Image credit :
NASA, ESA, and C.R. O'Dell

The intermediate neutron capture process in AGB stars

Arthur Choplin

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Collaborators

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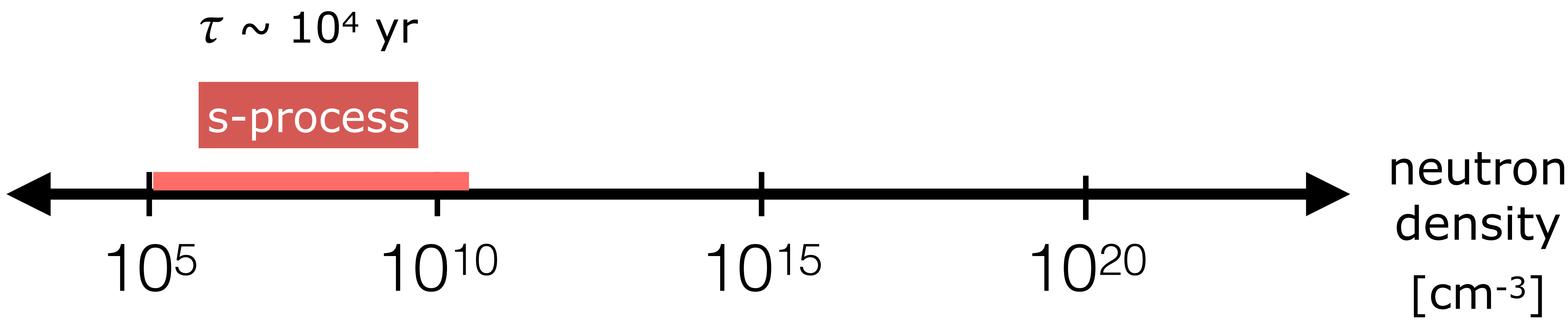
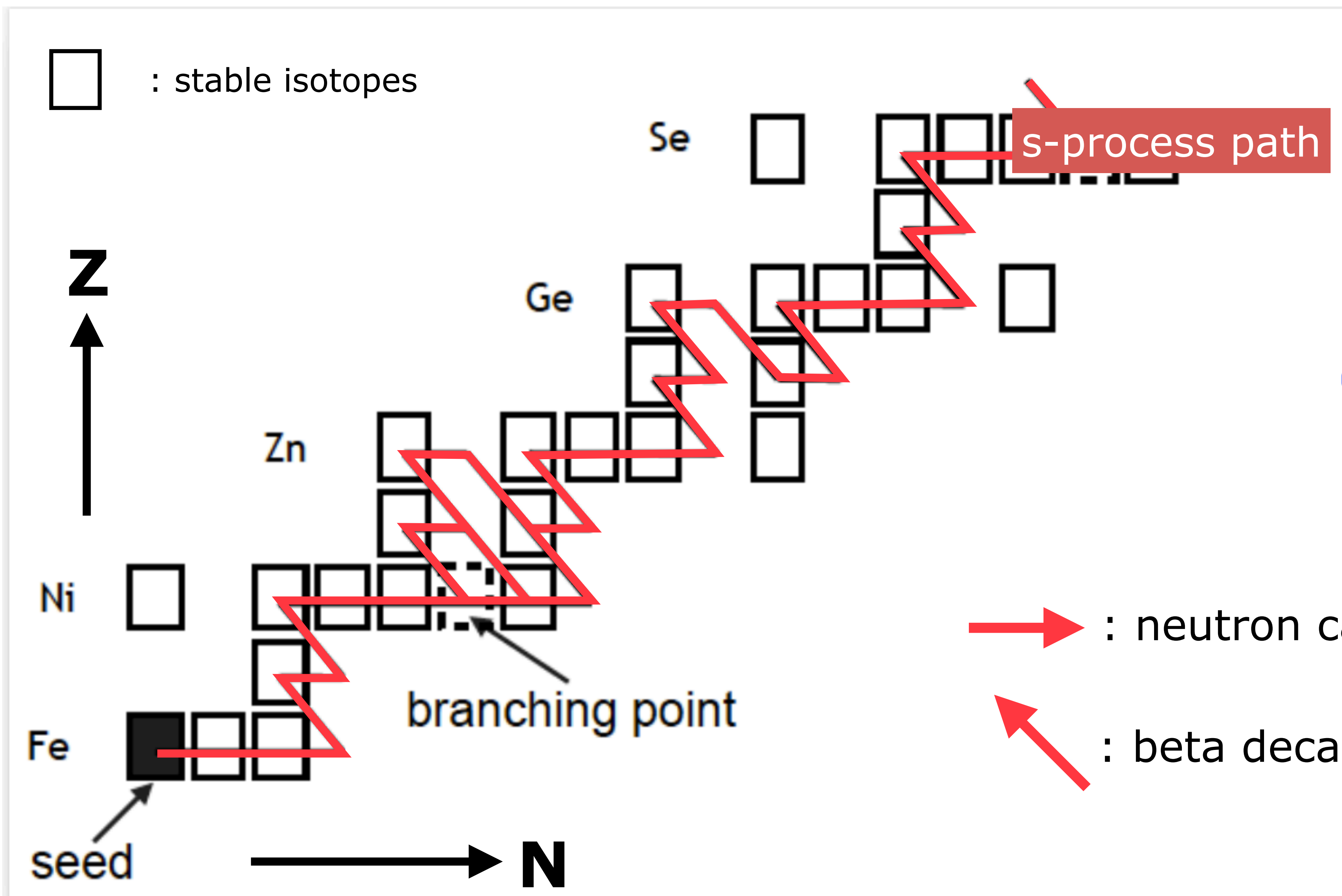
ULB

fnrs
FREEDOM TO RESEARCH

NPA XI, 15 - 20 September 2024

Neutron capture processes: slow, intermediate, rapid





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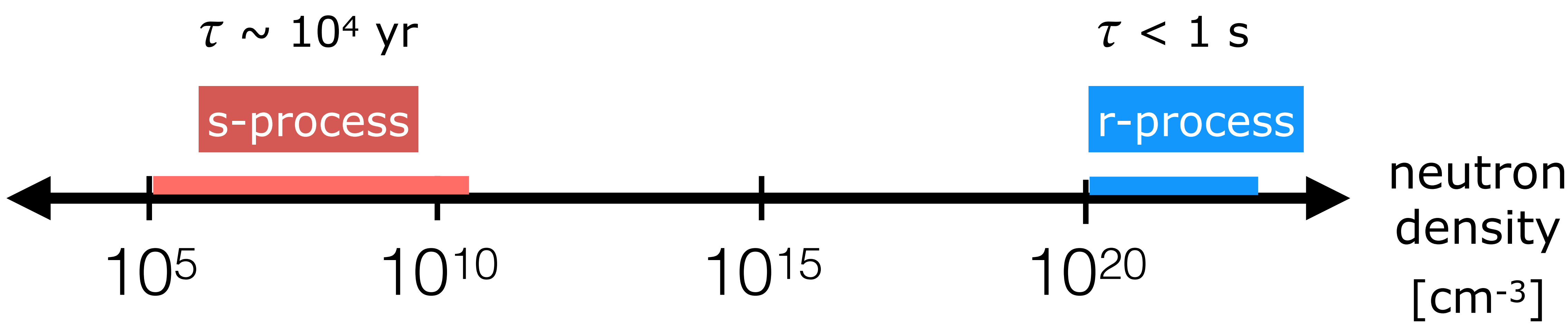

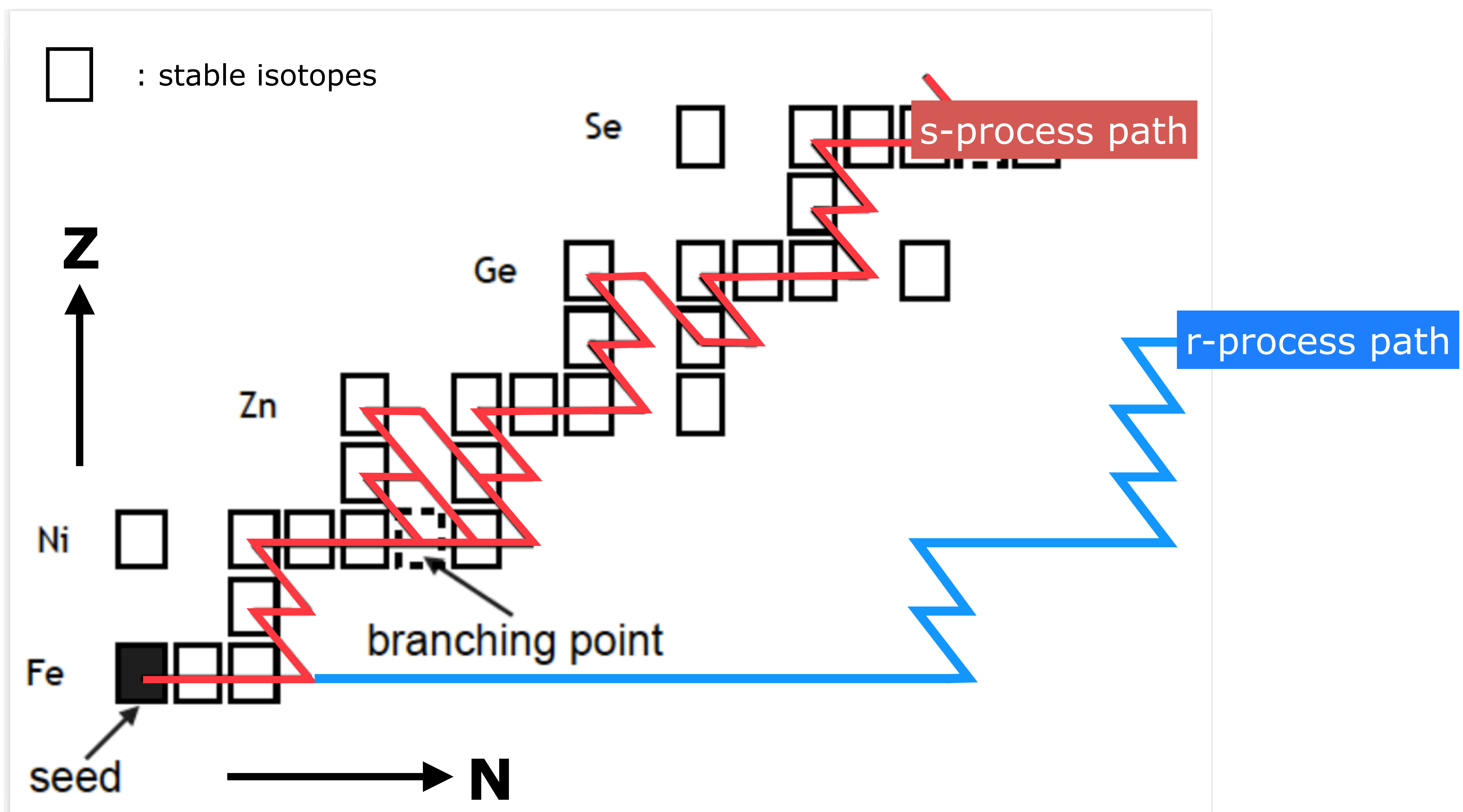

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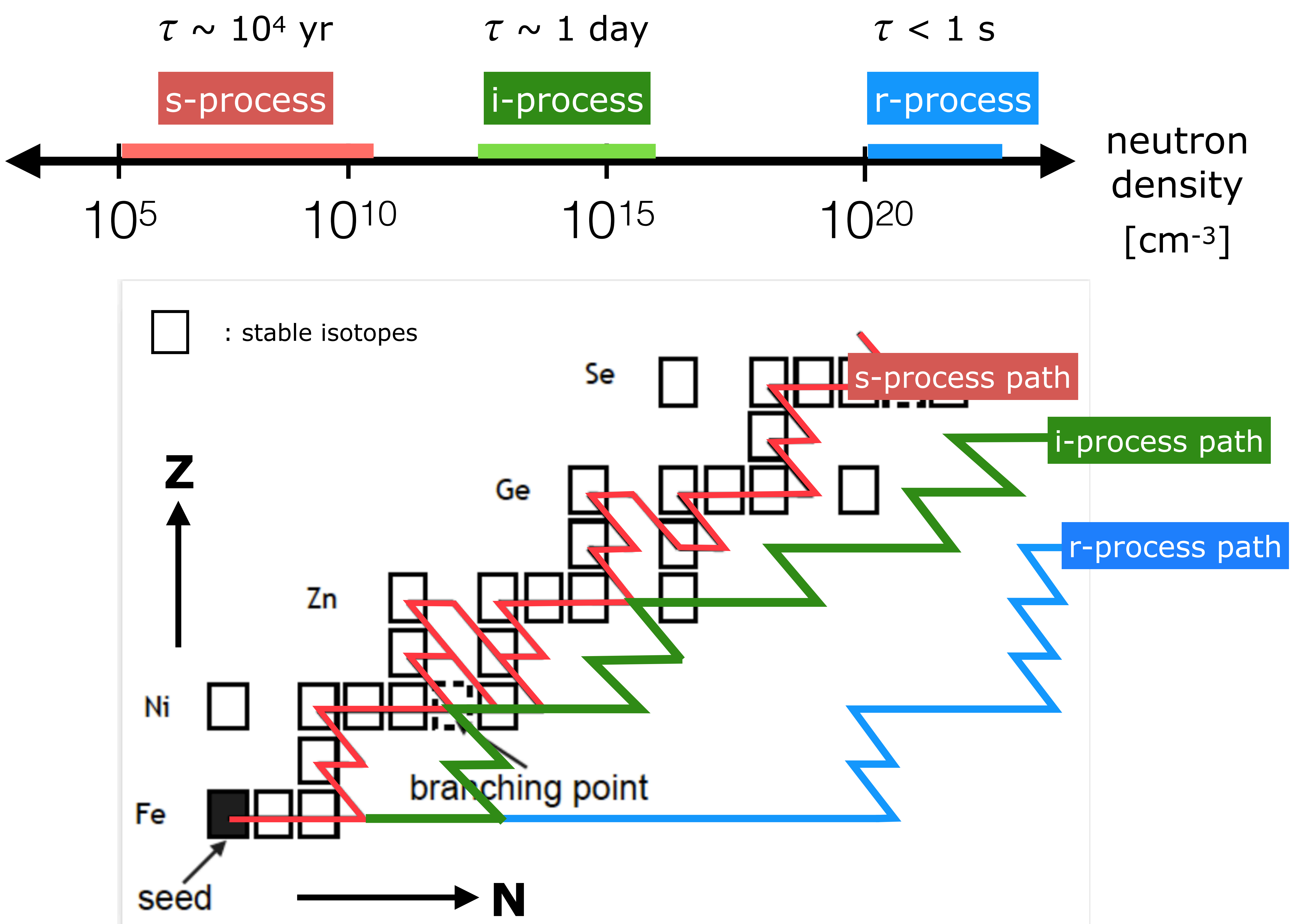
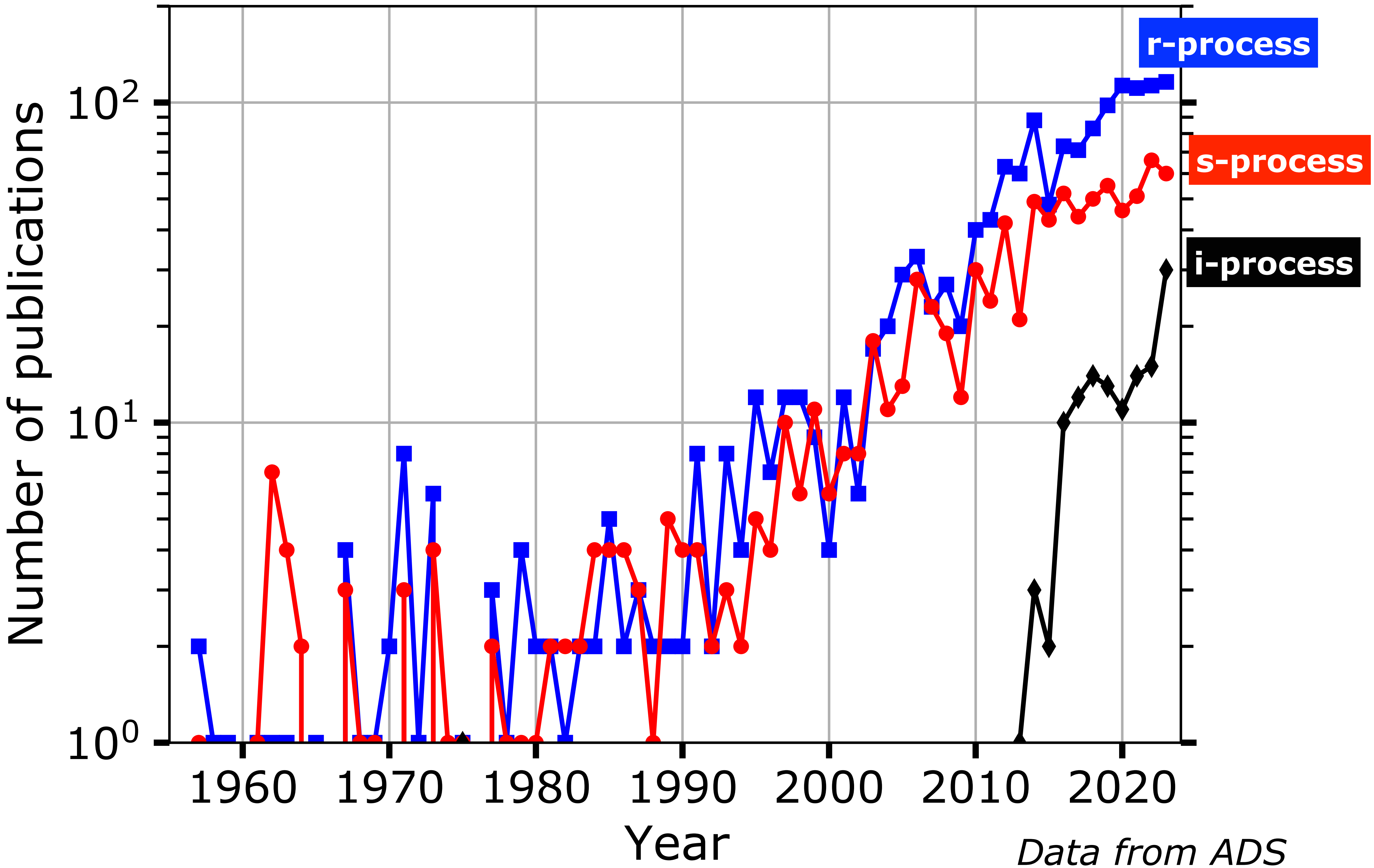
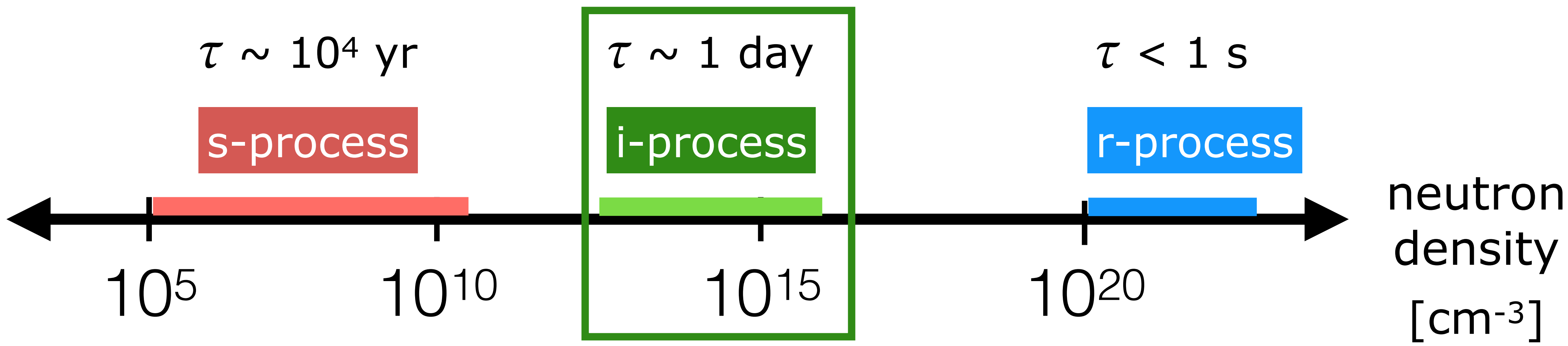


The i-process is a recent and growing topic



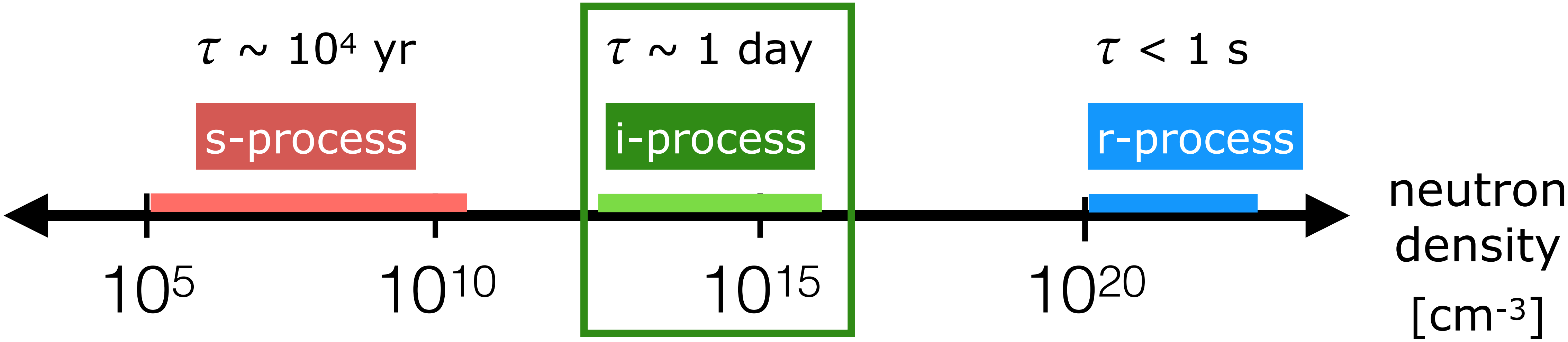
The intermediate neutron capture process



- **i-process** can happen when Hydrogen is mixed into a **convective** Helium-burning zone

proton ingestion

The intermediate neutron capture process



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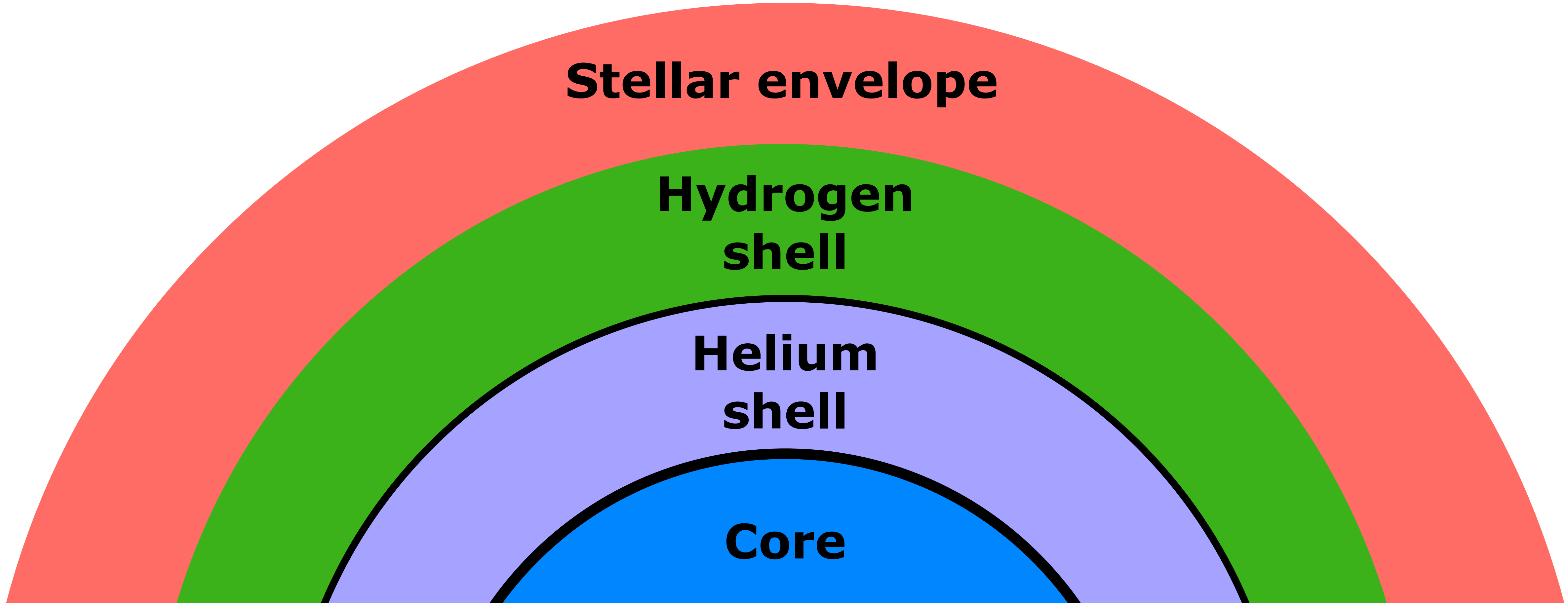

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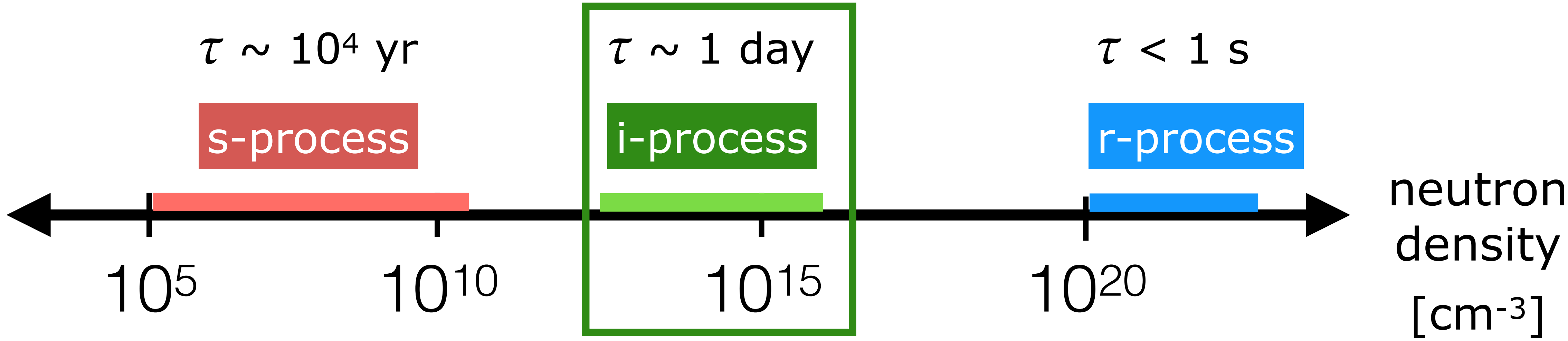

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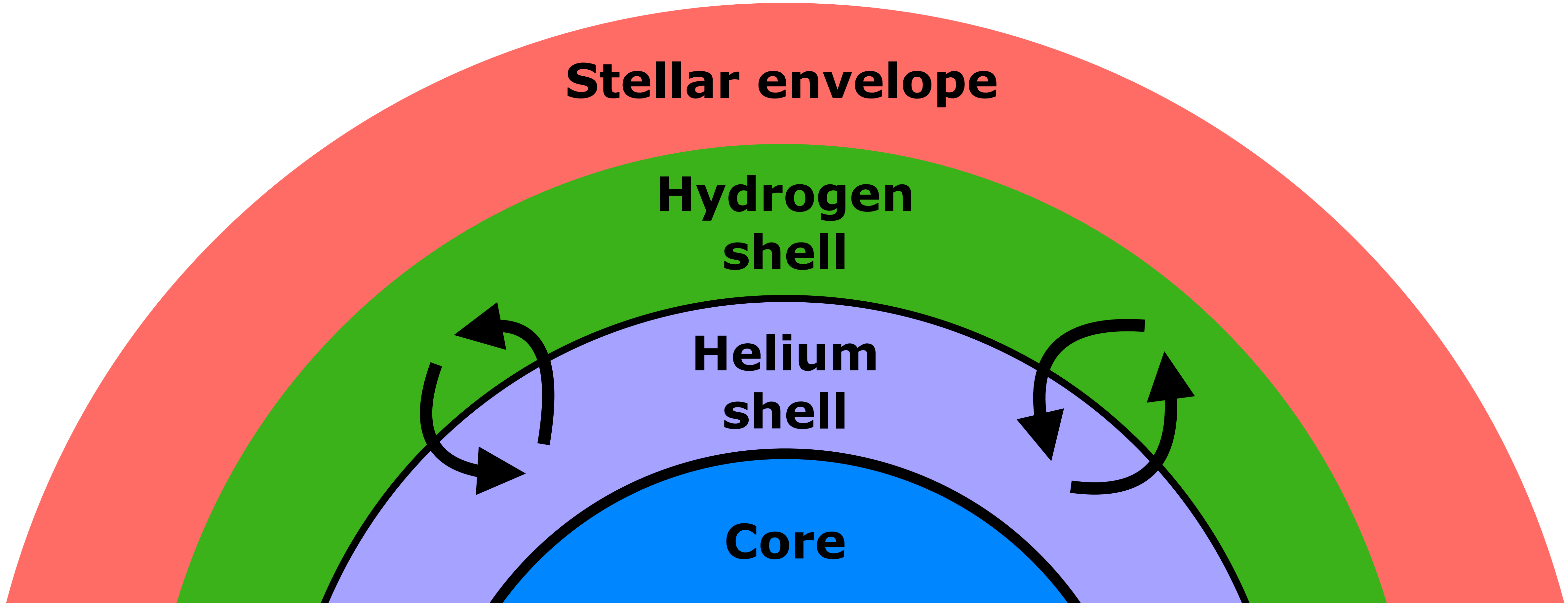

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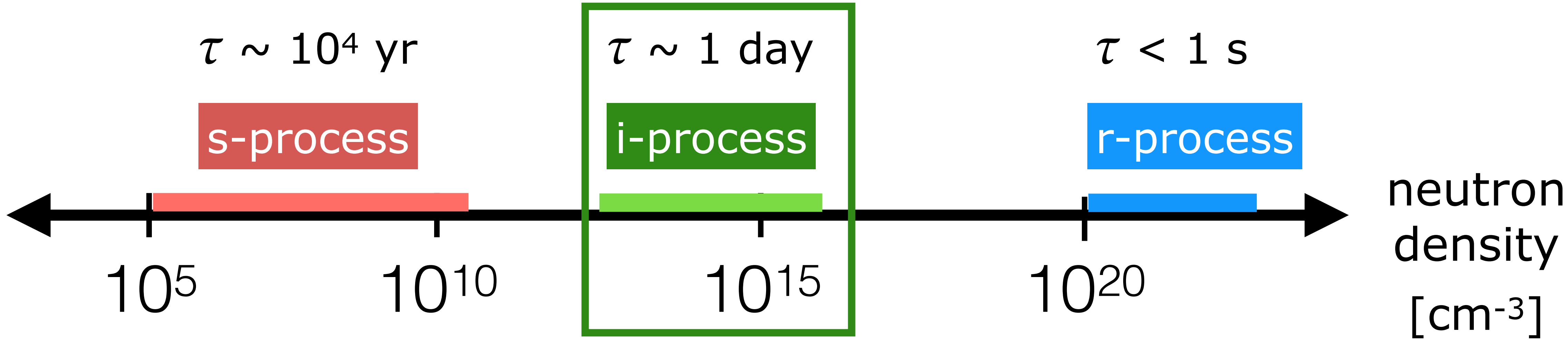

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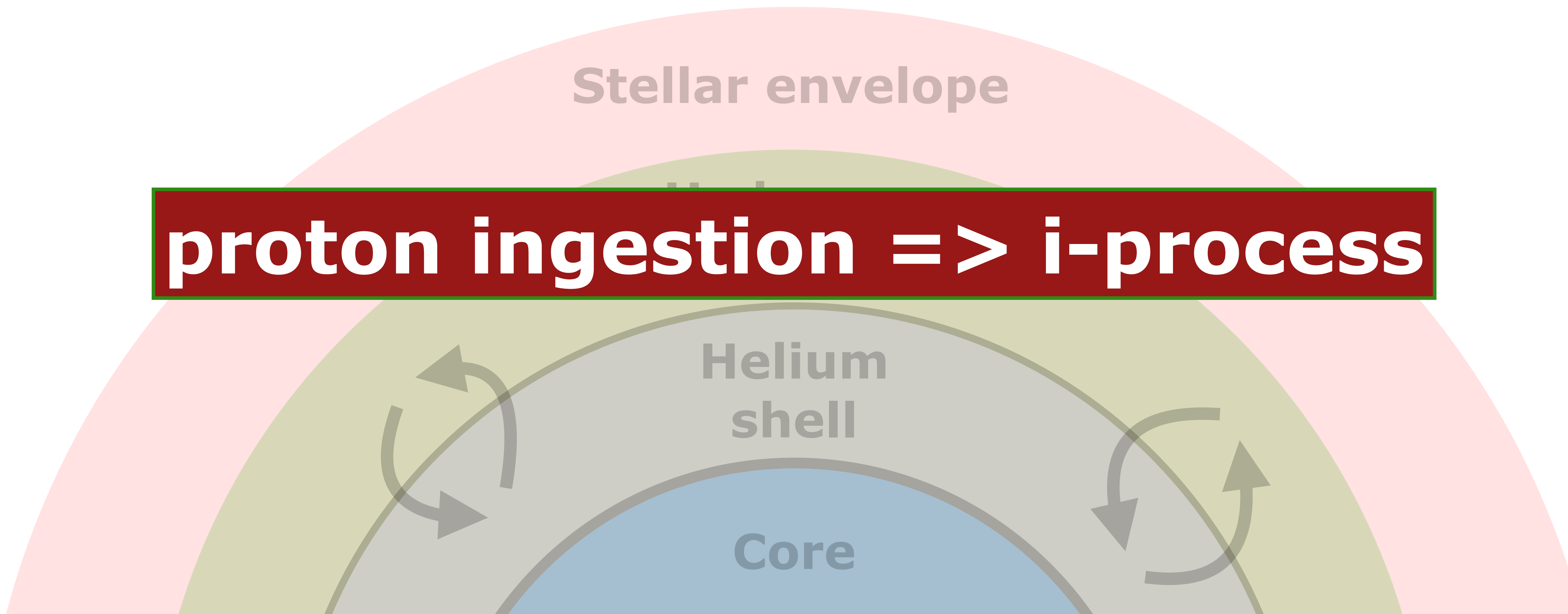

proton ingestion => i-process

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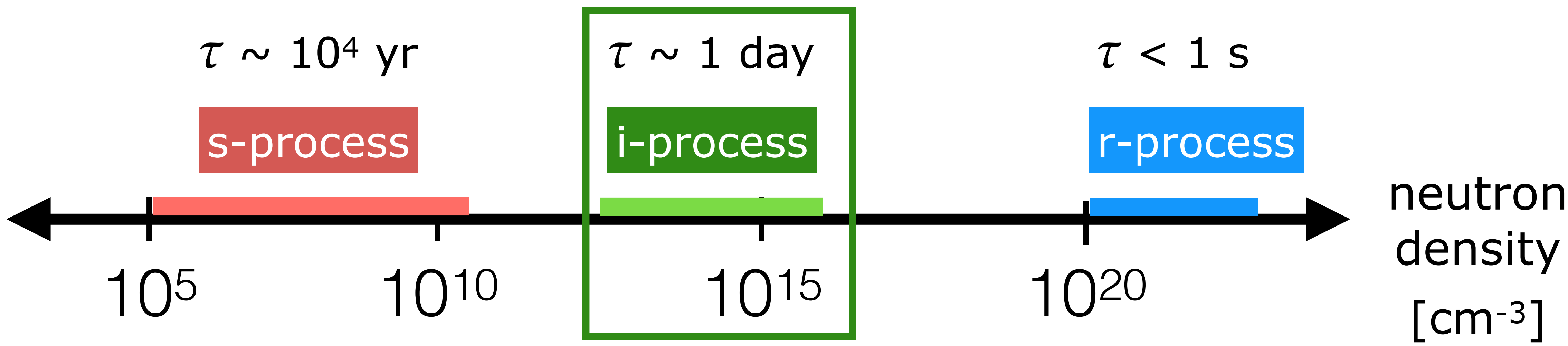


- **i-process** can happen when Hydrogen is mixed into a **convective** Helium-burning zone

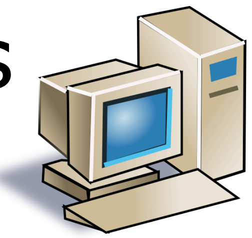
proton ingestion

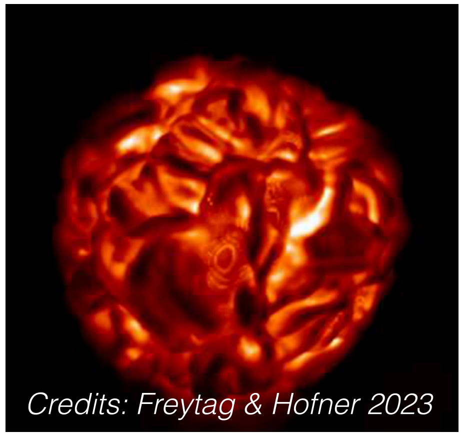
- **Observational motivation** :
  some stars are neither « s », nor « r » **—> i-process stars ?**

Jonsell+2006, Mishenina+2015, Roederer+2016, Caffau+2019, Karinkuzhi+2021,2023, Hansen+2023 …

—> talks by S. Van Eck, A. Skúladóttir

Astrophysical sites for proton ingestion / i-process





Credits: Freytag & Hofner 2023

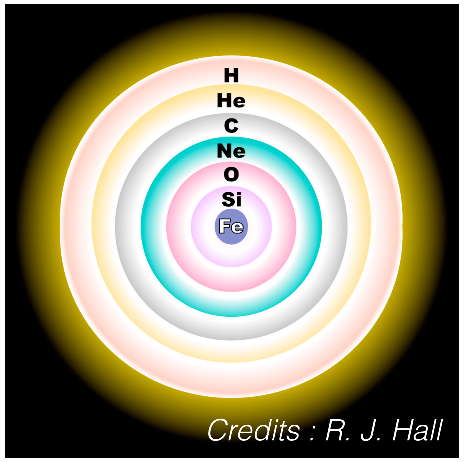
- Asymptotic giant branch (AGB) stars + super AGB

