

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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Periodic Table of Elements

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H Hydrogen 1.00794	2 He Helium 4.002602																
3 Li Lithium 6.941	4 Be Beryllium 9.012182																
5 Na Sodium 22.98976928	6 Mg Magnesium 24.3050																
7 K Potassium 39.0983	8 Ca Calcium 40.078	9 Sc Scandium 44.955912	10 Ti Titanium 47.887	11 V Vanadium 50.9415	12 Cr Chromium 51.9961	13 Mn Manganese 54.938045	14 Fe Iron 55.845	15 Co Cobalt 58.933195	16 Ni Nickel 58.6934	17 Cu Copper 63.546	18 Zn Zinc 65.38	19 Ga Gallium 69.723	20 Ge Germanium 72.64	21 As Arsenic 74.92160	22 Se Selenium 78.96	23 Br Bromine 79.904	24 Kr Krypton 83.798
25 Rb Rubidium 85.4678	26 Sr Strontium 87.62	27 Y Yttrium 88.90585	28 Zr Zirconium 91.224	29 Nb Niobium 92.90638	30 Mo Molybdenum 95.96	31 Tc Technetium (97.9072)	32 Ru Ruthenium 101.07	33 Rh Rhodium 102.90550	34 Pd Palladium 106.42	35 Ag Silver 107.8682	36 Cd Cadmium 112.411	37 In Indium 114.818	38 Sn Tin 118.710	39 Sb Antimony 121.760	40 Te Tellurium 127.60	41 I Iodine 126.90447	42 Xe Xenon 131.293
37 Cs Cesium 132.9054519	38 Ba Barium 137.327	39 La Lanthanum 138.90547	40 Ce Cerium 140.116	41 Pr Praseodymium 140.90765	42 Nd Neodymium 144.242	43 Pm Promethium (145)	44 Sm Samarium 150.36	45 Eu Europium 151.964	46 Gd Gadolinium 157.25	47 Tb Terbium 158.92535	48 Dy Dysprosium 162.500	49 Ho Holmium 164.93032	50 Er Erbium 167.259	51 Tm Thulium 168.93421	52 Yb Ytterbium 173.054	53 Lu Lutetium 174.9668	54 Hf Hafnium 178.49
55 Fr Francium (223)	56 Ra Radium (226)	57 Ac Actinium (227)	58 Th Thorium 232.03806	59 Pa Protactinium 231.03688	60 U Uranium 238.02891	61 Np Neptunium (237)	62 Pu Plutonium (244)	63 Am Americium (243)	64 Cm Curium (247)	65 Bk Berkelium (247)	66 Cf Californium (251)	67 Es Einsteinium (252)	68 Fm Fermium (257)	69 Md Mendelevium (258)	70 No Nobelium (259)	71 Lr Lawrencium (262)	72 Ta Tantalum 180.94788
73 Hf Hafnium 178.49	74 Ta Tantalum 180.94788	75 W Tungsten 183.84	76 Re Rhenium 186.207	77 Os Osmium 190.23	78 Ir Iridium 192.22	79 Pt Platinum 195.084	80 Au Gold 196.966569	81 Hg Mercury 200.59	82 Tl Thallium 204.3833	83 Pb Lead 207.2	84 Bi Bismuth 208.98040	85 Po Polonium (209)	86 At Astatine (210)	87 Rn Radon (222)	88 Fr Francium (223)	89 Ra Radium (226)	90 Ac Actinium (227)
101 Db Dubnium (261)	102 Sg Seaborgium (266)	103 Bh Bohrium (264)	104 Hs Hassium (277)	105 Mt Meitnerium (268)	106 Ds Darmstadtium (271)	107 Rg Roentgenium (272)	108 Uub Ununbium (285)	109 Uut Ununtrium (284)	110 Uuq Ununquadium (289)	111 Uup Ununpentium (288)	112 Uuh Ununhexium (292)	113 Uus Ununseptium (294)	114 Uuo Ununoctium (294)	115 Uus Ununseptium (294)	116 Uuo Ununoctium (294)	117 Uus Ununseptium (294)	118 Uuo Ununoctium (294)

For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

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Ptable.com

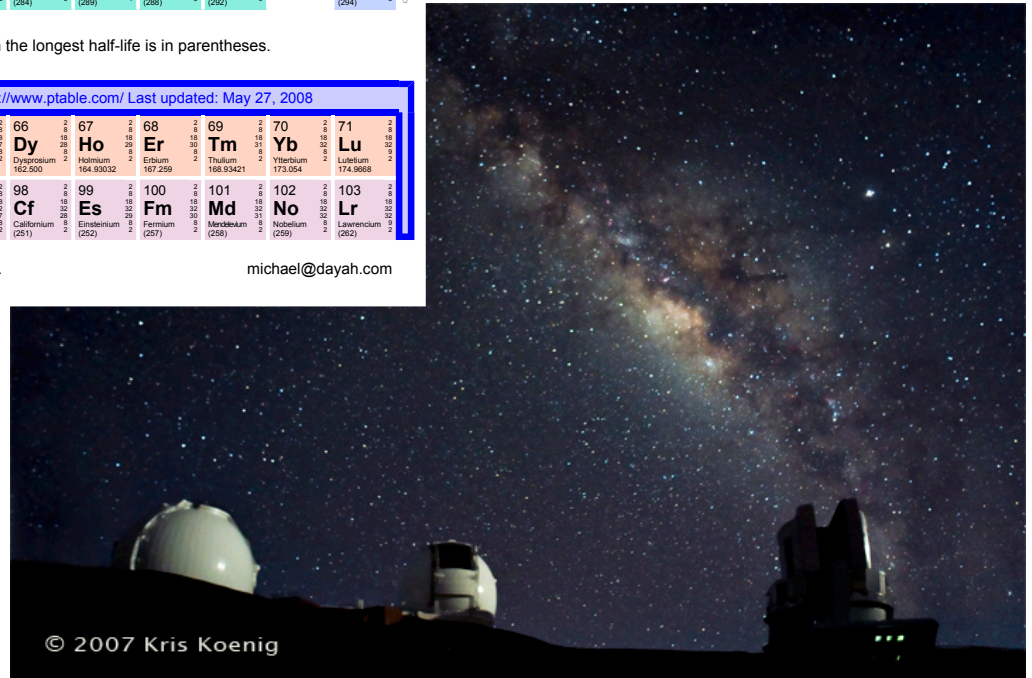
Michael Dayah

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stars make
“metals” after
the big bang

