The slow neutron capture process

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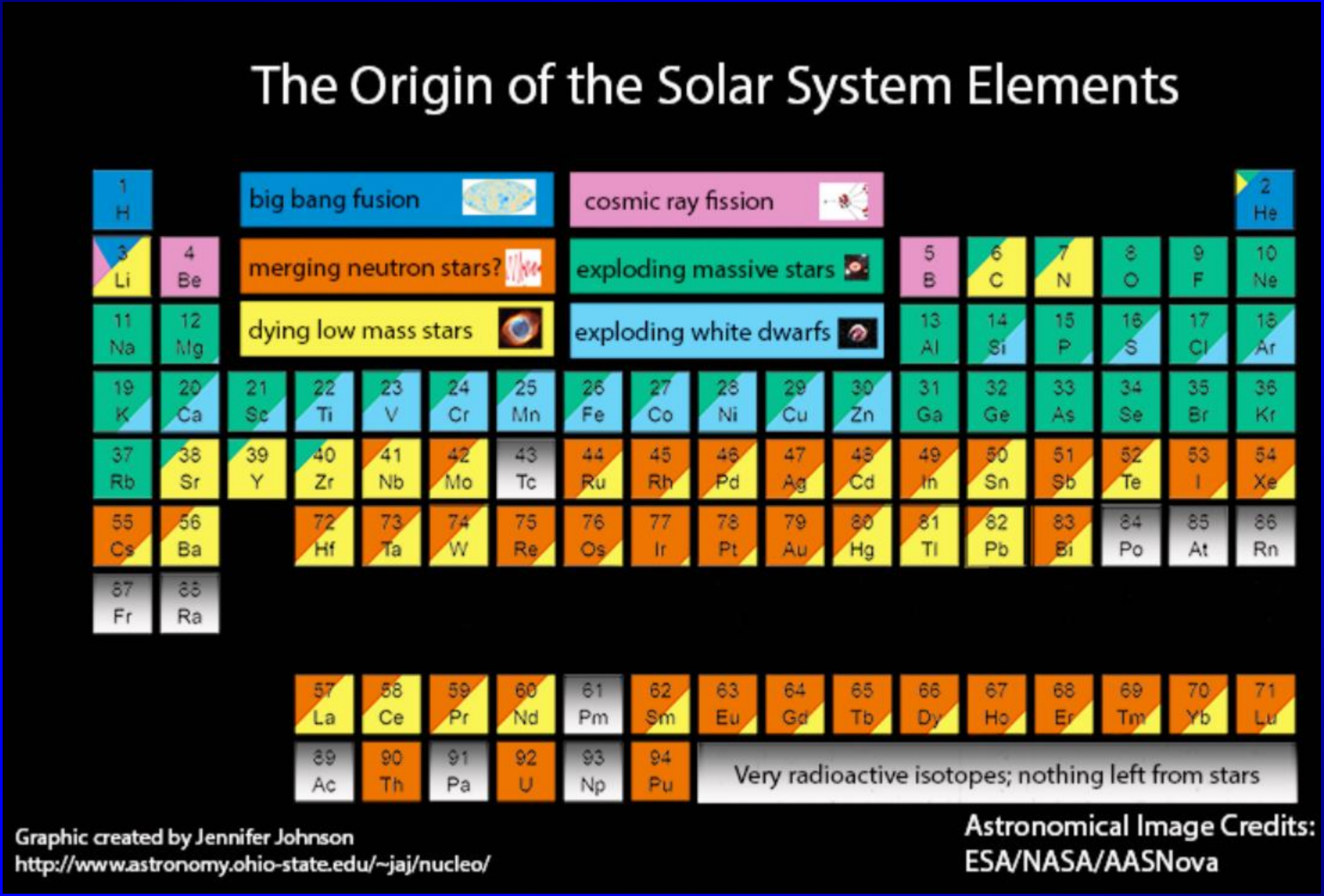
For the umpteenth time…



The r-process

B2FH

$\tau_\beta \gg \tau_n \quad \Leftrightarrow \quad N_n > 10^{20}\ n/cm^3$

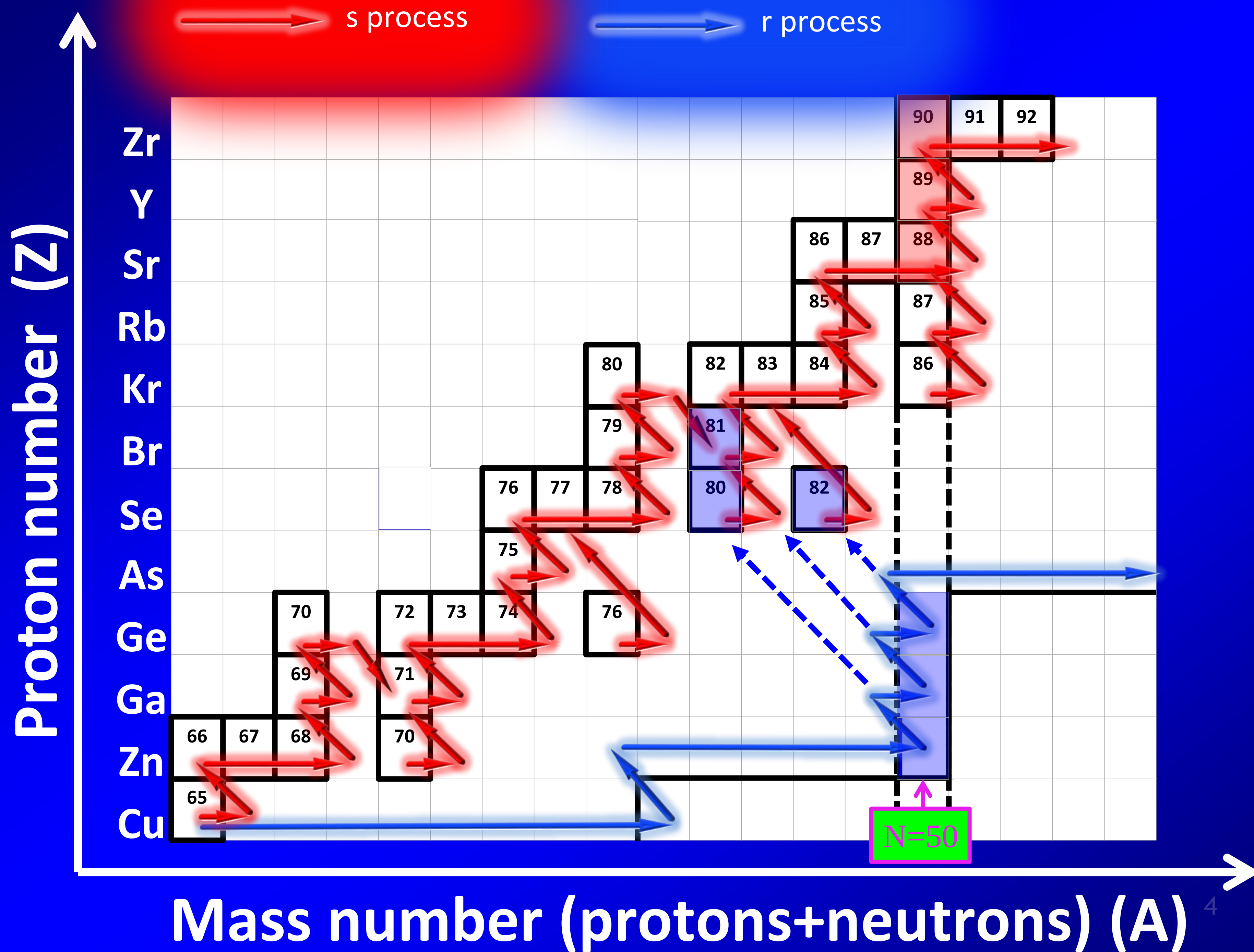
Unstable nucleus captures another neutron before decaying

The s-process

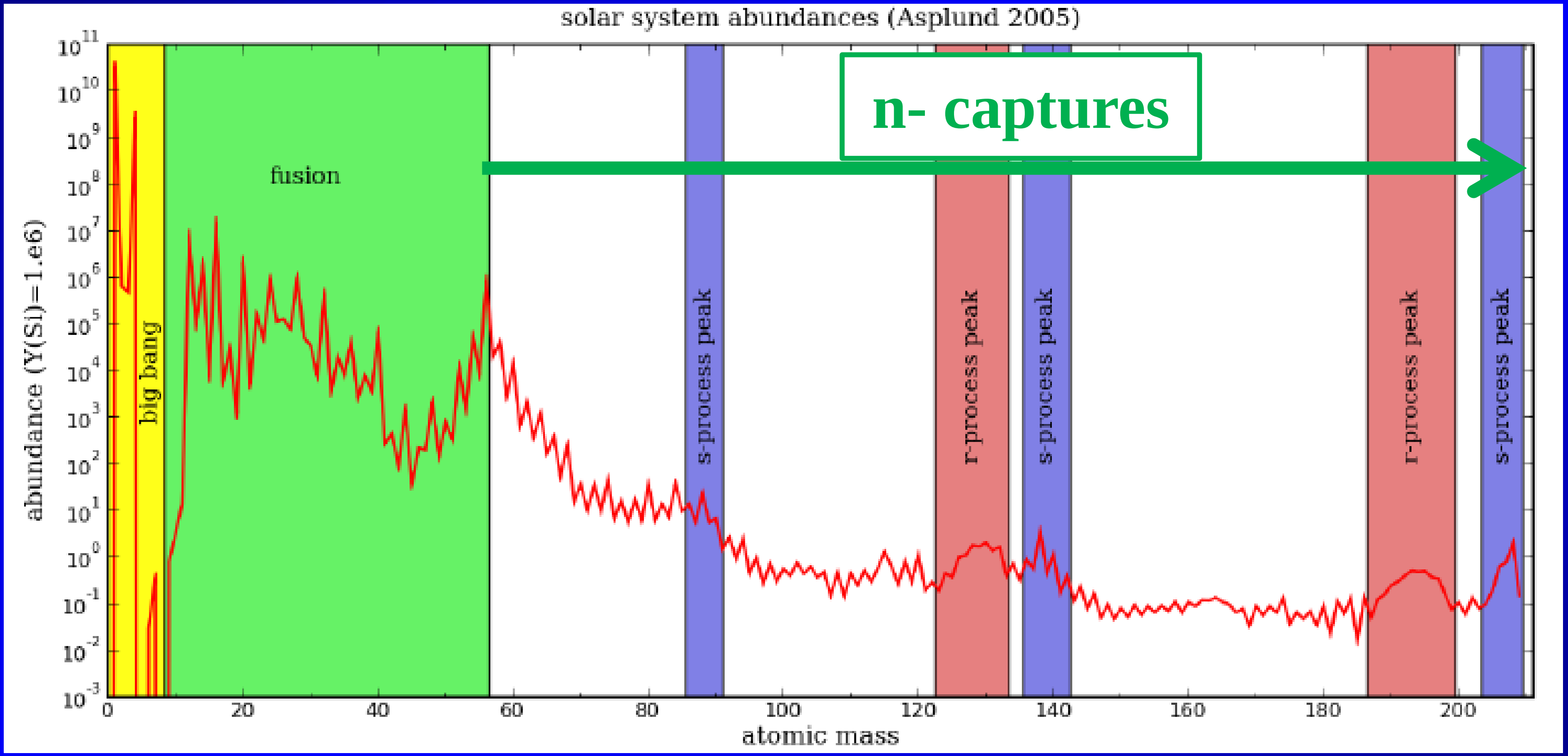
$\tau_\beta \ll \tau_n \quad \Leftrightarrow \quad N_n \sim 10^{7}\ n/cm^3$

Unstable nucleus decays before capturing another neutron

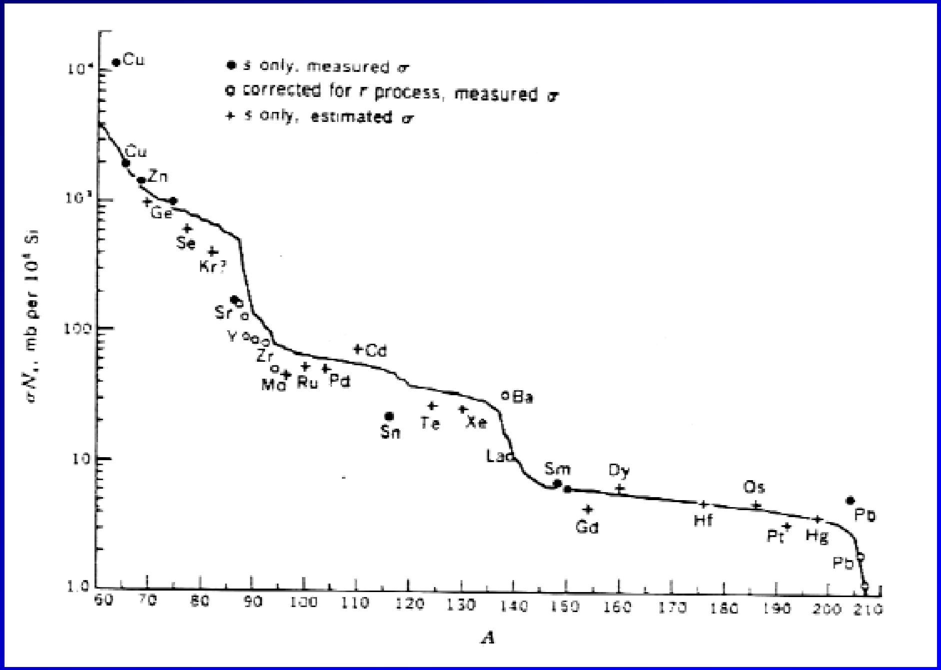
In principle one might expect to encounter astrophysical neutron fluxes in the large region between these two densities and have thereby intermediate processes between s and r. Such events are apparently not common, and it is one of the fortunate simplifications in the application theory of synthesis by neutron capture that the most common fluxes are either quite small or quite large... **if we ignore the i-process**.


s process
r process
Zr
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 (Z)
Mass number (protons+neutrons) (A)

Solar System Abundances



Cowan+2021

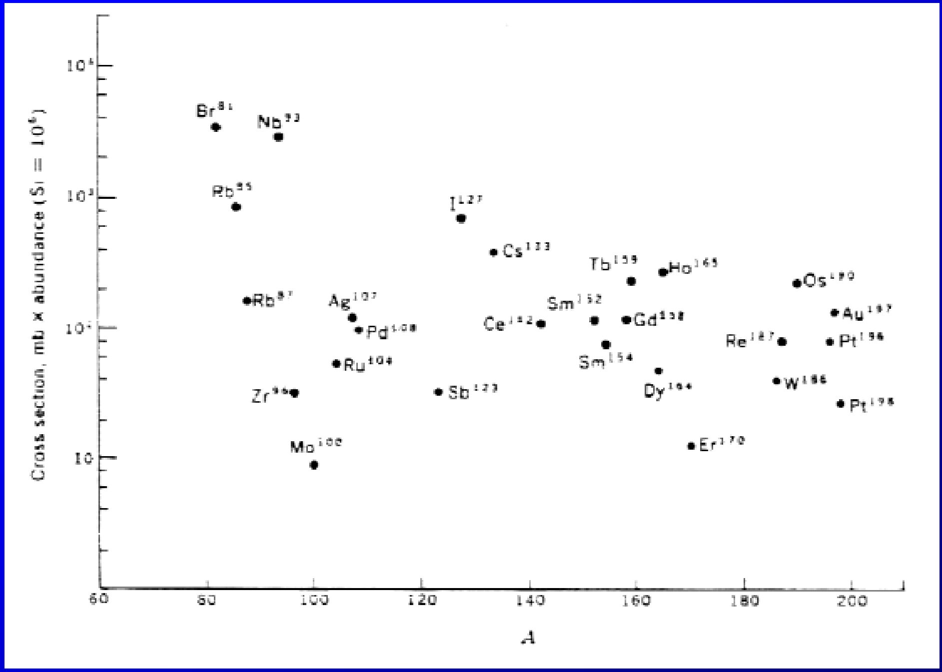


s-process

Easy to be reproduced with a series of neutron exposures (with an exponential distribution)

r-process

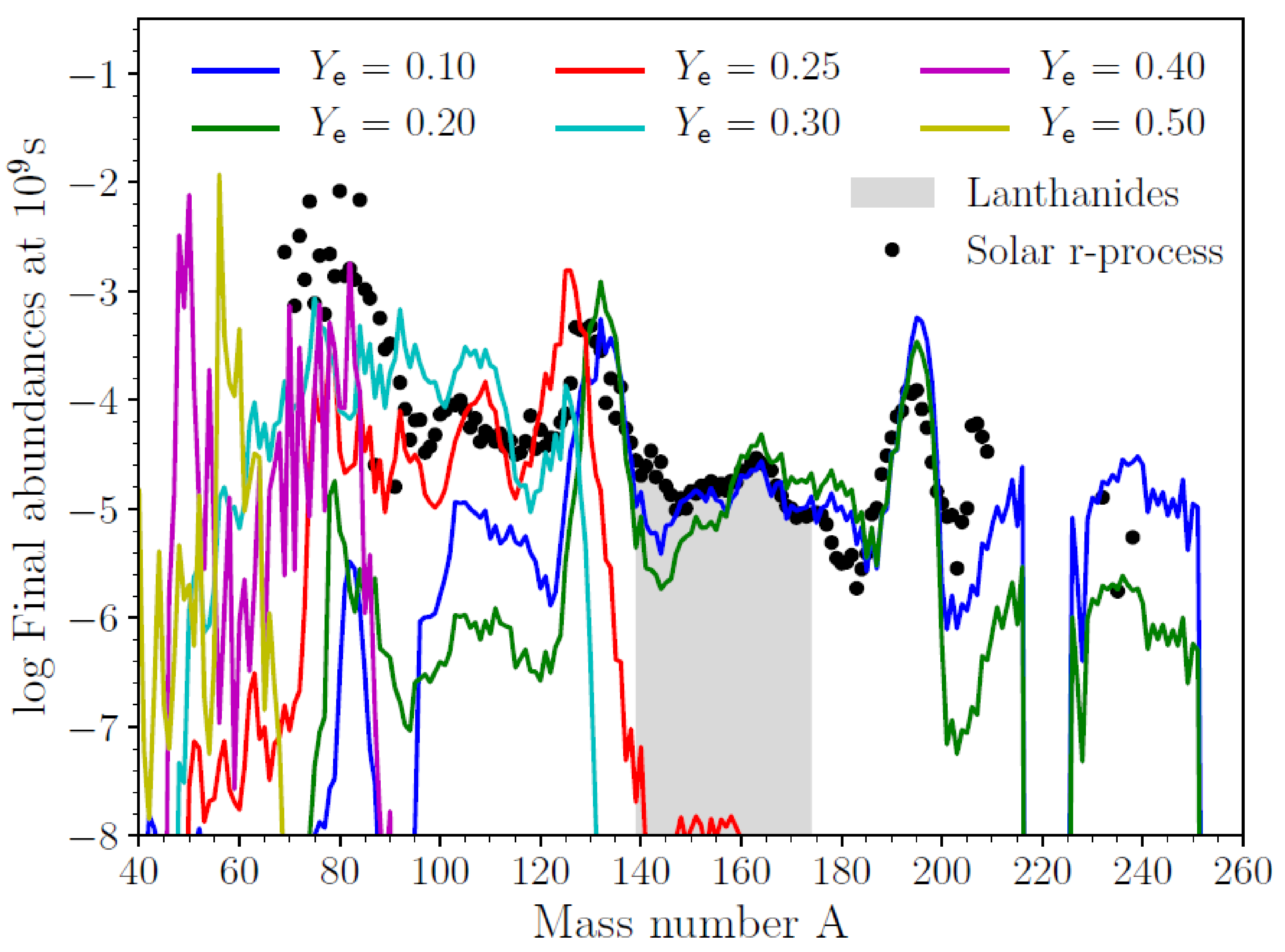
Do you see any distribution?