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

- Accreting white dwarfs

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

Credits: ESA and Justyn Maund



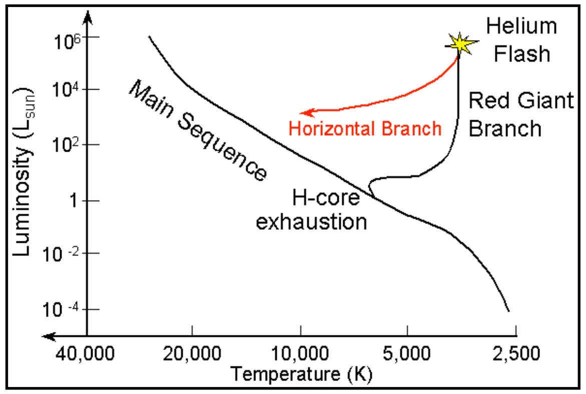
Credits : R. J. Hall

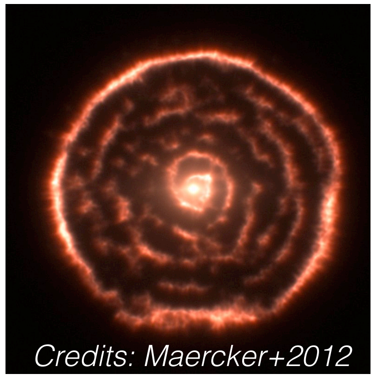
- Low metallicity massive stars

Pignatari+2015, Banerjee+2018, Clarkson+2018,2020…

- Core Helium flash at low metallicity

Fujimoto+1990, Schlattl+2001, Campbell+2010, Cruz+2013…





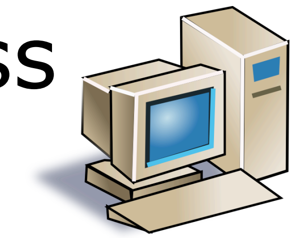
Credits: Maercker+2012

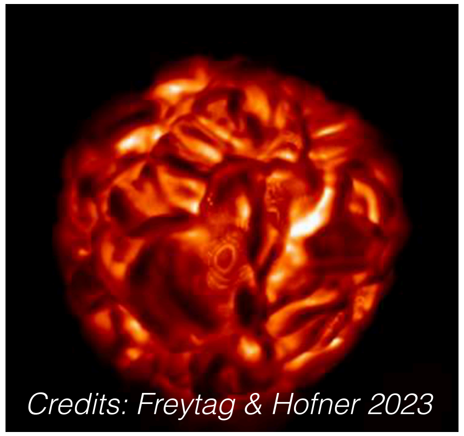
- Post-AGB stars (late thermal pulse)

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

—> talk by F. Herwig

Astrophysical sites for proton ingestion / i-process





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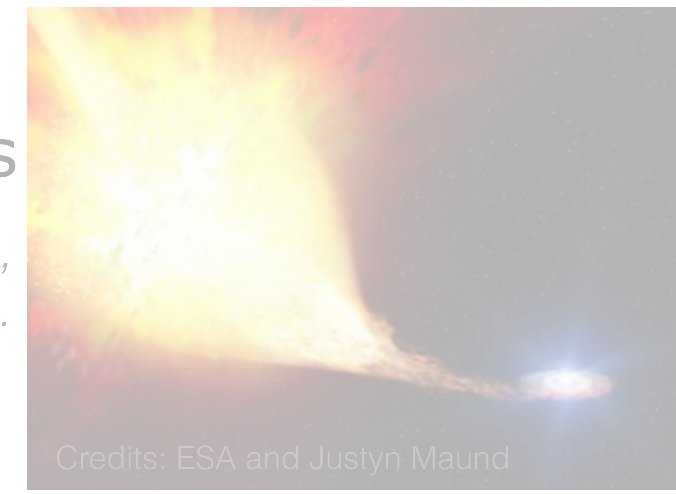

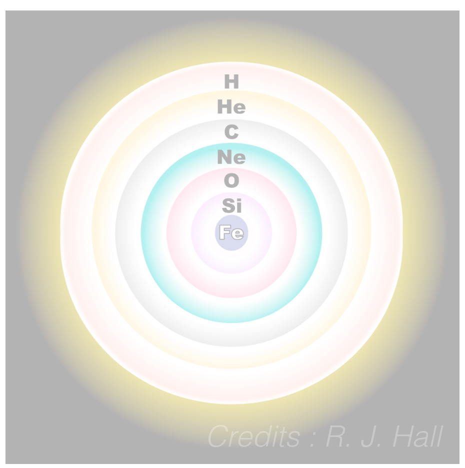

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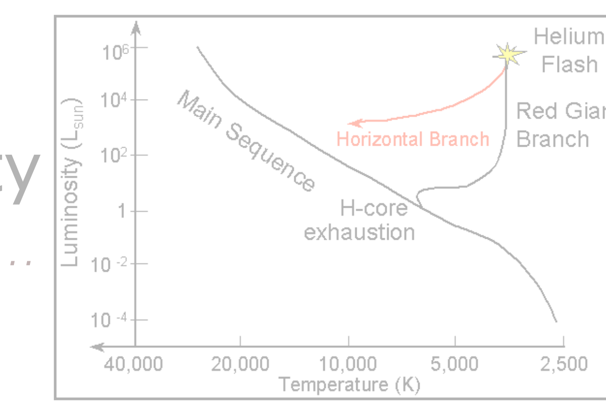

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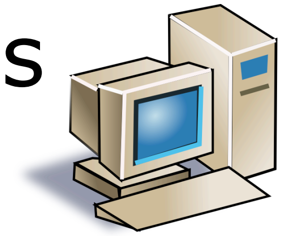

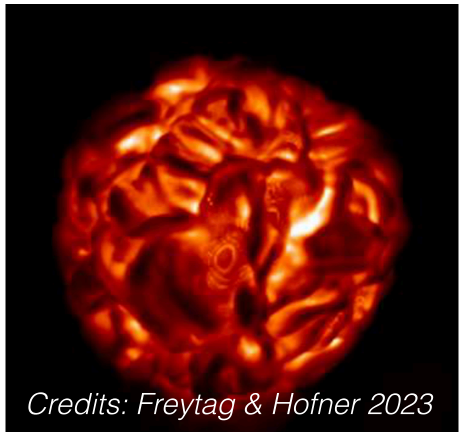

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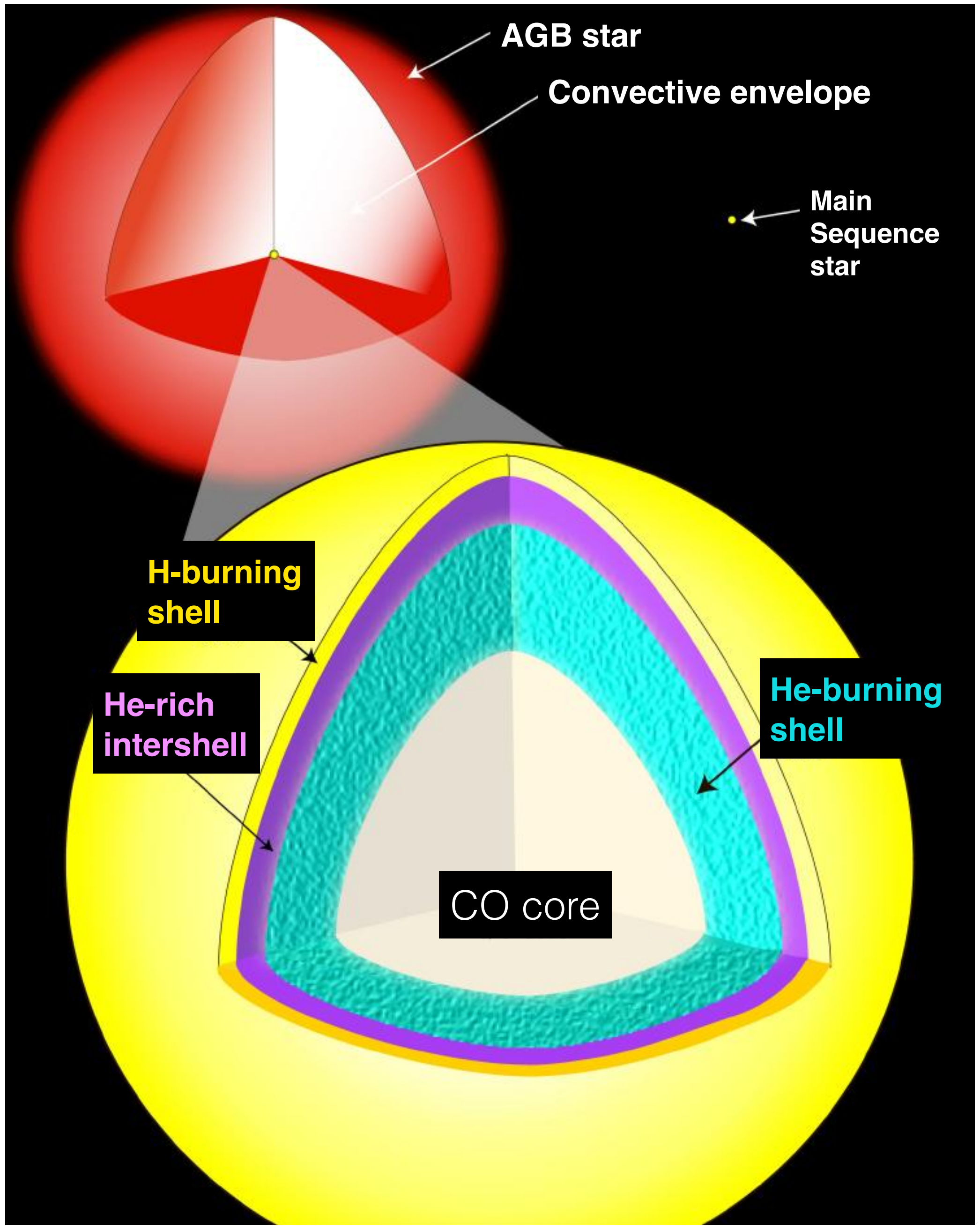
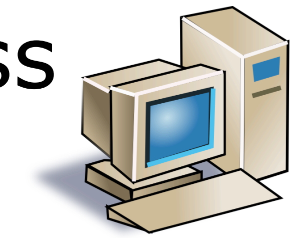
—> end of life of ~ 0.8 - 8 $M_\odot$ stars
—> strong stellar outflows / winds
—> complex interplay between nucleosynthesis and mixing

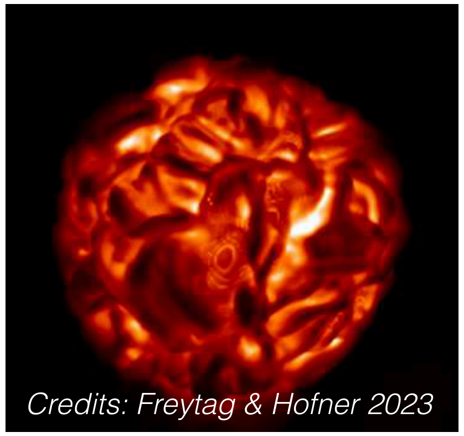


Reviews on AGB

- *Busso+1999, ARA&A*
- *Herwig 2005, ARA&A*
- *Karakas+2014, PASA*

Astrophysical sites for proton ingestion / i-process





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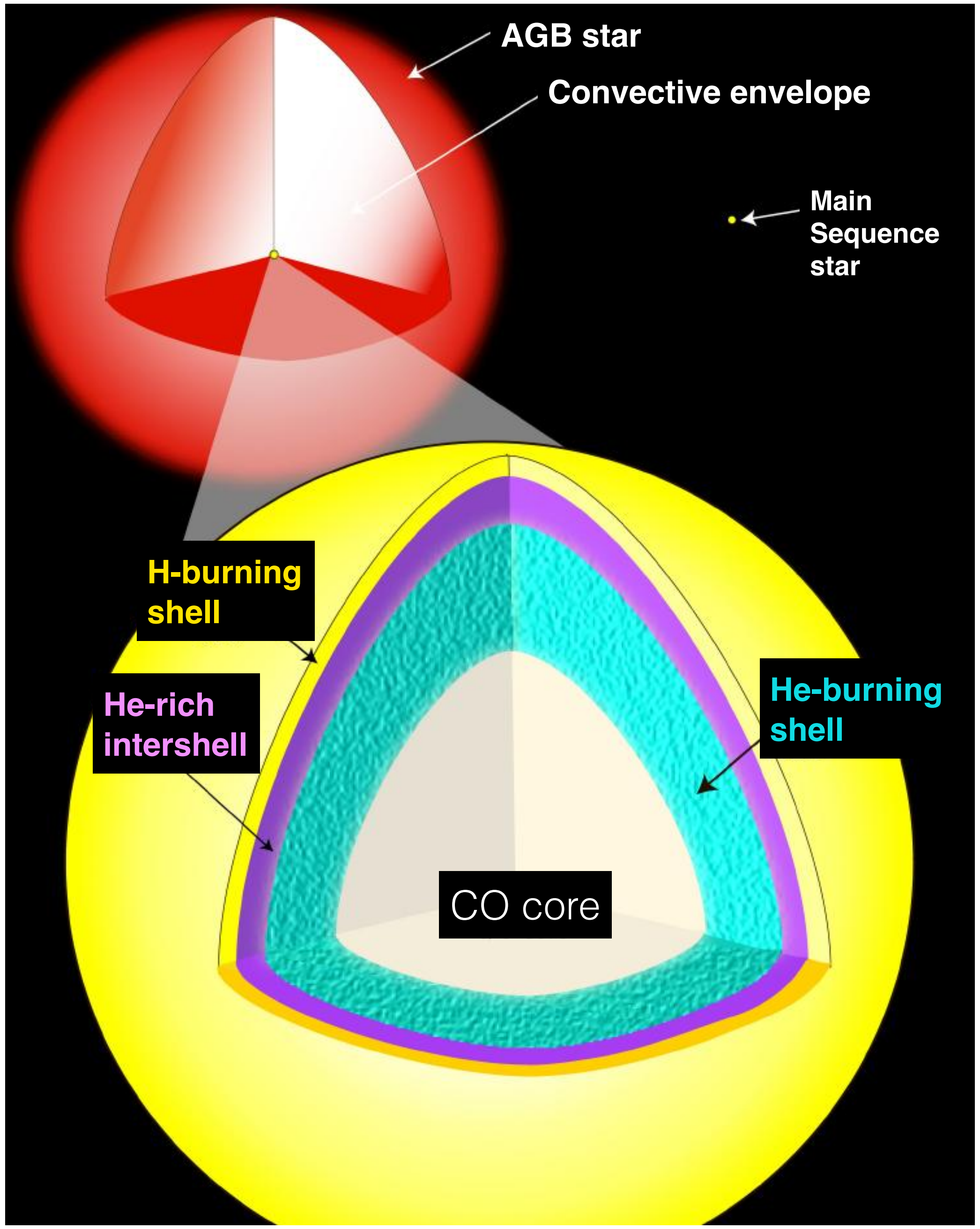
—> **ongoing heavy element nucleosynthesis** (because **Tc** is present)
Merrill 1952, …



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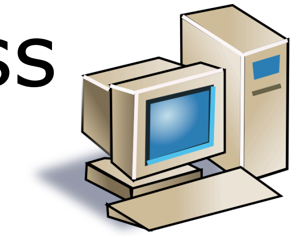

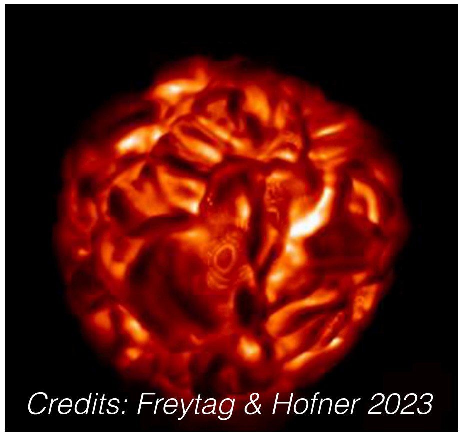

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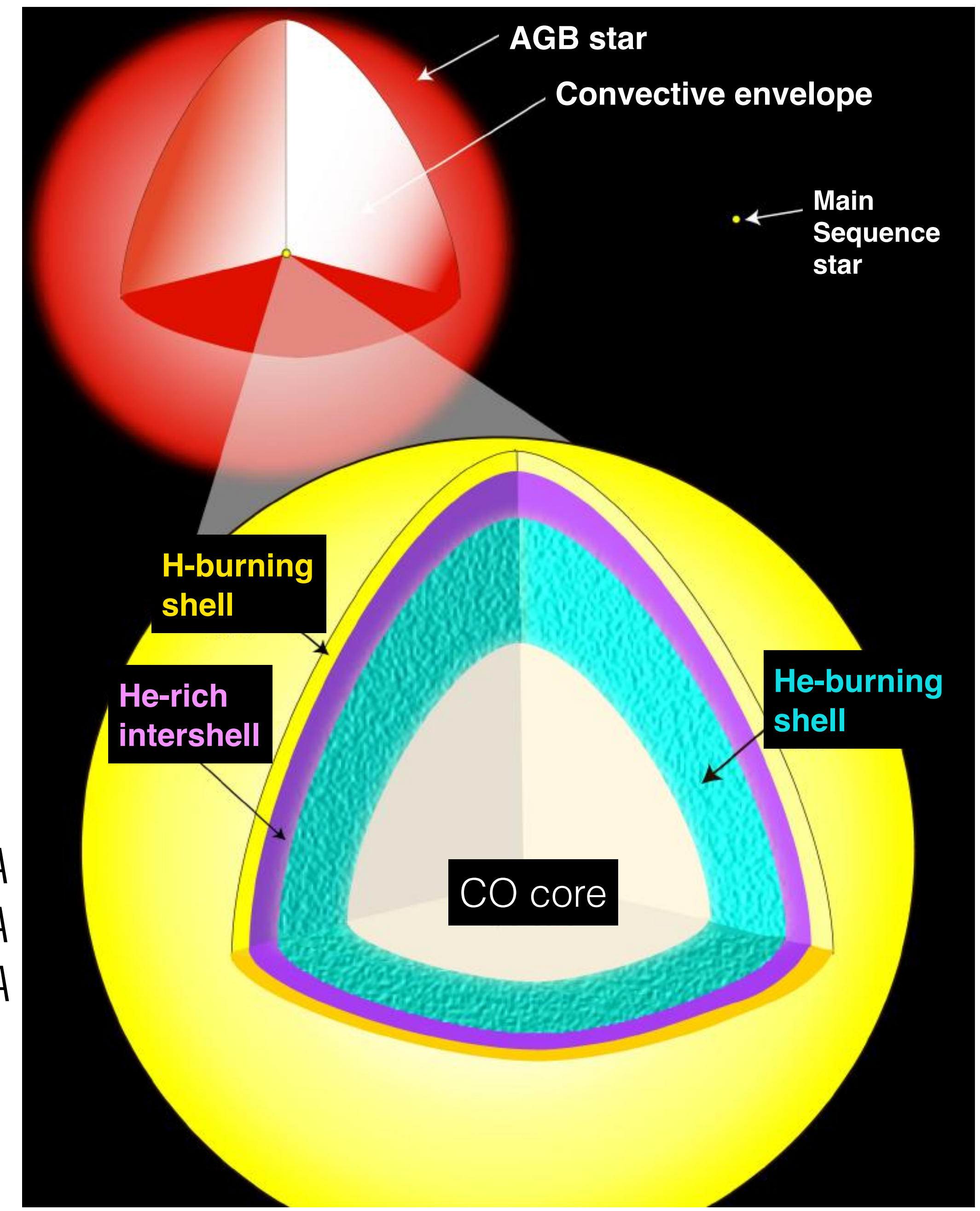
But how ?



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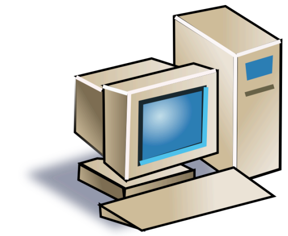
Stellar evolution modelling

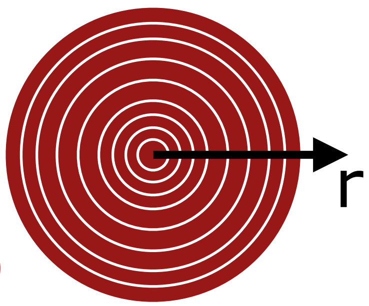


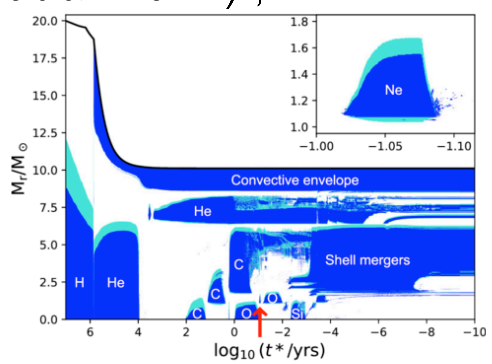
1D

MESA (*Paxton+2018*), **STAREVOL** (*Siess 2000*), **GENEC** (*Eggenberger+2008*), **KEPLER** (*Weaver & Woosley 1978*), **FRANEC** (*Chieffi & Limongi 2013*), **UN & YU** (*Umeda+2012*) , **...**

- **Full life / scale of stars**
- **Full nucleosynthesis**

- **Spherical symmetry**
- **Simplified theories for 3D processes** (e.g. convection)



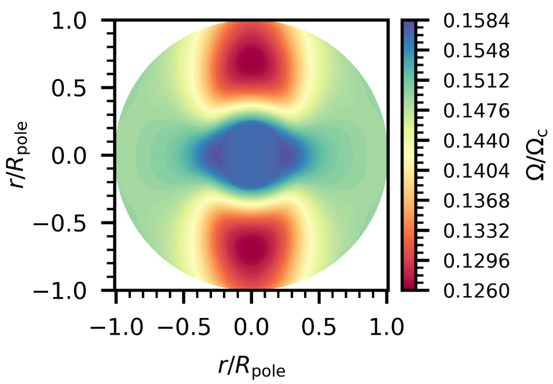


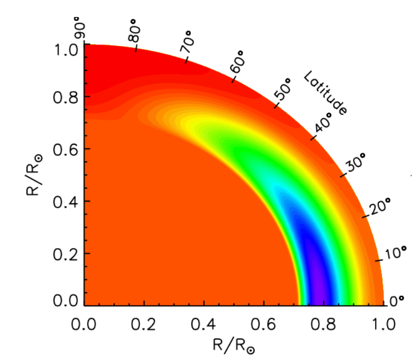
2D

ROTORC (*Deupree+1990, 2012*), **ESTER** (*Espinosa Lara & Rieutord 2013, Mombarg+2023*) + *Roxburgh+2004, Li+2009, Lovekin 2011,* **...**

- **Modelling of rotation**

- **Full stellar life / scale cannot be modeled**
- **Simplified theories for 3D processes**



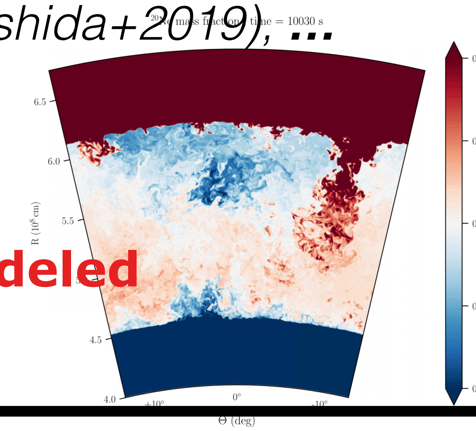


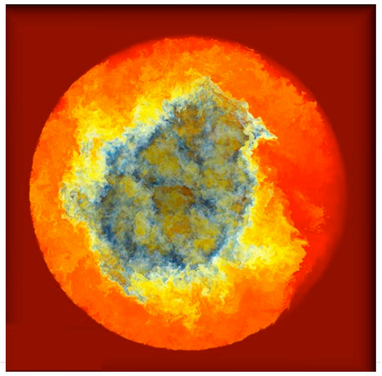
3D

PROMPI (*Meakin & Arnett 2007, Rizzuti+2023*), **PPMstar** (*Woodward+2015, Herwig+2023*), **FLASH** (*Couch+2015*), **DJEHUTY** (*Stancliffe+2011*), ***3DnSEV*** (*Yoshida+2019*), **...**

- **Proper modeling of 3D processes**

- **Only small parts of the star's life / scale can be modeled**
- **Initial conditions : depends on 1D models**





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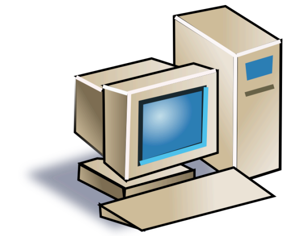

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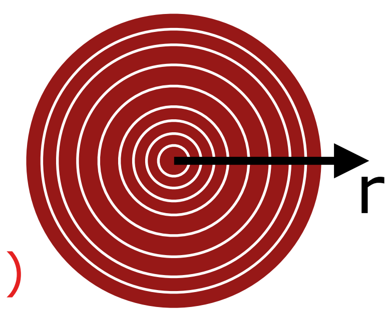

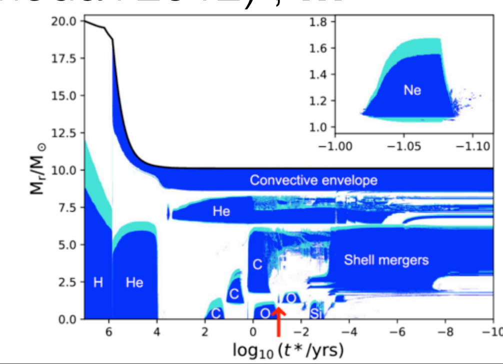

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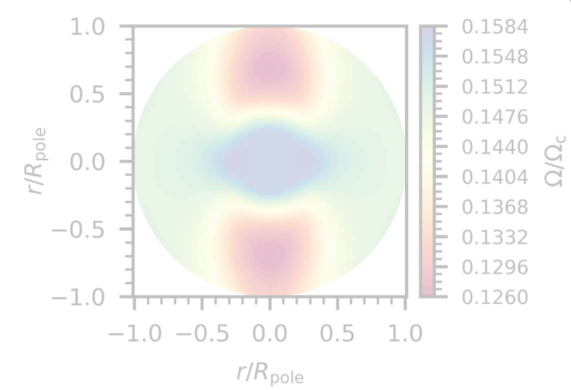

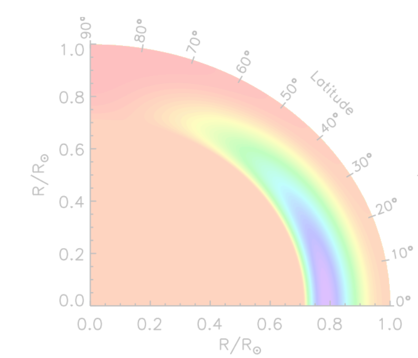

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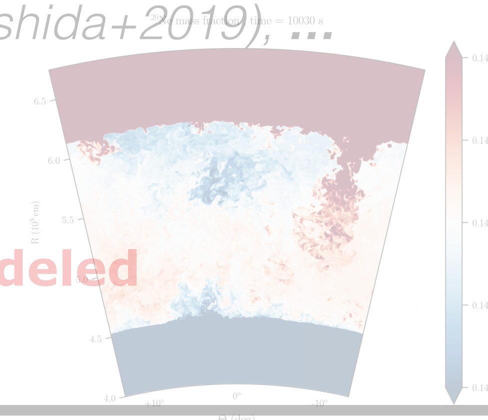
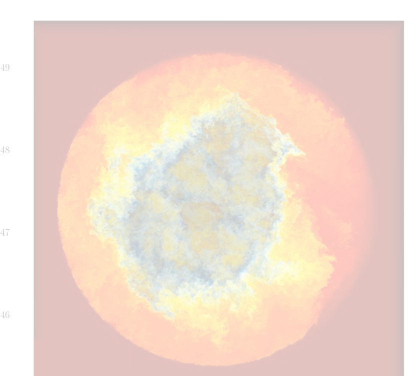
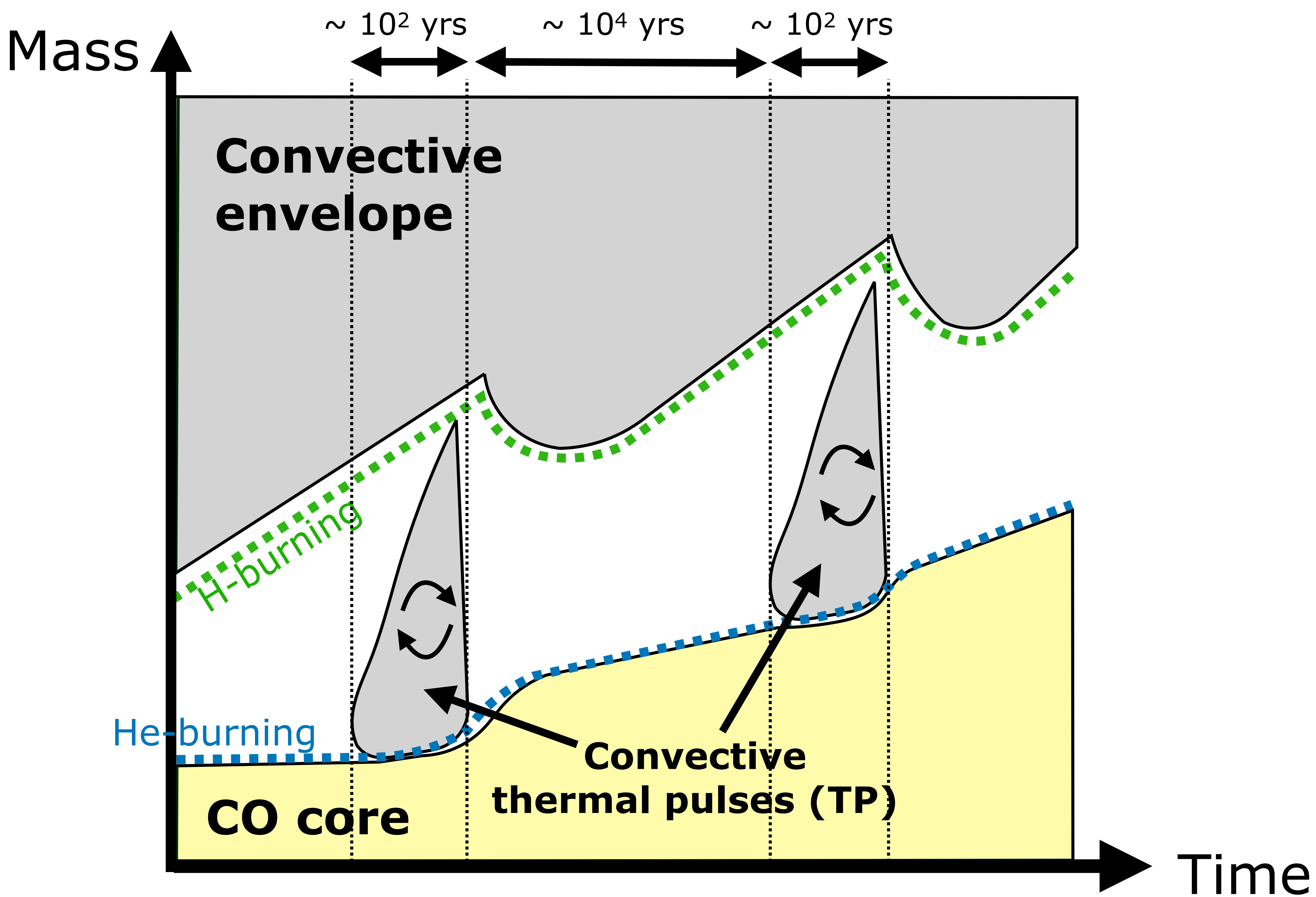




Structure evolution of an AGB star

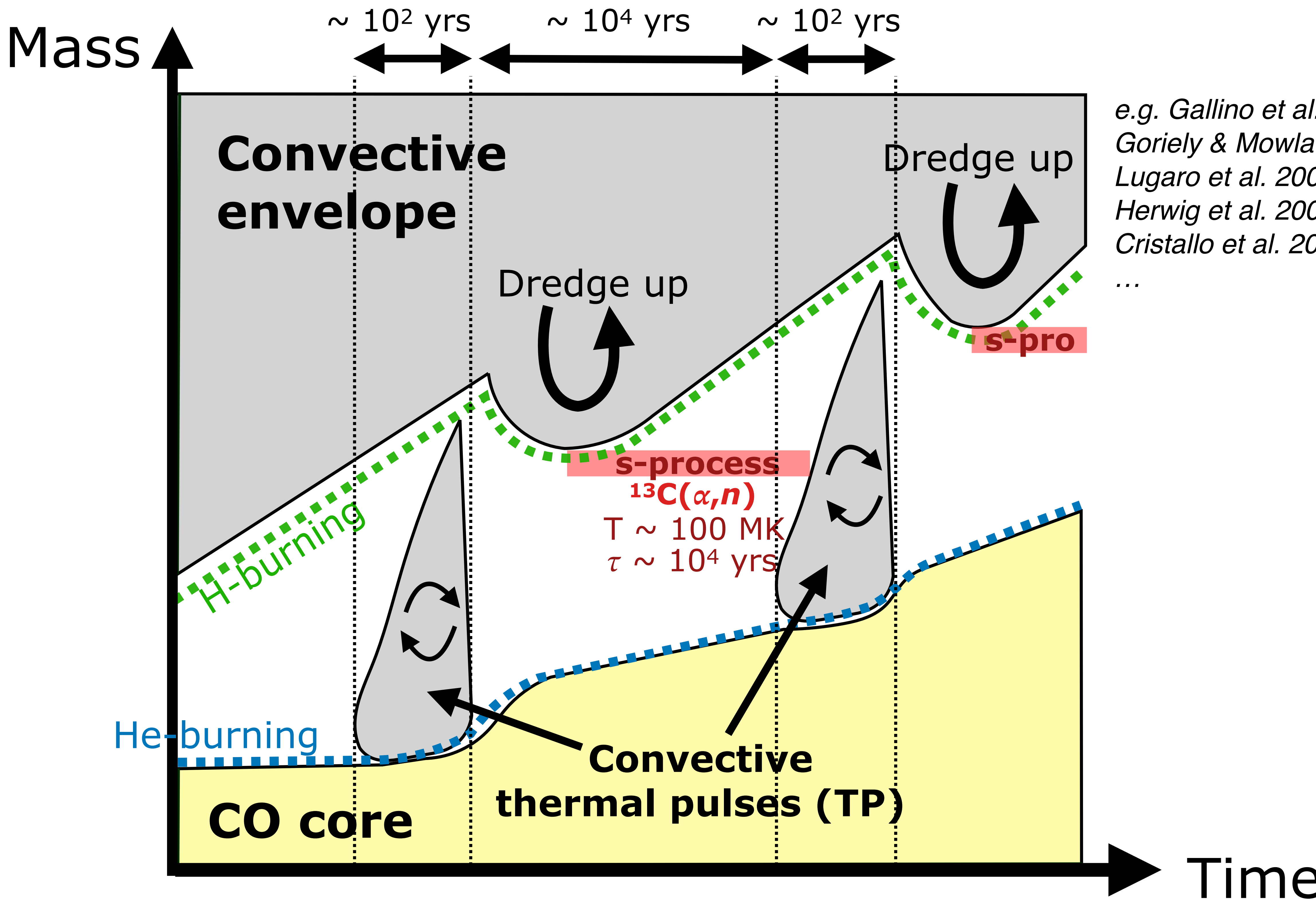
schematic view



Structure evolution of an AGB star

The s-process

schematic view



e.g. Gallino et al. 1998,
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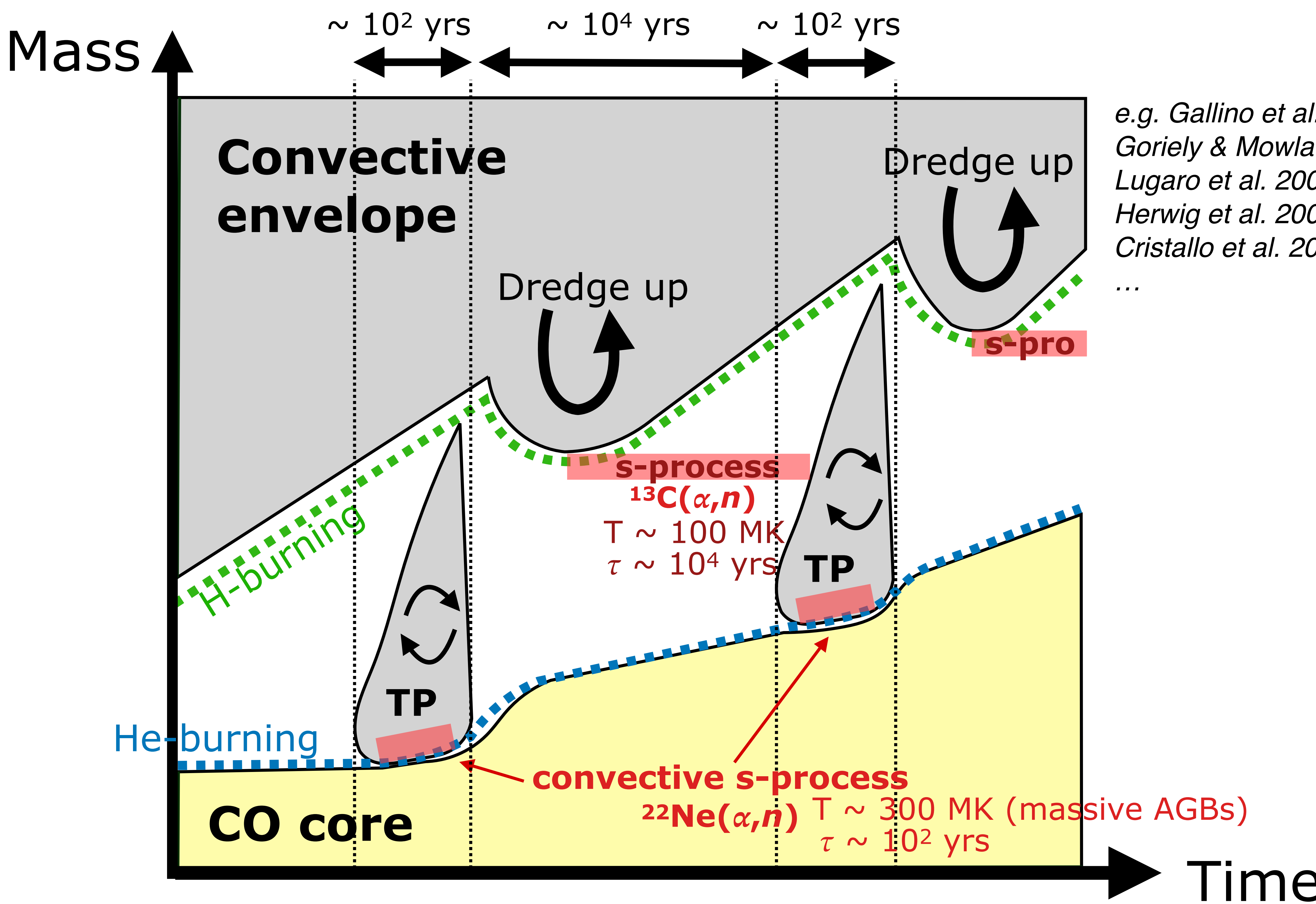
Structure evolution of an AGB star

