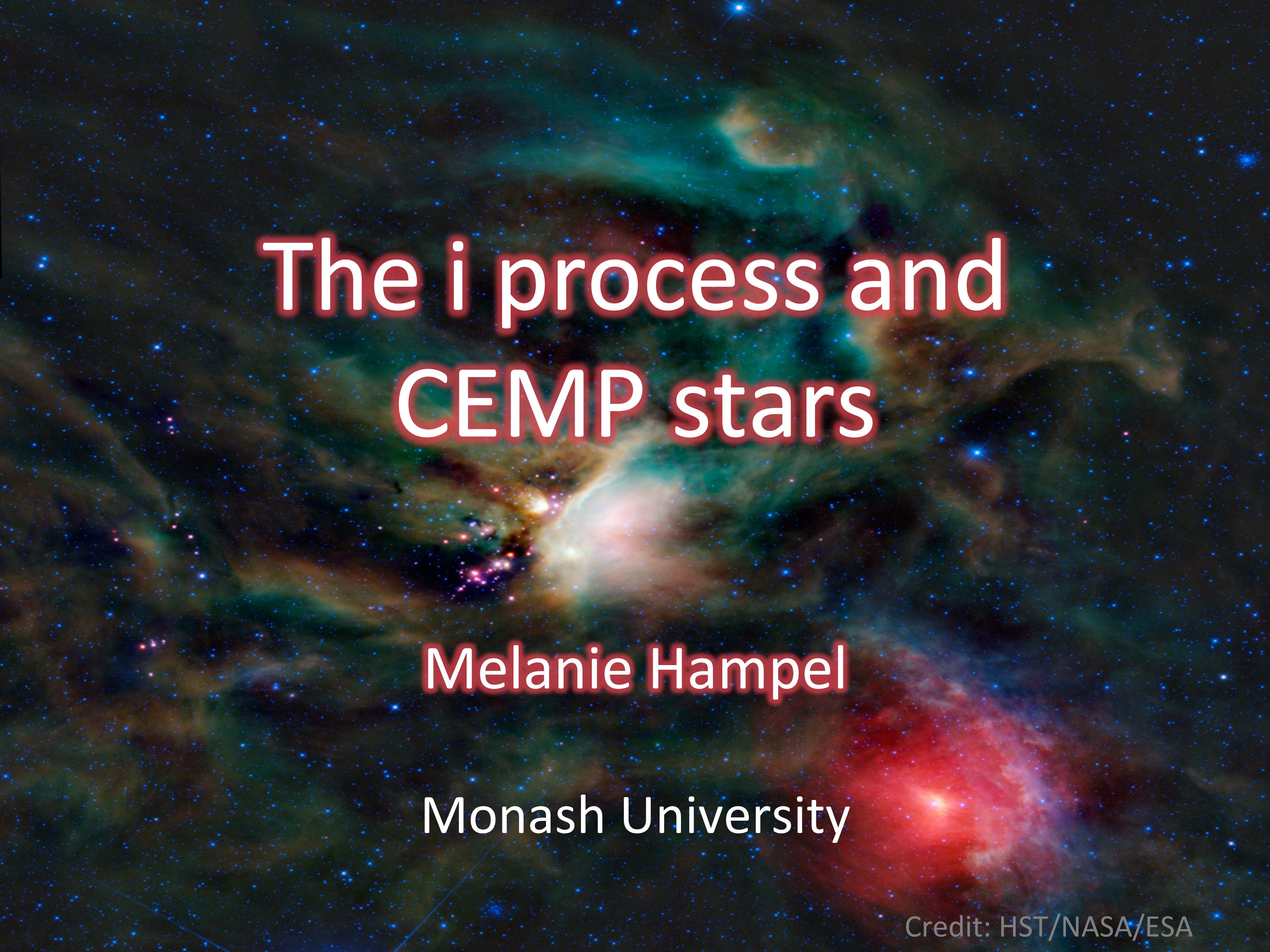
The i process and CEMP stars

Melanie Hampel

Monash University



Credit: HST/NASA/ESA

With thanks to…

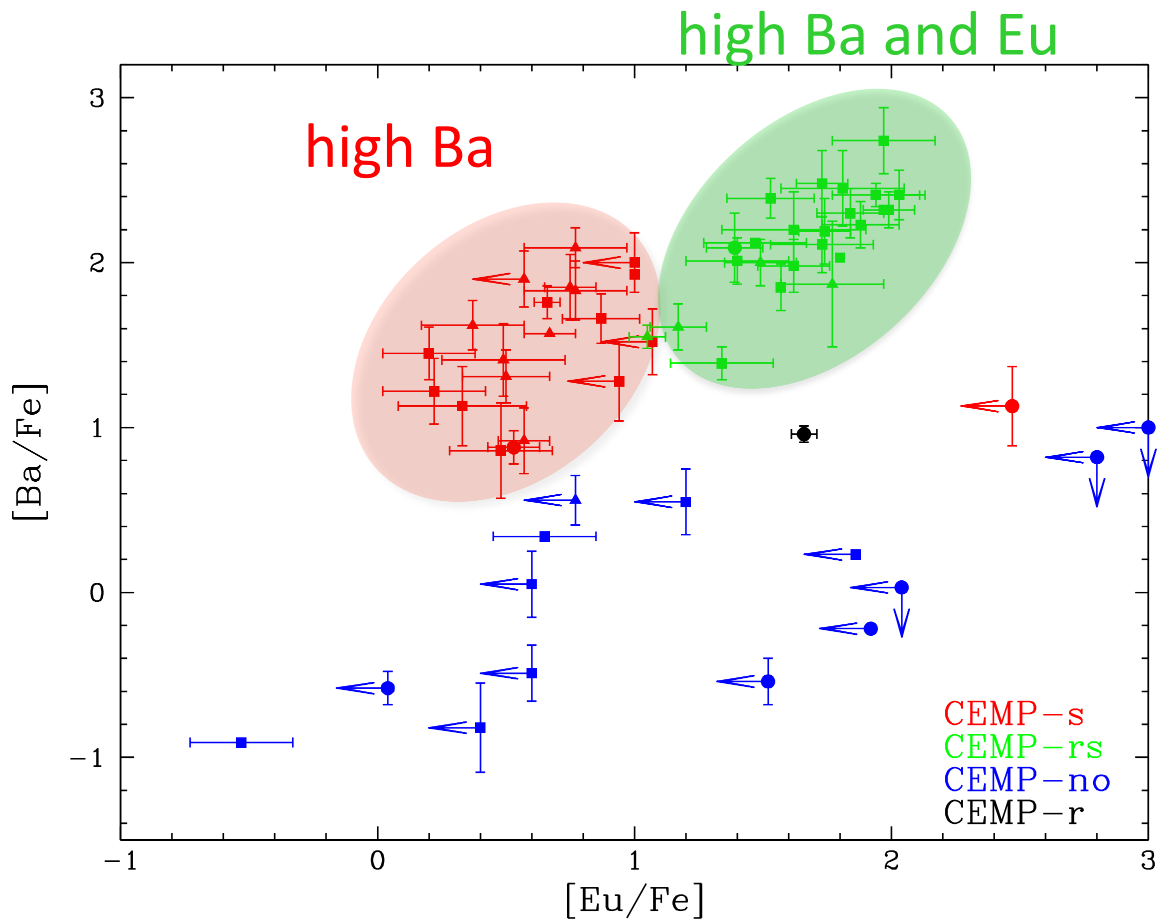
Richard J. Stancliffe

Maria Lugaro
(Budapest)

Bradley Meyer
(Clemson)

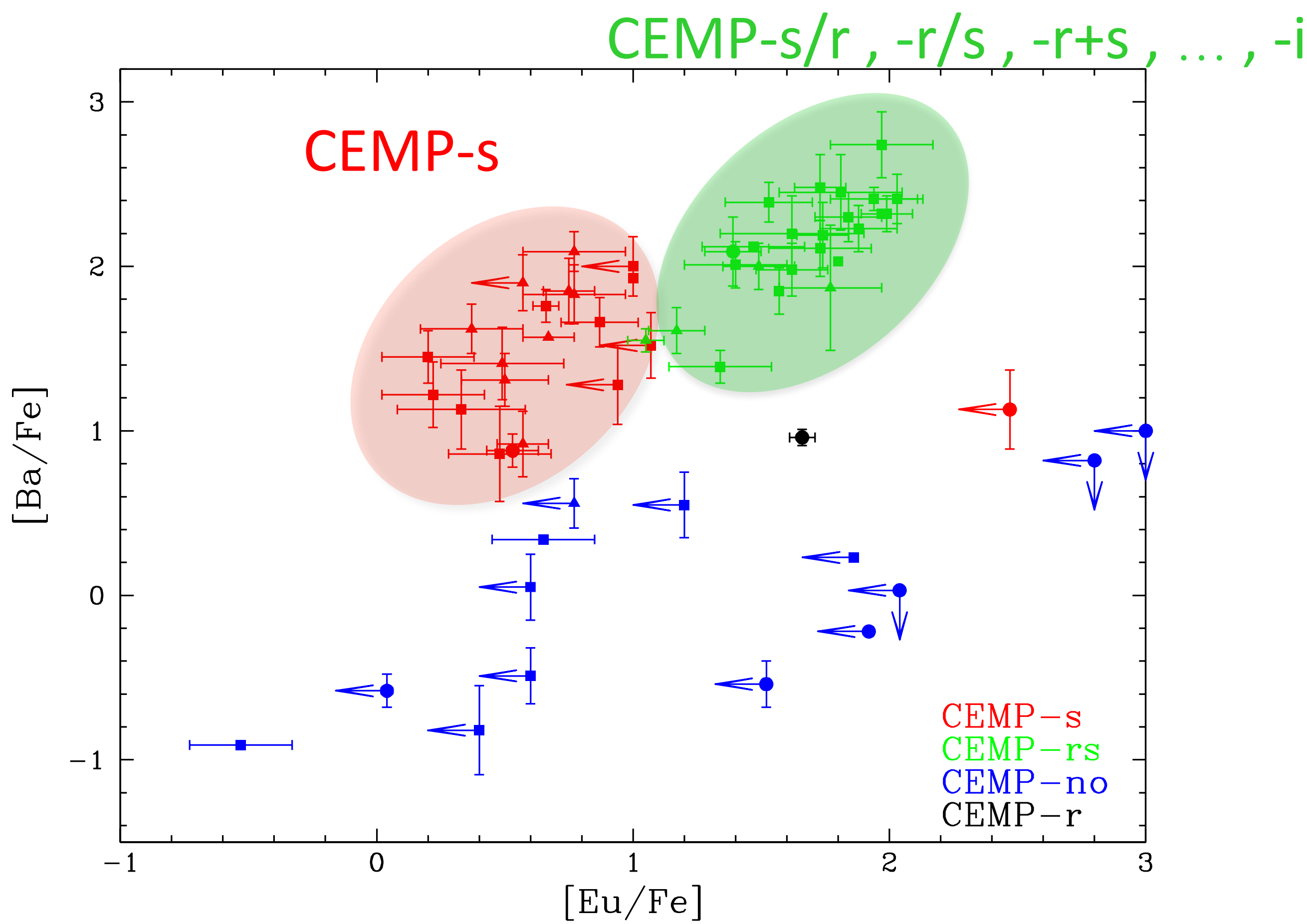
Credit: HST/NASA/ESA

CEMP stars: heavy elements



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

CEMP stars: heavy elements

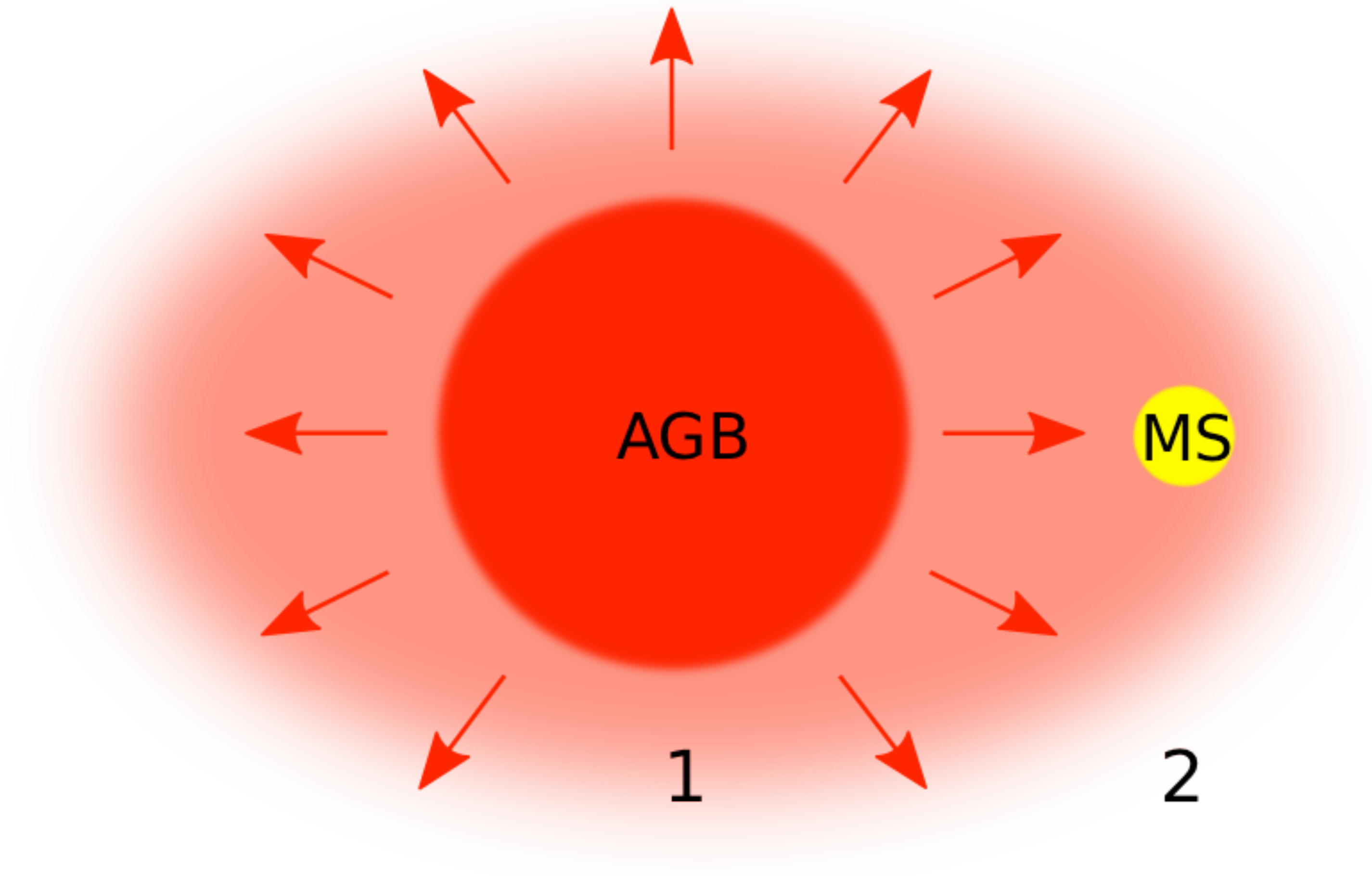


Lugaro et al. (2012), data from Masseron et al. (2010)

