Nuclear Astrophysics (II)

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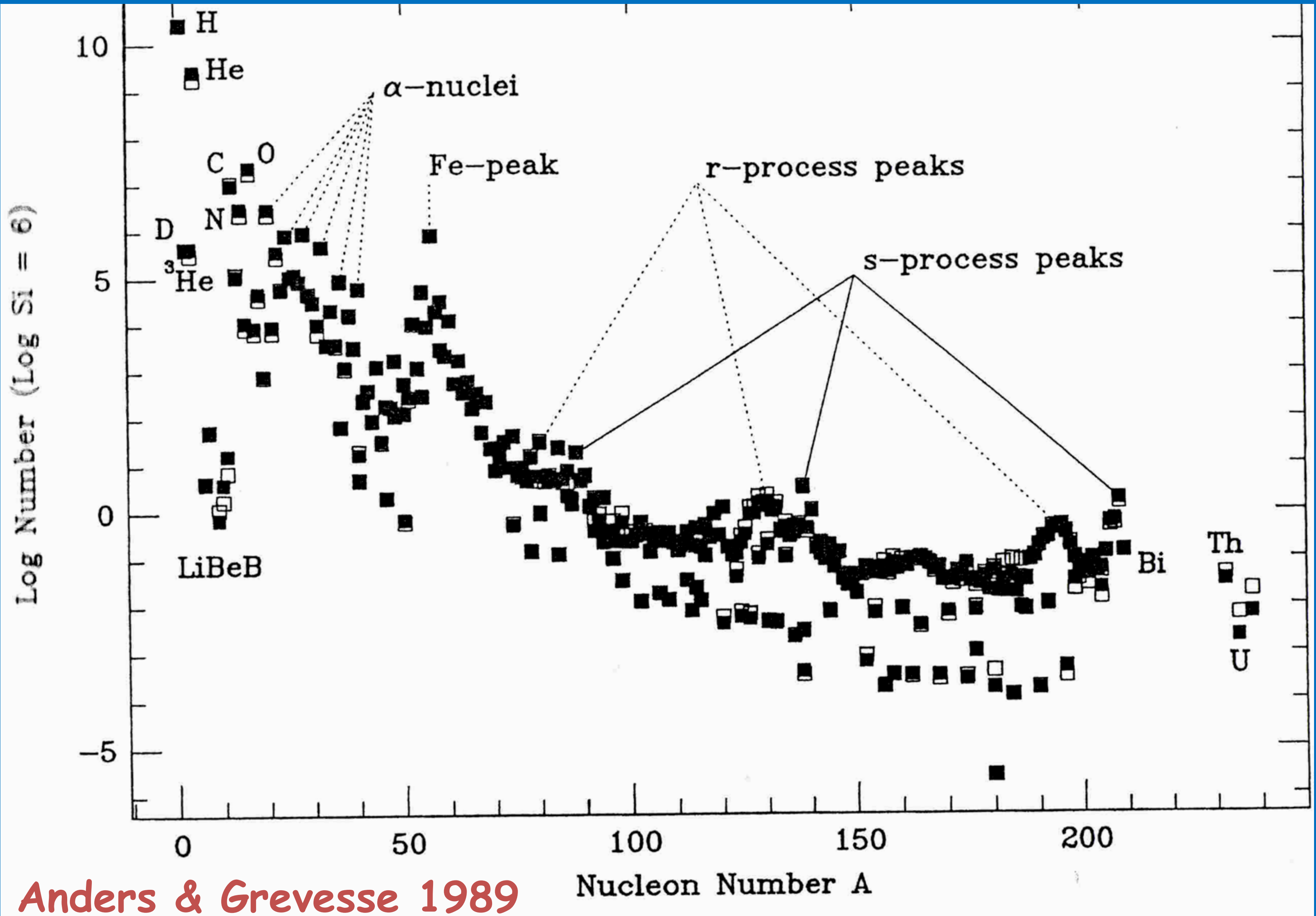
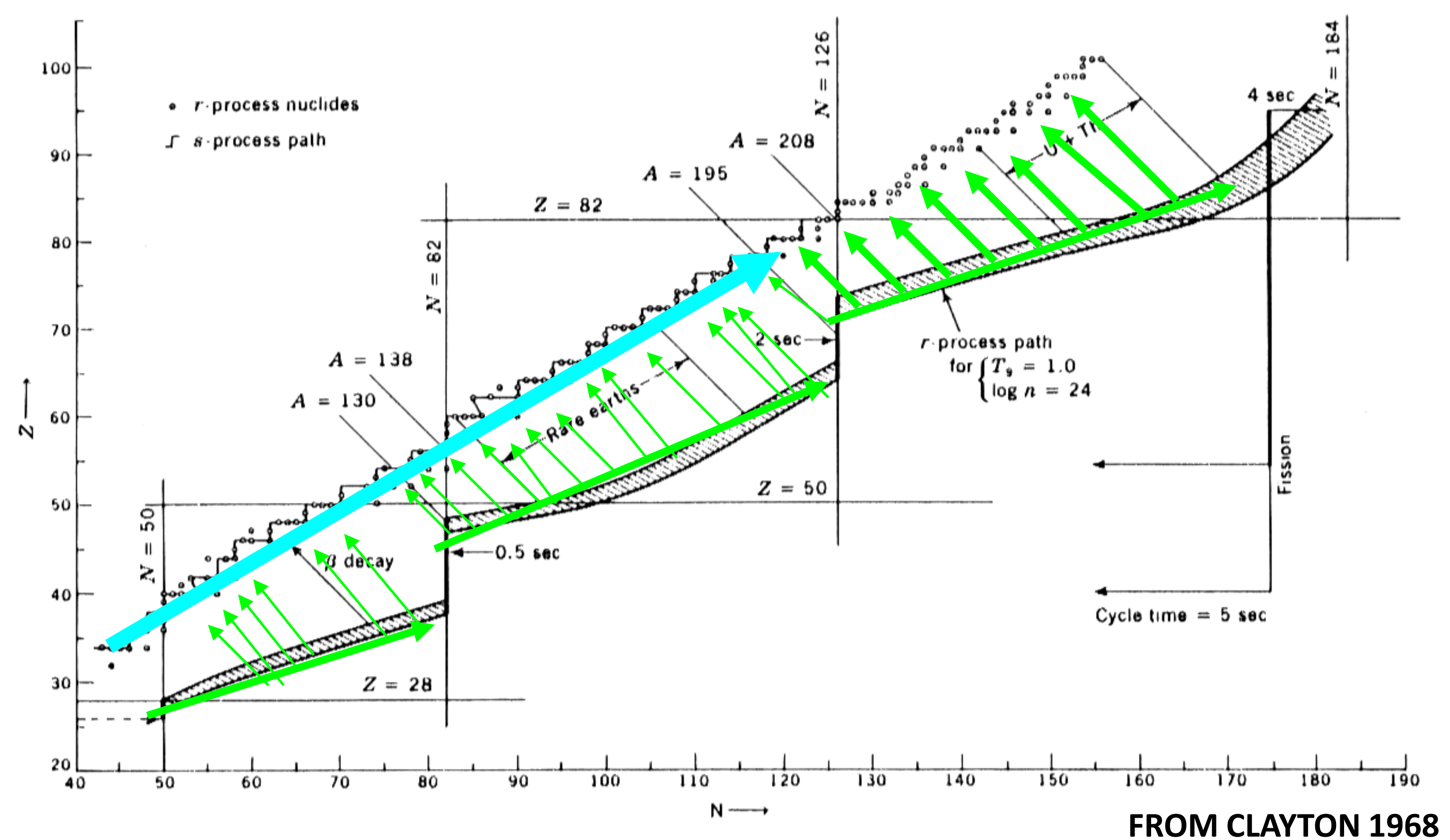
Solar System Abundances



Anders & Grevesse 1989
Cameron 1982



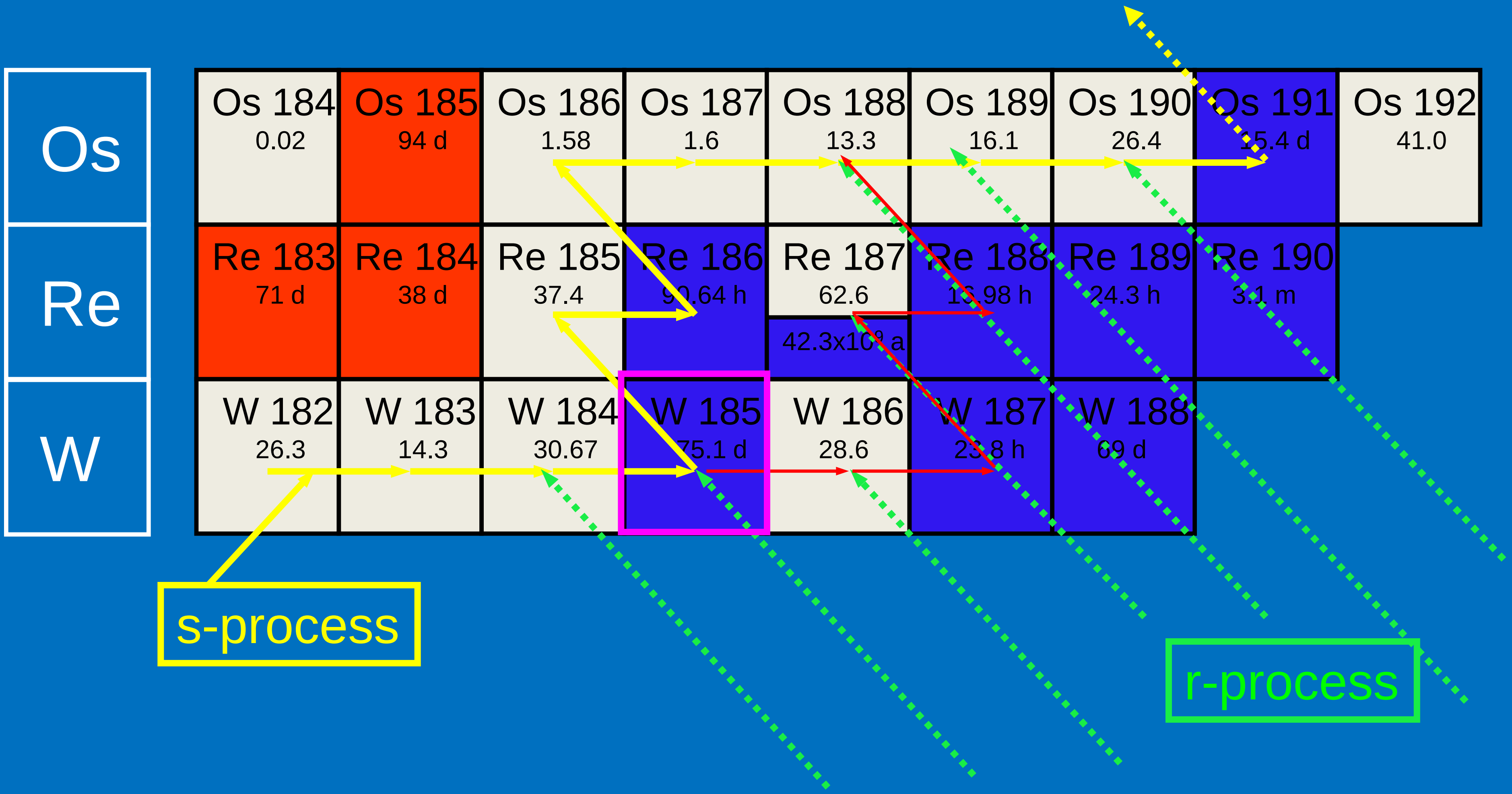
FROM CLAYTON 1968

***s*-process**

***r*-process**

The slow neutron capture process

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		

s-process

r-process

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

Seeds for the s-process

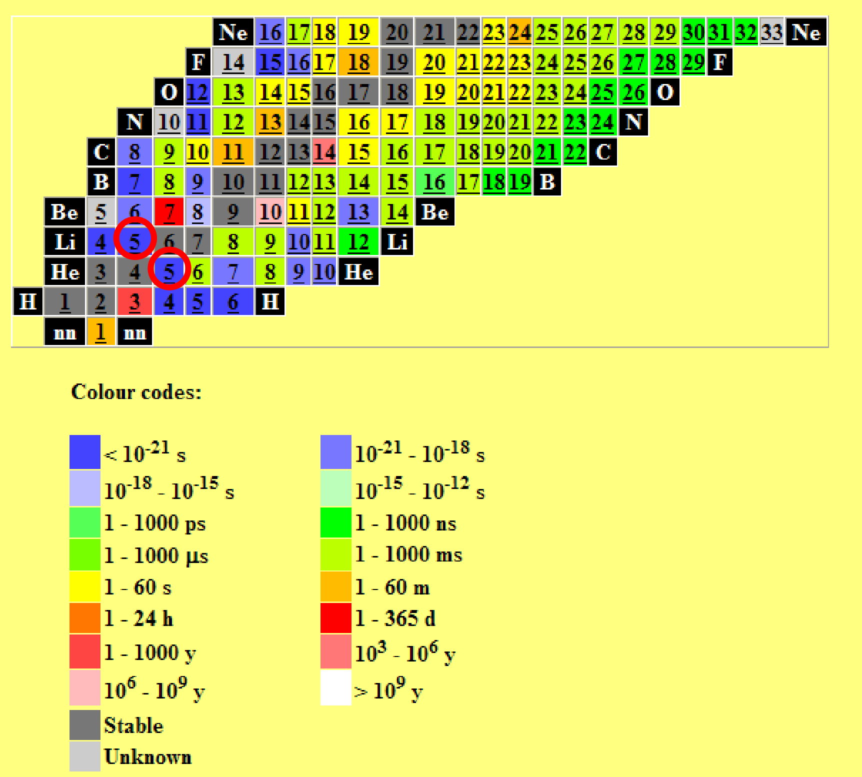
Main seeds are ^{56}Fe nuclei…
Why not the most abundant ^{1}H, ^{4}He or ^{12}C???

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

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

↓

10^{-12}

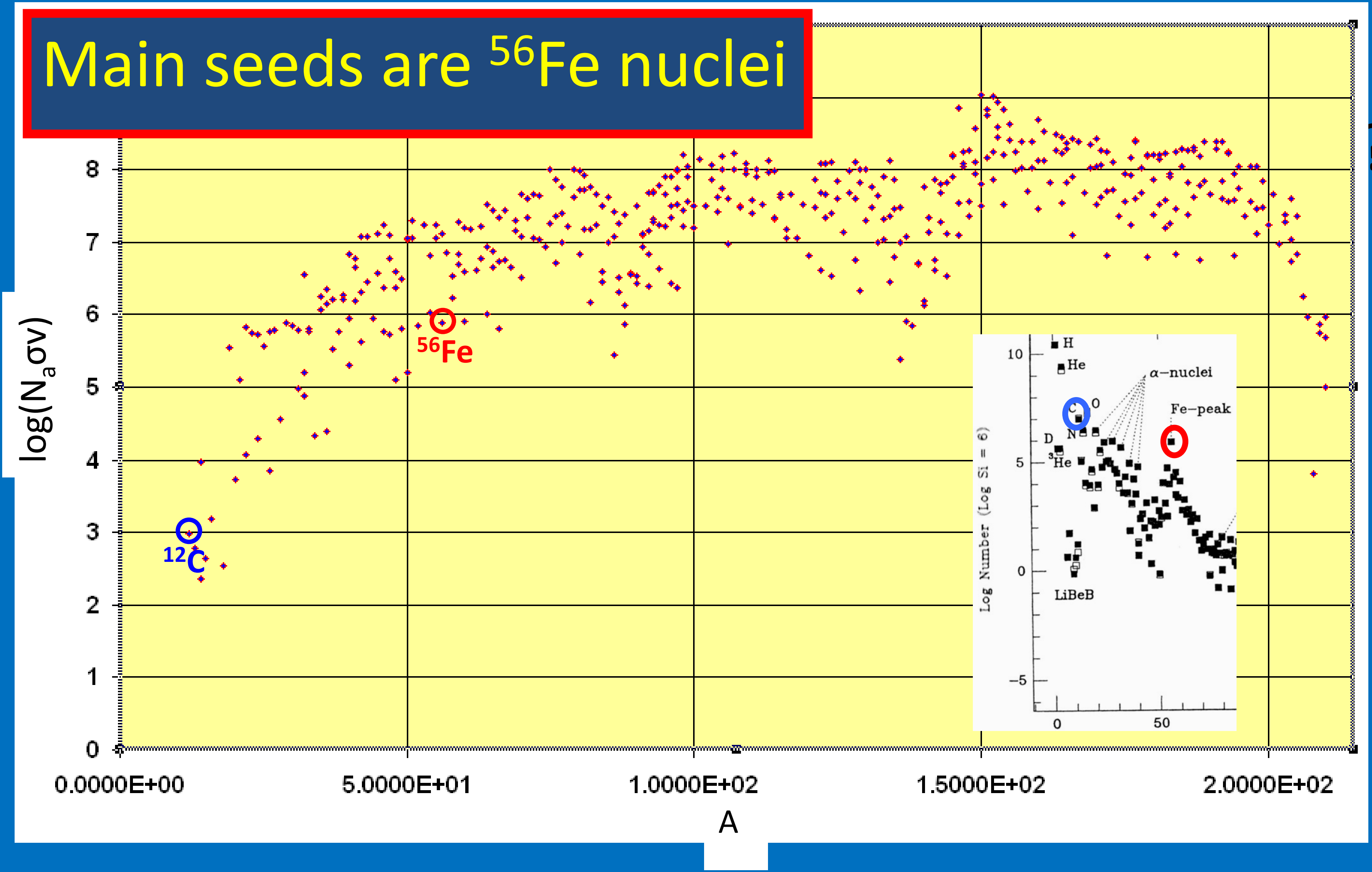


Ne 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 Ne
F 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 F
O 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 O
N 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 N
C 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 C
B 7 8 9 10 11 12 13 14 15 16 17 18 19 B
Be 5 6 7 8 9 10 11 12 13 14 Be
Li 4 5 6 7 8 9 10 11 12 Li
He 3 4 5 6 7 8 9 10 He
H 1 2 3 4 5 6 H
nn 1 nn

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

?

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**.

In the s-process, neutron capture cross sections are well determined (on average, but stay tuned!), and one the biggest remaining challenge is the supply of free neutrons over a large enough period of time.

