Neutrinos and the Origin of the Elements

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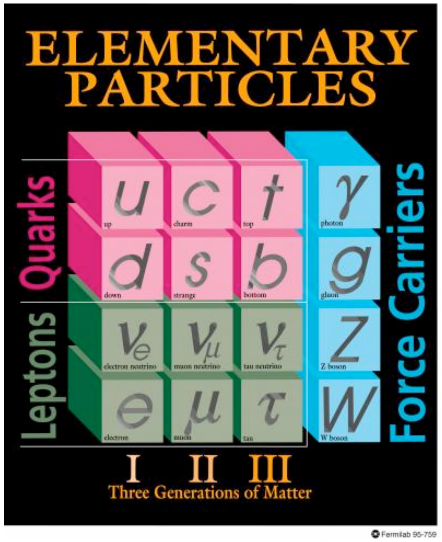
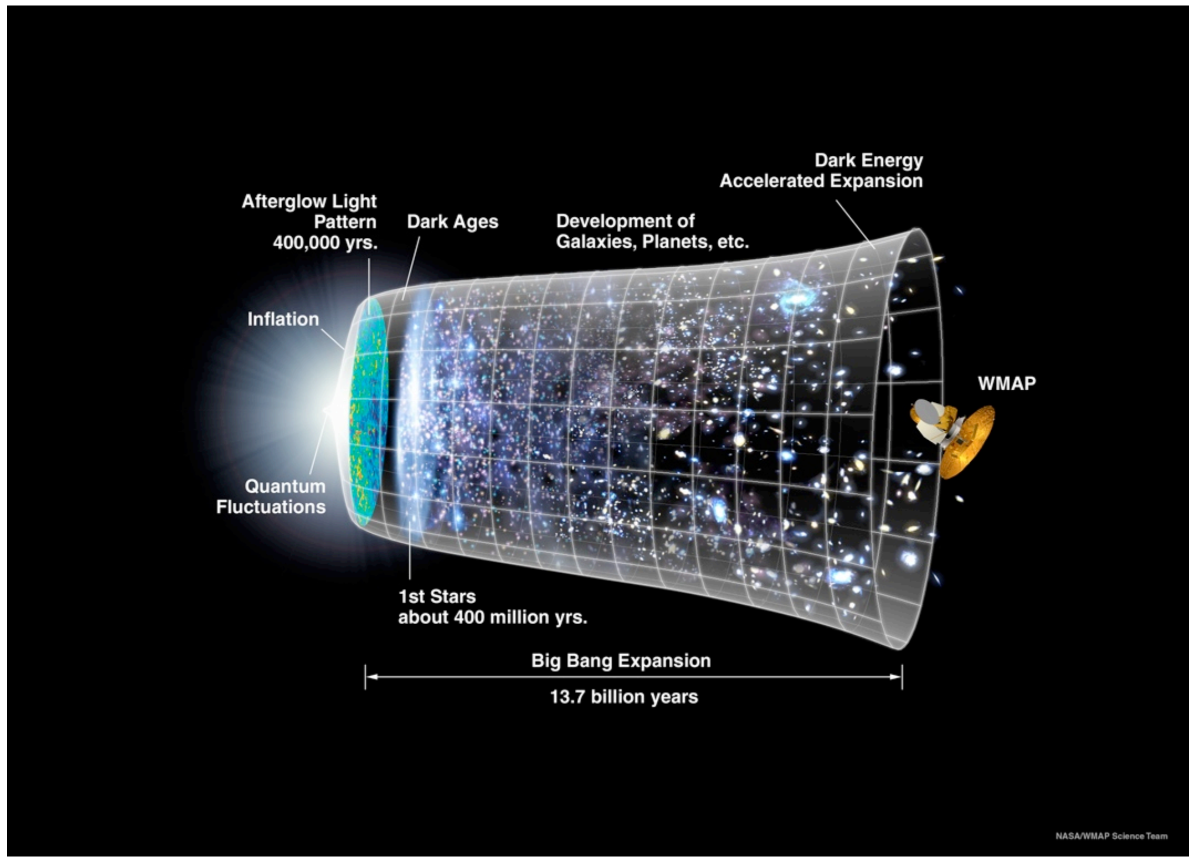


Some of the Biggest Questions Connecting Quarks and the Cosmos

Board on Physics and Astronomy
US National Academy of Sciences

- What are the masses of the neutrinos, and how have they shaped the evolution of the universe?

- How were the elements from iron to uranium made?



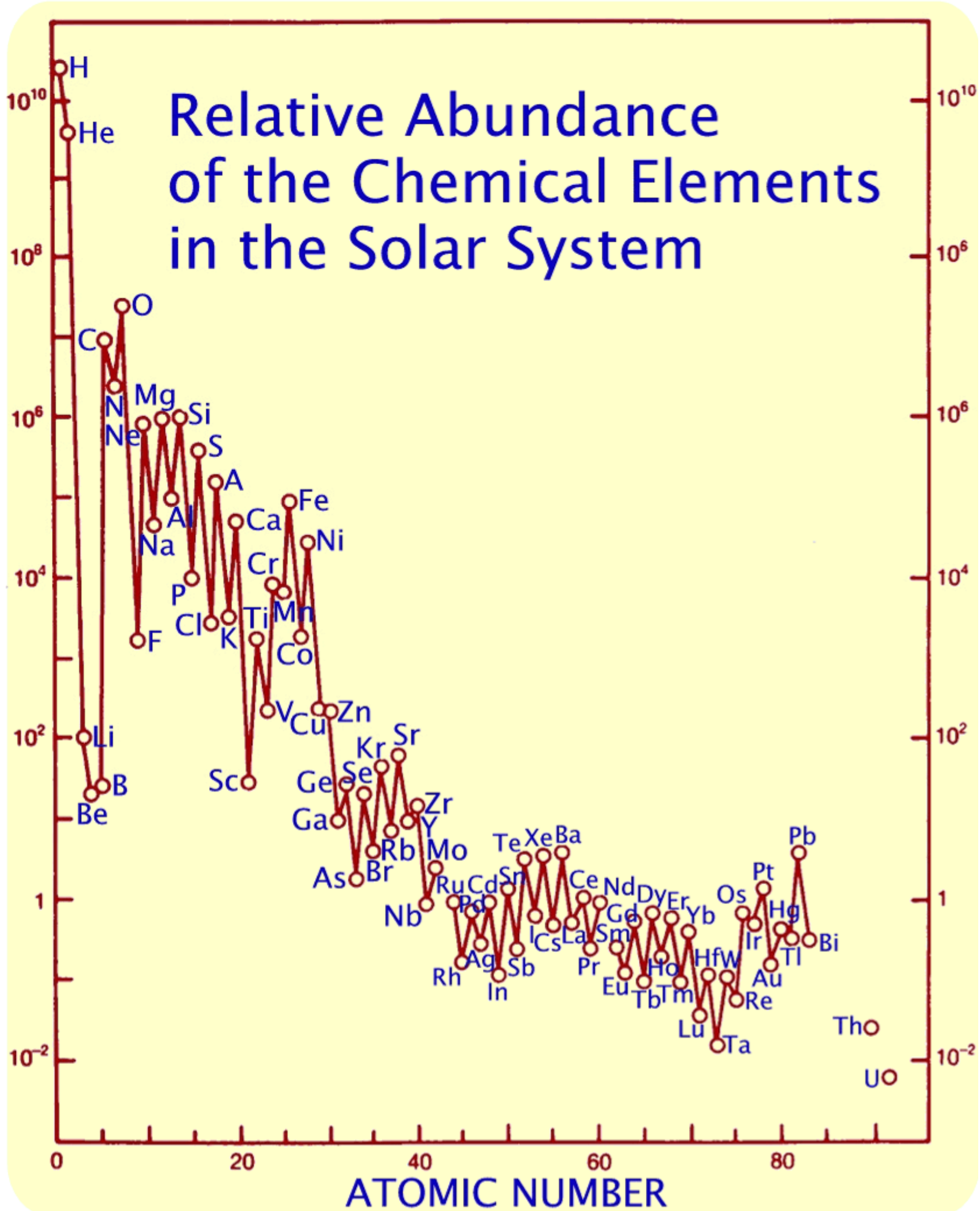
Big Bang:

75% H + 25% He
(by mass)

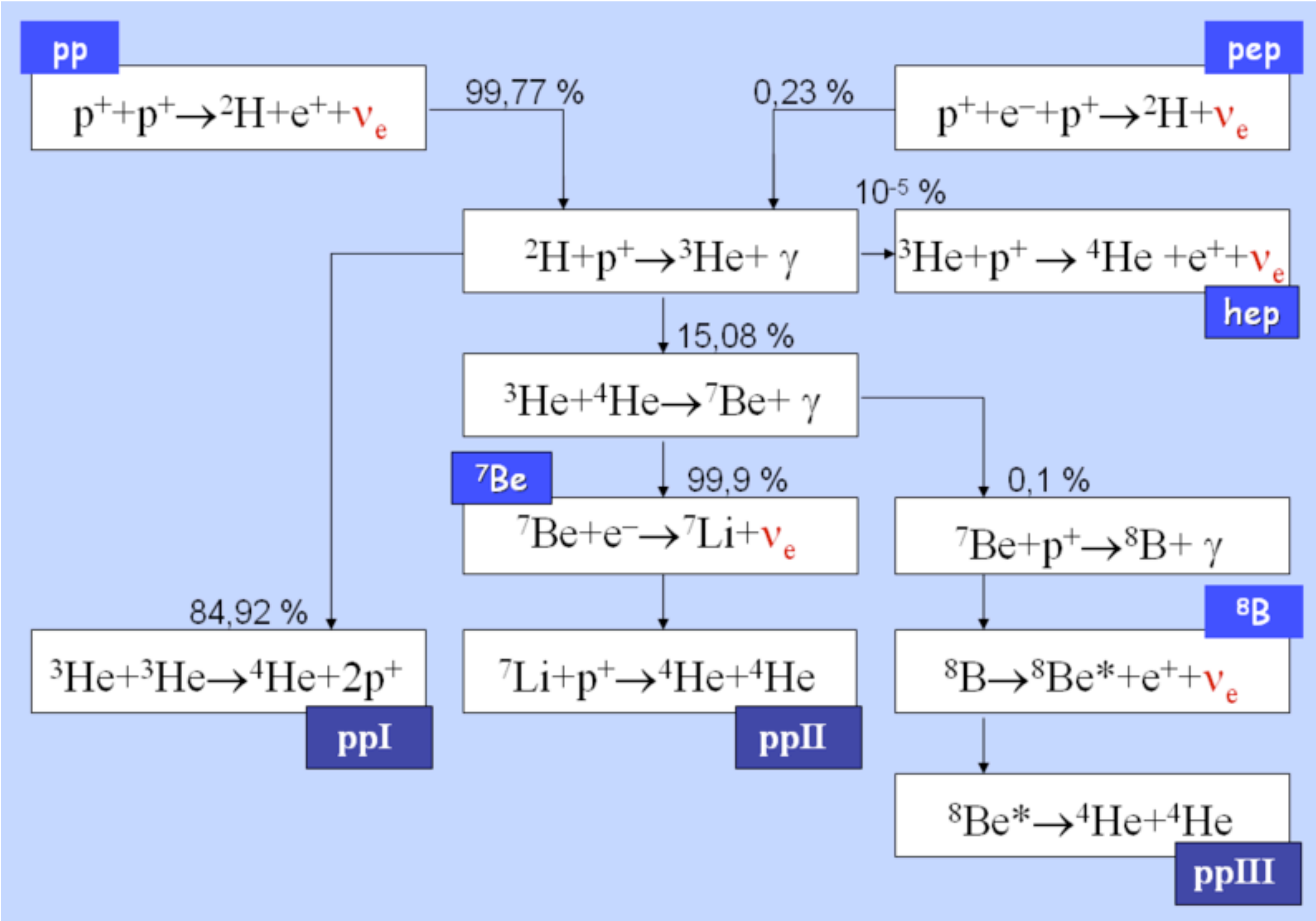
Sun:

71.5% H + 27.0% He
+1.4% “Metals”