Formation of CEMP-s stars

Credit: Carlo Abate

Formation of CEMP-s stars



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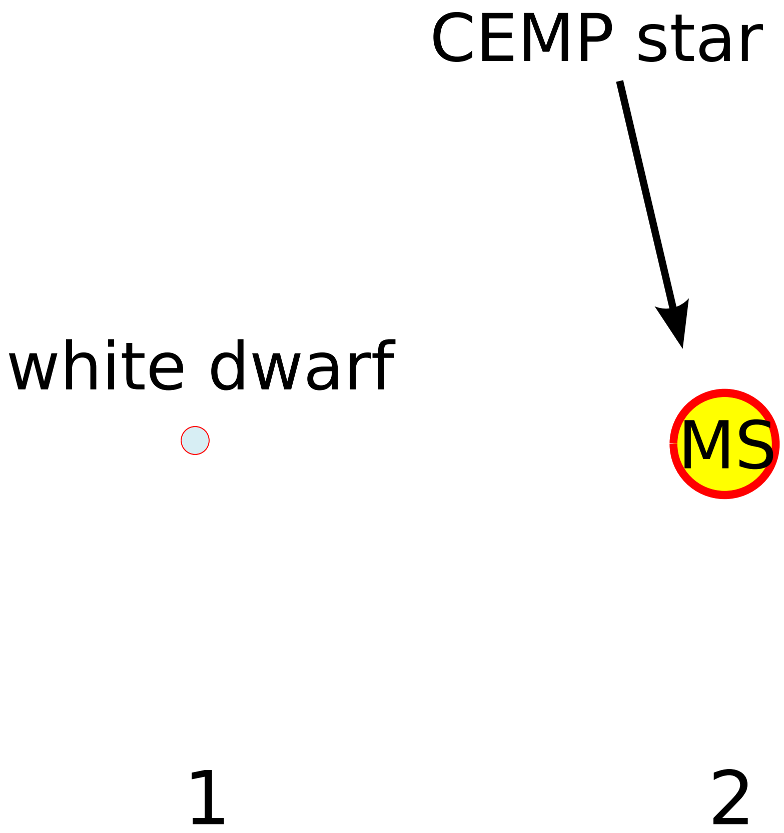
Formation of CEMP-s stars



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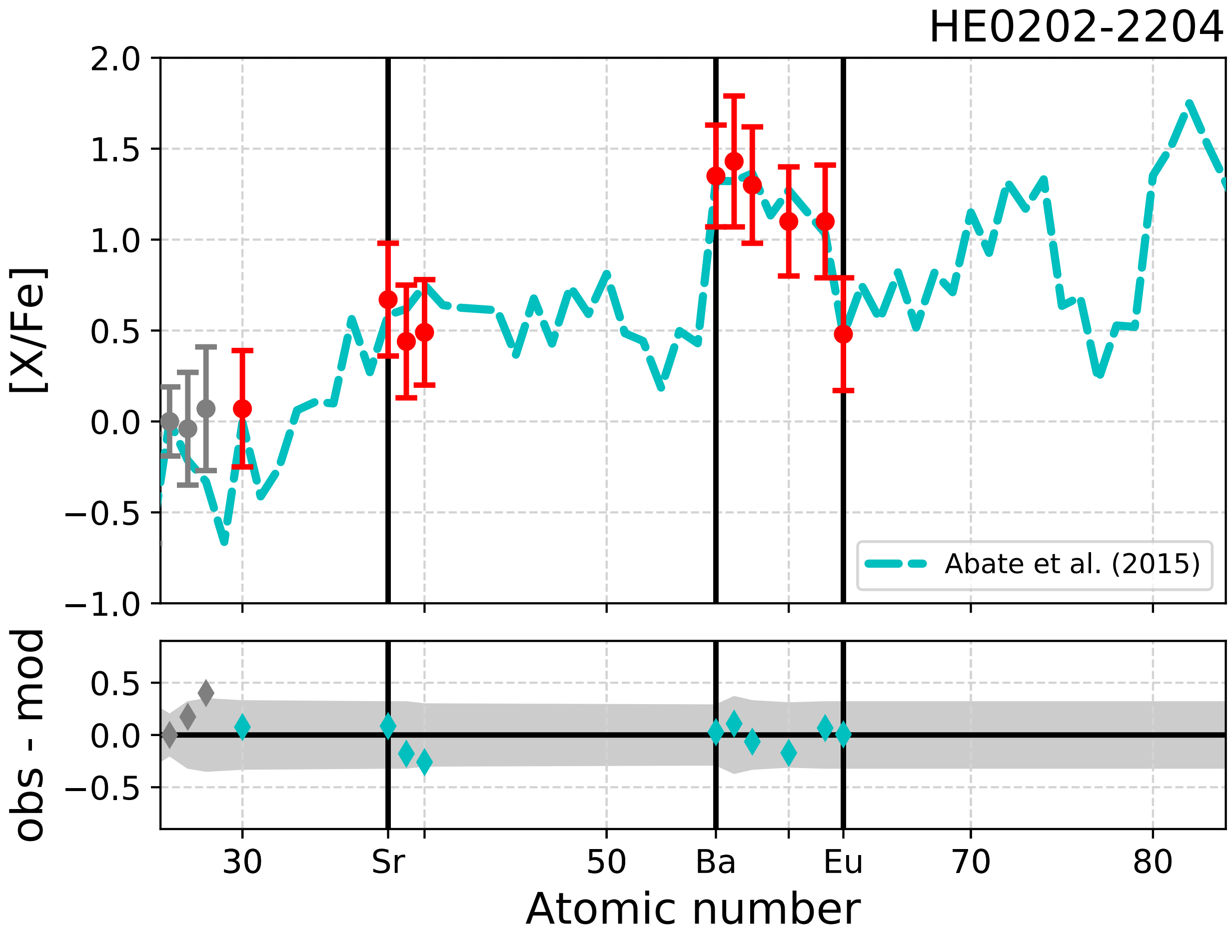
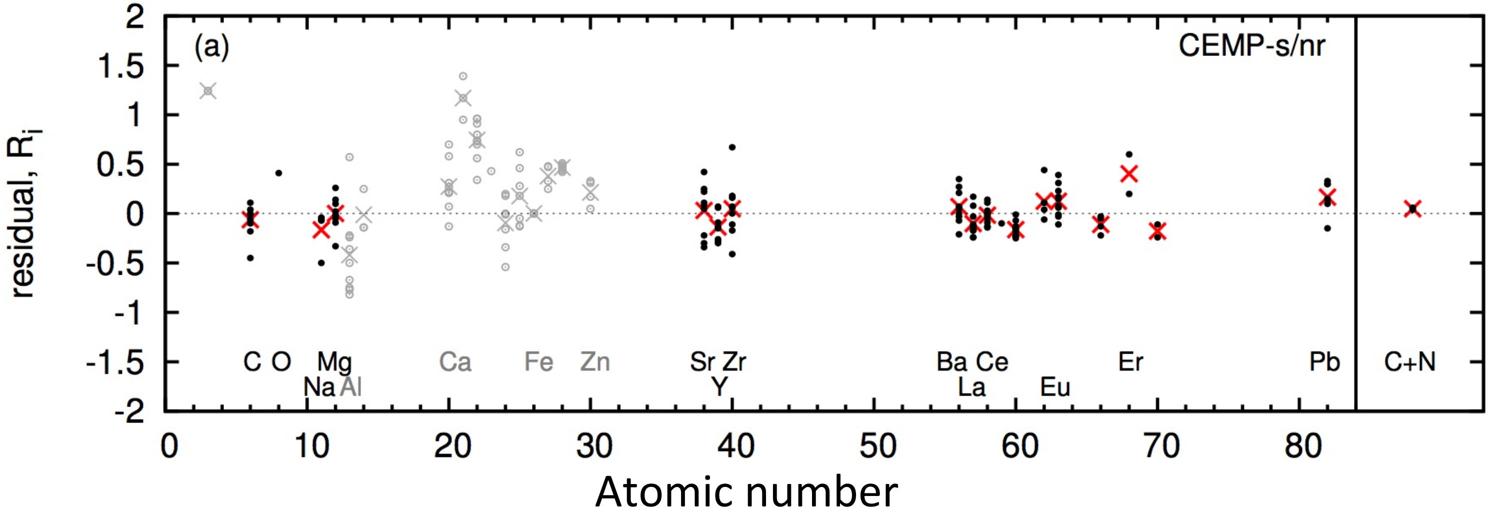
Binary evolution + AGB nucleosynthesis ?



Abate et al. (2015)

Binary evolution + AGB nucleosynthesis ?

CEMP-s



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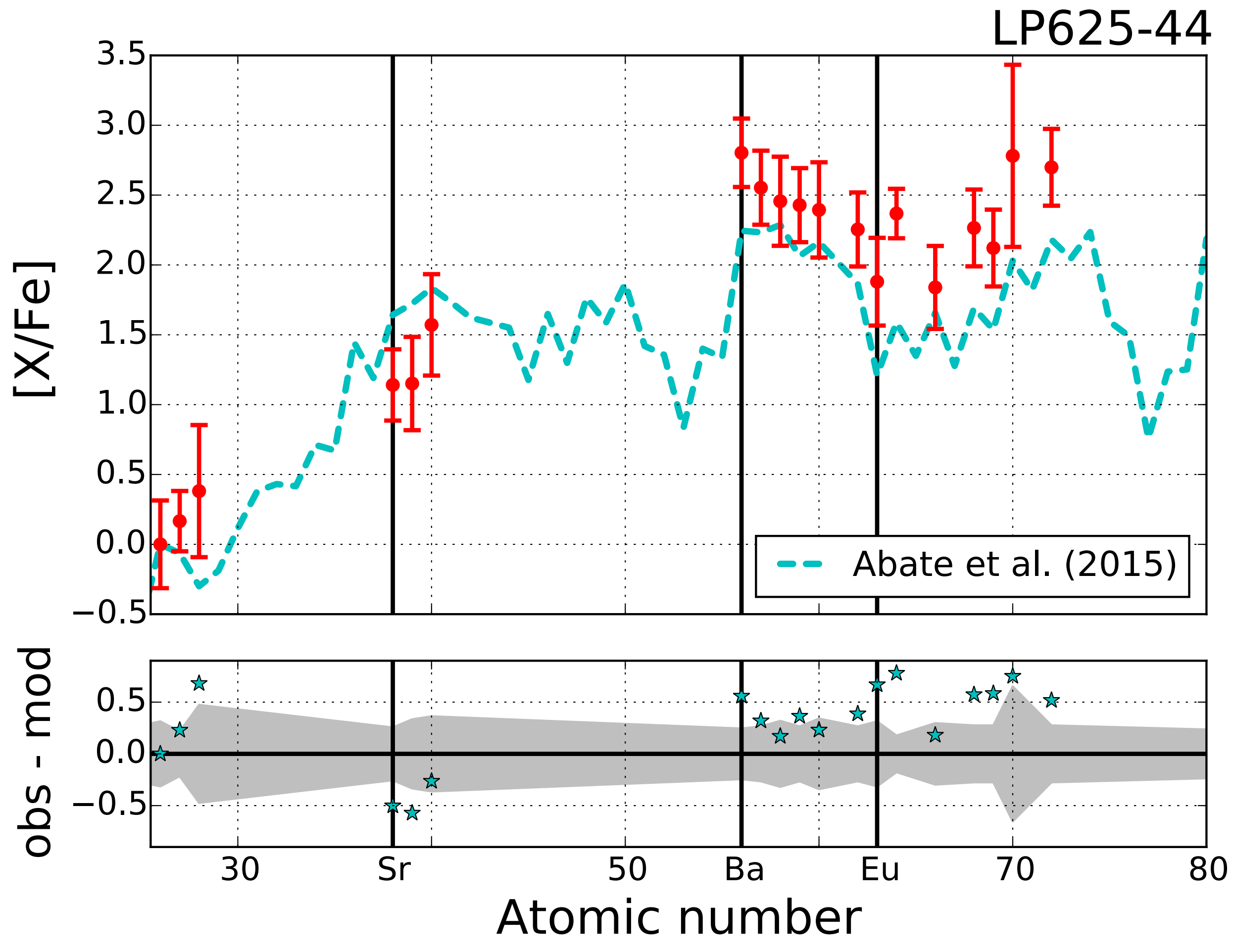

