Fluorine nucleosynthesis in AGB Stars

S. CRISTALLO[1,2]

in collaboration with D. Vescovi & L. Piersanti

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OUTLOOK

- Asymptotic Giant Branch (AGB) stars: evolution & nucleosynthesis (s-process)
- ^{19}F production in AGB stars
- Historical «disagreement» on ^{19}F abundances
- Fluorine and proton ingestions (i-process)
- The importance of nuclear reaction rates in the production/destruction of ^{19}F

Why AGBs are so important?

OBSERVATIONAL POINT OF VIEW

- **Excellent tracings of halo structures;**
- **IR emission (effects on integrated colors);**
- **tracers of intermediate age populations (IZw18);**
- **distance indicators (Mira).**

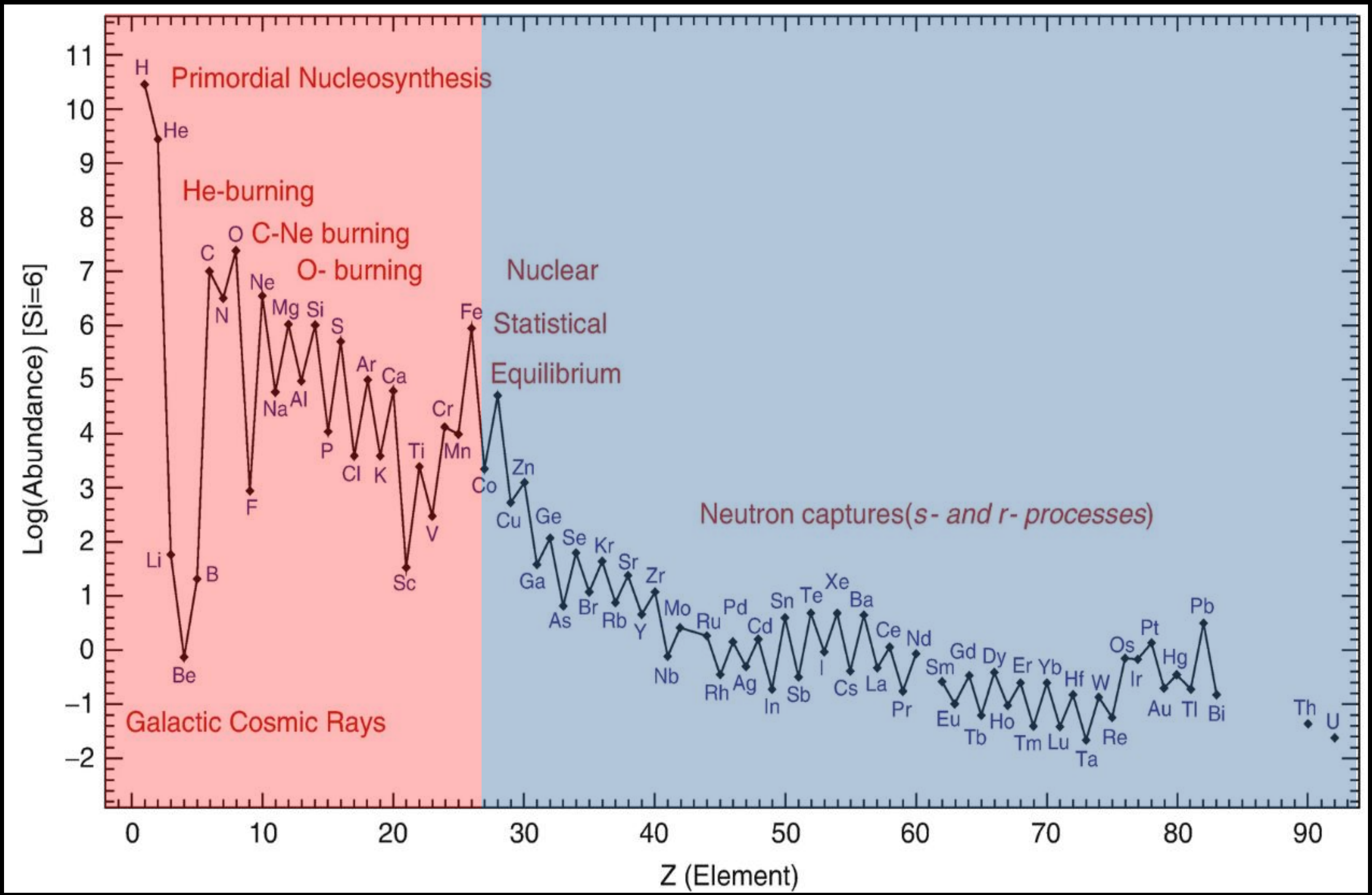
CHEMICAL POINT OF VIEW

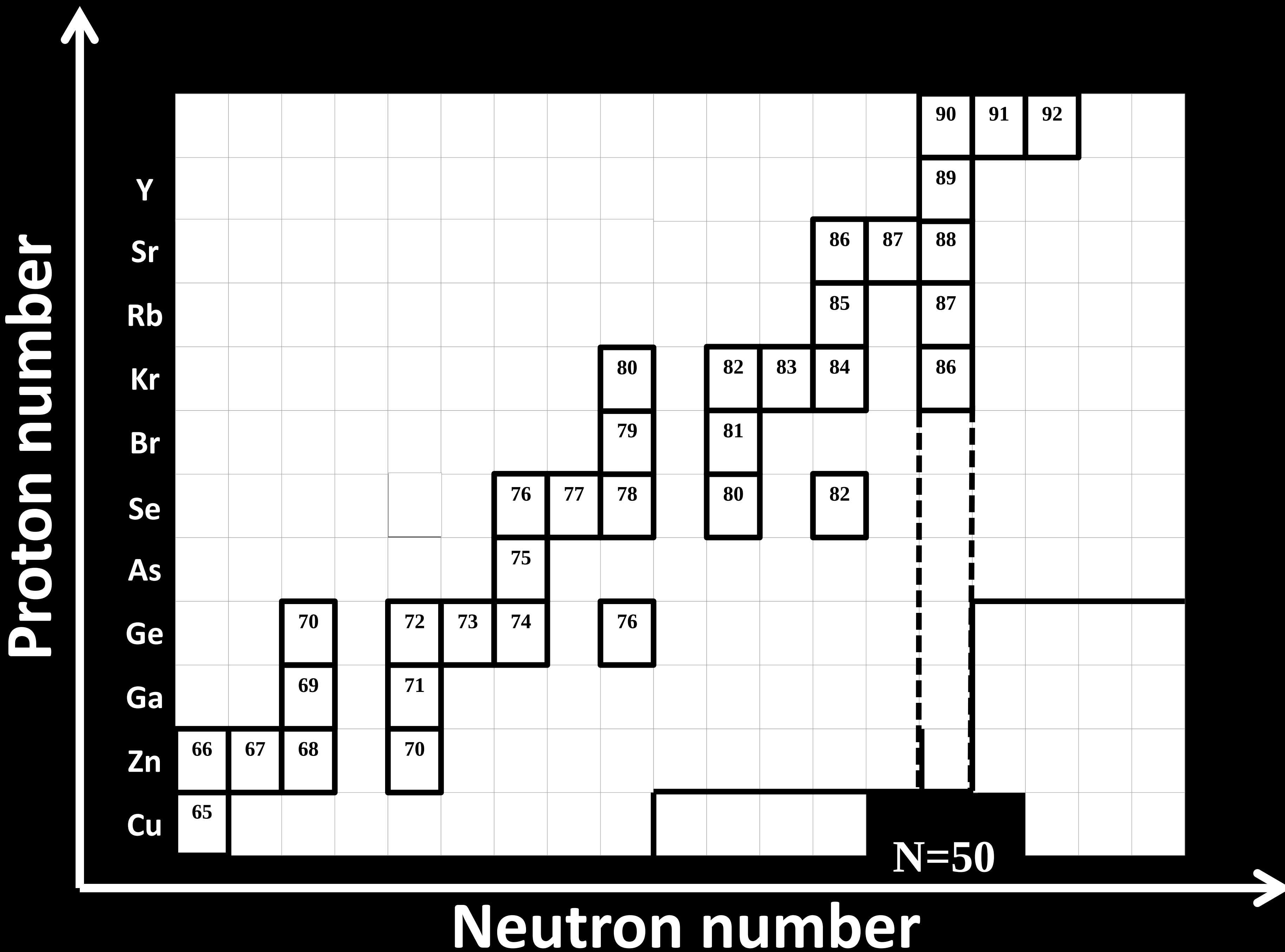
- **C and N (crucial for organic chemistry and life cycles), F and Na;**
- **Half of the heavy elements (A>56) are synthesized in these objects.**

The solar distribution

Fusion reactions between charged particles

Neutron capture processes




Proton number
Neutron number
Y
Sr
Rb
Kr
Br
Se
As
Ge
Ga
Zn
Cu
90
91
92
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86
87
88
85
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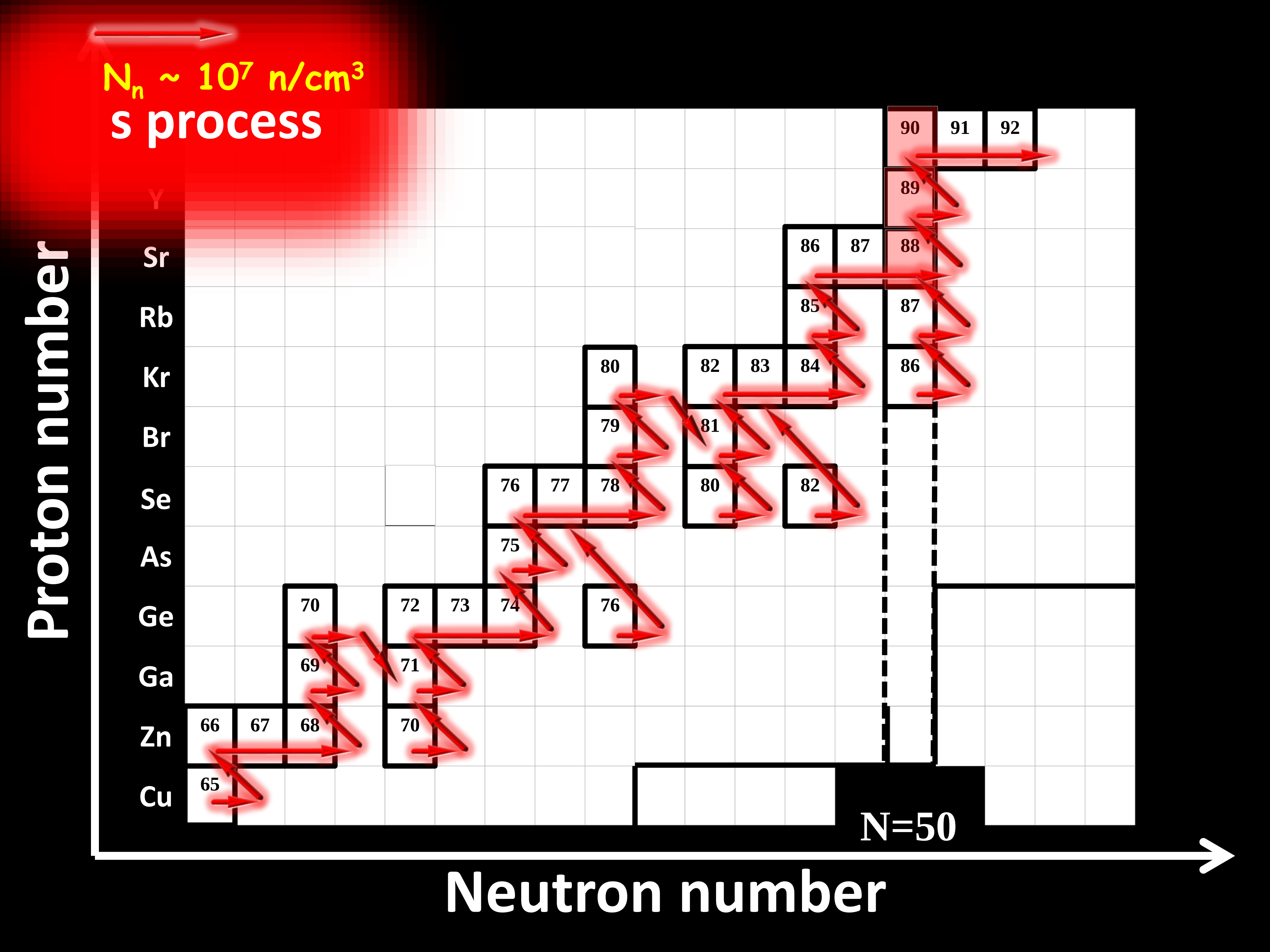
N=50



$N_n \sim 10^7$ n/cm^3
s process
Y
Sr
Rb
Kr
Br
Se
As
Ge
Ga
Zn
Cu
Proton number
Neutron number
N=50
90
91
92
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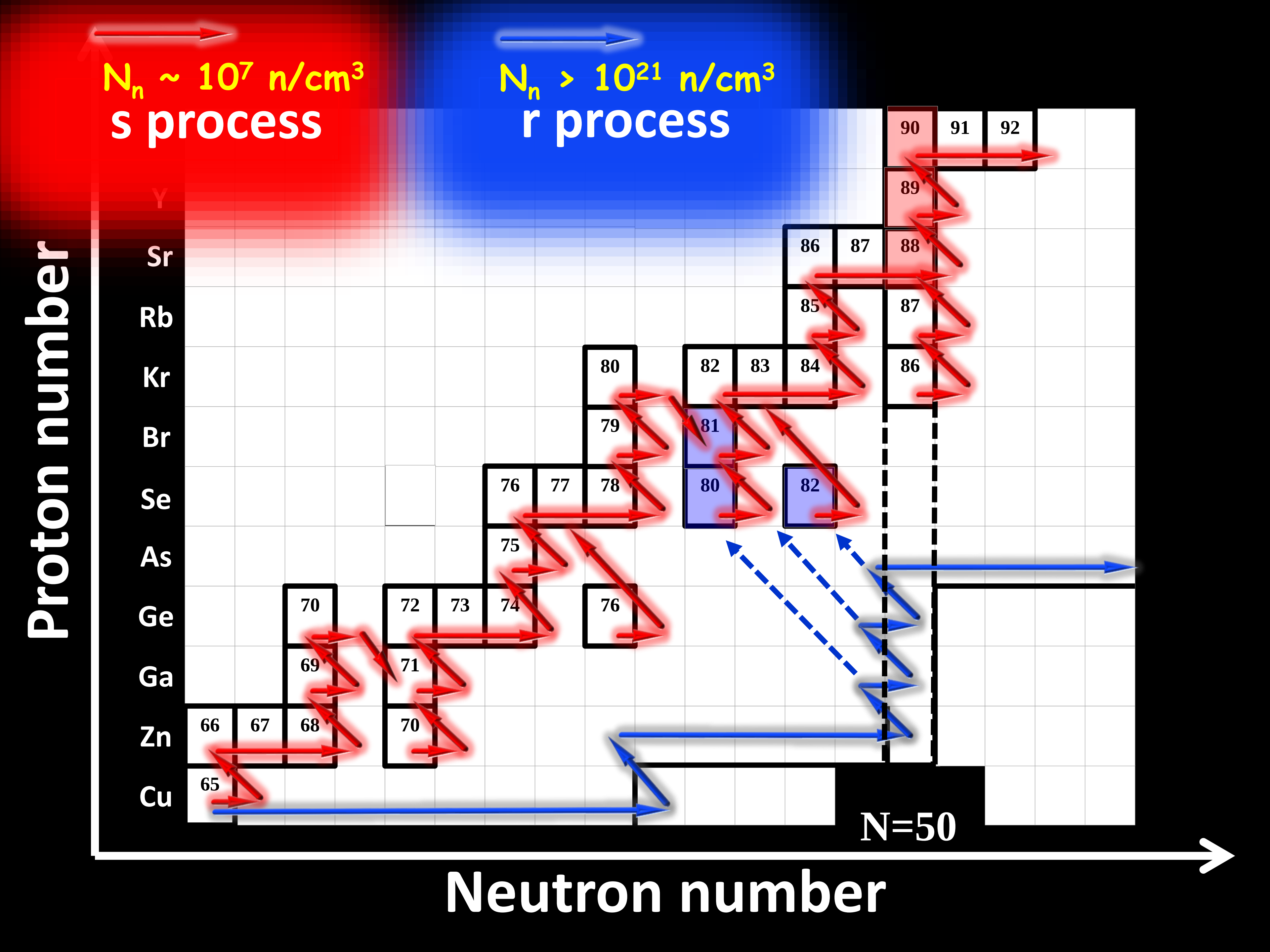

