# Origin of Heavy Elements in the Early Universe

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## Landau-Zener treatments of solar neutrino oscillations

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W. C. Haxton and Y.-Z. Qian

PHYSICAL REVIEW C VOLUME 55, NUMBER 3 MARCH 1997

## Neutrino-induced neutron spallation and supernova *r*-process nucleosynthesis

Y.-Z. Qian,[1] W. C. Haxton,[2] K. Langanke,[3,4] and P. Vogel[1]

VOLUME 78, NUMBER 14 PHYSICAL REVIEW LETTERS 7 APRIL 1997

## Neutrino-Induced Nucleosynthesis and the Site of the *r* Process

W.C. Haxton,[1] K. Langanke,[2,3] Y.-Z. Qian,[3] and P. Vogel[3]

PRL 106, 201104 (2011) PHYSICAL REVIEW LETTERS week ending 20 MAY 2011

**Long, Cold, Early *r* Process? Neutrino-Induced Nucleosynthesis in He Shells Revisited**

Projjwal Banerjee,[1,*] W. C. Haxton,[2,†] and Yong-Zhong Qian[1,‡]

PRL 110, 141101 (2013) PHYSICAL REVIEW LETTERS week ending 5 APRIL 2013

**New Primary Mechanisms for the Synthesis of Rare $^{9}$Be in Early Supernovae**

Projjwal Banerjee,[1,*] Yong-Zhong Qian,[2,†] W. C. Haxton,[1,‡] and Alexander Heger[3,§]

EPJ Web of Conferences **109**, 06001 (2016)
DOI: 10.1051/epjconf/201610906001


# Neutrino-Induced Nucleosynthesis in Helium Shells of Early Core-Collapse Supernovae

Projjwal Banerjee[1,a], Yong-Zhong Qian[1,5], Alexander Heger[2,5], and Wick Haxton[3,4]

nature COMMUNICATIONS

ARTICLE

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OPEN

# Evidence from stable isotopes and $^{10}$Be for solar system formation triggered by a low-mass supernova

Projjwal Banerjee[1], Yong-Zhong Qian[1], Alexander Heger[2,3] & W.C. Haxton[4]

Big Bang:

75% H + 25% He
(by mass)

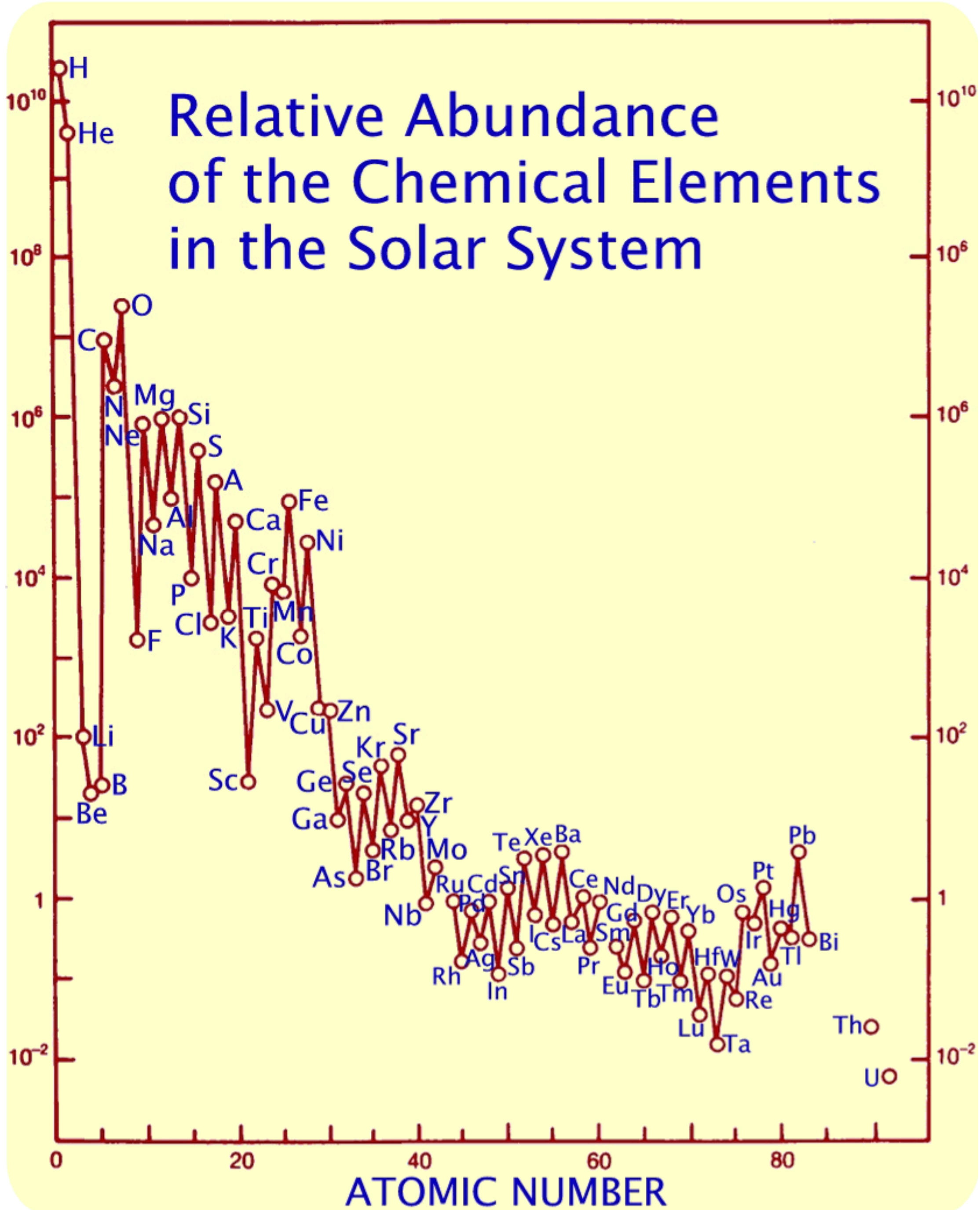
Sun:

71.1% H + 27.4% He
+1.5% "Metals"

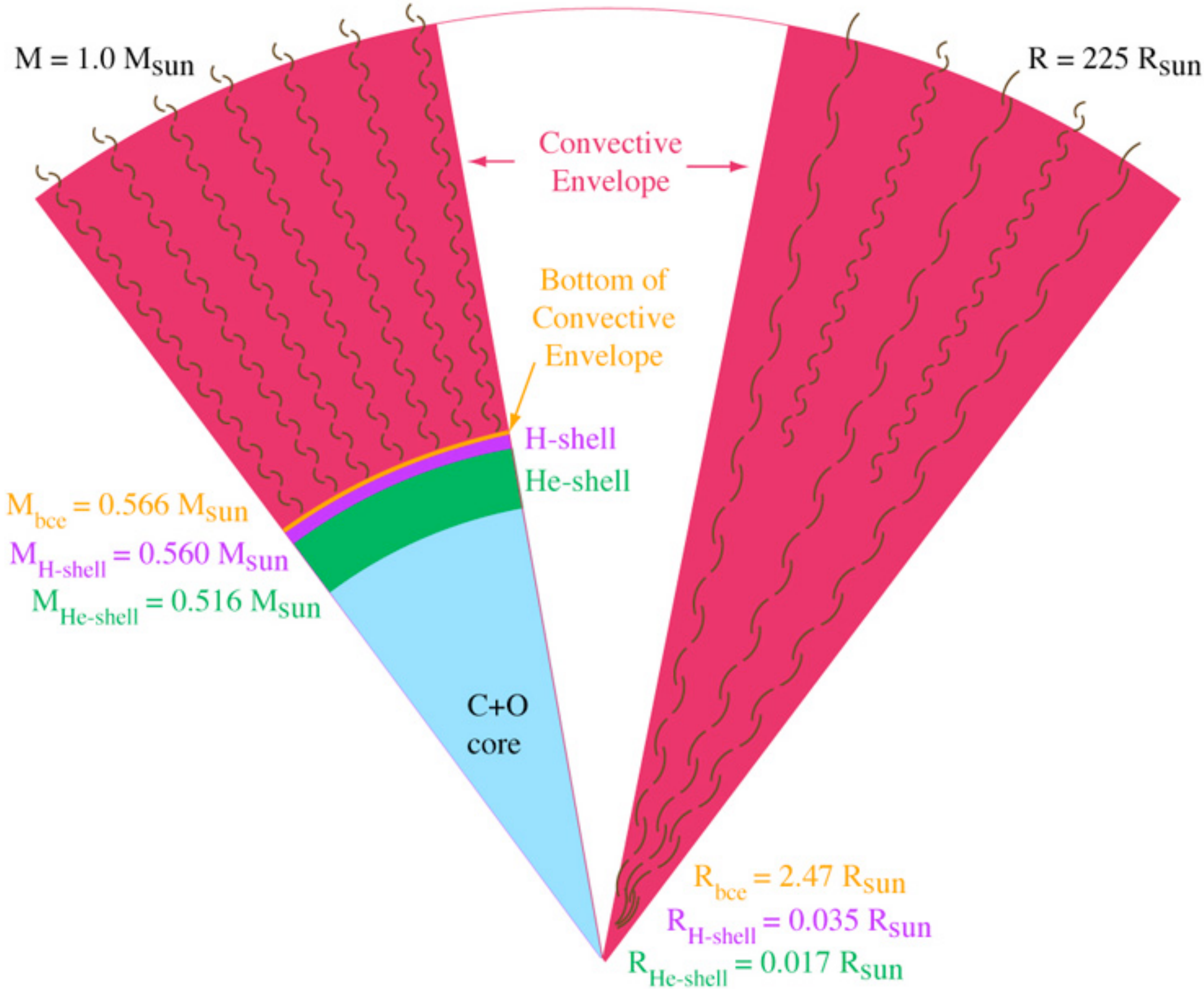
$$\text{"}p\text{"} \to \text{"}n\text{"} + e^+ + \nu_e$$

