炭素過剰超金属欠乏(CEMP)星で探る宇宙黎明期の星・連星系形成史

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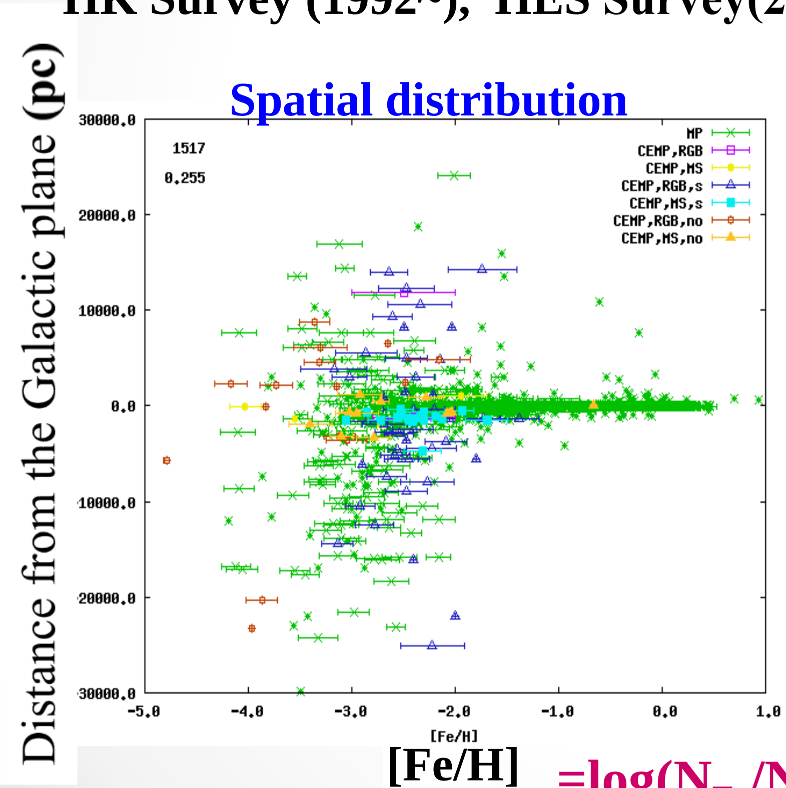
1. CEMP stars in the Galactic Halo

Extremely Metal-Poor (EMP) Stars in the Galactic Halo

Large-scaled survey of metal-poor stars in the Galactic halo

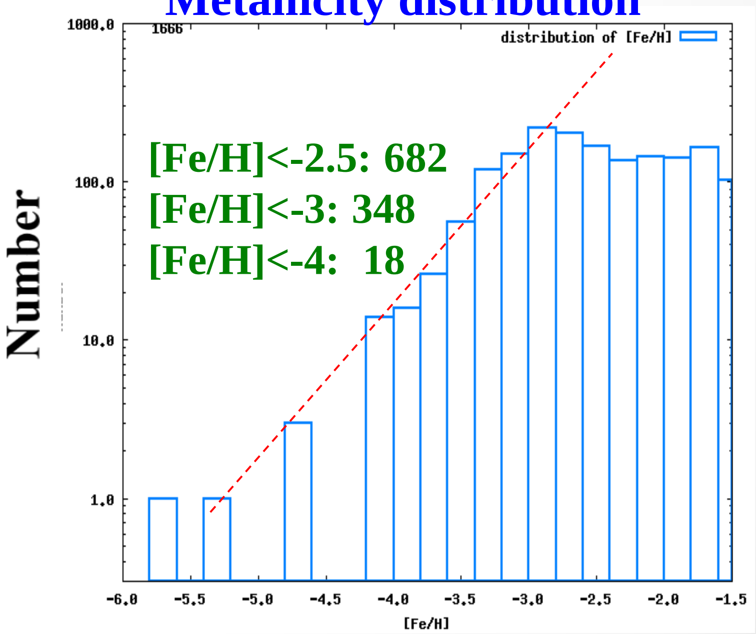
HK Survey (1992~), HES Survey(2001~), SEGUE(2004~), SMSS(2007~)….

Spatial distribution



[Fe/H] $= \log(N_{Fe}/N_H) - \log(N_{Fe}/N_H)_\odot$

Metallicity distribution

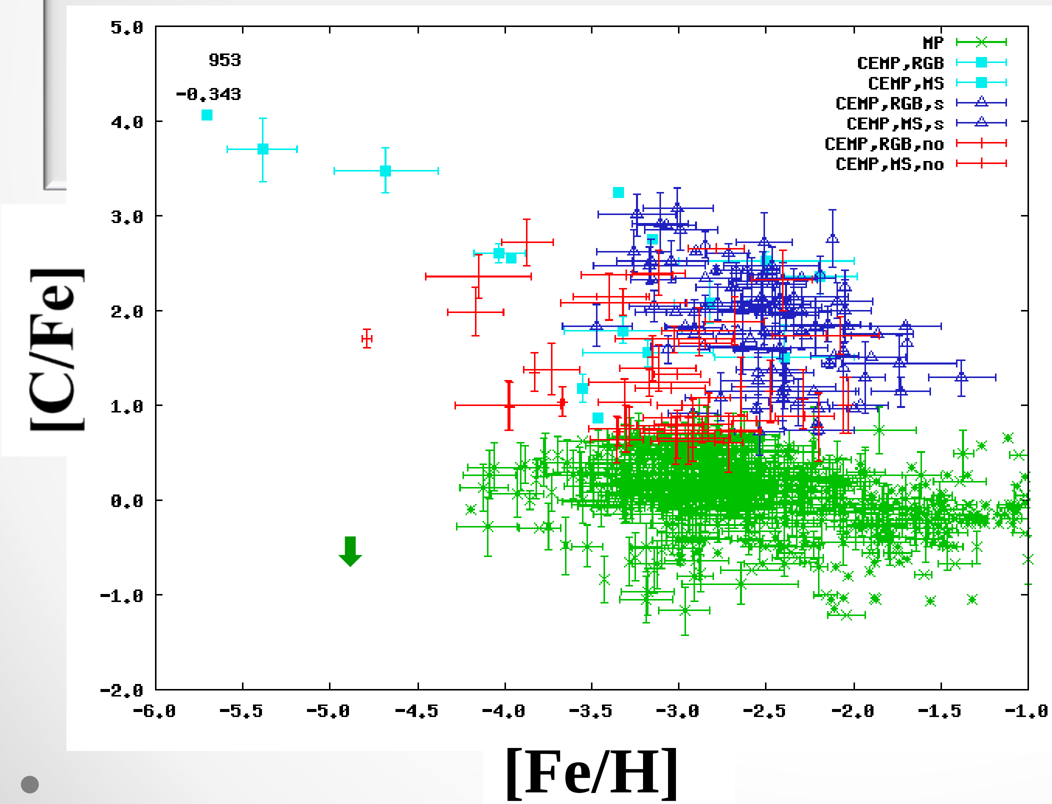


[Fe/H]

SAGA database: www.sagadatabase.jp (Suda et al.2008, 2011,2017)

Carbon Enhanced Metal-Poor (CEMP) Stars (Rossi+1999, Aoki+2002)

CEMP stars ([C/Fe]≥0.7) account for a large portion of EMP stars



Fraction of CEMP stars

Fe/H]<-2 : 30% (163/544)

