Role of the Light Mass Nuclear Reactions in the r-process Nucleosynthesis

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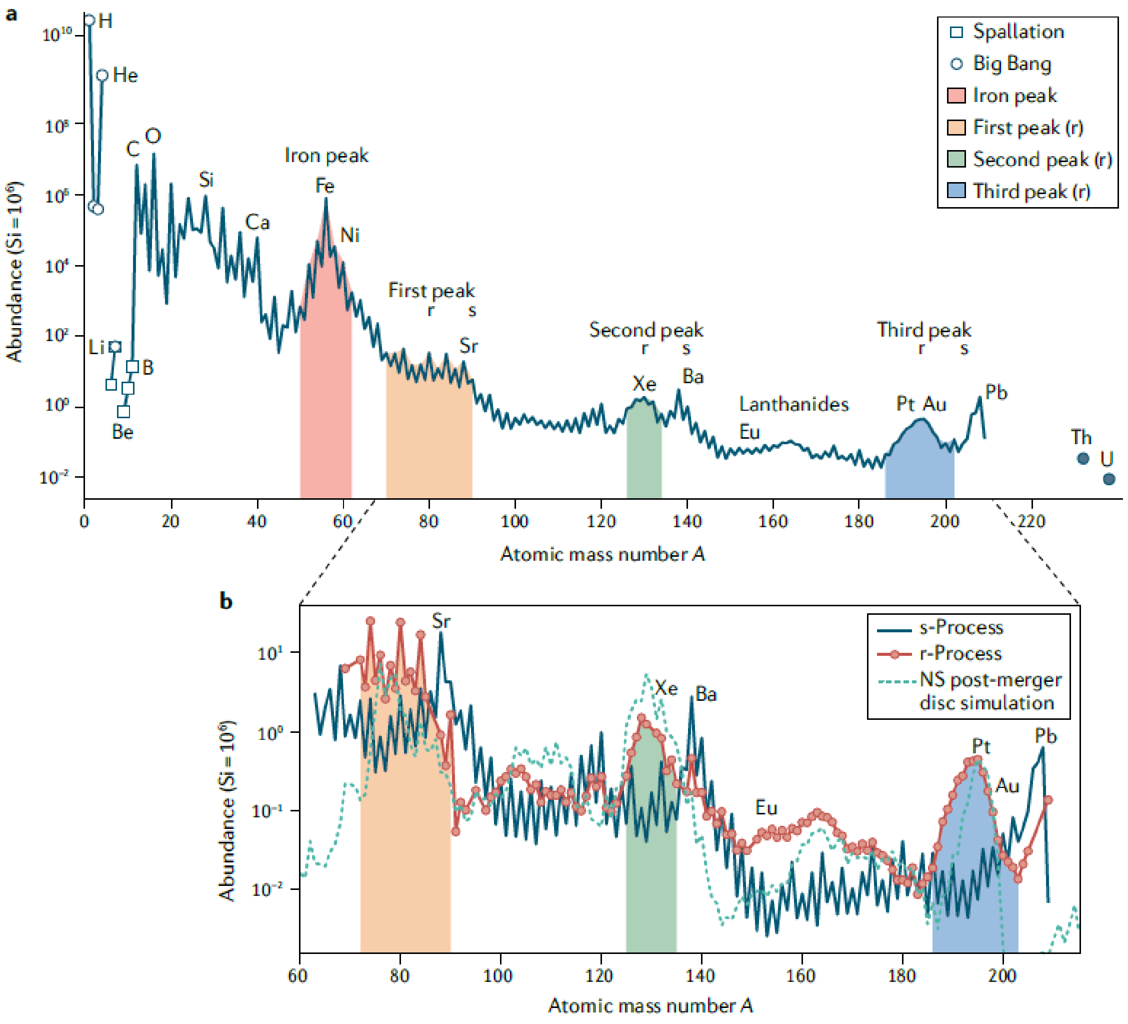
01 Motivations – Origin of Elements

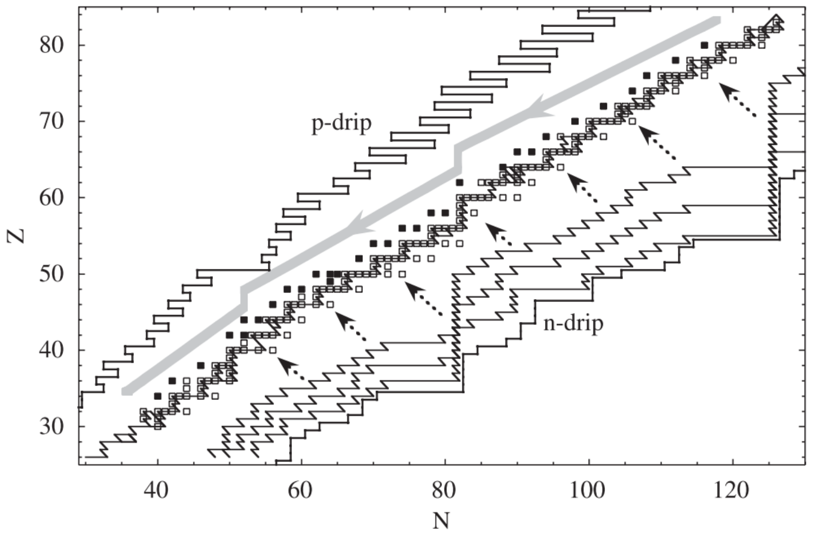
D. Siegel, Nature Reviews Physics (2022)



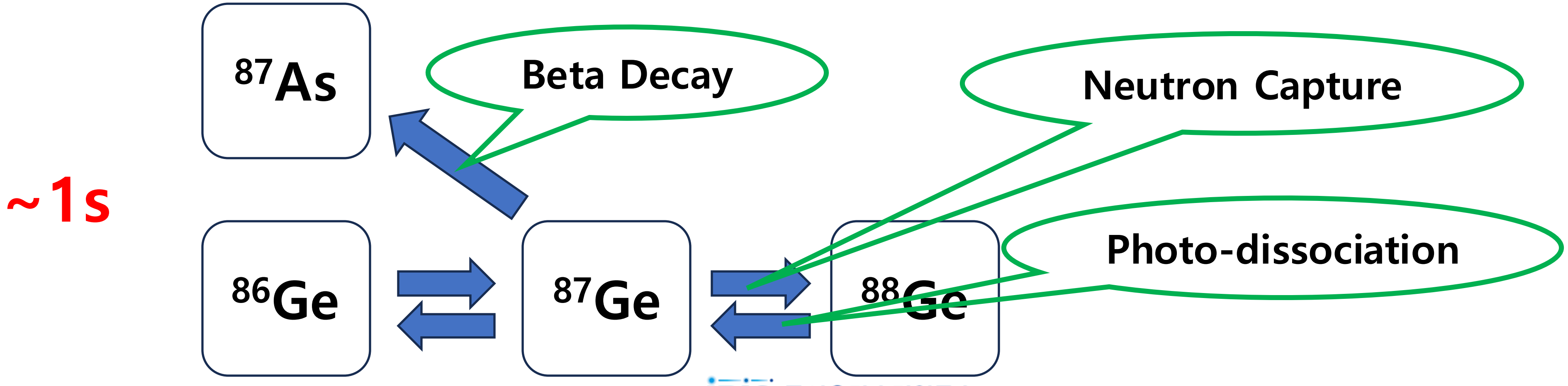
- We want to understand the solar abundances, i.e. t he ratios among elements in the solar system.
- One believe that the elements heavier than iron (Fe) are synthesized by neutron capture processes, hal f of them by s-process and another half by r-proce ss.
- The s-process is the slow neutron capture process which is one of the stellar burning process.
- The r-process is the rapid neutron capture process which is expected to occur in the explosive environ ment.
- The s-process is relatively well understood, but the r-process is not understood well.
- i-process, p-process, rp-process, **ν**-process, **ν**p-proc ess, …

01 Motivations – r-process?

M. Arnould et al. / Physics Reports 450 (2007) 97–213



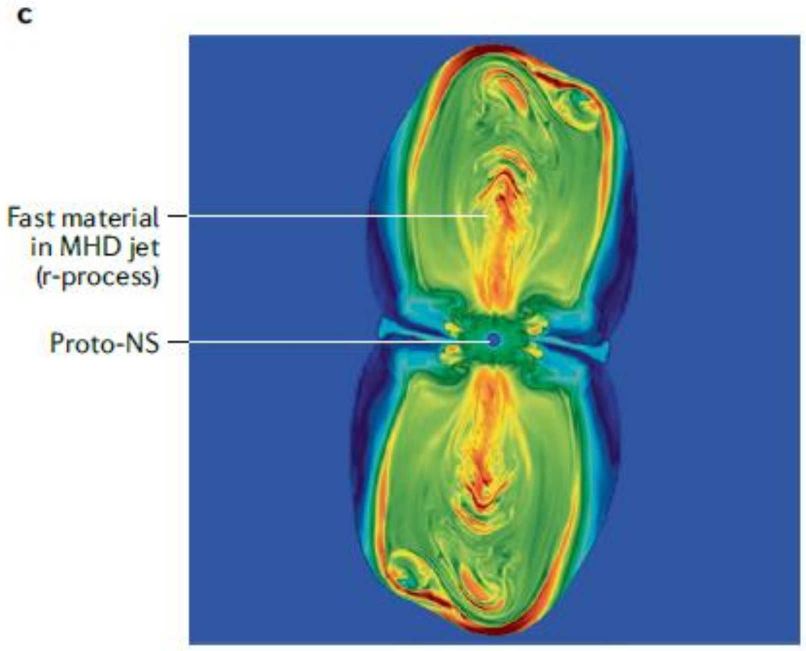
- Rapid neutron capture process -> r-process
- High temperature ($T>10^9K$) and high neutron density ($\rho_n>10^{22}cm^{-3}$) are required.
  - ➢ Explosive environment!
- The nuclear reactions including very neutron-rich isotopes are related.
  - ➢ Many reactions are very uncertain.
- Also, the reaction network includes thousands of nuclear reactions.
- The candidate sites and their environments are still under debate.



