Core-Collapse Supernovae as Sites (or not) of the r-Process

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INT Program on Electromagnetic Signatures of r-process Nucleosynthesis in Neutron Star Binary Mergers

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

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.

Generic models for producing elements heavier than Fe by the r-process & related mechanisms

- expansion from high temperature & density

  with typical initial composition of n & p

  hot r-process, QSE: $T \gtrsim 10^9$ 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

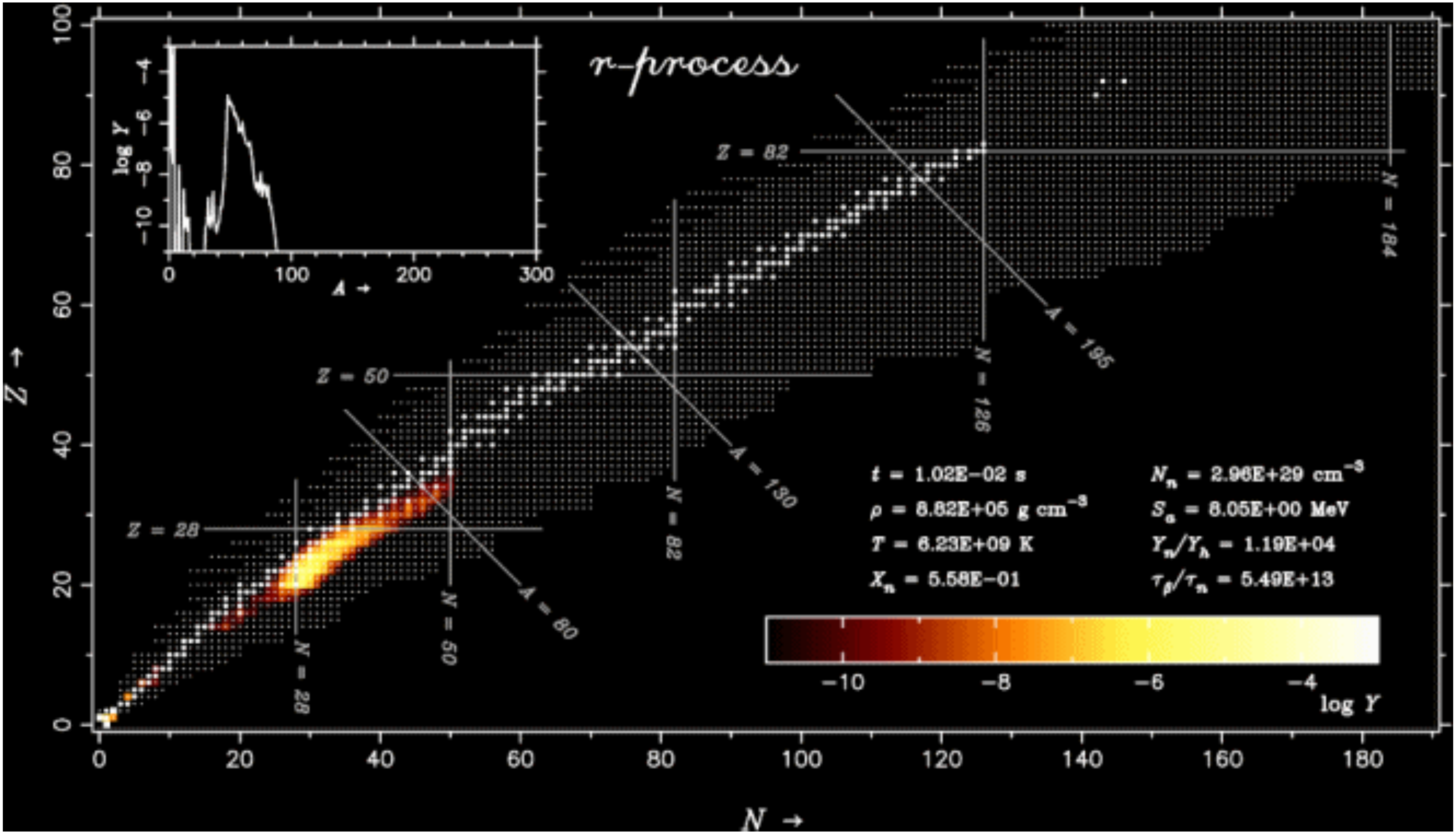
$$(n,\gamma), (p,\gamma), (n,p), (\alpha,\gamma), (\alpha,n), (\alpha,p)$$

