Image : Ring Nebula
credits : ESA/Webb, NASA, CSA, M. Barlow, N. Cox, R. Wesson

Theory of the intermediate neutron capture process

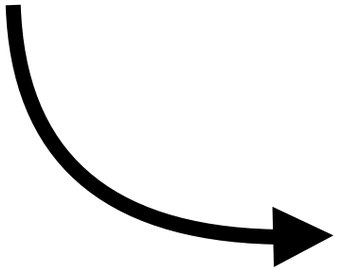
Arthur Choplin
Université Libre de Bruxelles, Belgium

sirEN conference, June 8 - 13, 2025

ULB

fnrs
FREEDOM TO RESEARCH

Neutron capture processes



—> responsible for the synthesis
of most heavy elements in the Universe

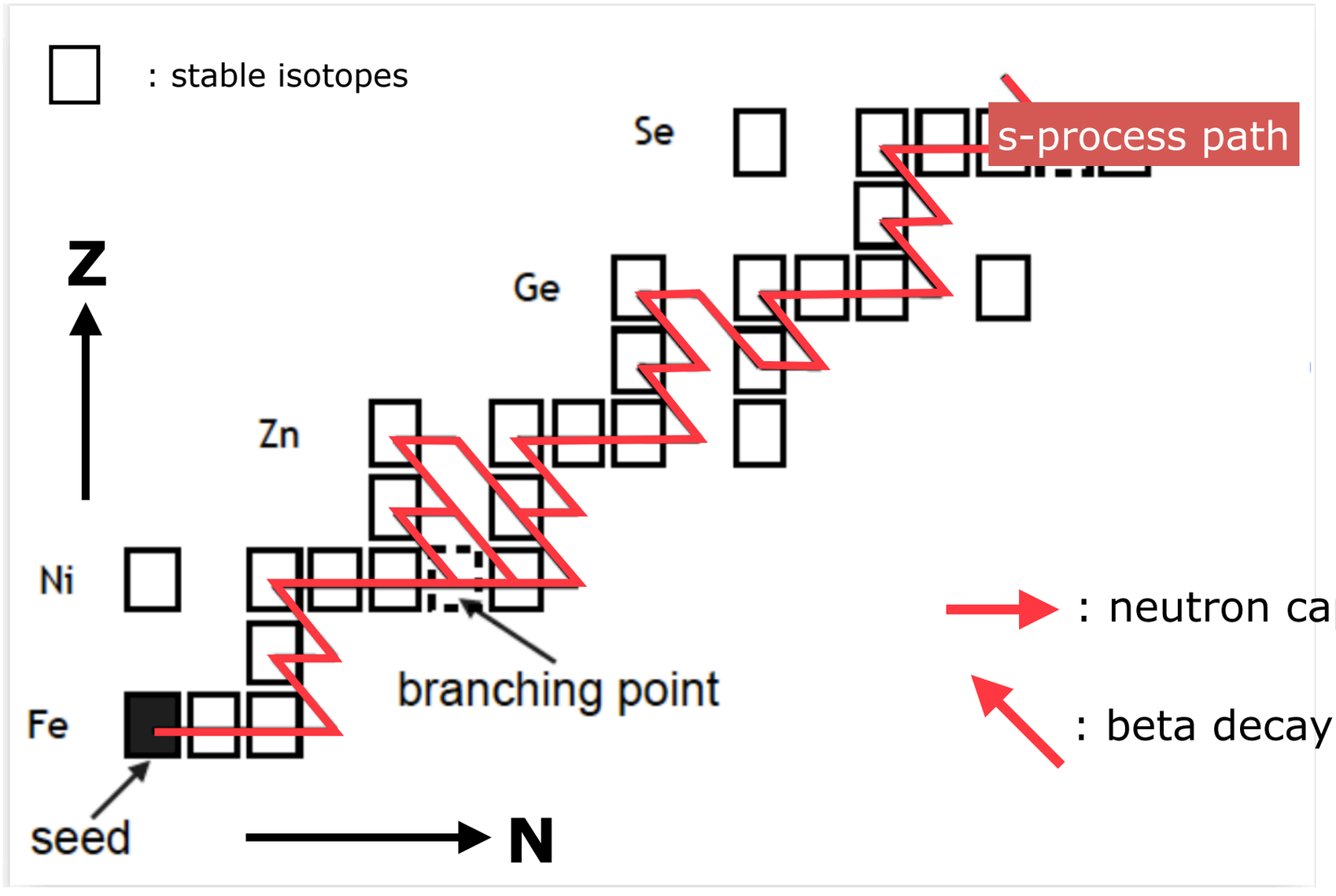
Neutron capture processes: slow

$\tau \sim 10^4$ yr

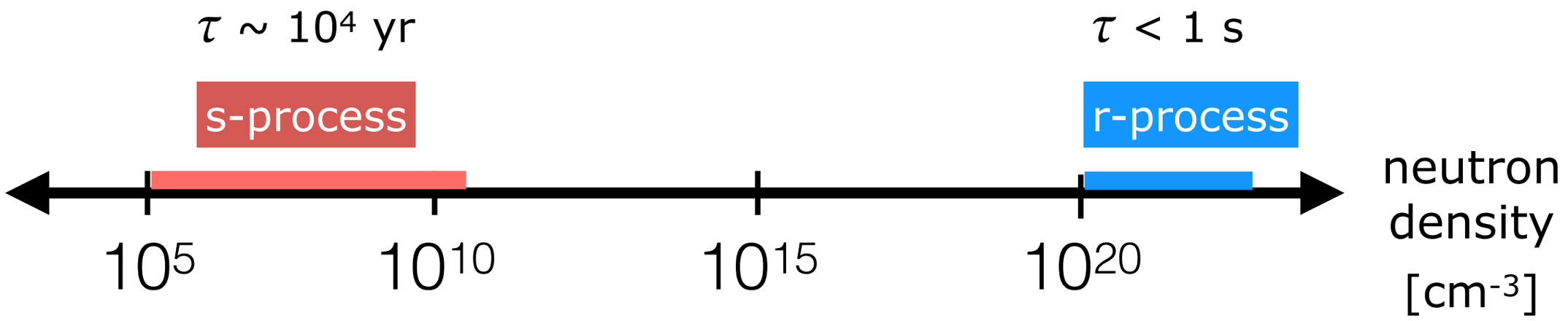
s-process

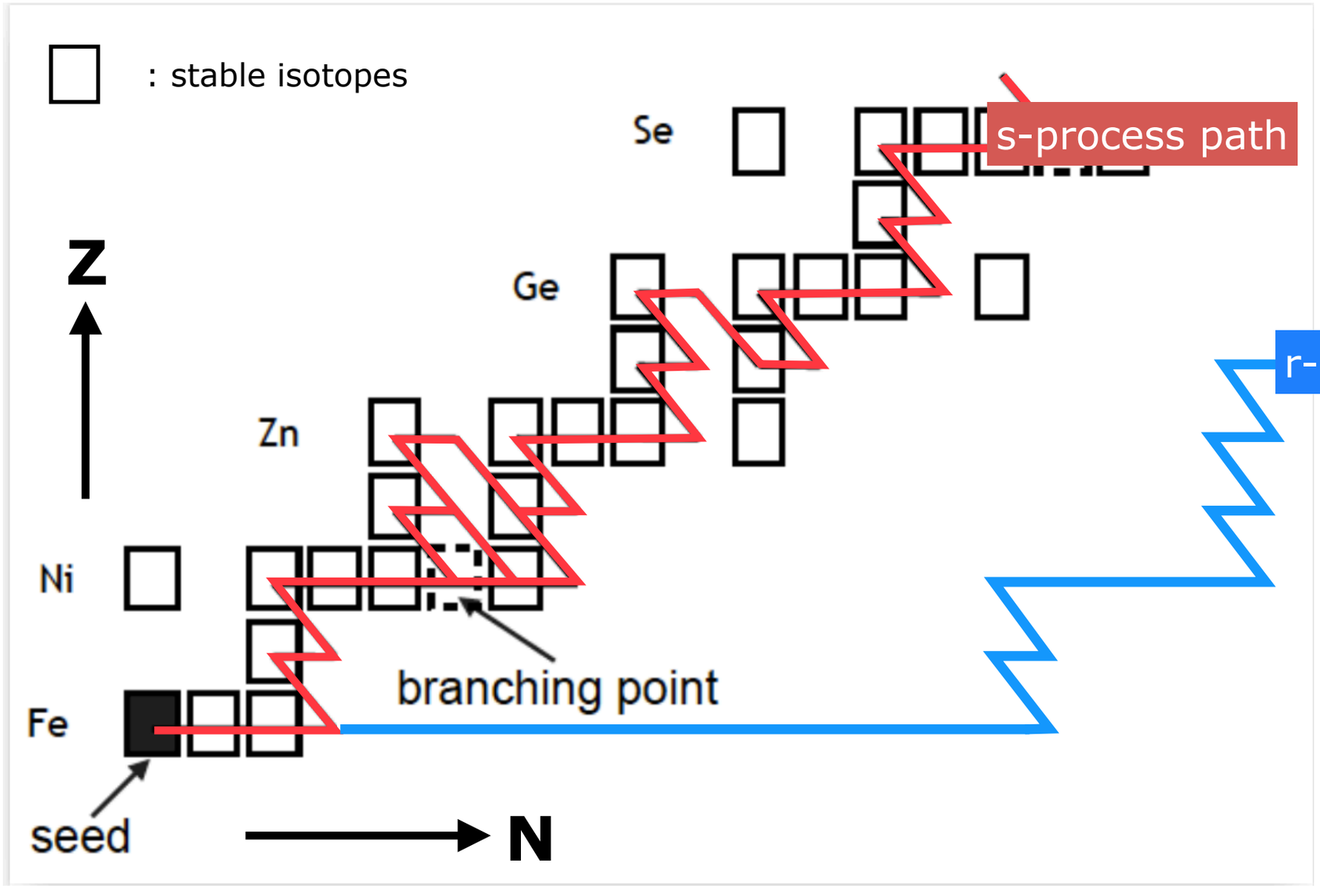
10^5 10^{10} 10^{15} 10^{20}

neutron density [cm^{-3}]

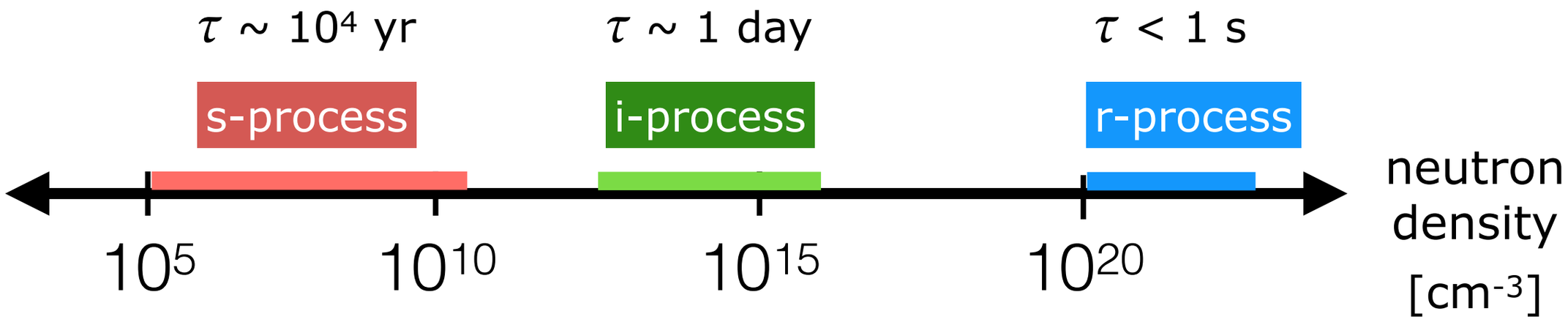


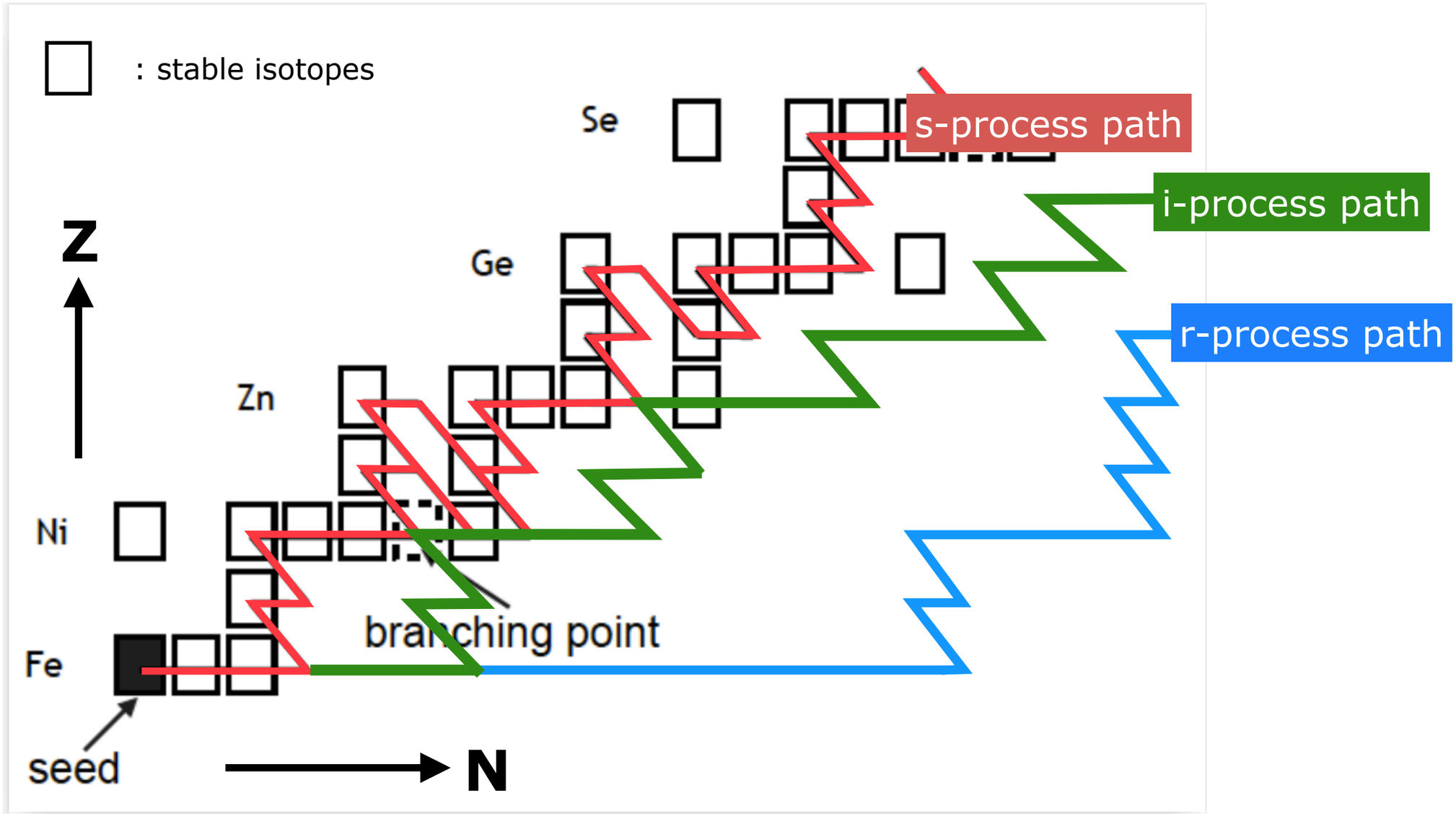
Neutron capture processes: slow, rapid



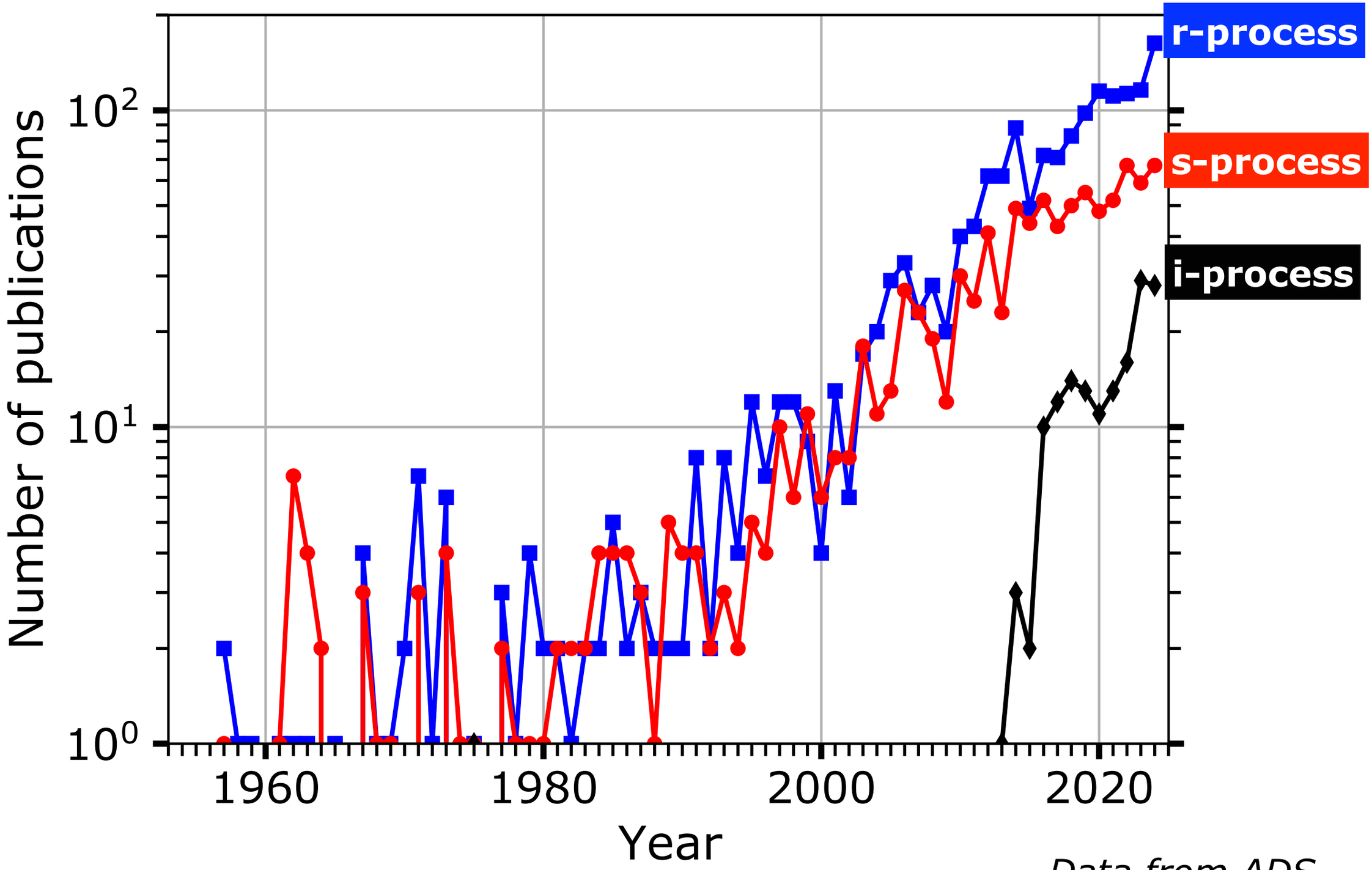


Neutron capture processes: slow, intermediate, rapid



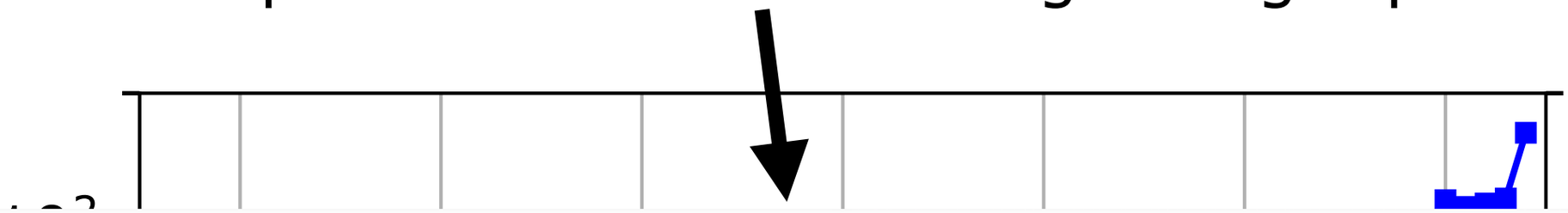


The i-process is a recent and growing topic



Data from ADS

The i-process is a ~~recent~~ and growing topic



ABSTRACT

We have evolved thermonuclear runaways in 1.1 $M_\odot$ and 1.25 $M_\odot$ white dwarfs where we have assumed extremely enhanced ^{12}C in the envelope. A "super" nova-type outburst results, in which peak temperatures exceeding 2×10^9 K and peak burning rates of 3×10^{24} ergs g^{-1} s^{-1} are achieved. A shock forms and ejects more than 10^{29} g moving with speeds up to 90,000 km s^{-1}. The subsequent β^+-decays provide enough additional energy to eject nearly 2×10^{30} g. The peak luminosity is 10^{10} $L_\odot$ at an effective temperature of nearly 3×10^5 K. One model produces a substantial neutron flux for a short time, sufficient to drive an intermediate neutron-capture process.

Subject headings: novae — stellar evolution — supernovae

Starrfield, Truran & Sparks, ApJ, ***1975***

Number

10^0

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.

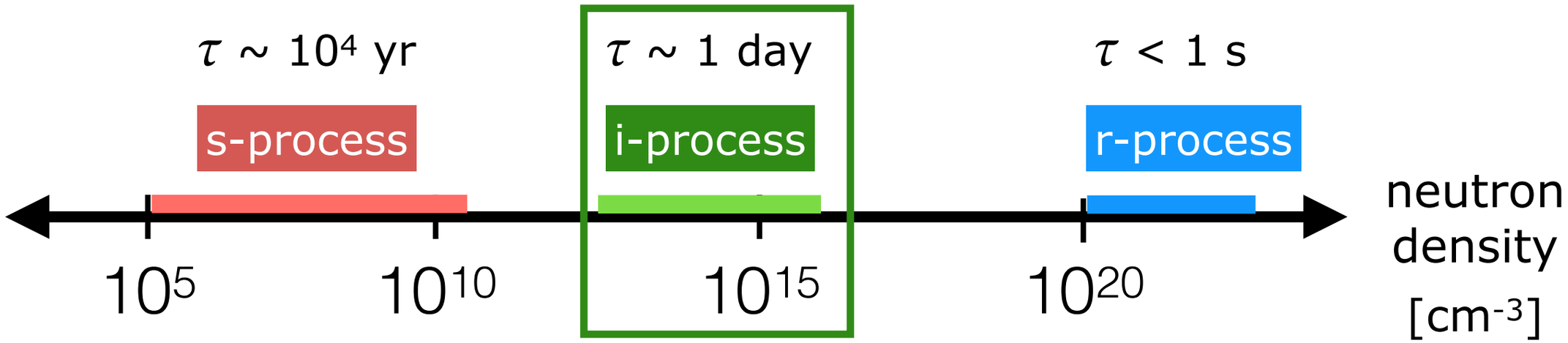
We find a neutron number density in the intershell region of $\sim 10^{15}$–10^{17} cm^{-3} and a flux of $\sim 10^{23}$–10^{25} cm^{-2} s^{-1}. This neutron flux is many orders of magnitude above the flux required for the classical *s*-process, and thus an intermediate neutron process (*i*-process) 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

Cowan & Rose, ApJ, ***1977***

The intermediate neutron capture process



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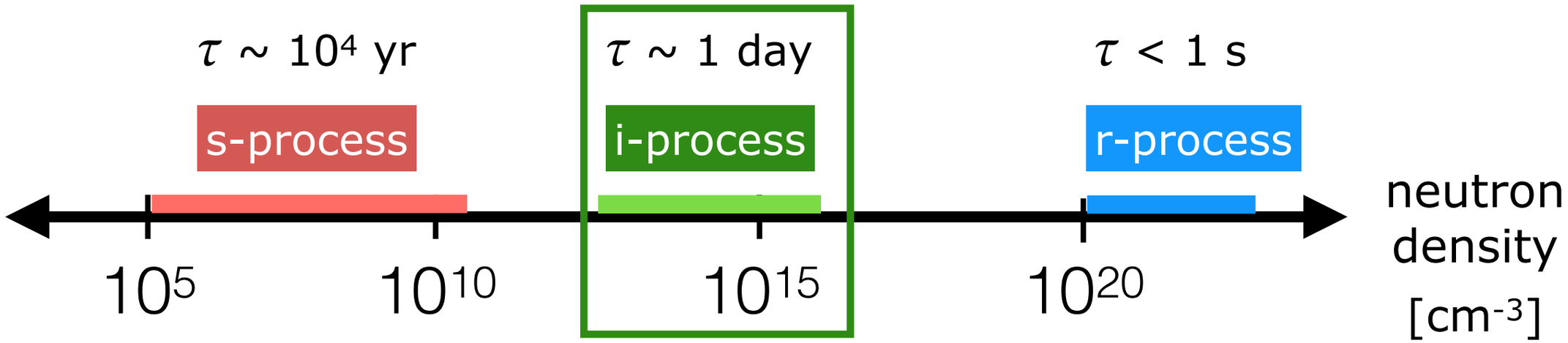
proton ingestion

The intermediate neutron capture process



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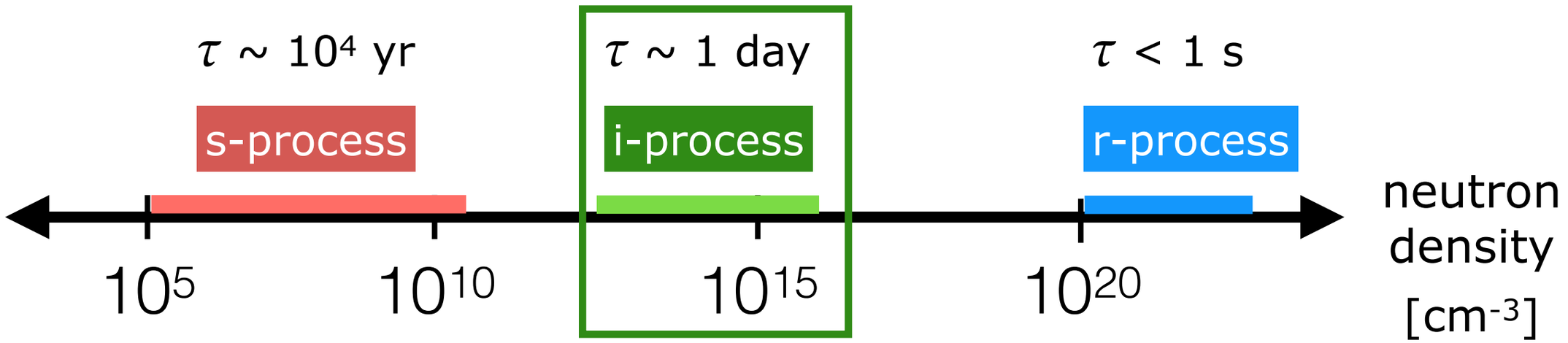
Alternative names :
- H-flash *(e.g. Iwamoto+2004)*
- Dual shell flash *(e.g. Campbell+2008)*
- He-flash driven deep mixing *(e.g. Suda+2010)*
- *…*

The intermediate neutron capture process



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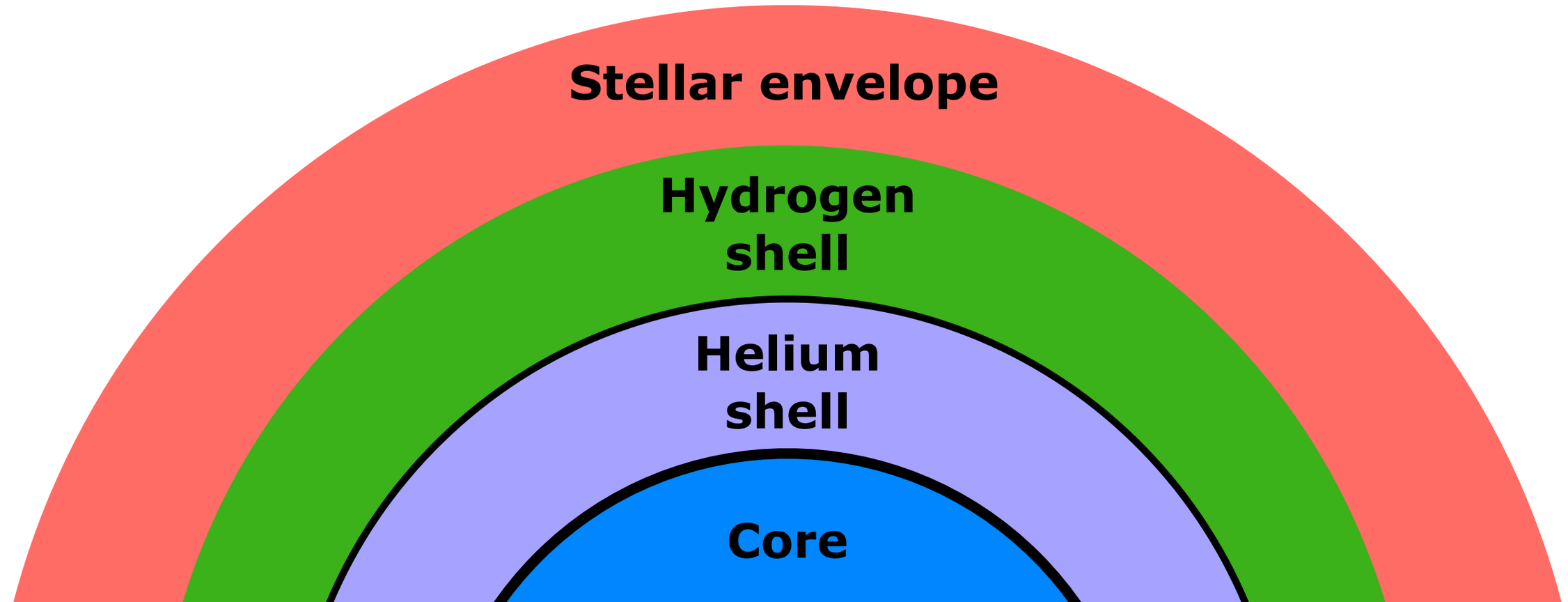

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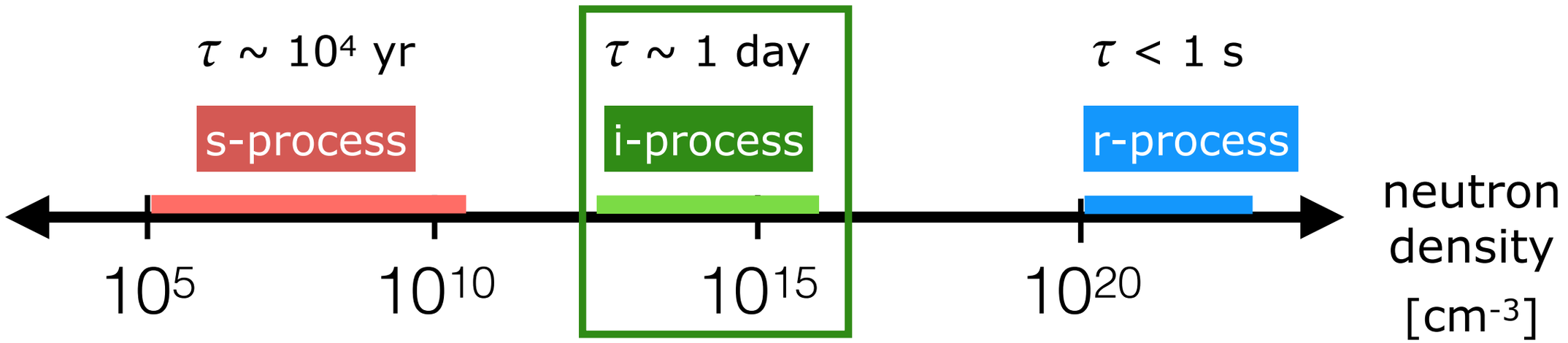

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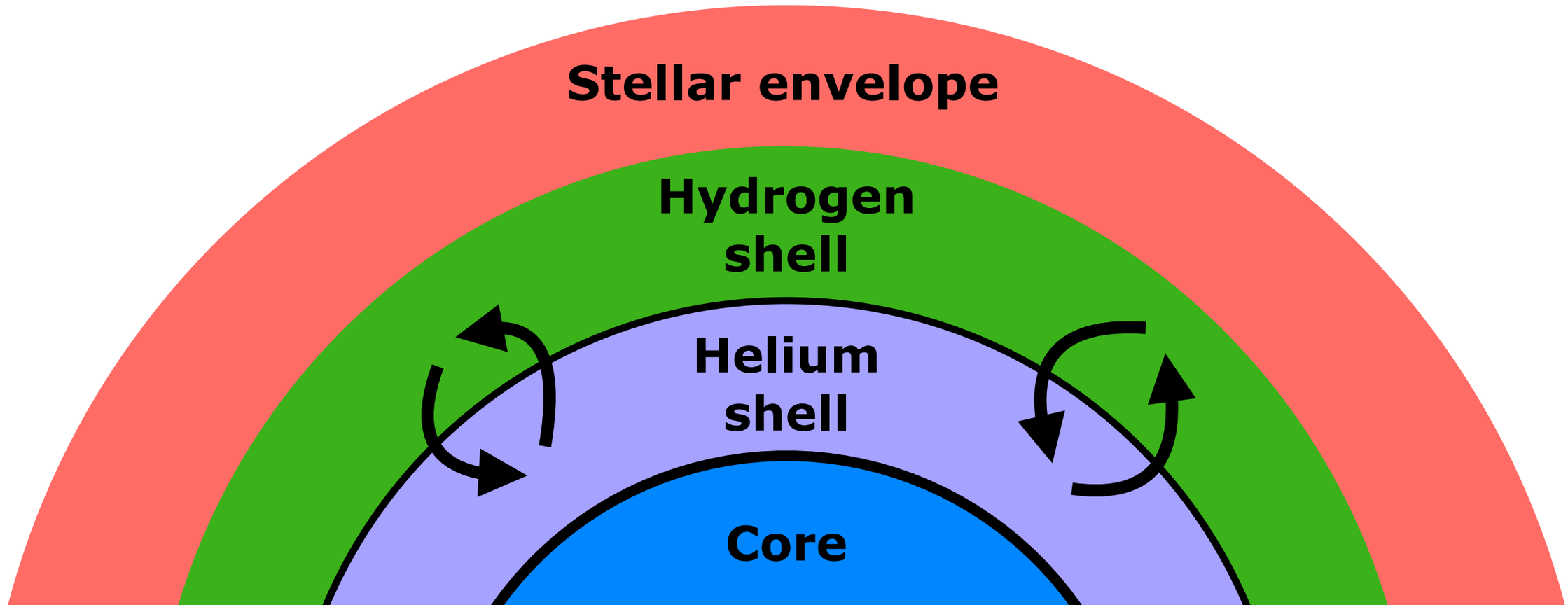

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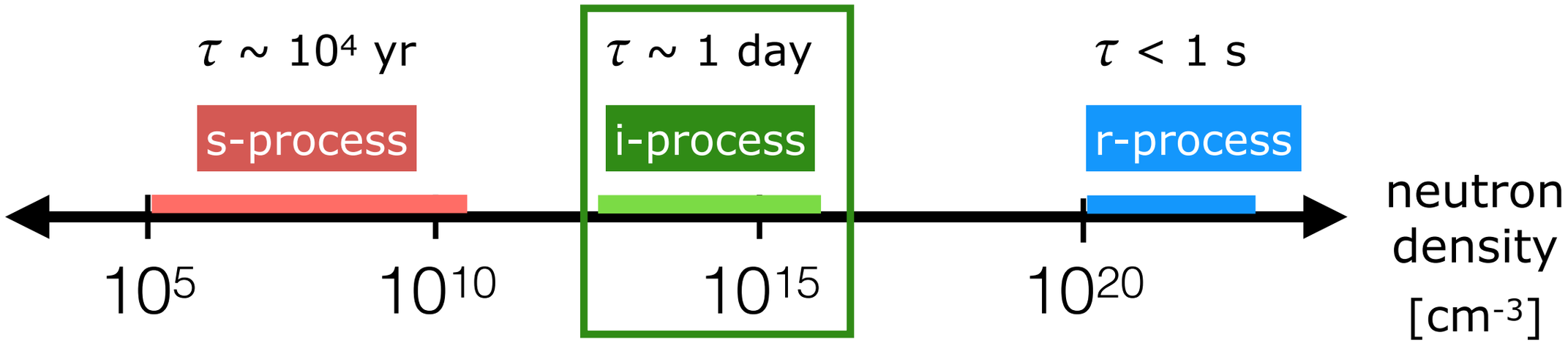

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proton ingestion ⛓ **i-process**

Observational indications of the i-process in…

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  Jonsell+2006, Roederer+2016, Caffau+2019, Goswami+2022, Karinkuzhi+2021,2023, Hansen+2023 …
- **Barium stars** *—> talk by B. Cseh*
  Roriz+2021,2024, Cseh+2022, den Hartogh+2023…
- **AGB / post-AGB stars**
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  Dorsch+2020, Battich+2025…
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  Mishenina+2015, …
- **Sakurai's object**
  Herwig+2011
- **Pre-solar grains** *—> talks by N. Liu, M. Jadhav*
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i-process is a possible solution

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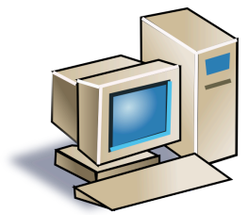
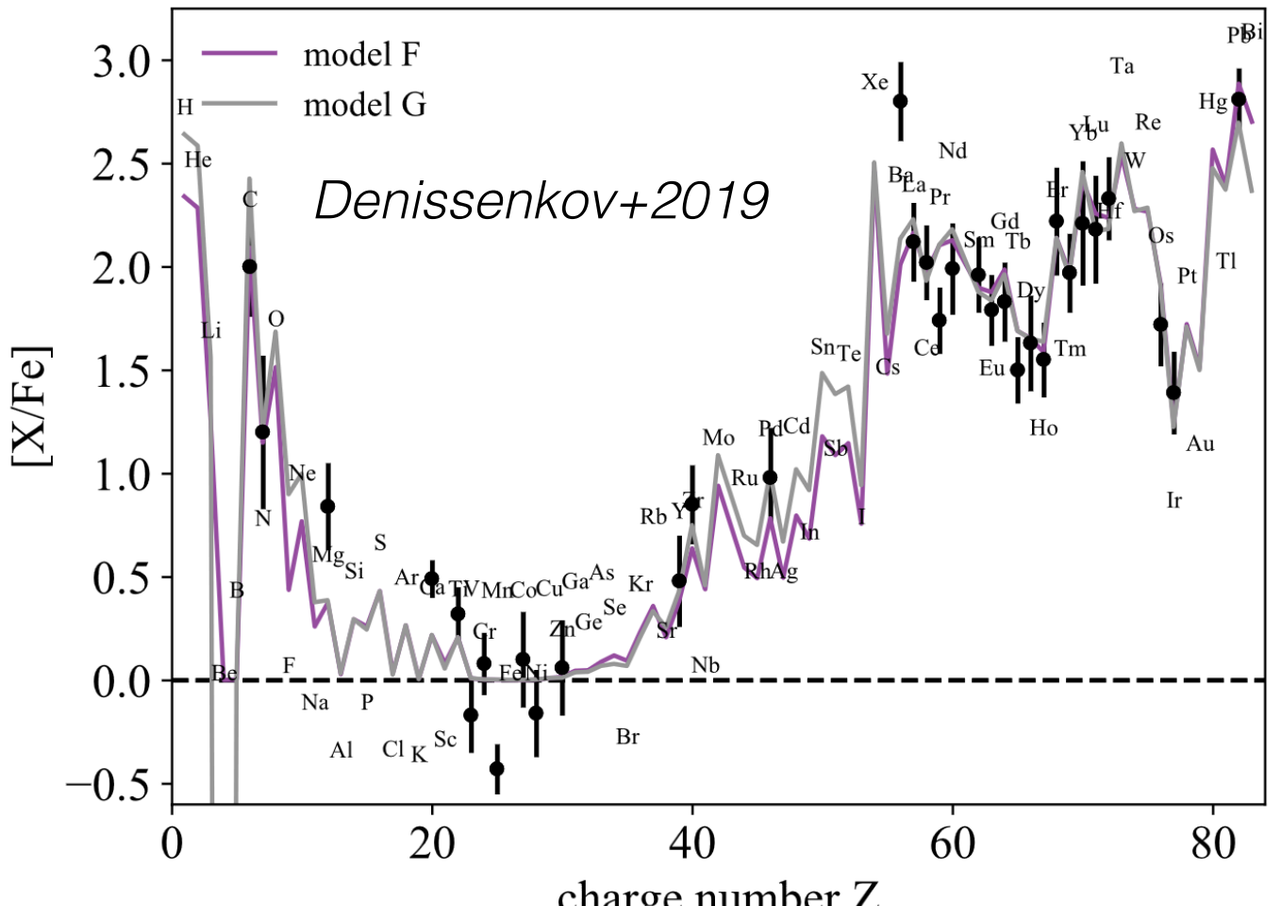
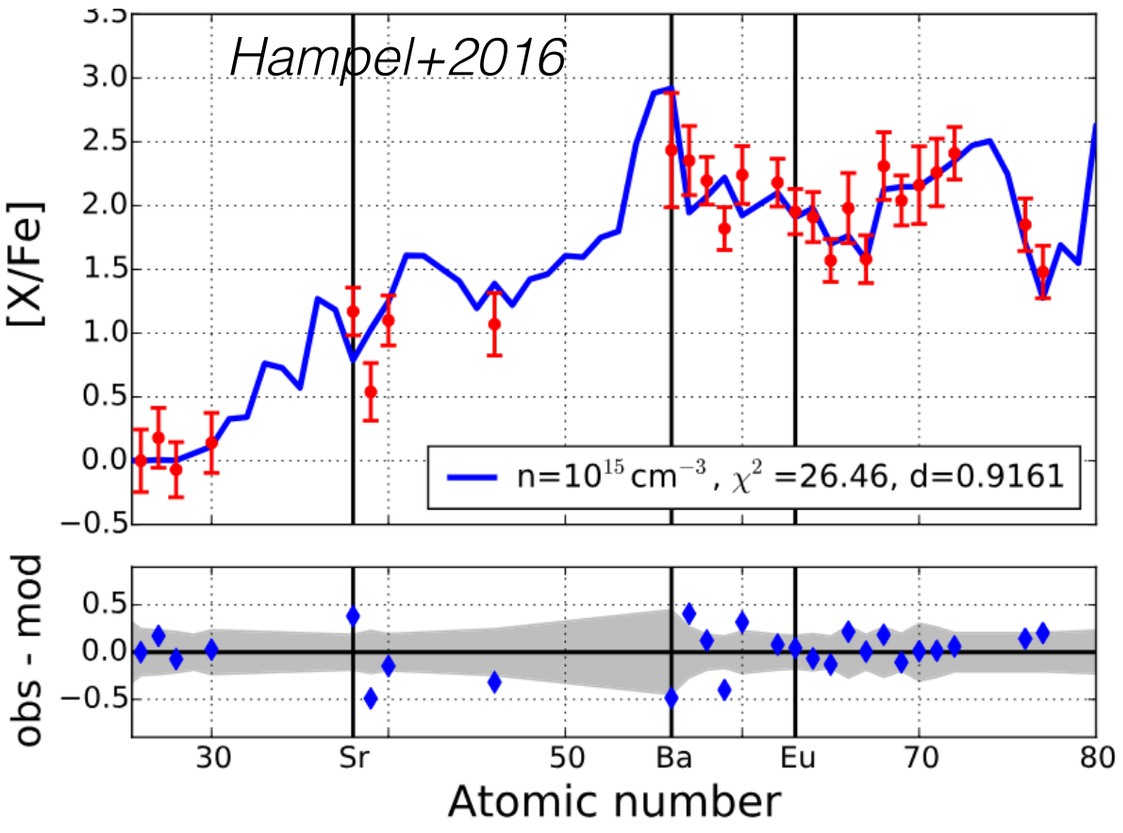
i-process models vs. CEMP-r/s stars

VS.







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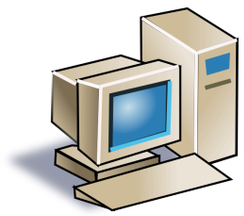
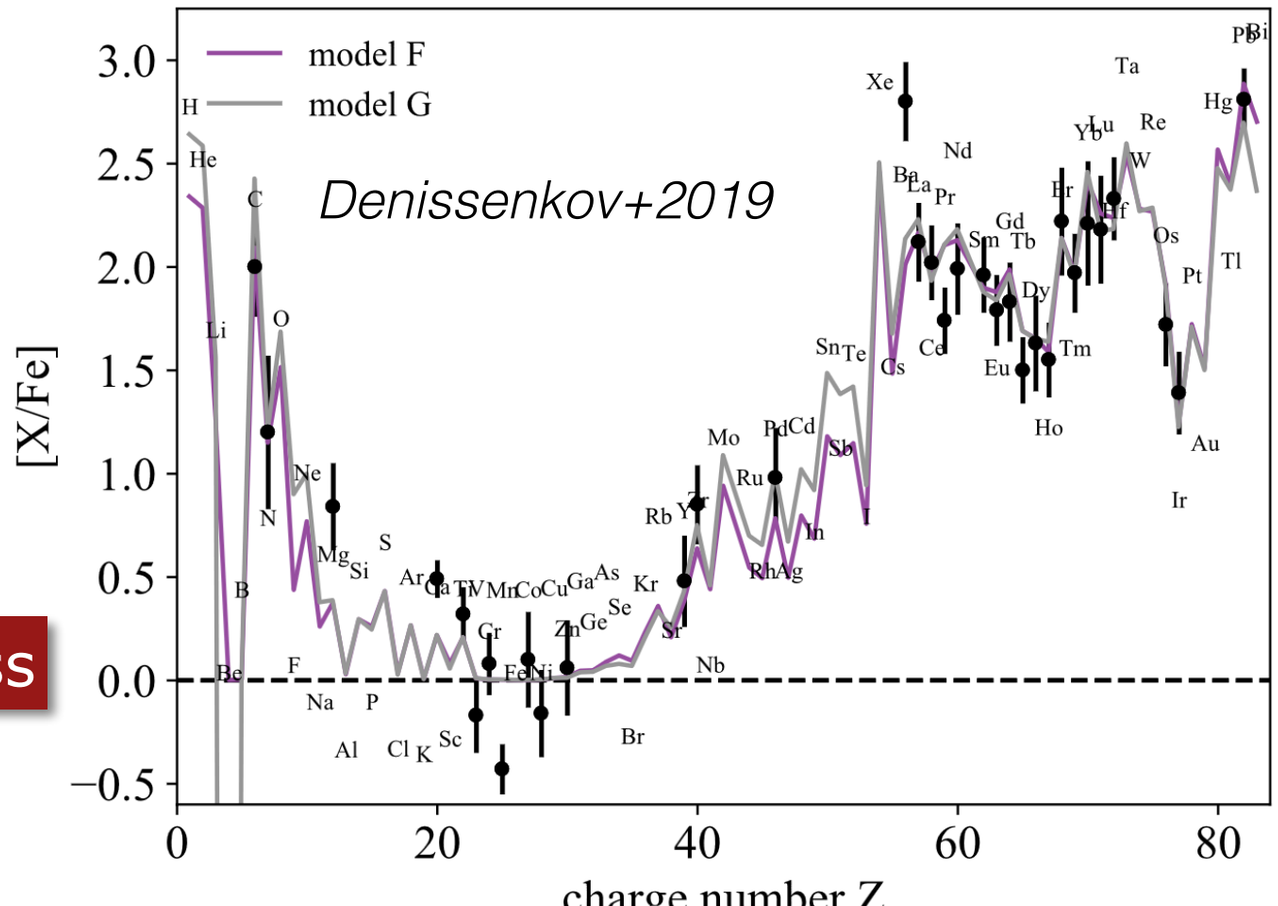
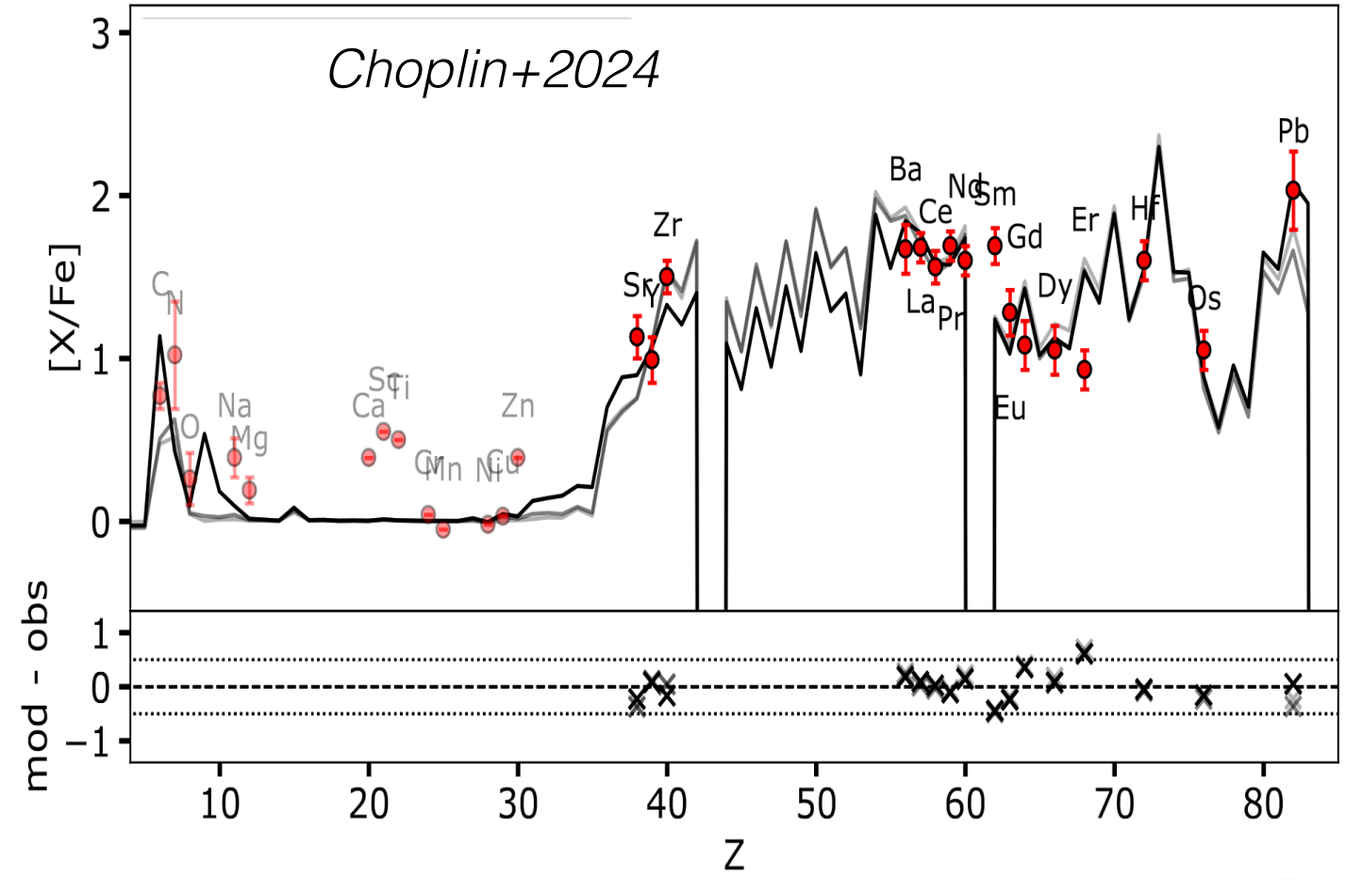
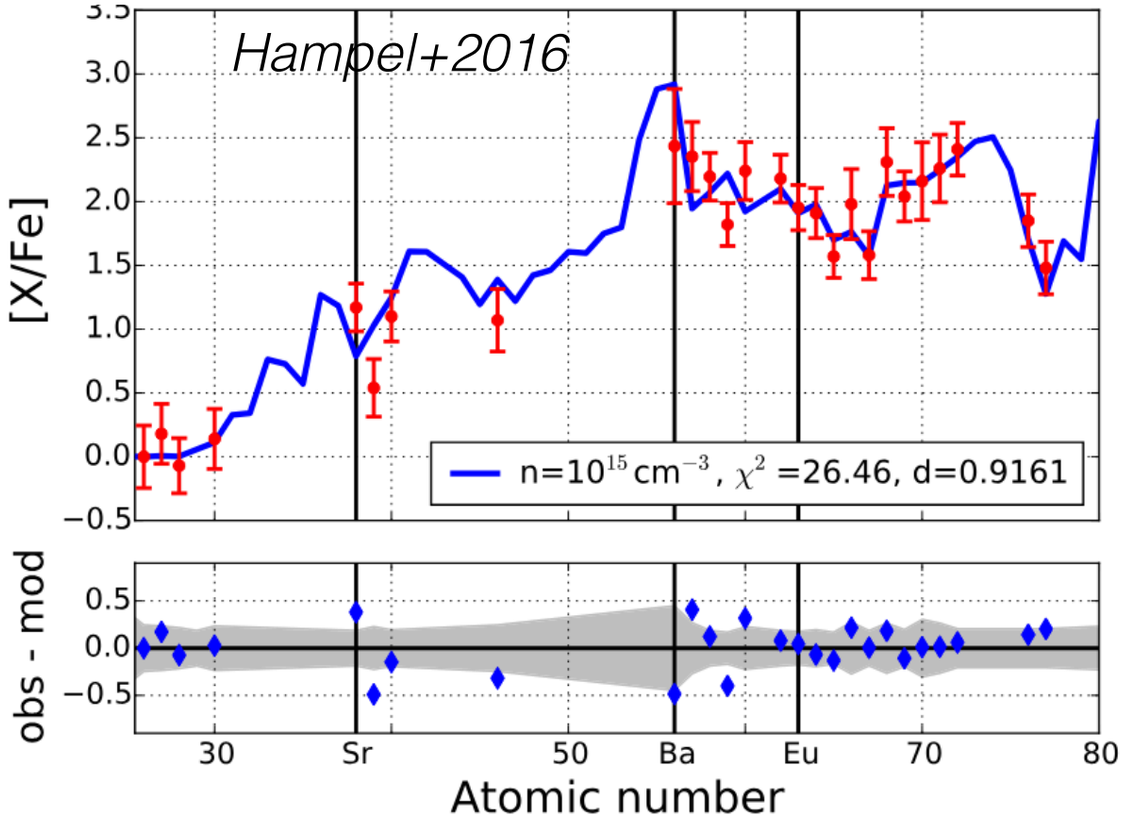


CEMP-r/s : hardly explainable with s-process, r-process or r+s…

but reasonable agreement with i-process







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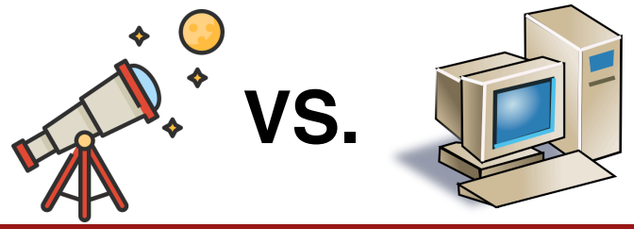

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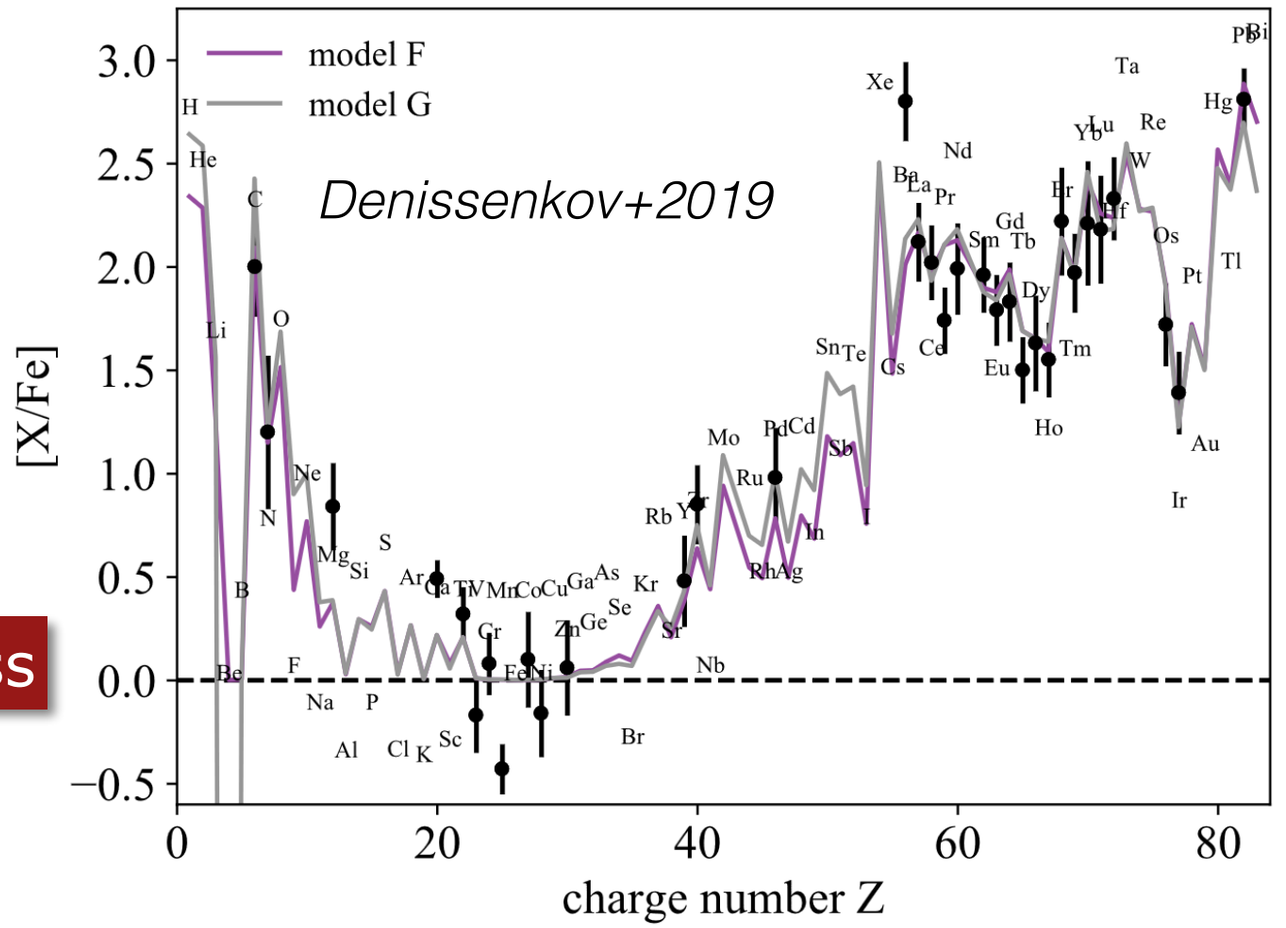
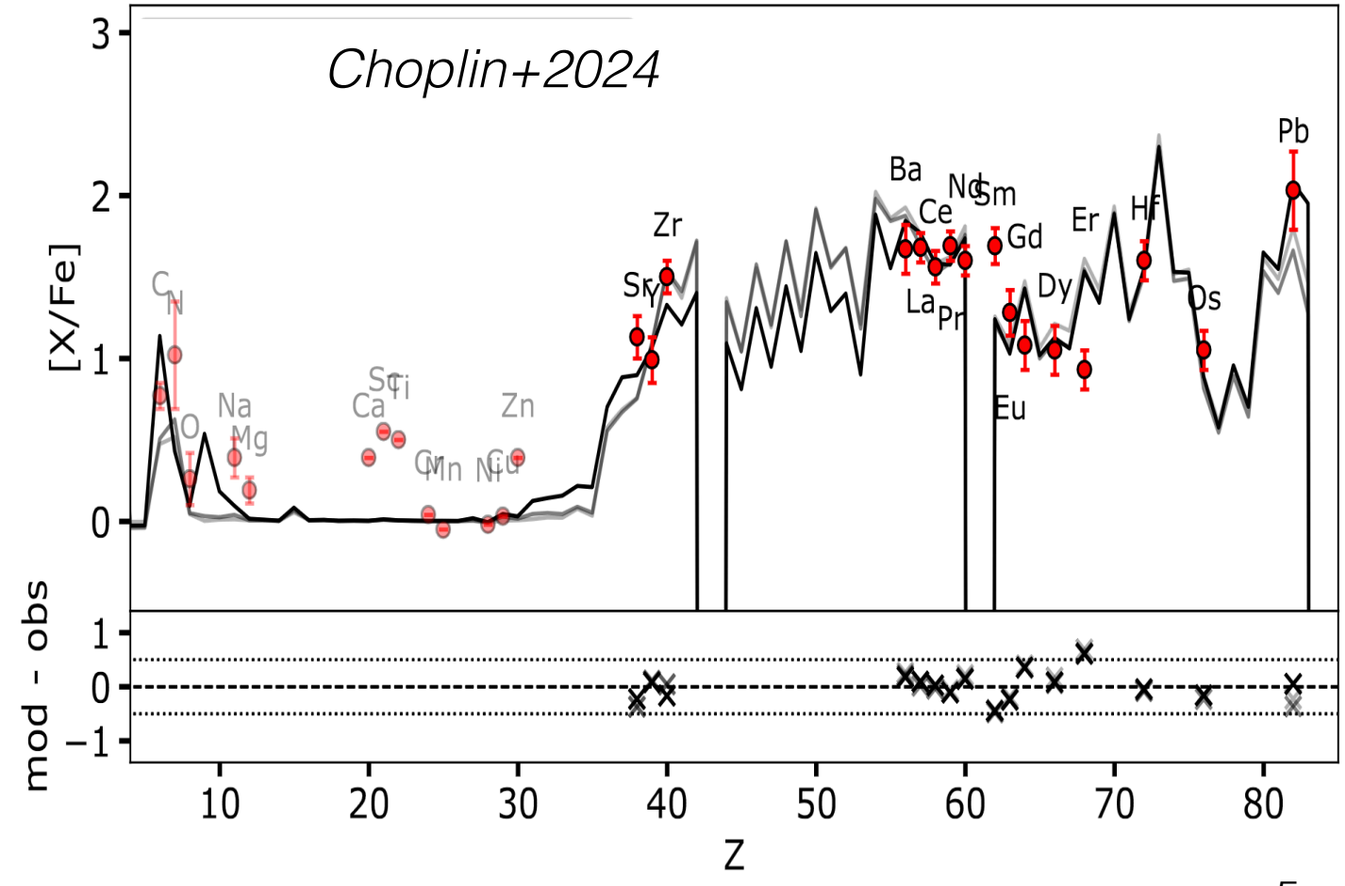
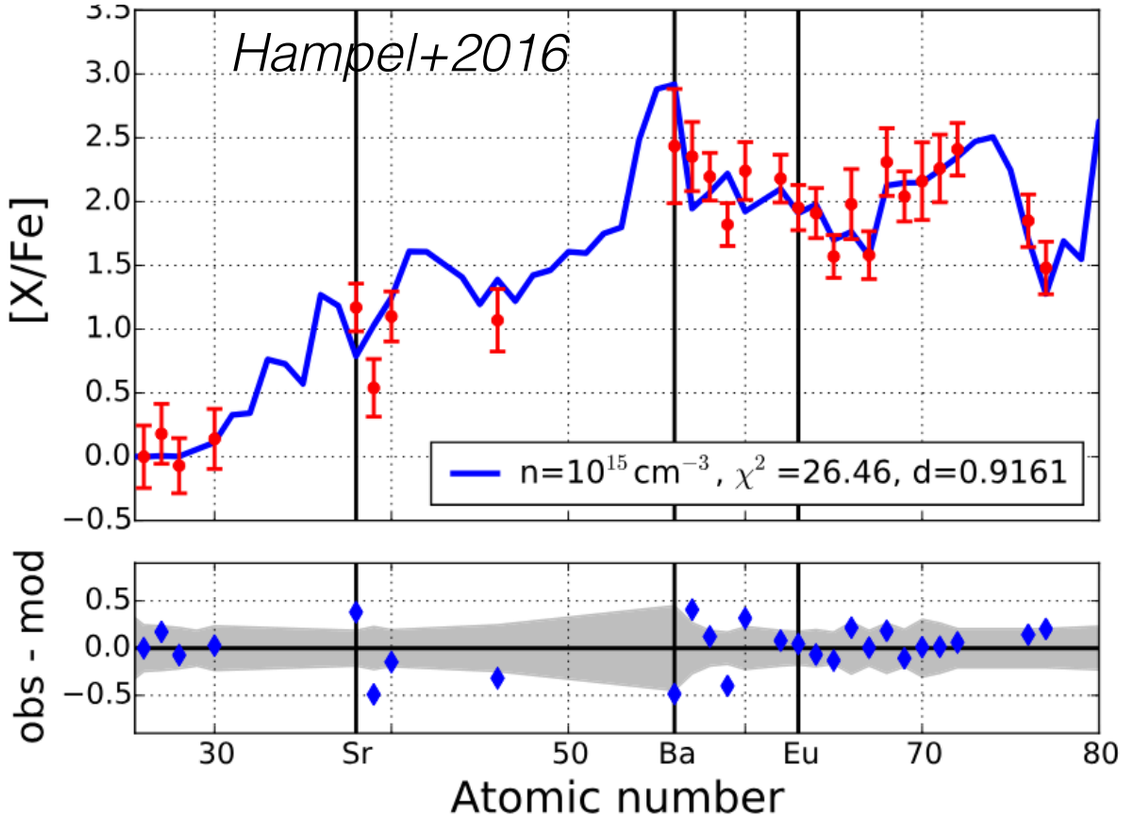
it gives some credence to the existence of the i-process







