The intermediate neutron capture process in AGB stars

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& the 3rd Perugia Workshop on Nuclear Astrophysics

June, 23rd

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Outline

- Context
- i-process in a 1 $M_\odot$ AGB model
- The i-process as a function of mass and metallicity
- Chemical fingerprint of the i-process and comparison to CEMP r/s-stars

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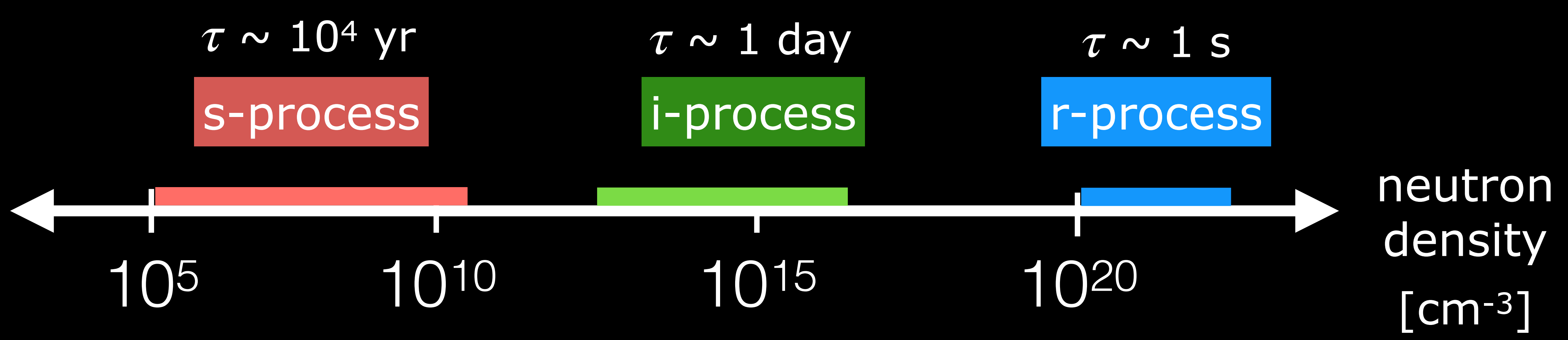
First named by Cowan & Rose 1977



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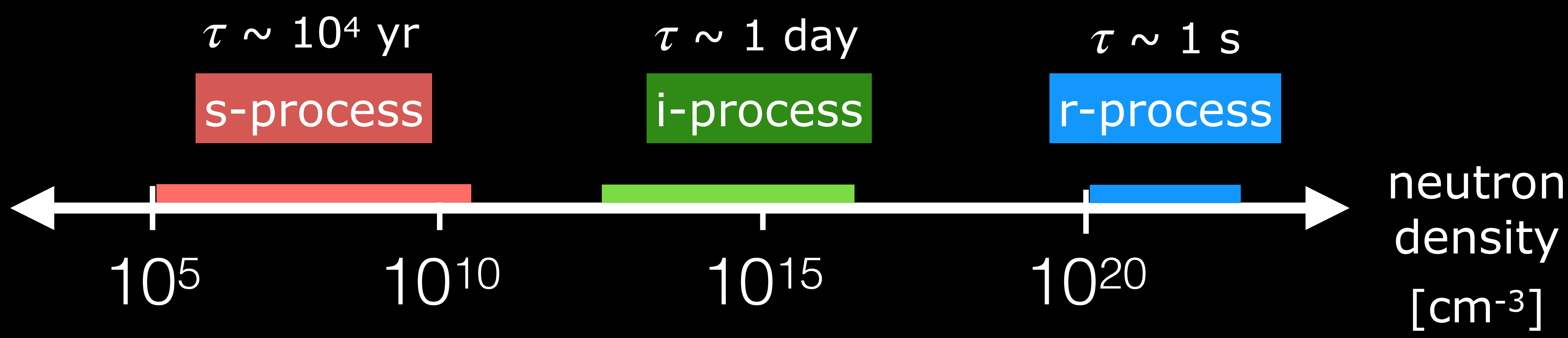

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proton ingestion

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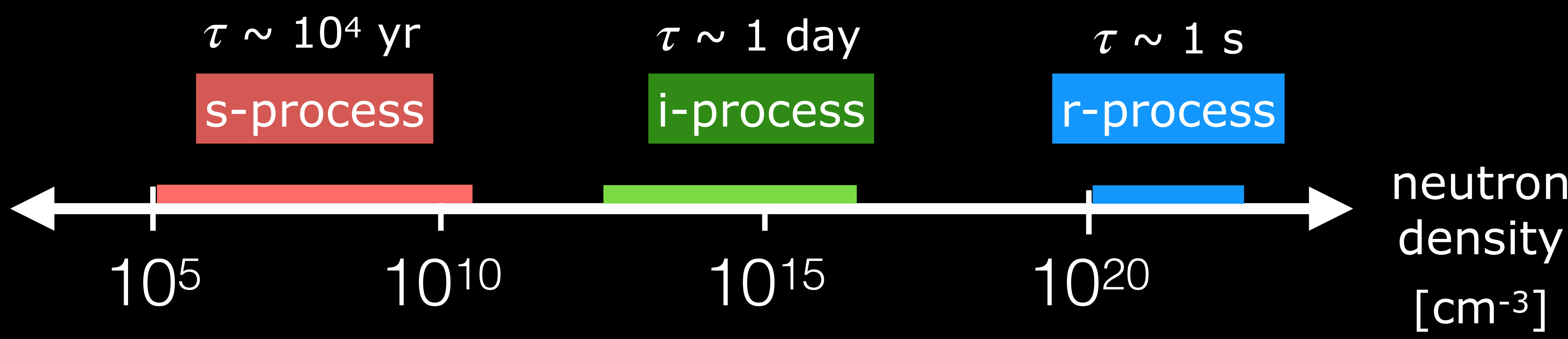

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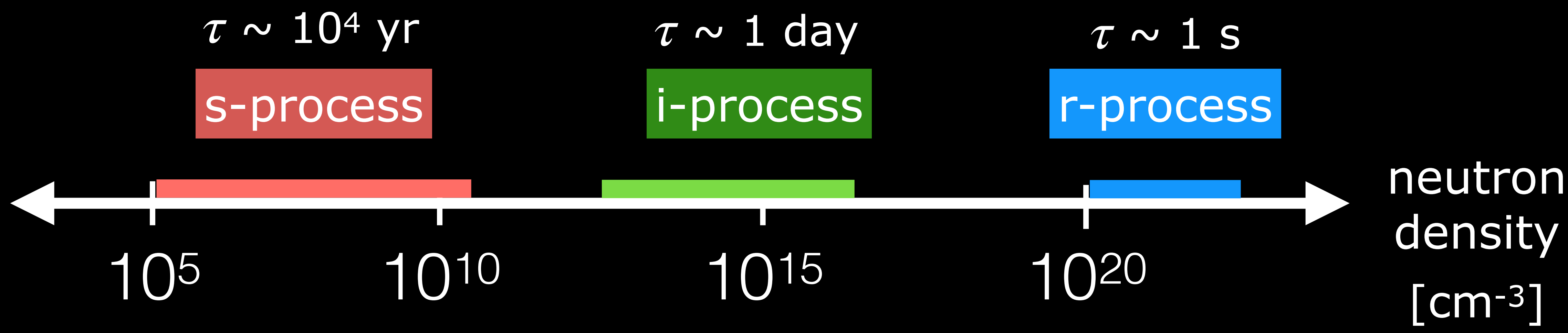

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- Observational signatures :
  - CEMP-r/s stars *Jonsell+2006, Roederer+2016, Karinkuzhi+2021*
  - Ba in open clusters *Mishenina+2015*
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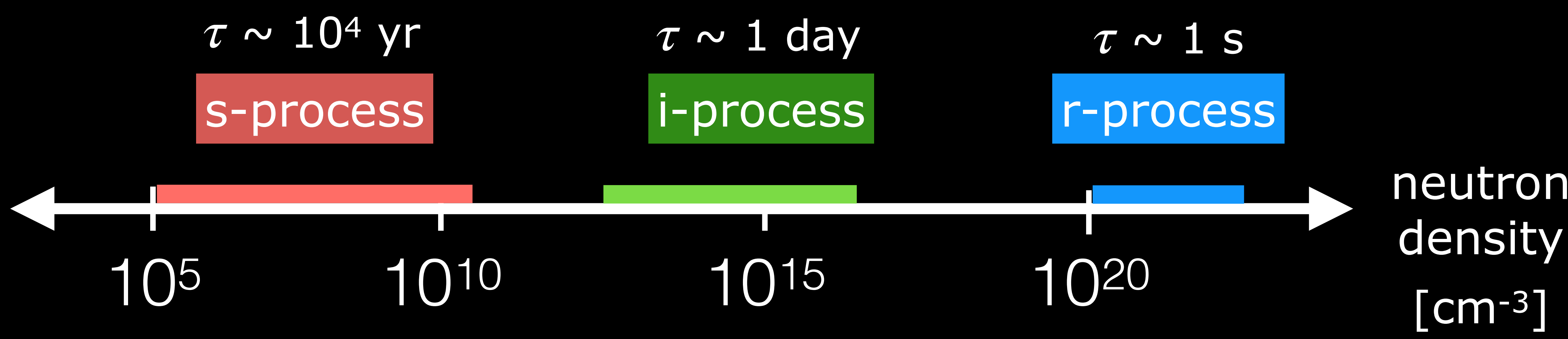

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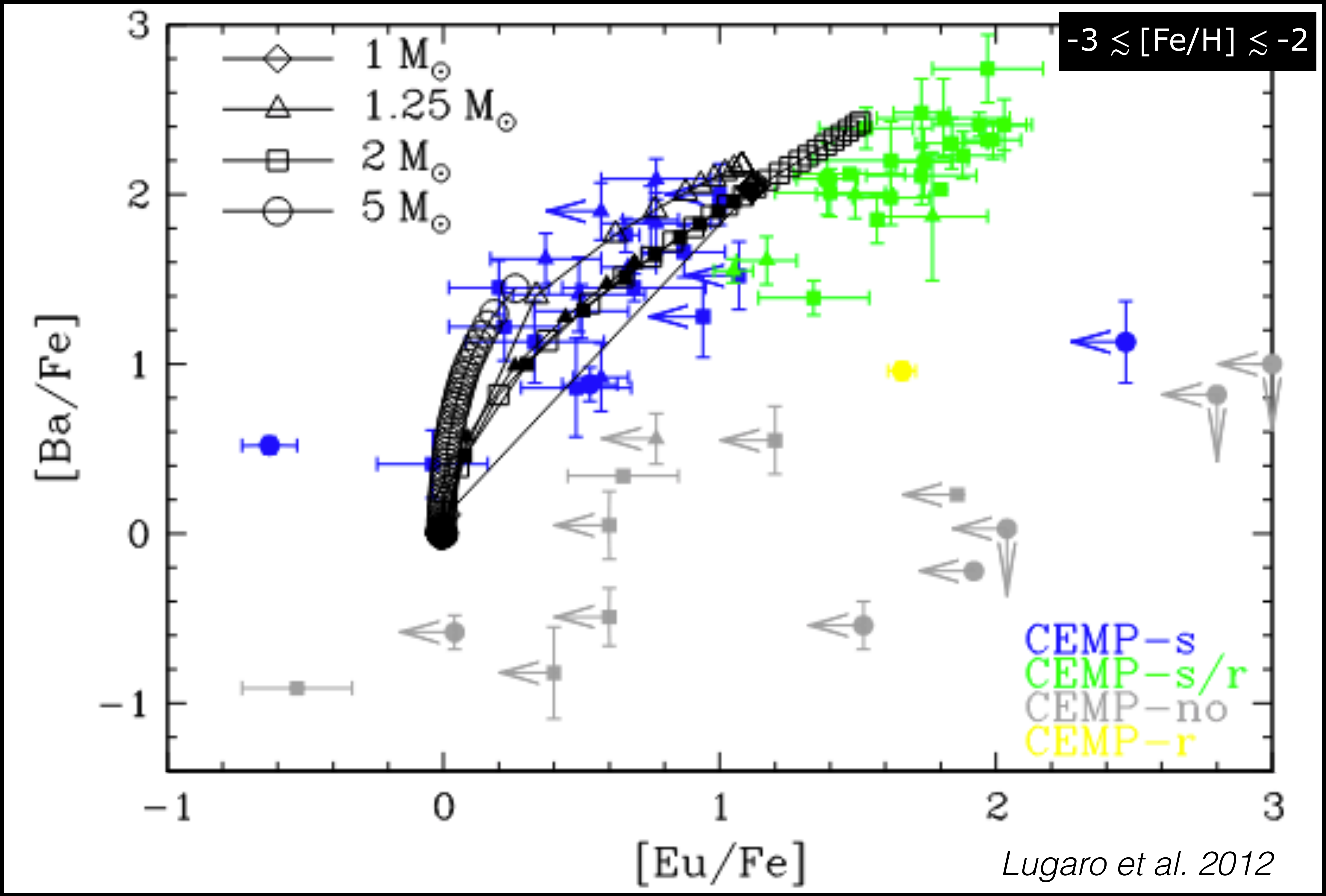
CEMP-r/s (and -s) stars



(also Bisterzo et al. 2011, Hampel el al. 2016)

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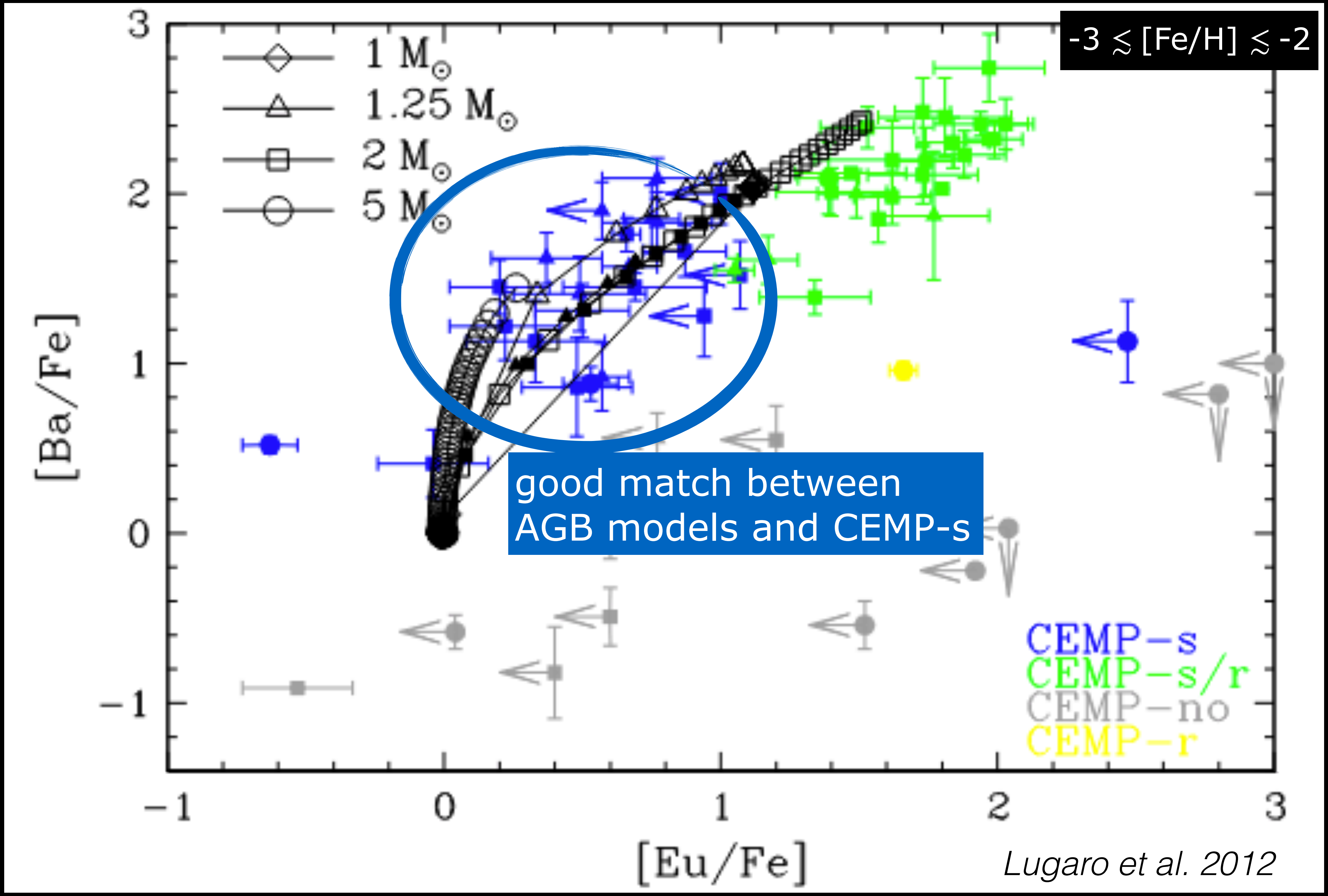

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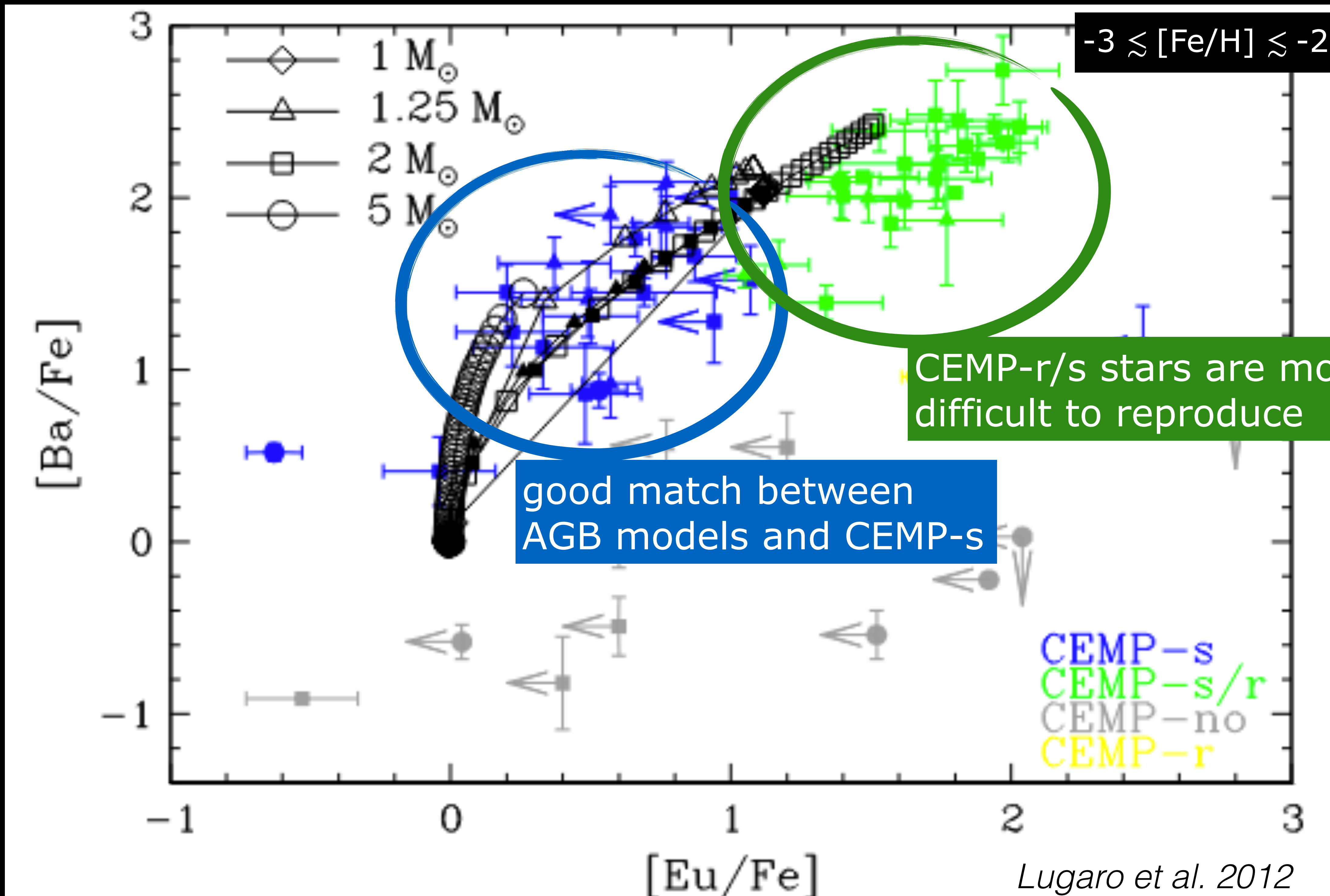

