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

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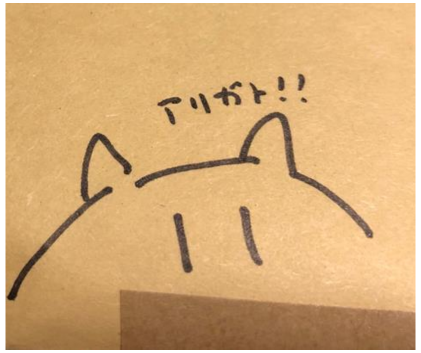
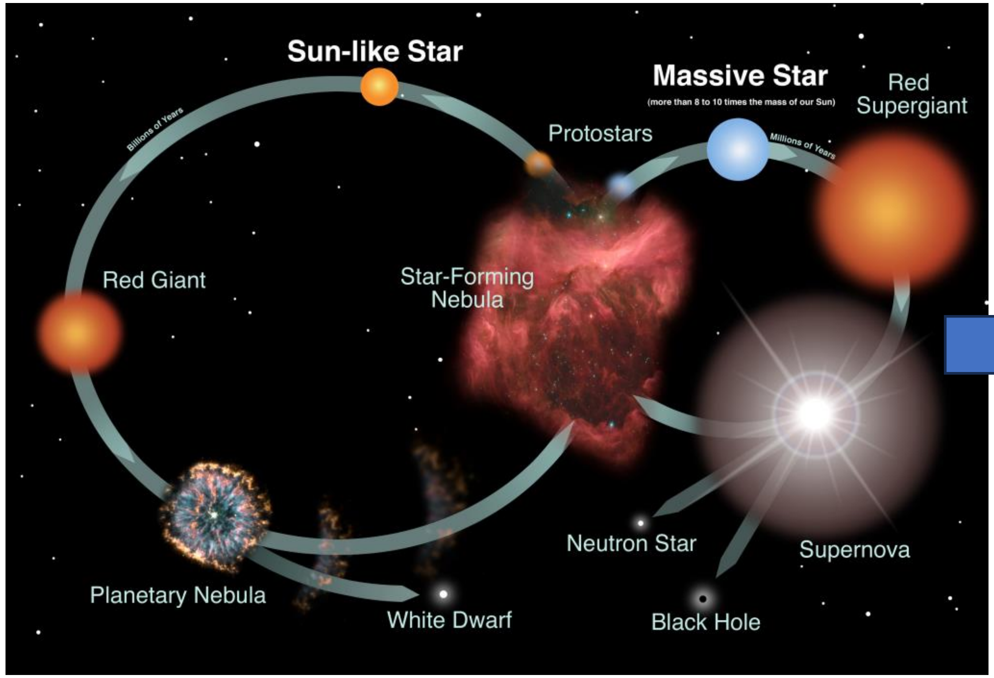
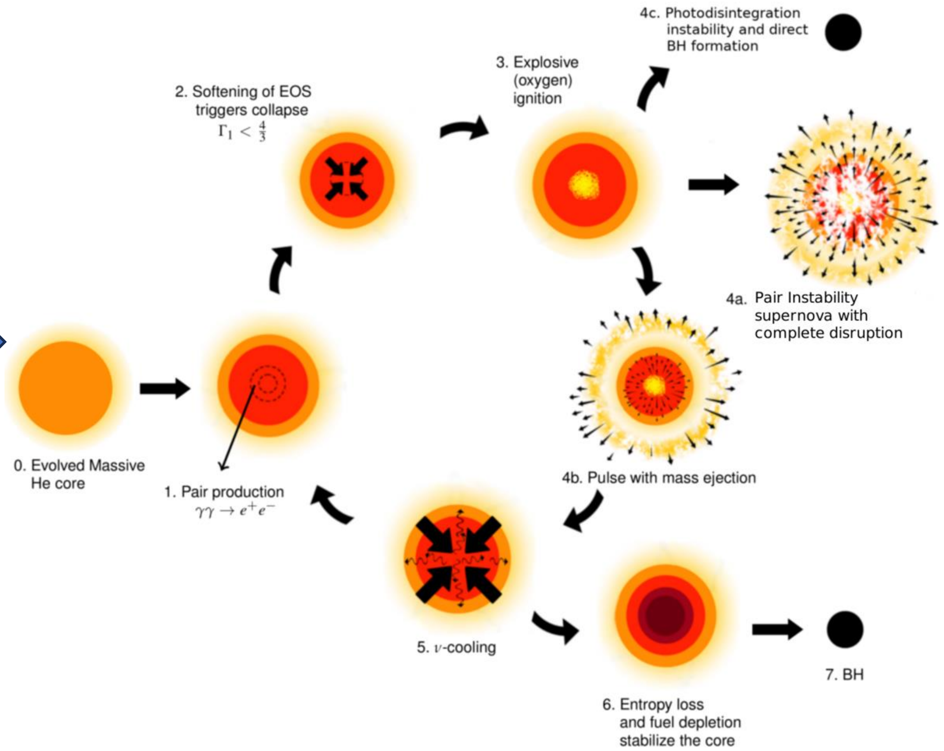


