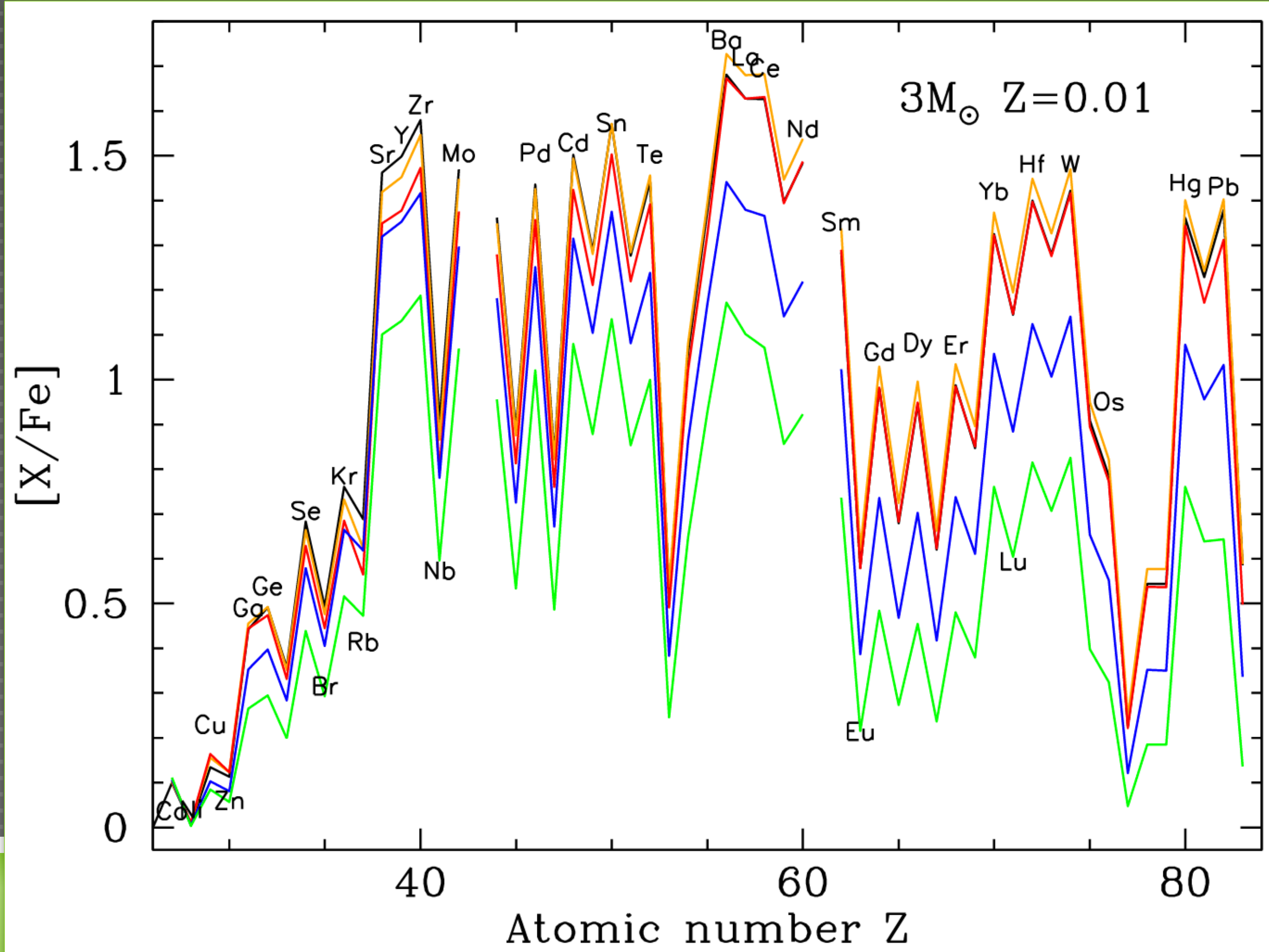
S PROCESS NUCLEOSYNTHESIS



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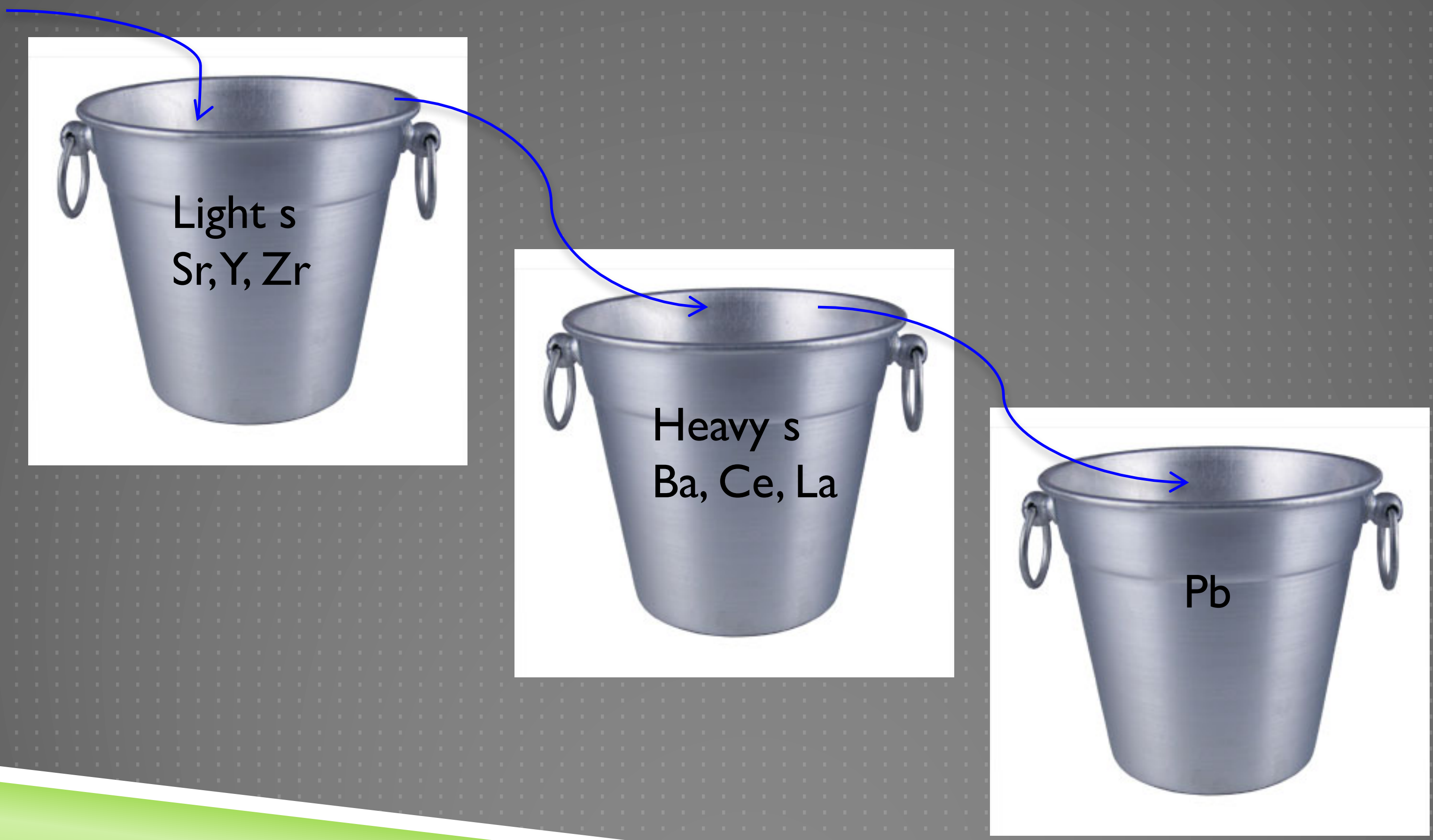
OVERVIEW

- S process basics
- Neutron sources
- Application to carbon-enhanced metal-poor stars
- Beyond the s process

s-process nucleosynthesis

S-PROCESS NUCLEOSYNTHESIS

Neutron source: $^{13}C(a,n)^{16}O$ or $^{22}Ne(a,n)^{25}Mg$



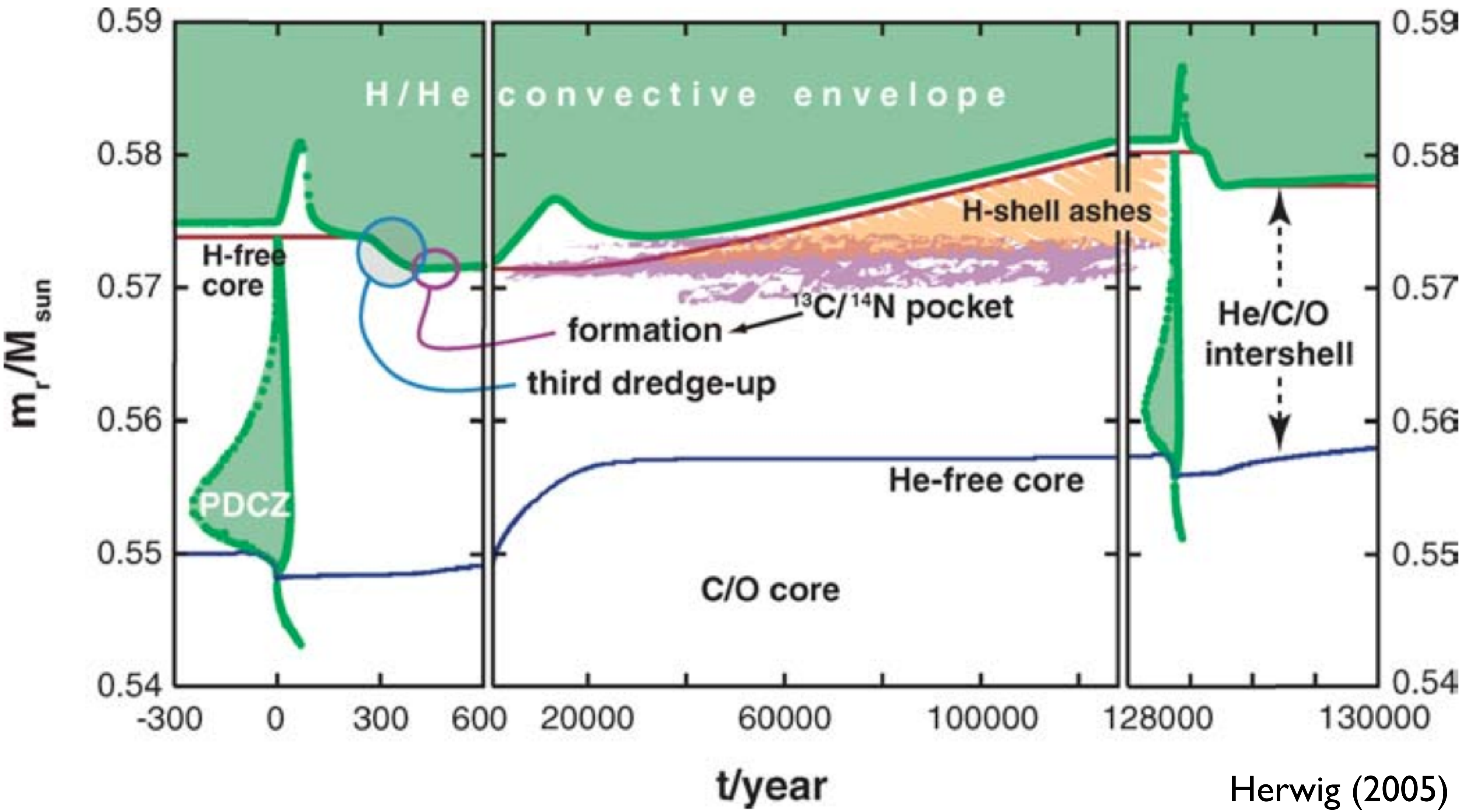
NEUTRON SOURCES FOR THE S-PROCESS

- There are two important neutron sources available during He-burning
- 1) $^{12}C(p,\gamma)^{13}N(\beta^{+}\nu)^{13}C(\alpha,n)^{16}O$
  - Requires the presence of both H and He in a He-burning region when normally there is no hydrogen
  - Requires mixing of protons into He-burning region
  - Occurs at T ~ 100 x 10^6 K, so in between thermal pulses, and under radiative conditions (t ~ 10^4 years)
  - Dominant neutron source in low-mass AGB stars (1 to 3Msun stars)
  - He-shell flashes imply many exposures to neutron source, produces heavy s-process elements A > 80

