Stellar Archaeology as a Time Machine to First Stars
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s-Process Nucleosynthesis in the Progenitors of Carbon-Enhanced Metal-Poor Stars

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in collaboration with

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Overview of Carbon-Enhanced Metal-Poor (CEMP) Stars

Origin of Extremely Metal-Poor (EMP) Stars

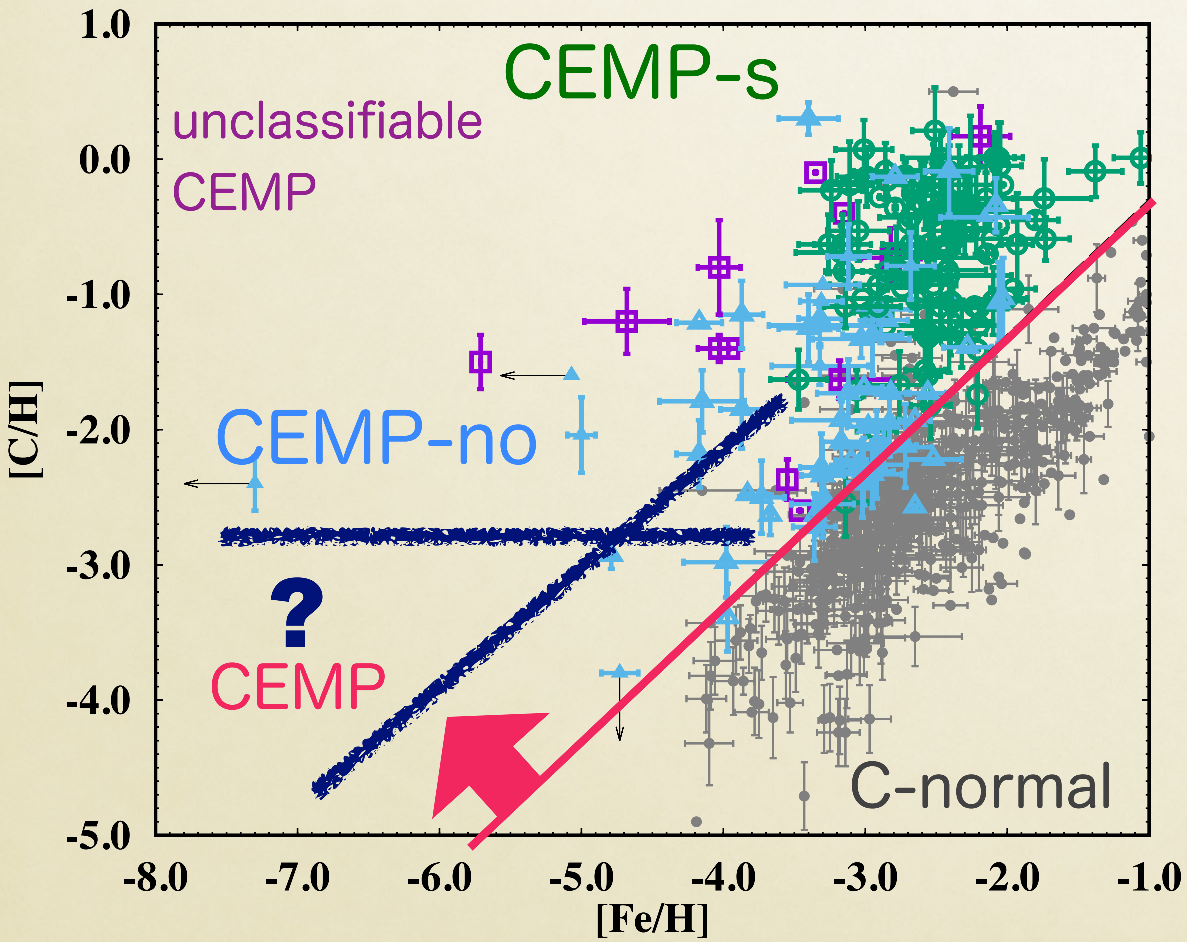
- common in Extremely Metal-Poor (EMP) stars
  - > 20 % for [Fe/H] < -2 with [C/Fe] ≧ 0.7
- divided into subclasses
  - CEMP-s (s-process) [Ba/Fe] ≧ 0.5
  - CEMP-no (no s-proces) [Ba/Fe] < 0.5
    - lower and higher CEMP-no (Bonifacio+15)
  - CEMP-r (r-process), CEMP-r/s (s+r), etc.