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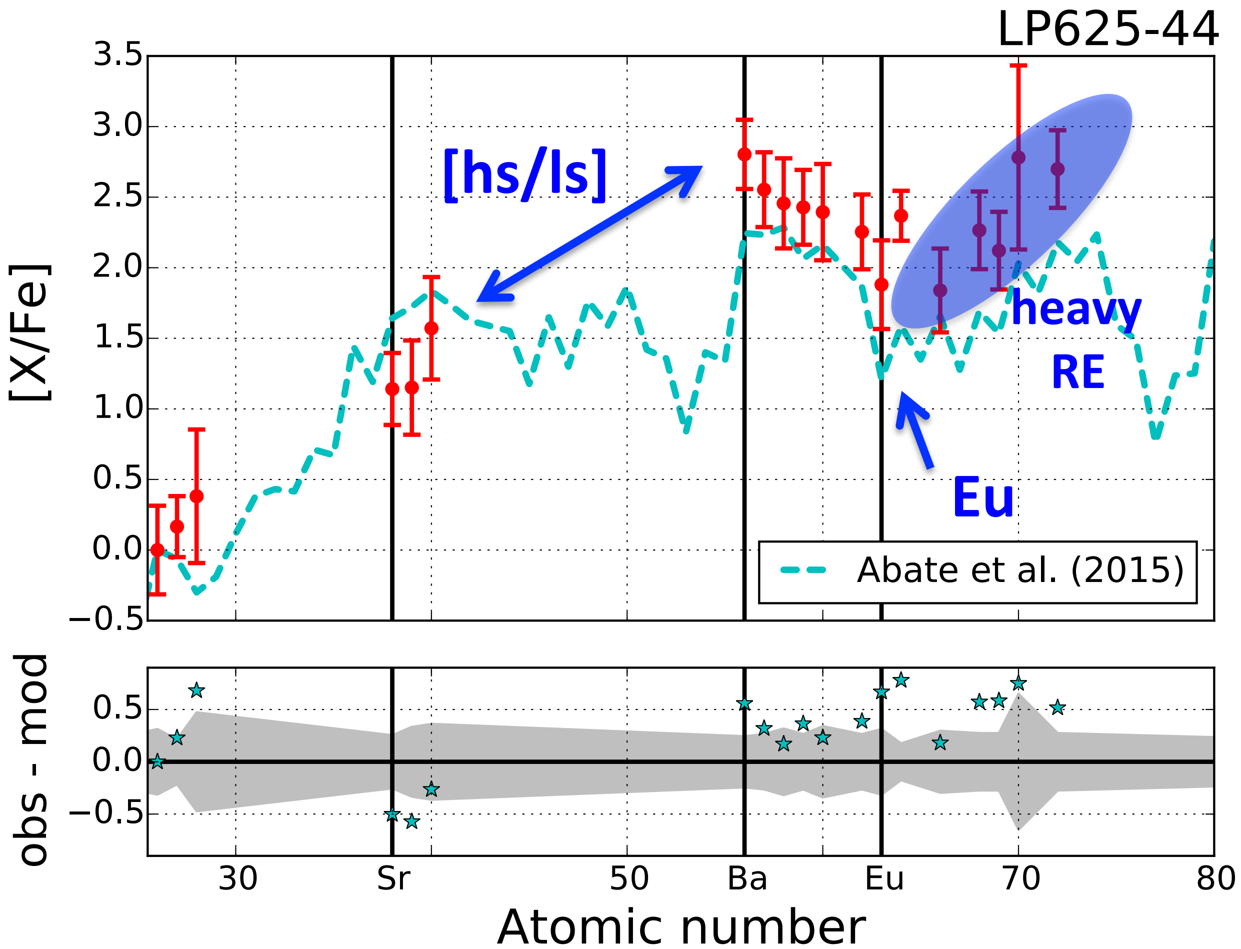
Binary evolution + AGB nucleosynthesis ?

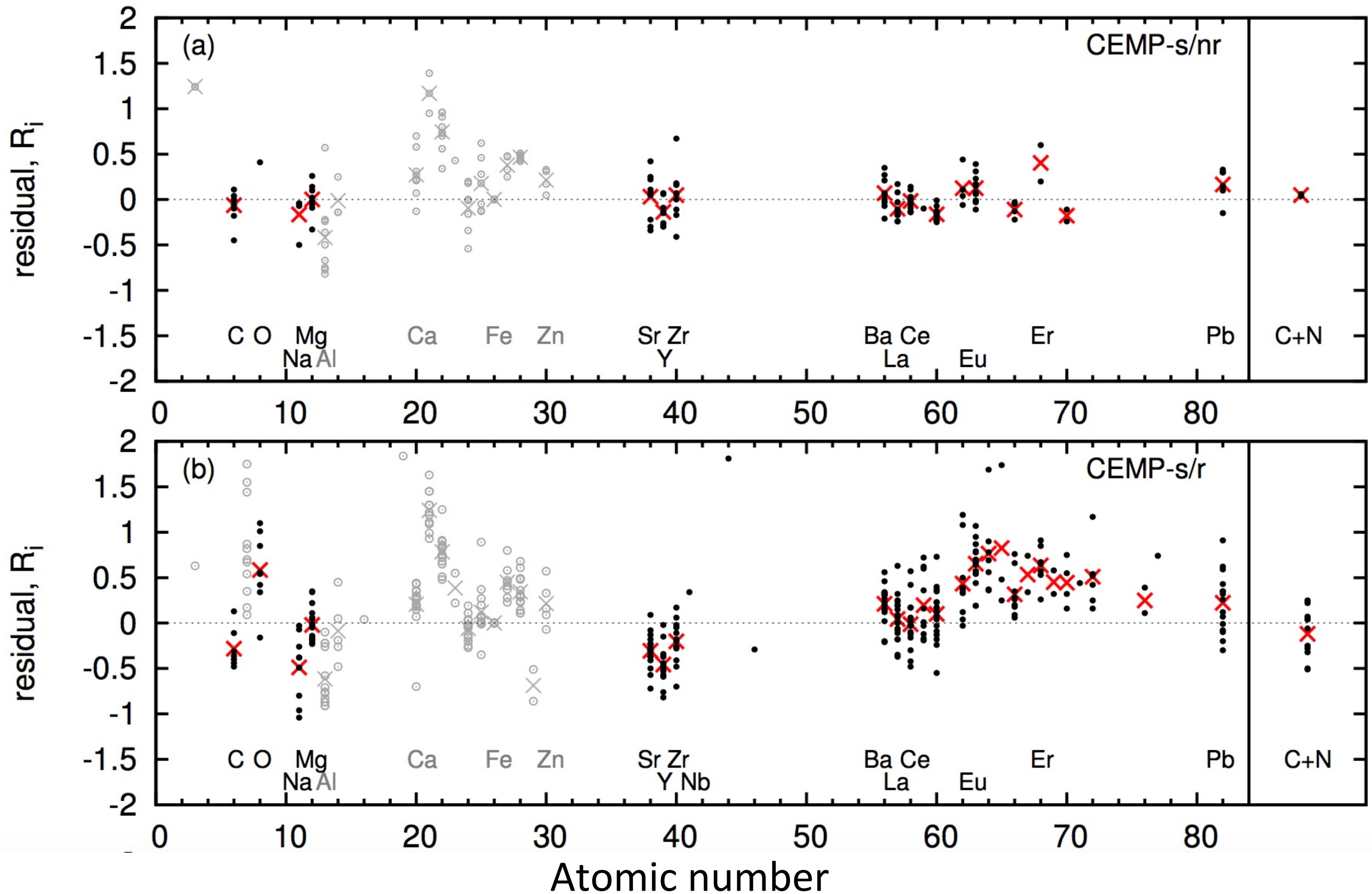


Abate et al. (2015)

Binary evolution + AGB nucleosynthesis ?

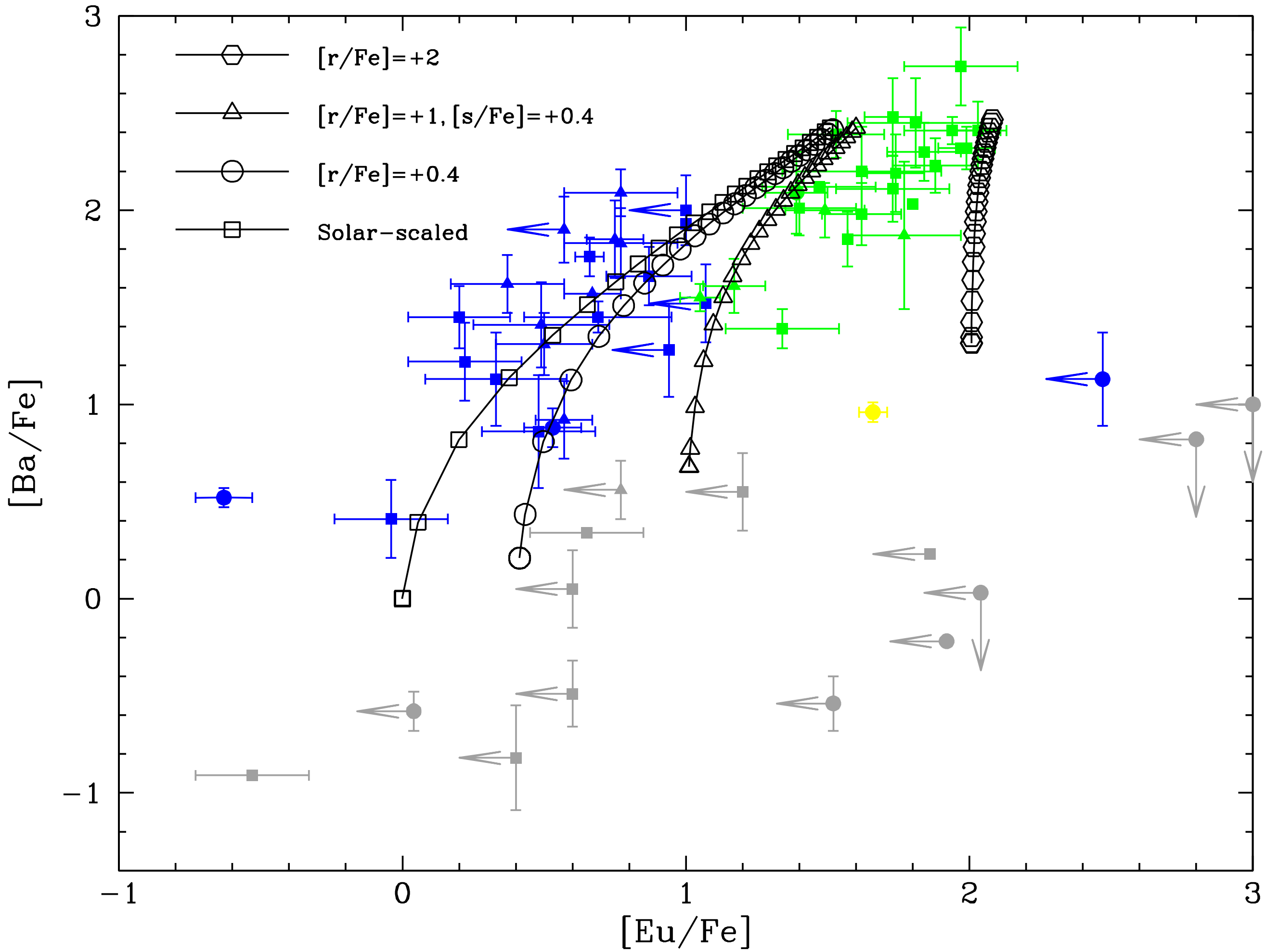
CEMP-s

CEMP-s/r



Abate et al. (2015)

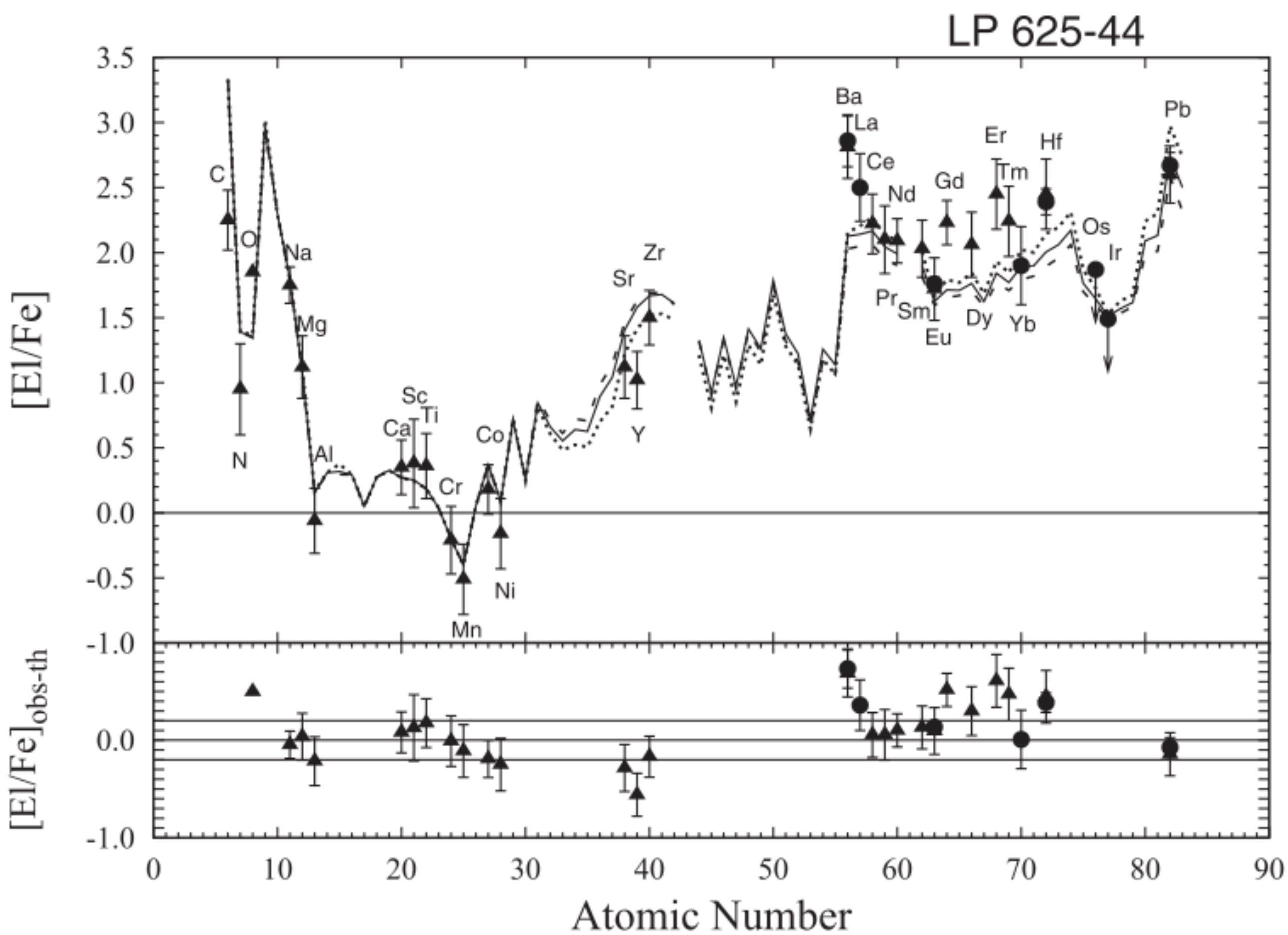
R-process pre-enhancement ?



