

The slow neutron capture process






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For the umpteenth time...

The Origin of the Solar System Elements

1 H	big bang fusion 						cosmic ray fission 						2 He																						
3 Li	4 Be	merging neutron stars? 						exploding massive stars 						5 B	6 C	7 N	8 O	9 F	10 Ne																
11 Na	12 Mg	dying low mass stars 						exploding white dwarfs 						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/>

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 ESA/NASA/AASNova

The r-process

B2FH

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

Unstable nucleus captures another neutron before decaying

The s-process

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

Unstable nucleus decays before capturing another neutron

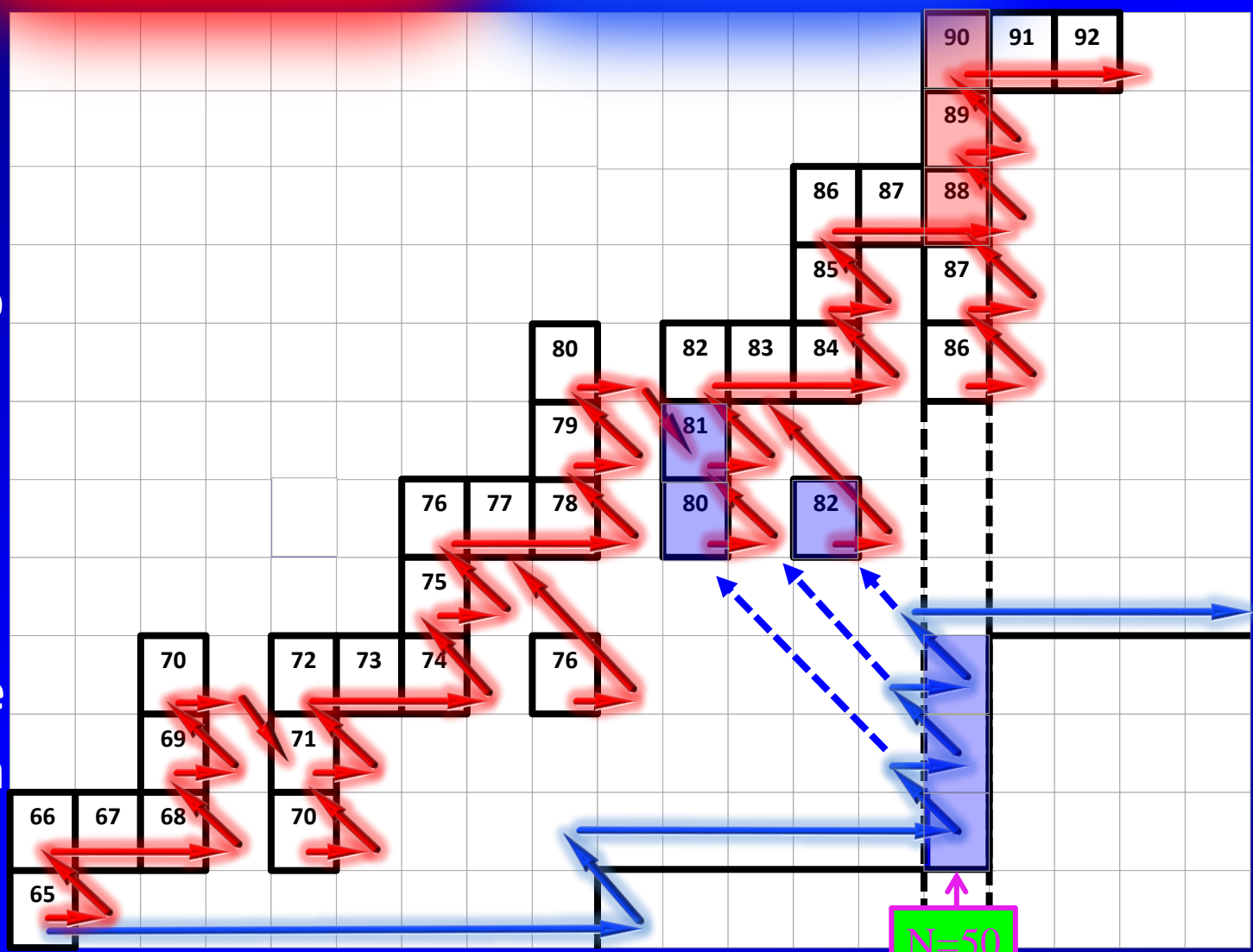
In principle one might expect to encounter astrophysical neutron fluxes in the large region between these two densities and have thereby intermediate processes between s and r. Such events are apparently not common, and it is one of the fortunate simplifications in the application theory of synthesis 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

Proton number (Z)

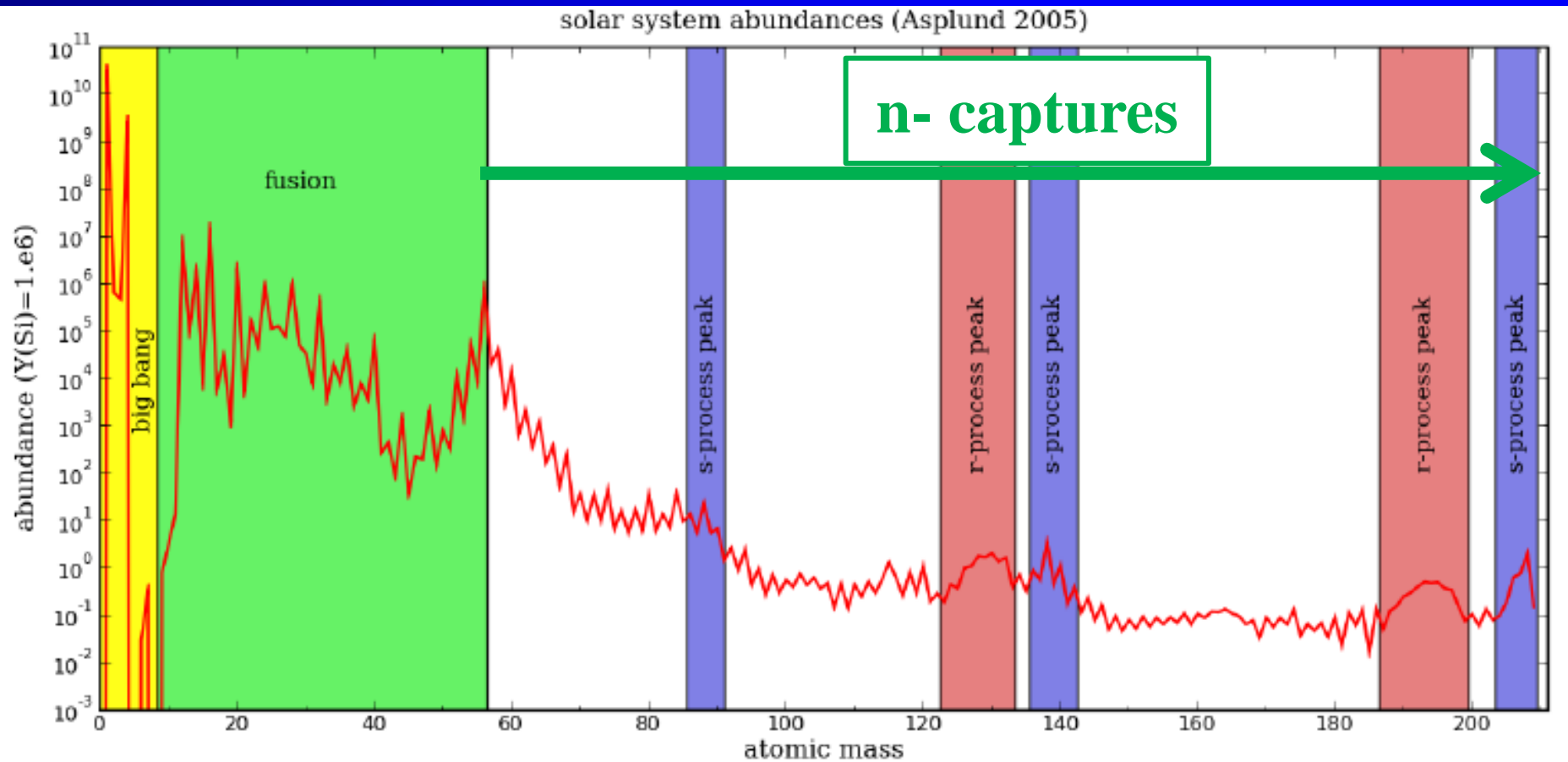
Zr
Y
Sr
Rb
Kr
Br
Se
As
Ge
Ga
Zn
Cu

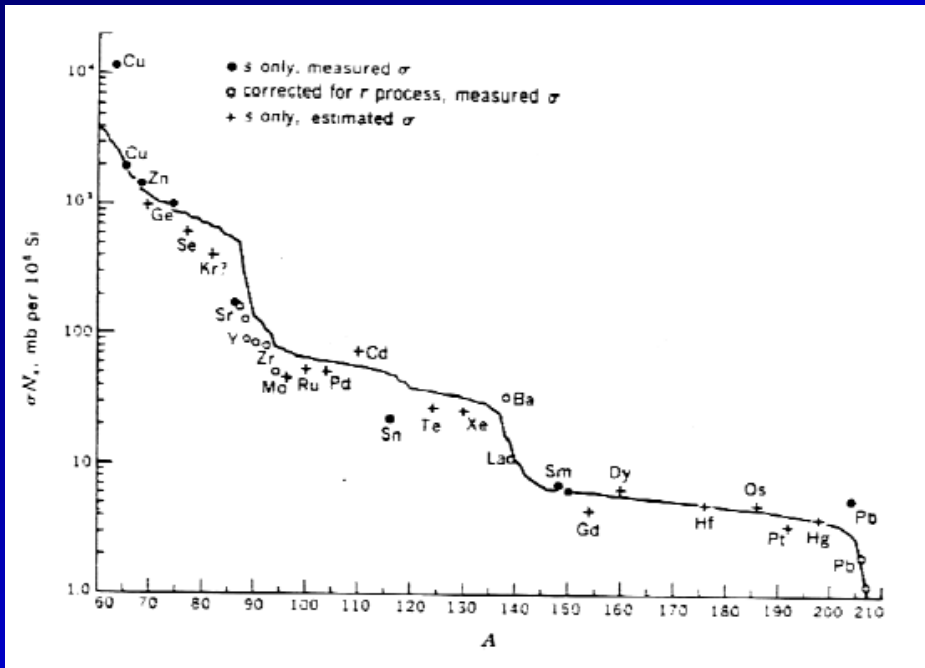


N=50

Mass number (protons+neutrons) (A)

Solar System Abundances



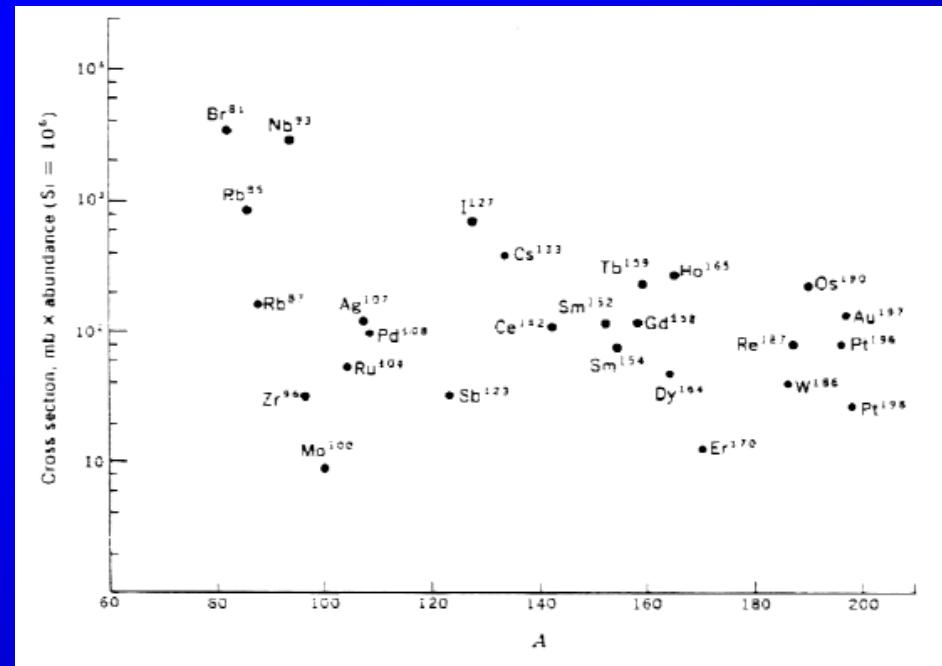


s-process

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

r-process

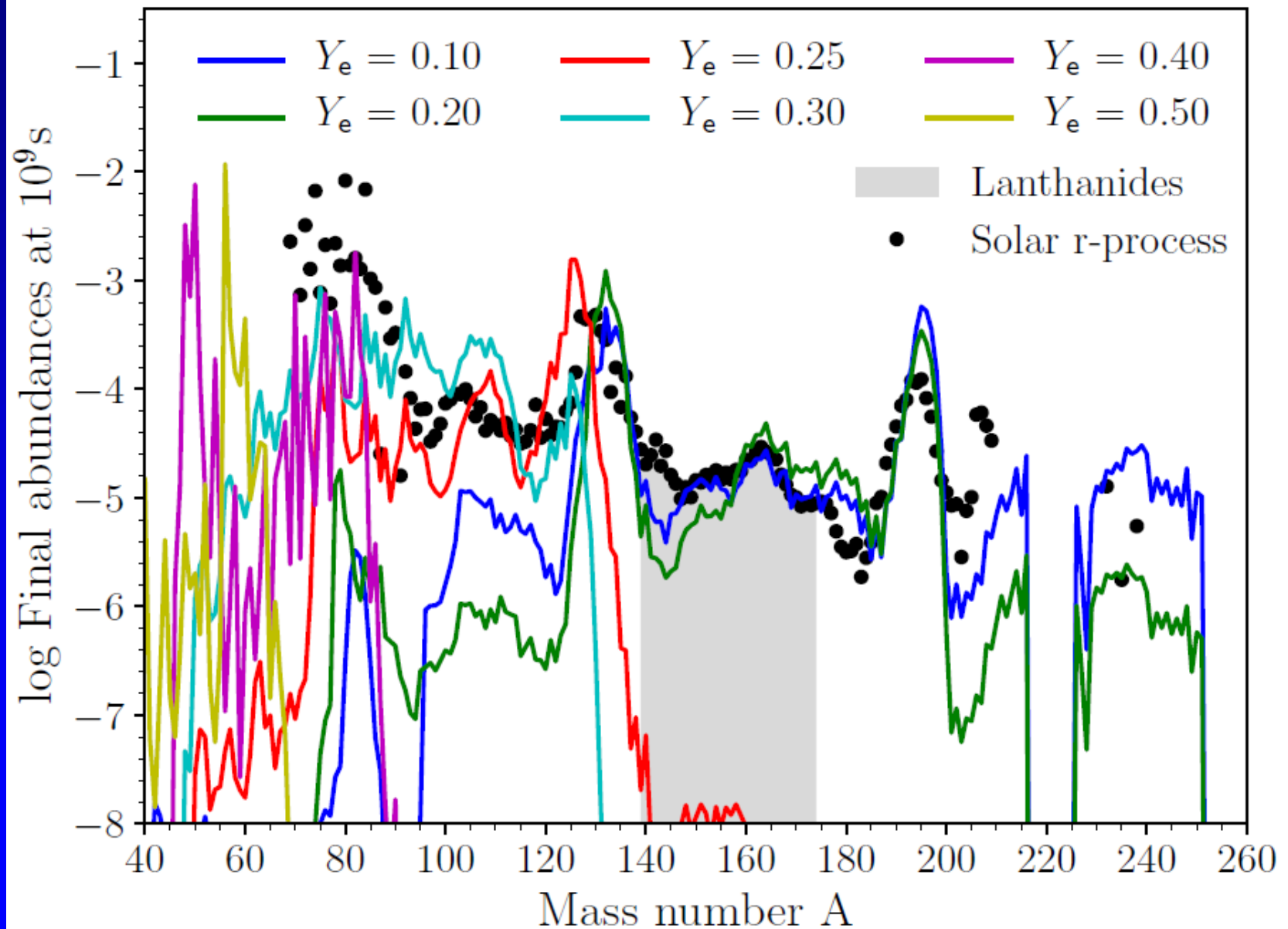
Do you see any distribution?



