r-process nucleosynthesis and chemical evolution in the early Galaxy

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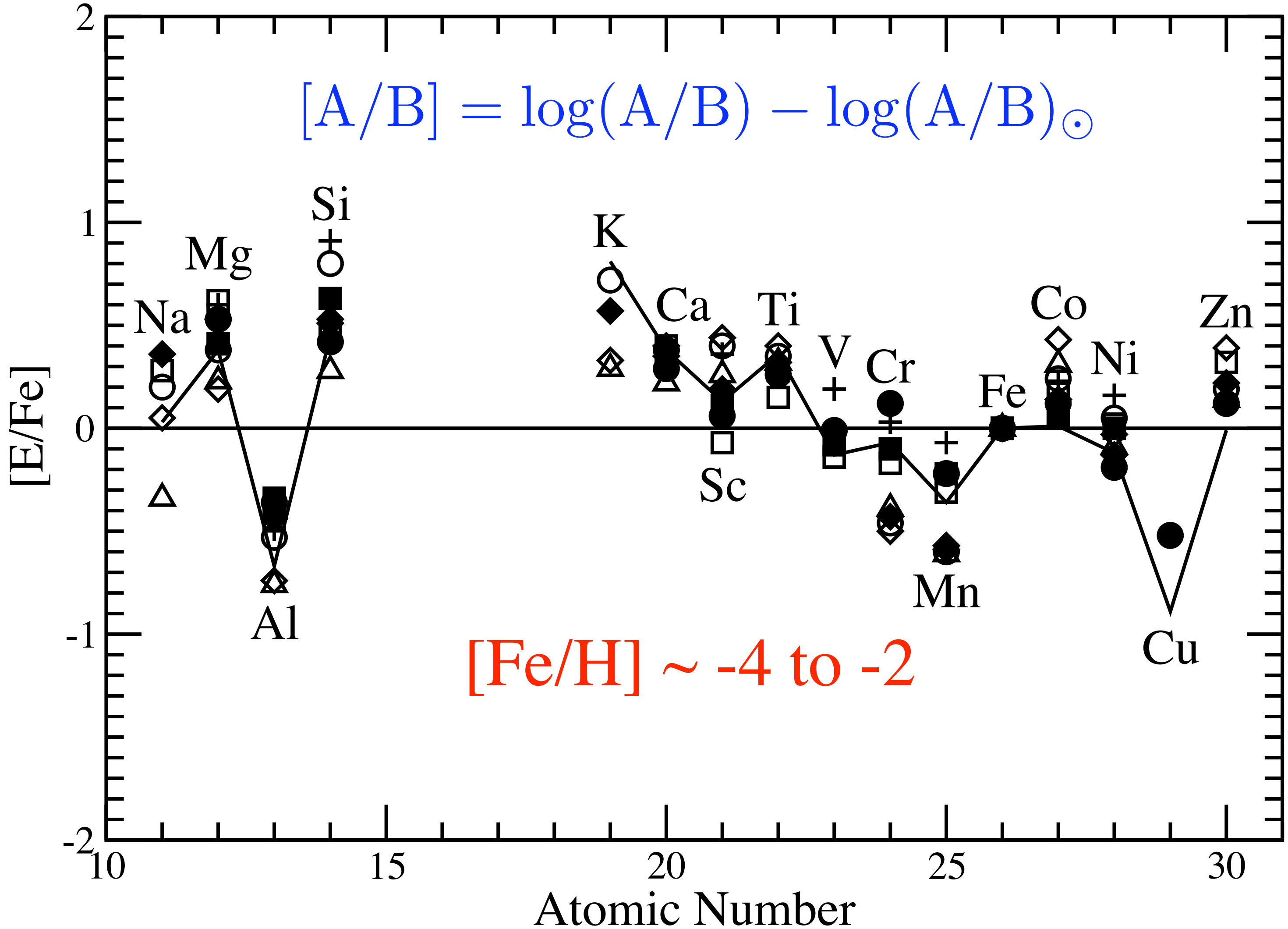
November 18, 2011

Elemental abundances in metal-poor stars

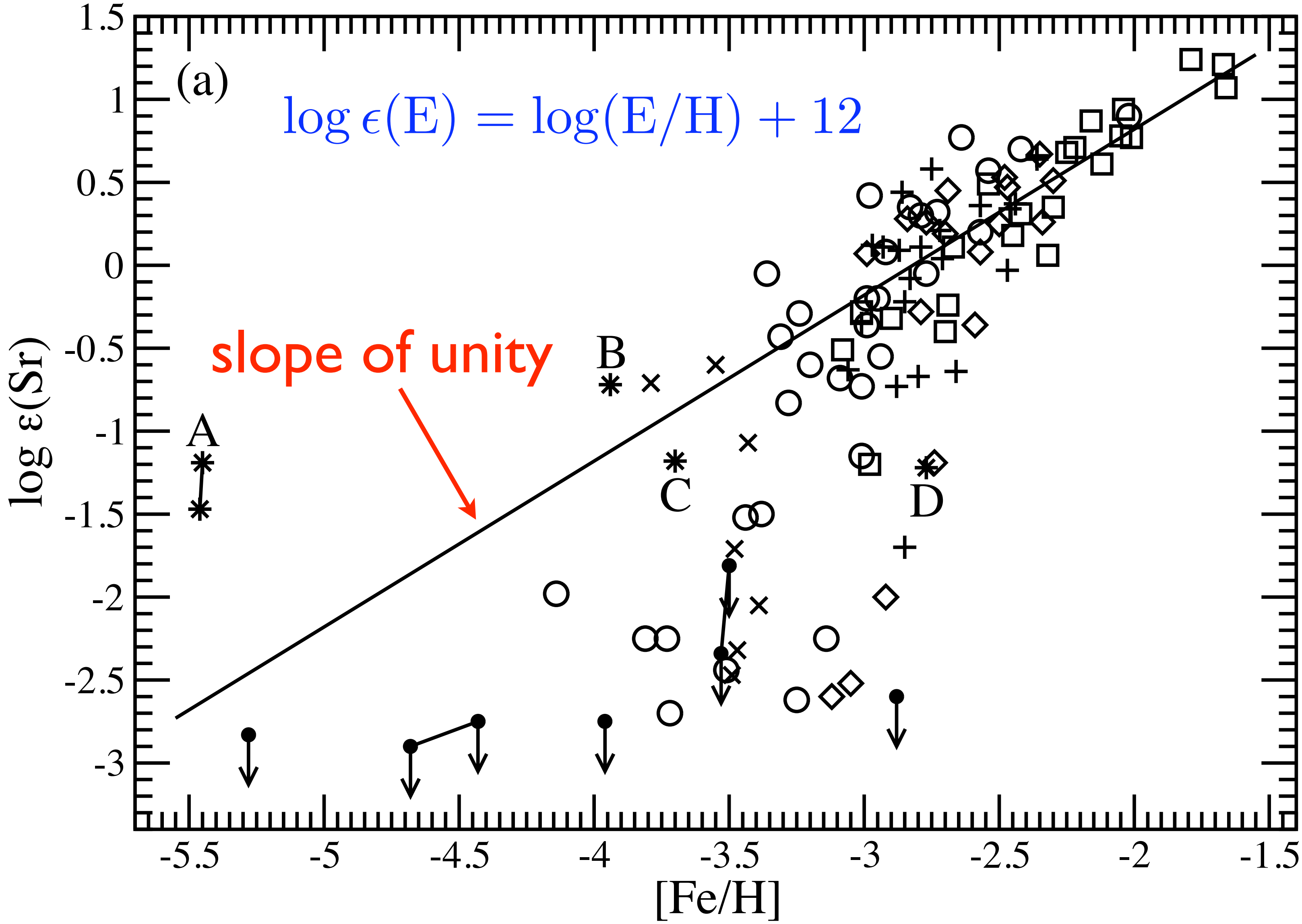
(Johnson 2002; Honda et al. 2004; Aoki et al. 2005; Francois et al. 2007; Cohen et al. 2007)

