Relics from the Dawn of Time: Chemical Abundances of Extreme metal poor (EMP) stars

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Overview

First Stars – *How massive?*

First Supernovae – *Chemical yields*

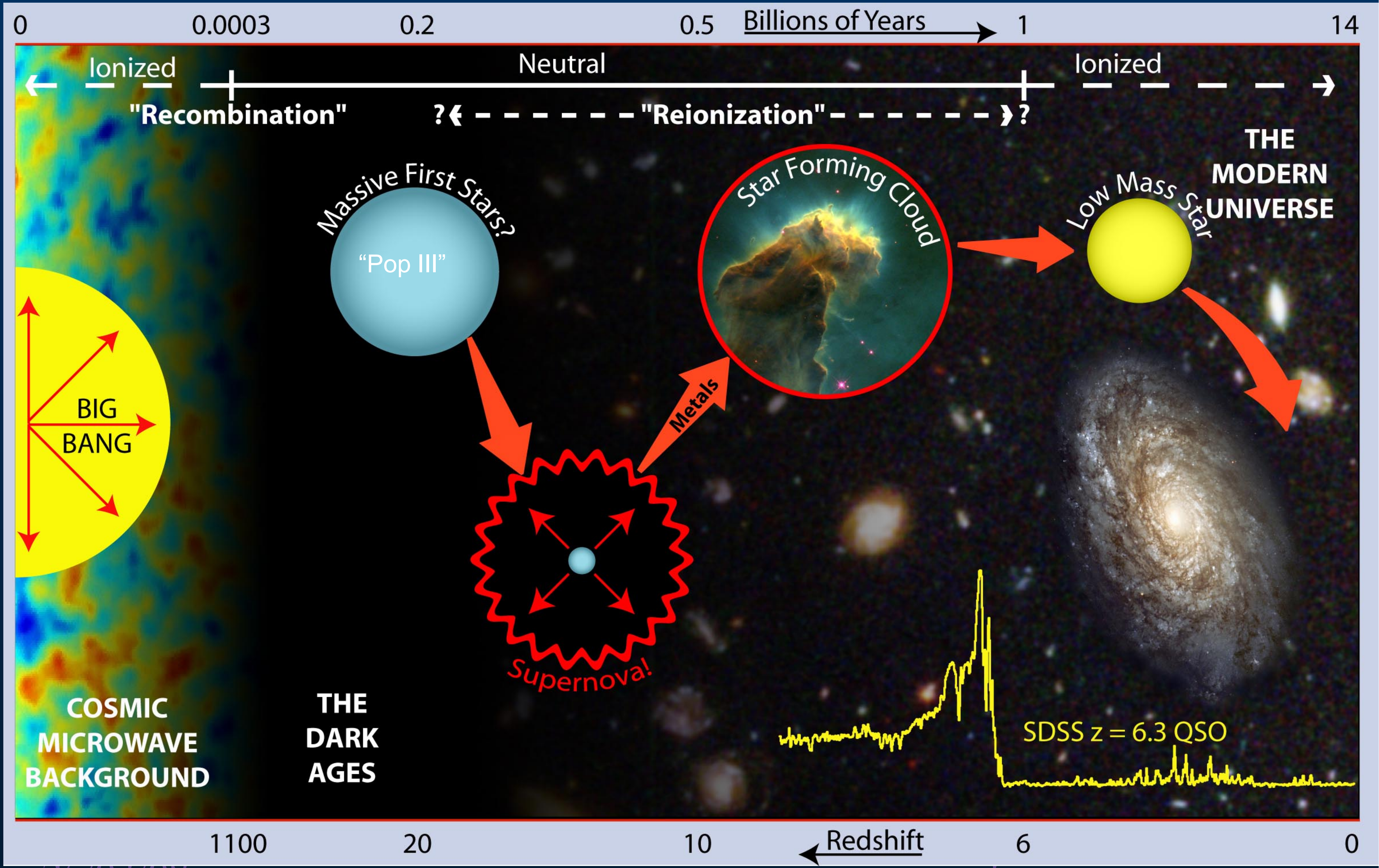
EMP stars of the Galaxy – *Abundances and the early IMF*

The first low mass stars - *Hyper metal poor (HMP) stars ([Fe/H] ~ -5.2) -high C and N low Li*

Carbon enhanced metal poor stars (CEMP) – Binaries → probing the unseen massive IMF → *CMB based IMF?*

Future surveys – are we looking at the right place?

Epoch of the First Stars



Courtesy Jason Tumlinson

Definitions:

First Stars (Pop III): Formed from the cloud with Primordial composition of BBN

Second generation stars: Polluted only by
the First Supernovae (PopIII SN) – EMP stars?

[Fe/H] = log(N(Fe)/N(H))star –log(N(Fe)/N(H))sun

Metallicity – Abundance of stellar made nuclei

[Fe/H] = 0.0 solar metallicity

[Fe/H] = -1.5 Halo or (PopII)

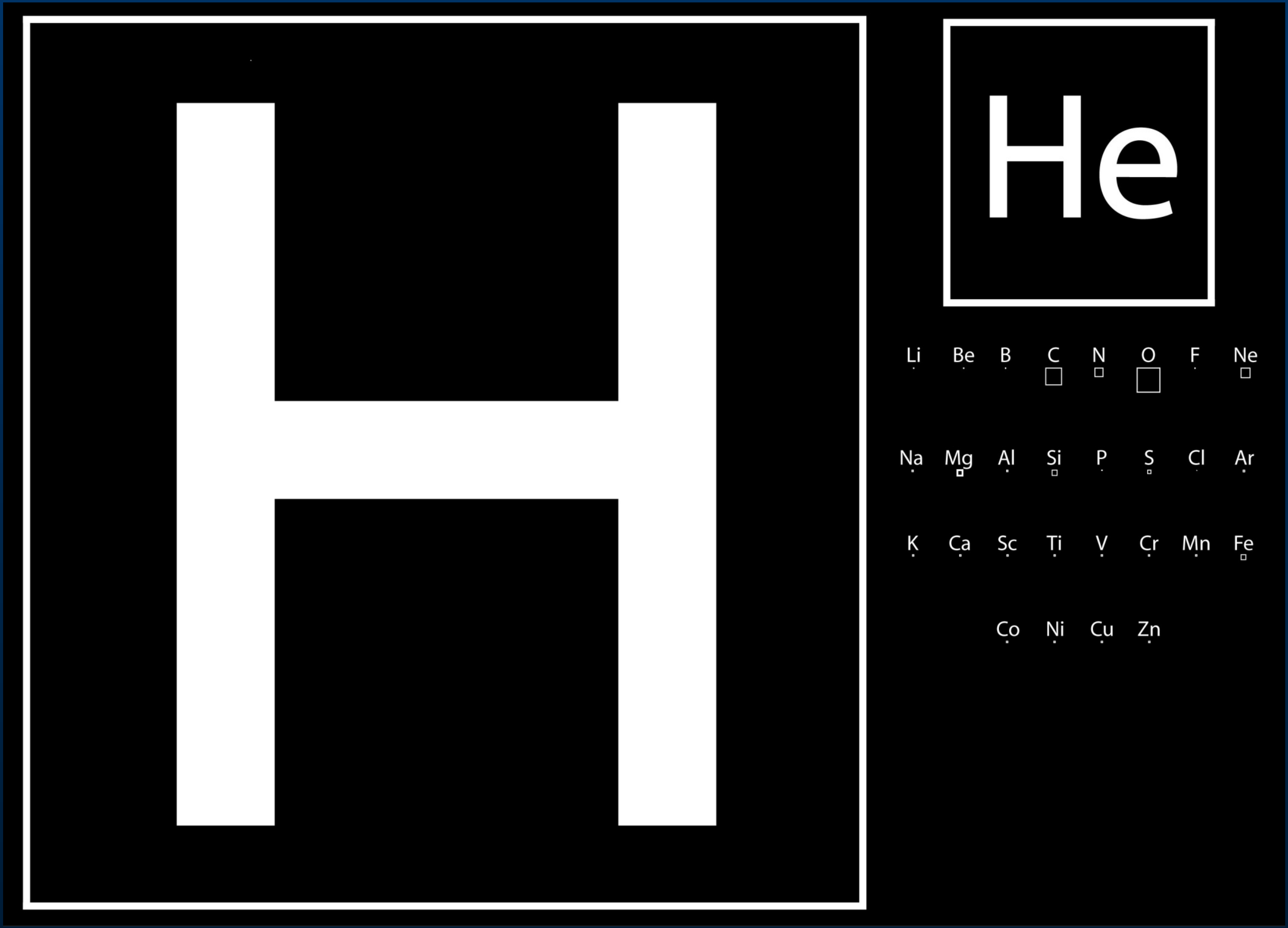
[Fe/H] = -2.5 metal poor Globular clusters

[Fe/H] < -2.5 extreme metal poor (EMP) stars [Fe/H] < -5.0 hyper metal poor (HMP) stars

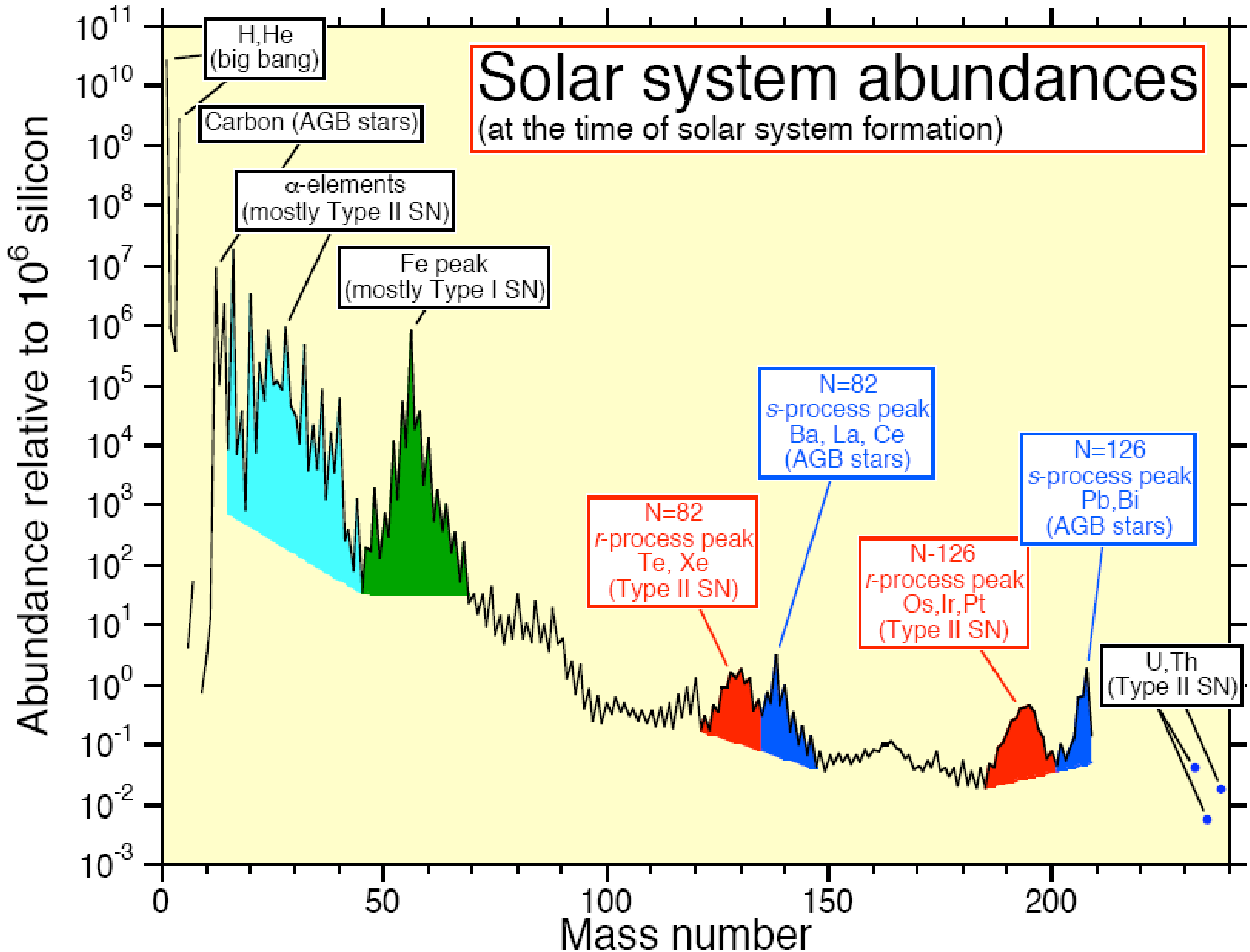
First Stars

Reionization
Metal Enrichment
High redshift SN & GRBs?

CMB, NIR bkg. (Spitzer), Ly_alpha clouds
EMP stars.


H
He
Li Be B C N O F Ne
Na Mg Al Si P S Cl Ar
K Ca Sc Ti V Cr Mn Fe
Co Ni Cu Zn

Cosmic Abundances



Primary Nucleosynthesis Sites and Timescales

- **Massive stars ($M > 10\ M_\odot$) and SNe II: synthesis of most of the nuclear species from oxygen through zinc, and of the r-process heavy elements ($\tau < 10^8$ years)**

- **Red Giant Stars ($1 < M < 10\ M_\odot$): synthesis of both ^{12}C and heavy s-process elements ($\tau > 10^9$ years)**

- **SNe Ia: synthesis of the 1/2-2/3 of the iron peak nuclei not produced by SNe II ($\tau > 1.5\text{-}2\ x10^9$ years)**

Time scales

EMP stars →

Red Shift	Age of the Universe
∞	0 Gyr
10 (First Stars -	0.5
6 - SNe II)	1.0
5	1.2
4 (AGB Stars)↓	1.6
3	2.3
2 (SNe Ia)↓	3.5
1	6.2
0.5	9.1
~0.4 Birth of Sun	9.9
0	14.5

First Stars – How massive?

Observations: No true zero metallicity low mass stars observed today ==> Very Massive First stars?

low mass stars have fewer UV flux to re-ionize the universe

Theoretically: Inefficient cooling of the primodial gas ==> massive stars

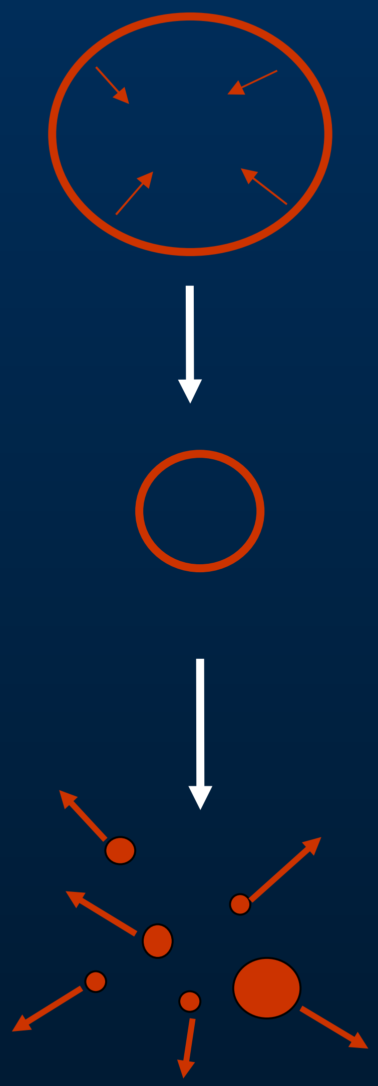
H_2 can cool primordial gas to $T \sim 200$ K.

