Kyushu University 100th 2011
知の新世紀を拓く

Stellar Evolution and Nucleosynthesis in Massive Stars

What can do ....

M. Hashimoto

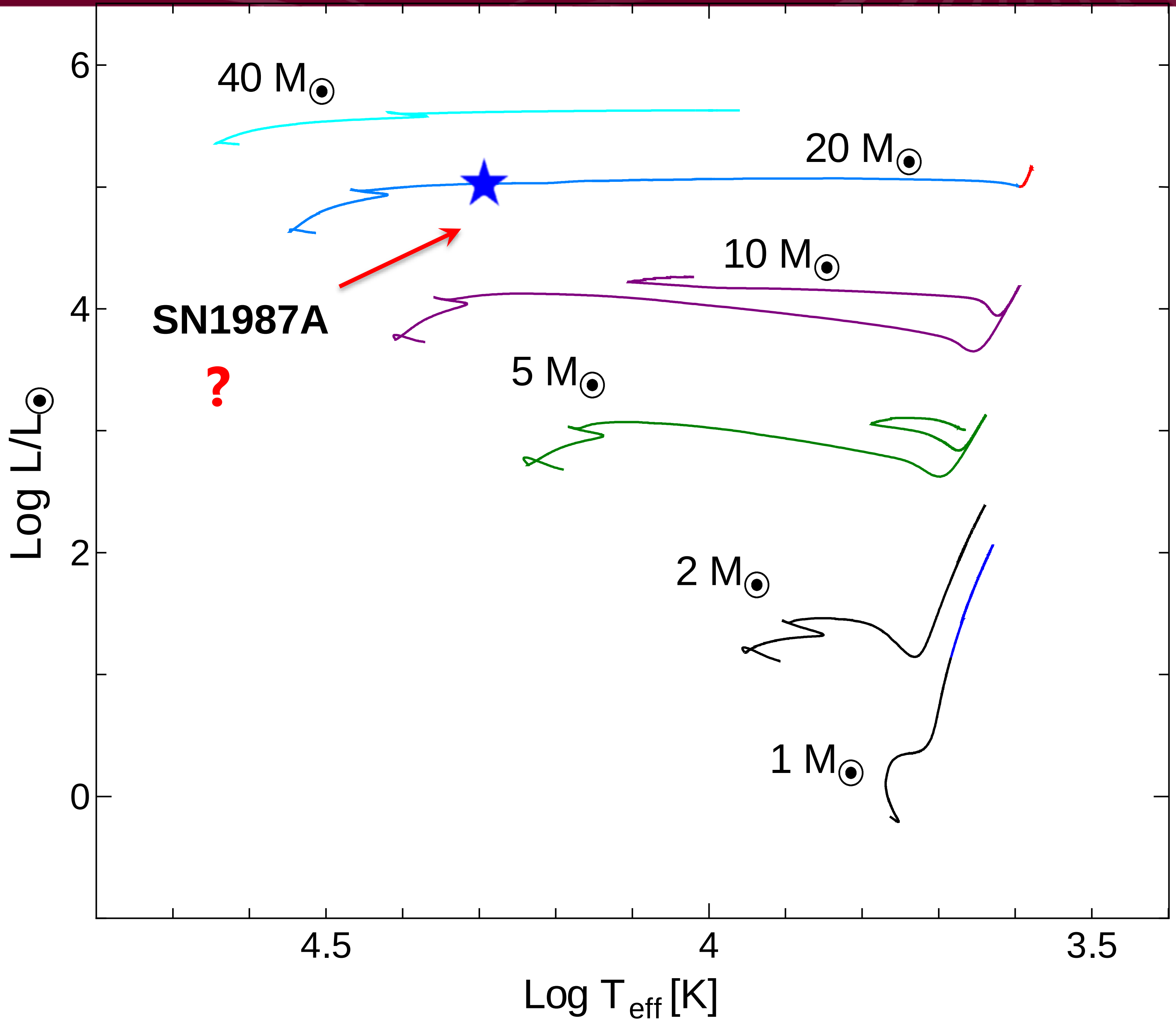
2018年10月17日

九州大学

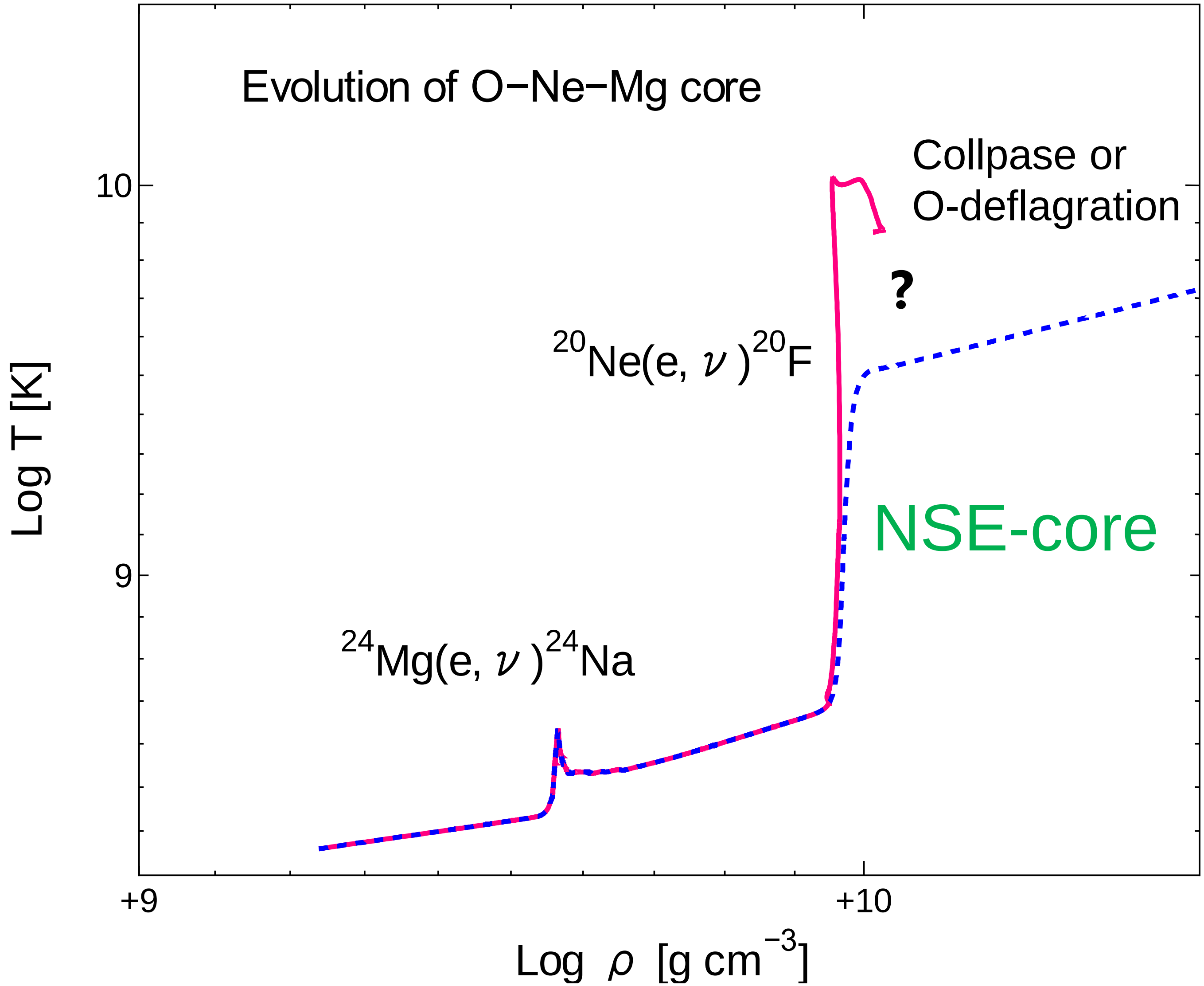
- Brief Introduction
- **Models of stellar evolution**
- **Nucleosynthesis of Heavy elements**
- **(Uncertainties of triple-α and $^{12}C(\alpha,\gamma)^{16}O$ reaction rates)**
- **The evolution of massive stars for 15-70 $M_\odot$**
- **Nucleosynthesis during the stellar evolution of 25 $M_\odot$**
- **Nucleosynthesis during the supernova explosion of 25 $M_\odot$**

INTRODUCTION

Models of stellar evolution


40 M⊙
20 M⊙
10 M⊙
5 M⊙
2 M⊙
1 M⊙
SN1987A
?
Log L/L⊙
Log T_eff [K]
6
4
2
0
4.5
4
3.5

Central Evolution of M_{ms}~$9M_{\odot}$

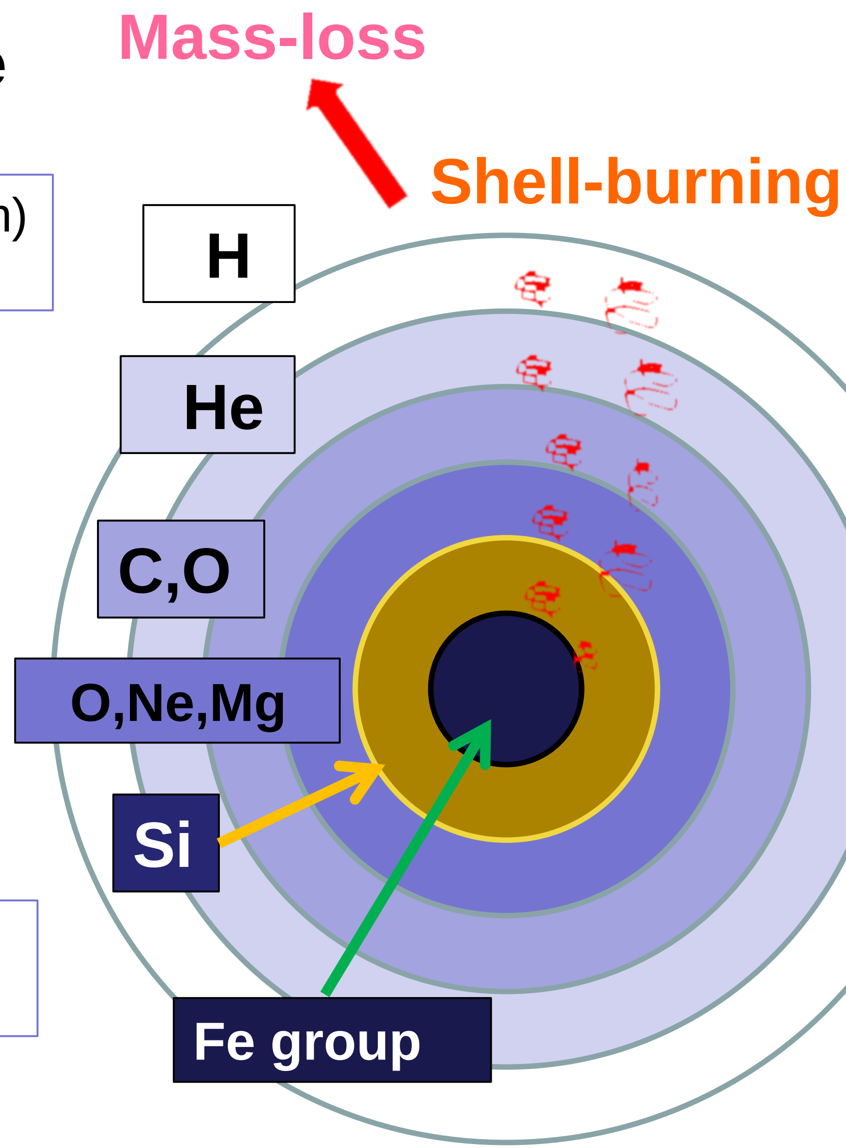


Late stage evolution in massive stars ($M > 10\ M_{\odot}$)