$$\bar{\nu}_e + \text{"}p\text{"} \to \text{"}n\text{"} + e^+$$

$$e^- + \text{"}p\text{"} \to \text{"}n\text{"} + \nu_e$$



# The Beginning of the End



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

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

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

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

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

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

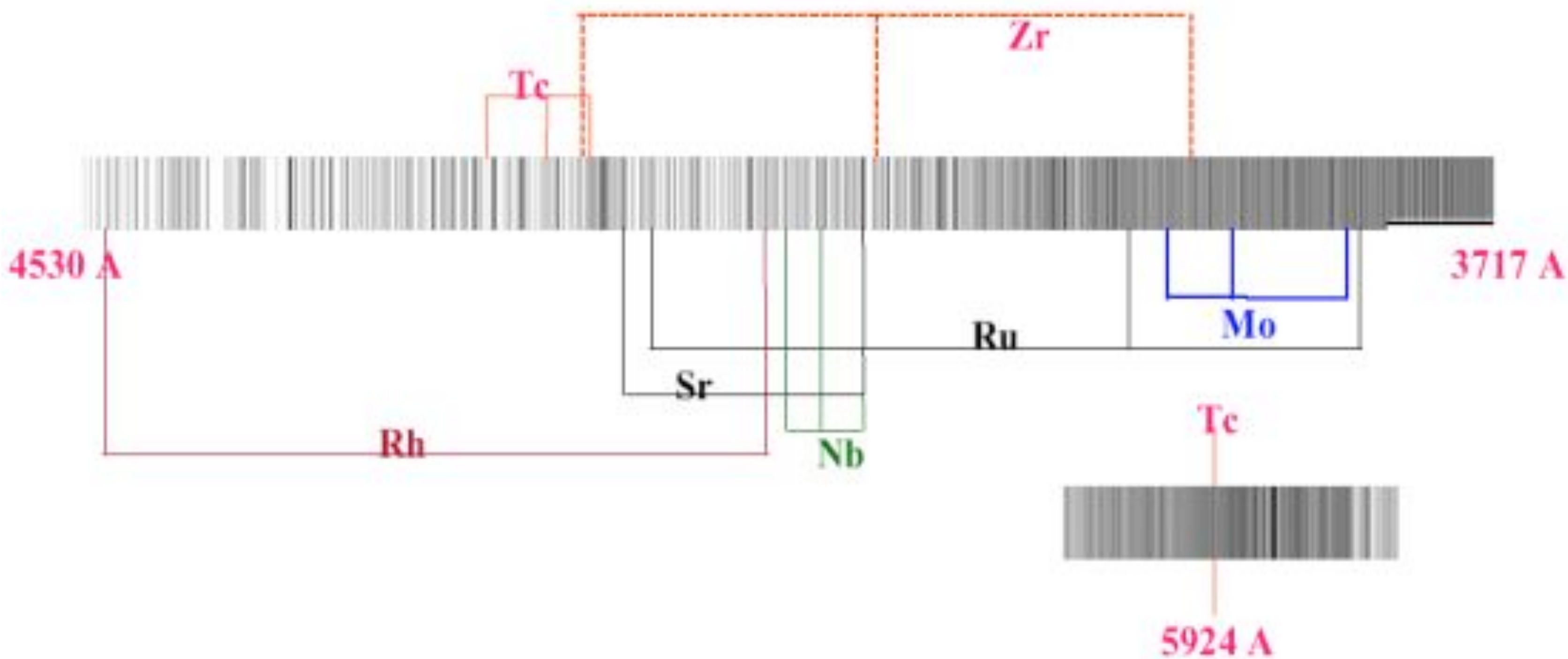
$$\boxed{4\ {}^{4}\mathrm{He} + p \rightarrow n + e^{+} + \nu_e + {}^{16}\mathrm{O}}$$

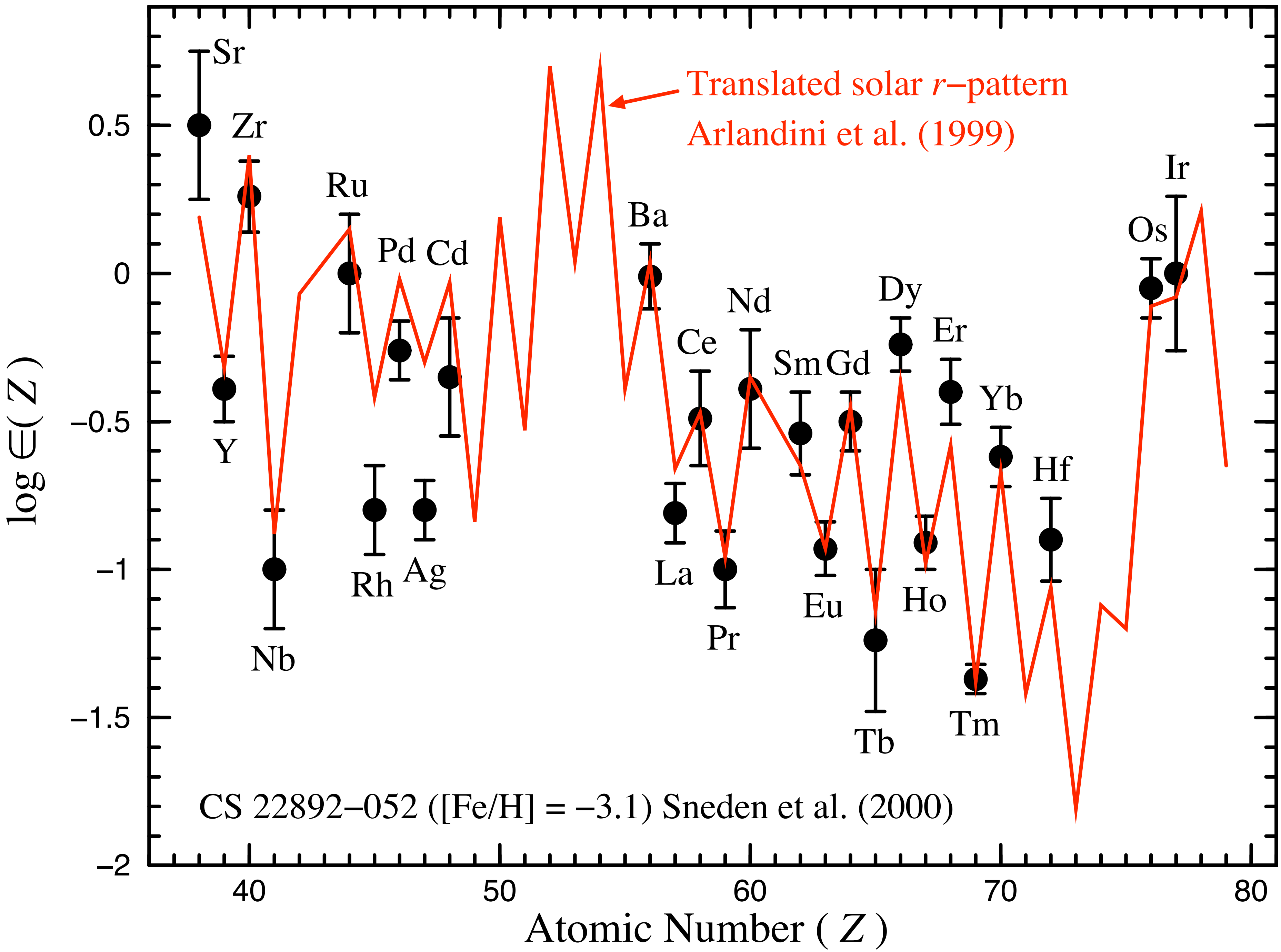
# Evidence for s-process in low & intermediate-mass stars

discovery of Tc spectral lines in stars by Merrill in 1952

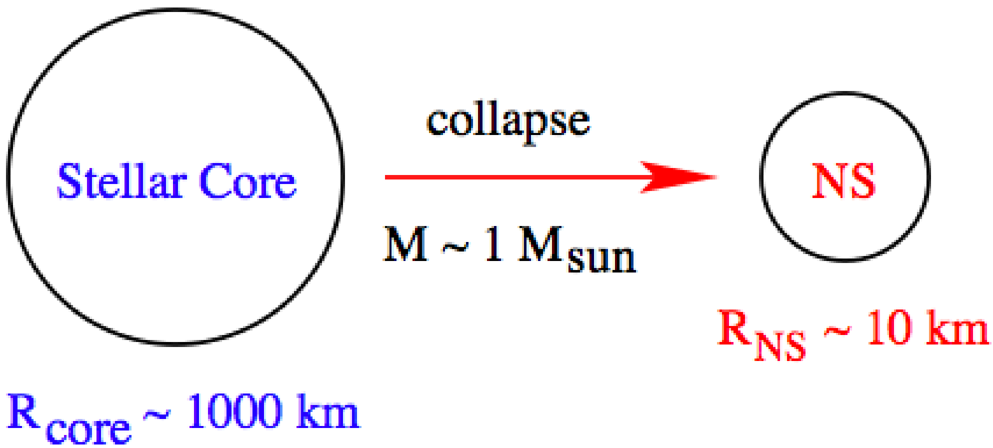
Tc has no stable isotopes; the half-lives of the longest-lived isotopes are:

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




Translated solar r–pattern
Arlandini et al. (1999)
CS 22892–052 ([Fe/H] = –3.1) Sneden et al. (2000)
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
log ∈( Z )
Atomic Number ( Z )
0.5
0
–0.5
–1
–1.5
–2
40
50
60
70
80

