



# 元素合成と恒星進化モデルで探る 極超金属欠乏星の起源

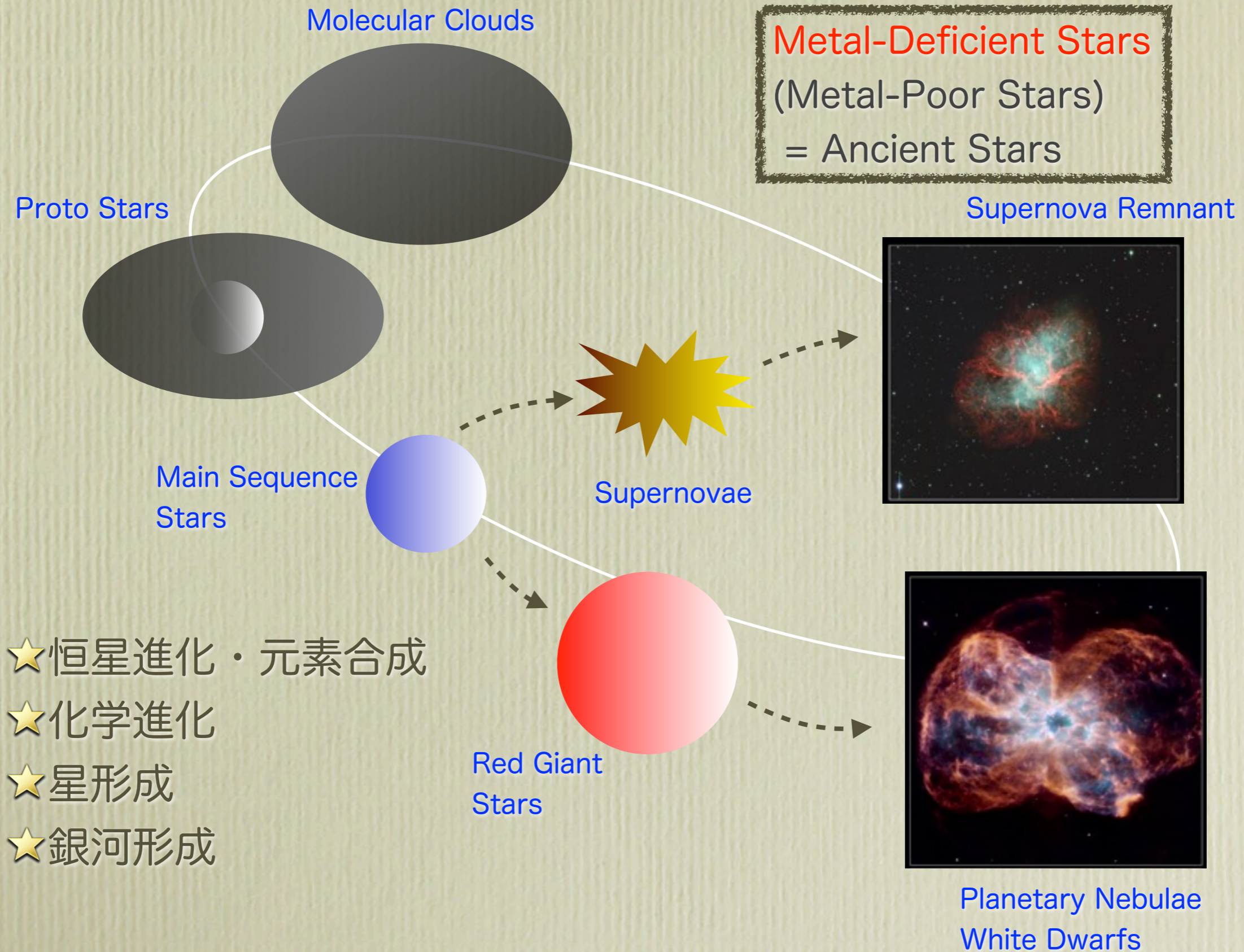
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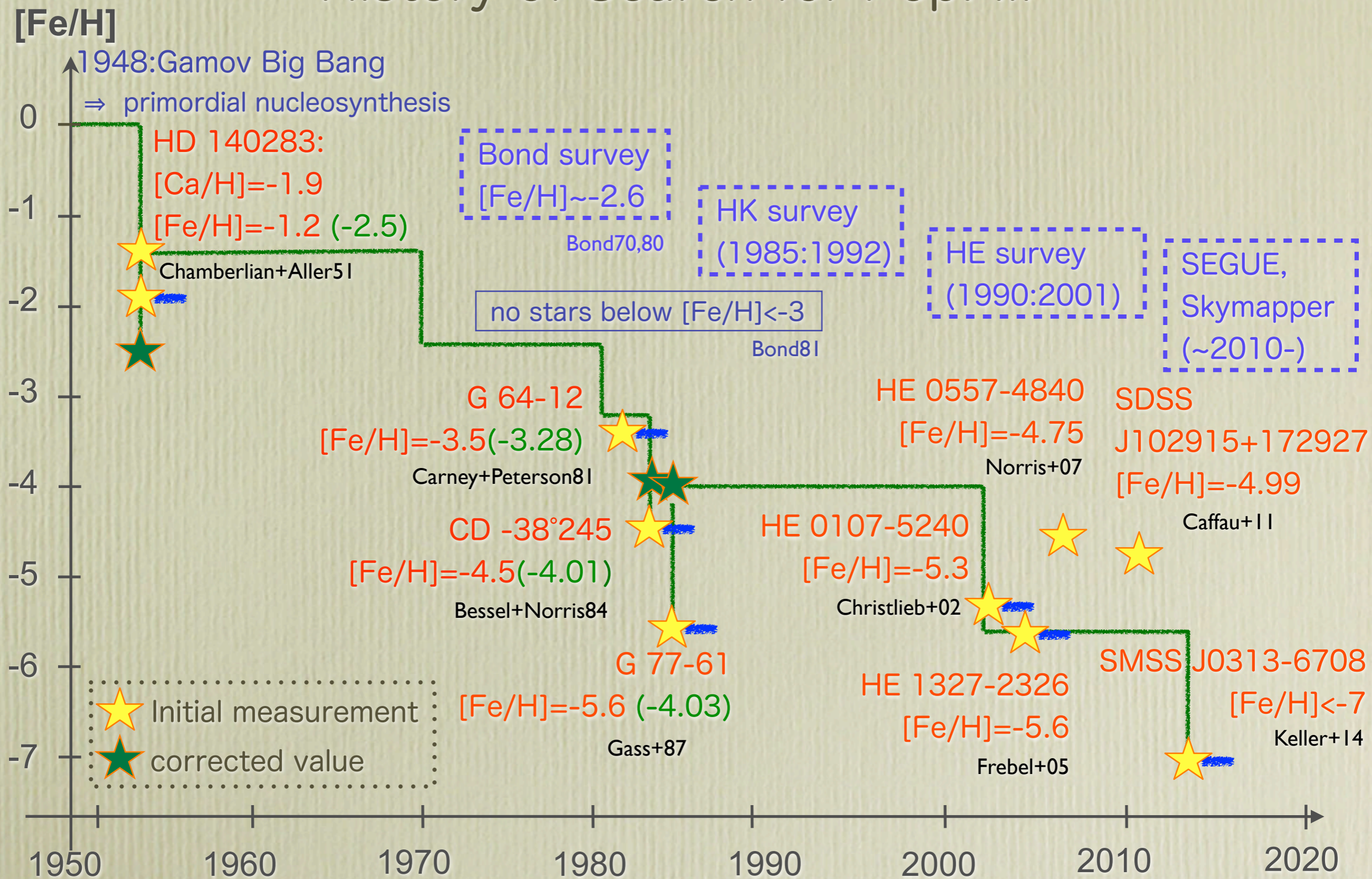
共同研究者

小宮 悠 (東大RESCEU), 山田 志真子 (北大), 藤本 正行 (北海学園大)