- hot r-process

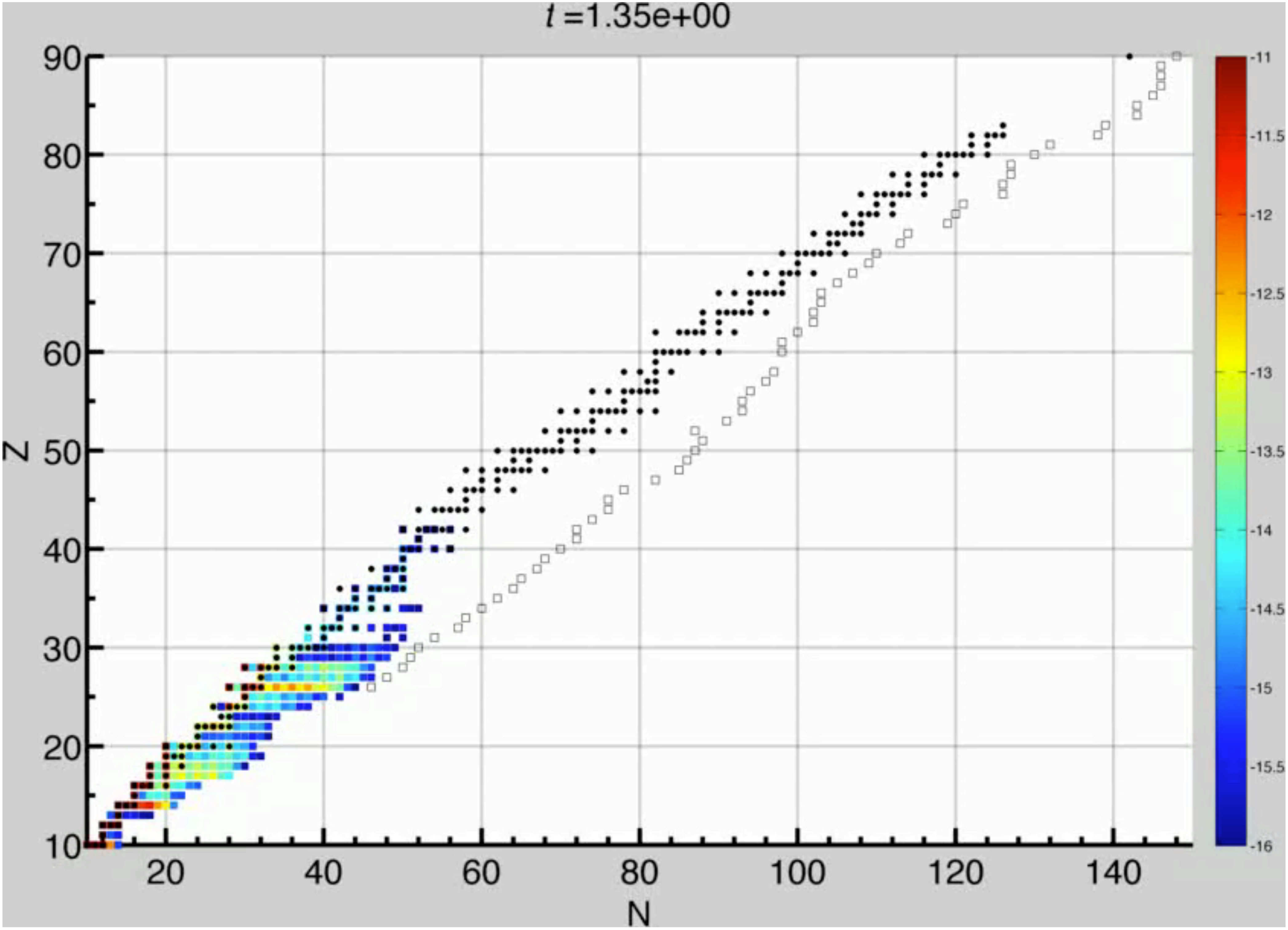
QSE within each isotopic chain only

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

Rapid Neutron Capture: the r-Process



Wanajo et al. 2004

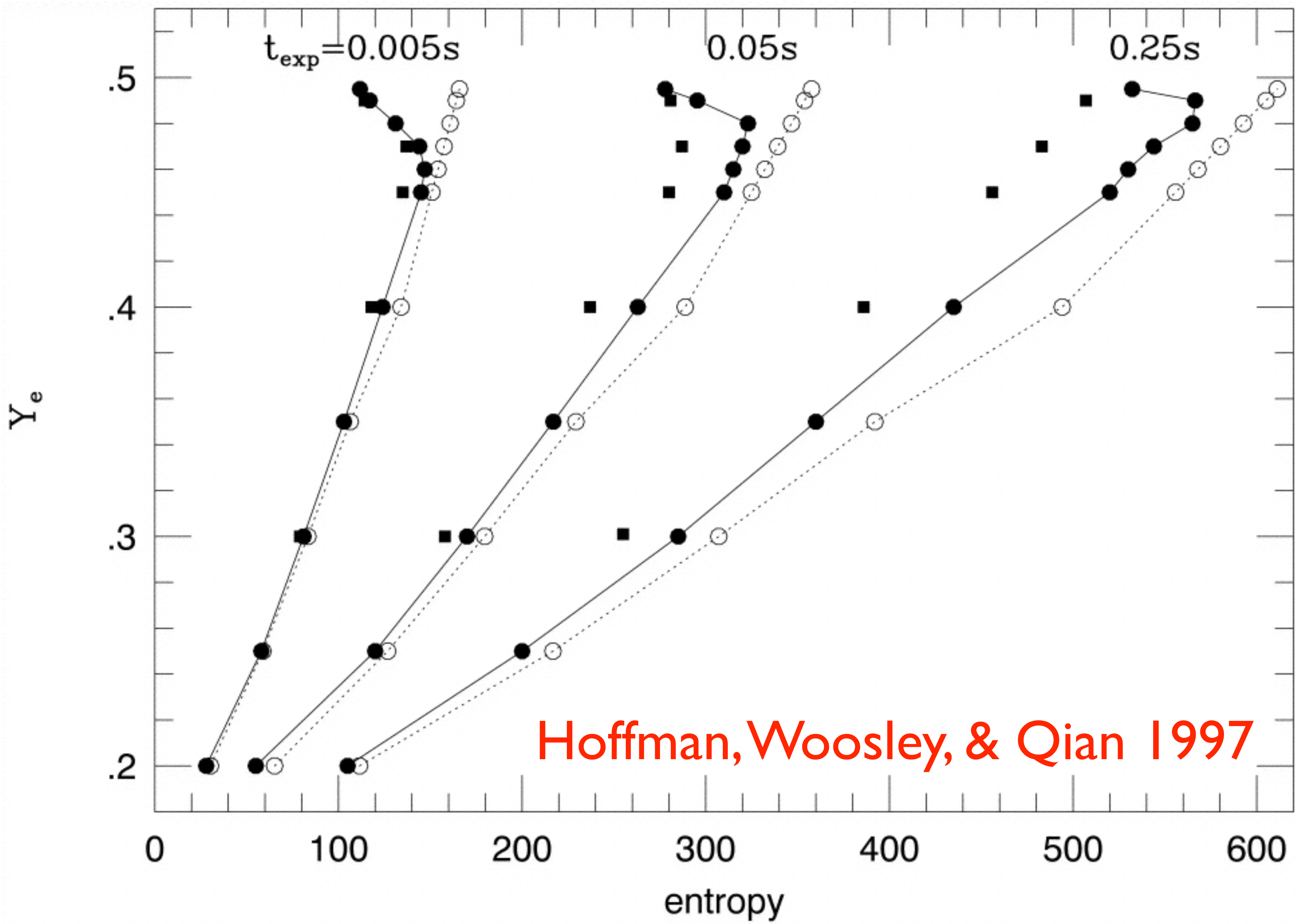


t =1.35e+00
Z
N
10
20
30
40
50
60
70
80
90
20
40
60
80
100
120
140
-11
-11.5
-12
-12.5
-13
-13.5
-14
-14.5
-15
-15.5
-16

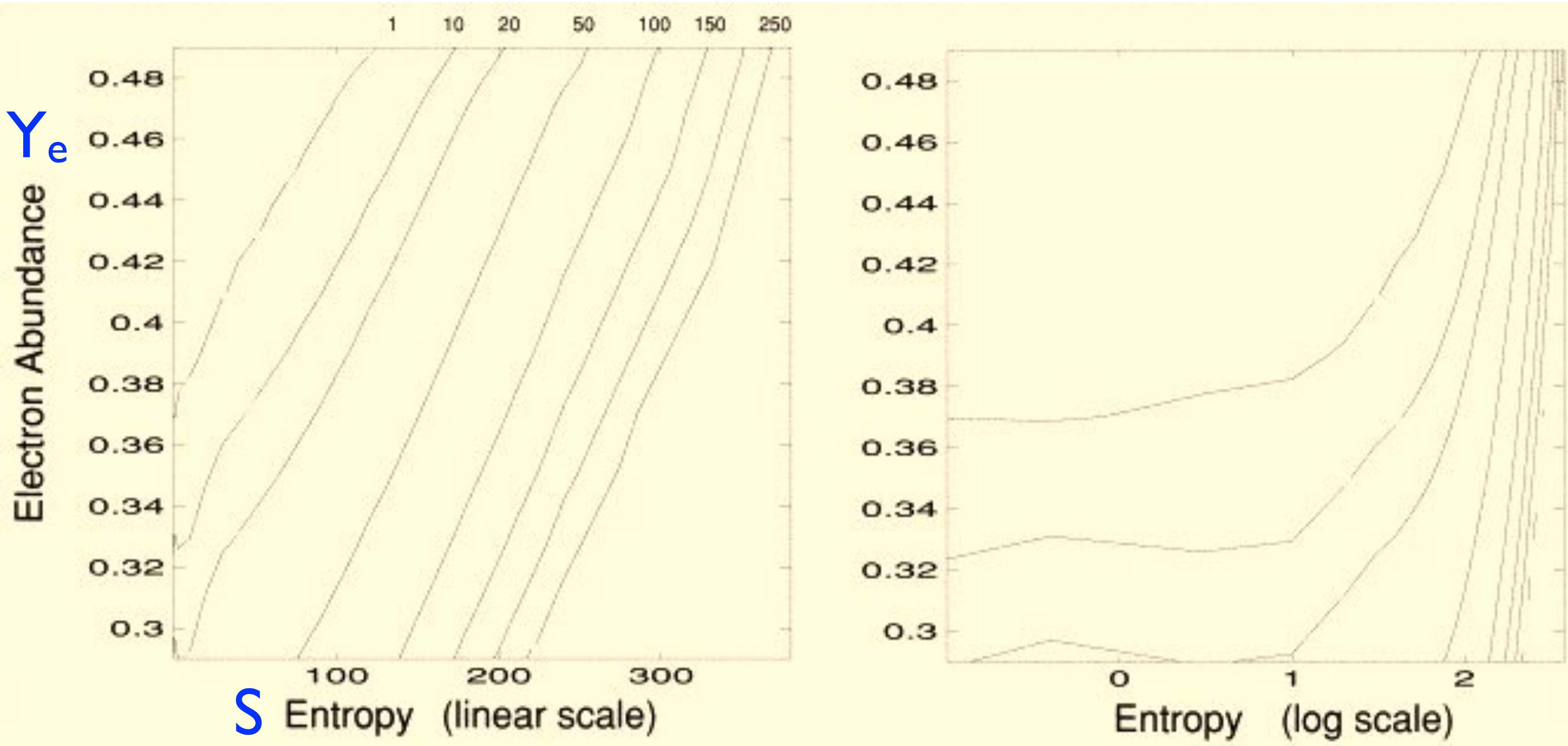
Four Scenarios

- expansion from a hot, neutron-rich initial state in winds
- fast expansion of shocked ejecta with neutron excess
- fast ejection of neutron-rich matter in bubbles & jets
- neutron capture on pre-existing seeds

Conditions for producing r-nuclei with A~200



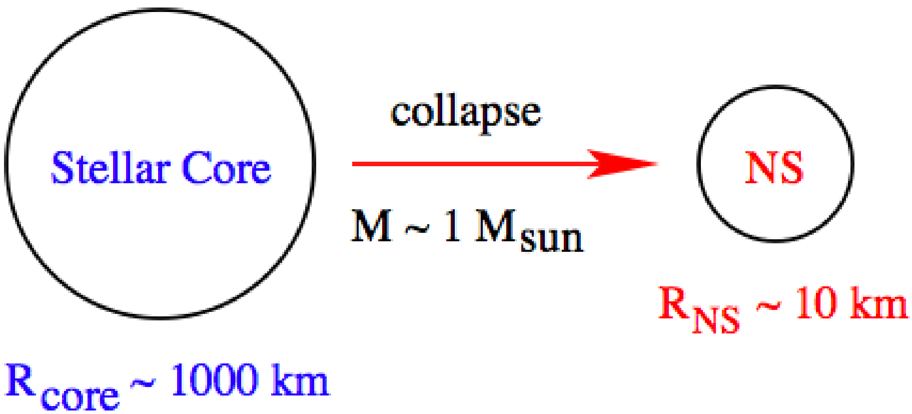
neutron-to-seed ratio as function of Y_e and S