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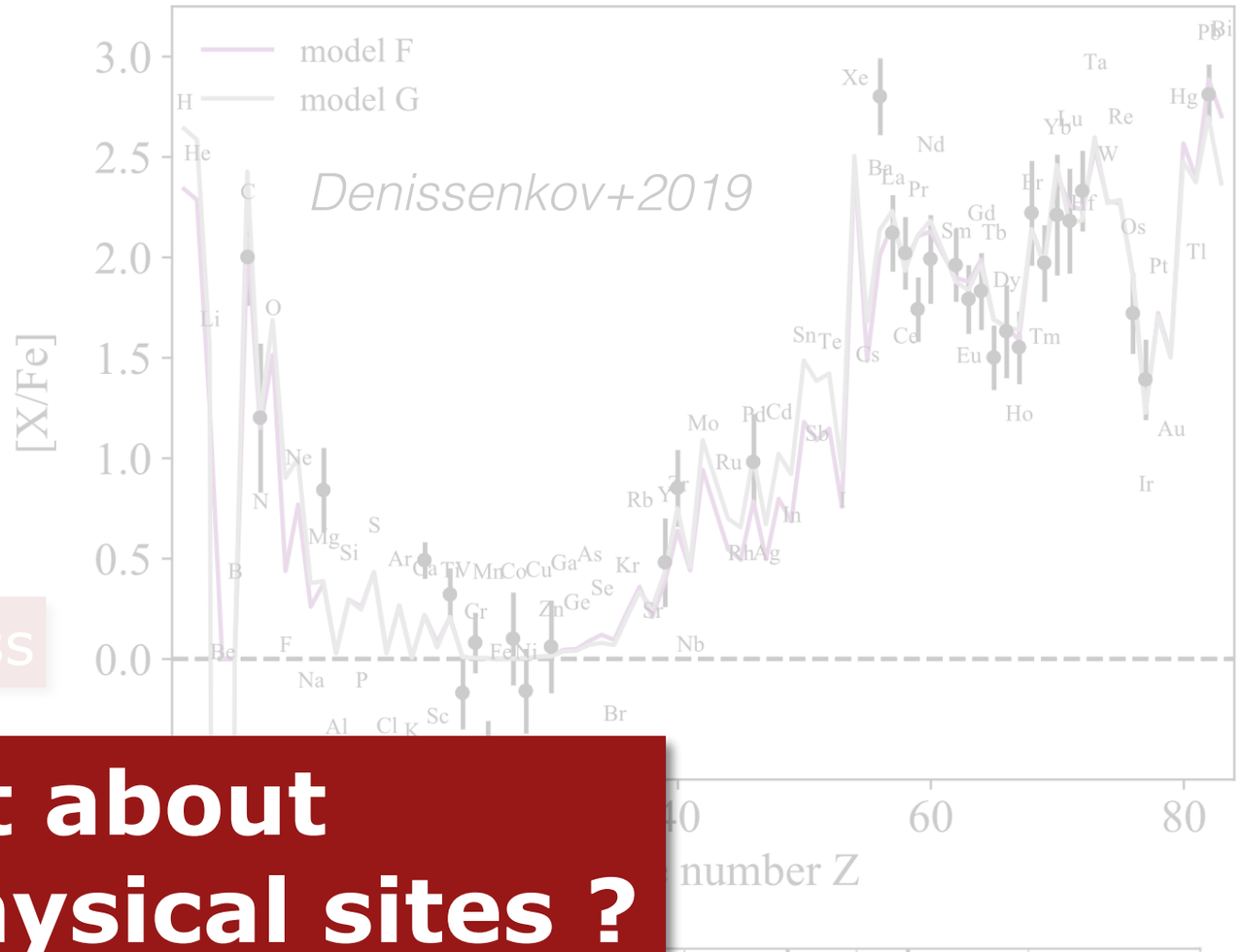
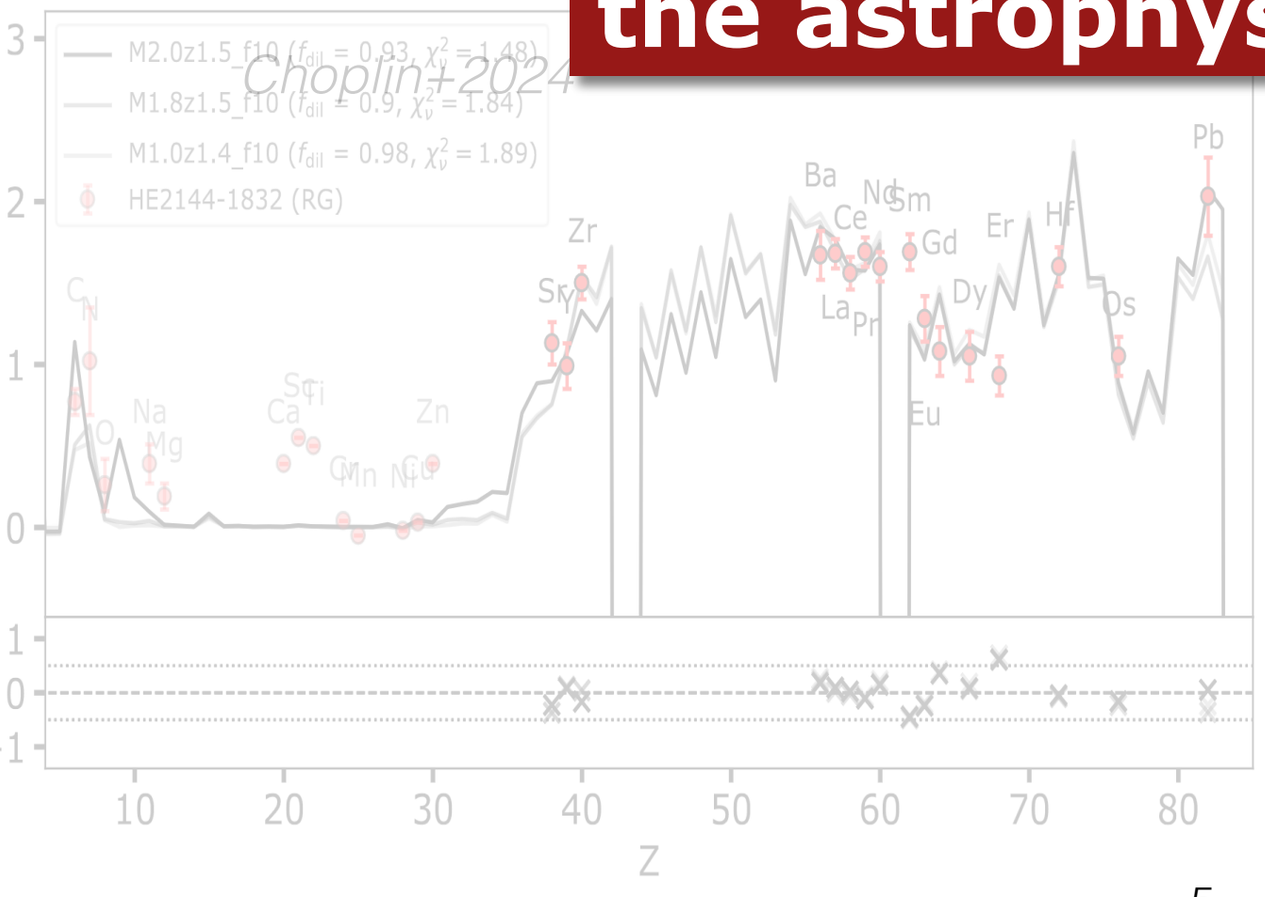
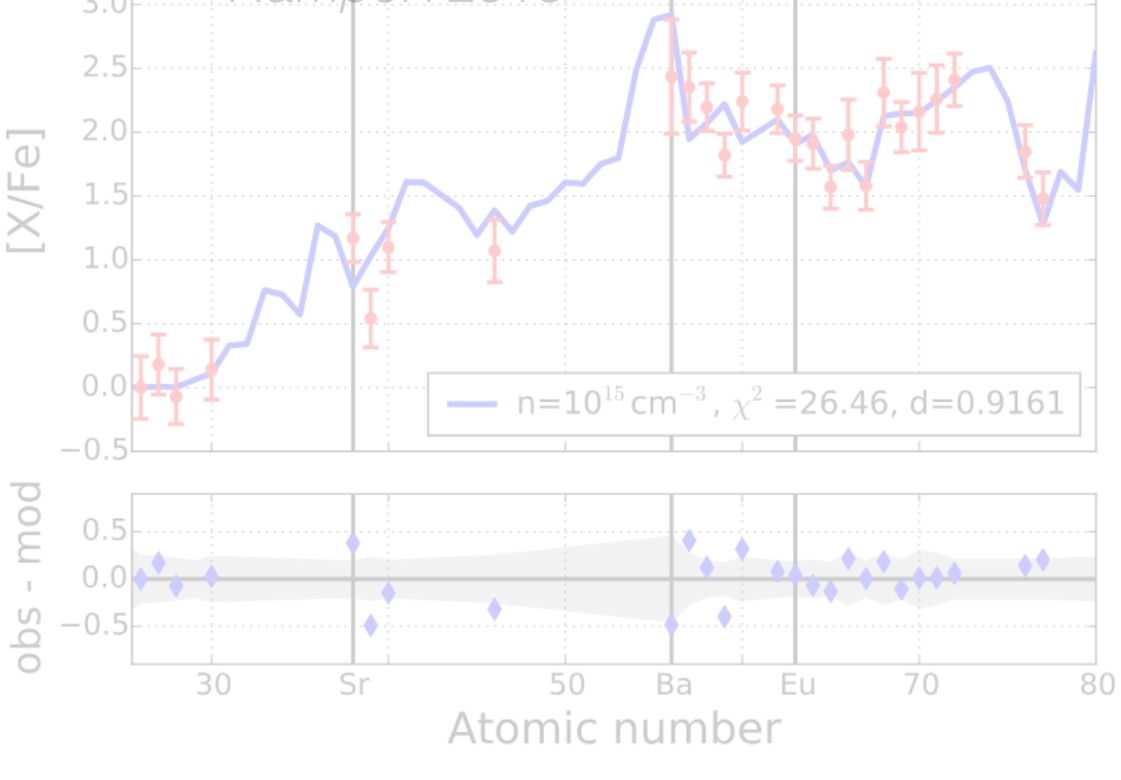
What about the astrophysical sites ?







Astrophysical sites for proton ingestion / i-process

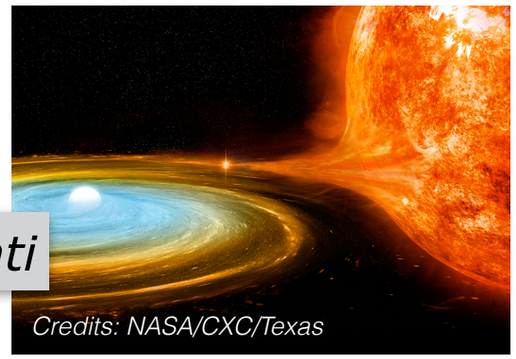
• Asymptotic giant branch (AGB) stars + super AGB

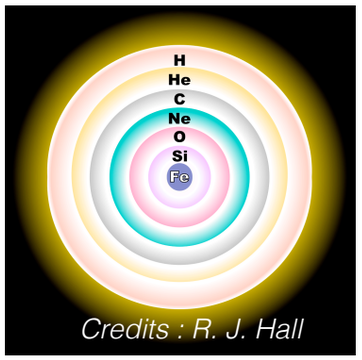
Fujimoto+2000, Iwamoto+2004, Siess+2007, Campbell+2008, Lau+2009, Suda+2010, Stancliffe+2011, Cristallo+2009,2016,2018, Jones+2016, Choplin+2021,2022,2024,2025 Goriely+2021, Gil-Pons+2022, Remple+2024…

• Accreting white dwarfs

Denisenkov+2017,2019,2021, Piersanti+2019, Stephens+2021 …

—> talk by L. Piersanti





• Massive stars

Marigo+2001, Hirschi 2007, Ekstrom+2008, Heger+2010, Limongi+2012, Pignatari+2015, Choplin+2017, Ritter+2018, Banerjee+2018, Clarkson+2018,2021…

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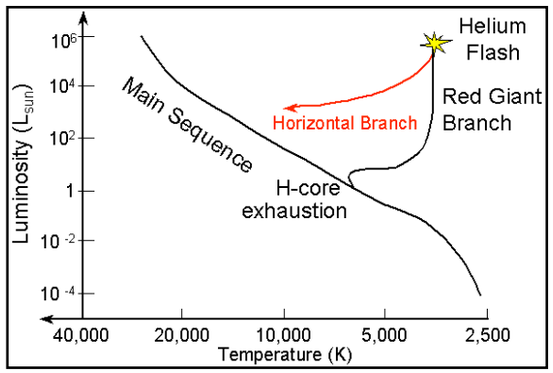

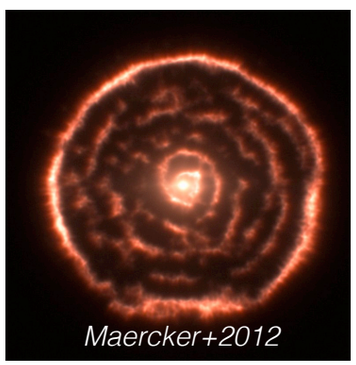

• Post-AGB stars

Herwig+2001, Miller Bertolami 2006, Herwig+2011…

• Collapsars jets (?)

He+2024

—> talk by Z. He

(No proton ingestion —> different mechanism)

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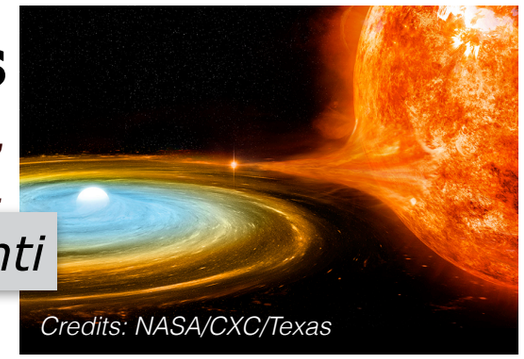

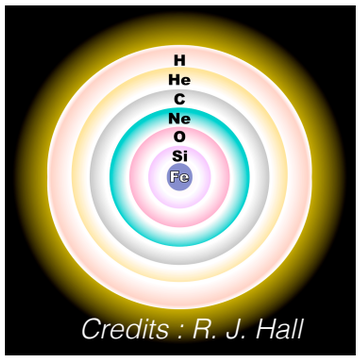

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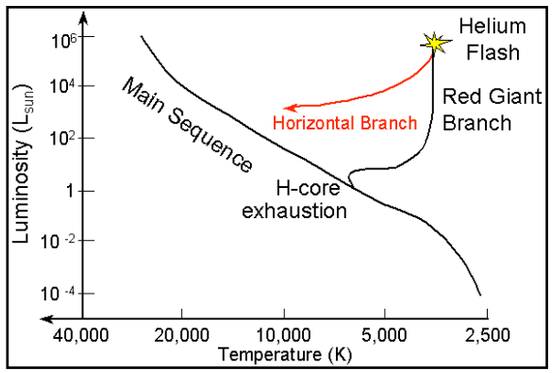

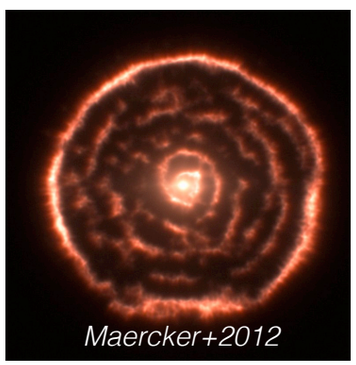

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models following i-process nucleosynthesis

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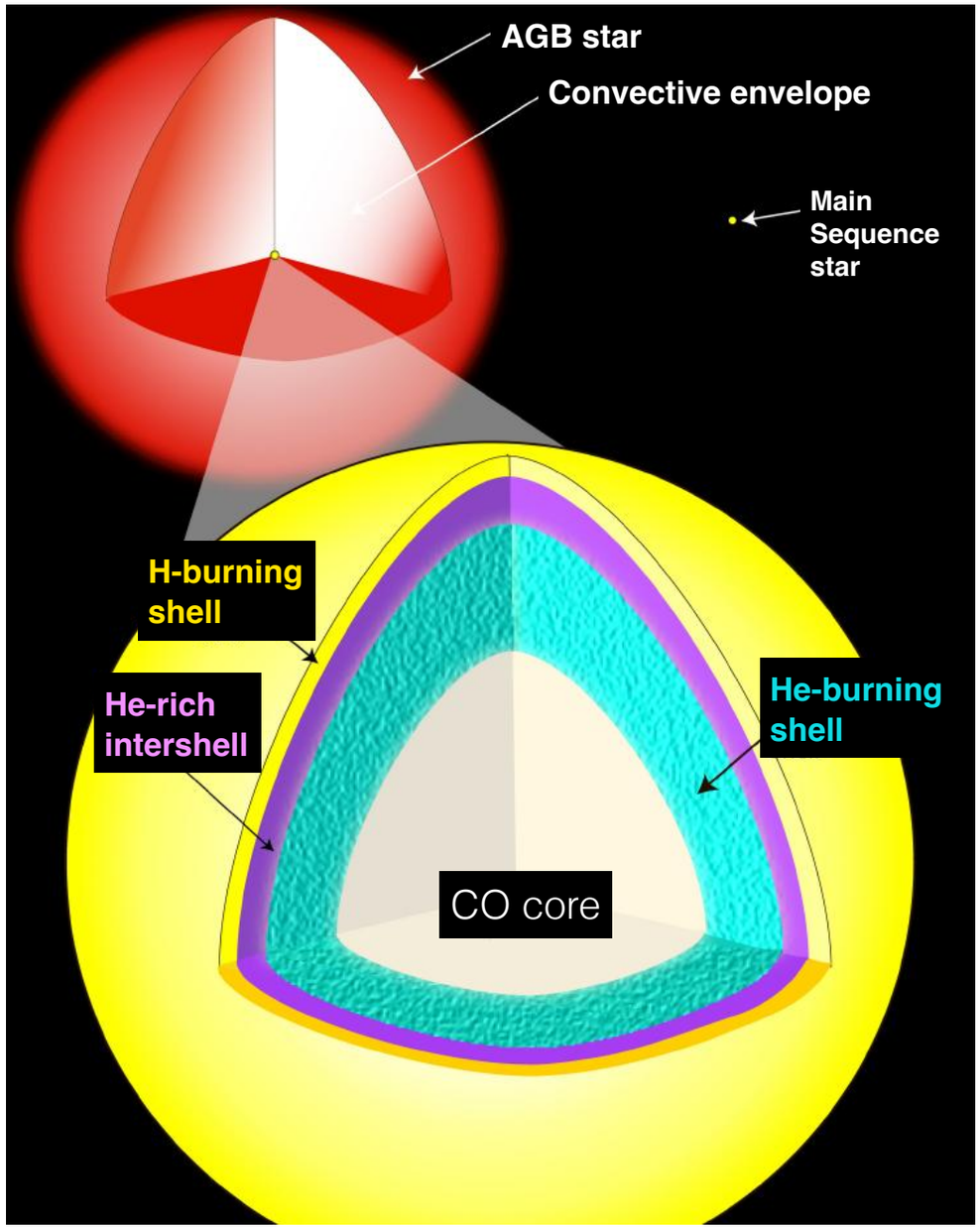
Fujimoto+2000, Iwamoto+2004, Siess+2007, Campbell+2008, Lau+2009, Suda+2010, Stancliffe+2011, Cristallo+2009,2016,2018, Jones+2016, Choplin+2021,2022,2024,2025 Goriely+2021, Gil-Pons+2022, Remple+2024…

—> **end of life** of ~ 0.8 - 8 $M_\odot$ stars
—> strong **stellar winds**
—> complex interplay between **nucleosynthesis and mixing**



Reviews on AGB

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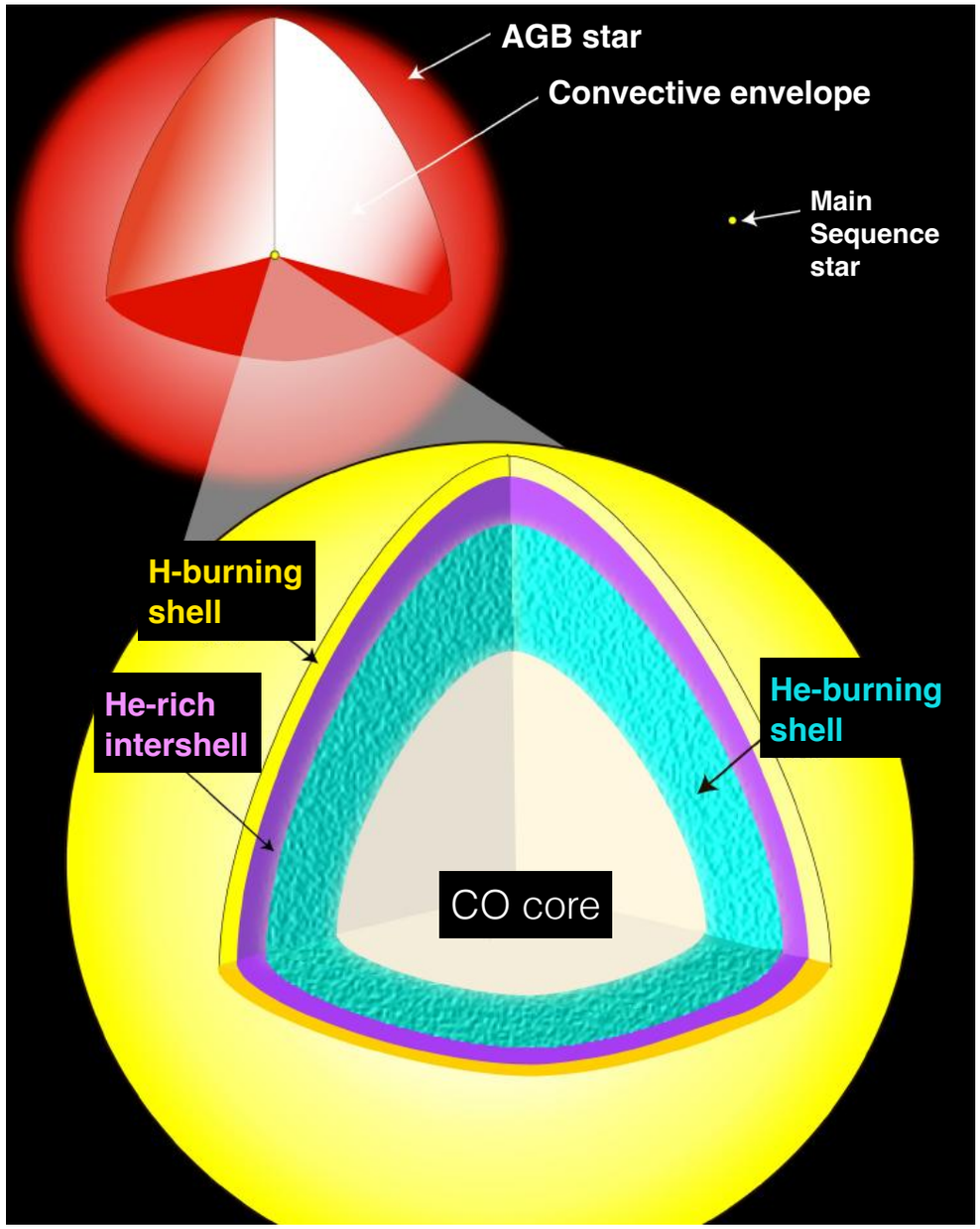

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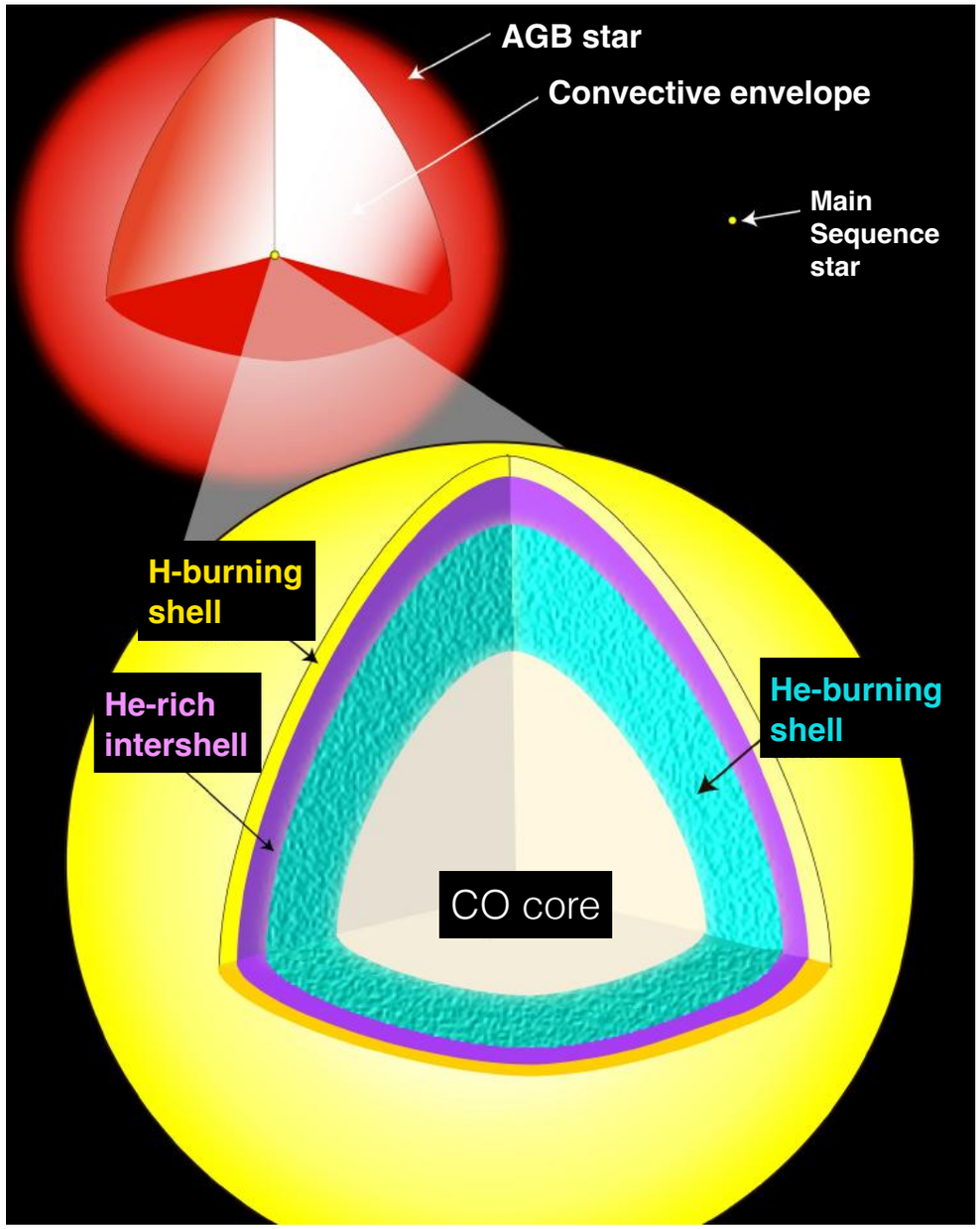

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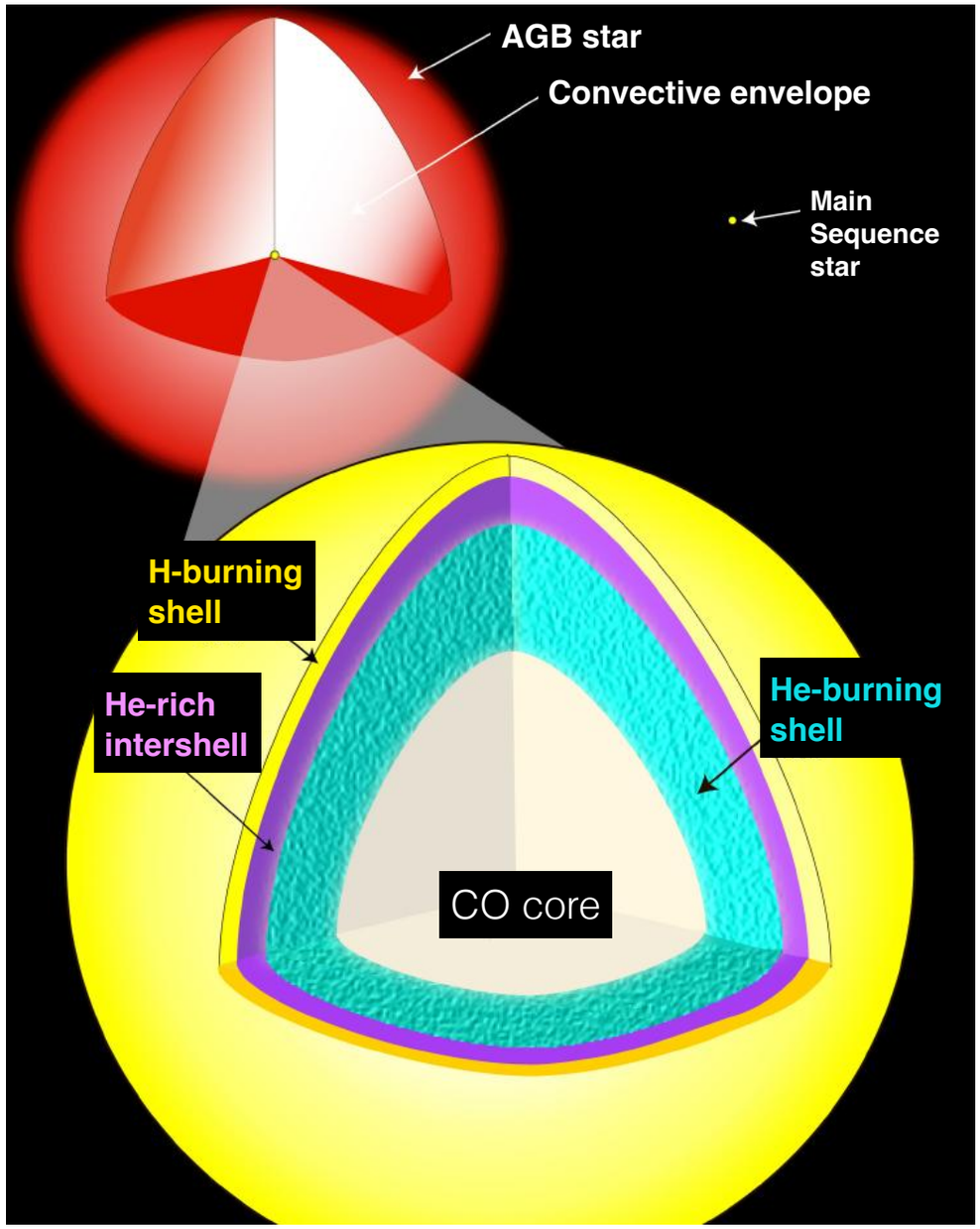


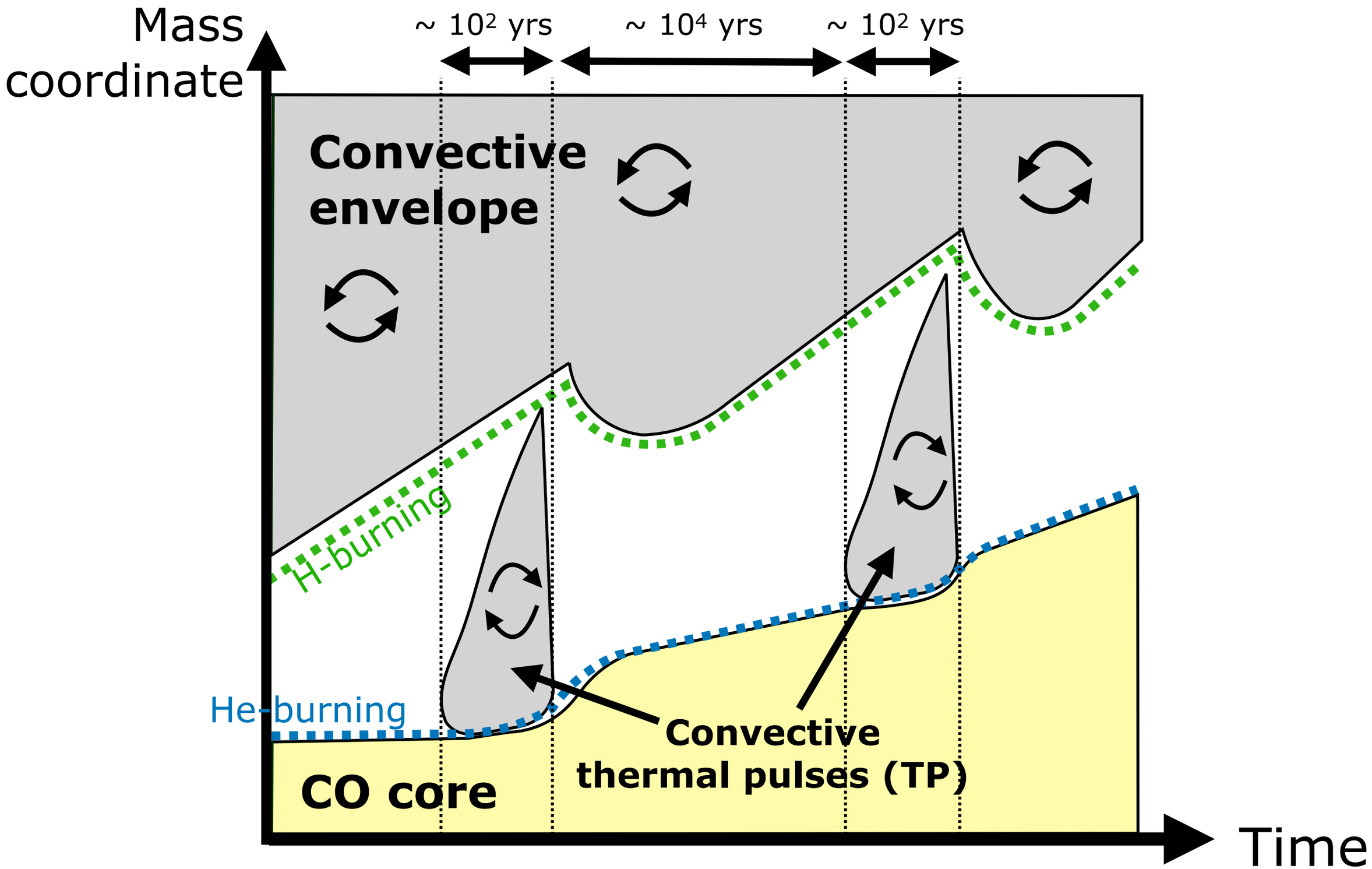
Stellar evolution in 1D

MESA, STAREVOL, GENEC, KEPLER, FRANEC, …

- **Full life / scale of stars**
- **Full nucleosynthesis**
- **Spherical symmetry**
- **Simplified theories for 3D processes**

Structure evolution of an AGB star

schematic view



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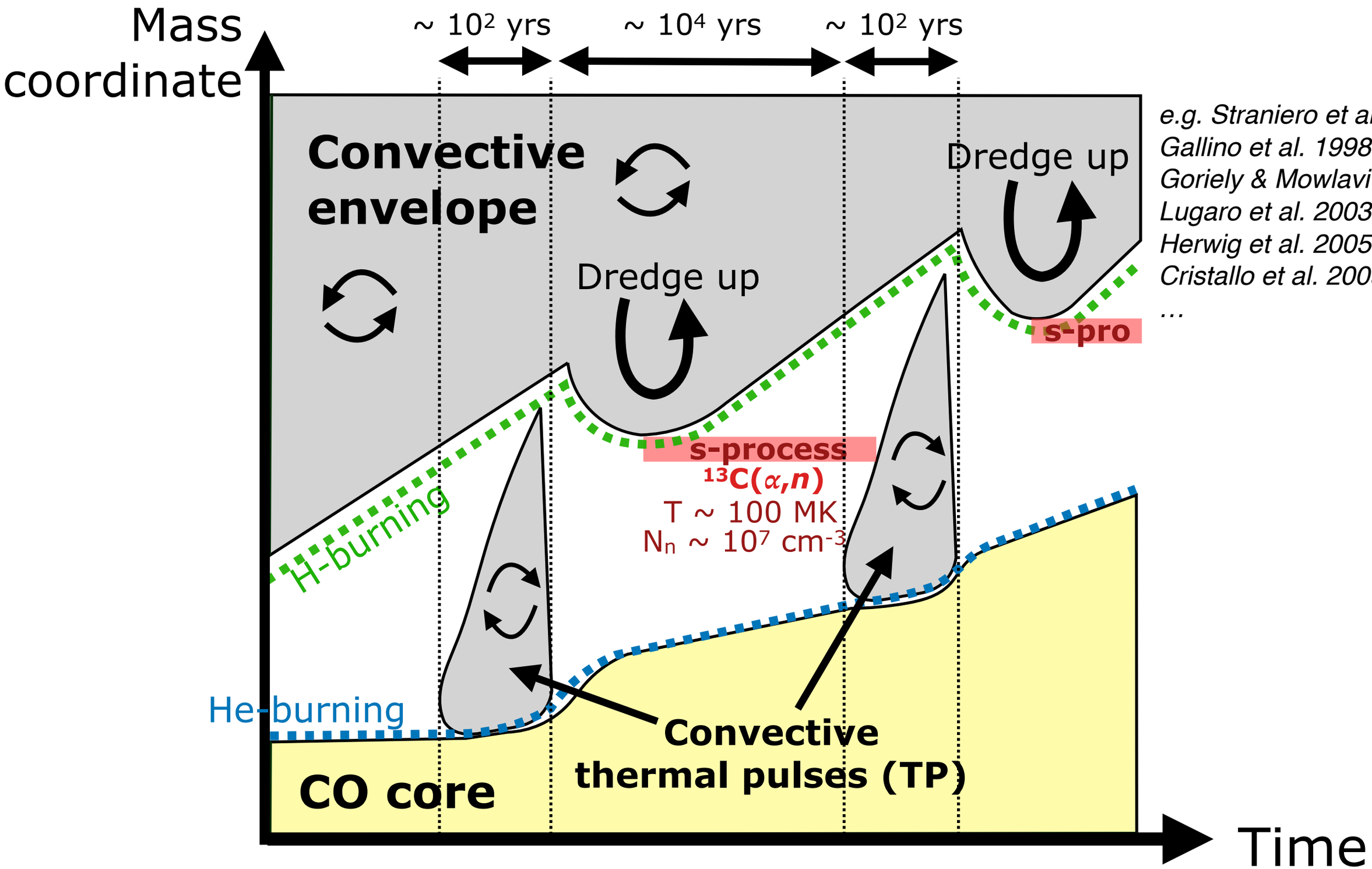
The s-process —> *talk by M. Busso*



e.g. Straniero et al. 1995, Gallino et al. 1998, Goriely & Mowlavi 2000, Lugaro et al. 2003, Herwig et al. 2005 Cristallo et al. 2009 …

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schematic view

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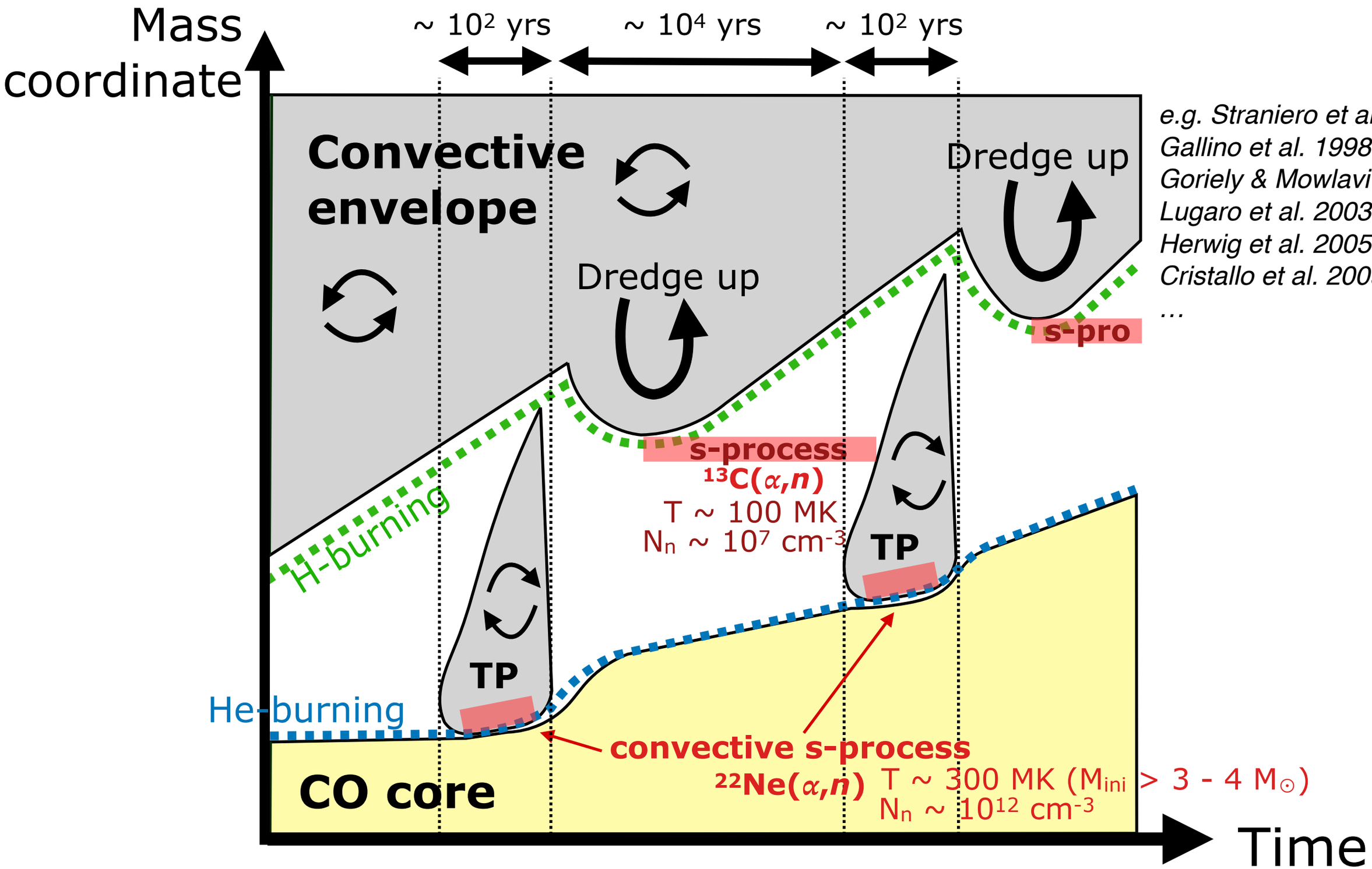

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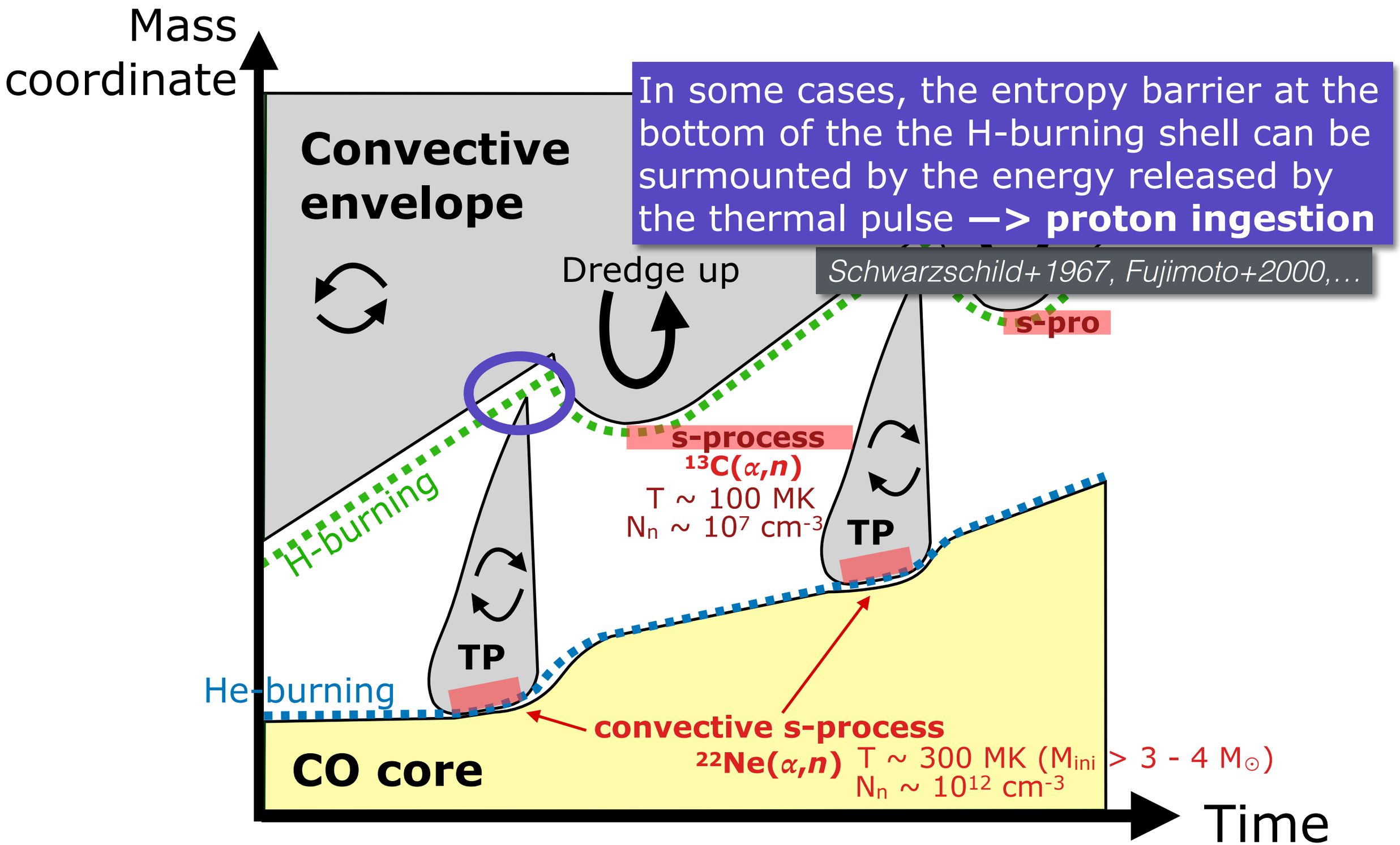

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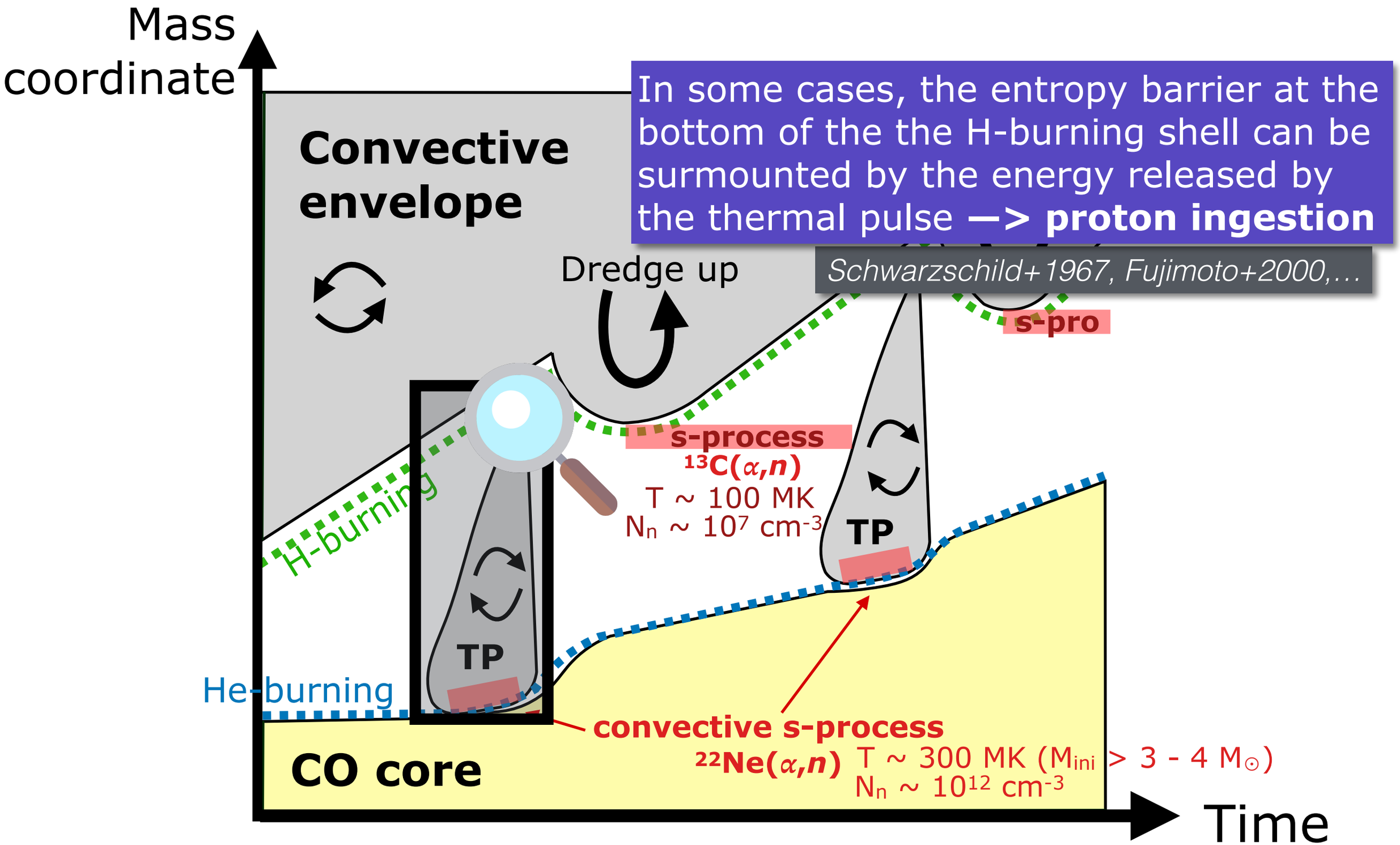
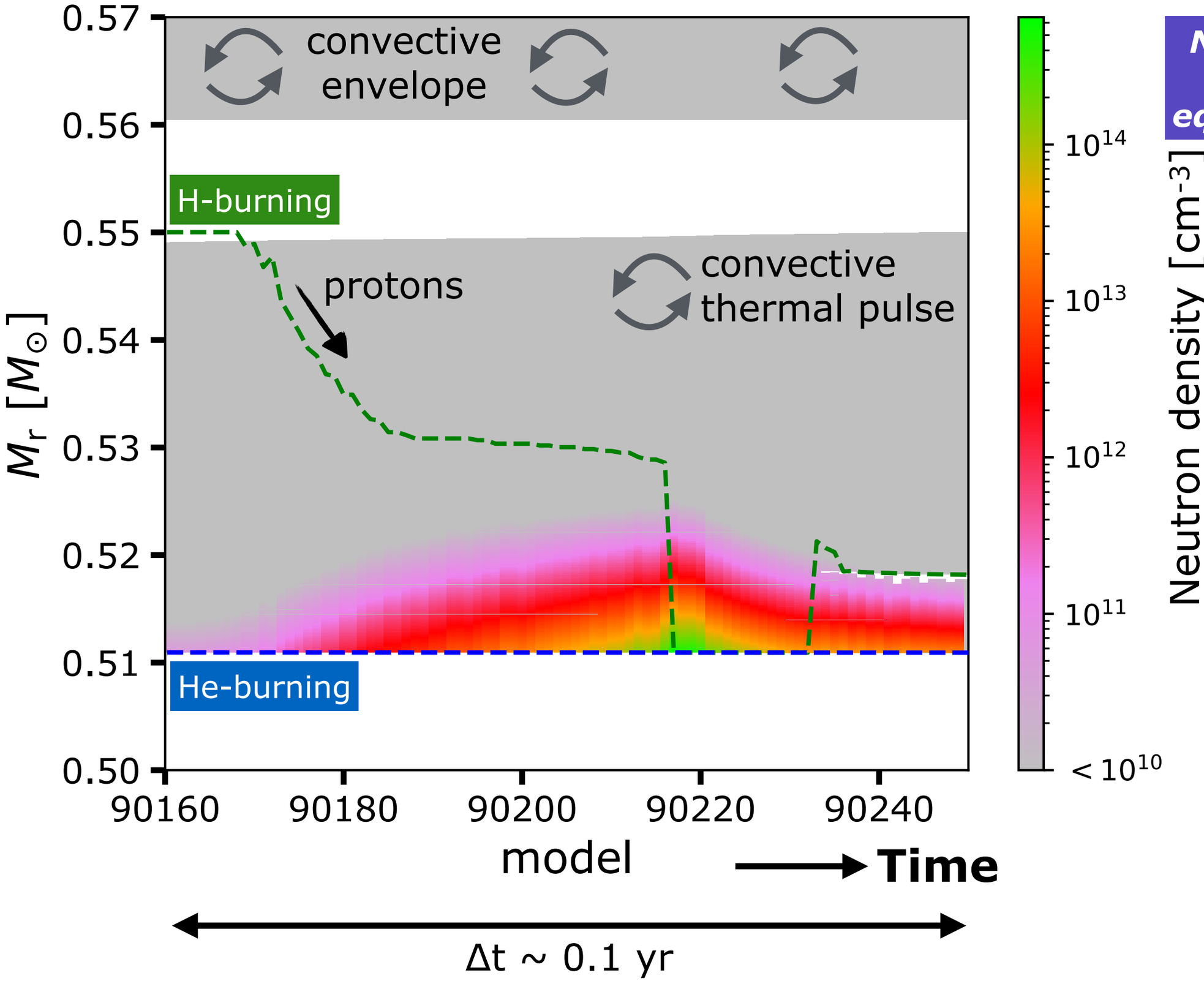


The i-process engine (1 $M_{\odot}$, [Fe/H] = -2.5, AGB model)

STAREVOL code

Nucleosynthesis & transport equations coupled



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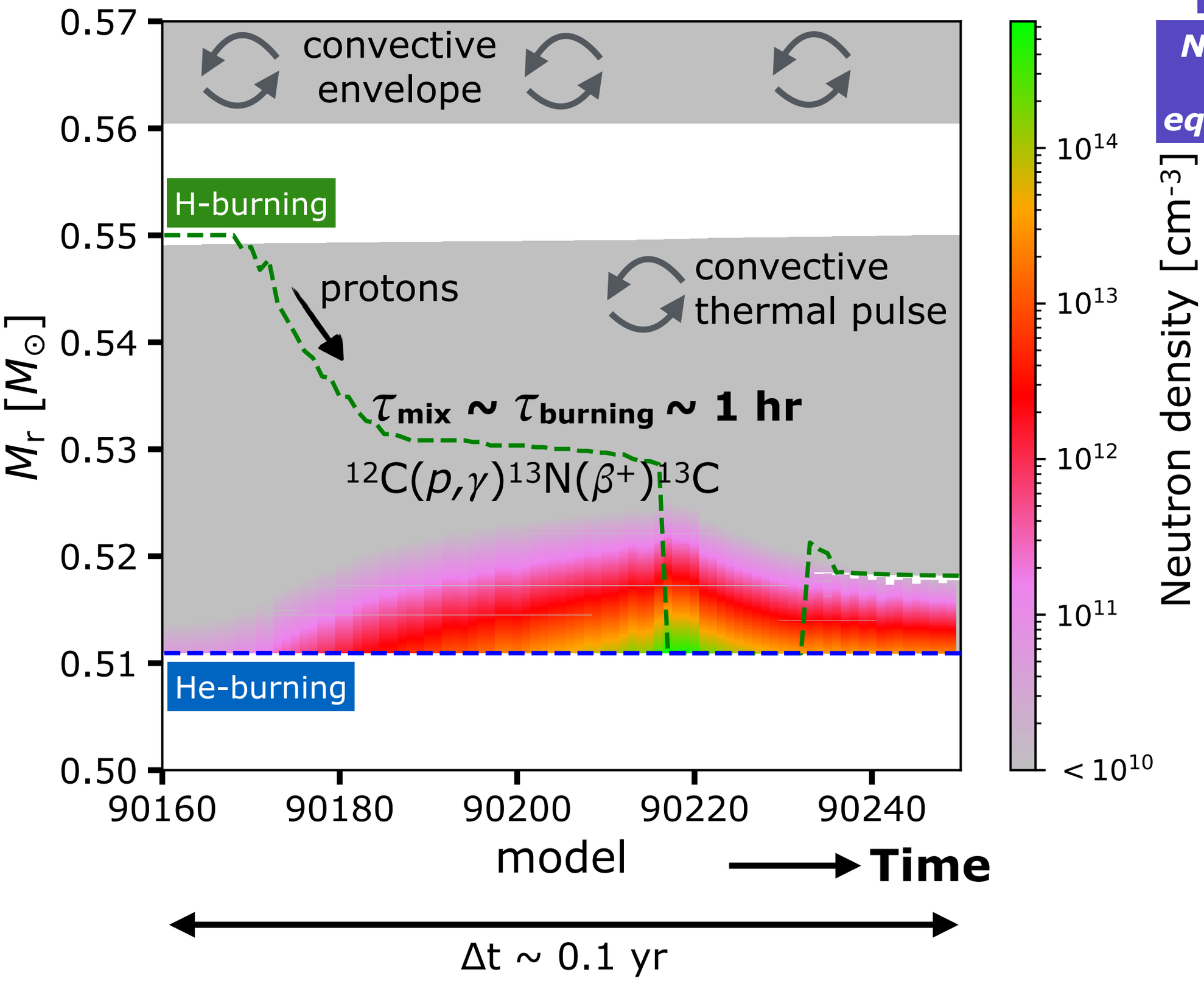

