s-process & i-process

S. Cristallo

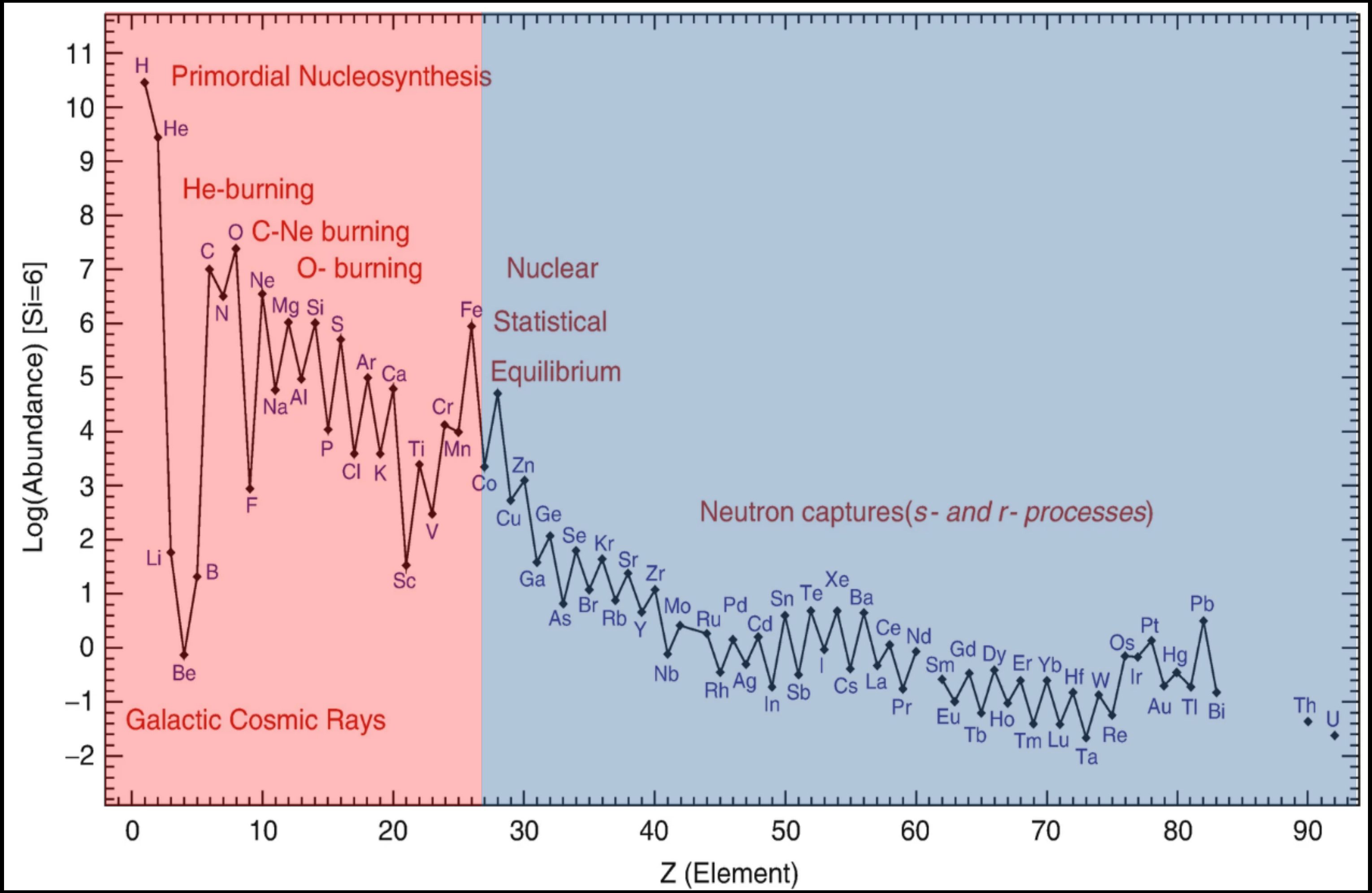
In collaboration with D. Vescovi, L. Piersanti & M.Bezmalinovich

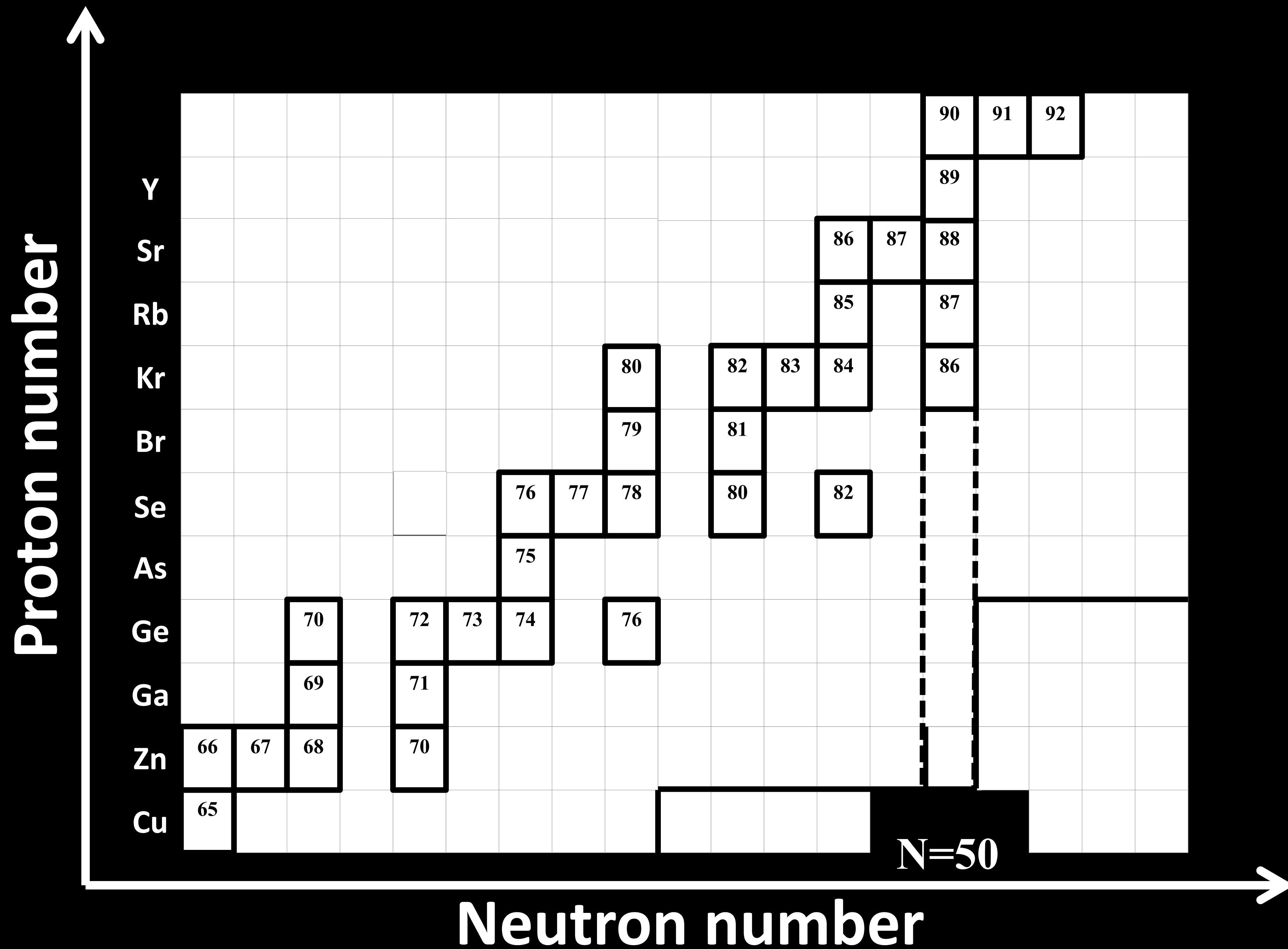
INAF - Osservatorio Astronomico d'Abruzzo

The solar distribution

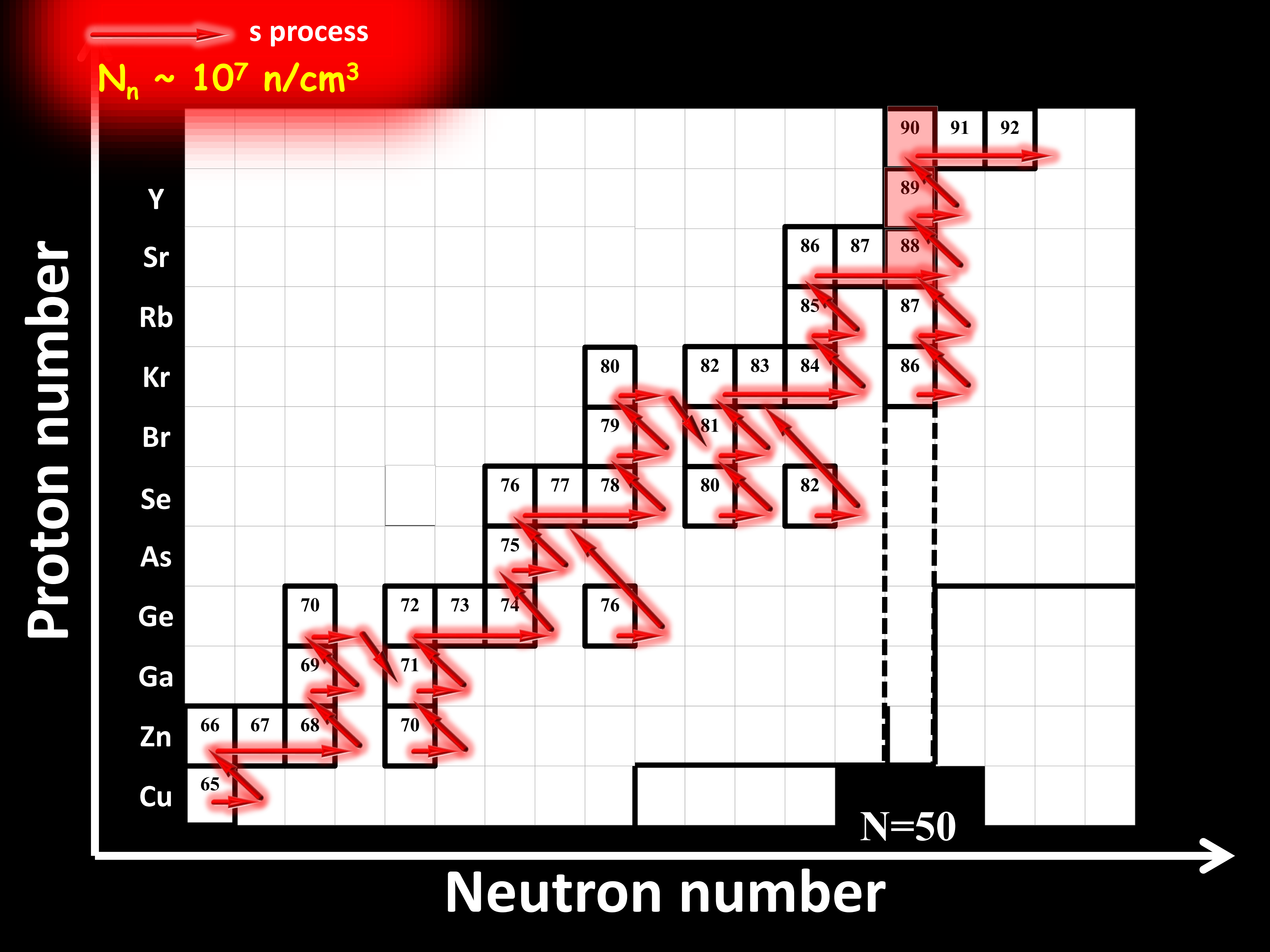
Fusion reactions between charged particles

Neutron capture processes





Proton number
Y
Sr
Rb
Kr
Br
Se
As
Ge
Ga
Zn
Cu
90
91
92
89
86
87
88
85
87
80
82
83
84
86
79
81
76
77
78
80
82
75
70
72
73
74
76
69
71
66
67
68
70
65
N=50
Neutron number



s process
$N_n \sim 10^7$ n/cm^3
Proton number
Neutron number
Y
Sr
Rb
Kr
Br
Se
As
Ge
Ga
Zn
Cu
90
91
92
89
86
87
88
85
87
80
82
83
84
86
79
81
76
77
78
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75
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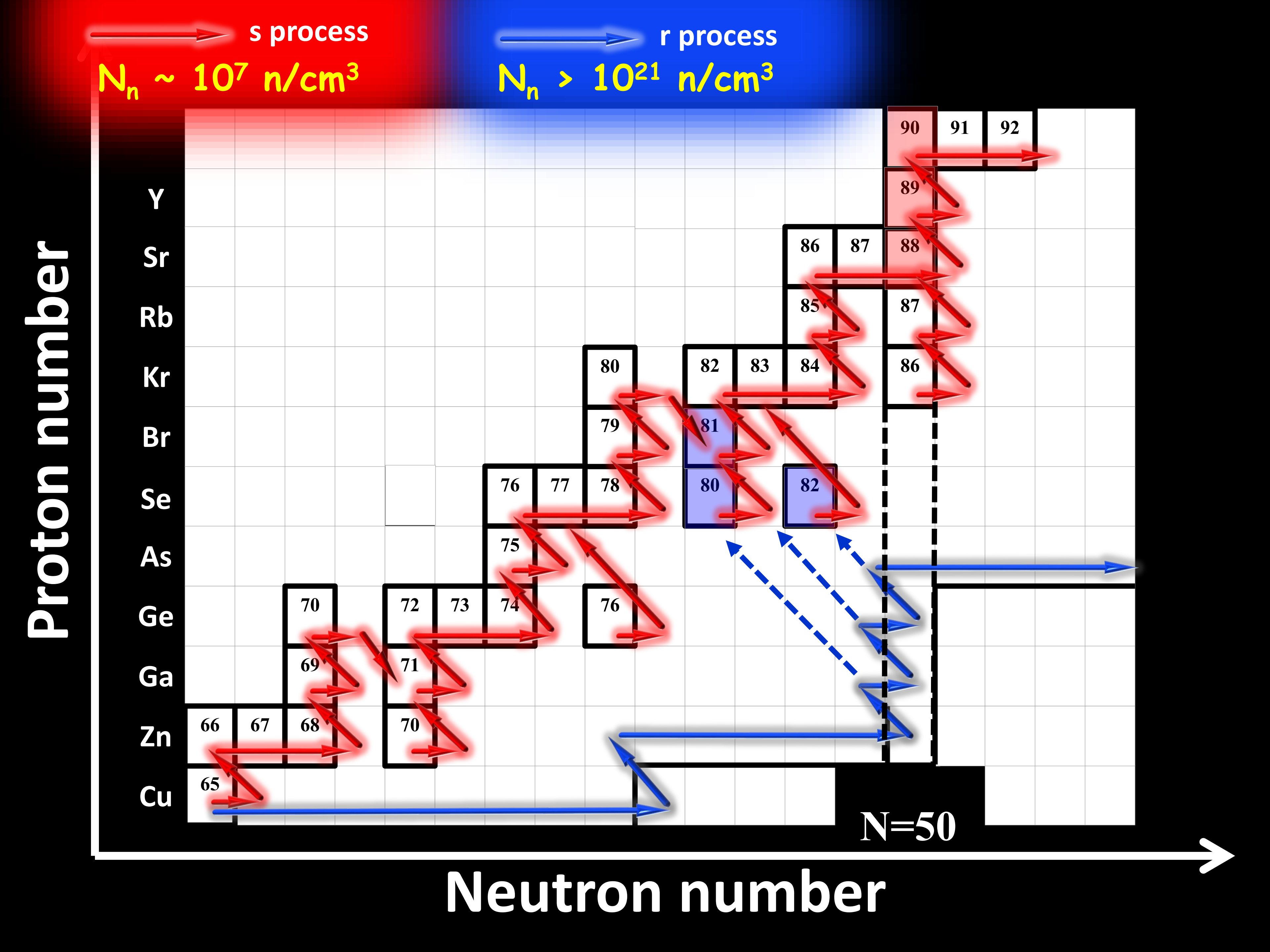
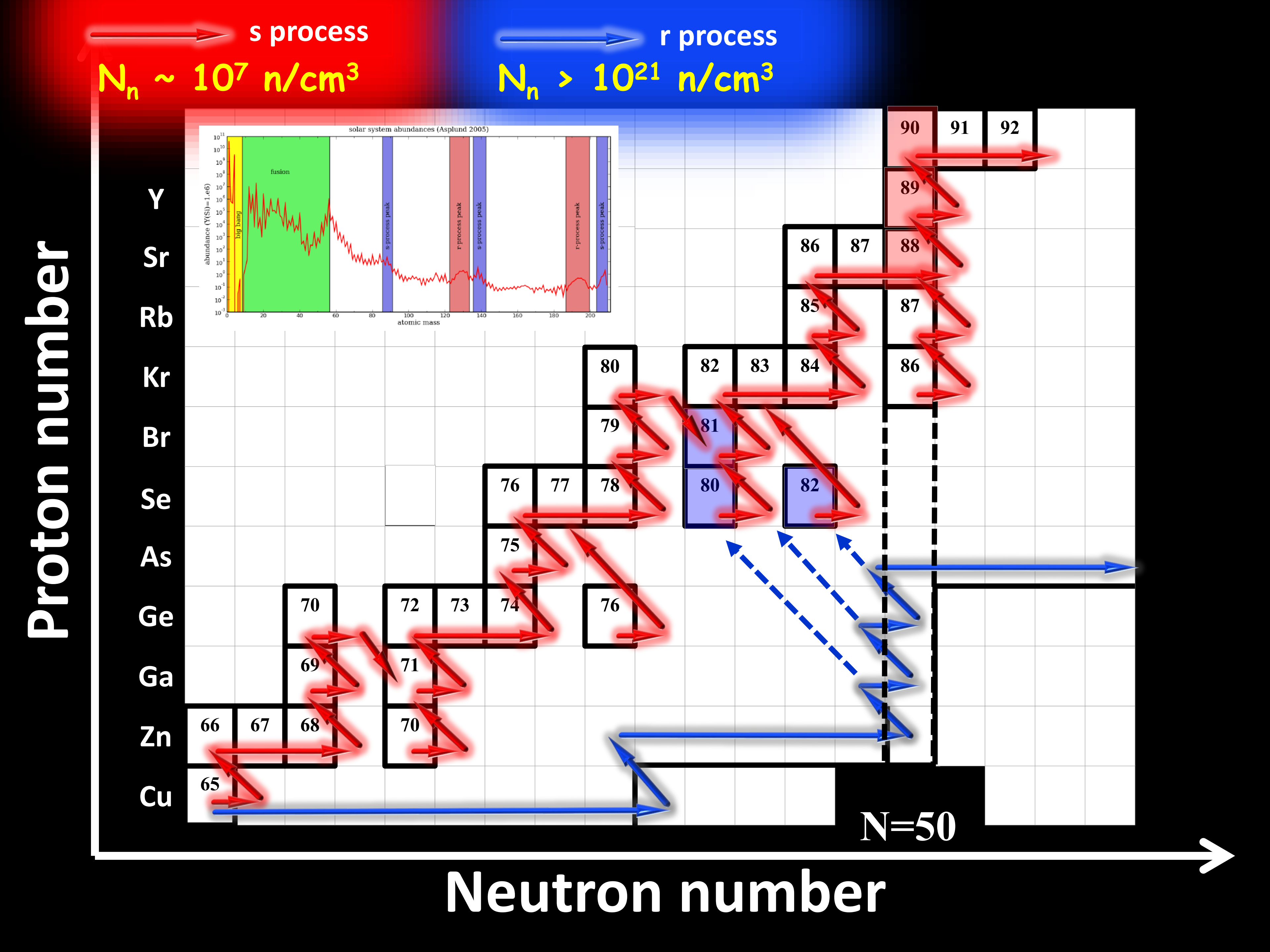
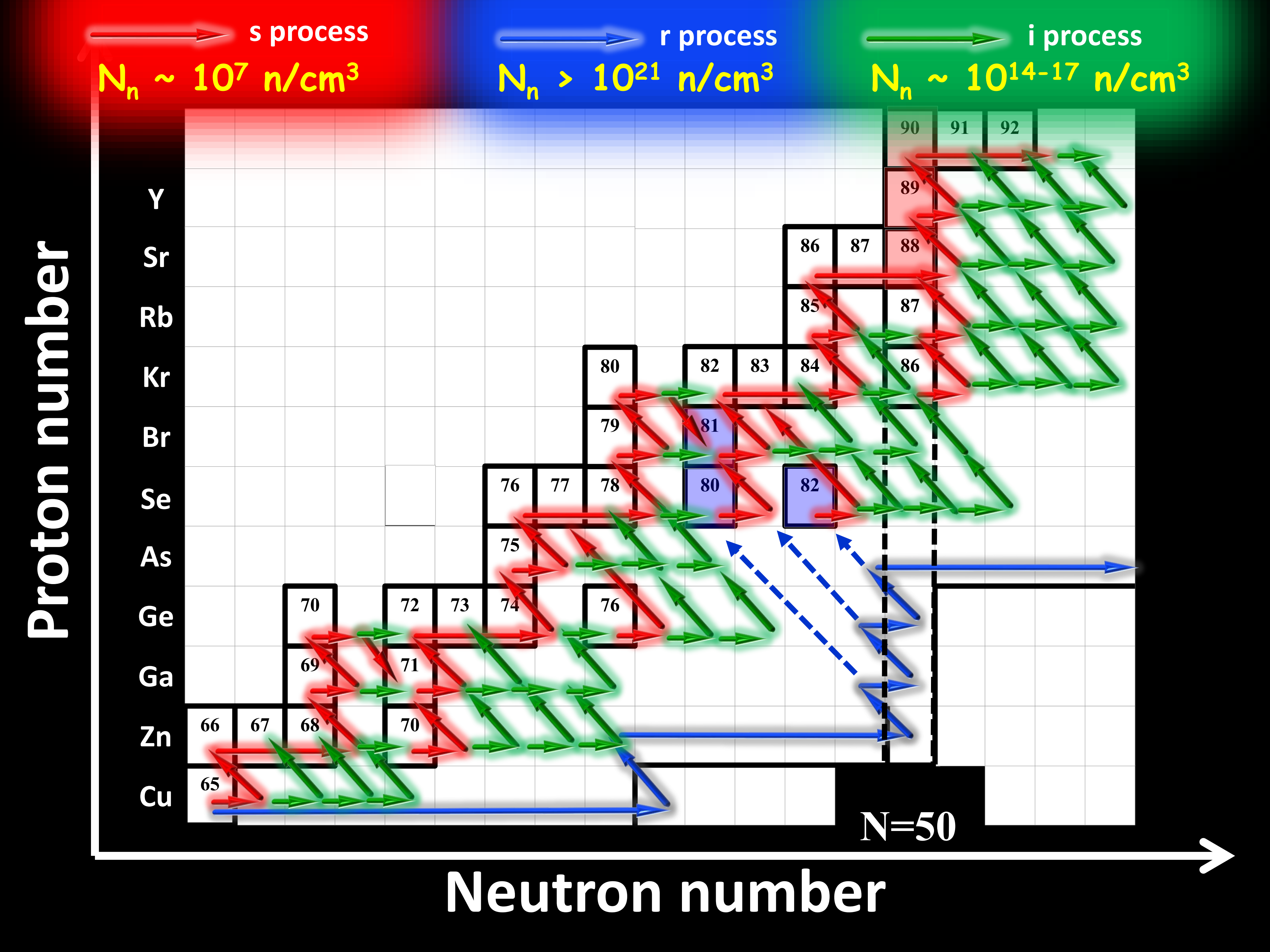
72
73
74
76
69
71
66
67
68
70
65
N=50