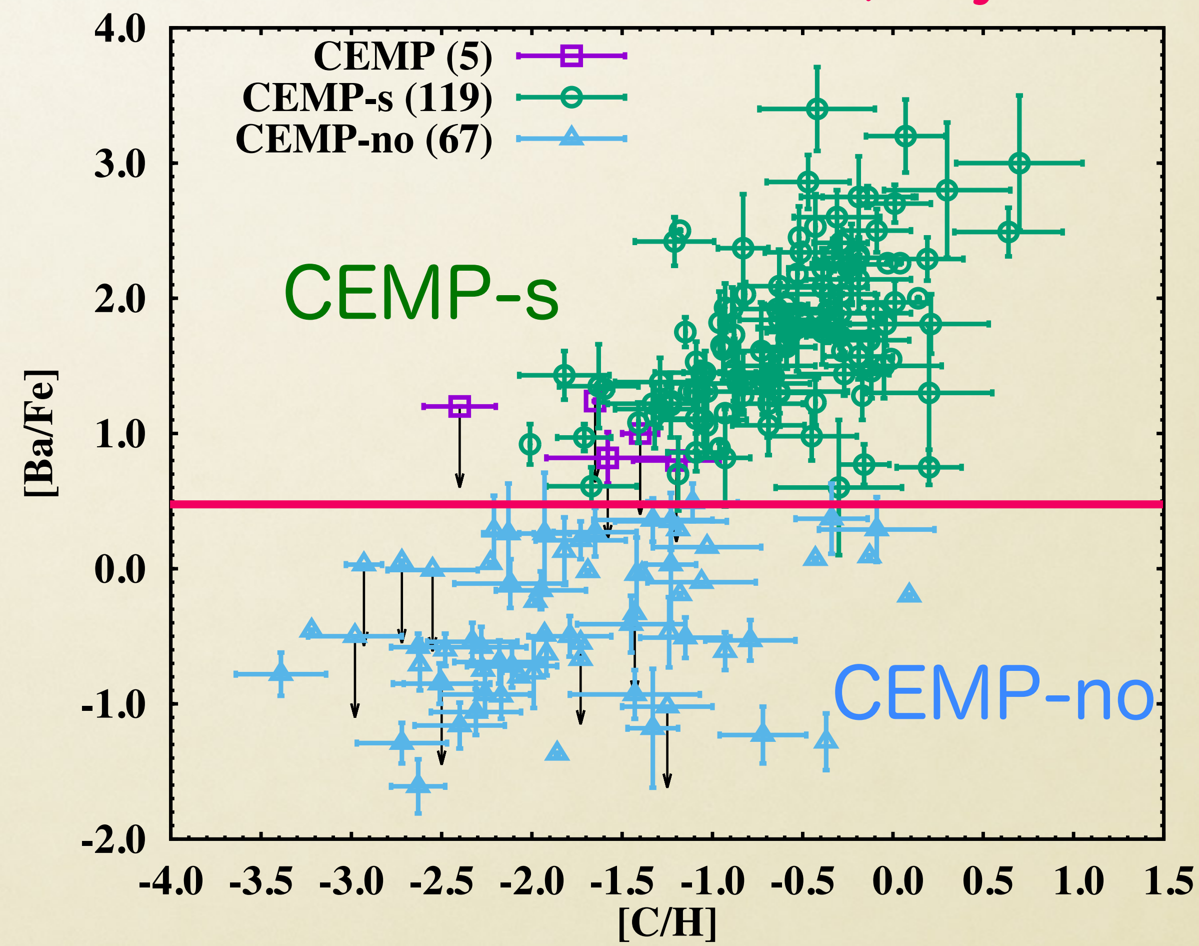
- Possible origins

I) CEMP-s and no come from binary mass transfer

II)CEMP-no from supernova models (Umeda+02)

III)CEMP-no from rotating massive stars (Meynet+06)





See also discussions by Aoki+07, Bonifacio+15, Yoon+16, Matsuno+17, etc.

Data taken from SAGA database (TS+08,11,17, Yamada+13)