$N_n \sim 10^7$ n/cm^3
s process
$N_n > 10^{21}$ n/cm^3
r process
Proton number
Neutron number
Y
Sr
Rb
Kr
Br
Se
As
Ge
Ga
Zn
Cu
90
91
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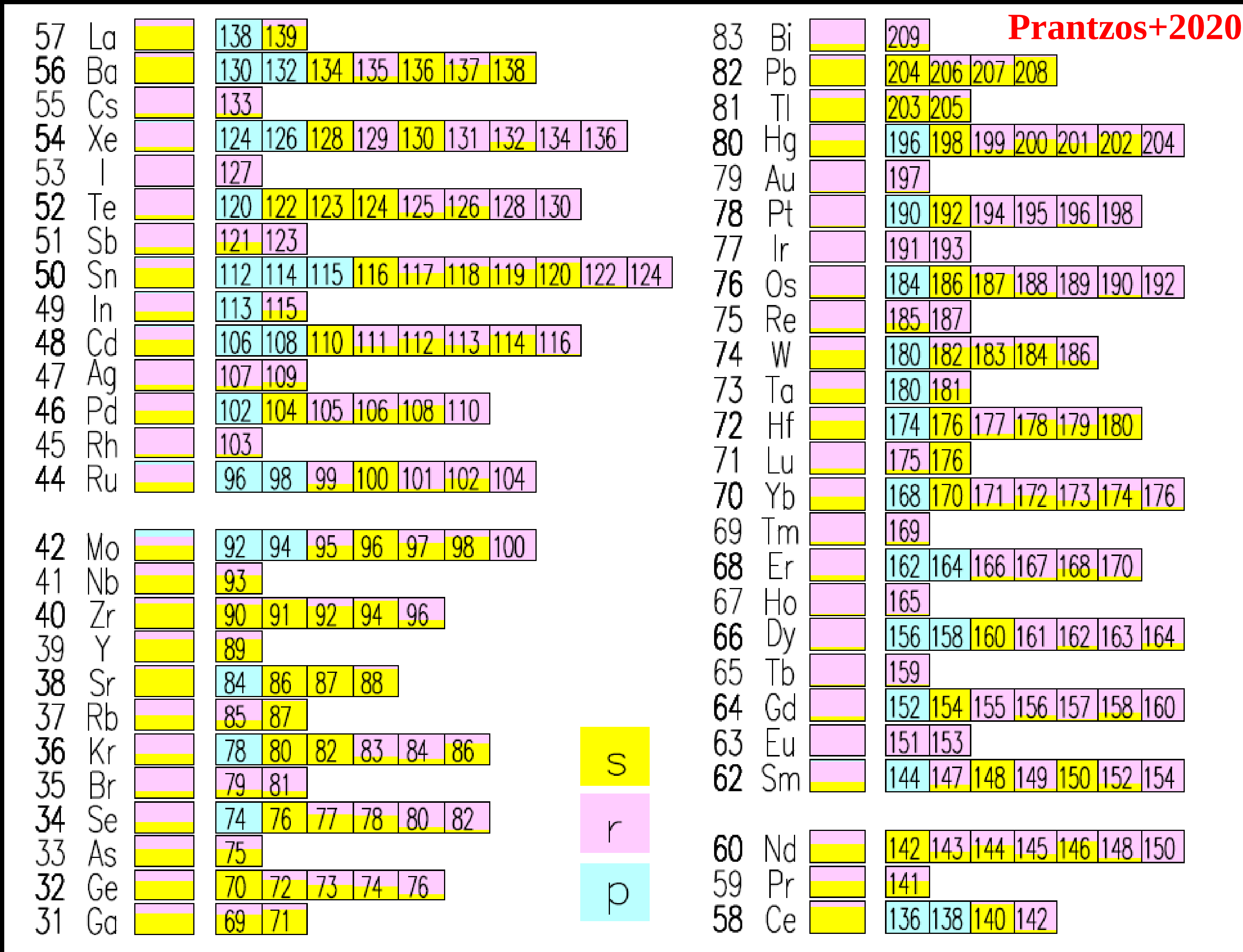
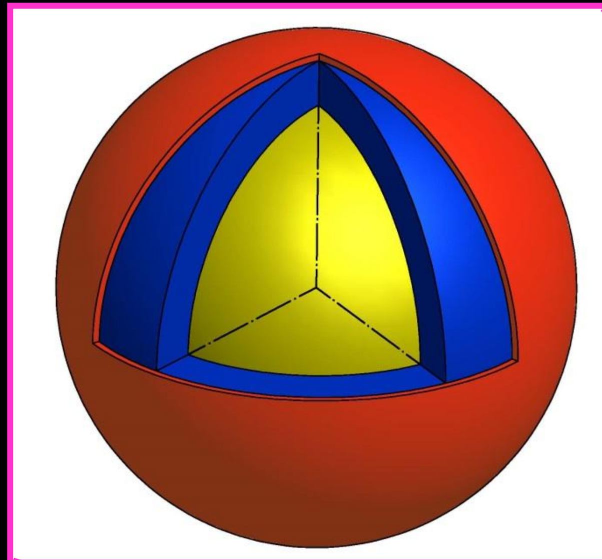
N=50

AGBs in the Periodic Table



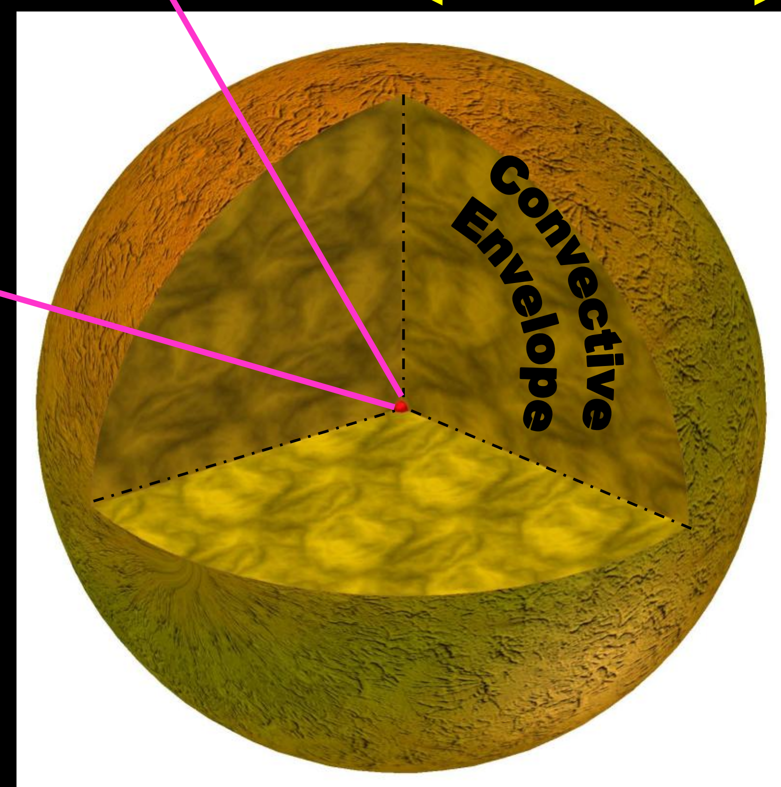
AGB structure

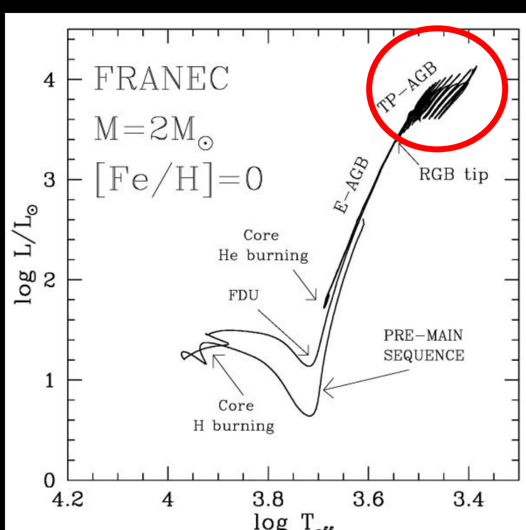
Earth radius (~10^{-2} R_{SUN})



CO Core
He-shell
H-shell

Earth-Sun
(~200 R_{SUN})





AGB structure

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He-shell
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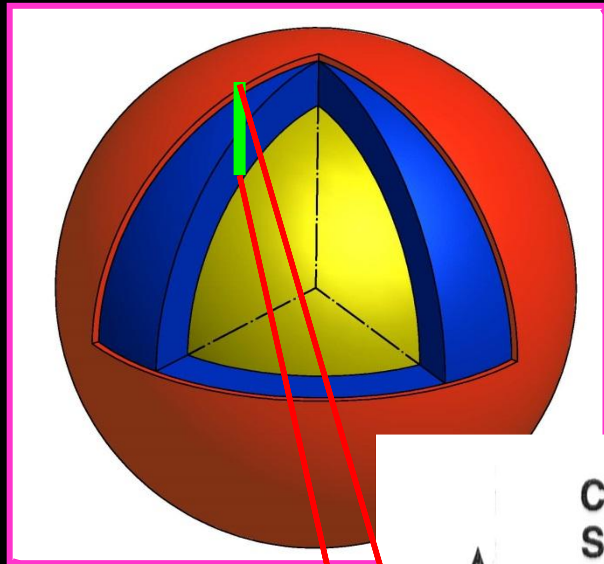
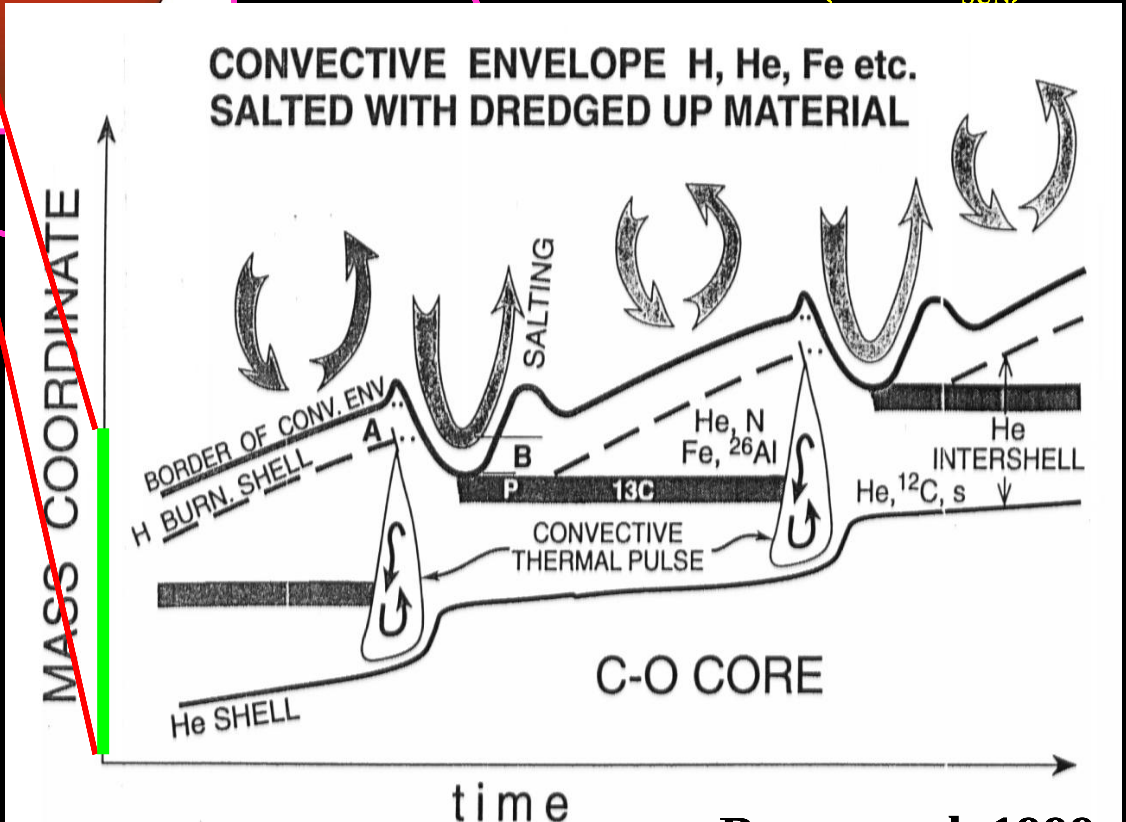
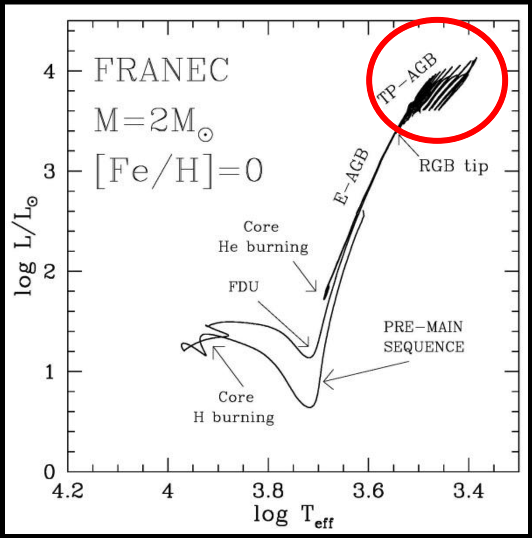


Earth-Sun (~200 R_{SUN})



Busso et al. 1999



The ^{13}C-pocket: formation

Protons can penetrate into the He-rich region at each **TDU (Third Dredge-Up) phenomenon**

Which is the physical mechanism?

TOP-DOWN MECHANISMS

Opacity-induced overshoot (Cristallo+2009,2011,2015)

Convective Boundary Mixing (Battino+2016)

BOTTOM-UP MECHANISMS

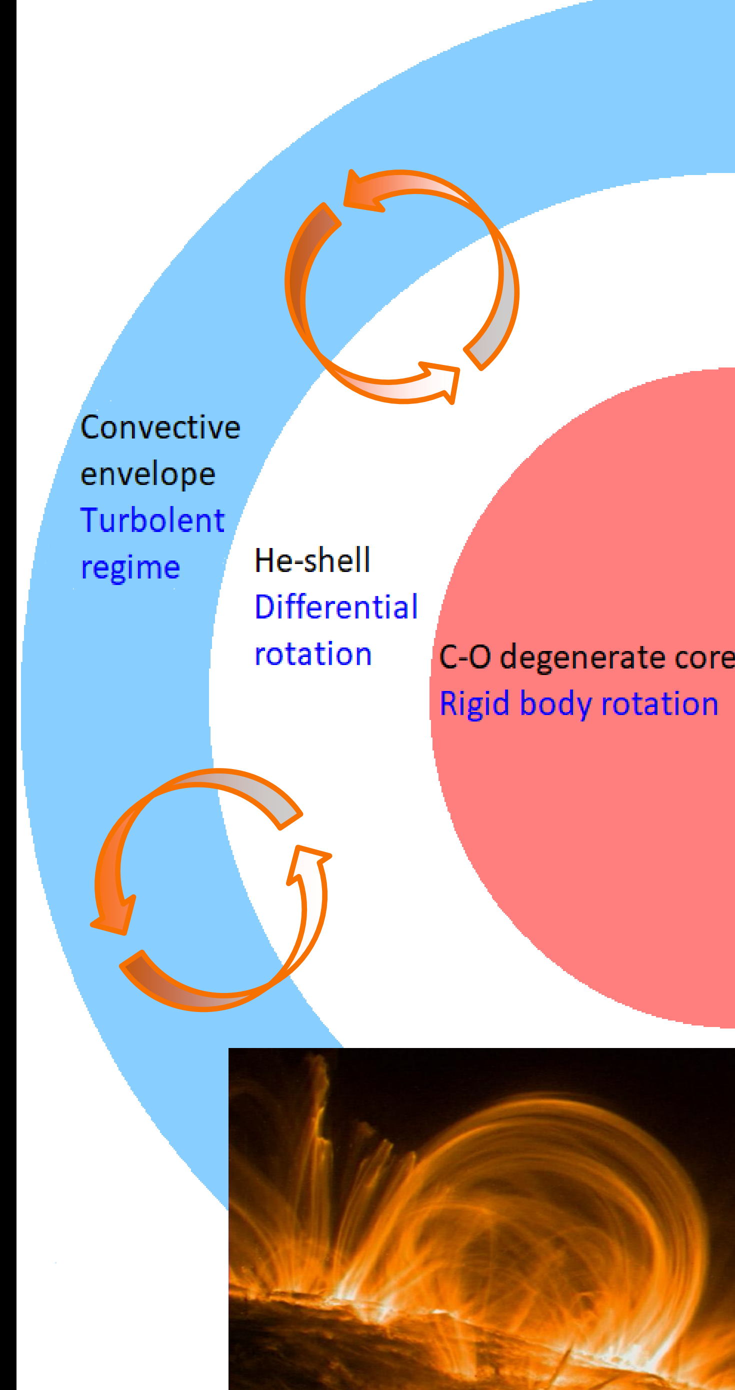
Magnetic fields (Trippella+2016; Palmerini+2018)

MagnetoHydroDynamics (**MHD**) solutions (Nucci & Busso 2014):

No numerical approximations (**exact analytic solution**)

Simple geometry: toroidal magnetic field

$$\rho(r) = \frac{\rho_p}{r_p^k} r^k$$



Magnetic-buoyancy-induced mixing

Magnetic contribution (Vescovi+2020) to the dowflow velocity $\boldsymbol{v_d}$, acting when the density distribution is $\rho \propto r^{k}$

$$v_d(r) = u_{\rm p} \left(\frac{r_{\rm p}}{r} \right)^{k+2}$$

Parameters:

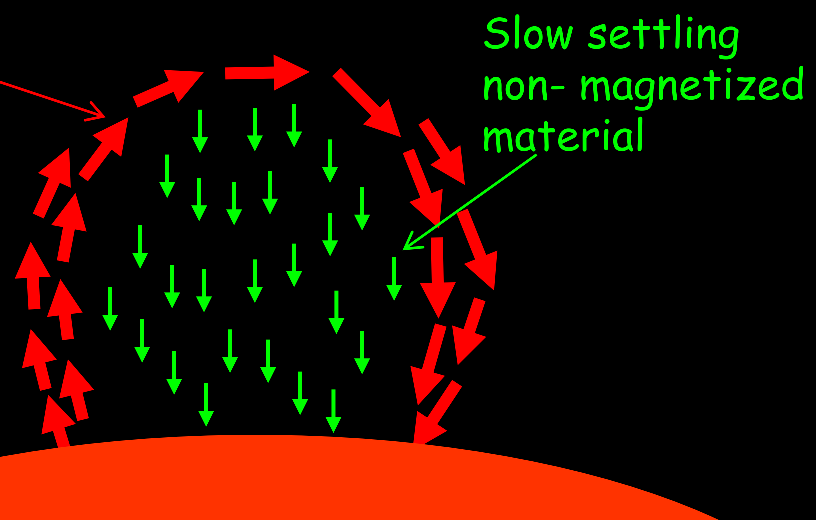
Layer "**p**" at the deepest coordinate from which buoyancy starts

(can be identified from the corresponding **critical toroidal $\boldsymbol{B_\varphi}$** value)

$$B_\varphi \gtrsim \left(4\pi\rho r N^2 H_{\rm p} \frac{\eta}{K} \right)^{1/2}$$

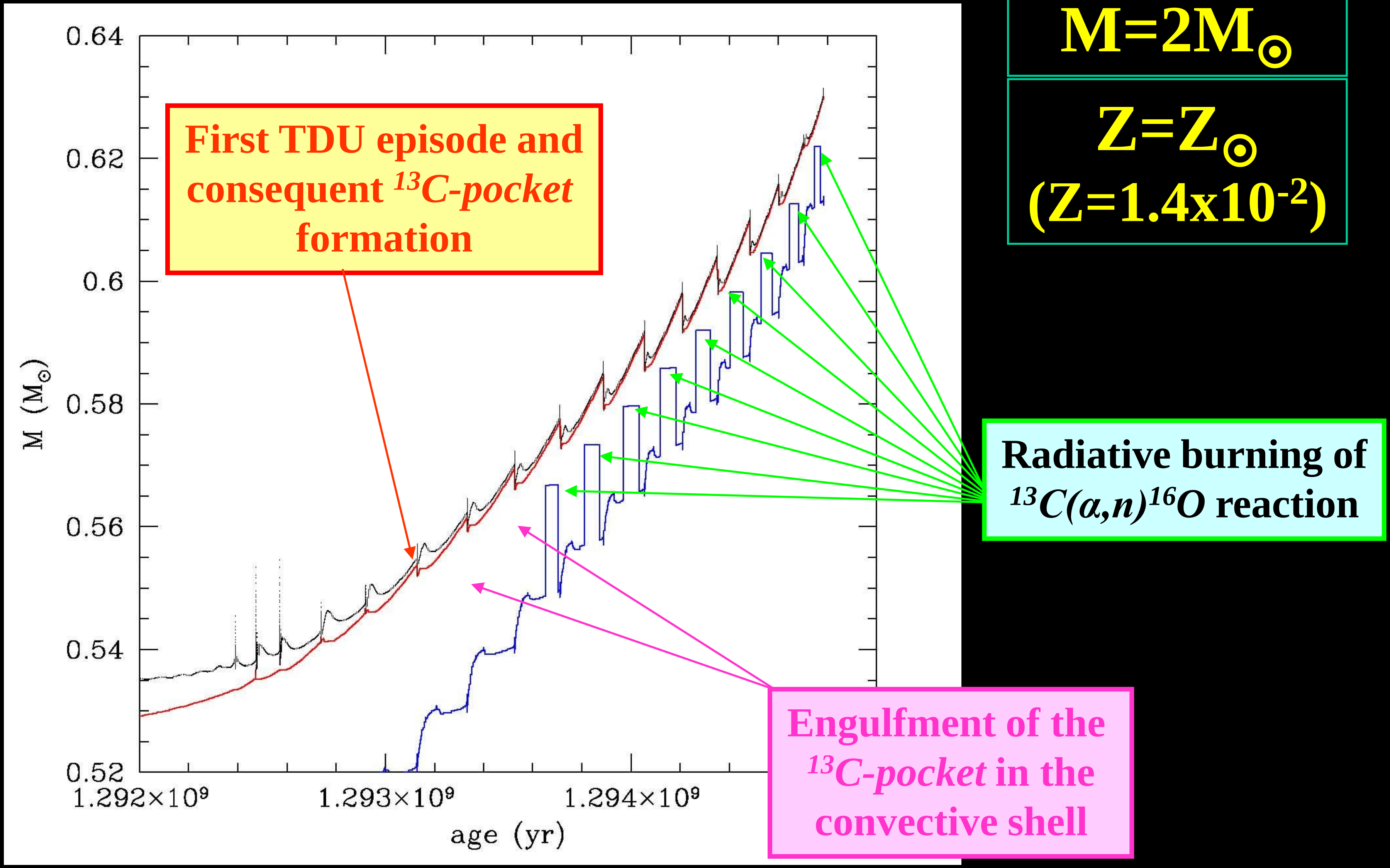
Starting velocity $\boldsymbol{u_p}$ of the buoyant material

<u>Calibration</u> is needed!