schematic view

The s-process



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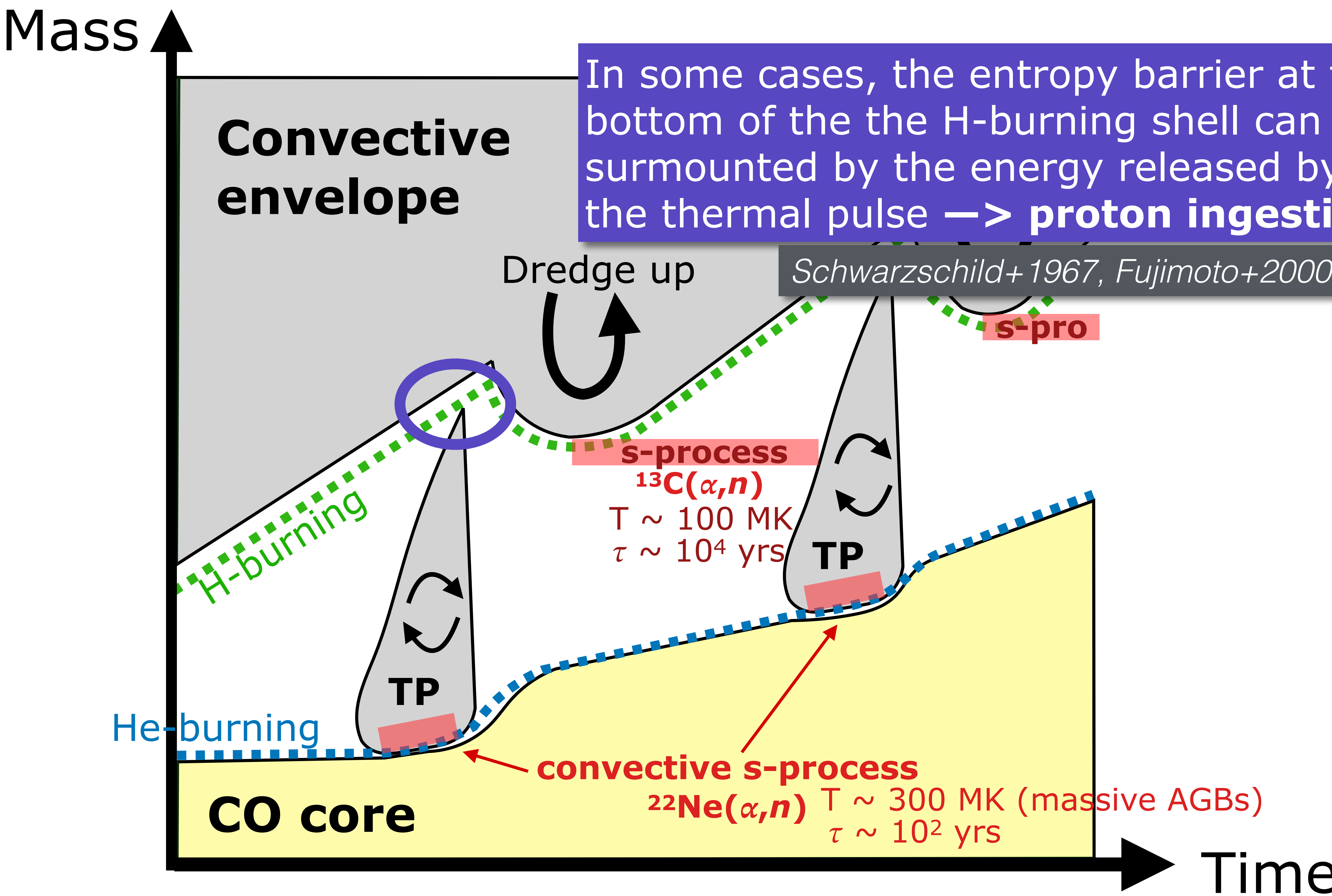
Structure evolution of an AGB star

schematic view

The s-process



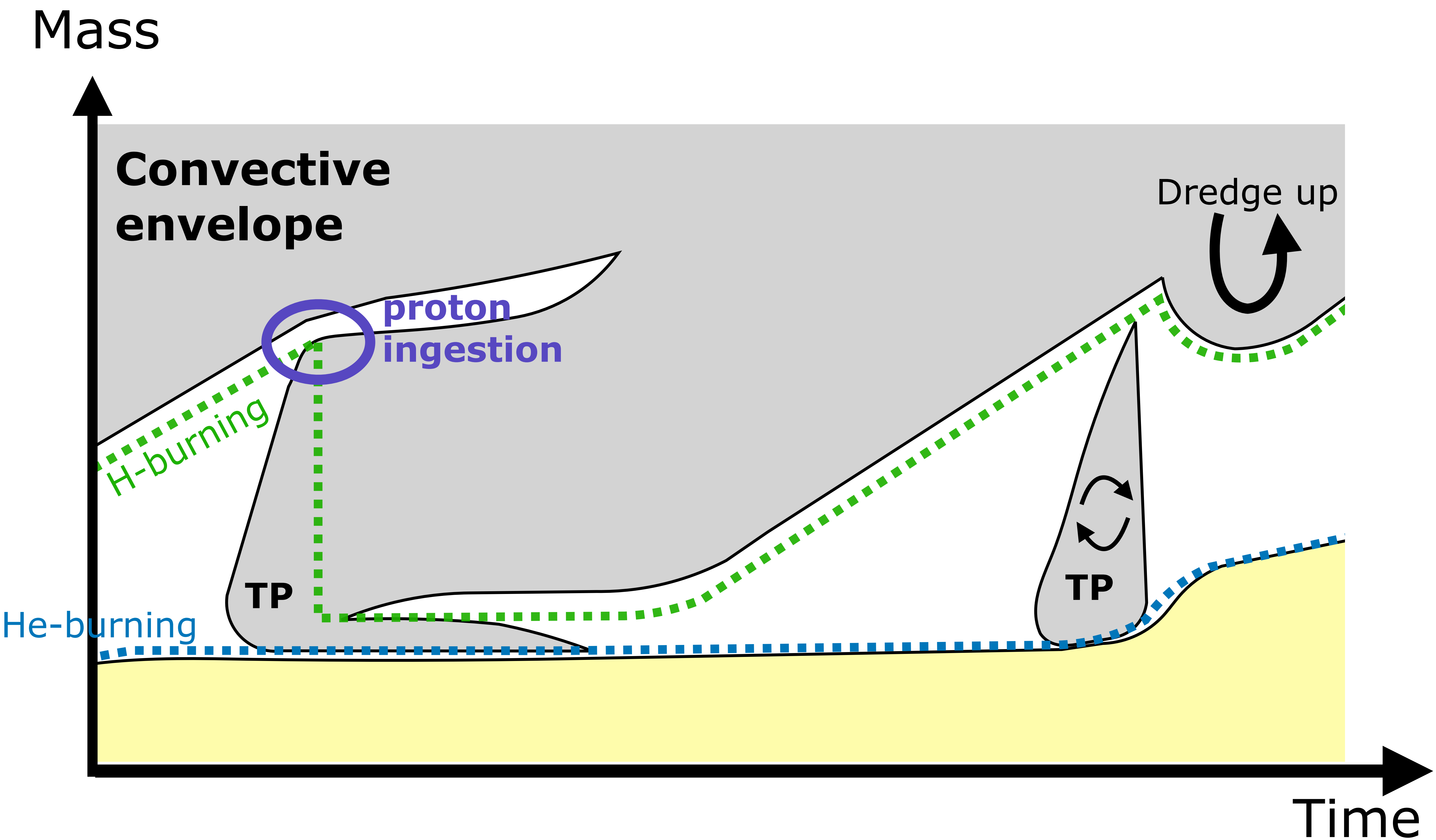
In some cases, the entropy barrier at the bottom of the the H-burning shell can be surmounted by the energy released by the thermal pulse **—> proton ingestion**

Schwarzschild+1967, Fujimoto+2000,…

Structure evolution of an AGB star

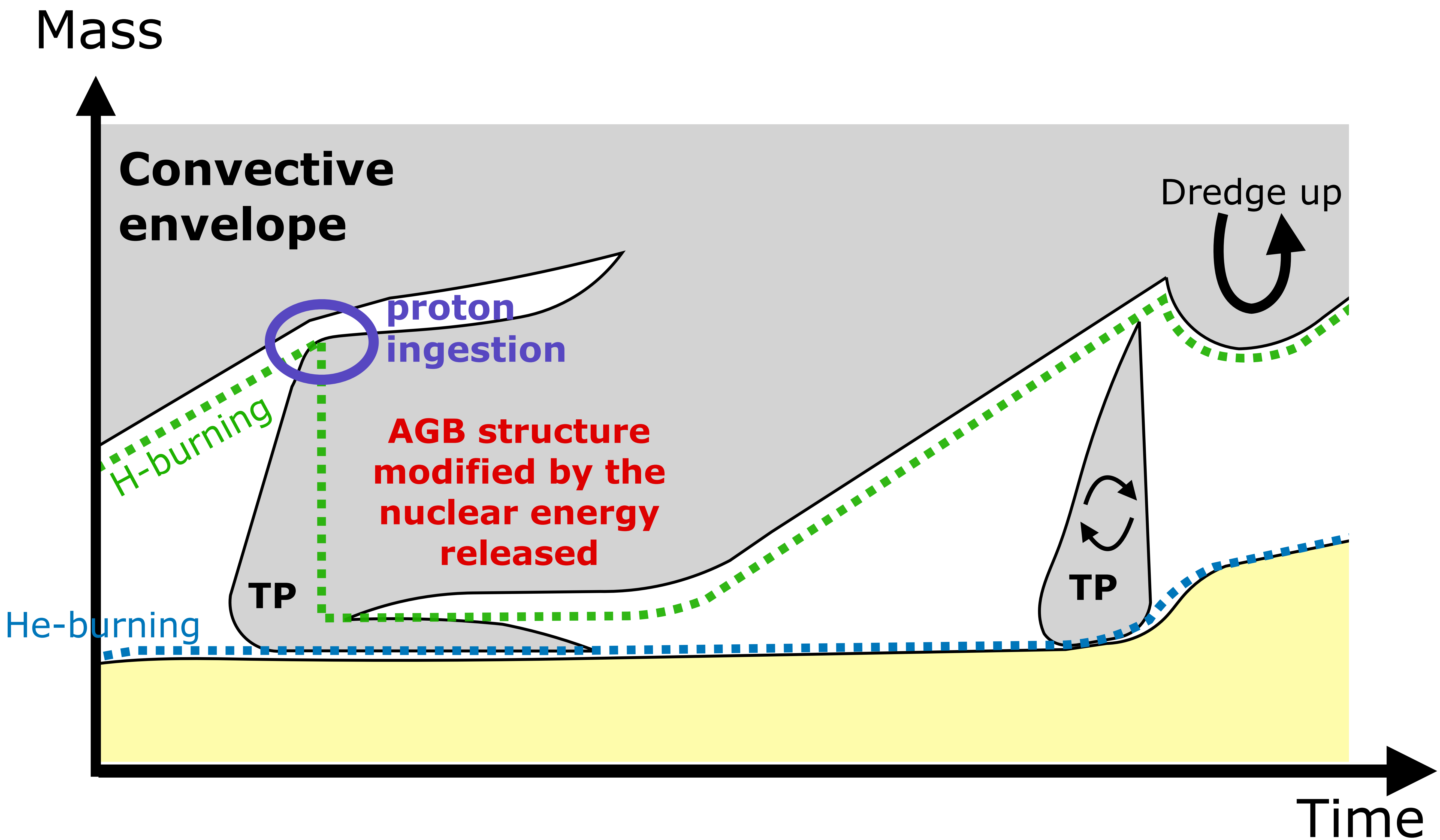
schematic view

The i-process



Structure evolution of an AGB star *schematic view*

The i-process



Structure evolution of an AGB star

schematic view

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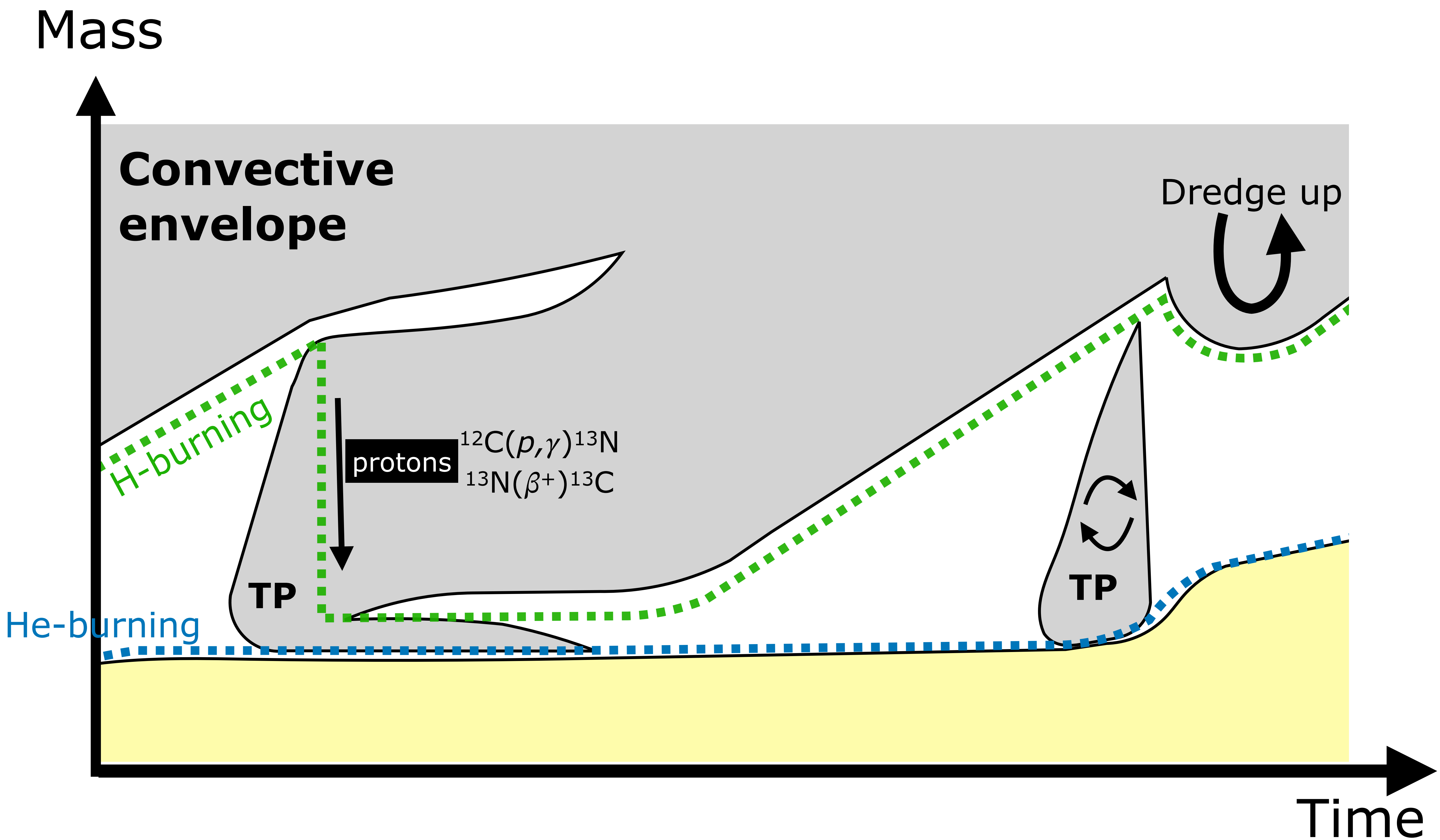

Structure evolution of an AGB star

schematic view

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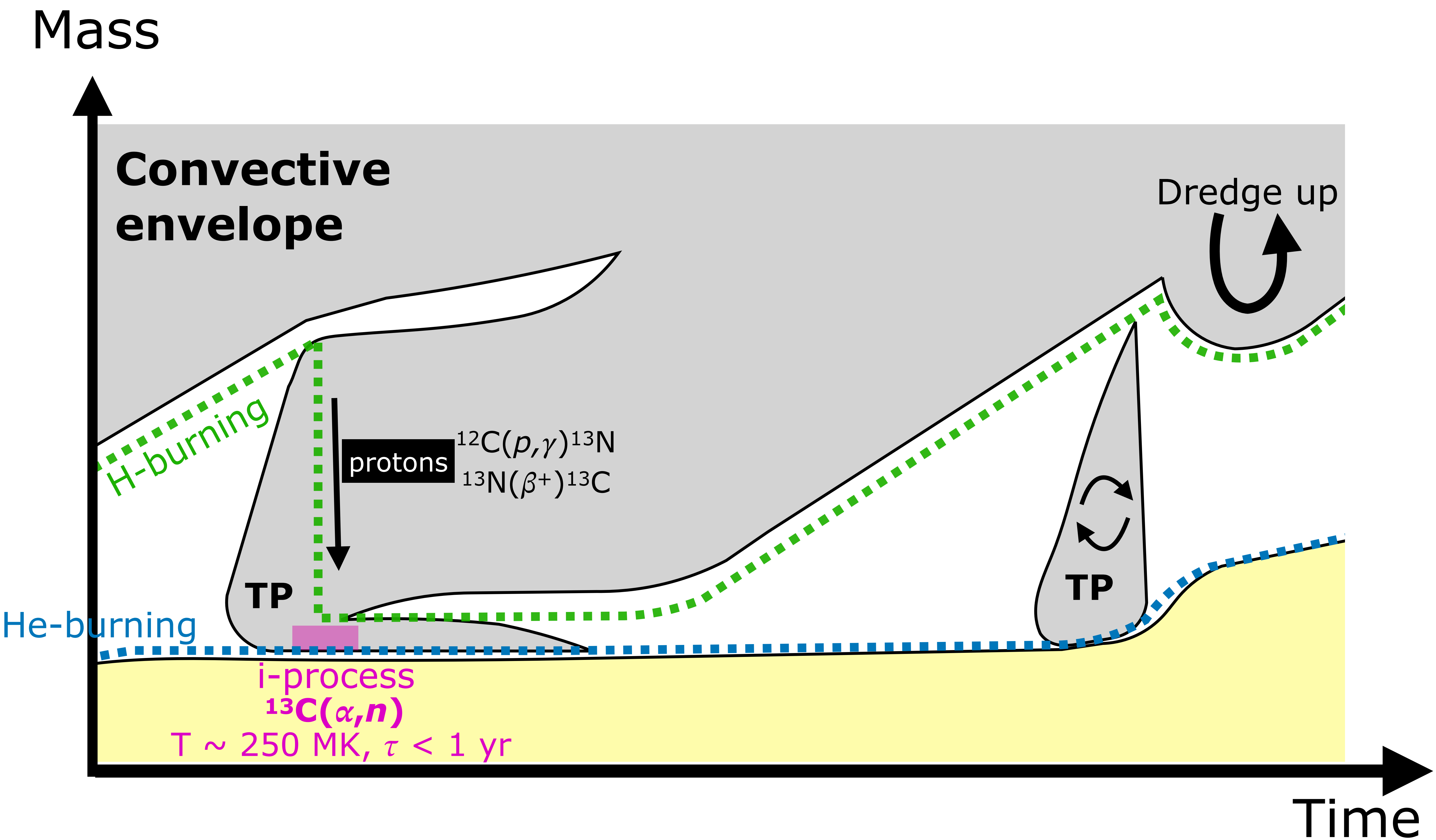

Structure evolution of an AGB star

schematic view

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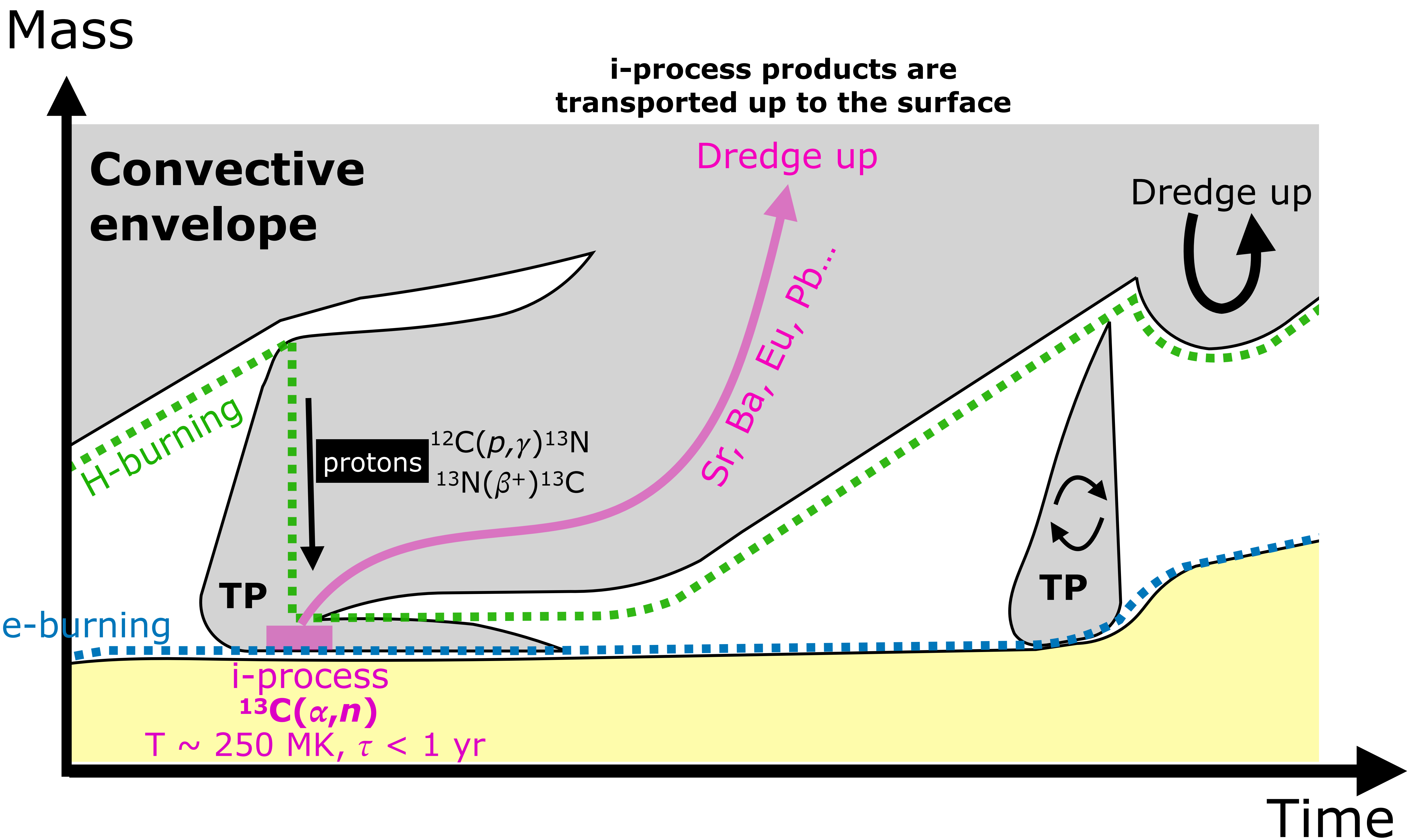

Structure evolution of an AGB star

schematic view

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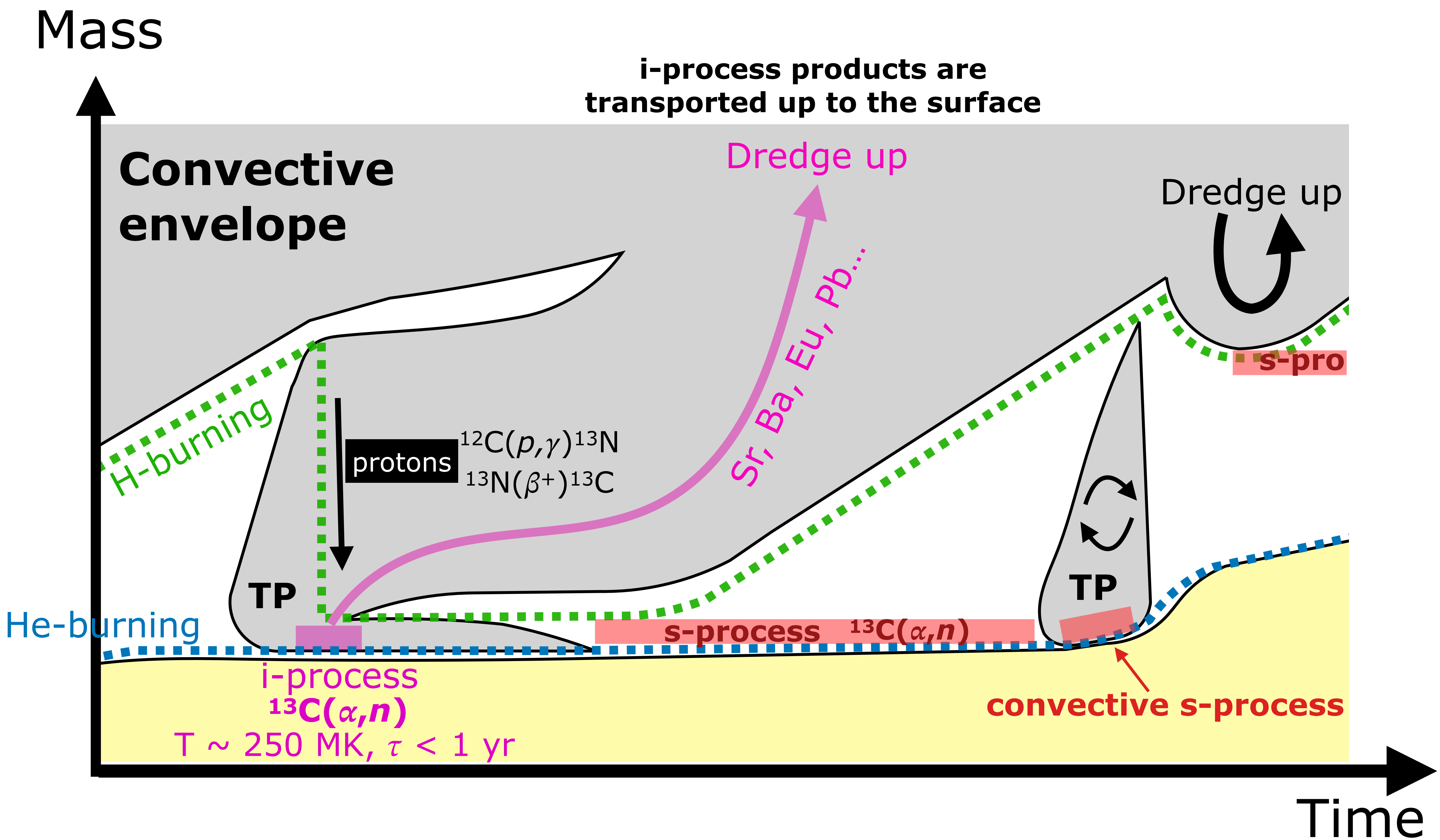

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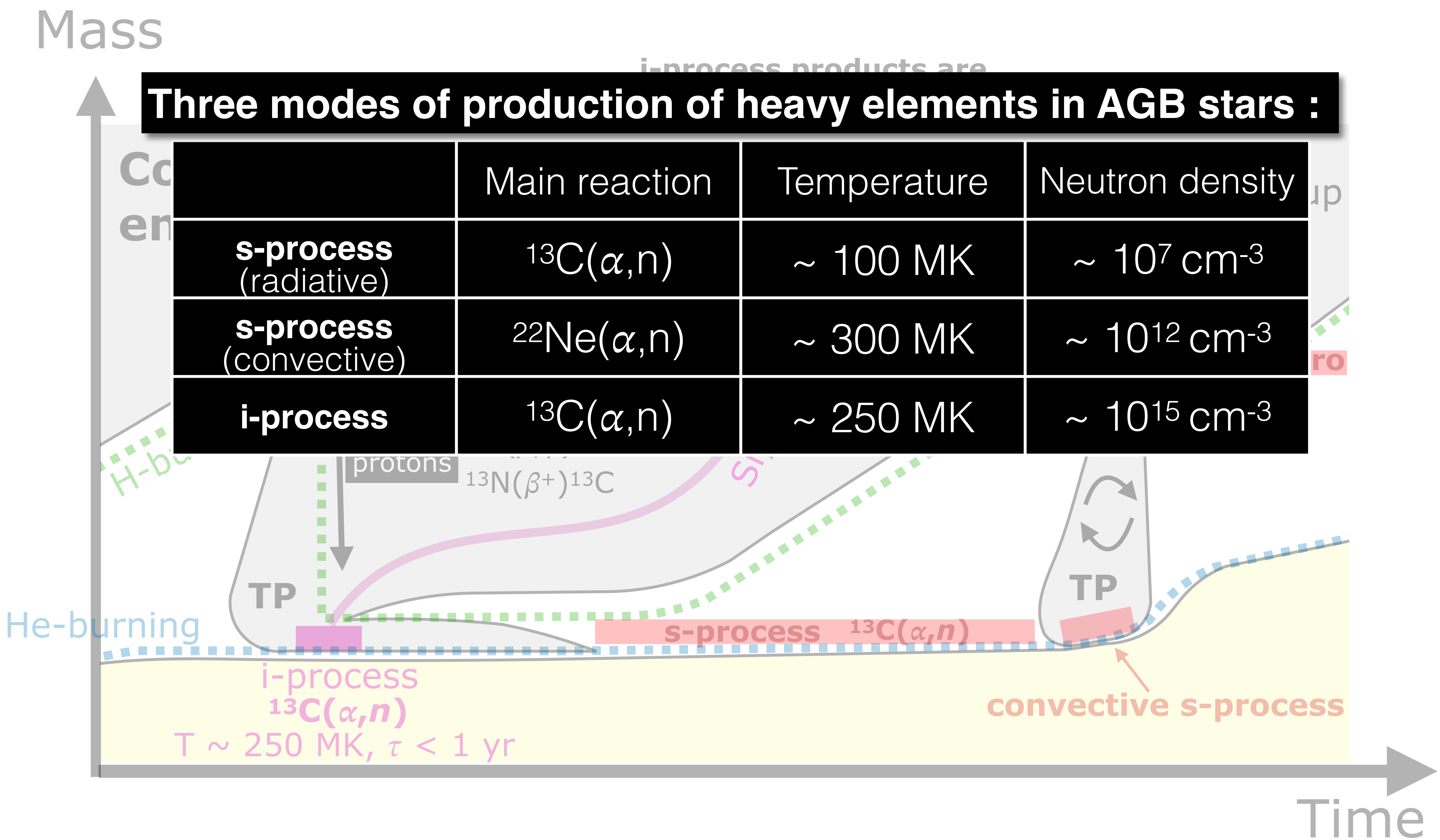

Three modes of production of heavy elements in AGB stars :

	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}

Structure evolution of an AGB star

schematic view

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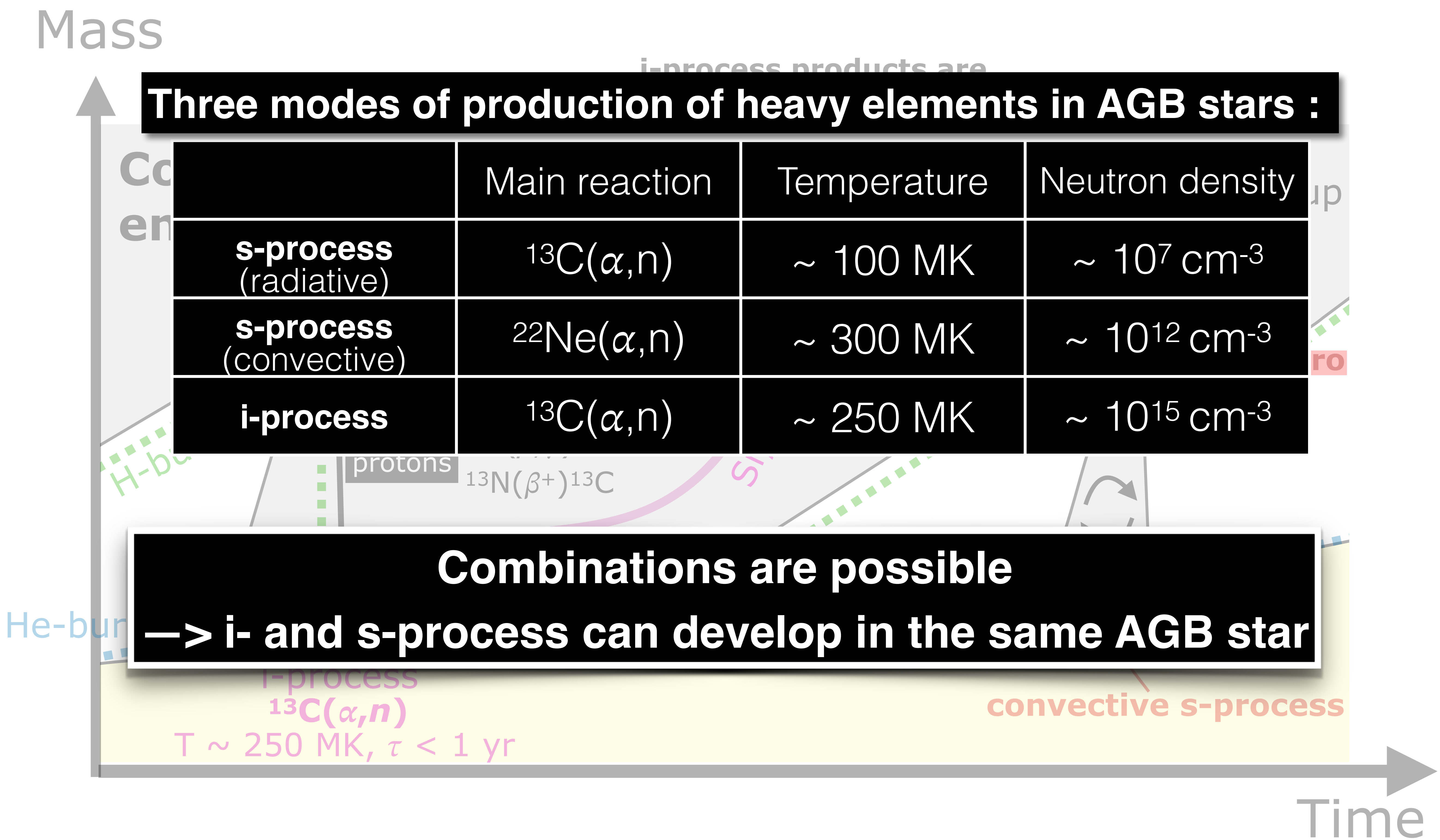
Combinations are possible

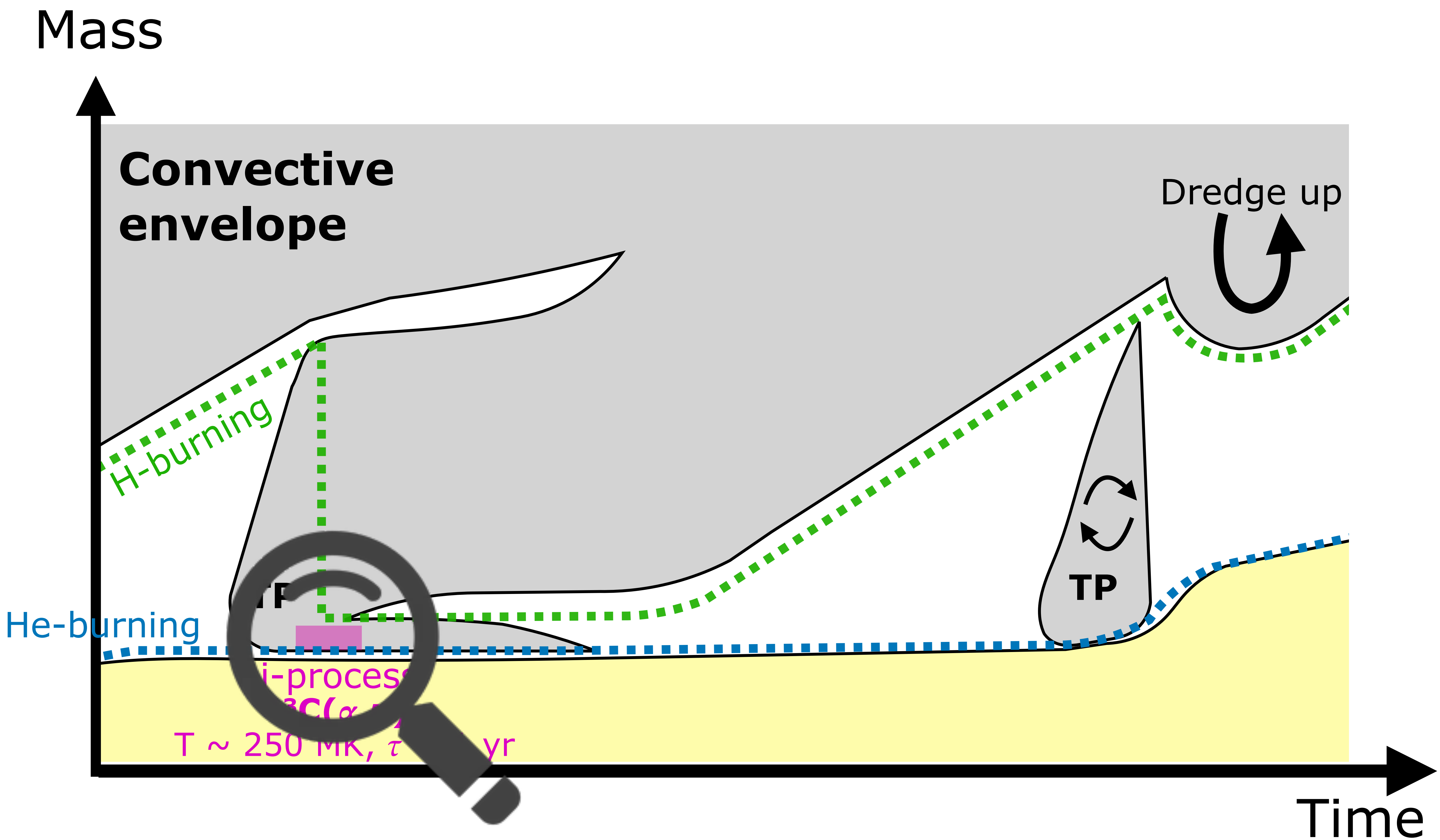
—> i- and s-process can develop in the same AGB star