# Chemical Evolution of the Universe

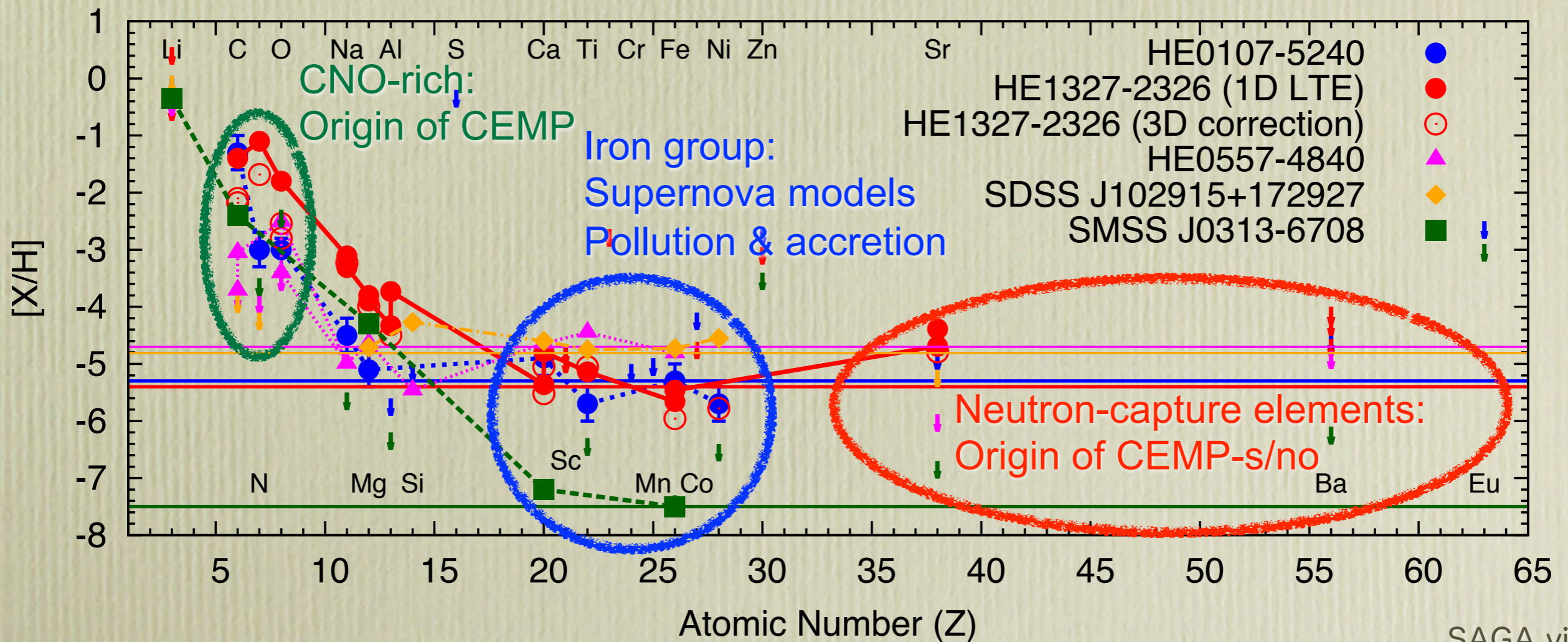


# History of Search for Pop. III



# Carbon-Enhanced Metal-Poor (CEMP) Stars and Hyper/Ultra Metal-Poor Stars

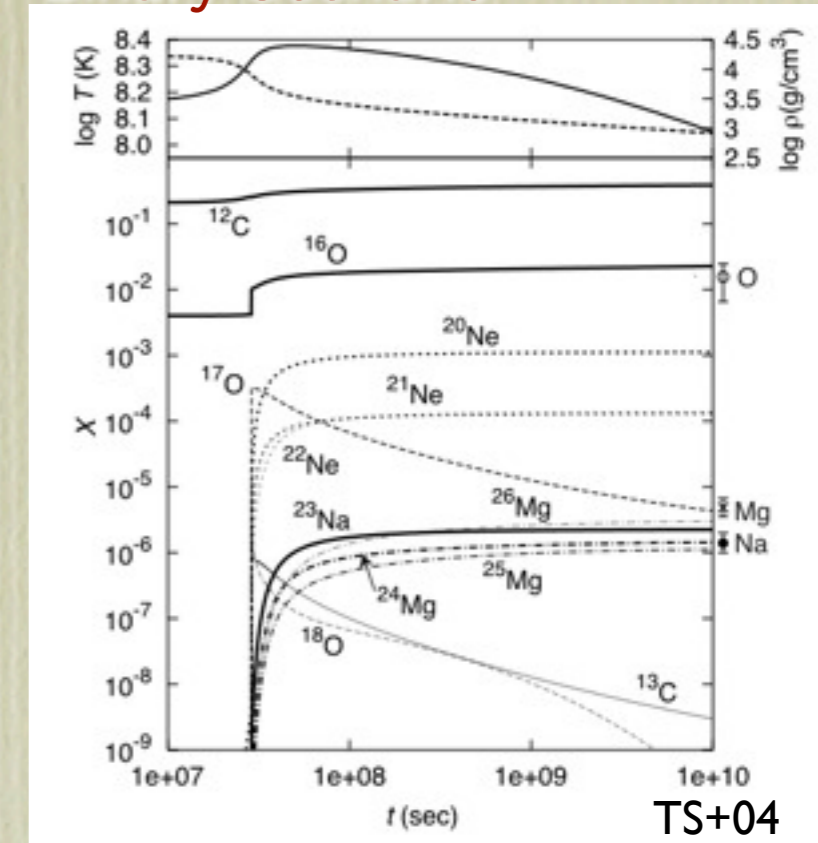
- HMP stars as the candidates of the first stars
- related to low-mass star ( $\sim 0.8M_{\odot}$ ) formation
  - What is the minimum metallicity to form low-mass stars?
- CEMP stars are common among Extremely Metal-Poor (EMP) stars (CEMP/EMP  $\sim 0.2$ ).



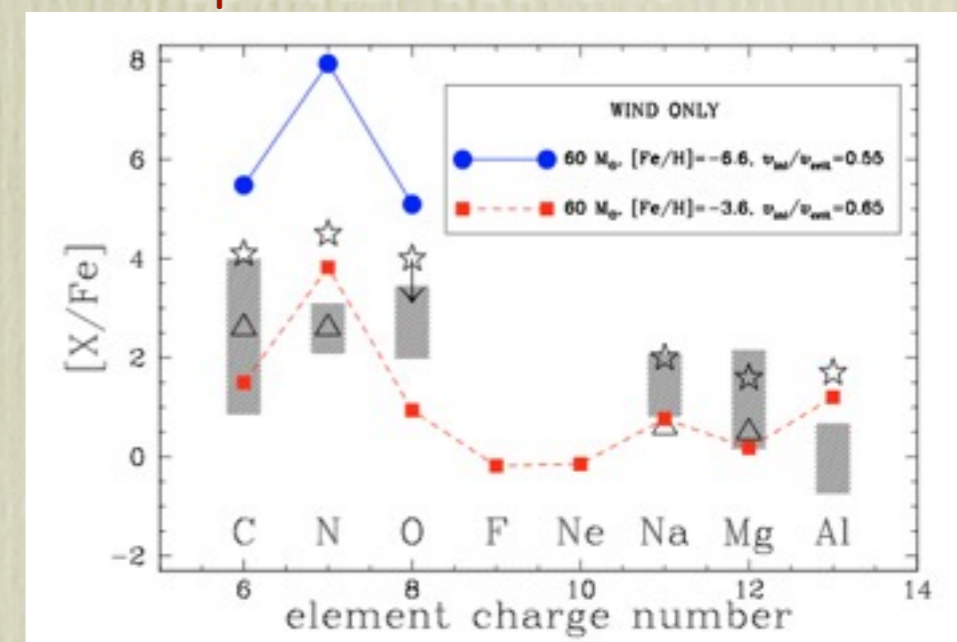
# Proposed Scenarios for the Origins of CEMP Stars

- Origin of EMP stars
- Star formation from the gas influenced by SNe in the very early universe.
- Origin of CEMP stars
  - **Mass transfer from AGB stars** in binary systems (TS+04)
    - CEMP-s stars are thought to belong to binary systems (Lucatello+05), but not for CEMP-no.
  - Star formation from gas affected by **peculiar supernovae** in the earliest generation of massive stars (Umeda+03, Limongi+04)
    - Abundance patterns are well reproduced by mixing and fallback models.
  - Star formation affected by **massive fast-rotating stars** (Meynet+06)
    - Abundance patterns are well reproduced by rotational mixing.

