Transition of Stellar Initial Mass Function Explored with a Binary Population Synthesis for Extremely Metal-Poor Stars

Takuma Suda (NAOJ)

Yutaka Komiya, Wako Aoki (NAOJ), Shimako Yamada, Yutaka Katsuta, Masayuki Y. Fujimoto (Hokkaido), Pilar Gil-Pons (UPC), Carolyn L. Doherty, Simon, W. Campbell (Monash), Peter R. Wood (ANU)

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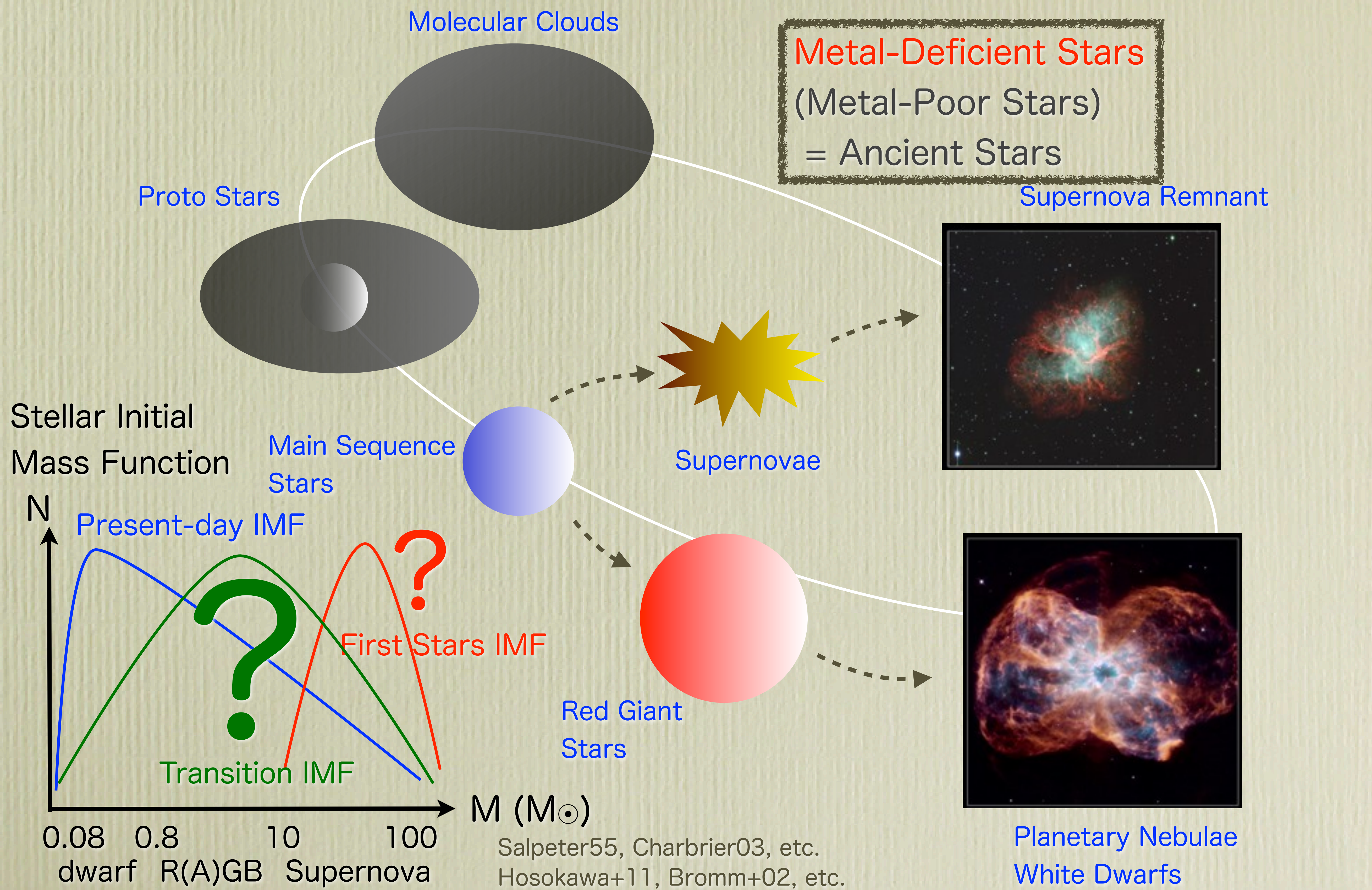
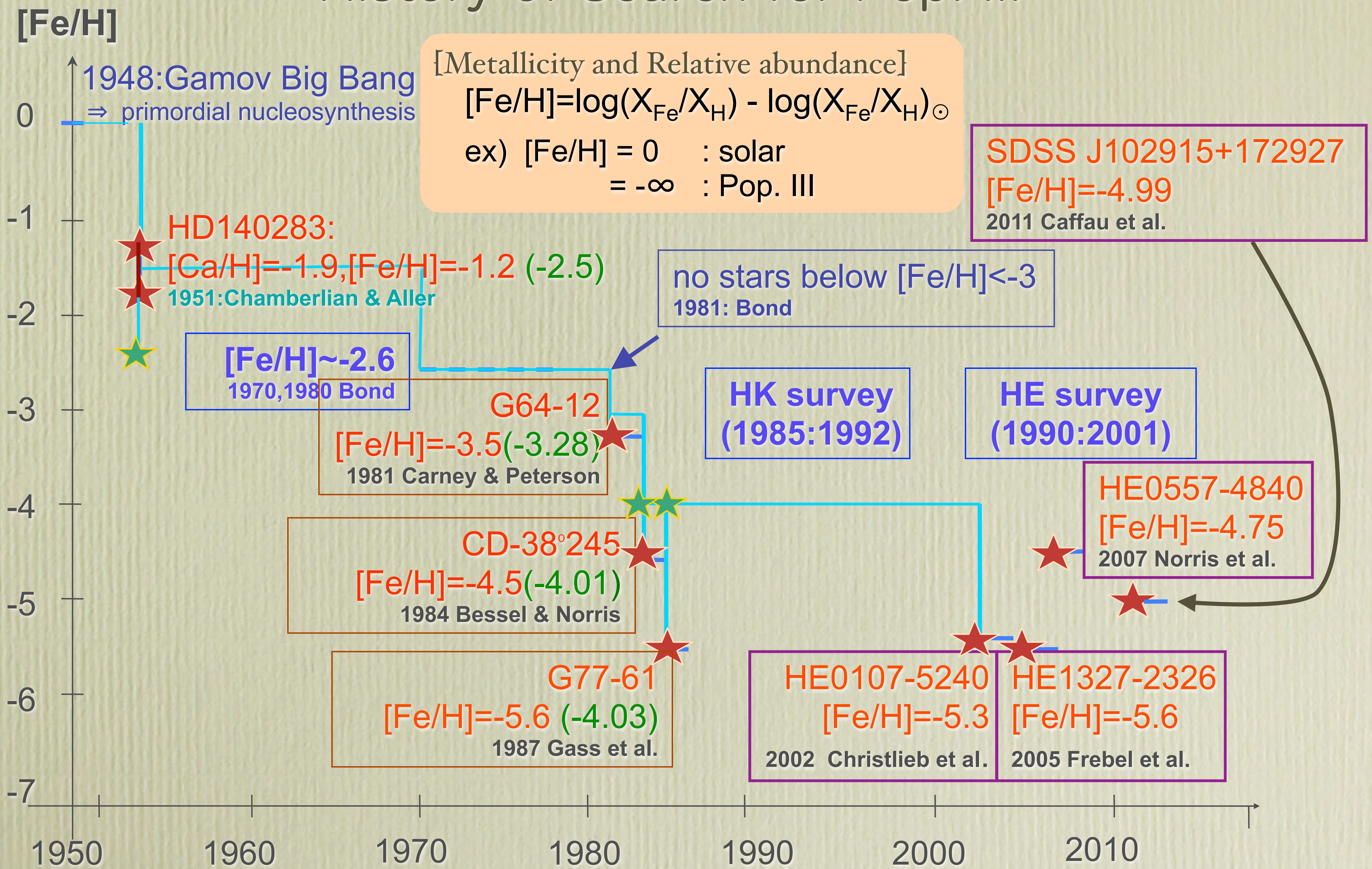
Chemical Evolution and Stellar Initial Mass Function



