Discovering the most important temperatures of helium burning reactions in pair-instability supernova nucleosynthesis

Nucleosynthesis and Evolution of Neutron Stars
@Kyoto University Yoshida Campus 2025/01/29

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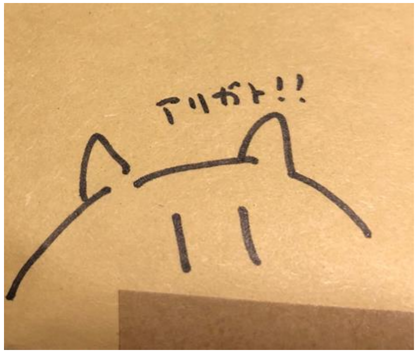

With
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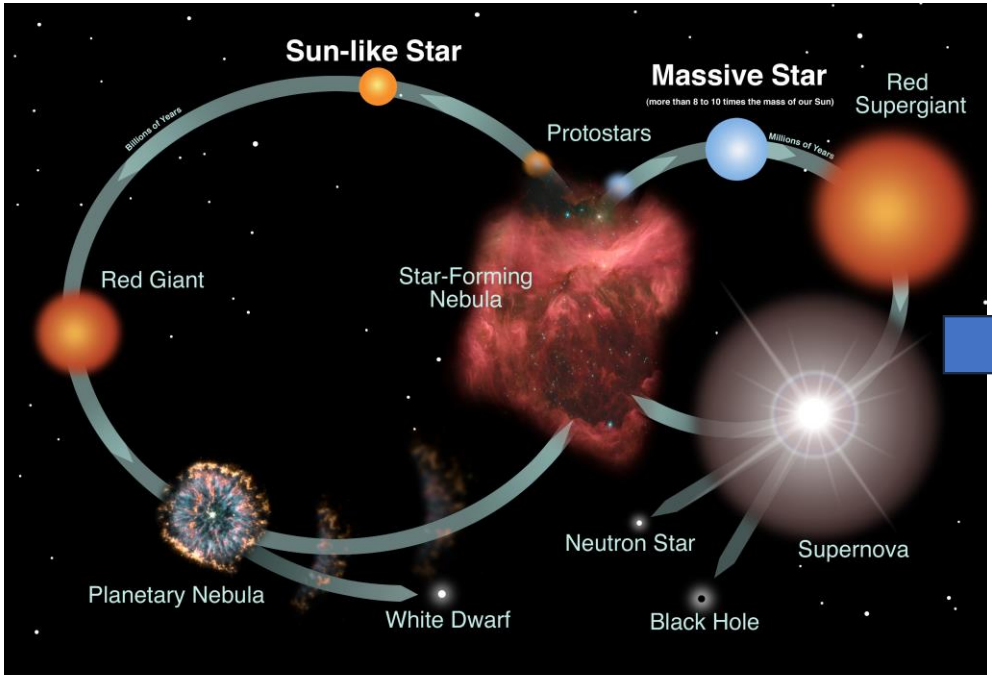
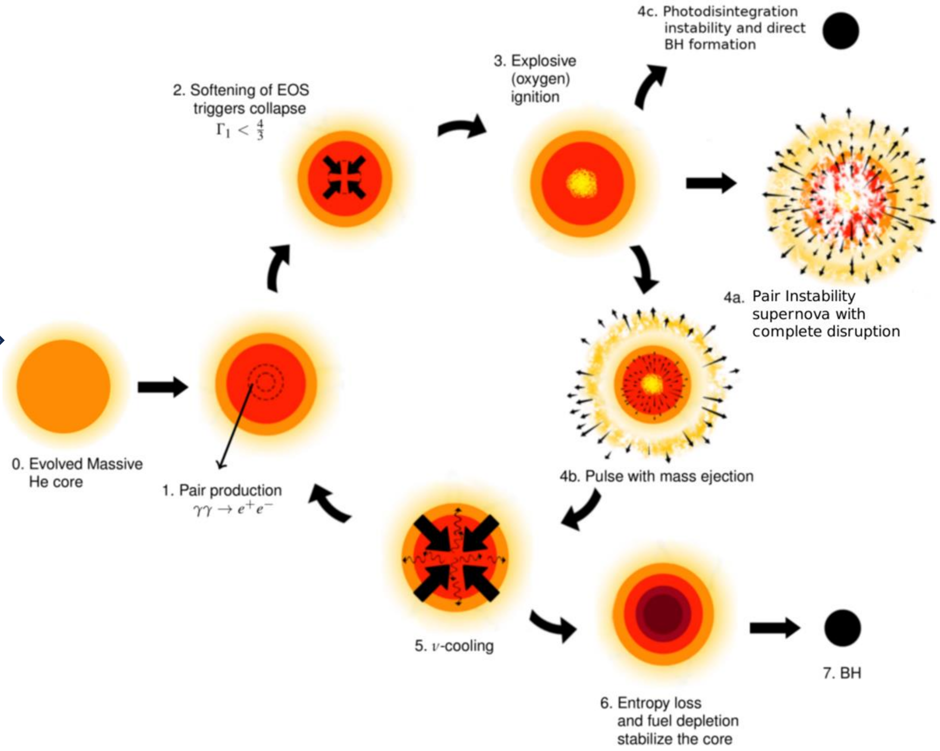
Masaaki Kimura (RIKEN Nishina)
Yudai Suwa (UTokyo Komaba, YITP)

Introduction
Final fates of stars



NASA



M. Renzo *et al.* A&A **640**, A56 (2020)

~8$M_\odot$: White dwarf

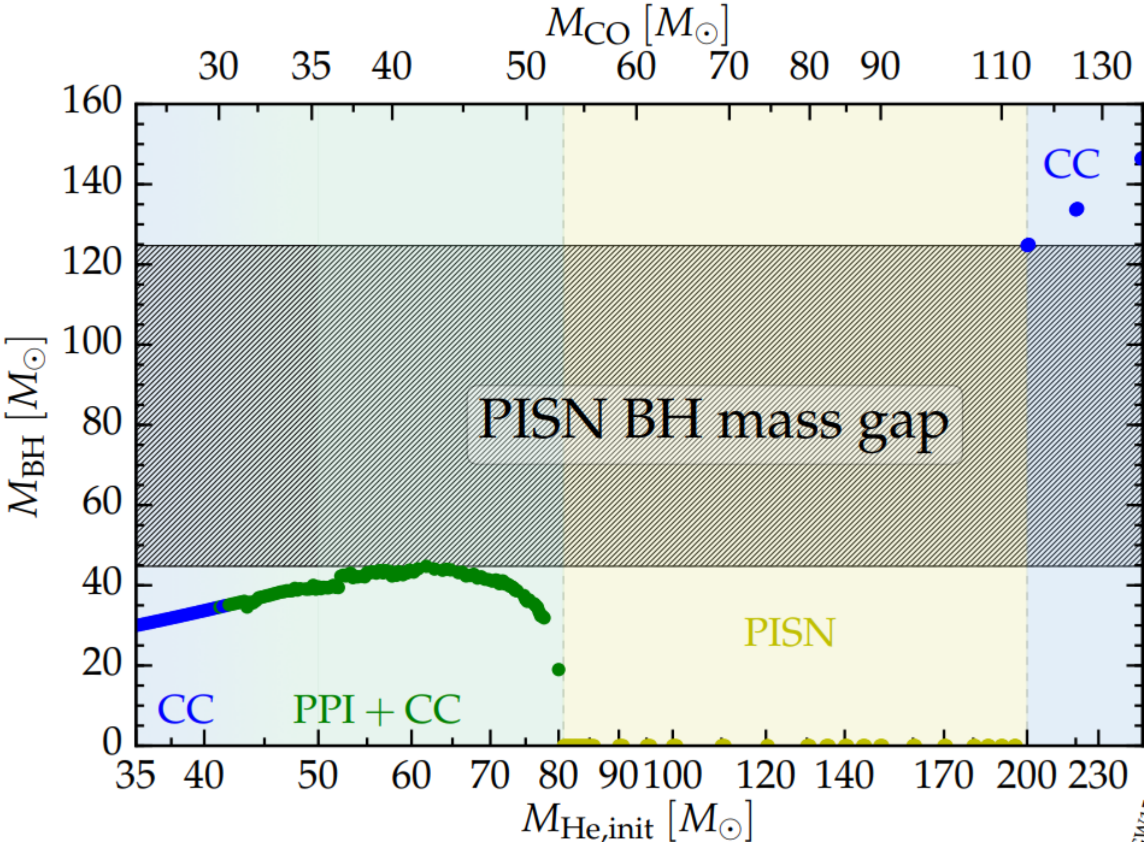
~30(?)$M_\odot$: Core-Collapse supernova (Neutron star, Black hole)

~140$M_\odot$: Black hole (Direct collapse/ Falied supernova)