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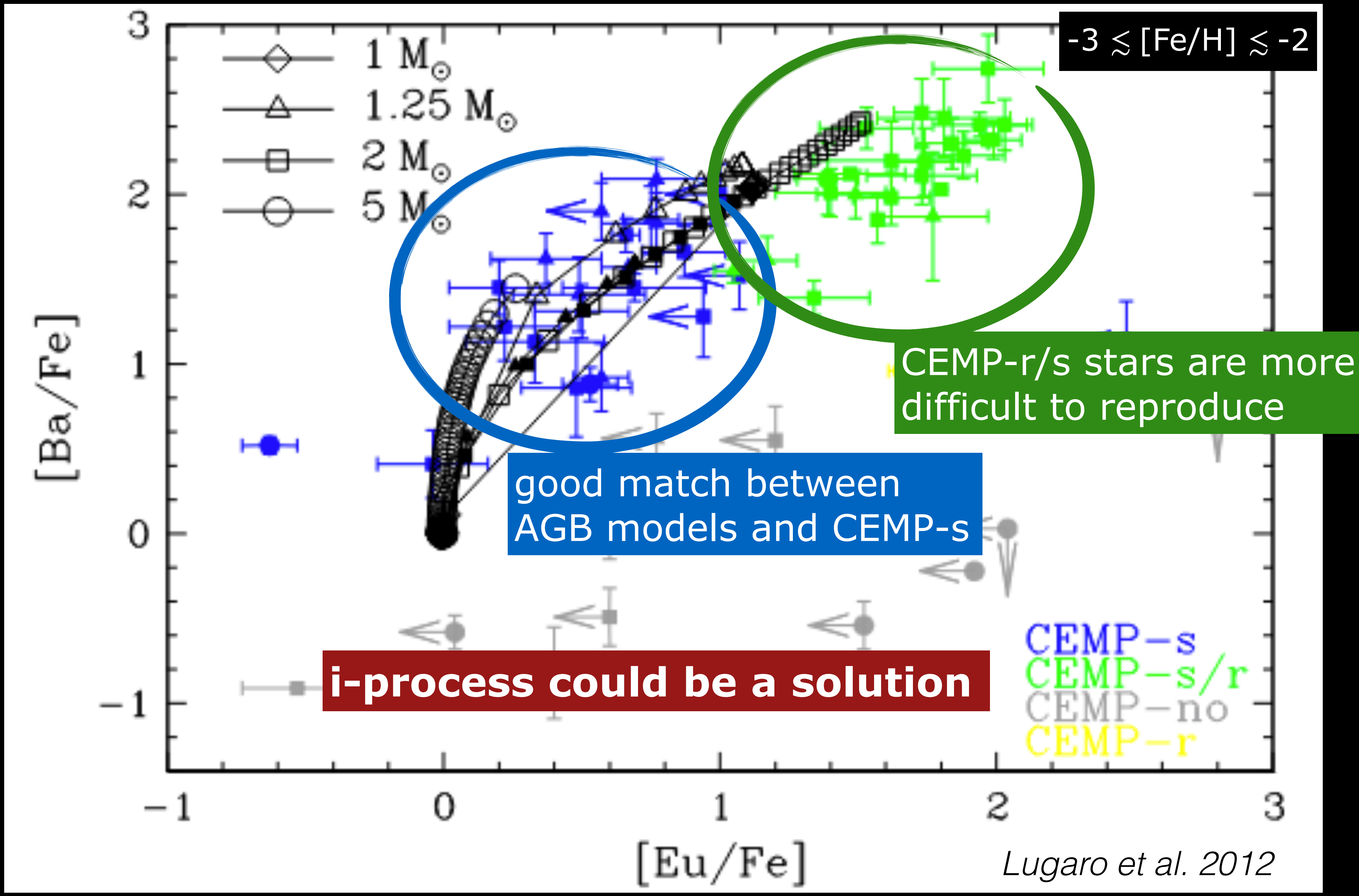

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One site where proton ingestion (hence i-process) can occur :

AGB phase of low-metallicity low-mass stars

e.g. Fujimoto+2000, Iwamoto+2004, Campbell+2008, Cristallo+2009, …

+ talks from Gil-Pons, Cirillo

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- ***Paper I*** *(Choplin+2021)* —> i-process in 1 $M_\odot$ AGB model
- ***Paper II*** *(Goriely+2022)* —> nuclear uncertainties
- ***Paper III*** *(in prep.)* —> (small) grid of AGB models (i-process yields)

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Models characteristics

- stellar evolution code STAREVOL
- 1 $M_\odot$ < initial mass < 3 $M_\odot$
- -3 < [Fe/H] < -2
- network of 1160 isotopes / 2100 reactions
- nucleosynthesis coupled to transport of chemicals
- no extra mixing process (overshoot, …)

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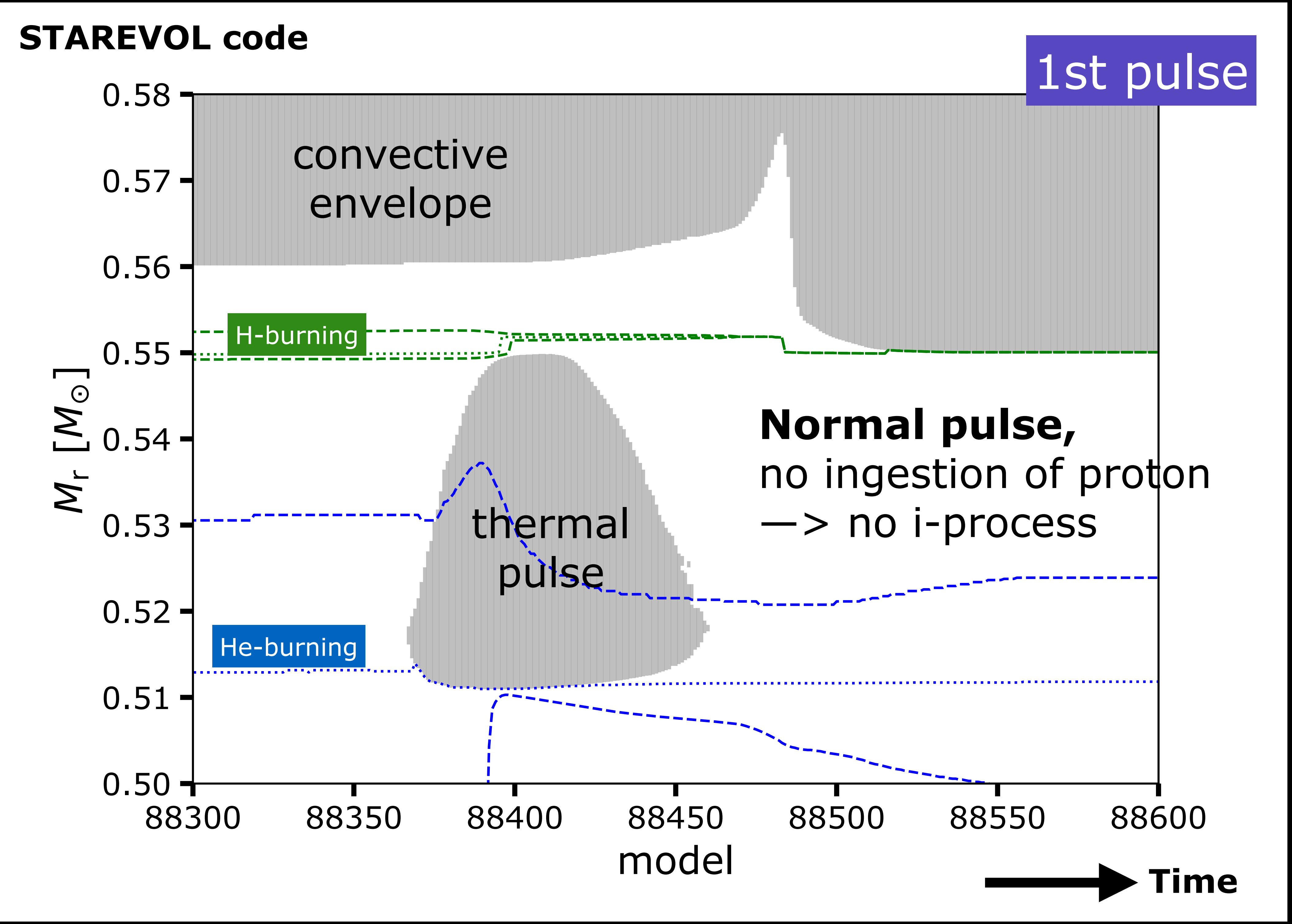
The **i-process** in a 1 $M_\odot$, [Fe/H] = -2.5 AGB model

(Z = 4 x 10^{-5})



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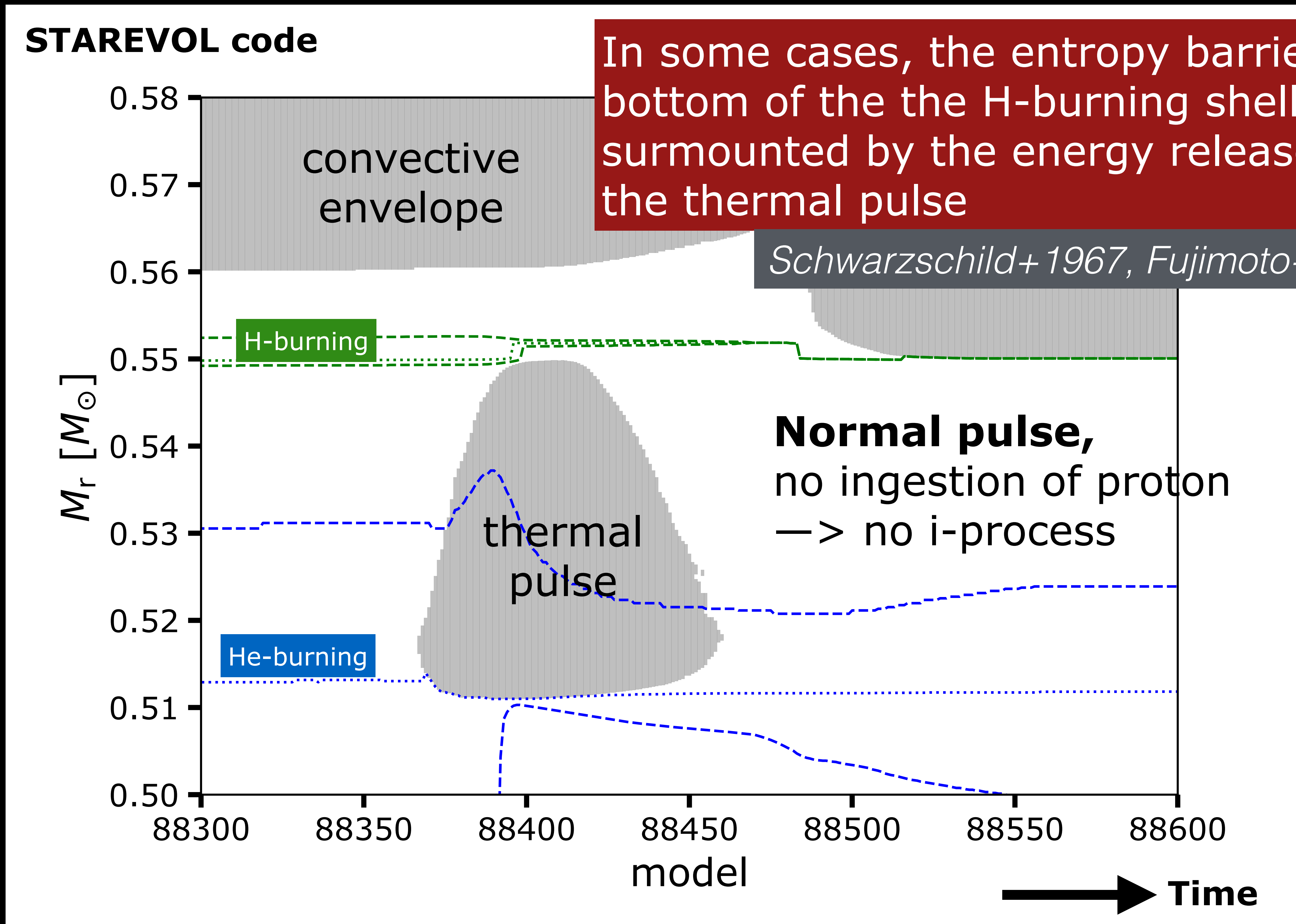
In some cases, the entropy barrier at the bottom of the the H-burning shell can be surmounted by the energy released by the thermal pulse

Schwarzschild+1967, Fujimoto+2000,…



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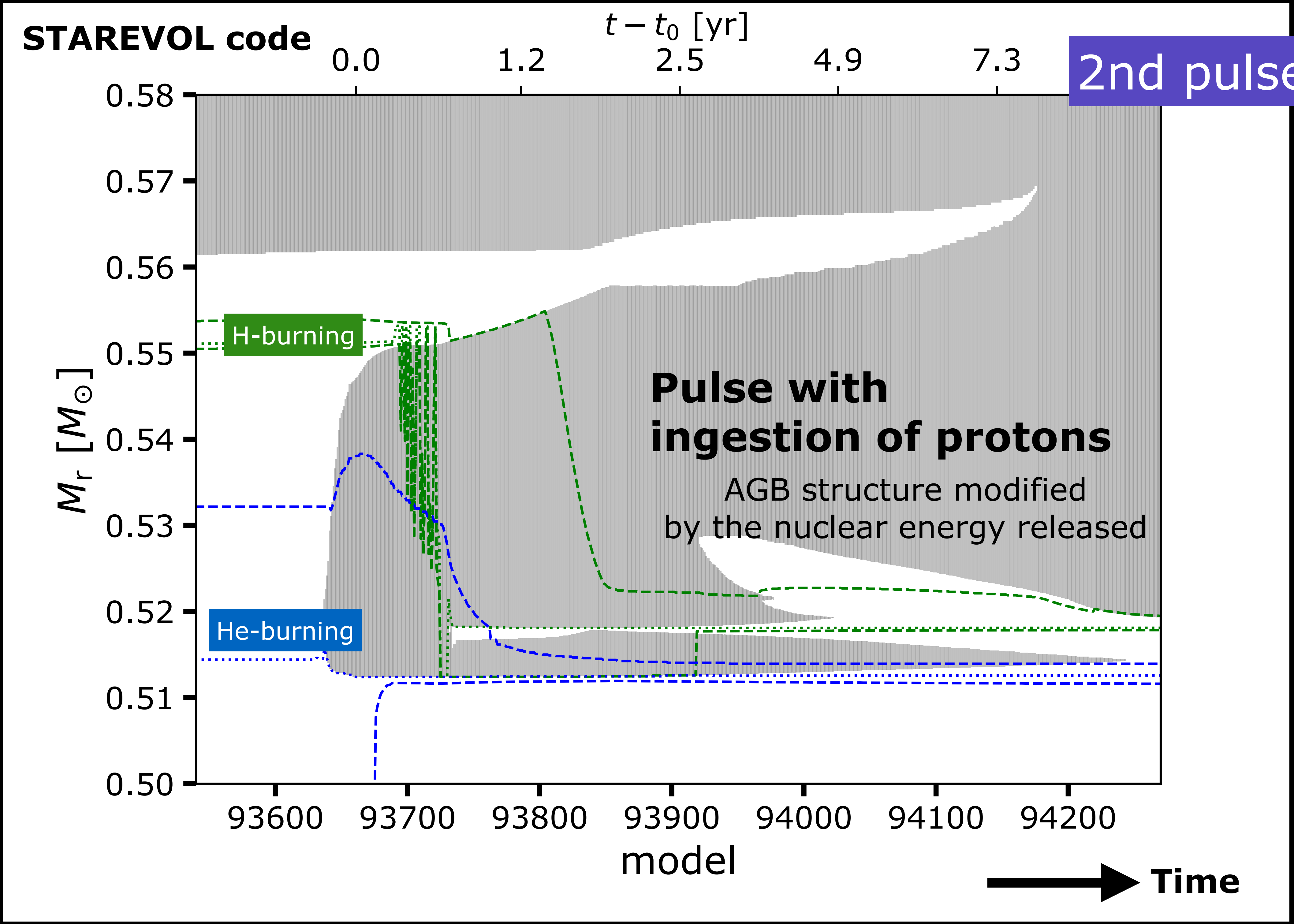

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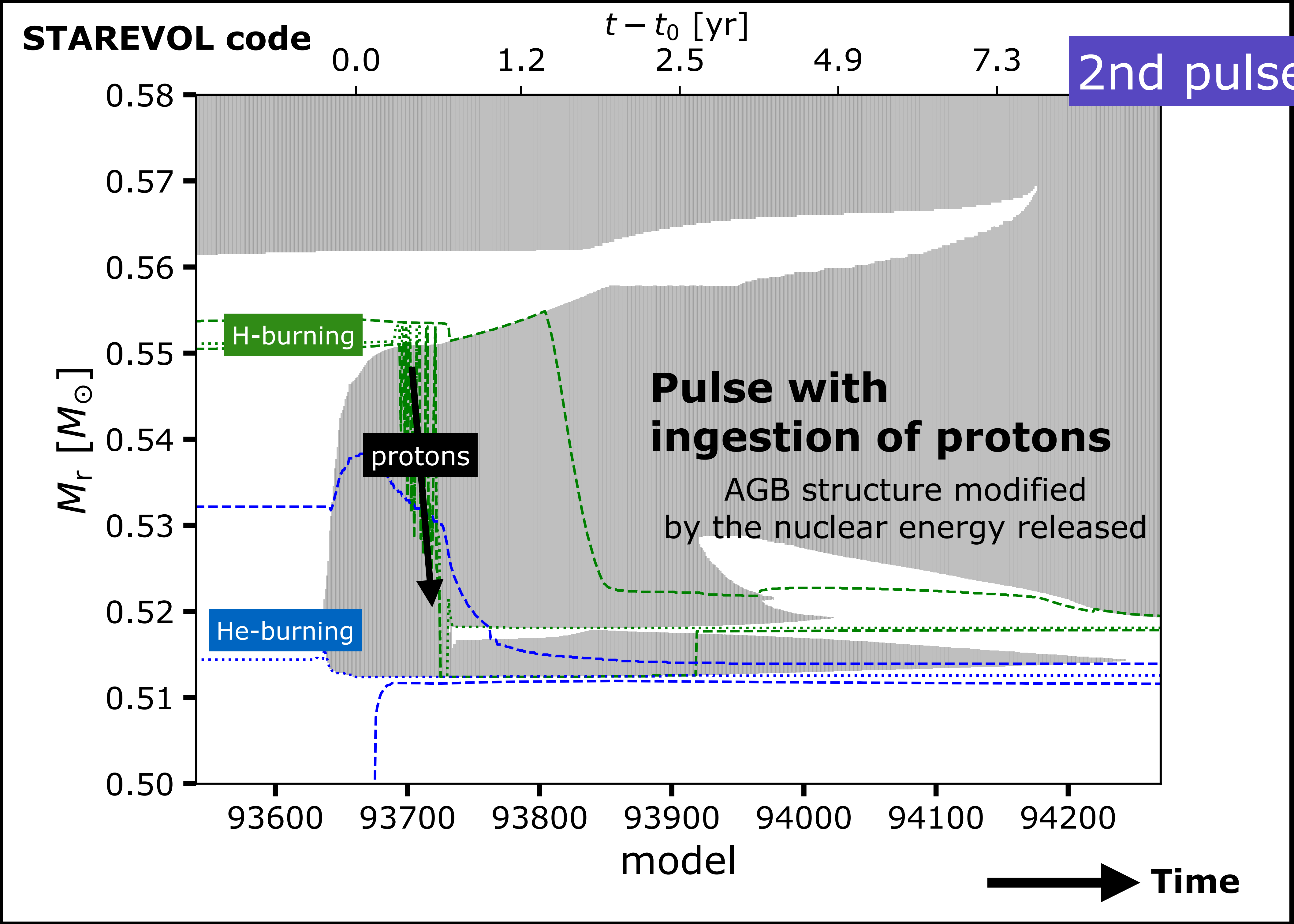