$M_J \sim 100 - 1000\ M_{\odot}$ ***(Bromm, Coppi, & Larson 1999; 2002, Abel, Bryan, & Norman 2002)***

"Warmer Primordial gas forms heavier stars"

Physics of Pair-instability Supernovae

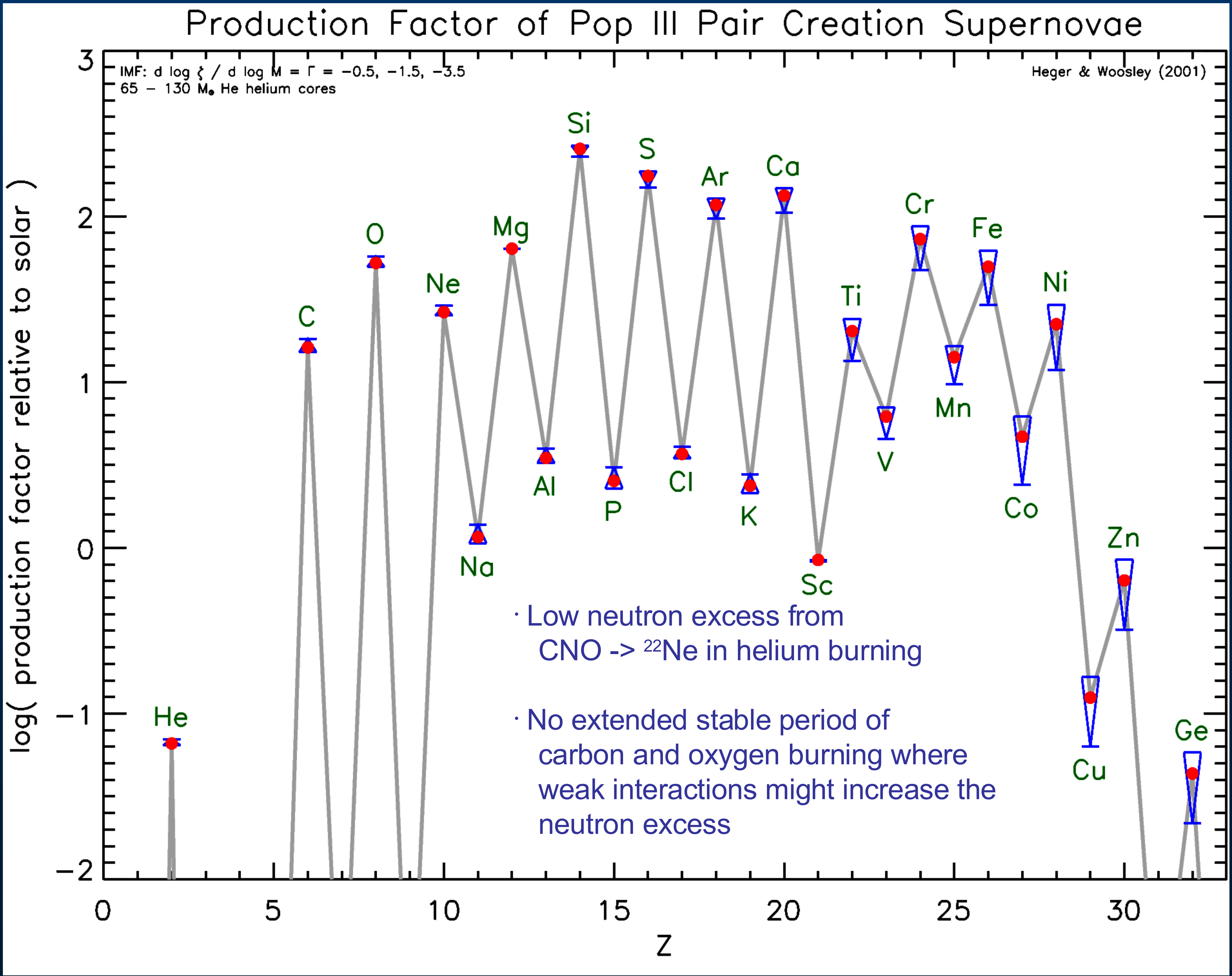
$M \sim 140 - 260\ M_o$



- $T > 10^9 K$
- ph+ph → $e^- e^+$
- grav. runaway collapse

- large jump in core T
- explosive nuclear burning
- implosion ⟶ explosion

- no compact remnant
- all heavy elements dispersed
- distinct nucleosynthetic pattern


Production Factor of Pop III Pair Creation Supernovae
IMF: d log ξ / d log M = Γ = −0.5, −1.5, −3.5
65 − 130 M☉ He helium cores
Heger & Woosley (2001)
log(production factor relative to solar)
Z
3
2
1
0
−1
−2
0
5
10
15
20
25
30
He
C
O
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ge
· Low neutron excess from CNO -> 22Ne in helium burning
· No extended stable period of carbon and oxygen burning where weak interactions might increase the neutron excess

PISN yields

High yields of Fe-peak elements.

Odd-even effect in the abundance pattern

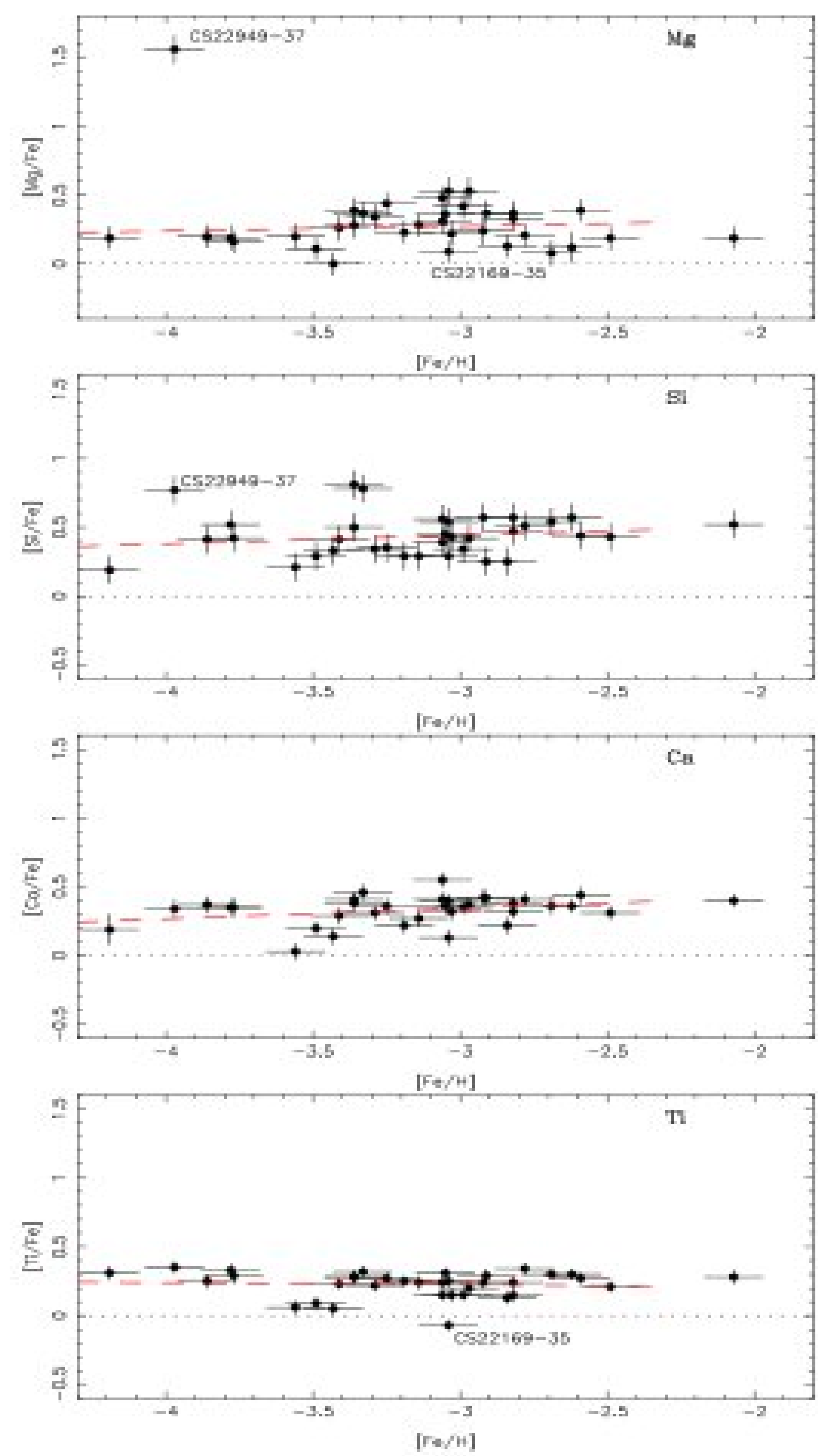
Low [N/O] .