NEUTRON SOURCES: ^{22}NE SOURCE

- 2) $^{14}N(\alpha,\gamma)^{18}F\ (\beta^{+}\nu)^{18}O(\alpha,\gamma)^{22}Ne(\alpha,n)^{25}Mg$
  - Plenty of ^{14}N left over from CNO cycling to produce the ^{22}Ne
  - Occurs during thermal pulses when the temperature exceeds about 300 x 10^6 K, under convective conditions
  - These temperatures are not reached in the He-shells of low-mass AGB stars, except perhaps in the last few TPs
  - So only in:
  - a) the cores of massive stars ($M > 12\ M_{sun}$)
  - b) massive AGB stars (~3 to 8Msun) during He-shell flashes

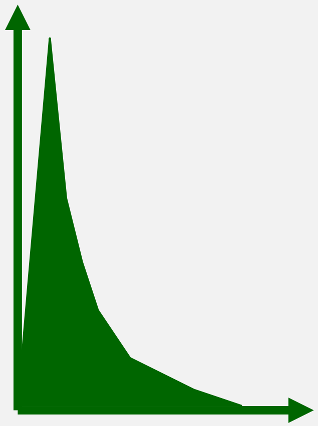
WHERE DOES IT HAPPEN?



Herwig (2005)

THEORETICAL MODELS

Typical neutron density profile in time:

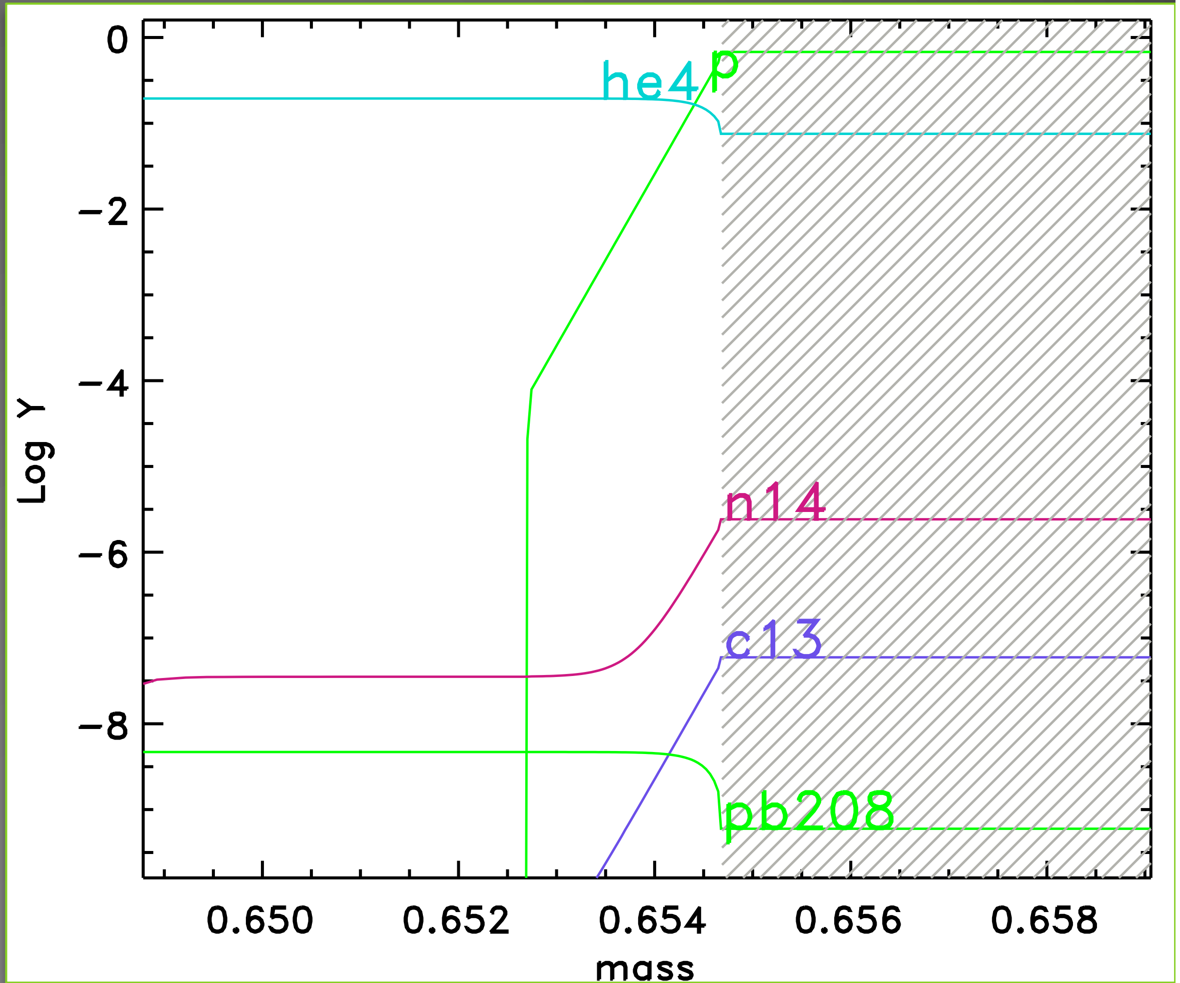


	Low mass	Intermediate mass
Neutron source	$^{13}C(a,n)^{16}O$	$^{22}Ne(a,n)^{25}Mg$
Maximum neutron density	10^{8} n/cm^{3}	10^{13} n/cm^{3}
Timescale	10,000 yr	10 yr
Neutron exposure	0.3 mbarn^{-1}	0.02 mbarn^{-1}

(at solar metallicity)

ADDING A ^{13}C POCKET

- We don't know how to make a ^{13}C pocket.
- Some non-convective mixing mechanism?
  - Convective overshooting (Herwig 2000)
  - Rotation (Langer et al. 1999)
  - Gravity waves (Denissenkov & Tout 2003)
  - Magnetic fields (Trippella et al. 2016)
- Or just add it in by hand



