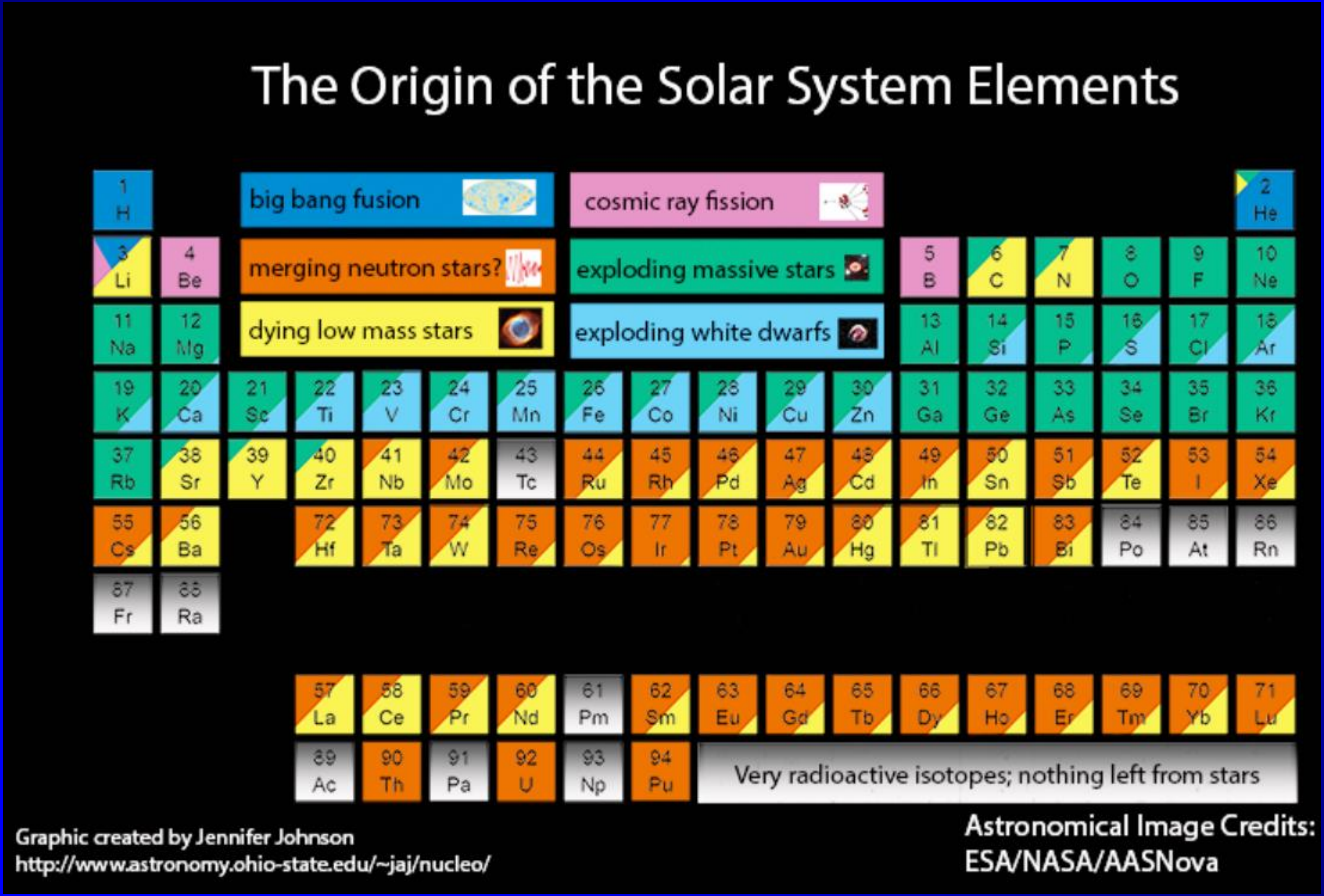
s-process in stellar sites

Sergio Cristallo

INAF – Osservatorio Astronomico d’Abruzzo (Italy)
INFN – Sezione di Perugia (Italy)

Astronomy Picture of the Day



The Origin of the Solar System Elements

big bang fusion

cosmic ray fission

merging neutron stars?

exploding massive stars

dying low mass stars

exploding white dwarfs

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra																
			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
			89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	Very radioactive isotopes; nothing left from stars								

Graphic created by Jennifer Johnson
http://www.astronomy.ohio-state.edu/~jaj/nucleo/

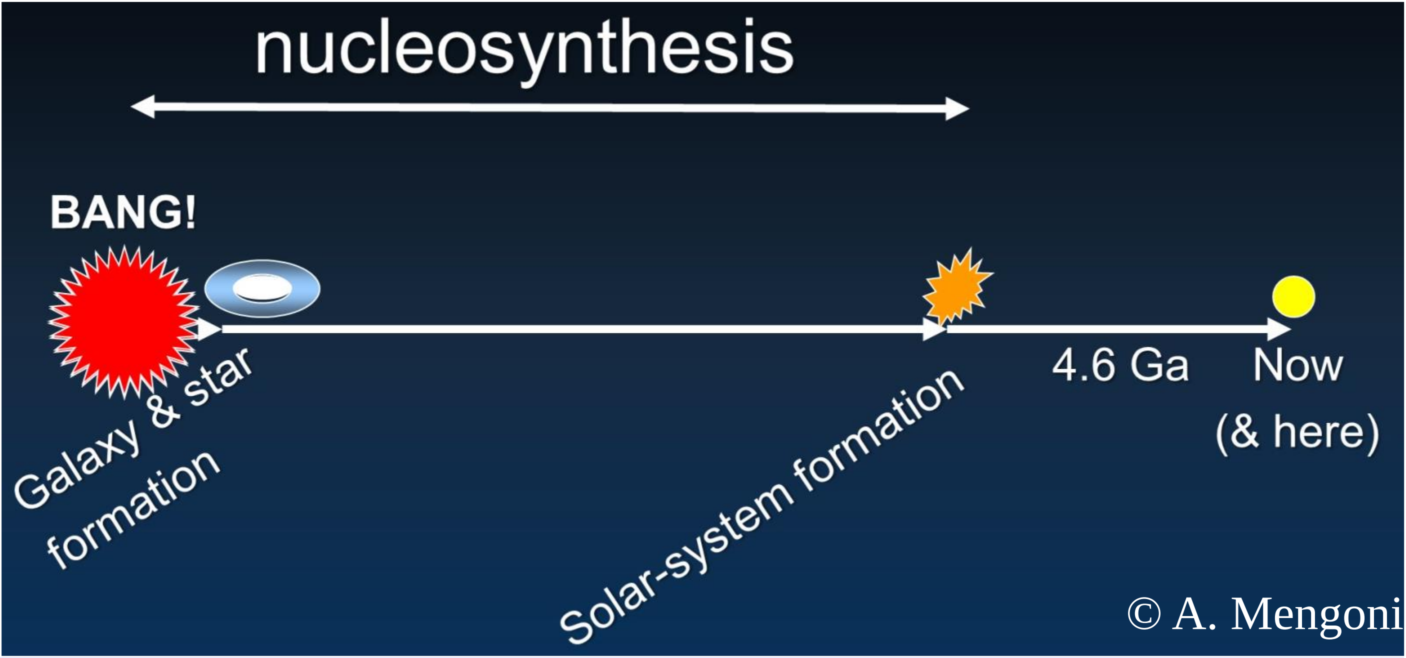
Astronomical Image Credits:
ESA/NASA/AASNova

https://apod.nasa.gov/apod/ap171024.html

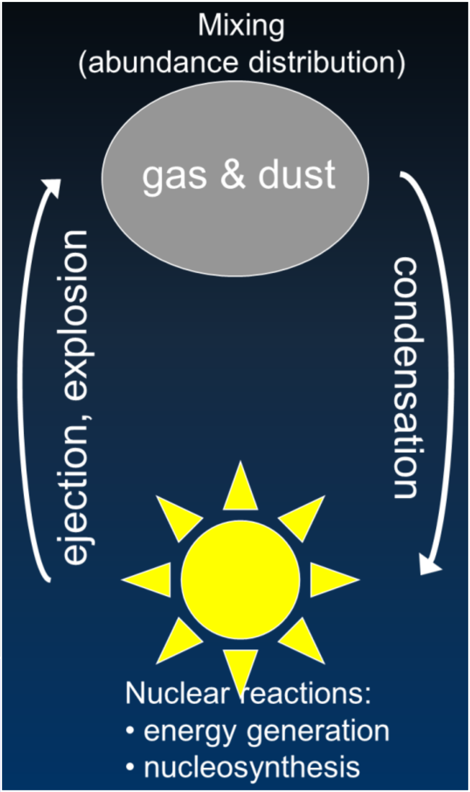
Some minutes after the BIG BANG (Δt=0) there were basically only hydrogen (≈75%) and helium (≈25%). At the FORMATION OF THE SUN (Δt≈9.1 Gyr) there were 71% of hydrogen and 27% of helium. The remaining 2% are heavy elements (or metals). TODAY (Δt=13.7 Gyr) , in star forming regions hydrogen is about 65%, helium is about 31% and metal constitute the remaining 4%

H ↓ He ↑ Metals ↑

Our Galactic "heritage"



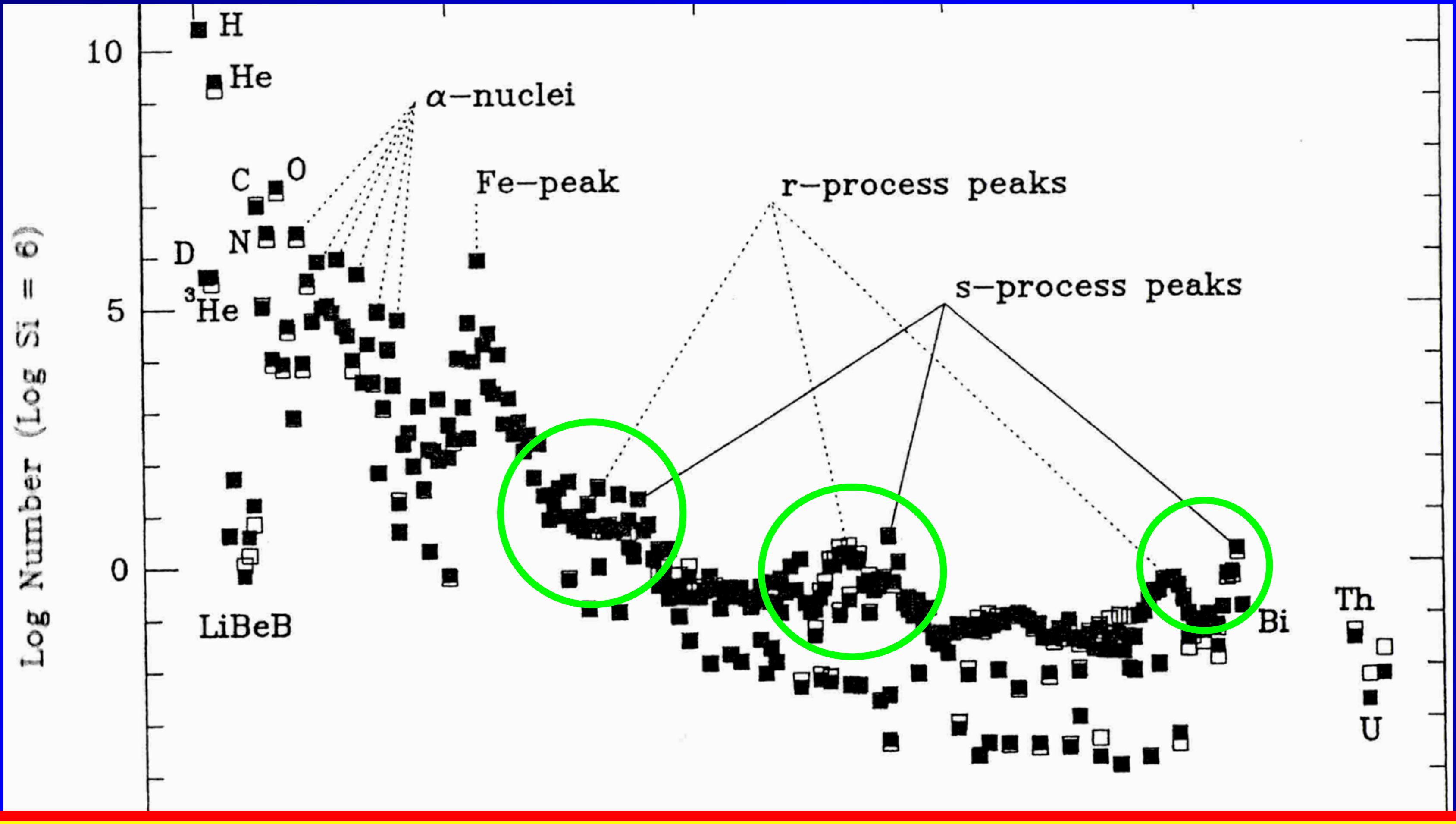
© A. Mengoni



"We are stardust"

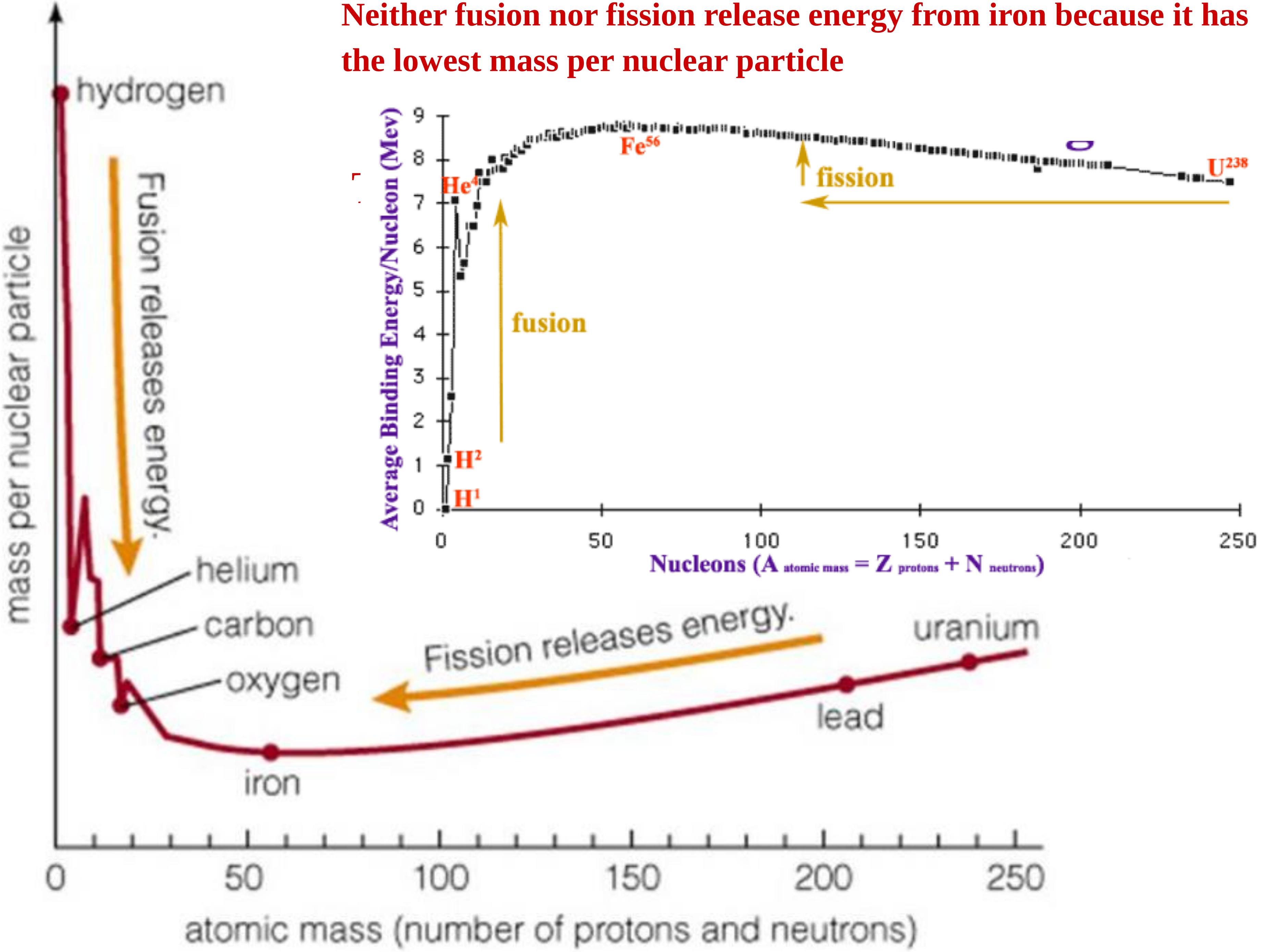
Joni Mitchell, Woodstock

Solar System Abundances



Their natural abundances cannot be reproduced by nuclear statistical equilibrium, so that they seem to require a non-equilibrium mechanism.