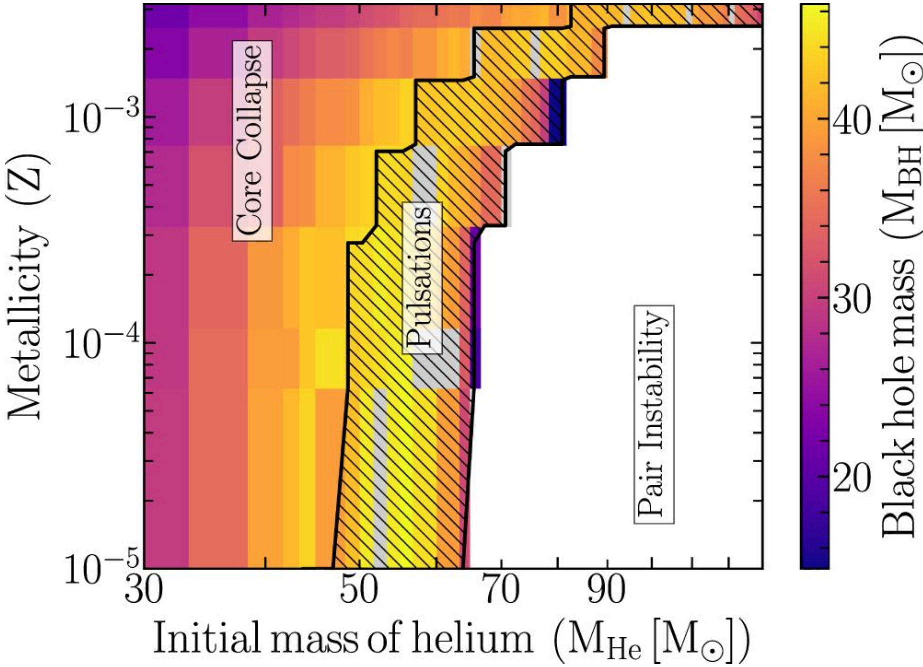
~260$M_\odot$: Pair-instability supernova

260$M_\odot$~ : Black hole (Direct collapse?)

Introduction
Final fates of stars



M. Renzo *et al.* A&A **640**, A56 (2020)



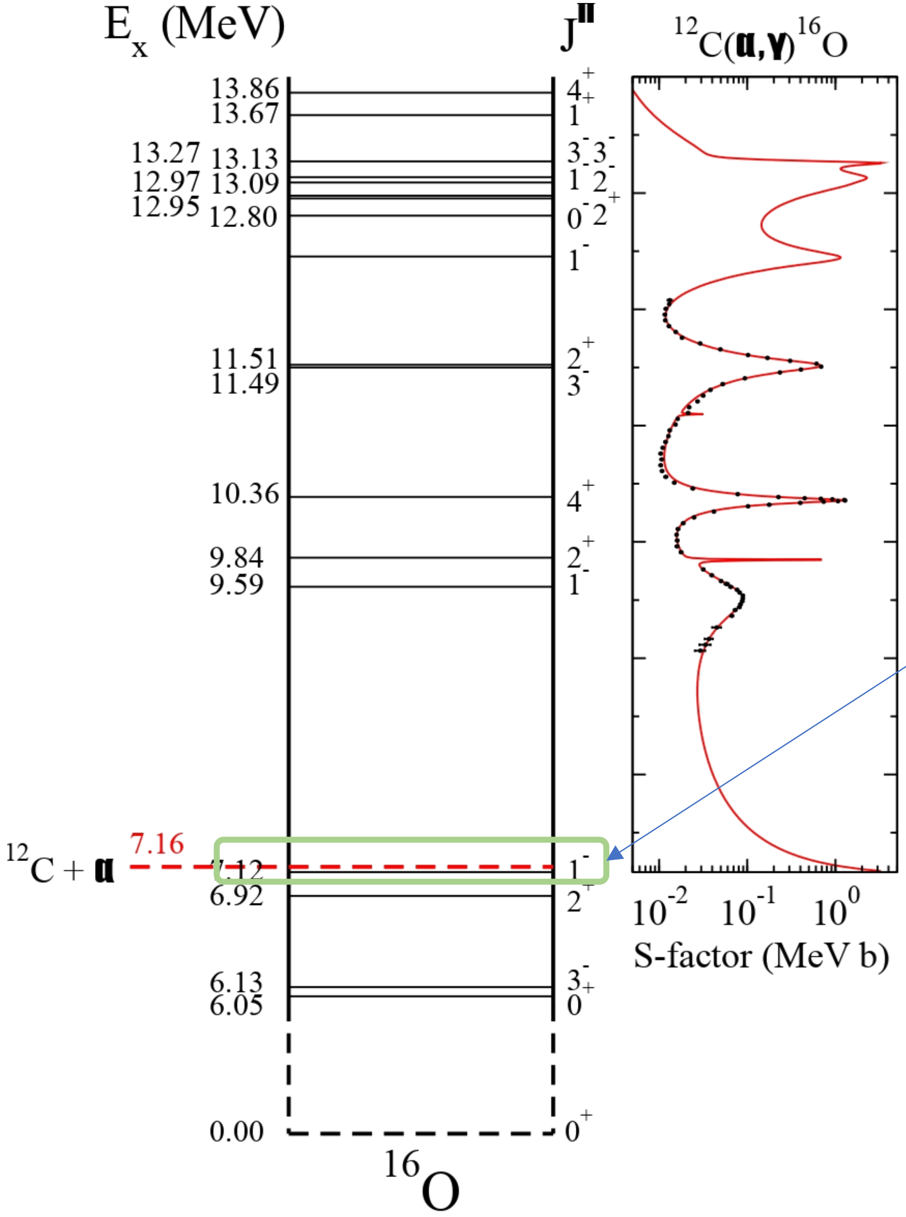
R. Farmer *et al.* ApJ. **887**, 53 (2019)

Final fate of ZAMS 140-260$M_\odot$ low metal very massive star

→Pair-instability supernova

Complete destruction →No compact object (remnant)

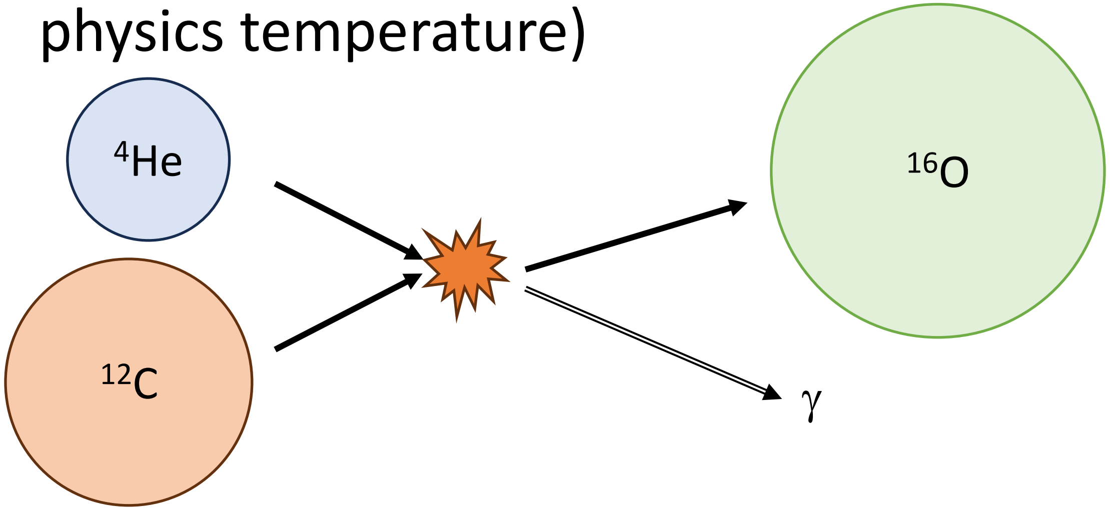
Introduction
^{12}C (α,γ)^{16}O reaction rate uncertainty



deBoer *et al.* Rev. Mod. Phys. **89**, 035007 (2017).