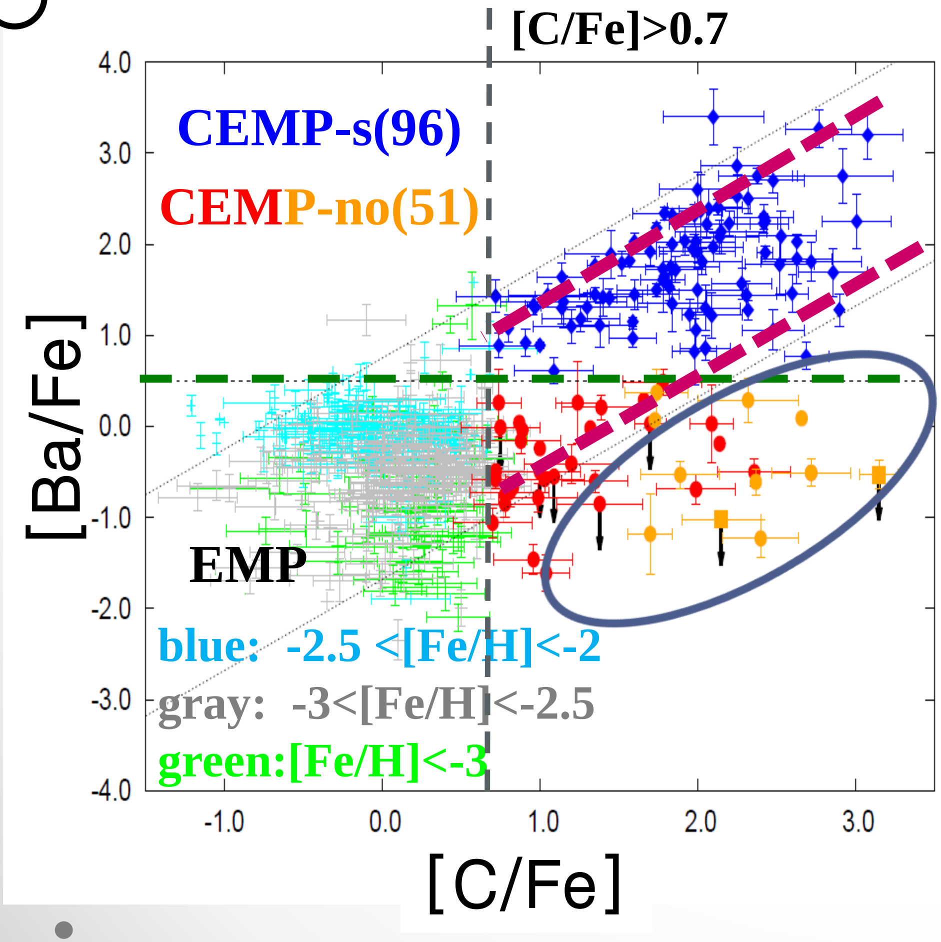
Fe/H]<-3 : 27% (57/211)

Fe/H]<-4 : 60% (9/15)

SAGA database (2015)

Variations of Neutron-Capture Elements (Sr, Ba, Eu, Pb)

Aoki, Norris + 2002,
Aoki, Beers + 2007



Classification

CEMP-s : [Ba/Fe] ≥ 0.5

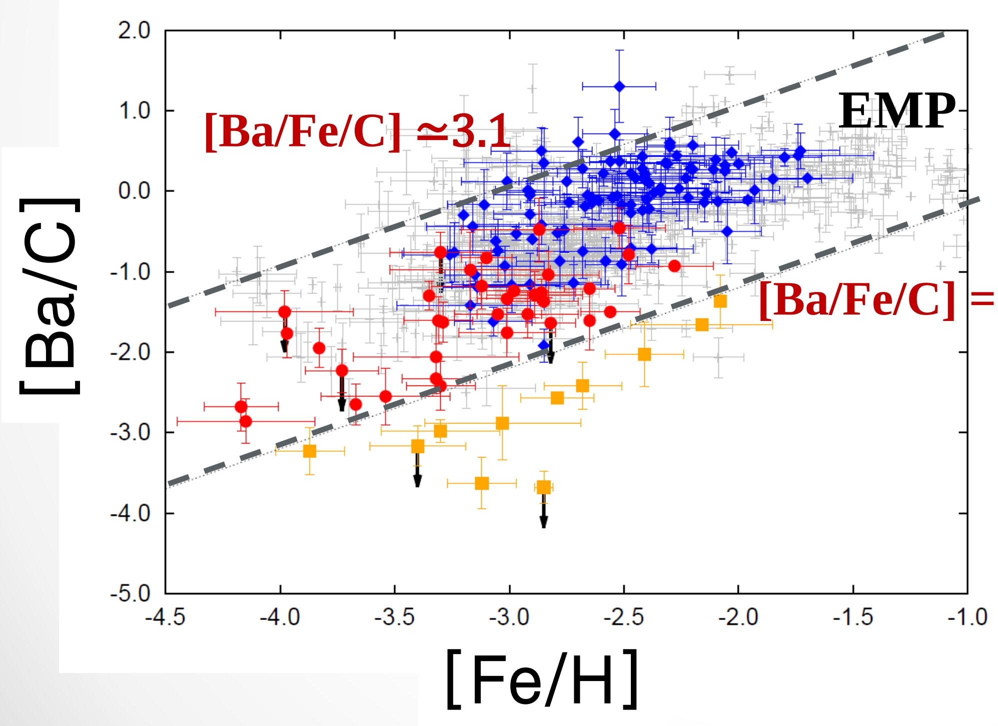
Ba enhanced ⇒
s-process yields from AGB
stars in the binary systems

CEMP-no : [Ba/Fe] < 0.5

Ba = normal (not enhanced)

Re-classification of CEMP Stars

CEMP-no ⇒ Lo-CEMP-no (40)
Hi-CEMP-no (11)



S-process nucleosynthesis

○ **Ba ∝ Fe**
⇒ **s-process with Fe as seed**

○ **The efficiency of s-process nucleosynthesis:**
[Ba/Fe/C]≡[Ba/Fe]-[C/H]
=[Ba/C]-[Fe/H]
Large variations in (~ over several dex)

○ **Different grouping**

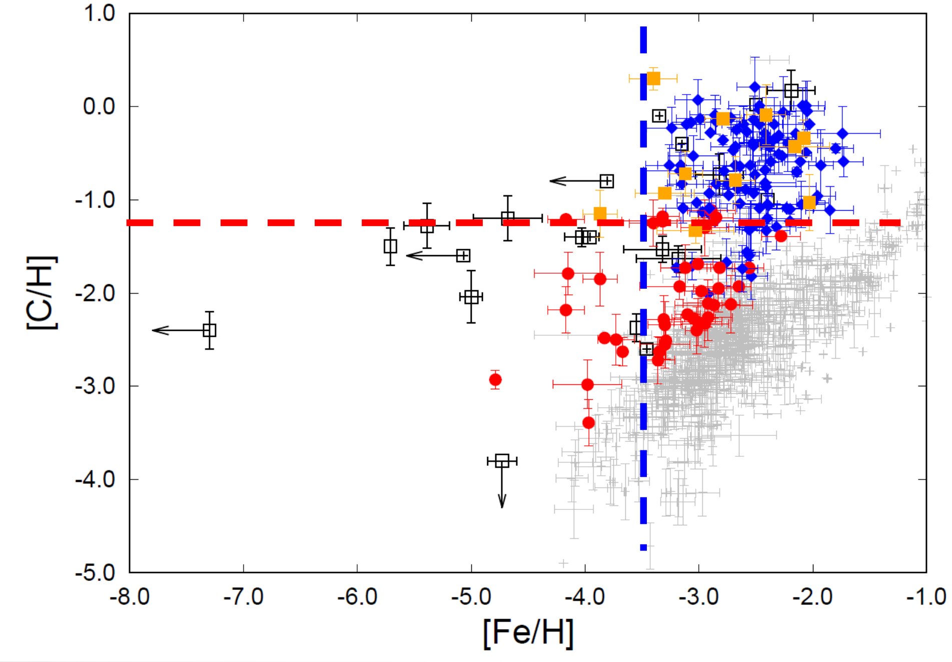
(1) CEMP-s + Lo-CEMP-no
[Ba/Fe/C] ≥ 0.8

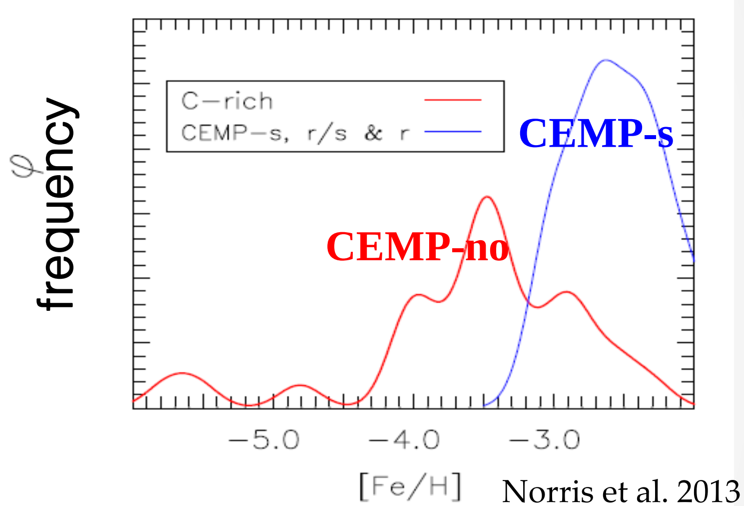
(2) Hi-CEMP-no
[Ba/Fe/C] < 0.8

Metallicity Distribution of CEMP Stars

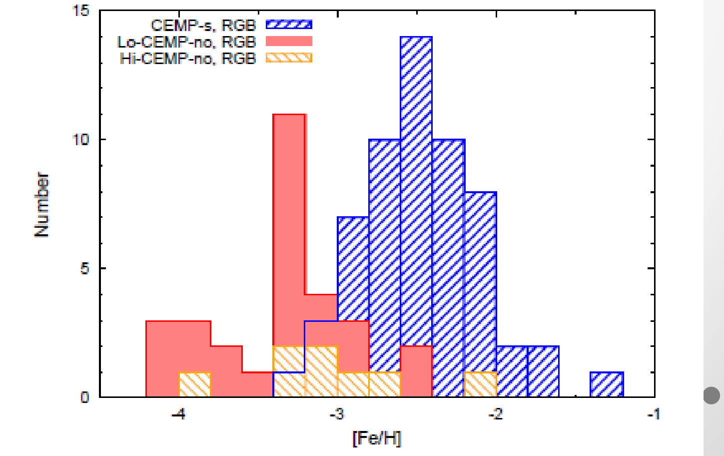
Norris+ 2013, etc.

