Sensitivity of r-process nucleosynthesis to the light mass nuclear reactions

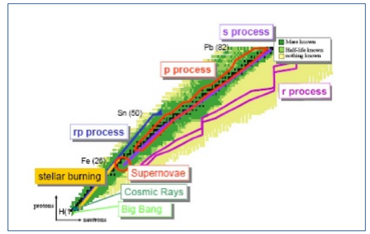
Kyungil Kim

CENuM-RULiC Workshop, Nov. 1, 2019

in collaboration with Toshitaka Kajino, Shota Shibagaki (NAOJ)
Youngman Kim (IBS)

Motivation

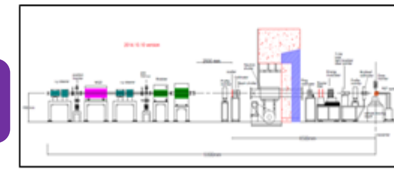
RAON



8그룹
Theory

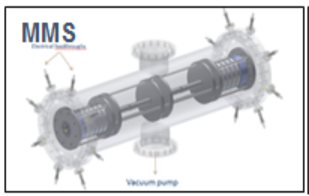
- 핵구조 연구
- 우주 열 핵반응 및 핵합성 연구

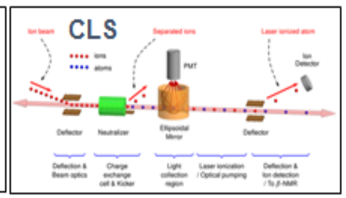
7그룹
BIS



- 암 치료 연구
- 새로운 육종 연구

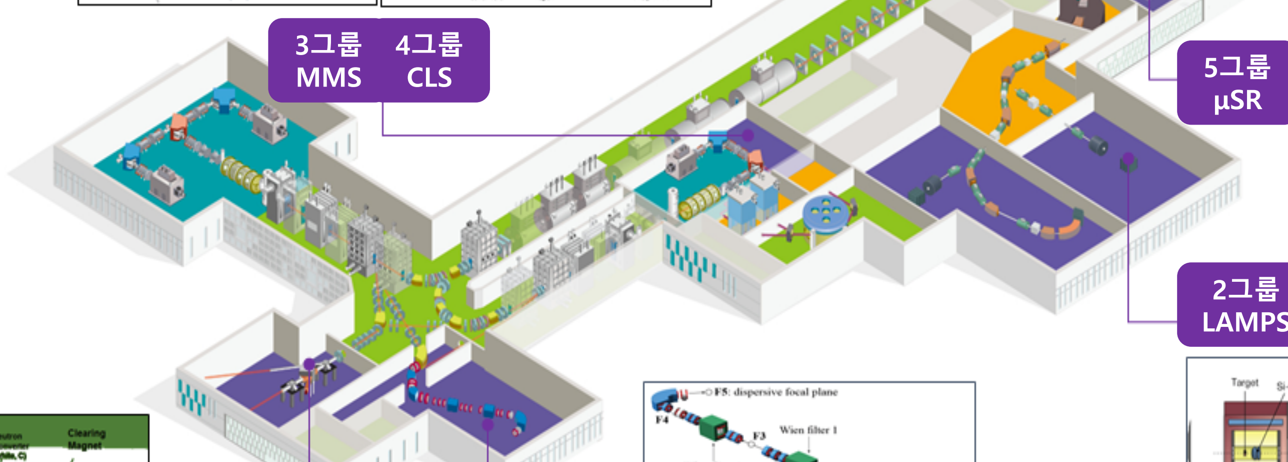
- 동위원소 질량 측정
- Charge Radius 측정



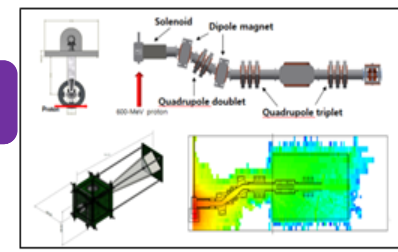


3그룹
MMS

4그룹
CLS



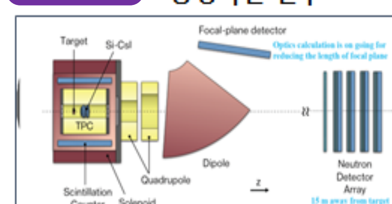
- 물성 연구

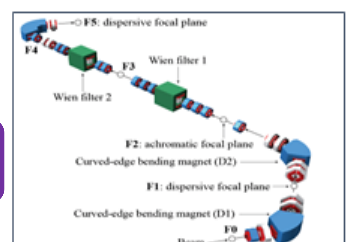


5그룹
μSR

2그룹
LAMPS

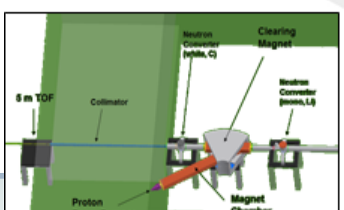
- 핵 물질 연구
- 중성자별 연구





1그룹
KOBRA

- Astrophysics
- 핵 구조 연구

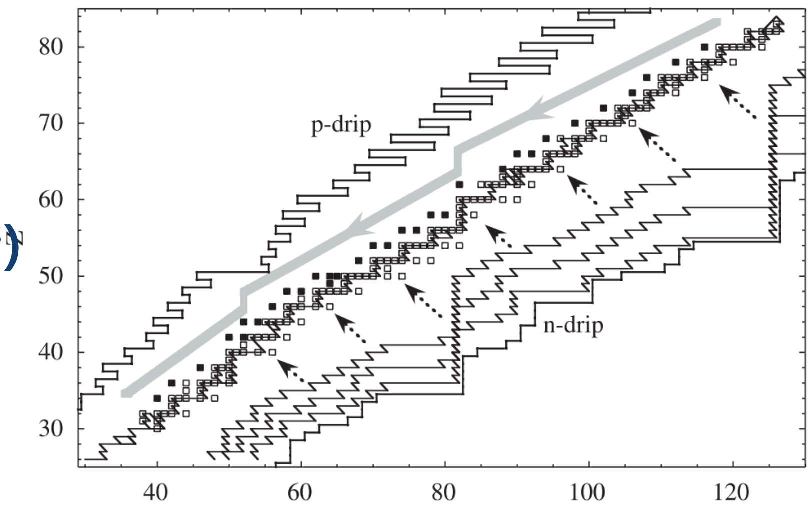


6그룹
NDPS

- 핵자료 연구

r-process ?

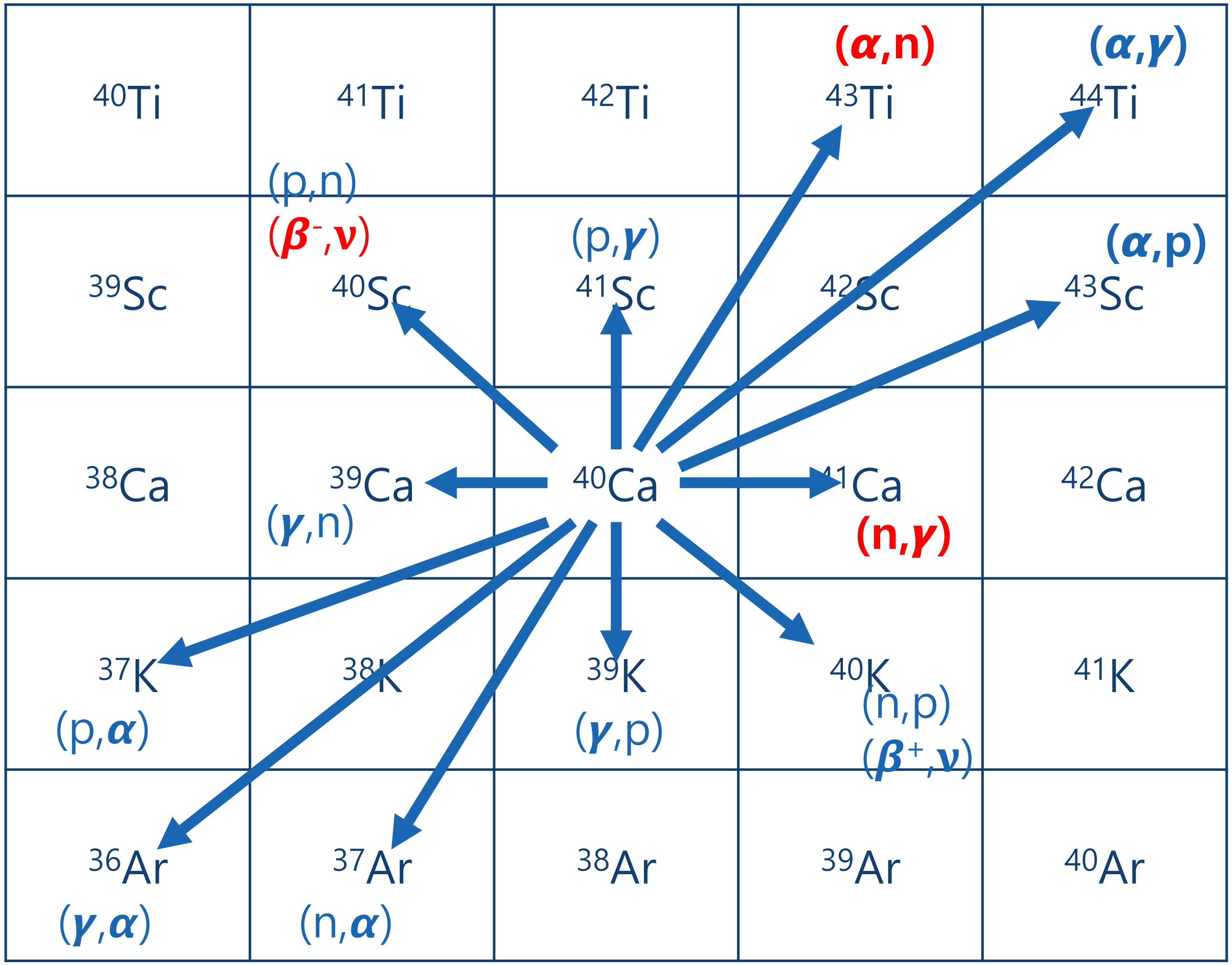
M. Arnould et al. / Physics Reports 450 (2007) 97–213



