r-process nucleosynthesis and early chemical evolution

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Neutron Matter in Astrophysics: from Neutron Stars to the r-Process (EMMI, GSI)
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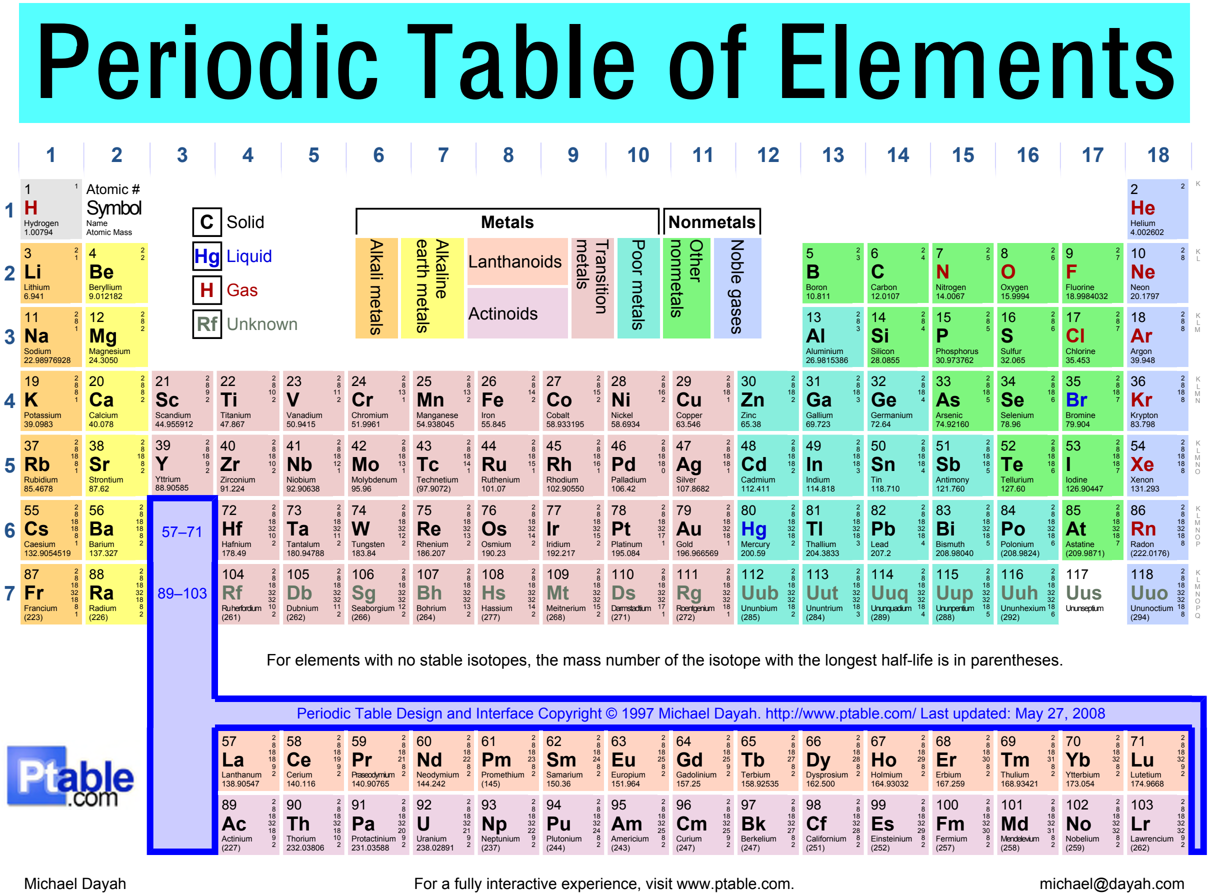
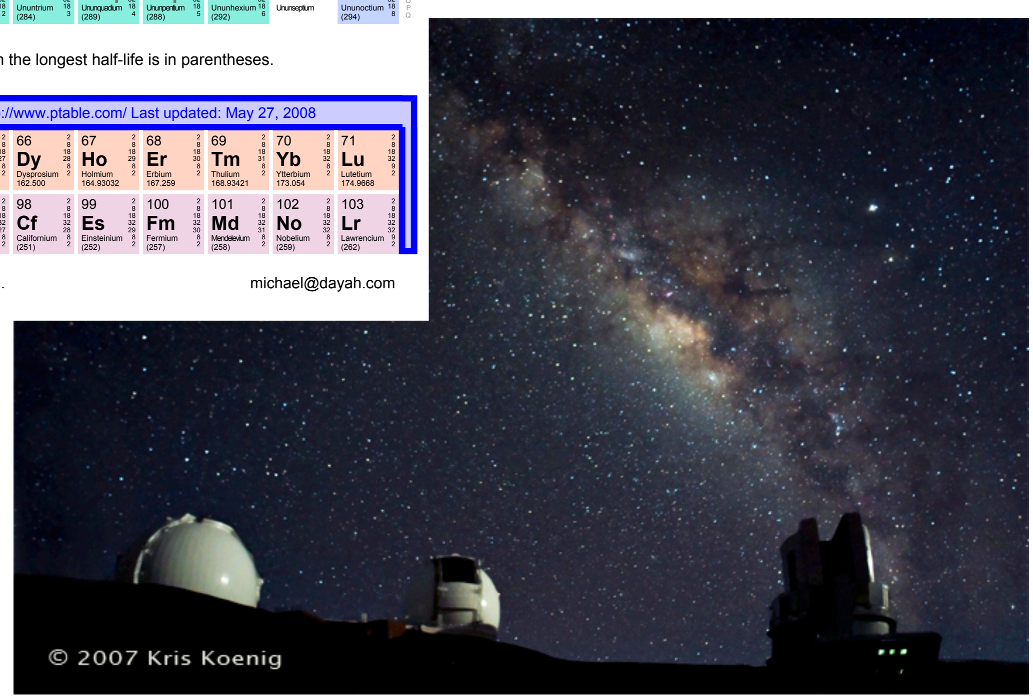