- 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

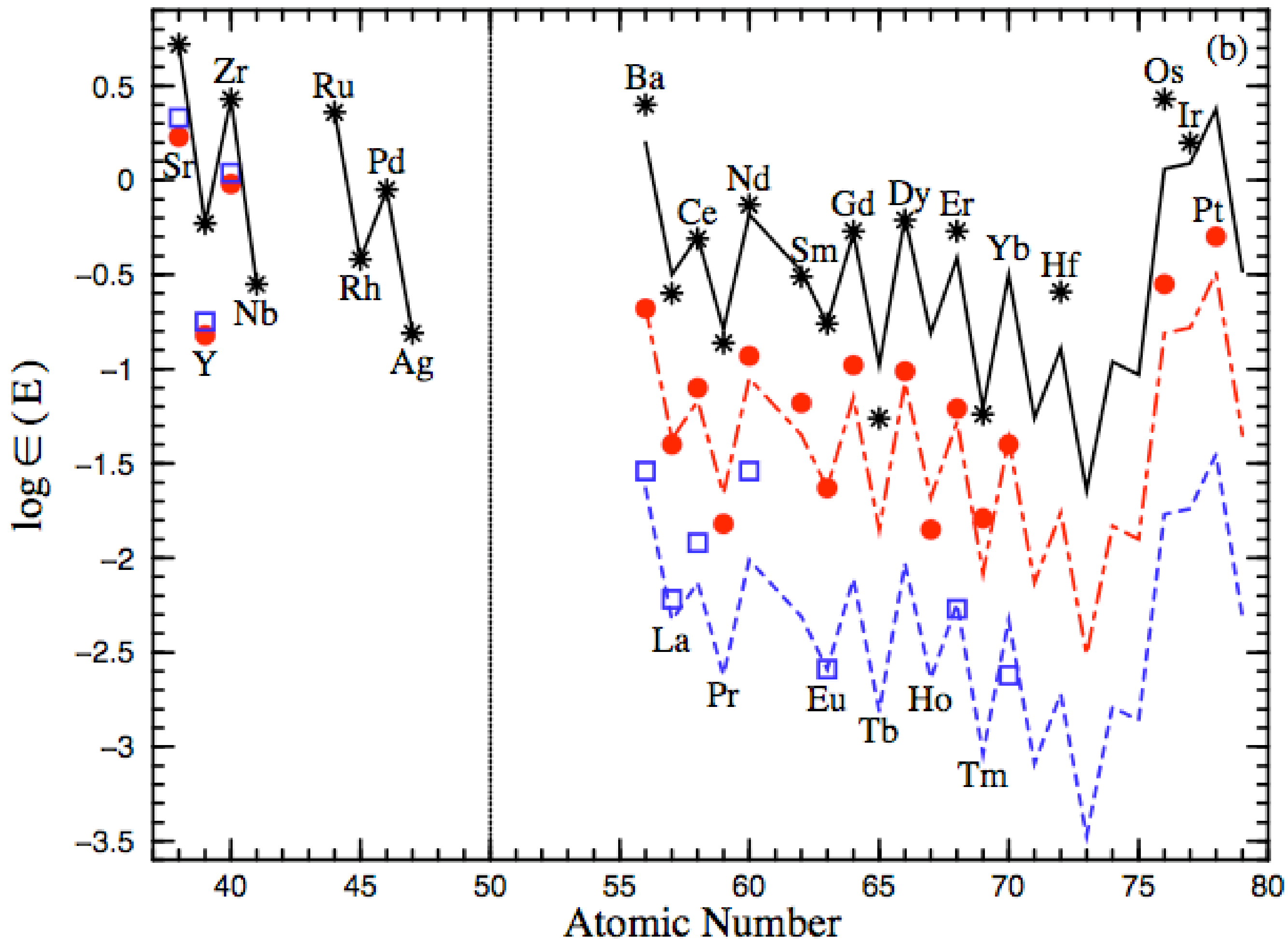


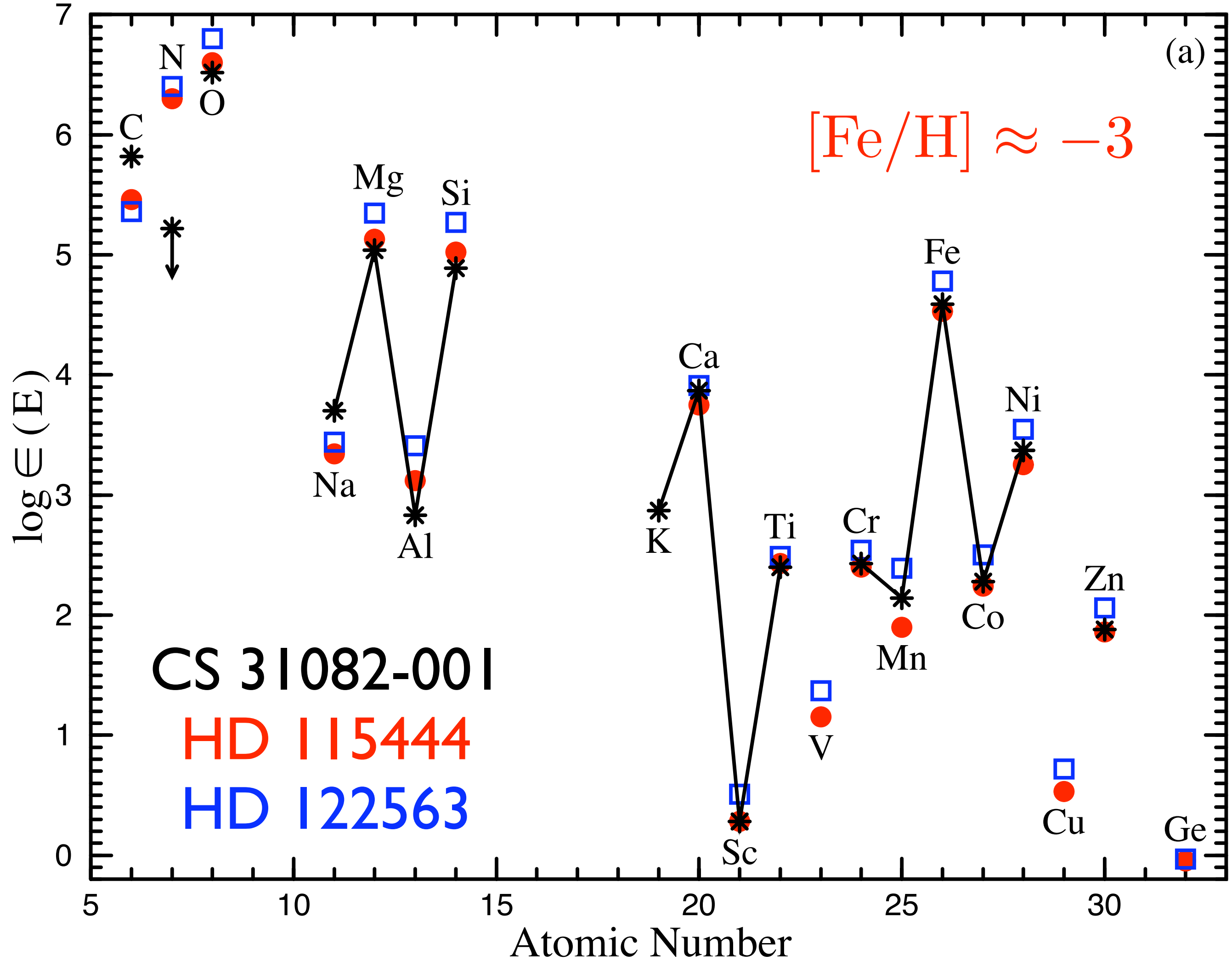
Evolution of Sr with Fe



Observations of Sr- & Ba-like elements

(Westin et al. 2000; Hill et al. 2002)