observations of
metal abundances by
Keck, VLT, Subaru



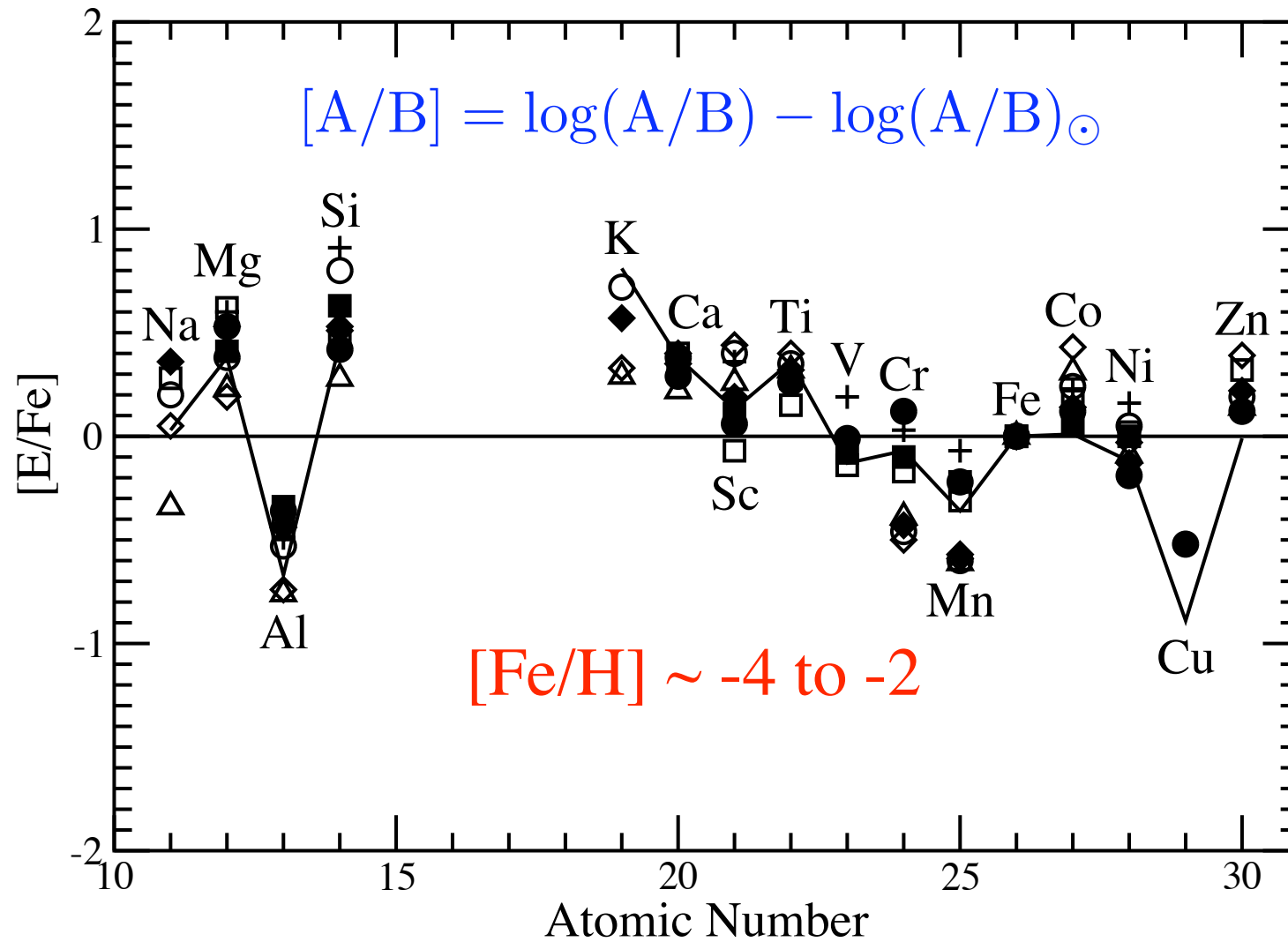
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Elemental abundances in metal-poor stars

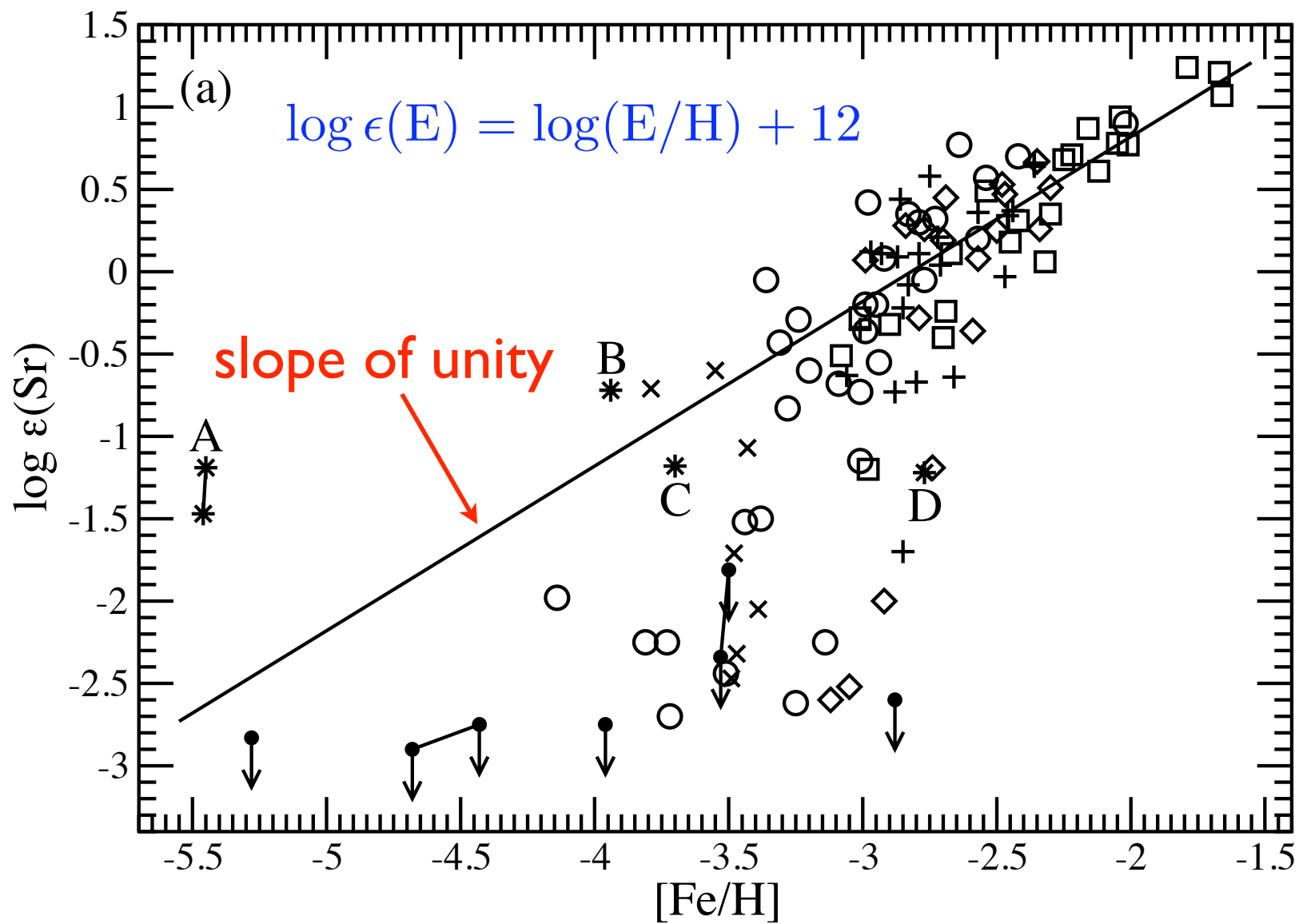
(Johnson 2002; Honda et al. 2004; Aoki et al. 2005;
Francois et al. 2007; Cohen et al. 2007)