s process
$N_n \sim 10^7\ n/cm^3$
r process
$N_n > 10^{21}\ n/cm^3$
Y
Sr
Rb
Kr
Br
Se
As
Ge
Ga
Zn
Cu
90 91 92
89
86 87 88
85 87
80 82 83 84 86
79 81
76 77 78 80 82
75
70 72 73 74 76
69 71
66 67 68 70
65
N=50
Proton number
Neutron number



s process
$N_n \sim 10^7$ n/cm^3
r process
$N_n > 10^{21}$ n/cm^3
solar system abundances (Asplund 2005)
fusion
big bang
s-process peak
r-process peak
s-process peak
r-process peak
s-process peak
abundance (Y(Si)=1.e6)
atomic mass
Y
Sr
Rb
Kr
Br
Se
As
Ge
Ga
Zn
Cu
90 91 92
89
86 87 88
85 87
80 82 83 84 86
79 81
76 77 78 80 82
75
70 72 73 74 76
69 71
66 67 68 70
65
N=50
Proton number
Neutron number



s process
$N_n \sim 10^7$ n/cm^3
r process
$N_n > 10^{21}$ n/cm^3
i process
$N_n \sim 10^{14-17}$ n/cm^3
Proton number
Y
Sr
Rb
Kr
Br
Se
As
Ge
Ga
Zn
Cu
90
91
92
89
86
87
88
85
87
80
82
83
84
86
79
81
76
77
78
80
82
75
70
72
73
74
76
69
71
66
67
68
70
65
N=50
Neutron number

Origin of the heavy elements

A large neutron flux is difficult to be maintained!!!!

s(low) process

Mild neutron density $n_n \sim 10^7$ (and $\sim 10^{11}$)

Asymptotic giant branch (AGB) and massive stars

i(ntermediate) process

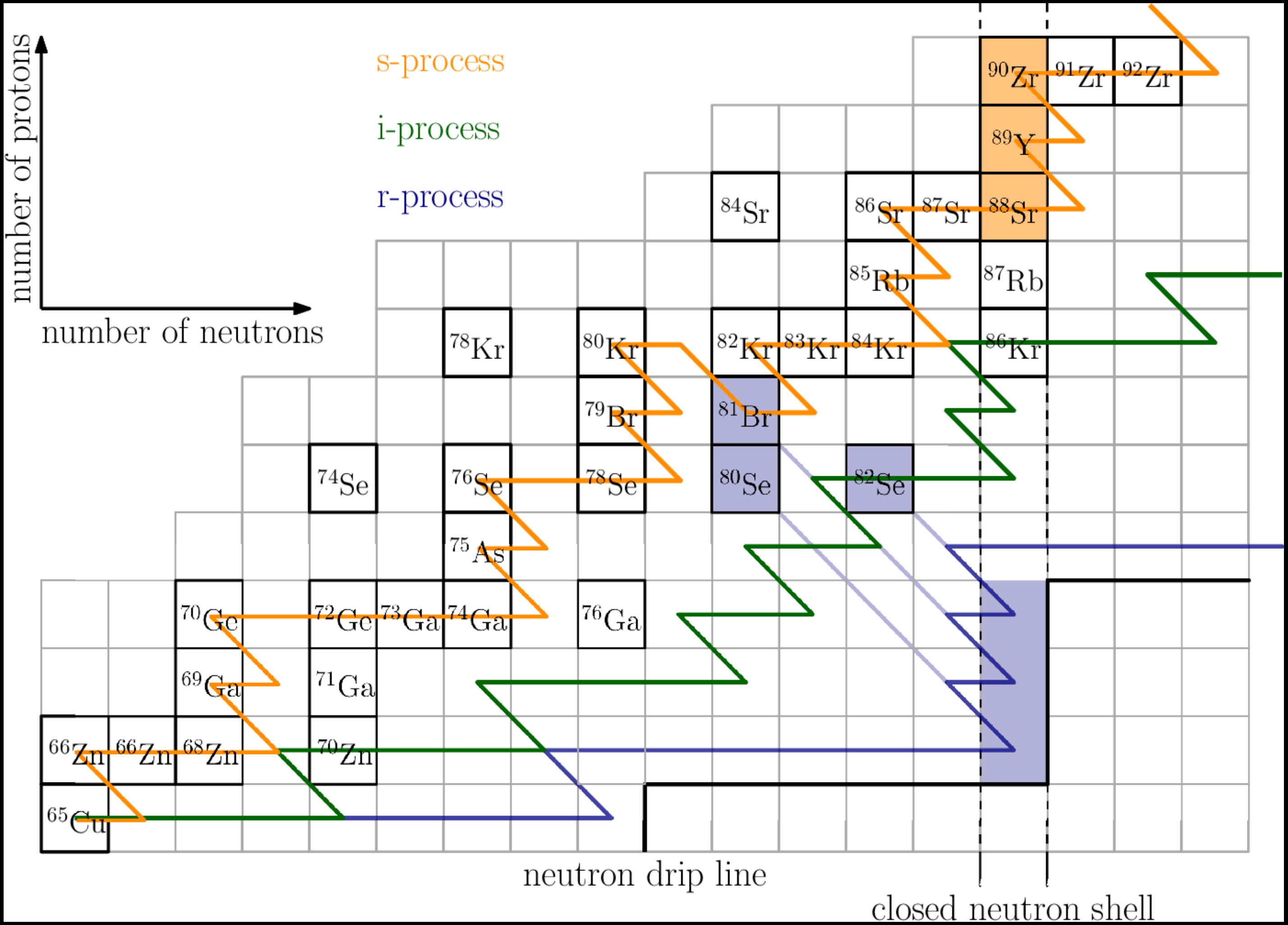
Intermediate neutron density $n_n \sim 10^{15}$

AGB, rapidly accreting white dwarfs, massive stars, etc.

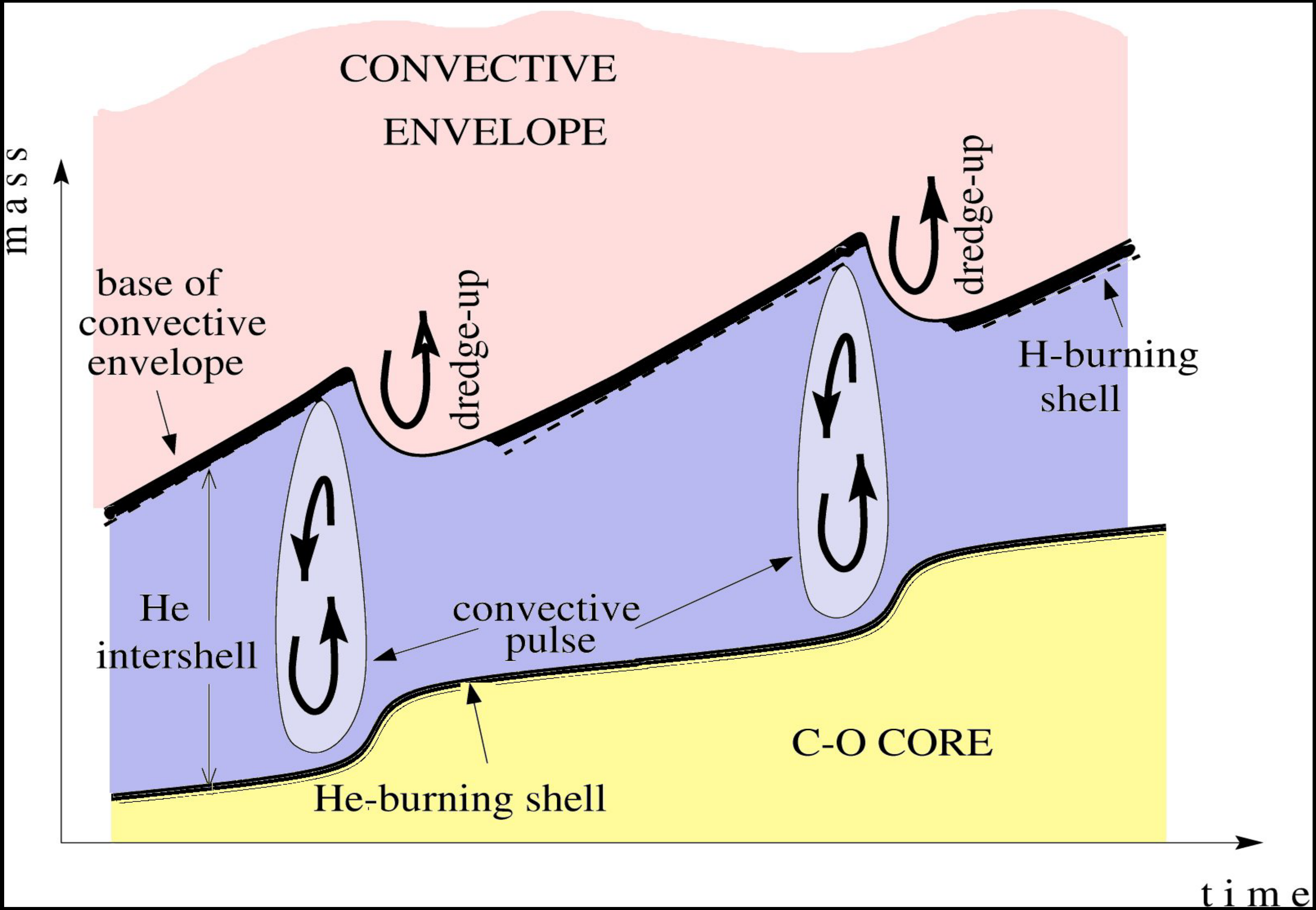
r(apid) process

High neutron density $n_n \gtrsim 10^{21}$

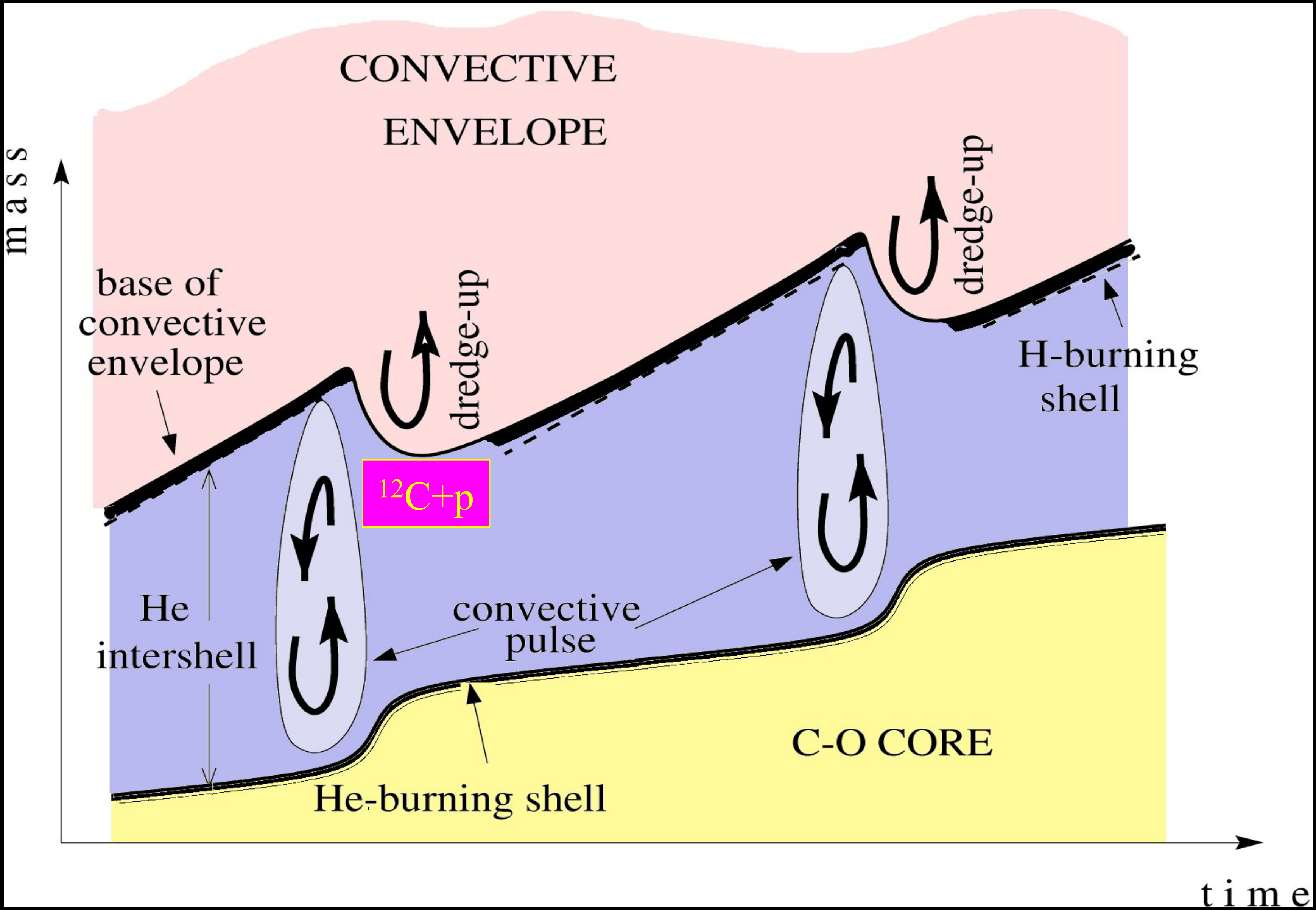
Collapsars, magnetars and compact binary mergers