Carbon Abundance/Metallicity

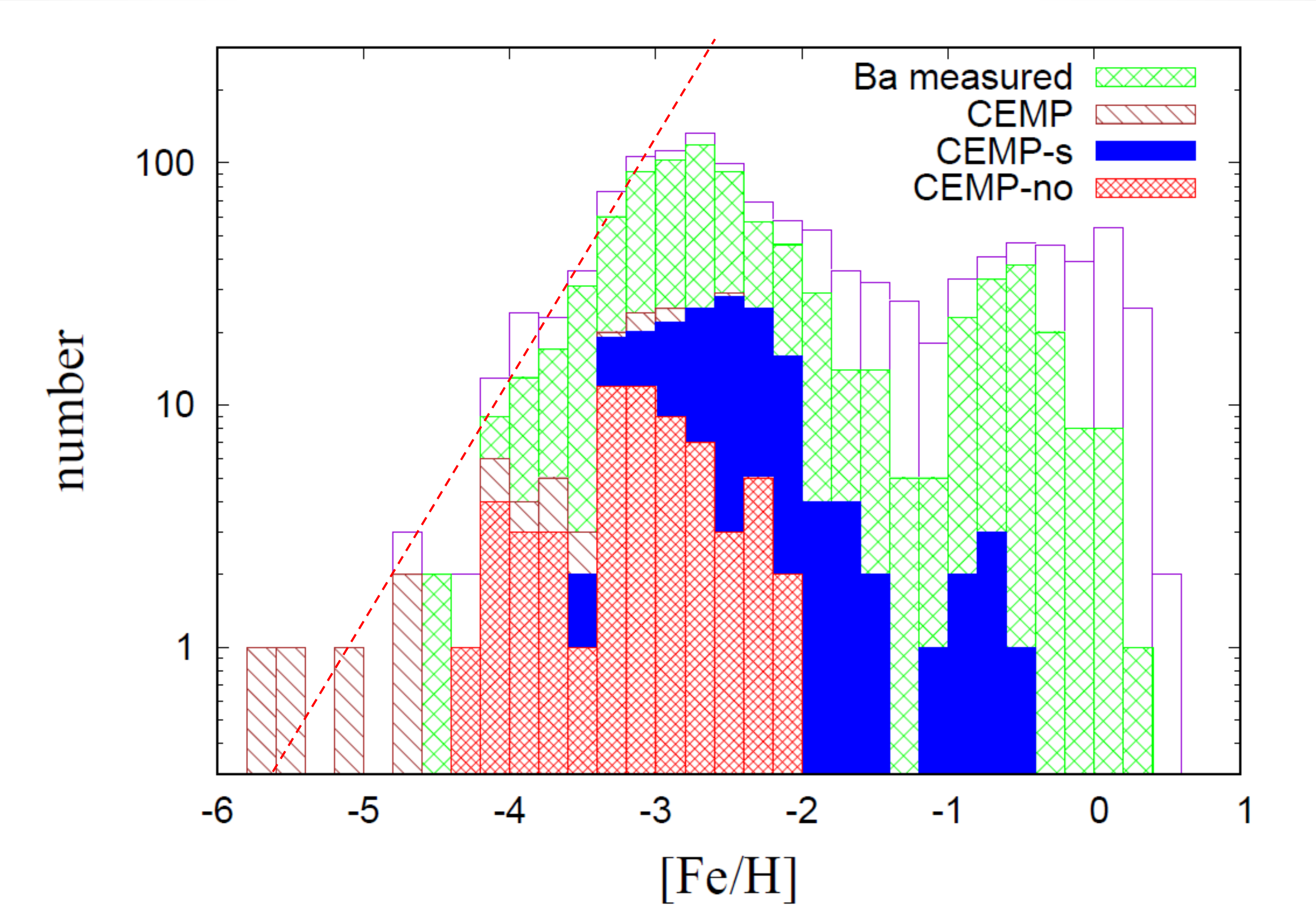




Norris et al. 2013



Summary: observed distributions

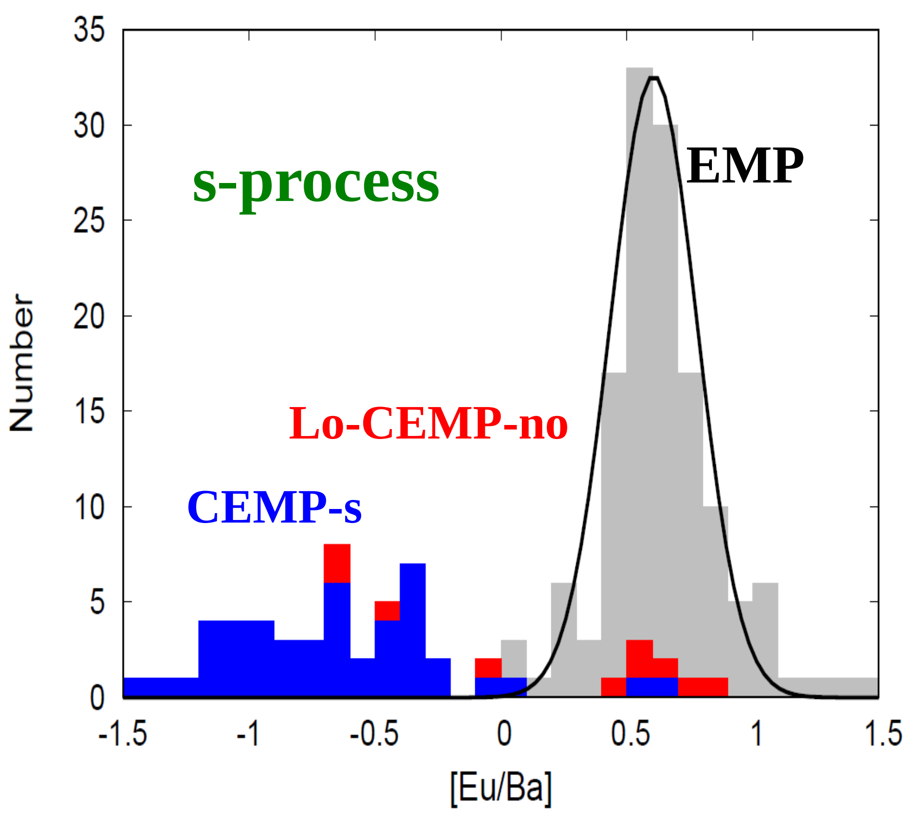


2. Origin of neutron-capture elements

中性子捕獲元素合成過程

(1) *r*-process (rapid neutron-capture process):
- site(s): neutron star merger +
- origin: incorporated from the interstellar gas = EMP 星と共通

(2) *s*-process (slow neutron-capture process):
- site: AGB stars
- origin: mass transfer with carbon in the binary systems



EMP星での s-process の特性

(1) s-process の進行は metallicity に依らない ([Fe/H] ≲ -2)

- **中性子密度: ^{16}O の吸収で決まる。**
- **s-processの効率 = [Sr/Fe/C], [Ba/Fe/C], [Eu/Fe/C] で表現**

(2) 中性子源

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

   ヘリウム殻フラッシュの対流層が水素を取り込む。 $^{12}C(p, \gamma)\, ^{13}N\, (e^+ \nu)\, ^{13}C$

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

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

   ヘリウム殻フラッシュで浚渫された^{12}C を水素燃焼で ^{14}N に変換、
   ヘリウム対流層での α 捕獲で ^{22}Ne を生成 $^{12}C \rightarrow {}^{14}N\, (\alpha, \gamma)\, ^{18}F\, (e^+ \nu)\, ^{18}O\, (\alpha, \gamma)$