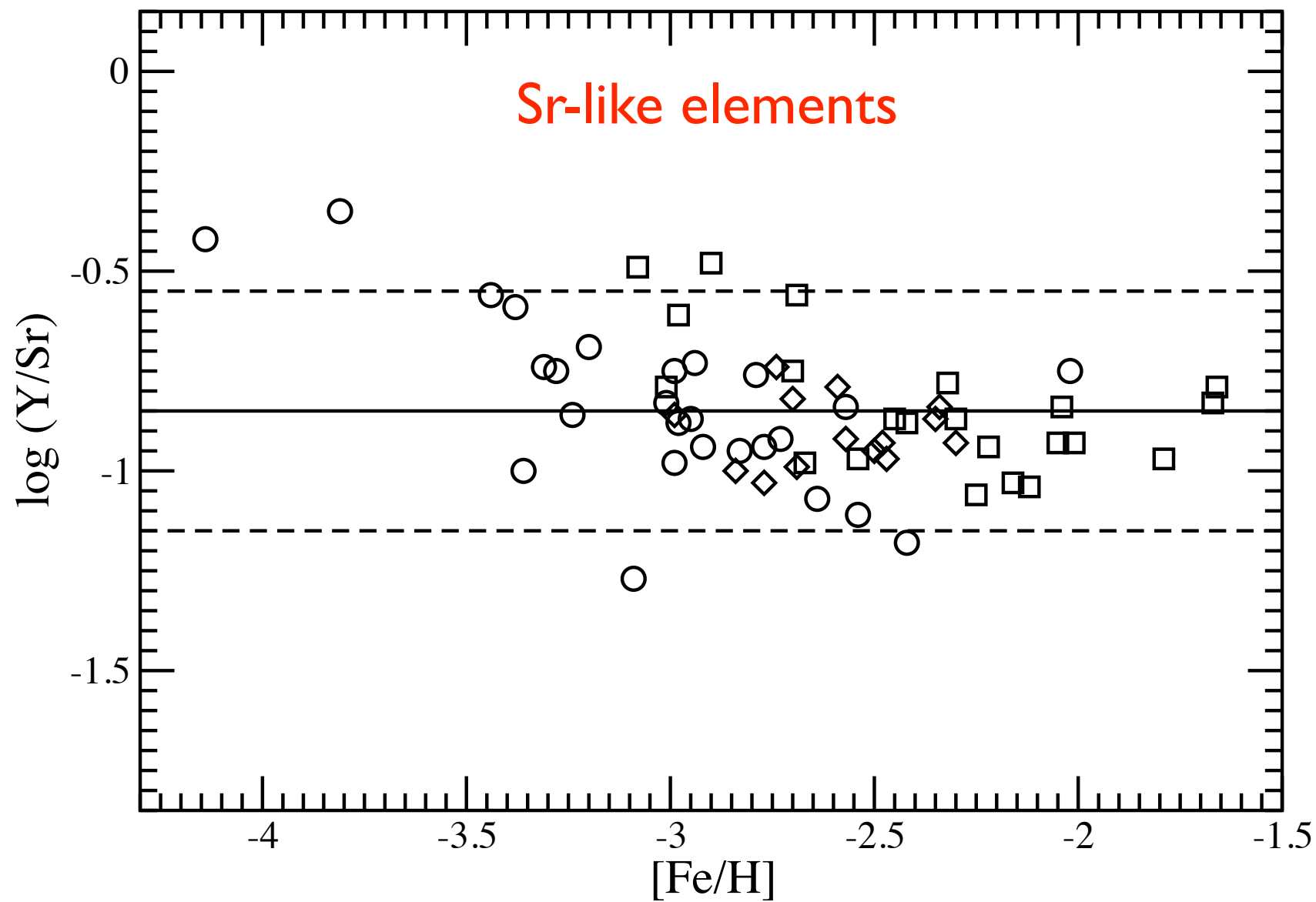
- Fe-like elements ($A \sim 23$ to 70)
Na, Mg, Al, Si, ..., Fe, ..., Zn
- Sr-like elements ($A \sim 88$ to 110)
Sr, Y, Zr, ..., Ag
- Ba-like elements ($A > 130$)
Ba, ..., Eu, ..., Pt, ..., Th, ..., U, ...