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

57	La		138	139								
56	Ba		130	132	134	135	136	137	138			
55	Cs		133									
54	Xe		124	126	128	129	130	131	132	134	136	
53	I		127									
52	Te		120	122	123	124	125	126	128	130		
51	Sb		121	123								
50	Sn		112	114	115	116	117	118	119	120	122	124
49	In		113	115								
48	Cd		106	108	110	111	112	113	114	116		
47	Ag		107	109								
46	Pd		102	104	105	106	108	110				
45	Rh		103									
44	Ru		96	98	99	100	101	102	104			

42	Mo		92	94	95	96	97	98	100
41	Nb		93						
40	Zr		90	91	92	94	96		
39	Y		89						
38	Sr		84	86	87	88			
37	Rb		85	87					
36	Kr		78	80	82	83	84	86	
35	Br		79	81					
34	Se		74	76	77	78	80	82	
33	As		75						
32	Ge		70	72	73	74	76		
31	Ga		69	71					

Prantzios+2002

Prantzos+2020

83	Bi		209							
82	Pb		204	206	207	208				
81	Tl		203	205						
80	Hg		196	198	199	200	201	202	204	
79	Au		197							
78	Pt		190	192	194	195	196	198		
77	Ir		191	193						
76	Os		184	186	187	188	189	190	192	
75	Re		185	187						
74	W		180	182	183	184	186			
73	Ta		180	181						
72	Hf		174	176	177	178	179	180		
71	Lu		175	176						
70	Yb		168	170	171	172	173	174	176	
69	Tm		169							
68	Er		162	164	166	167	168	170		
67	Ho		165							
66	Dy		156	158	160	161	162	163	164	
65	Tb		159							
64	Gd		152	154	155	156	157	158	160	
63	Eu		151	153						
62	Sm		144	147	148	149	150	152	154	

60	Nd		142	143	144	145	146	148	150
59	Pr		141						
58	Ce		136	138	140	142			

S

r

p

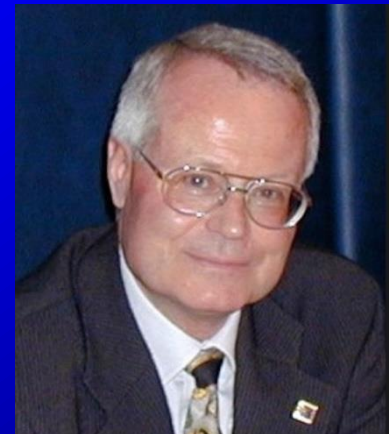
$$r = 1 - s$$



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

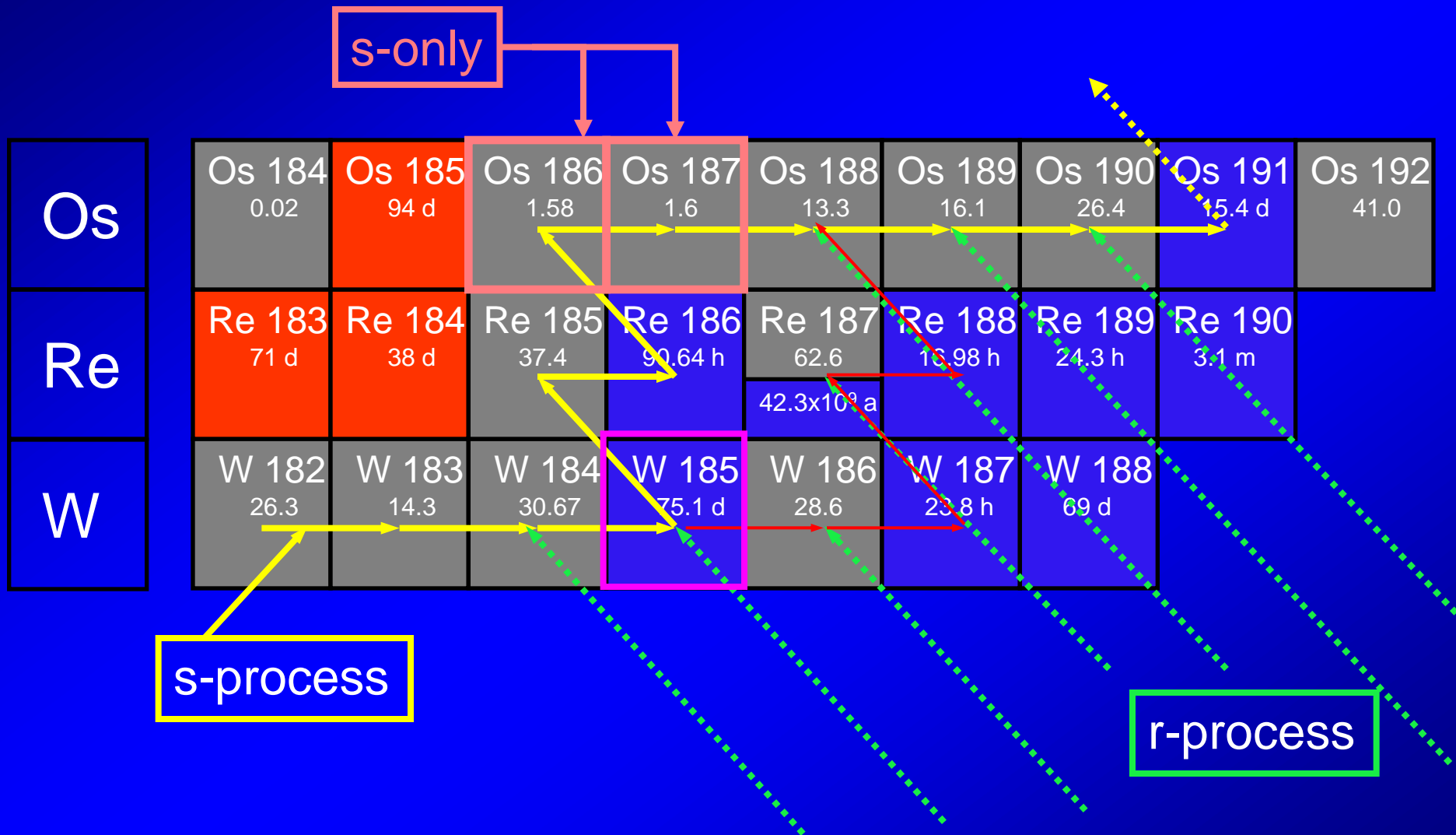
VS

$$s = 1 - r$$



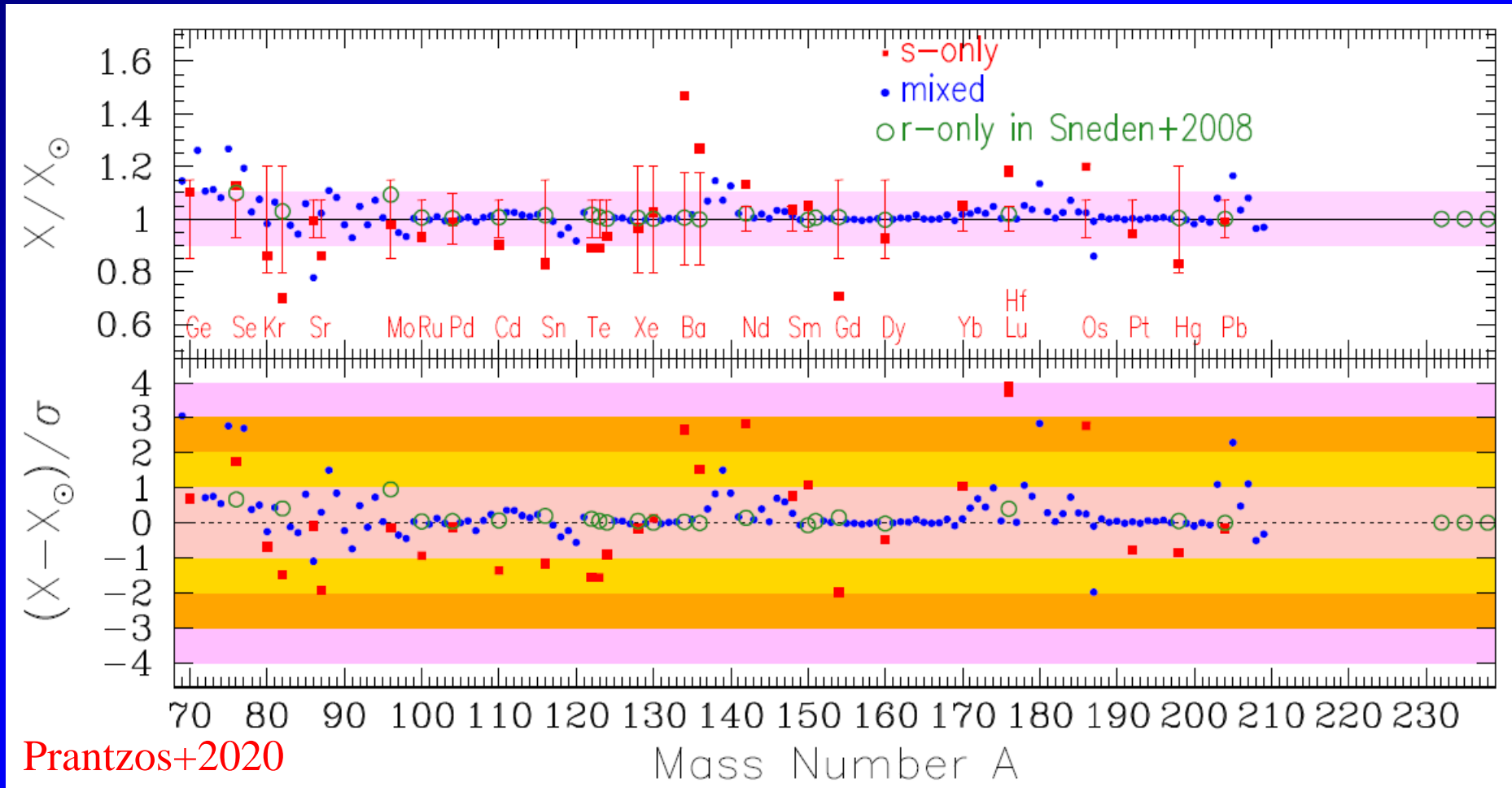
Busso, Kratz, Palmerini + 2022

How s-process neutron captures work?



Branching points: 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 ^1H , ^4He or ^{12}C ???

Seeds for the s-process

Main seeds are ^{56}Fe nuclei...

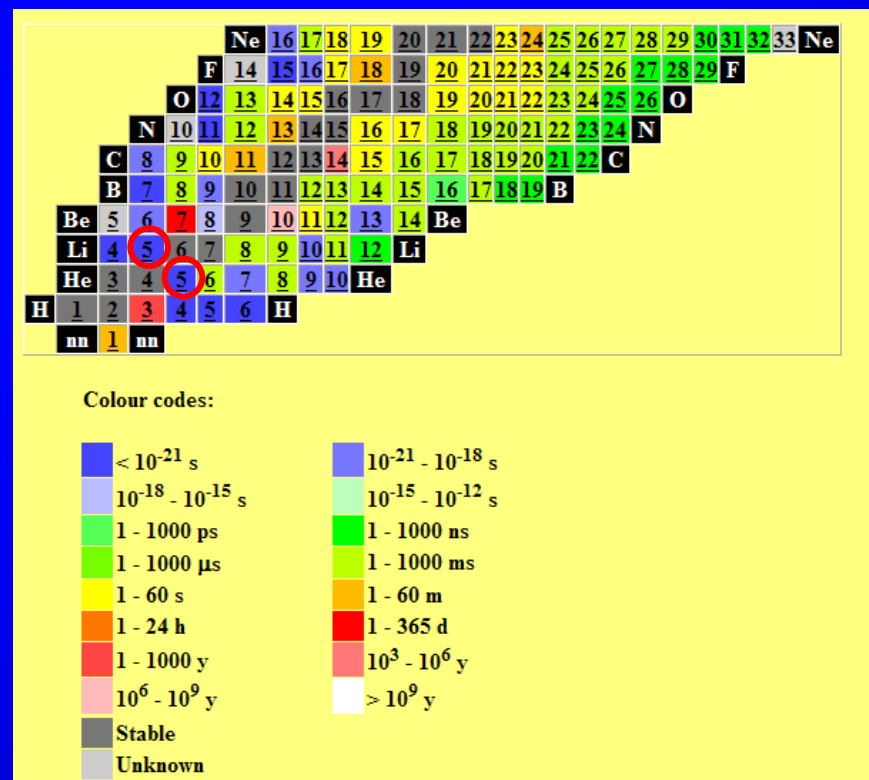
Why not the most abundant ^1H , ^4He or ^{12}C ???