Vescovi+2020

THE ^{13}C BURNING



M=2M$_\odot$

Z=Z$_\odot$
(Z=1.4x10^{-2})

The FUNS (FUll Network Stellar) Evolutionary Code

(Straniero+ 2006; Cristallo+ 2007,2009)

About 500 isotopes, linked by more than 700 reactions

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

(FUNS Repository of Updated Isotopic Tables & Yields)

On line at http://fruity.oa-abruzzo.inaf.it/

Cristallo+ 2011,2015

Masses[M_{SUN}]: 1.3 → 6.0 [Fe/H]: $2x10^{-5}$ → $2x10^{-2}$

Martini

A platform dedicated to stars!

s-process-AGBs

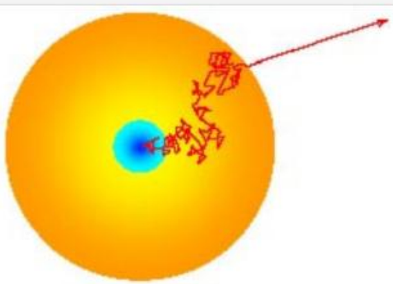
Go to data

r-process-NSMs

Go to data

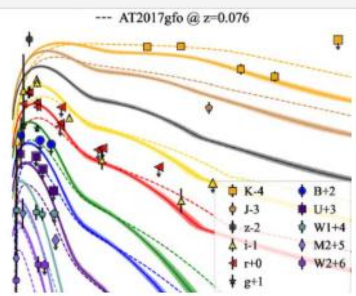
Dust-AGB

Go to data



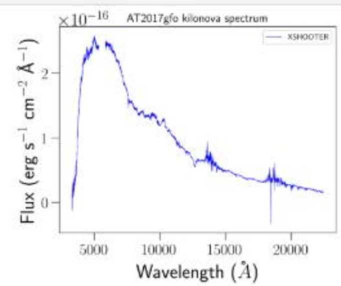
Atomic-Opacities

Go to data



KNe-lightcurves

Go to data



KNe-spectra

Go to data

A wider project also including r-process, dust, atomic physics & kilonovae

^{19}F production in AGBs

Forestini et al. 1992
Lugaro et al. 2004
Abia et al. 2009

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

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

$^{14}C(\alpha,\gamma)^{18}O$

$^{14}N(\alpha,\gamma)^{18}F(\beta^{+})^{18}O$

$^{18}O(p,\alpha)^{15}N$

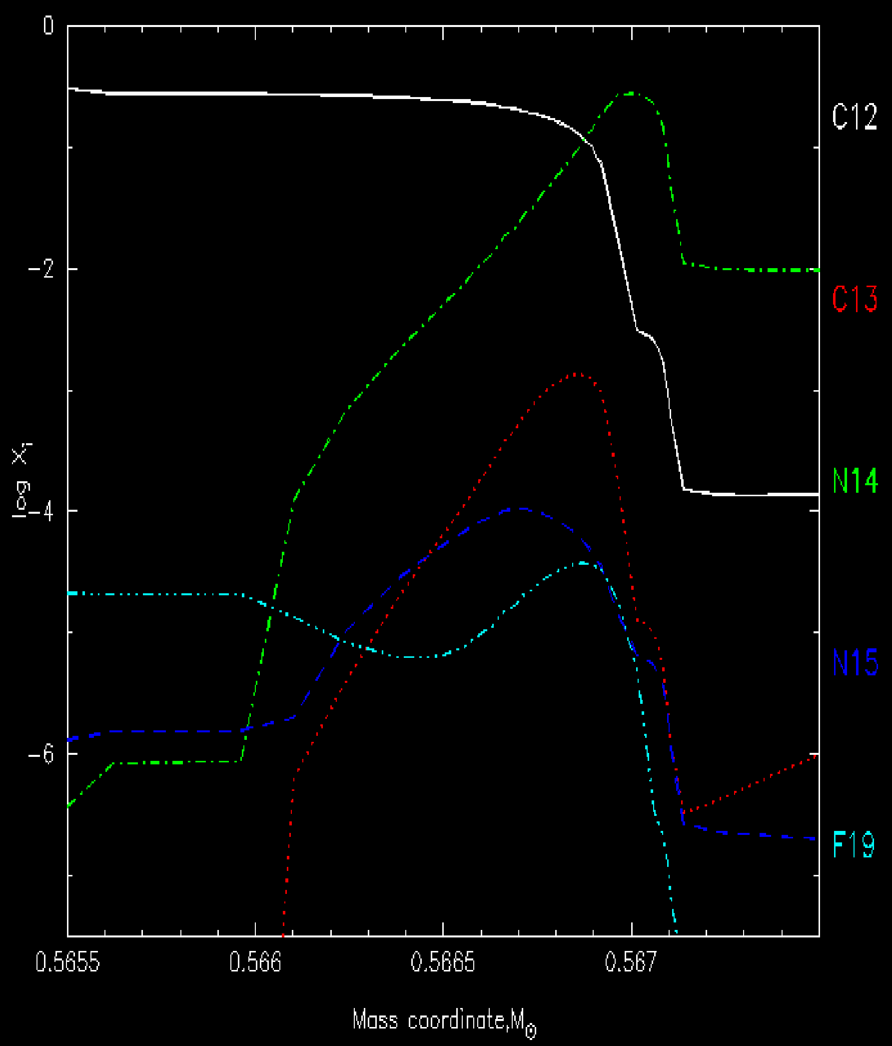
$^{15}N(\alpha,\gamma)^{19}F$

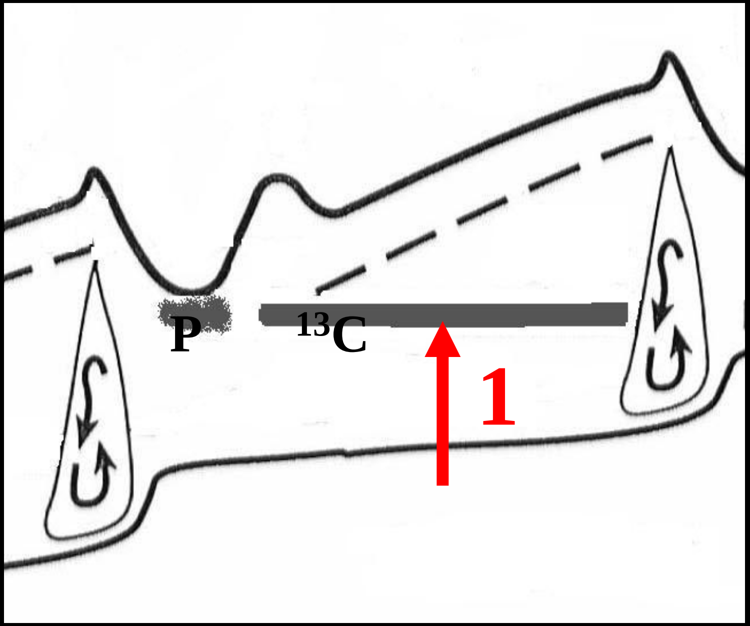
$^{18}O(n,\gamma)^{19}O(\beta^{-})\,^{19}F$