Introduction
Final fates of stars



NASA



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~8M$_\odot$: White dwarf

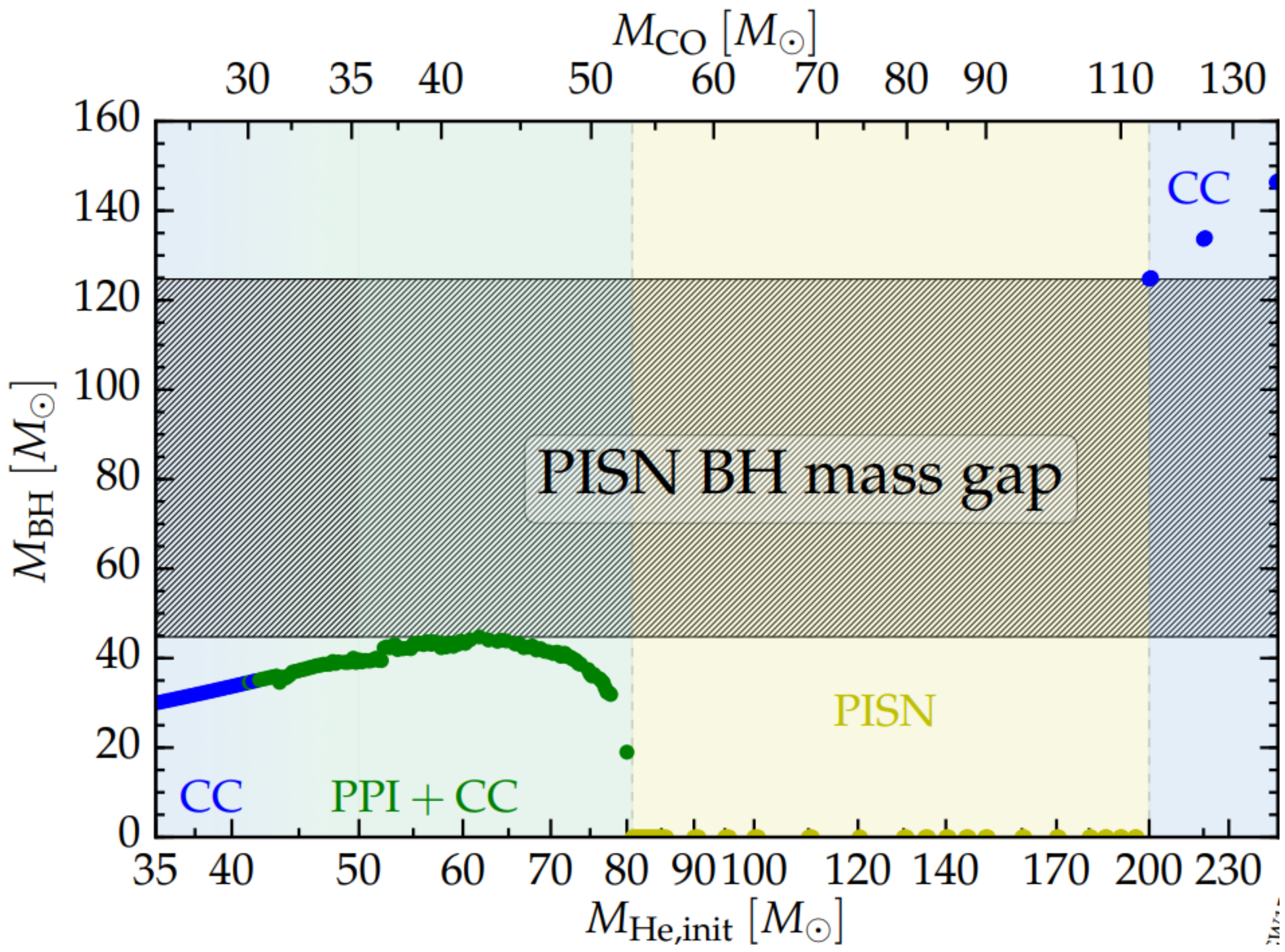
~30(?)M$_\odot$: Core-Collapse supernova (Neutron star, Black hole)