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

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

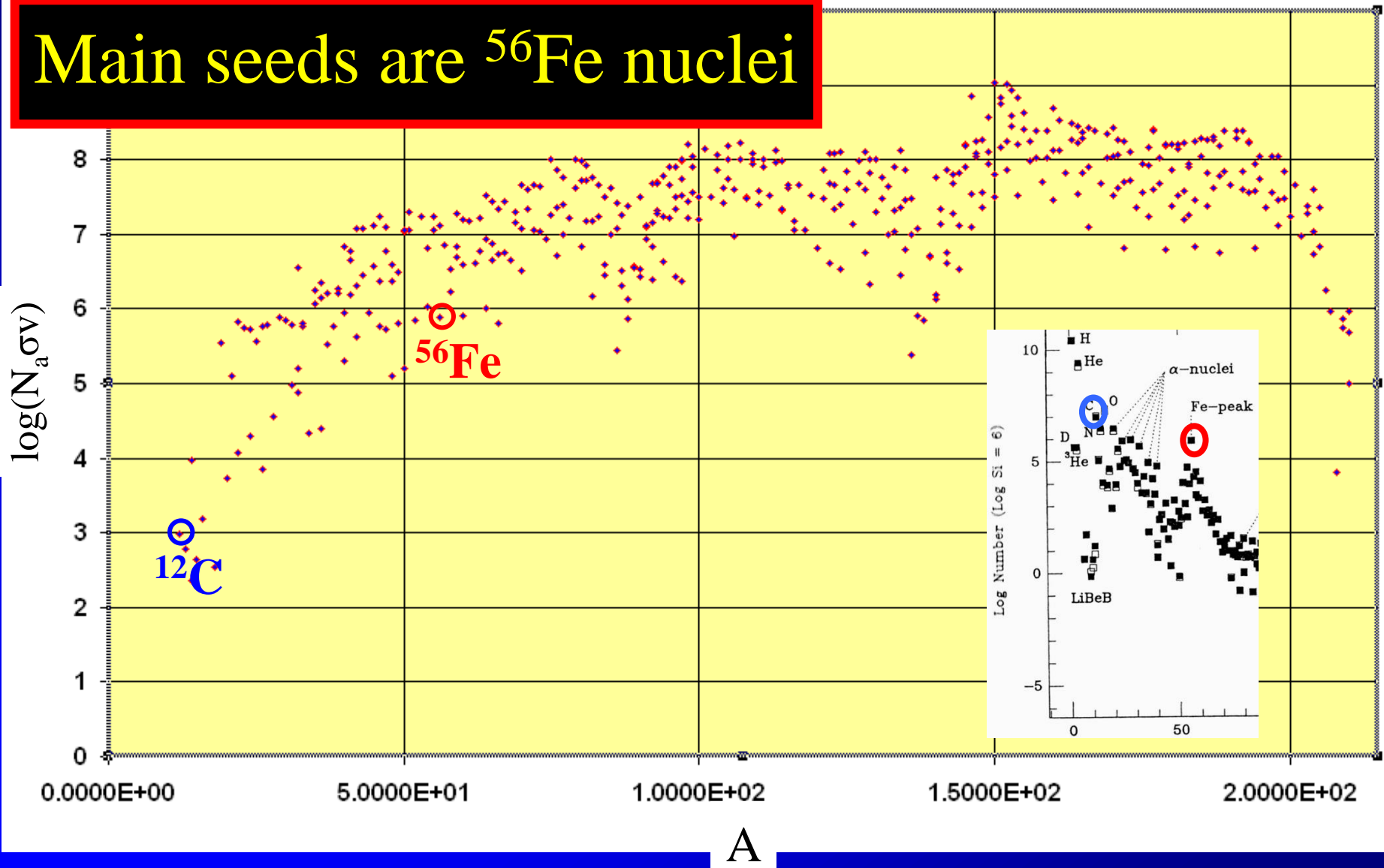
$$\downarrow$$

$$10^{-12}$$



Seeds for the s-process

Main seeds are ^{56}Fe nuclei

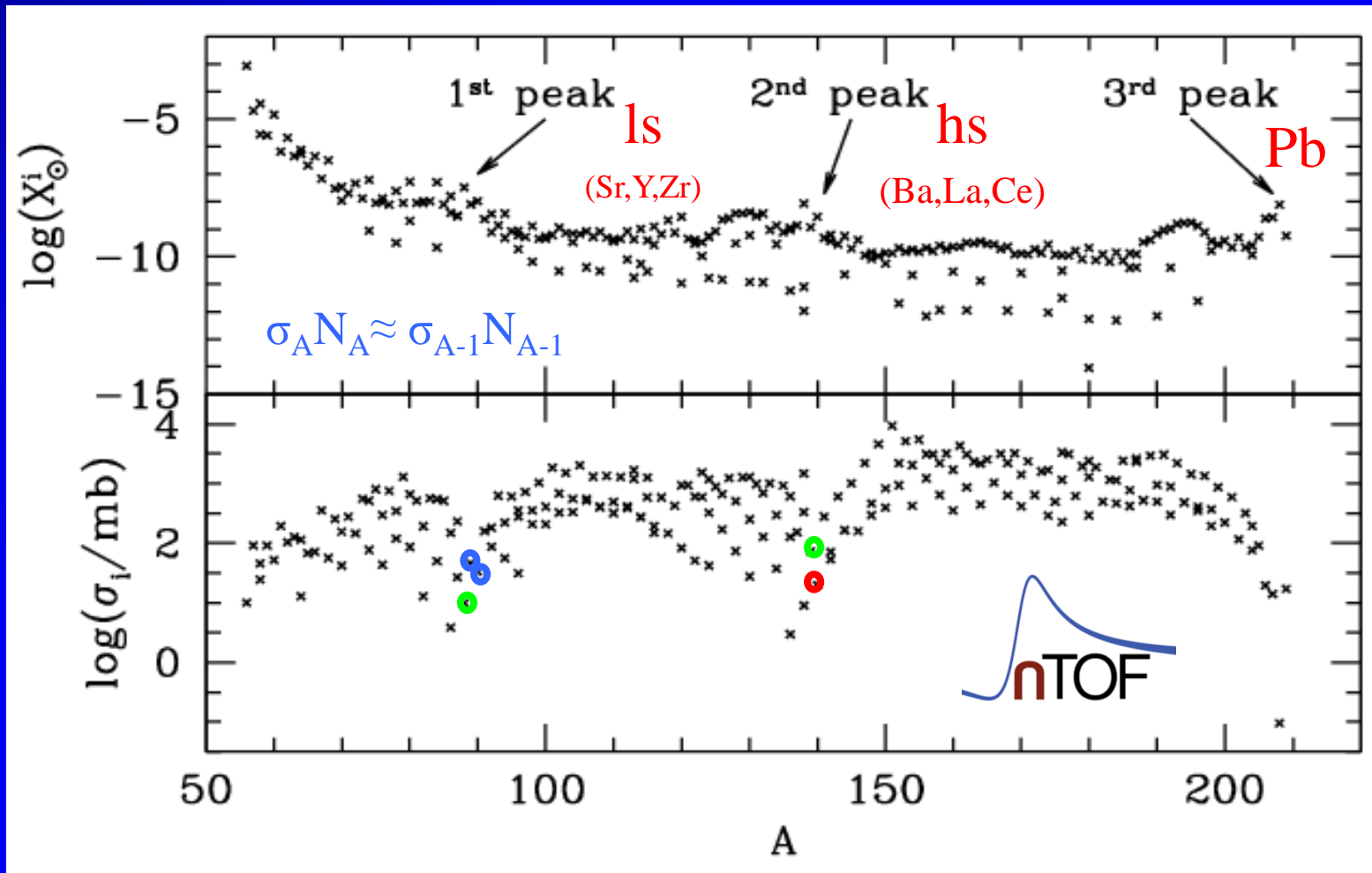


MAGIC NUCLEI

very small $\sigma(n,\gamma)$
at neutron magic numbers



abundance curve for
elements beyond iron

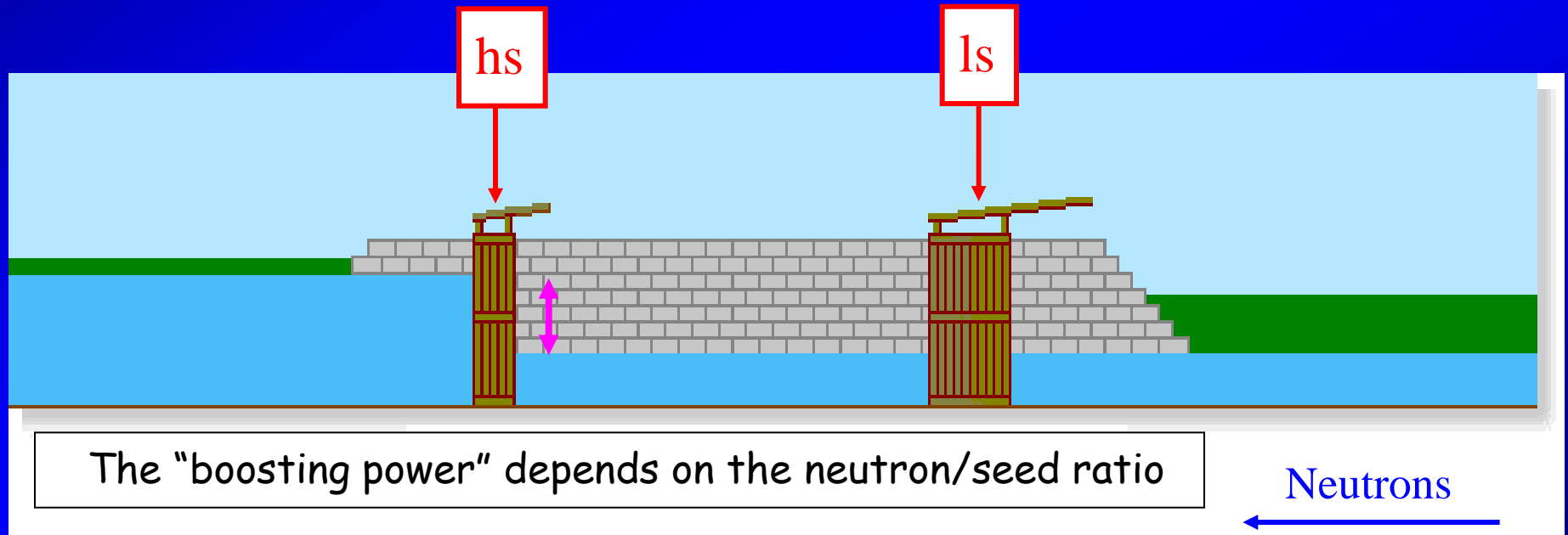


The three s-process peaks

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

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

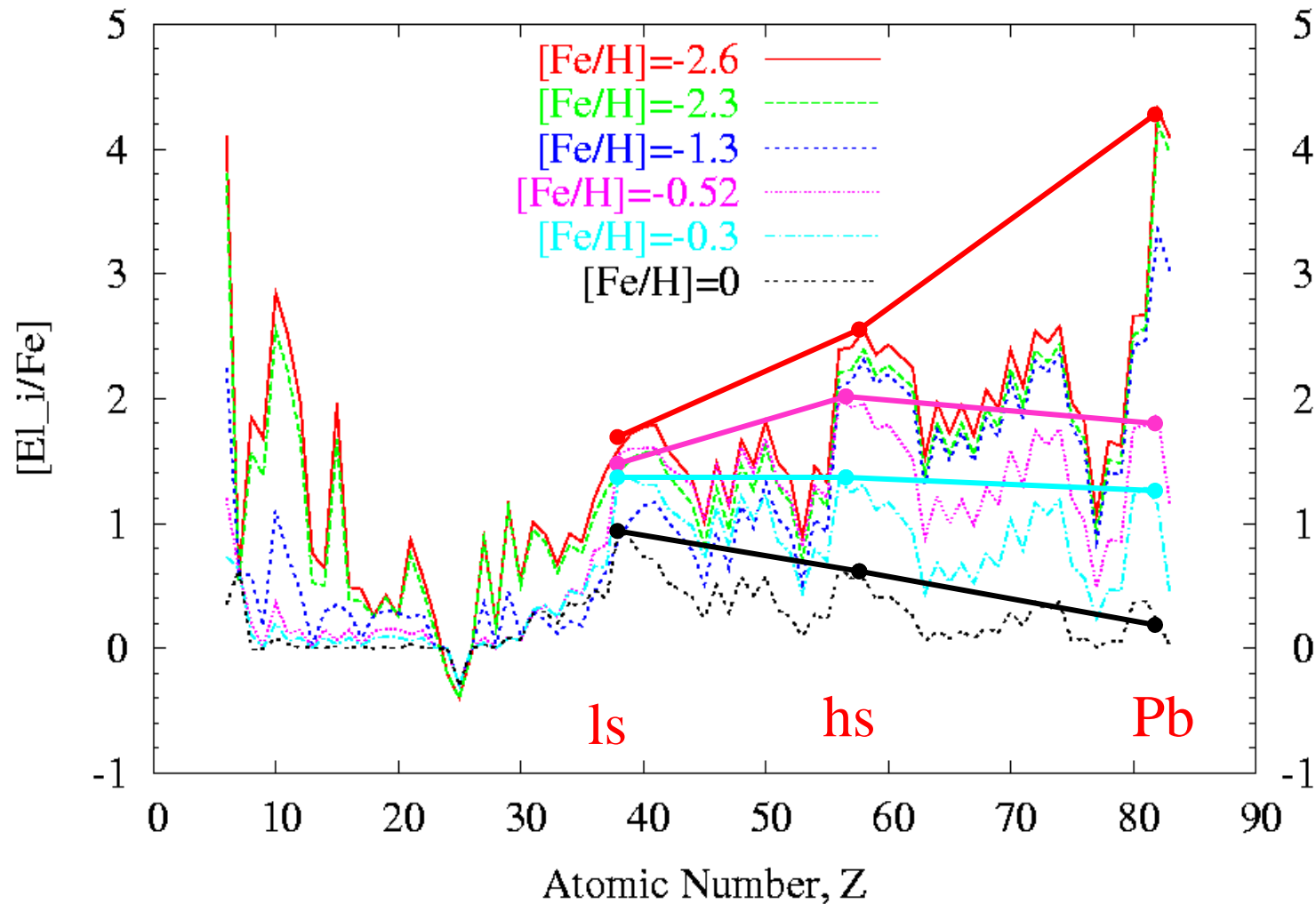
3rd peak → lead (^{208}Pb) [N=126 & P=82]



A sluice system with opening bulkheads

SURFACE DISTRIBUTION

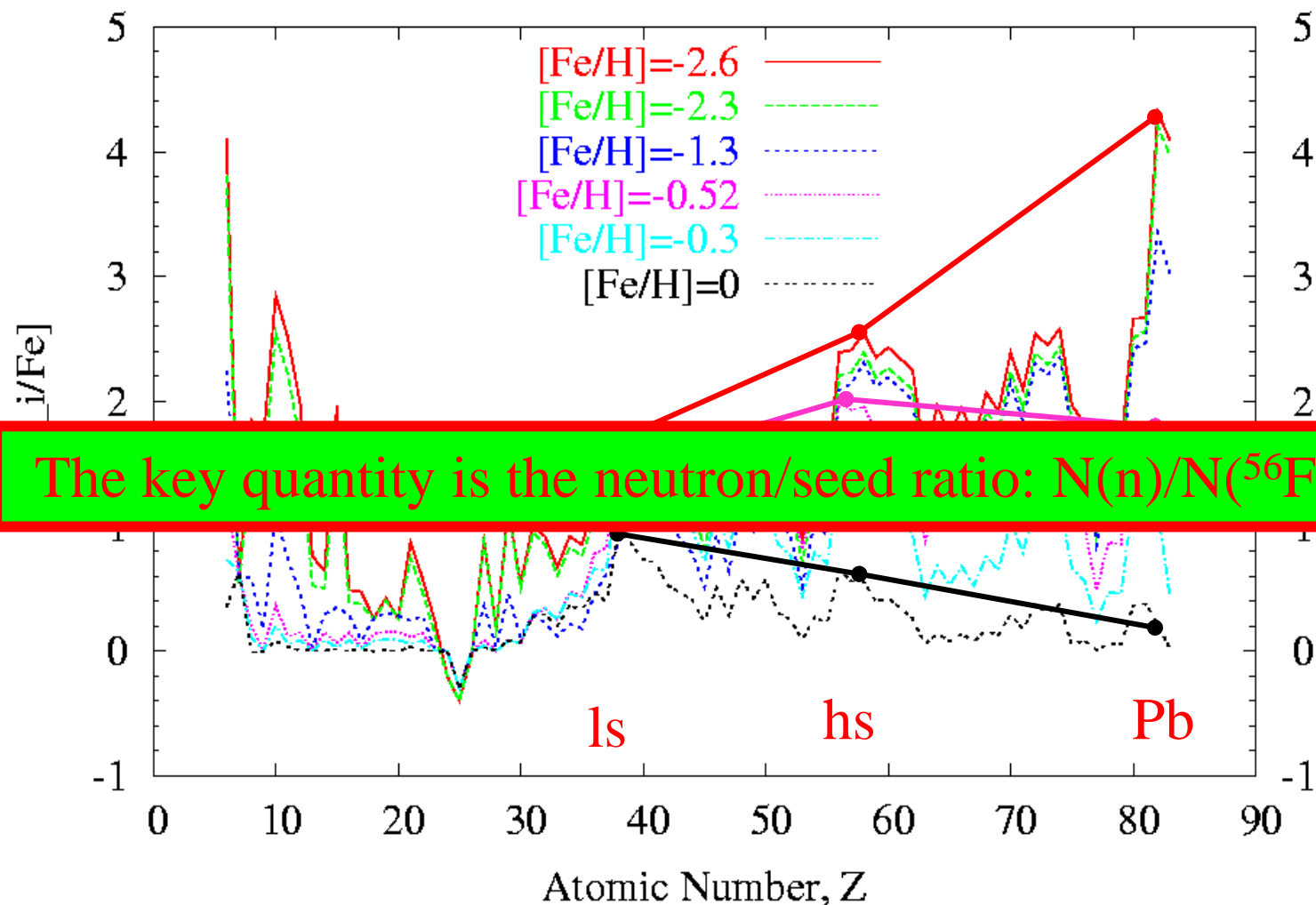
AGB $M=1.5M_{\text{sun}}$



R. Gallino's models

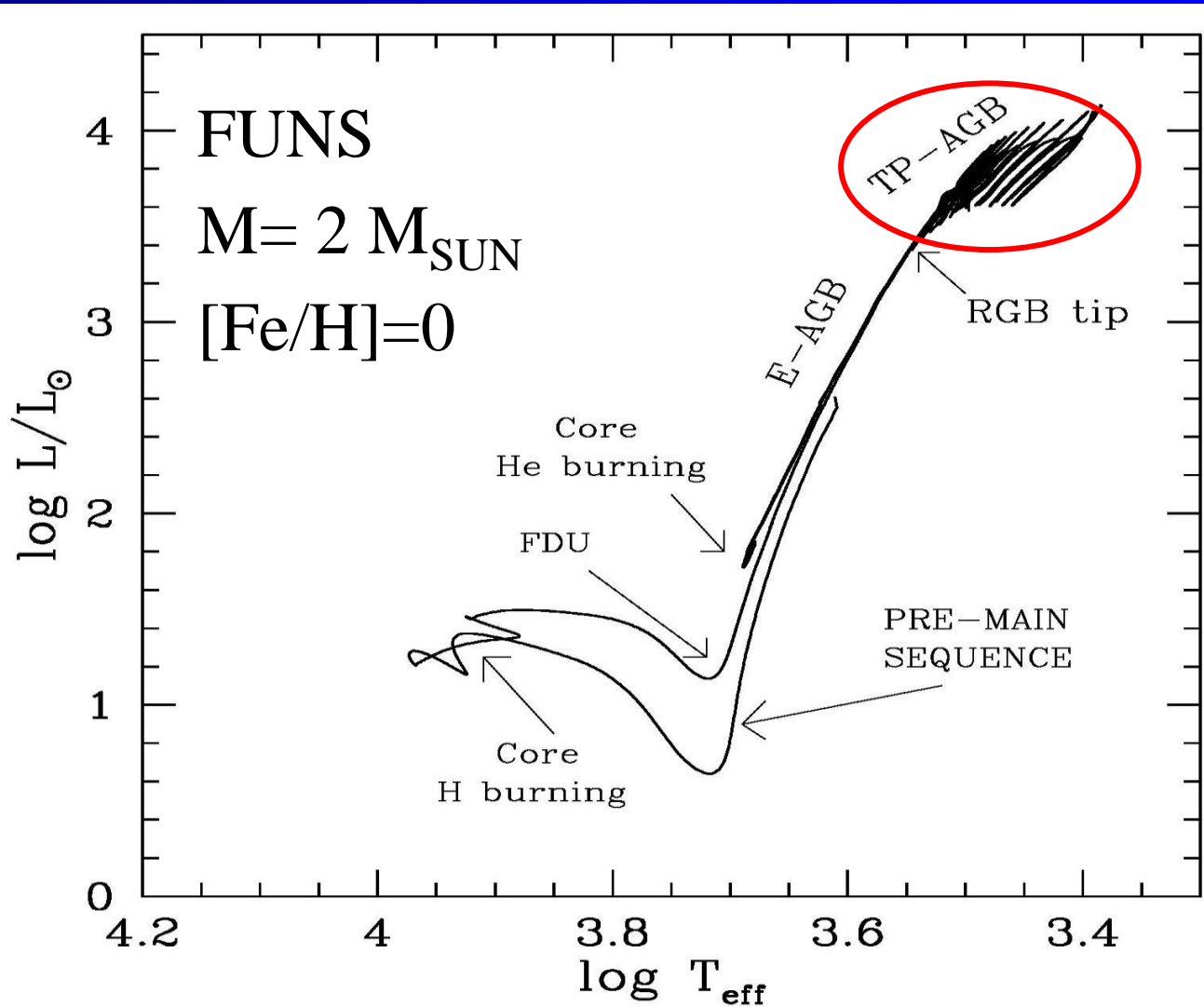
SURFACE DISTRIBUTION

AGB $M=1.5M_{\text{sun}}$



R. Gallino's models

Asymptotic Giant Branch (AGB) stars

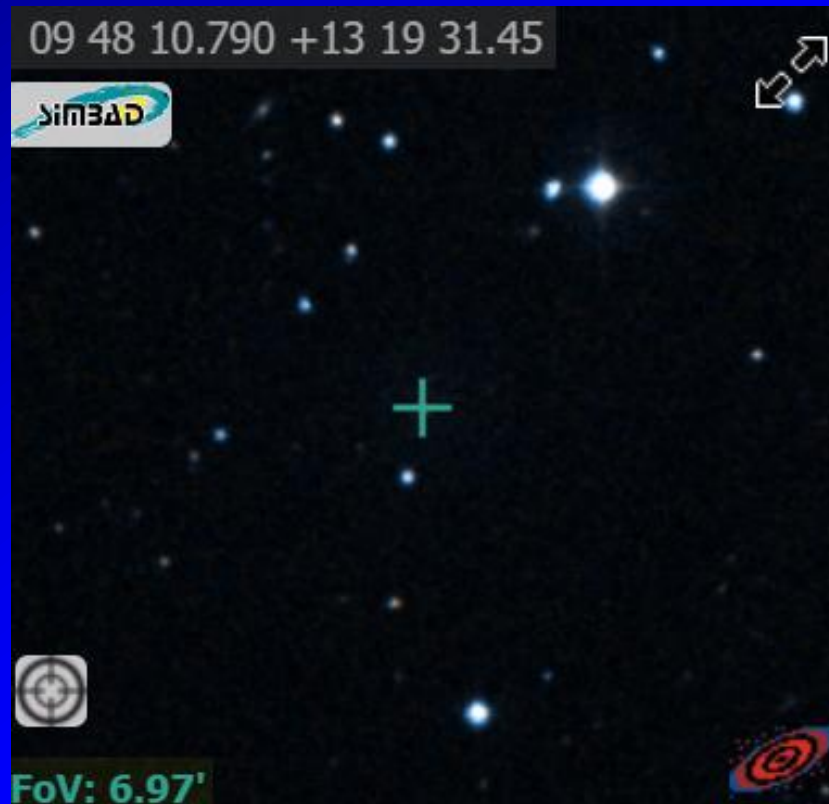


$$\tau_{\text{MS}} \approx 1 \text{ Gyr}$$

$$\tau_{\text{AGB}} \approx 1 \text{ Myr}$$

Can we see an AGB star in the sky?

