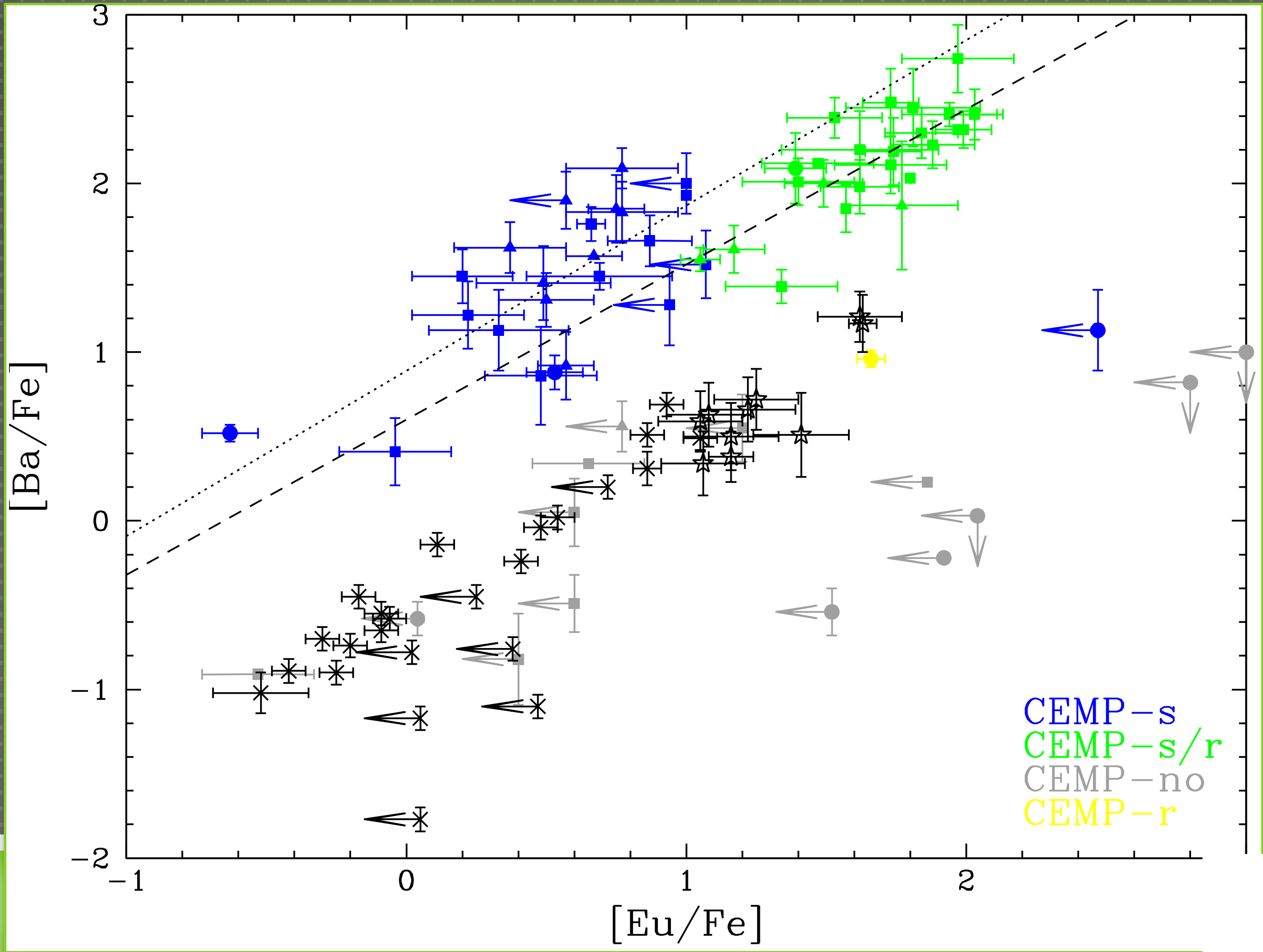
CARBON ENHANCED METAL POOR STARS AND AGB NUCLEOSYNTHESIS



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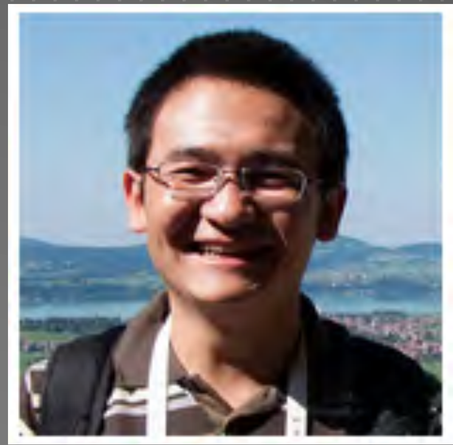
WITH THANKS TO…

Melanie Hampel



Zhengwei Liu

Carlo Abate

Elvijs Matrozis

OVERVIEW

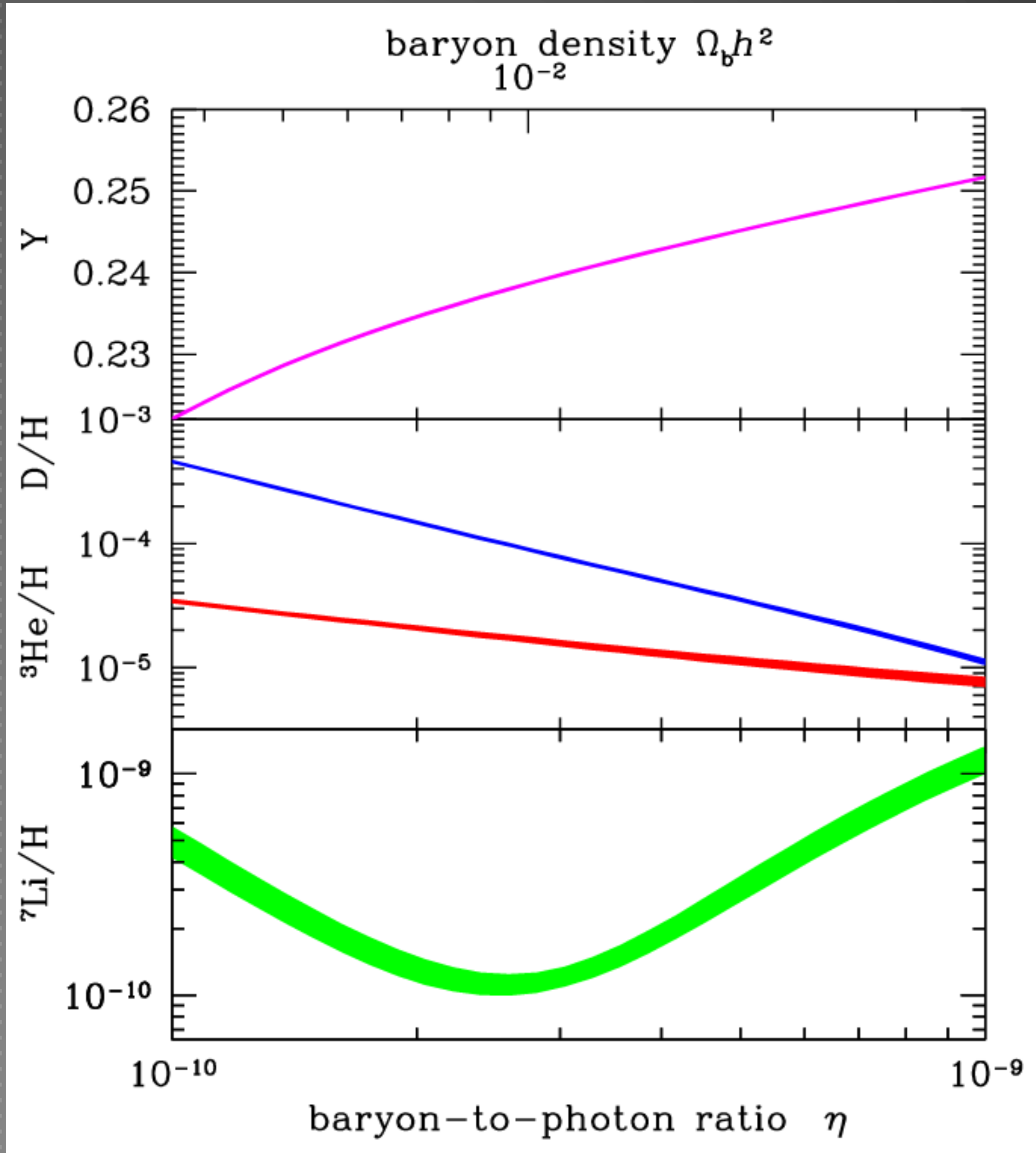
- Review of heavy element production
- Carbon-rich stars in the early Universe
- The CEMP-rs subgroup
- The intermediate neutron capture process

In the beginning…

In the beginning the Universe was created. This has made a lot of people very angry and been widely regarded as a bad move.

-- Douglas Adams, The Hitchhikers Guide to the Galaxy

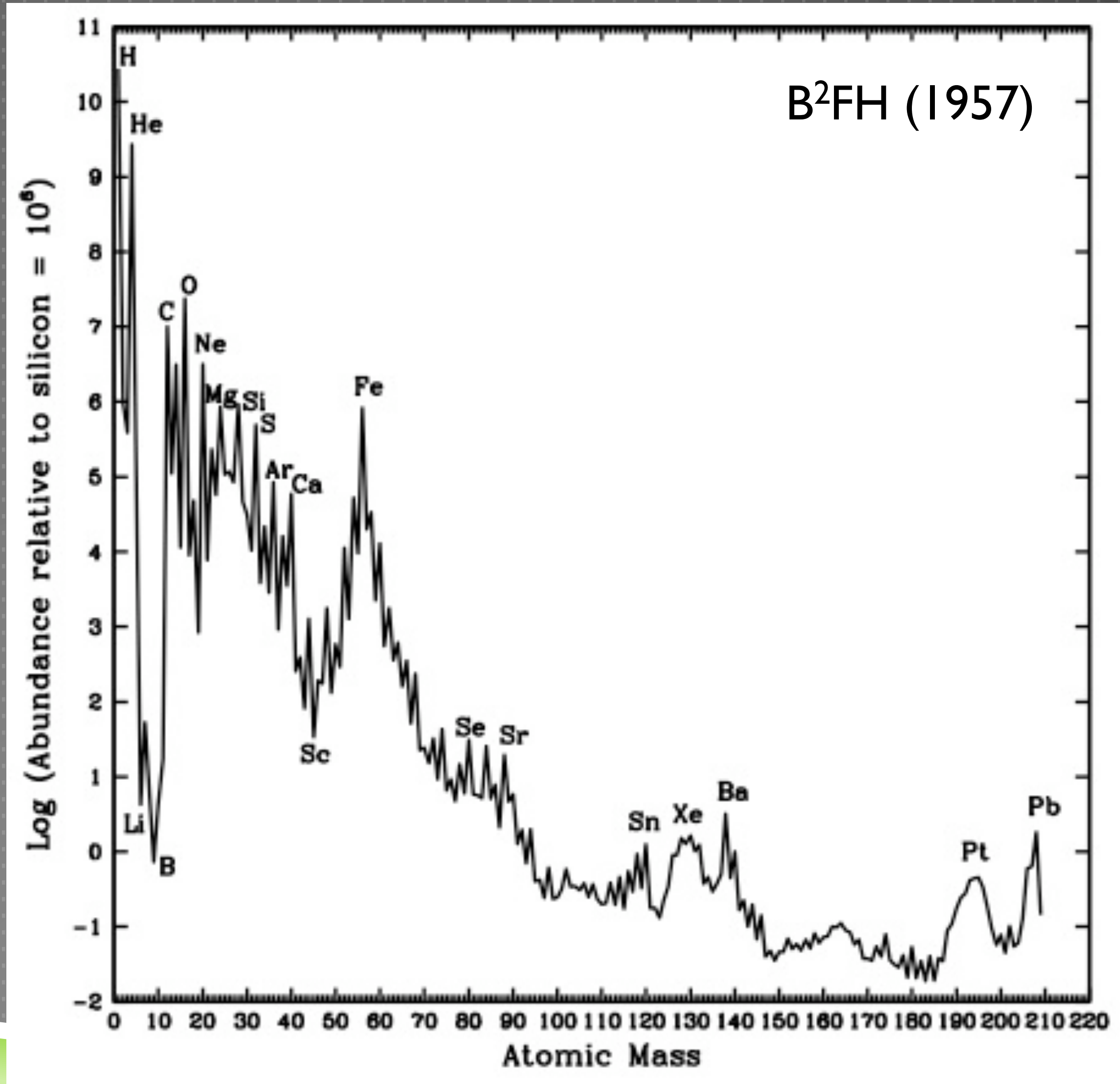
- Big Bang Nucleosynthesis
- Baryon density extremely well constrained from Planck
  - 0.02218±0.00026
- Y = 0.24725±0.00032
- And not a lot of anything else…
  - CNO/H = 5-30x10^{-15} (Coc et al. 2014)

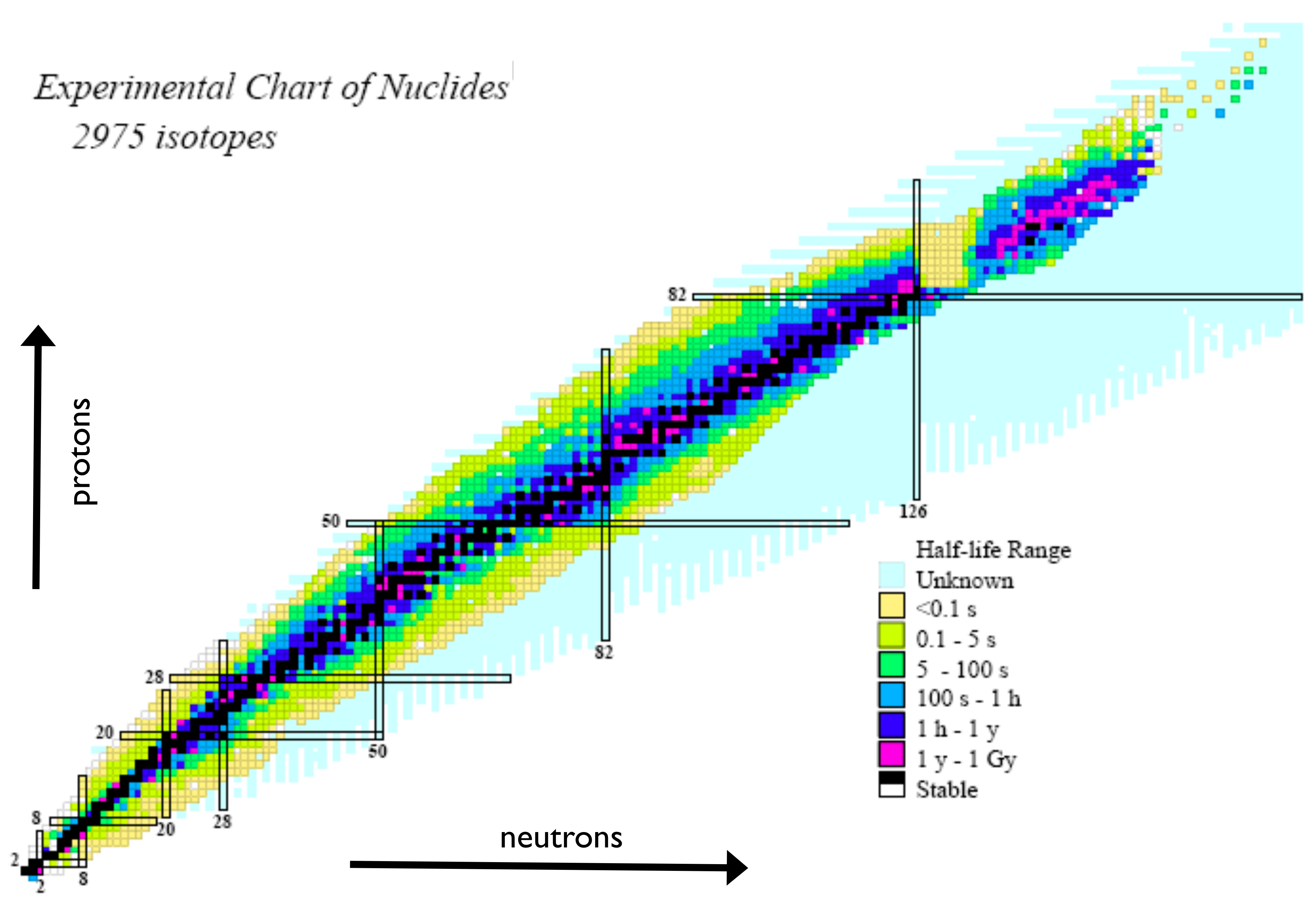


Cyburt et al. (2016)

PRESENT DAY ABUNDANCES

- Stellar nucleosynthesis over time accounts for everything else.
- Heavy element production beyond iron
  - Neutrons
- Nuclear structure tells you about how nucleosynthesis happens
  - s and r processes