History of Search for Pop. III

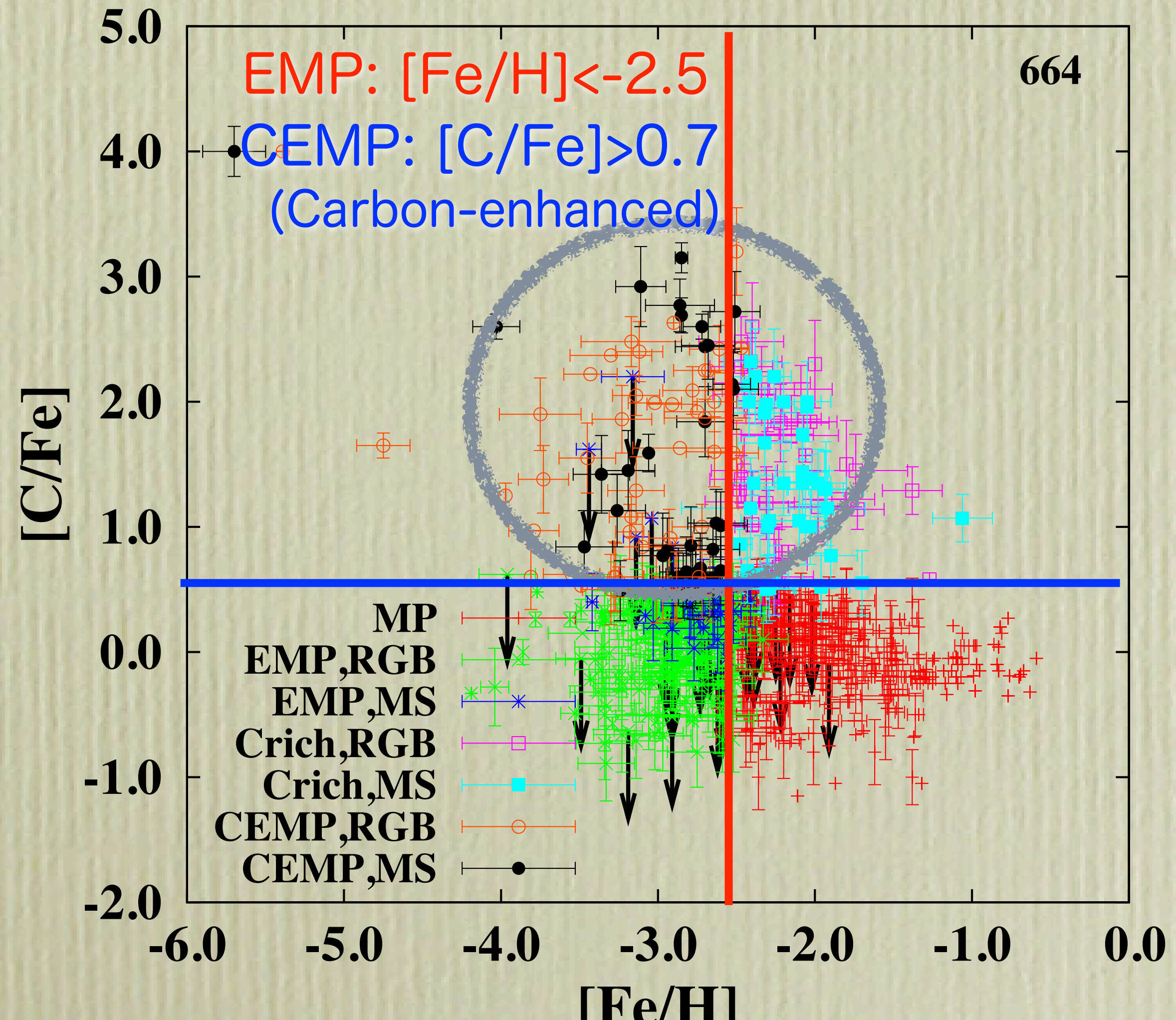


Properties of Known EMP (Extremely Metal-Poor) Stars

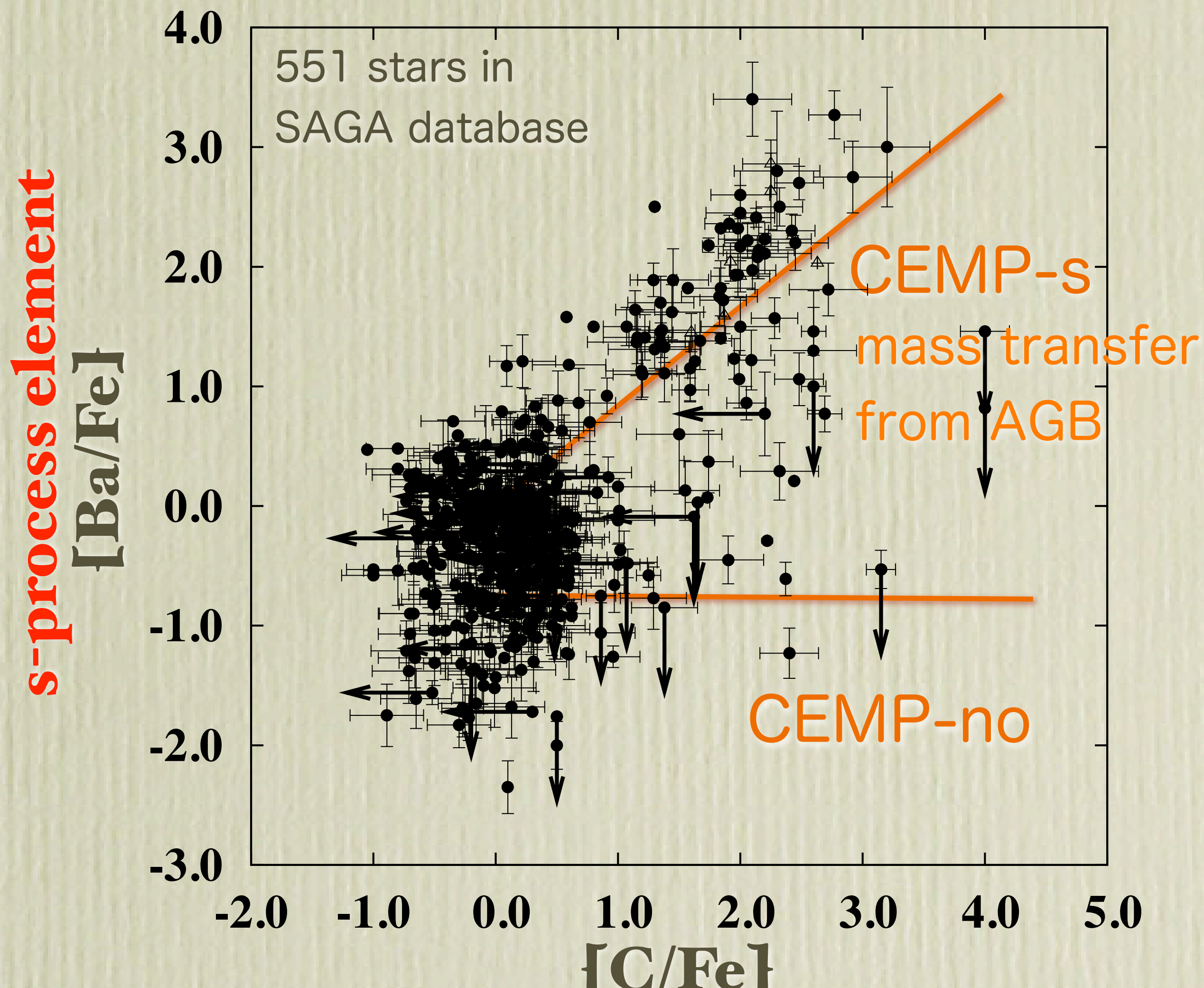
Observation

- CEMP/EMP = 20-25%
- CEMP-s / CEMP-no = 1-3
- NEMP / CEMP ~ 0.1
- Binary frequency: unknown
  - spectroscopic binary: 3/100

(Nitrogen-enhanced)



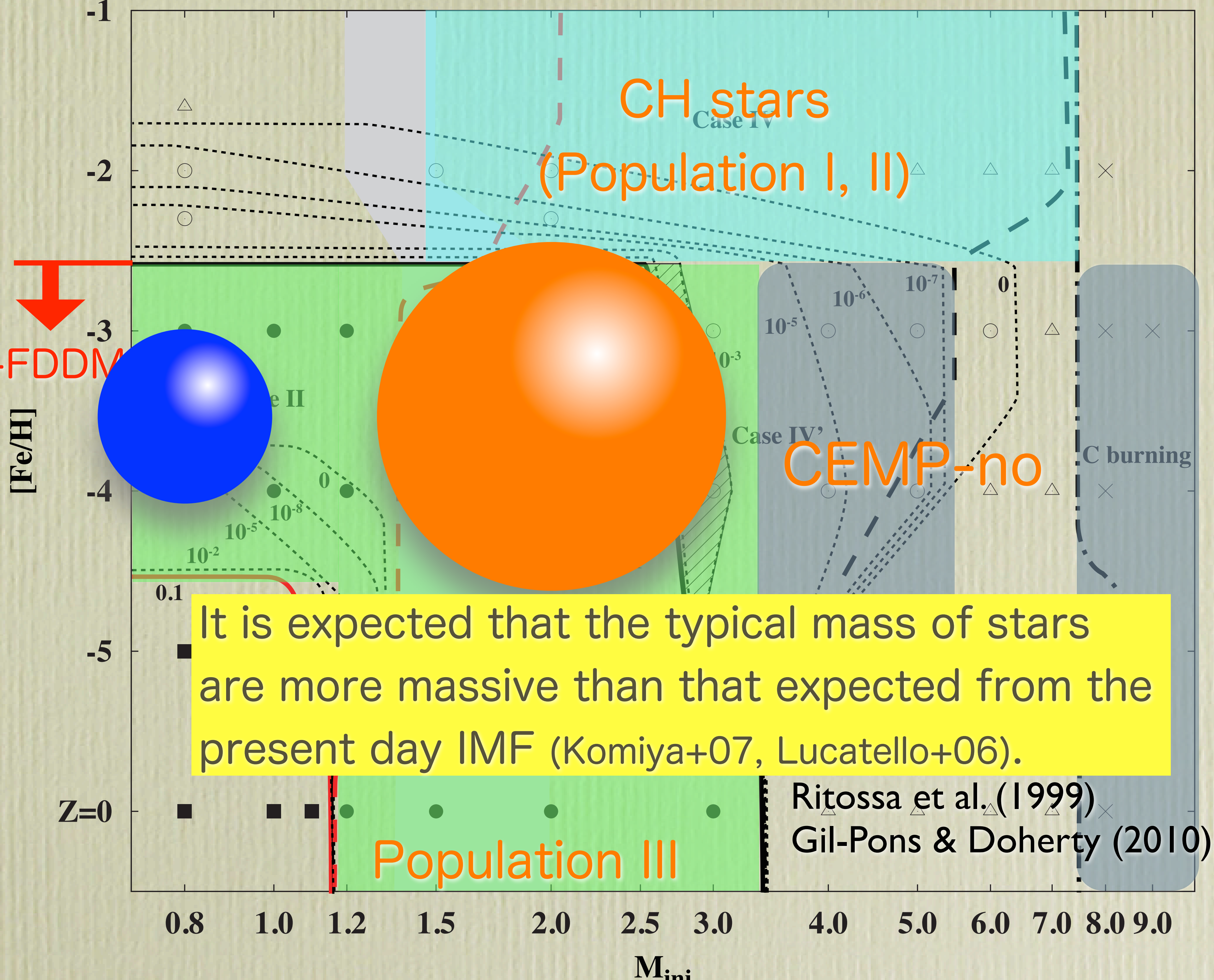
Data from SAGA database
(Suda et al. 2008) http://saga.sci.hokudai.ac.jp



see also Aoki et al. (2002), Ryan et al. (2005)