CW Leonis



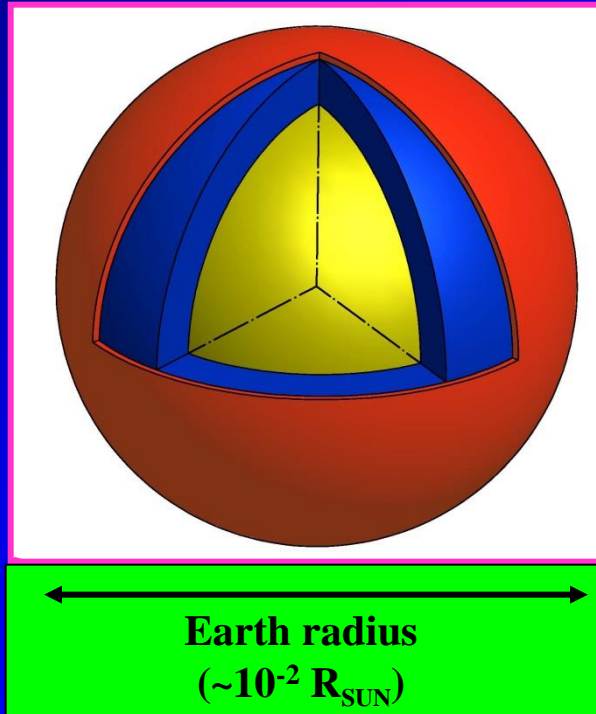
OPTICAL BAND



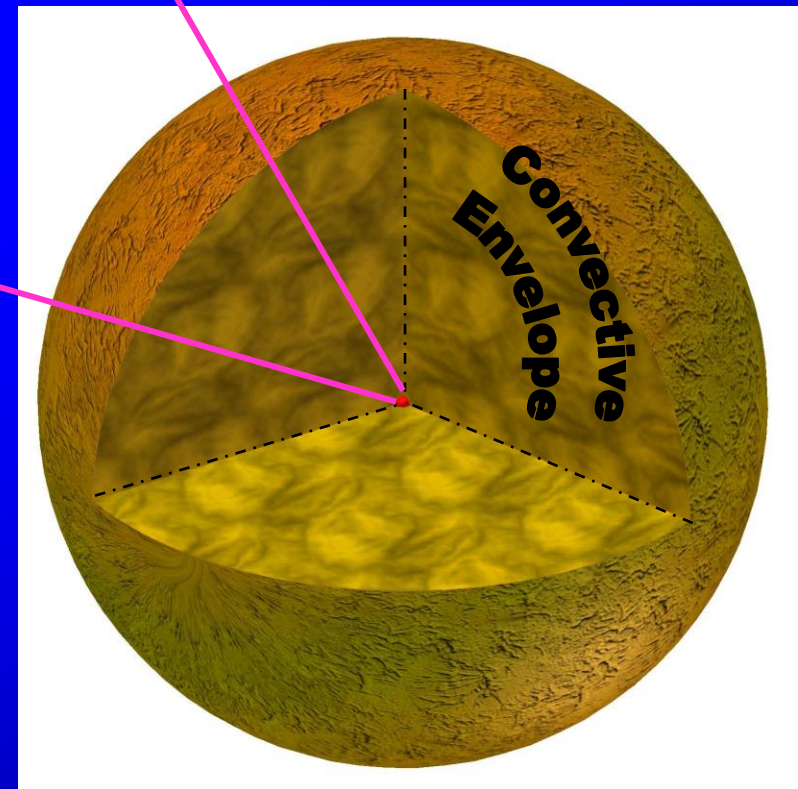
INFRARED BAND

AGB structure

CO Core
He-shell
H-shell



Earth-Sun
(~200 R_{SUN})



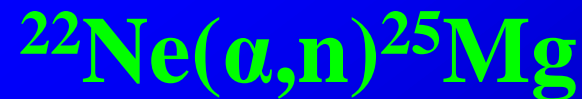
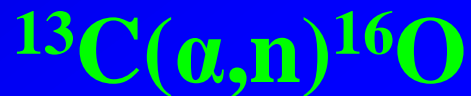
It's like you put a nut
in a 300 mts hot air balloon!!!

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

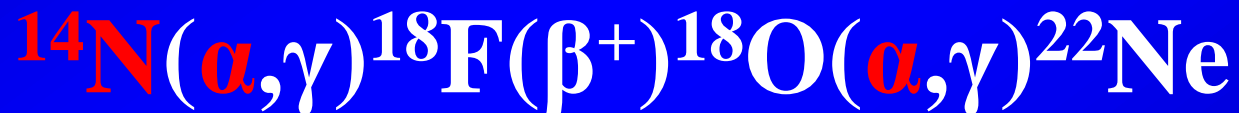


The nuclear paths

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

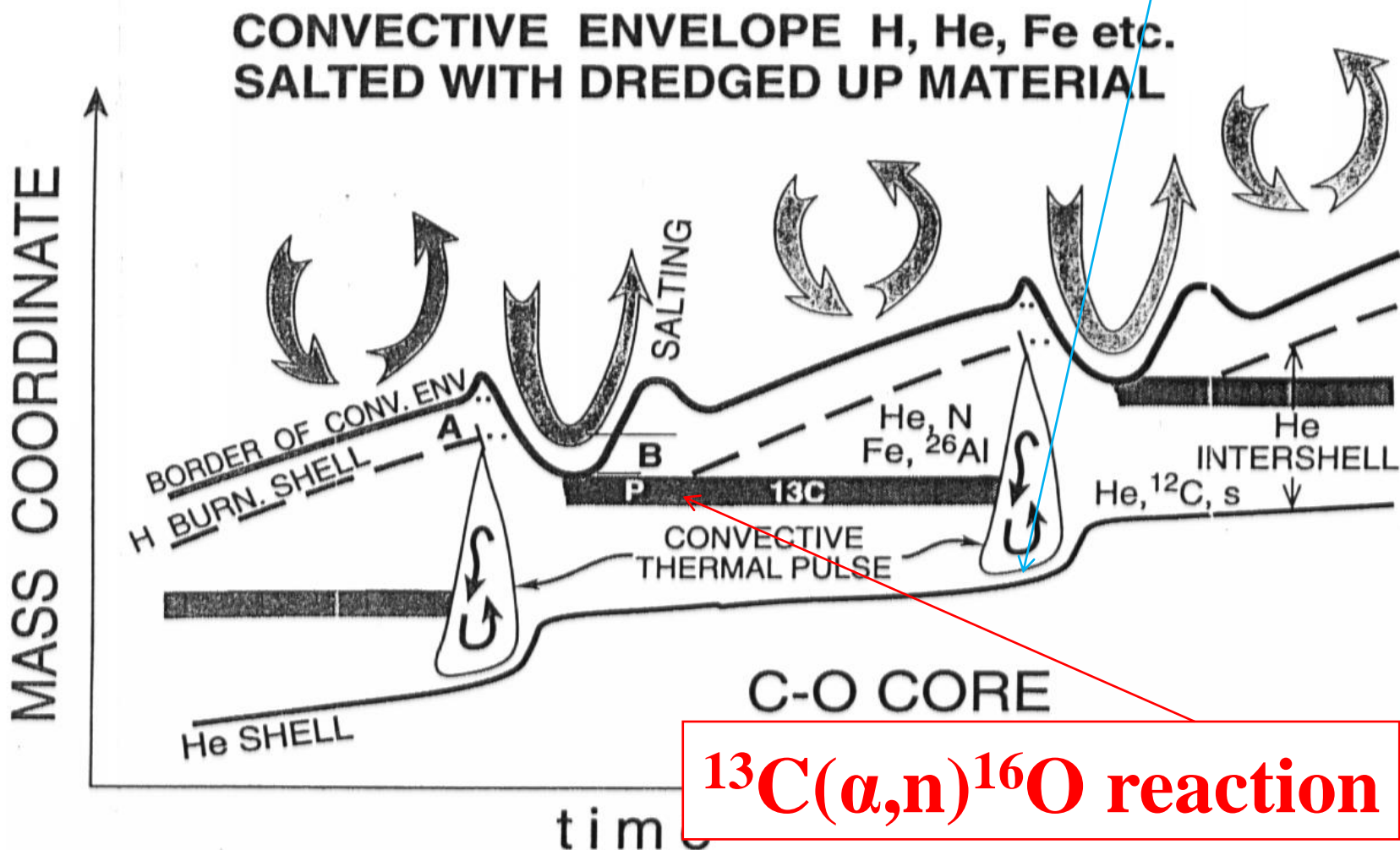


^{22}Ne : main source for the Weak component



The s-process in AGB stars

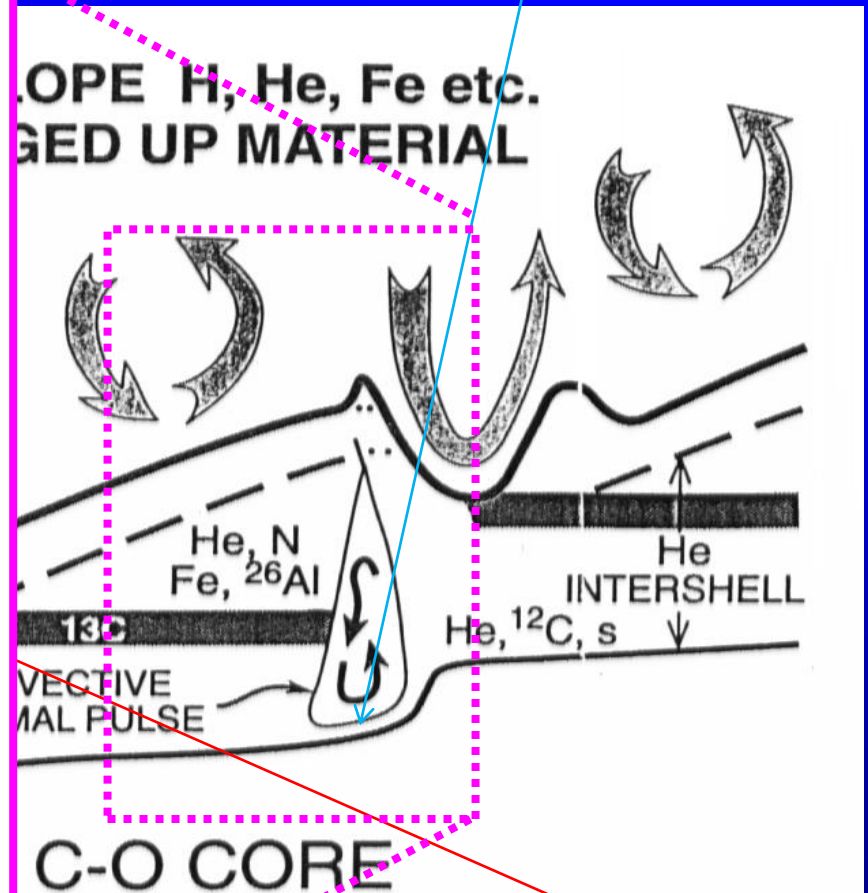
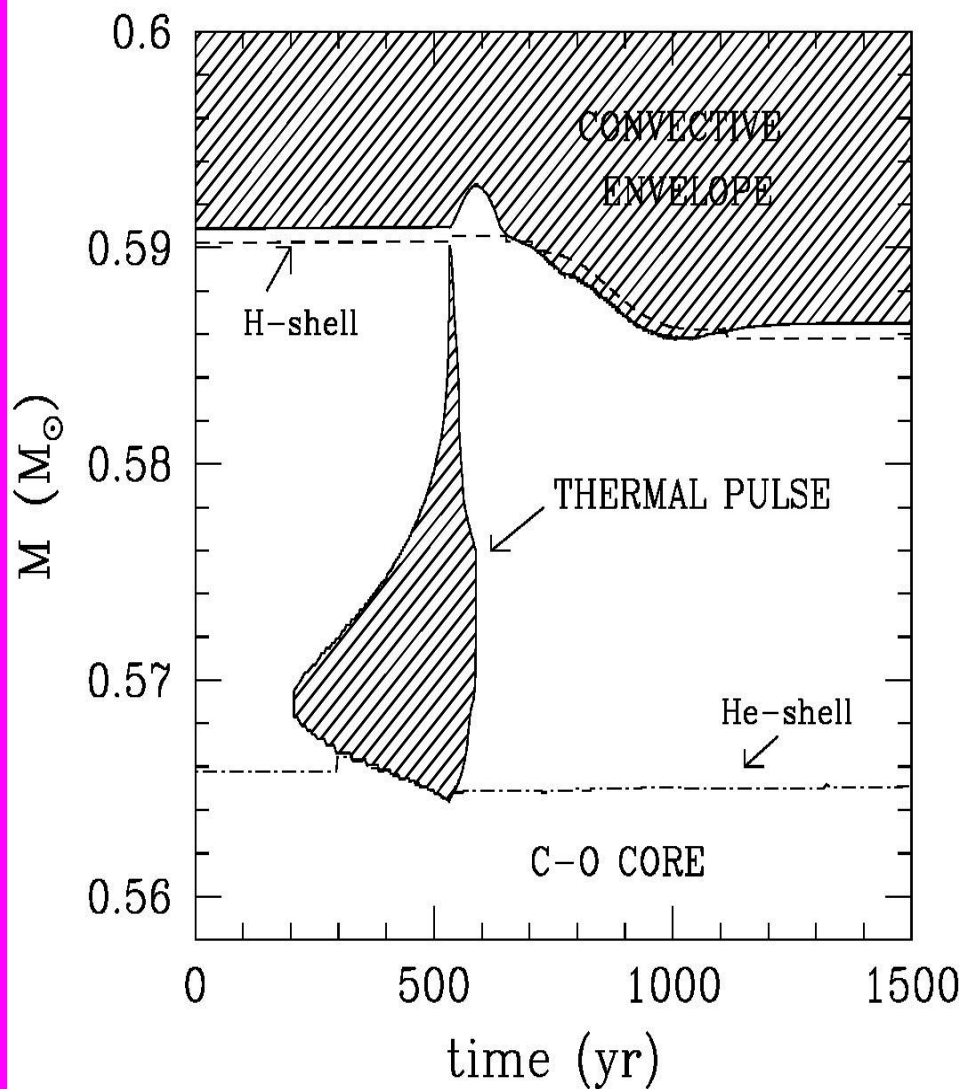
$^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction



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

The s-process in AGB stars

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



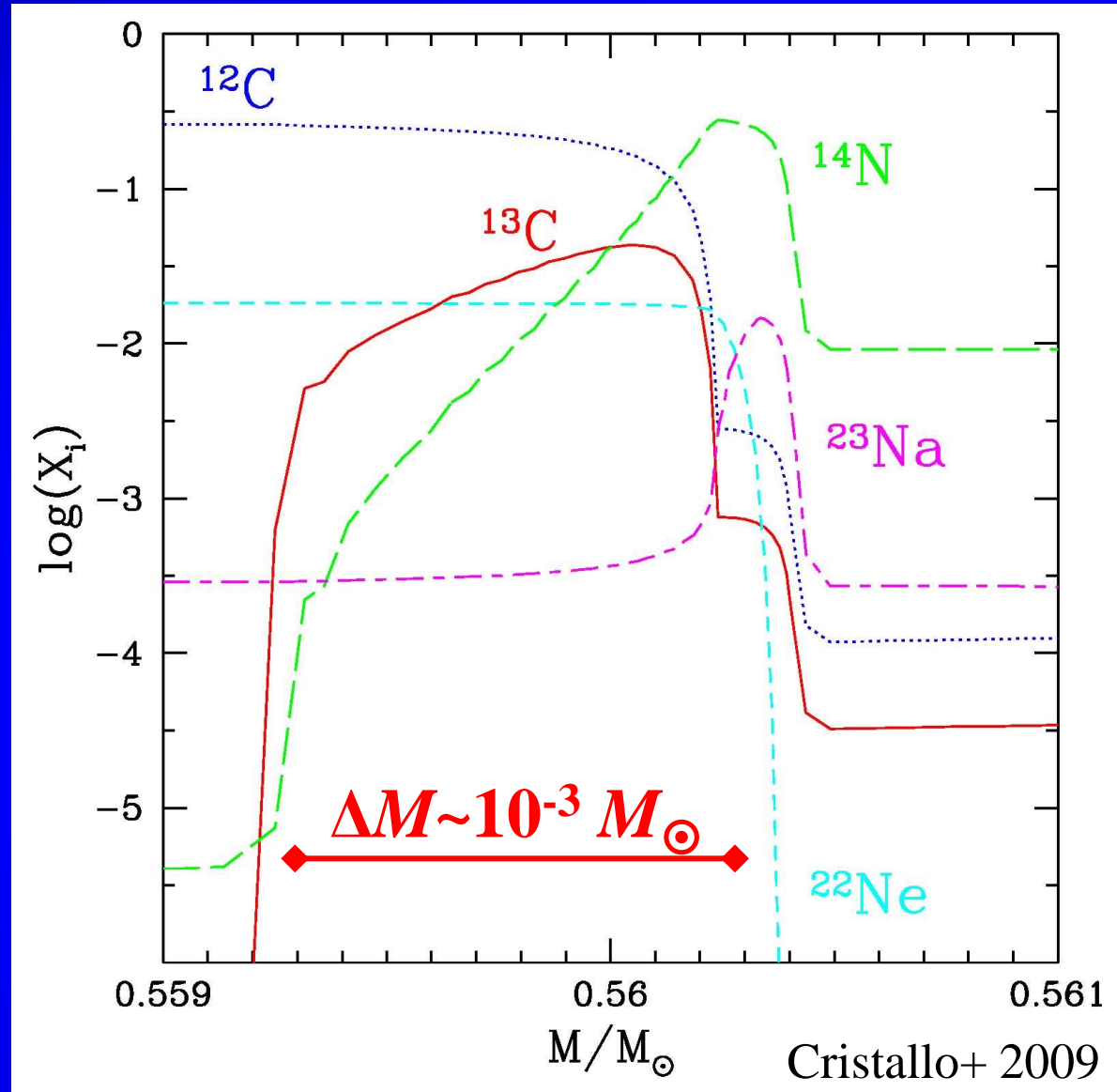
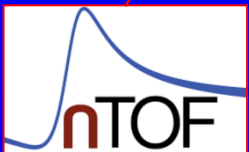
$^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction

The formation of the ^{13}C pocket

^{13}C -pocket

^{14}N -pocket

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



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?

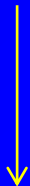
- ✓ **Rotation-induced mixing** (Herwig+ 2003; Siess+ 2004; Piersanti+ 2013)

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

$$\dot{v} \propto -k v^{-2}$$



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

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

- 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.