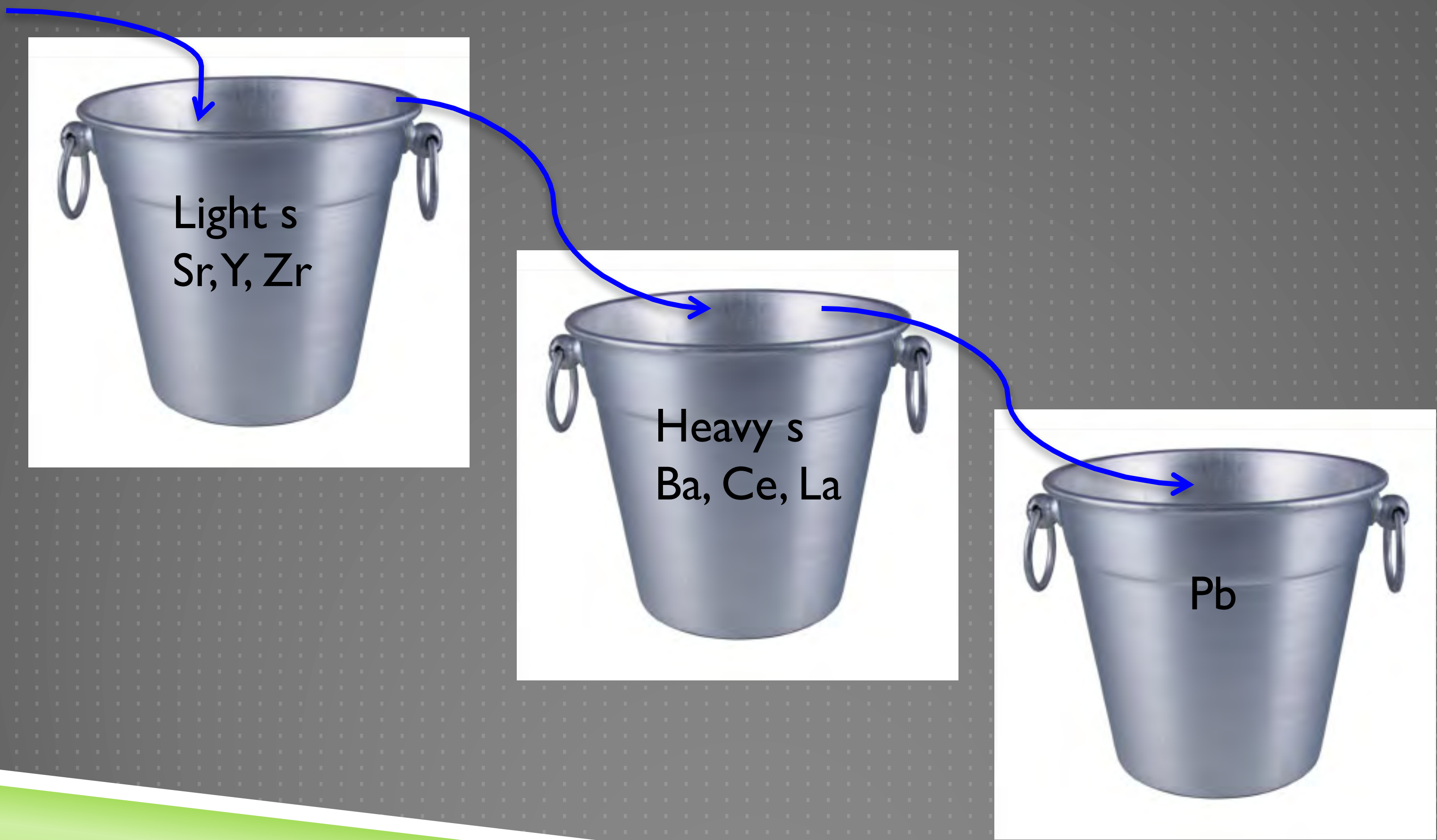


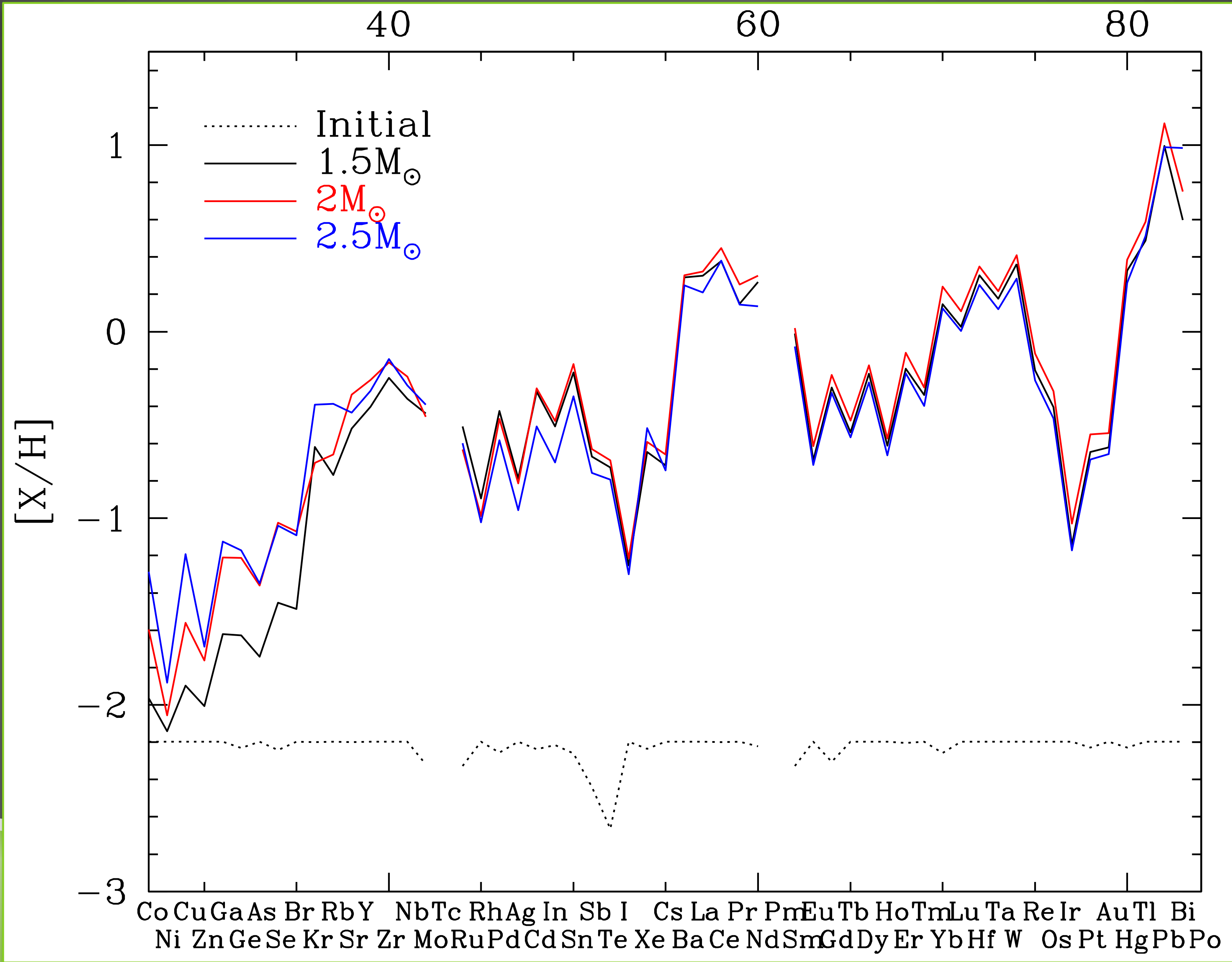
Experimental Chart of Nuclides
2975 isotopes
protons
neutrons
Half-life Range
Unknown
<0.1 s
0.1 - 5 s
5 - 100 s
100 s - 1 h
1 h - 1 y
1 y - 1 Gy
Stable
2
8
20
28
50
82
126

s-process nucleosynthesis

S-PROCESS NUCLEOSYNTHESIS

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

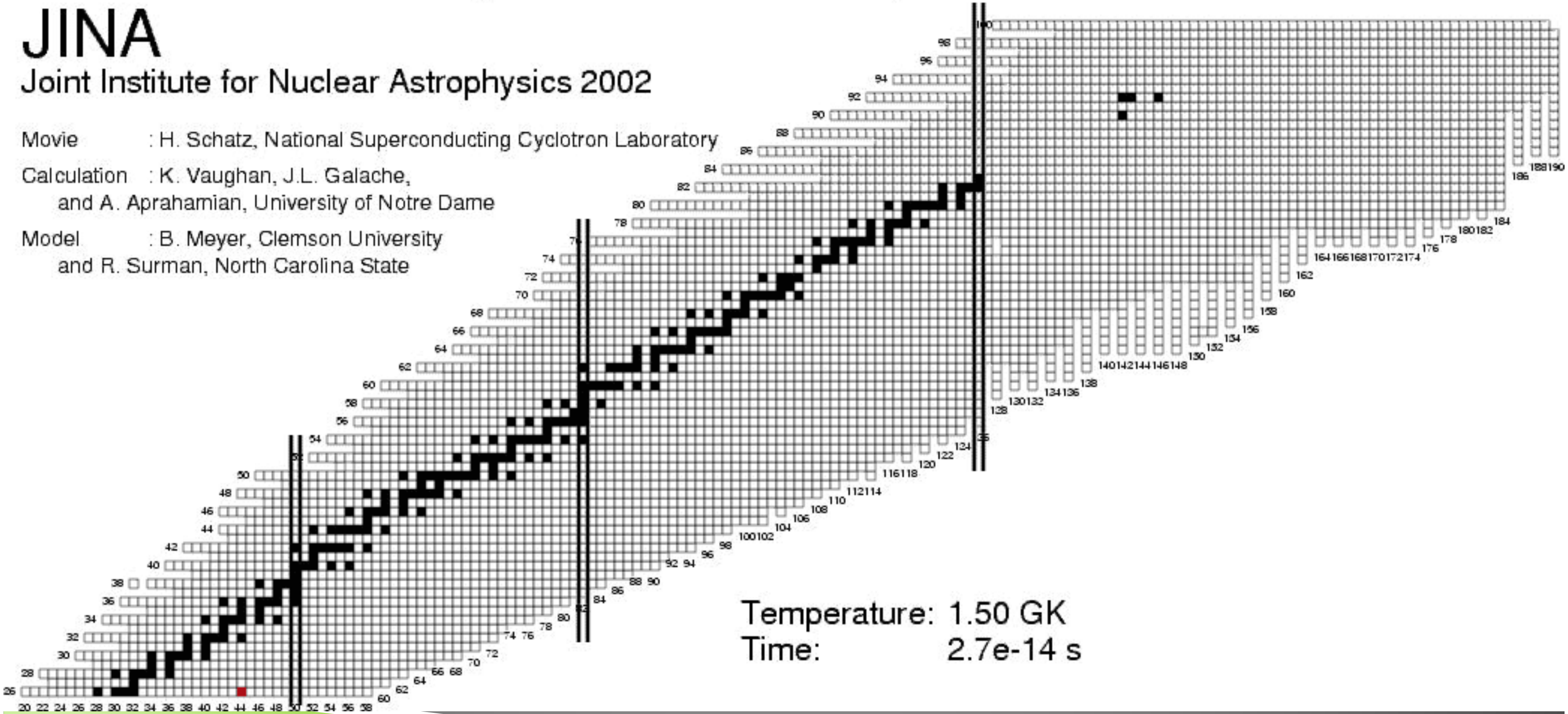




40
60
80
Initial
1.5M⊙
2M⊙
2.5M⊙
1
0
−1
−2
−3
[X/H]
Co Cu Ga As Br Rb Y Nb Tc Rh Ag In Sb I Cs La Pr Pm Eu Tb Ho Tm Lu Ta Re Ir Au Tl Bi
Ni Zn Ge Se Kr Sr Zr Mo Ru Pd Cd Sn Te Xe Ba Ce Nd Sm Gd Dy Er Yb Hf W Os Pt Hg Pb Po