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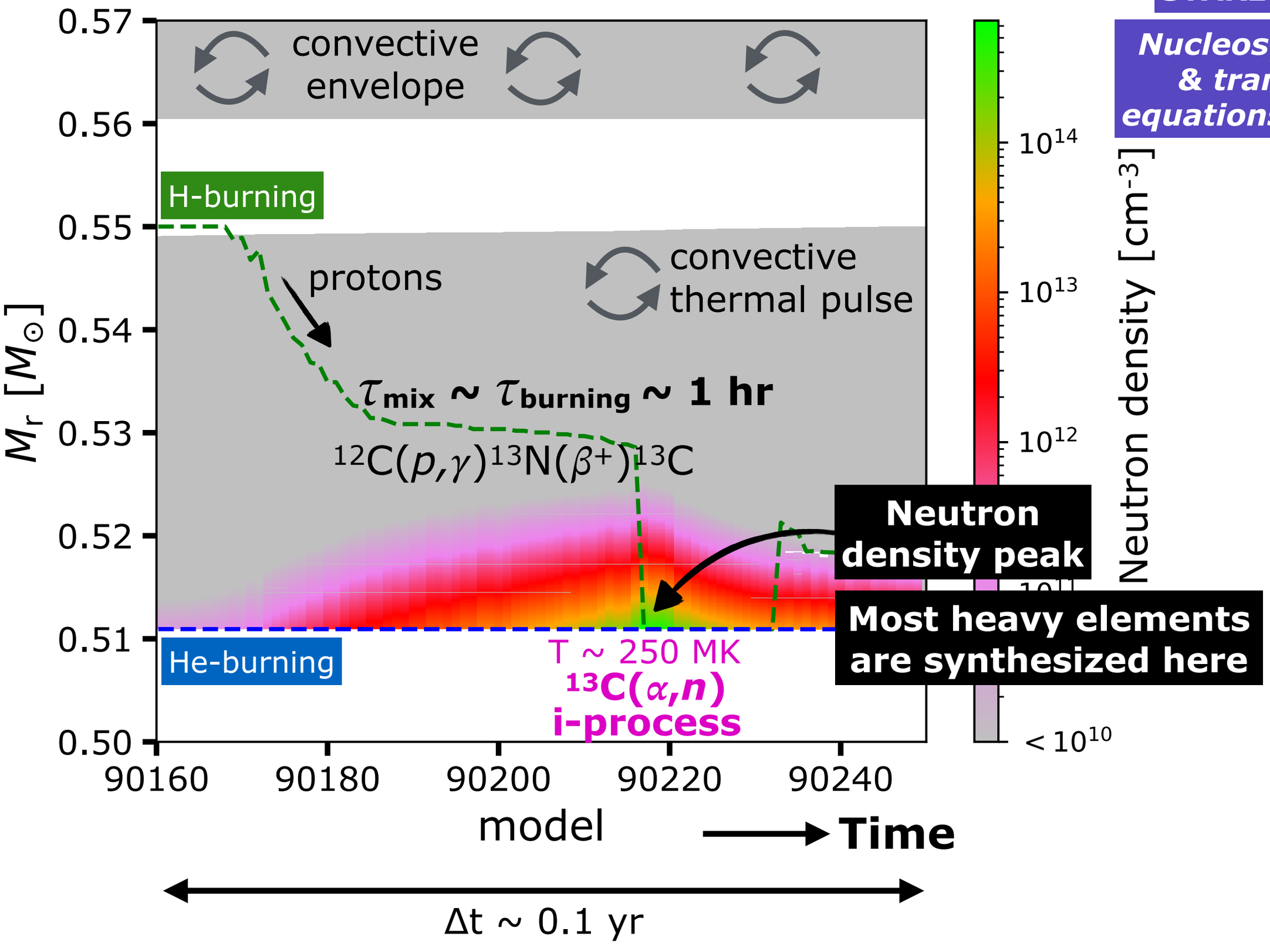

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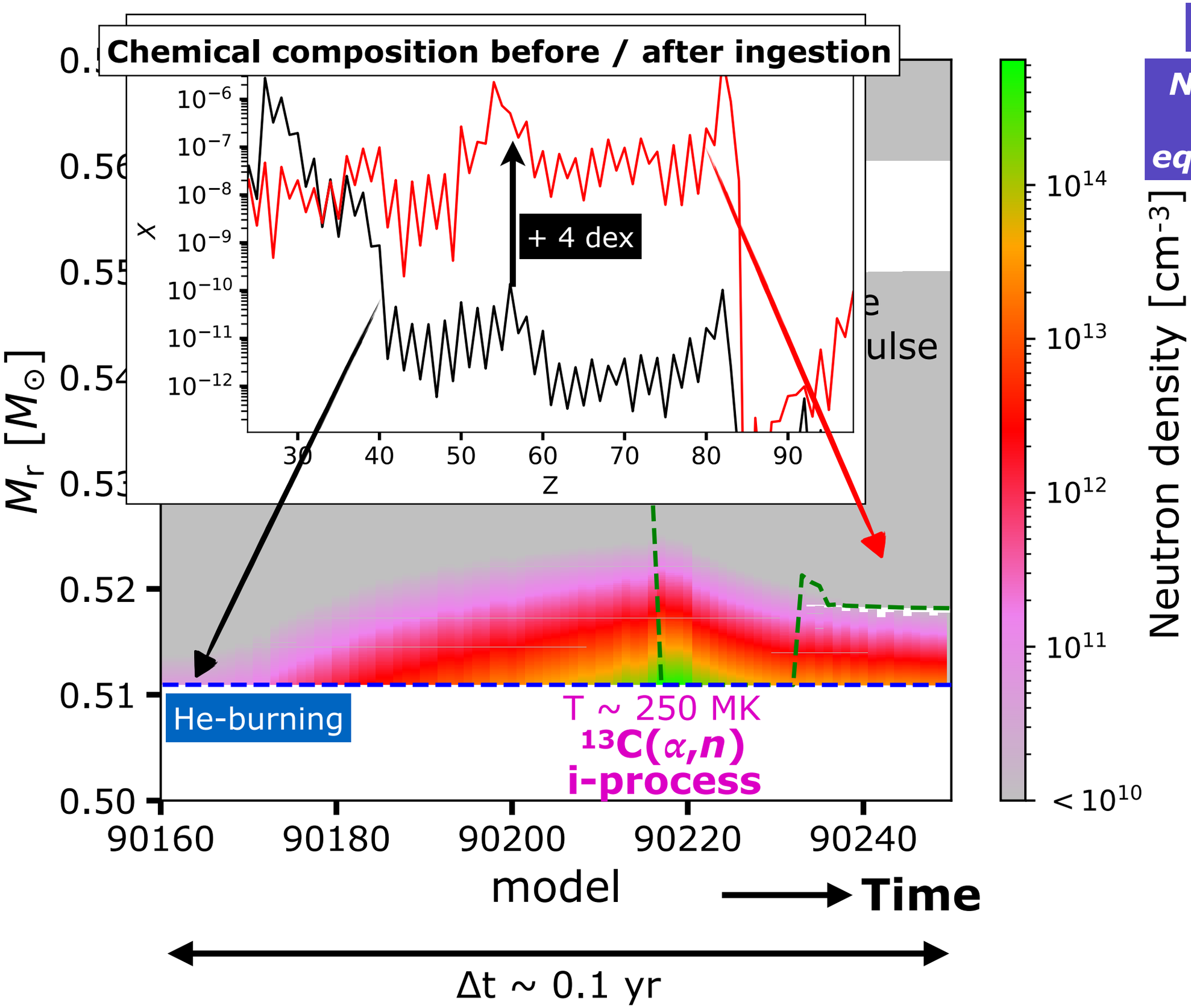

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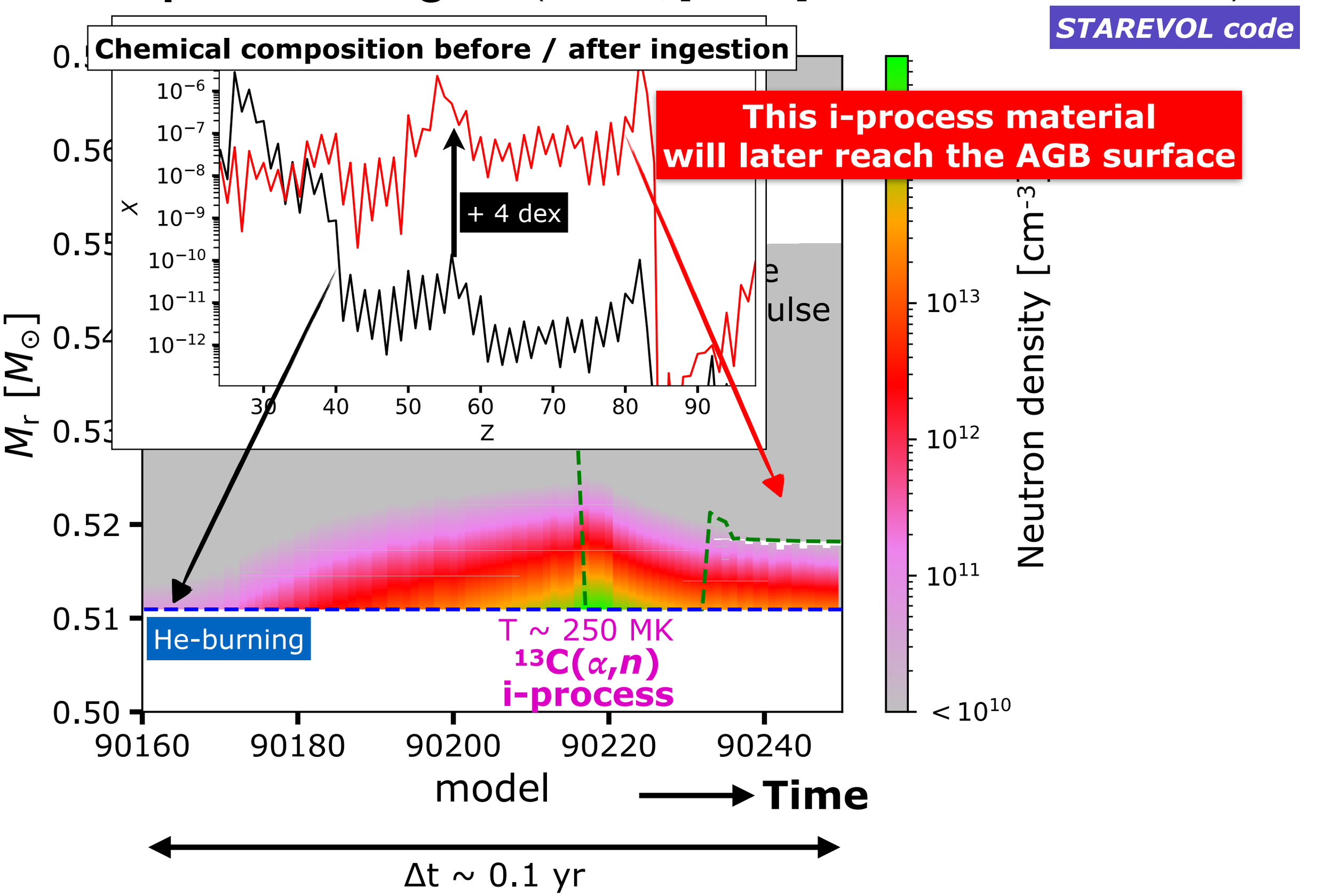

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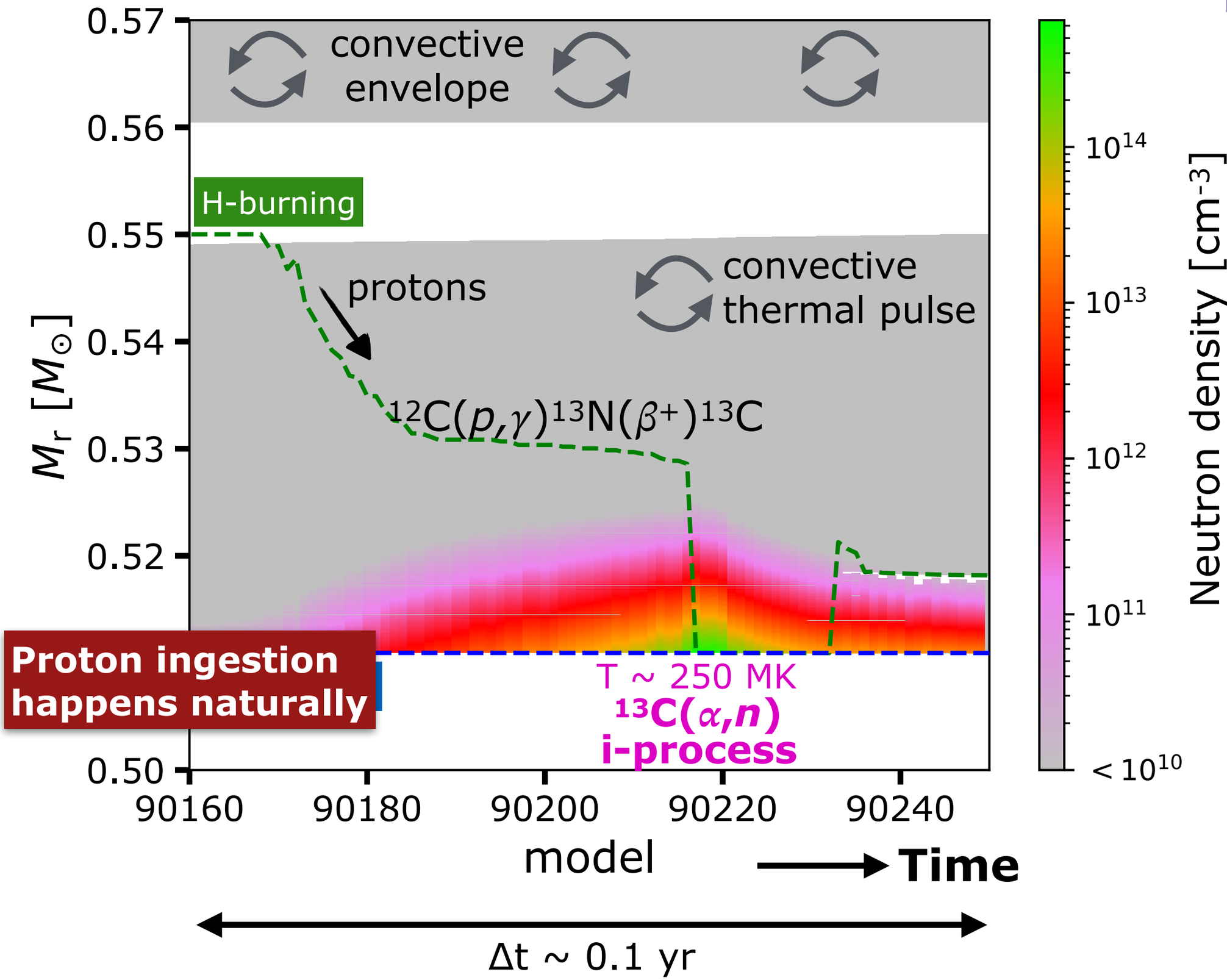

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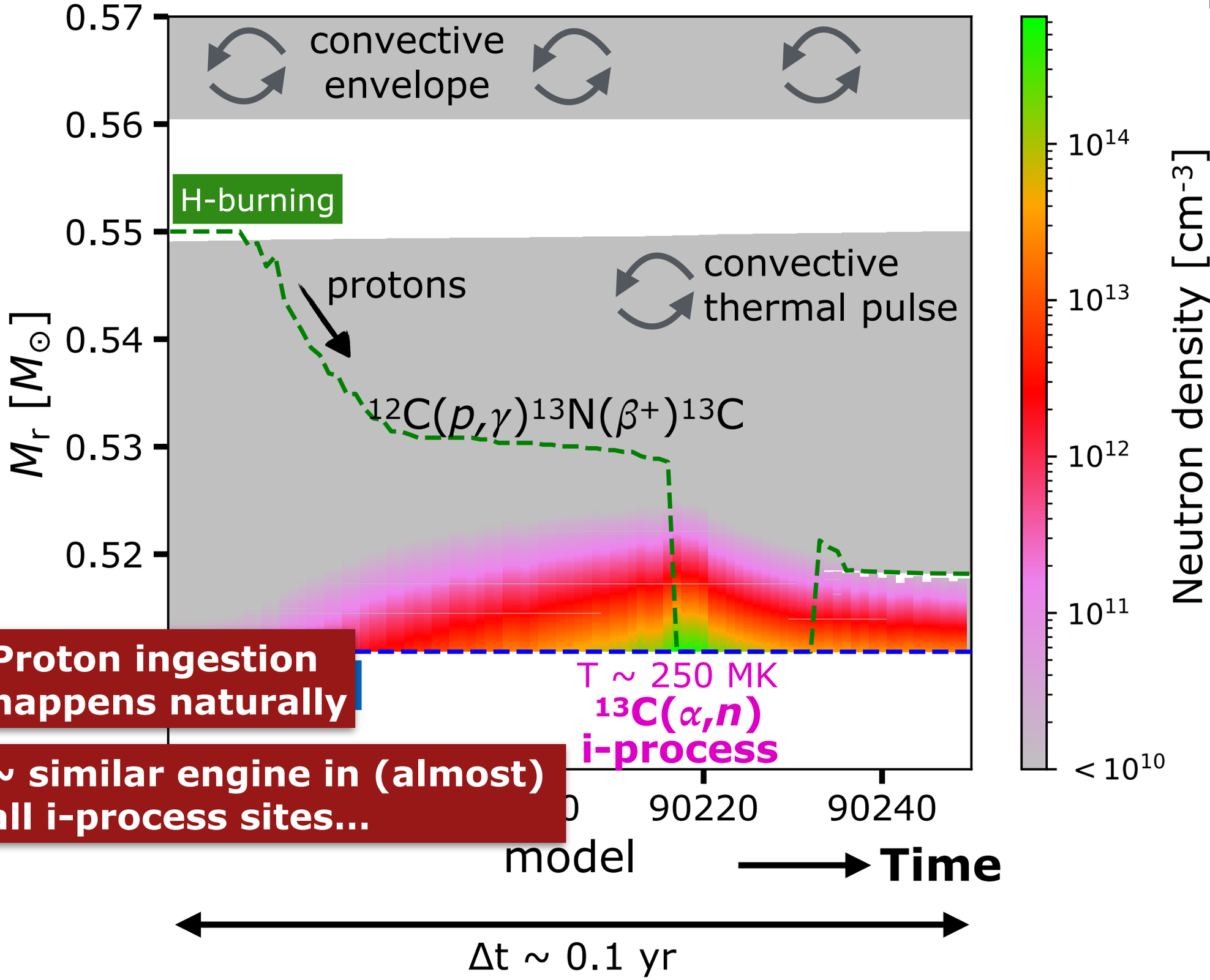

Proton ingestion happens naturally

~ similar engine in (almost) all i-process sites…

The i-process engine (1 $M_\odot$, [Fe/H] = -2.5, AGB model)

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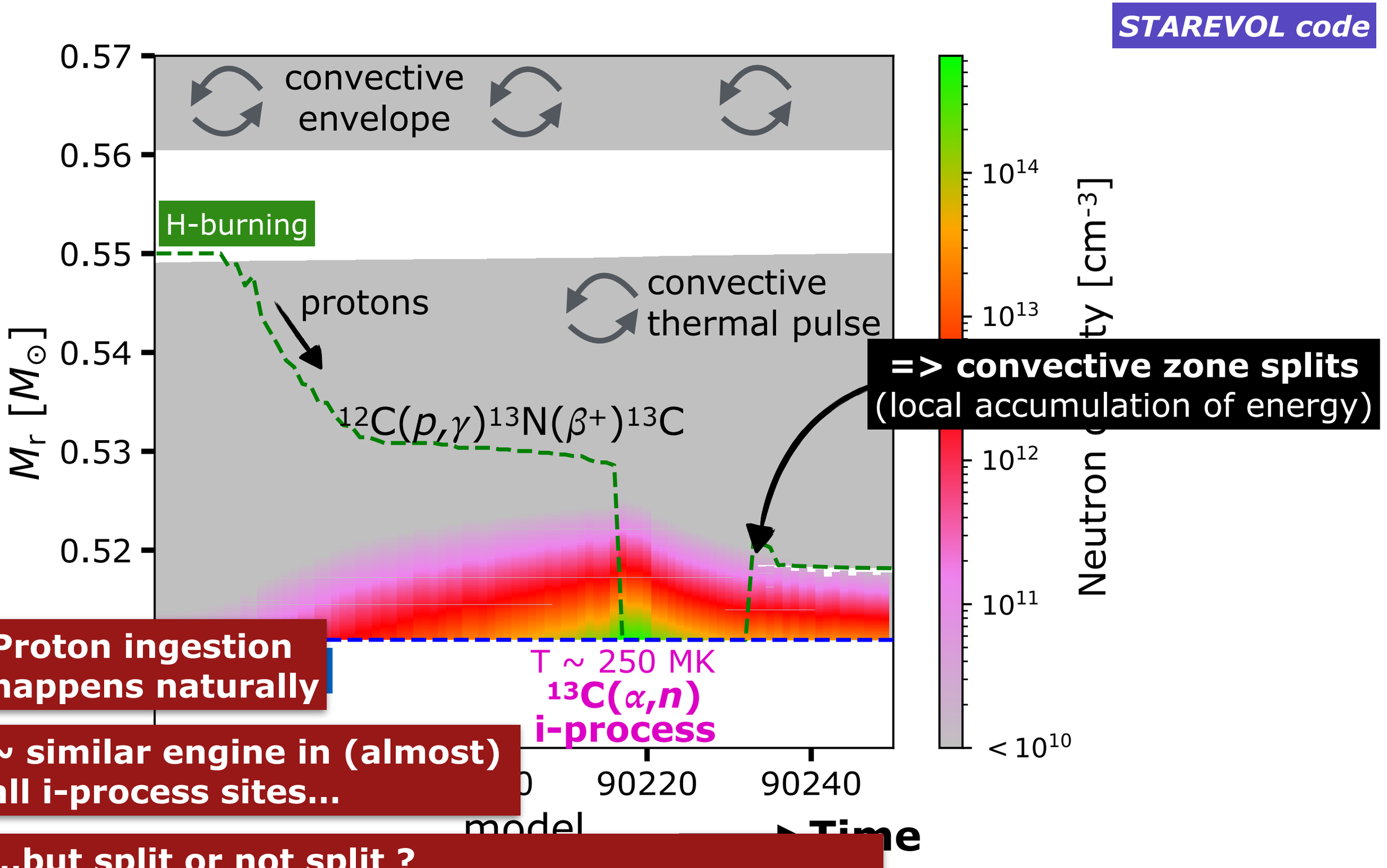
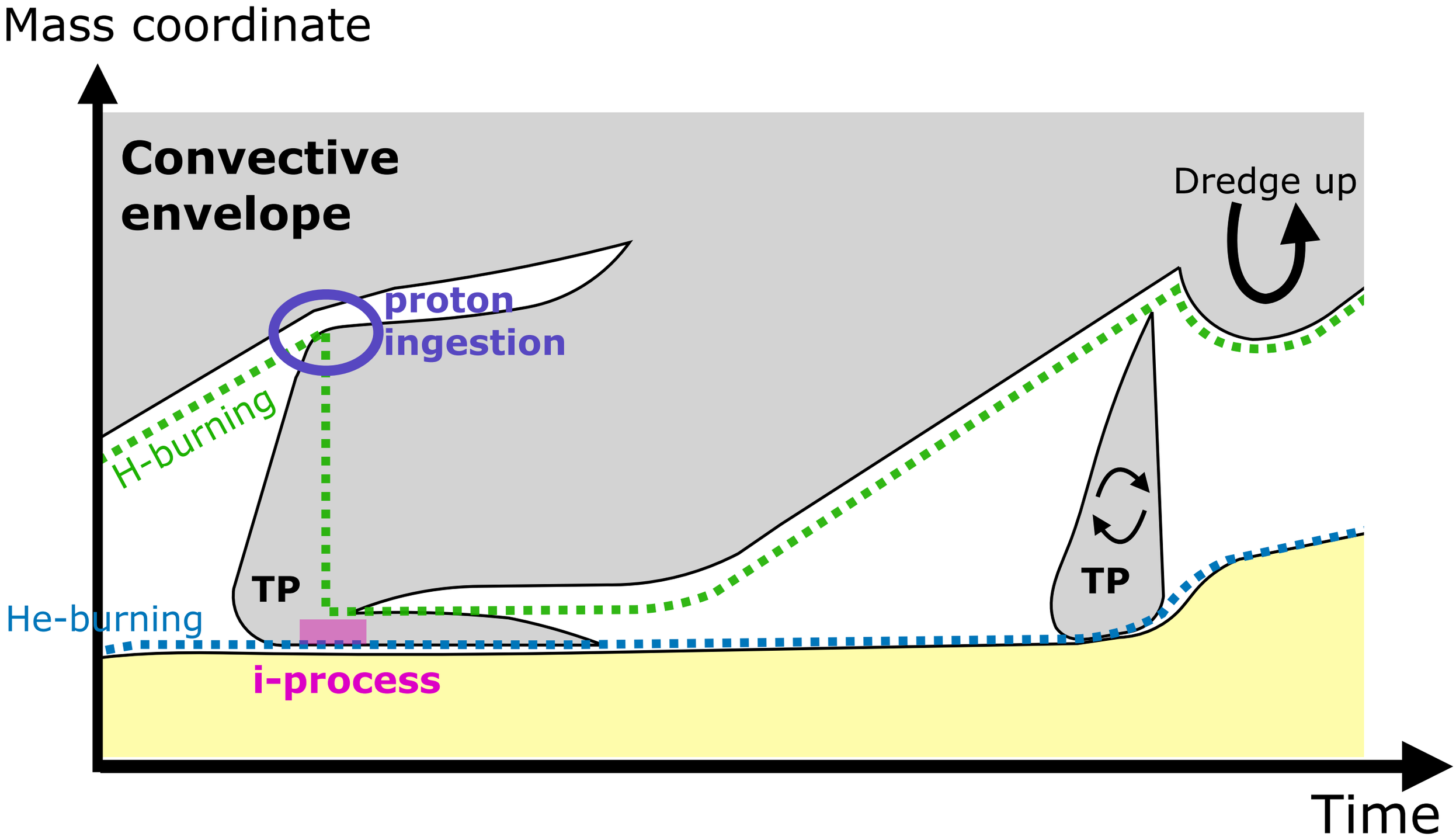


e.g. Herwig+2014,Choplin+2022, …

Structure evolution of an AGB star

schematic view

The i-process



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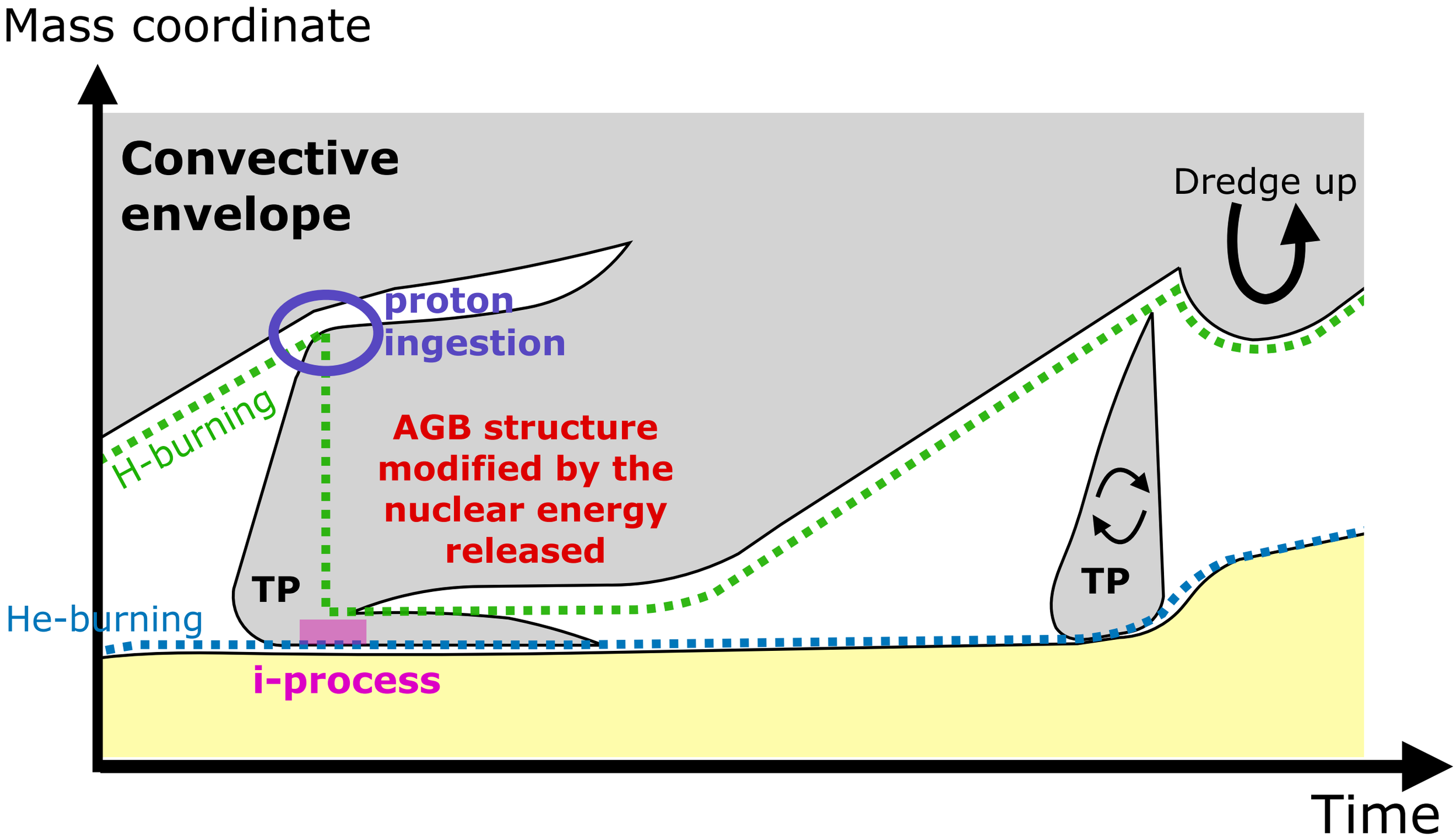

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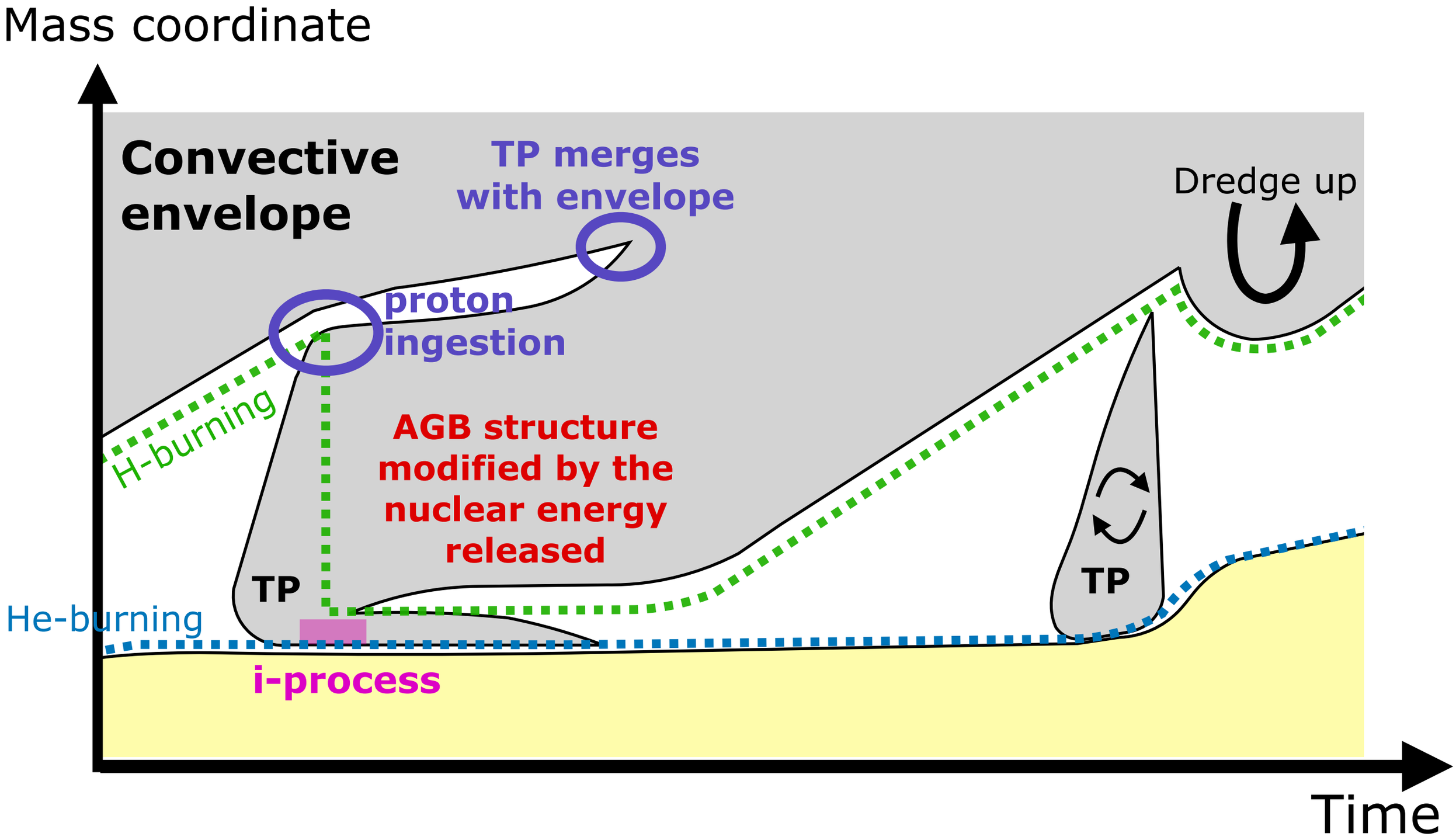

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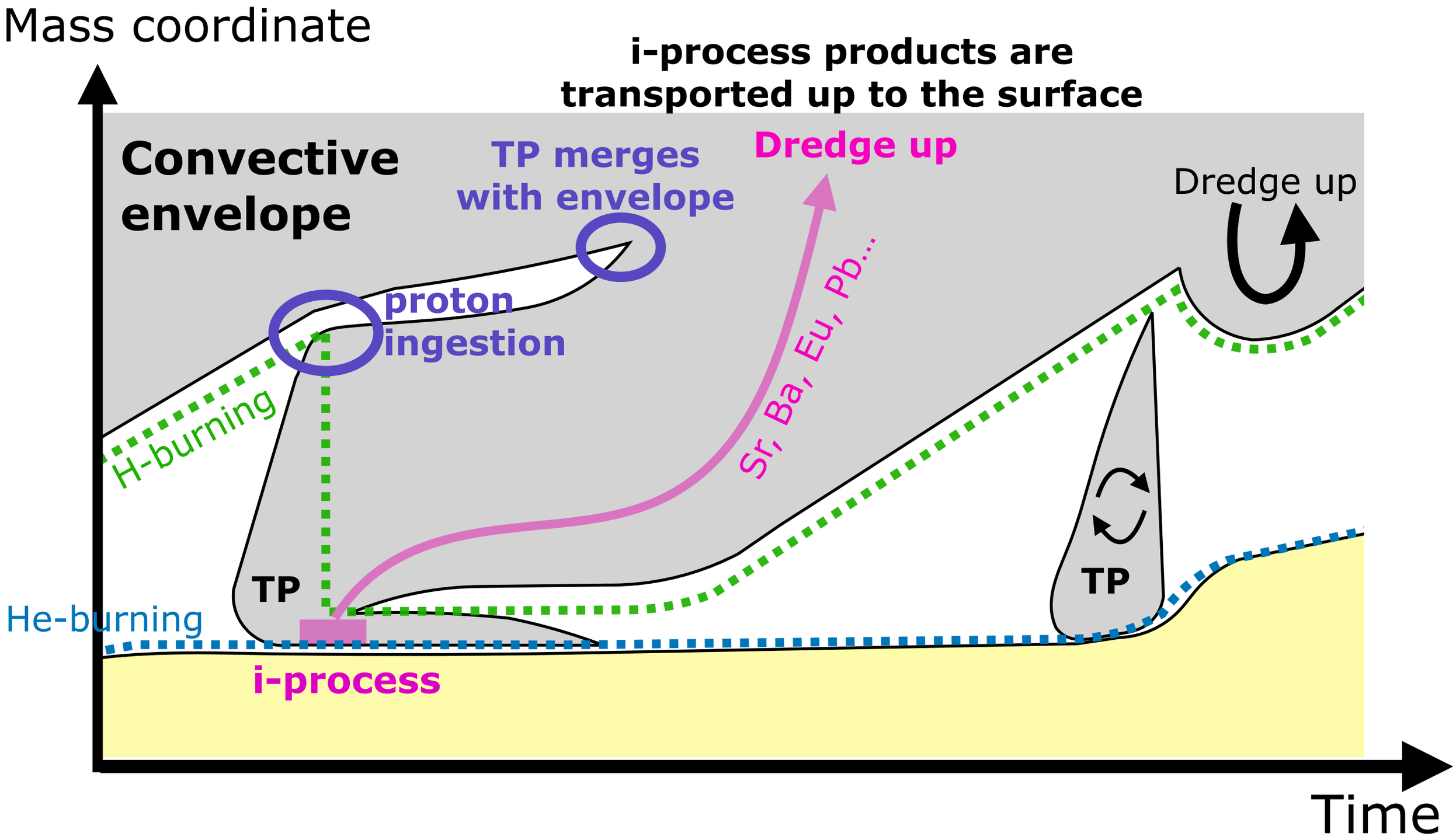

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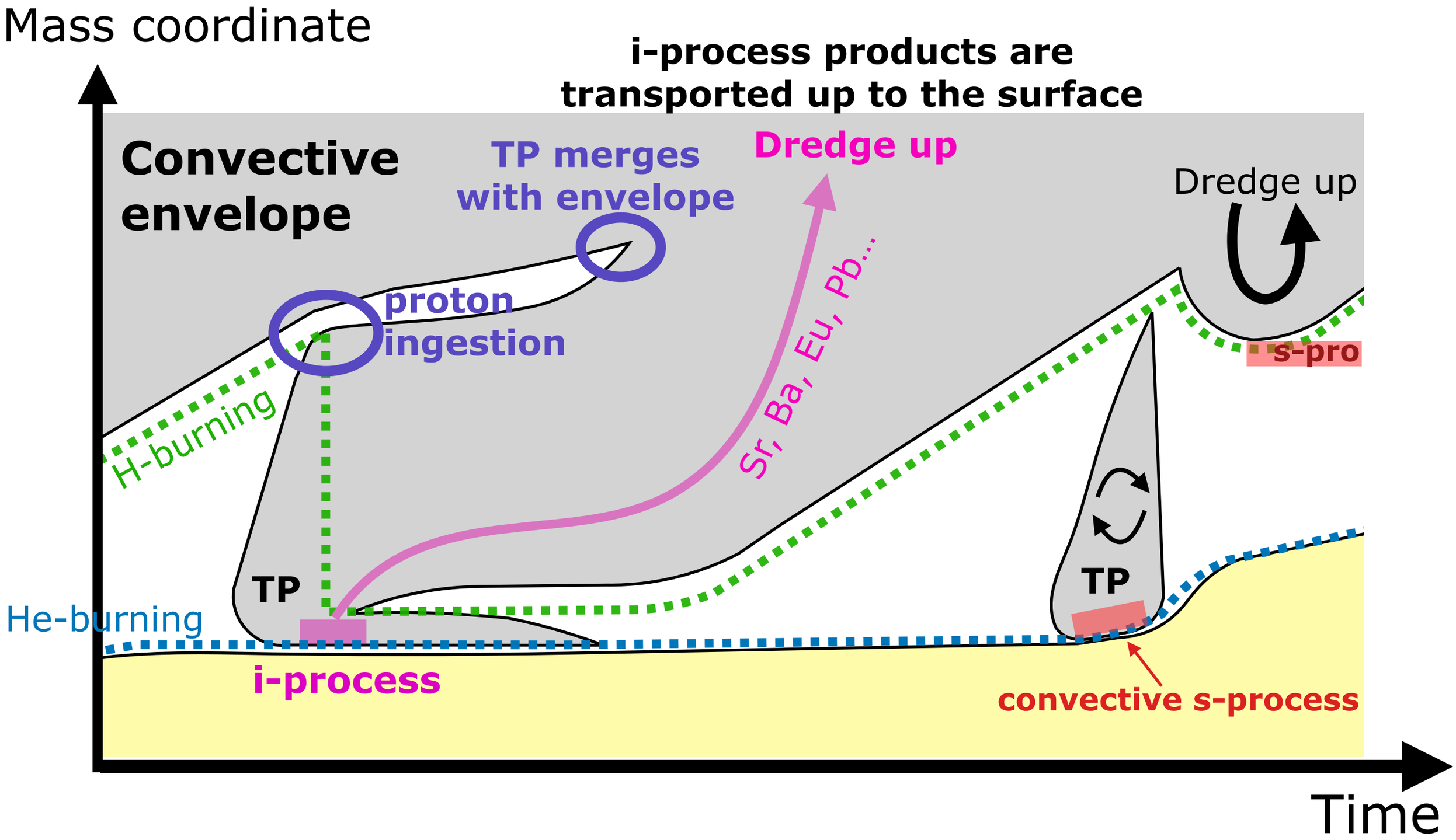

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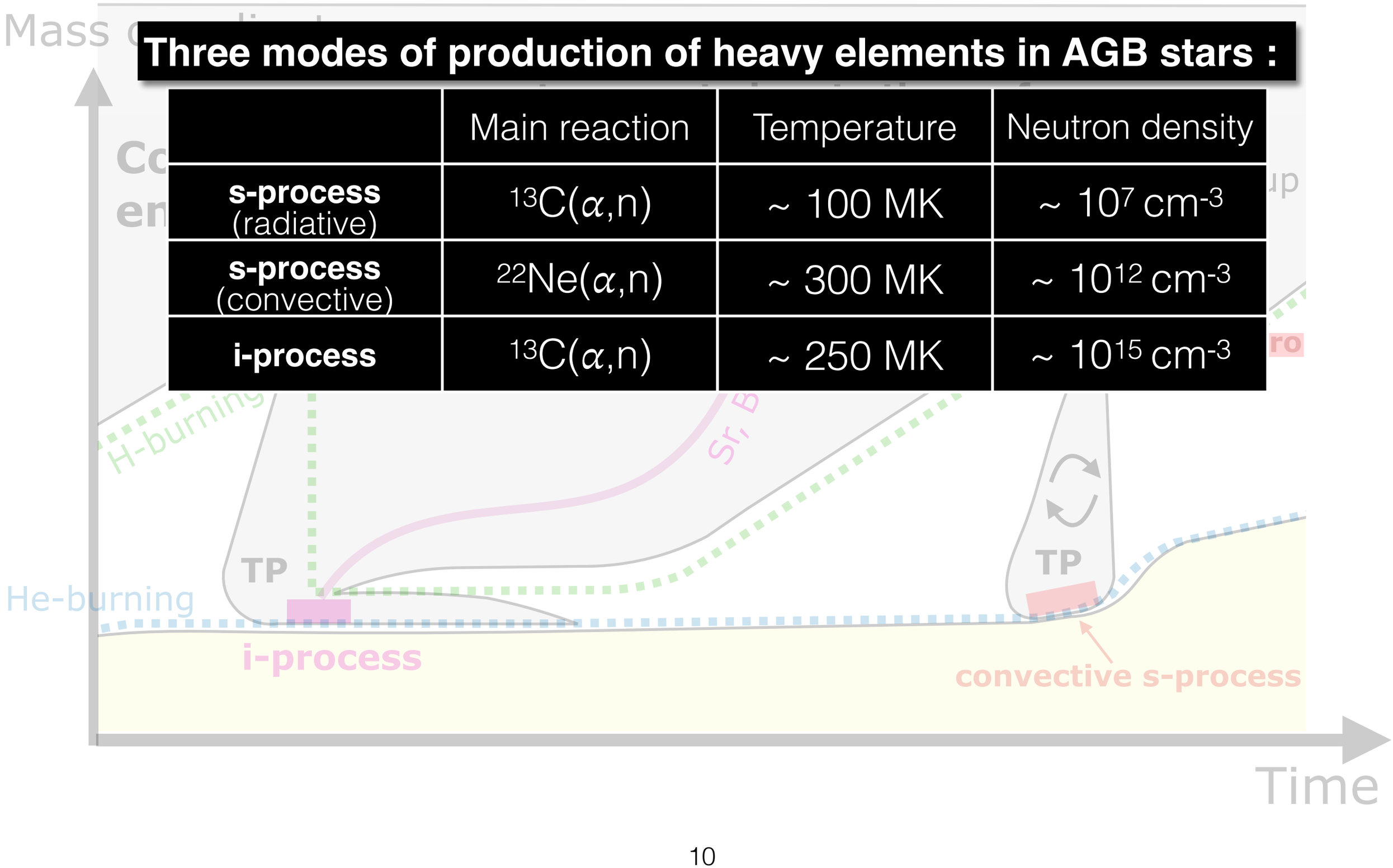
The i-process

Three modes of production of heavy elements in AGB stars :

	Main reaction	Temperature	Neutron density
s-process (radiative)	$^{13}C(\alpha,n)$	~ 100 MK	~ 10^{7} cm^{-3}
s-process (convective)	$^{22}Ne(\alpha,n)$	~ 300 MK	~ 10^{12} cm^{-3}
i-process	$^{13}C(\alpha,n)$	~ 250 MK	~ 10^{15} cm^{-3}



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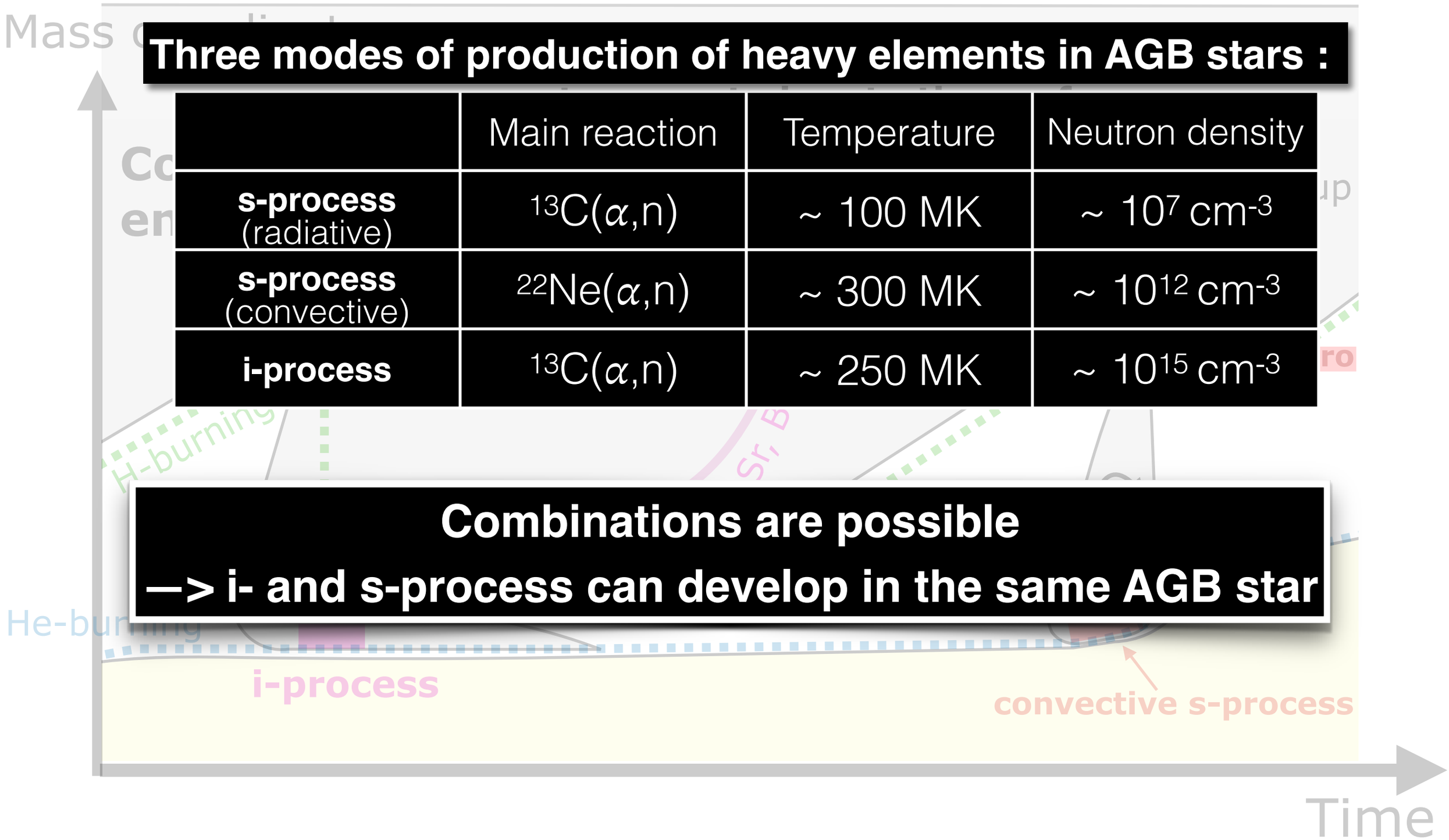
Combinations are possible
—> i- and s-process can develop in the same AGB star



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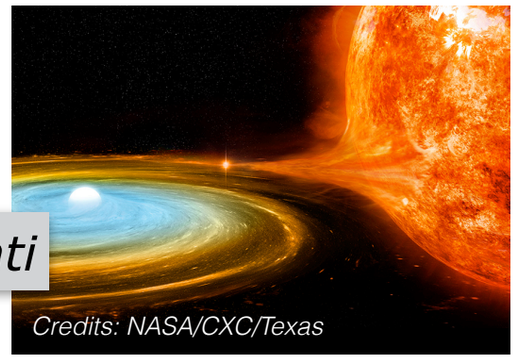

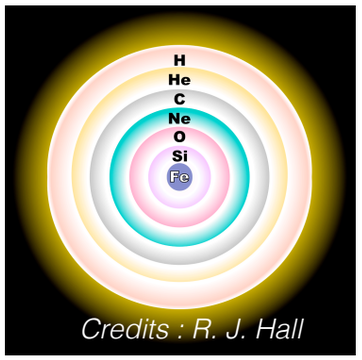

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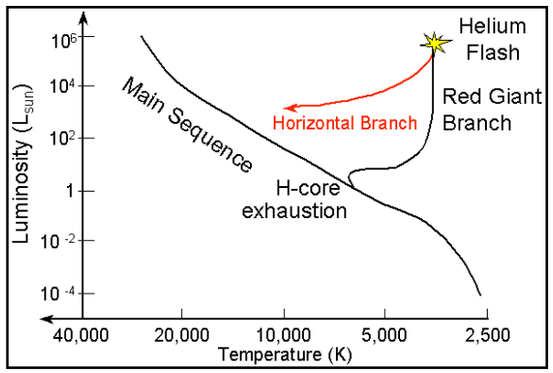
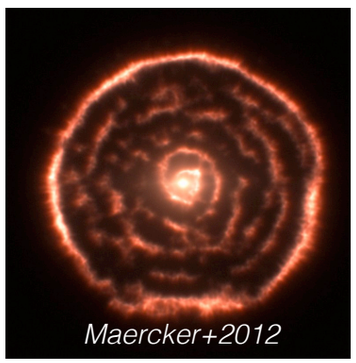




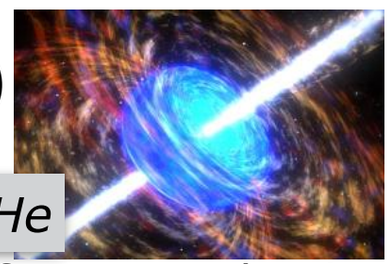
• Post-AGB stars

Herwig+2001, Miller Bertolami 2006, Herwig+2011…

• Collapsars jets (?)

He+2024

—> talk by Z. He



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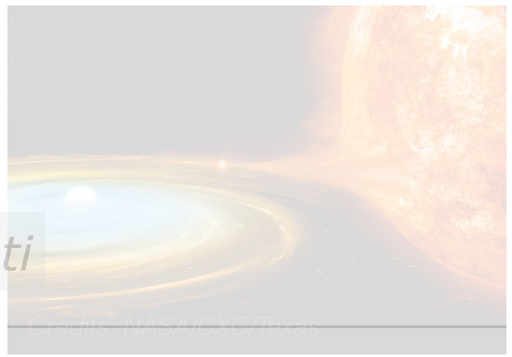

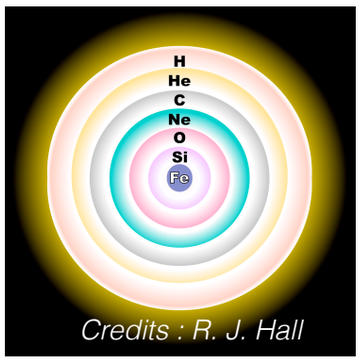

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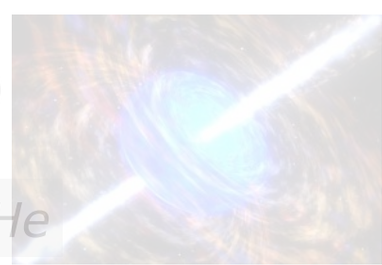

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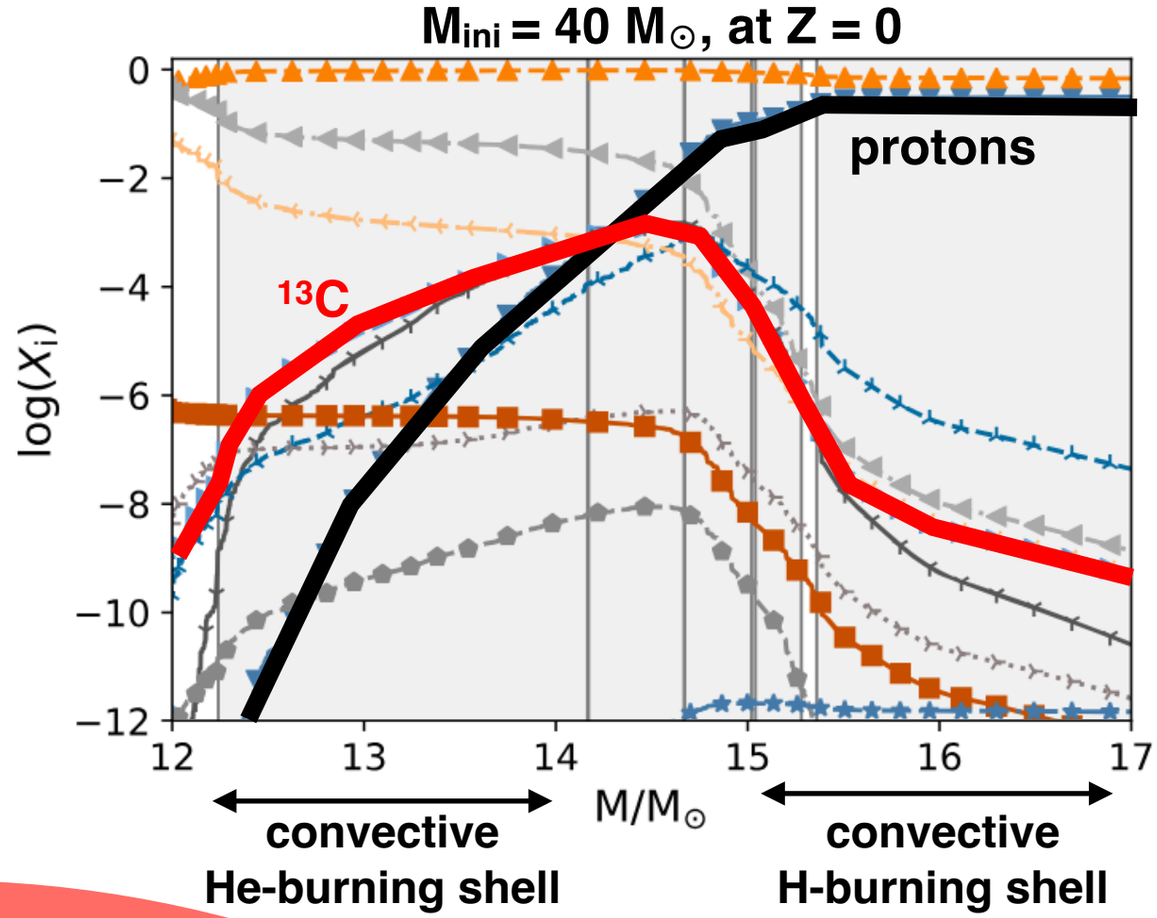
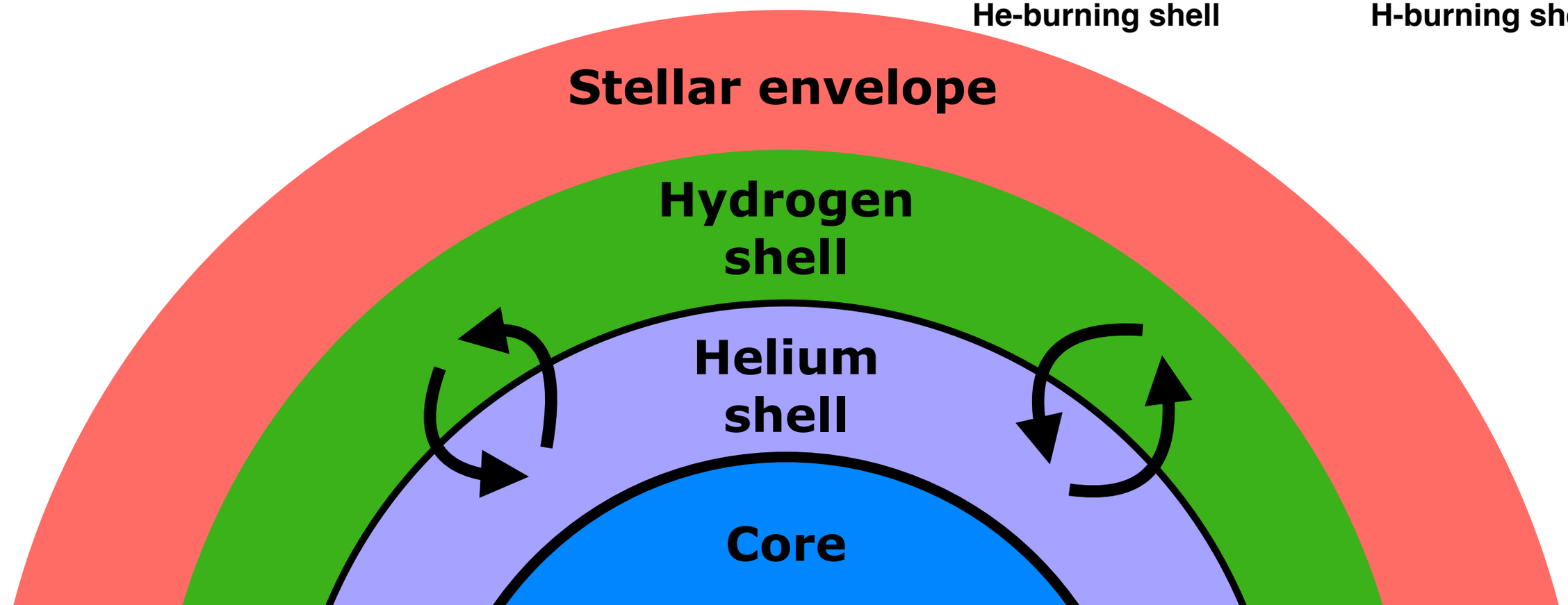
proton ingestion / i-process in massive stars

M_{ini} = 15 - 140 $M_\odot$ at zero metallicity
—> Different kind of H-He interactions
—> in some cases (~10%) : i-process
—> T_{max} = 250 MK
—> Neut. dens. max ~ 10^{13} cm^{-3}

Clarkson+2018, 2021

see also Banerjee+2018





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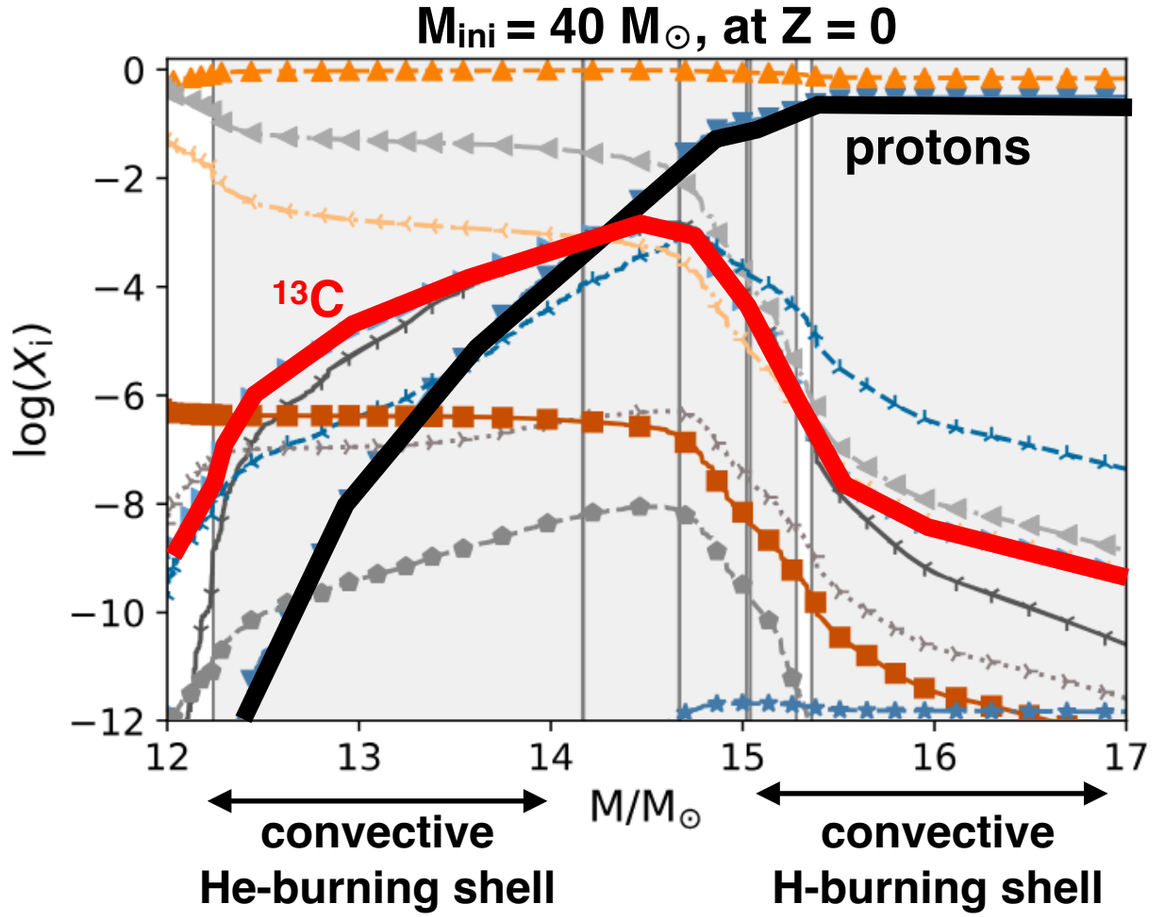