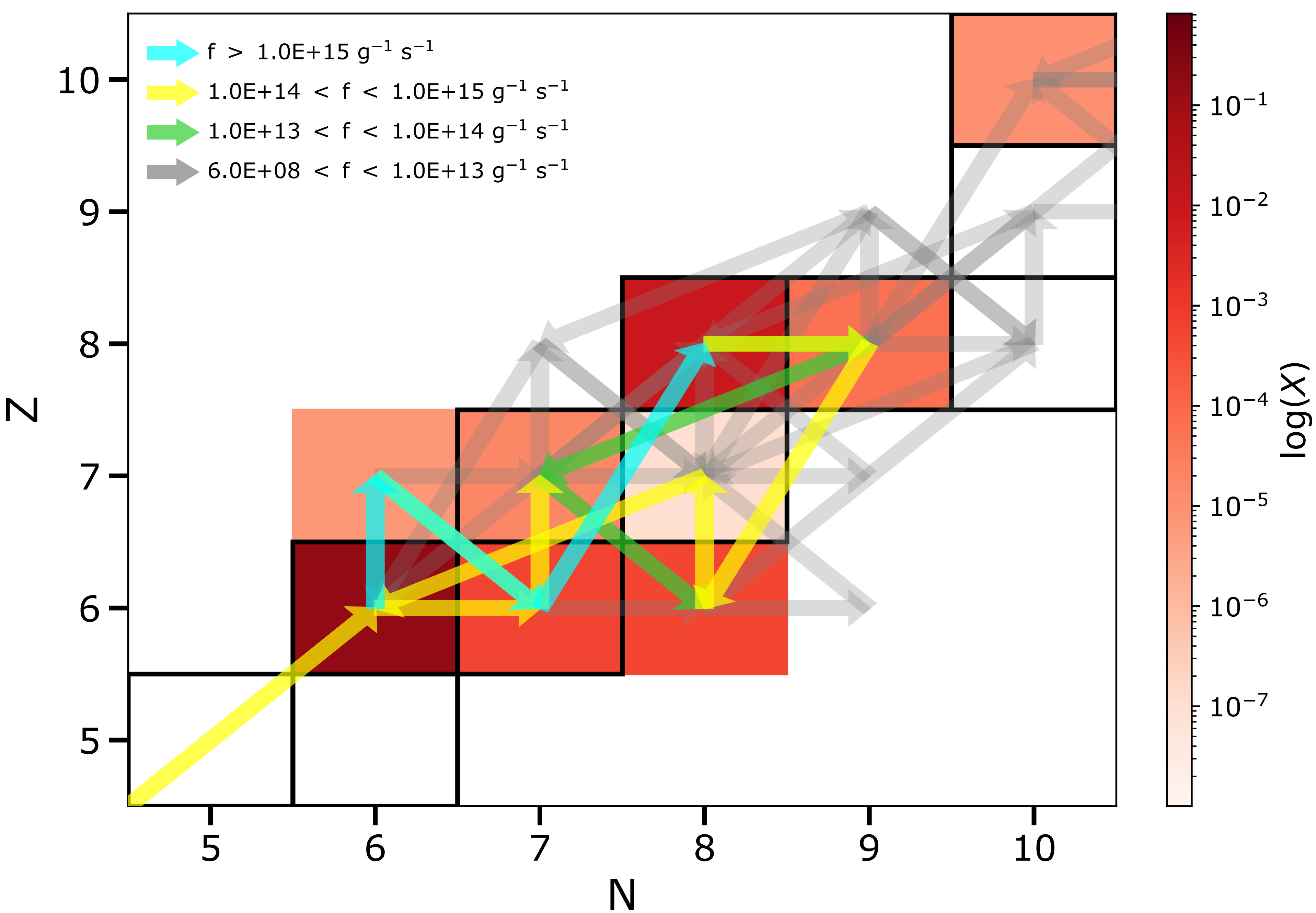
Structure evolution of an AGB star

schematic view

The i-process



Fluxes of some reactions during proton ingestion



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

$^{12}\mathrm{C}(n,\gamma)^{13}\mathrm{C}$

$^{13}\mathrm{C}(p,\gamma)^{14}\mathrm{N}$

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

$^{14}\mathrm{C}(p,\gamma)^{15}\mathrm{N}$

$^{13}\mathrm{N}(\beta^{+})^{13}\mathrm{C}$

$^{13}\mathrm{N}(n,p)^{13}\mathrm{C}$

$^{14}\mathrm{N}(n,p)^{14}\mathrm{C}$

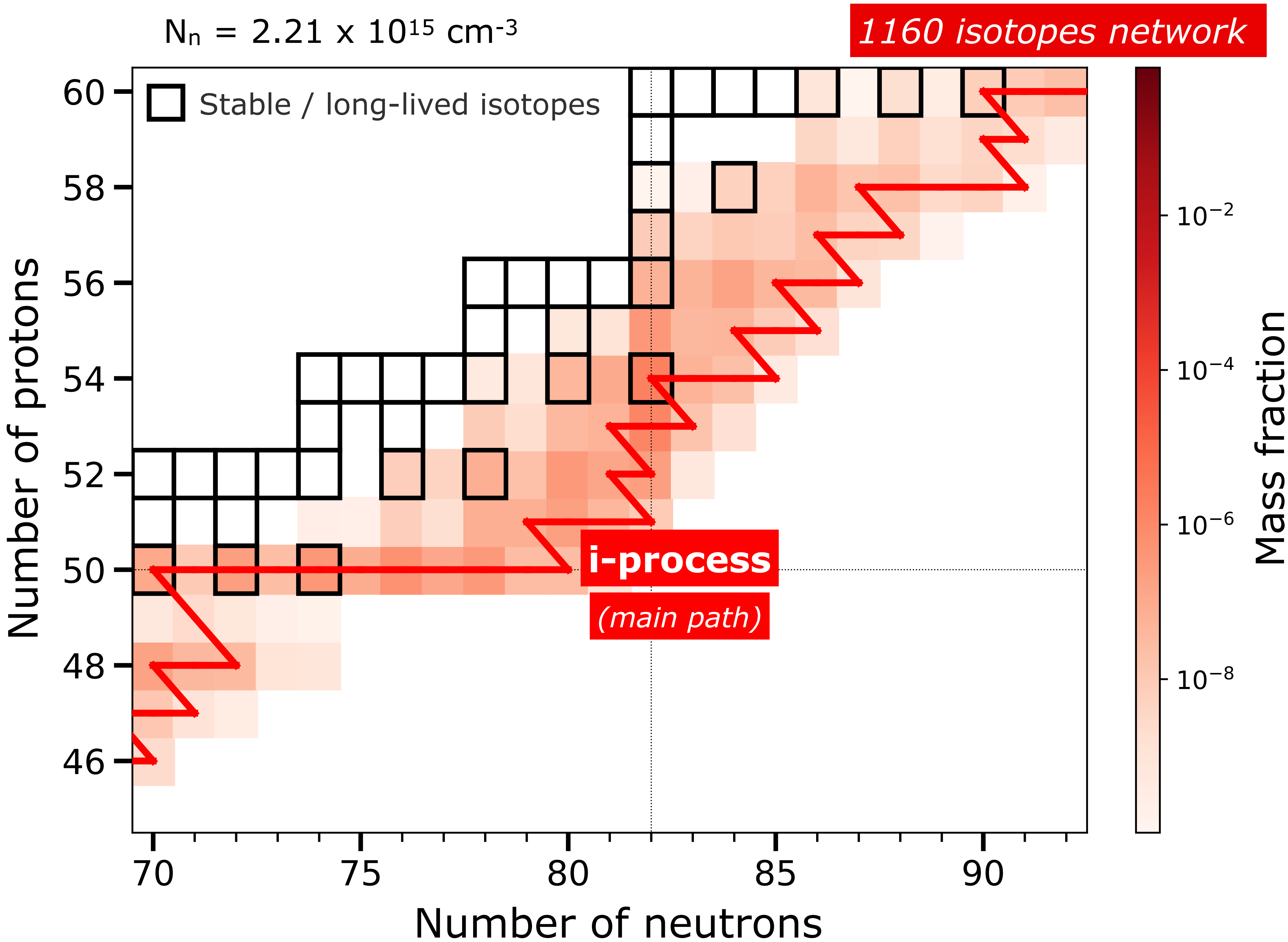
$^{15}\mathrm{N}(p,\alpha)^{12}\mathrm{C}$

$^{16}\mathrm{O}(n,\gamma)^{17}\mathrm{O}$

$^{17}\mathrm{O}(n,\alpha)^{14}\mathrm{C}$

$^{17}\mathrm{O}(p,\alpha)^{14}\mathrm{N}$

i-process at the bottom of the thermal pulse



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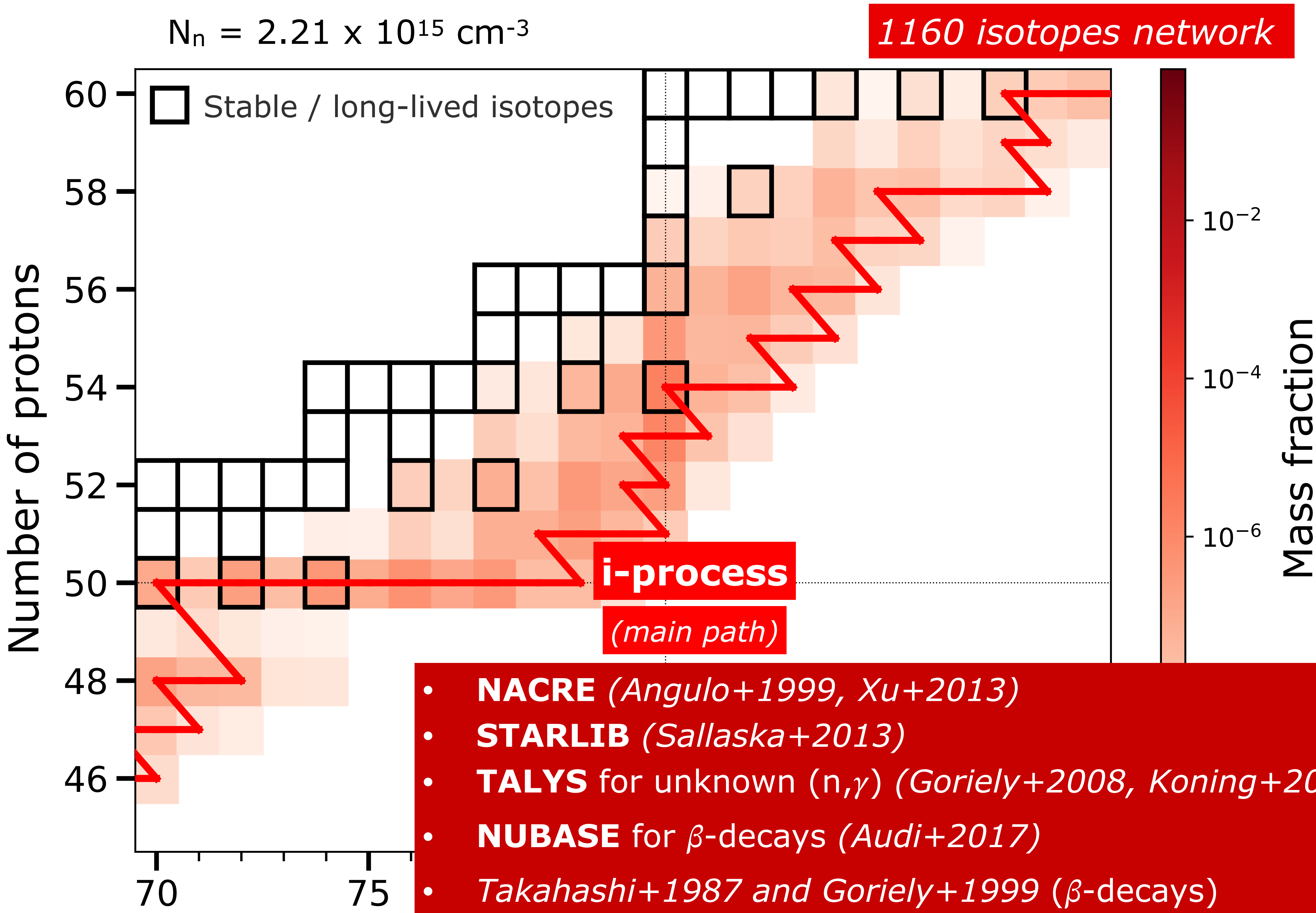

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- **STARLIB** *(Sallaska+2013)*
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- *…*

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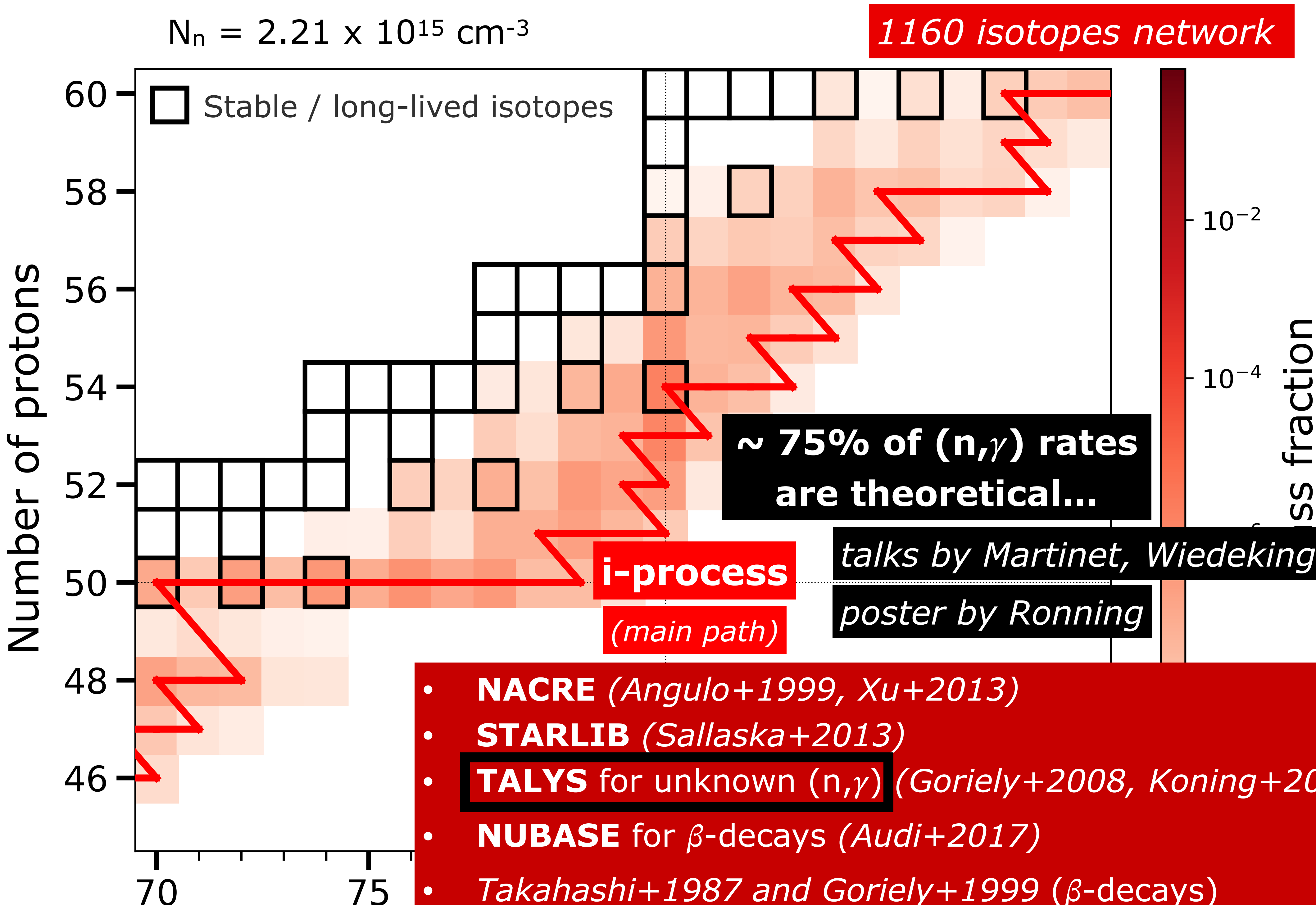

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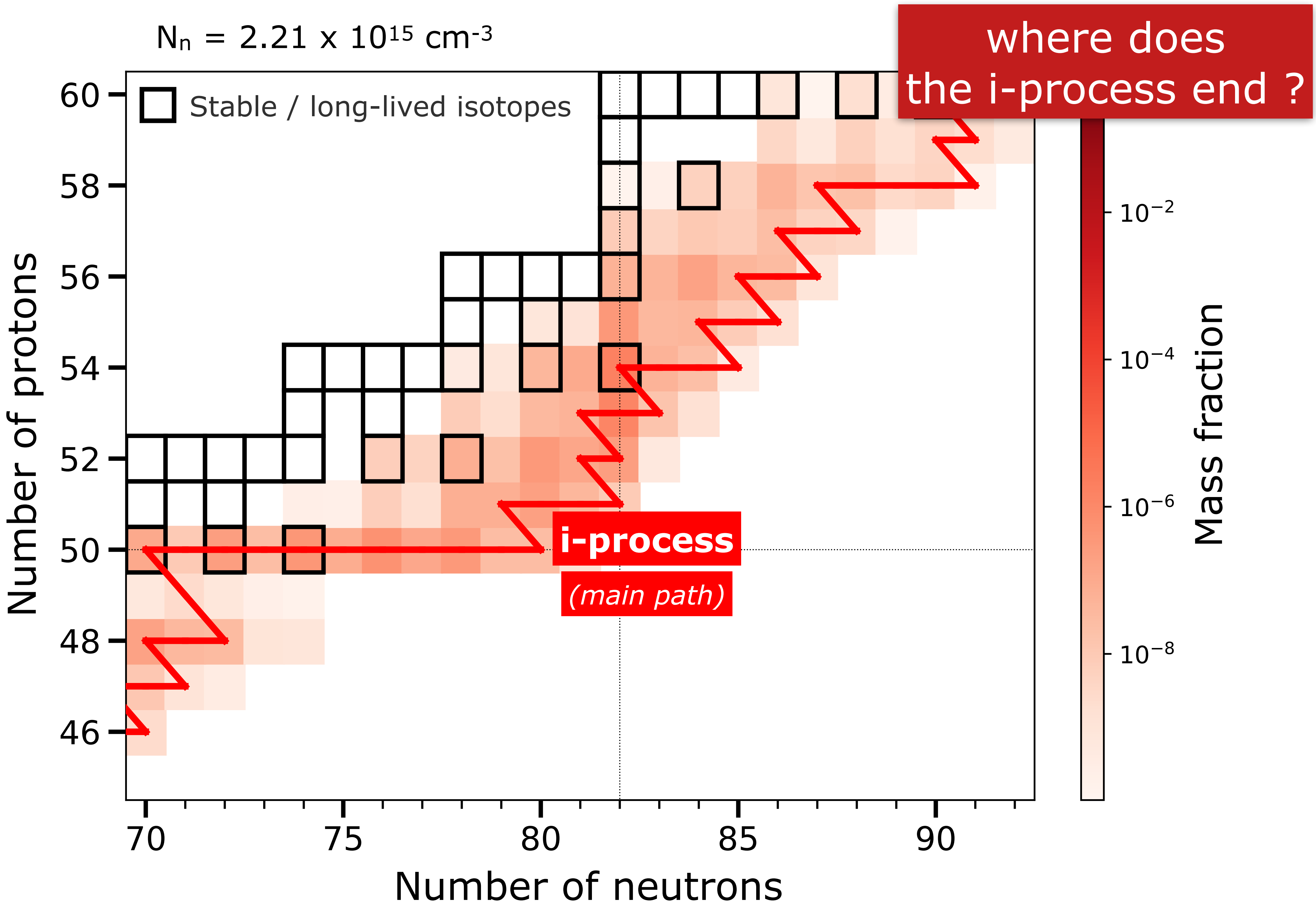
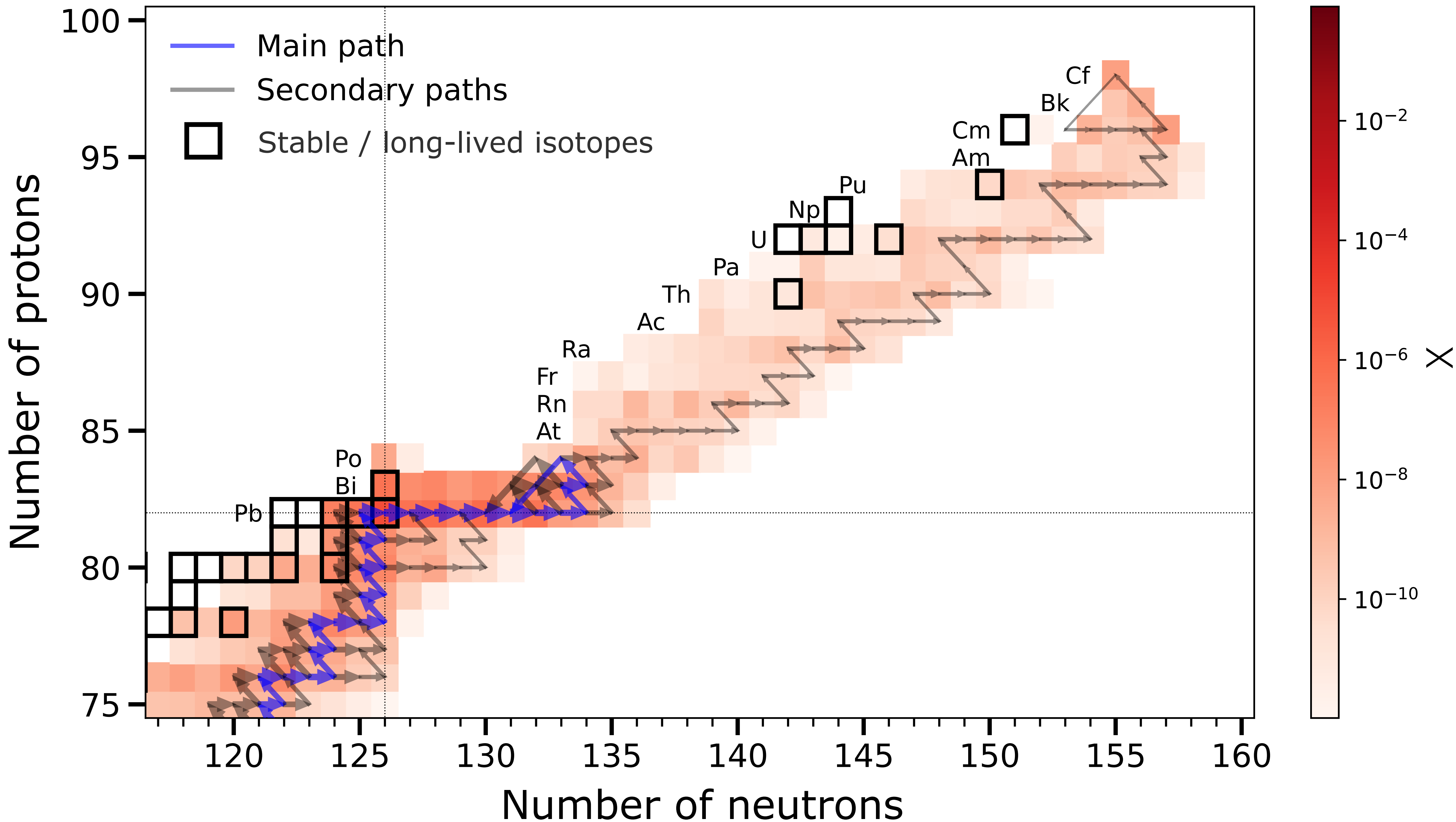


i-process flow at the bottom of the thermal pulse

Production of actinides

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



Choplin,+2022

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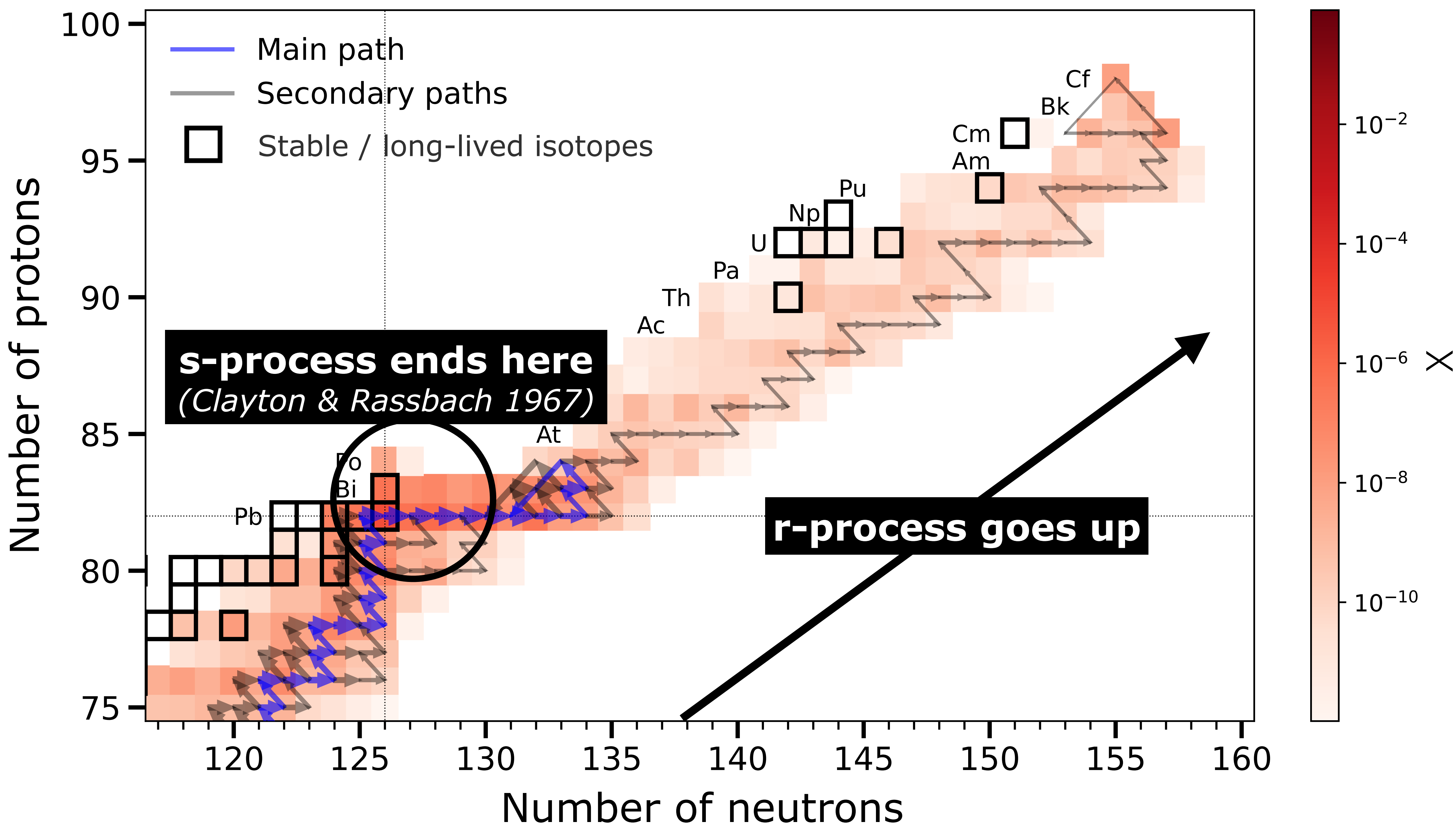

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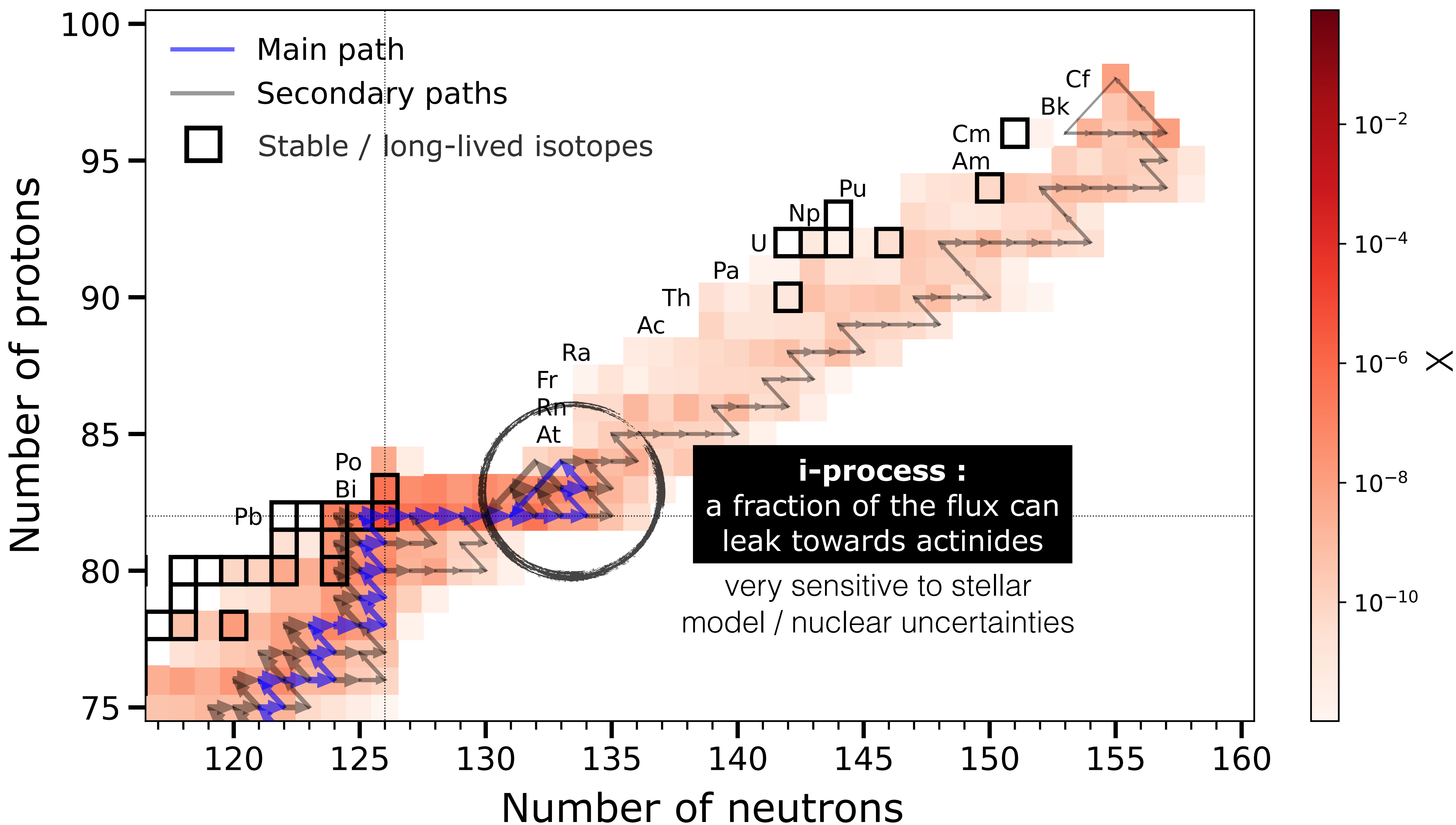

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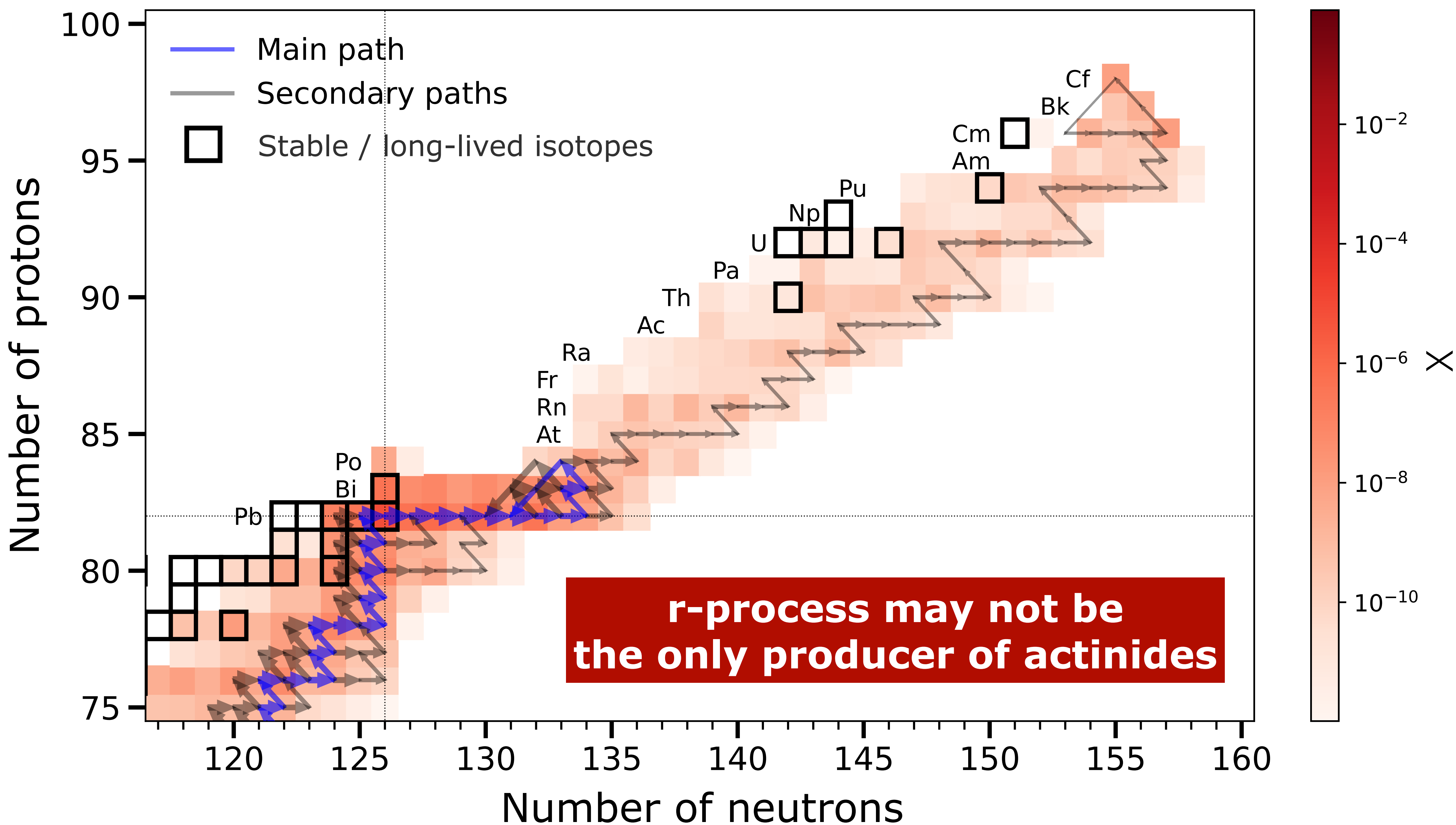
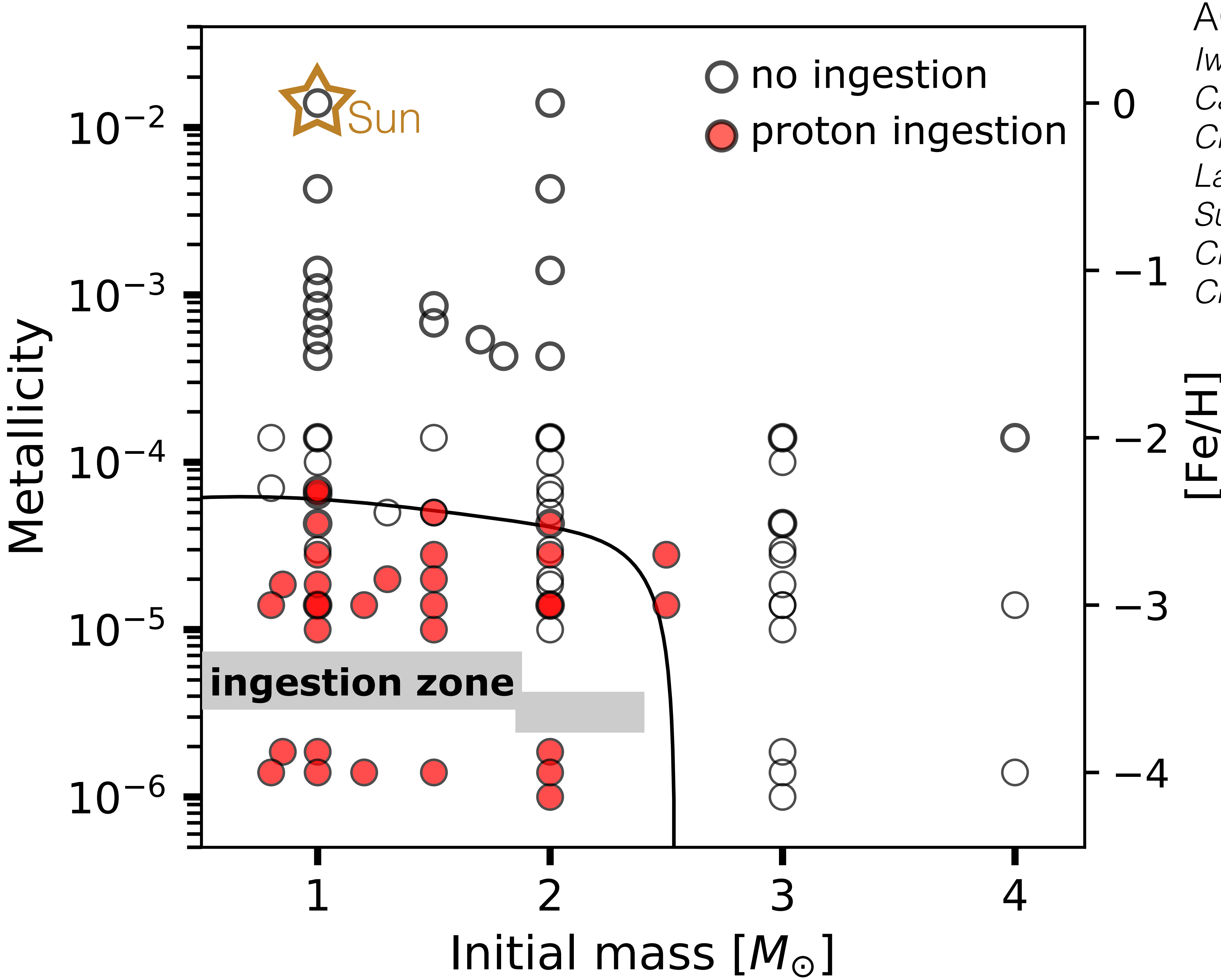