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

Model vs. observation

$$-4.5 < [\mathrm{Fe/H}] < -2$$

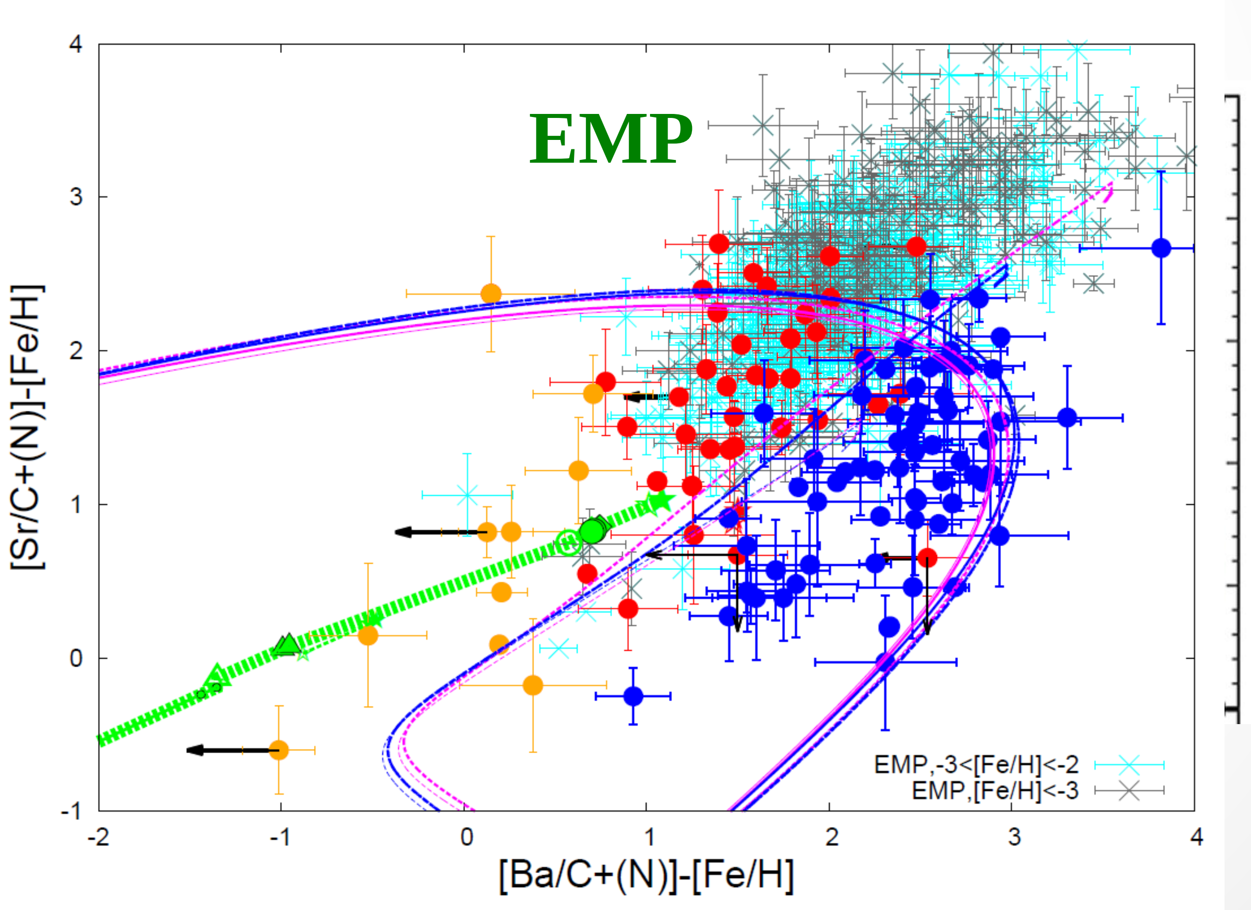
$^{13}C(\alpha,n)^{16}$

dilution l

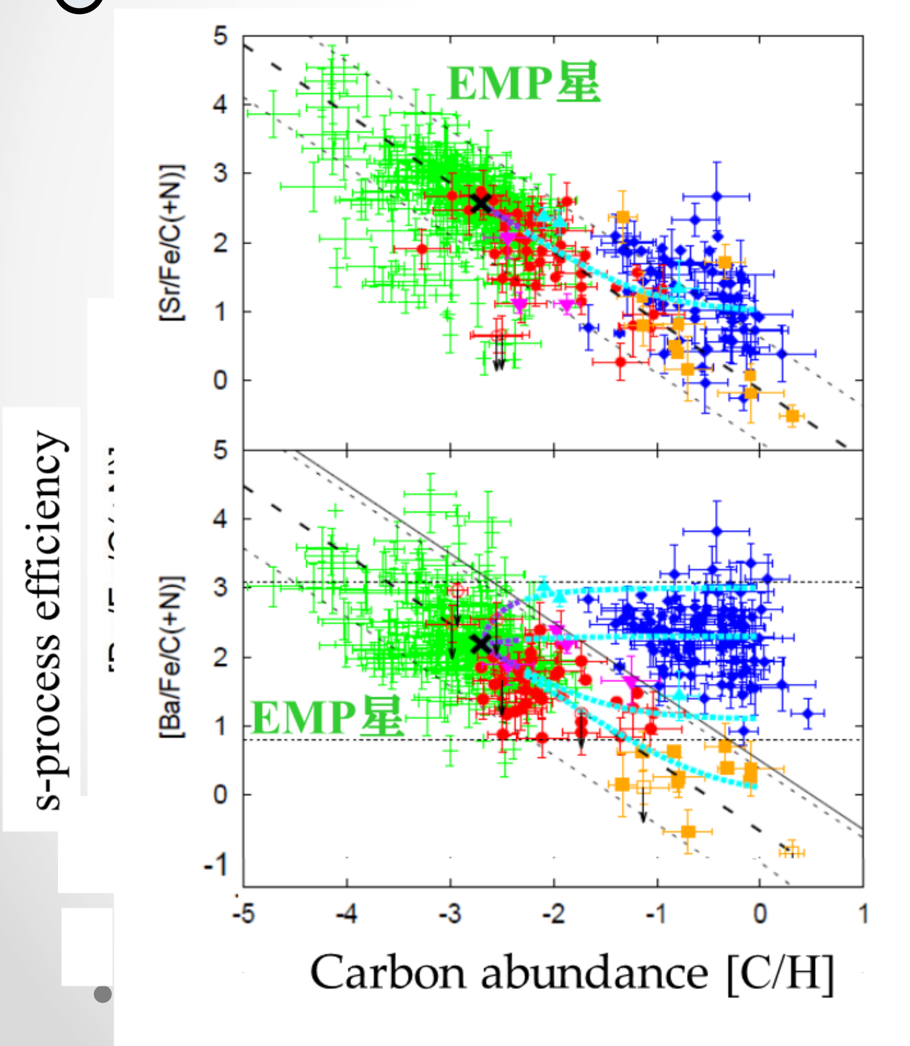
carbon la

dredged

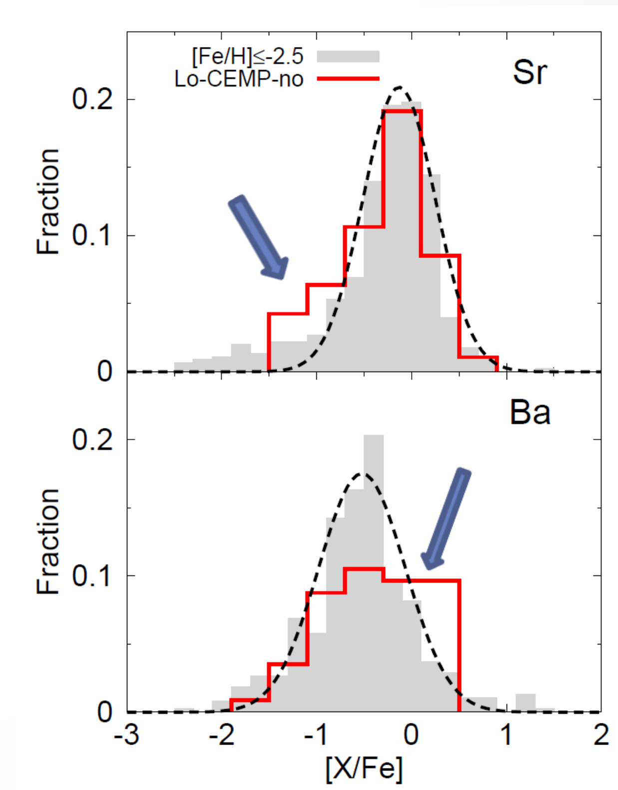
$^{22}Ne(\alpha,n)$



Binary origin of CEMP stars



Lo-CEMP-no 星とEMP星の [Ba/Fe] と [Sr/Fe] の比較

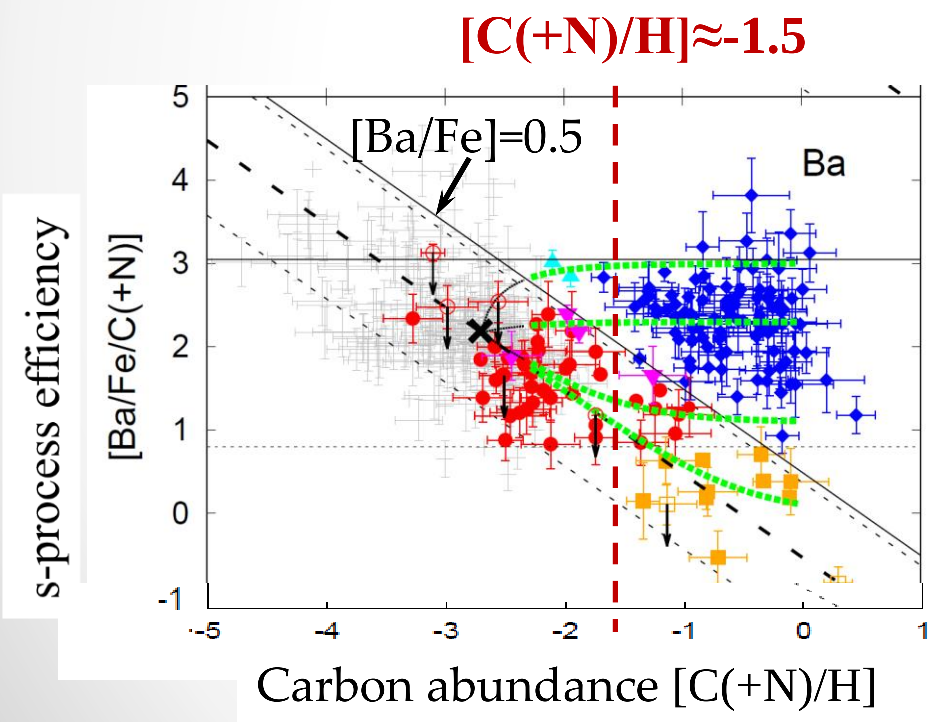


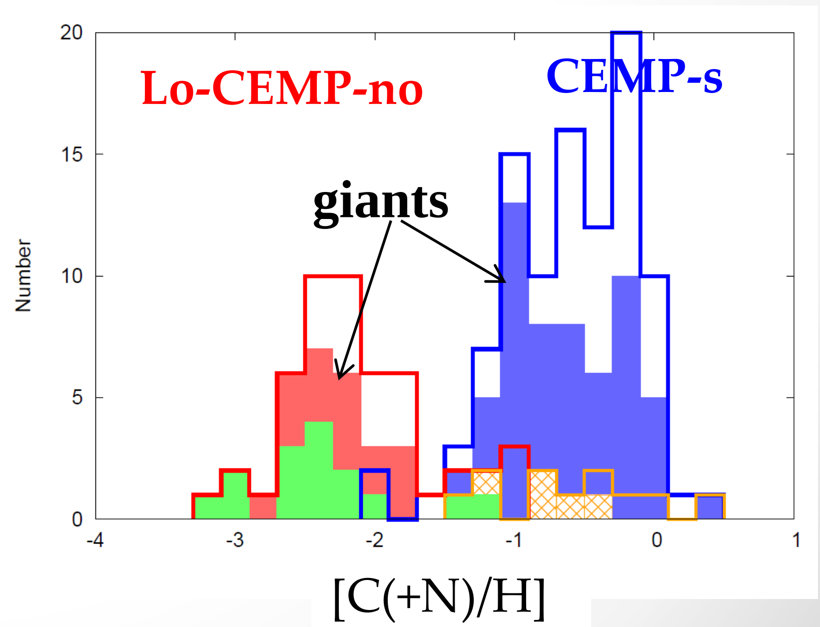
3. Binary characteristics

Bi-modal Distribution of Carbon Abundances

Difference between CEMP-s and Lo-CEMP-no stars

amount of mass transferred ⇒ binary separation