No elements beyond Ni is produced → low Zn

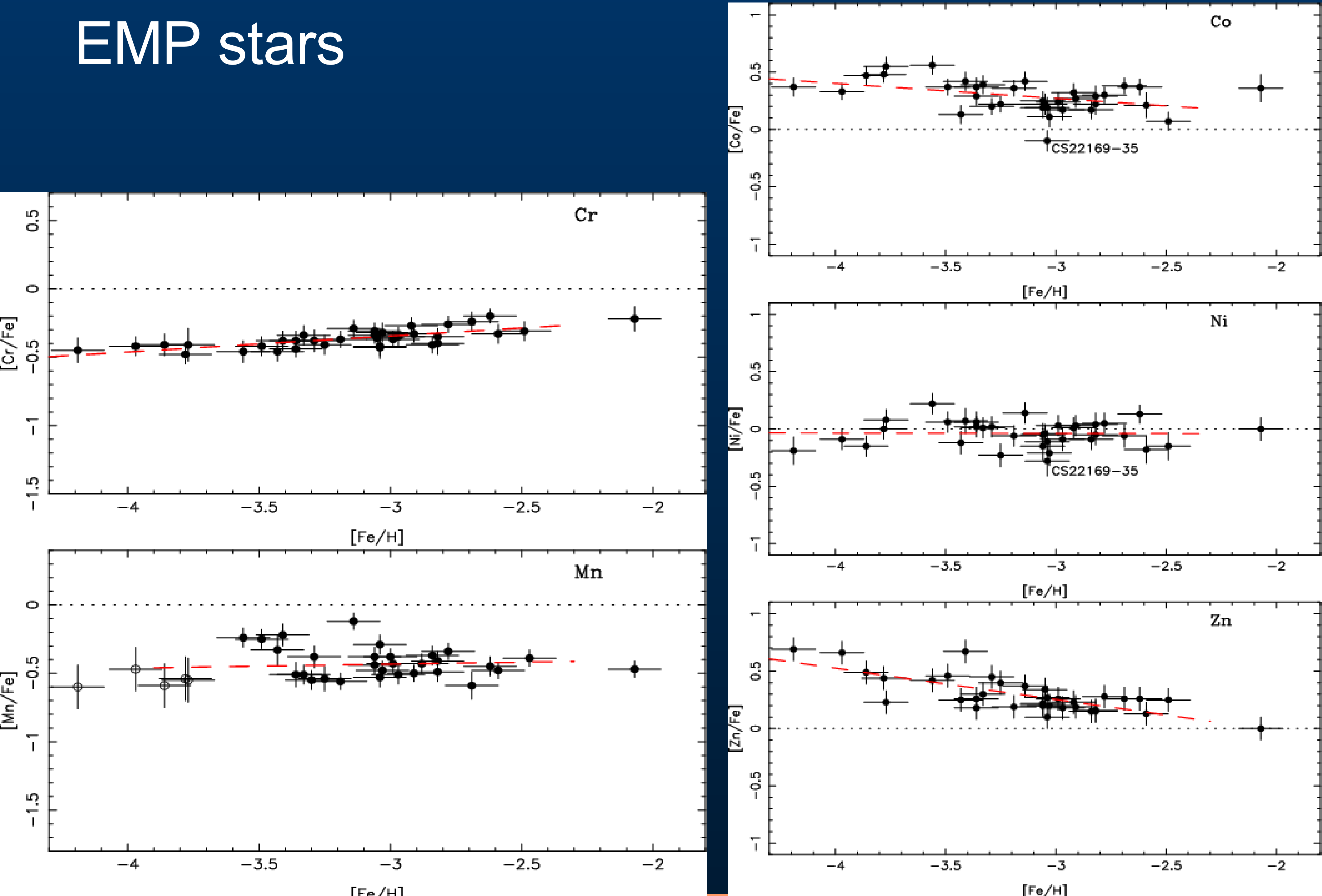
No r-process

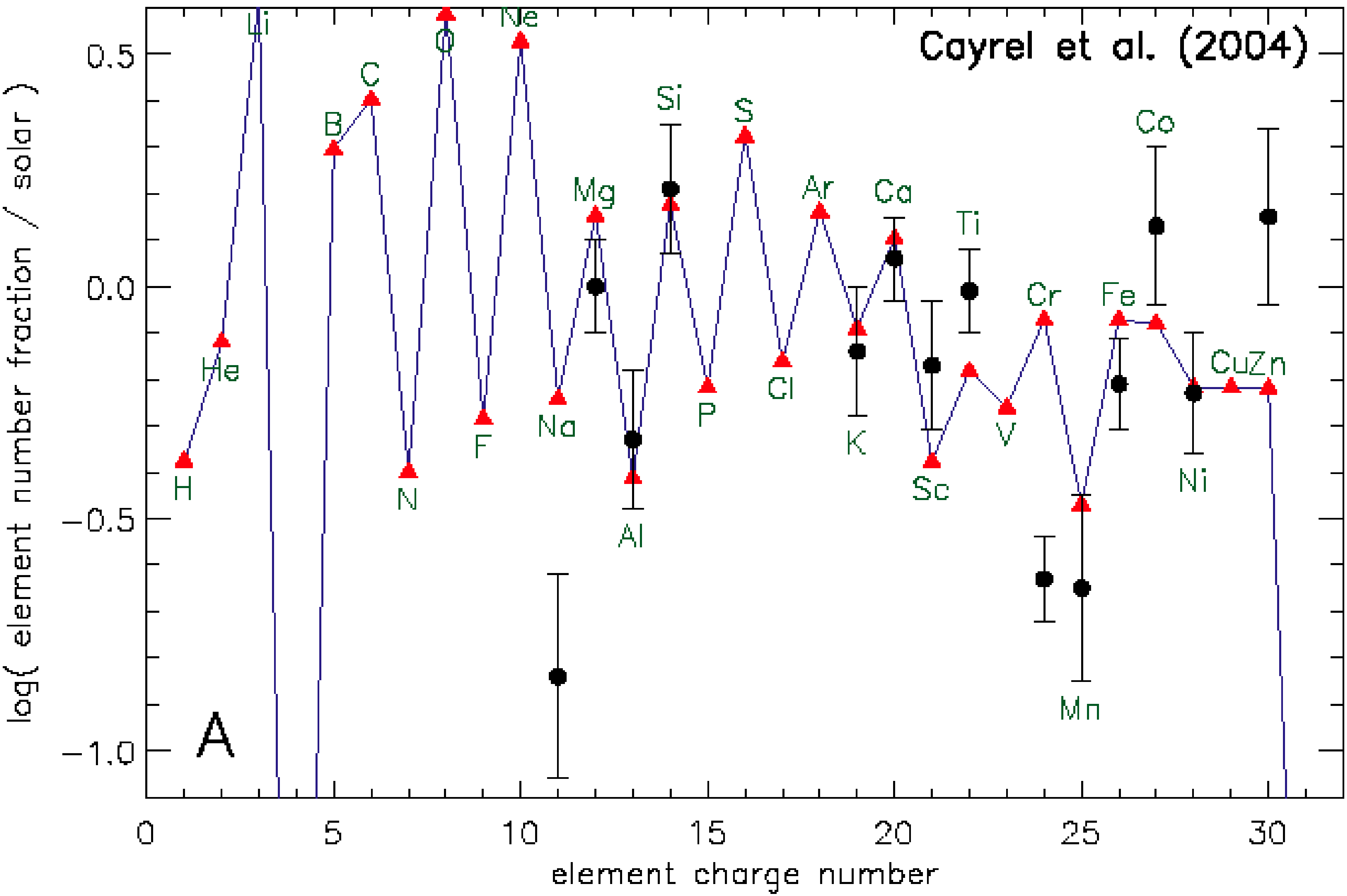
Abundances of EMP stars

ESO-VLT program Cayrel et al.



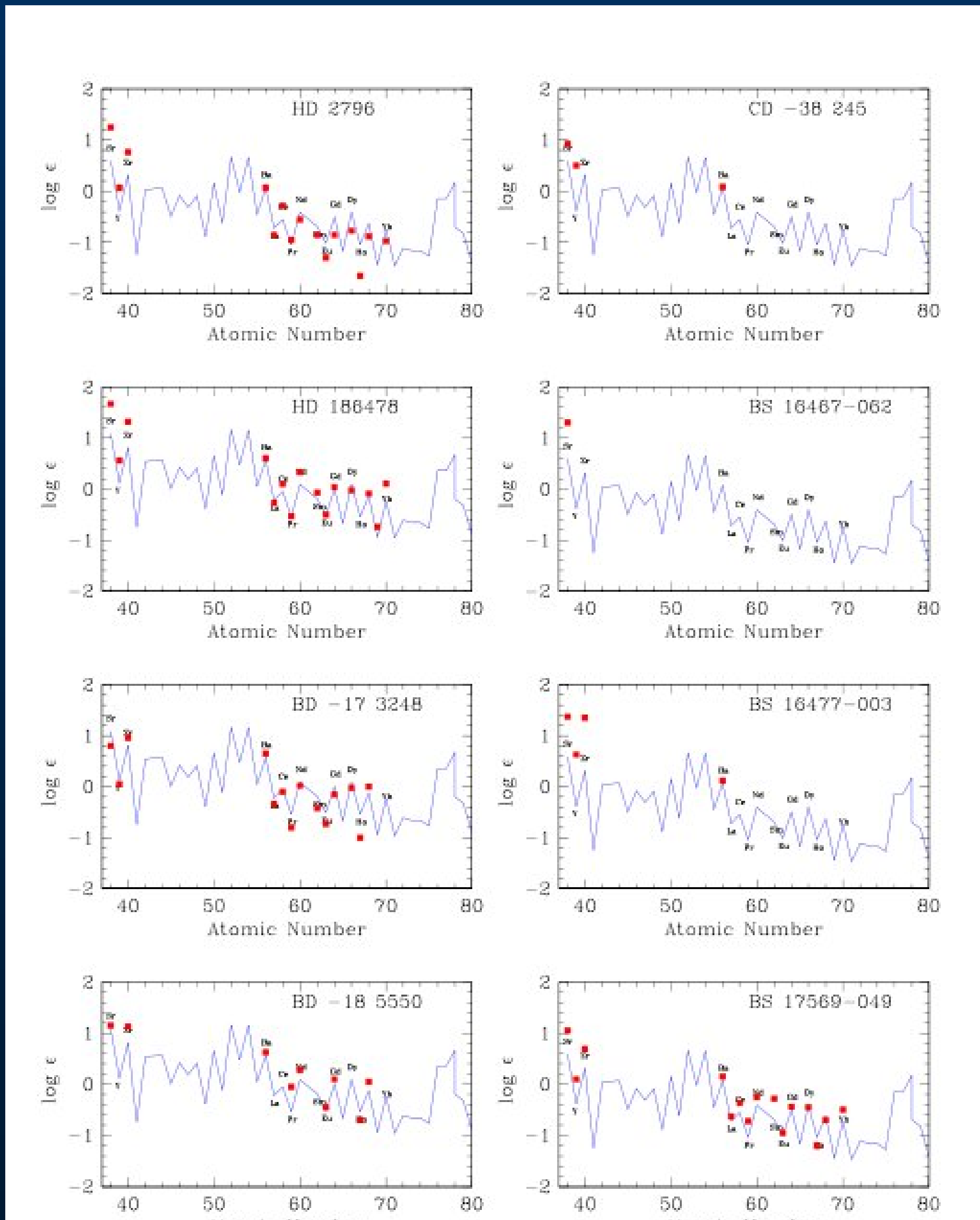
EMP stars

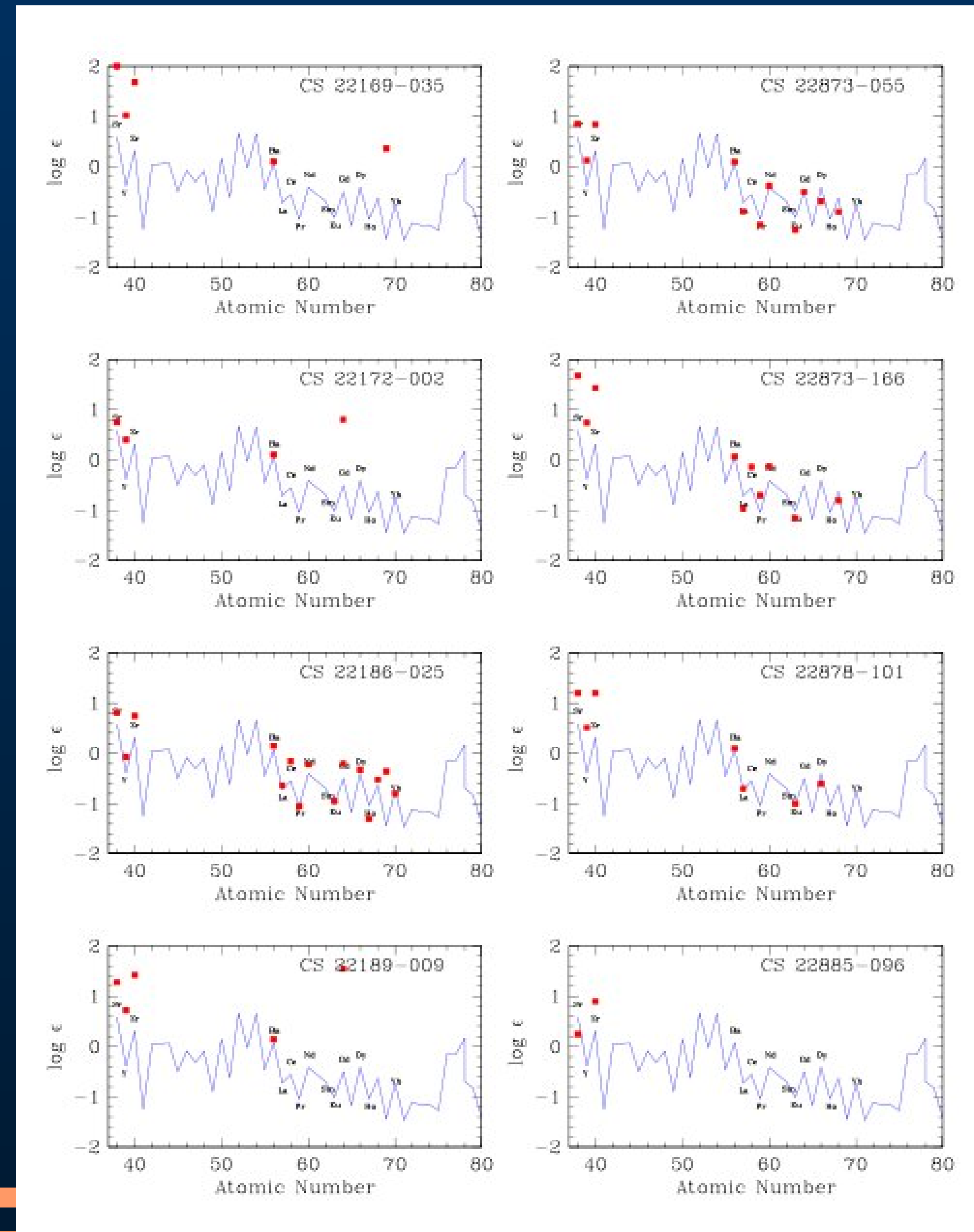

Cr
[Cr/Fe]
[Fe/H]
Mn
[Mn/Fe]
[Fe/H]
Co
[Co/Fe]
CS22169-35
[Fe/H]
Ni
[Ni/Fe]
CS22169-35
[Fe/H]
Zn
[Zn/Fe]
[Fe/H]