- **Rapid neutron capture process**
- **High temperature ($T>10^9$K)**
- **High neutron density ($\rho_n>10^{22}cm^3$)**
- **Near neutron-drip line**
- **Reaction network with thousands of nuclear reactions**
  - ➢ **Many of reactions are still uncertain!**
- **Very sensitive to the temperature and density trajectory of r-process site**
  - ➢ **Still candidate sites of r-process are under debate!**

Related Nuclear Reactions

Possible reactions from each cell in the nuclear chart



$^{17}C(n,\gamma)^{18}C$ Reaction

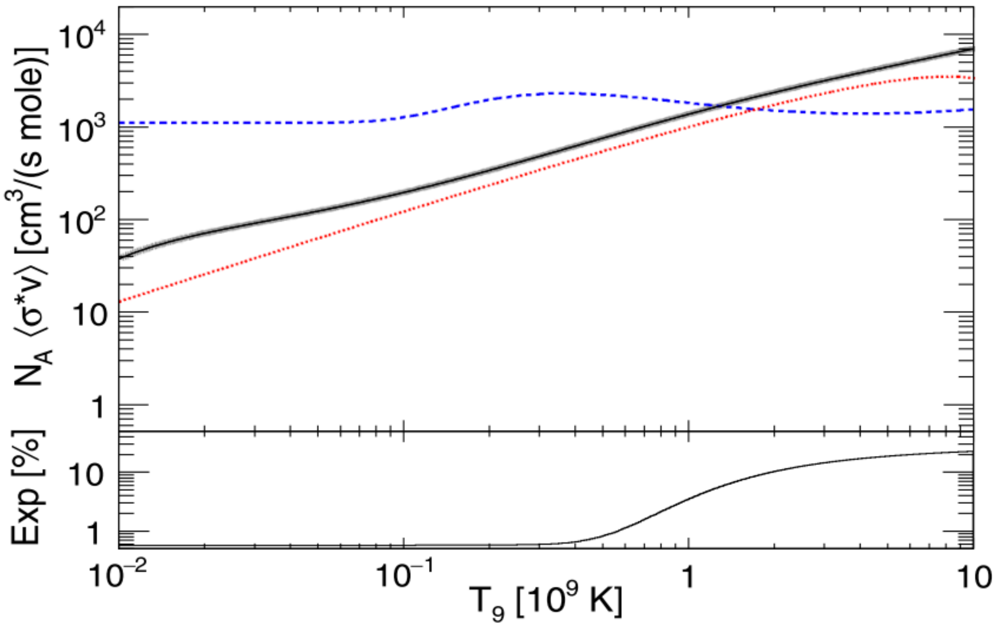
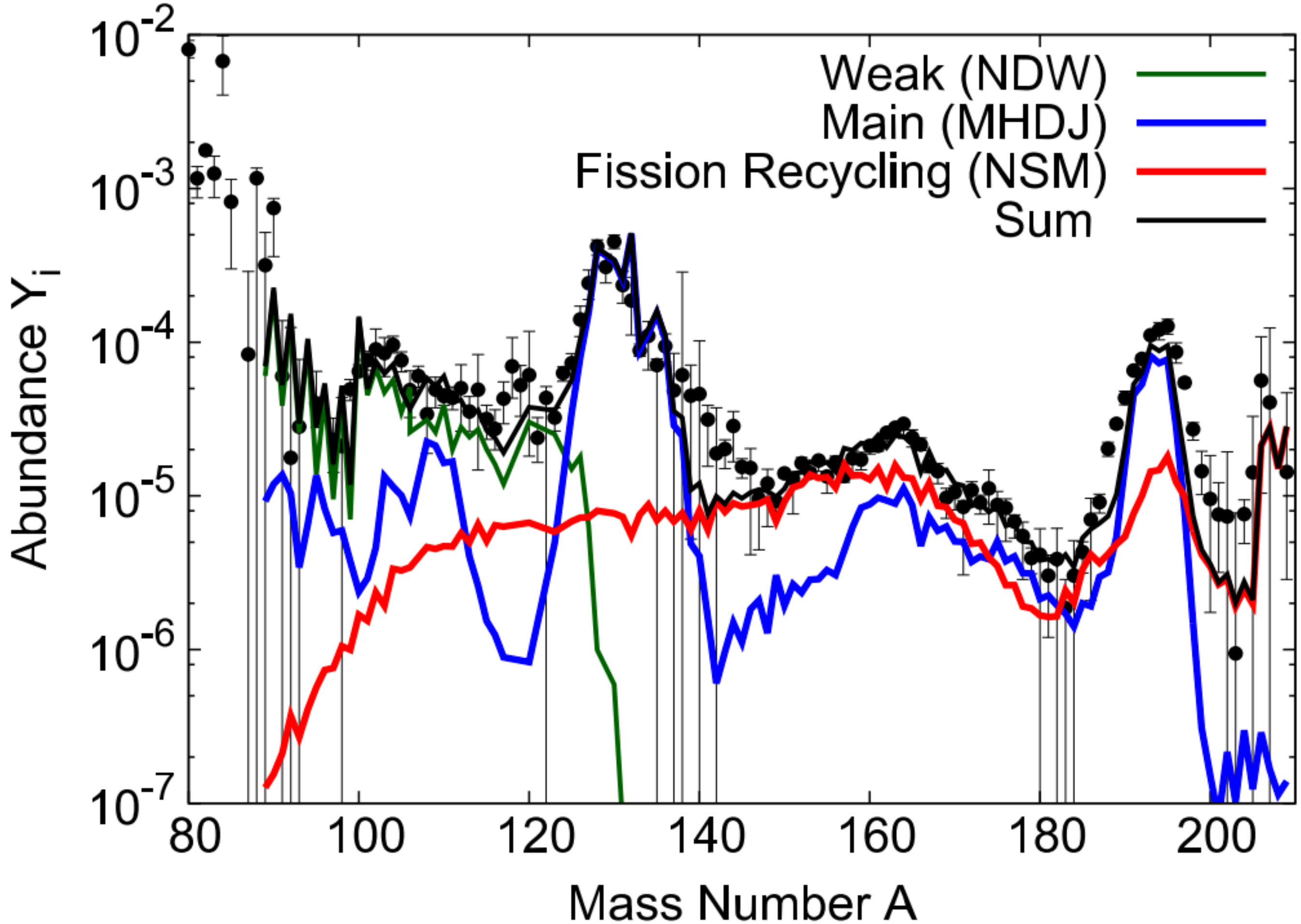


FIG. 5. (Upper panel) Reaction rate for neutron capture on ^{17}C with respect to the stellar temperature T_9. Present data (grey band) are compared to Hauser-Feshbach rates [9] (dashed blue line) and a direct capture model [29] (dotted red line) calculation. In the lower panel the actual contribution of experimental data, i.e., transitions to the ground state in ^{18}C, is displayed.

ref.) M.Heine et al. PRC 95, 014613 (2017)

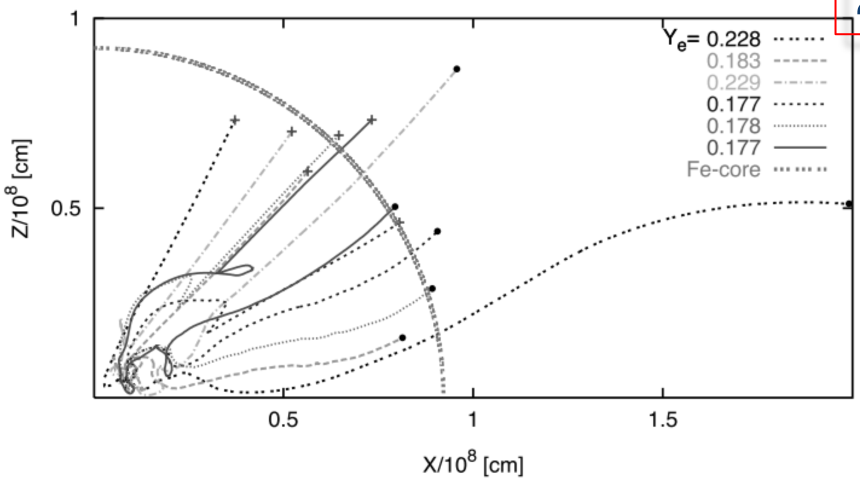
Introduction

Comparison with Experiment

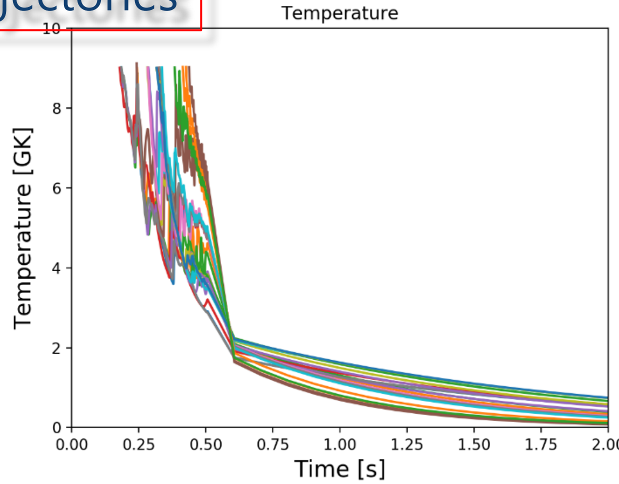


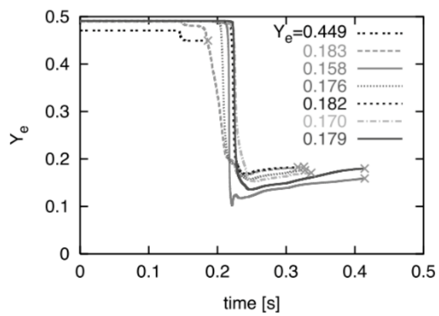
ref.) S. Shibagaki, T. Kajino, G. J. Mathews, S. Chiba, S. Nishimura, and G. Lorusso, Astrophys. J. 816,79 (2016)