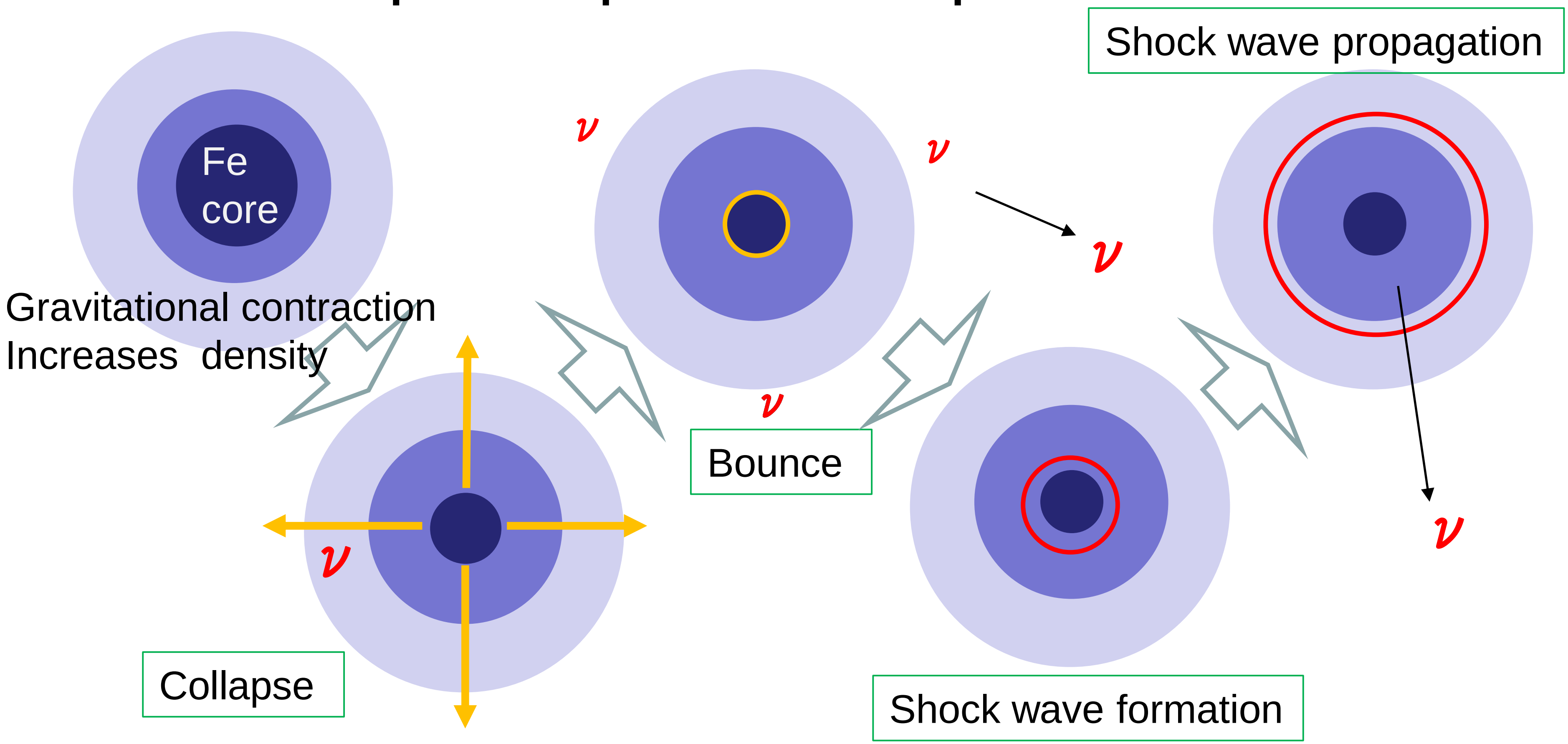
He burning $T \sim 2 \times 10^8$ K	$^4He(\alpha\alpha,\gamma)^{12}C$ (triple α reaction) $^{12}C(\alpha,\gamma)^{16}O$
C burning $T \sim 6 \times 10^8$ K	$^{12}C(^{12}C,\alpha)^{20}Ne$ $^{12}C(^{12}C,\gamma)^{24}Mg$ $^{12}C(^{12}C,p)^{23}Na$
Ne burning $T \sim 1.3 \times 10^9$ K	$^{20}Ne(\gamma,\alpha)^{16}O$ $^{20}Ne(\alpha,\gamma)^{24}Mg$ $^{24}Mg(\alpha,\gamma)\,^{28}Si$
O burning $T \sim 3 \times 10^9$ K	$^{16}O(^{16}O,\alpha)^{28}Si$ $^{16}O(^{16}O,p)^{31}P$ $^{16}O(^{16}O,\gamma)^{32}S$
Si burning $T \sim 4 \times 10^9$ K	$^{28}Si+\alpha \rightarrow \cdots \rightarrow {}^{56}Ni$ (α process) $^{56}Ni(\beta^-)^{56}Fe$

⇩

Core collapse supernova



Core collapse supernova explosion



Electron capture $p + e^{-} \rightarrow n + \nu_e$

^{56}Fe photodisintegration $^{56}\mathrm{Fe} \rightarrow 13\ ^{4}\mathrm{He} + 4n - 124.4\,\mathrm{MeV}$

^{4}He photodisintegration $^{4}\mathrm{He} \rightarrow 2p + 2n - 28.3\ \mathrm{MeV}$

Explosive nucleosynthesis （$T_9 = T/10^9$ K）

The shock wave coming out from the core heats up the matter

(Theilemann, Nomoto, Hashimoto 1990)

・T_9 > 5.0 : Explosive Si and O burnings produces NSE elements : ^{56}Ni, ^{57,58}Ni, ^{44}Ti , …….

$$^{56}\mathrm{Ni} \xrightarrow{6.10\,\mathrm{day}} {}^{56}\mathrm{Co} + \gamma + \nu_e \quad \text{(electron capture)}$$

$$^{56}\mathrm{Co} \xrightarrow{77.12\,\mathrm{day}} \begin{cases} ^{56}\mathrm{Fe} + \gamma + \nu_e & \text{(electron capture)} \\ ^{56}\mathrm{Fe} + e^{+} + \gamma + \nu_e & (\beta^{+}-\text{decay}) \end{cases}$$

・5.0 > T_9 > 4.0 : Incomplete Si burning and explosive Oxygen burning products : ^{28}Si, ^{32}S, ^{36}Ar, ^{40}Ca …….

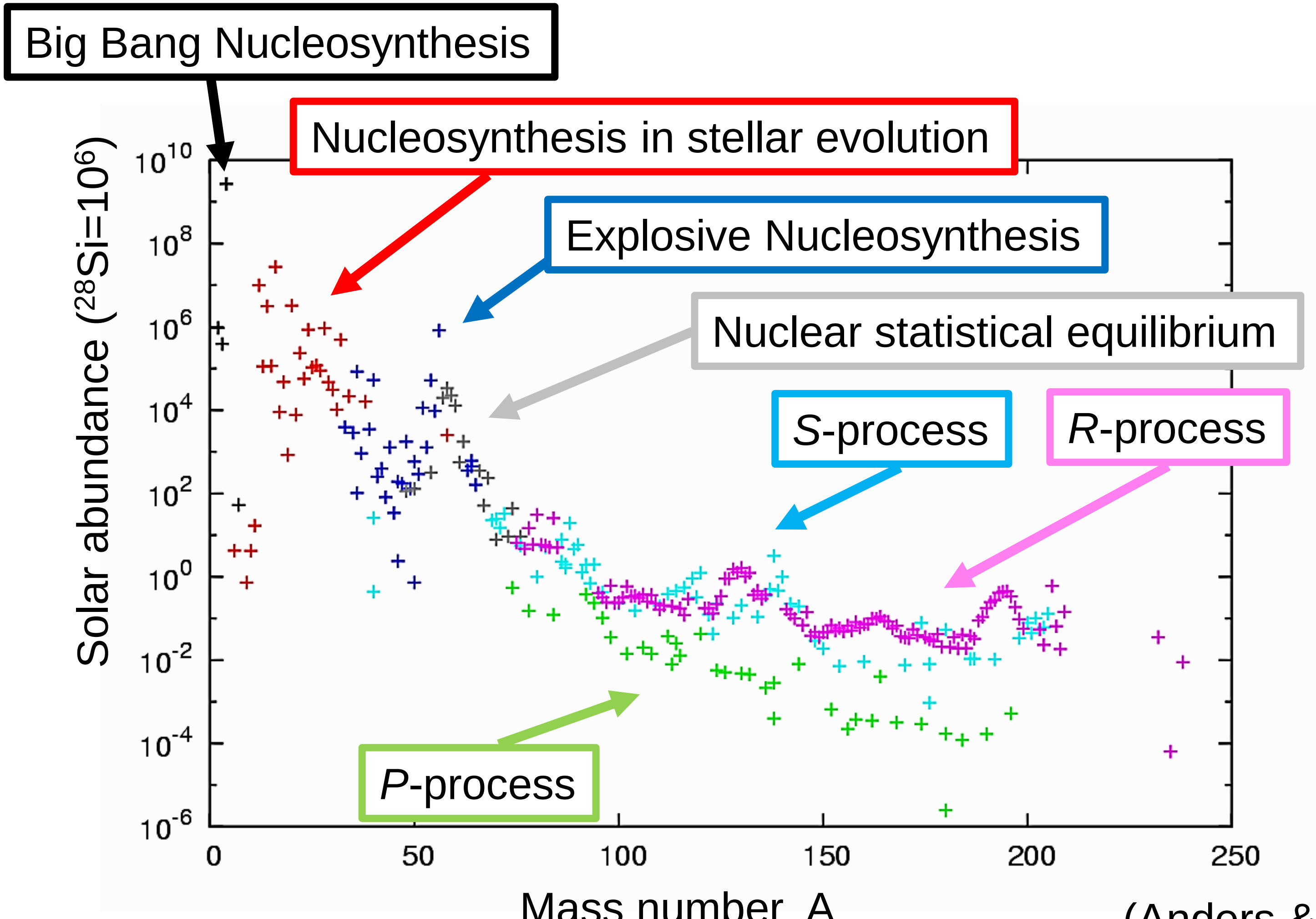
・4.0 > T_9 > 3.5 : Explosive Ne burning products : ^{16}O, ^{28}Si, ^{32}S, ……