Binary Scenario for the Origin of CEMP Stars

Suda+Fujimoto10, see also Fujimoto+00

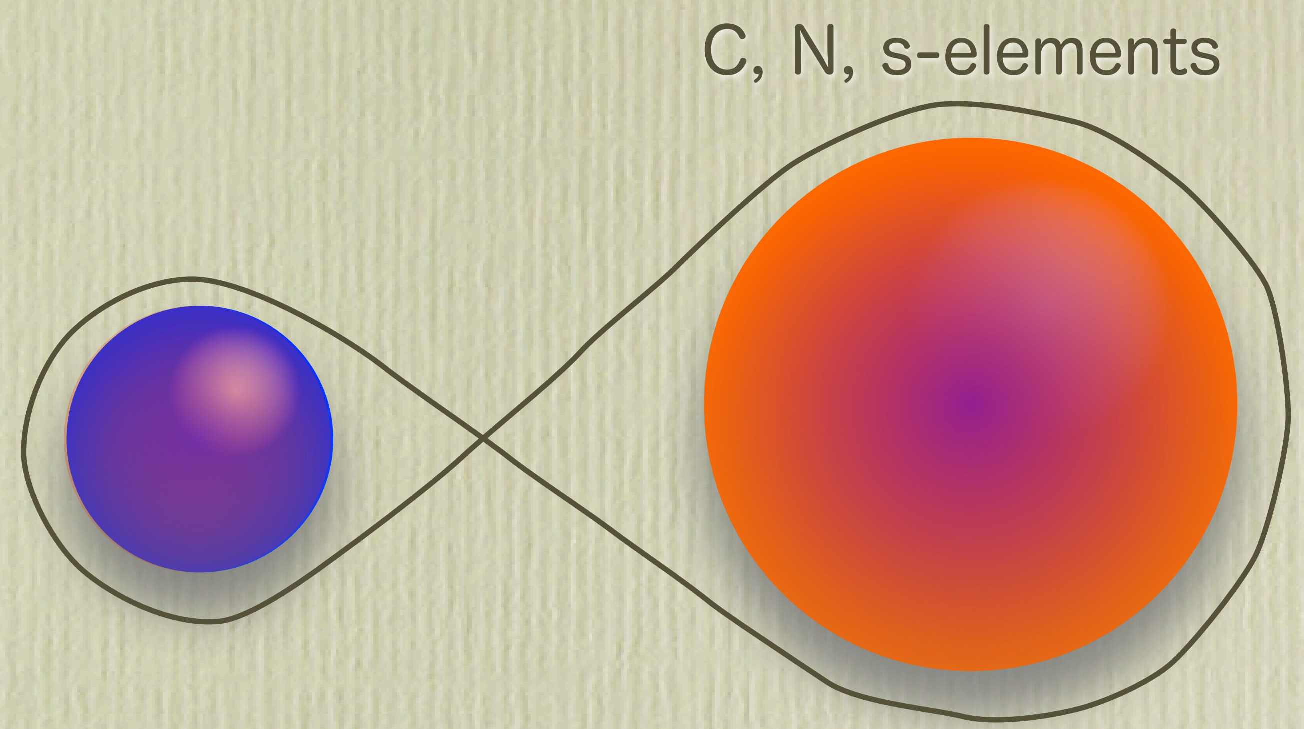


It is expected that the typical mass of stars are more massive than that expected from the present day IMF (Komiya+07, Lucatello+06).

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+Fujimoto10

Stellar Evolution & Binary Evolution



Roche Lobe overflow or <u>Wind accretion</u>?

-> 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

Parameter Ranges of the IMF

Search for typical mass (M_{md}) consistent with observations. ($\Delta_M = 0.33$)

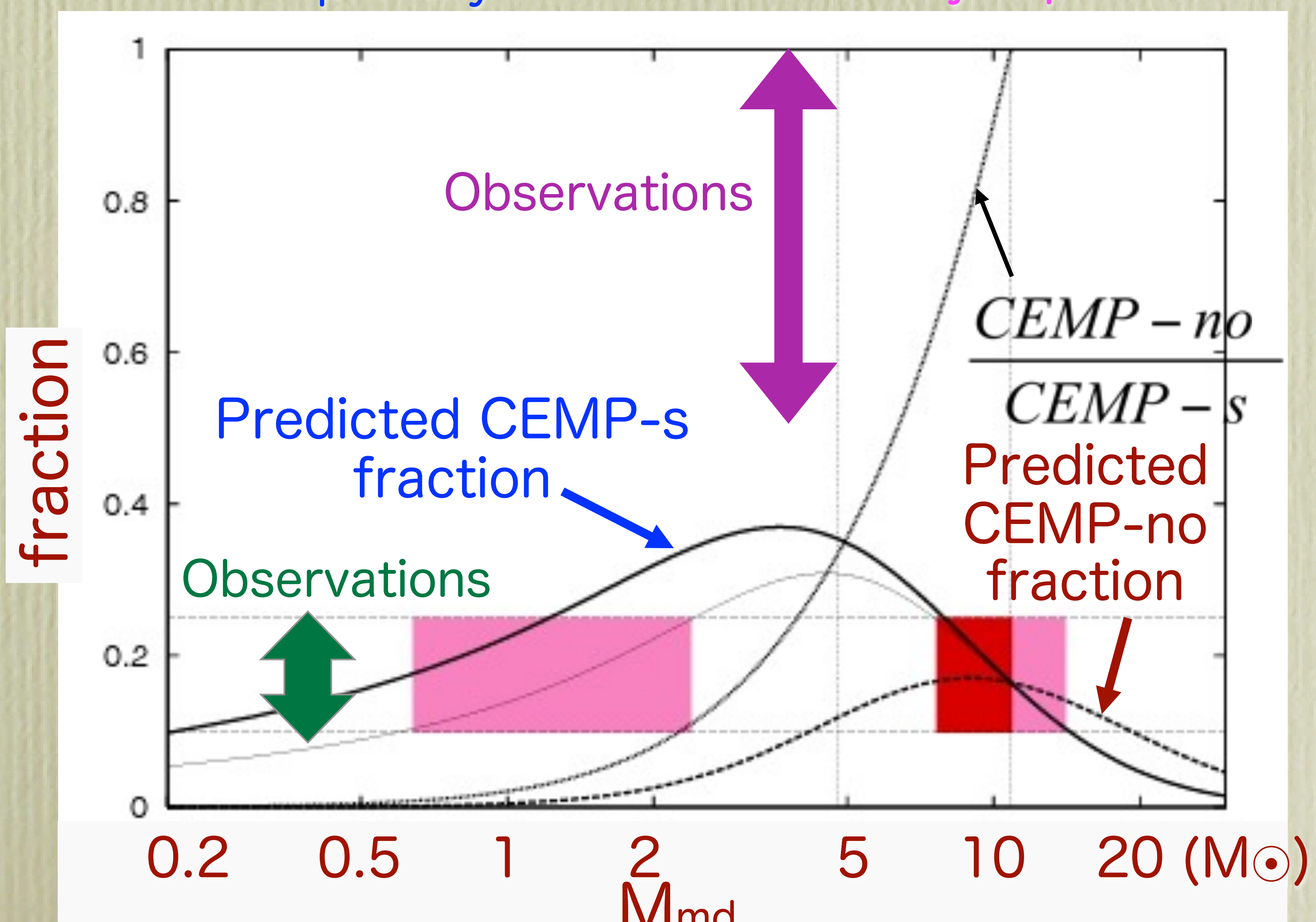
CEMP-s fraction is predicted from

$$\psi_{CEMP-s} = \int_{0.8}^{3.5} \xi(m_1) \frac{n(m_2/m_1)}{m_1} dm_1 \int_{A_{He-FDDM}(M_1)}^{A_M(M_1)} f(A) dA$$

- $\int_{0.8}^{3.5} \xi(m_1)$: mass range of primary
- $\frac{n(m_2/m_1)}{m_1}$: mass ratio distribution
- $\int_{A_{He-FDDM}(M_1)}^{A_M(M_1)} f(A) dA$: distribution of binary separation

log normal IMF

$$\xi(\log m) \propto \exp\left(-\frac{(\log m - \log M_{md})^2}{2 \times \Delta_M^2}\right)$$



Required range of M_{md} to account for CEMP-s fraction

: ~1M⊙ and ~10 M⊙

Required range of M_{md} to account for CEMP-s ~ CEMP-no

: ~10 M⊙

Effect on r-process?

Komiya et al. (2007)

Binary Population Synthesis with Various IMF by Pols et al.(2008) and Izzard et al. (2009)

Table 2. Number fractions of CEMP and NEMP stars among halo stars at [Fe/H] = −2.3 and $\log g < 4.0$ as in Table 1, for the default physical ingredients while varying the input distributions.