How can we determine the r-process contribution to the solar distribution?

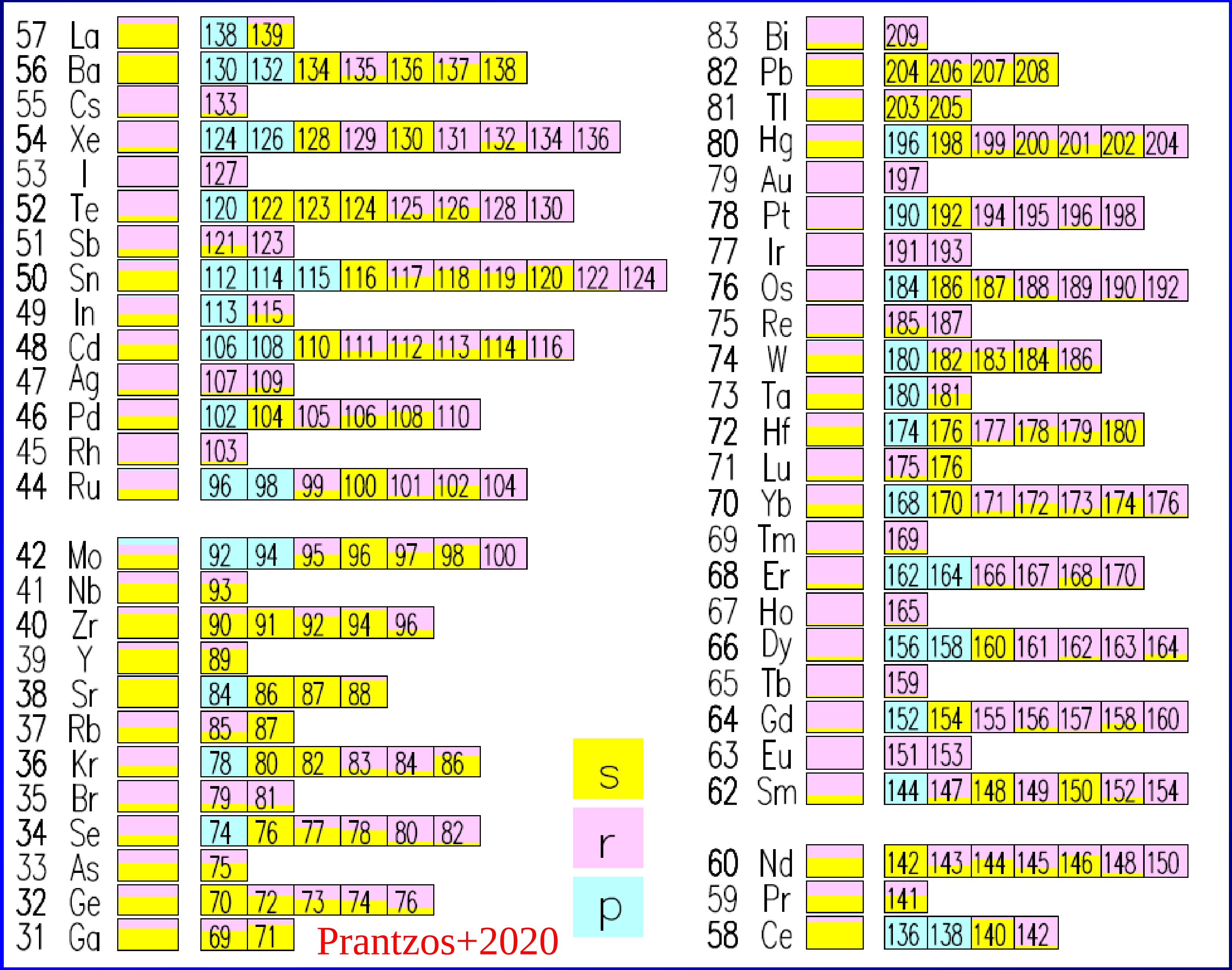
$$r = 1 - s$$

Typical r-process distributions



Solar r-process residuals from Prantzos+2020

Various contributions to isotopic abundances

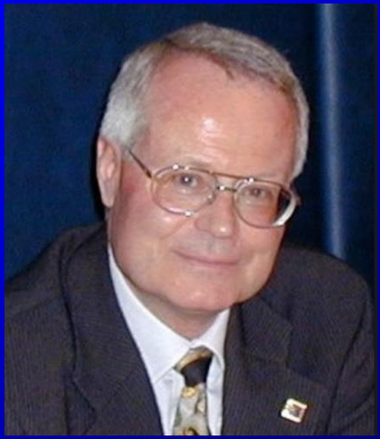


$$r = 1 - s$$

Arlandini+1999; Goriely+1999; Simmerer+2004; Bisterzo+2018; Prantzos+2020

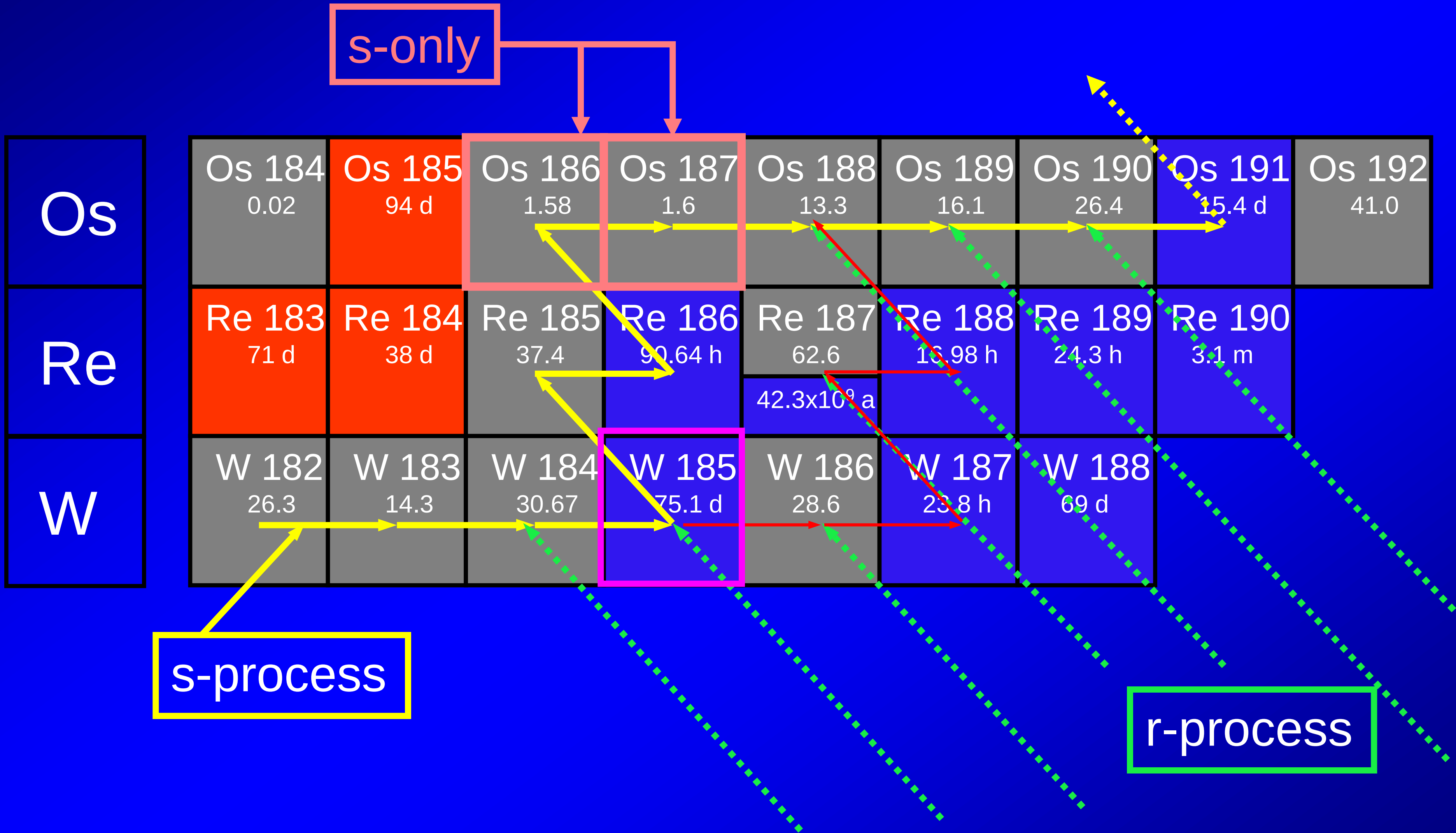
vs

$$s = 1 - r$$



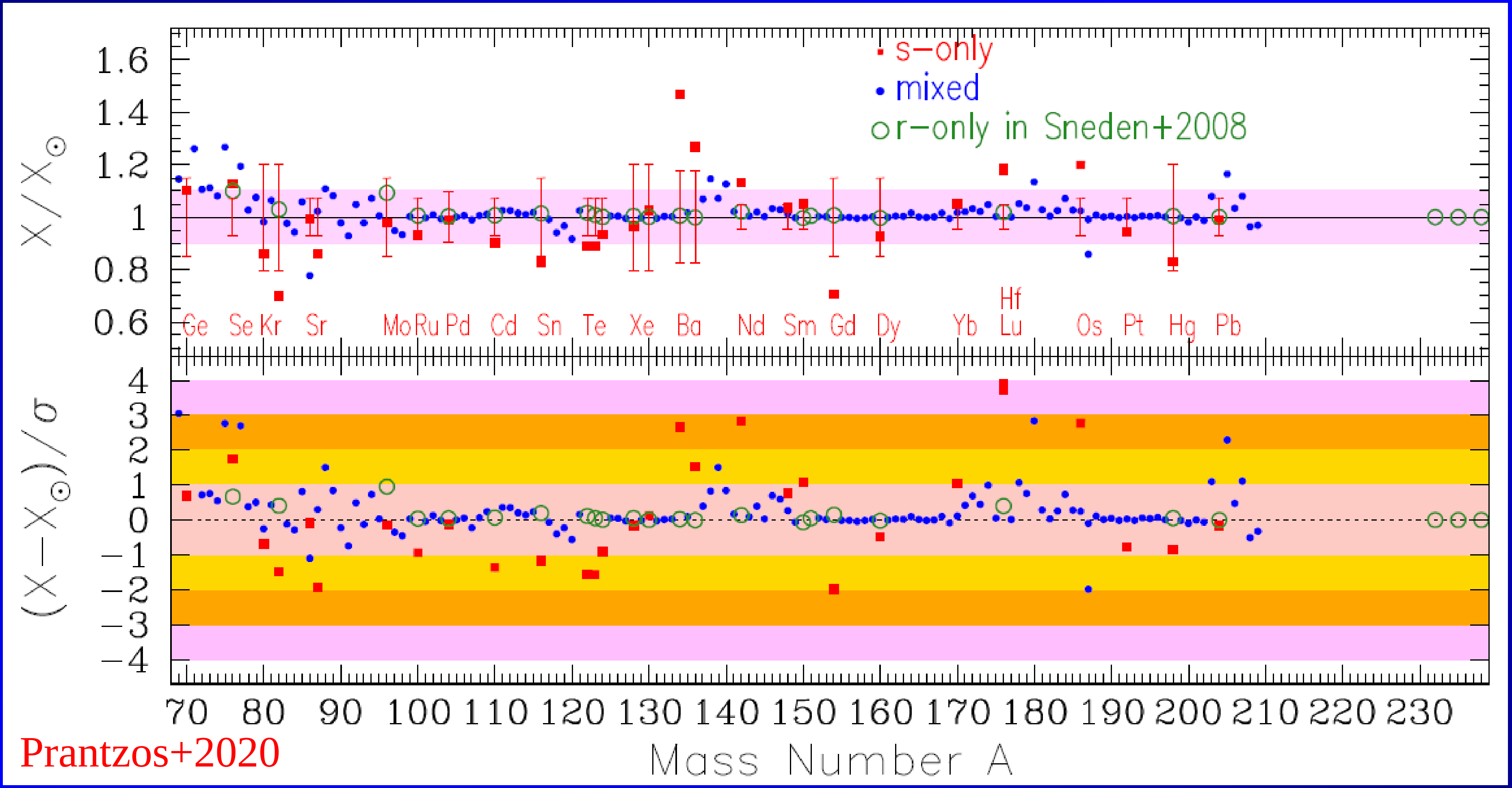
Busso,Kratz,Palmerini + 2022

How s-process neutron captures work?



<u>Branching points</u>: if $\tau_\beta \sim \tau_n$ $\Rightarrow$ several paths are possible

The importance of s-only isotope distribution



They can be used to test stellar model & nucleosynthesis robustness.

Seeds for the s-process

Main seeds are ^{56}Fe nuclei…

Why not the most abundant ^{1}H, ^{4}He or ^{12}C???

Seeds for the s-process

Main seeds are ^{56}Fe nuclei…

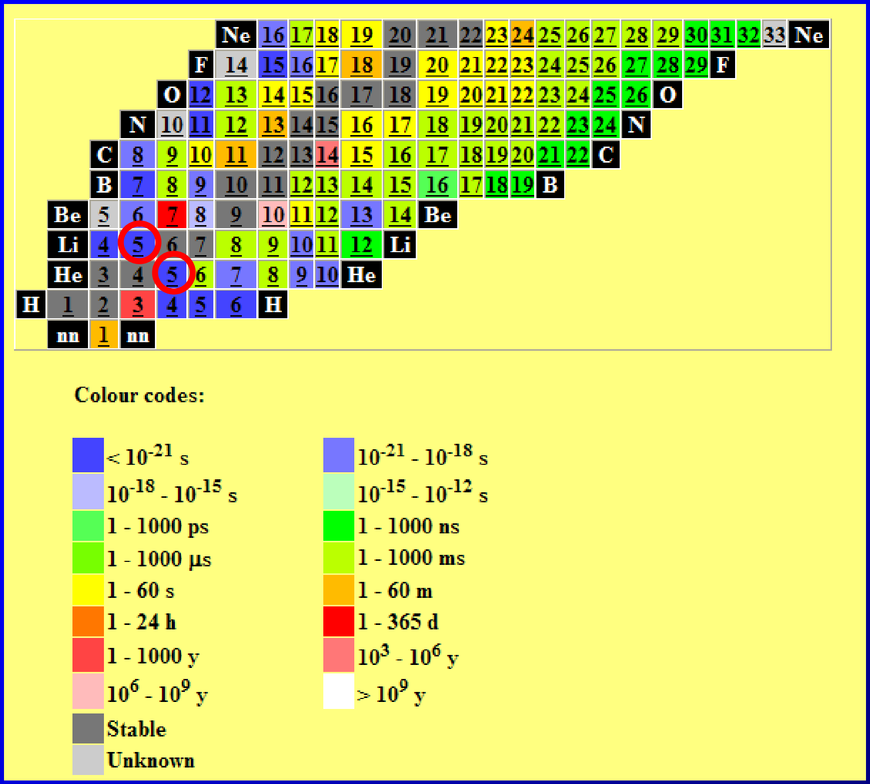
Why not the most abundant ^{1}H, ^{4}He or ^{12}C???

The reason lies in the nuclear structure of nuclei…and in the stars!!

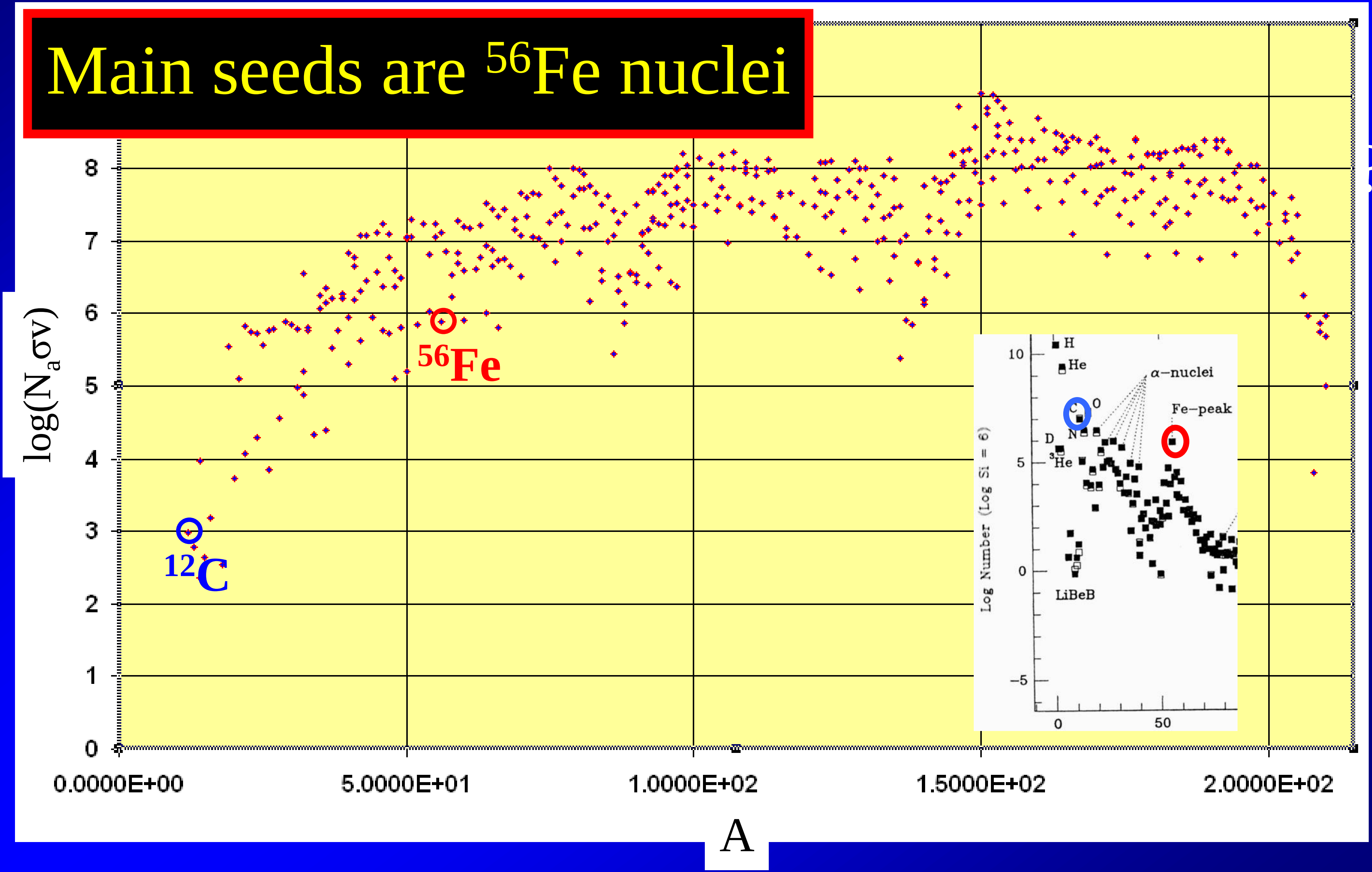
RATE[H(n,γ)^{2}H]∝N(H)