Choplin,+2022

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



AGB models from :

Iwamoto+2004
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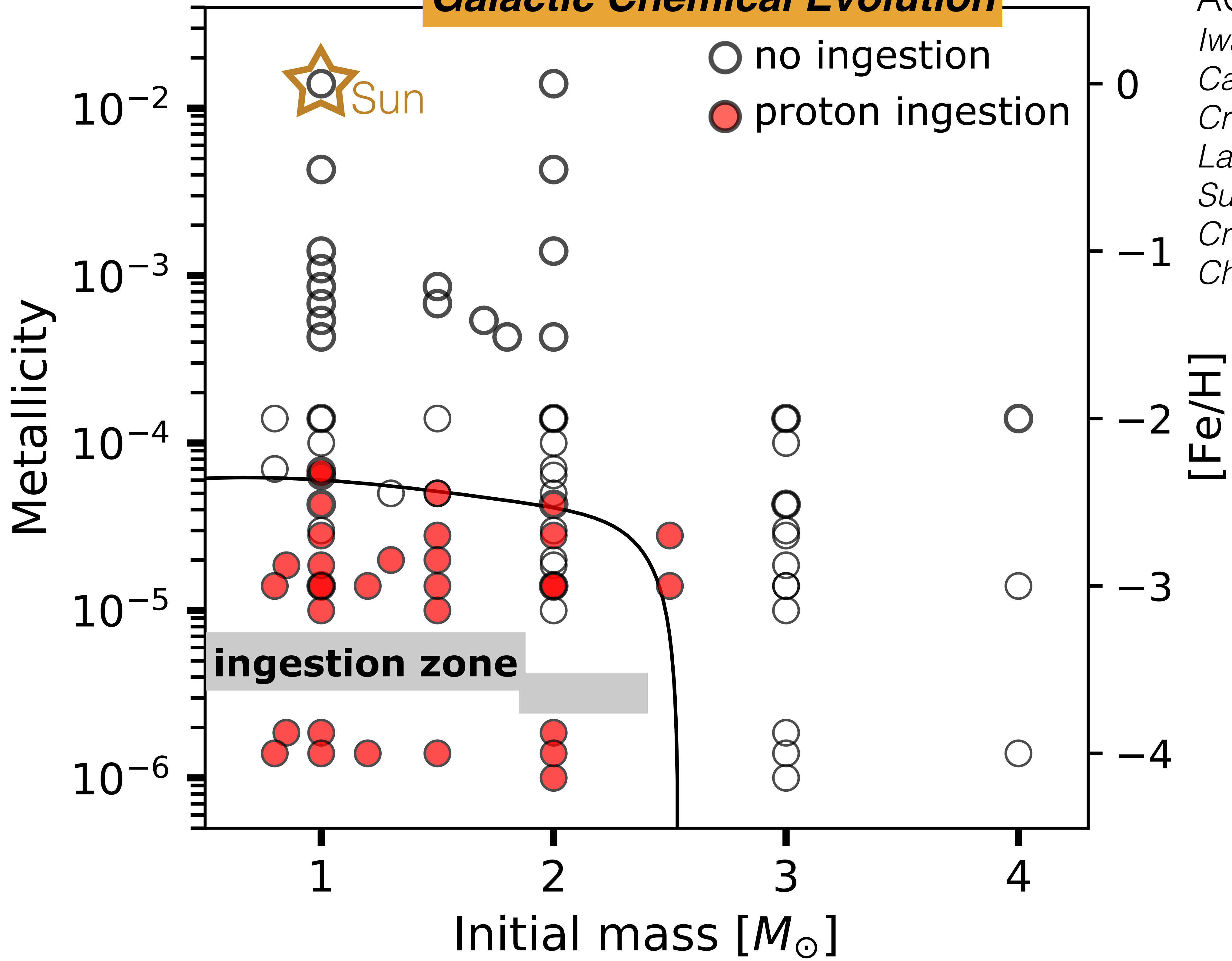
Important for Galactic Chemical Evolution



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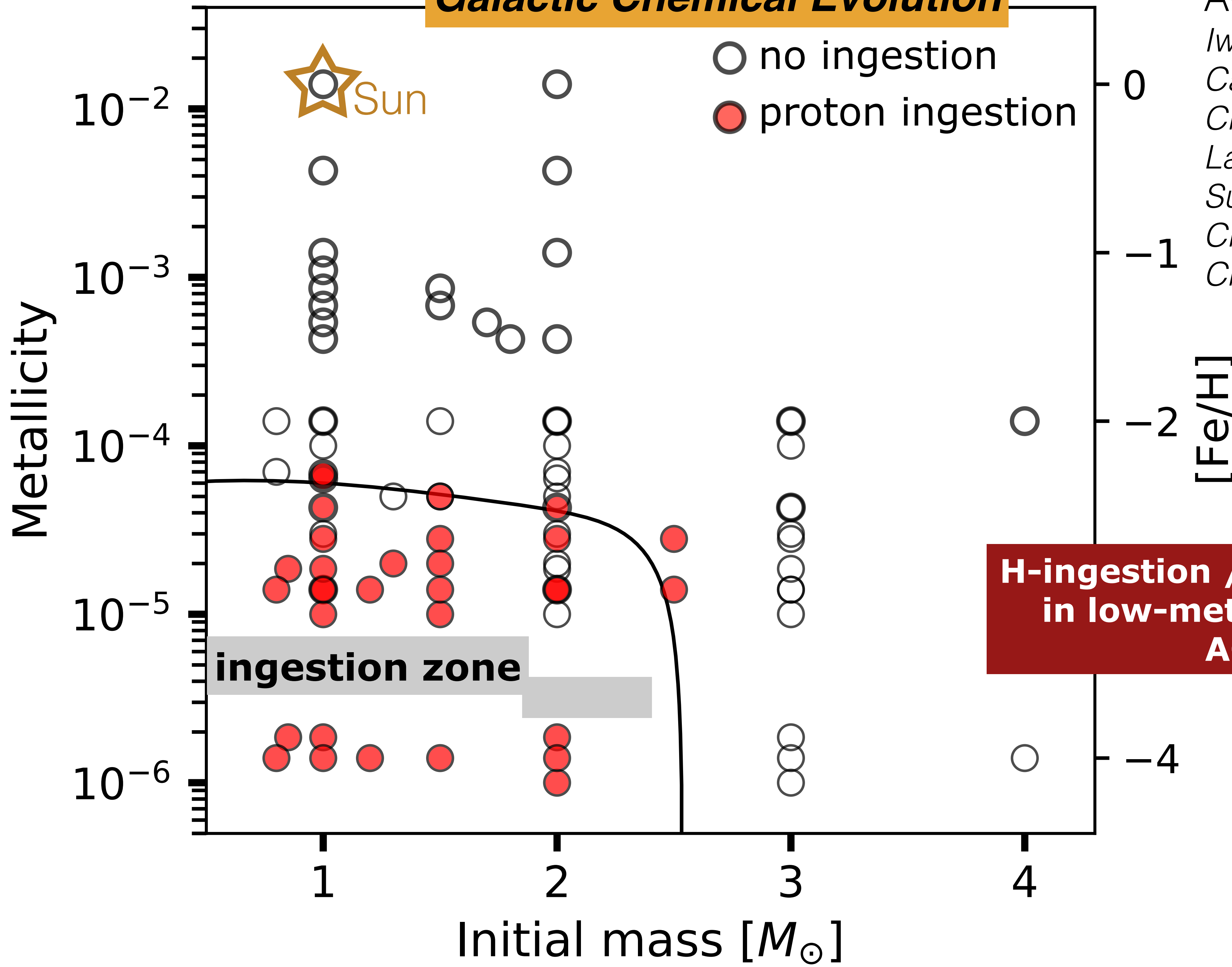

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H-ingestion / i-process happens in low-metallicity low-mass AGB stars

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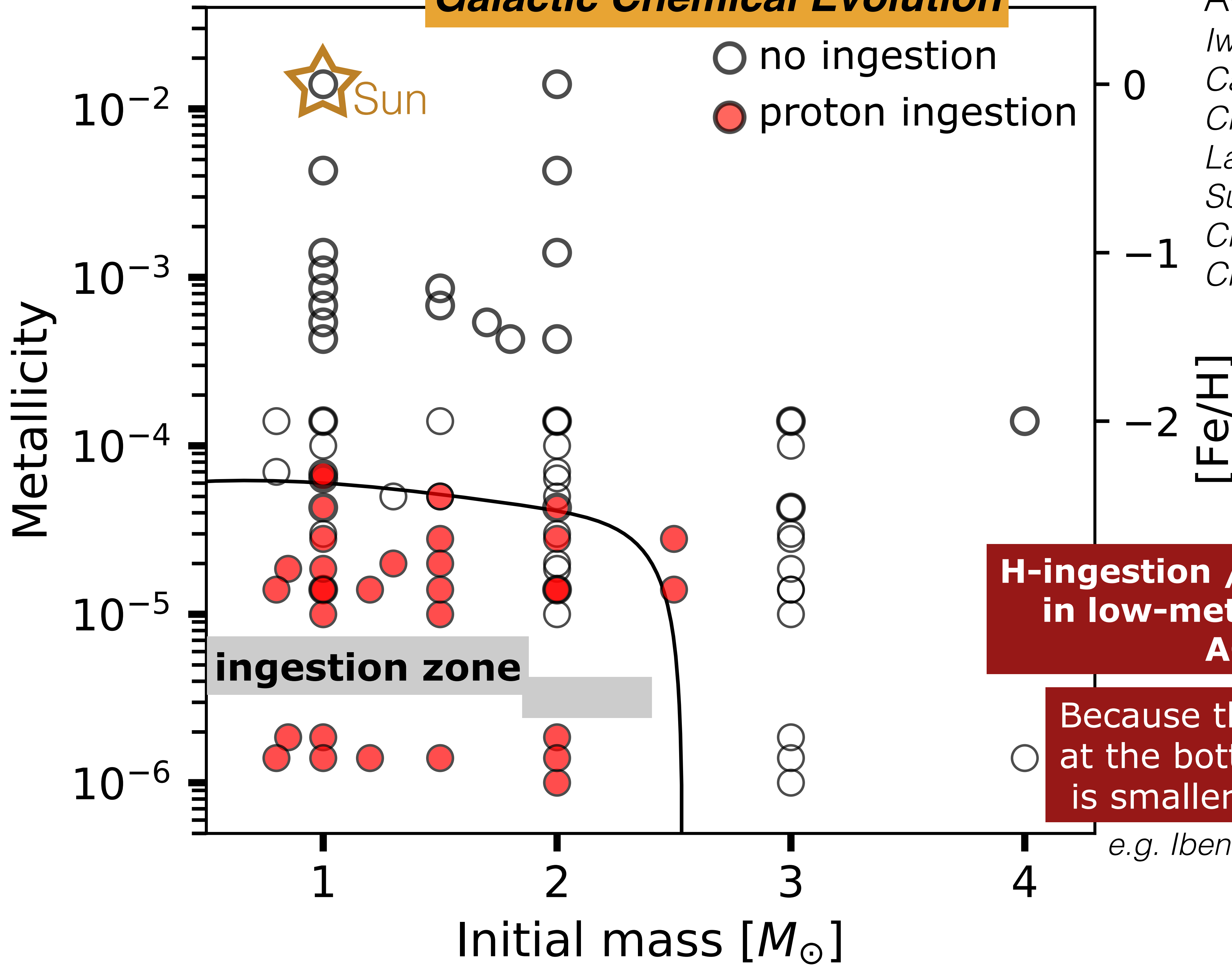

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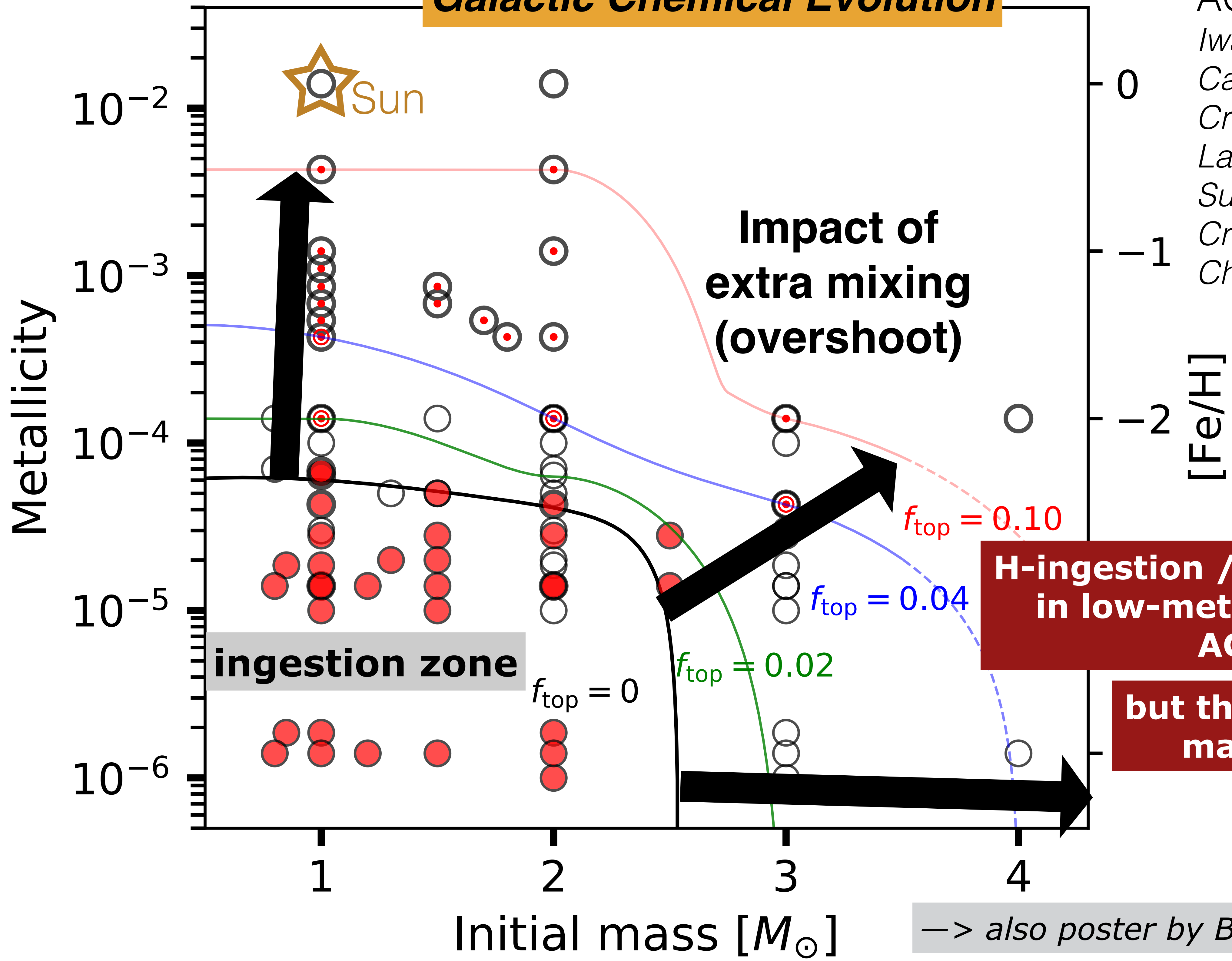
H-ingestion / i-process happens in low-metallicity low-mass AGB stars

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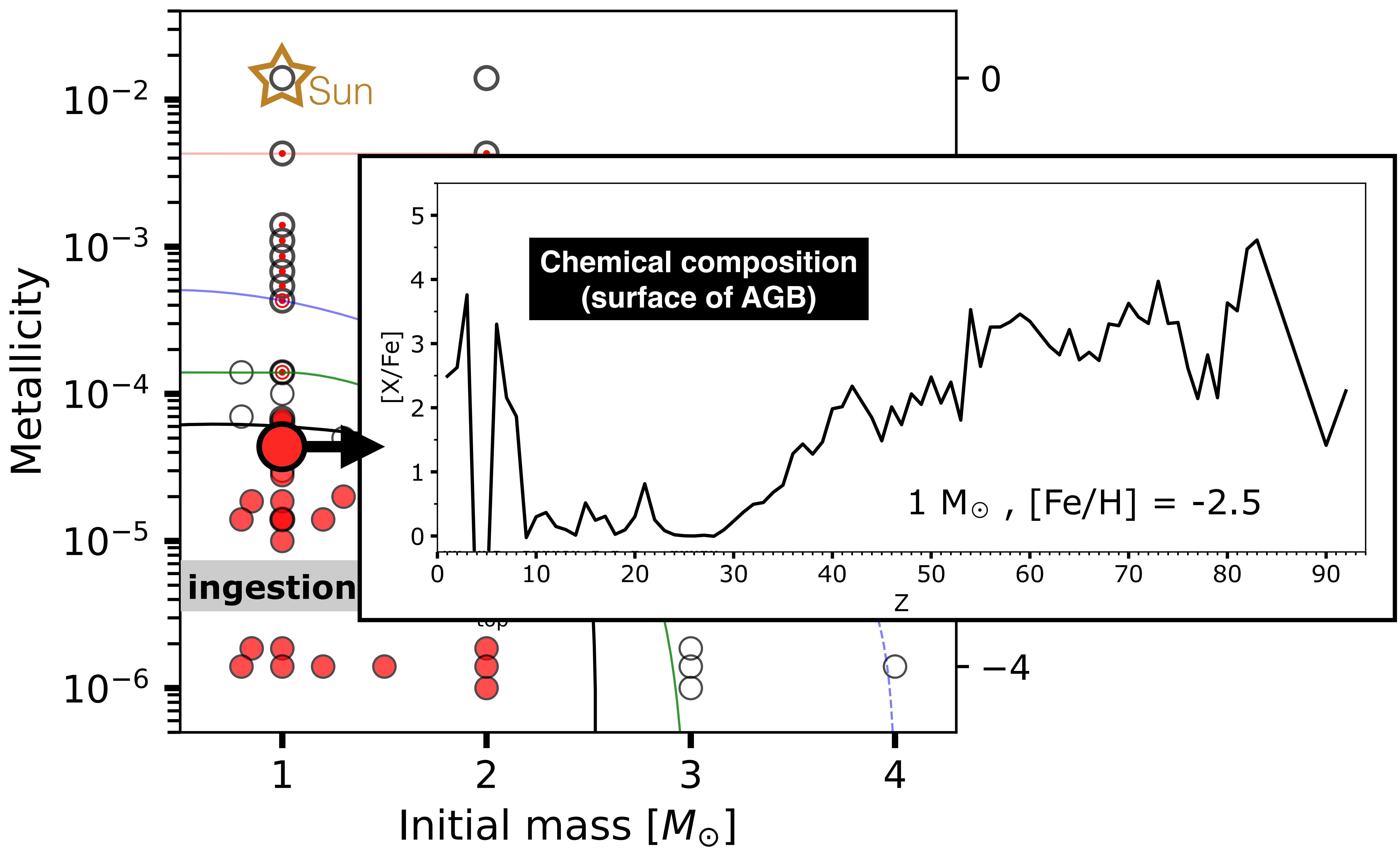
H-ingestion / i-process happens in low-metallicity low-mass AGB stars

but the ingestion zone may be bigger…

—> also poster by Bryce Remple

AGB surface abundances after proton ingestion



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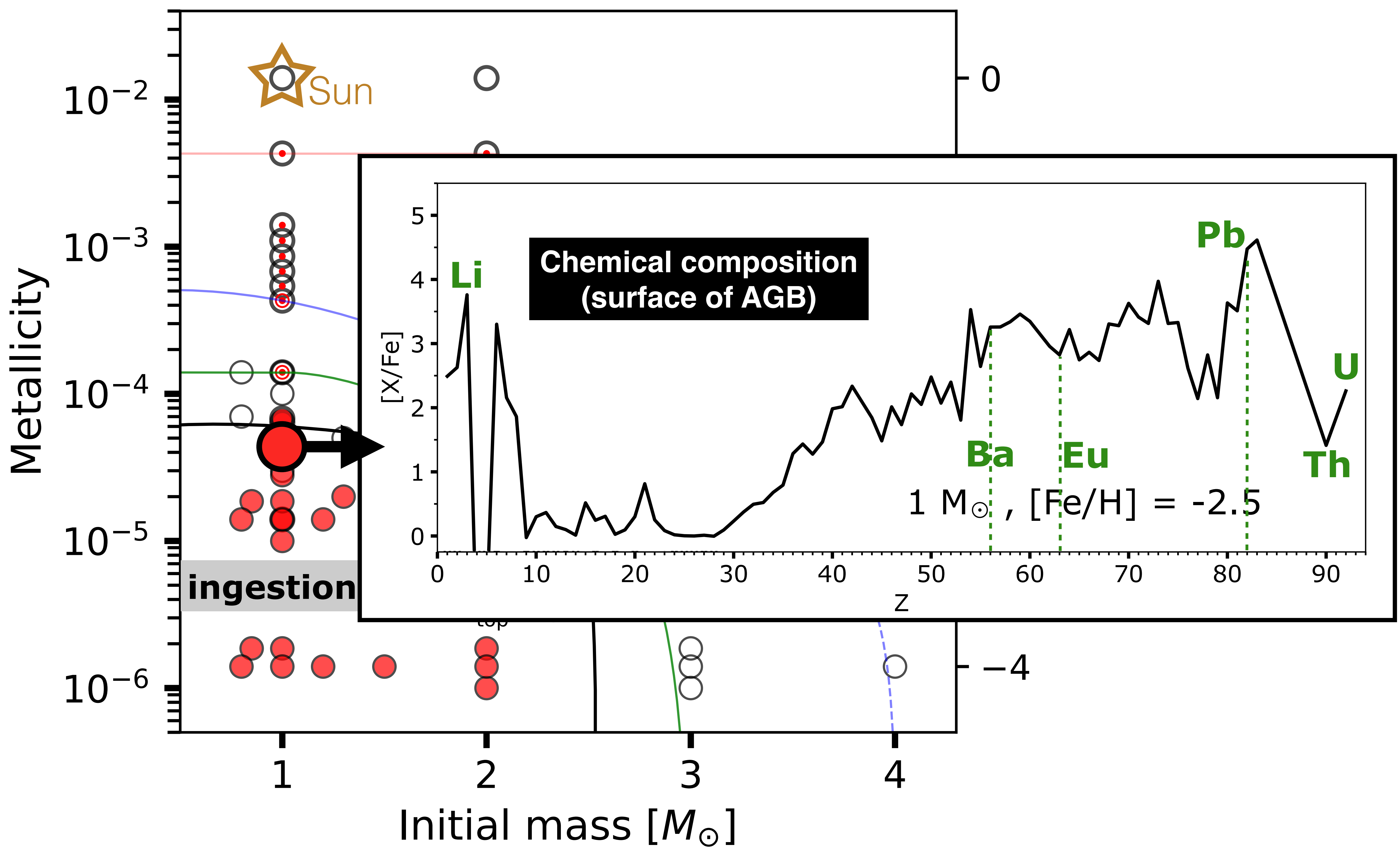

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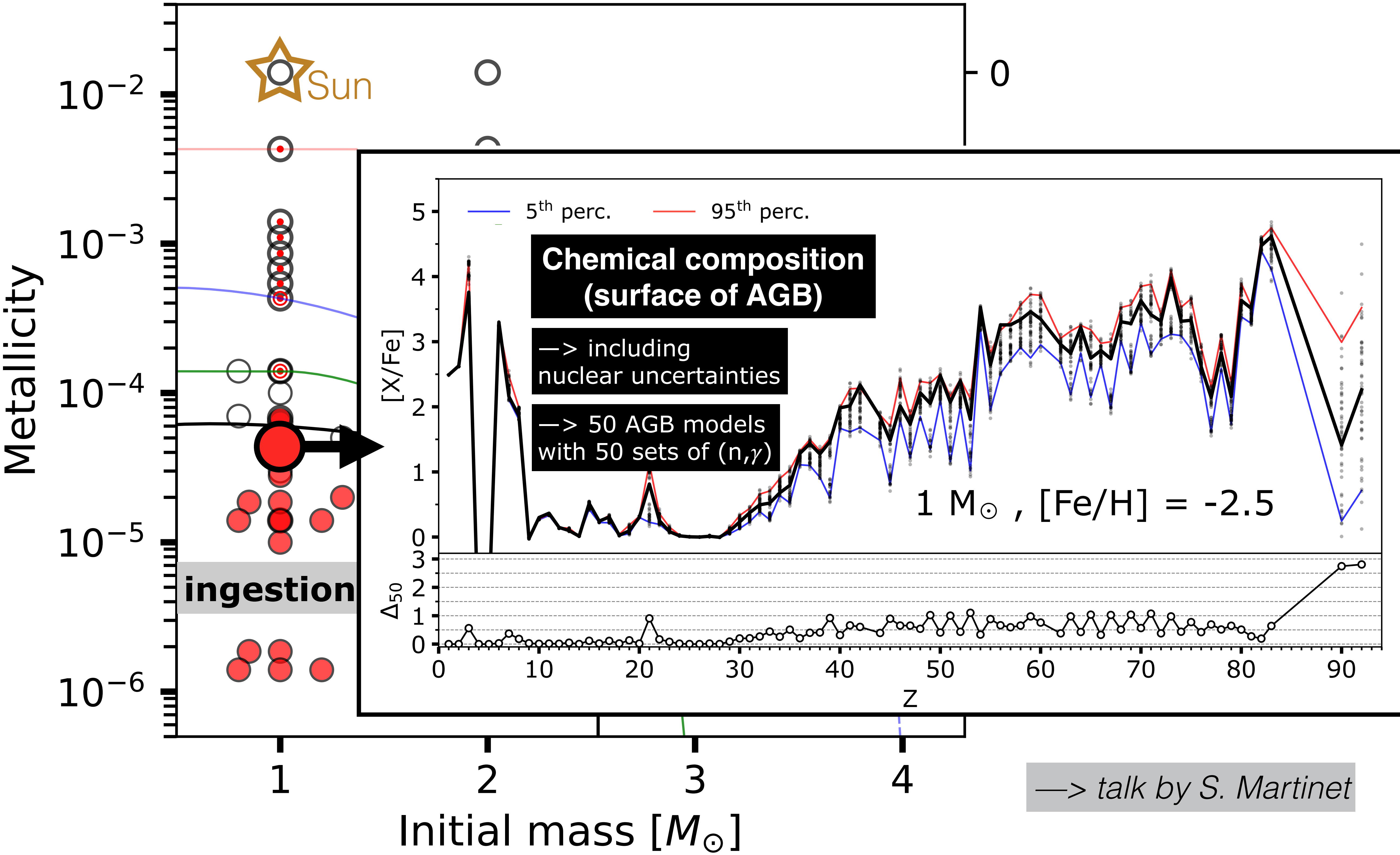

—> *talk by S. Martinet*

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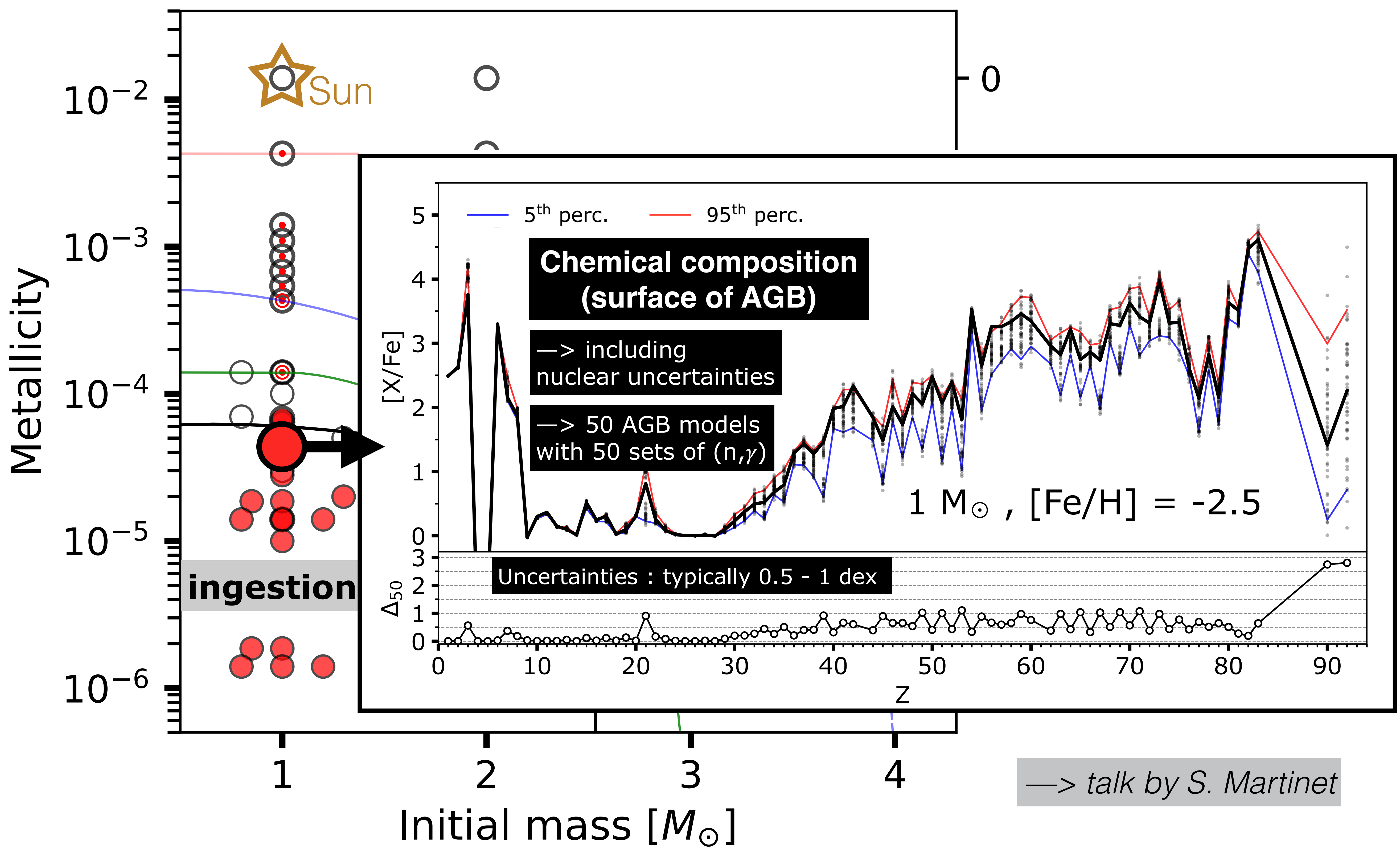

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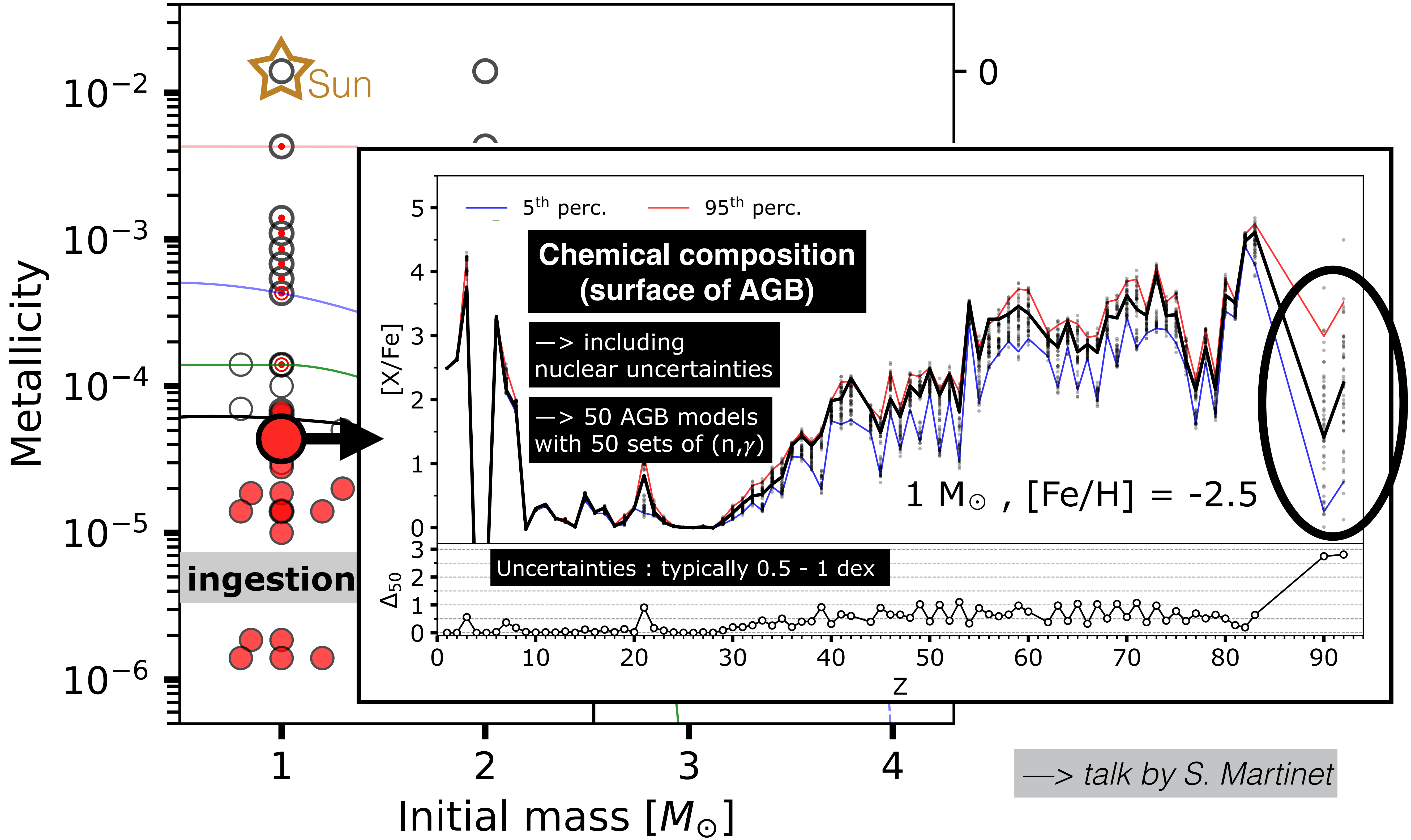

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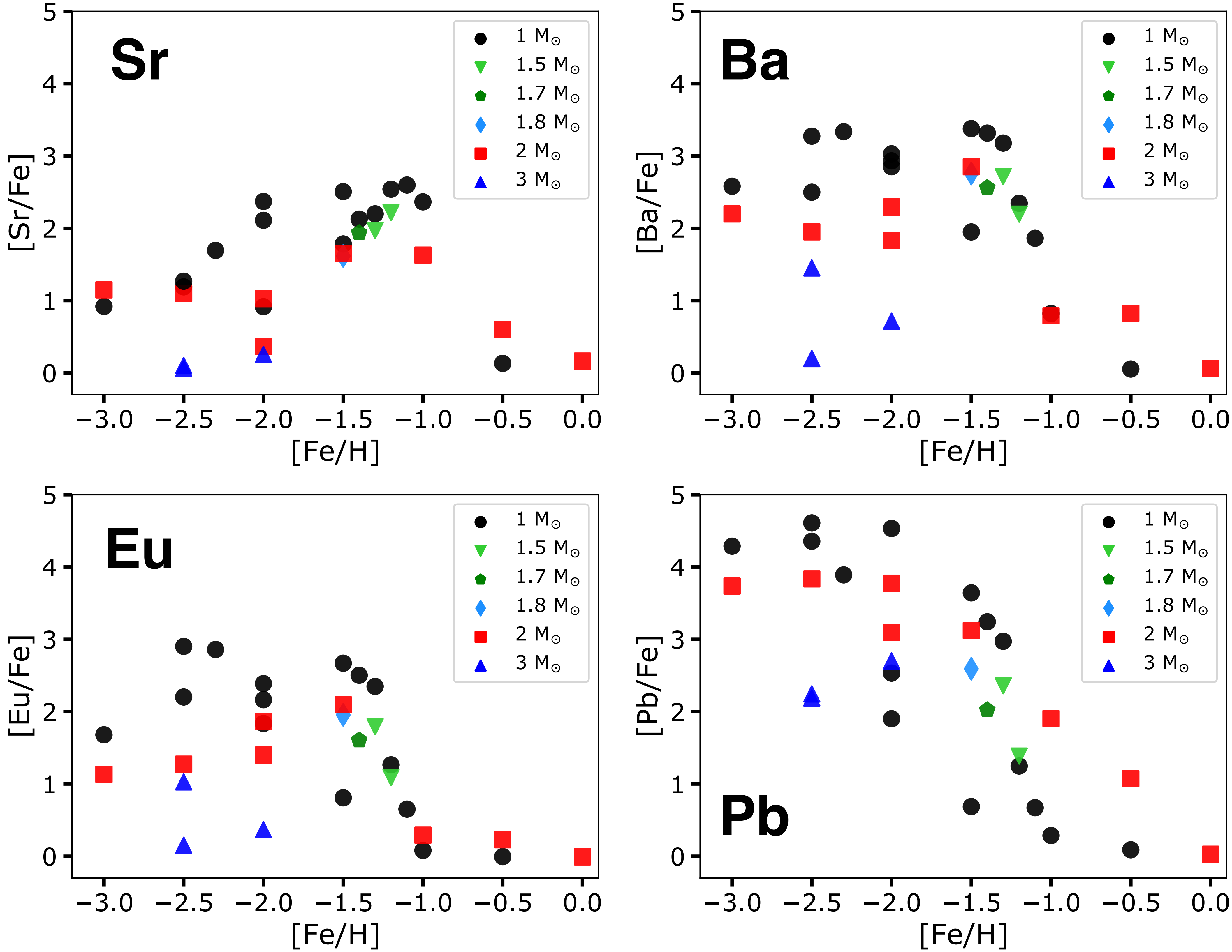
Nucleosynthetic yields of AGB experiencing H-ingestion