Major neutron sources of the s-process

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

The sources of the s-process

^{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…

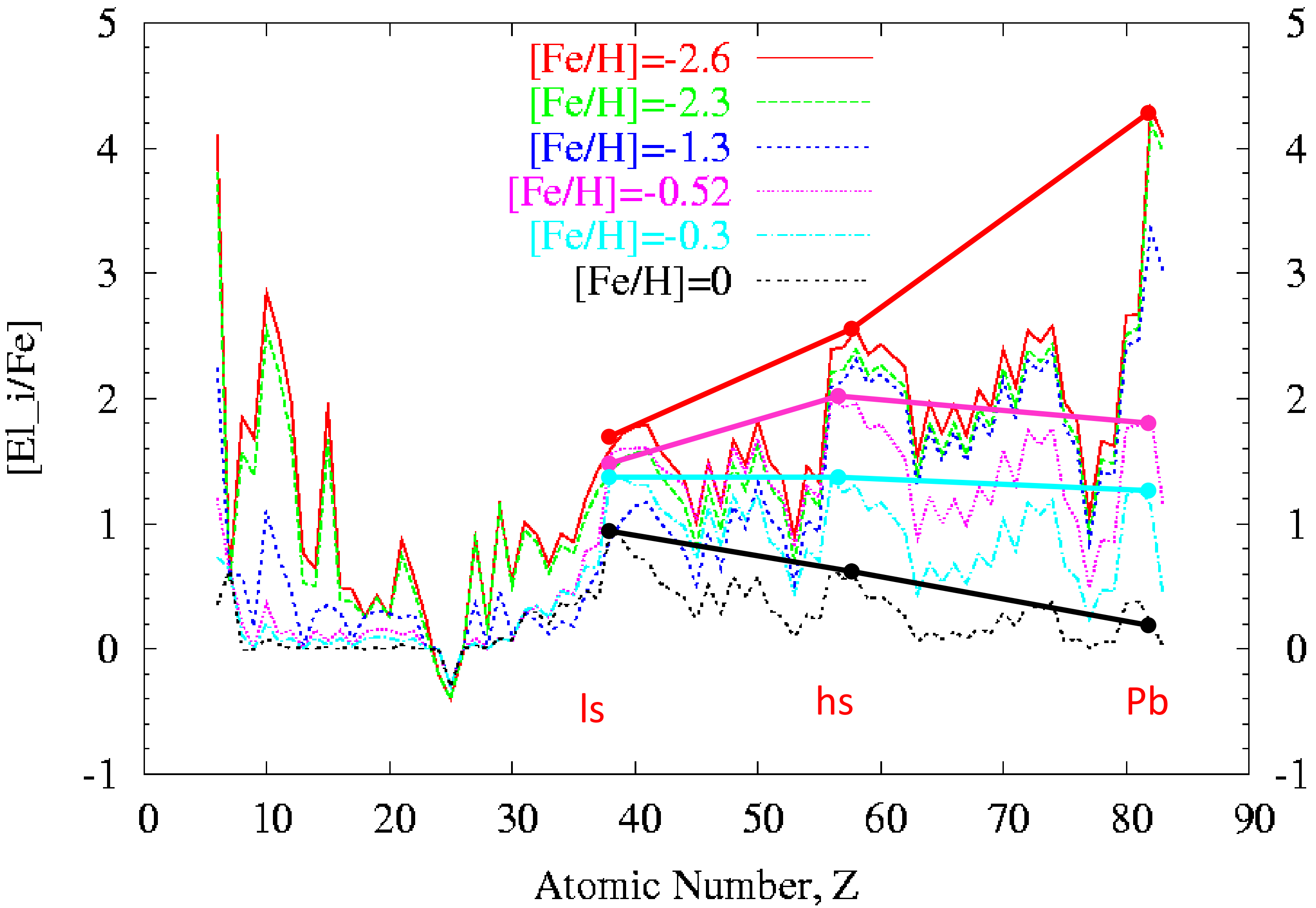
The ^{13}C is primary like

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 DISTRIBUTIONS



$[X/Fe]=\log(N_X/N_{Fe})_{STAR}-\log(N_X/N_{Fe})_{SUN}$

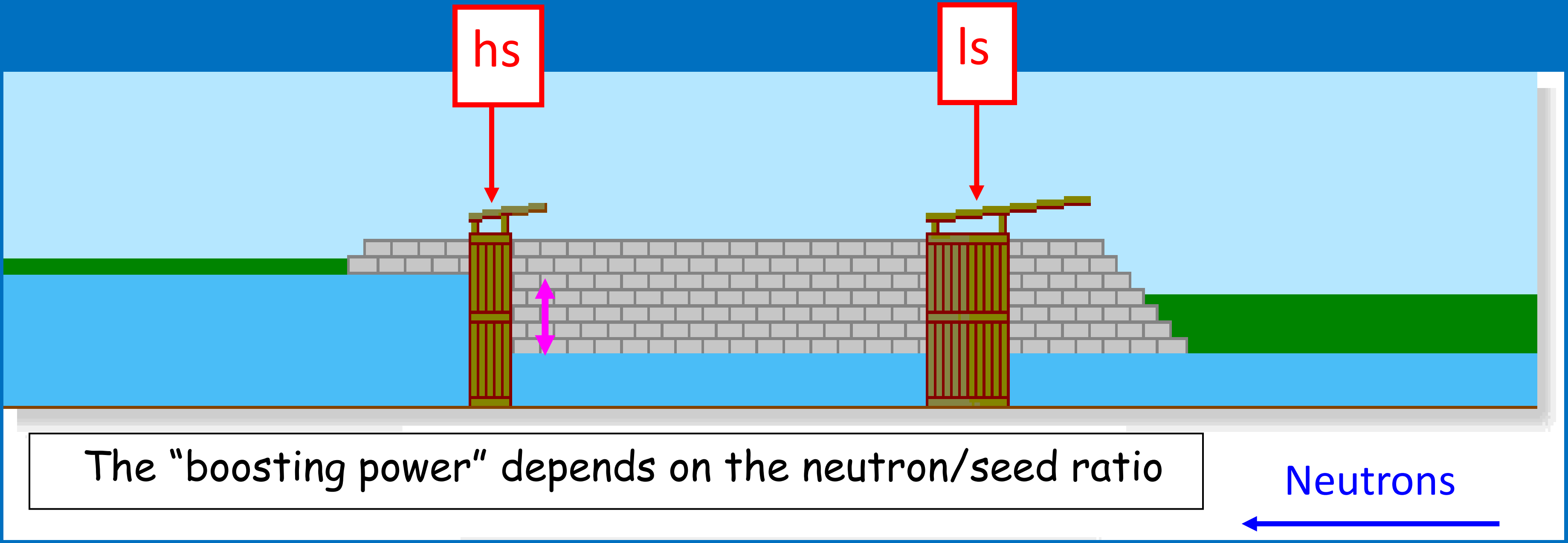
TORINO models

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]



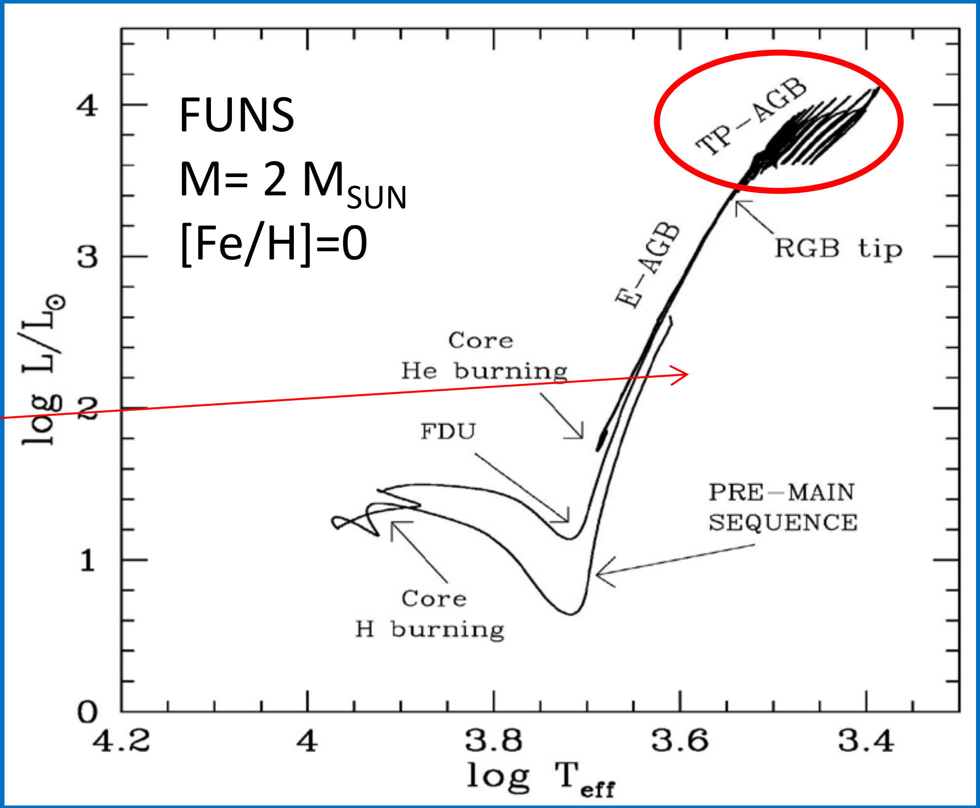
The “boosting power” depends on the neutron/seed ratio