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

~260M$_\odot$: Pair-instability supernova

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

Introduction
Final fates of stars



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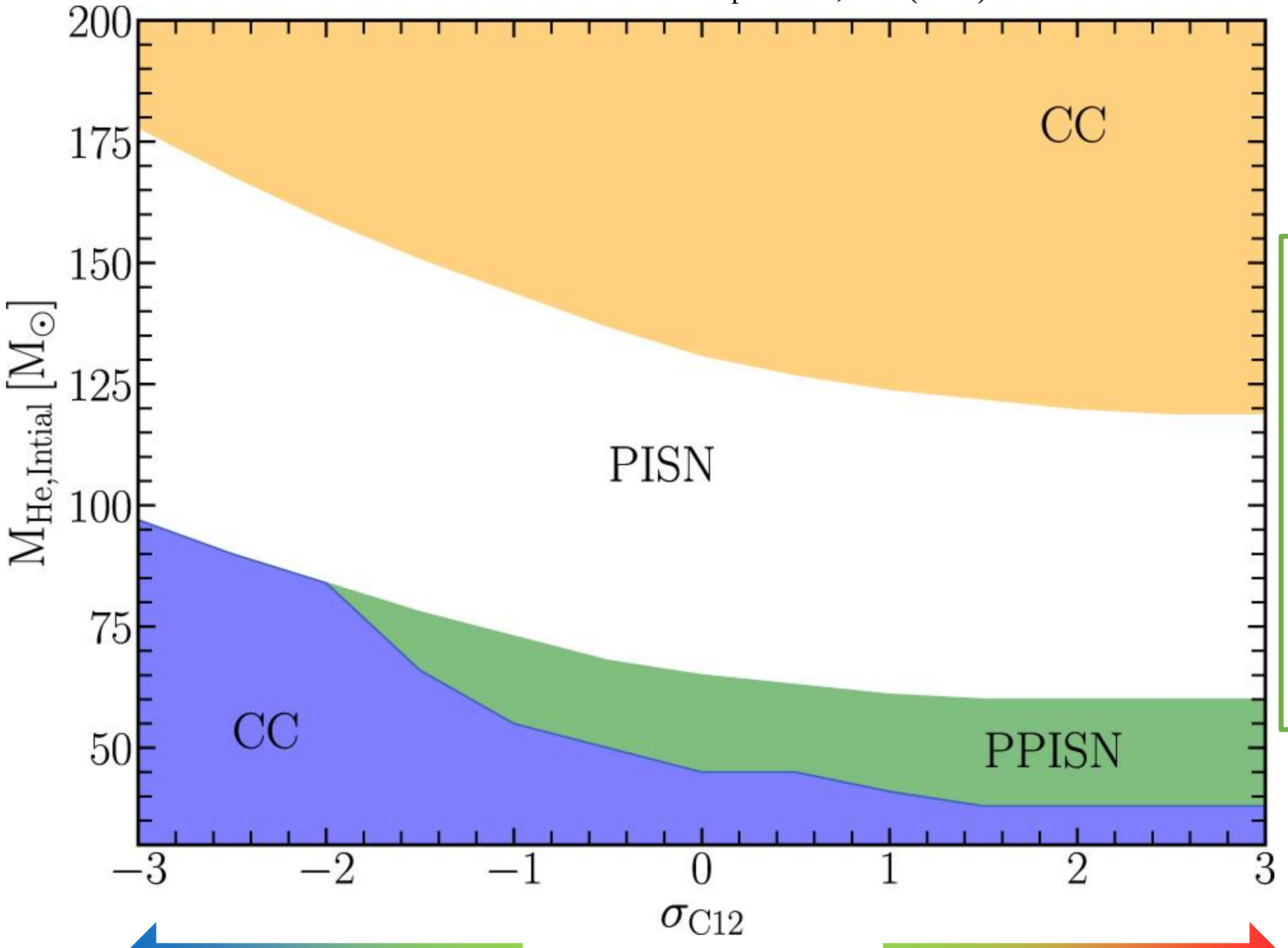
Final fate of ZAMS 140-260$M_\odot$ low metal very massive star

→Pair-instability supernova

Complete destruction →No compact object (remnant)