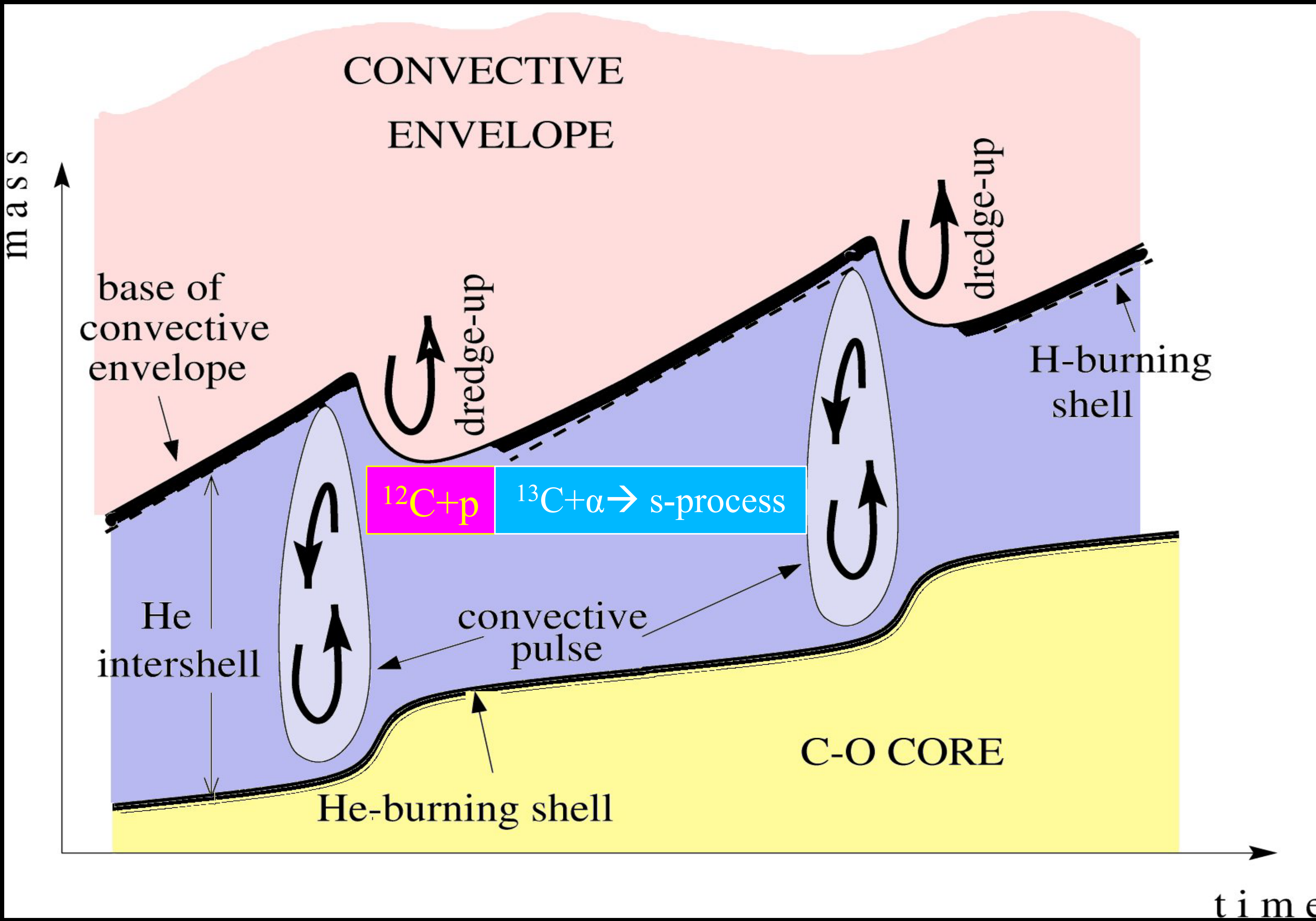
AGB structure



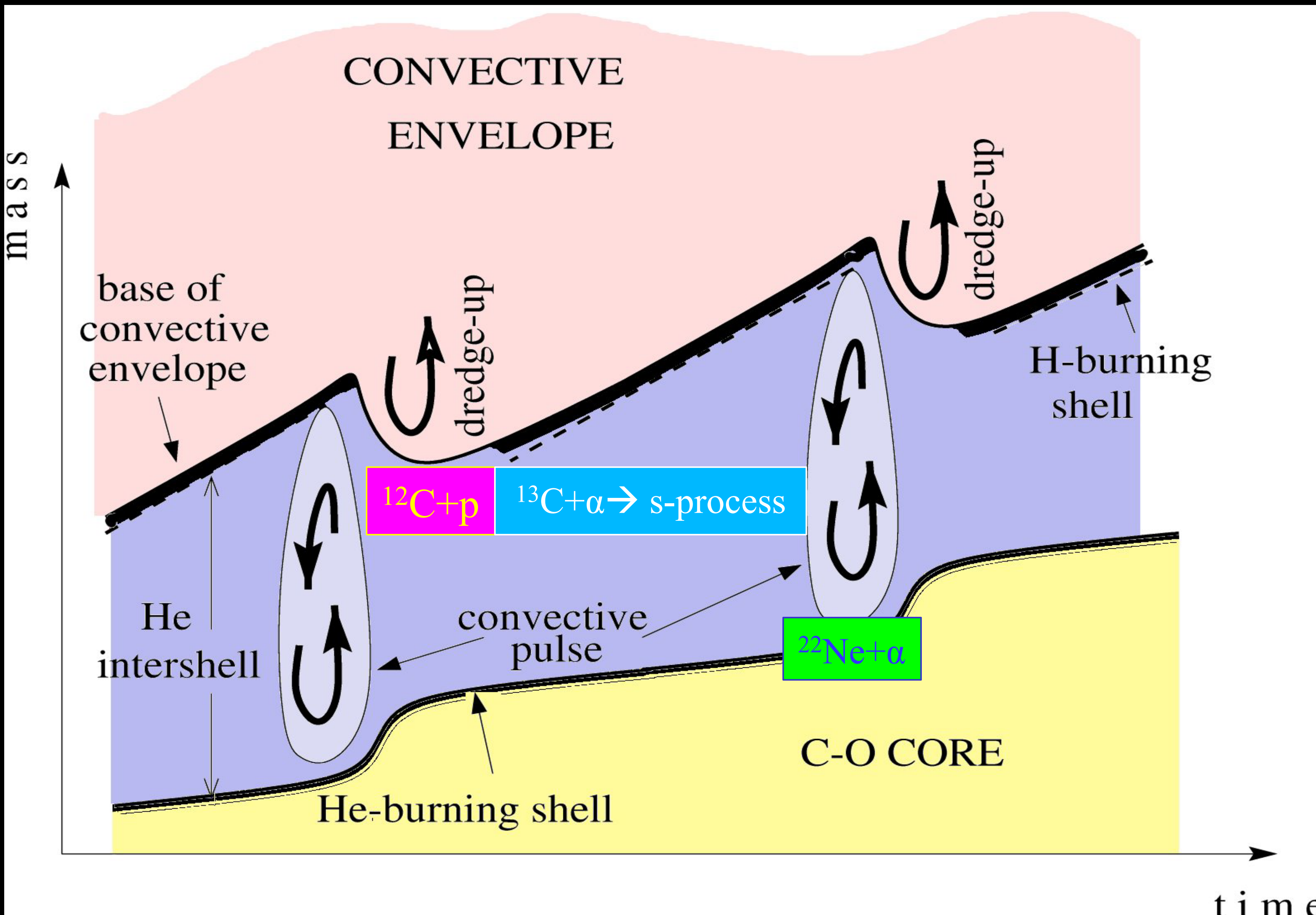
AGB structure



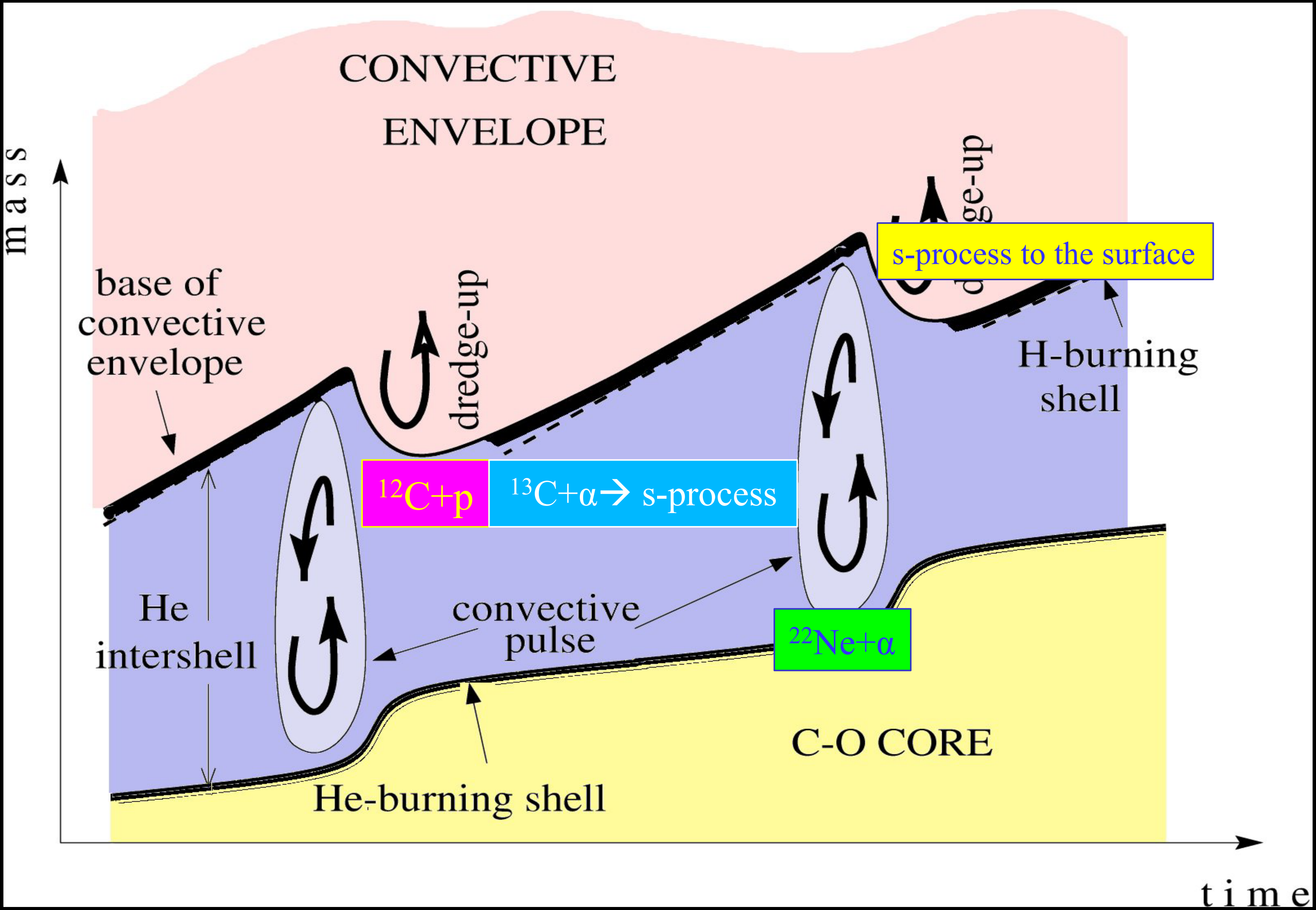
AGB structure



AGB structure

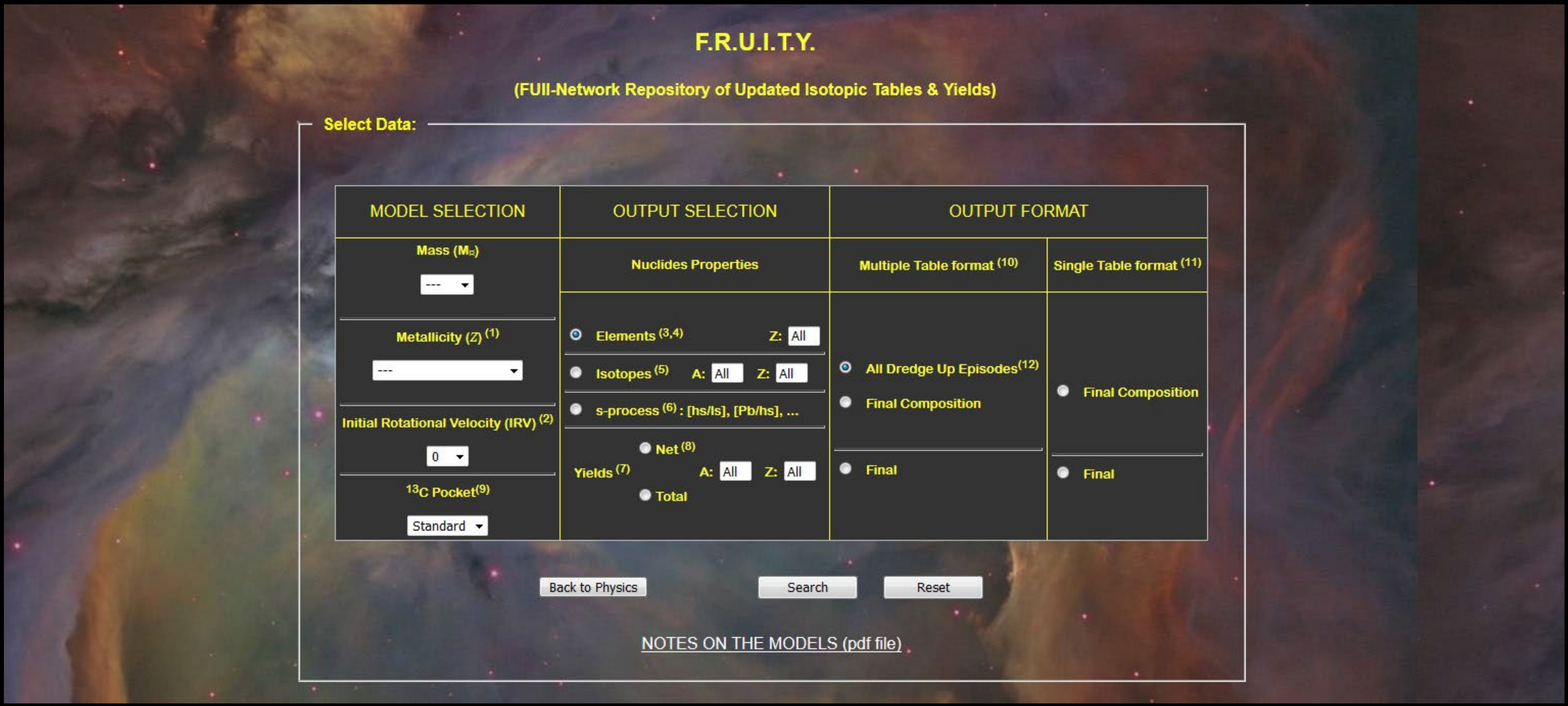


AGB structure



F.R.U.I.T.Y.