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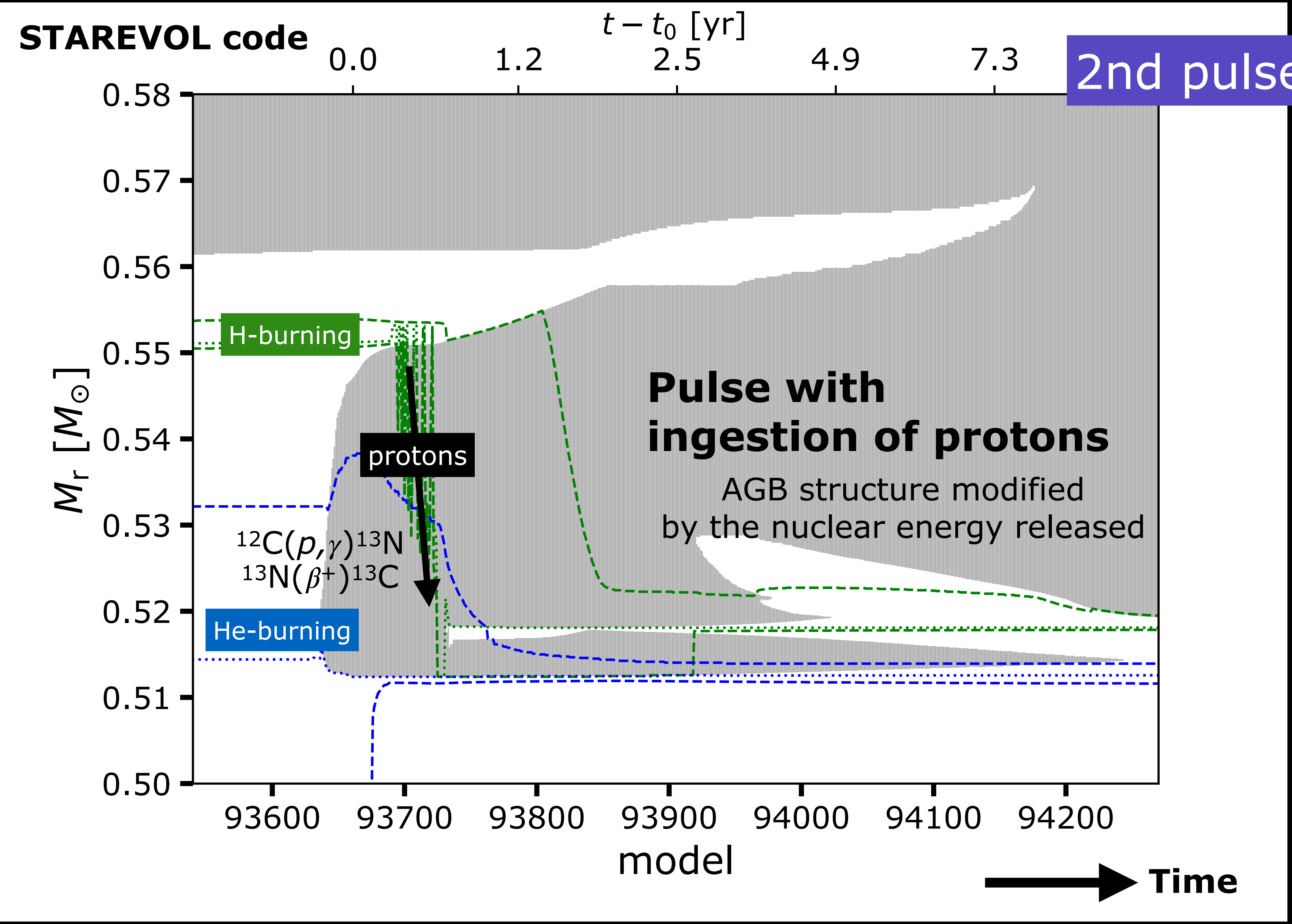

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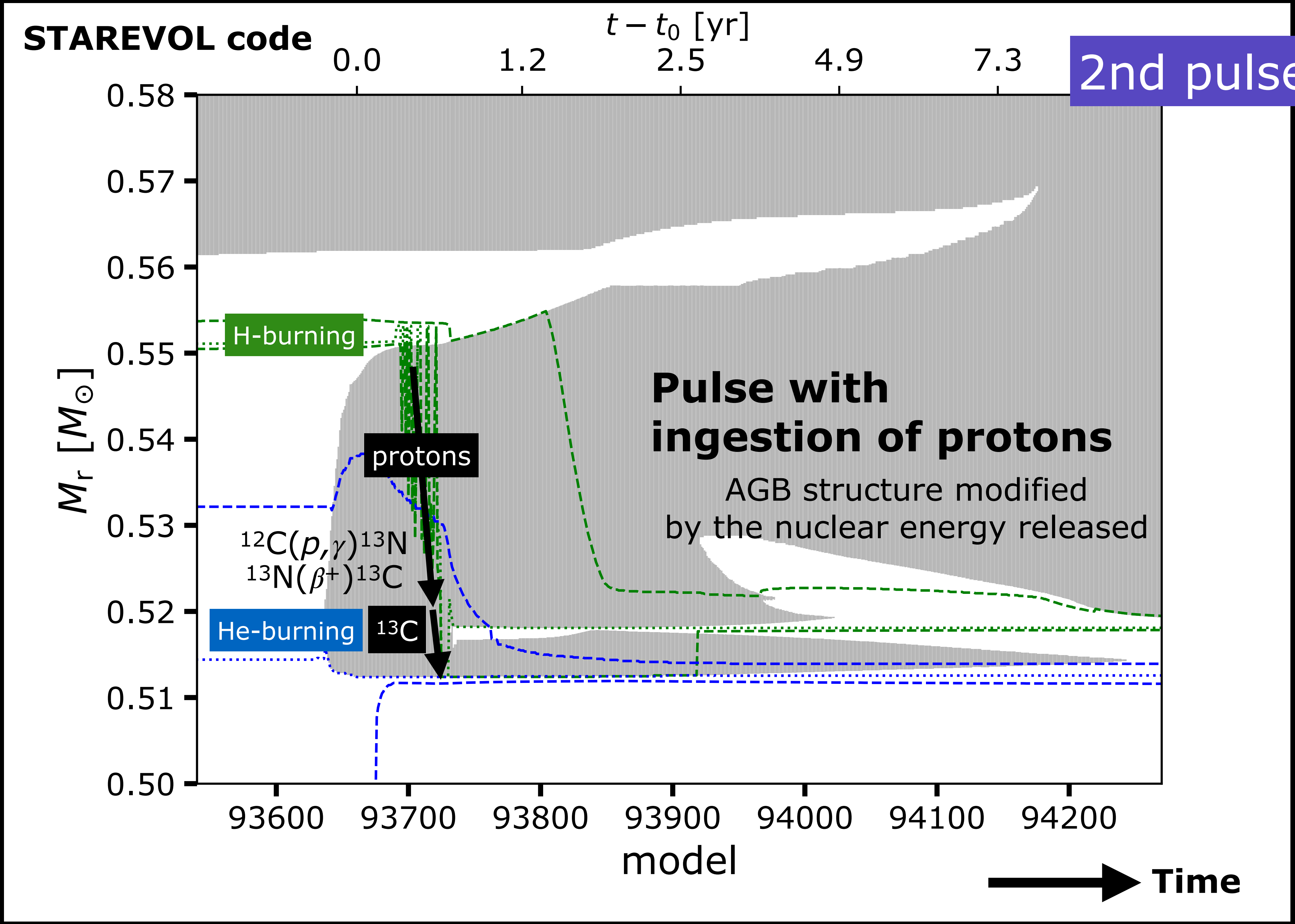

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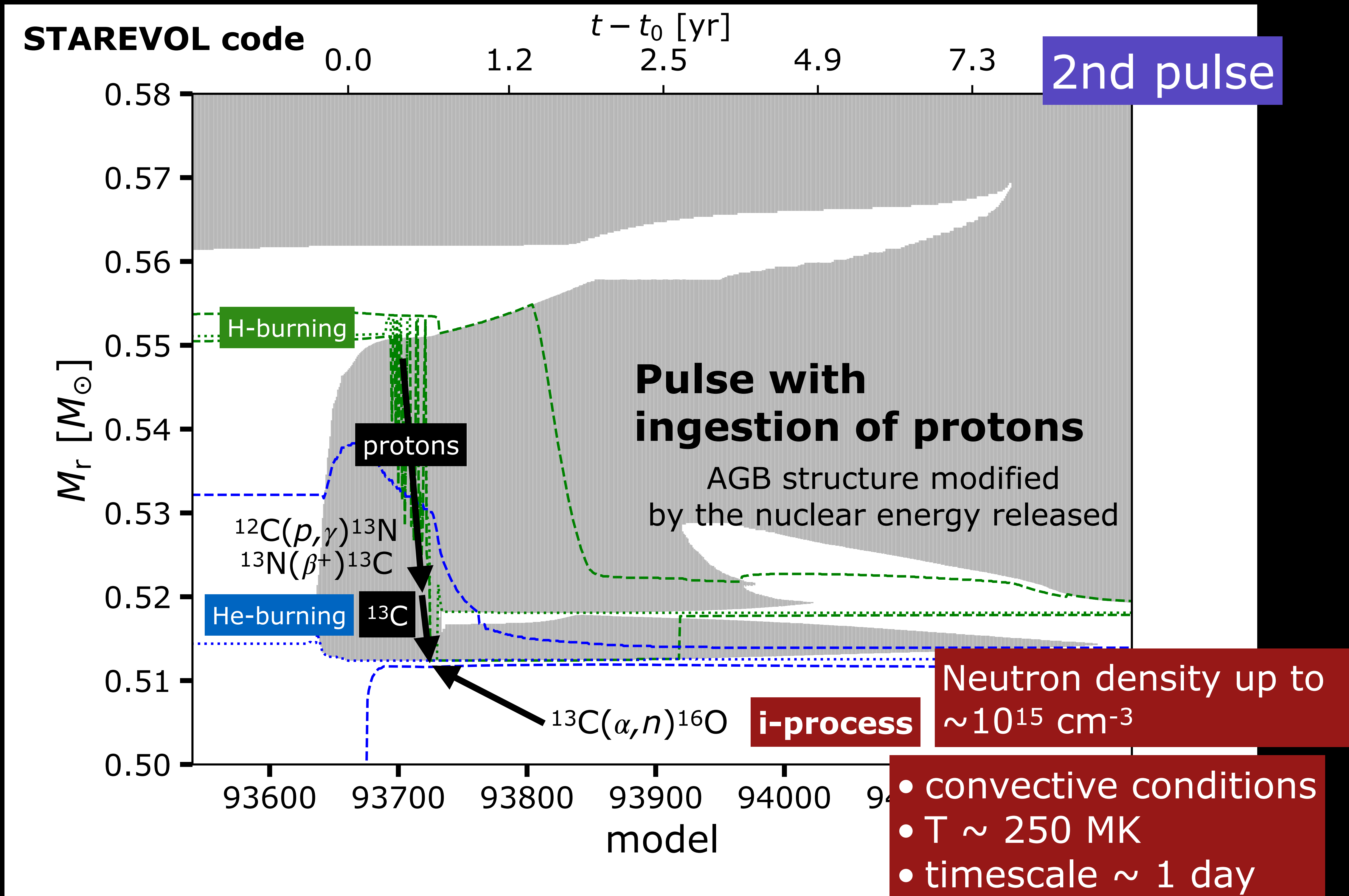

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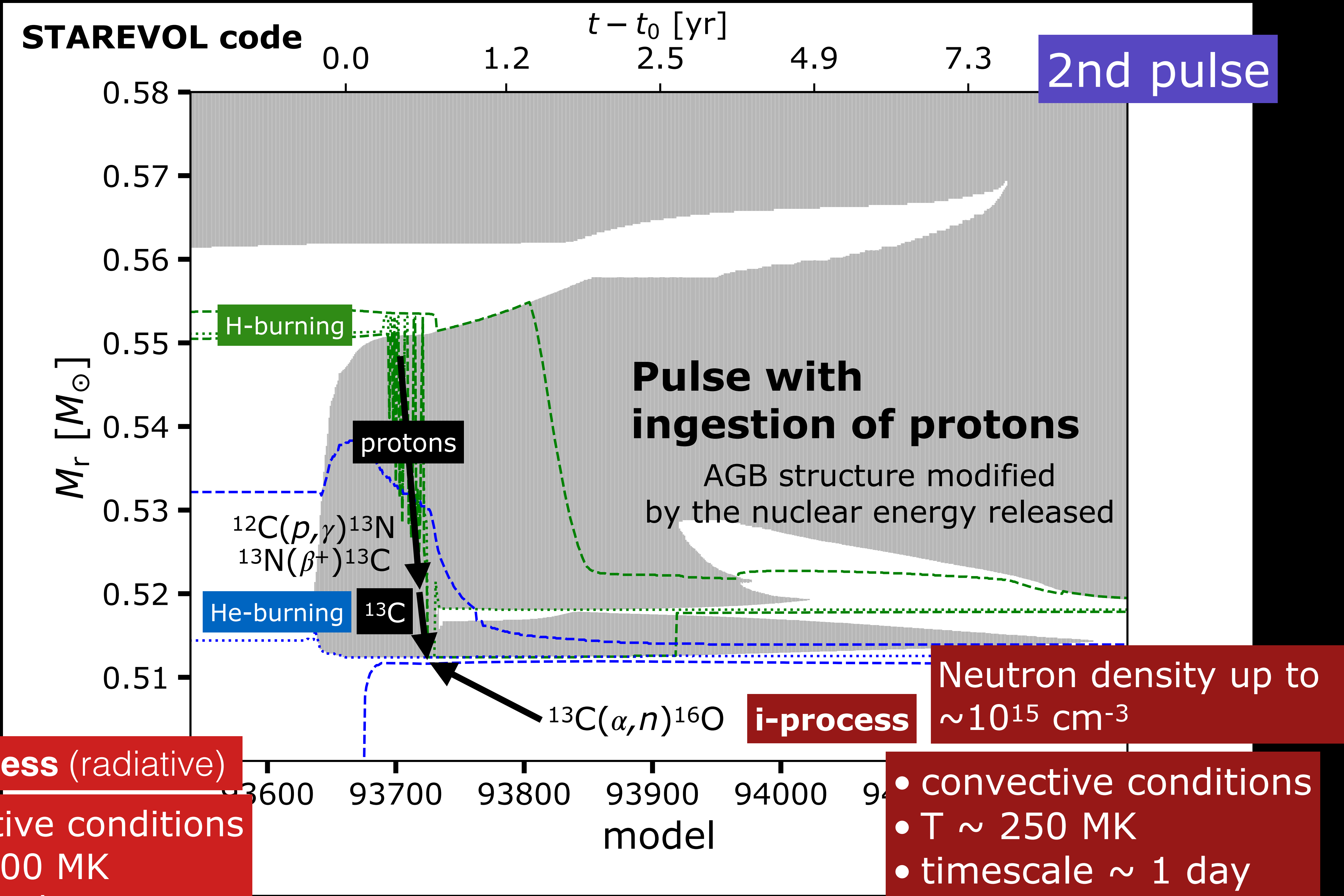

s-process (radiative)
- radiative conditions
- T ~ 100 MK
- timescale ~ 10^4 yr

- convective conditions
- T ~ 250 MK
- timescale ~ 1 day

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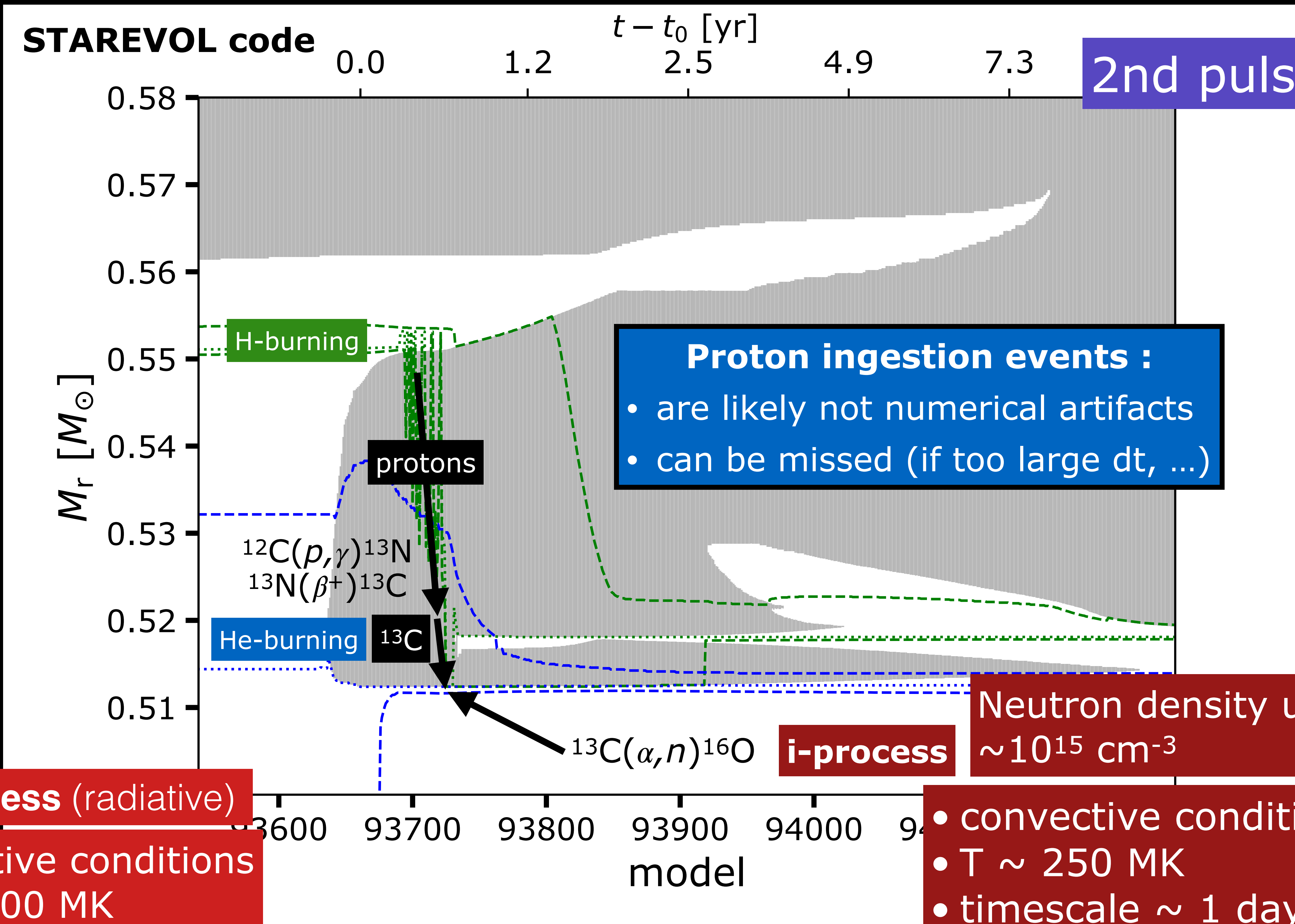


