r-process nucleosynthesis and chemical evolution in the early Galaxy

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three areas of r-process study

properties of neutron-rich nuclei far from stability

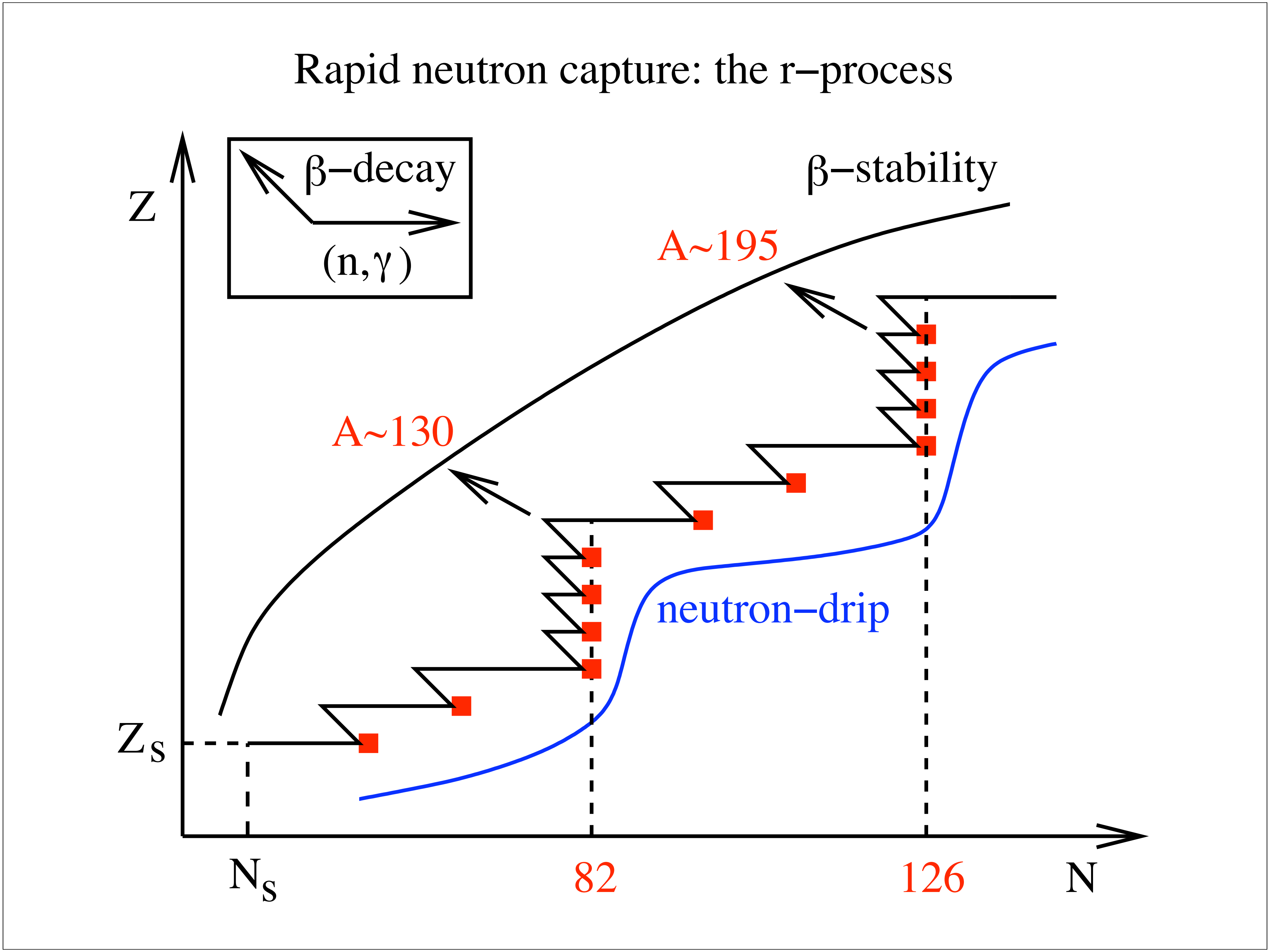
→ detailed production pattern

conditions in astrophysical sites

→ neutron-to-seed ratio

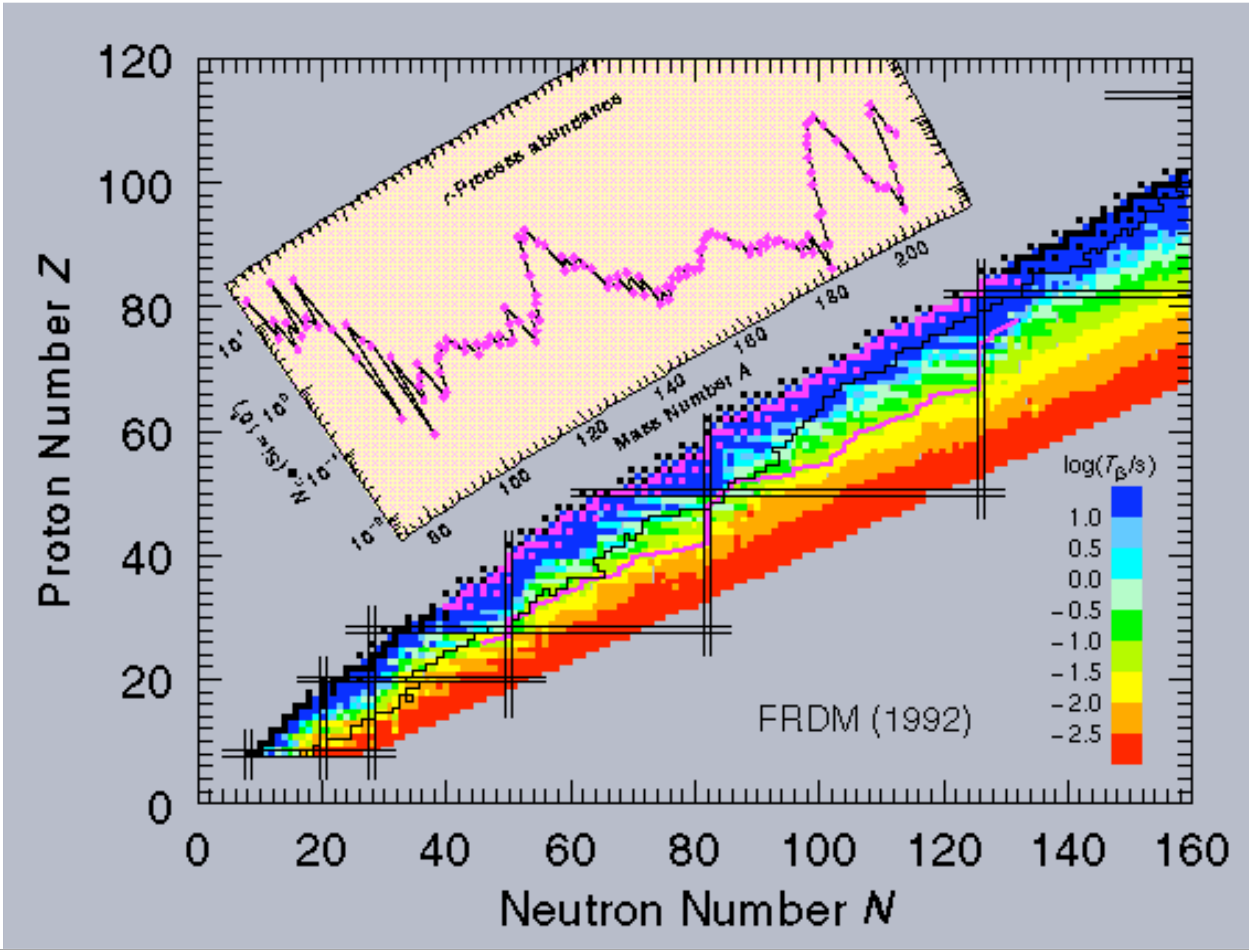
rates & other characteristics of r-process sources