FUll-Network Repository of Updated Isotopic Tables & Yields

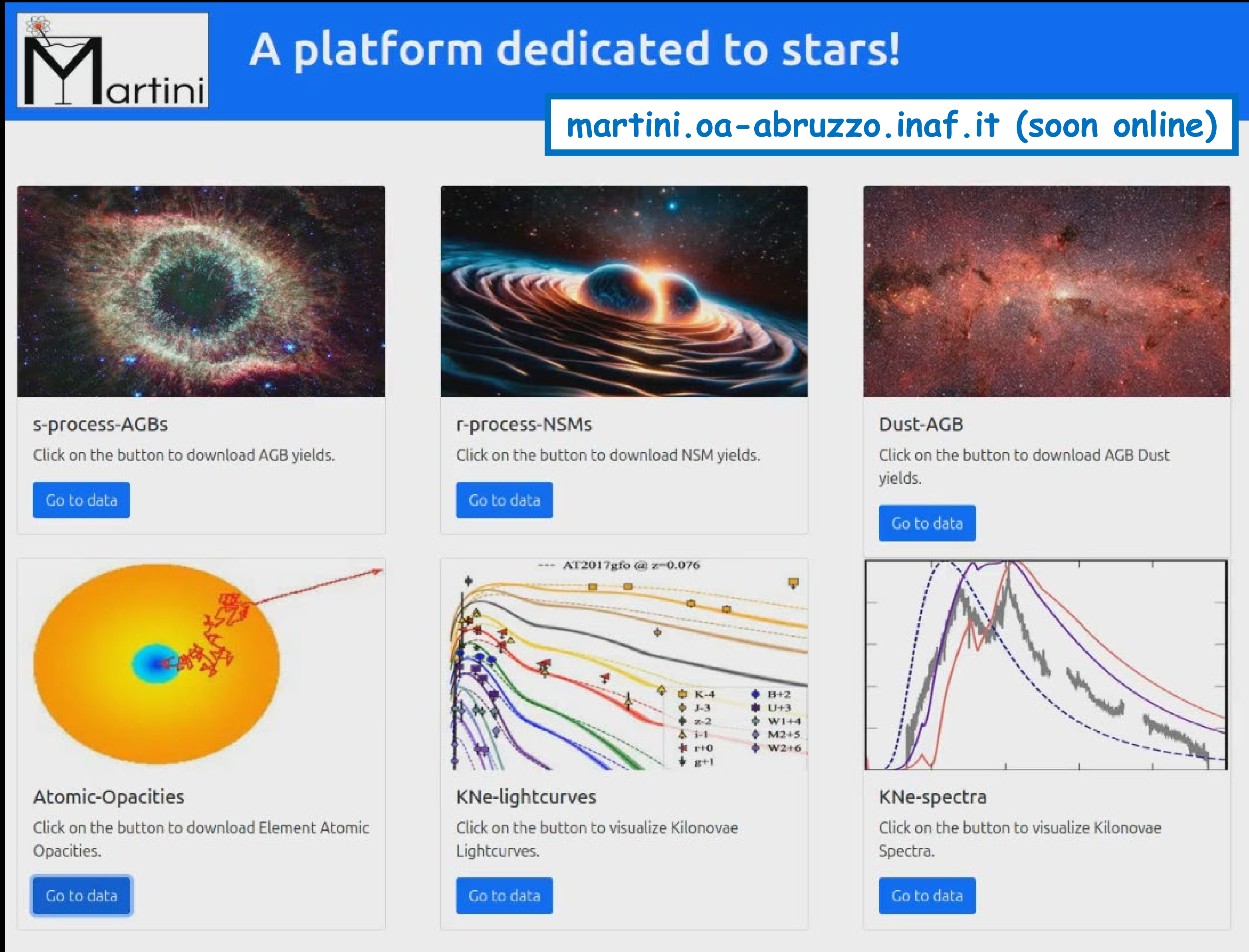


SC+ 2011,2015

fruity.oa-abruzzo.inaf.it

$-2.85 \leq [Fe/H] \leq +0.3$

$1.3 \leq M/M_{sun} \leq 6.0$

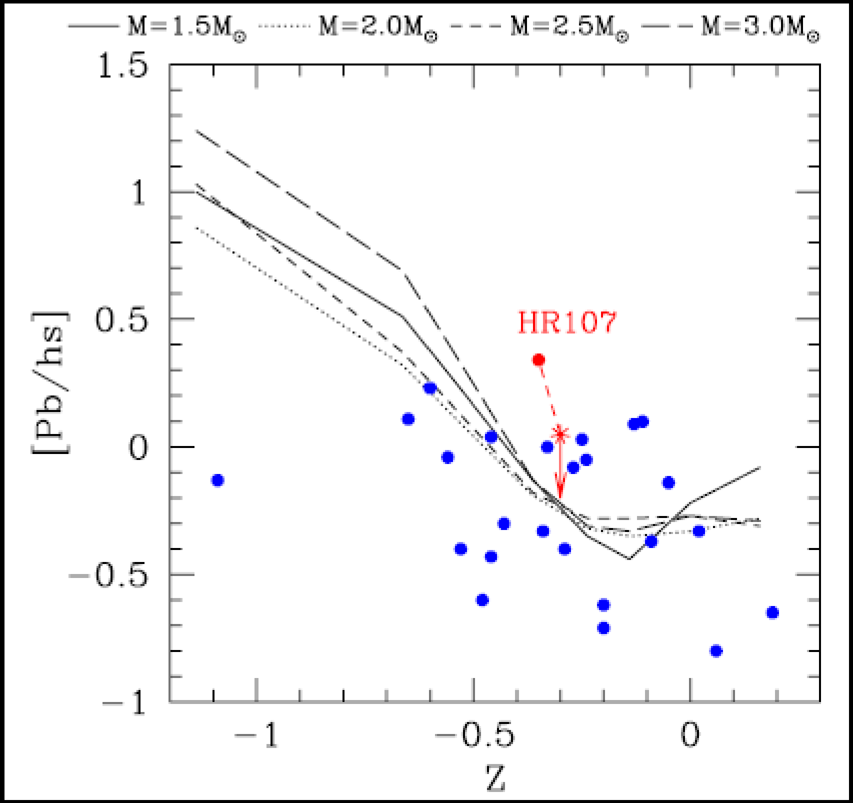


A wider project also including atomic physics (see M. Bezmalinovich talk)

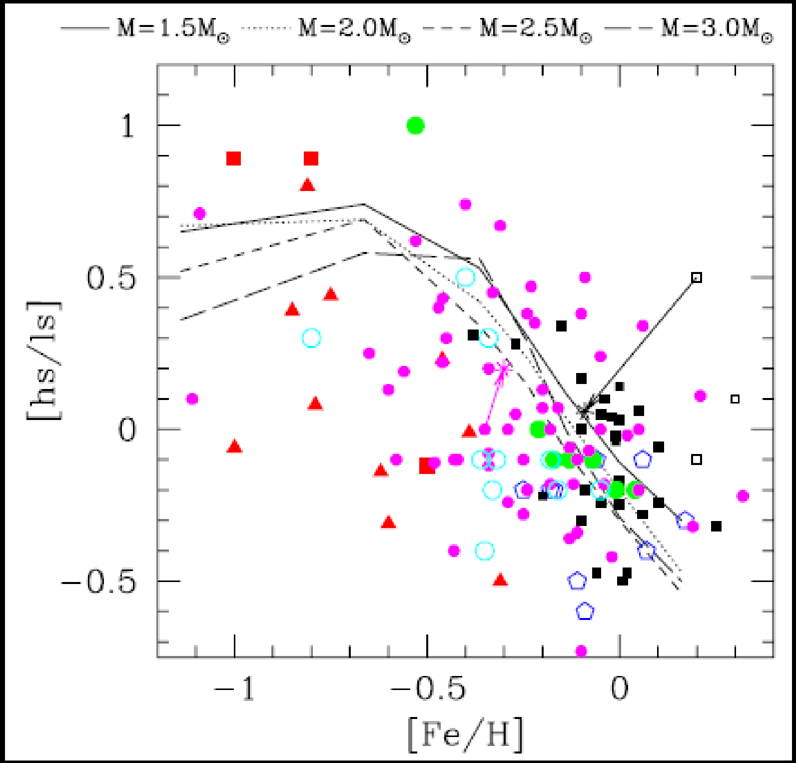
CONSTRAINTS (I)

OBSERVATIONS (spectroscopy)

Third to second s-process peak



Second to first s-process peak



SC+ 2011

[ls/Fe]= [Sr,Y,Zr/Fe]

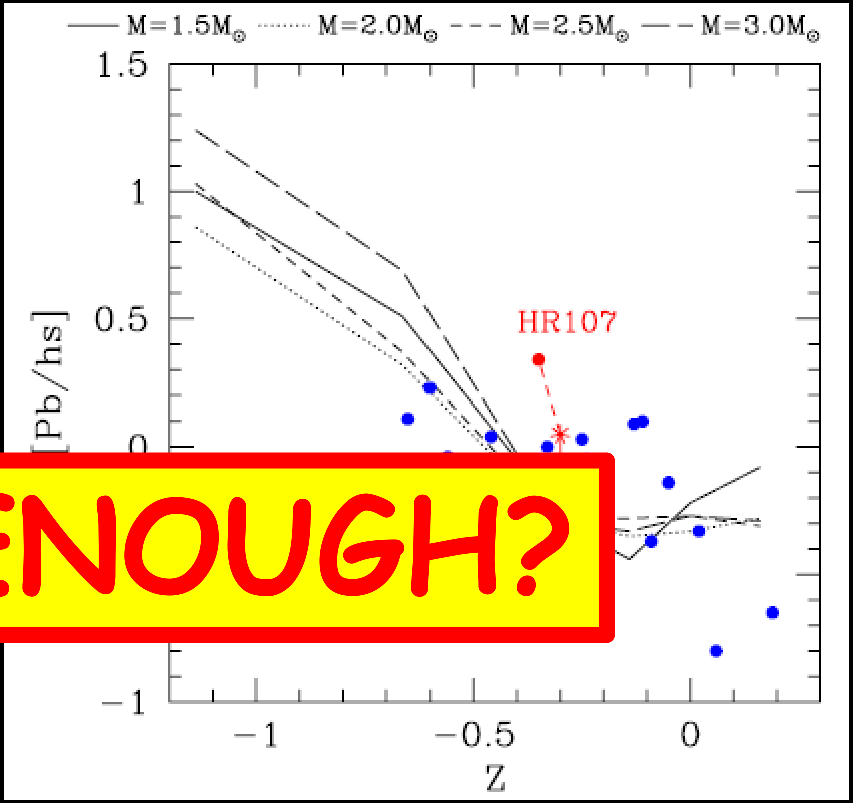
[hs/Fe]= [Ba,La,Ce,Nd/Fe]

[hs/ls]=[hs/Fe]-[ls/Fe]

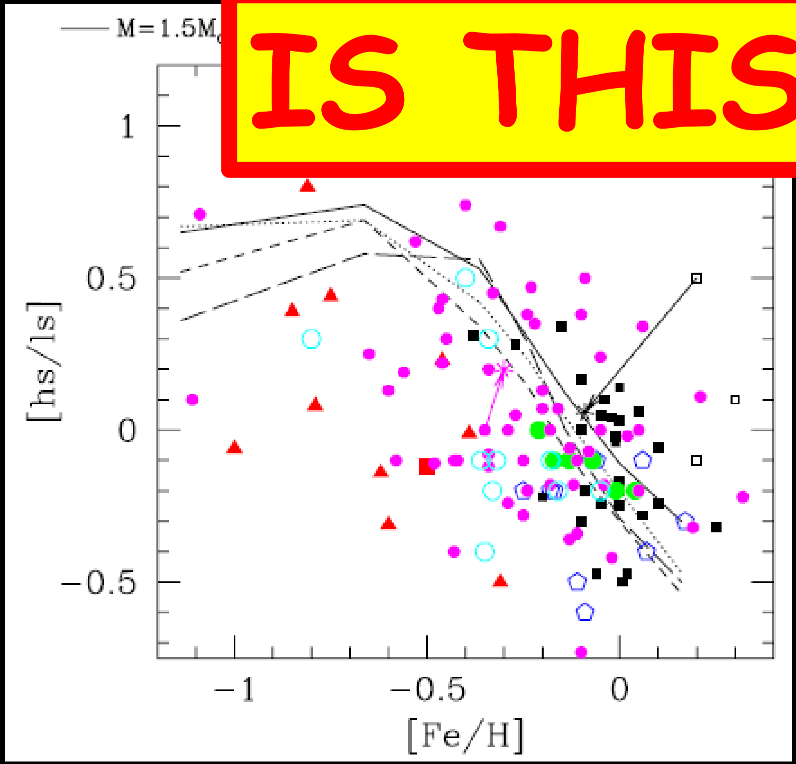
CONSTRAINTS (I)

OBSERVATIONS
(spectroscopy)

Third to second s-process peak



Second to first s-process peak

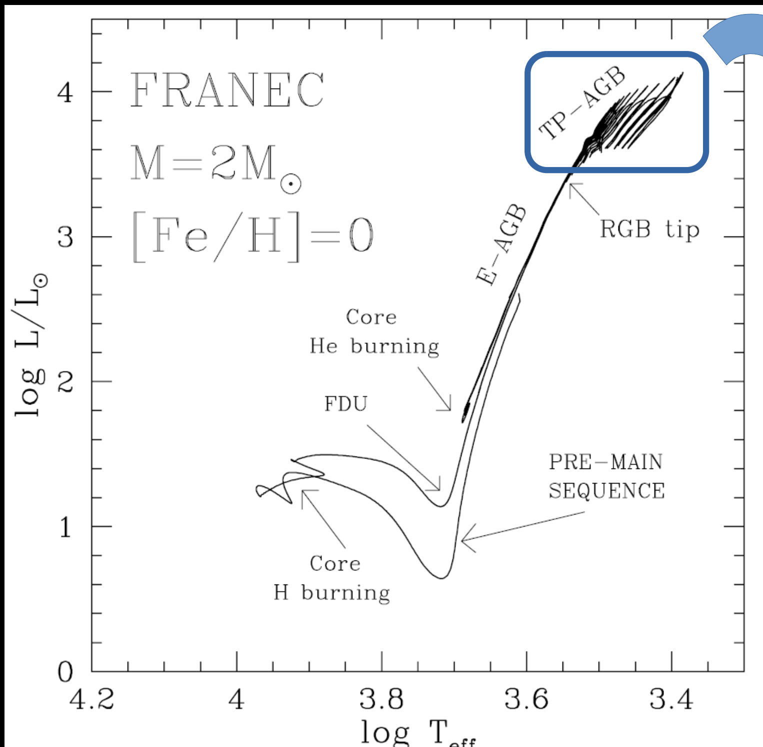


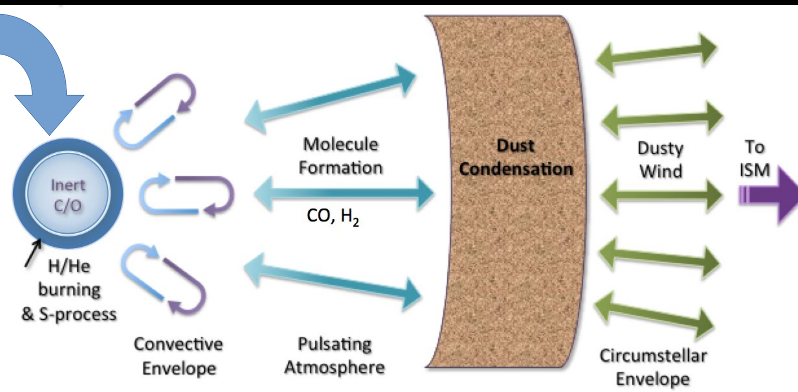
IS THIS ENOUGH?

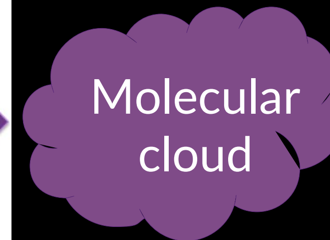
SC+ 2011

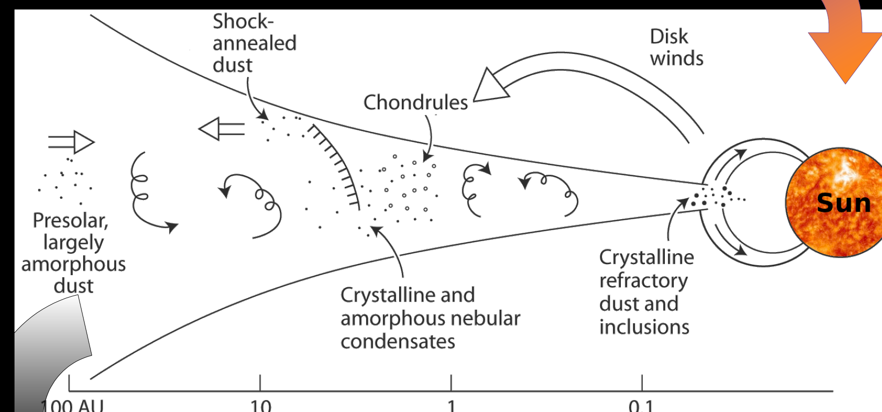
[ls/Fe]= [Sr,Y,Zr/Fe]
[hs/Fe]= [Ba,La,Ce,Nd/Fe]
[hs/ls]=[hs/Fe]-[ls/Fe]