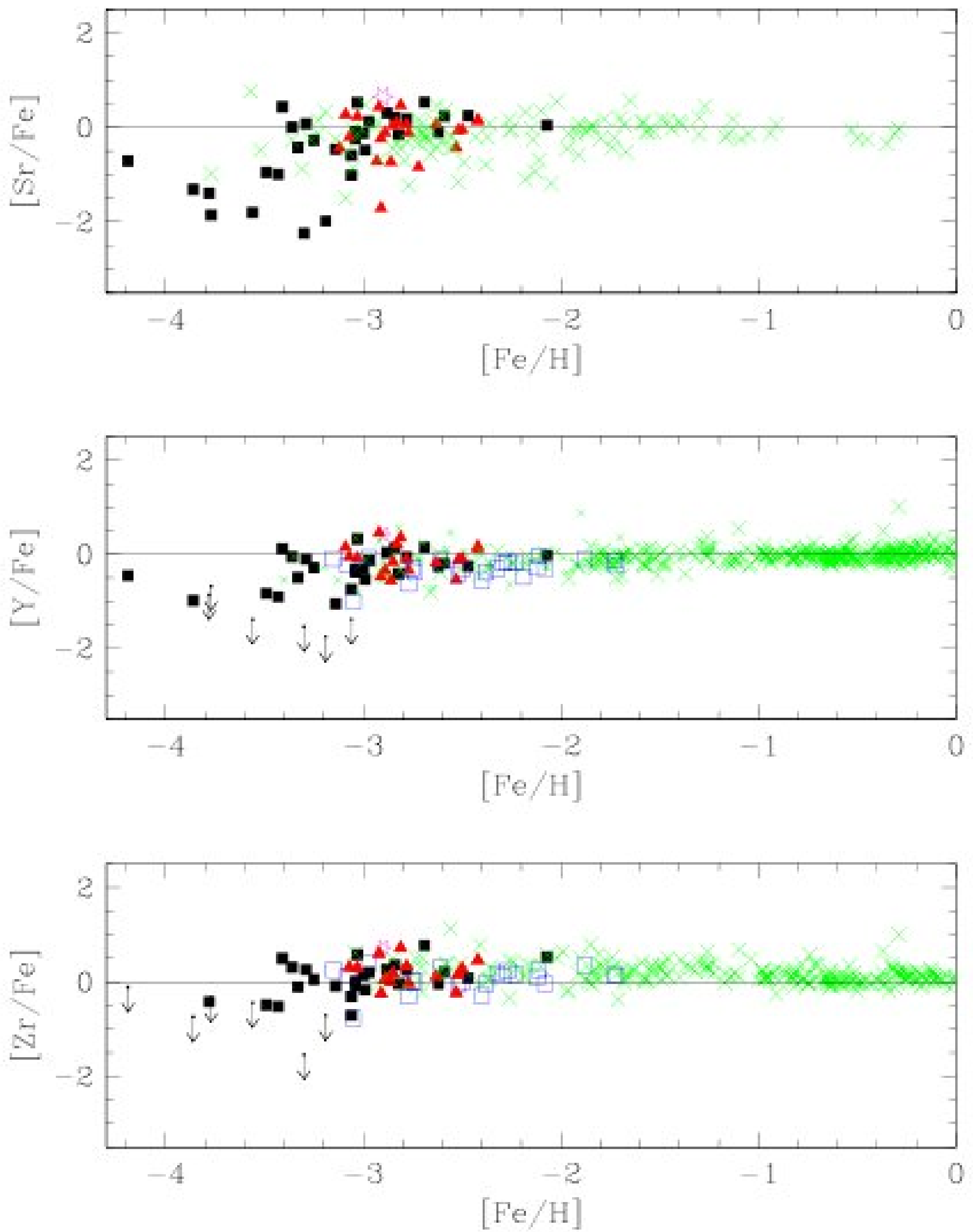
"Standard model" 10 - 100 solar masses

N-capture in EMPs

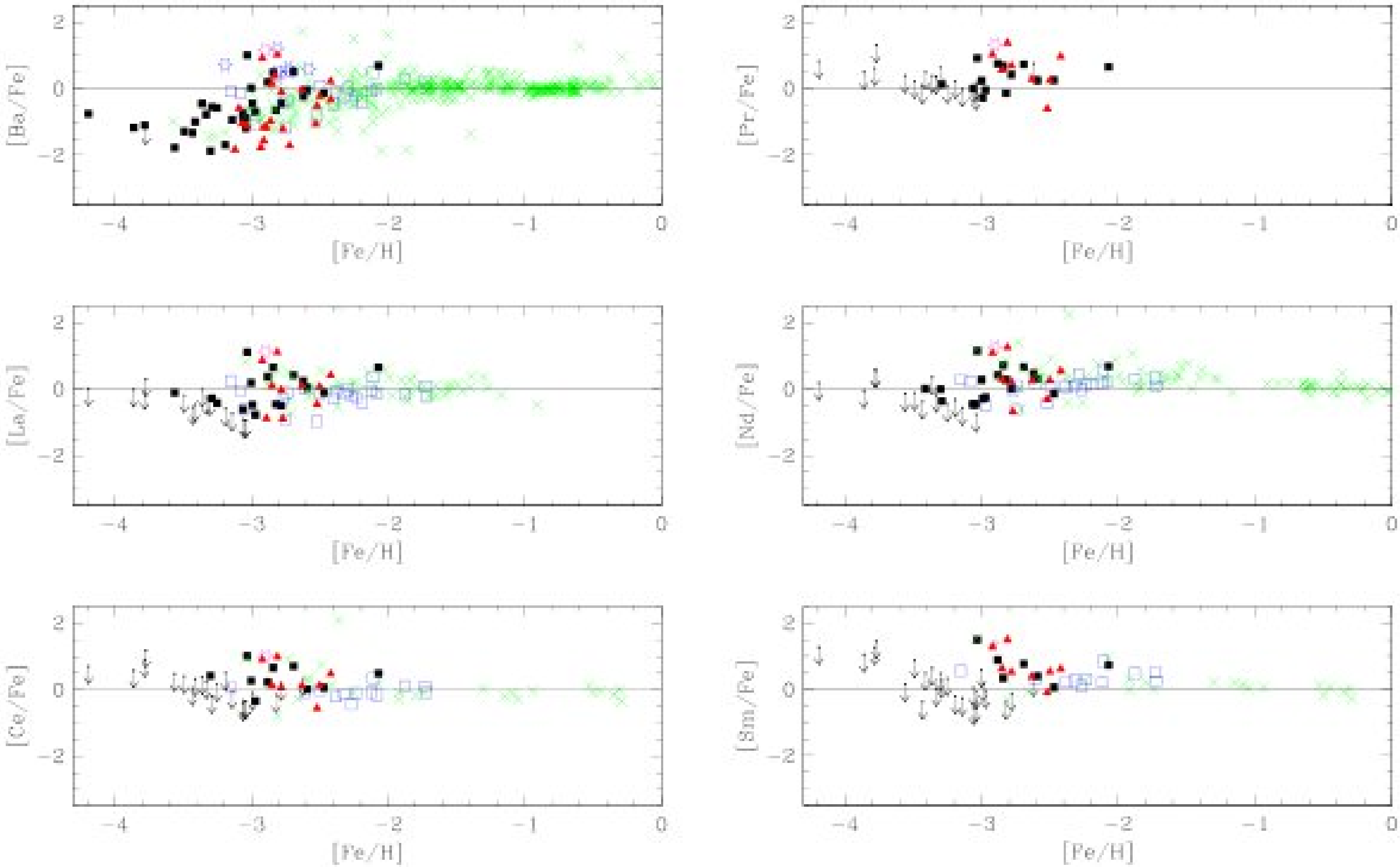




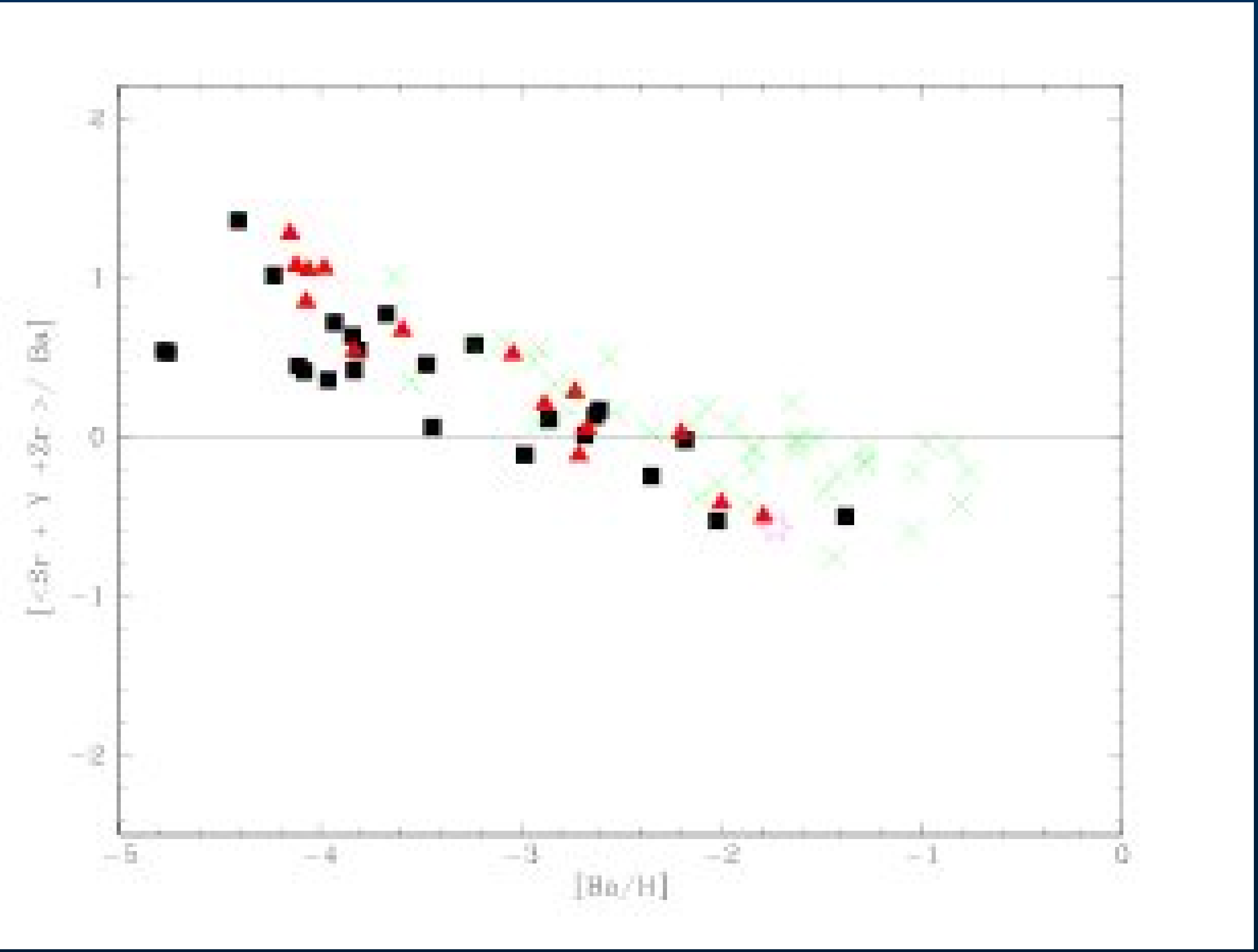
Lighter N-capture in EMPs



Heavy n-capture in EMPs



N-capture elements in EMP stars



Results

Small scatter => All First SNs produce same ratios and mixes same amount of primordial gas to produce same [Fe/H]

No significant odd even effect – No PISN

High [Zn/Fe], high [N/O], some amount of r-process present. – No PISN

Results

R-process abundance- scatter is very high compared to Fe-peak ➔ only certain mass range of SN produce r-process

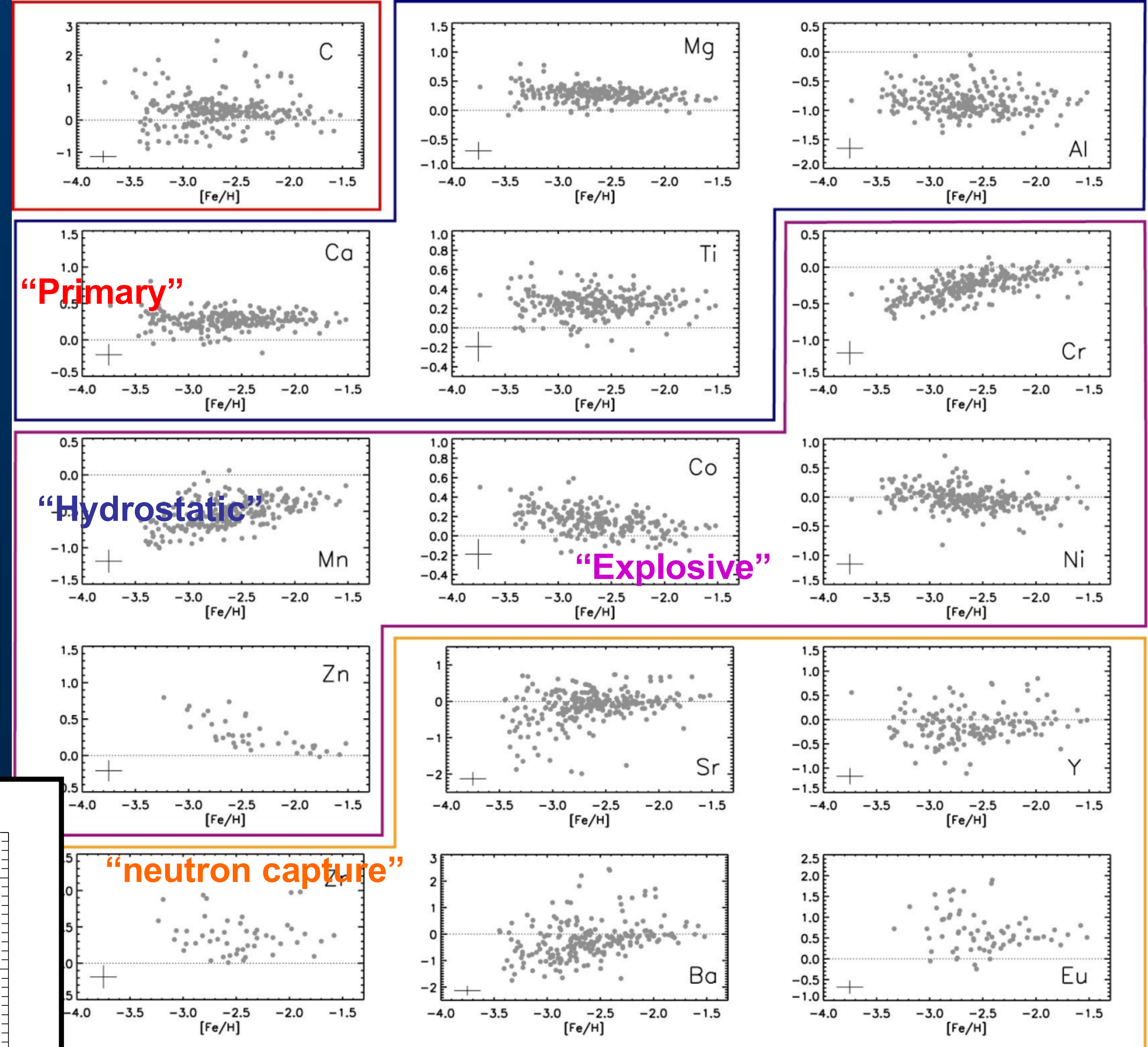
No significant r-process contribution below [Fe/H] < -3.0

[Sr/Ba] increases at low metallicities.

SNs with ~ 10Msun are responsible for the main r-process production. R-rich stars ([r_process/Fe] > 1.0]) found only betn. -3.0 - -2.0

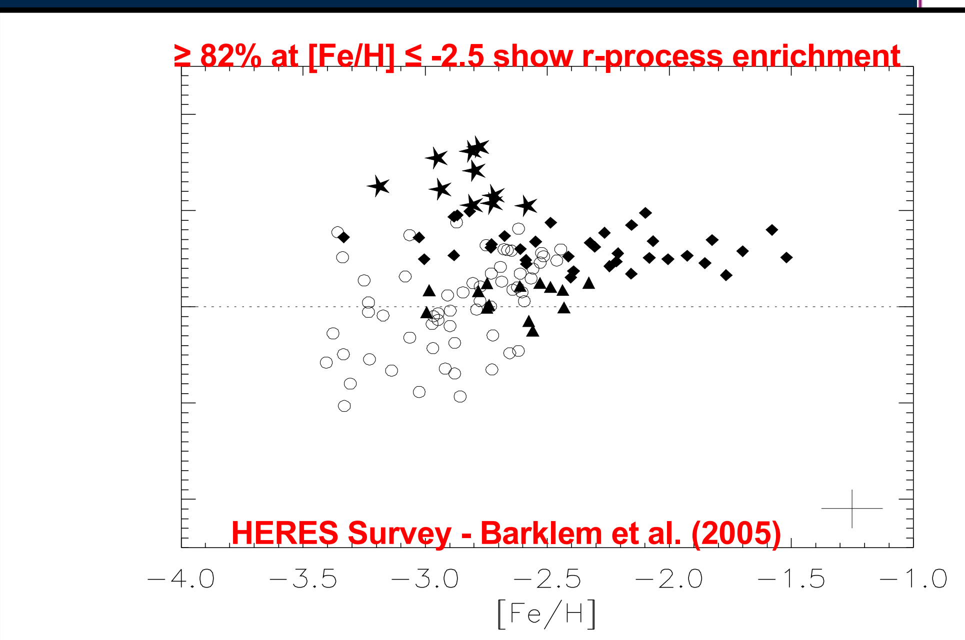
There is an alternative r-process path at low metallicities producing high [Sr/Ba]. High Sr in HMP star.