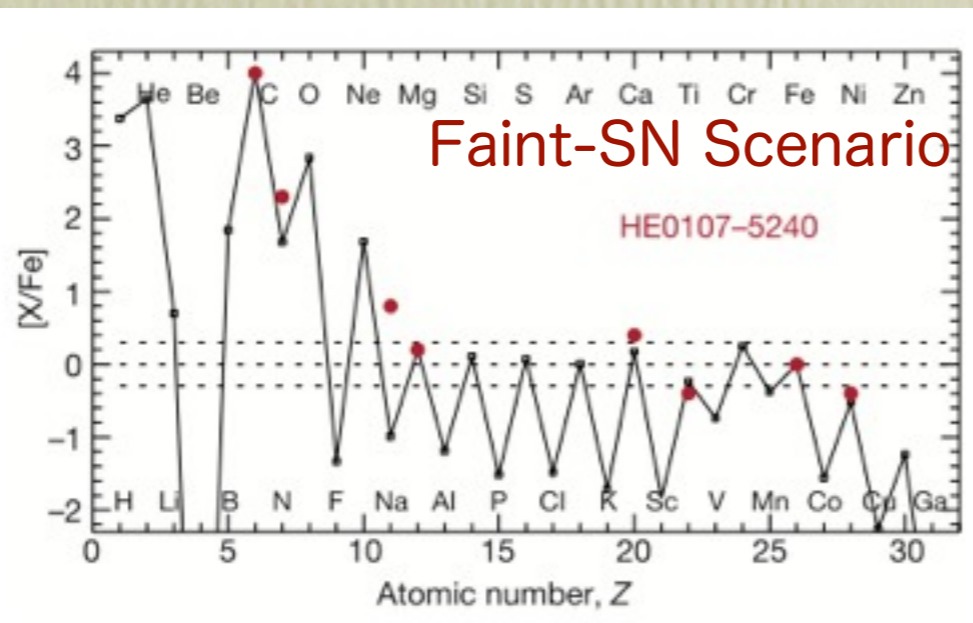
## Binary Scenario



## Spinstar Scenario

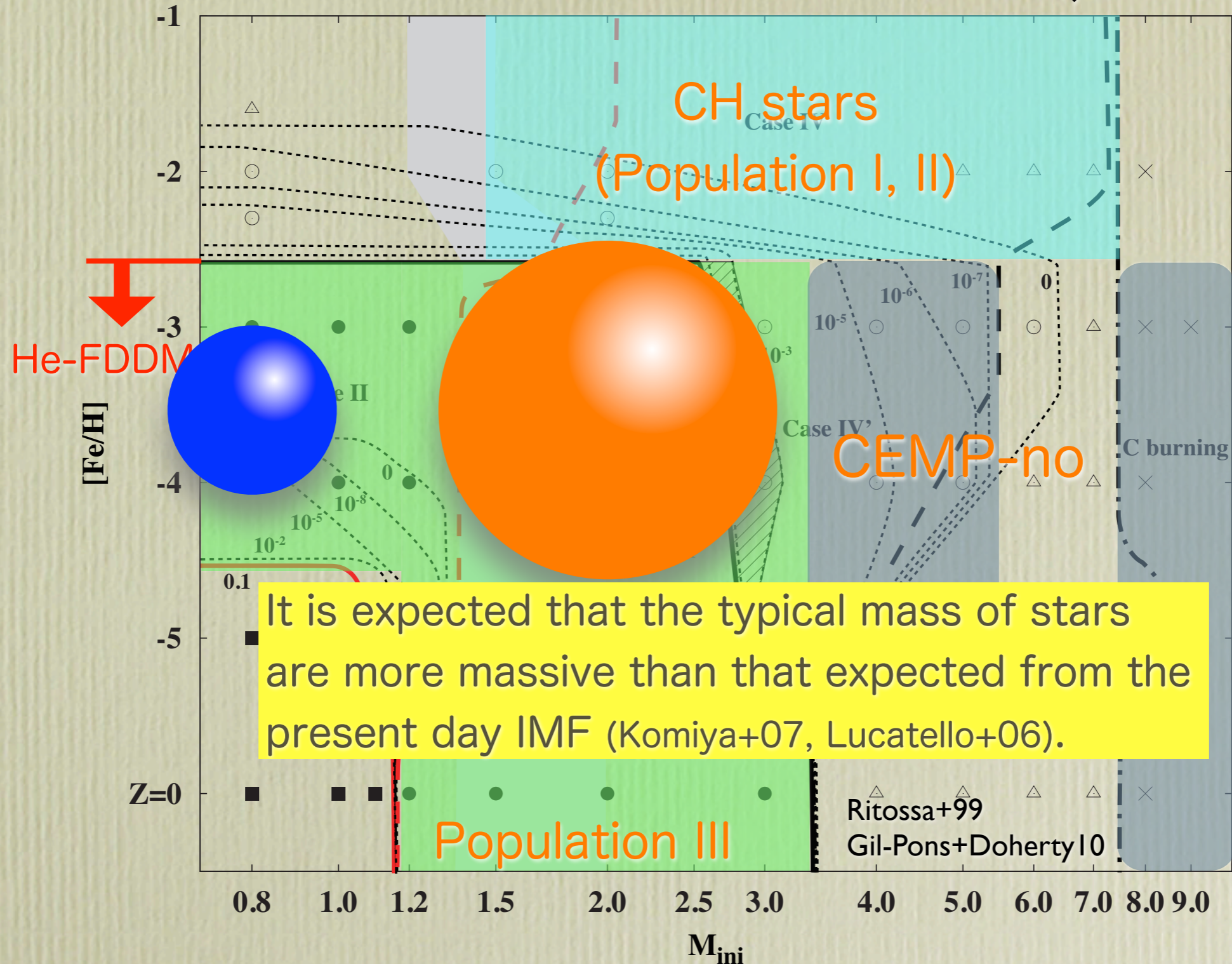


## Faint-SN Scenario



# Binary Scenario for the Origin of CEMP Stars

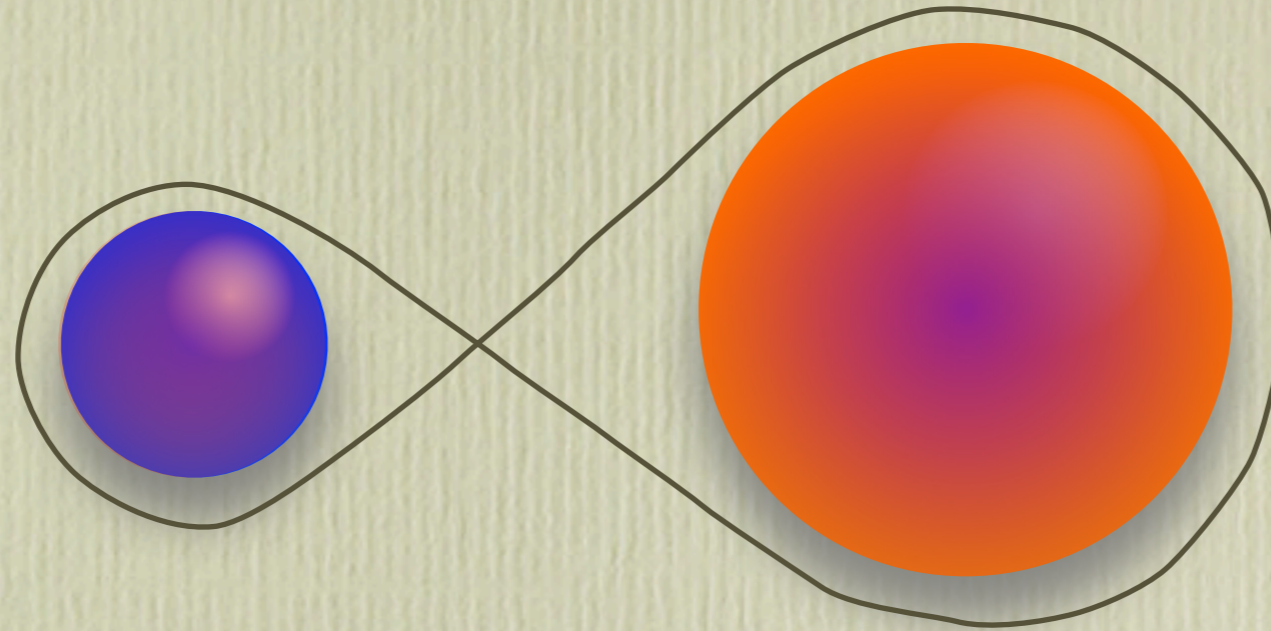
TS+Fujimoto 10, see also Fujimoto+00



**He-Flash Driven Deep Mixing:** H-ingestion into the He-flash convective zone  
 Fujimoto+90, Hollowell+90, Cassisi+96, Fujimoto+00, Schlattl+02, Suda+04, Iwamoto  
 +04, Picardi+04, Herwig+05, Campbell+Lattanzio+08, Lau+09, Cristallo+09,  
 Iwamoto09, Campbell+09, Suda+Fujimoto 10, Cruz+13

# Stellar Evolution & Binary Evolution

C, N, s-elements



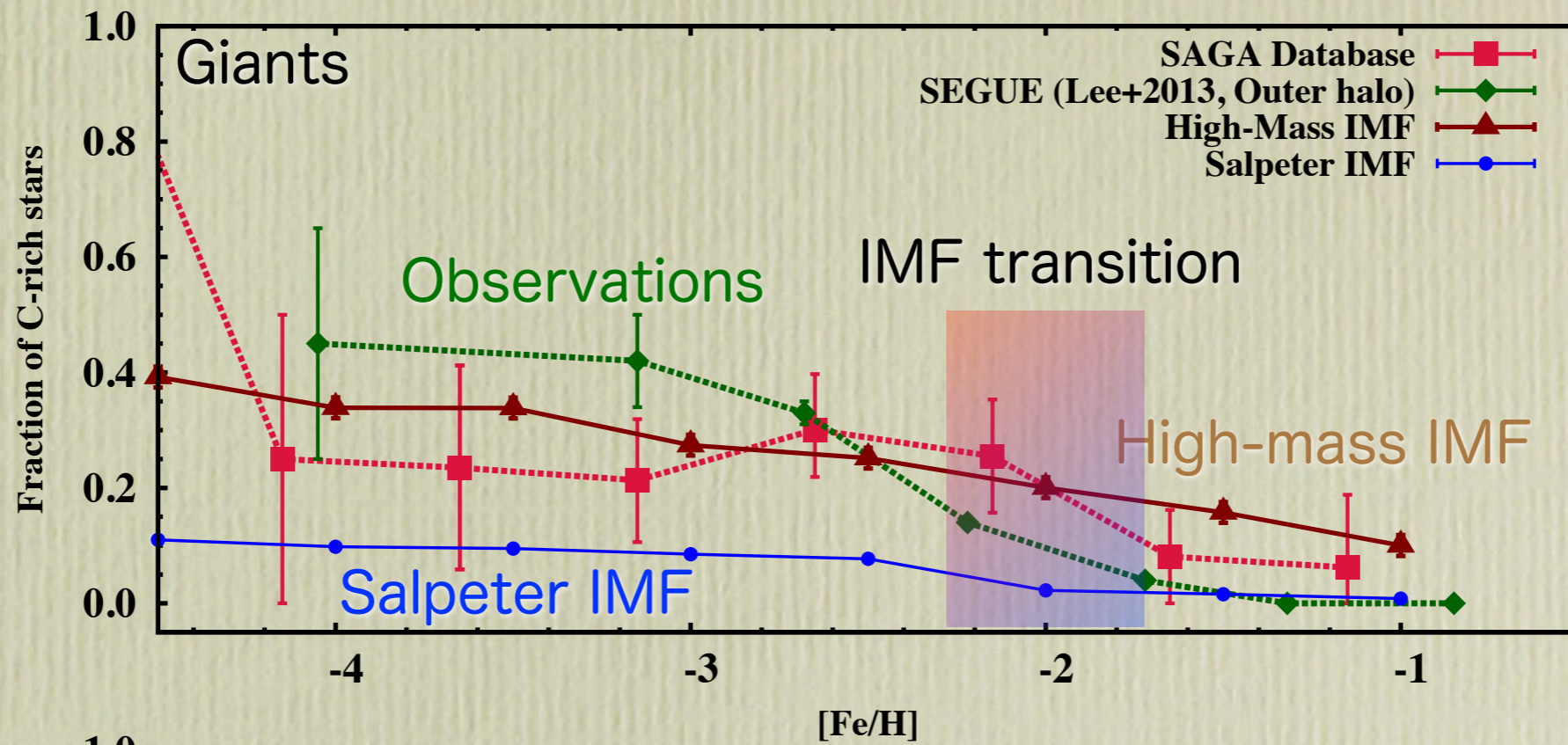
Roche Lobe overflow or Wind accretion?  
-> depends on separation and mass ratio.

The fraction of CEMP (or NEMP) stars can be estimated by assuming

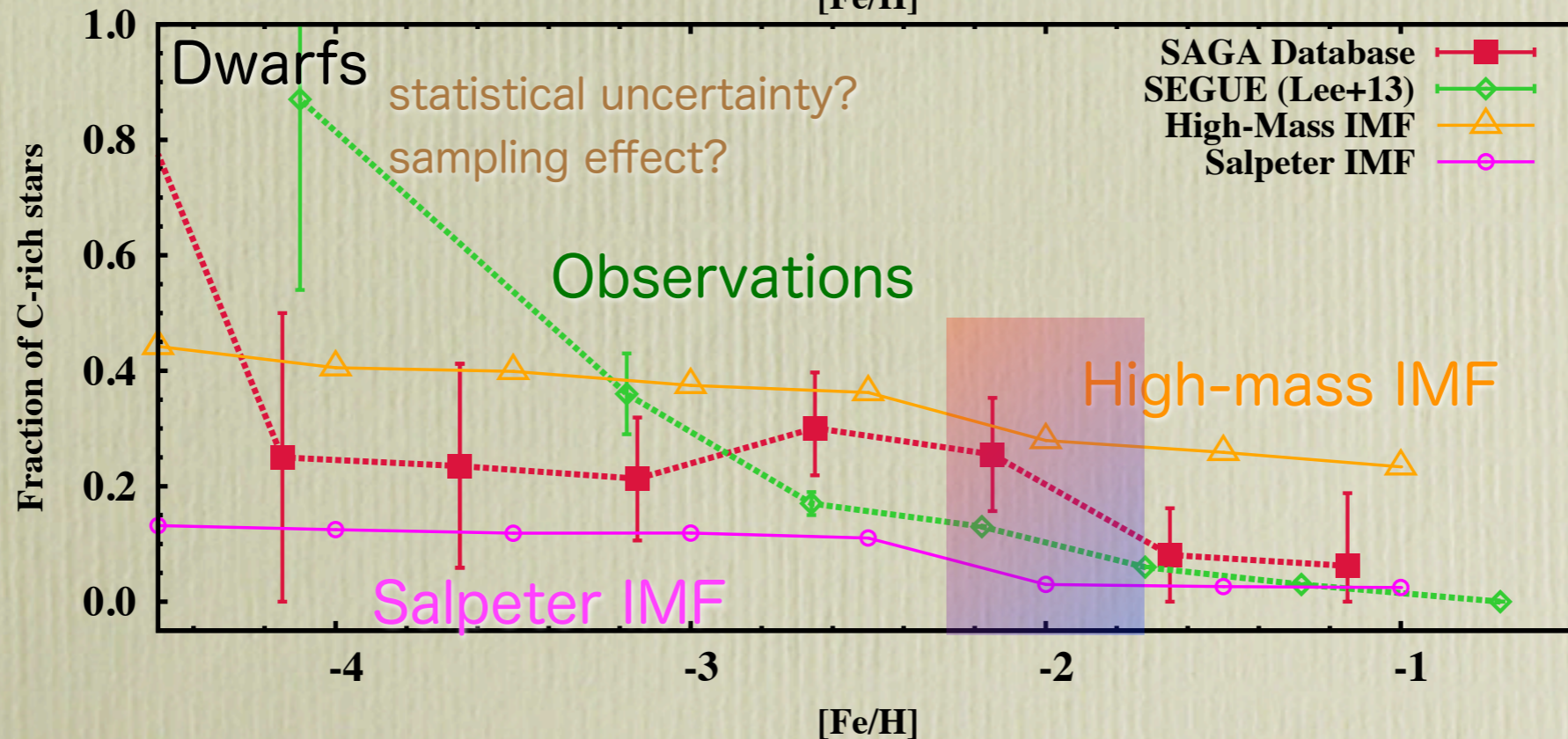
- ★ Initial mass function
- ★ distribution function of binary mass ratio
- ★ distribution function of binary period