Initial r-process enrichment: at least [r/Fe] > 1 dex

Lugaro et al. (2012)

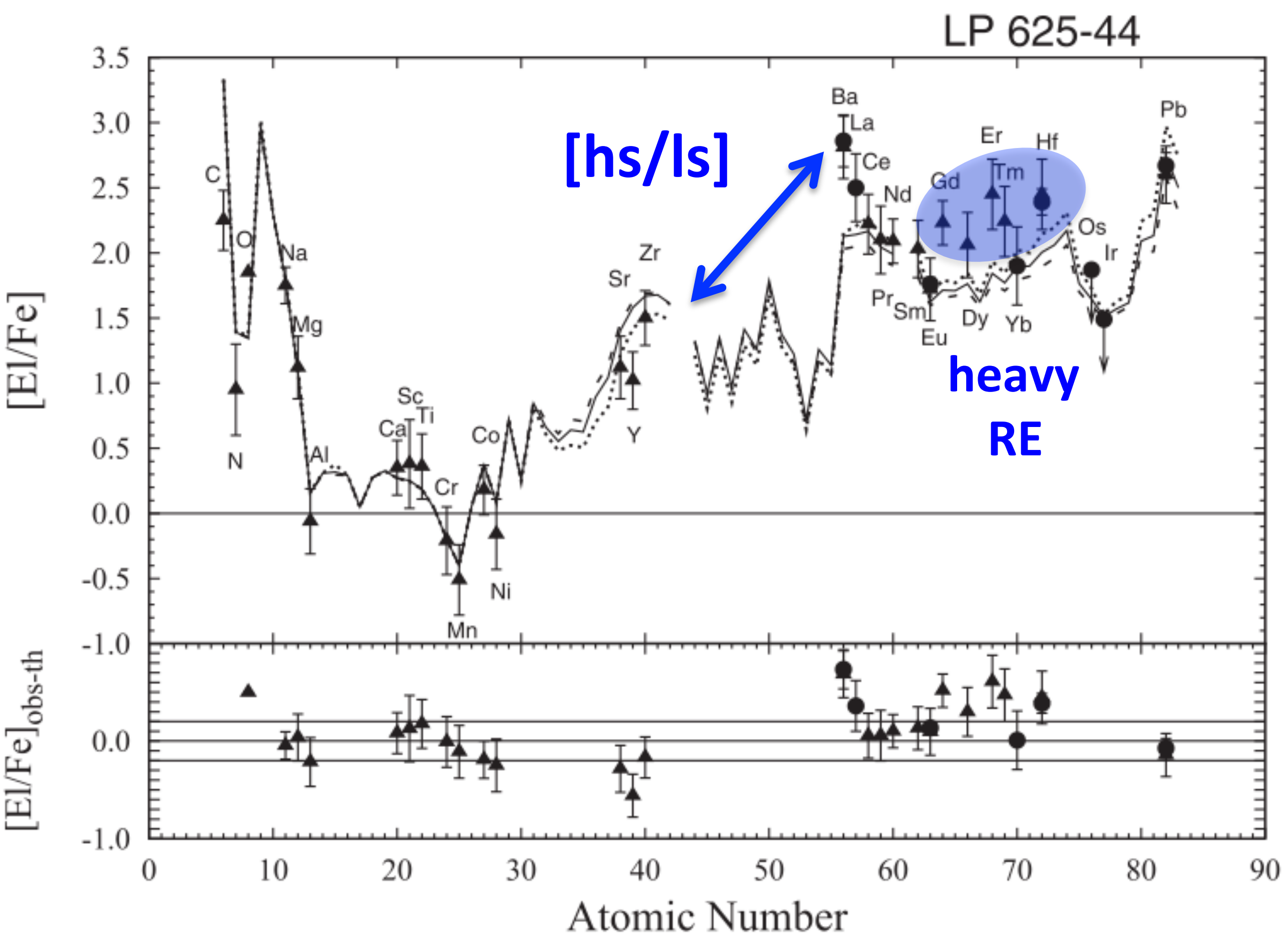
R-process pre-enhancement ?



Initial
r-process
Enrichment:
[r/Fe] = 1.5 dex

Bisterzo et al. (2012)

R-process pre-enhancement ?



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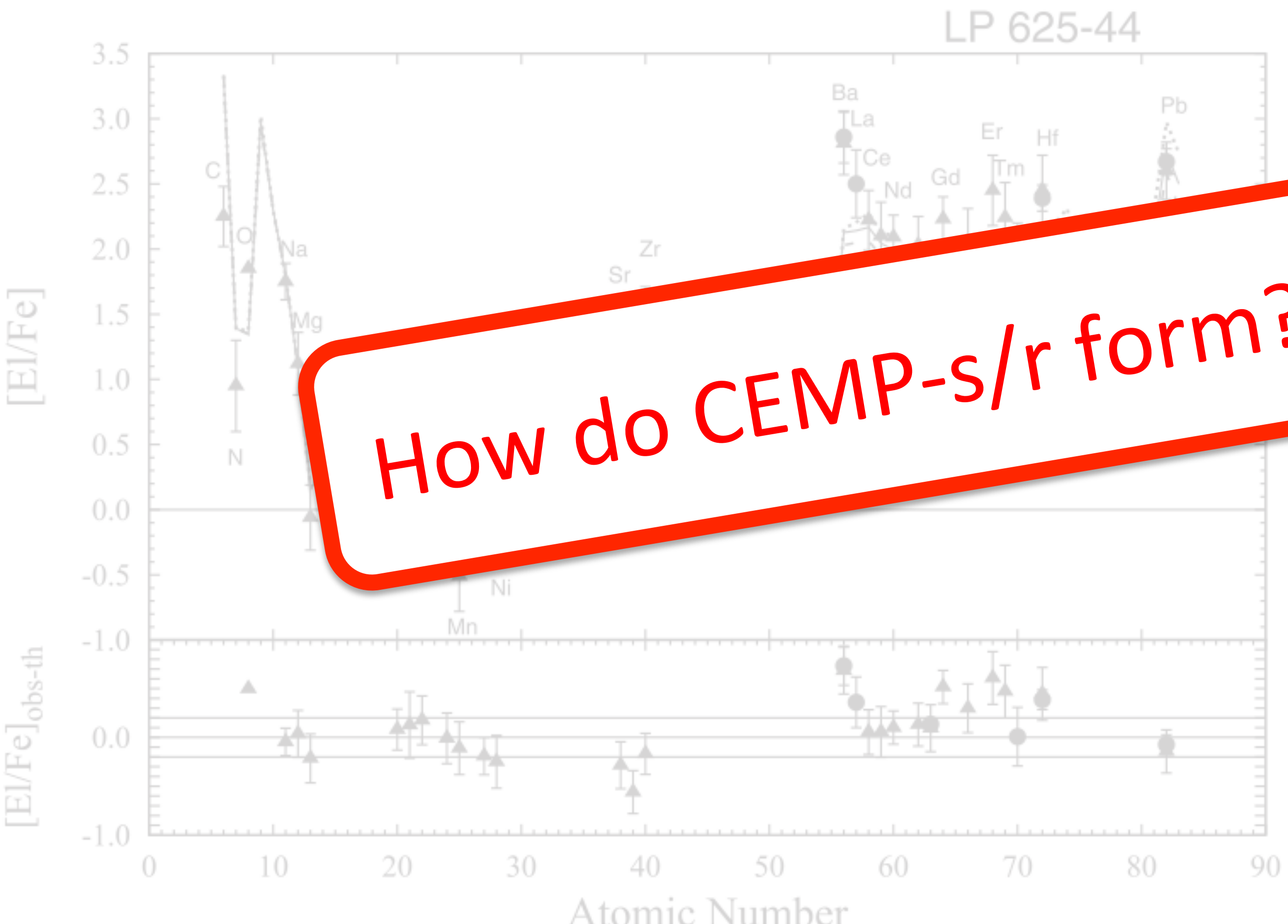
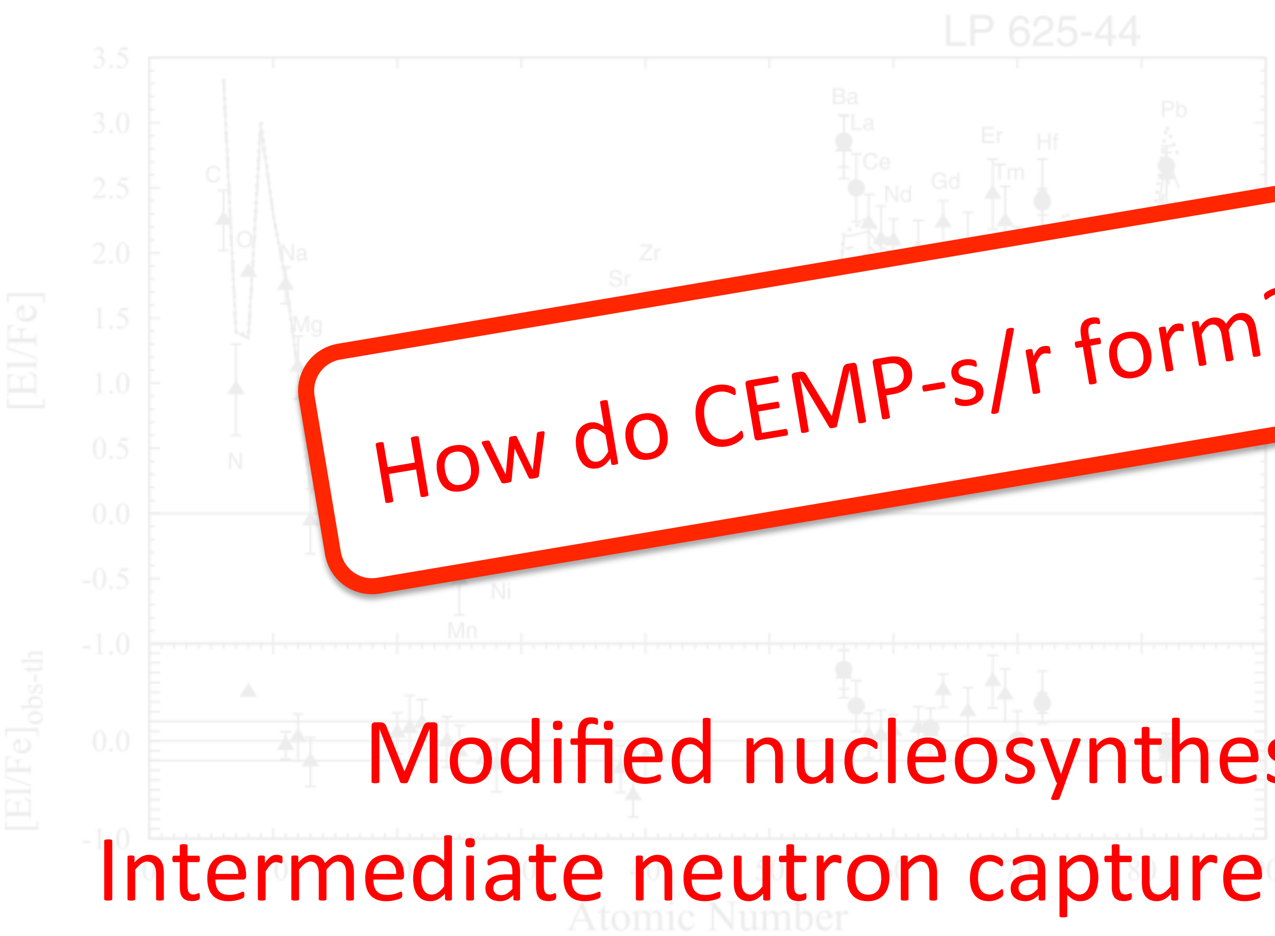


How do CEMP-s/r form???

Initial r-process Enrichment: [r/Fe] = 1.5 dex

Bisterzo et al. (2012)

R-process pre-enhancement ?



How do CEMP-s/r form???

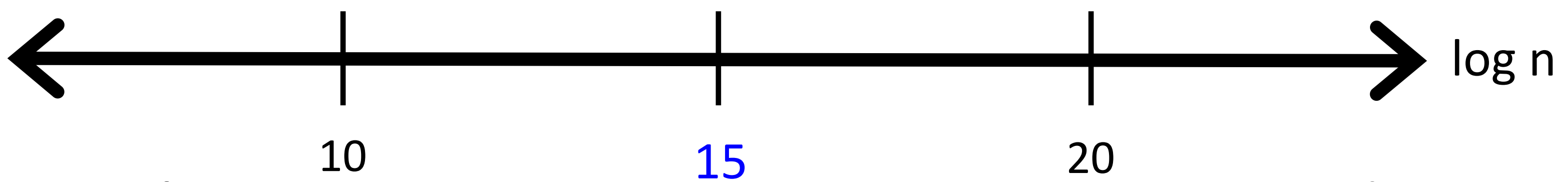
Initial r-process Enrichment: [r/Fe] = 1.5 dex

Modified nucleosynthesis?

Intermediate neutron capture process?