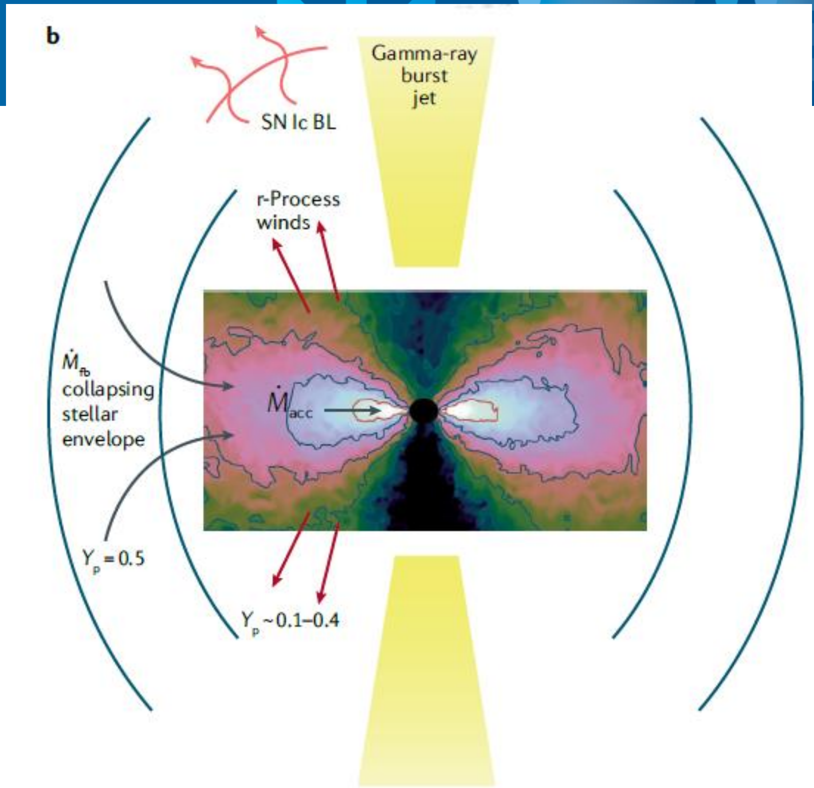
01 Motivations – r-process Candidate Sites

D.Siegel, Nature Reviews Physics (2022)

MHD Jets (Supernovae)

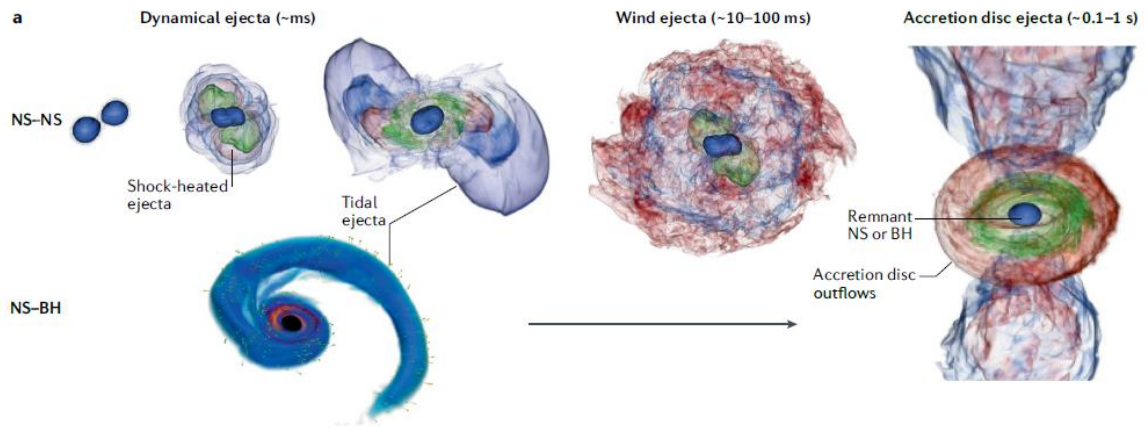


Collapsars

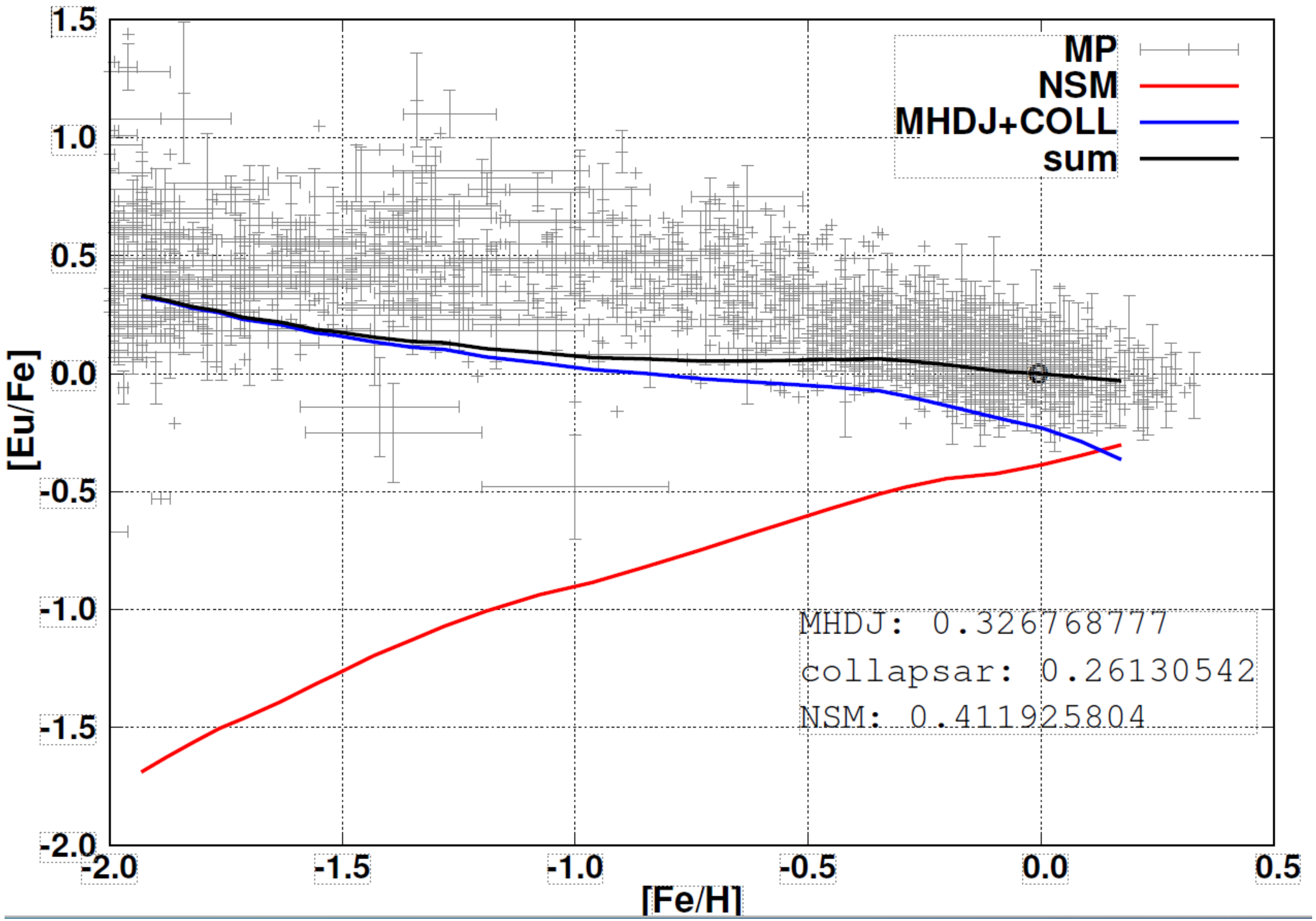


Explosive Environments!!

