The r-process: status and challenges

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What is an r-process?

Unstable nuclei are produced by capturing neutrons more rapidly than these nuclei can beta decay

$$n_n\langle v\sigma_{n,\gamma}(Z,A)\rangle > \lambda_\beta(Z,A)$$

Studies of the r-process

- nuclear physics input

$$\sigma_{n,\gamma}(Z,A), \lambda_\beta(Z,A), \text{etc.}$$

- astrophysical models

$$\{Y_i(Z,A)\}, n_n(t), T(t) \to \{Y_f(Z,A)\}$$

- observational consequences

[E/H] vs. [Fe/H], etc.

astrophysical models $\{Y_i(Z,A)\}, n_n(t), T(t)$

nuclear physics input $\sigma_{n,\gamma}(Z,A), \lambda_\beta(Z,A), \mathrm{etc.}$

input for photo-disintegration, fission,
neutrinos for some models

model results $\{Y_f(Z,A)\}$

ejecta mass, frequency of occurrences

observations [E/H] vs. [Fe/H], etc.

Uncertainties in r-process studies

- astrophysical conditions

  stellar models, dynamic evolution

- properties of unstable n-rich nuclei

+ reactions for n budget in some models

- interpretation of observations

multiple sources for elements heavier than Fe

QSE, r, νp, p, weak s, & main s processes

Generic models for producing elements heavier than Fe by sources associated with massive stars

- expansion from high temperature & density
  with typical initial composition of n & p
  hot r-process, QSE, νp: $T \gtrsim 10^9$ K
- n capture on pre-existing seeds

with n produced by passage of neutrinos or shock

cold r-process: $T \sim 10^8$ K

Expansion from high temperature & density

- nuclear statistical equilibrium (NSE)

all strong & electromagnetic reactions in equilibrium

$$(A-Z)n + Zp \rightleftharpoons (Z,A) + \gamma$$

- quasi-statistical equilibrium (QSE)

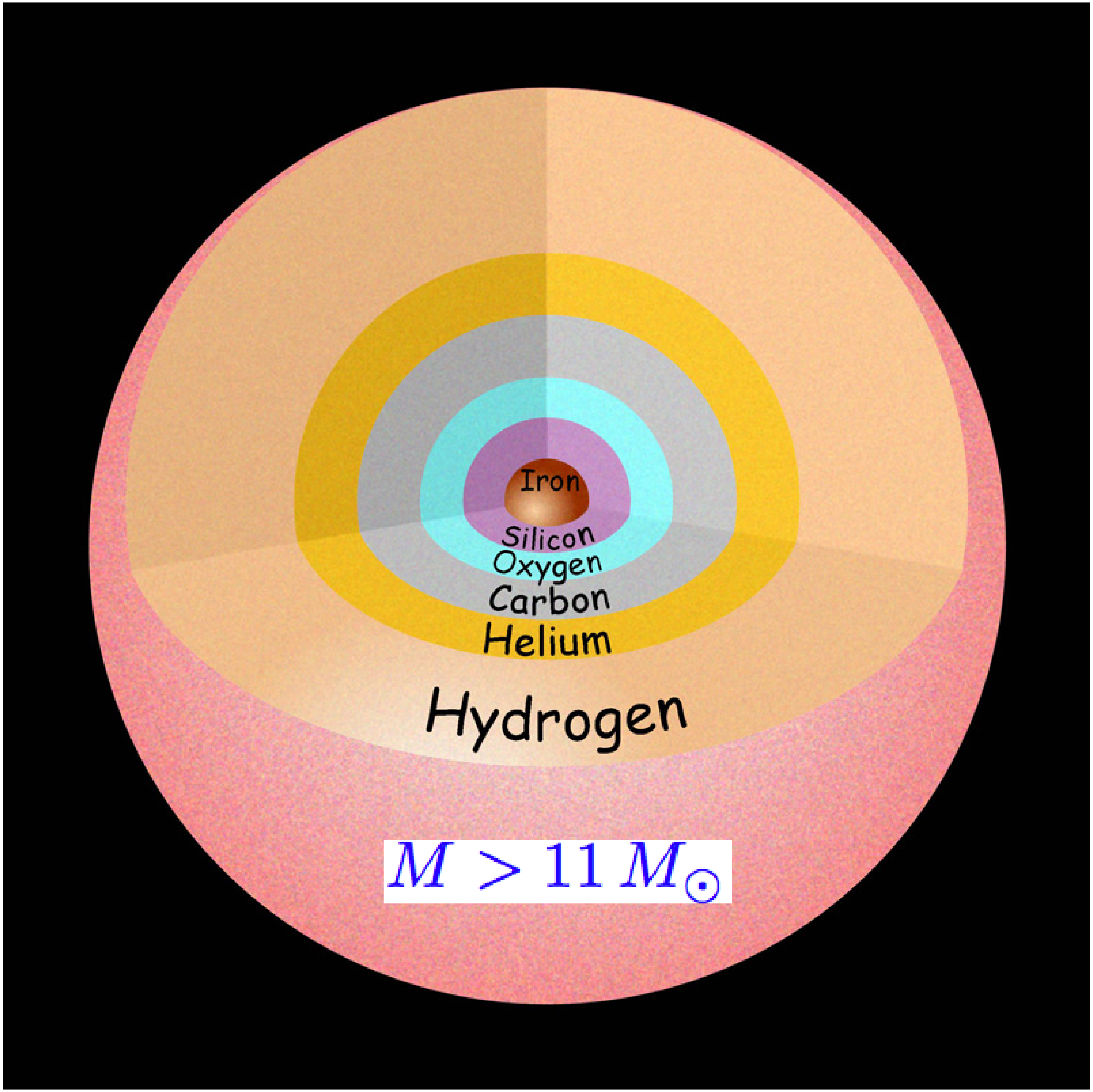
clusters of nuclei form & reactions involving n, p, & light nuclei in equilibrium within each cluster

$$(n,\gamma), (p,\gamma), (n,p), (\alpha,\gamma), (\alpha,n), (\alpha,p)$$

- hot r-process

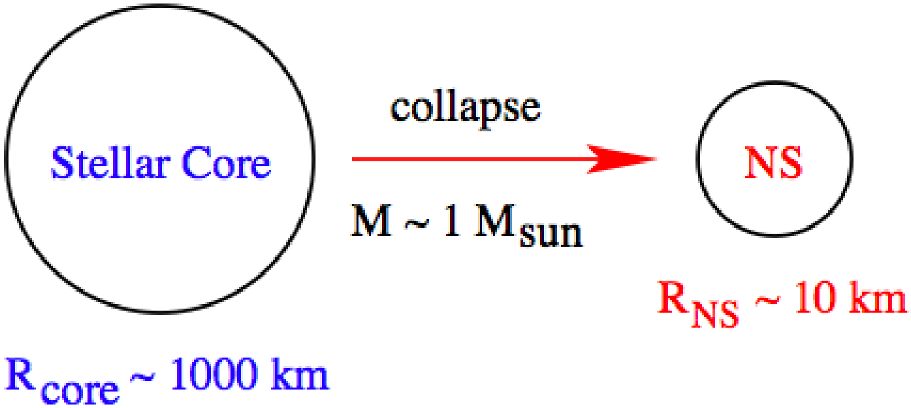
QSE within each isotopic chain only

$$(n,\gamma) \rightleftharpoons (\gamma,n) \text{ equilibrium}$$



Iron
Silicon
Oxygen
Carbon
Helium
Hydrogen
$M > 11\, M_\odot$

Supernovae as a neutrino phenomenon

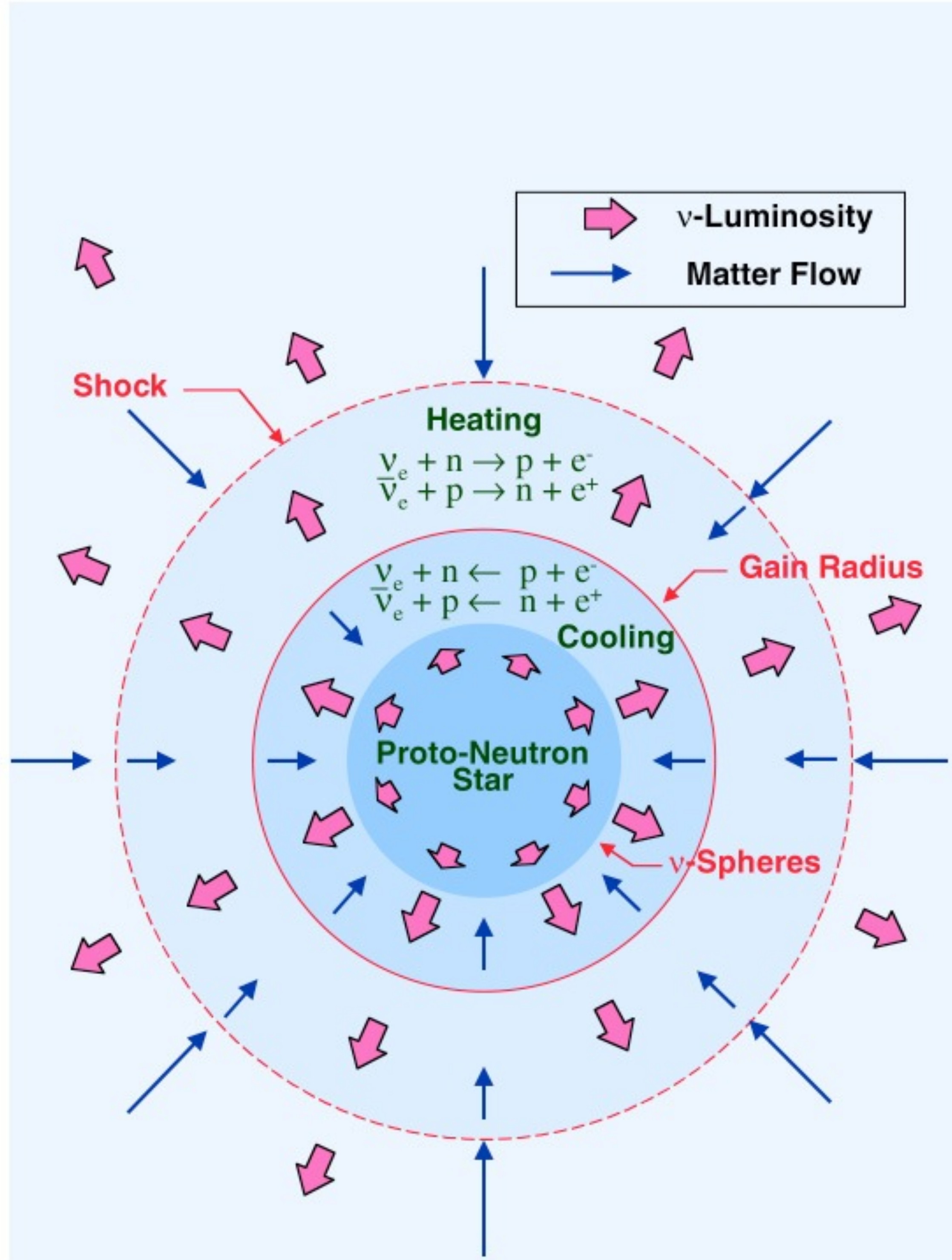


$$e^+ + e^- \to \nu + \bar{\nu}$$

$$N + N \to N + N + \nu + \bar{\nu}$$

$$\frac{GM^2}{R_{\rm NS}} \sim 3 \times 10^{53}\ \text{erg}$$

$$\Rightarrow \nu_e,\ \bar{\nu}_e,\ \nu_\mu,\ \bar{\nu}_\mu,\ \nu_\tau,\ \bar{\nu}_\tau$$



Characteristics of Supernova Neutrino Emission

- momentum transfer

$$\nu + N \rightarrow \nu + N \Rightarrow t_{\rm diff} \sim 10 \text{ s}$$

$$L_{\nu_e} \approx L_{\bar{\nu}_e} \approx L_{\nu_{\mu(\tau)}} \approx L_{\bar{\nu}_{\mu(\tau)}} \sim 10^{51} \text{ erg/s}$$

- energy transfer

$$\nu + e^- \rightarrow \nu + e^-$$

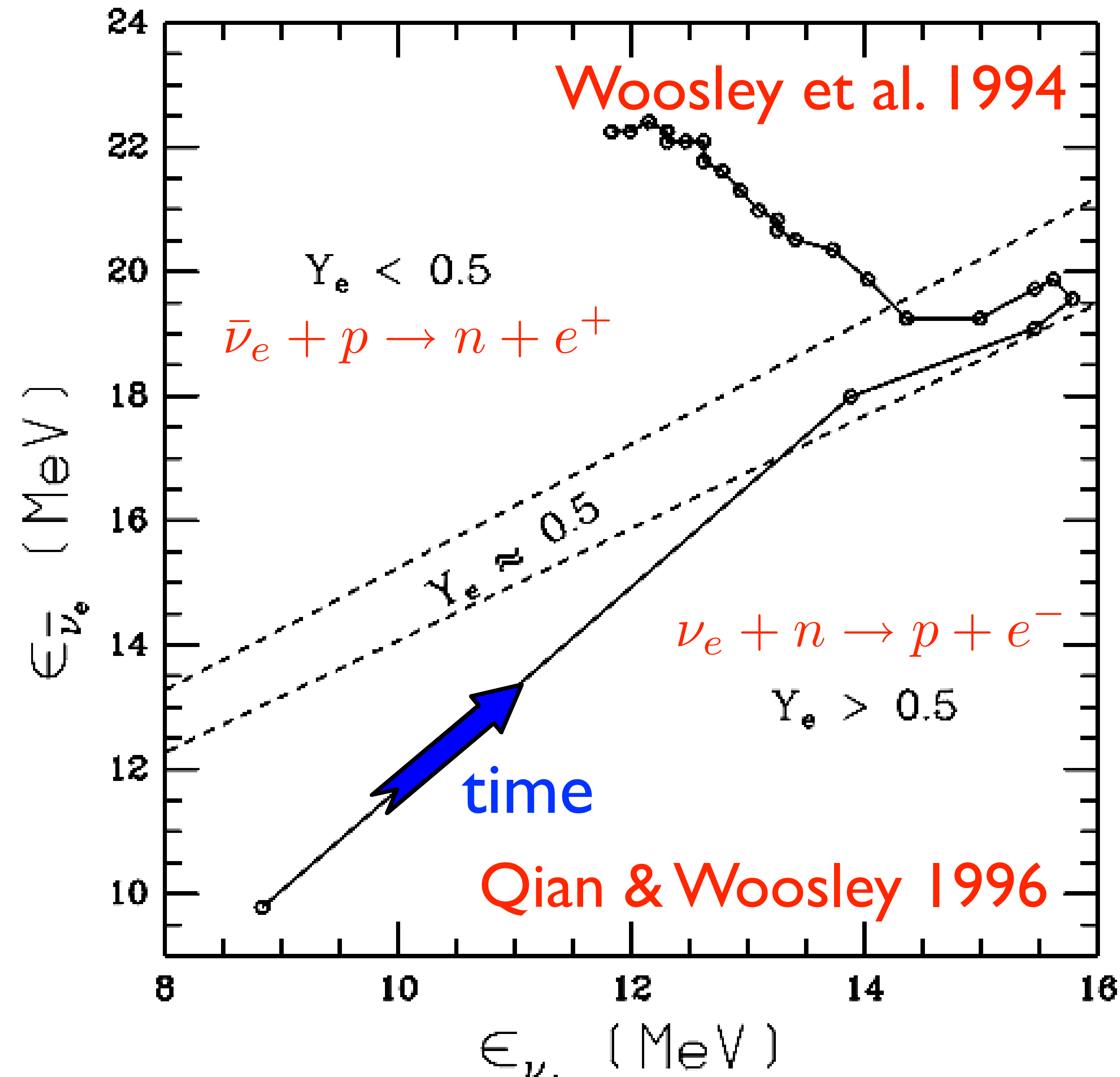
$$\nu_e + n \rightleftharpoons p + e^-, \; \bar{\nu}_e + p \rightleftharpoons n + e^+$$

$$\langle E_{\nu_e} \rangle \approx 11 \text{ MeV}, \; \langle E_{\bar{\nu}_e} \rangle \approx 16 \text{ MeV}$$

$$\langle E_{\nu_{\mu(\tau)}} \rangle \approx \langle E_{\bar{\nu}_{\mu(\tau)}} \rangle \approx 25 \text{ MeV}$$

numerical results sensitive to neutrino opacities!