・3.5 > T_9 > 2.0 : Explosive C burning products : ^{20}Ne, ^{24}Mg, ….

Nucleosynthesis of heavy elements

Nucleosynthesis of heavy elements

Sites for the solar system abundances



(Anders & Grevesse 1989)

▪ Two types of the *s*-process

Weak *s*-process

- Site : Massive stars $M \gtrsim 10\ M_\odot$
- Stage : He to C burning stage
- Source reaction : ^{22}Ne(α,n)^{25}Mg
- Elements : $60 \lesssim A \lesssim 90$

  Zn ~ Zr

Main *s*-process

- Site : Mediate stars $2\ M_\odot \lesssim M \lesssim 10\ M_\odot$
- Phase : AGB phase
- Source reaction : ^{13}C(α,n)^{16}O
- Elements $90 \lesssim A \lesssim 210$

  Zr ~ Pb

Details of the weak *s*-process

- Site : Massive stars $M \gtrsim 10\ M_{\odot}$
- Elements : $60 \lesssim A \lesssim 90$

Main reactions during the *s*-process

He-b	$^{4}He(\alpha\alpha,\gamma)^{12}C$	**C-b**	$^{12}C(^{12}C,\alpha)^{20}Ne$
	$^{12}C(\alpha,\gamma)^{16}O$		$^{12}C(^{12}C,\gamma)^{24}Mg$
			$^{12}C(^{12}C,p)^{23}Na$

Reactions responsible for neutron production

He-burning

$^{14}N(\alpha,\gamma)^{18}F(\beta^{+})^{18}O(\alpha,\gamma)^{22}Ne \rightarrow {}^{22}Ne(\alpha,n)^{25}Mg$

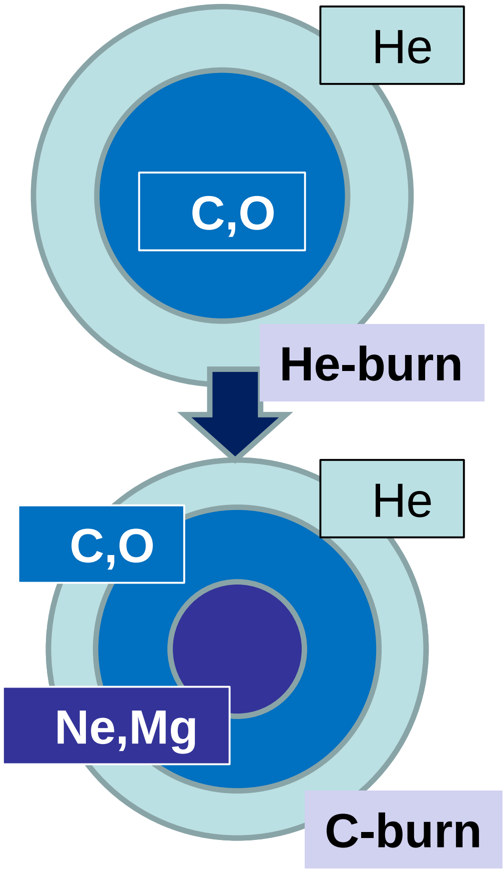
α : produced by pp-chain.

^{14}N : produced by CNO cycle

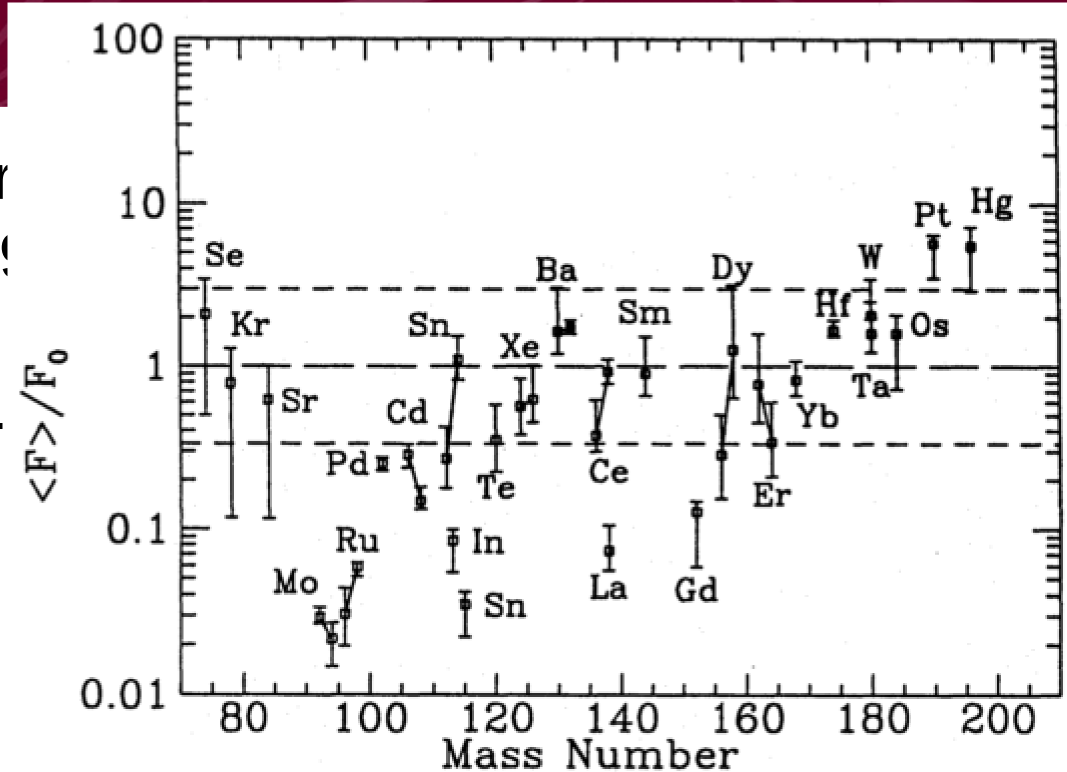
C-burning

$^{12}C(^{12}C,\alpha)^{20}Ne \rightarrow {}^{22}Ne(\alpha,n)^{25}Mg$

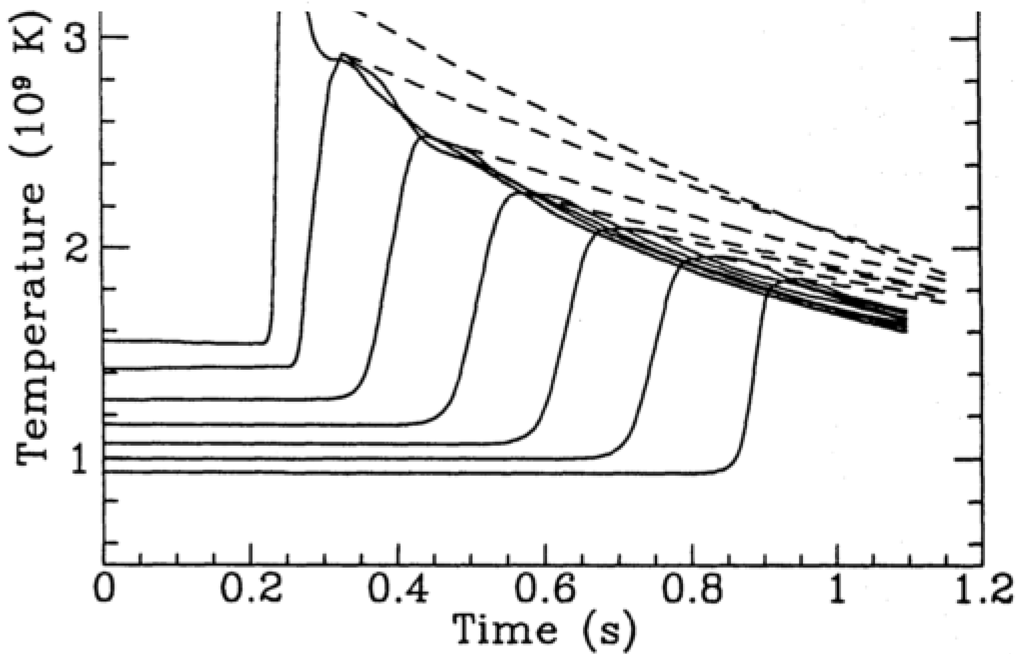
$^{12}C(^{12}C,n)^{23}Mg$ (less than 1% of $^{12}C+^{12}C$ reactions)