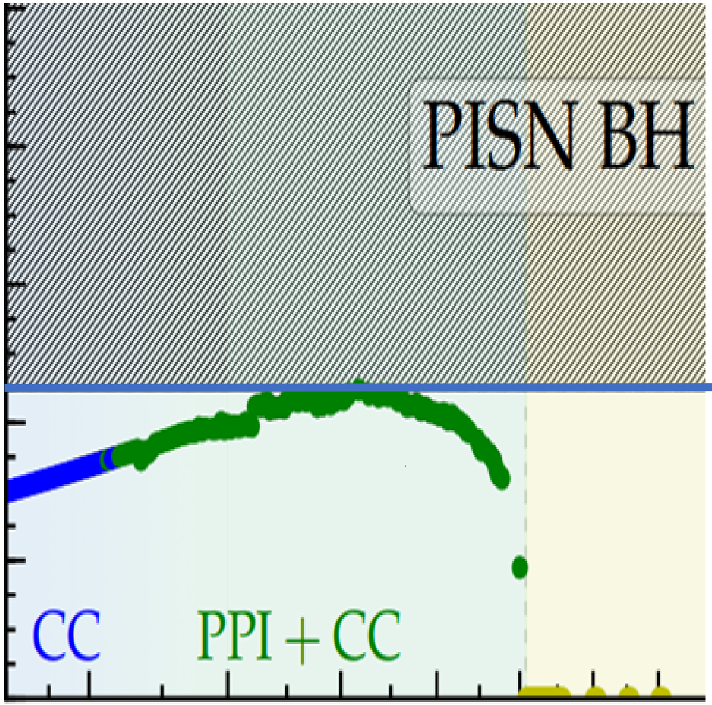
$$S(E) = \sigma(E)E\left(\exp\frac{2\pi Z_1 Z_2 e}{\hbar v}\right)$$

Too difficult to id. Astronomical S-factor (convert: 0.1MeV ~ 10^9 K: typical stellar physics temperature)

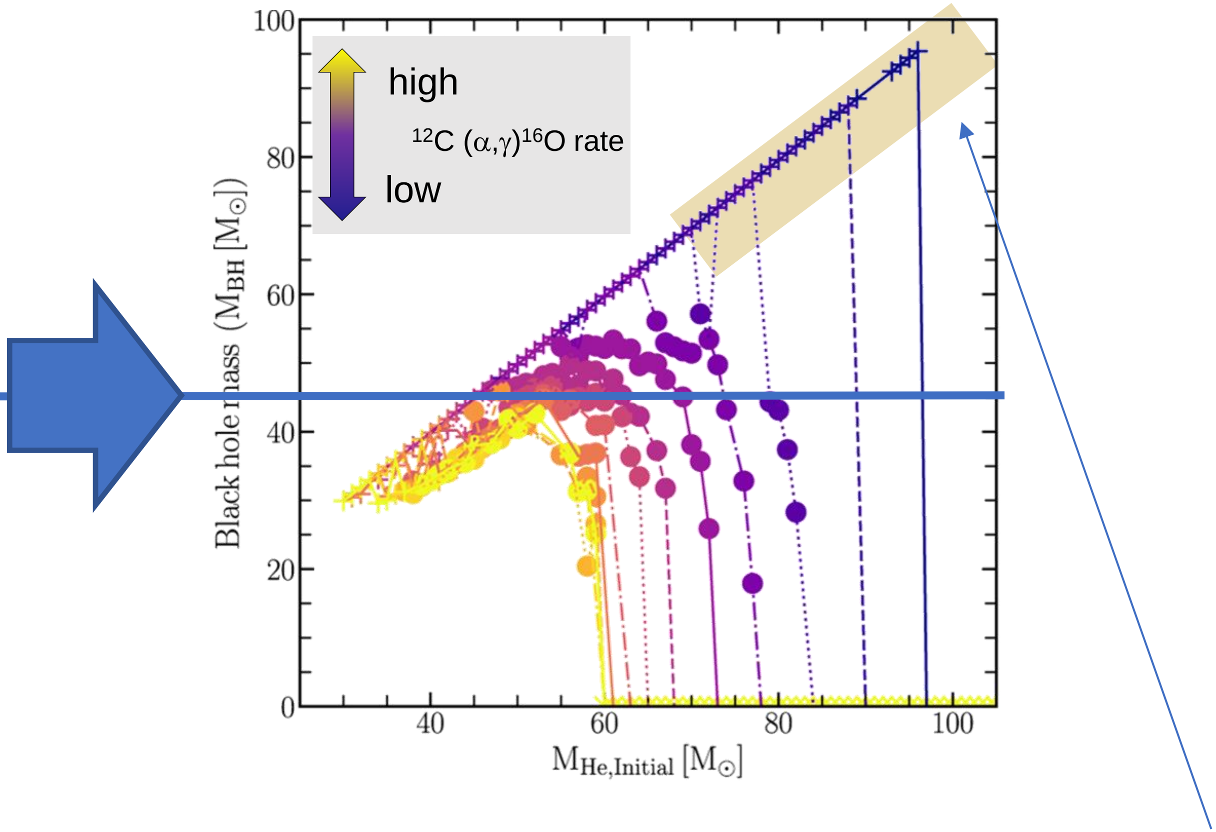


Introduction
PI mass gap and $^{12}C\ (\alpha,\gamma)^{16}O$ rate

M. Renzo *et al.* A&A **640**, A56 (2020)



R. Farmer *et al.* ApJL. **902**, L36 (2020).

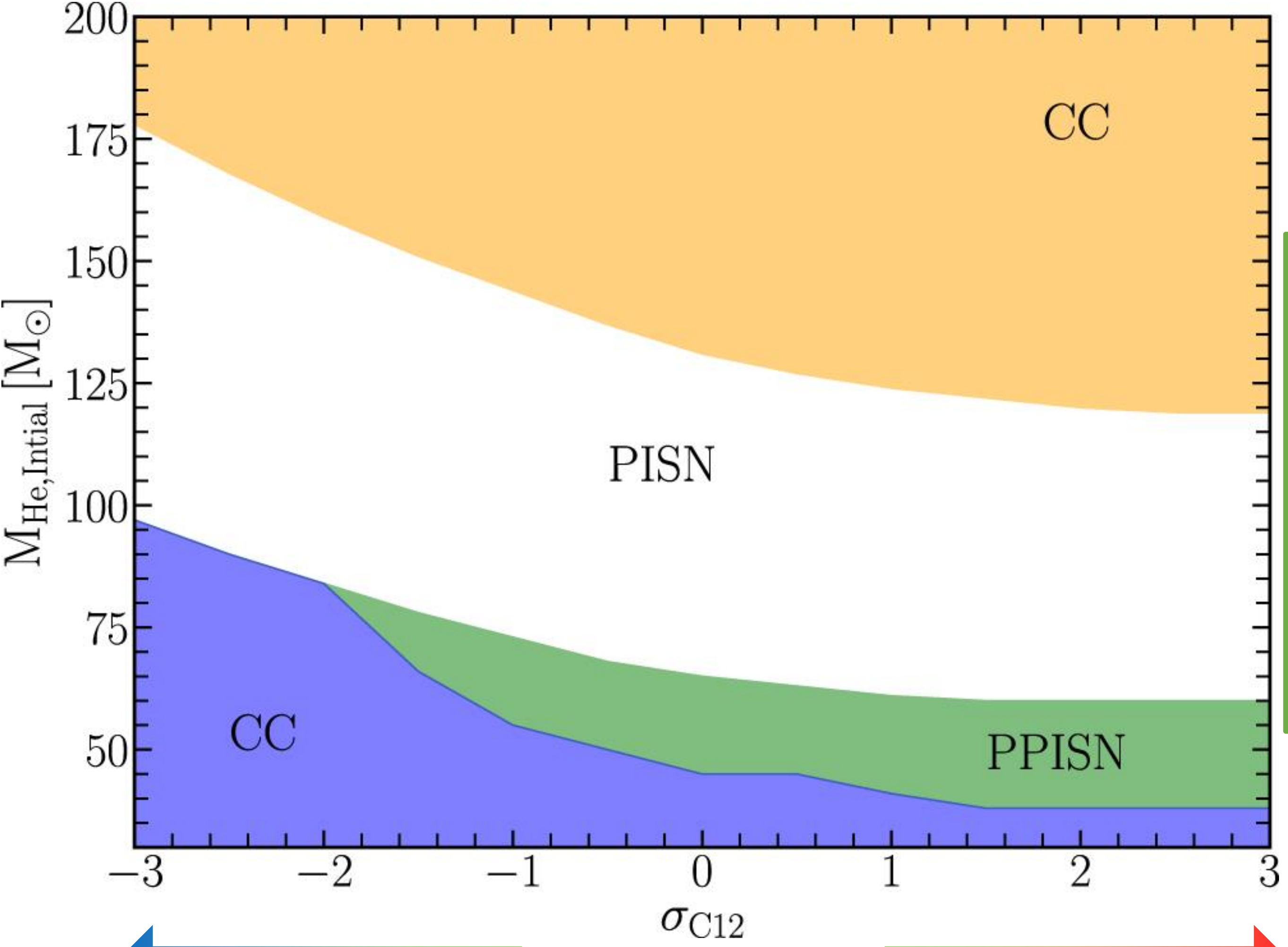


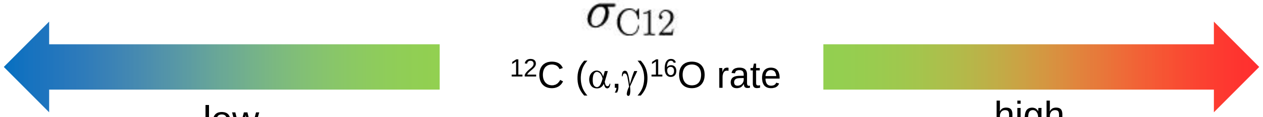
Lower limit of PI mass gap is affected by
Nuclear reaction（especially $^{12}C(\alpha,\gamma)^{16}O$）