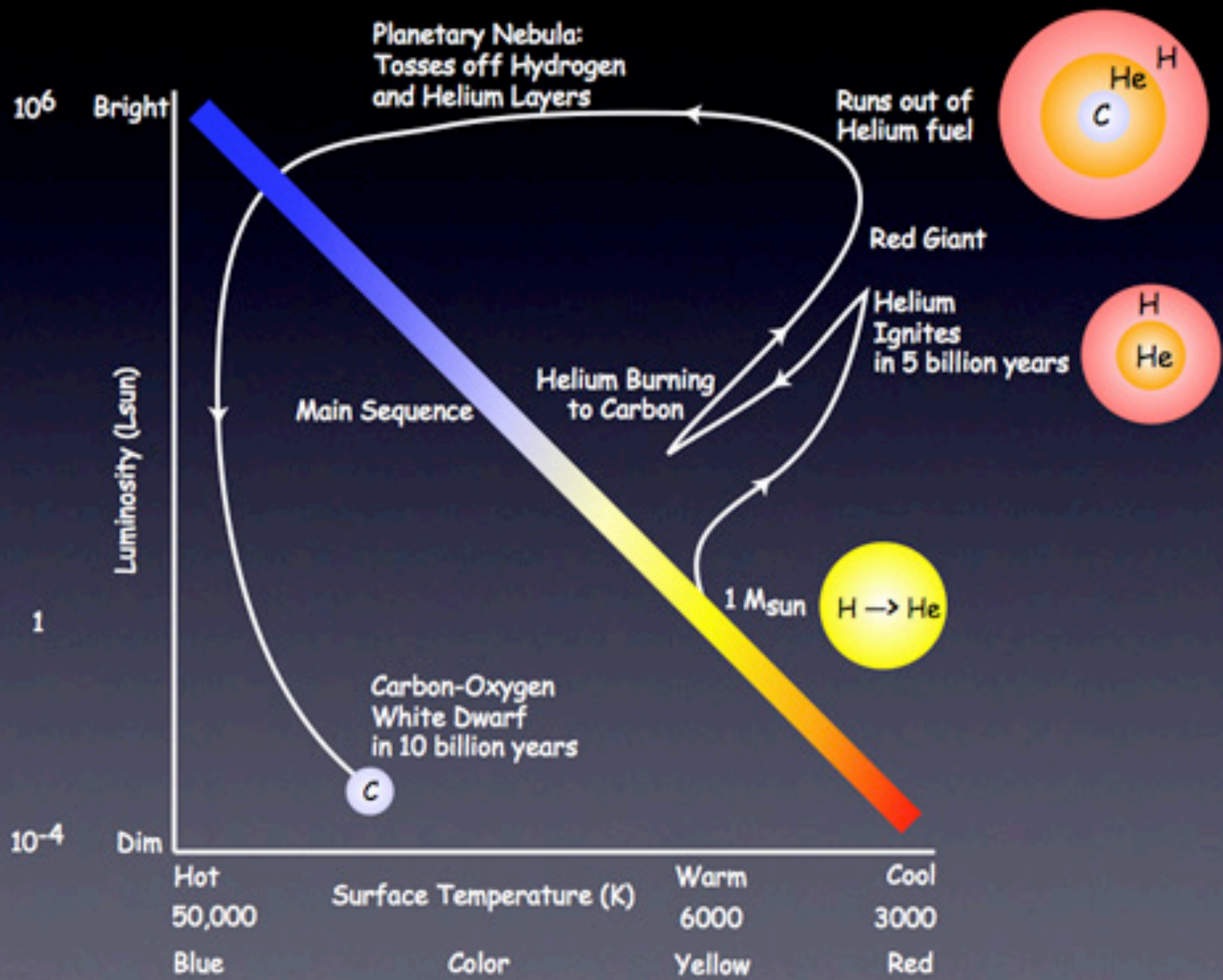
$$\text{“}p\text{”} \rightarrow \text{“}n\text{”} + e^+ + \nu_e$$

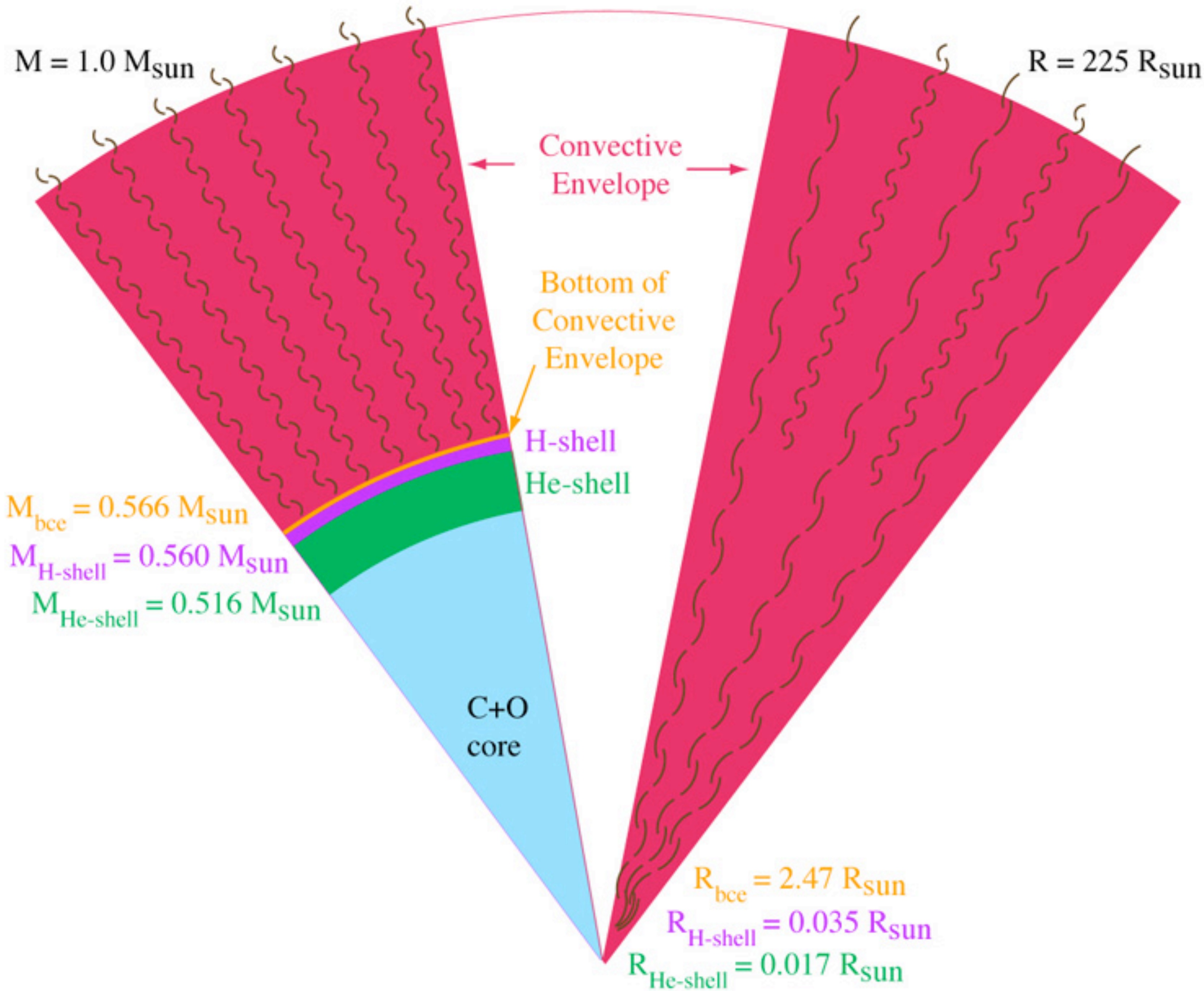


Solar fusion & neutrinos: $4p \to {}^4\mathrm{He} + 2e^+ + 2\nu_e$

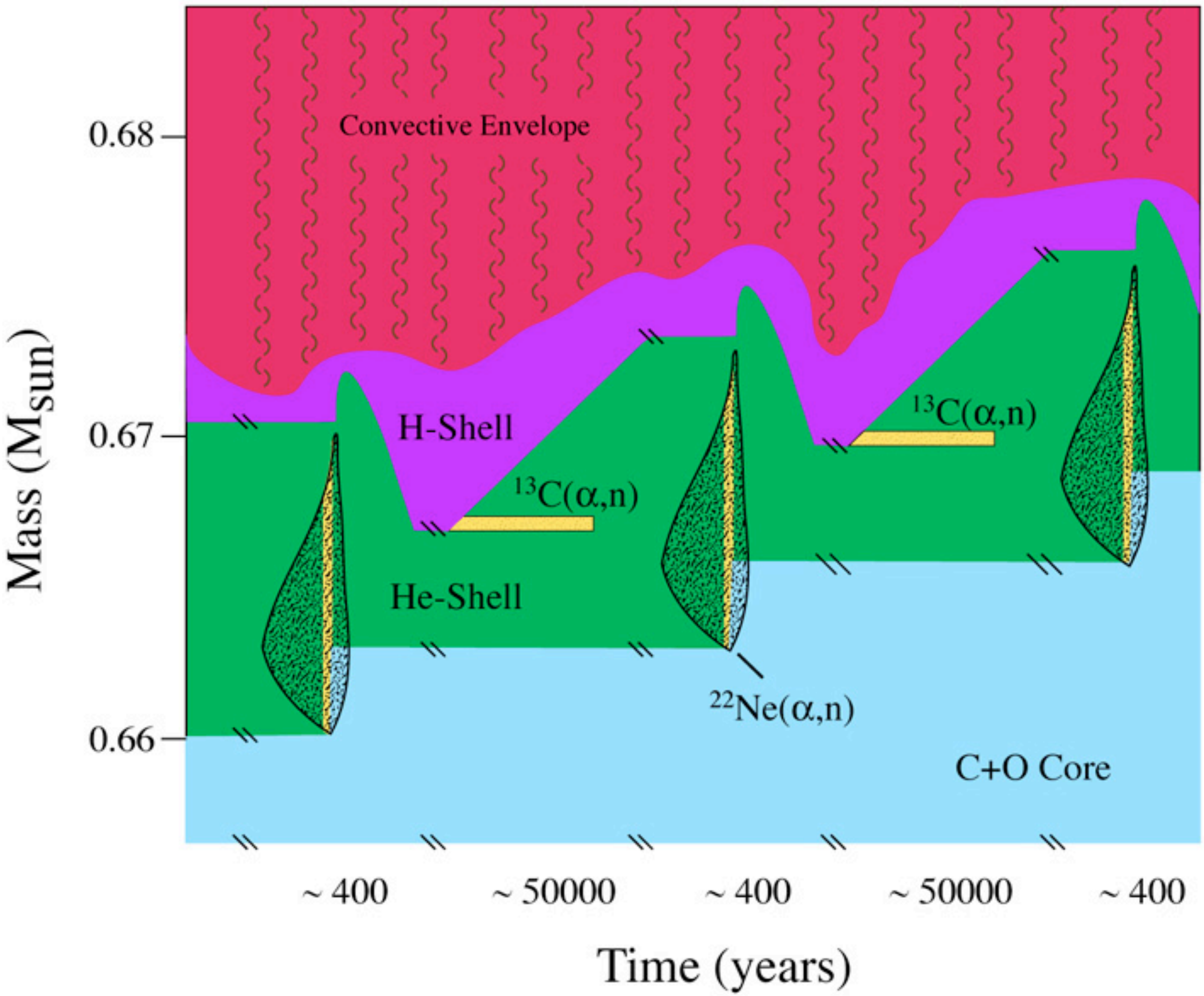


The final fate of stars like the Sun are carbon-oxygen white dwarfs.