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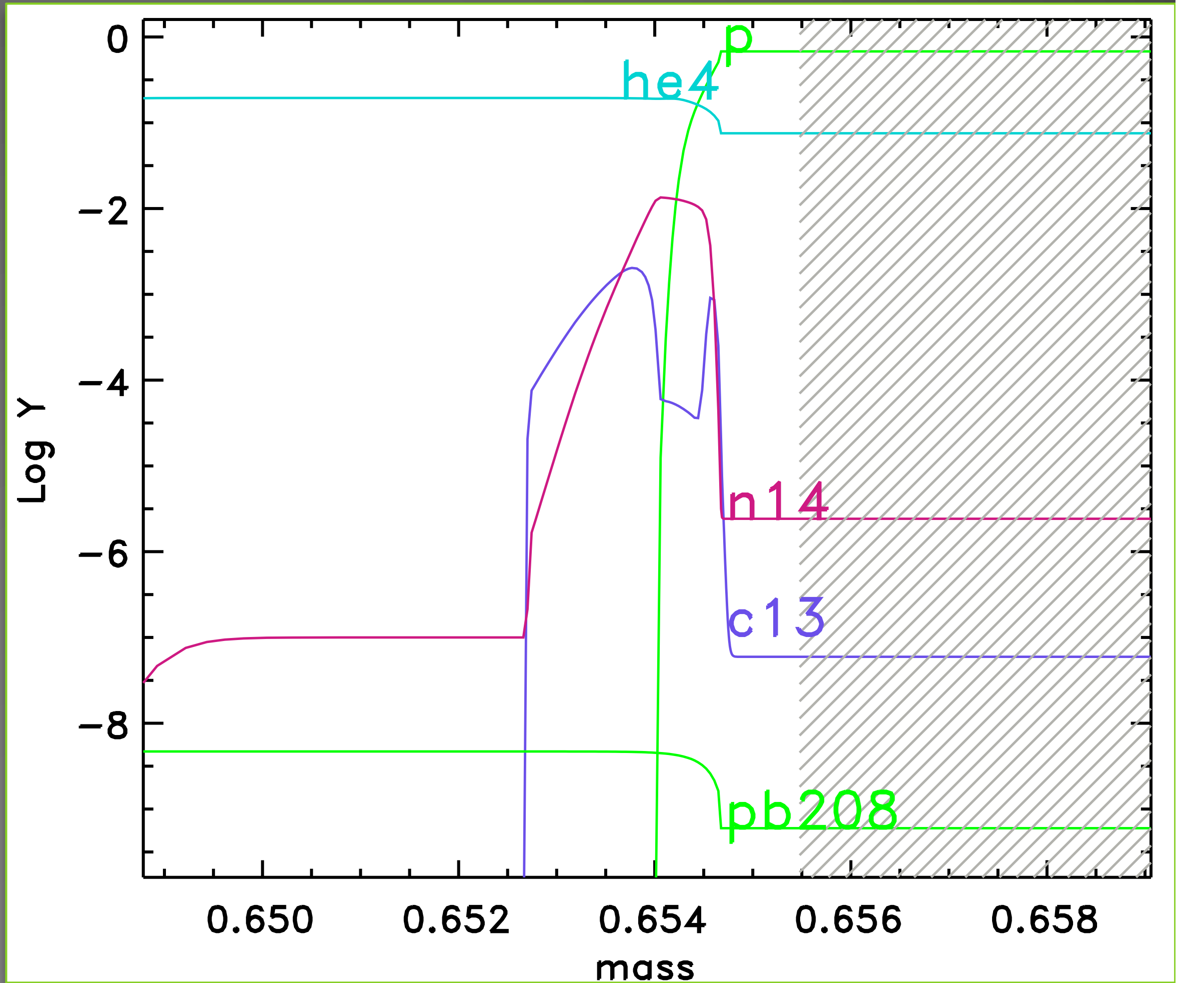
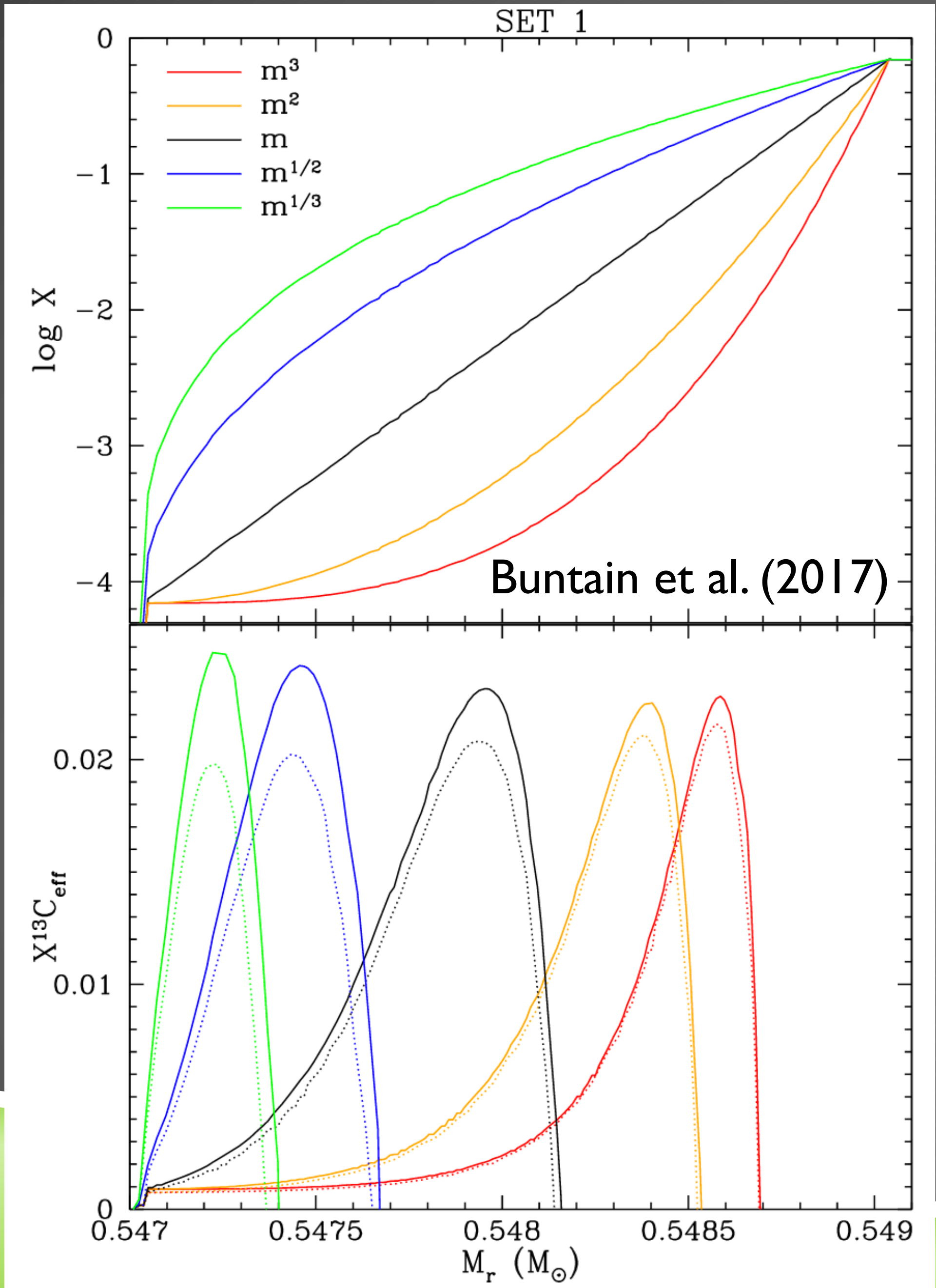
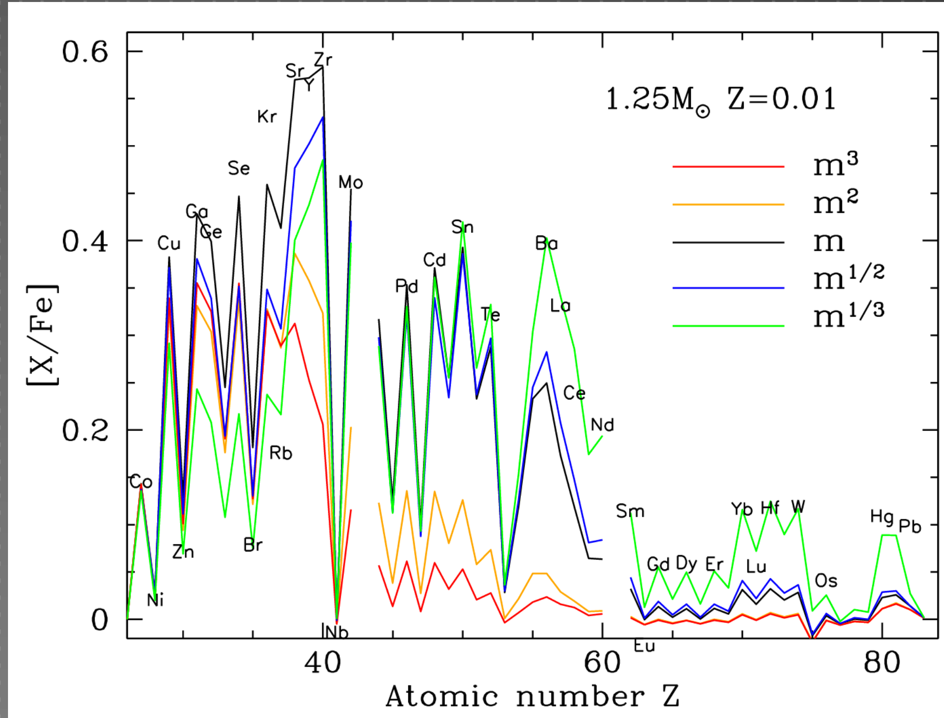
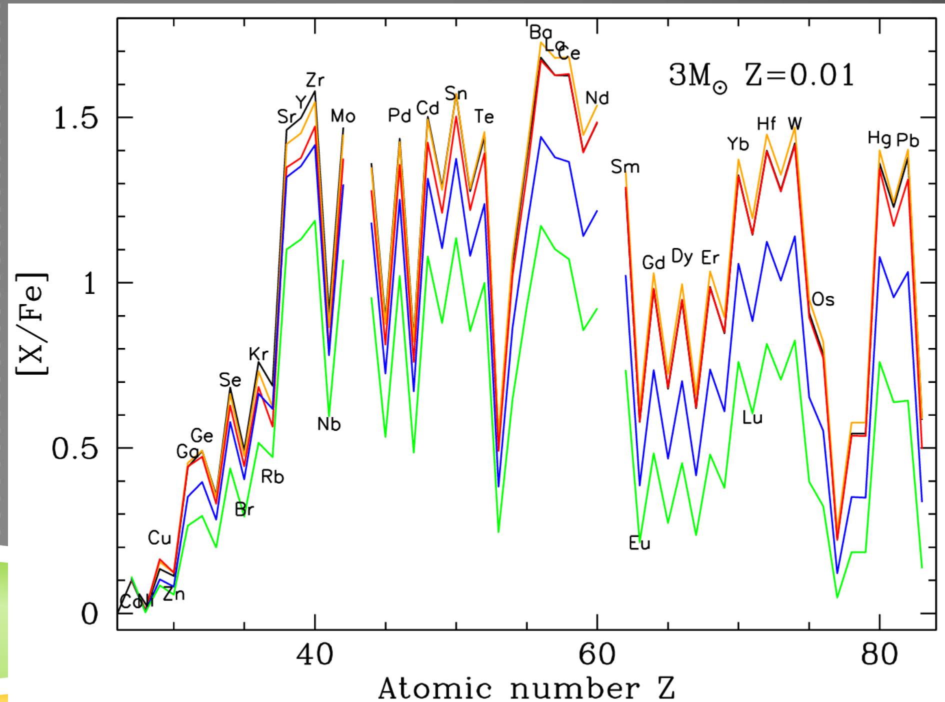
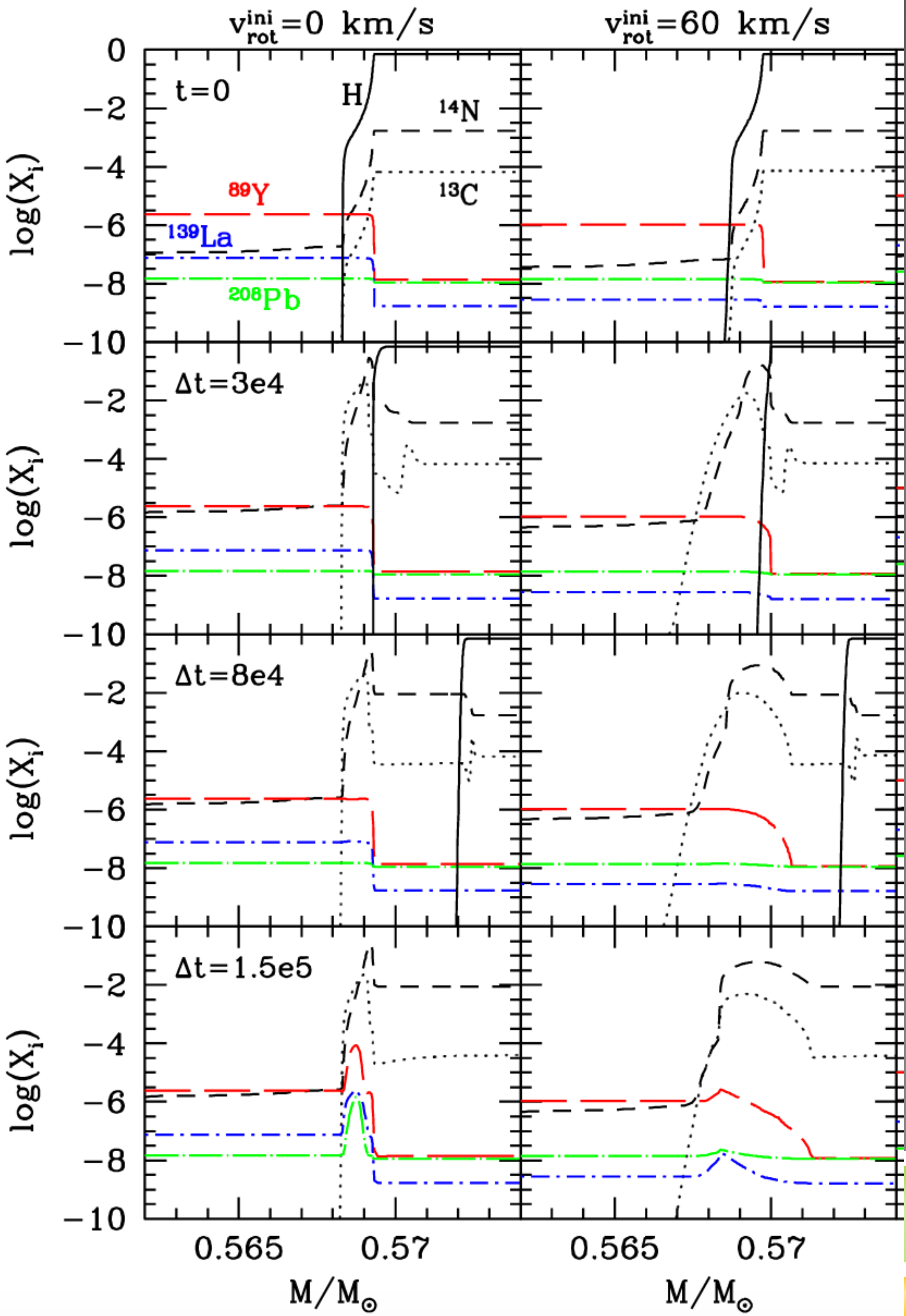