A sluice system with opening bulkheads

Asymptotic Giant Branch (AGB) stars

$\tau_{MS} \approx 1$ Gyr

$\tau_{AGB} \approx 1$ Myr



FUNS

$M = 2\ M_{SUN}$

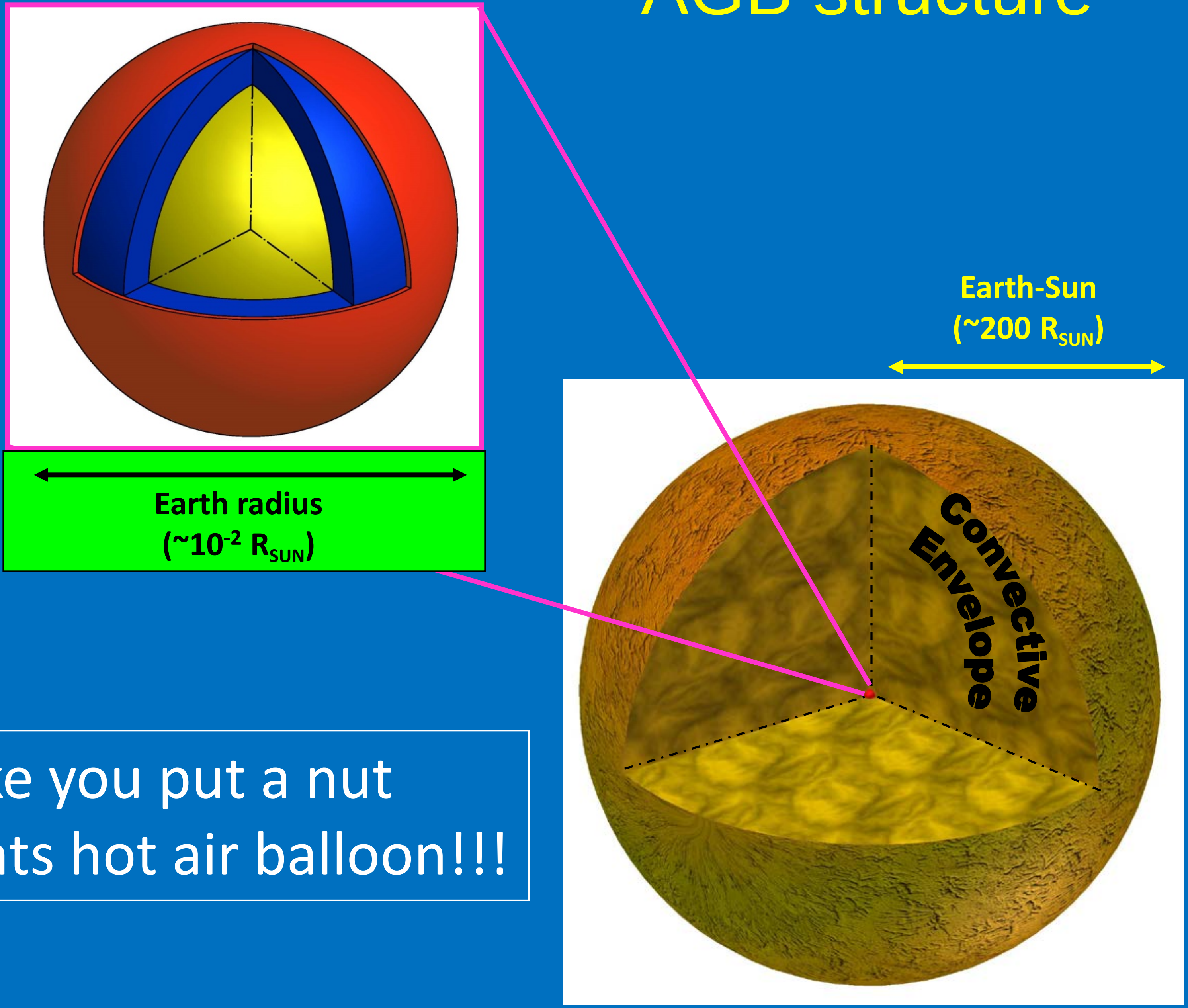
$[Fe/H]=0$

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

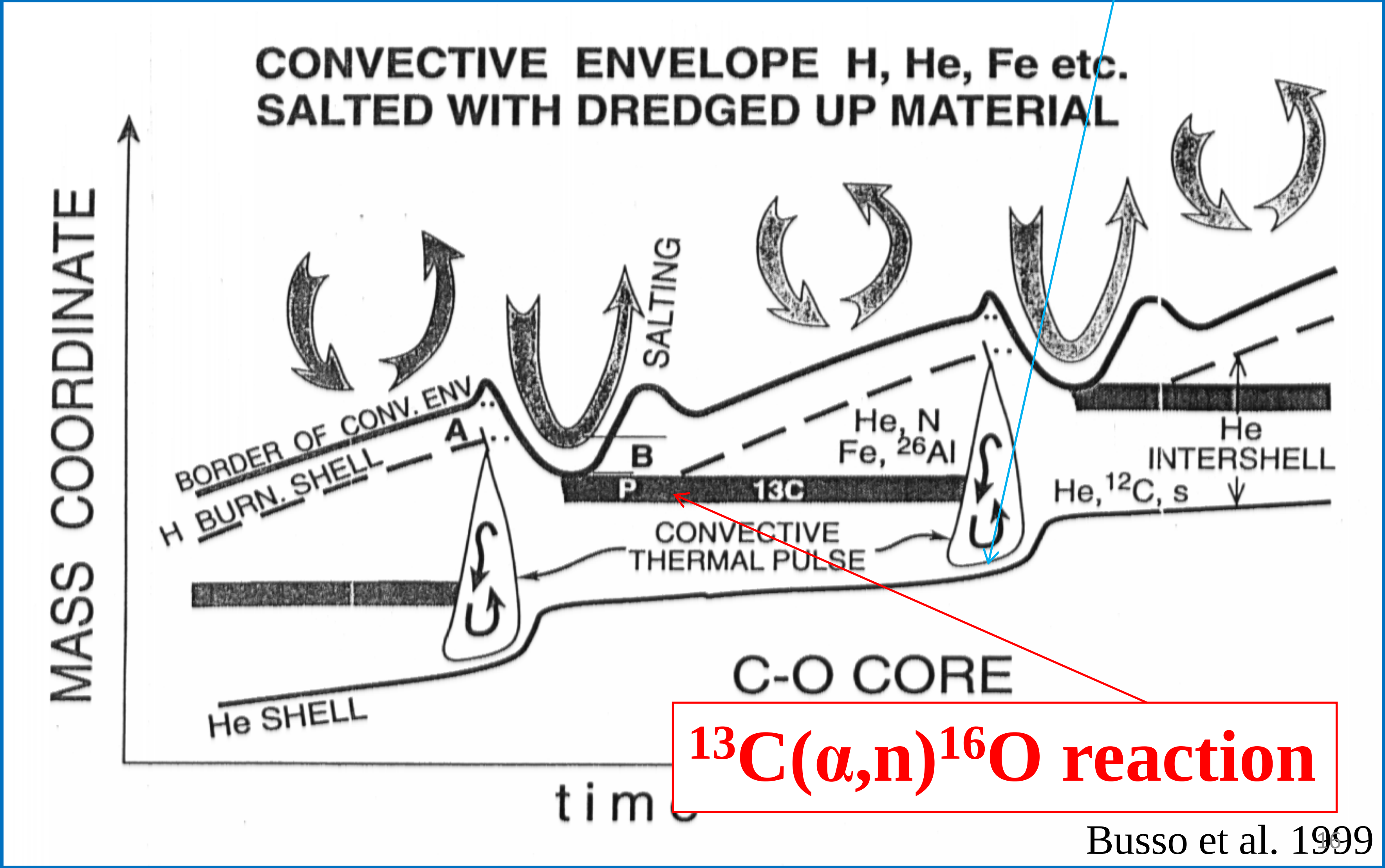
CO Core
He-shell
H-shell



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

The s-process in AGB stars

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

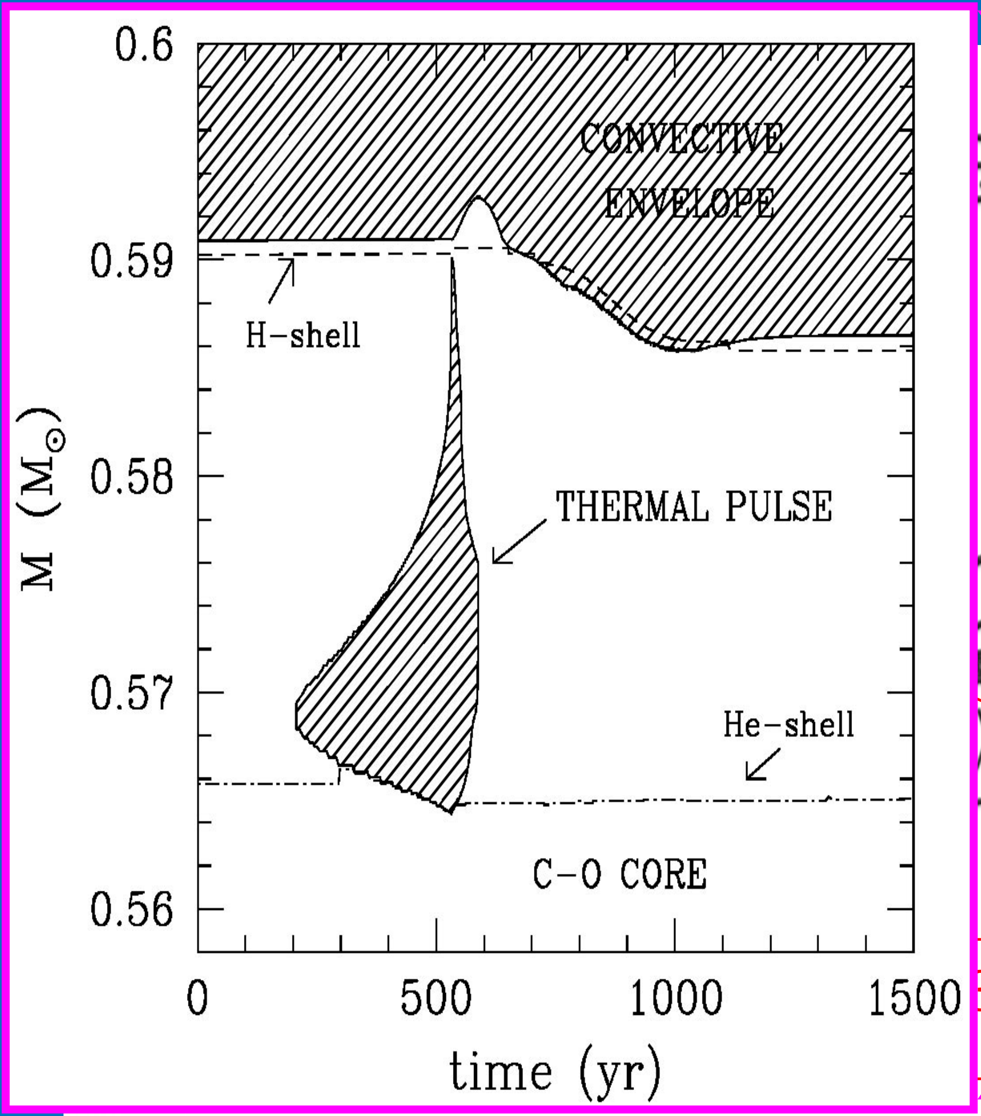


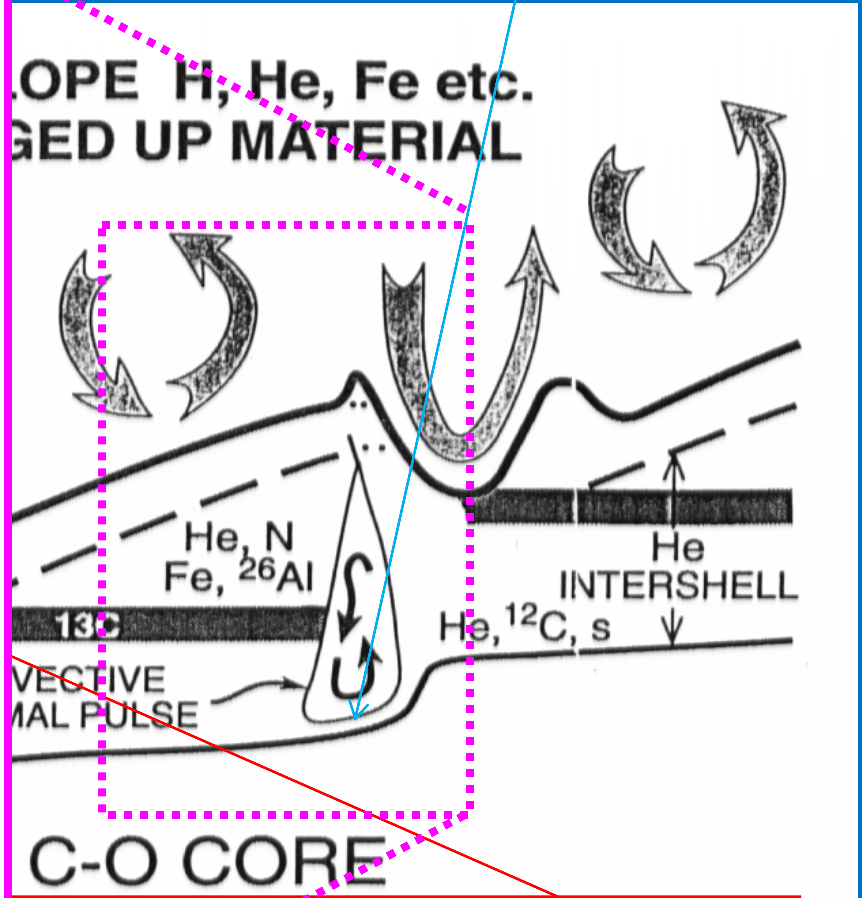
$^{13}C(\alpha,n)^{16}O$ reaction

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 (Cristallo+ 2009)
- ✓ Convective Boundary Mixing + Gravity waves (Battino+ 2016)
- ✓ Magnetic fields (Trippella+ 2014)

How does the ^{13}C pocket change?

- ✓ Rotation mixing (Piersanti+ 2013)
- ✓ Magnetic fields (Trippella+ 2014)

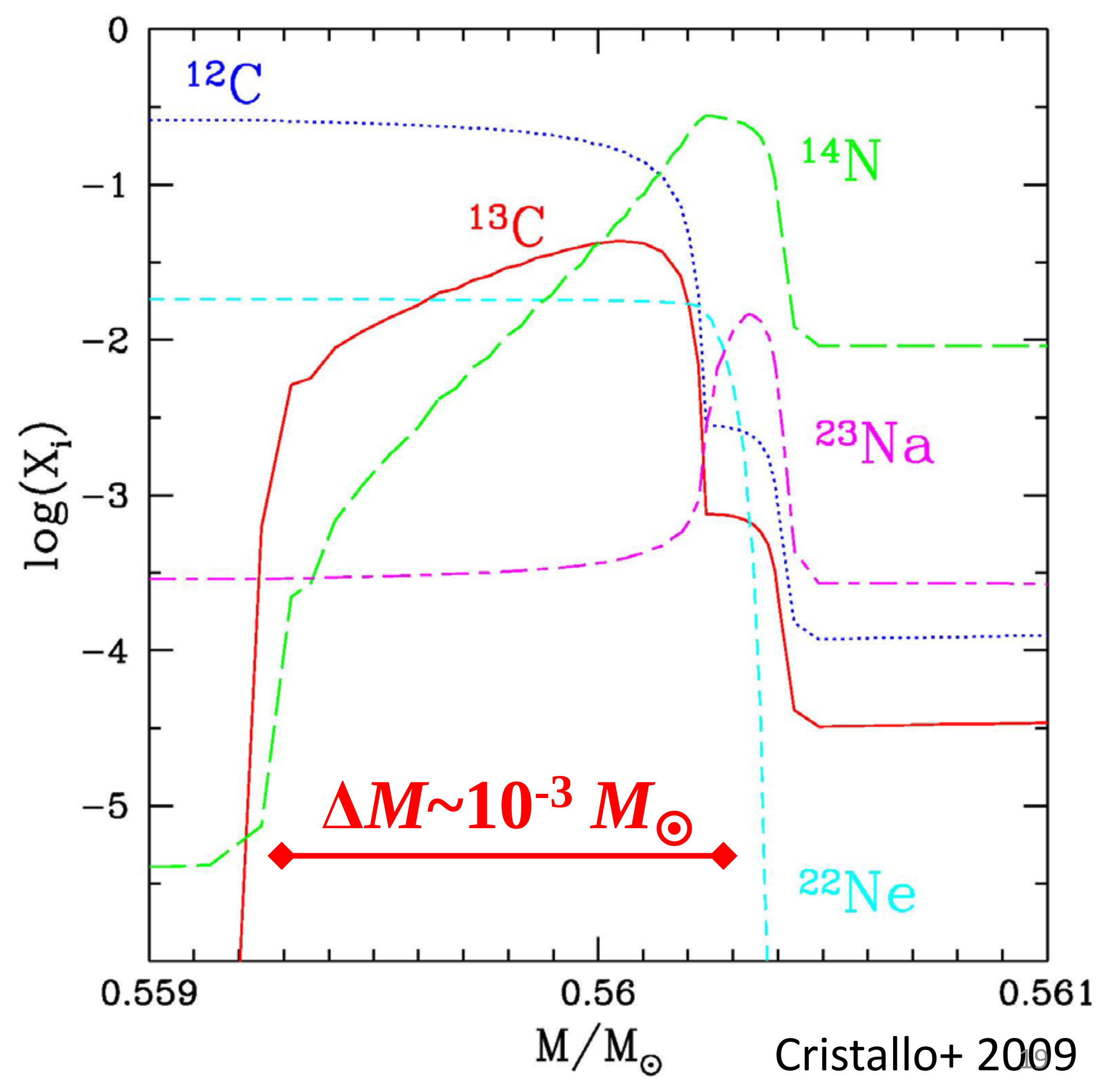
The formation of the ^{13}C pocket

^{13}C-pocket

^{14}N-pocket

^{23}Na-pocket

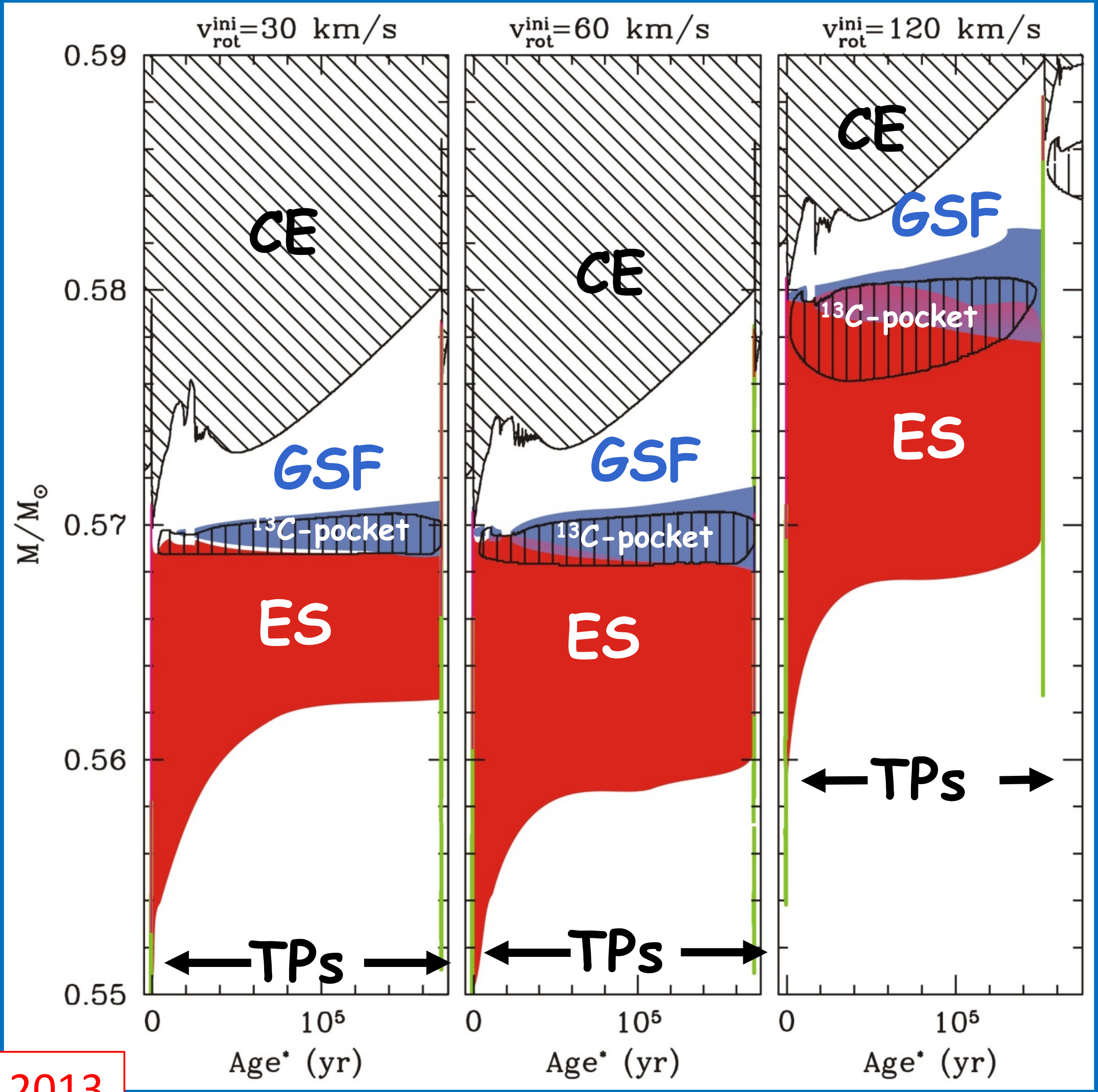
^{14}N strong neutron poison via ^{14}N(n,p)^{14}C reaction



$\Delta M \sim 10^{-3}\ M_\odot$

Cristallo+ 2009

Rotation induced instabilities during the AGB phase

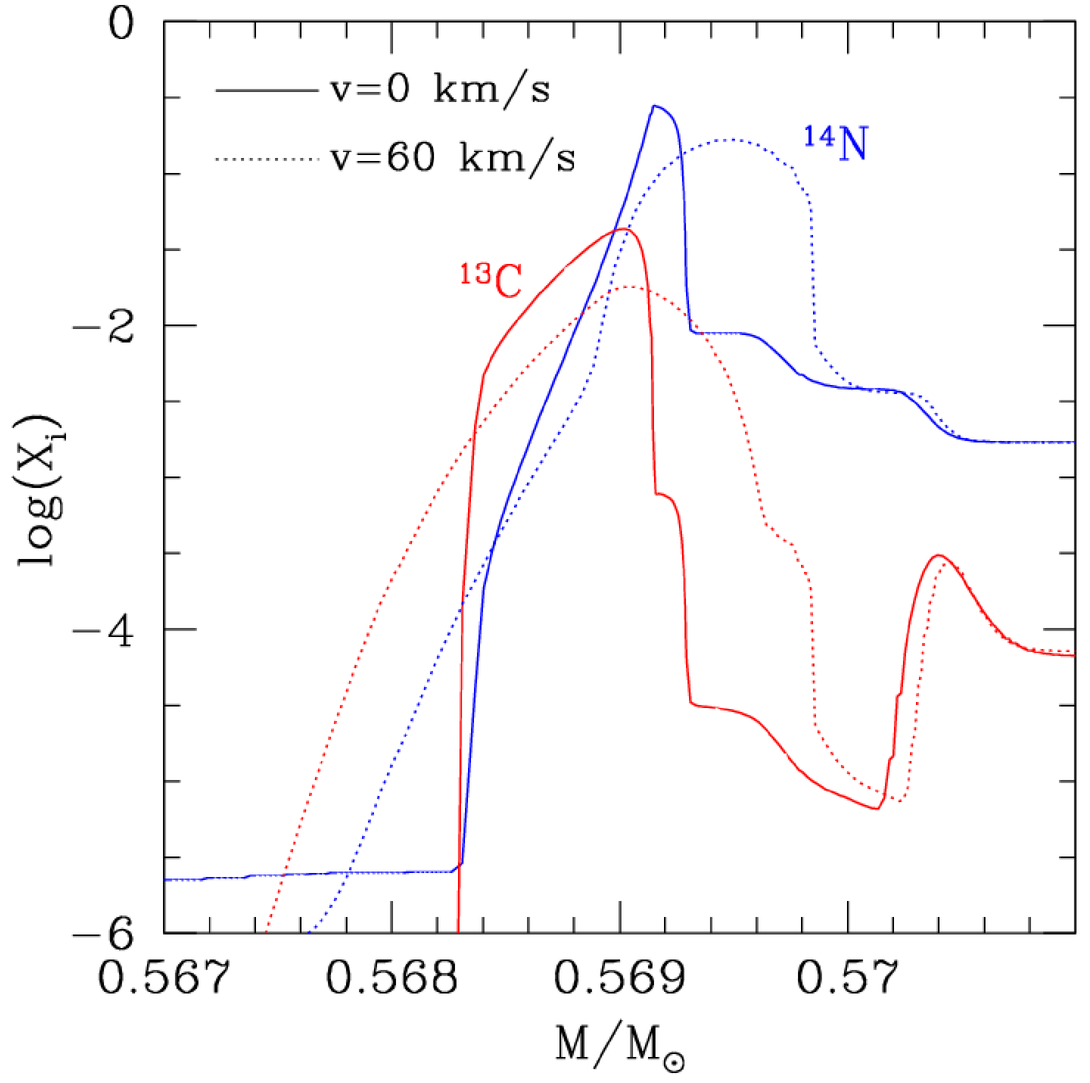


M=2.0 M_{SUN}
[Fe/H]=0

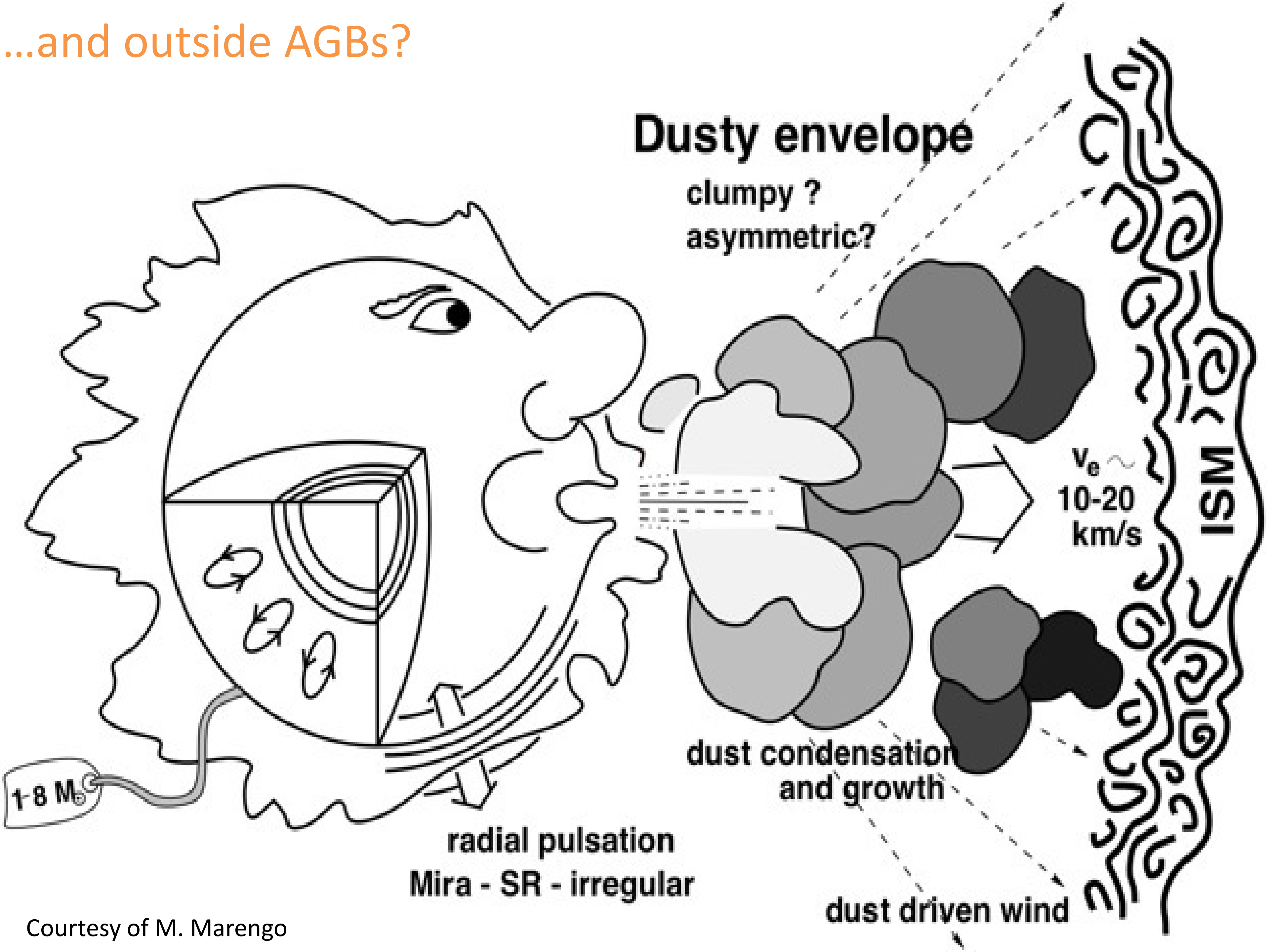
Piersanti+ 2013

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.