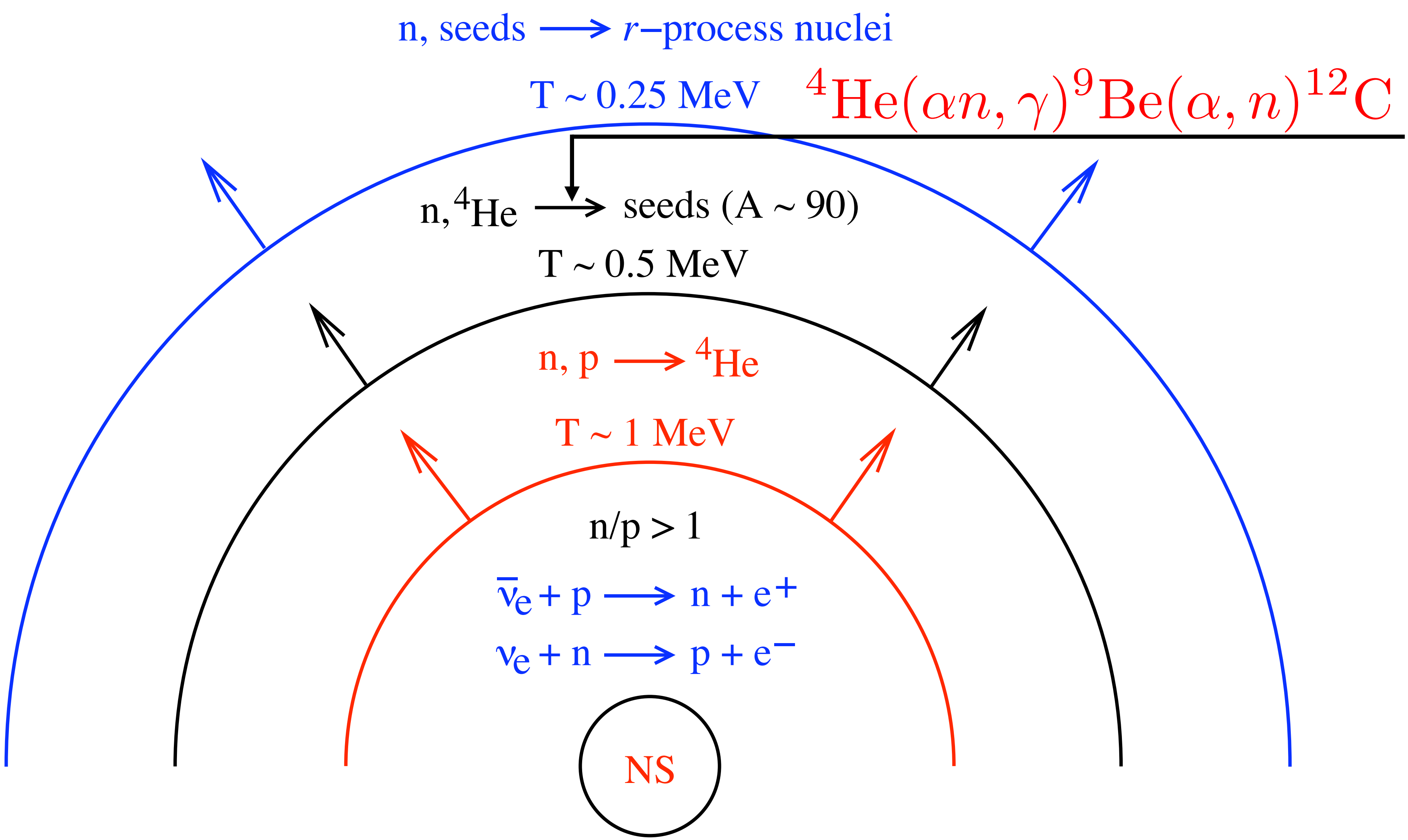
(Martinez-Pinedo et al. 2012; Roberts & Reddy 2012)



Woosley et al. 1994
Qian & Woosley 1996
$Y_e < 0.5$
$\bar{\nu}_e + p \rightarrow n + e^+$
$Y_e \approx 0.5$
$\nu_e + n \rightarrow p + e^-$
$Y_e > 0.5$
time
$\epsilon_{\bar{\nu}_e}$ (MeV)
ϵ_{ν_e} (MeV)
8
10
12
14
16
18
20
22
24

r–Process in Neutrino–driven Wind

(e.g., Woosley & Baron 1992; Meyer et al. 1992; Woosley et al. 1994)



Conditions in the ν-driven wind

$Y_e \sim 0.4\text{–}0.5,\ \ S \sim 10\text{–}100,\ \ \tau_{\rm dyn} \sim 0.01\text{–}0.1\ {\rm s}$

(Witti et al. 1994; Qian & Woosley 1996;
Wanajo et al. 2001; Thompson et al. 2001;
Fischer et al. 2010; Roberts et al. 2010)

Sr, Y, Zr (A~90) readily produced in the ν-driven wind,
up to Pd & Ag (A~110) likely, all by QSE

(Woosley & Hoffman 1992; Arcones & Montes 2011)

production of r-nuclei up to A~130 possible,
but very hard to make A>130

(Hoffman et al. 1997; Wanajo 2013)

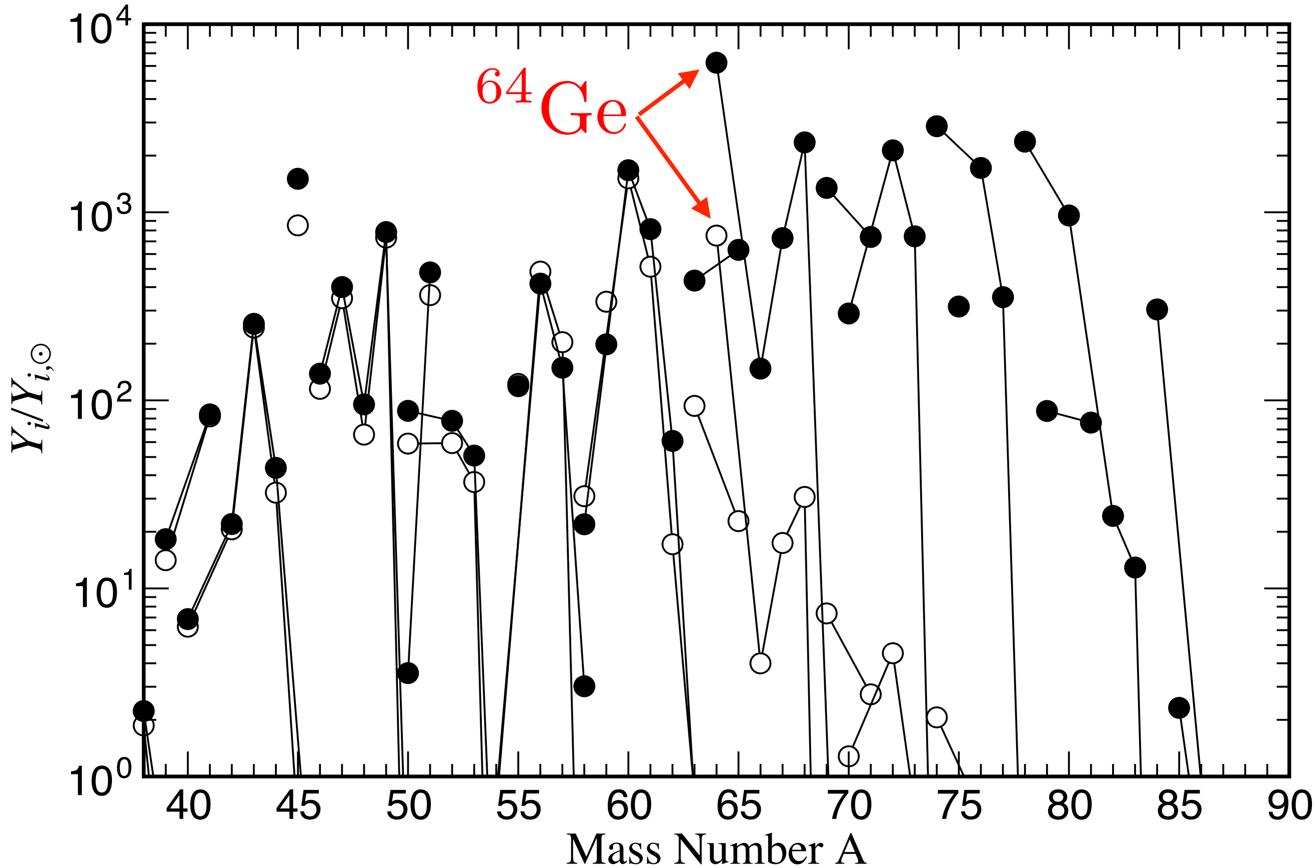
The νp-process in p-rich ν-driven winds

(Frohlich et al. 2006a,b; Pruet et al. 2005,2006)

$$(p,\gamma) \rightleftharpoons (\gamma,p) \text{ equilibrium} \Rightarrow \text{waiting point}$$

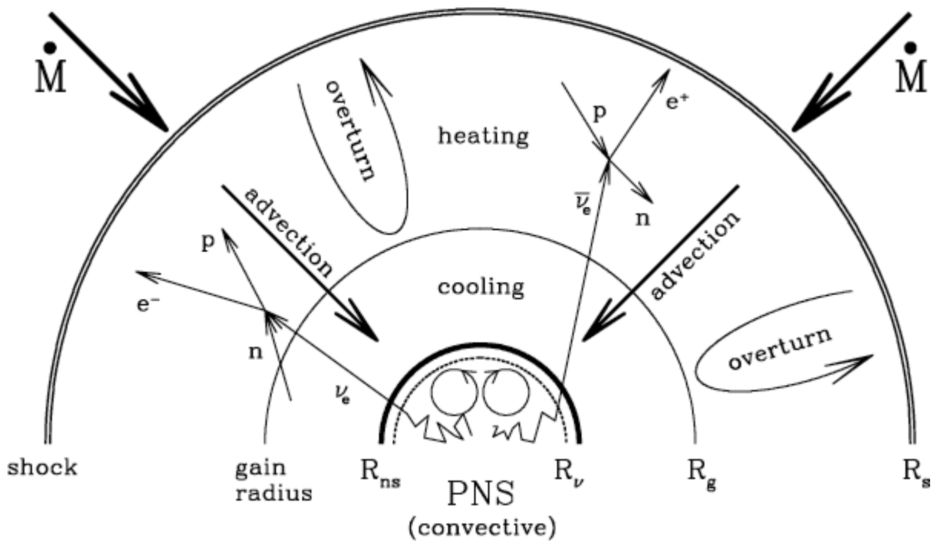
break through waiting-point nuclei with slow beta decay:

$$\bar{\nu}_e + p \to n + e^+, \ (Z,A) + n \to p + (Z-1,A)$$



$Y_e \downarrow, \;\; S \uparrow, \;\; \tau_{\rm dyn} \downarrow \Rightarrow$ heavier r-nuclei

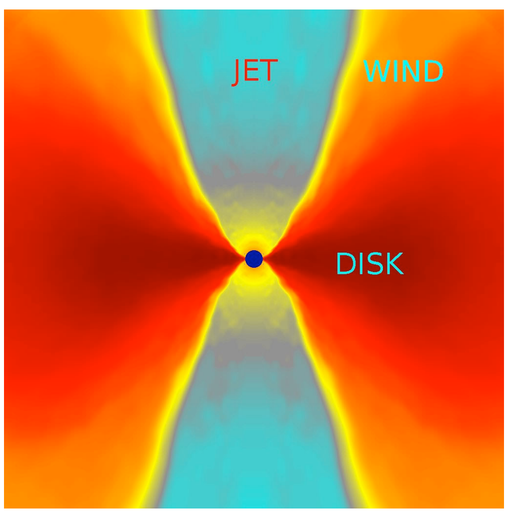
- bubbles driven by convection



seen in low-mass SN models

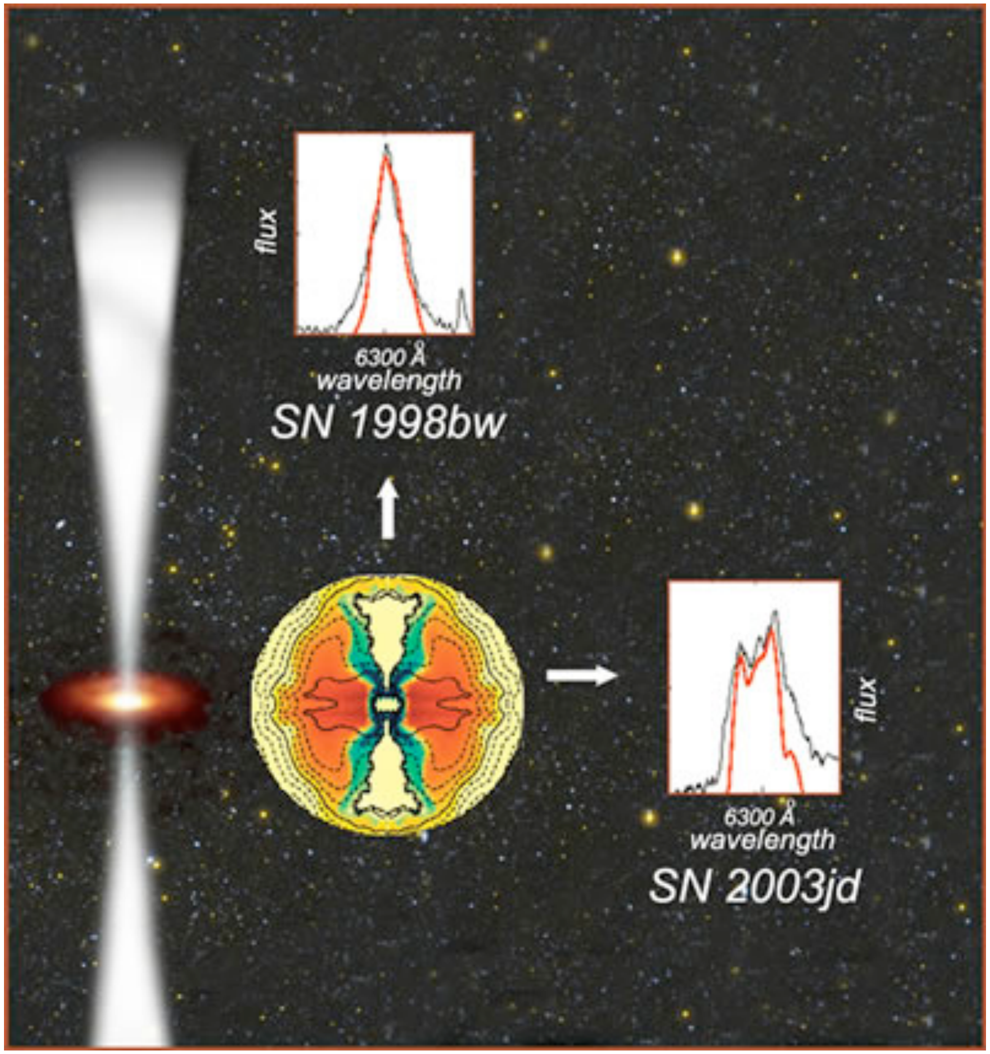
(Wanajo et al. 2011)