IS HE 0107−5240 A PRIMORDIAL STAR? THE CHARACTERISTICS OF EXTREMELY METAL-POOR CARBON-RICH STARS

2004, ApJ, 611, 476

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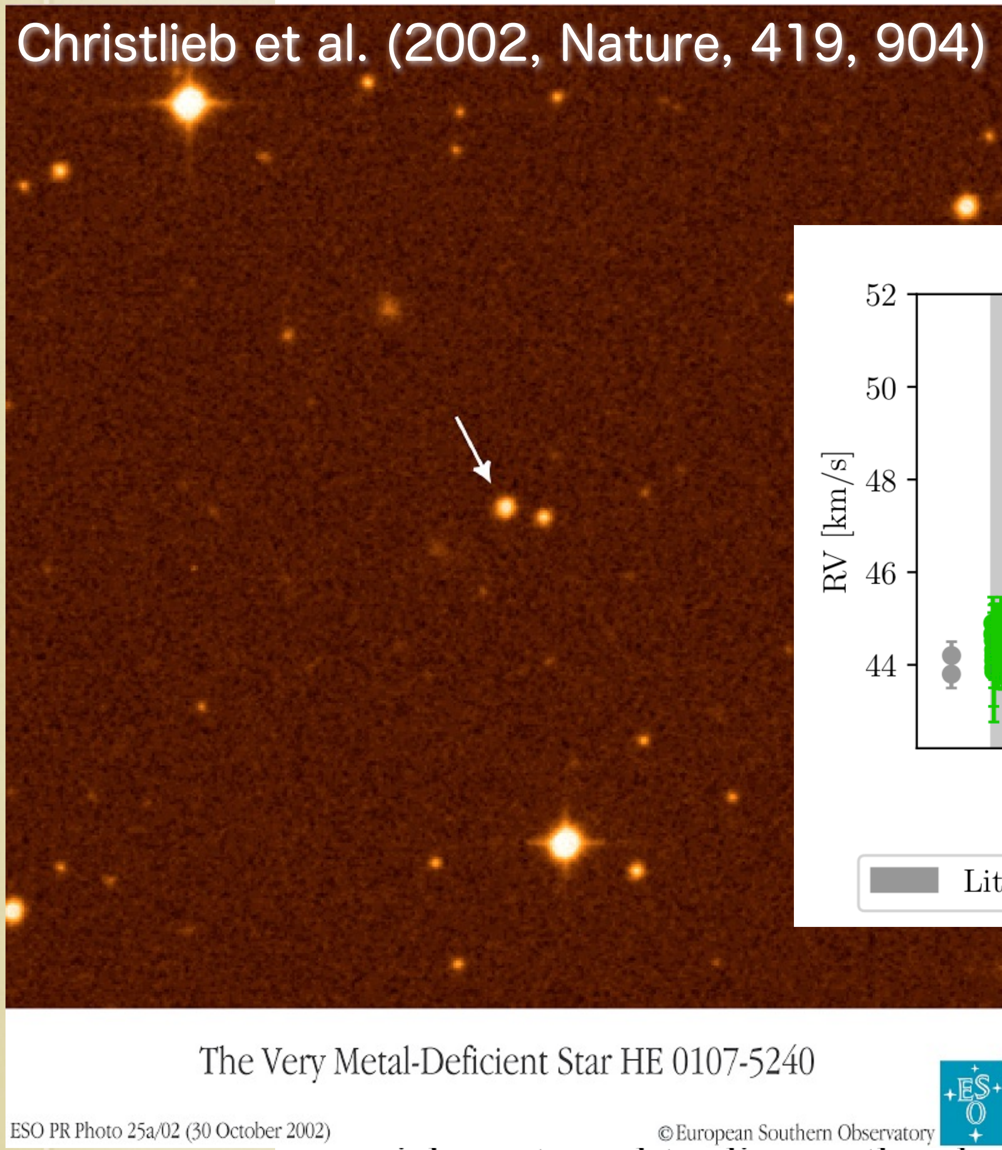
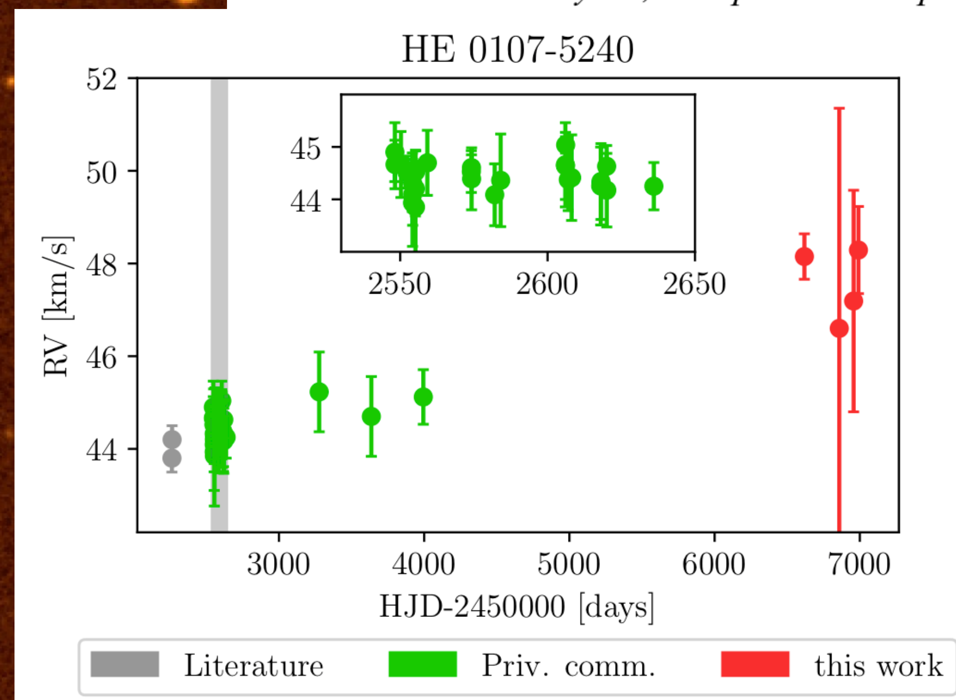
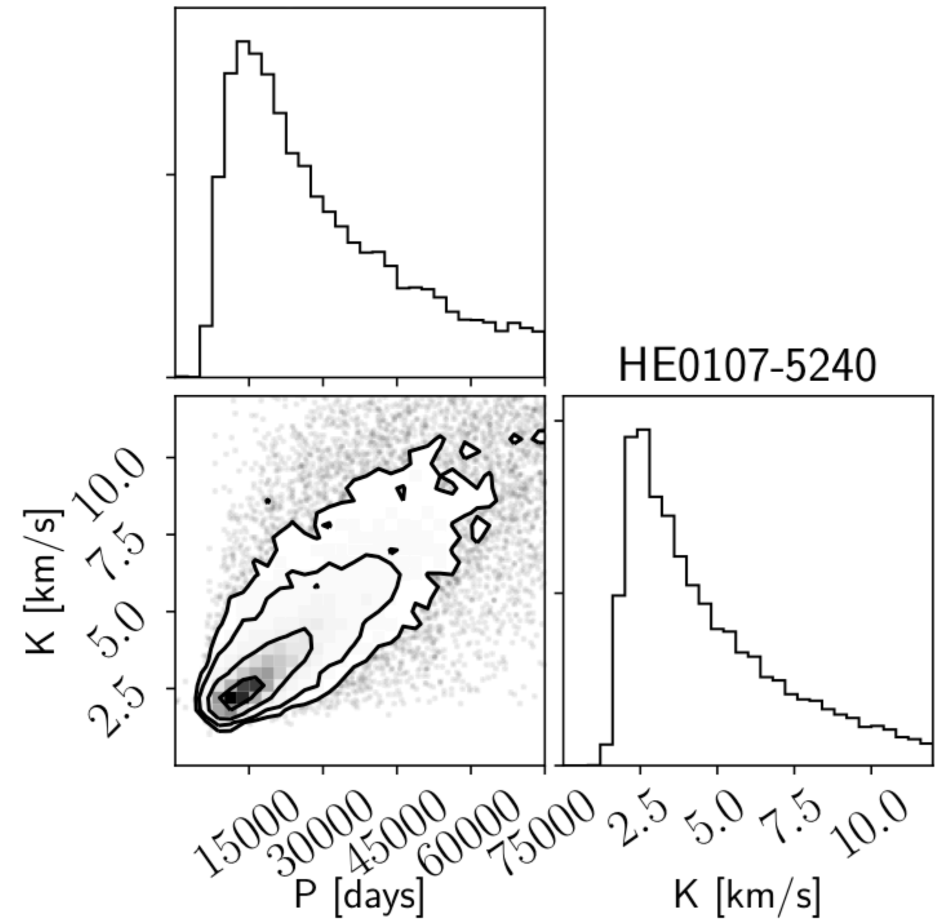