Bisterzo et al. (2012)

i process: $n \approx 10^{15}\ cm^{-3}$

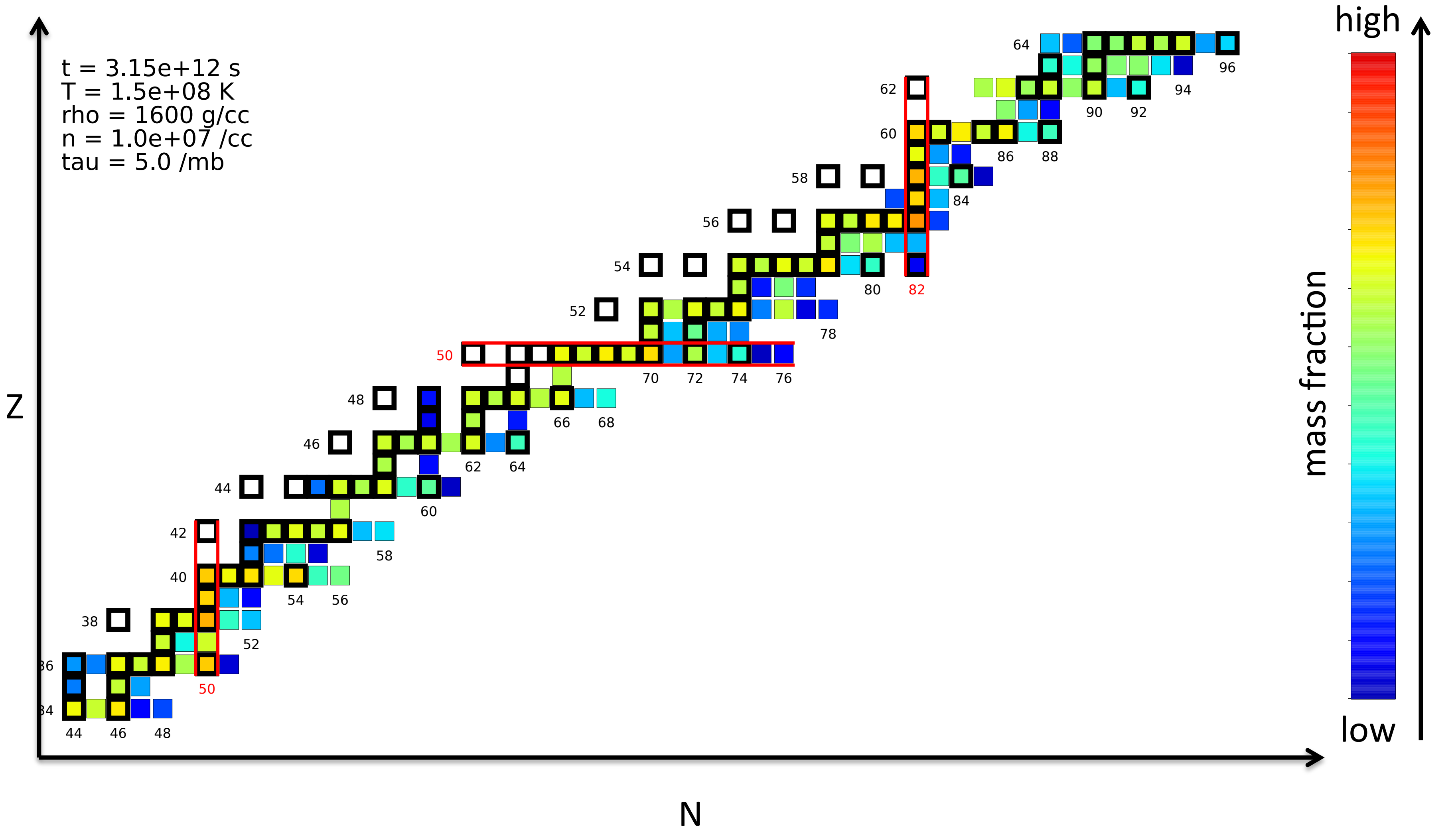


slow
neutron
captures
$n \approx 10^{7}\ cm^{-3}$

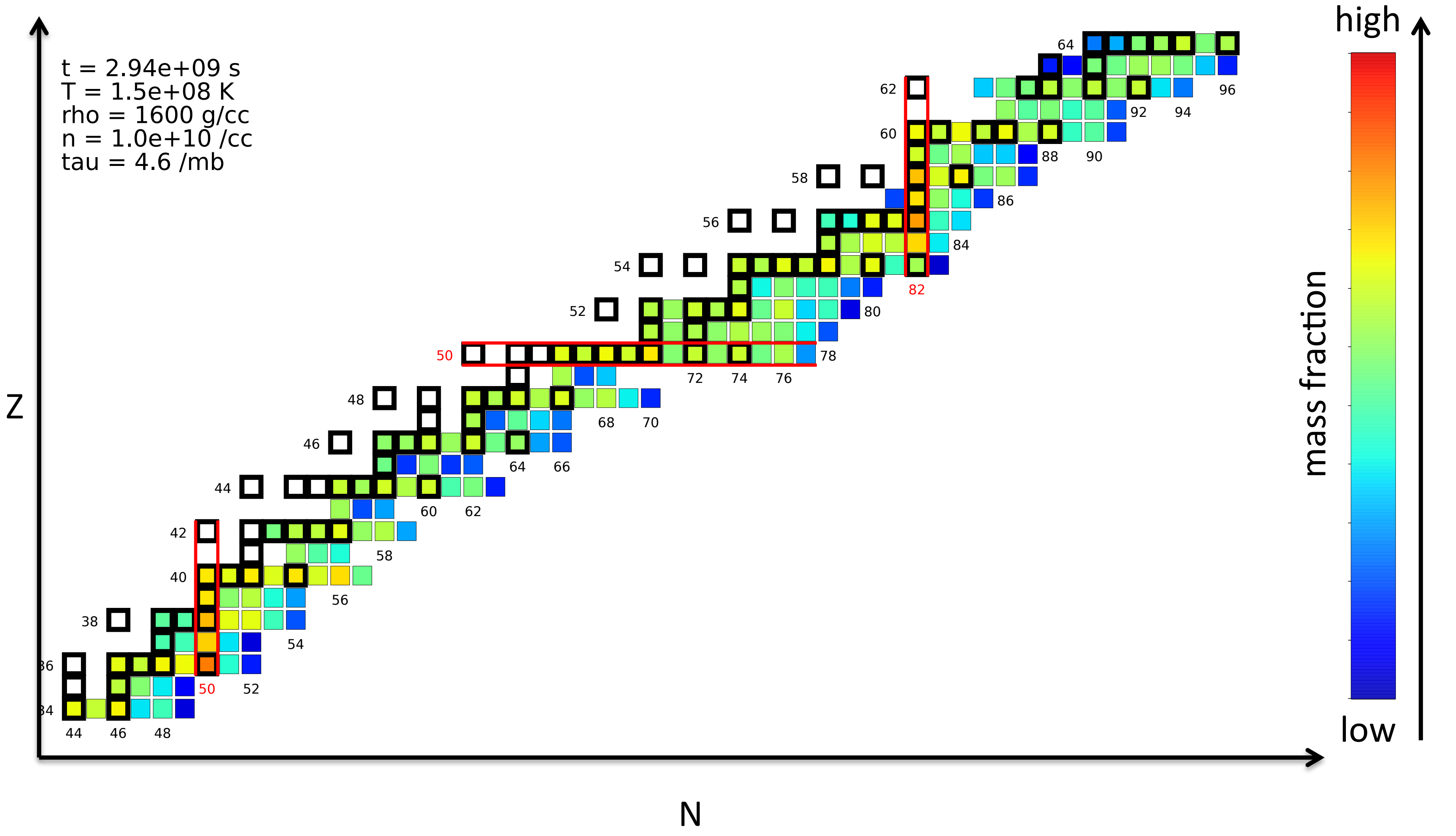
intermediate
neutron
captures
$n \approx 10^{15}\ cm^{-3}$

rapid
neutron
captures
$n > 10^{20}\ cm^{-3}$

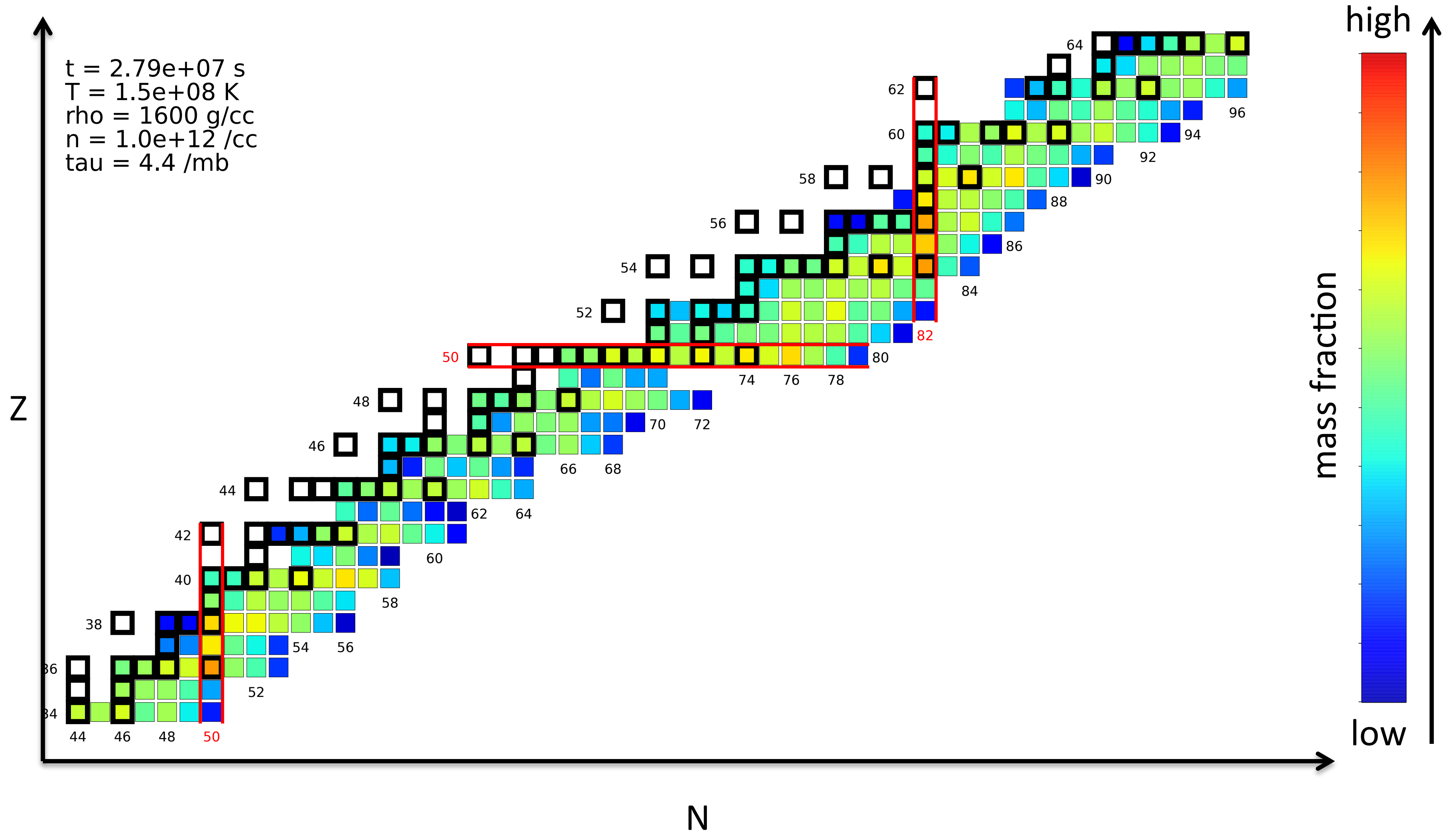
s process: $n = 10^7$ cm^{-3}



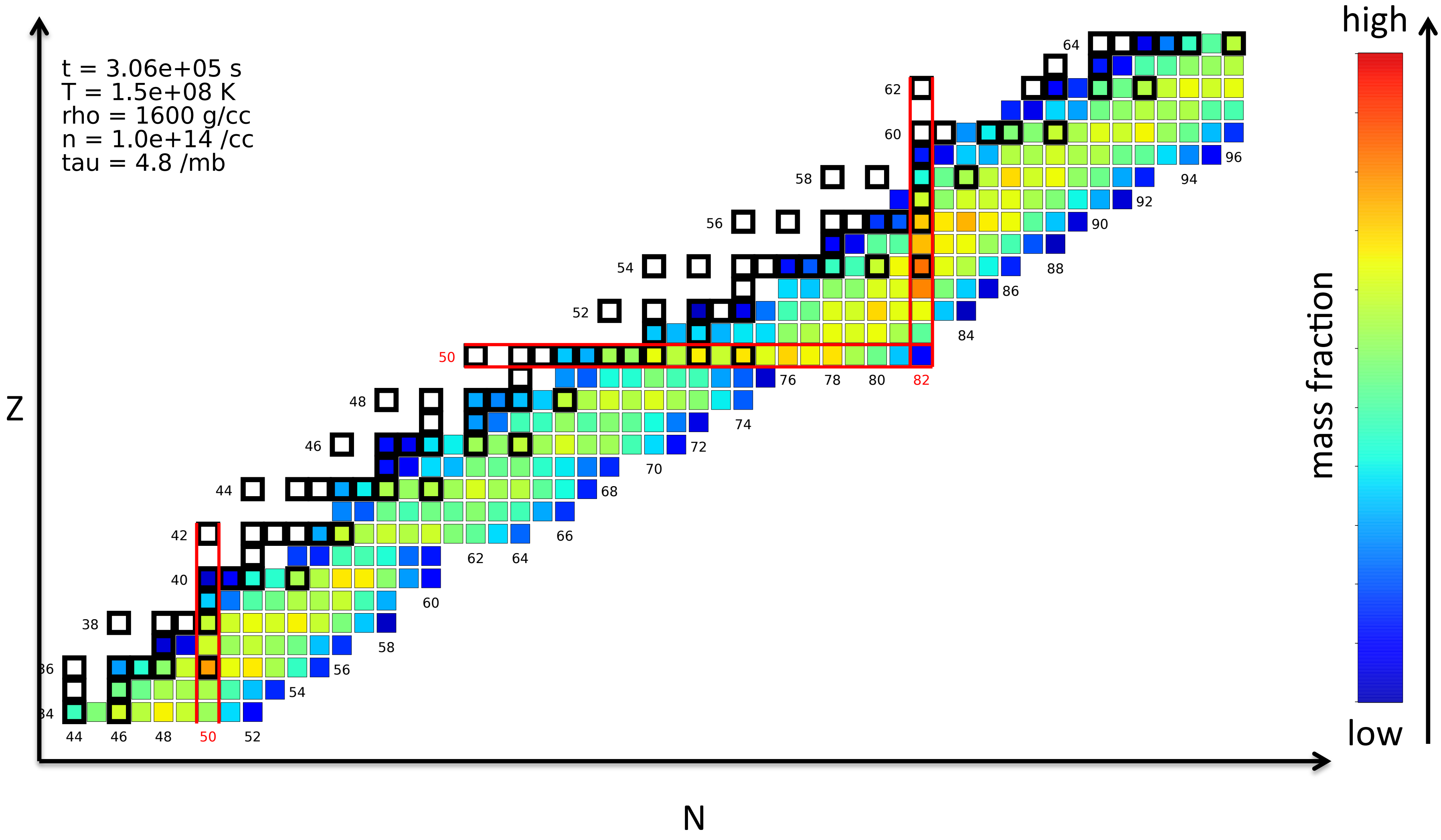
Higher neutron densities: $n = 10^{10}\ cm^{-3}$