Introduction
PISNe details (final fate) with rate

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



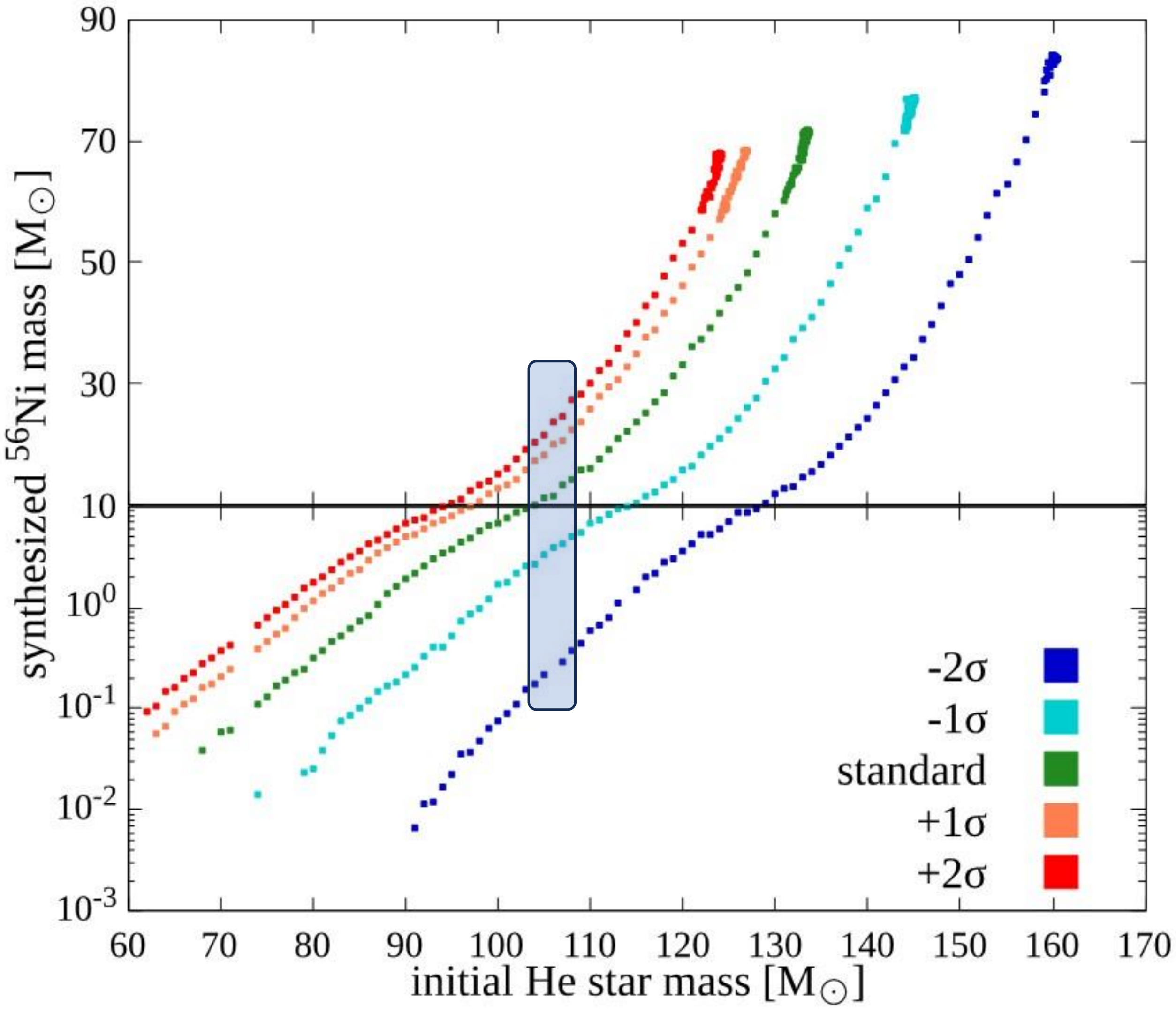
$^{12}C\ (\alpha,\gamma)^{16}O$ rate

low

high

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

Introduction
^{56}Ni synthesis



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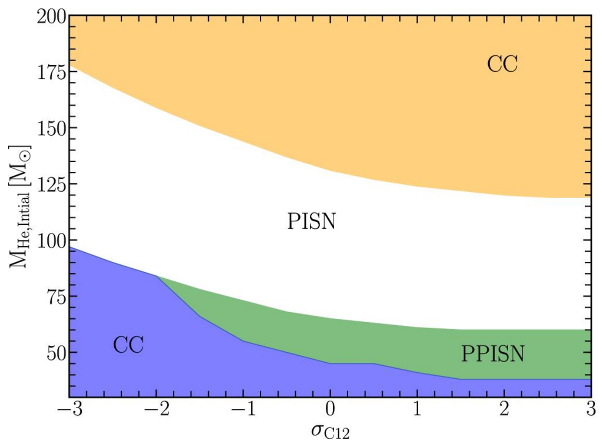
Focusing on the same initial mass, high ^{12}C $(\alpha,\gamma)^{16}$O reaction rate series makes more ^{56}Ni