Arentsen+, arXiv:1811.01975





…chemically evolved companion, which …
…ed in the binary, we rely on the results …
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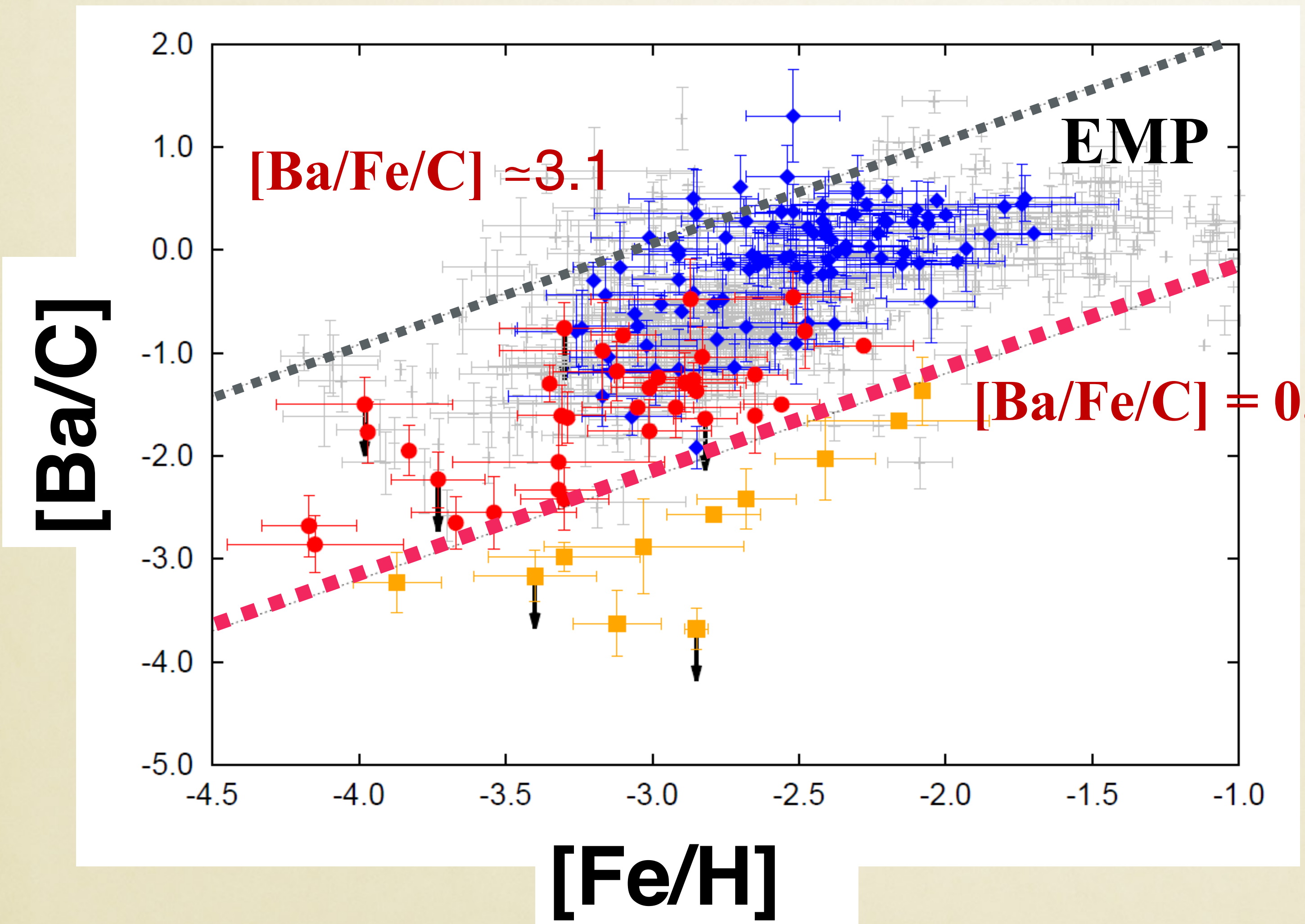
…ved, allowing us to explain the origin in …
enrichments and to discuss the abundances of *s*-process elements. From th… that HE 0107−5240 has evolved from a wide binary (of initial separation ∼20 AU) with a primary of initial mass in the range 1.2–3 $M_\odot$. On the assumption that the system now consists of a white dwarf and a red giant, the present binary separation and period are estimated at ≃34 AU and a period of ≃150 yr, respectively. We also conclude that the abundance distribution of heavy *s*-process elements may hold the key to a satisfactory understanding of the origin of HE 0107−5240. An enhancement of [Pb/Fe] ≃ 1–2 should be observed if HE 0107−5240 is a second-generation star, formed from gas already polluted with iron-group elements. If the enhancement of main-line *s*-process elements is not detected, HE 0107−5240 may be a first-generation secondary in a binary system with a primary of mass less than 2.5 $M_\odot$, born from gas of primordial composition, produced in the big bang, and subsequently subjected to surface pollution by accretion of gas from the parent cloud metal-enriched by mixing with the ejectum of a supernova.