NS-NS, NS-BH mergers

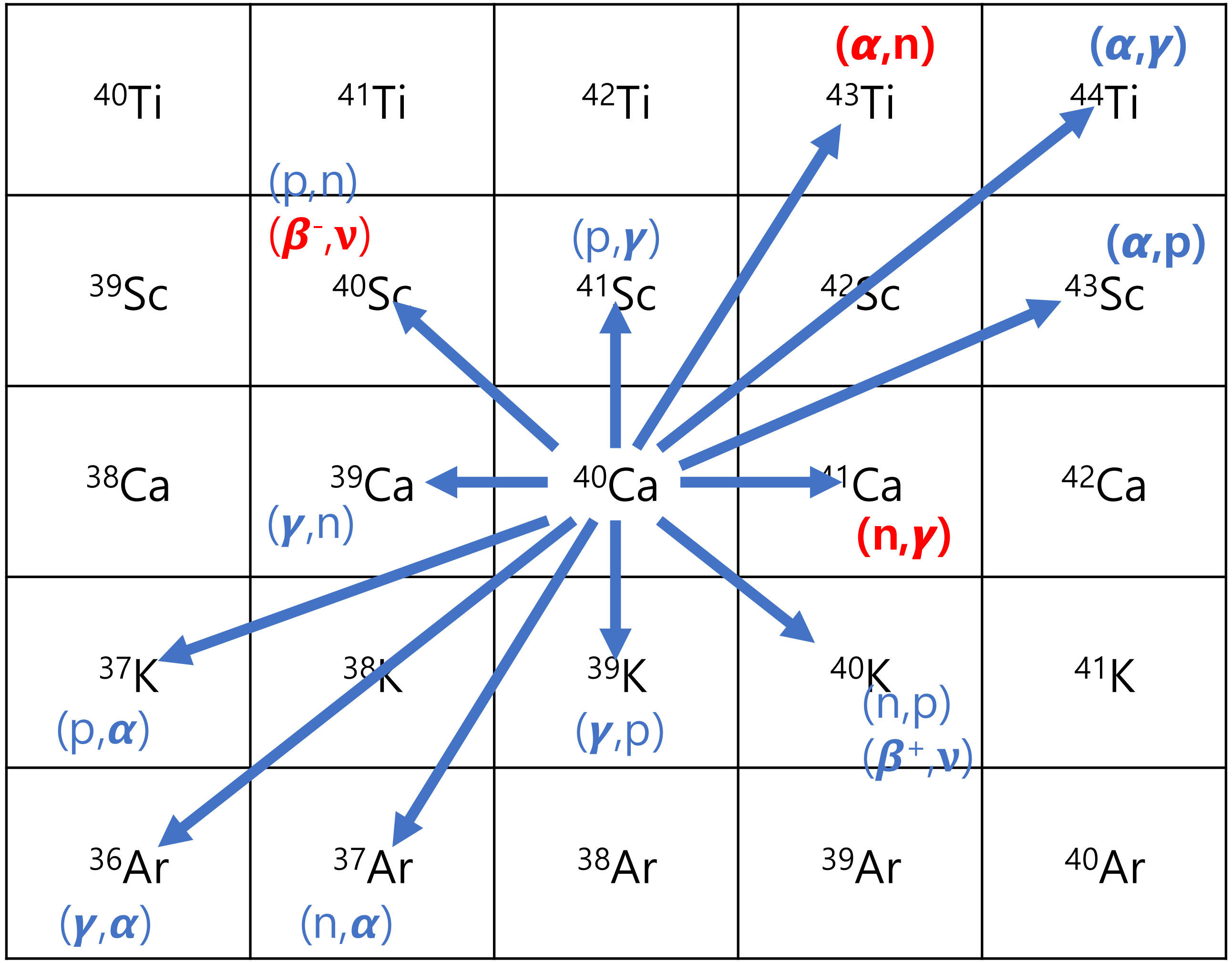


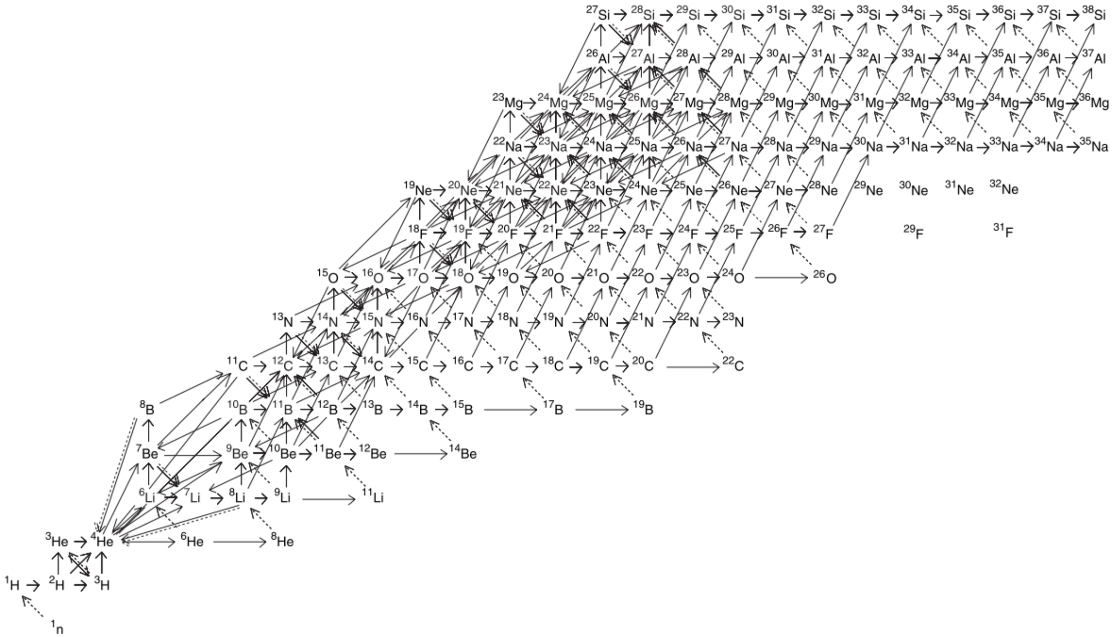
01 Motivations – Galactic Chemical Evolution



01 Motivations – Nuclear Reactions

Possible reactions from each cell in the nuclear chart

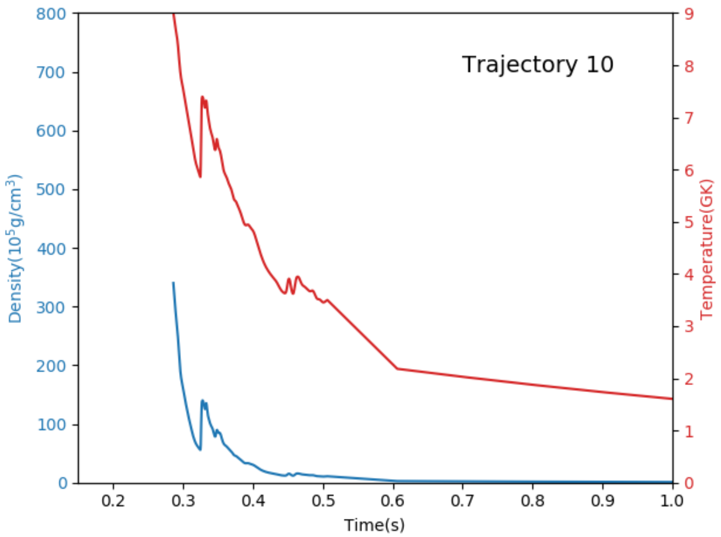


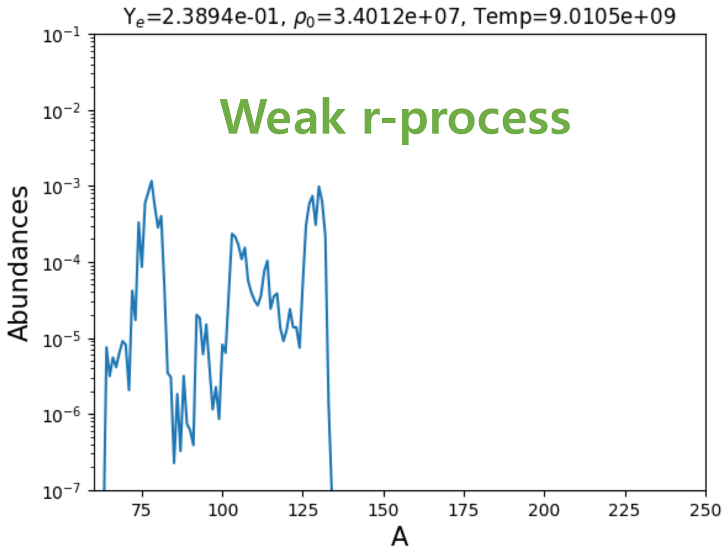


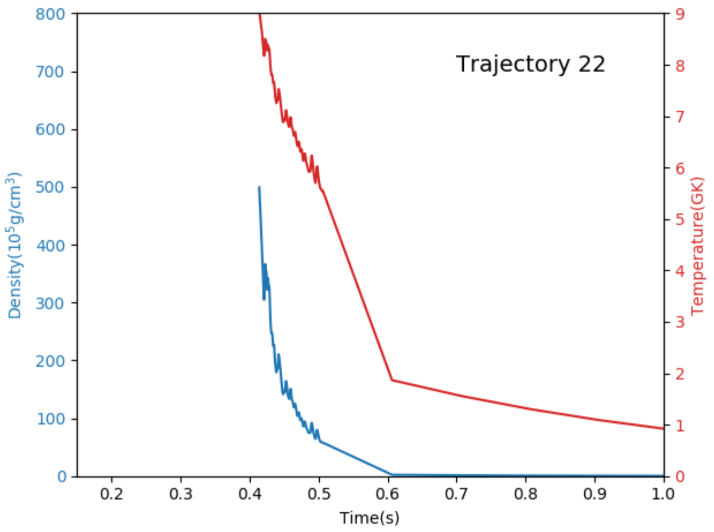
Reaction networks at low mass region

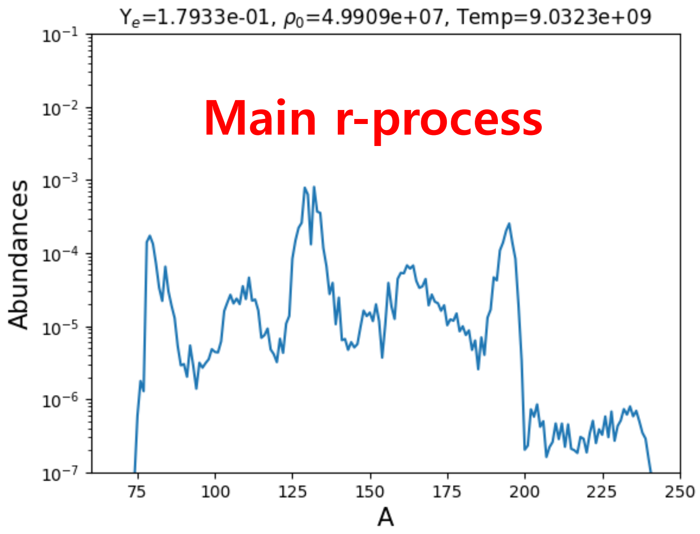
ref.) Terasawa et al. APJ 562, 470 (2001)