dynamic timescale fixed at 0.05 s

Freiburghaus et al. 1999

Supernovae as a neutrino phenomenon

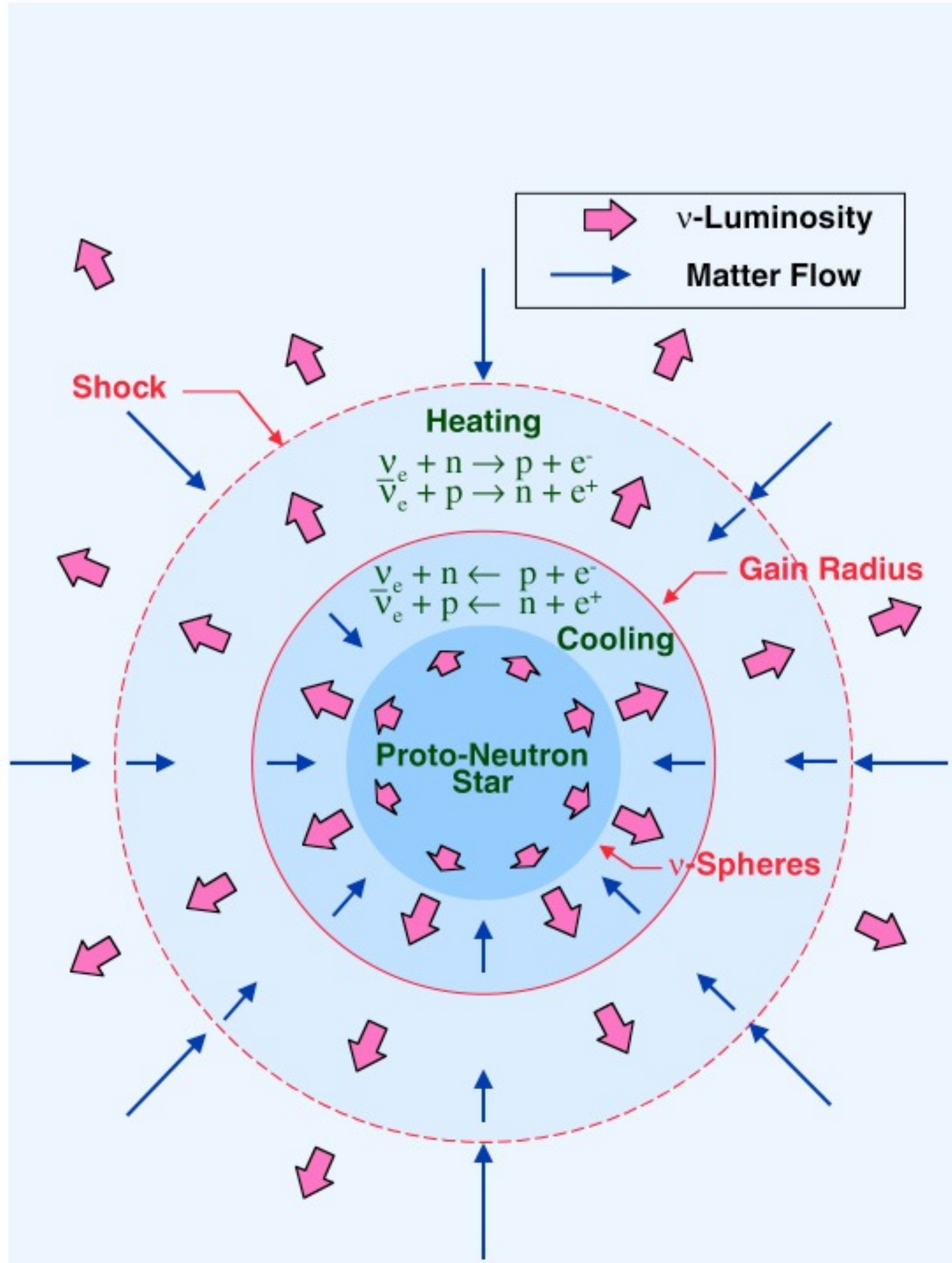


$$e^+ + e^- \to \nu + \bar{\nu}$$

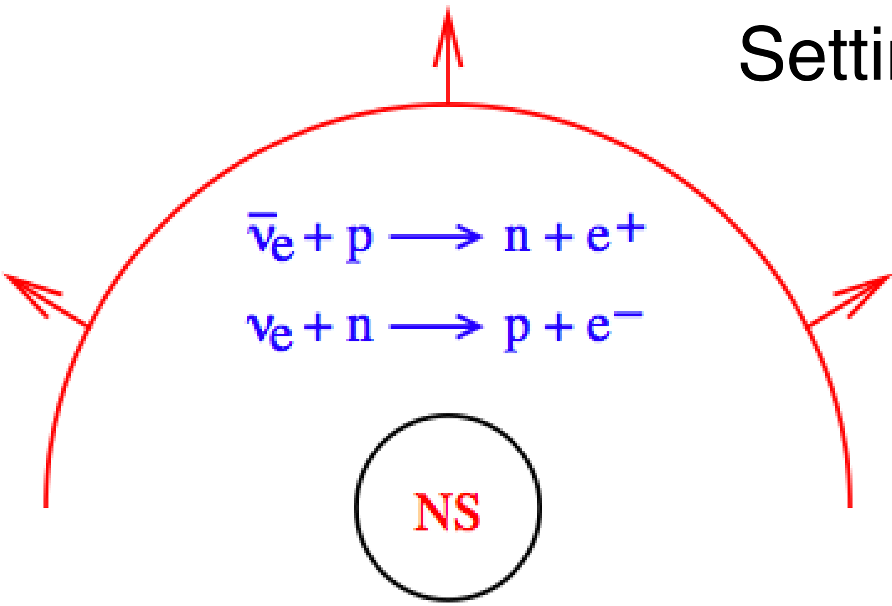
$$N + N \to N + N + \nu + \bar{\nu}$$

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

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



Setting n/p in the Neutrino-Driven Wind



$$n/p > 1 \Rightarrow Y_e < 0.5$$

Qian et al. 1993
Qian & Woosley 1996
McLaughlin et al. 1996
Horowitz & Li 1999

$$\sigma_{\nu N} \propto (E_\nu \mp \Delta_{np})^2$$

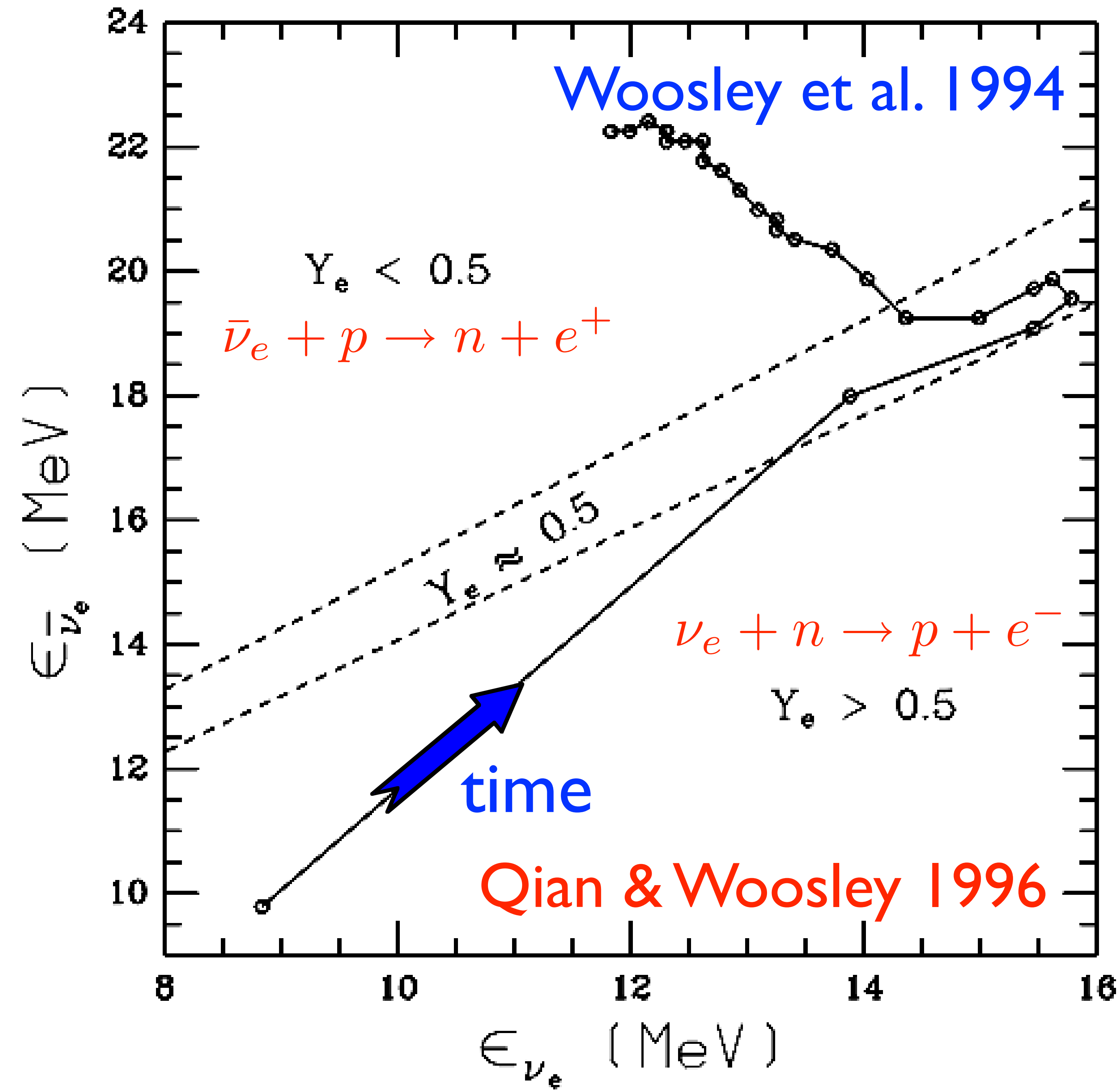
$$\lambda_{\bar{\nu}_e p} = \frac{L_{\bar{\nu}_e}}{4\pi r^2}\frac{\langle \sigma_{\bar{\nu}_e p}\rangle}{\langle E_{\bar{\nu}_e}\rangle} \propto L_{\bar{\nu}_e}\left(\frac{\langle E^2_{\bar{\nu}_e}\rangle}{\langle E_{\bar{\nu}_e}\rangle} - 2\Delta_{np}\right)$$

$$\lambda_{\nu_e n} = \frac{L_{\nu_e}}{4\pi r^2}\frac{\langle \sigma_{\nu_e n}\rangle}{\langle E_{\nu_e}\rangle} \propto L_{\nu_e}\left(\frac{\langle E^2_{\nu_e}\rangle}{\langle E_{\nu_e}\rangle} + 2\Delta_{np}\right)$$

$$\frac{\langle E^2_{\bar{\nu}_e}\rangle}{\langle E_{\bar{\nu}_e}\rangle} - \frac{\langle E^2_{\nu_e}\rangle}{\langle E_{\nu_e}\rangle} > 4\Delta_{np} \approx 5.2\ \text{MeV} \Rightarrow \frac{n}{p} > 1$$

Neutrino Opacities!