Re-Classification of CEMP Stars

- **Lo-CEMP-no (40)**
  - **Low-carbon band stars (SN origin)**
- **Hi-CEMP-no (11)**
  - **High-carbon band stars (AGB origin)**



s-process nucleosynthesis

○ [Ba/C] unchanged during mass transfer.

○ The efficiency of s-process nucleosynthesis:

[Ba/Fe/C] = [Ba/Fe]-[C/H]
= [Ba/C]-[Fe/H]

3-4 dex variations

s-Process Nucleosynthesis Modeling

Mixing Mechanisms and Neutron Sources

① Helium-Flash Driven Deep Mixing (He-FDDM) during the AGB phase for [Fe/H] < -2.5 (Fujimoto+90, 00, TS+04, 10)

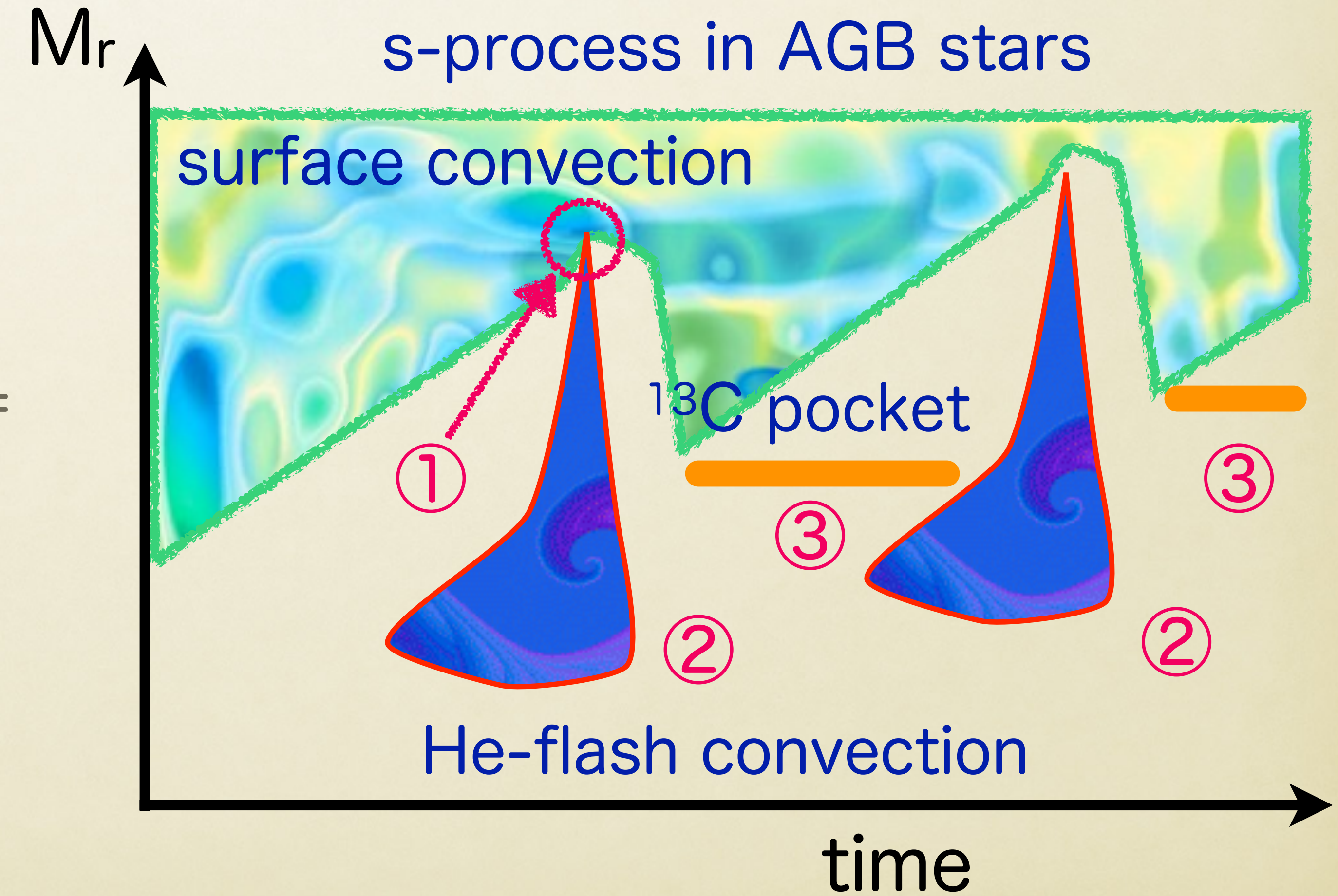
- $^{13}C(\alpha,n)^{16}O$ in the He-flash convective zones
- ^{13}C abundance as a free parameter