- winds from accretion disks of BHs



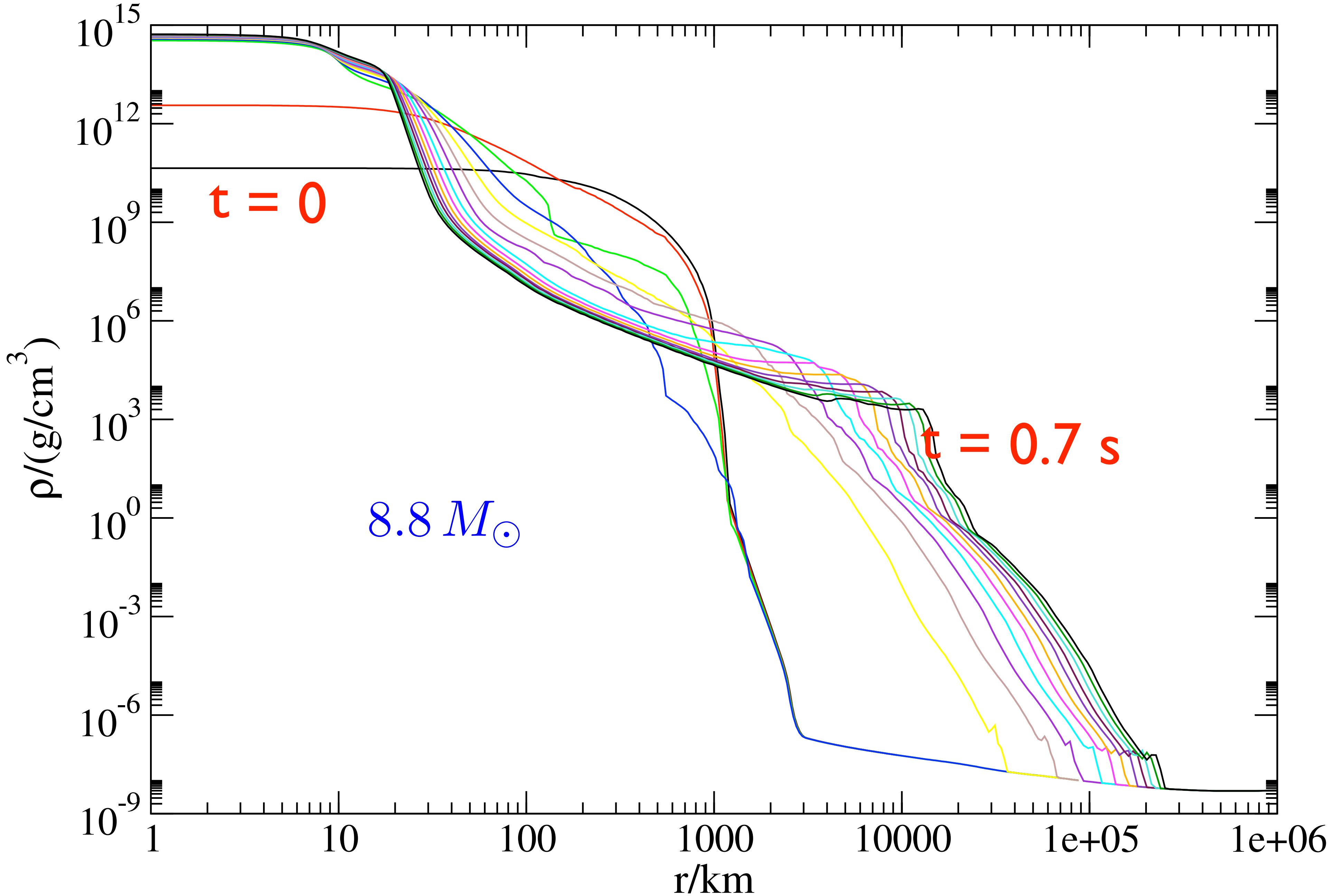
(Pruet et al. 2003; Surman et al. 2006, 2008; Wanajo & Janka 2012; Fernandez & Metzger 2013)

- jets driven by rotation, magnetohydrodynamics, etc.

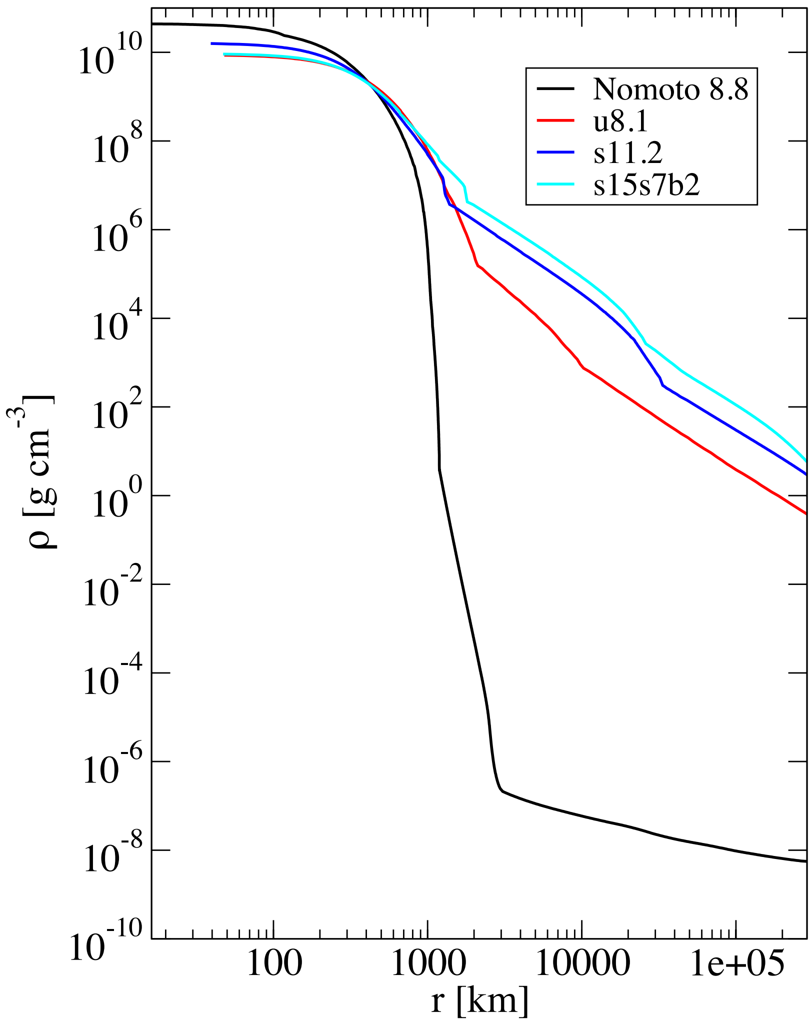


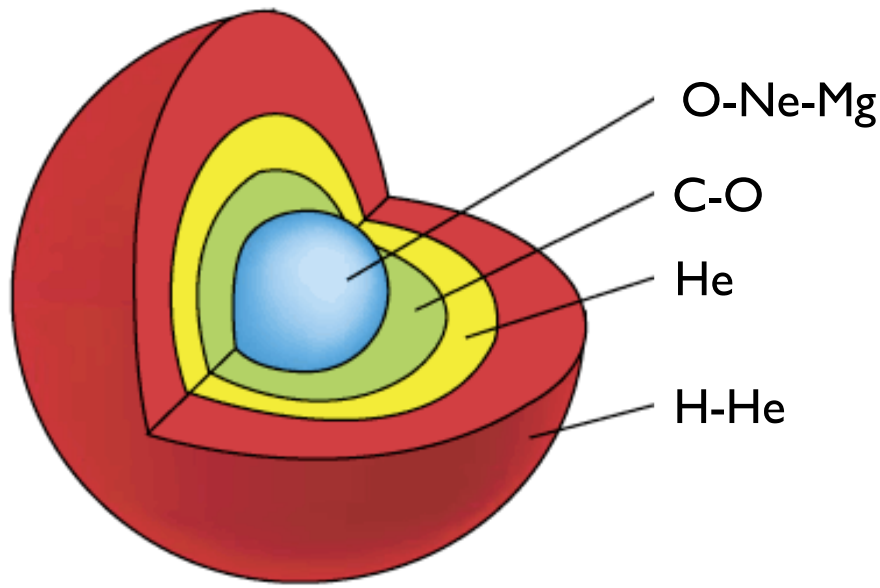
(Symbalisty et al. 1985;
Nishimura et al. 2006;
Fujimoto et al. 2007;
Winteler et al. 2012;
Papish & Soaker 2012)

low-mass SNe (Janka et al. 2008)



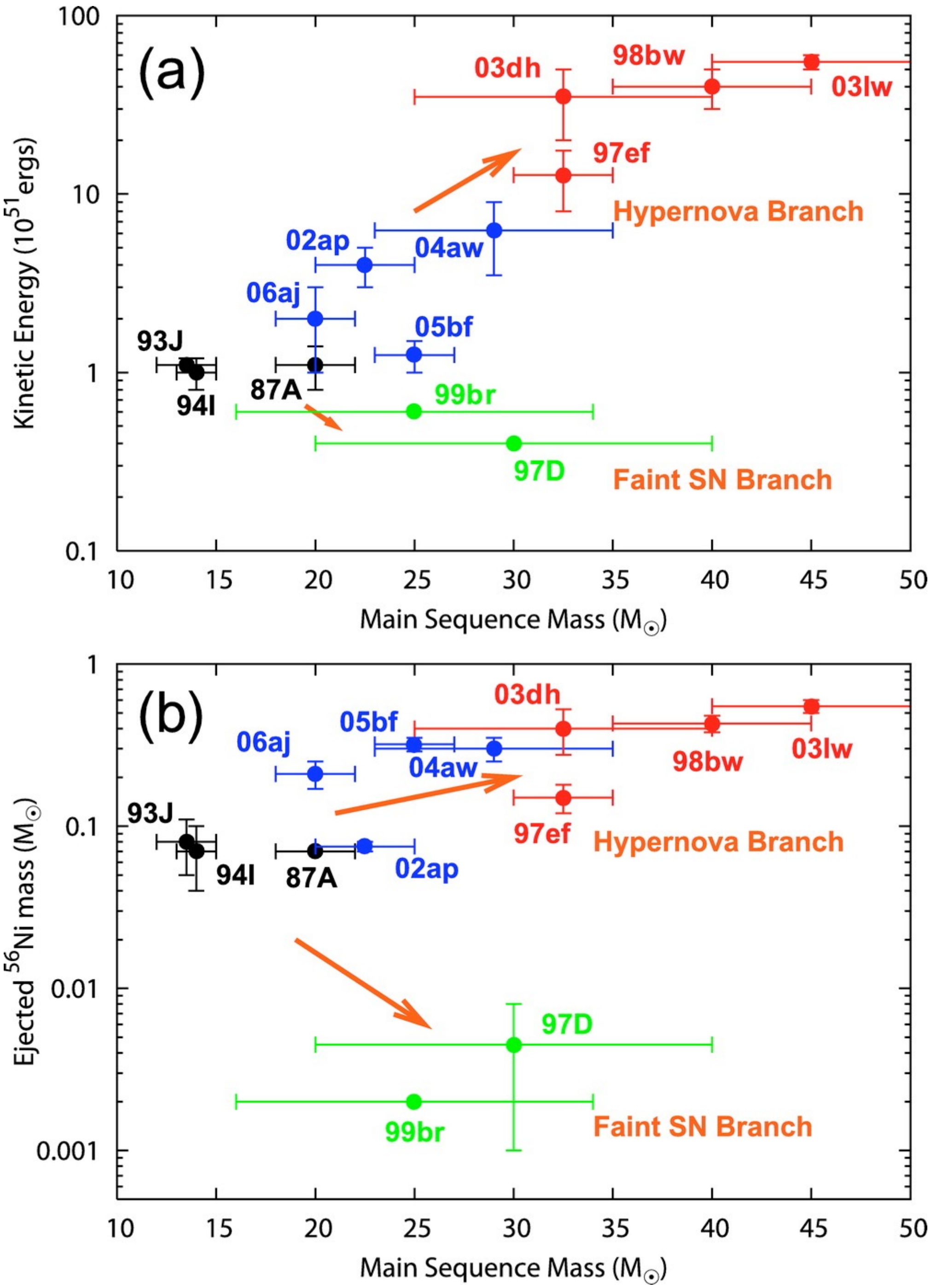
fast expansion of shocked ejecta with neutron excess