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

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

three areas of r-process study

properties of neutron-rich nuclei far from stability

→ detailed production pattern

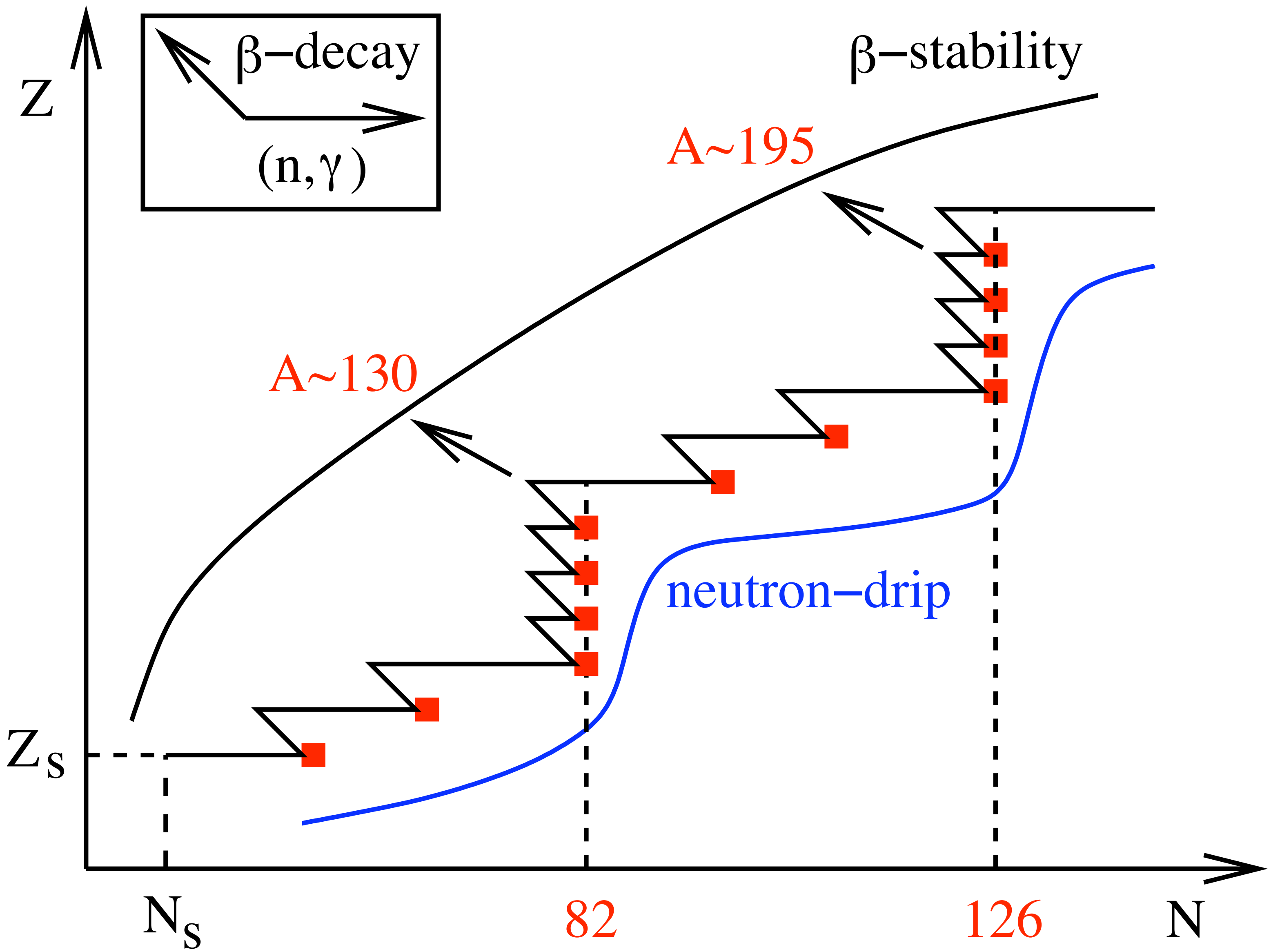
conditions in astrophysical sites

→ n_n, T, neutron-to-seed ratio

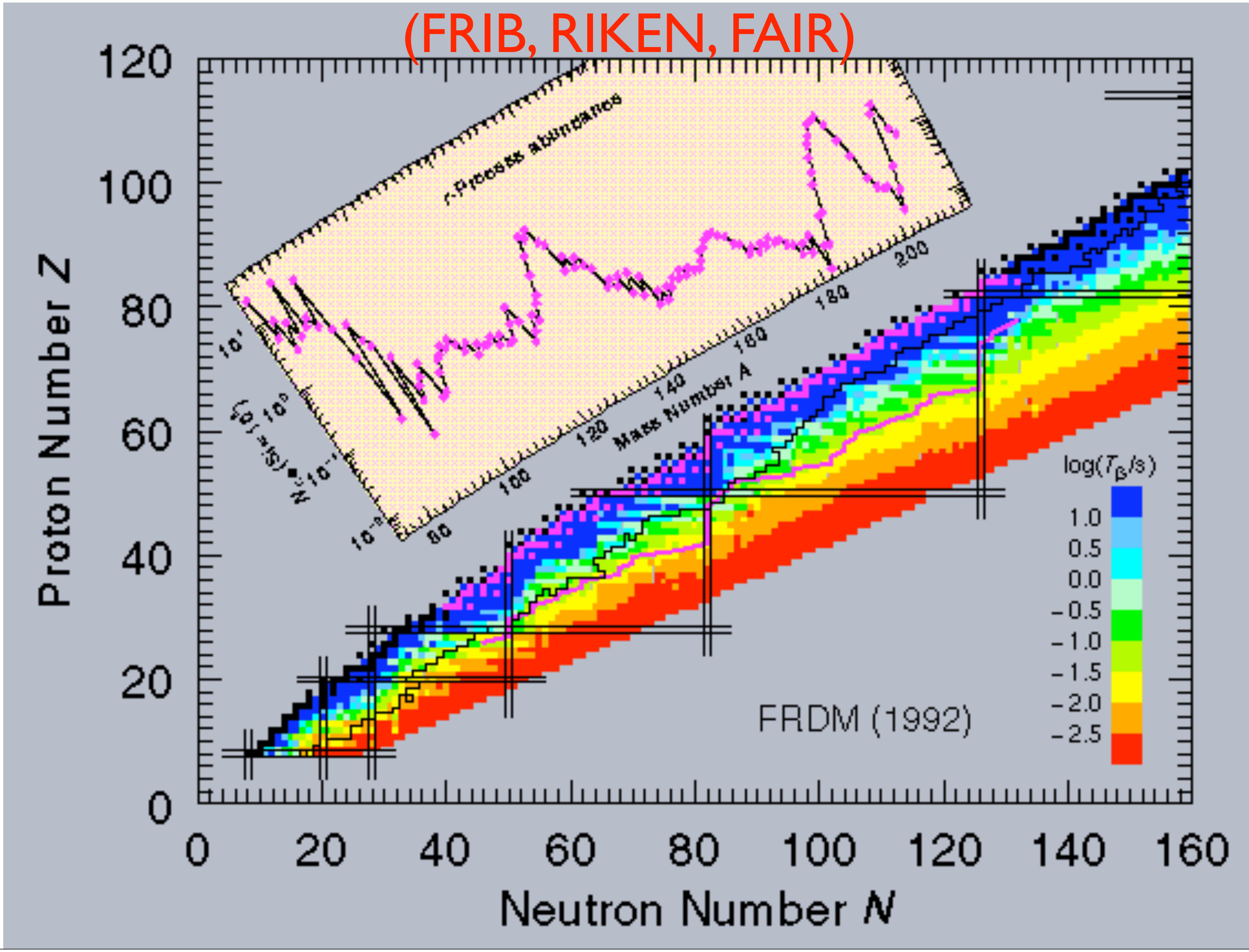
rates & other characteristics of r-process sources

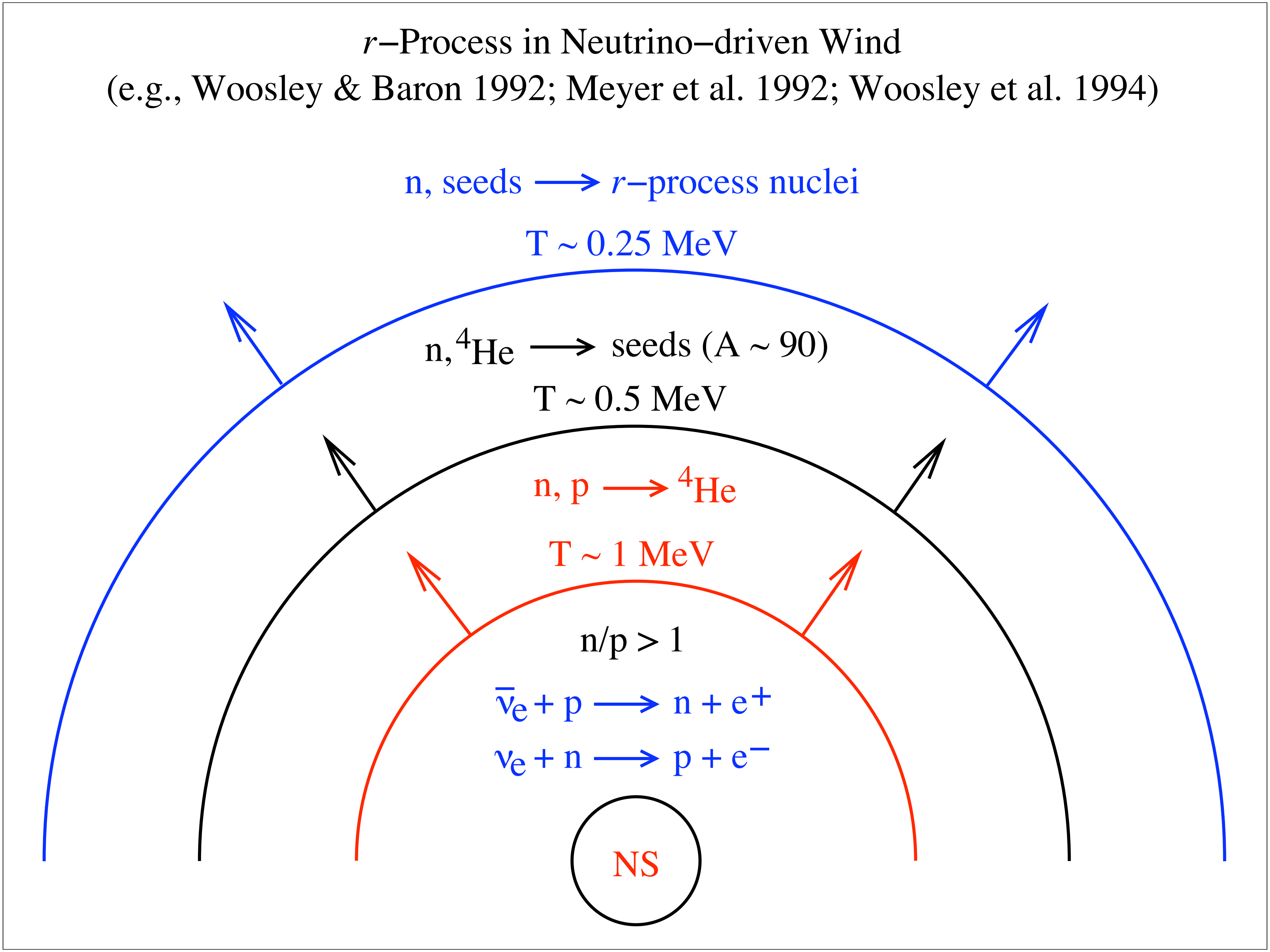
→ chemical evolution of the Galaxy

Rapid neutron capture: the r–process



r-Process & Facility for Rare Isotope Beams (FRIB, RIKEN, FAIR)





r–Process in Neutrino–driven Wind
(e.g., Woosley & Baron 1992; Meyer et al. 1992; Woosley et al. 1994)
n, seeds ⟶ *r*–process nuclei
T ~ 0.25 MeV
n, ^{4}He ⟶ seeds (A ~ 90)
T ~ 0.5 MeV
n, p ⟶ ^{4}He
T ~ 1 MeV
n/p > 1
$\bar{\nu}_e + p \longrightarrow n + e^+$
$\nu_e + n \longrightarrow p + e^-$
NS

summary of neutrino-driven wind results

Witti, Janka, & Takahashi 1994;
Qian & Woosley 1996;
Wanajo, Kajino, Mathews, & Otsuki 2001;
Thompson, Burrows, & Meyer 2001;
Fischer et al. 2010;
Roberts, Woosley, & Hoffman 2010