（GW190521 like）
Massive BH formation

Introduction
PISNe details (final fate) with rate

R. Farmer *et al*. ApJL. **902**, L36 (2020).





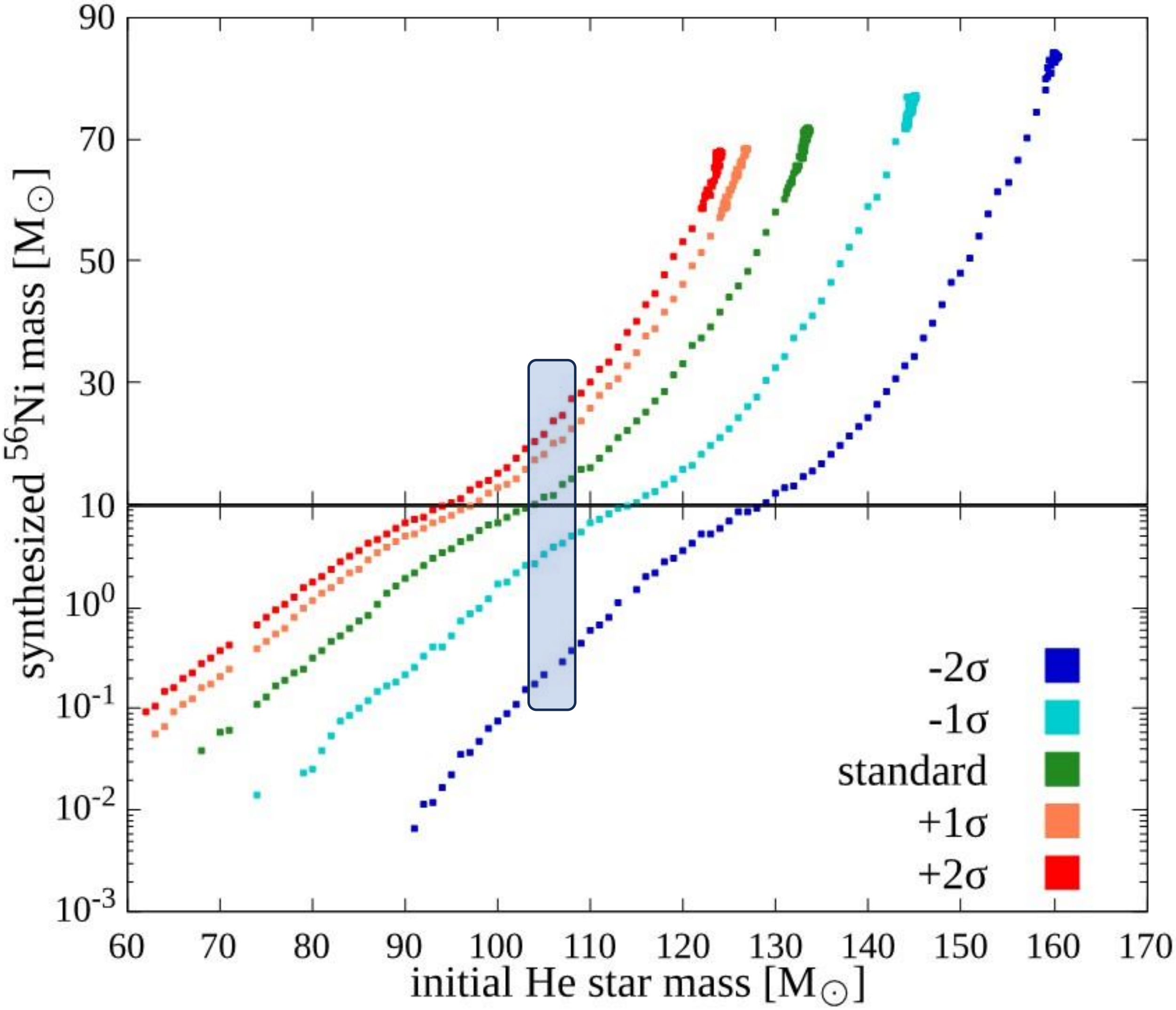
low

$^{12}C\ (\alpha,\gamma)^{16}O$ rate

high

PISN final fate → strongly effected from $^{12}C\ (\alpha,\gamma)^{16}O$ reaction rate

Introduction
^{56}Ni synthesis



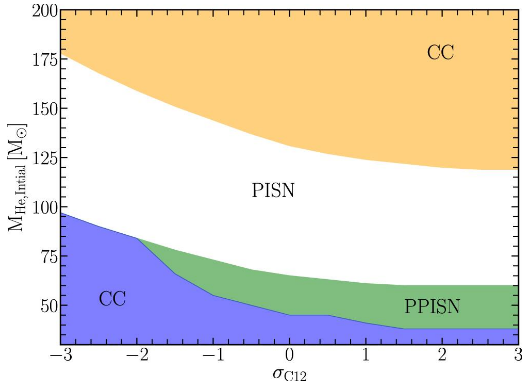
H. Kawashimo *et al.* MNRAS **531**, 2786 (2024)

Focusing on the same initial mass,
high ^{12}C $(\alpha,\gamma)^{16}$O reaction rate series makes more ^{56}Ni

In this work…

VMS final fate, PISN Ni synthesis are strongly effected from $^{12}C(\alpha,\gamma)^{16}O$ reaction rate.

However, all of works considered for “high” of “low” reaction rate, without specific temperature importance.



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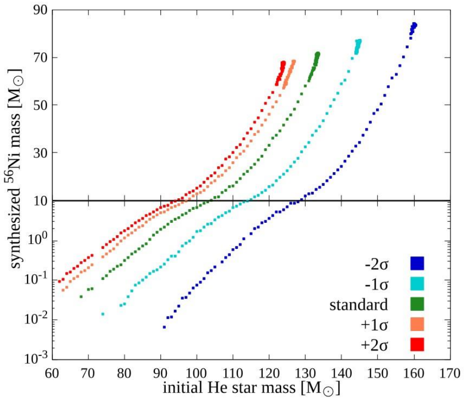

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We investigate where is the most important temperature for nickel synthesis in $^{12}C(\alpha,\gamma)^{16}O$ reaction by Monte-Carlo method

Method
Stellar evolution

MESA r15140 (Paxton+ 2011 etc.)

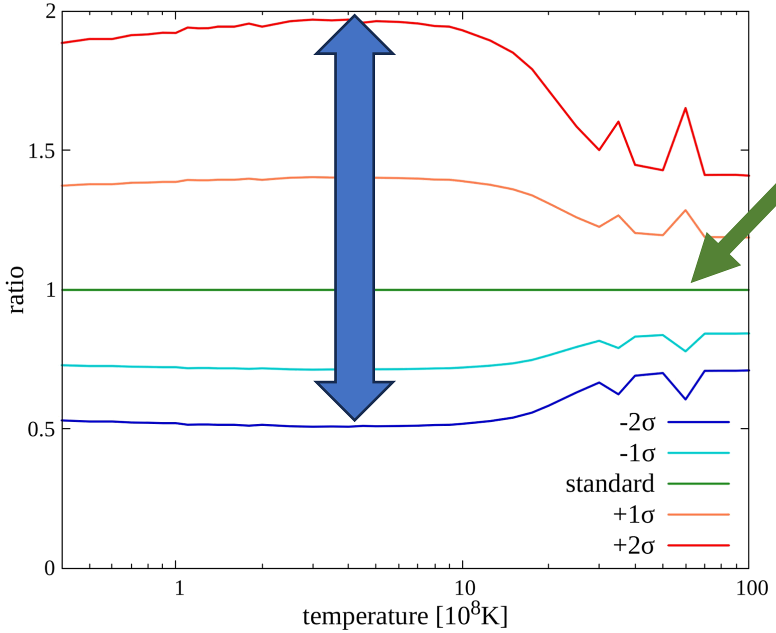
Initial conditions and setups: Marchant+ 2019

- He star (Main sequence terminated + H envelope removed)
- Metallicity $Z = 10^{-5}$
- Initial mass $M = 100\ M_\odot$

Methods

How to make reaction rate tables

- Get “standard” reacton rates between 4.0×10^{8} K and 1.0×10^{10} K from STARLIB (and it bases on Kunz+ 2002) → $p_{\mathrm{std}}(T)$
- Generate random value in 0.5 ~ 2 for each STARLIB temperature points → $f_{\mathrm{ptn}}(T)$