M = 1.0 M$_{sun}$
R = 225 R$_{sun}$
Convective Envelope
Bottom of Convective Envelope
H-shell
He-shell
M$_{bce}$ = 0.566 M$_{sun}$
M$_{H\text{-shell}}$ = 0.560 M$_{sun}$
M$_{He\text{-shell}}$ = 0.516 M$_{sun}$
C+O core
R$_{bce}$ = 2.47 R$_{sun}$
R$_{H\text{-shell}}$ = 0.035 R$_{sun}$
R$_{He\text{-shell}}$ = 0.017 R$_{sun}$



Convective Envelope
H-Shell
He-Shell
^{13}C(α,n)
^{13}C(α,n)
^{22}Ne(α,n)
C+O Core
0.68
0.67
0.66
Mass (M$_{sun}$)
~ 400
~ 50000
~ 400
~ 50000
~ 400
Time (years)

Nucleosynthesis via slow neutron capture (s-process)
in low & intermediate-mass stars

$$3\ {}^{4}\mathrm{He} \rightarrow {}^{12}\mathrm{C} + \gamma$$

$${}^{12}\mathrm{C} + p \rightarrow {}^{13}\mathrm{N} + \gamma$$

$${}^{13}\mathrm{N} \rightarrow {}^{13}\mathrm{C} + e^{+} + \nu_e$$

$${}^{13}\mathrm{C} + {}^{4}\mathrm{He} \rightarrow {}^{16}\mathrm{O} + n$$

$$n + {}^{56}\mathrm{Fe} \rightarrow s\text{-process nuclei}$$

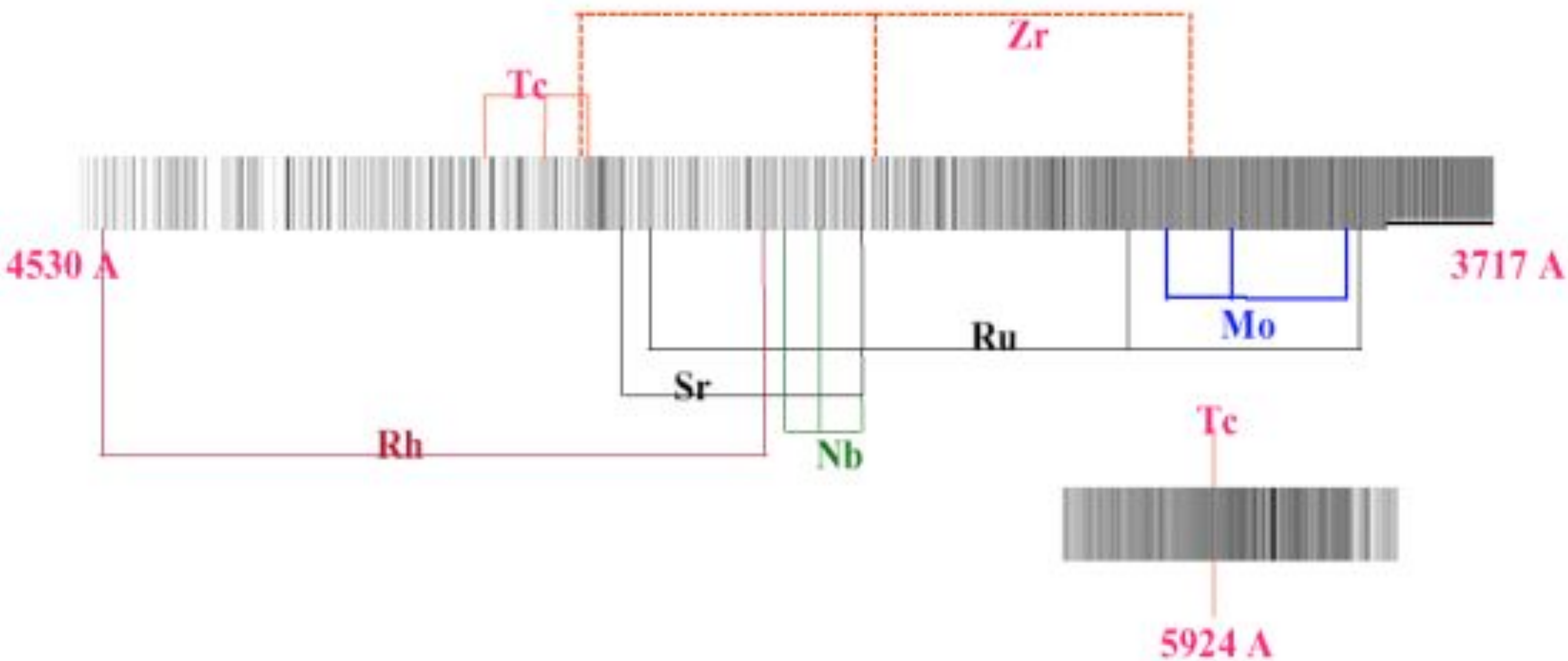
$$\boxed{4\ {}^{4}\mathrm{He} + p \rightarrow n + e^{+} + \nu_e + {}^{16}\mathrm{O}}$$

Evidence for s-process in low & intermediate-mass stars

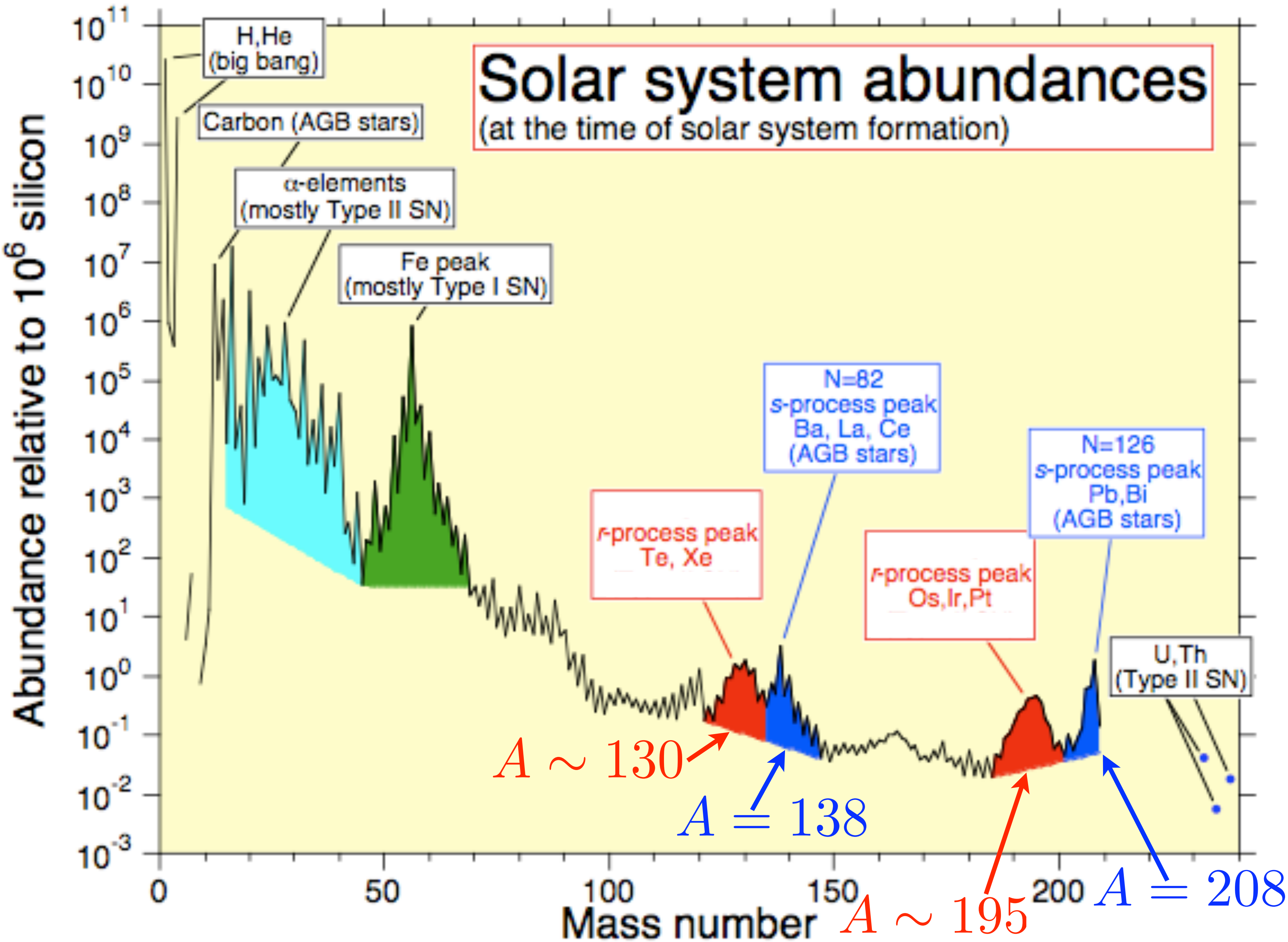
discovery of Tc spectral lines in stars by Merrill in 1952

Tc has no stable isotopes; the half-lives of the longest-lived isotopes are:

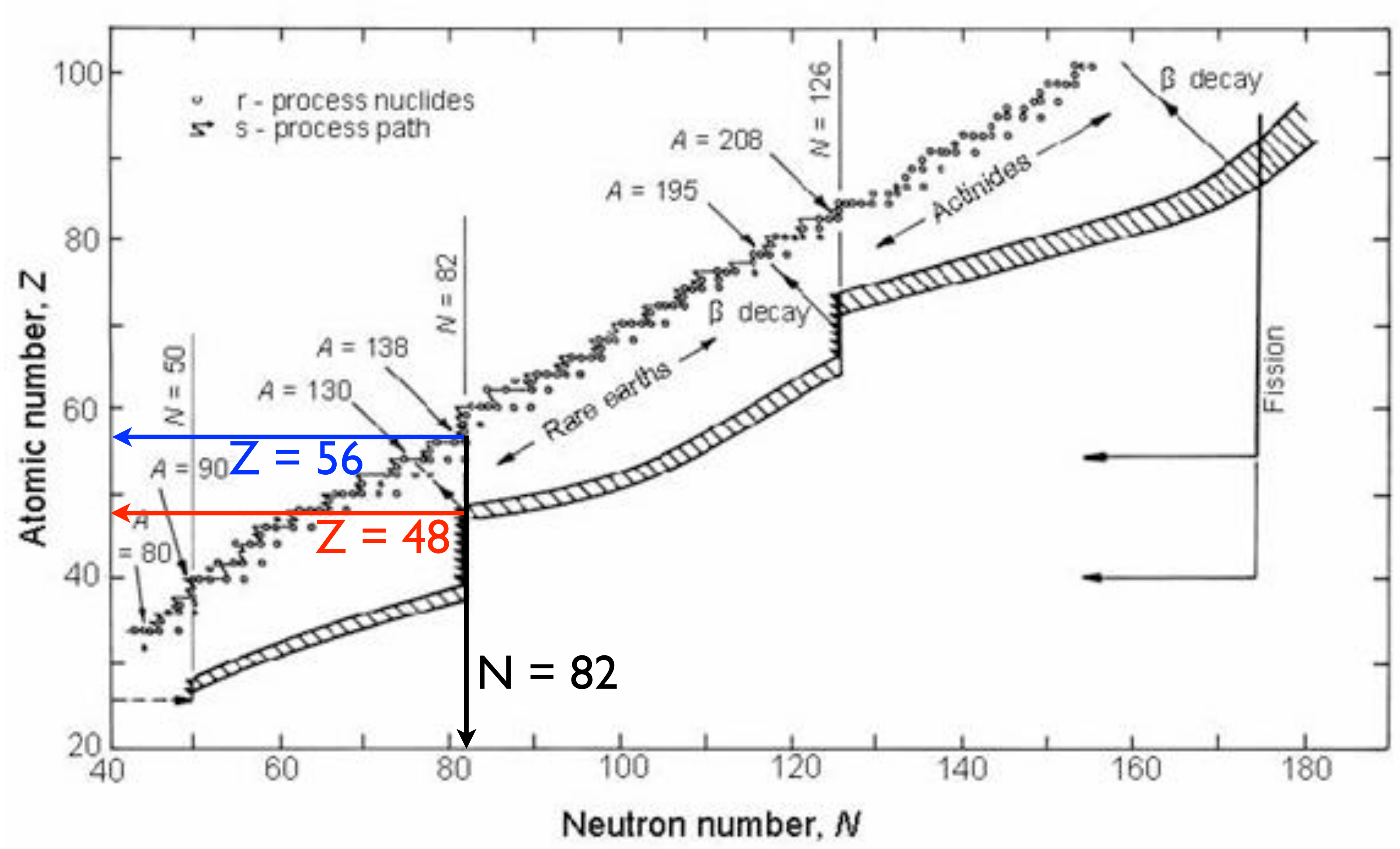
$$2.6 \times 10^6,\ 4.2 \times 10^6,\ 2.1 \times 10^5 \text{ yr for } {}^{97}\text{Tc},\ {}^{98}\text{Tc},\ {}^{99}\text{Tc}$$