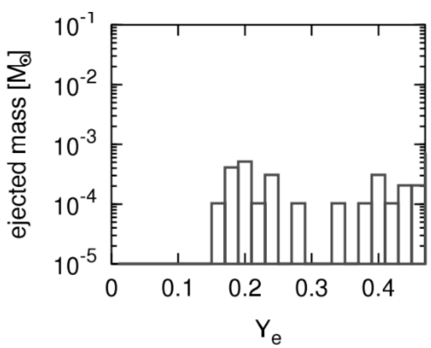
Magnetohydrodynamic Jet

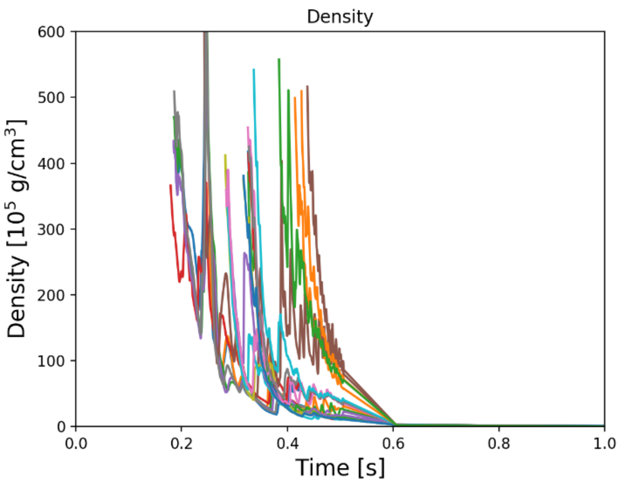


23 Trajectories





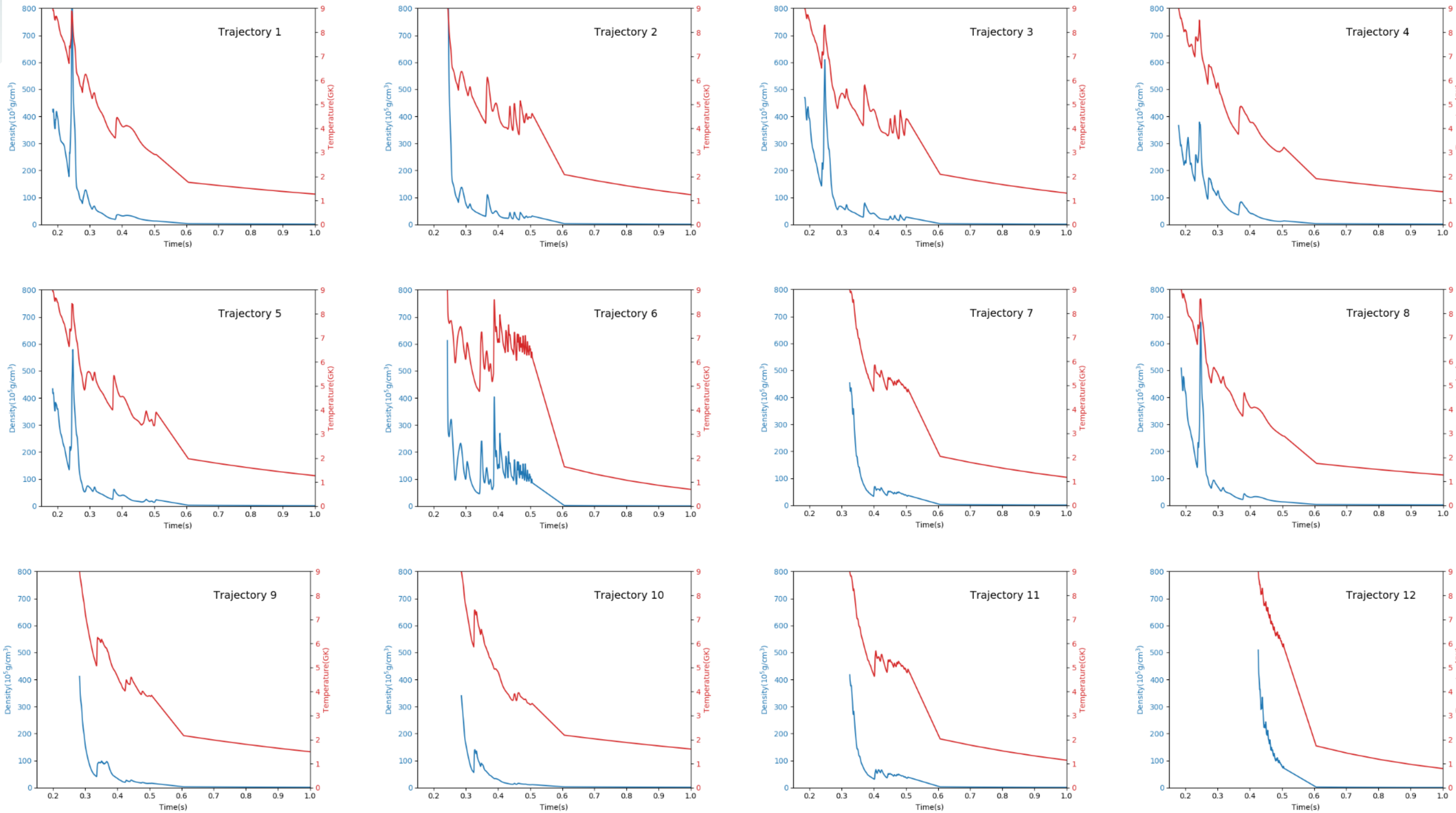




ref.) S.Nishimura, et al., Astrophys. J. 642,410 (2006)

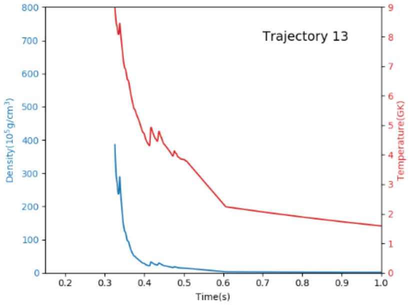
MHD Jet Trajectories 1

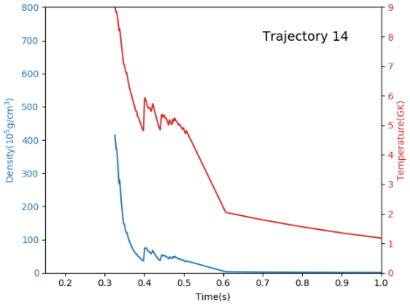
Temperature and Density

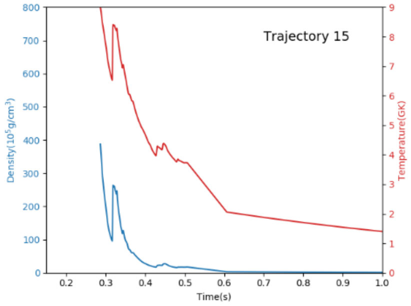


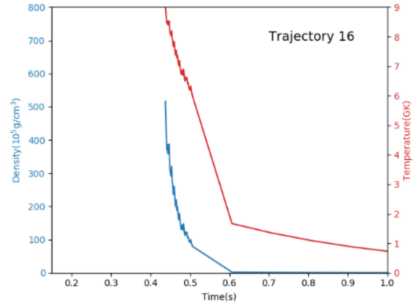
MHD Jet Trajectories 2

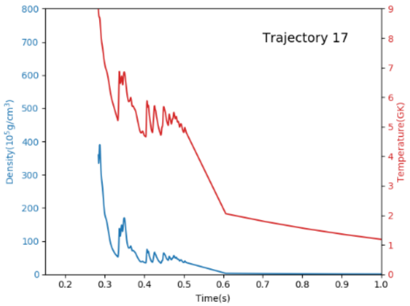
Temperature and Density

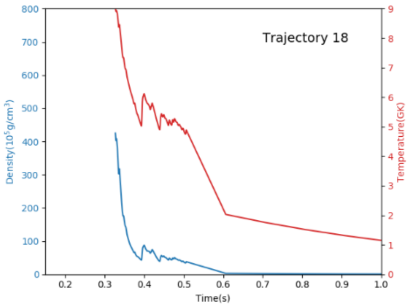


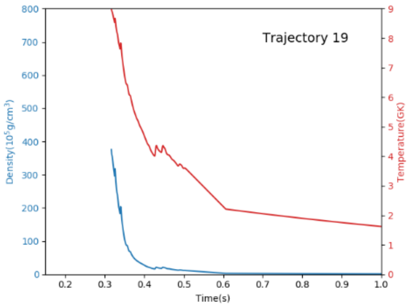


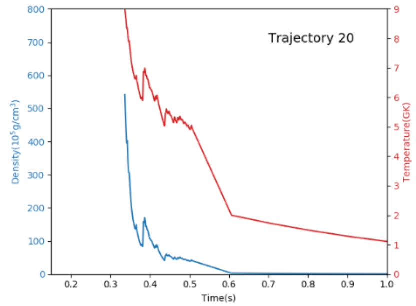


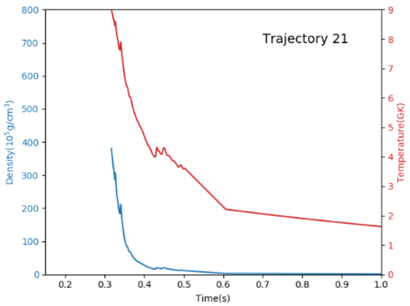


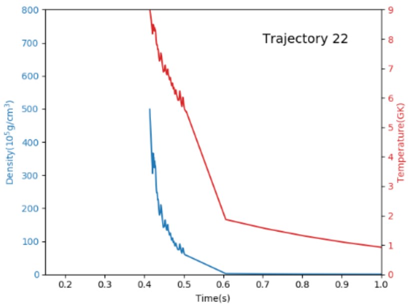


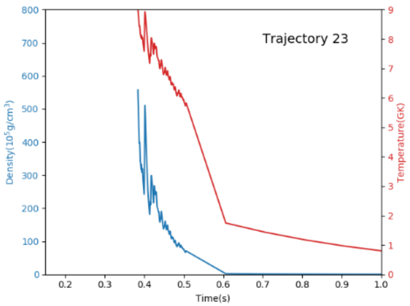












Clemson Code

Bradley S. Meyer https://sourceforge.net/u/mbradle/blog/?page=4

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Changing input conditions for our first network calculation

Our first network calculation began with 100% of the mass in ^{1}H and ran at constant temperature of 1.5 x 10^7 K (t9 = 0.015) and density of 150 g/cc. Let's now compare with a detailed standard solar model.