↓

10^{-12}

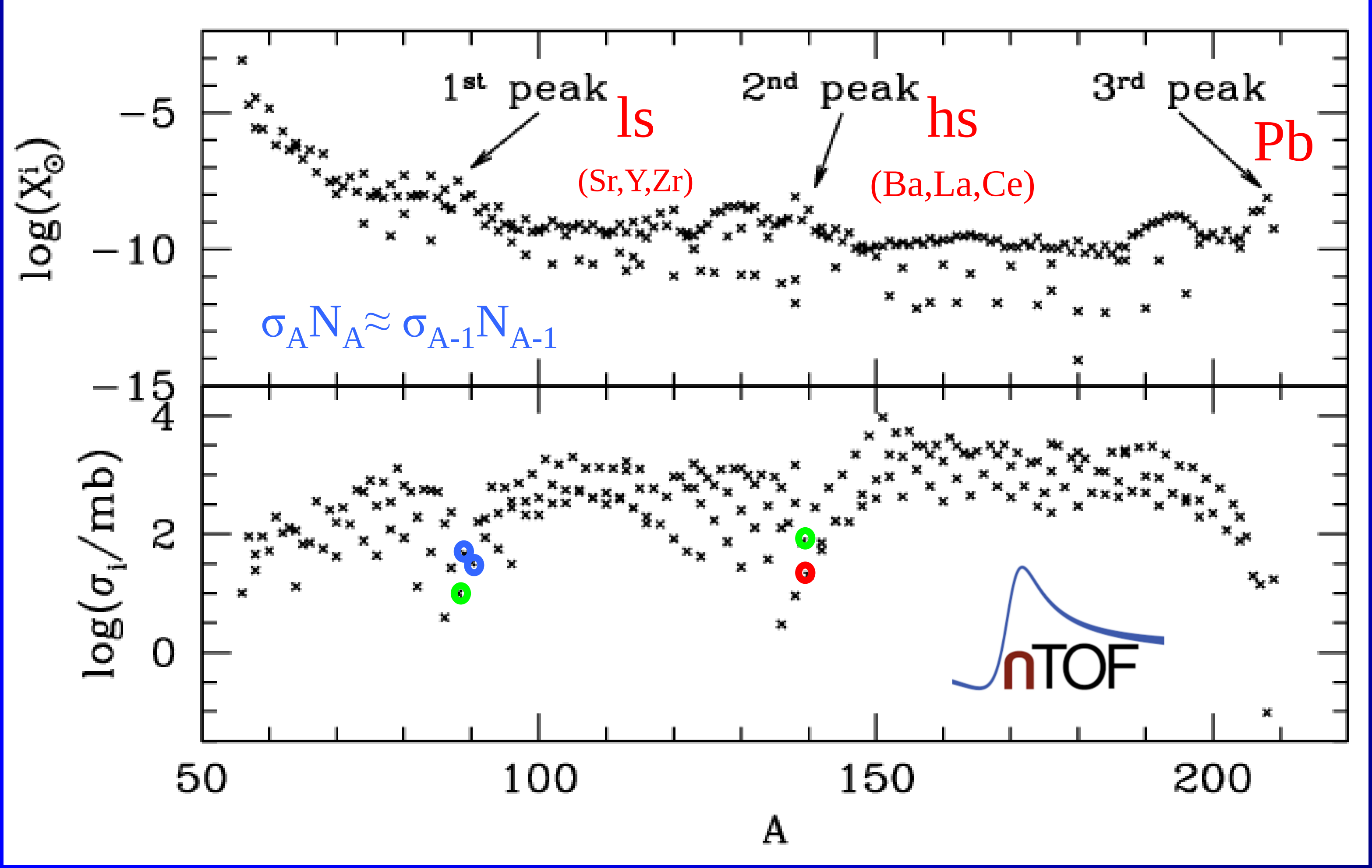


Seeds for the s-process



MAGIC NUCLEI

very small $\sigma(n,\gamma)$ at neutron magic numbers ⇄ abundance curve for elements beyond iron

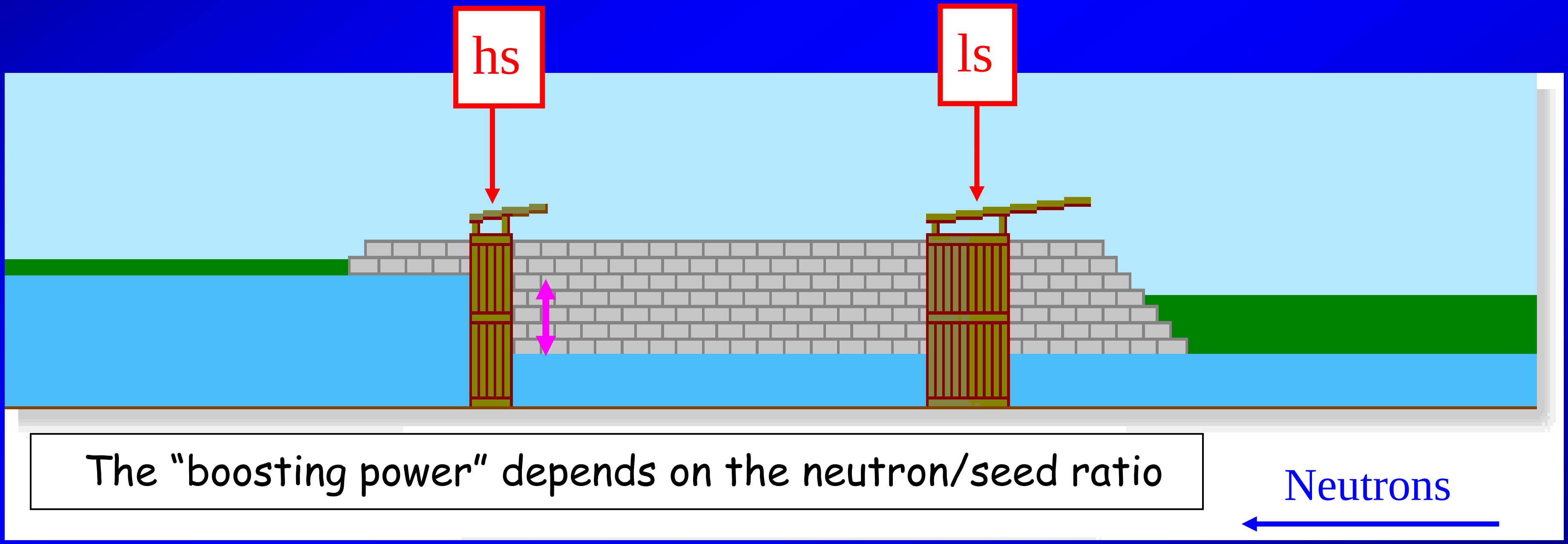


The three s-process peaks

1st peak → ls elements (Sr,Y,Zr) [N=50]

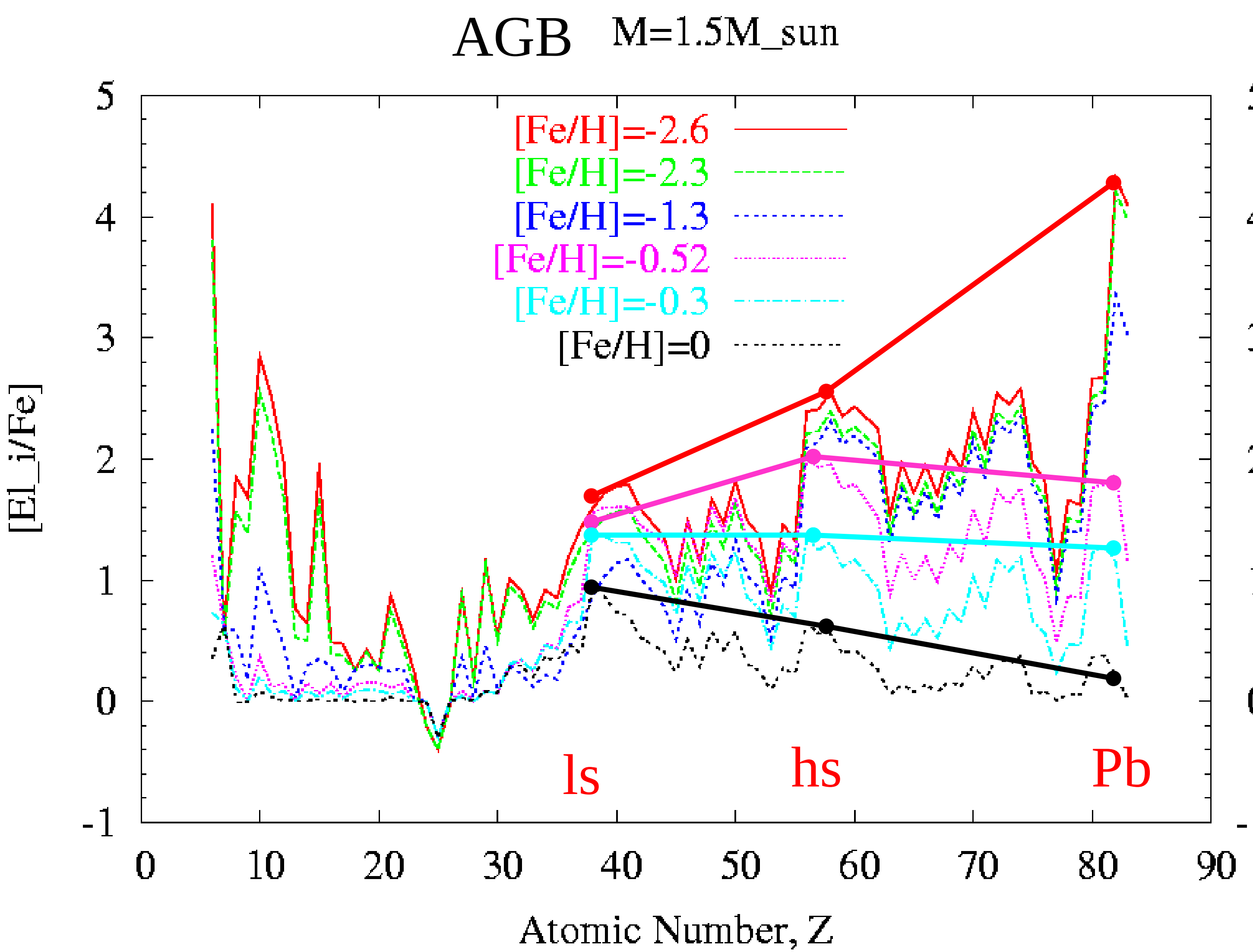
2nd peak → hs elements (Ba,La,Ce,Nd,Sm) [N=82]

3rd peak → lead (^{208}Pb) [N=126 & P=82]



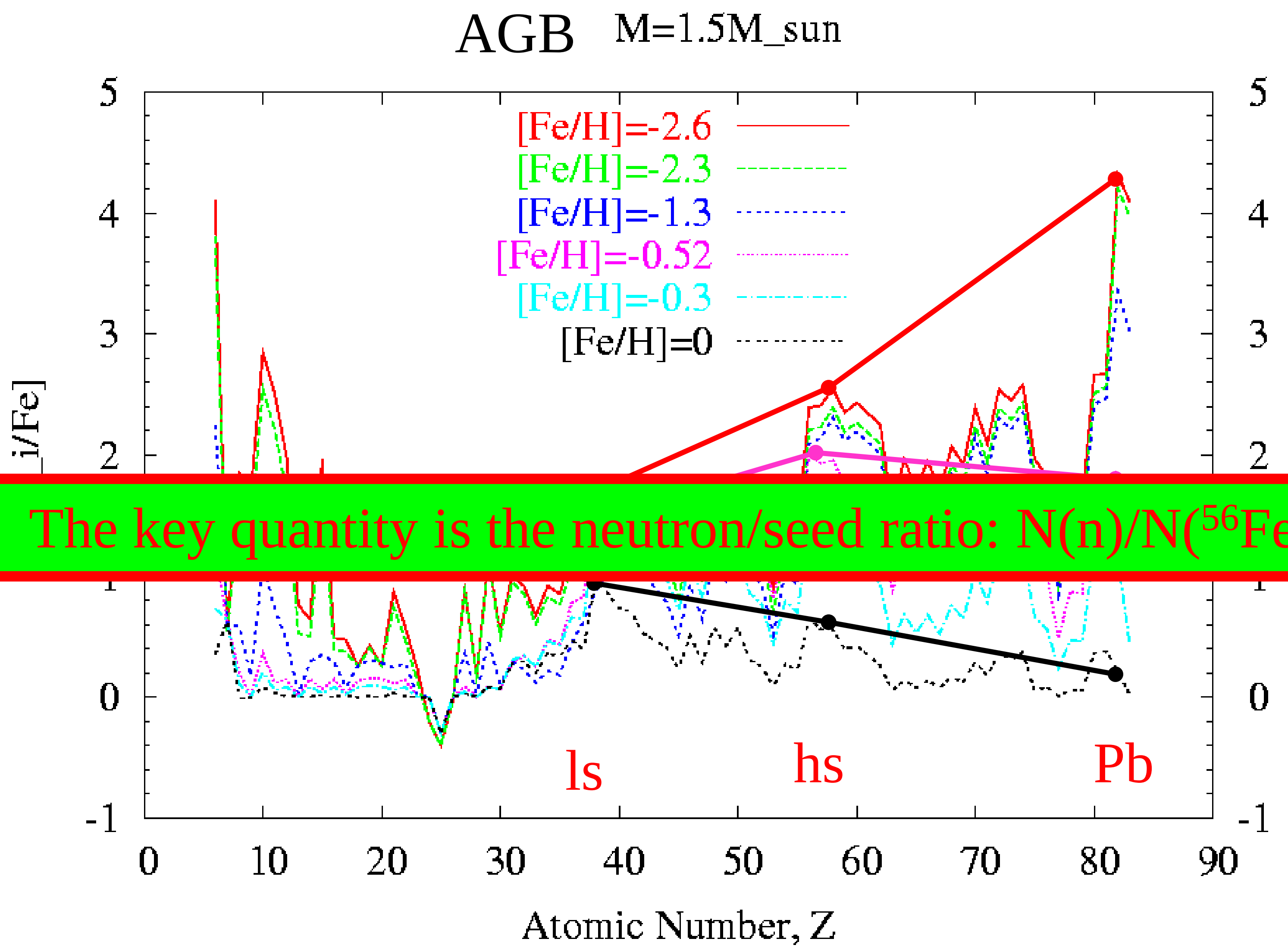
A sluice system with opening bulkheads

SURFACE DISTRIBUTION



R. Gallino's models

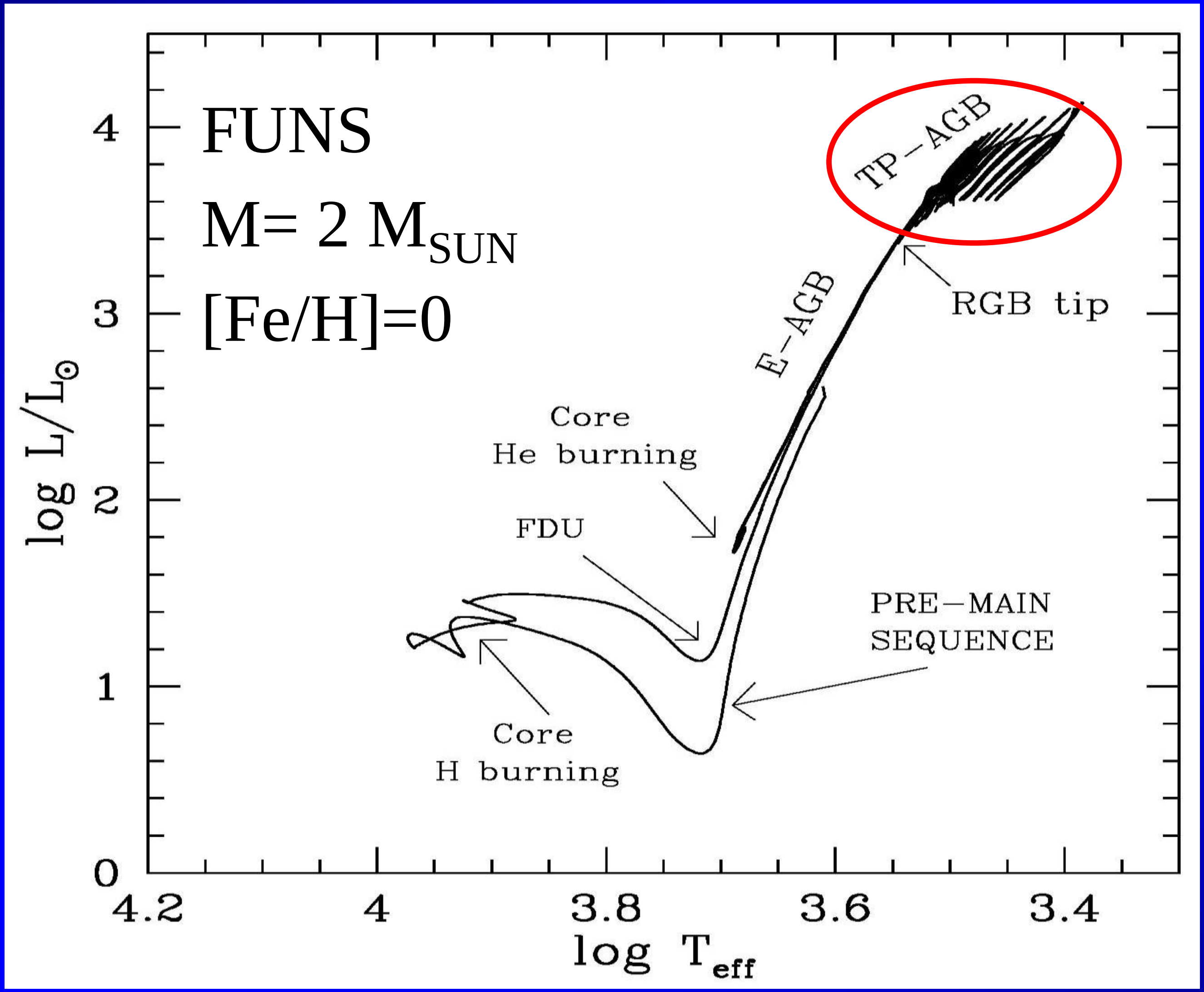
SURFACE DISTRIBUTION



The key quantity is the neutron/seed ratio: N(n)/N(^{56}Fe)

R. Gallino’s models

Asymptotic Giant Branch (AGB) stars

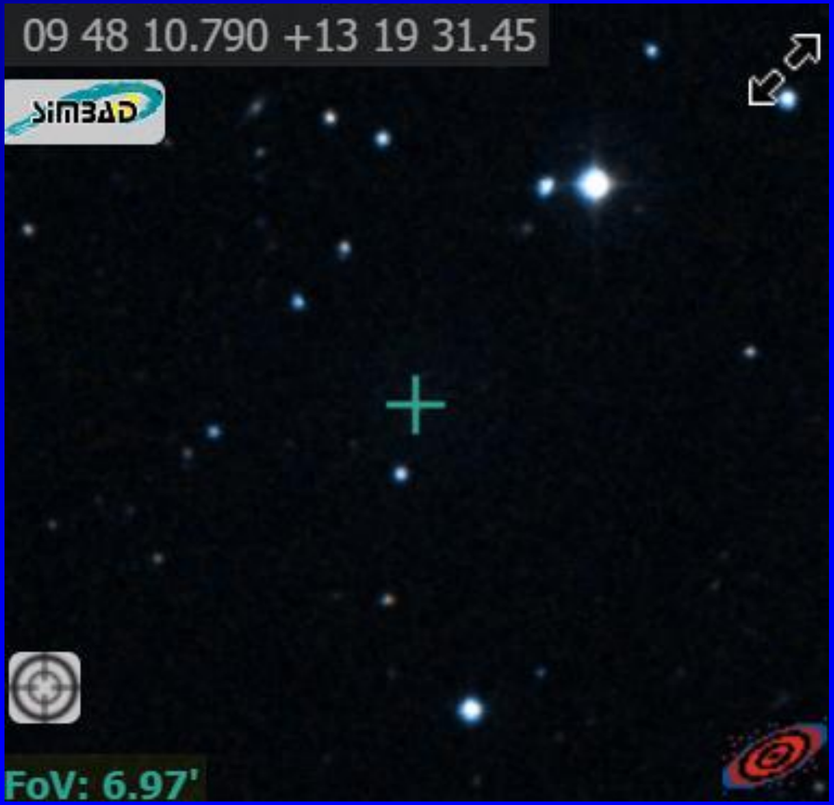


$\tau_{MS} \approx 1$ Gyr

$\tau_{AGB} \approx 1$ Myr

Can we see an AGB star in the sky?