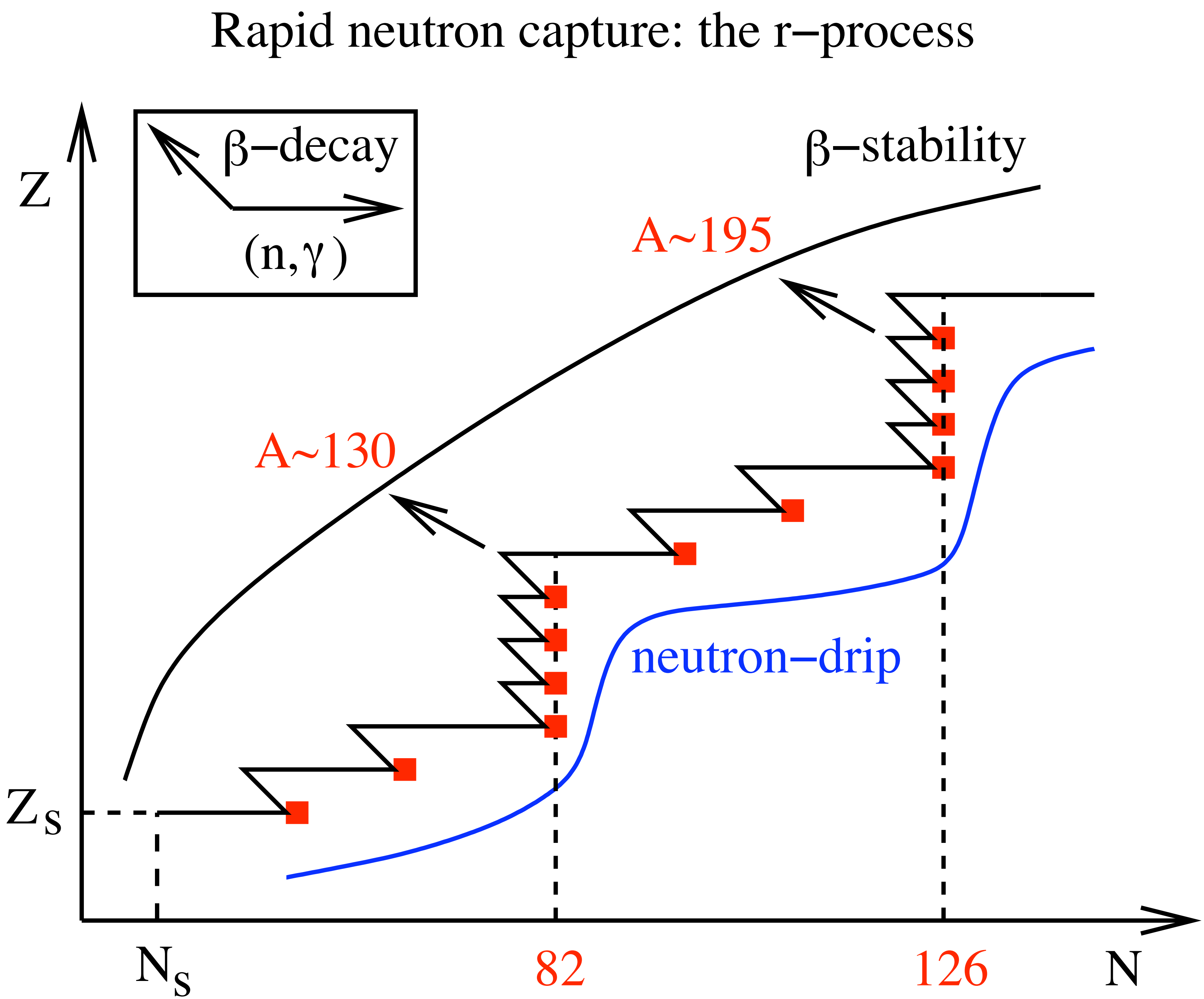


Cosmic Abundances

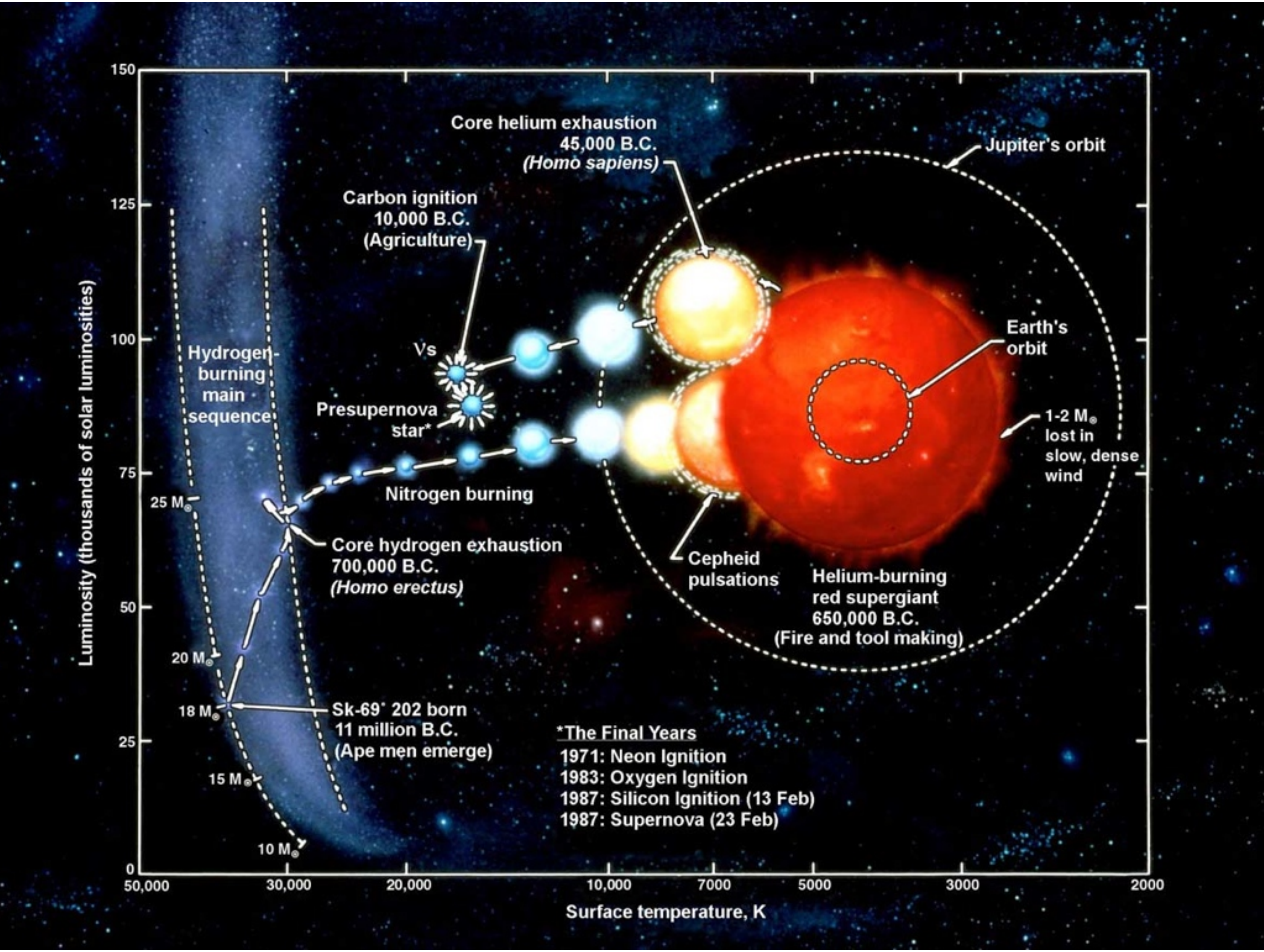


slow (s) and rapid (r) neutron capture processes

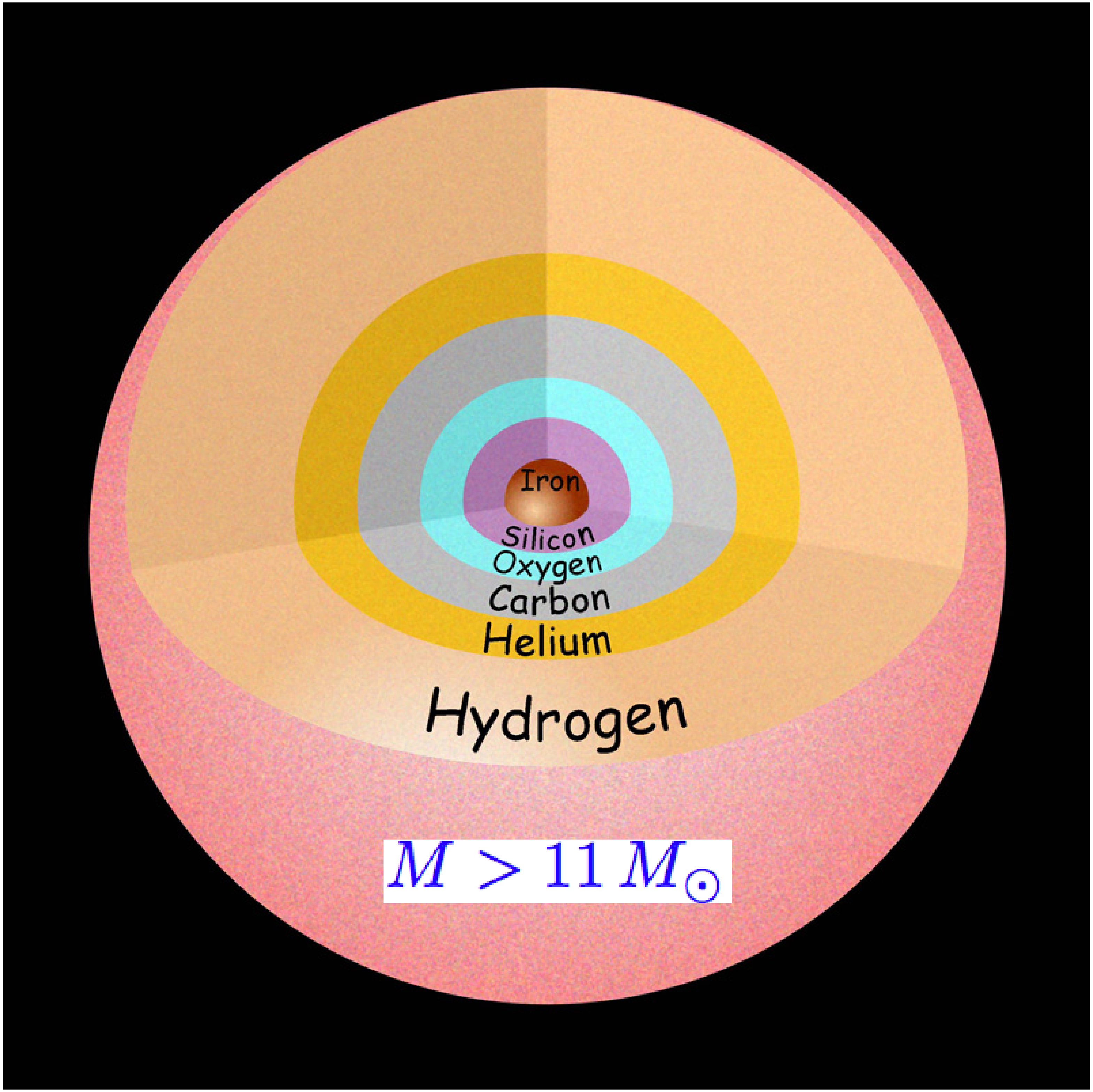




Rapid neutron capture: the r–process
Z
β–decay
(n,γ)
β–stability
A~195
A~130
neutron–drip
Z_S
N_S
82
126
N

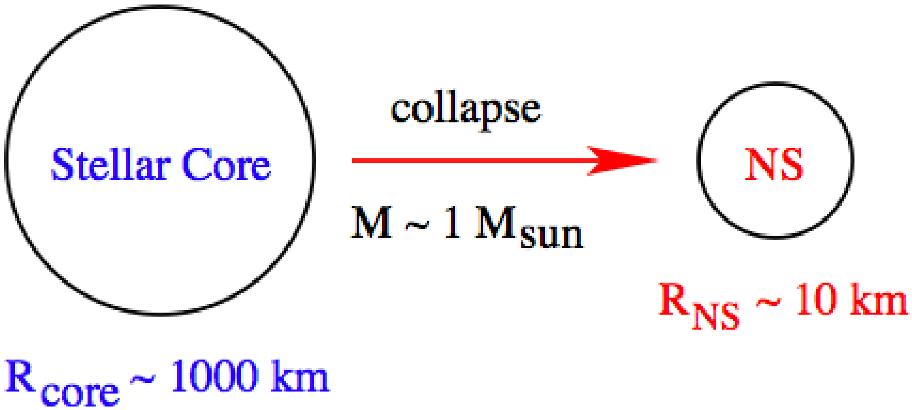


Luminosity (thousands of solar luminosities)
150
125
100
75
50
25
0
Surface temperature, K
50,000
30,000
20,000
10,000
7000
5000
3000
2000
Hydrogen-burning main sequence
25 M⊙
20 M⊙
18 M⊙
15 M⊙
10 M⊙
Sk-69° 202 born
11 million B.C.
(Ape men emerge)
Core hydrogen exhaustion
700,000 B.C.
(Homo erectus)
Nitrogen burning
Presupernova star*
Vs
Carbon ignition
10,000 B.C.
(Agriculture)
Core helium exhaustion
45,000 B.C.
(Homo sapiens)
Jupiter's orbit
Earth's orbit
1-2 M⊙ lost in slow, dense wind
Cepheid pulsations
Helium-burning red supergiant
650,000 B.C.
(Fire and tool making)
*The Final Years
1971: Neon Ignition
1983: Oxygen Ignition
1987: Silicon Ignition (13 Feb)
1987: Supernova (23 Feb)