# Neutrino Emission from Proto-NS Cooling




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

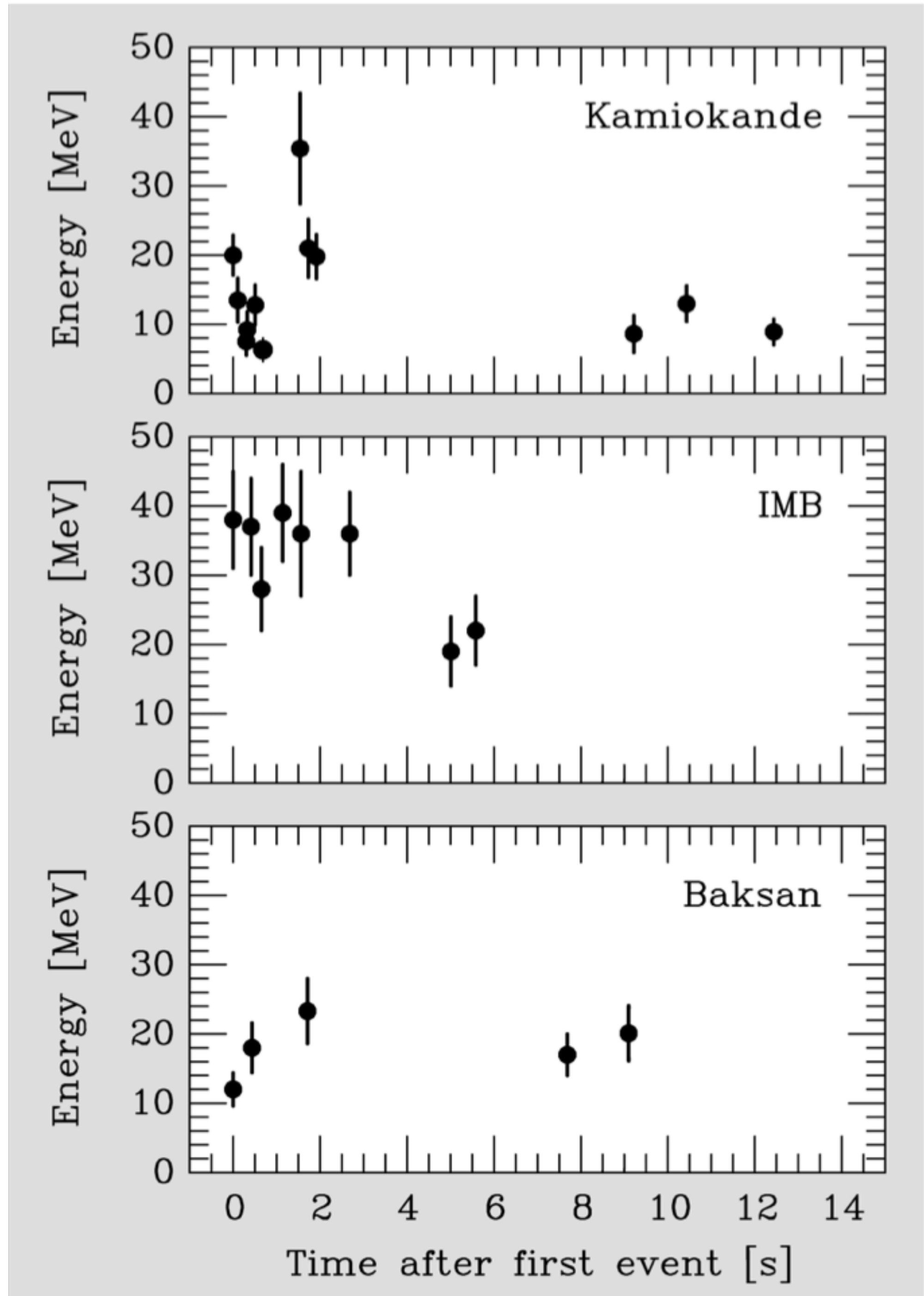
$$N + N \to N + N + \nu + \bar{\nu}$$

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

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

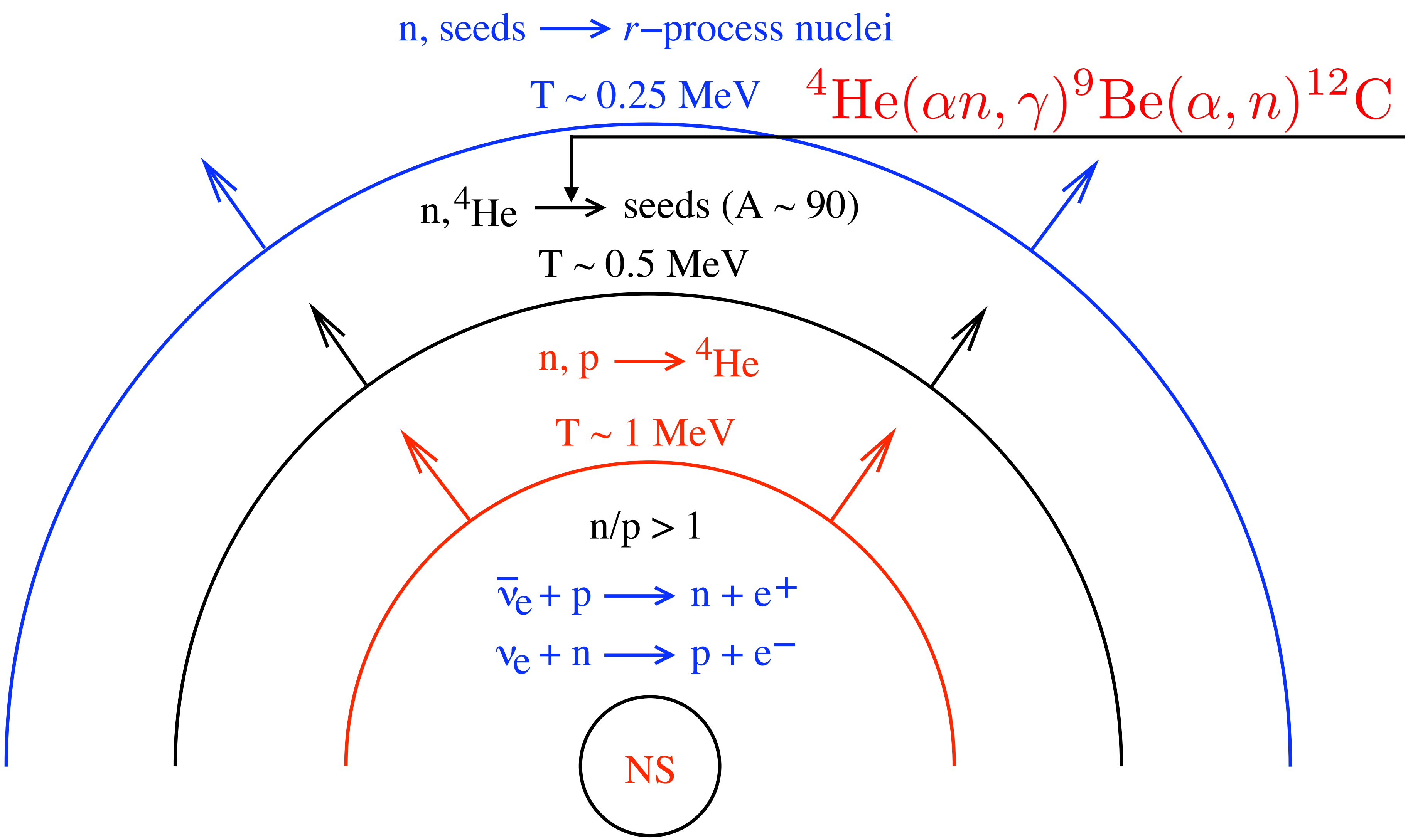
excess $\nu_e$ from $e^- + p \to n + \nu_e$

neutronization



*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

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

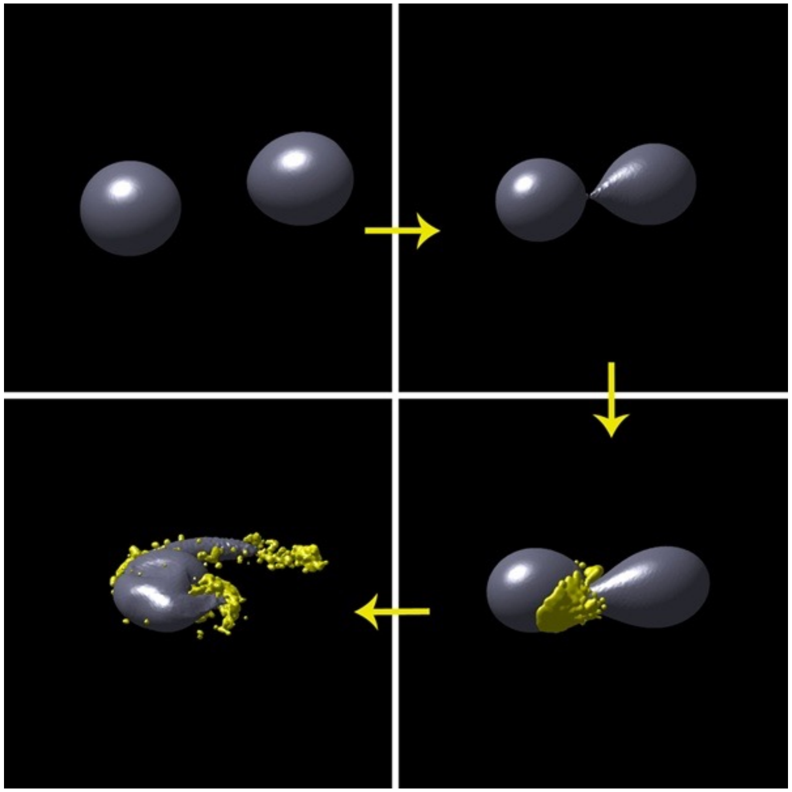
(Witti et al. 1994; Qian & Woosley 1996; Wanajo et al. 2001; Thompson et al. 2001; Fischer et al. 2010; Roberts et al. 2010)