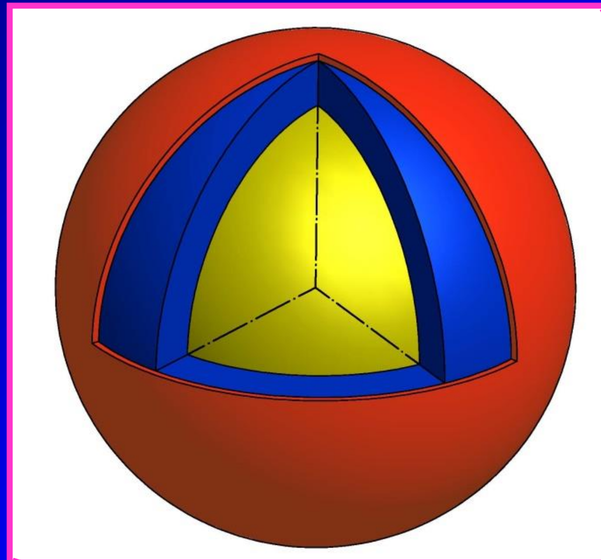
CW Leonis



OPTICAL BAND **INFRARED BAND**

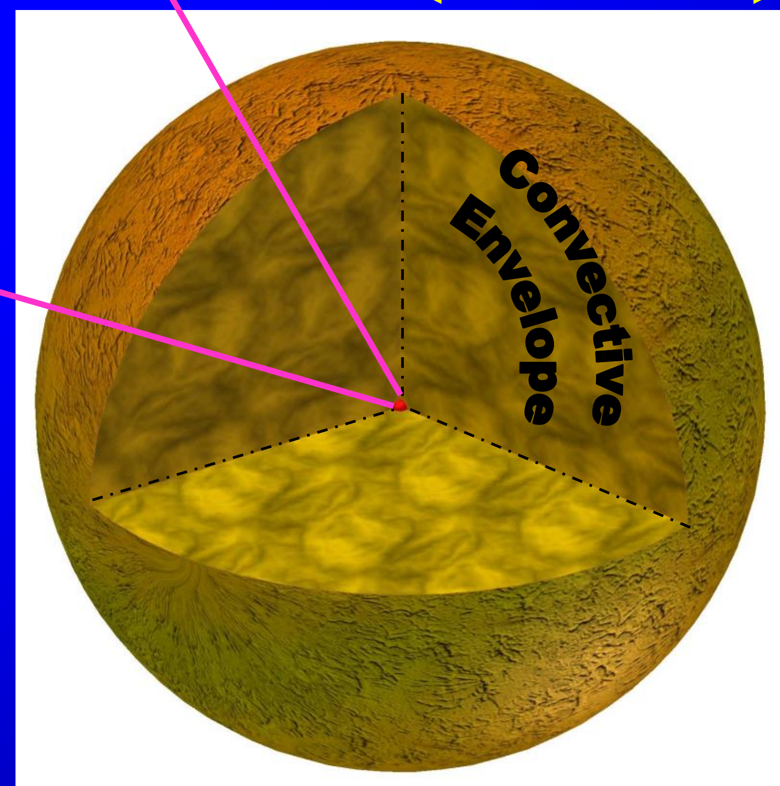
AGB structure

CO Core
He-shell
H-shell



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

Earth-Sun
(~200 R_{SUN})



It's like you put a nut
in a 300 mts hot air balloon!!!

Where do s-process neutrons come from?

Free neutrons are NOT abundant in the major phases of nuclear burnings.

Neutrons are liberated to some extent by secondary reactions during helium burning in **Asymptotic Giant Branch (AGB) stars**, as well as during **core-He and shell-C burnings of massive stars**.

Major neutron sources of the s-process

$^{13}C(\alpha,n)^{16}O$ $^{22}Ne(\alpha,n)^{25}Mg$

The nuclear paths

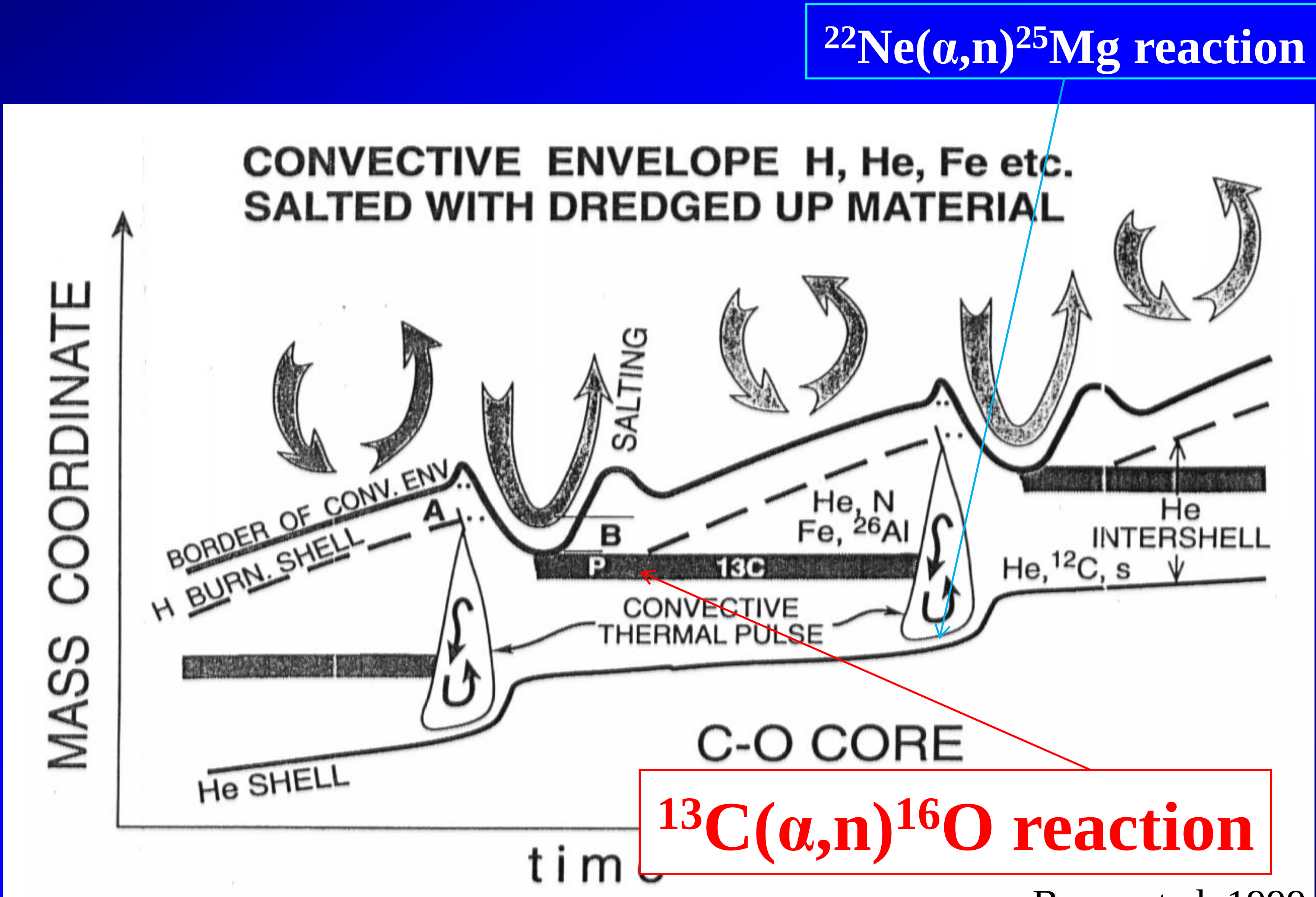
^{13}C: main source for the Main component

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

^{22}Ne: main source for the Weak component

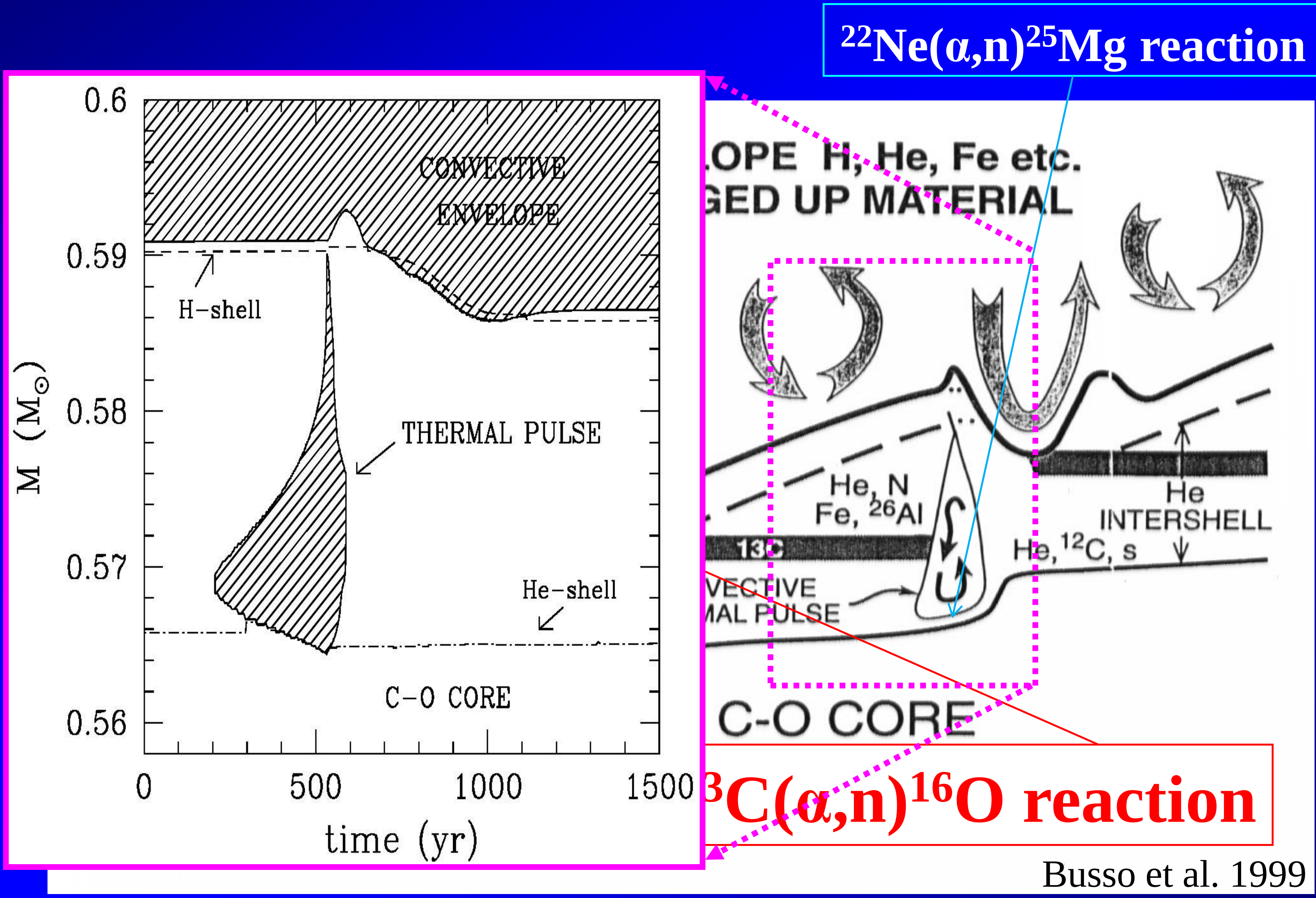
$$^{14}N(\alpha,\gamma)^{18}F(\beta^+)^{18}O(\alpha,\gamma)^{22}Ne$$

The s-process in AGB stars



Busso et al. 1999

The s-process in AGB stars



Busso et al. 1999

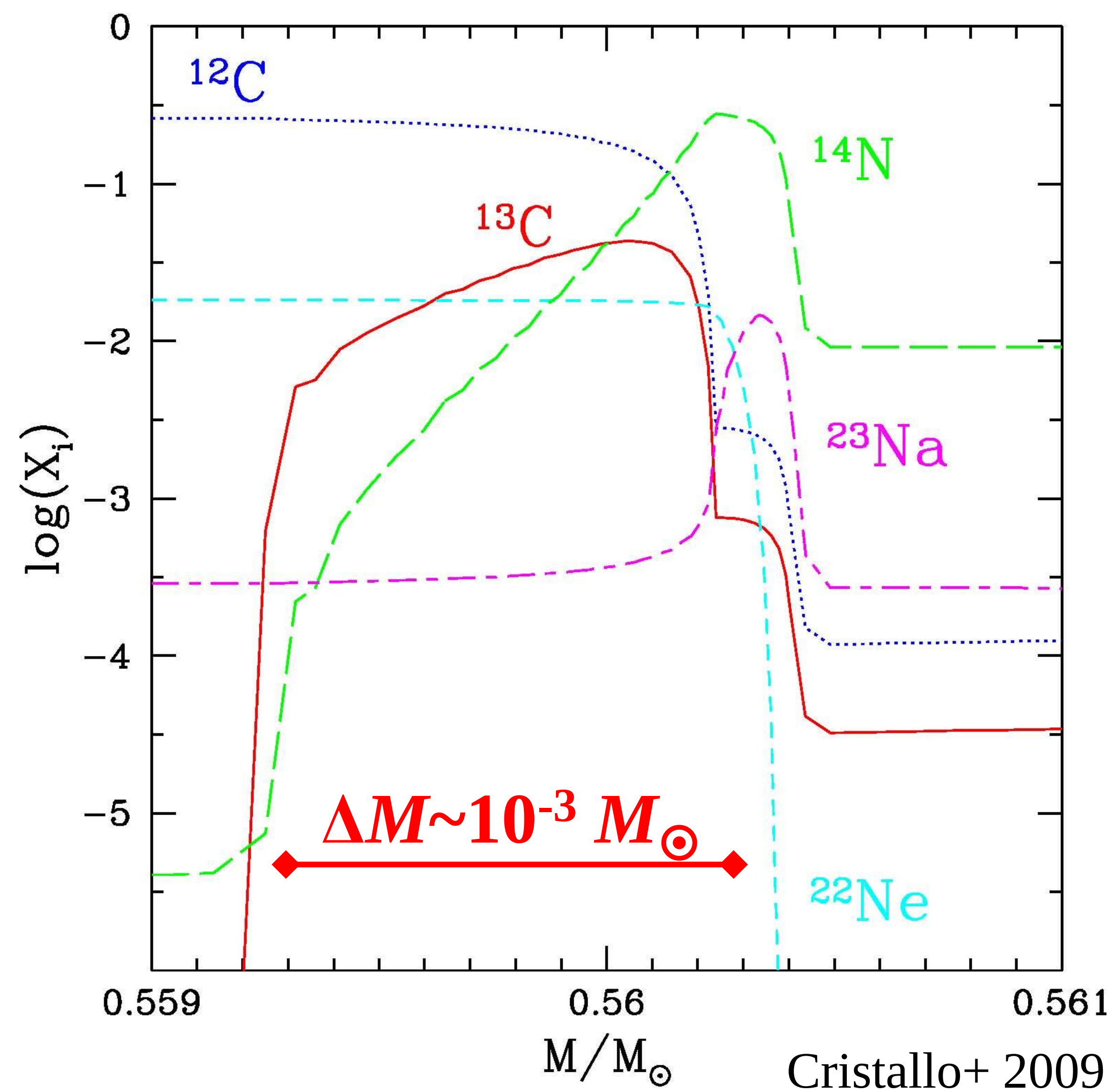
The formation of the ^{13}C pocket

^{13}C-pocket

^{14}N-pocket

^{14}N strong neutron poison via $^{14}N(n,p)^{14}C$ reaction

nTOF



Cristallo+ 2009

The ^{13}C pocket in stellar evolutionary models

- ✓ **Opacity induced overshoot (SC+…)**
- ✓ **Convective Boundary Mixing + Gravity Waves (Battino+ 2017)**

The ^{13}C pockets in post-process calculations:

- ✓ **n-zones profile (Gallino+…)**
- ✓ **Exponential hydrogen profile (Lugaro+…)**
- ✓ **Magnetic-induced mixing (Trippella+ 2014)**

How does the ^{13}C pocket change?

- ✓ **Rotation-induced mixing (Herwig+ 2003; Siess+ 2004; Piersanti+ 2013)**

Opacity induced overshoot: a ballistic approach

Let's assume that the deceleration is proportional to the square of the velocity, as it happens to a body moving in a sufficiently dense fluid:

Viscosity

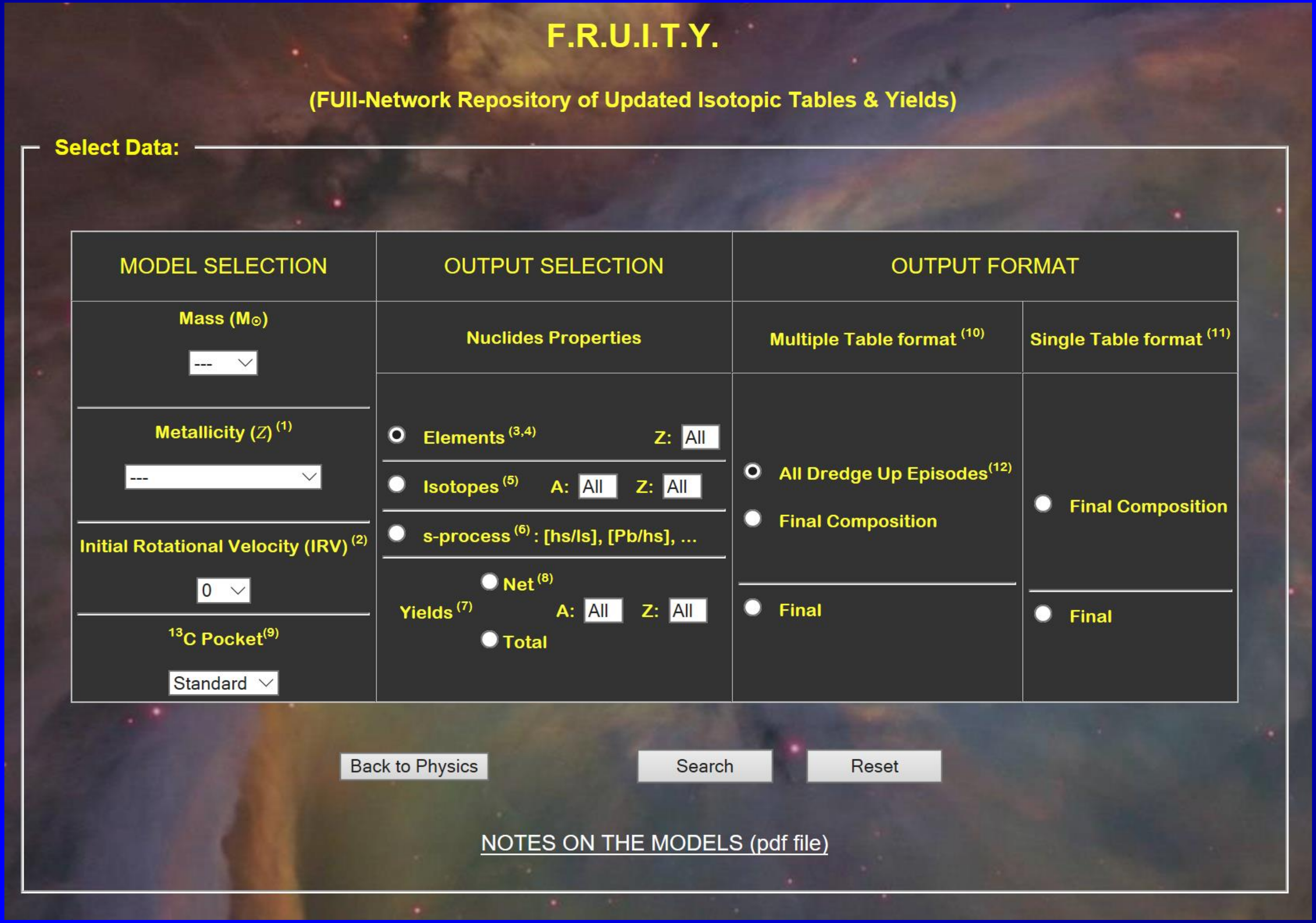
$$\ddot{r} \propto -kv^{-2}$$

$$v = v_0 \exp[-k(r-r_0)]$$

$$v = v_{bce} \cdot \exp(-d/\beta H_p)$$

- V_{bce} is the convective velocity at the inner border of the convective envelope (*CE*)
- d is the distance from the *CE*
- H_p is the scale pressure height
- $\beta = 0.1$