# Binary Population Models and Comparisons with Observed CEMP Fractions

炭素過剰星の割合  
 $[C/Fe] > 0.7$   
 Aoki+07  
 TS+11



炭素過剰星の割合



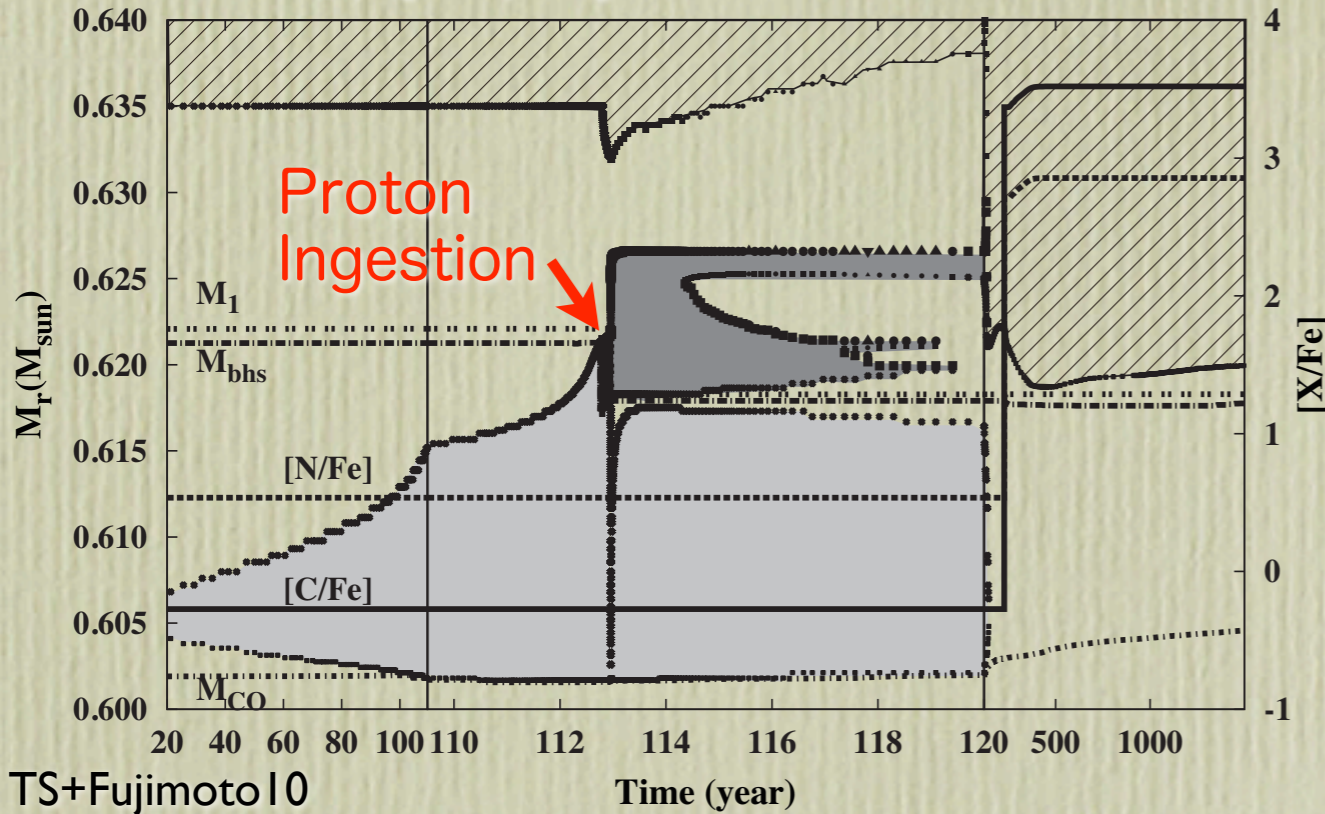
TS+13  
 Lee, TS+14



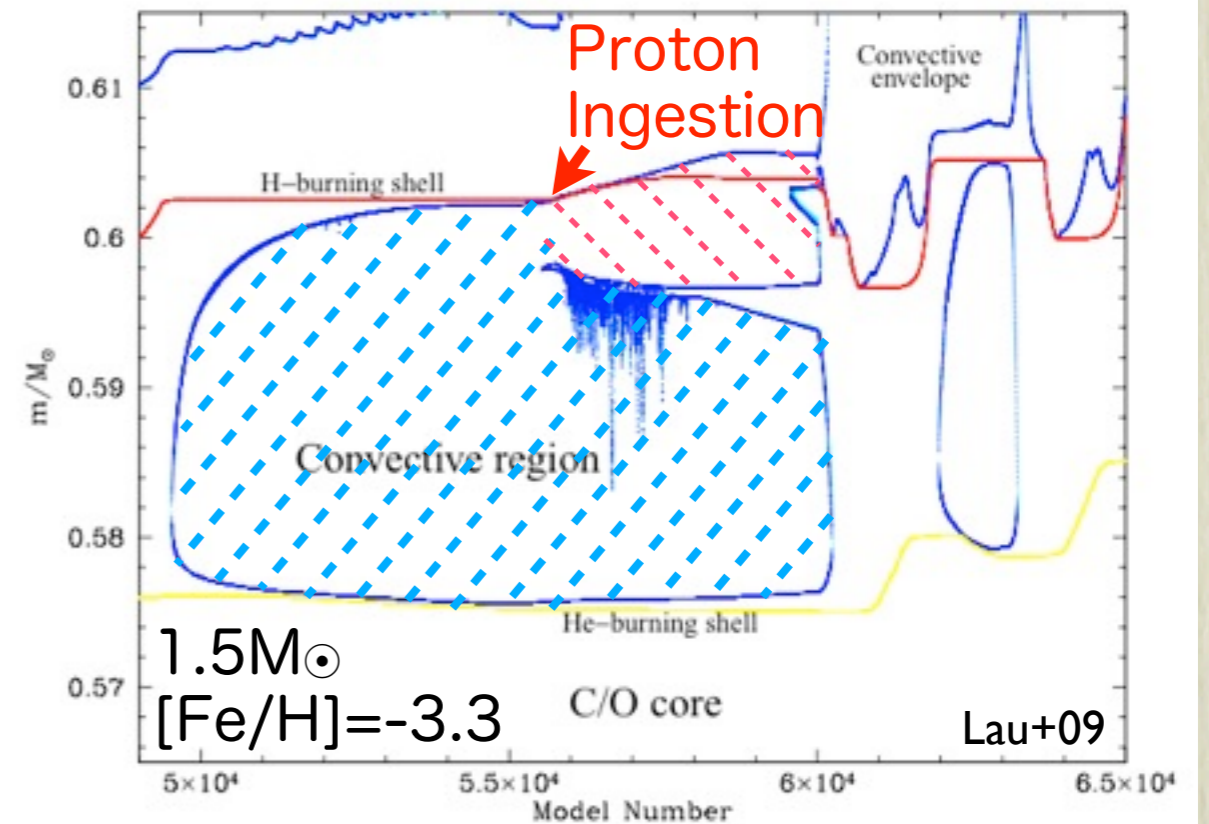
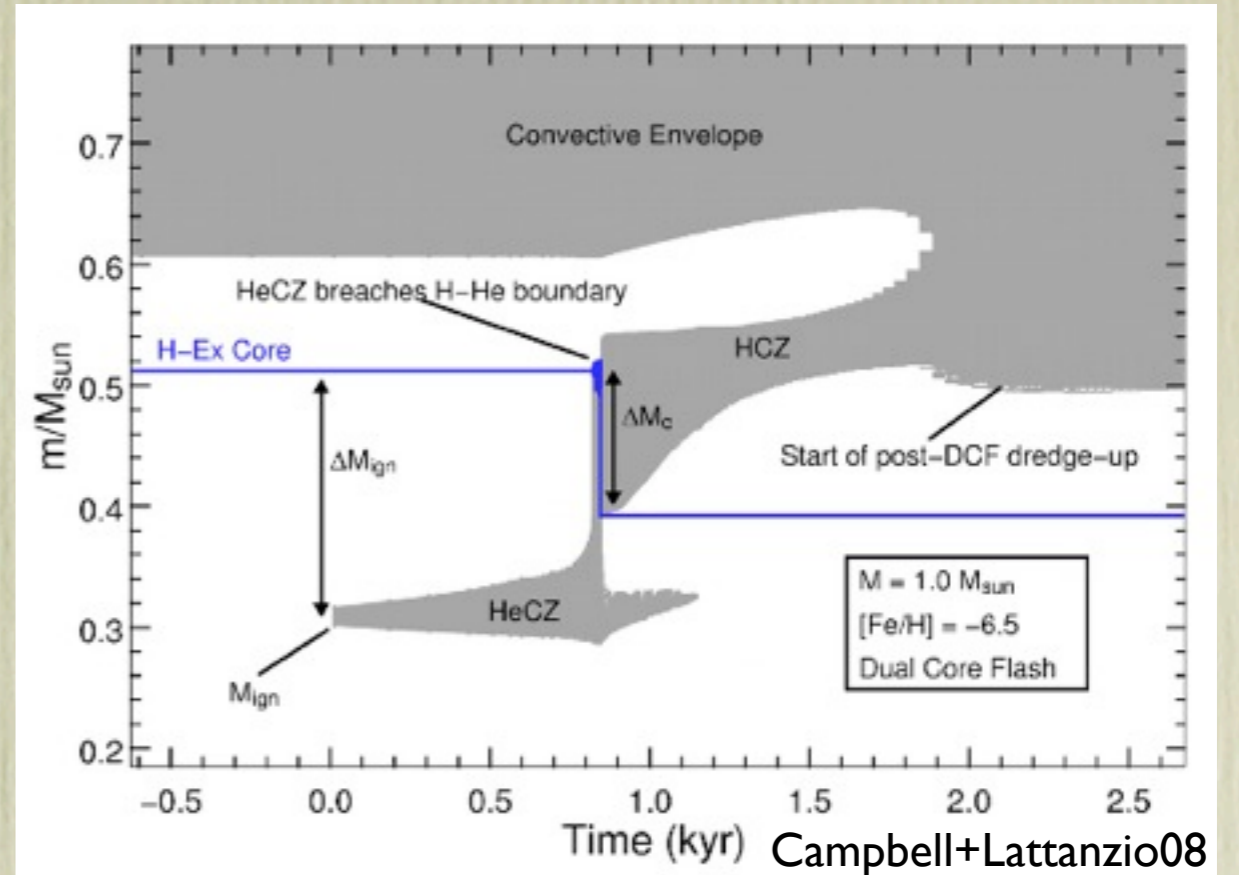
# CNO, 軽元素, 中性子捕獲元素の起源