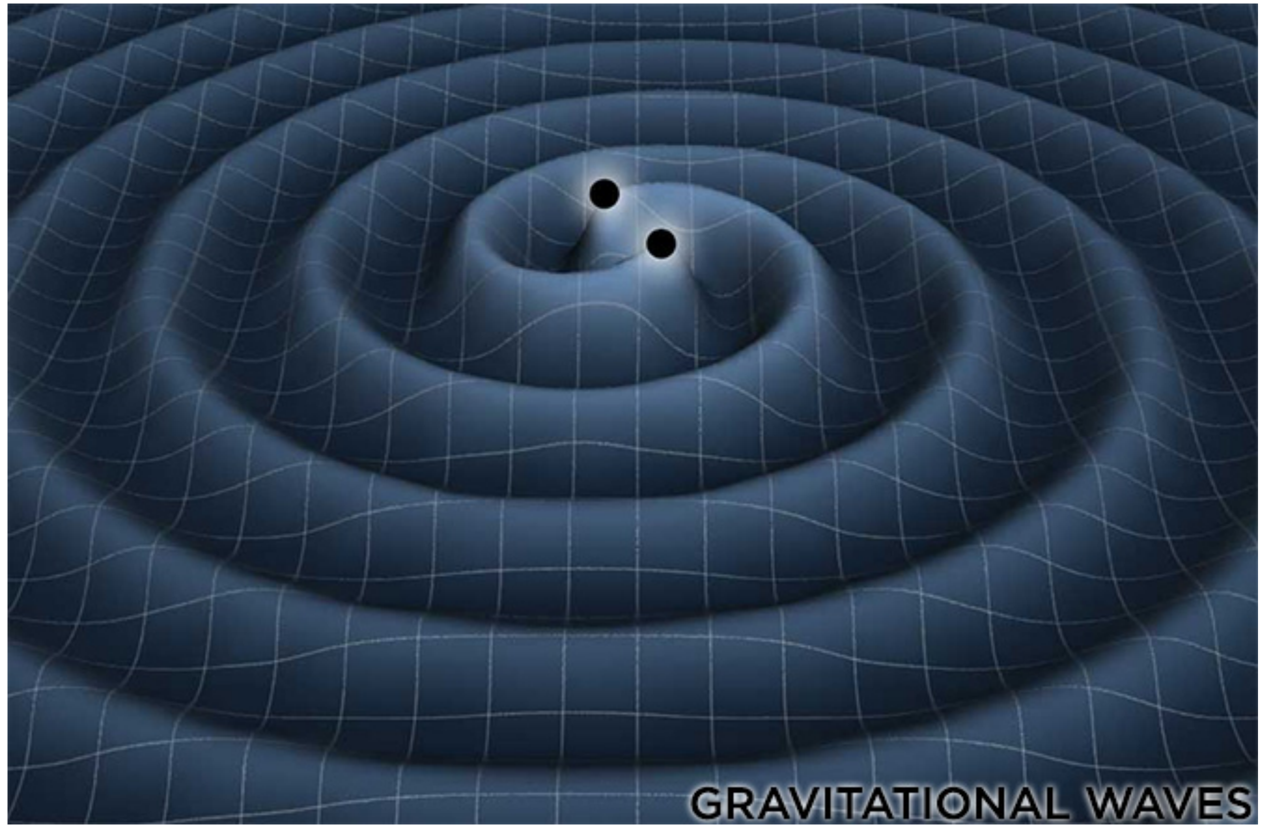
Sr, Y, Zr (A~90) readily produced in the ν-driven wind, up to Pd & Ag (A~110) likely, all by QSE

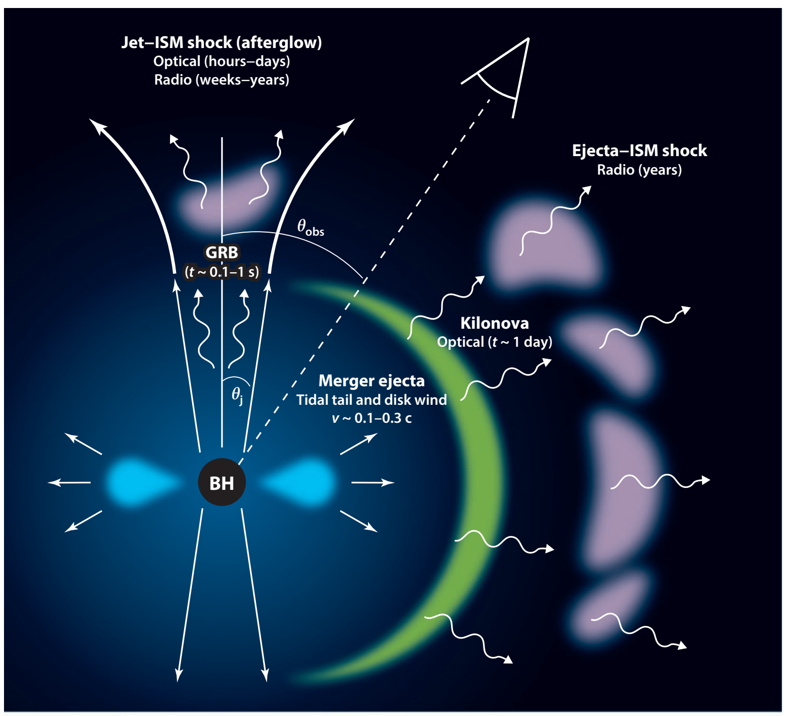
(Woosley & Hoffman 1992; Arcones & Montes 2011)

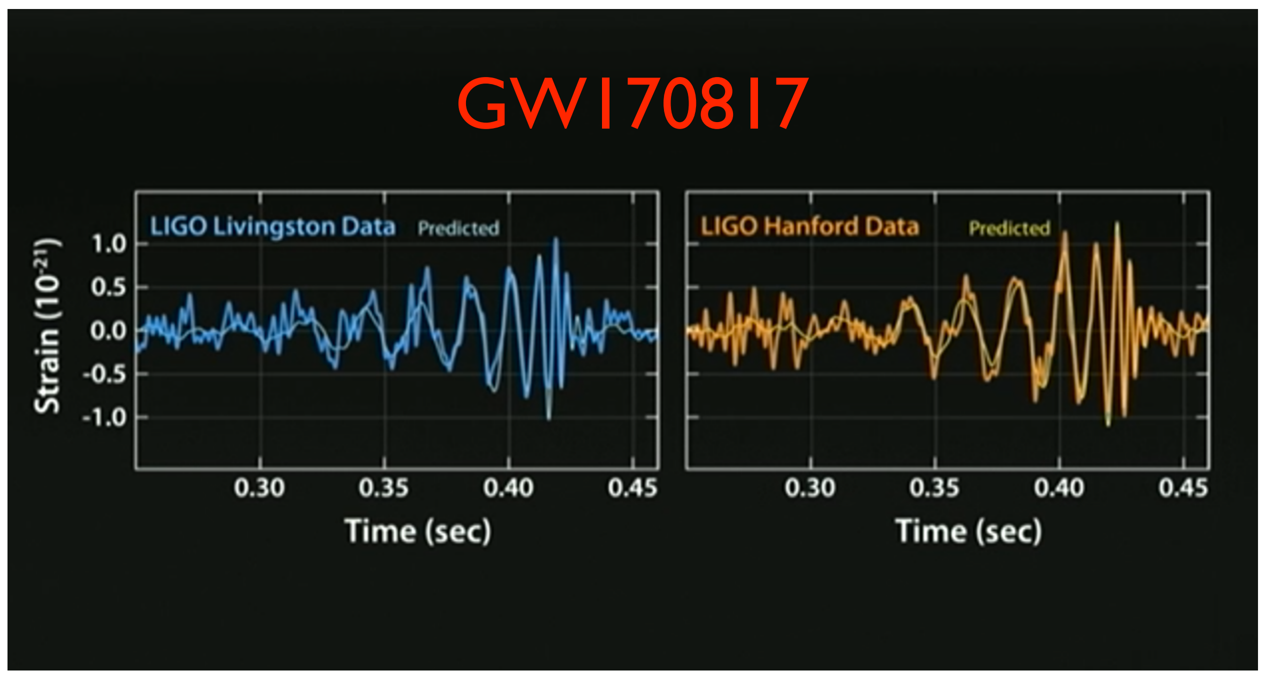
production of r-nuclei up to A~130 possible, but very hard to make A>130