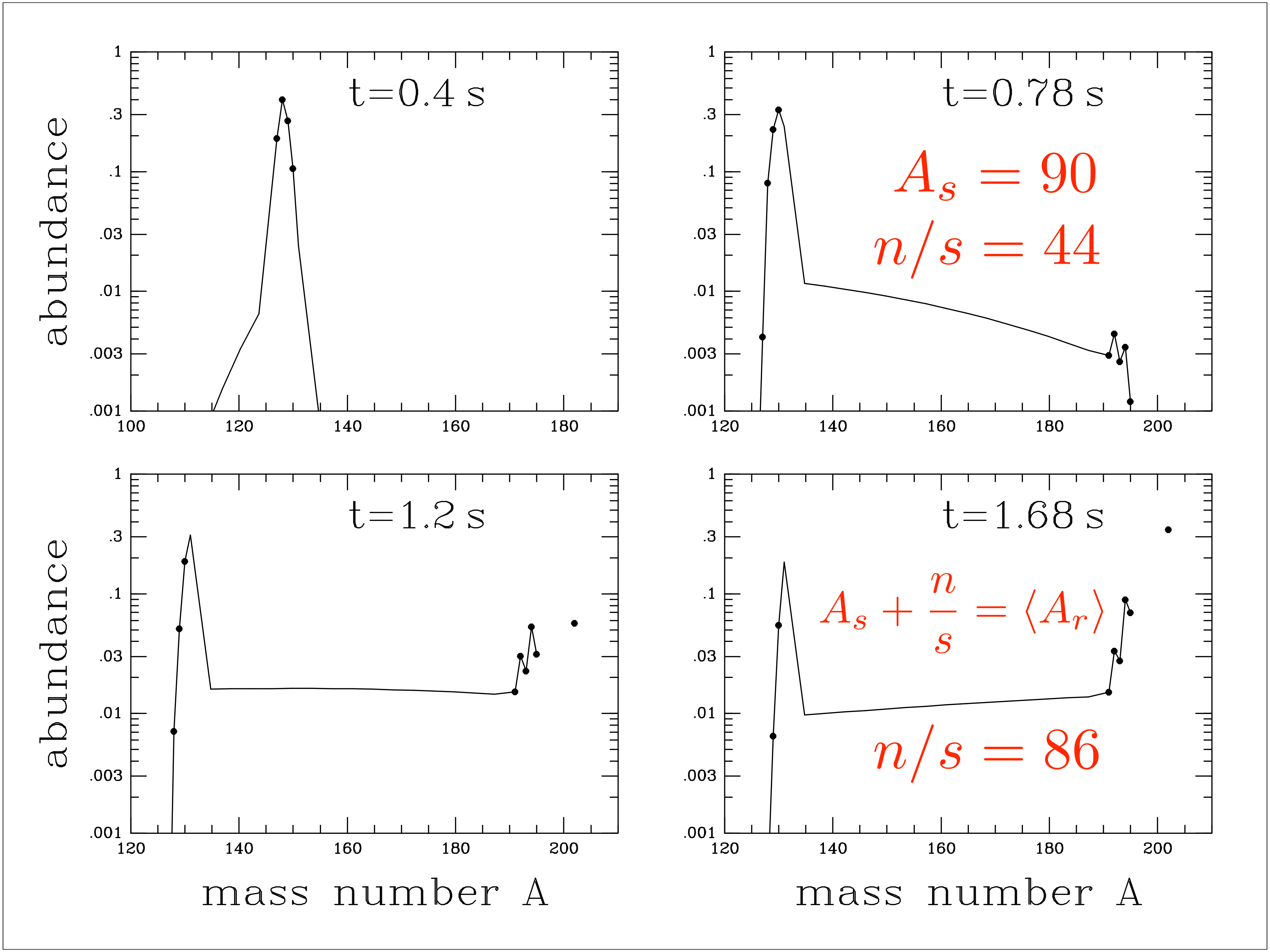
→ chemical evolution of the Galaxy



Rapid neutron capture: the r−process
β−decay
(n,γ)
β−stability
A~195
A~130
neutron−drip
Z
Z_S
N_S
82
126
N

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

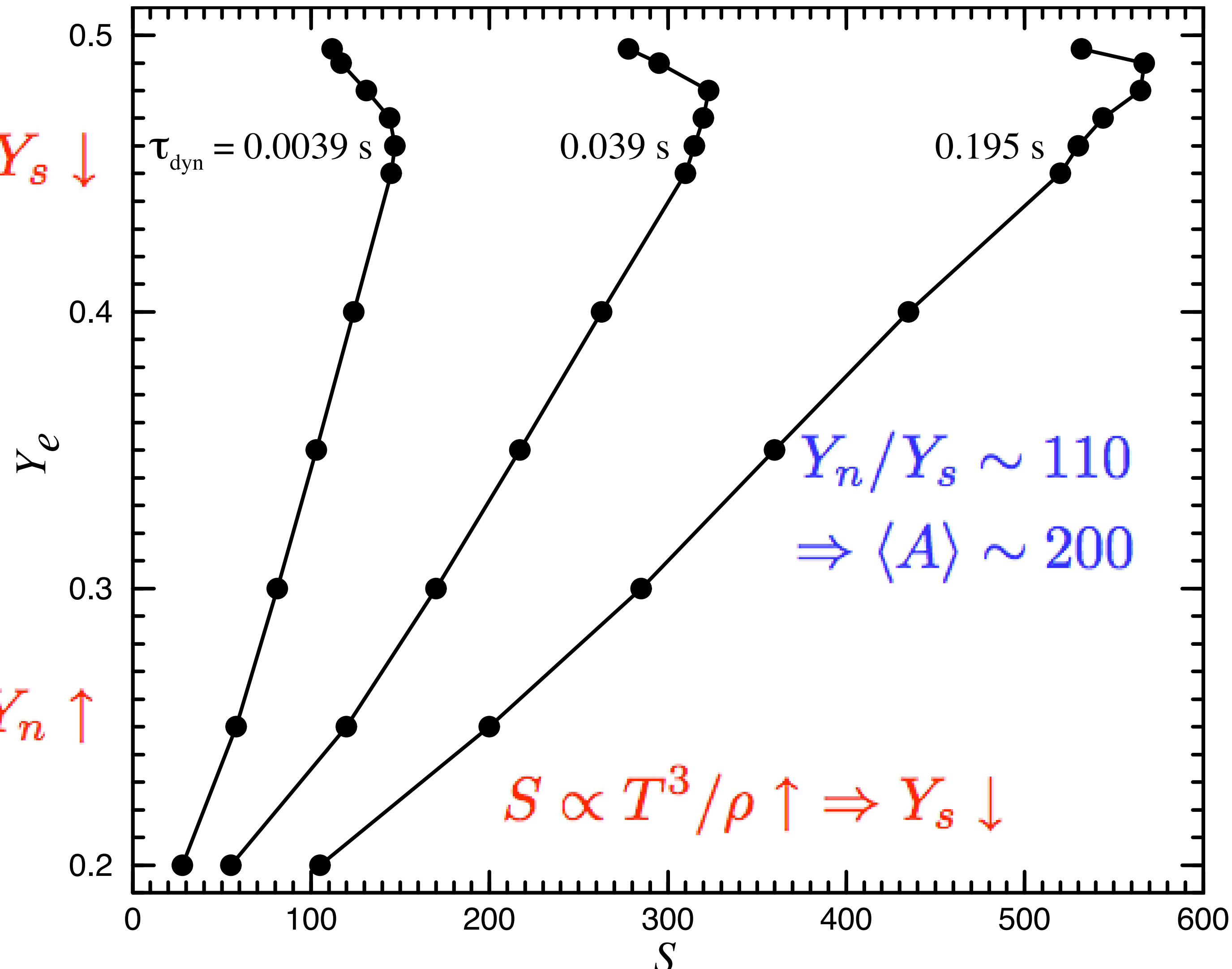




t=0.4 s
t=0.78 s
t=1.2 s
t=1.68 s
$A_s = 90$
$n/s = 44$
$A_s + \frac{n}{s} = \langle A_r \rangle$
$n/s = 86$
abundance
mass number A

(Hoffman et al. 1997; Meyer & Brown 1997; Freiburghaus et al. 1999)

$\tau_{\rm dyn} \downarrow \Rightarrow Y_s \downarrow$



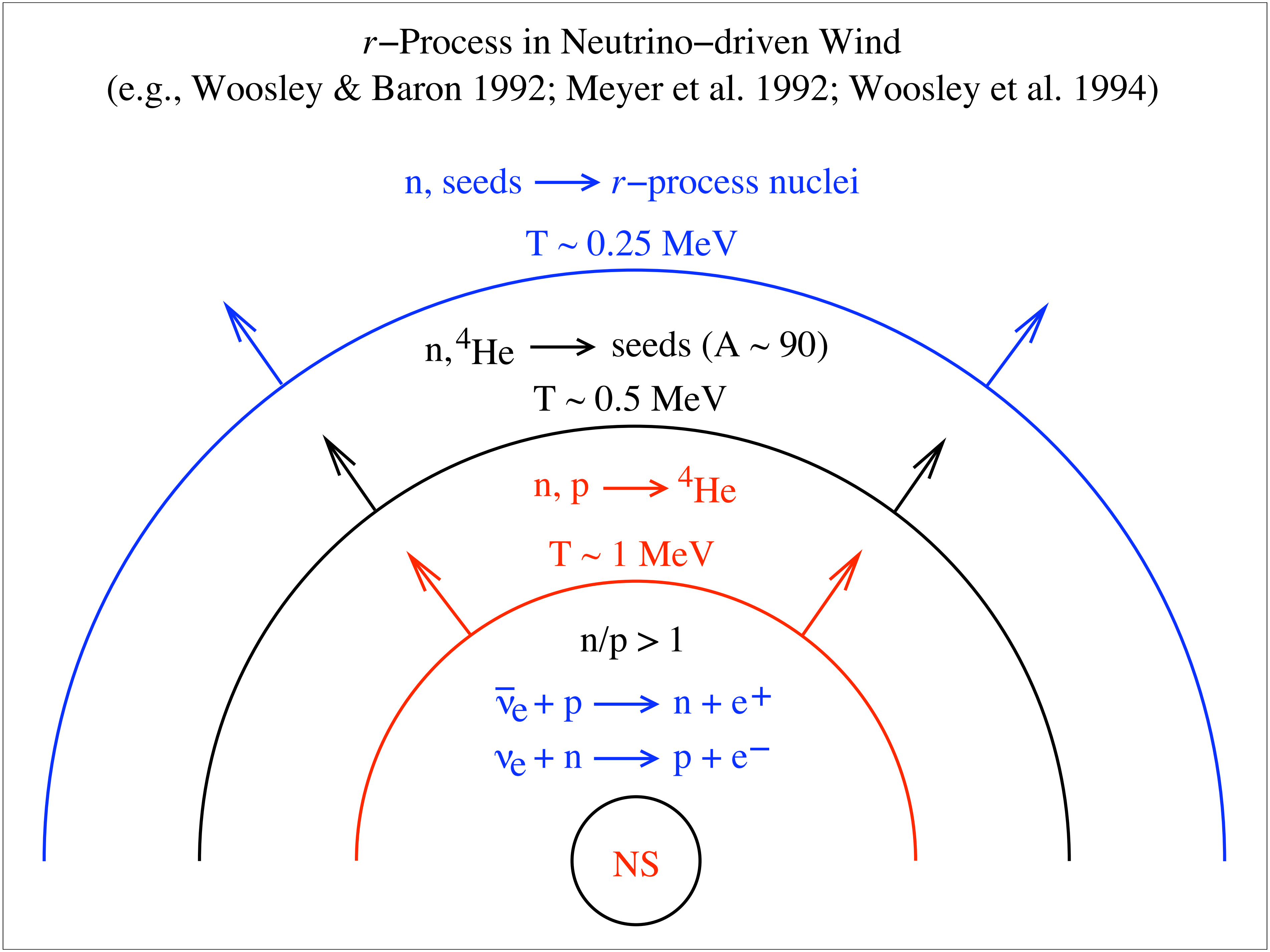
$Y_n/Y_s \sim 110$

$\Rightarrow \langle A \rangle \sim 200$

$Y_e \downarrow \Rightarrow Y_n \uparrow$

$S \propto T^3/\rho \uparrow \Rightarrow Y_s \downarrow$

$\alpha + \alpha + n \rightleftharpoons {}^9\mathrm{Be} + 1.573\ \mathrm{MeV}$


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, 4He ⟶ seeds (A ~ 90)
T ~ 0.5 MeV
n, p ⟶ 4He
T ~ 1 MeV
n/p > 1
ν̄e + p ⟶ n + e+
νe + n ⟶ p + e−
NS