Neither fusion nor fission release energy from iron because it has the lowest mass per nuclear particle



Neutron capture reactions

$$^{A}X_{Z}(n,\gamma)\,^{A+1}X_{Z}$$

With NO Coulomb barrier to overcome, heavy elements capture neutrons easily, even at extremely low energies.

Neutron cross section, in fact, generally INCREASES with decreasing energy

$(Z,A) + n \rightarrow (Z,A+1) + \gamma$

If the nucleus (Z,A+1) is stable, it waits until it captures another neutron, and so on.

If the nucleus (Z,A+1) is radioactive, the question whether it β-decays to (Z+1,A+1) or captures a second neutron depends upon the relative lifetimes of (Z,A+1) against β-decay and against capture of neutrons.

DEFINITION: $\tau_n(X) = \dfrac{1}{N_n < \sigma v >}$

Mean lifetime of nucleus X
against destruction by a neutron capture

($<\sigma v>$ represents the destruction rate of the nucleus)

τ_β = beta-decay lifetime (seconds → years)

if $\tau_n > \tau_\beta \Rightarrow$ unstable nucleus decays
if $\tau_n < \tau_\beta \Rightarrow$ unstable reacts

The r-process

B2FH

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

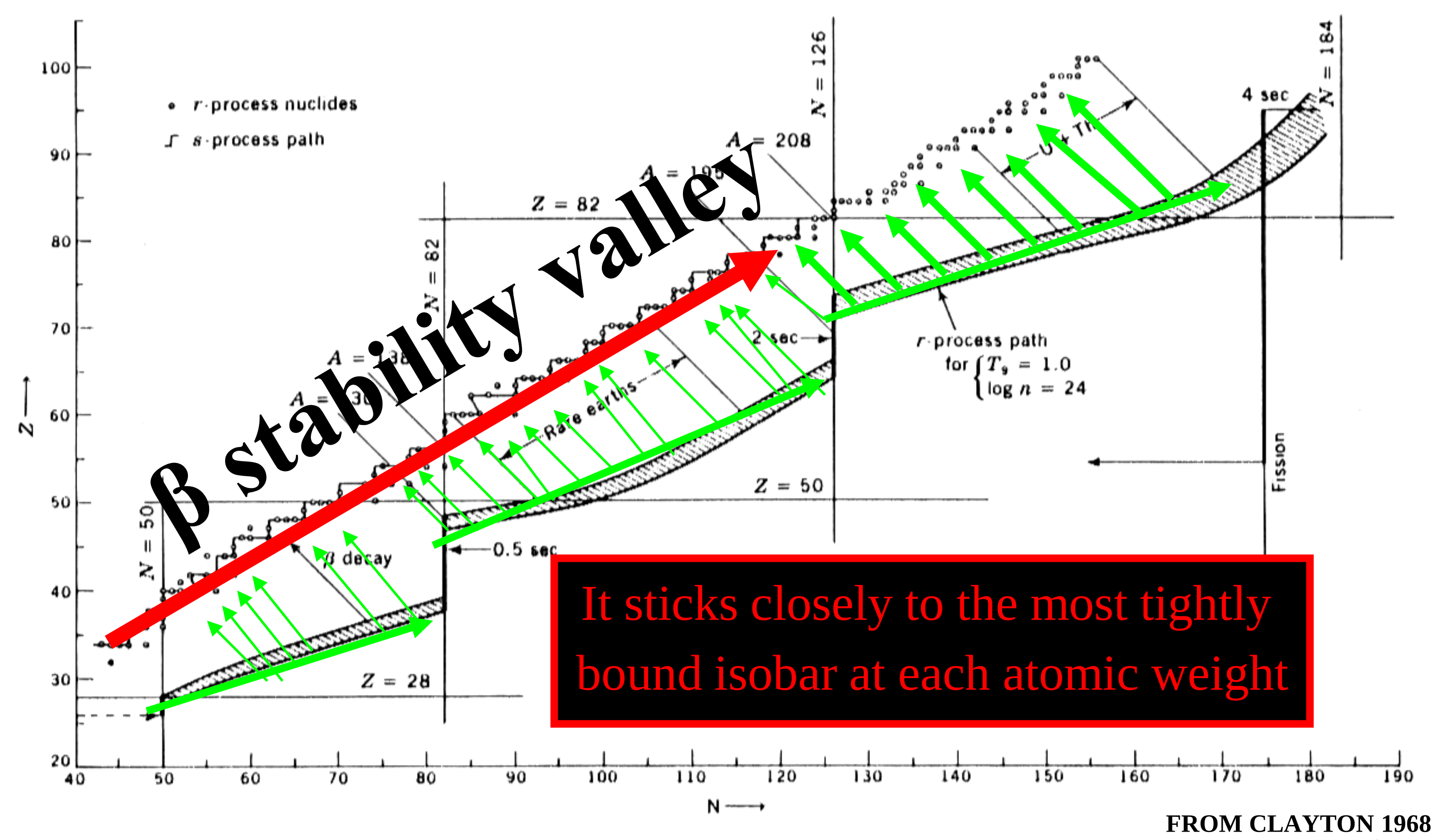
Unstable nucleus captures another neutron before decaying

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**.



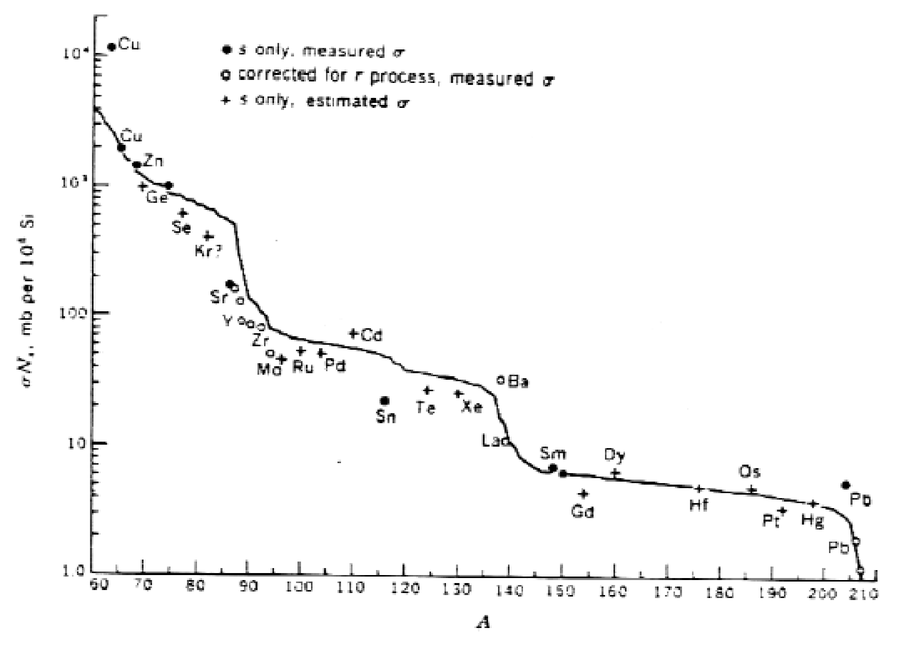
β stability valley

It sticks closely to the most tightly bound isobar at each atomic weight

FROM CLAYTON 1968

***s*-process**

***r*-process**

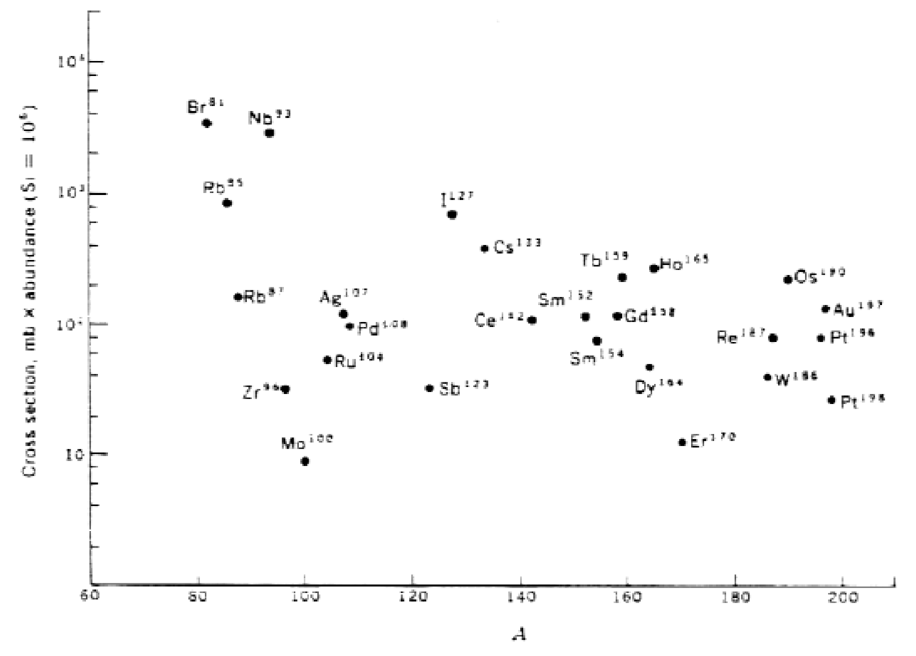


s-process

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?

$$r = 1 - s$$

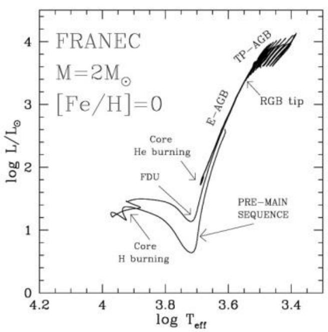
$$r = 1 - s$$

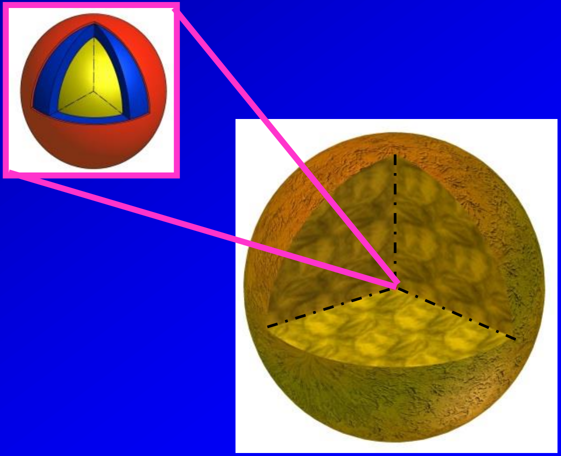
vs

$$s = 1 - r$$

Main s-process (A≥90)

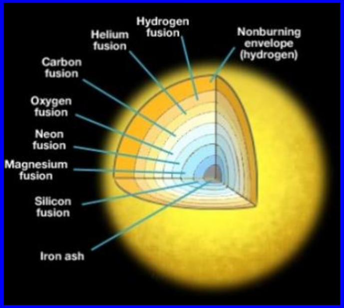
ASYMPTOTIC GIANT BRANCH STARS

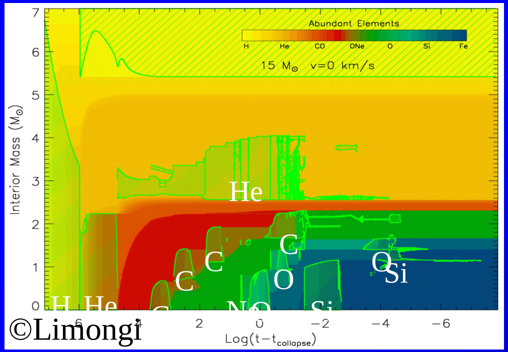




Weak s-process (A≤90)

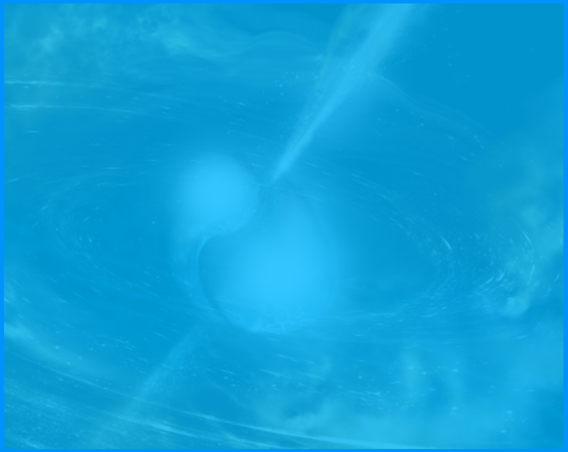
QUIESCENT BURNINGS OF MASSIVE STARS





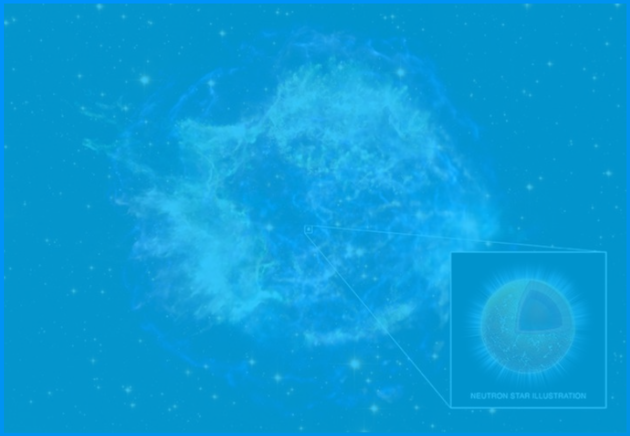
Main r-process (A≥130)

NEUTRON STARS MERGERS?