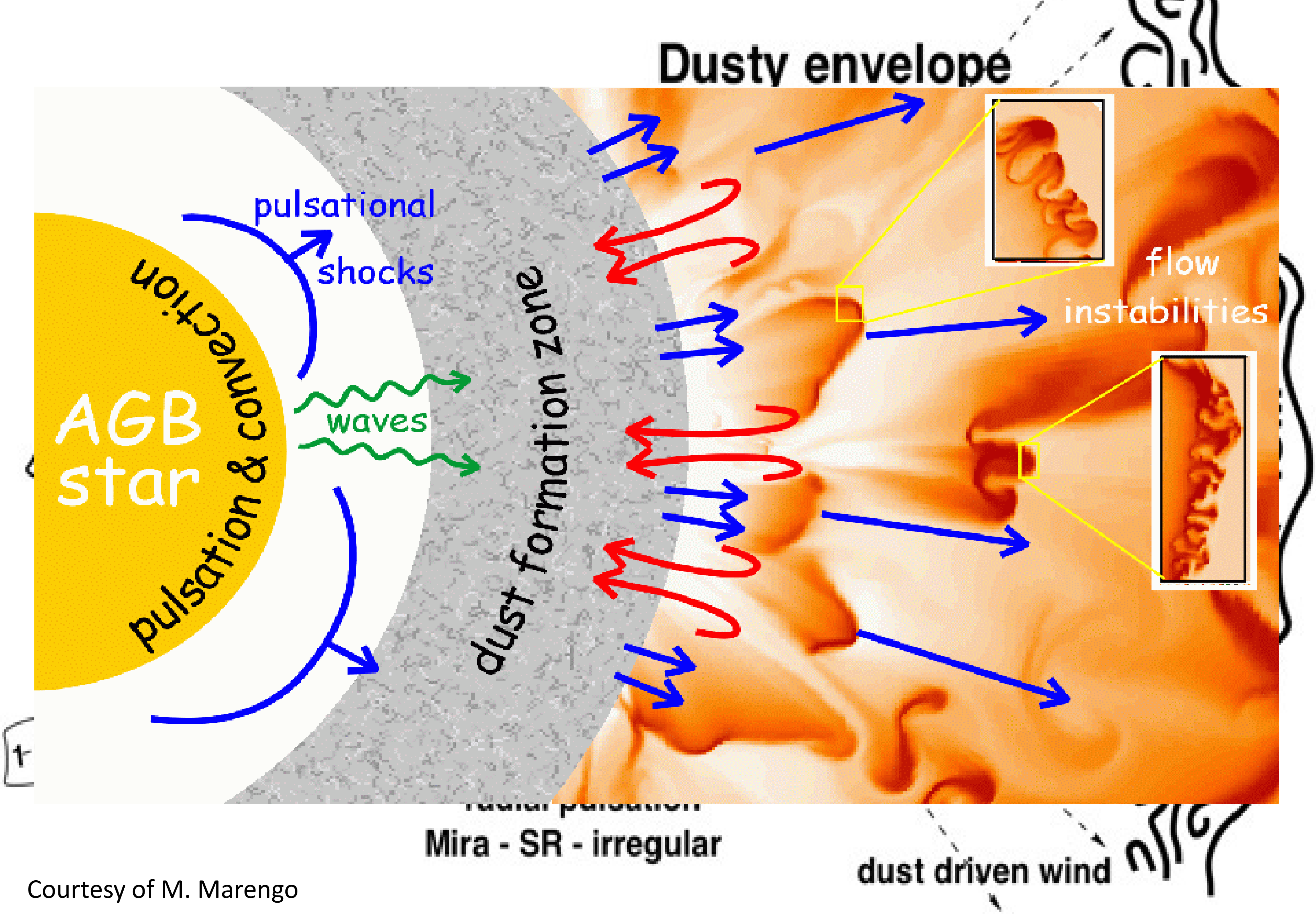


…and outside AGBs?



Courtesy of M. Marengo

…and outside AGBs?



Courtesy of M. Marengo

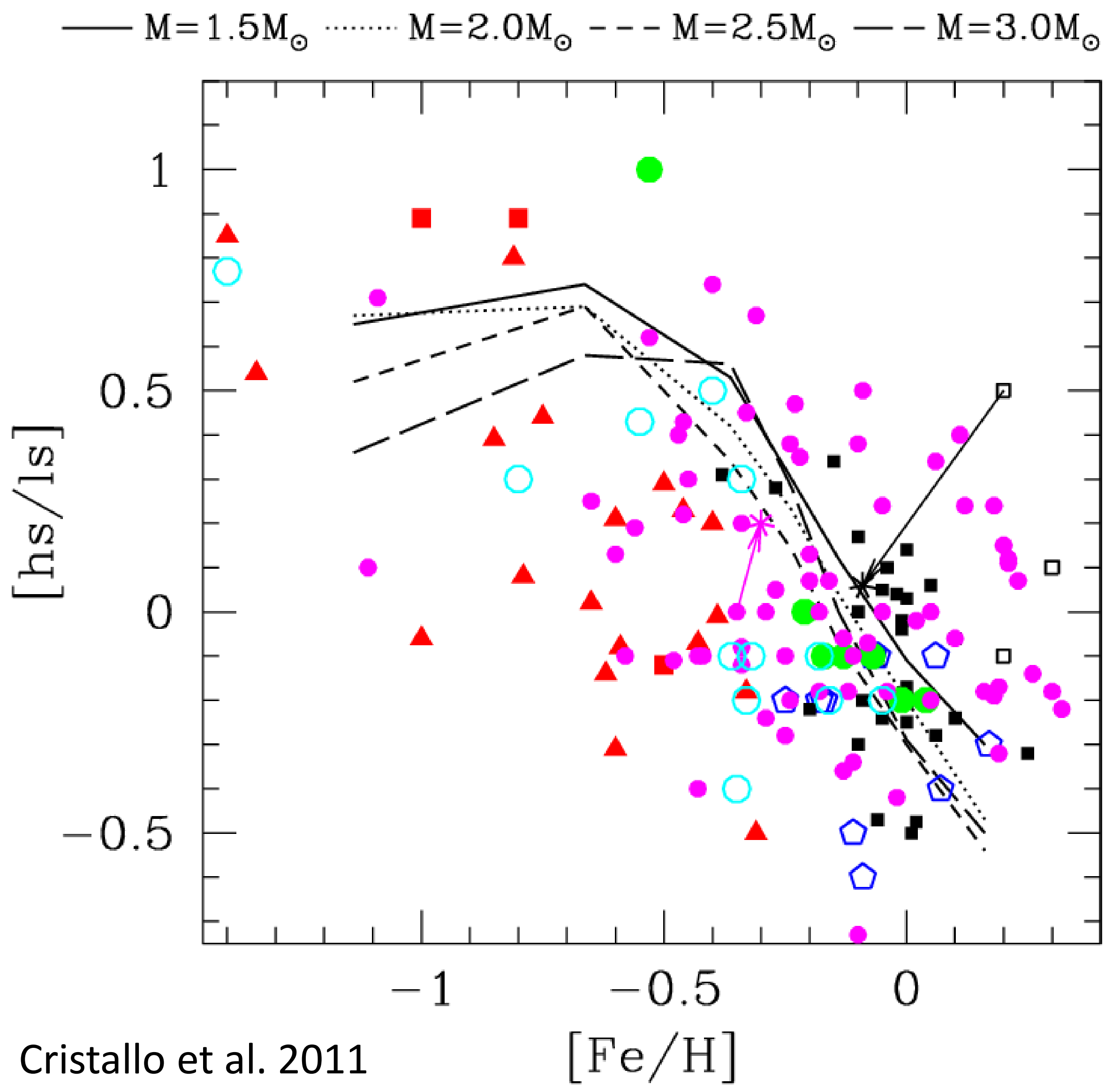
Testing theoretical s-process models

1. Spectroscopic observations;

2. Pre-solar grains;

3. Solar distribution of s-only isotopes

s-process [hs/ls]



Cristallo et al. 2011

- ● Ba & CH stars
- ▲ Post-AGBs
- ■ Intrinsic C-rich
- ⬟ Intrinsic O-rich

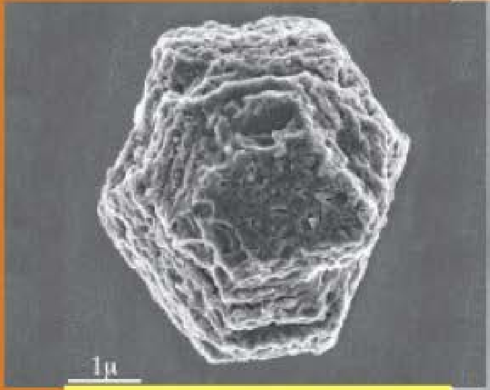
$[ls/Fe]=([Sr/Fe]+[Y/Fe]+[Zr/Fe])/3$

$[hs/Fe]=([Ba/Fe]+[La/Fe]+[Nd/Fe] +[Sm/Fe])/4$

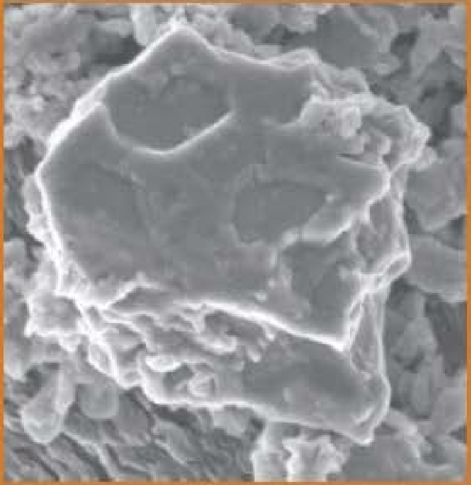
Meteorites

Allende (Mexico, 1969)

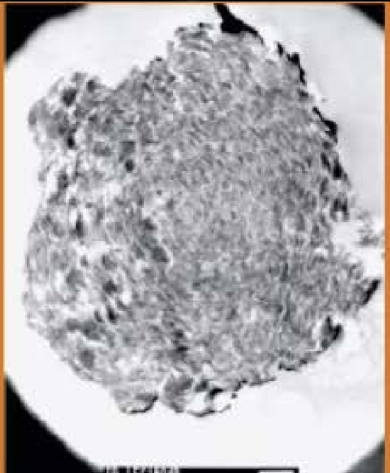
Murchison (Australia, 1969)

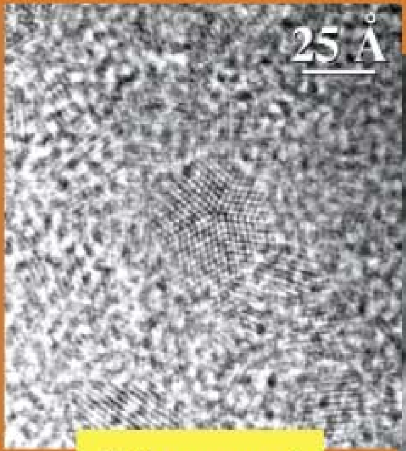


Silicon Carbide



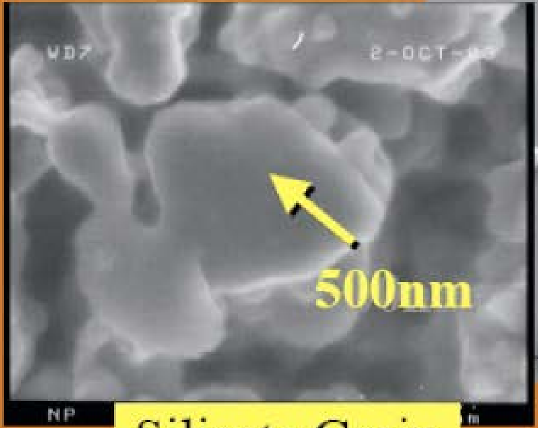
Graphite Grains



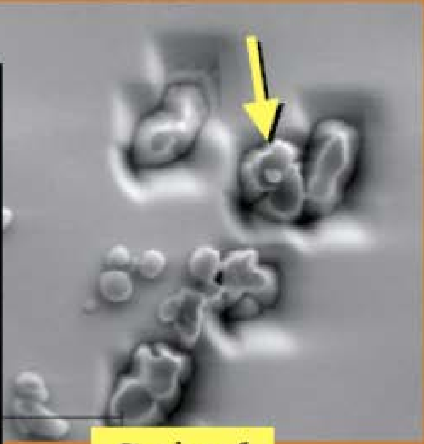


Diamond

Corundum



Silicate Grain



Spinel

The majority of SiC, Silicates and Oxides, as well as 50% fo Graphite, come from AGB stars