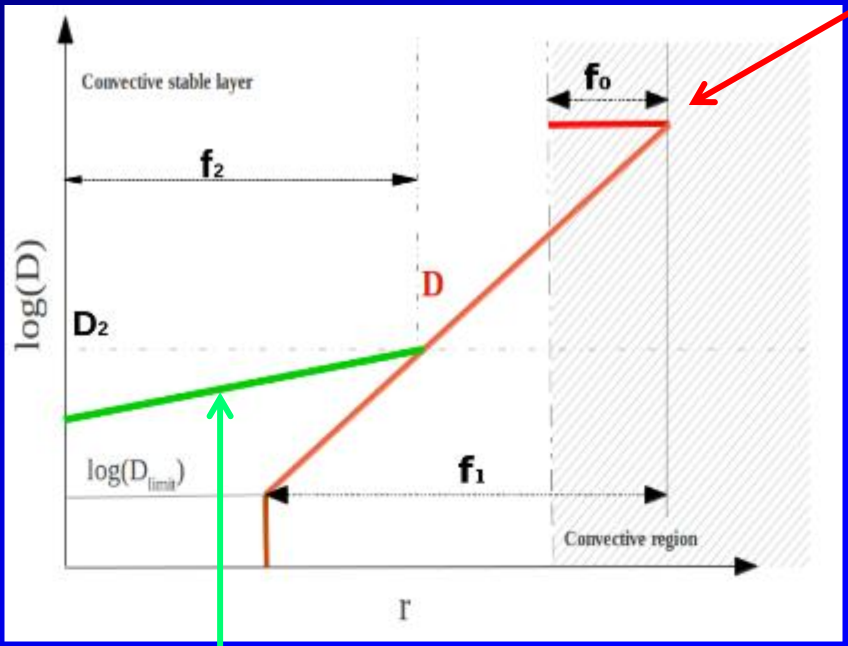
F.R.U.I.T.Y.



On line at www.oa-abruzzo.inaf.it/fruity

Convective Boundary Mixing + Gravity Waves

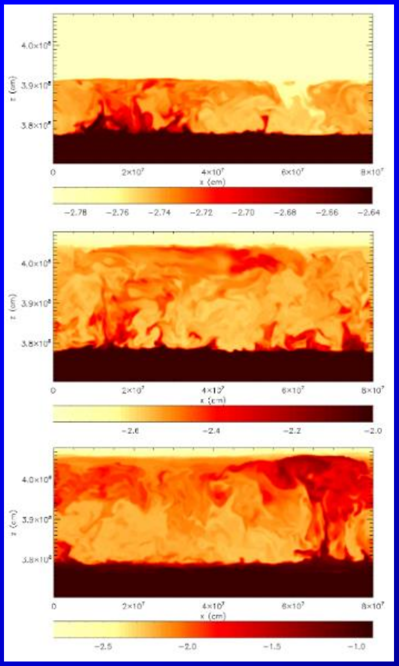
Battino+ 2016



Gravity waves

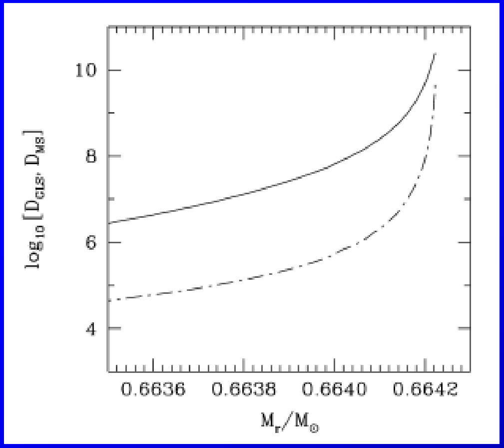
Kelvin-Helmholtz (shear) instability

Casanova+ 2016



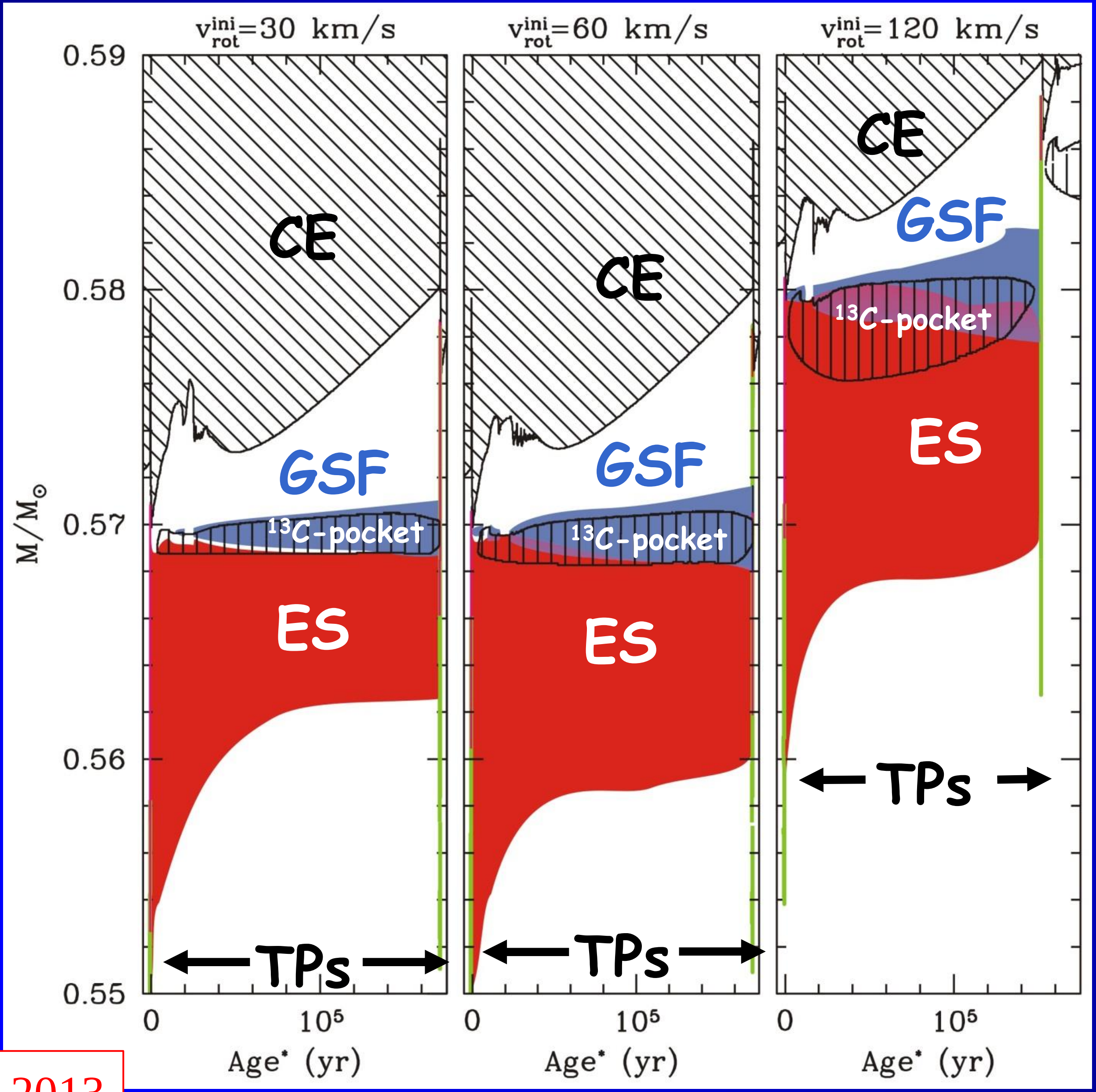
Depending on the velocity difference across the interface, K-H instability may induce mixing if:

$N^2/(dv/dr)^2 < 0.25$



Denissenkov & Tout 2003

Rotation induced instabilities during the AGB phase

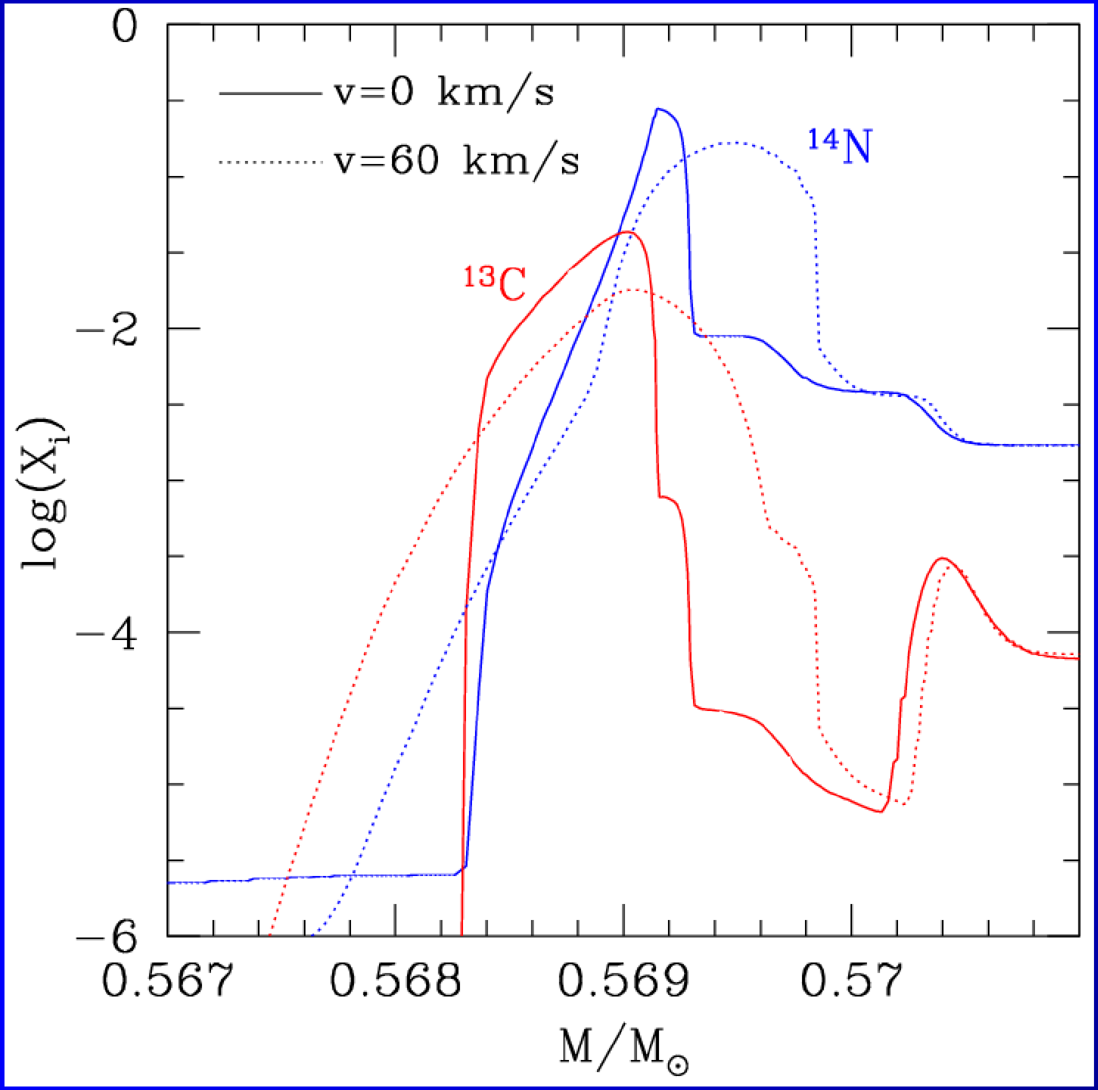


M=2.0 M_{SUN}
[Fe/H]=0

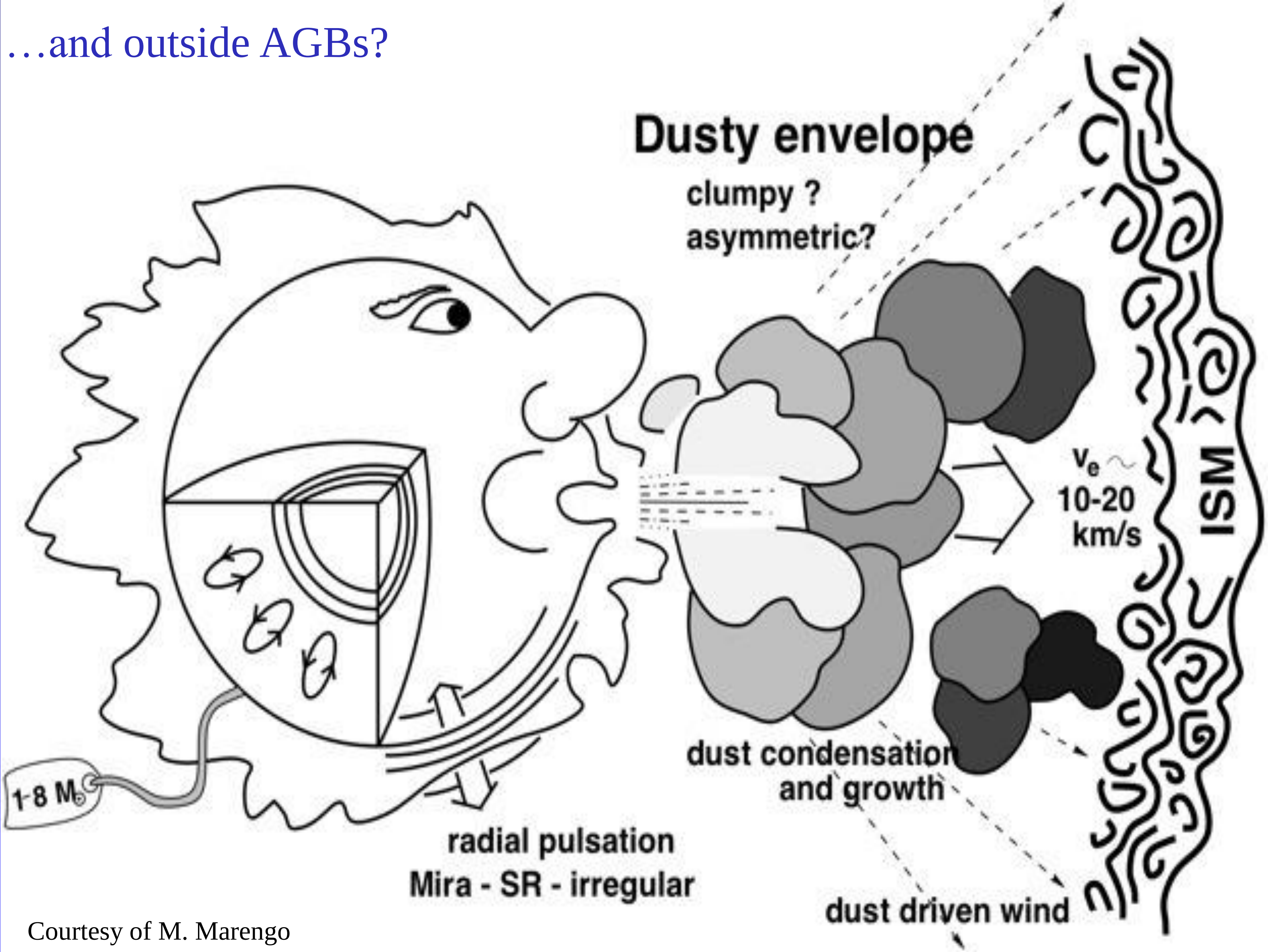
Piersanti+ 2013

NET EFFECT

It mixes ^{14}N in ^{13}C-rich layers (and viceversa), thus implying a decrease of the local neutron density and an increase of the iron seeds. As a consequence, the surface s-process distributions change.



…and outside AGBs?



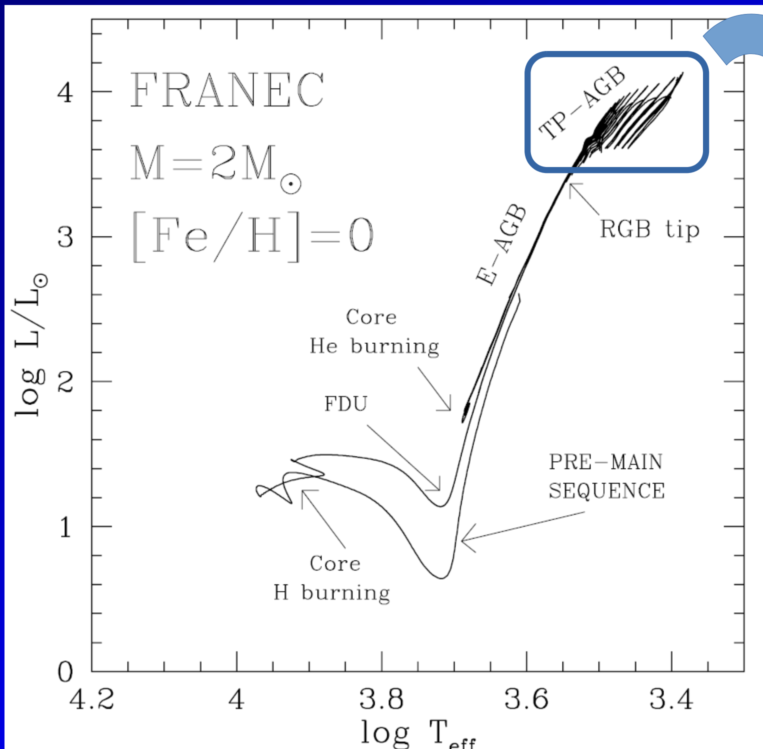
Courtesy of M. Marengo

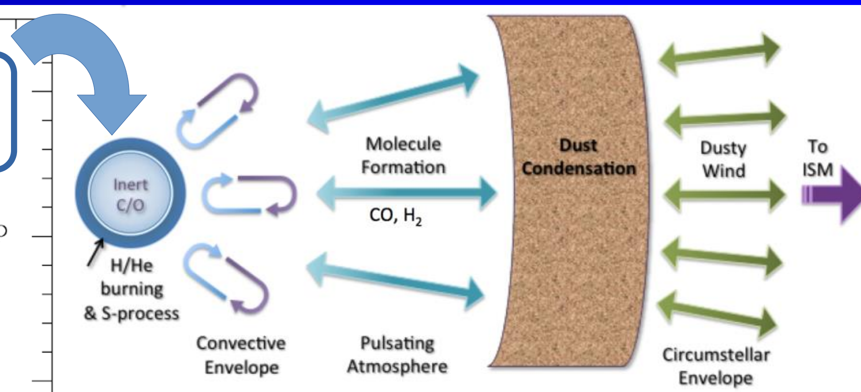
Meteorites


Allende (Mexico, 1969)