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



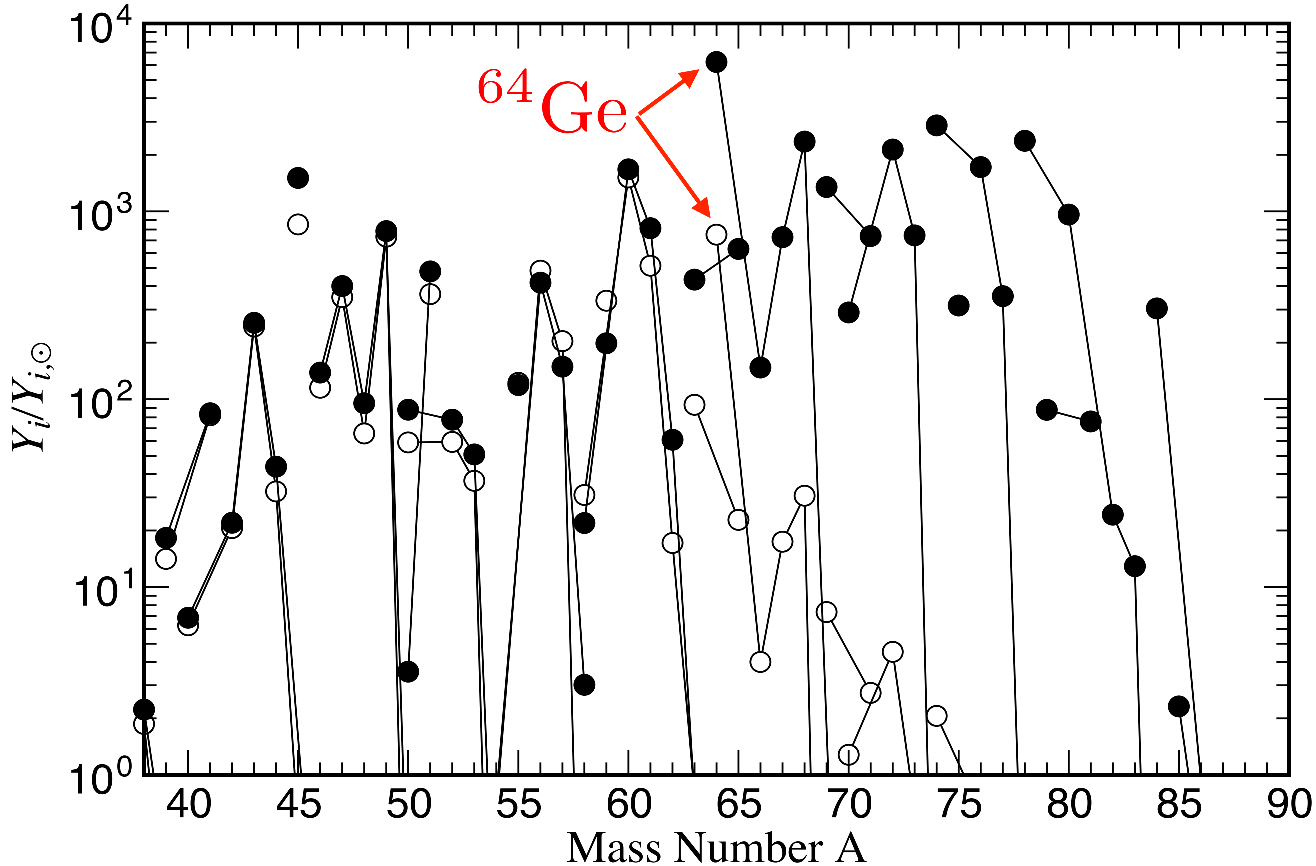
Woosley et al. 1994
$Y_e < 0.5$
$\bar{\nu}_e + p \rightarrow n + e^+$
$Y_e \approx 0.5$
$\nu_e + n \rightarrow p + e^-$
$Y_e > 0.5$
time
Qian & Woosley 1996
24
22
20
18
16
14
12
10
8
10
12
14
16
$\epsilon_{\bar{\nu}_e}$ (MeV)
ϵ_{ν_e} (MeV)

The νp-process in p-rich ν-driven winds
(Frohlich et al. 2006a,b; Pruet et al. 2005,2006)

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

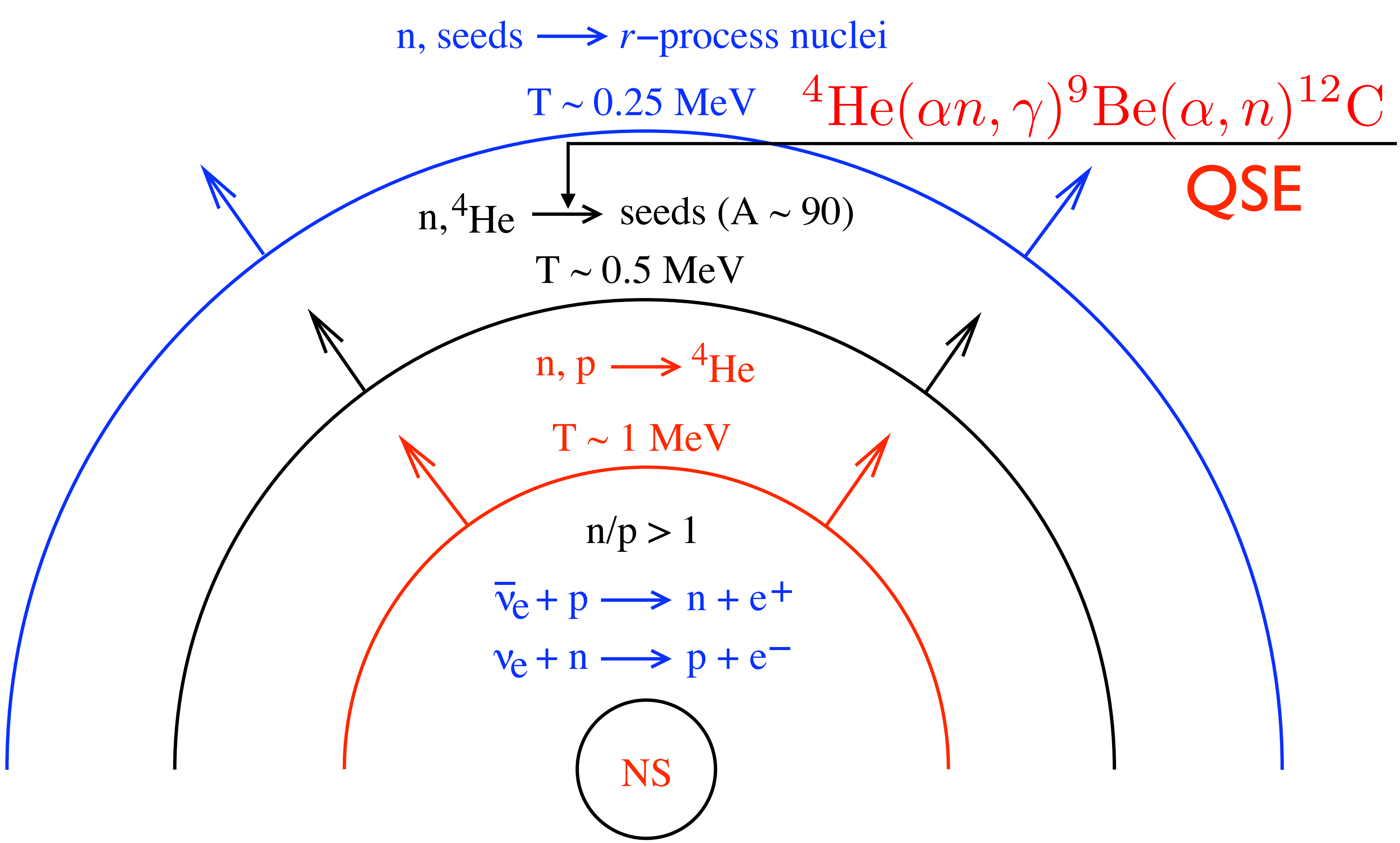
break through waiting-point nuclei with slow beta decay:

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



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)

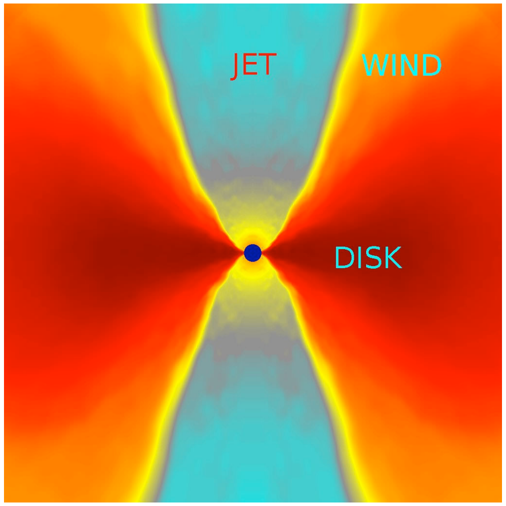
Sr, Y, Zr (A~90) readily produced in the ν-driven wind,
up to Pd & Ag (A~110) likely, all by QSE
(Woosley & Hoffman 1992; Arcones & Montes 2011)

production of r-nuclei up to A~130 possible,
but very hard to make A>130
(Hoffman et al. 1997; Wanajo 2013)