Binary Origin of CEMP stars

Suda et al. (2004), Komiya et al. (2007)

Assumptions:

(1) Log-normal distribution of orbital periods

(2) Bondi Accretion rate

(3) Wind: [C/H] = 0, $v_{\mathrm{wind}} = 20$ km s^{-1}

(4) Limited to Giants with the surface convection of $\sim 0.2M_\odot$

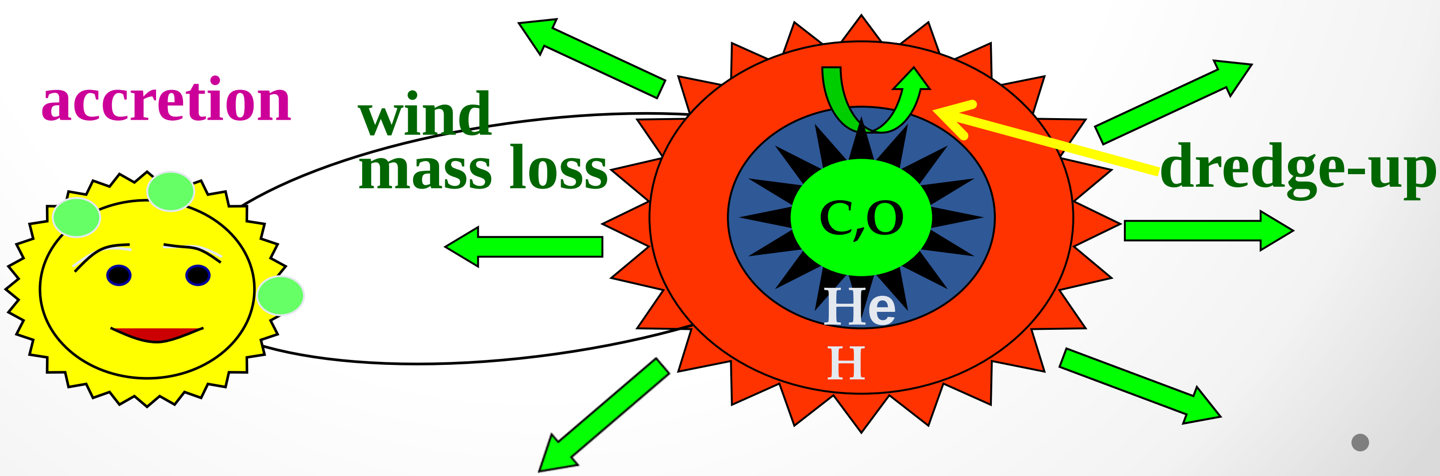
$$\frac{dM_2(t)}{dt} = -\frac{G^2 M_2^2(t)}{A(t)^2 v_{\mathrm{rel}}^4(t)} \frac{v_{\mathrm{rel}}(t)}{v_{\mathrm{wind}}} \frac{dM_1(t)}{dt}$$

CEMP star

Primary AGB stars ($0.8M_\odot < M \lesssim 8M_\odot$)

Low-mass EMP star ($M \sim 0.8M_\odot$)

:



母連星の周期分布

Bi-modal distributions

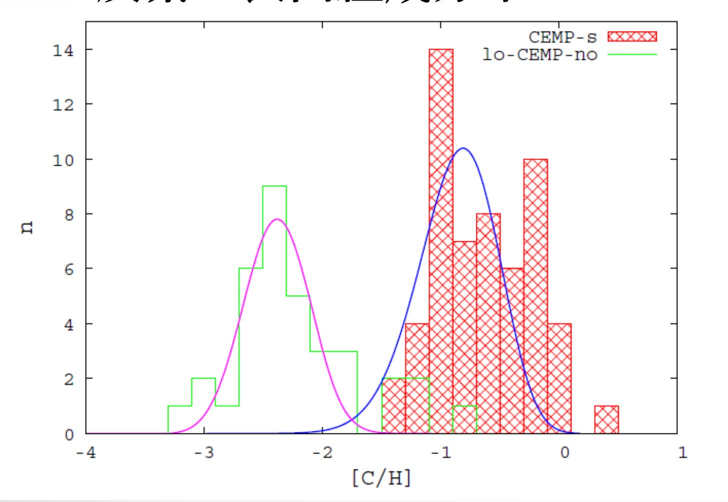
CEMP-s:

log P (day) = **3.0 ± 0.35**

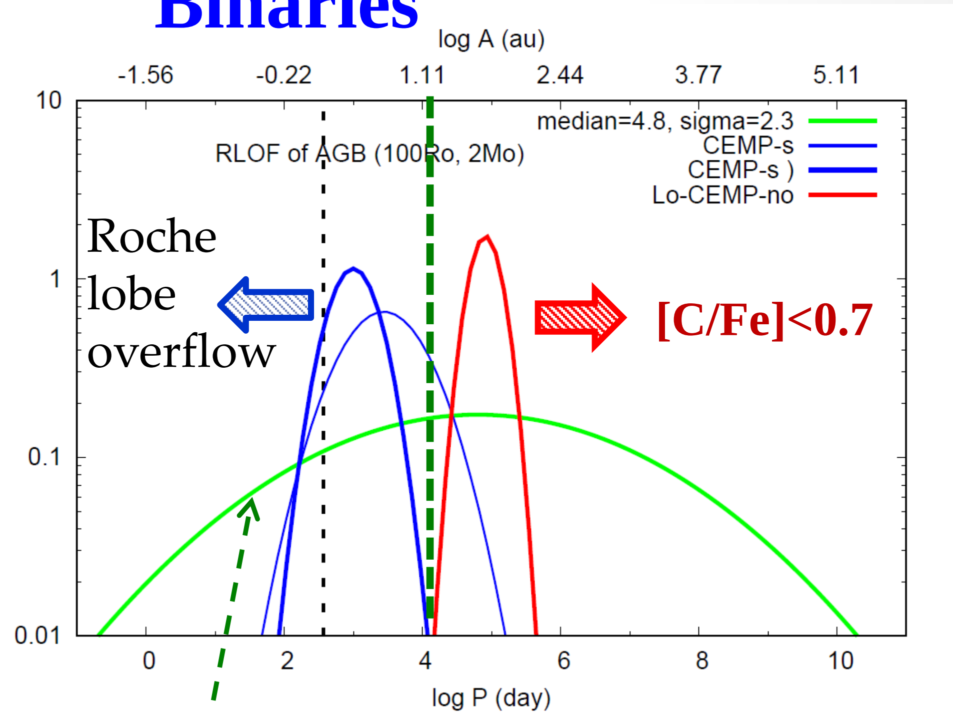
Lo-CEMP-no:

log P (day) = **4.91± 0.23**

炭素の表面組成分布



Short- & Long-Period Binaries



Solar neighborhood (主星=G-type stars)
(Duquennoy & Mayer 1991)

CEMP星の母連星の特性

1) CEMP-s, Hi-CEMP-no の親連星 = 短周期 (P <10^4 days)

主星: CEMP-s = low-mass AGB 星 ($M < 3.5M_{\odot}$)

Hi-CEMP-no = high-mass AGB 星 ($M \gtrsim 3.5M_{\odot}$)

2) CEMP-s, Hi-CEMP-no は [Fe/H] > -3.5 のみに存在

⇒ [Fe/H] < -3.5 には AGB星 + 低質量星 ($M \leq 0.8M_{\odot}$) の 短周期連星 が存在しない。

3) Lo-CEMP-no 星

⇒ 長周期 (P >10^4 days) の親連星 (AGB星+低質量星)が metallicity に依らずに（-5 ≲ [Fe/H]＜-2）存在;

- low-mass AGB星を主星とするものは, 全て [Fe/H] > -3.5

4. Stars and Binary Formation in the Early Universe

Formation History

Periodicity

Metallicity

Close Binaries

$P \approx 10^4$ days

Wide Binaries

短周期連星

長周期連星

[Fe/H] ≈ -2:

○ CEMP-s 星

○ Hi-CEMP-no 星

主星: low-mass AGB 星 (1~3 $M_{\odot}$), high-mass AGB 星 (≳3$M_{\odot}$)

○ Lo-CEMP-no 星

主星: low-mass AGB星とhigh-mass AGB 星のどちらも

[Fe/H] ≈ -3.5:

No CEMP stars

伴星 ($M \leq 0.8\ M_{\odot}$), かつ主星が AGB星の母連星がない

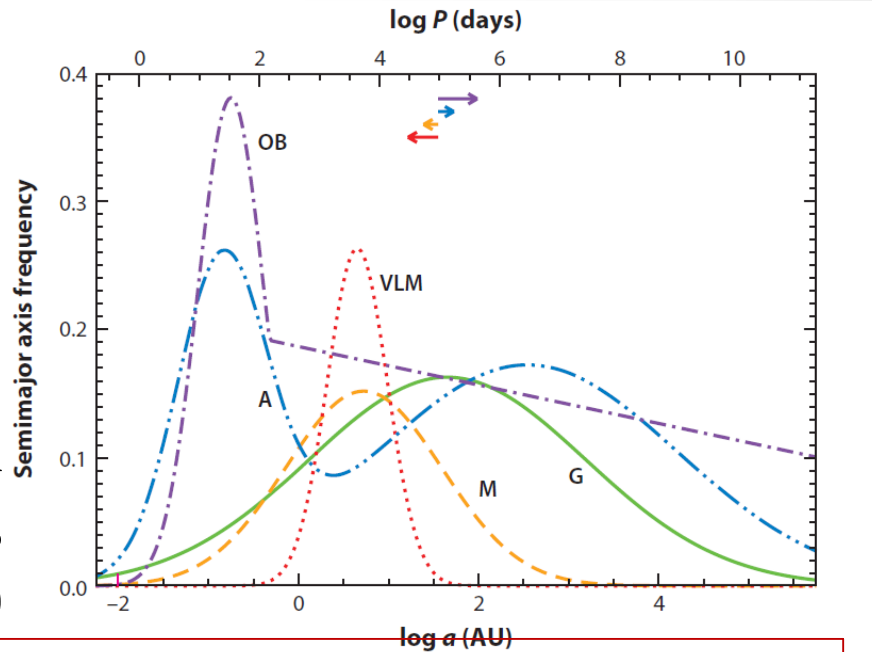
○ Lo-CEMP-no 星

主星: high-mass AGB 星のみ (?)

Formation Mechanisms

CEMP 母連星:

伴星 = 低質量星 (≤ 0.8$M_\odot$)
主星 = AGB星 (1~8 $M_\odot$),
主系列G型～A型、B型



Schematic forms of the orbital period distribution for field binaries (Duchene & Kraus, 2013, ARAA)

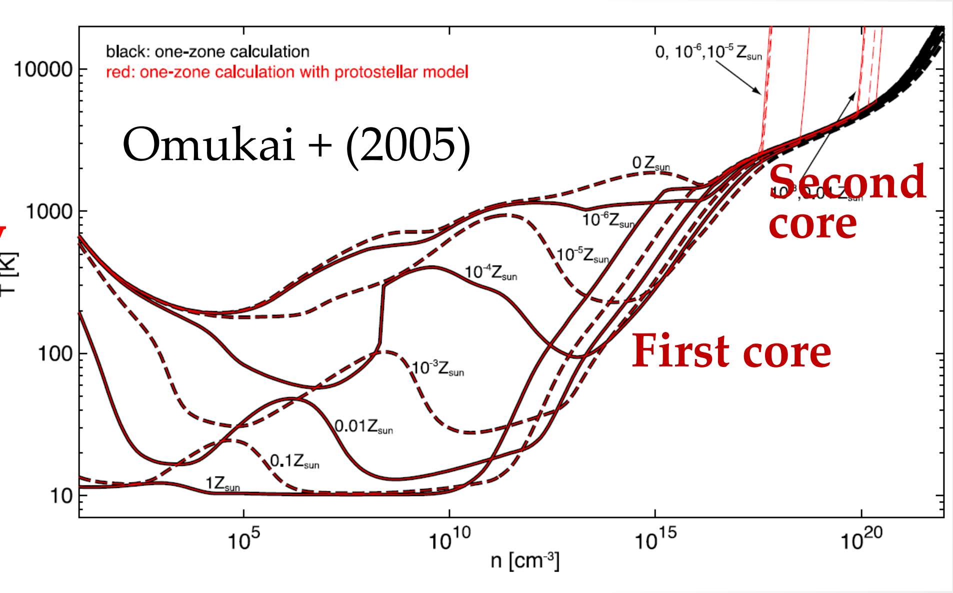
Binary formation mechanisms (e.g., Tohline 2002, ARAA)

1. **fragmentation of turbulent gas cores and filaments**
2. **fragmentation of protostellar disk**
   the first core (short period binaries)
   the second core (close binaries)
3. **capture (and exchange) of single stars …..**

Core contraction ⇒ metallicity dependence

(1) [Fe/H] ≳-5: dust cooling (Omukai+ 2005)

(2) [Fe/H] ≲ -4: heating by 3-body H2 formation: H2 is formed on dust for [Fe/H] ≳ -3 (Tsuribe+Omukai 2008)