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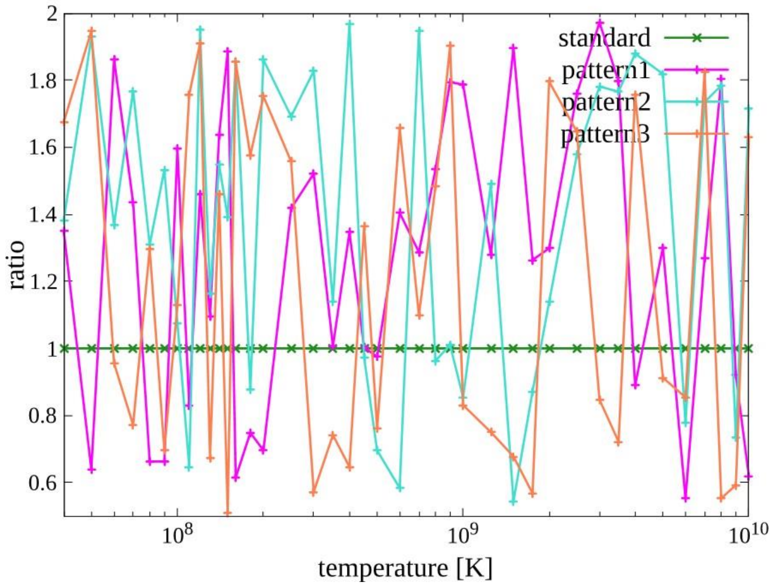
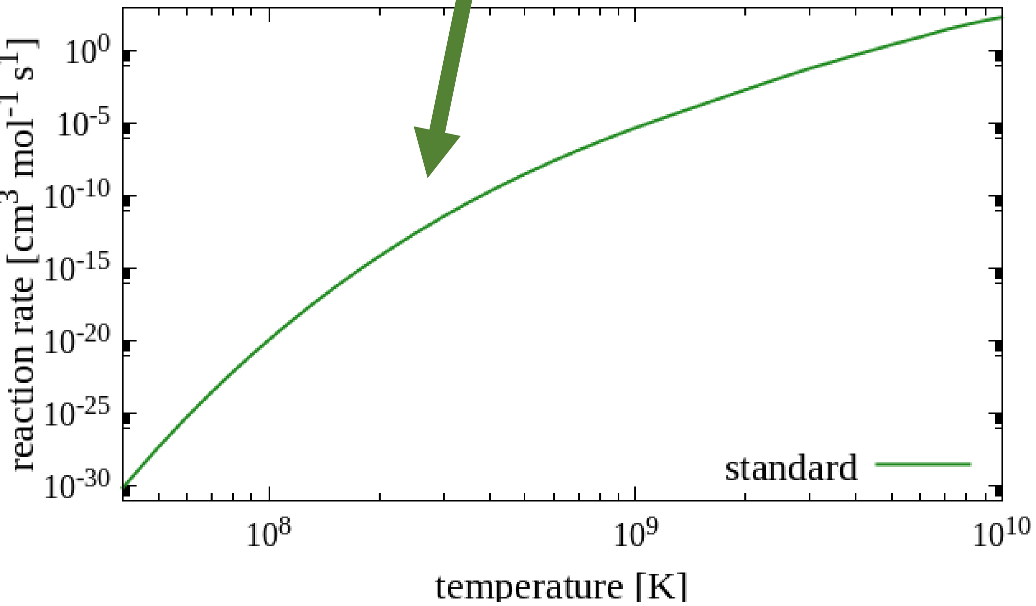


^{12}C (α,γ)^{16}O random factors examples

Methods

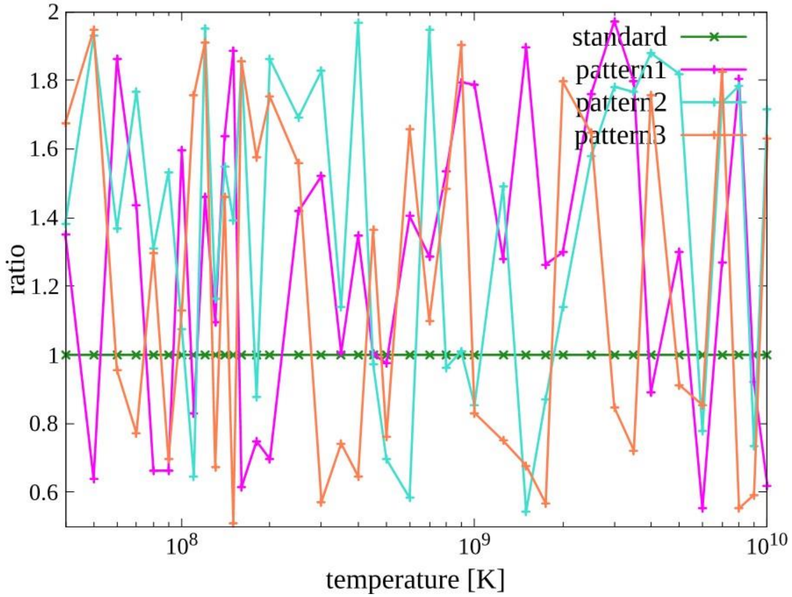
How to make reaction rate tables

- Get “standard” reacton rates between 4.0×10^8 K and 1.0×10^{10} K from STARLIB (and it bases on Kunz+ 2002) → $p_{\mathrm{std}}(T)$
- Generate random value in 0.5 ~ 2 for each STARLIB temperature points → $f_{\mathrm{ptn}}(T)$
- Calculate $p_{\mathrm{std}}(T) \times f_{\mathrm{ptn}}(T)$ → We obtaion randomized reaction rate!



^{12}C (α,γ)^{16}O standard reaction rate

×



^{12}C (α,γ)^{16}O random factors examples

Methods

How to consider the strength of corr.

- Finally we obtain synthesized ^{56}Ni mass $M_{56\mathrm{Ni,ptn}}$. Therefore, we get this table below:

Pattern number →

Temperature ↓

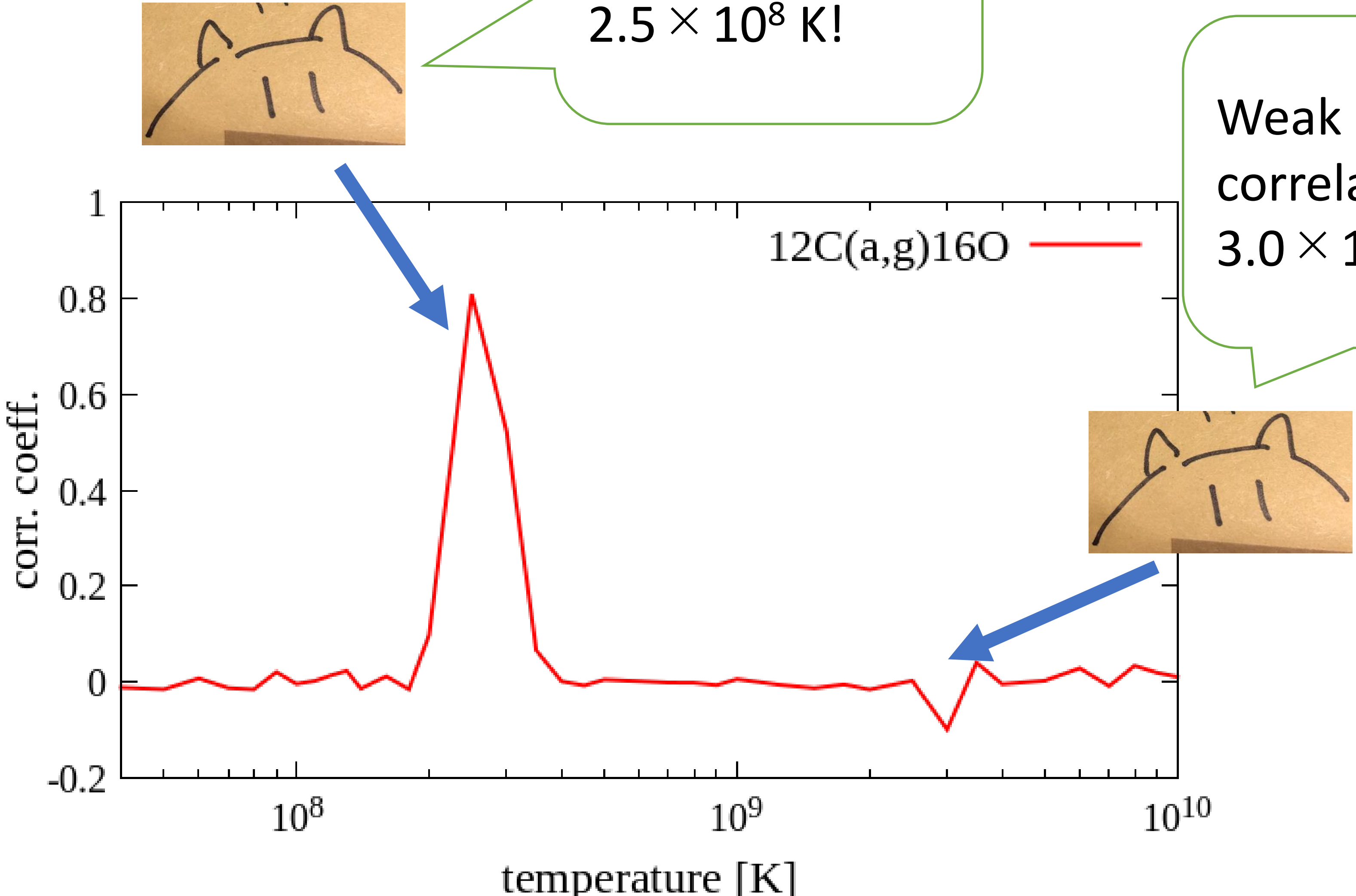
$M_{56\mathrm{Ni,ptn}}$	$M_{56\mathrm{Ni},1}$	$M_{56\mathrm{Ni},3}$	$M_{56\mathrm{Ni},3}$	…
$f_{\mathrm{ptn}}(T_1)$	$f_1(T_2)$	$f_2(T_1)$	$f_3(T_1)$	…
$f_{\mathrm{ptn}}(T_2)$	$f_1(T_2)$	$f_2(T_2)$	$f_3(T_2)$	…
$f_{\mathrm{ptn}}(T_3)$	$f_1(T_3)$	$f_2(T_3)$	$f_3(T_3)$	…
$f_{\mathrm{ptn}}(T_4)$	$f_1(T_4)$	$f_2(T_4)$	$f_3(T_4)$	…
…	…	…	…	…