- *P*-process vs. temperatur
(Rayet/Hashimoto et al. 19



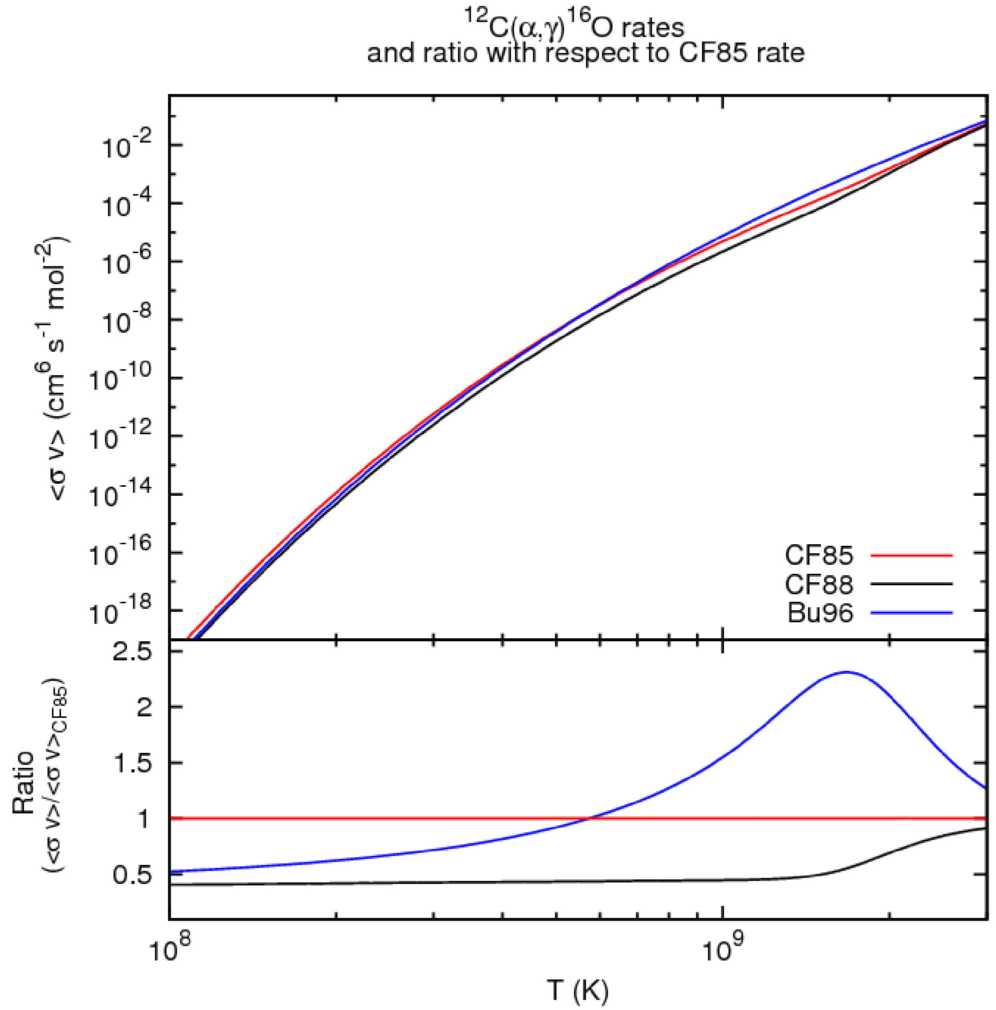
- $T_9 \sim 2$ (T_9 =T/10^9K)
  (γ,n) reactions are dominant.
- $2.2 \leqq T_9 \leqq 2.4$
  (γ,α) and (γ,p) become also
- $2.4 \leqq T_9 \leqq 2.6$
  All *N* > 82 seed nuclei ar
  by photo-
- $2.7 \leqq T_9 \leqq 3.0$
  Intermediate nuclei (50 <
  are destroyed by photo
- $T_9 \geqq 3.0$
  p-nuclei (*N* > 50) are de
  by photo



.40)

Remark of uncertainties of Helium burning reaction rates

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



- Direct experimental measurements and extrapolation to the low energy
  - Caughlan et al. 1985 (CF85)
  - Caughlan and Fowler 1988 (CF88)

However, the extrapolation is difficult

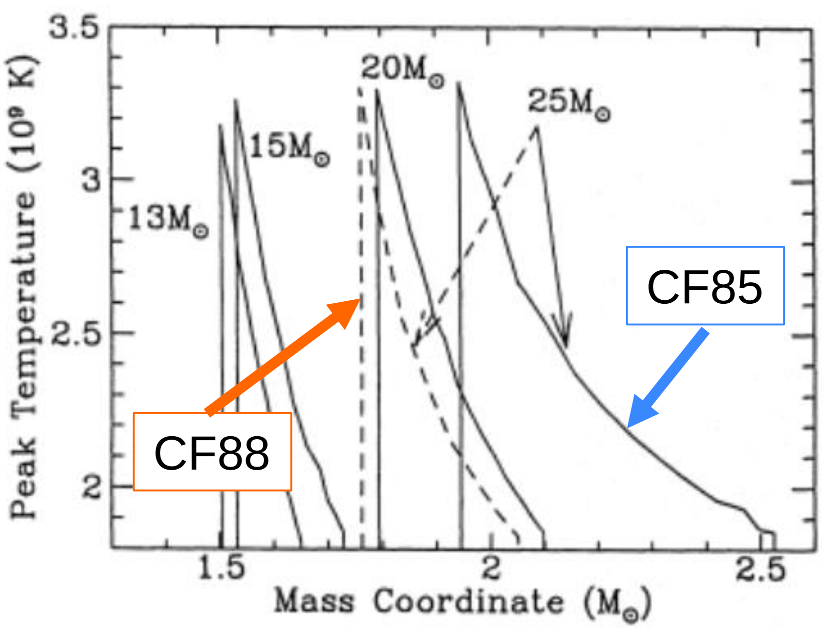
- β delayed α decay of ^{16}N reaction [$^{16}N(\beta,\alpha)^{12}C$]
  - Buchman et al. 1996 (Bu96)

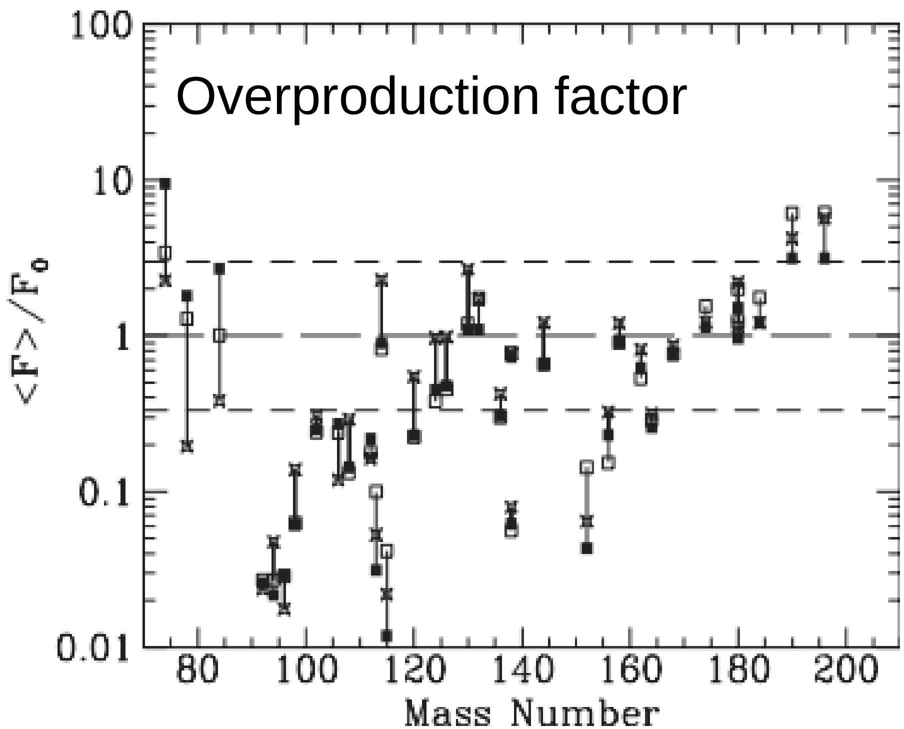
Influence of $^{12}C(\alpha,\gamma)^{16}O$ rate on the *p*-process (Rayet at al. 1995)

Nucleosynthesis during the stellar evolution and supernova explosion

Three different 25 $M_\odot$ explosion models:

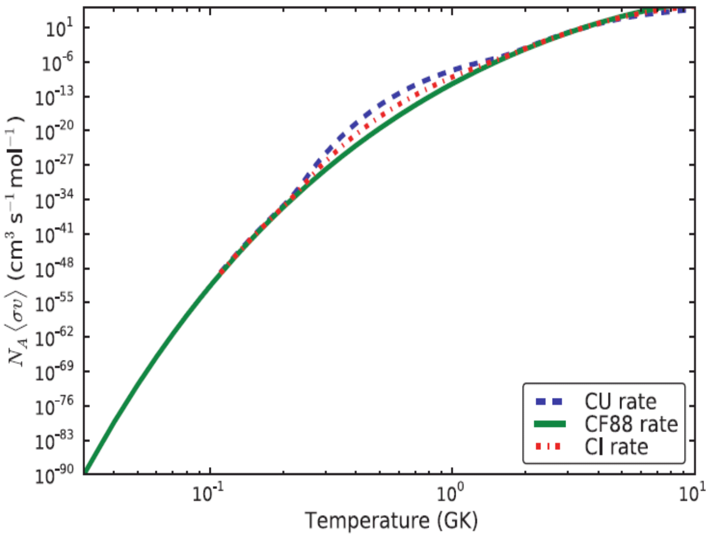
- Open square : normal case, $^{12}C(\alpha,\gamma)^{16}O$ rate with CF85
- Asterisk : $^{12}C(\alpha,\gamma)^{16}O$ rate divided by a factor 2.5 with CF88
- Black square : explosion energy increased by a factor of 1.5

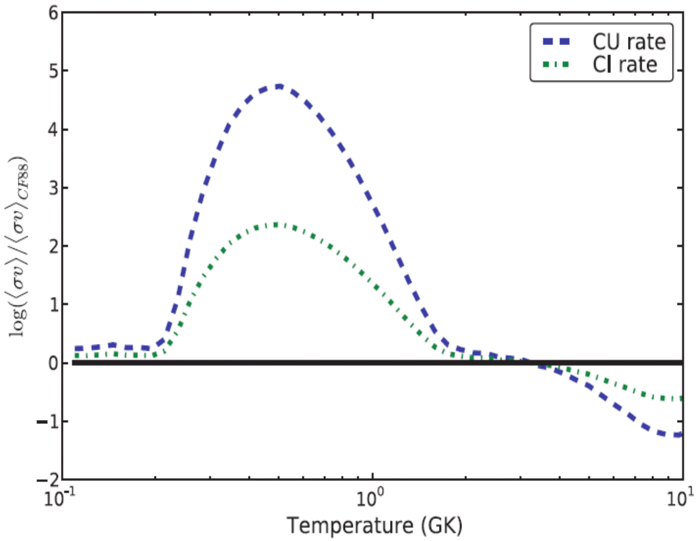




The other reaction rate uncertainty

$^{12}C+^{12}C$ reaction rate uncertainty (Bennett et al. 2012)