## Hydrogen Ingestion Into the He-Flash Convective Zone

$2M_{\odot}$ ,  $[\text{Fe}/\text{H}] = -4$



He対流層への水素の混入。水素層との entropy barrierが少ないために起こる。水素flashを伴い、その後の表面对流層の侵入によってCNが増大。

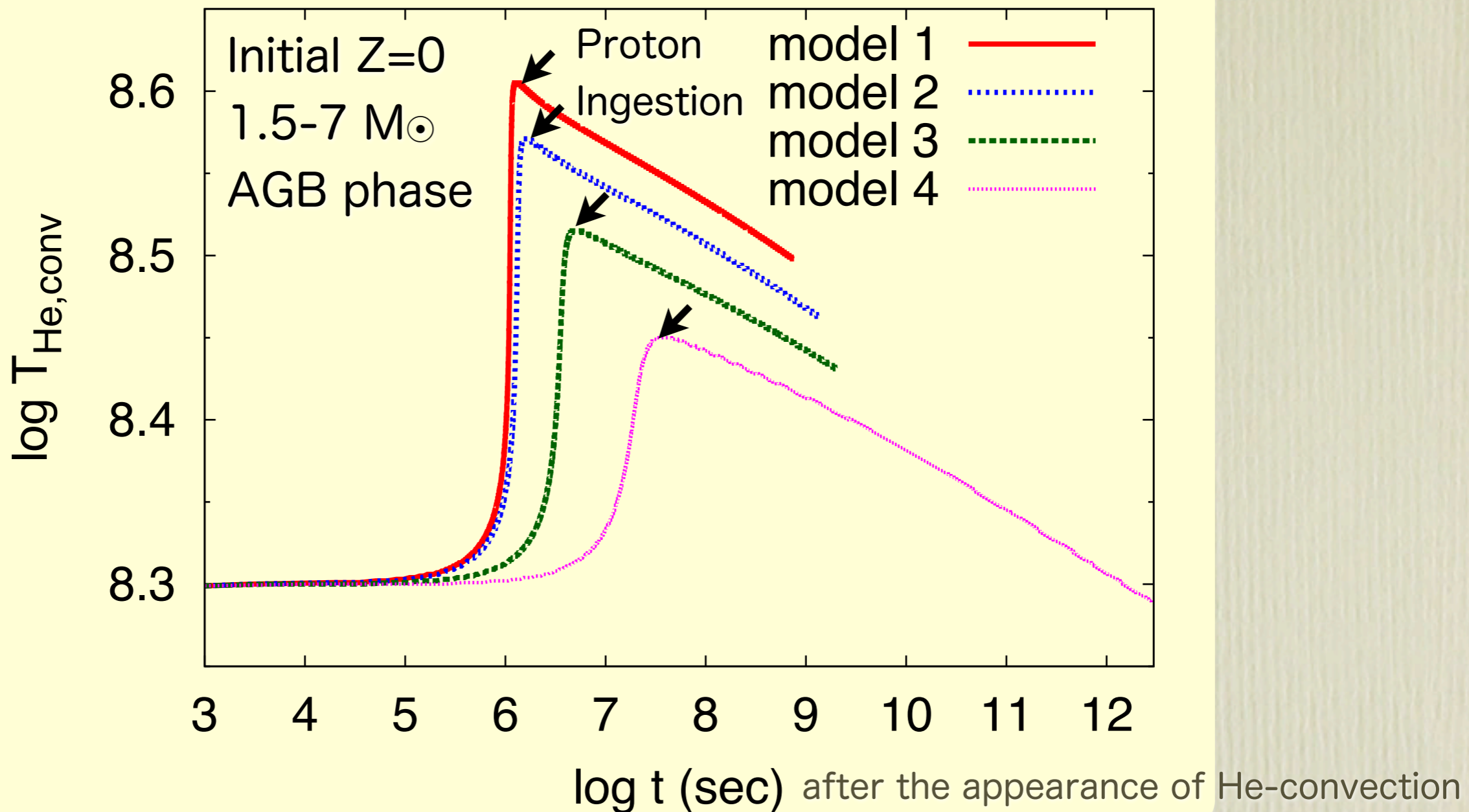


# CNO, 軽元素, 中性子捕獲元素の起源

## Nucleosynthesis models

- One zone approximation during the He shell flashes (Fujimoto+99, Aikawa+01)
- p-,  $\alpha$ -,  $\beta$ -, n-reactions up to  $^{84}\text{Po}$  are included in nuclear network (Aikawa+01, Nishimura+08, Yamada+, in prep.).

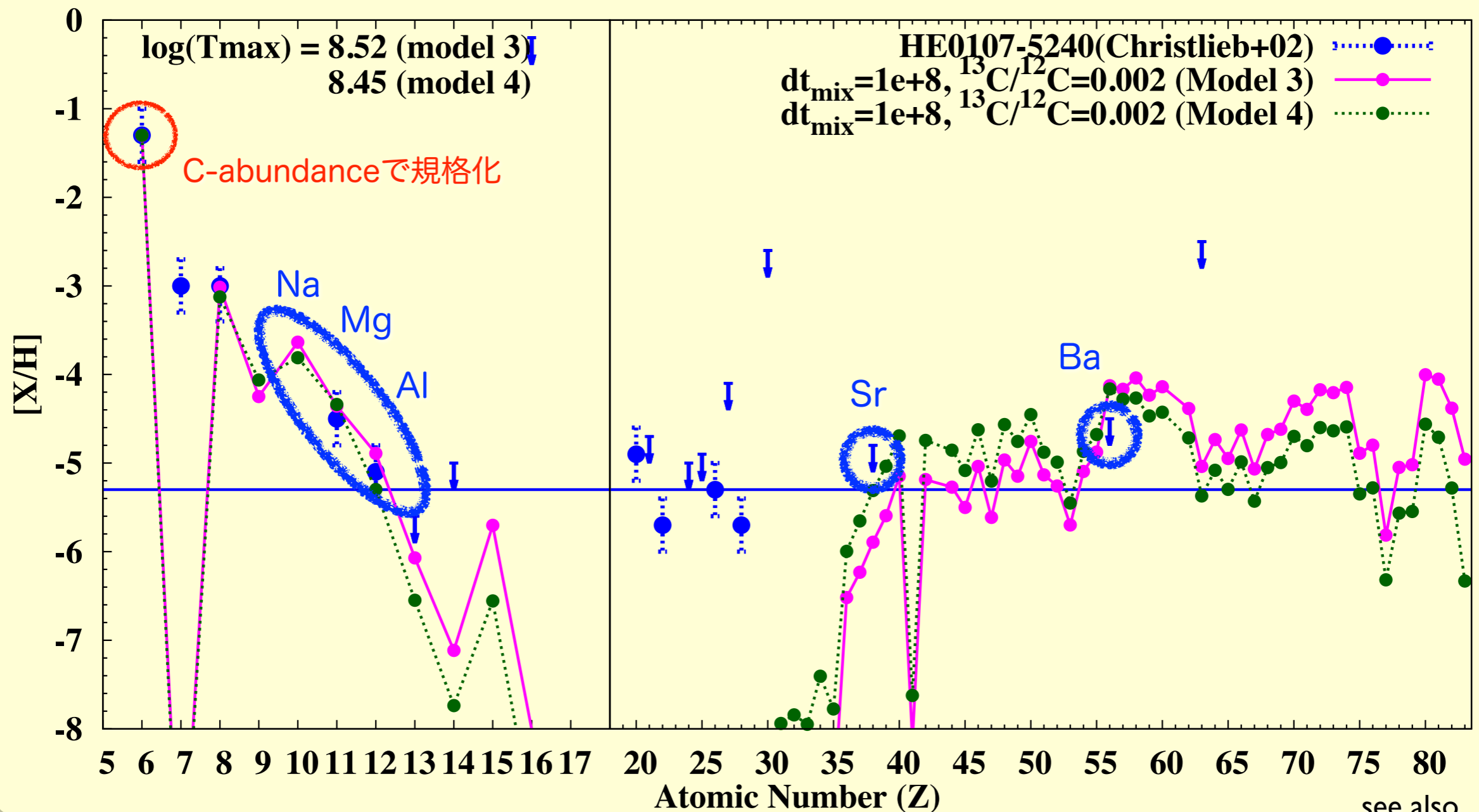
He flash対流層の底の温度



# CNO, 軽元素, 中性子捕獲元素の起源

## Comparisons of Models with Observations

### Case: HE 0107-5240

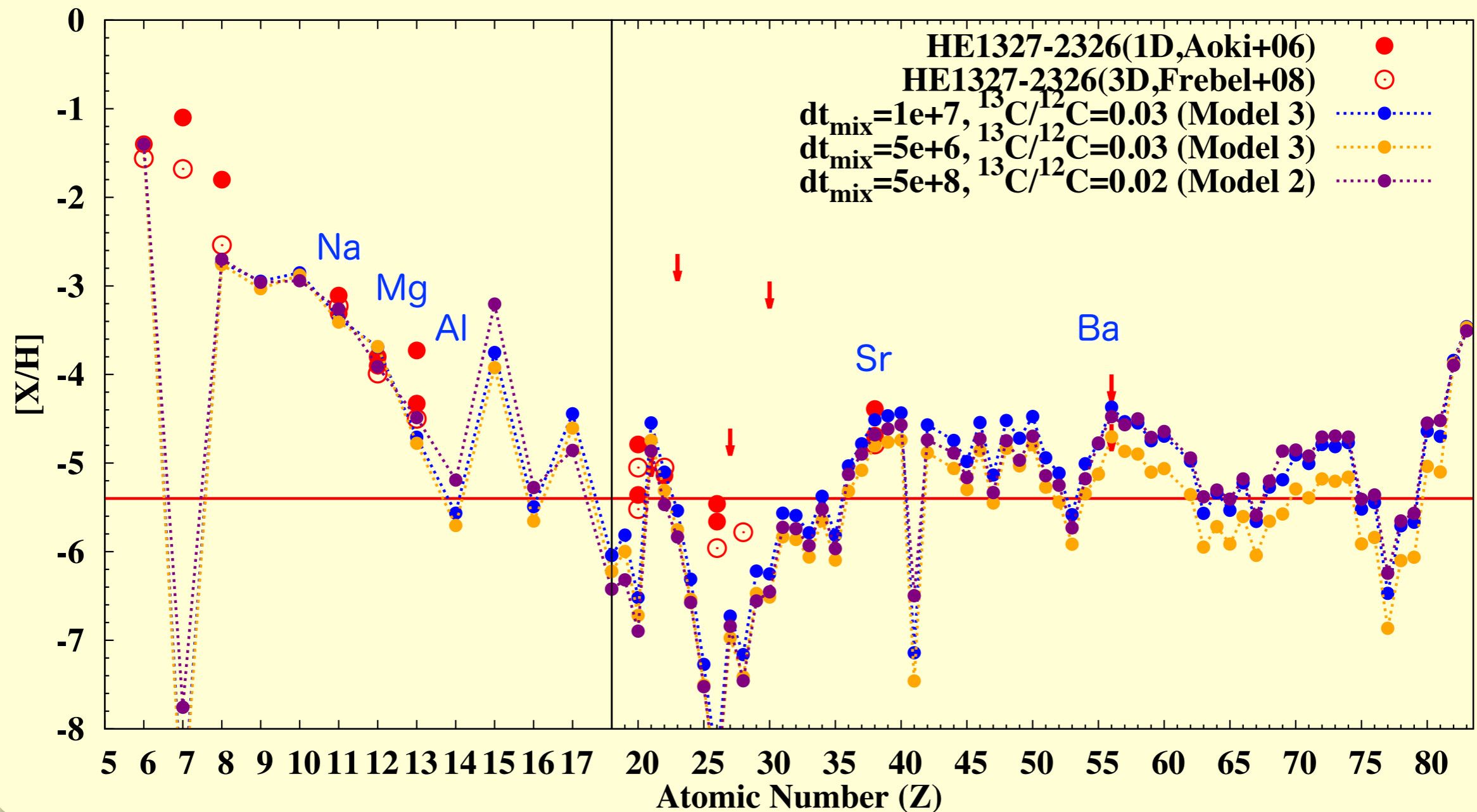


- ★ 少量の水素混合
- ★ He-FDDMによるNa, Mg, Alの生成(TS+04)
- ★ low- or intermediate-mass AGB stars