We can calculate correlation coefficients $r(T_b)$ between $M_{56\mathrm{Ni,ptn}}$ and each random factors f_{ptn} focusing on T_b as

$$r(T_b) = \frac{\frac{1}{n}\sum_{\mathrm{ptn}=1}^{n}\left(M_{56\mathrm{Ni,ptn}} - \overline{M_{56\mathrm{Ni}}}\right)\left(f_{\mathrm{ptn}}(T_b) - \overline{f_{\mathrm{ptn}}(T_b)}\right)}{\sqrt{\frac{1}{n}\sum_{\mathrm{ptn}=1}^{n}\left(M_{56\mathrm{Ni,ptn}} - \overline{M_{56\mathrm{Ni}}}\right)^2}\sqrt{\frac{1}{n}\sum_{\mathrm{ptn}=1}^{n}\left(f_{\mathrm{ptn}}(T_b) - \overline{f_{\mathrm{ptn}}(T_b)}\right)^2}}$$

Results

Correlation Coefficients

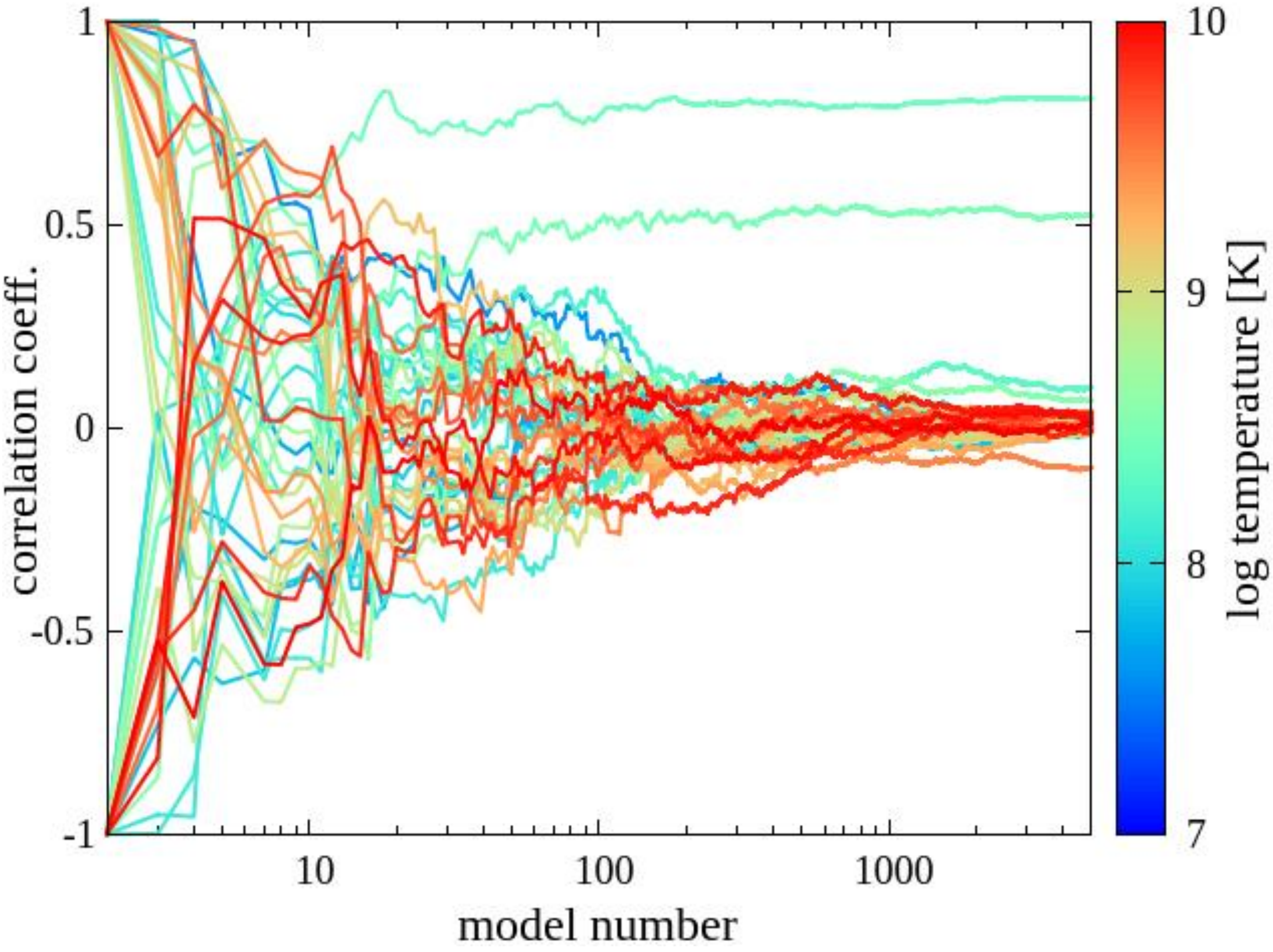


Very strong correlation at 2.5×10^8 K!

Weak negative correlation at 3.0×10^8 K?

Results

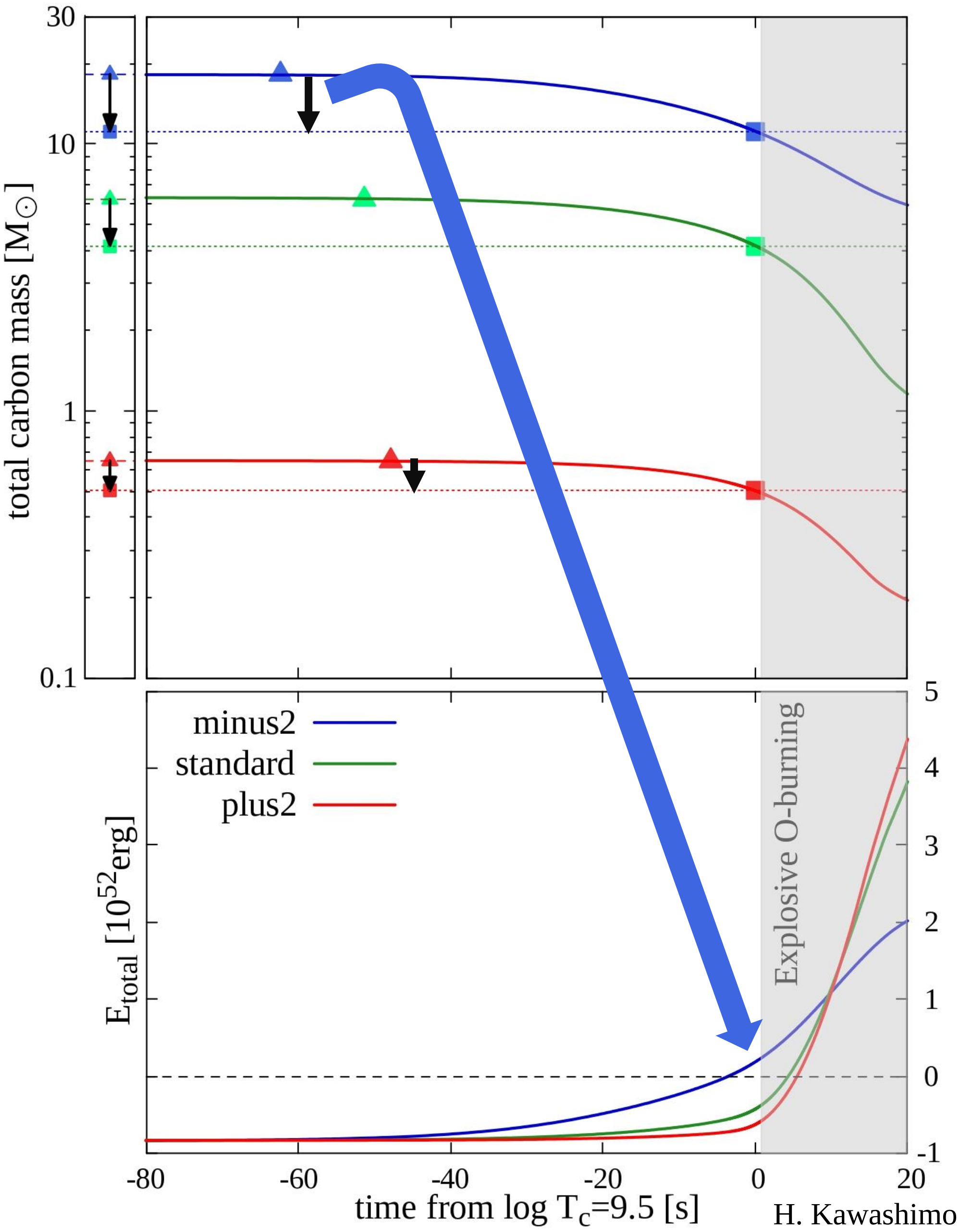
Convergence speed



100 models:
roughly converged

1000 models:
almost converged

Discussion
Carbon "pre-heating"