- $^{12}C+^{12}C$ reactions — probability

$^{12}C(^{12}C,\alpha)^{20}Ne$	65%
$^{12}C(^{12}C,p)^{23}Na$	35%
$^{12}C(^{12}C,n)^{23}Mg$	less than 0.1%

- Three $^{12}C+^{12}C$ reaction rate

ST : 'standard' rate of Caughlan & Fowlar 1988 (CF88)

CU : Upper limit of CF88 rate

CI : Intermediate rate of the two rates

Summary of introduction

Massive stars (M > 10 $M_\odot$)

- evolve to onion like structure (He,C,O,Si,Fe-group nuclei)
- collapse --- supernova explosion

Heavy elements (A > 60)

- synthesized by the *s*-, *p*-, *r*-process
- weak *s*-process : He, C burning in massive stars
- *p*-process : photodisintegration
  (supernova explosion/stellar evolution)

Outline

- Introduction
- The final fate of stellar evolution
- Nucleosynthesis of Heavy elements
- Uncertainties of triple-α and $^{12}C(\alpha,\gamma)^{16}O$ reaction rates

Model Calculations

- Evolution of massive stars for 15-70 $M_{\odot}$
- Nucleosynthesis during the stellar evolution of 25 $M_{\odot}$
- Nucleosynthesis during the supernova explosion of 25 $M_{\odot}$

STELLAR EVOLUTION

Method of the stellar evolution calculation

・Including 30 nuclei

n, p, ^{4}He, ^{12}C, ^{14}N, ^{16,18}O, $^{20\text{-}22}$Ne, ^{23}Na, $^{24\text{-}26}$Mg, ^{26,27}Al, $^{28\text{-}30}$Si, ^{30,31}P, $^{31\text{-}34}$S, ^{35}Cl, ^{36,38}Ar, ^{39}K, ^{40}Ca

・Models

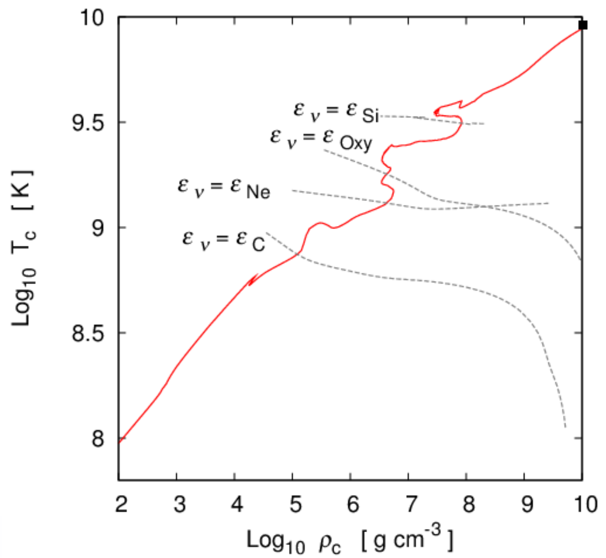
- Zero age main sequence (ZAMS) : 15, 18, 20, 25, 40, 70 $M_\odot$
  (He core mass : 4, 5, 6, 8, 16, 32 $M_\odot$)
- Reaction rates
  - Triple alpha : OKK rate (Ogata et al. 2009)
    : Fynbo rate (Fynbo et al. 2005)
  - ^{12}C(α,γ)^{16}O : CF85 rate (Caughlan et al. 1985)
    : Bu96 rate (Buchmann et al. 1996)

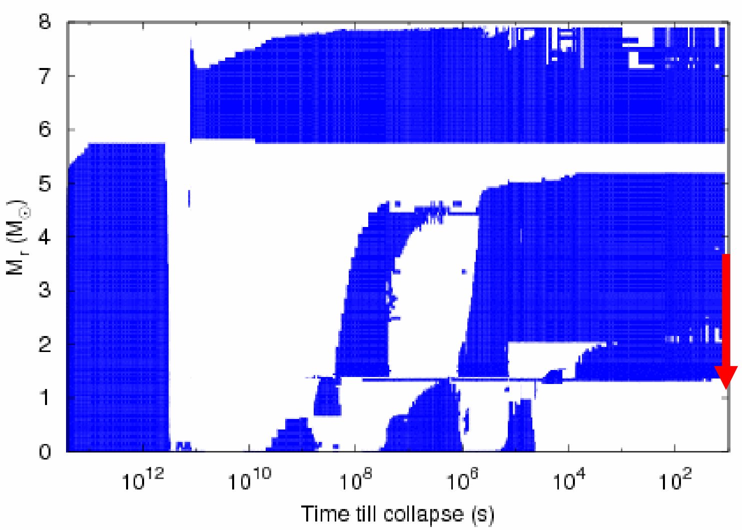
Fynbo-CF85
OKK-CF85
Fynbo-Bu96
OKK-Bu96

× 6 models (***M***$_{\mathrm{ms}}$ mass) = 24 models

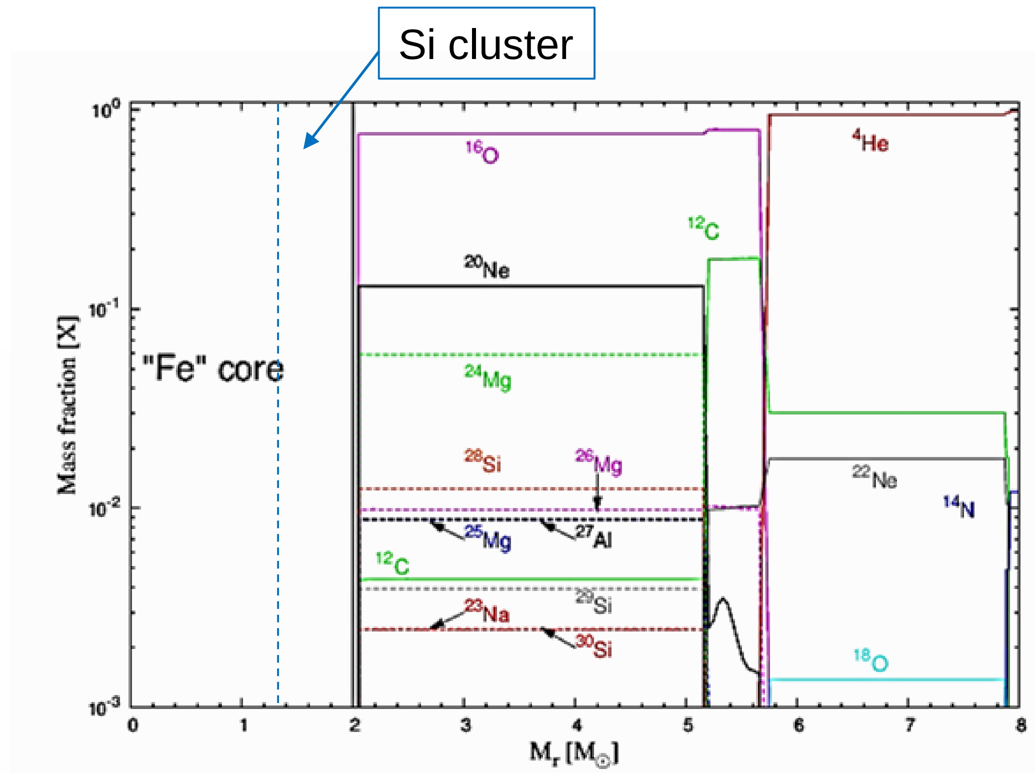
RESULTS OF STELLAR EVOLUTION CALCULATION

Stellar evolution (Fynbo-CF85) : presupernova





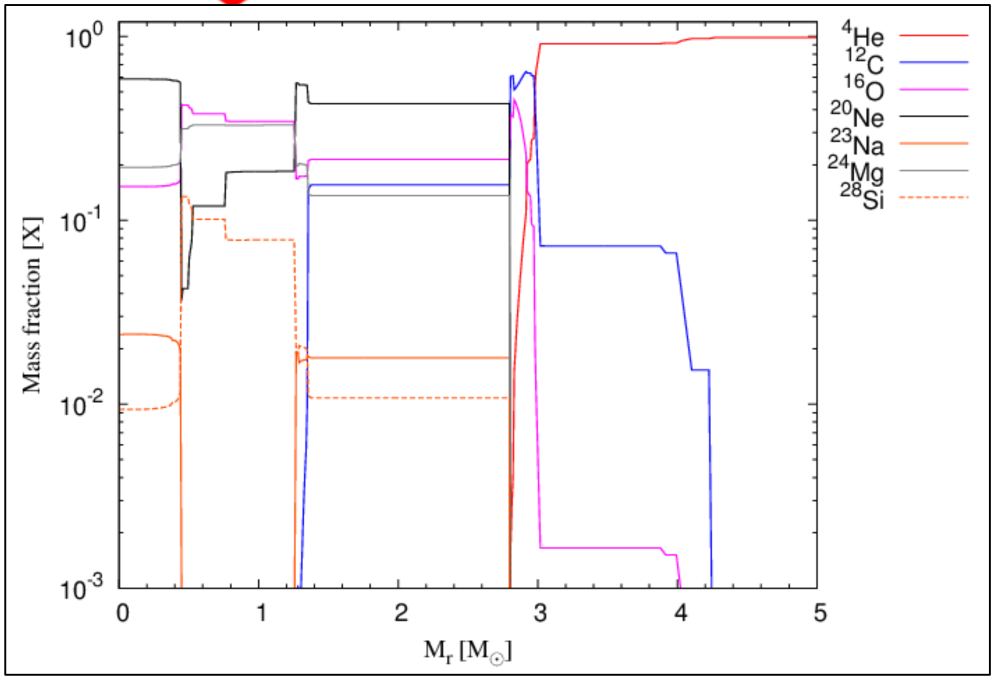
“Fe” core : Fe cluster + Si cluster
($1.36\ M_\odot < M$)