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⁾ ---	<input type="radio"/> Elements ^(3,4) Z: All	<input type="radio"/> All Dredge Up Episodes ⁽¹²⁾	<input type="radio"/> Final Composition
Initial Rotational Velocity (IRV) ⁽²⁾ 0	<input type="radio"/> Isotopes ⁽⁵⁾ A: All Z: All	<input type="radio"/> Final Composition	
^{13}C Pocket ⁽⁹⁾ Standard	<input type="radio"/> s-process ⁽⁶⁾ : [hs/ls], [Pb/hs], ...		
	<input type="radio"/> Net ⁽⁸⁾	<input type="radio"/> Final	<input type="radio"/> Final
	Yields ⁽⁷⁾ A: All Z: All		
	<input type="radio"/> Total		

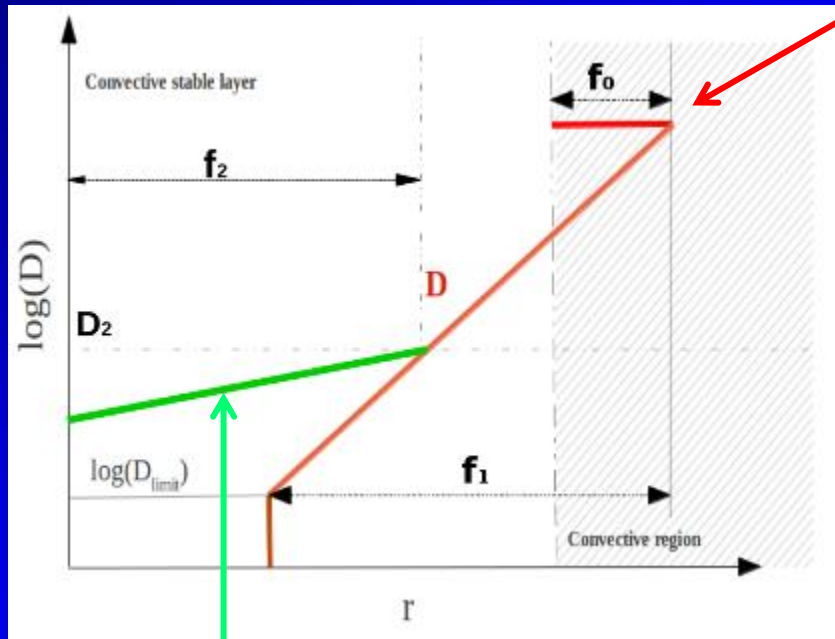
[Back to Physics](#) [Search](#) [Reset](#)

[NOTES ON THE MODELS \(pdf file\)](#)

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

Convective Boundary Mixing + Gravity Waves

Battino+ 2016



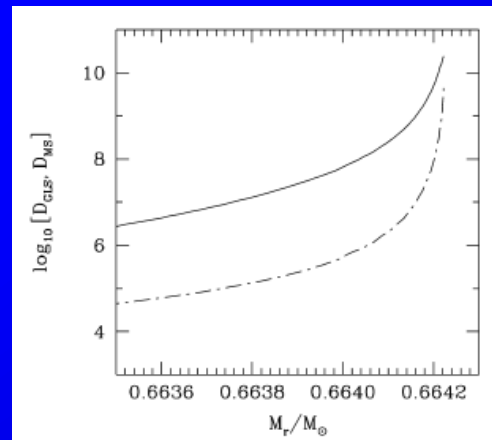
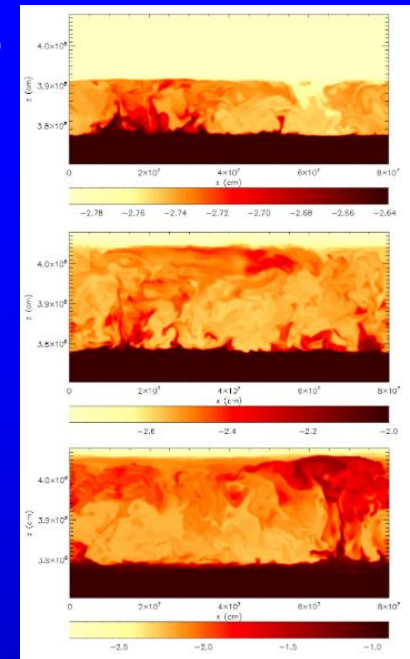
Gravity waves

Kelvin-Helmholtz (shear) instability

Casanova+ 2016

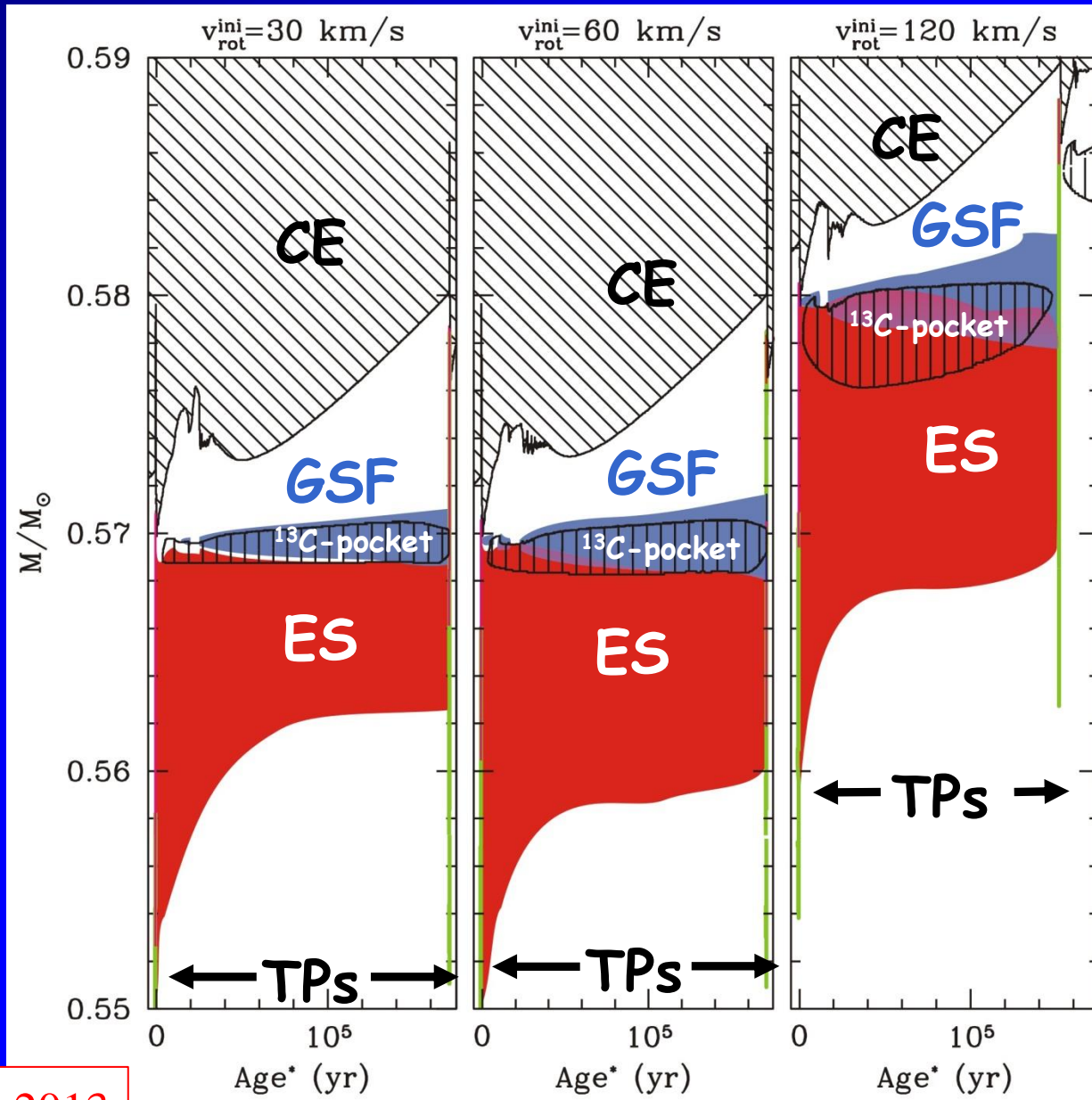
Depending on the velocity difference across the interface, K-H instability may induce mixing if:

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



Denissenkov & Tout 2003

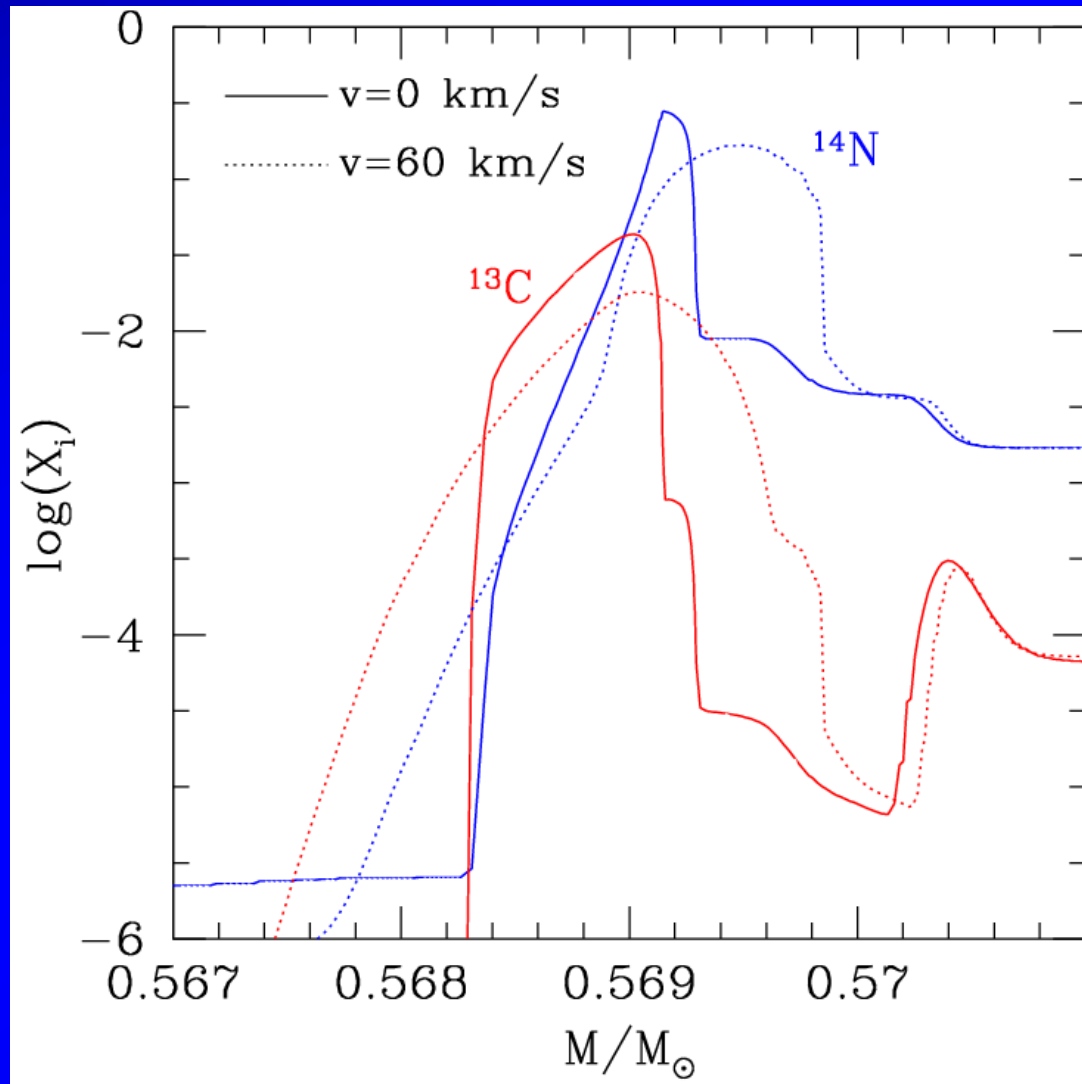
Rotation induced instabilities during the AGB phase



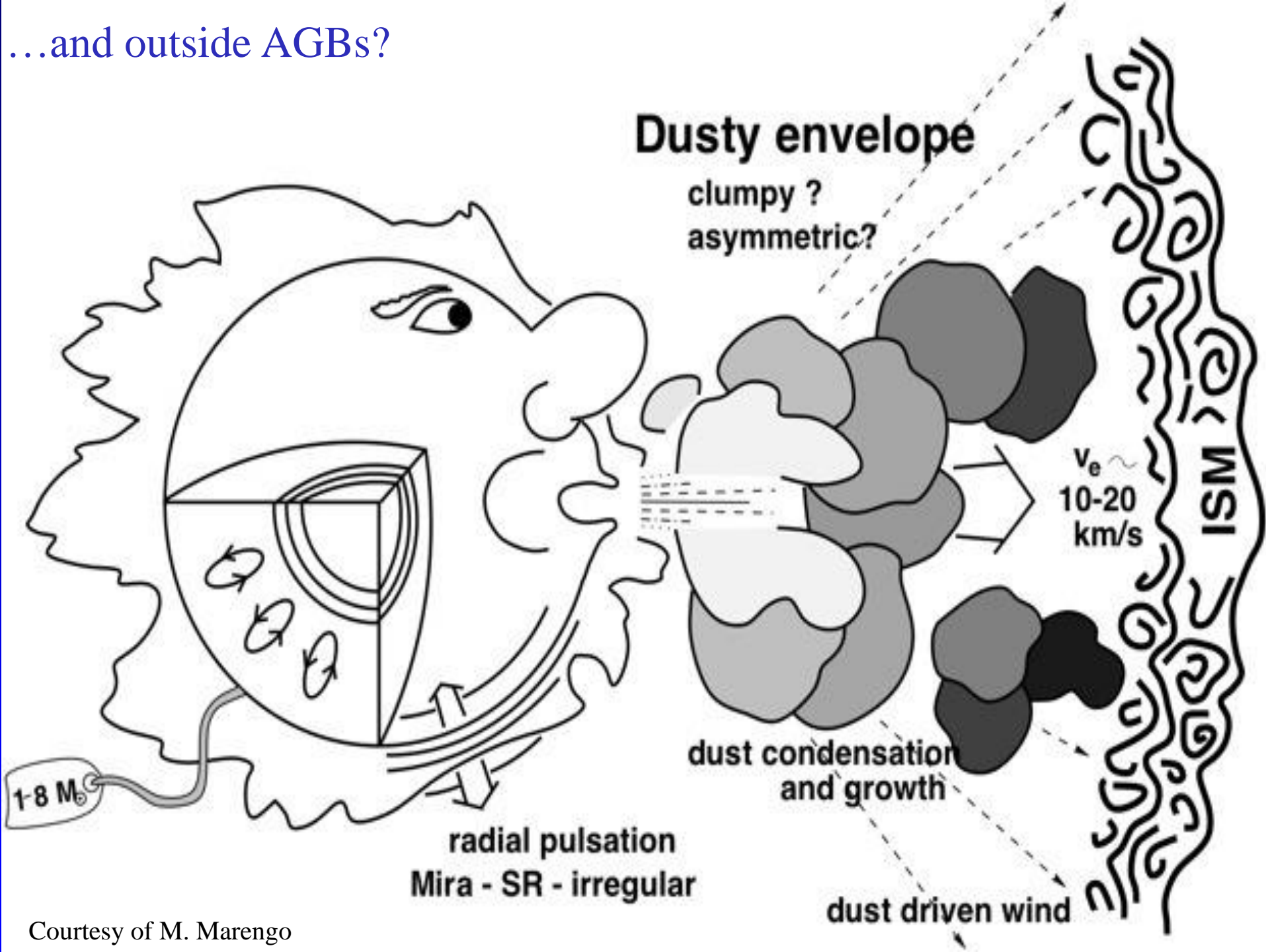
$M = 2.0 M_{\text{SUN}}$
 $[\text{Fe}/\text{H}] = 0$

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?



Meteorites

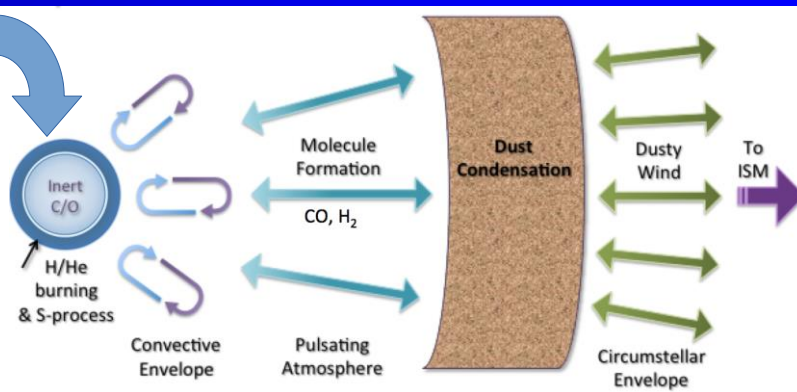
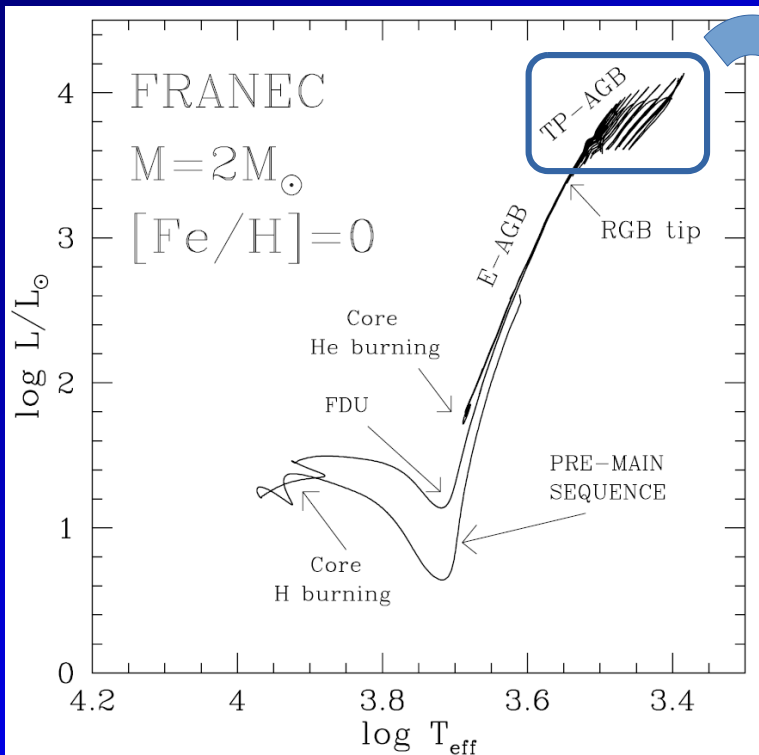


Allende (Mexico, 1969)

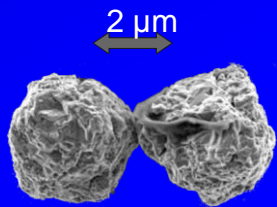
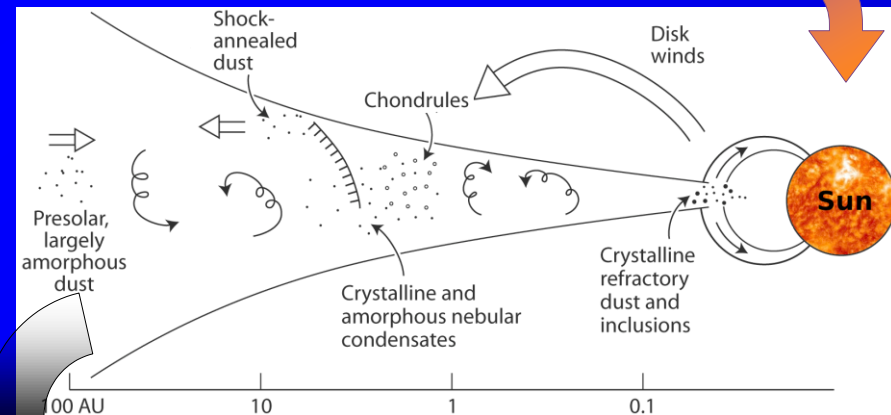
Murchison (Australia, 1969)