But see Metzger et al. 2007 for winds from
rotating magnetized neutron stars

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

- winds from accretion disks of BHs



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

- fast expansion of shocked ejecta with neutron excess

(Ning, Qian, & Meyer 2007; Eichler et al. 2012)
but see Janka et al. 2008

- bubbles driven by convection

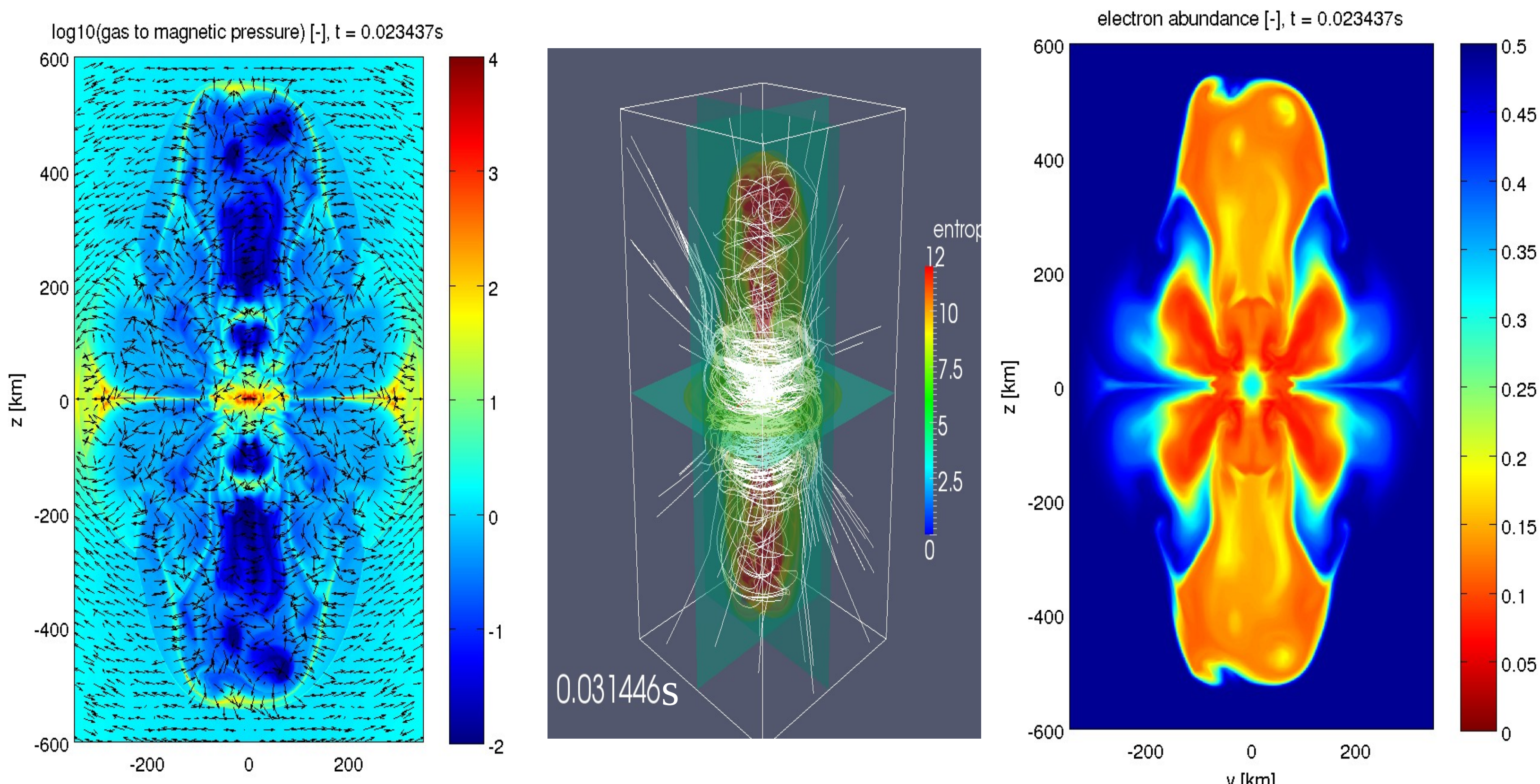
seen in low-mass SN models (Wanajo et al. 2011)

• jets driven by rotation, magnetohydrodynamics, etc.

3D Collapse of Fast Rotator with Strong Magnetic Fields:

15 M_{sol} progenitor (Heger Woosley 2002), shellular rotation with period of 2s at 1000km, magnetic field in z-direction of 5 x10^{12} Gauss,

results in 10^{15} Gauss neutron star



3D simulations by C. Winteler, R. Käppeli, M. Liebendörfer et al. 2012
Eichler et al. 2013

(also Symbalisty + 1985; Nishimura + 2006; Fujimoto + 2007) 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

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

Banerjee, Haxton, & Qian 2011

determination of n abundance in outer He shells

n production

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

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

n destruction

by preexisting nuclei ^{12}C, ^{16}O, ^{56}Fe

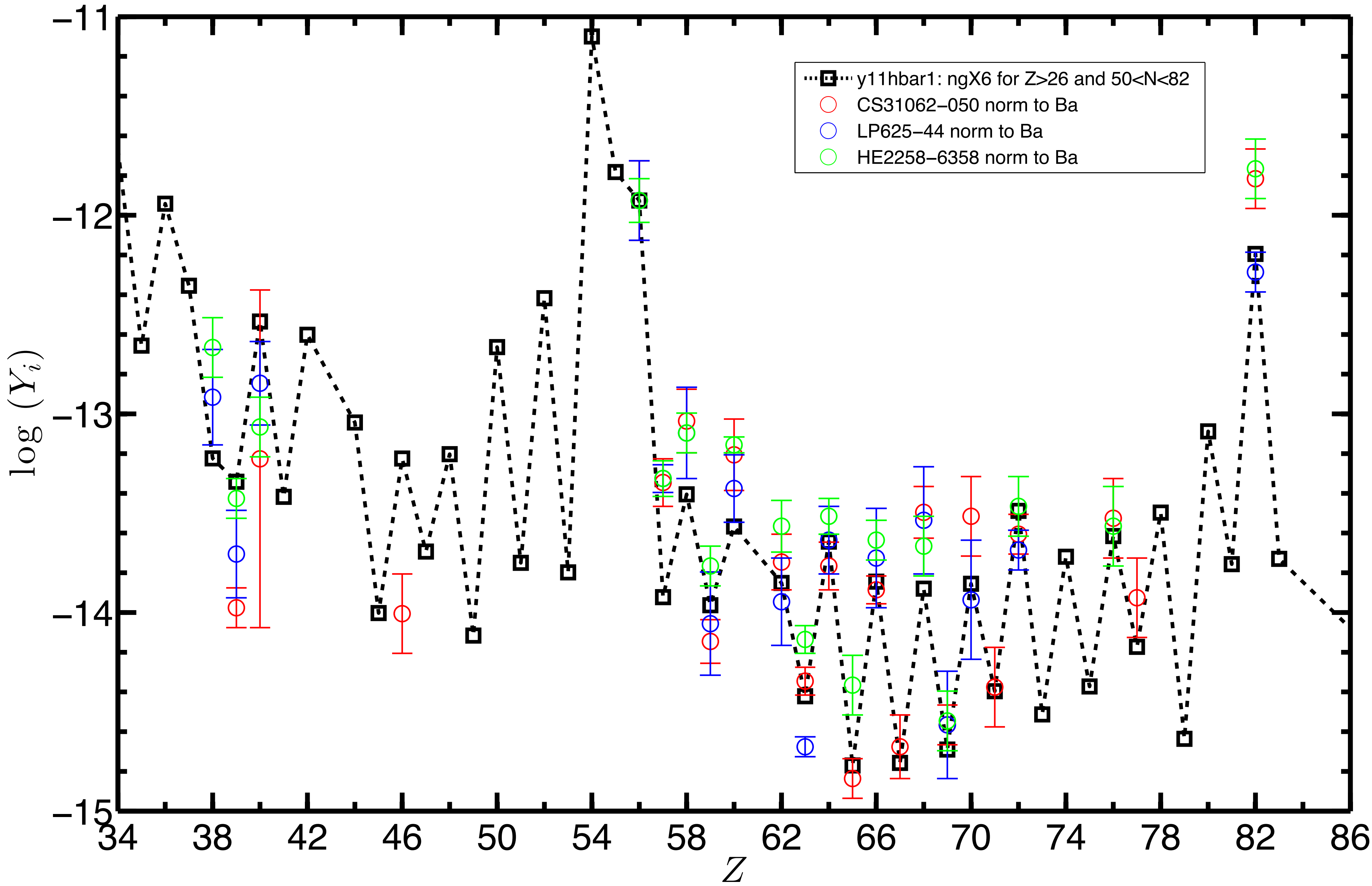
important evaluations of measurements
by ENDF, JENDL, etc.