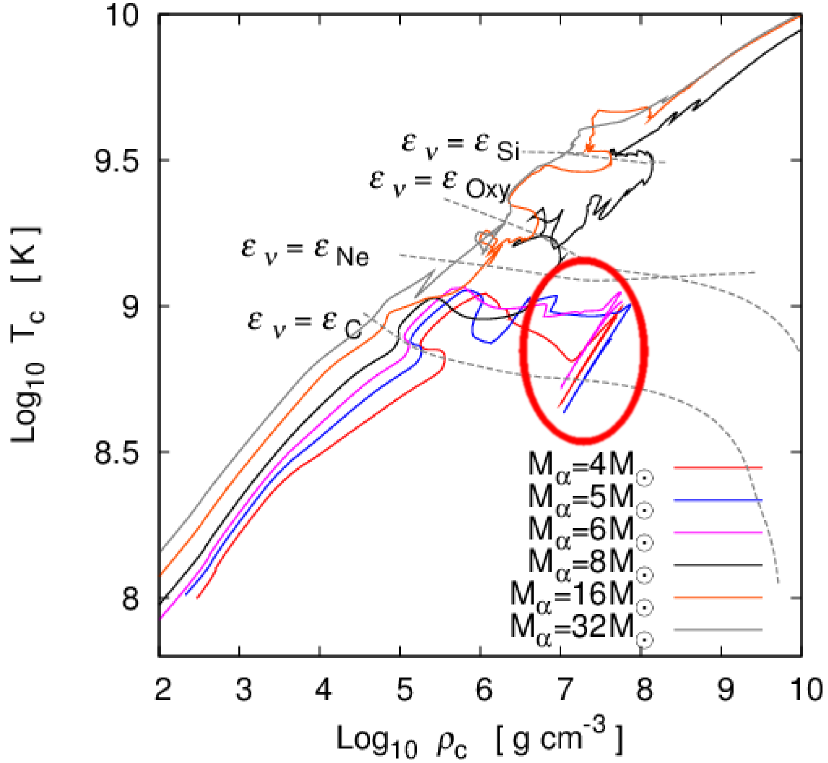
Results : Off center burning

OKK-CF85 $M_\alpha = 4\ M_\odot$
OKK-Bu96 $M_\alpha = 4, 5, 6\ M_\odot$

^{20}Ne off center burning



OKK-Bu96



Results： Off center burning

Final fate of stellar evolution (Nomoto and Hashimoto 1986)

・**For 10-13 $M_{\odot}$**, neon is ignited at the off-center.

(in a semi-degenerate O+Ne+Mg core)

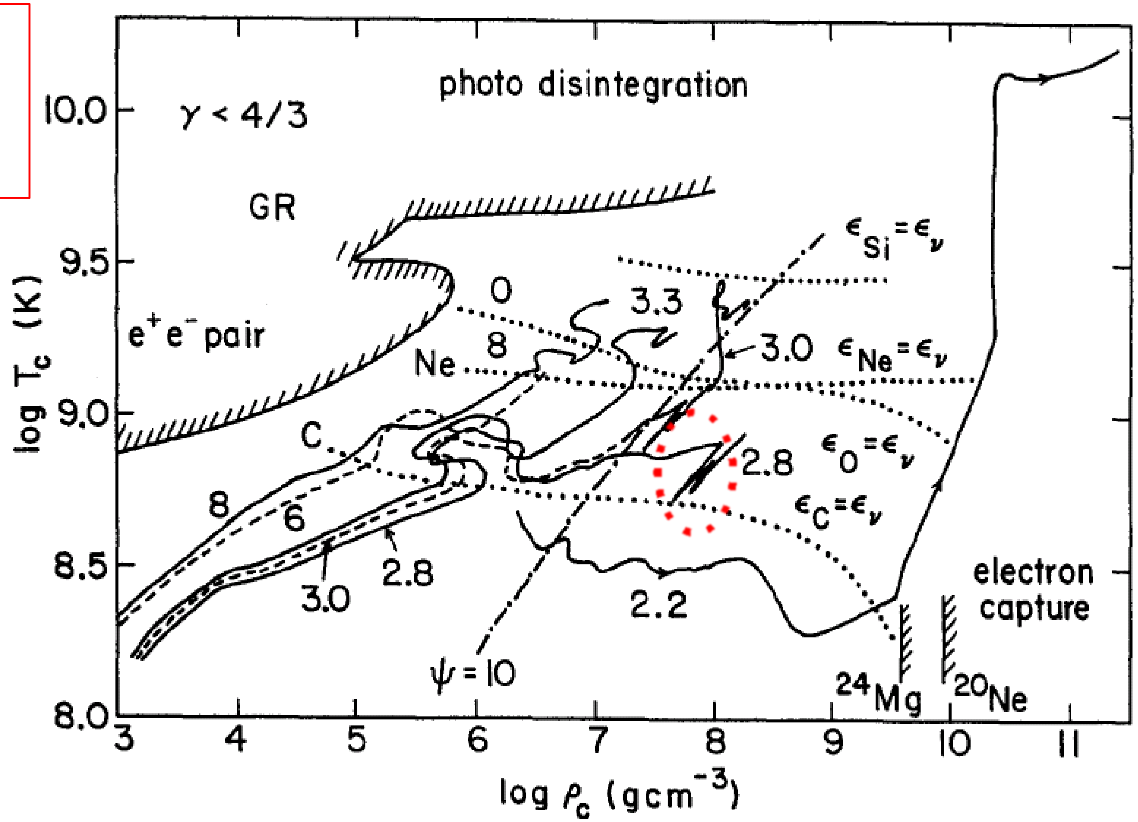
Evolution tracks of 2.2-8.0 $M_{\odot}$ He core

（8-25 M_{ms}）

Off center burning models

・OKK-CF85 M_{ms} = 15 $M_{\odot}$

・OKK-Bu96 M_{ms} = 15, 18, 20 $M_{\odot}$



IMF averaging

Salpeter's Initial Mass Function (IMF) $\phi(M) \propto M^{-2.35}$
(Coefficient of the number of single stars interval *M* to *M* + *dM*)

$$X_{\rm IMF}(i) = \frac{\int_{M_1}^{M_2} X(i, M) M_{\rm ej} \phi(M) dM}{\sum_j \int_{M_1}^{M_2} X((j, M) M_{\rm ej} \phi(M) dM}$$

Erni et al. (2006)
Stars have been only feedback zero-metallicity stars with M ~ 10 - 50 $M_\odot$.([O/H] ~ -2.5)

M_1=15 $M_\odot$ M_2＝50 $M_\odot$

EFFECTS OF UNCERTAINTIES OF REACTION RATES ON HEAVY NUCLEI

Post process nucleosynthesis calculation

Stellar evolution calculations include 30 elements.
For *s*-, *p*-processes, it is required to inclue many elements.

Re-calculation of nucleosynthesis with a larger network
by using evolution data => (post process)

・stellar model : $8M_{\odot}$ He core (M_{ZAMS} = 25 $M_{\odot}$)
・Input physics : Density, Temperature, convective regions as a function of time

・Initial abundances
- Solar system abundances (Anders and Grevesse 1989)
- C,O $\rightarrow$ ^{14}N (CNO cycle)

S-PROCESS TILL THE END OF C BURNING

Effects of a New Triple-α Reaction on the s-Process in Massive Stars

Y. Kikuchi, M. Ono, Y. Matsuo, M. Hashimoto, and S. Fujimoto

Progress of Theoretical Physics Vol. 127, No. 1, pp 171-178 (2012)

Effects of a New Triple-α Reaction on the s-Process in Massive Stars (Kikuchi et al. 2012)

We have investigated the influence of the OKK rate for the weak *s*-process nucleosynthesis.

Stage : He burning to C burning
Model : $8M_\odot$ He core ($M_{ms} = 25\ M_\odot$)

Reaction rates

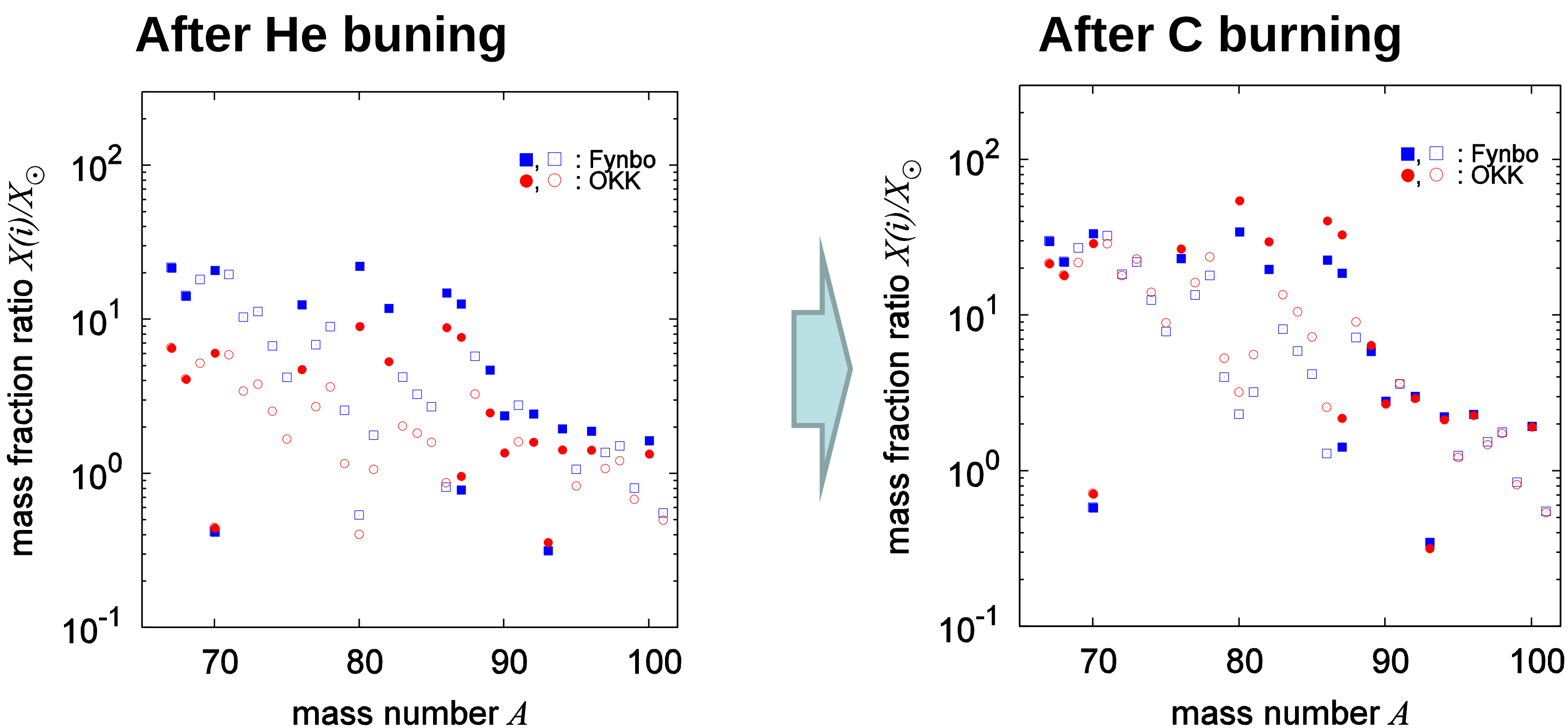
Triple-α : Fynbo rate or OKK rate

$^{12}C(\alpha,\gamma)^{16}O$: CF85 rate
post process : Bu96 rate (JINA REACLIB)