2nd pulse

Proton ingestion events :
- are likely not numerical artifacts
- can be missed (if too large dt, …)

i-process

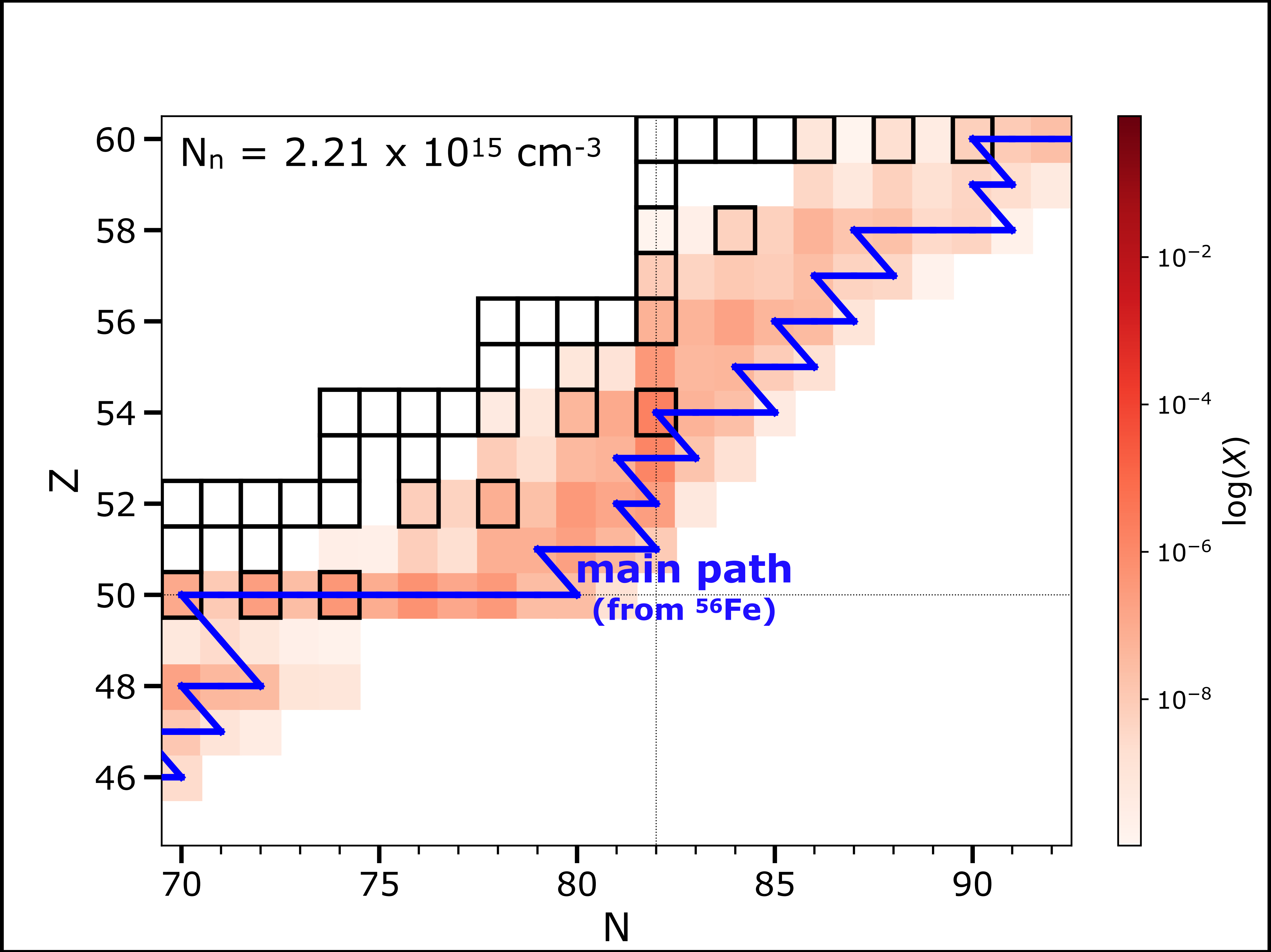
Neutron density up to ~10^{15} cm^{-3}

- convective conditions
- T ~ 250 MK
- timescale ~ 1 day

s-process (radiative)

- radiative conditions
- T ~ 100 MK
- timescale ~ 10^4 yr

i-process path at the bottom of the thermal pulse



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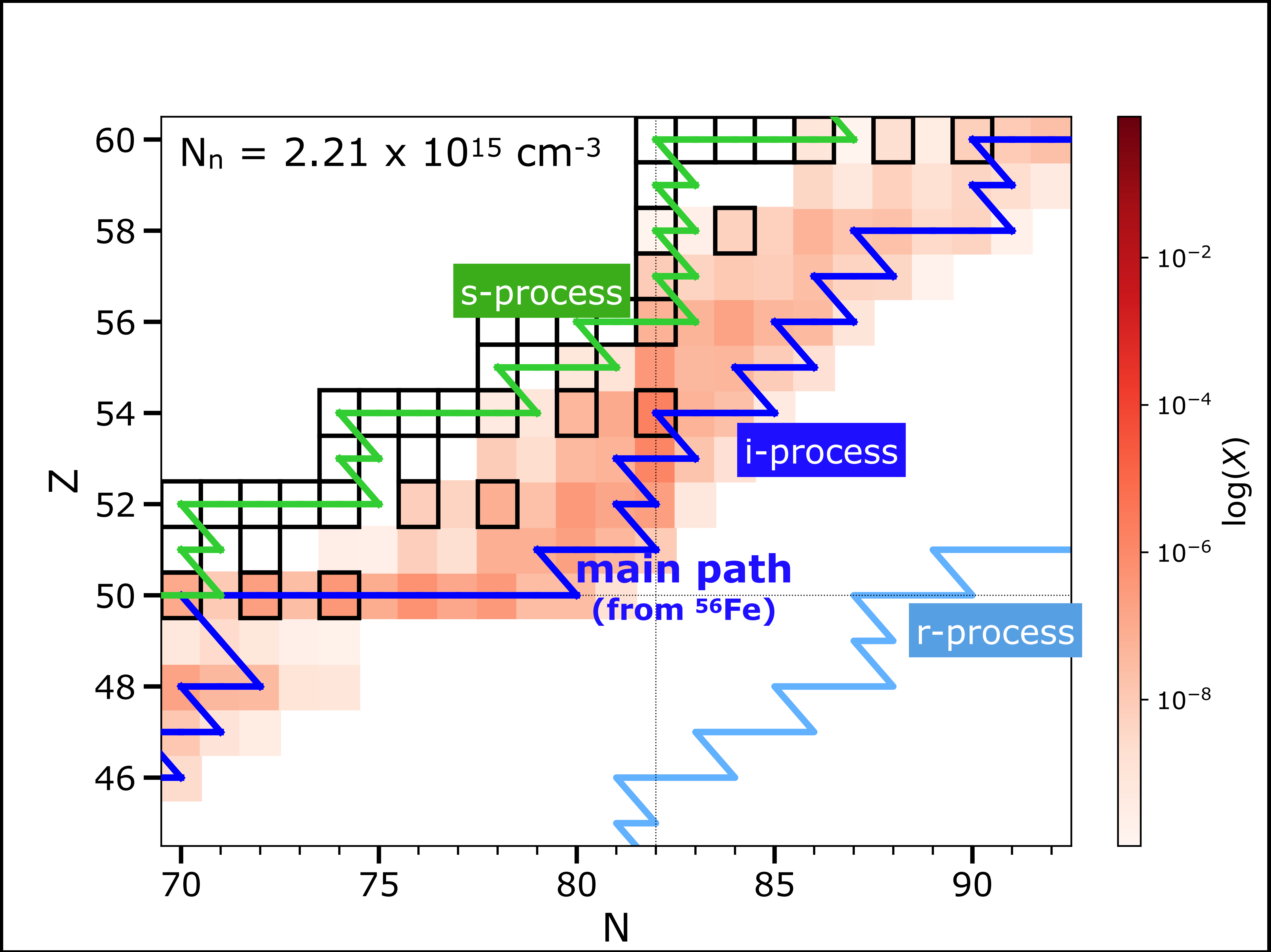
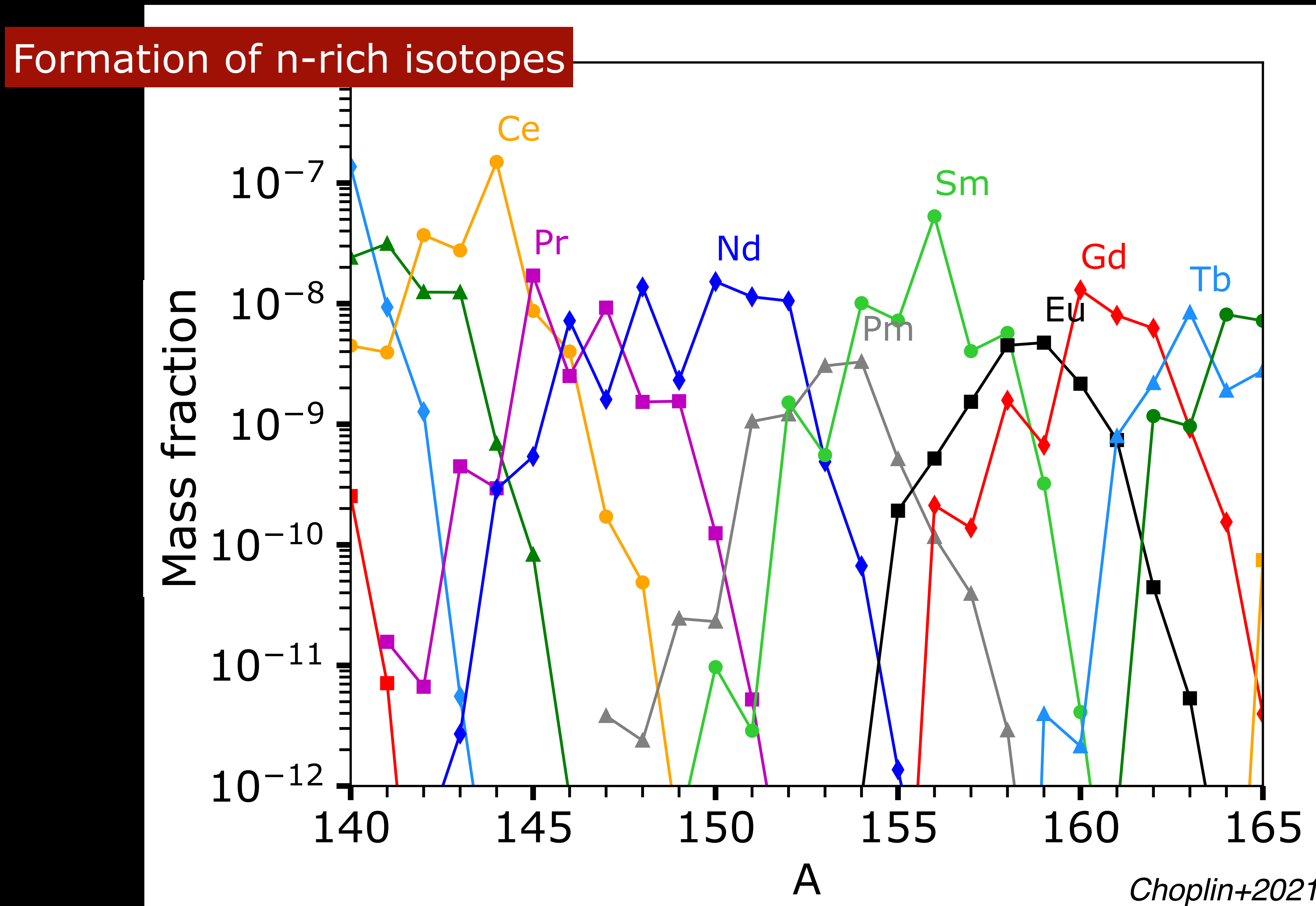
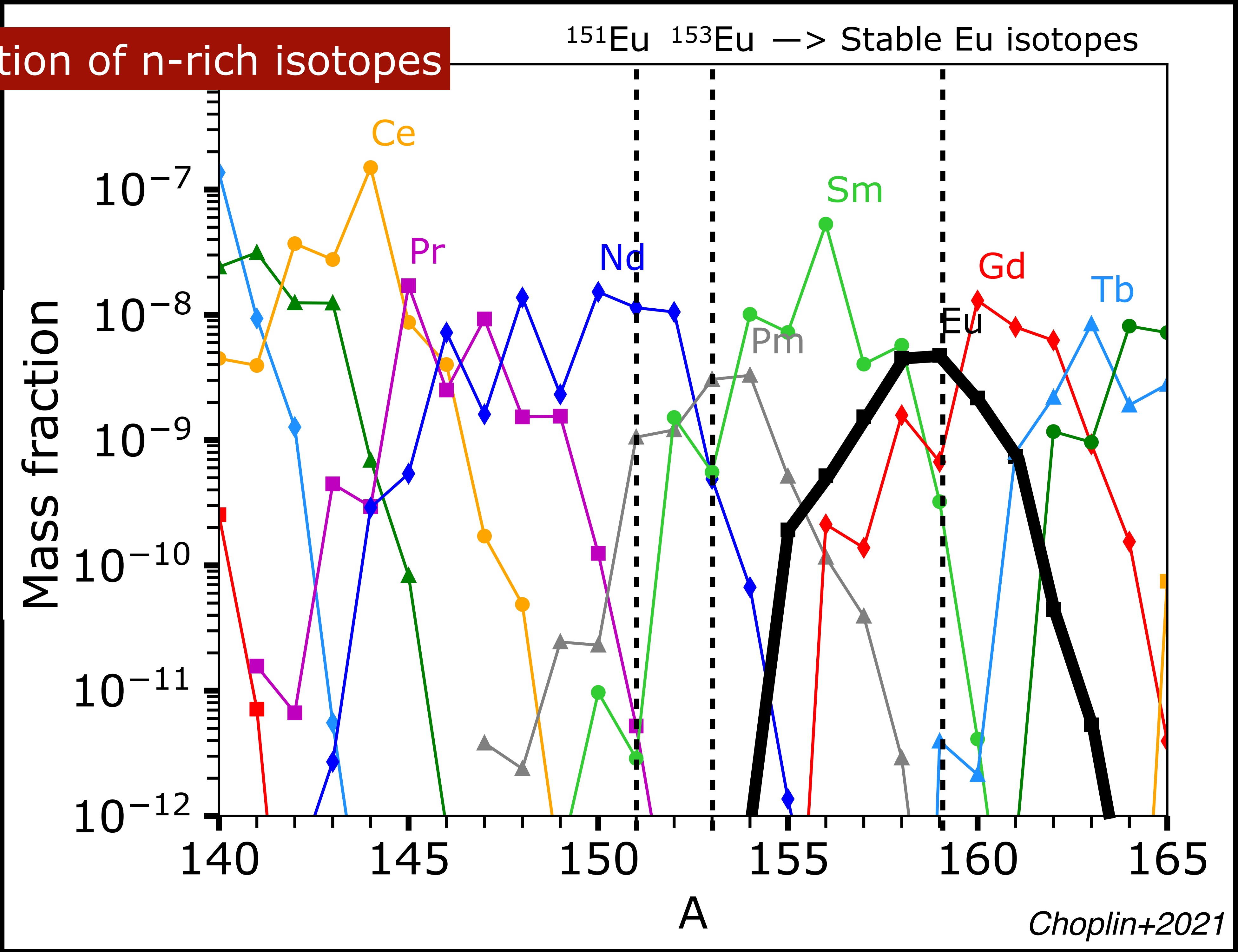


Chemical composition during the i-process



Chemical composition during the i-process

Formation of n-rich isotopes



^{159}Eu half-life ~ 20 min

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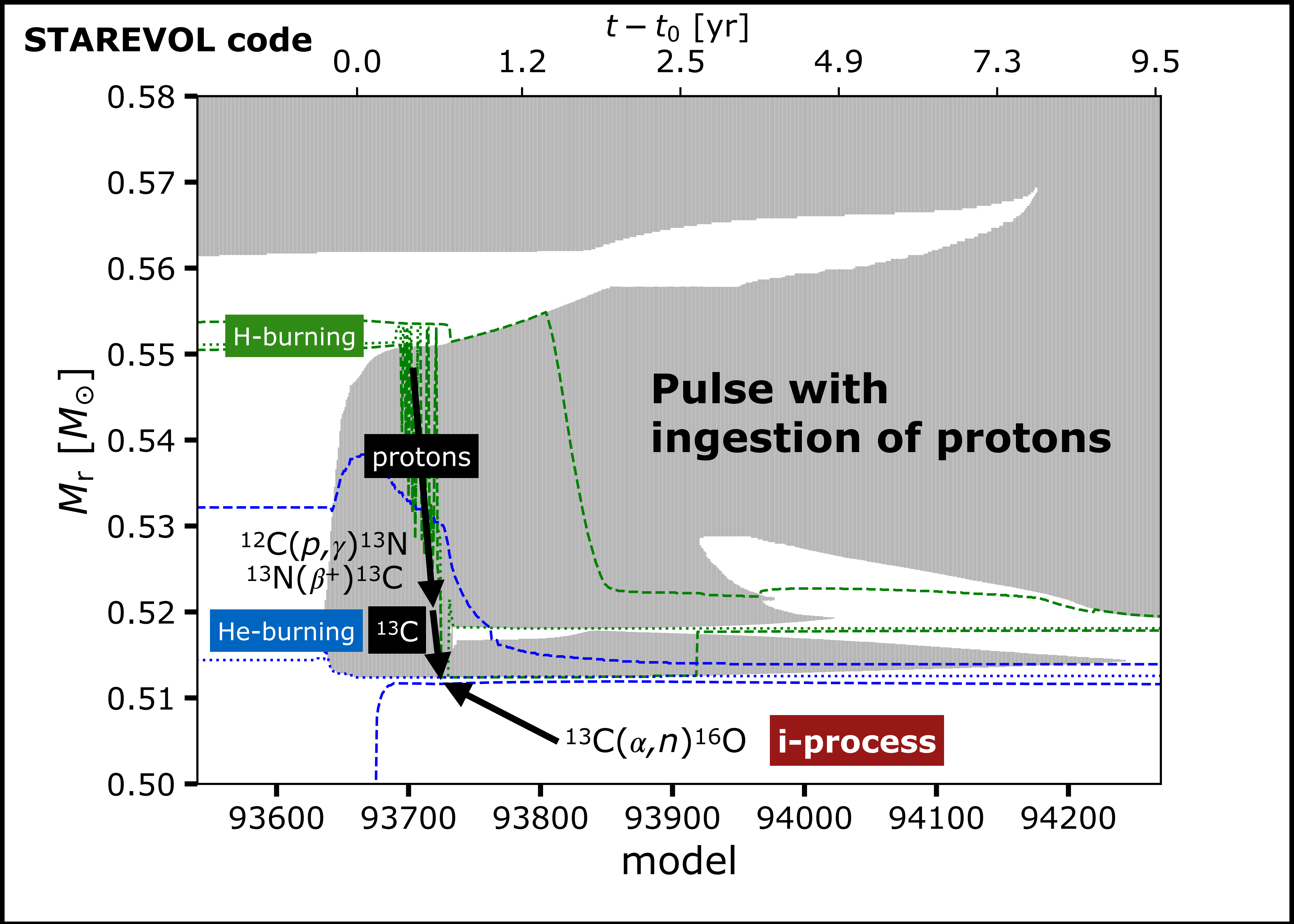