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- **Preferentially at low metallicity**

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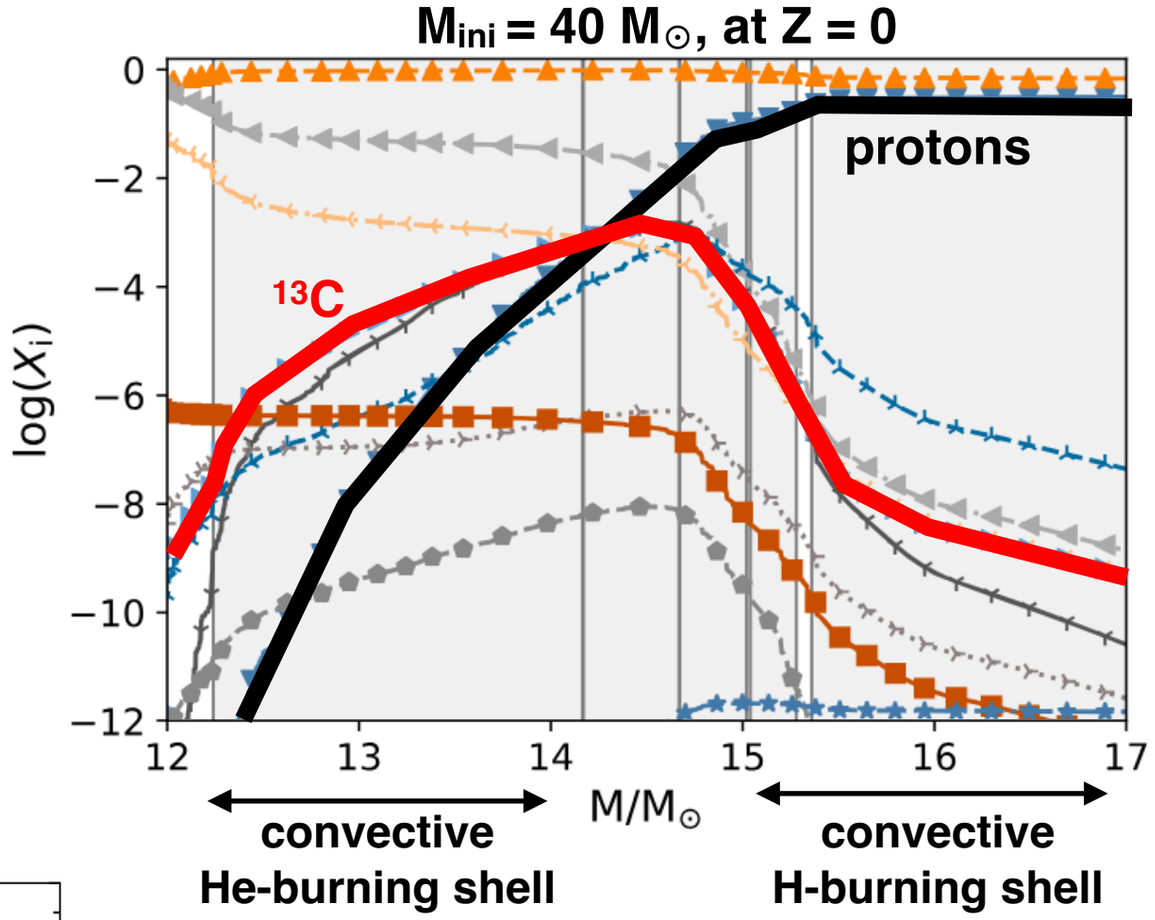

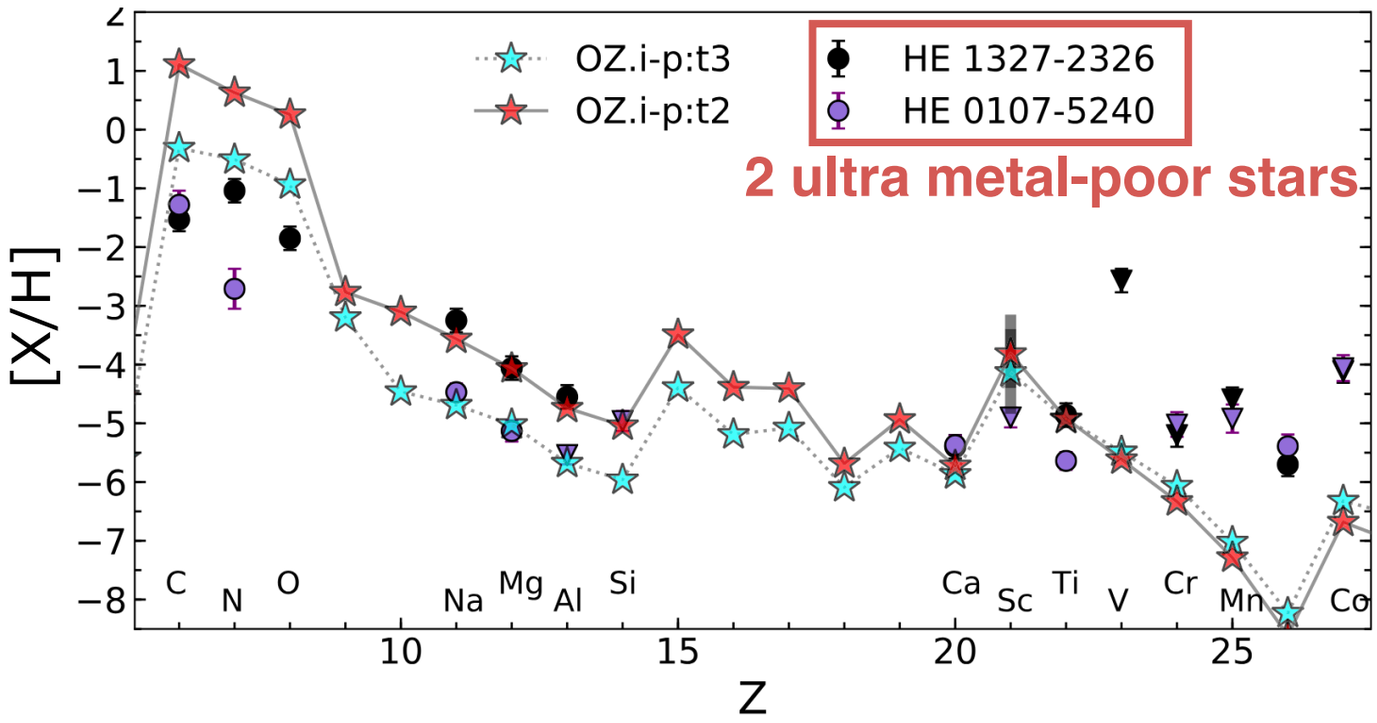

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- **Possible signature in (the most) metal-poor stars**

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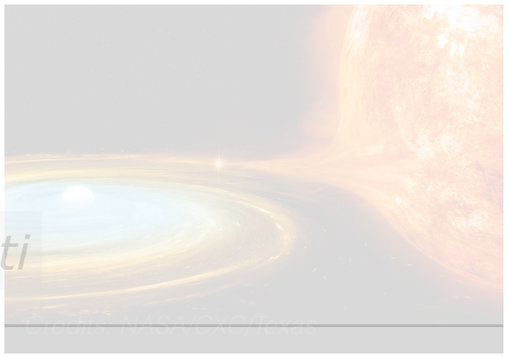

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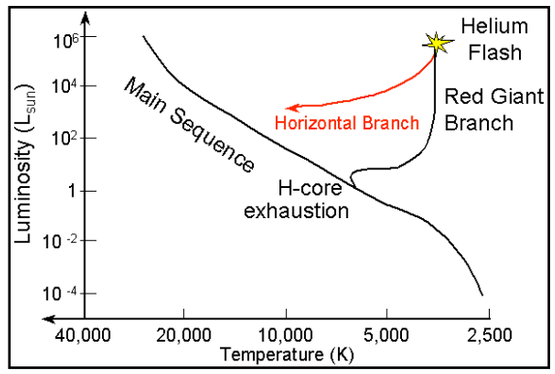
Marigo+2001, Hirschi 2007, Ekstrom+2008, Heger+2010, Limongi+2012, Pignatari+2015, Choplin+2017, Ritter+2018, Banerjee+2018, Clarkson+2018,2021…

- **Core Helium flash**

Fujimoto+1990, Schlattl+2001, Campbell+2010, Cruz+2013, Battich+2023, 2025…



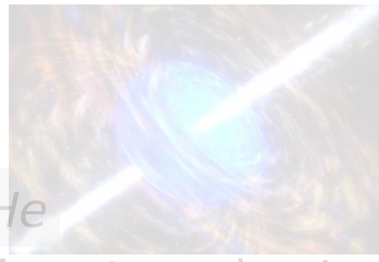
- **Post-AGB stars**

Herwig+2001, Miller Bertolami 2006, Herwig+2011…

- **Collapsars jets (?)**

He+2024

—> talk by Z. He



(No proton ingestion —> different mechanism)

Core helium flash (in hot-subdwarfs)

Hot-subdwarfs stars are : *—> e.g. Heber 2016*

—> stripped red giants (due to binary interaction ?) with thin (~10^{-4} $M_\odot$) H-rich envelope left

—> chemically peculiar (most of them)

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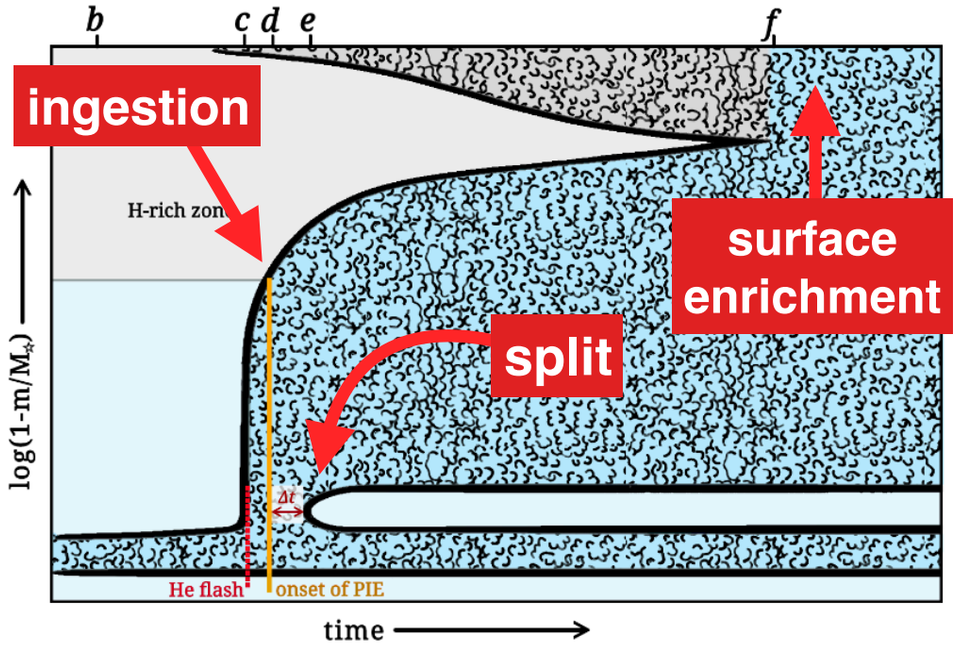

Battich+2023, 2025

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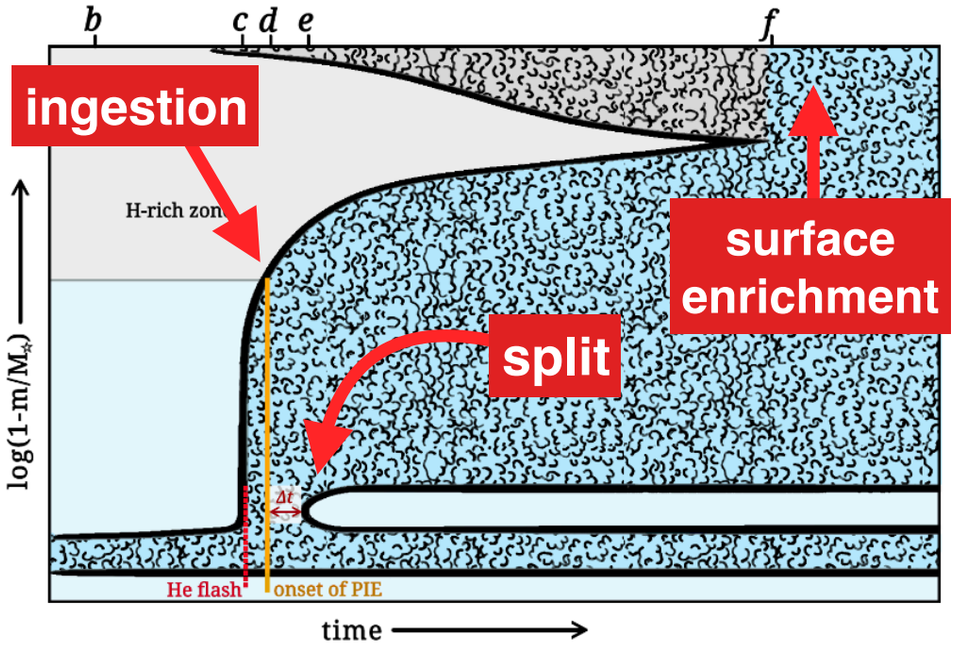

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+ ANT (post-processing)
1200 isotopes

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$Z_\odot$	**10^9 - 10^{10}**
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i-process can develop

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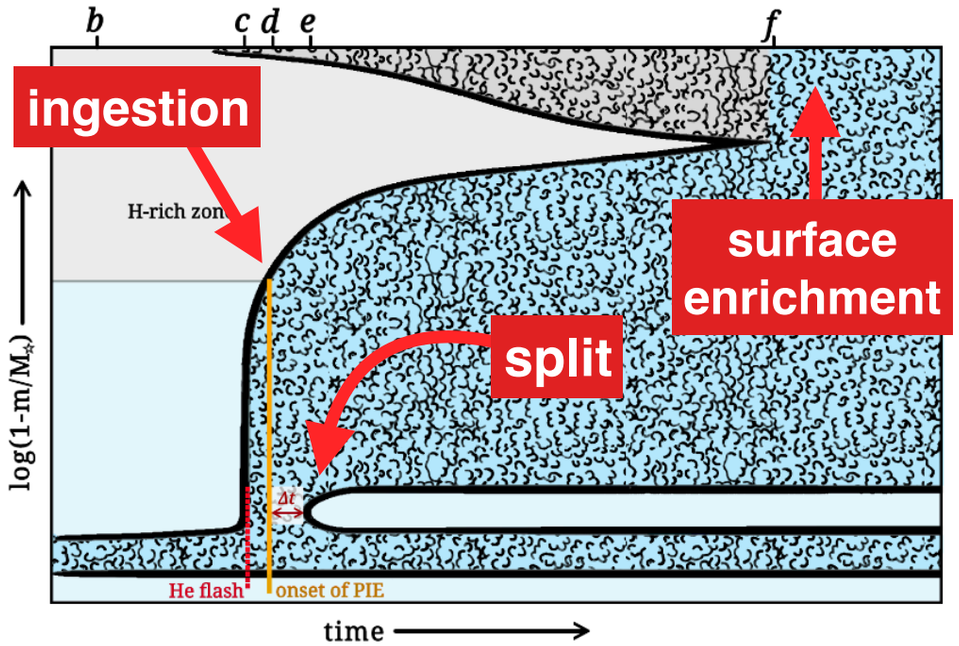

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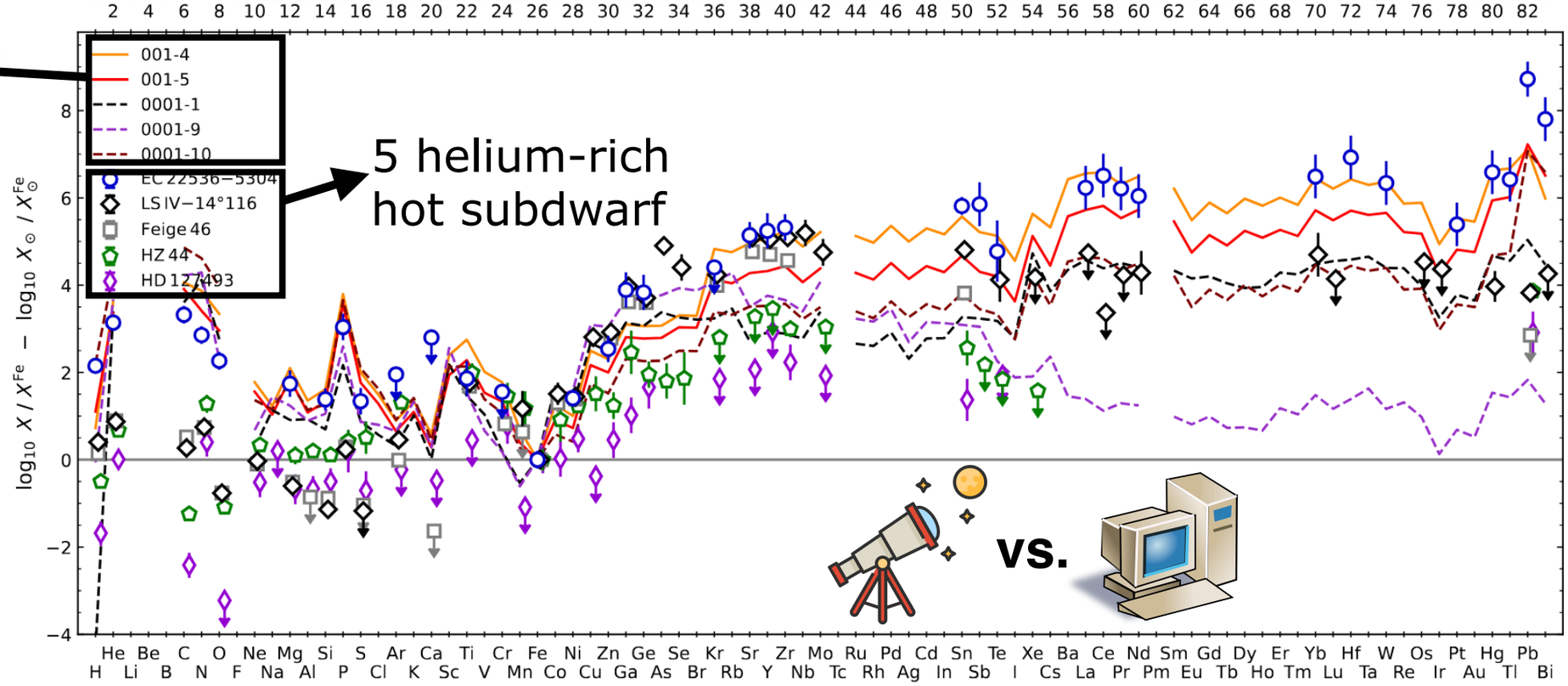

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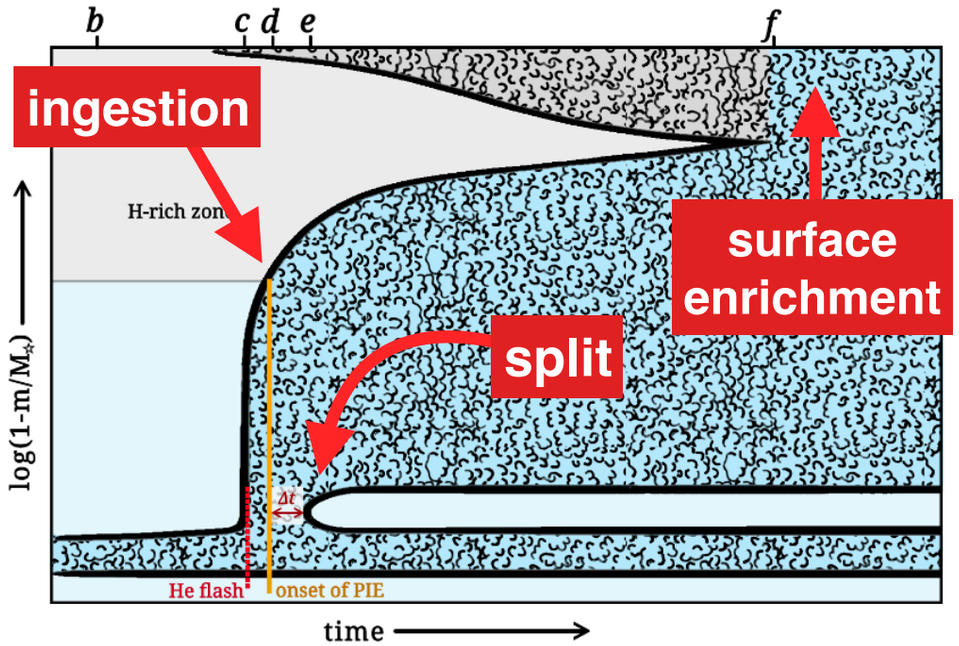

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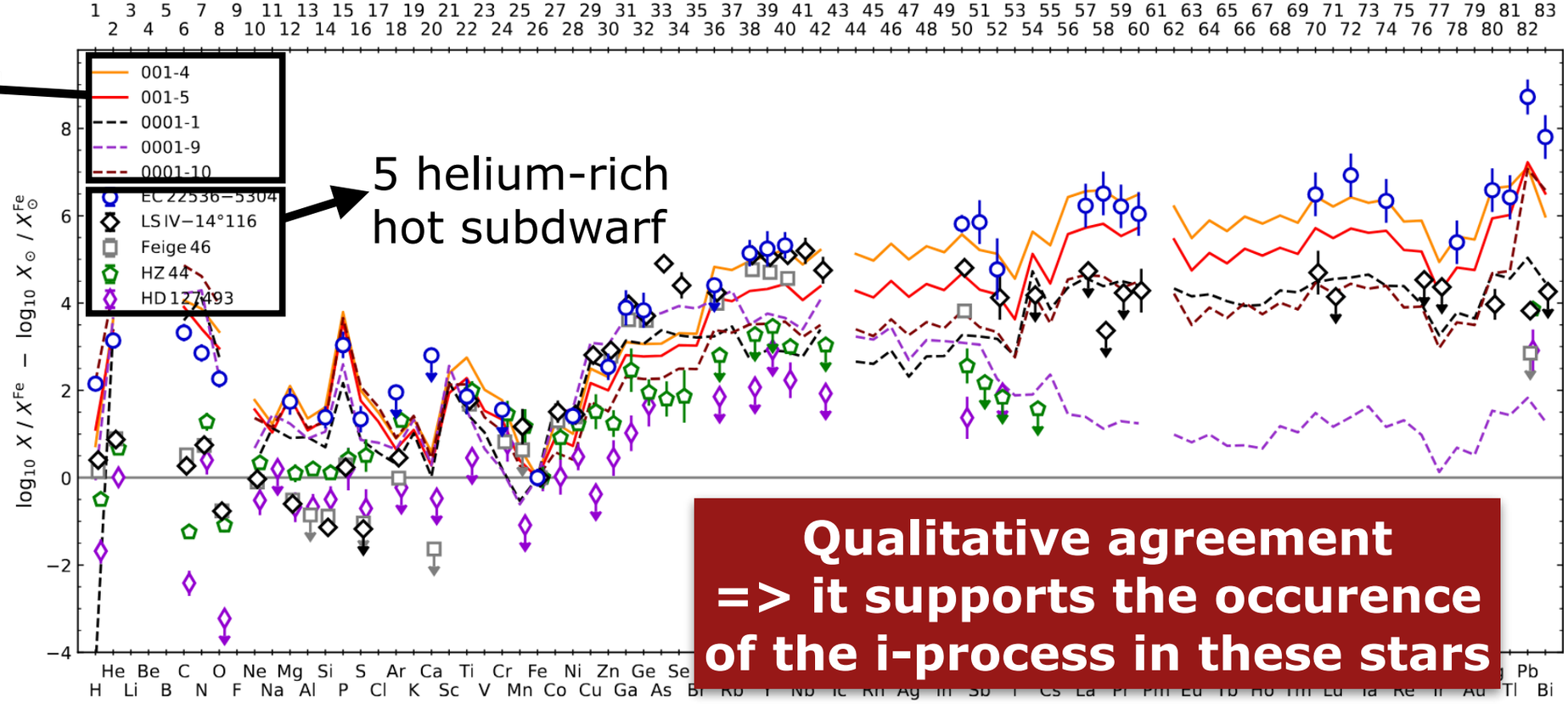
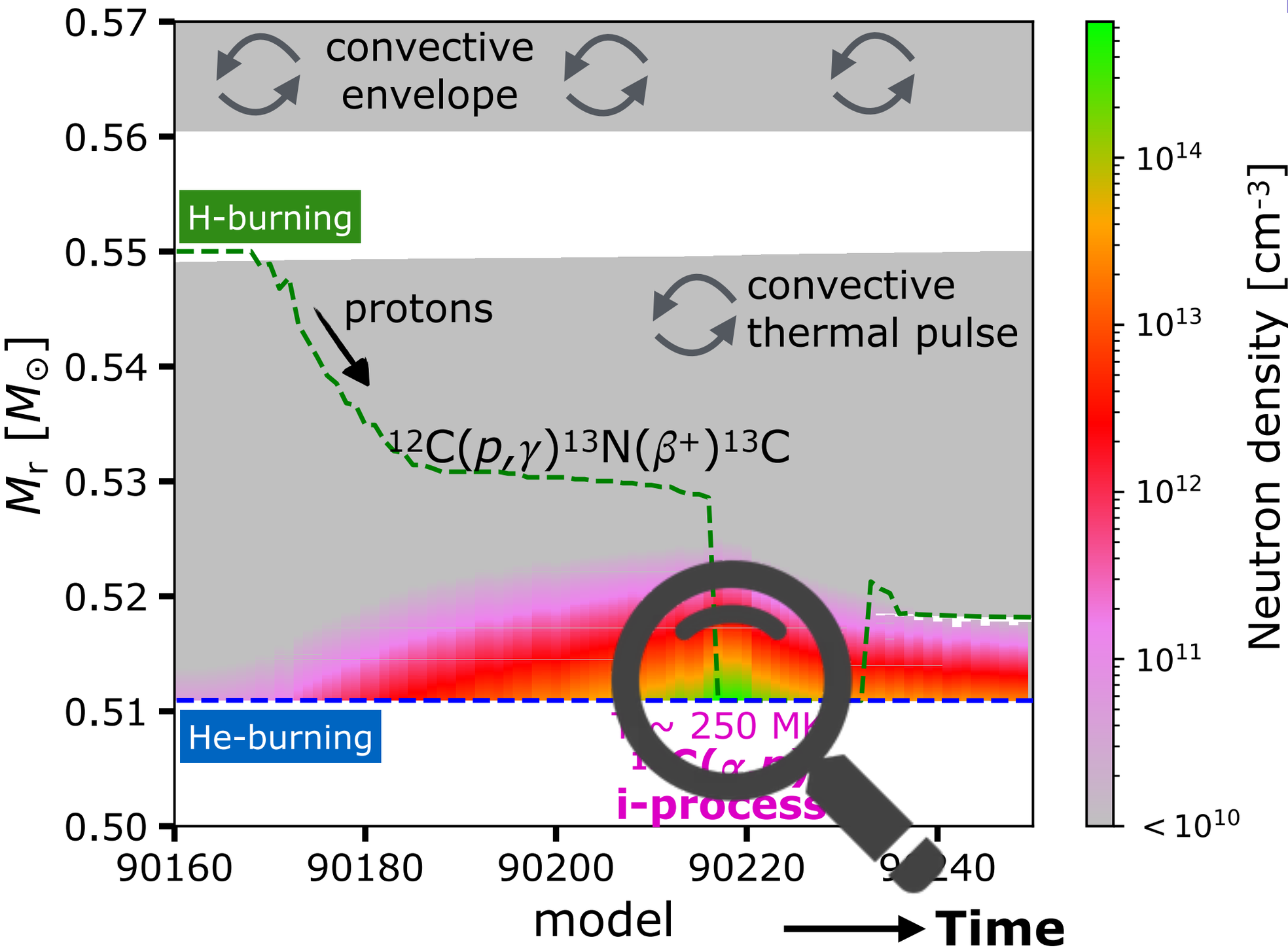


Qualitative agreement => it supports the occurence of the i-process in these stars

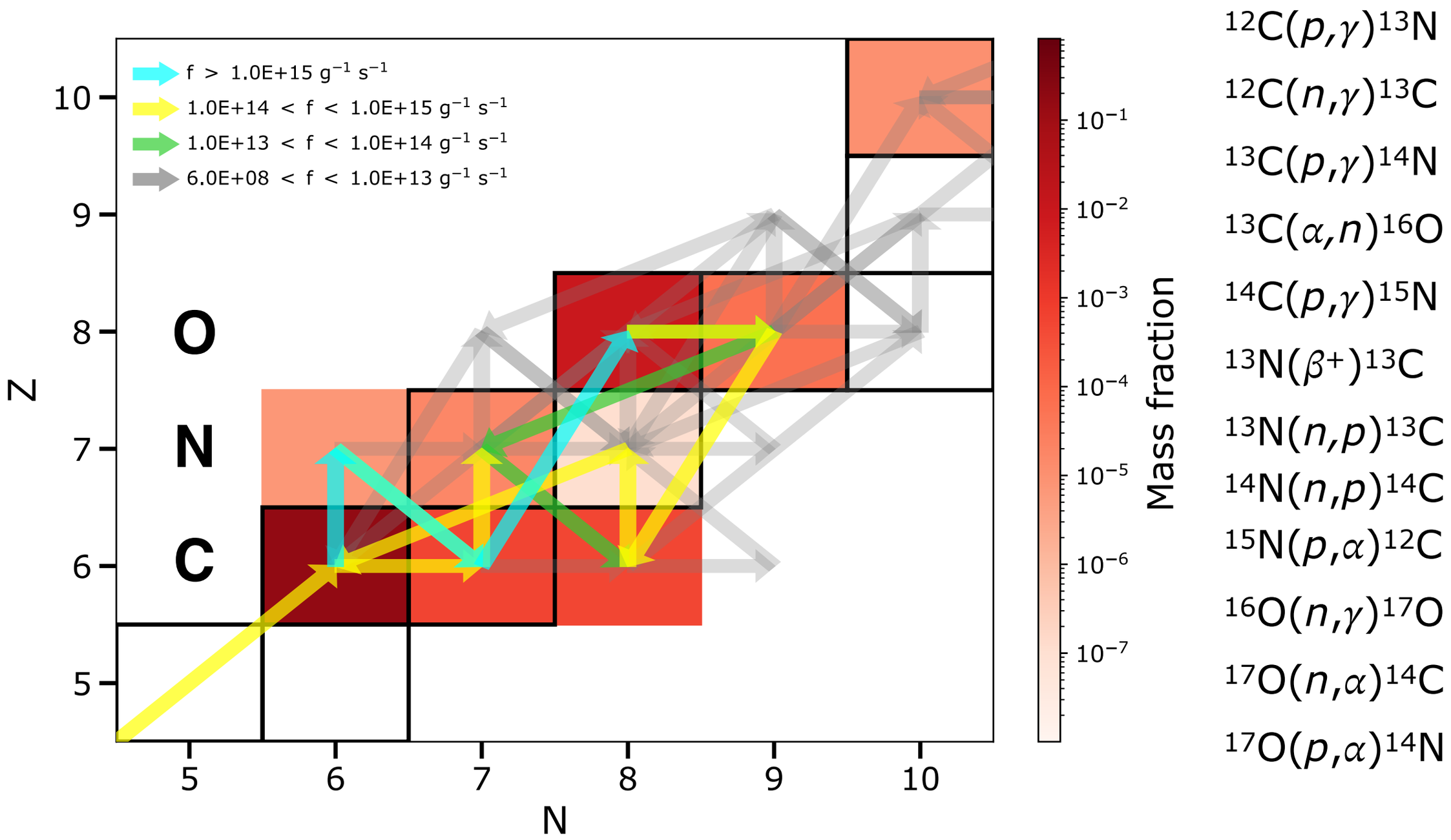
Battich+2023, 2025

The i-process engine (1 $M_{\odot}$, [Fe/H] = -2.5, AGB model)

STAREVOL code



Fluxes of some reactions during proton ingestion in AGB



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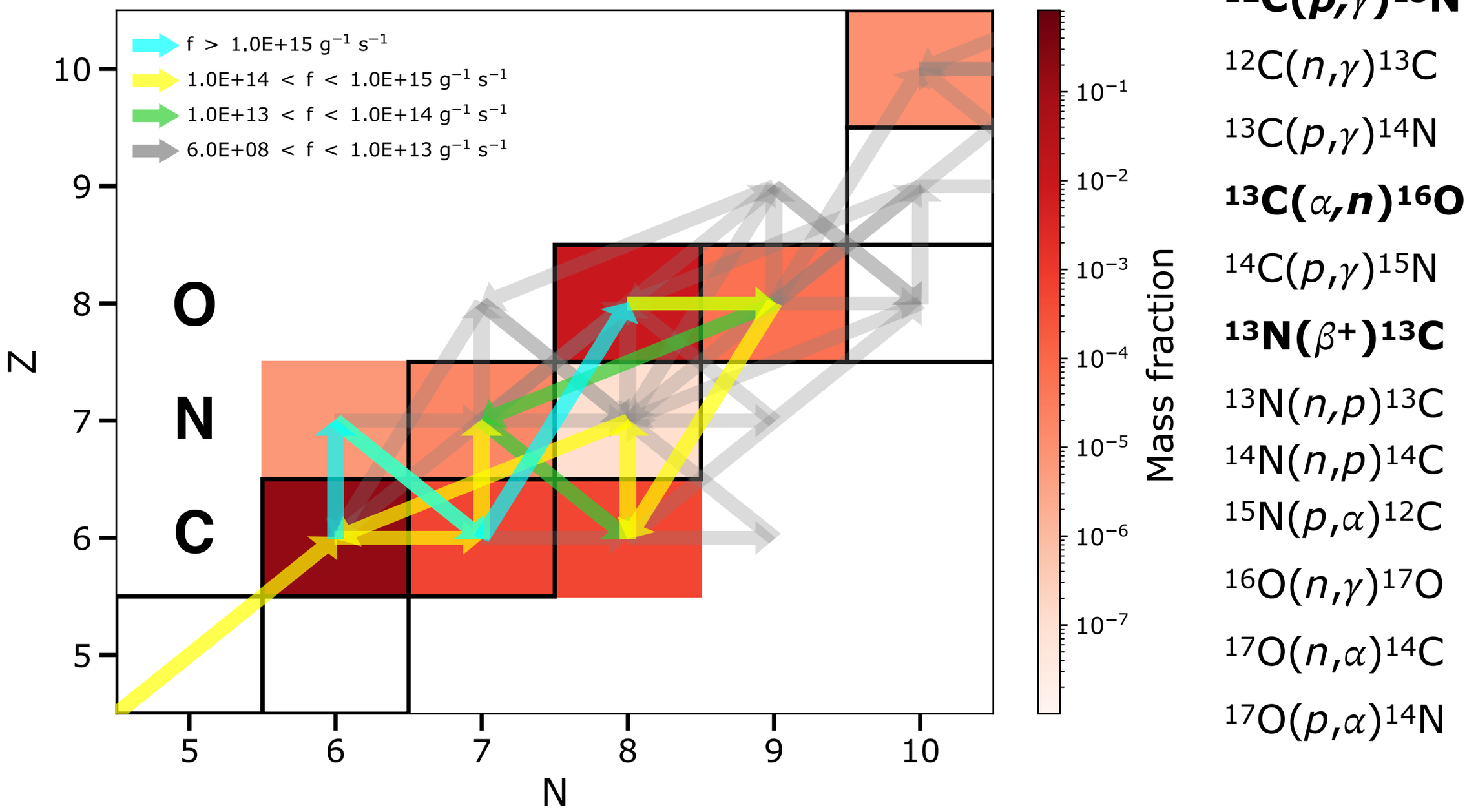

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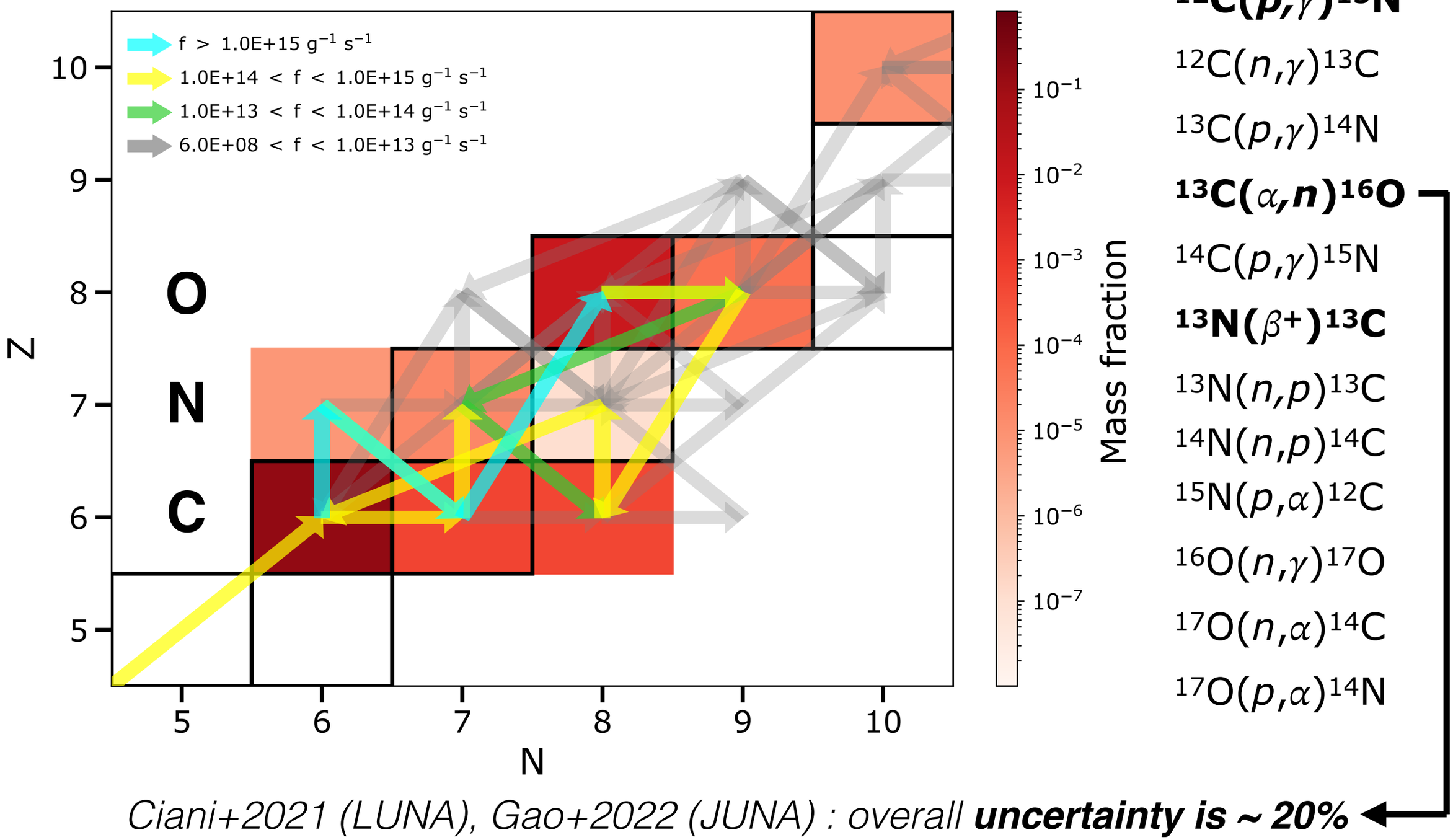
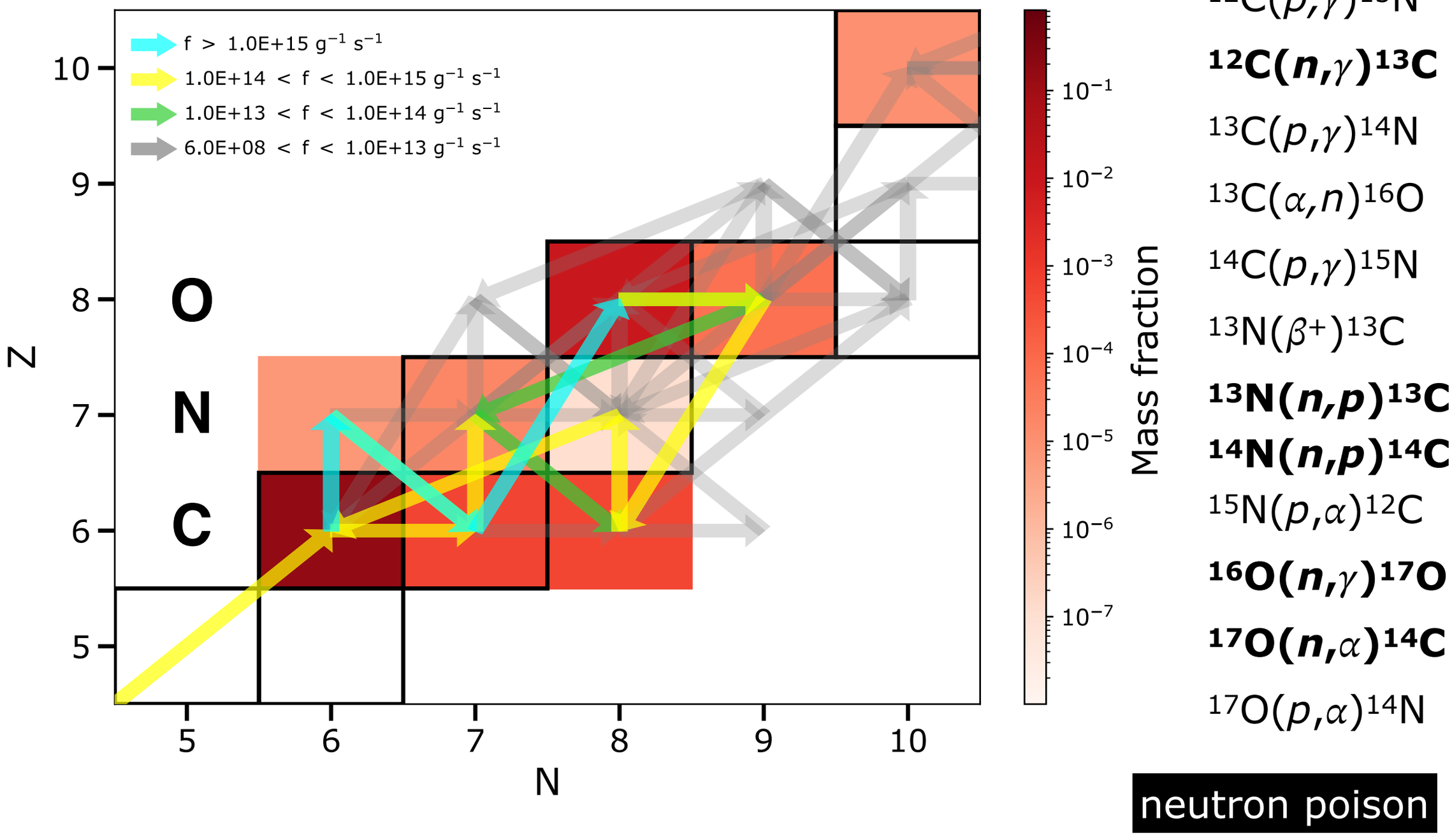
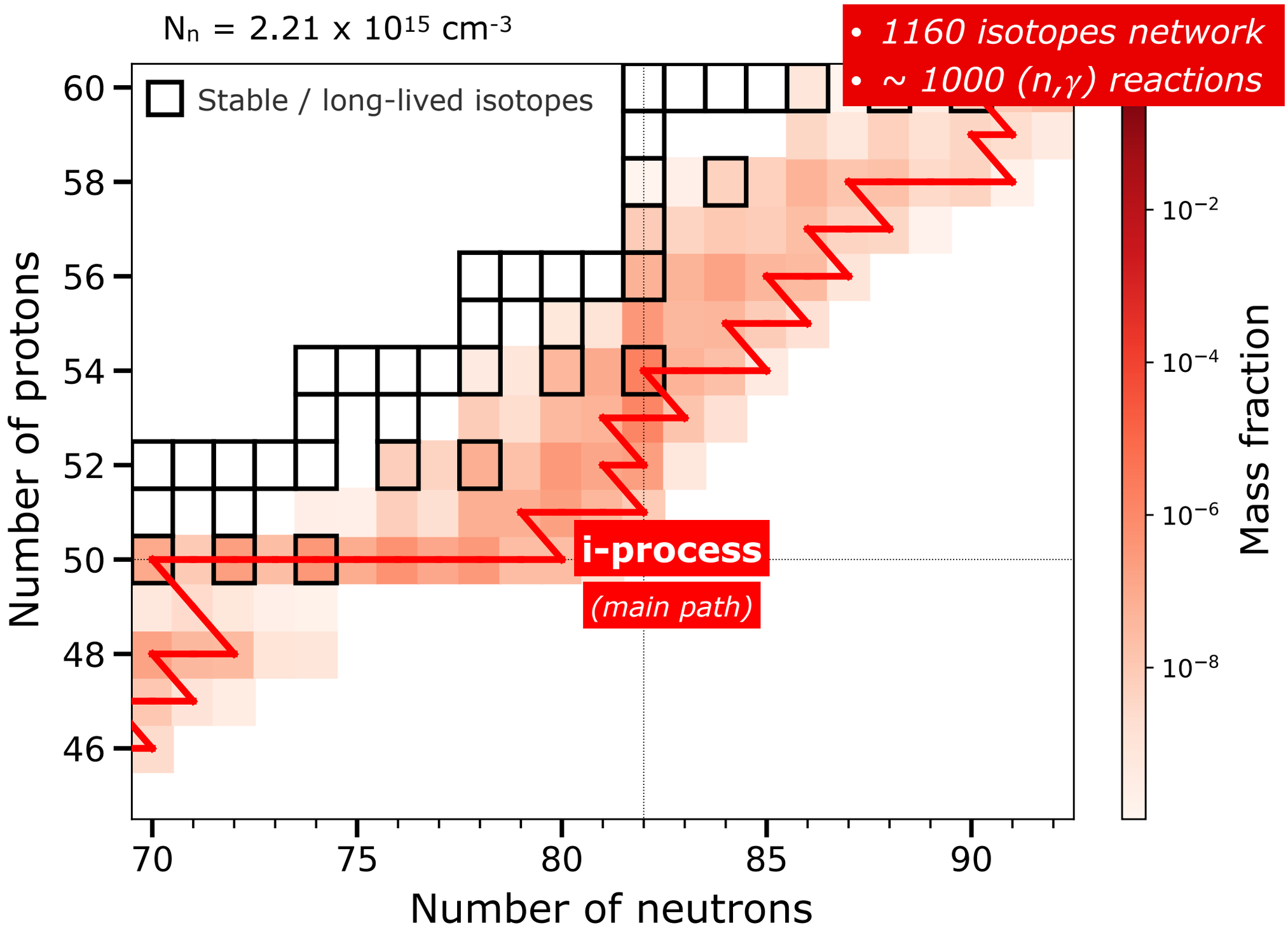


Ciani+2021 (LUNA), Gao+2022 (JUNA) : overall ***uncertainty is ~ 20%***

Fluxes of some reactions during proton ingestion in AGB



i-process at the bottom of the thermal pulse



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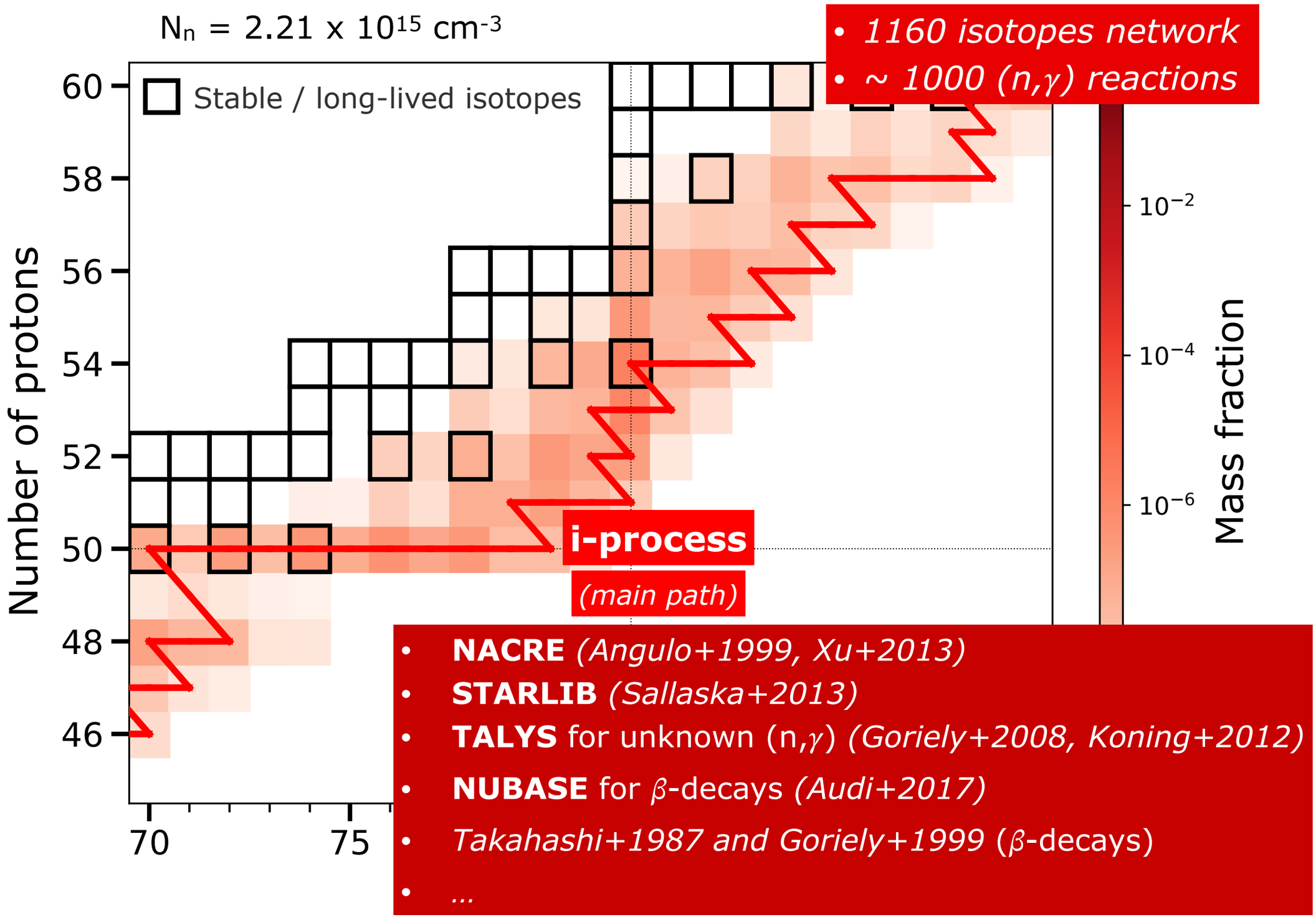

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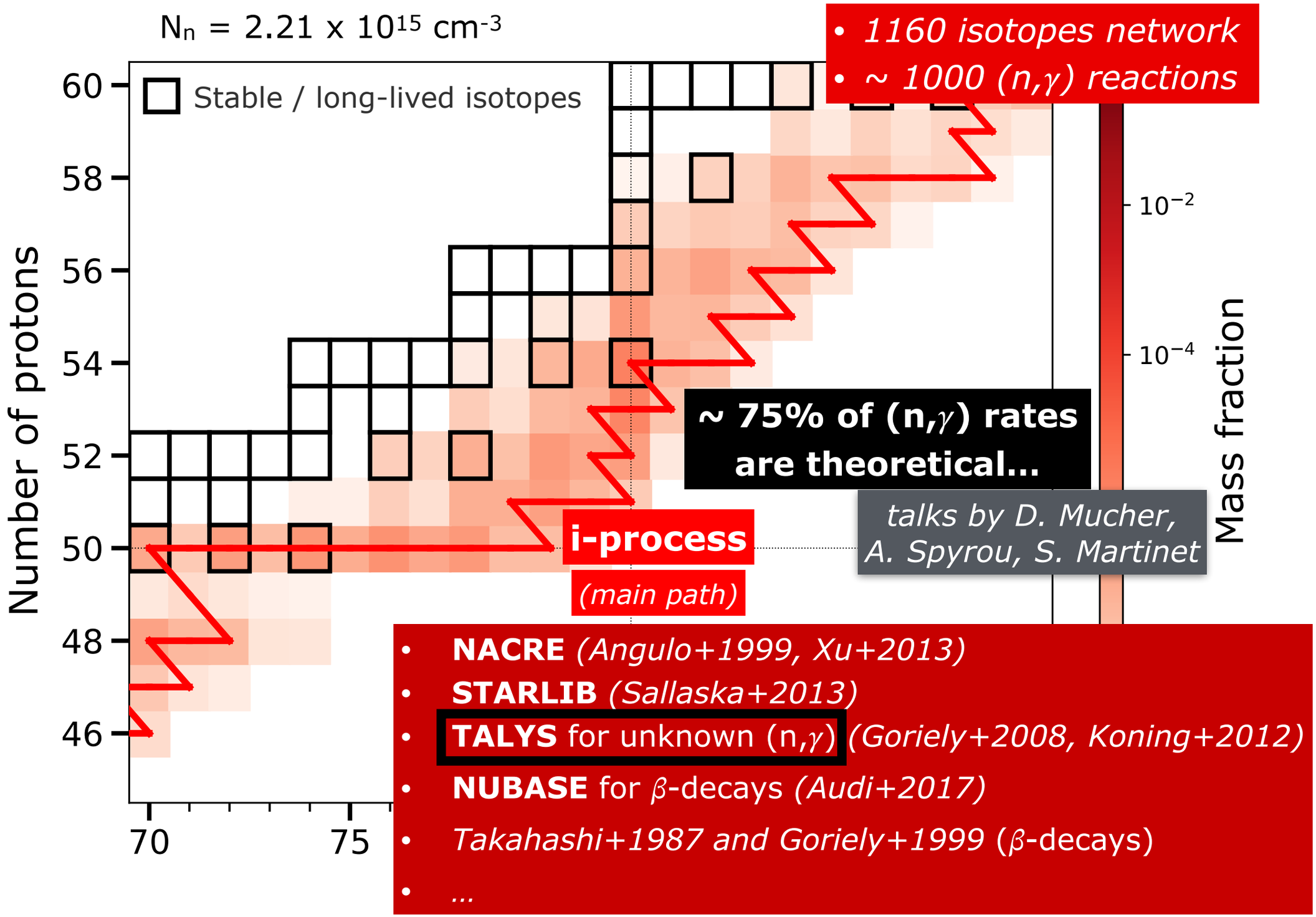

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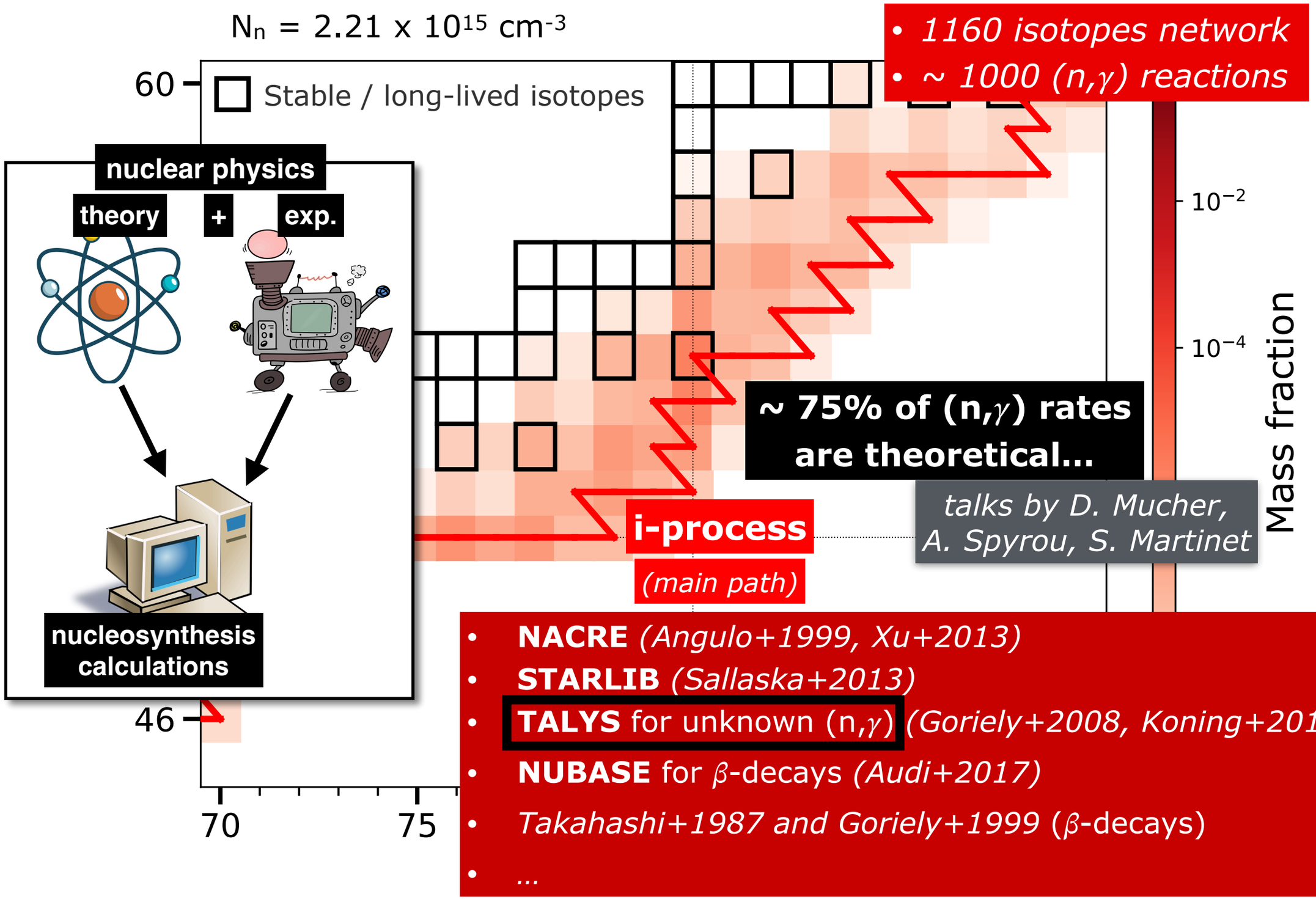

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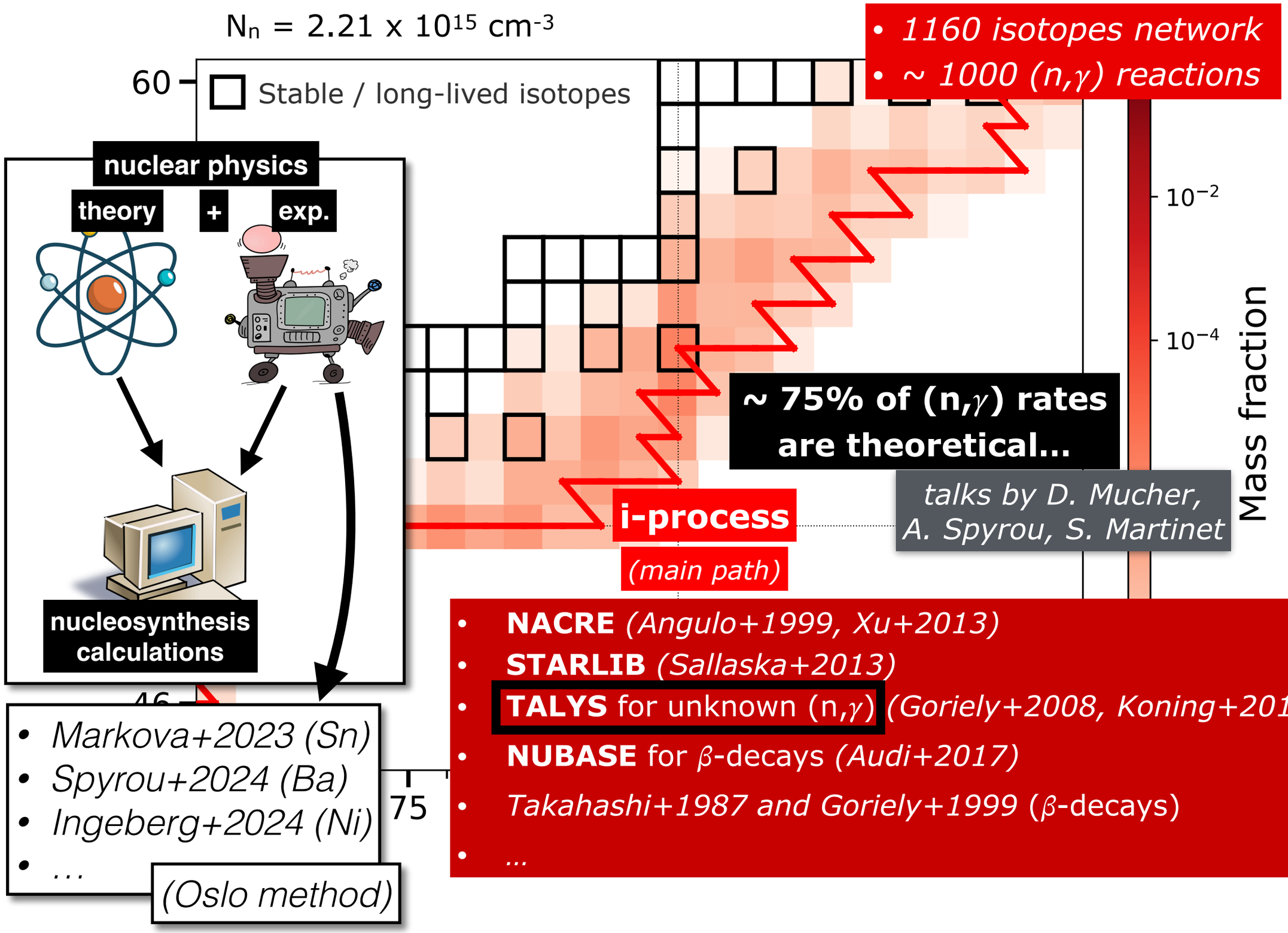