Products of the *s*-process

Overproduction factor (X(i)/X_0(i))

Fynbo pure ■
OKK pure ●
Fynbo other □
OKK other ○



OKK model : enhanced during C burning

S-PROCESS DURING STELLAR EVOLUTION BEFORE CORE-COLLAPSE

Nucleosynthesis during whole stellar evolution stage

OKK rate affects the nucleosynthesis during He burning.

Consistent for evolution and post process reaction rate

Recalculation from He burning to presupernova stage

Fynbo-CF85 Fynbo-Bu96 OKK-CF85 OKK-Bu96

Summary

The *s*-process calculation till presupernova stage

OKK rate (triple-α reaction rate), proceeds very fast :

-the *s*-process is restrained during He burning

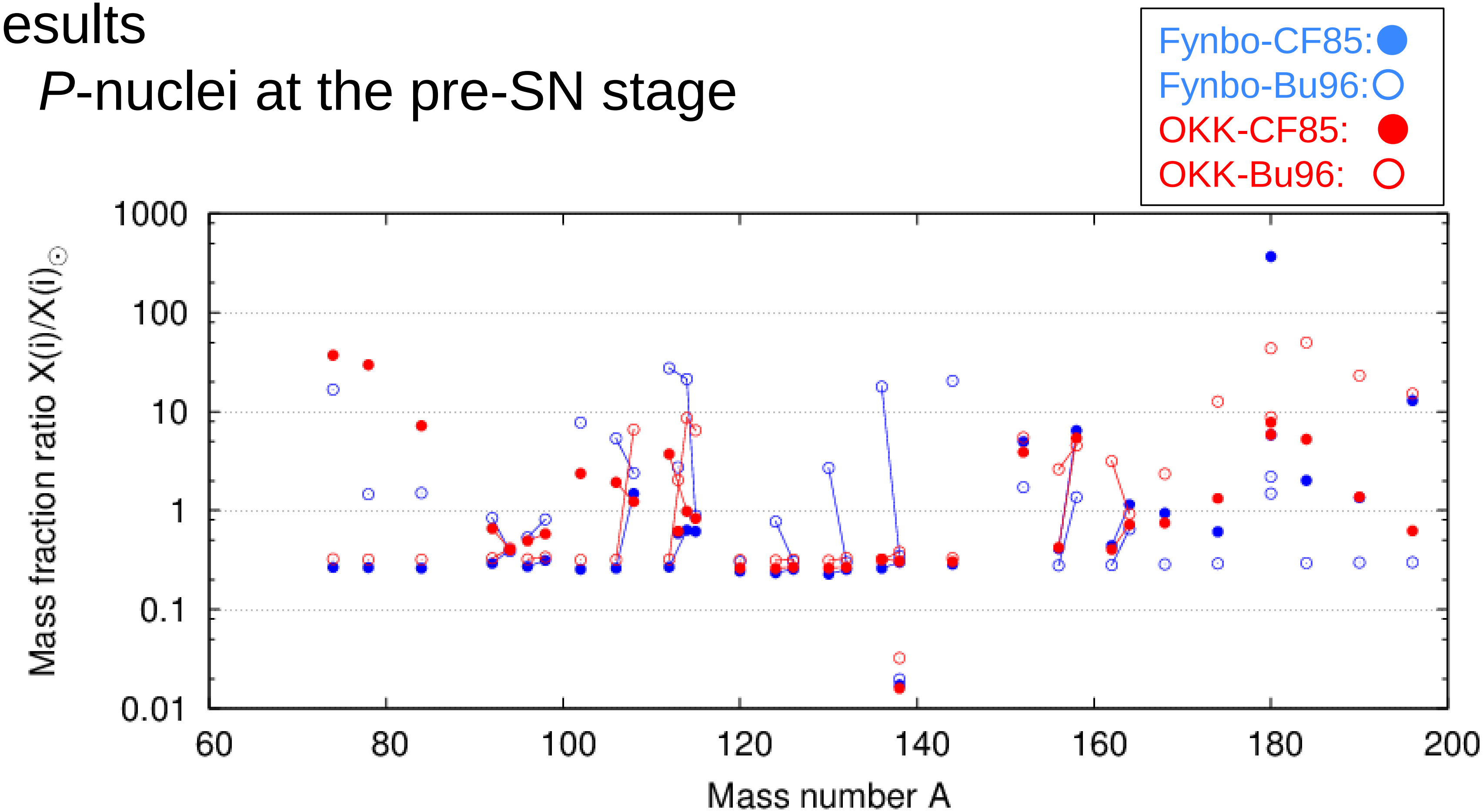
- revitalizes the *s*-process during C burning stage

but the overproduction is influenced also

by $^{12}C(\alpha,\gamma)^{16}O$ reaction.

Results

P-nuclei at the pre-SN stage



OKK-CF85 : enhanced light *p*-nuclei (60 < *A* < 90)
Fynbo-Bu96 : enhanced light and intermediate *p*-nuclei (90 < *A* < 150)
OKK-Bu96 : enhances heavy *p*-nuclei (*A* > 150)

Summary

P-process till presupernova stage (using 4 reaction rate sets)

- Different distributions of main elements (C, O…) are changed by combination of reaction rates
  → influence on temperature and density distribution
- Temperature and density at the presupernova :

  high -- low

  Fynbo-CF85 OKK-Bu96 OKK-CF85 Fynbo-Bu96

  - Fynbo-CF85：gravitational contraction effectively
  - The others： expansion by C shell burning above the O+Ne shell

- *p*-nuclei production : affected by the temperature distribution

NUCLEOSYNTHESIS IN SUPERNOVA EXPLOSION

Estimate of the ejected yields

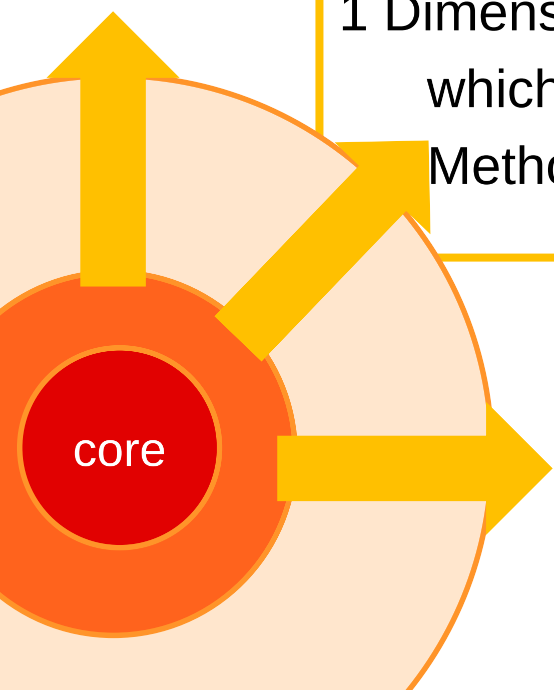
Supernovae explosion calculation

Supernova explosion mechanism has not been established yet.

Neutrino transport, standing shock instability, multi-dimensional simulation…

We only want to estimate the ejected mass of elements

1 Dimensional Hydrodynamic Code (Johnston & Yahil 1984),
which was developed for the studies of SN1987A .
Method of thermal bomb (artificial explosion without collapse)



Supernova explosion calculation

1 Dimensional Hydrodynamic Code(Johnston & Yahil 1984)

Thermal bomb method (only explosion without collapse)

$$\begin{cases} \dfrac{\partial V}{\partial t} - \dfrac{\partial(4\pi r^2 v)}{\partial m} = 0, \\ \dfrac{\partial q}{\partial t} + \dfrac{\partial(4\pi r^3 p)}{\partial m} = v^2 + \dfrac{3p}{\rho} - \dfrac{Gm}{r} - 4\pi r^3 \rho \dfrac{\partial \Phi}{\partial m}, \\ \dfrac{\partial e}{\partial t} + \dfrac{\partial(4\pi r^2 v p)}{\partial m} = H - C. \end{cases}$$

$$V = \rho^{-1}$$

$$q = \boldsymbol{v} \cdot \boldsymbol{r}$$

$$e = \frac{v^2}{2} + U - \frac{GM}{r} + \phi$$

m : the mass coordinate

V : the specific volume

r : the radius

v : the velocity

q : a scalar specific momentum

ρ : the mass density

e : the specific energy

U : the specific internal energy

G : the gravitational constant

Φ : an external potential (assumed to be time independent)

P: the pressure

$H - C$: the net energy source term, Heating and Cooling

Nuclear reaction

α-network：13 spices

^{4}He, ^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, ^{36}Ar, ^{40}Ca, ^{44}Ti, ^{48}Cr, ^{52}Fe, ^{56}Ni

Supernovae explosion calculation

Input models

Pre supernova models : $M_{ms} = 25\ M_{\odot}$($M_{\alpha} = 8\ M_{\odot}$)
(Fynbo-CF85, Fynbo-Bu96, OKK-CF85, OKK-Bu96)
Distributions of Temperature, density, pressure and mass fraction