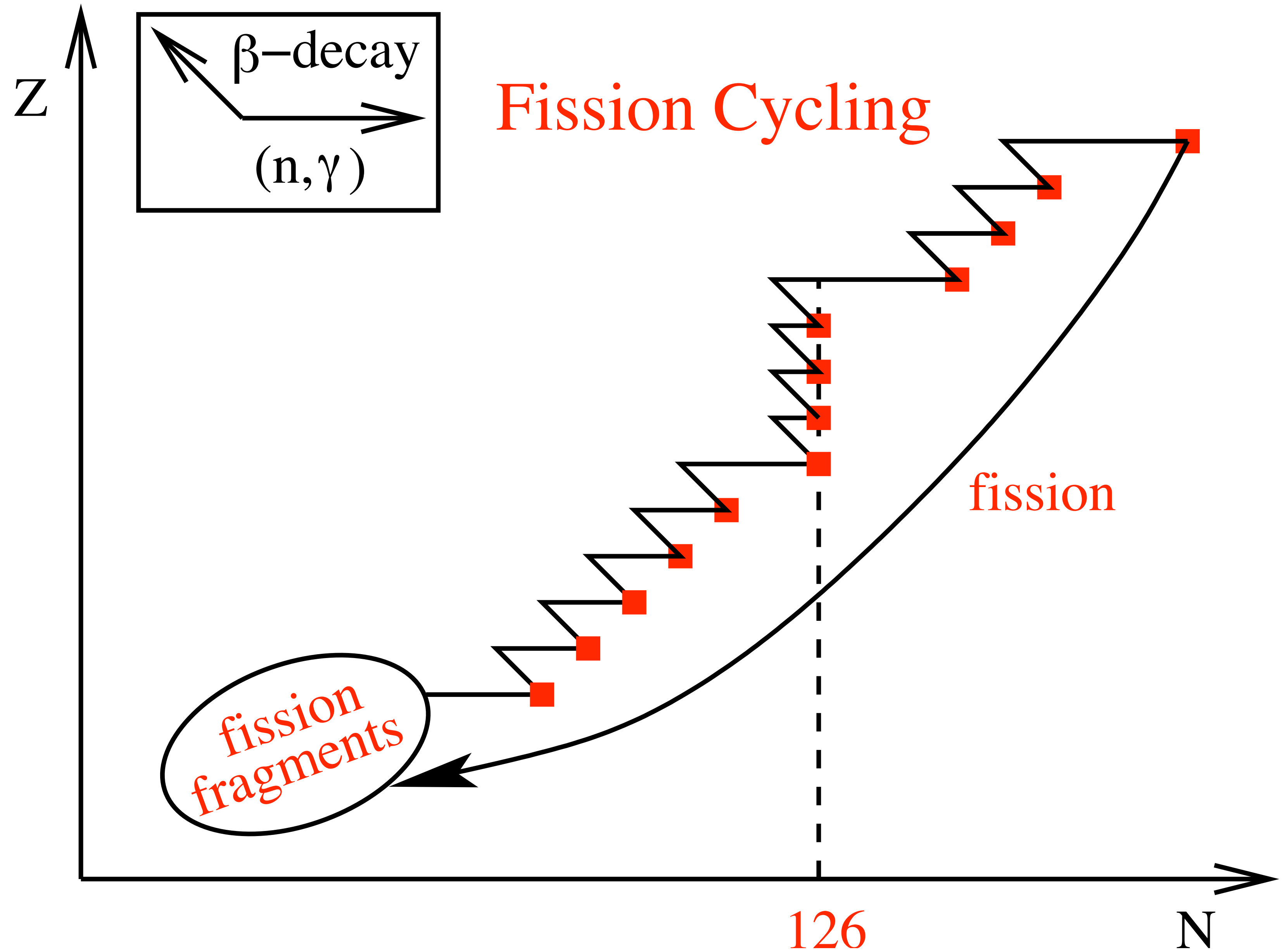
(Hoffman et al. 1997; Wanajo 2013)




GRAVITATIONAL WAVES

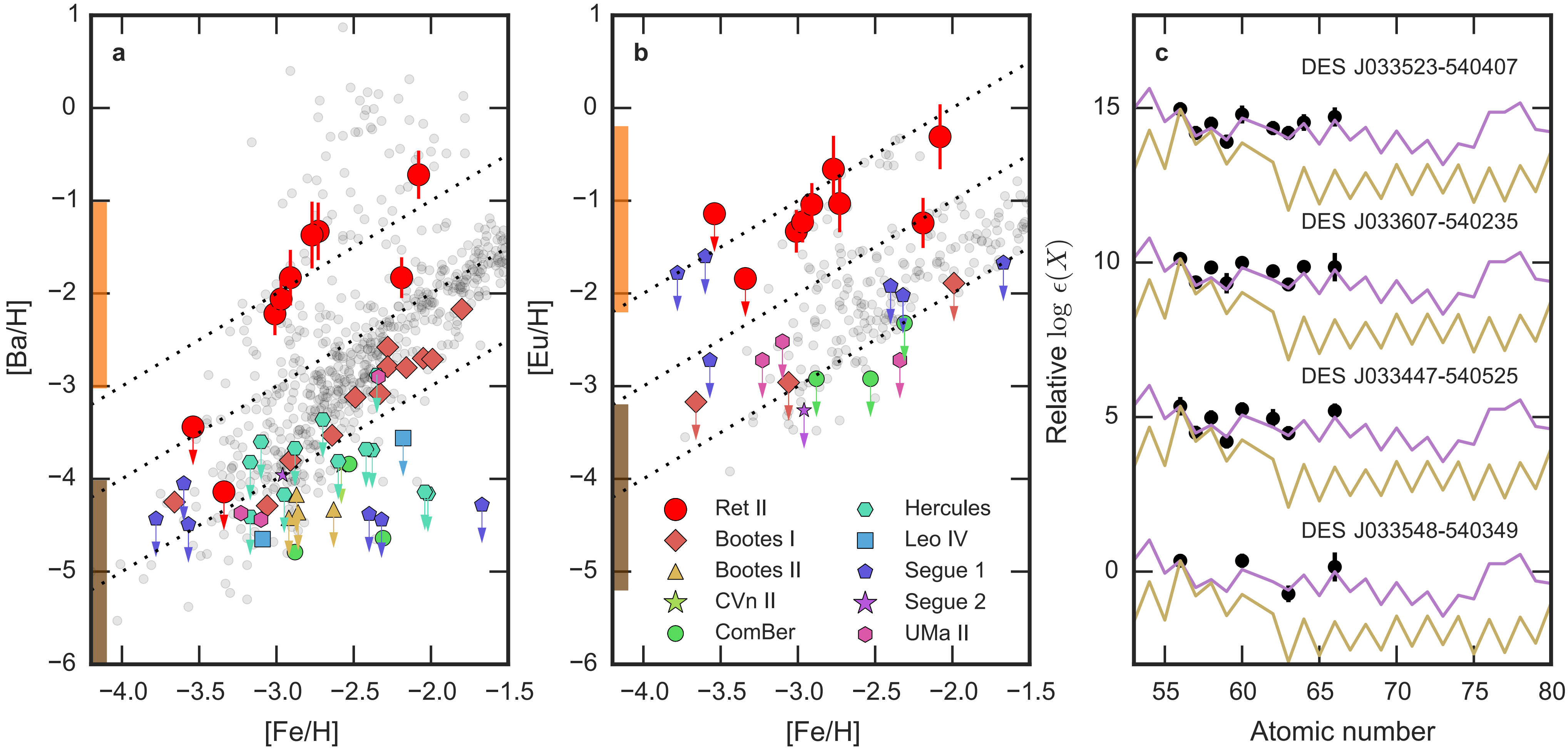

Jet–ISM shock (afterglow)
Optical (hours–days)
Radio (weeks–years)
Ejecta–ISM shock
Radio (years)
$\theta_{obs}$
GRB
($t \sim$ 0.1–1 s)
Kilonova
Optical ($t \sim$ 1 day)
$\theta_j$
Merger ejecta
Tidal tail and disk wind
$v \sim$ 0.1–0.3 c
BH

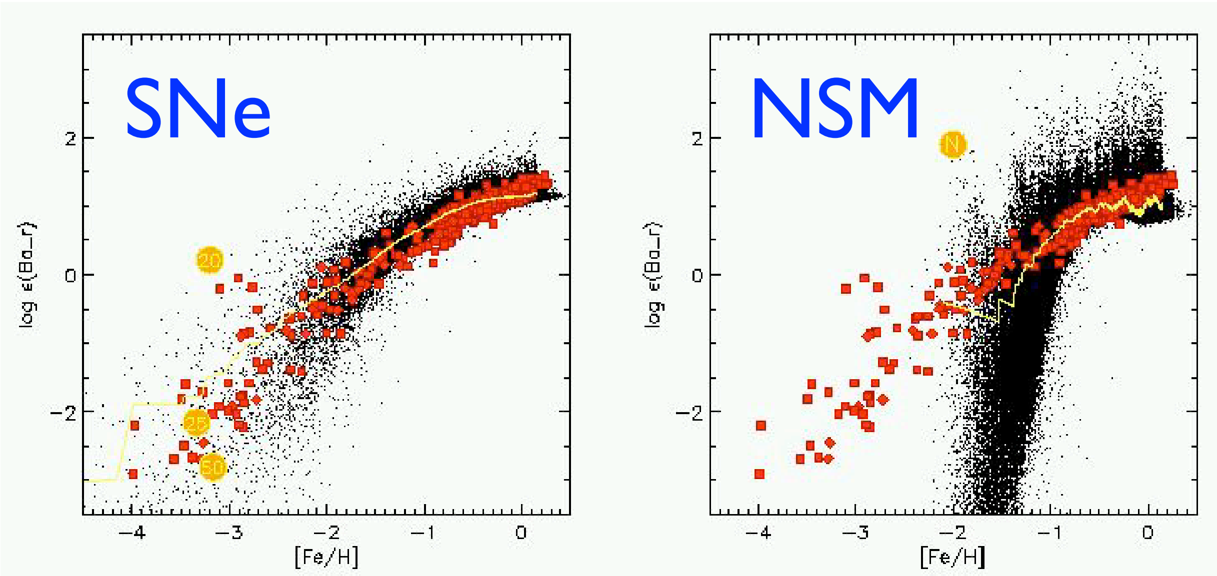

GW170817
LIGO Livingston Data
Predicted
LIGO Hanford Data
Predicted
Strain ($10^{-21}$)
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)
0.30
0.35
0.40
0.45
Time (sec)