(Ning, Qian, & Meyer 2007; Eichler et al. 2012; Qian 2013)

but see Janka et al. 2008



Tominaga et al. (2007)

normal SNe

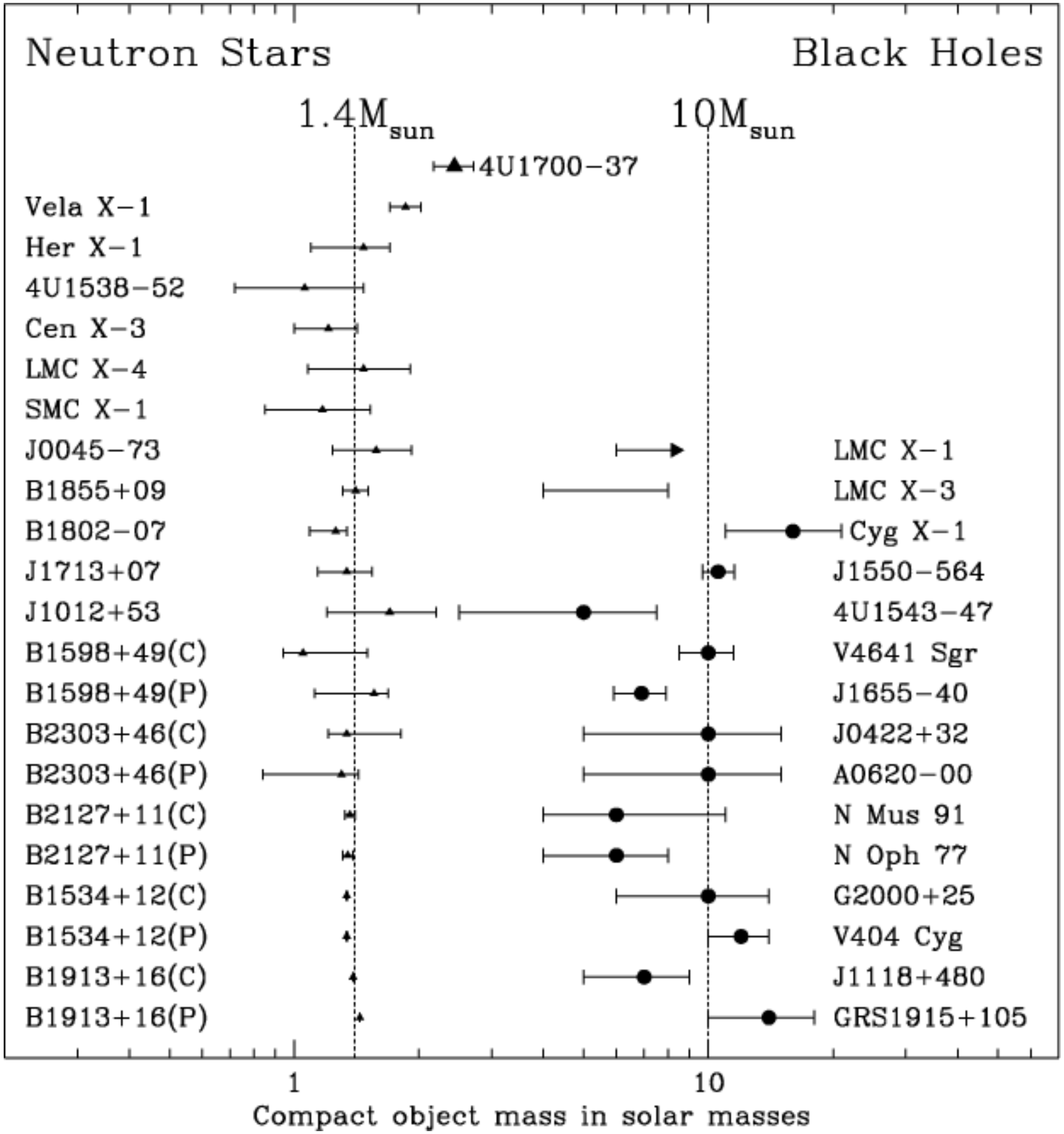
$M \sim 12\text{–}25\, M_\odot$

HNe

$M \sim 25\text{–}50\, M_\odot$

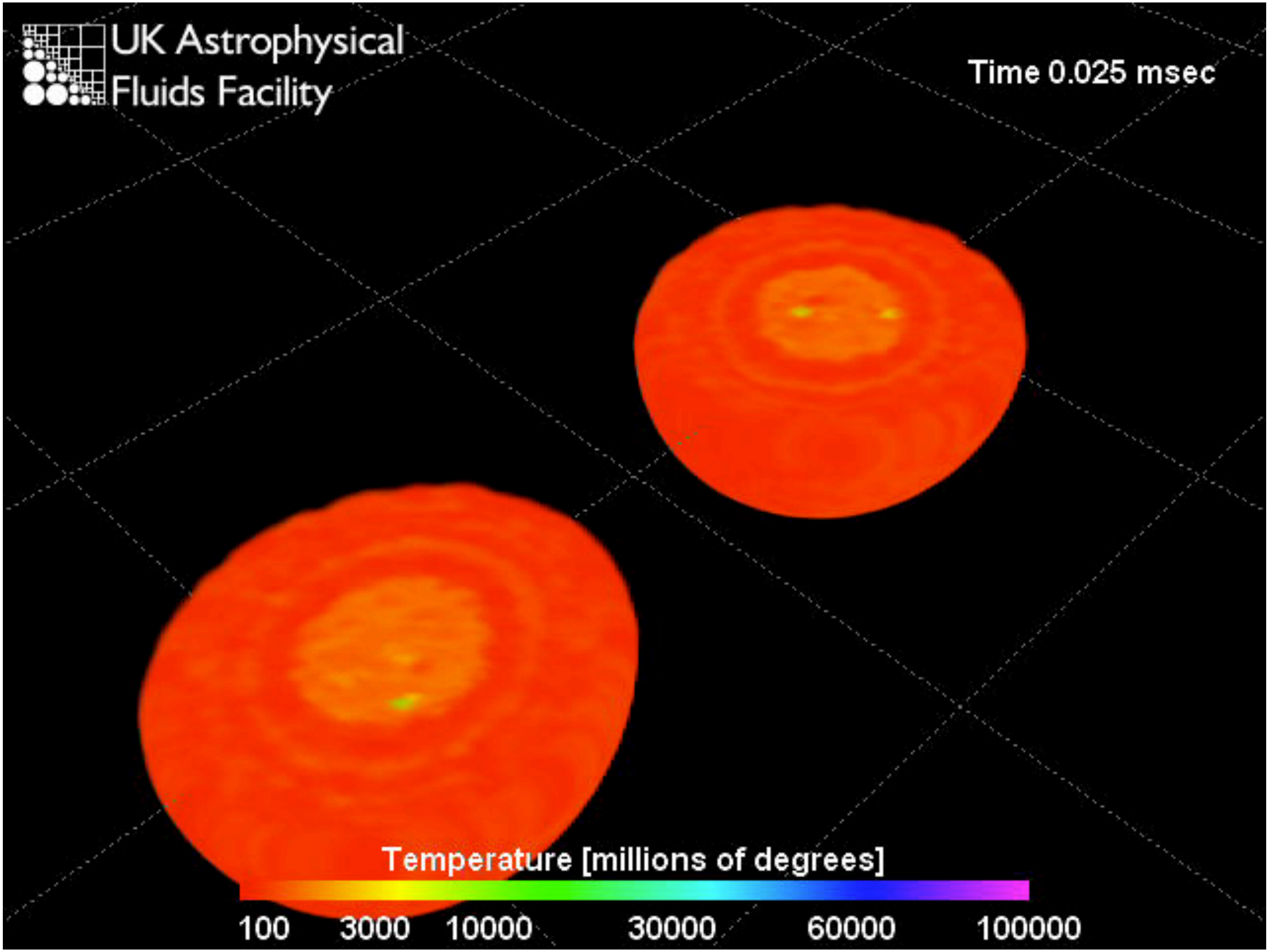
faint SNe

$M \sim 25\text{–}50\, M_\odot$

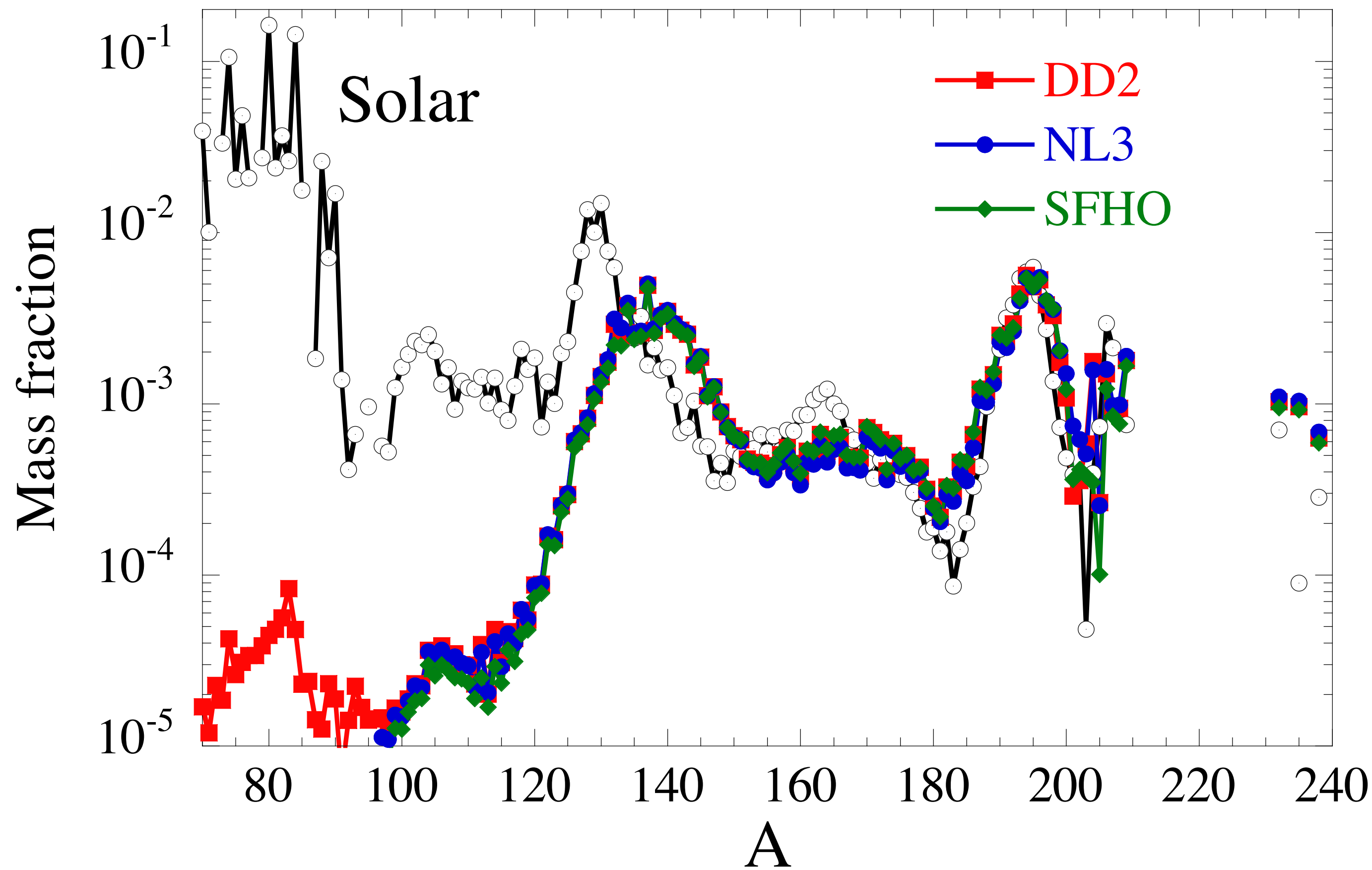


Neutron Stars
Black Holes
1.4M sun
10M sun
4U1700−37
Vela X−1
Her X−1
4U1538−52
Cen X−3
LMC X−4
SMC X−1
J0045−73
B1855+09
B1802−07
J1713+07
J1012+53
B1598+49(C)
B1598+49(P)
B2303+46(C)
B2303+46(P)
B2127+11(C)
B2127+11(P)
B1534+12(C)
B1534+12(P)
B1913+16(C)
B1913+16(P)
LMC X−1
LMC X−3
Cyg X−1
J1550−564
4U1543−47
V4641 Sgr
J1655−40
J0422+32
A0620−00
N Mus 91
N Oph 77
G2000+25
V404 Cyg
J1118+480
GRS1915+105
1
10
Compact object mass in solar masses

Neutron star mergers



decompression of cold neutron star matter



(Goriely, Bauswein, & Janka 2011, 2013)

also see Lattimer et al. 1977;

Freiburghaus, Rosswog, & Thielemann1999;

Korobkin et al. 2012

neutron capture on pre-existing seeds

- shocked-induced neutron sources in He shells

rotation-induced mixing → $^{13}\mathrm{C},\ ^{22}\mathrm{Ne}$

$$^{13}\mathrm{C}(^4\mathrm{He},n)^{16}\mathrm{O},\ \ ^{22}\mathrm{Ne}(^4\mathrm{He},n)^{25}\mathrm{Mg}$$

(Hilebrandt & Thielemann 1977; Thielmann et al. 1979
Truran, Cowan, & Cameron 1978-85)

- neutrino-induced neutron sources in He shells

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

(Epstein, Colgate, & Haxton 1988)

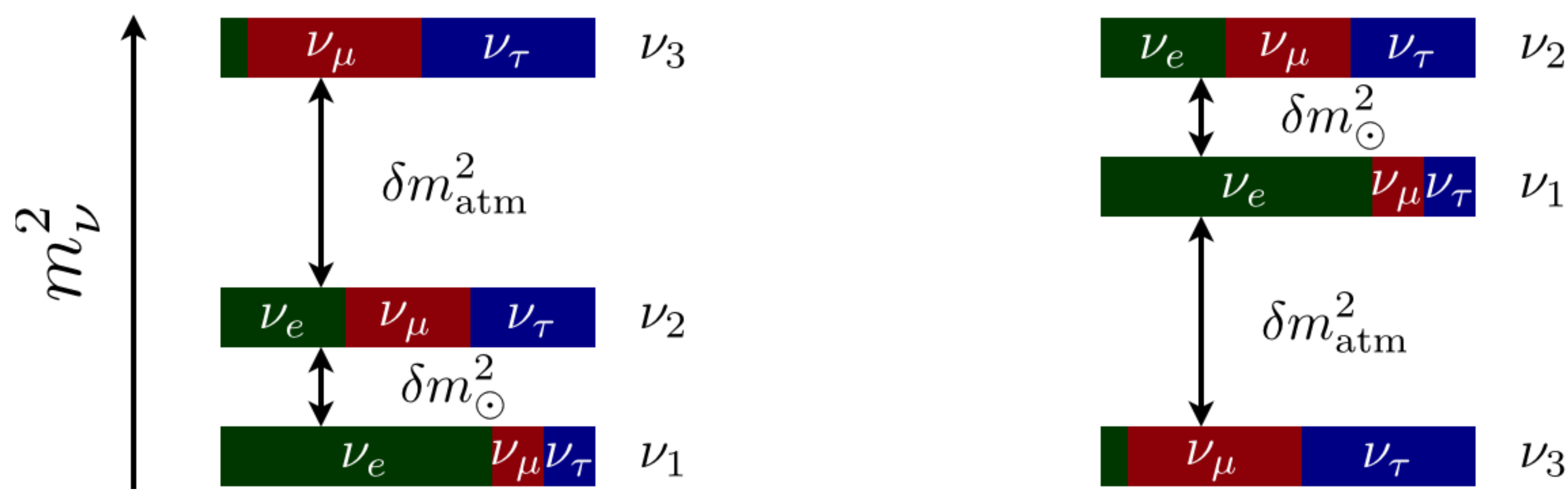
$$\bar{\nu}_e + {}^4\mathrm{He} \to {}^3\mathrm{H} + n + e^+,\ \ \lambda_{\bar{\nu}_e\alpha,n} \propto T_{\bar{\nu}_e}^{5\text{–}6}\ !$$