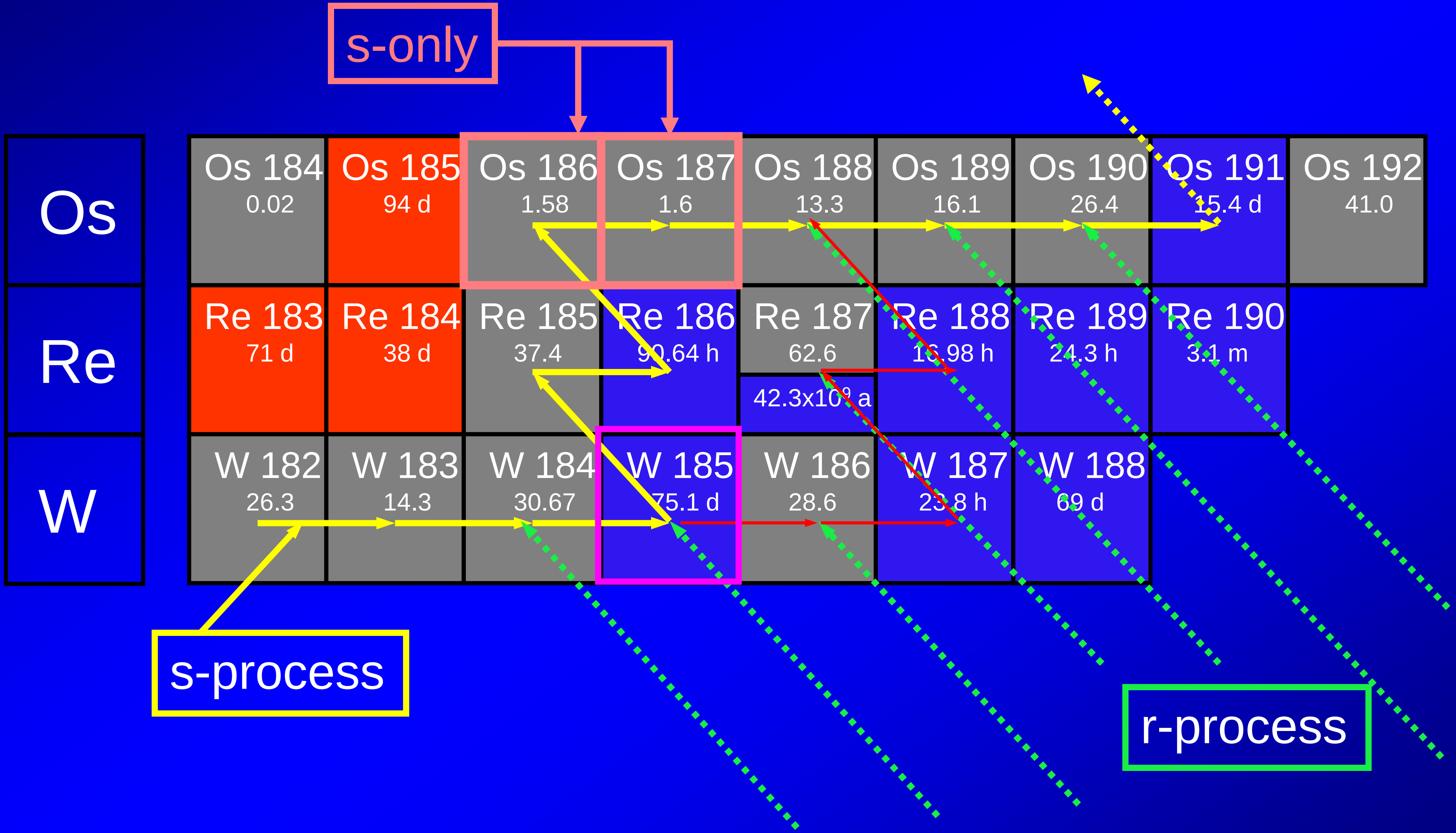


Weak r-process (A≤130)

EXPLOSIVE PHASE OF MASSIVE STARS?



How s-process neutron captures work?



Os	Os 184 0.02	Os 185 94 d	Os 186 1.58	Os 187 1.6	Os 188 13.3	Os 189 16.1	Os 190 26.4	Os 191 15.4 d	Os 192 41.0
Re	Re 183 71 d	Re 184 38 d	Re 185 37.4	Re 186 90.64 h	Re 187 62.6 42.3x10^9 a	Re 188 16.98 h	Re 189 24.3 h	Re 190 3.1 m	
W	W 182 26.3	W 183 14.3	W 184 30.67	W 185 75.1 d	W 186 28.6	W 187 23.8 h	W 188 69 d		

Branching points:: if $\tau_\beta \sim \tau_n$ ⇒ several paths are possible

Seeds for the s-process

Main seeds are ^{56}Fe nuclei…

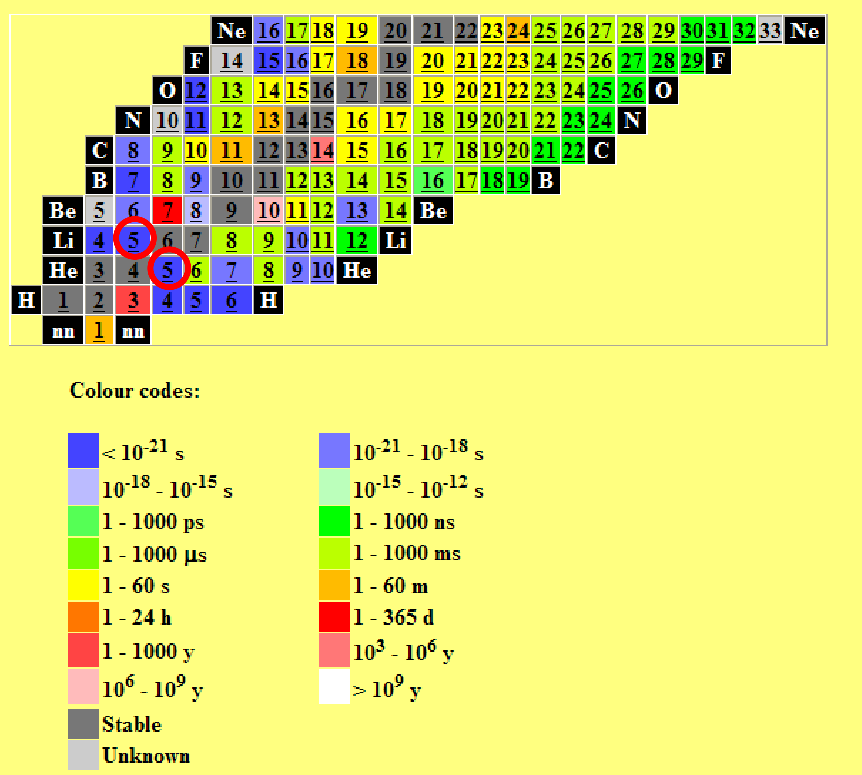
Why not the most abundant ^{1}H, ^{4}He or ^{12}C???

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

$$\mathrm{RATE}[\mathrm{H}(n,\gamma)^{2}\mathrm{H}] \propto N(\mathrm{H})$$

↓

$$10^{-12}$$

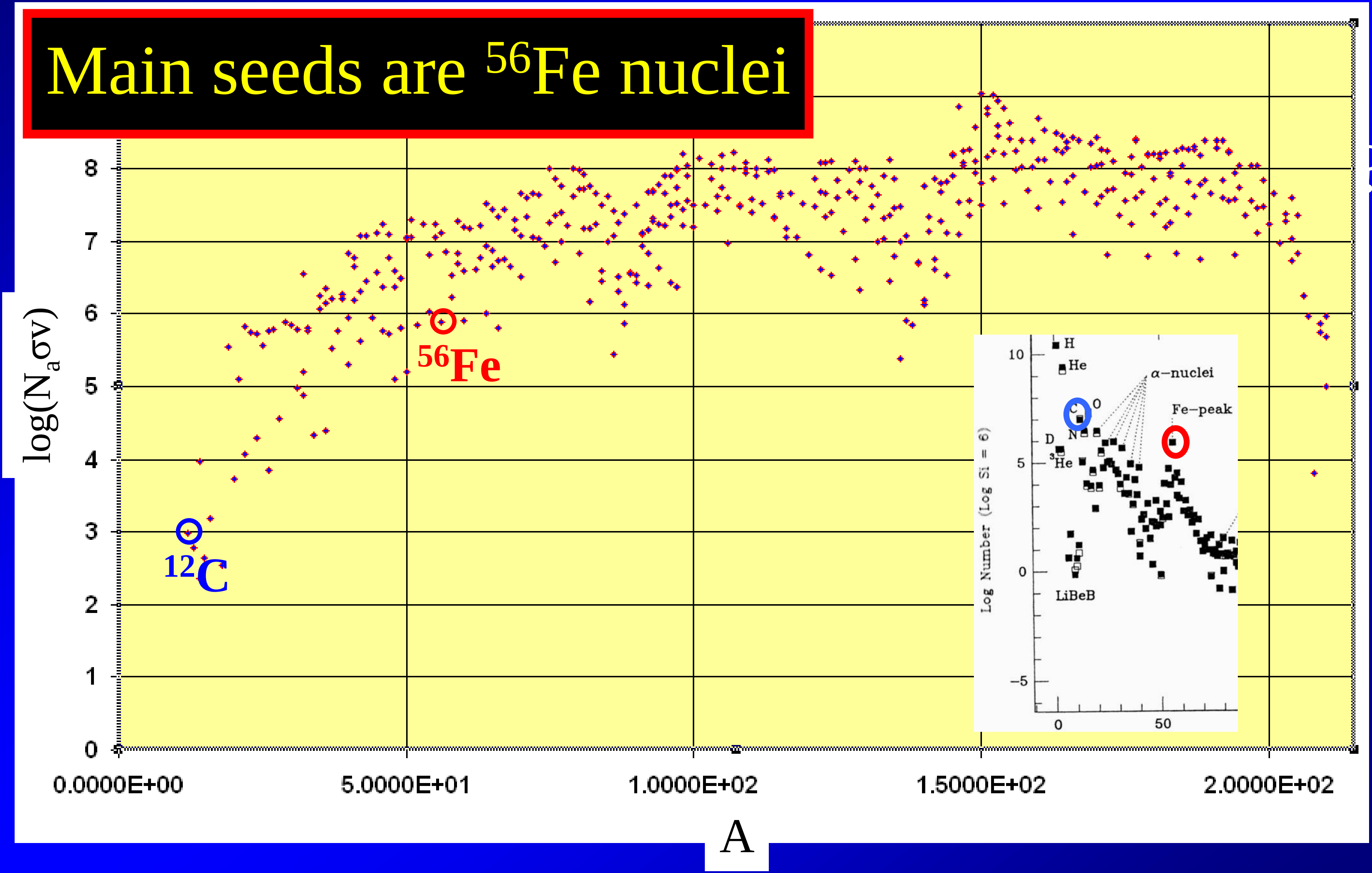


Colour codes:

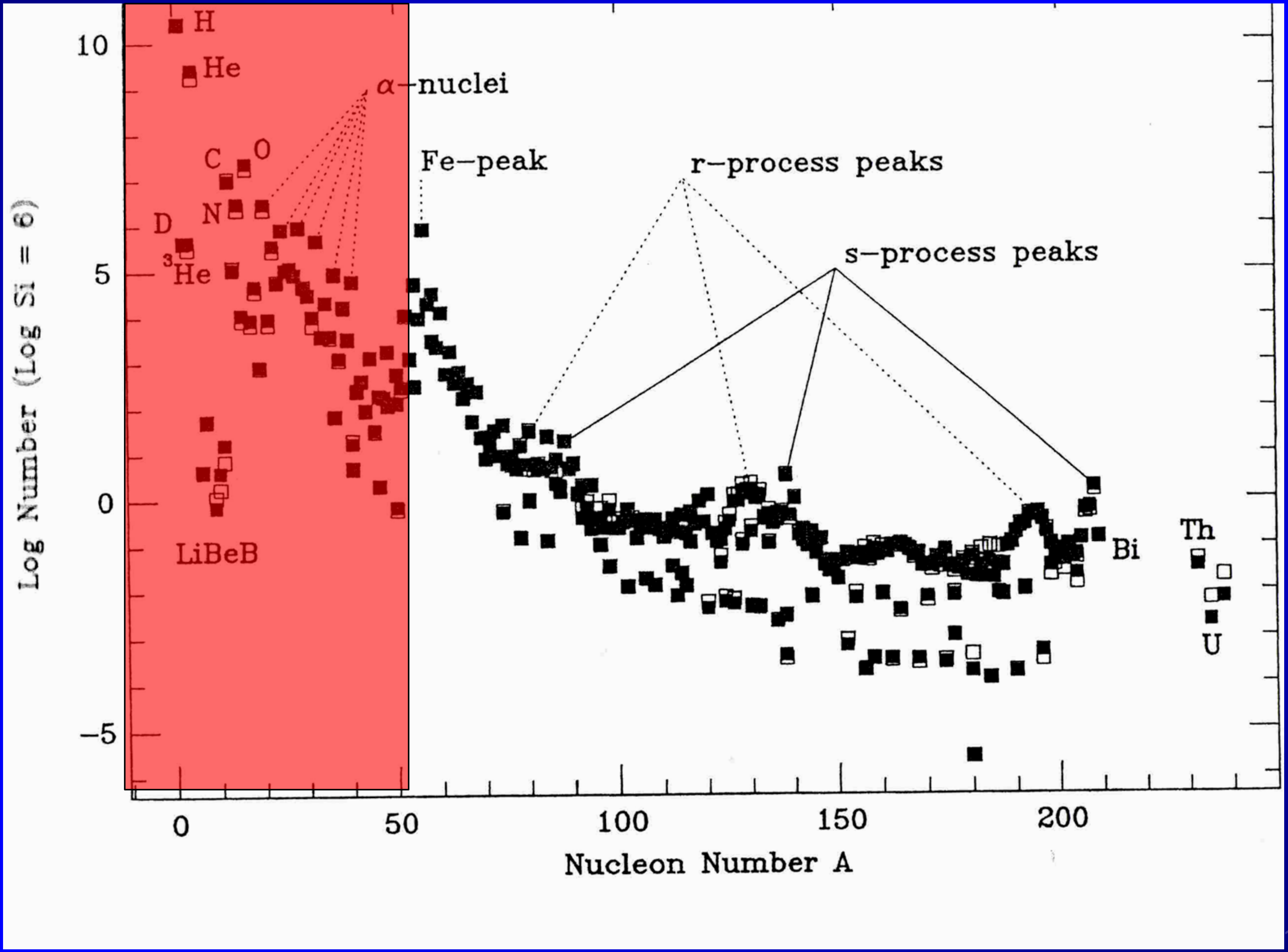
$< 10^{-21}$ s	10^{-21} - 10^{-18} s
10^{-18} - 10^{-15} s	10^{-15} - 10^{-12} s
1 - 1000 ps	1 - 1000 ns
1 - 1000 µs	1 - 1000 ms
1 - 60 s	1 - 60 m
1 - 24 h	1 - 365 d
1 - 1000 y	10^{3} - 10^{6} y
10^{6} - 10^{9} y	$> 10^{9}$ y
Stable	
Unknown	