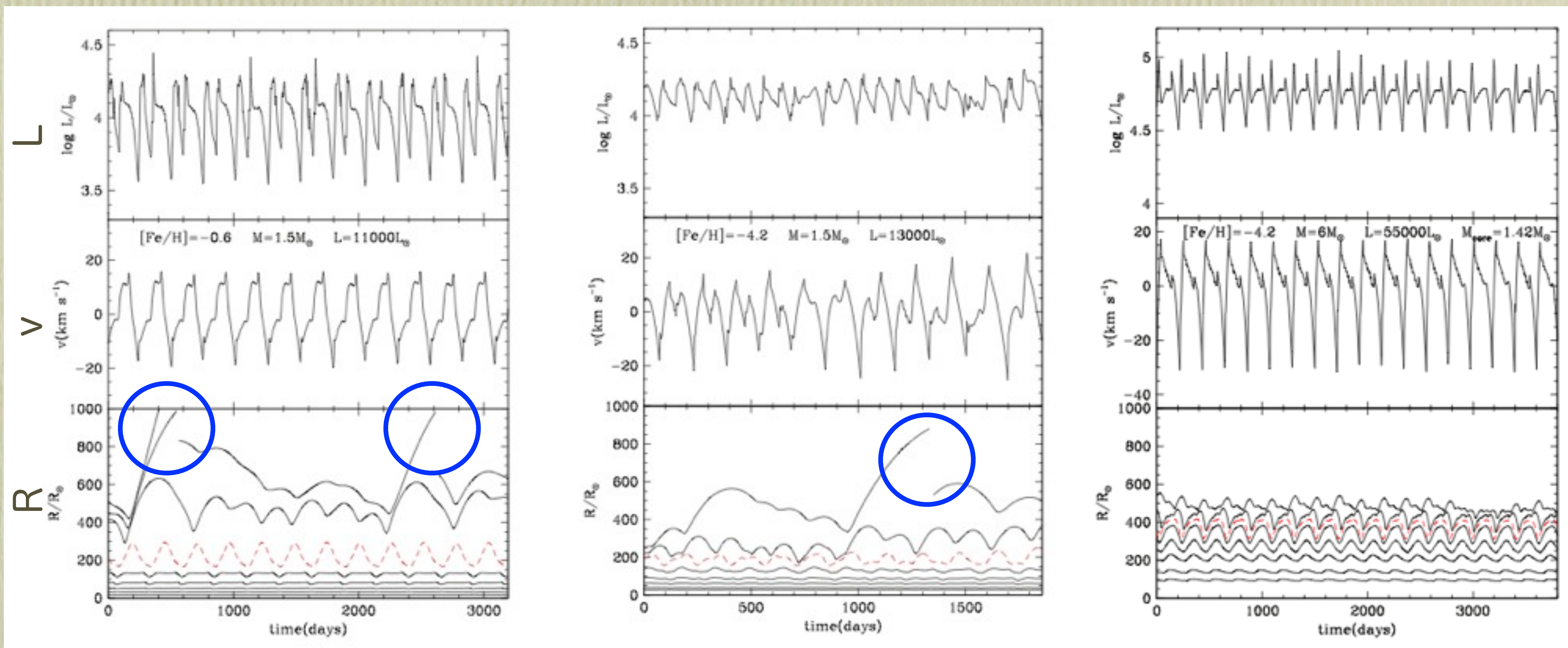
model		f(CEMP)	f(NEMP)	$\frac{\text{NEMP}}{\text{CEMP}}$
1A	default $N(M_1, q, P)$	2.30 %	0.35 %	0.15
1B	$N(q, P)$ from Duquennoy & Mayor (1991)	3.50 %	0.71 %	0.20
1C	$N(M_1)$ from Miller & Scalo (1979)	3.15 %	0.62 %	0.20
1D	$N(M_1)$ from Lucatello *et al.* (2005b)	4.81 %	1.35 %	0.28
1E	$N(M_1)$ from Komiya *et al.* (2007)	13.47 %	26.61 %	1.98

- Using models 1C and 1D "results in a larger CEMP fraction but still falls short of the observed value".
- "Model 1D also shows an increased NEMP fraction, the result of a larger weight of intermediate-mass stars (with M > 2.7 M⊙ undergoing HBB) in this IMF".
- Although the IMF suggested by Komiya et al. (2007) "gives rise to a substantial CEMP fraction, the CEMP stars are outnumbered by NEMP stars by a factor of two. This is not compatible with the observed limit on the number fraction of NEMP stars."

Suppression of Mass Loss during the AGB Phase

Wood (2011)

1.5M⊙, [Fe/H]=-0.6 | 1.5M⊙, [Fe/H]=-4.2 | 6M⊙, [Fe/H]=-4.2

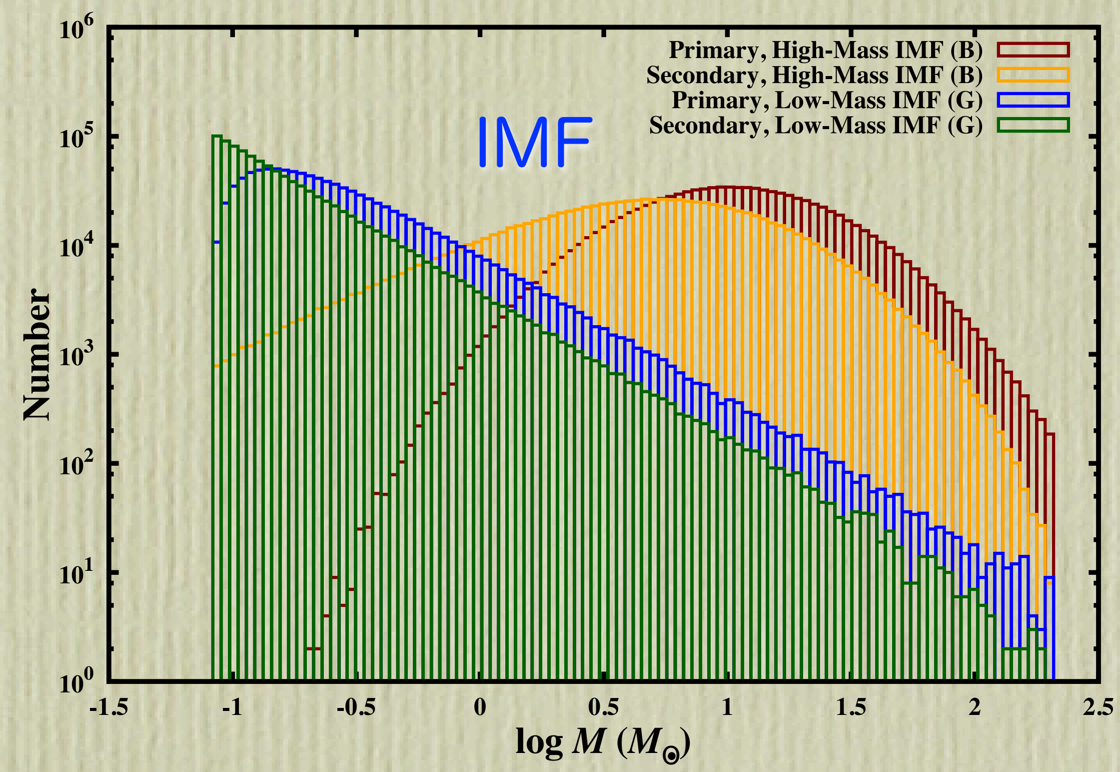


Growth of pulsations during the thermal pulses on the AGB phase

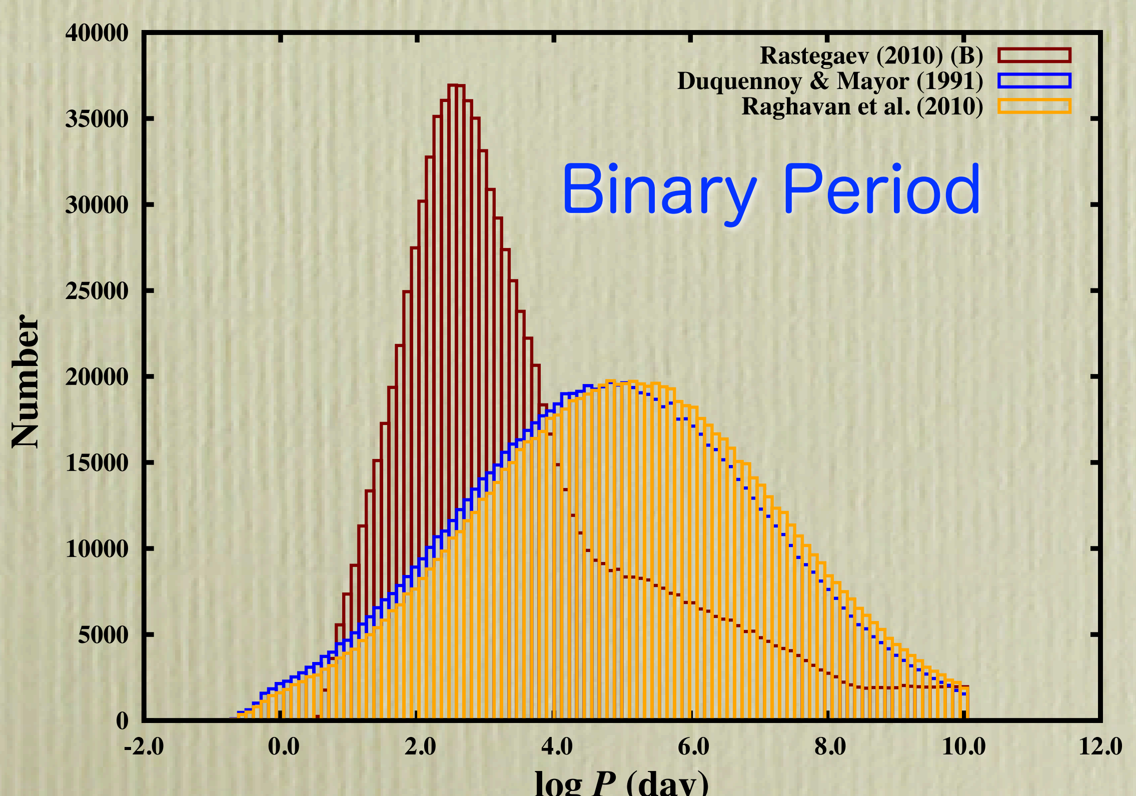
Luminosity is increased from 11,000 L⊙ to 13,000 L⊙.