$Y_e \sim 0.4\text{–}0.5$

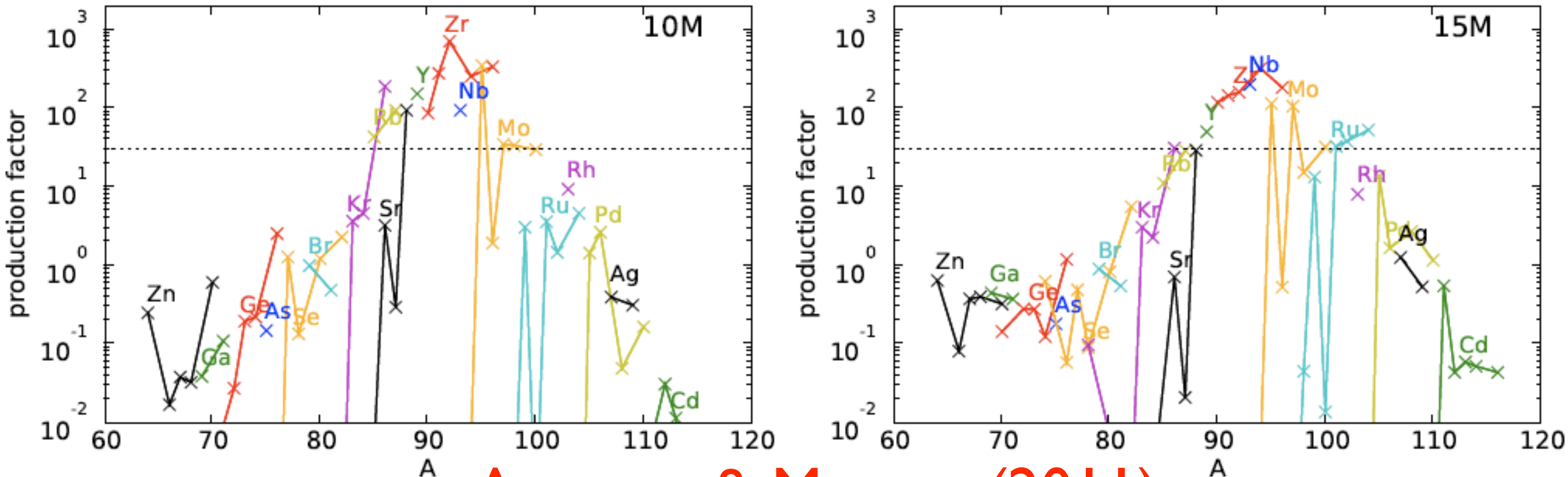
→ $S \lesssim 100$

$\tau_{\rm dyn} \sim 0.01\text{–}0.1\ {\rm s}$

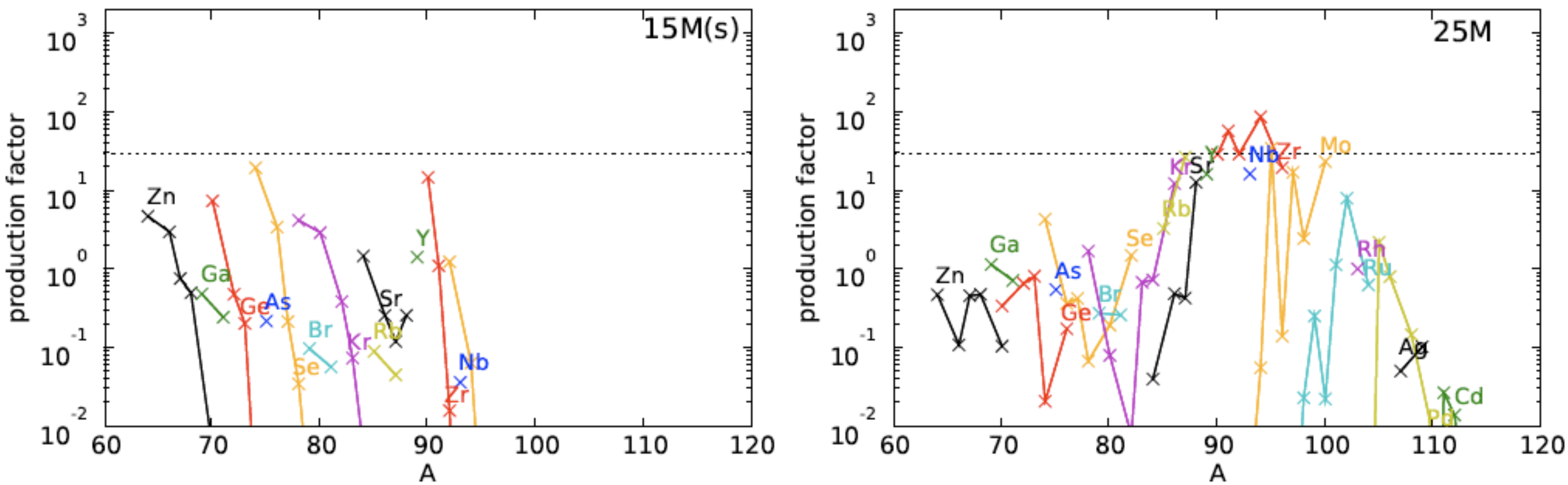
recent neutrino transport results
(Hudepohl et al. 2010; Fischer et al. 2010)

→ $Y_e \gtrsim 0.5$

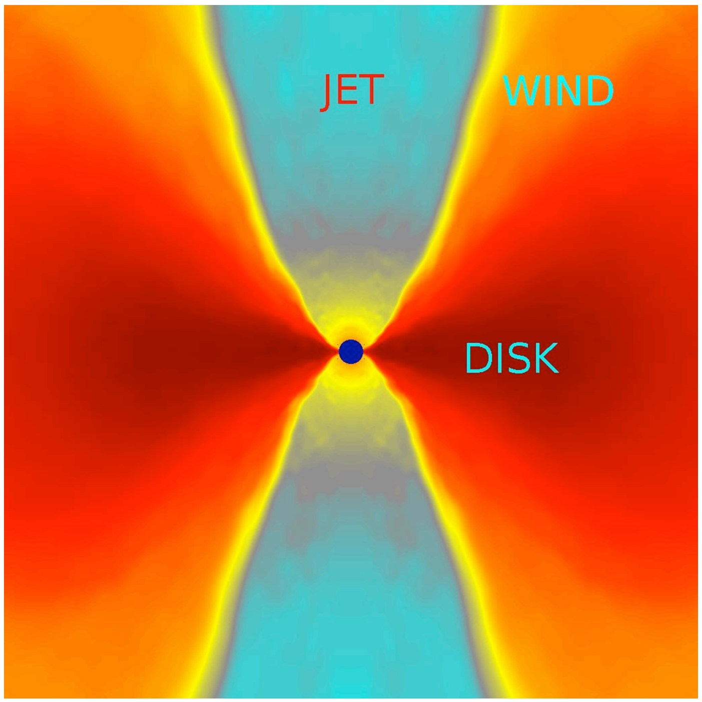
p-rich winds: Pruet et al. 2005; Frohlich et al. 2006



Arcones & Montes (2011)



r-process in winds from accretion disks surrounding black holes?

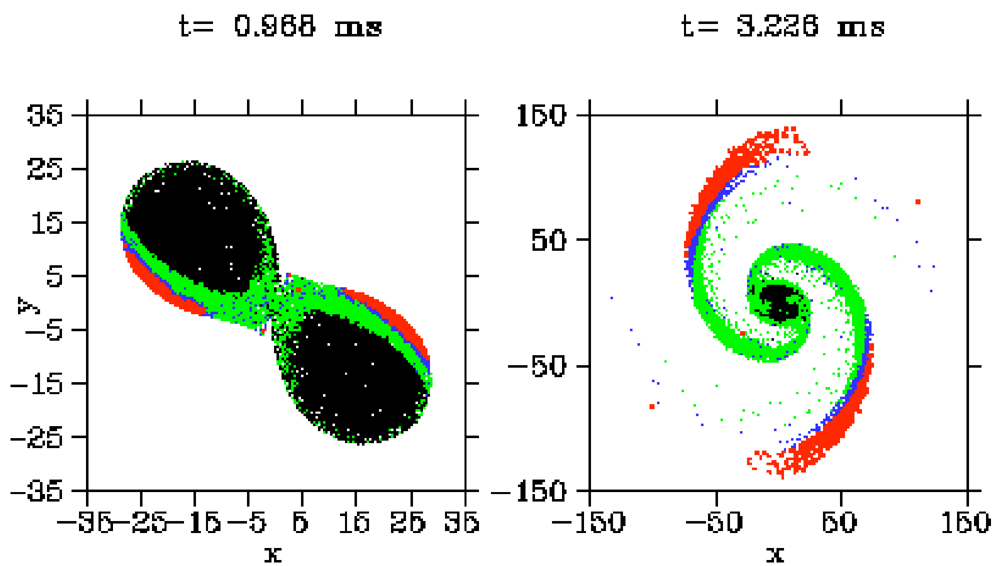


Pruet, Woosley, & Hoffman 2003;
Surman, McLaughlin, & Hix 2006;
Surman et al. 2008;
Wanajo & Janka 2011