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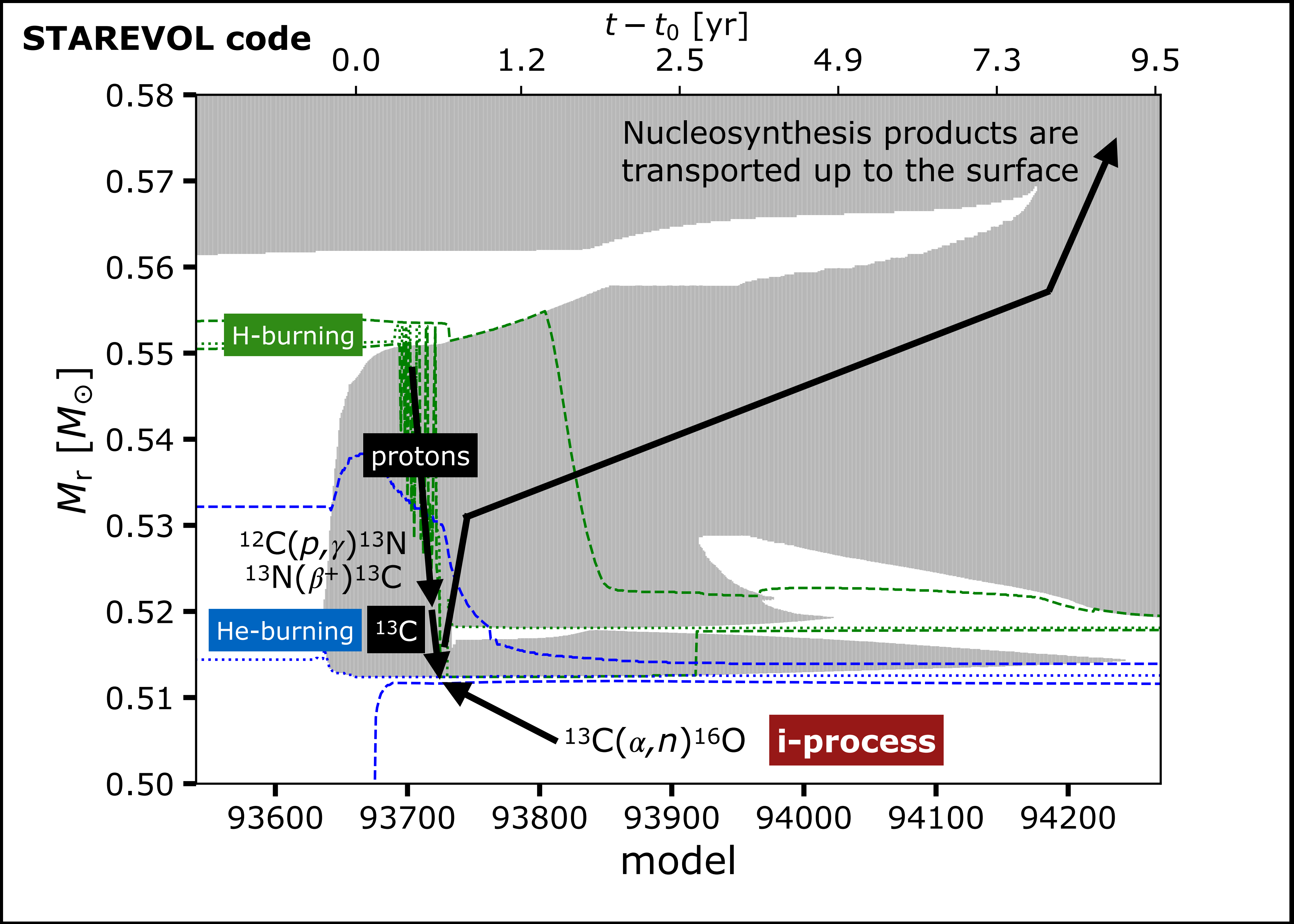

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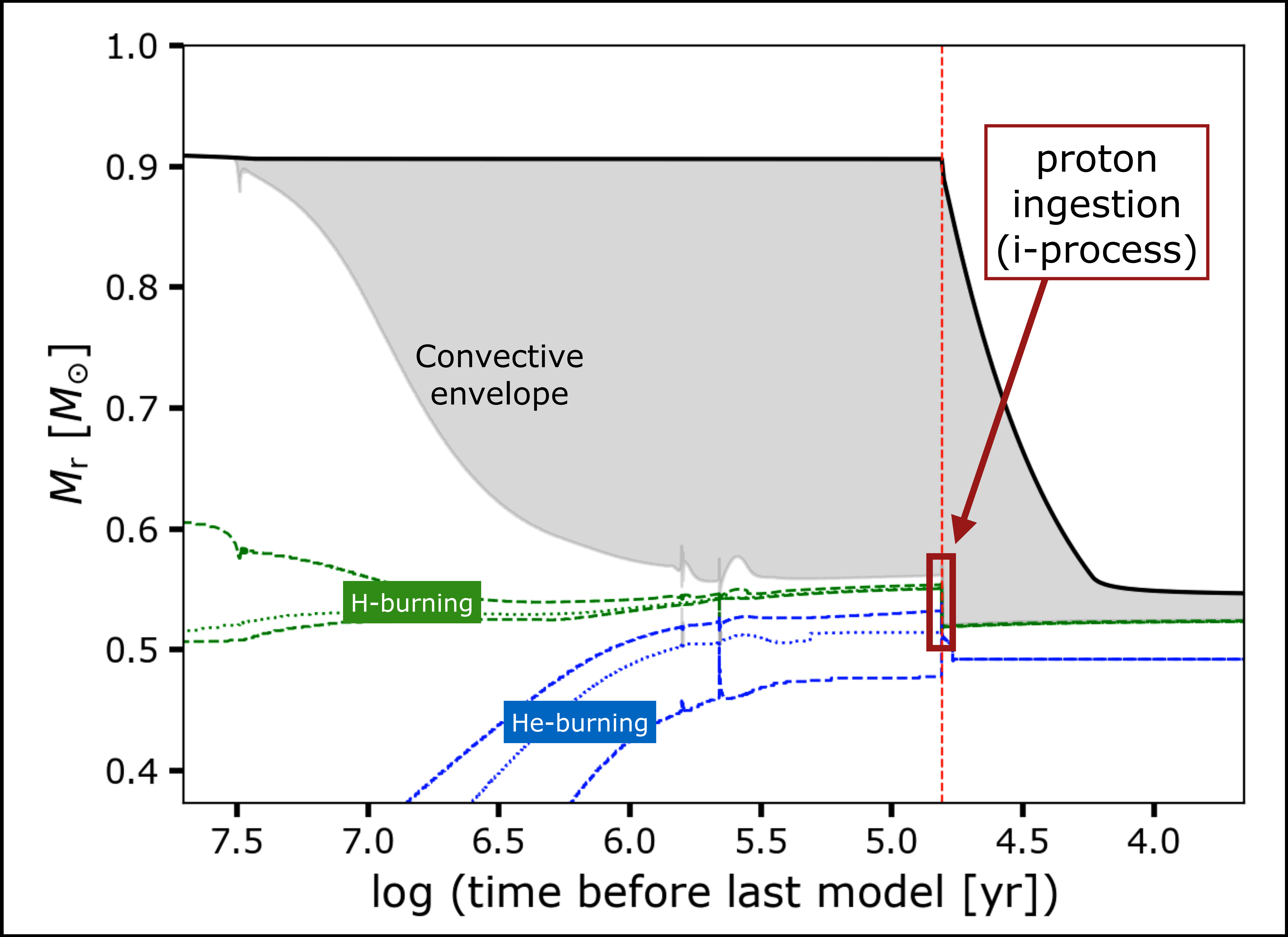

The **i-process** in a 1 $M_\odot$, [Fe/H] = -2.5 AGB model
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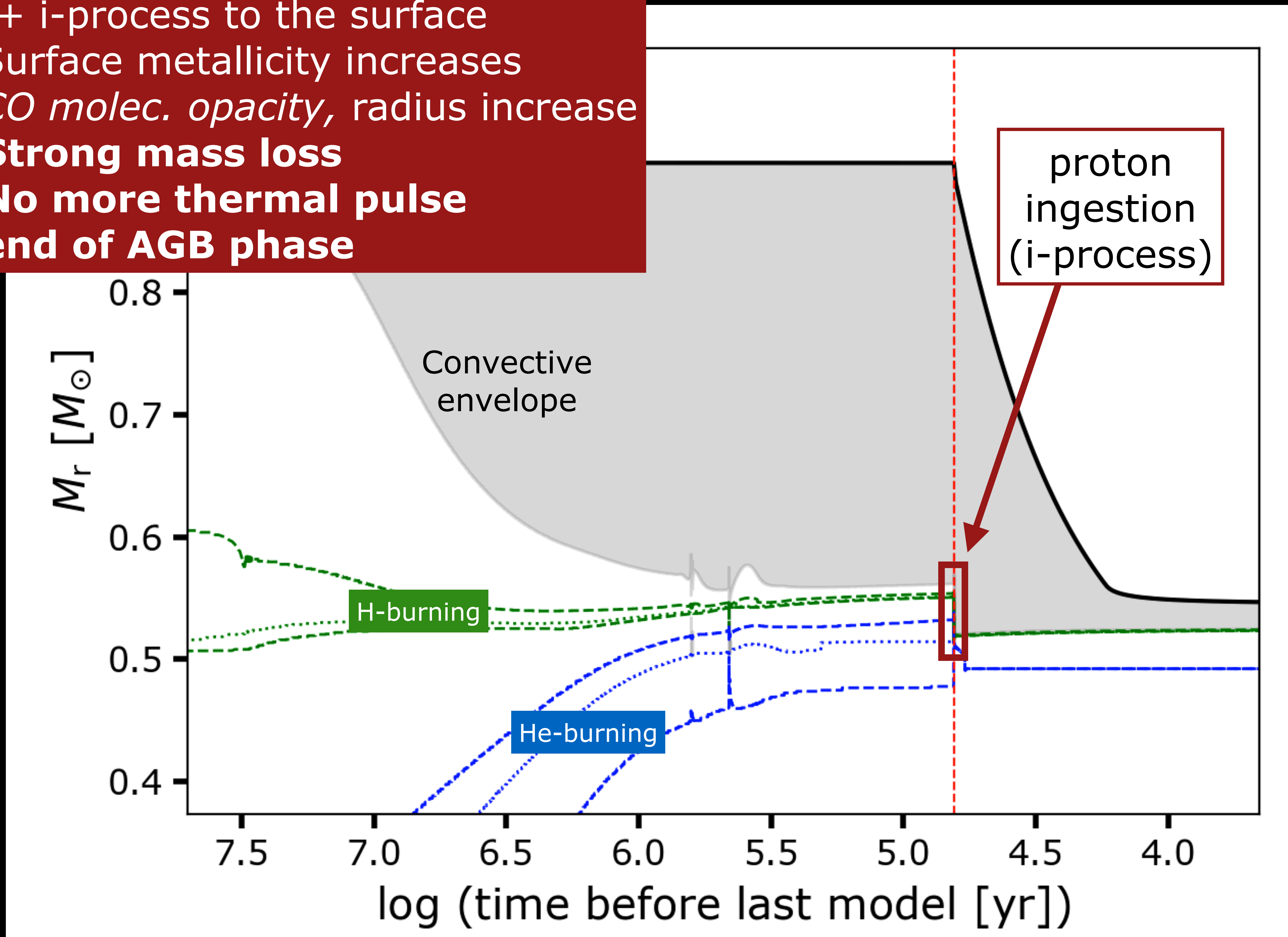
CNO + i-process to the surface
—> Surface metallicity increases
—> *CO molec. opacity,* radius increase
—> Strong mass loss
—> No more thermal pulse
—> end of AGB phase



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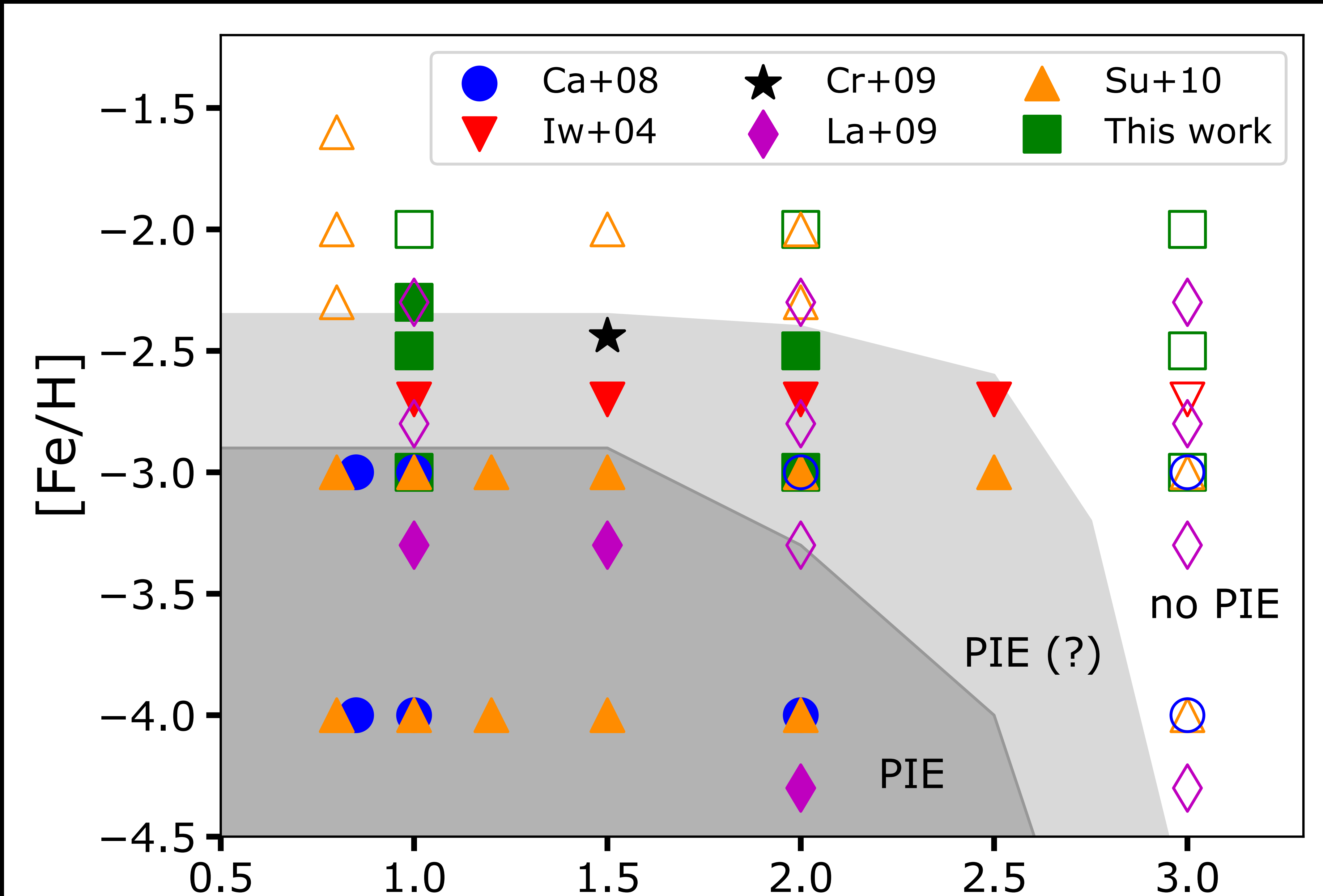

- filled symbol : ingestion
- open symbol : no ingestion

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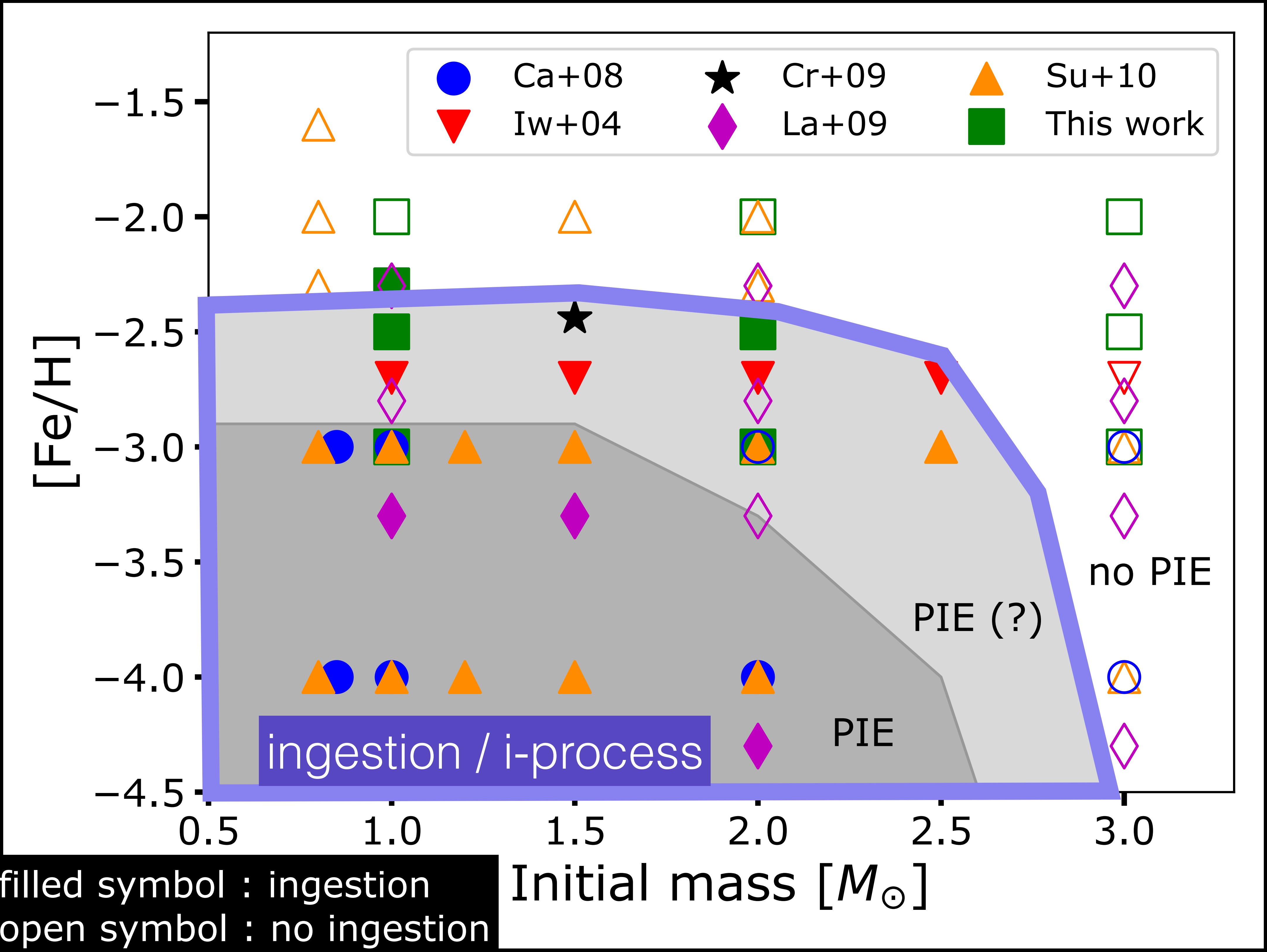