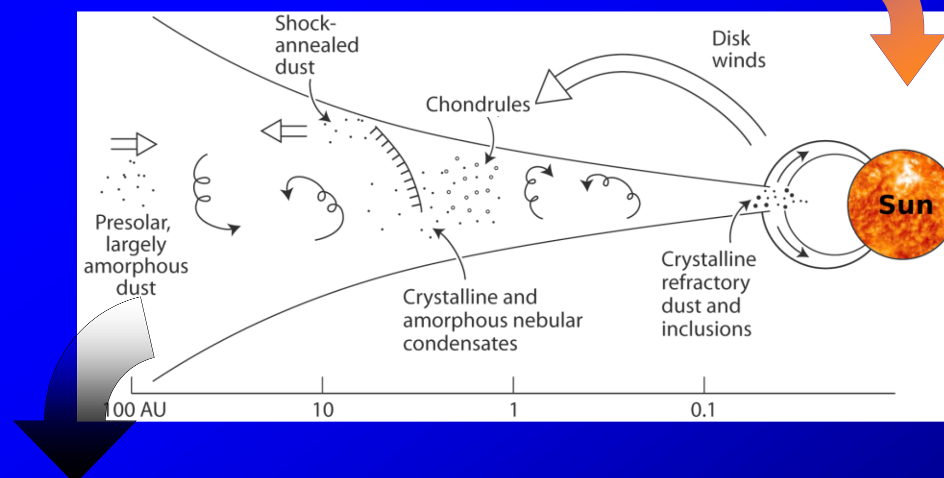
Murchison (Australia, 1969)

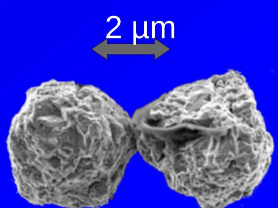
AGB stars and presolar SiC grains





Molecular cloud

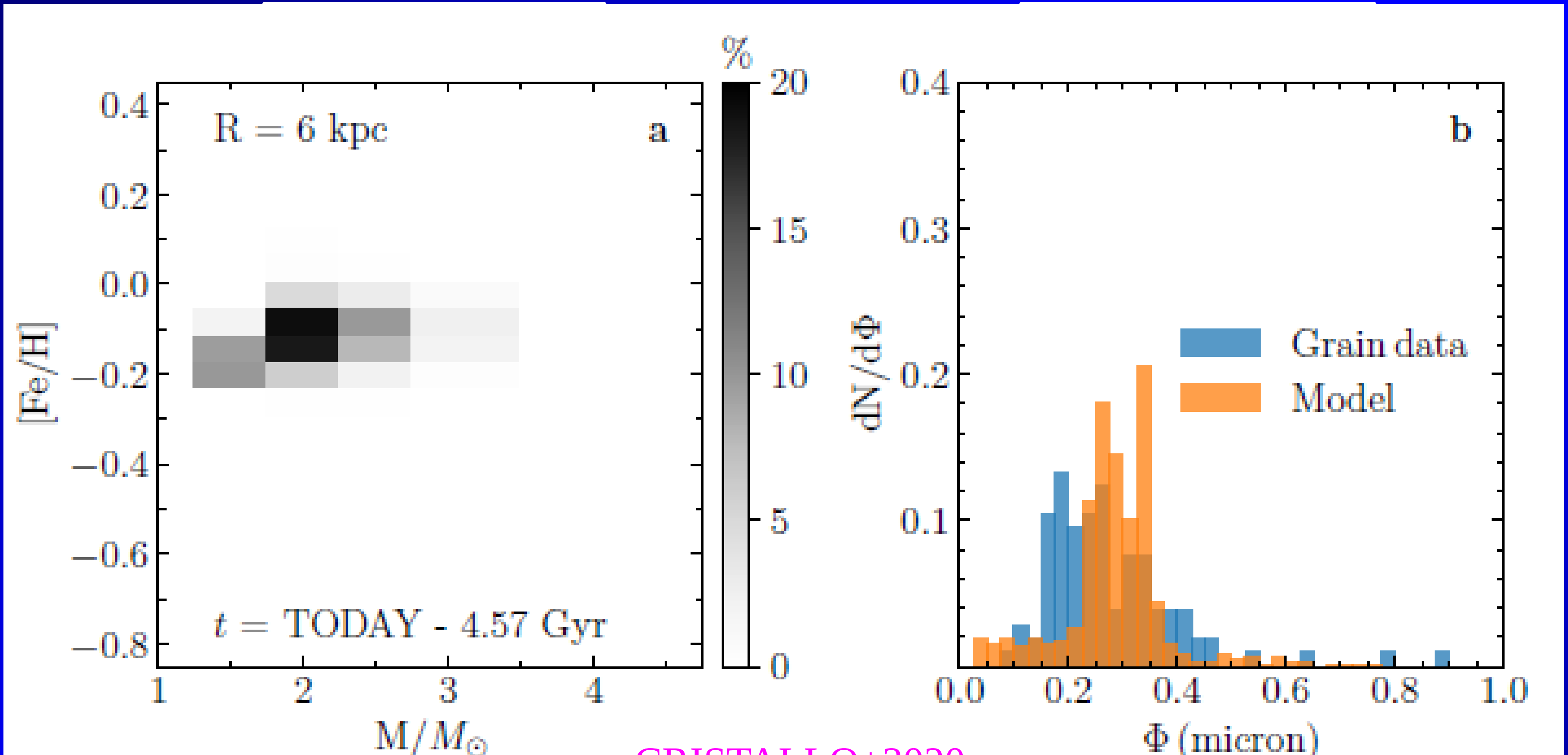




Meteorites and asteroids

Presolar grains

Important question is: which stars are progenitor of pre-solar SiC grains?

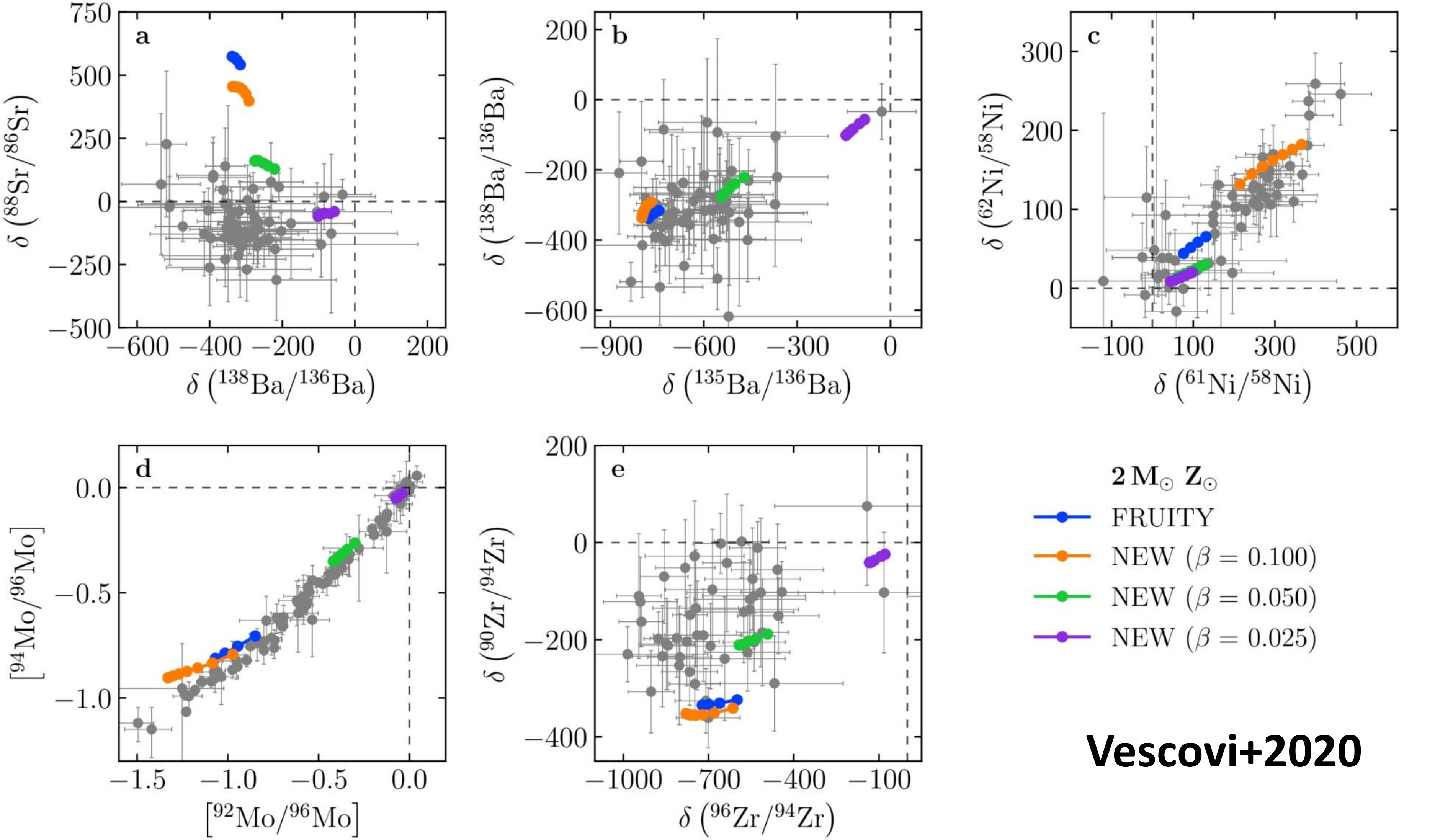


CRISTALLO+2020

Our models predict that the SiC production at the epoch of the Solar System formation is dominated by contributions from AGB stars with **$M \approx 2M_{SUN}$ and $Z \approx Z_{SUN}$**, which are thus likely <u>the parent stars of presolar SiC grains identified in extraterrestrial materials</u>.

SiC Grains I

- **Isotopic data** including Ni, Sr, Zr, Mo, and Ba isotope ratios in **presolar SiC grains**
- Stellar models with **same initial mass** (2 $M_\odot$) and **solar metallicity**



Vescovi+2020

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

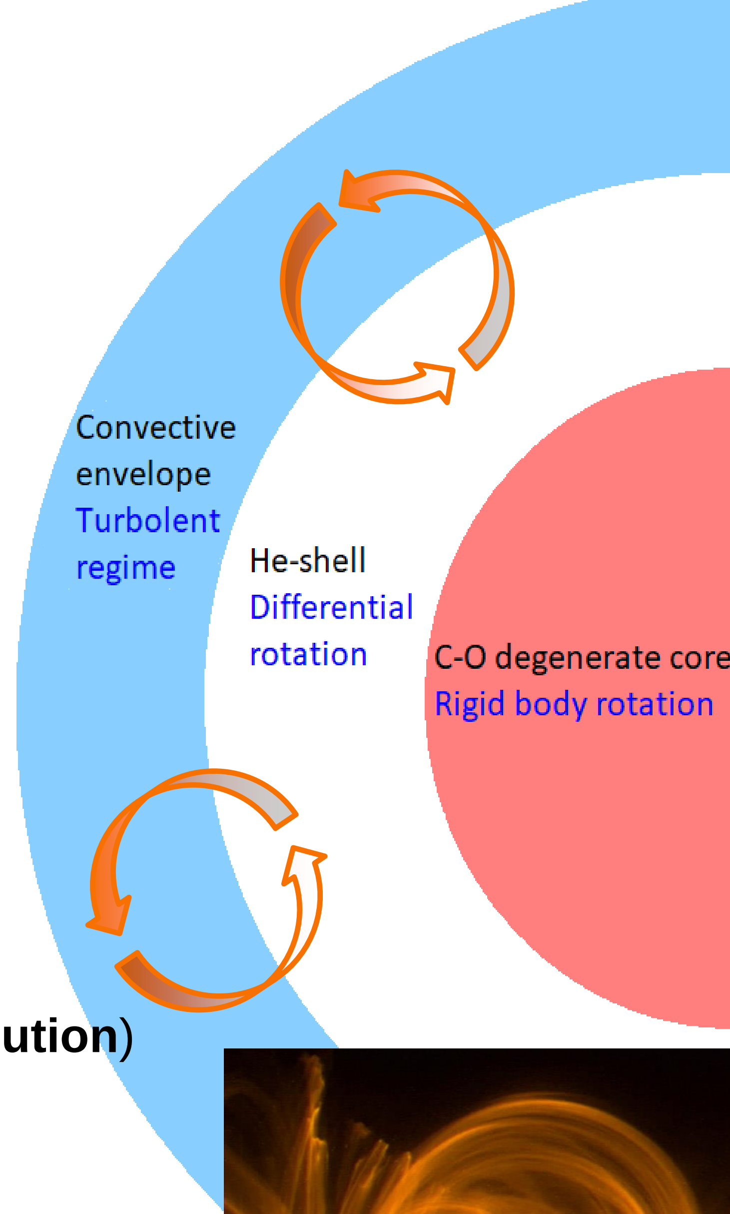
- Opacity-induced overshoot (Cristallo+2009,2011,2015)
- Convective Boundary Mixing (Battino+2016)

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 $\rho \propto r^k$:

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

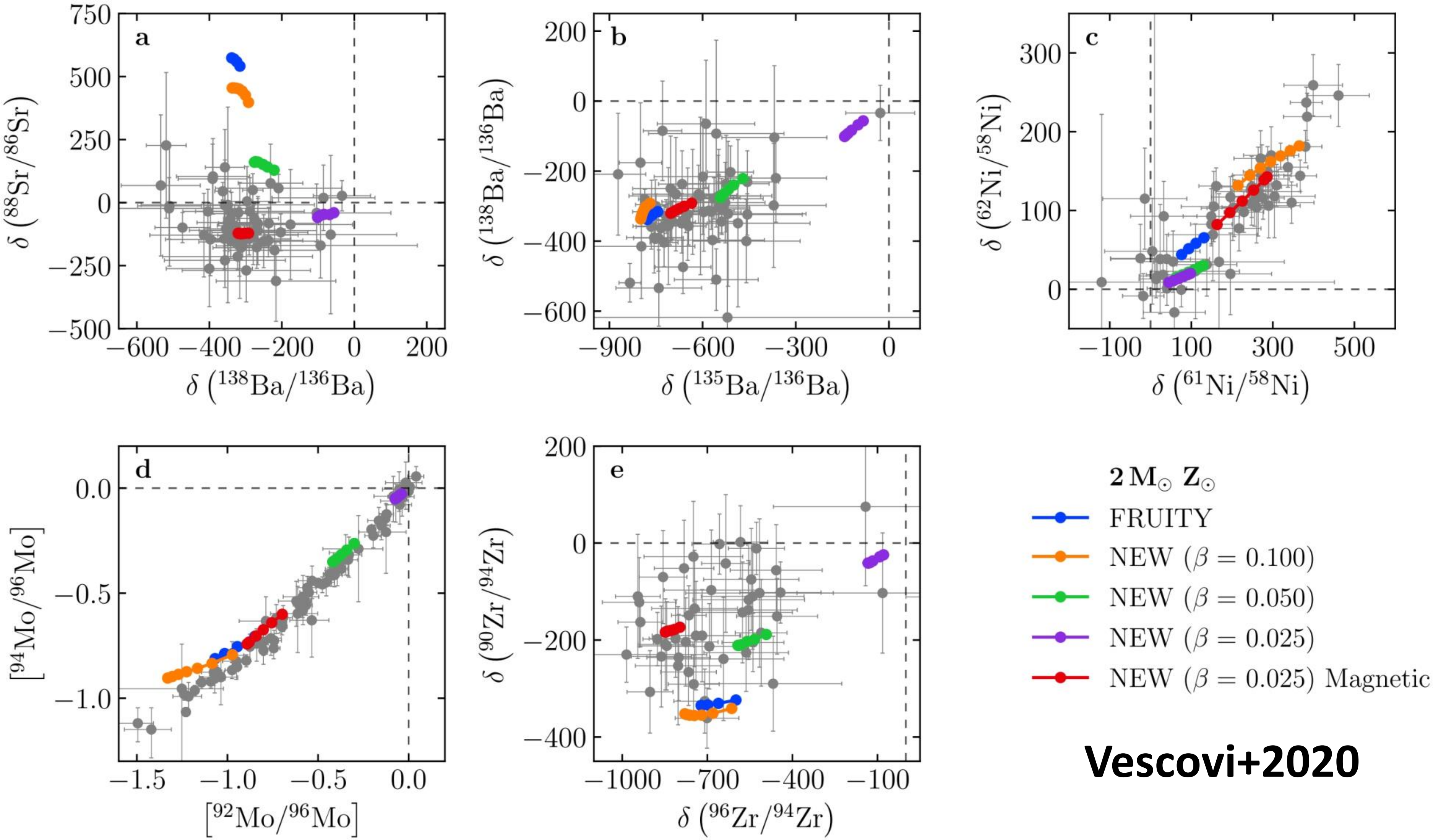
- Parameters:
  - Layer "**p**" at the deepest coordinate from which buoyancy starts
  - (can be identified from the corresponding **critical toroidal** $\boldsymbol{B_\varphi}$ value)
  - Starting velocity $\boldsymbol{u_p}$ of the buoyant material

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

➔ <u>Calibration</u> is needed!