Input parameters

Two parameters Input energy & input location of mass cut

① Mass cut : just above the Fe core

② Input energy determined from the explosion energy : 10^{51} erg

Models	Fynbo,CF85	Fynbo,Bu96	OKK,CF85	OKK,Bu96
input energy($\times 10^{51}$erg)	1.44	1.06	1.30	1.16
input point($M_{\odot}$)	1.22-1.37	1.22-1.29	1.21-1.26	1.31-1.36

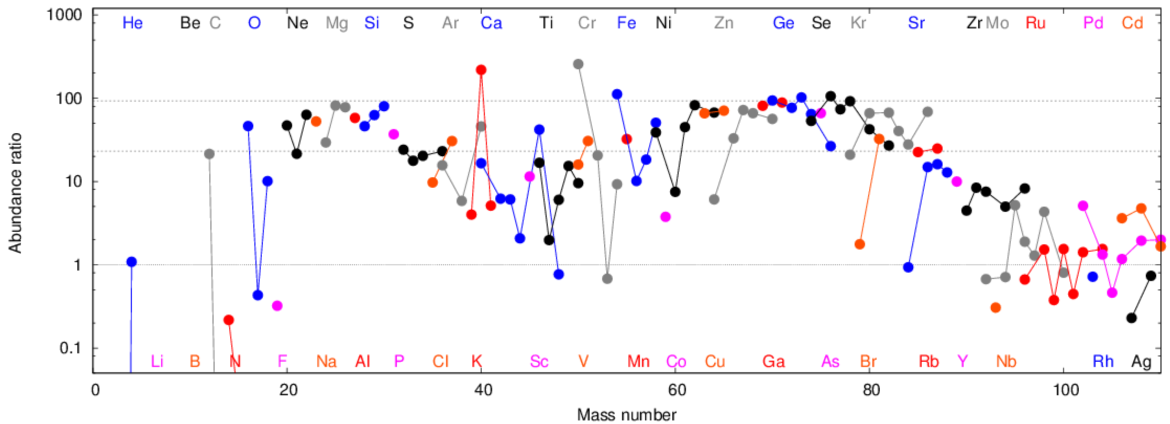
Overproduction factors (A < 110): CF85

- Normalized overproduction factors by that of most popular nuclei $^{16}O \times 2^{\pm 1}$

FynboCF85

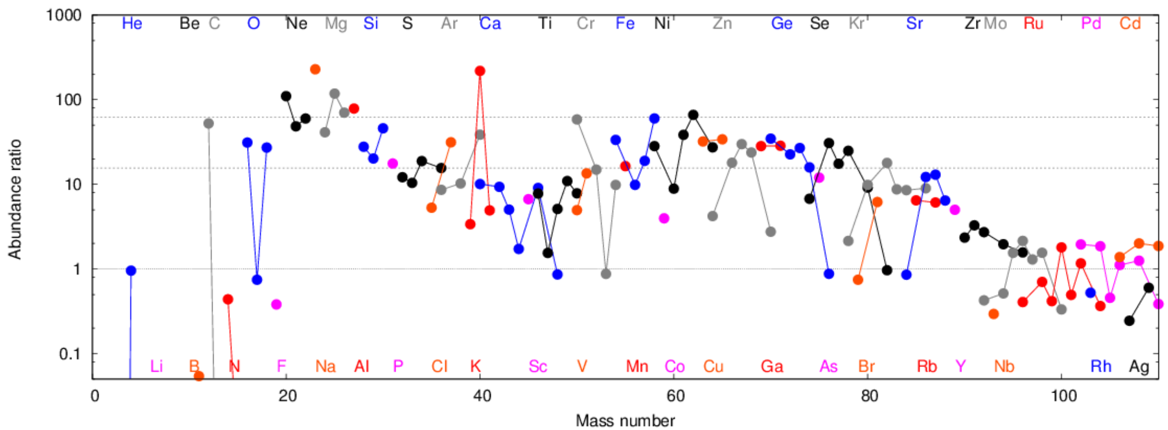
- $20 \leqq A < 32$:
  well reproduced

- *s*-process :
  well reproduced



OKKCF85 :

- ^{22}Ne, ^{23}Na, ^{25}Mg
  over produced
  $27 \leqq A \leqq 32$:
  well reproduced
- *s*-process :
  well reproduced
  the least in the 4 models



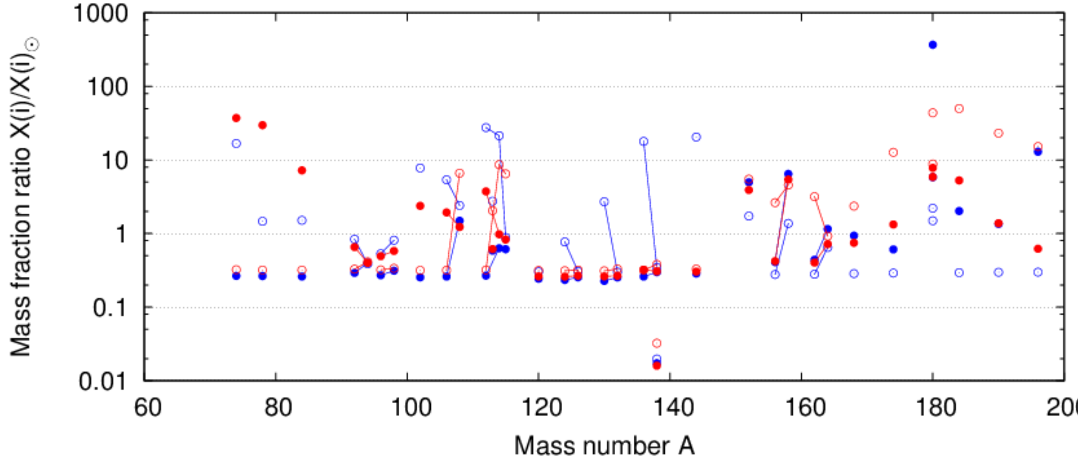
Results of *p*-elements

FynboCF85: ●
FynboBu96: ○
OKKCF85: ●
OKKBu96: ○

Before supernova explosion

OKKCF85
enhanced light p-nuclei

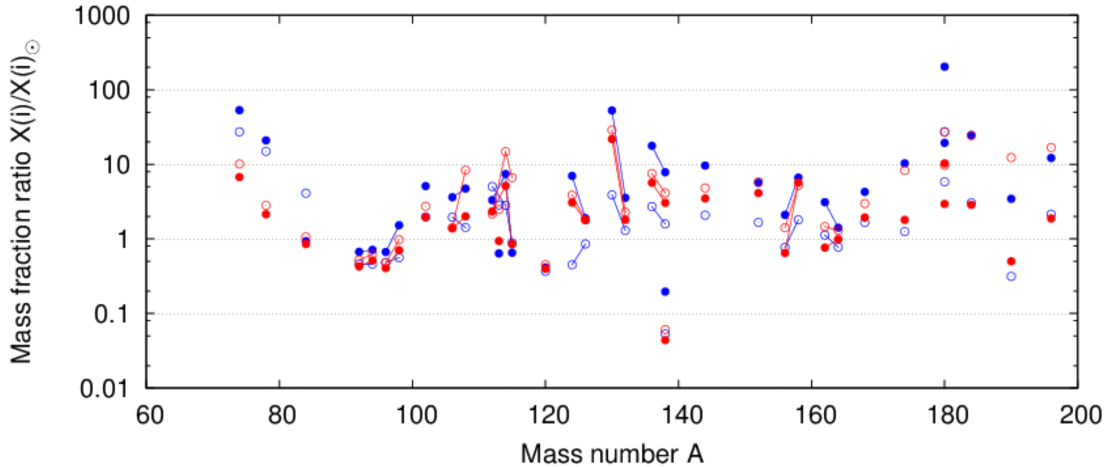
FynboBu96
enhanced light and
intermediate p-nuclei



After supernova explosion

Decayed their elements
FynboCF85 most enhanced

The pattern is similar.



Summary of nucleosynthesis in supernova explosion

- We calculate supernova explosion and the nucleosynthesis by using results of stellar evolution calculations ($M_\alpha = 8\ M_\odot$ with 4 reaction rate models).
- OKK models : the elements (Ne, Mg, Na) are overproduced against ^{16}O
- *s*-nuclei : For all models, no deviation from pre-supernova stage

  - He and C burning are significantly important.
- *p*-nuclei : no drastically change by reaction rate dependence

  but, the yields relate to peak temperatures

  and the size of the *p*-process layers

Conclusion

Nucleosynthesis in massive stars and supernova explosions

Comparison with the solar abundances

・$20<A<32$ nuclei :

Fynbo rate-sets are consistent (in particular Fynbo-CF85)

OKK rate sets overproduce the elements.

・*s*-process : Element production is affected by the combination of reaction rate sets.

However the ejecta of supernova becomes similar (except OKK-CF85)

・*p*-process : temperature distribution before supernova is important.

Concluding remarks

Big-Bang

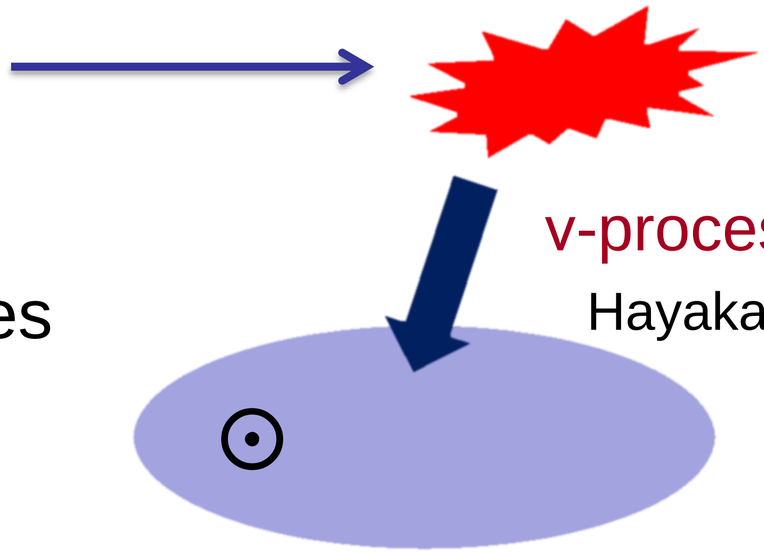
First Star

Stellar evolution Supernova explosion

Nucleosynthesis

Chemical evolution of each elements

Supernova(e)



Solar system abundances

Now we can do it !