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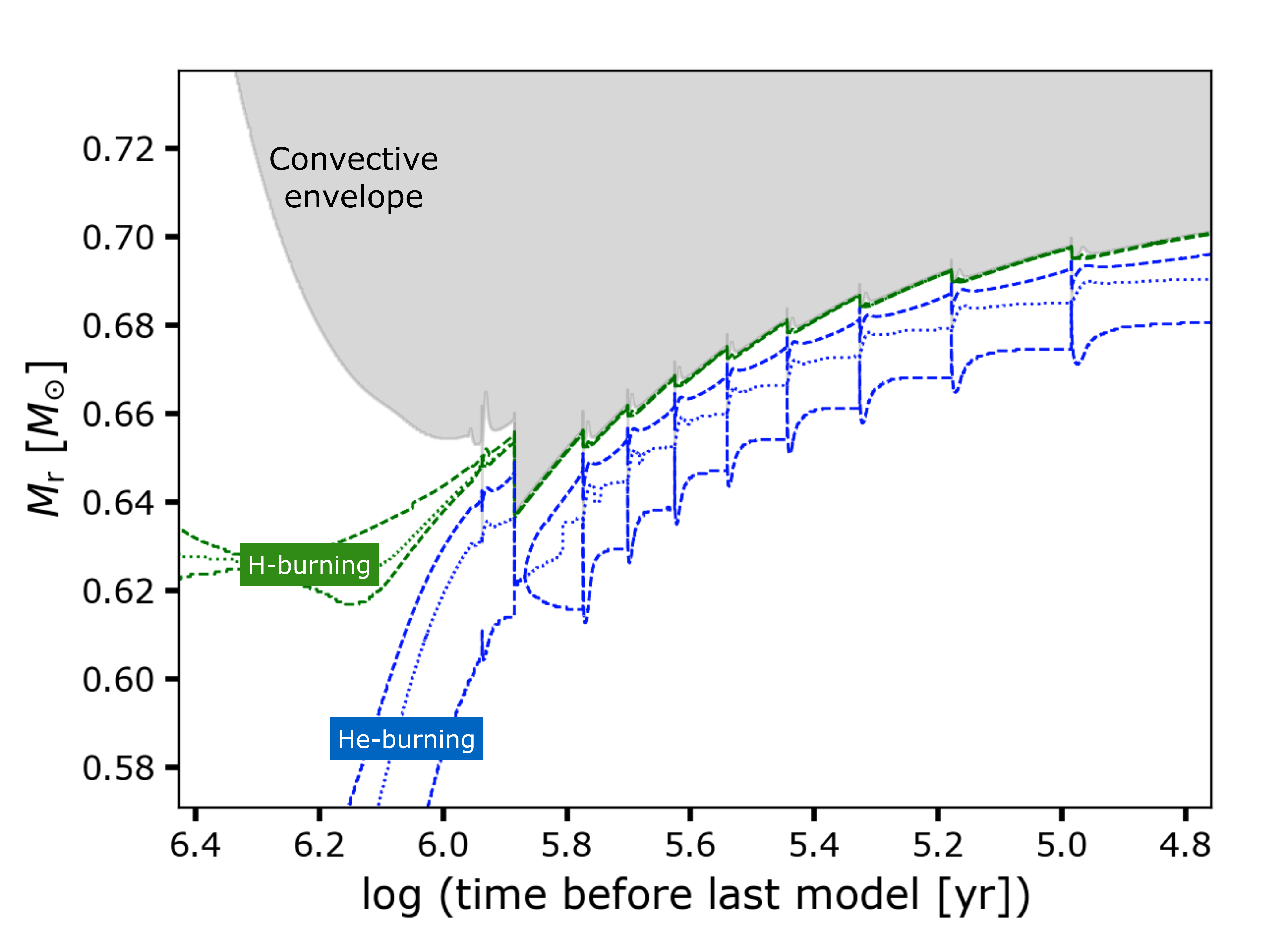
The case of a 2 $M_\odot$, [Fe/H] = -2.5 AGB model
($Z = 4 \times 10^{-5}$)



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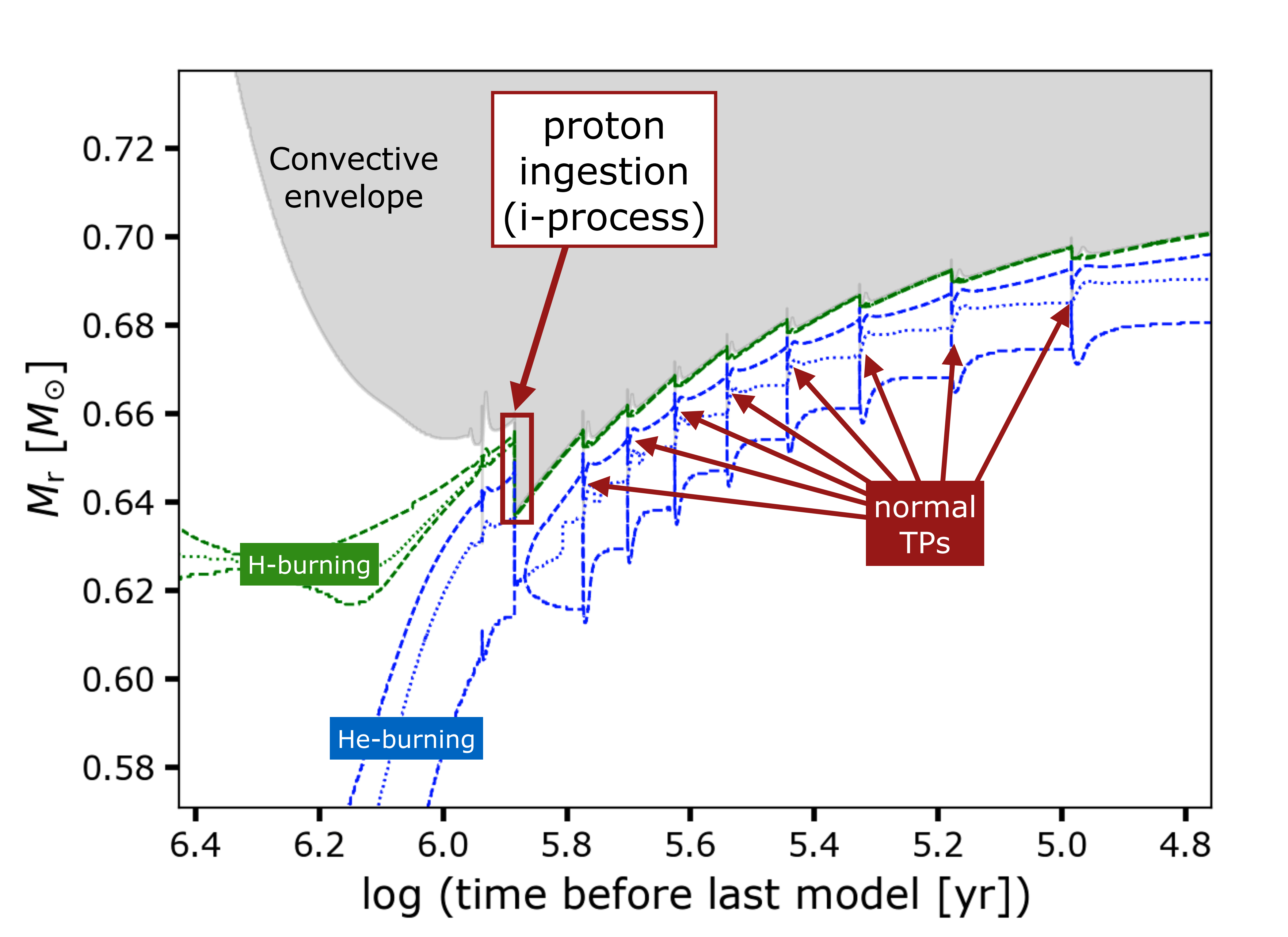

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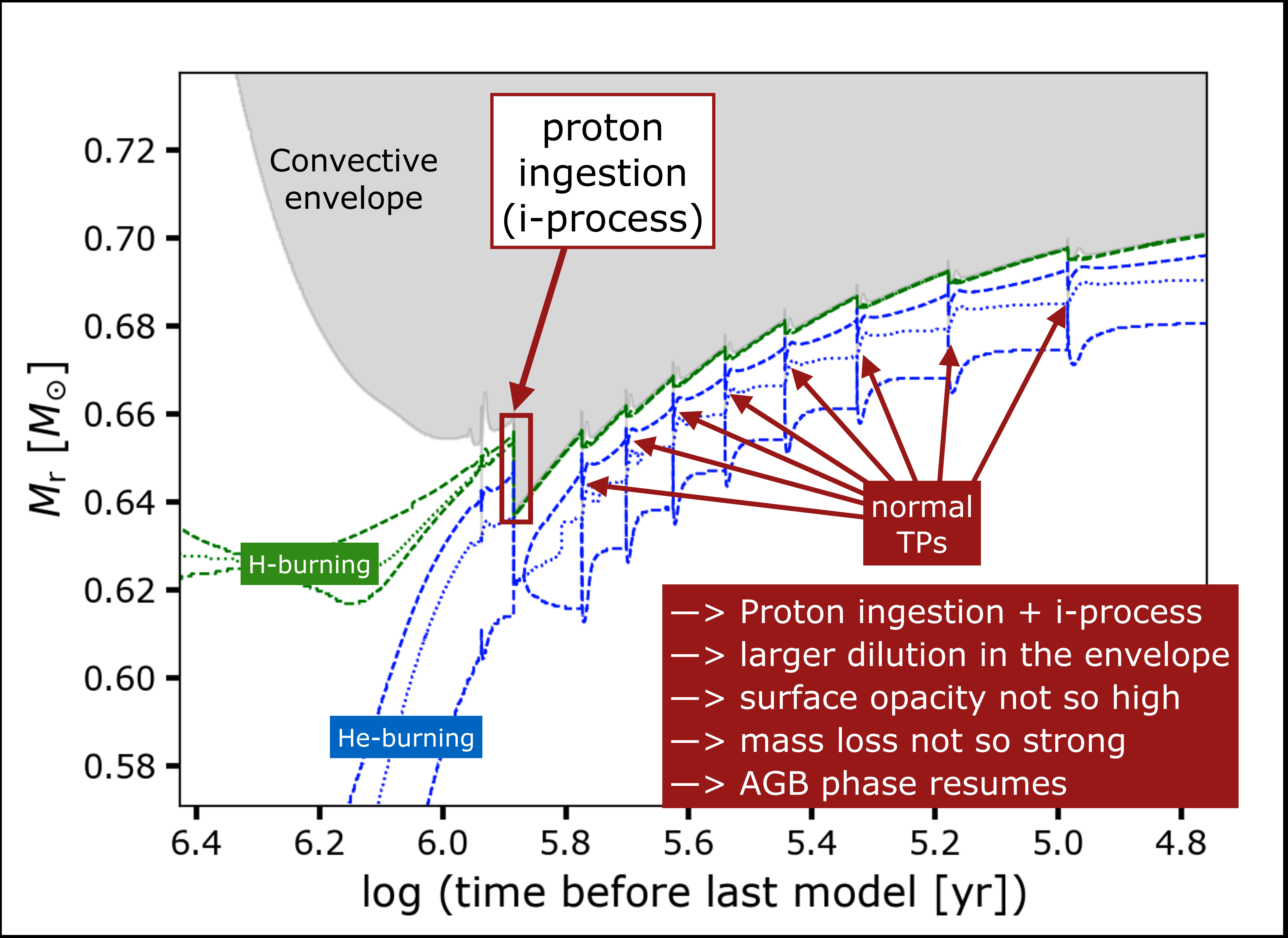
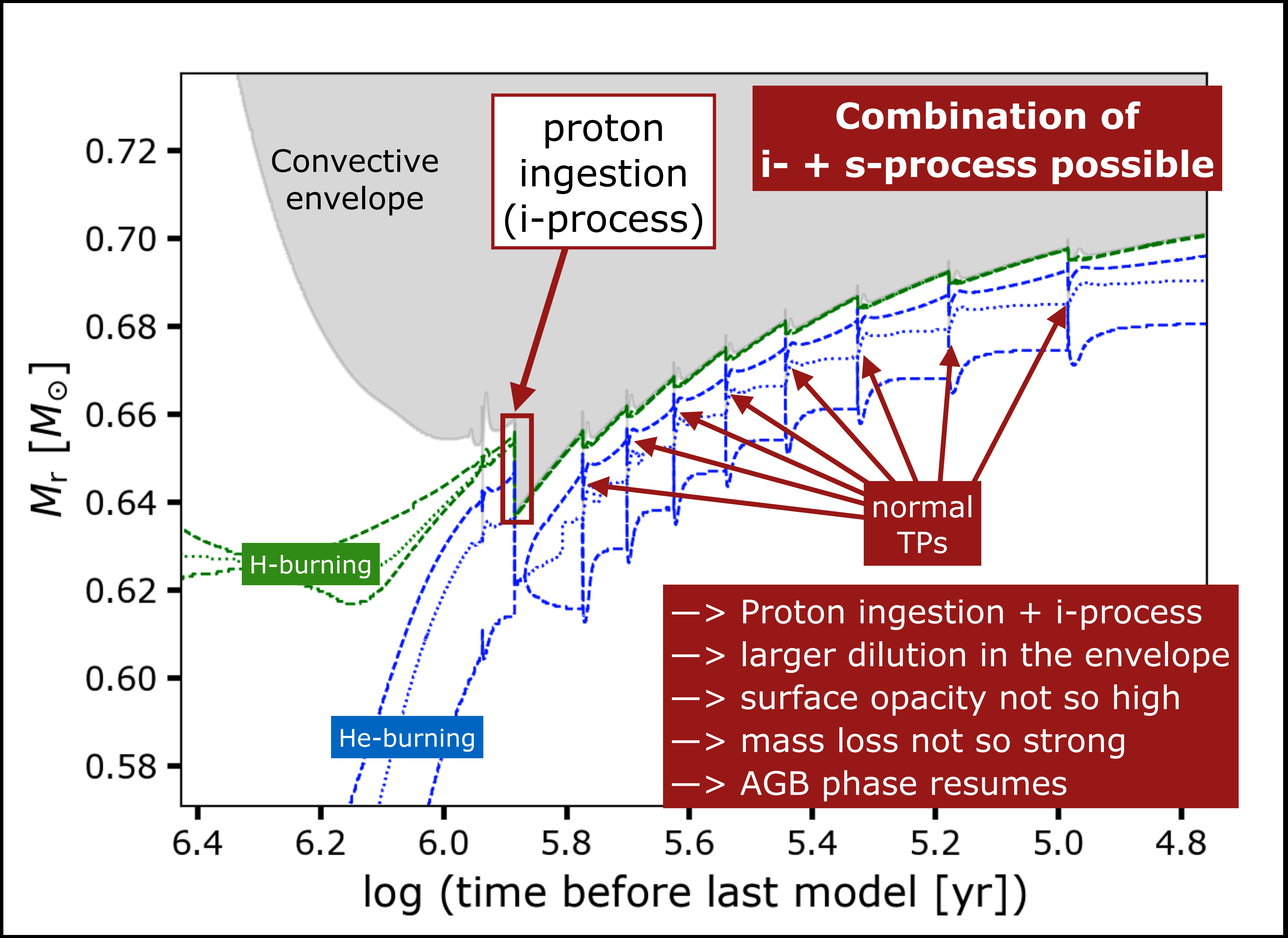


—> Proton ingestion + i-process
—> larger dilution in the envelope
—> surface opacity not so high
—> mass loss not so strong
—> AGB phase resumes

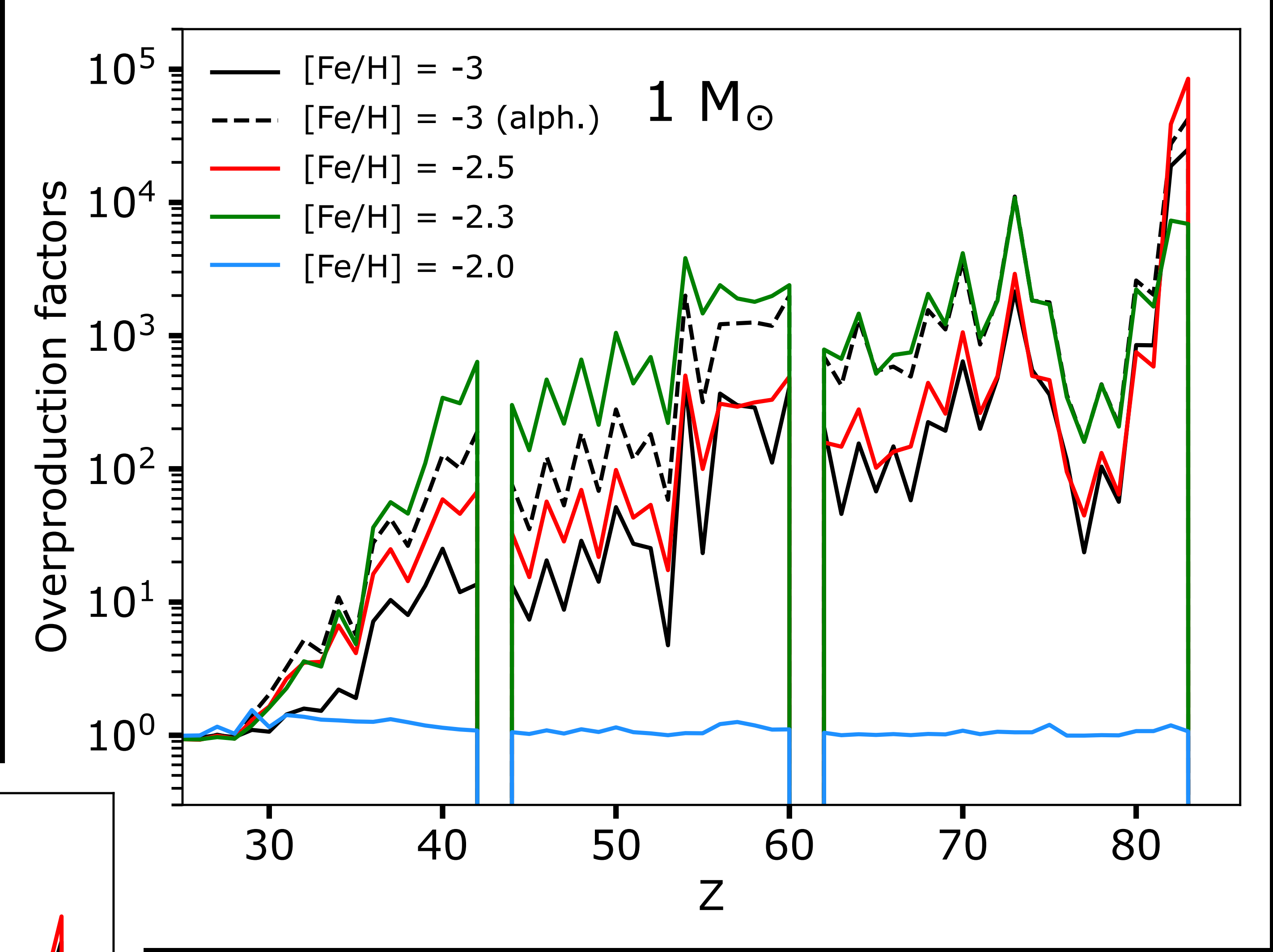
The case of a 2 M⊙, [Fe/H] = -2.5 AGB model