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

Supernovae as a neutrino phenomenon

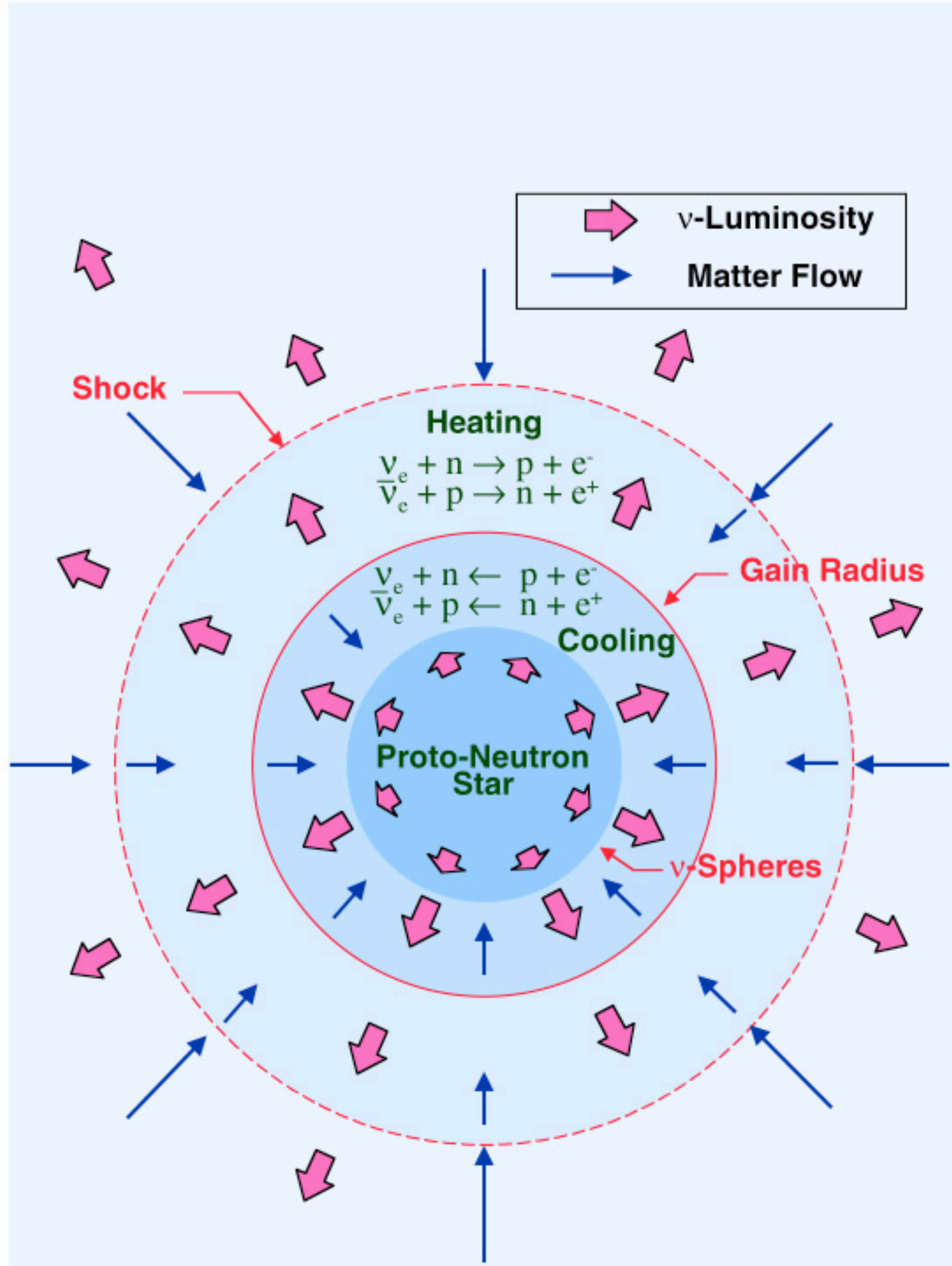


$$e^+ + e^- \rightarrow \nu + \bar{\nu}$$

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

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

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



Characteristics of Supernova Neutrino Emission

- momentum transfer

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

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

- energy transfer

$$\nu + e^- \to \nu + e^-$$

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

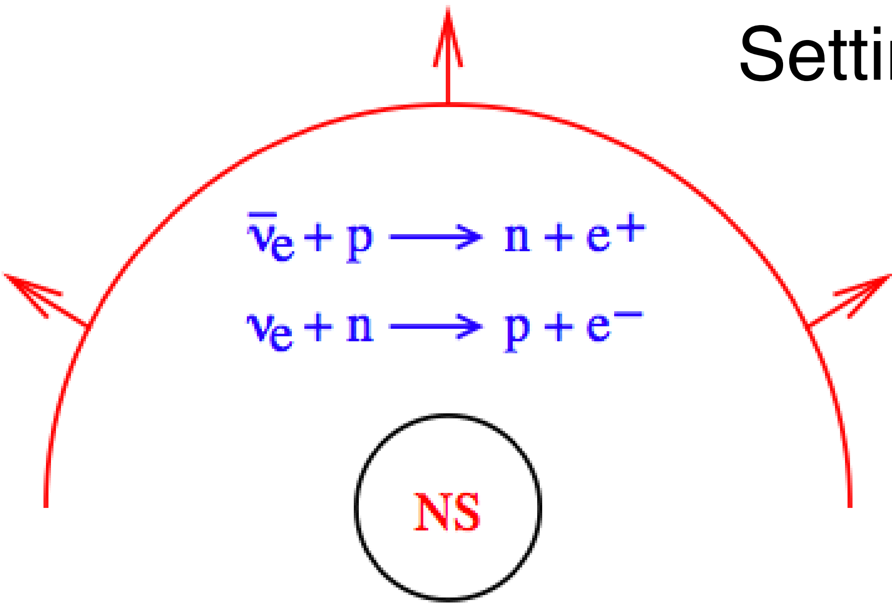
$$\langle E_{\nu_e} \rangle \approx 11 \text{ MeV}, \ \langle E_{\bar{\nu}_e} \rangle \approx 16 \text{ MeV}$$

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

numerical results sensitive to neutrino opacities!

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

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

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

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

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

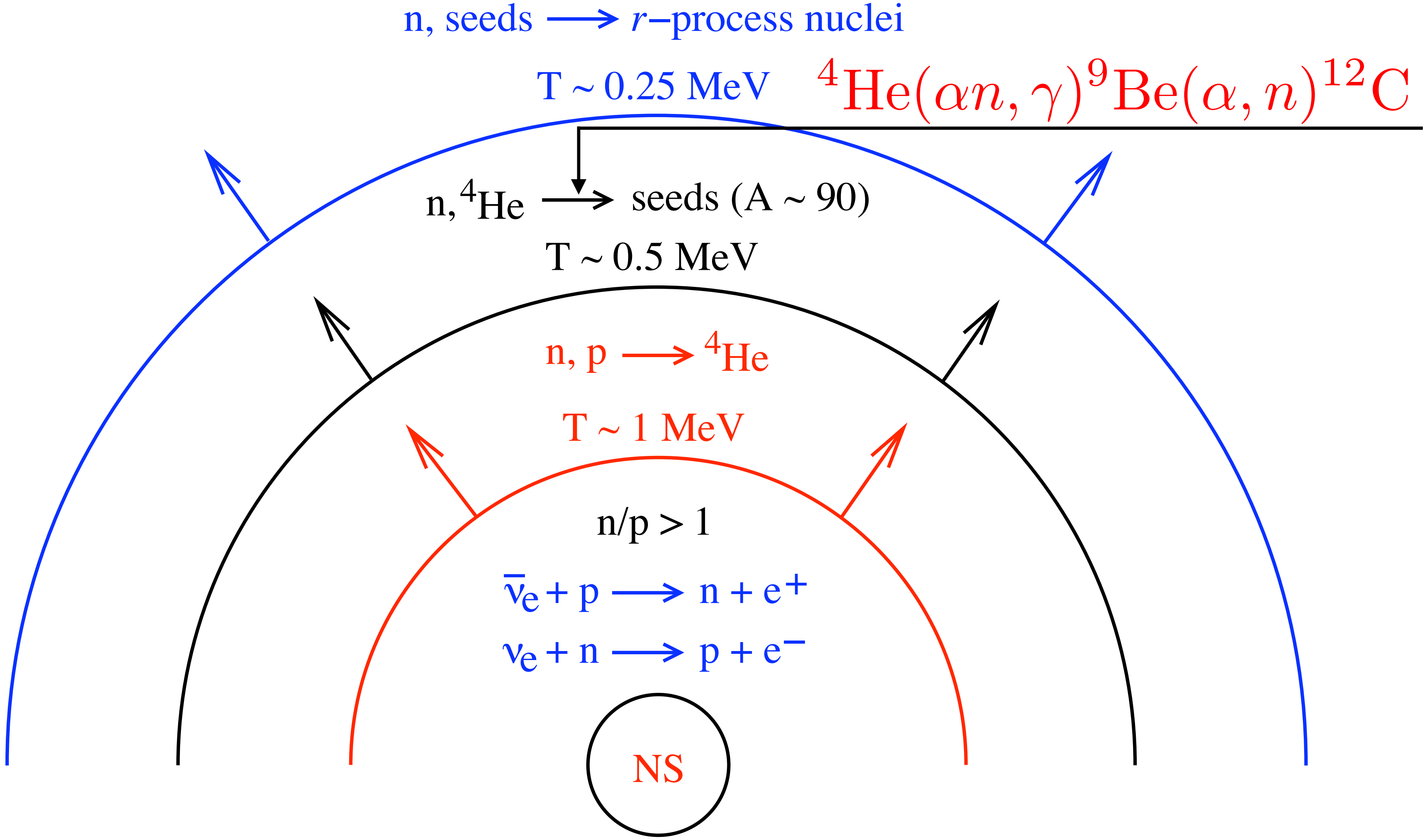
$$\frac{\langle E^2_{\bar{\nu}_e} \rangle}{\langle E_{\bar{\nu}_e} \rangle} - \frac{\langle E^2_{\nu_e} \rangle}{\langle E_{\nu_e} \rangle} > 4\Delta_{np} \approx 5.2\ \mathrm{MeV} \Rightarrow \frac{n}{p} > 1$$

Neutrino Opacities!

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

r–Process in Neutrino–driven Wind

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



Conditions in the Neutrino-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)

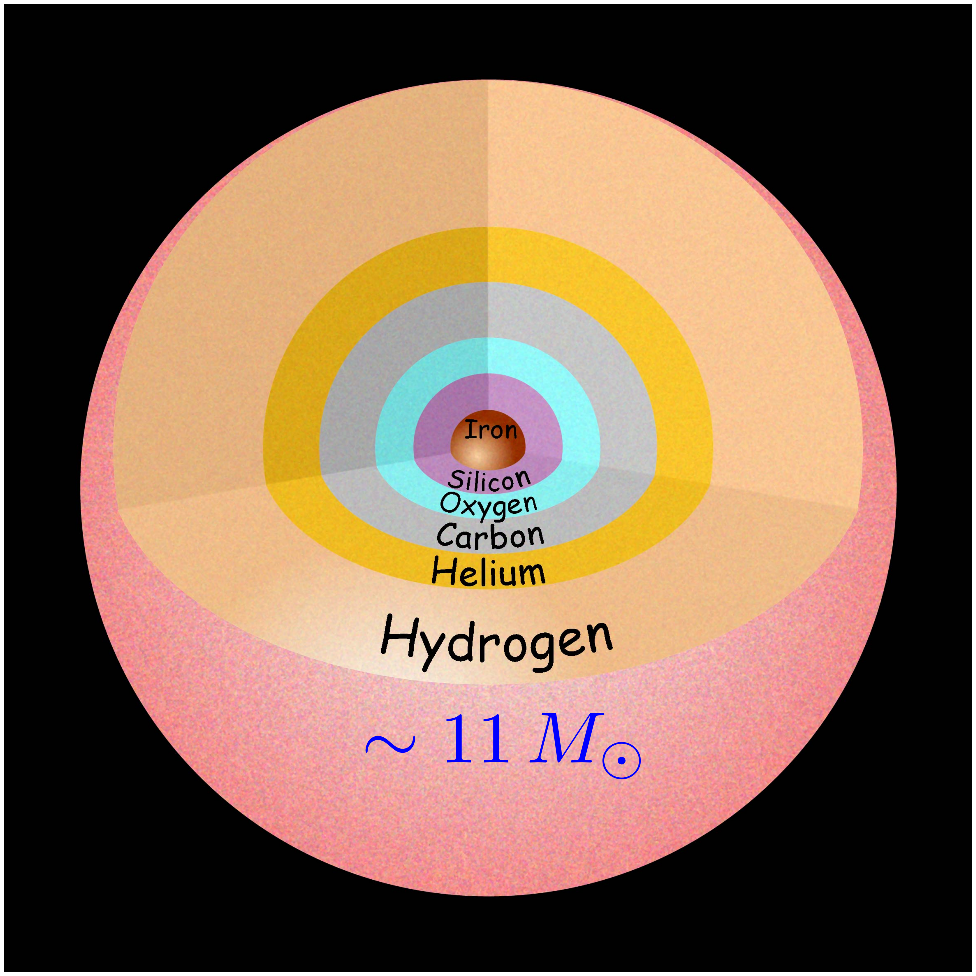
Sr, Y, Zr (A~90) readily produced in the wind, up to Pd & Ag (A~110) likely