② Third dredge-up + $^{22}Ne(\alpha,n)^{25}Mg$

- $T > 3 \times 10^8$ K at the He-conv. ($M > 3.5 M_\odot$)
- (Boothroyd+Sackmann98, Busso+88, Blocker95)

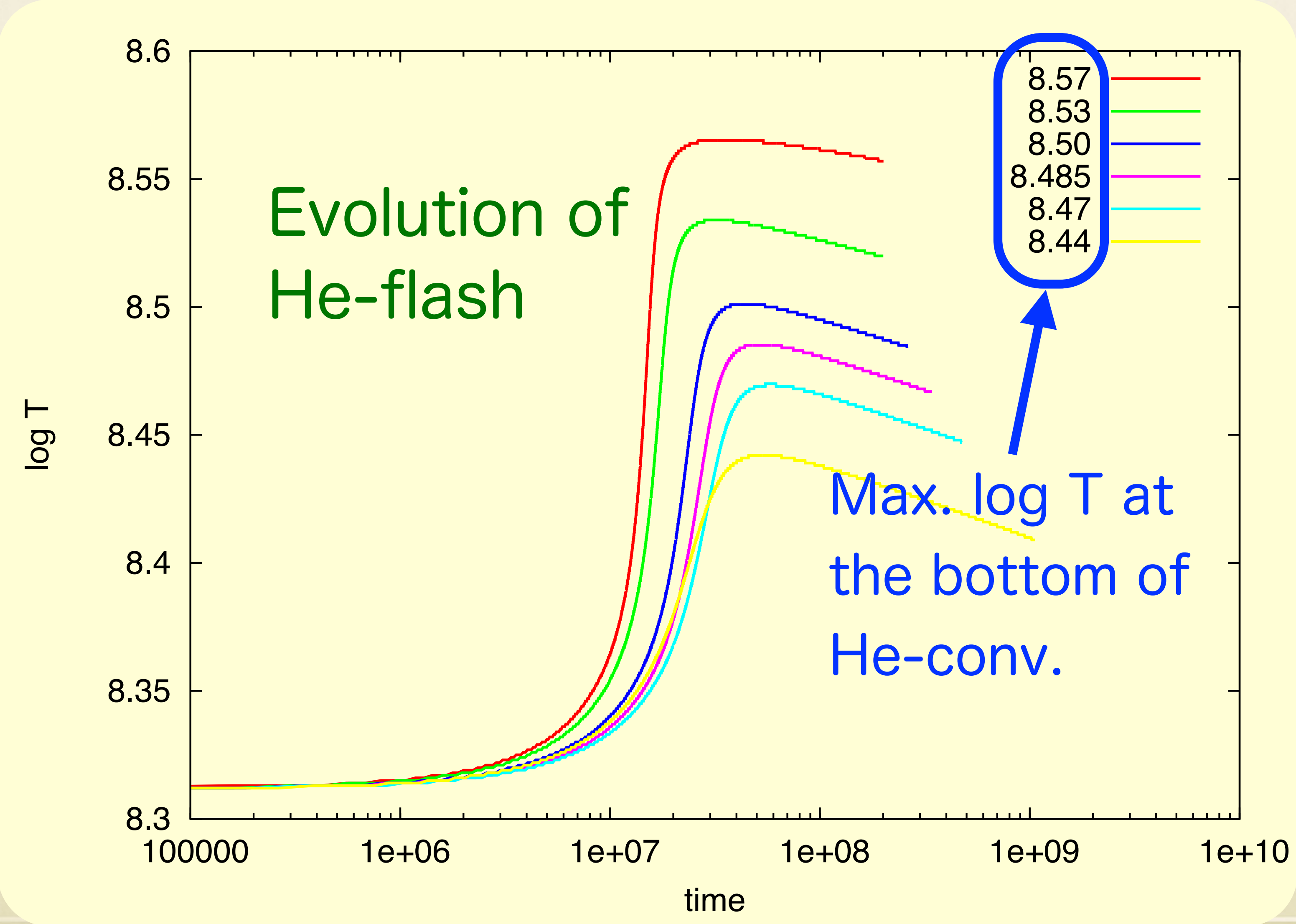
③ Third dredge-up + radiative ^{13}C mixing

- ^{13}C pocket: $^{13}C(\alpha,n)^{16}O$
  - $X(^{13}C) = 5 \times 10^{-3}$, $X(^{14}N) = 1.7 \times 10^{-4}$ (Bisterzo+10)