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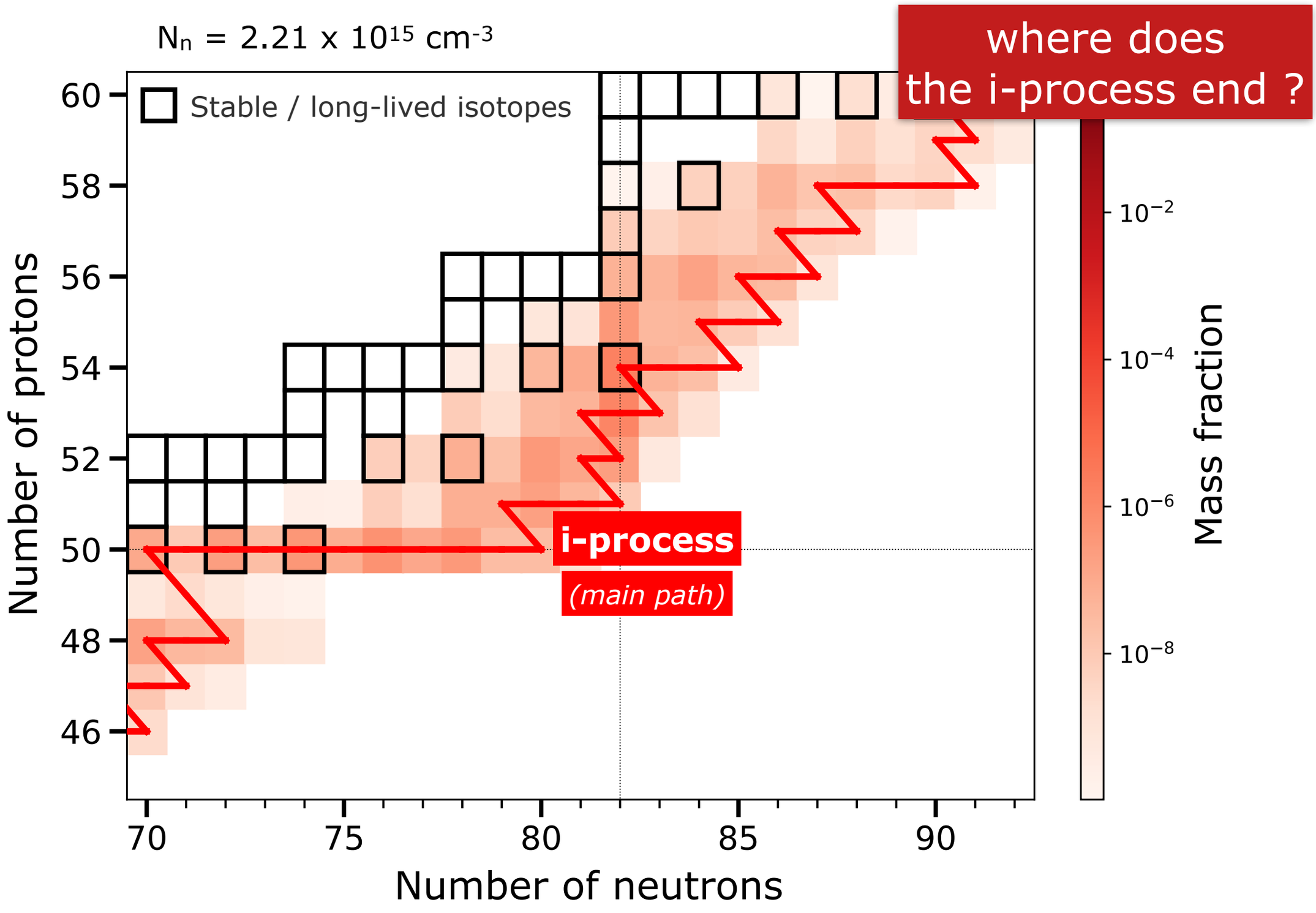
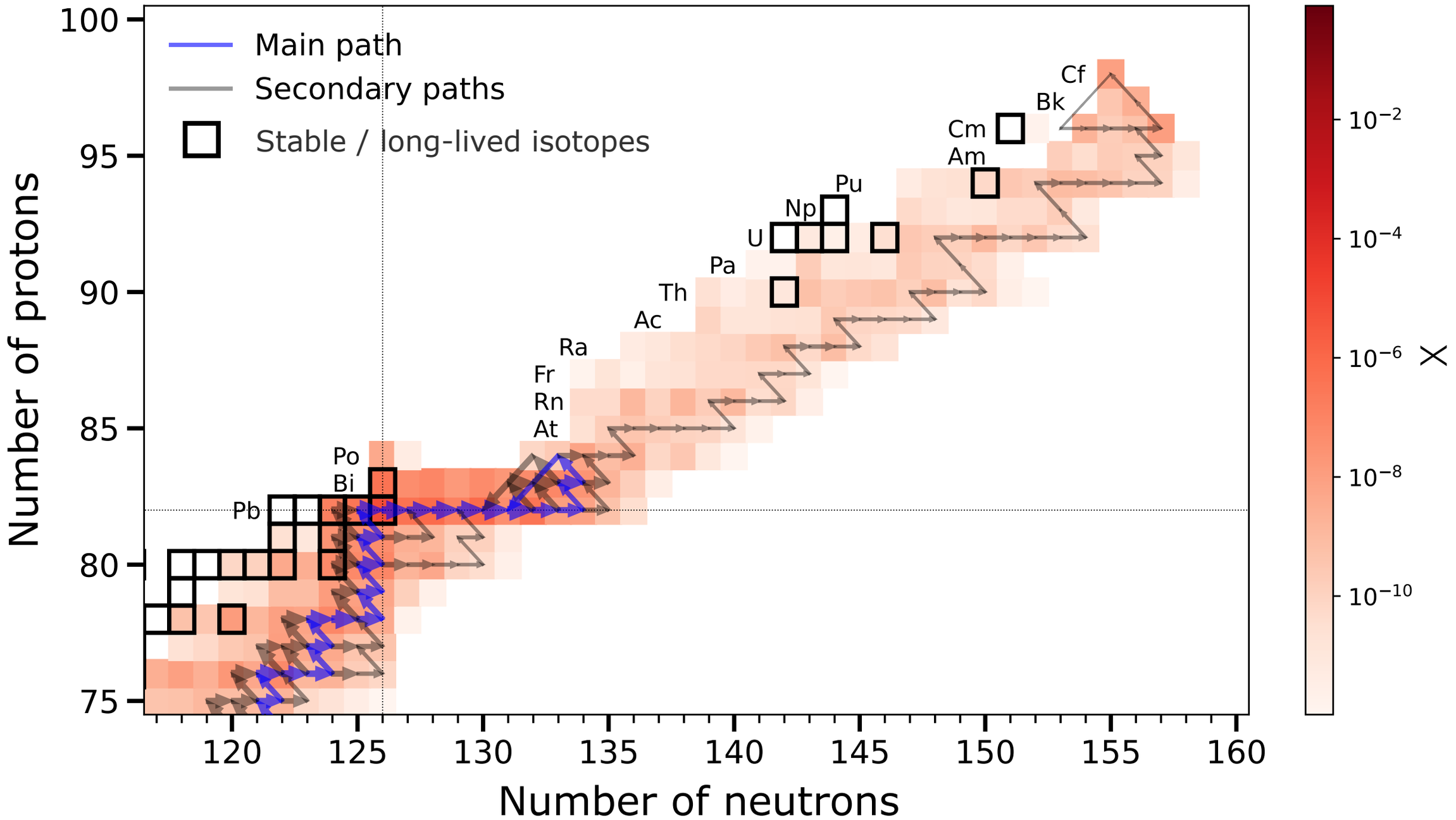


i-process flow at the bottom of the thermal pulse

Production of actinides (Th and U)

1 $M_\odot$, [Fe/H] = -2.5, $N_{n,max}$ = 2.2 x 10^{15} cm^{-3}



Choplin+2022,2025 Vassh+2024

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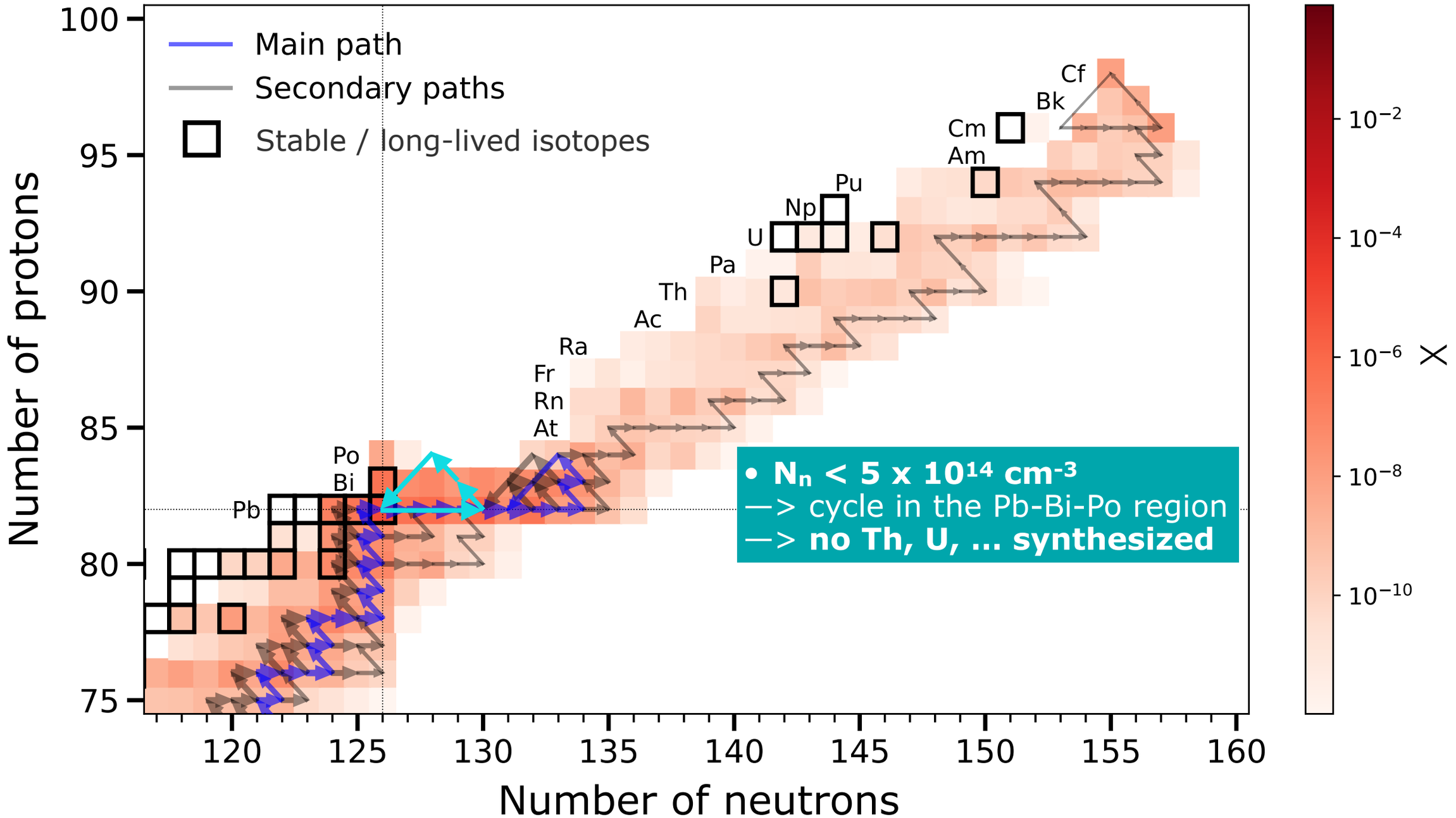

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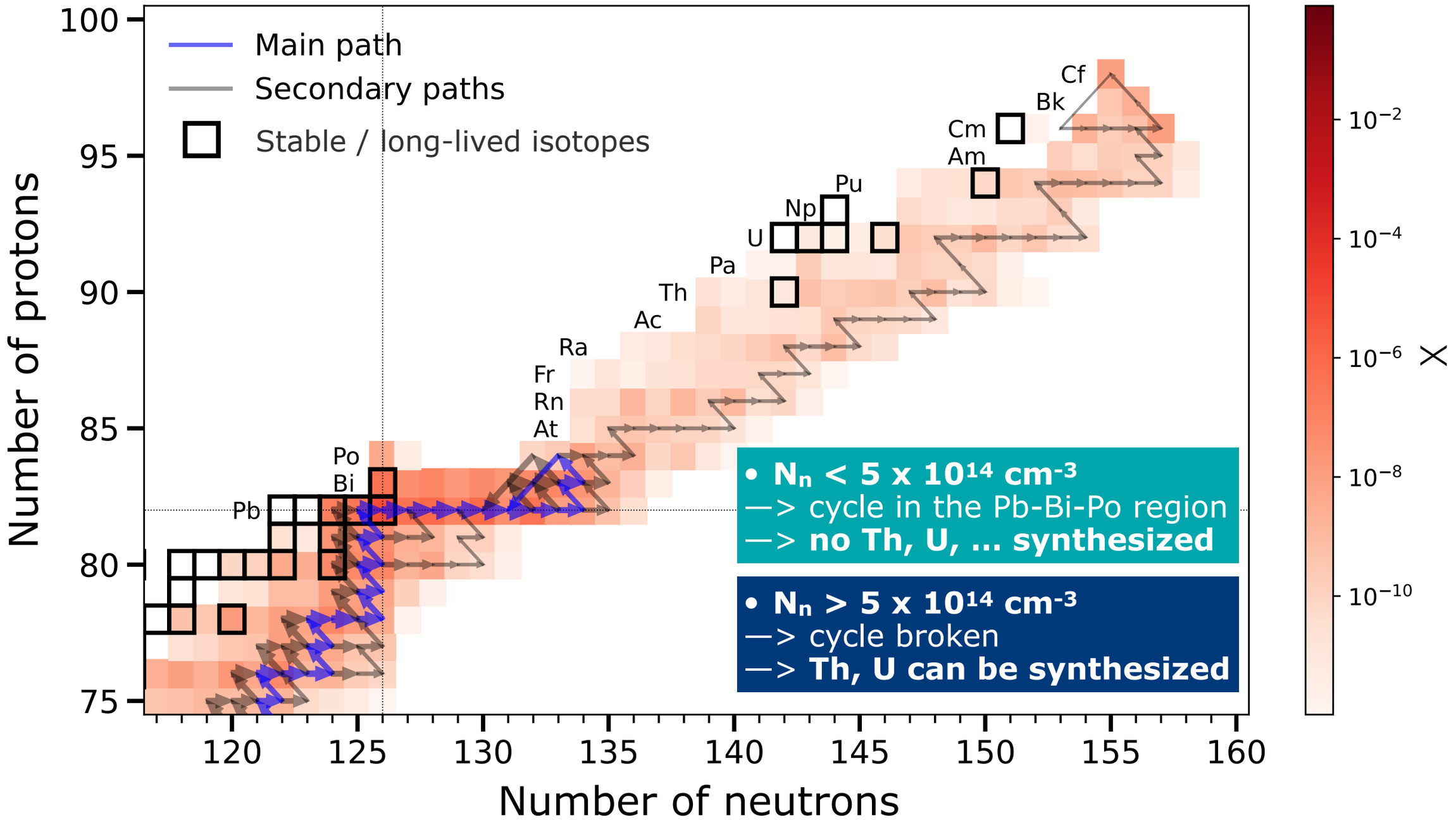

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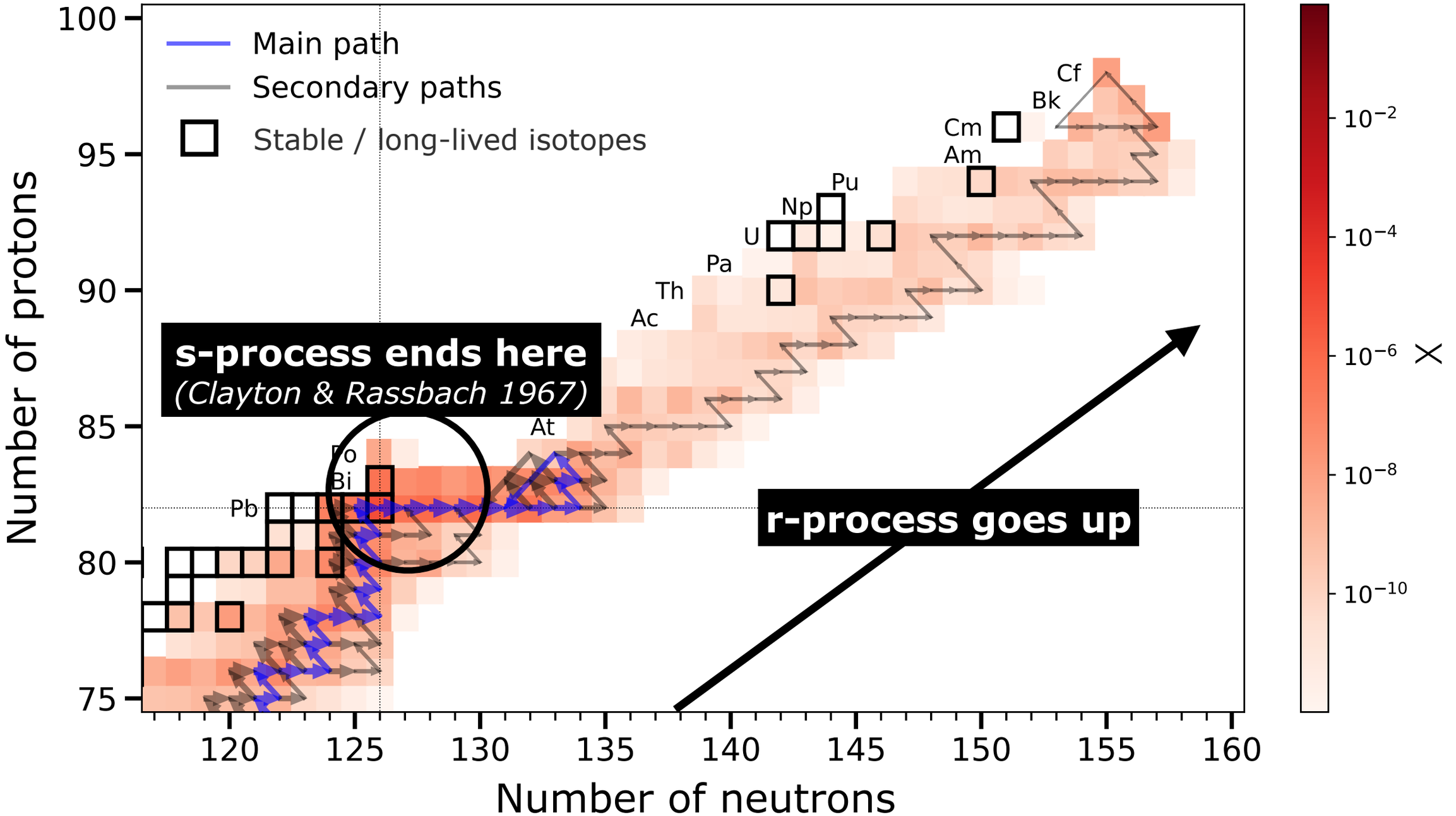

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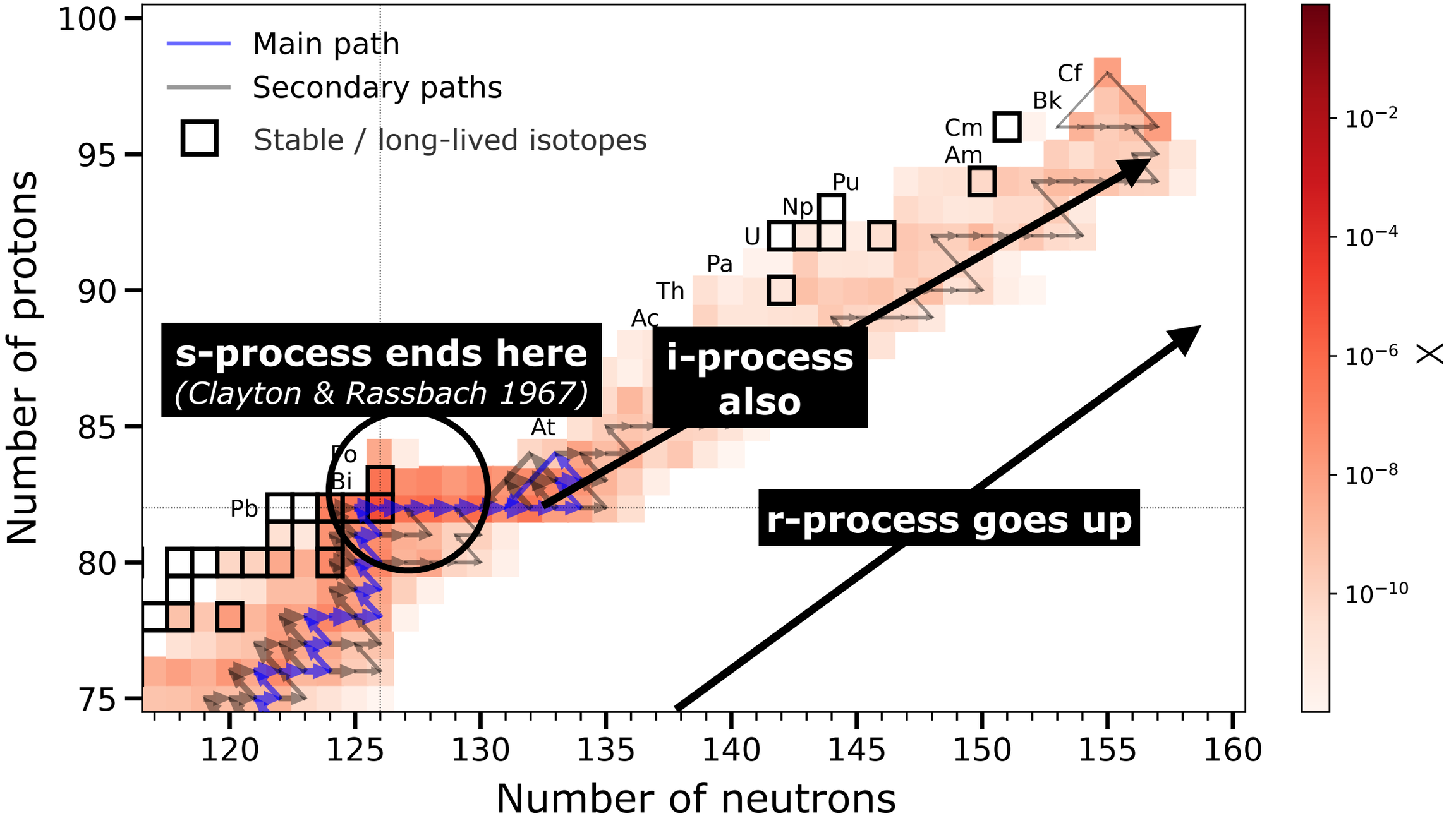

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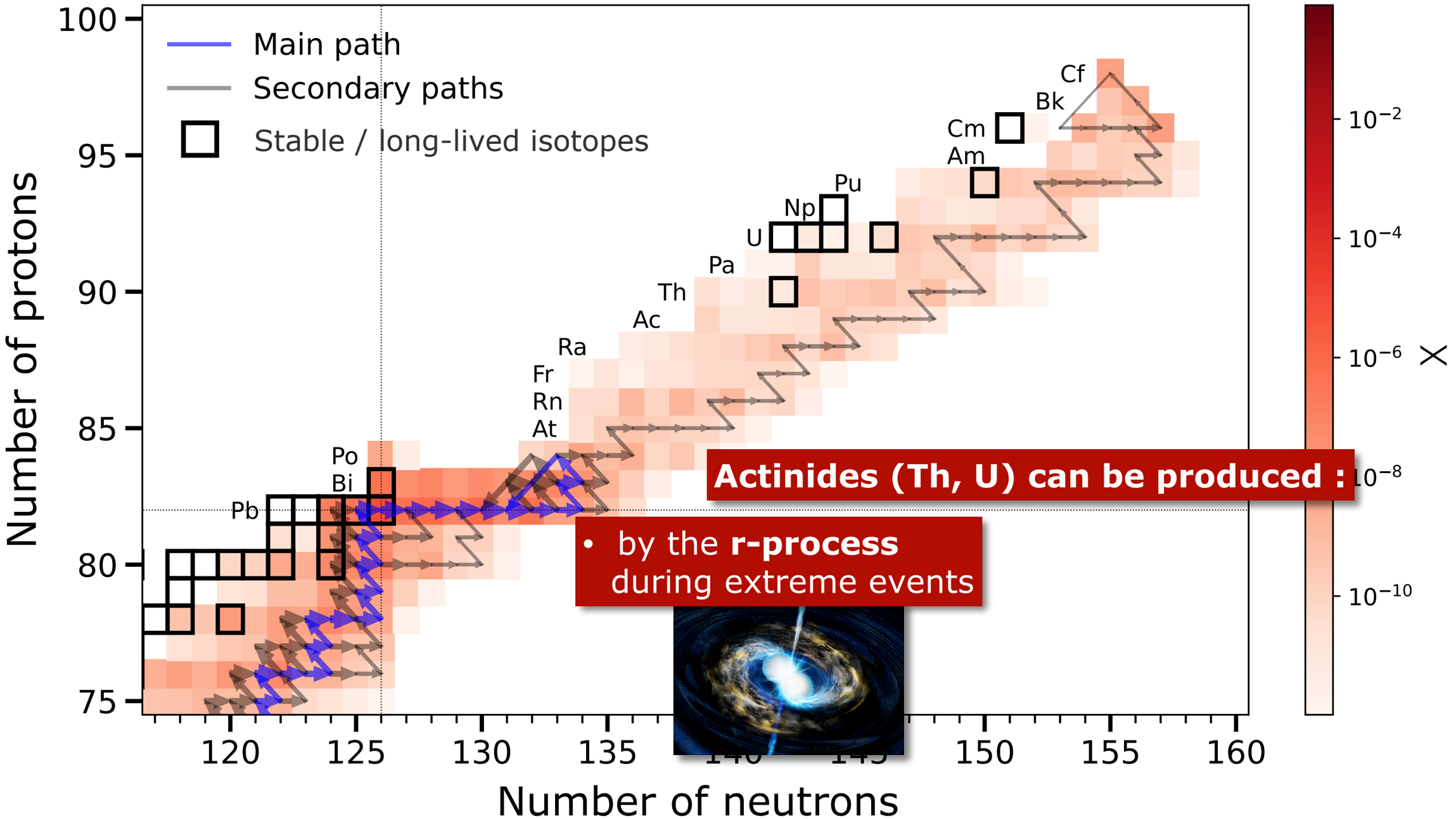

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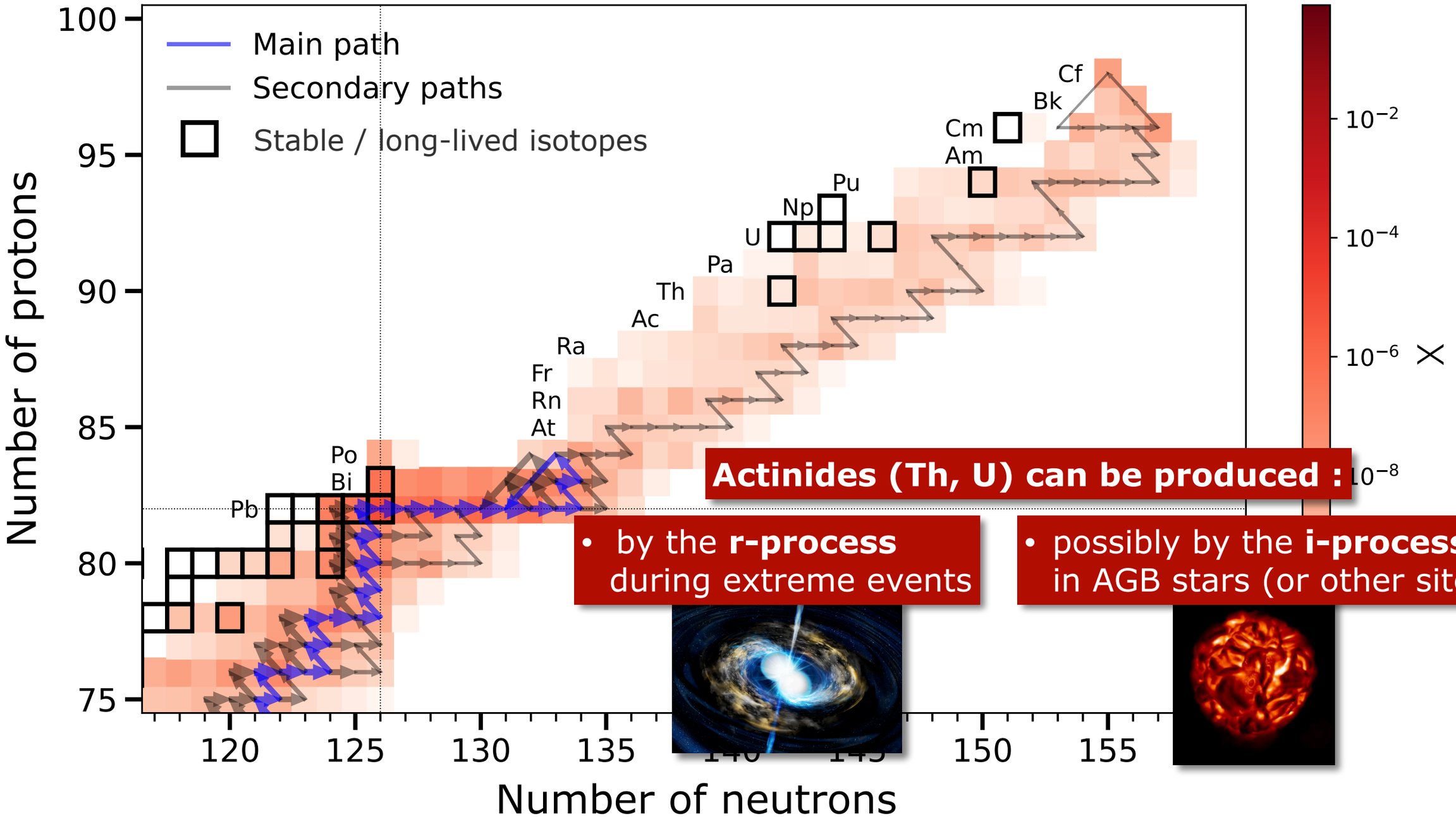

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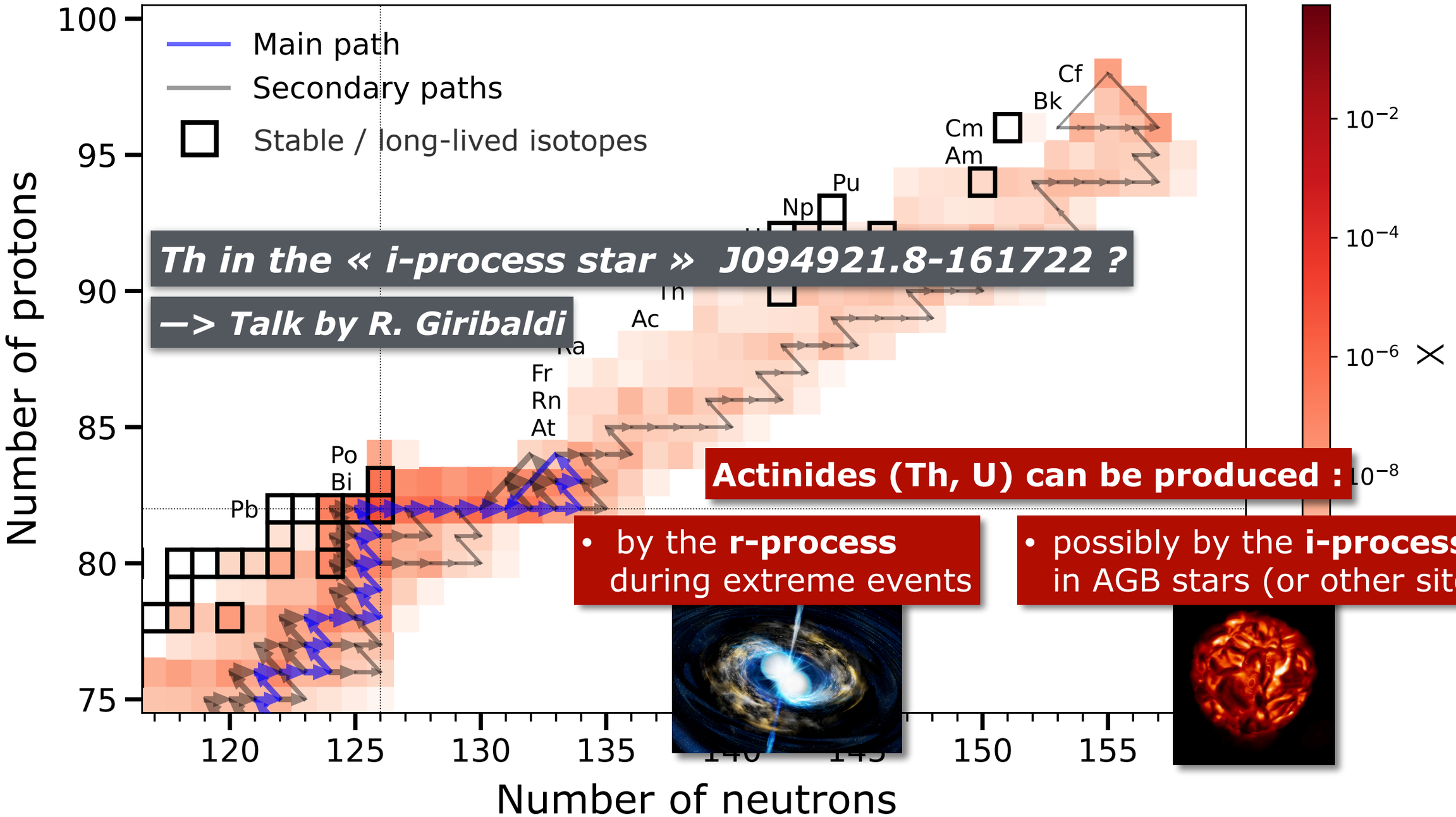

Choplin+2022,2025 Vassh+2024

At what mass and metallicity does H-ingestion / i-process occur ?

Important for Galactic Chemical Evolution

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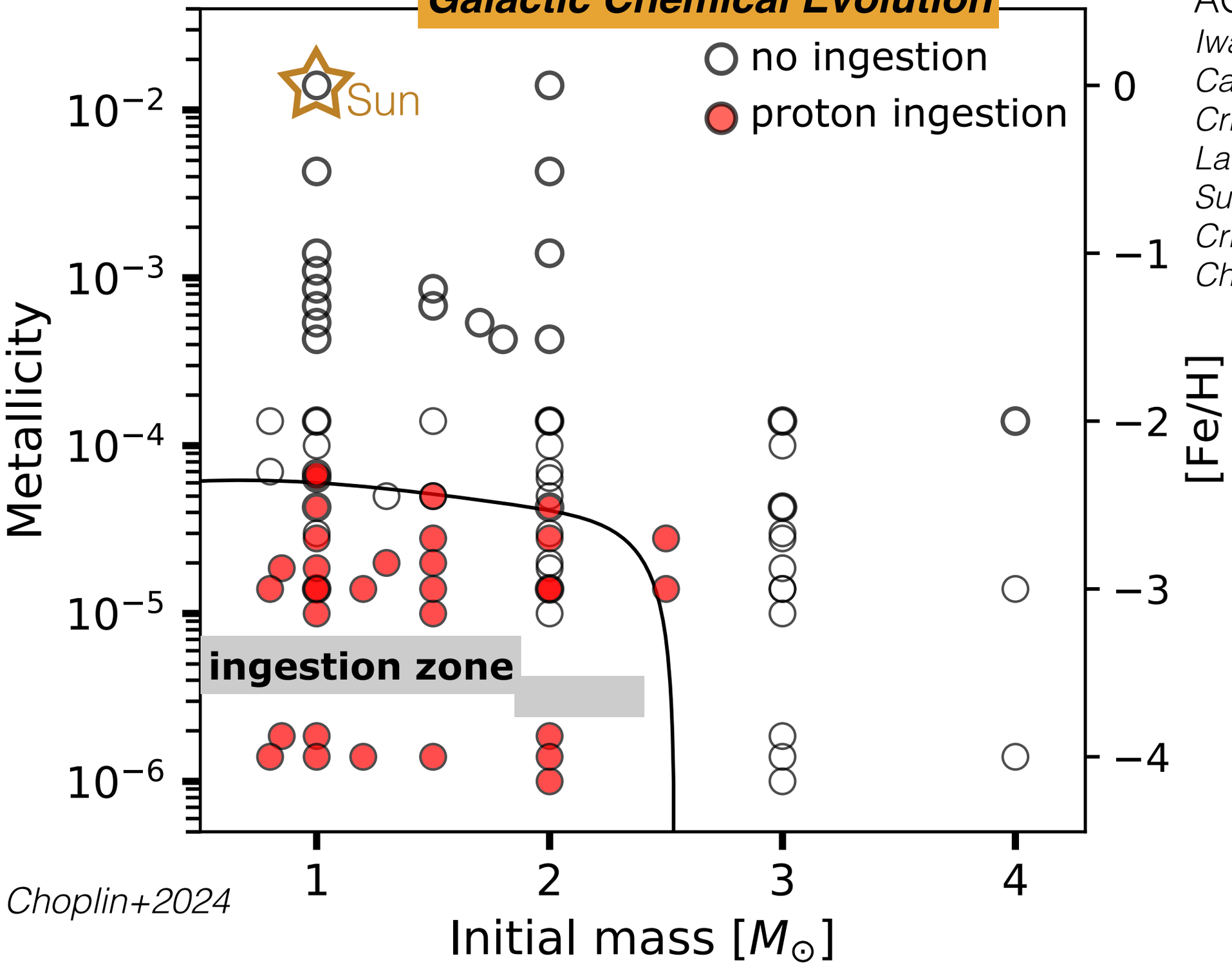

Choplin+2024

AGB models from :
Iwamoto+2004
Campbell & Lattanzio 2008
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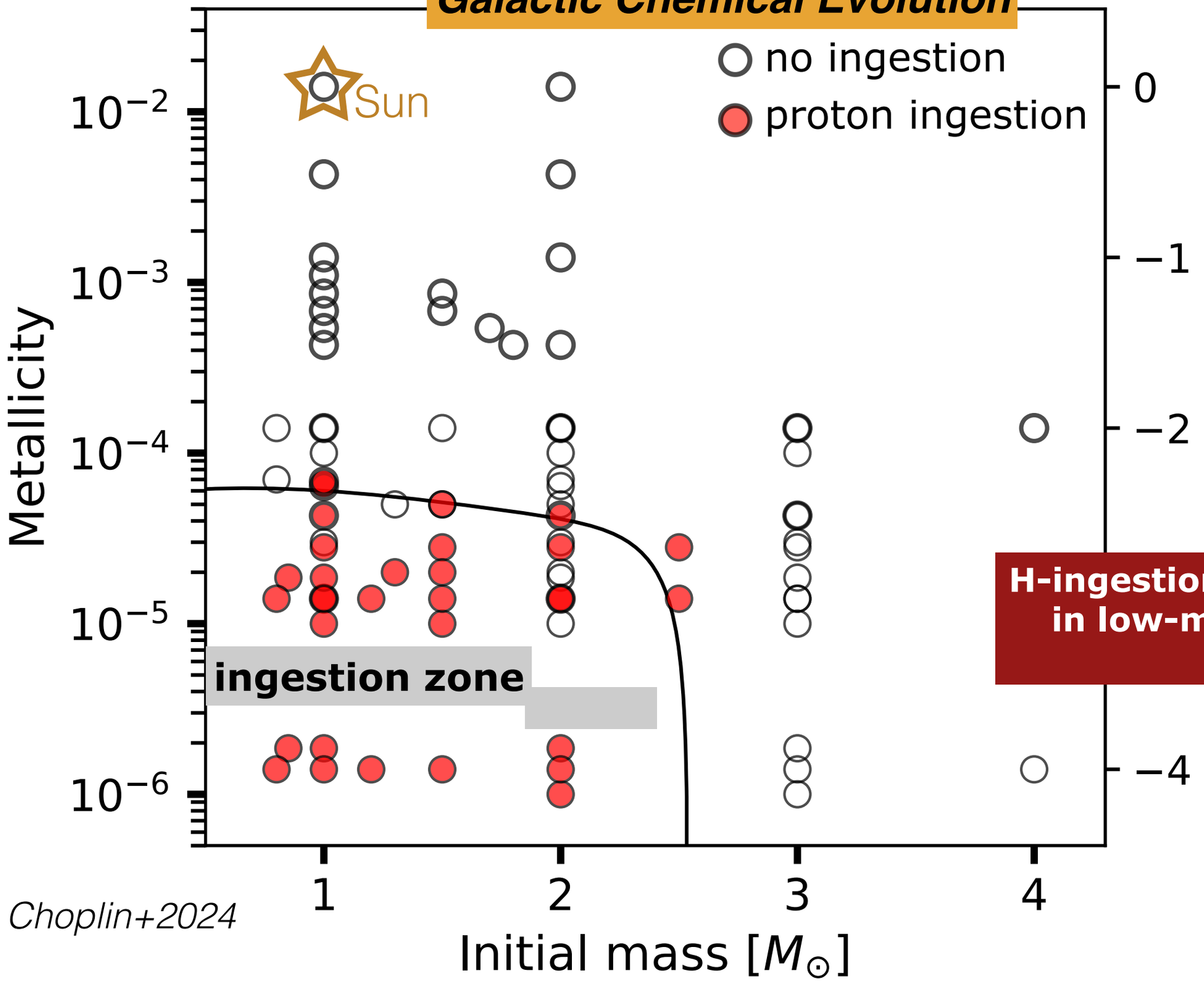

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H-ingestion / i-process happens in low-metallicity low-mass AGB stars

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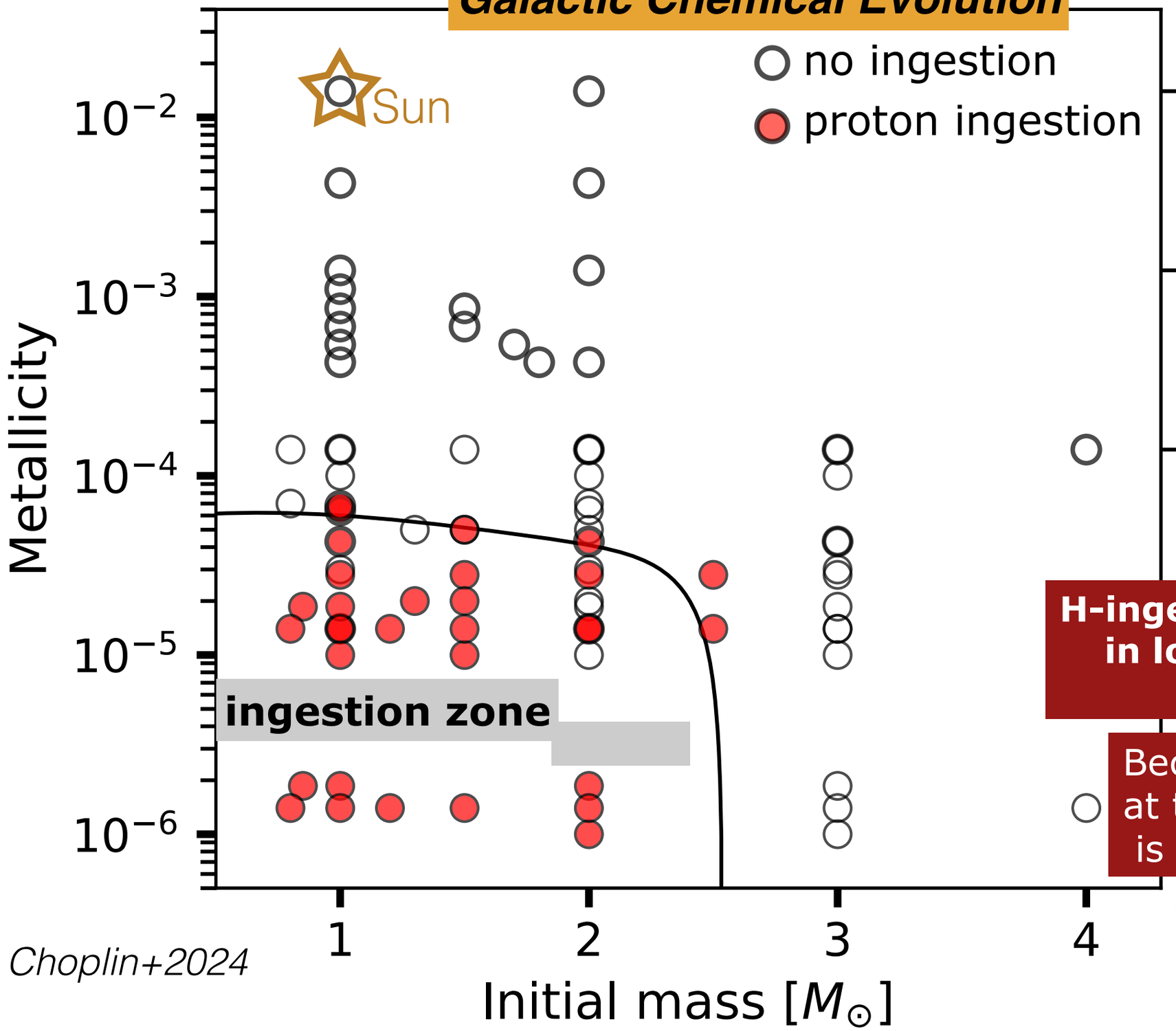

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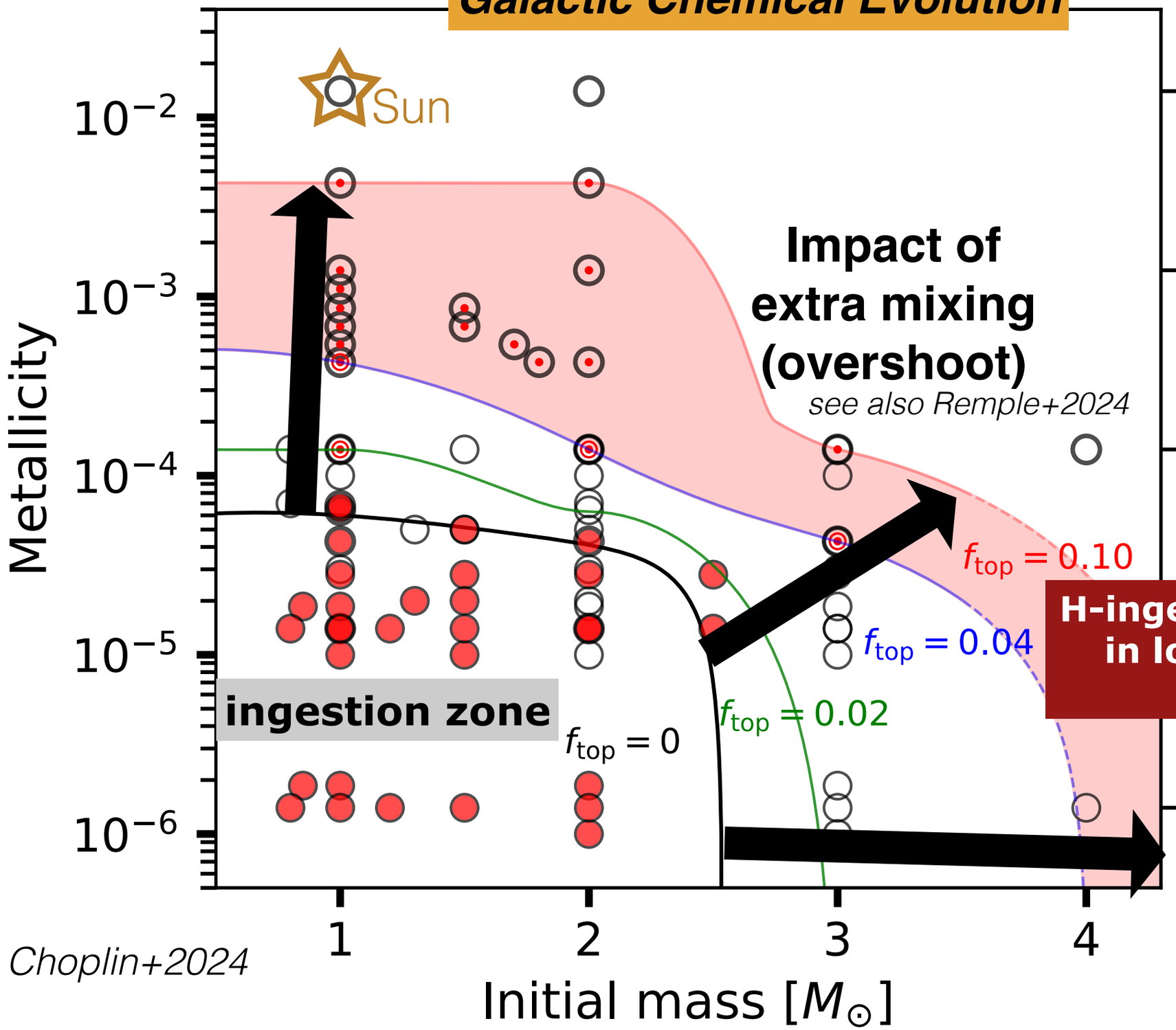
H-ingestion / i-process happens in low-metallicity low-mass AGB stars

Because the entropy barrier at the bottom of the H-shell is smaller (easier to cross)

e.g. Iben+1977, Fujimoto+1990

At what mass and metallicity does H-ingestion / i-process occur ?

Important for Galactic Chemical Evolution



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but the ingestion zone may be bigger…

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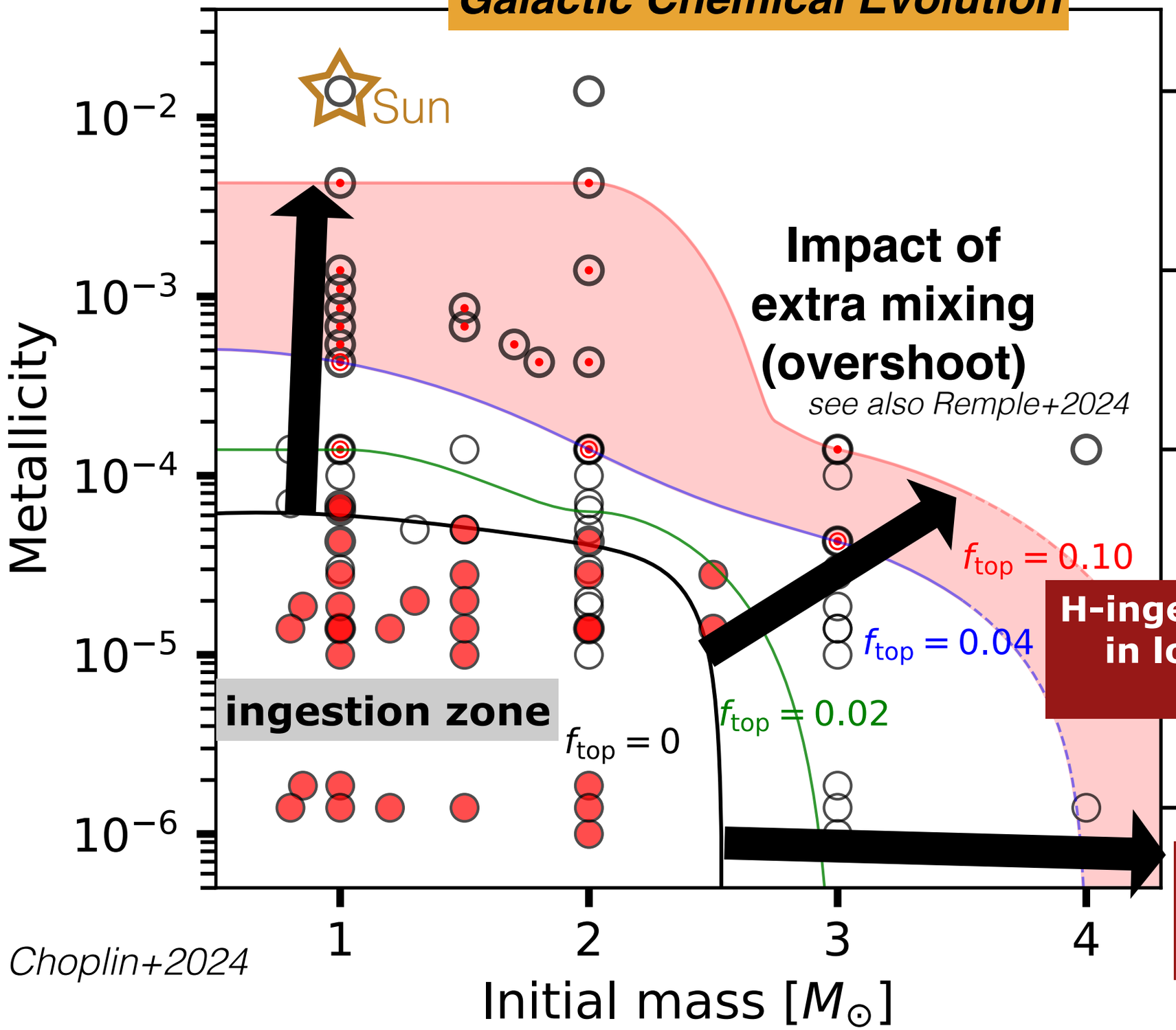

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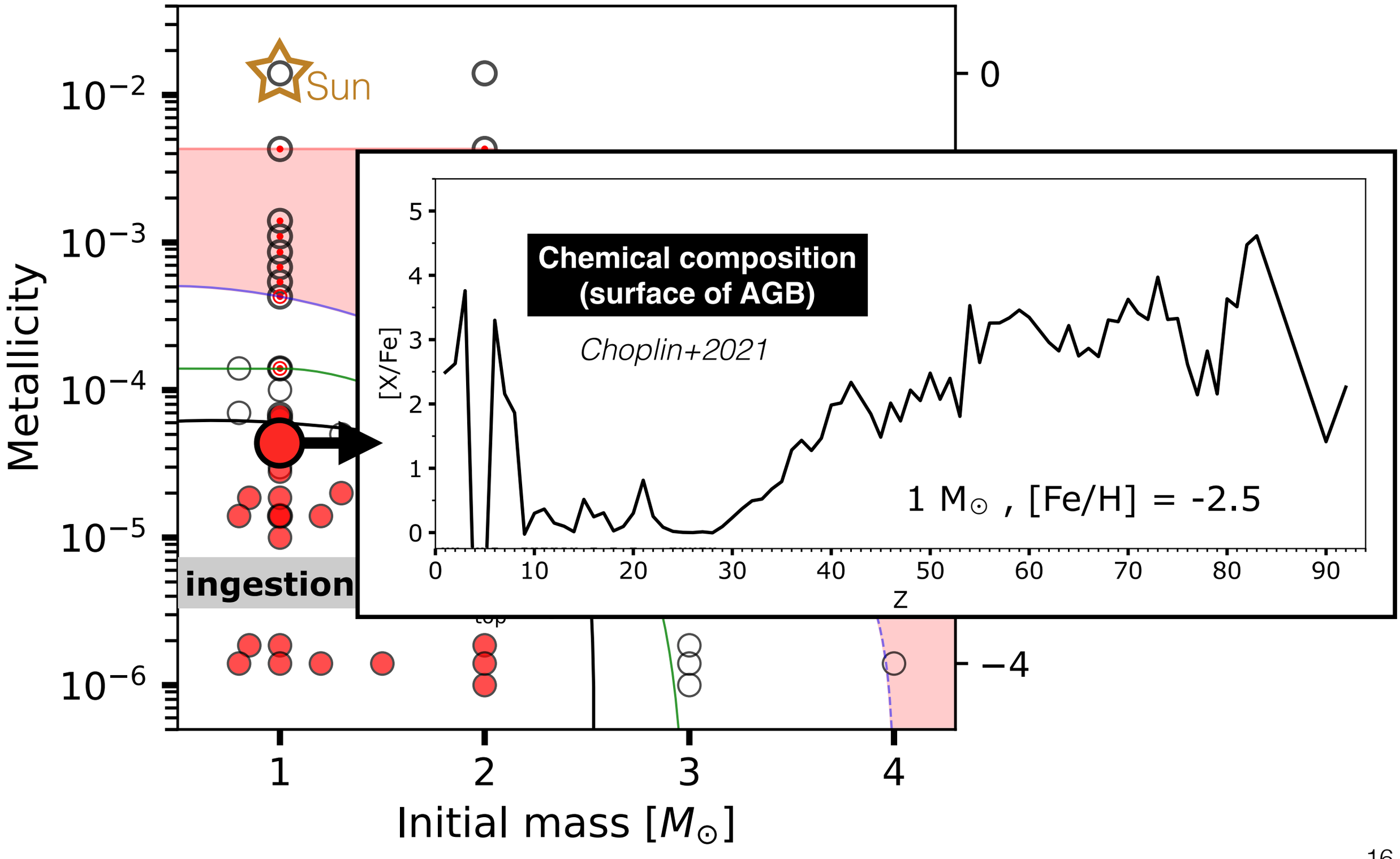
H-ingestion / i-process happens in low-metallicity low-mass AGB stars

but the ingestion zone may be bigger…

Strong overshoot => proton ingestion in ~ solar metallicity AGB

also Karinkuzhi+2023

AGB surface abundances after proton ingestion



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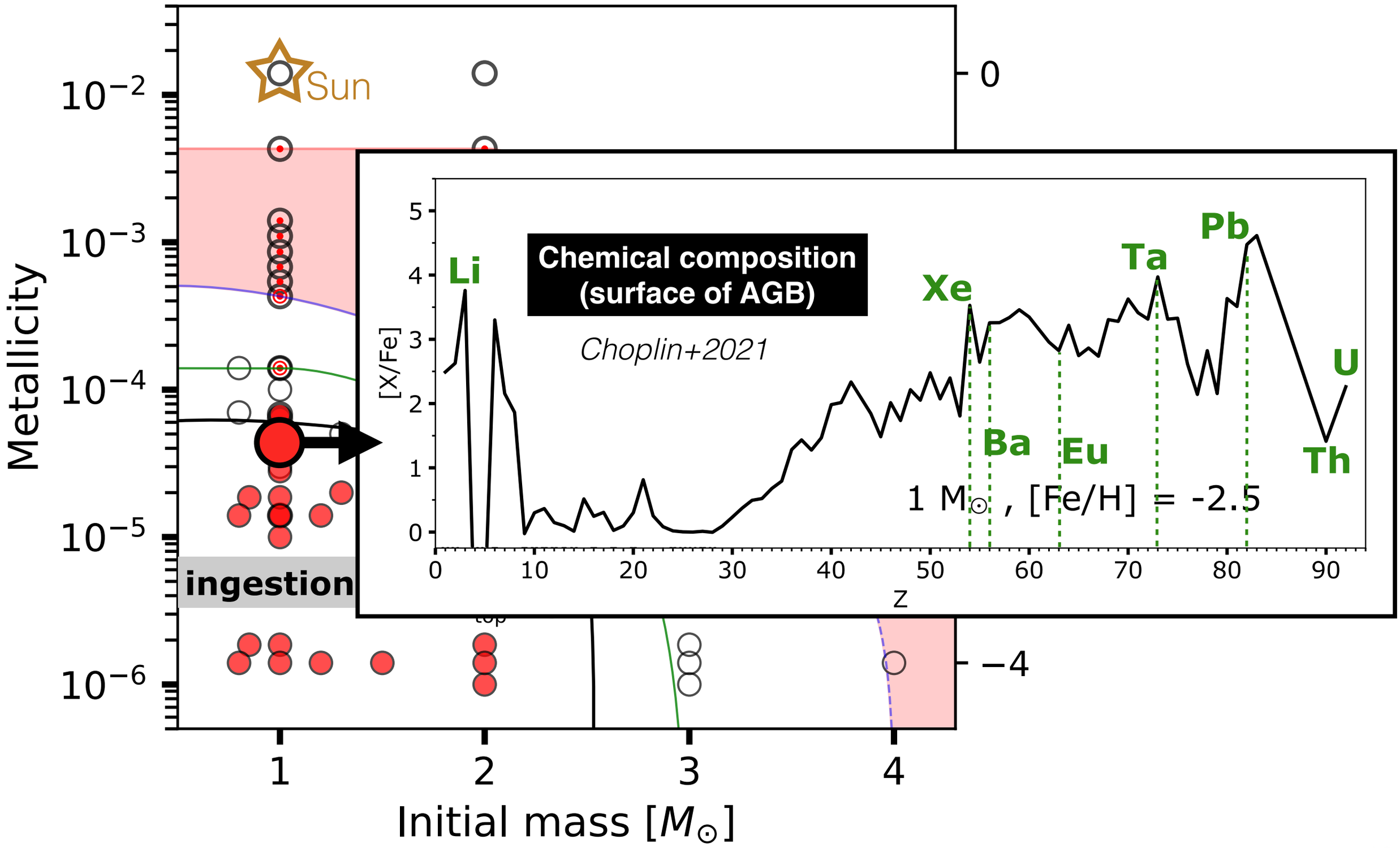