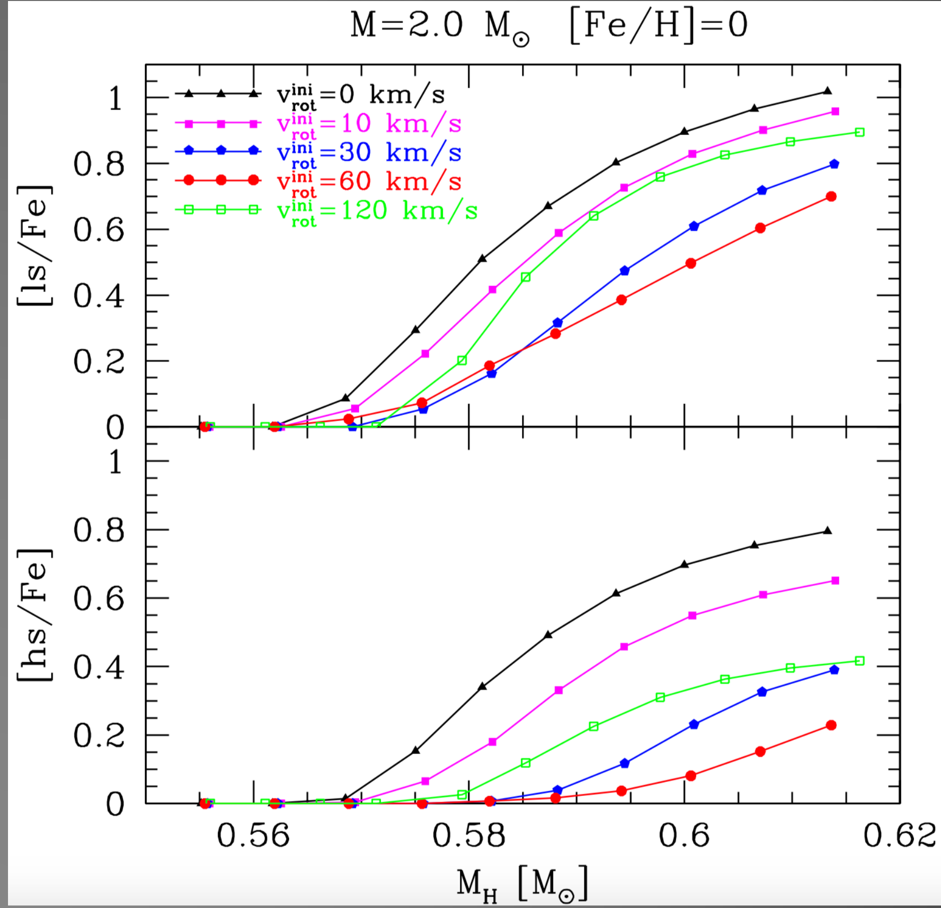

SET 1
m³
m²
m
m^1/2
m^1/3
log X
Buntain et al. (2017)
X13Ceff
Mr (M⊙)


1.25M⊙ Z=0.01
m³
m²
m
m^1/2
m^1/3
[X/Fe]
Atomic number Z


3M⊙ Z=0.01
[X/Fe]
Atomic number Z

Rotation and the ^{13}C pocket





Piersanti et al., 2013

REACTION RATE UNCERTAINTIES

^{13}C pocket

Strongest globally affecting reactions during the ^{13}C-pocket, sorted by their impact. The impact is given by the number of affected isotopes with a sensitivity over the threshold of ±0.1.

Reaction	Type of effect	Affected isotopes
^{56}Fe(n, γ)	Competing capture	196
^{64}Ni(n, γ)	Competing capture	183
^{14}N(n, p)	Neutron poison	175
^{12}C(p, γ)	Neutron donator	158
^{13}C(p, γ)	Neutron poison	150
^{16}O(n, γ)	Neutron poison	145
^{22}Ne(n, γ)	Neutron poison	144
^{88}Sr(n, γ)	Competing capture	131
^{13}C(α, n)	Neutron donator	114
^{58}Fe(n, γ)	Competing capture	112
^{14}C(α, γ)	Neutron poison	102
^{14}C(β^-)	Neutron poison	95
^{138}Ba(n, γ)	Competing capture	95
^{140}Ce(n, γ)	Competing capture	93
^{139}La(n, γ)	Competing capture	92
^{142}Nd(n, γ)	Competing capture	87

Koloczek et al. (2016)

^{22}Ne source

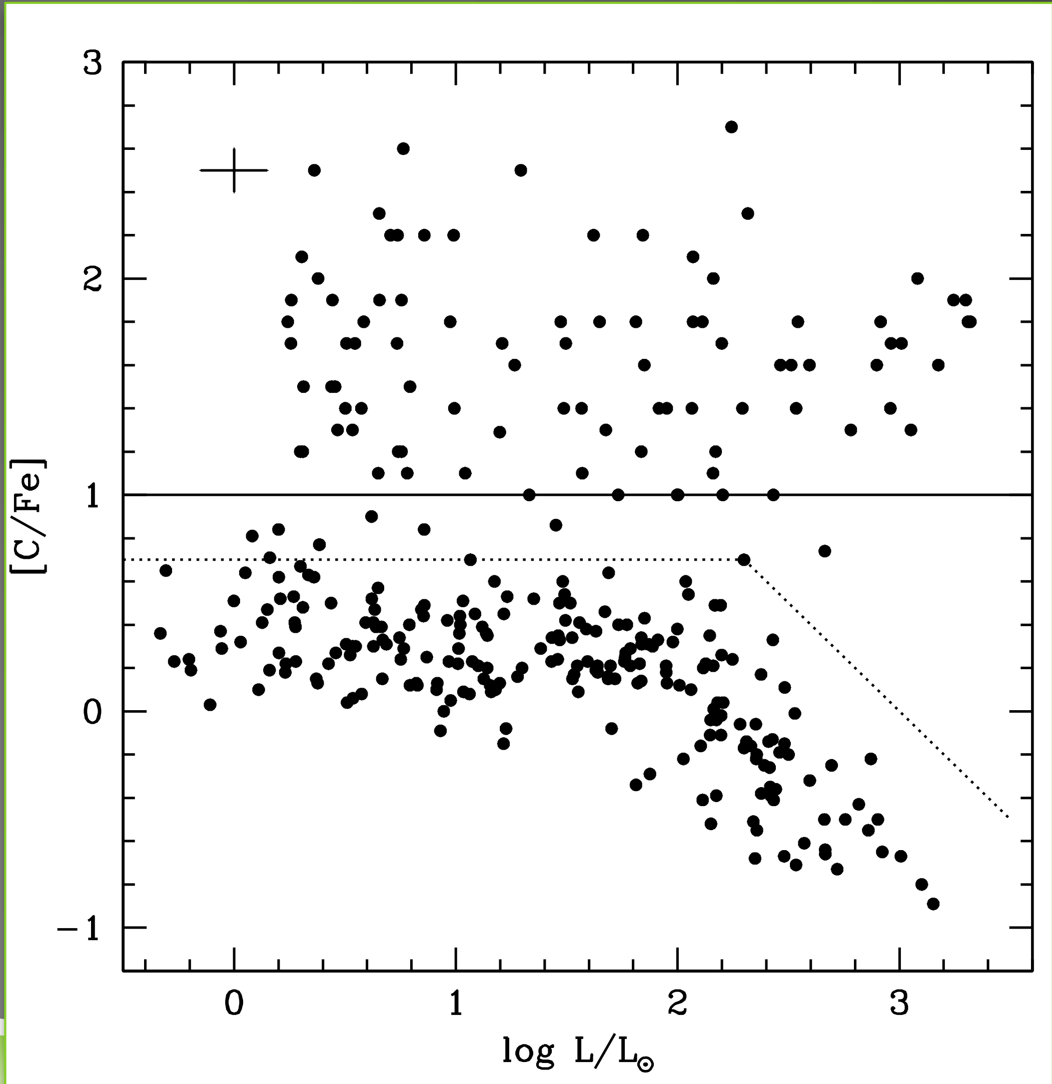
Strongest globally affecting reactions during the TP, sorted by their impact. Only few rates have a global influence, because the TP has a short life-span and is convective. Cumulative effects will therefore not account under these conditions. The impact is given by the number of affected isotopes with a sensitivity over the threshold of ±0.1.

Reaction	Type of effect	Affected isotopes
^{22}Ne(α, n)	Neutron donator	191
^{25}Mg(n, γ)	Neutron poison	67
^{142}Nd(n, γ)	Competing capture	41
^{144}Nd(n, γ)	Competing capture	41
^{56}Fe(n, γ)	Competing capture	38
^{140}Ce(n, γ)	Competing capture	33
^{146}Nd(n, γ)	Competing capture	29
^{22}Ne(n, γ)	Neutron poison	25
^{94}Zr(n, γ)	Competing capture	24
^{141}Pr(n, γ)	Competing capture	23
^{58}Fe(n, γ)	Competing capture	21

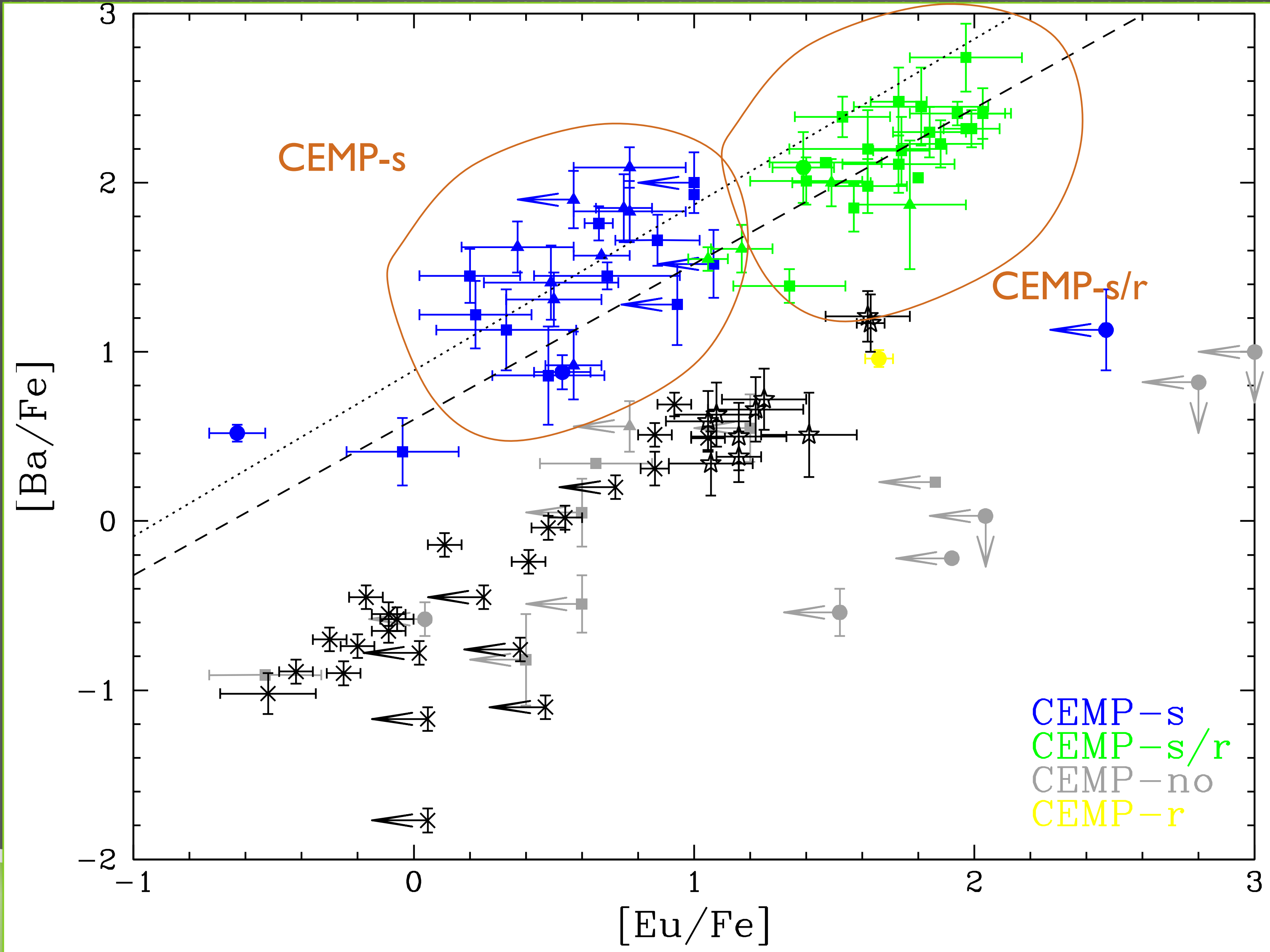
CARBON-ENHANCED STARS

Lucatello et al. (2006)