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

# r-Process Enrichment of Reticulum II Dwarf Galaxy

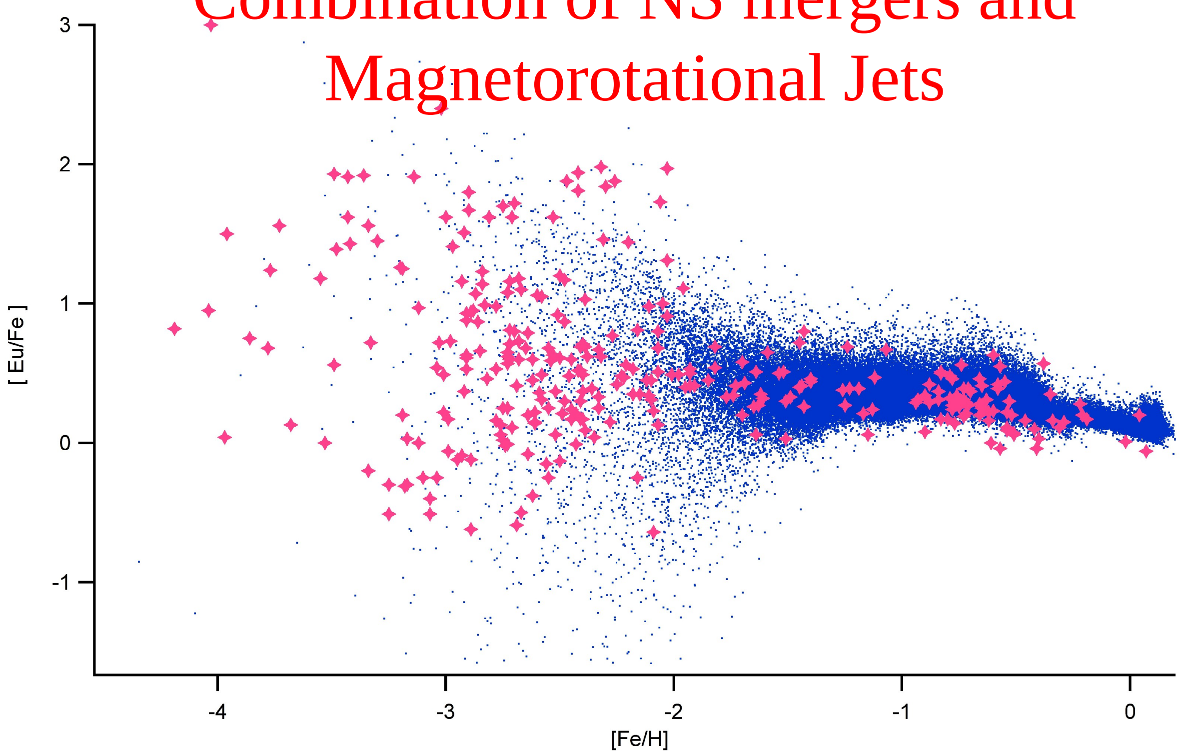
## Ji et al. 2016






# Chemical Evolution in the Early Galaxy

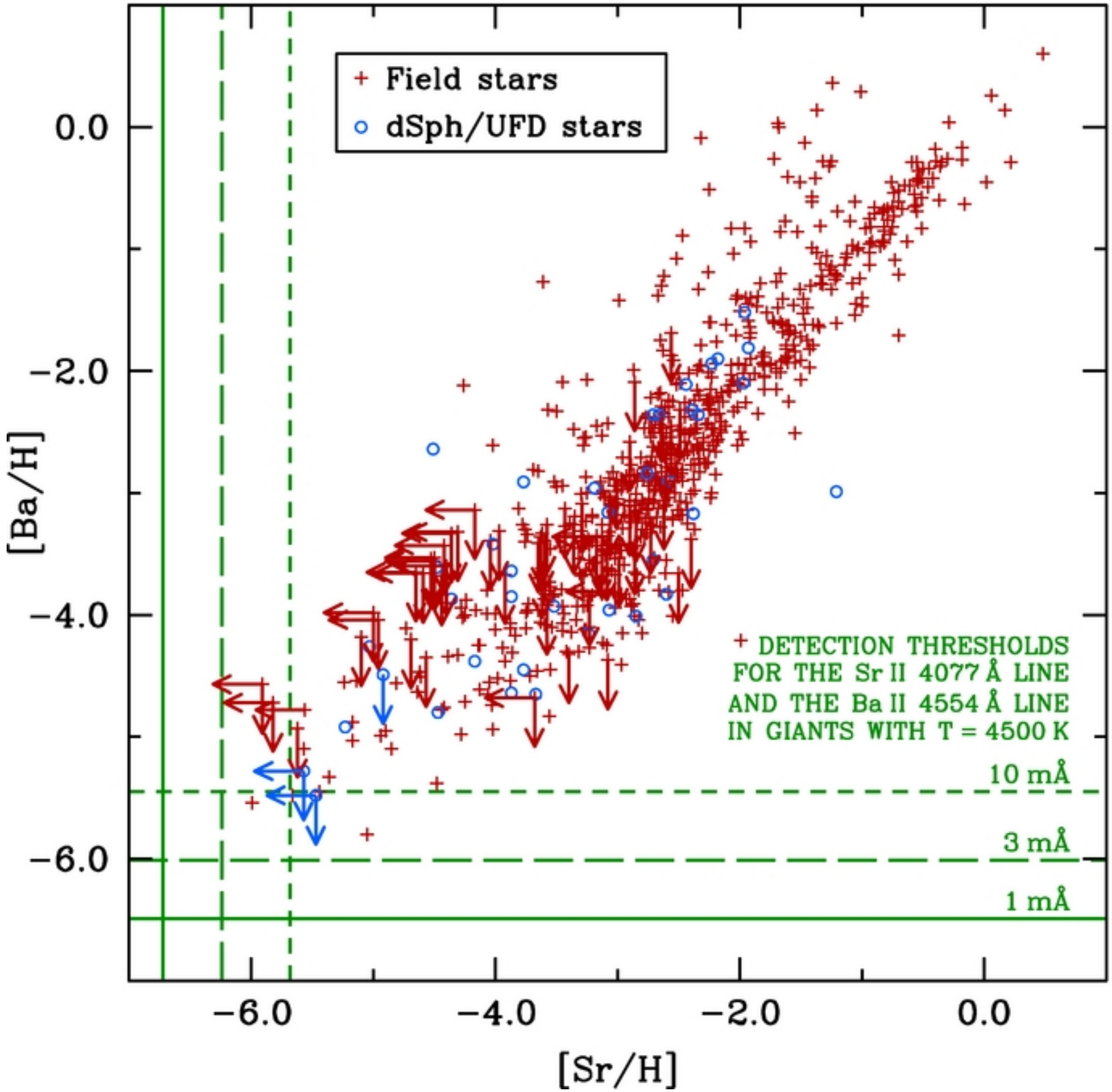
Argast + 2004
(also Qian 2000)



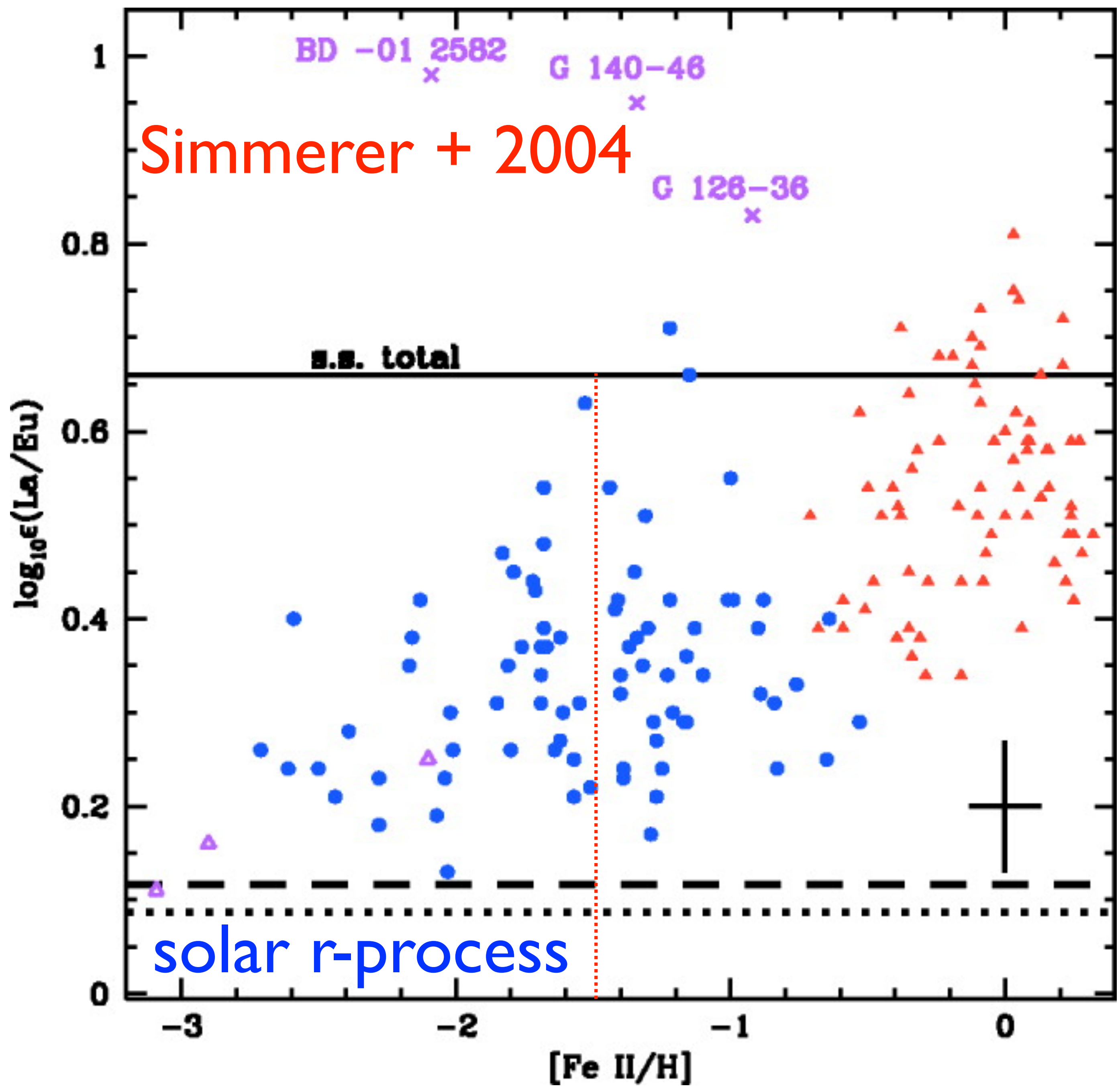

Wehmeyer et al. (2014)

but see
De Donder & Vanbeveren 2004;
Matteucci + 2014;
Tsujimoto & Shigeyama 2014;
Shen + 2014;
Ishimaru + 2015