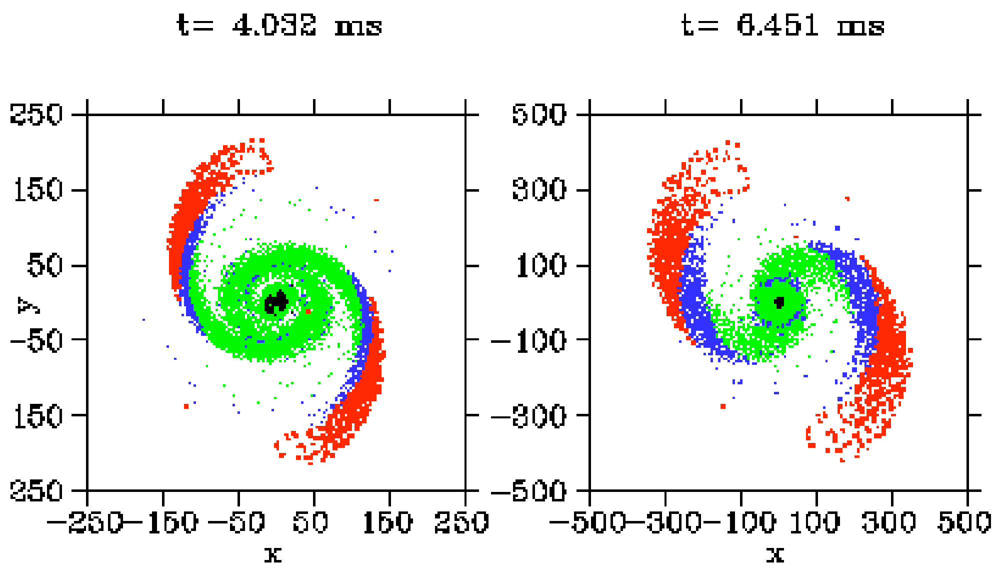
accretion disks form around BHs from core-collapse SNe (GRBs), NS-NS & NS-BH mergers