Increase the neutron density even further

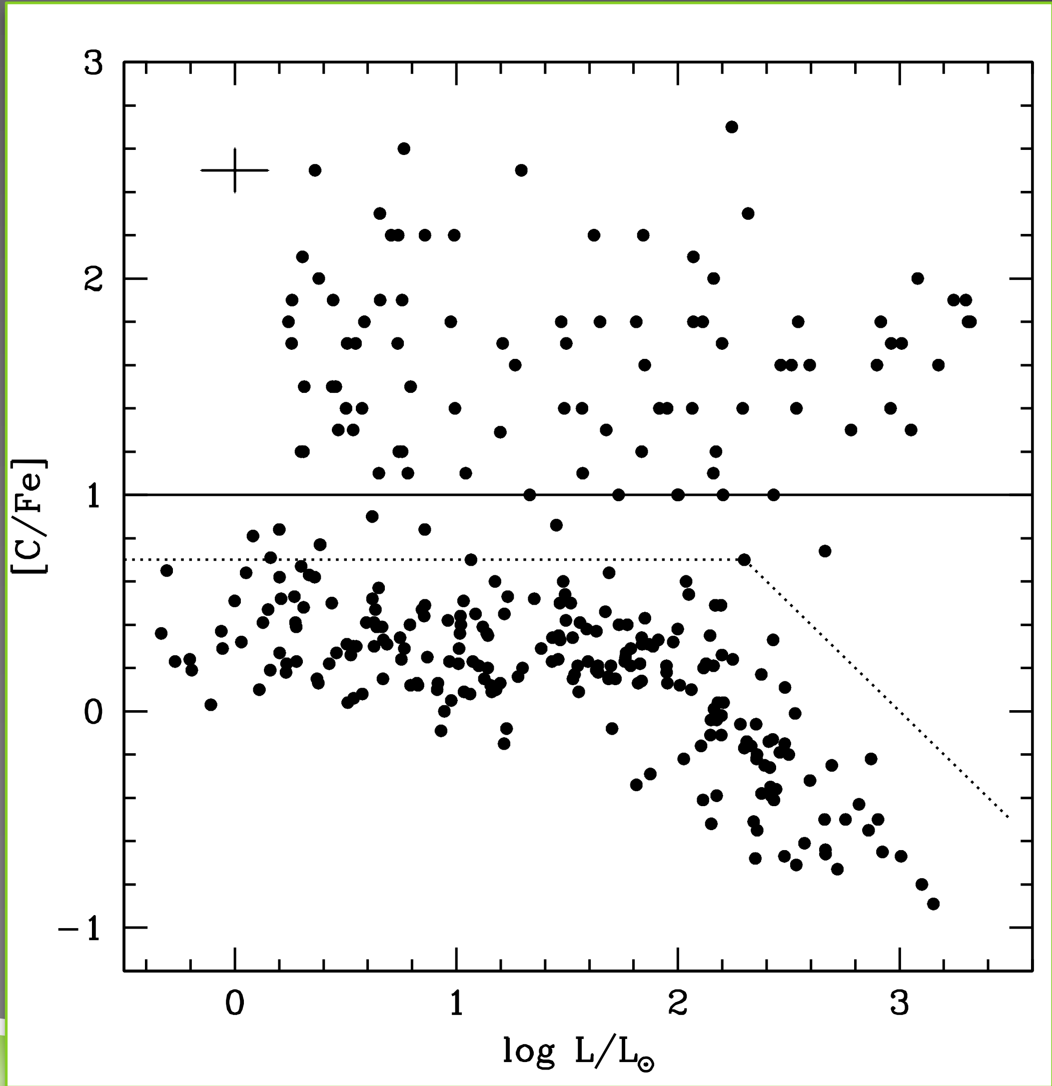
Nucleosynthesis in the r-process



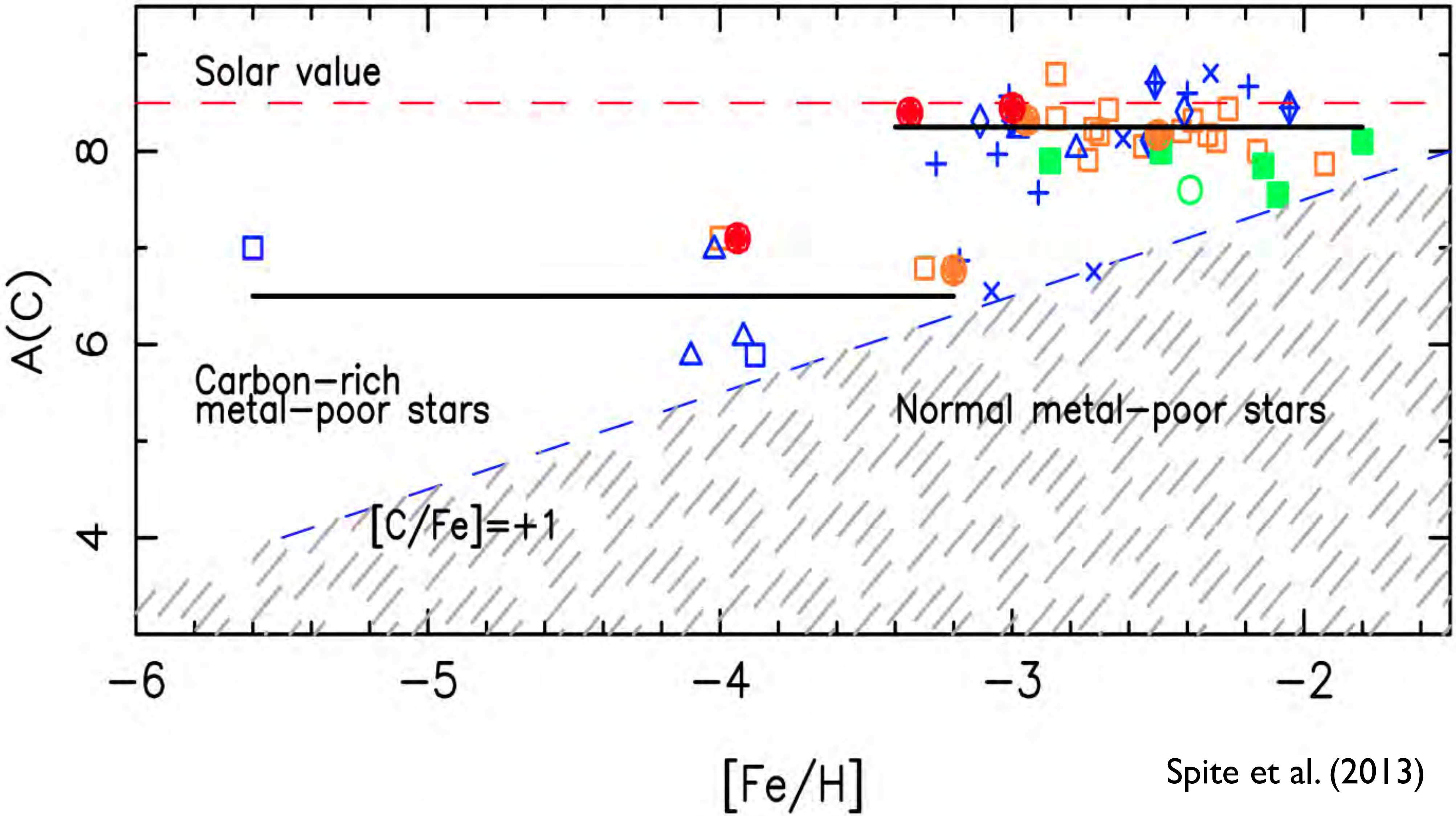
CARBON-ENHANCED STARS

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…

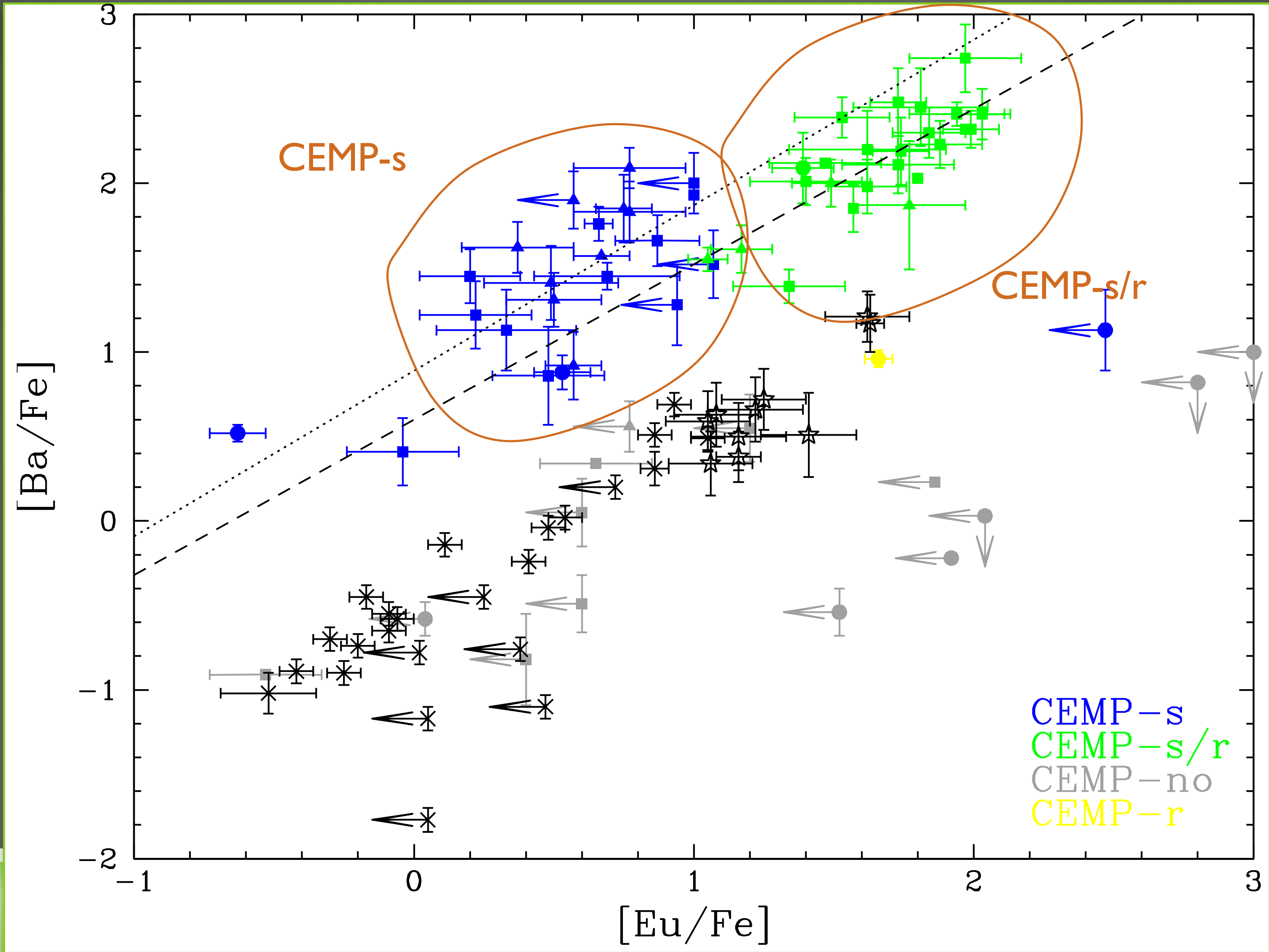


C abundances distinct for low- and very low metallicities?



Spite et al. (2013)

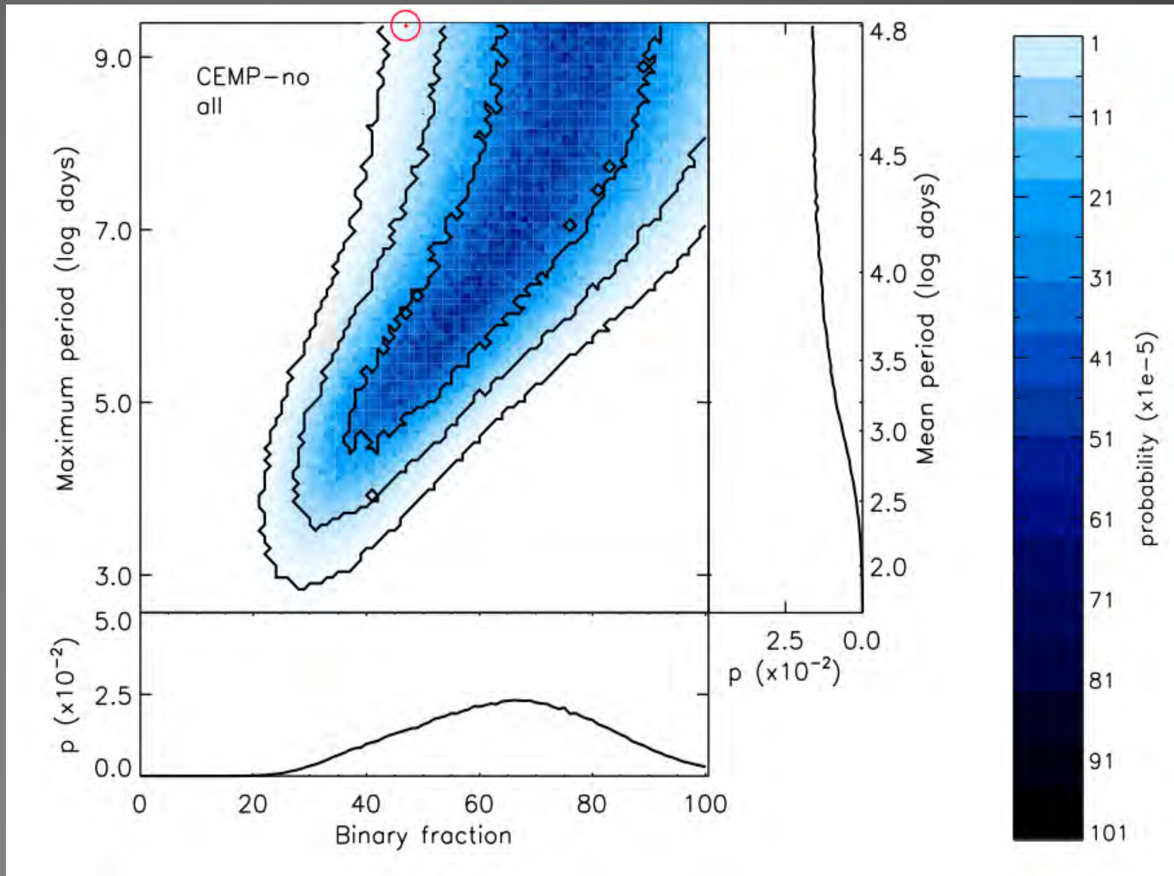
HEAVY ELEMENTS



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

BINARITY

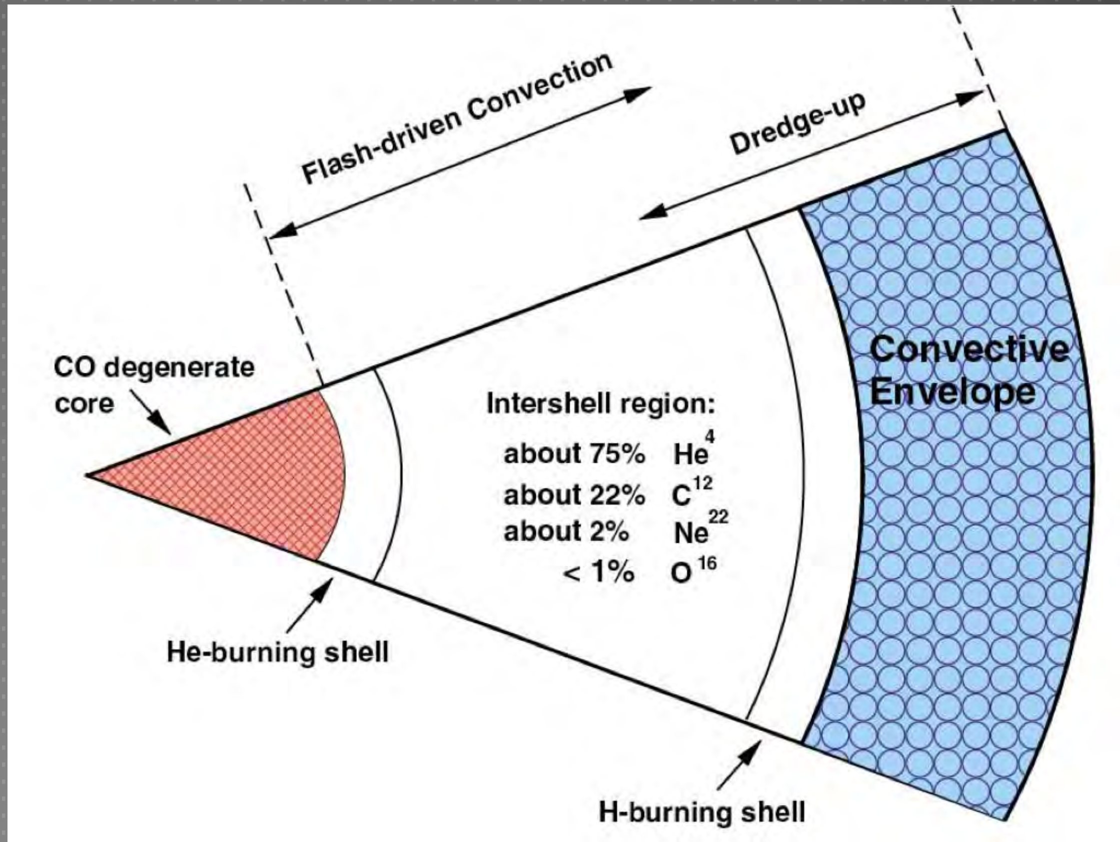
- Binarity of CEMP-s stars firmly established
- Connection to CH stars
- Quite distinct from the CEMP-no stars



Starkenburg et al. (2014)

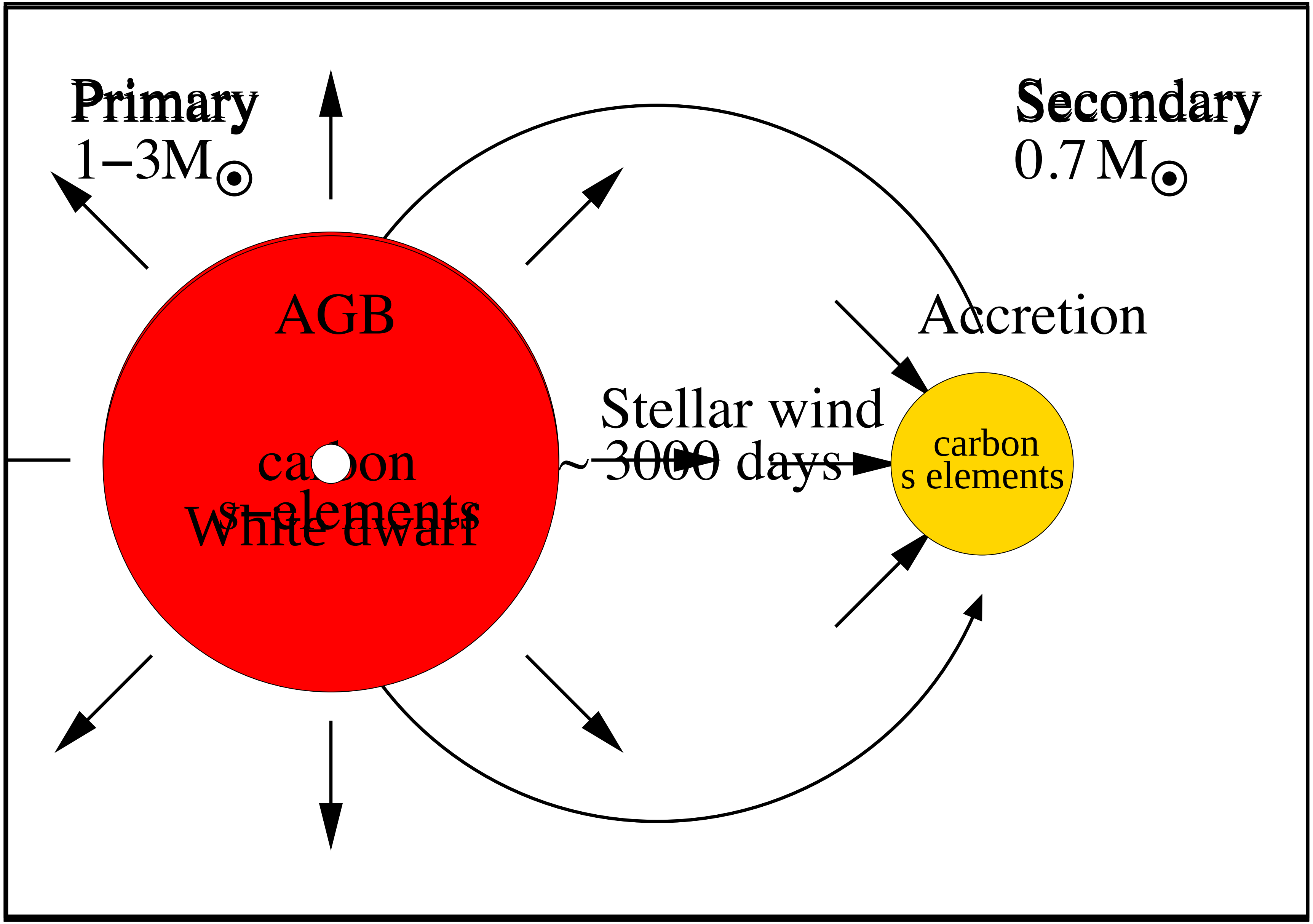
ASYMPTOTIC GIANT BRANCH STARS

- Final stage of the life of a low mass star
- Unstable double shell burning – thermal pulses
- Third dredge-up
- Strong winds erode the envelope



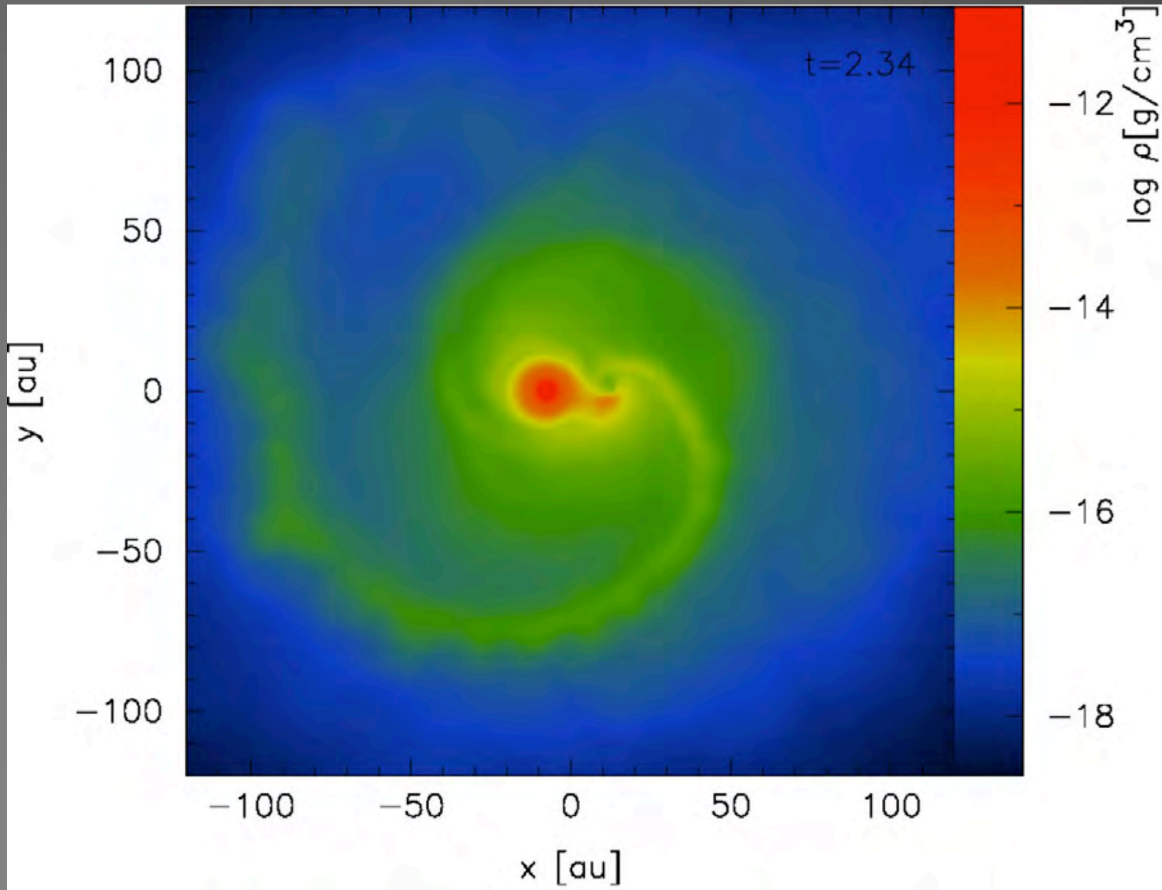
Karakas et al. (2002)