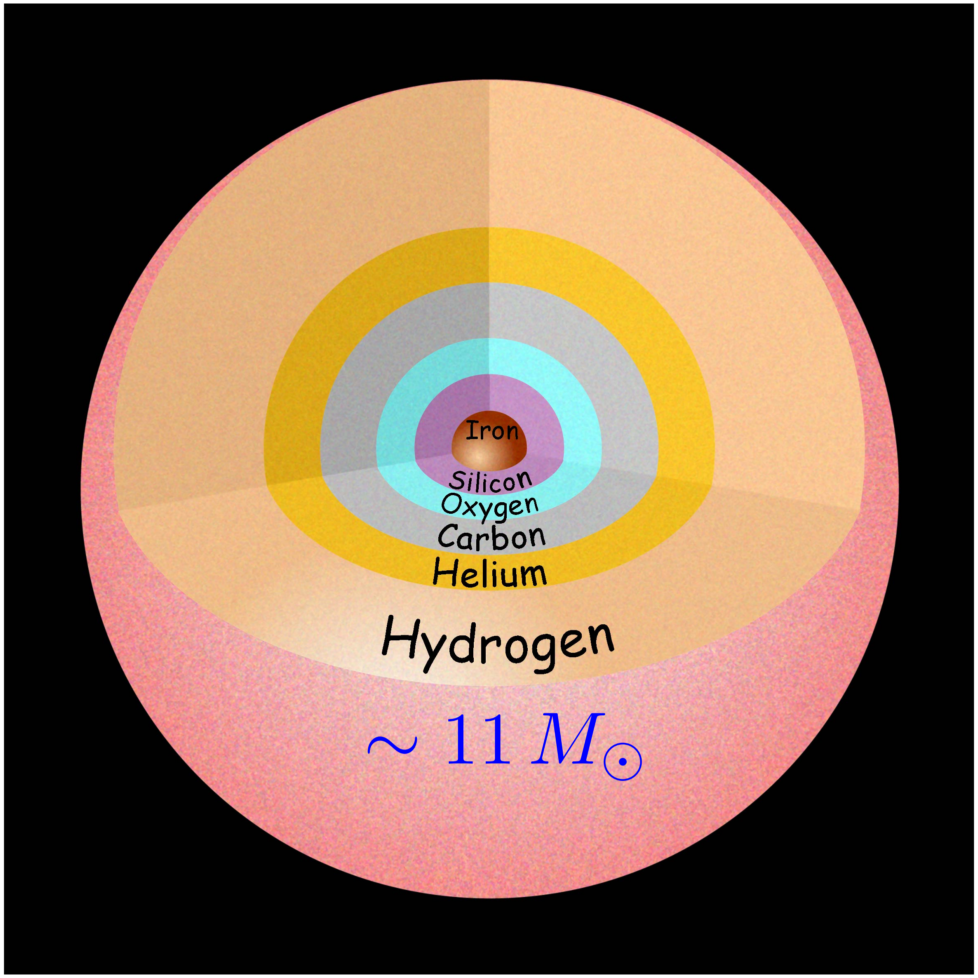
# Ubiquity of Sr and Ba (Roederer 2013)