(Banerjee, Haxton, & Qian 2011)

neutrino spectra & flavor oscillations

$$T_{\nu_e} \sim 3\text{–}4 \text{ MeV}, \; T_{\bar{\nu}_e} \sim 4\text{–}5 \text{ MeV}, \; T_{\nu_{\mu,\tau}} = T_{\bar{\nu}_{\mu,\tau}} \sim 6\text{–}8 \text{ MeV}$$

normal mass hierarchy | inverted mass hierarchy



in supernovae

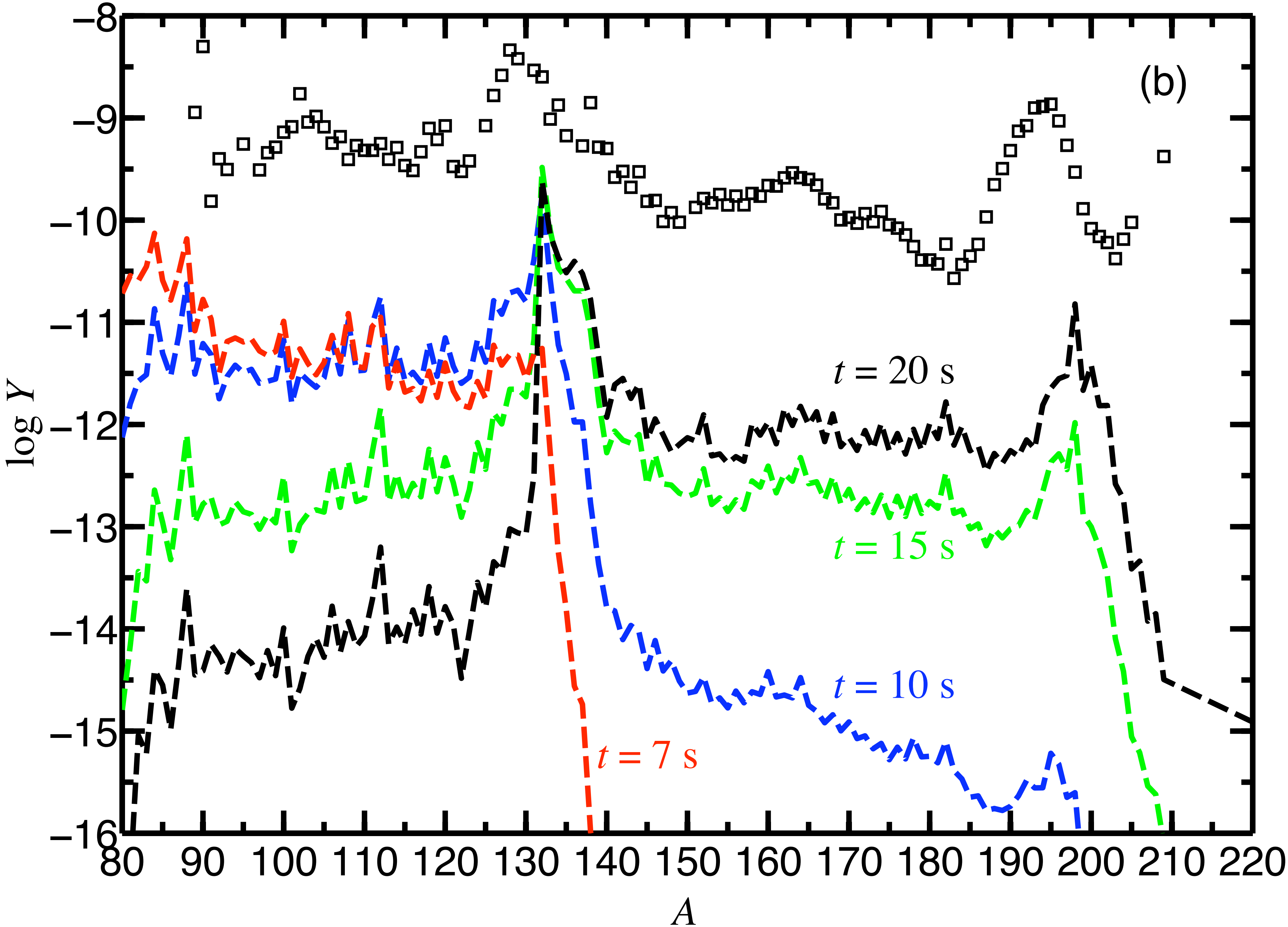
$\nu_e \rightleftharpoons \nu_{\mu,\tau}$

$^4\text{He}(\nu_e, e^- p)^3\text{He}$

$\bar{\nu}_e \rightleftharpoons \bar{\nu}_{\mu,\tau}$

$^4\text{He}(\bar{\nu}_e, e^+ n)^3\text{H}$

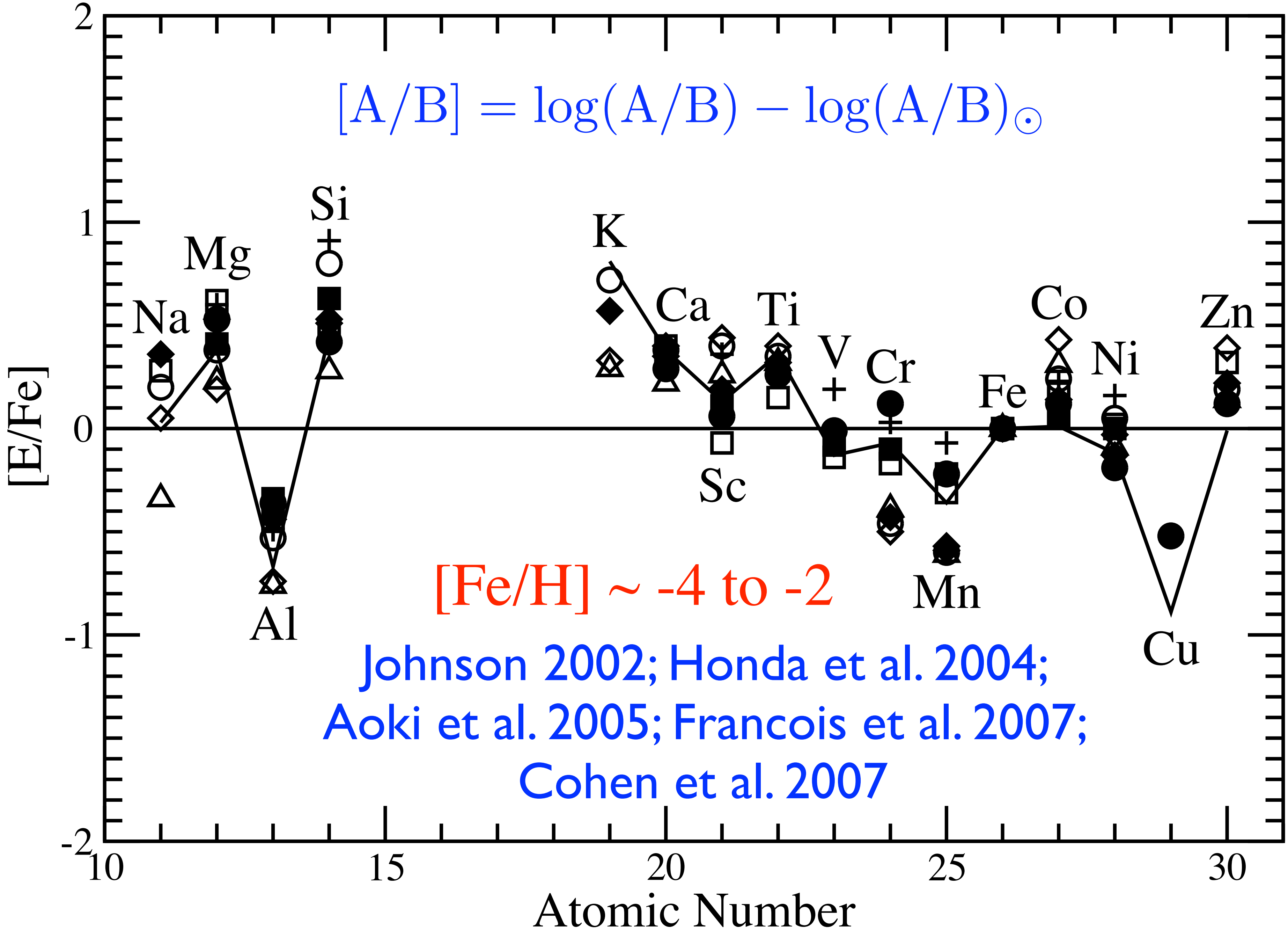
Banerjee, Haxton, & Qian (2011)



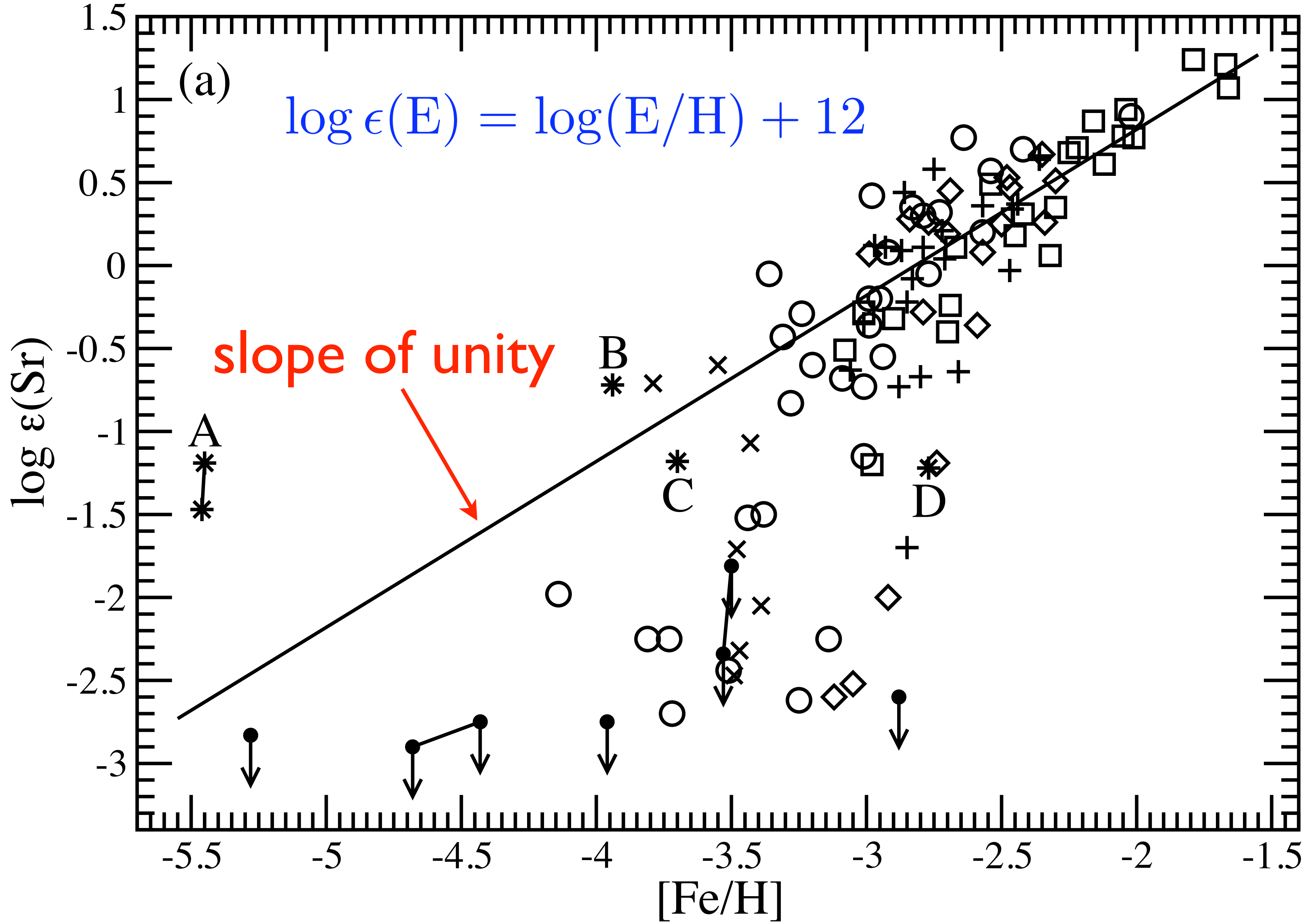
Elemental abundances in metal-poor stars

- Fe-like elements (A ~ 23 to 70)
  Na, Mg, Al, Si, ..., Fe, ..., Zn (?)
- Sr-like elements (85 < A <125)
  Rb (?), Sr, Y, Zr, ..., Ag, ..., Sb (?)
- Ba-like elements (125 < A <190)
  Te (?), ..., Ba, ..., Eu, ..., Re (?)
- Pt-like elements (A >190)
  Os (?), ..., Pt, ..., Th, ..., U, ...

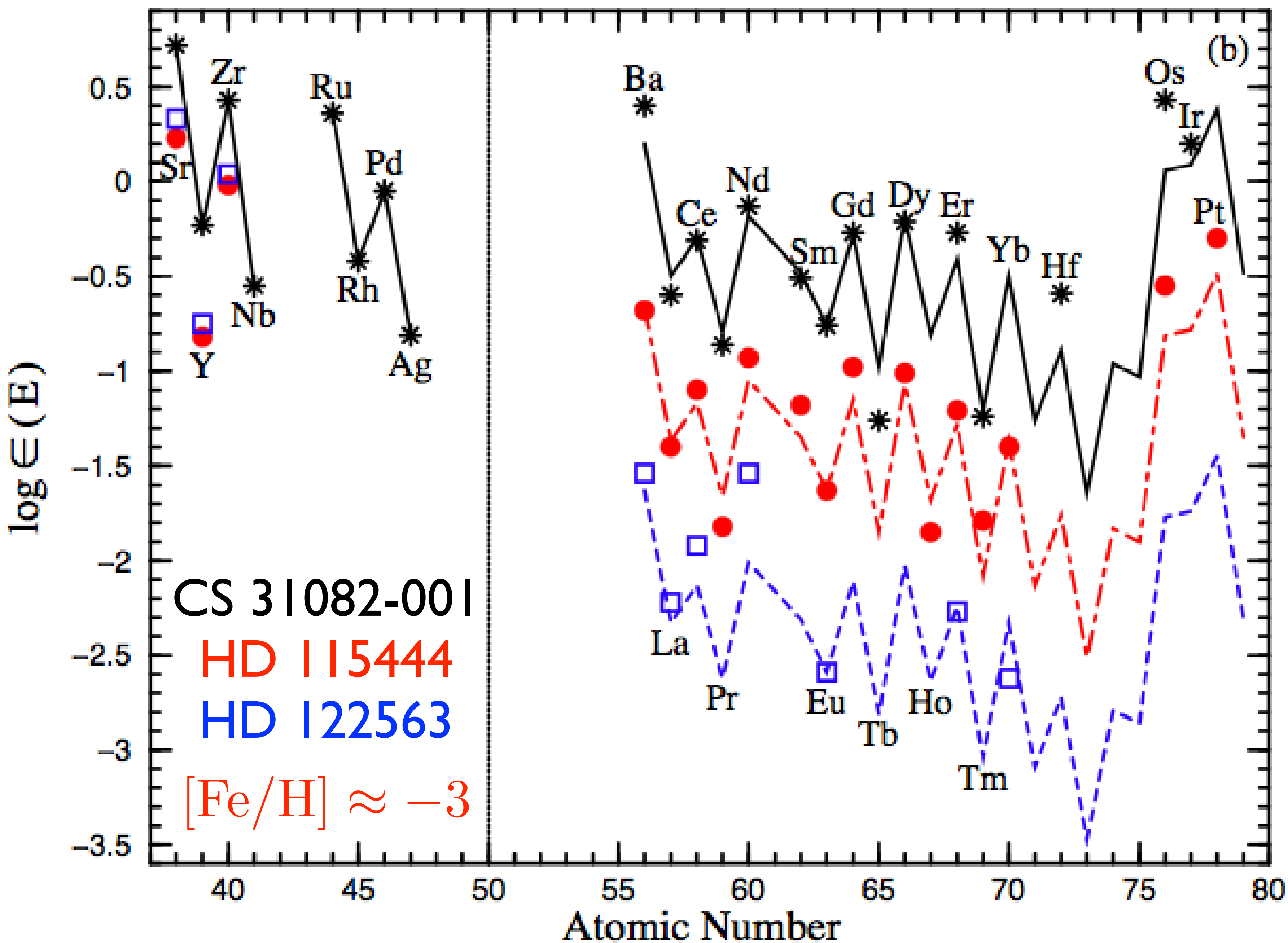
Quasi-uniform pattern of Fe-like elements