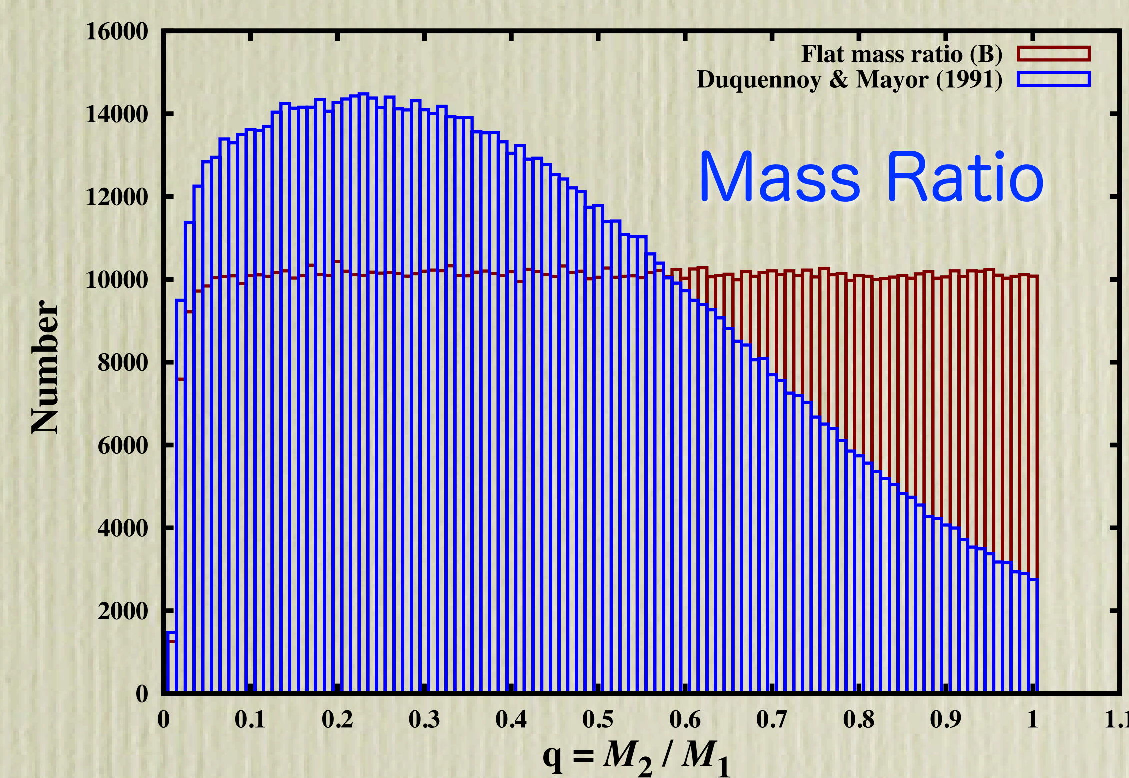
Luminosity is taken for maximum possible value for an AGB star that is not undergoing HBB.

Monte-Carlo Simulations of Binary Population



- ☆ What happens if we include as many ingredients for stellar evolution and binary evolution as possible?
- ☆ Is Salpeter-like IMF acceptable at low-metallicity?





Input Model Parameters

Stellar Evolution

- AGB mass range: 0.8 - 8.0 $M_\odot$,AGB Yield (Suda & Fujimoto 2010; Karakas 2010))
- SNe: $M > 10.0\ M_\odot$
- He-FDDM (CEMP-s): $M < 3.5\ M_\odot$ (Suda & Fujimoto 2010)
- CEMP-nos: $3.5 < M / M_\odot < 5$
  - C-enhancement by only TDU
  - ^{13}C pocket efficiency is assumed to be negligible.
- HBB: $4.5 < M / M_\odot < 8.0$
- Suppression of mass loss for $5 < M / M_\odot < 8$ at [Fe/H] ≦ -2.5. (Wood 2011)
  - growth of pulsation is smaller for lower metallicity.
- Contribution of Super AGB stars ($8 < M / M_\odot < 10$) (Gil-Pons & Doherty 2010)
  - deep 2nd dredge-up and carbon dredge-out (Ritossa et al. 1999). -> CEMP-no

Parameter

Binary Evolution

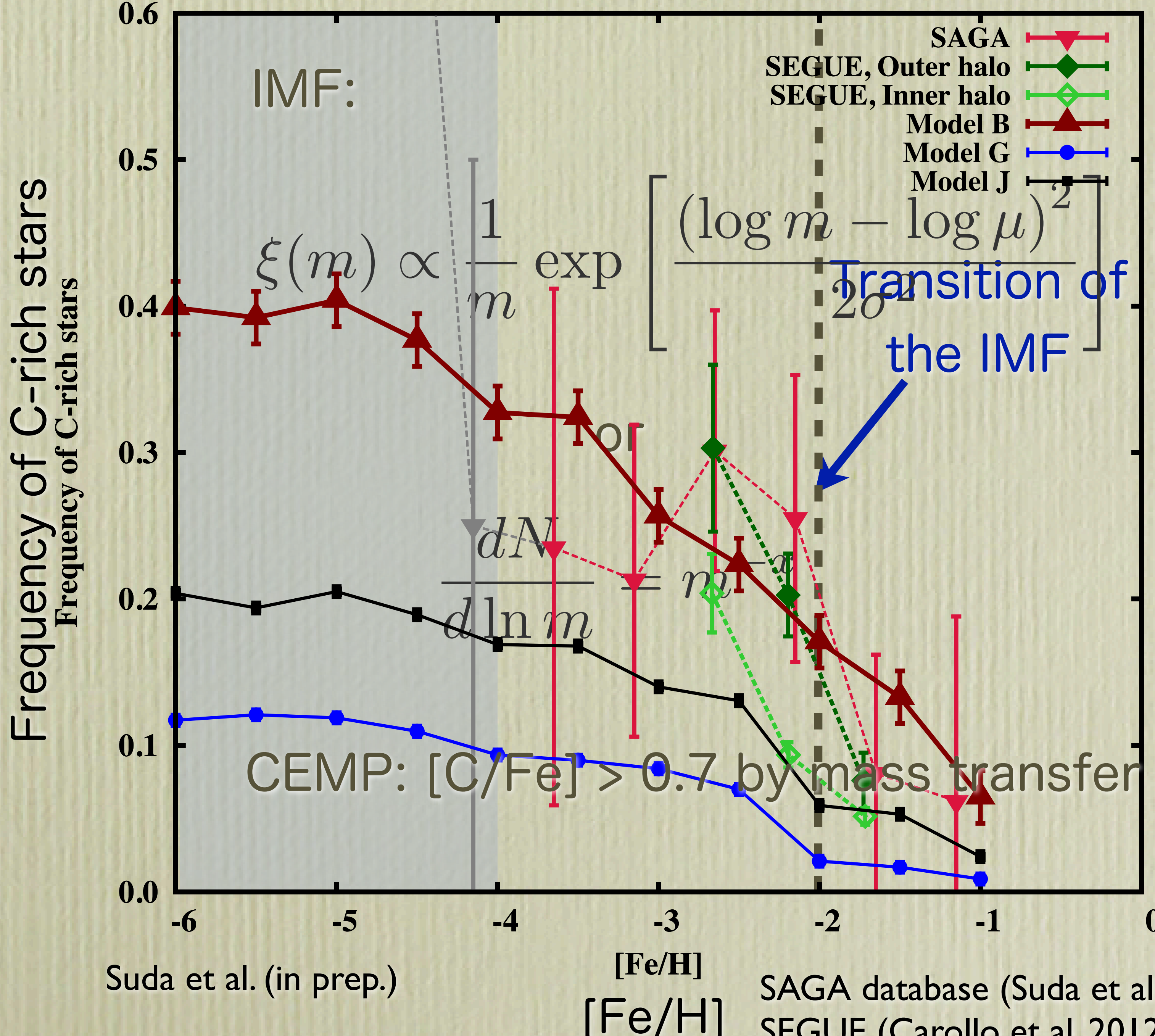
- Roche Lobe overflow (Hurley et al. 2002)
- Wind accretion (Komiya et al. 2007)
- Ejected envelope mass from WD initial-final mass relation (Han et al. 1994)
- Mass of convective envelope: 0.35 $M_\odot$ (giants), 0.0035 $M_\odot$ (dwarfs)
- Flat mass ratio function (Raghavan et al. 2010)
- Binary Frequency: 0.5

See also
Izzard et al. 2009
Pols et al. 2012

Transition to Low-mass IMF

Observations imply high-mass star dominated IMF.