SiC Grains II

- **Magnetic** contribution account for SiC data!!
- Best fit for $u_p = 5 \times 10^{-5}$ **cm/s** and $B_\varphi = 5 \times 10^4$ **G**

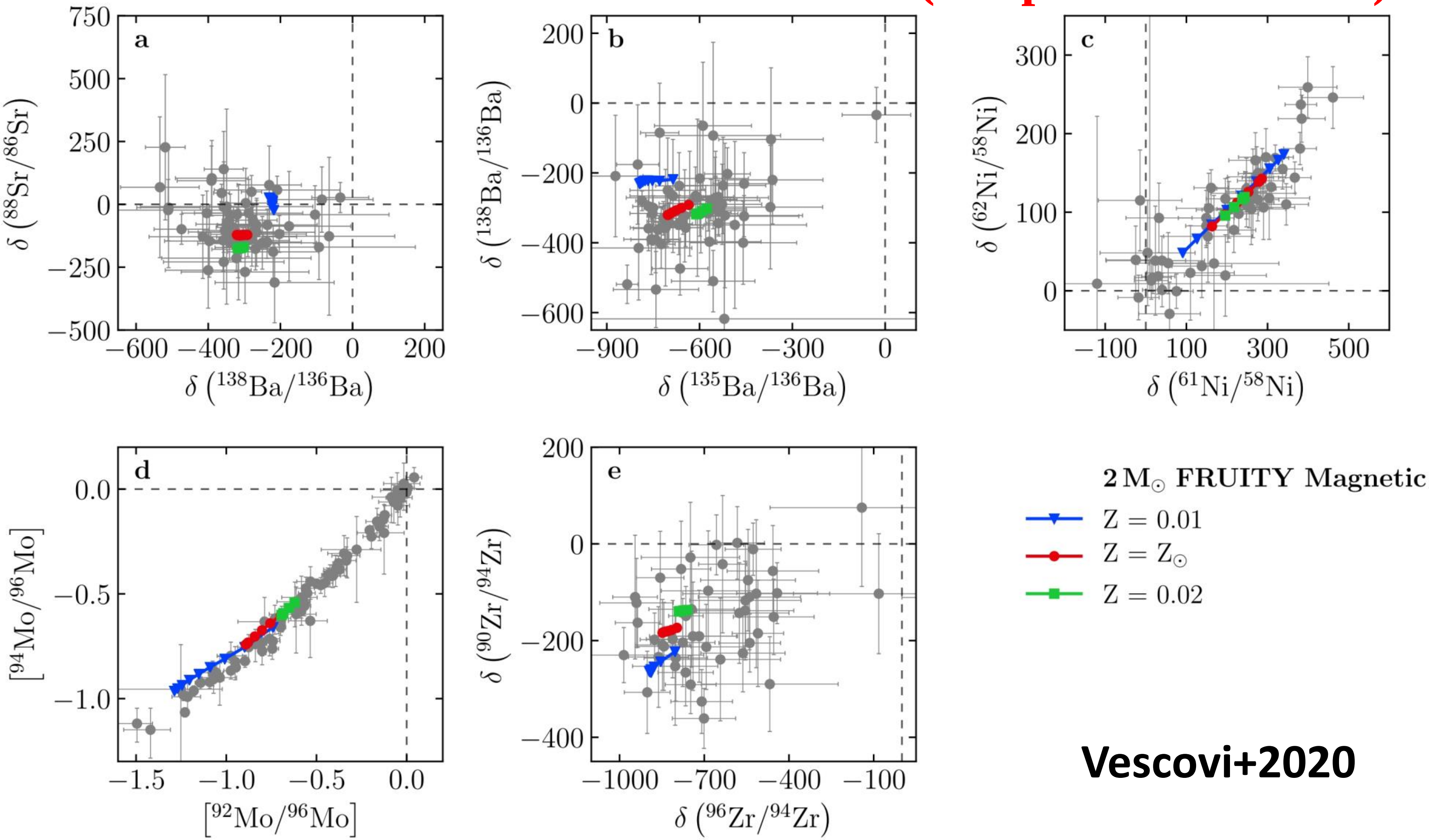


Vescovi+2020

SiC Grains III

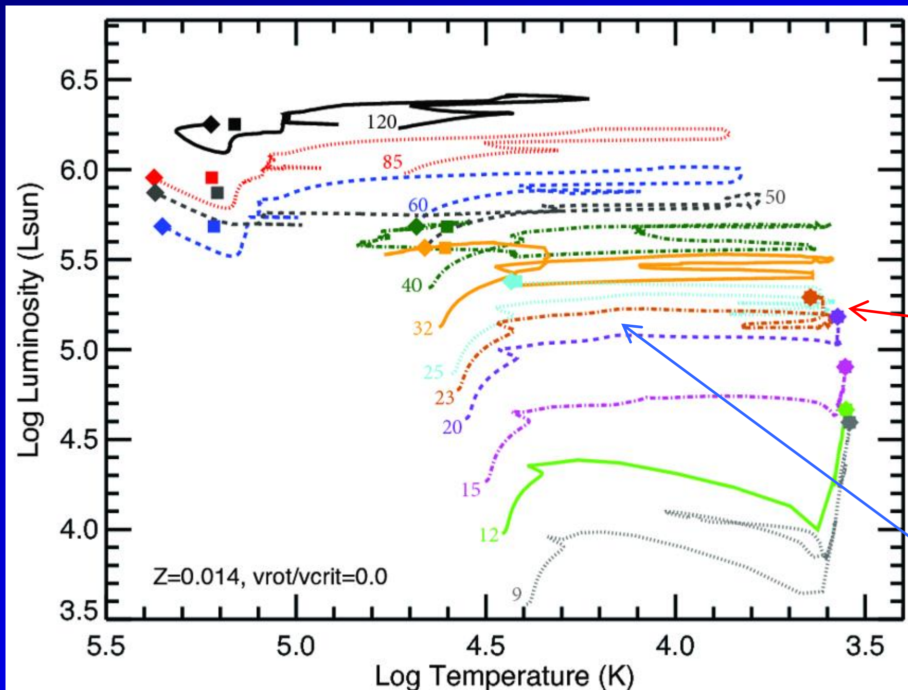
- Stellar models with **same initial mass** (2 $M_\odot$) and **close-to-solar metallicity**
- **Magnetic** contribution

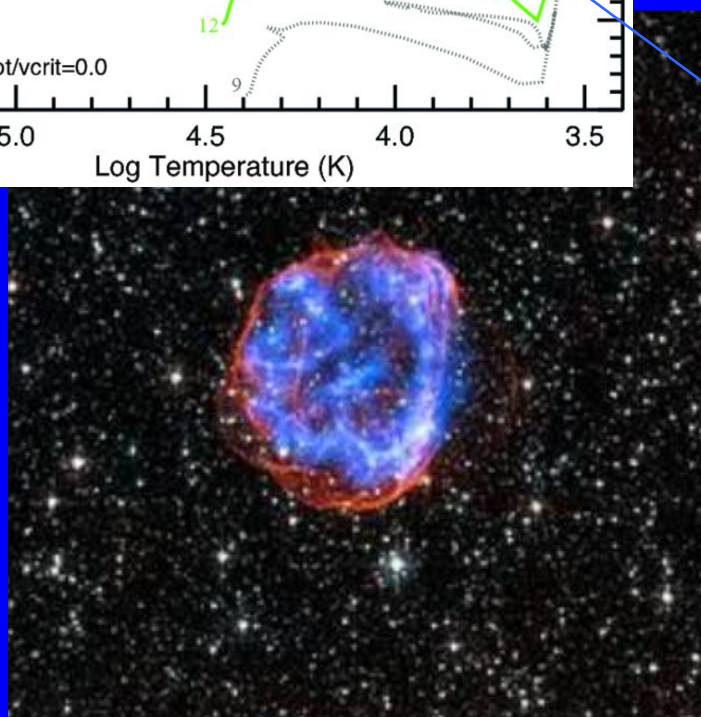
What about ^{64}Ni? (See posters 9 and 10)

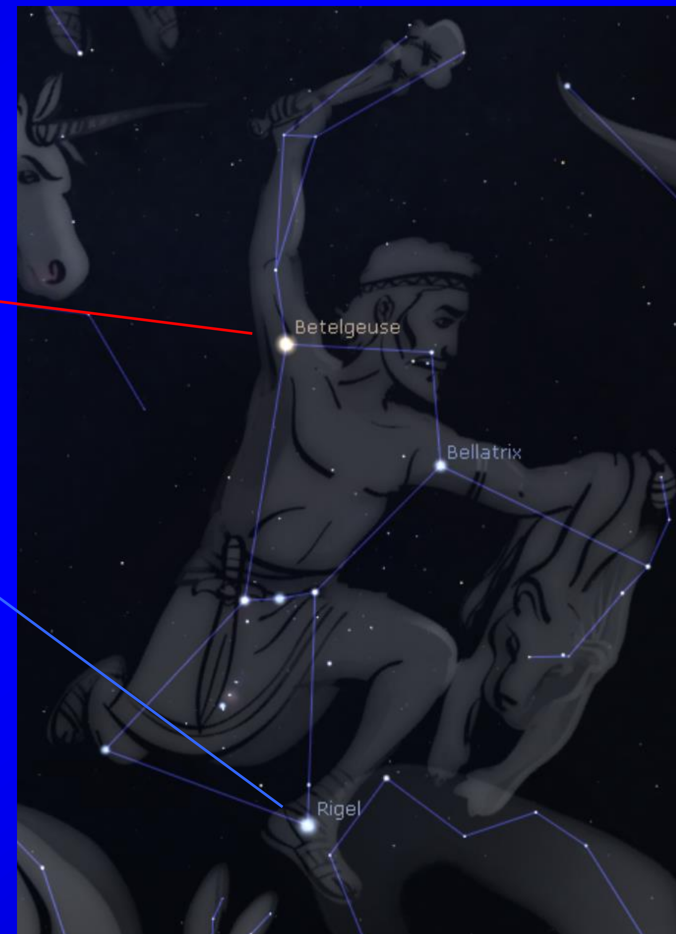


Vescovi+2020

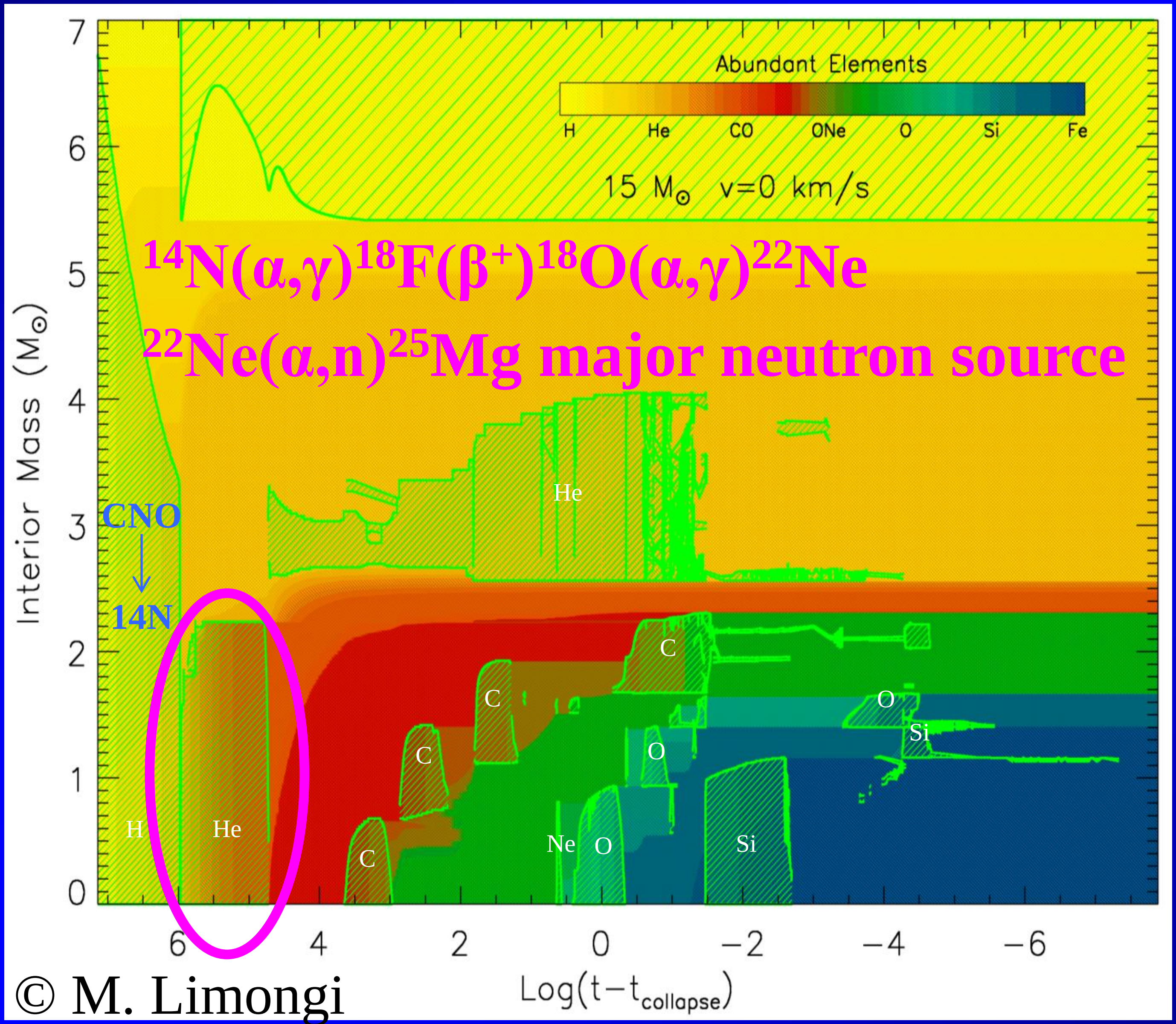
The weak s-process in massive stars



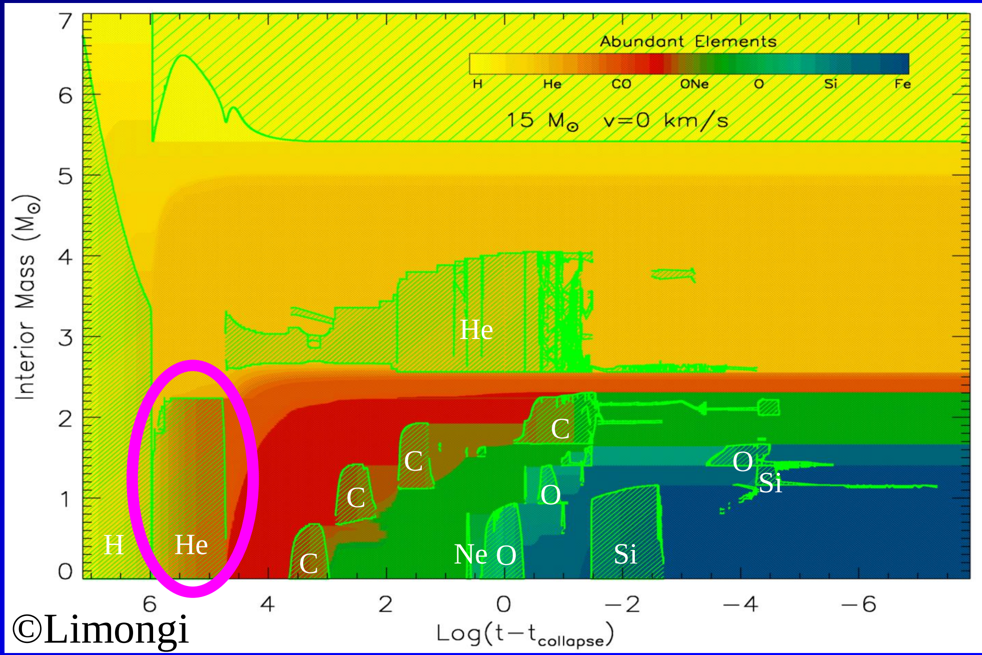




The weak s-process and the evolution of massive stars



Core He-burning phase



$3\alpha \rightarrow {}^{12}C$

${}^{12}C(\alpha,\gamma){}^{16}O$

${}^{14}N(\alpha,\gamma){}^{18}F(\beta^+){}^{18}O(\alpha,\gamma){}^{22}Ne$

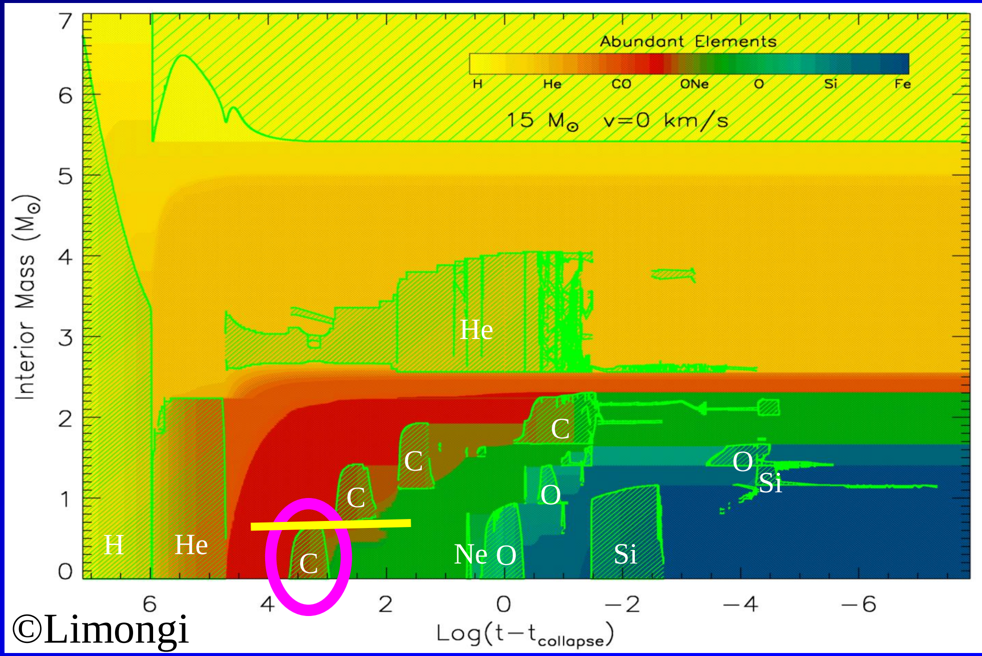
$\tau \approx 1$ Myr

When T~3x10^8 K the **${}^{22}Ne(\alpha,n){}^{25}Mg$ is efficiently activated**

The resulting neutron density is low (~10^6 n/cm^3)

Similar to the s-process

Core C-burning phase



$^{12}C(^{12}C,\alpha)^{20}Ne$

$^{12}C(^{12}C,p)^{23}Na$

$^{12}C(^{12}C,n)^{23}Mg^{*}$

$\tau \approx 1$ Kyr

Some ^{22}Ne is left after He burning

All (α,n) channels are activated:

$^{13}C(\alpha,n)^{16}O$ - $^{17}O(\alpha,n)^{20}Ne$

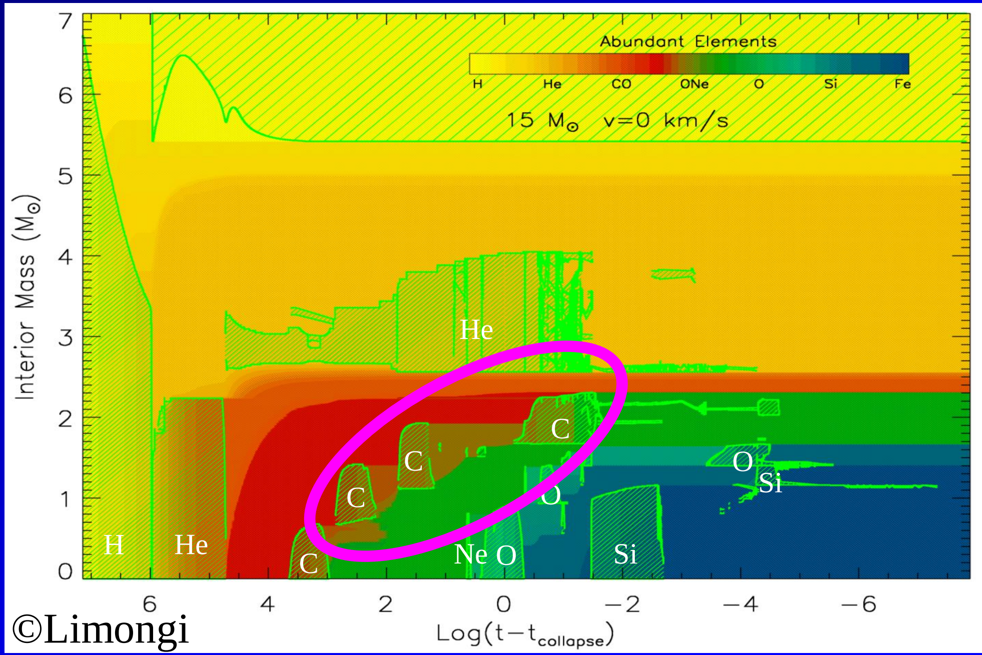
$^{18}O(\alpha,n)^{21}Ne$ - $^{21}Ne(\alpha,n)^{24}Mg$

$^{22}Ne(\alpha,n)^{25}Mg$ - $^{25}Mg(\alpha,n)^{28}Si$

$^{26}Mg(\alpha,n)^{29}Si$

The resulting neutron density is very high, BUT…

Shell C-burning phase



$^{12}C(^{12}C,\alpha)^{20}Ne$

$^{12}C(^{12}C,p)^{23}Na$

$^{12}C(^{12}C,n)^{23}Mg^{*}$

Why not the $^{13}C(\alpha,n)^{16}O$?
Because at $T \sim 1 x 10^{9}$ K
the $^{13}N(\gamma,p)^{12}C^{*}$ works!!