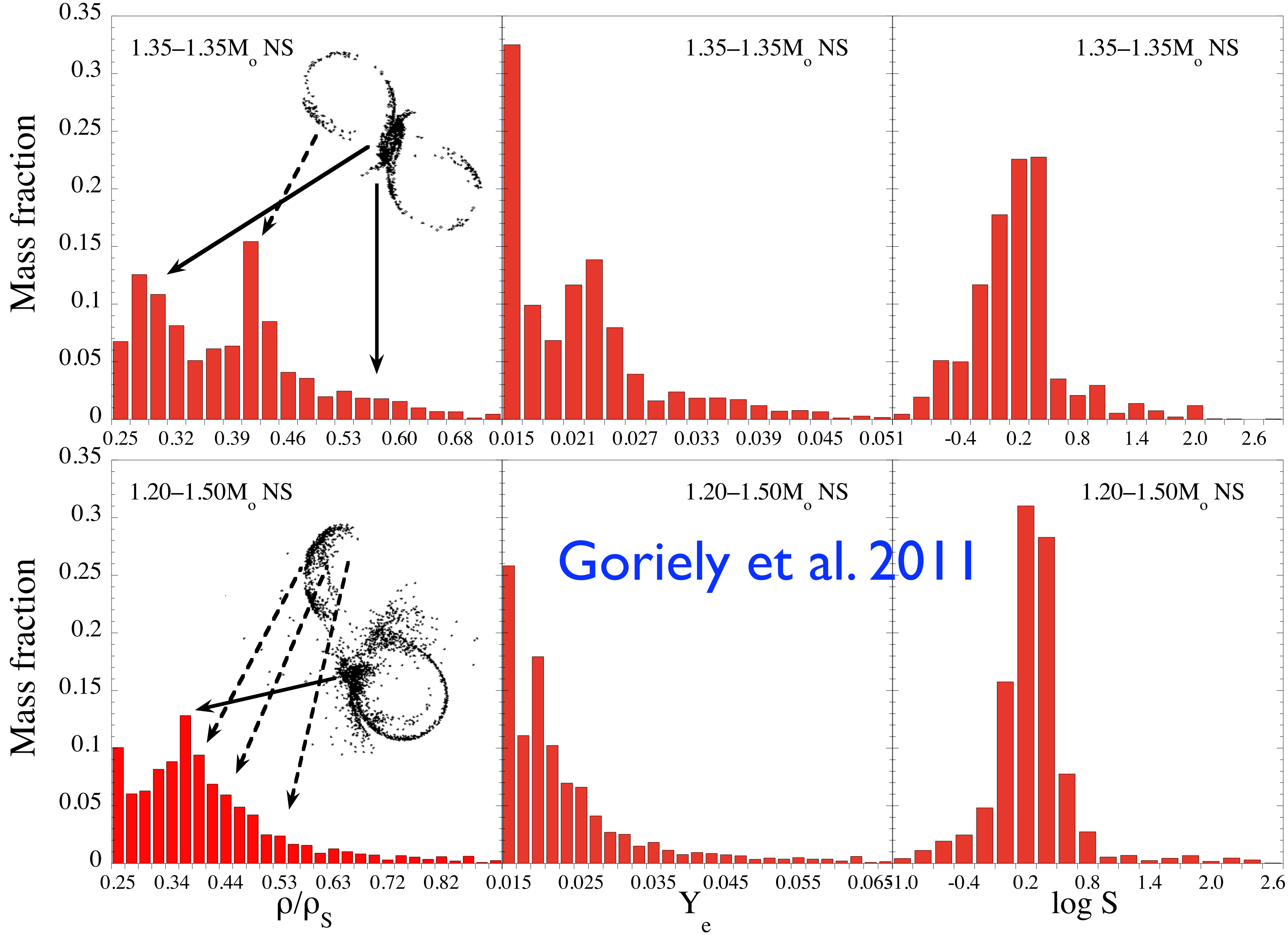
low Ye in winds → r-process

Neutron Star Mergers

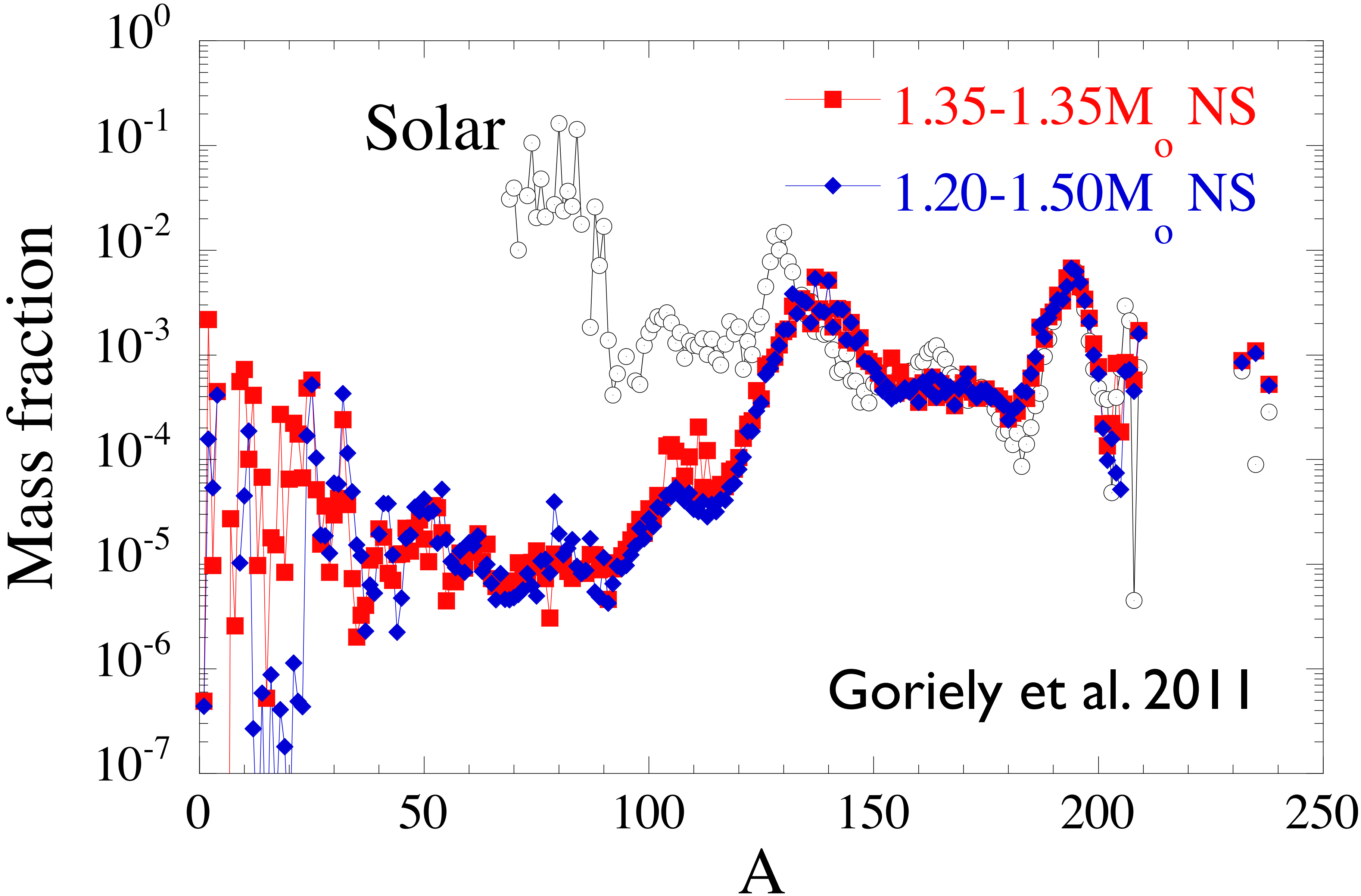


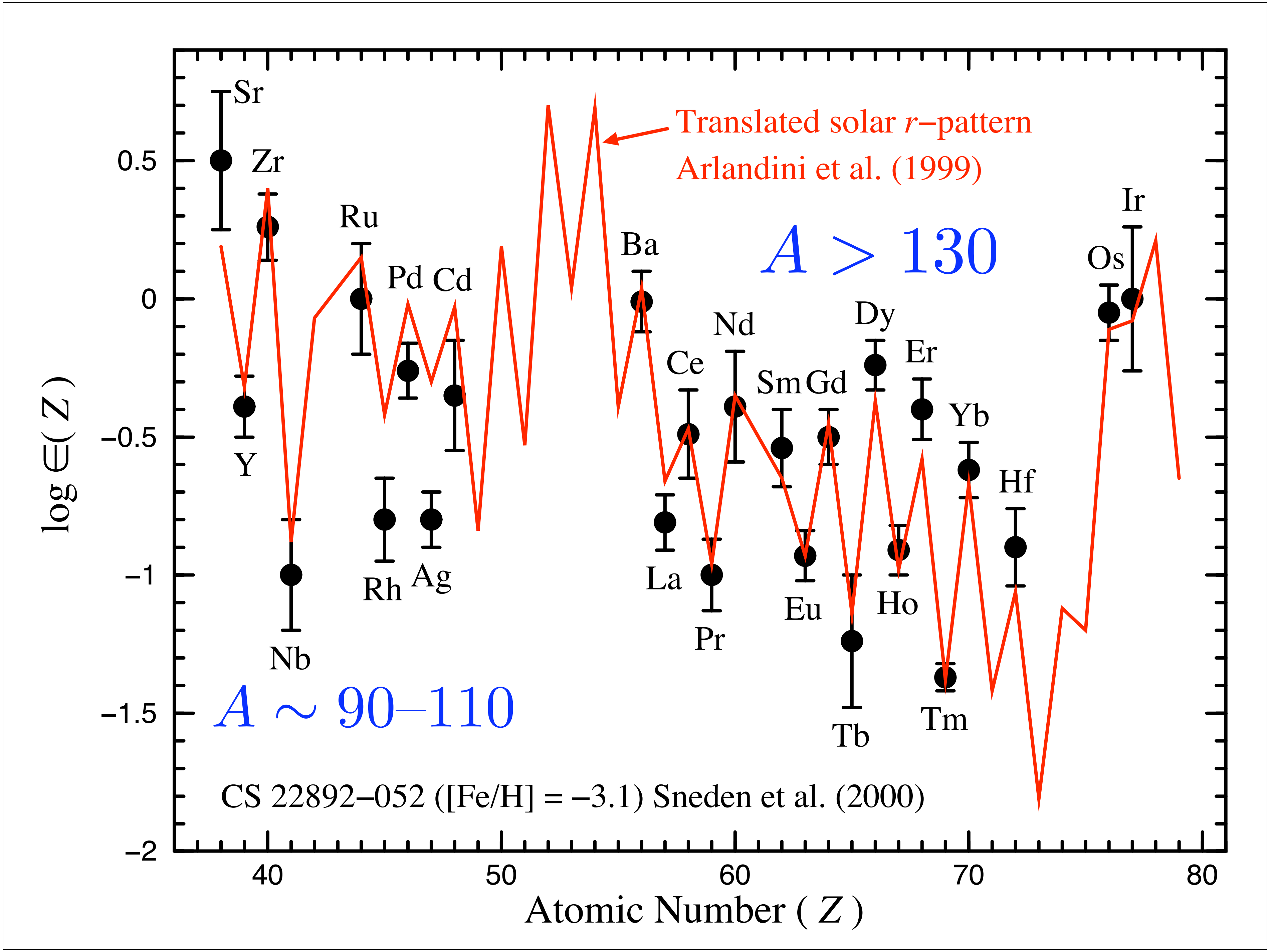
Freiburghaus et al. 1999; Rosswog et al. 2001





Mass fraction
1.35–1.35M$_o$ NS
1.20–1.50M$_o$ NS
Goriely et al. 2011
ρ/ρ_S
Y_e
log S


Solar
1.35-1.35M$_o$ NS
1.20-1.50M$_o$ NS
Goriely et al. 2011
Mass fraction
A
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0
50
100
150
200
250

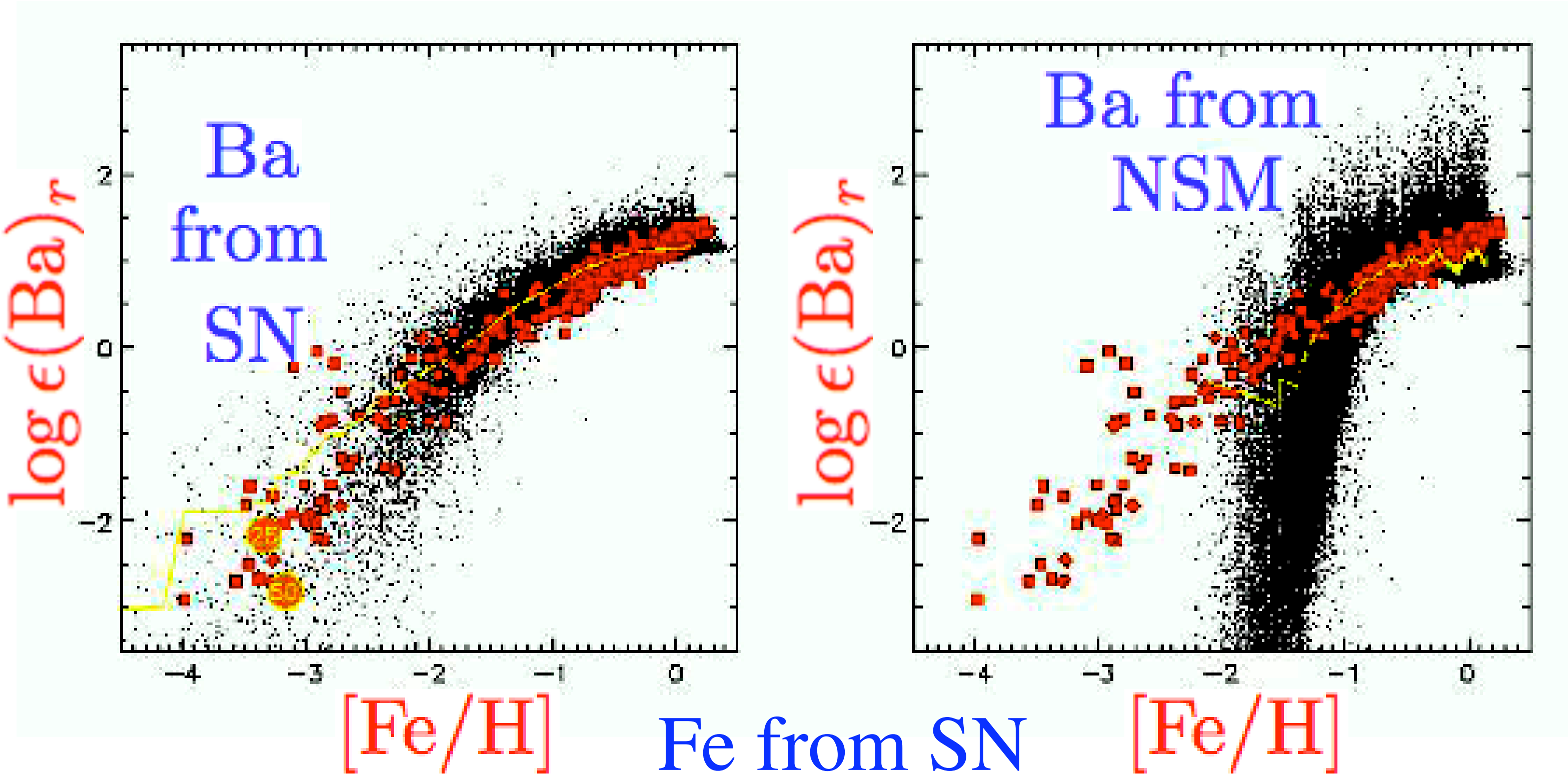


Translated solar r–pattern
Arlandini et al. (1999)
A > 130
A ~ 90–110
CS 22892–052 ([Fe/H] = –3.1) Sneden et al. (2000)
Sr
Zr
Y
Nb
Ru
Pd
Cd
Rh
Ag
Ba
La
Ce
Pr
Nd
Sm
Gd
Eu
Tb
Dy
Ho
Er
Tm
Yb
Hf
Os
Ir
log ∈(Z)
Atomic Number (Z)
0.5
0
–0.5
–1
–1.5
–2
40
50
60
70
80

Supernovae vs. Neutron Star Mergers

(Qian 2000; Argast et al. 2004)

$$f_{\mathrm{SN}} \sim 10^{-2}\ \mathrm{yr}^{-1},\ f_{\mathrm{NSM}} \sim 10^{-5}\ \mathrm{yr}^{-1}$$