# CNO, 軽元素, 中性子捕獲元素の起源

## Comparisons of Models with Observations

### Case: HE 1327-2326



★ 大量の水素混合

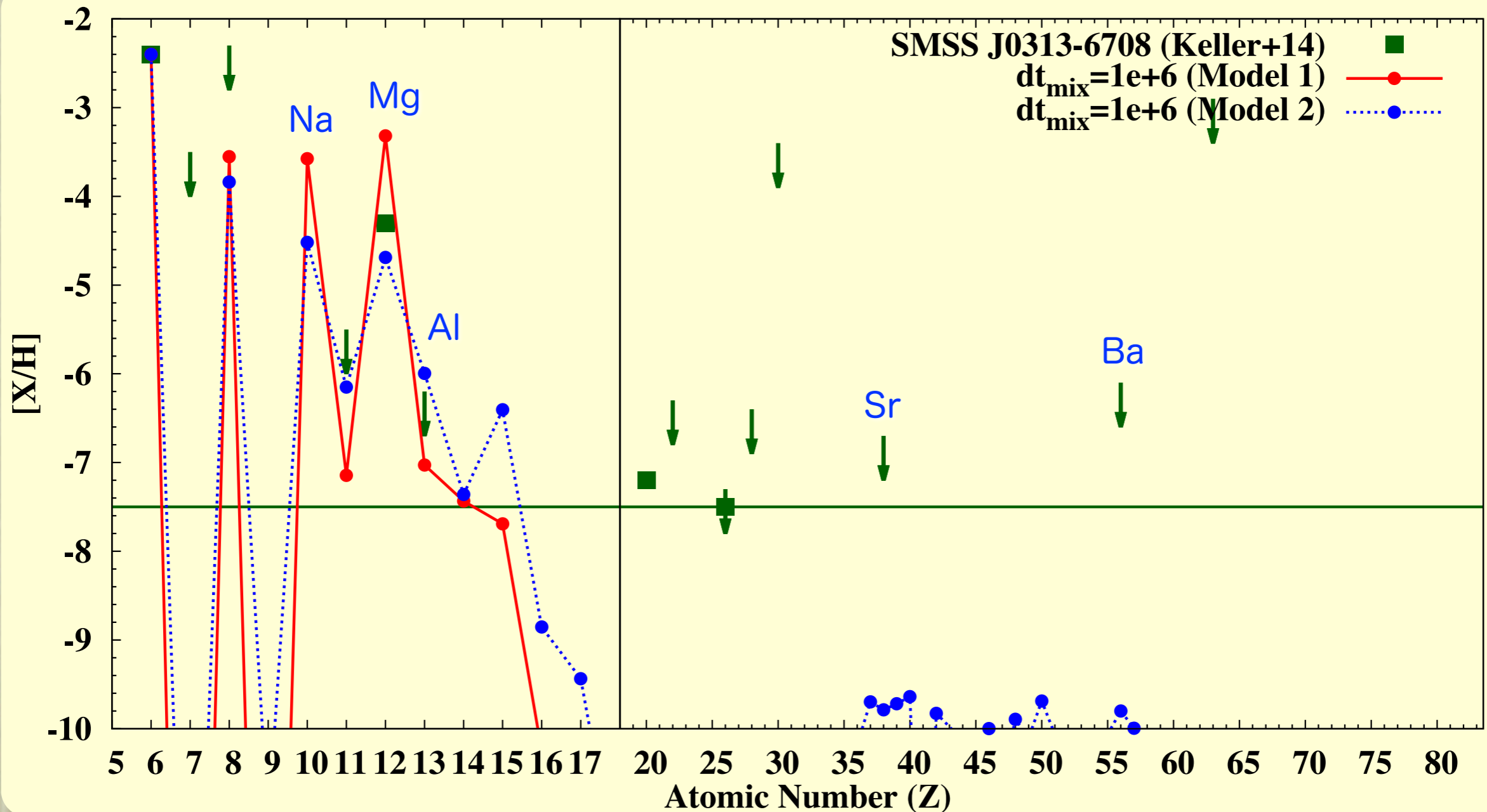
★ He-FDDMによるNa, Mg, Alの生成、Sr/Ba大

★ low-mass AGB stars

# CNO, 軽元素, 中性子捕獲元素の起源

## Comparisons of Models with Observations

### Case: SMSS J0313-6708



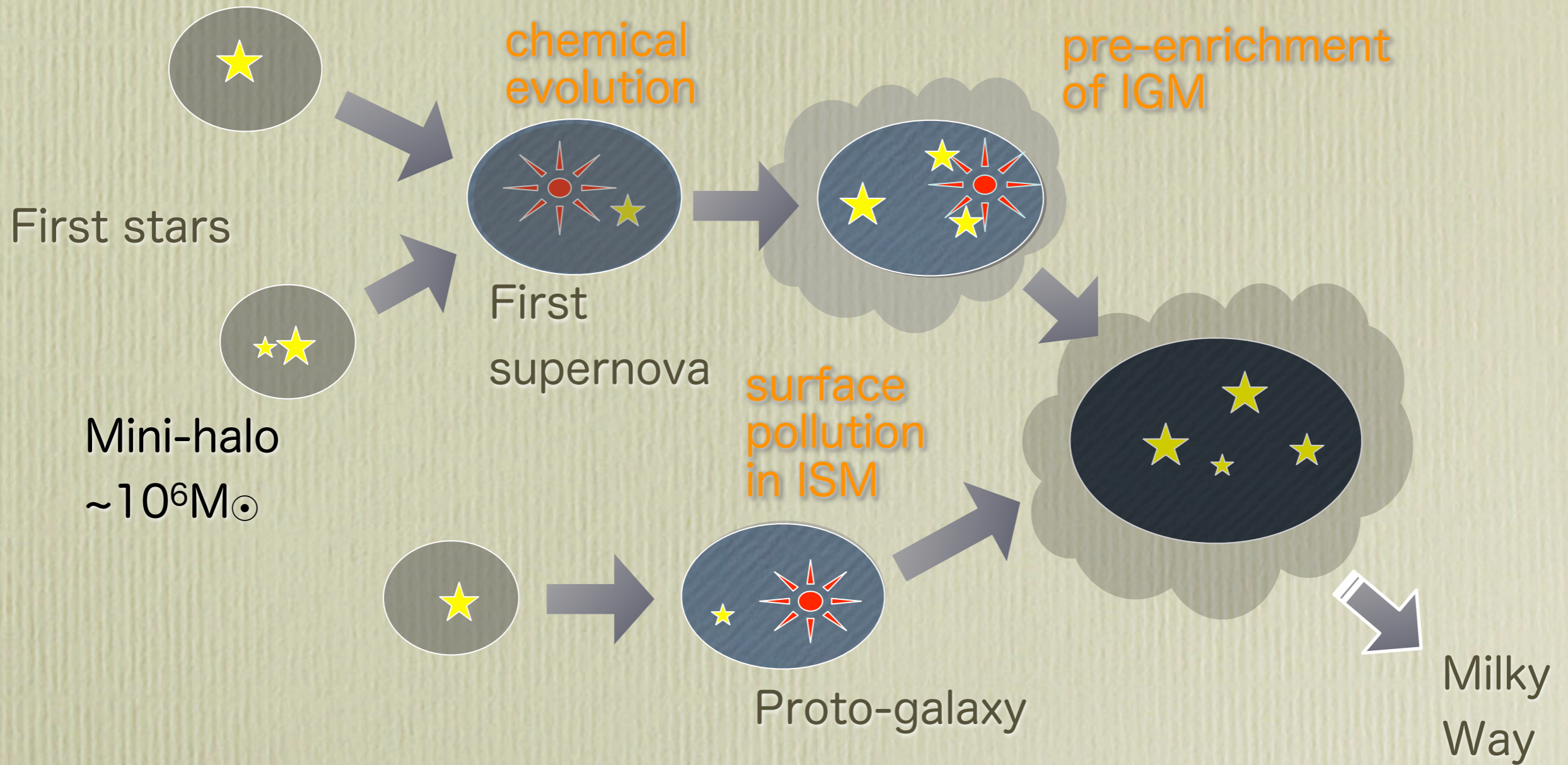
★  $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ 起源のs-process

★ high-mass AGB stars (core mass大 or  $\log T > 8.5$ )

☆  $^{22}\text{Ne}$ を効率よく燃やさない限り $^{23}\text{Na}$ がoverproduction

# 鉄属元素の起源

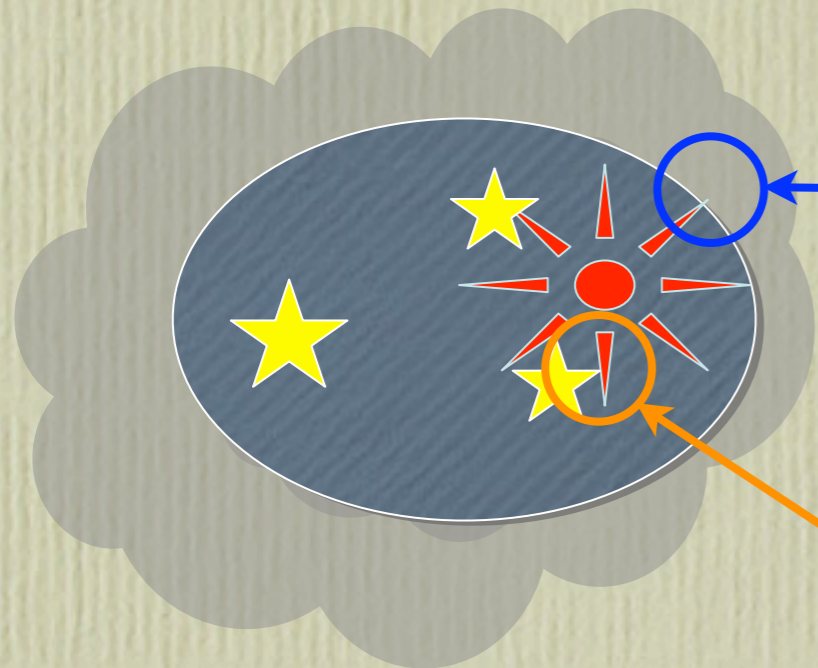
## Hierarchical clustering scenario



- ★ IGM: inter-galactic medium, SN ejecta can pollute other mini-halos
- ★ ISM: inter-stellar medium, SN ejecta can pollute other stars within the mini-halo

# 鉄属元素の起源

## Pollution and Accretion



SN ejecta pollute the IGM and potentially pollute other mini-halos.

SN ejecta pollute the ISM and the stellar envelopes with metals.