Isotopic ratios in pre-solar SiC grains

Liu+ 2015

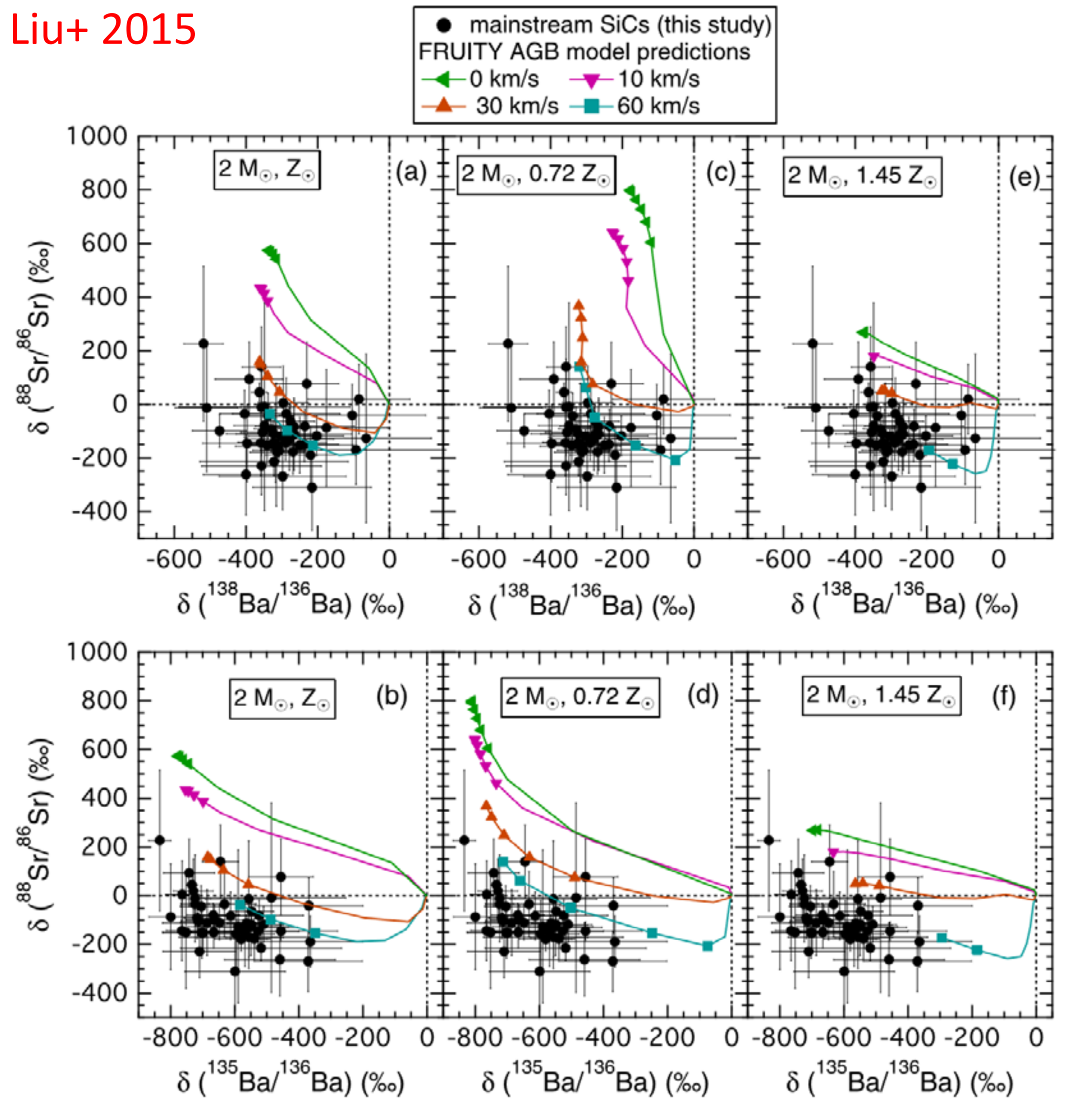
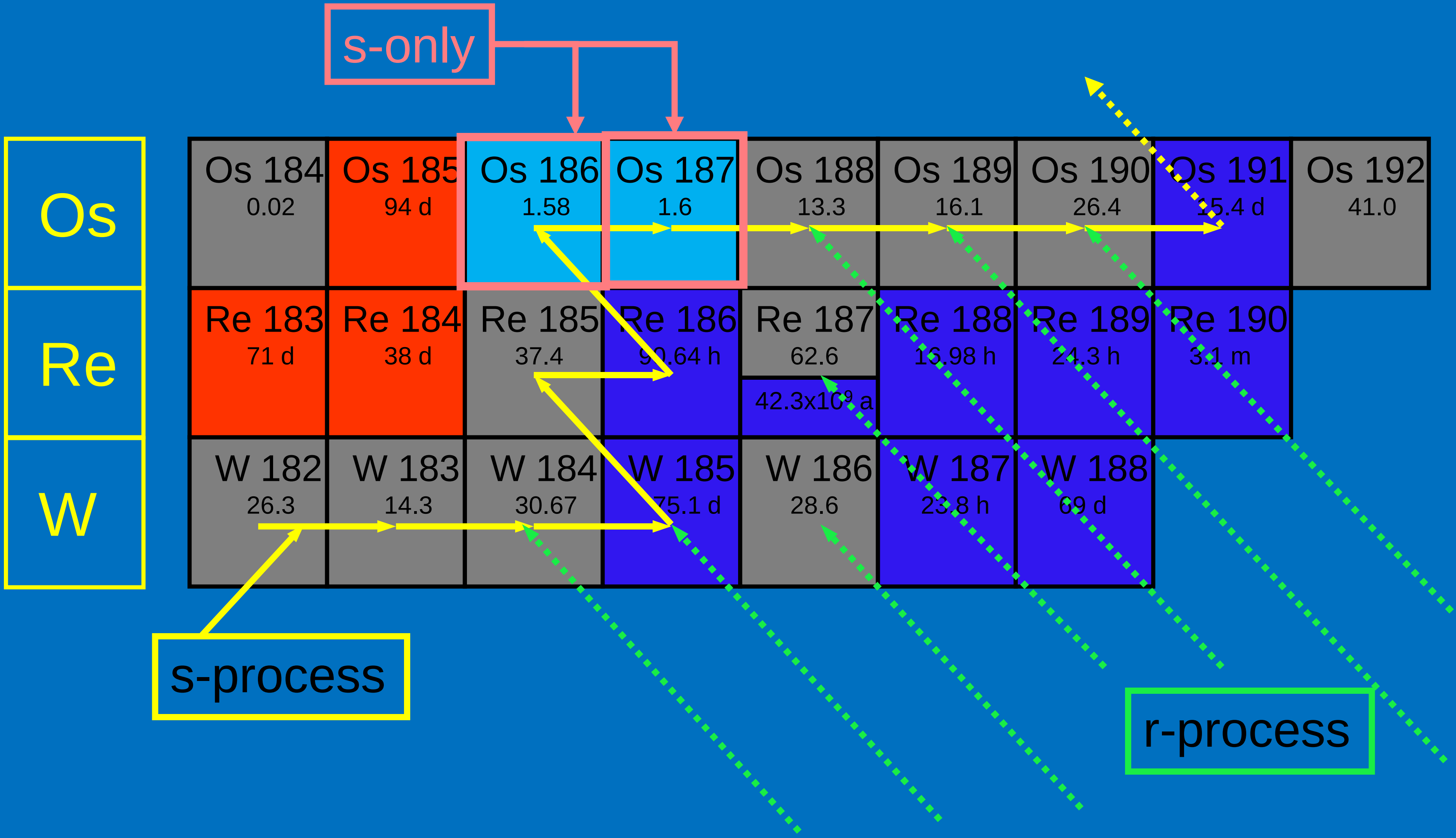


Figure 14. Four-isotope plots of $\delta(^{88}Sr/^{86}Sr)$ vs. $\delta(^{138}Ba/^{136}Ba)$ in (a, c, e) and $\delta(^{88}Sr/^{86}Sr)$ vs. $\delta(^{135}Ba/^{136}Ba)$ in (b, d, f). The mainstream SiC grain data from this study are compared to FRUITY rotating model predictions for 2 $M_\odot$ AGB stars with metallicities at 0.72 $Z_\odot$, $Z_\odot$, and 1.45 $Z_\odot$ by Piersanti et al. (2013).

$$\delta(^iX/^jX) \equiv [(^iX/^jX)\mathrm{measured}/(^iX/^jX)_{SUN} - 1] \times 1000$$

The solar s-only distribution



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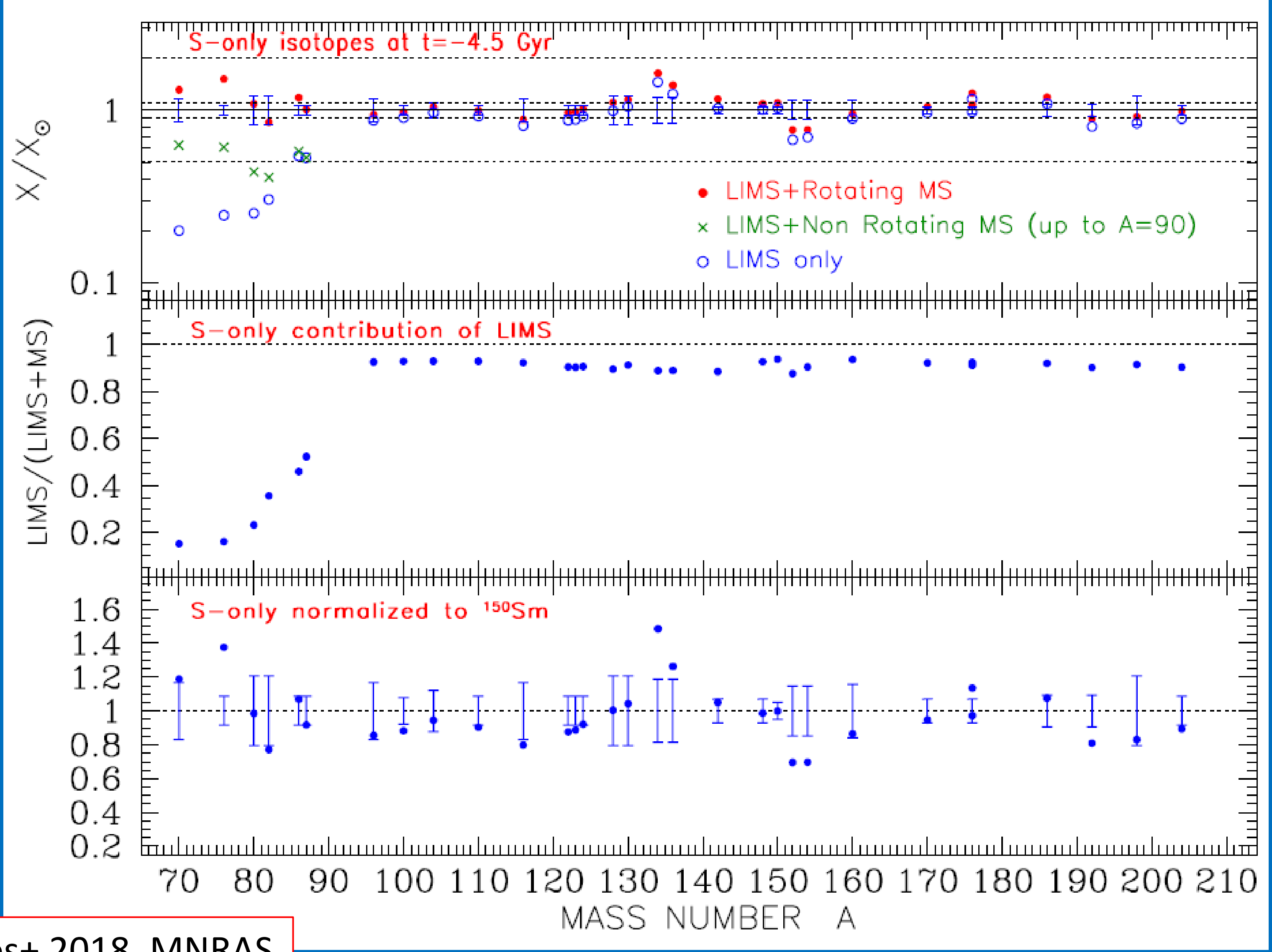
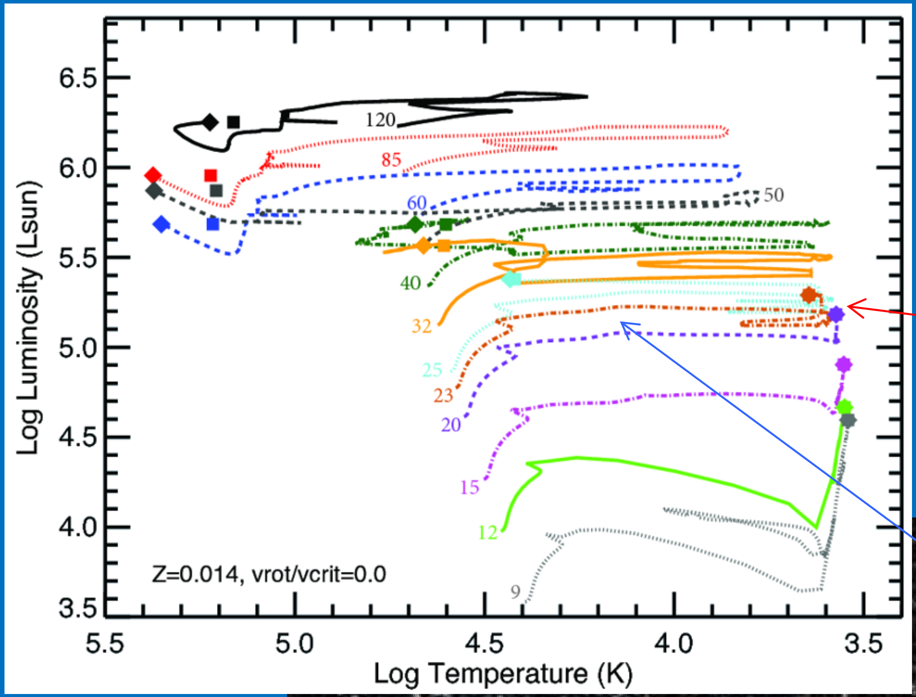
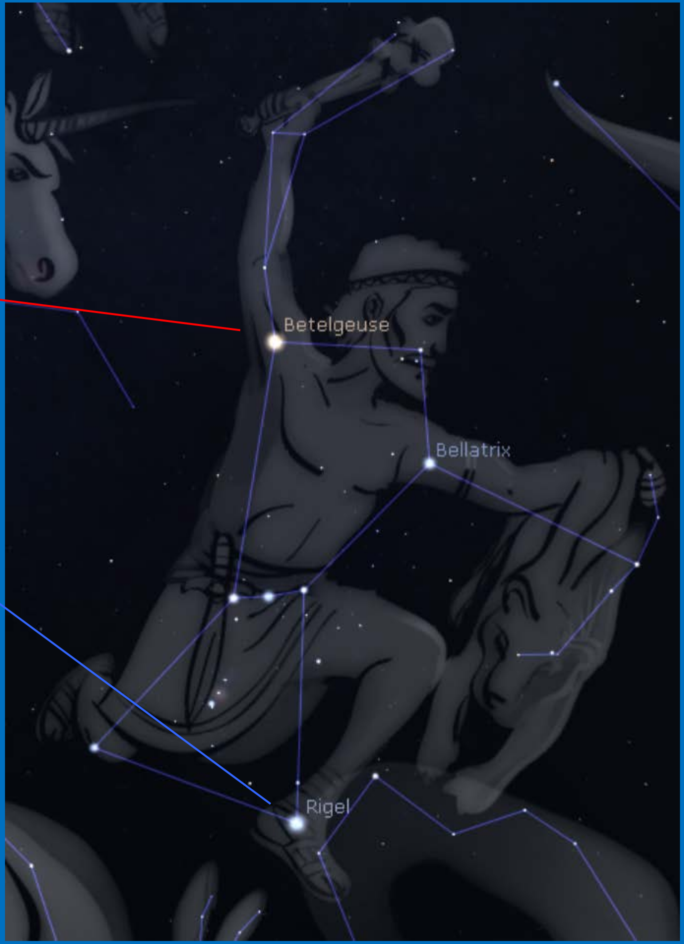
The solar s-only distribution



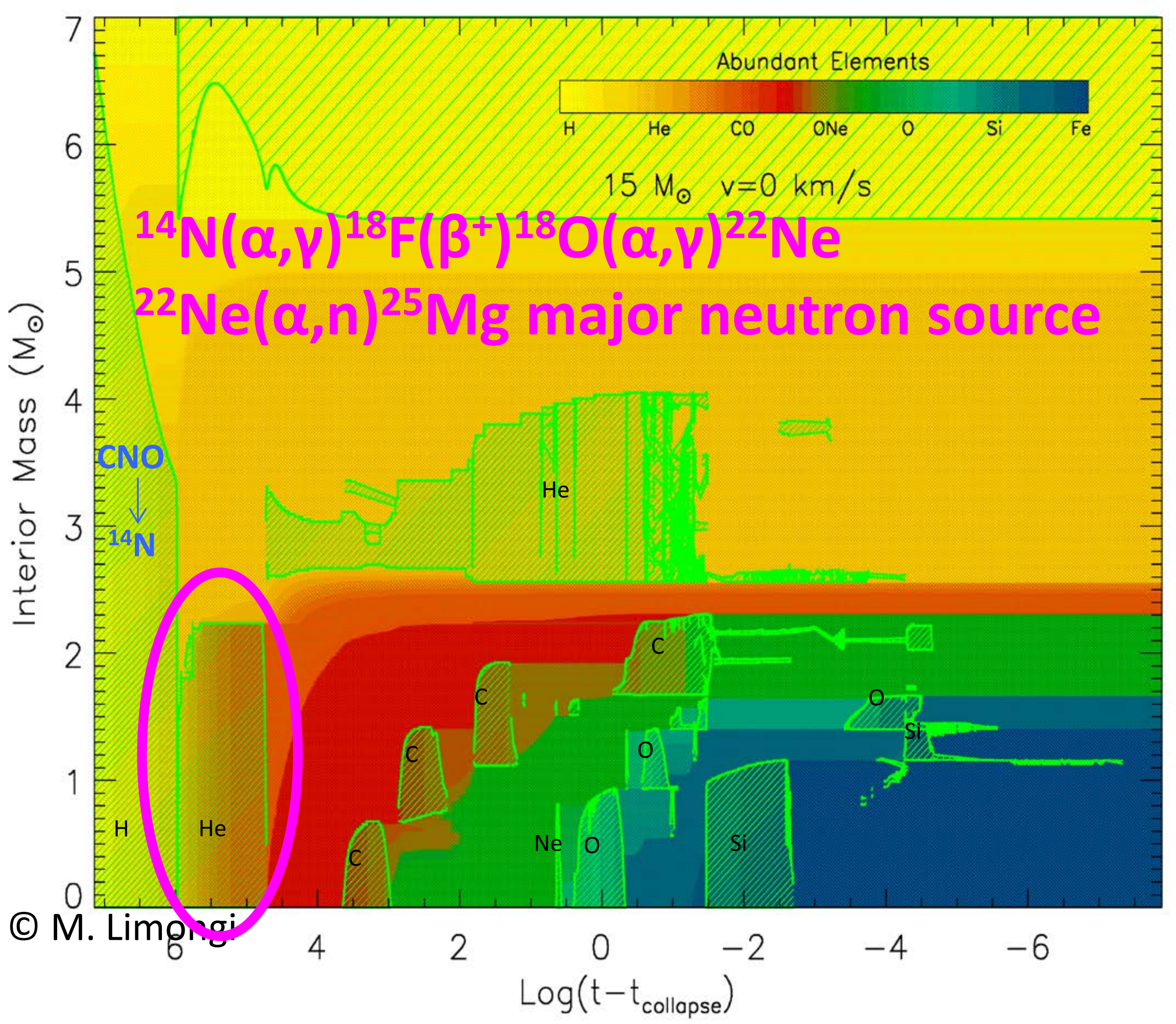
Prantzos+ 2018, MNRAS

The weak s-process in massive stars





The weak s-process and the evolution of massive stars



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

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

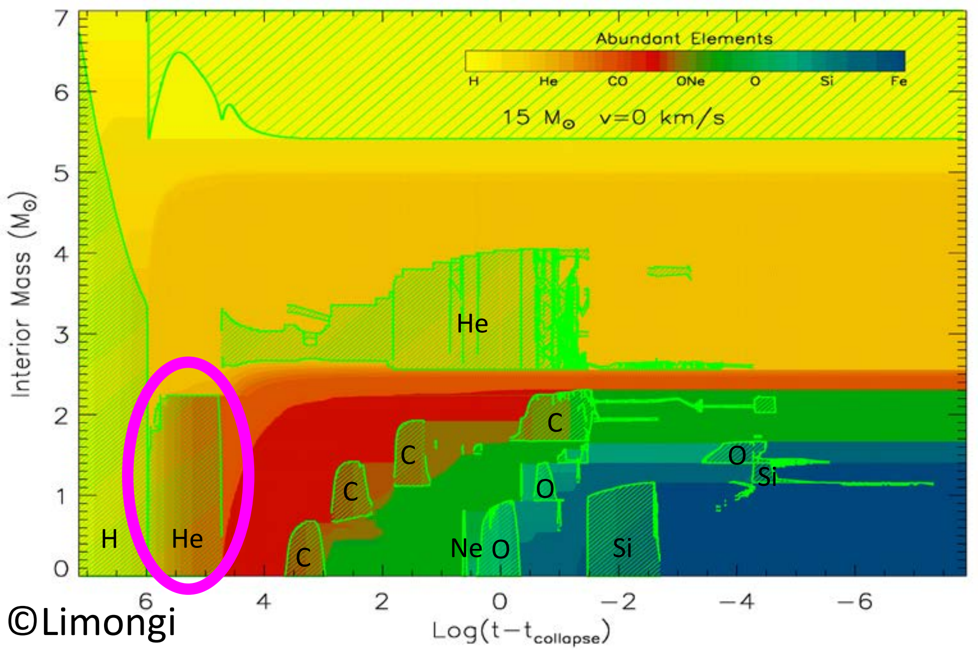
CNO

↓

$^{14}\mathrm{N}$

© M. Limongi

Core He-burning phase



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

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

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

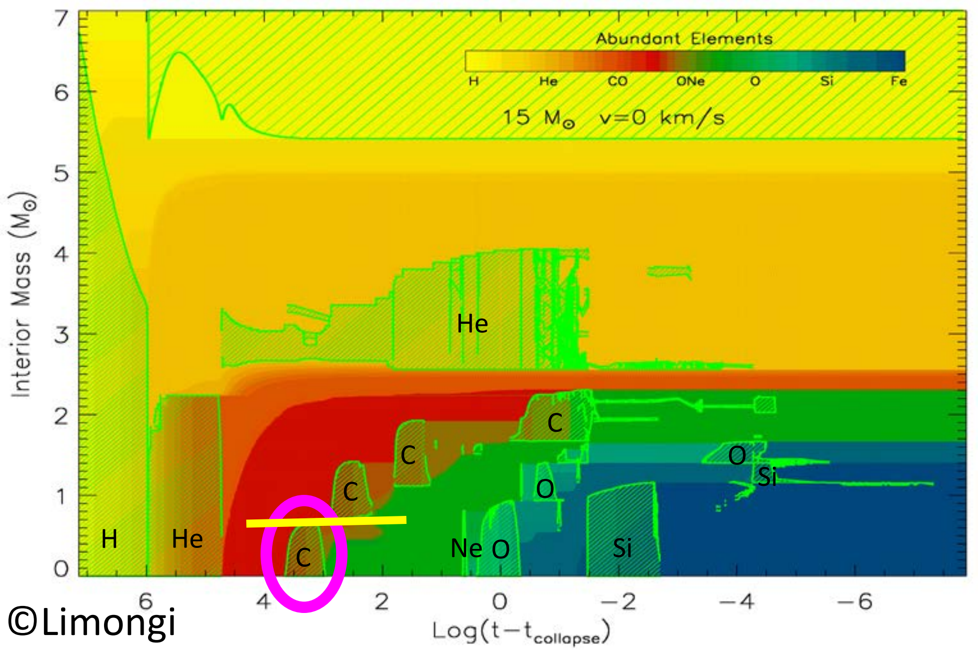
$\tau \approx 1$ Myr

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



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

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

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

$\tau \approx 1$ Kyr

Some ^{22}Ne is left after He burning

All (α,n) channels are activated:

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

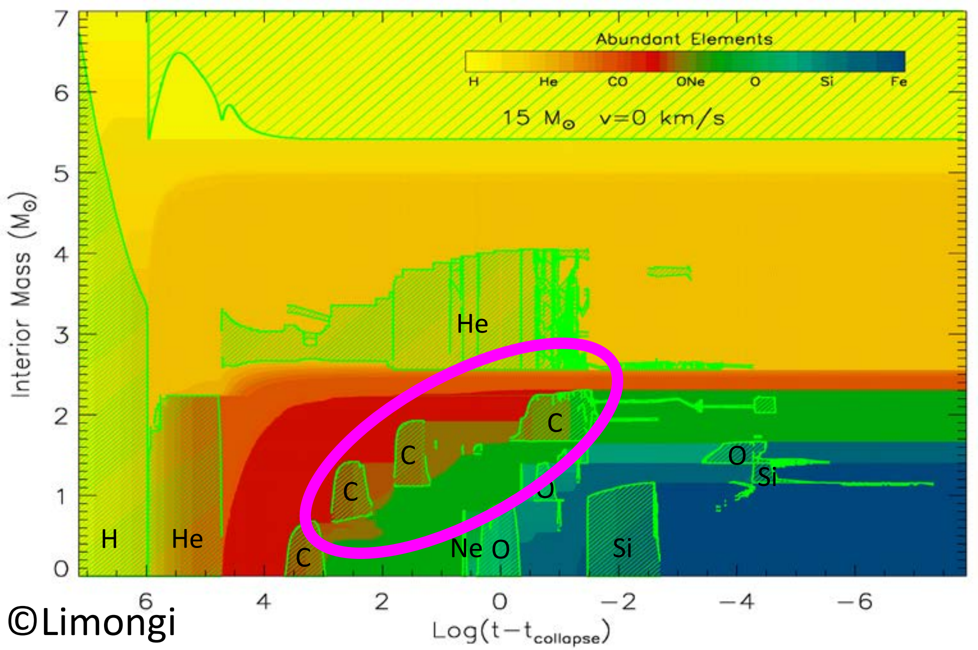
$^{18}O(\alpha,n)^{21}Ne$ - $^{21}Ne(\alpha,n)^{24}Mg$

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

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

The resulting neutron density is very high, BUT…

Shell C-burning phase



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

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

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

Why not the $^{13}C(\alpha,n)^{16}O$?
Because at T~1×10^{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 higher:
10^{11}-10^{12} n/cm^{3}

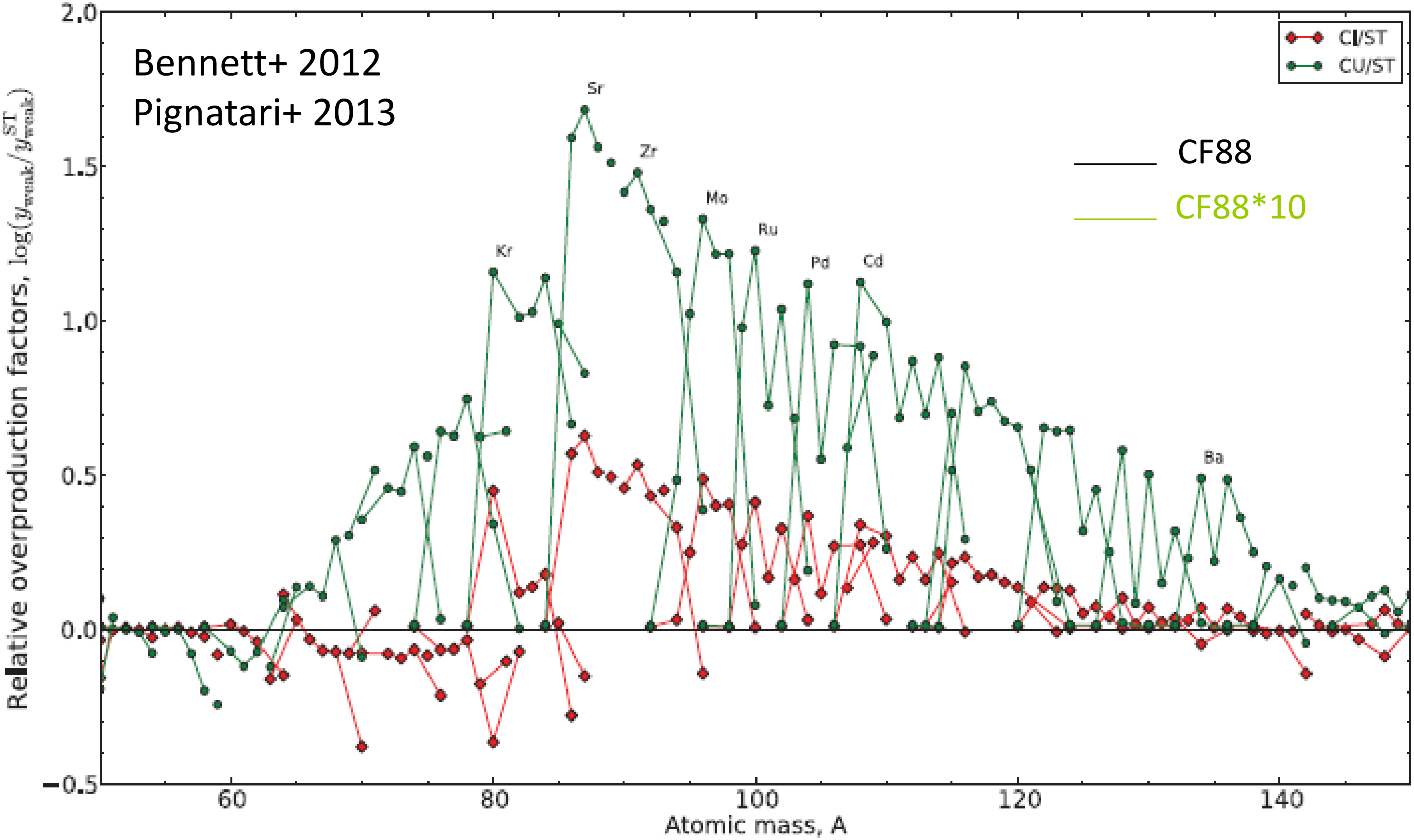
Uncertainties of the weak s-process: cross sections

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

Orders of magnitude uncertainty: ↓ ↑

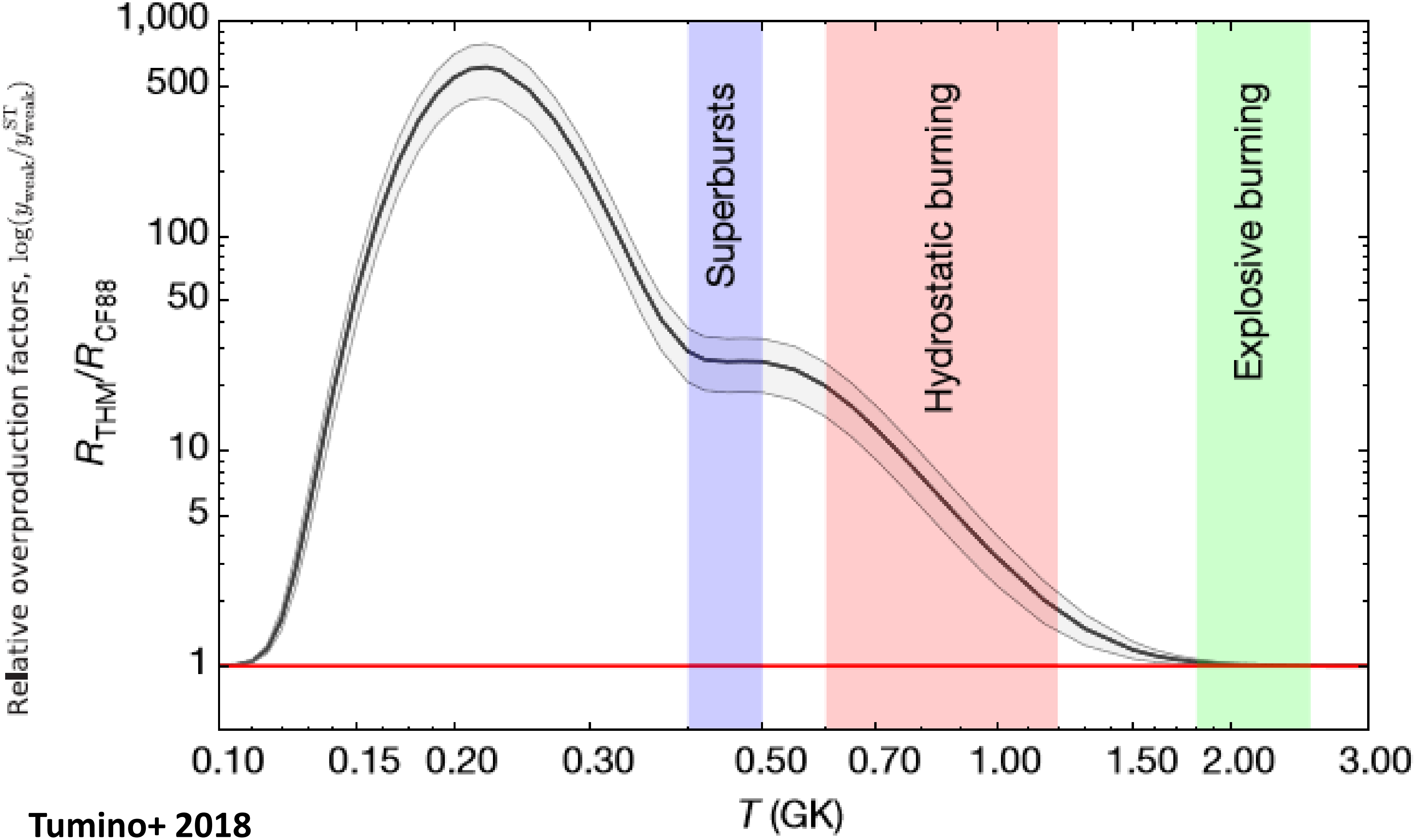
Uncertainties of the weak s-process: cross sections

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



Uncertainties of the weak s-process: cross sections

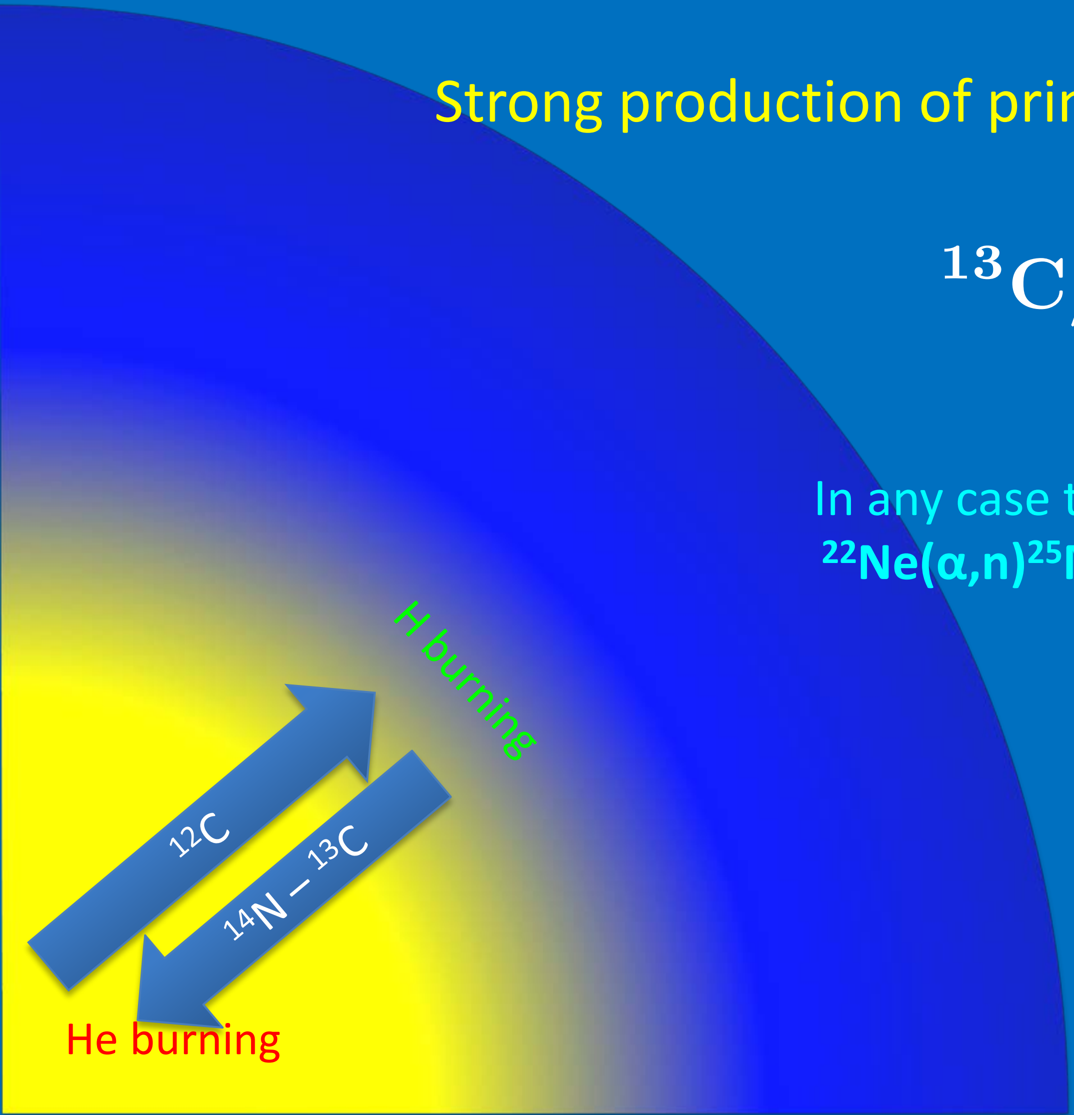
$^{12}C(^{12}C,x)x$ - $^{22}Ne(\alpha,x)x$ - $^{12}C(\alpha,\gamma)^{16}O$



Tumino+ 2018

Uncertainties of the weak s-process: stellar modelling

Convection - Rotation



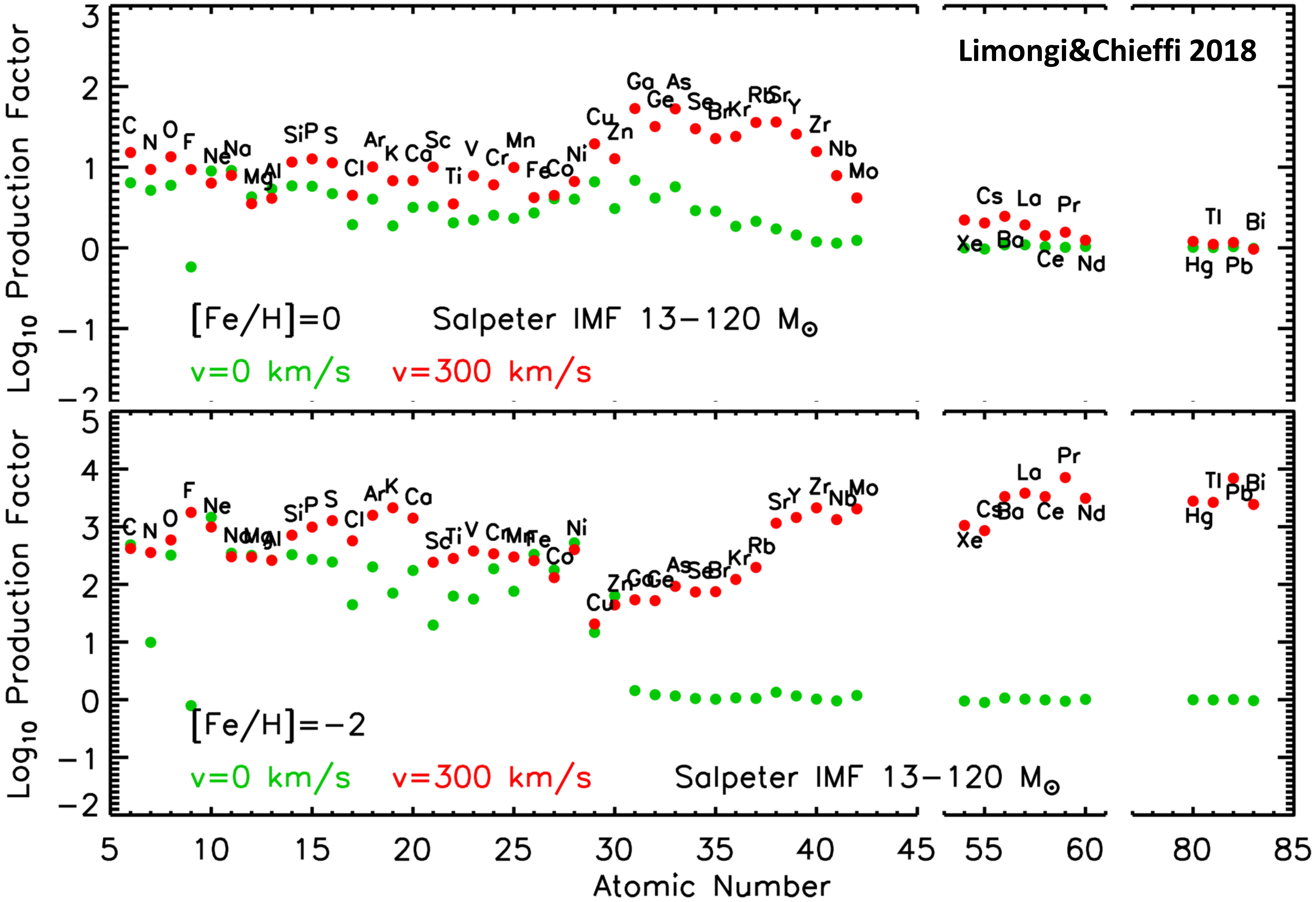
Strong production of primary ^{14}N at low metallicities