02 Magnetohydrodynamic (MHD) Jets





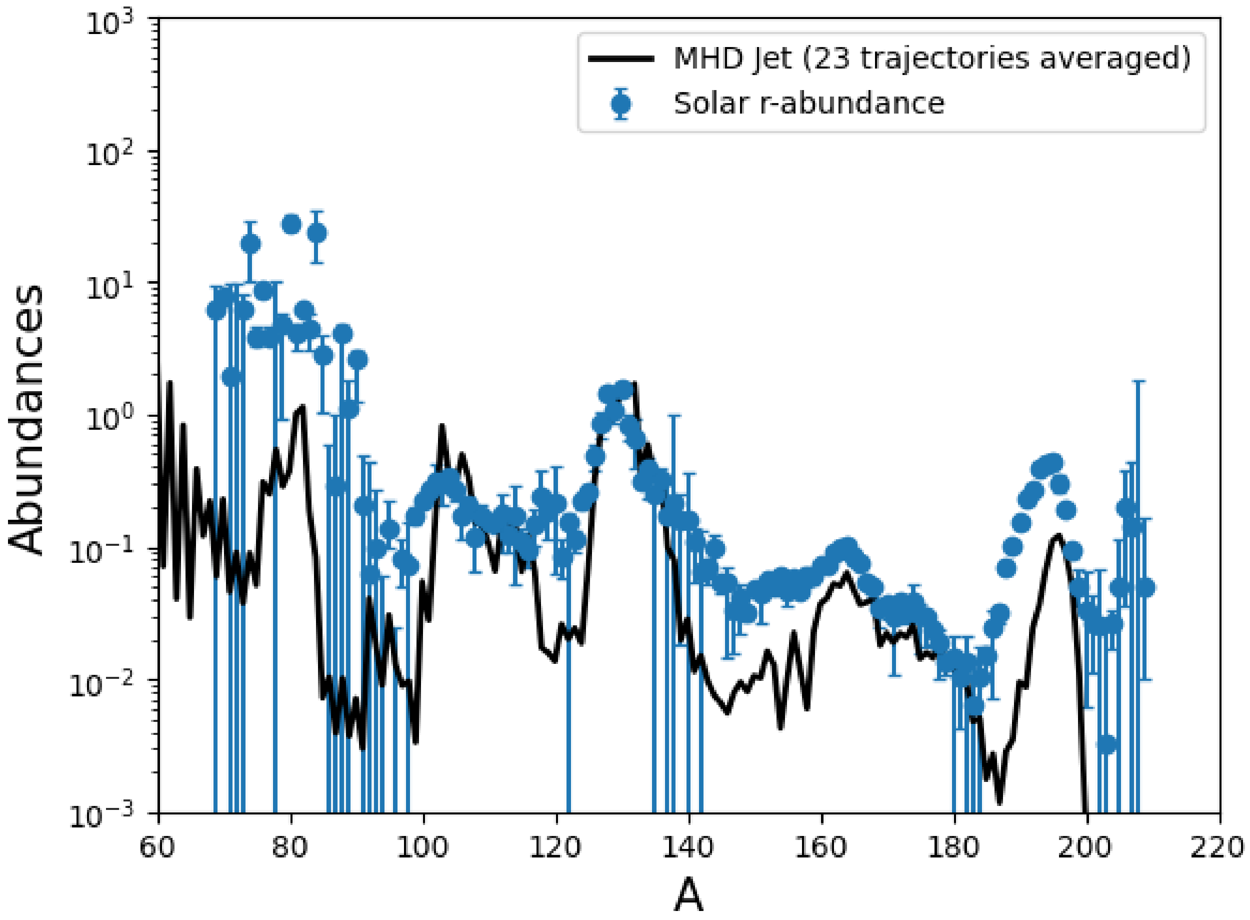




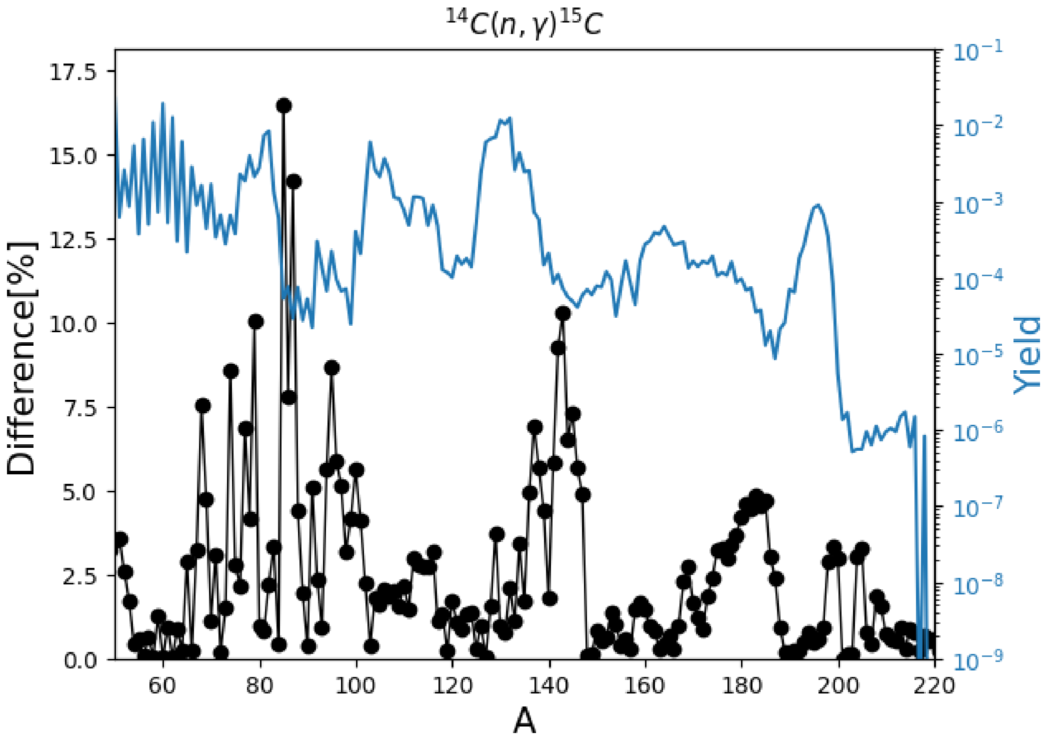
- Various MHD jet trajectories contain both weak and main r-process envir onments!
- The temperatures and the densities are not much different, but the dyn amic time scales are different.

02 MHD Jets

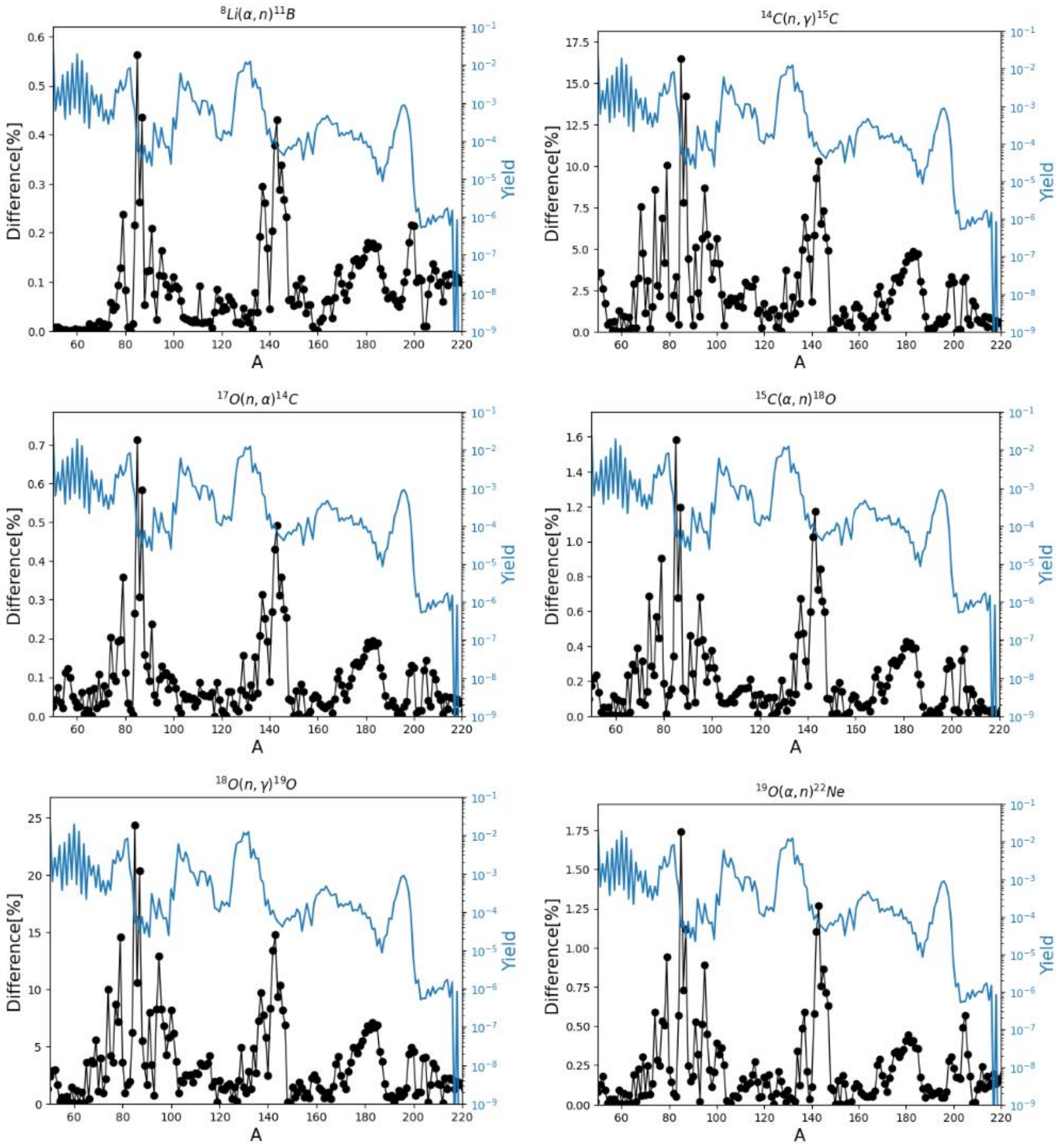
Averaged r-abundance



- The averaged r-abundances describe the second and third peaks of the solar r-abundances.