Quasi-uniform pattern of Fe-like elements

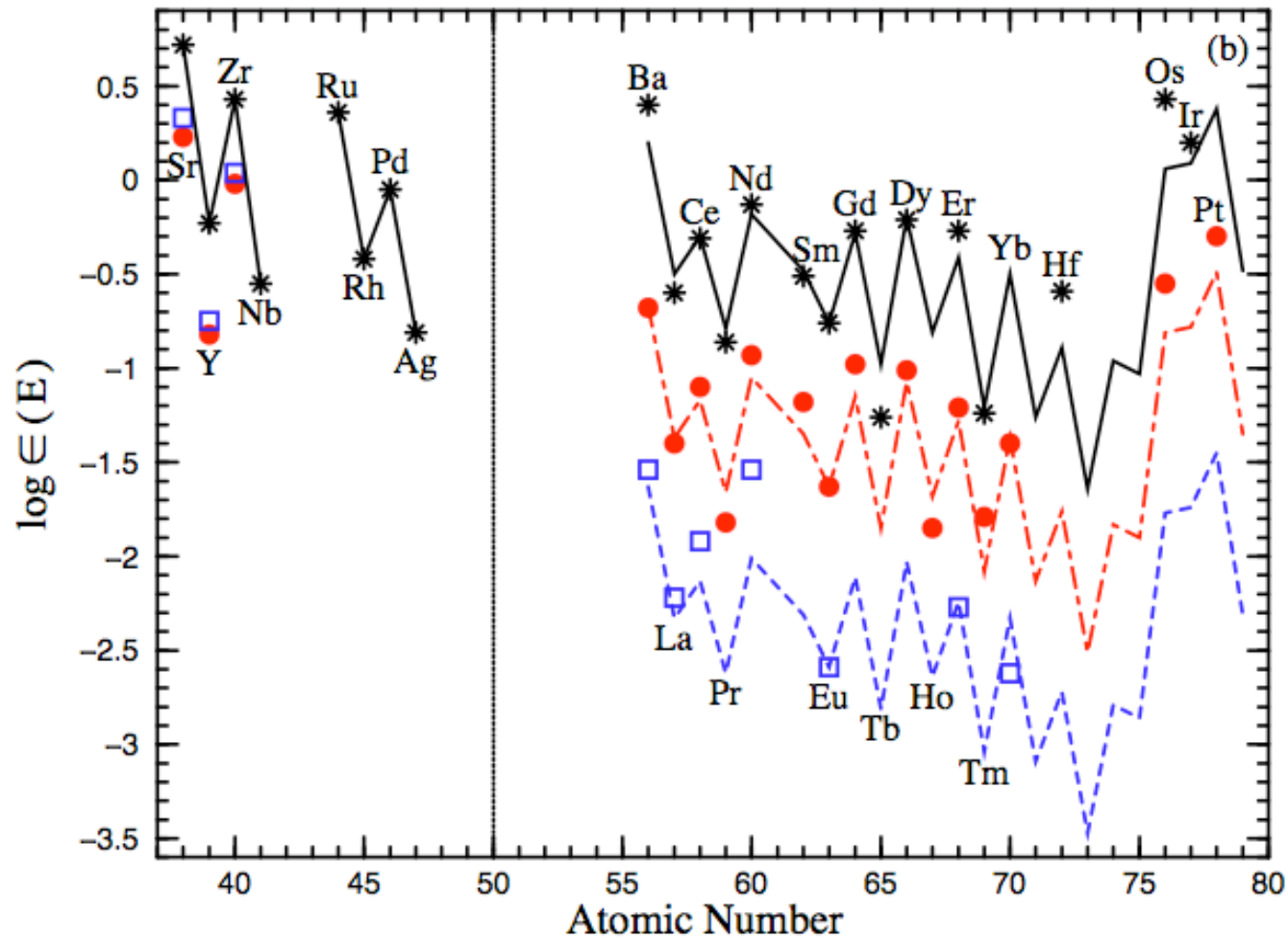


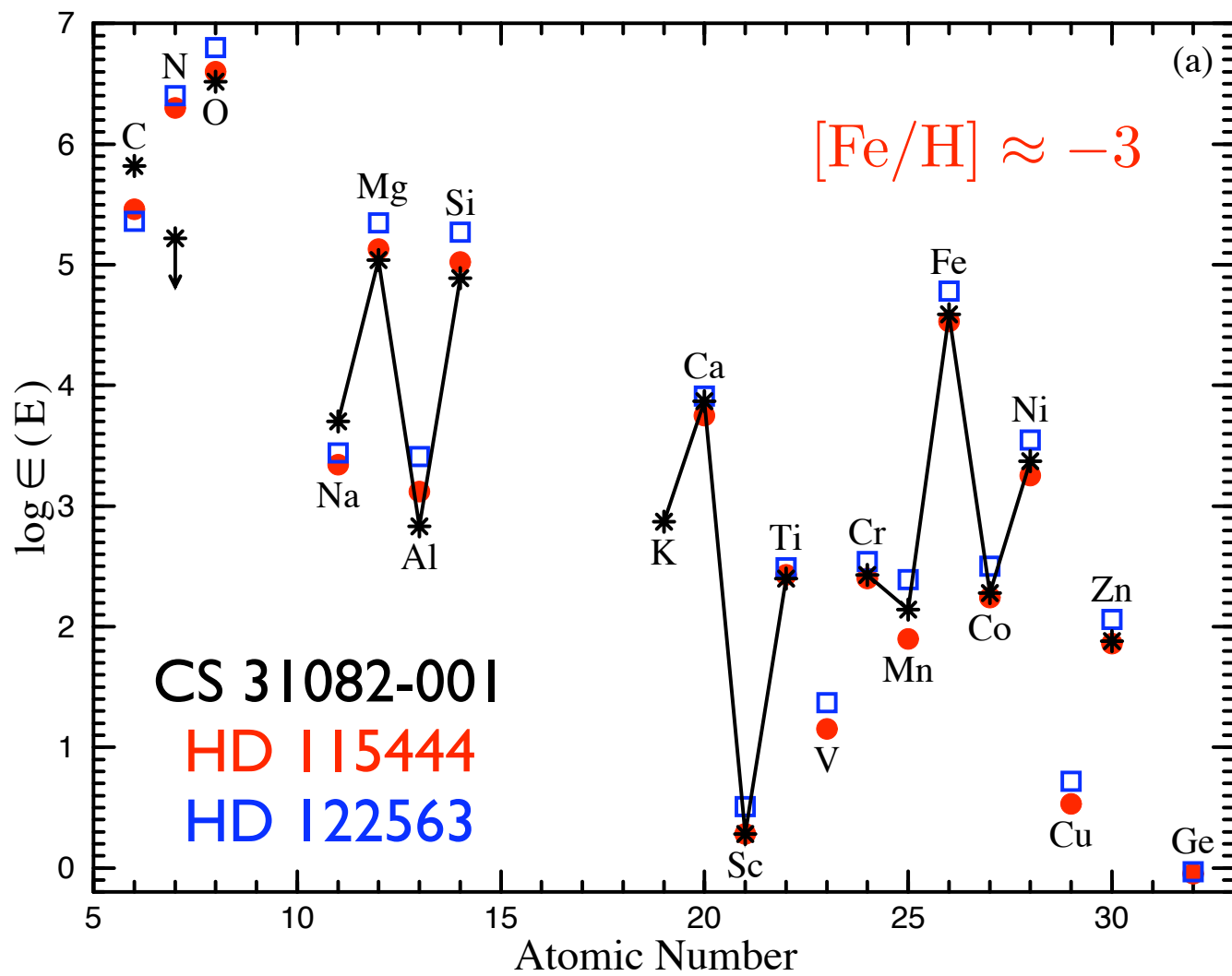
Evolution of Sr with Fe

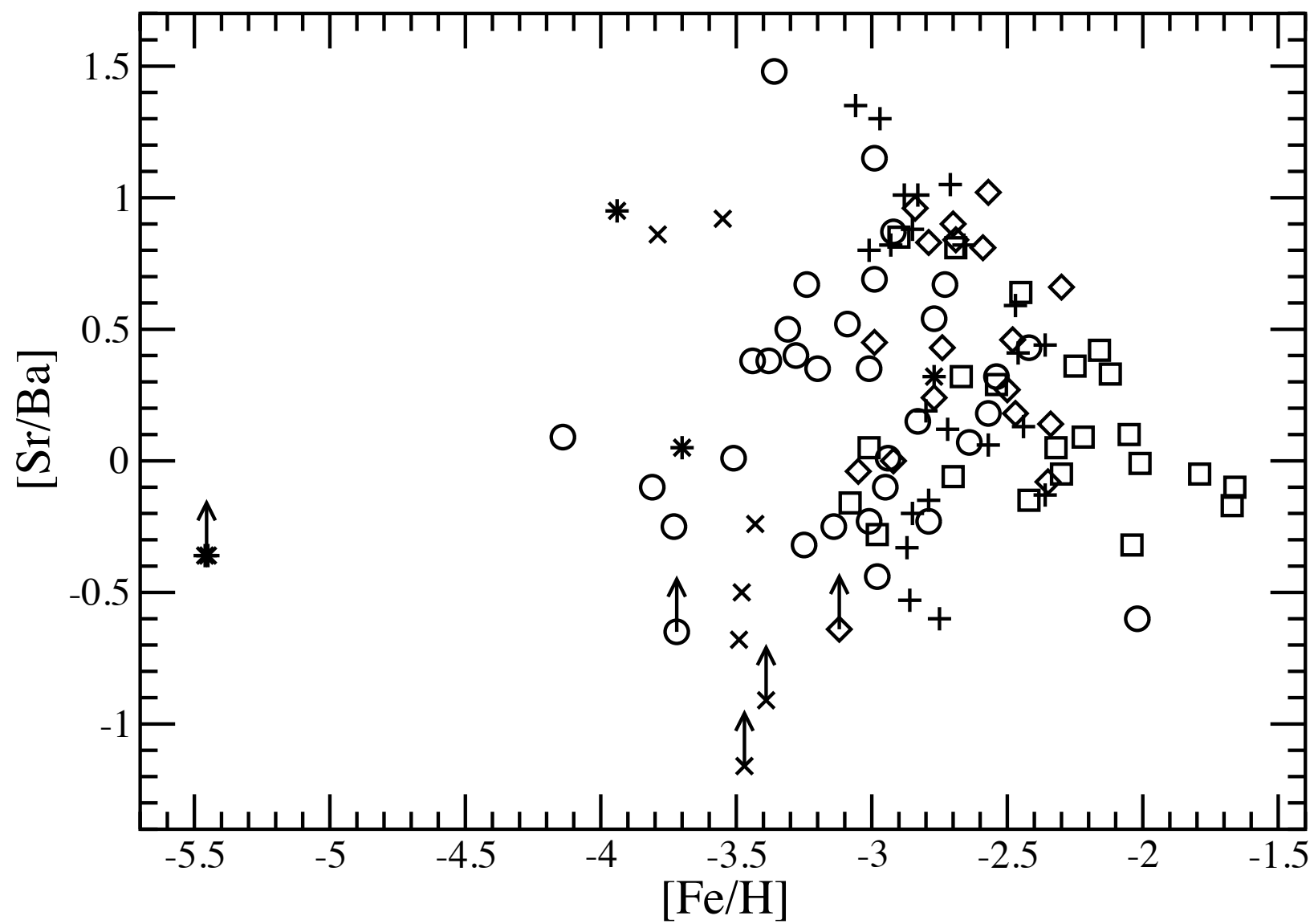


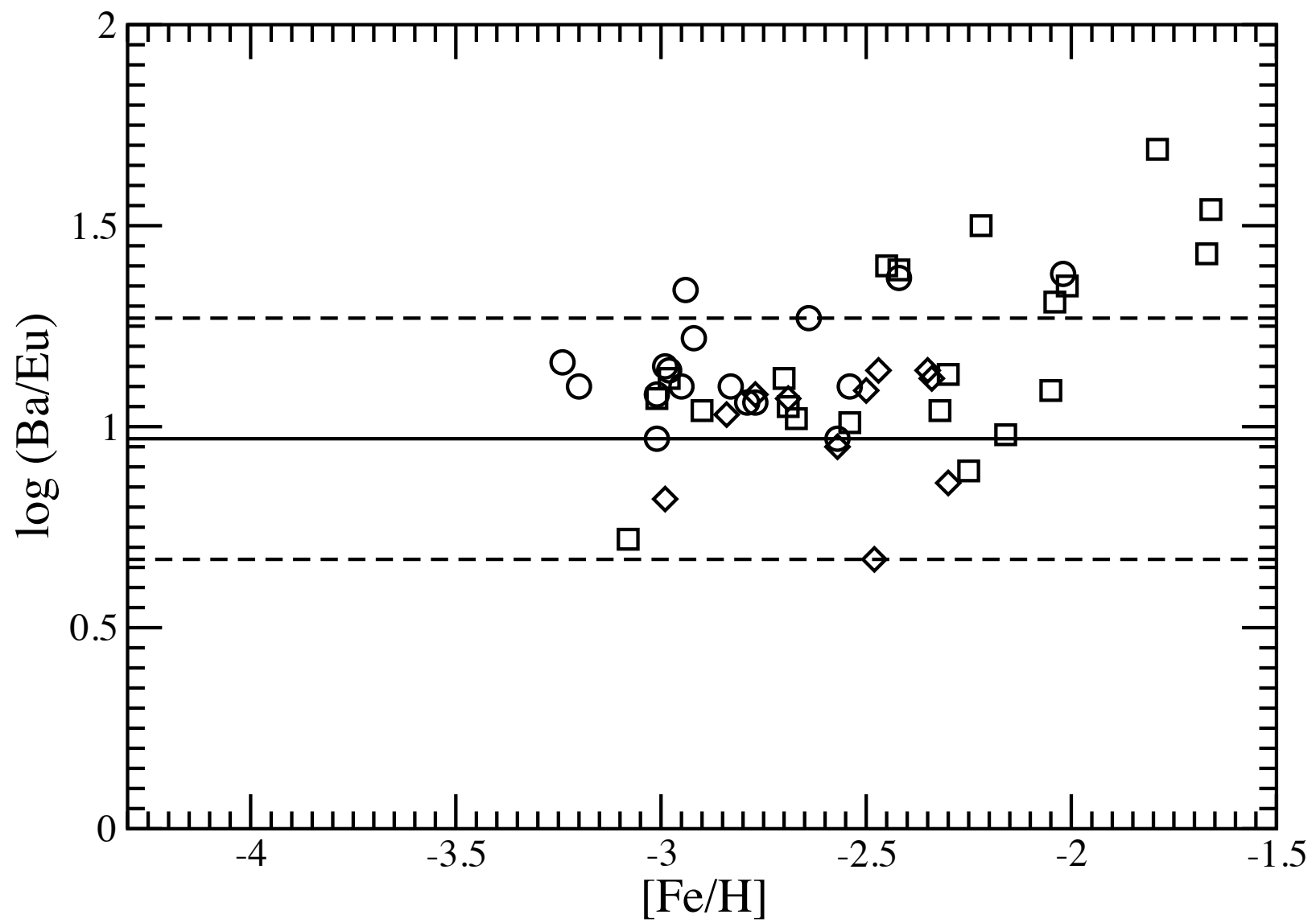


Observations of Ba-like elements
(Westin et al. 2000; Hill et al. 2002)









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 $M \gtrsim 8 M_{\odot} \Rightarrow \tau \lesssim 30 \text{ Myr}$