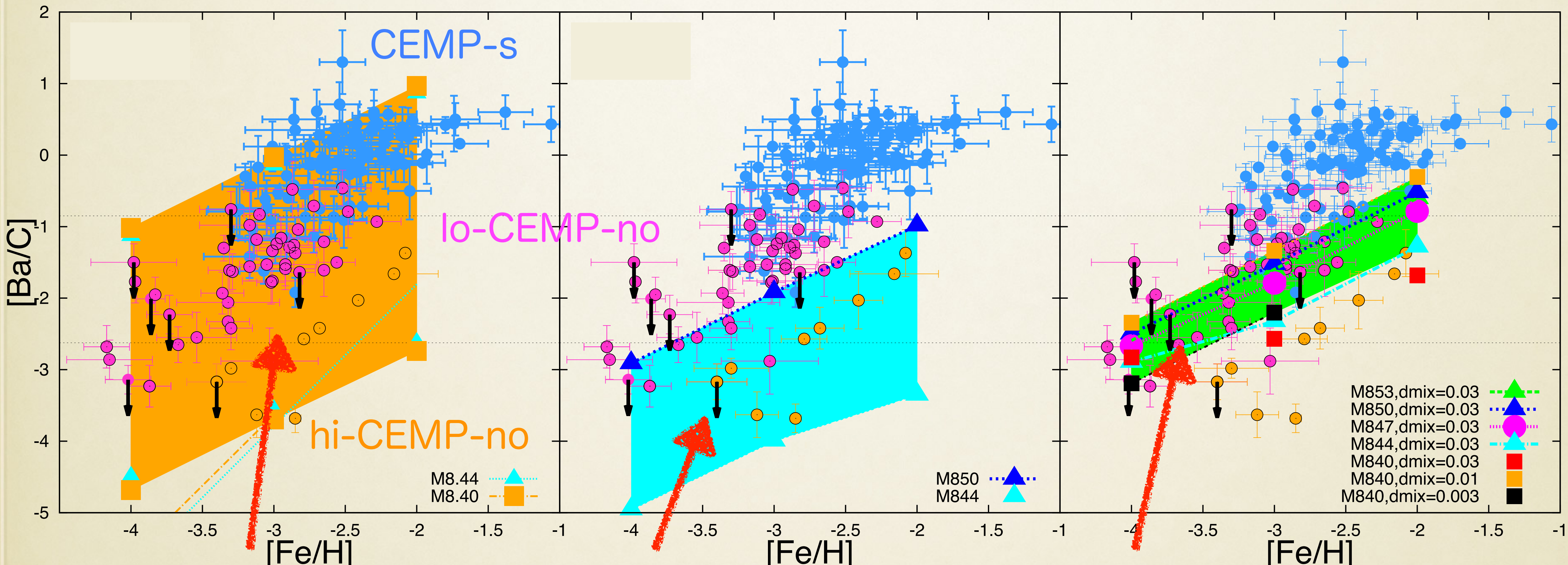
Nucleosynthetic Models

- Nuclear network models (Nishimura+08, Yamada+):
  - One-zone approximation (Sugimoto+Fujimoto78, Fujimoto82)
  - 318 isotopes of 84 elements: ^{1}H to ^{210}Po
  - p-, α-, n-captures and β-decays.
    - NACRE, Caughlan+Fowler88, and Bao+00 rates



Contribution to the s-Process

① Convective ^{13}C burning ② Convective ^{22}Ne burning ③ Radiative ^{13}C pocket



Final abundances covered by reasonable model parameters.

^{13}C pocket does not play a role in the s-process in CEMP stars.

unless we assume thick ^{13}C pocket layer as large as He-conv. zone.

similar results obtained by Bisterzo+10,11,12; Abate+15

saga

s-Process in EMP Stars

(1) s-process nucleosynthesis is metallicity independent at [Fe/H] ≲ -2.

- ^{16}O plays a crucial role in neutron density.
- s-process efficiency can be measured by [Sr/Fe/C], [Ba/Fe/C], or [Eu/Fe/C].

(2) AGB progenitors are classified by neutron sources.

1. Convective ^{13}C-burning: $^{13}C(\alpha,n)^{16}O$

   proton-capture of ^{12}C in the He-flash convective zones: $^{12}C(p,\gamma)\,^{13}N\,(e^{+}\nu)\,^{13}C$

   - Low-mass AGB stars $(M \lesssim 3.5 M_\odot)$:
   - High efficiency [Ba/Fe/C] ≃ 0.8-3.1

   CEMP-s & Lo CEMP-no

2. Convective ^{22}Ne burning: $^{22}Ne(\alpha,n)^{25}Mg$

   Dredged-up ^{12}C are converted to ^{14}N, which are converted to ^{22}Ne by α-captures:
   $^{12}C \rightarrow\, ^{14}N\,(\alpha,\gamma)\,^{18}F\,(e^{+}\nu)\,^{18}O\,(\alpha,\gamma)$