Seeds for the s-process

Main seeds are ^{56}Fe nuclei



MAGIC NUCLEI



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

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

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**

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

Primary and secondary elements (or isotopes)

* **Primary element:** produced from H & He directly: ^{12}C, ^{16}O…

* **Secondary element:** its production requires the presence of some metals: ^{14}N, ^{27}Al…

The ^{13}C is primary like

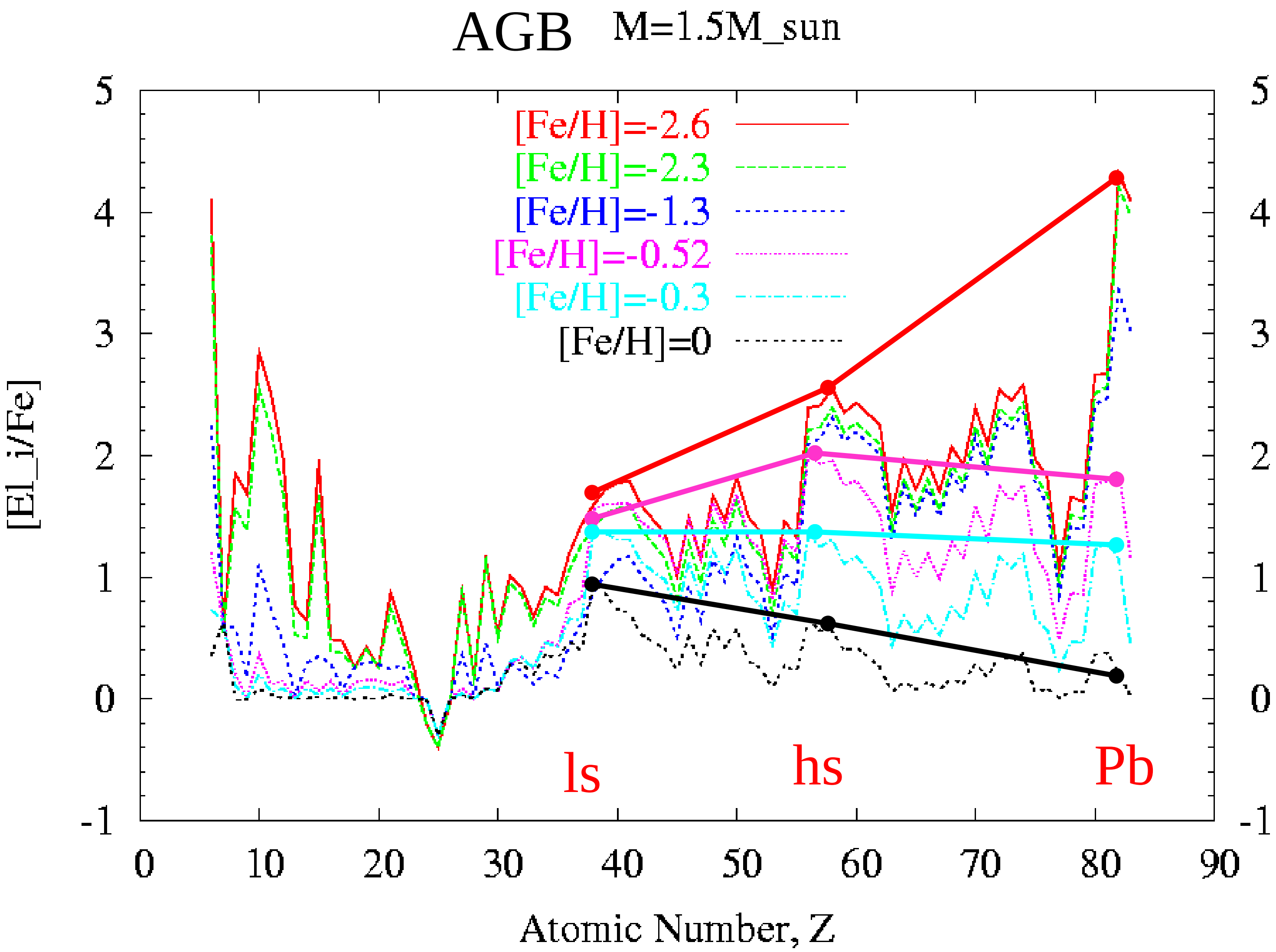
The ^{22}Ne is (mostly) secondary like

Iron seeds (^{56}Fe) are secondary like

The key quantity is the neutron/seed ratio, for example:

$N(^{13}C)/N(^{56}Fe)$

SURFACE DISTRIBUTION



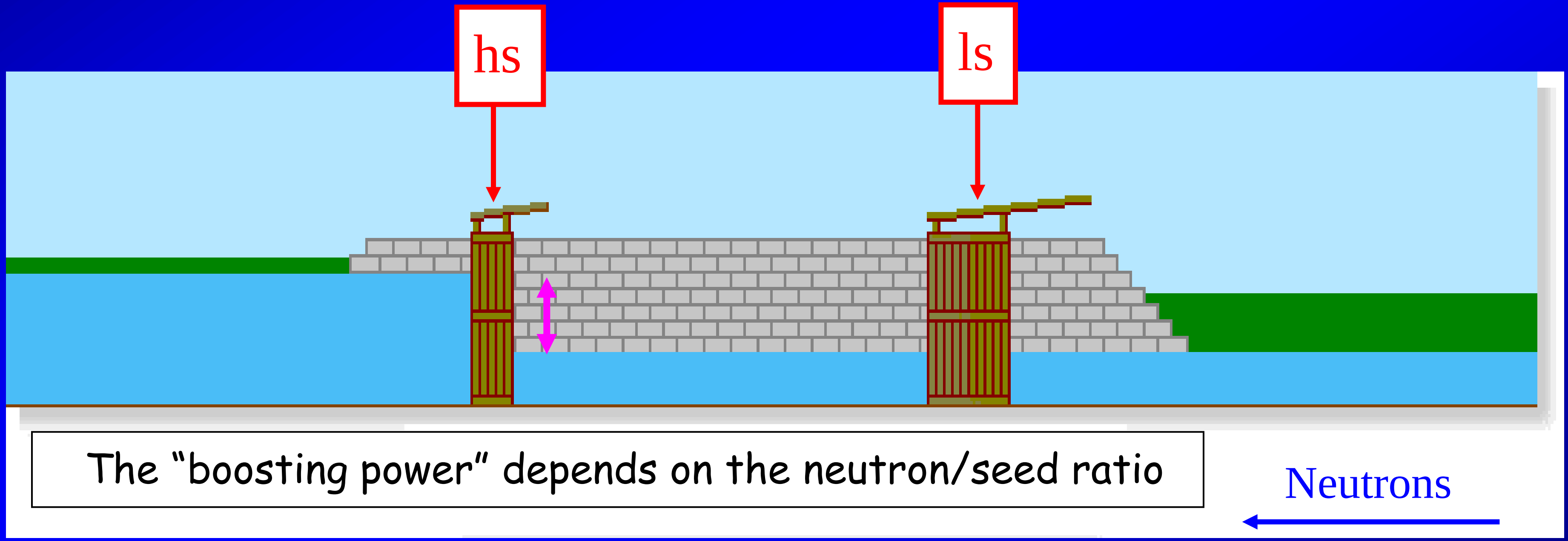
Gallino’s models

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]



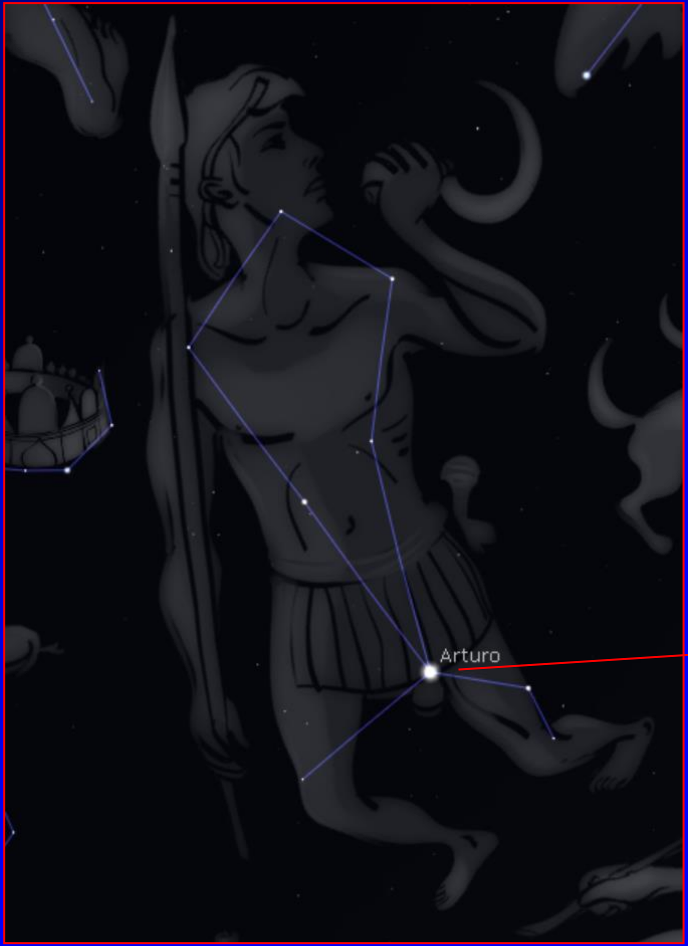
The "boosting power" depends on the neutron/seed ratio

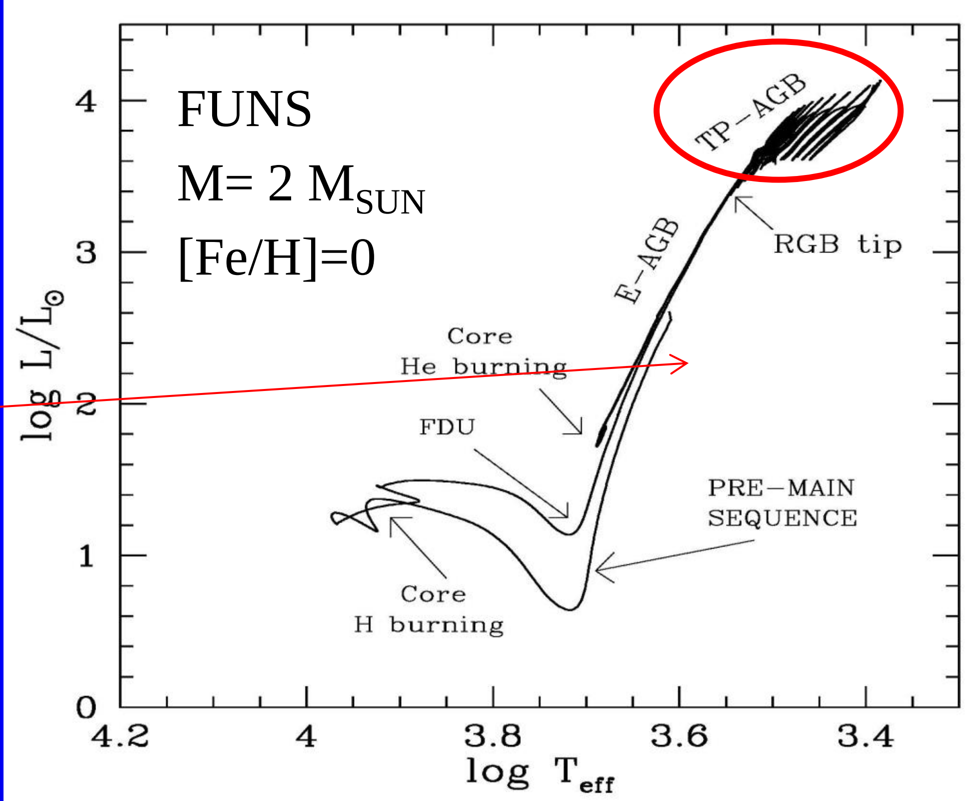
A sluice system with opening bulkheads

Asymptotic Giant Branch (AGB) stars

$\tau_{MS} \approx 1$ Gyr

$\tau_{AGB} \approx 1$ Myr



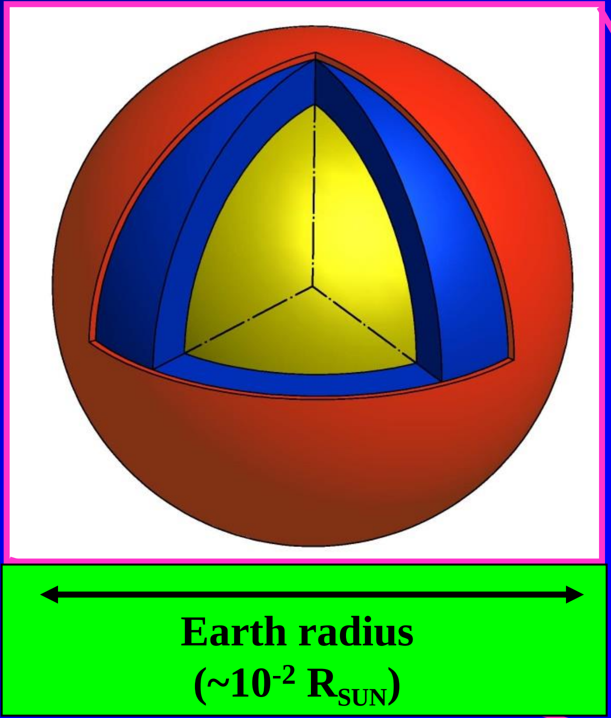


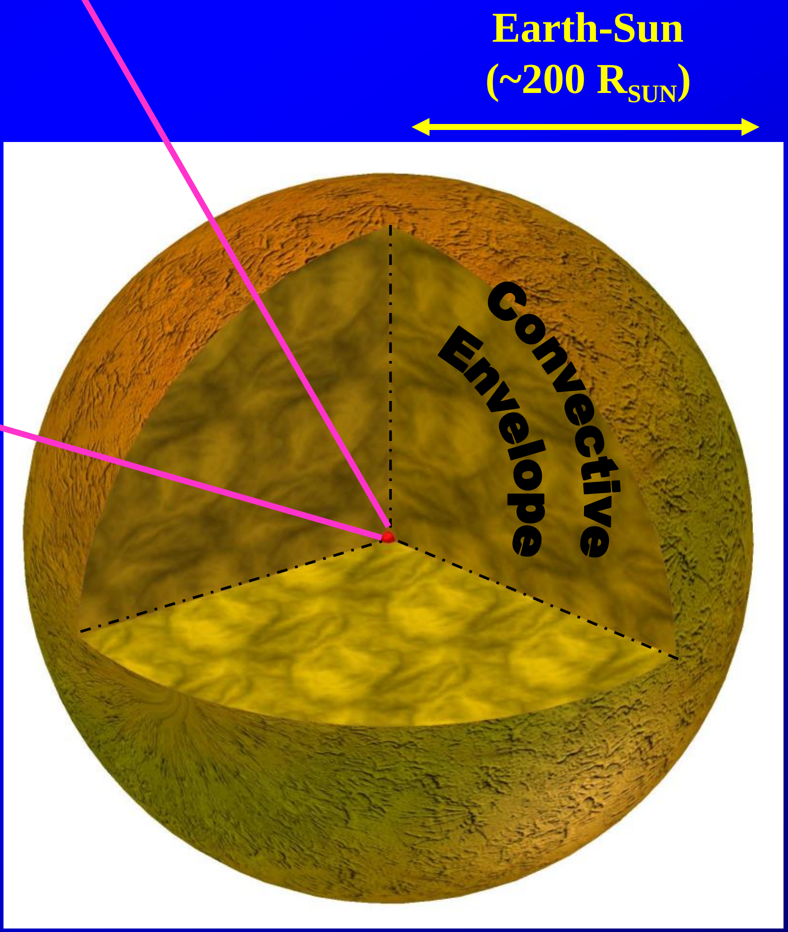
AGBs: marvellous stellar cauldrons

- C (1.5-4.0 M_{SUN})
- N (4.0-7.0 M_{SUN})
- F (1.5-4.0 M_{SUN})
- Na (all)
- Mg&Al (5.0-7.0 M_{SUN})
- Half of the heavy elements is synthesized in AGBs