FORMATION MECHANISM

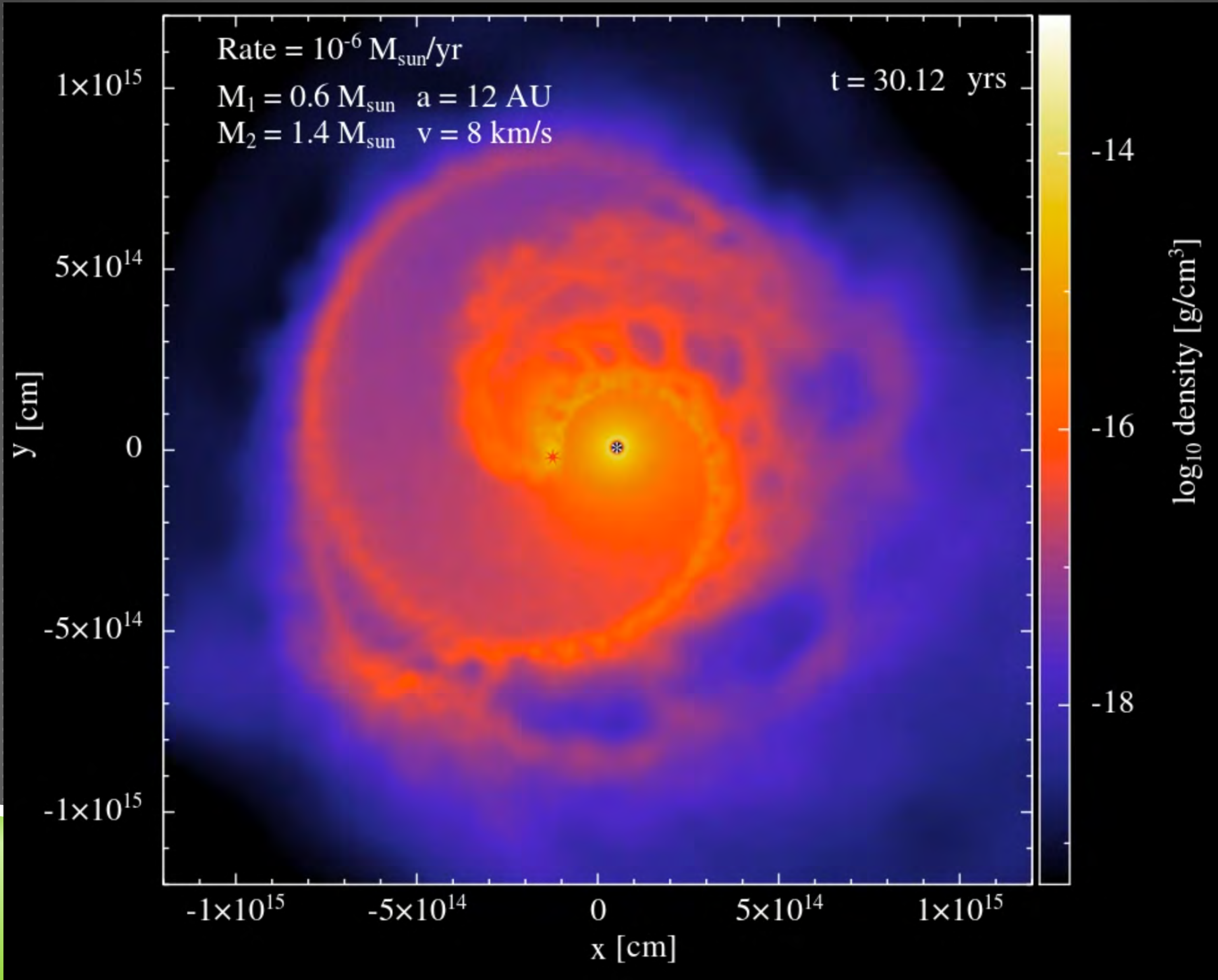


MASS TRANSFER

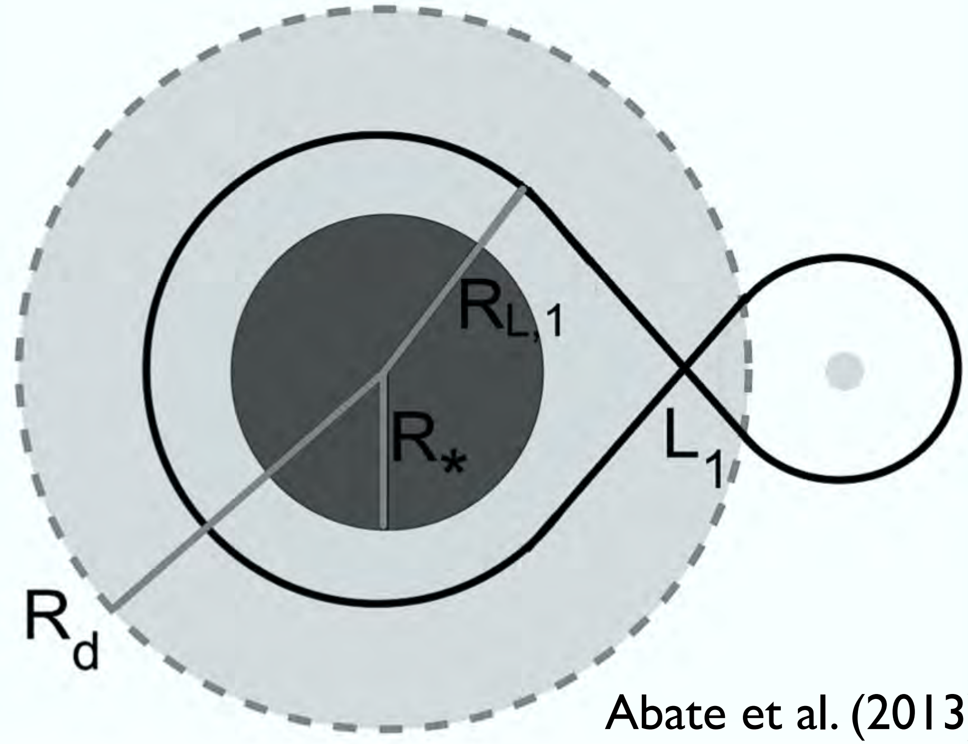
- Typically assume Bondi-Hoyle accretion from wind
- But AGB winds are slow (10 km/s)
- For wide binaries, the orbital speed is similar
- Accretion is not so simple…
- Need hydro to help!



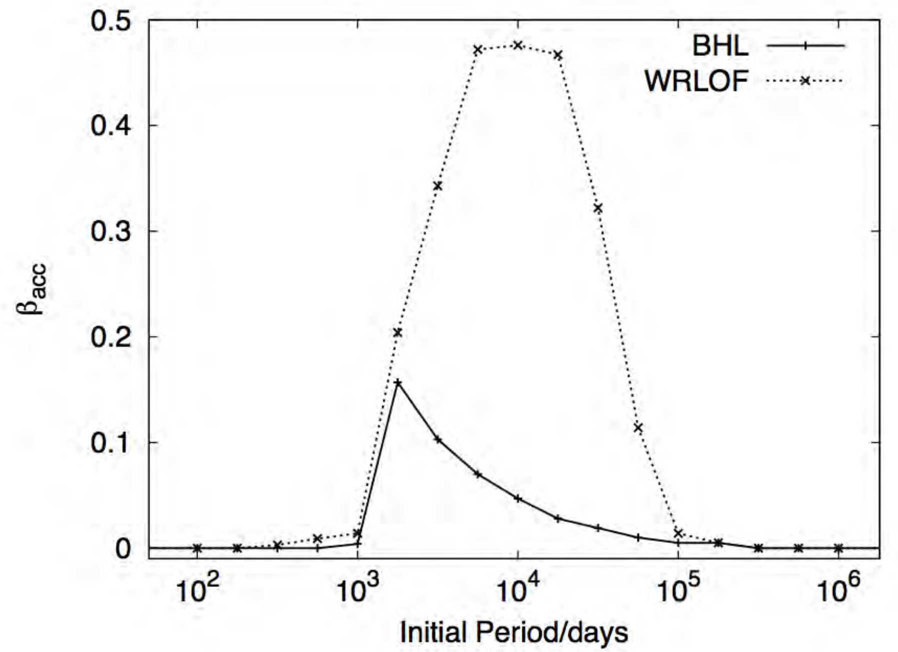
Mohamed & Podsiadlowski (2007)


Rate = 10^{-6} M_{sun}/yr
M_1 = 0.6 M_{sun} a = 12 AU
M_2 = 1.4 M_{sun} v = 8 km/s
t = 30.12 yrs
y [cm]
x [cm]
$\log_{10}$ density [g/cm^3]
1×10^{15}
5×10^{14}
0
-5×10^{14}
-1×10^{15}
-14
-16
-18

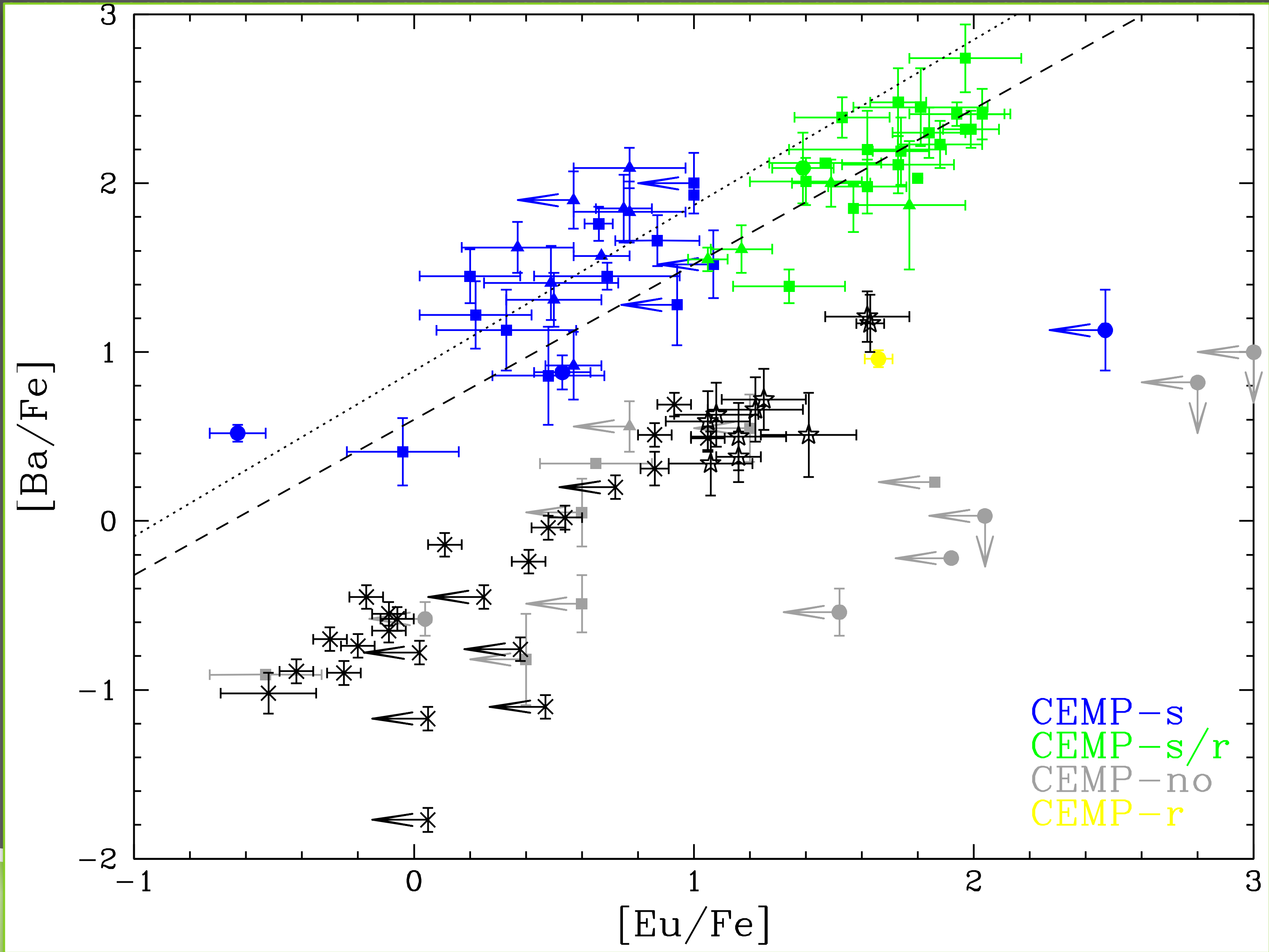
- Dust acceleration radius, R_d is key
- If this lies outside the Roche Lobe efficient mass transfer can occur
- Wind Roche Lobe Overflow
- Could be about 5 times as efficient as Bondi Hoyle wind accretion
- Needs to be followed up with detailed sweep of binary configurations



Abate et al. (2013)

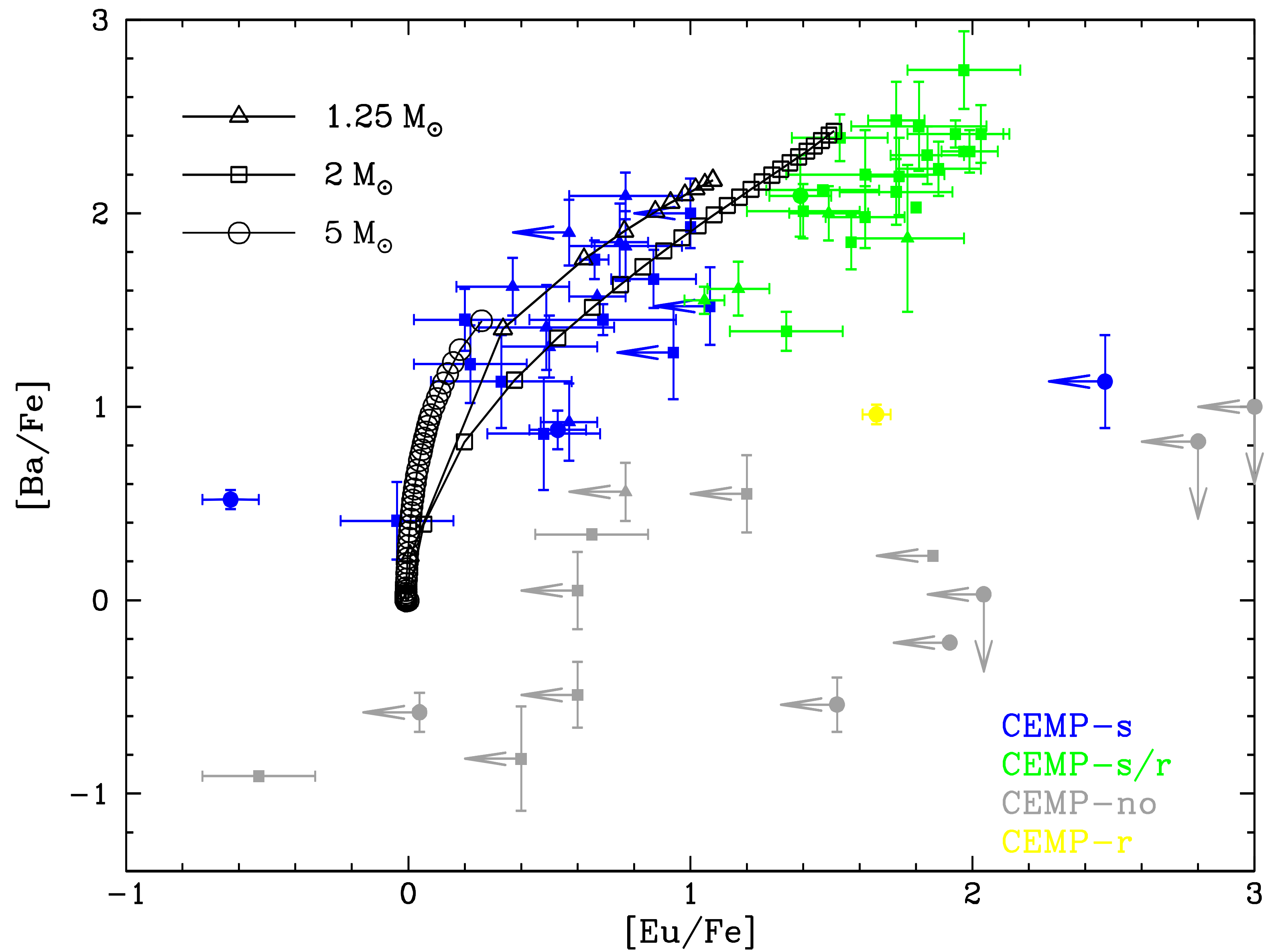


S-PROCESS NUCLEOSYNTHESIS



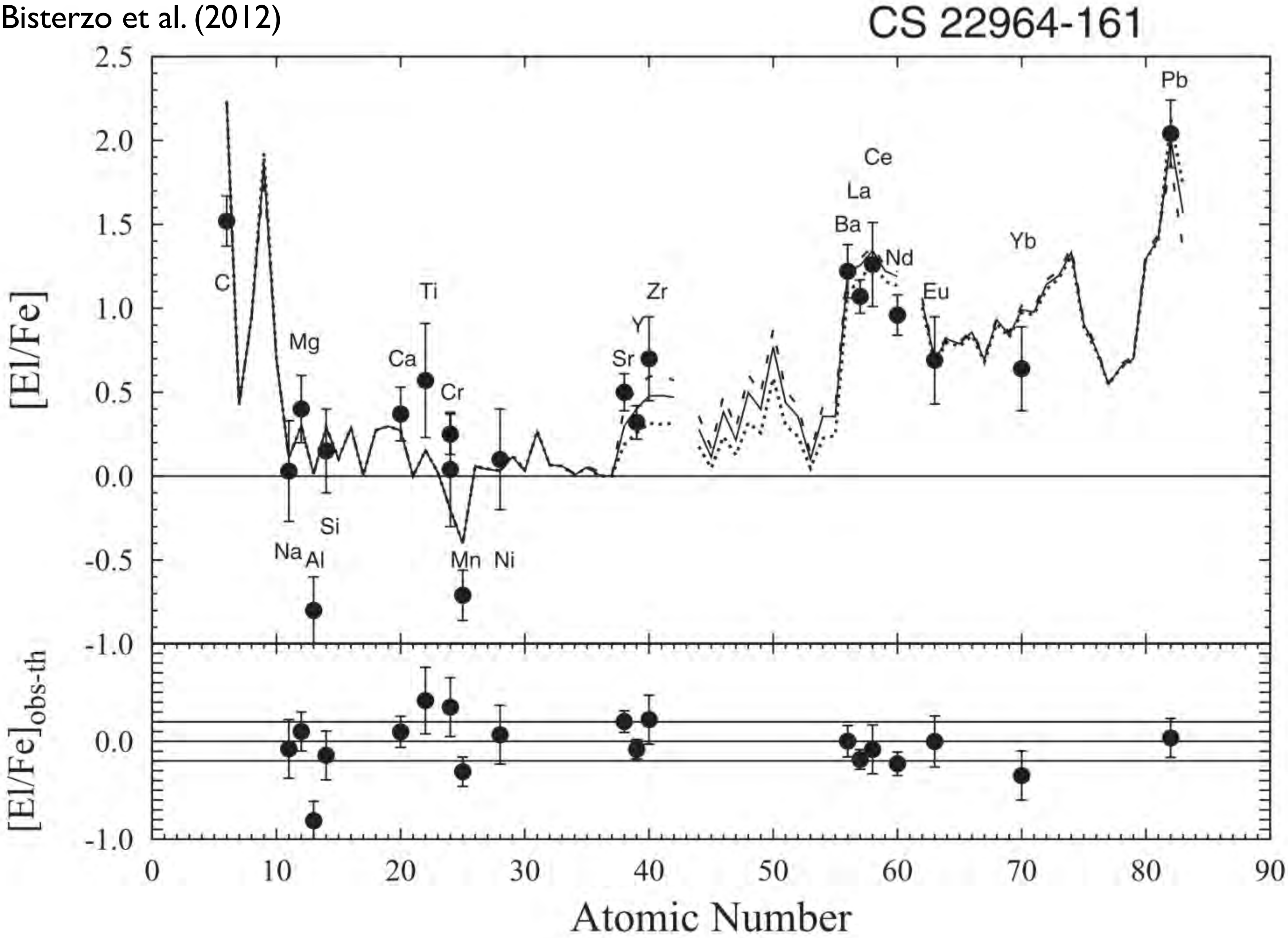
Lugaro et al. (2012), data from Masseron et al. (2010)