core-collapse SNe: neutron stars, black holes

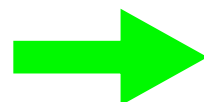
low- and intermediate-mass stars

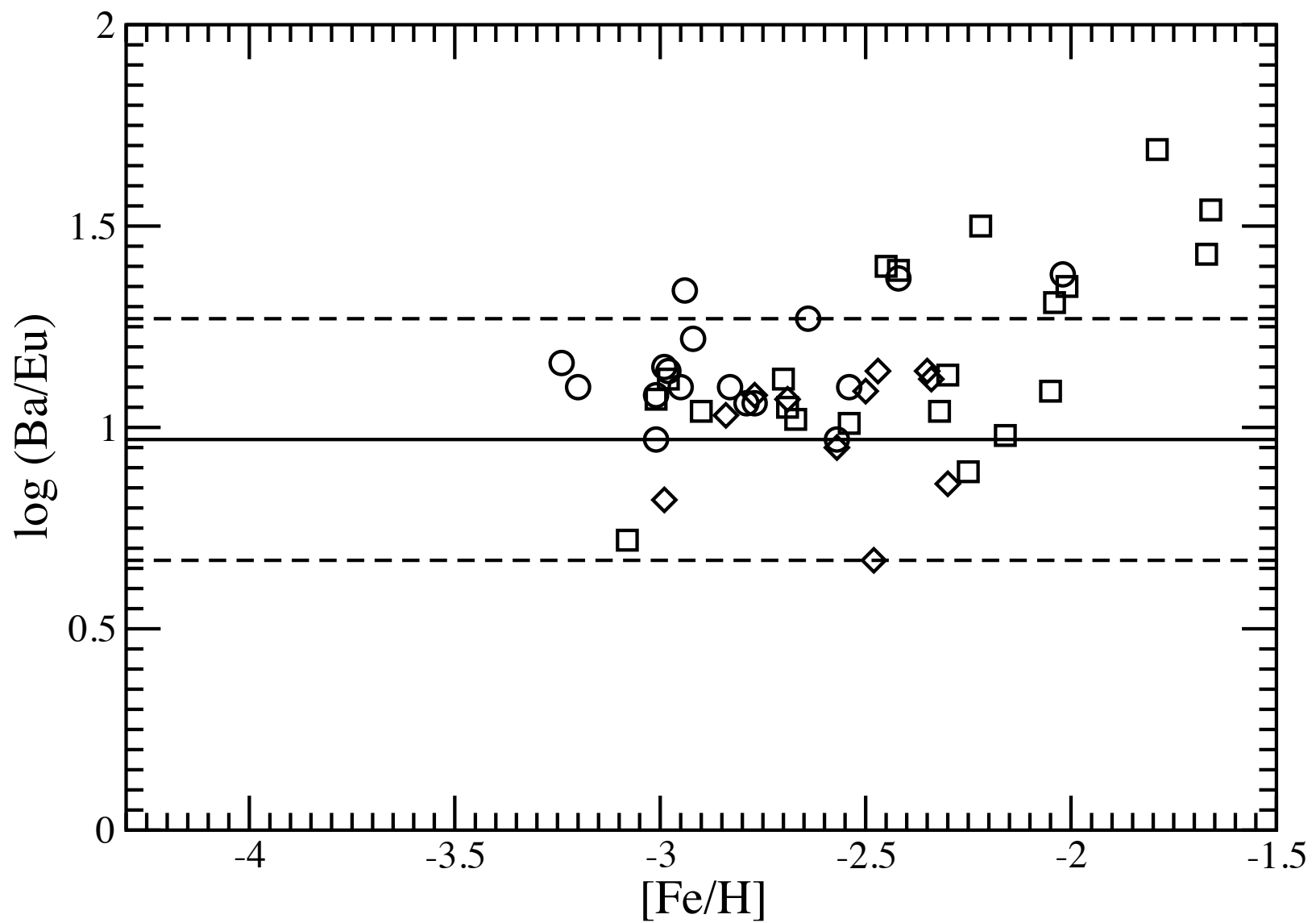
$M \sim 1\text{--}8 M_{\odot}, \langle M \rangle \sim 2 M_{\odot} \Rightarrow \tau \sim 1 \text{ Gyr}$

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

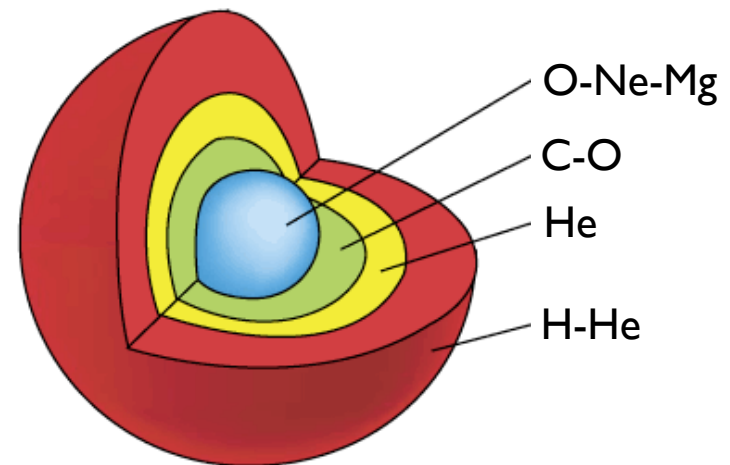
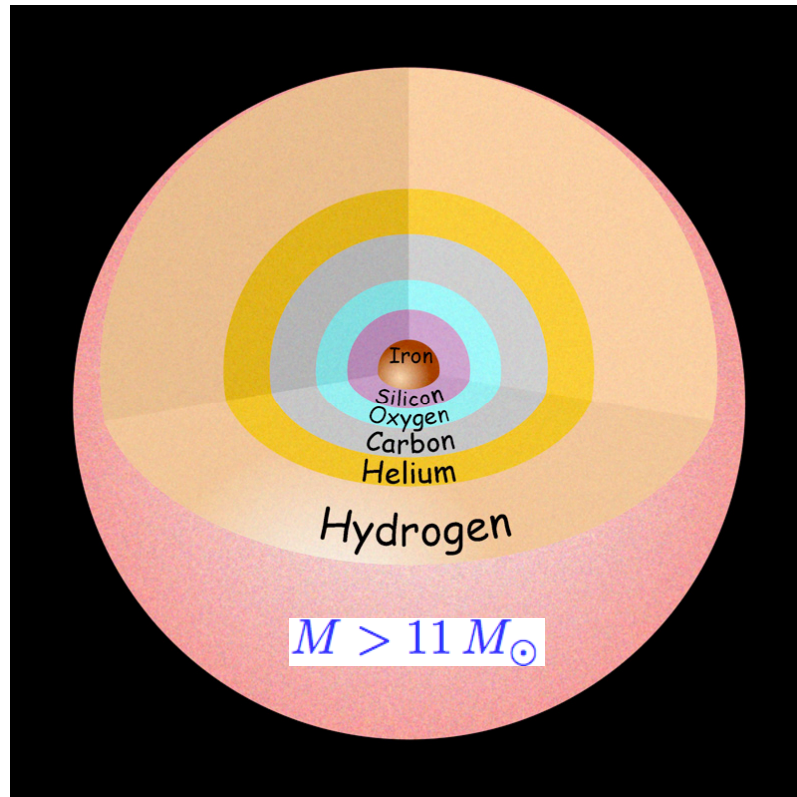
WDs in binaries: SNe Ia (Fe group, $A \sim 56$)