AGB structure

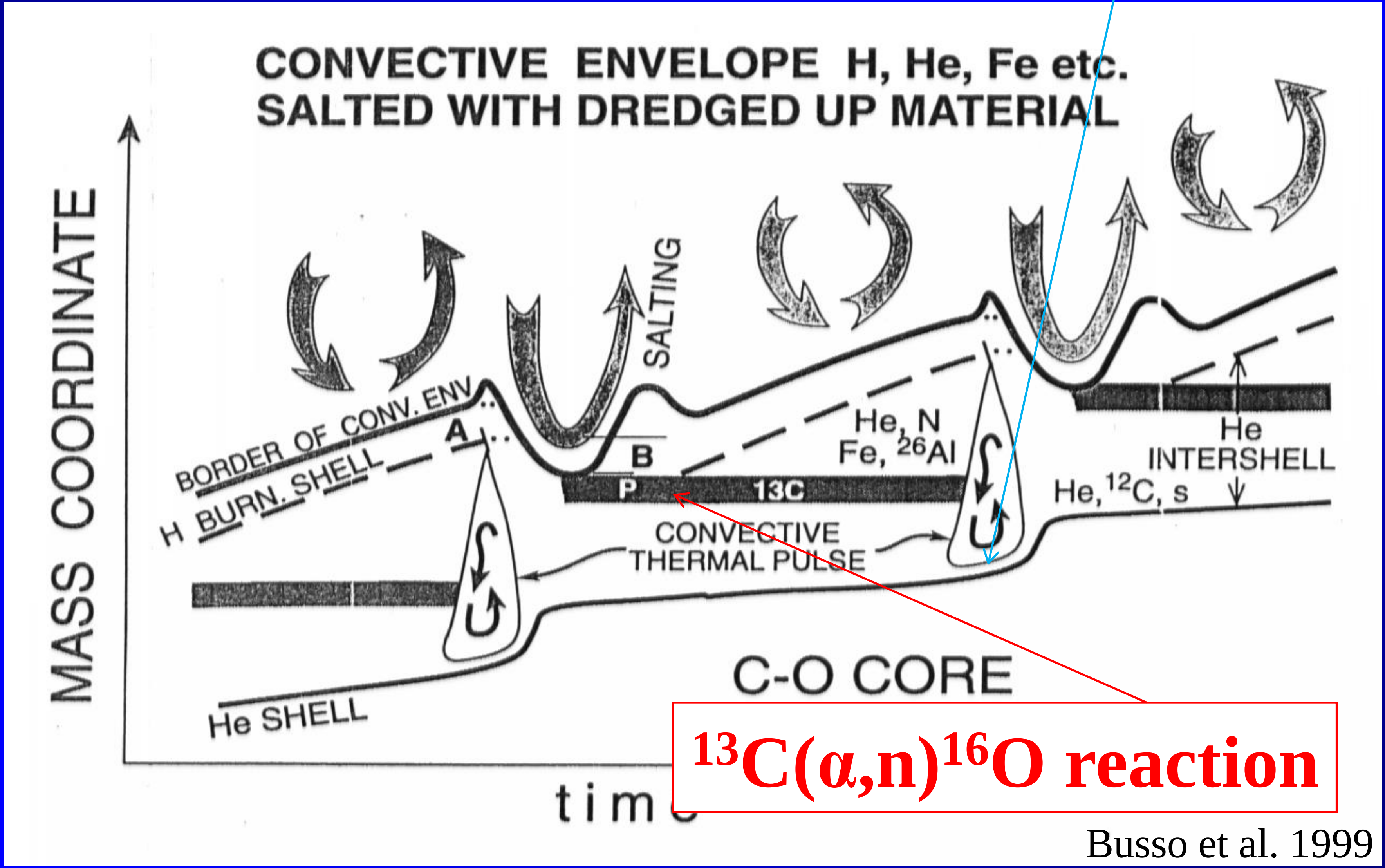
CO Core
He-shell
H-shell





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

The s-process in AGB stars



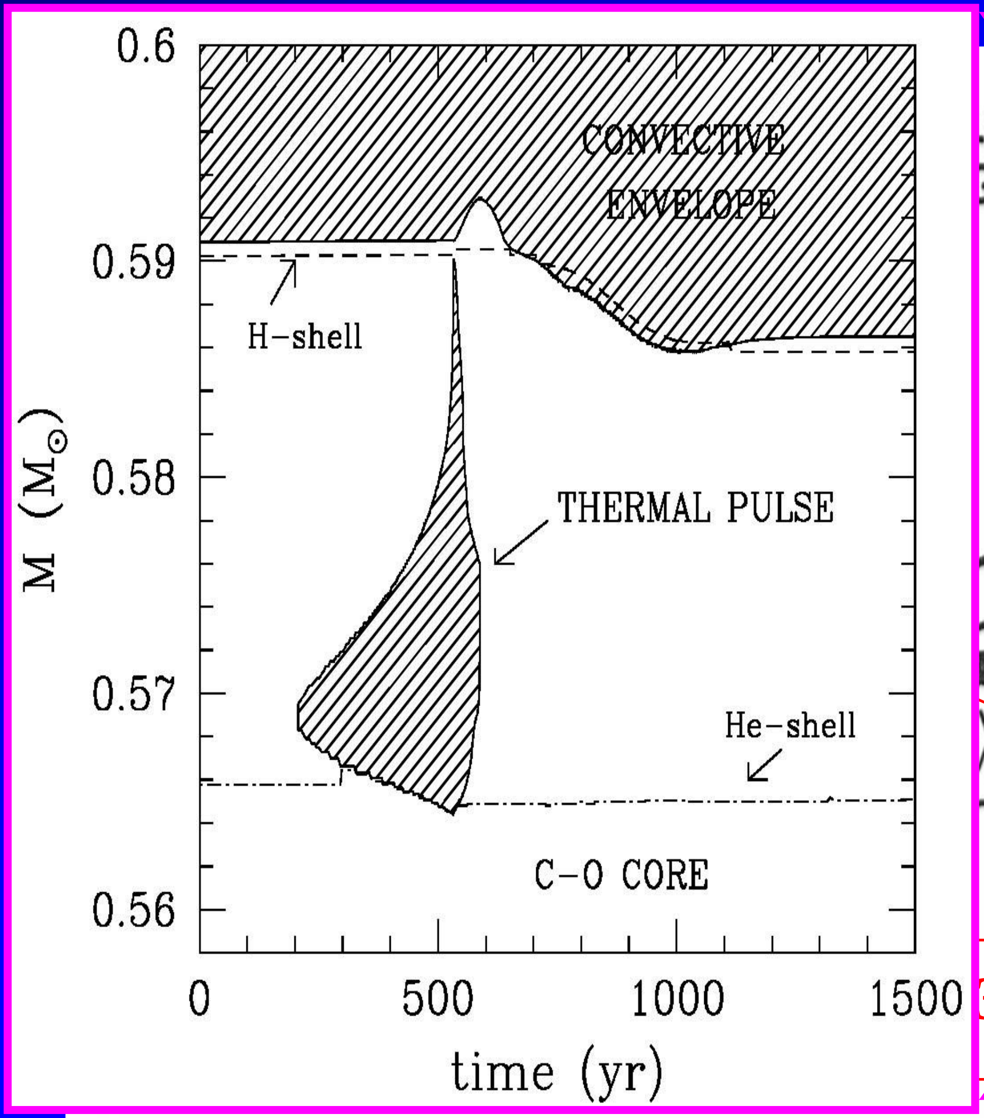
^{22}Ne(α,n)^{25}Mg reaction

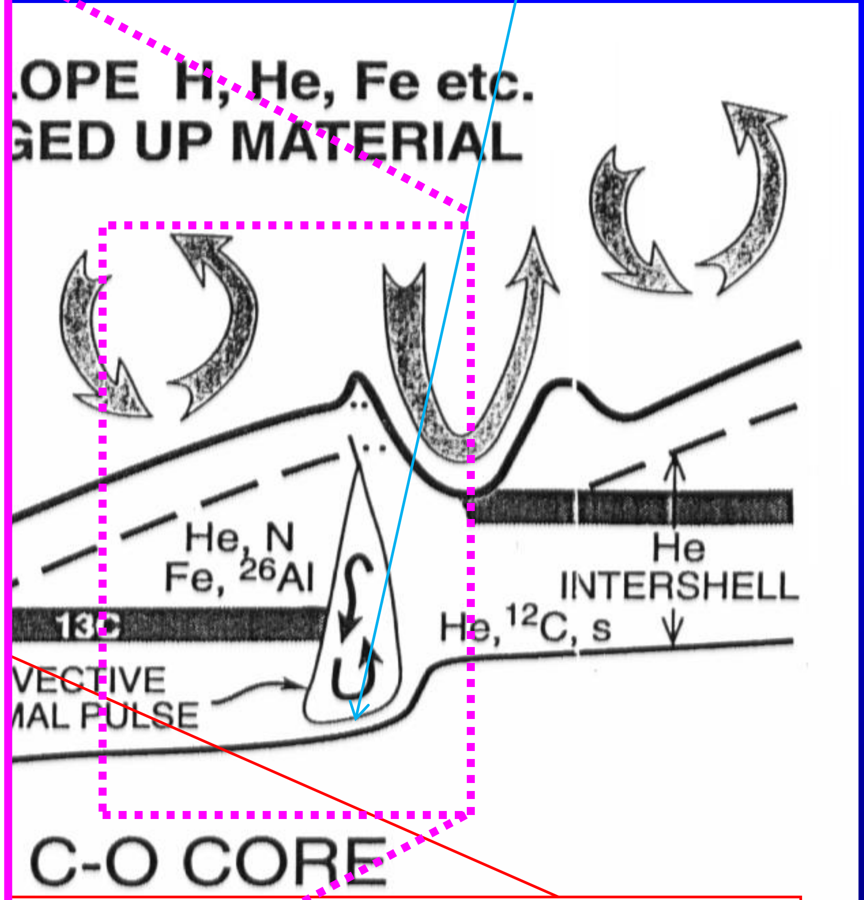
^{13}C(α,n)^{16}O reaction

Busso et al. 1999

The s-process in AGB stars

^{22}Ne(α,n)^{25}Mg reaction





^{3}C(α,n)^{16}O reaction

Busso et al. 1999

How does the ^{13}C pocket form?

- ✓ Opacity induced overshoot
- ✓ Convective Boundary Mixing
- ✓ Magnetic fields

How does the ^{13}C pocket change?