summary of neutrino-driven wind results

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

$Y_e \sim 0.4$–0.5

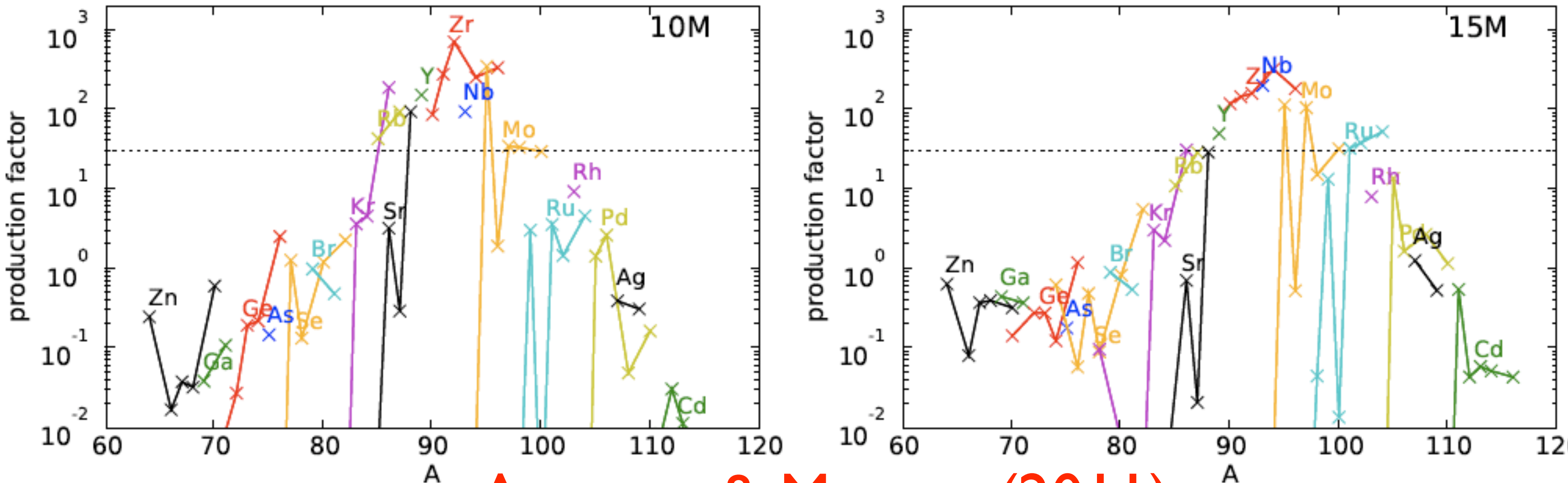
→ $S \lesssim 100$

$\tau_{\rm dyn} \sim 0.01$–0.1 s

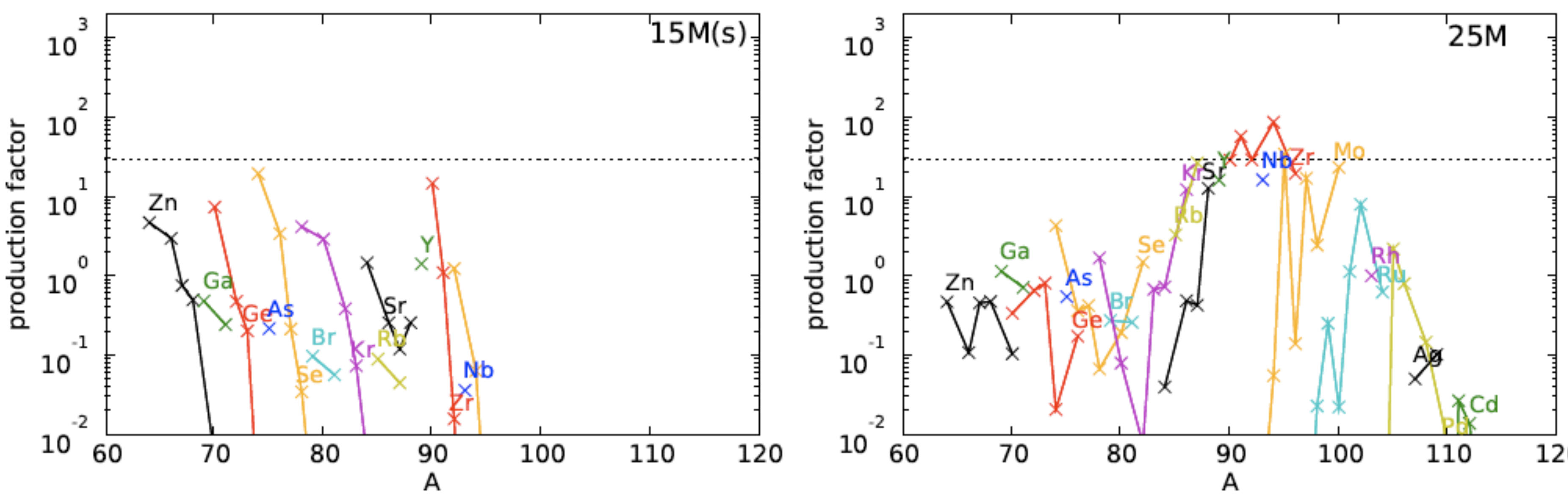
recent neutrino transport results
(Hudepohl et al. 2010; Fischer et al. 2010)

→ $Y_e \gtrsim 0.5$

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



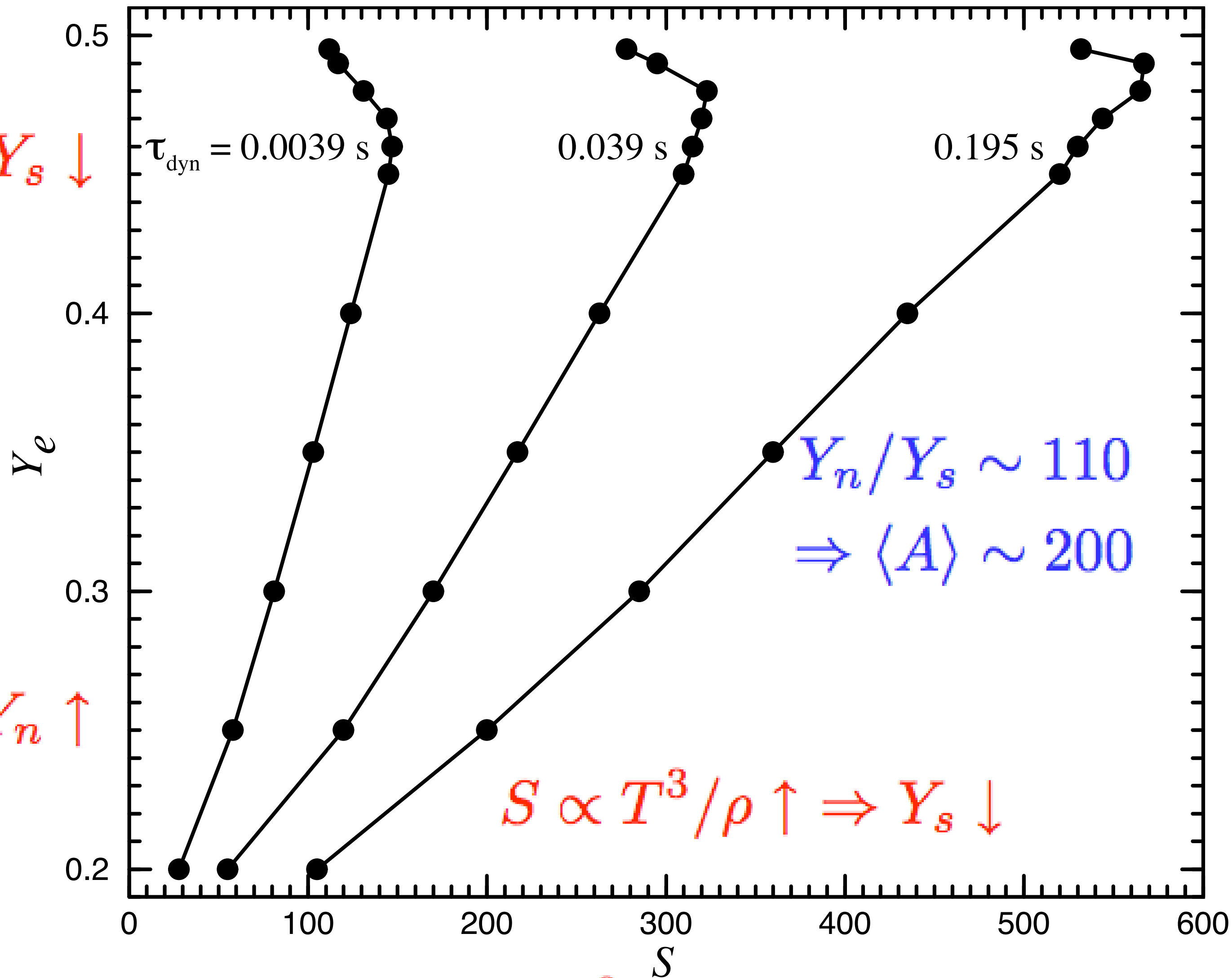
Arcones & Montes (2011)