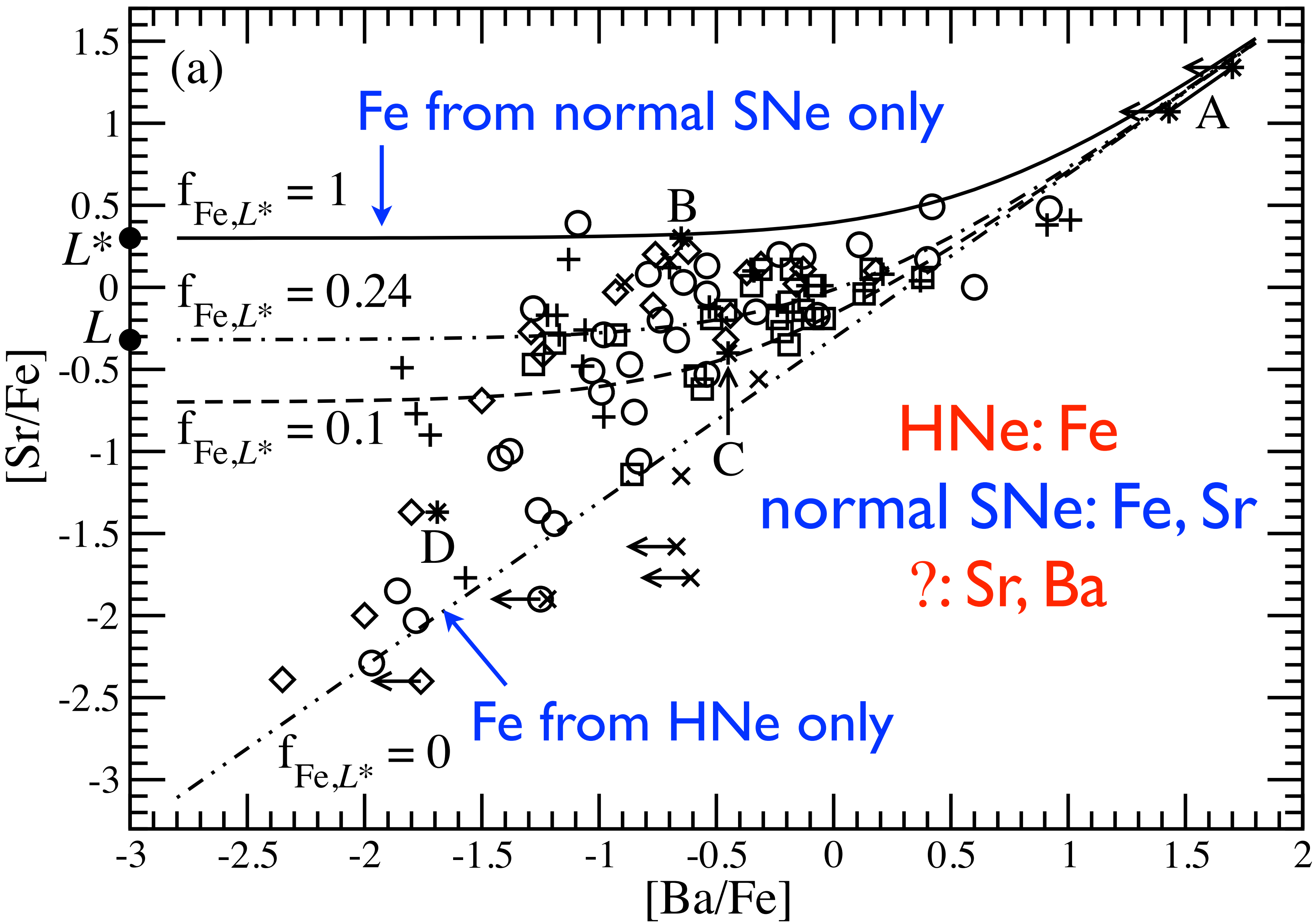
Evolution of Sr with Fe



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

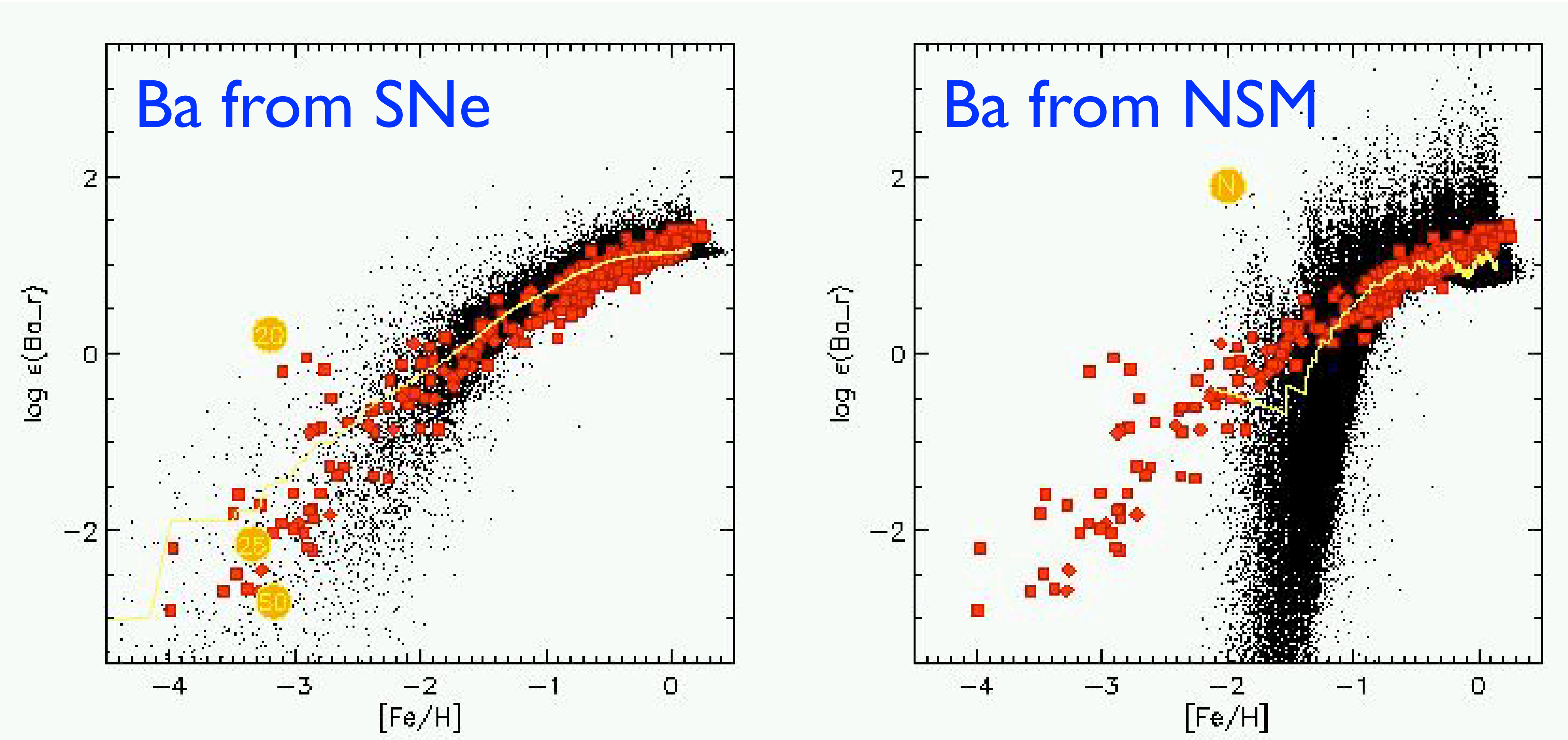


3-component model (Qian & Wasserburg 2008)