- ✓ Rotation mixing
- ✓ Magnetic fields

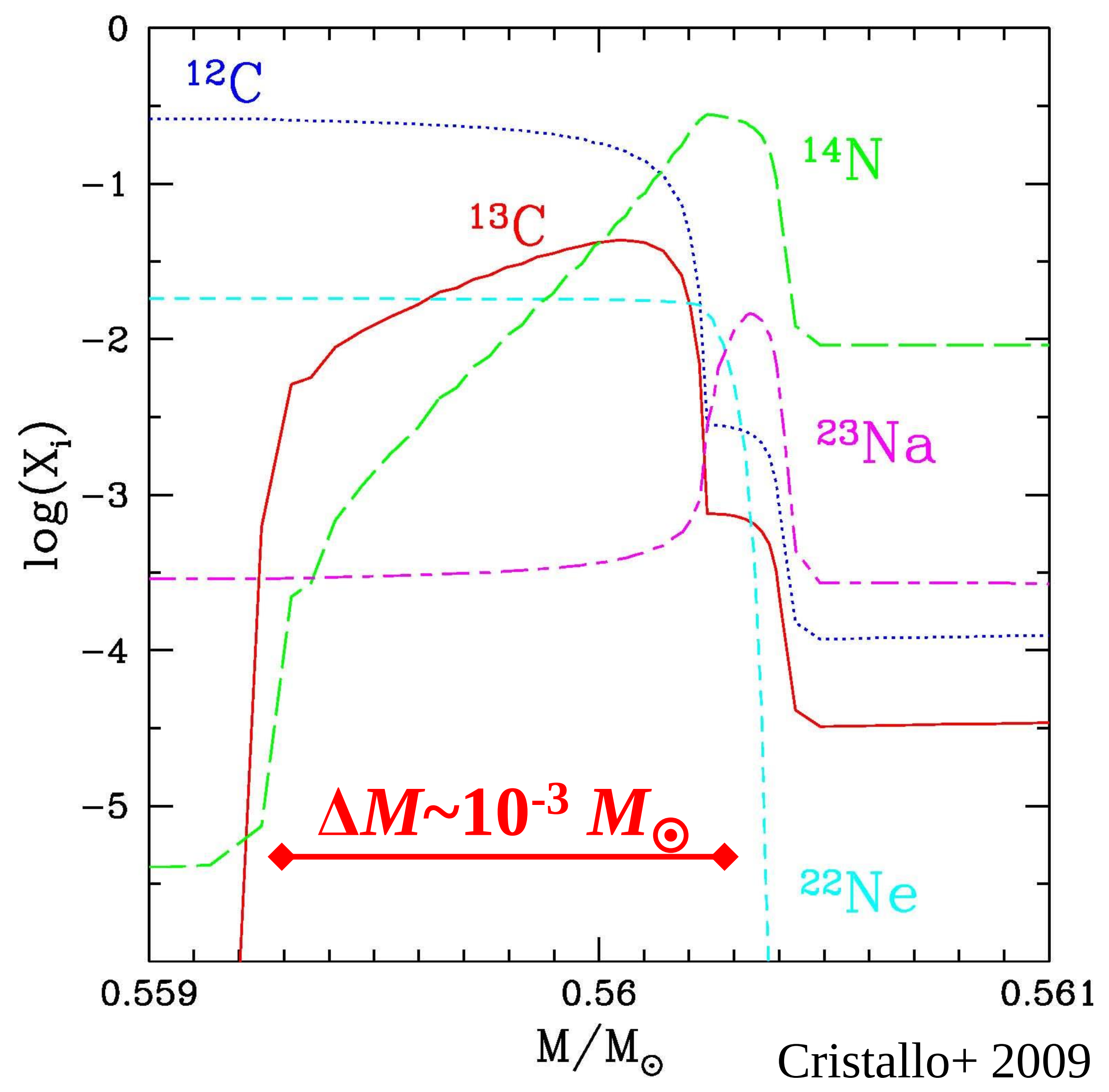
The formation of the ^{13}C pocket

^{13}C-pocket

^{14}N-pocket

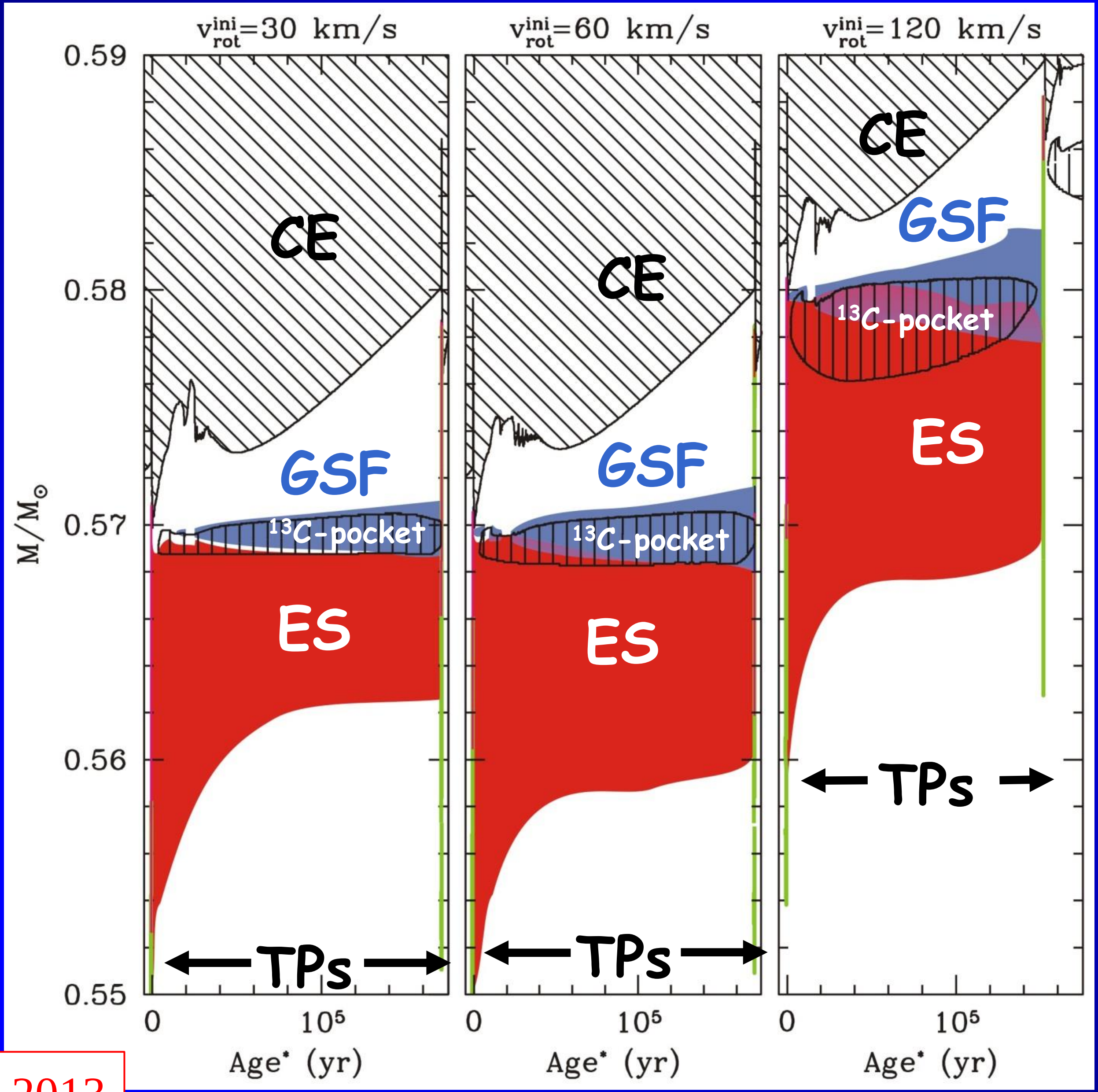
^{23}Na-pocket

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



Cristallo+ 2009

Rotation induced instabilities during the AGB phase

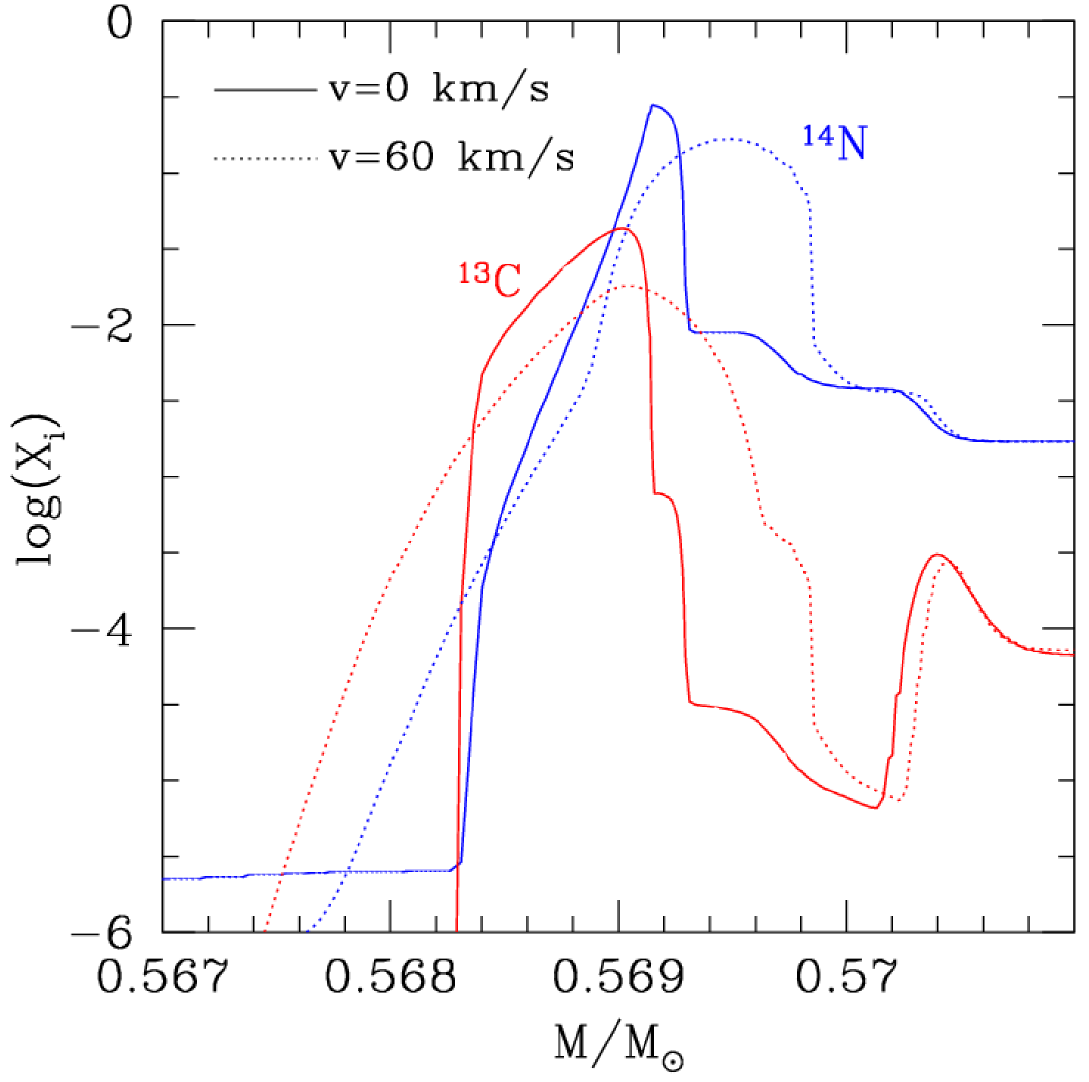


M=2.0 M_{SUN}
[Fe/H]=0

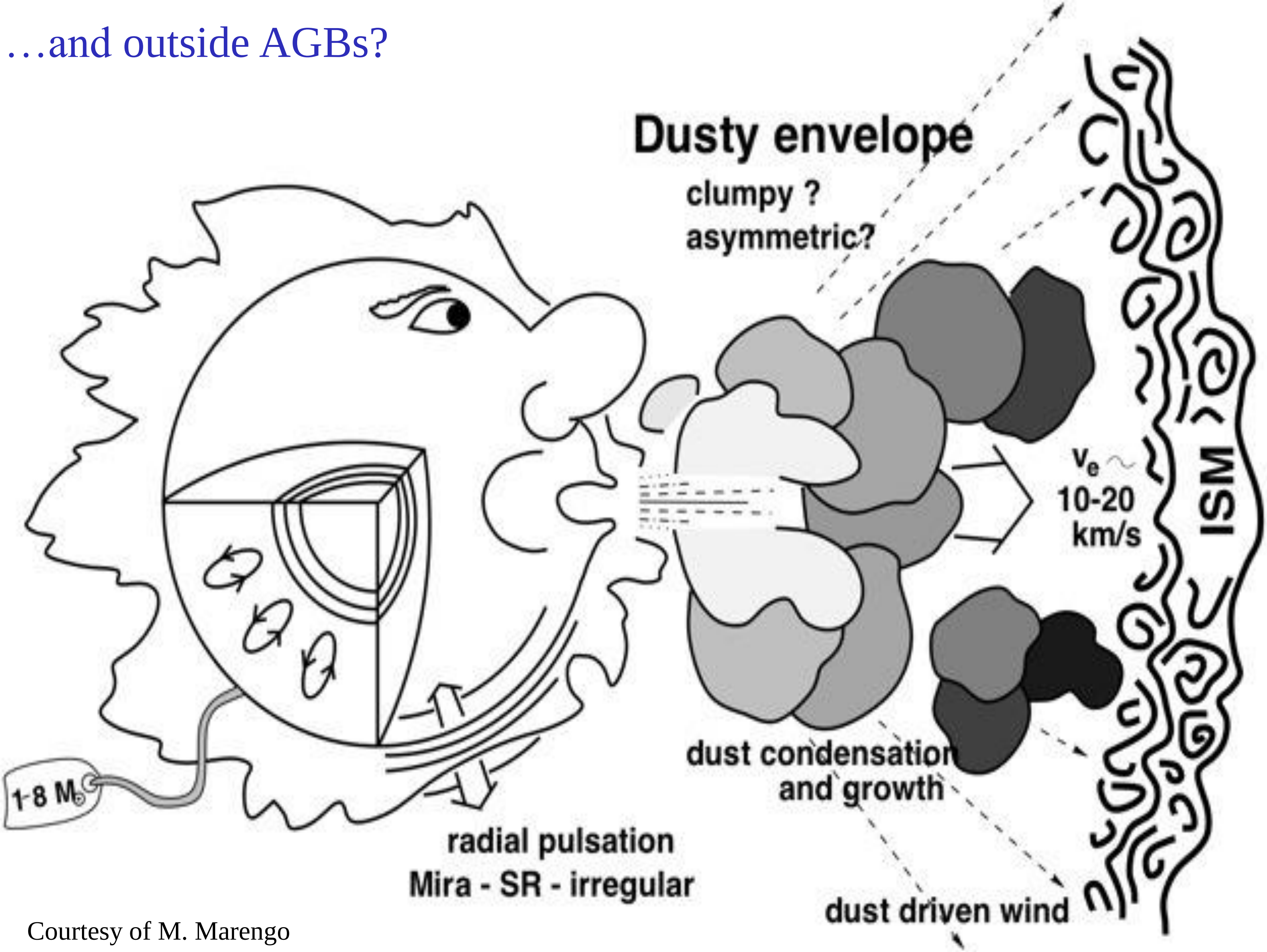
Piersanti+ 2013

NET EFFECT

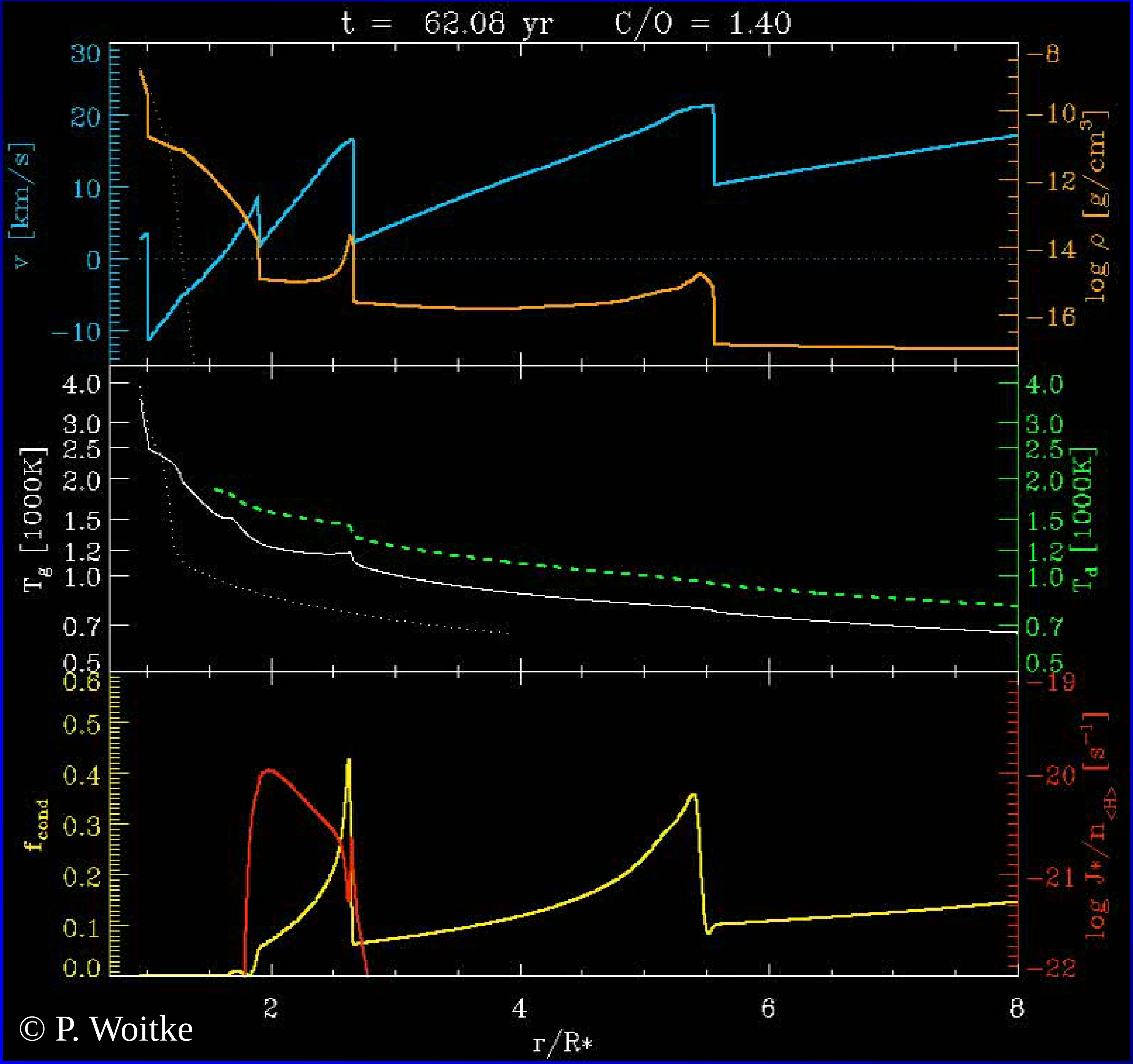
It mixes ^{14}N in ^{13}C-rich layers (and viceversa), thus implying a decrease of the local neutron density and an increase of the iron seeds. As a consequence, the surface s-process distributions change.