- A large fraction of metal-poor stars are carbon-rich
- Perhaps as many as 20%
- Some show enrichments of heavy elements, particularly of s-process elements
- Many of these also show radial velocity variations…

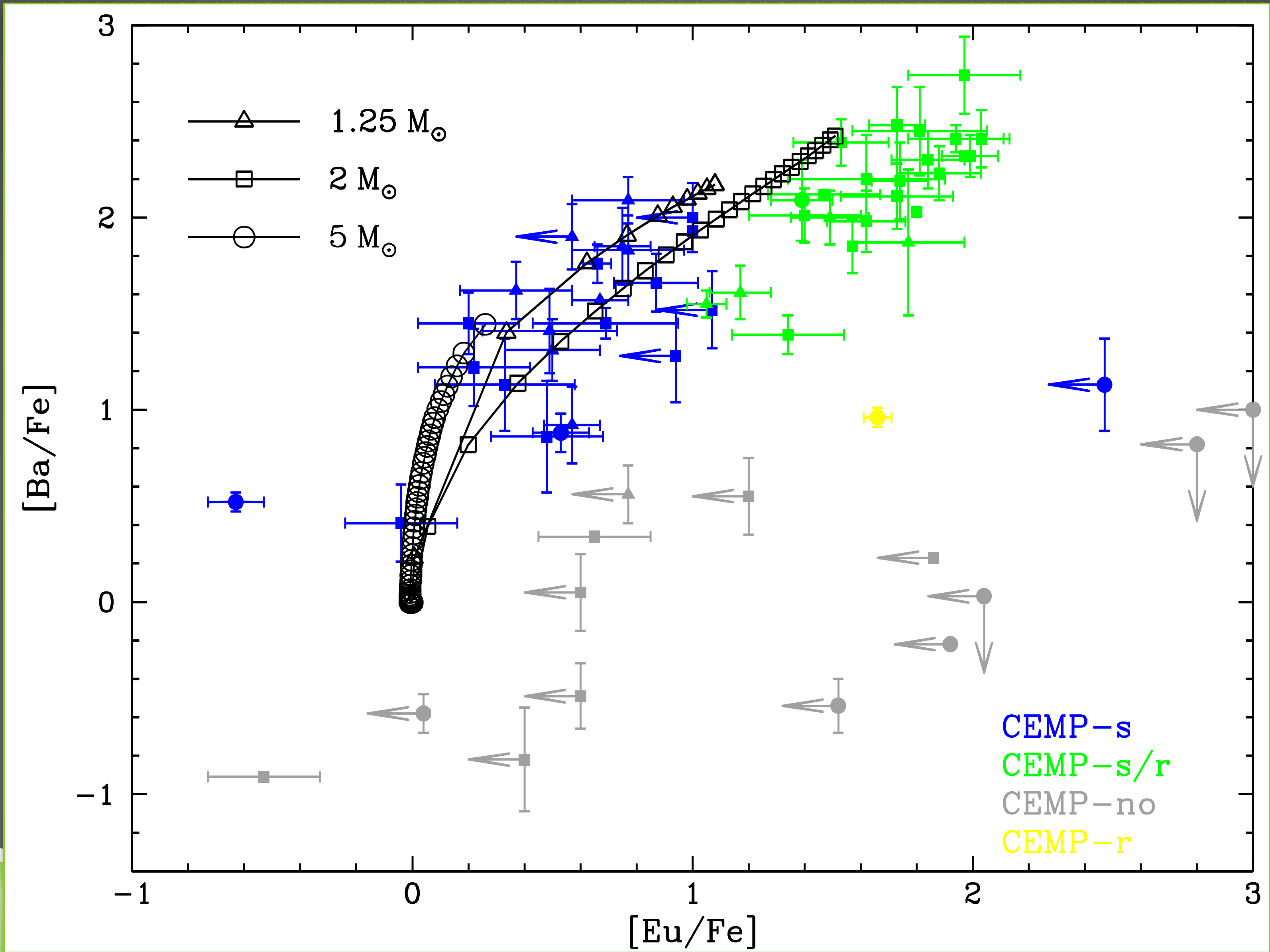


HEAVY ELEMENTS



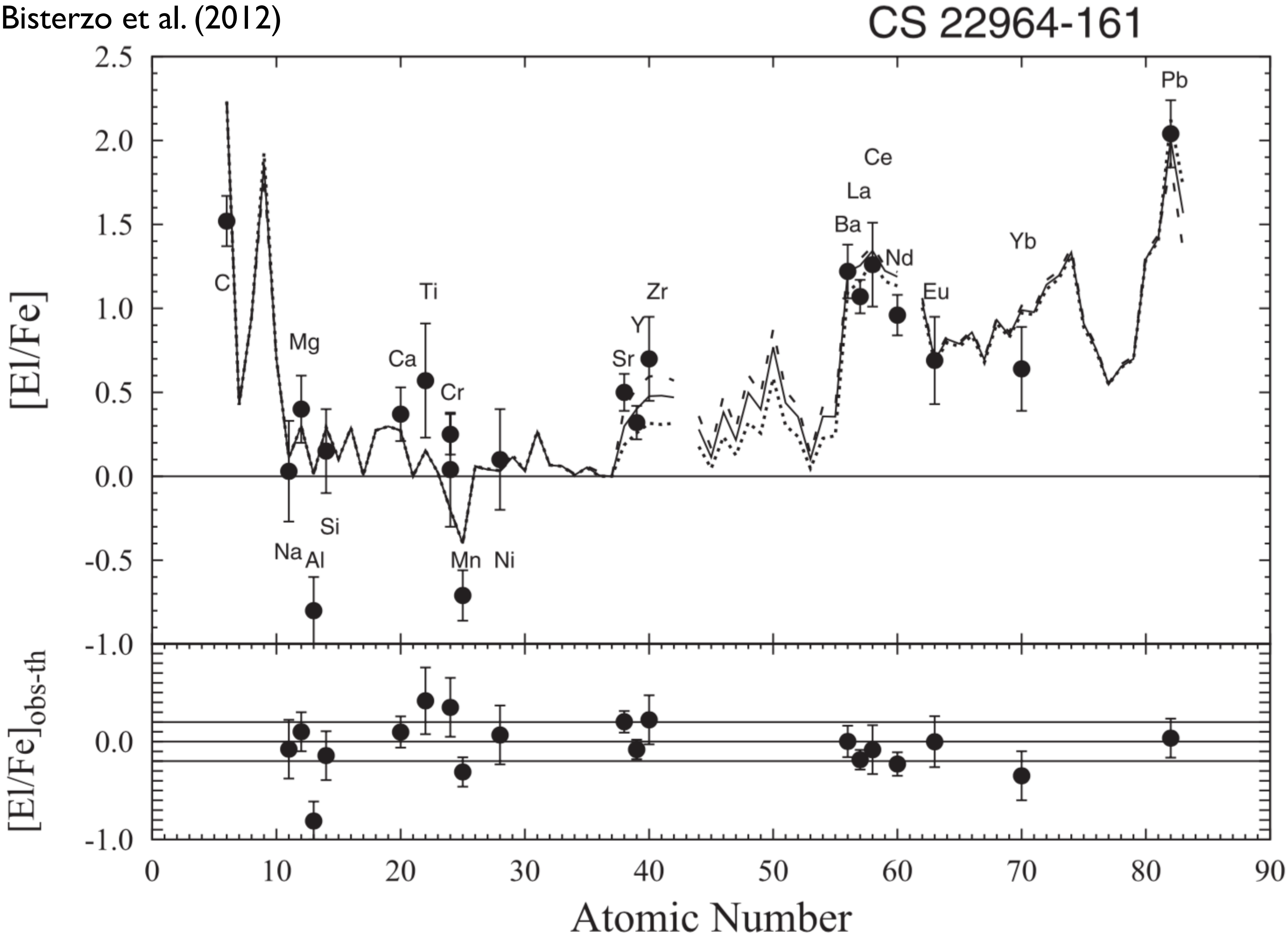
Lugaro et al. (2012), data from Masseron et al. (2010)