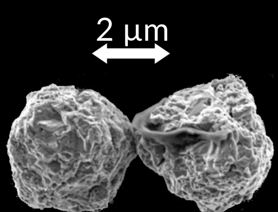
AGB stars and presolar SiC grains









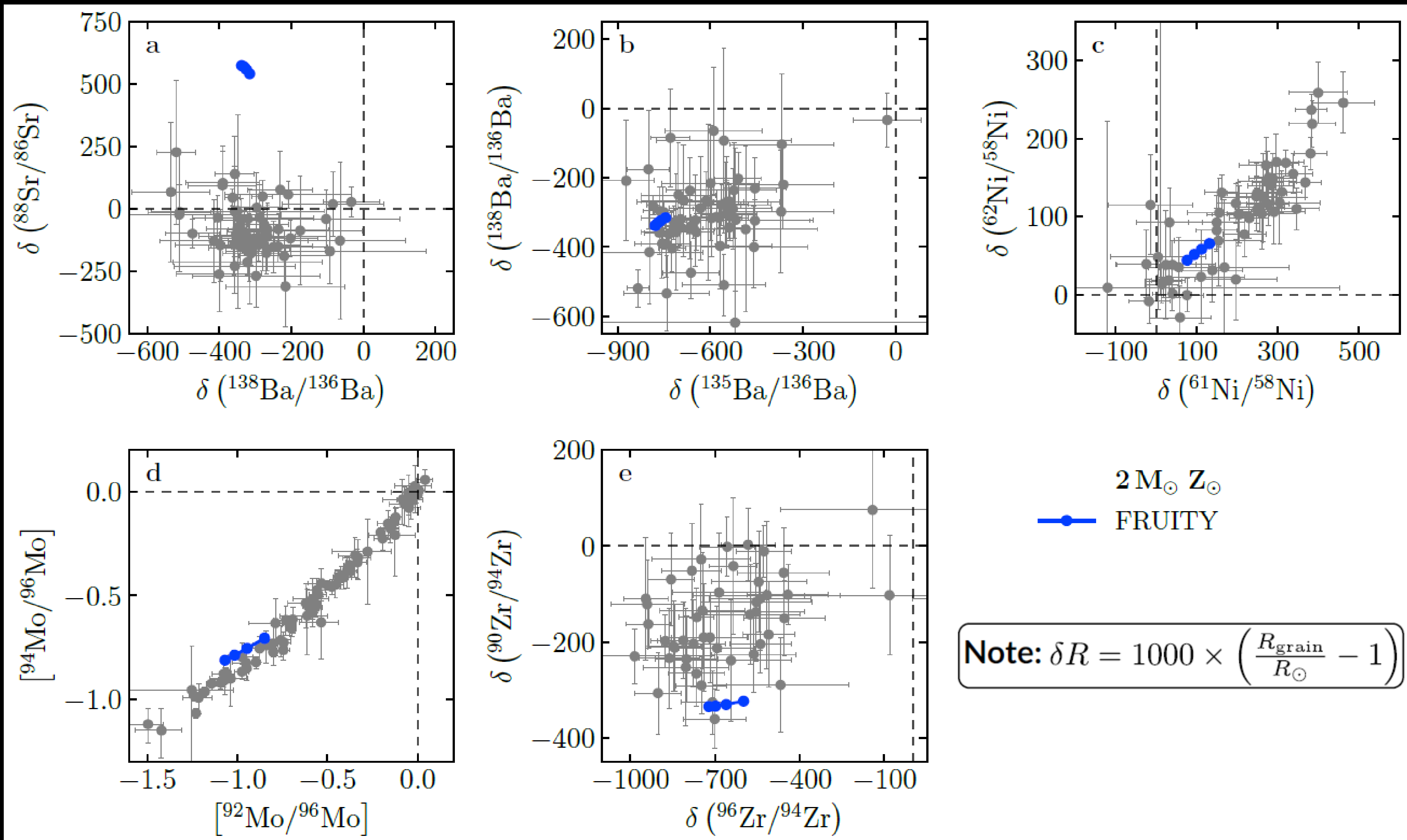


Presolar grains

Meteorites and asteroids

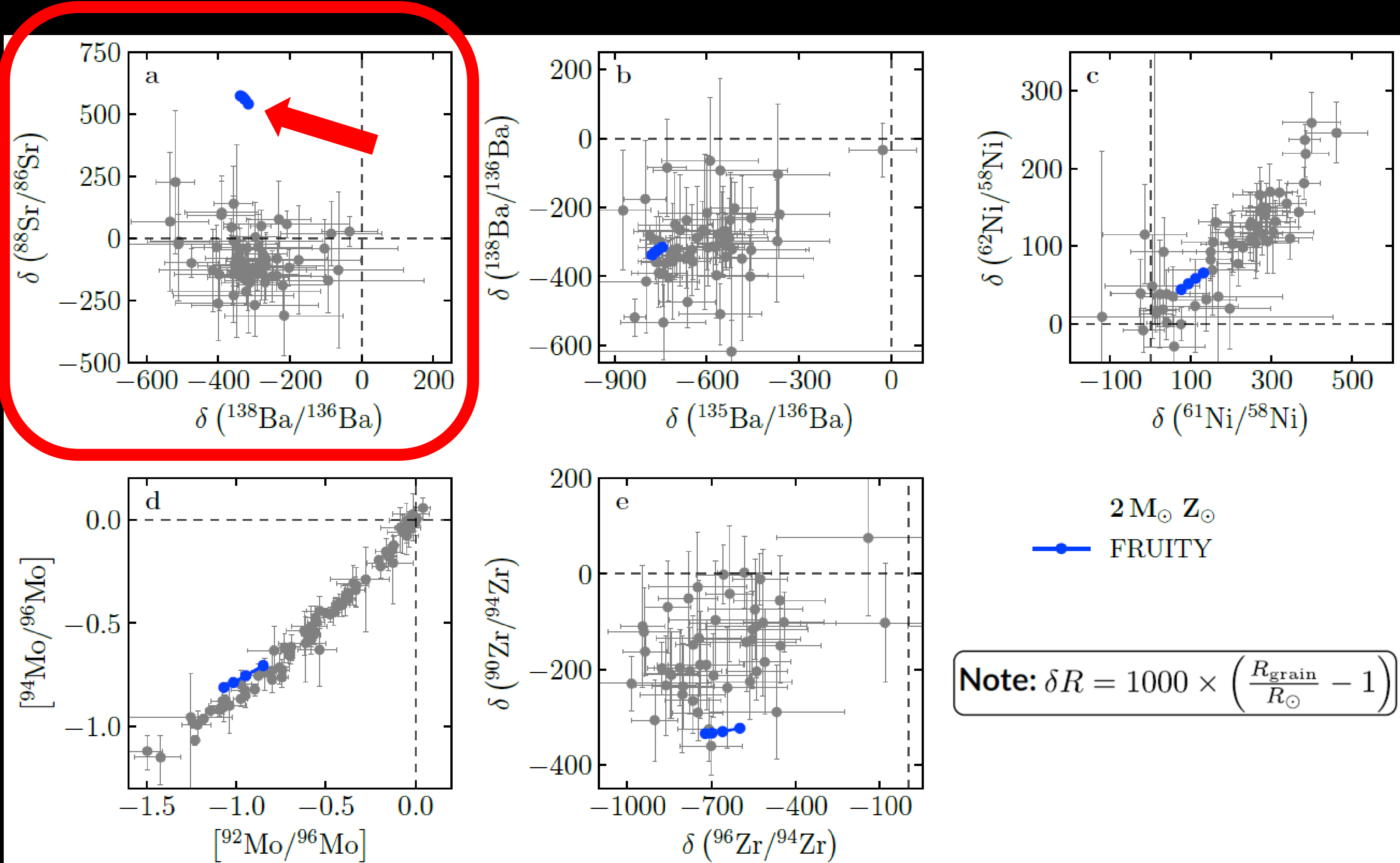
CONSTRAINTS (II)

LABORATORY (presolar grains)



CONSTRAINTS (II)

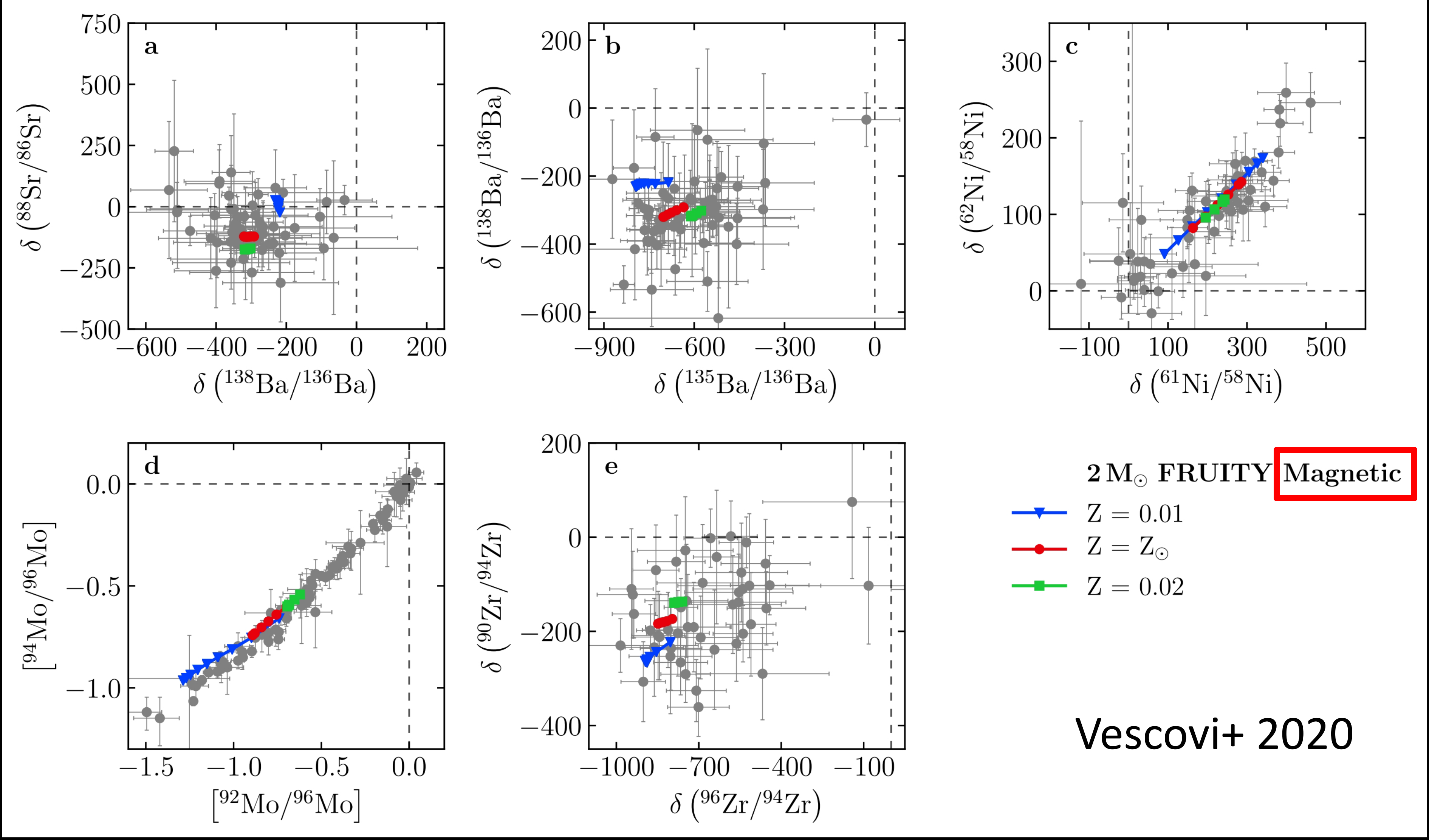
LABORATORY (presolar grains)



Note: $\delta R = 1000 \times \left(\frac{R_{grain}}{R_\odot} - 1\right)$

CONSTRAINTS (II)

LABORATORY (presolar grains)



Vescovi+ 2020

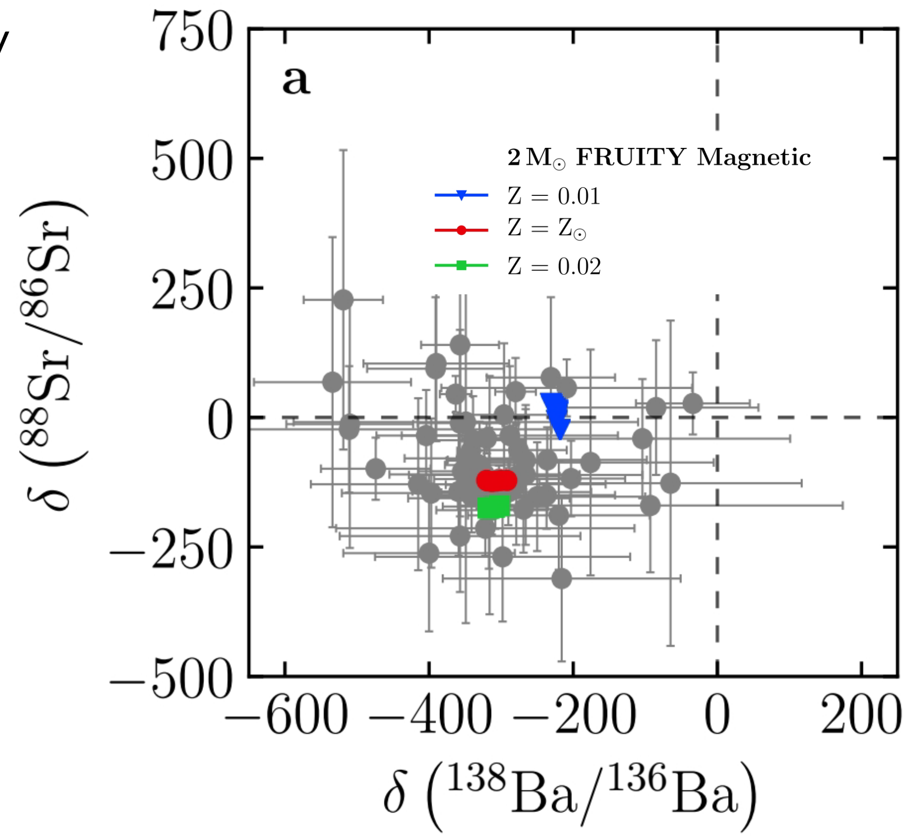
The effectiveness of presolar grain measurements

- **Correlated Sr and Ba isotope analyses** of more MS grains using the new generation of instruments are needed to better quantify the MS grain distribution to determine the data variability, which will help to assess the primary mechanism responsible for the ^{13}C formation

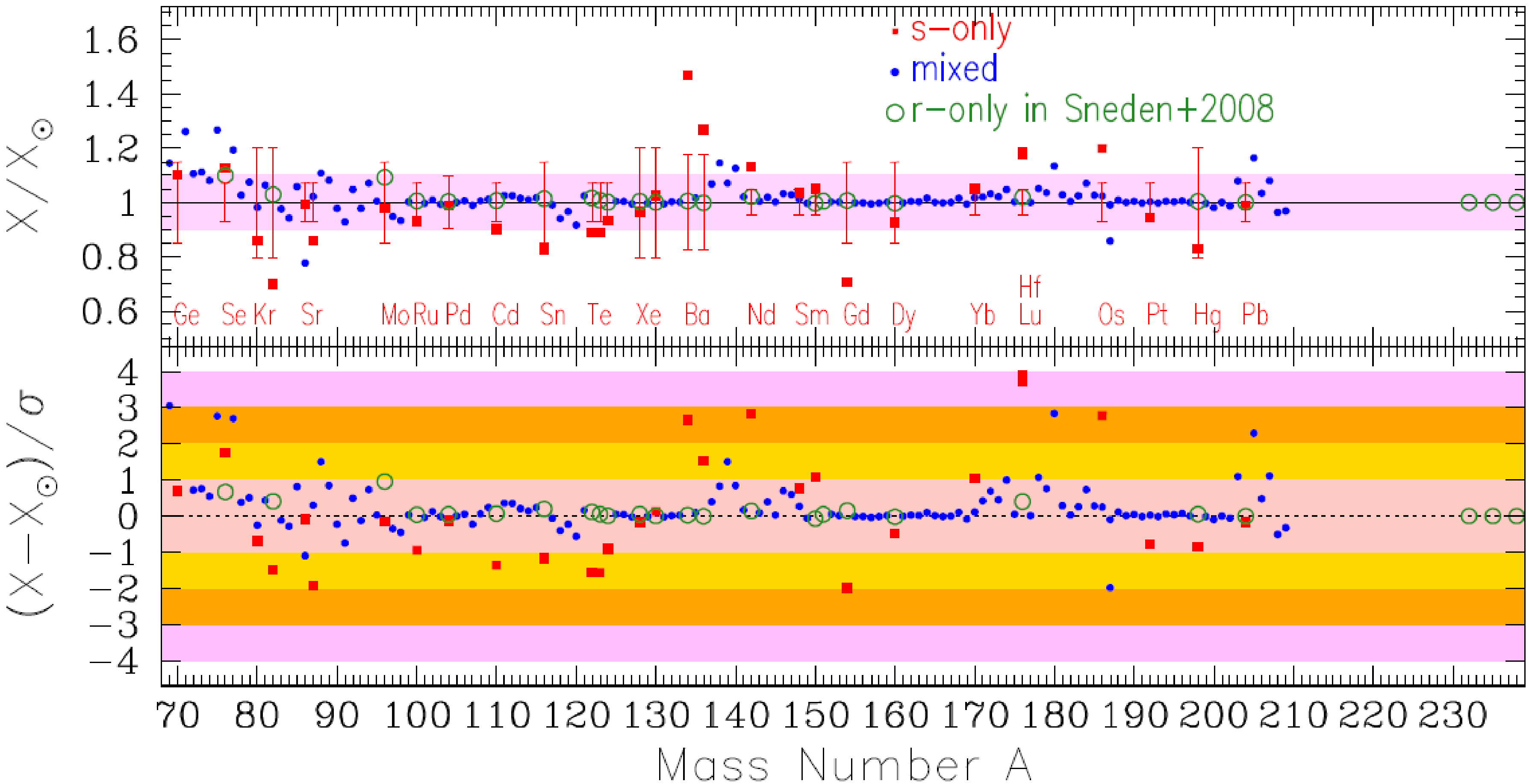
- **Nuclear Experiments**: AGB model predictions for $\delta^{88}Sr$ and $\delta^{138}Ba$ rely directly on the MACS values of ^{86}Sr, ^{88}Sr, ^{136}Ba, and ^{138}Ba

- Current AGB model uncertainties in $\delta^{88}Sr$ and $\delta^{138}Ba$ are controlled by uncertainties in the **^{86}Sr** (±10%) and **^{136}Ba** (±3%) MACS values, respectively, which correspond to ~200‰ and ~50‰ uncertainties, respectively

→ As the full range of $\delta^{88}Sr$ values observed among MS grains is only ~400‰, new measurements of **^{86}Sr MACS** values are needed to reduce model uncertainties



Second effective constraint for the s-process: s-only Solar distribution



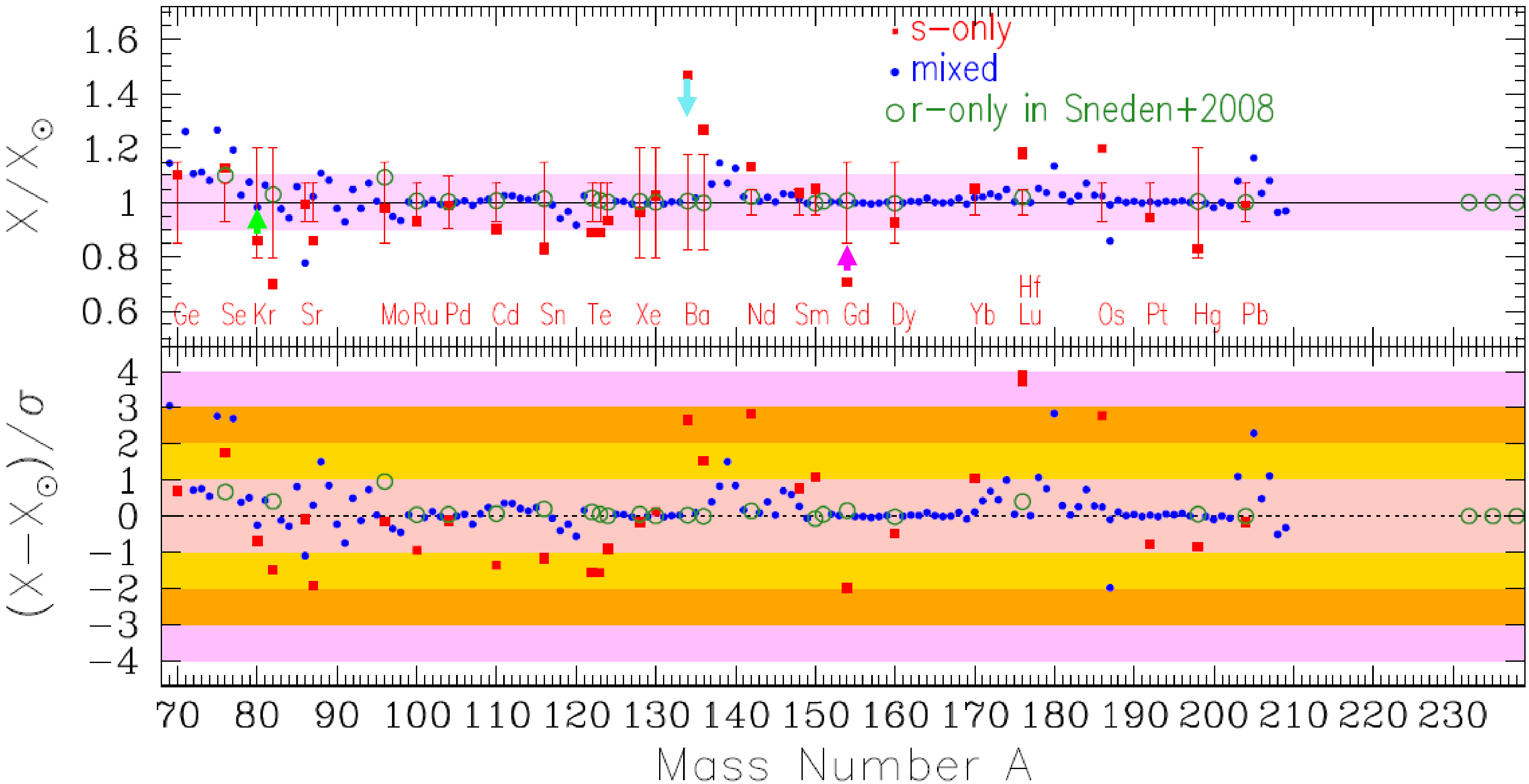
Prantzos+ 2020

Second effective constraint for the s-process: s-only Solar distribution

Mazzone+ 2020

Tessler+2021

Taioli+2022

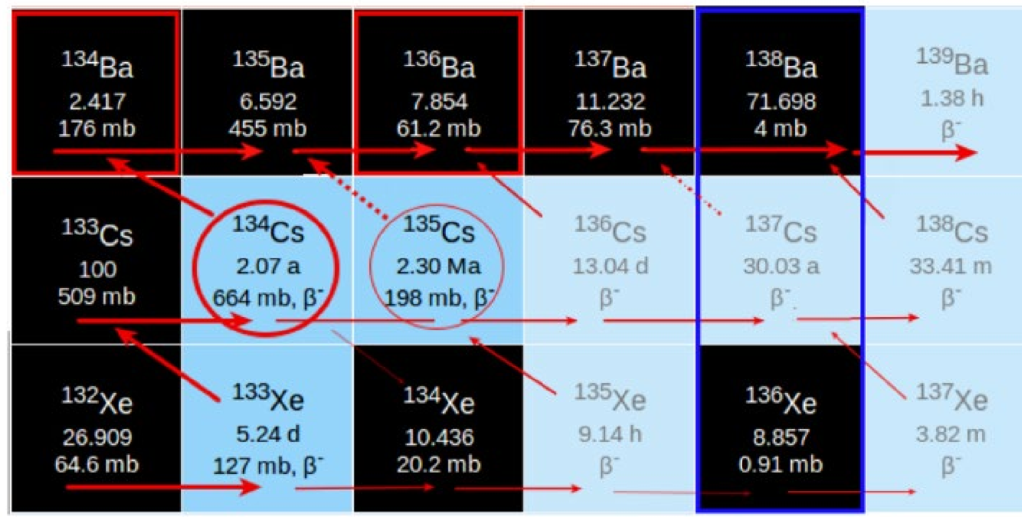


Prantzos+ 2020

Branchings in the s-process: Cesium isotopes

- The chain of branching points at the Cs isotopes is of particular interest not only for understating the ^{135}Cs/^{133}Cs ratio in the Early Solar System
- It affects the isotopic composition of Ba and in particular the relative abundances of the two s-only nuclei **^{134}Ba** and **^{136}Ba** → important for explaining their <u>measured ratio</u> in meteorites (e.g., Busso+ 21, Palmerini+21, Taioli+ 22)