AGB stars and presolar SiC grains



Molecular cloud

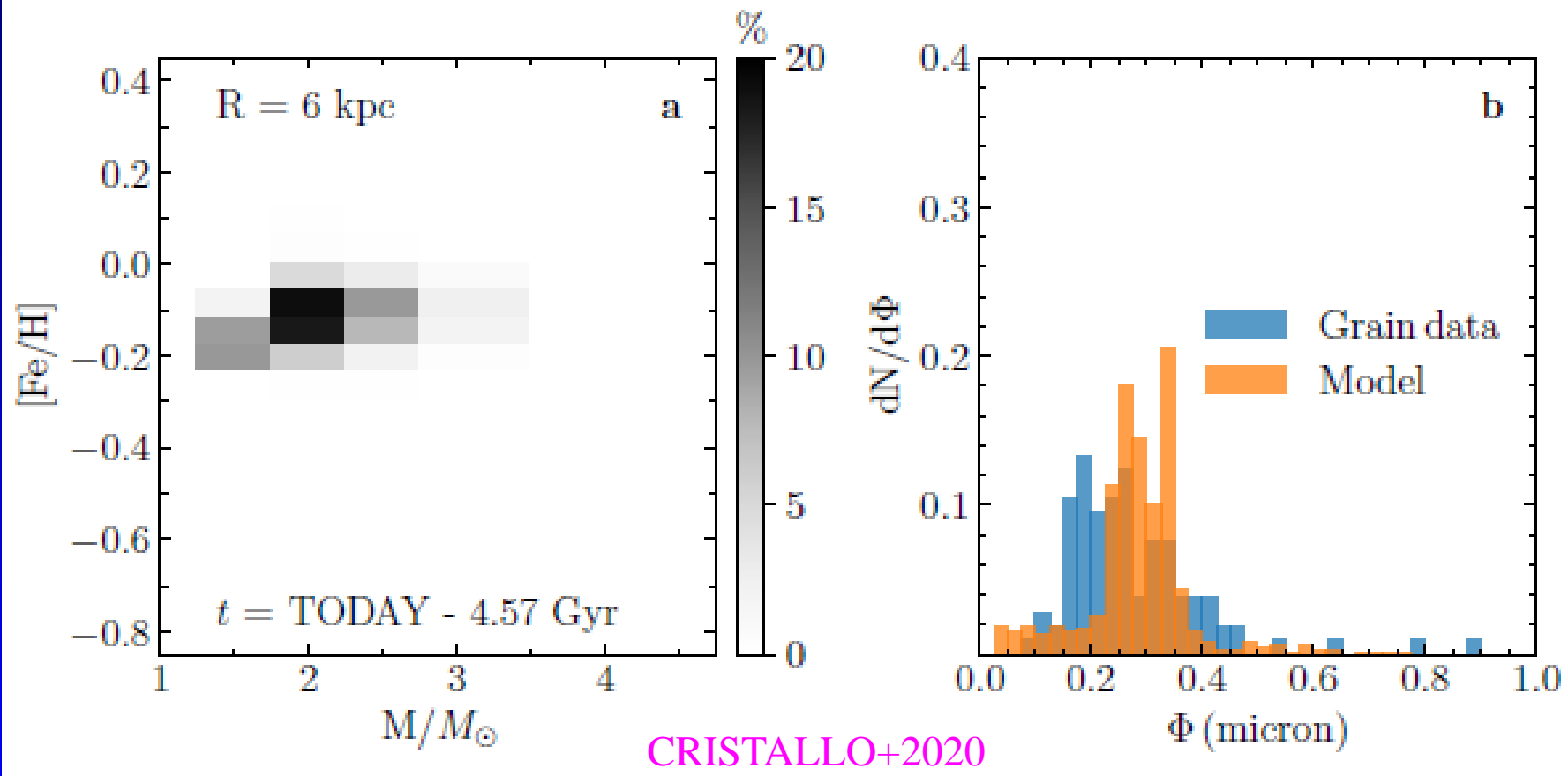


Presolar grains



Meteorites and asteroids

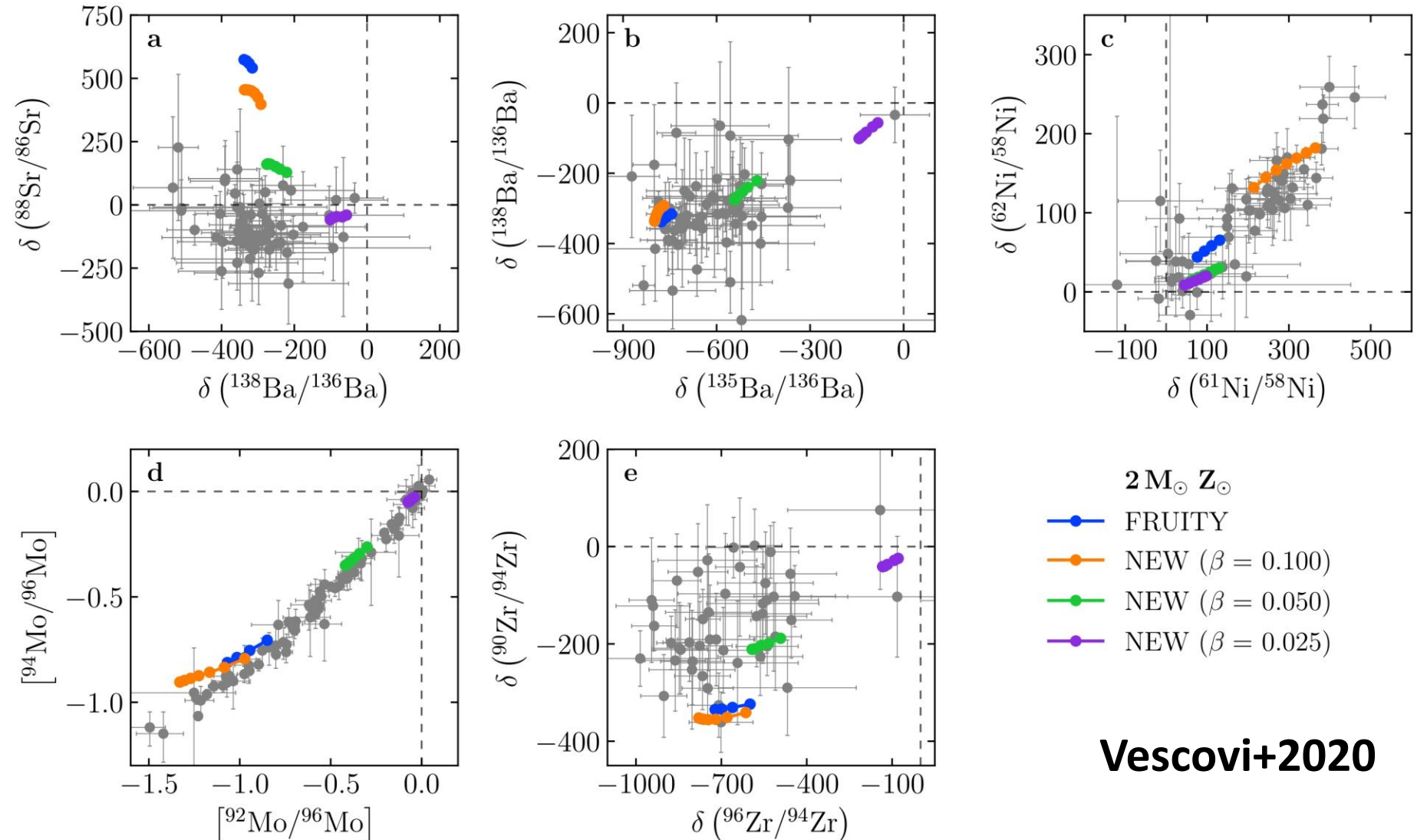
Important question is: which stars are progenitor of pre-solar SiC grains?



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

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**



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?

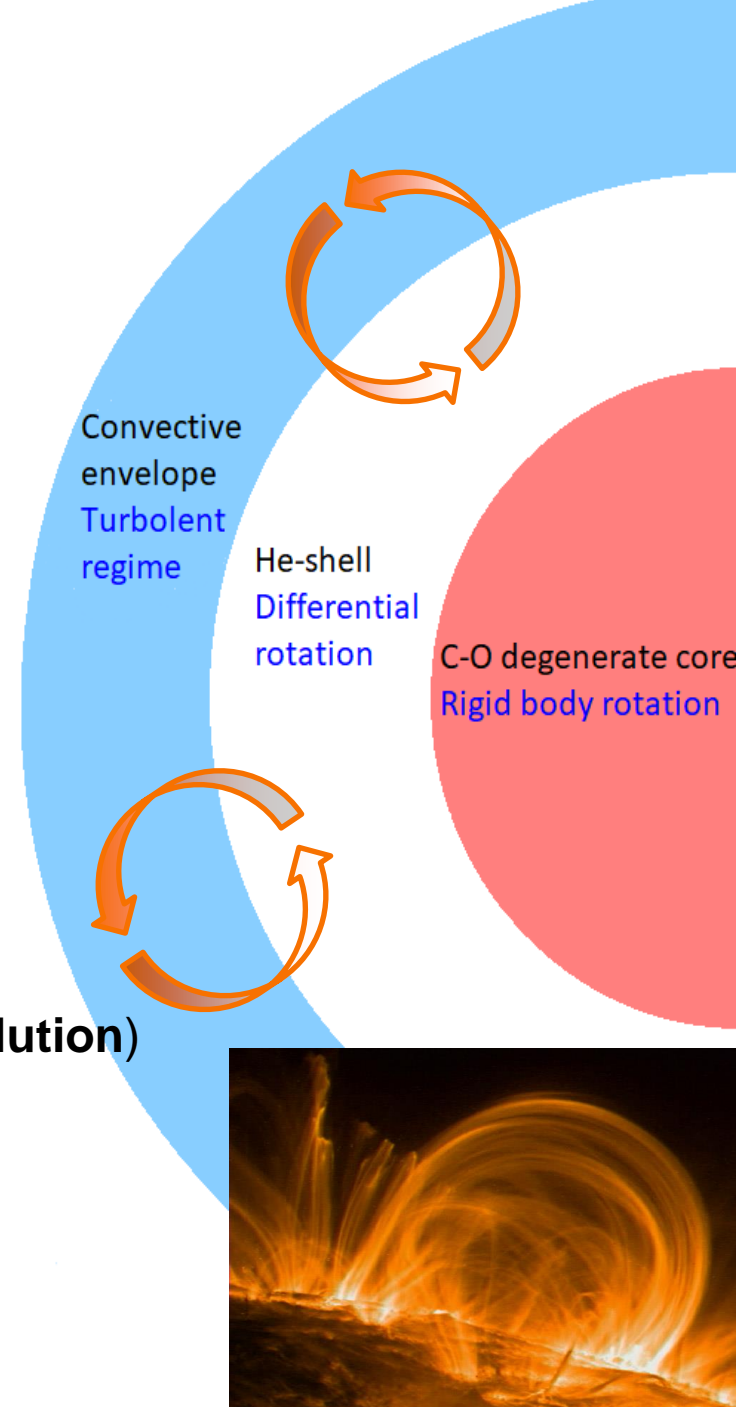
TOP-DOWN MECHANISMS

- 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 \mathbf{v}_d , acting when the density distribution is $\rho \propto r^k$:

→
$$v_d(r) = u_p \left(\frac{r_p}{r} \right)^{k+2}$$

• Parameters:

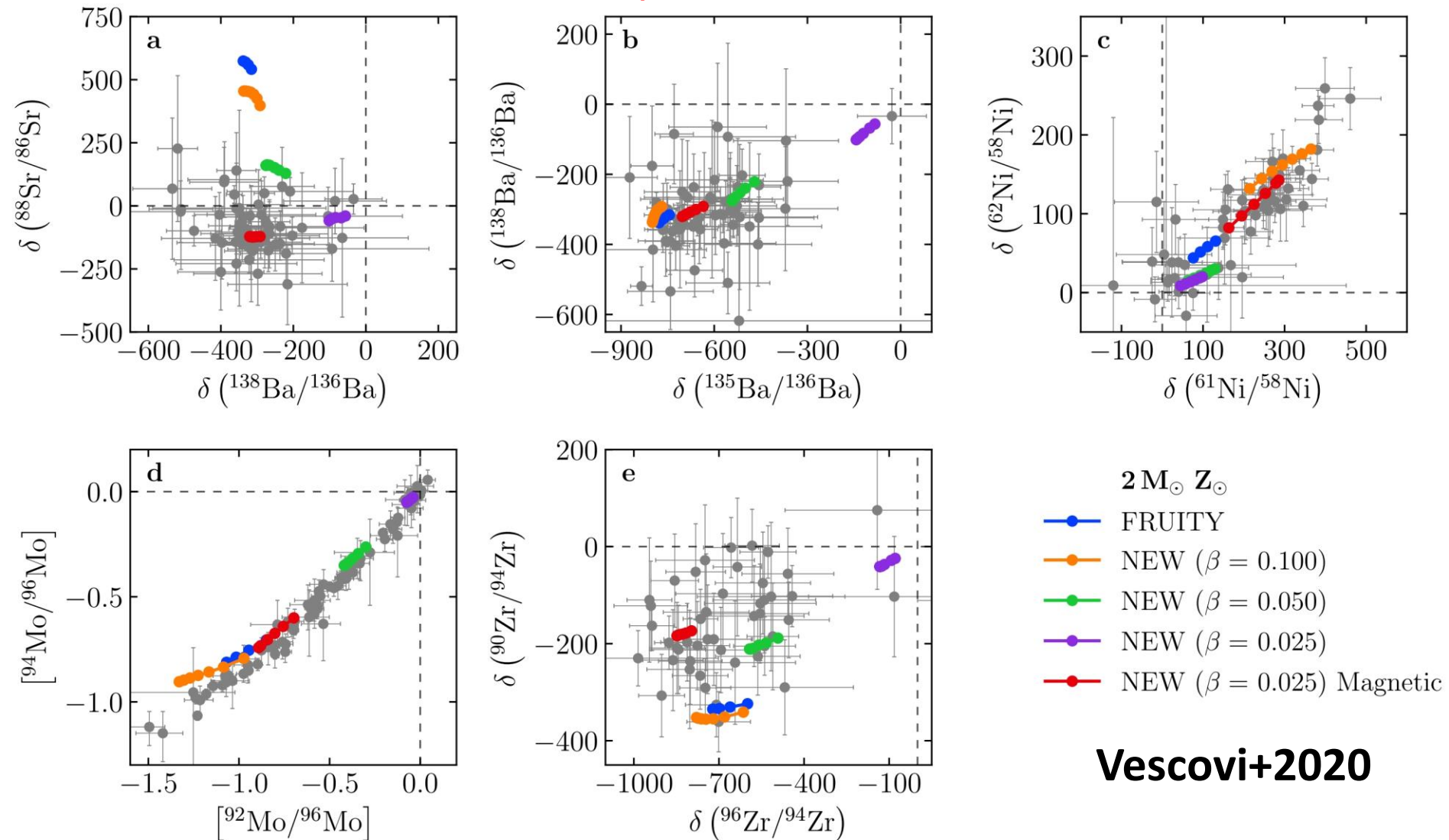
- Layer “**p**” at the deepest coordinate from which buoyancy starts
- (can be identified from the corresponding **critical toroidal** B_φ value)
- Starting velocity u_p of the buoyant material

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

→ Calibration is needed!