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

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

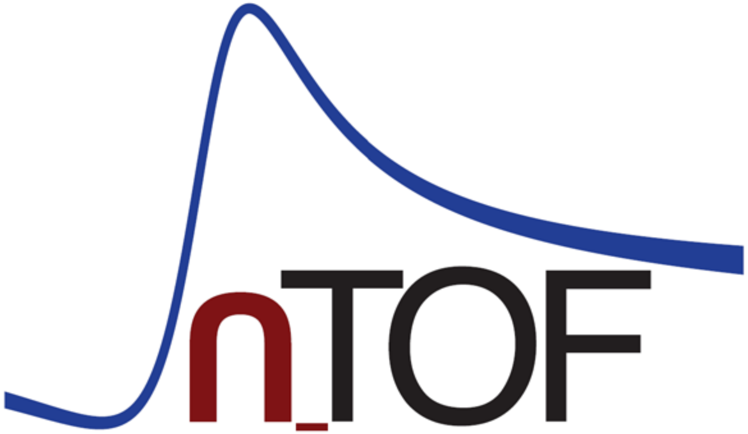
Courtesy of A. Chieffi

The effect of rotation: differences in the stellar ejecta

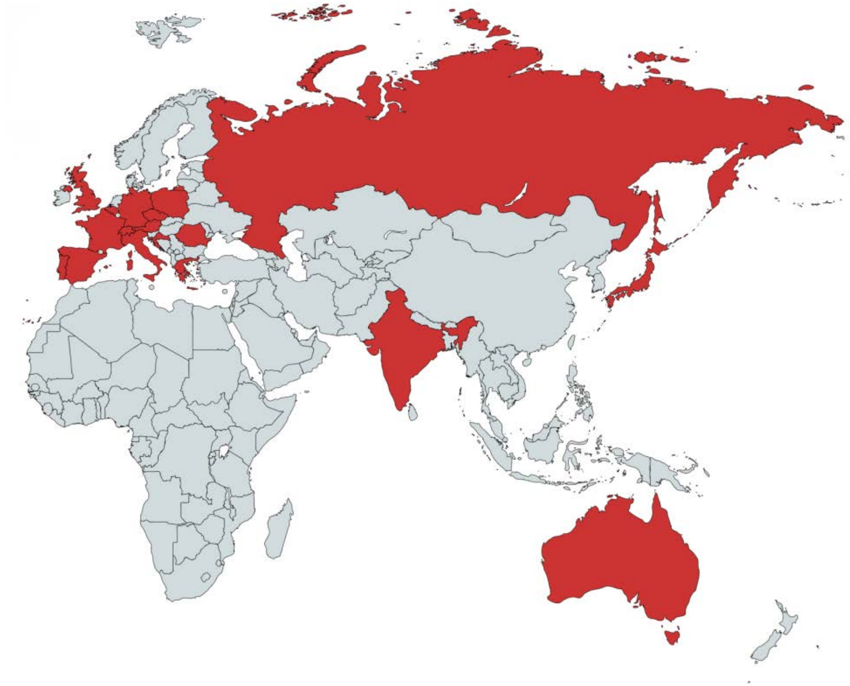


Nuclear Astrophysics

A case study: the n_TOF experiment

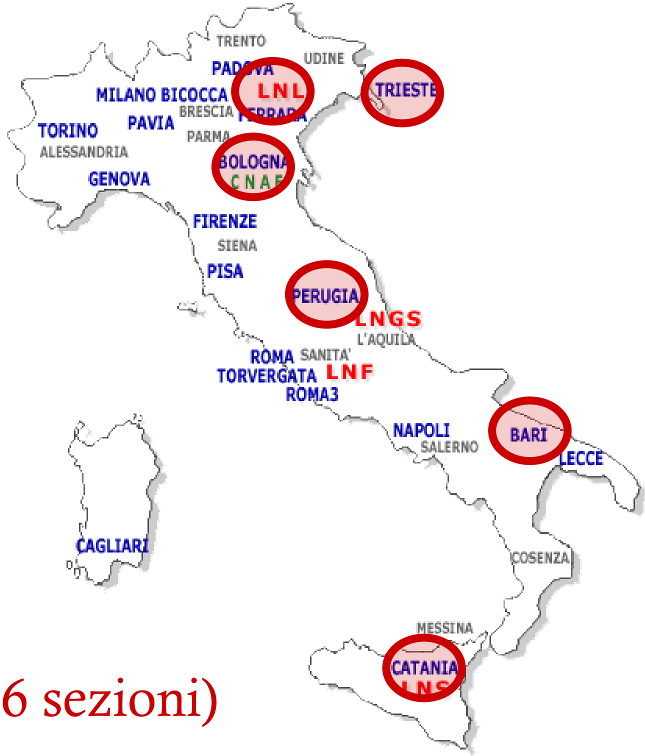


n_TOF collaboration



18 Countries
50 Institutes
124 Collaborators
38 PhD

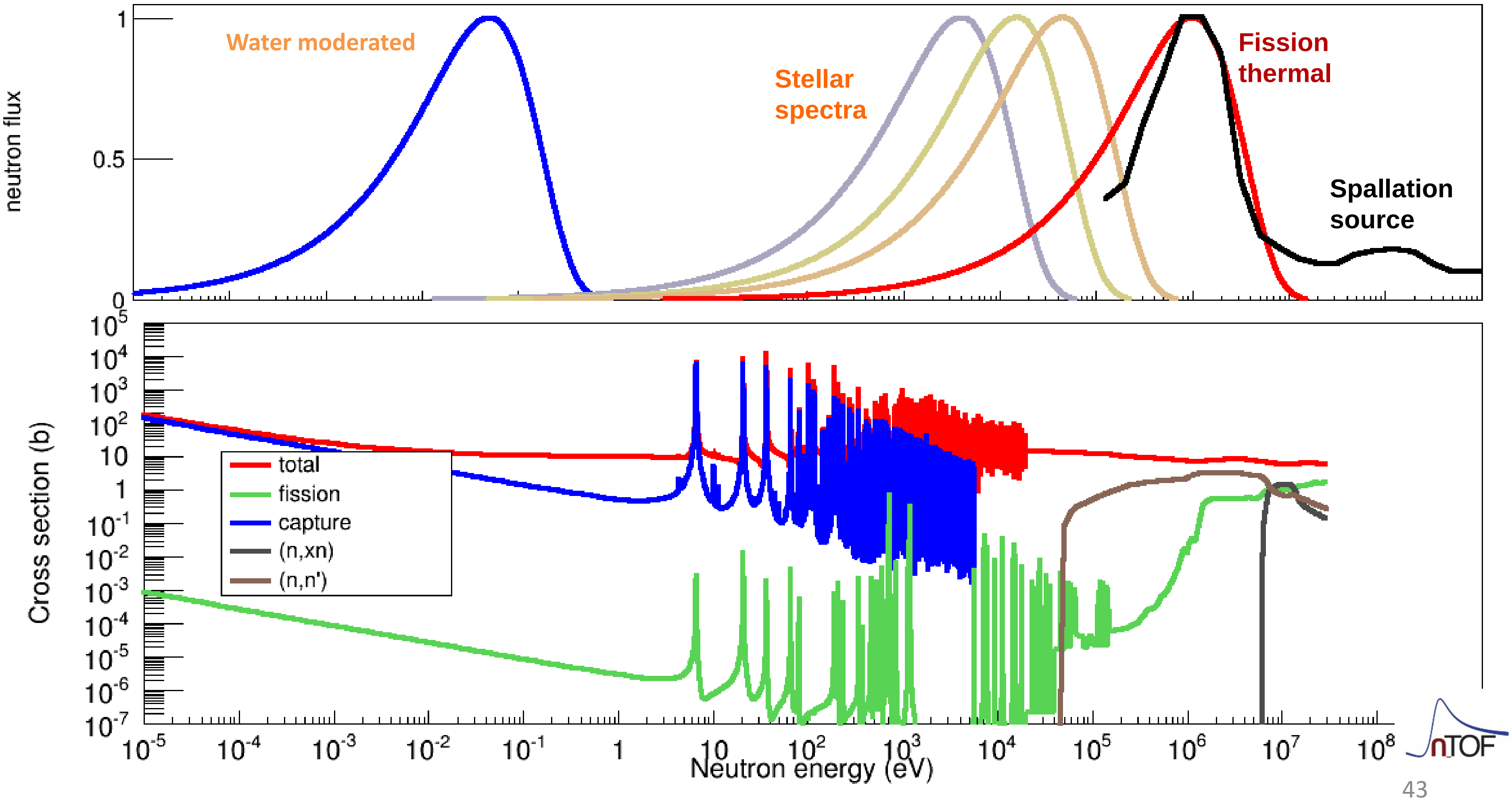
n_TOF - Italia



INFN (6 sezioni)

- **Bari**
- **Bologna**
- **LNL**
- **LNS**
- **Perugia**
- **Trieste**

Neutron energies of interest

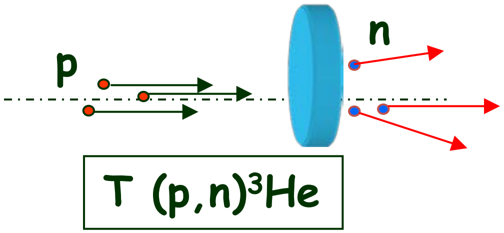


nTOF

Experimental techniques: how to obtain neutron beams?

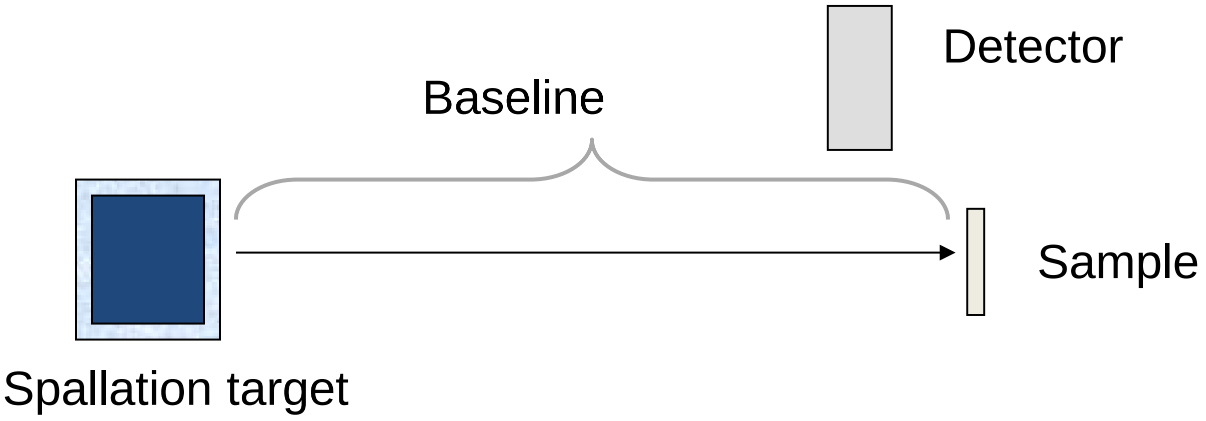
- Thermal Neutrons
  - Reactors → very high flux
  - Accelerators+ moderators, neutron beams less intense

- Mono-energetic neutron sources
  - Based on (p,n) - (d,n) - etc.
  - Low energy accelerators
  - Neutron energy can be varied (up to 20 MeV)

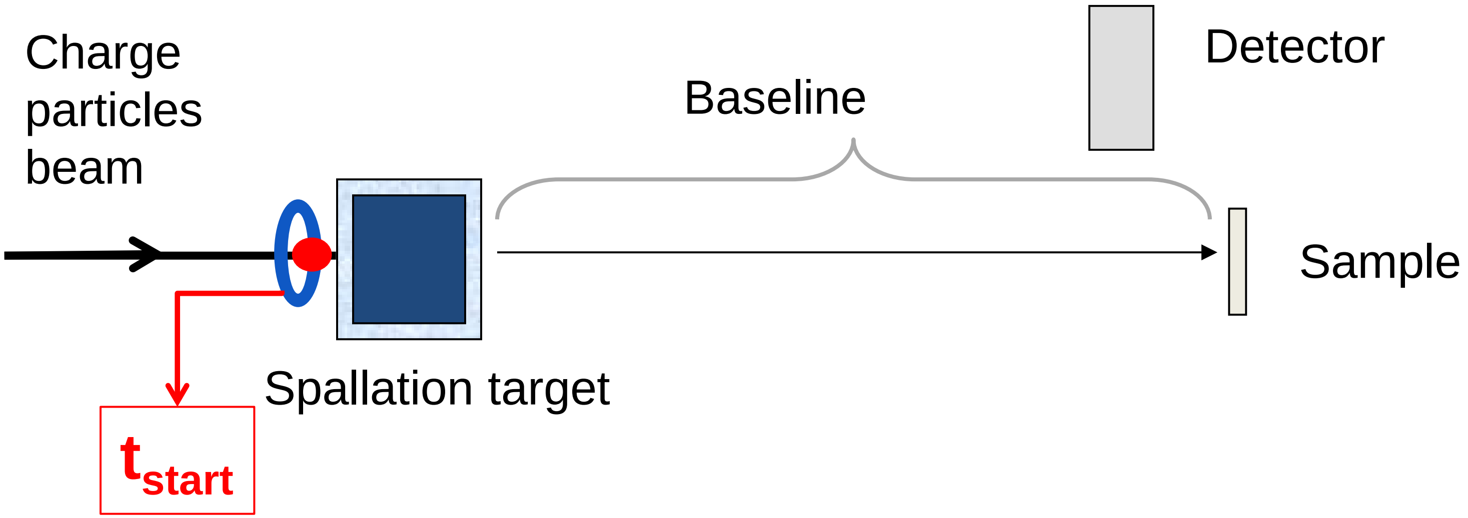


- *Facilities* for Time Of Flight: neutrons with large energetic spectrum
  - **Large energetic spectrum (meV – MeV or meV - GeV)**
  - High energetic resolution
  - More complicated accelerators (pulsed, high energy, high intensity)