stars make
"metals" after
the big bang

observations of
metal abundances by
Keck, VLT, Subaru

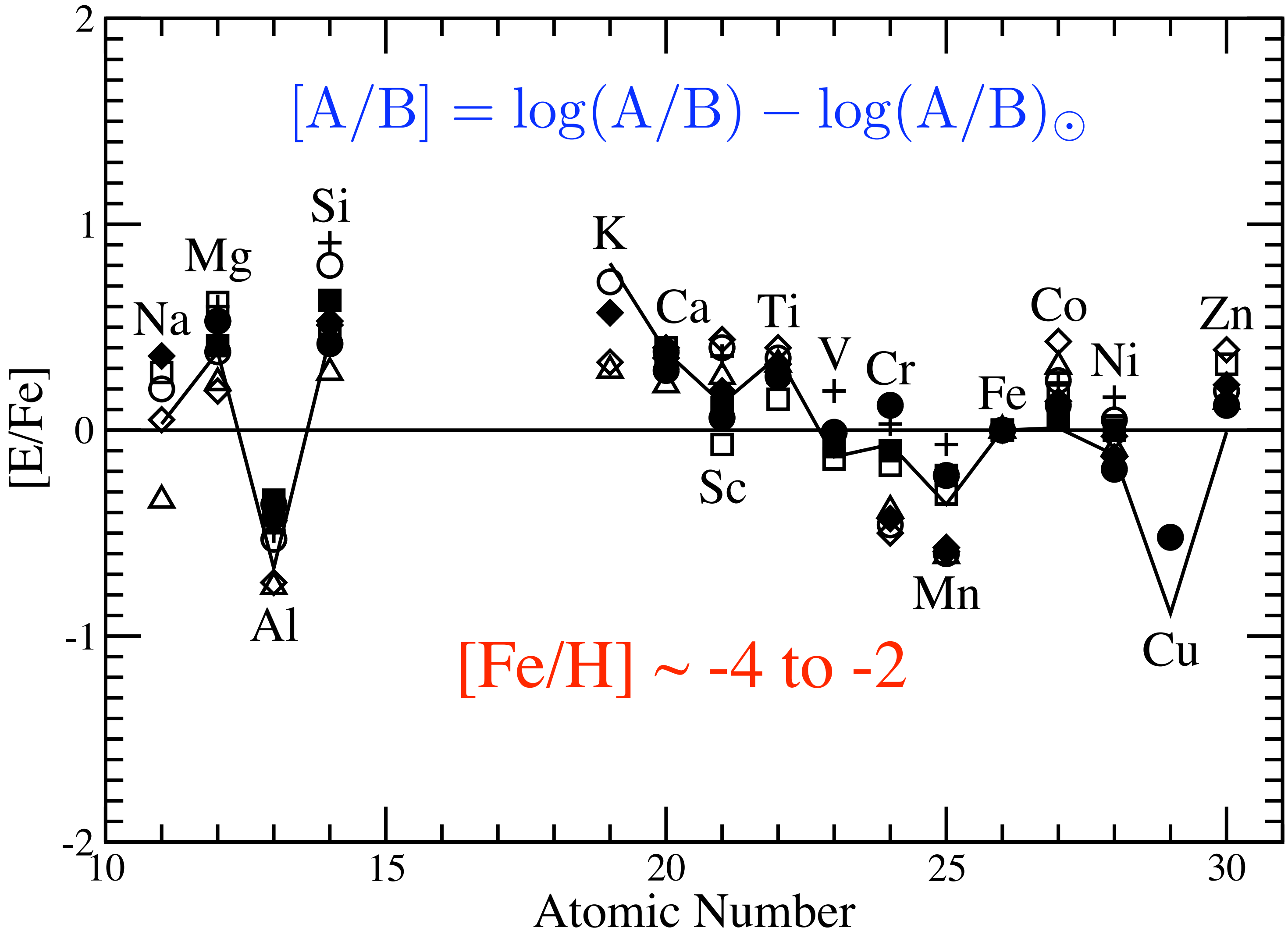


Elemental abundances in metal-poor stars

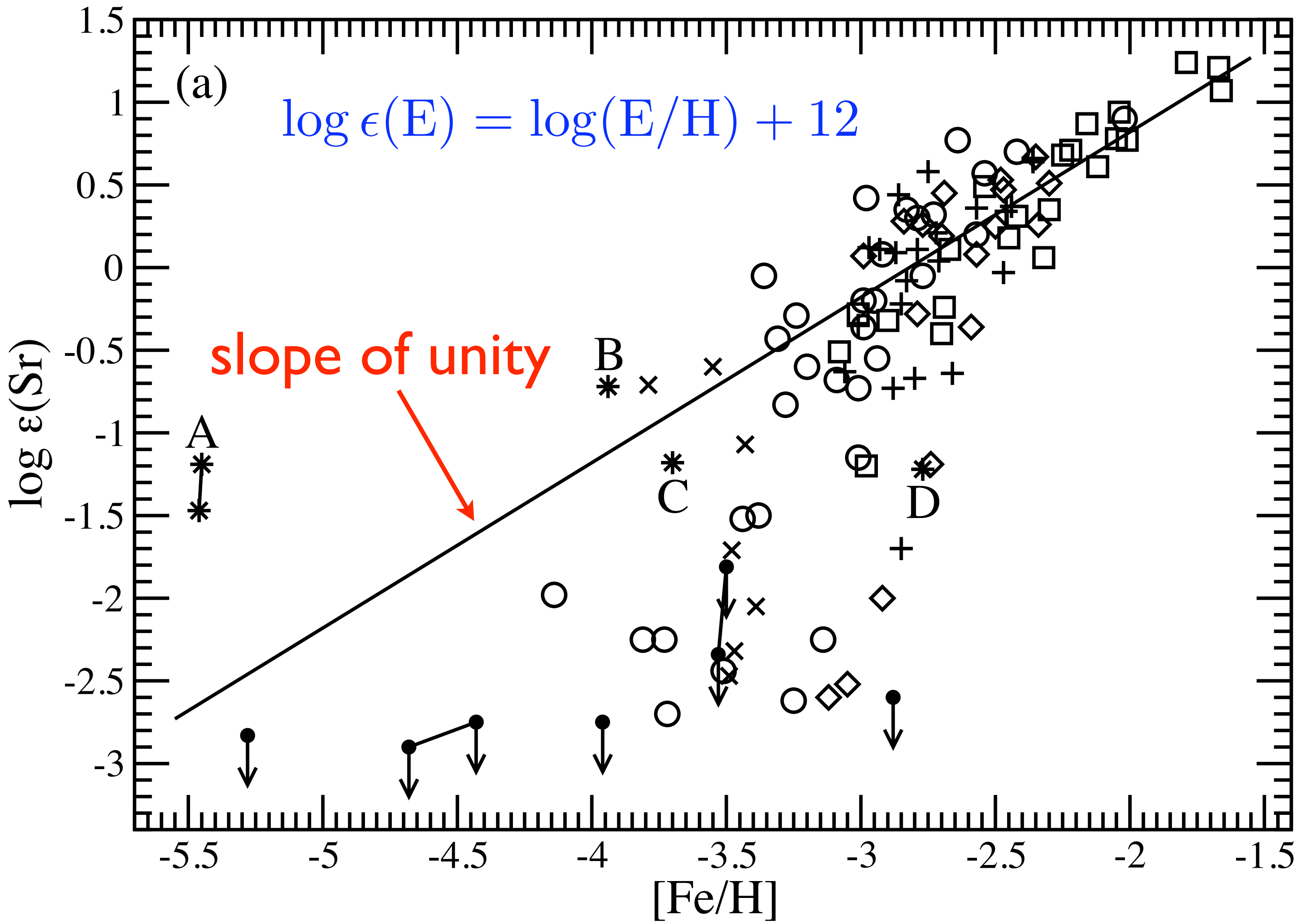
(Johnson 2002; Honda et al. 2004; Aoki et al. 2005; Francois et al. 2007; Cohen et al. 2007)