CEMP fraction vs. [Fe/H]



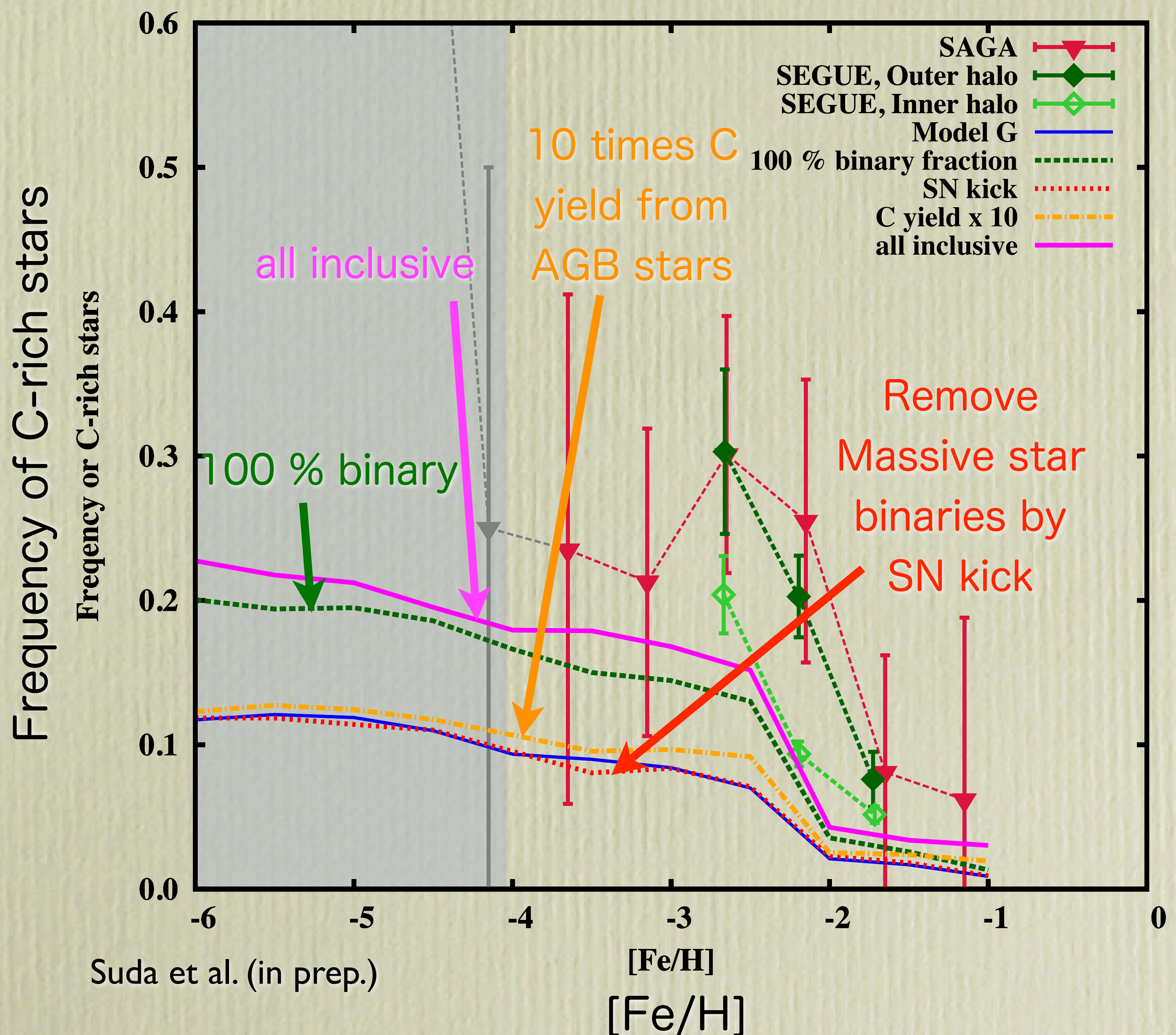
Suda et al. (in prep.)

SAGA database (Suda et al. 2008, 2011)
SEGUE (Carollo et al. 2012)

Model	IMF	CEMP/EMP
A	μ=5, σ=0.6	0.19
B	(10, 0.4)	0.25
C	(20, 0.45)	0.19
D	(30, 0.5)	0.17
E	(50, 0.6)	0.18
F	(0.79, 0.51)	0.031
G	x = 1.35	0.08
H	0.85	0.10
I	0.35	0.12
J	0.0	0.14

Non-Universality of the Low-mass IMF

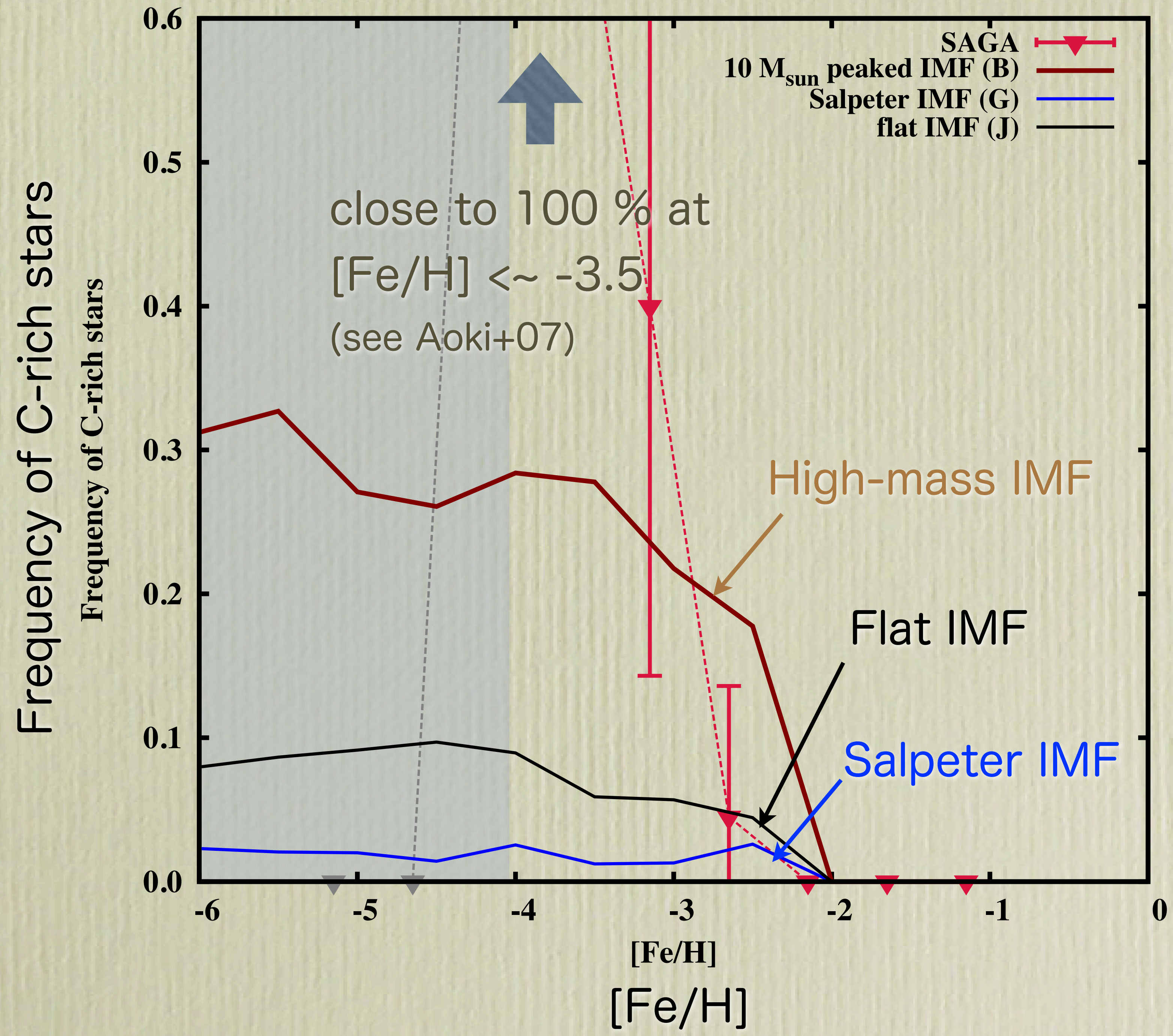
low-mass IMF cannot reach the CEMP fraction with >> 20 %.



Suda et al. (in prep.)

Metallicity Dependence of CEMP-no Fraction

Trend of CEMP-no frequency cannot be reproduced by any models.