# Diversity of La/Eu: more than one n-capture process



# Neutrino-Induced n Capture 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

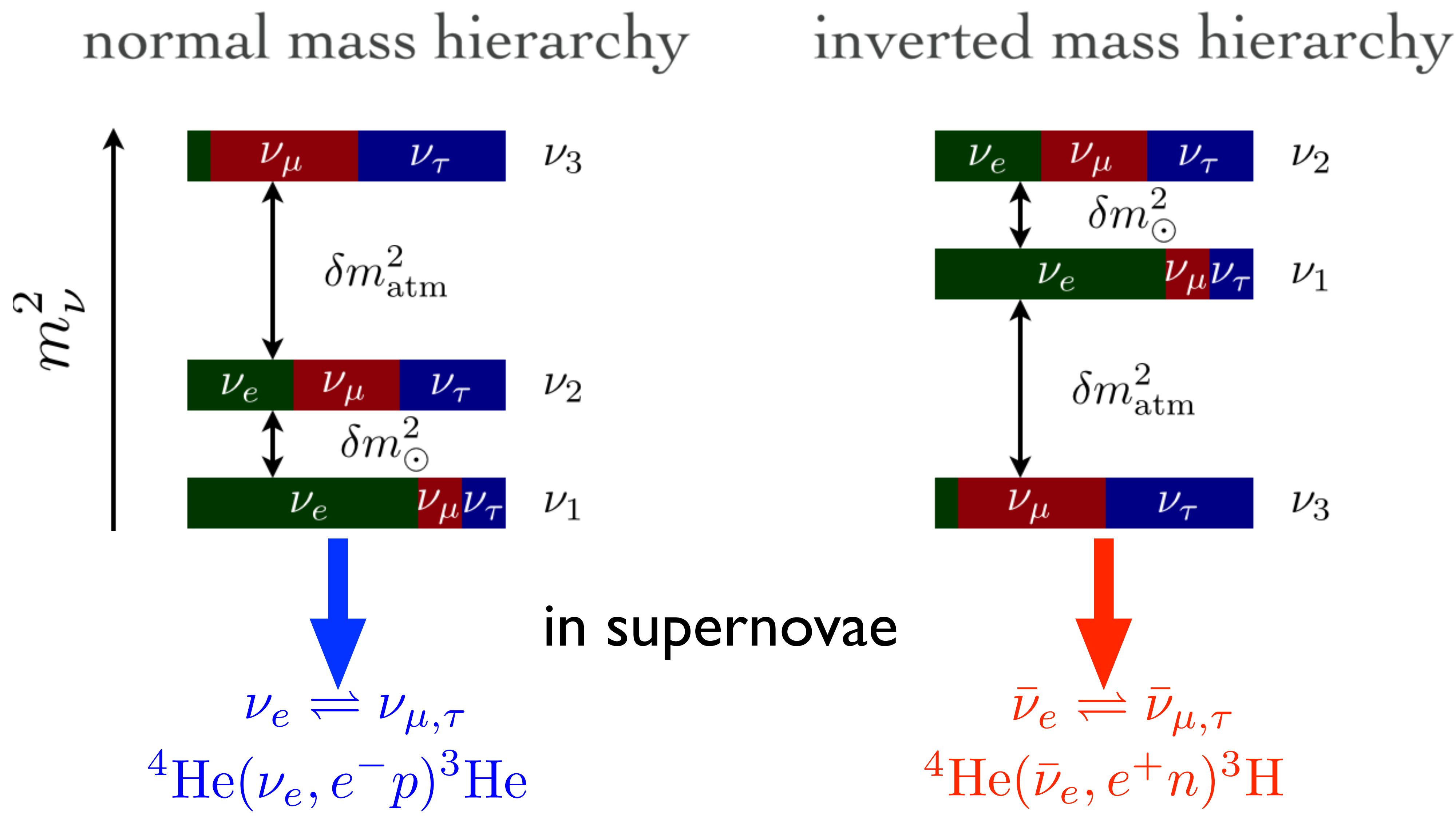
→ early SNe

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

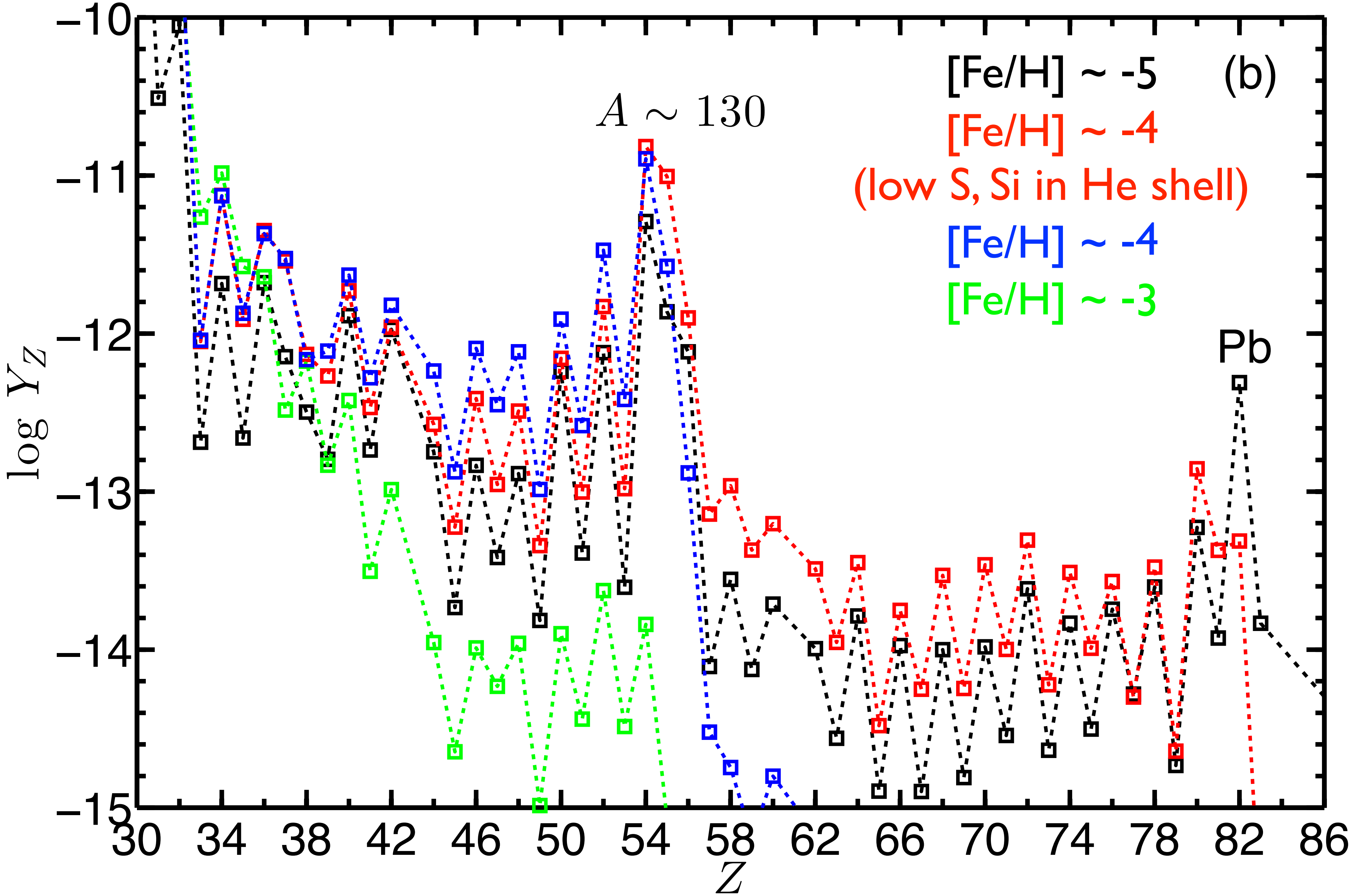
Banerjee, Haxton, & Qian 2011

# Neutrino Spectra & Flavor Oscillations

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

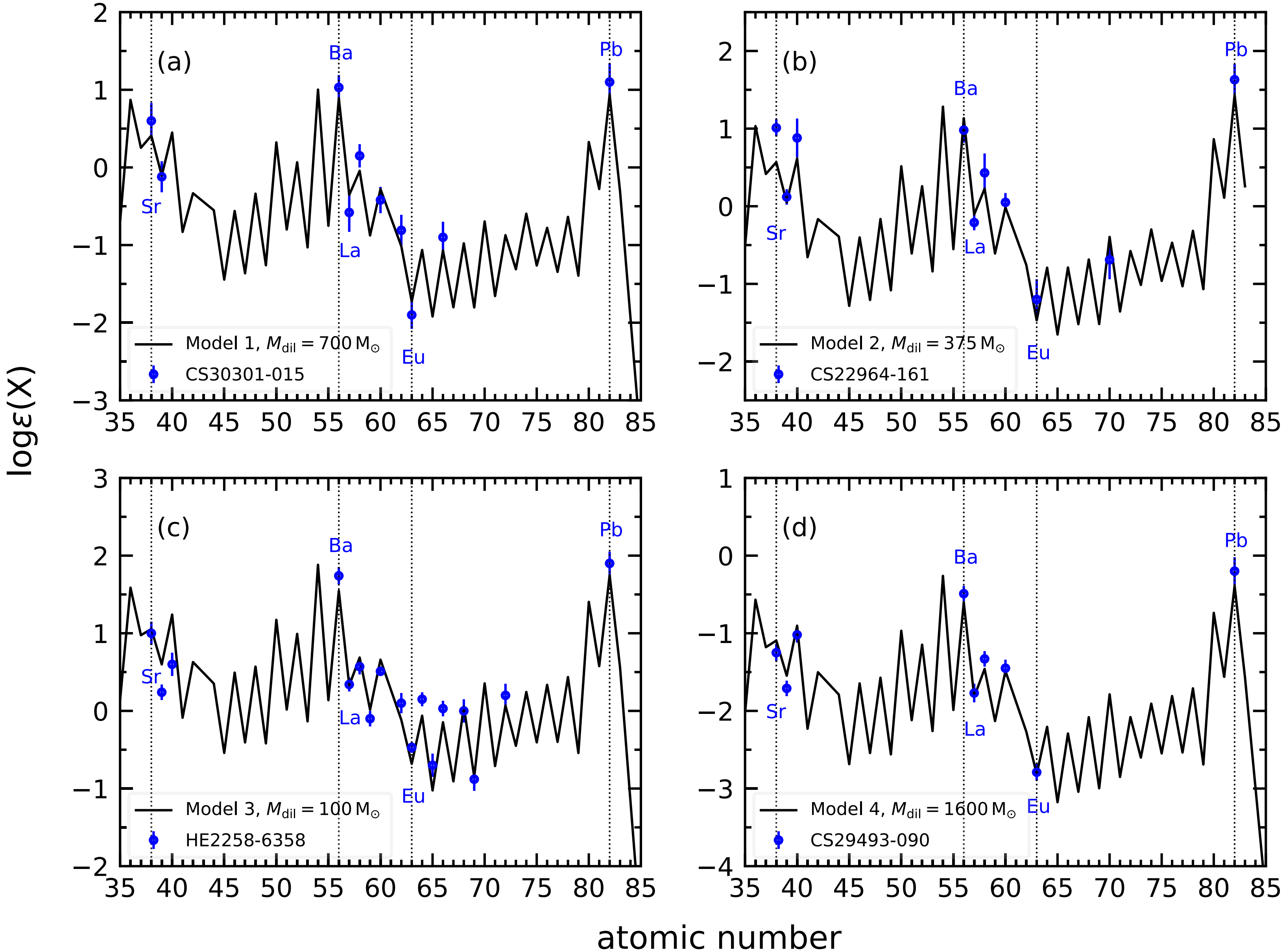


# Banerjee, Qian, Heger, & Haxton 2016



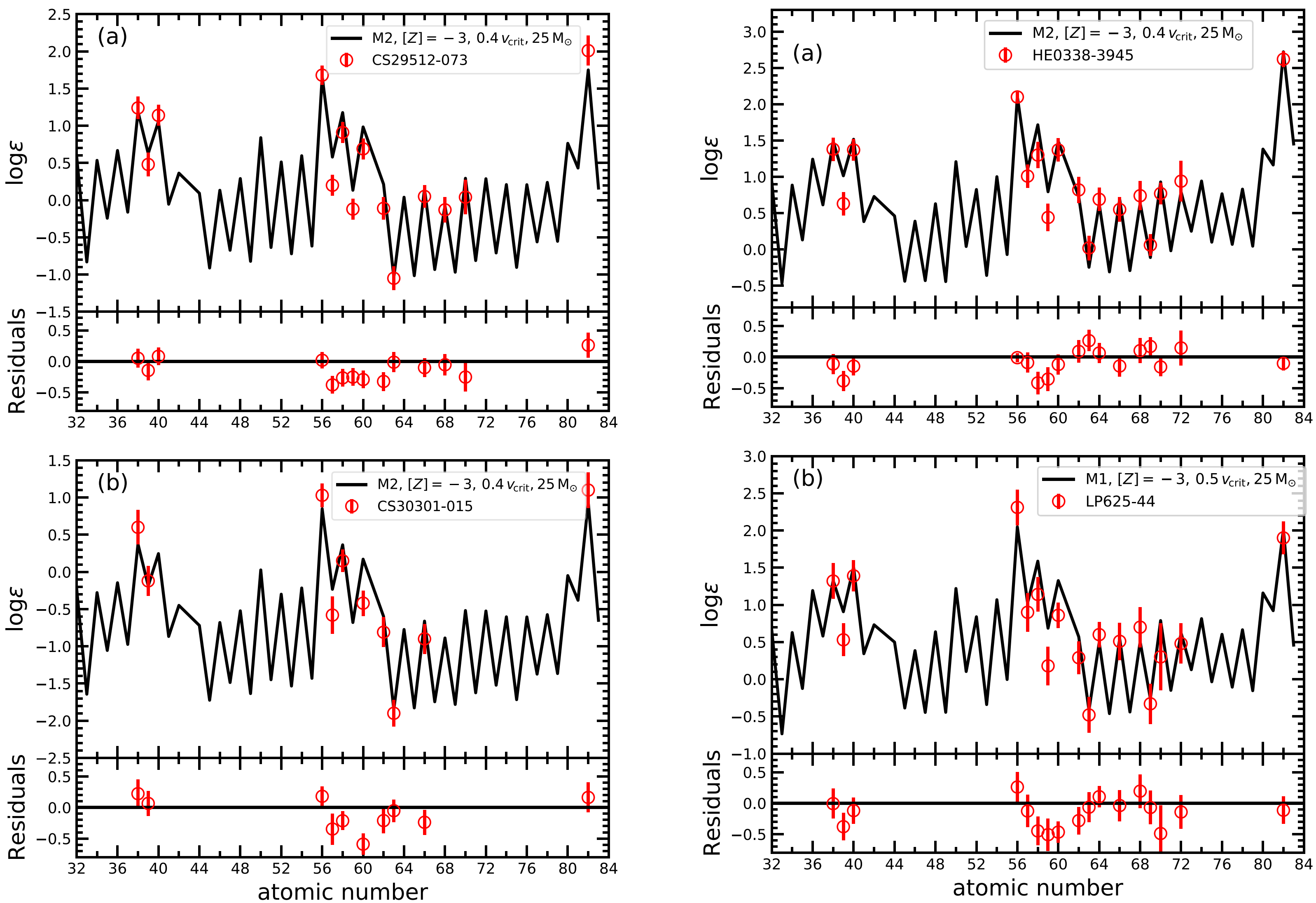
# New Neutron-Capture Site in Massive Pop III and Pop II Stars as a Source for Heavy Elements in the Early Galaxy

Banerjee, Qian, & Heger 2018



# New s-Process Mechanism in Rapidly Rotating Massive Population II Stars

## Banerjee, Heger, & Qian 2019



# Summary

1. Ubiquity of Sr & Ba at low [Fe/H]
unlikely explained by NS-NS or NS-BH mergers
due to their rare occurrences

2. Diversity of La/Eu at low metallicities
requires more than one n-capture process

3. n capture from p mixing during pre-supernova evolution
and the s-process in massive stars
can explain ubiquity of Sr & Ba + diversity of La/Eu at low [Fe/H]

4. Neutrino-induced n capture in supernovae
may also contribute heavy elements at low [Fe/H]