S-PROCESS NUCLEOSYNTHESIS

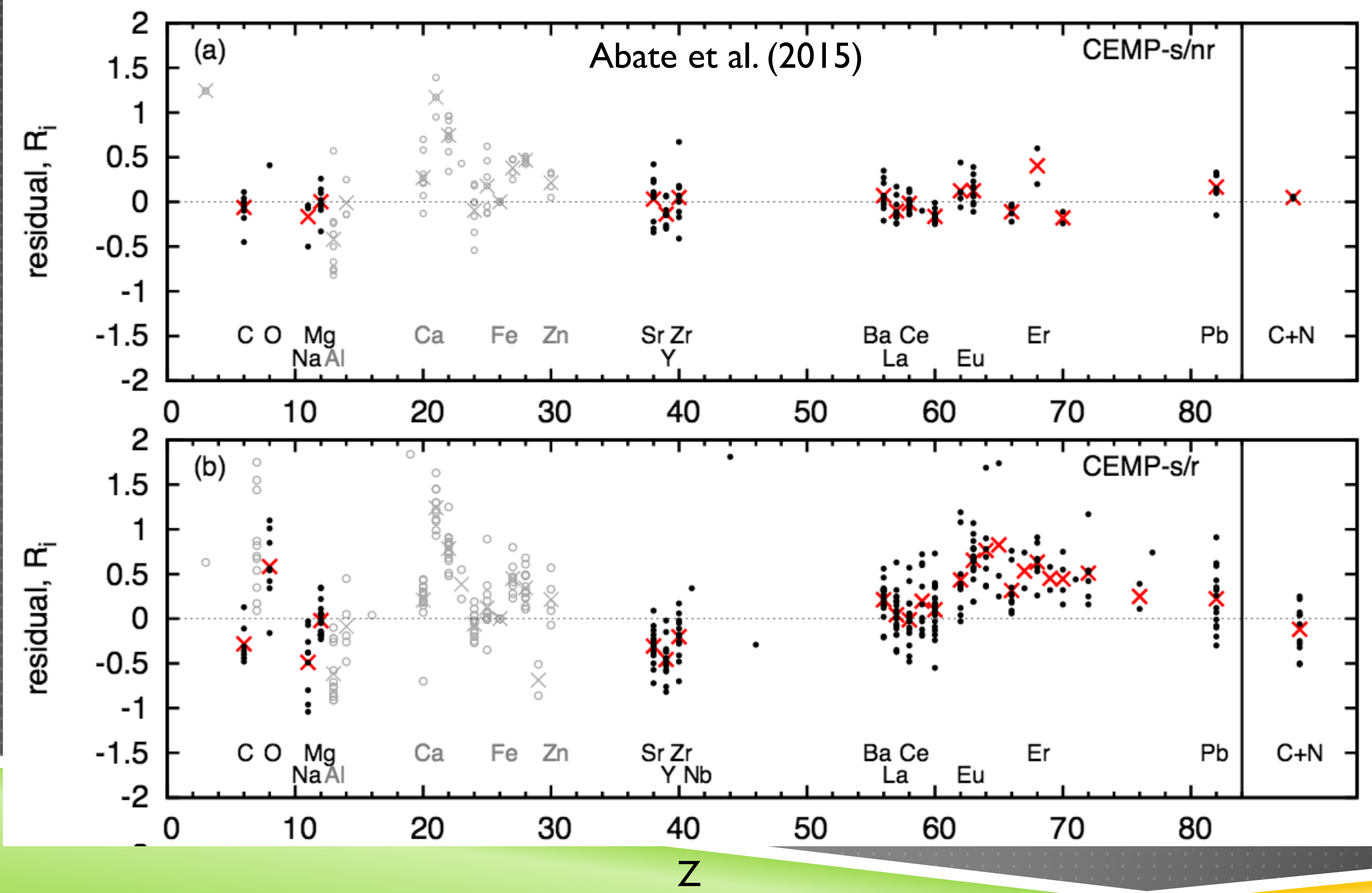


Lugaro et al. (2012)

Bisterzo et al. (2012)



ODDBALLS OF ODDBALLS



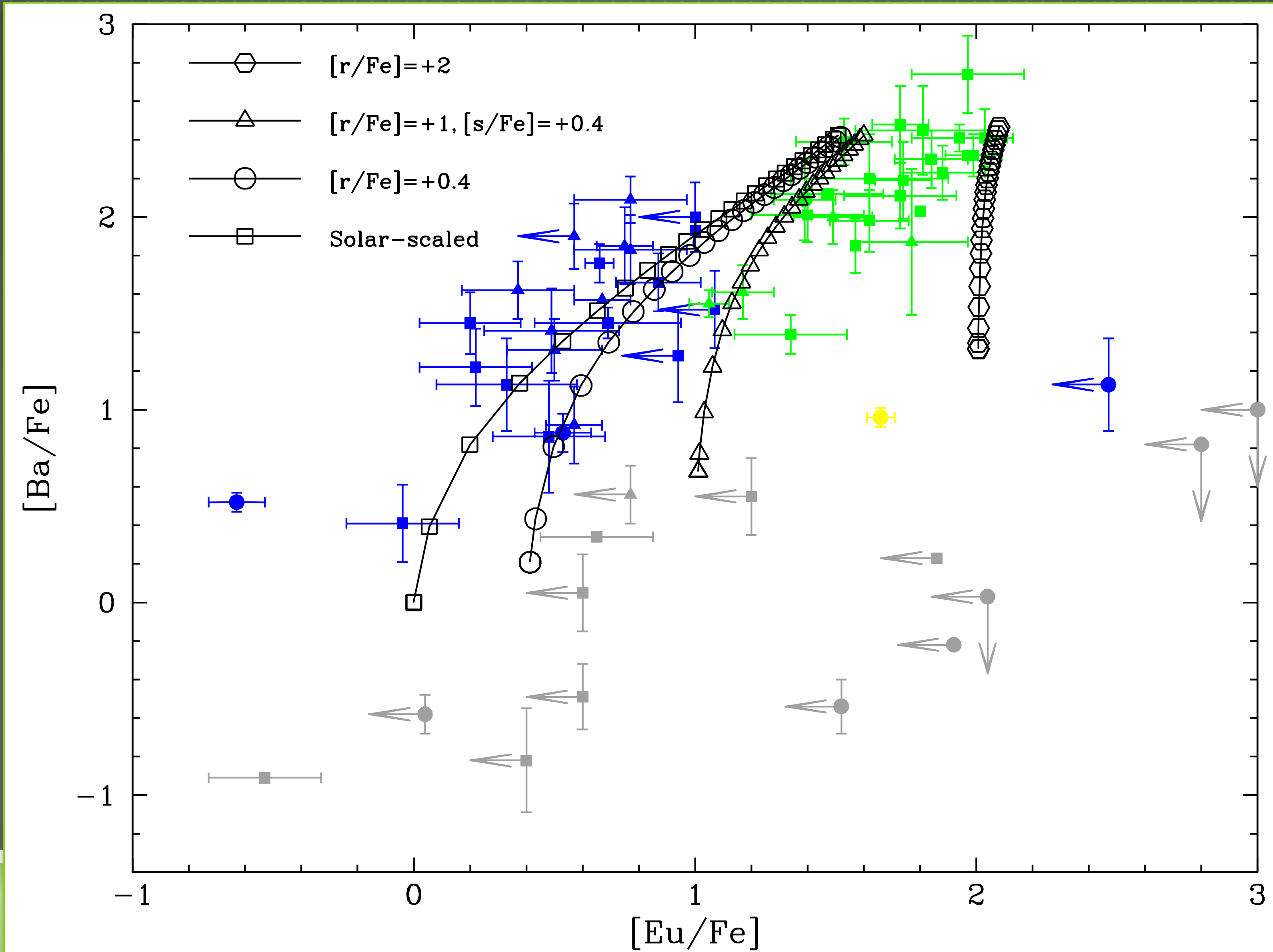
CEMP-RS FORMATION?

Problems

- Self-pollution
- Pollution from supernova?
  - Triple system
  - Type 1.5 SN
- Accretion induced collapse?
- Pre-pollution + s-process?

- Cannot self-pollute early enough. Radial velocity variations
-
  - Numbers not favourable
  - Nucleosynthesis and remnant
- Requires three phases of mass transfer, not likely!

CEMP-RS?