(Hoffman et al. 1997; Meyer & Brown 1997; Freiburghaus et al. 1999)

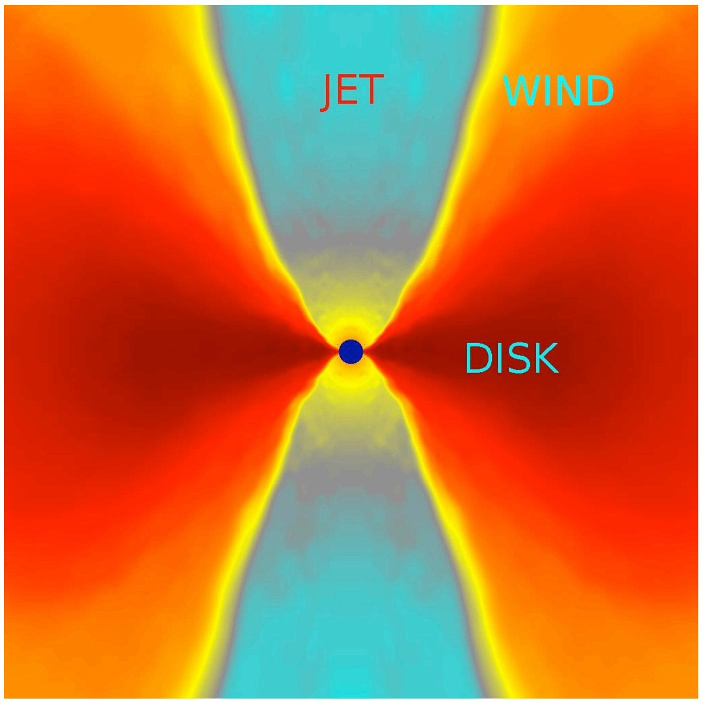
$\tau_{\rm dyn}\downarrow\;\Rightarrow Y_s\downarrow$

$Y_e\downarrow\;\Rightarrow Y_n\uparrow$



$$\alpha+\alpha+n \rightleftharpoons {}^{9}\mathrm{Be}+1.573\ \mathrm{MeV}$$

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

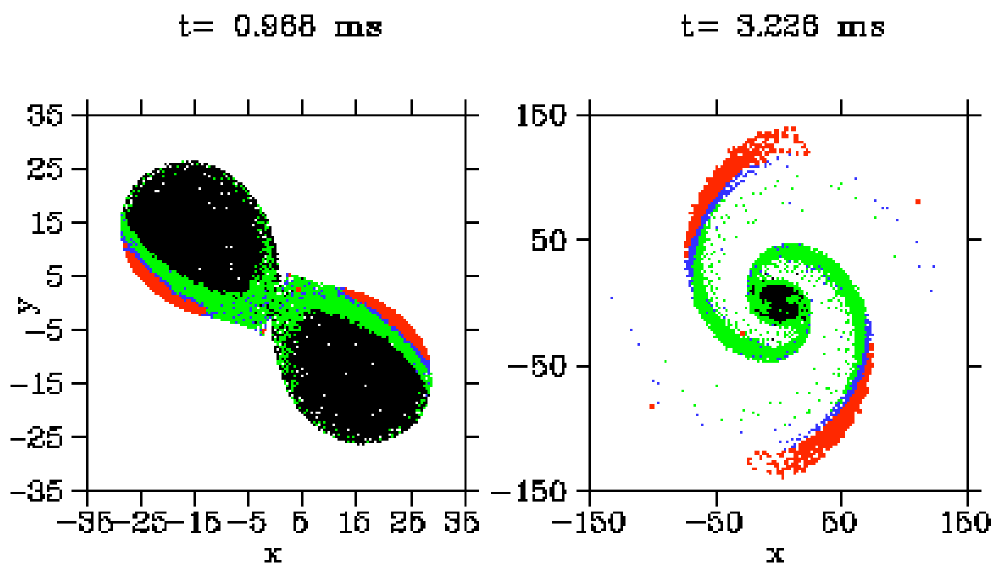


Pruet, Woosley, & Hoffman 2003;
Surman, McLaughlin, & Hix 2006;
Surman et al. 2008;
Wanajo & Janka 2011

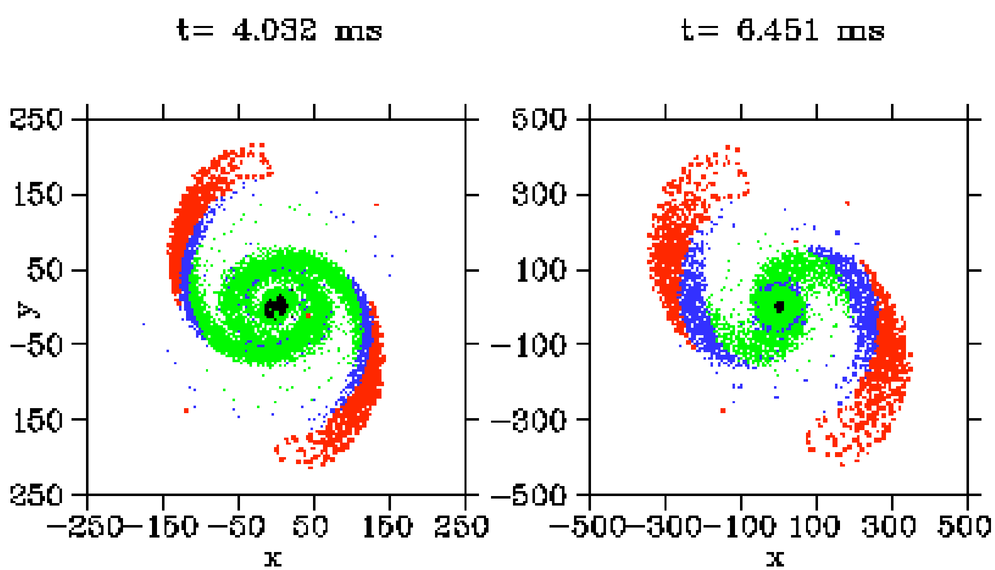
accretion disks form around BHs from core-collapse SNe (GRBs), NS-NS & NS-BH mergers