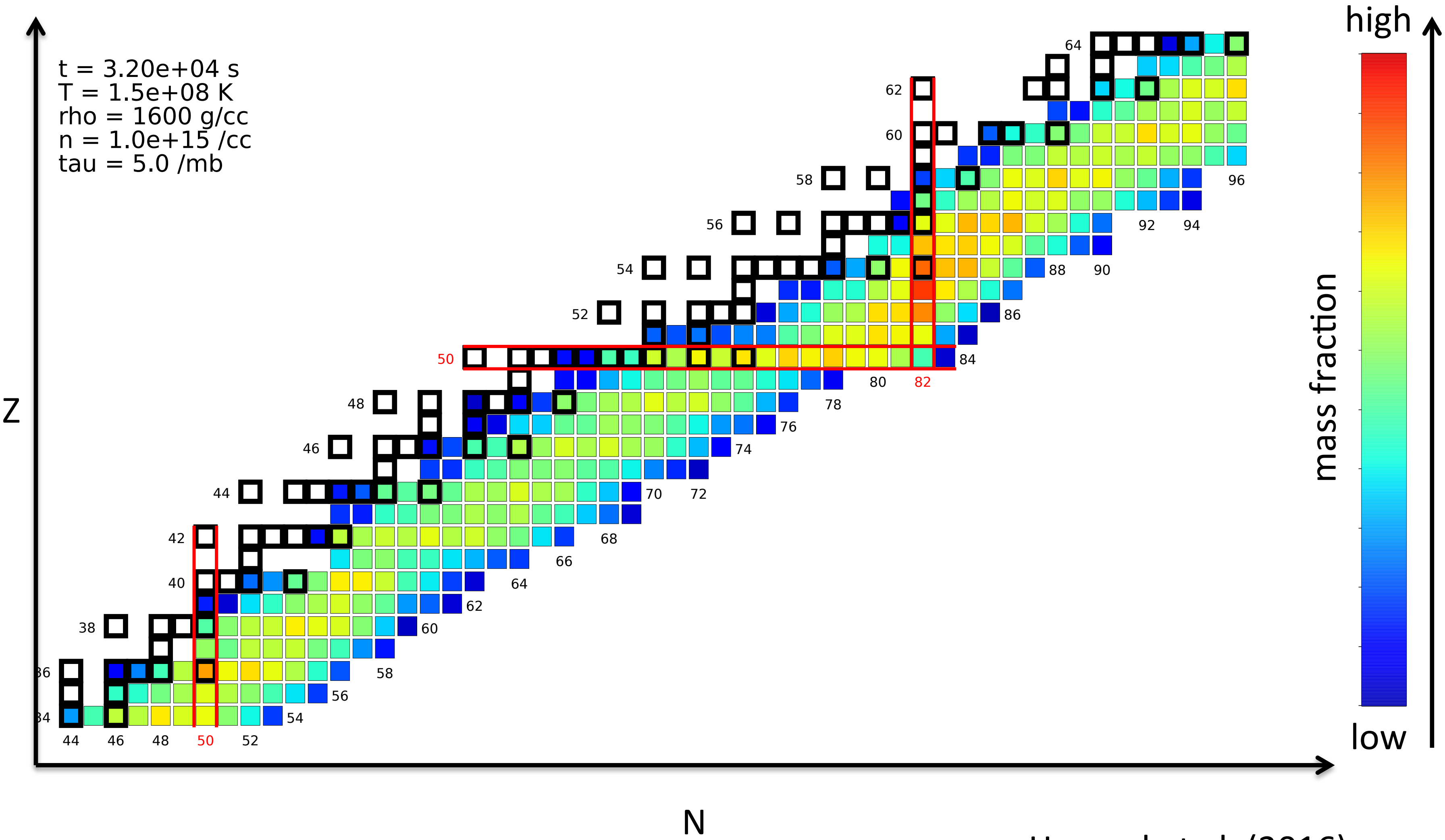
Higher neutron densities: $n = 10^{12}$ cm^{-3}



Higher neutron densities: $n = 10^{14}\ cm^{-3}$

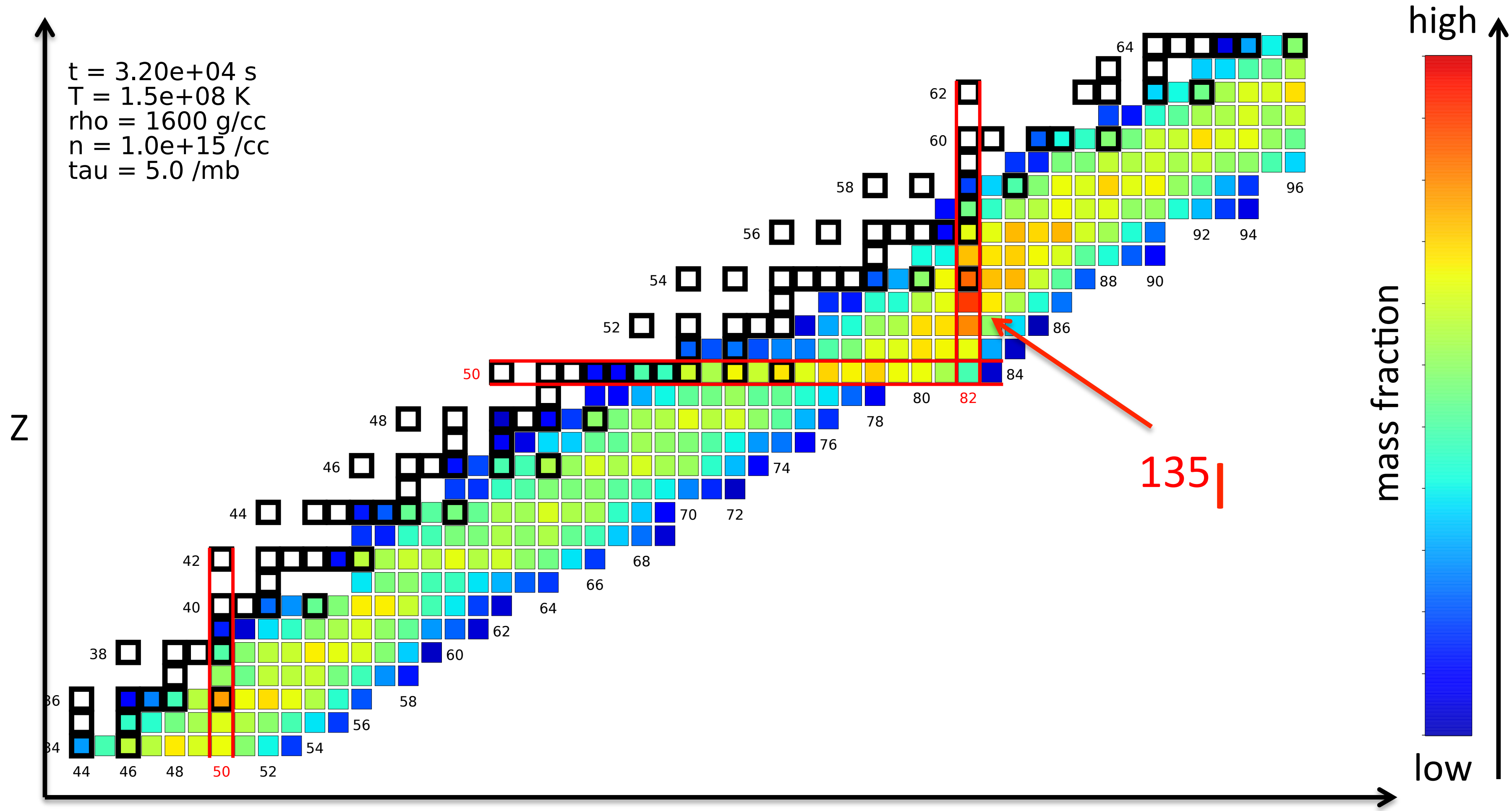


Higher neutron densities: n = 10^{15} cm^{-3}



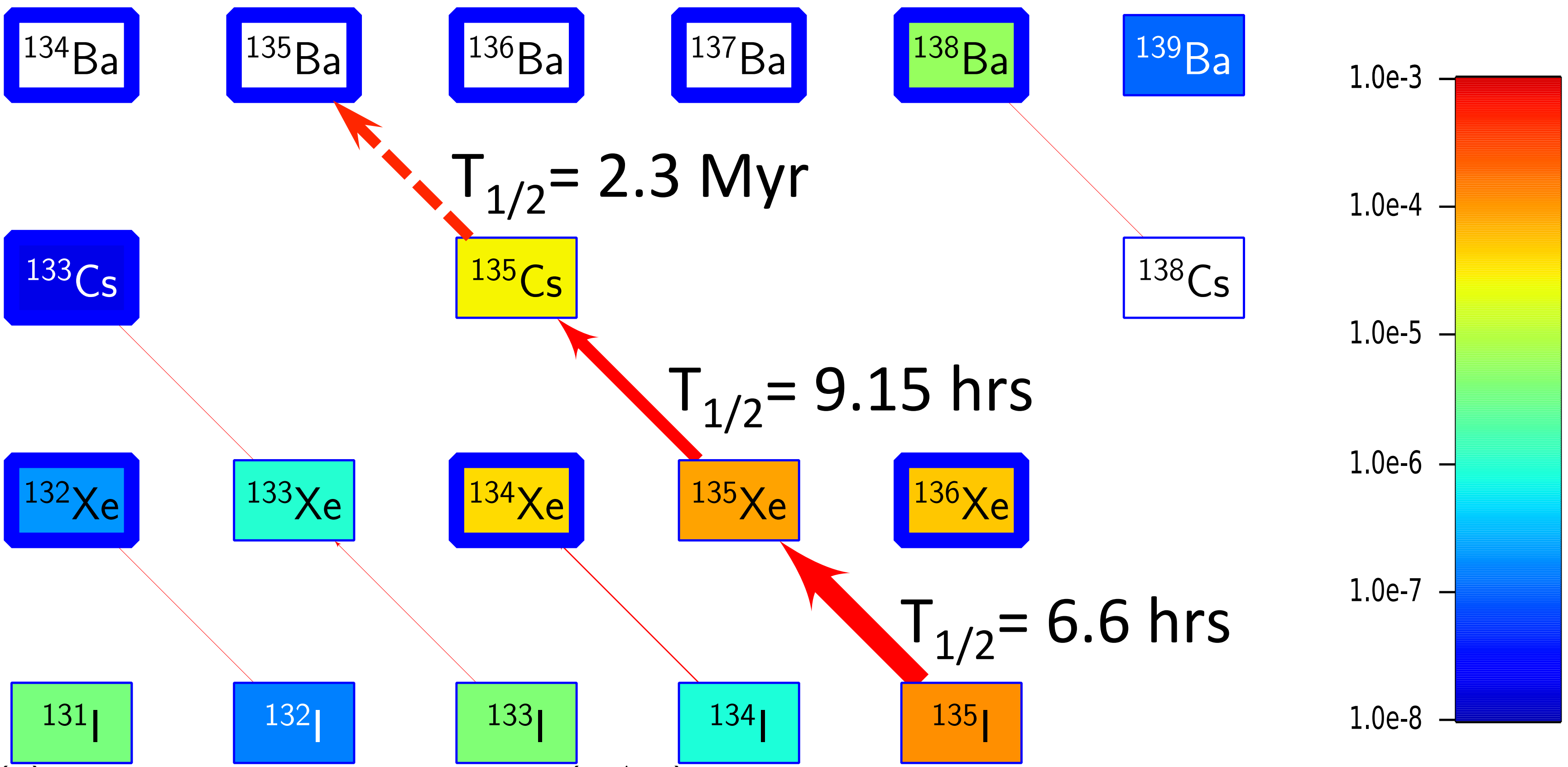
Hampel et al. (2016)

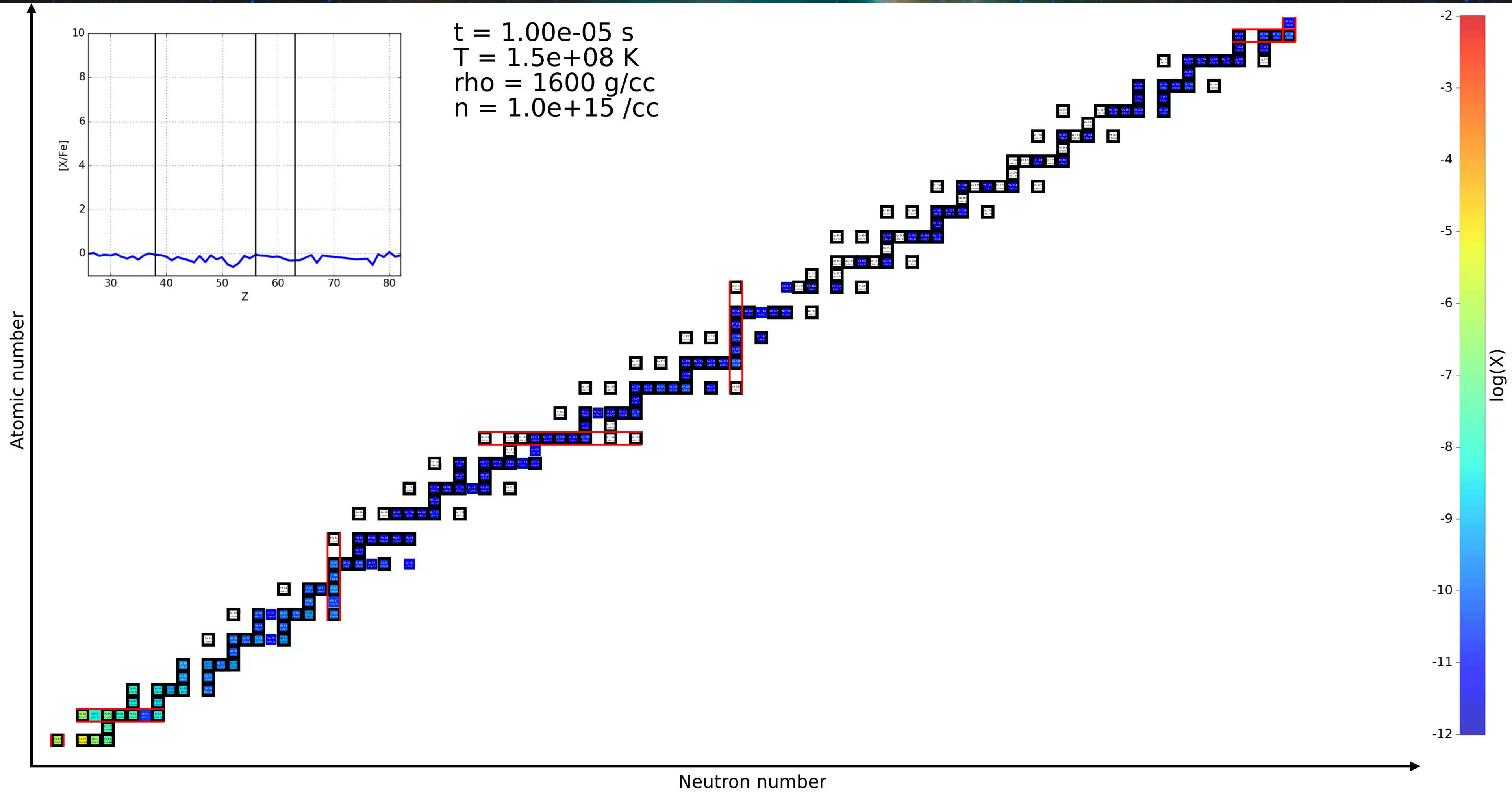
Higher neutron densities: $n=10^{15}$ cm^{-3}