From the standard solar model table, we see that the center of the Sun (the first data line in the table) has a current temperature of 1.548 x 10^7 K and a mass density of 1.505 x 10^2 g/cc. The current age of the Sun is about 4.56 Gyr, which is about 1.44 x 10^{17} seconds.... read more

Posted by *2012-07-08*

Labels: *network calculation input pp-chain*

Analyzing a first network calculation

In the previous post, I went through the steps to run a simple network calcula
nuclear reactions occurring in the center of the Sun, which is burning hydroge
hydrogen and helium mass fractions versus time.

Change into the analysis directory from the network directory:... read more

Posted by *2012-07-07*

Labels: *network calculation analysis pp-chain*

The JINA Center for the Evolution of the Elements

REACLIB Database

you are not logged in | [login] [sign up]

Welcome to the JINA Reaclib Database!

This is a database for nuclear reaction rates to be used in astrophysical model calculations.
To get help please visit the help page.

For more details and REACLIB citation, see Cyburt et al., ApJS 189 (2010) 240.

Database:

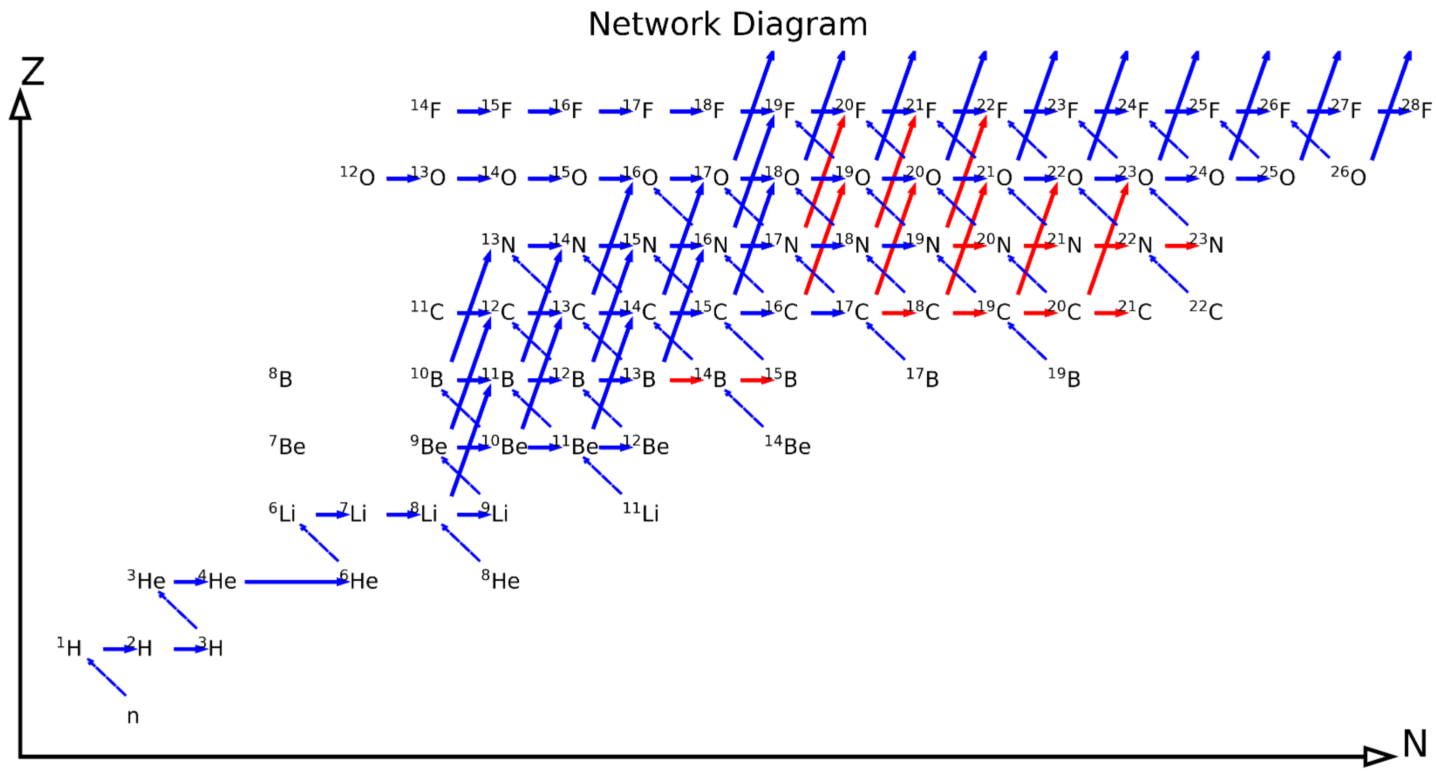
Contains multiple versions of each rate with one recommended rate.
One can find rates using our search engine
or by typing in the specific reaction URL
[e.g. http://groups.nscl.msu.edu/jina/reaclib/db/na21(p,g)]
It is continuously updated as documented on the status/discussion page.

News:

ReaclibV2.2
2016-11-14 Submitted By: Steven Sneed
In reaclib v2.2. we fixed some reverse rate issues. The snapshot is now available.

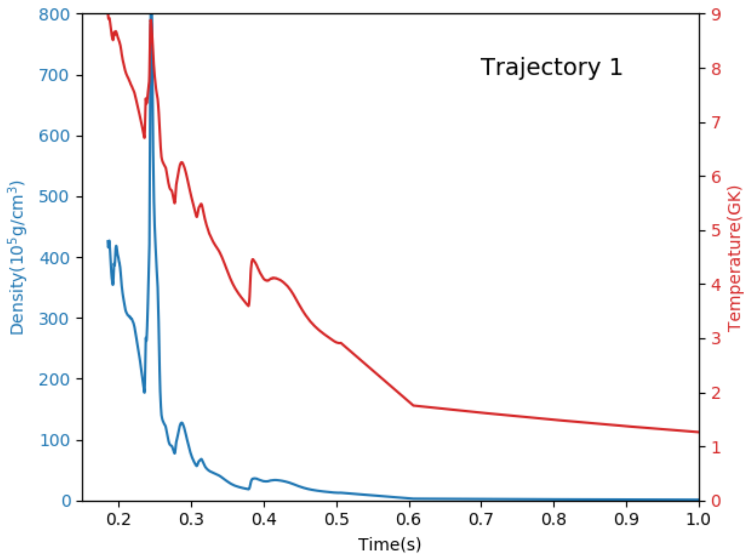
Server Maintenance
2015-02-20 Submitted By: Richard Cyburt
Expect some outages 2-20-2015 due to server maintenance.