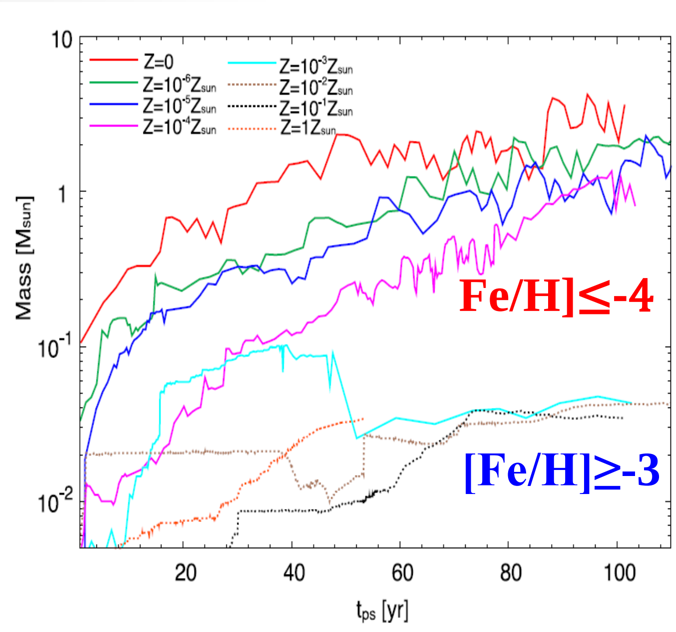
(3) [Fe/H] ≳-3: dust cooling ⇒ low cloud temperature ⇒ low accretion rate ⇒ 降着による星の成長が遅くなり、星周円盤が薄く安定に。

(Machida & Nakamura 2015)

Disk Fragmentation ⇒ short-period AGB binaries

(Machida & Nakamura 2015)

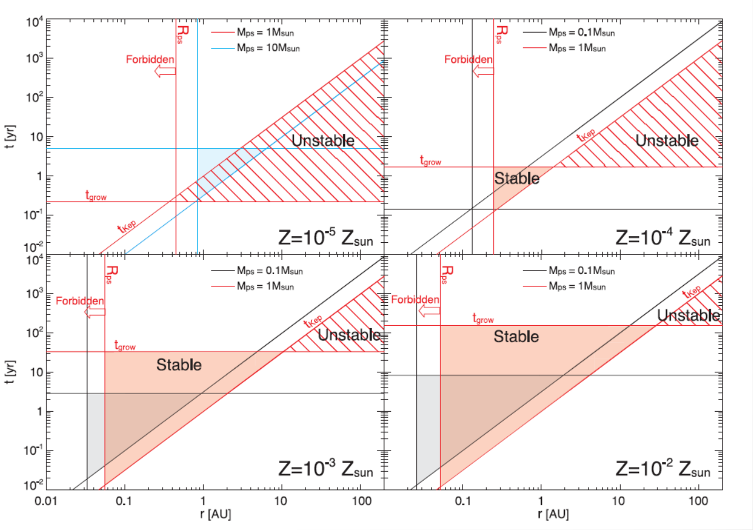
Mass growth of Protostars



massive stars

low-mass AGB stars

Formation of stable thin- disk

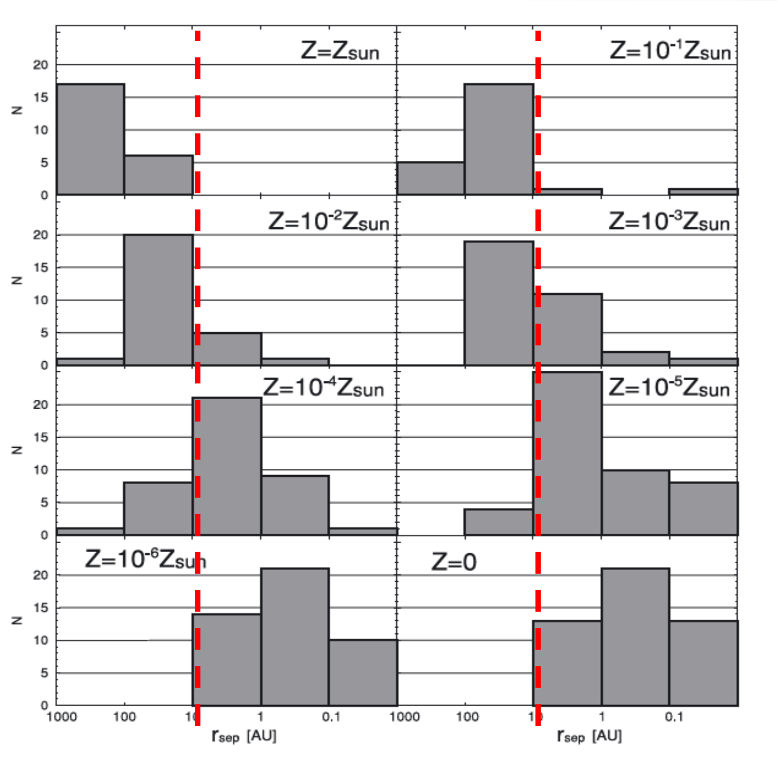


fragmentsは安定disk の外縁で (r≳10 au) ⇒ 伴星

Binary in the low-metallicity

[Fe/H]≤-4: Short-period (or close) massive binaries の形成:

1) cloudは冷えず、降着率が高い
   ⇒ Proto starsは massive に。
2) disk も厚く、不安定
   ⇒ 伴星もPSの近傍でも形成。(右図)
3) 中心近くでは、伴星も massive に、離れると、降着が小さく low-mass の伴星が形成され、星団が形成される（competitive accretion: Bonnell & Bate 2006; or Pop III stars: e.g., Stacy + 2016)
4) low-mass 伴星はできても、 dynamical 3-body interactions で ejectされる



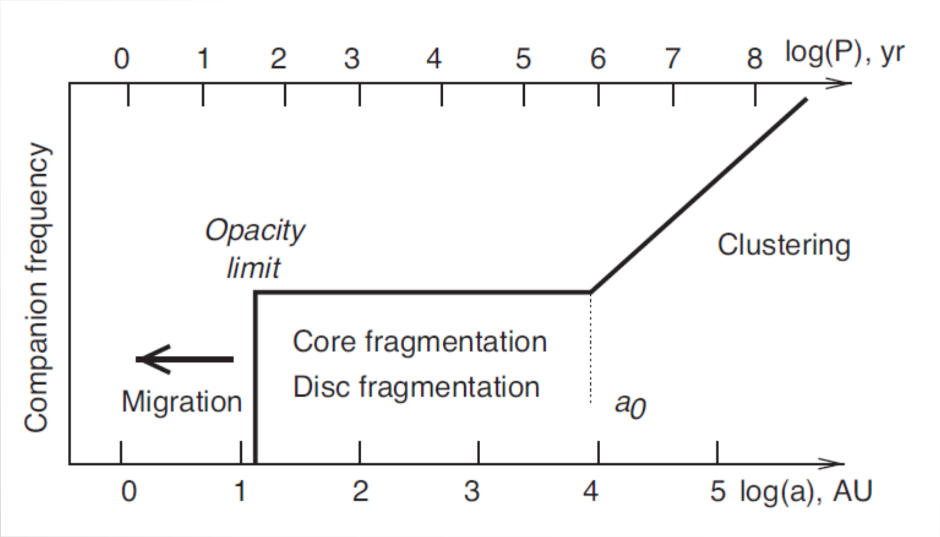
Machida et al. (2009)

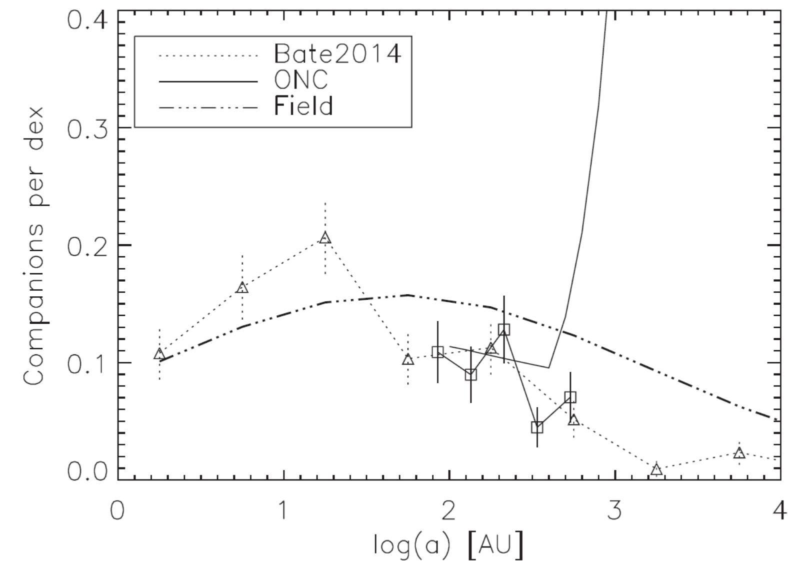
Long-period CEMP Binaries

Massive star formation の 副産物として低質量星

⇒ 星団の中で他の fragments (AGB星) と binaries

⇒ core からeject されて、近傍の cores との gravitational interactionで binaries や multiple systems を形成 (Tokovinin 2017)