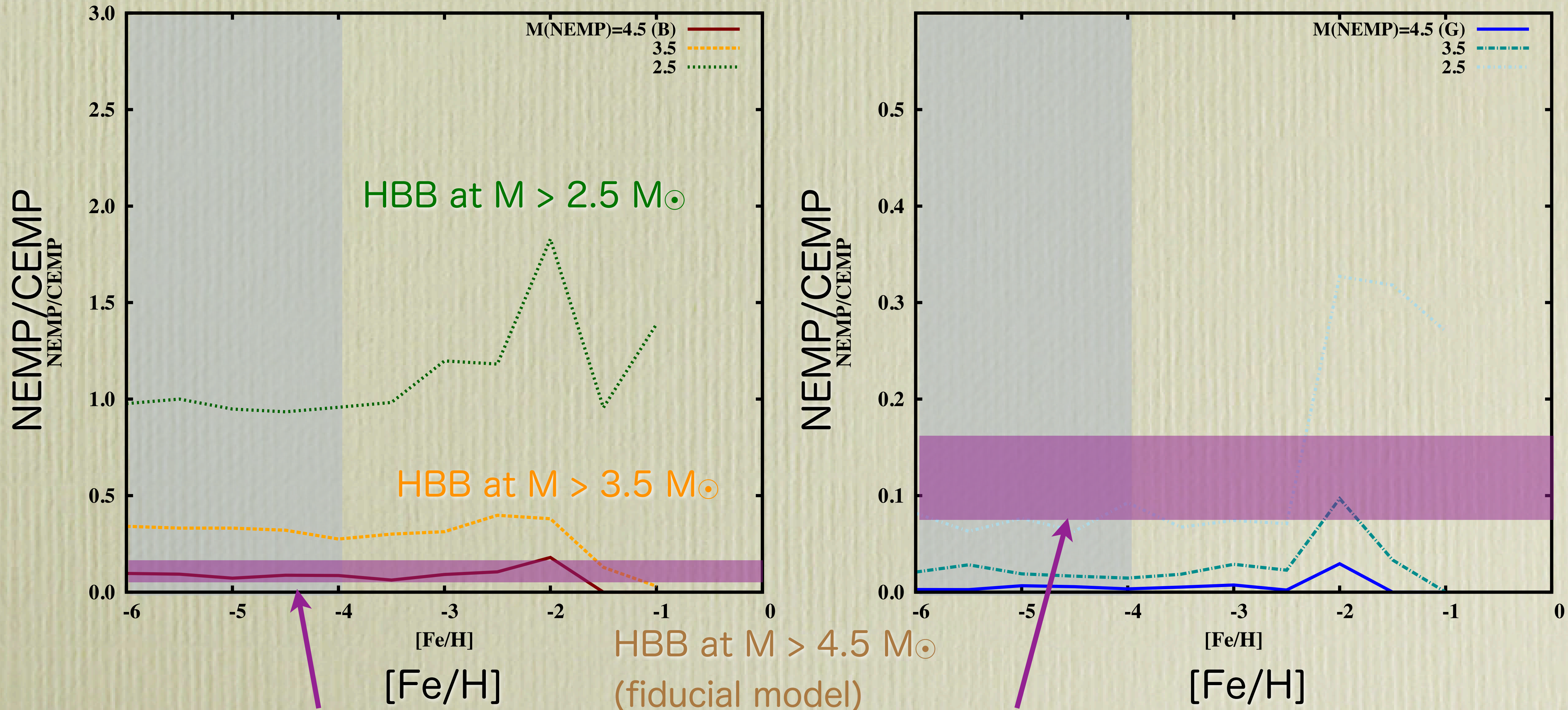
NEMP Star Frequency

Too small NEMP/CEMP is achieved for Salpeter IMF.

Changing boundary mass for hot bottom burning (NEMP progenitors)

High-mass IMF

Salpeter IMF



Observations suggests NEMP/CEMP ~ 0.1 (Suda+11, Pols+12)

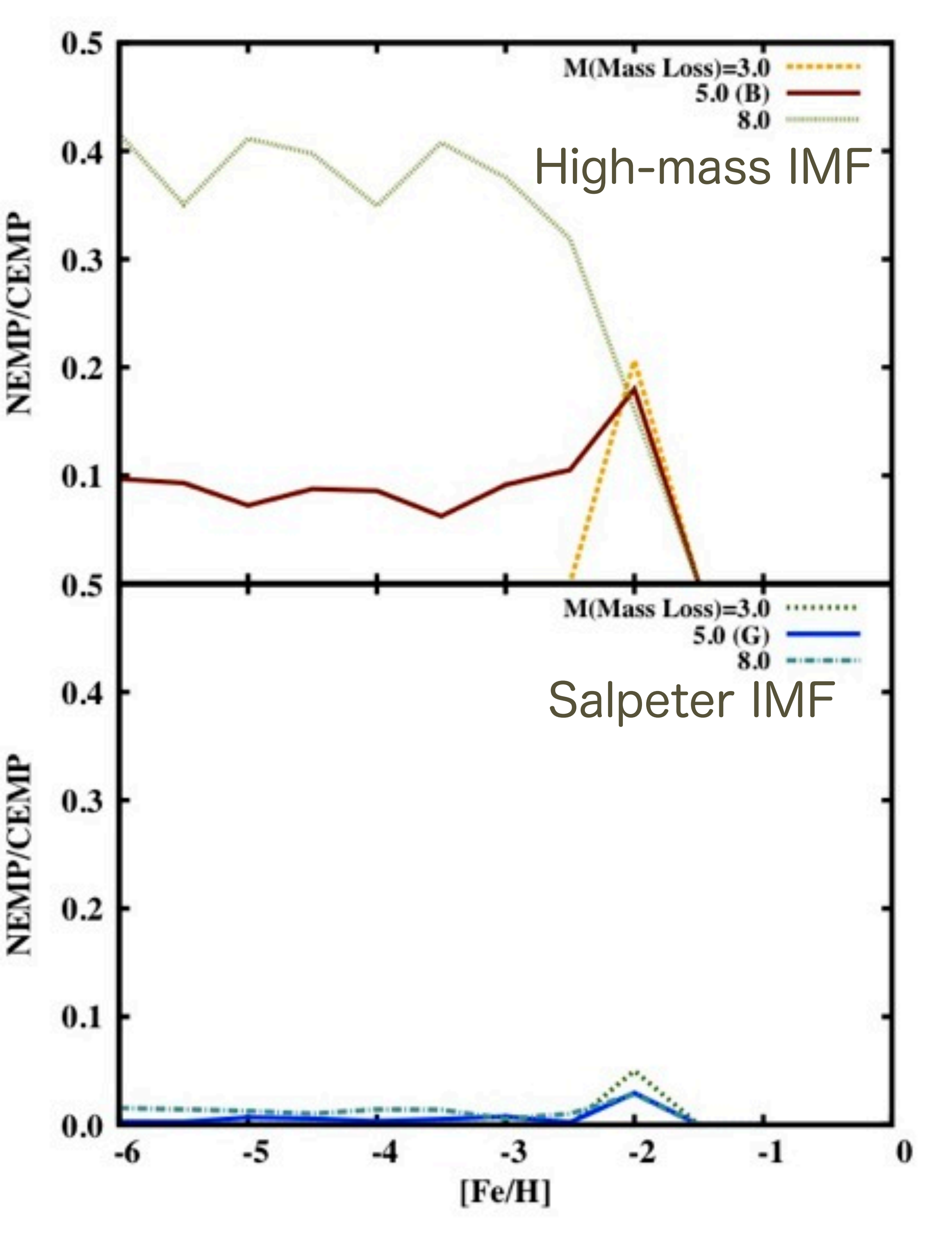
Effect of Type I.5 Supernovae on Galactic Chemical Evolution

- AGB star without mass loss evolves to Type I.5 supernova when the mass of the helium core approaches Chandrasekhar mass limit.
- The iron yields of Type I.5 SNe are much larger (~1 $M_\odot$, Sim et al. 2010) compared with those of Type II SNe (~0.07 $M_\odot$).
- Type I.5 SN is characterized by the yields with low [α/Fe] (Nomoto et al. 1984).
- The number of Type I.5 SN progenitors is comparable to the number of Type II progenitors under the Salpeter IMF. This implies:
  - Rapid metal enrichment in the host halo.
  - Abundance trends dominated by Type I.5 SNe.
- Current observations do not support the trend of [α/Fe] dominated by Type I.5 SNe.