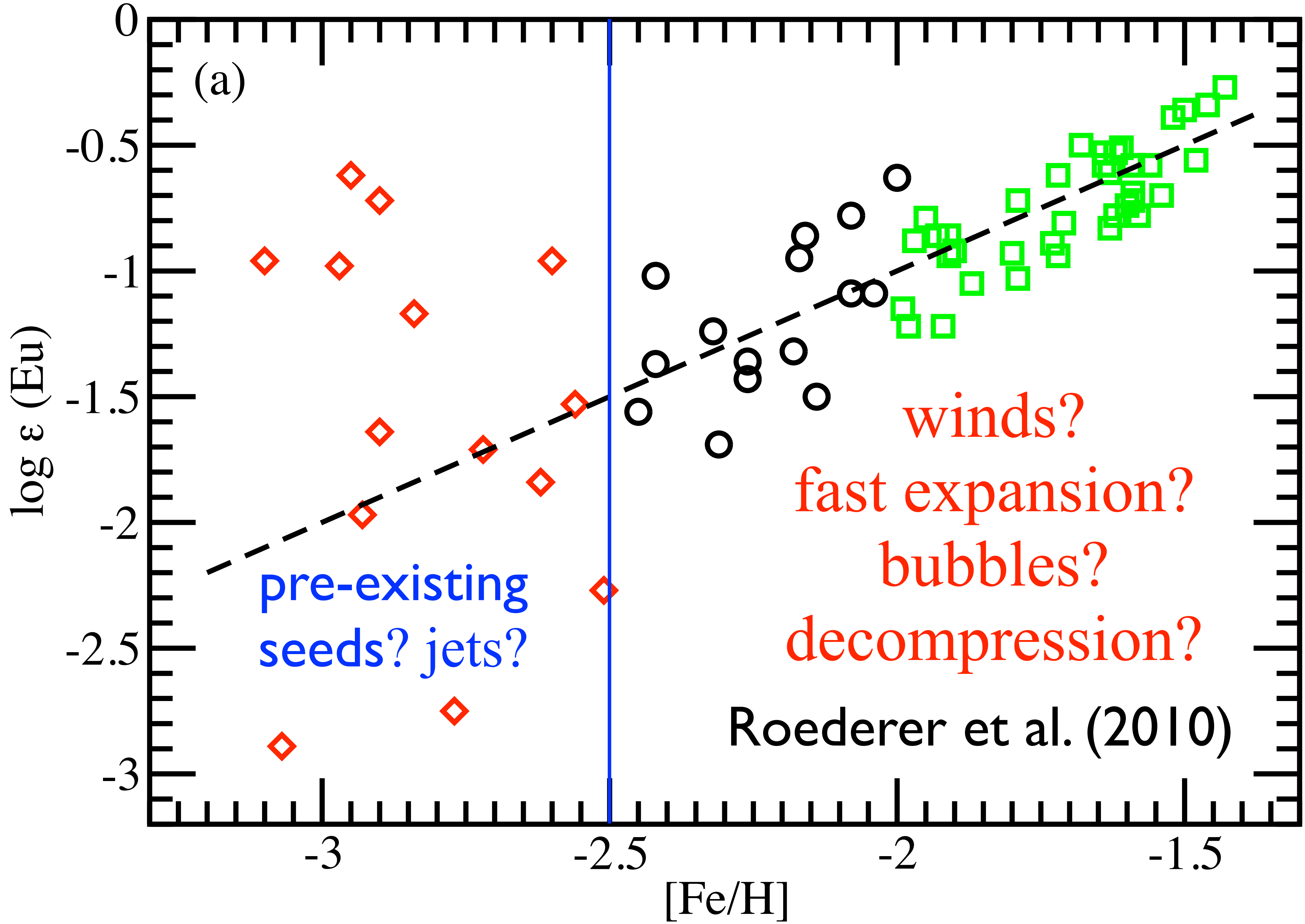


SNe vs. NSM as the r-process site

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



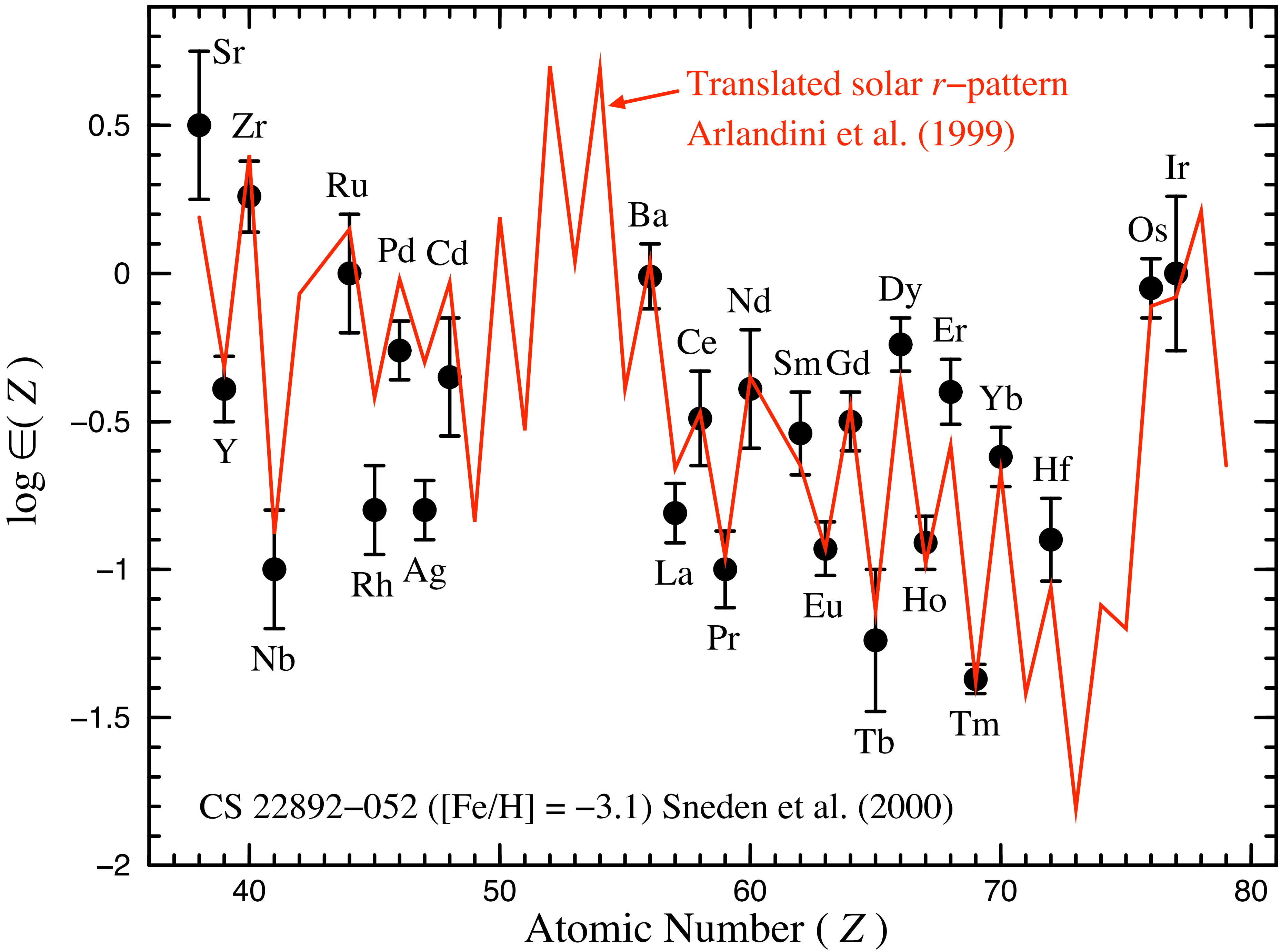
Fe from SNe



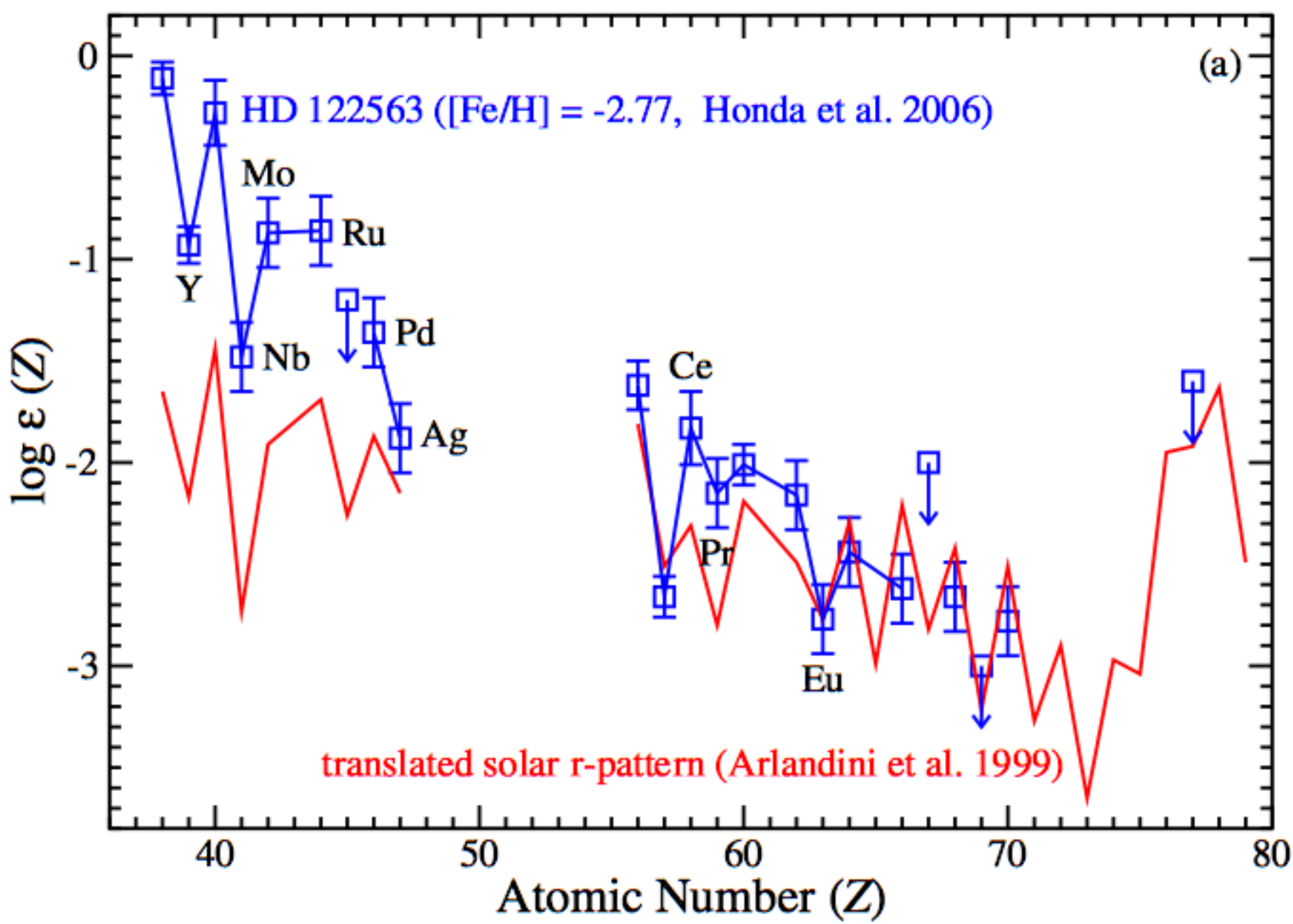
0
-0.5
-1
-1.5
-2
-2.5
-3
log ε (Eu)
-3
-2.5
-2
-1.5
[Fe/H]
(a)
pre-existing
seeds? jets?
winds?
fast expansion?
bubbles?
decompression?
Roederer et al. (2010)

P: progenitor, N: neutrino physics, D: dynamics

	P, D/N	P, N, D	P, D	P, D	P, D
	pre-existing seeds + shock/ neutrino (metal-poor SNe)	NS/BH winds (SNe, NSMs)	fast expansion (low-mass SNe)	bubbles /jets (SNe)	decompress. (NS mergers)
Sr-like	?/yes	yes/?	yes	yes/?	no
Ba-like	?/yes	?	?	?	yes
Pt-like	?	?	?	?	yes

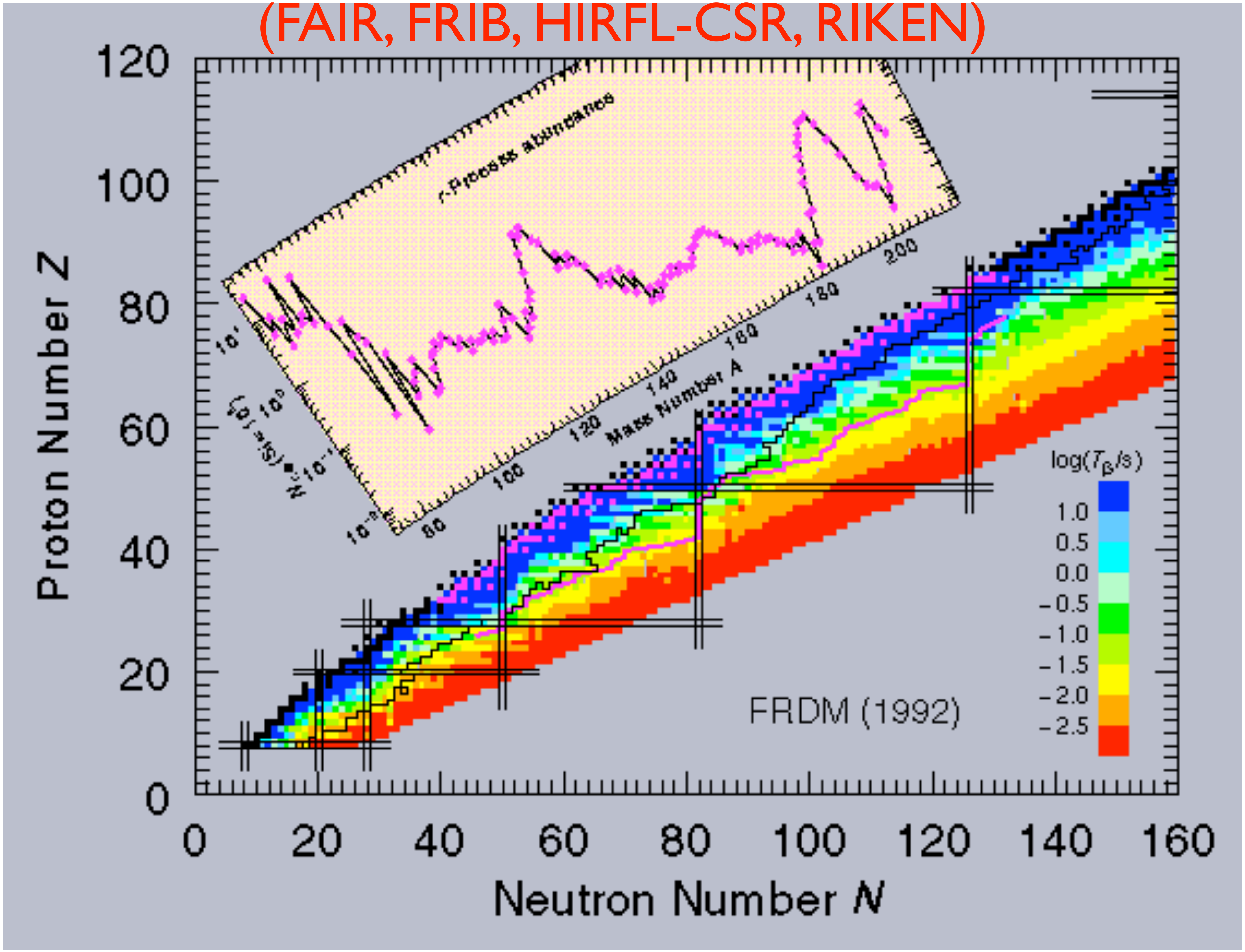


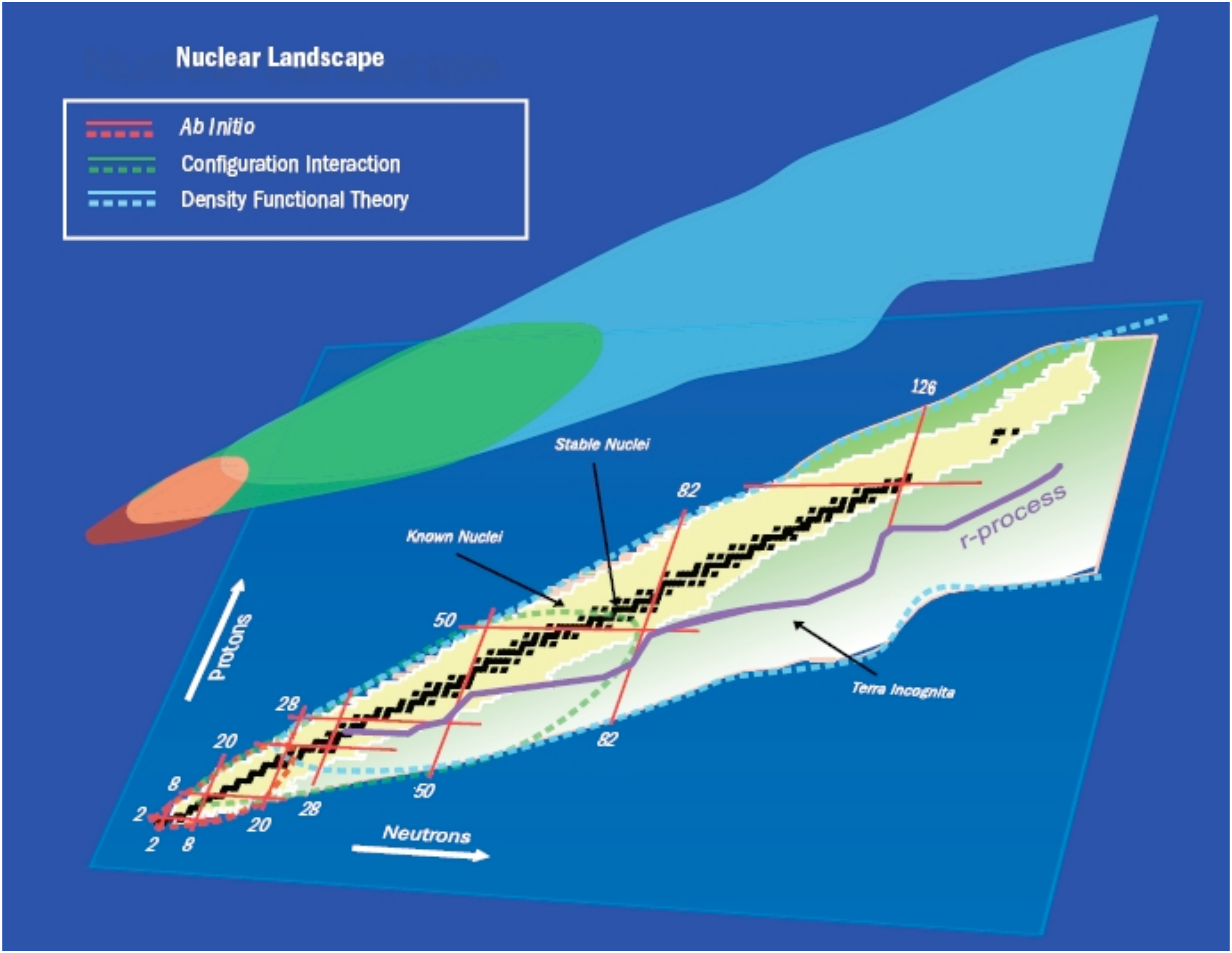
Translated solar r−pattern
Arlandini et al. (1999)
Sr
Zr
Y
Nb
Ru
Rh
Pd
Ag
Cd
Ba
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Hf
Os
Ir
CS 22892−052 ([Fe/H] = −3.1) Sneden et al. (2000)
log ∈(Z)
Atomic Number (Z)
0.5
0
−0.5
−1
−1.5
−2
40
50
60
70
80