超金属欠乏星の組成特性

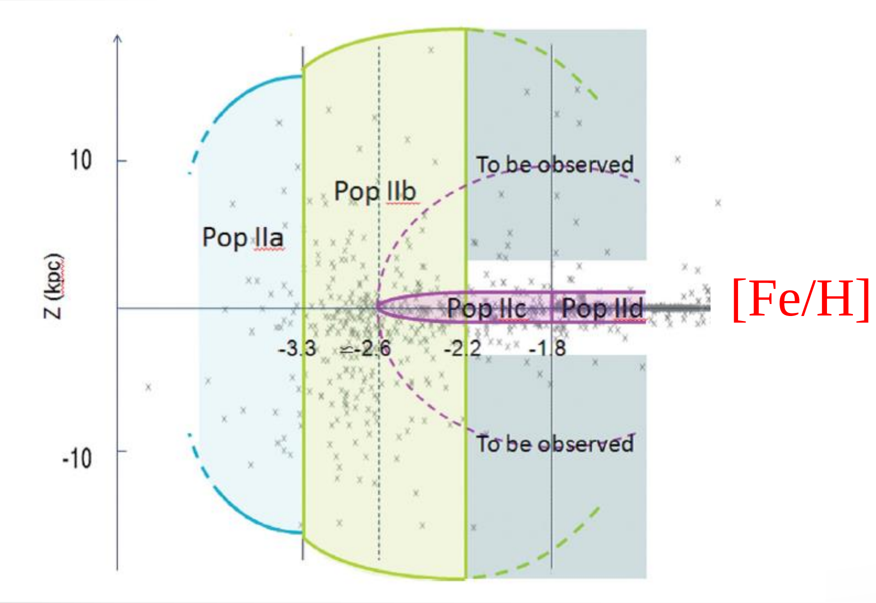
(Yamada et al. 2013)

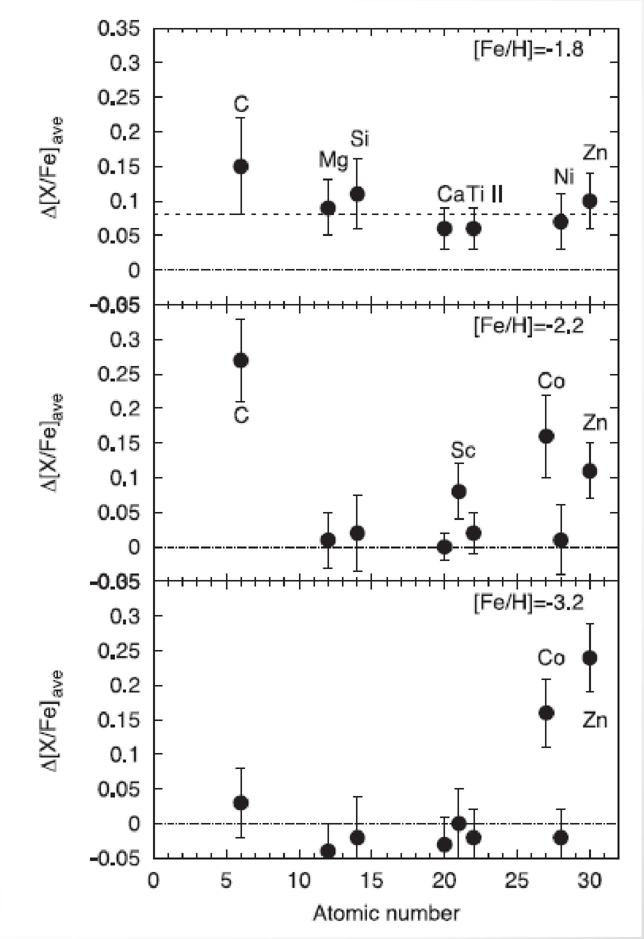
平均組成の変動

1) [Fe/H]≃-3.2: Δ[Zn, Co/Fe] ≃ 0.2

2) [Fe/H]≃-1.8: Δ[M/Fe] ≃ 0.1

3) [Fe/H]≃-2.2: Halo → Disk



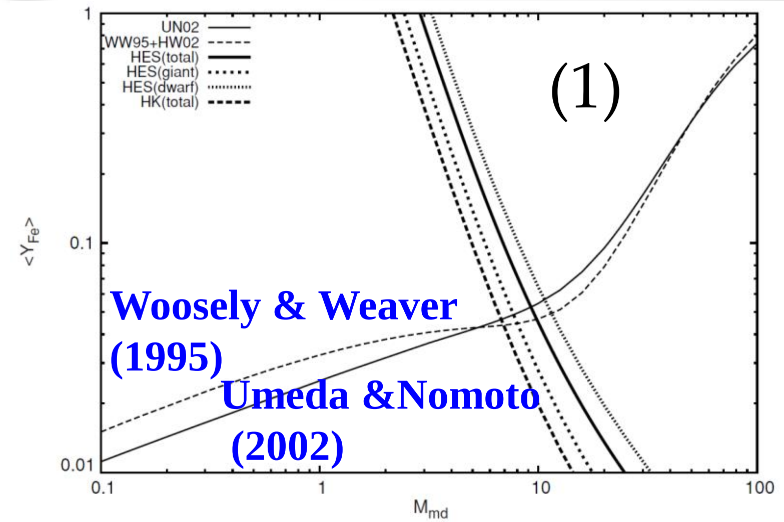


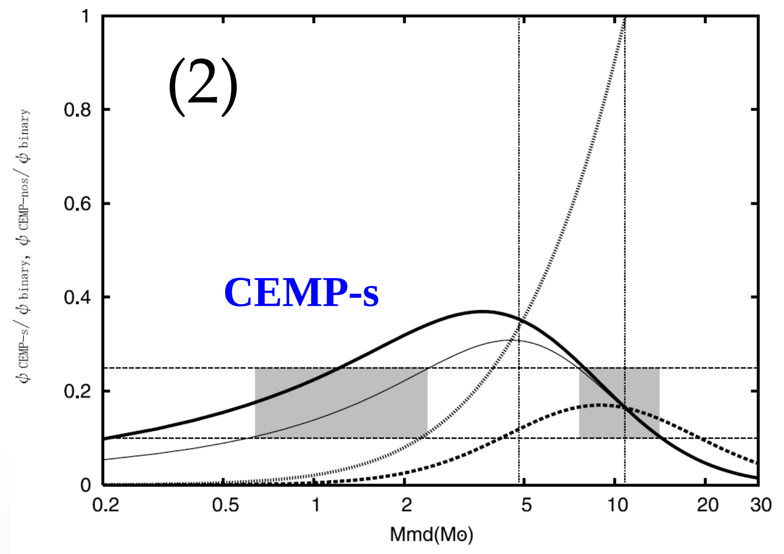
Top Heavy IMF despite the dust cooling

(1) HK, HES survey 観測されたEMP ([Fe/H]<-2.5) からの求めたSN1個当たりのFe 生成率（Komiya + 2009）

(2) CEMP-s星の fraction (Komiya+2007)

$$M_{\mathbf{md}} \simeq 10 M_{\odot}$$





assumption

- Top heavy IMF: log normal form with the medium mass, M_{md}, and the dispersion, ΔM(=0.4, 0.33).
- The binary period distribution: the same as Duquennoy & Mayor (1991)
- Binary fraction: f_b=0.5
- Uniform distribution of mass ratio of binary components

Summary: 連星系形成史

1. [Fe/H] ≳ -3.5: 短周期 (P < 10^4d) , 低質量 + AGB 連星
   - CEMP-s stars: [C/H] ≳ -1.5: 主星, low-mass AGB stars ($M \lesssim 3.0\ M_{\odot}$) 、中性子源 12C
   - Hi-CEMP-no stars: [C/H] ≳ -1.3 : 主星, massive AGB stars ($M > 3.0\ M_{\odot}$)、中性子源 22Ne

   Dust cooling ⇒ low accretion rate + circumstellar disk

2. [Fe/H] ≲ -3.5: 短周期 (P < 10^4d) の 低質量 + AGB 連星 は無し。
   - High temperature ⇒ large accretion rates（$\propto C_s^3/G$)
   - massive protostar + massive fragments at short (or close) periods
     stellar cluster ⇒ low-mass stars at larger distance + kicked off by the dynamical interaction

   - ⇒short-period (close) binaries of massive stars

3. 長周期（P > 10^4d）連星 ⇔ Lo-CEMP-no stars (-5<[Fe/H]<-2)
   - 低質量星 ＝ massive stars 形成の副産物（AGB 星も）

4. Top Heavy IMF for [Fe/H] ≲ -2.5
   星の質量： assembly of gas mass Jeans instability は必要条件