Hampel et al. (2016)

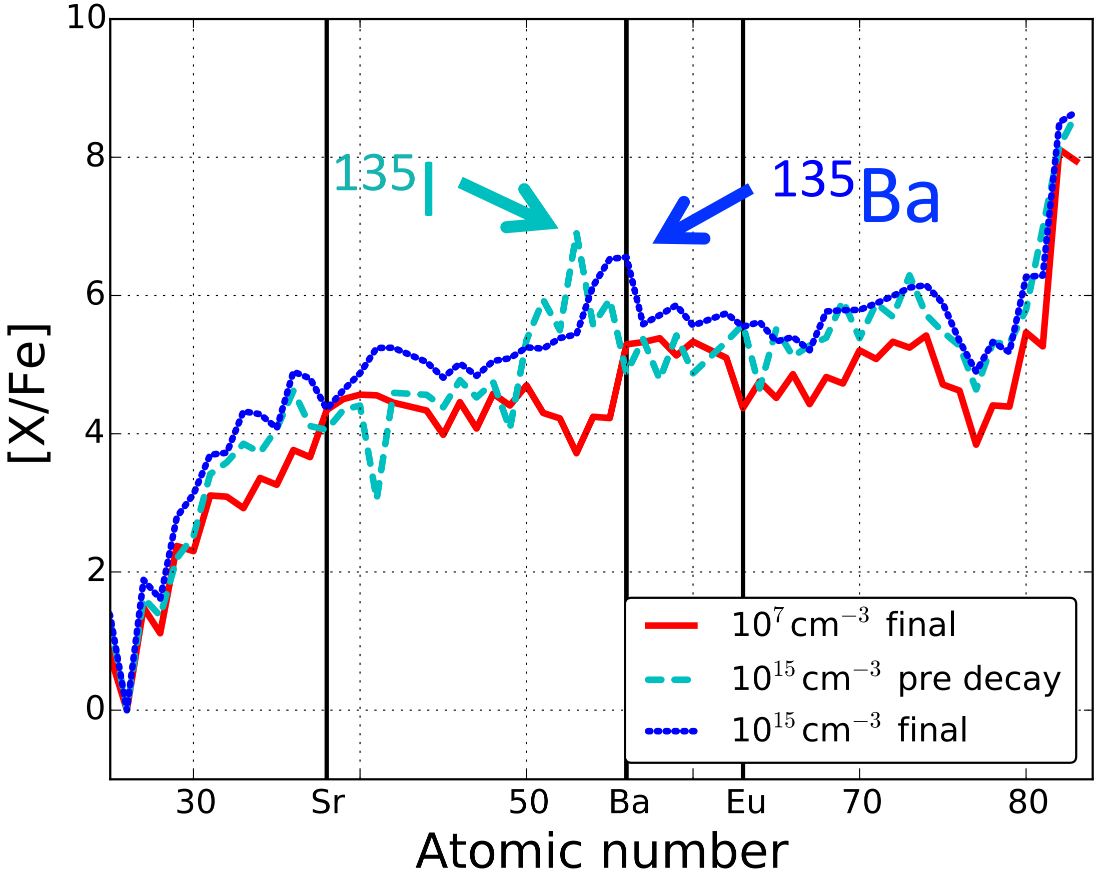
i process: decays





Credit: HST/NASA/ESA

i process abundance pattern



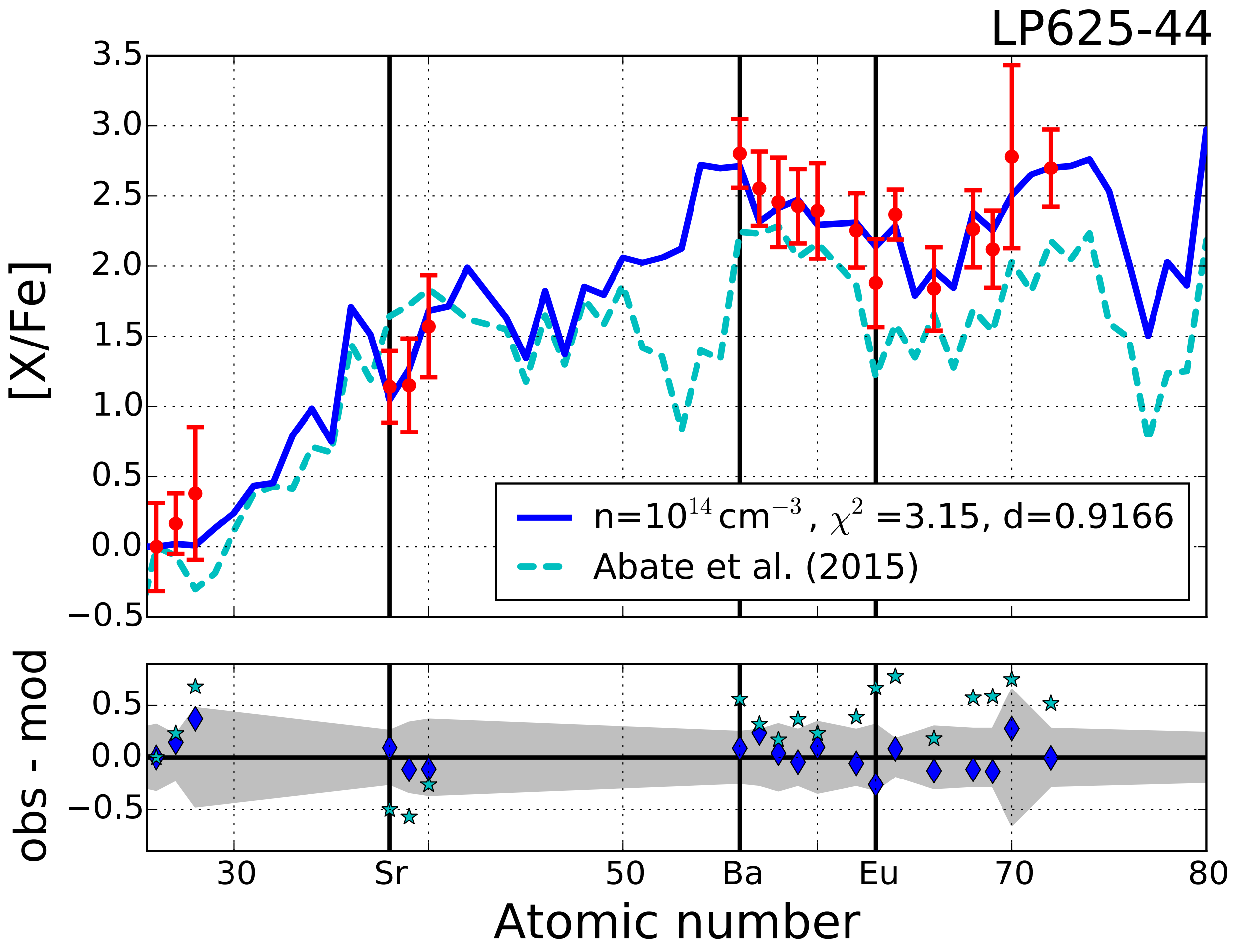
- Higher [Ba/Fe]
  very little ^{138}Ba
- Higher [Eu/Fe]
- Same [Sr/Fe]

→ higher [hs/ls]

also, [Ba/La] > 0

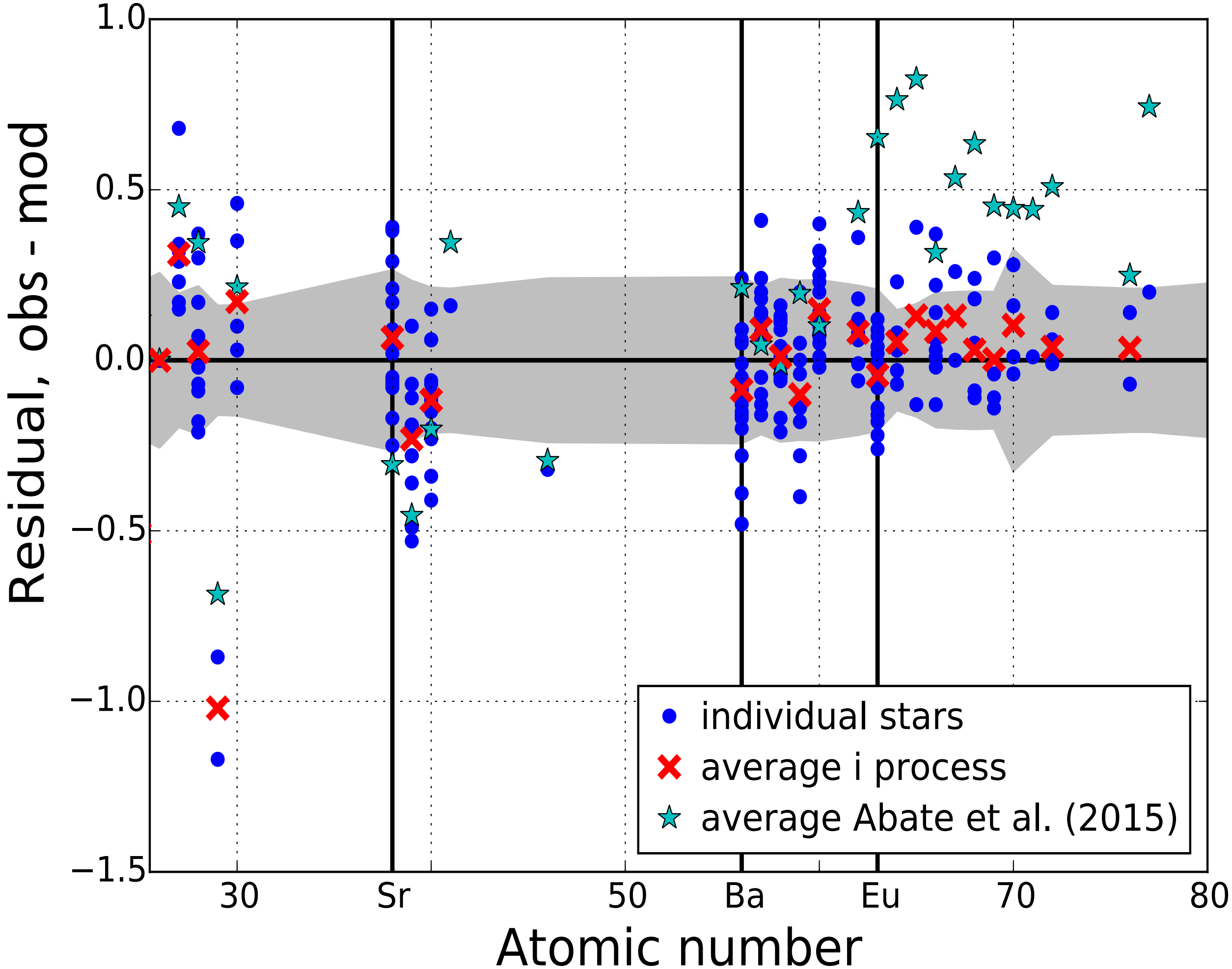
Hampel et al. (2016)

CEMP-i star: LP625-44



Hampel et al. (2016)

CEMP-i stars: Residuals



Hampel et al. (2016)

The i process …

- … is not a new idea → Cowan & Rose (1977)

PRODUCTION OF ^{14}C AND NEUTRONS IN RED GIANTS

John J. Cowan and William K. Rose
Astronomy Program, University of Maryland, College Park
Received 1976 June 28

ABSTRACT

We have examined the effects of mixing various amounts of hydrogen-rich material into the intershell convective region of red giants undergoing helium shell flashes. We find that significant amounts of ^{14}C can be produced via the $^{14}N(n, p)^{14}C$ reaction. If substantial portions of this intershell region are mixed out into the envelopes of red giants, then ^{14}C may be detectable in evolved stars.

We find a neutron number density in the intershell region of $\sim 10^{15}$–10^{17} cm^{-3} and a flux of $\sim 10^{23}$–10^{25} cm^{-2} s^{-1}. This neutron flux is many orders of magnitude above the flux required for the classical *s*-process, and thus an intermediate neutron process (*i*-process) may operate in evolved red giants. The neutrons are principally produced by the $^{13}C(\alpha, n)^{16}O$ reaction.

In all cases studied we find substantial enhancements of ^{17}O. These mixing models offer a plausible explanation of the observations of enhanced ^{17}O in the carbon star IRC 10216. For certain physical conditions we find significant enhancements of ^{15}N in the intershell region.