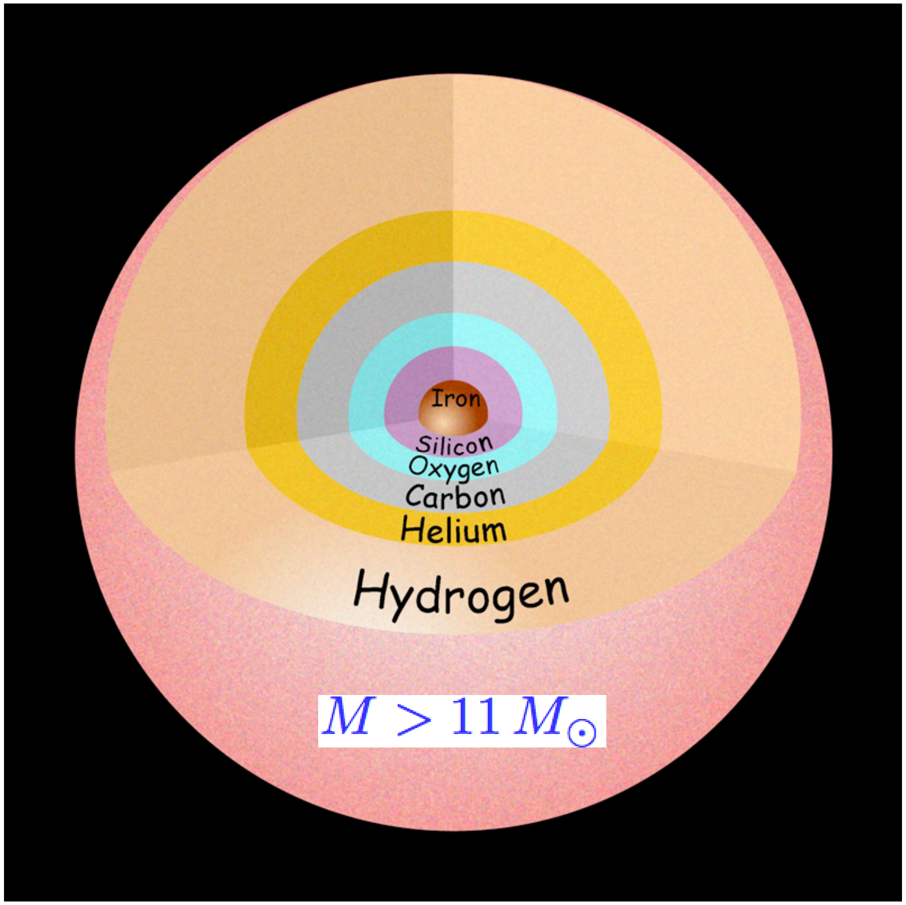


Fe from SN

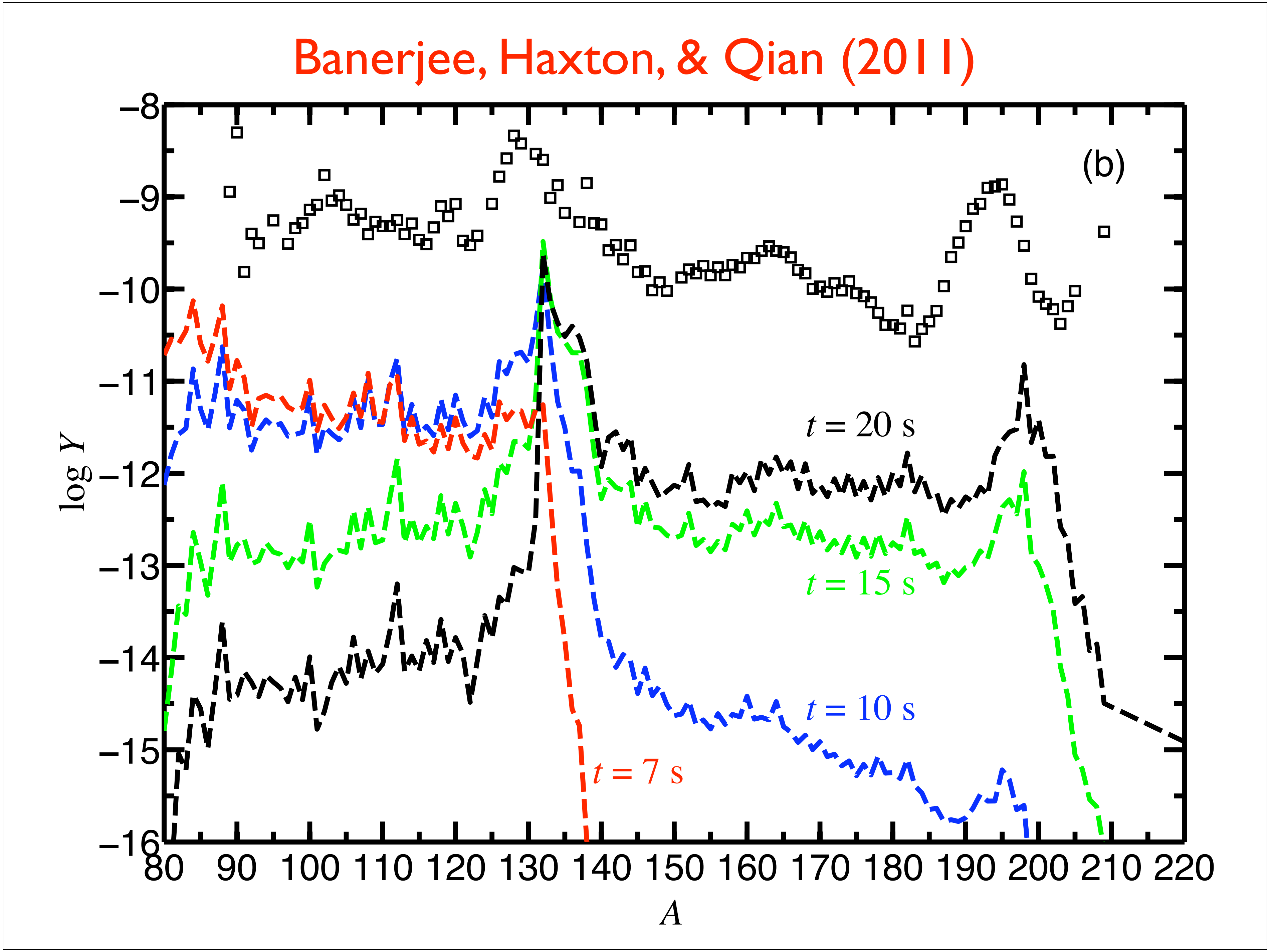
Neutrino-induced r-process in He shell

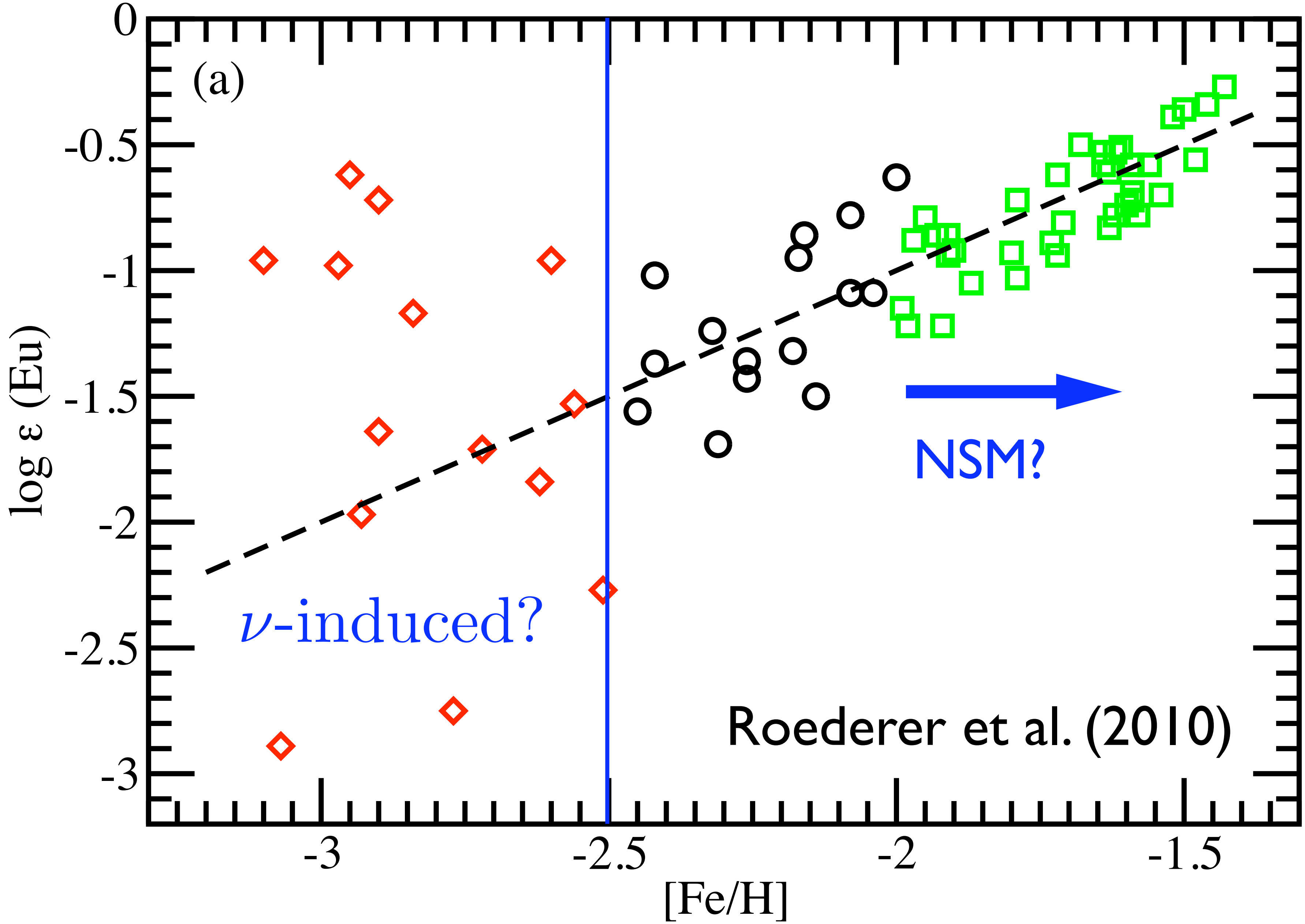
(Epstein, Colgate, & Haxton 1988)

$$^{4}\mathrm{He}(\nu,\nu n)^{3}\mathrm{He}(n,p)^{3}\mathrm{H}(^{3}\mathrm{H},2n)^{4}\mathrm{He}$$



$$\bar{\nu}_e + {}^{4}\mathrm{He} \rightarrow {}^{3}\mathrm{H} + n + e^{+},\ \ \lambda_{\bar{\nu}_e\alpha,n} \propto T_{\bar{\nu}_e}^{5\text{–}6}\ !$$