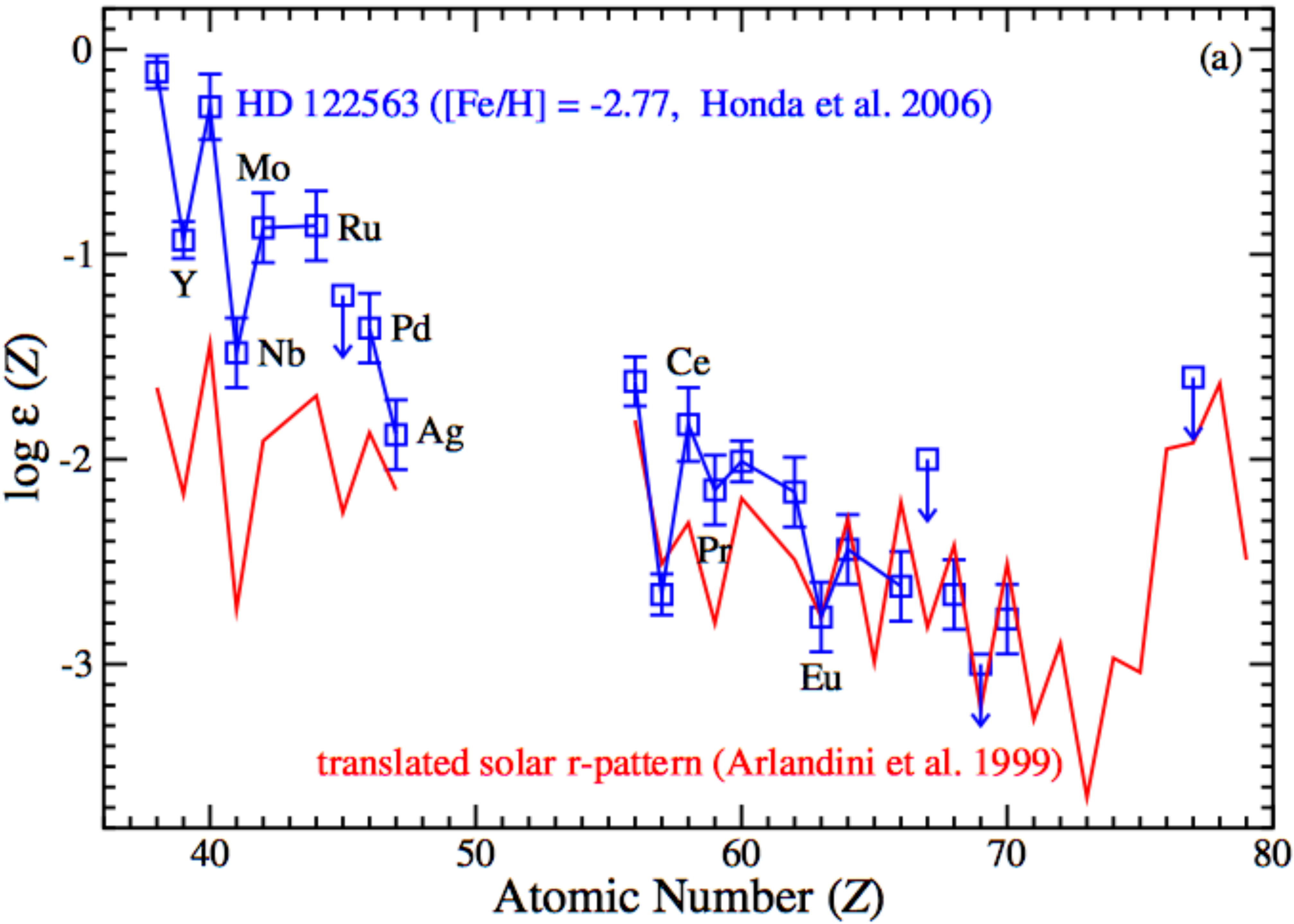
by newly synthesized nuclei

$$^3\mathrm{H} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Li} + \gamma$$

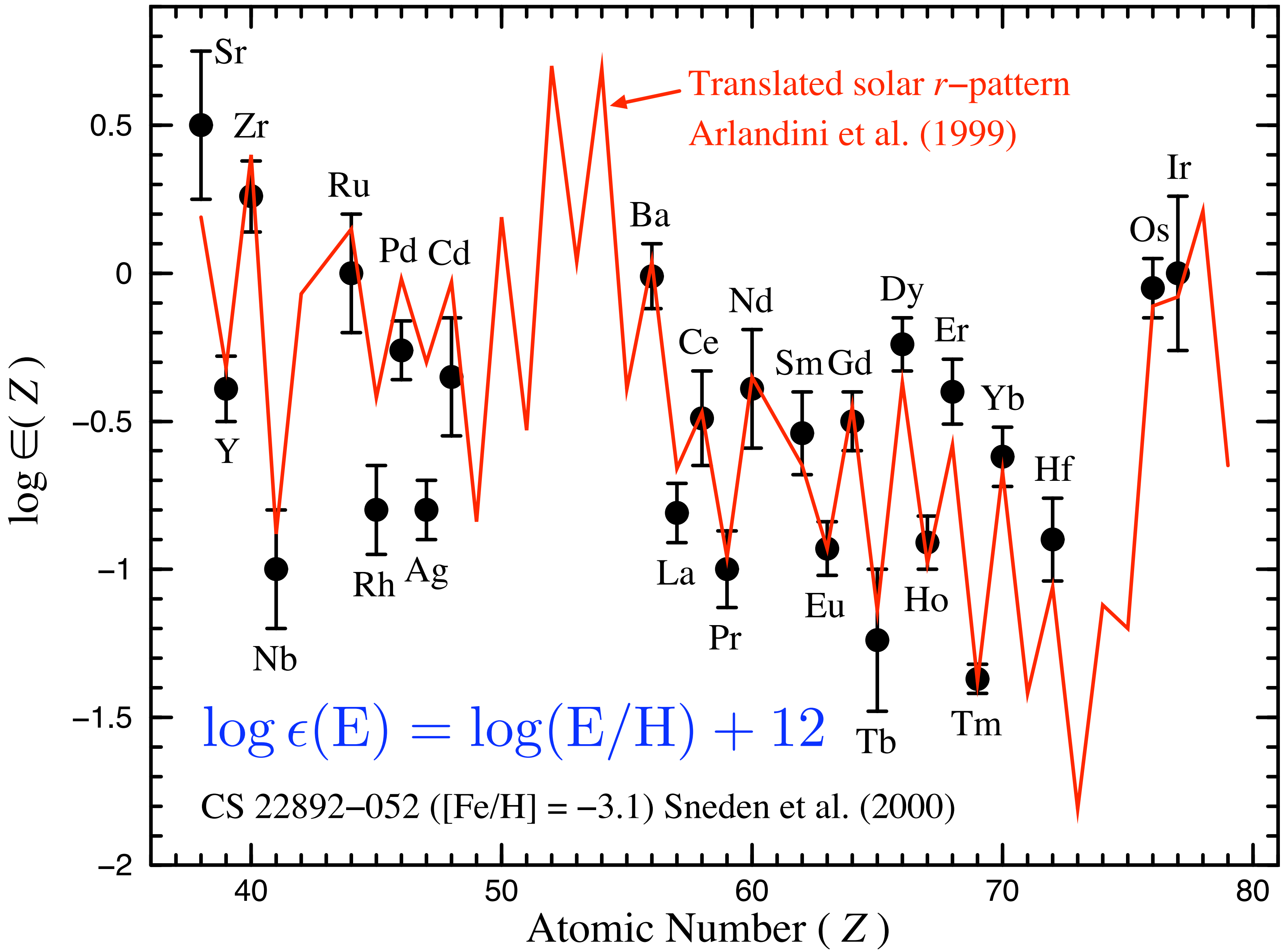
$$^3\mathrm{H} + {}^7\mathrm{Li} \rightarrow 2\,{}^4\mathrm{He} + 2n$$ (ineffective!)

Banerjee, Qian, Haxton, & Heger 2016





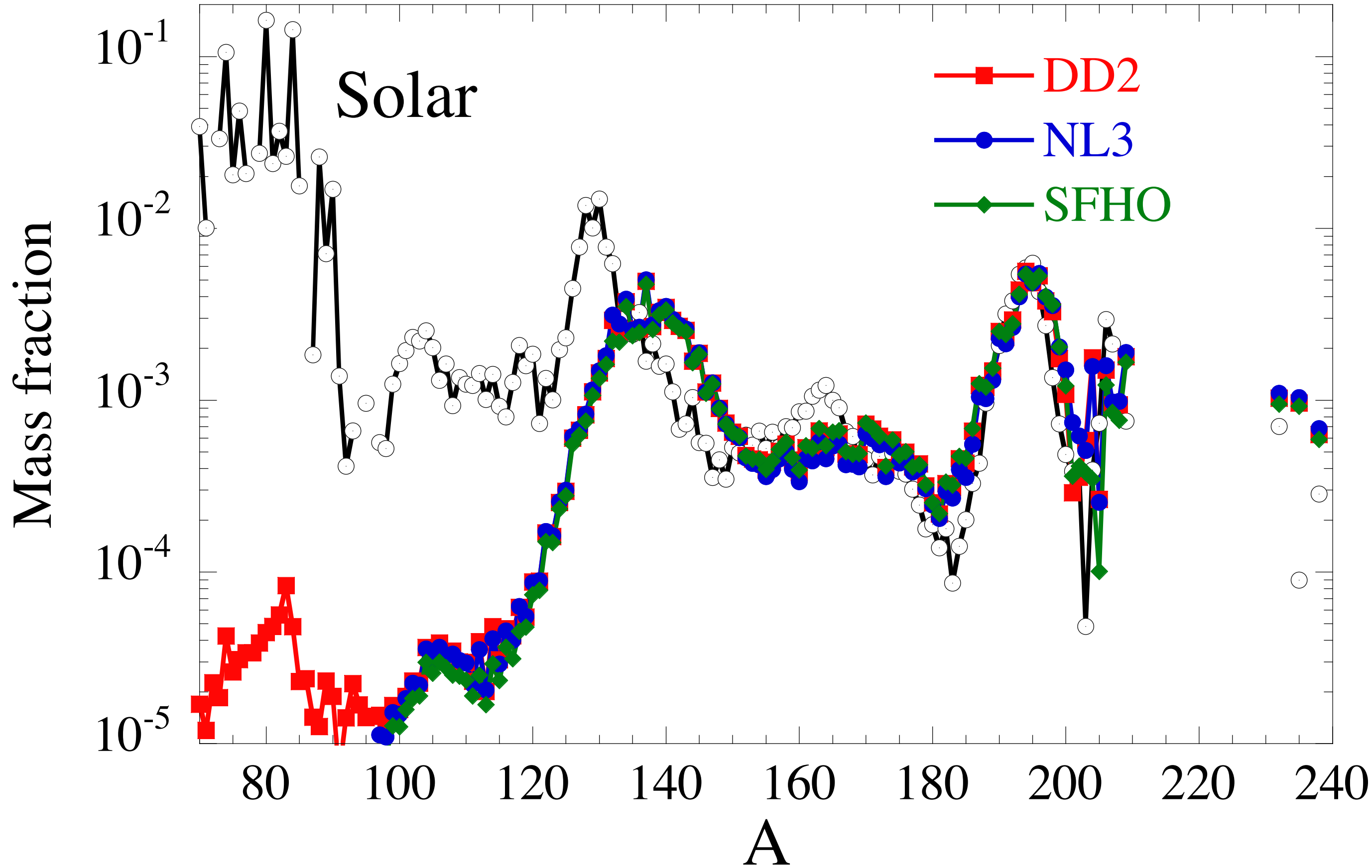
(a)
HD 122563 ([Fe/H] = -2.77, Honda et al. 2006)
Mo
Ru
Y
Nb
Pd
Ag
Ce
Pr
Eu
translated solar r-pattern (Arlandini et al. 1999)
log ε (Z)
Atomic Number (Z)
0
-1
-2
-3
40
50
60
70
80



