reaction network's intricacies, particularly in the most crucial freeze out phase of r process, when the competition of neutron capture, photon dissociation and beta decays determine the final abundance pattern.

## Acknowledgements

## References

• Figure 1 credit: Bartos Group, University of Florida
• [1] M. Li, B. Meyer. GrRproc: A graph-based method to calculate r-process abundances. (In prep)
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