### Ingredients for galaxy/star formation/evolution

★ Extended Press-Schechter theory

★ High-mass IMF w. const. SF rate

$$\xi(\log m_1) \propto \exp\left(-\frac{\log(m_1/10M_\odot)^2}{2 \times 0.4^2}\right)$$

★ Binary evolution

★ mass ratio function

★ period distribution

★ mass transfer

★ Chemical evolution

★ semi-closed boxes in each mini-halo

★ **Accretion of SN ejecta**

★ Bondi-Hoyle accretion

★ Accretion onto binaries

★ **IGM pollution/accretion**

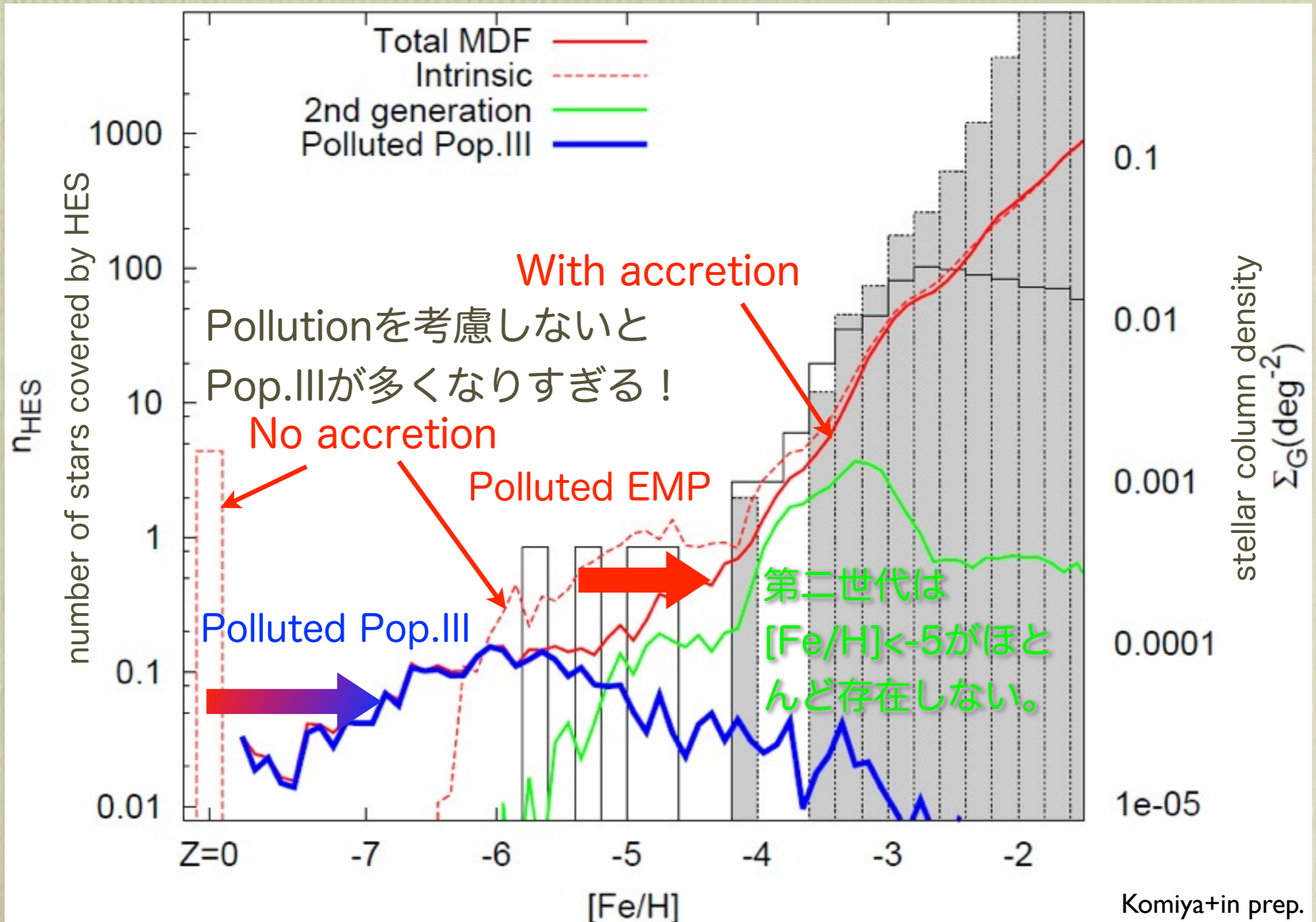
★ outflow from proto-galaxies

★ evolution of the Galactic wind

★ pre-enrichment of proto-galaxies

# 鉄属元素の起源

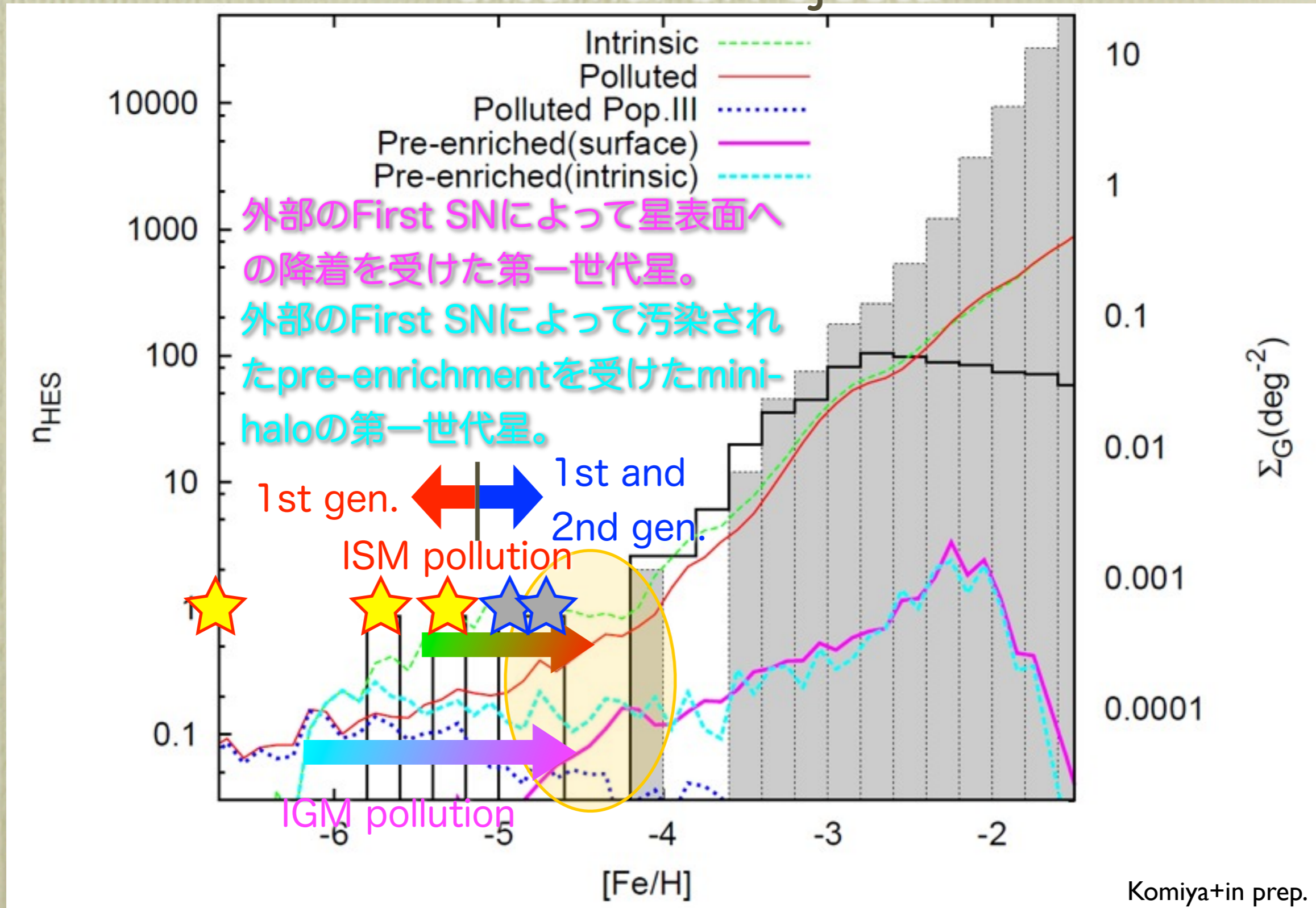
## Surface pollution by interstellar medium