metal-poor star update:
Roederer +, Frebel +, Hansen +

meteoritic hints:
Wasserburg + 1996
Qian + 1998

decompression of cold neutron star matter

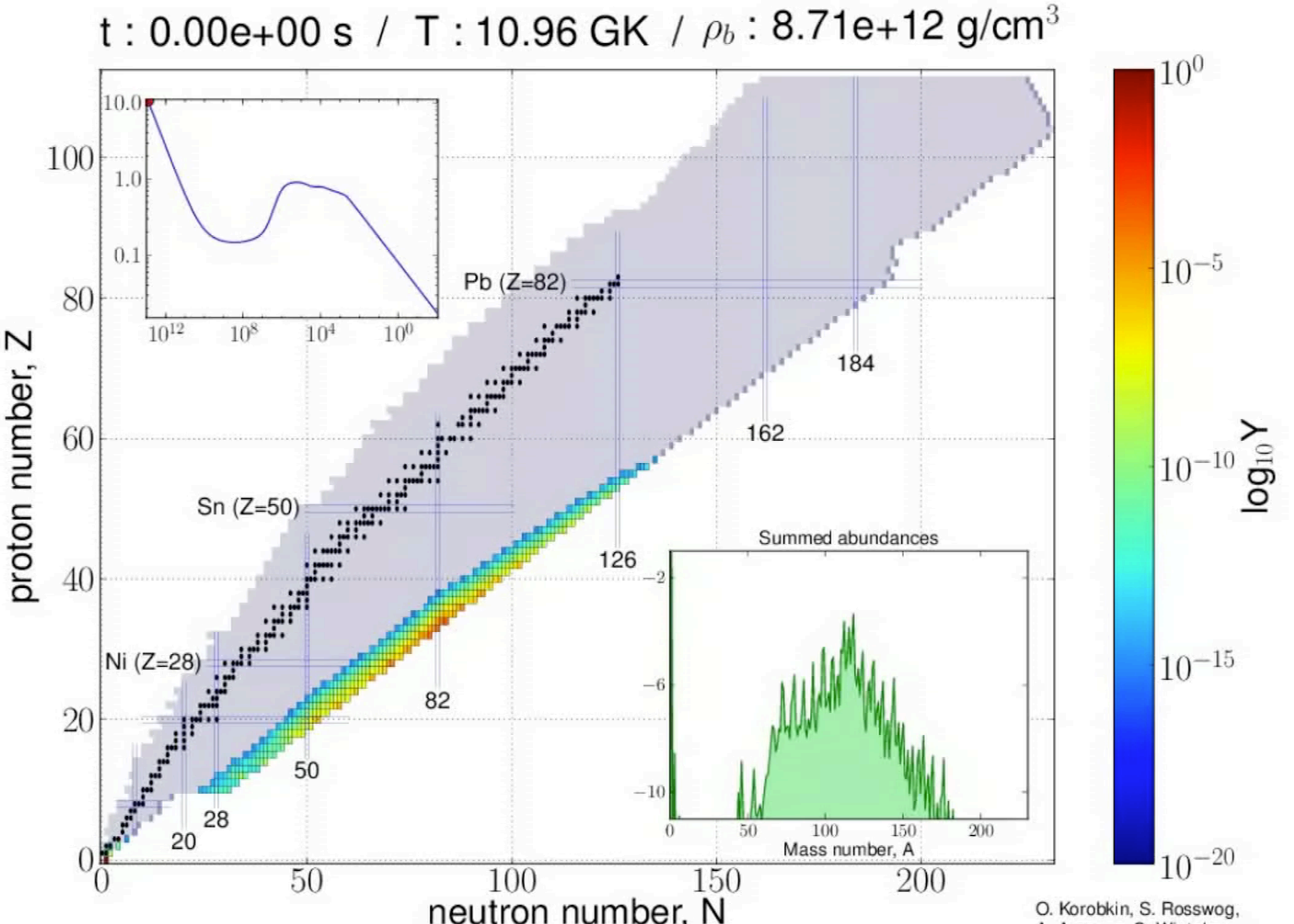


(Goriely, Bauswein, & Janka 2011, 2013)

also see Lattimer et al. 1977;

Freiburghaus, Rosswog, & Thielemann1999;

Korobkin et al. 2012

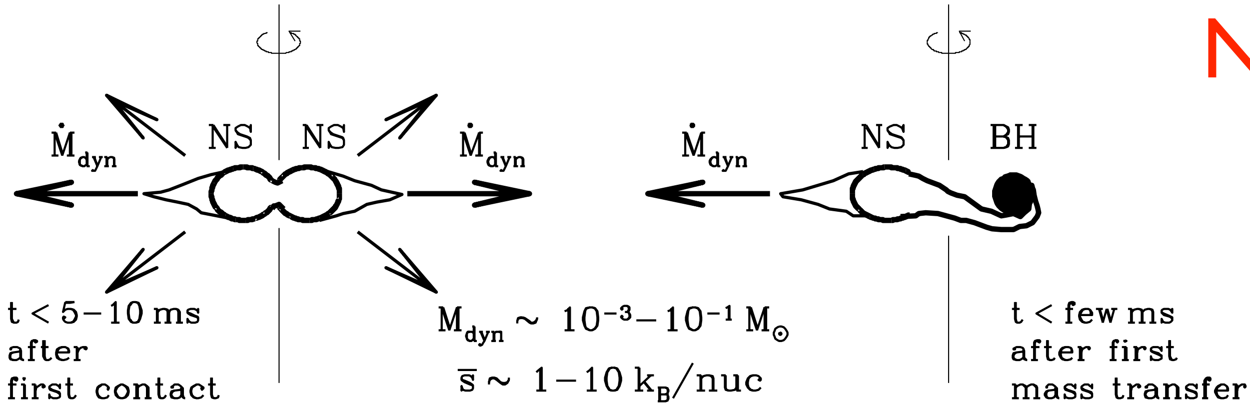


O. Korobkin, S. Rosswog,
A. Arcones, C. Winteler,
arXiv:1206.2379

Mass Loss Phases During NS–NS and NS–BH Merging

Merger Phase: Prompt/dynamical ejecta

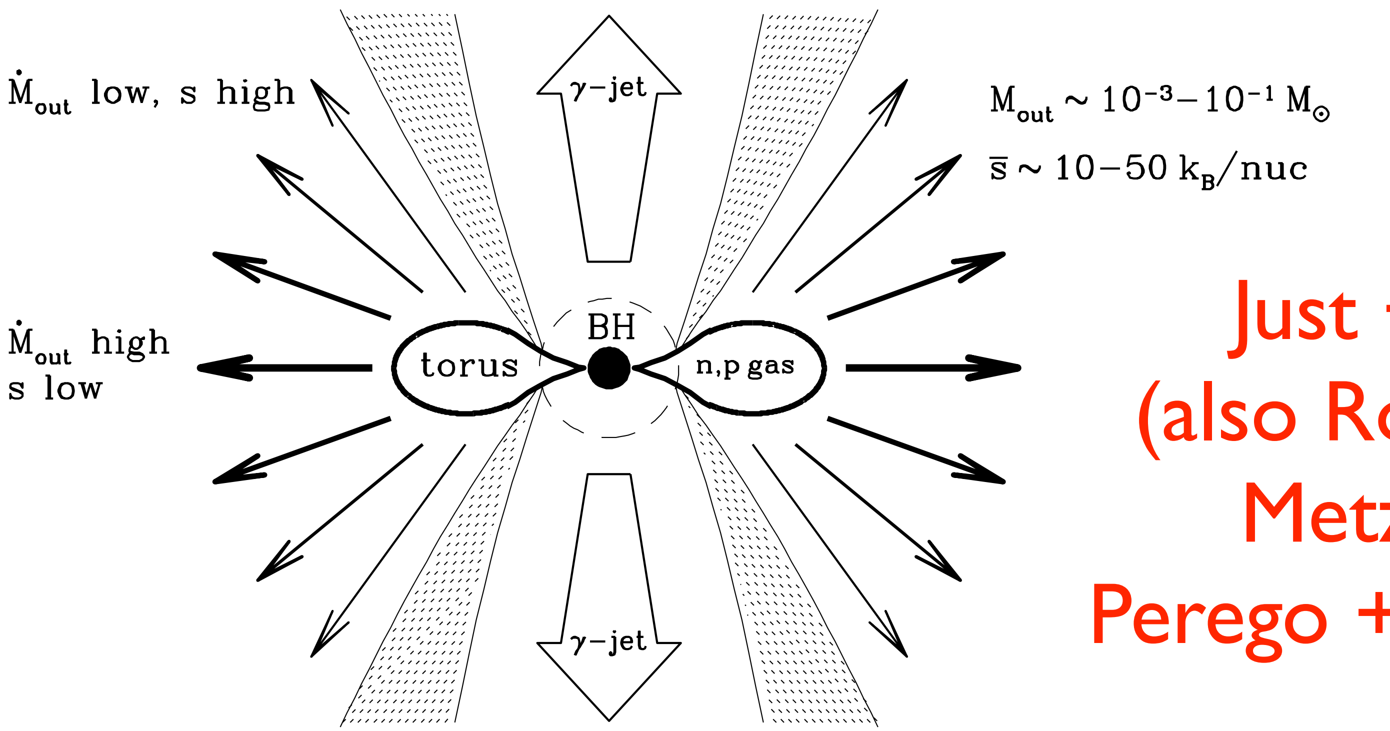
(due to dynamic binary interaction)