(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)

Neutrino-Induced r-Process in He Shell of early SNe



neutron production by

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

Epstein, Colgate, & Haxton 1988

neutron capture by ^{56}Fe

high n_n requires few ^{56}Fe

→ early SNe

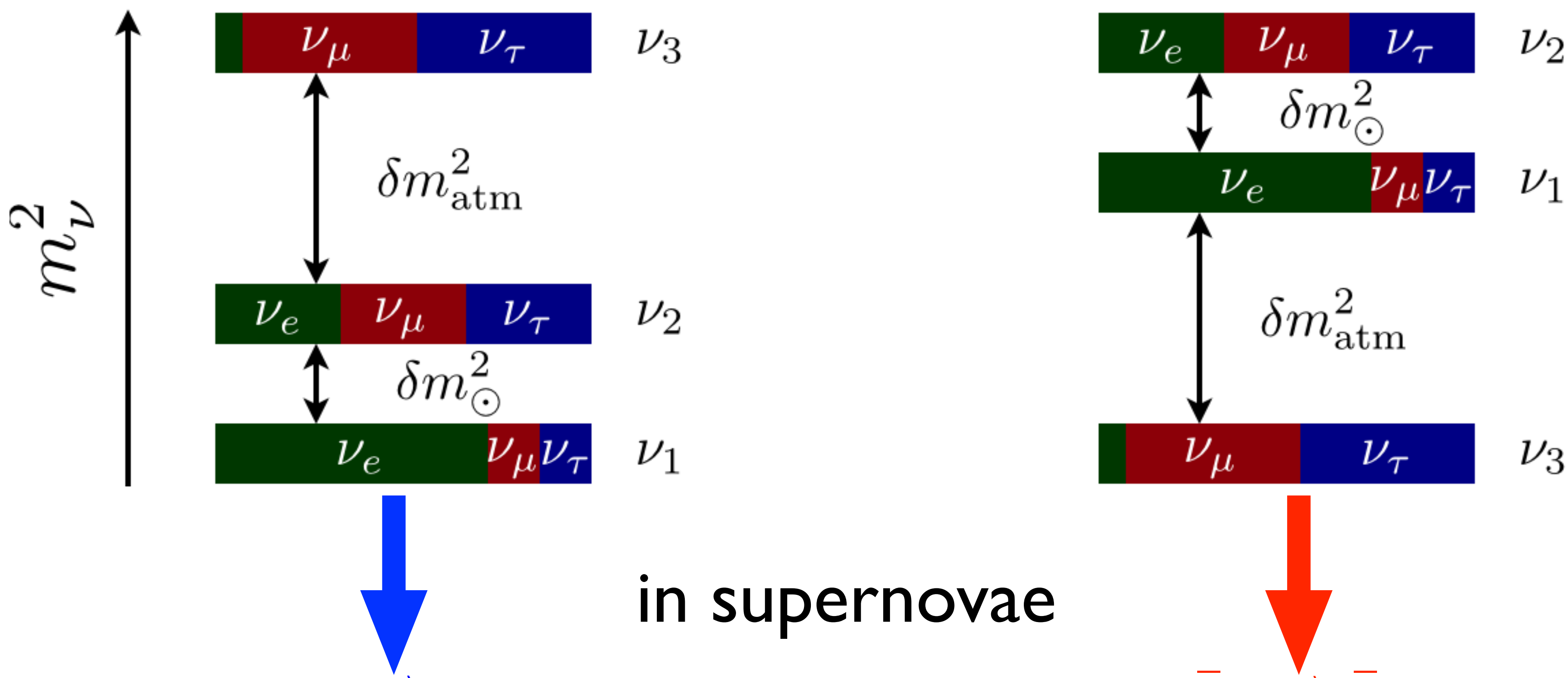
$$\bar{\nu}_e + {}^4\mathrm{He} \rightarrow {}^3\mathrm{H} + n + e^+, \;\; \lambda_{\bar{\nu}_e \alpha, n} \propto T_{\bar{\nu}_e}^{5-6} \; !$$

Banerjee, Haxton, & Qian 2011

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

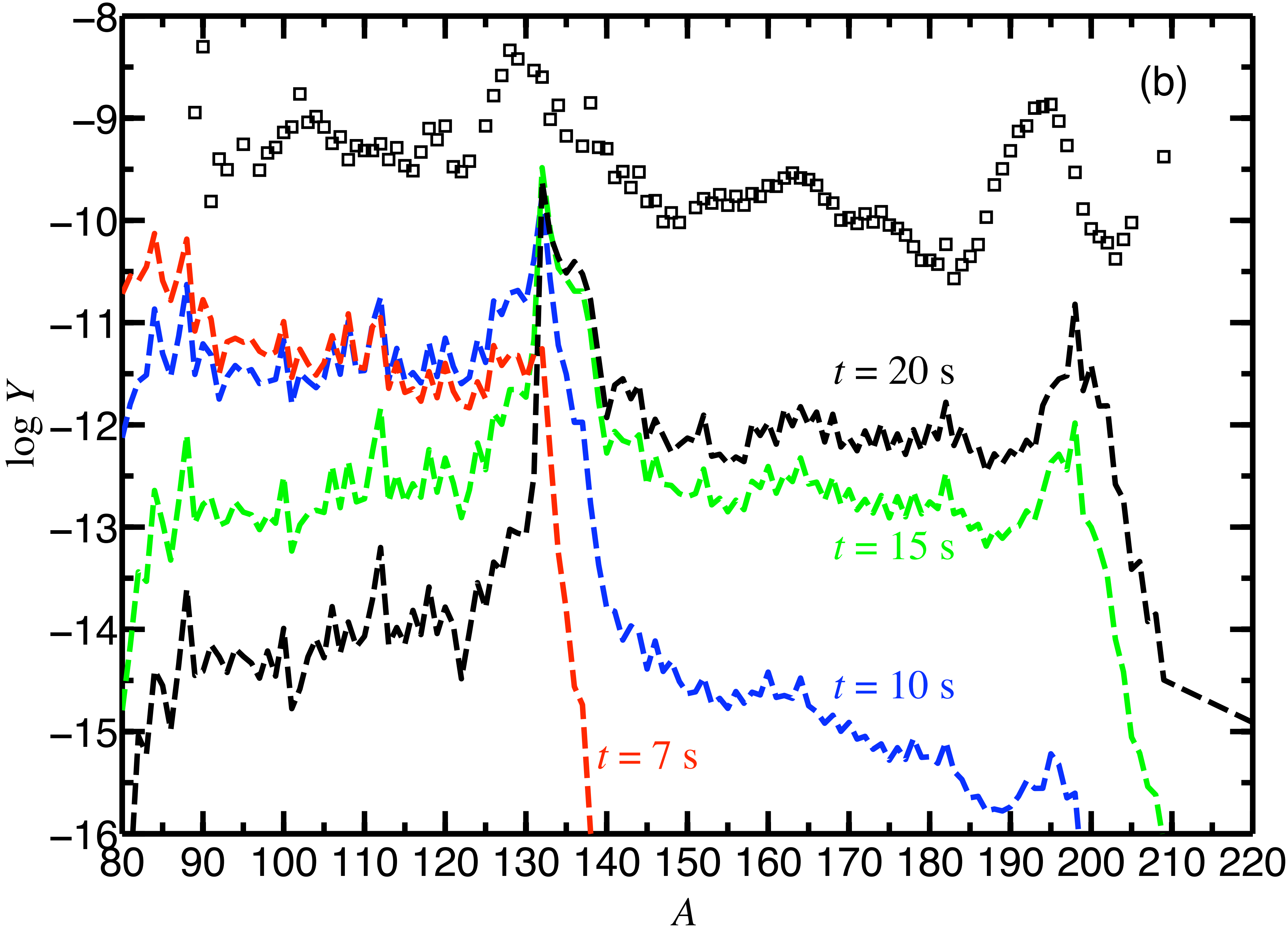
$\nu_e \rightleftharpoons \nu_{\mu,\tau}$

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

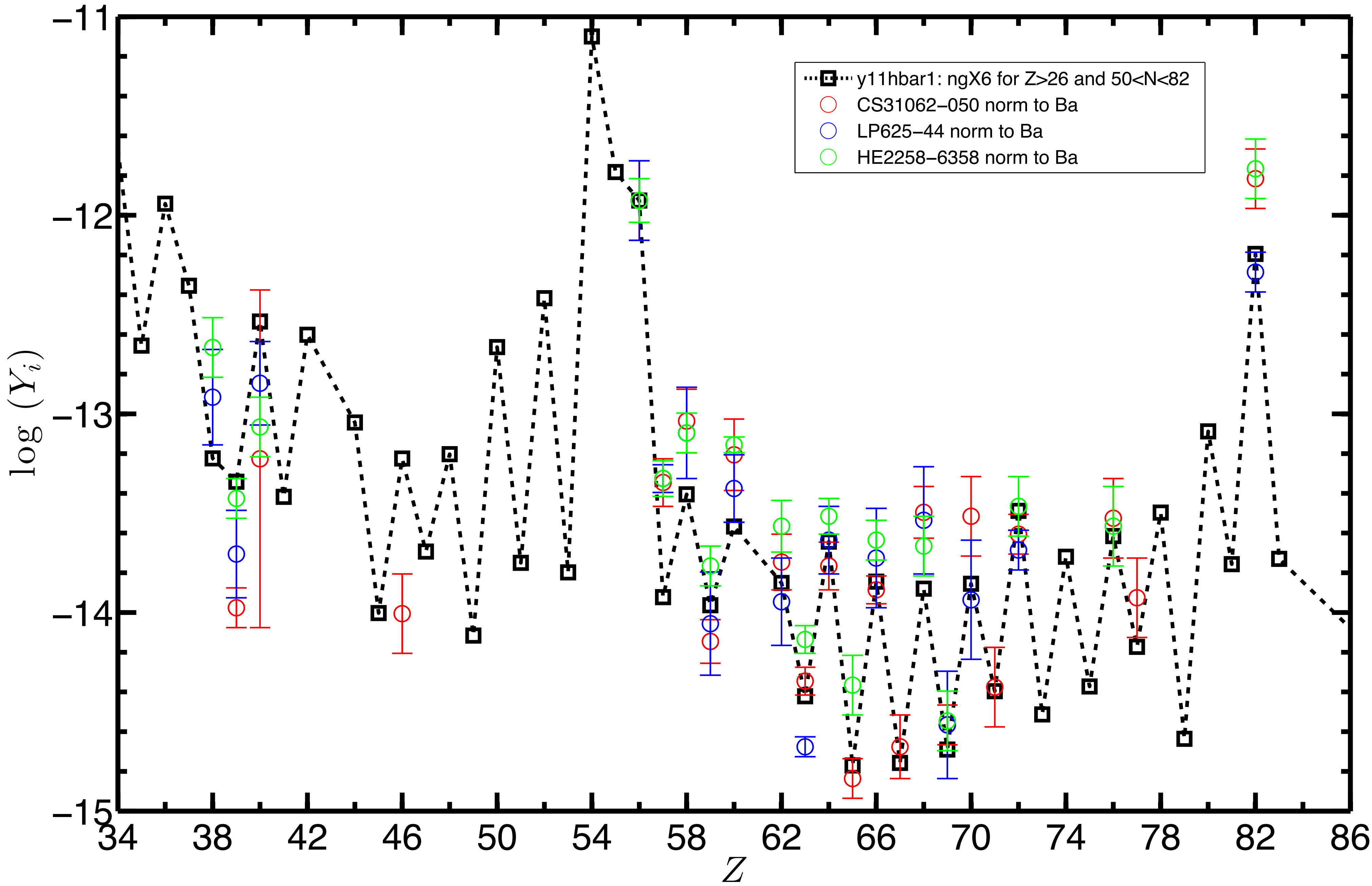
$\bar{\nu}_e \rightleftharpoons \bar{\nu}_{\mu,\tau}$