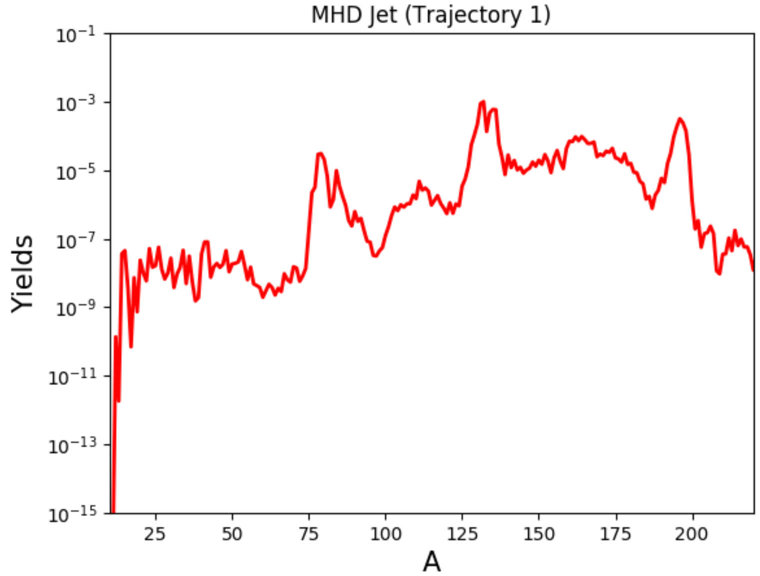
Extended Network

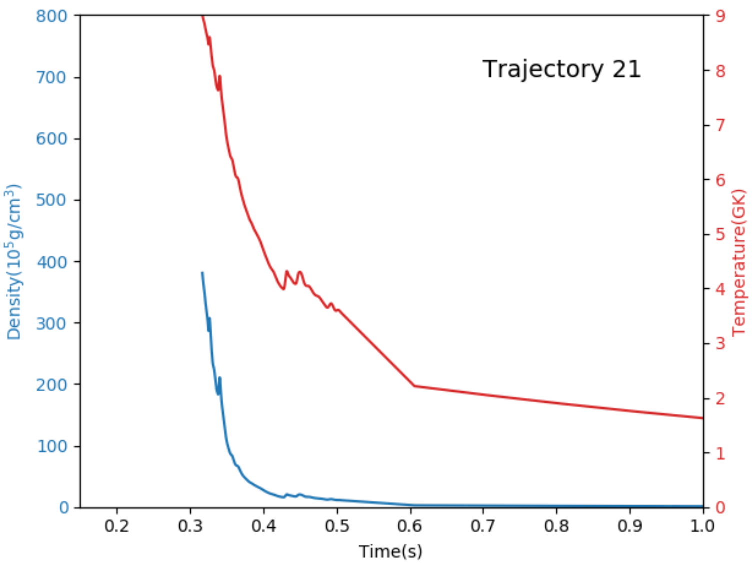


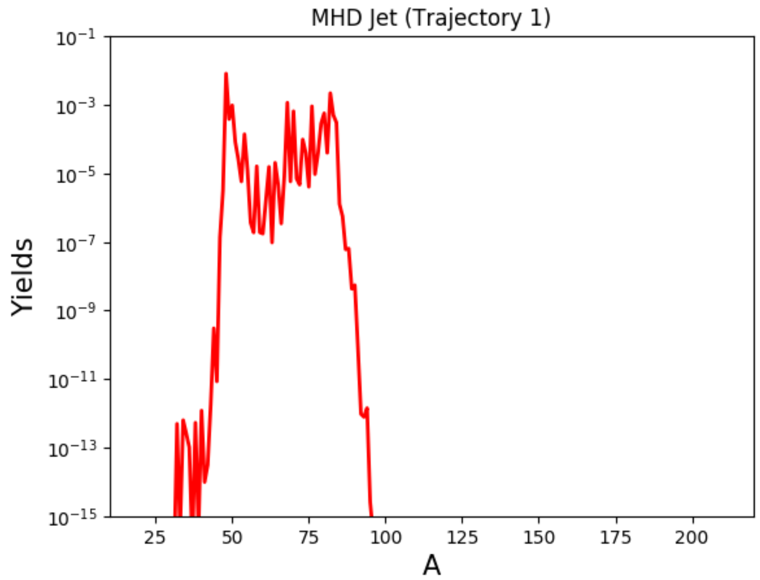
The blue lines are already included in JINA-REACLIB database and the red lines are newly added or modified reaction rates.

r-abundance Results

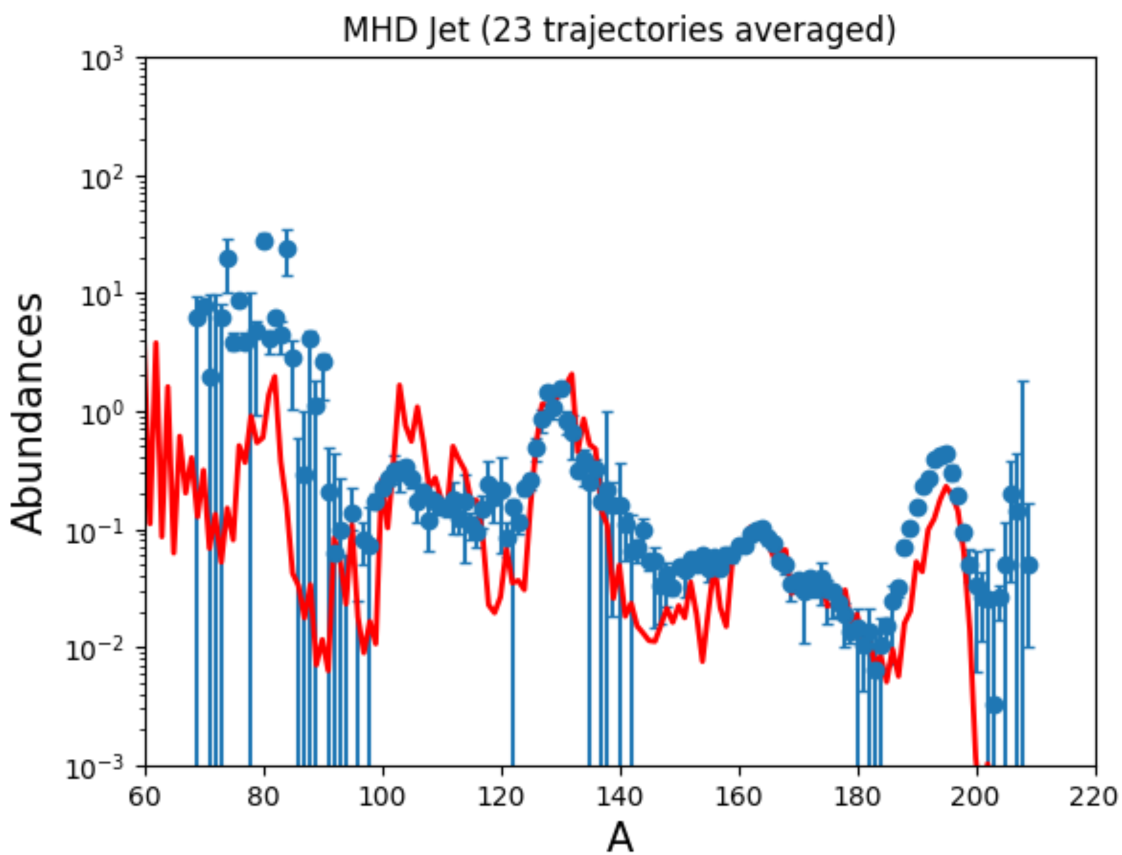








Averaged r-abundance



Exponential Expansion Model

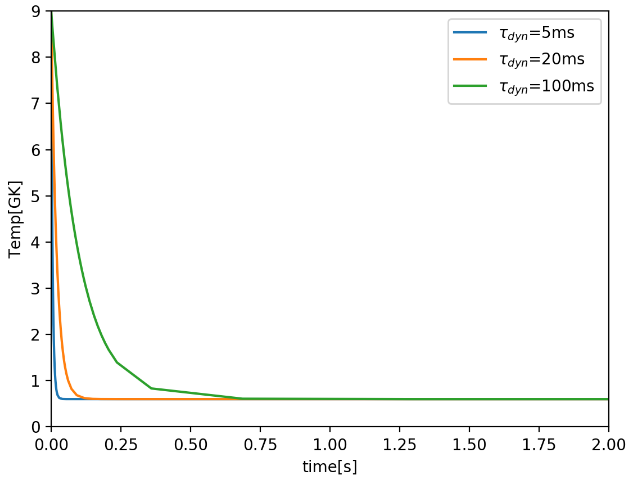
<Temperature and density>

$$T_9(t) = T_9(0)\exp(-t/\tau_{dyn}) + T_a,$$

$$\rho(t) = \rho(0)(T/T_0)^3,$$

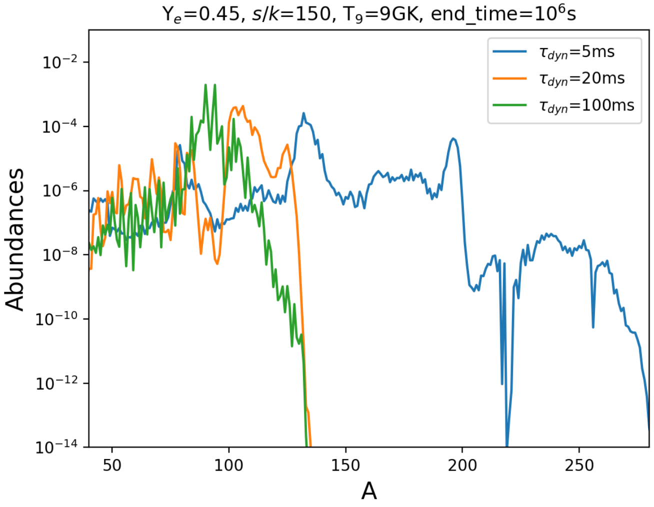
with constant entropy,

$$s = \frac{11\pi^2}{45\rho N_{AV}}\left(\frac{kT}{\hbar c}\right)^3 = 3.34 \times \frac{T_9^3}{\rho_5} = \text{const},$$



<r-abundance with different τ_{dyn}>

- τ_{dyn}=5ms : r-process upto second and third peak
- τ_{dyn}=20, 100ms : weak r-process upto A~130



Collision Timescale

The collision timescale of (n,**γ**) reaction,

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

τ means the mean time of collisions of (n,**γ**) reaction for the unit density of the isotope.

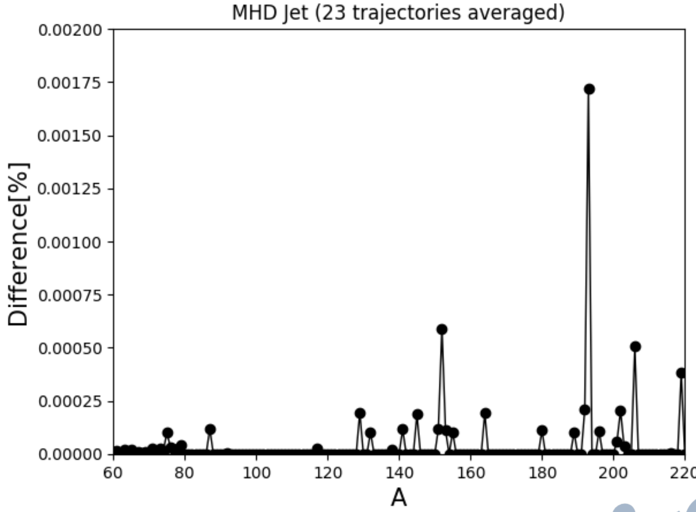
The inverse of **τ** means the reaction rate per unit density of the isotope.