Banerjee, Haxton, & Qian (2011)
(b)
log Y
A
t = 20 s
t = 15 s
t = 10 s
t = 7 s
−8
−9
−10
−11
−12
−13
−14
−15
−16
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220



(a)
0
-0.5
-1
-1.5
-2
-2.5
-3
log ε (Eu)
-3
-2.5
-2
-1.5
[Fe/H]
NSM?
ν-induced?
Roederer et al. (2010)

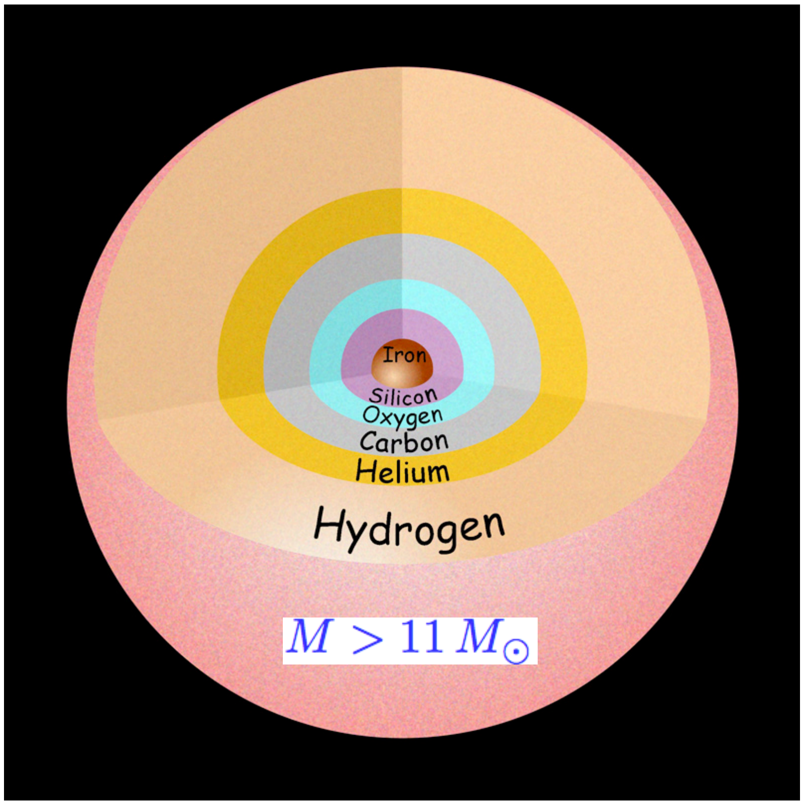
Summary

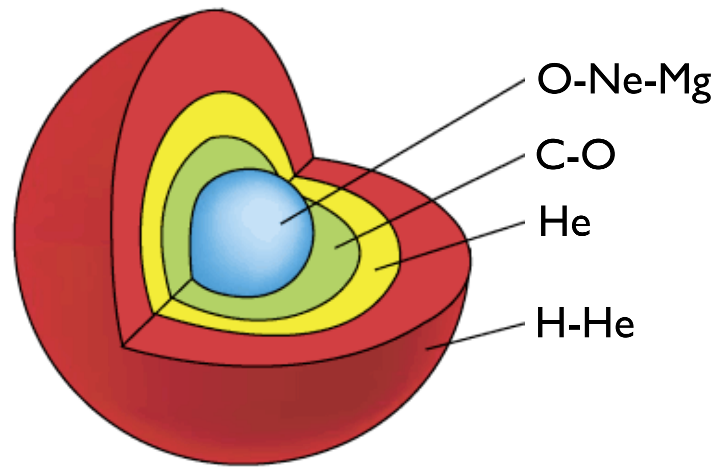
neutrino-driven winds from neutron stars are very likely sources of Sr, Y, Zr, ..., Pd, Ag (A ~ 88 to 110), but not likely sources for heavy r-process nuclei (A >130)

winds from black hole accretion disks & ejecta from neutron star mergers are likely sources of heavy r-nuclei, but have difficulty accounting for such nuclei at [Fe/H] < -2.5

depending on neutrino spectra and flavor oscillations, neutrino-induced r-process in supernova He shells can produce r-process nuclei at [Fe/H] < -3 only

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

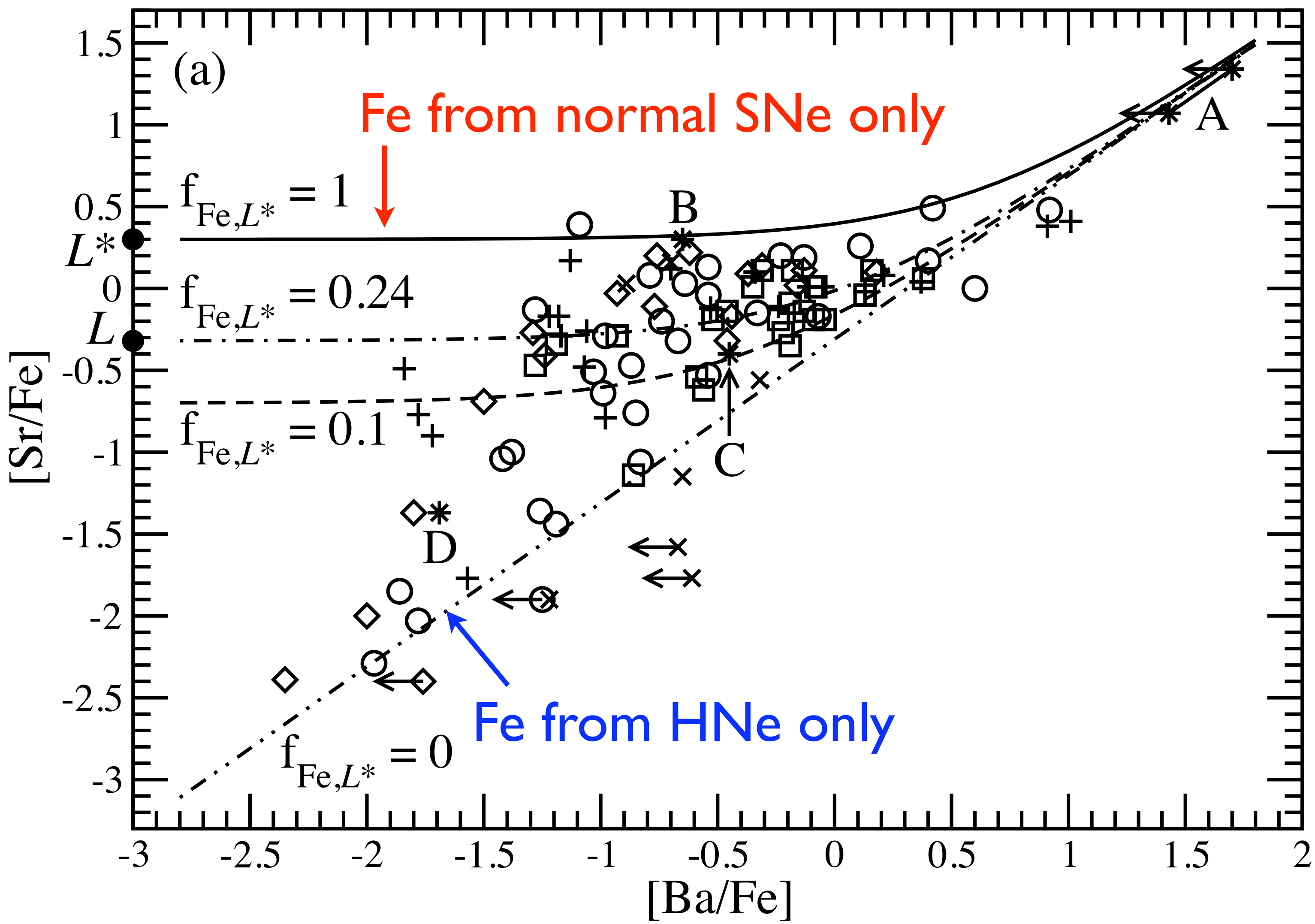
Characteristics of stellar sources

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

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)



唯有实验才可以裁决

真正的实证方法是这样的：先点亮蜡烛，让烛光指引方向；从适当整理编类过的而不是杂乱无章的经历出发，抽取原理，再在已经验证过的原理的基础上进行新的实验

...... the true method of experience first lights the candle, and then by means of the candle shows the way; commencing as it does with experience duly ordered and digested, not bungling or erratic, and from it educing axioms, and from established axioms again new experiments ......

Novum Organum **(1620)**

Francis Bacon