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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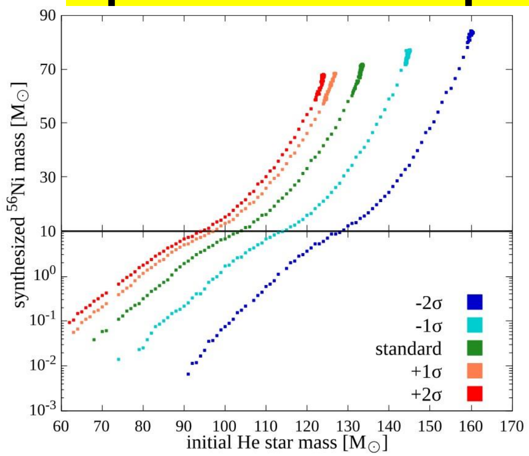

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We investigate where is the most important temperature for ^{56}Ni synthesis in He-bunring ($^{12}C(\alpha,\gamma)^{16}O$ and 3α) reaction by Monte-Carlo method

Method

Stellar evolution

MESA r15140 (Paxton+ 2011 etc.)

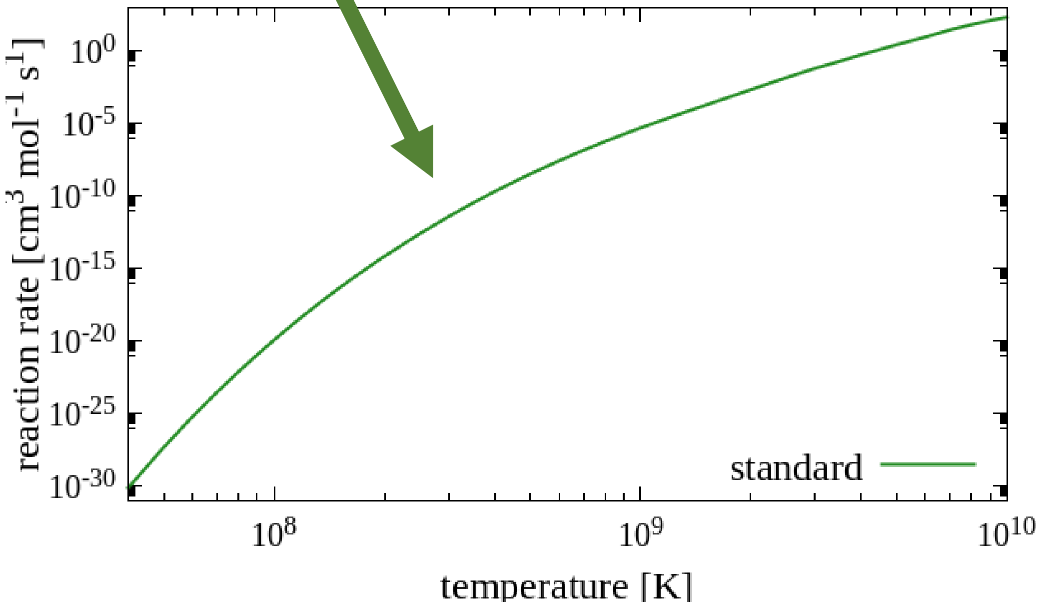
Initial conditions and setups: Marchant+ 2019

- 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

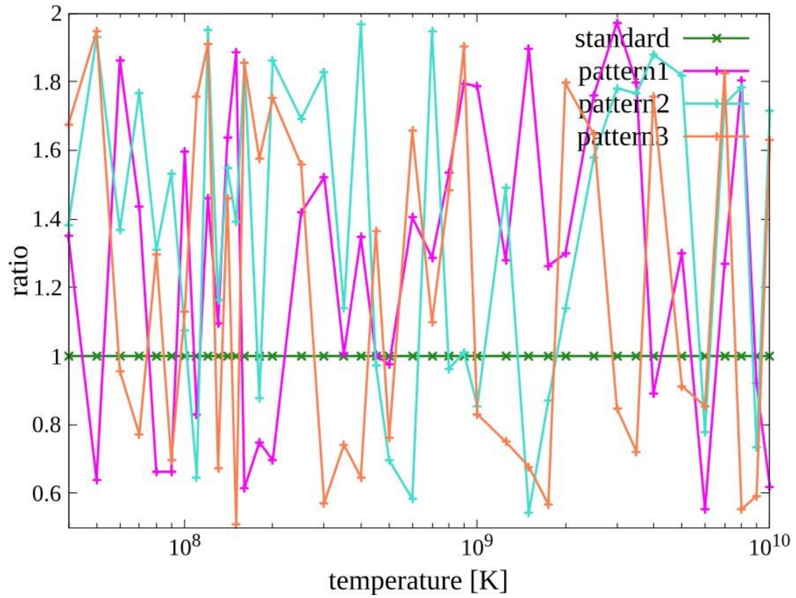
- Get “standard” reacton rates between 4.0×10^8 K and 1.0×10^{10} K from STARLIB (and it bases on Kunz+ 2002 ($^{12}C(\alpha,\gamma)^{16}O$) and Angulo+ 1999 ($3\alpha$)) $\rightarrow p_{\mathrm{std}}(T)$
- Generate random value in 0.5 ~ 2 for each STARLIB temperature points $\rightarrow f_{\mathrm{ptn}}(T)$
- Calculate $p_{\mathrm{std}}(T) \times f_{\mathrm{ptn}}(T) \rightarrow$ We obtain randomized reaction rate!