~90%

~10%

Main ^{15}N (and then ^{19}F) sources





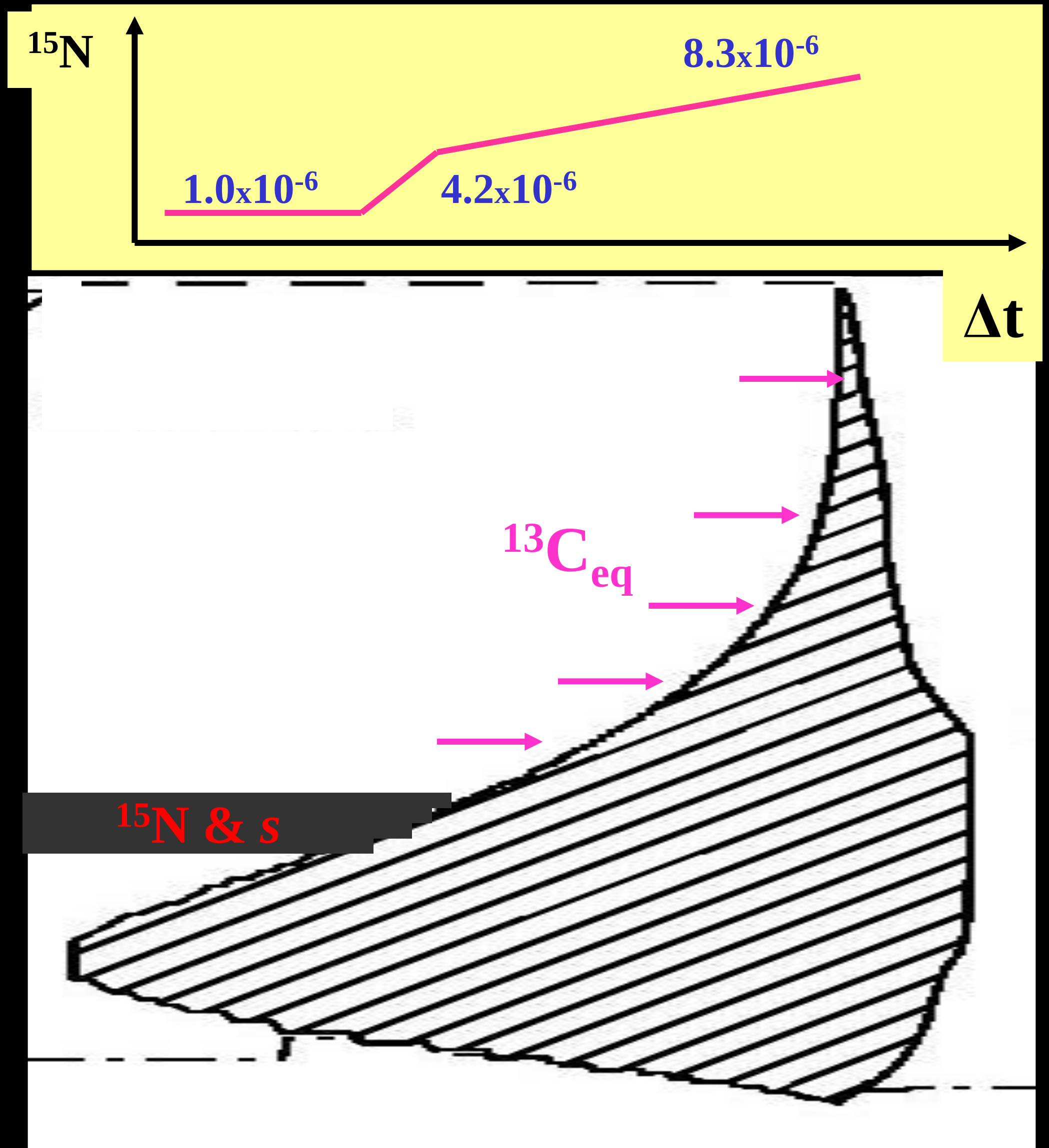
$^{13}C(\alpha,n)^{16}O$

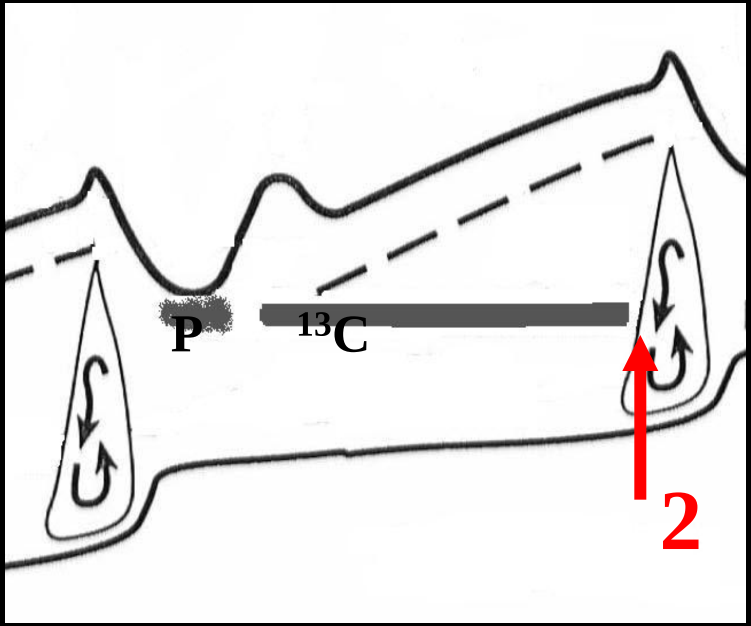
$^{14}N(n,p)^{14}C$

$^{18}O(p,\alpha)^{15}N$

1

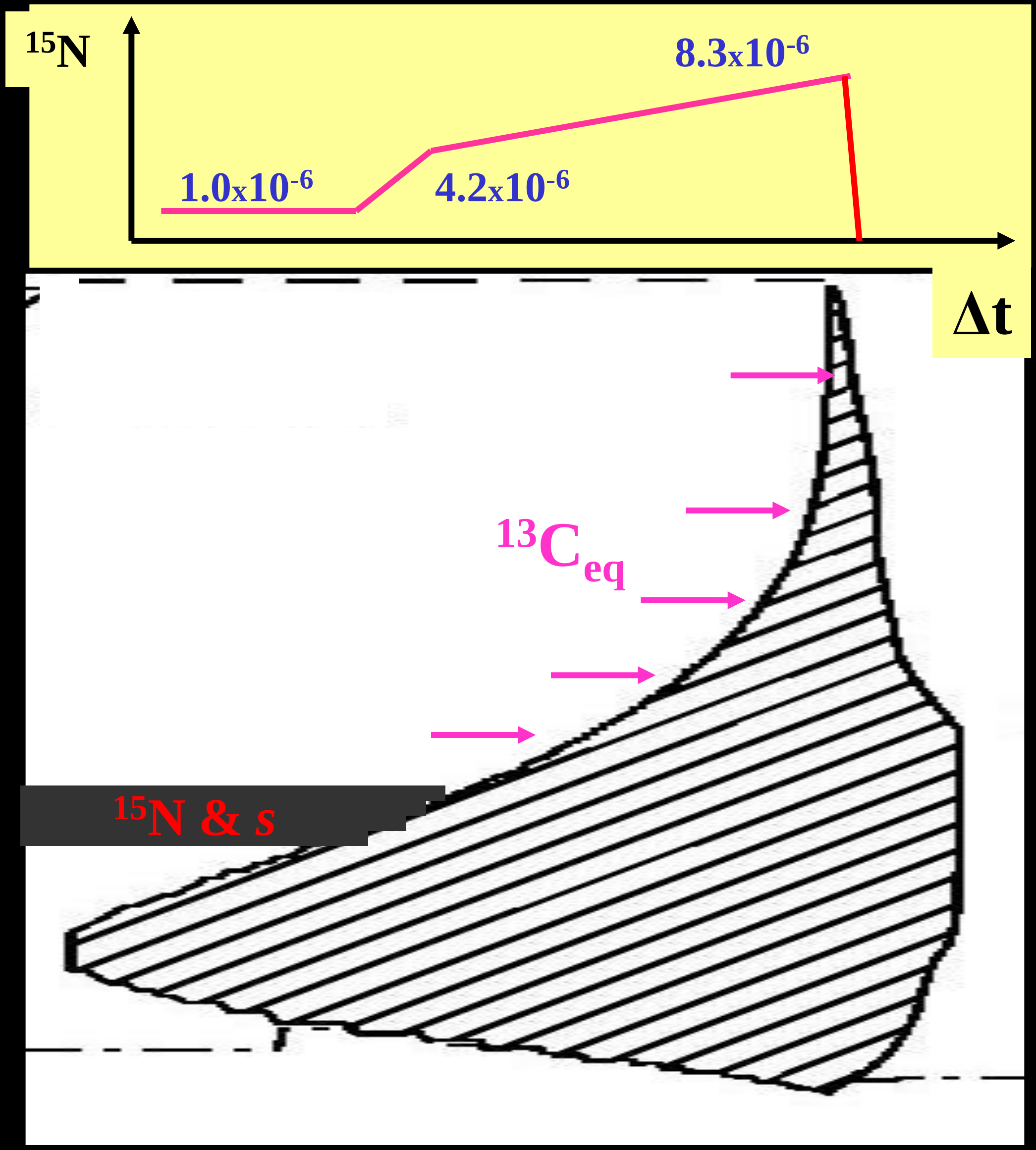
Main ^{15}N (and then ^{19}F) sources

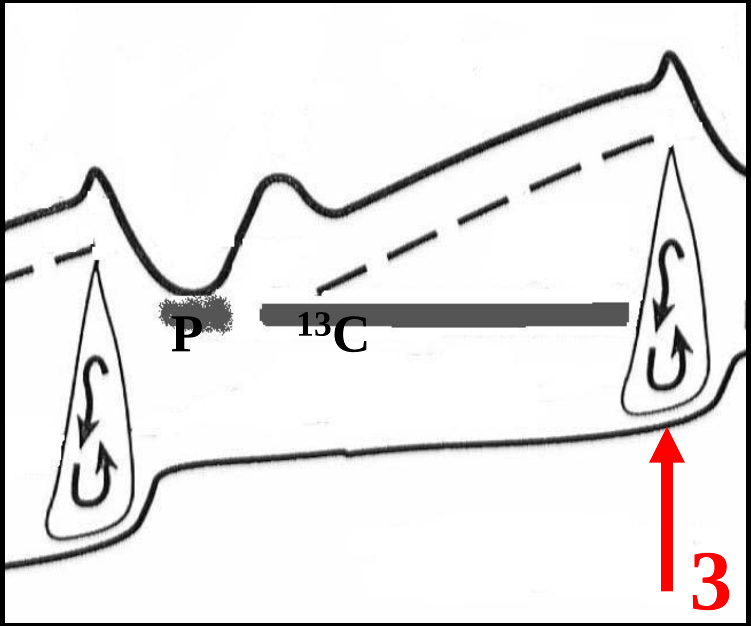




2

Main ^{15}N (and then ^{19}F) sources

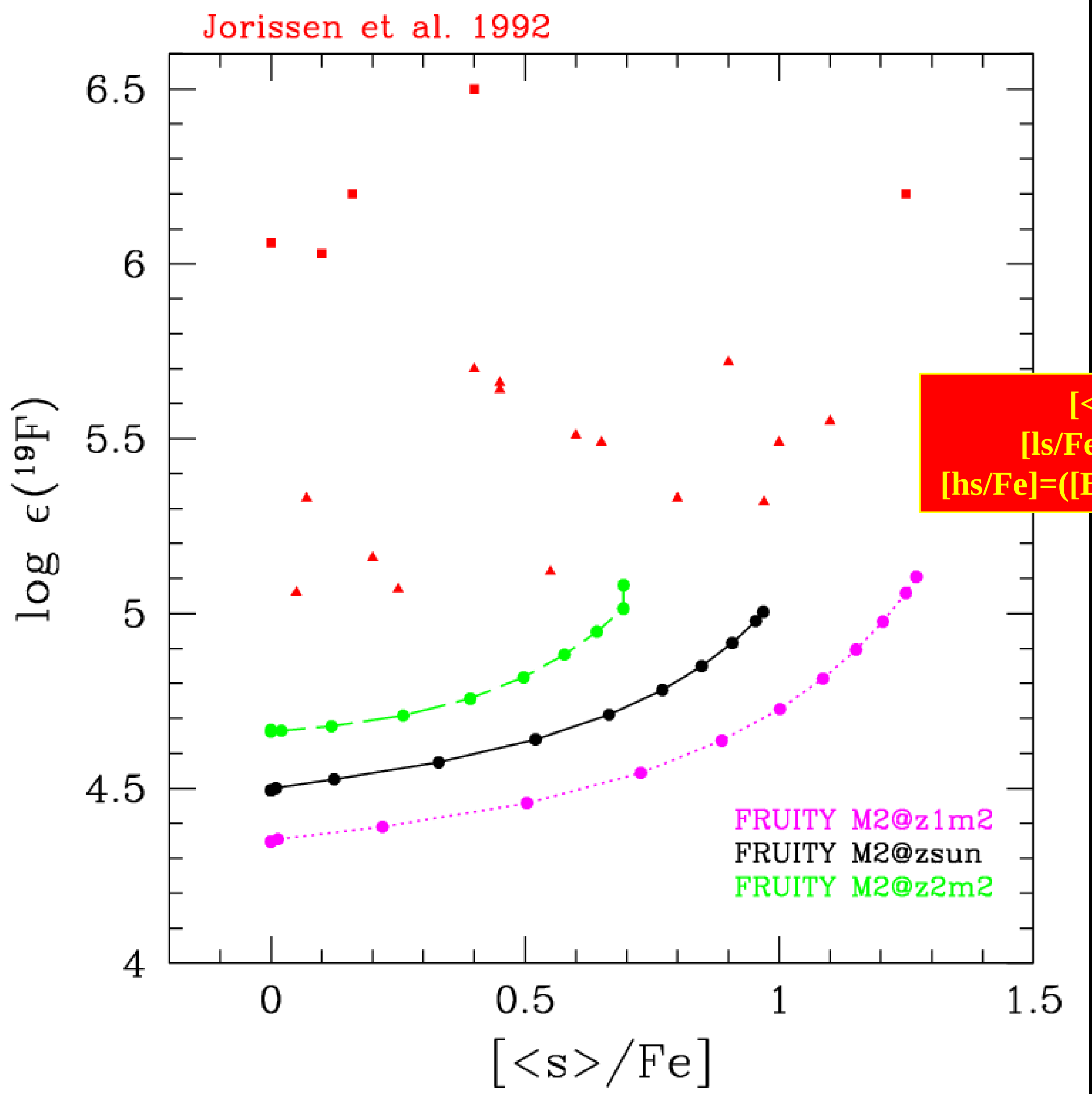




$^{15}N(\alpha,\gamma)^{19}F$

3

Why fluorine is so interesting?



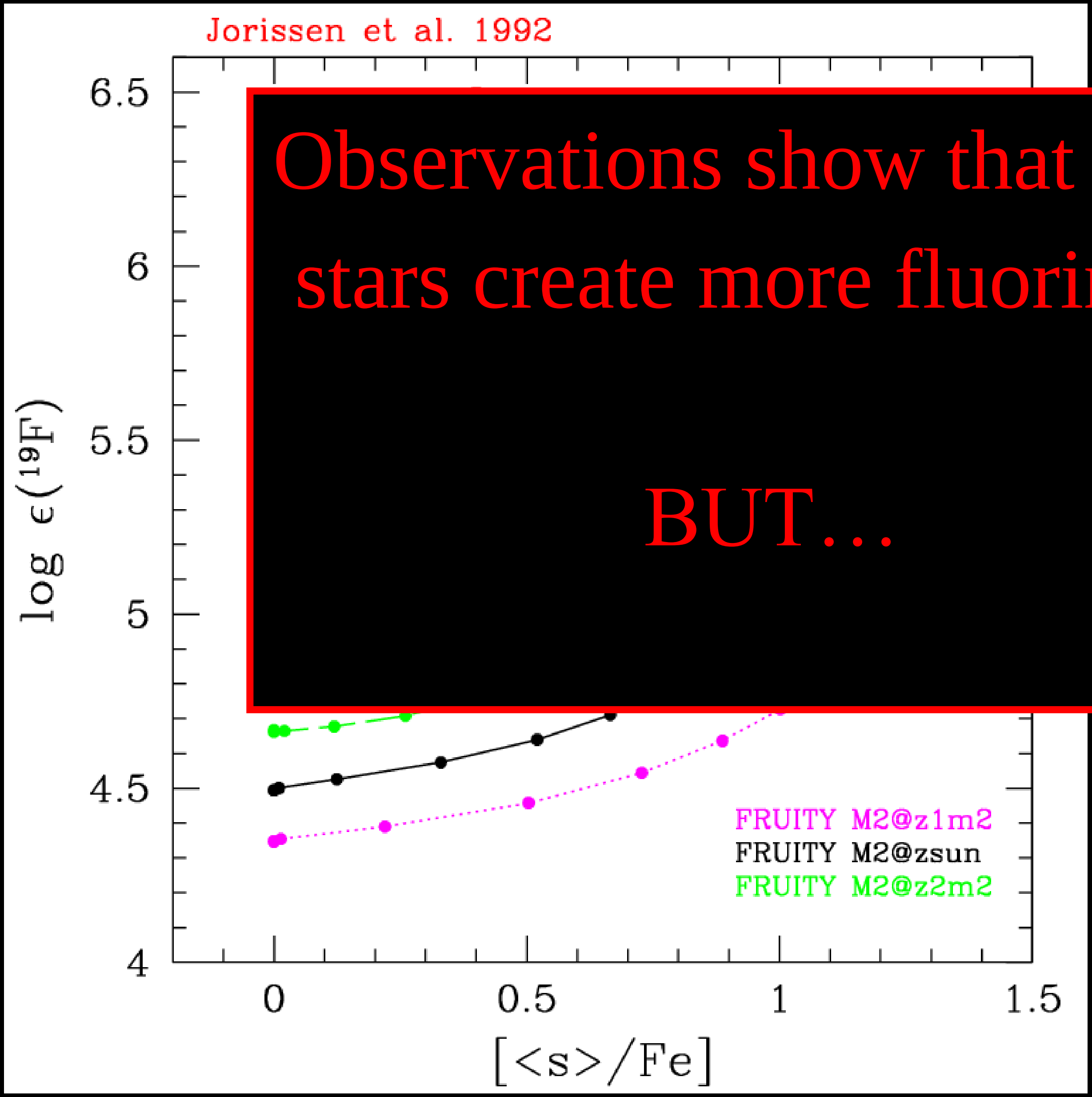
■ C(J)

▲ C(N)

[<s>/Fe]=([ls/Fe]+[hs/Fe])/2)
[ls/Fe]=([Sr/Fe]+[Y/Fe]+[Zr/Fe])/3)
[hs/Fe]=([Ba/Fe]+[La/Fe]+[Ce/Fe]+[Nd/Fe])/4)

OBSERVATIONAL DATA
Jorissen et al. 1992 A&A 261, 164

Why fluorine is so interesting?



Observations show that AGB stars create more fluorine!!!

BUT…

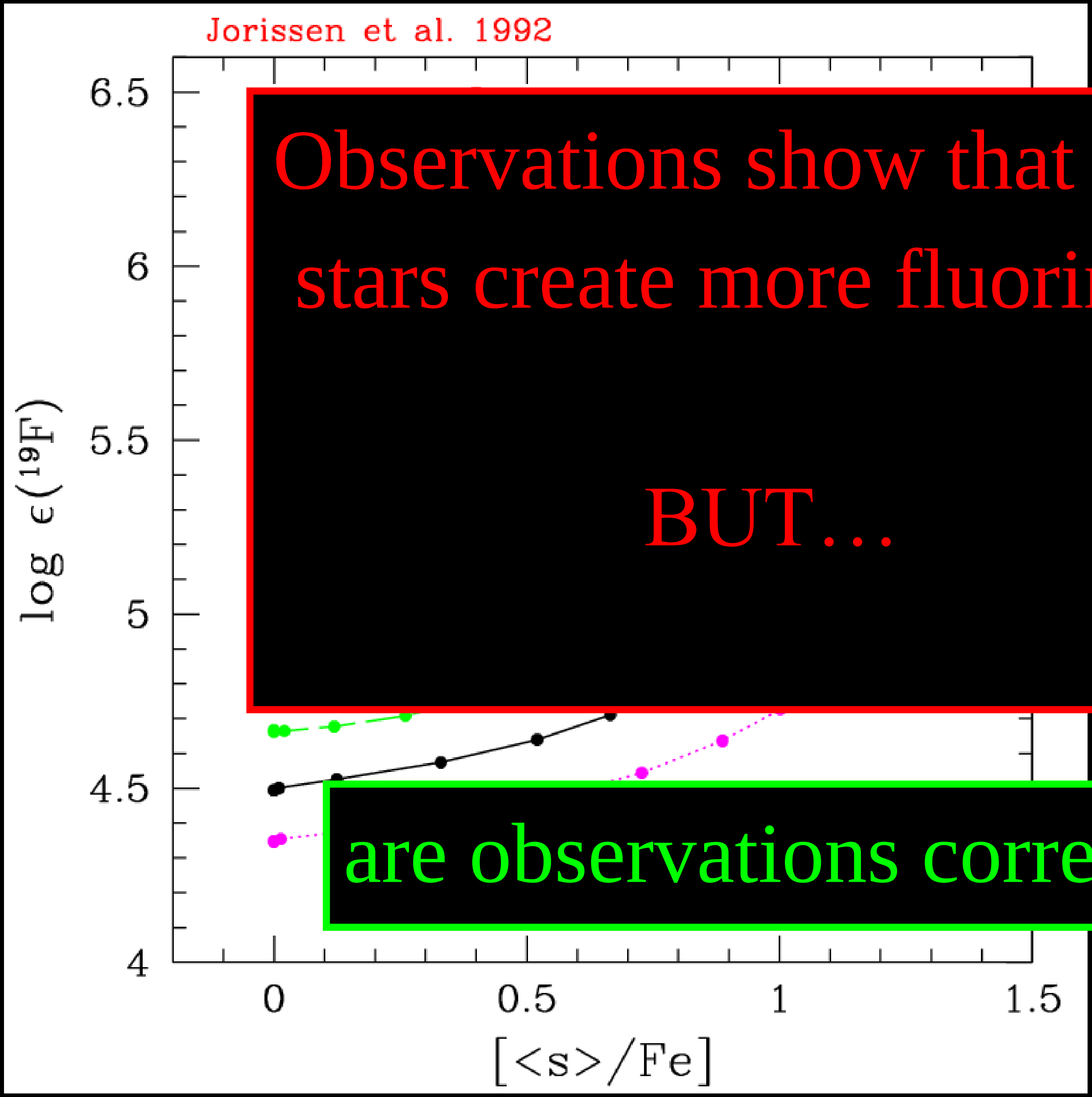
(J)

(N)

[ls/Fe]+[hs/Fe])/2]

OBSERVATIONAL DATA
Jorissen et al. 1992 A&A 261, 164

Why fluorine is so interesting?



Observations show that AGB stars create more fluorine!!!

BUT…

are observations correct?

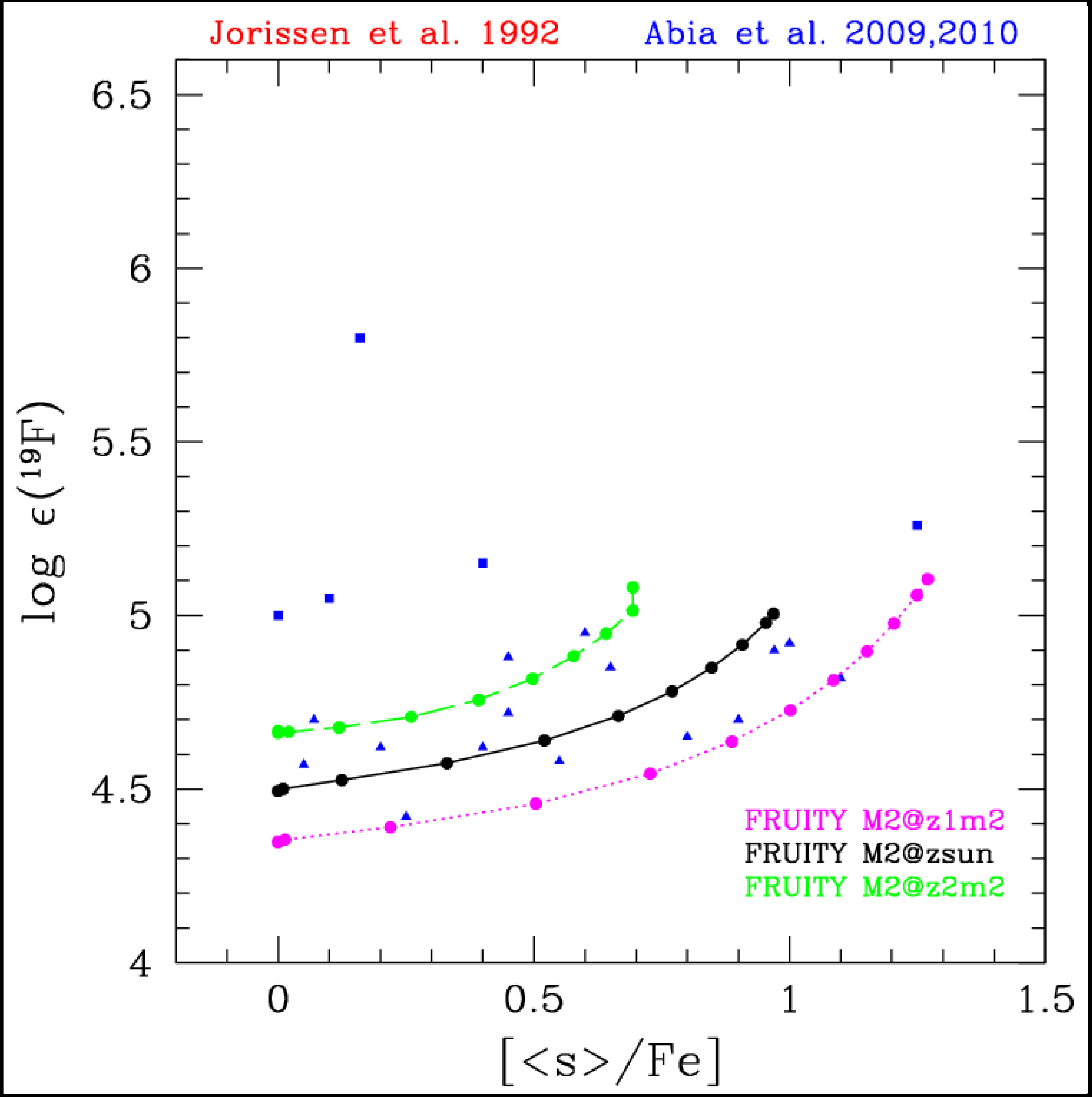
C(J)

(N)

[ls/Fe]+[hs/Fe])/2]

OBSERVATIONAL DATA
Jorissen et al. 1992 A&A 261, 164

Why fluorine is so interesting?