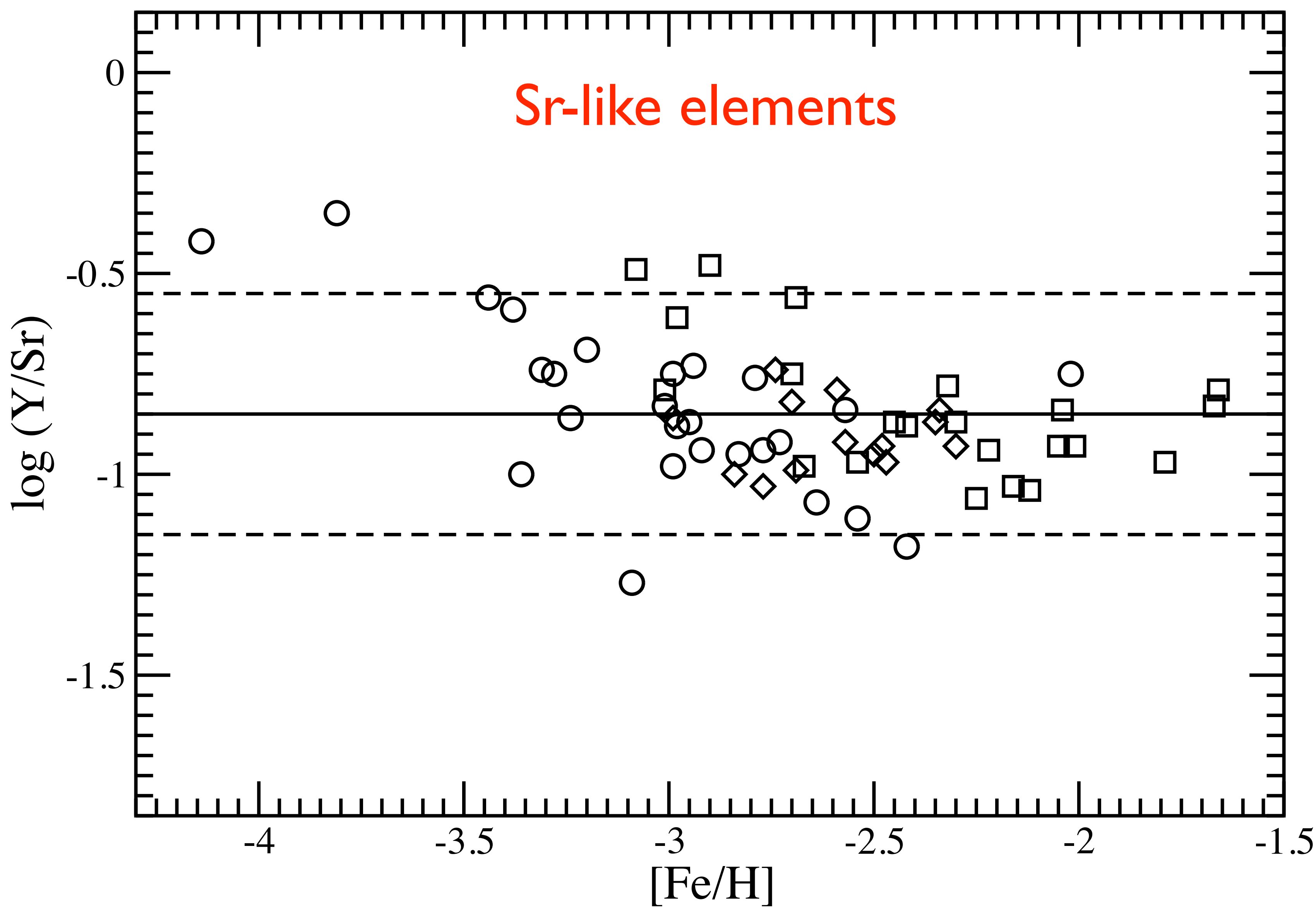
- Fe-like elements (A ~ 23 to 70)
  Na, Mg, Al, Si, ..., Fe, ..., Zn
- Sr-like elements (A ~ 88 to 110)
  Sr, Y, Zr, ..., Ag
- Ba-like elements (A > 130)
  Ba, ..., Eu, ..., Pt, ..., Th, ..., U, ...