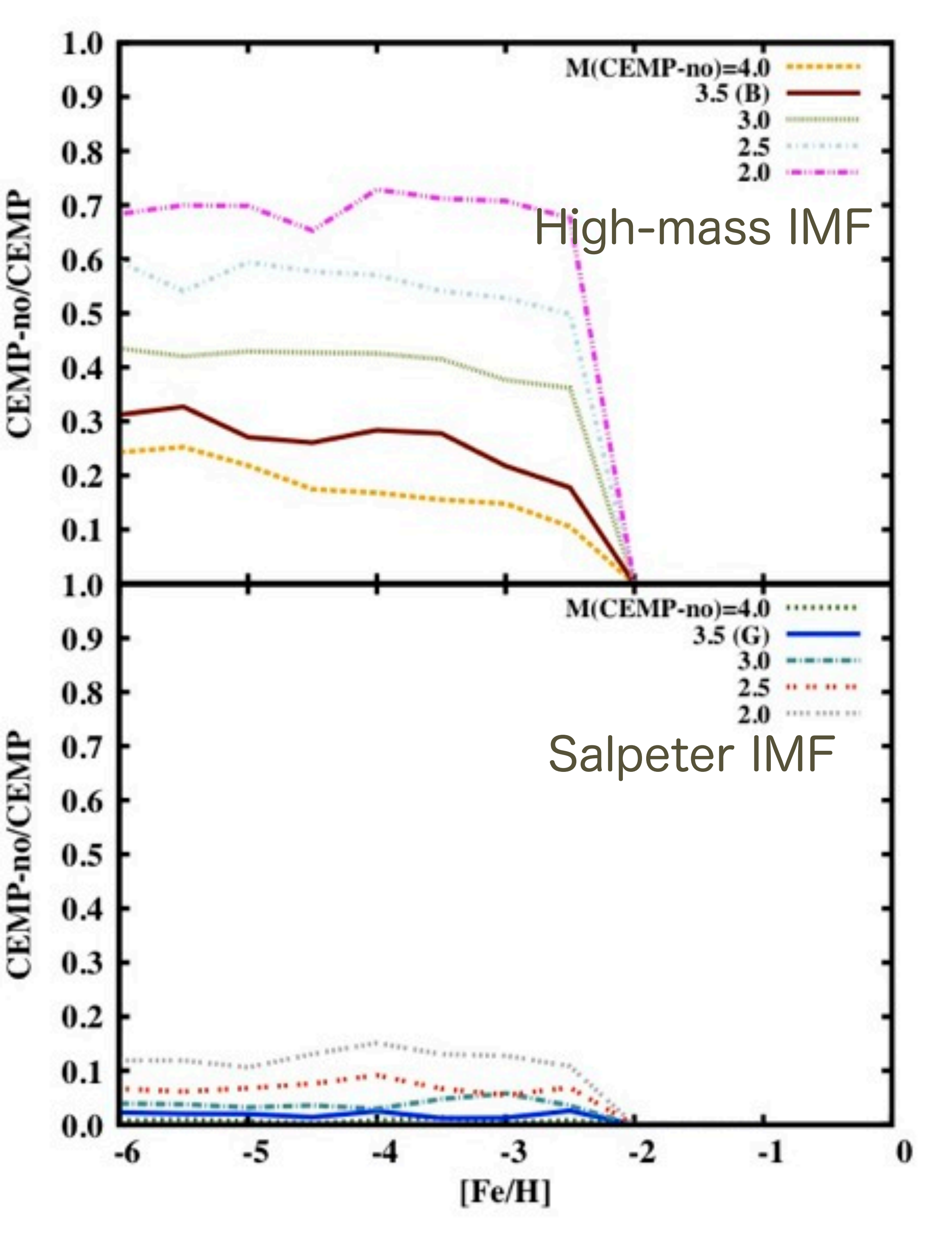
Conclusions

- We try to explain large frequency of carbon-enhanced metal-poor stars observed in Our Galaxy.
  - Formation of carbon-enhanced stars at [Fe/H]<-2.5 and binary scenario
  - Binary evolution models with IMF peaked at $10M_\odot$
- It is important to determine the metallicity dependence of the fraction of carbon-enhanced stars.
  - The transition of the IMF at [Fe/H]~-2 apparently agrees with the metallicity dependence of CEMP star frequency.
- Using Salpeter IMF at low-metallicity cannot reproduce the CEMP frequency, CEMP-no/CEMP-s ratio, NEMP/CEMP ratio, and the potential value of [α/Fe].
- Suppression of mass loss at low-metallicity ([Fe/H] <~ -2.5) well reproduce the observations under the high-mass IMF.
  - CEMP-no progenitors should have initial masses: 3 <~ M / $M_\odot$ <~ 3.5
  - NEMP progenitors should have initial masses: 3.5 <~ M / $M_\odot$ <~ 4.5
  - Mass loss should be suppressed for initial masses: 5 < M / $M_\odot$ <~ 8
- Type I.5 supernovae will dominate the chemical evolution using low-mass IMF.
  - There are no supporting evidence of low [α/Fe] resulting from Type I.5 SNe (Nomoto+84).

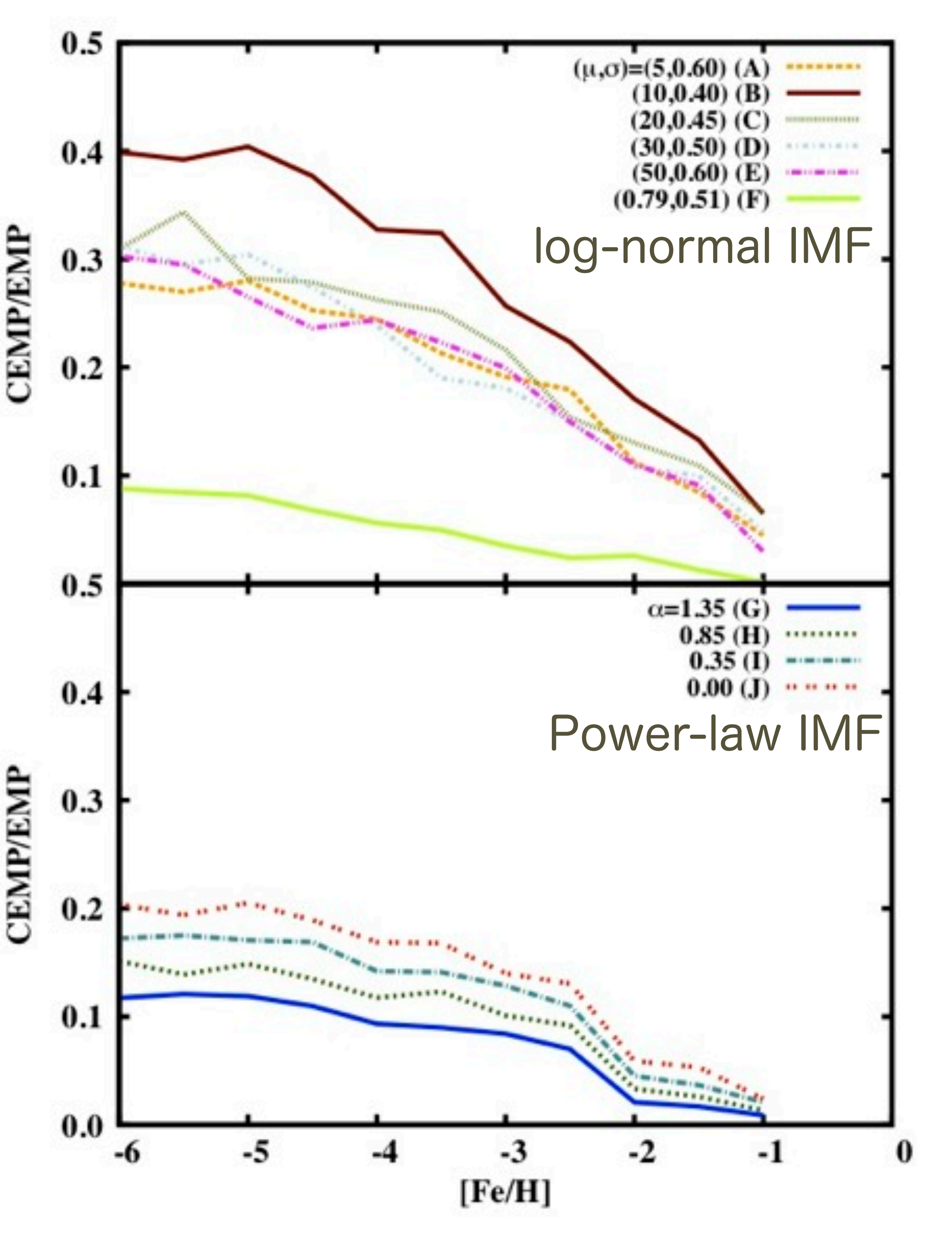
Parameter Dependence - Mass Loss



Parameter Dependence - CEMP-no

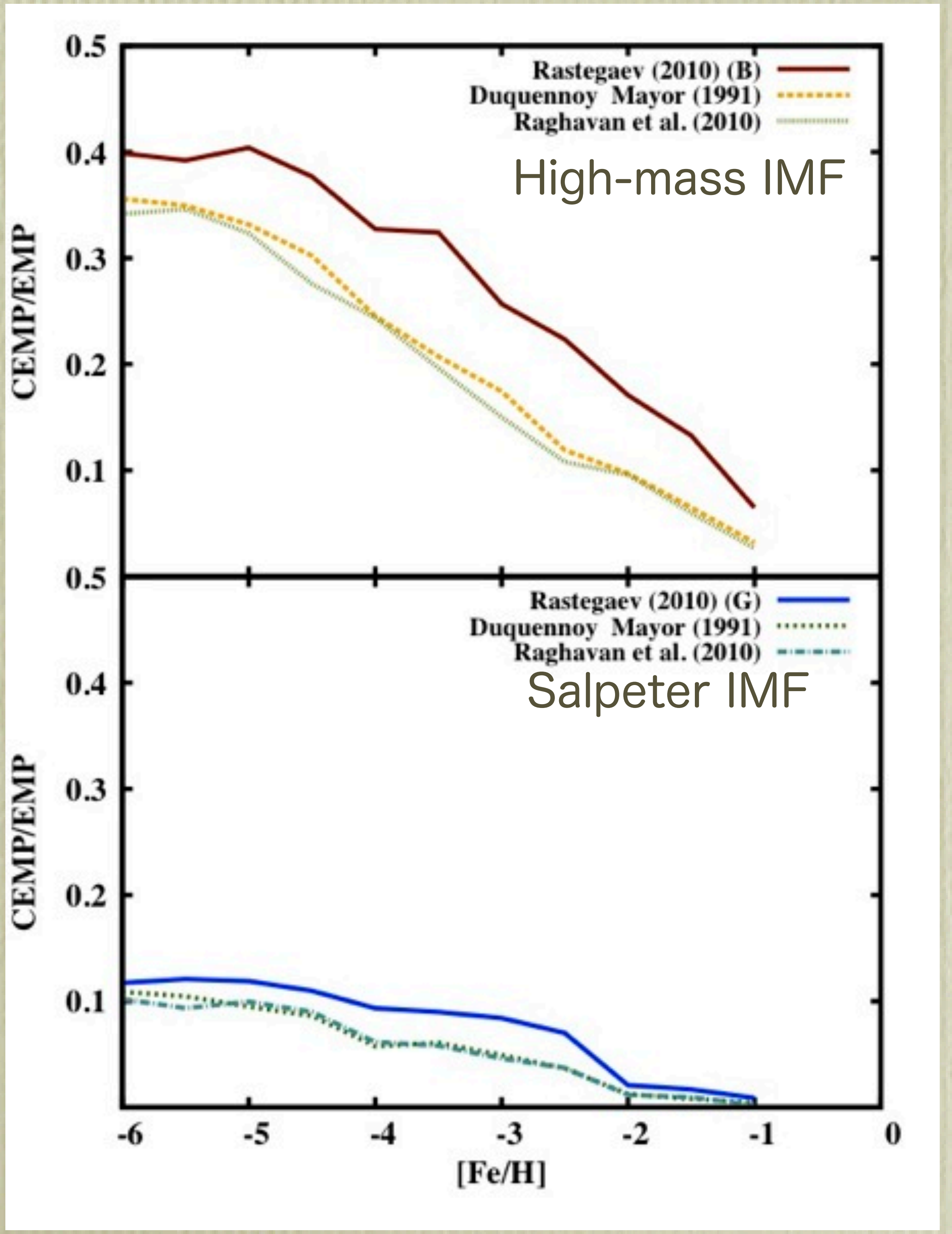


Parameter Dependence - IMF



Parameter Dependence - Binary Parameters

Binary Period



Mass Ratio