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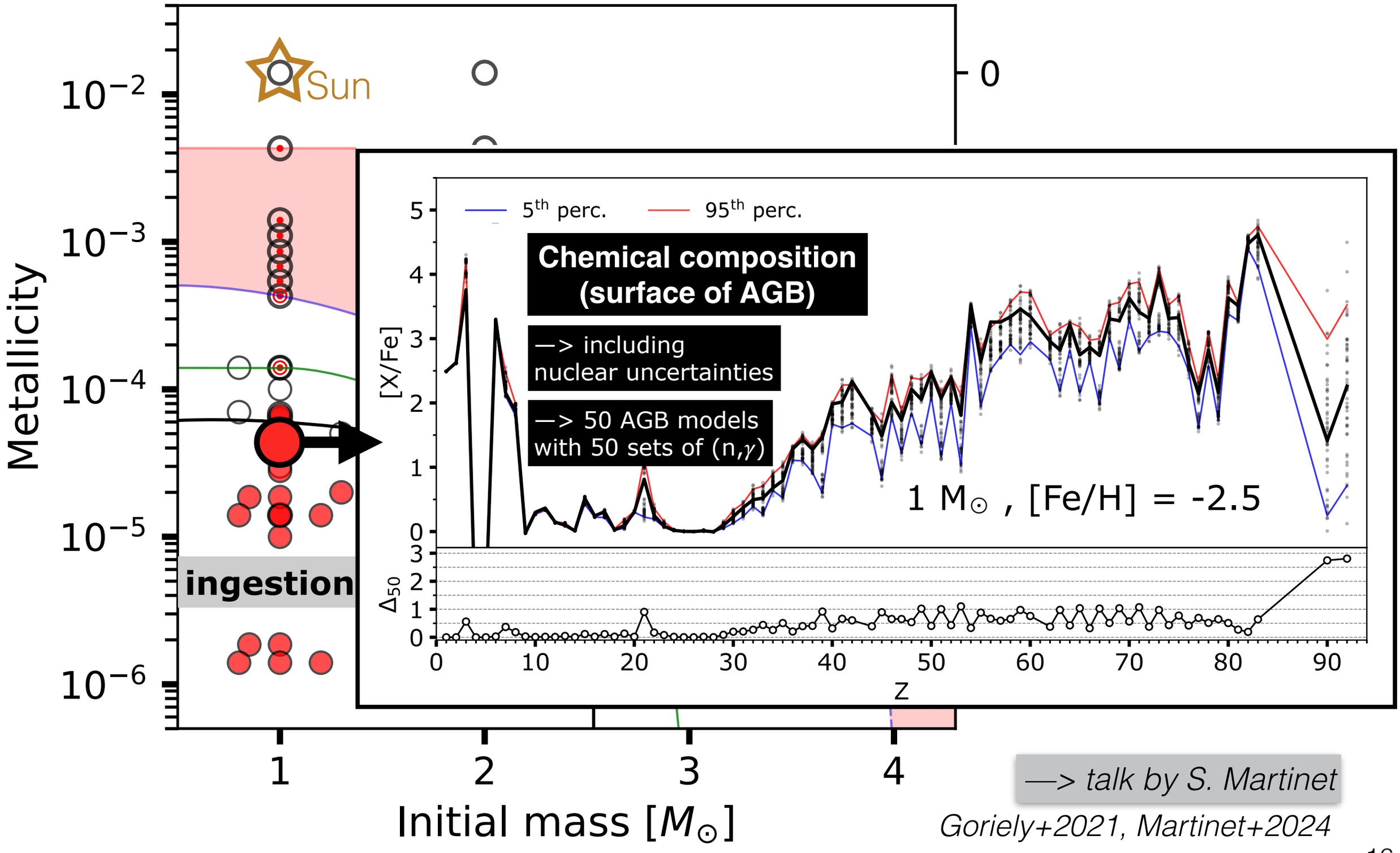
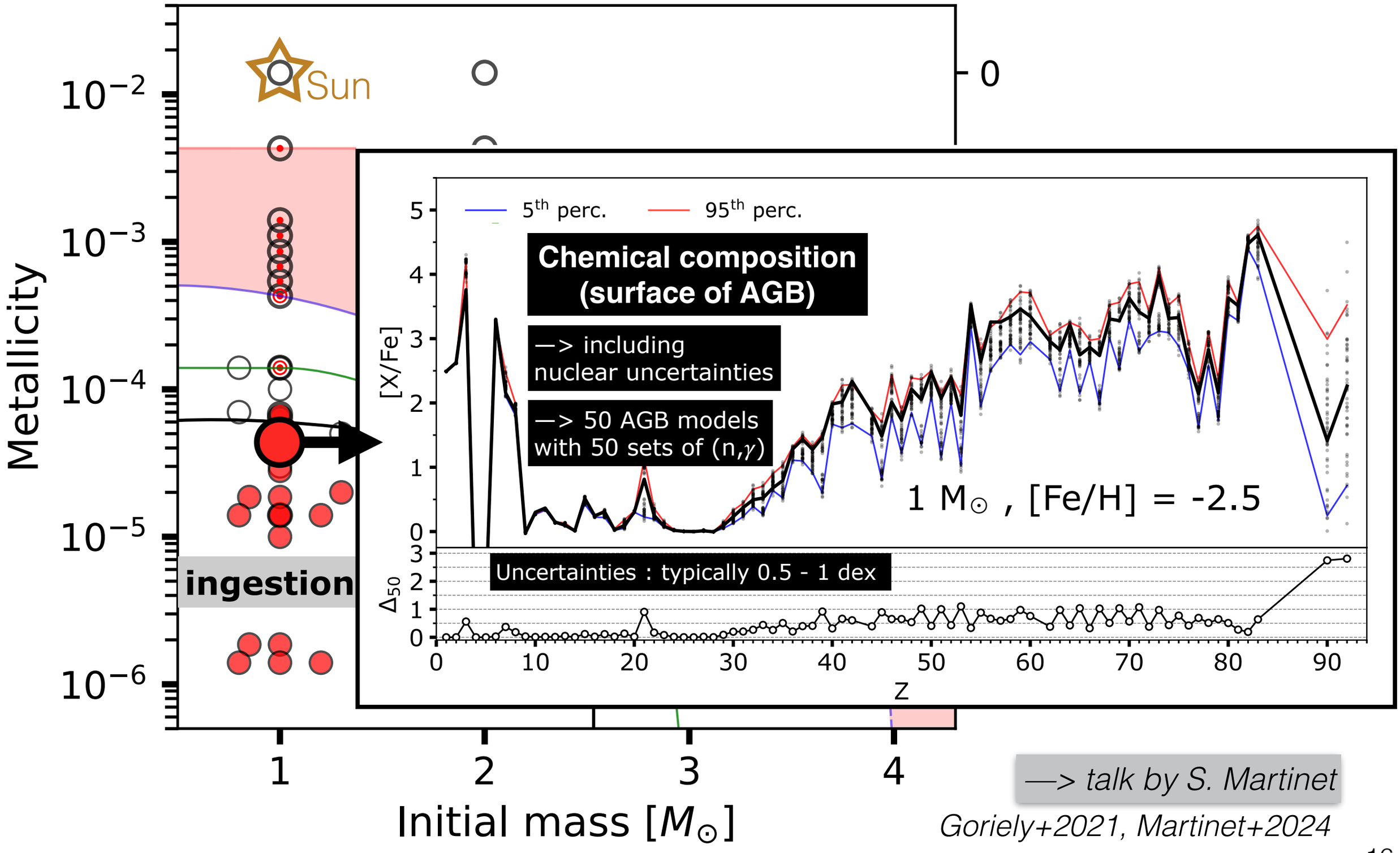


—> *talk by S. Martinet*

Goriely+2021, Martinet+2024

AGB surface abundances after proton ingestion



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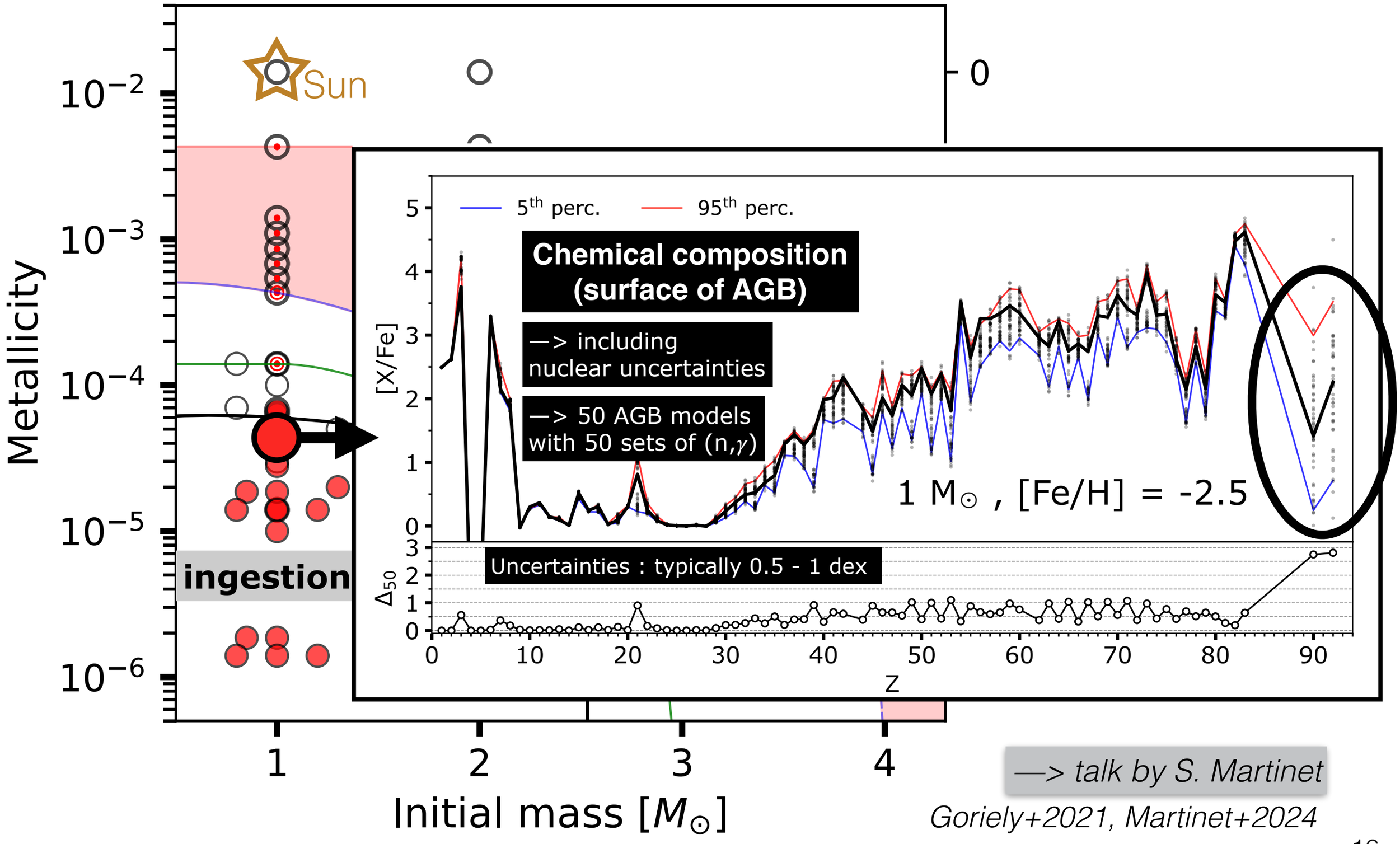

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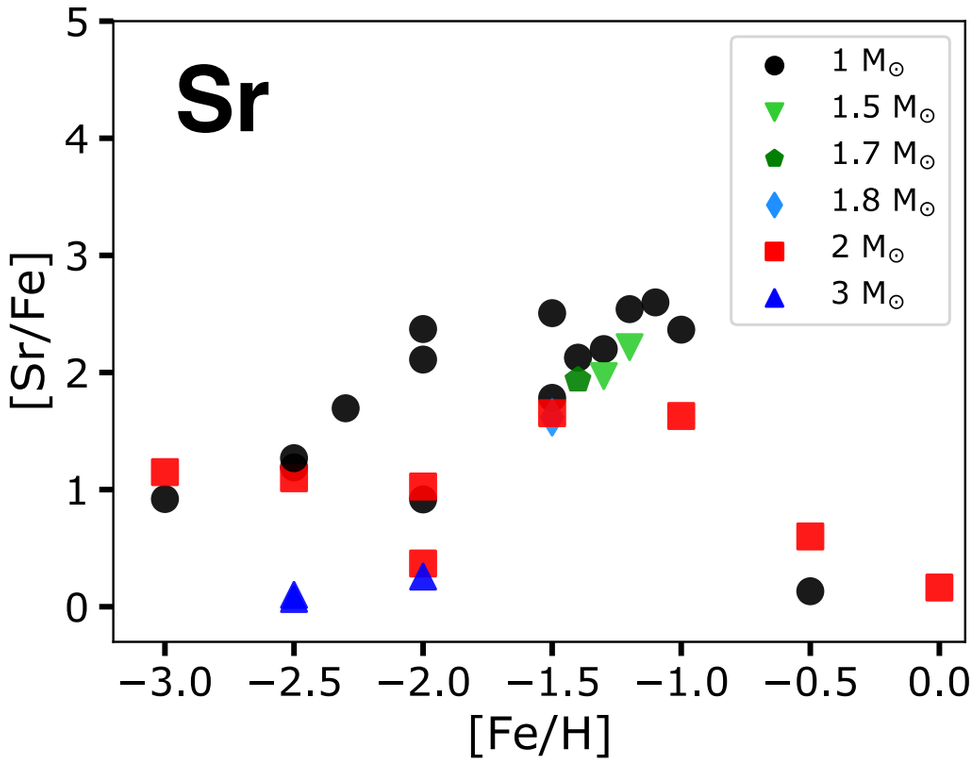
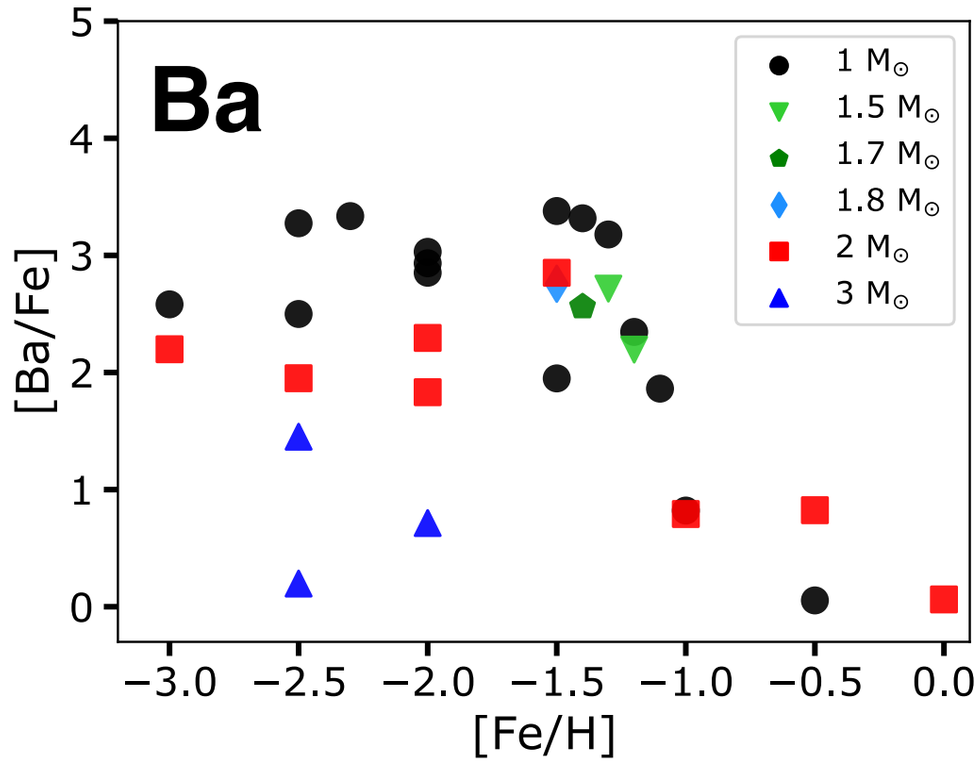
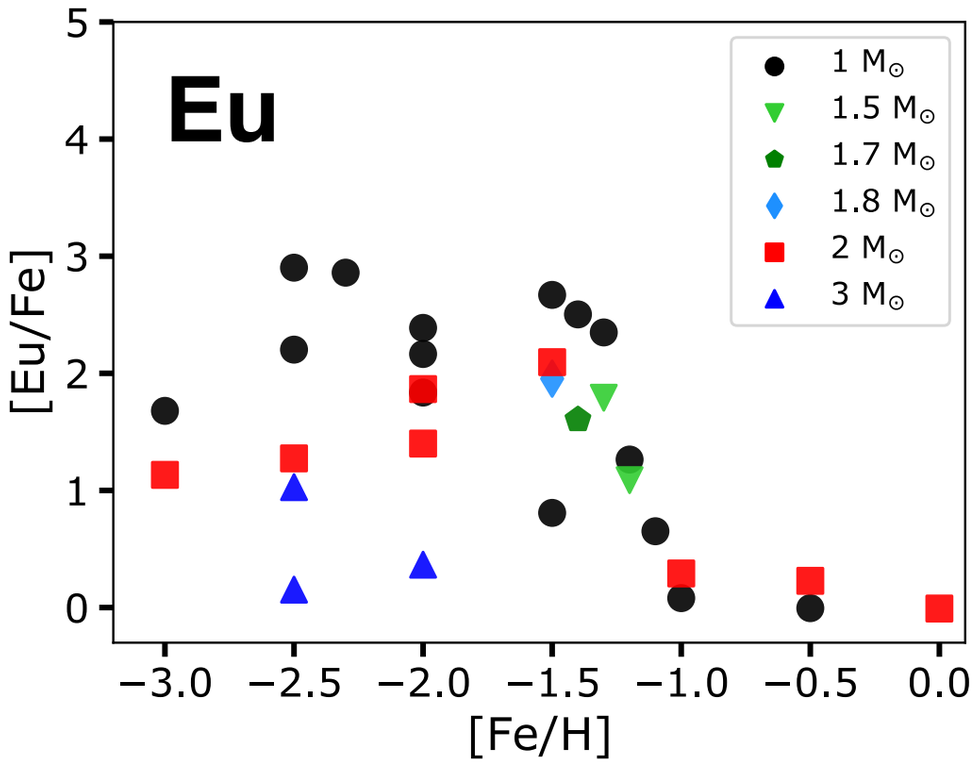
Goriely+2021, Martinet+2024

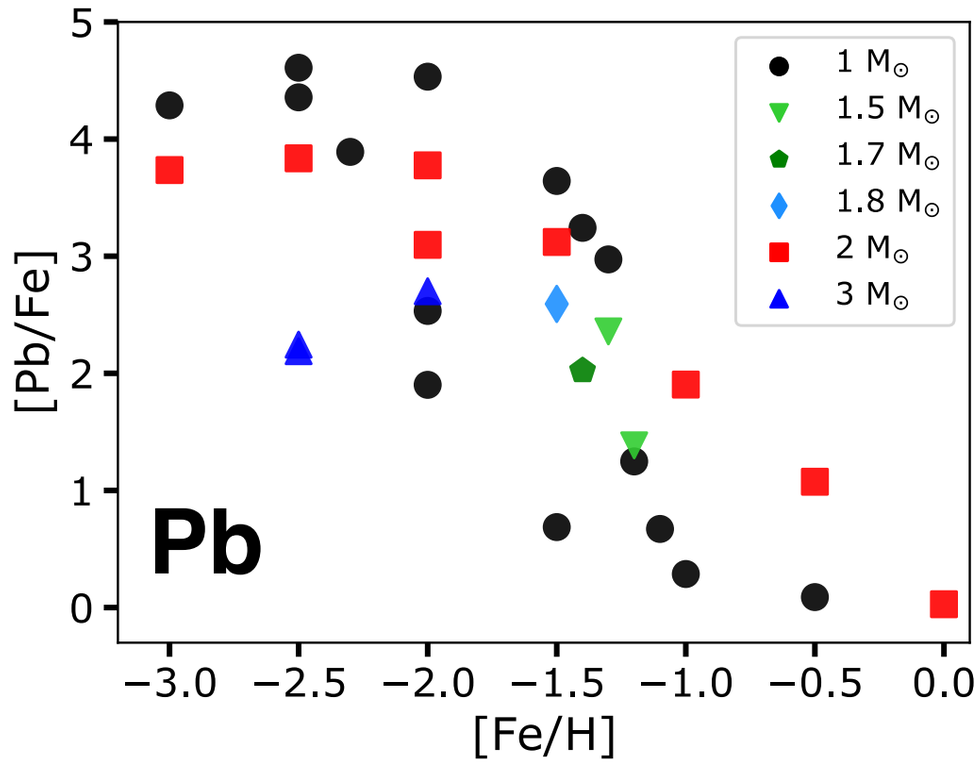
Nucleosynthetic yields of AGB experiencing H-ingestion

Choplin+2022, Choplin+2024





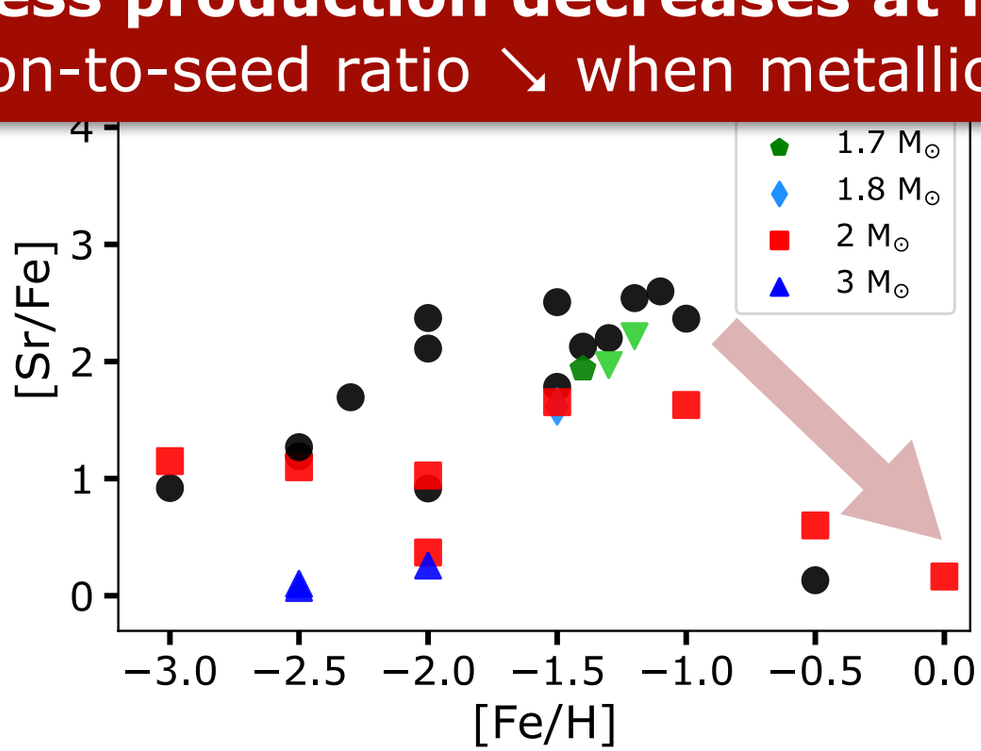


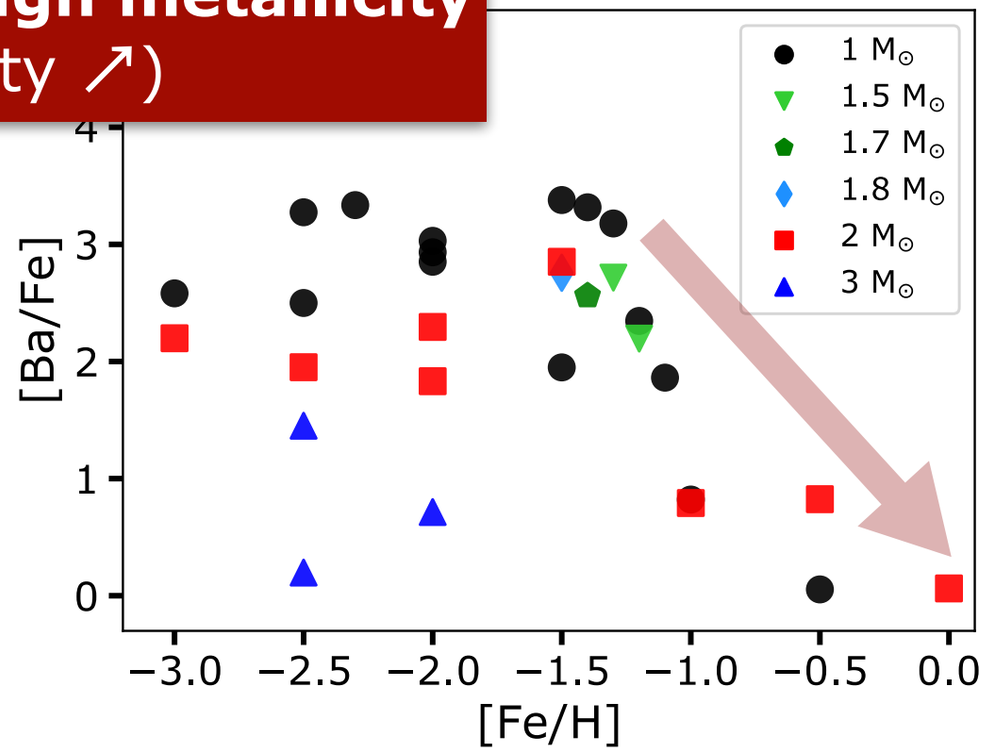


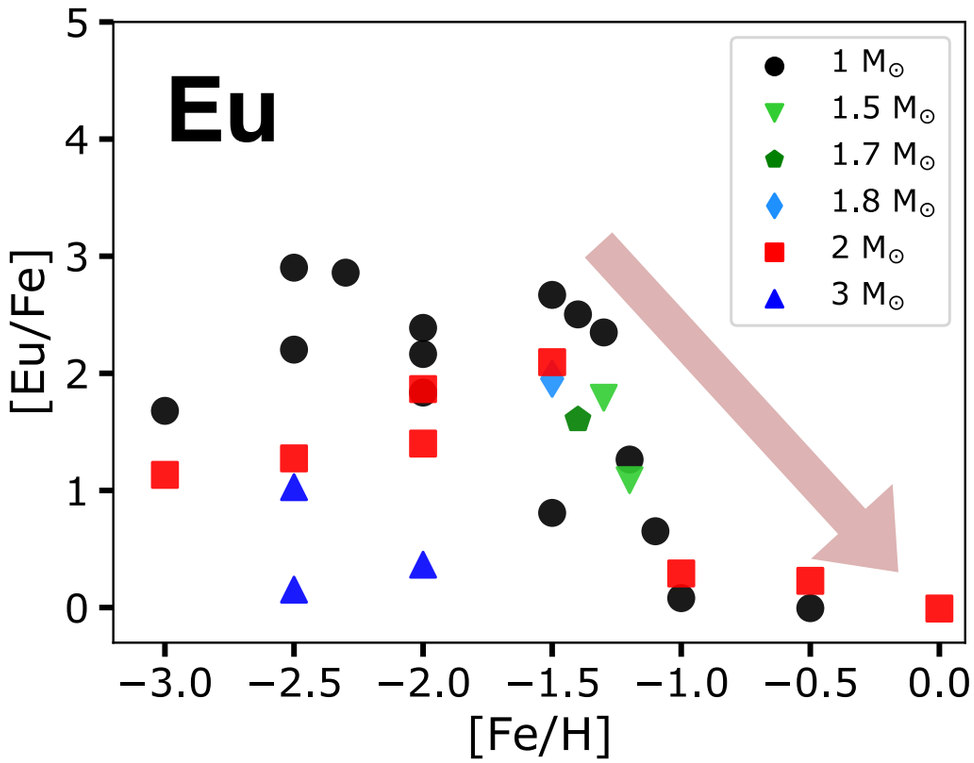
Nucleosynthetic yields of AGB experiencing H-ingestion

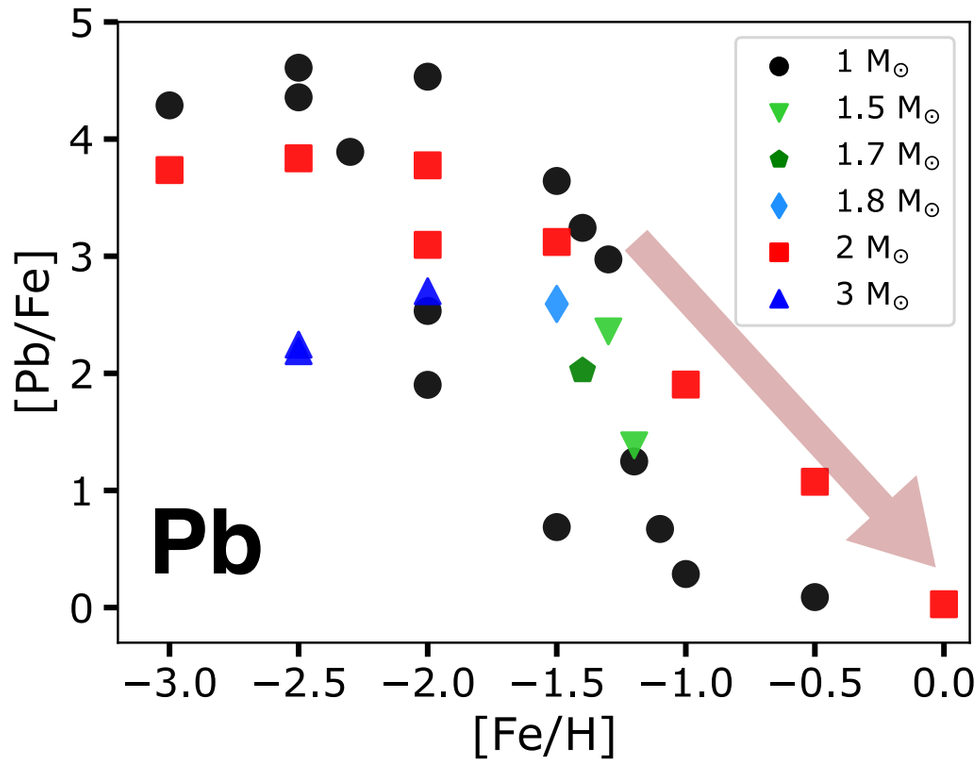
Choplin+2022, Choplin+2024

i-process production decreases at high metallicity
(neutron-to-seed ratio ↘ when metallicity ↗)







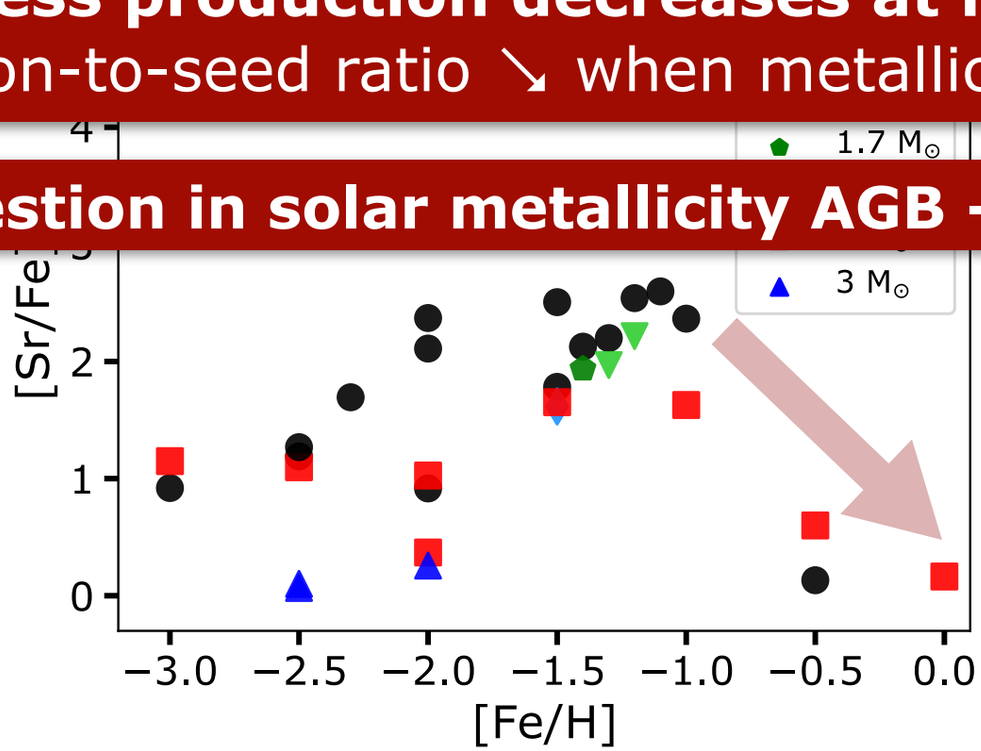


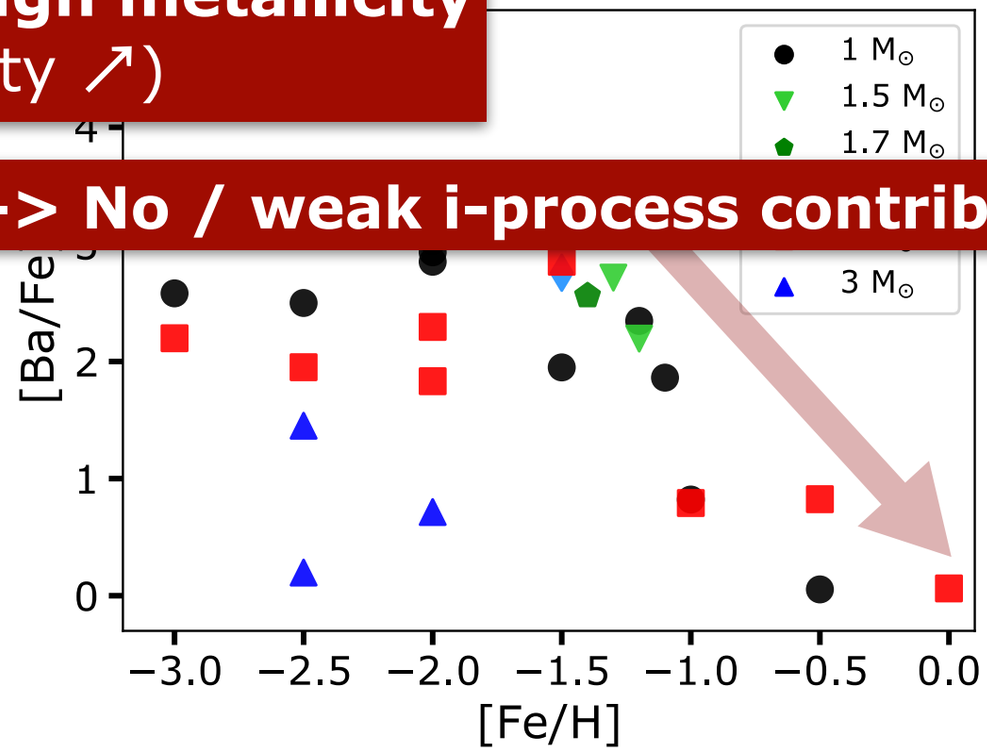
Nucleosynthetic yields of AGB experiencing H-ingestion

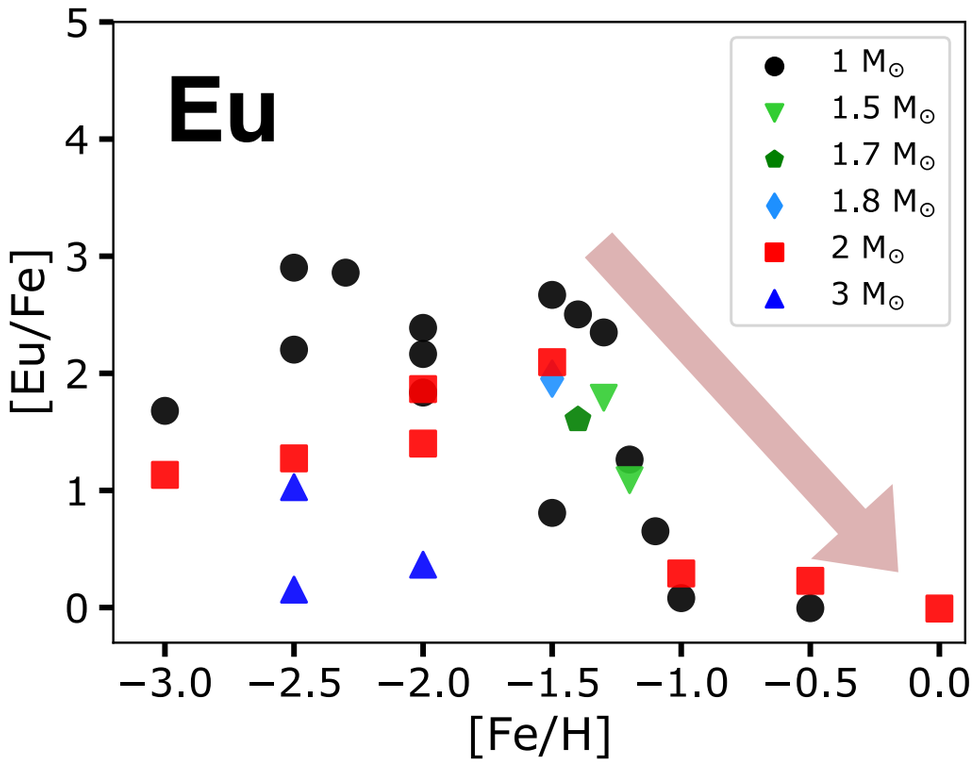
Choplin+2022, Choplin+2024

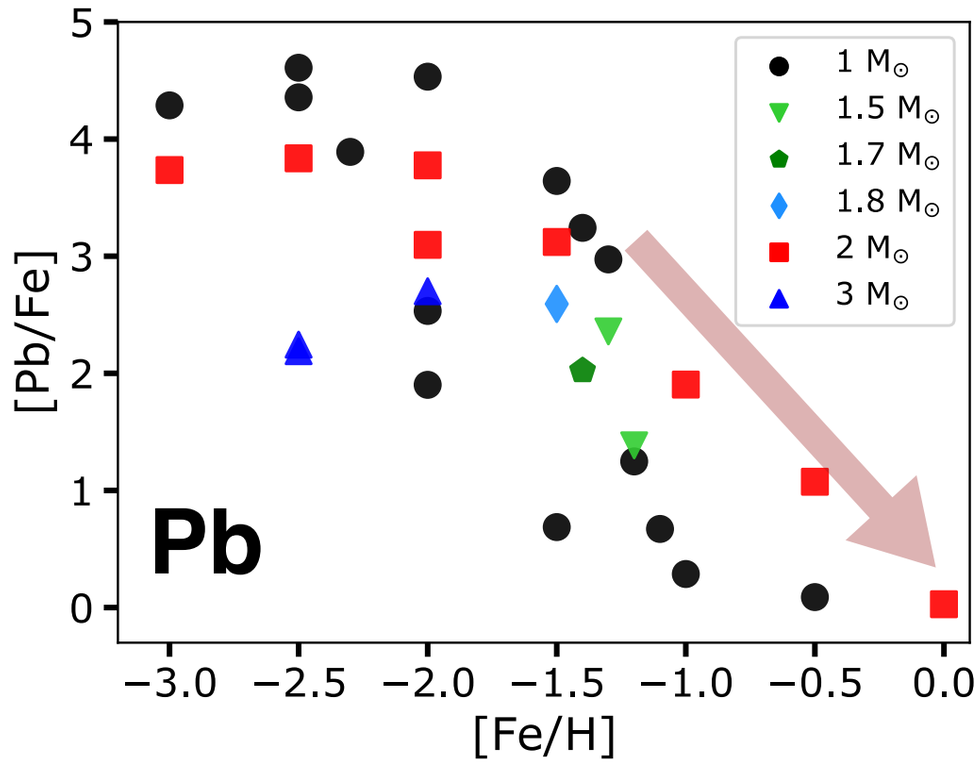
i-process production decreases at high metallicity
(neutron-to-seed ratio ↘ when metallicity ↗)

H-ingestion in solar metallicity AGB —> No / weak i-process contribution



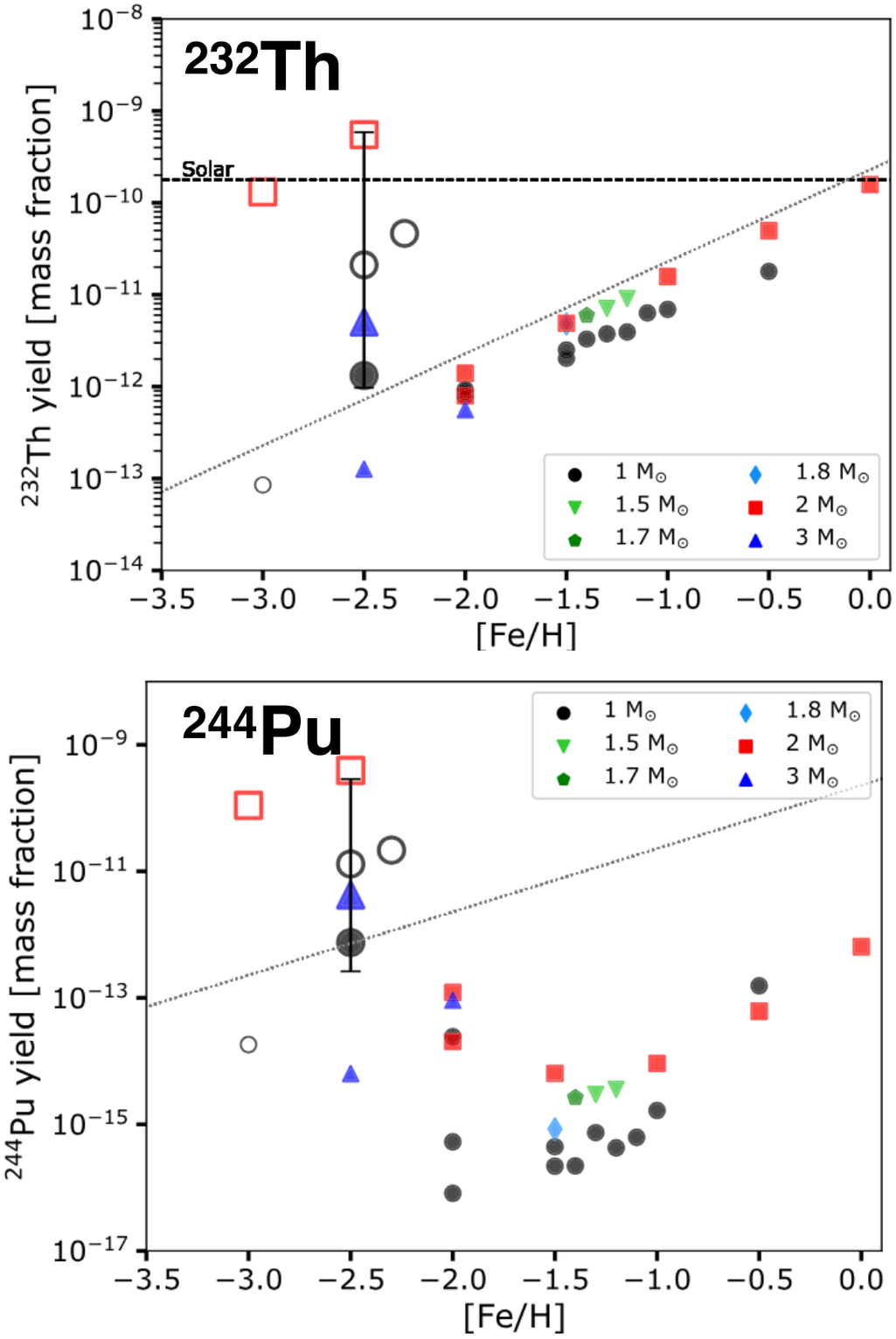


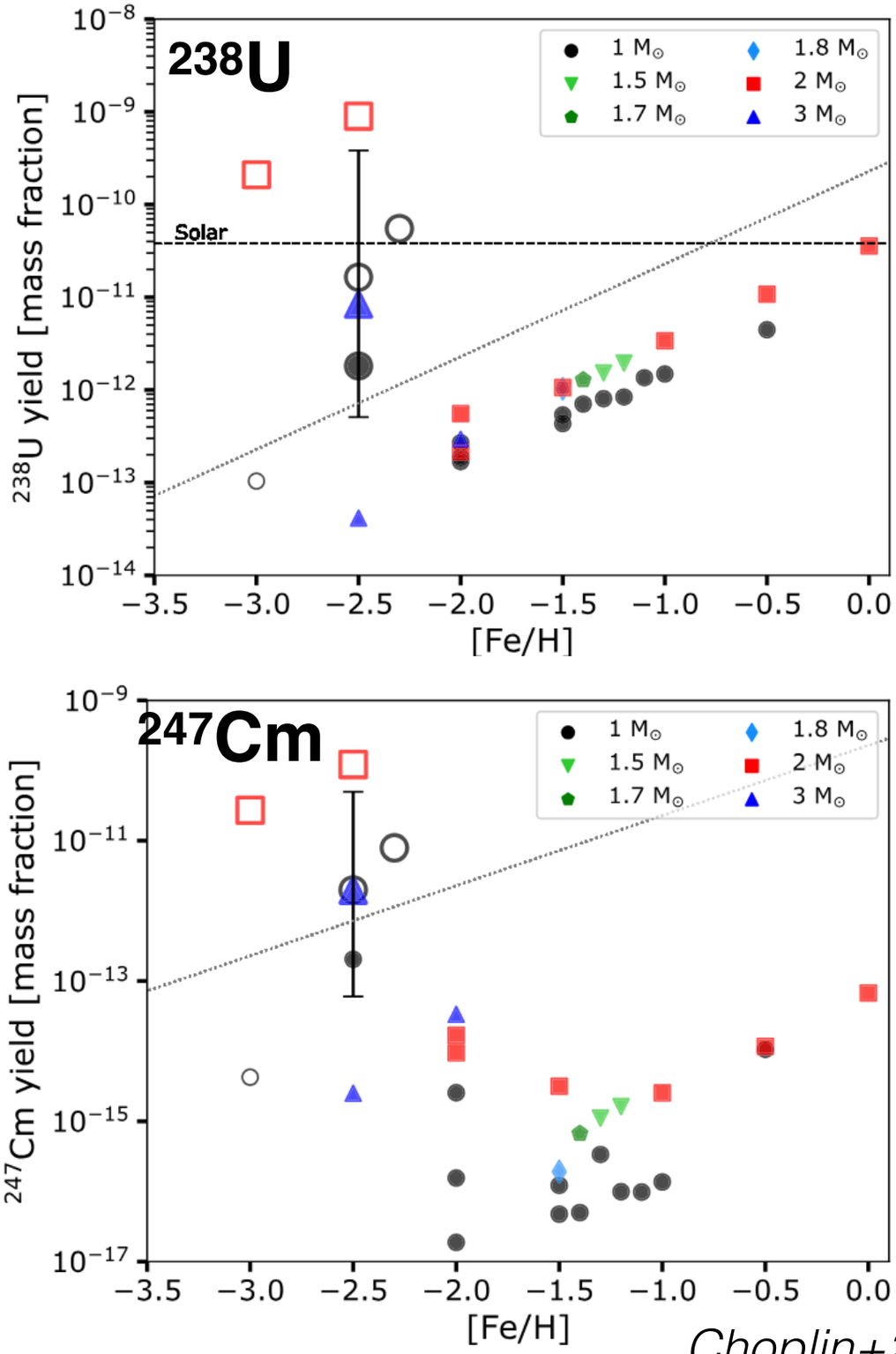




Nucleosynthetic yields of AGB experiencing H-ingestion

Actinides / short lived radionuclides





Choplin+2025

Nucleosynthetic yields of AGB experiencing H-ingestion

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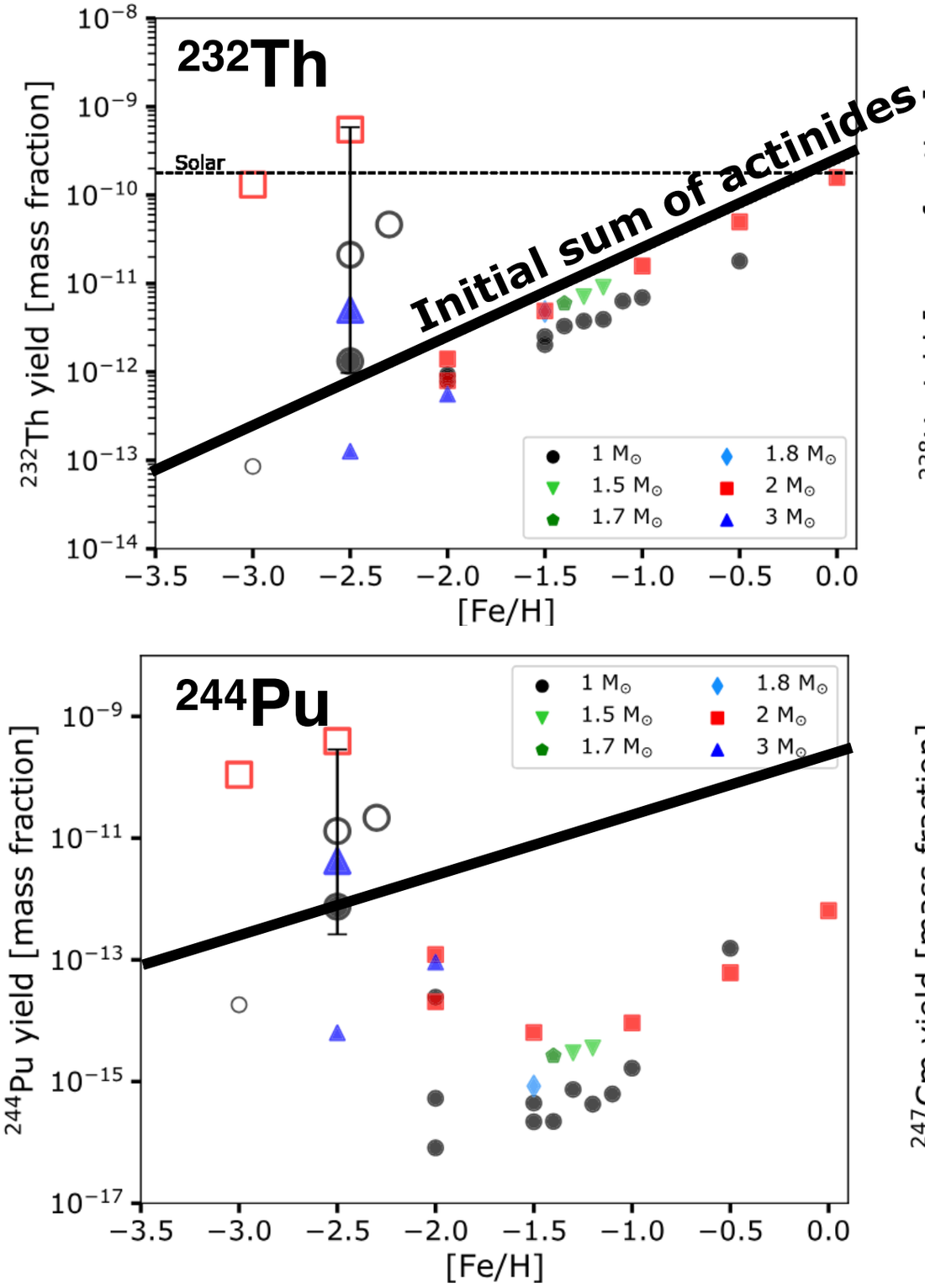

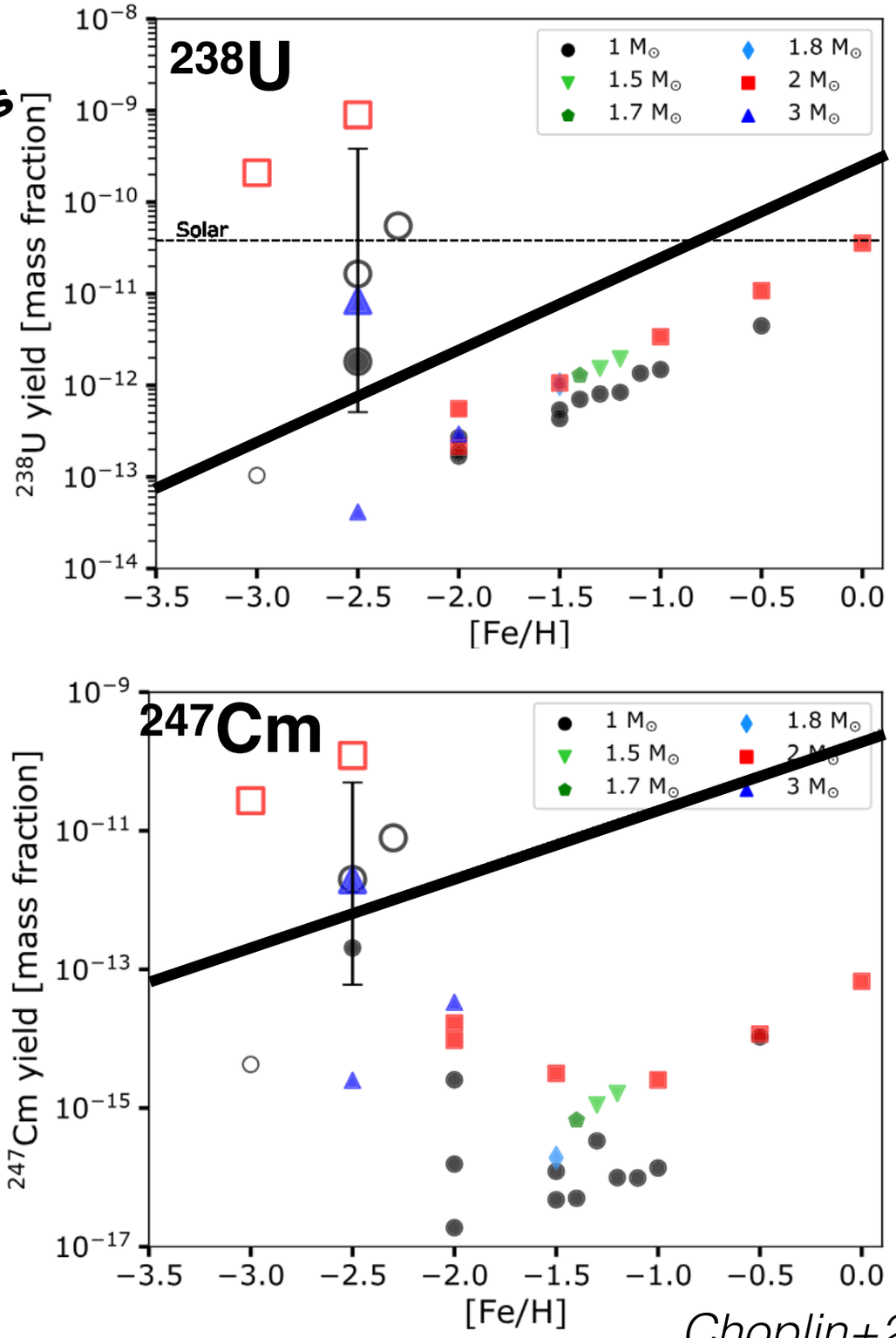

Choplin+2025

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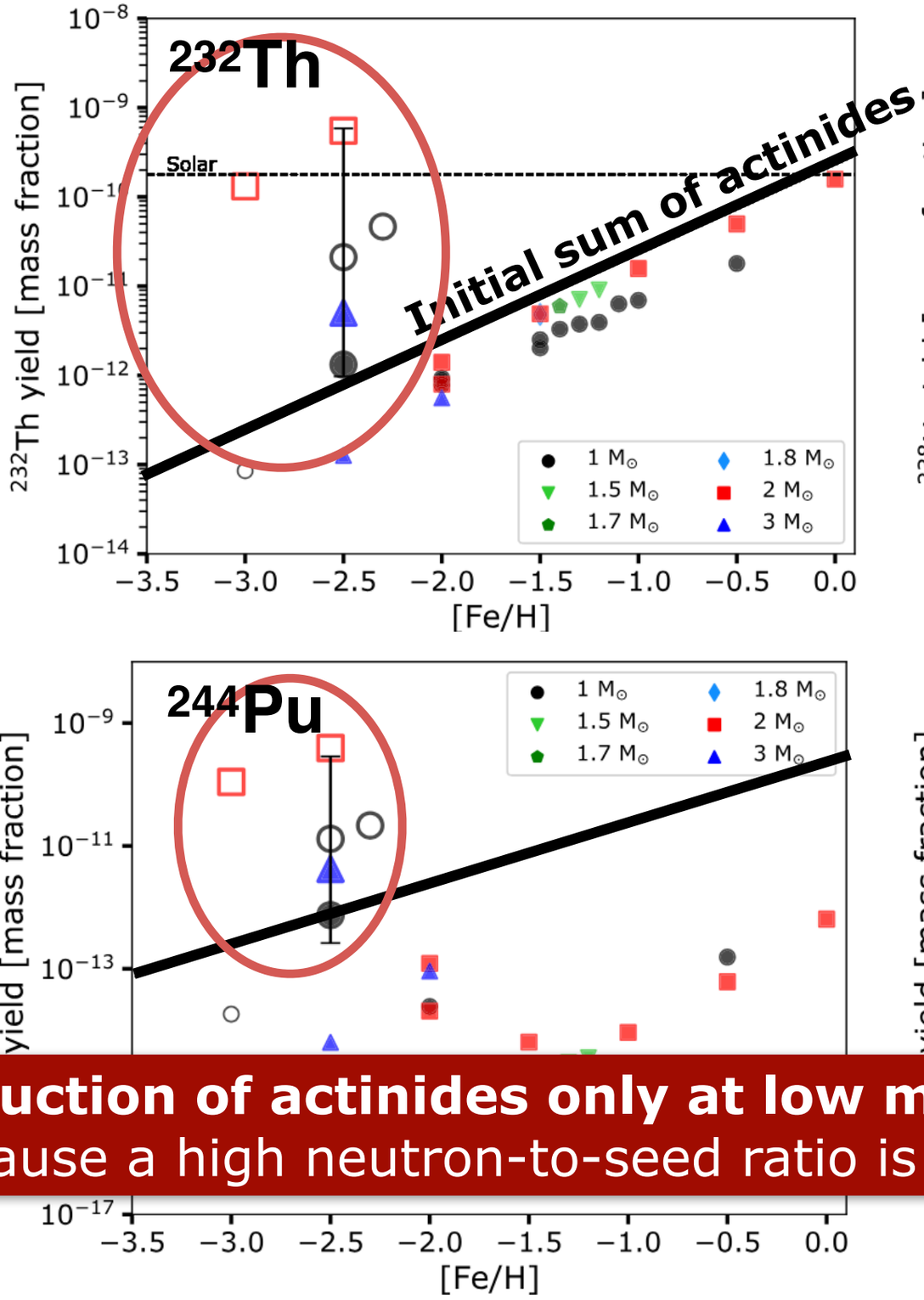

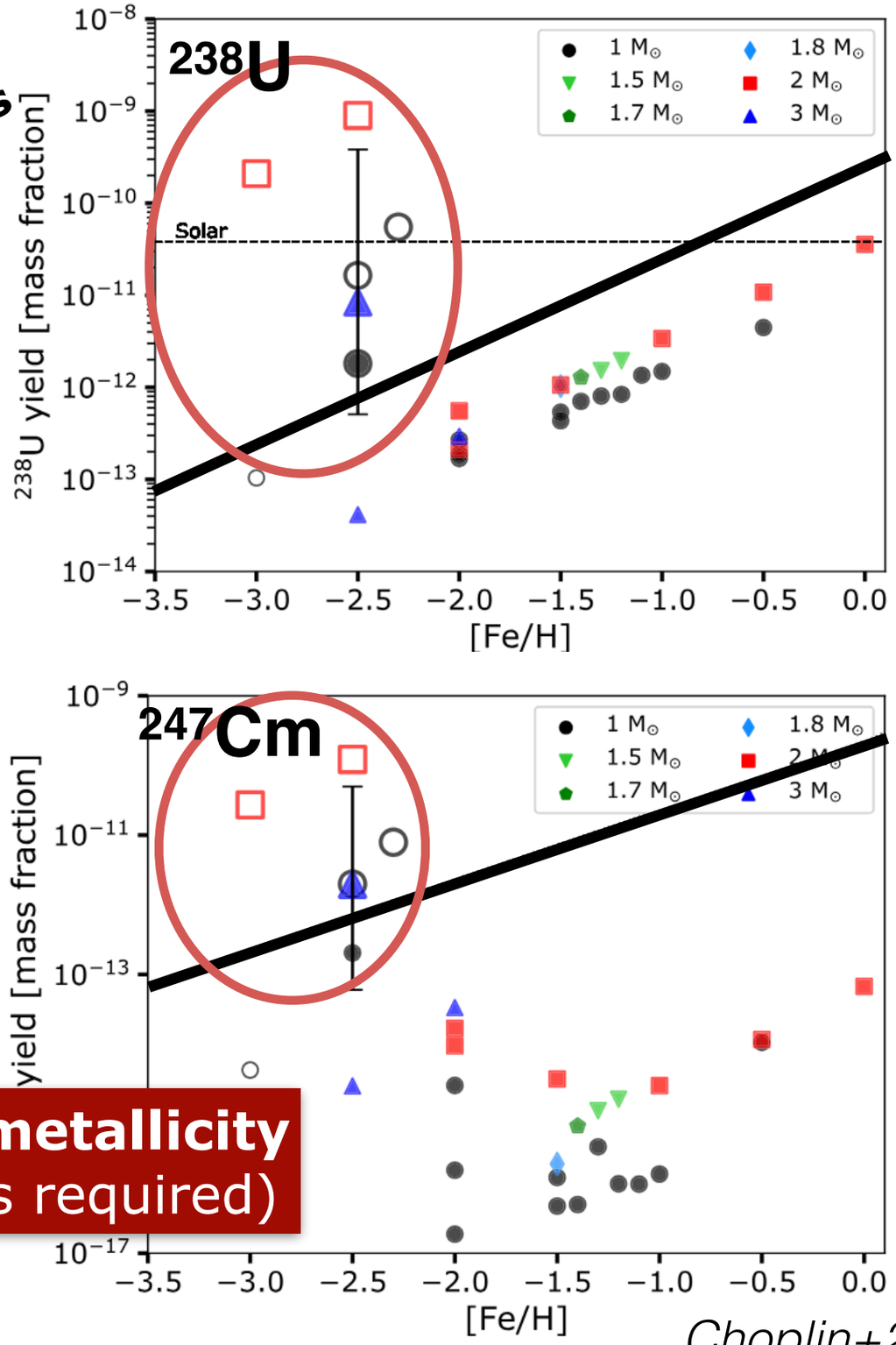

Production of actinides only at low metallicity
(because a high neutron-to-seed ratio is required)