Quasi-uniform pattern of Fe-like elements



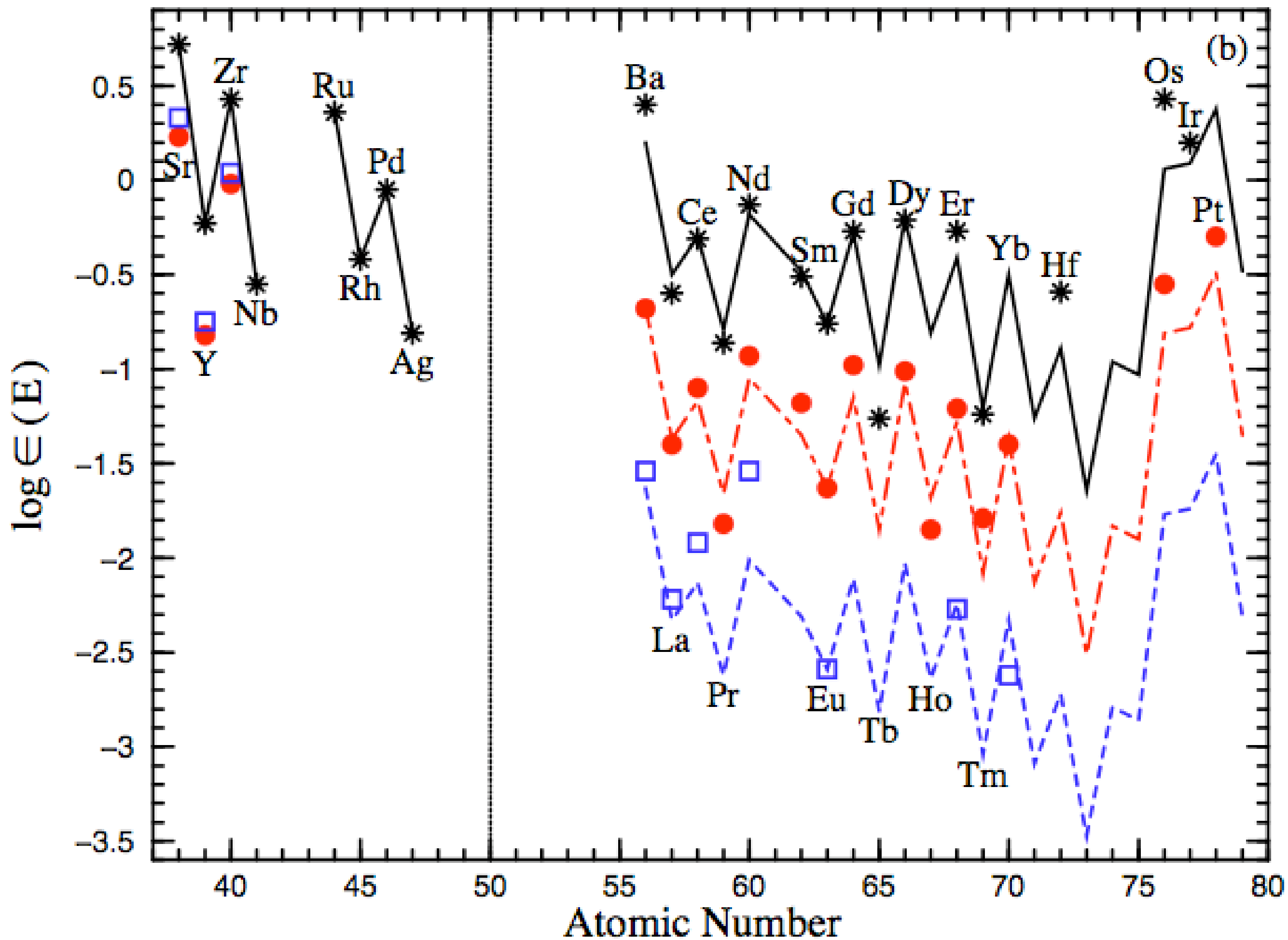
Evolution of Sr with Fe

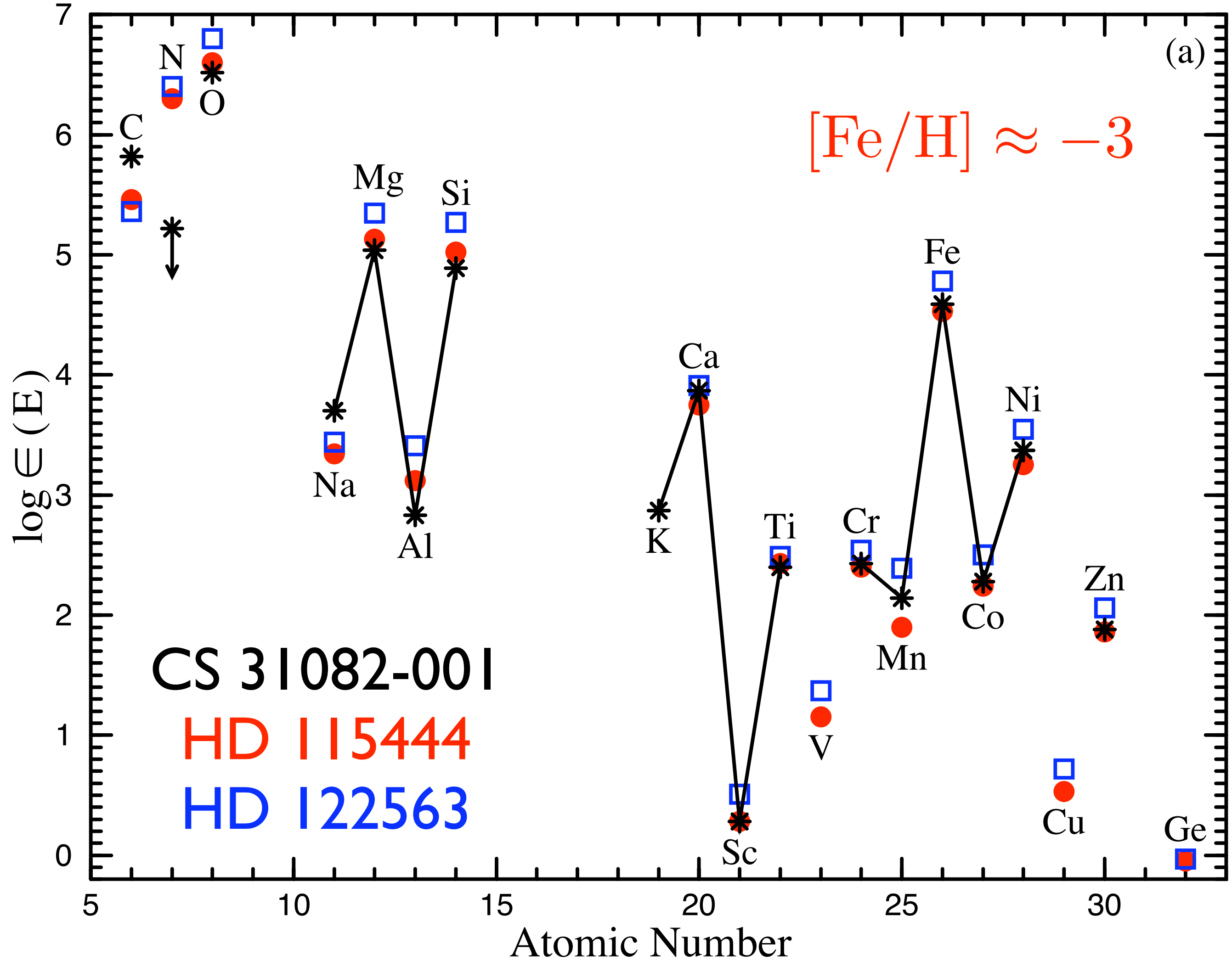




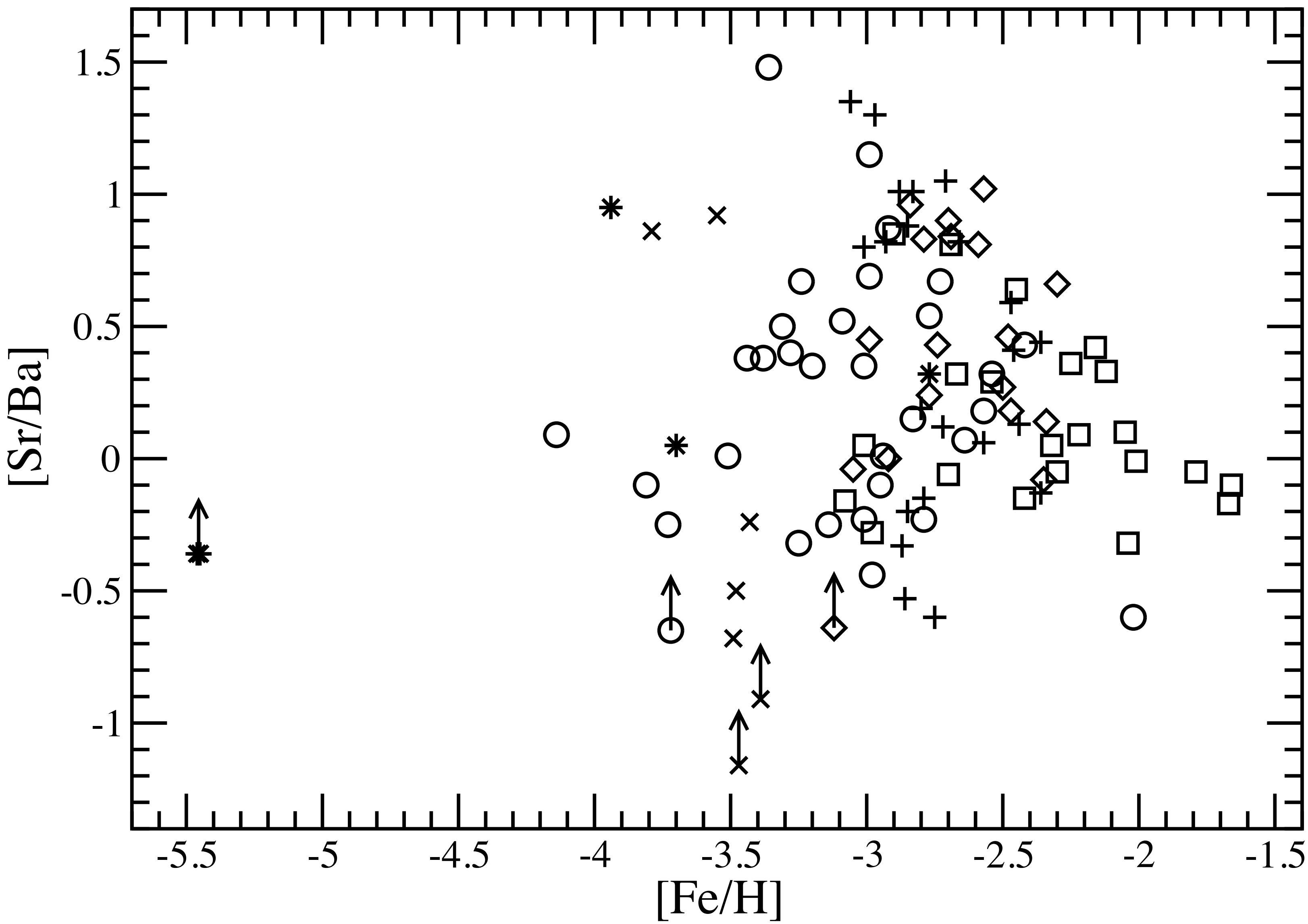
Sr-like elements
0
-0.5
-1
-1.5
log (Y/Sr)
-4
-3.5
-3
-2.5
-2
-1.5
[Fe/H]