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



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

×



$^{12}C(\alpha,\gamma)^{16}O$ random factors examples

Methods
How to consider the strength of corr.

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

Pattern number →

Temperature ↓

$M_{\mathrm{56Ni,ptn}}$	$M_{\mathrm{56Ni,1}}$	$M_{\mathrm{56Ni,2}}$	$M_{\mathrm{56Ni,3}}$	…
$f_{\mathrm{ptn}}(T_1)$	$f_1(T_1)$	$f_2(T_1)$	$f_3(T_1)$	…
$f_{\mathrm{ptn}}(T_2)$	$f_1(T_2)$	$f_2(T_2)$	$f_3(T_2)$	…
$f_{\mathrm{ptn}}(T_3)$	$f_1(T_3)$	$f_2(T_3)$	$f_3(T_3)$	…
$f_{\mathrm{ptn}}(T_4)$	$f_1(T_4)$	$f_2(T_4)$	$f_3(T_4)$	…
…	…	…	…	…

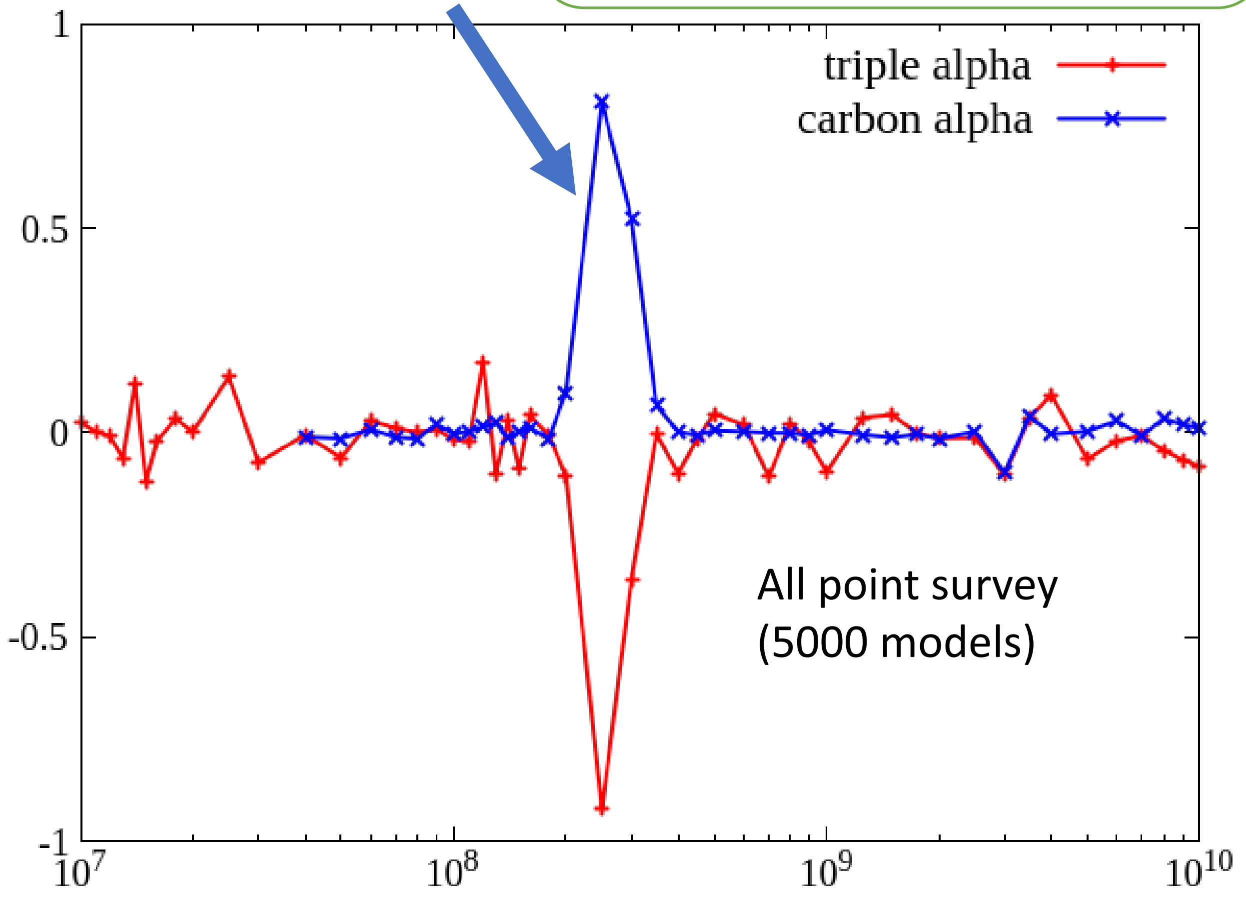
We can calculate correlation coefficients $r(T_b)$ between $M_{\mathrm{56Ni,ptn}}$ and each random factors f_{ptn} focusing on T_b as