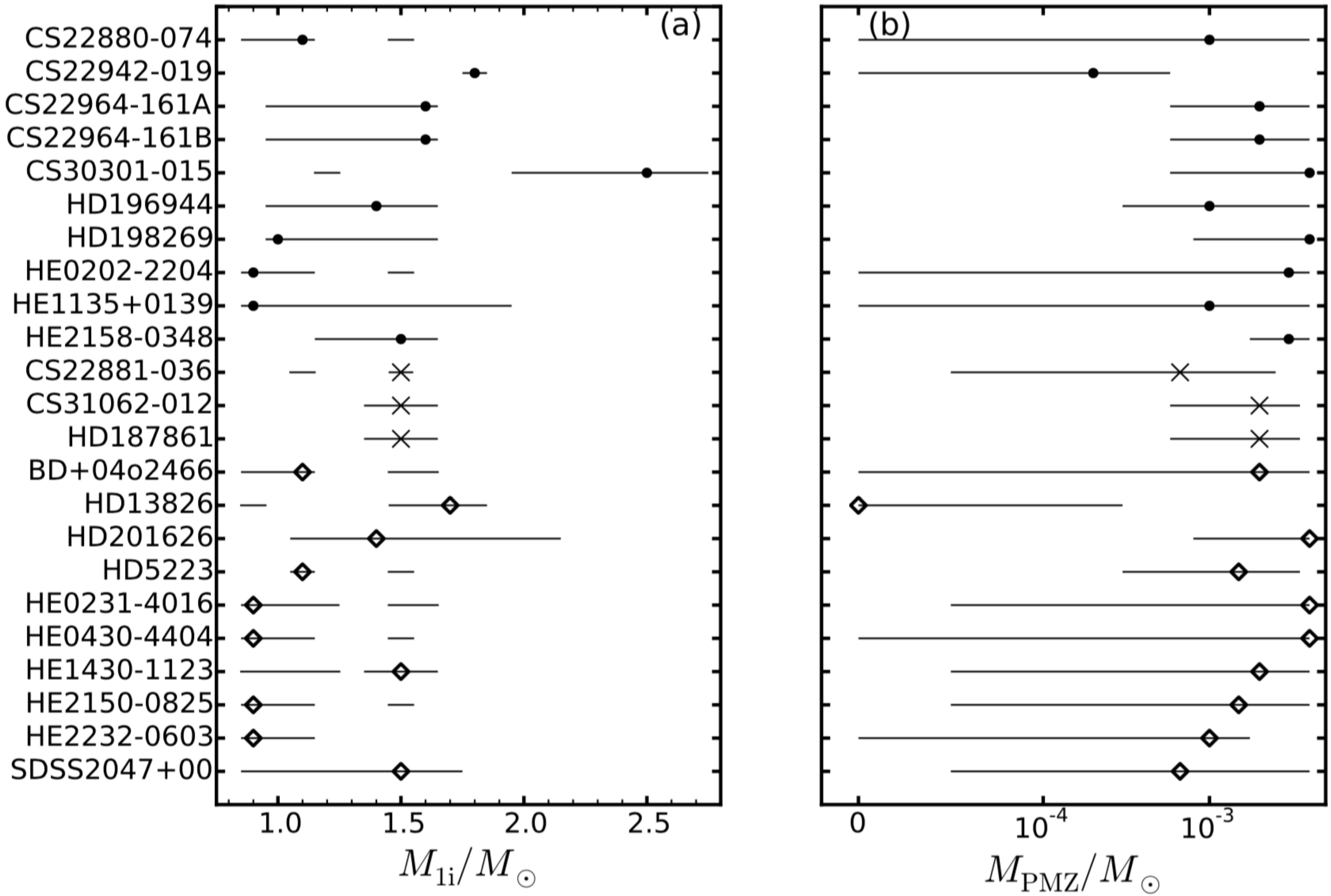
S-PROCESS NUCLEOSYNTHESIS



Lugaro et al. (2012)

Bisterzo et al. (2012)



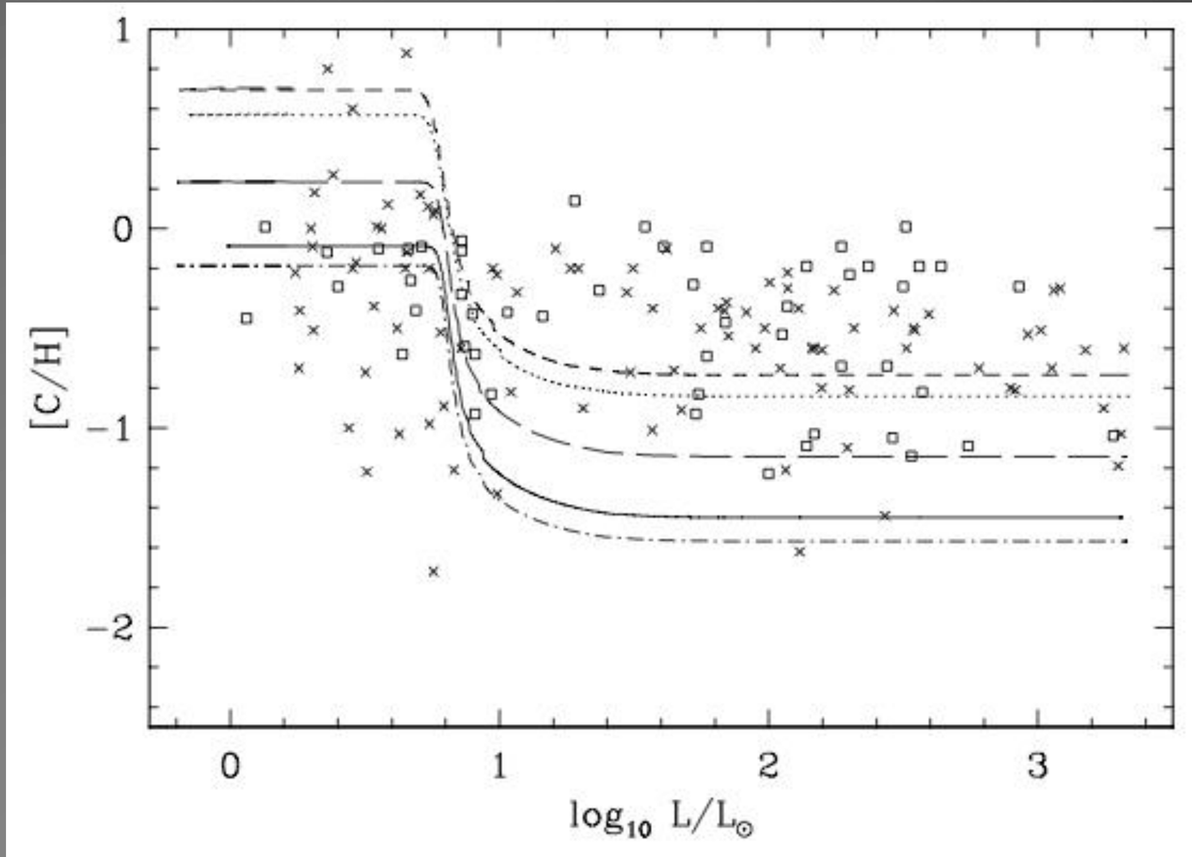


Abate et al. (2015)

MIXING IN THE SECONDARY

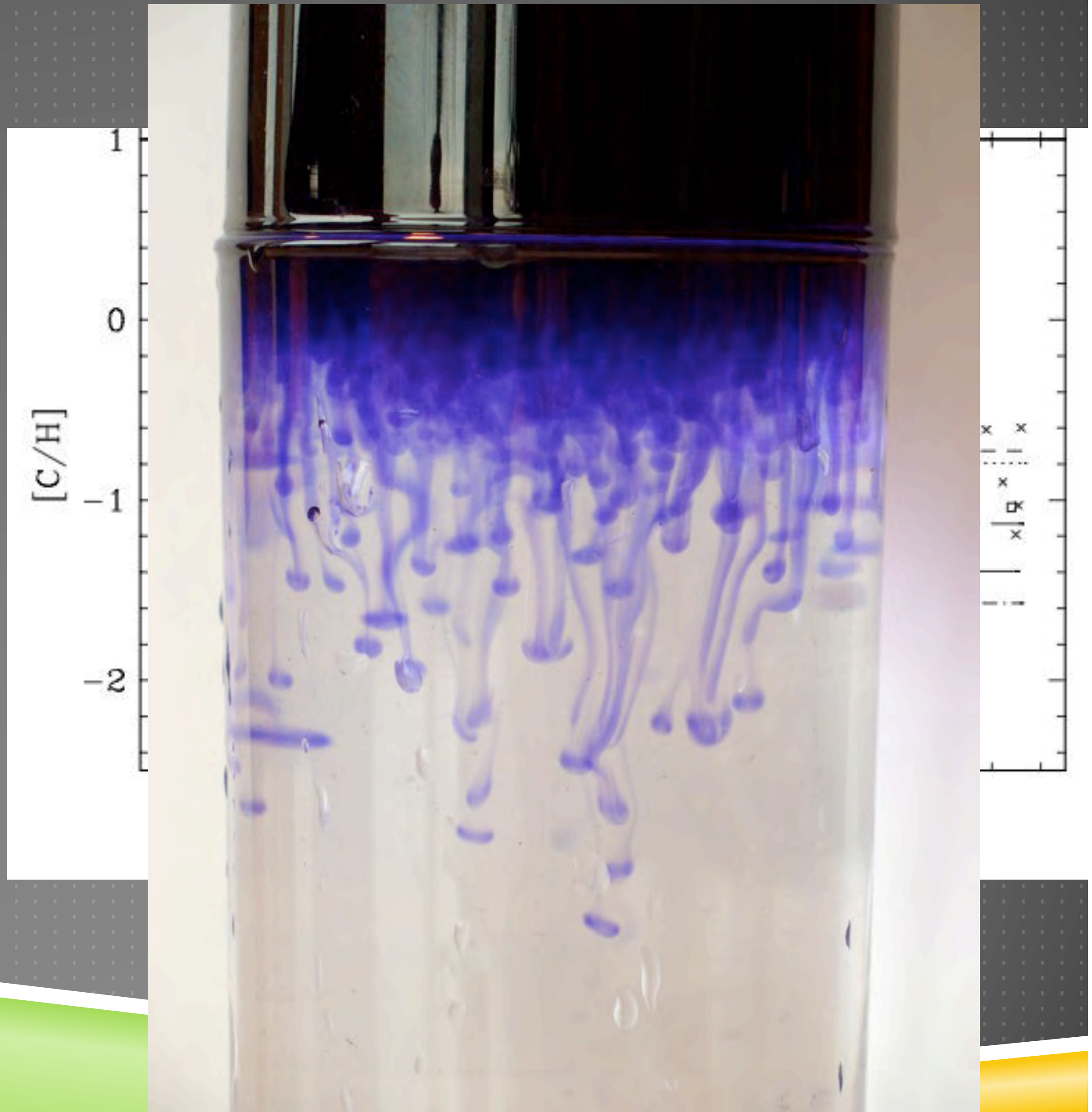
- Low mass stars at $Z=10^{-4}$ have almost no convective envelope
- Accreted material remains at the surface until the onset of first dredge-up
- The material then gets diluted by the deepening of the convective envelope

Stancliffe & Glebbeek (2008)

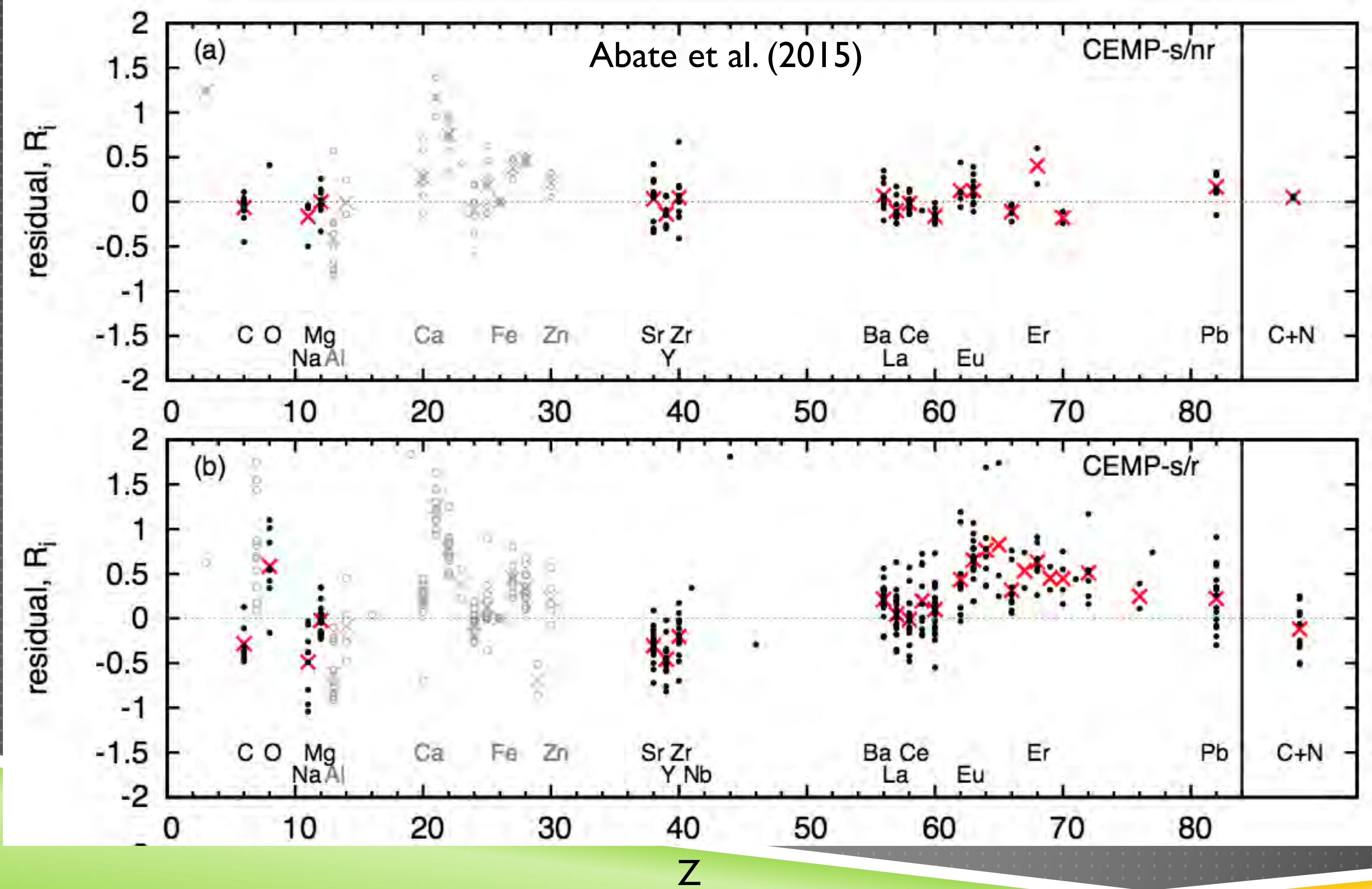


MISSING PHYSICS!