HERES Survey - Barklem et al. (2005) – 15 elements in 253 stars



[X/Fe]

[Fe/H]

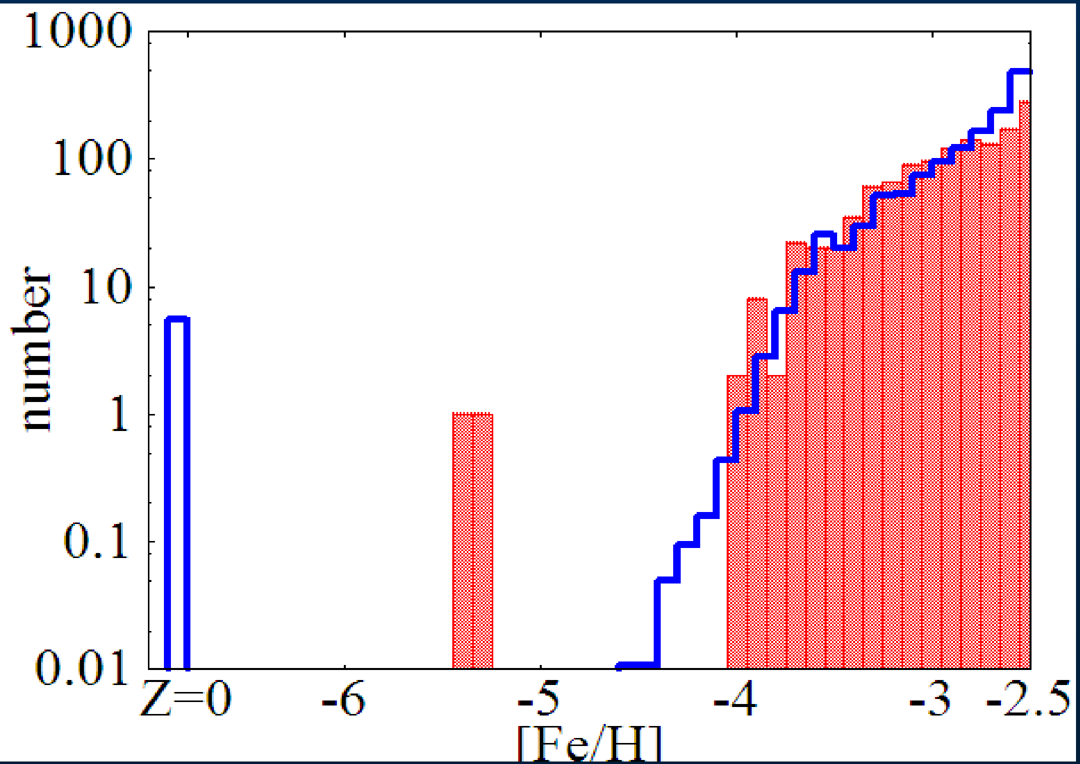


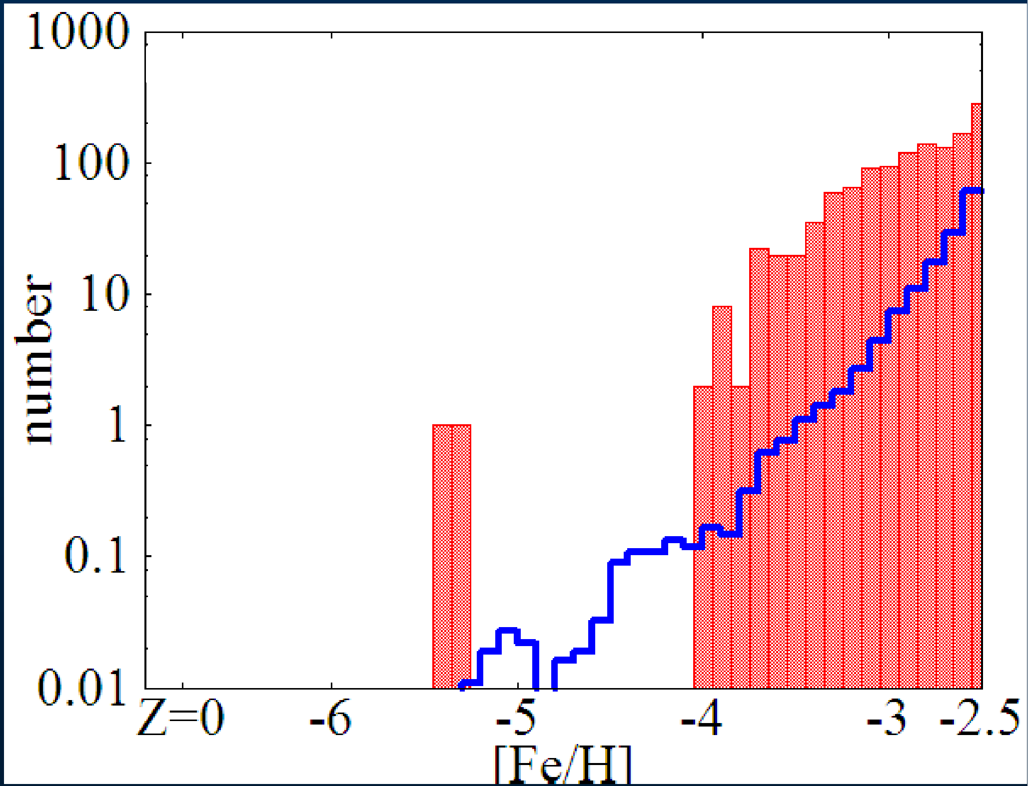
First star – not PISN

M_{md} =100 $M_\odot$ for Z=0.

Pair-Instability supernovae

(Fe yield: 10$M_\odot$)

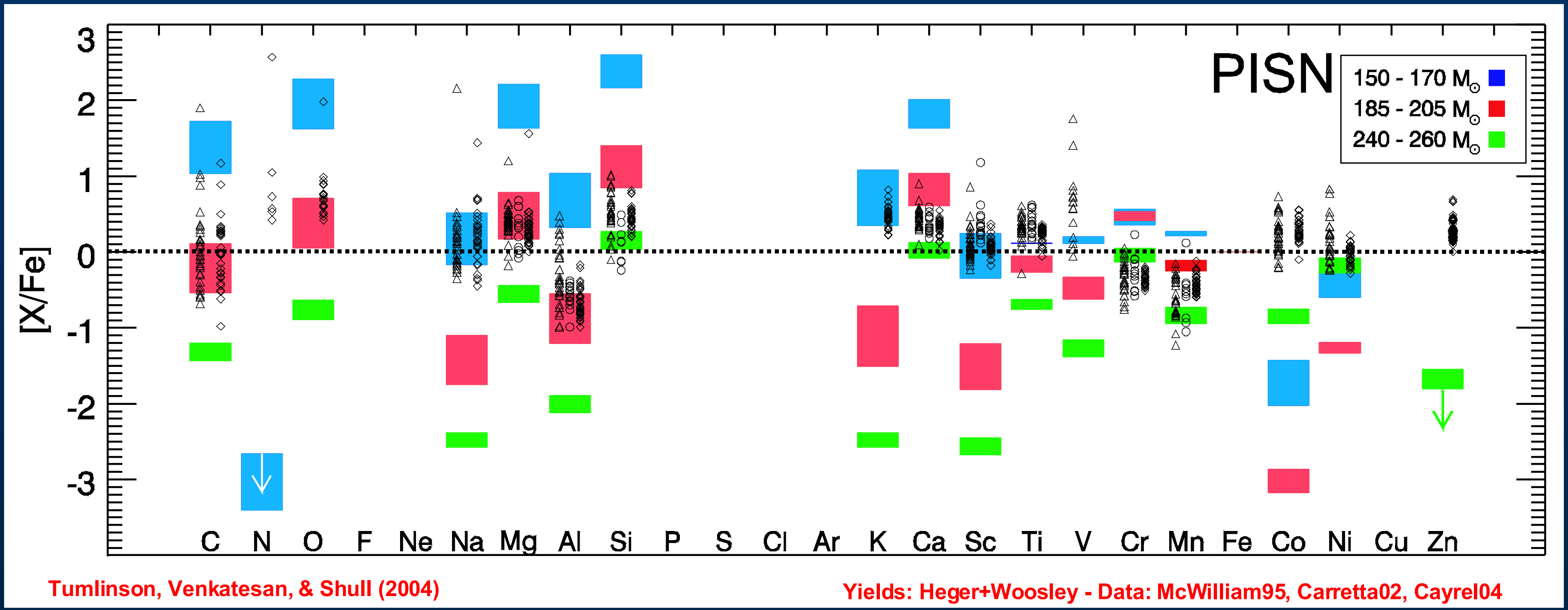




First star : massive

not PISN.

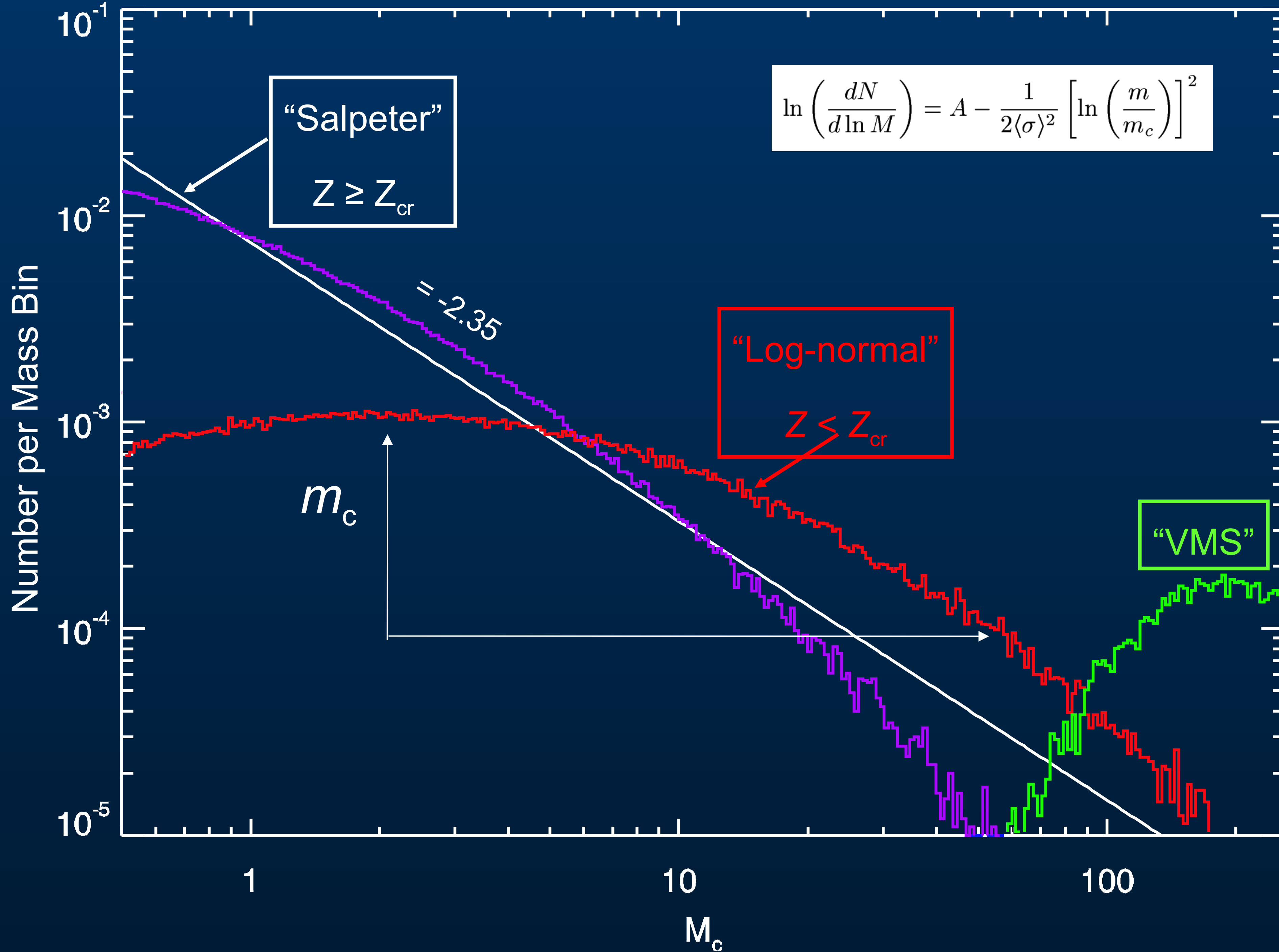
Komiya et al. 2007



PISNe yields are characterized by big “Odd Even Effect” and **no** neutron capture nucleosynthesis.

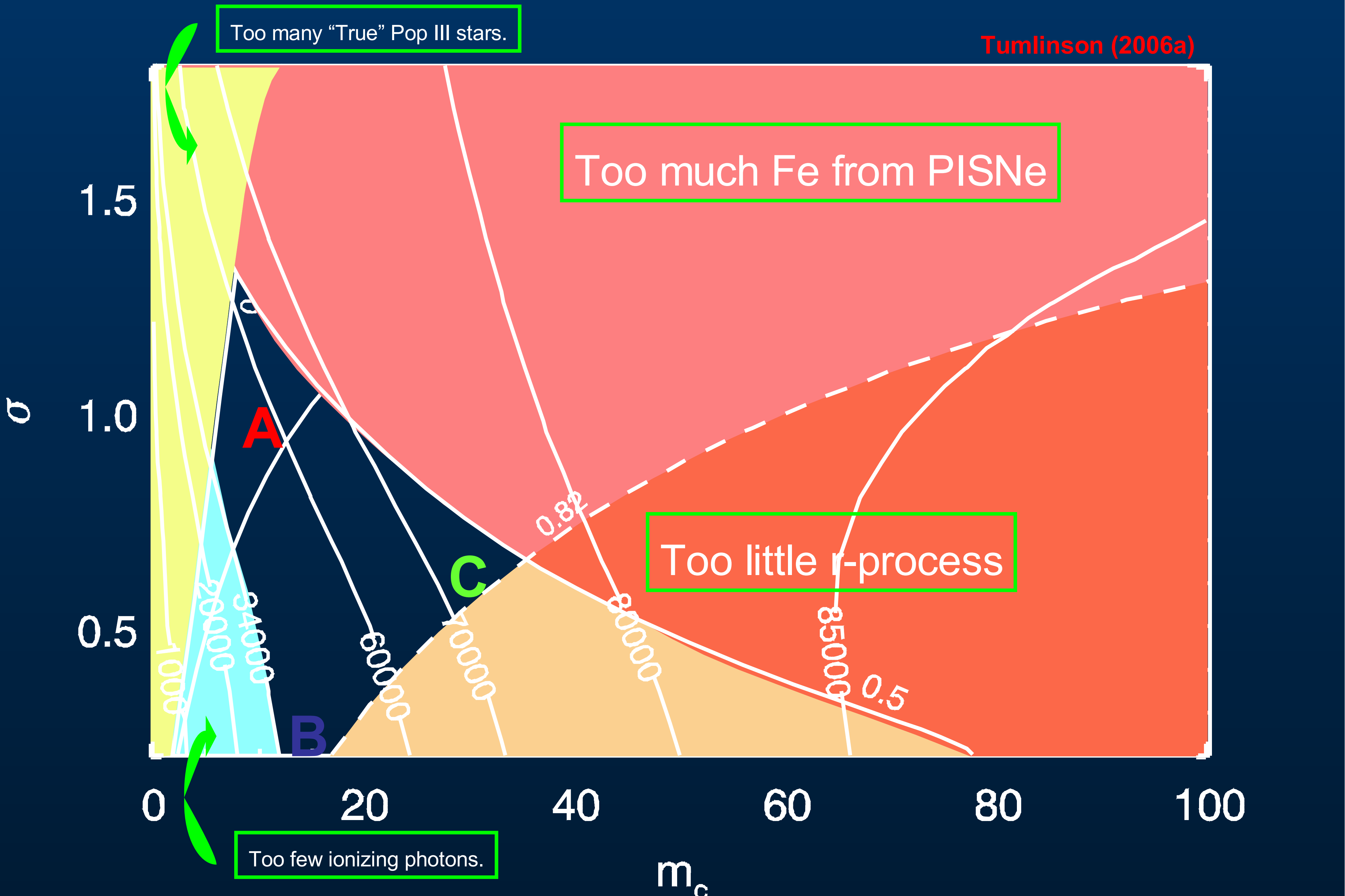
Observed Fe-peak, eg. [Zn/Fe], require ≤ ½ of Fe from PISNe.