CCSNe over 10 Gyr: $\sim 1/3$ of solar Fe

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



Three types of core-collapse SNe

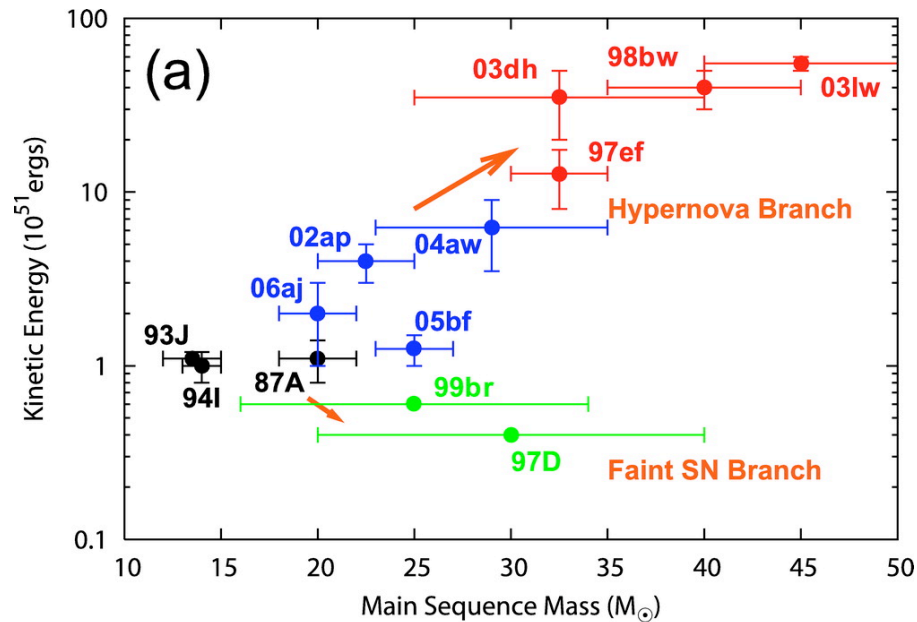


$$M \sim 8-11 M_{\odot}$$

Low-mass SNe: NS

$M \sim 12-25 M_{\odot}$ normal SNe: NS

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



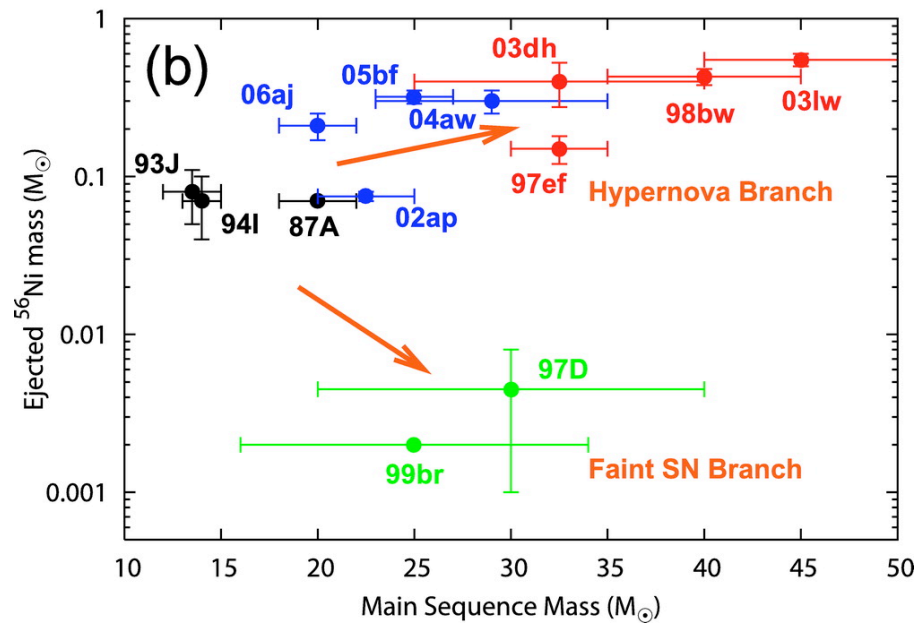
Tominaga et al. (2007)