…and outside AGBs?



Courtesy of M. Marengo


t = 62.08 yr C/O = 1.40
v [km/s]
30
20
10
0
−10
log ρ [g/cm^3]
−8
−10
−12
−14
−16
T$_g$ [1000K]
T$_d$ [1000K]
4.0
3.0
2.5
2.0
1.5
1.2
1.0
0.7
0.5
f$_{cond}$
0.6
0.5
0.4
0.3
0.2
0.1
0.0
log J$_*$/n$_{<H>}$ [s^{-1}]
−19
−20
−21
−22
2
4
6
8
r/R*

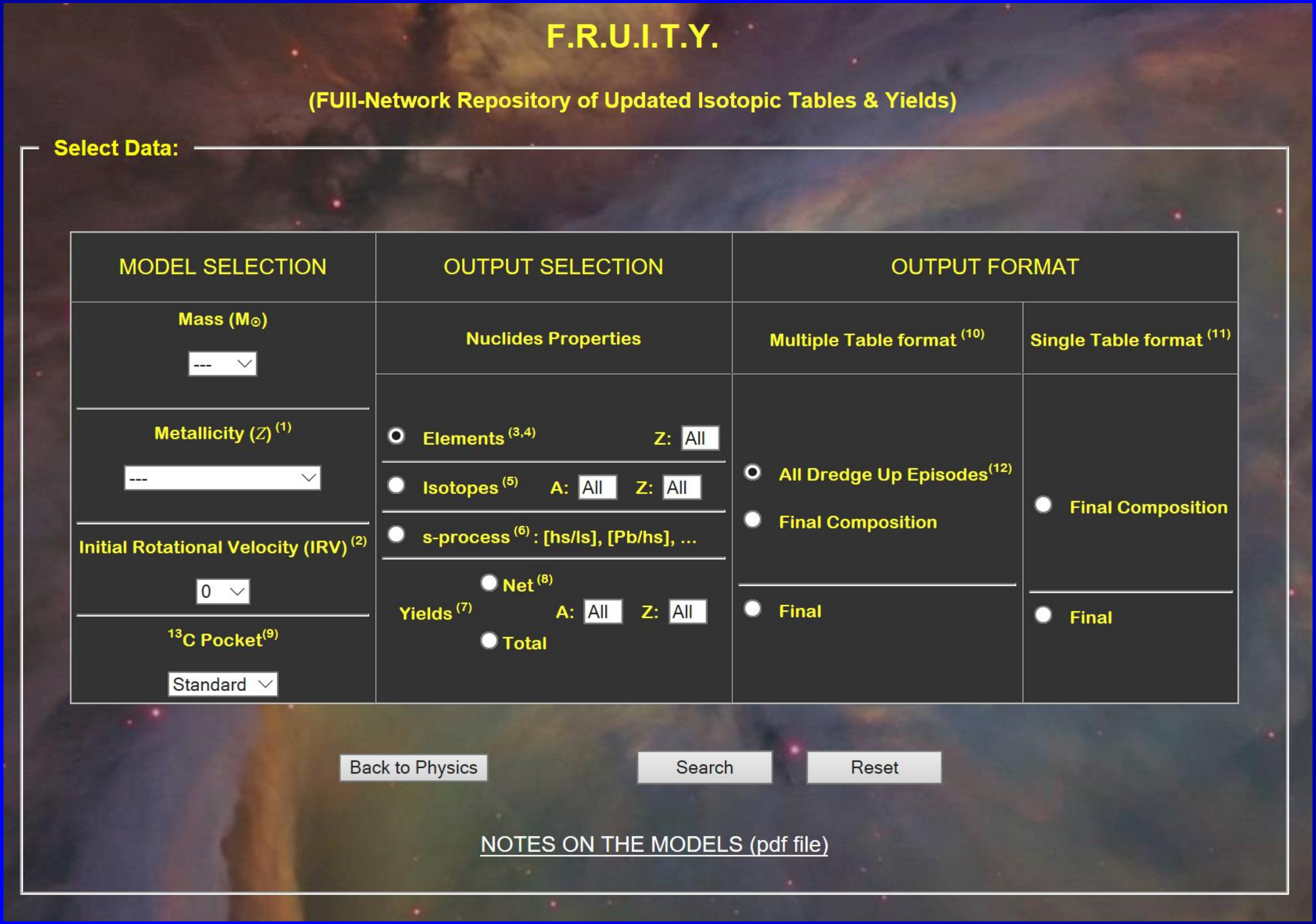
© P. Woitke

Meteorites

Allende (Mexico, 1969)

Murchison (Australia, 1969)

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



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

(FUll-Network Repository of Updated Isotopic Tables & Yields)

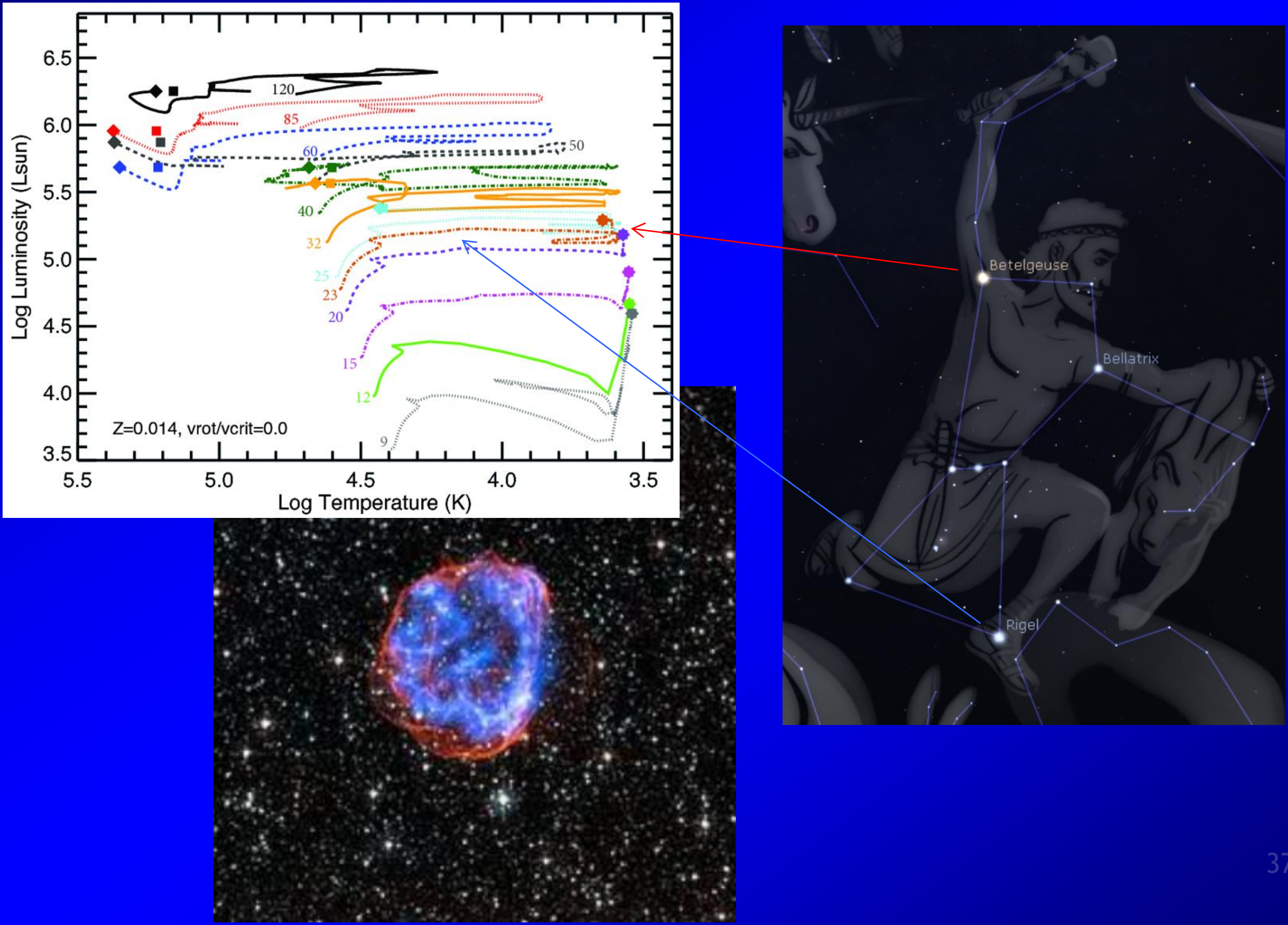
Select Data:

MODEL SELECTION	OUTPUT SELECTION	OUTPUT FORMAT	
Mass ($M_\odot$) ---	**Nuclides Properties**	**Multiple Table format (10)**	**Single Table format (11)**
Metallicity (Z) (1) ---	● **Elements (3,4)** Z: All	● **All Dredge Up Episodes(12)**	○ **Final Composition**
Initial Rotational Velocity (IRV) (2) 0	○ **Isotopes (5)** A: All Z: All	○ **Final Composition**	
^{13}C Pocket(9) Standard	○ **s-process (6) : [hs/ls], [Pb/hs], ...**	○ **Final**	○ **Final**
	Yields (7) ○ **Net (8)** ○ **Total** A: All Z: All		

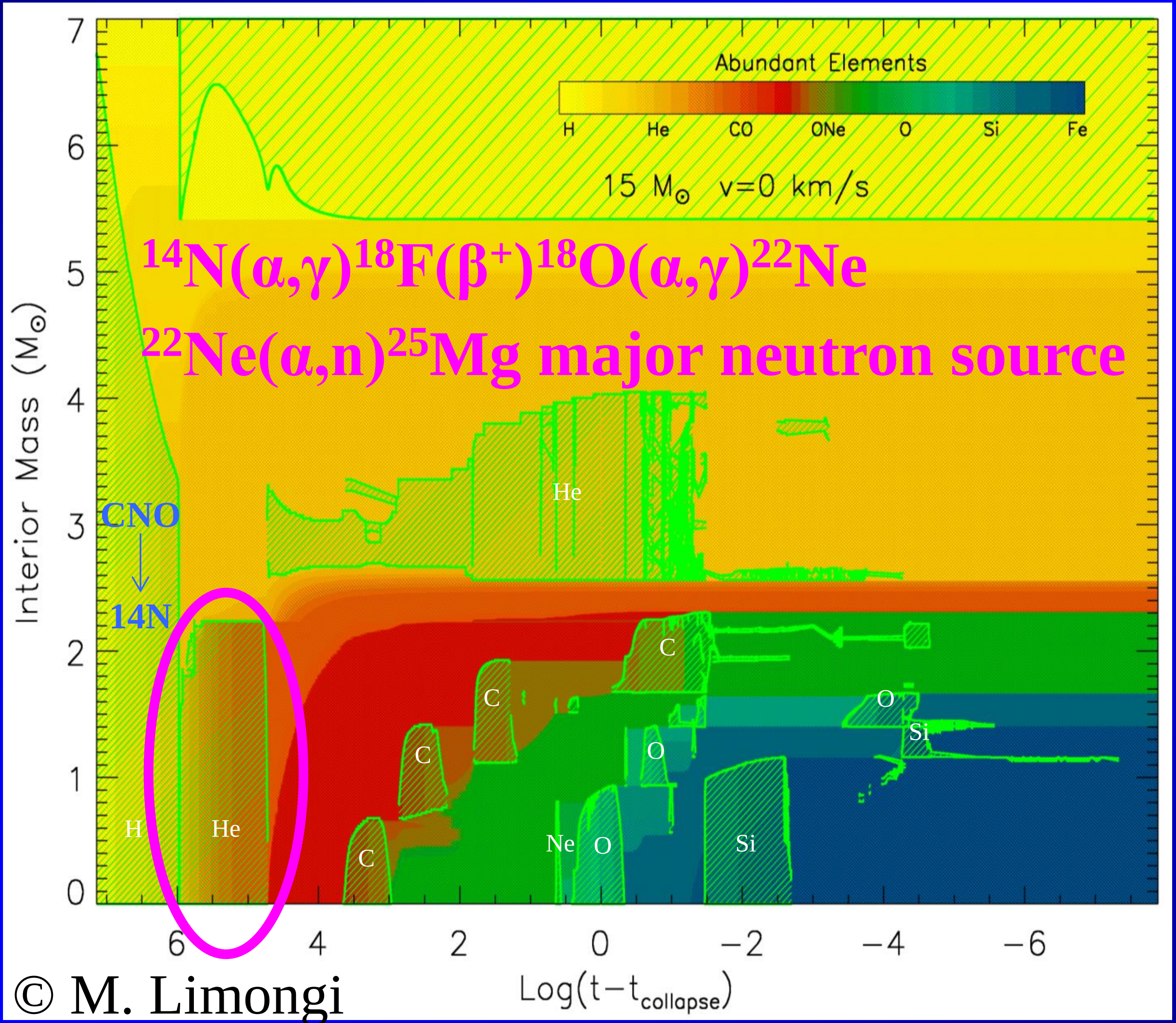
NOTES ON THE MODELS (pdf file)