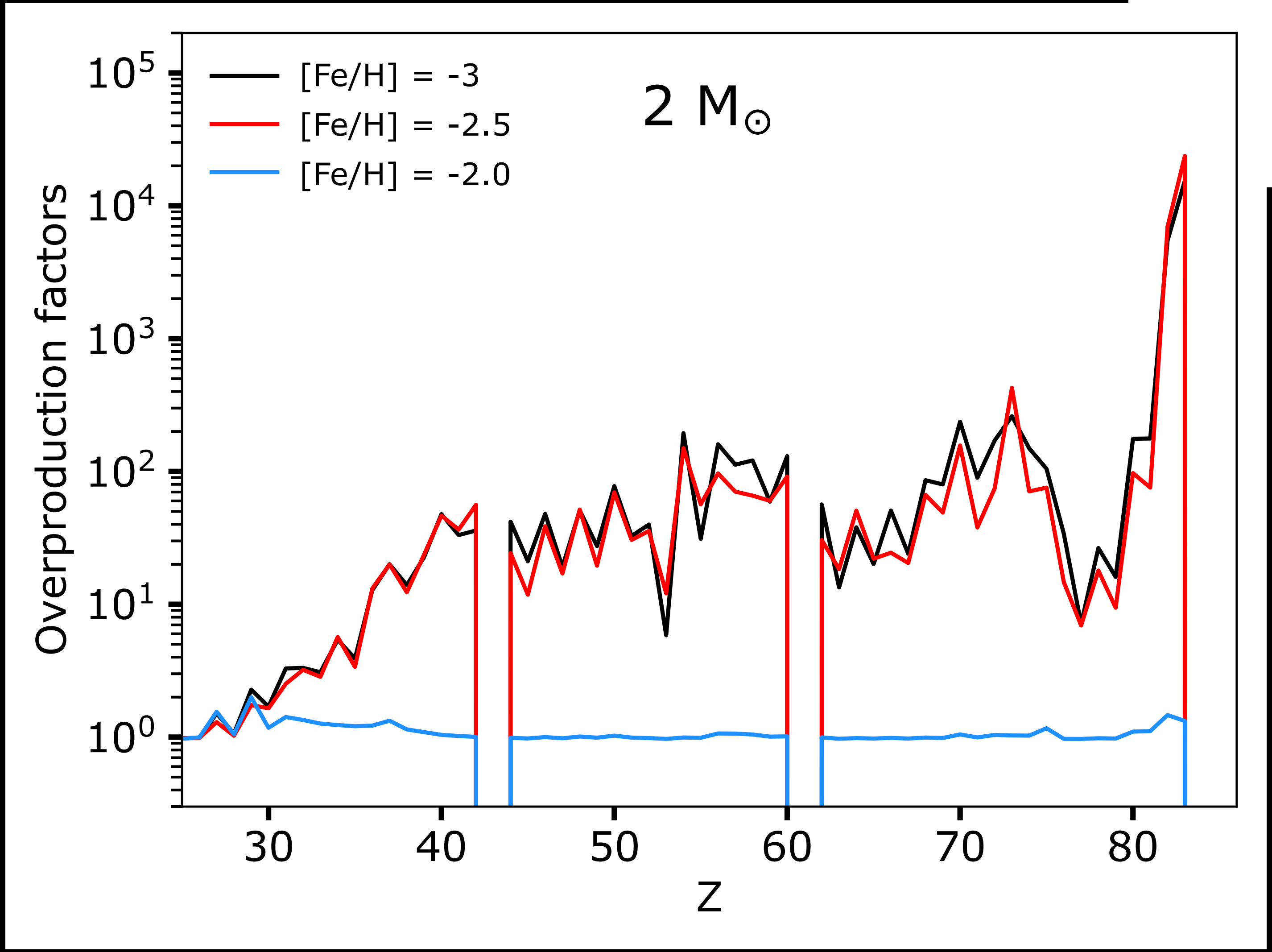
($Z = 4 \times 10^{-5}$)



Yields of 1 - 3 M⊙ models with -3 < [Fe/H] < -2

no extra mixing





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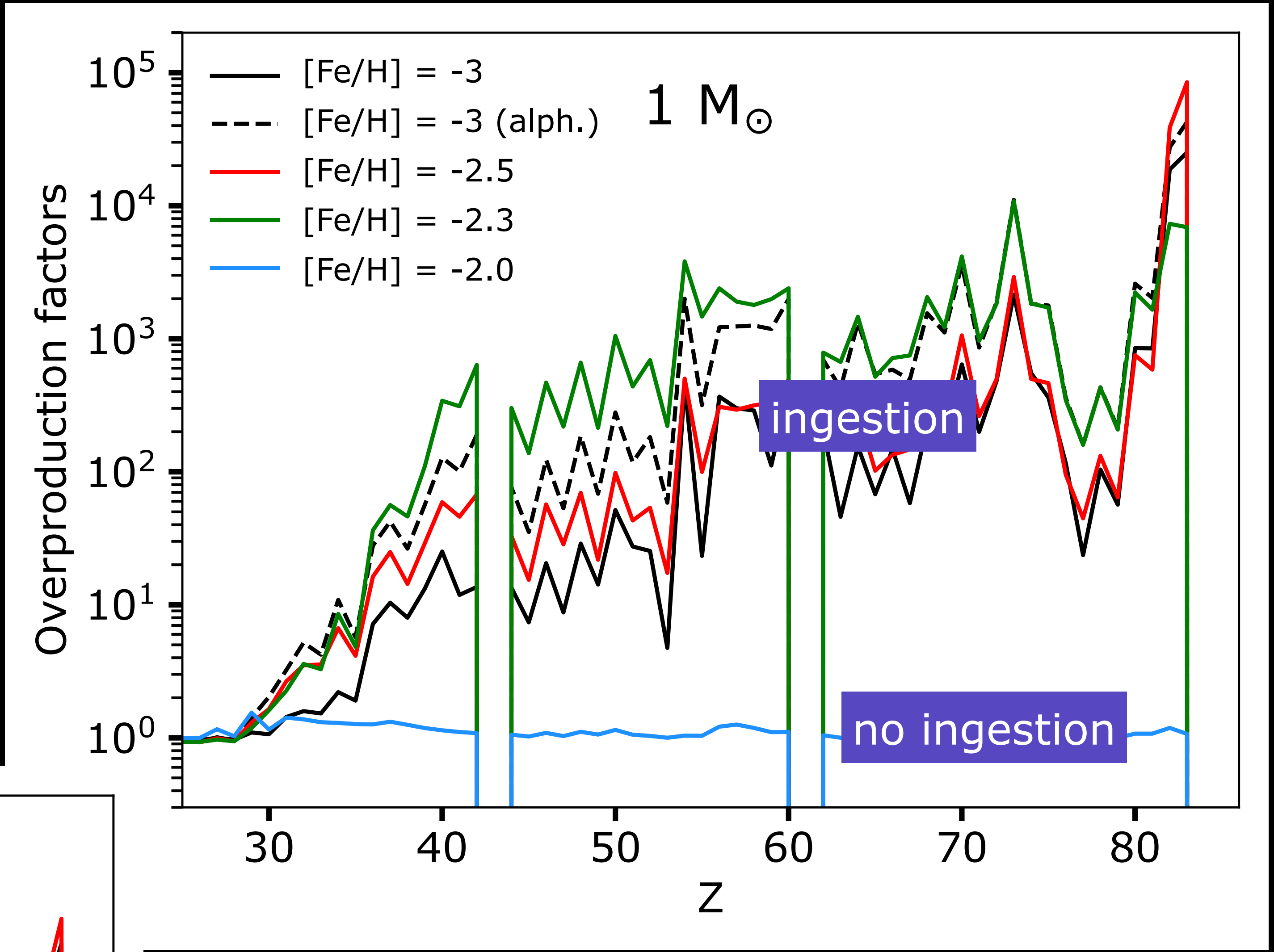

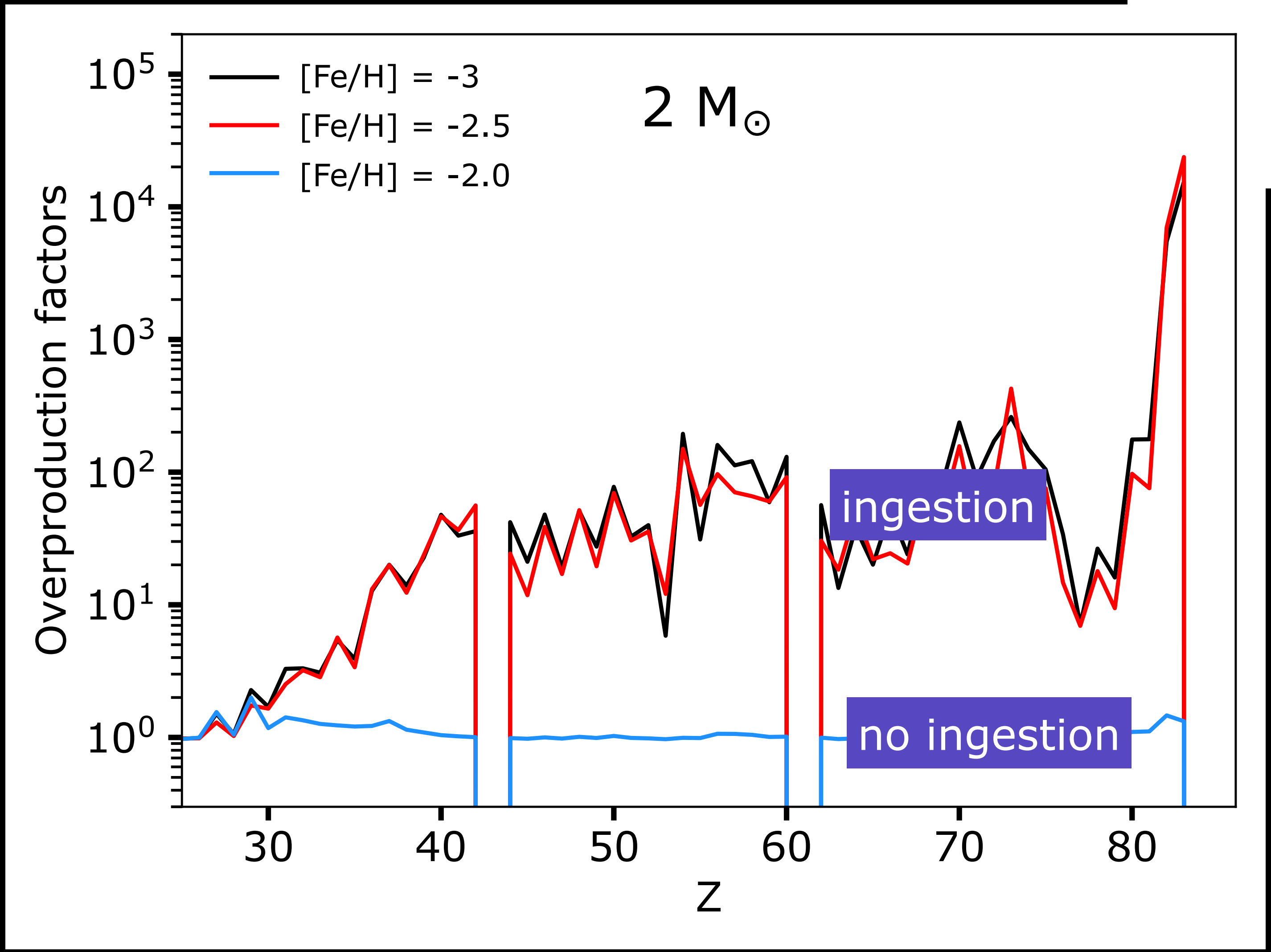

All models with proton ingestion give similar abundance distributions

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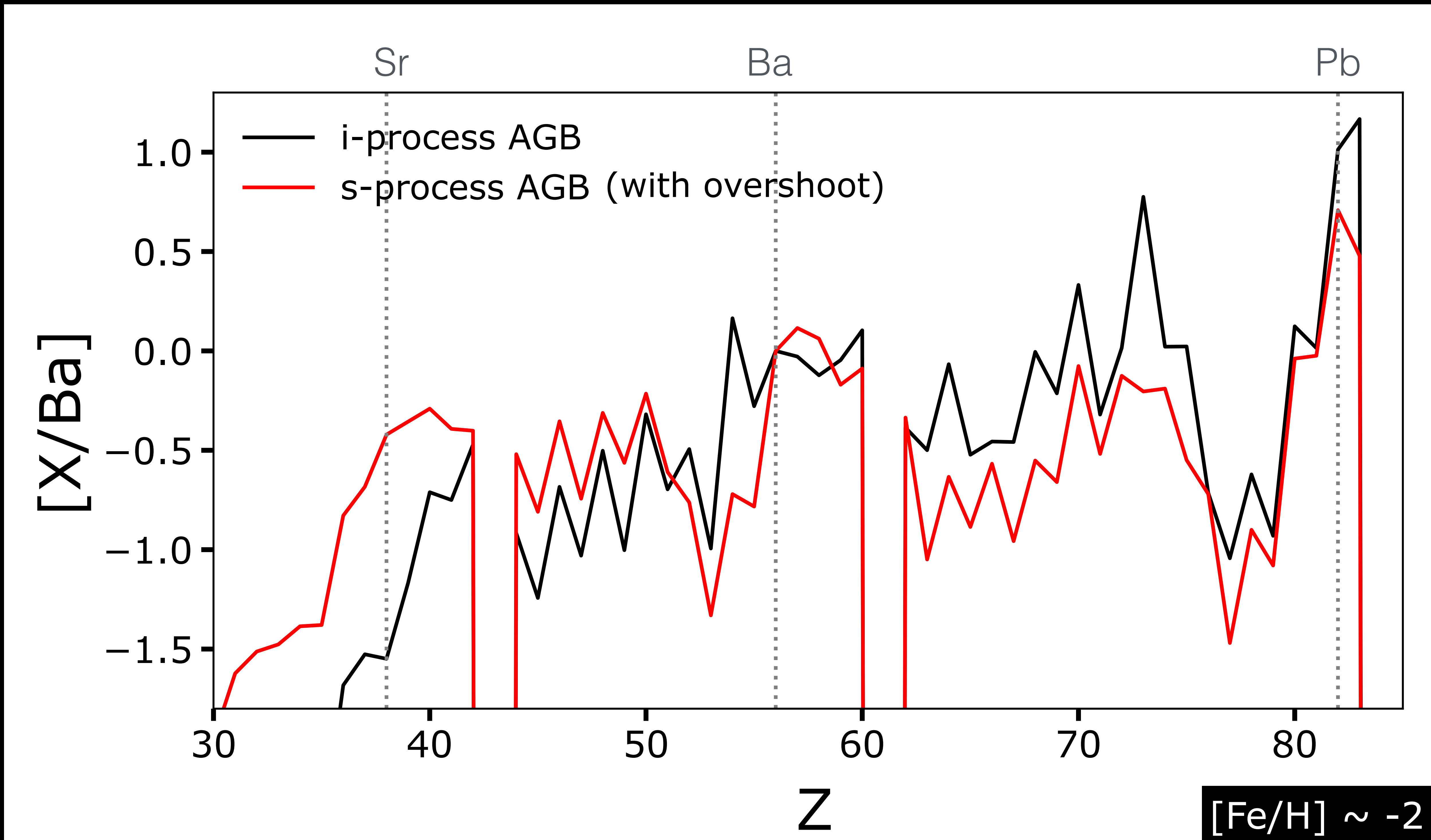

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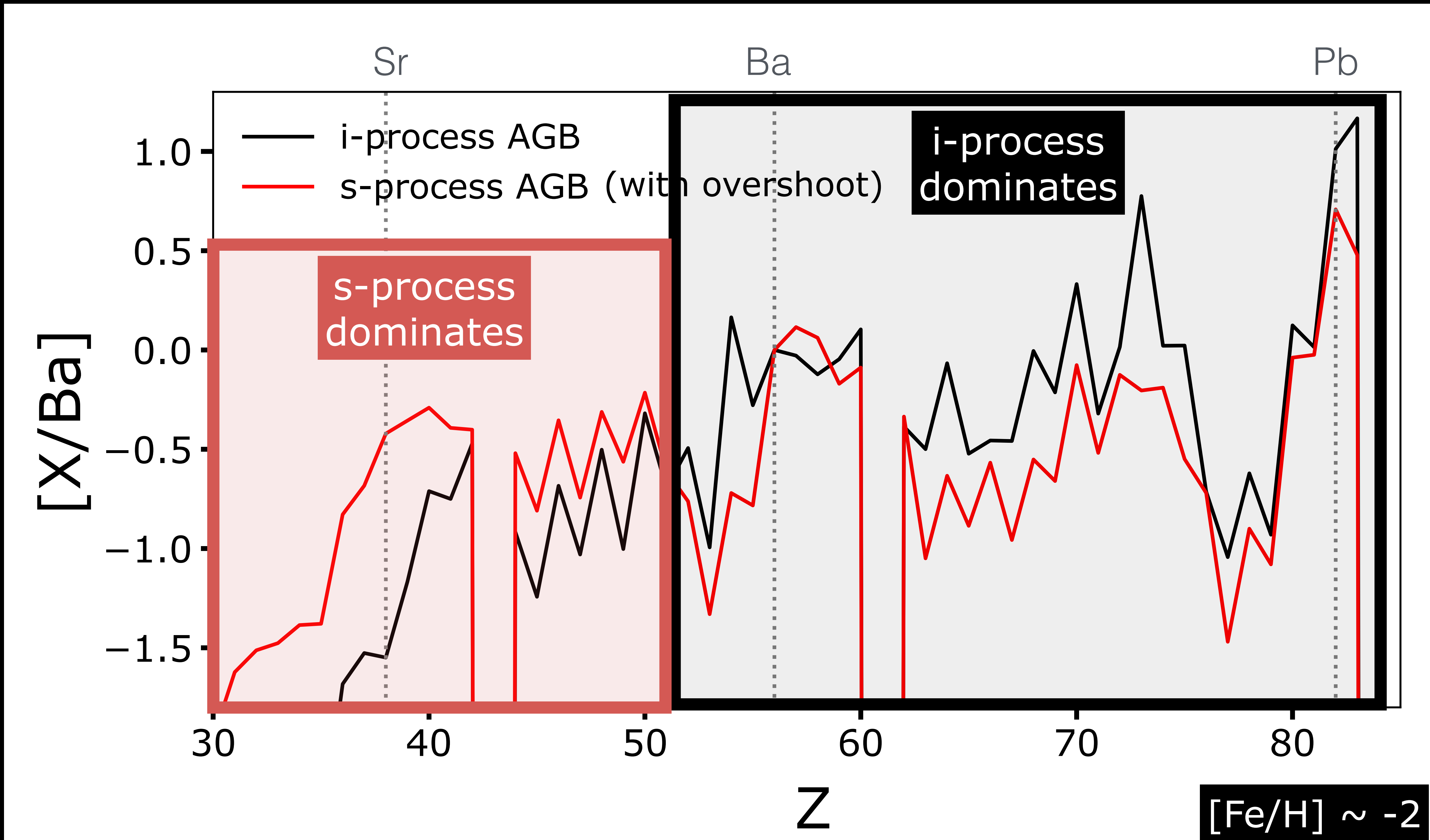