■ C(J)

▲ C(N)

[<s>/Fe]=([ls/Fe]+[hs/Fe])/2]

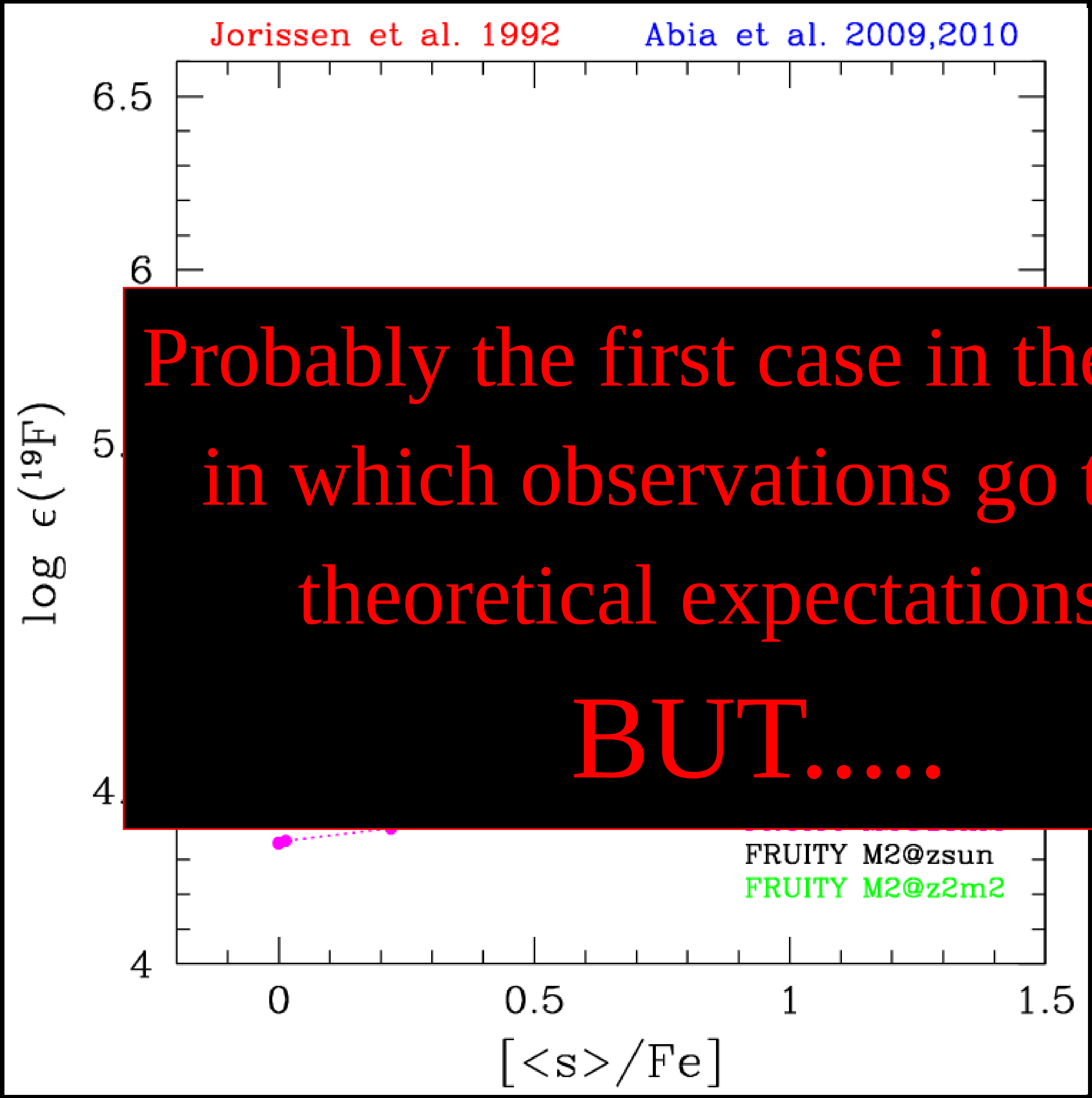
Blending effect on CN and C_2 not properly taken into account

Abia et al. 2009 (ApJ 694, 971)

Abia et al. 2010 (ApJL 715, 94)

OBSERVATIONAL DATA
Jorissen et al. 1992 A&A 261, 164

Why fluorine is so interesting?



■ C(J)

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|+[hs/Fe])/2]

n CN and C_2
n into account

(ApJ 694, 971)

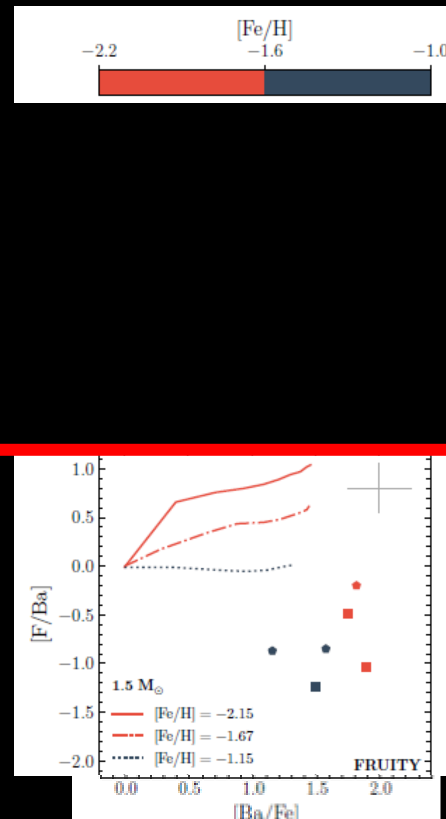
Abia et al. 2010 (ApJL 715, 94)

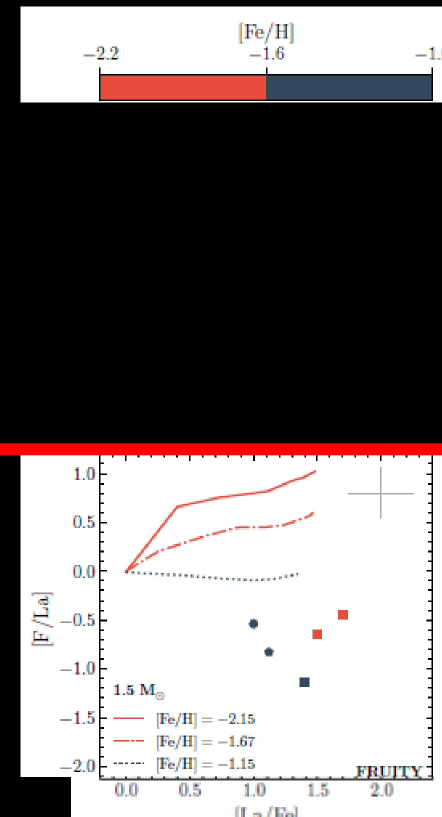
OBSERVATIONAL DATA
Jorissen et al. 1992 A&A 261, 164

Probably the first case in the history in which observations go toward theoretical expectations!!!!

BUT.....

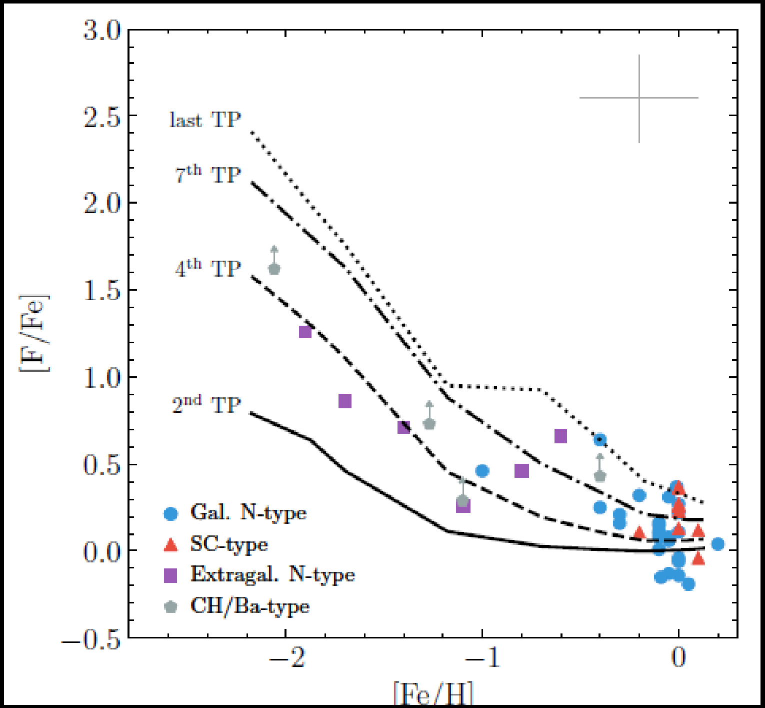
Fluorine observations at low metallicities

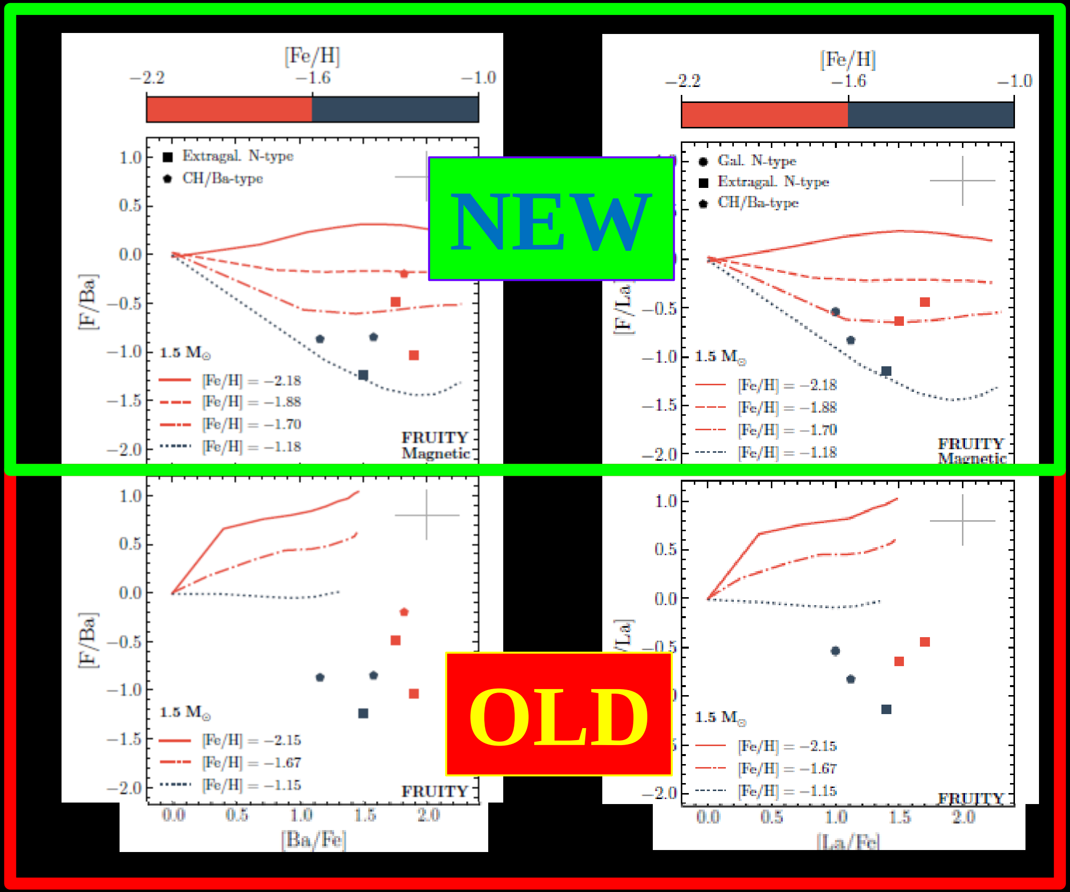




Vescovi+2021

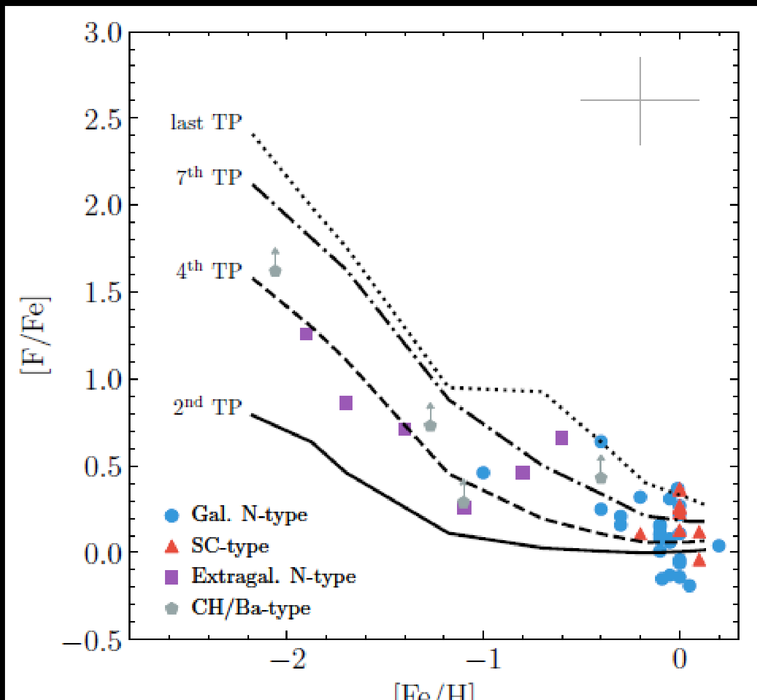
Fluorine observations at low metallicities

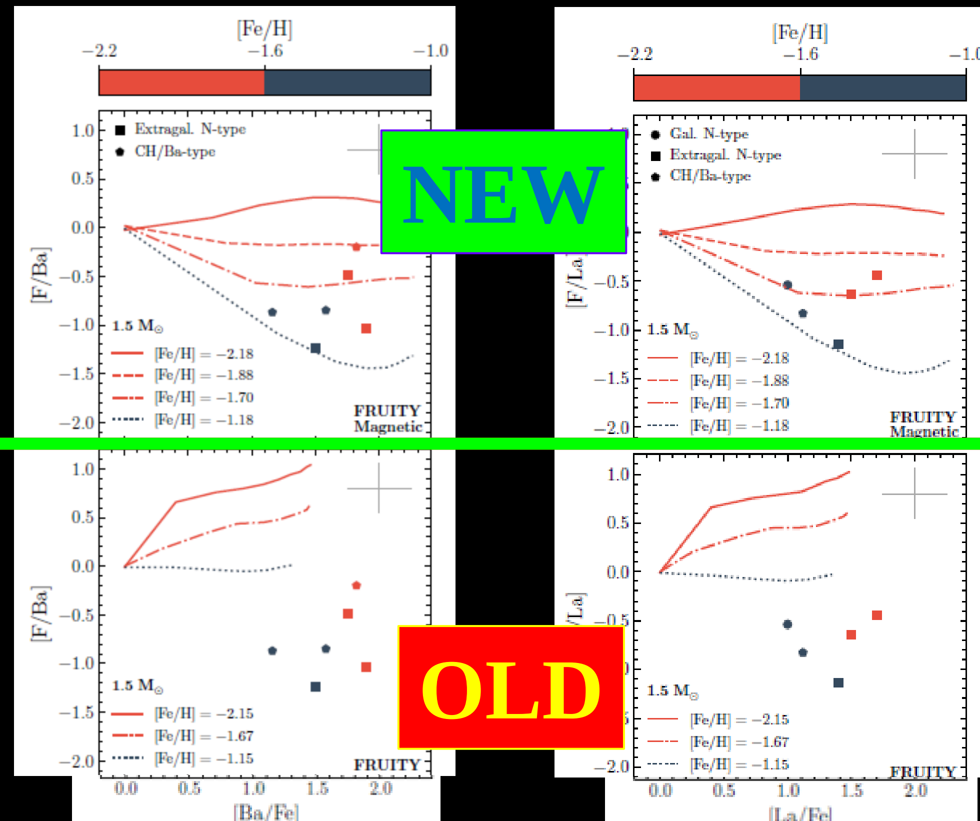




Vescovi+2021

Fluorine observations at low metallicities

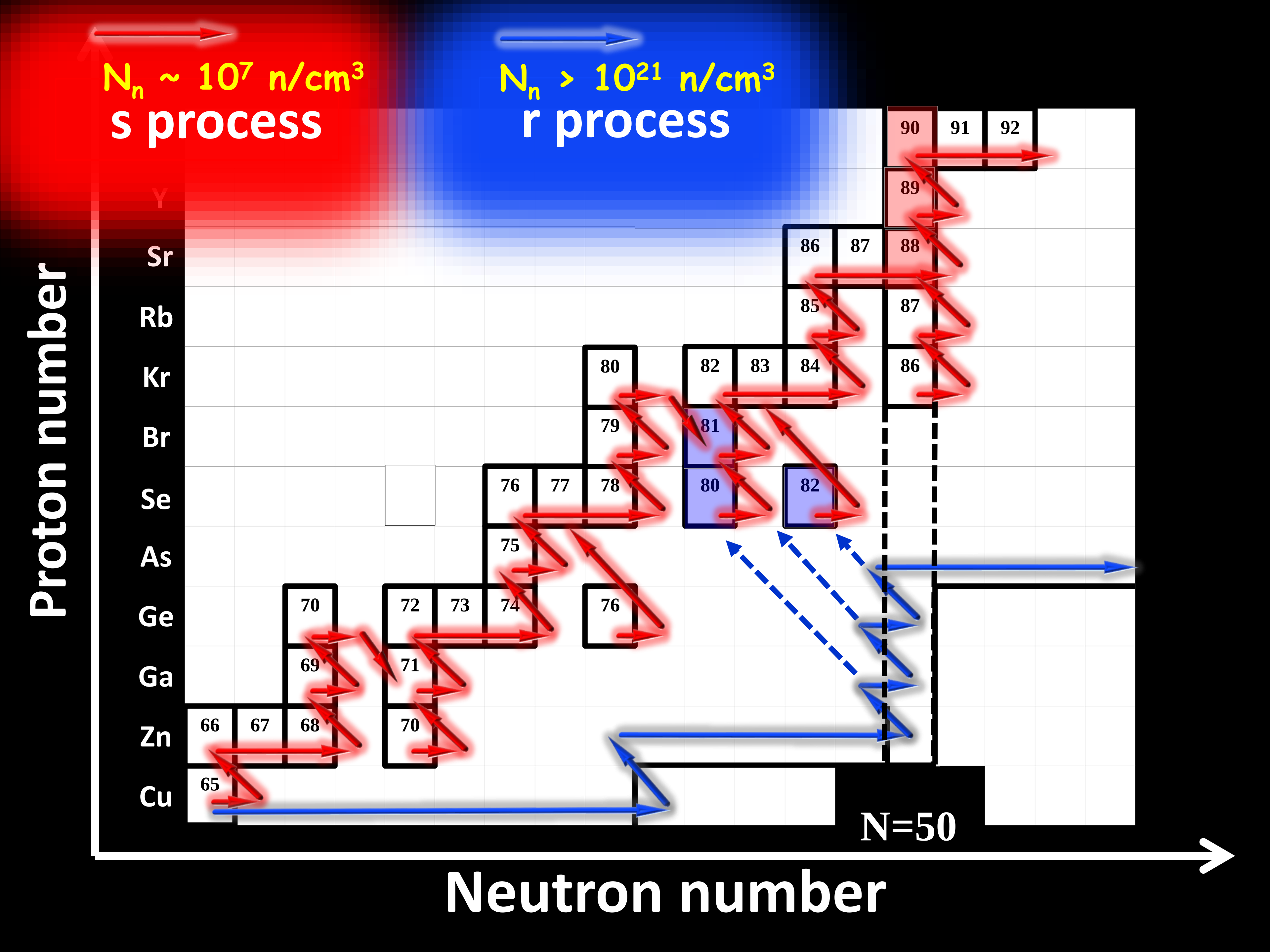




Vescovi+2021

This time, the agreement is reached with improved theoretical modeling:

new MAGNETIC AGB models



s process
r process
Nn ~ 10^7 n/cm^3
Nn > 10^21 n/cm^3
Proton number
Neutron number
N=50
Y
Sr
Rb
Kr
Br
Se
As
Ge
Ga
Zn
Cu
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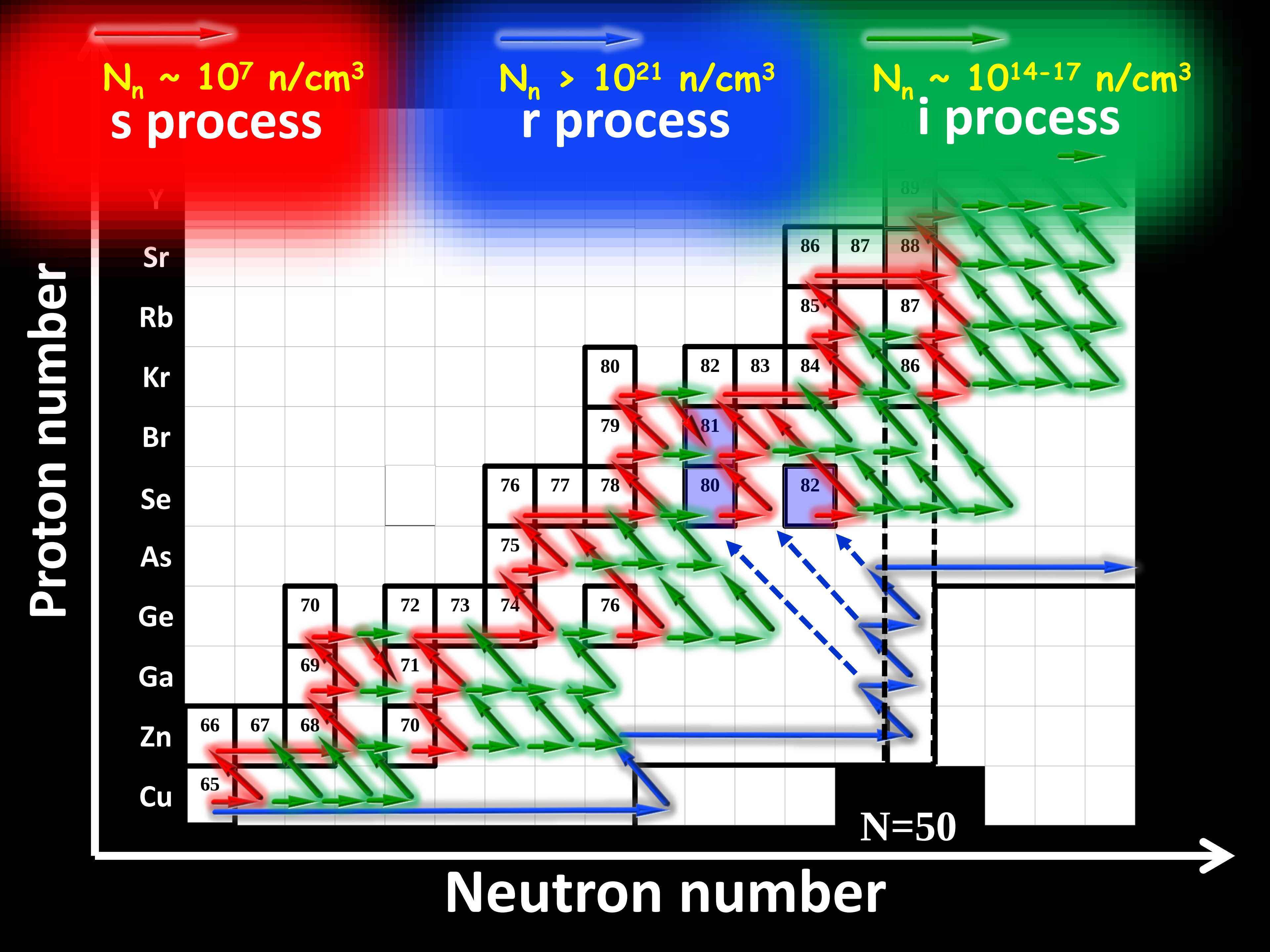

$N_n \sim 10^7$ n/cm^3
s process
$N_n > 10^{21}$ n/cm^3
r process
$N_n \sim 10^{14-17}$ n/cm^3
i process
Proton number
Neutron number
Y
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Rb
Kr
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Zn
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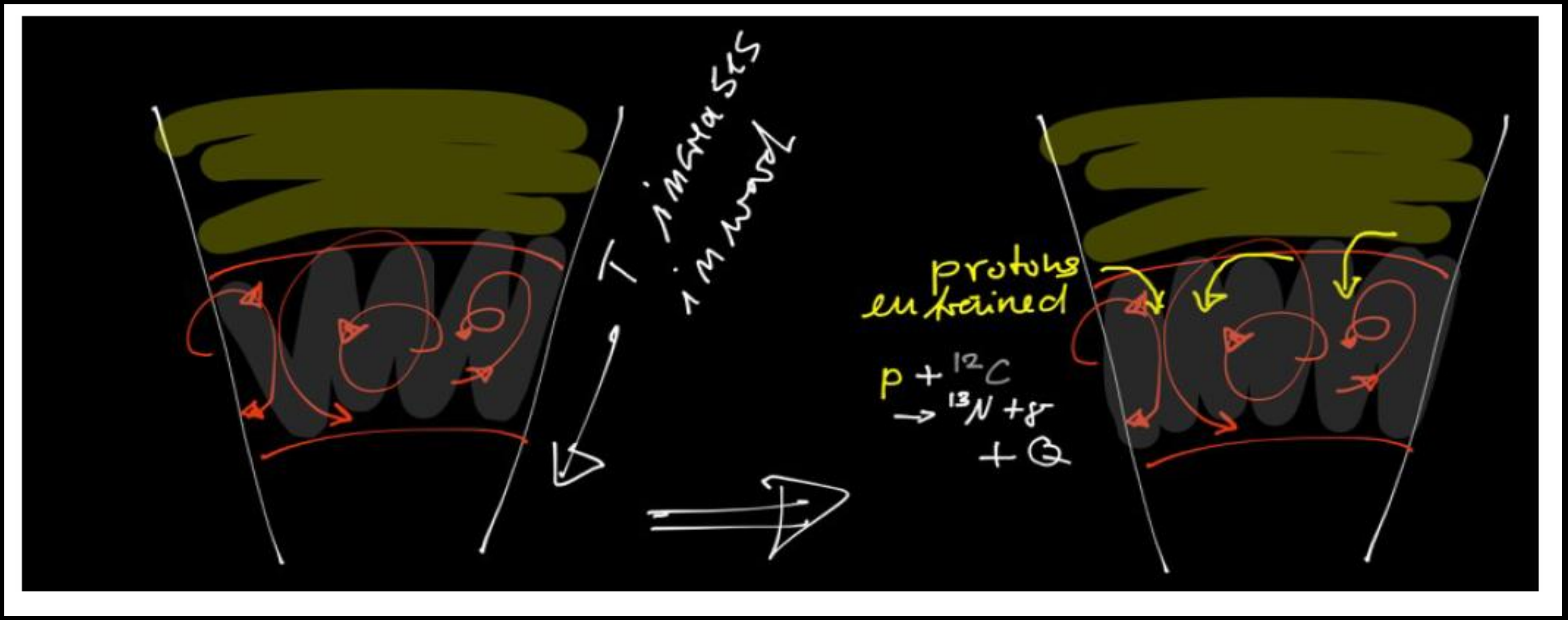
N=50

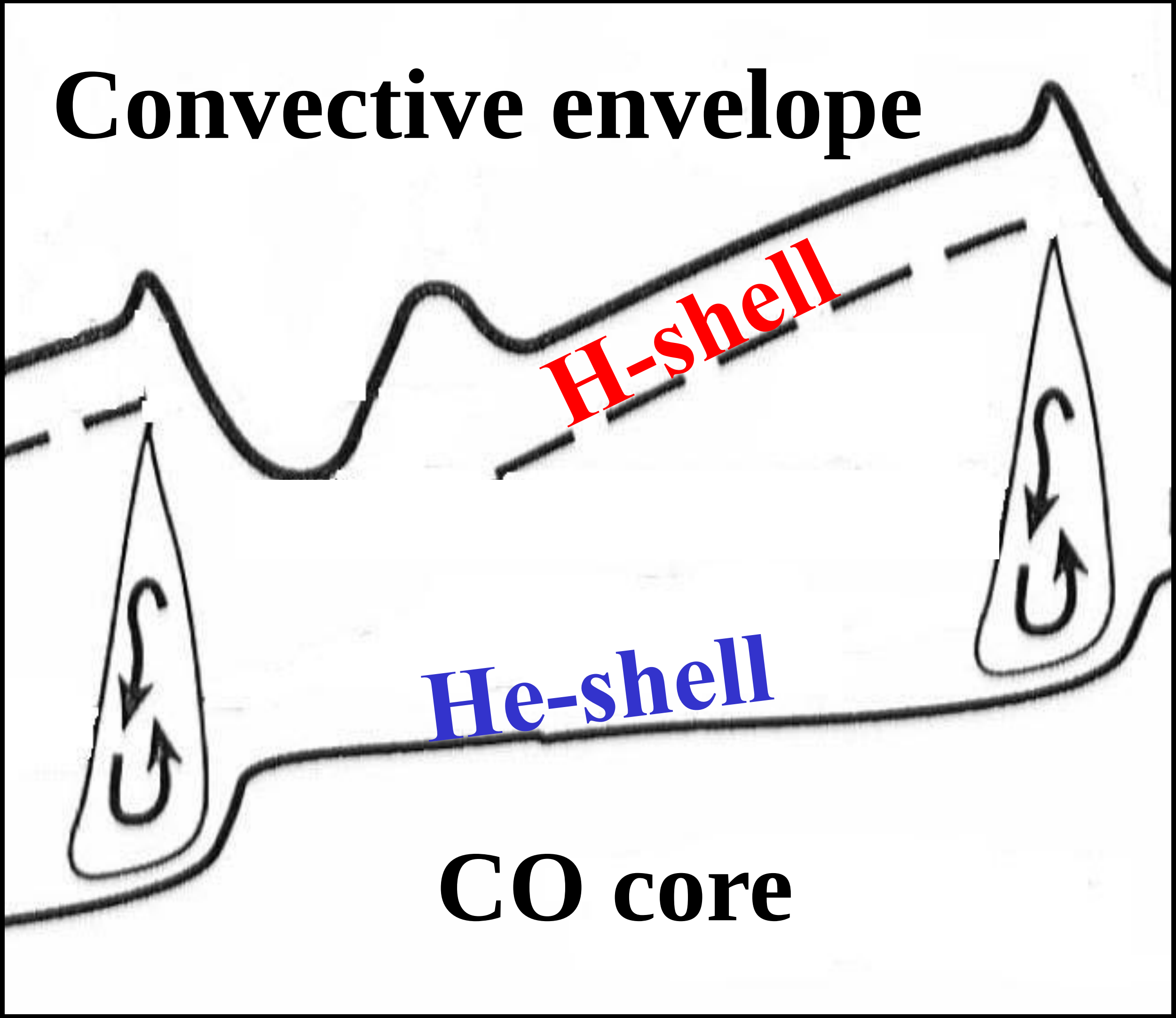
i-process and fluorine

An <u>"intermediate" neutron capture process</u> occurs whenever protons are mixed in regions with typical He-burning temperatures (T > 200 MK).

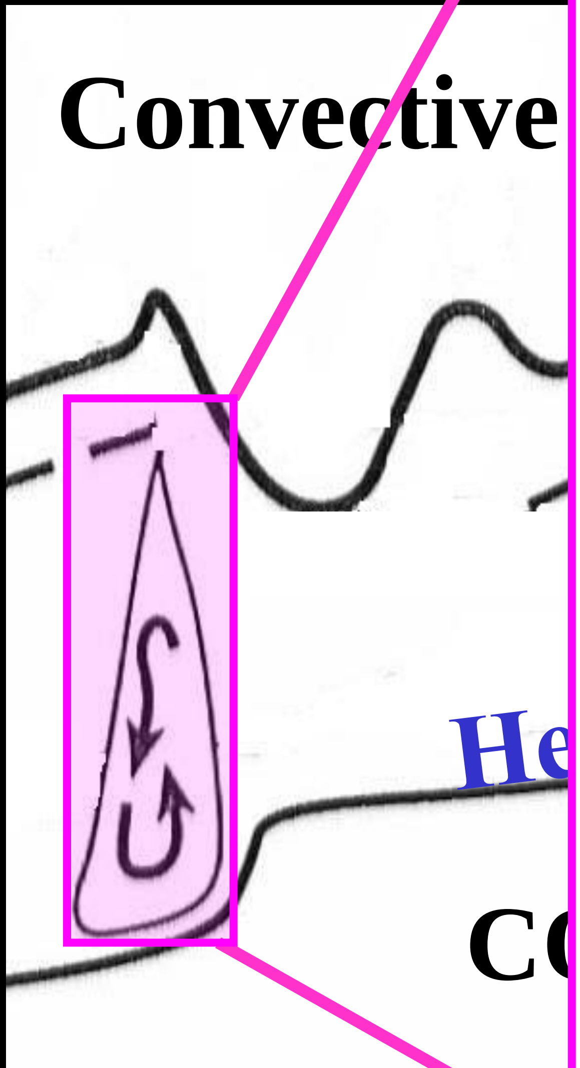


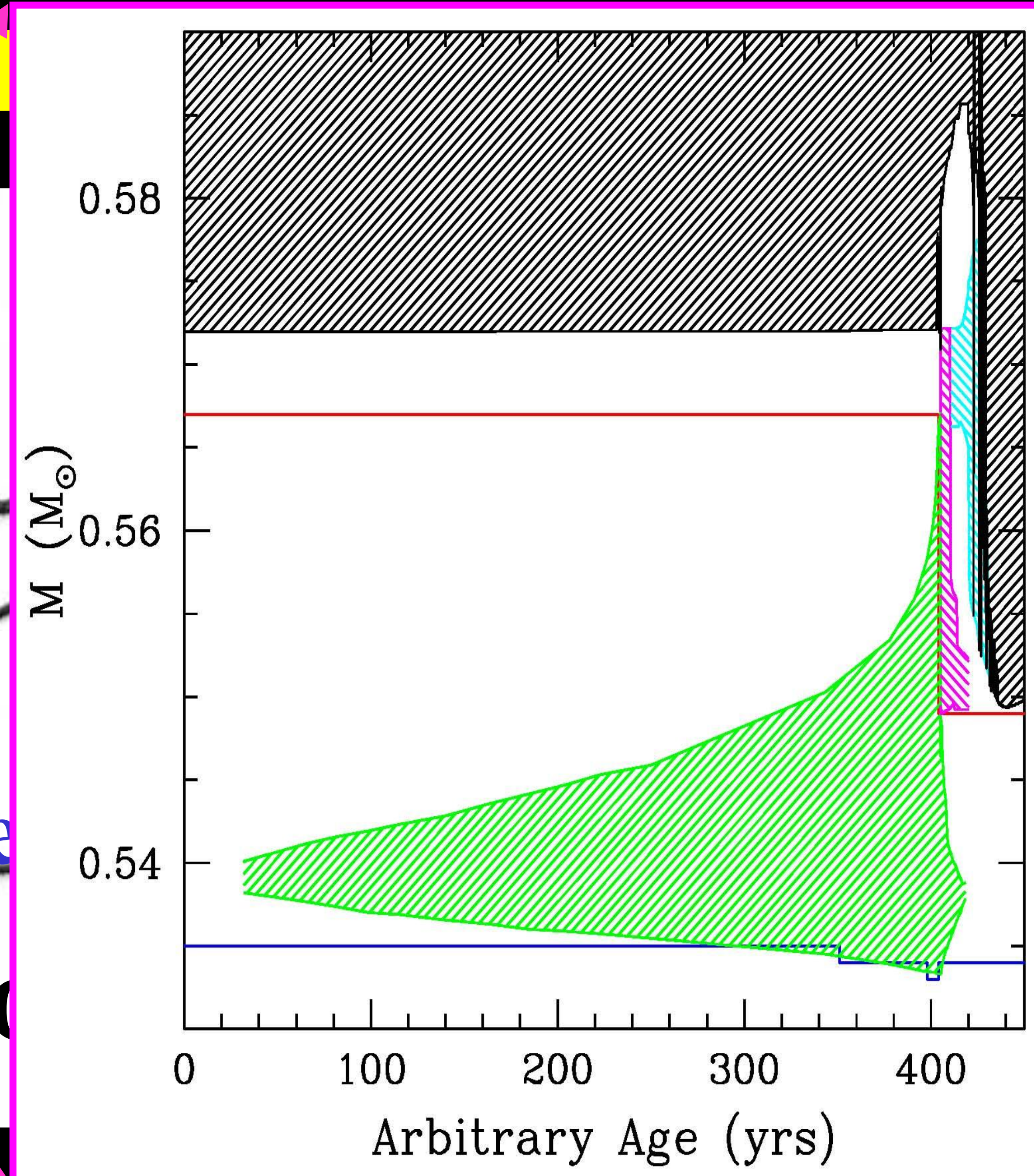
During proton ingestions, a lot of hydrogen is mixed in a ^{12}C-rich region, thus producing ^{13}N and, consequently, ^{13}C. The typical timescale is of the order of hours. In these conditions, fluorine production could, in principle, be activated.