PISNe have no r-process, so cannot give 82% of EMPs with Ba.



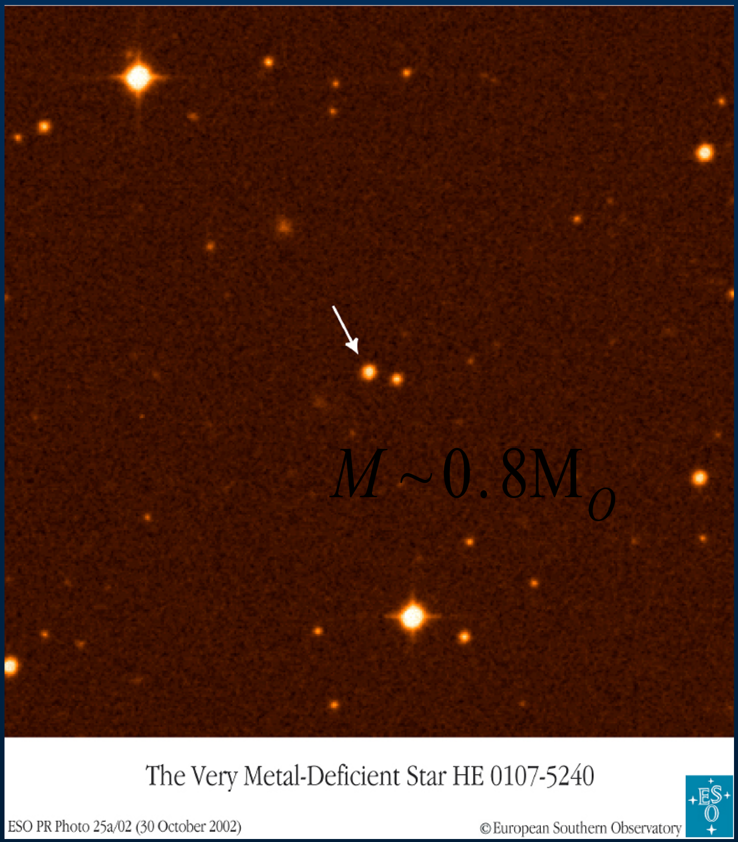
$\ln\left(\frac{dN}{d\ln M}\right) = A - \frac{1}{2\langle\sigma\rangle^2}\left[\ln\left(\frac{m}{m_c}\right)\right]^2$
"Salpeter"
$Z \geq Z_{cr}$
= -2.35
"Log-normal"
$Z < Z_{cr}$
m_c
"VMS"
Number per Mass Bin
M_c
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
1
10
100

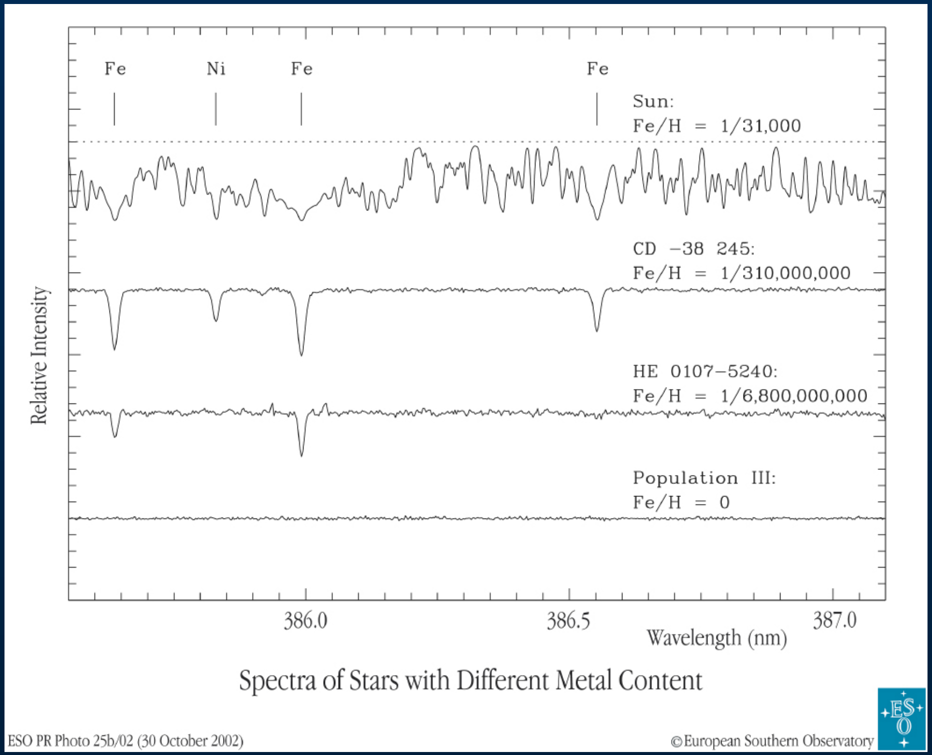
Four Constraints on the Primordial IMF



Hyper metal poor stars

- **HE0107-5240**: [Fe/H] = - 5.2 (Christlieb et al. 2002)
- **HE1327-2326**: [Fe/H] = - 5.4 (Frebel et al. 2005)





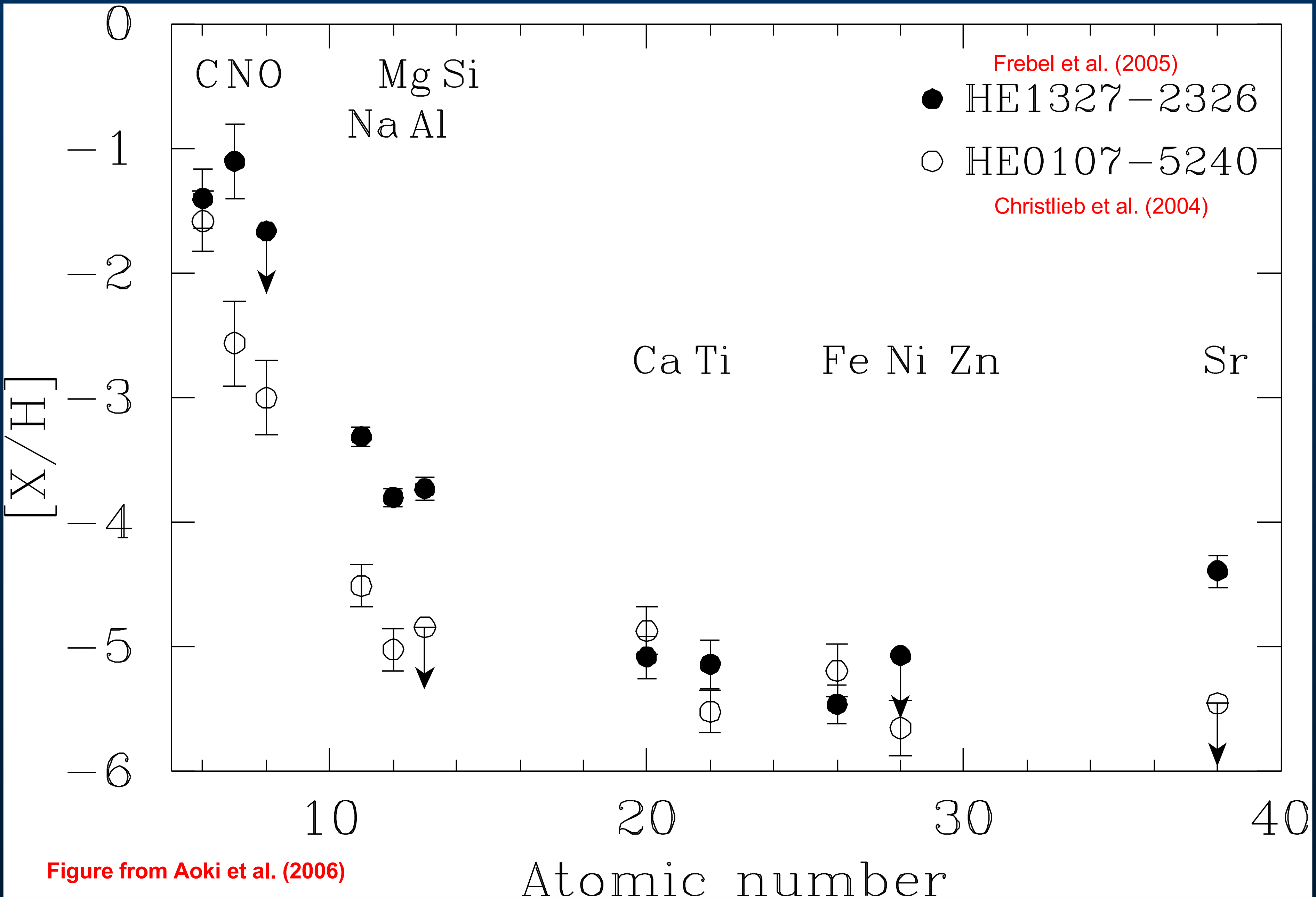
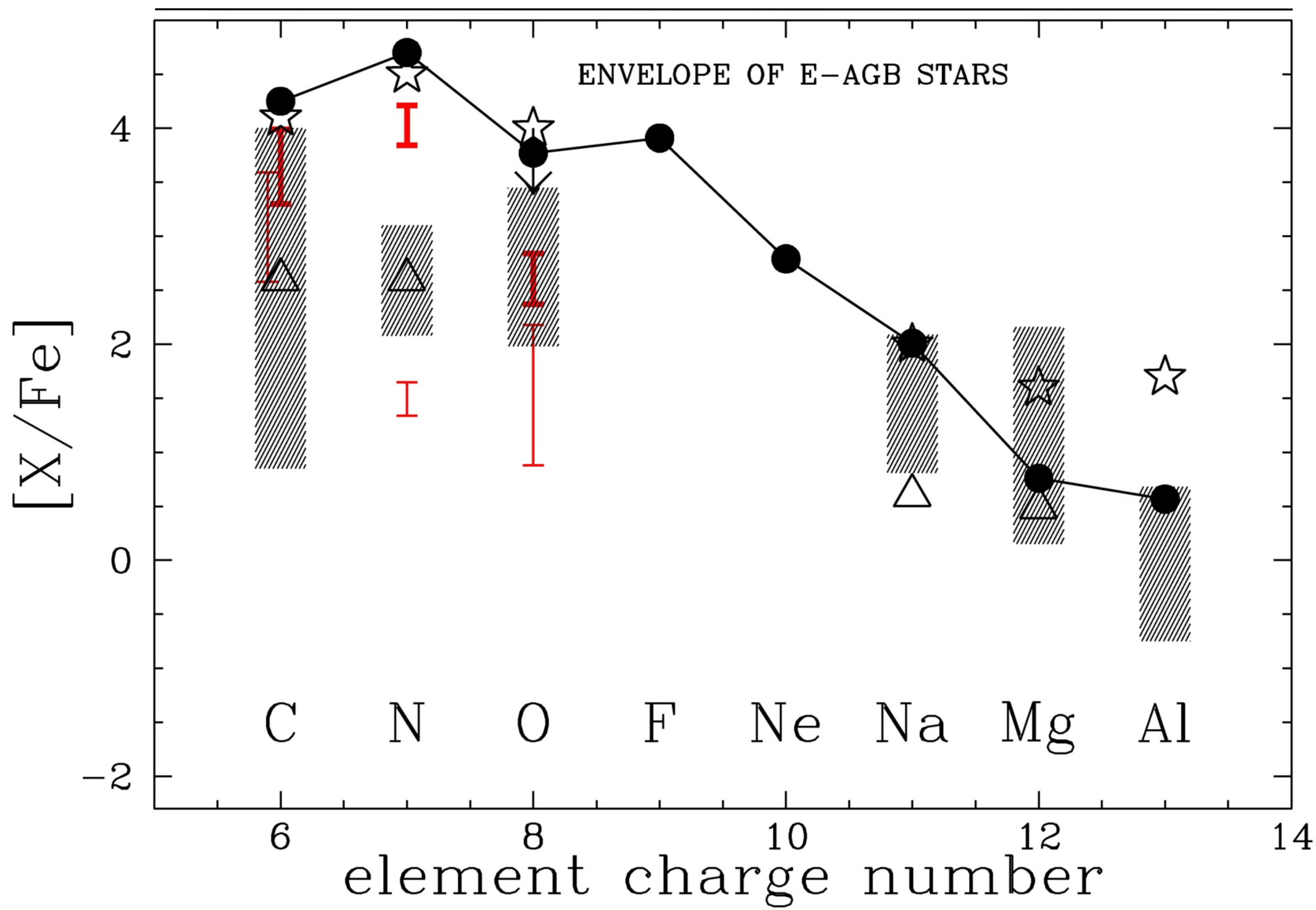


Figure from Aoki et al. (2006)