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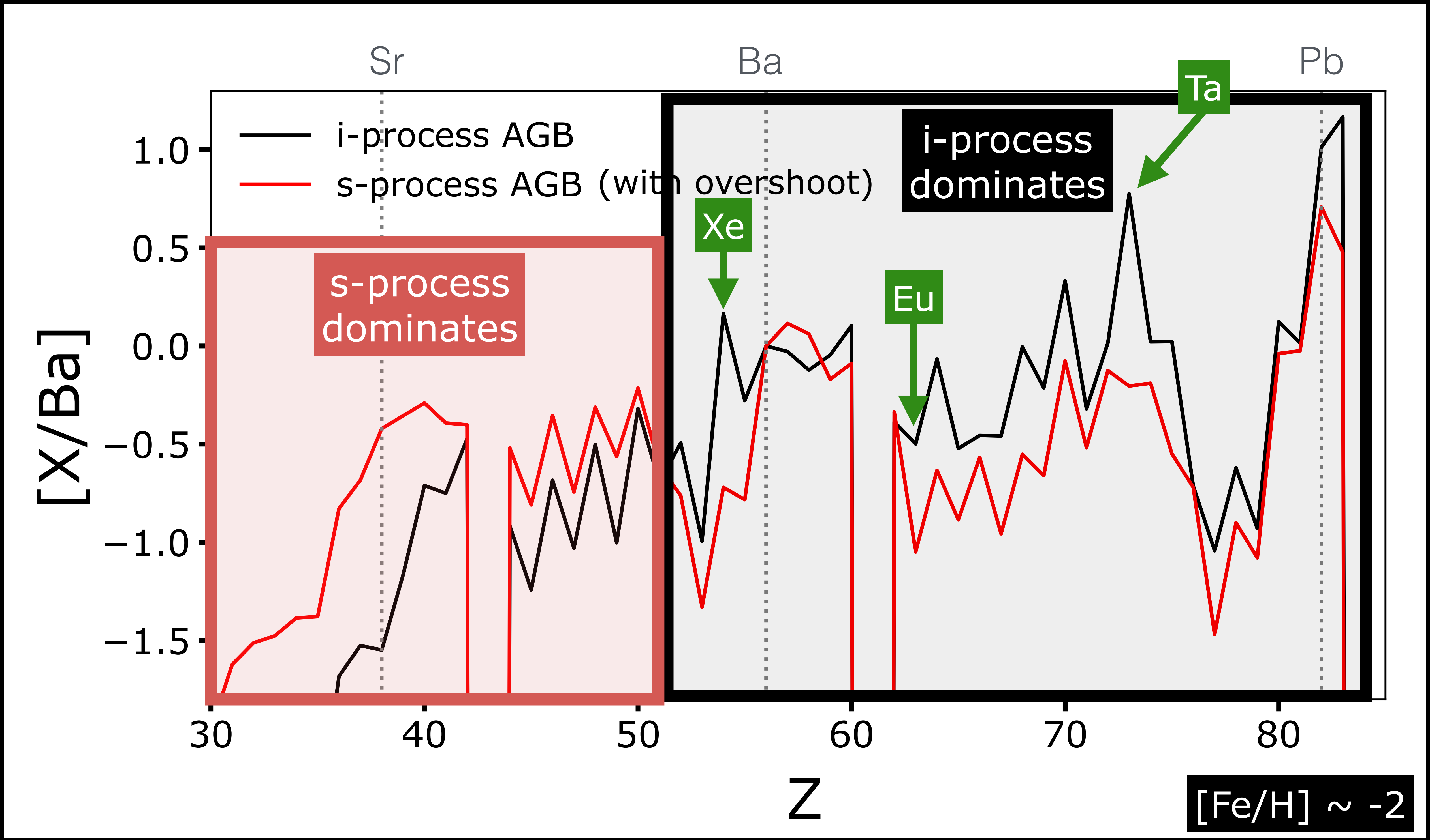
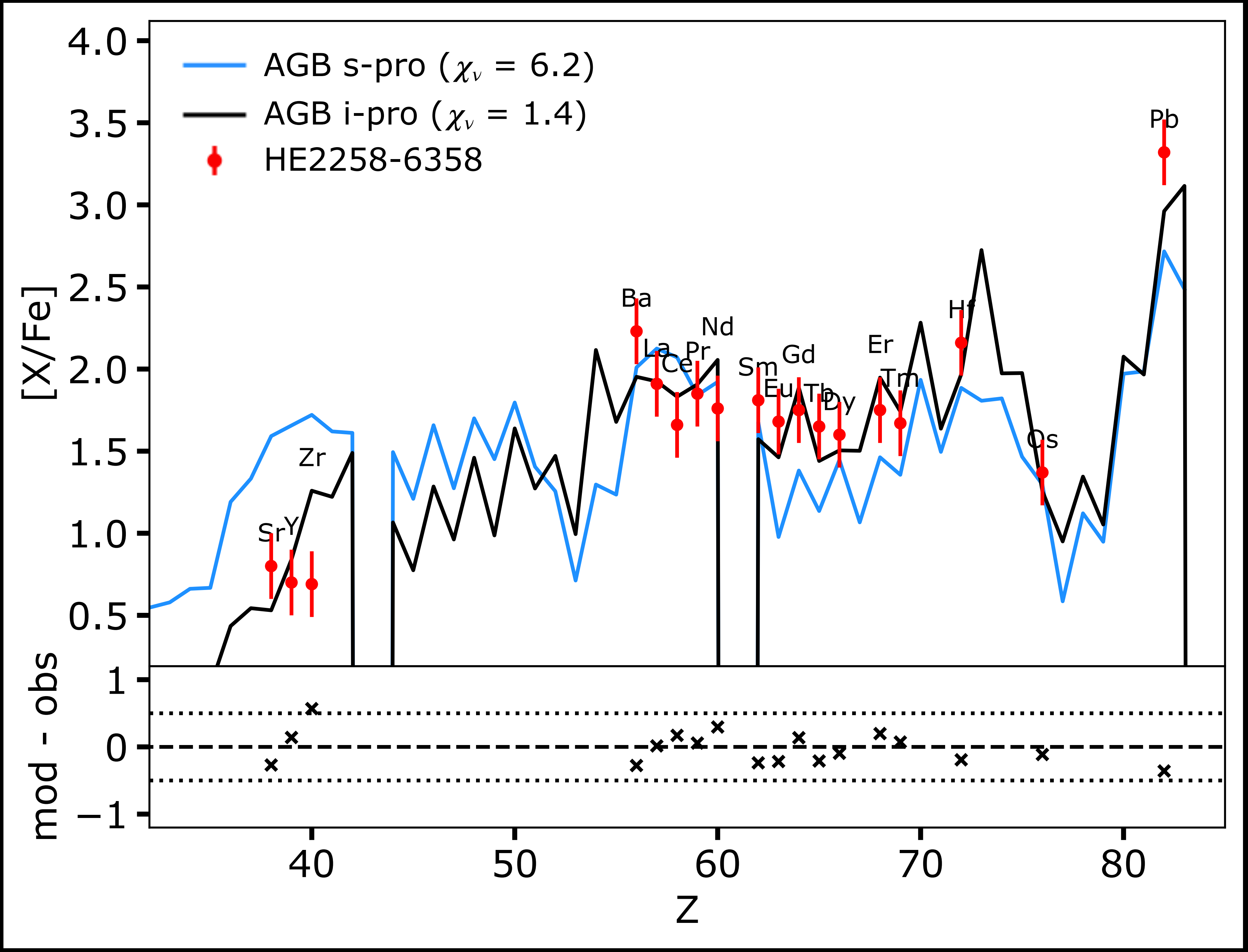


Comparison of i-process AGB models with CEMP-r/s stars



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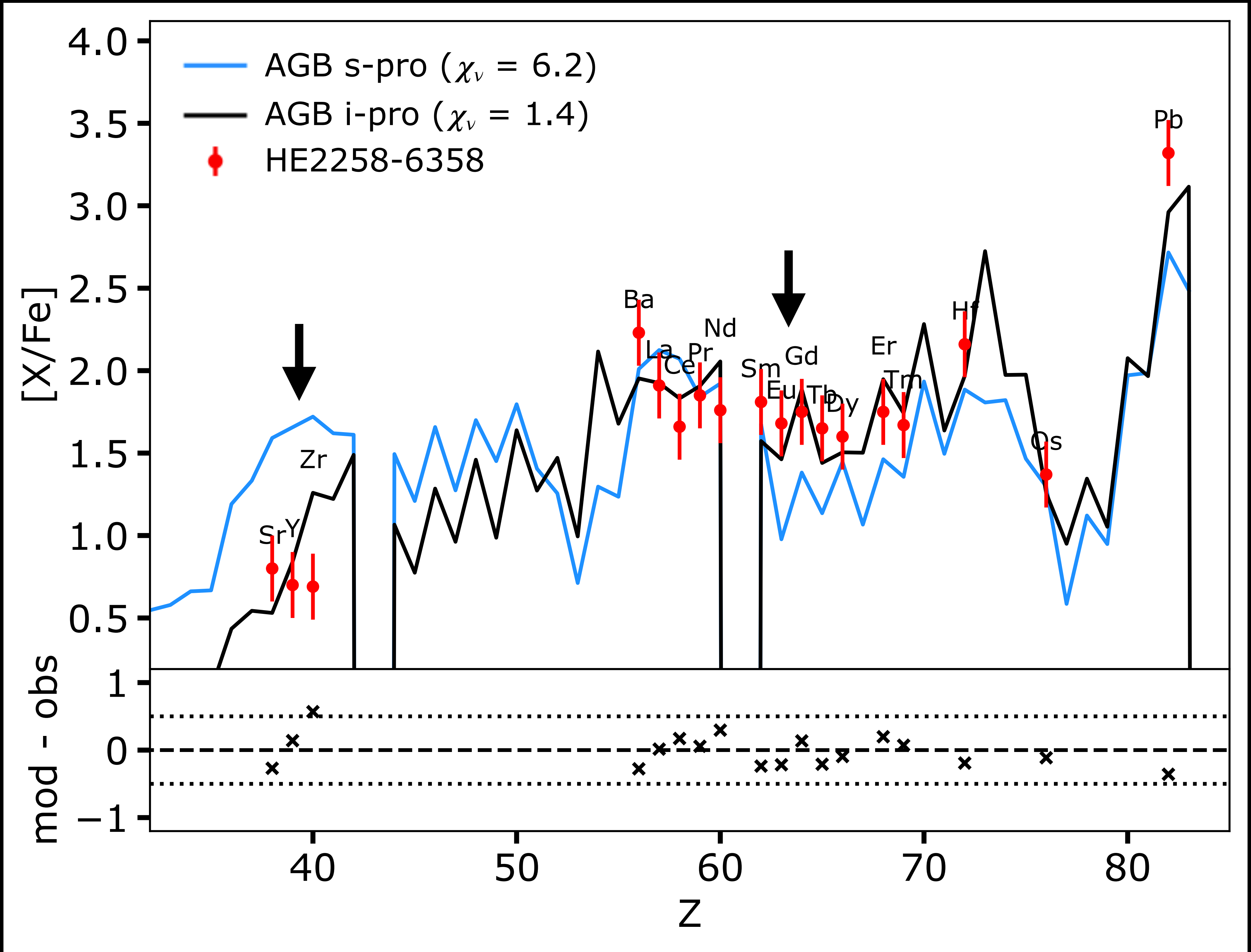

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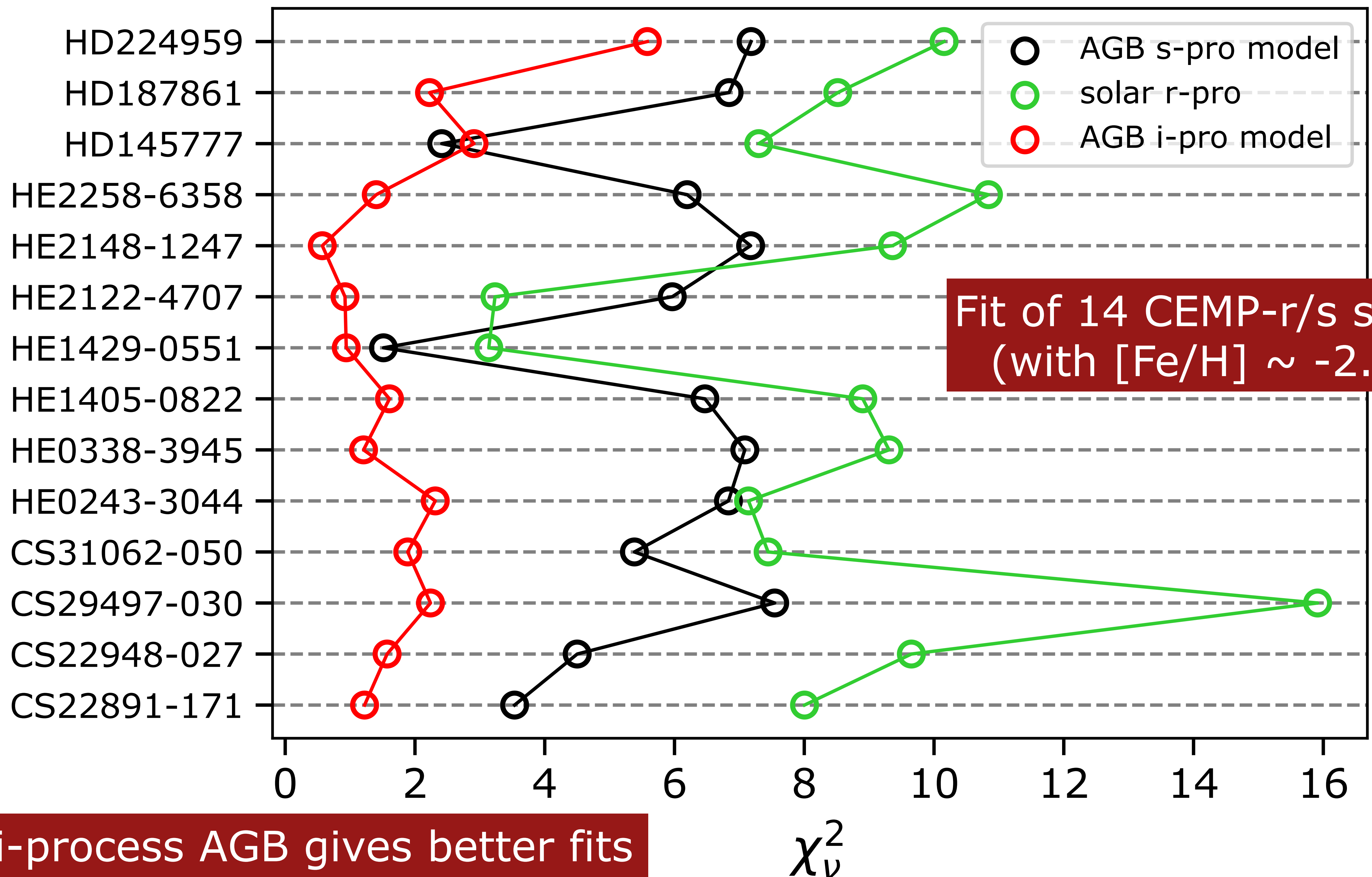
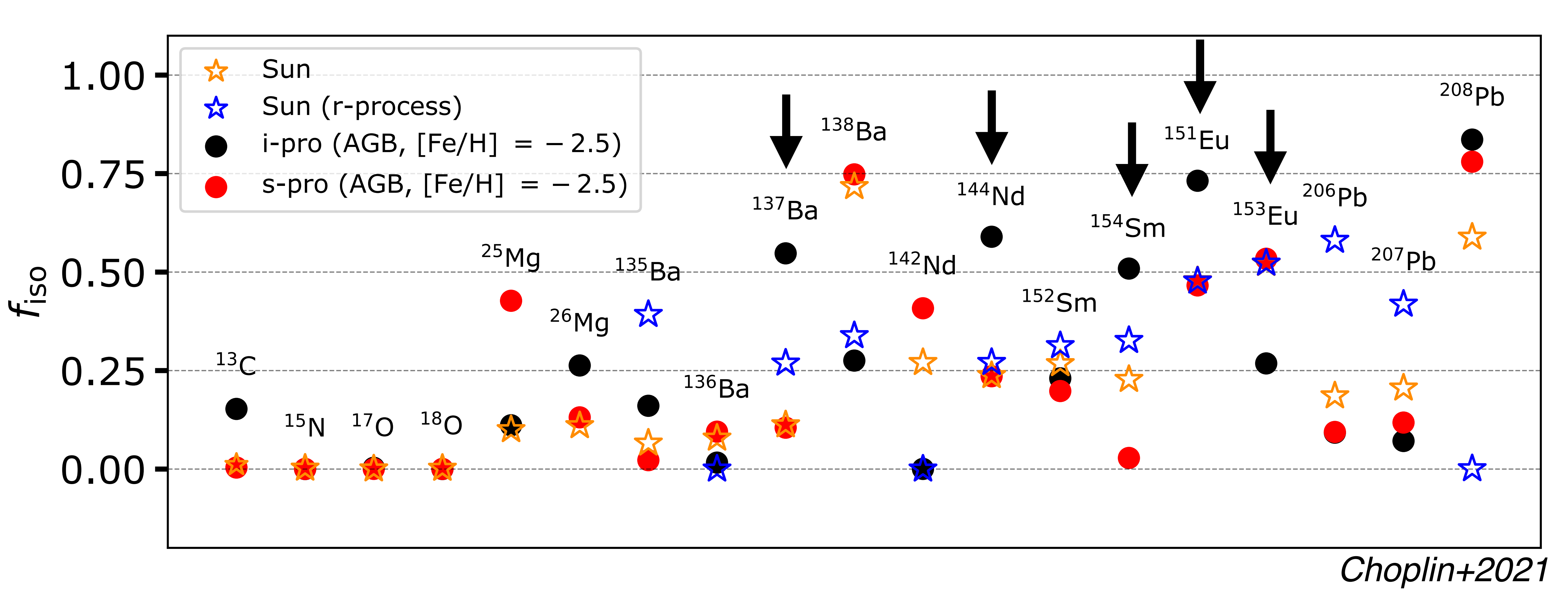


Fit of 14 CEMP-r/s stars (with [Fe/H] ~ -2.5)

i-process AGB gives better fits (lower χ^2) than s- or r-process

Choplin+2021 + corrigendum (2022)

Some chemical fingerprints of the i-process



$$f_{\text{iso}} = \frac{\text{Abundance of isotope}}{\text{Total mass of element}}$$

(after beta-decays)

« Observed » isotopic ratios in metal-poor stars

Ba : *Magain 1995, Mashonkina+2006, Gallagher+2012, Meng+2016…*

Eu : *Sneden+2002, Aoki+2003a,b, Roederer+2008*

Sm : *Lundqvist+2007, Zhang+2010, Roederer+2008*

Nd : *Roederer+2008*

Summary

- proton ingestion / i-process in AGB with [Fe/H] < -2 and M_{ini} < 3 $M_{\odot}$
  - $N_n \sim 10^{14-16}$ cm^{-3}
  - AGB evolution / structure can be impacted

if no extra mixing

- i-process AGB vs. s-process AGB —> [X/Ba]
  - Z < 50 underproduced by i-pro
  - Z > 50 overproduced by i-pro (Xe, Eu, Ta)

- AGB with i-process can explain most of the observed CEMP r/s-stars

- **AGB : viable site for i-process nucleosynthesis** but see also :
  - *post-AGB* *Herwig+2011*
  - *RAWD* *Denissenkov+2017*
  - *very low metallicity massive stars* *Banerjee+2018, Clarkson+2018*
  - ...

- i-process AGB grid in progress… (+ impact of mixing ?)