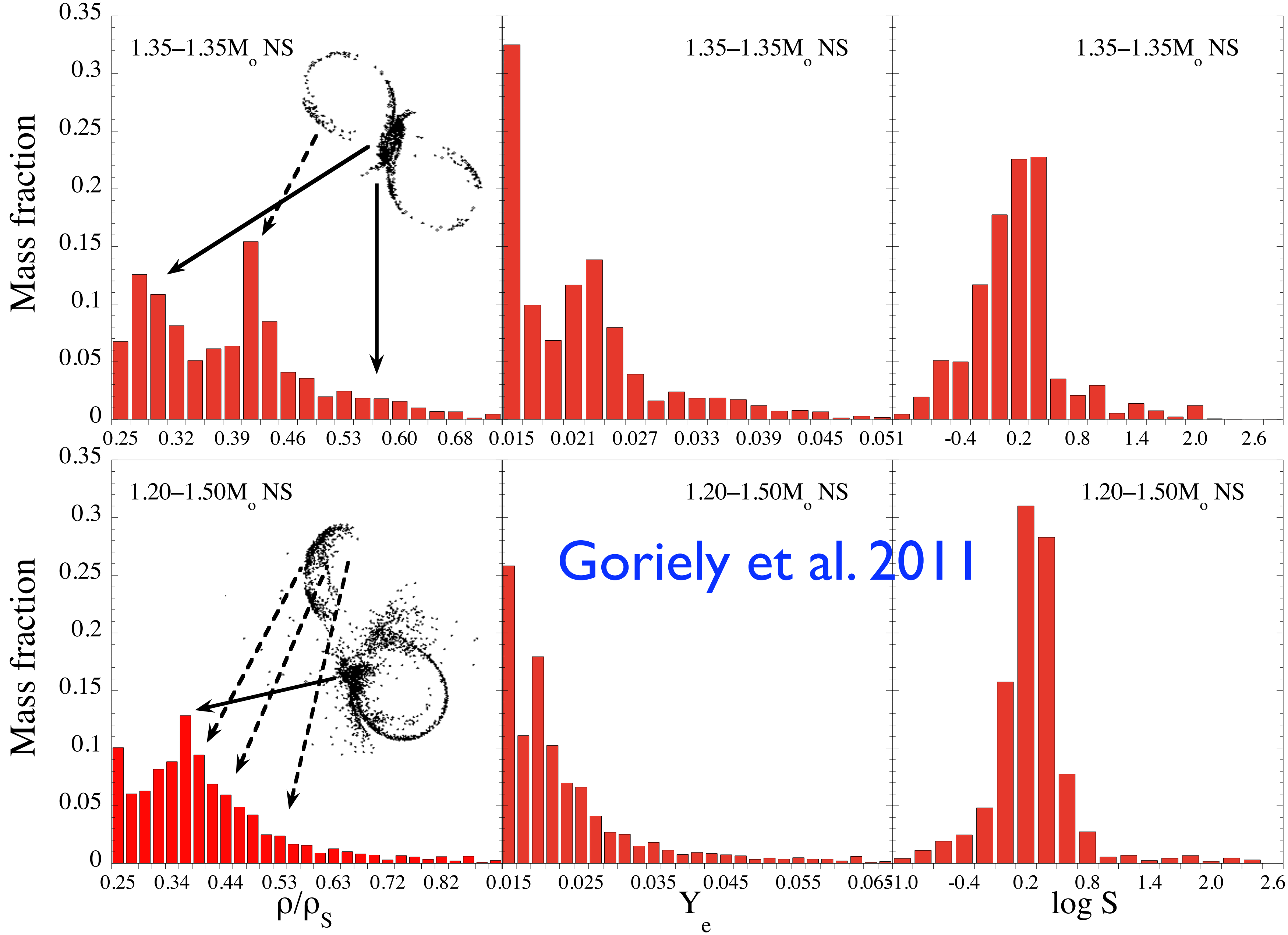
low Ye in winds → r-process

Neutron Star Mergers

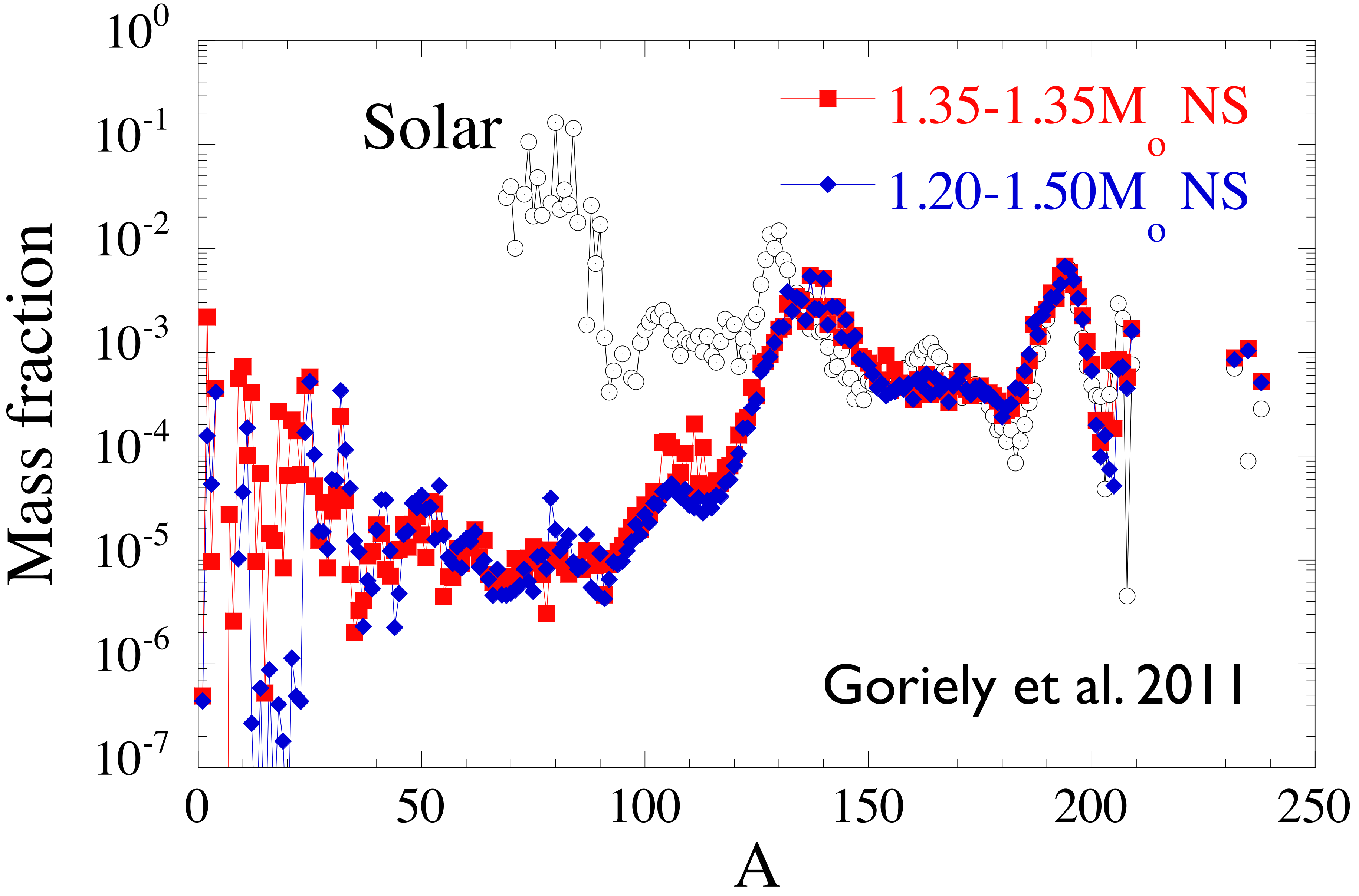


Freiburghaus et al. 1999; Rosswog et al. 2001

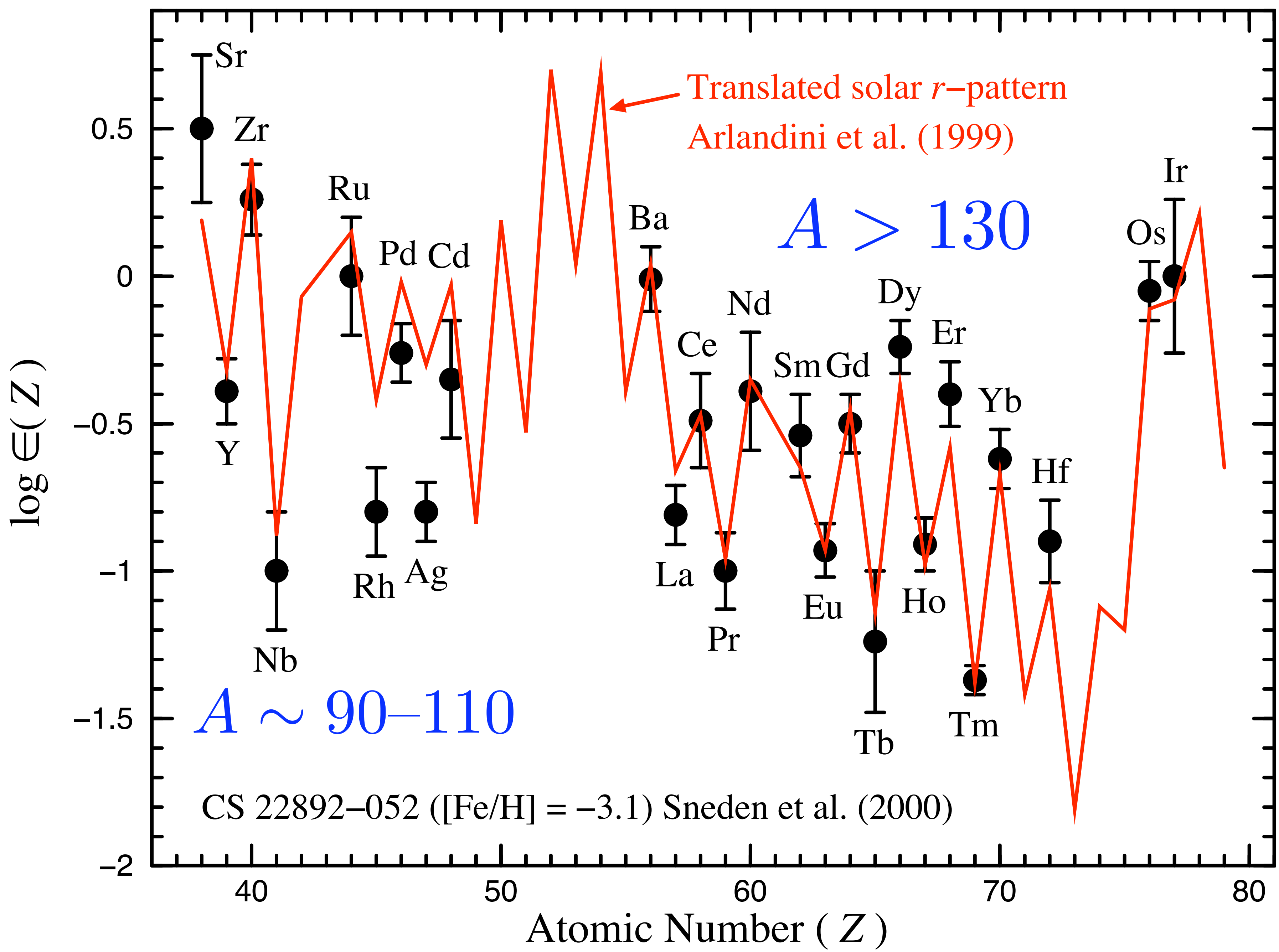




Mass fraction
1.35–1.35M$_o$ NS
1.20–1.50M$_o$ NS
ρ/ρ_S
Y_e
log S
Goriely et al. 2011