- Accreted material has undergone nuclear burning
- It has a higher mean molecular weight than the rest of the secondary
- It will mixing by thermohaline mixing
- Efficient – takes around 10% of the MS lifetime



ODDBALLS OF ODDBALLS



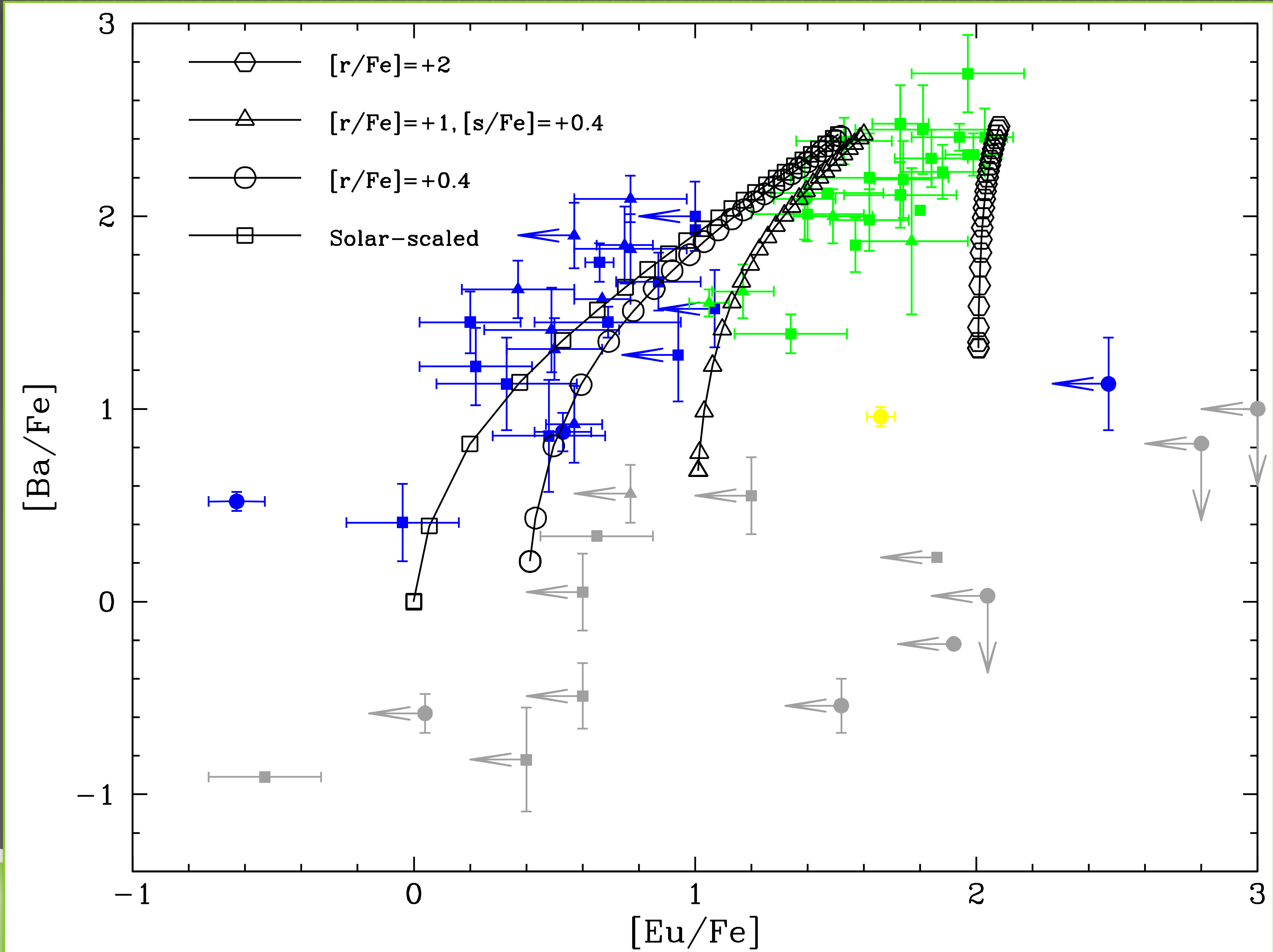
CEMP-RS FORMATION?

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

Problems

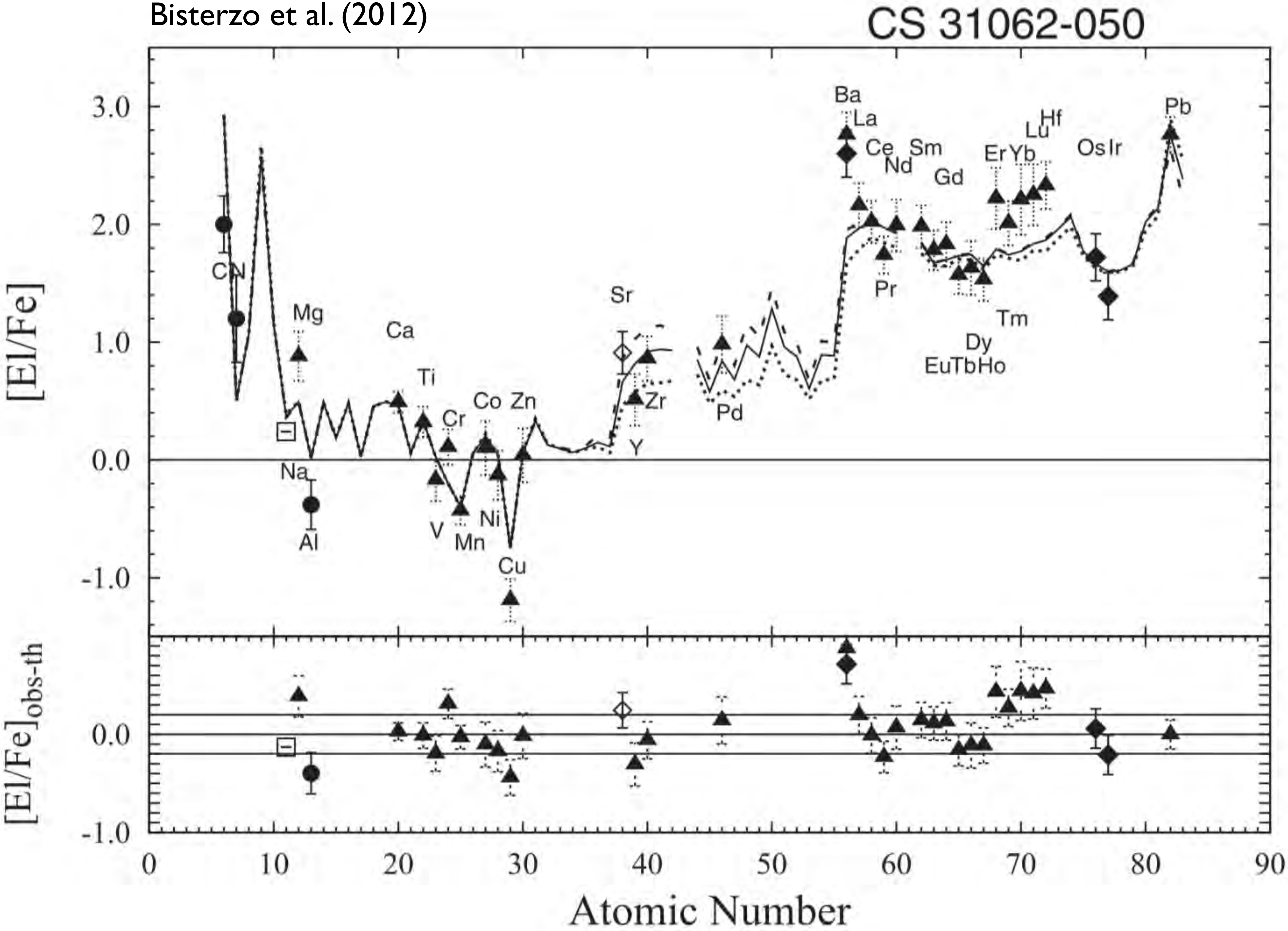
- Cannot self-pollute early enough. Radial velocity variations
-
  - Numbers not favourable
  - Nucleosynthesis and remnant
- Requires three phases of mass transfer, not likely!

CEMP-RS?

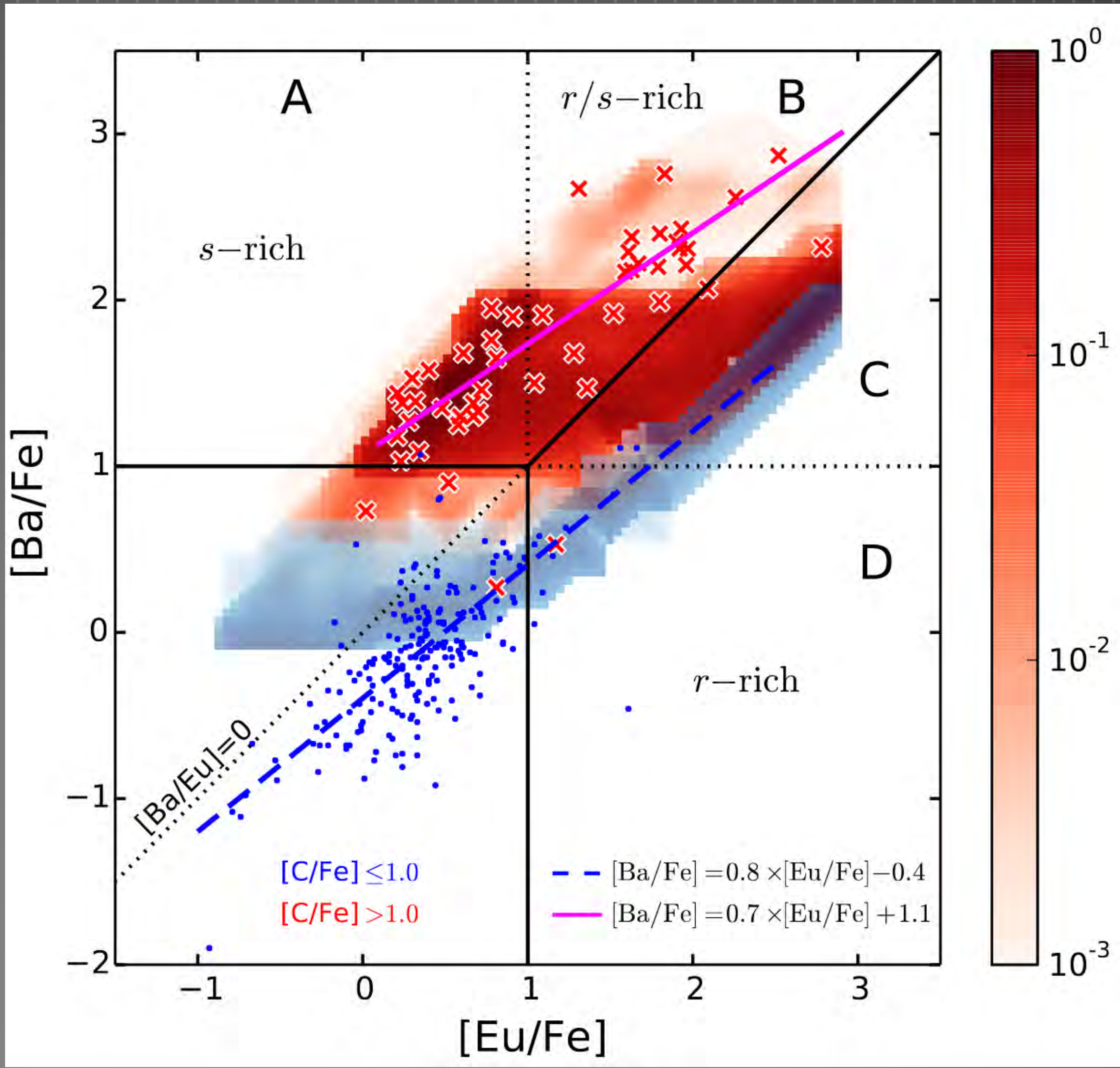


Lugaro et al. (2012)

Bisterzo et al. (2012)

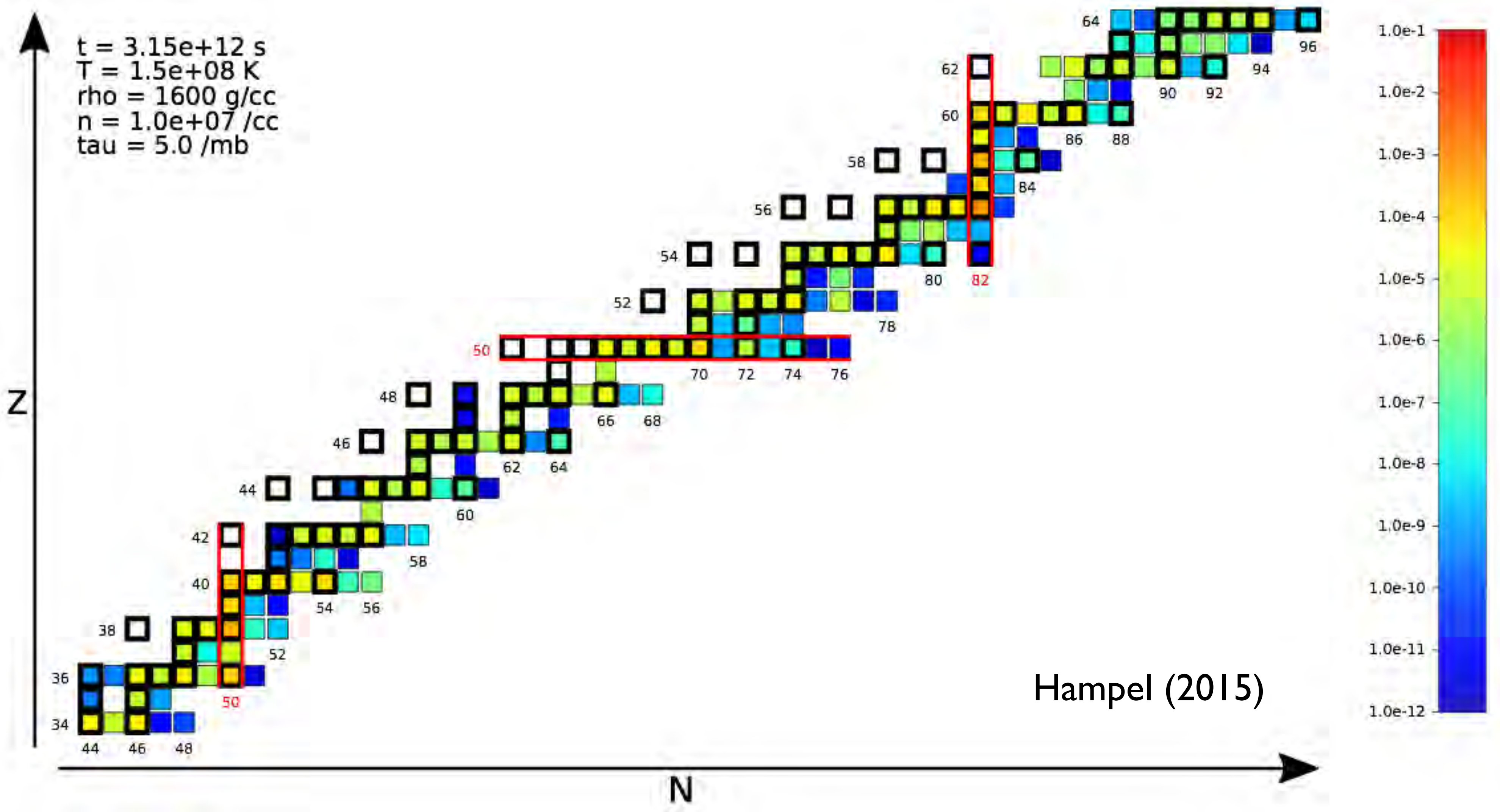


- Population arguments
- Assume the initial population covers the [Eu/Fe] range
- Pollute with s-process
- Too few very Ba-rich stars
- Too many Eu-rich C-normals

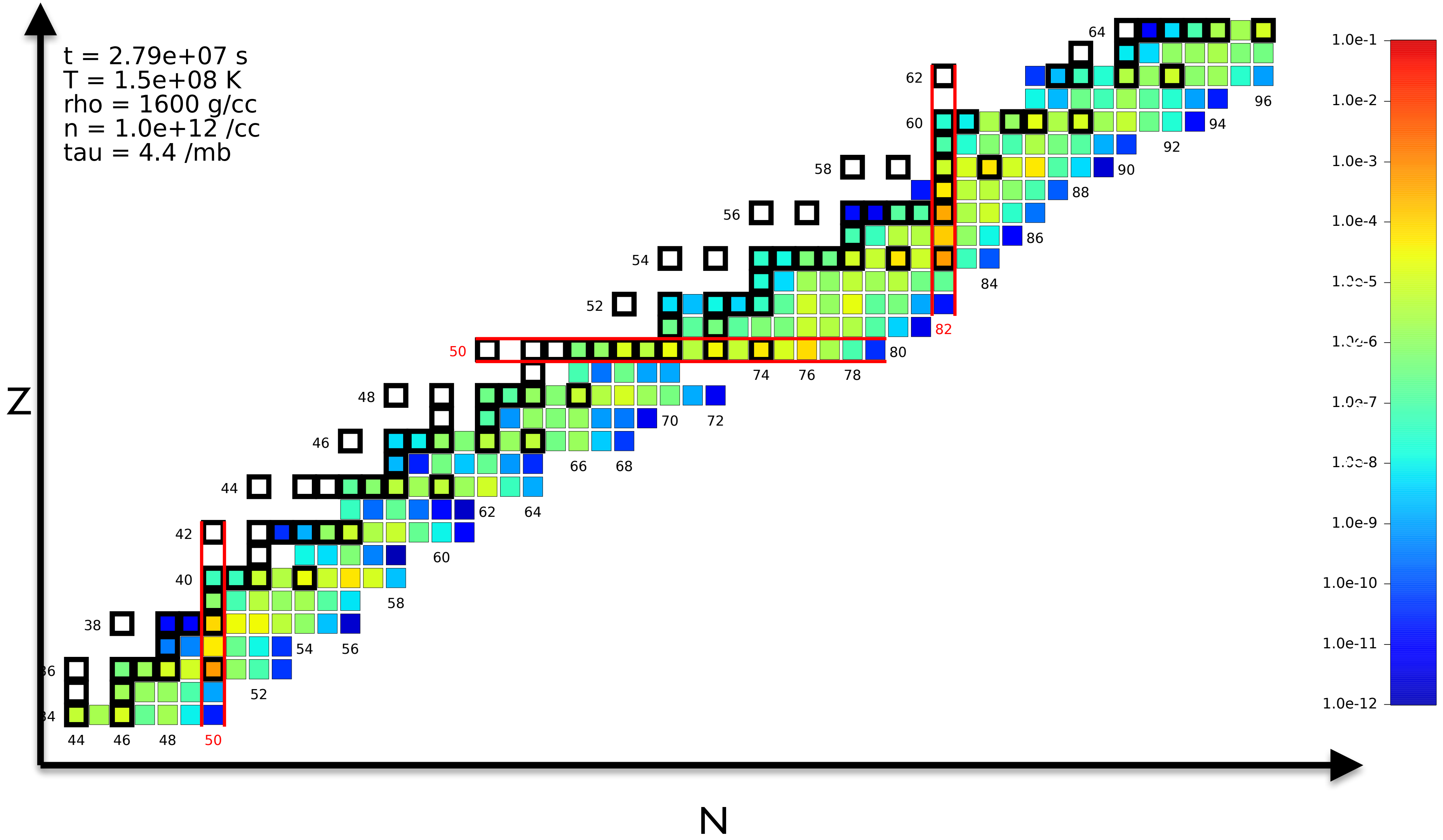


Abate, Stancliffe & Liu (2016)