Low metallicity low mass AGBs

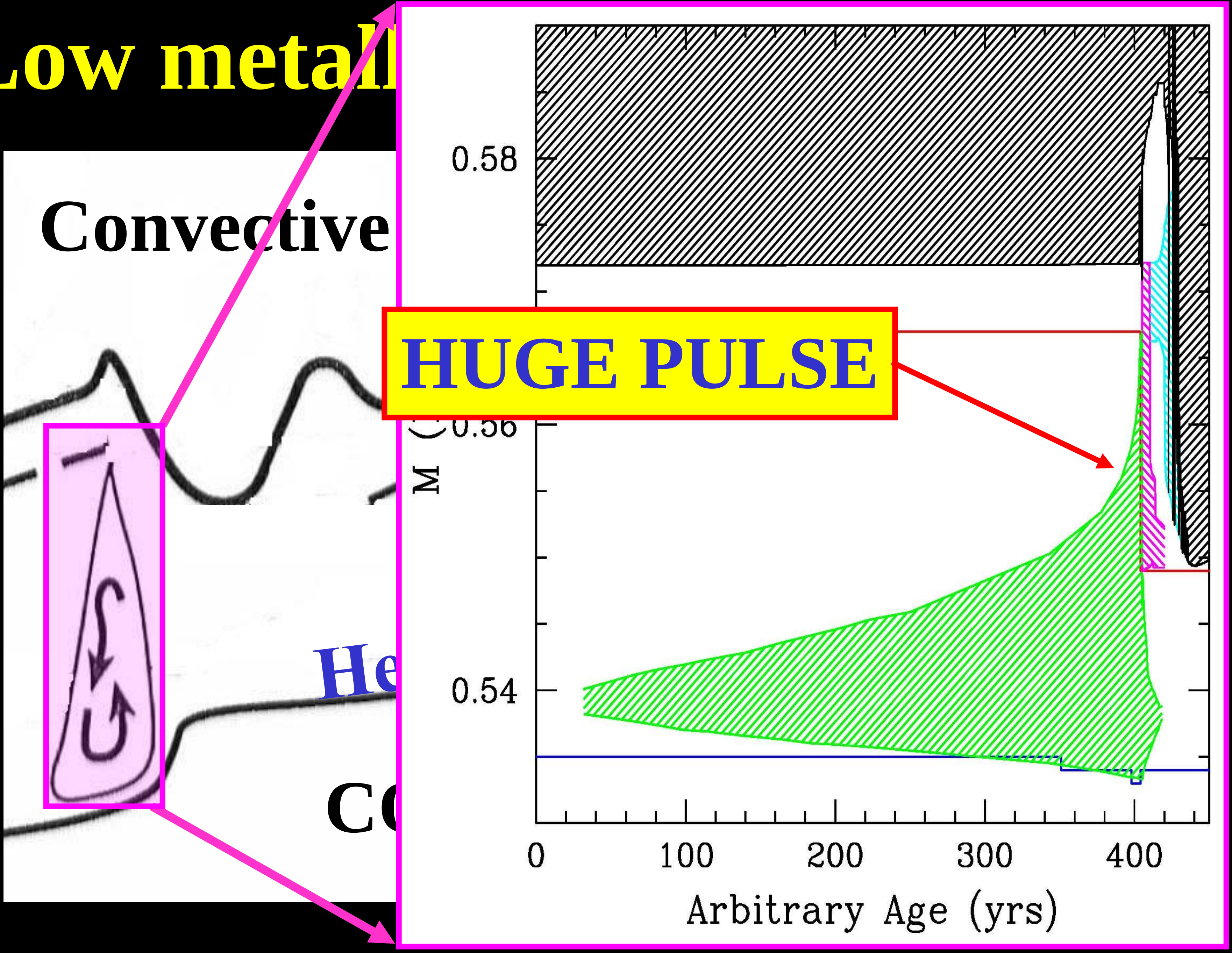


Low metall


Convective
He

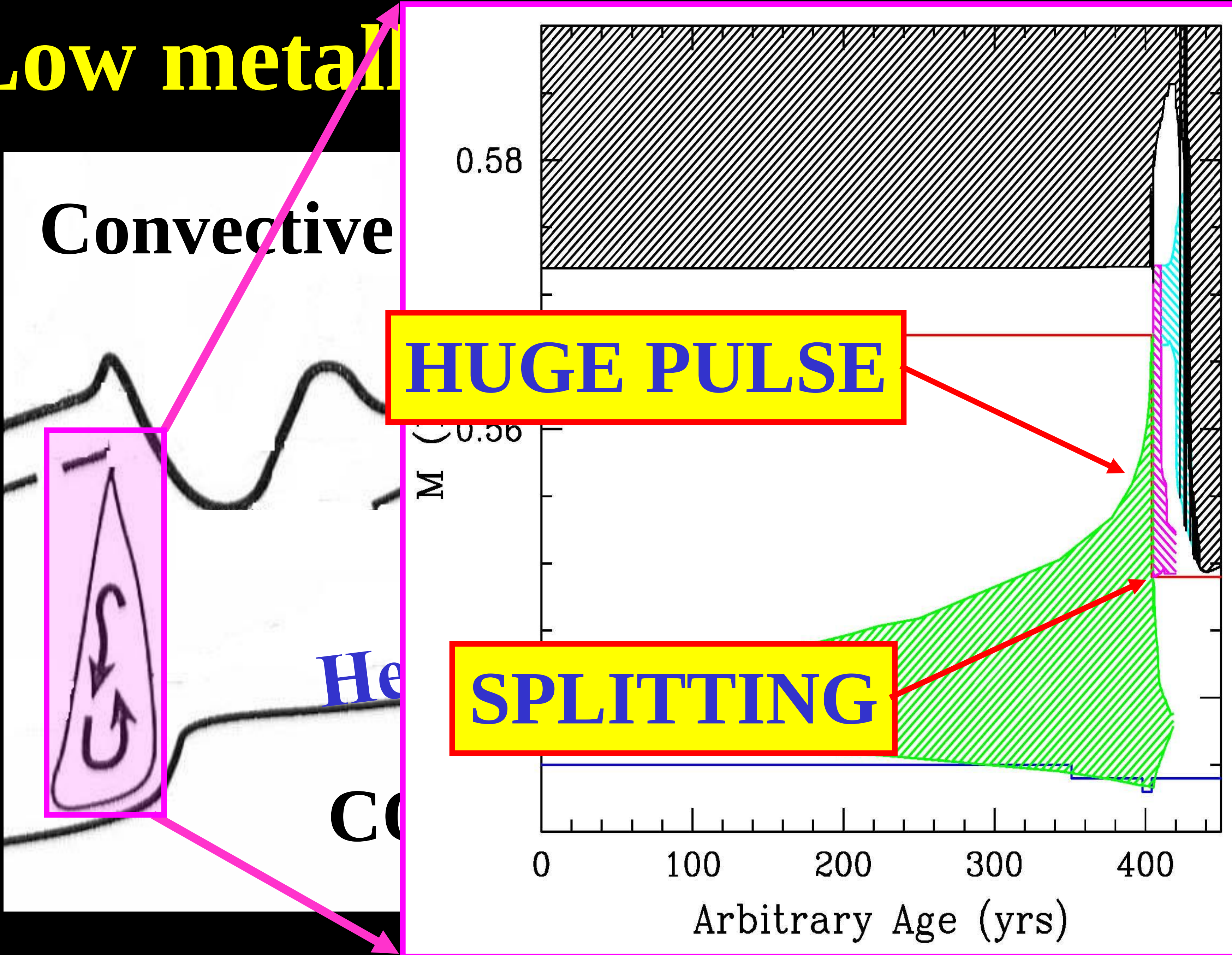

0.58
0.56
0.54
M (M$_\odot$)
0
100
200
300
400
Arbitrary Age (yrs)

Low metall



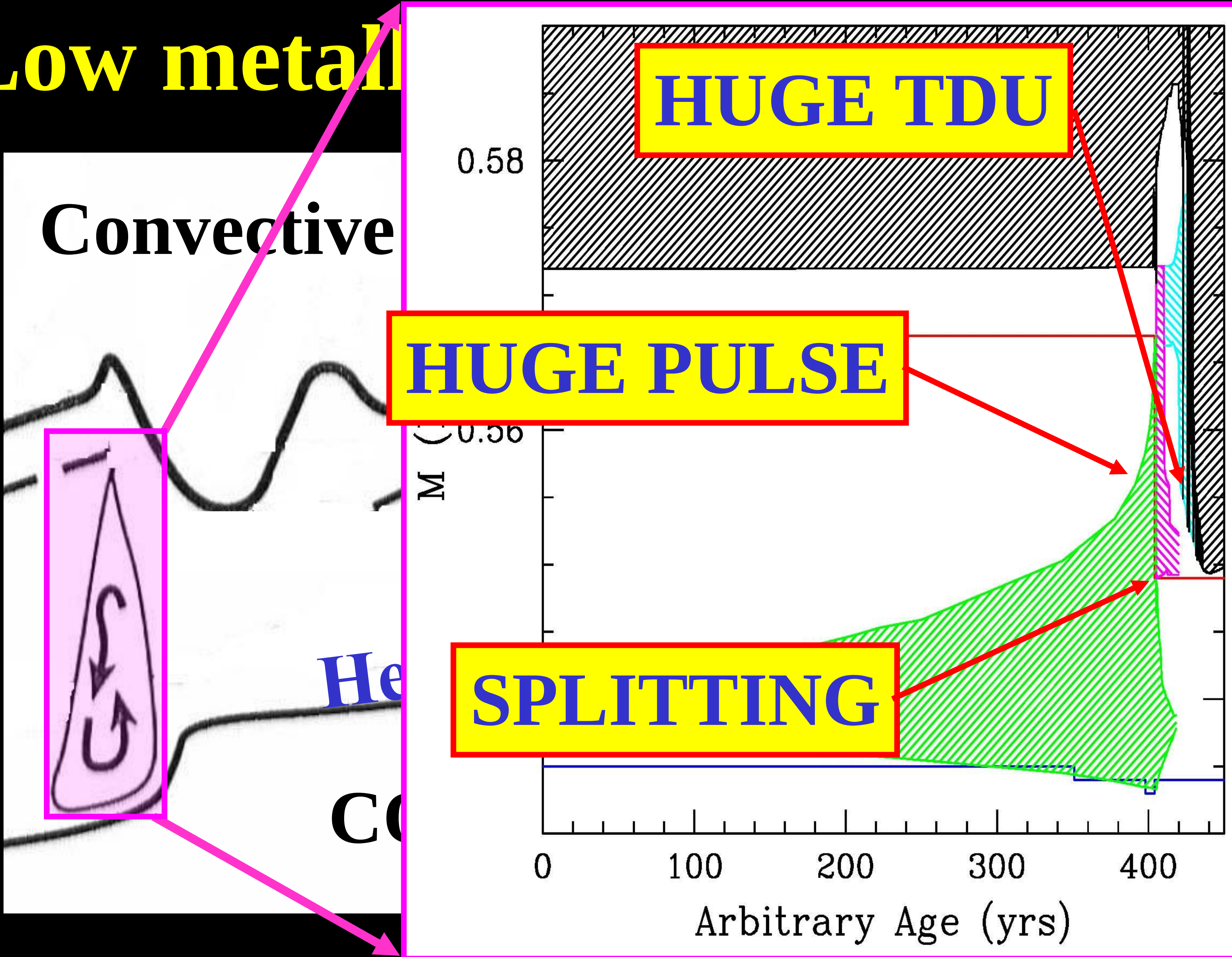
Convective
He
HUGE PULSE
0.58
0.56
0.54
M
0
100
200
300
400
Arbitrary Age (yrs)

Low metall



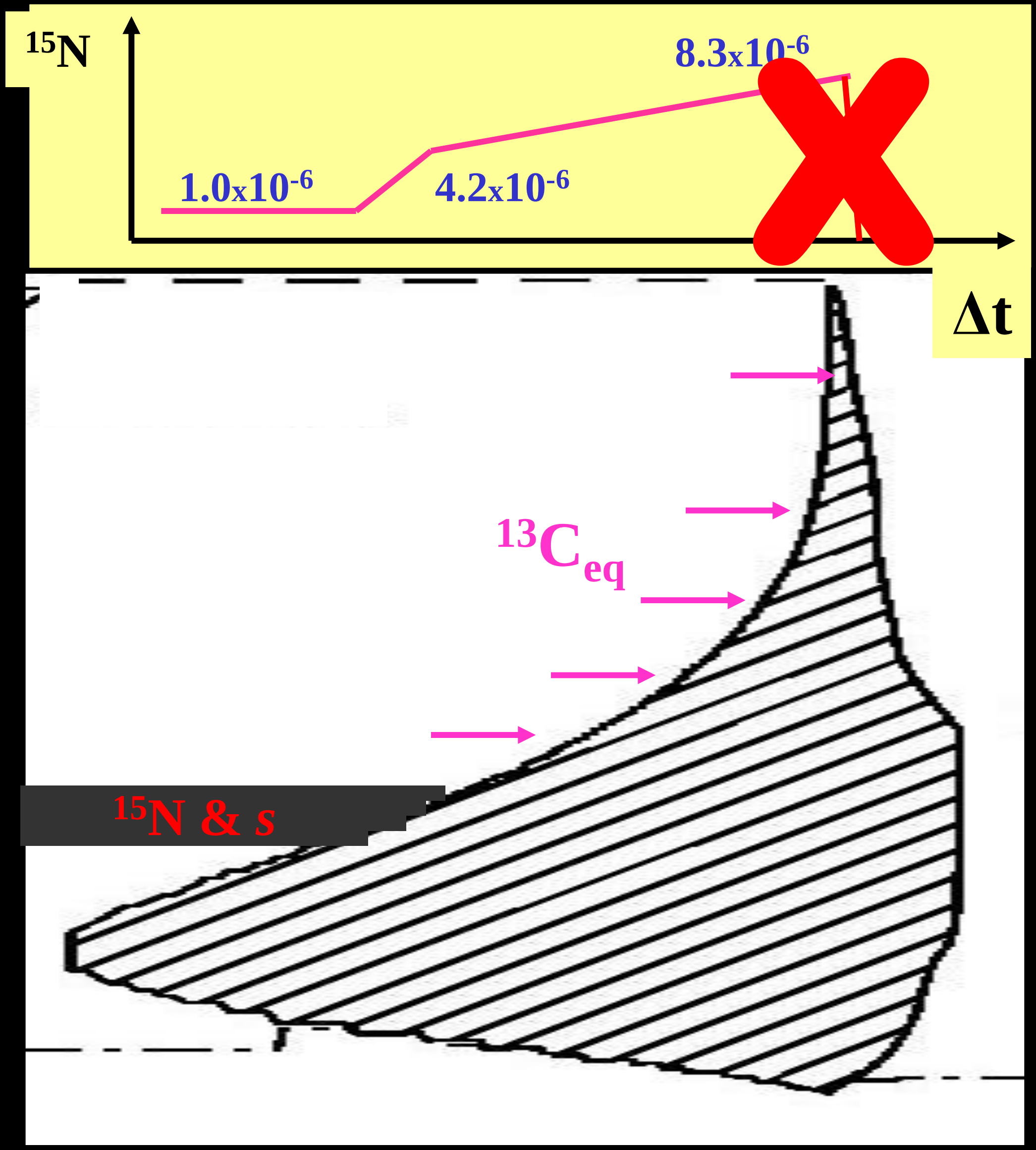
Convective
He
CO
0.58
0.56
M
HUGE PULSE
SPLITTING
0
100
200
300
400
Arbitrary Age (yrs)

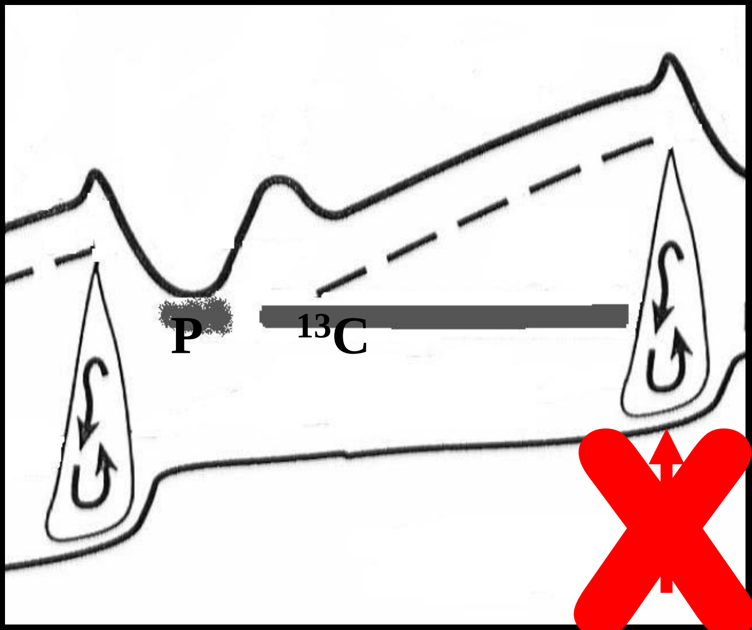
Low metall



Convective
He
CO
HUGE TDU
HUGE PULSE
SPLITTING
0.58
0.56
M
0
100
200
300
400
Arbitrary Age (yrs)