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

Results

Correlation Coefficients

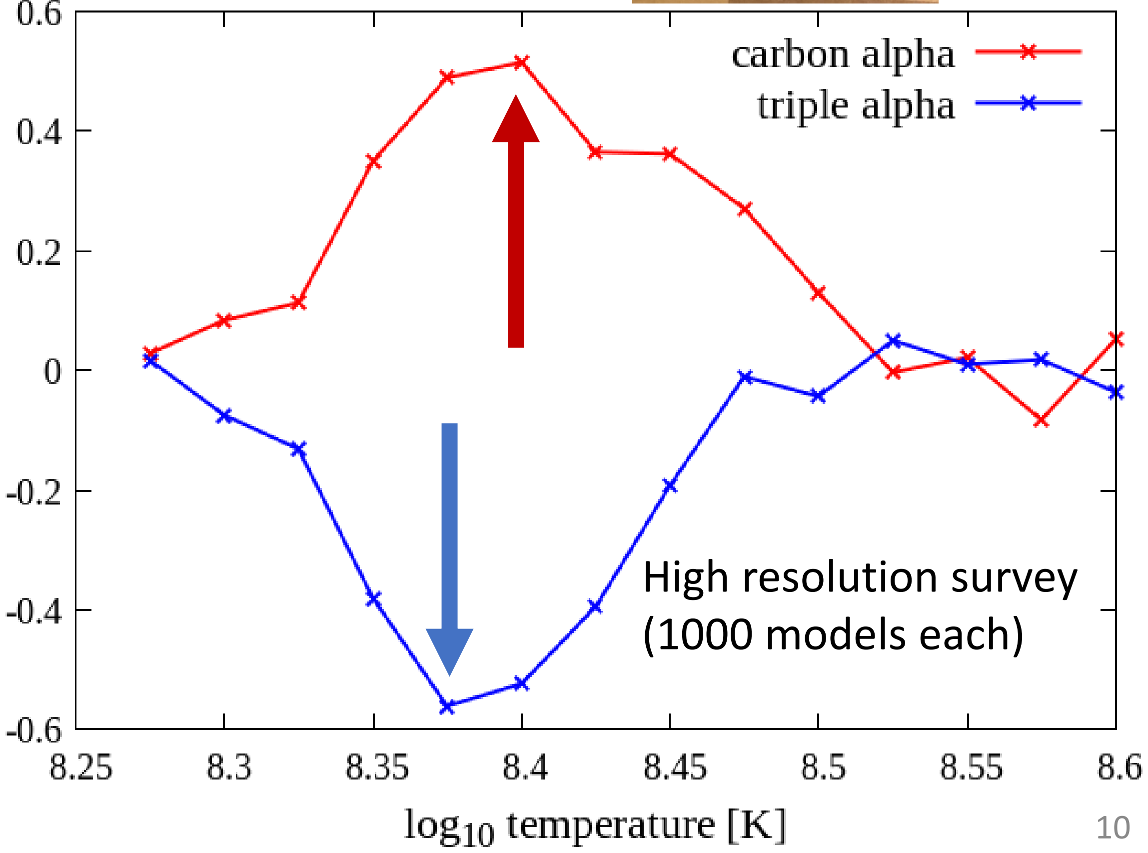
Very strong correlation at 2.5×10^{8} K!