Observations of Ba-like elements
(Westin et al. 2000; Hill et al. 2002)

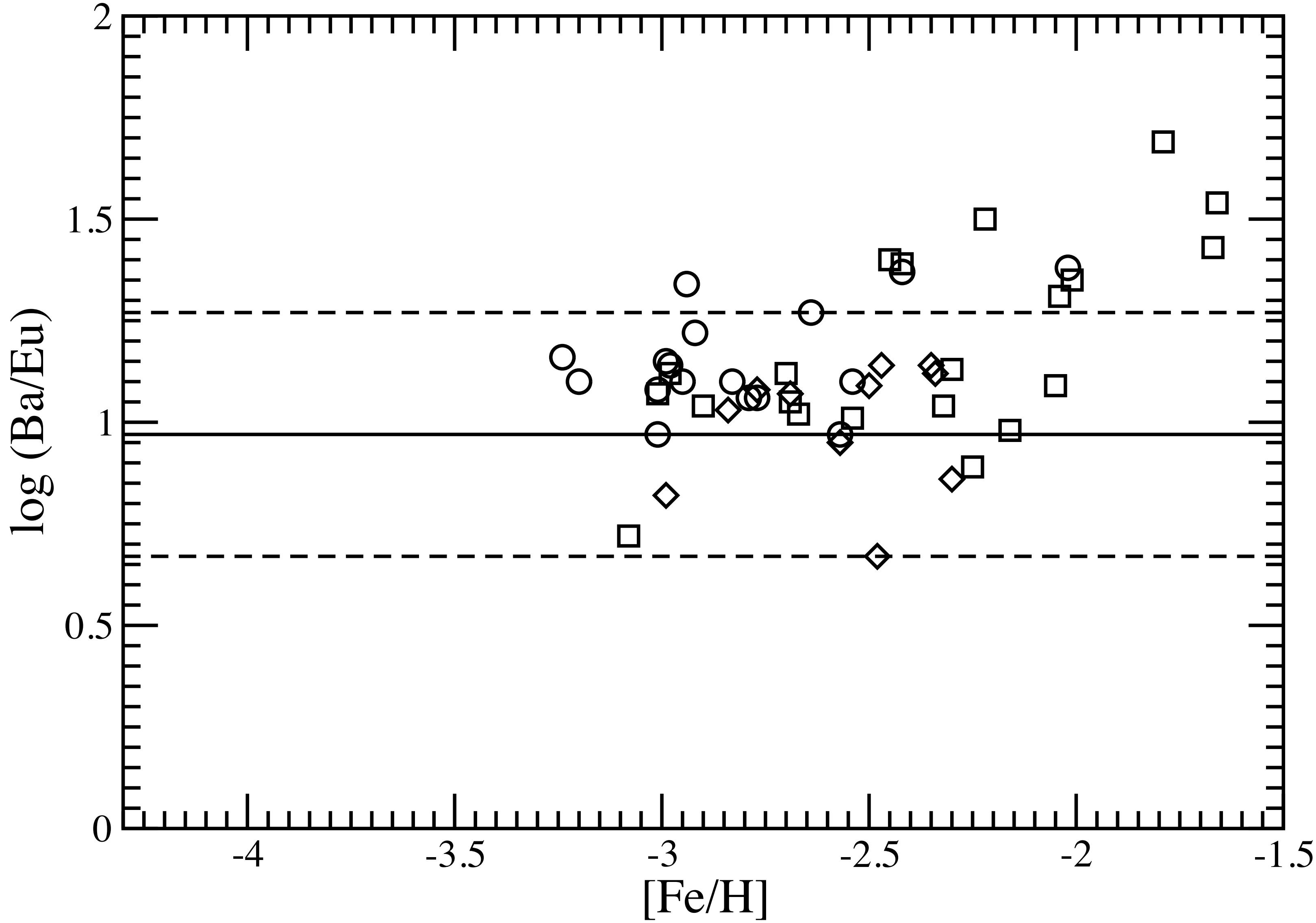




(a)
[Fe/H] ≈ −3
CS 31082-001
HD 115444
HD 122563
C
N
O
Na
Mg
Al
Si
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ge
log ∈ (E)
Atomic Number



1.5
1
0.5
0
-0.5
-1
[Sr/Ba]
-5.5
-5
-4.5
-4
-3.5
-3
-2.5
-2
-1.5
[Fe/H]



2
1.5
1
0.5
0
log (Ba/Eu)
-4
-3.5
-3
-2.5
-2
-1.5
[Fe/H]

Summary of observations

- nearly fixed pattern for elements within each of the 3 groups
- wide variations in the ratio of elements between any 2 groups
- Ba-like elements decoupled from Fe-like elements

→ three distinct types of sources

Stellar sources for early chemical evolution

massive stars $M \gtrsim 8\,M_\odot \Rightarrow \tau \lesssim 30$ Myr

core-collapse SNe: neutron stars, black holes

low- and intermediate-mass stars

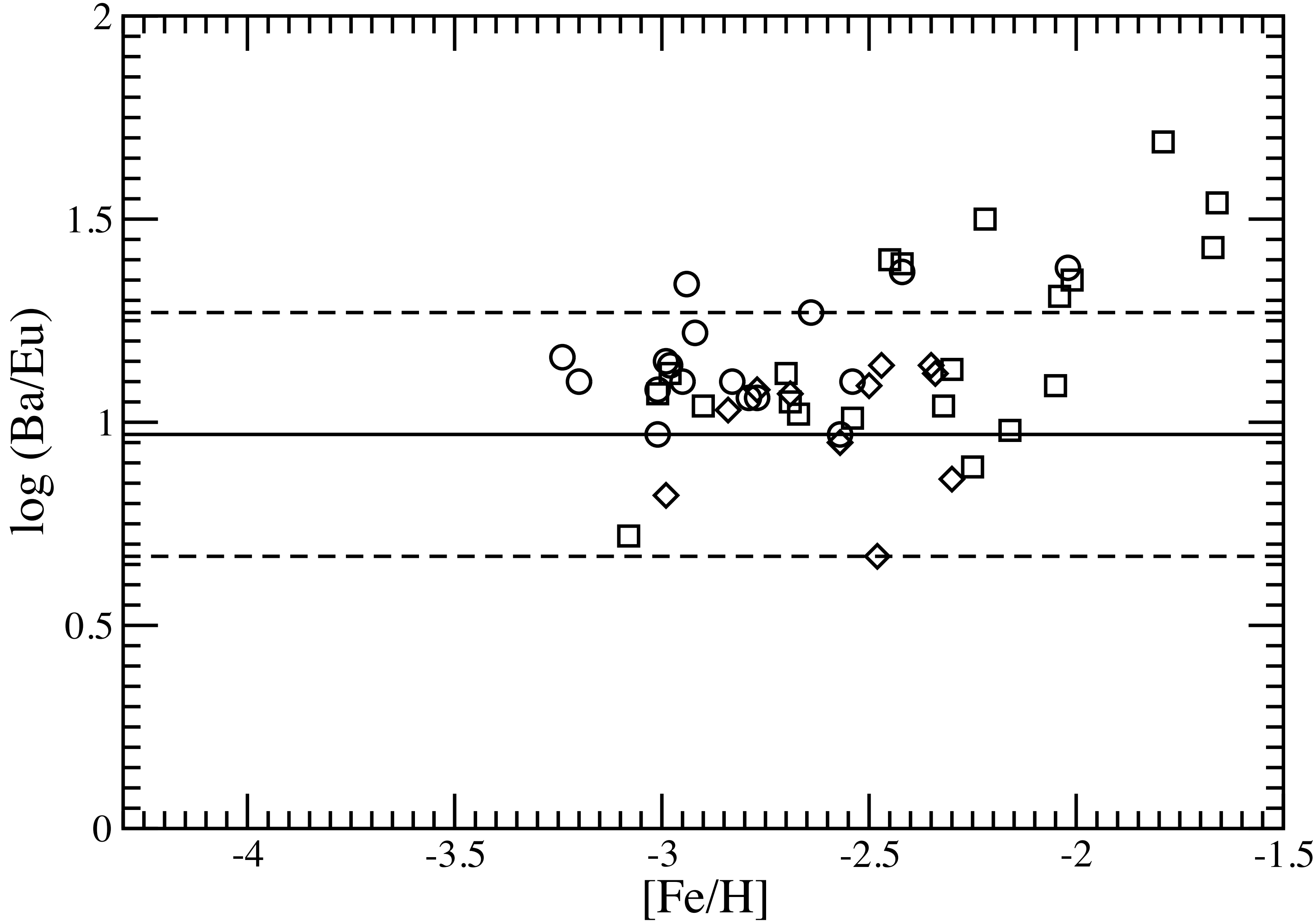
$M \sim 1\text{–}8\,M_\odot,\ \langle M \rangle \sim 2\,M_\odot \Rightarrow \tau \sim 1$ Gyr