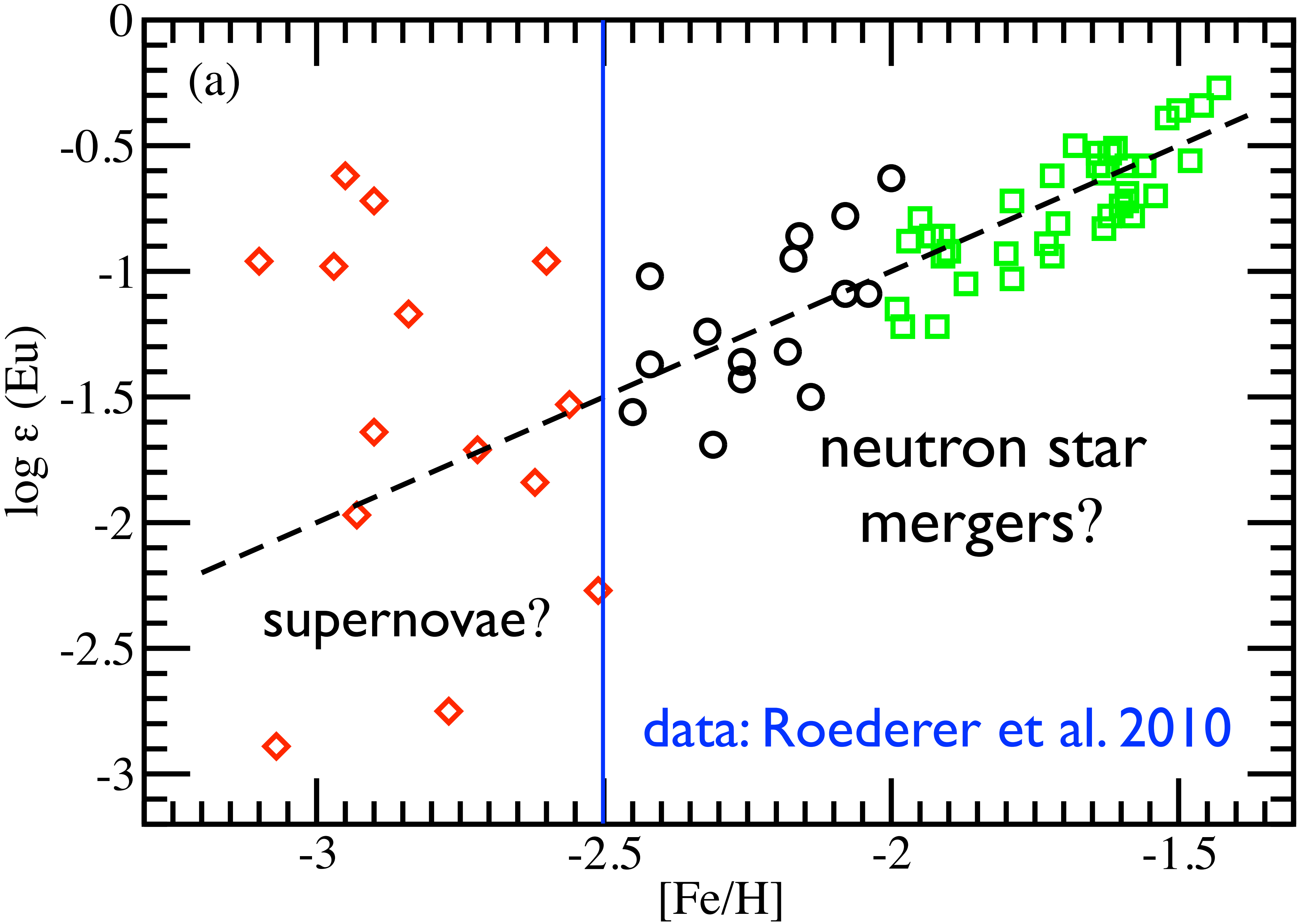
$^4\text{He}(\bar{\nu}_e, e^+ n)^3\text{H}$

Banerjee, Haxton, & Qian (2011)

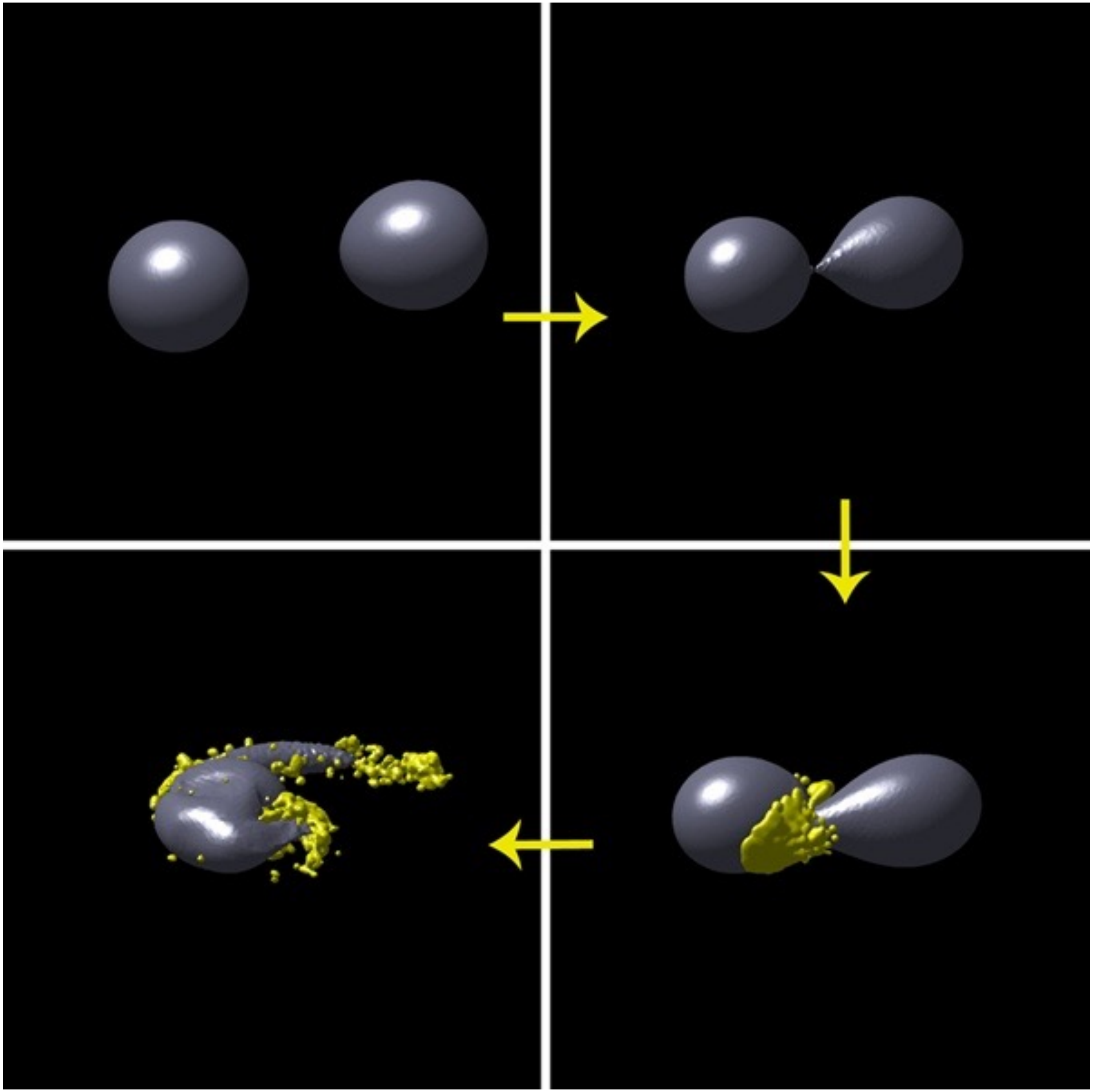


Banerjee, Qian, Heger, & Haxton 2016





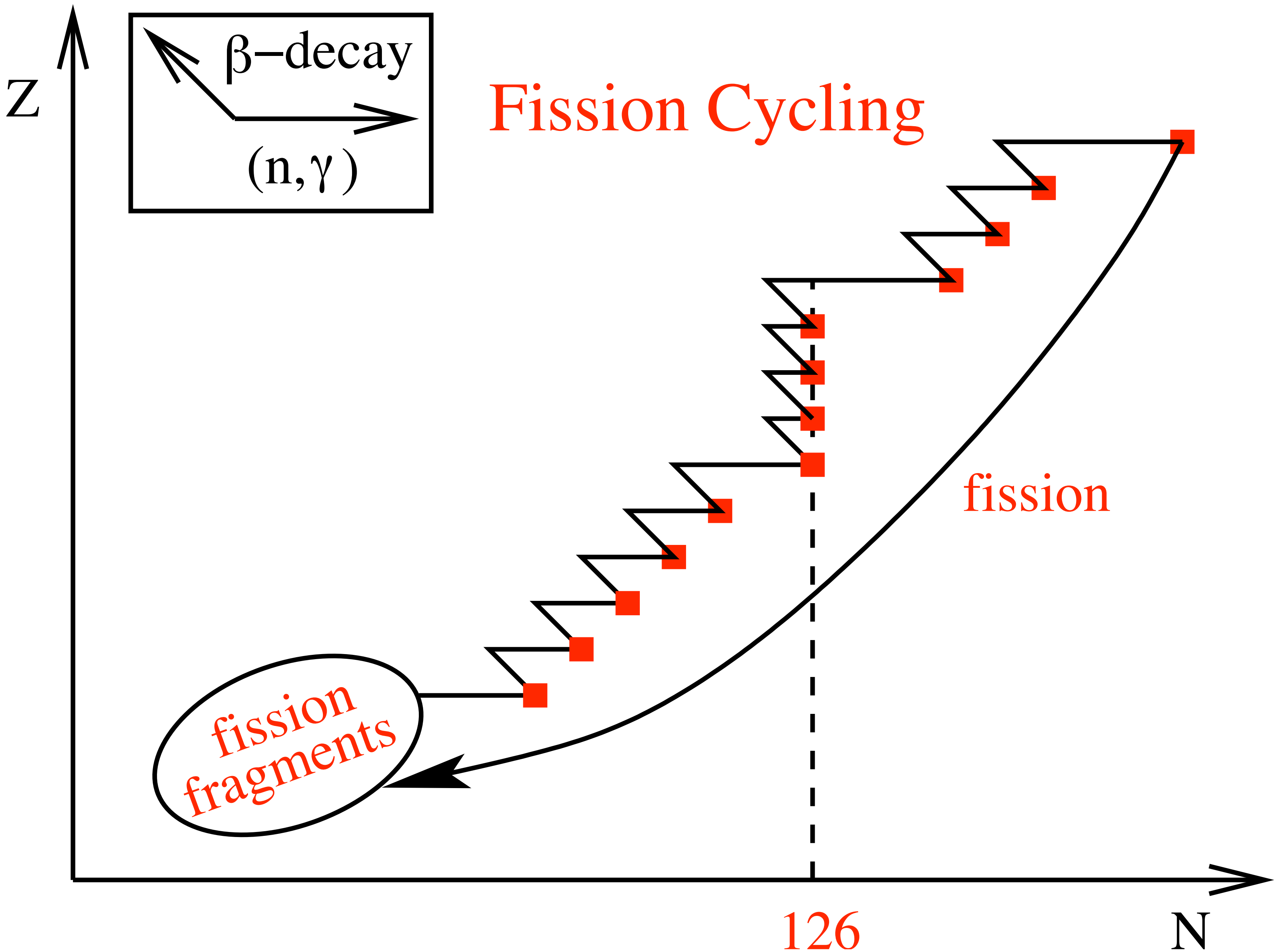
(a)
0
-0.5
-1
-1.5
-2
-2.5
-3
log ε (Eu)
-3
-2.5
-2
-1.5
[Fe/H]
neutron star
mergers?
supernovae?
data: Roederer et al. 2010