(with overshoot)



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low-mass stars => higher [X/Fe] (less dilution at low mass)

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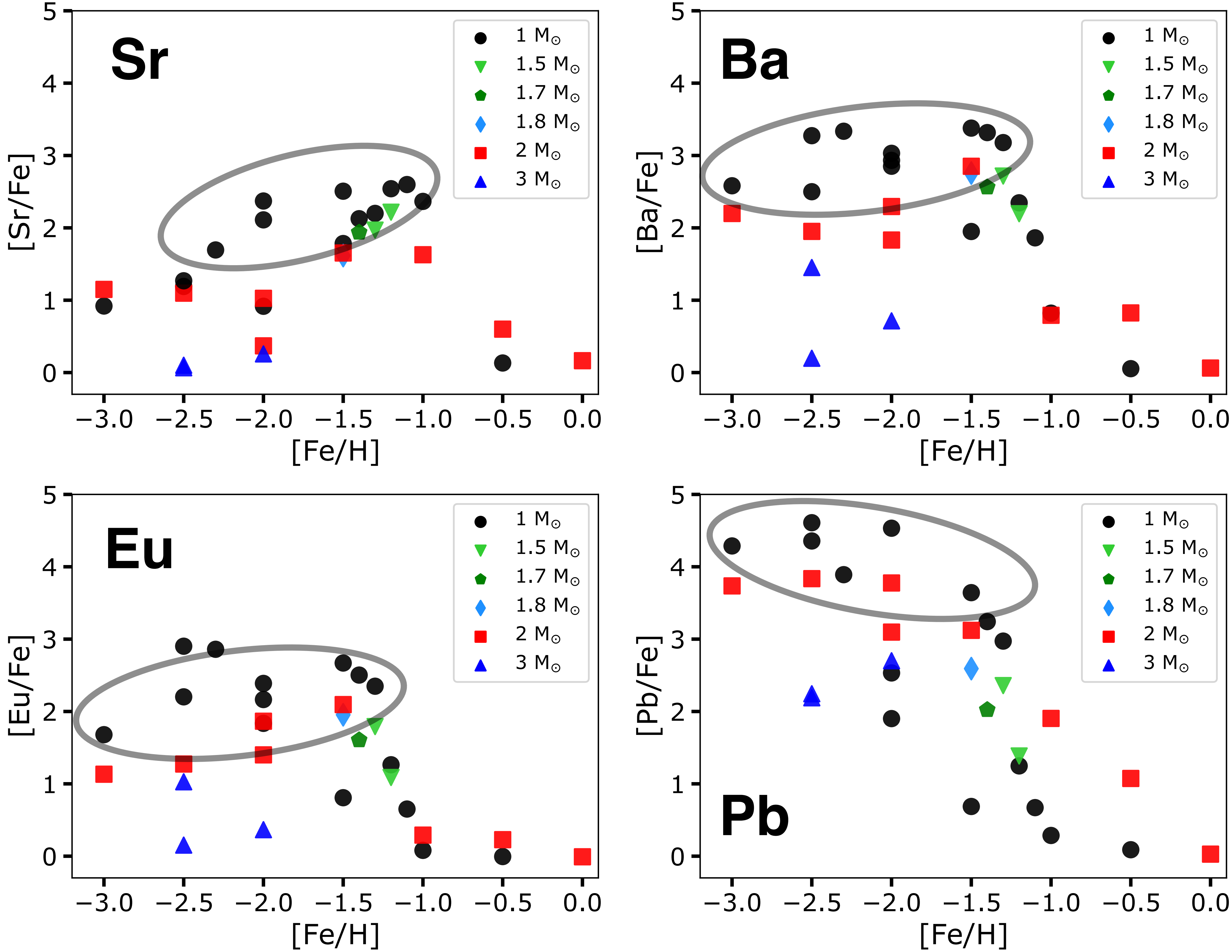

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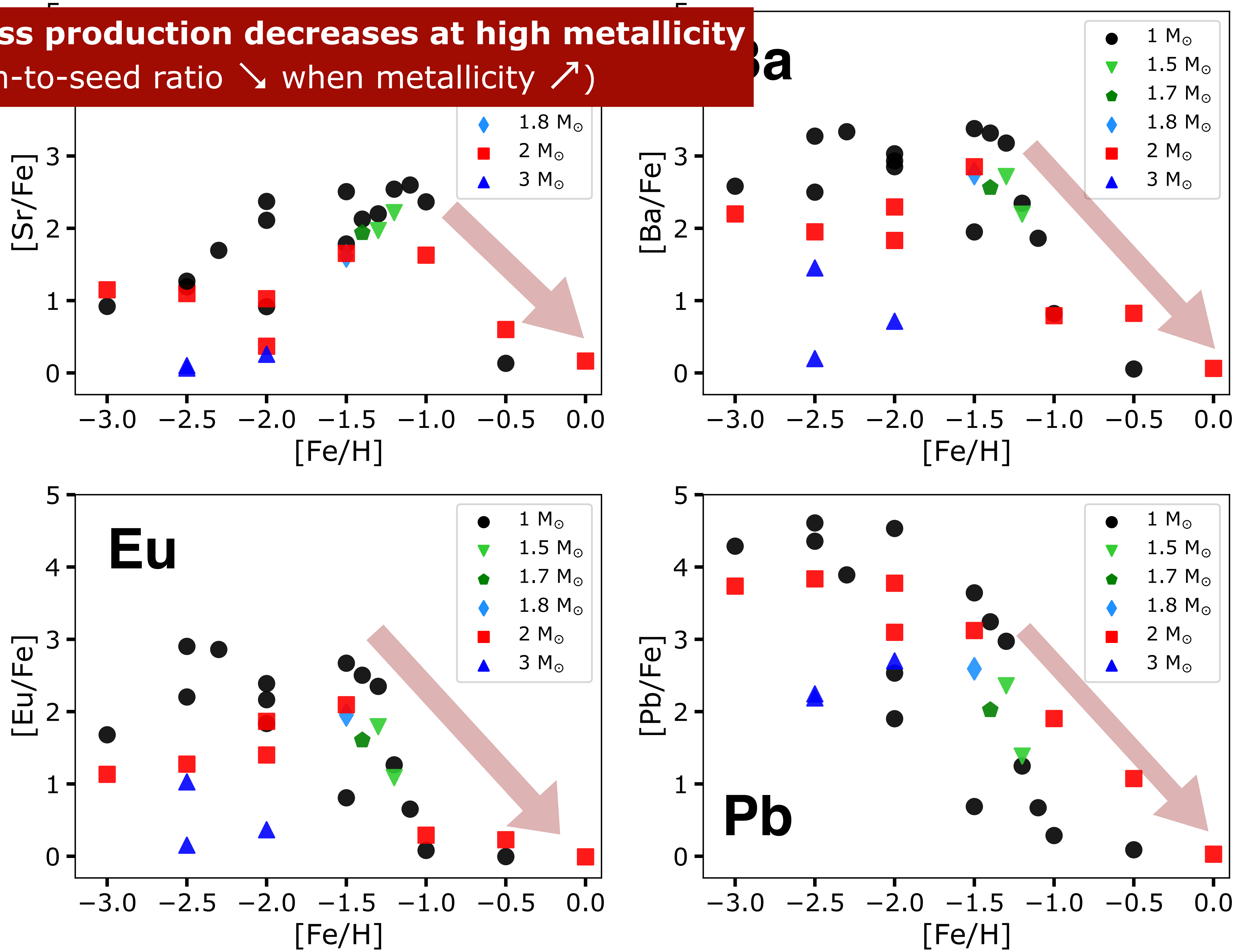

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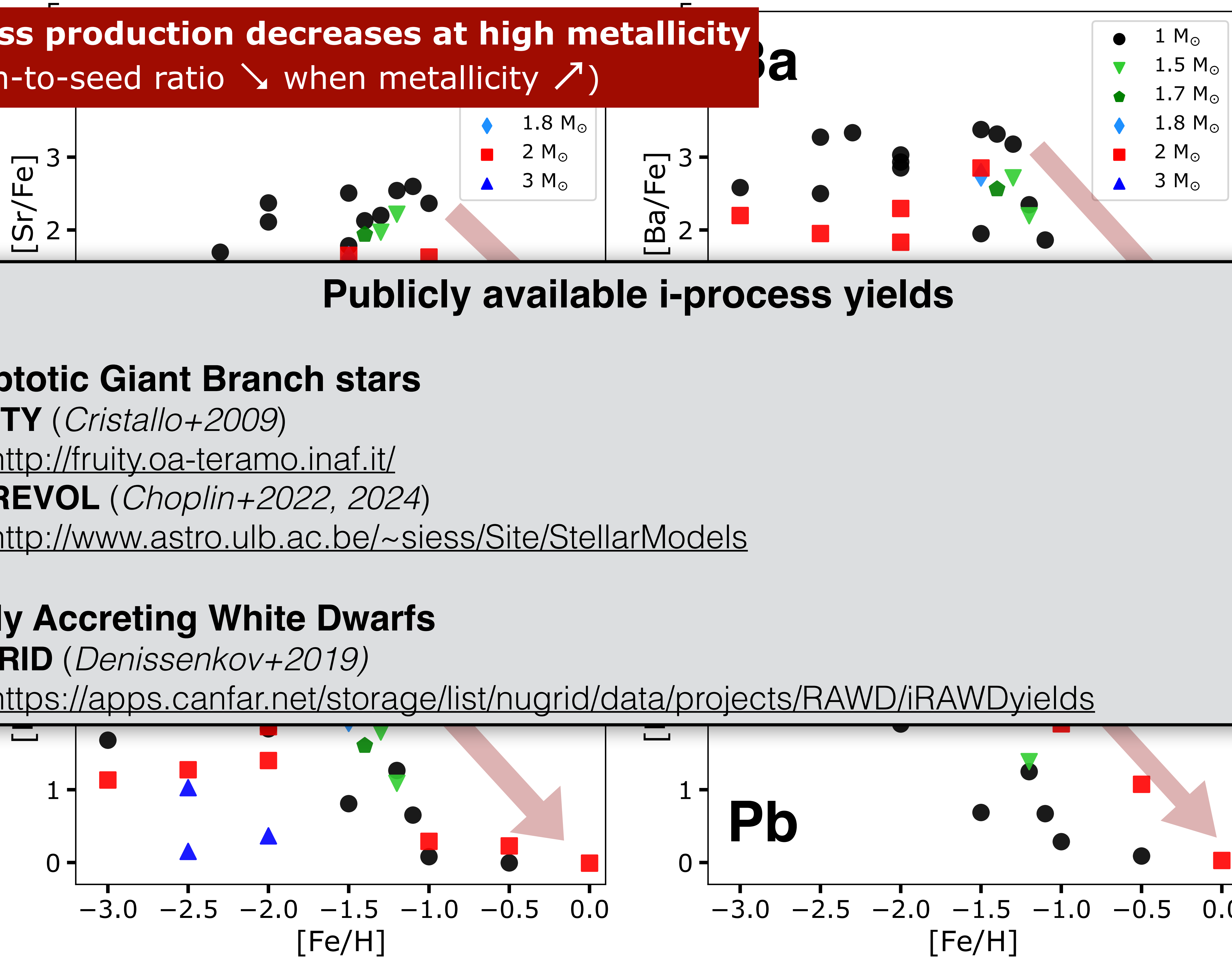


Publicly available i-process yields

Asymptotic Giant Branch stars

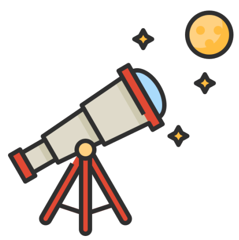
- **FRUITY** (*Cristallo+2009*)
  —> http://fruity.oa-teramo.inaf.it/
- **STAREVOL** (*Choplin+2022, 2024*)
  —> http://www.astro.ulb.ac.be/~siess/Site/StellarModels

Rapidly Accreting White Dwarfs

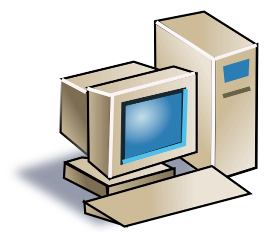
- **NUGRID** (*Denissenkov+2019)*
  —> https://apps.canfar.net/storage/list/nugrid/data/projects/RAWD/iRAWDyields

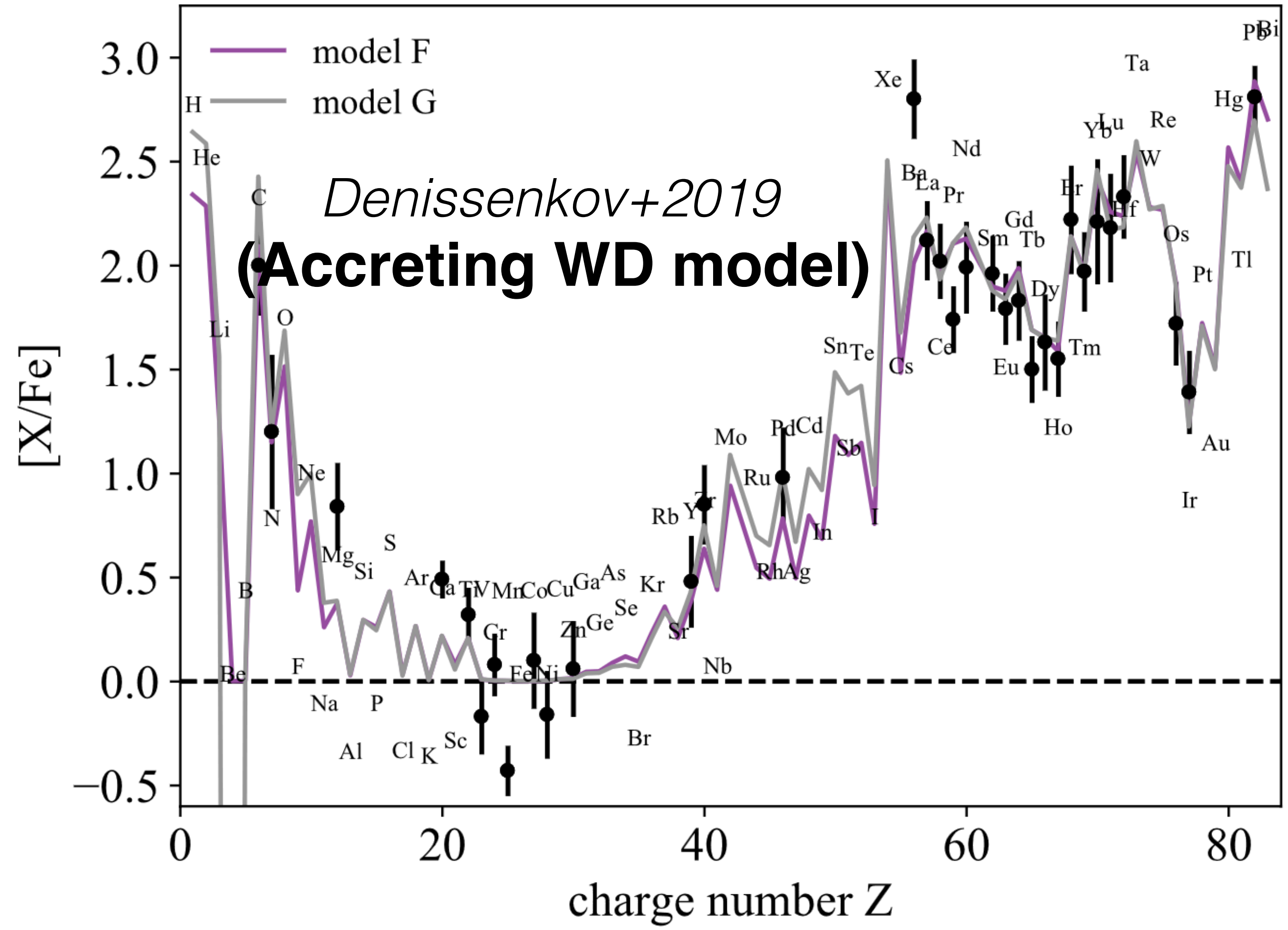
i-process models vs. observed « i-stars »

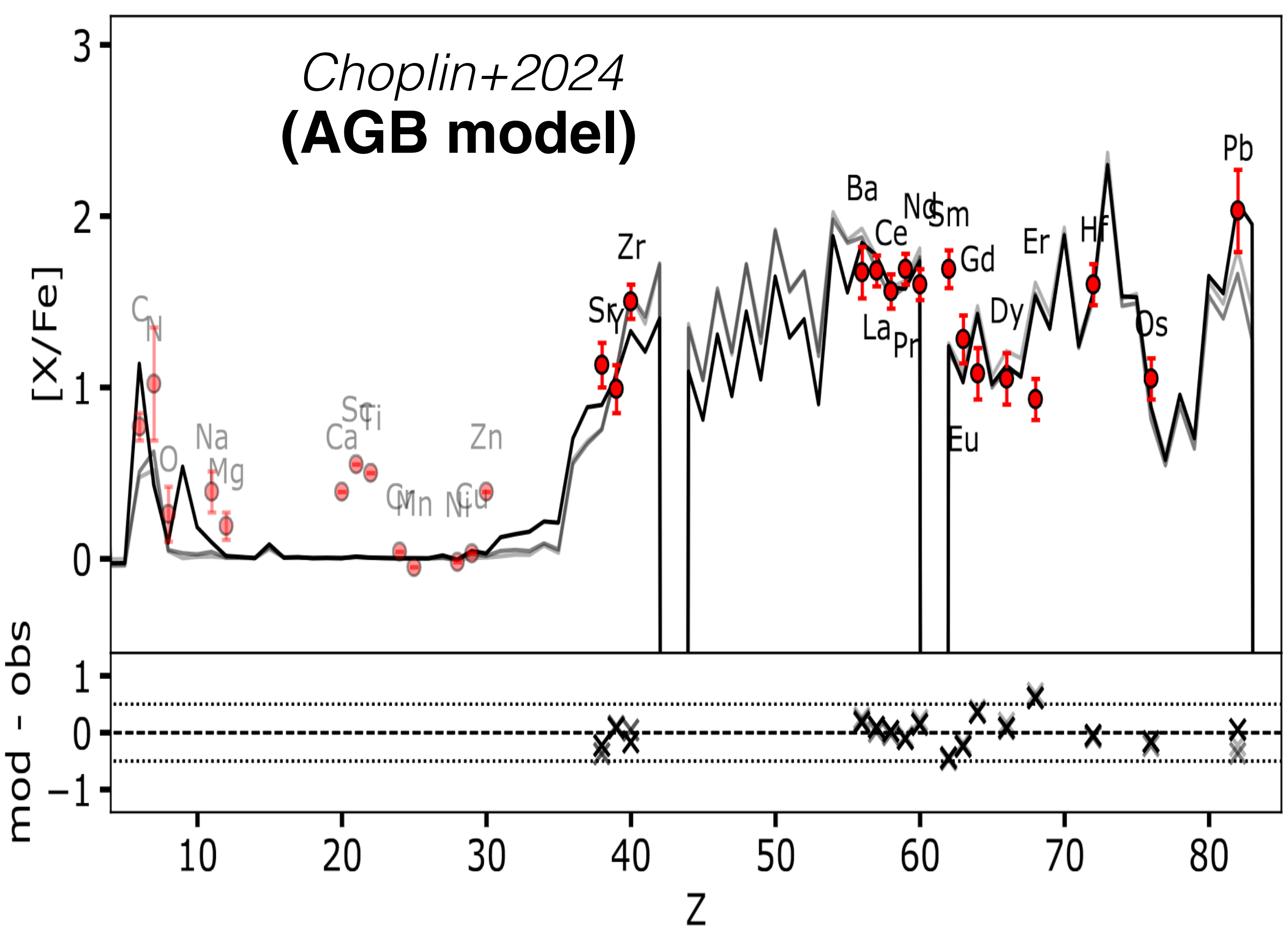
- Some stars are neither « s », nor « r ». They are compatible with i-process models

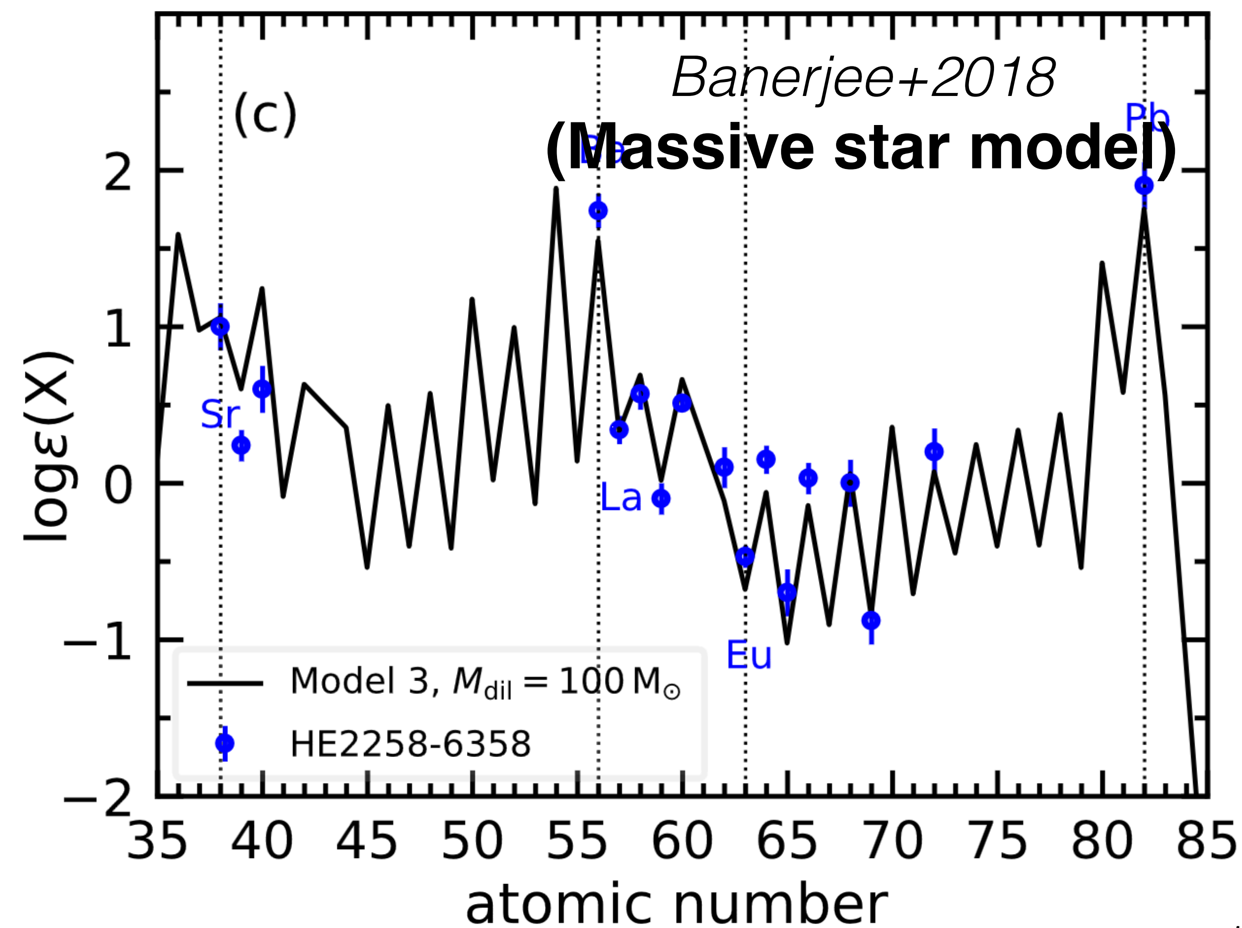


VS.









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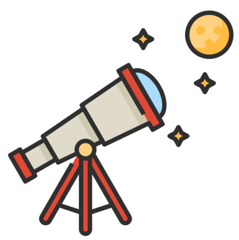

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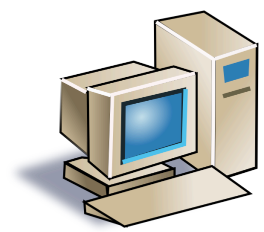
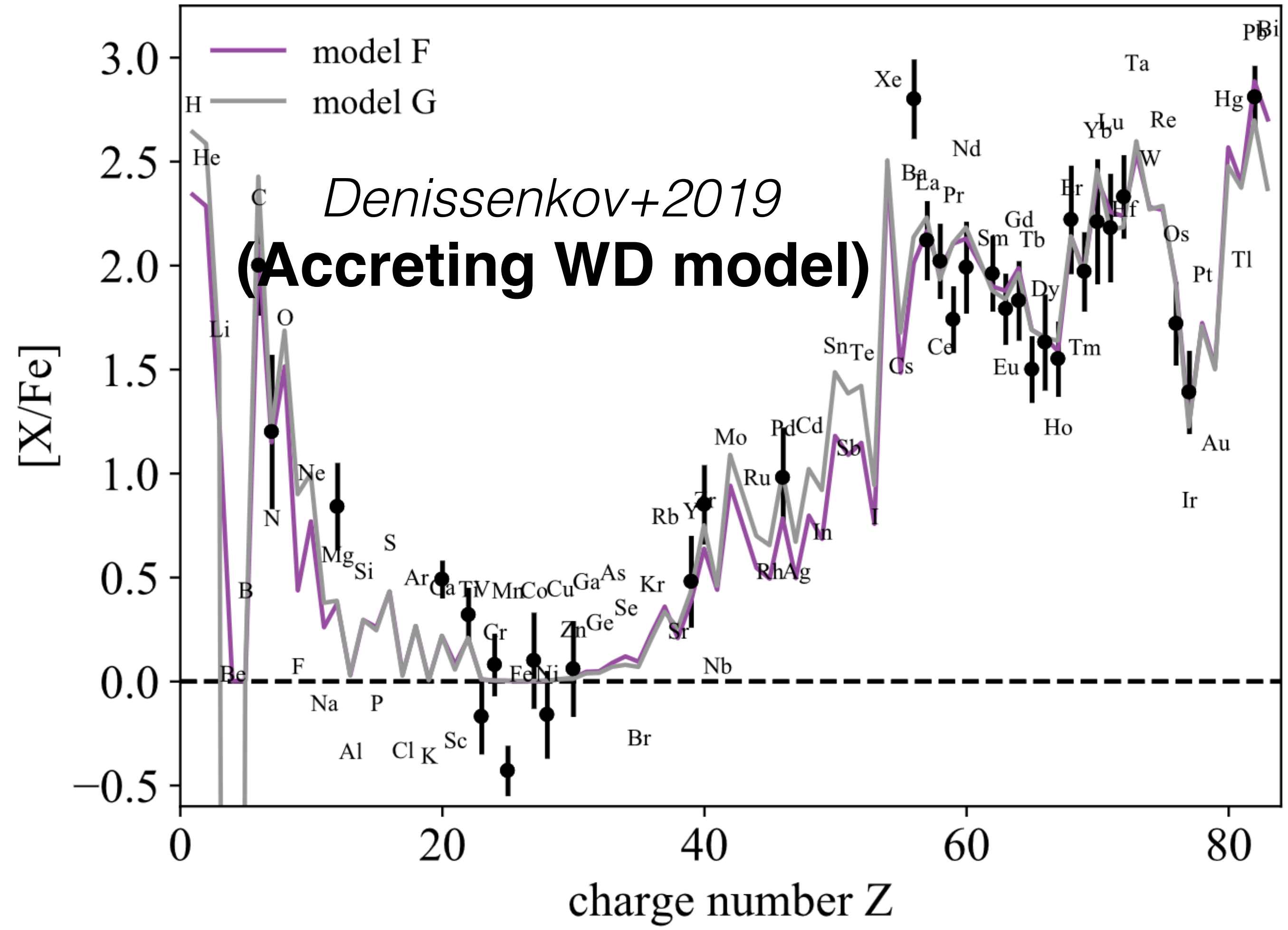
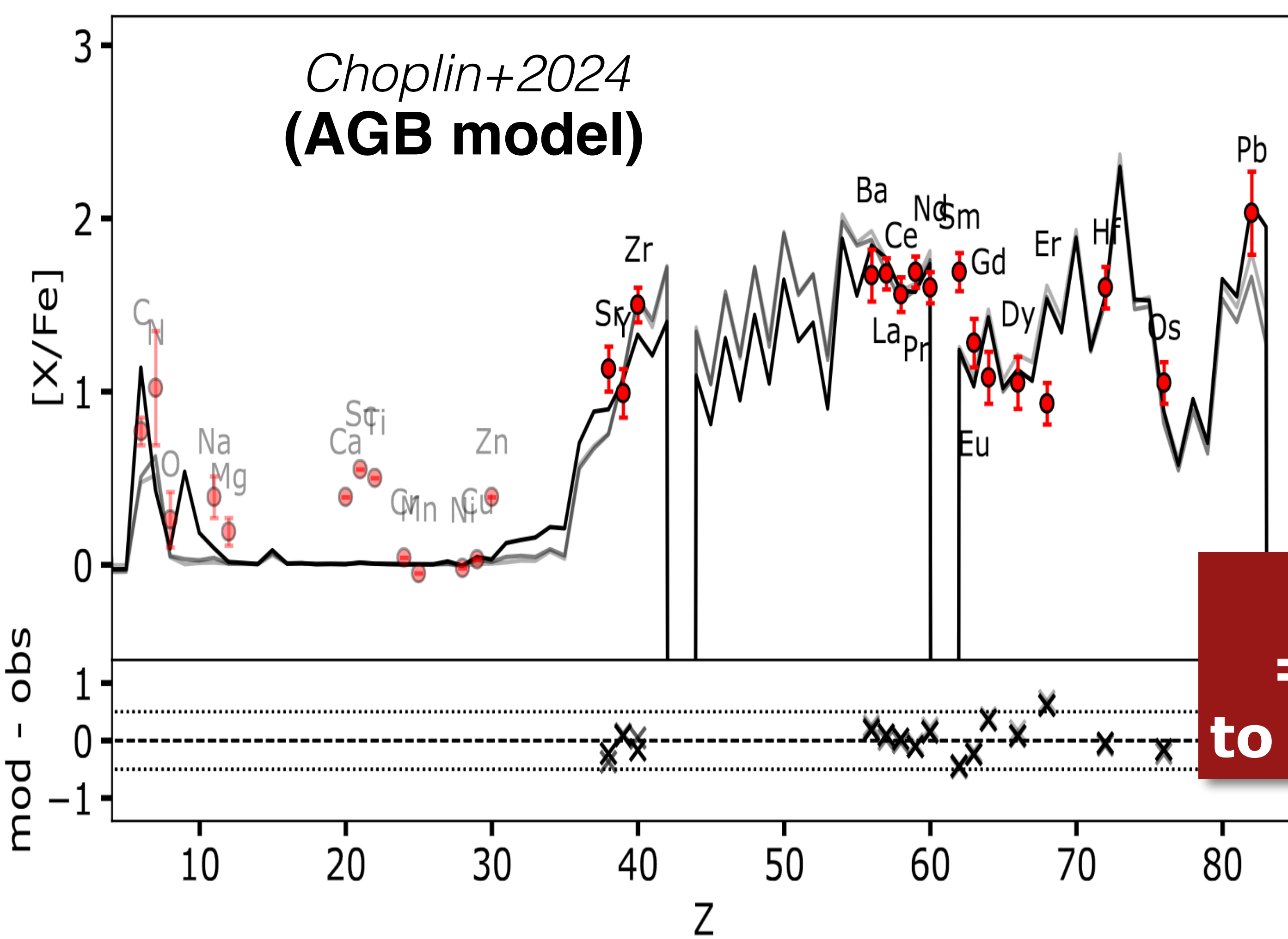
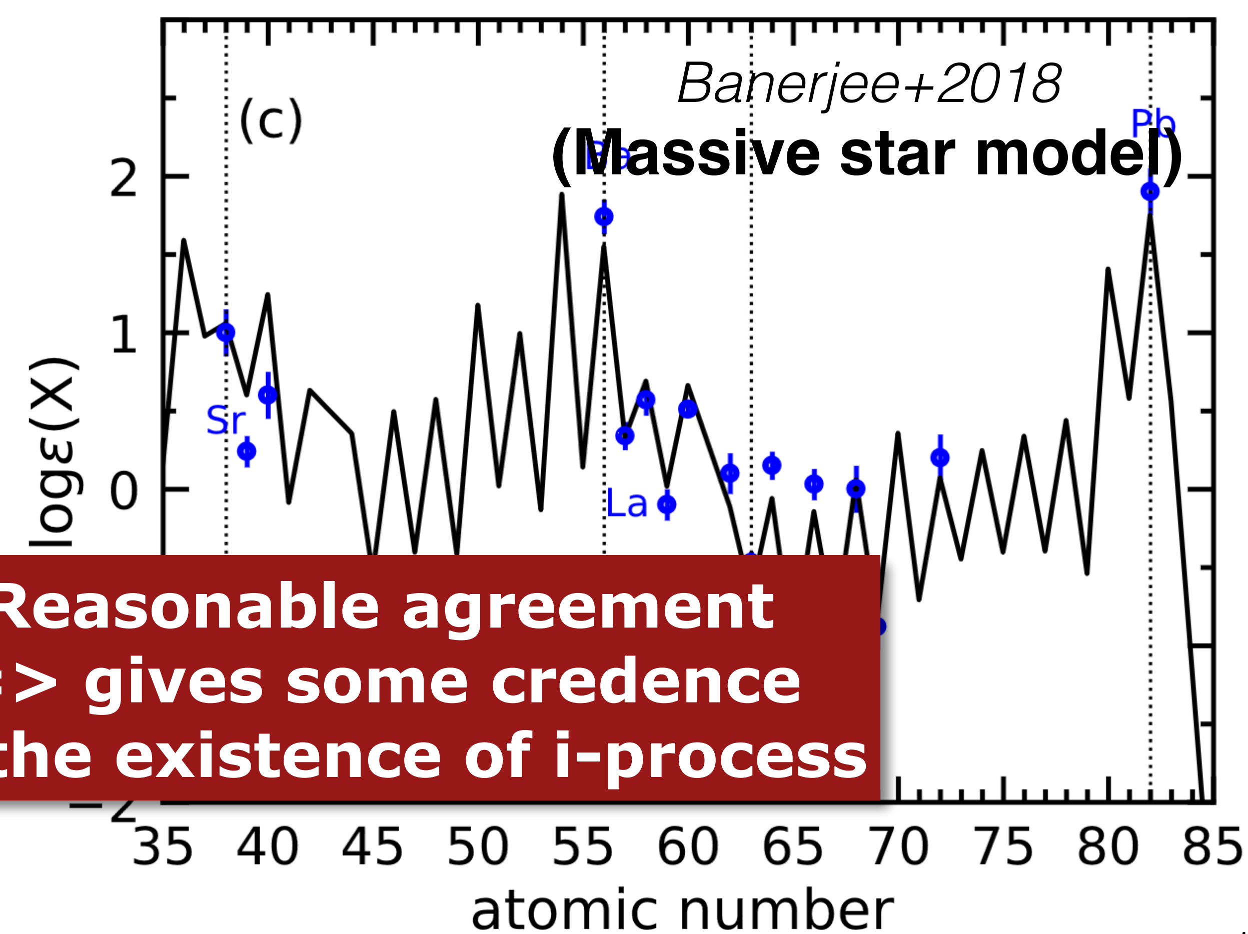