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

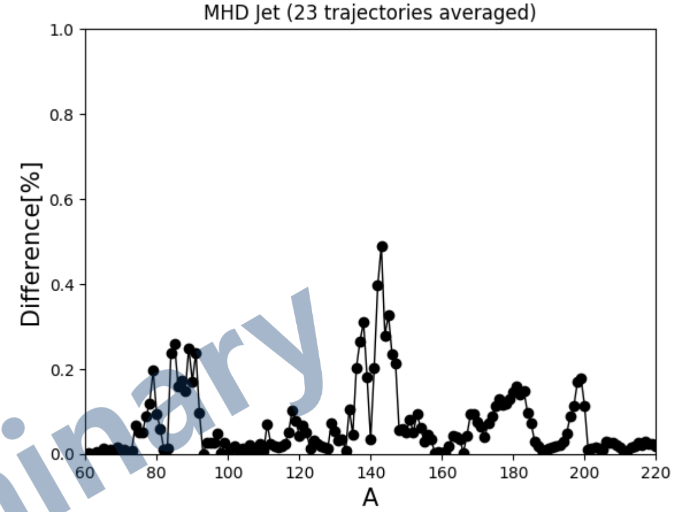
Results

Sensitivity

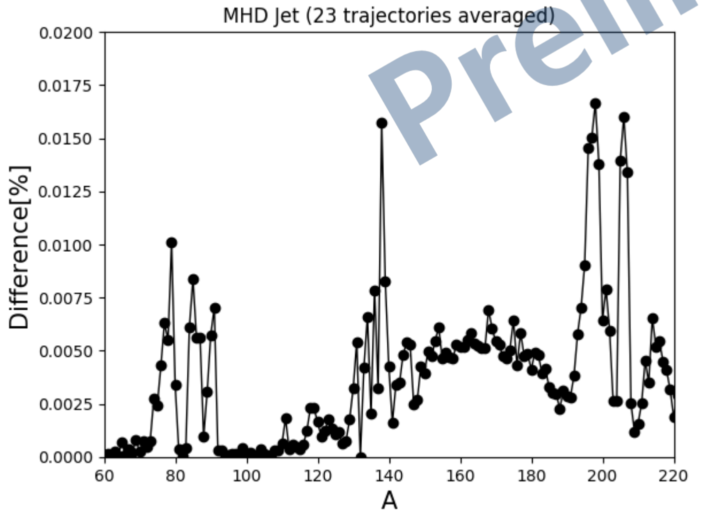
$\alpha(\alpha n,\gamma)^{9}Be$ x10



$^{8}Li(\alpha,n)^{11}B$ x10



$^{13}B(\alpha,n)^{16}N$x10

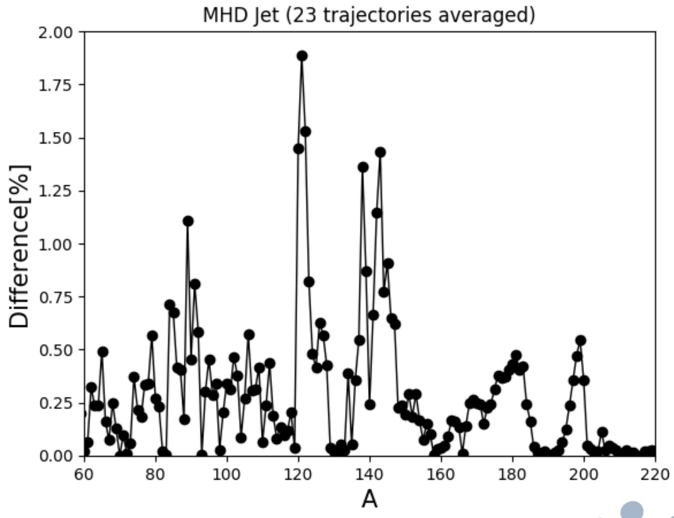


Preliminary

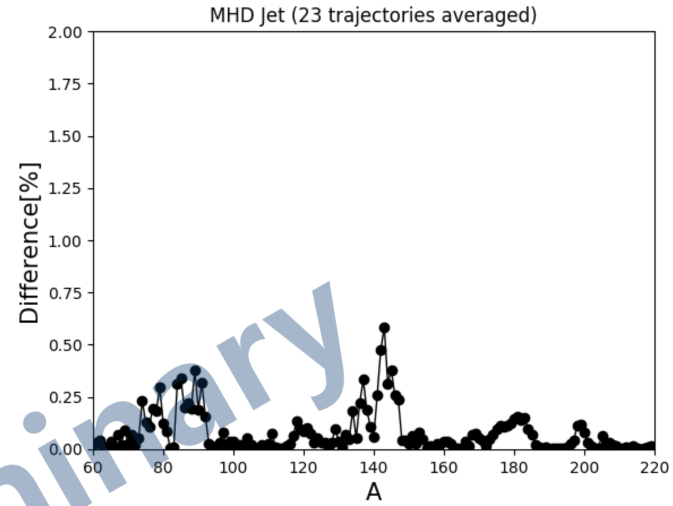
Sensitivity

RAON

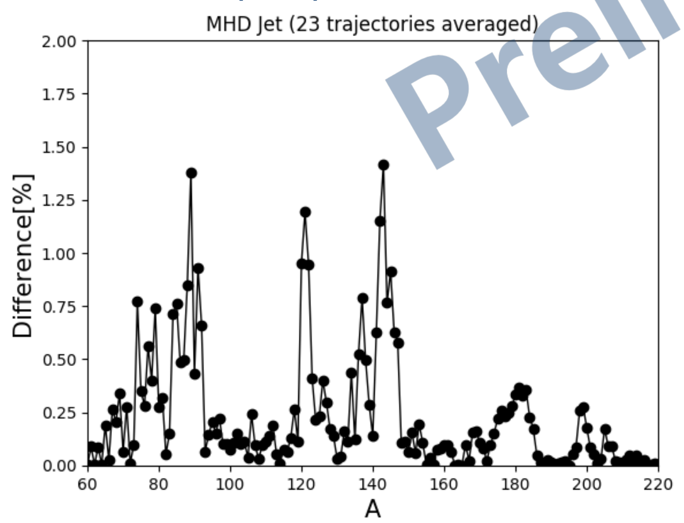
$^{13}C(\alpha,n)^{16}O$ x10



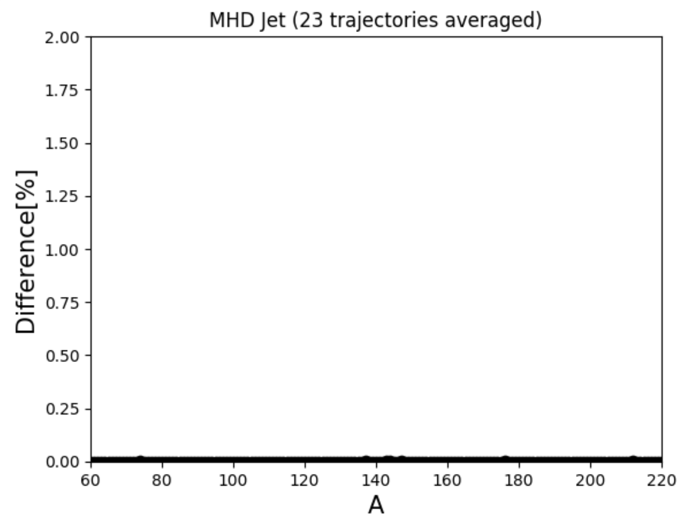
$^{14}C(\alpha,n)^{17}O$ x10



$^{15}C(\alpha,n)^{18}O$ x10

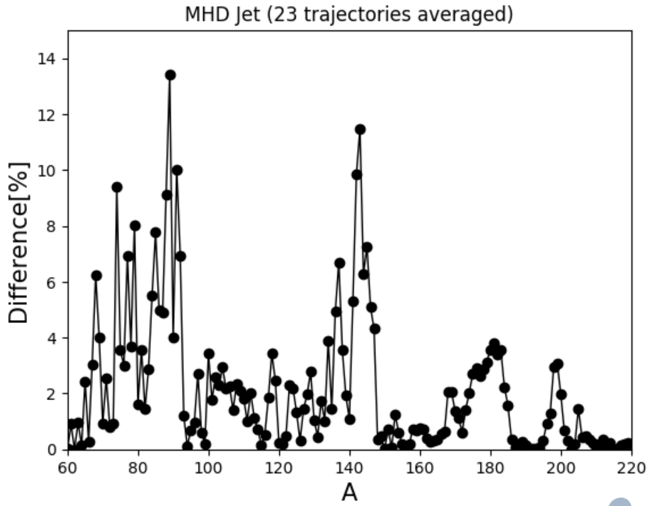


$^{16}C(\alpha,n)^{19}O$ x10

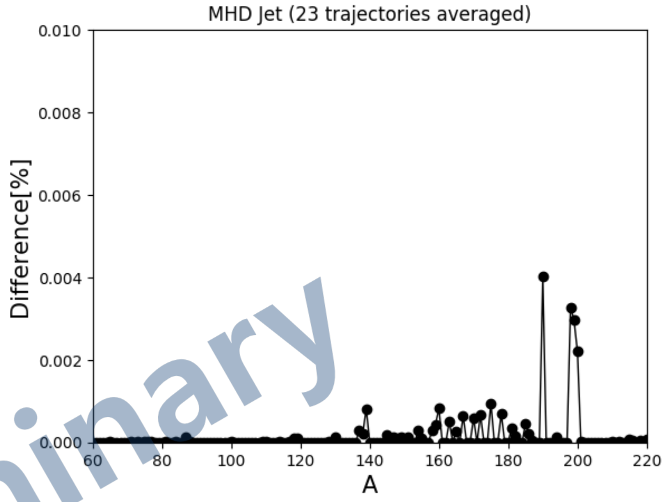