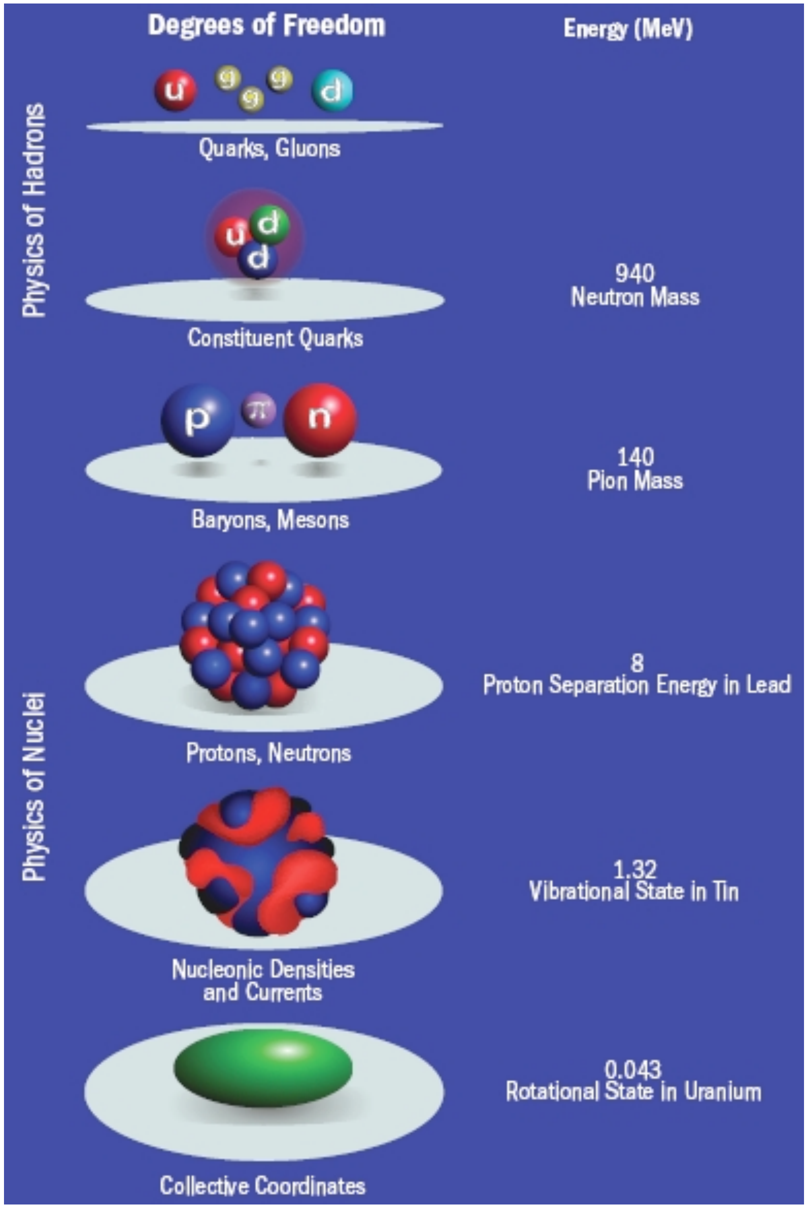
(a)
HD 122563 ([Fe/H] = -2.77, Honda et al. 2006)
translated solar r-pattern (Arlandini et al. 1999)
Y
Mo
Nb
Ru
Pd
Ag
Ce
Pr
Eu
log ε (Z)
Atomic Number (Z)
0
-1
-2
-3
40
50
60
70
80

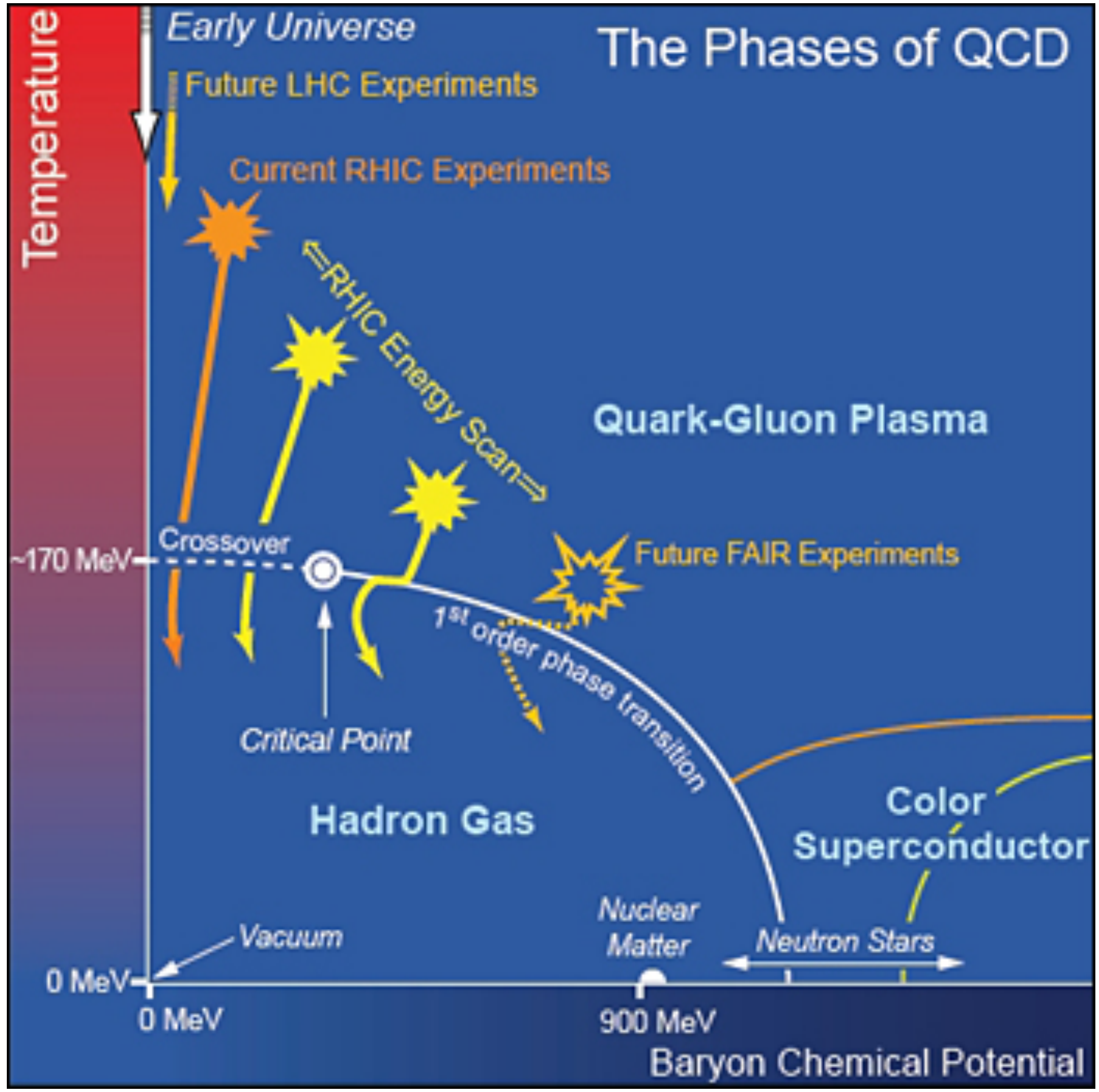
r-Process & Facility for Rare Isotope Beams
(FAIR, FRIB, HIRFL-CSR, RIKEN)



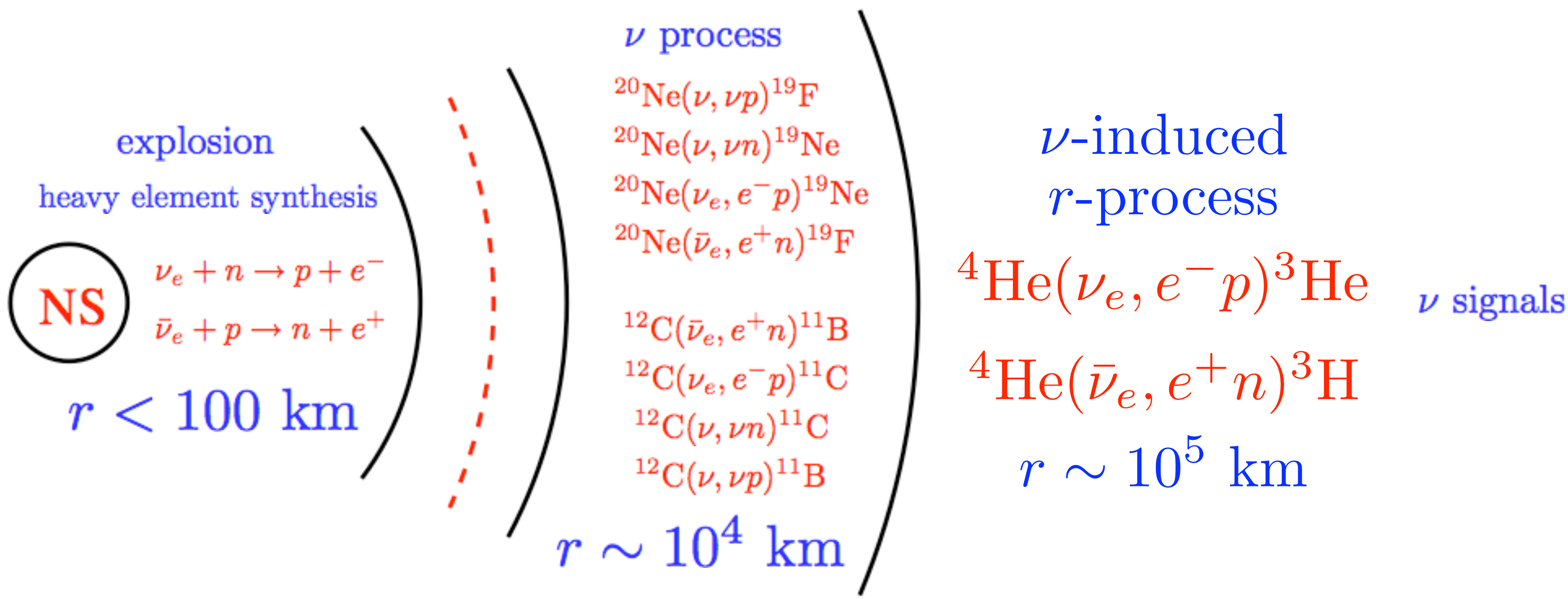

Nuclear Landscape
Ab Initio
Configuration Interaction
Density Functional Theory
Stable Nuclei
Known Nuclei
126
82
50
28
20
8
2
r-process
Terra Incognita
Protons
Neutrons

From Quarks to Nuclei & Neutron stars

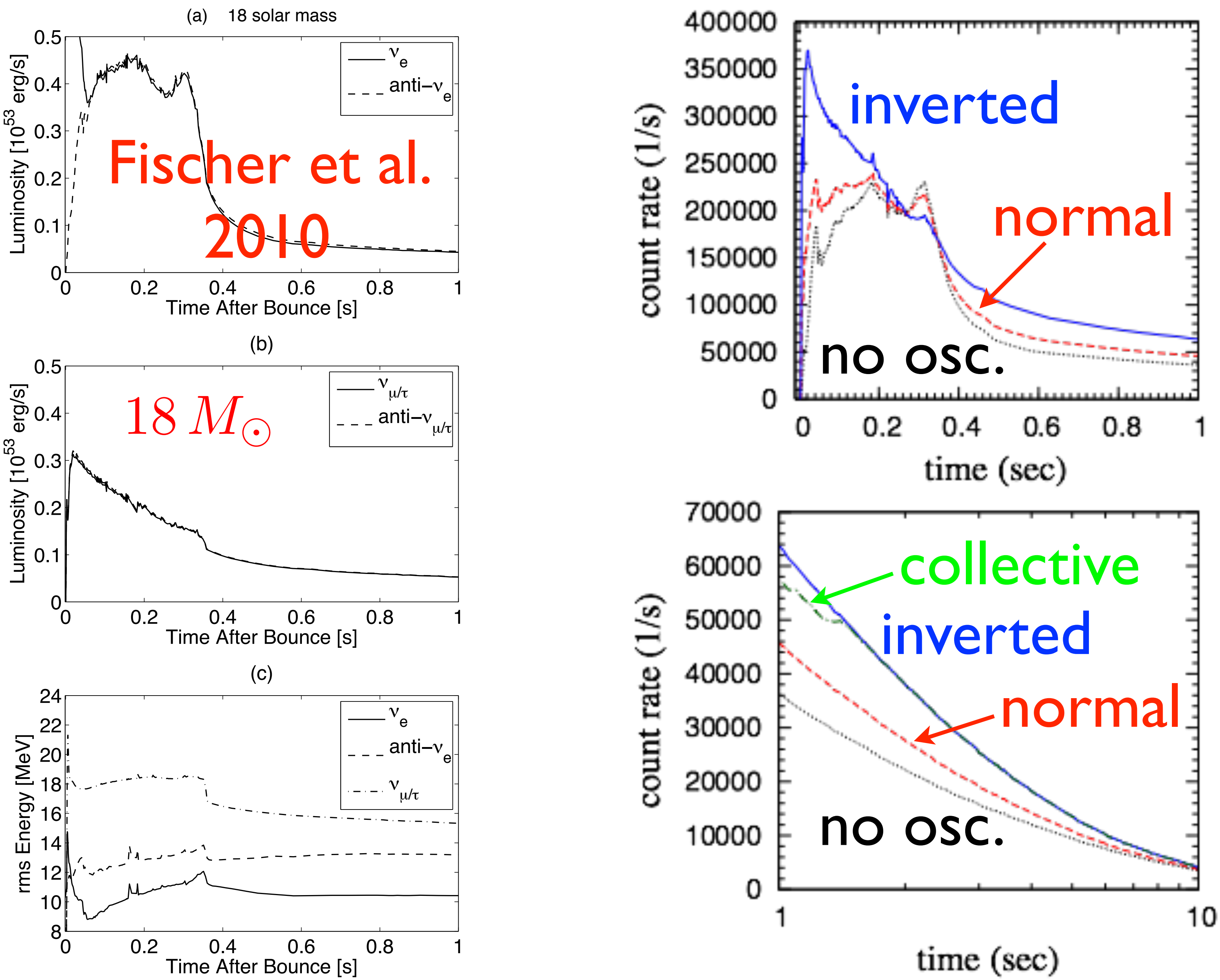




Interplay between Nucleosynthesis and Neutrino Physics



$\bar{\nu}_e + p \to n + e^+$ in IceCube (Wu et al. 2013)

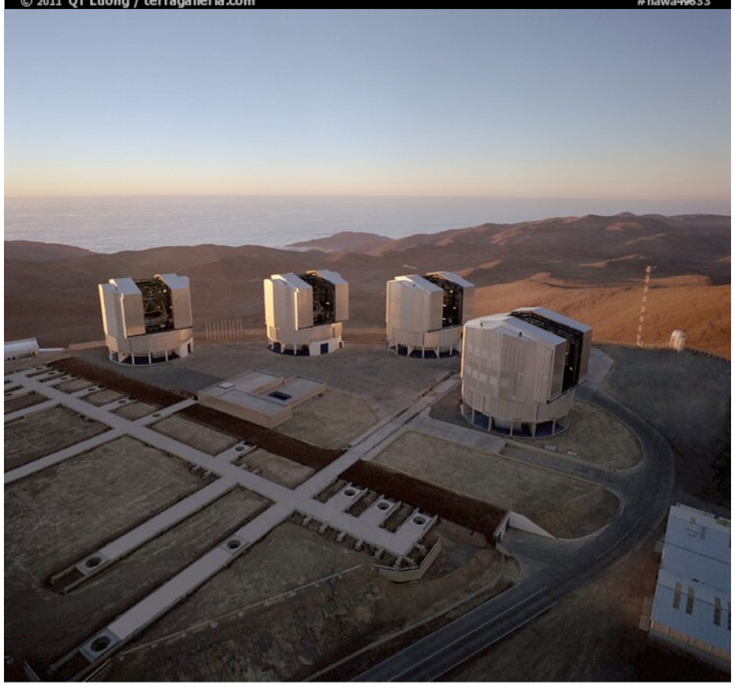


FACILITY FOR RARE ISOTOPE BEAMS

FAIR

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

RIKEN NISHINA CENTER
RIKEN Nishina Center for Accelerator-Based Science



Main Injector Neutrino Oscillation Search

Daya Bay θ_{13}