All (α,n) channels are activated:

$^{13}C(\alpha,n)^{16}O$ - $^{17}O(\alpha,n)^{20}Ne$

$^{18}O(\alpha,n)^{21}Ne$ - $^{21}Ne(\alpha,n)^{24}Mg$

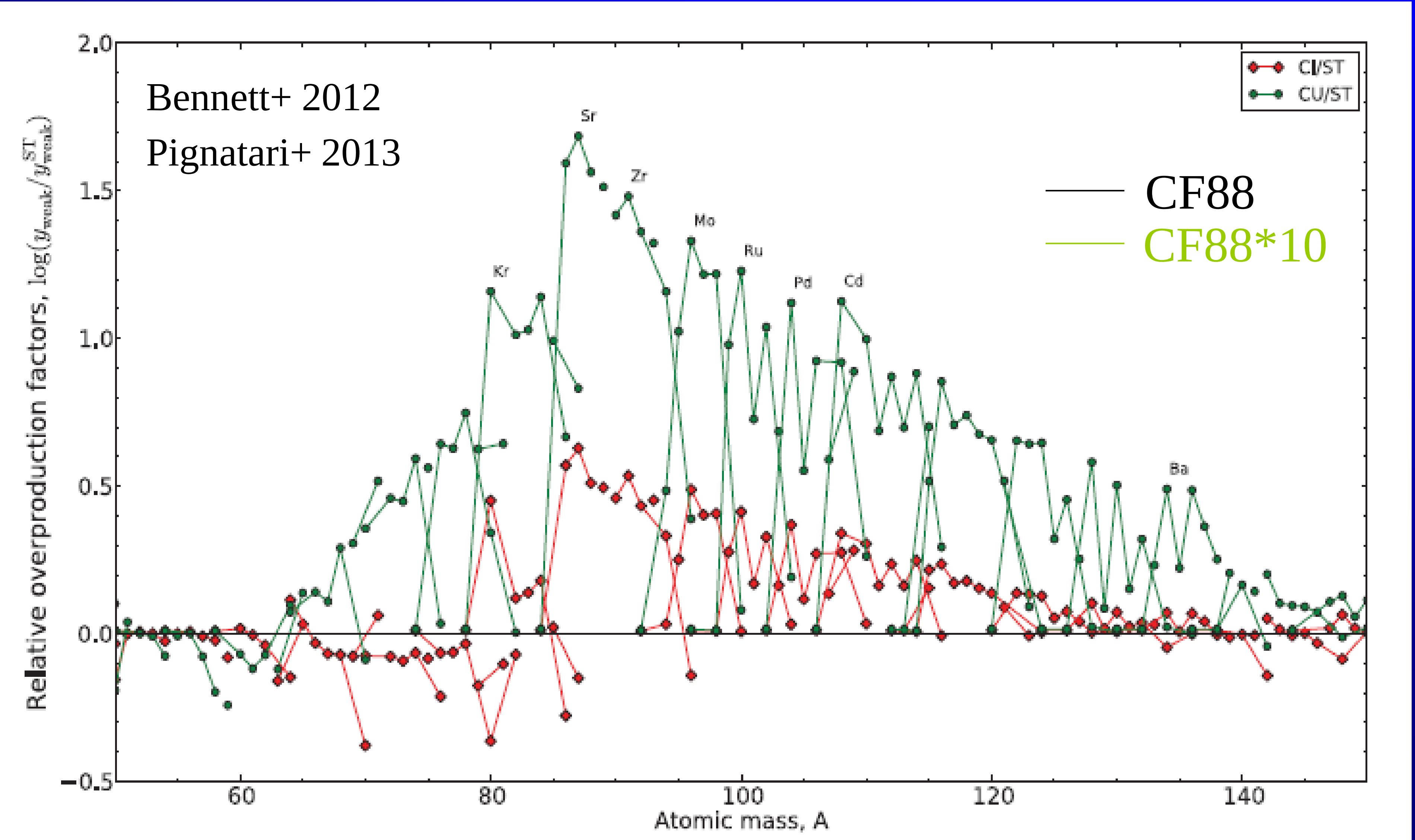
$^{22}Ne(\alpha,n)^{25}Mg$ - $^{25}Mg(\alpha,n)^{28}Si$

$^{26}Mg(\alpha,n)^{29}Si$

The resulting neutron density is very high:
10^{11}-10^{12} n/cm^{3}

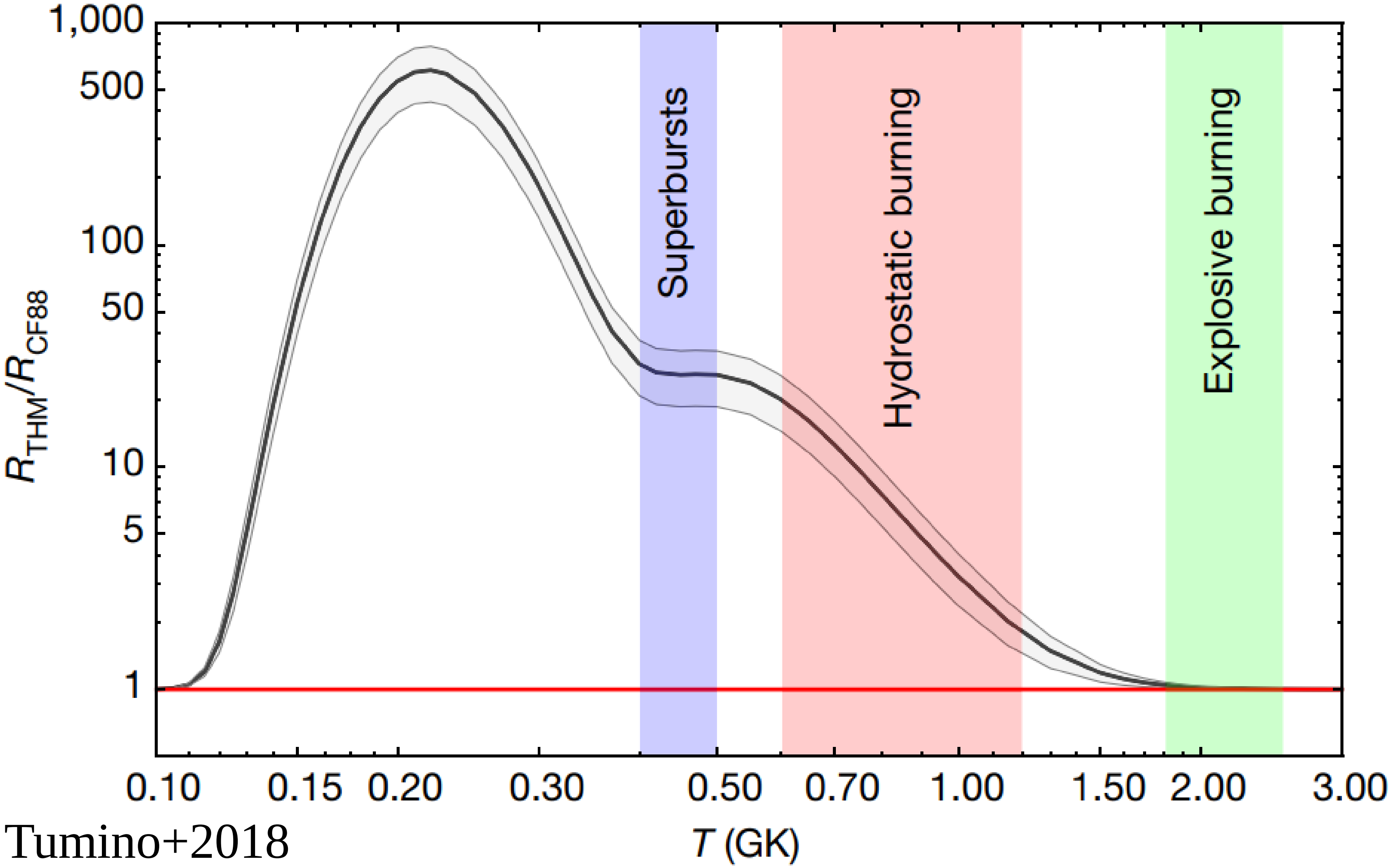
Uncertainties of the weak s-process: cross sections

$^{12}C(^{12}C,x)x$ - $^{22}Ne(\alpha,x)x$ - $^{12}C(\alpha,\gamma)^{16}O$



Uncertainties of the weak s-process: cross sections

$^{12}C(^{12}C,x)x$ - $^{22}Ne(\alpha,x)x$ - $^{12}C(\alpha,\gamma)^{16}O$



Tumino+2018

Uncertainties of the weak s-process: cross sections

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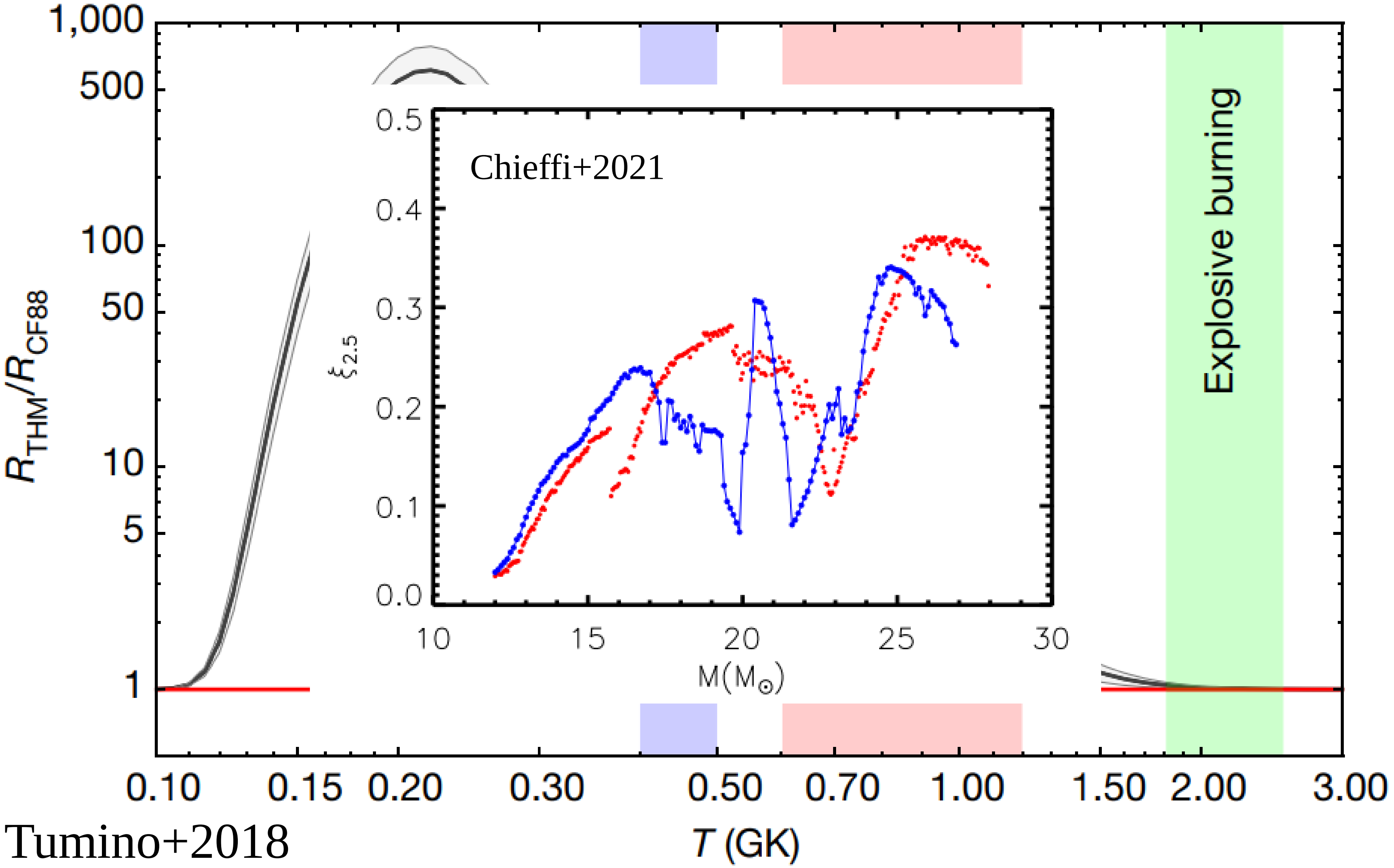


Tumino+2018

Uncertainties of the weak s-process: stellar modelling

Convection - Rotation

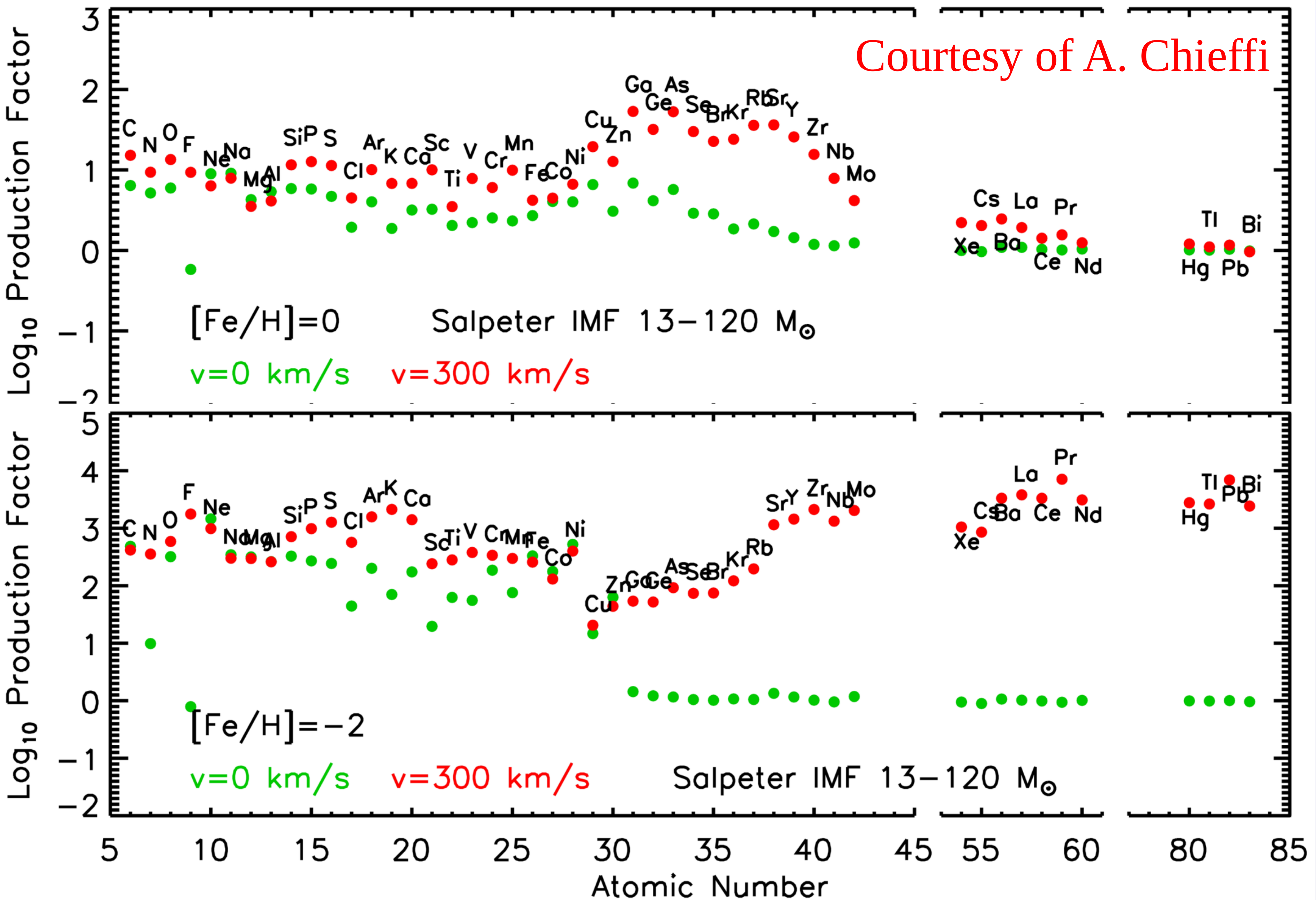
Strong production of primary ^{14}N at low metallicities

$$^{13}C/^{14}N \simeq 5.7 \cdot 10^{-3}$$

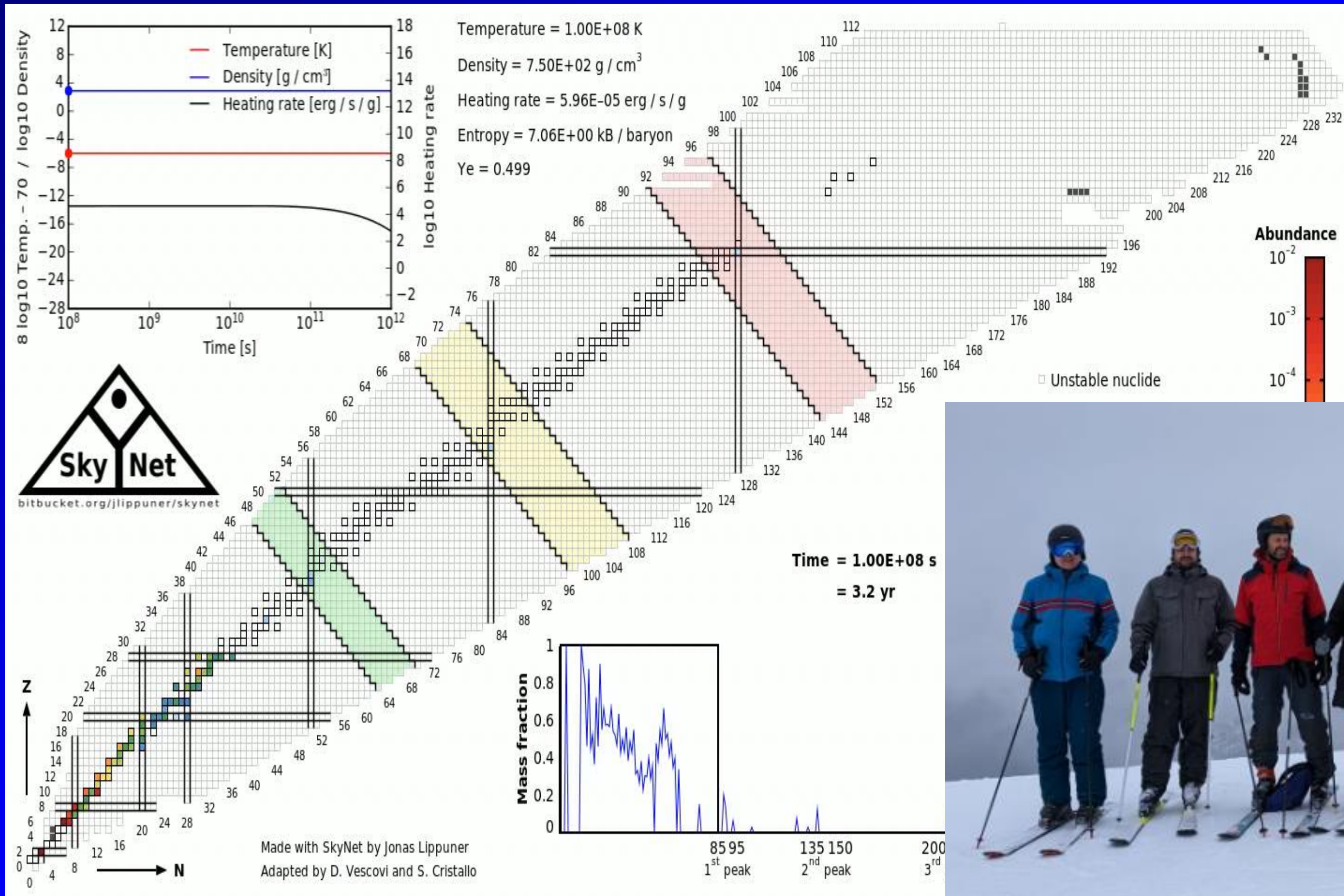
In any case the dominant source is the **$^{22}Ne(\alpha,n)^{25}Mg$**

Courtesy of A. Chieffi

The effect of rotation: differences in the stellar ejecta



THAT'S ALL FALKS!!!



SAPIENZA
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