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

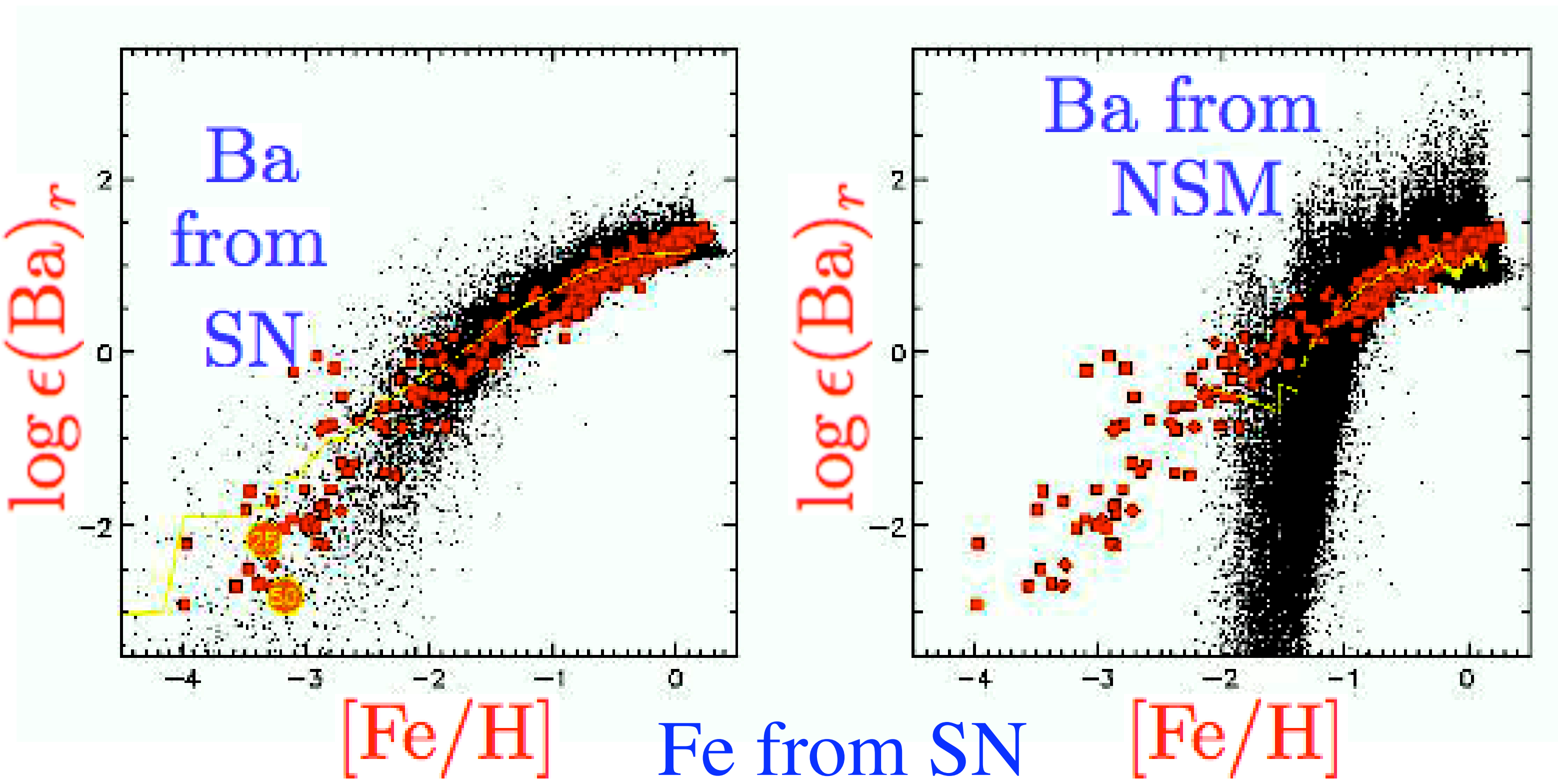


Sr
Zr
Y
Nb
Ru
Pd
Cd
Rh
Ag
Ba
La
Ce
Pr
Nd
Sm
Gd
Eu
Tb
Dy
Ho
Er
Tm
Yb
Hf
Os
Ir
Translated solar r–pattern
Arlandini et al. (1999)
A > 130
A ~ 90–110
CS 22892–052 ([Fe/H] = –3.1) Sneden et al. (2000)
log ∈(Z)
Atomic Number (Z)
0.5
0
–0.5
–1
–1.5
–2
40
50
60
70
80

Supernovae vs. Neutron Star Mergers

(Qian 2000; Argast et al. 2004)

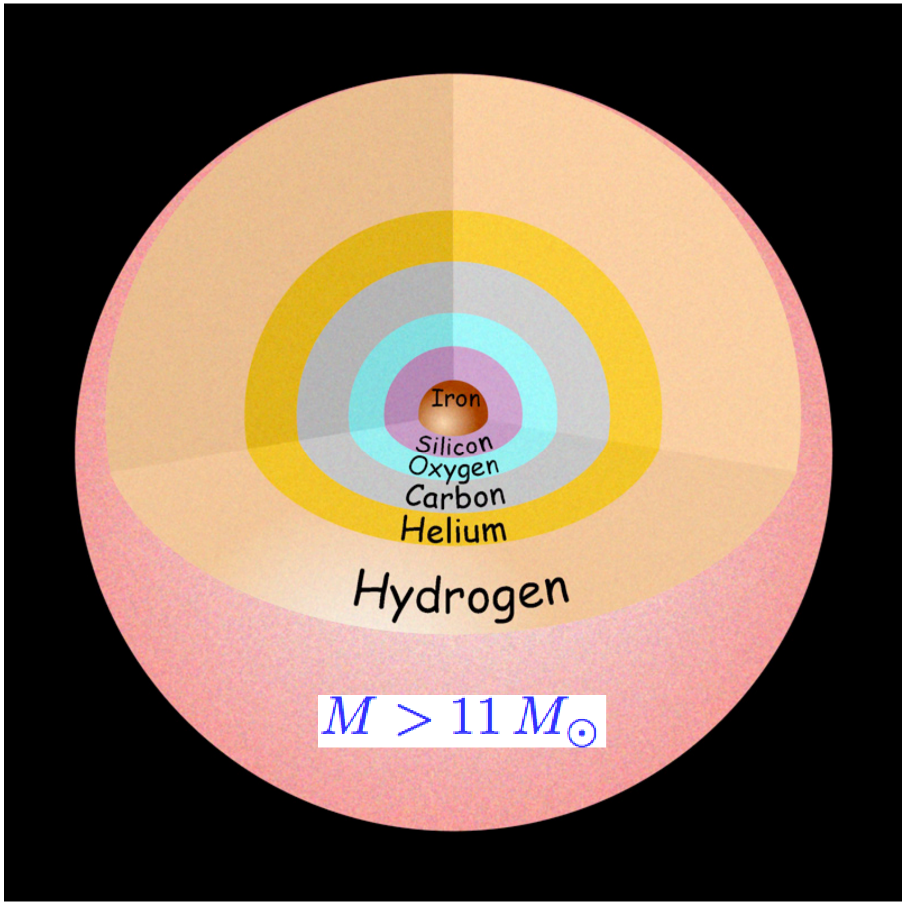
$$f_{\rm SN} \sim 10^{-2}\ {\rm yr}^{-1},\ \ f_{\rm NSM} \sim 10^{-5}\ {\rm yr}^{-1}$$



Neutrino-induced r-process in He shell

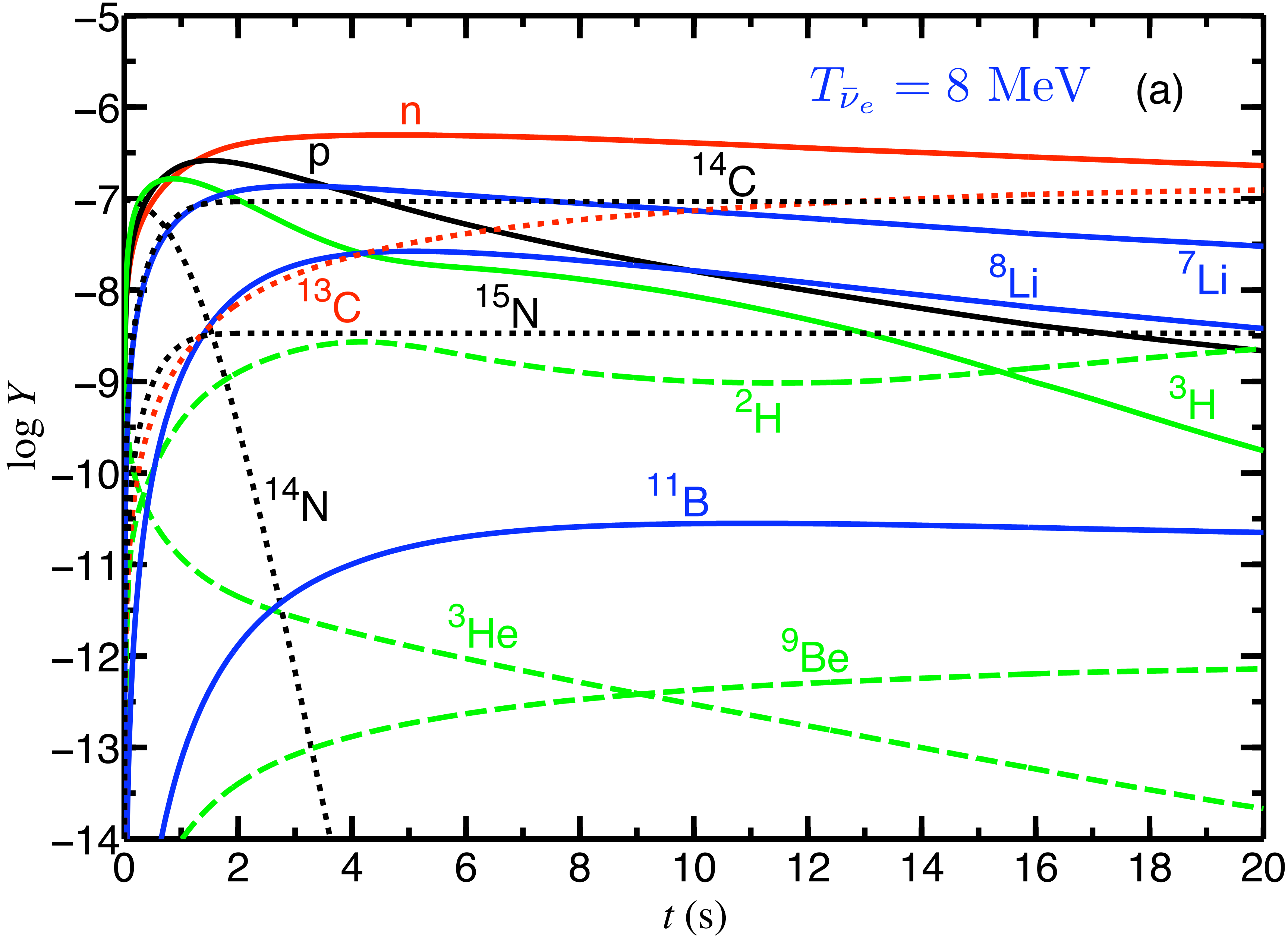
(Epstein, Colgate, & Haxton 1988)