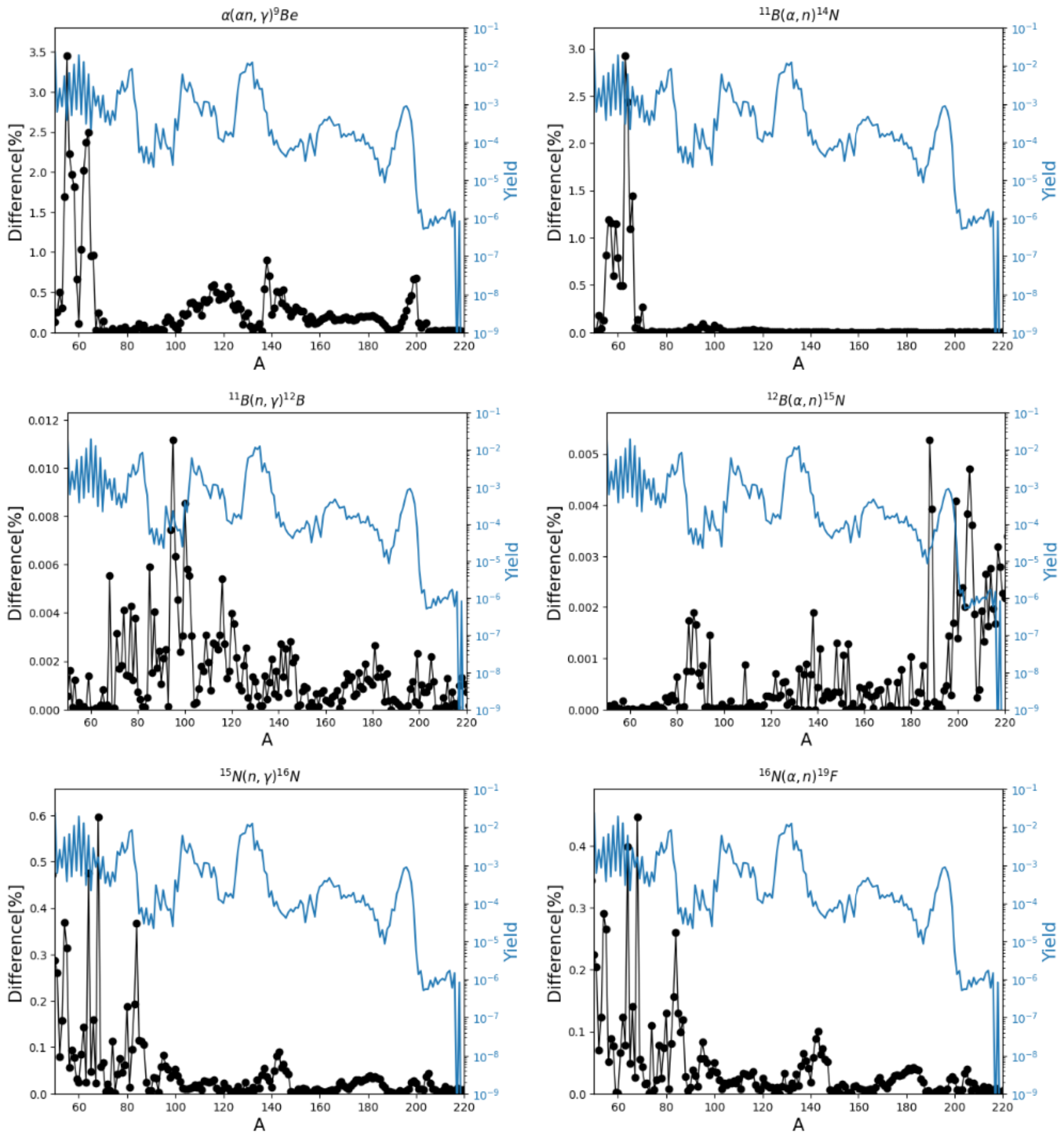


02 MHD Jets - Sensitivities



- As expected, the change of the light mass nuclear reaction rates gives the change of whole mass region.
- Observed sensitivities of the group which have similarities.
- The differences of this group have a maximum at A=85 and two more peaks near A=143 and A=180.
- Here, dots are differences between r-abundances with non-modified and modified reaction rates and the solid line is the connected line for easy seeing.
- For reference, averaged r-abundances are shown with the blue line.

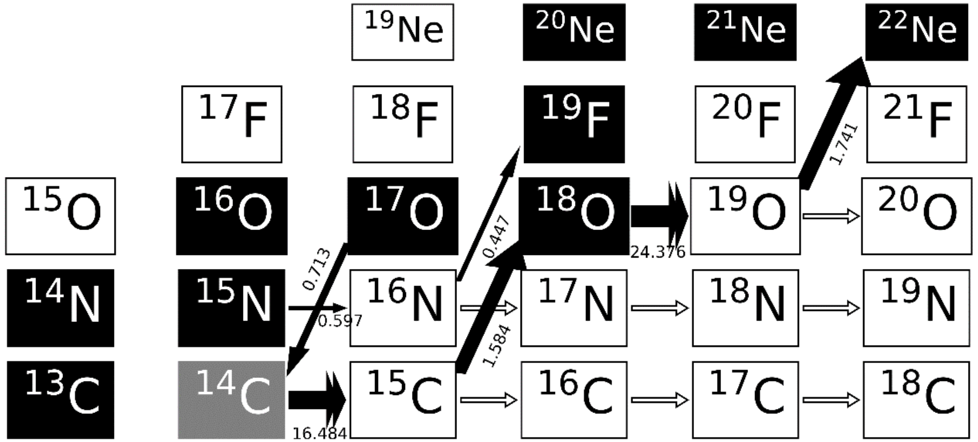
02 MHD Jets - Sensitivities



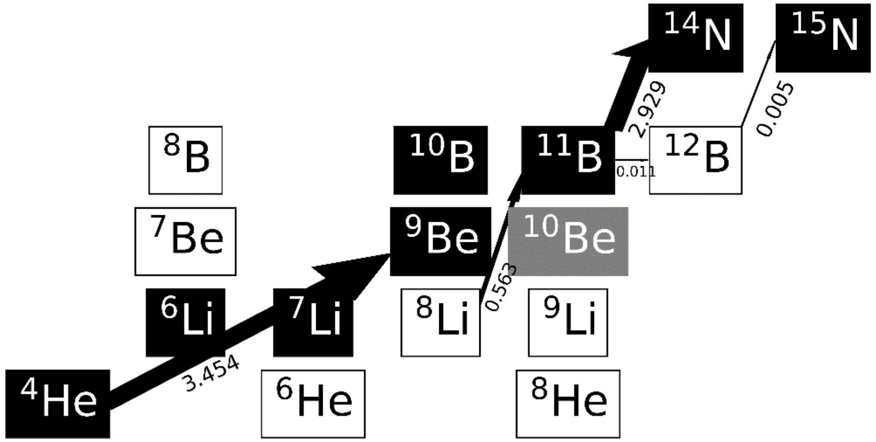
- These are the results of the reaction rate changes which don't give similar pattern in the previous page, but meaningful r-abundance change.

02 MHD Jets - Sensitivities

- The main r-process path is not far from the stability line for the MHD jet environment.

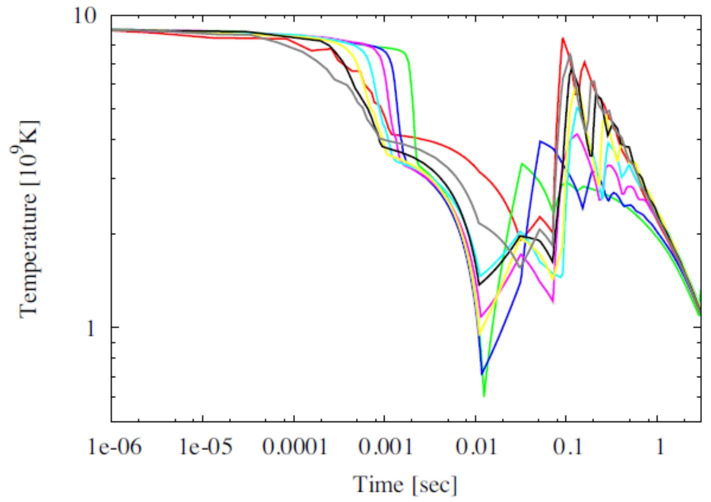


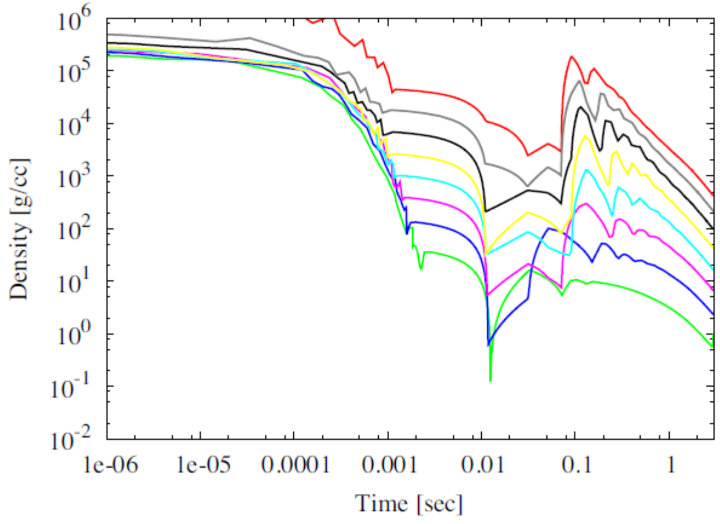
- The loop caused by $^{17}O(n,\alpha)^{14}C$ reaction makes the large flow.