SiC Grains II

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

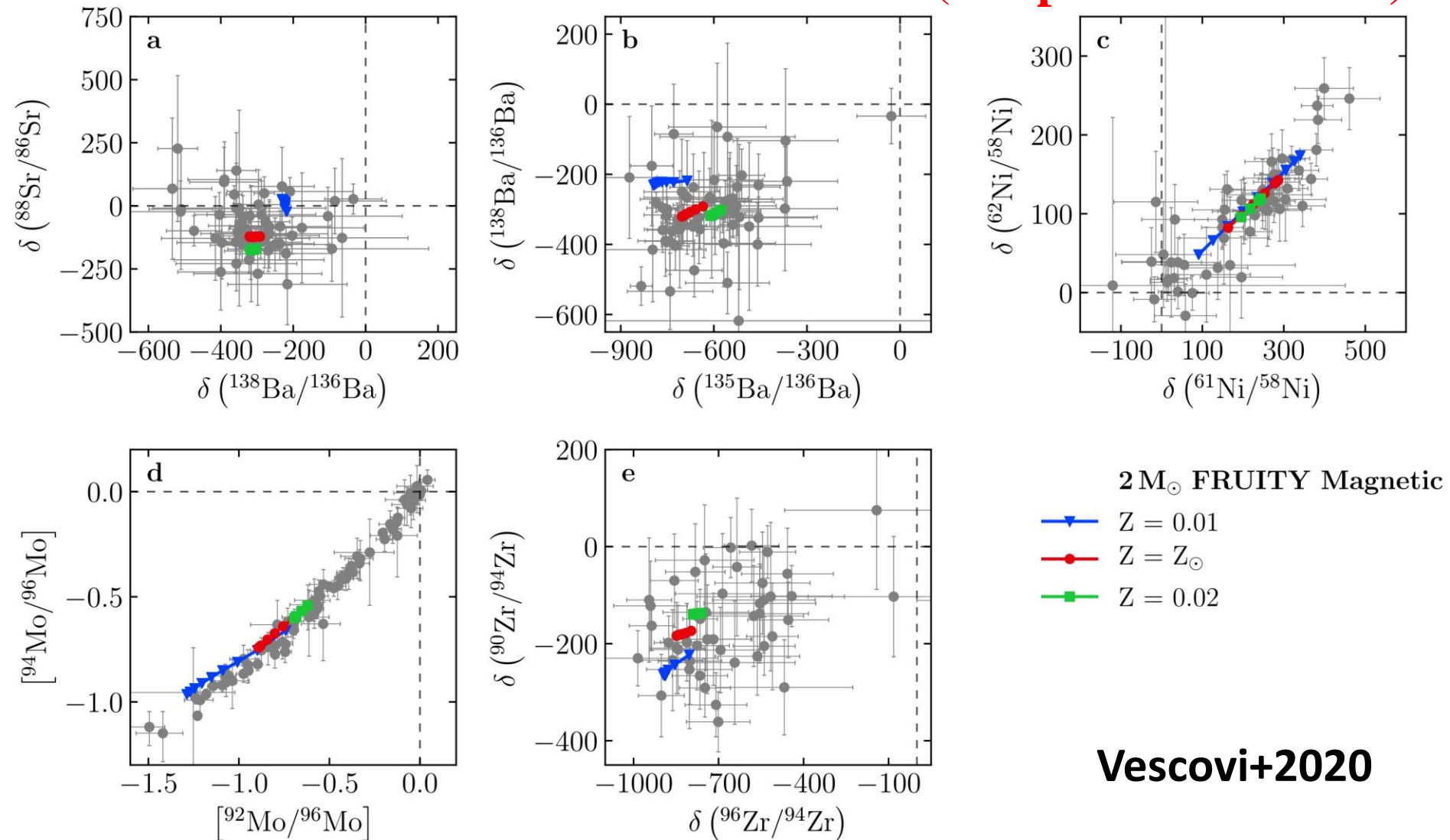


Vescovi+2020

SiC Grains III

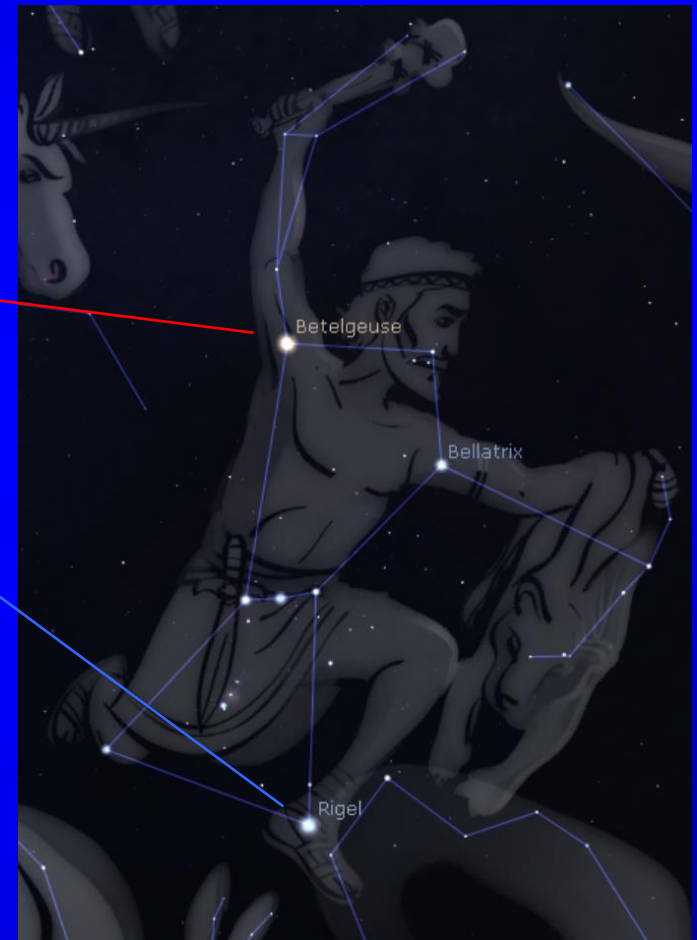
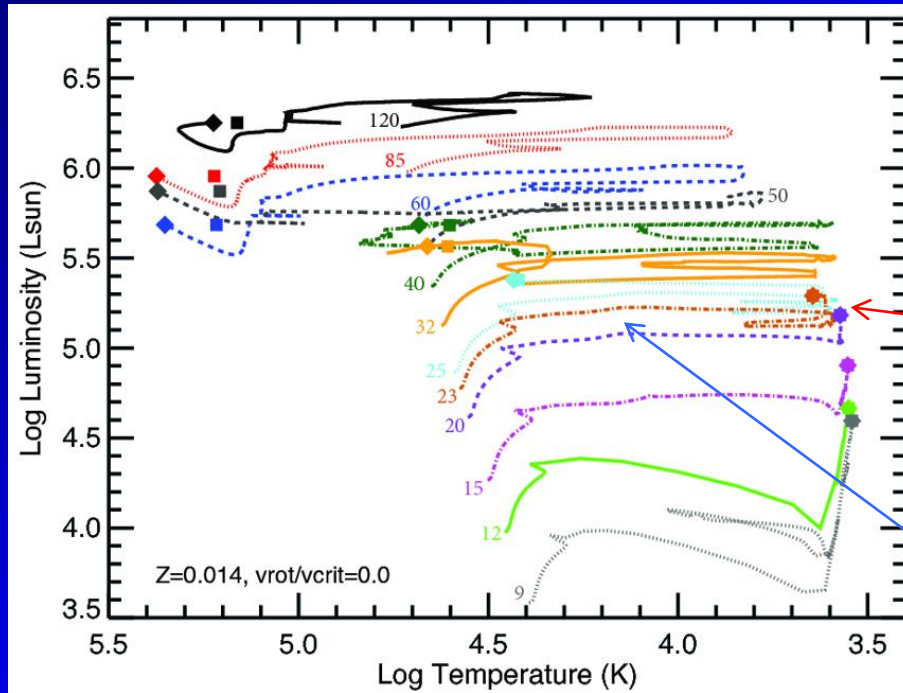
- Stellar models with **same initial mass** ($2 M_{\odot}$) and **close-to-solar metallicity**
- Magnetic** contribution

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

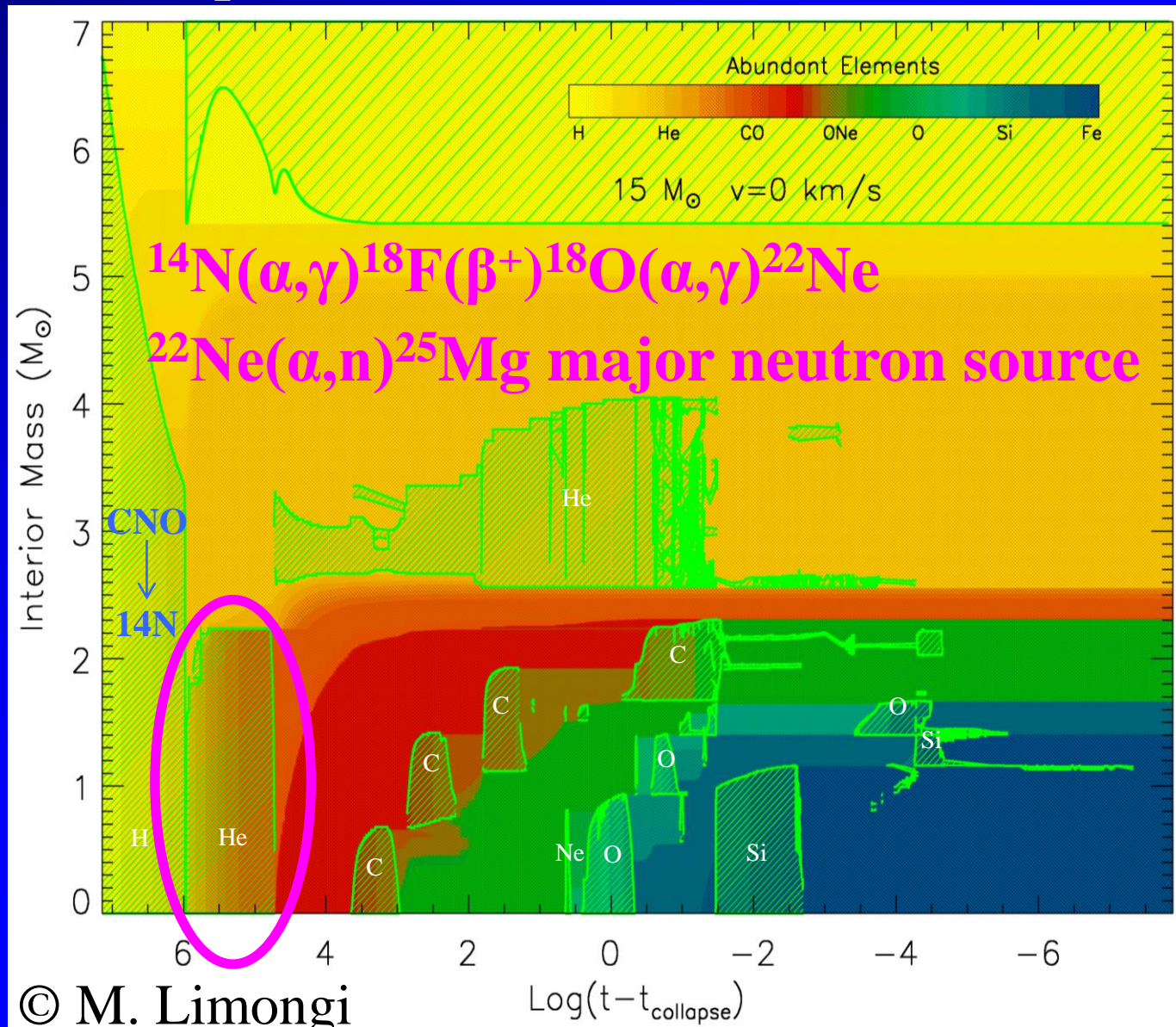


Vescovi+2020

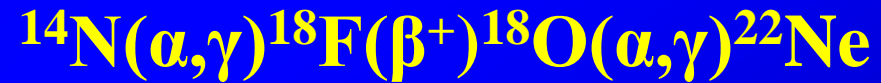
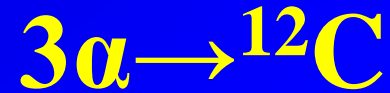
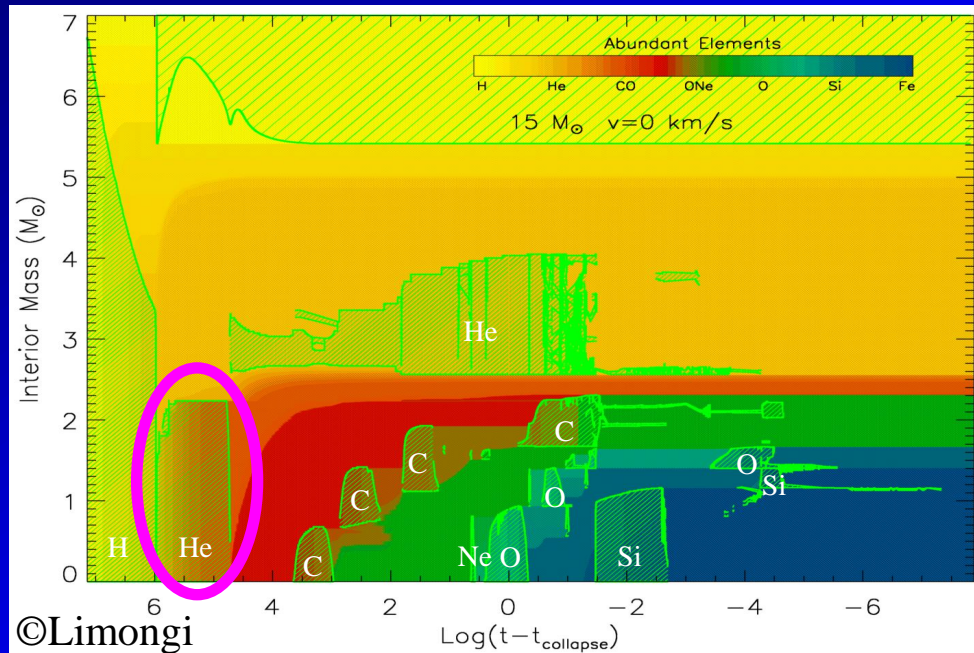
The weak s-process in massive stars



The weak s-process and the evolution of massive stars



Core He-burning phase



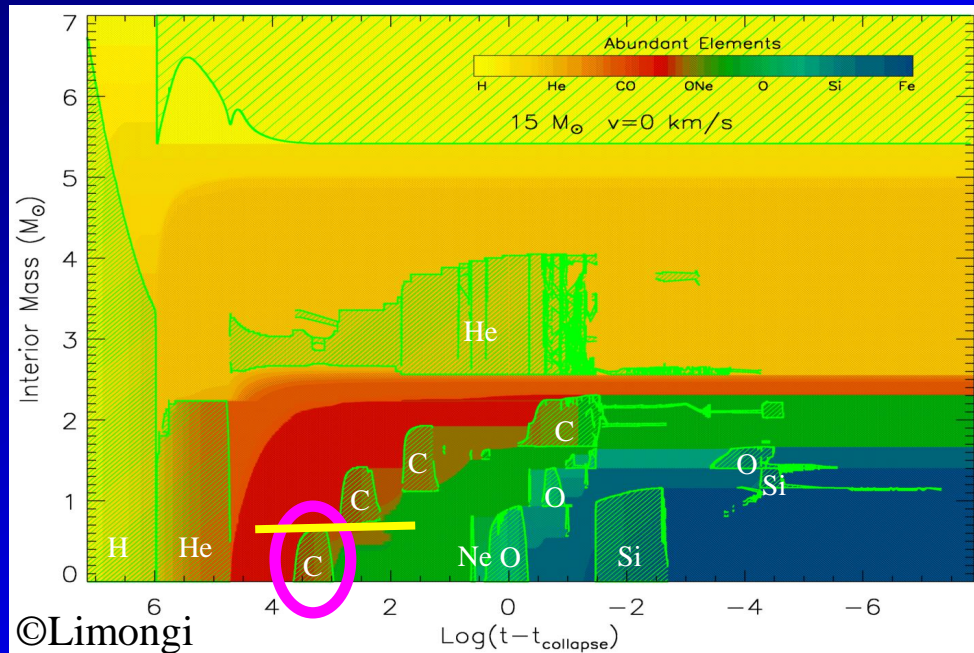
$$\tau \approx 1 \text{ Myr}$$

When $T \sim 3 \times 10^8$ K the ${}^{22}\text{Ne}(\alpha, n){}^{25}\text{Mg}$ is efficiently activated

The resulting neutron density is low ($\sim 10^6$ n/cm³)

Similar to the s-process

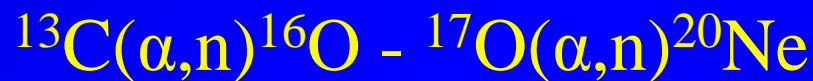
Core C-burning phase



$$\tau \approx 1 \text{ Kyr}$$

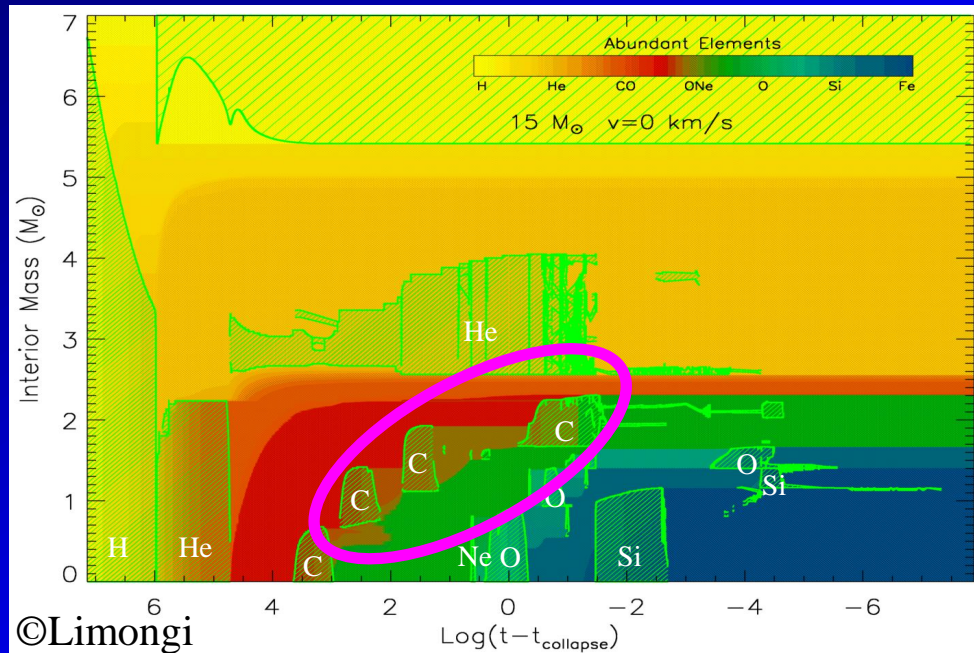
Some ^{22}Ne is left after He burning

All (α,n) channels are activated:



The resulting neutron density is
very high, BUT...

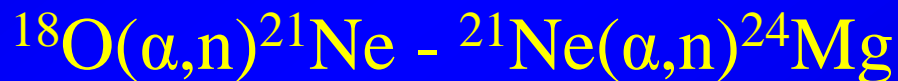
Shell C-burning phase



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

Because at $T \sim 1 \times 10^9$ K
the $^{13}\text{N}(\gamma,p)^{12}\text{C}^*$ works!!