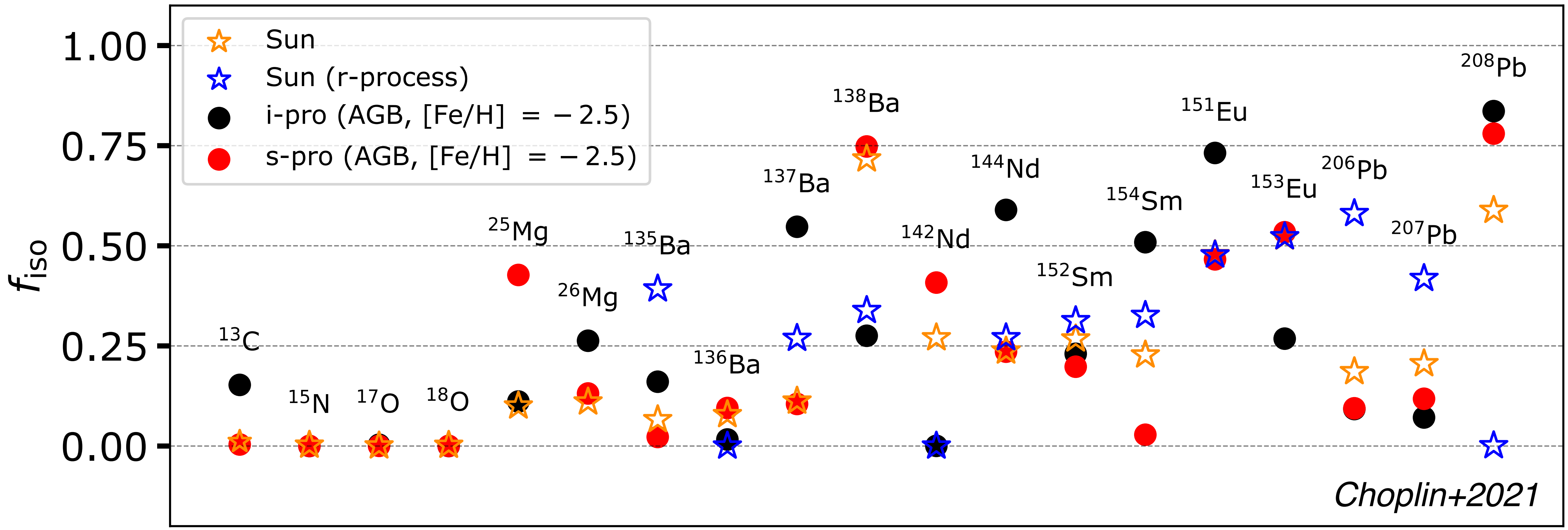






Reasonable agreement => gives some credence to the existence of i-process

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



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

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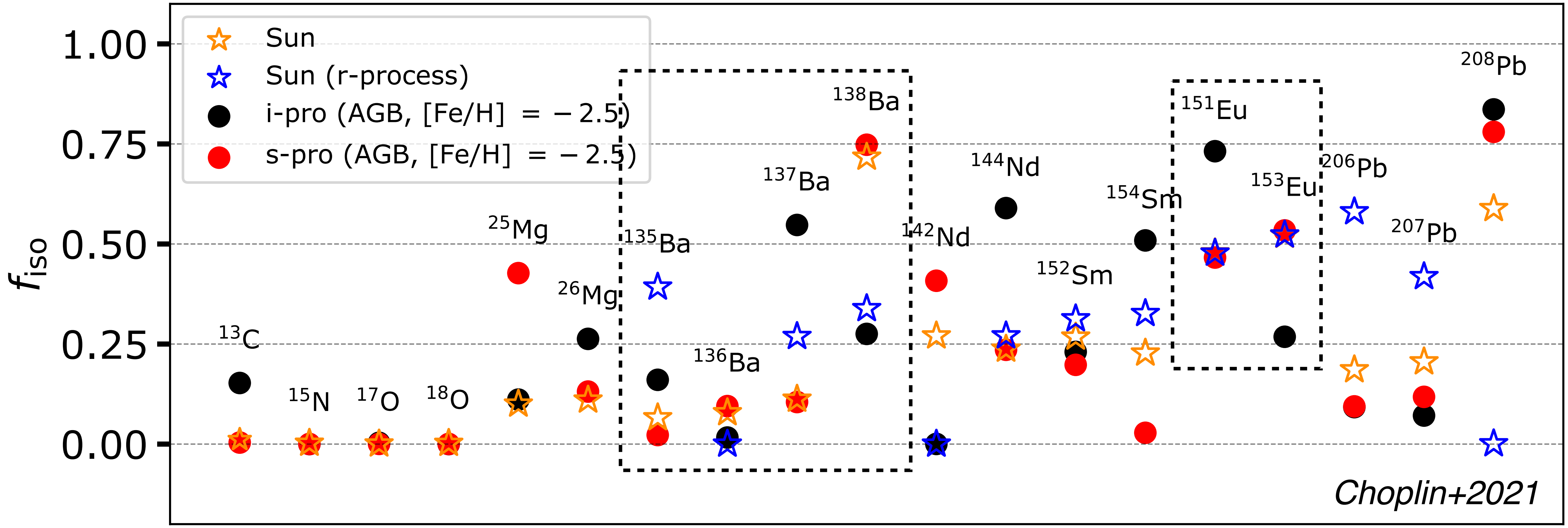

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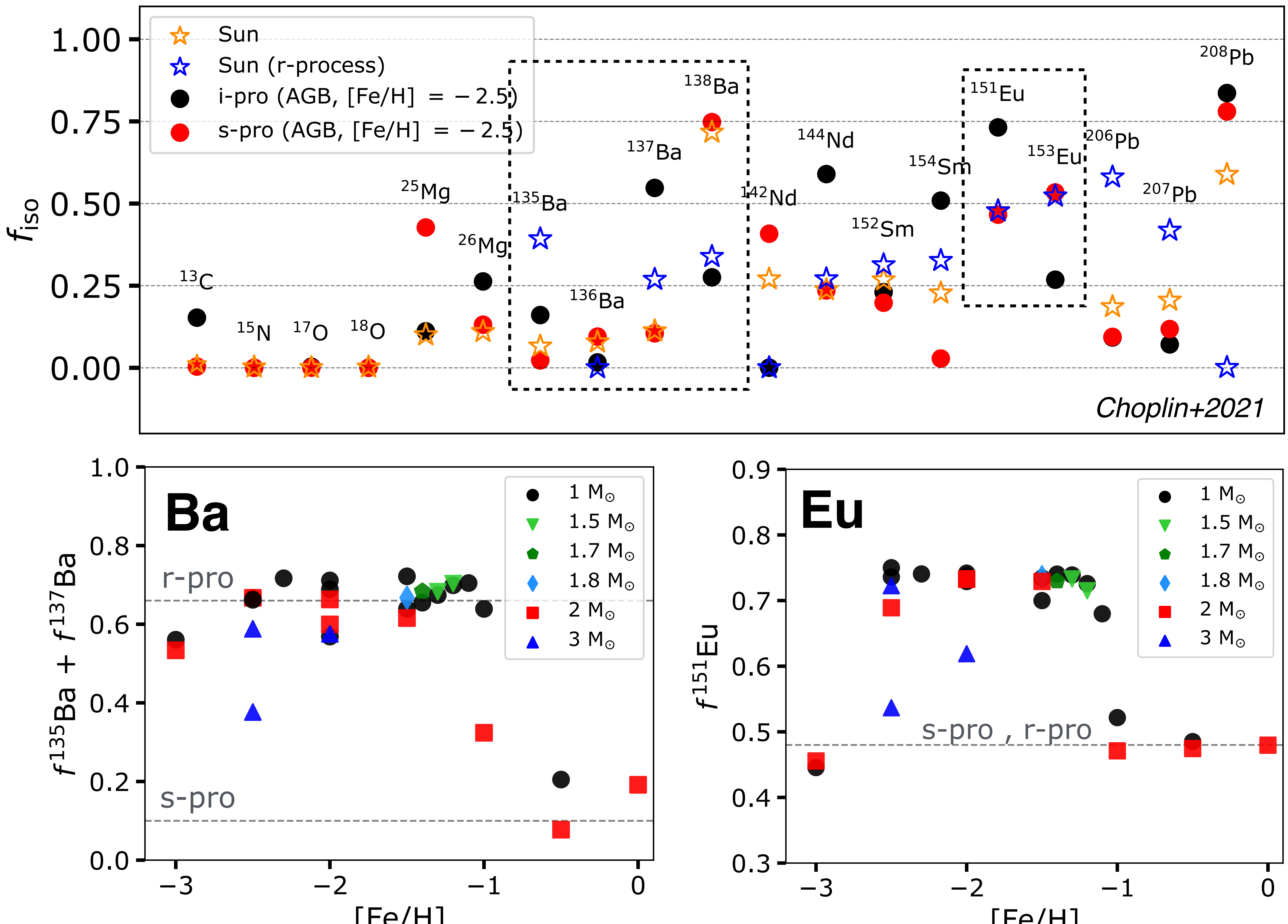

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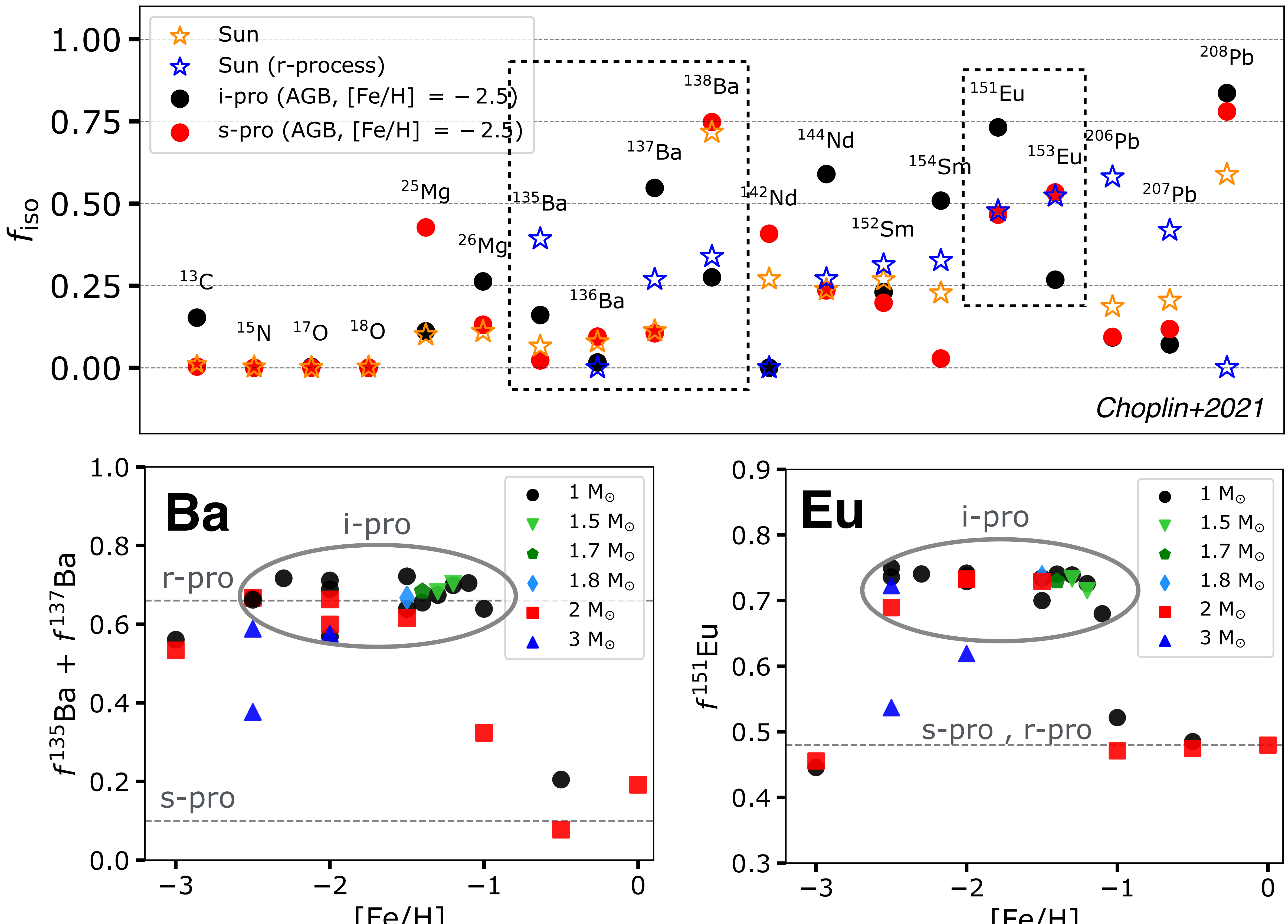

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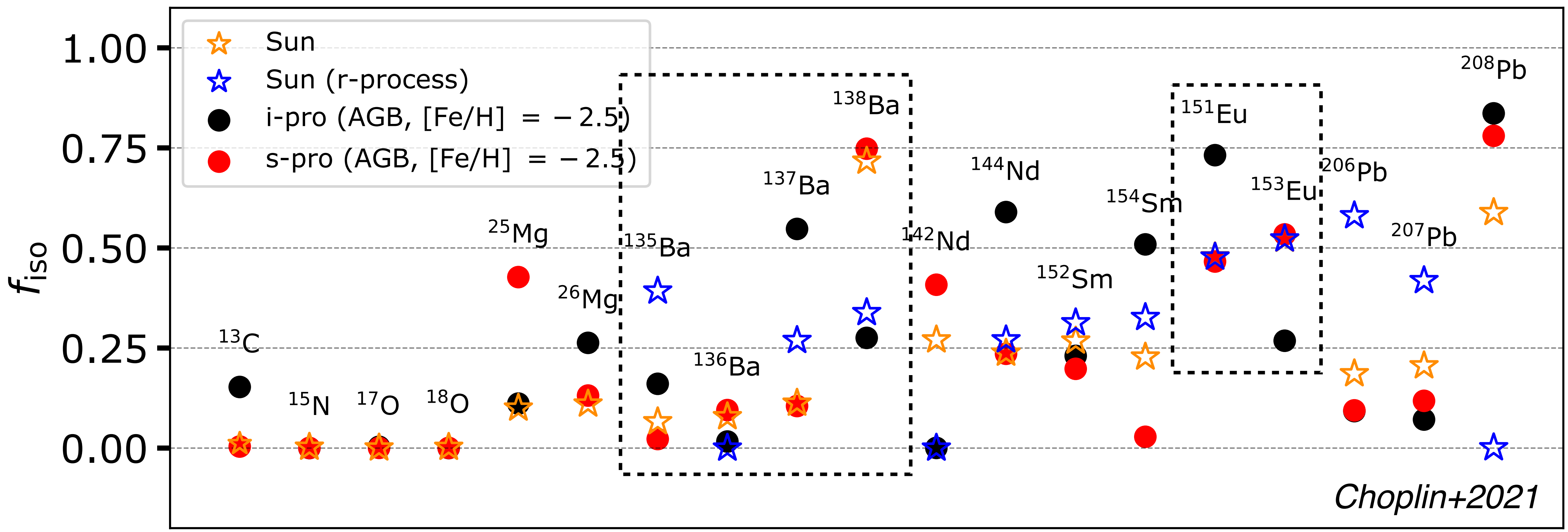

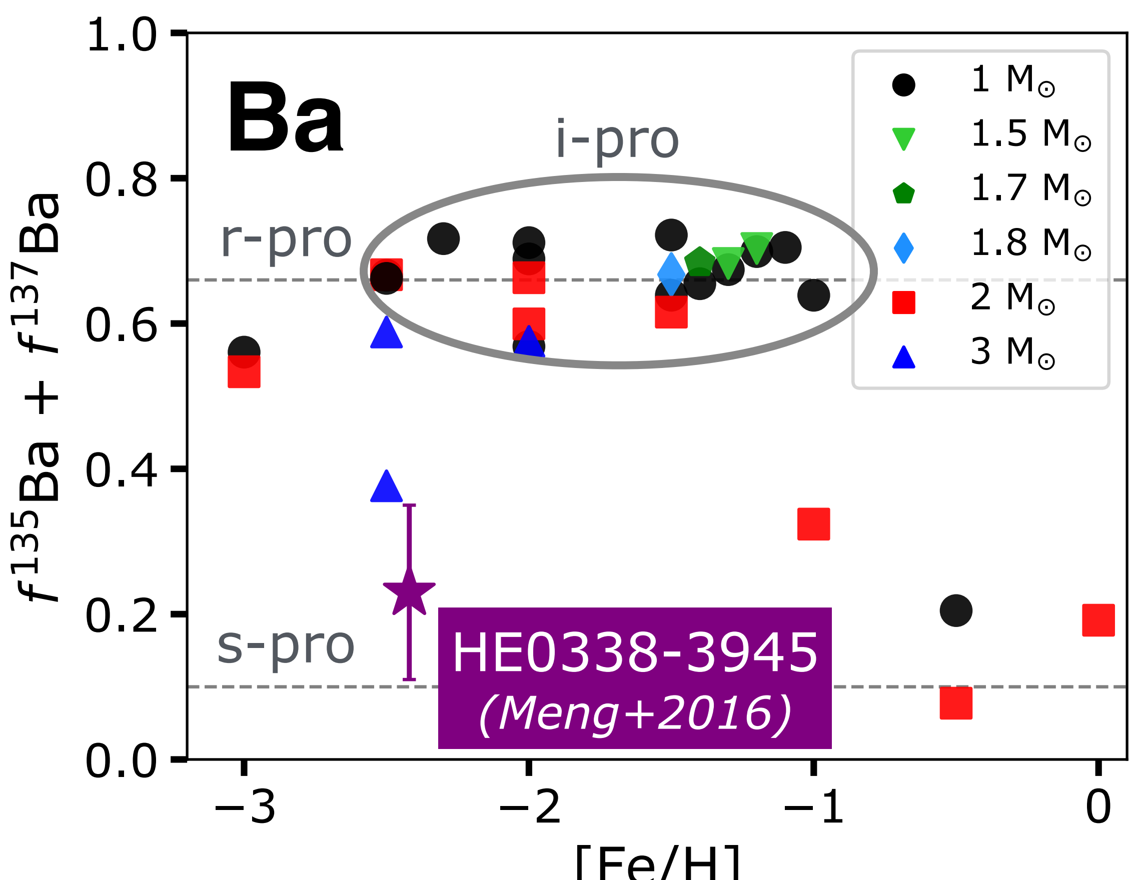

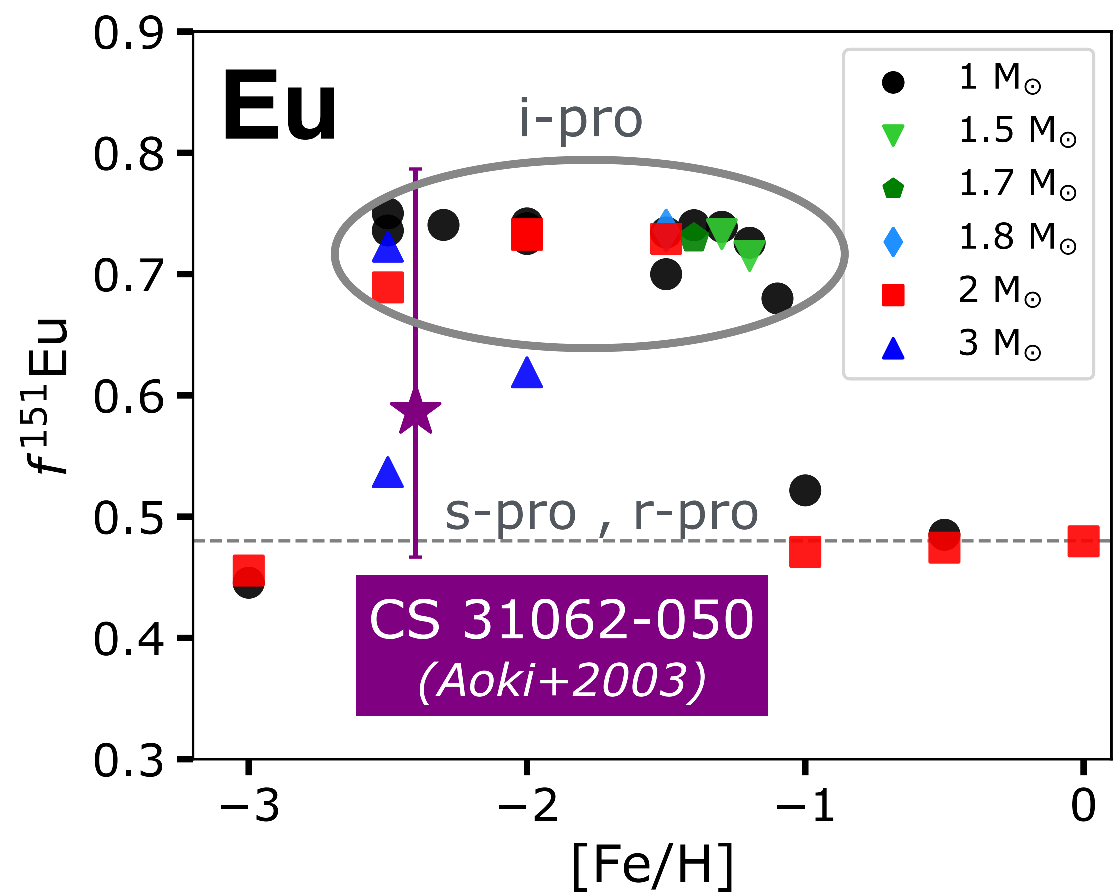

The i-process in AGB stars : summary

- **i-process** ($N_n \sim 10^{15}$ cm^{-3}) when **protons are ingested** in a convective He-burning zone
  —> it can happen in AGB stars

- Overshoot **[OFF]** —> H-ingestion / i-process in AGB with $M < 3\ M_\odot$, [Fe/H] < -2
- Overshoot **[ON]** —> facilitates proton ingestion (up to ~ solar metallicity)

- **Actinides** (Th and U) can be produced by the i-process

- i- and s-process (radiative & convective) can develop in the same AGB

- i-process chemical signature is small at [Fe/H] > -1 (in AGBs)

- Growing evidence of the existence of (low-metallicity) **i-process stars**
  —> isotopic ratios ?

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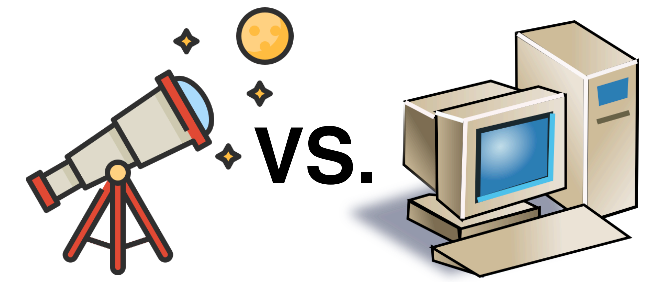
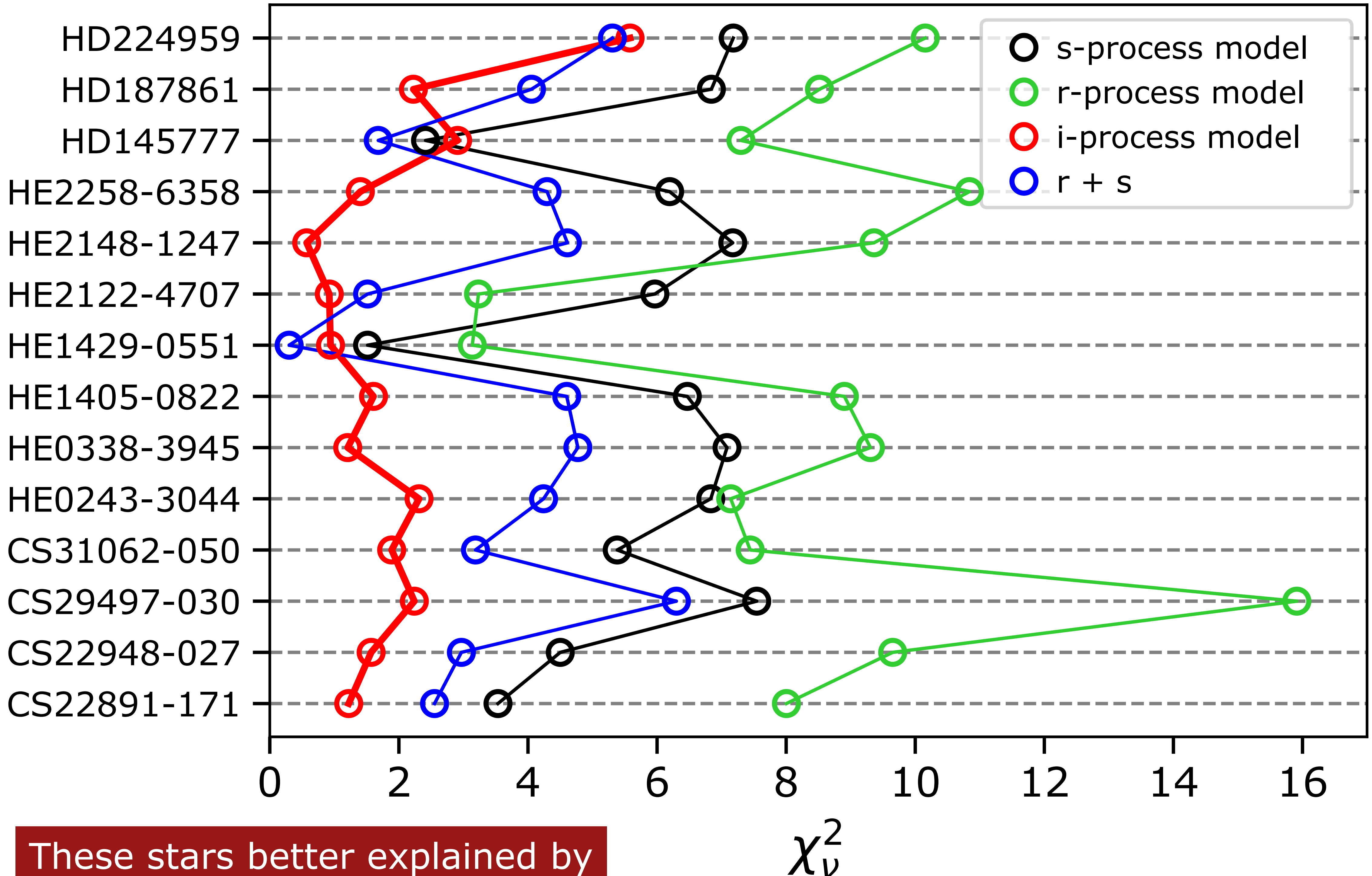
  —> isotopic ratios ?

—> Effect of ≠ overshoot, rotation, ... ?
—> Nuclear uncertainties *—> cf. talk by S. Martinet*
—> Relative contribution of the different i-process sites ?
—> Constraints from 3D models (overshoot, ...)

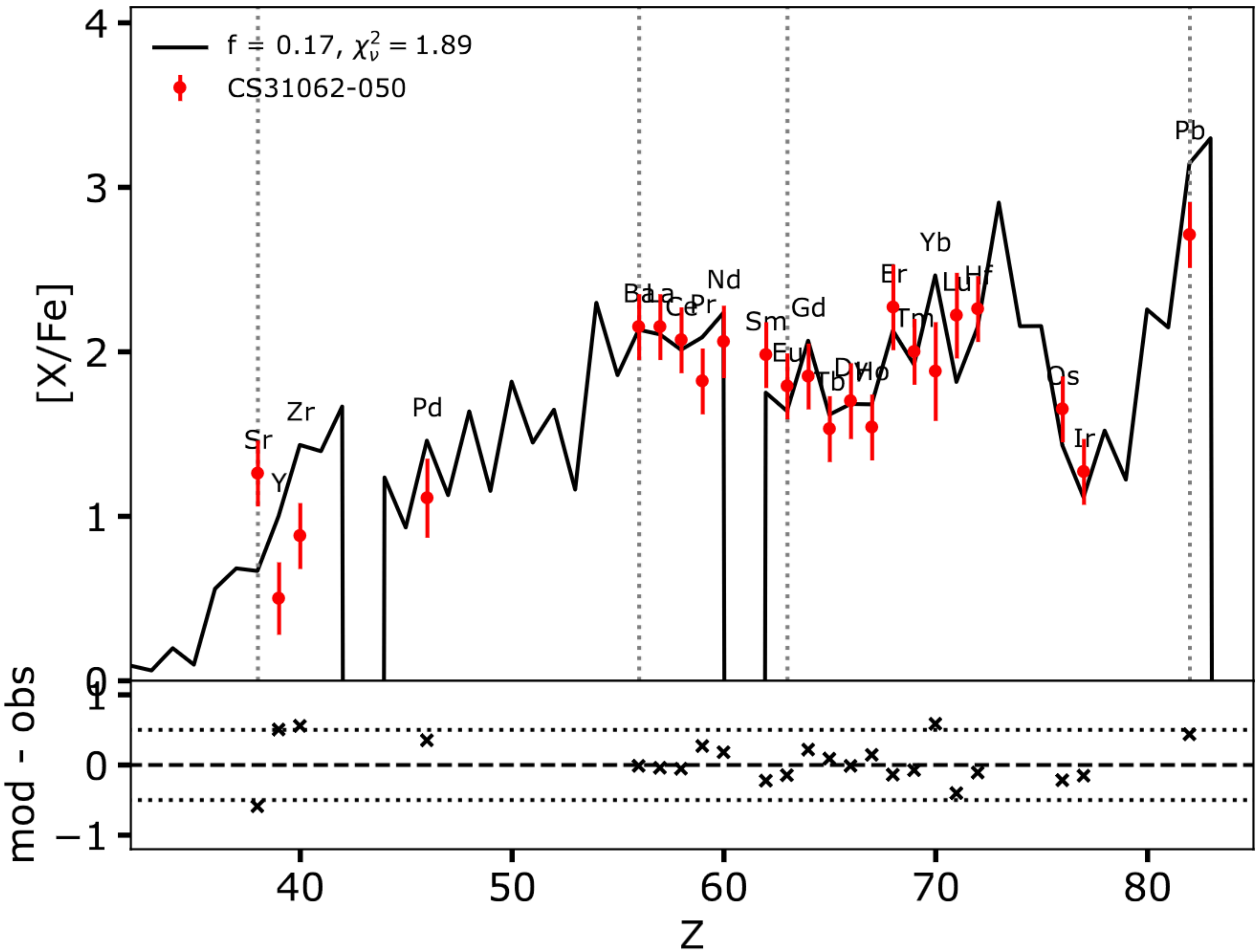
i-process AGB models vs. observed « i-stars »





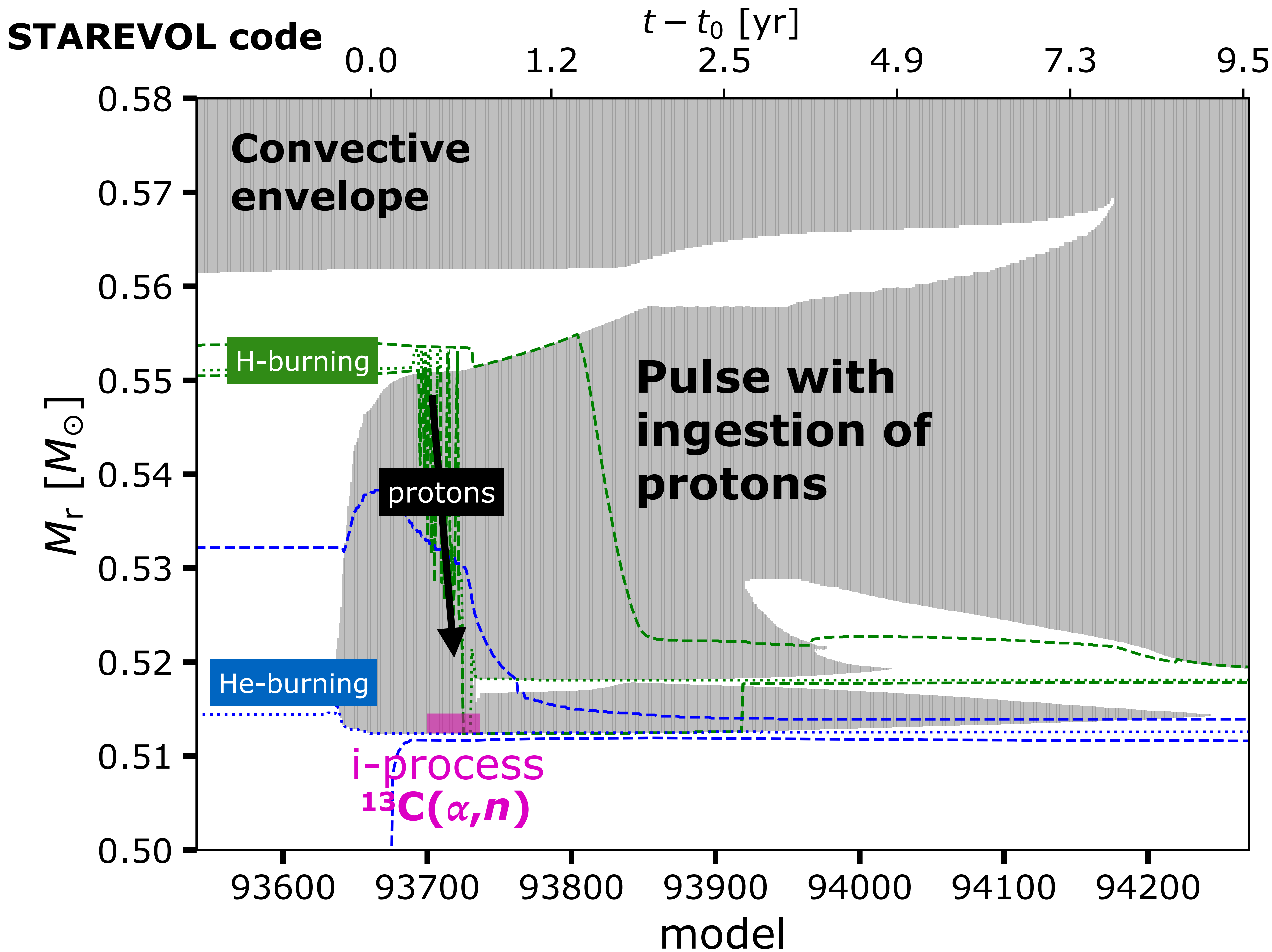
These stars better explained by i-process than s- or r-process

Choplin+2021, A&A + corrigendum

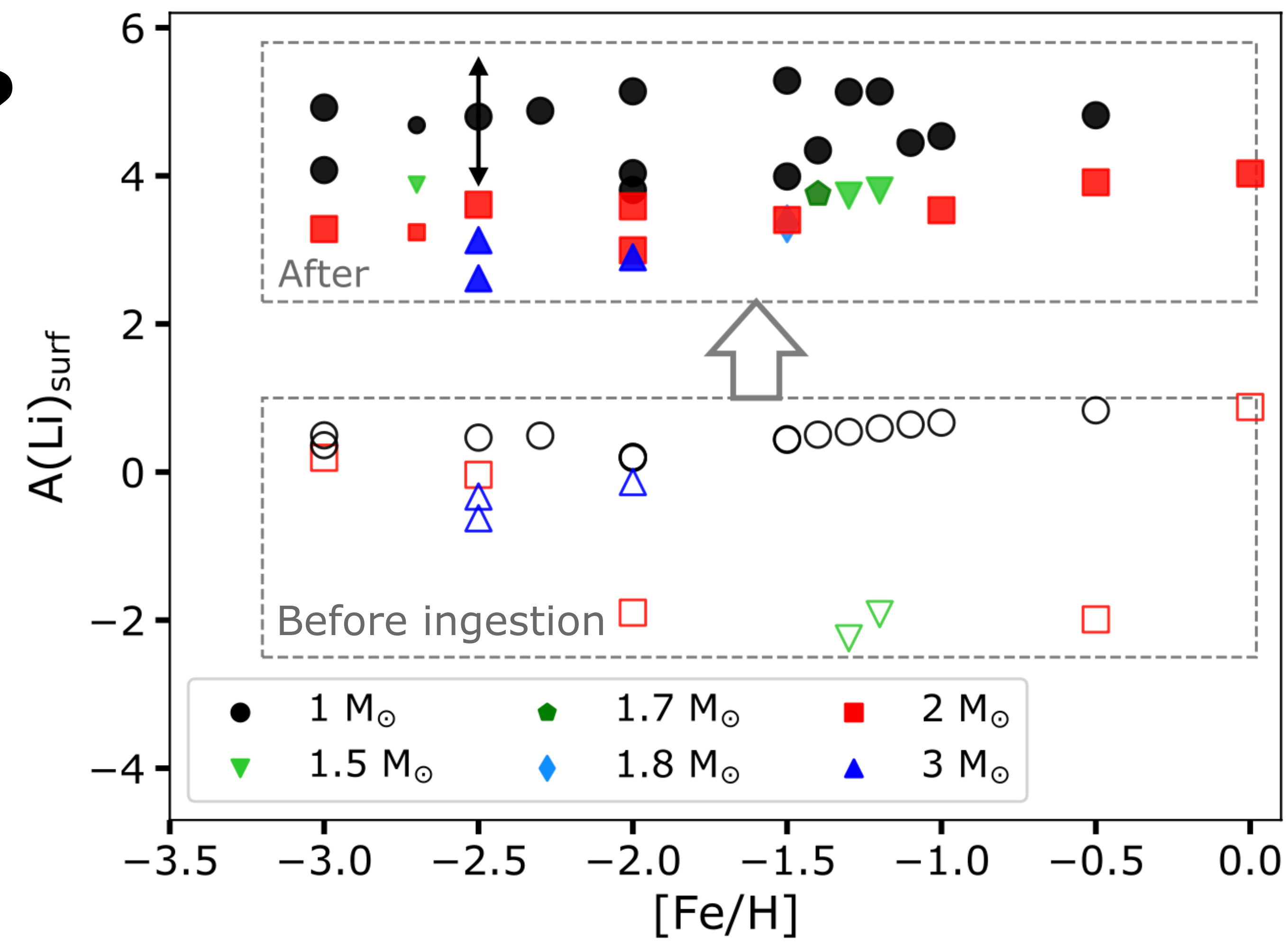


f = 0.17, $\chi^2_\nu = 1.89$
CS31062-050
[X/Fe]
mod - obs
Z
Sr
Y
Zr
Pd
Ba
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
Hf
Os
Ir
Pb

Structure evolution of a 1D AGB model
with proton ingestion

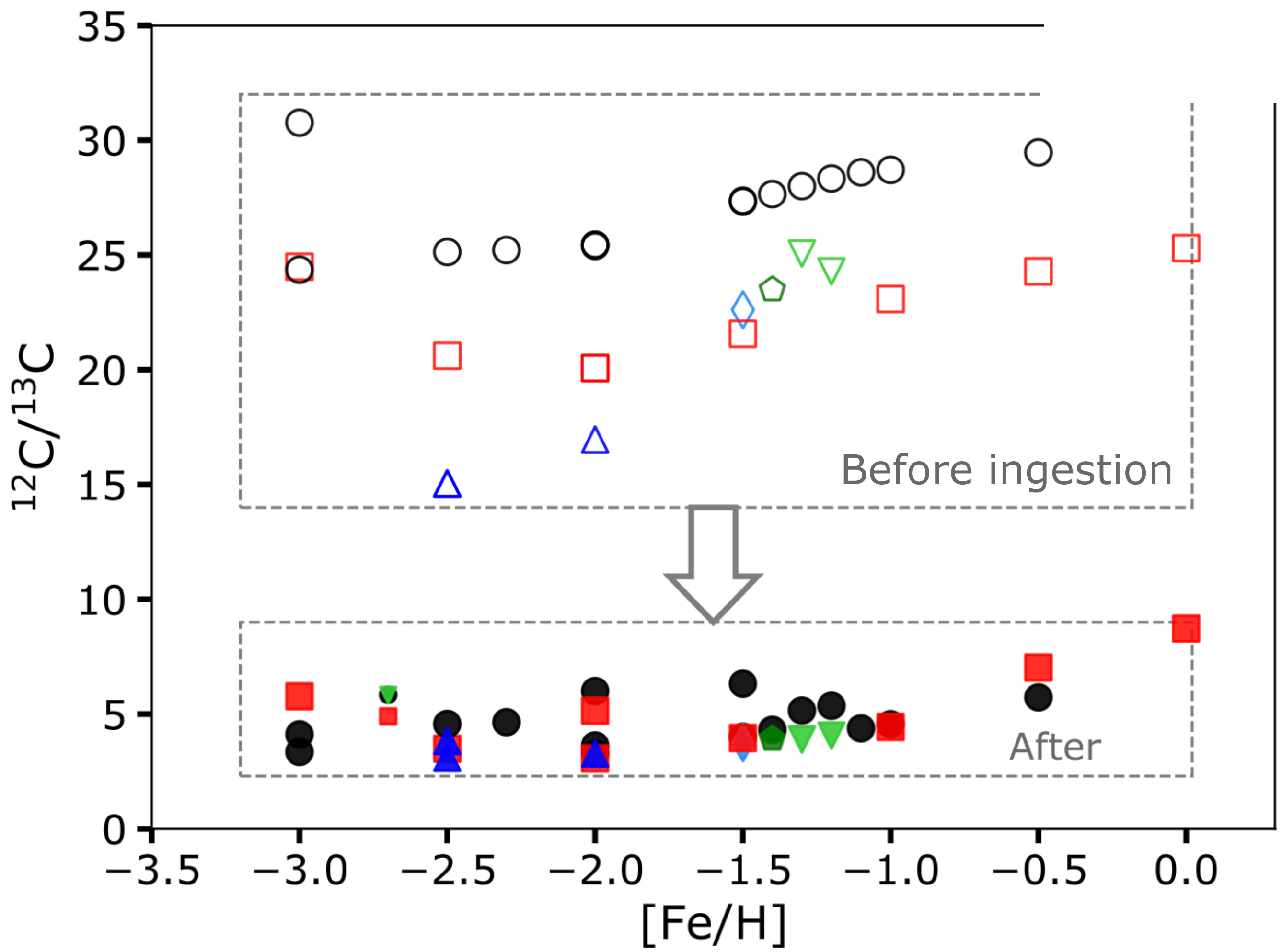


What about light elements ?