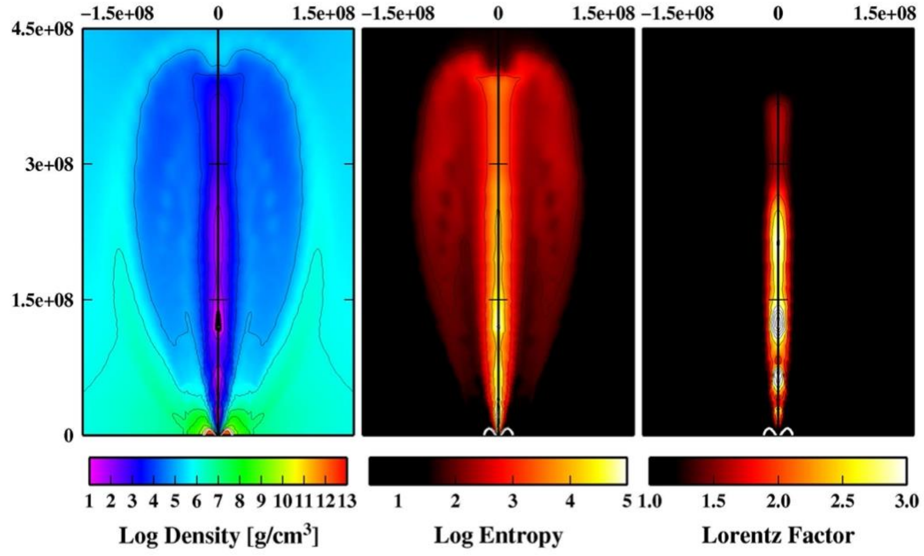


03 Collapsars

Temperature and density trajectories

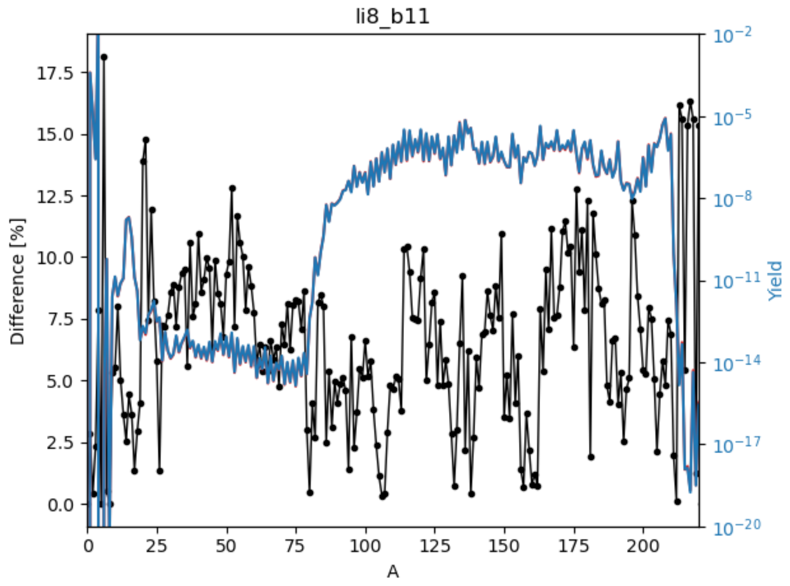






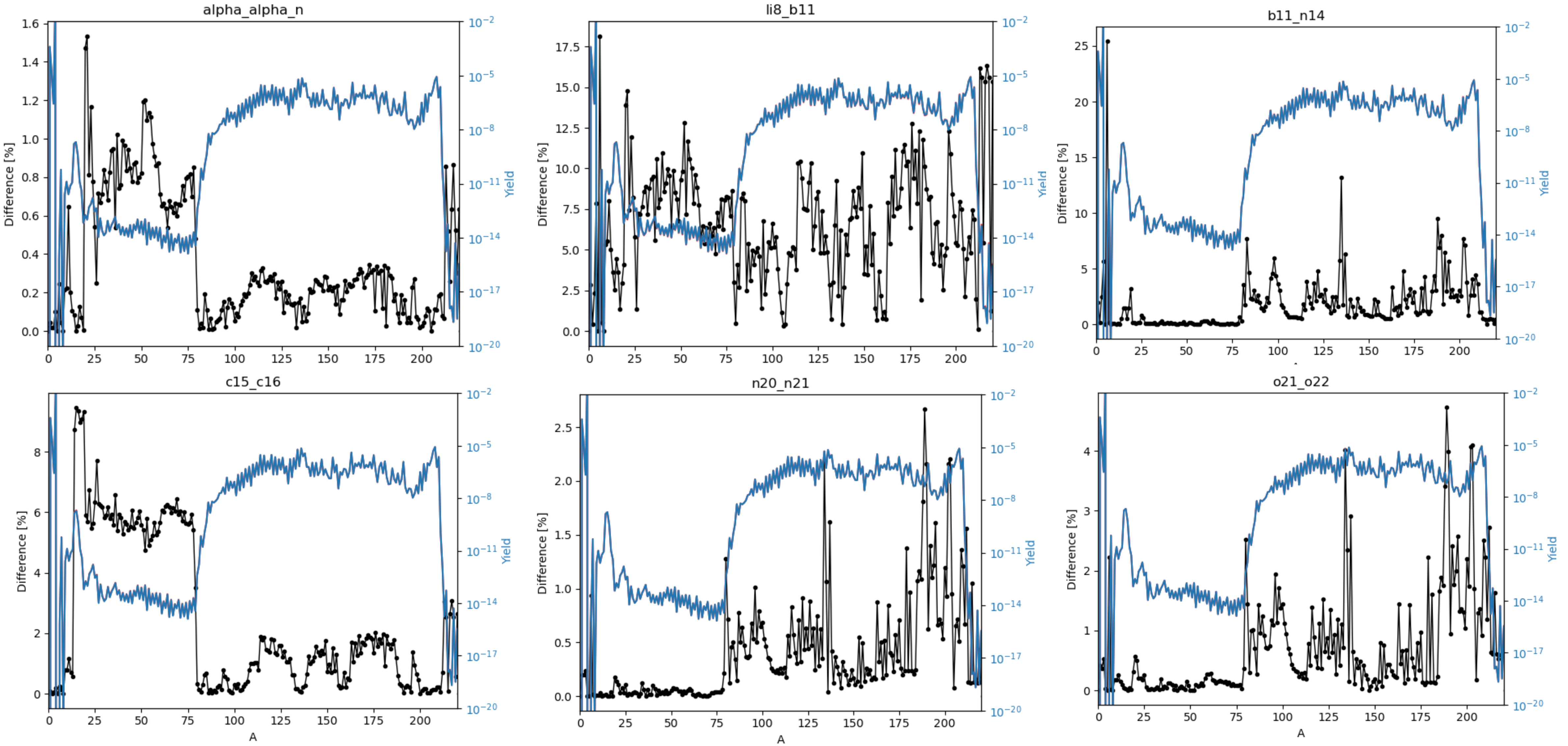
The collapsar jet

The blue line is the averaged r-abundances in the collapsar environment.



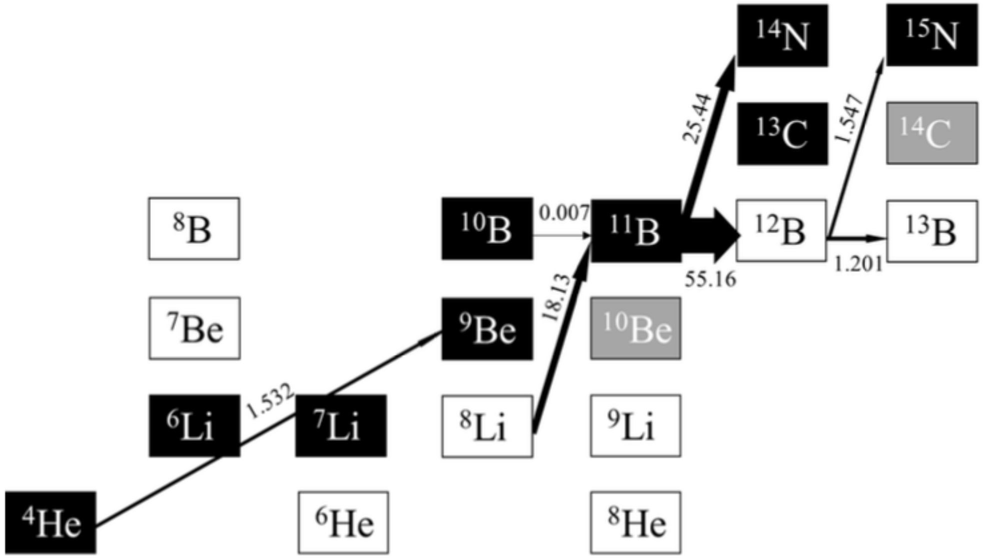
K.Nakamura et al. IJMPE (2013)

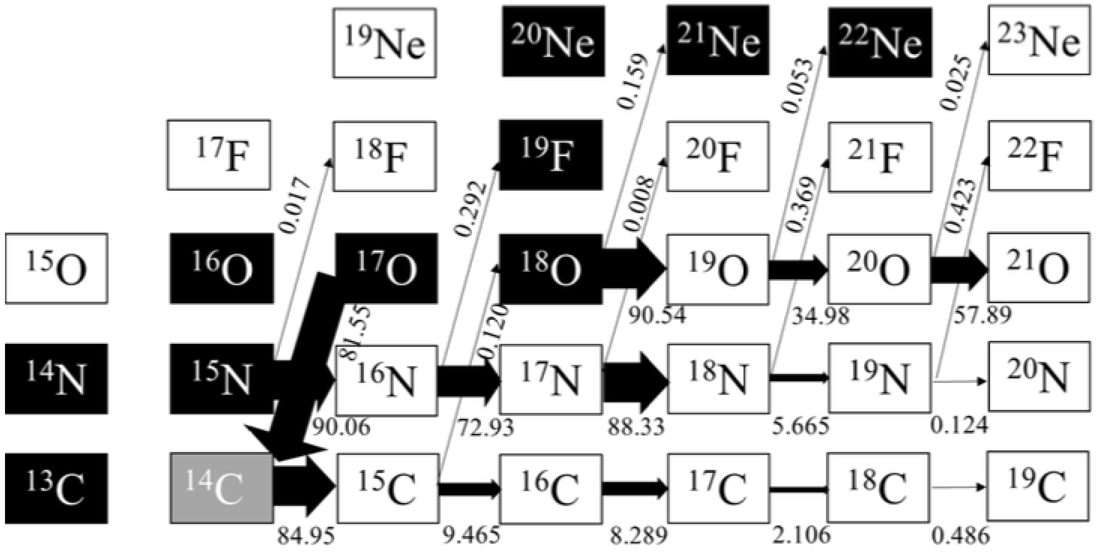
03 Collapsars - Sensitivities



03 Collapsars - Sensitivities

- The main r-process path is not far from the stability line for the collapsar environment, also.
- More explosive environment gives more neutron-rich path.





- The loop caused by $^{17}O(n,\alpha)^{14}C$ reaction is still working.