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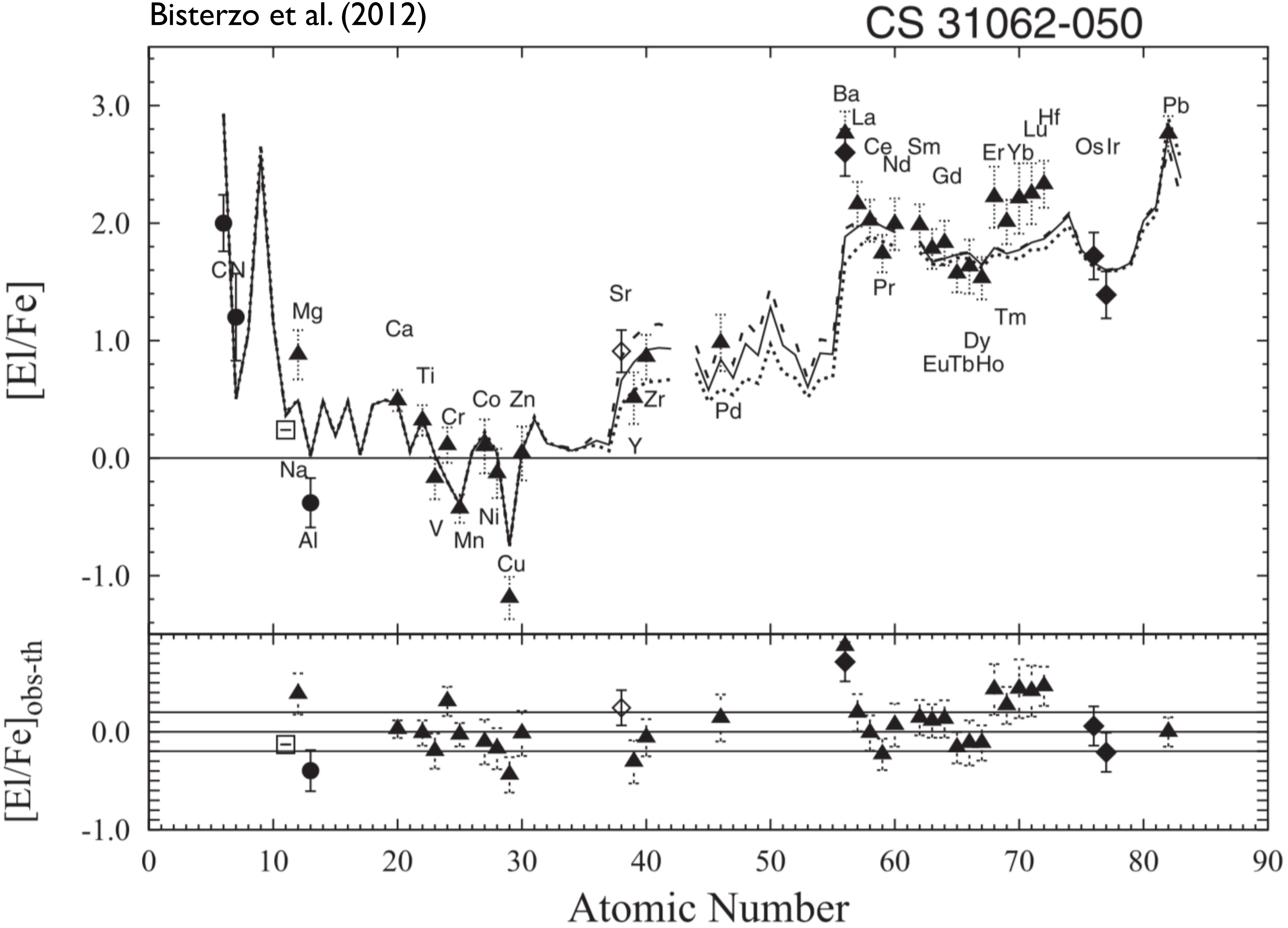
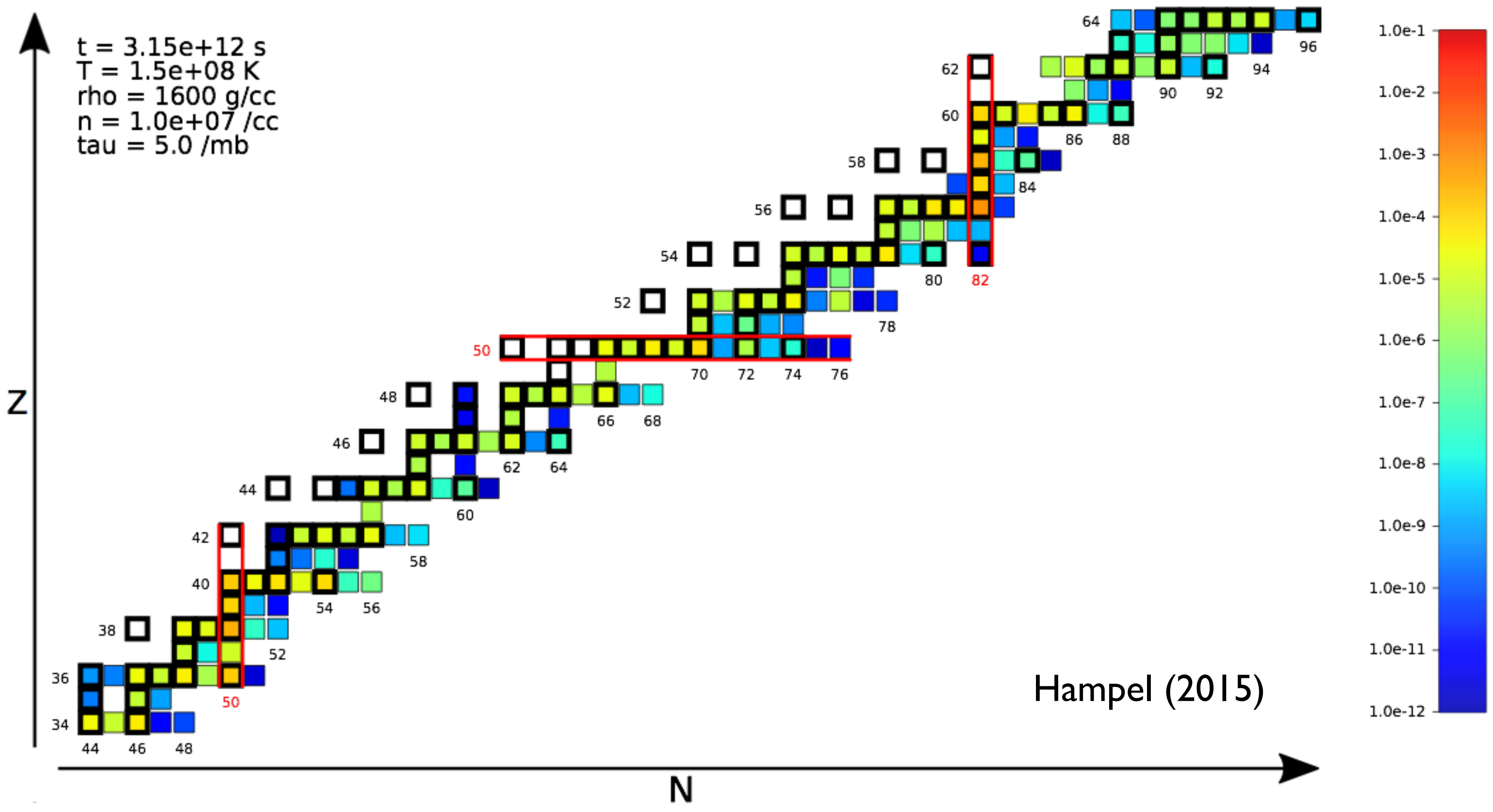
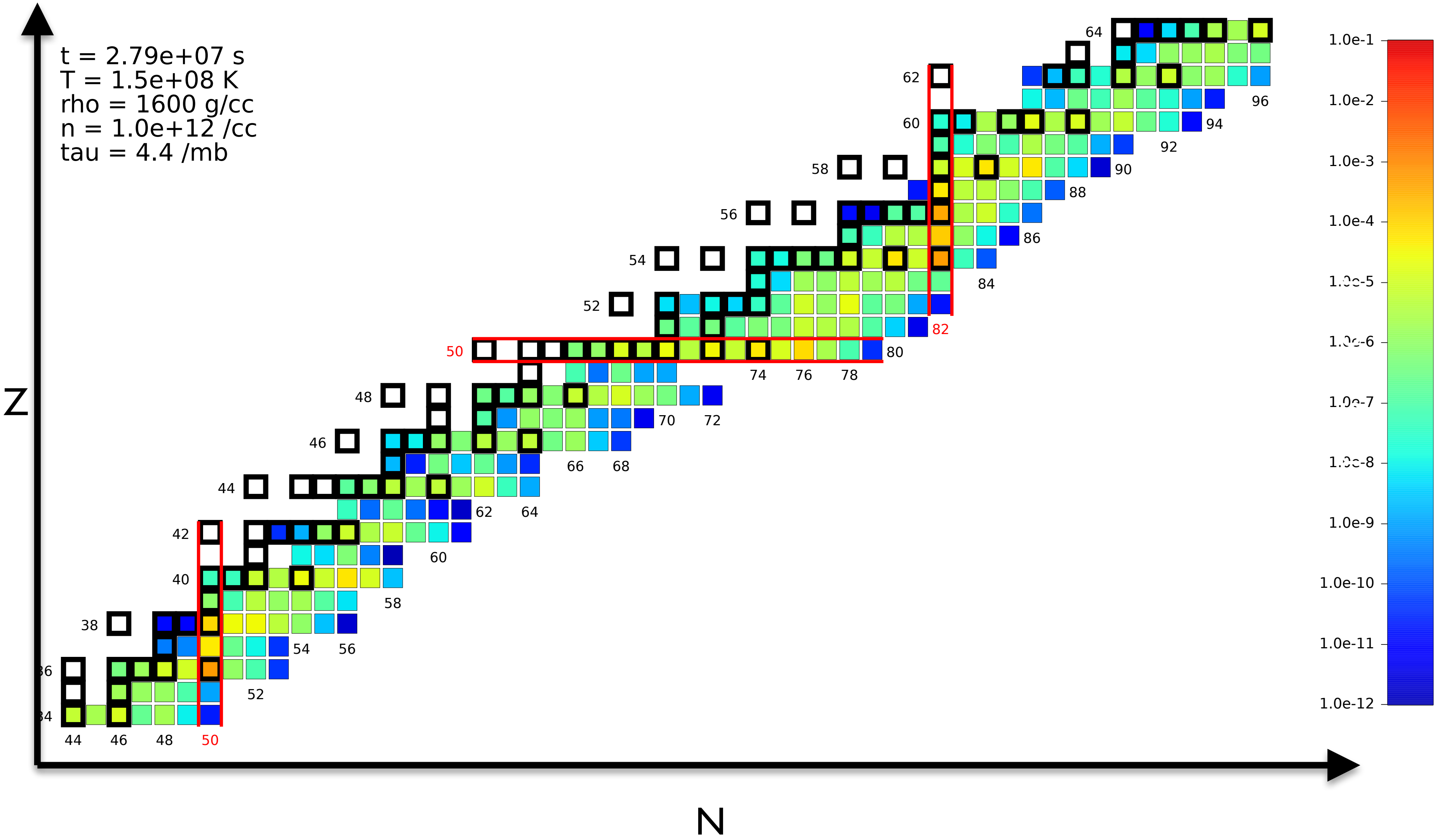