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

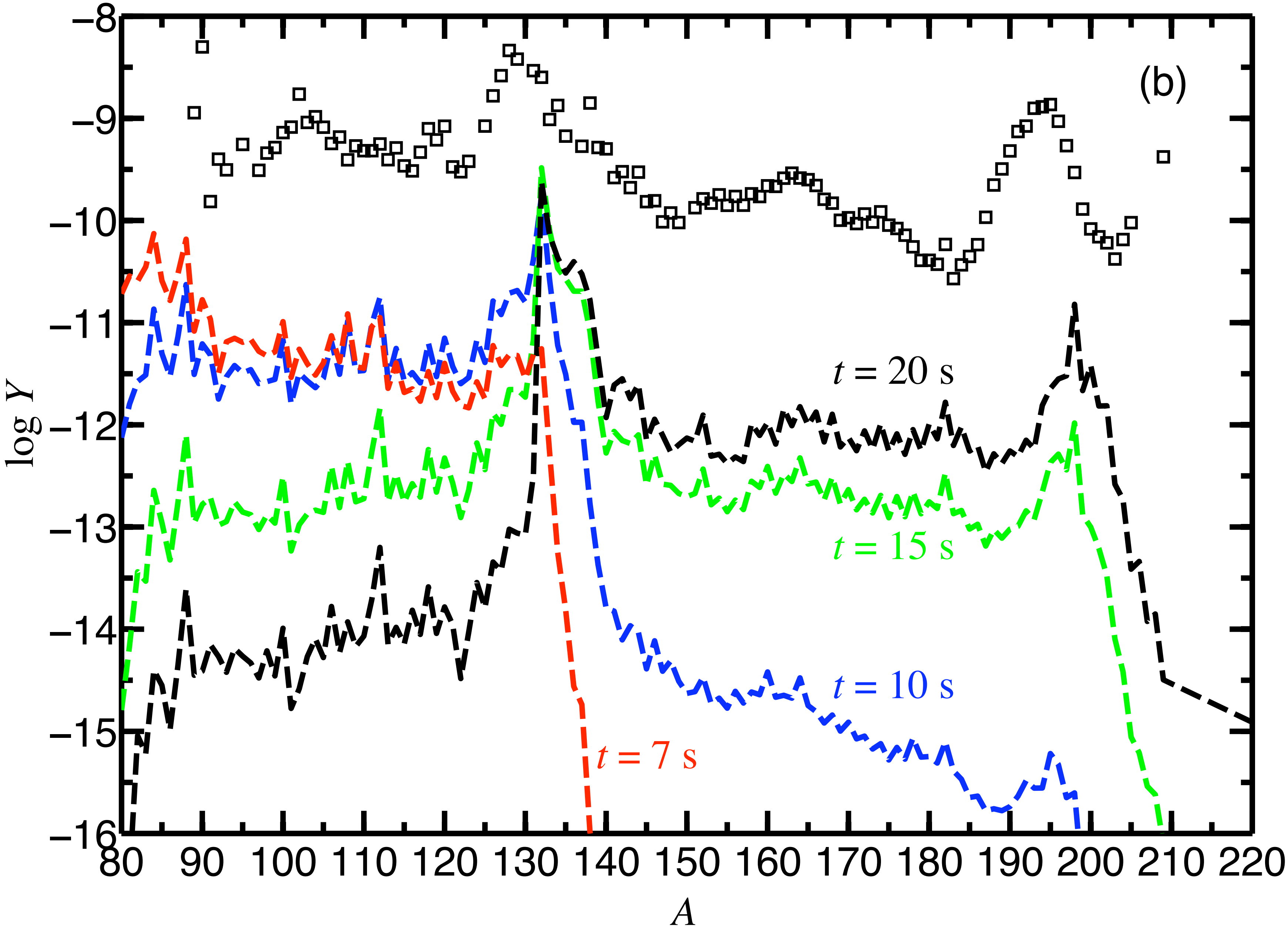


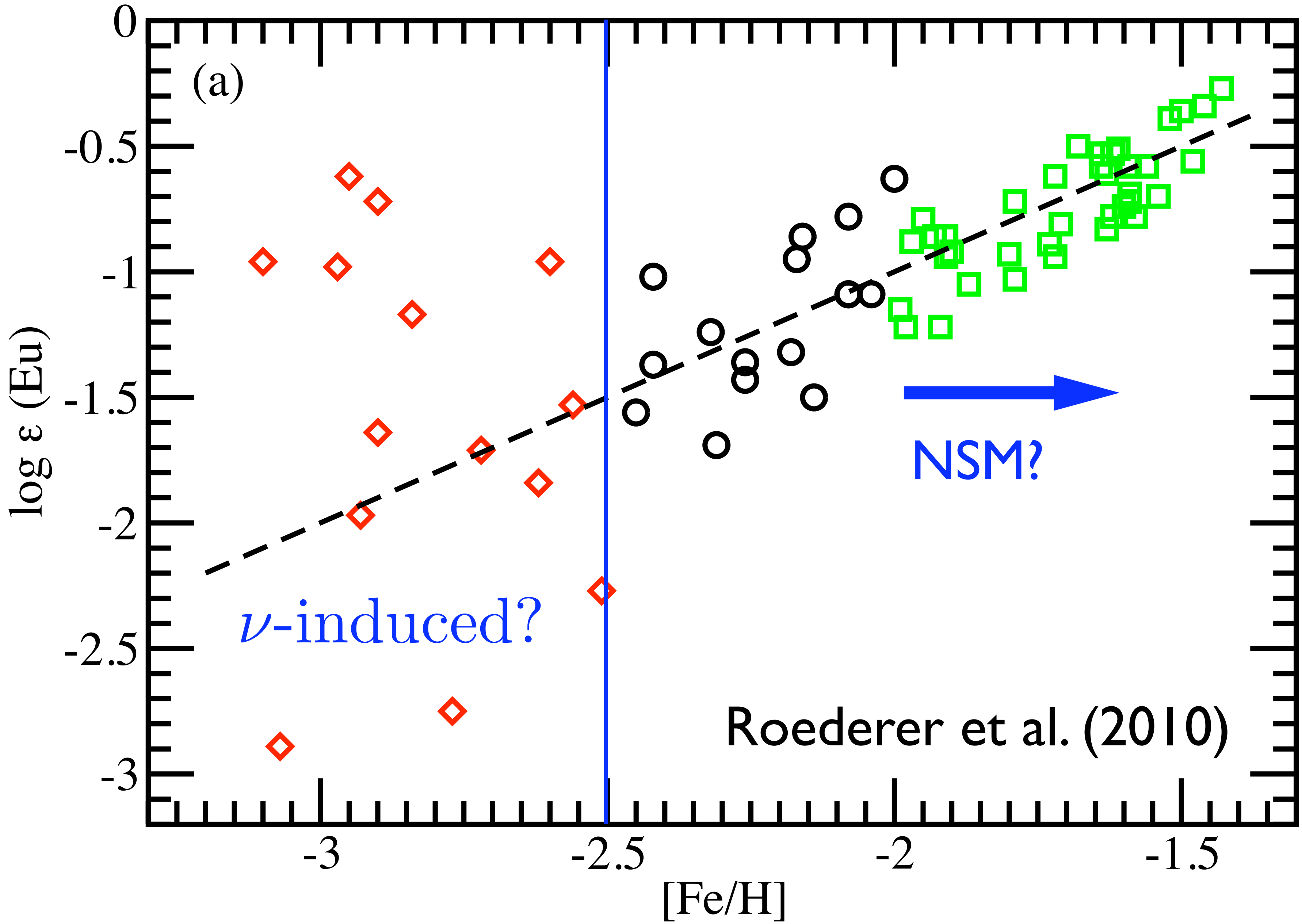
$$\bar{\nu}_e + {}^4\text{He} \rightarrow {}^3\text{H} + n + e^+,\;\; \lambda_{\bar{\nu}_e\alpha,n} \propto T_{\bar{\nu}_e}^{5\text{–}6}\;!$$

Banerjee, Haxton, & Qian (2011)



Banerjee, Haxton, & Qian (2011)

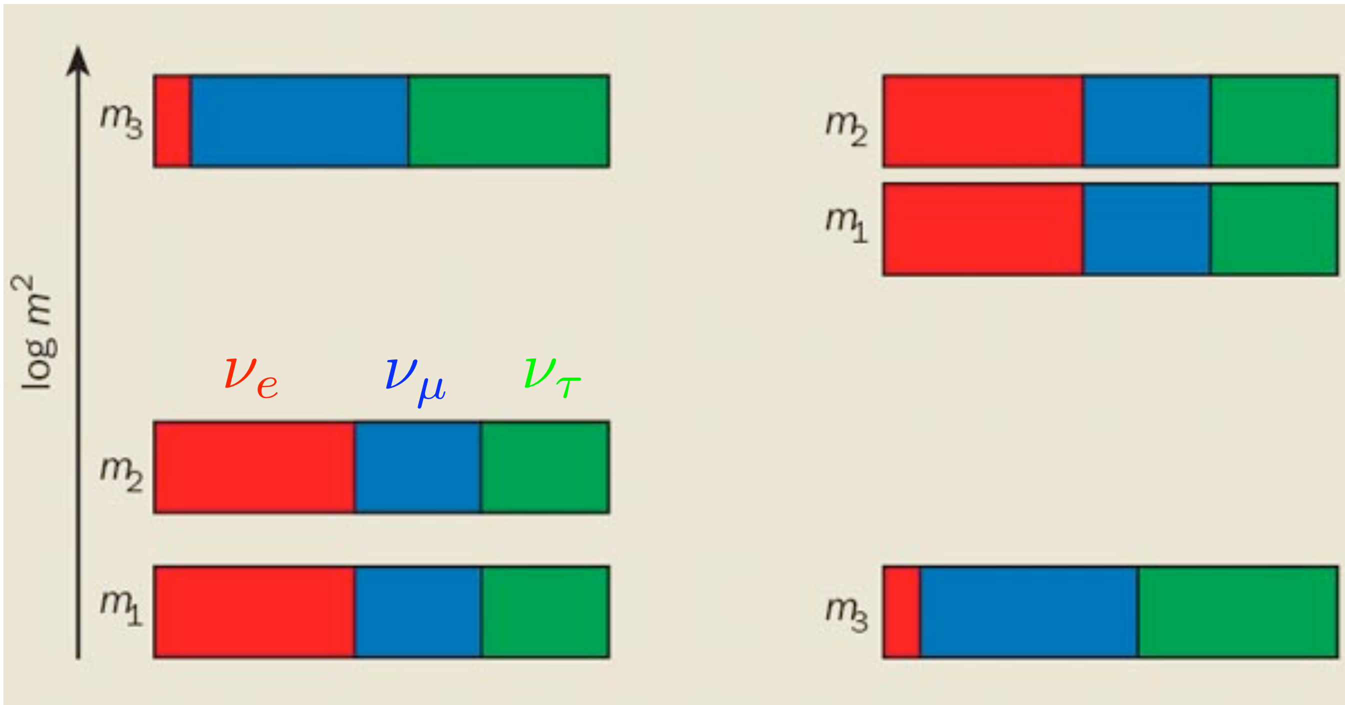




(a)
log ε (Eu)
0
-0.5
-1
-1.5
-2
-2.5
-3
-3
-2.5
-2
-1.5
[Fe/H]
NSM?
ν-induced?
Roederer et al. (2010)