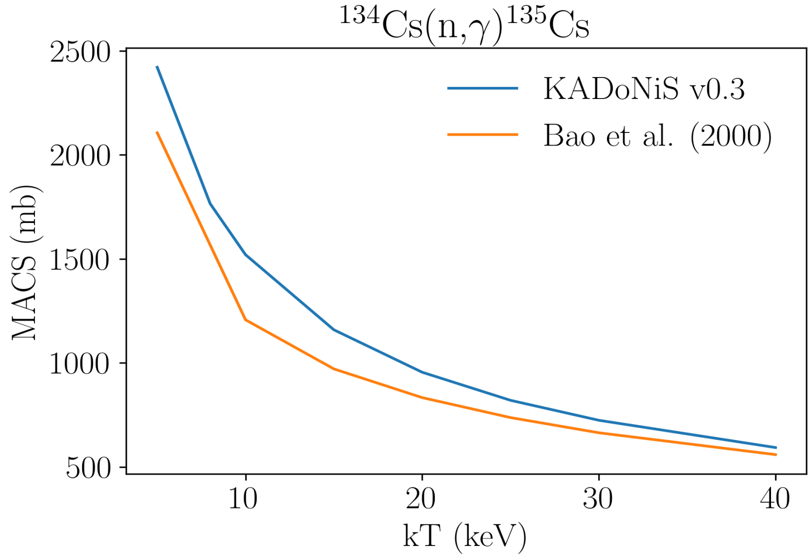
Bisterzo+ 15, MNRAS

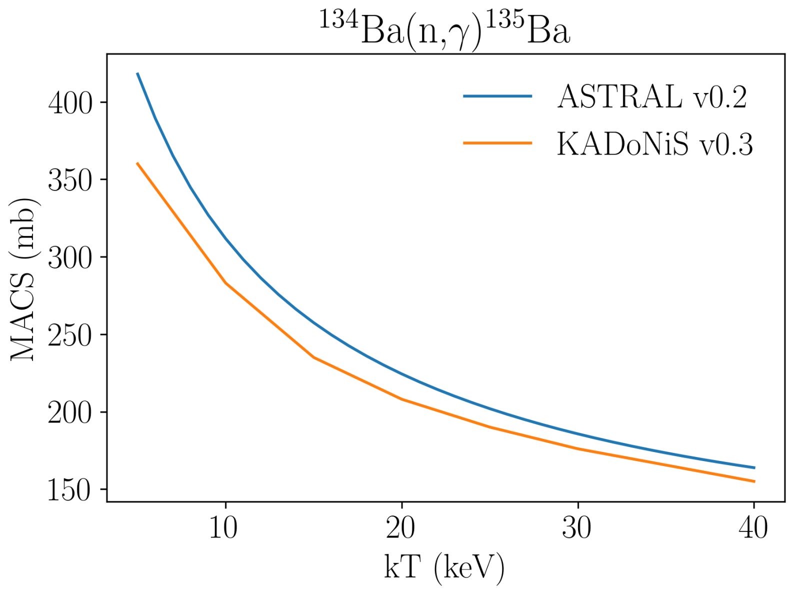


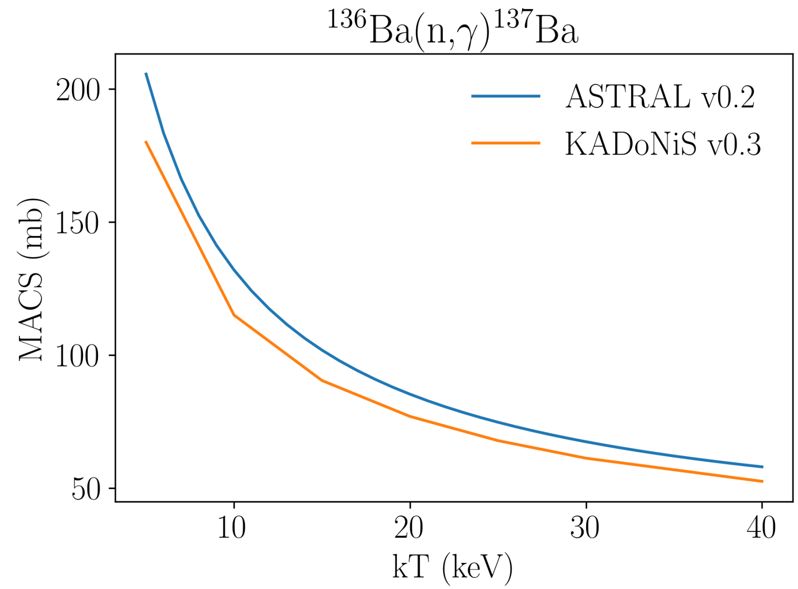
- The half lives of both ^{134}Cs and ^{135}Cs decrease by orders of magnitude in stellar conditions → act as branching point
- The branching point at ^{134}Cs ($T_{1/2}$ = 2 Myr) allows the production of the long-living isotope ^{135}Cs

Branchings in the s-process: Cesium isotopes

- The neutron-capture cross section of ^{135}Cs has been experimentally determined, while the **^{134}Cs(n,γ)** cross section has **only** been **semi-empirically estimated** (Patronis+ 04)





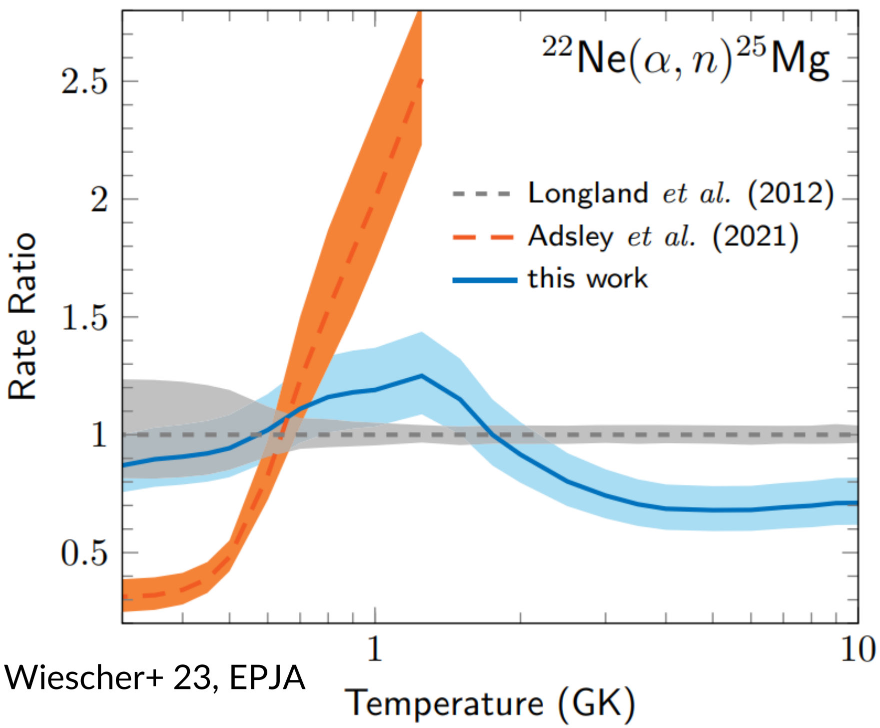


- Re-evaluated cross sections, → systematically higher due to the new (higher by ~5%) adopted gold cross section as a reference

Branchings in the s-process: Cesium isotopes

Neutron sources

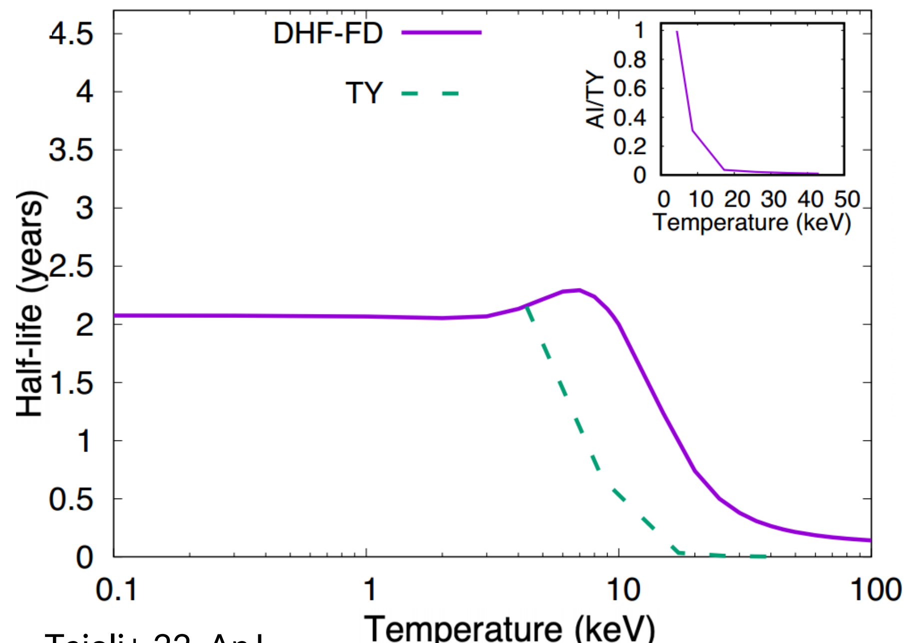
- $^{22}Ne(\alpha,n)^{25}Mg$ reaction rate uncertain by a **factor ~3**: direct and indirect measurements (e.g., Adsley+21, Shahina+ 24)



Wiescher+ 23, EPJA

β decays

- Theoretical ^{134}Cs β^- rate is reduced up to a factor of 8 for $T > 10^8$ K w.r.t Takahashi & Yokoi 87 (Li+ 21, Taioli+ 22)



Taioli+ 22, ApJ

Branchings in the s-process: Cesium isotopes

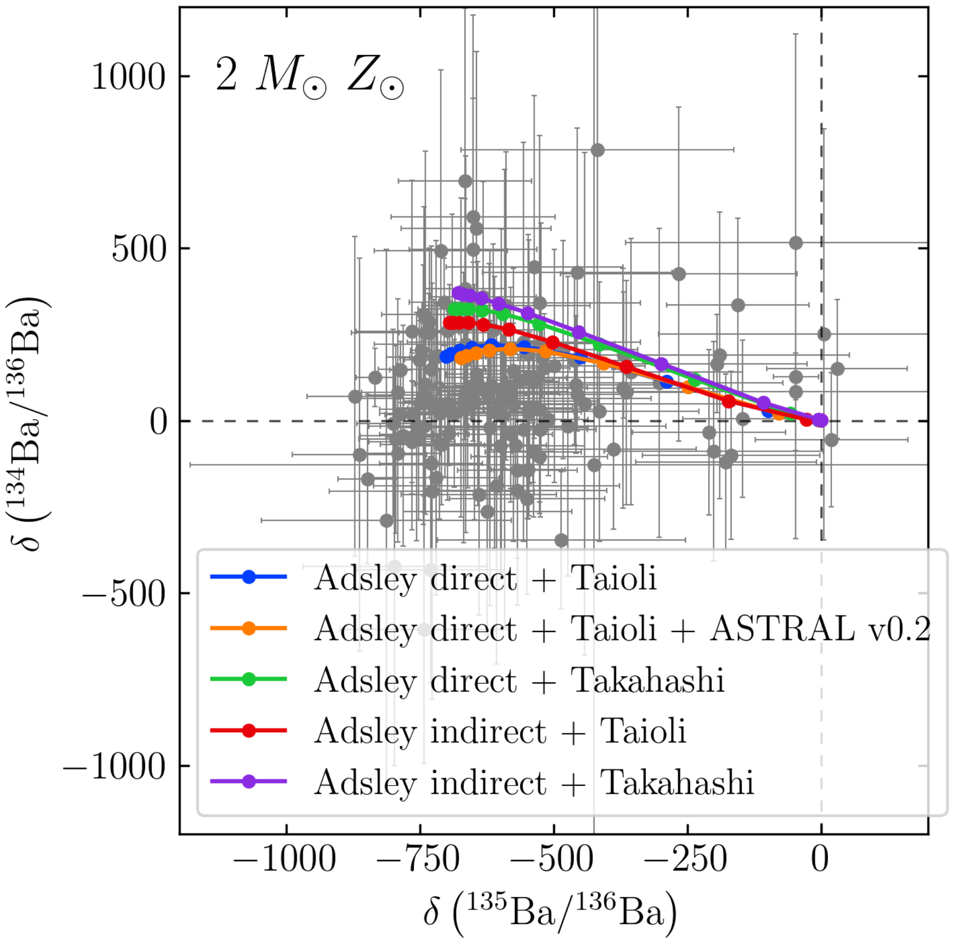
- $^{22}Ne(\alpha,n)^{25}Mg$ reaction rate from Adsley+ 21 with indirect data and with direct data only
- $^{134}Ba(n,\gamma)$ and $^{136}Ba(n,\gamma)$ from ASTRAL v0.2
- ^{134}Cs β^- rate from Takahashi & Yokoi 87 and Taioli+ 22

→ $^{134}Ba/^{136}Ba$ ratio decreases with enhanced $^{22}Ne(\alpha,n)^{25}Mg$ rate computed from directed data only

→ $^{134}Ba/^{136}Ba$ ratio decreases with new ^{134}Cs β^- rate

→ $^{134}Ba/^{136}Ba$ ratio almost unchanged with revised n-capture rates

→ **Better agreement: Adsley direct + Taioli model**



The i-process

1. H-ingestion in low-Z low-mass AGB stars

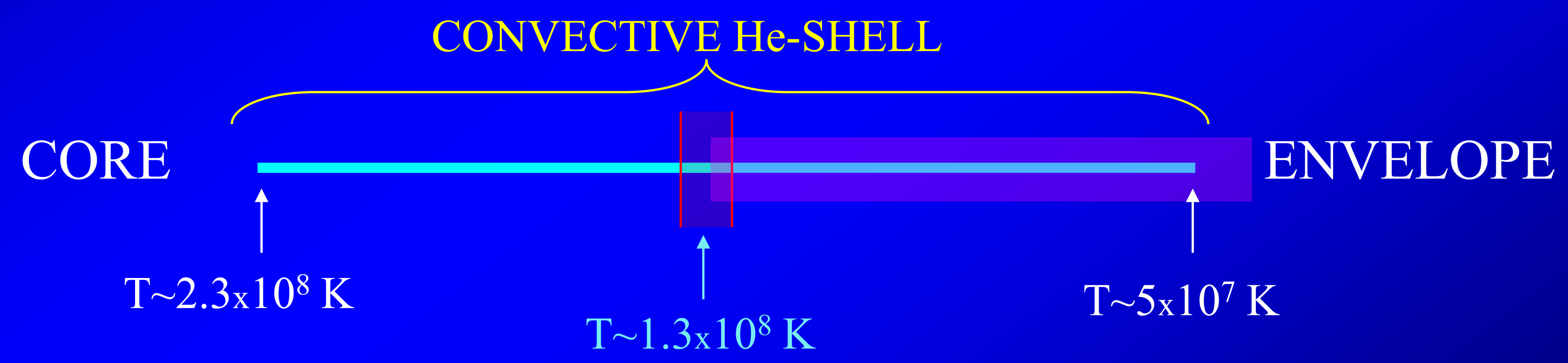
2. H-ingestion in rapidly accreting WDs

3. Massive AGBs stars at low Z

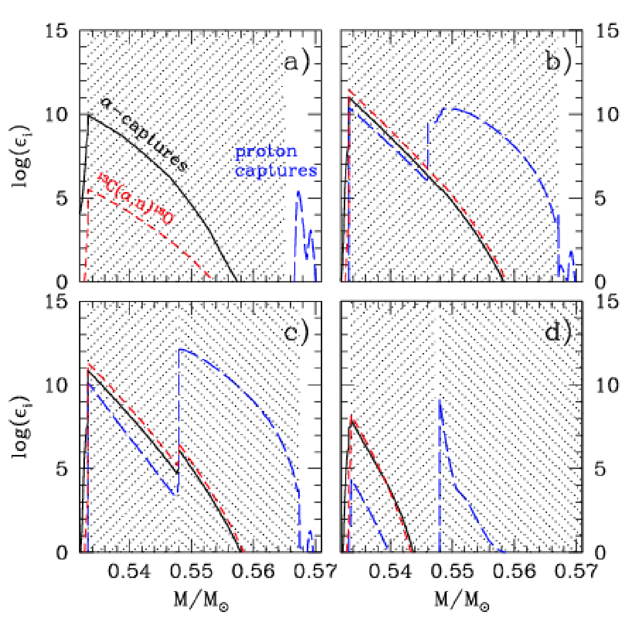
4. He-accreting WDs

Proton Ingestion Episode (PIE) and the intermediate neutron capture process (i-process)