Increase the neutron density even further

s process, n = 10^7 cm^{-3}

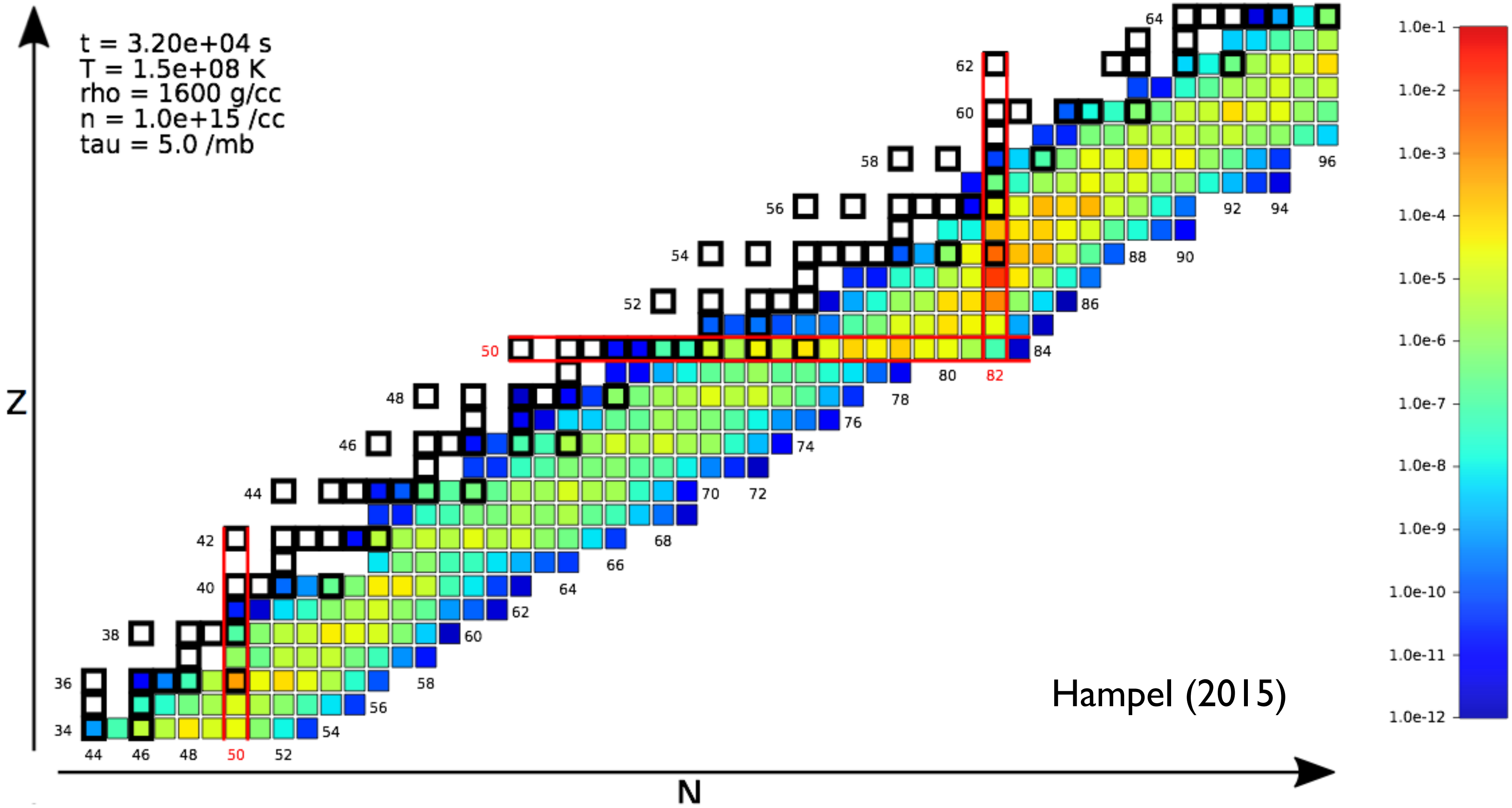


$n = 10^{12}\ cm^{-3}$

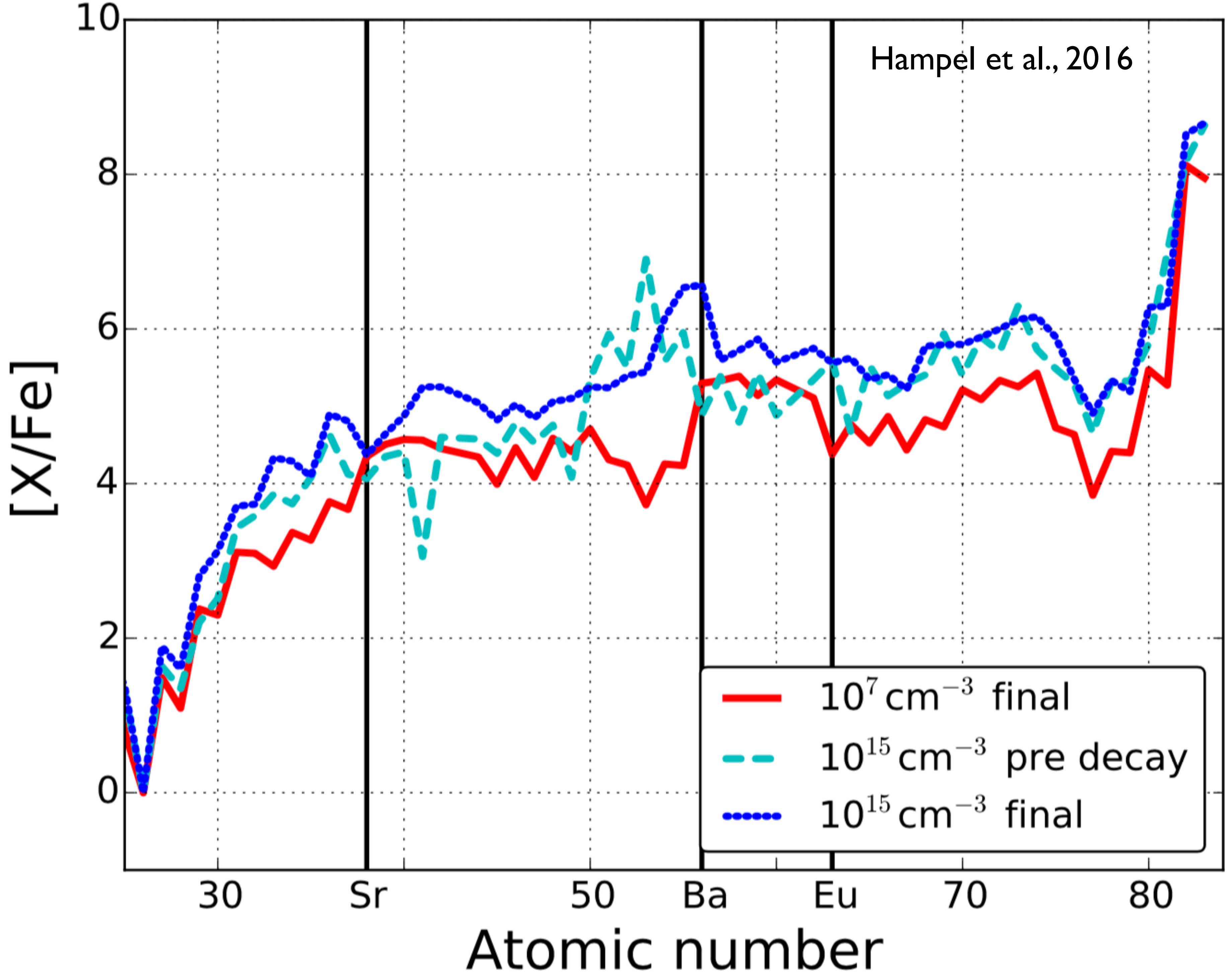


t = 2.79e+07 s
T = 1.5e+08 K
rho = 1600 g/cc
n = 1.0e+12 /cc
tau = 4.4 /mb
Z
N
1.0e-1
1.0e-2
1.0e-3
1.0e-4
1.0e-10
1.0e-11
1.0e-12

$n = 10^{15}\ cm^{-3}$



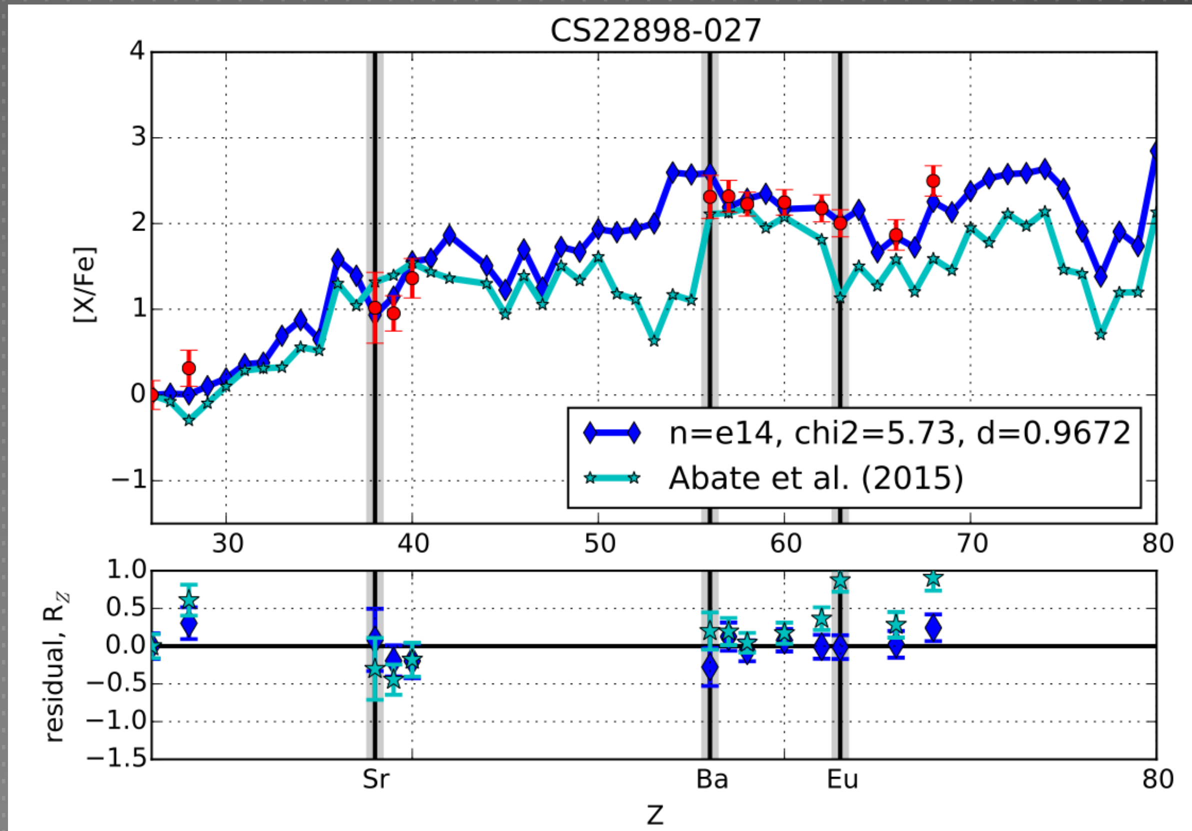
Hampel (2015)



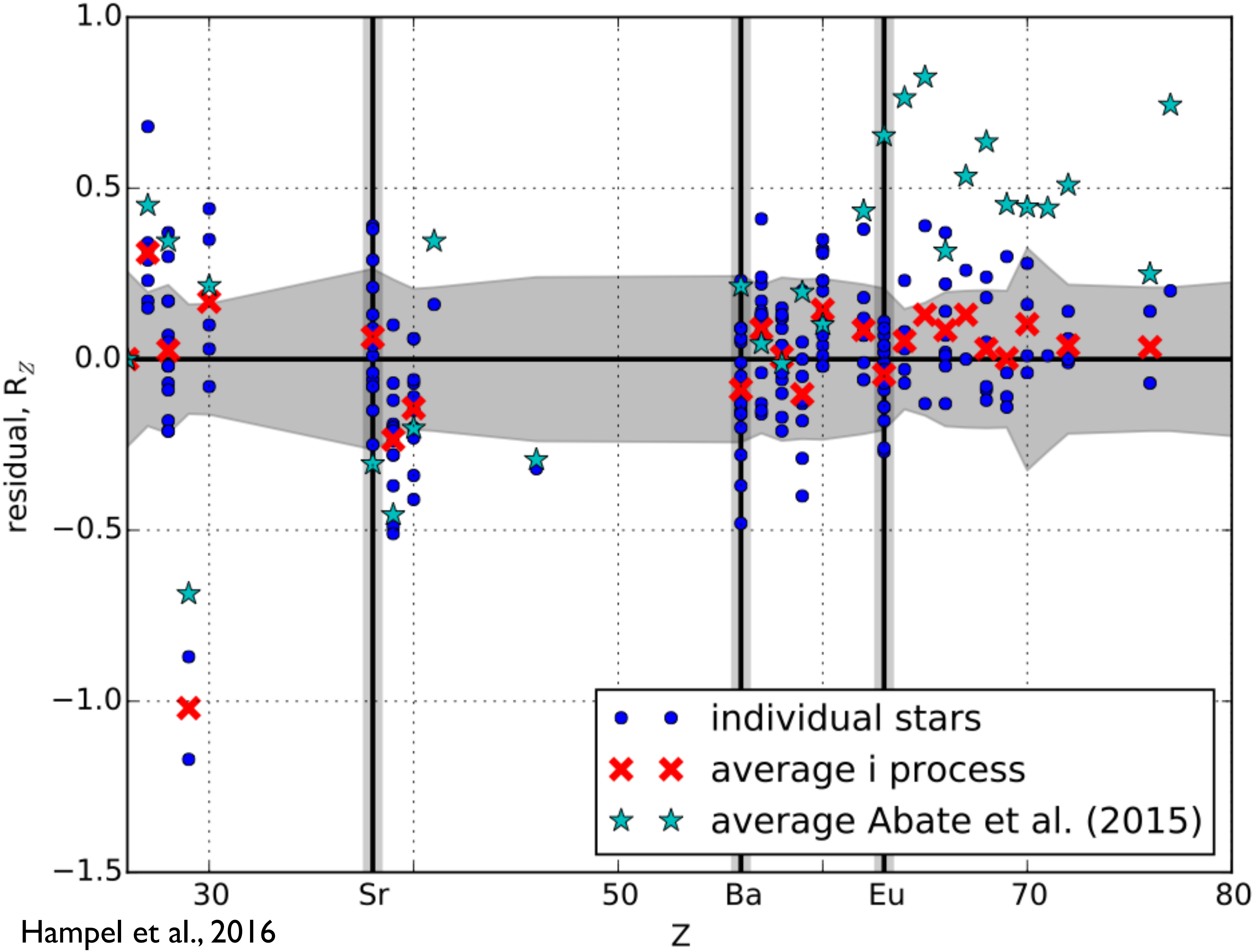
Hampel et al., 2016
10
8
6
4
2
0
[X/Fe]
30
Sr
50
Ba
Eu
70
80
Atomic number
10^{7} cm^{-3} final
10^{15} cm^{-3} pre decay
10^{15} cm^{-3} final

ONE ZONE I-PROCESS MODELS

- Cowan & Rose (1977) dubbed this the intermediate process
- Can a high neutron intensity reproduce the –rs pattern?
- Additional Ba and Eu production for same Zr,Y
- Significant nuclear reaction uncertainties (Bertolli et al. 2013)



Hampel et al., 2016



Hampel et al., 2016

SUMMARY

- S process nucleosynthesis in low mass stars requires the formation of a ^{13}C pocket
- How to form this pocket is still the biggest unceratinty in s-process nuclesynthesis!
- We can match s-process patterns in low metallicity stars reasonably well
- Something beyond the s-process might be needed…