04 Collision Time Scale

Two nuclear species 1 and 2 in a plasma, with number density n_1, n_2. For a specific relative velocity v, flux of particle 1,

$j = n_1 v$ particles / unit time / unit area

The total reaction rate per second per unit volume

$$r_{12} = n_1 n_2 \sigma v$$

If the distribution of relative velocities is given by $\boldsymbol{\phi}$(v),

$$\langle \sigma v \rangle = \int_0^\infty \sigma(E)\Phi(v)v\,dv$$

The total reaction rate per second per unit volume

$$r_{12} = n_1 n_2 \langle \sigma v \rangle$$

The collision timescale of (n,$\boldsymbol{\gamma}$) reaction,

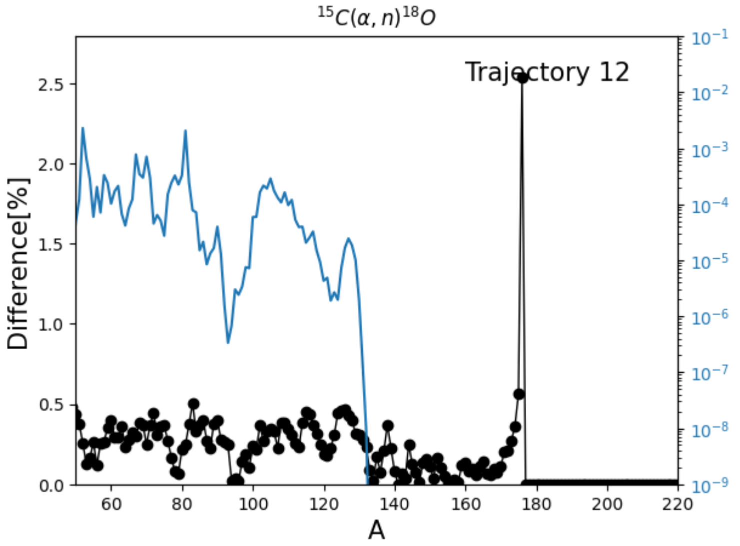
$$\tau_{(n,\gamma)} = (n_n < \sigma_{(n,\gamma)} v_n >)^{-1}$$

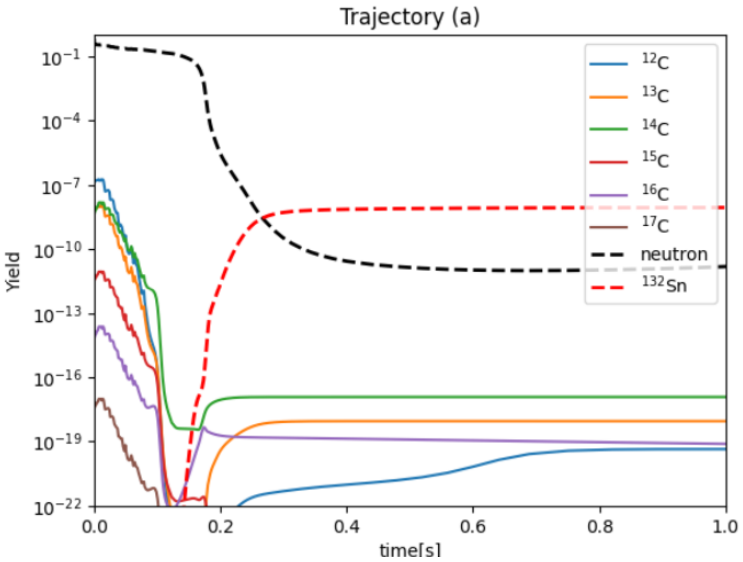
$\boldsymbol{\tau}$ means the mean time of collisions of (n,$\boldsymbol{\gamma}$) reaction for the unit density of the isotope.

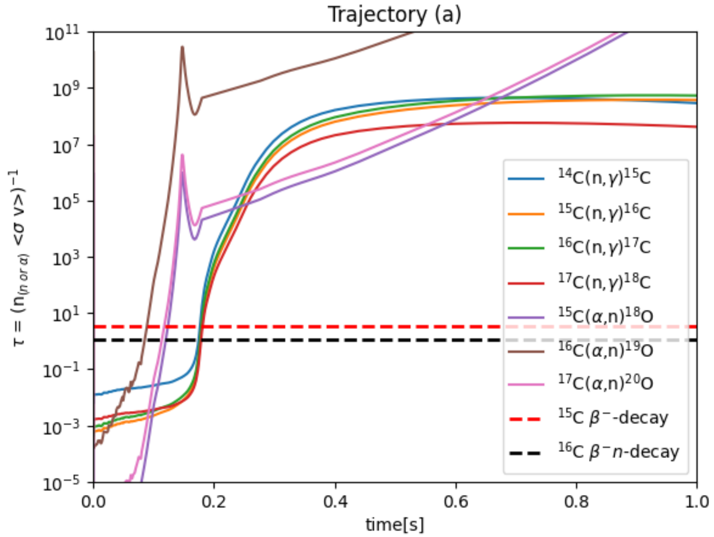
The inverse of $\boldsymbol{\tau}$ means the reaction rate per unit density of the isotope.

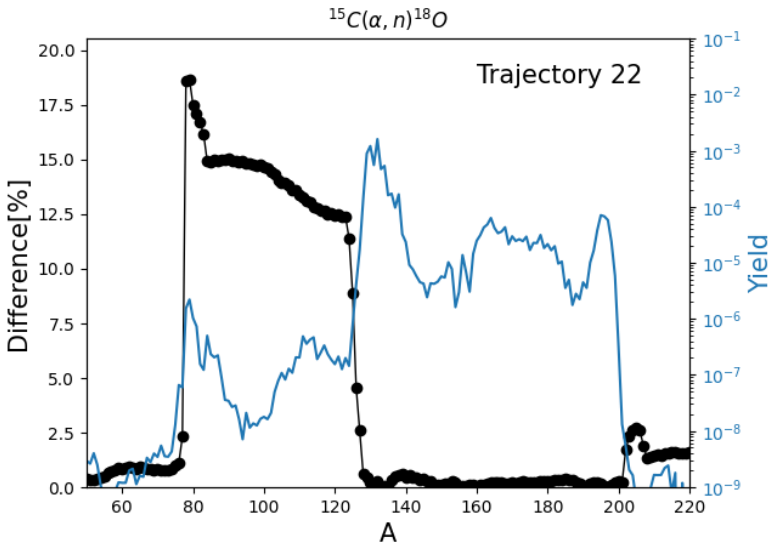
cf.) Typical meaning of the collision timescale is the mean time of collisions between two objects in the certain thermodynamic environment.