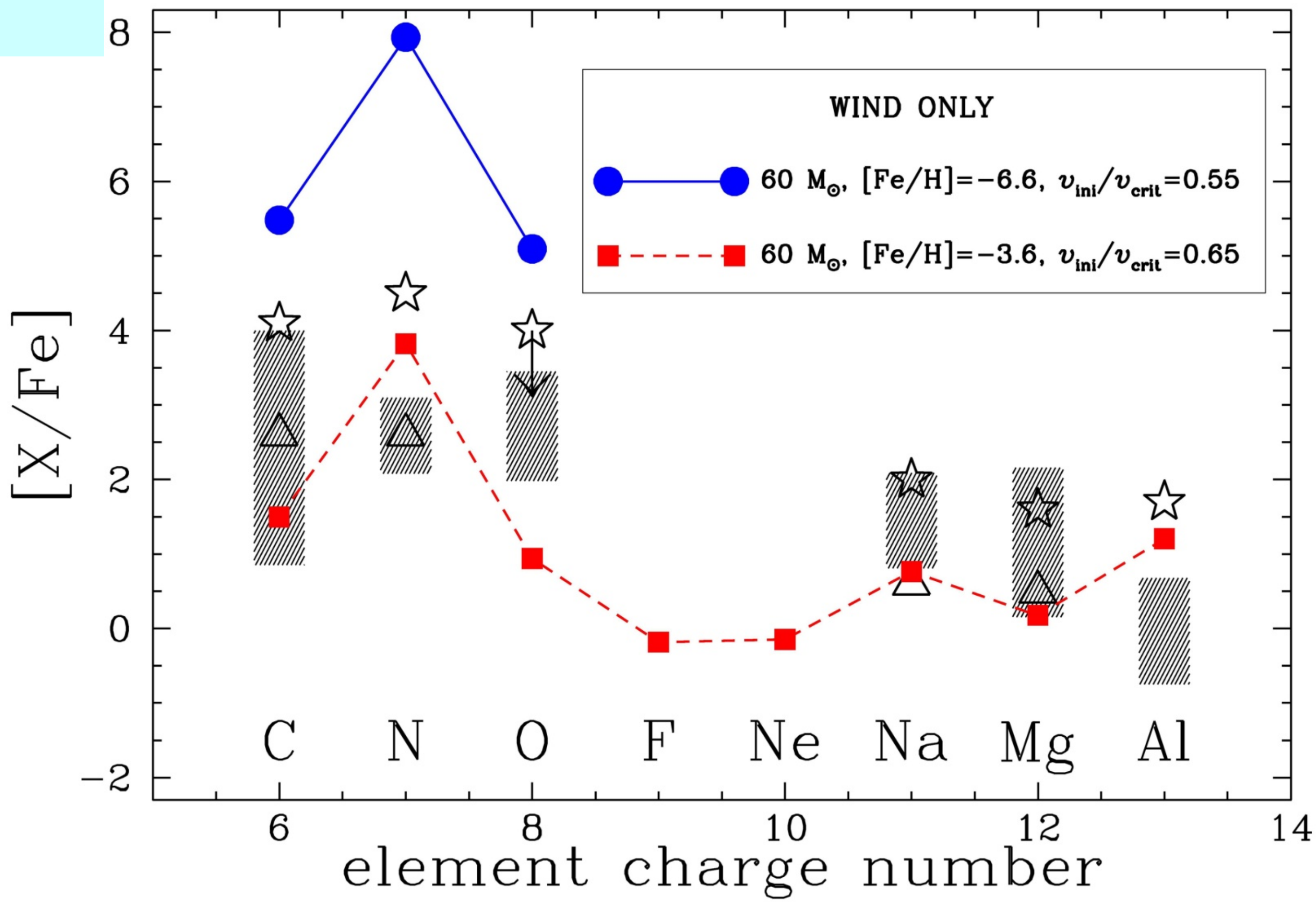
7 M_{sol} , Z=0.00001, V_{ini}=800 km s^{-1}



Meynet, Ekström, Maeder (2006)

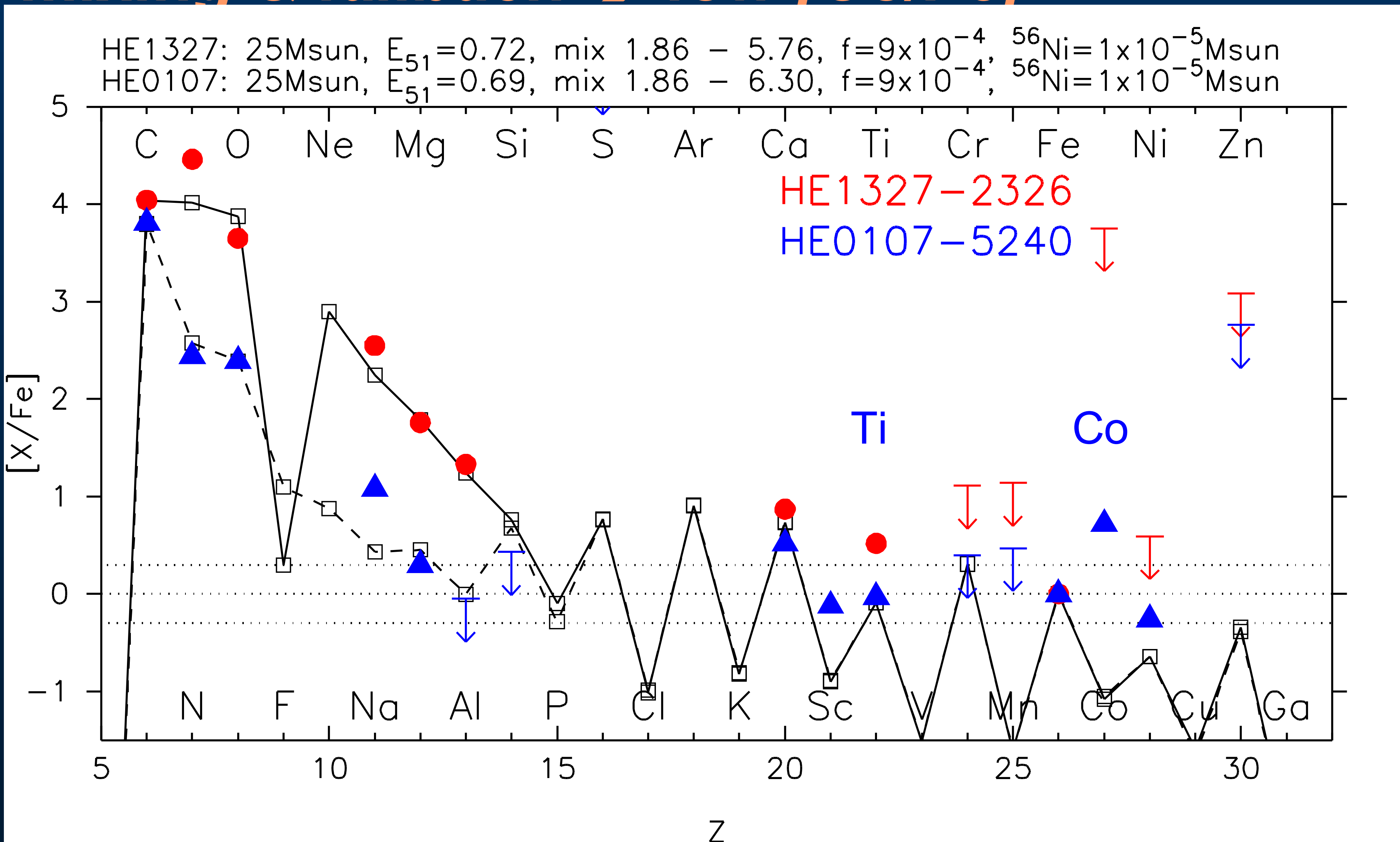
Observations
Frebel et al 04,06 (stars)
Plez & Cohen 05 (triangle),
Aoki et al 05
Christlieb et al 04,
Norris et al 04,
Depagne et al 02

Theory
- Limongi et al 2003
- Umeda & Nomoto 2003
- Suda et al 2004



Meynet et al. 2006; Hirschi 2006

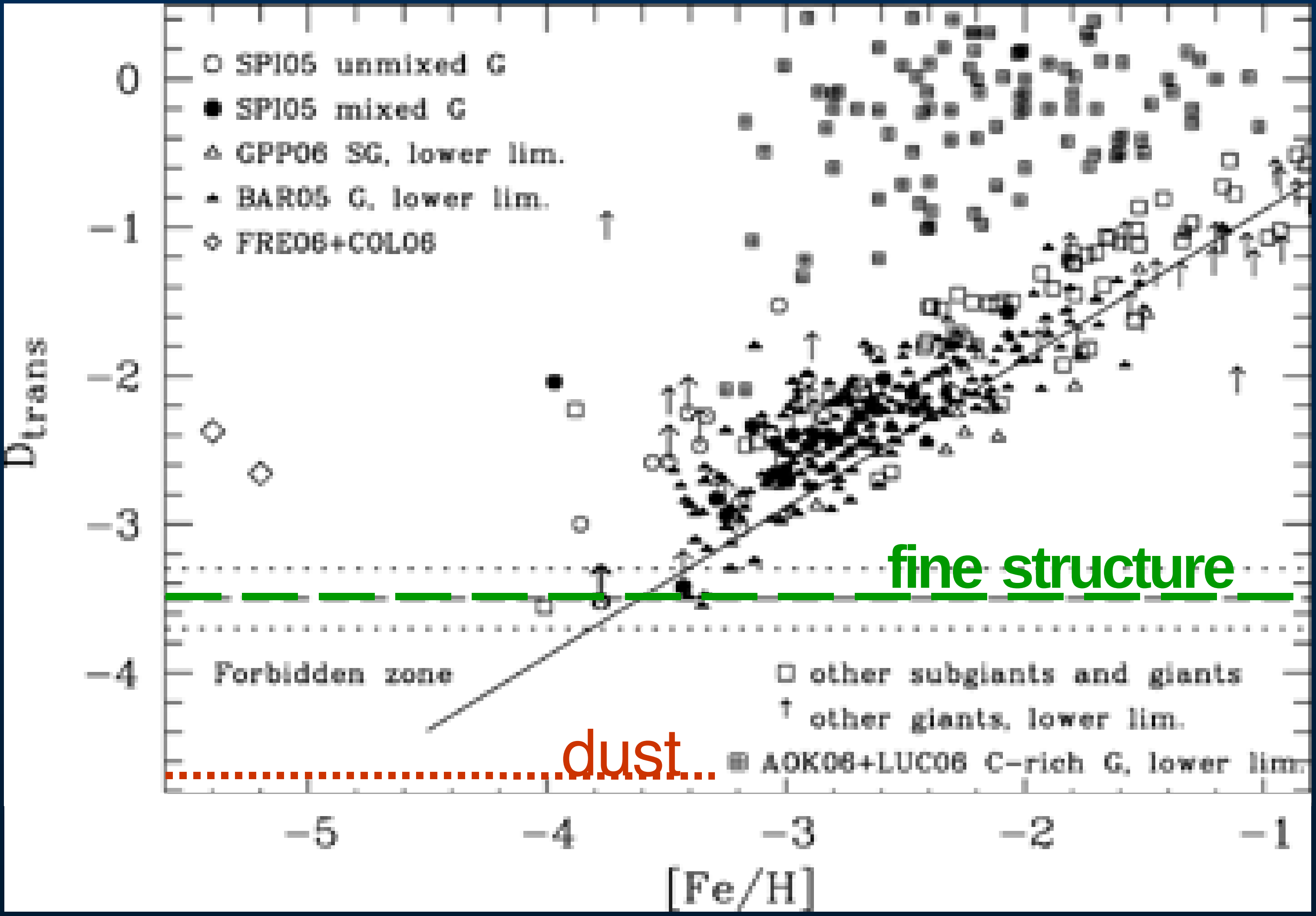
HMP stars: 1D Low E models (E_{51}< 1)
mixing & fallback → low [Co/Fe]



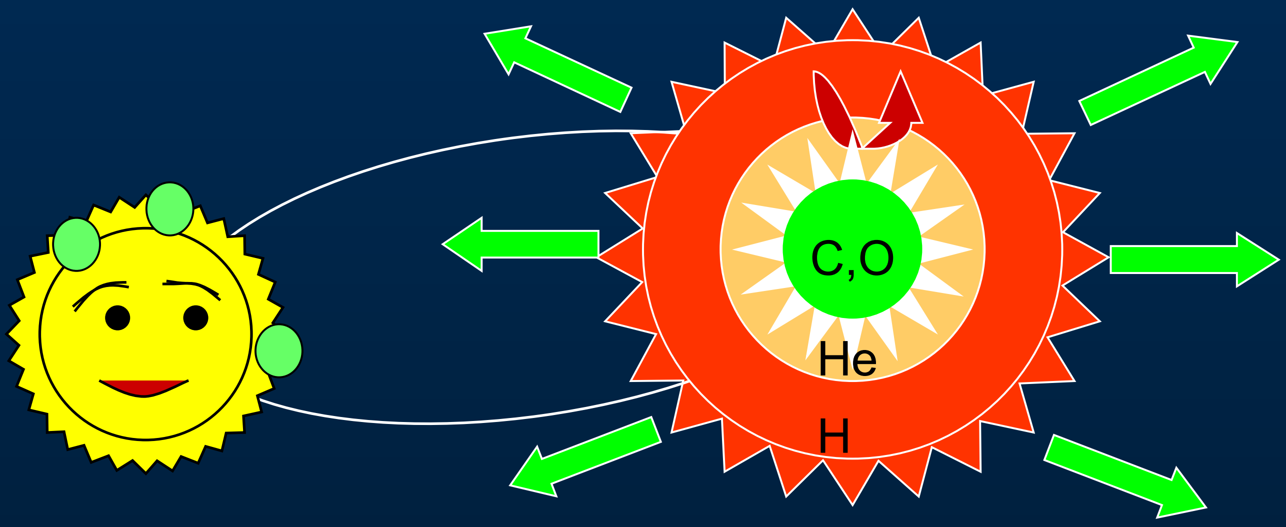
Low Li in HMP stars ?

HMP star - the First Low-mass Stars?

All stars below [Fe/H] = -4.0 are carbon rich



Carbon enhanced metal poor stars
IMF of the 2nd generation stars



Binary – Probe into missing more massive EMP stars

How to estimate the IMF from observation of CEMP star.

Evolution of a primary star affects abundances of a secondary star.

Observed feature of a CEMP star

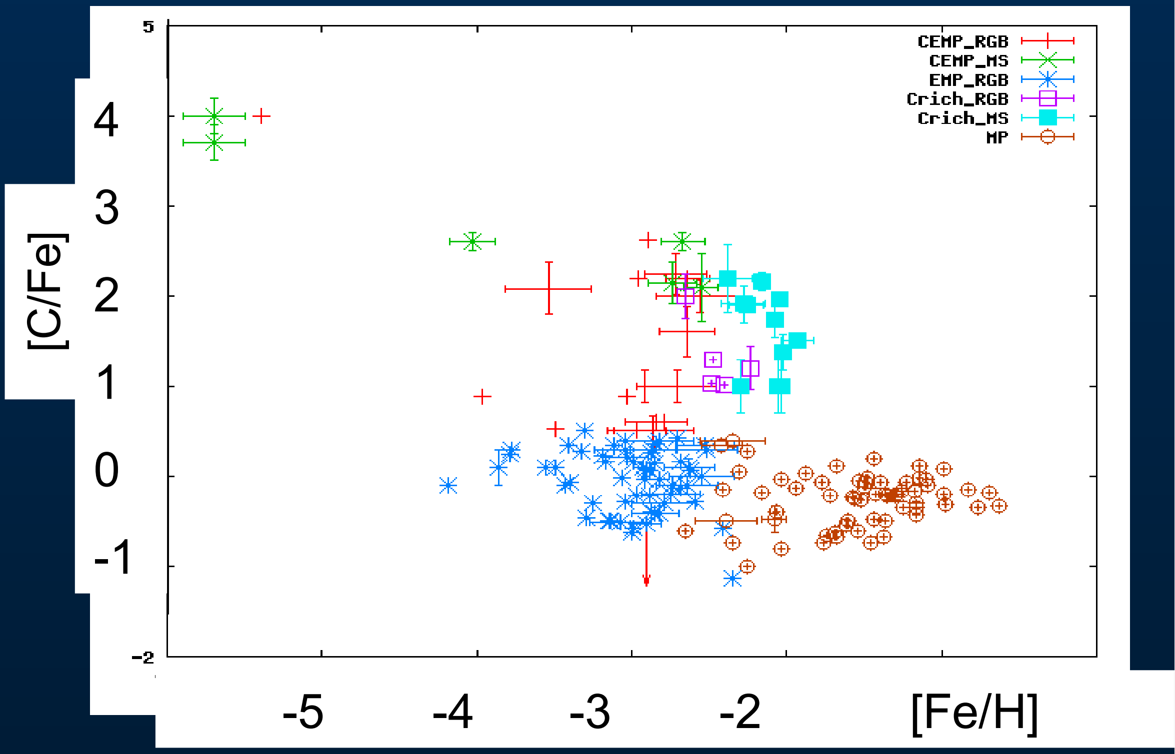
◇

Mass of a primary star.