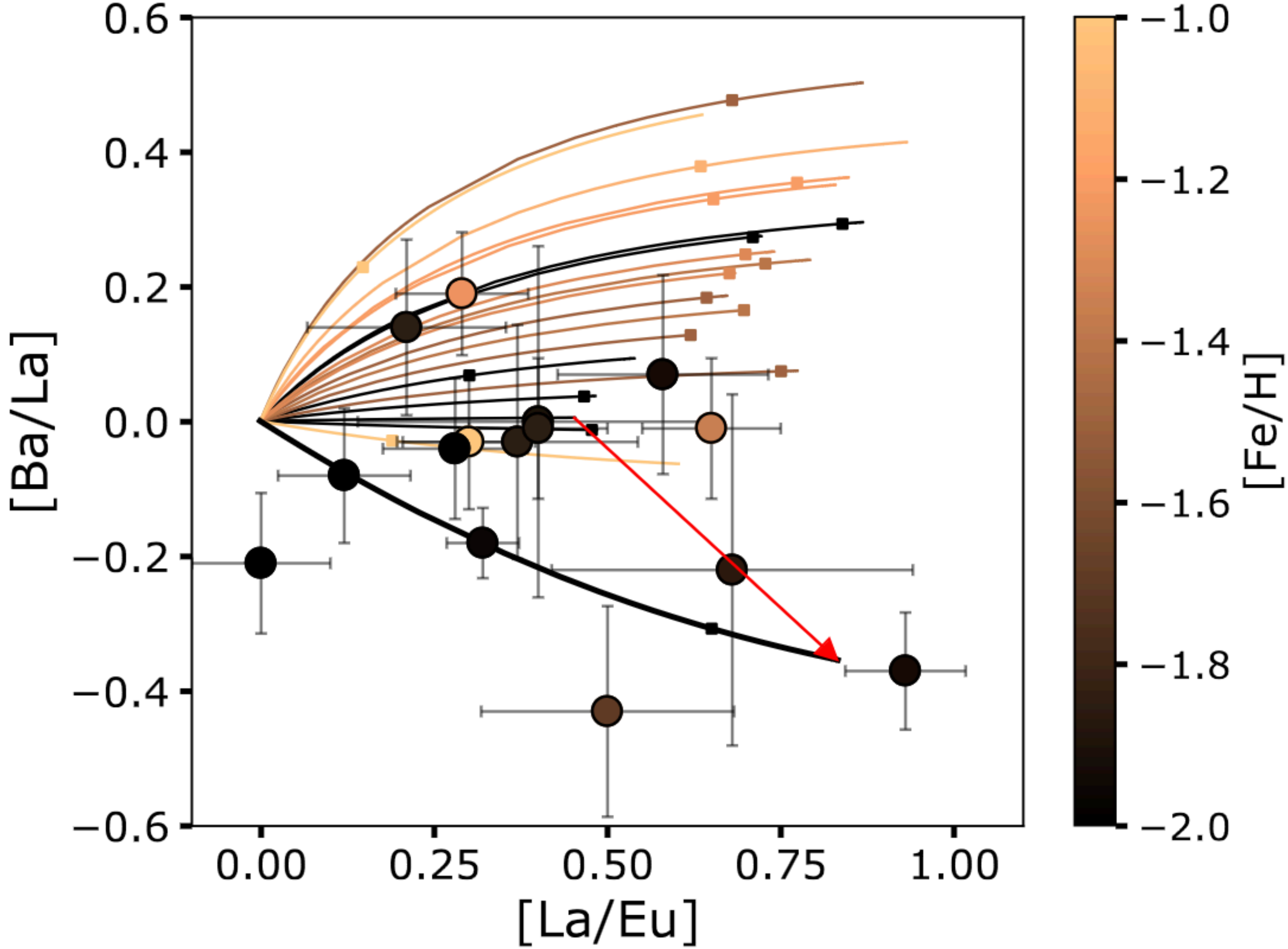
Proton ingestion produces Lithium
(Cameron & Fowler mechanism)

Cameron & Fowler 1971
Iwamoto+2004
Cristallo+2009



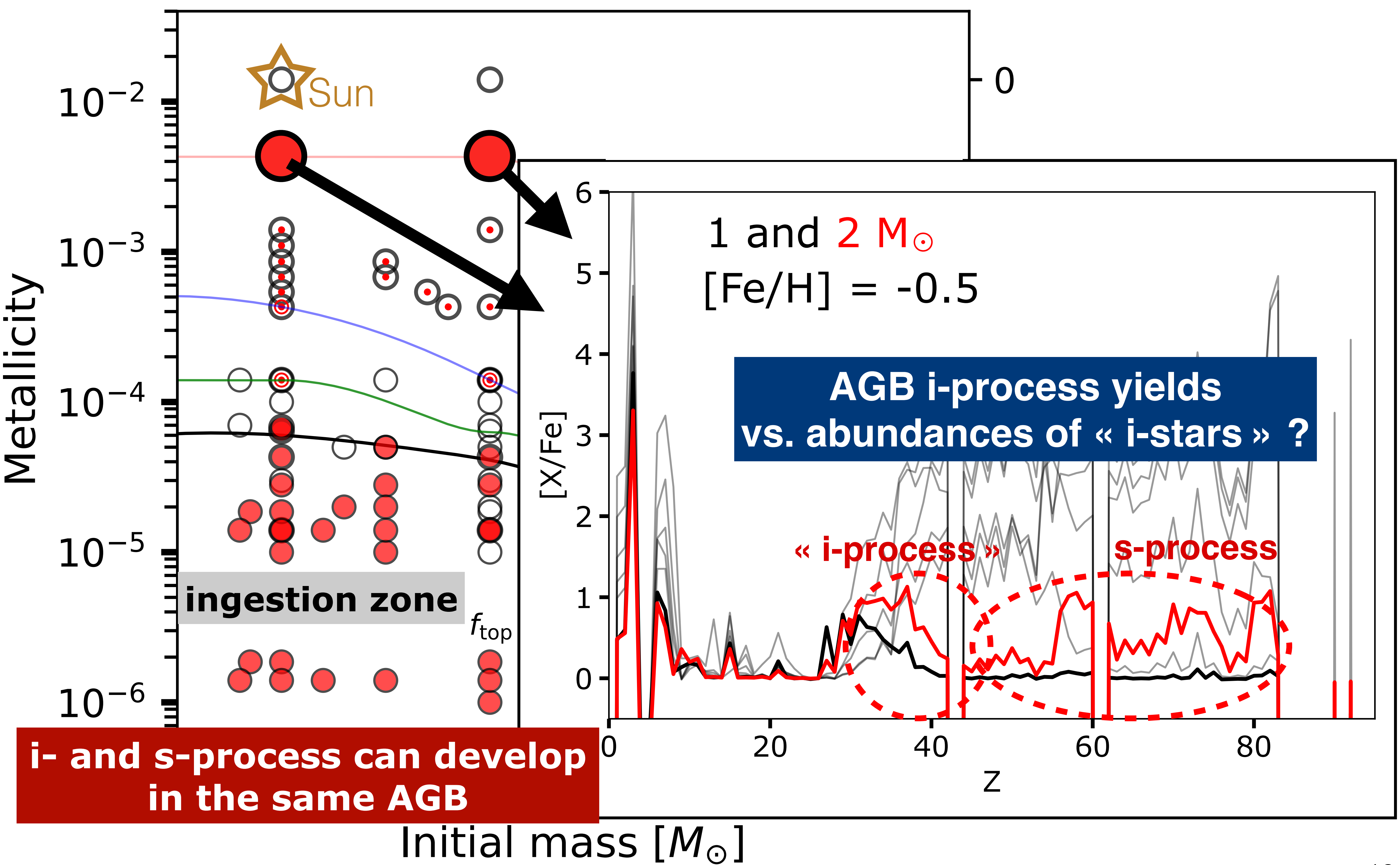
Proton ingestion produces ^{13}C

proton ingestion / i-process
=> high Li, low $^{12}C/^{13}C$



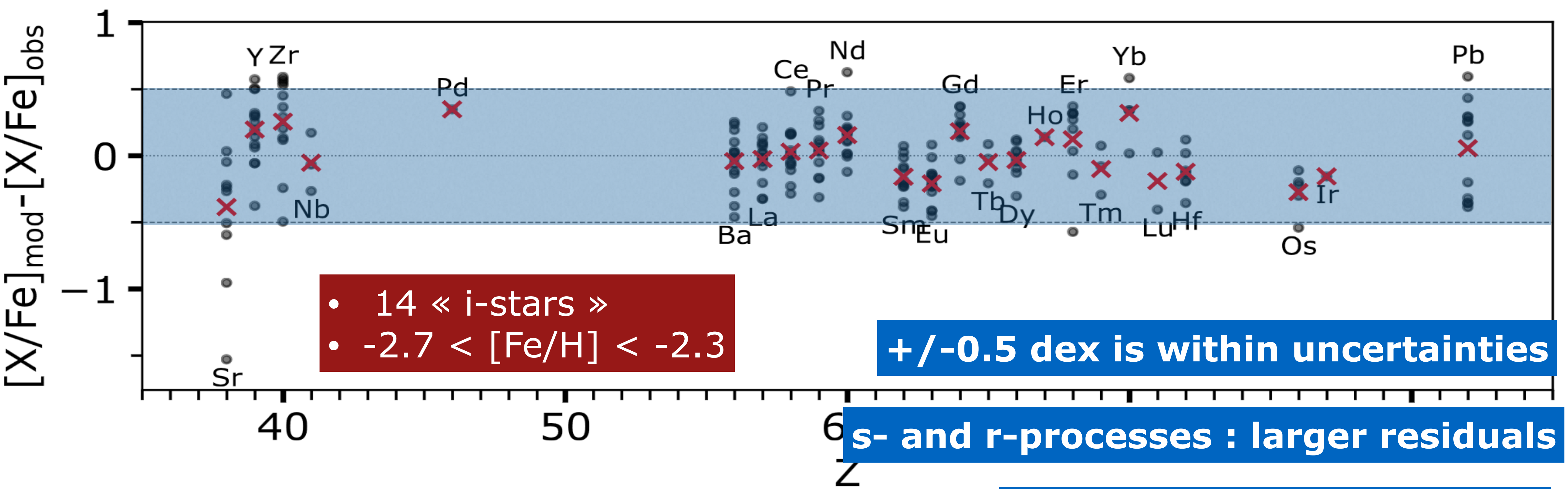
[Ba/La]
[La/Eu]
[Fe/H]
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
0.00
0.25
0.50
0.75
1.00
−1.0
−1.2
−1.4
−1.6
−1.8
−2.0

Nucleosynthetic yields of AGB experiencing H-ingestion



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

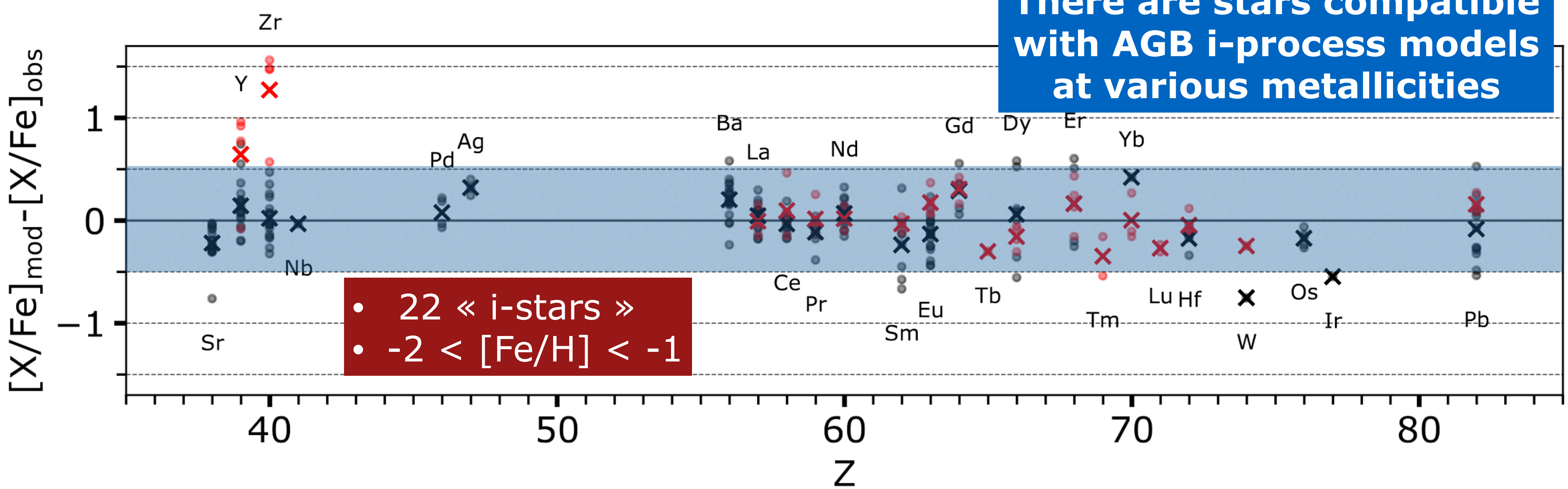
residuals after chi² fitting procedure



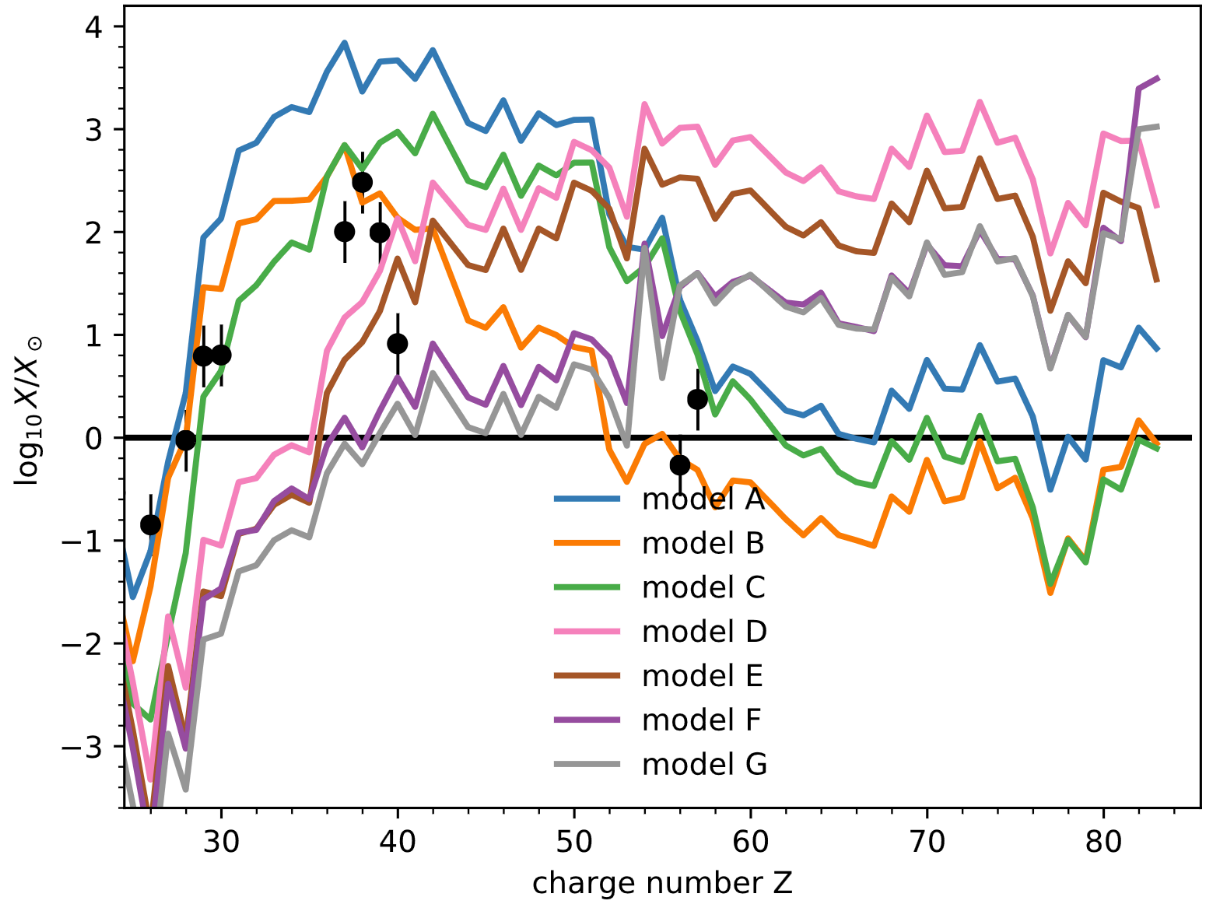
+/-0.5 dex is within uncertainties

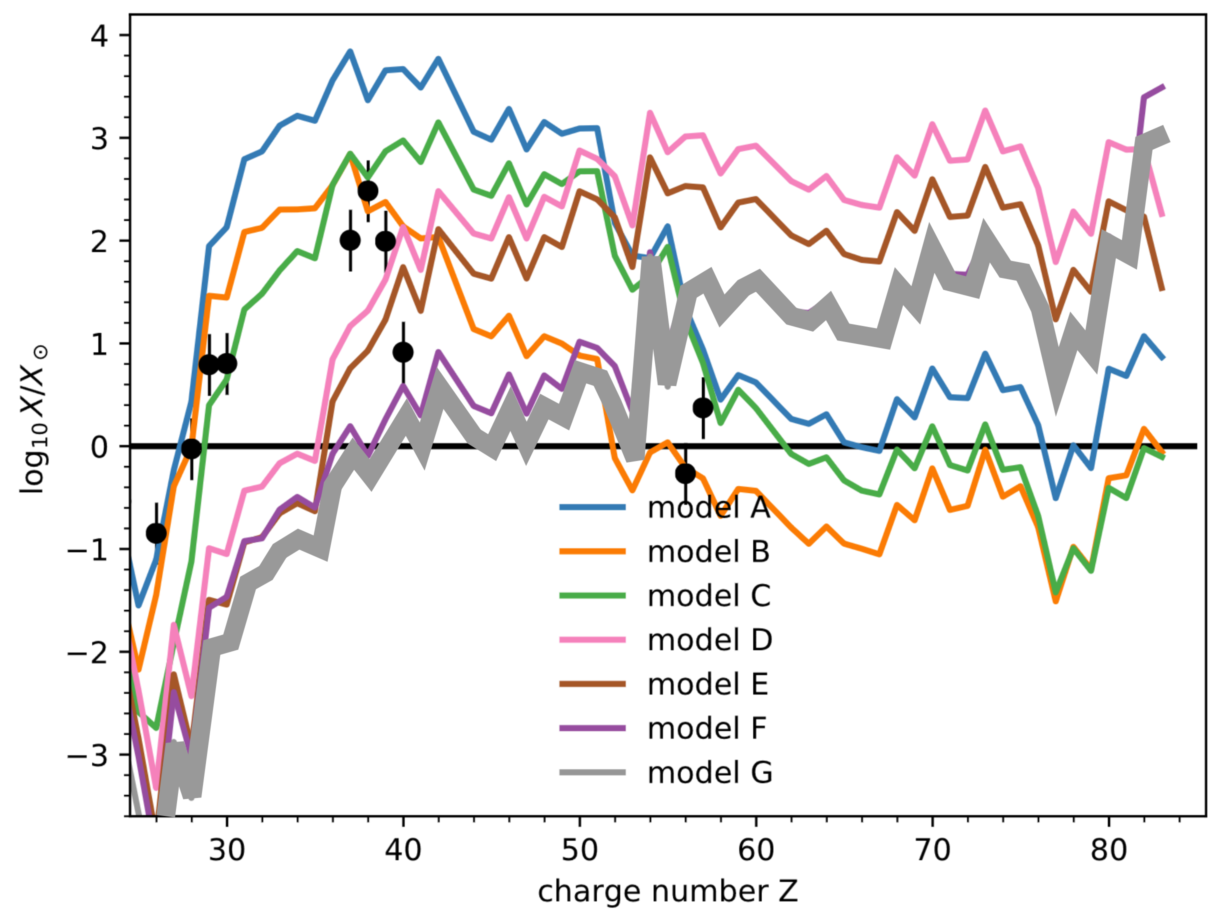
s- and r-processes : larger residuals

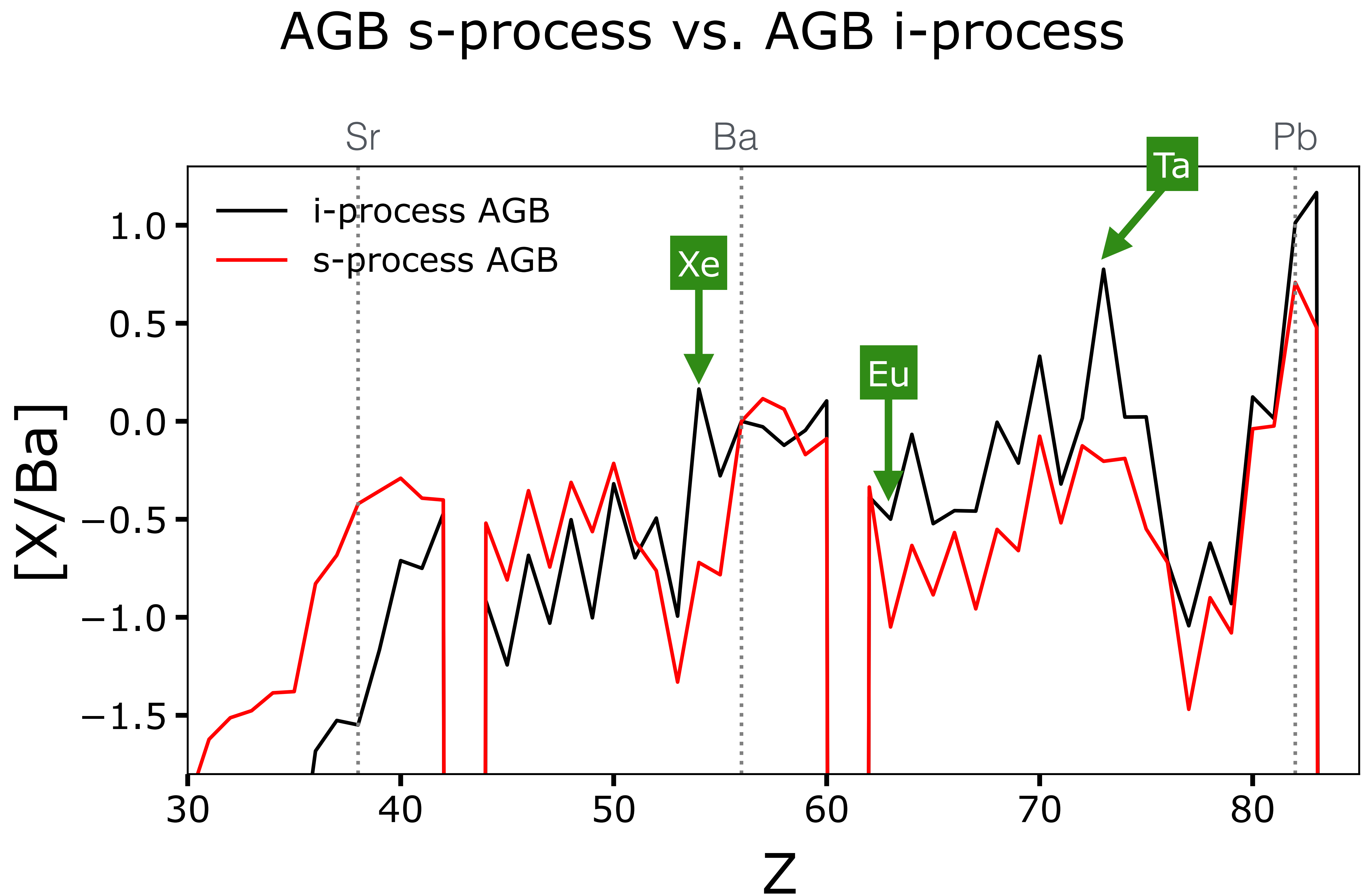
There are stars compatible with AGB i-process models at various metallicities



Choplin, Siess, Goriely, Martinet 2021 & 2024, A&A

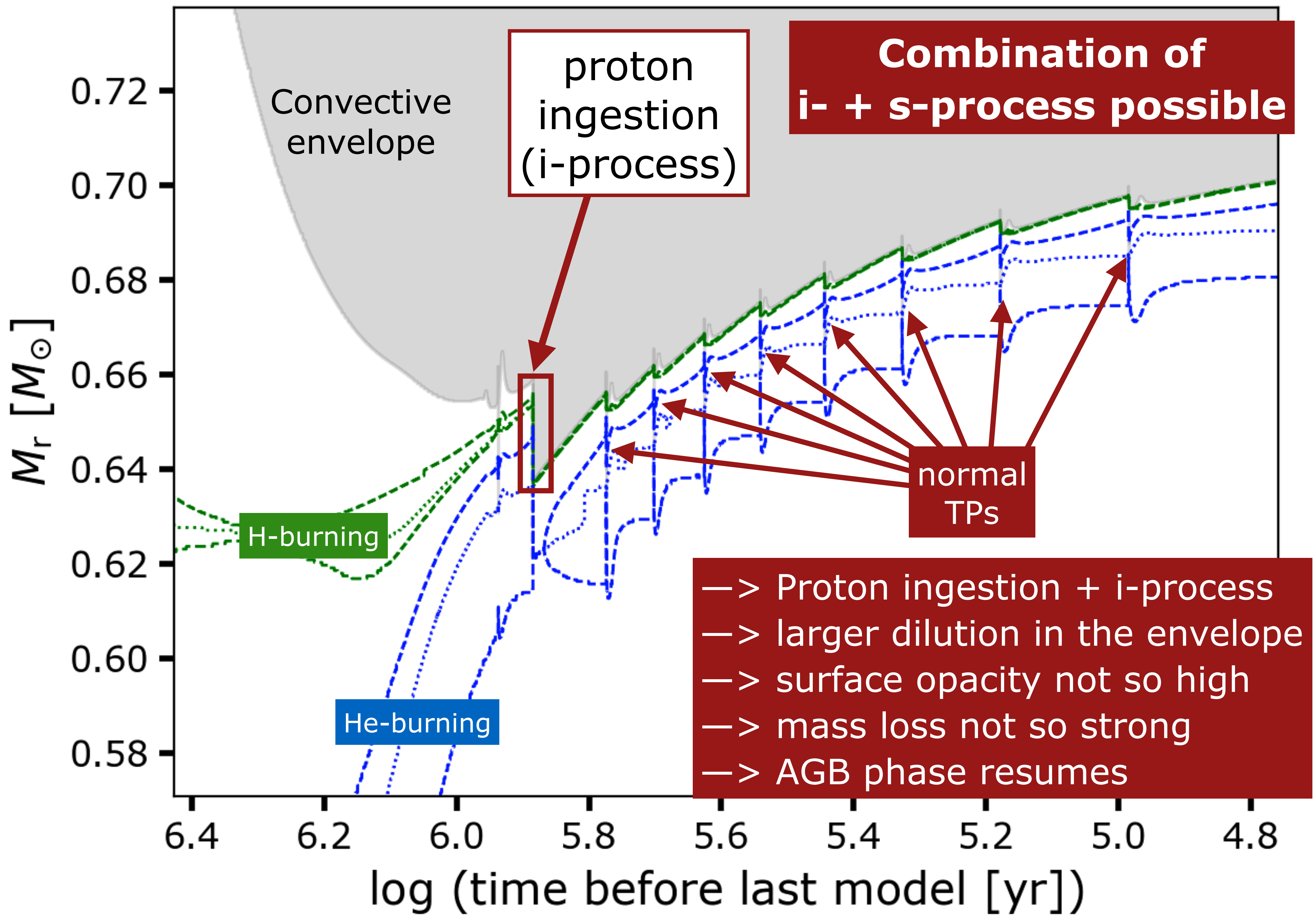

model A
model B
model C
model D
model E
model F
model G
charge number Z
$\log_{10} X/X_\odot$


model A
model B
model C
model D
model E
model F
model G
charge number Z
$\log_{10} X/X_\odot$


AGB s-process vs. AGB i-process
Sr
Ba
Pb
Ta
Xe
Eu
i-process AGB
s-process AGB
1.0
0.5
0.0
−0.5
−1.0
−1.5
[X/Ba]
30
40
50
60
70
80
Z

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

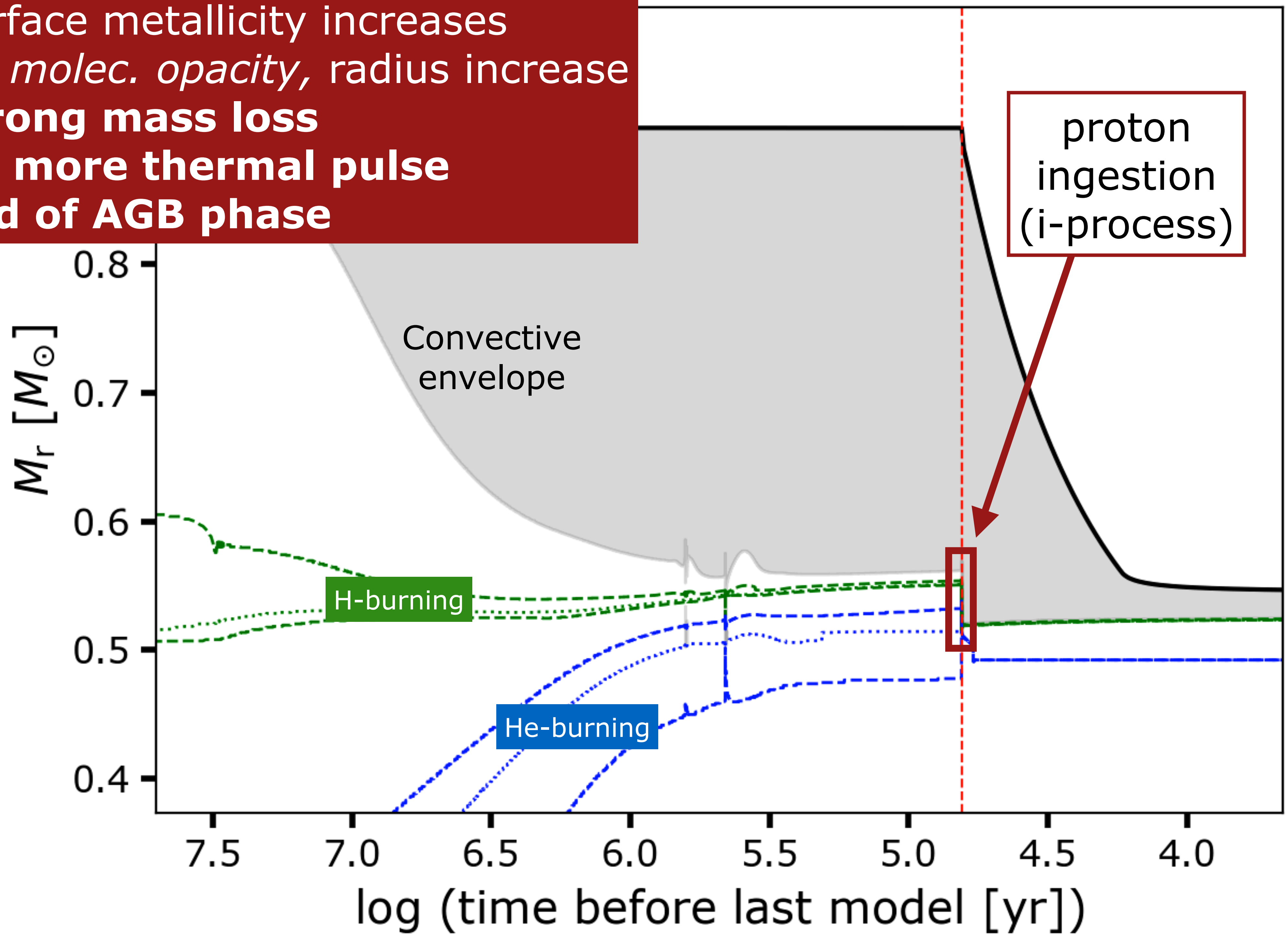
($Z = 4 \times 10^{-5}$)

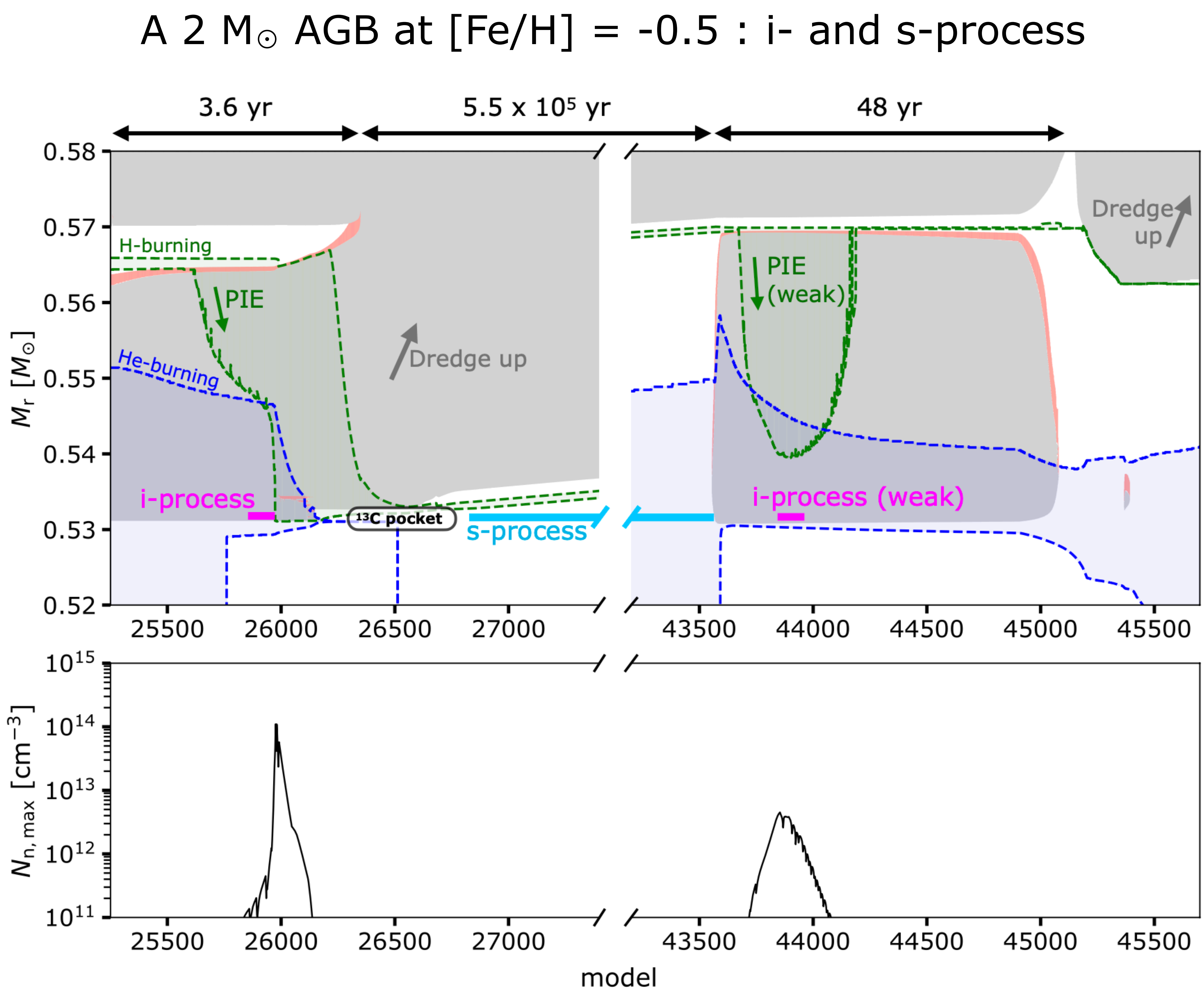


The **i-process** in a 1 $M_\odot$, [Fe/H] = -2.5 AGB model

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

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⊙ AGB at [Fe/H] = -0.5 : i- and s-process
3.6 yr
5.5 x 10⁵ yr
48 yr
H-burning
PIE
He-burning
Dredge up
i-process
13C pocket
s-process
PIE (weak)
i-process (weak)
Dredge up
Mr [M⊙]
Nn, max [cm−3]
model