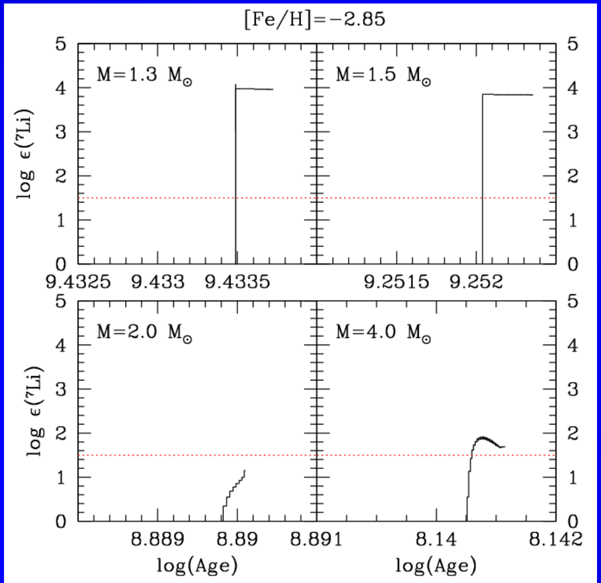
- Low time steps → Time dependent mixing
- Rapid structure reaction → Coupling between phisical and chemical evolution
- Large neutron densities ($n_n > 10^{15}$ cm^{-3}) → 700 isotopes & 1000 reactions

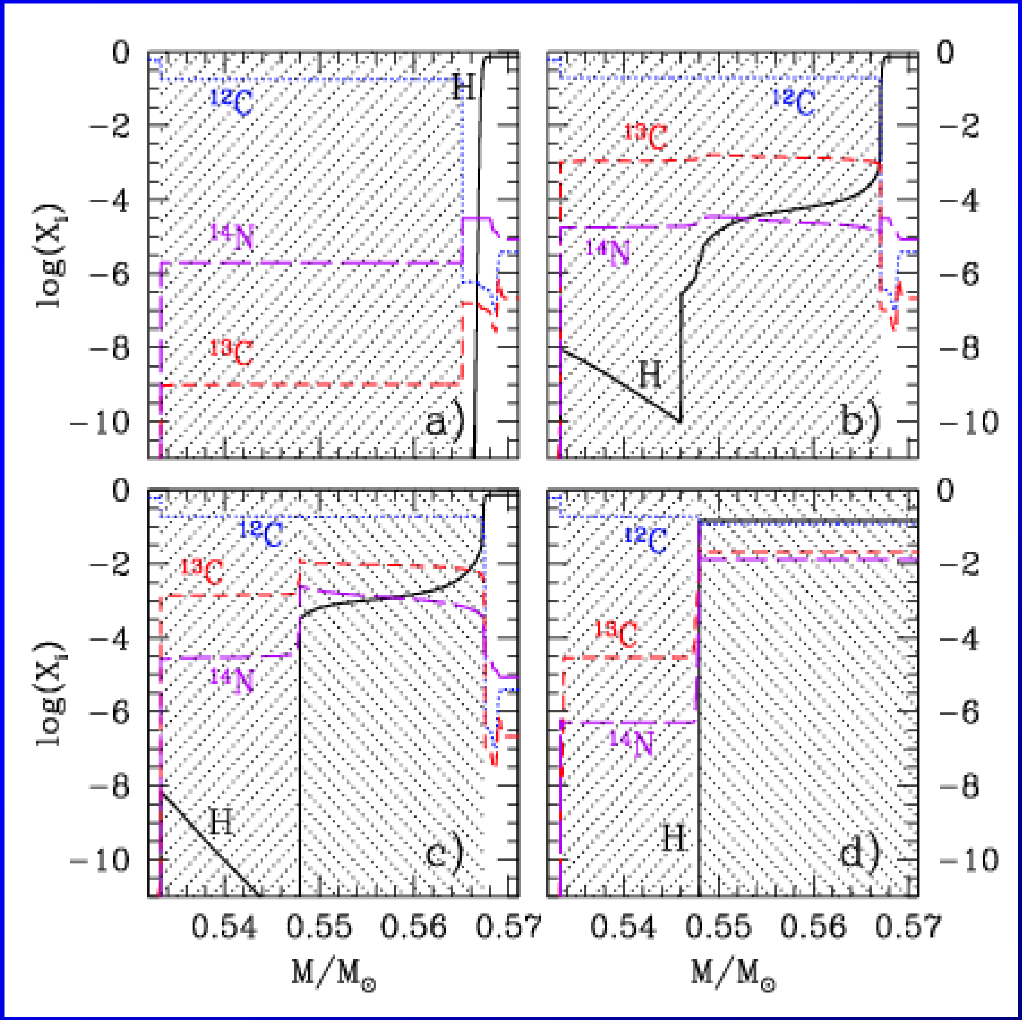


Heavy (and light) elements in PIE episodes

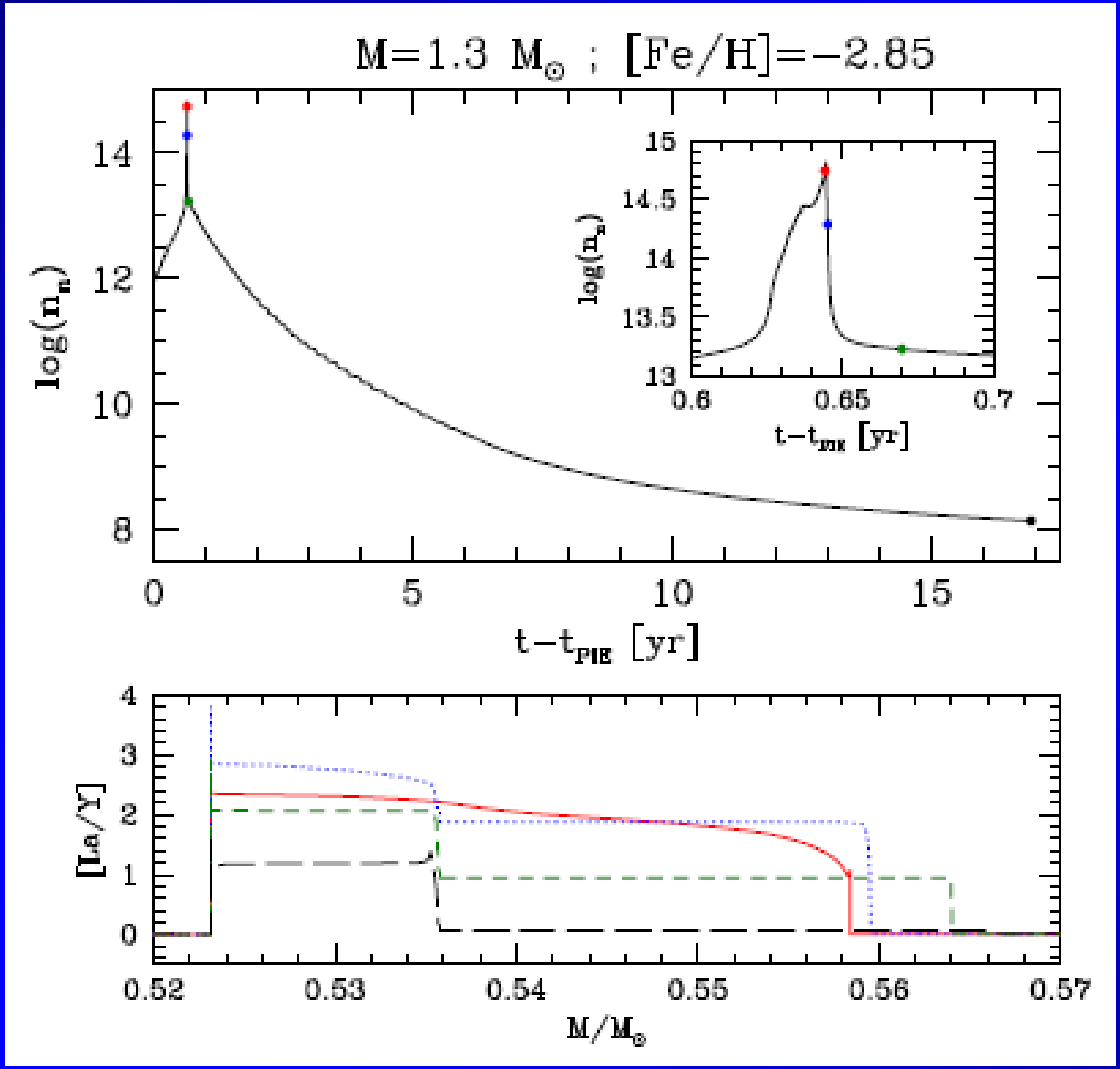


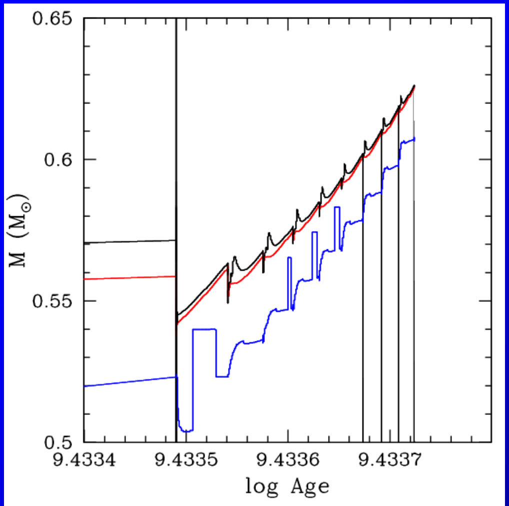
Cristallo+2009





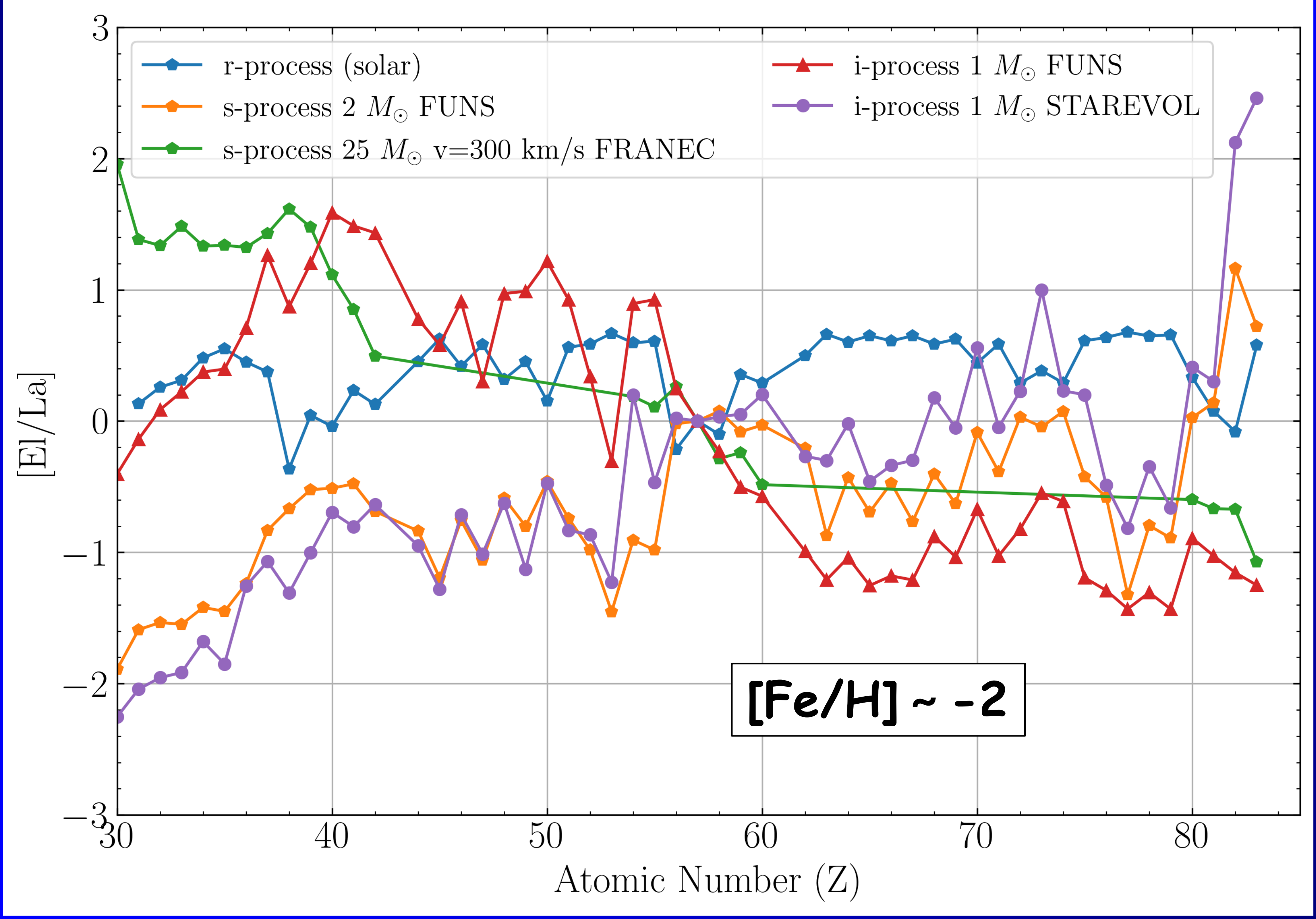
PIEs: transient phase or destructive episode?





Cristallo+2016

How can we distinguish processes?



Can we use isotopic ratios?

Ref.	$^{85}Rb / ^{tot}Rb$	$(^{135}Ba + ^{137}Ba) / ^{tot}Ba$	$(^{142}Nd + ^{144}Nd) / ^{tot}Nd$	$(^{152}Sm + ^{154}Sm) / ^{tot}Sm$	$^{151}Eu / ^{tot}Eu$
s-proc (Teramo)	0.50	0.08	0.62	0.27	0.46
i-proc (Bruxelles, AGBs)	0.13	0.70	0.59	0.74	0.73
i-proc (Teramo, AGBs)	0.30	0.94	0.46	0.54	0.49
i-proc (Victoria; RAWDs)	0.22	0.44	0.51	0.59	0.65
r-process (residual)	0.97	0.70	0.26	0.64	0.48
r-process (polar)	0.16	0.98	0.19	0.09	0.77
r-process (equatorial)	0.45	0.50	0.21	0.53	0.60

Can we use isotopic ratios?

Ref.	$^{85}Rb / ^{tot}Rb$	$(^{135}Ba+^{137}Ba) / ^{tot}Ba$	$(^{142}Nd+^{144}Nd) / ^{tot}Nd$	$(^{152}Sm+^{154}Sm) / ^{tot}Sm$	$^{151}Eu / ^{tot}Eu$
s-proc (Teramo)	0.50	0.08	0.62	0.27	0.46
i-proc (Bruxelles, AGBs)	0.13	0.70	0.59	0.74	0.73
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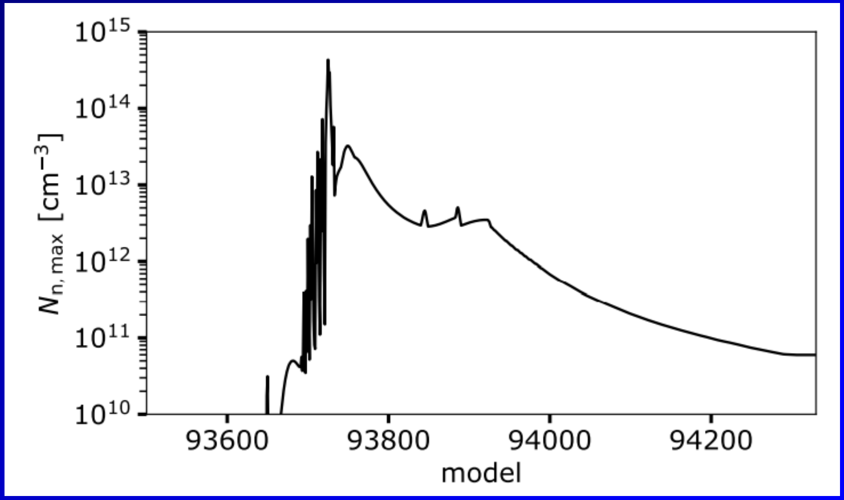
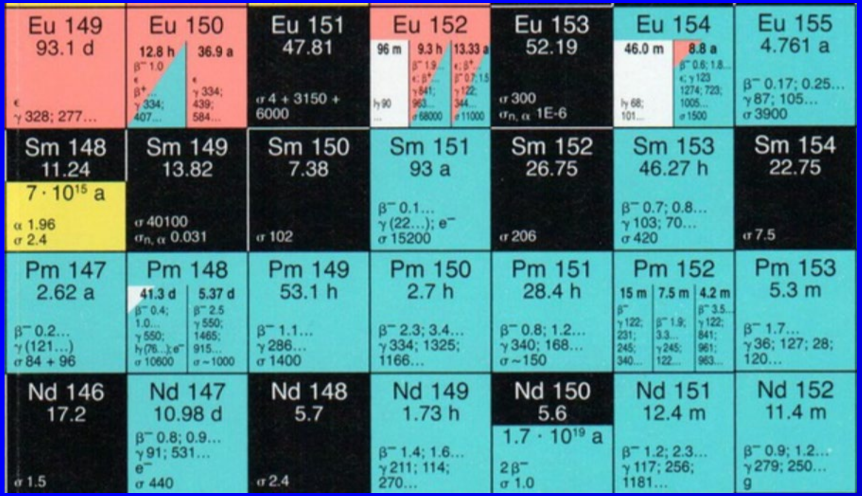
i-proc (Victoria; RAWDs)	0.22	0.44	0.51	0.59	0.65
r-process (residual)	0.97	0.70	0.26	0.64	0.48
r-process (polar)	0.16	0.98	0.19	0.09	0.77
r-process (equatorial)	0.45	0.50	0.21	0.53	0.60

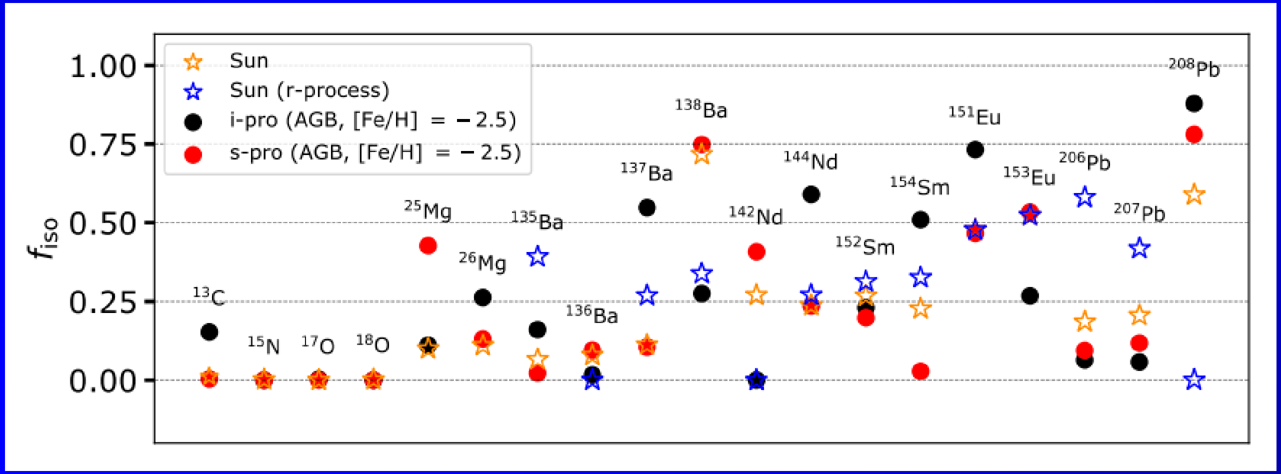
N.B.: $^{135}Ba/^{137}Ba$ ratio largely changes among models!