AGB: s-process (A > 70), white dwarfs

WDs in binaries: SNe Ia (Fe group, A ~ 56)

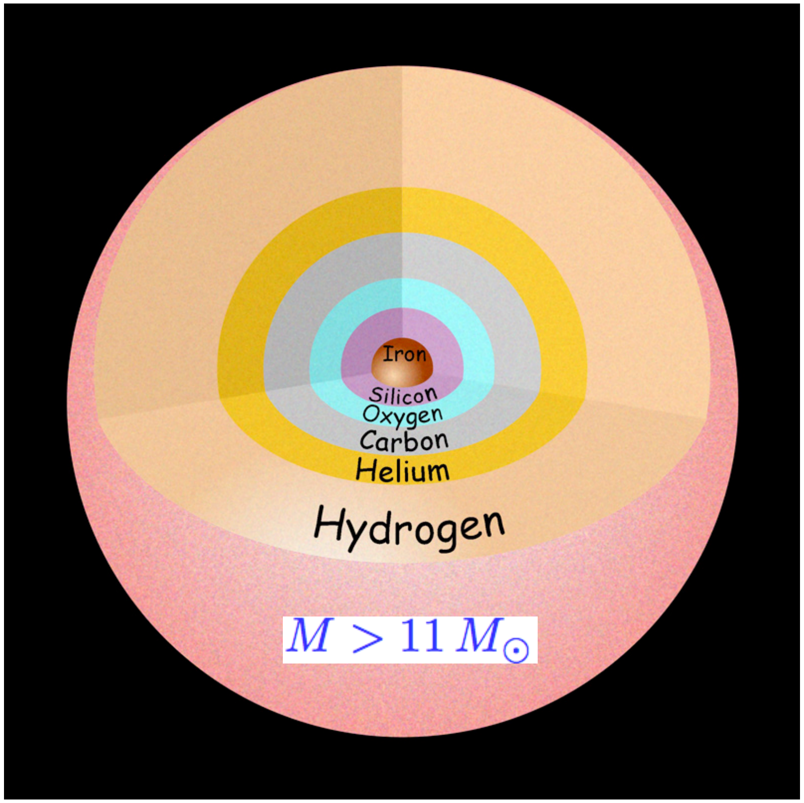
CCSNe over 10 Gyr: ~1/3 of solar Fe

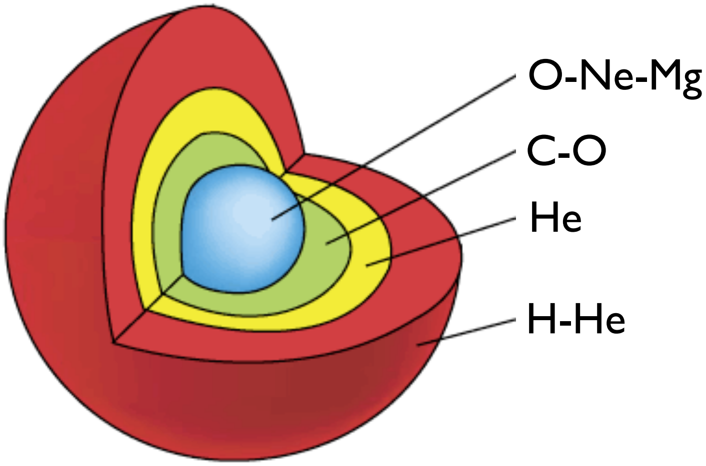
→ early (first Gyr): $[\mathrm{Fe/H}] \lesssim -1.5$



log (Ba/Eu)
2
1.5
1
0.5
0
-4
-3.5
-3
-2.5
-2
-1.5
[Fe/H]