neutrino spectra & flavor oscillations

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

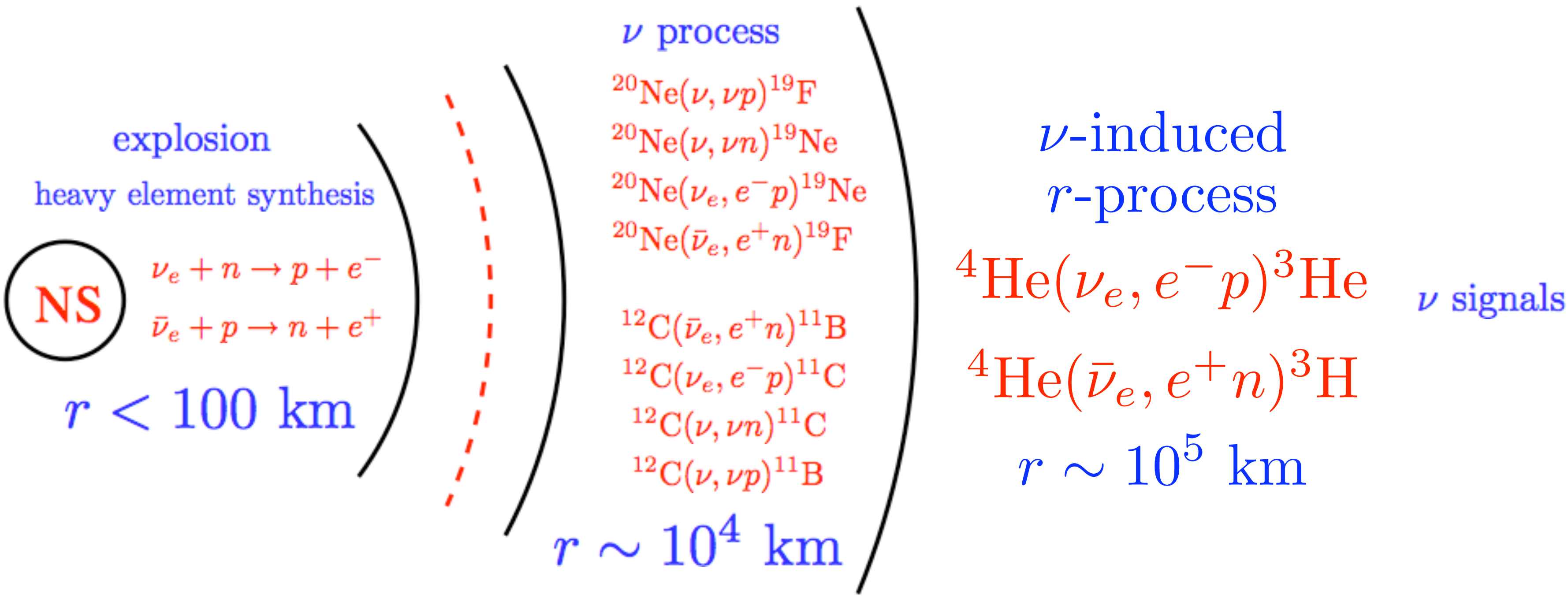


in supernovae

$\nu_e \rightleftharpoons \nu_\tau$

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

Interplay between Supernova and Neutrino Physics



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

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A MODEL FOR ABUNDANCES IN METAL-POOR STARS

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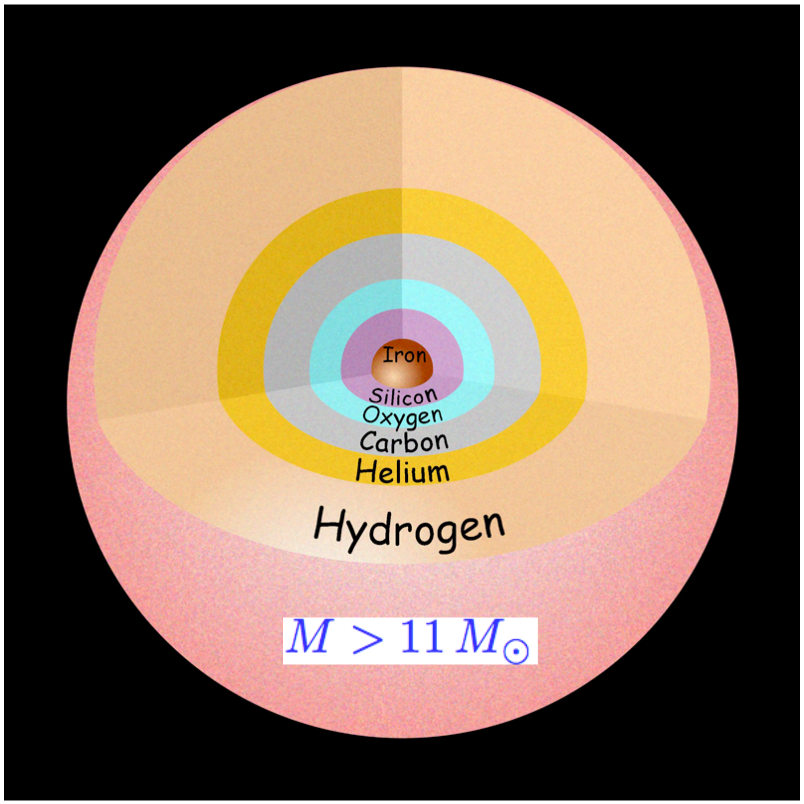
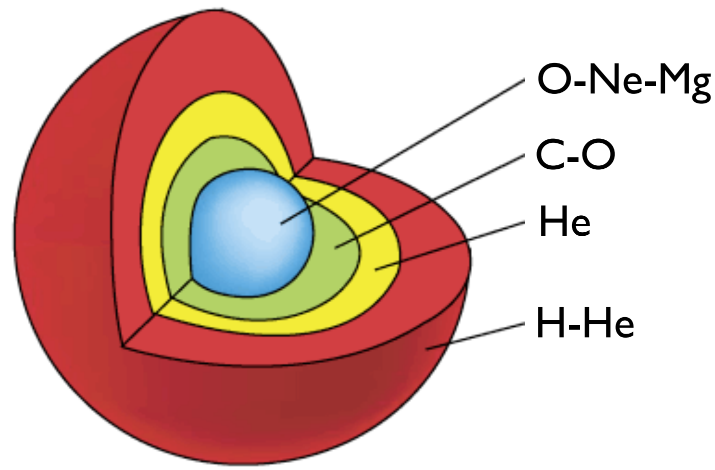
ABSTRACT

A model is presented that seeks to explain quantitatively the stellar abundances of *r*-process elements and other elements associated with the *r*-process sites. It is argued that the abundances of all these elements in stars with $-3 \lesssim [\mathrm{Fe/H}] < -1$ can be explained by the contributions of three sources. The sources are the first generations of very massive ($\gtrsim 100\ M_{\odot}$) stars that are formed from big bang debris and are distinct from Type II supernovae (SNe II) and two types of SNe II, the *H* and *L* events, which can occur only at $[\mathrm{Fe/H}] \gtrsim -3$. The *H* events are of high frequency and produce dominantly heavy ($A > 130$) *r*-elements but no Fe (presumably leaving behind black holes). The *L* events are of low frequency and produce Fe and dominantly light ($A \lesssim 130$) *r*-elements (essentially none above Ba). By using the observed abundances in two ultra–metal-poor stars and the solar *r*-abundances, the initial or prompt inventory of elements produced by the first generations of very massive stars and the yields of *H* and *L* events can be determined. The abundances of a large number of elements in a star can then be calculated from the model by using only the observed Eu and Fe abundances. To match the model results and the observational data for stars with $-3 < [\mathrm{Fe/H}] < -1$ requires that the solar *r*-abundances for Sr, Y, Zr, and Ba must be significantly increased from the standard values. No such changes appear to be required for all other elements. If the changes in the solar *r*-abundances for Sr, Y, Zr, and Ba are not permitted, the model fails at $-3 < [\mathrm{Fe/H}] < -1$ but still works at $[\mathrm{Fe/H}] \approx -3$ for these four elements. By using the corrected solar *r*-abundances for these elements, good agreement is obtained between the model results and data over the range $-3 < [\mathrm{Fe/H}] < -1$. No evidence of *s*-process contributions is found in this region, but all the observational data in this region now show regular increases of Ba/Eu above the standard solar *r*-process value. Whether the solar *r*-components of Sr, Y, Zr, and Ba used here to obtain a fit to the stellar data can be reconciled with those obtained from solar abundances by subtracting the *s*-components calculated from models is not clear.

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

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)