Choplin+2025

Nucleosynthetic yields of AGB experiencing H-ingestion

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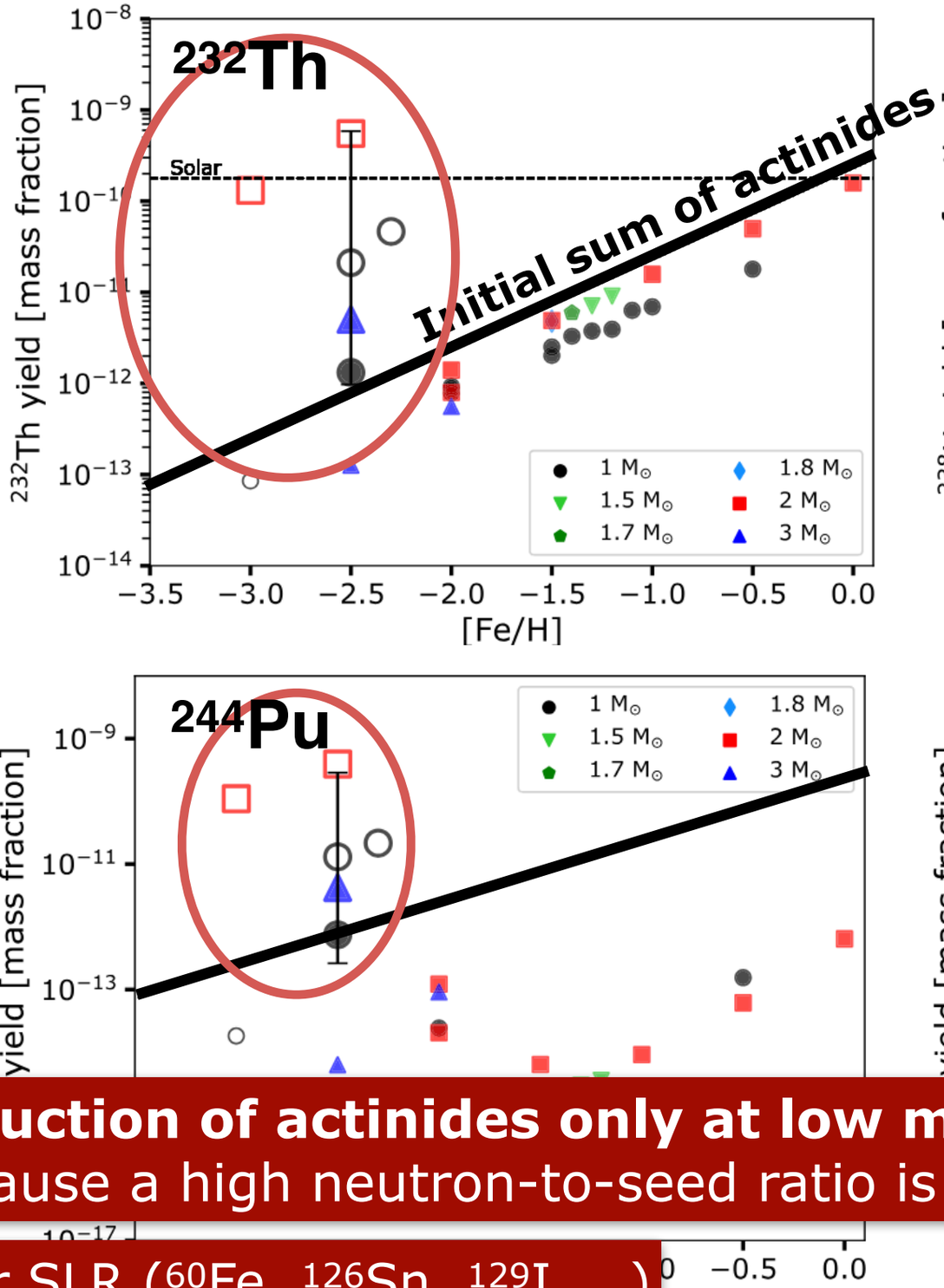
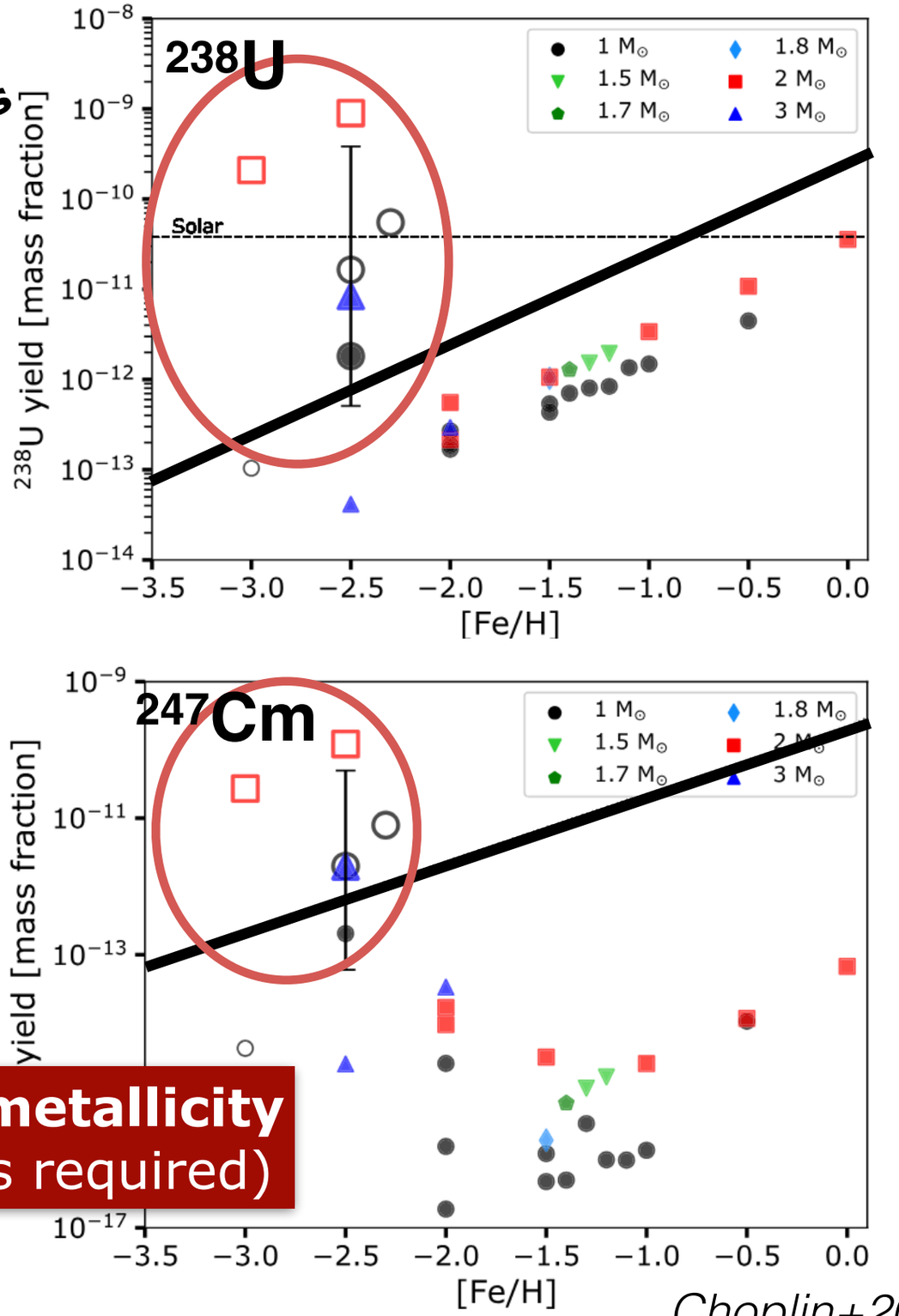




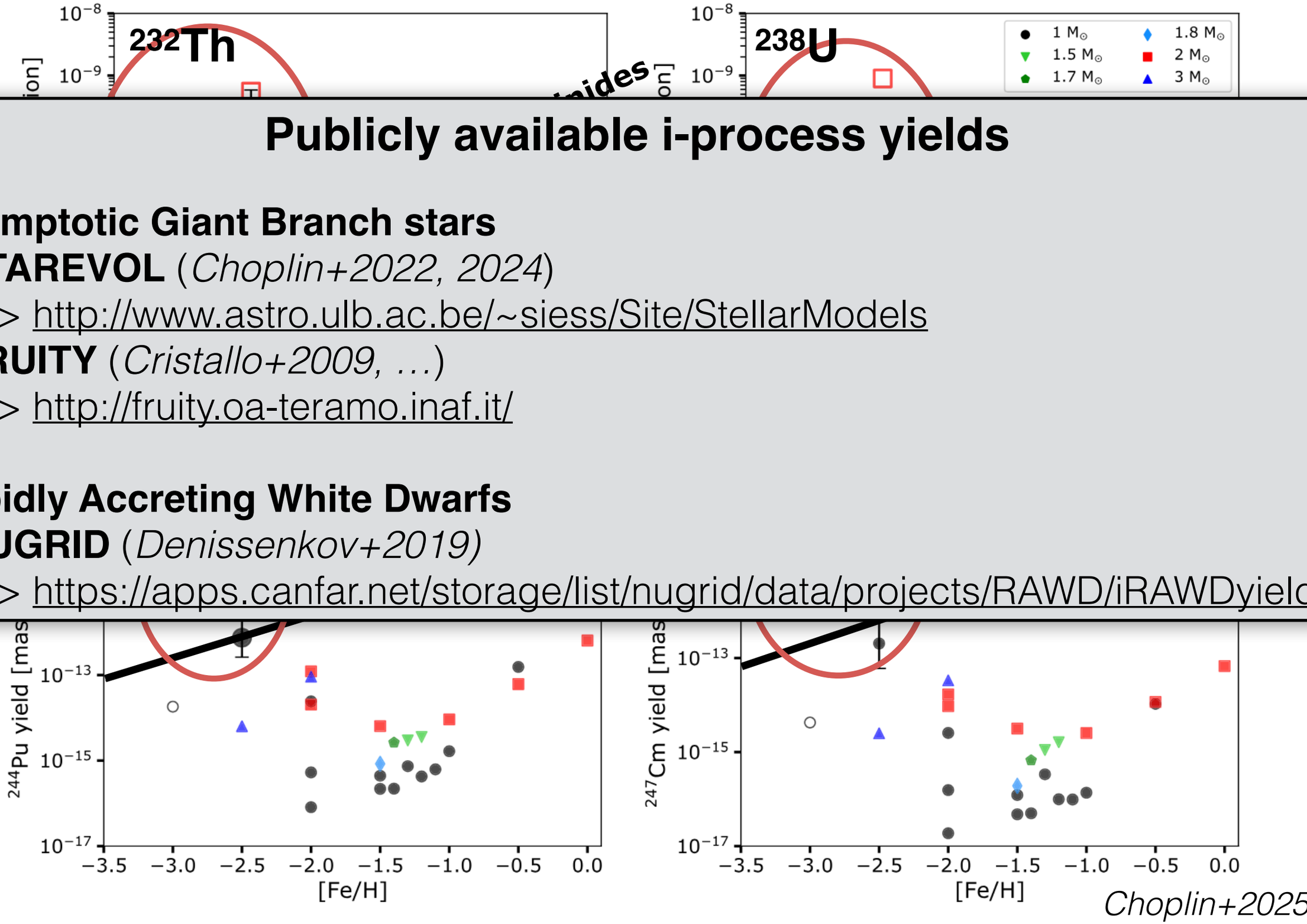
Production of actinides only at low metallicity
(because a high neutron-to-seed ratio is required)

Other SLR (^{60}Fe, ^{126}Sn, ^{129}I, …) are also produced

Choplin+2025

Nucleosynthetic yields of AGB experiencing H-ingestion

Actinides / short lived radionuclides



Publicly available i-process yields

Asymptotic Giant Branch stars

- **STAREVOL** (*Choplin+2022, 2024*)
  —> http://www.astro.ulb.ac.be/~siess/Site/StellarModels
- **FRUITY** (*Cristallo+2009, …*)
  —> http://fruity.oa-teramo.inaf.it/

Rapidly Accreting White Dwarfs

- **NUGRID** (*Denissenkov+2019*)
  —> https://apps.canfar.net/storage/list/nugrid/data/projects/RAWD/iRAWDyields

Choplin+2025

Nucleosynthetic yields of AGB experiencing H-ingestion

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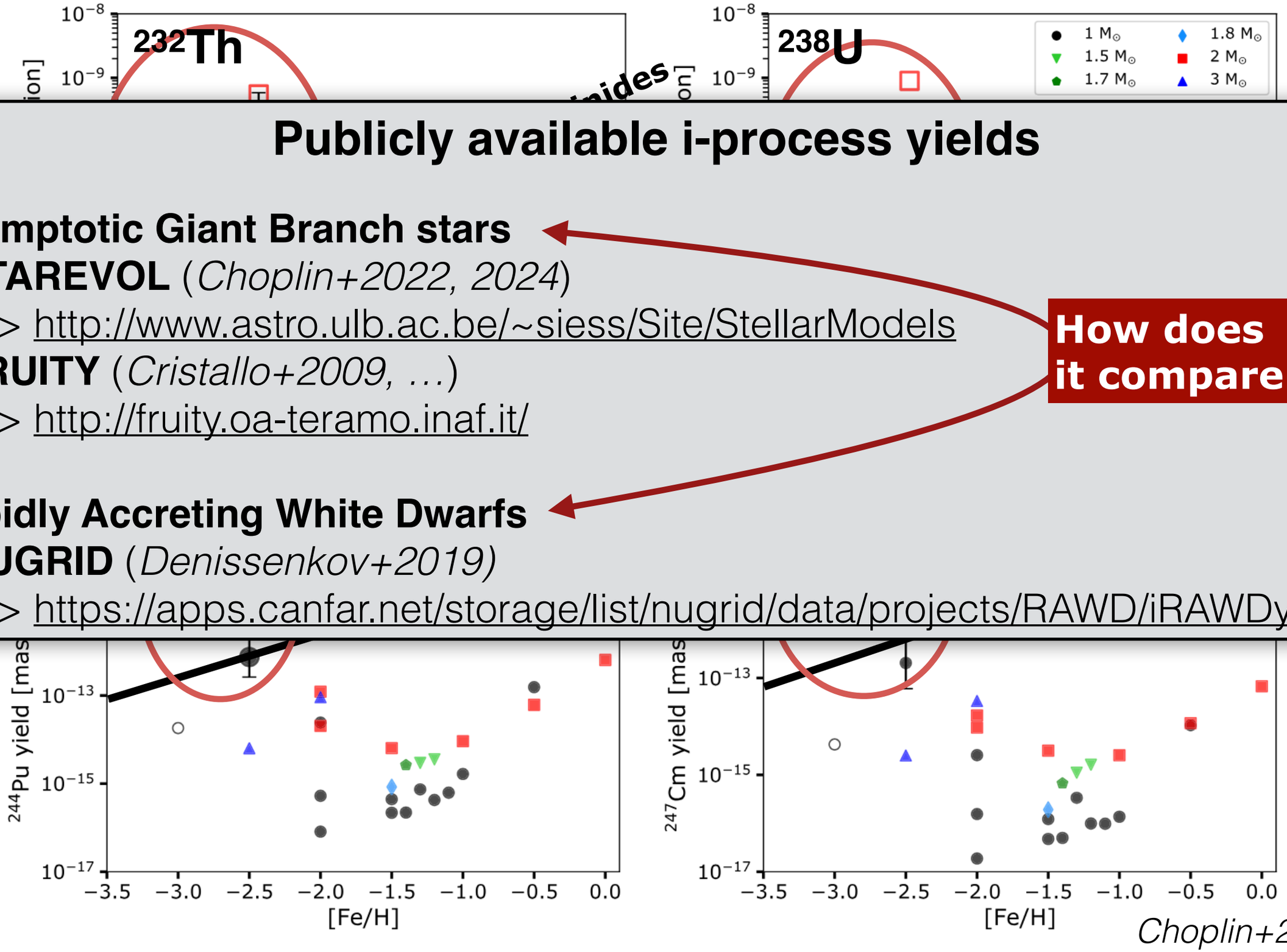

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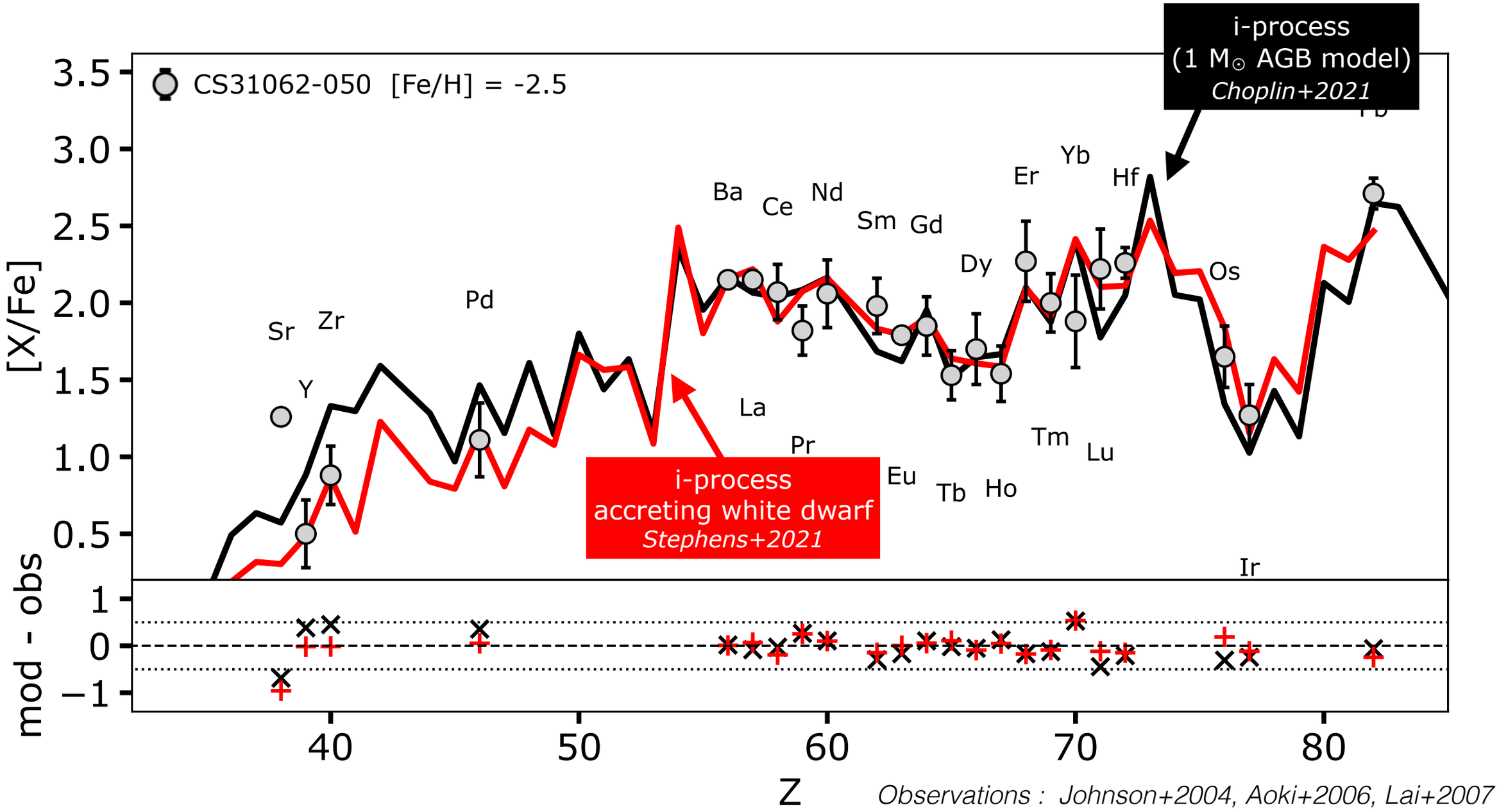
How does it compare ?

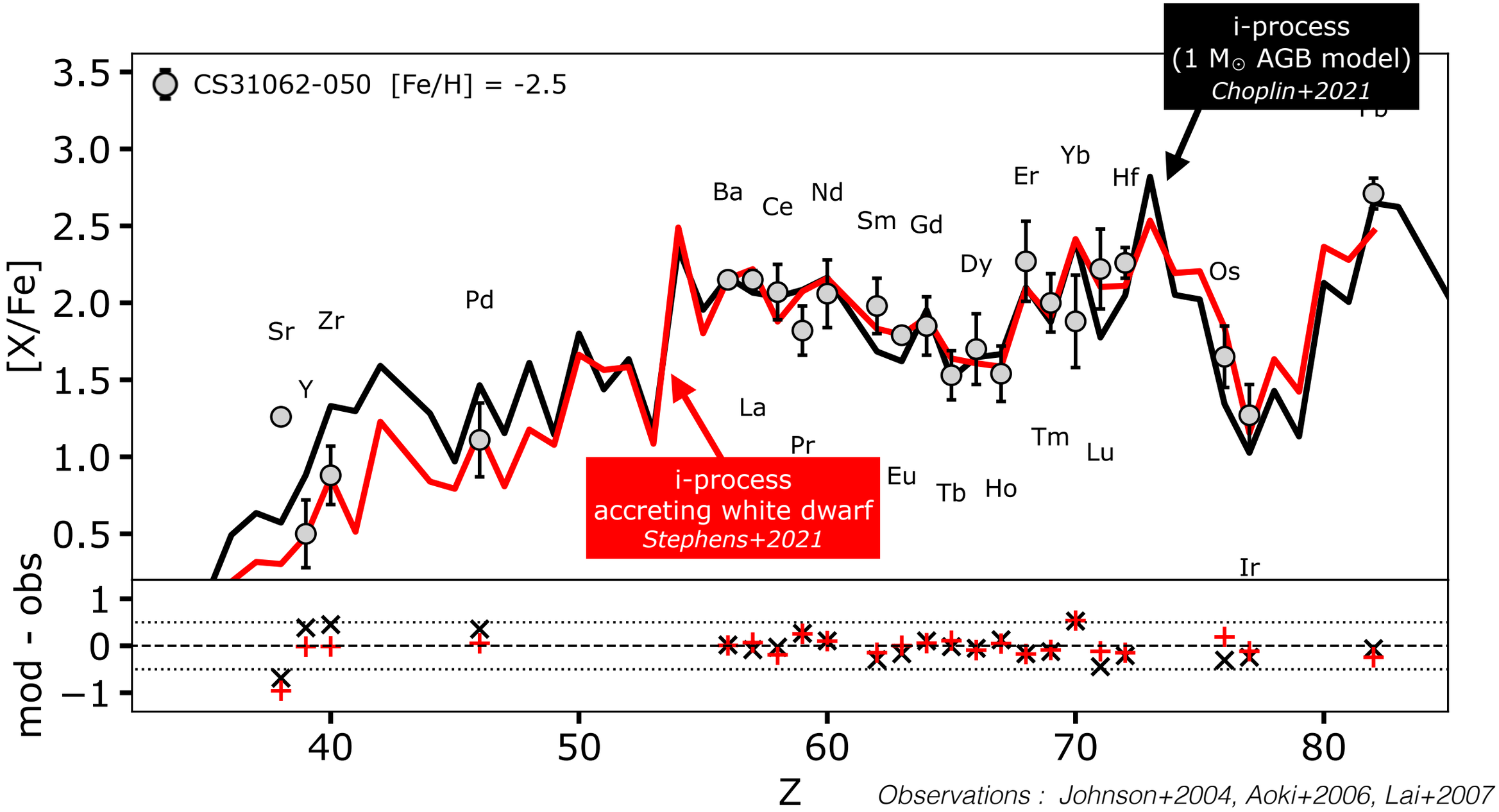
Choplin+2025

i-process in accreting white dwarfs and AGB stars



Observations : Johnson+2004, Aoki+2006, Lai+2007

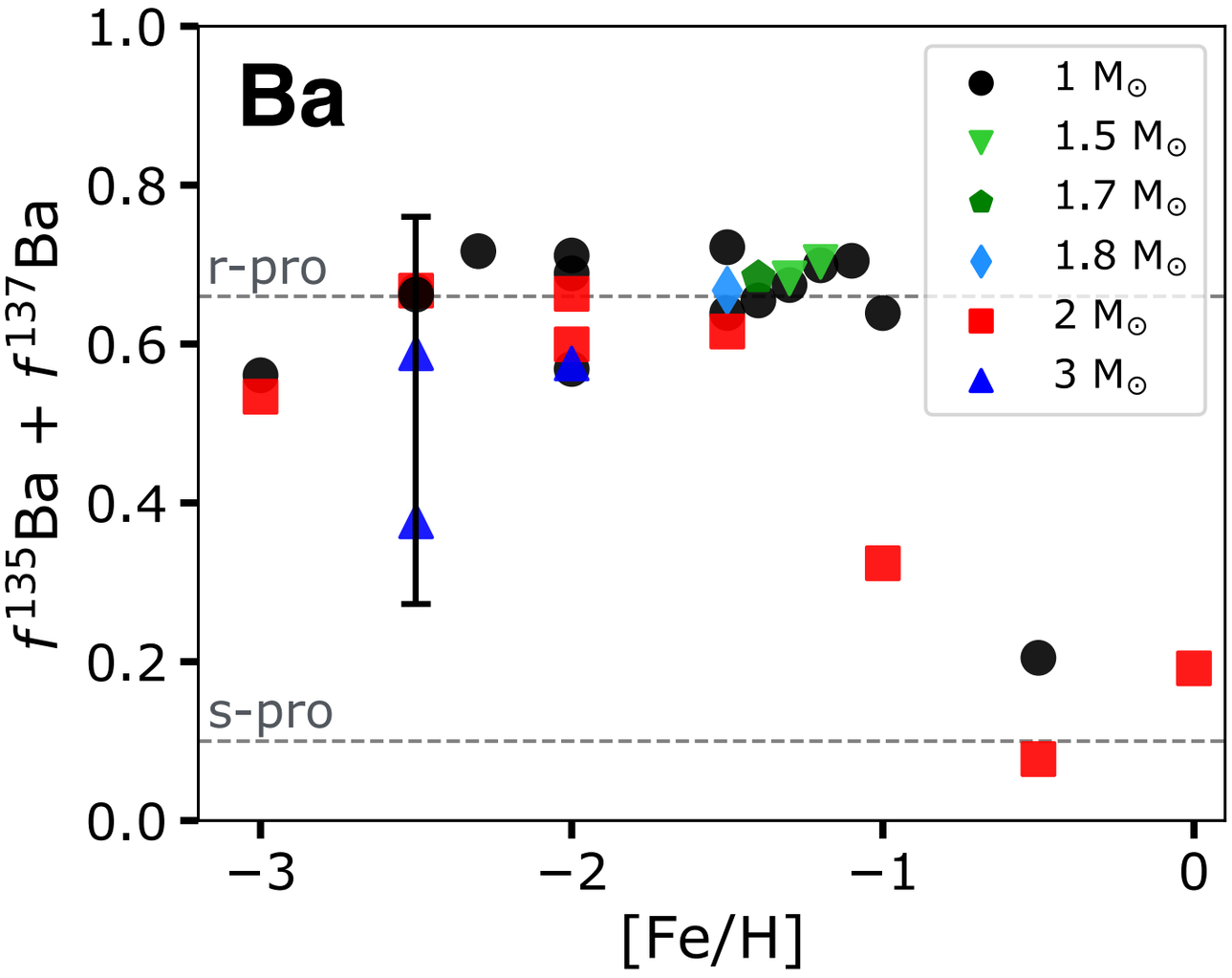
i-process in accreting white dwarfs and AGB stars

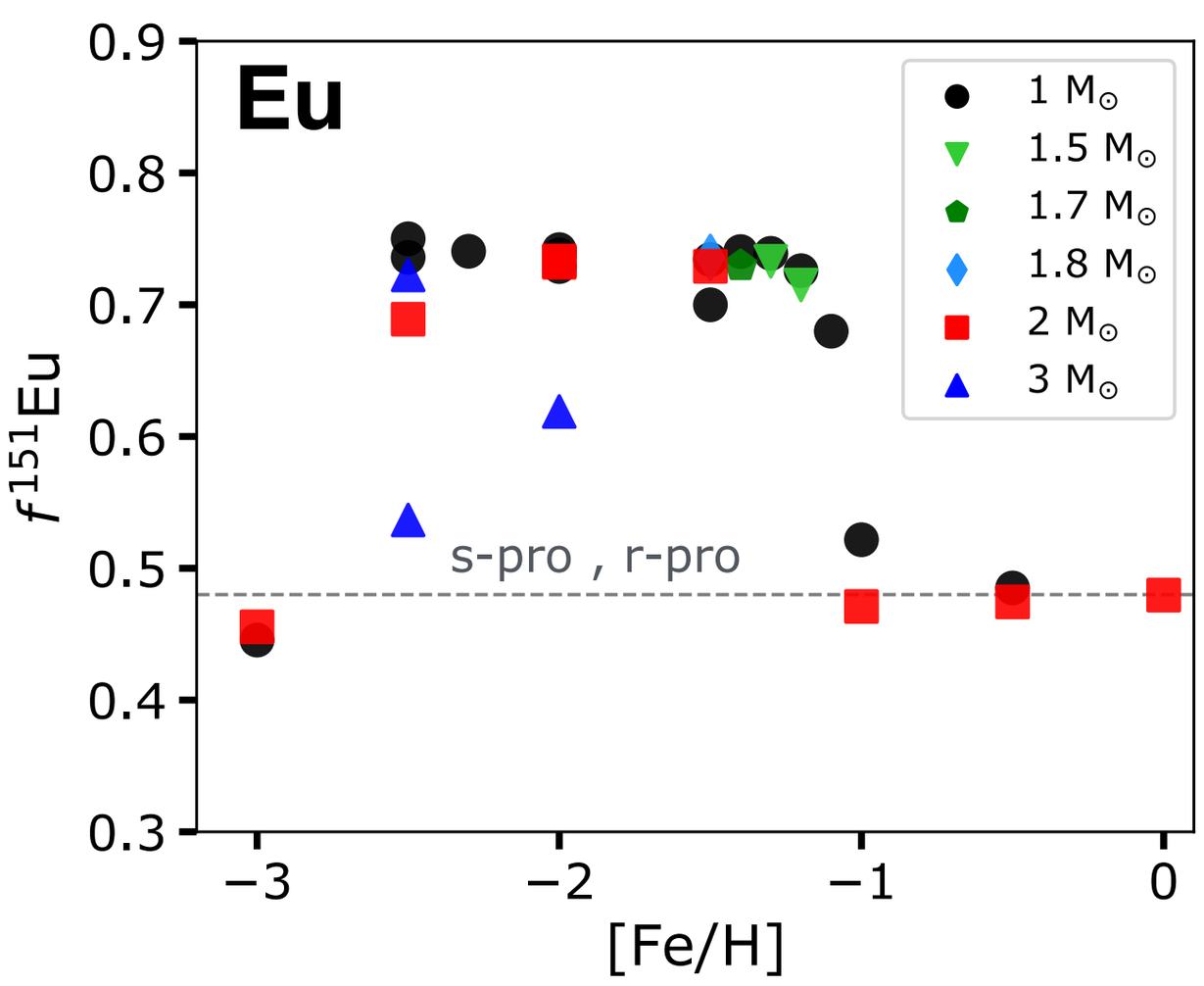


i-process nucleosynthesis is similar in AGB and accreting white dwarfs

Isotopic ratios predicted by s-, i- and r-processes

Choplin+2021, 2025





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

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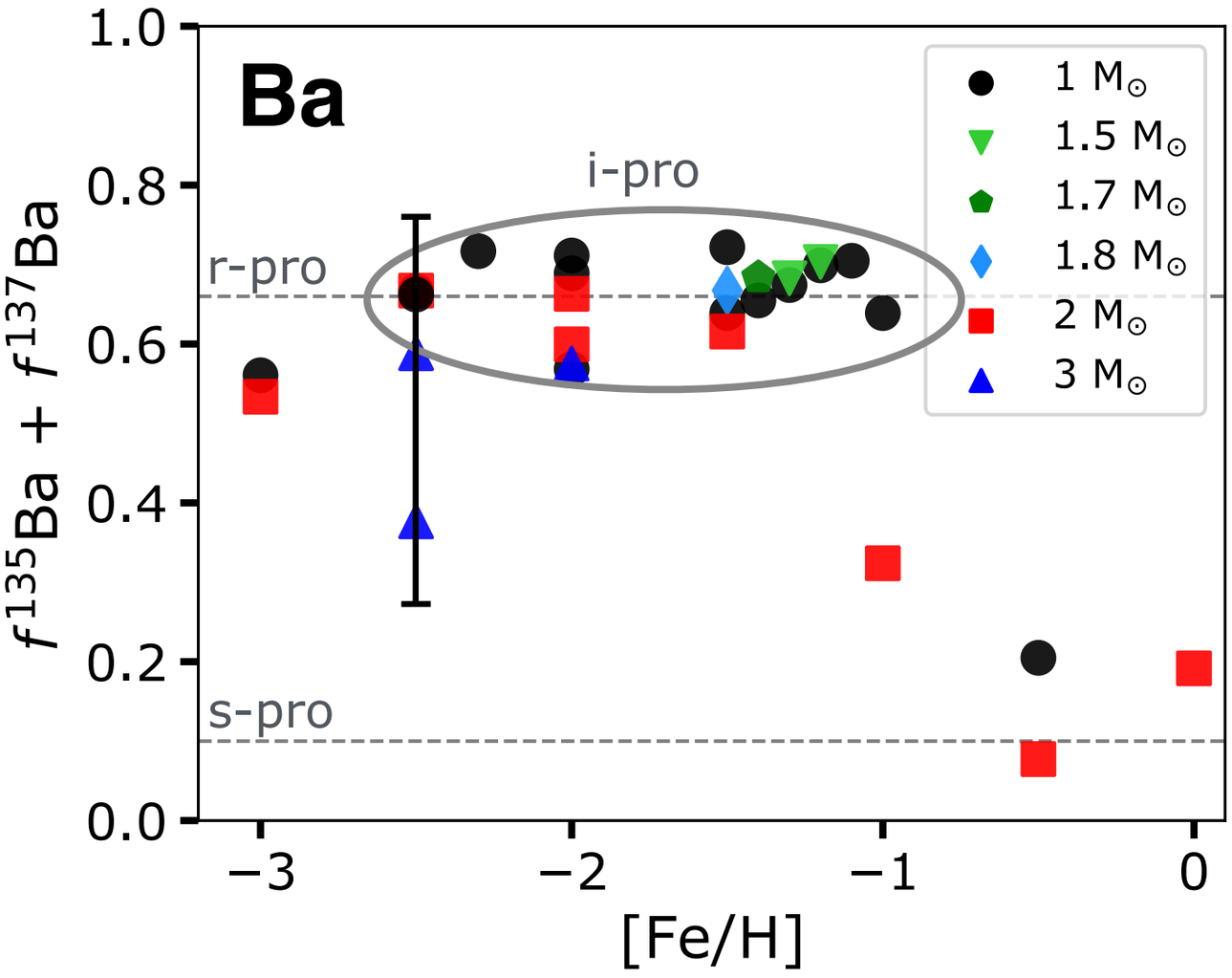
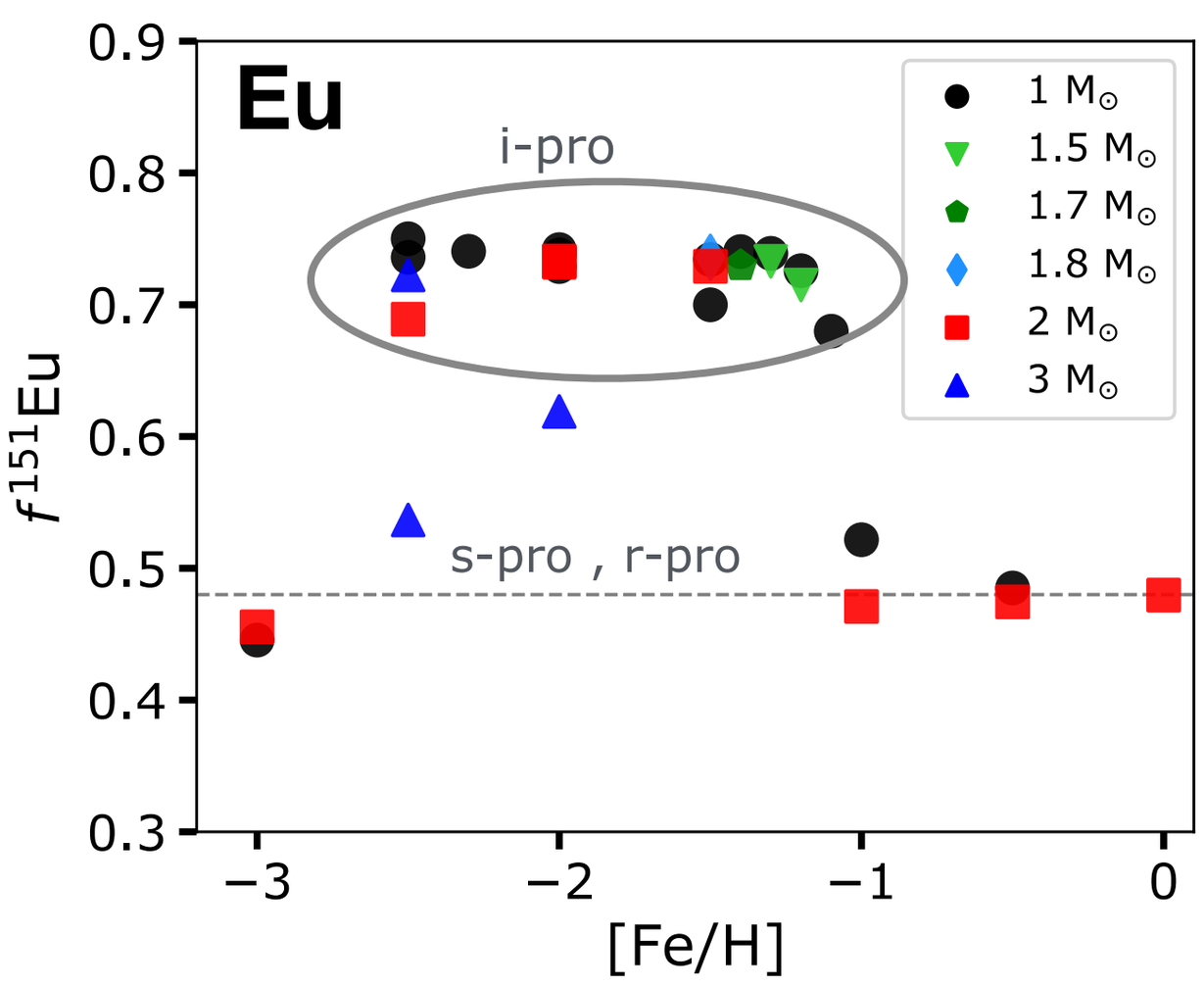
Choplin+2021, 2025





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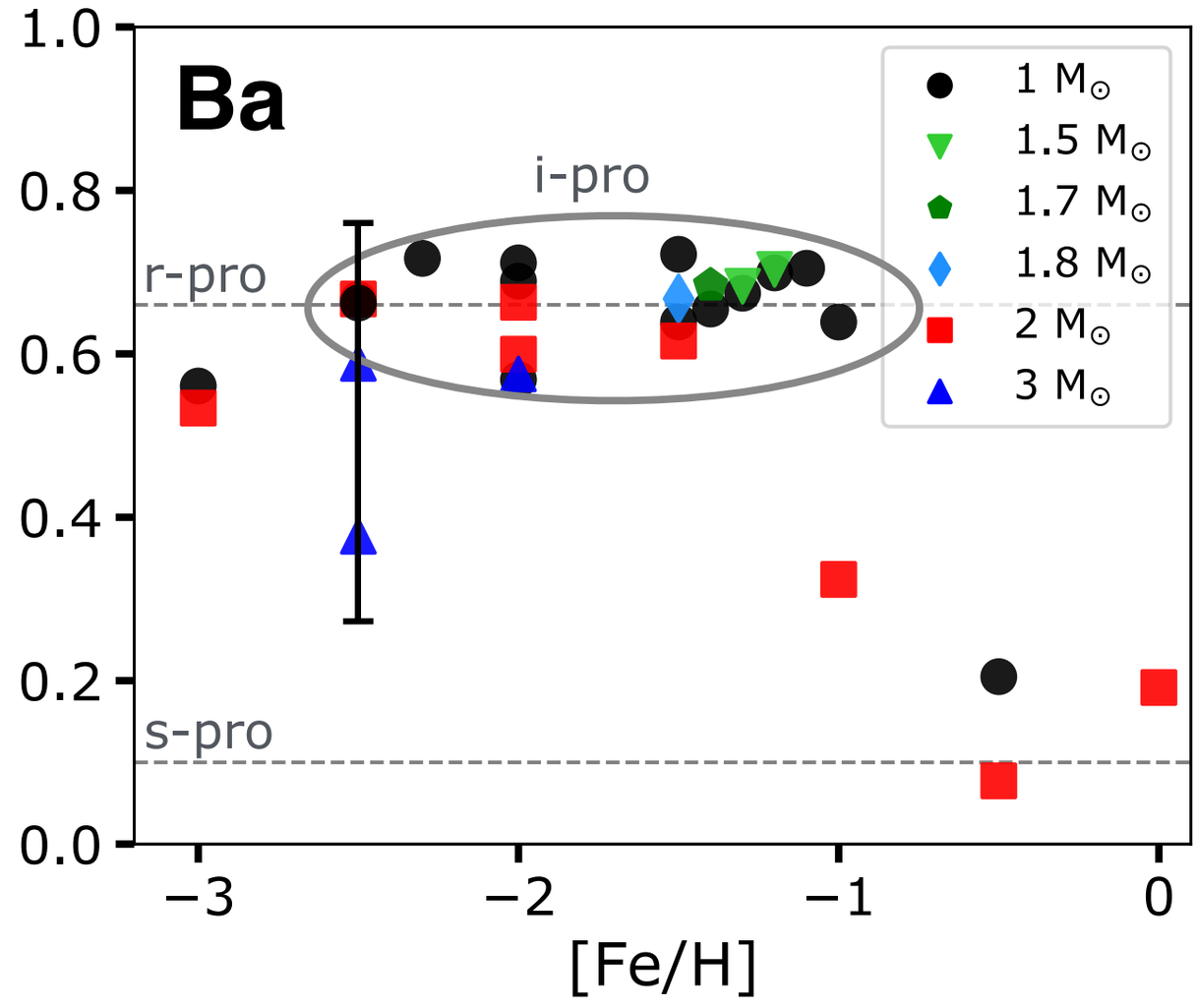
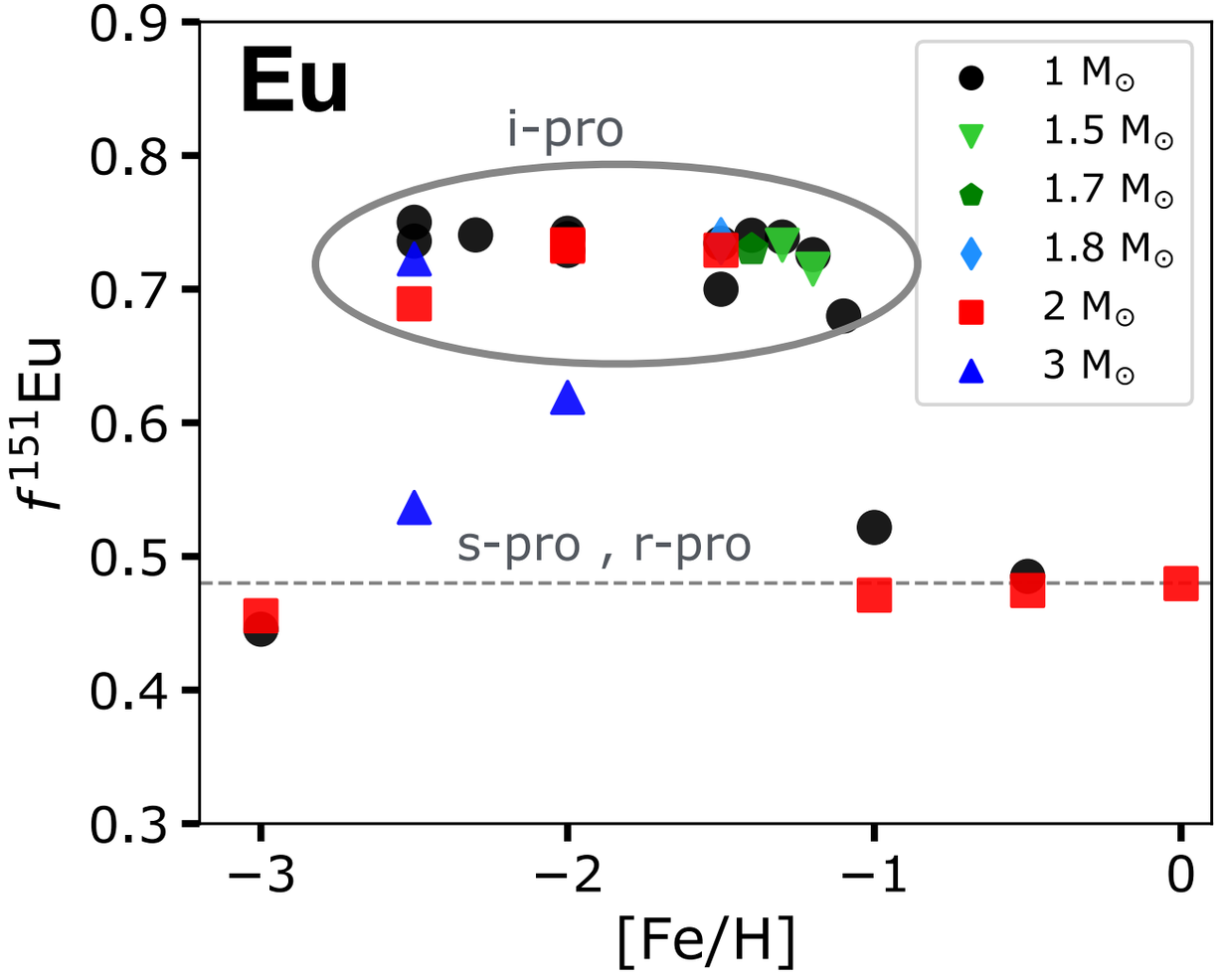
Choplin+2021, 2025





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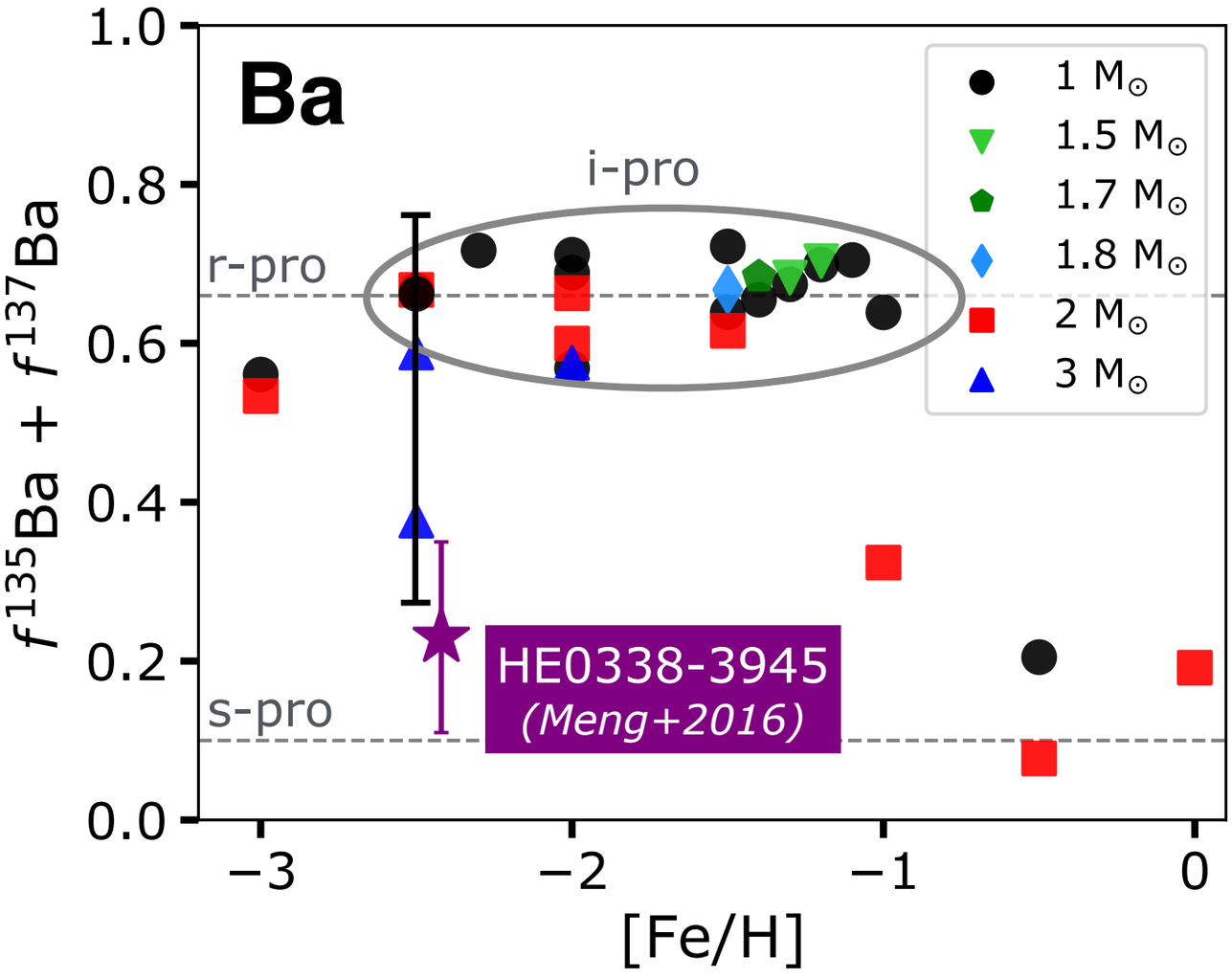
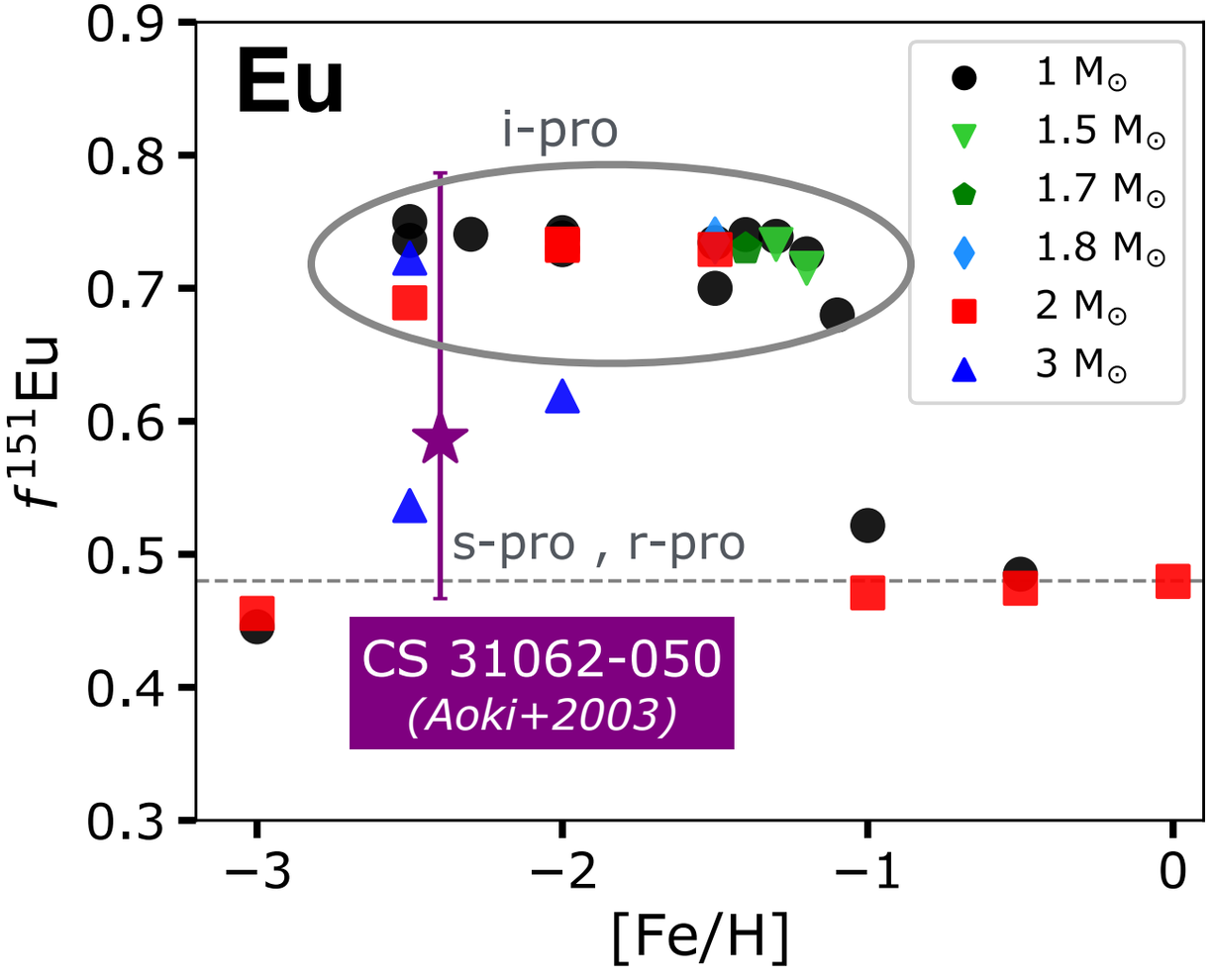
i-process —> distinct isotopic signature

Isotopic ratios predicted by s-, i- and r-processes

Choplin+2021, 2025





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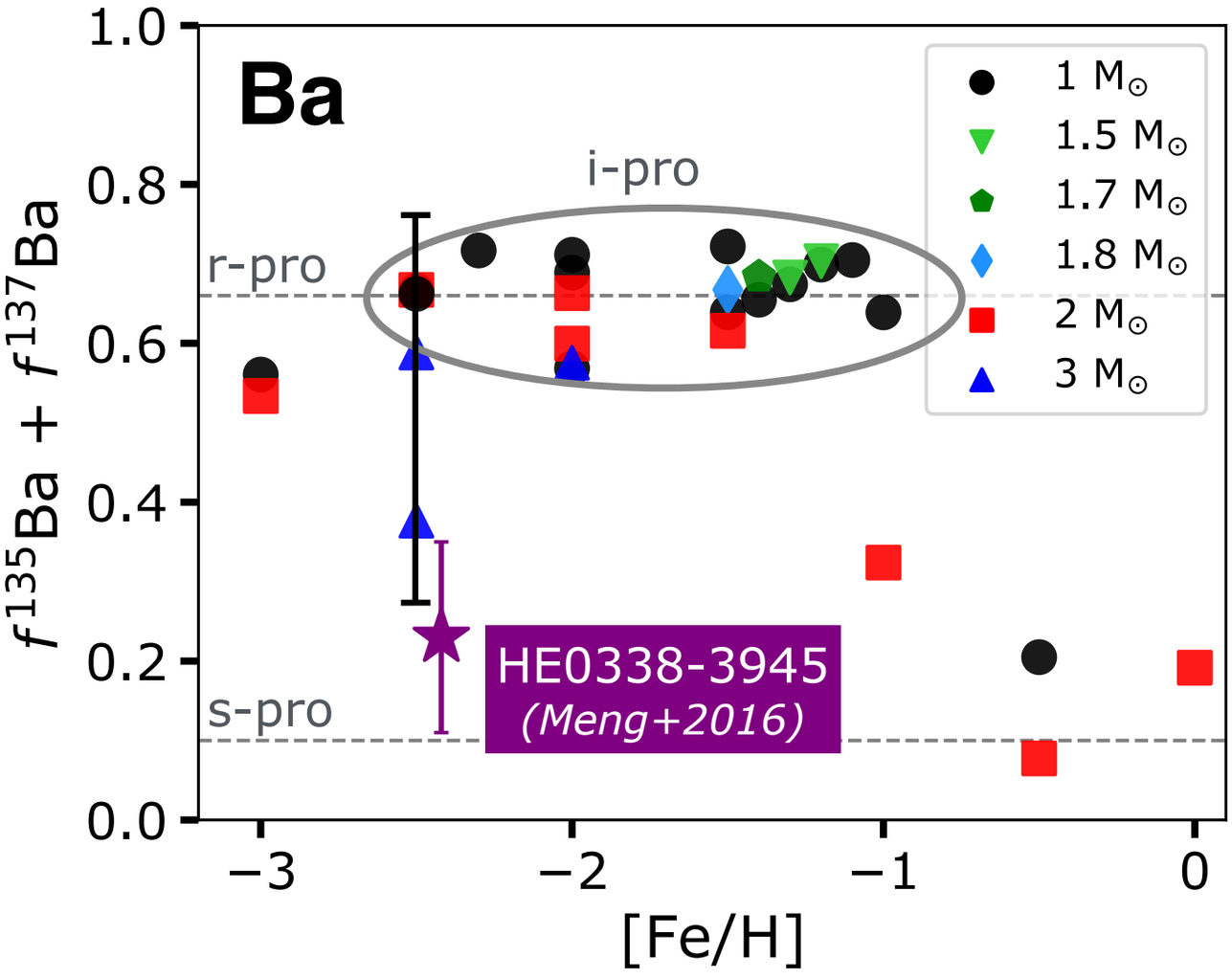

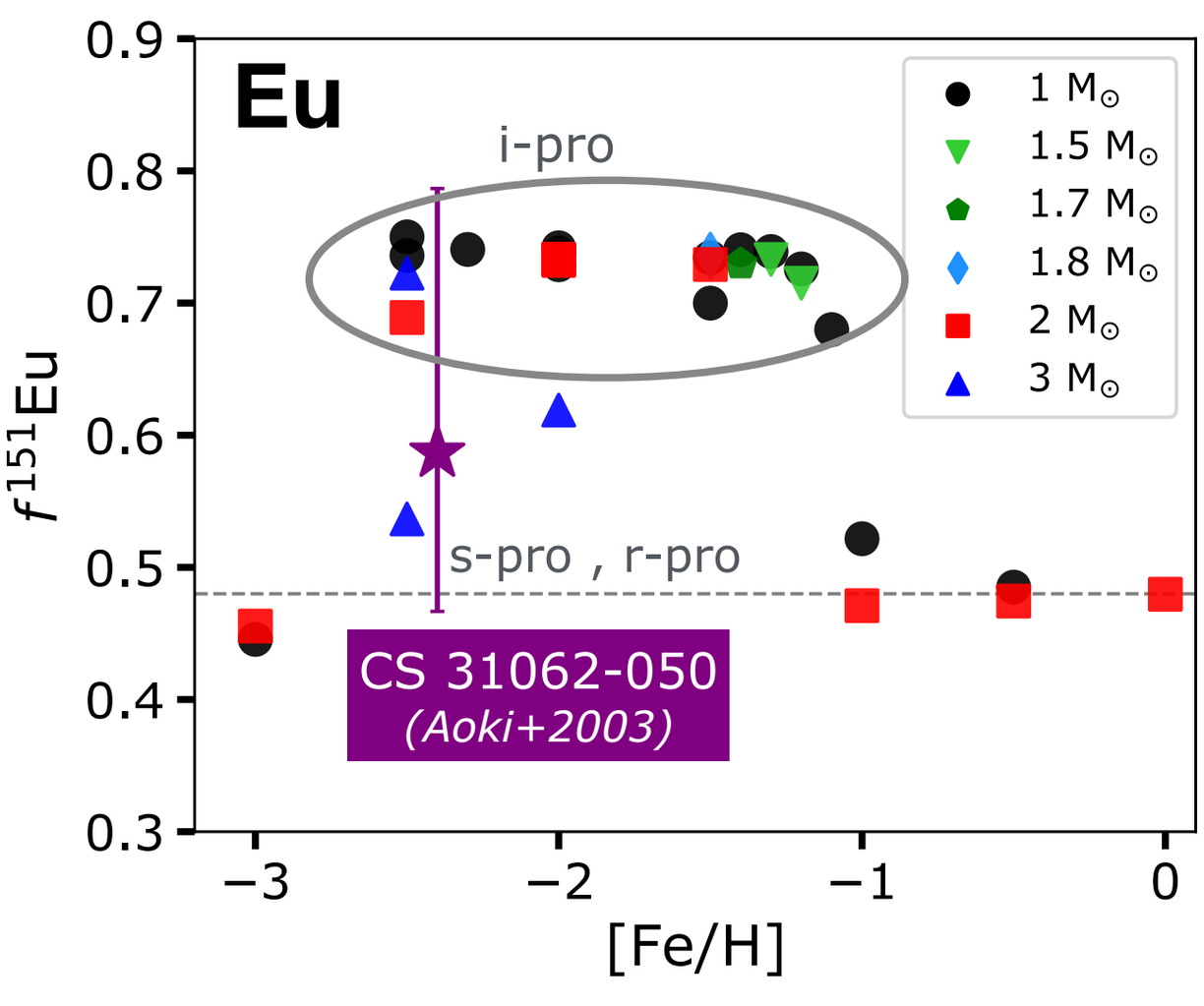

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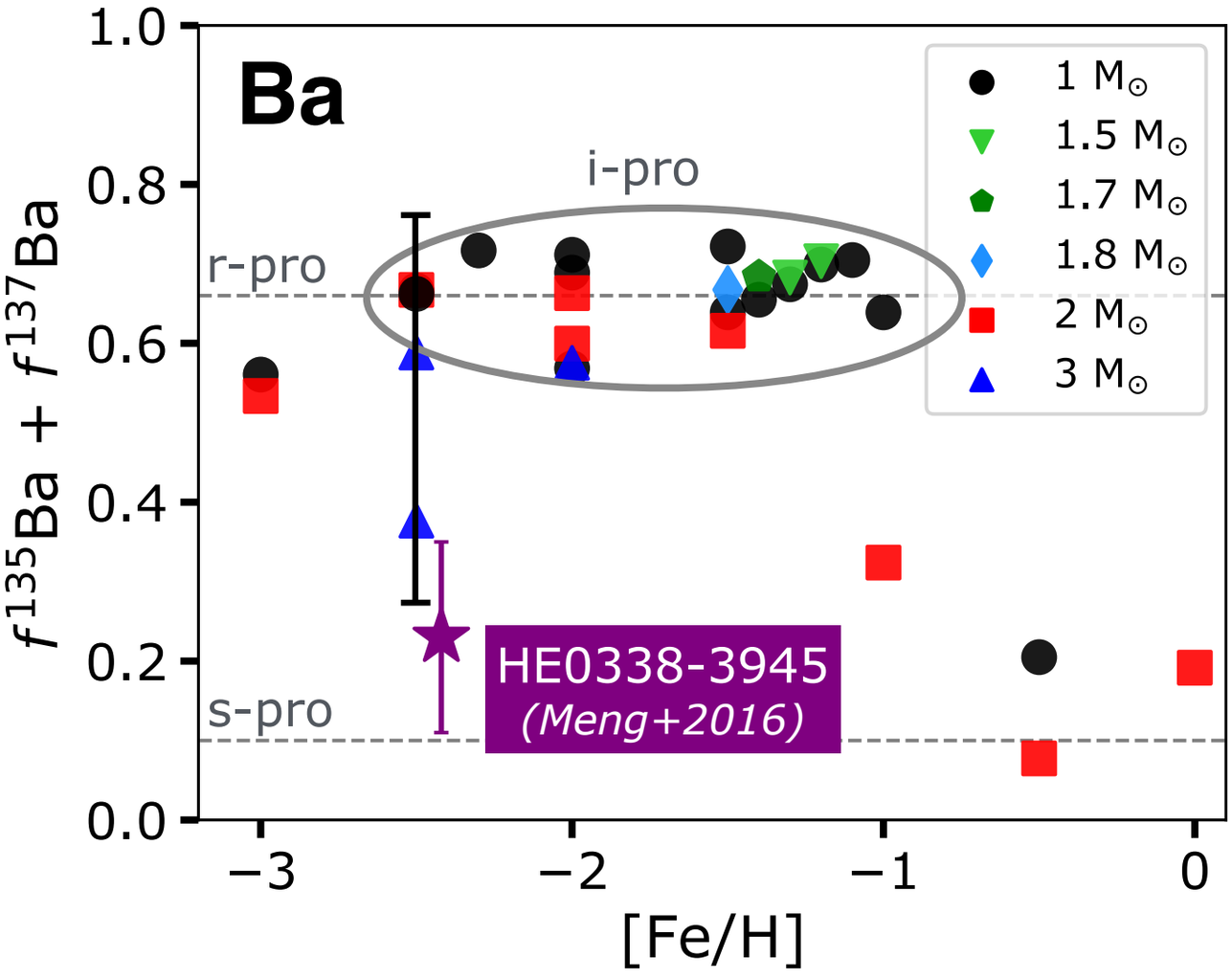
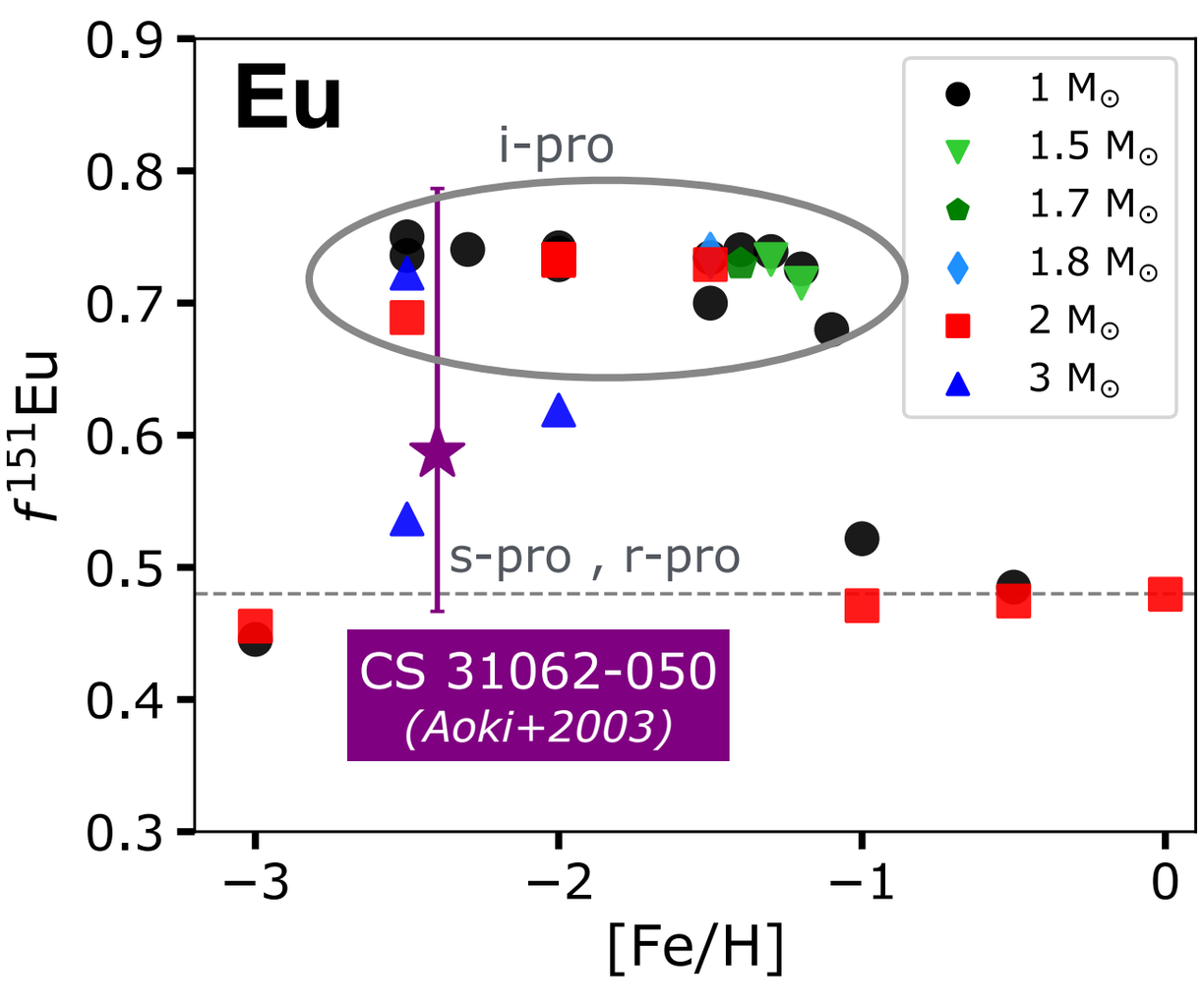
i-process —> distinct isotopic signature

What are the isotopic ratios (Ba, Eu, …) in « i-process » stars ?