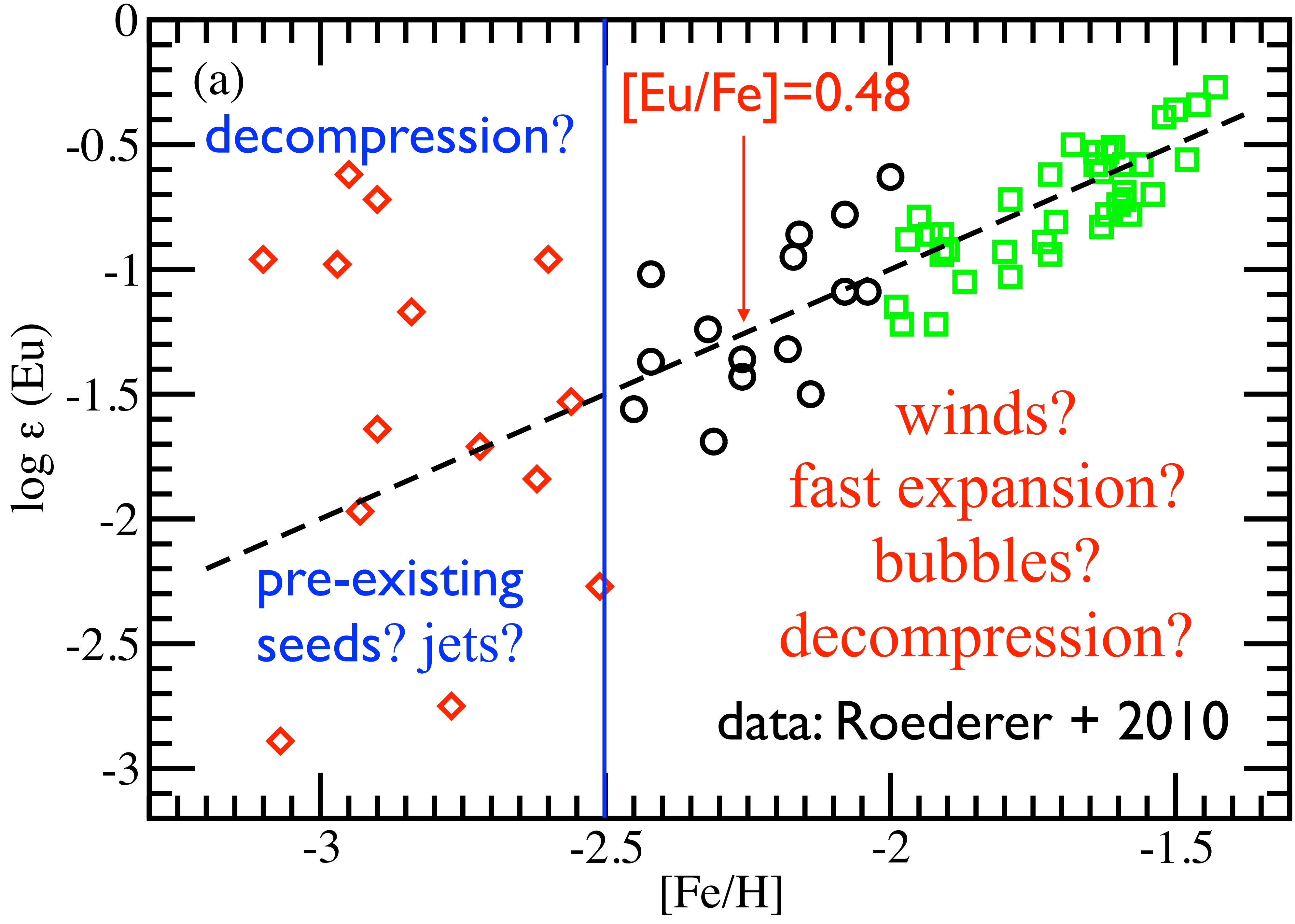
NS matter
+ winds

BH–Torus Phase: Disk ejecta

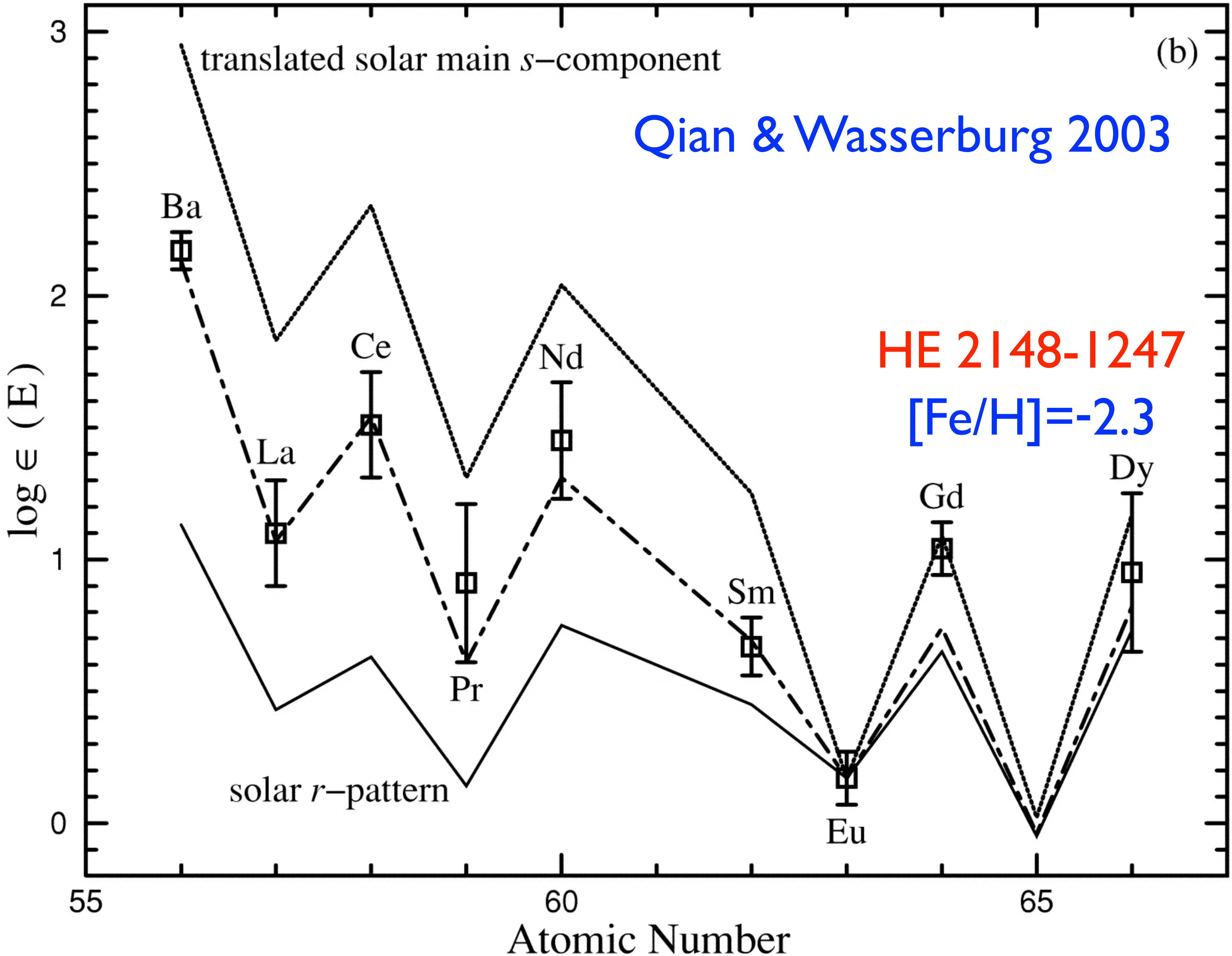
(due to ν heating, viscosity/magn. fields, recombination)



Just + 2014
(also Rosswog +;
Metzger +;
Perego +; Martin +)



(a)
decompression?
[Eu/Fe]=0.48
pre-existing
seeds? jets?
winds?
fast expansion?
bubbles?
decompression?
data: Roederer + 2010
log ε (Eu)
[Fe/H]
0
-0.5
-1
-1.5
-2
-2.5
-3
-3
-2.5
-2
-1.5


translated solar main s–component
(b)
Qian & Wasserburg 2003
HE 2148-1247
[Fe/H]=-2.3
Ba
La
Ce
Pr
Nd
Sm
Eu
Gd
Dy
solar r–pattern
log ∈ (E)
3
2
1
0
55
60
65
Atomic Number