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

The weak s-process in massive stars



The weak s-process and the evolution of massive stars

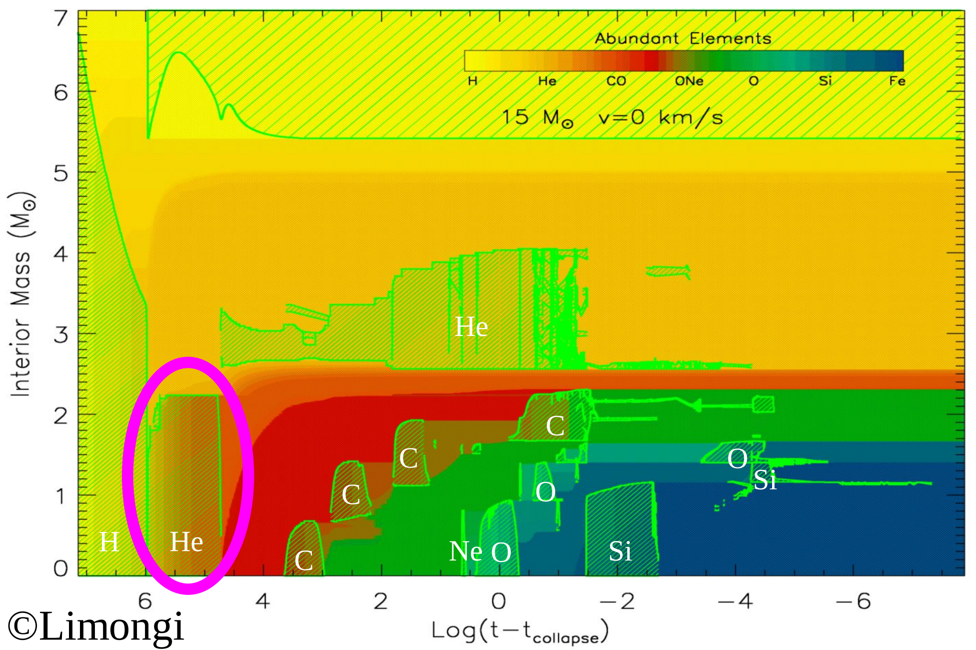


$^{14}N(\alpha,\gamma)^{18}F(\beta^+)^{18}O(\alpha,\gamma)^{22}Ne$

$^{22}Ne(\alpha,n)^{25}Mg$ major neutron source

© M. Limongi

Core He-burning phase



©Limongi

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

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

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

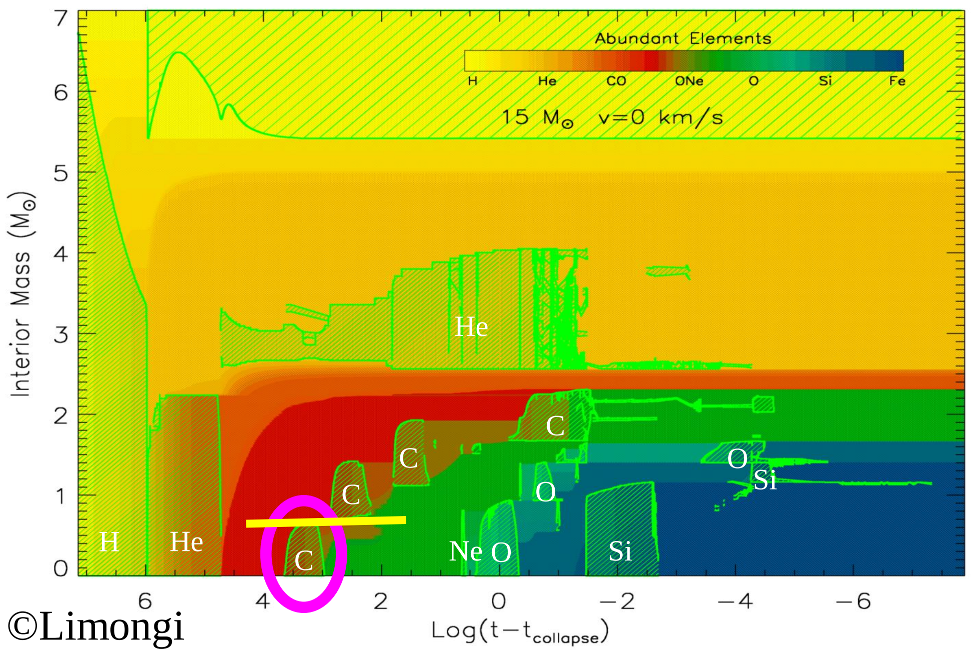
$\tau \approx 1$ Myr

When T~3x10^8 K the **^{22}Ne(α,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



©Limongi

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

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

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

$\tau \approx 1$ Kyr

Some ^{22}Ne is left after He burning

All (α,n) channels are activated:

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

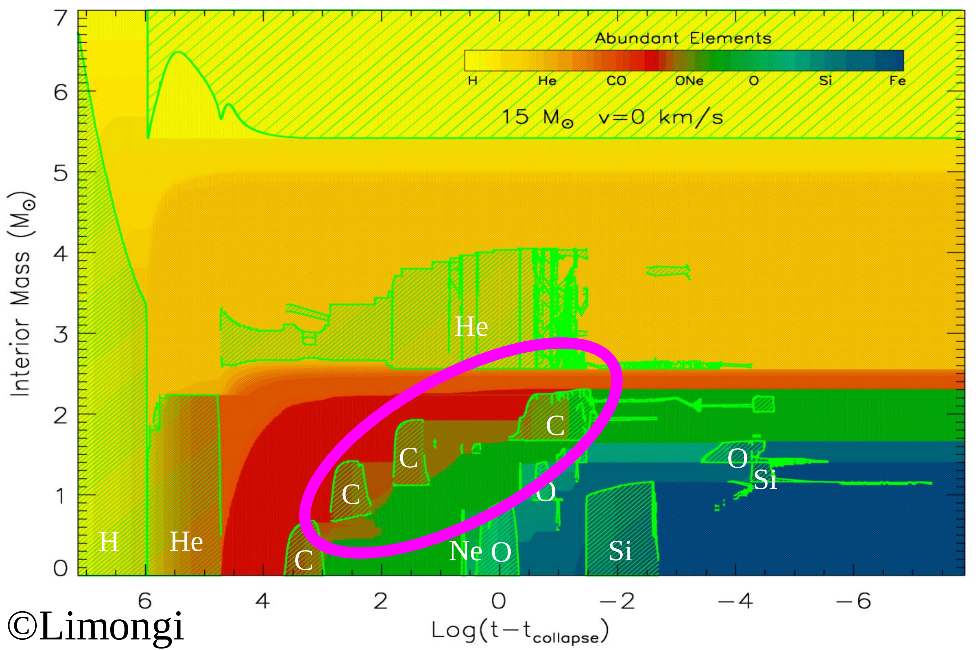
$^{18}O(\alpha,n)^{21}Ne$ - $^{21}Ne(\alpha,n)^{24}Mg$

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

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

The resulting neutron density is very high, BUT…

Shell C-burning phase



©Limongi

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

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

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

All (α,n) channels are activated:

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

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

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

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

Why not the $^{13}C(\alpha,n)^{16}O$?

Because at T~1x10^{9} K

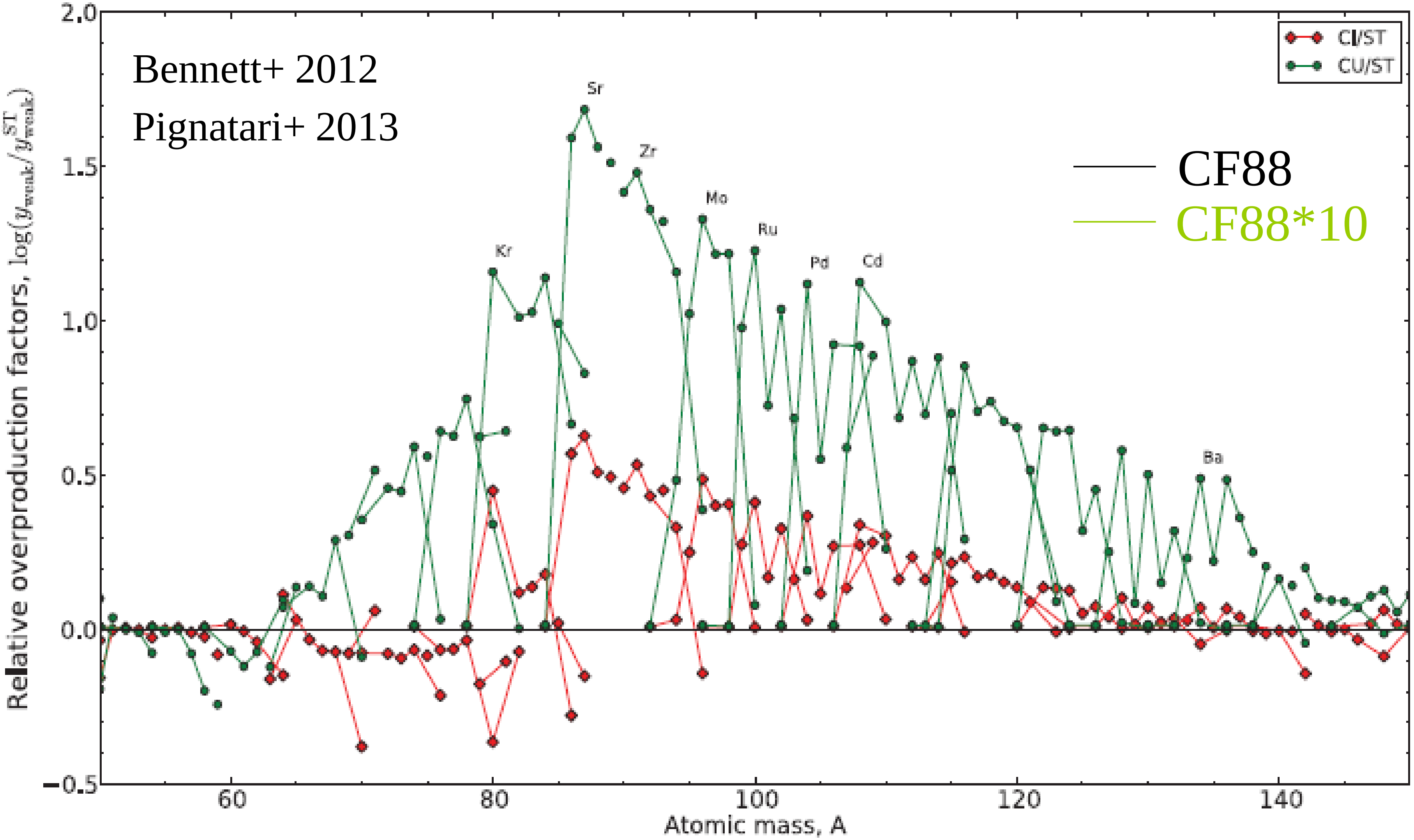
the $^{13}N(\gamma,p)^{12}C^*$ works!!

The resulting neutron density is very high:

10^{11}-10^{12} n/cm^3

Uncertainties of the weak s-process: cross sections

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



Bennett+ 2012

Pignatari+ 2013

CF88

CF88*10

Uncertainties of the weak s-process: stellar modelling

Convection - Rotation

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

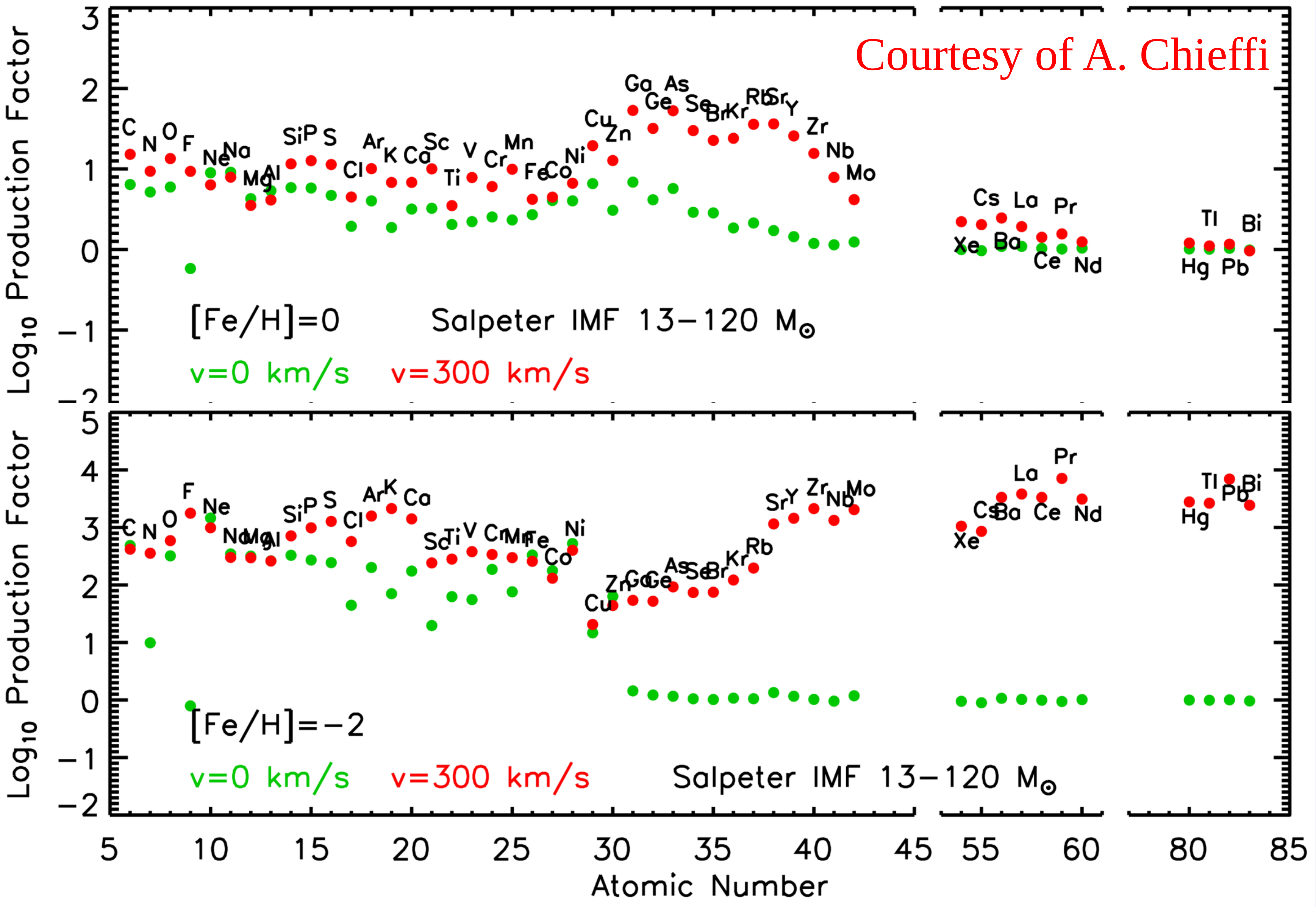
$$^{13}\mathrm{C}/^{14}\mathrm{N} \simeq 5.7 \cdot 10^{-3}$$

In any case the dominant source is the

$^{22}\mathrm{Ne}(\alpha,n)^{25}\mathrm{Mg}$

Courtesy of A. Chieffi

The effect of rotation: differences in the stellar ejecta



The end