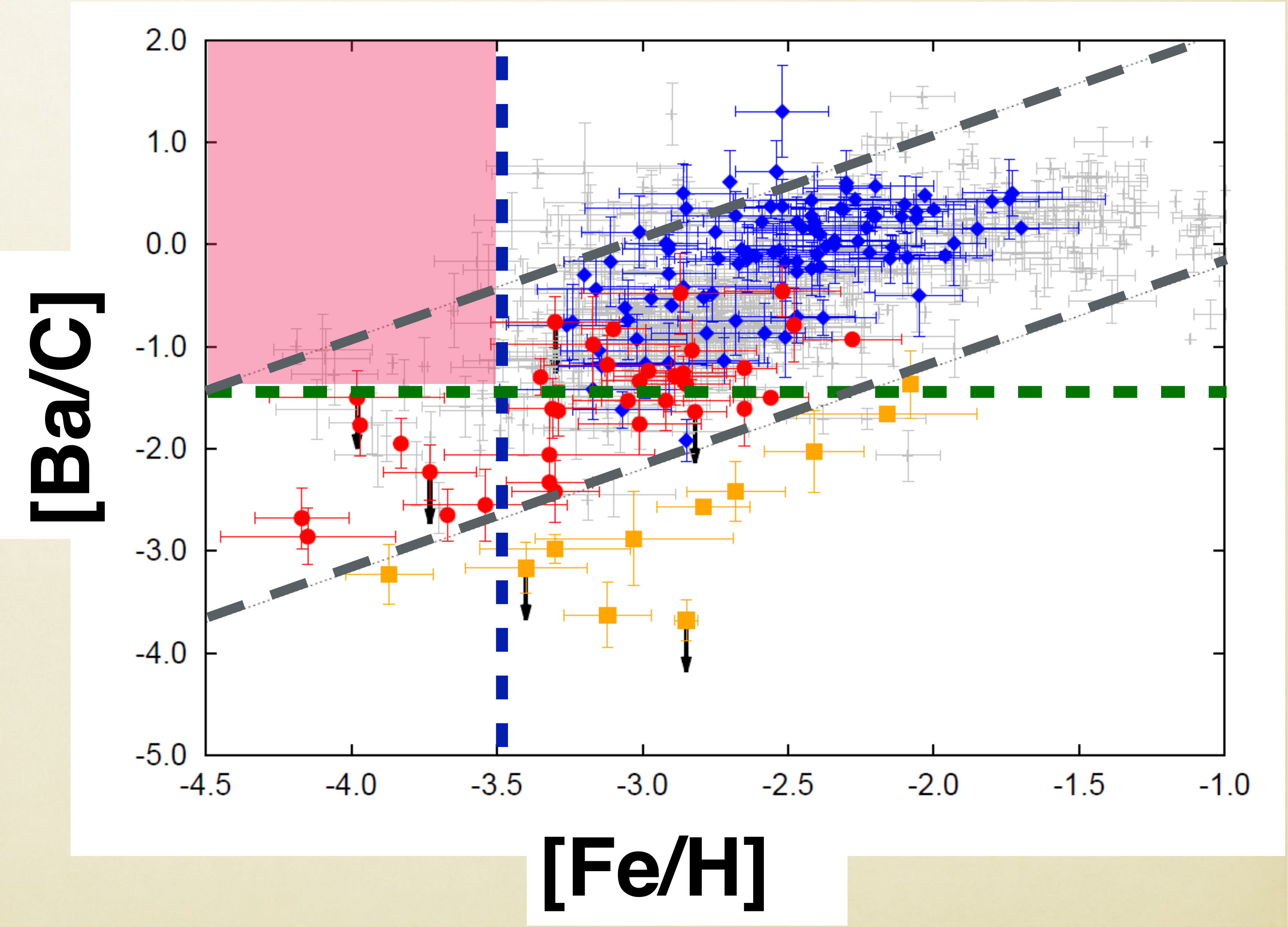
   - High-mass AGB stars $(M \gtrsim 3.5 M_\odot)$:
   - Low efficiency [Ba/Fe/C] < 0.8

   Hi CEMP-no

CEMP Star Formation in Binary Systems

CEMP Progenitor Binaries

- CEMP-s & Hi CEMP-no: larger accretion and larger metallicity
  - Short period binaries (P < 10^4 days) with [Fe/H] ≳ -3.5
    - CEMP-s: low-mass AGB stars (M ≲ 3.5 M☉)
    - Hi CEMP-no: high-mass AGB stars (M ≳ 3.5 M☉)
- Lo CEMP-no: smaller accretion
  - Long period binaries (P > 10^4 days)
  - No low-mass AGB stars (M ≲ 3.5 M☉) at [Fe/H] ≲ -3.5



Formation History of CEMP Stars

[Fe/H]

Short period binaries | $P \approx 10^4$ d | Long period binaries

IMF transition: normal SF (TS+13)

≈-2

$M_1 = 1$-$3\ M_\odot$: CEMP-s

$M_1 \gtrsim 3\ M_\odot$: Hi CEMP-no

$1\ M_\odot \leqq M_1 \lesssim 8\ M_\odot$:

Lo CEMP-no

≈-3.5

No CEMP stars

- No binaries with $0.8\ M_\odot$ + AGB stars

$3\ M_\odot \lesssim M_1 \lesssim 8\ M_\odot$:

Lo CEMP-no

- Primaries are only high-mass AGB stars

-∞

Summary

I) s-process nucleosynthesis

- convective ^{13}C-burning responsible for CEMP-s and Lo CEMP-no
- convective ^{22}Ne-burning responsible for Hi CEMP-no

II) CEMP star formation in binary mass transfer hypothesis

Class	Definition	Binary companion	Binary period	[Fe/H] criterion
CEMP-s	[Ba/Fe] ≧ 0.5	Low-mass AGB	$\lesssim 10^4$ d	$\gtrsim$ -3.5
Hi CEMP-no	[Ba/Fe/C] < 0.8	High-mass AGB	$\lesssim 10^4$ d	$\gtrsim$ -3.5
Lo CEMP-no	[Ba/Fe] < 0.5 and [Ba/Fe/C] ≧ 0.8	Low- and High-mass AGB	$\gtrsim 10^4$ d	All range