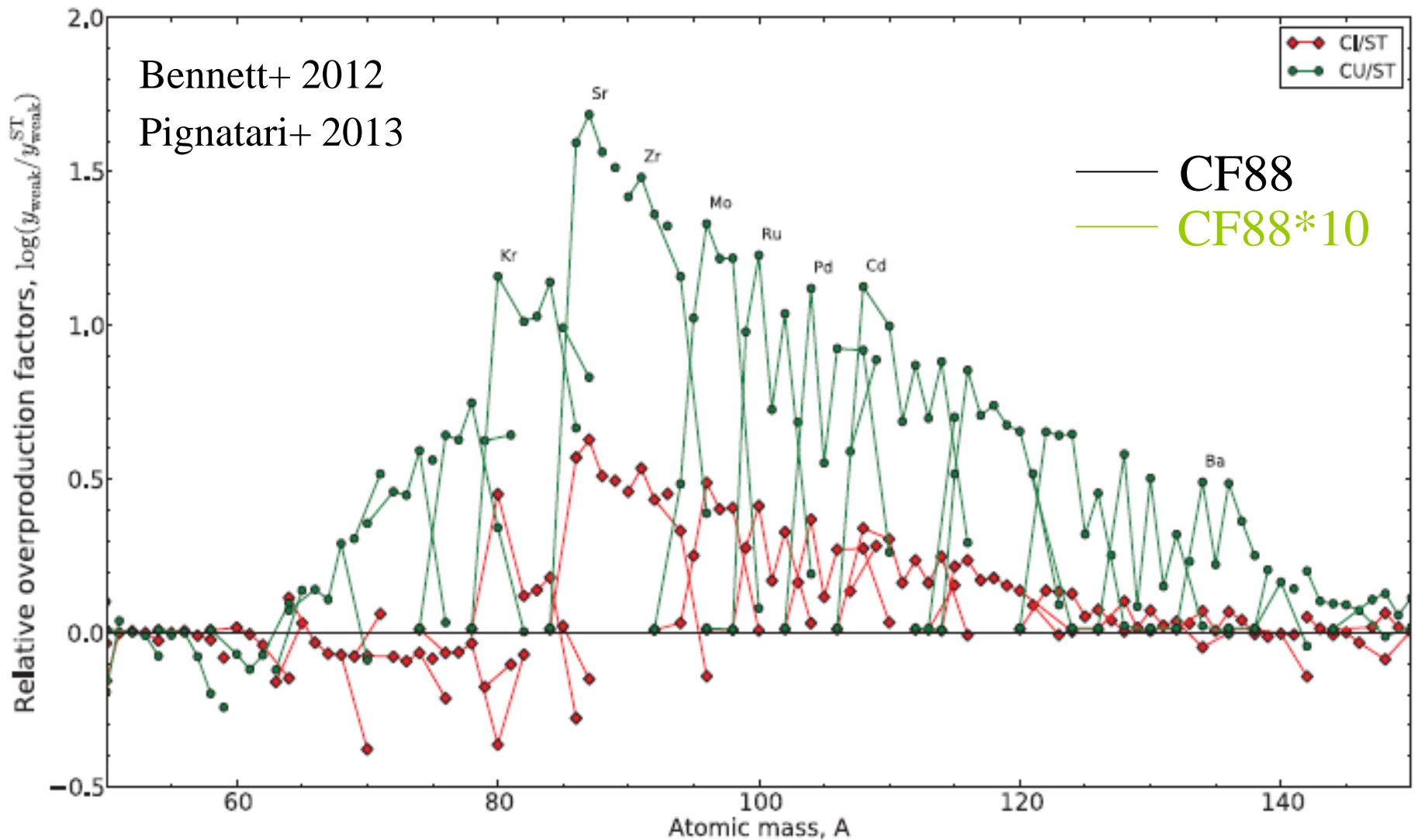
All (α,n) channels are activated:



The resulting neutron density is
very high:

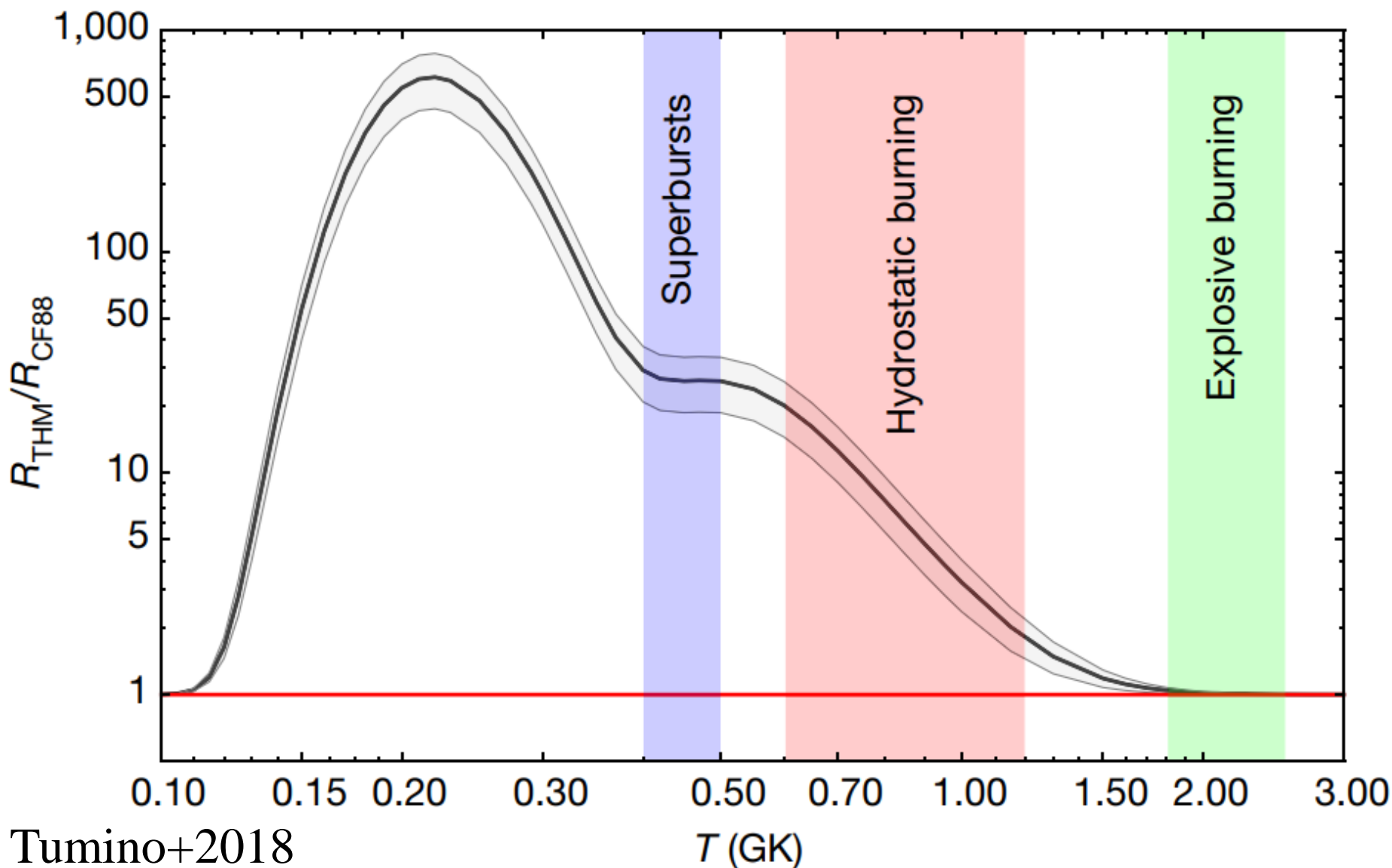
$$10^{11} - 10^{12} \text{ n/cm}^3$$

Uncertainties of the weak s-process: cross sections



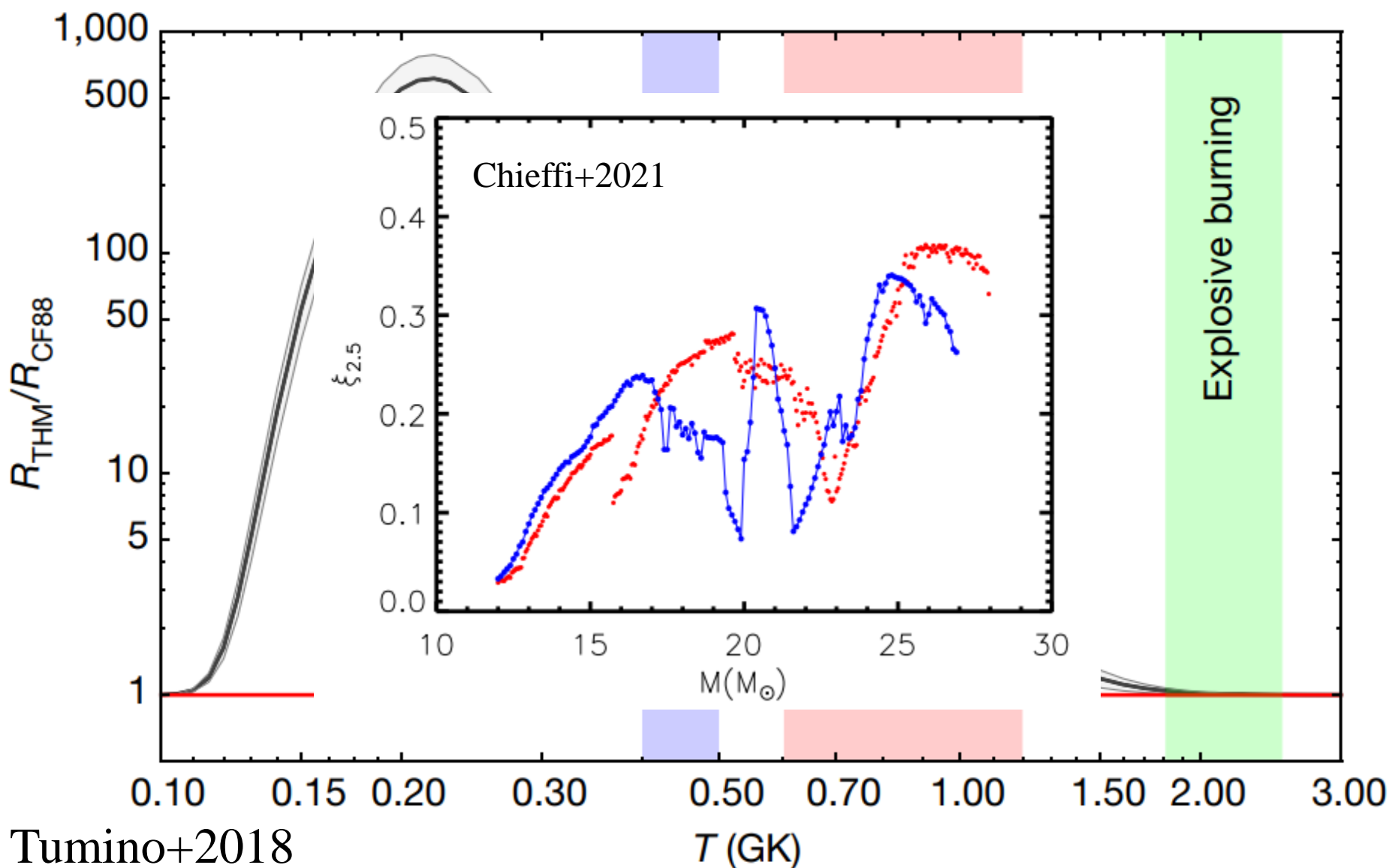
Uncertainties of the weak s-process: cross sections

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



Uncertainties of the weak s-process: cross sections

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



Uncertainties of the weak s-process: stellar modelling

Convection - Rotation

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

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

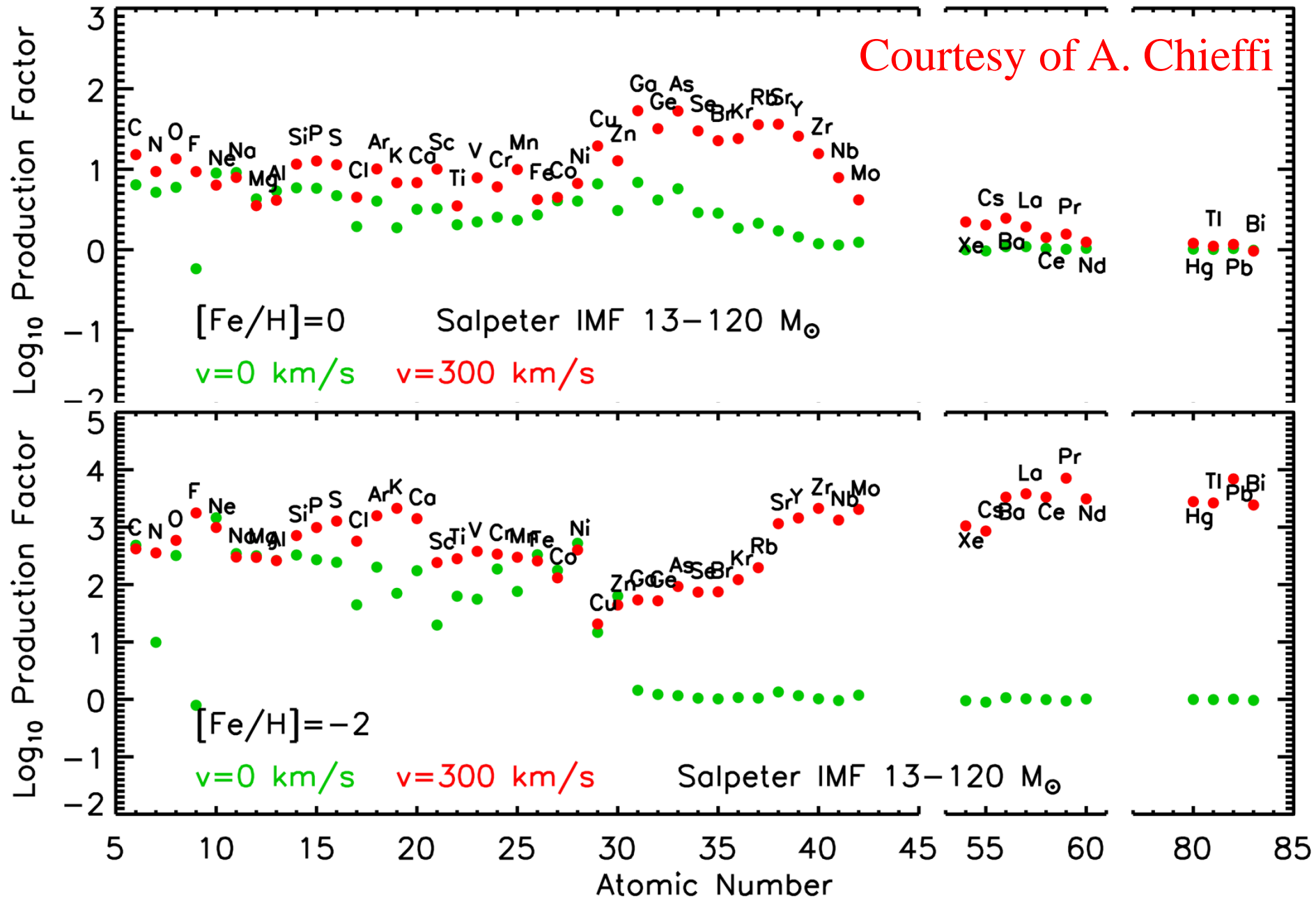
In any case the dominant source is the



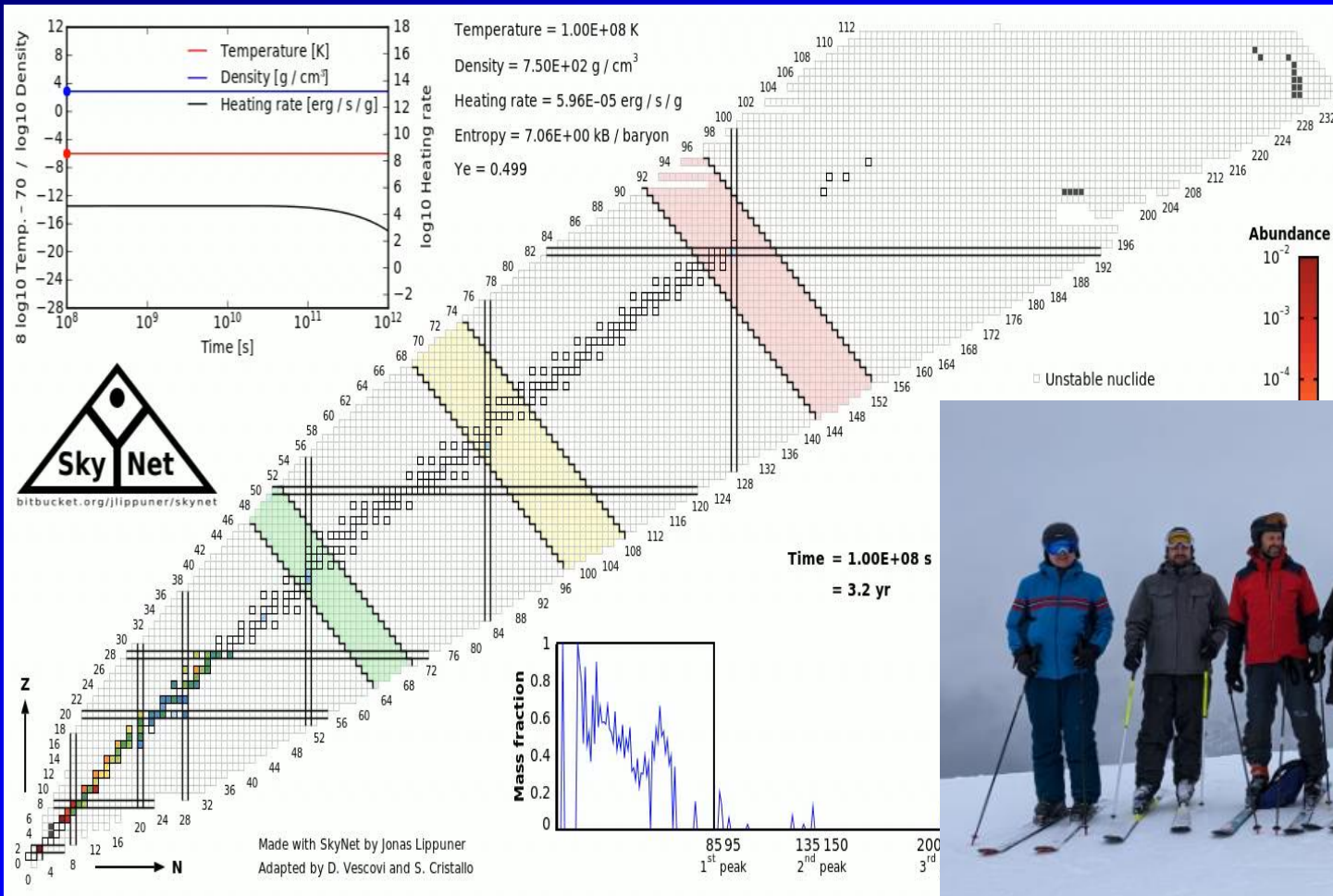
Courtesy of A. Chieffi

The effect of rotation: differences in the stellar ejecta

Courtesy of A. Chieffi



THAT'S ALL FALKS!!!



SAPIENZA
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Phd in ASTRONOMY ASTROPHYSICS AND SPACE SCIENCE



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ISTITUTO NAZIONALE DI ASTROFISICA
OSSERVATORIO ASTRONOMICCO D'ABRUZZO