Subject headings: nucleosynthesis — stars: abundances — stars: interiors — stars: late-type

The i process …

- … is not a new idea → Cowan & Rose (1977)

PRODUCTION OF ^{14}C AND NEUTRONS IN RED GIANTS

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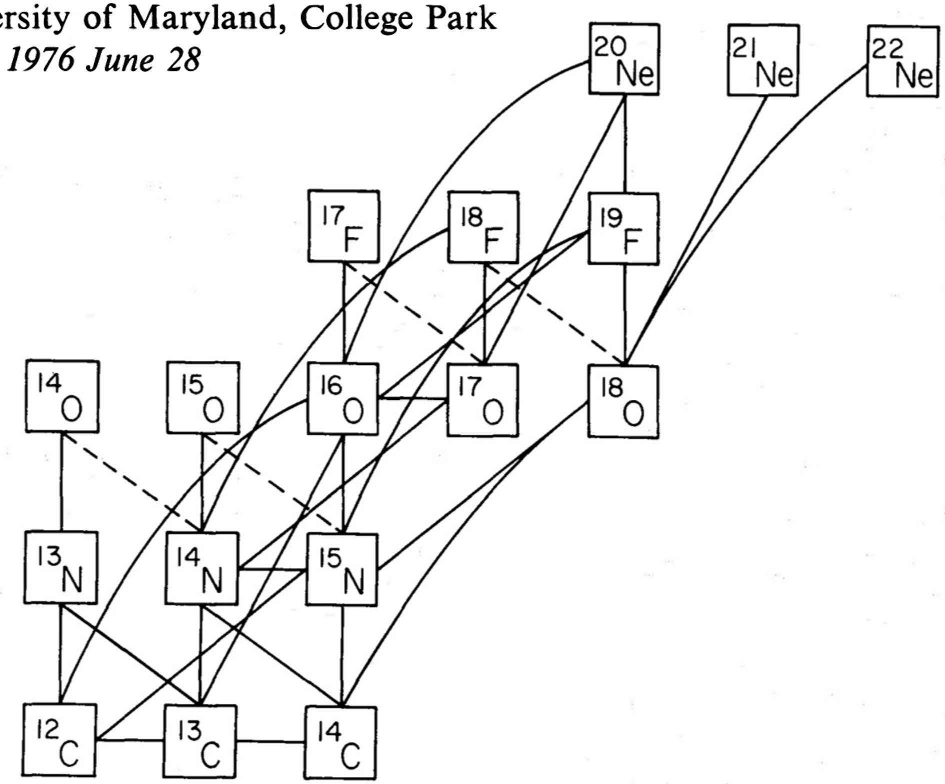
- … needs a source of neutrons:



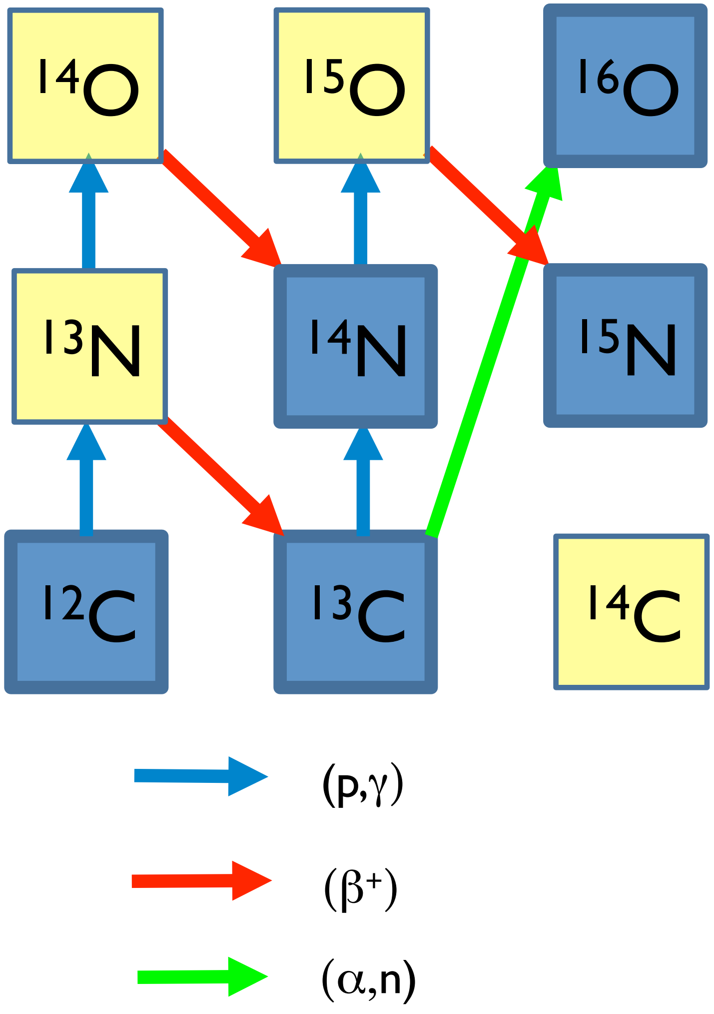
Producing neutrons

$^{13}C(\alpha,n)^{16}O$

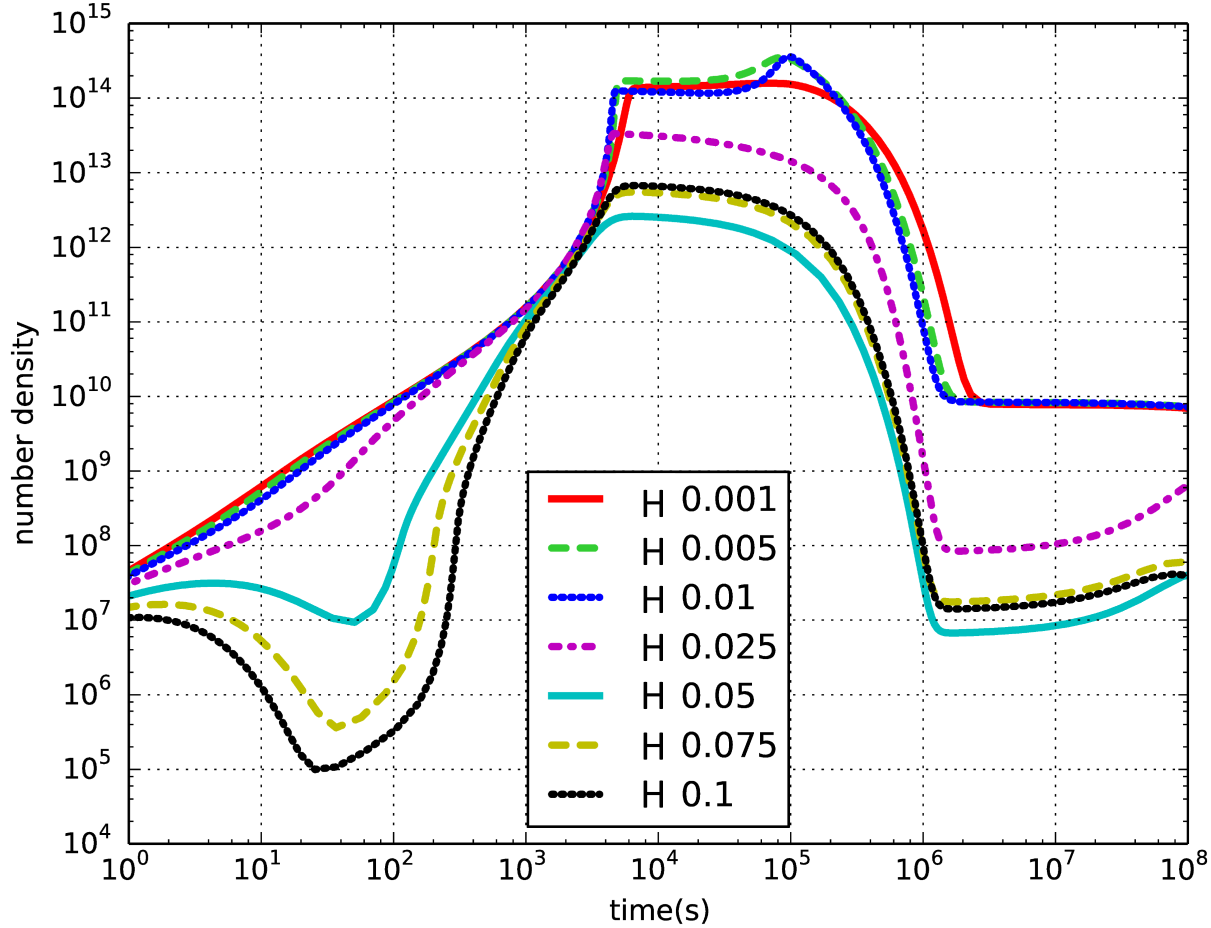
- Take ^{12}C and add protons:

  $$^{12}C(p,\gamma)^{13}N(\beta^+)^{13}C$$

- Need high temperatures
- Proton abundance determines neutron density
- It's a bit messy…

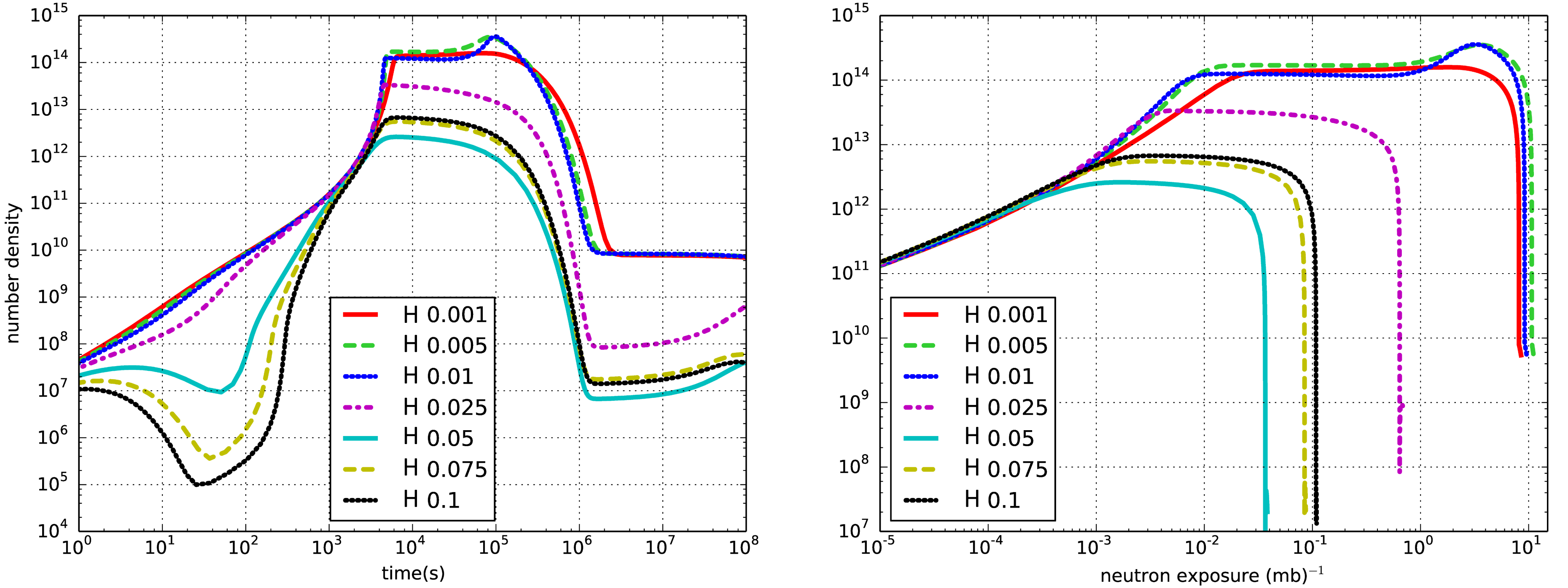


Neutron Profiles



Hampel + 2018 in prep.

Neutron Profiles: Less is More!

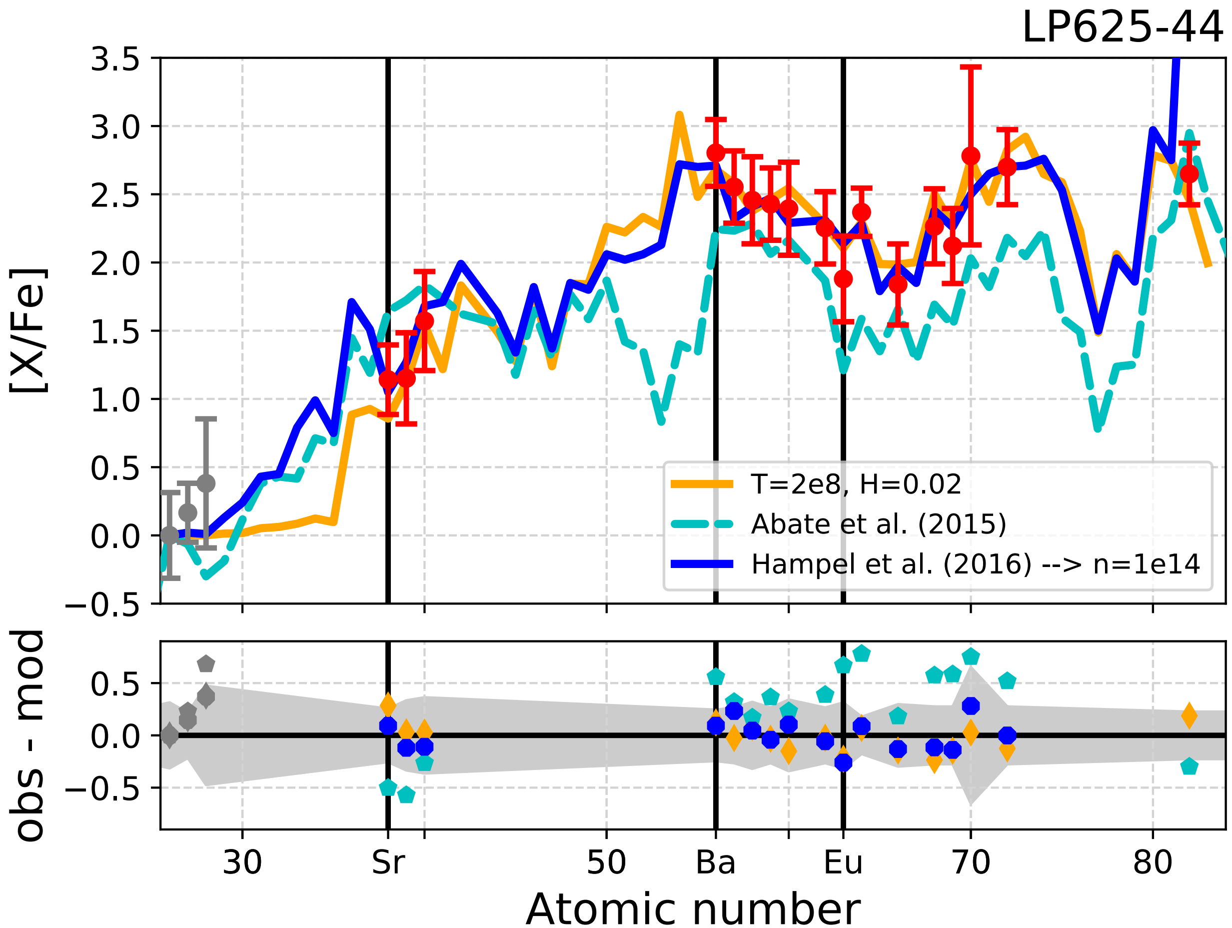


Total neutron exposure: $\tau = \int n v_T dt$

Too high proton fractions

→ too little neutron exposure

CEMP-i star: LP625-44



Hampel + 2018 in prep.

Conclusions

- CEMP-s/r stars not readily explained by a combination of s- and r-process

- An intermediate n-capture process does a much better job!
  → CEMP-i

- Need to identify a possible source
  → proton ingestion episodes

  - Low Z AGB stars (e.g. Fujimoto et al. 1990,
    see Simon Campbell's talk…)
  - Super AGB stars (Jones et al. 2016)
  - Massive Stars (see Banerjee's talk)
  - …