$^{12}C(\alpha,\gamma)^{16}O$: $10^{8.4}$ K

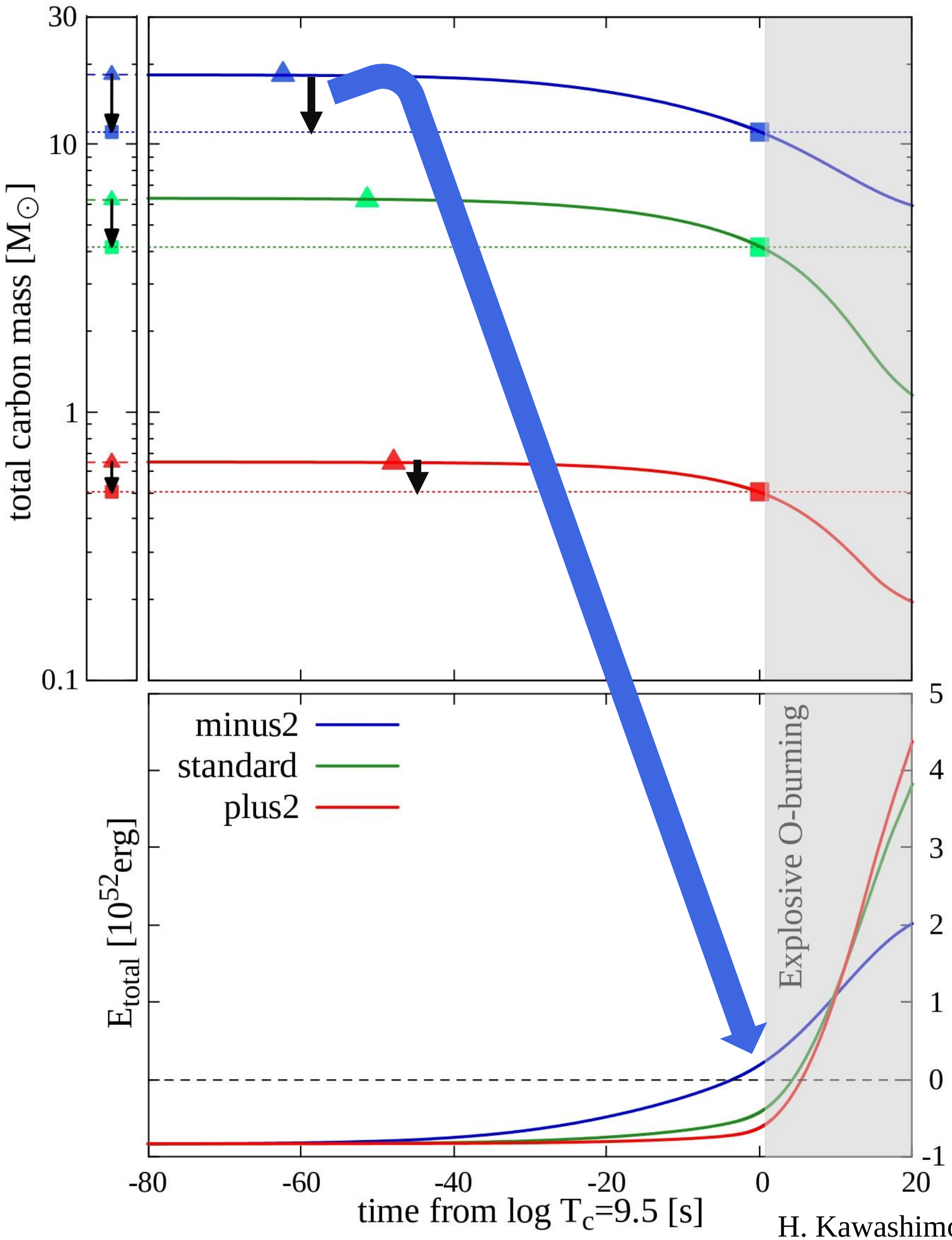
Triple alpha : $10^{8.375}$ K

3α produce ^{12}C → $^{12}C(\alpha,\gamma)^{16}O$ consume ^{12}C



Discussion

Carbon “pre-heating”



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

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

Result

The most important temperature(s) for ^{56}Ni synthesis are

- $^{12}C(\alpha,\gamma)^{16}O$: $10^{8.4}$ K (1)
- Triple alpha : $10^{8.375}$ K (2)

In our work…

- Generate randomized He burning reaction rate tables
- Calculate the correlation between synthesized ^{56}Ni mass and speeds of He burning reaction for each temperatures

Discussion

- Result (1) > Result (2) :
  $^{12}C(\alpha,\gamma)^{16}O$ consumes ^{12}C, product of 3α reaction
- Result (1) supports the “carbon-preheating” effect.