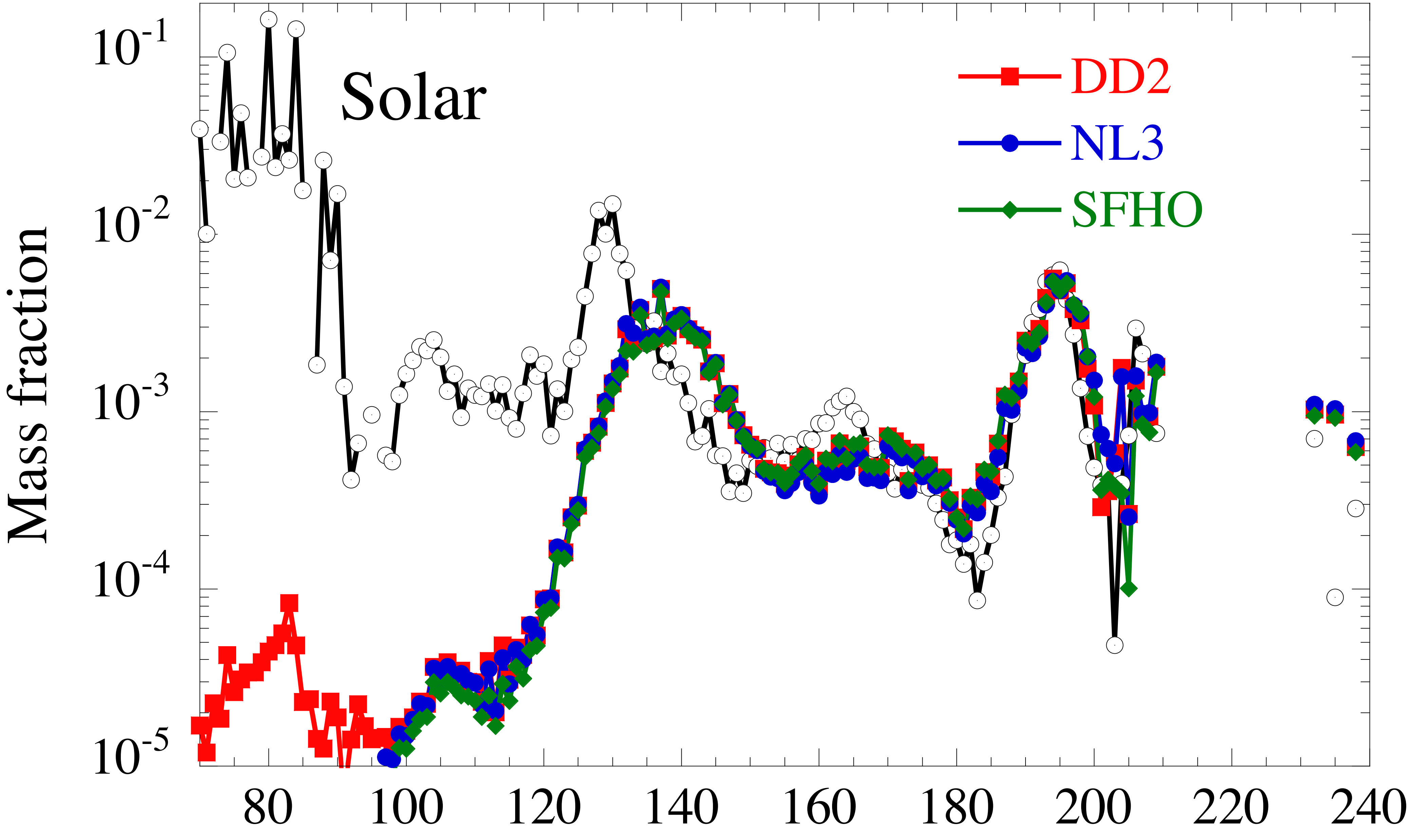
Neutron Star Mergers

Goriely, Bauswein, & Janka 2011

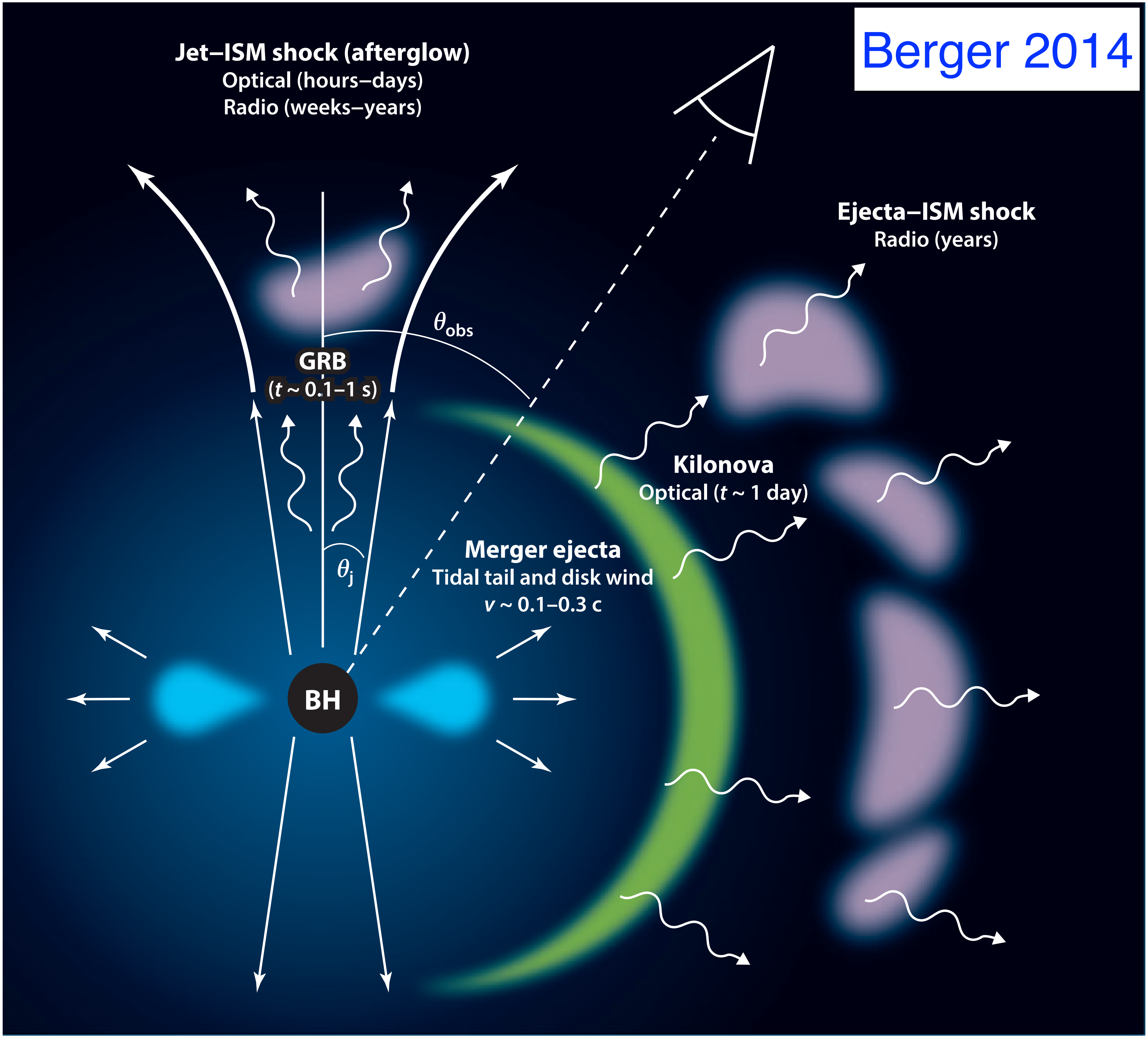
Rosswog et al. 1999, 2014



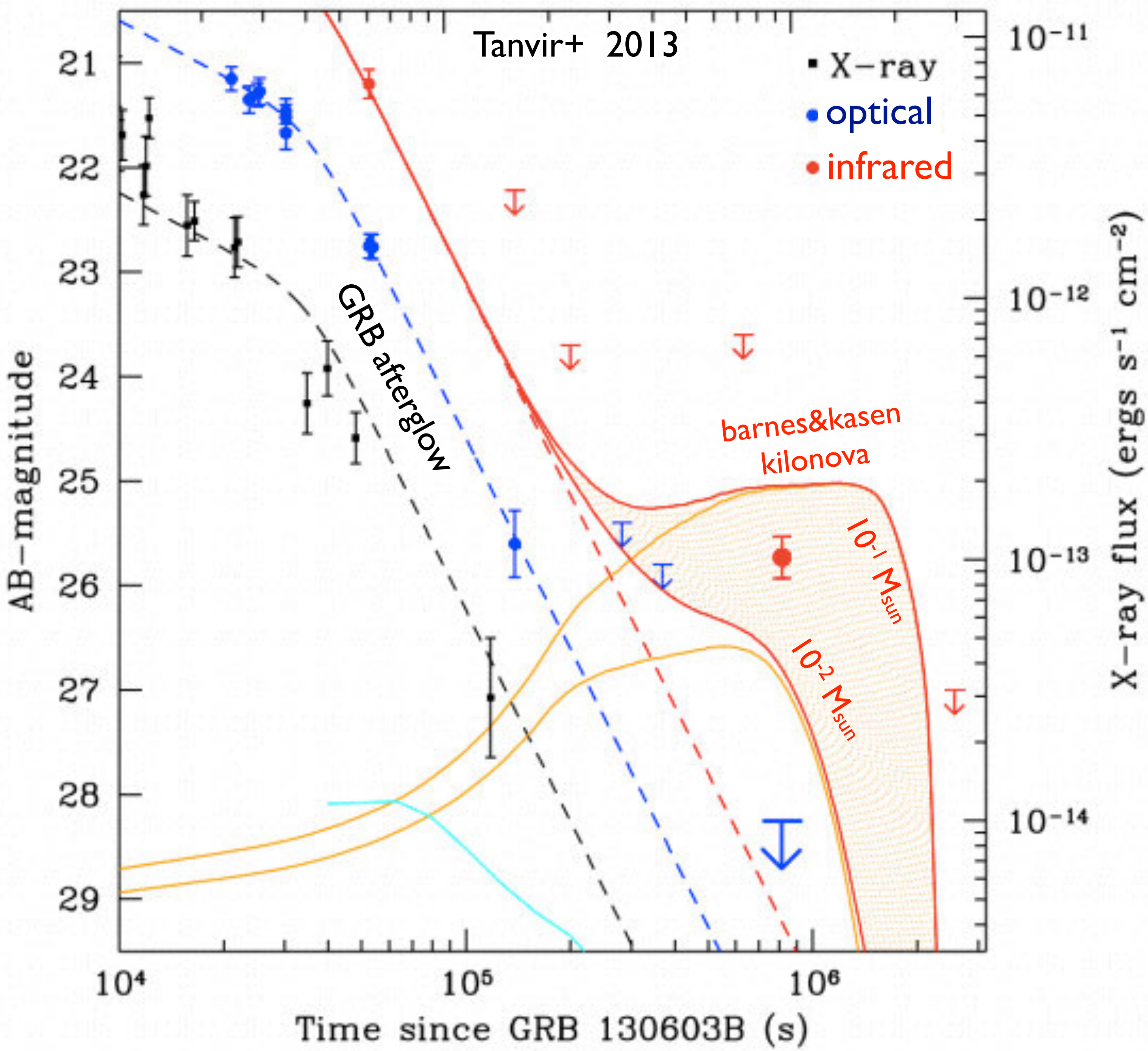
Z
β−decay
(n,γ)
Fission Cycling
fission
fission
fragments
126
N



Goriely, Bauswein, & Janka 2011, 2013


Berger 2014
Jet–ISM shock (afterglow)
Optical (hours–days)
Radio (weeks–years)
Ejecta–ISM shock
Radio (years)
θ_{obs}
GRB
(t ~ 0.1–1 s)
Kilonova
Optical (t ~ 1 day)
Merger ejecta
Tidal tail and disk wind
v ~ 0.1–0.3 c
θ_j
BH

discovery of an r-process kilonova?



Summary

Stars of ~1.5-3 M_{sun} are the dominant source for the main s-process elements by providing neutrons via $^{12}C(p,g)^{13}N(e^{+}v_{e})^{13}C(a,n)^{16}O$

SNe of ~8-40 M_{sun} can provide neutrons for the r-process by

$$1.\ \bar{\nu}_e + p \rightarrow n + e^+$$

in neutrino-driven winds: up to A~130

$$2.\ \bar{\nu}_e + {}^4\mathrm{He} \rightarrow {}^3\mathrm{H} + n + e^+$$

in early SNe ([Fe/H] < -3): up to A>200

3. leaving behind an NS

for NS mergers: A>130