Sensitivity

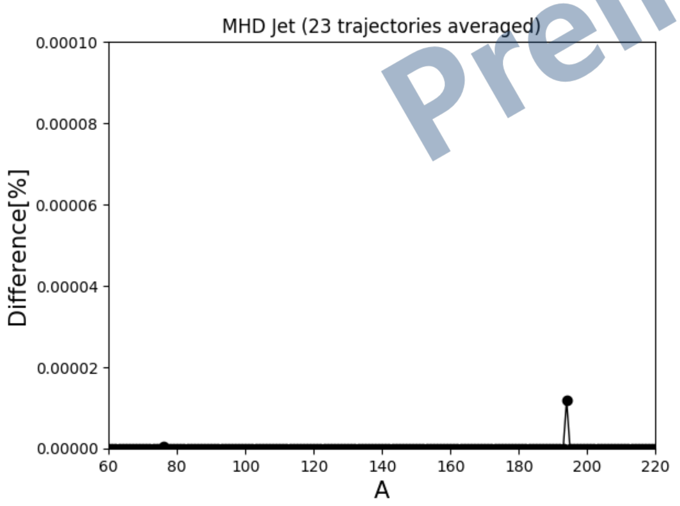
$^{14}C(n,\gamma)^{15}C$ x10



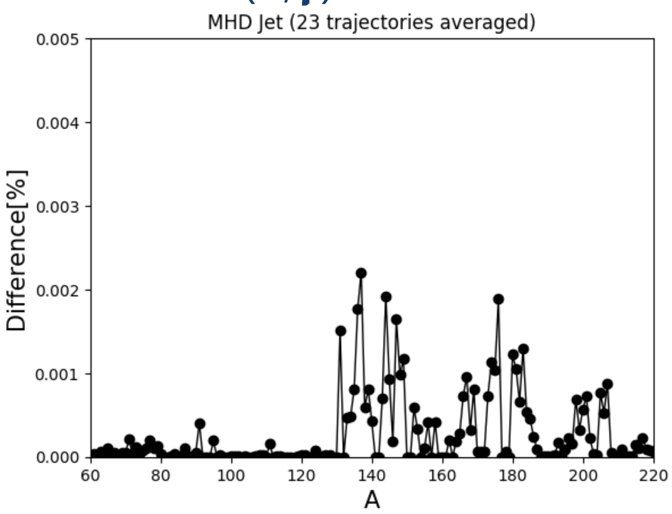
$^{15}C(n,\gamma)^{16}C$ x10



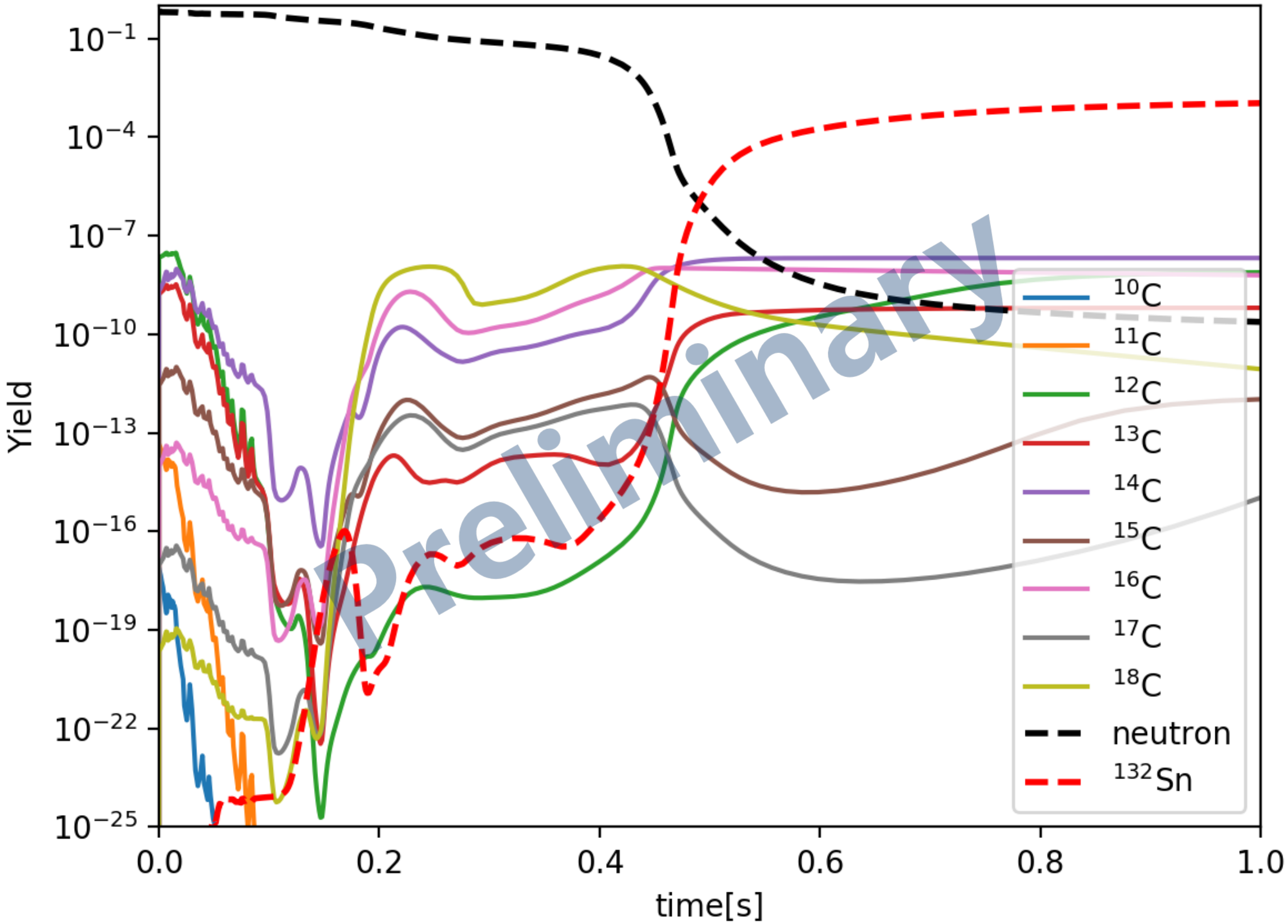
$^{16}C(n,\gamma)^{17}C$ x10



$^{17}C(n,\gamma)^{18}C$ x10



Carbon Yield (MHD Jet)



Exponential Expansion Model

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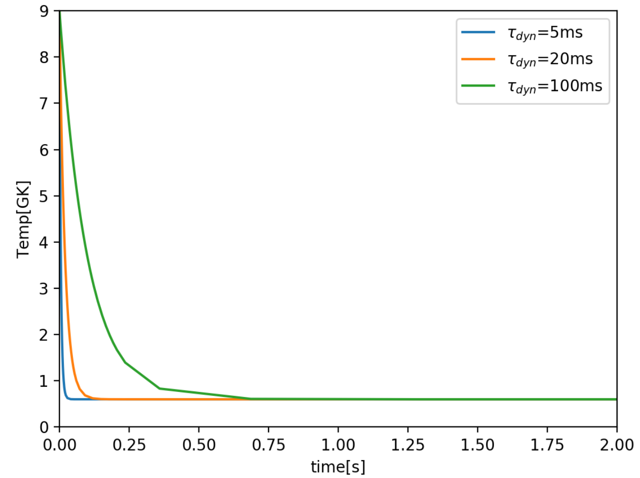

<r-abundance with different τ_{dyn}>

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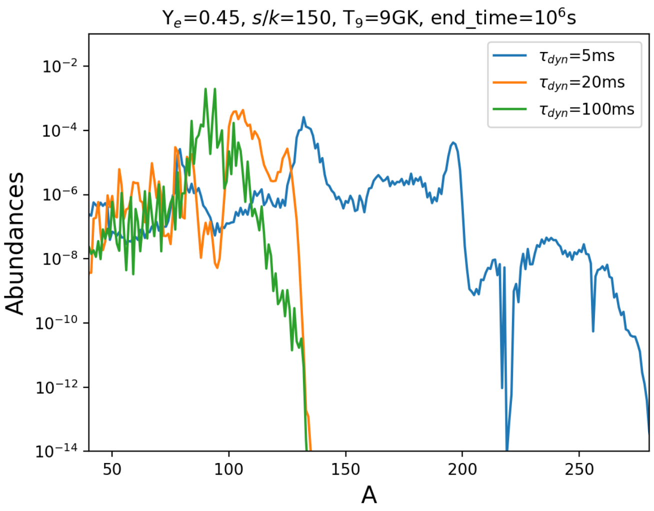
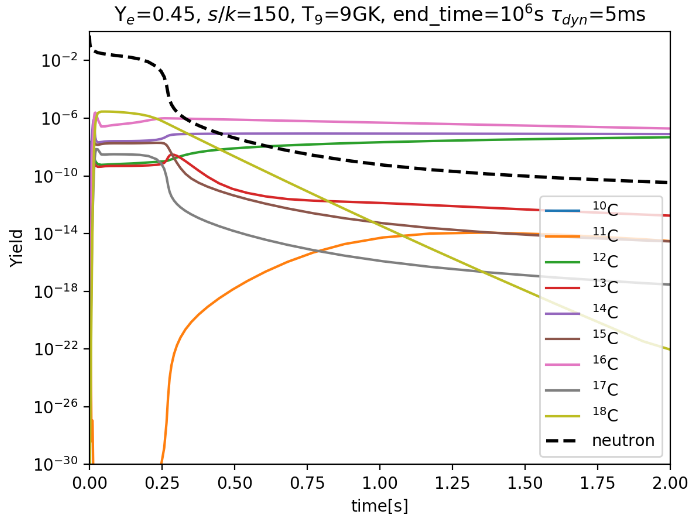
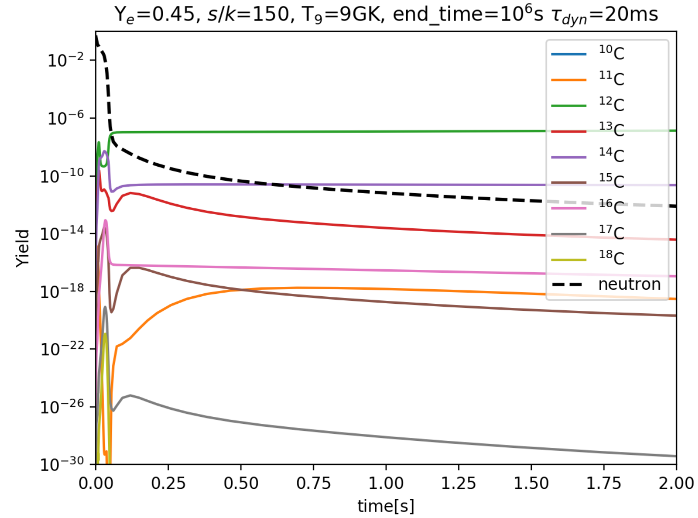
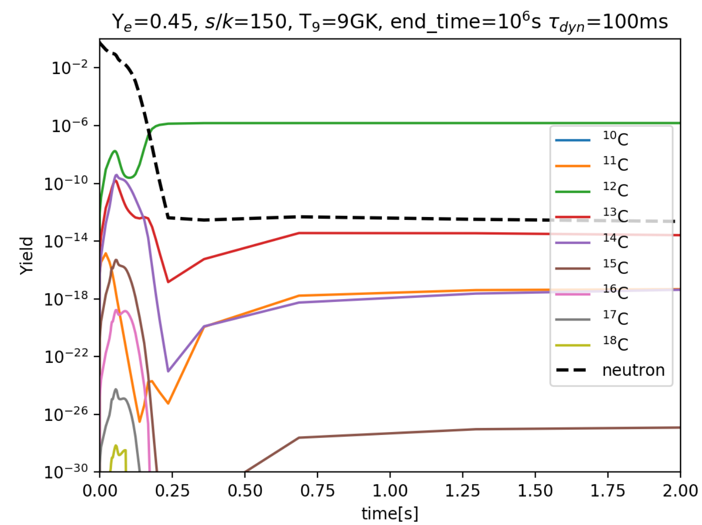