Isotopic ratios predicted by s-, i- and r-processes

Choplin+2021, 2025





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Nuclear uncertainties are large…

Summary

- **Ingestion of protons** in a convective He-burning zone **can** trigger the **i-process** **($N_n \sim 10^{15}$ cm^{-3})**
  —> it can **happens naturally** in **many sites**, including **AGB stars**

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- Different **observationnal indication of the i-process**
- **i- and s-process** (radiative & convective) can develop **in the same AGB**
- **Actinides** (Th and U) can be produced by the i-process
- **Nuclear uncertainties** ~ 0.5 - 1 dex (but > 2 dex for actinides)
- **Extra mixing** (overshoot) facilitates proton ingestion (up to ~ solar metallicity)
- **i-process chemical signature** becomes small at [Fe/H] > -1 (in AGBs)

Summary & some open questions

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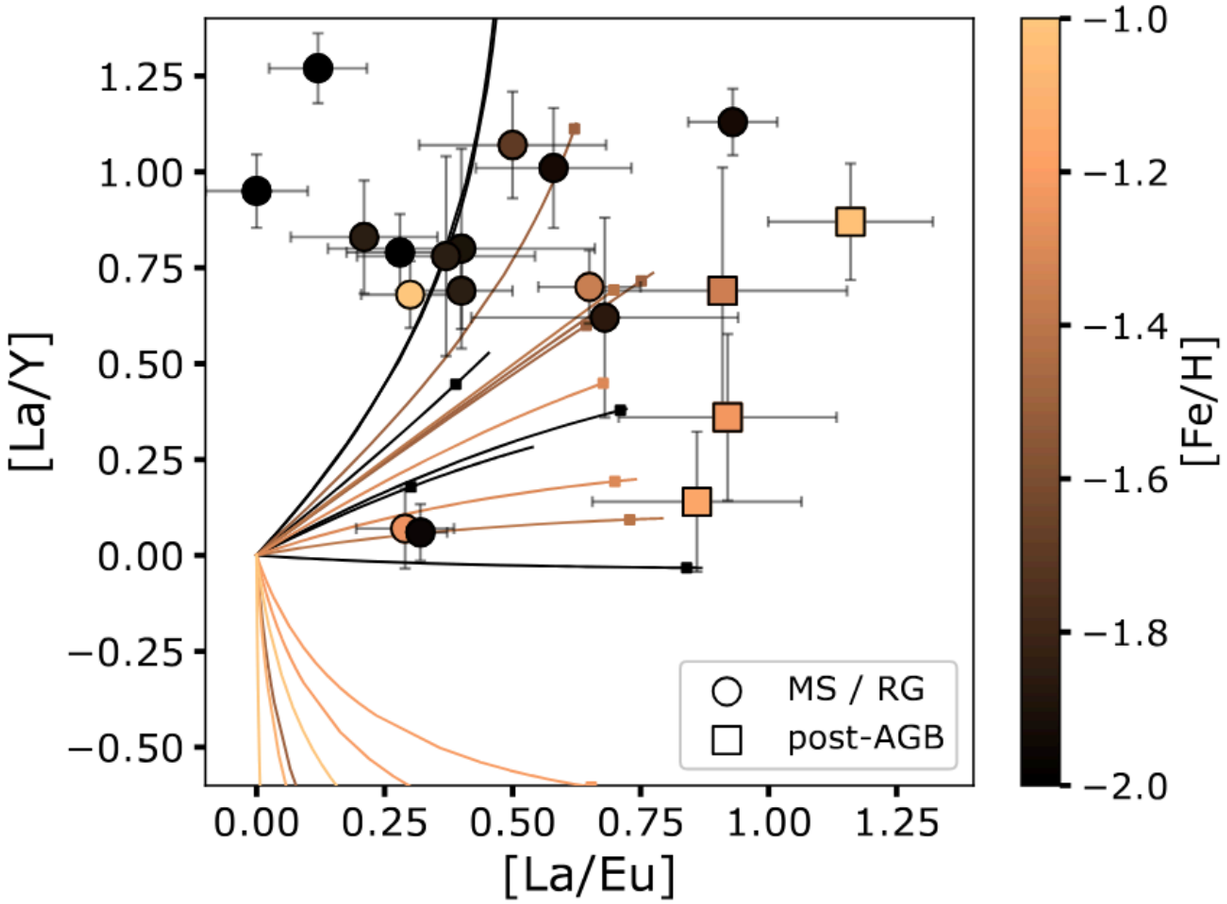
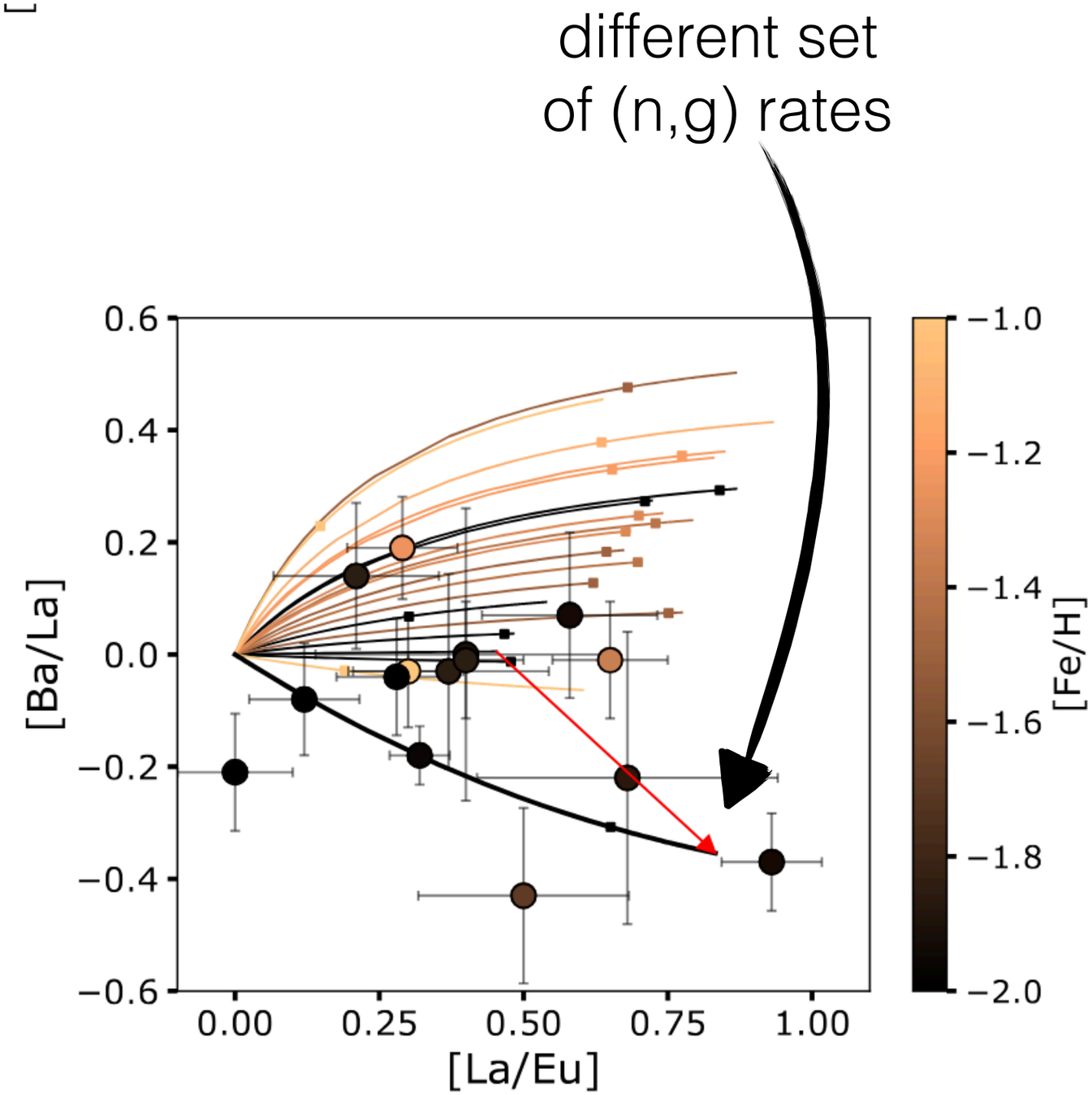
- *What is / are the i-process sites and their relative contribution ?*
- *Effect of rotation / magnetic fields ?* —> *e.g. Piersanti+2013, den Hatogh+2019 for s-process*
- *Experimental constraints on critical (n,γ) rates* —> *e.g. Oslo method*
- *Galactic chemical evolution modeling of the i-process* —> *e.g. Coté+2018 for accreting WD*
- *Th and isotopic ratios in « i-process stars » ?*
- *Dedicated studies on the « split » ? (1D and 3D)*
- *Results from 3D models can improve 1D models*
  —> *e.g. Stephens+2021, Rizzuti+2023, …*



Lines : dilution curves of the AGB material

Choplin+2024

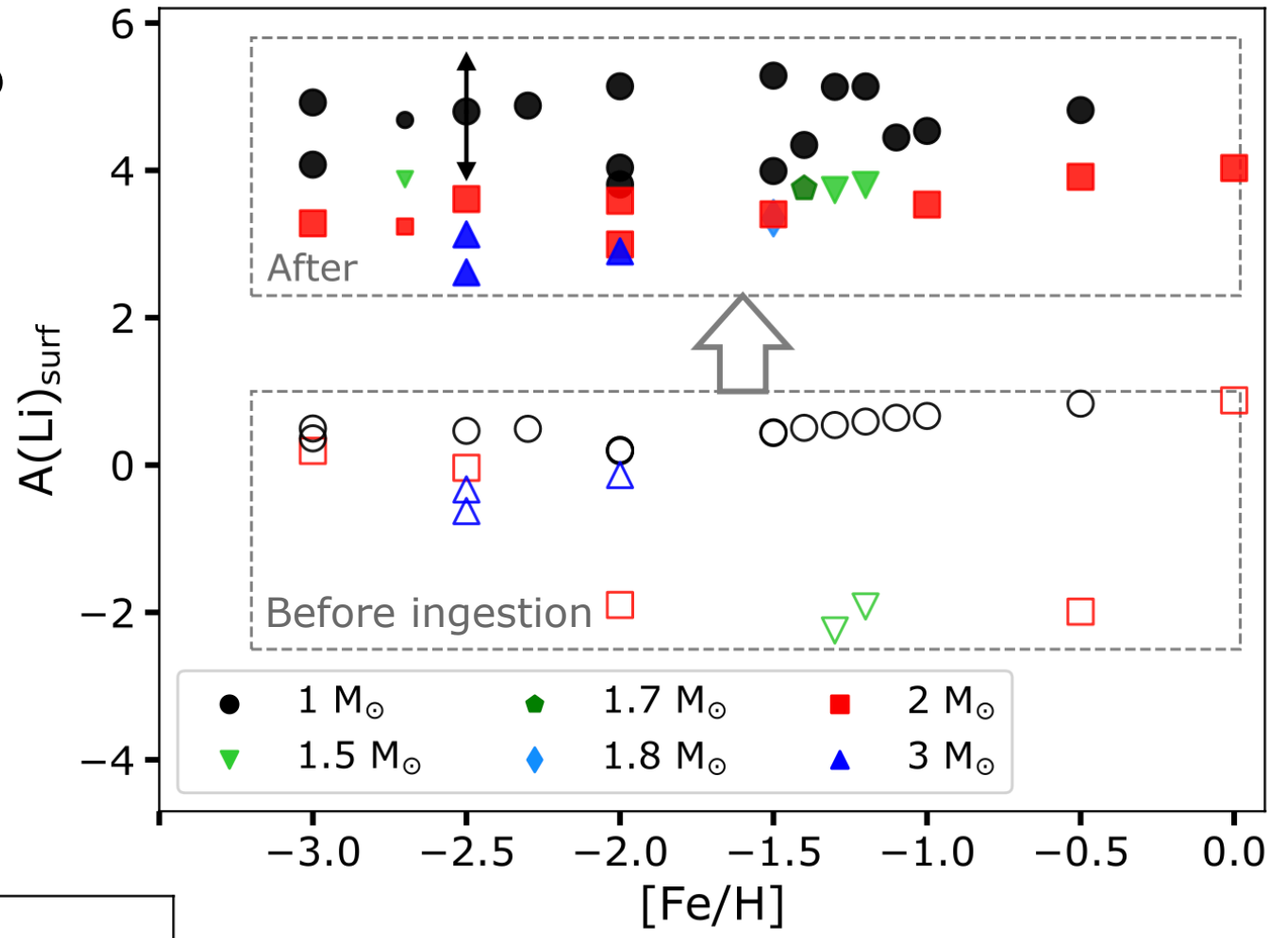


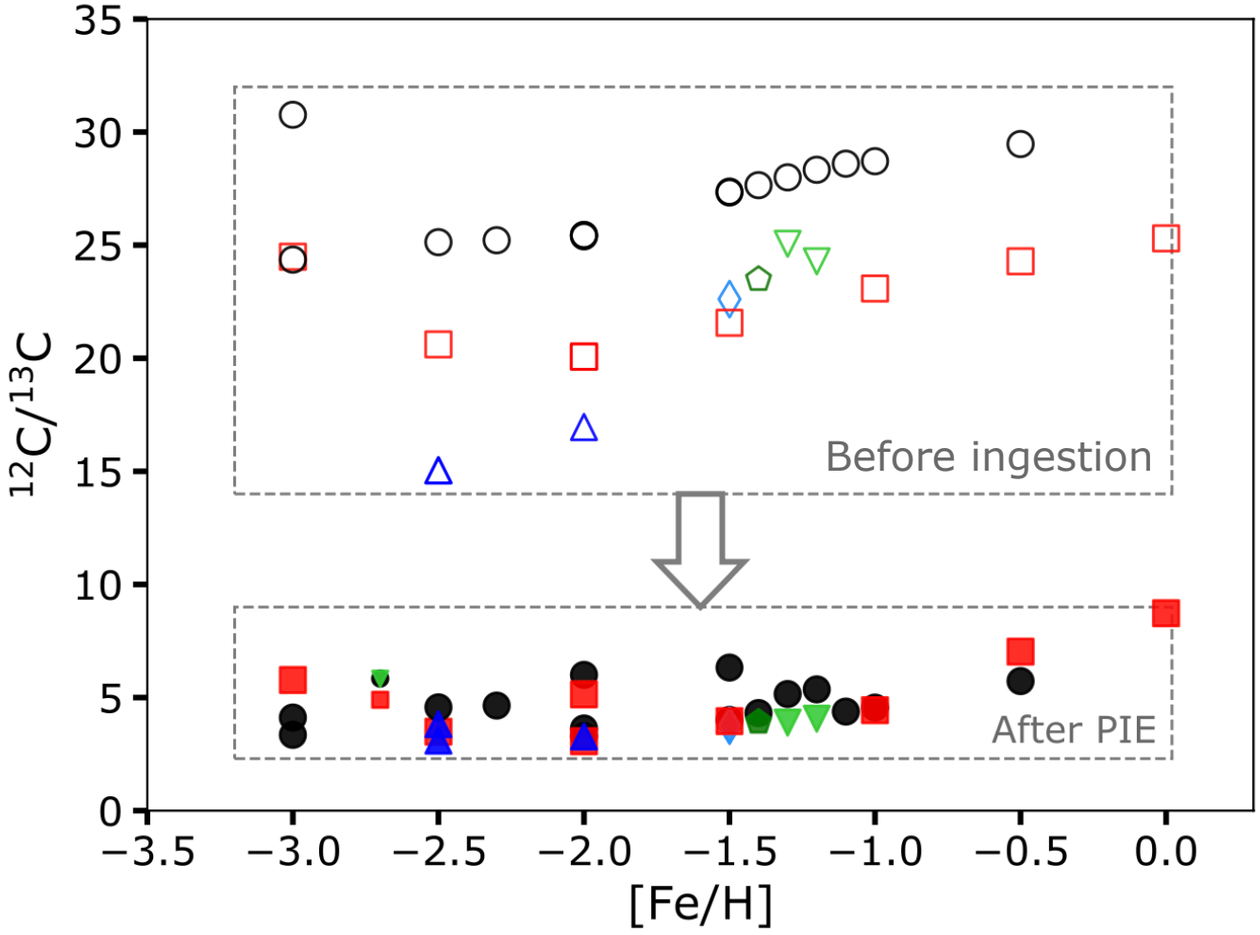
What about light elements ?
(in AGB)

Proton ingestion produces Lithium

$^{3}He(\alpha,\gamma)^{7}Be(e^{-},\nu_e)^{7}Li$

Iwamoto+2004, Cristallo+2009, Choplin+2024



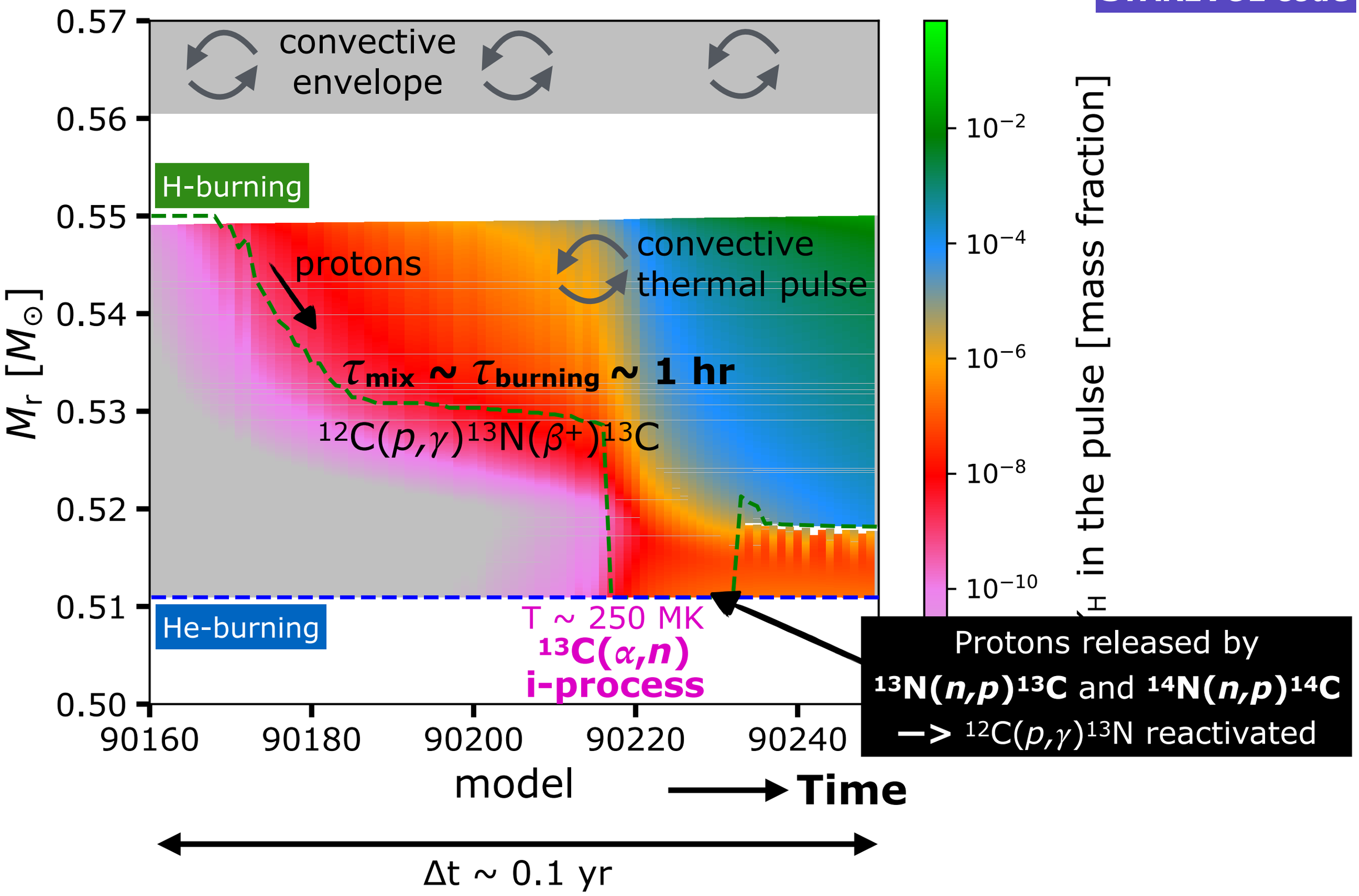


Proton ingestion produces ^{13}C

i-process (in AGB) comes with low $^{12}C/^{13}C$ ratios and Li enrichment

The i-process engine (1 $M_\odot$, [Fe/H] = -2.5, AGB model)

STAREVOL code



The i-process engine (1 $M_{\odot}$, [Fe/H] = -2.5, AGB model)

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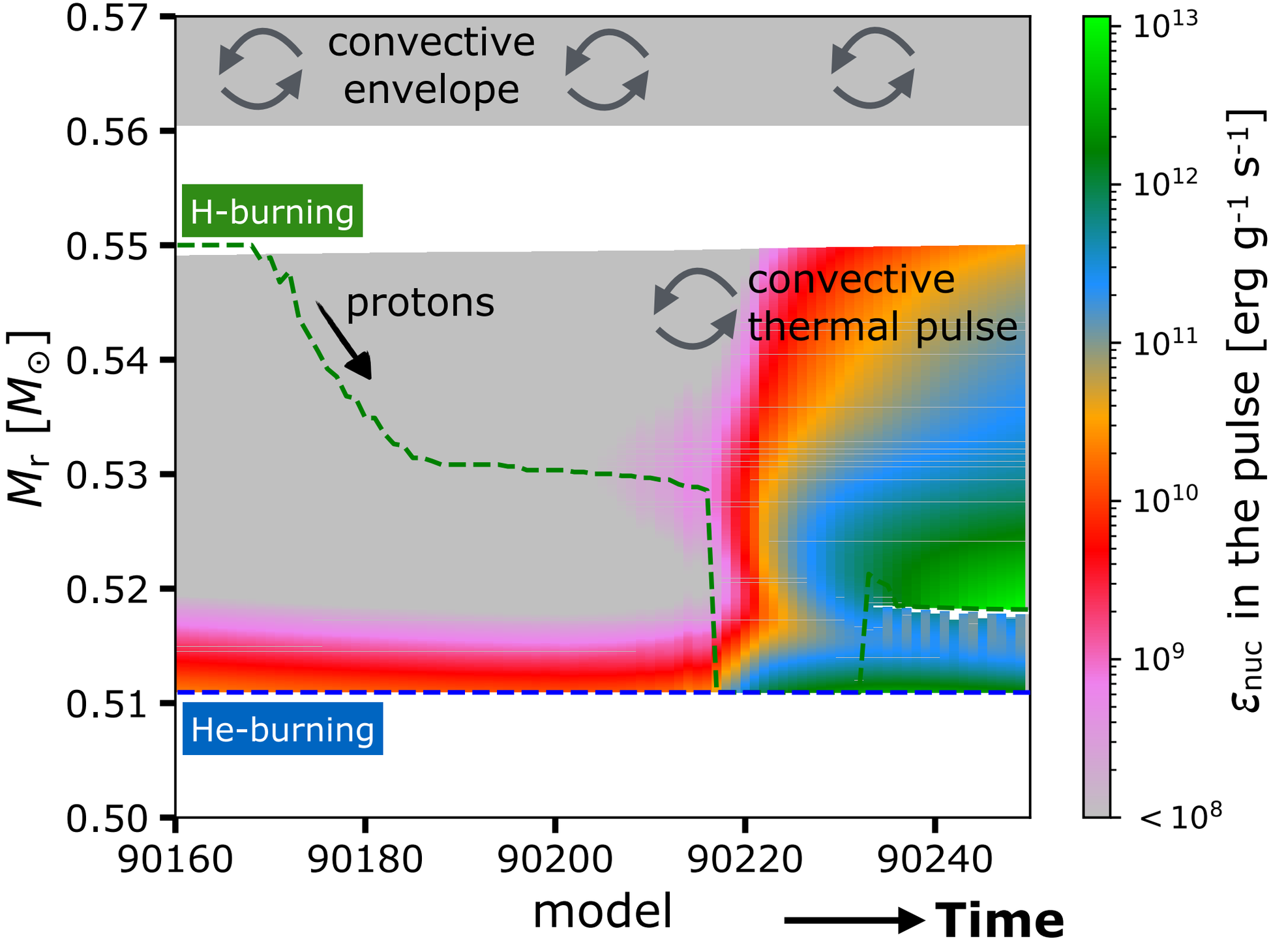


Proton ingestion in a 1 $M_\odot$, [Fe/H] = -2.5, AGB model

STAREVOL code

Abundance variation of nucleus *i* with time

transport nucleo.

$$\frac{\partial X_i}{\partial t} = \frac{\partial}{\partial m_r}\left[(4\pi r^2 \rho)^2 D \frac{\partial X_i}{\partial m_r}\right] + \left.\frac{\partial X_i}{\partial t}\right|_{\rm nuc}$$

mixing timescale = burning timescale = 1 hr

=> nucleosynthesis and transport of chemicals are solved simultaneously

Requires many inversions of (N x K) x (N x K) matrices

N : # of shells
K : # of chemical species

=> ~ 10^6 x 10^6 matrices

(but sparse)

protons

He-burning

i-process

M_r [$M_\odot$]

0.57
0.56
0.55
0.54
0.53
0.52
0.51
0.50

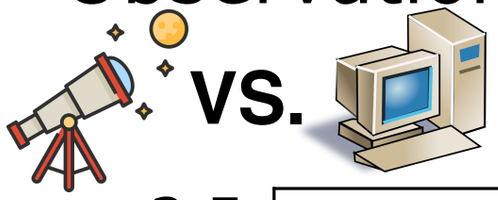
90100 90200 90300 90400 90500 90600 90700

model → **Time**

Neutron density [cm^{-3}]

10^{14}
10^{12}
10^{11}
$< 10^{10}$

Observational indications of the i process in a CEMP-r/s star



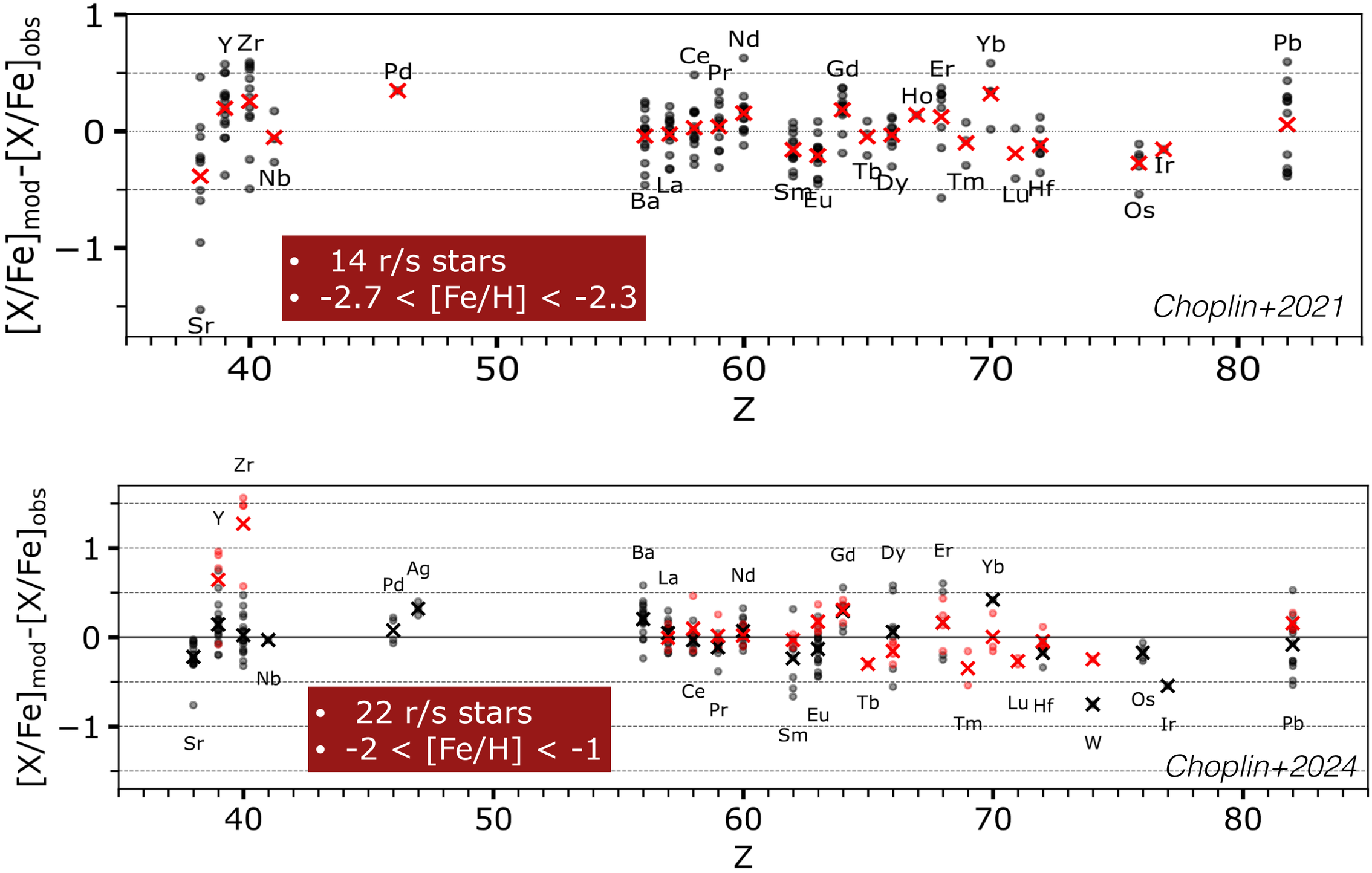
vs.

Observations : Johnson+2004, Aoki+2006, Lai+2007

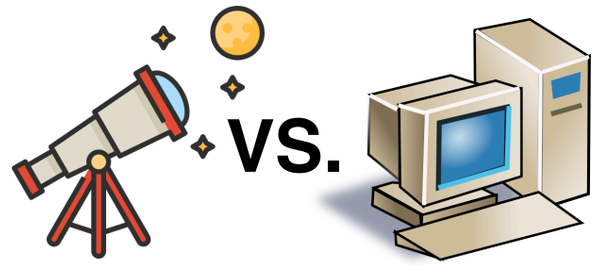
	s-pro	r-pro	r+s	i-pro
χ^2	5.38	7.44	3.20	1.73

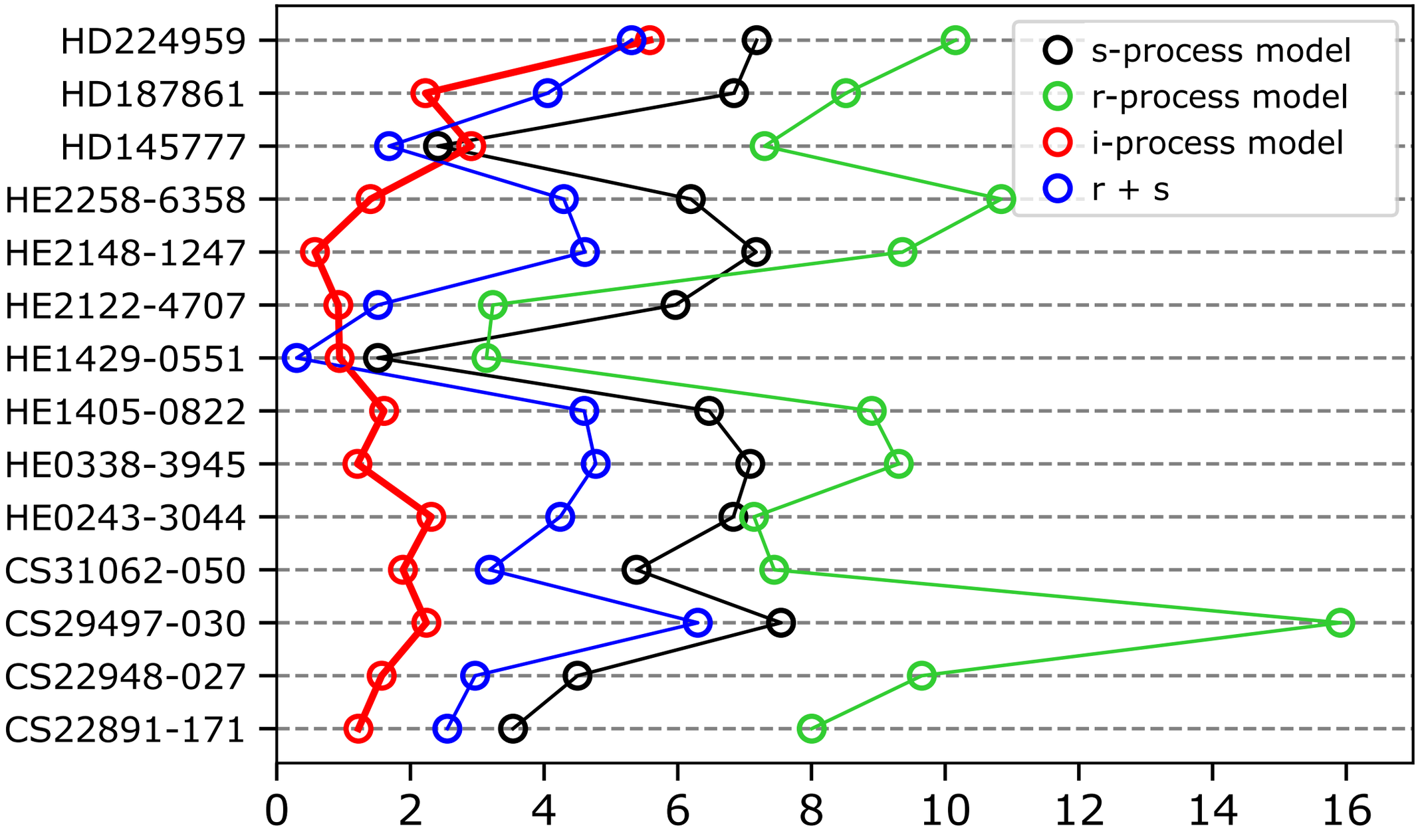
i-process gives the best solution

i-process AGB models vs. observed r/s-stars (residuals)



i-process AGB models vs. observed « i-stars »

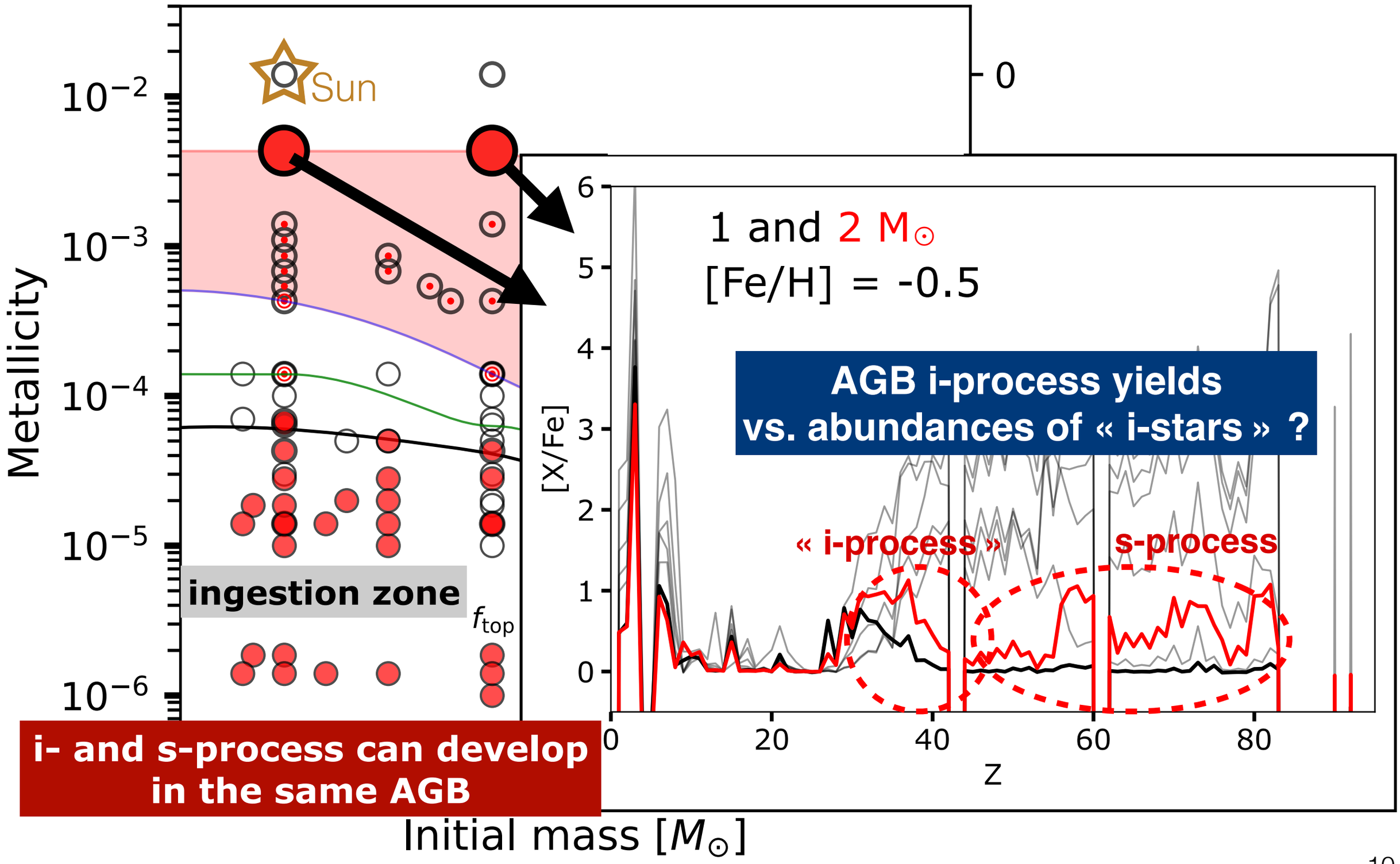




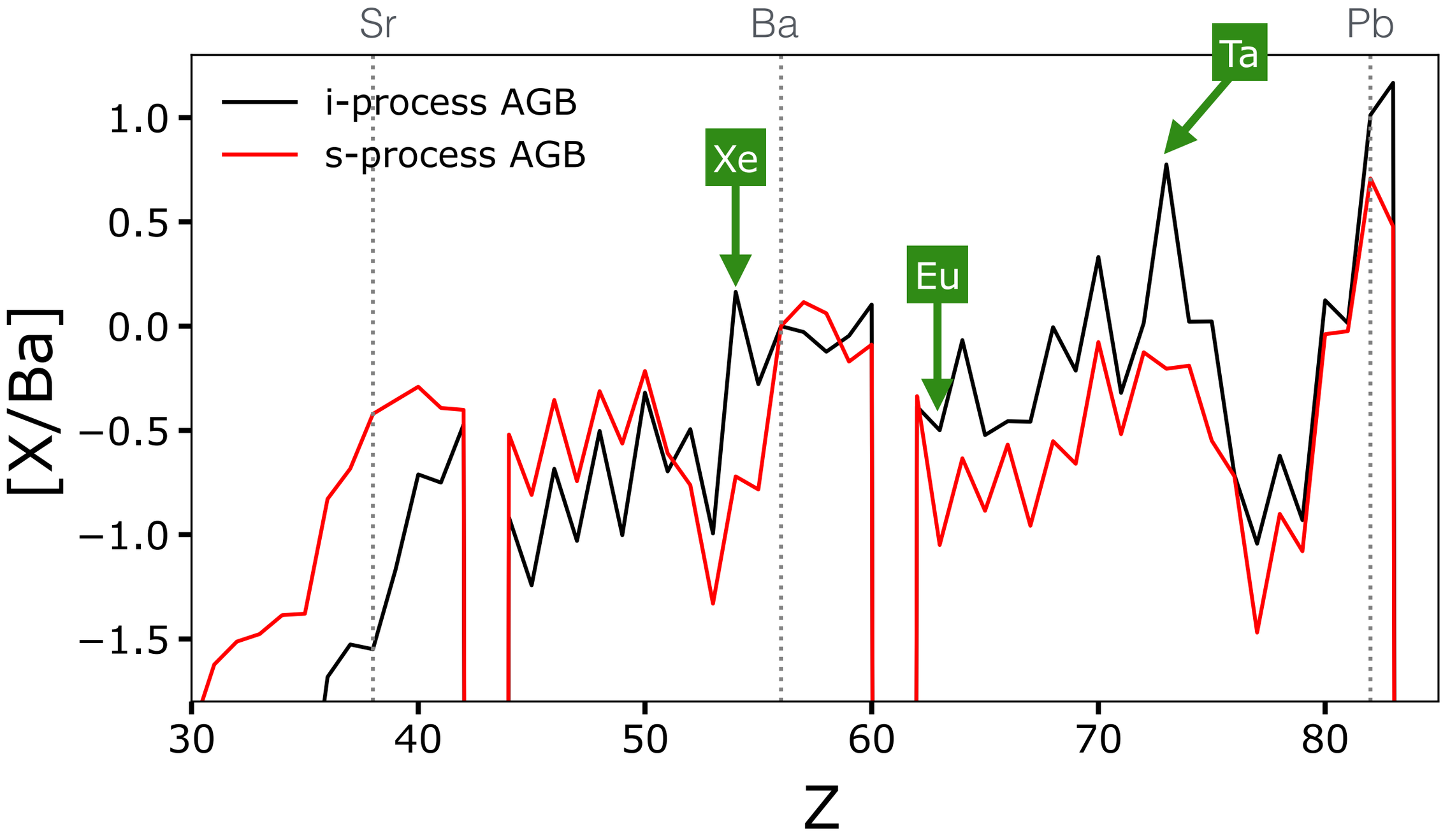
These stars better explained by i-process than s- or r-process

Choplin+2021, A&A + corrigendum

Nucleosynthetic yields of AGB experiencing H-ingestion

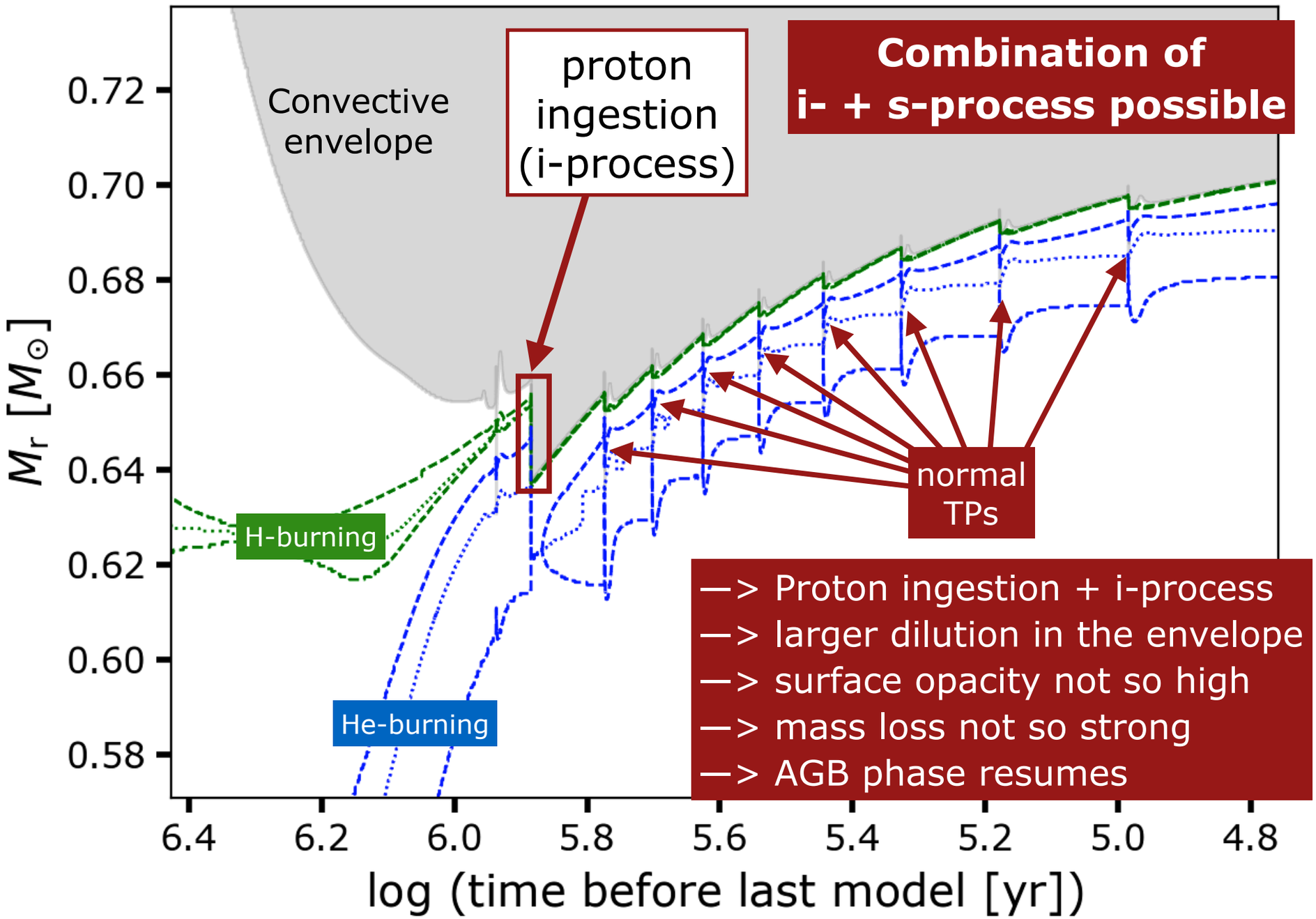


AGB s-process vs. AGB i-process



The case of a 2 $M_\odot$, [Fe/H] = -2.5 AGB model

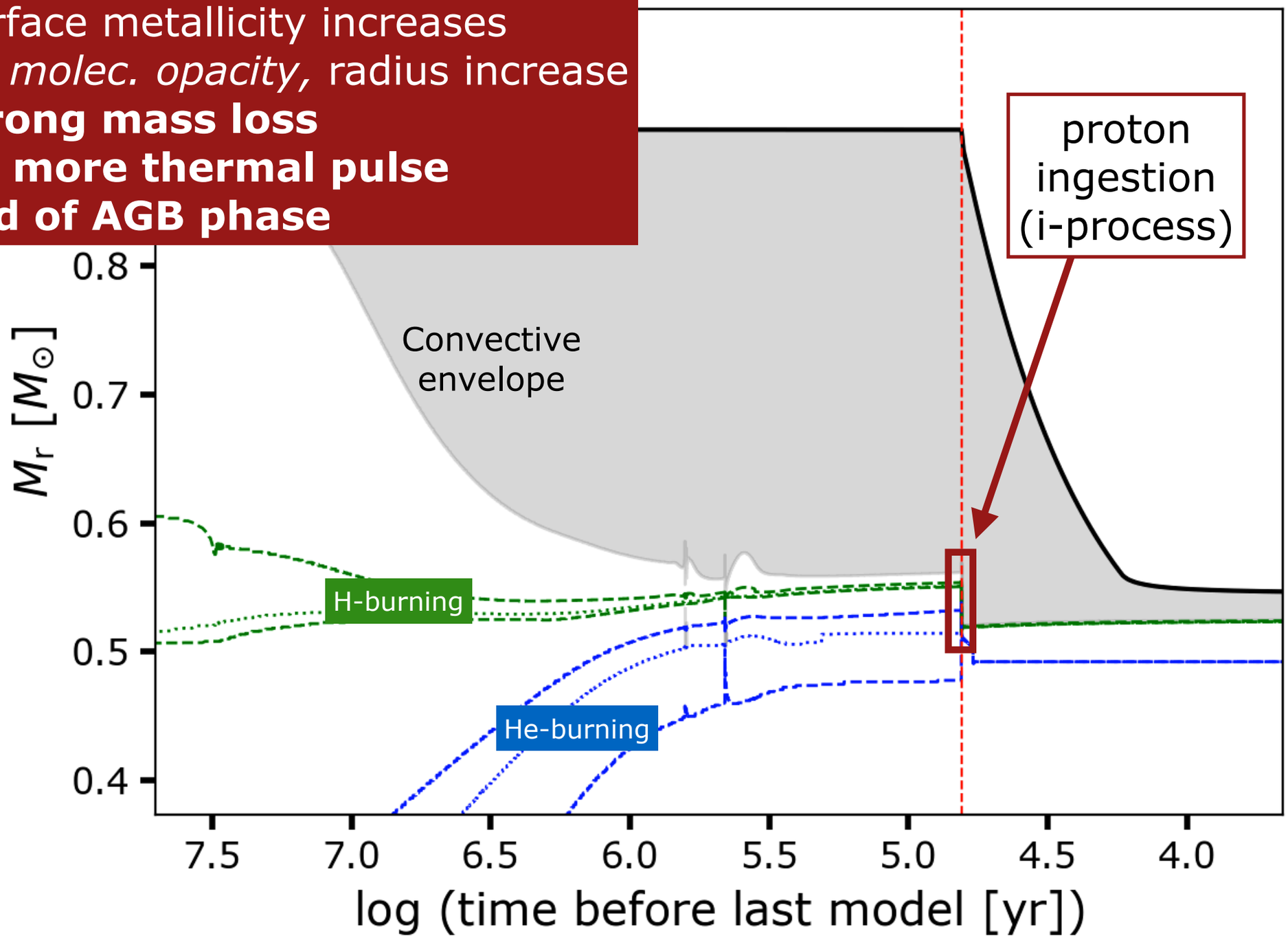
($Z = 4 \times 10^{-5}$)



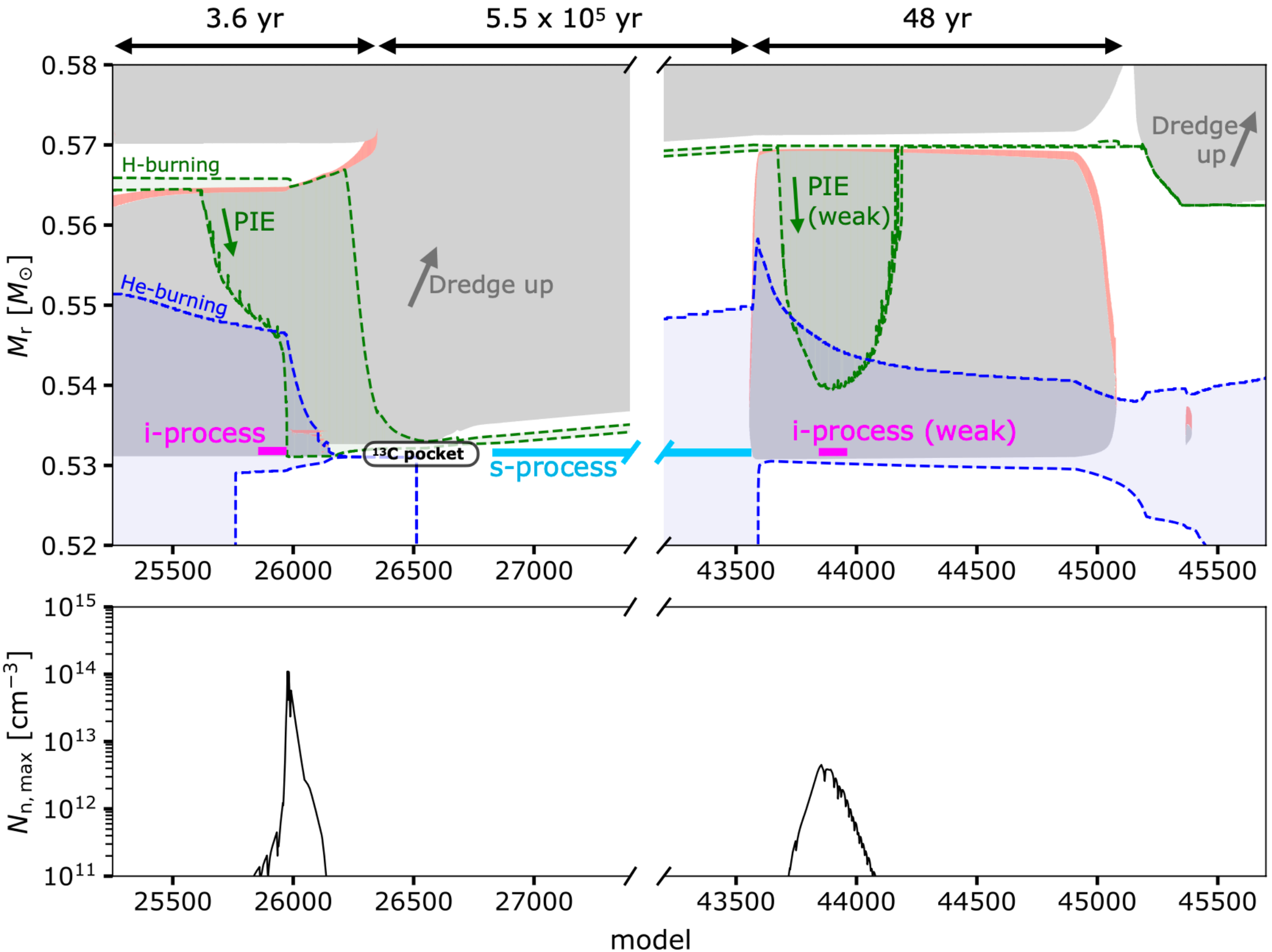
The **i-process** in a 1 $M_\odot$, [Fe/H] = -2.5 AGB model

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

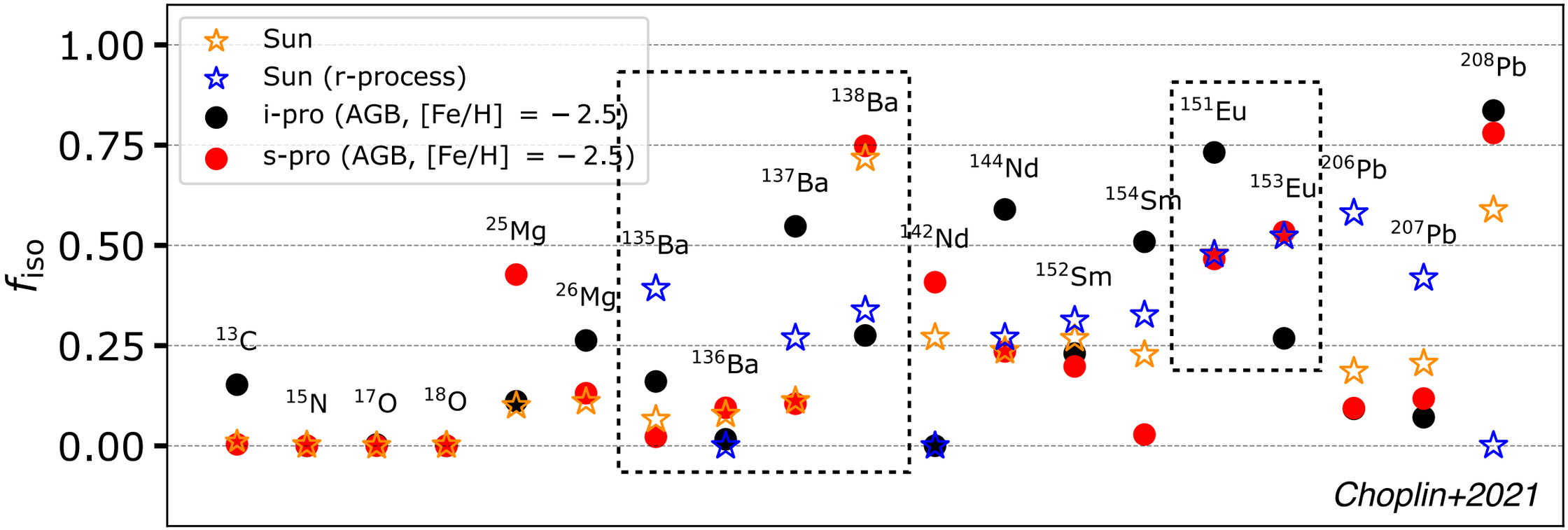
CNO + i-process to the surface
—> Surface metallicity increases
—> *CO molec. opacity,* radius increase
—> Strong mass loss
—> No more thermal pulse
—> end of AGB phase



A 2 $M_\odot$ AGB at [Fe/H] = -0.5 : i- and s-process



Isotopic ratios predicted by s-, i- and r-processes



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