Low metallicity low mass AGBs: an independent confirmation

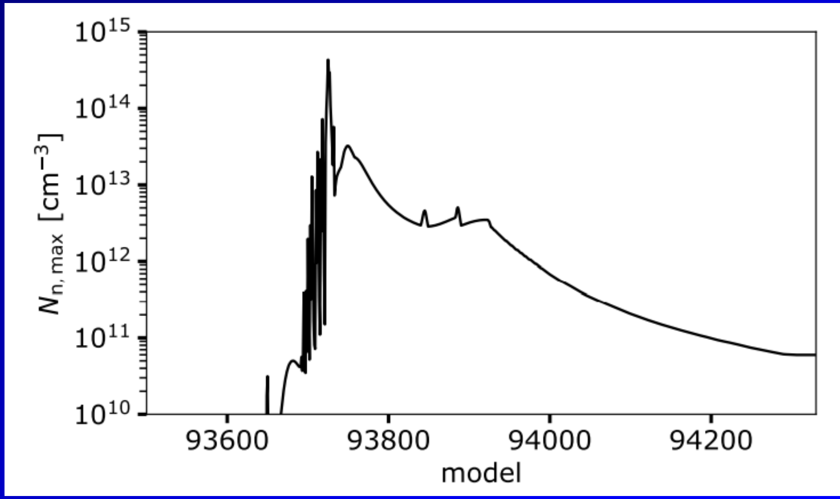


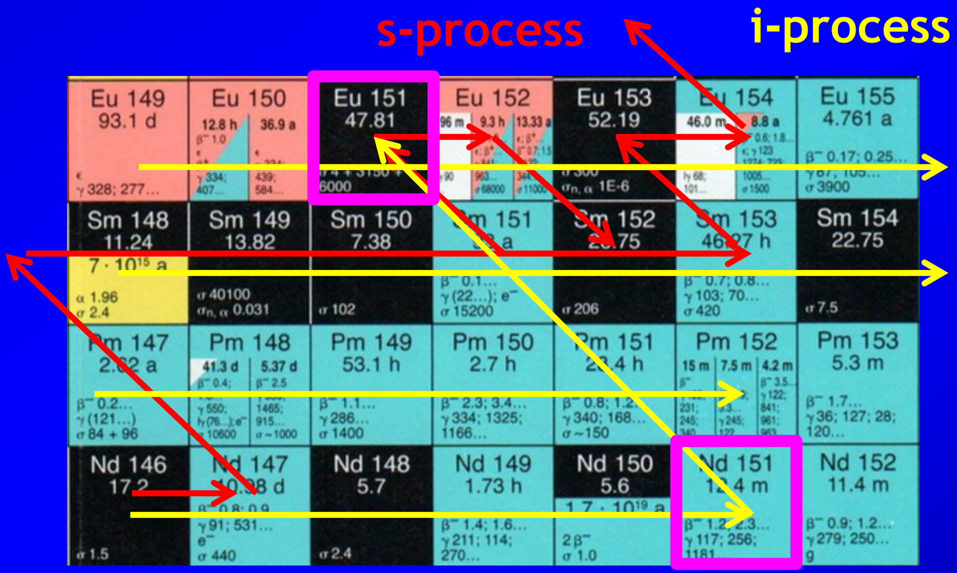


Choplin+2021

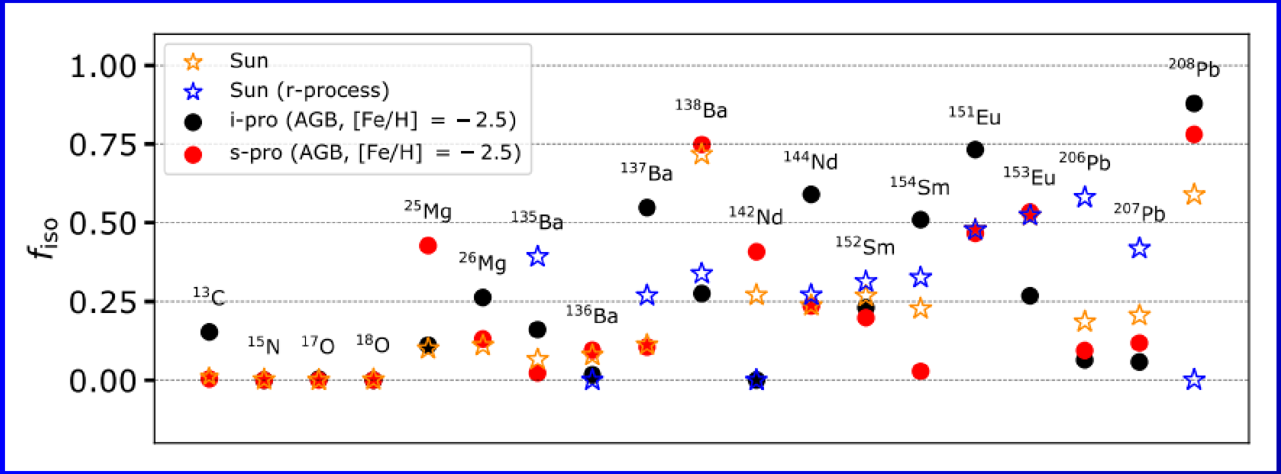


Low metallicity low mass AGBs: an independent confirmation

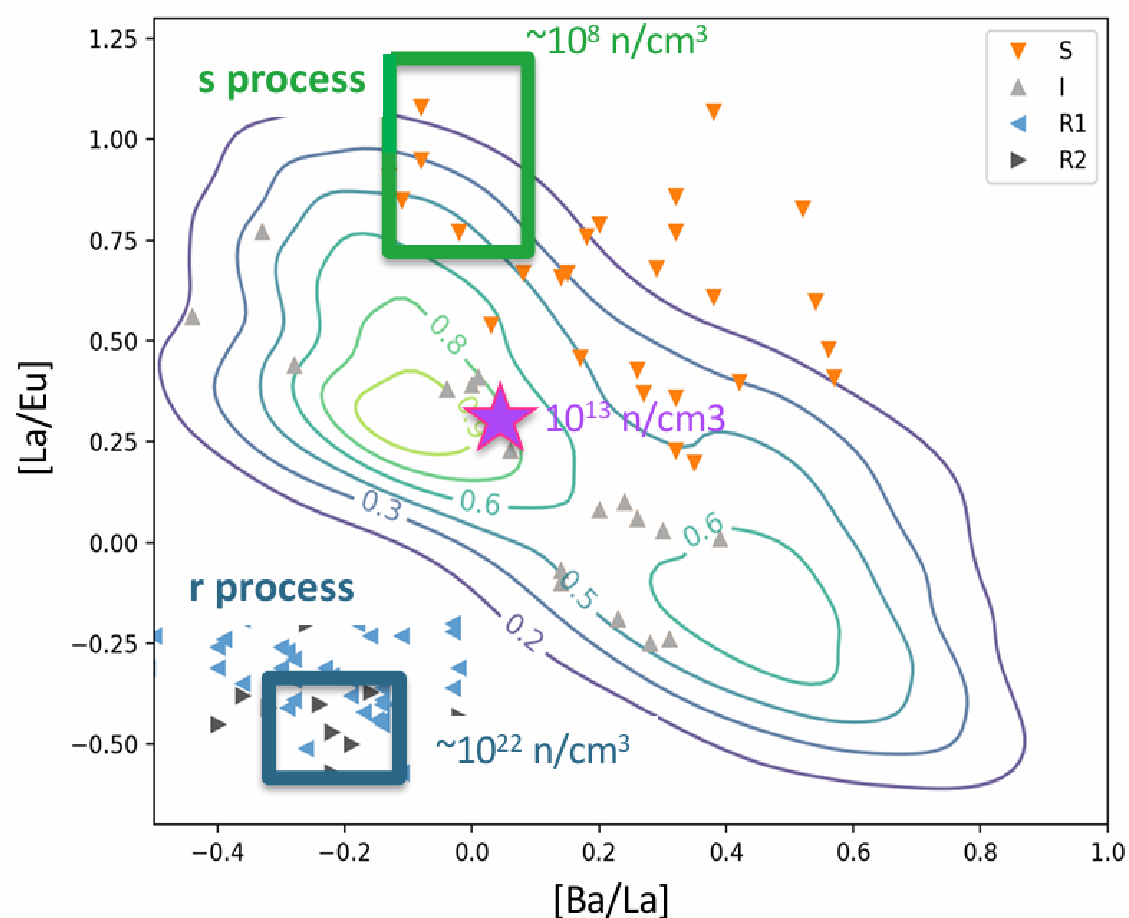




Choplin+2021



The effect of n-capture cross sections

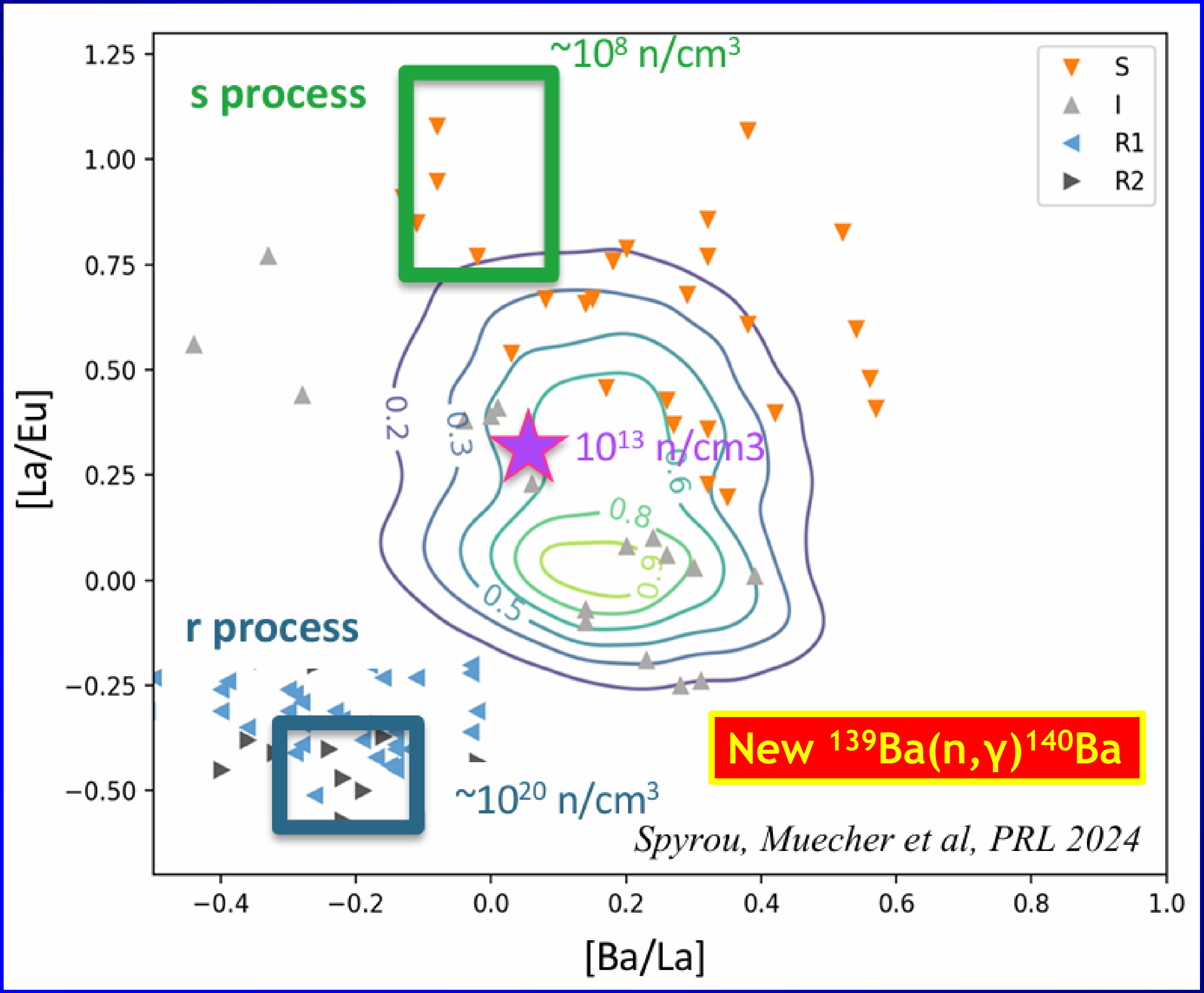


Spyrou+2024

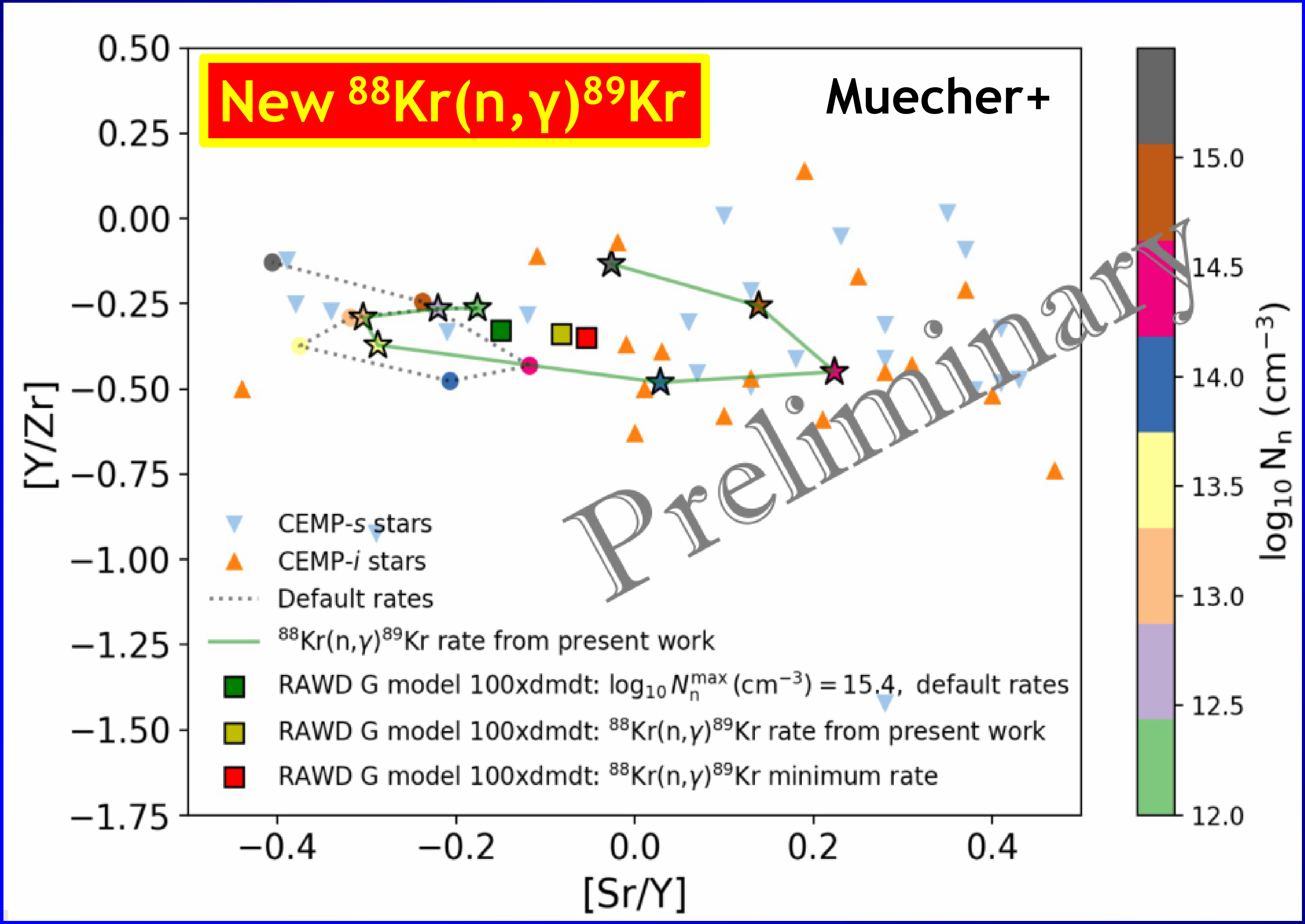
Element	Reaction	$r_{\mathrm{P}}(f_i, X_k/X_{k,0})$
Ba	^{134}I	+0.3689
	^{137}Cs	-0.6842
La	^{139}Cs	-0.2558
	^{139}Ba	-0.8651
Eu	^{151}Nd	-0.5975
	^{151}Pm	-0.4975

Denissenkov, et al, MNRAS (2019)

The effect of n-capture cross sections



The effect of n-capture cross sections



Take home message

- Presolar grains are powerful tools to calibrate stellar models;
- Accurate nuclear data are needed to further constrain stellar models;
- The i-process hosting site is still unknown and difficult to be modelled;
- A new series of challenging measurements are needed to constrain the i-process.


That's all Folks!