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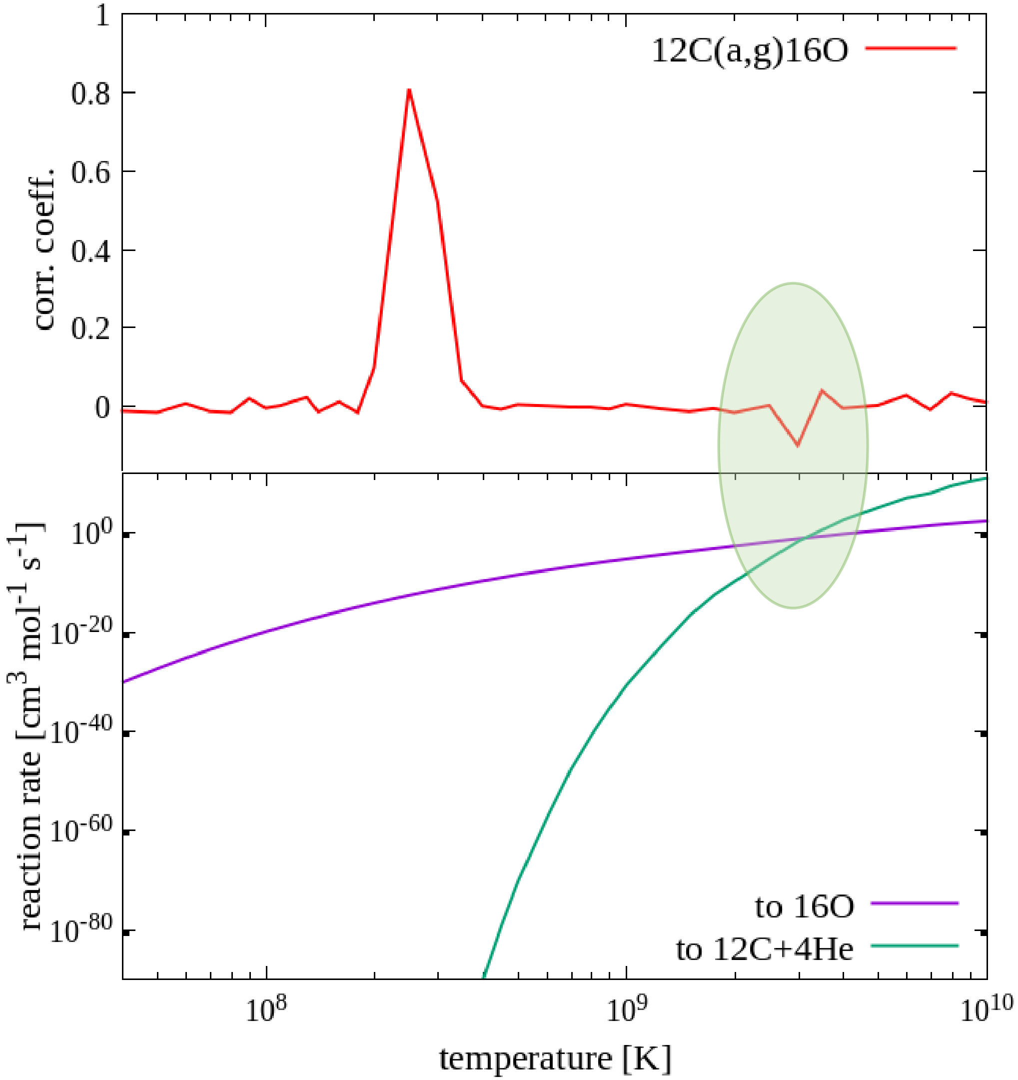
Low reaction rate
→ C rich CO core
C burning process
makes star "softer"

Discussion

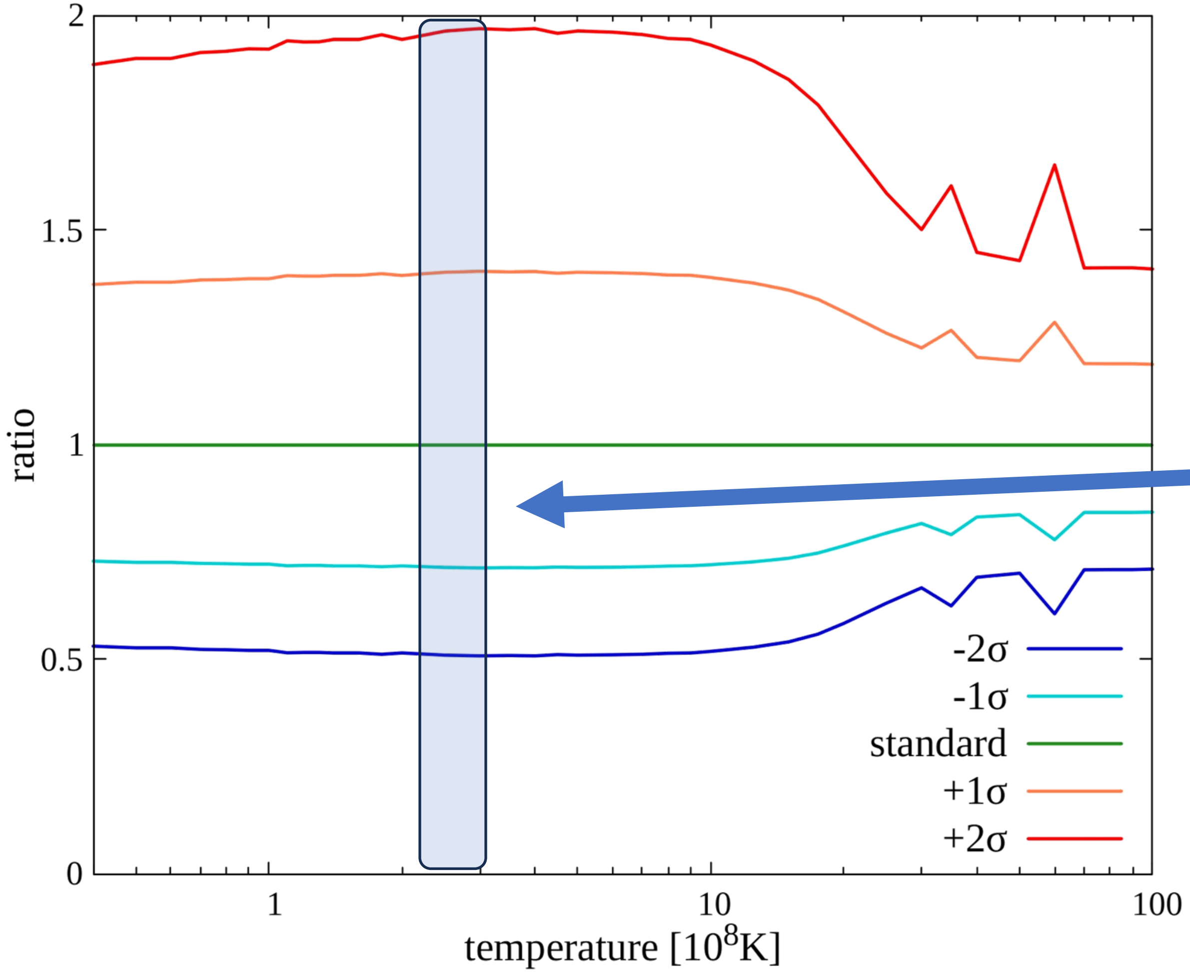
Neg. corr. at high temperature



2.5×10^8 K: switch point of ^{12}C (α,γ)^{16}O and ^{16}O(γ, α) ^{12}C (reverse reaction)