# 鉄属元素の起源

Pre-enrichment of host halo due to pollution by external SN ejecta



# Open Questions: CEMP-no/CEMP-s ratio

(1)  $[\text{Fe}/\text{H}] < -3.5$  で CEMP-no が支配的

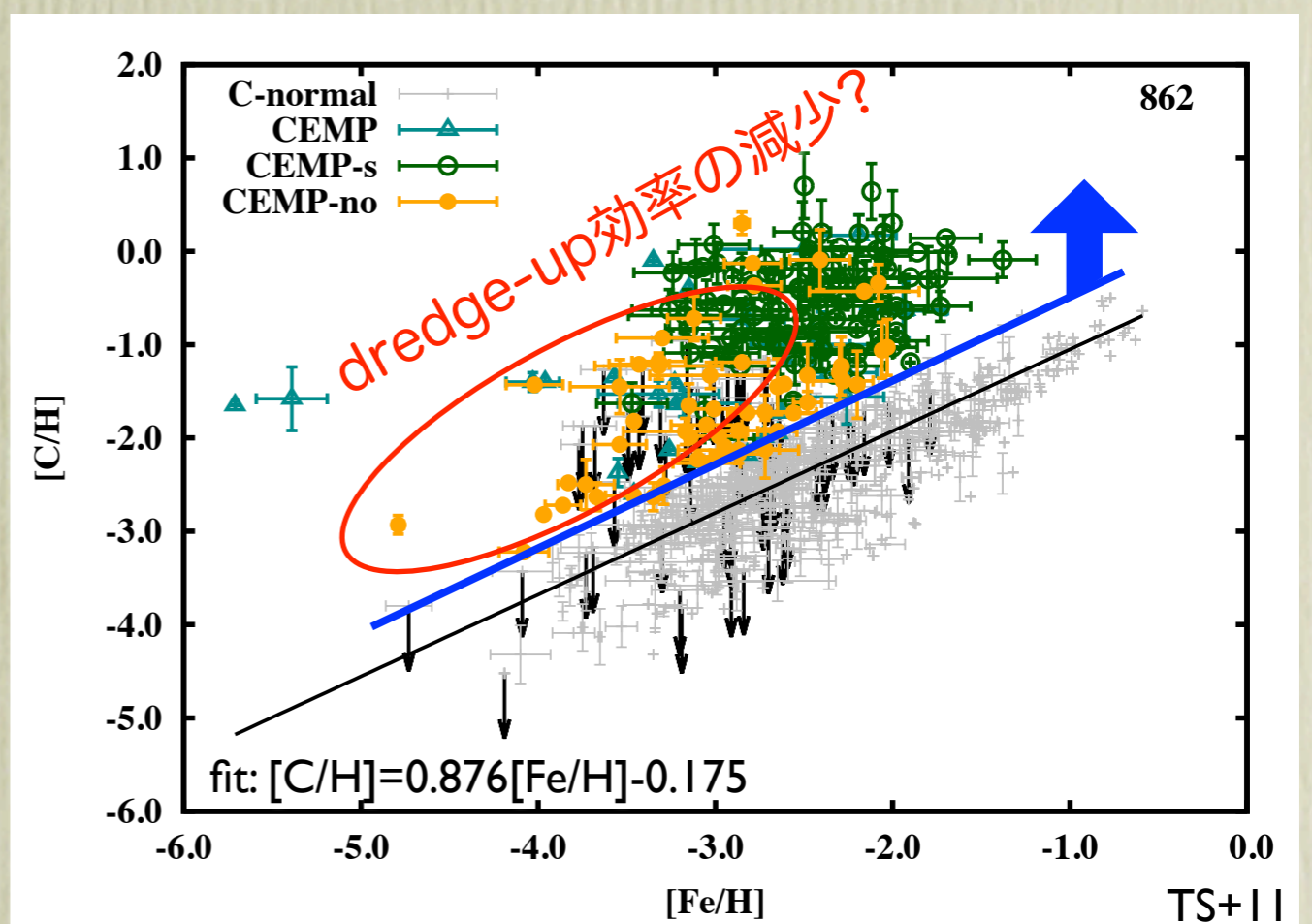
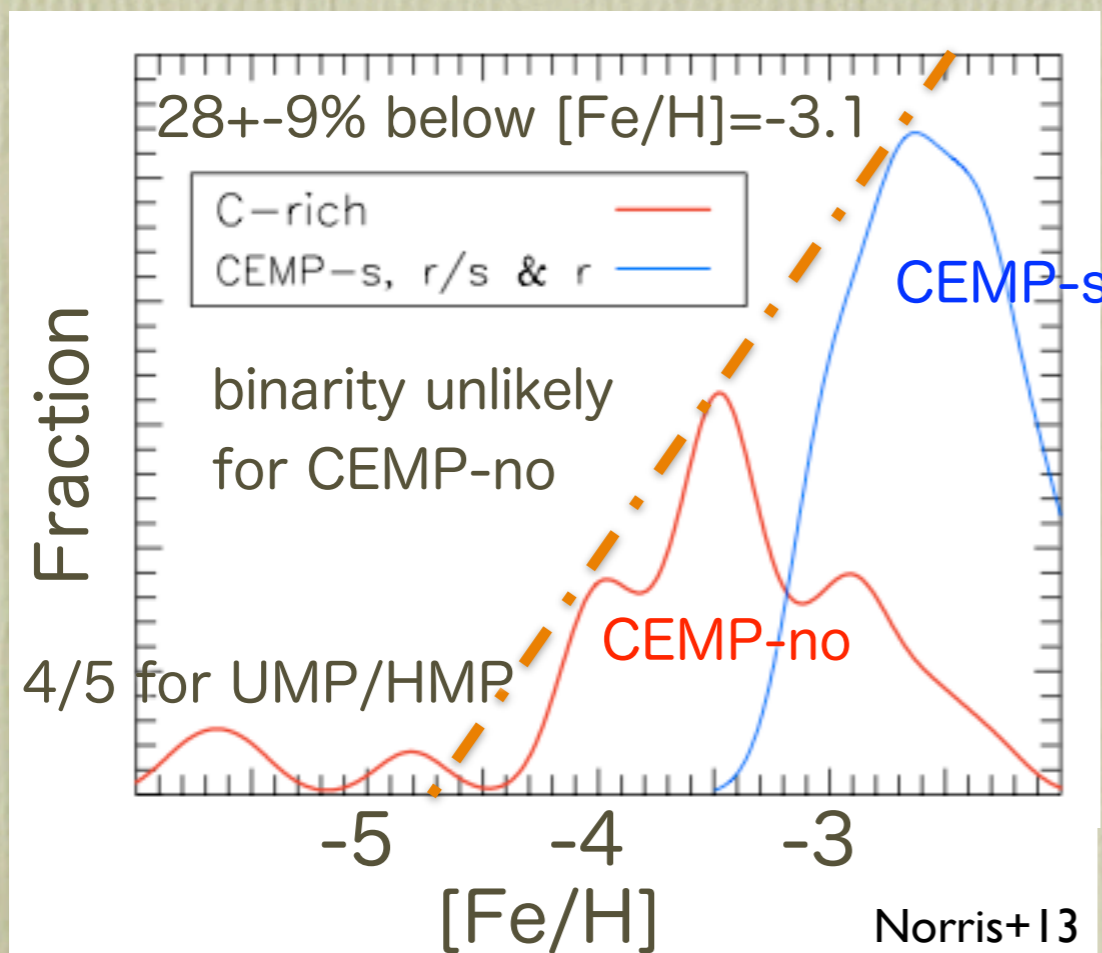
- CEMP-s が  $[\text{Fe}/\text{H}] < -3.5$  で消滅!?
- CEMP-no は  $[\text{Fe}/\text{H}] = -3.5$  から増加
- CEMP-s + CEMP-no は連続

s-process が  $[\text{Fe}/\text{H}]$  依存性を持っていると考えるのが妥当

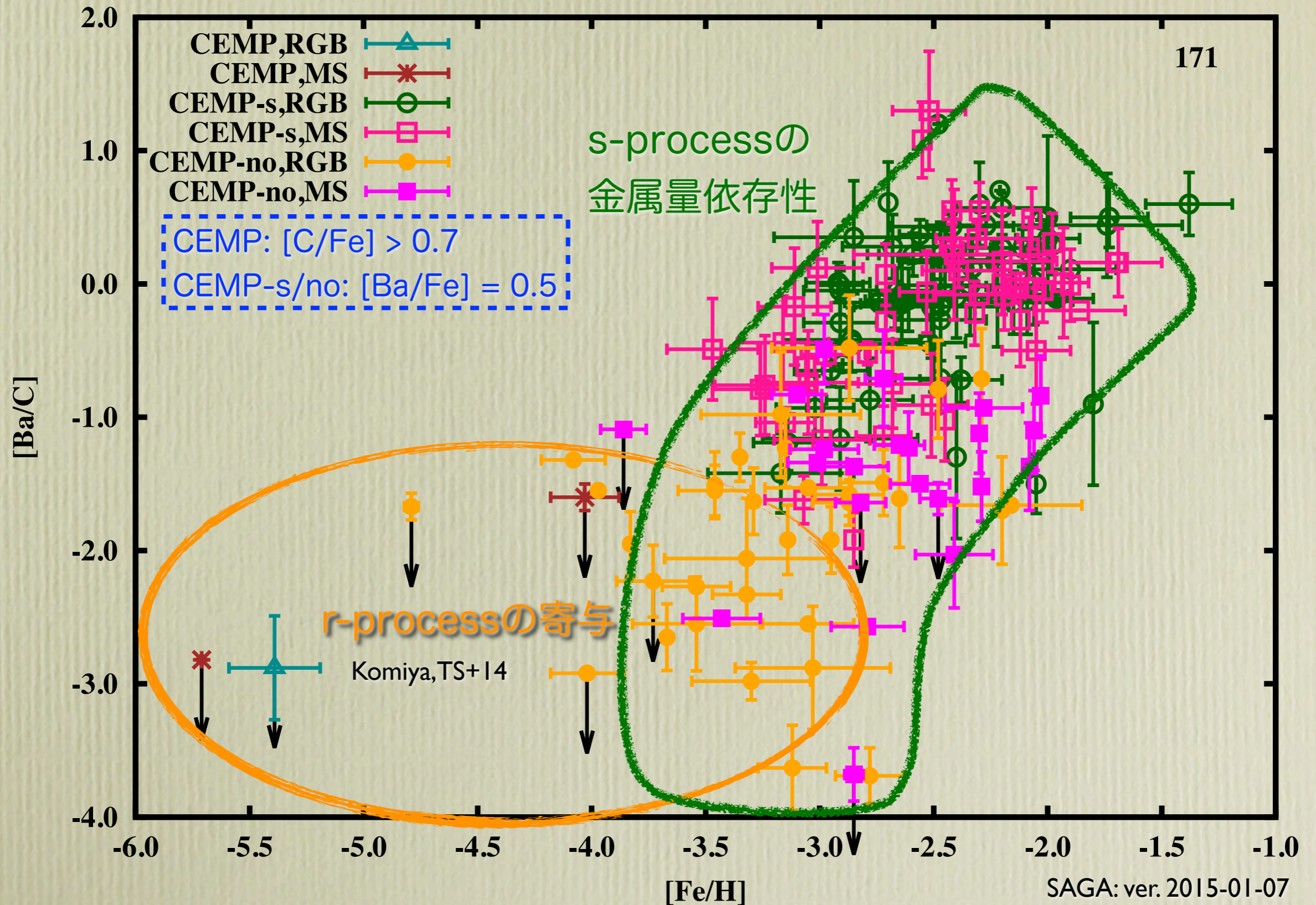
(2)  $[\text{Fe}/\text{H}] < -3.5$  で C の増大量が異なる

- $[\text{C}/\text{H}] \sim 0$  at  $[\text{Fe}/\text{H}] > -3$ .
- $[\text{C}/\text{H}] < \sim -1$  at  $[\text{Fe}/\text{H}] < -3.5$ .
- TDU の効率が減少
  - $[\text{Fe}/\text{H}] < -4$  で flash が弱くなる (TS+10)

$[\text{C}/\text{Fe}]$  and  $[\text{C}/\text{H}] \downarrow$  with  $[\text{Fe}/\text{H}] \downarrow$



# s-process efficiency dependent on metallicity?



# まとめと議論

## ★ 超金属欠乏(EMP)星( $[Fe/H] < -2.5$ )の特徴

- ★ 炭素過剰星(CEMP)星の割合が大きい。
- ★ CEMP星はCEMP-s (s-processの増大あり)とCEMP-no (s-process増大なし)に分類される。
- ★ EMPに対するCEMP-s / -no割合に $[Fe/H]$ 依存性が見られる。
- ★ 連星として確認された割合が異なり、CEMP-sはAGBからの質量輸送で説明可能。

## ★ なぜ金属欠乏星には炭素過剰(CEMP)星が多いのか？

- ★ 炭素過剰星の割合はAGB星からの質量輸送とhigh-mass IMFで説明可能。
- ★ 炭素過剰星割合の変化から、初期質量関数は $[Fe/H] \sim -2$ の時代に変遷があった可能性がある。

## ★ いわゆるHyper Metal-Poor Stars ( $[Fe/H] < -5$ )はAGB星からの質量輸送の影響を受け、かつ星間空間で汚染を受けた星である可能性が高い。

- ★ 特異な元素組成パターンの再現。
- ★ 極端に少ない鉄属元素量の実現。

## ★ なぜCEMP-no/CEMP比は $[Fe/H] < -3.5$ で大きくなるのか？

- ★ 通常モデルでは、intermediate-mass AGBでCEMP-noが作られると仮定すると(Suda et al. 2004, 2010)、CEMP-no/CEMP $\sim 0.2$  (High-mass IMF) となり、観測値を説明するのは困難。
  - ★ Low-mass IMFでは、CEMP-no/CEMP $< 0.02$ とさらに少ない。
- ★ EMP AGB星におけるs-processが金属量依存性を持つ可能性がある。
- ★ EMP星では短周期連星が作られやすい？ (Aoki, TS+15)
  - ★ metal-poor stars (not EMP)では1000日以下の連星が最も多い(Rastegaev10)