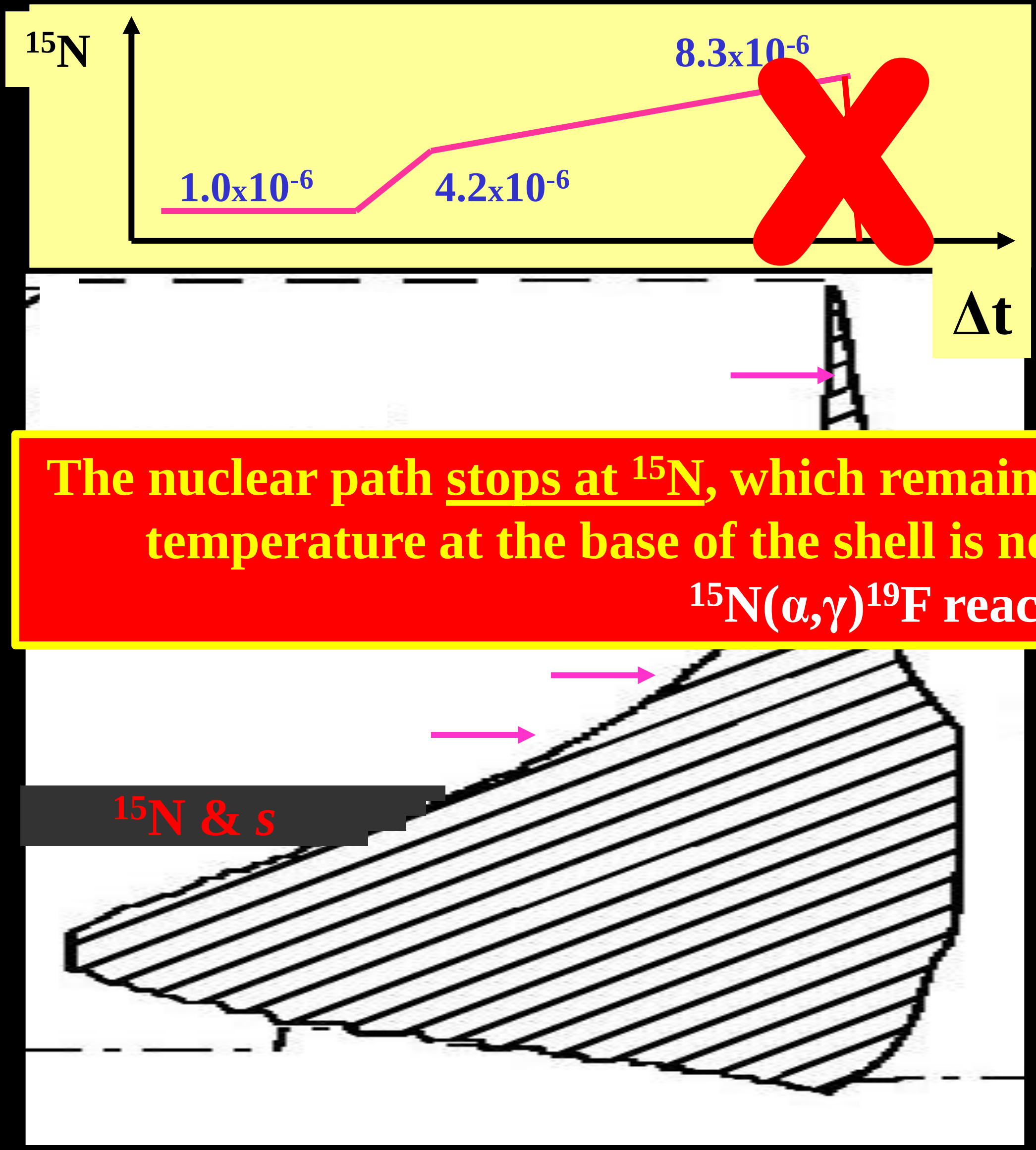
Main ^{15}N (and then ^{19}F) sources

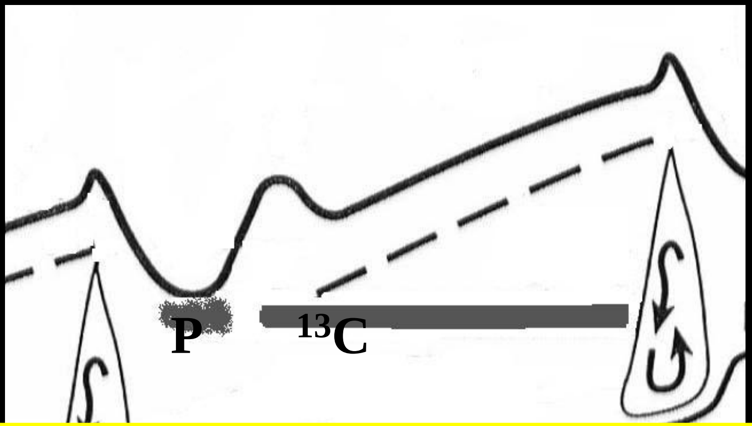




$^{15}N(\alpha,\gamma)^{19}F$

Main ^{15}N (and then ^{19}F) sources

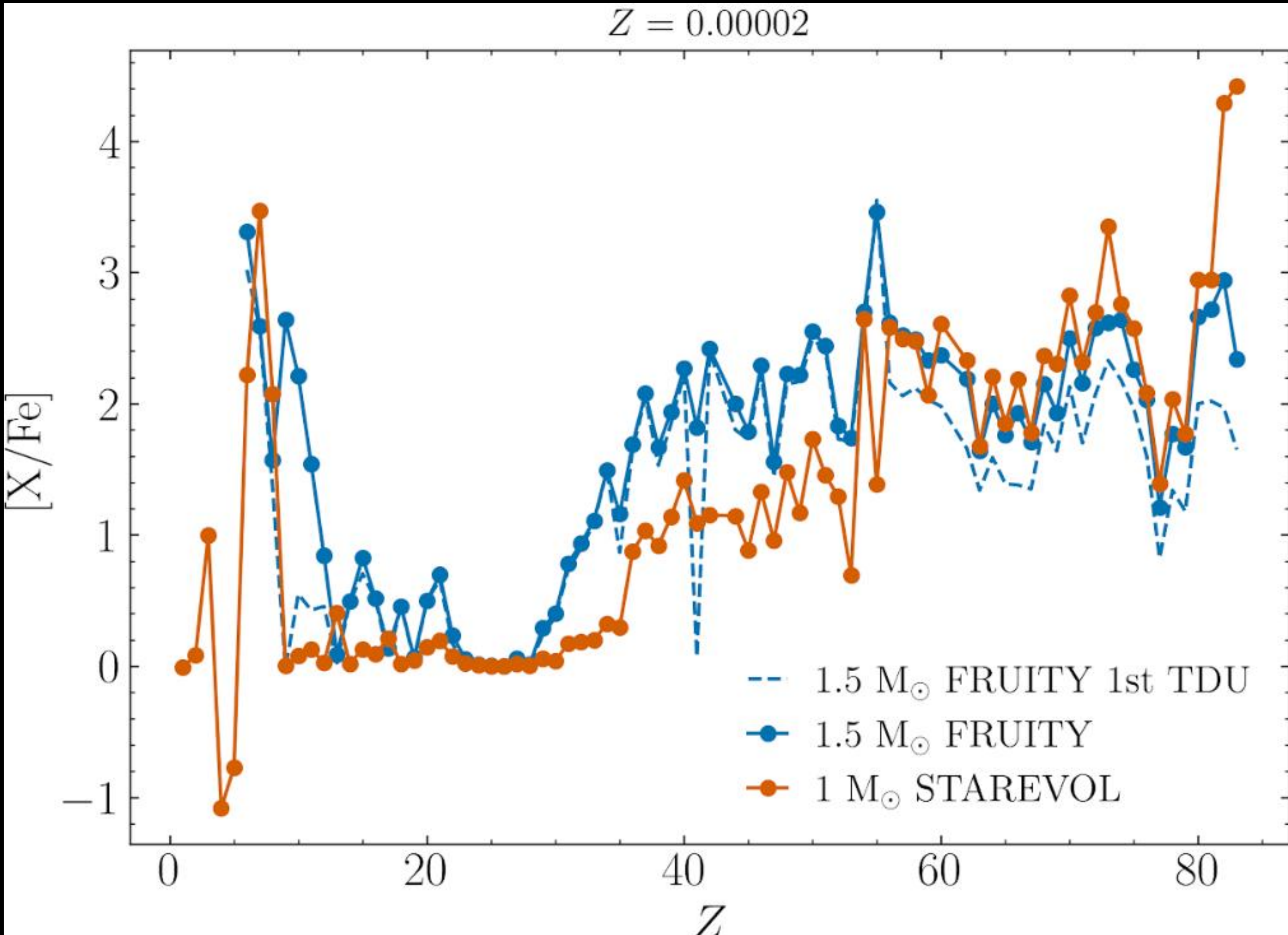




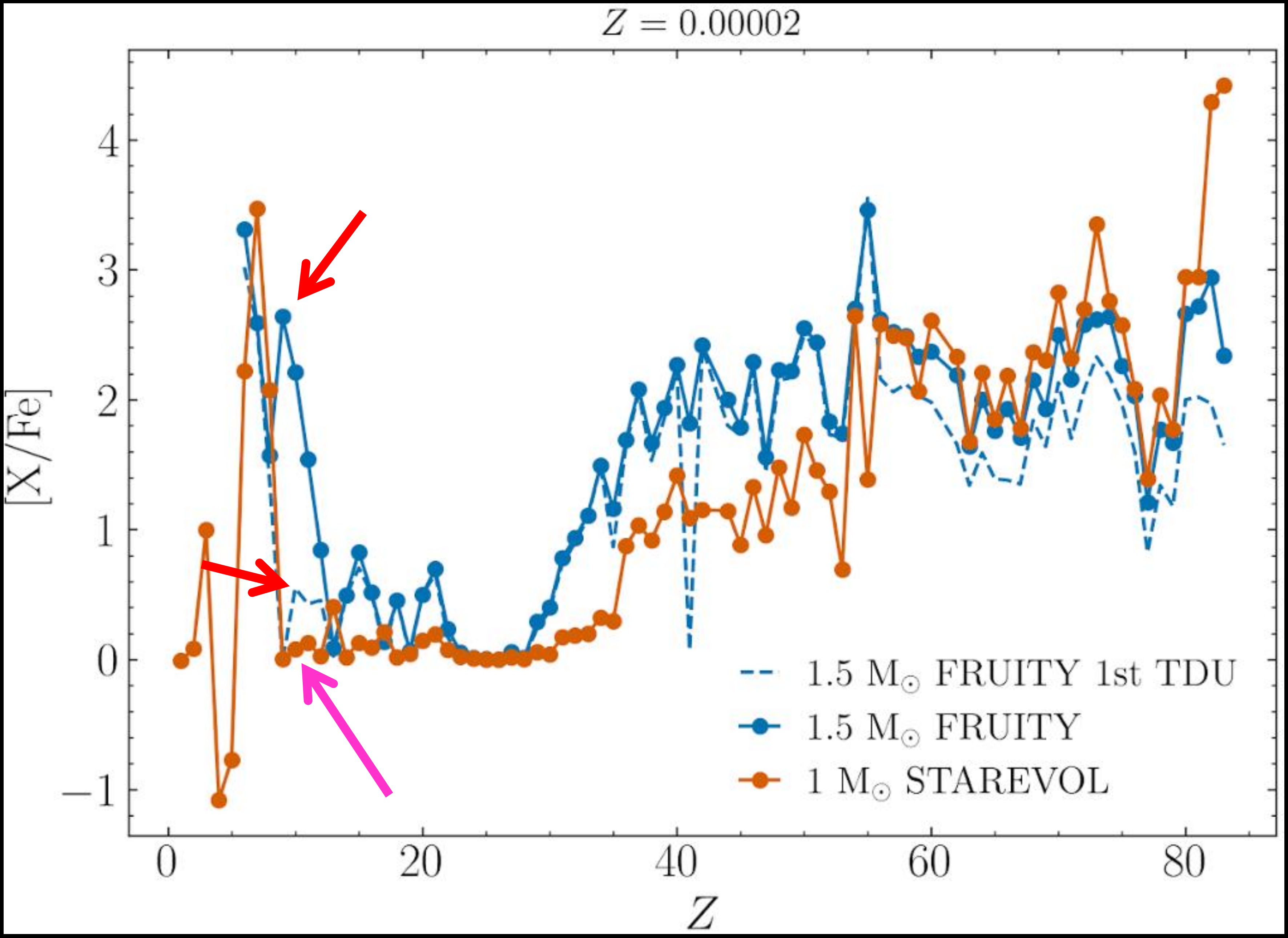
The nuclear path stops at ^{15}N, which remains unburnt due to the fact that the temperature at the base of the shell is not large enough to trigger the $^{15}N(\alpha,\gamma)^{19}F$ reaction.

$$^{15}N(\alpha,\gamma)^{19}F$$

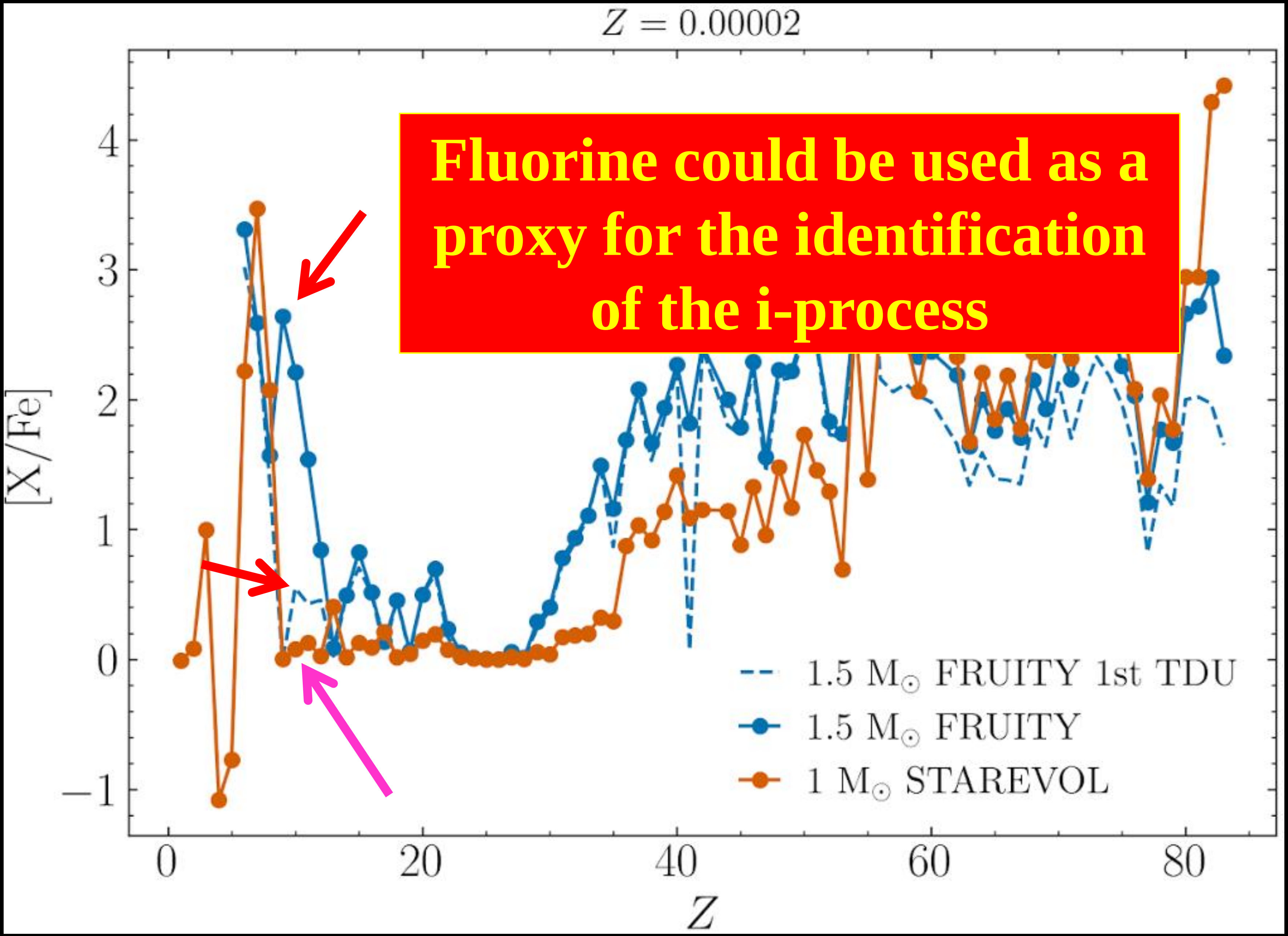
PIE vs. standard TDU



PIE vs. standard TDU



PIE vs. standard TDU



Effects of nuclear cross sections on ^{19}F production (I)

Effects of nuclear cross sections on ^{19}F nucleosynthesis at low metallicities
(Research Note)

S. Cristallo[1,2], A. Di Leva[3,2], G. Imbriani[3,2], L. Piersanti[1,2], C. Abia[4], L. Gialanella[5,2], and O. Straniero[1,2]

Conclusions:

Variations in key reaction rates within 2σ have little effect on the final fluorine surface abundances and [F/s] ratios

Reaction rate	sf	$R(^{19}\mathrm{F})$	$R(\mathrm{F}/\langle s\rangle)$
^{13}C(α,n)^{16}O	0.01	4.70	2.80
^{13}C(α,n)^{16}O	100	0.62	0.67
^{14}C(α,γ)^{18}O	0.01	1.03	1.59
^{14}C(α,γ)^{18}O	100	1.04	1.61
^{14}N(α,γ)^{18}F	0.01	3.03	5.14
^{14}N(α,γ)^{18}F	100	0.64	1.10
^{15}N(α,γ)^{19}F	0.01	0.11	0.12
^{15}N(α,γ)^{19}F	100	0.96	1.50
^{18}O(α,γ)^{22}Ne	0.01	2.21	2.01
^{18}O(α,γ)^{22}Ne	100	0.52	0.52
^{19}F(α,p)^{22}Ne	0.01	1.05	1.19
^{19}F(α,p)^{22}Ne	100	0.08	0.14

Investigated other possible, although unlikely, scenarios in which some α capture rates are varied by a factor 100.
The largest variations are obtained by reducing the ^{15}N(α,γ)^{19}F rate or by increasing the ^{19}F(α,p)^{22}Ne rate.

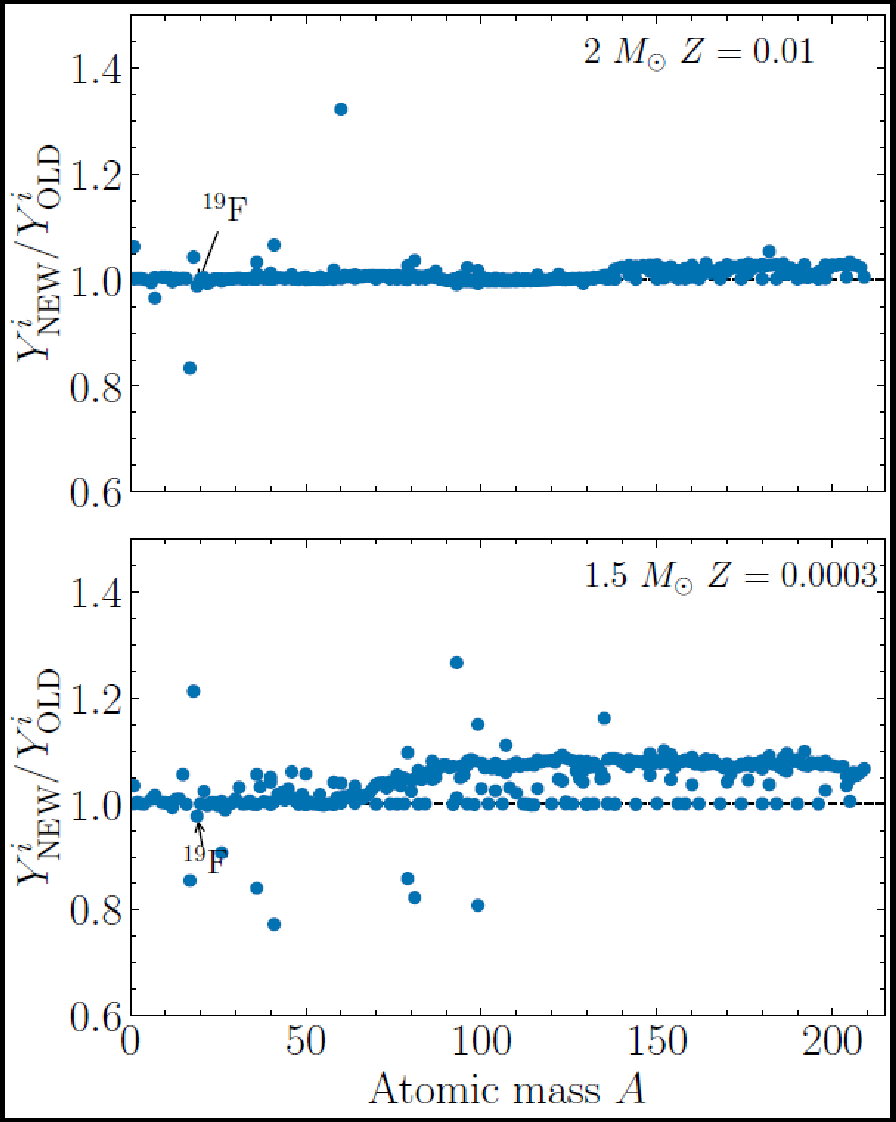
Cristallo+2014

Effects of nuclear cross sections on ^{19}F production (II)

A more recent exploration (2025) with new available nuclear rates.

$^{17}O(p,\alpha)^{14}N$ Rapagnani+ 2025
$^{17}O(p,\gamma)^{18}F$ Rapagnani+ 2025
$^{18}O(p,\gamma)^{19}F$ Best+ 2019
$^{18}O(p,\alpha)^{15}N$ Bruno+ 2019
$^{19}F(p,\alpha)^{16}O$ DeBoer+ 2021
$^{13}C(\alpha,n)^{16}O$ Ciani+ 2021
$^{18}O(\alpha,\gamma)^{22}Ne$ Wang+ 2023
$^{19}F(\alpha,p)^{22}Ne$ D'Agata+ 2018

$^{15}N(\alpha,\gamma)^{19}F$???




That's all Folks!