➡ **Estimate of the IMF**

CEMP among EMPs

- ~1000 EMP stars are observed in the Galactic halo.
- *Only low mass stars still alive.*
- 20~25% of EMP stars show carbon enhancement (CEMP).



Theory (Komiya et al.2007)

$M_{Primary}$ = 0.8~3$M_\odot$

Separation = 1~100AU

$M_{Primary}$ = 4~6$M_\odot$

Separation = 3~100AU

→ CEMP-s ⇔ 10~25% of EMP star

→ CEMP-nos ⇔ 1/3~1/4 of CEMP star

Observation

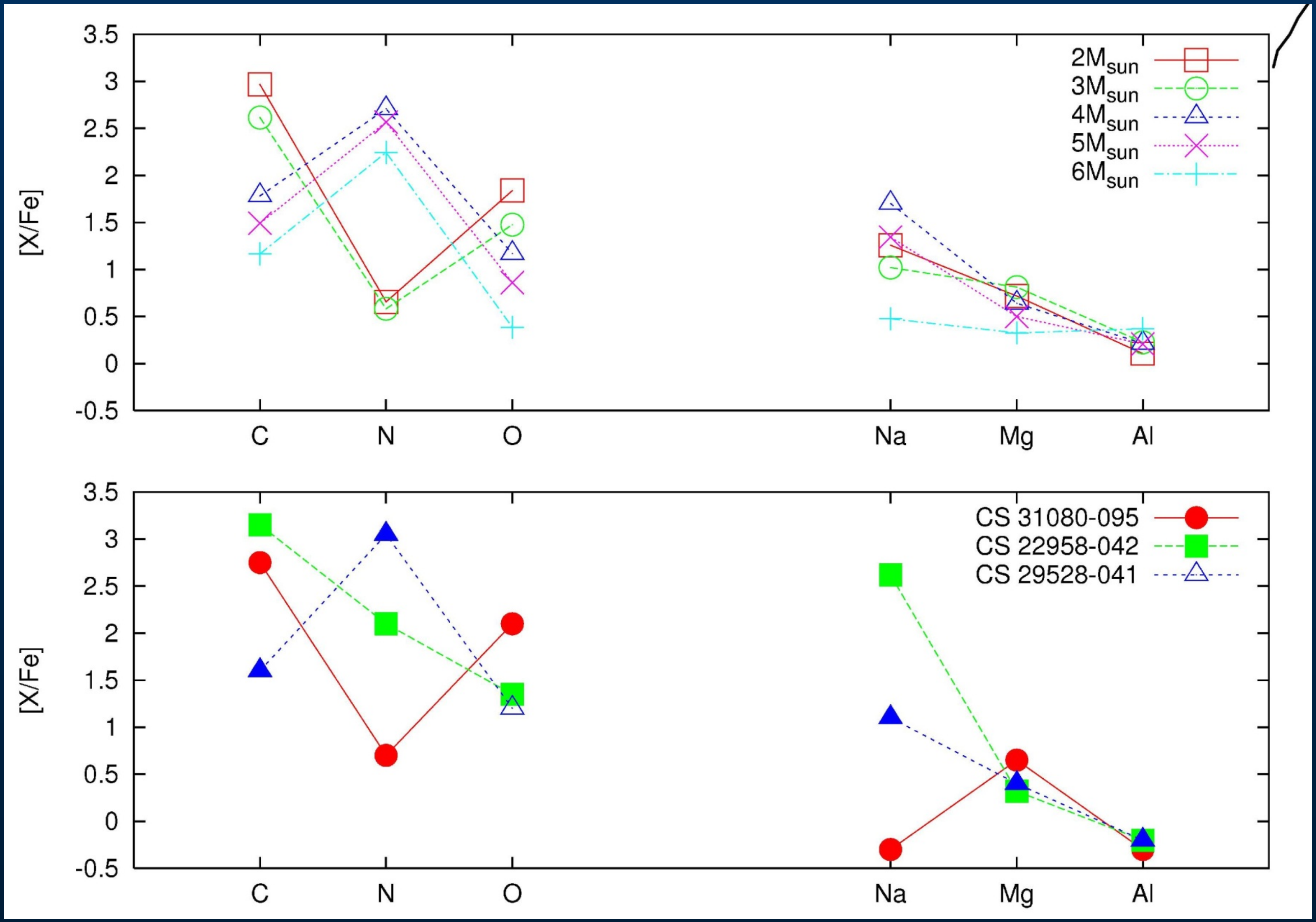
10~25% of EMP star

1/3~1/4 of CEMP star

Many intermediate mass stars (especially 4~6$M_\odot$)

IMF with peak at larger mass

Where are the intermediate AGB binaries?



Sivarani et al. 2006

The CMB and the Characteristic Stellar Mass

Studies of local star formation (Larson '98,'05; Jappsen et al. '05) suggest that the characteristic mass of stars responds to the minimum *T* at which gas becomes optically thick to cooling radiation and thermally coupled to dust.

At low redshift, Z = Zmin = 10 K is set by metal and dust cooling.

But at high *z*, the CMB itself is the minimum gas temperature!

z = 5, 10, 20 T_{CMB} = 16, 30, 57 K M_c = 2, 6, 17 $M_\odot$

Thus stars formed early in MW history, at z > 5, should be affected!

Two Predictions of the CMB-IMF Hypothesis

f_{CEMP} should increase with declining [Fe/H].

Inside-out construction the halo causes extended epoch of star formation at fixed [Fe/H], so

f_{CEMP} should increase in “older” regions of the Galaxy and decrease in “younger” regions, at fixed metallicity.

In a sample of 174 bright HES stars, Frebel et al. (2006) find variation in f_{CEMP} with [Fe/H] and with scale height above the Galactic plane.

More observations

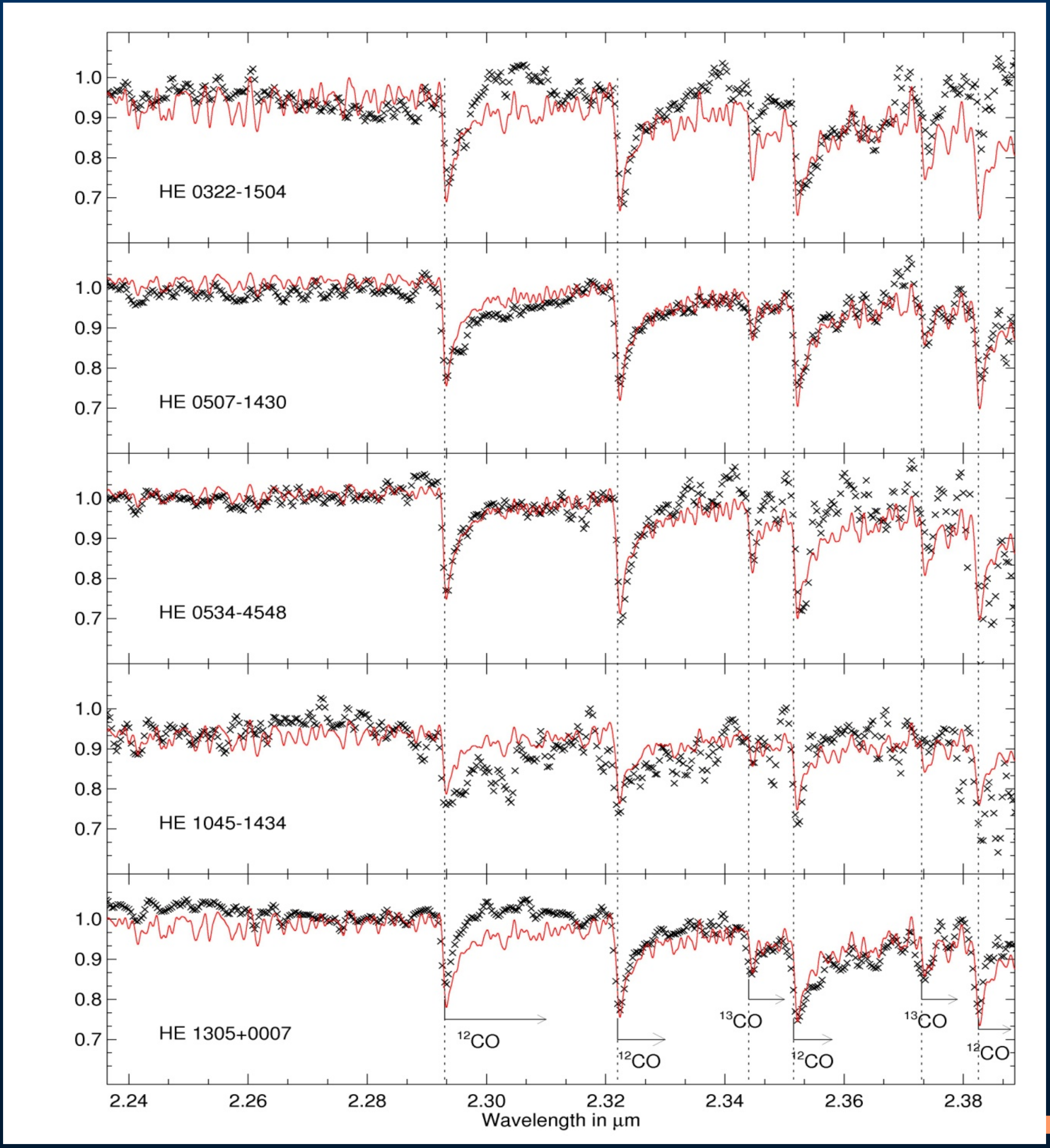
Phoenix – Gemini South Fluorine in cool EMPs
CRIES – VLT

Oxygen in CEMPs SOAR- MSU NIR

SDSS – EMP stars follow-up SUBARU-HDS,
HET-HiRes , VLT-UVES

Medium resolution Frequency of CEMPs at
Spectroscopy various parts of the Galaxy

Oxygen abundances in CEMPs – Pilot survey with SOAR-MSU



Conclusions

First SNs are not PISN → EMP abundances favor 10-100Msun SNs

Main r-process is due to 10Msun SN.

There is an alternate r-process site for lighter r-process.

CEMP binaries → Mc = 6-10 for 2nd generation stars
CMB influence on IMF ? More observations

The CMB and the Characteristic Stellar Mass

Studies of local star formation (Larson '98,'05; Jappsen et al. '05) suggest that the characteristic mass of stars responds to the minimum T at which gas becomes optically thick to cooling radiation and thermally coupled to dust.

$$M_J \sim M_\odot \left(\frac{n}{10^3\,cm^{-3}}\right)^{1/2} \left(\frac{T}{10K}\right)^{3/2}$$

At low redshift, $Z = Z_{min}$ = 10 K is set by metal and dust cooling.

But at high z, the CMB itself is the minimum gas temperature!

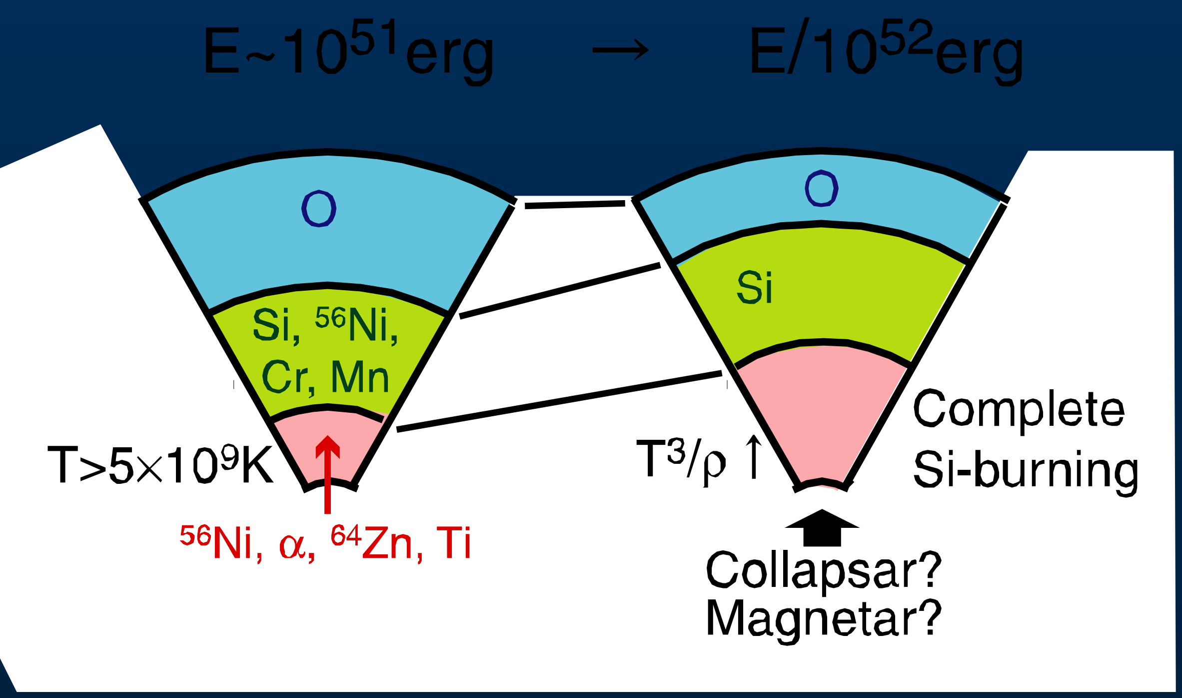
$$m_C \approx 0.9\ M_\odot\ [T_{CMB}/10K]^{1.70-3.35}$$

z = 5, 10, 20 → T_{CMB} = 16, 30, 57 K → M_C = 2, 6, 17 $M_\odot$

$$M_J = (3.4-4.2)\, M_{sun} \left(\frac{T_{CMB}}{10\,K}\right)^{1.7-3.3}$$

Thus stars formed early in MW history, at z > 5, should be affected!

SN and Hypernova Nucleosynthesis



Low energy High energy

AGB Nucleosynthesis depends on Mass

Yields from Karakas (2003)