Carbon Yield

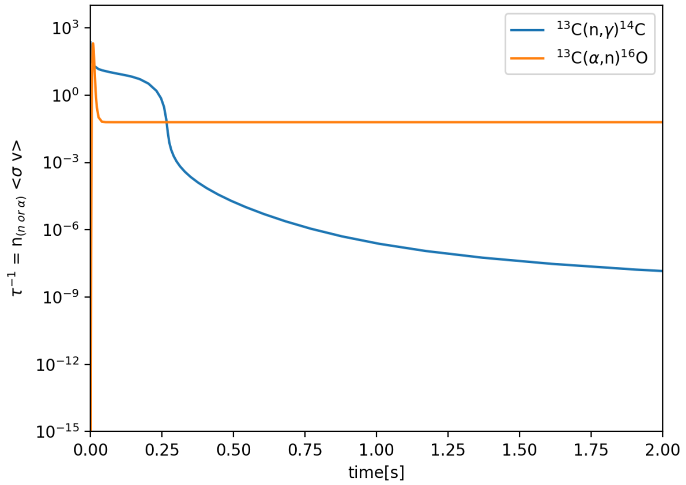


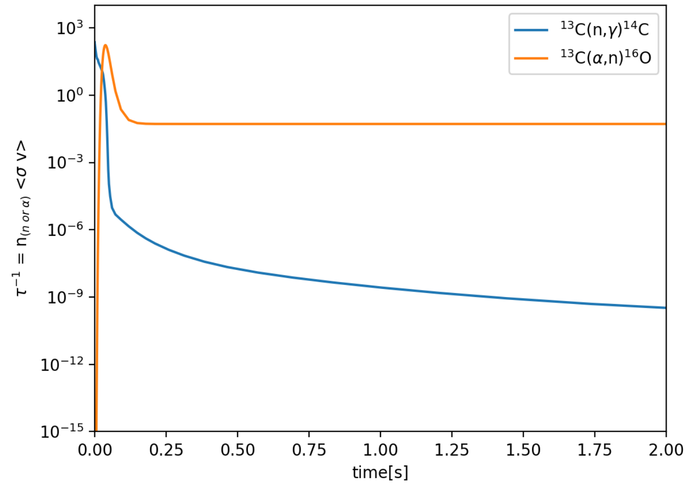


- τ_{dyn}=5ms : The production yield of ^{16}C is larger than other carbon isotopes.
- τ_{dyn}=20, 100ms : The stable carbon has larger yield than others.

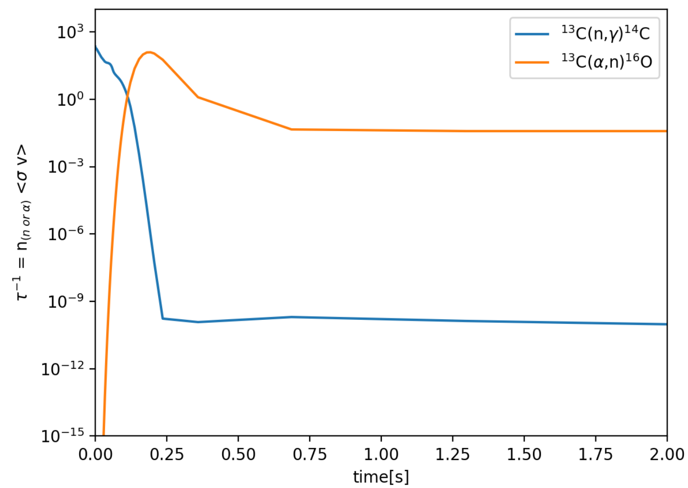


$^{13}C(n,\gamma)^{14}C$ and $^{13}C(\alpha,n)^{16}O$

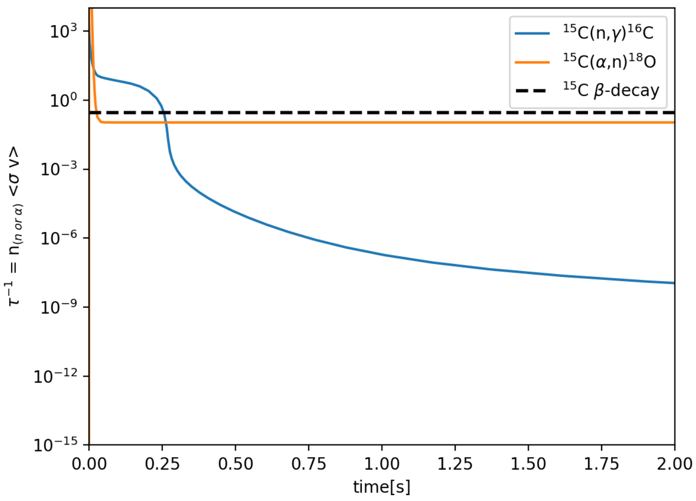


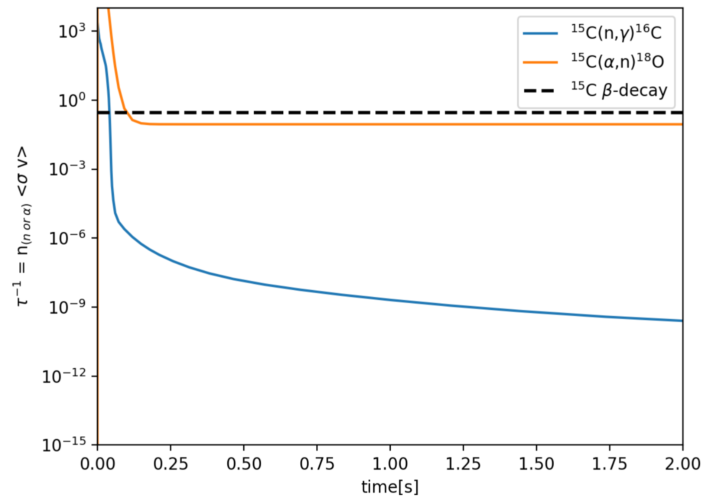


- For every τ_{dyn} , $^{13}C(n,\gamma)^{14}C$ reaction has shorter collision timescale than $^{13}C(\alpha,n)^{16}O$ reaction at the early of r-process.

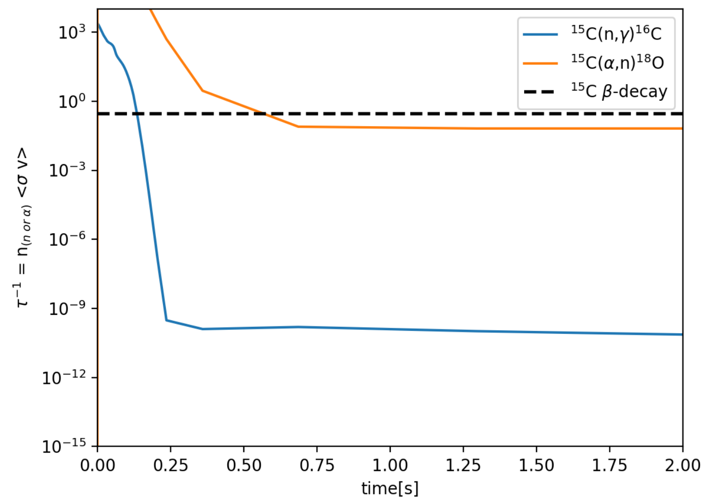


$^{15}C(n,\gamma)^{16}C$ and $^{15}C(\alpha,n)^{18}O$





- 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.



Summary

- RAON will be a good experimental facility for r-process related study.
- We are testing the sensitivity of C,N,O related reactions and the sensitivity of each trajectories for MHD jet.
- 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 very much for your attention!!!!