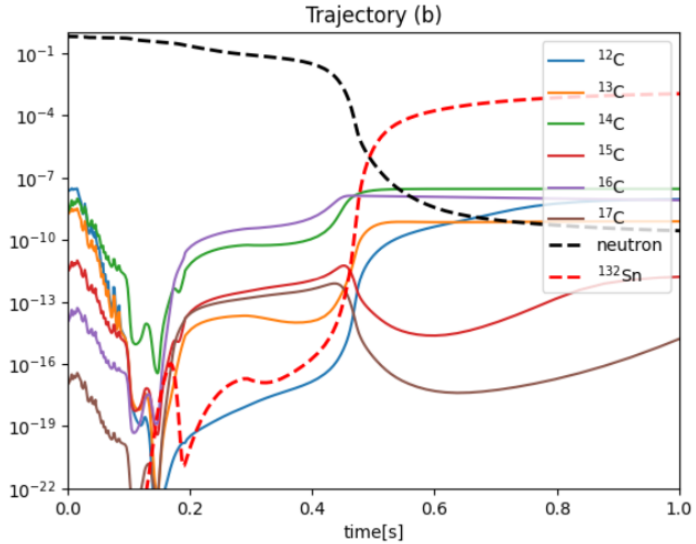
04 Collision Time Scale

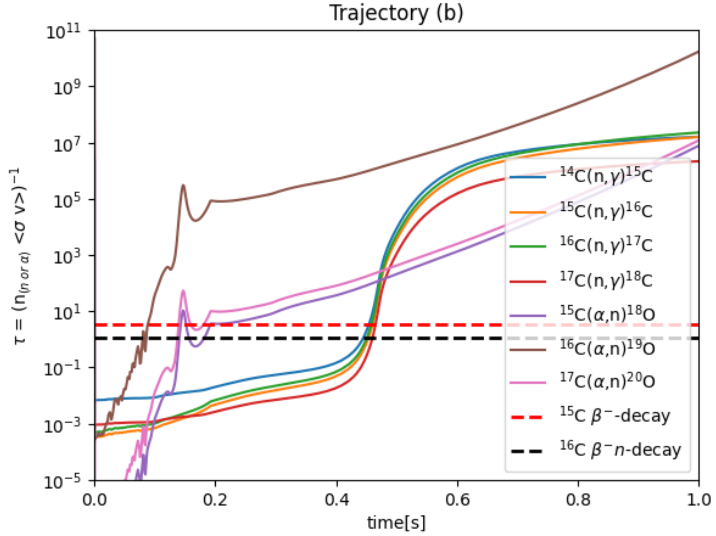




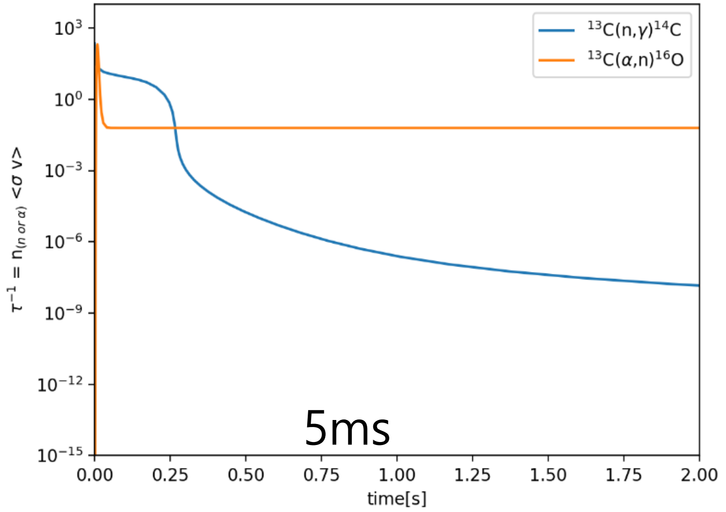


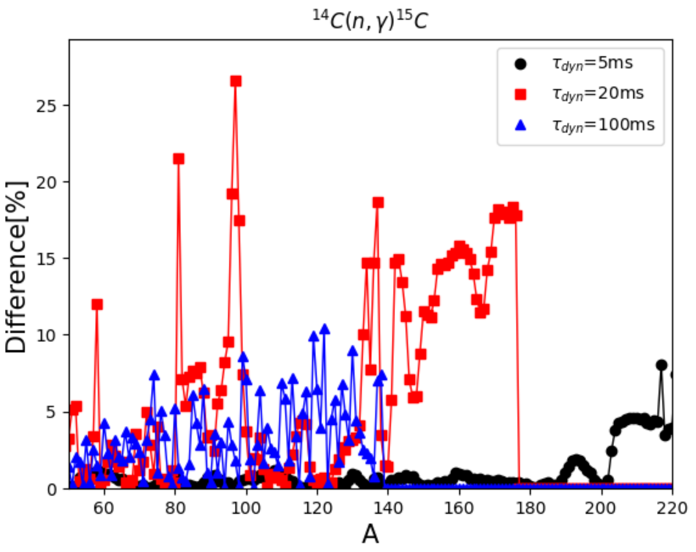


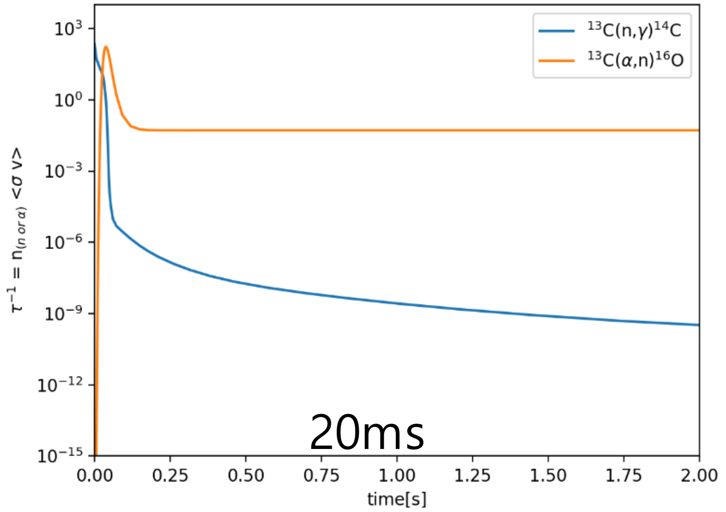


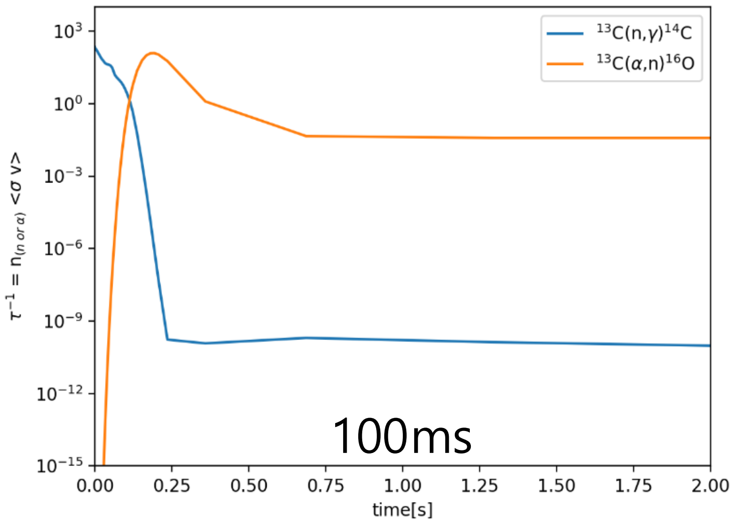


04 Collision Time Scale - $^{13}C(n,\gamma)^{14}C$ and $^{13}C(\alpha,n)^{16}O$



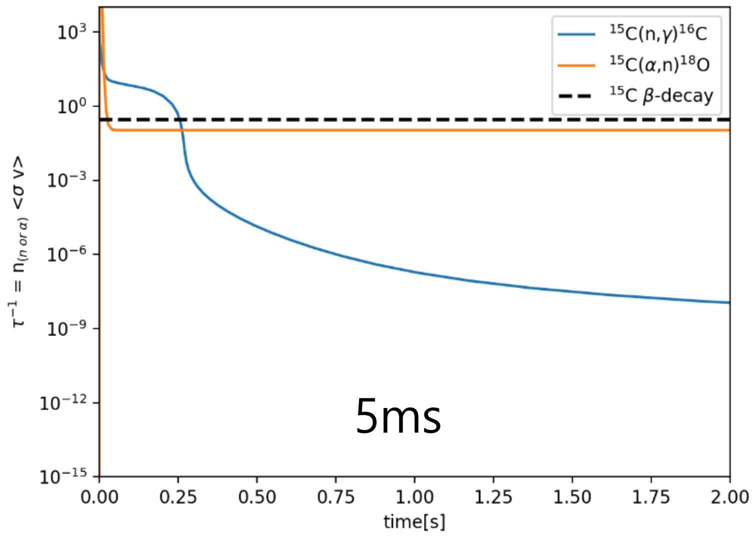


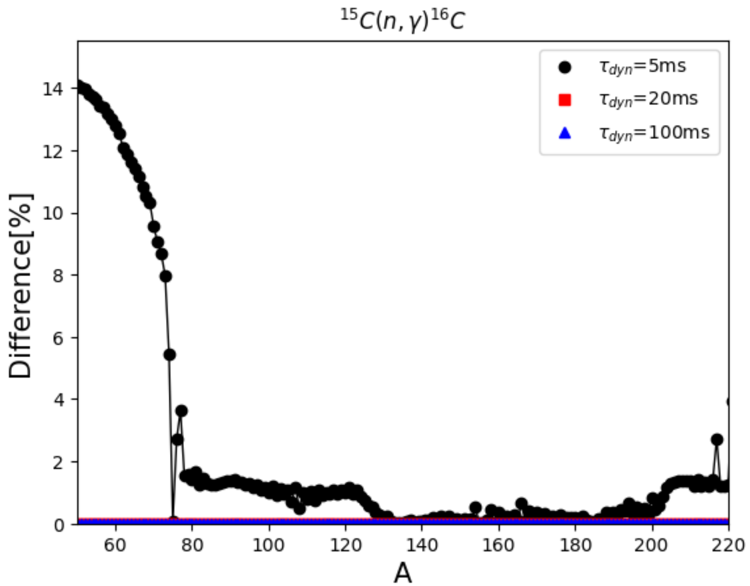


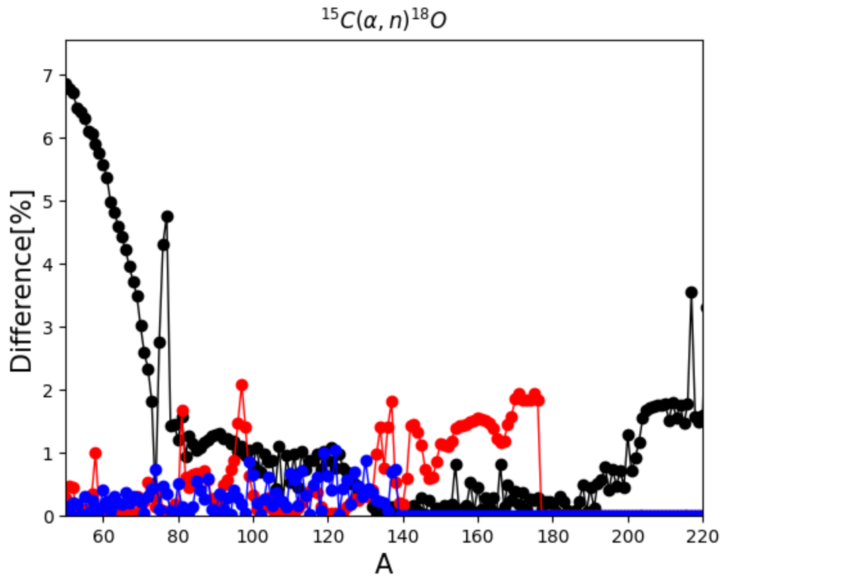


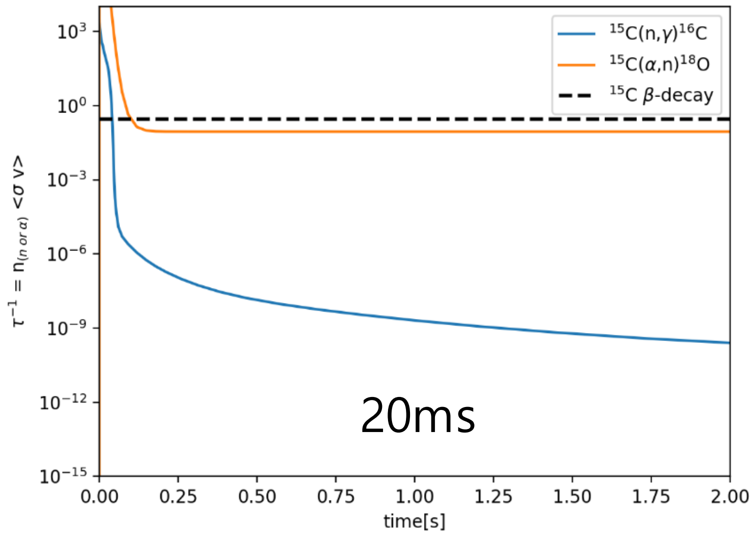
- For every τ_{dyn}, $^{13}C(n,\gamma)^{14}C$ reaction has shorter collision timescale than $^{13}C(\alpha,n)^{16}O$ reaction at the early of r-process.

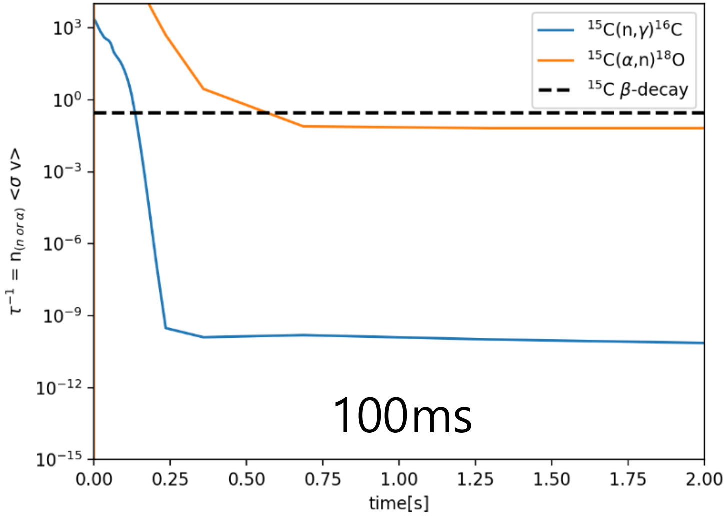
04 Collision Time Scale -$^{15}C(n,\gamma)^{16}C$ and $^{15}C(\alpha,n)^{18}O$











- For only τ_{dyn}=5ms $^{15}C(n,\gamma)^{16}C$ reaction has shorter collision timescale than $^{15}C(\alpha,n)^{18}O$ reaction at the early of r-process.

05 Summary

- We investigate the sensitivity of light nuclear reactions for MHD jet and collapsar environments.
- As well as neutron capture reactions, (α,n) reactions have also impacts on the r-process.
- The comparison among the collision timescale of various astrophysical reactions helps us to understand the r-process path.
- The different r-process path means that the importance of a nuclear reaction is different by the r-process scenarios.

Thank you for your attention!

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