Three types of core-collapse SNe



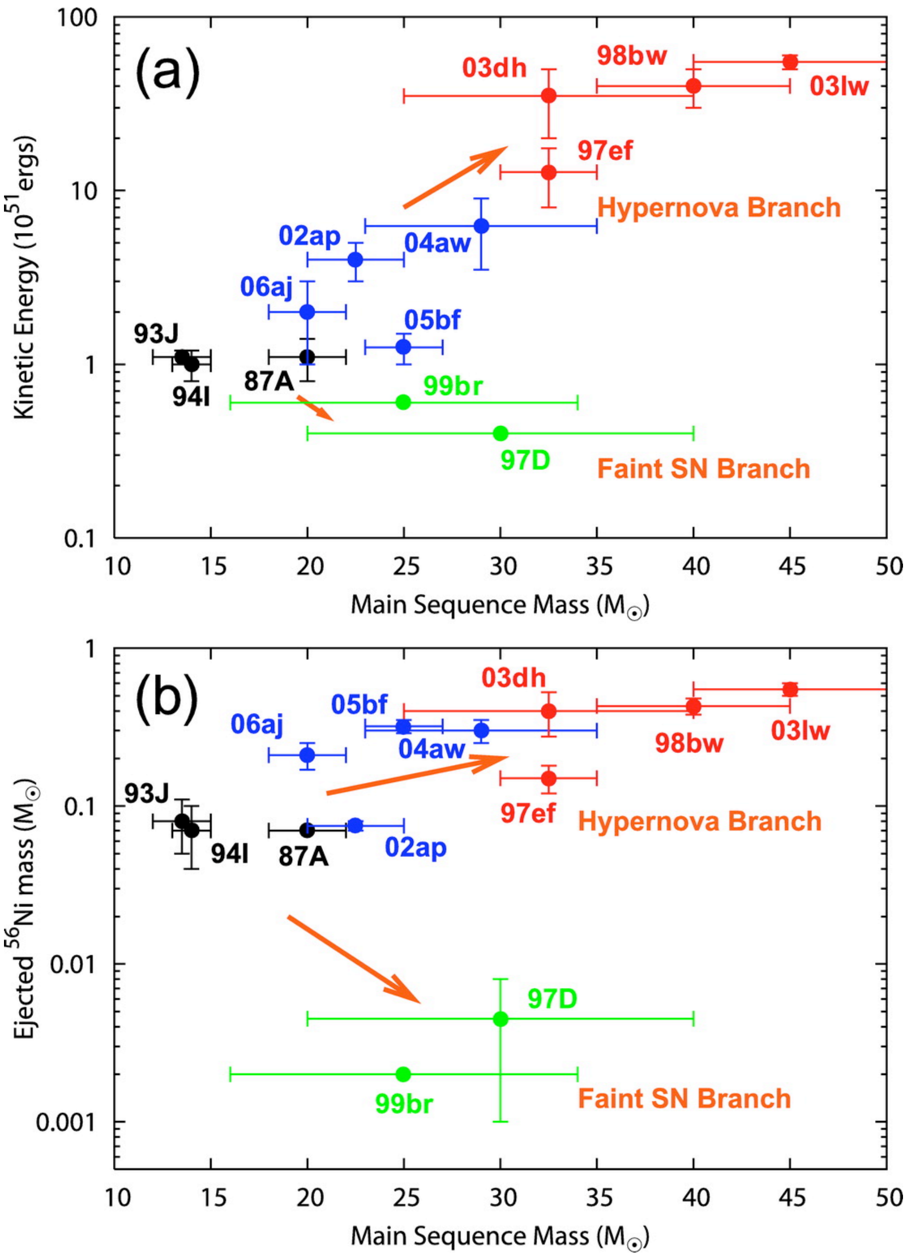


$M \sim 8\text{–}11\, M_\odot$

Low-mass SNe: NS

$M \sim\ 12\text{–}25\, M_\odot$ normal SNe: NS

$M \sim\ 25\text{–}50\, M_\odot$ hypernovae (HNe): BH



Tominaga et al. (2007)

normal SNe

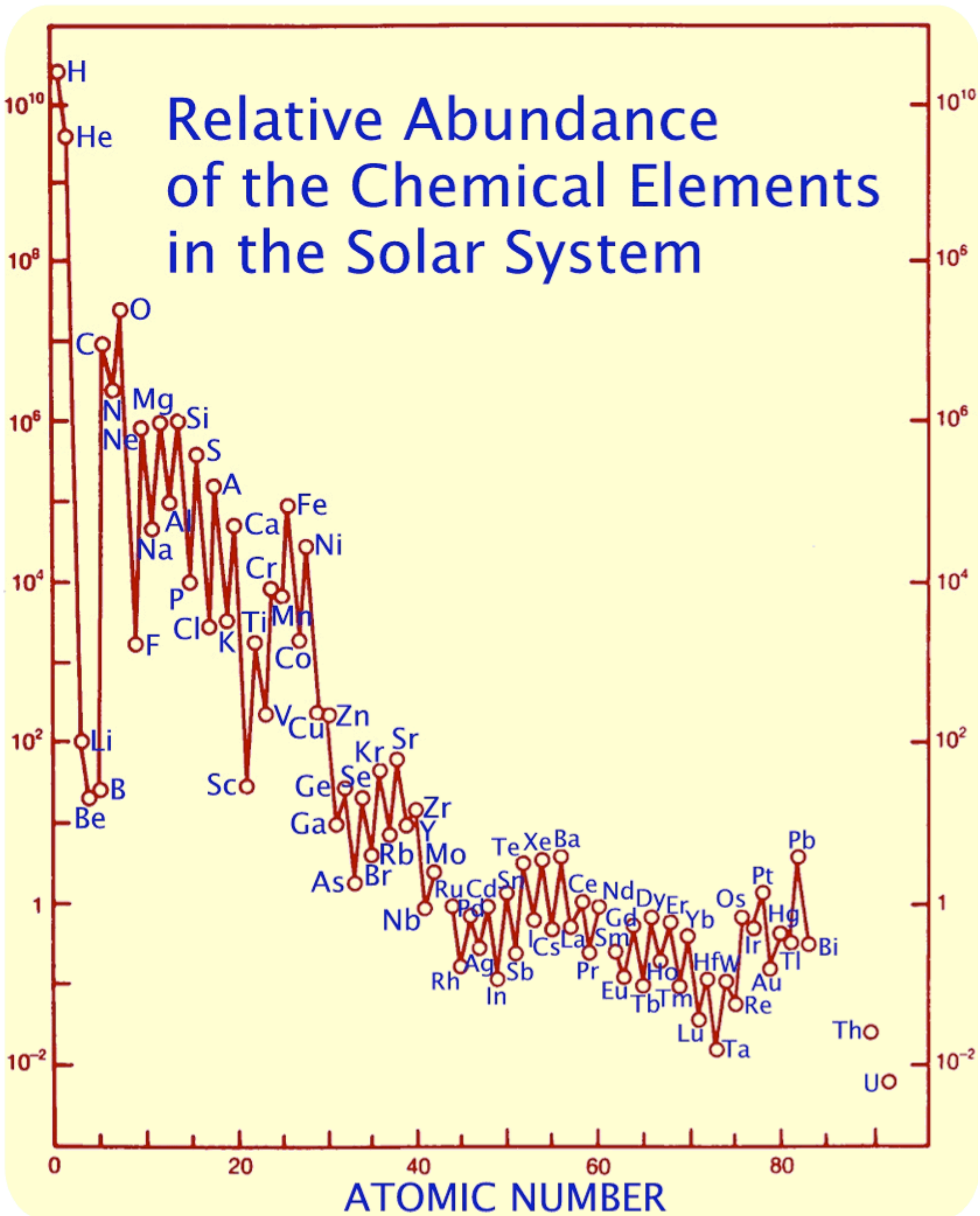
$M \sim 12–25\, M_\odot$

HNe

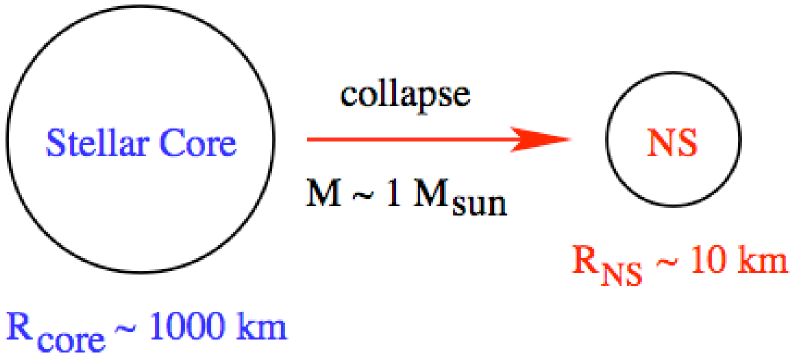
$M \sim 25–50\, M_\odot$

Characteristics of stellar sources

sources	nucleosynthesis	remnants
low-mass SNe	no Fe-like elements	NS
normal SNe	Fe-like elements	NS
HNe	Fe-like elements	BH



Relative Abundance of the Chemical Elements in the Solar System
ATOMIC NUMBER
0
20
40
60
80
10^10
10^8
10^6
10^4
10^2
1
10^-2
H
He
Li
Be
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
A
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Se
Br
Kr
Rb
Sr
Y
Zr
Nb
Mo
Ru
Rh
Pd
Ag
Cd
In
Sn
Sb
Te
I
Xe
Cs
Ba
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
Hf
Ta
W
Re
Os
Ir
Pt
Au
Hg
Tl
Pb
Bi
Th
U