normal SNe

$$M \sim 12\text{--}25 M_{\odot}$$

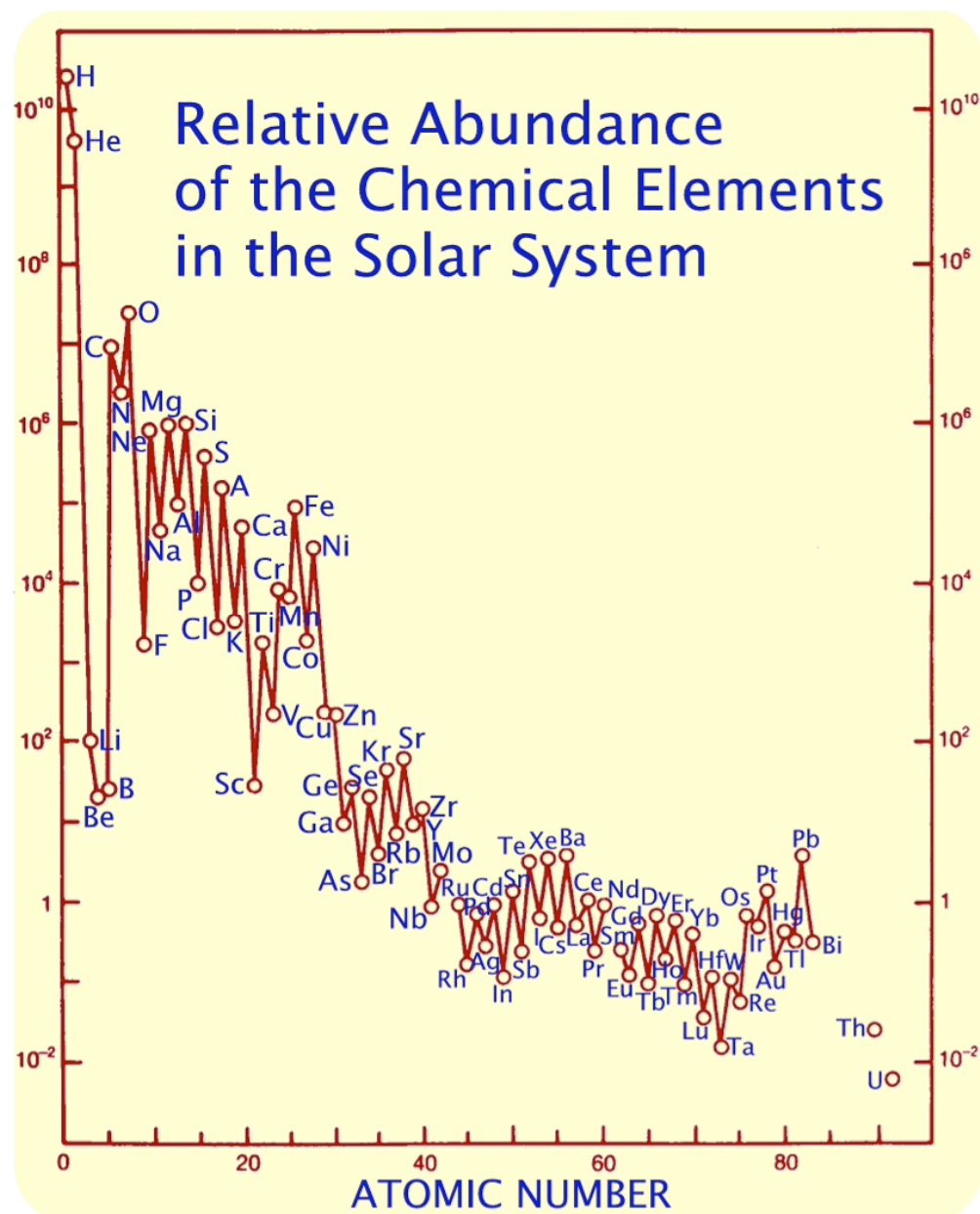
HNe

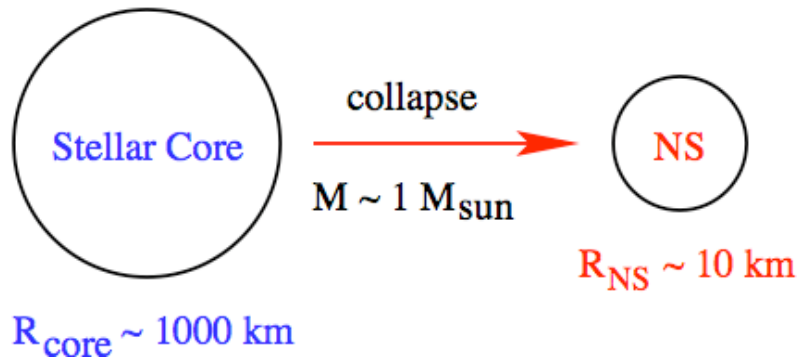
$$M \sim 25\text{--}50 M_{\odot}$$



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





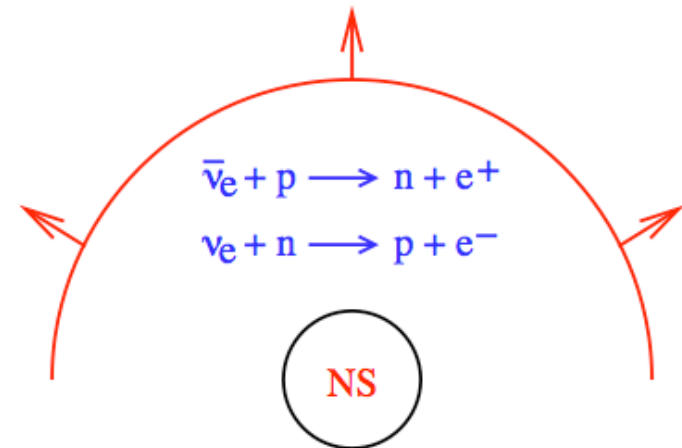
Supernovae as a neutrino phenomenon

$$e^+ + e^- \rightarrow \nu + \bar{\nu}, \quad N + N \rightarrow N + N + \nu + \bar{\nu}$$

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

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

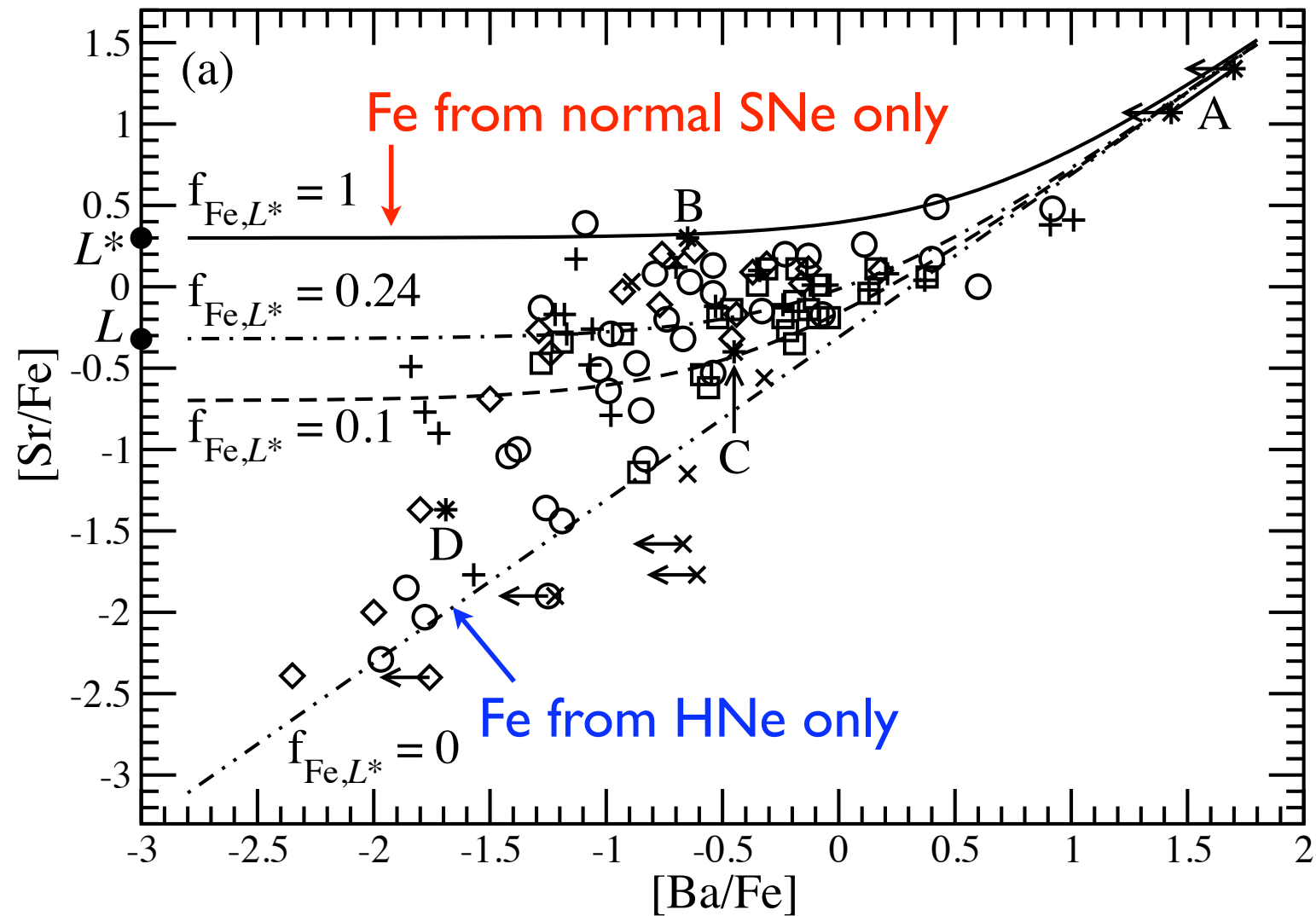
(Woosley & Hoffman 1992;
Frohlich et al. 2004, '06
Pruet et al. 2005)



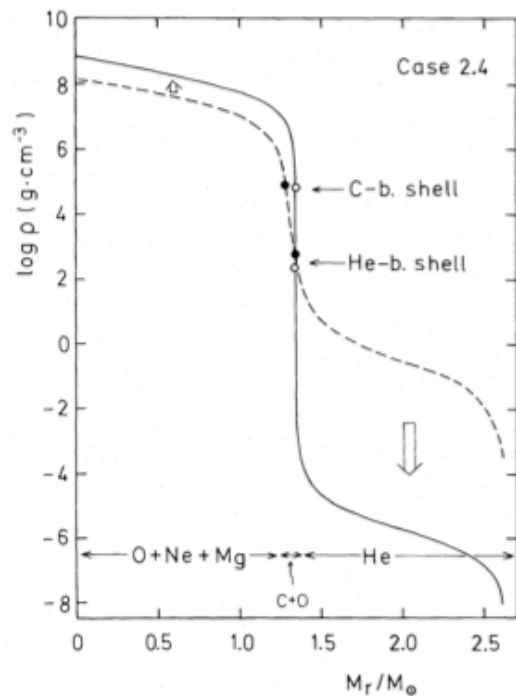
Stellar sources for elements

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)



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

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

$$\text{Shock} \rightarrow S \approx 139$$

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

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 $\sim 8\text{--}11, 12\text{--}25, 25\text{--}50 M_{\odot}$, respectively
- observations point to r-process production of Ba and heavier elements by low-mass SNe, but the detailed mechanism remains to be established