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

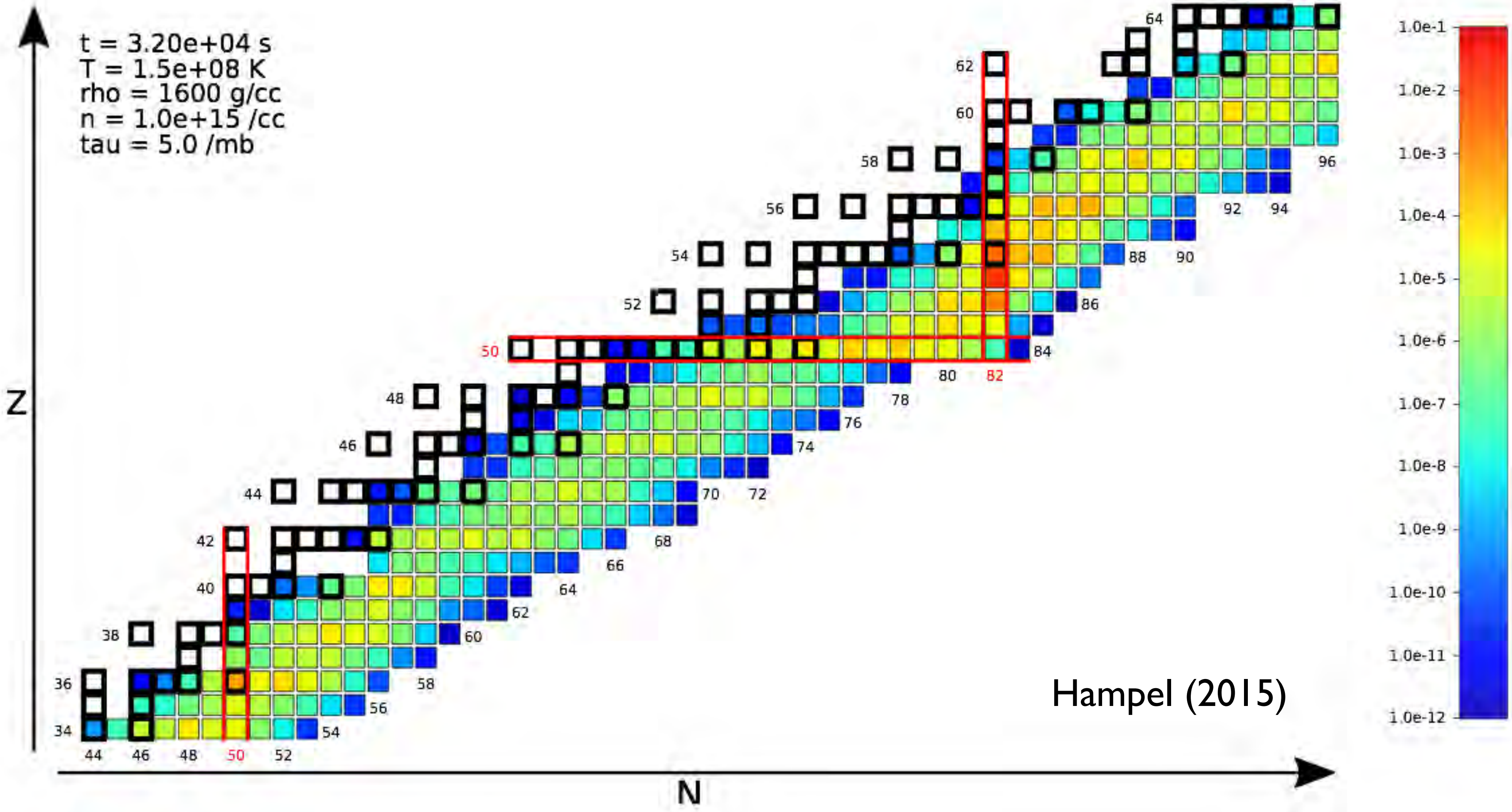


$n = 10^{12}\ cm^{-3}$

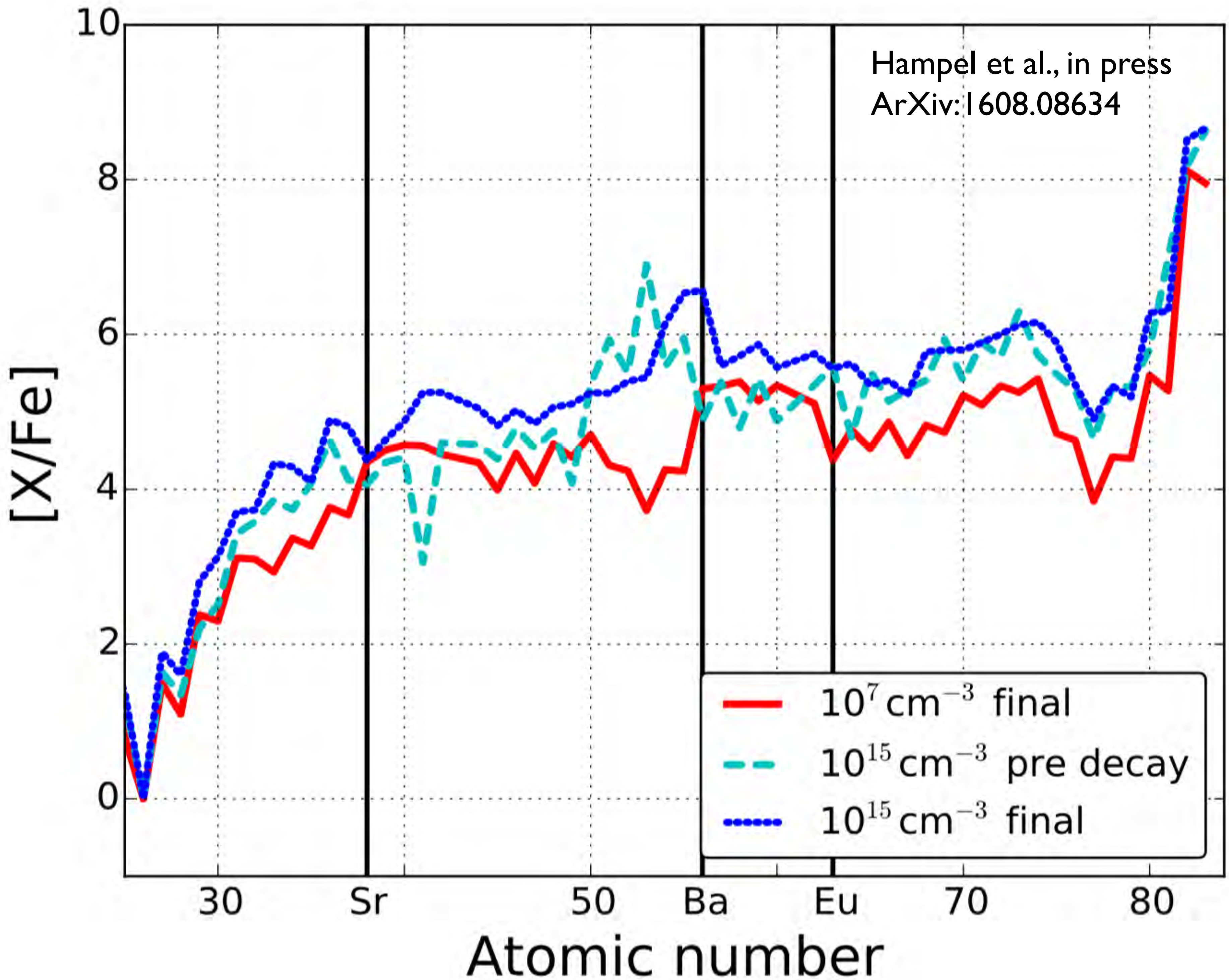


t = 2.79e+07 s
T = 1.5e+08 K
rho = 1600 g/cc
n = 1.0e+12 /cc
tau = 4.4 /mb
Z
N
1.0e-1
1.0e-2
1.0e-3
1.0e-4
1.0e-5
1.0e-6
1.0e-7
1.0e-8
1.0e-9
1.0e-10
1.0e-11
1.0e-12

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



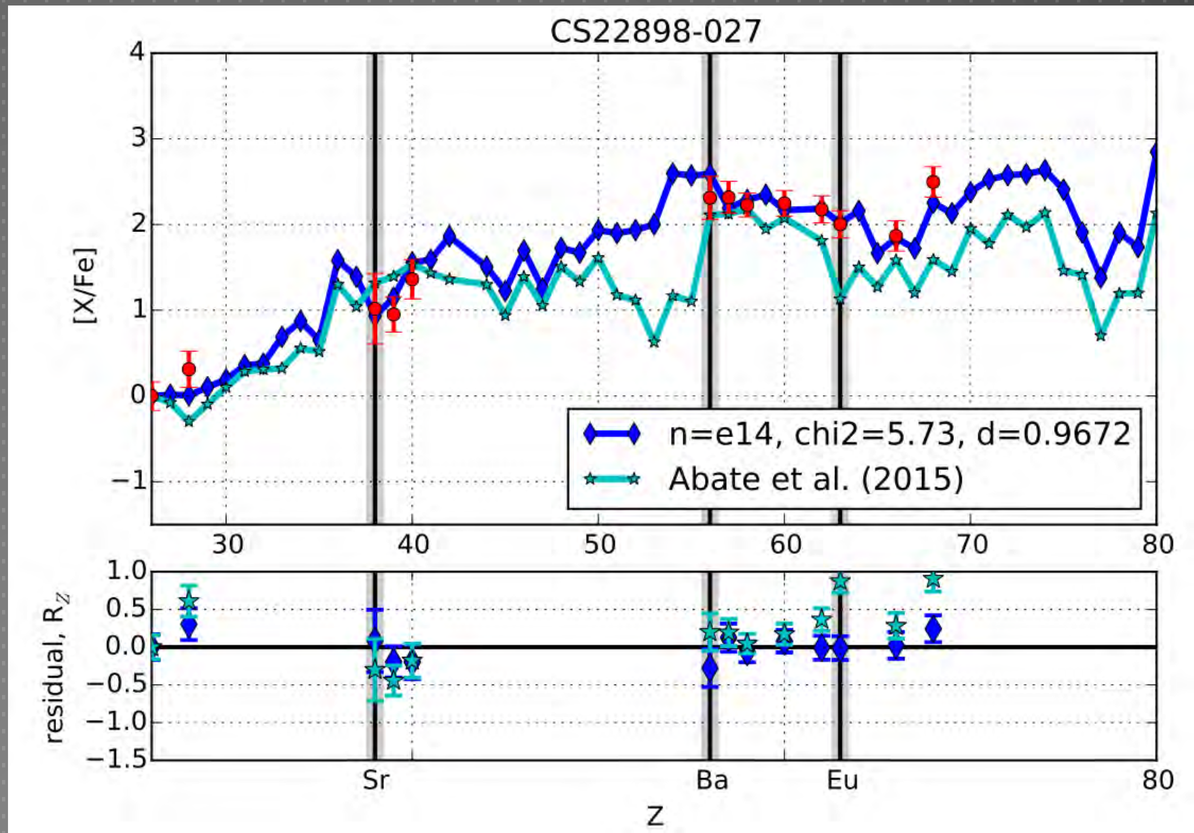
Hampel (2015)



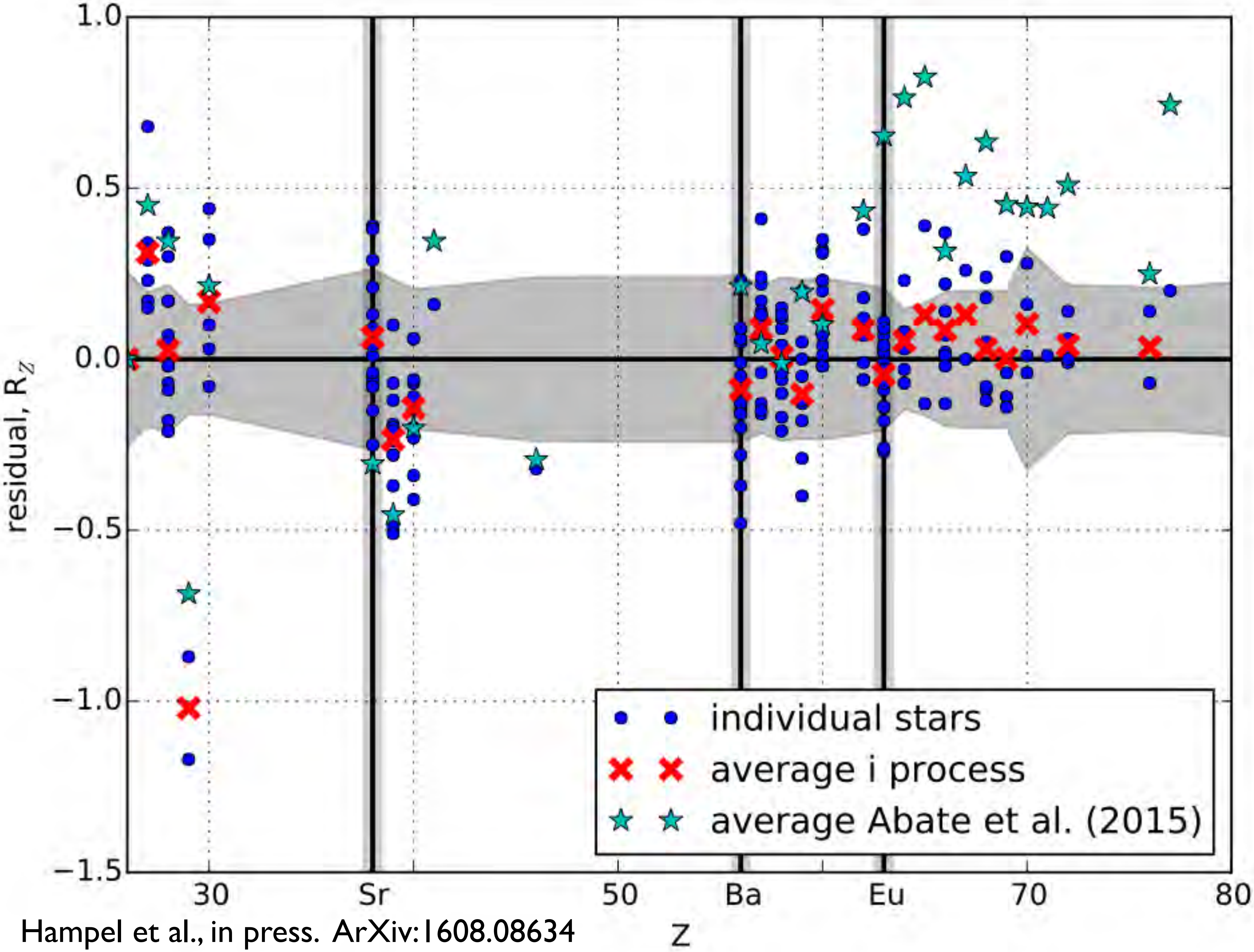
Hampel et al., in press
ArXiv:1608.08634
[X/Fe]
10
8
6
4
2
0
30
Sr
50
Ba
Eu
70
80
Atomic number
10^7 cm^{-3} final
10^{15} cm^{-3} pre decay
10^{15} cm^{-3} final

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, Denissenkov et al. 2016)