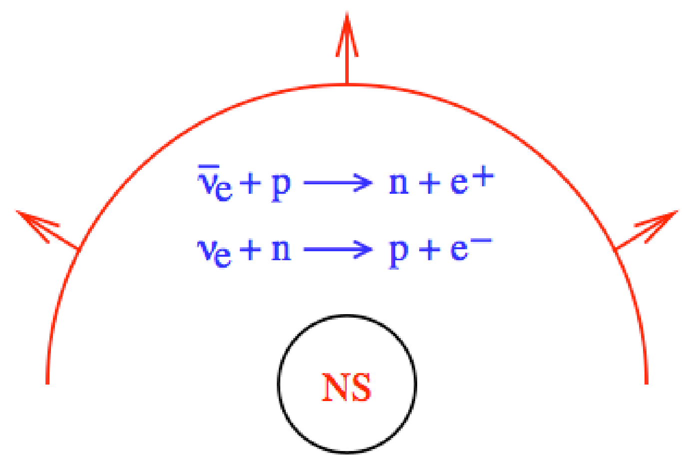
Supernovae as a neutrino phenomenon

$$e^+ + e^- \to \nu + \bar{\nu}, \; N + N \to N + N + \nu + \bar{\nu}$$

$$\frac{GM^2}{R_{\rm NS}} \sim 3 \times 10^{53} \text{ erg} \Rightarrow \nu_e, \; \bar{\nu}_e, \; \nu_{\mu(\tau)}, \; \bar{\nu}_{\mu(\tau)}$$

production of Sr-like elements in the neutrino-driven wind

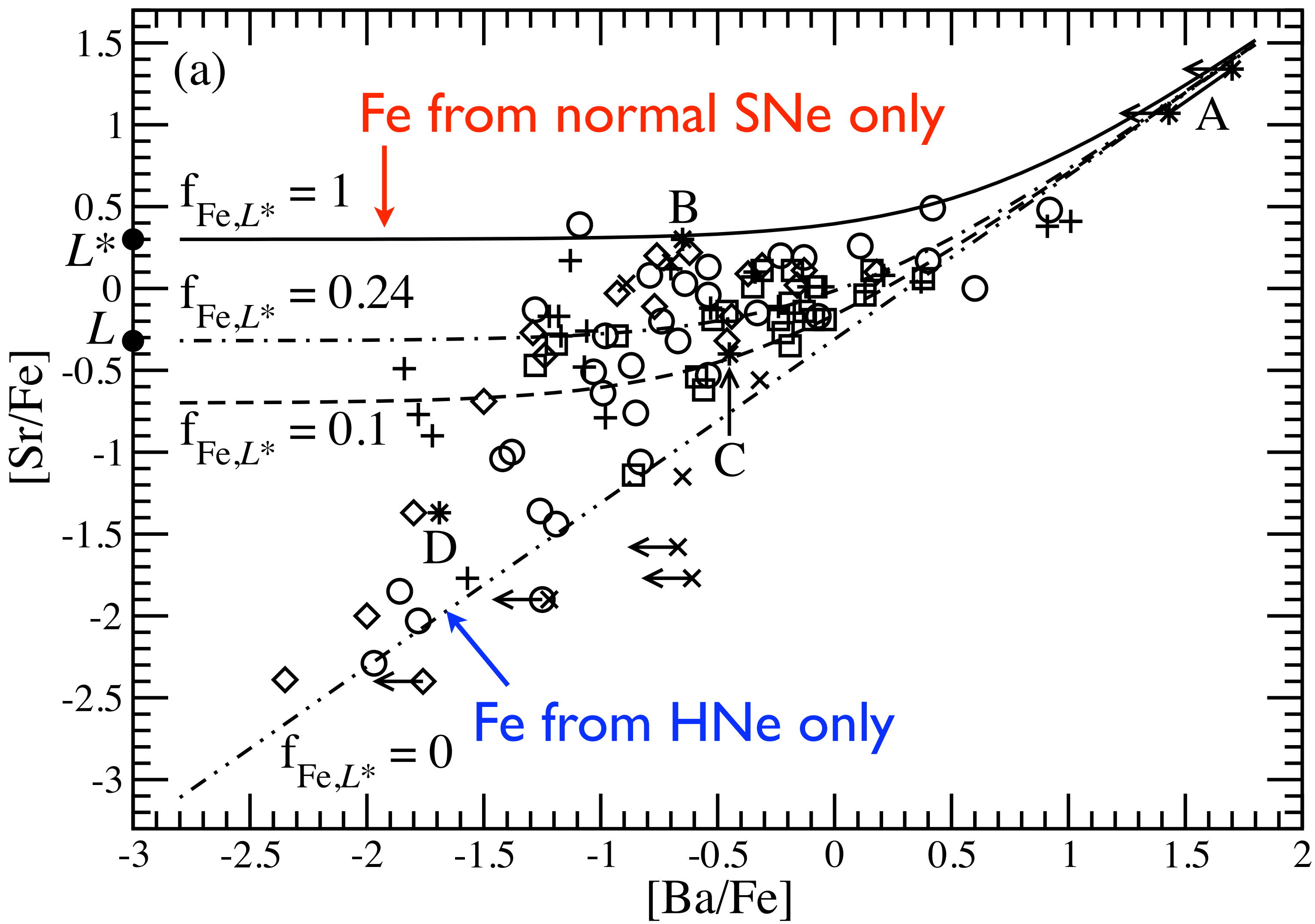
(Woosley & Hoffman 1992;
Frohlich et al. 2004, ’06
Pruet et al. 2005)



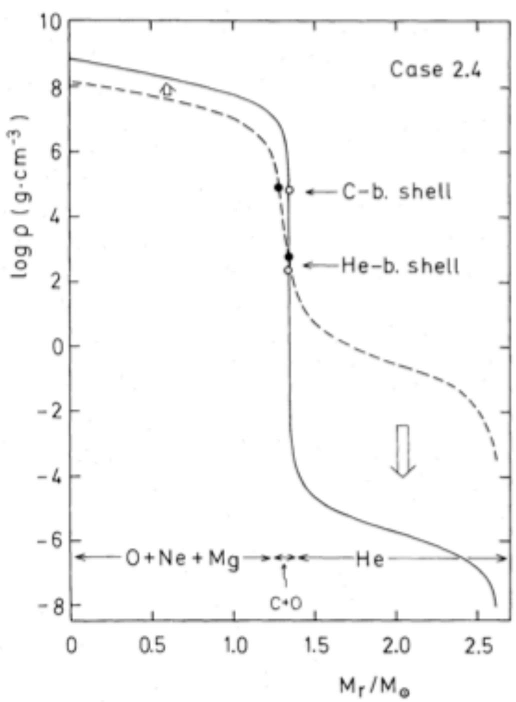
Stellar sources for elements

sources	Fe-like elements	Sr-like elements	Ba-like elements
low-mass SNe	No	Yes	Yes
normal SNe	Yes	Yes	No
HNe	Yes	No	No

3-component model (Qian & Wasserburg 2008)



Exploration of r-process in shocked C-O layer of O-Ne-Mg core (Ning, Qian, & Meyer 2007)



$Y_e \approx 0.495$ (from e.g., ^{13}C)

$T(0) \approx 10^{10}$ K

Shock ⟹ $S \approx 139$

$\tau_{\mathrm{dyn}} \approx 10^{-4}$ s

Such conditions are not obtained in current models of O-Ne-Mg cores & associated SNe (Janka et al. 2008).

Conclusions

- observations of abundances in metal-poor stars require three distinct massive stellar sources in the early universe
- these sources are consistent with low-mass SNe, normal SNe, and HNe from stars of ~ 8–11, 12–25, 25–$50\,M_\odot$, respectively
- observations point to r-process production of Ba and heavier elements by low-mass SNe, but the detailed mechanism remains to be established