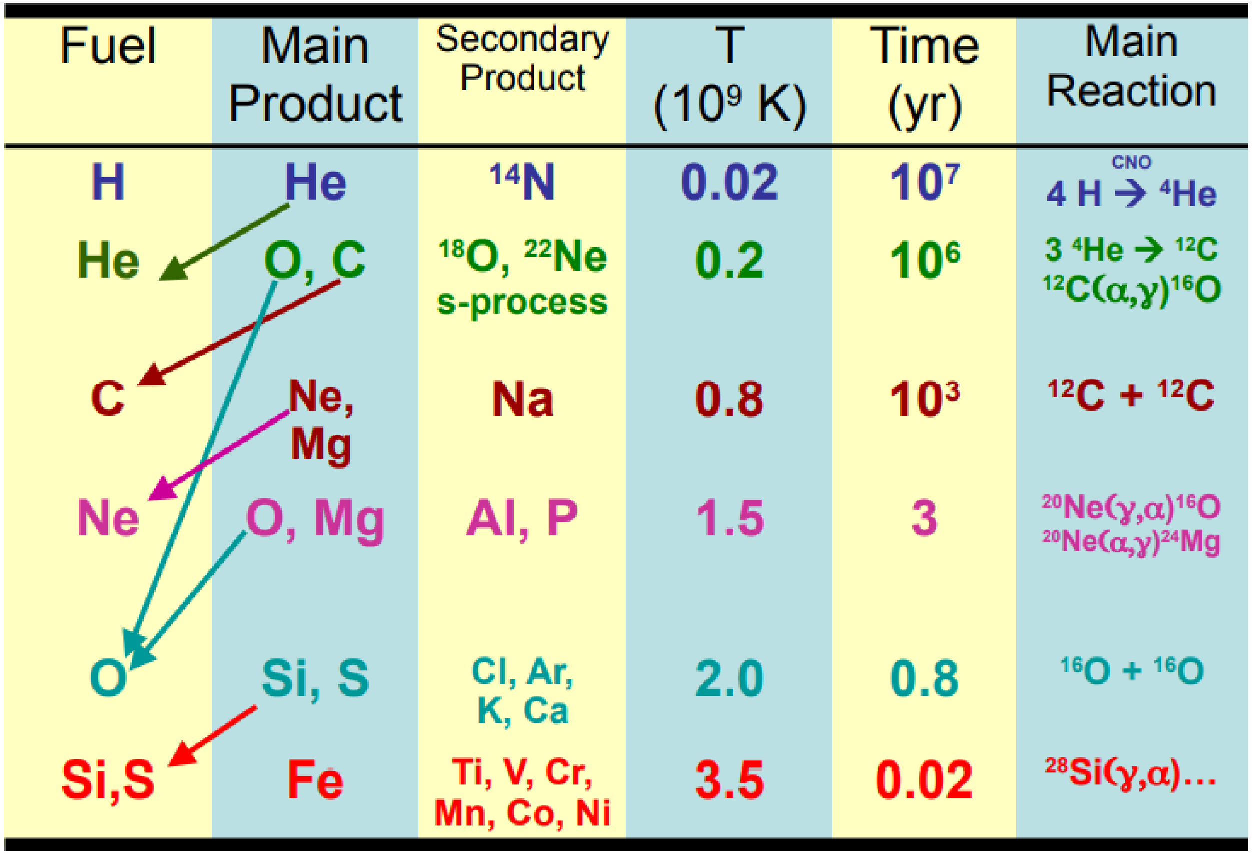
Energy absorption?

Discussion
The “constraintability”



PISN observational information will indicate the reaction rate of this temperature (?)

By the way…

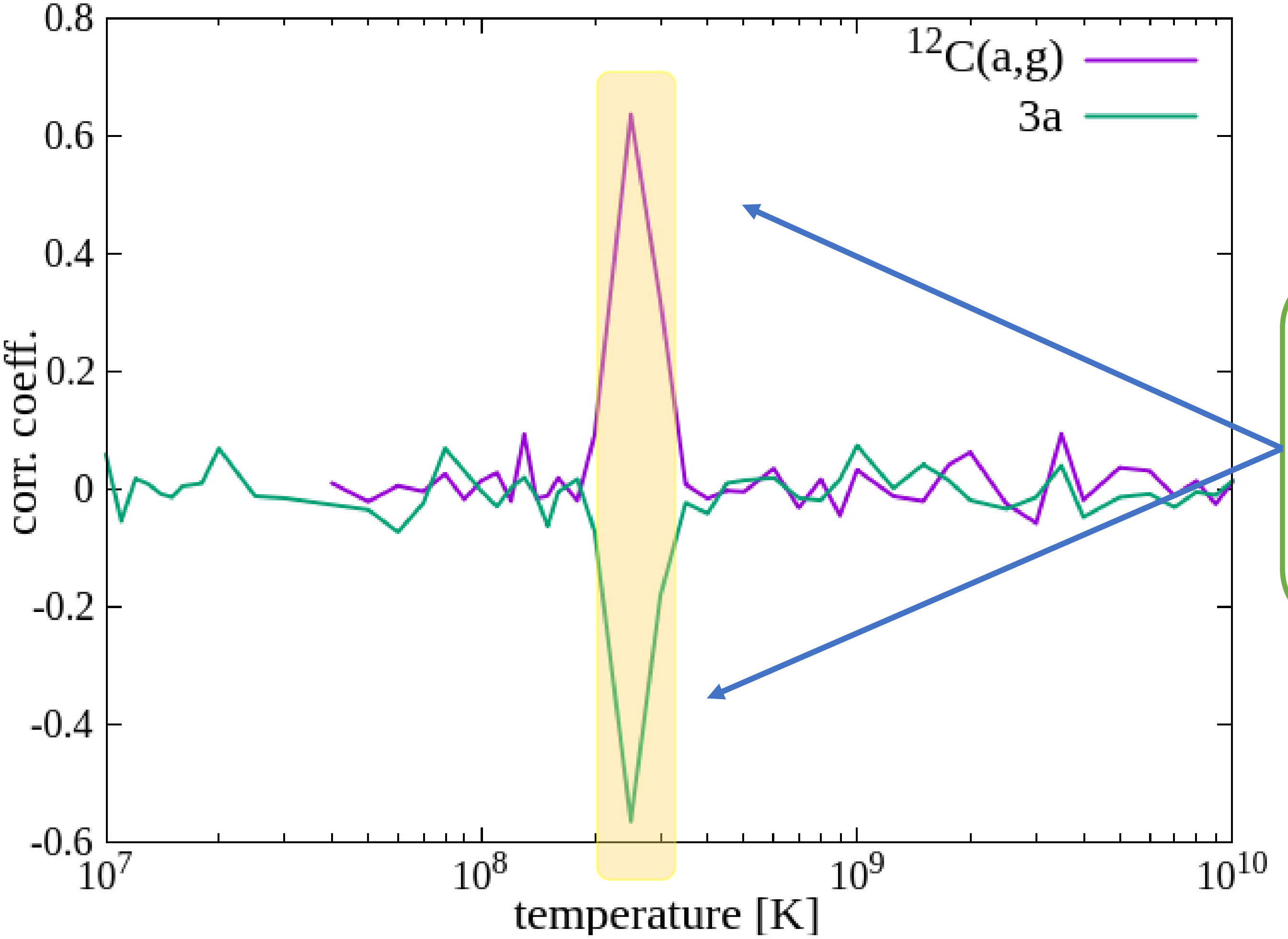


Fuel	Main Product	Secondary Product	T (10^9 K)	Time (yr)	Main Reaction
H	He	^{14}N	0.02	10^7	$4\,H \xrightarrow{CNO} {}^{4}He$
He	O, C	^{18}O, ^{22}Ne s-process	0.2	10^6	$3\,{}^{4}He \rightarrow {}^{12}C$ $^{12}C(\alpha,\gamma)^{16}O$
C	Ne, Mg	Na	0.8	10^3	$^{12}C + {}^{12}C$
Ne	O, Mg	Al, P	1.5	3	$^{20}Ne(\gamma,\alpha)^{16}O$ $^{20}Ne(\alpha,\gamma)^{24}Mg$
O	Si, S	Cl, Ar, K, Ca	2.0	0.8	$^{16}O + {}^{16}O$
Si,S	Fe	Ti, V, Cr, Mn, Co, Ni	3.5	0.02	$^{28}Si(\gamma,\alpha)$…

https://www2.yukawa.kyoto-u.ac.jp/~nuc2021/slides/heger_a.pdf

3α reaction is also important He burning component

Preliminary result about 3α reaction



Both ones have peak at 2.5×10^8 K.
Almost the same strength

Summary

Introduction

- $^{12}C(\alpha,\gamma)^{16}O$ plays an important role for PISN explosion
- Previous works based on “high” or “low” reaction rate without considerations for specific temperatures

In our work…

- Generate $^{12}C(\alpha,\gamma)^{16}O$ randomized reaction rate tables
- Calculate the correlation between synthesized ^{56}Ni mass and speeds of $^{12}C(\alpha,\gamma)^{16}O$ reaction for each temperatures

Result

- Strong positive correlation at $T=2.5\times10^{8}$ K (1)
- weak negative correlation at $T=3.0\times10^{9}$ K (2)

Discussion

- Result (1) supports the “carbon-preheating” effect.
- Result (2) will be from reverse reaction

Future works and Work In Progress

- 3α reaction is also important for the same context
- Preliminary result suggests these reaction effect are degenerated at 2.5×10^{8} K ?