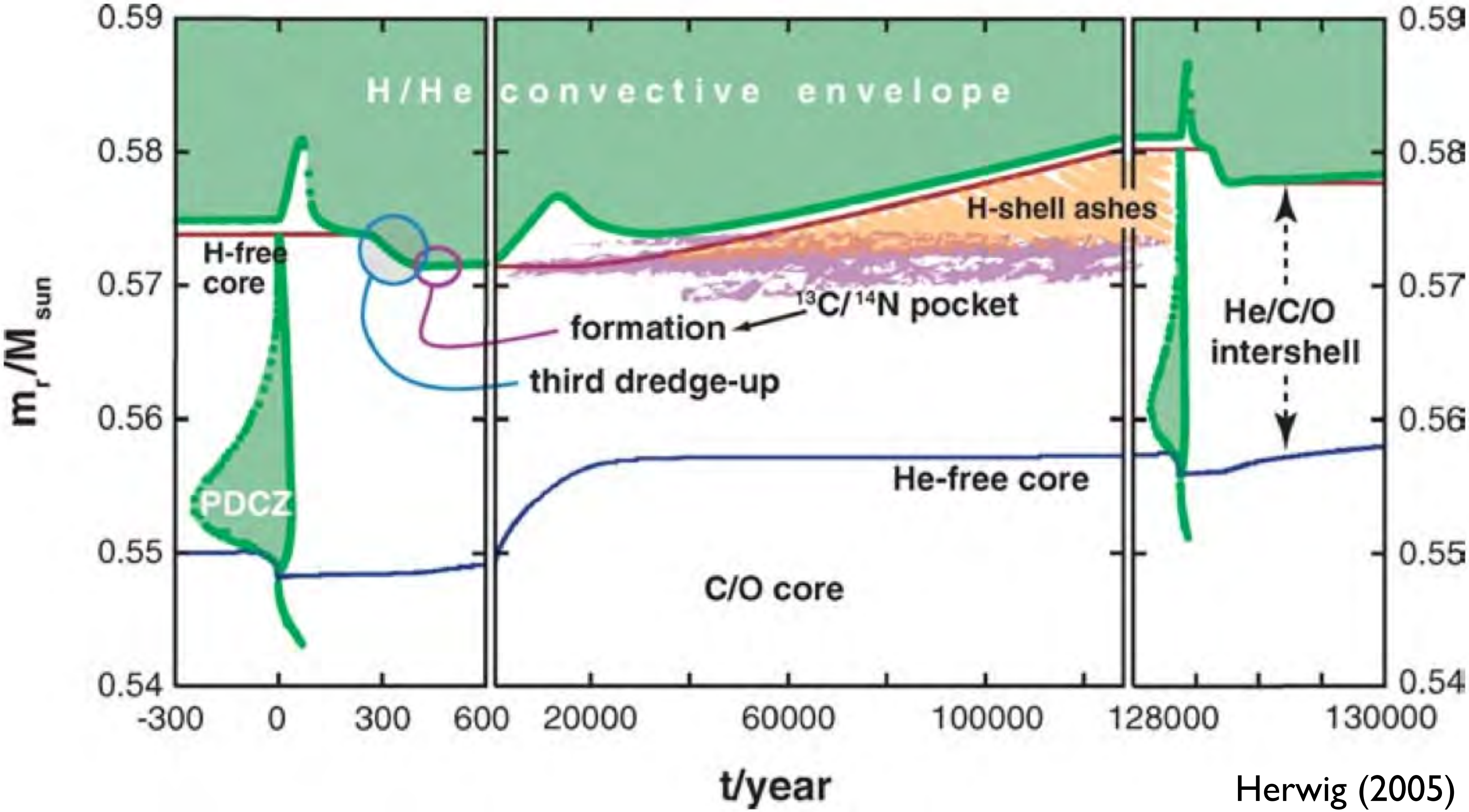


Hampel et al., in press



Hampel et al., in press. ArXiv:1608.08634

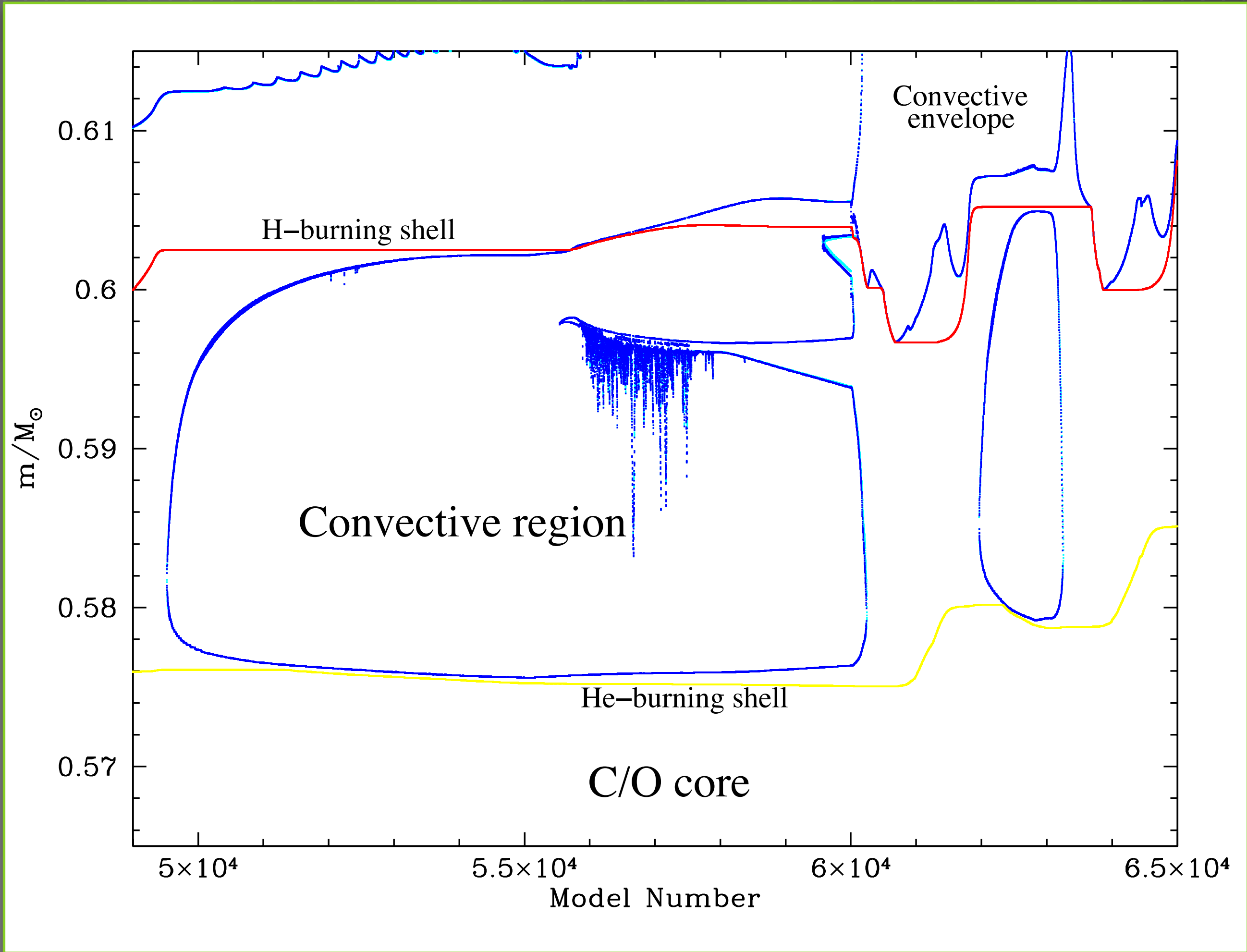
WHERE DOES IT HAPPEN?



Herwig (2005)

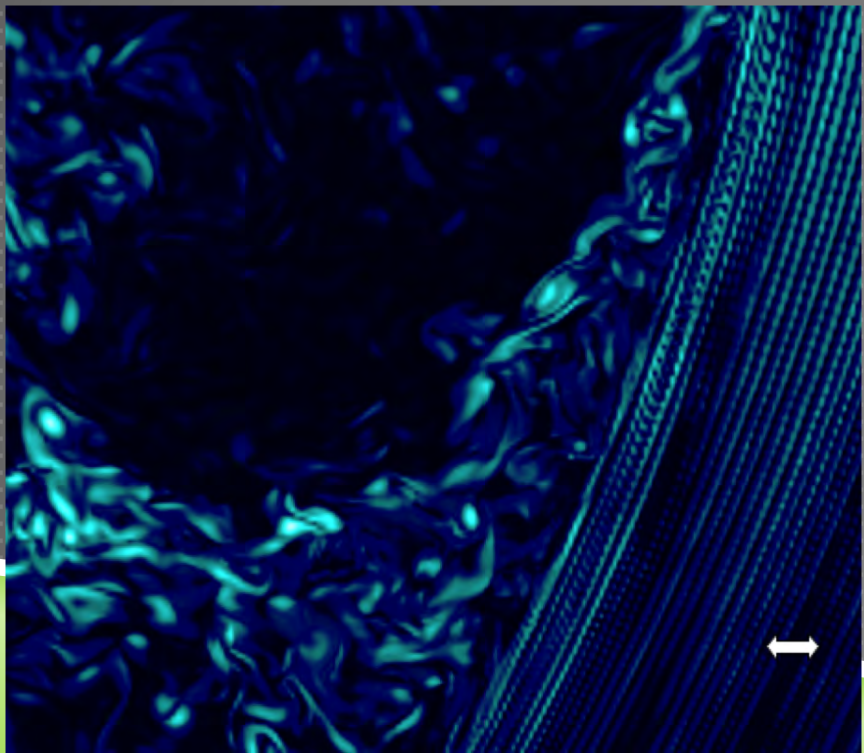
PROTON INGESTION

- Evolution changes at low metallicity
- He driven convection no longer trapped below the H-burning shells
- Proton can be drawn into the convective region
- Mixing, burning take place on similar timescales – hard to get this right in a 1D code!

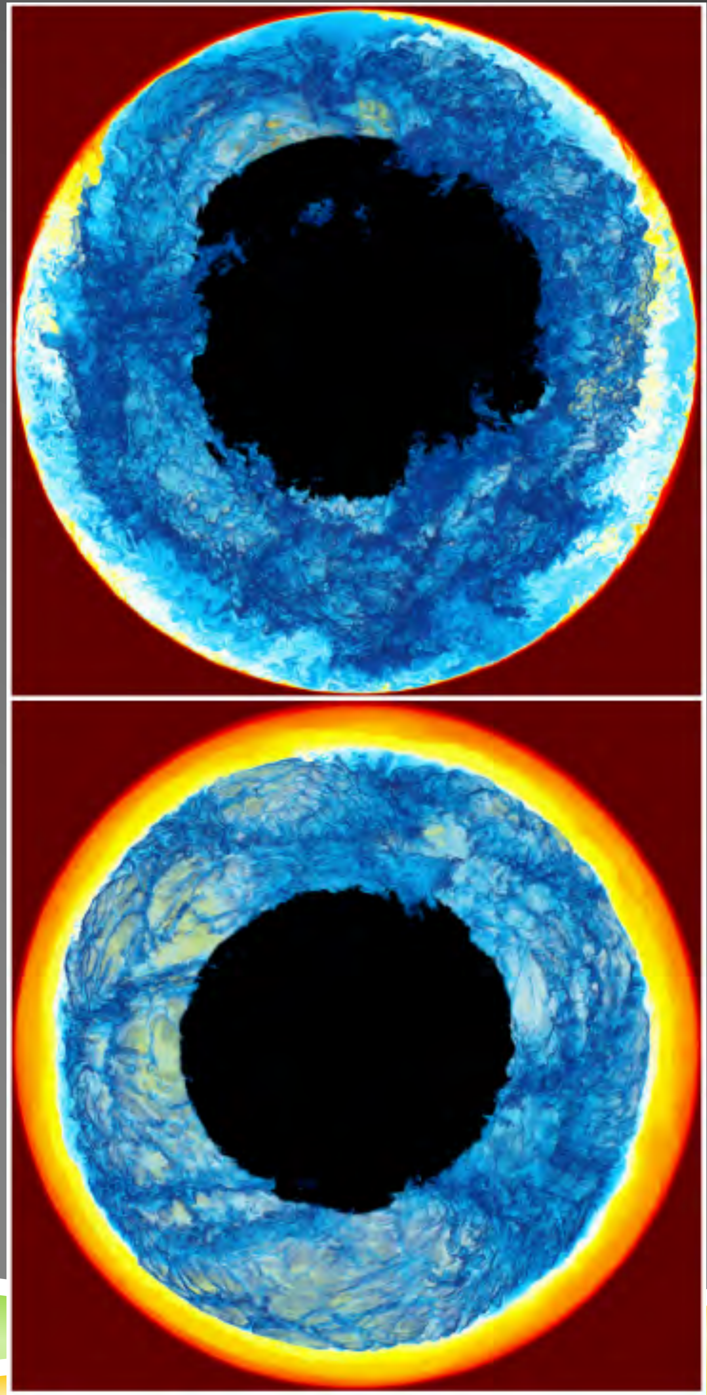


Lau, Stancliffe & Tout (2009)

- Exquisitely detailed simulations now being produced
- Highest resolution 1536^3
- VLTP – but ingestion physics should be the same
- Can we resolve the necessary details?



Herwig et al. (2014)

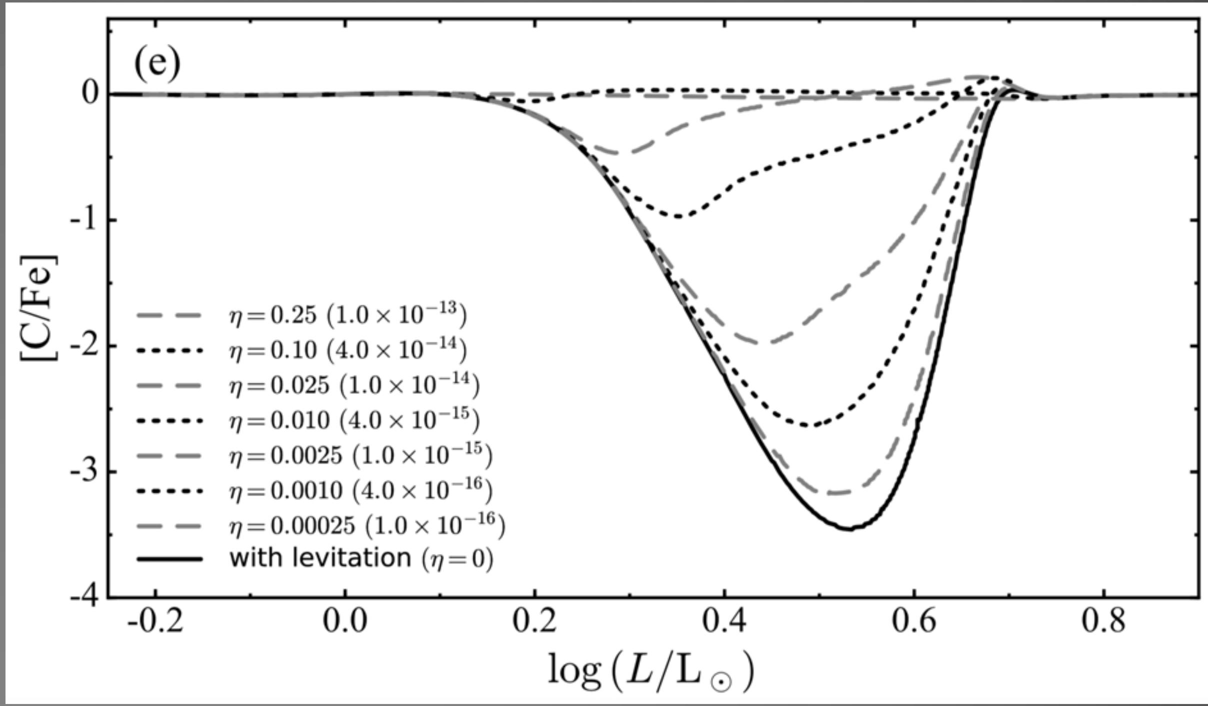


SUMMARY

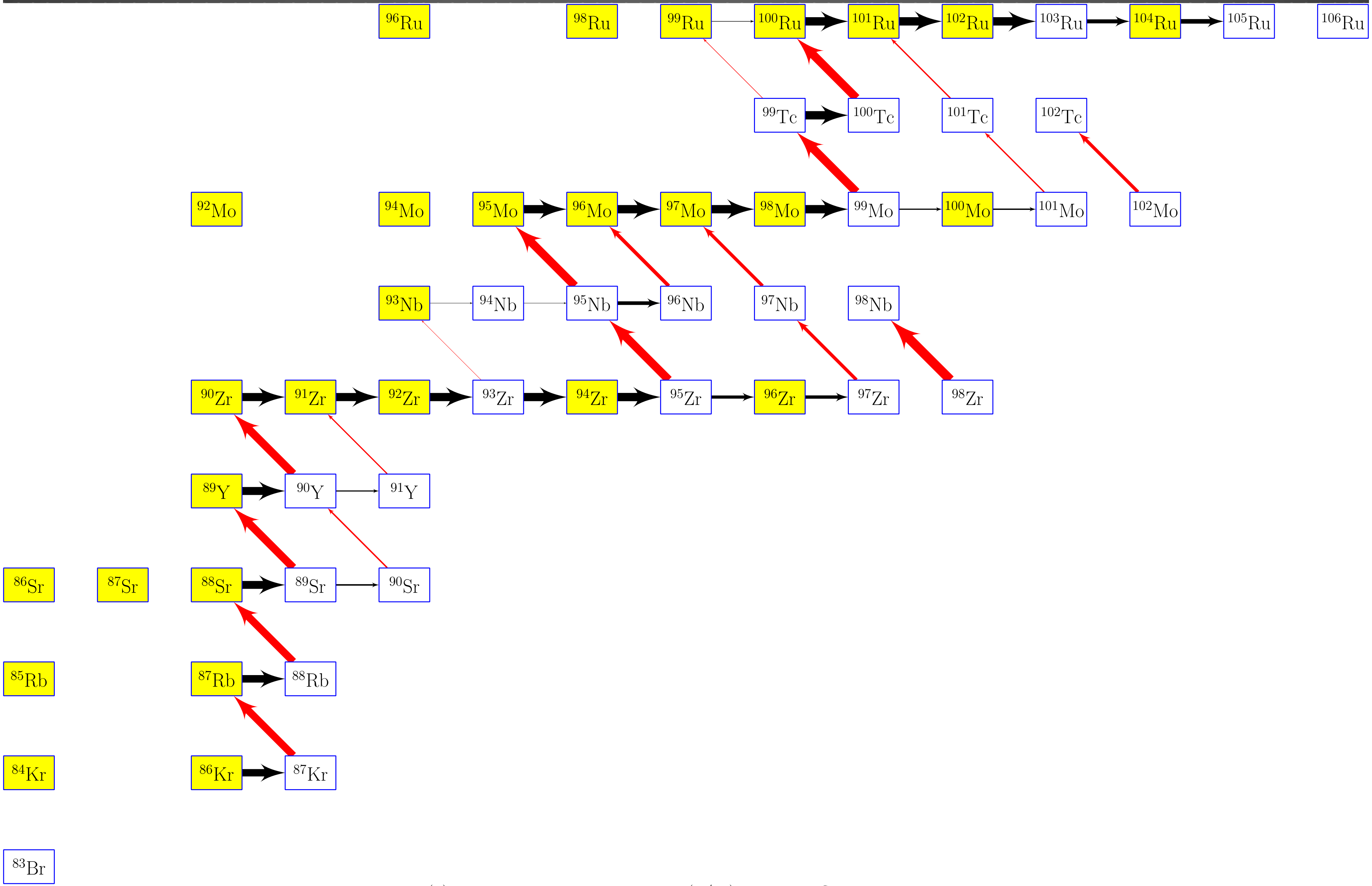
- CEMP stars with barium enhancement come from binary systems
  - Still issues with mass transfer, orbital properties
- CEMP-s/r stars not readily explained by current scenarios
- Moderate neutron densities n = 10^{14} cm^3 give an interemediate n-capture process
- This seems to fit very well
- But where does it take place???

OTHER MODIFICATIONS

- Settling and levitation
- Countered by something?
  - Mass loss
  - Ad hoc mixing (Richard et al. 2005)
- Rotation



Matrozis & Stancliffe (2016)



$time(s) = 2.046e + 12 \quad T_9 = 0.2 \quad \rho(g/cc) = 1000 \quad \text{flow}_{max} = 2.72e - 21$