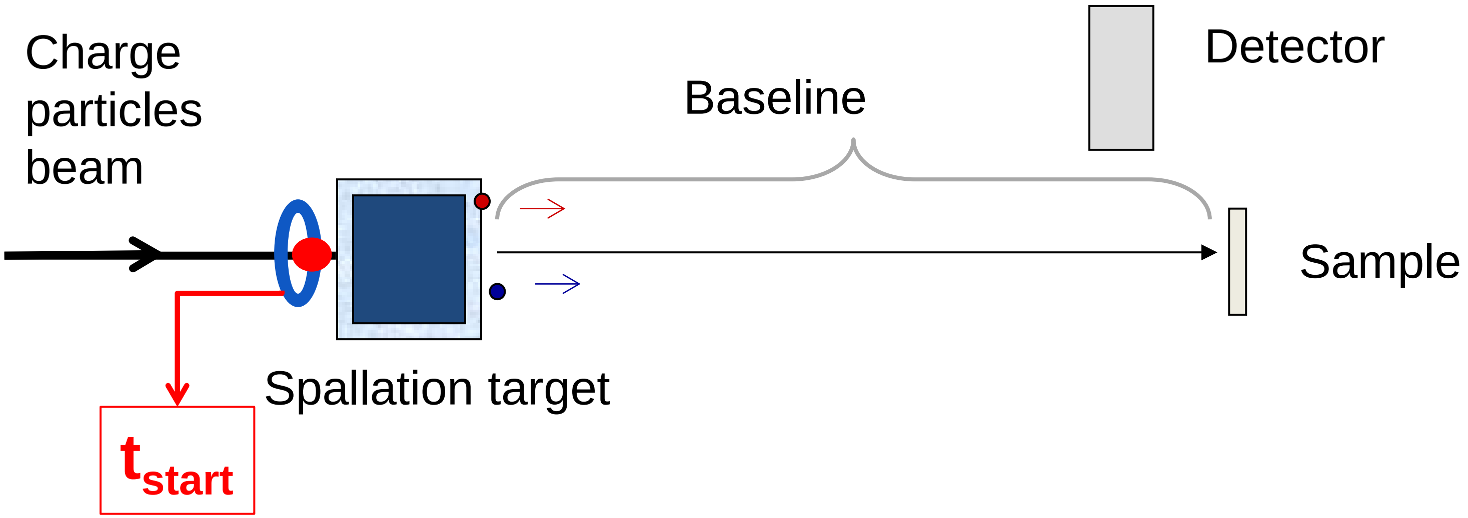
Time Of Flight facilities



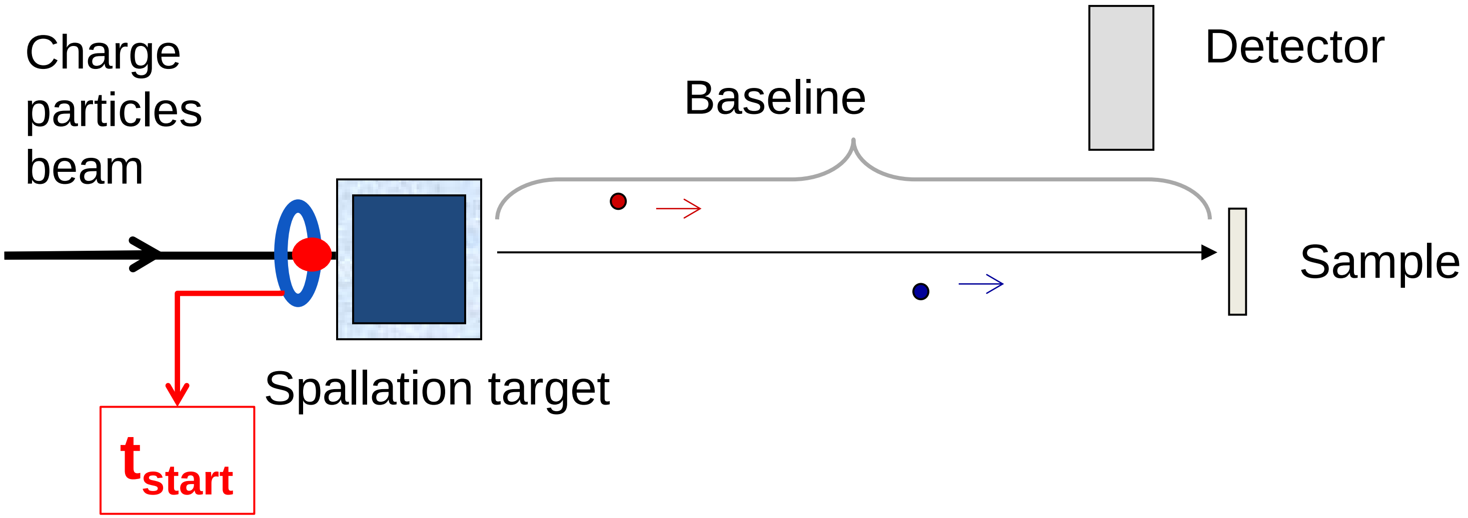
Time Of Flight facilities



Time Of Flight facilities



Time Of Flight facilities



Charge particles beam

Baseline

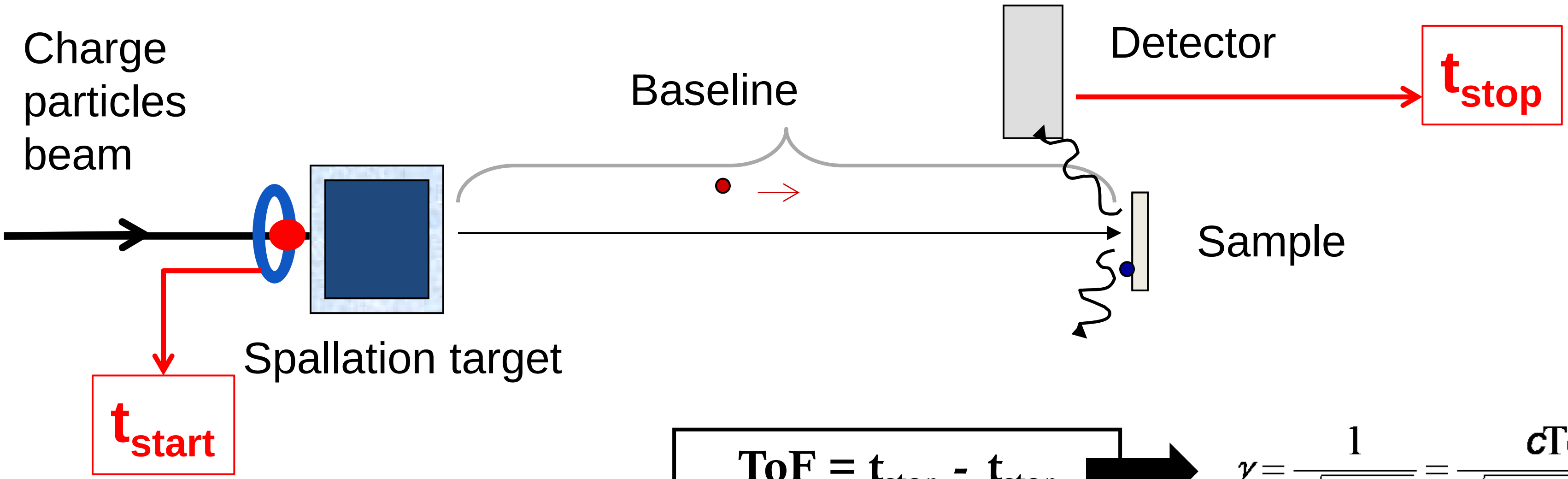
Detector

Sample

Spallation target

t_{start}

Time Of Flight facilities

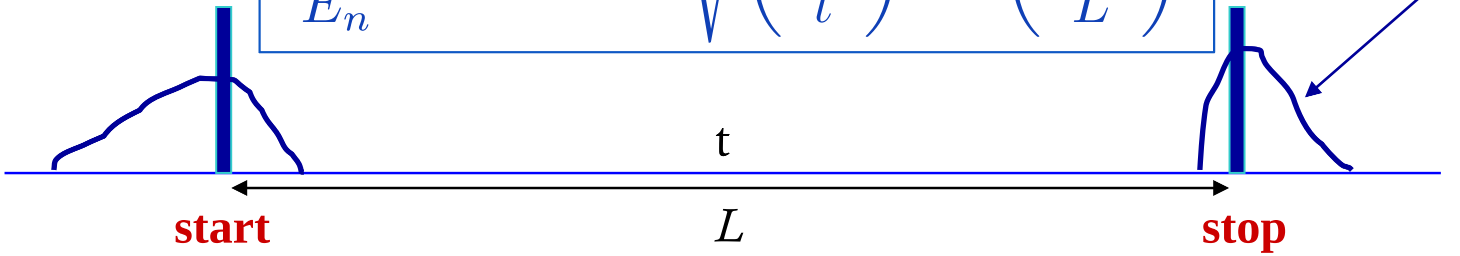


ToF = t_{stop} - t_{stop}

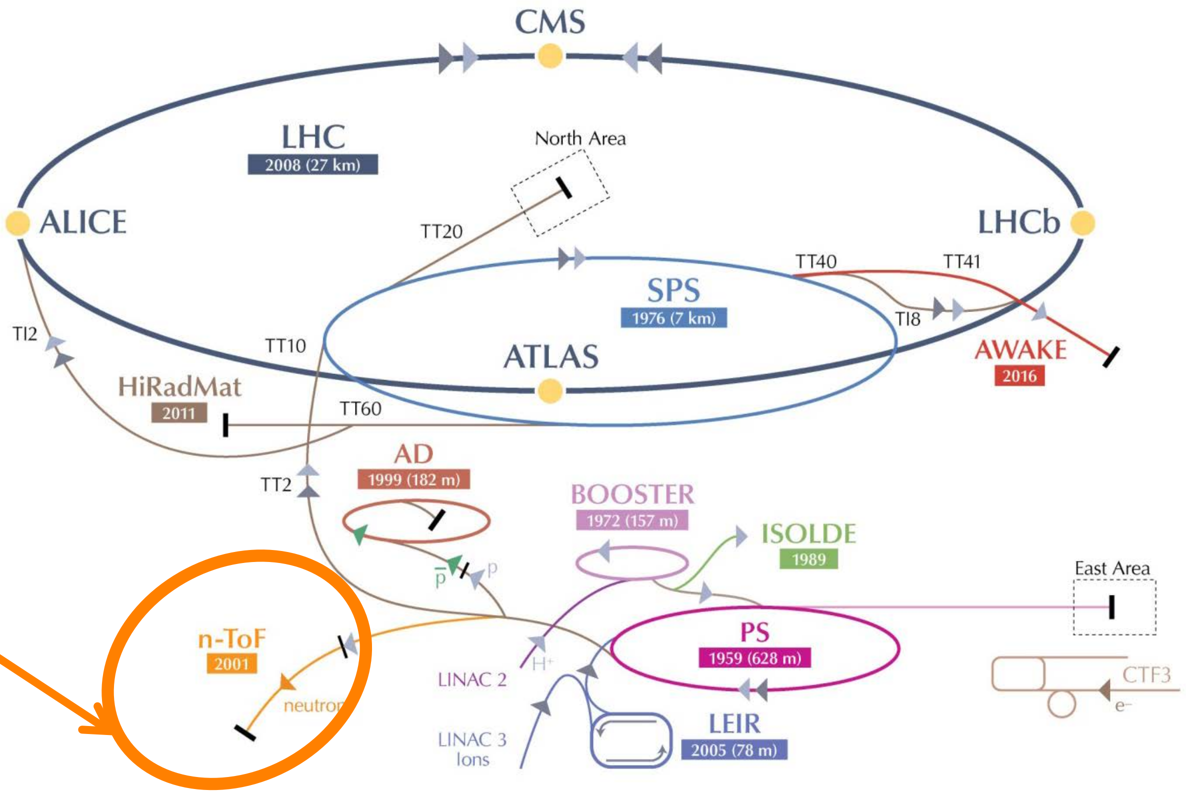
$$\gamma = \frac{1}{\sqrt{1-\beta^2}} = \frac{c\mathrm{ToF}}{\sqrt{c^2\mathrm{ToF}^2 - L^2}}$$

$$E_n = mc^2(\gamma - 1)$$

$$\frac{\Delta E_n}{E_n} = (\gamma + 1)\gamma\sqrt{\left(\frac{\Delta t}{t}\right)^2 + \left(\frac{\Delta L}{L}\right)^2}$$

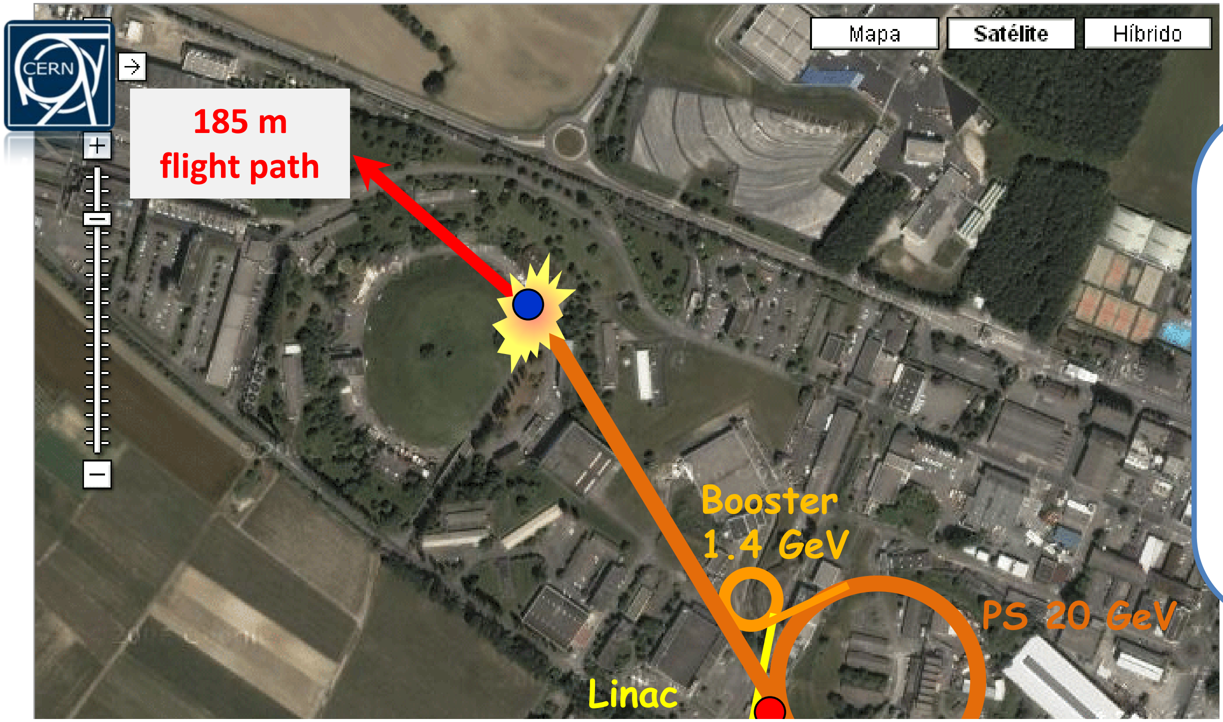


n_TOF @ CERN



Neutron Time-Of- Flight facility: **n_TOF**

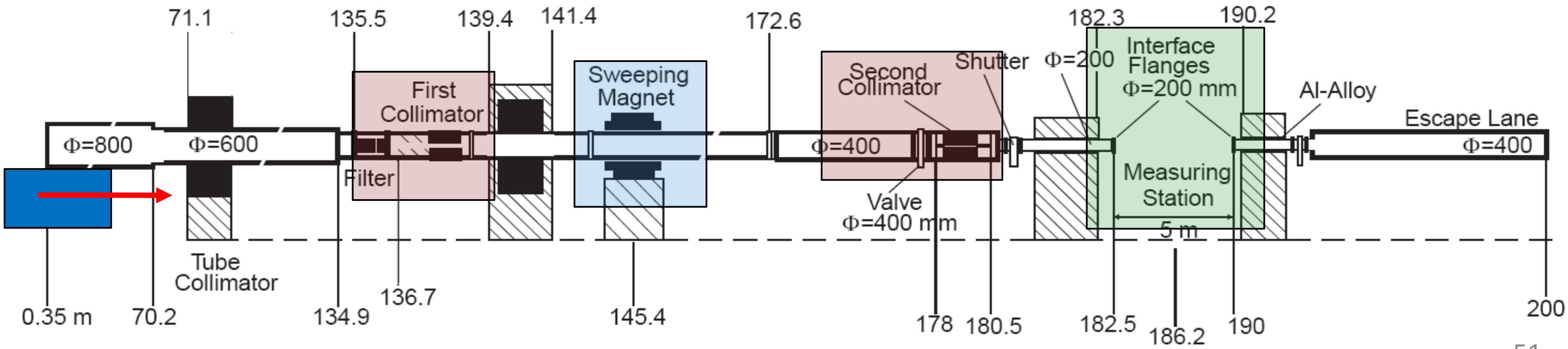
n_TOF @ CERN



n_TOF is a neutron spallation source based on PS at CERN with protons with **20 GeV/c** hitting a lead target (~360 neutrons per incoming proton).

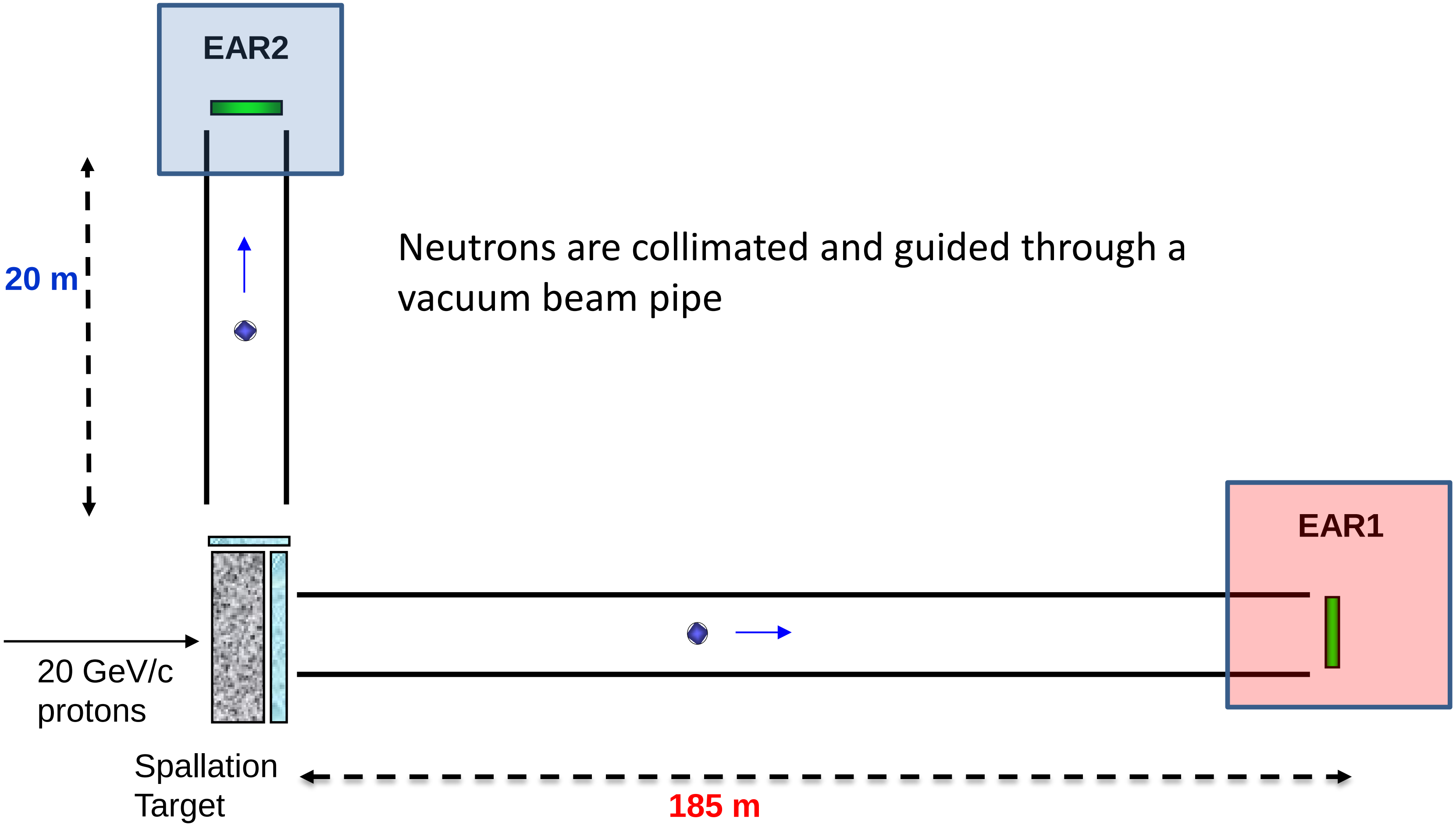
Experimental area at **185 m**.

7×10^{12} protons per burst



n_TOF @ CERN

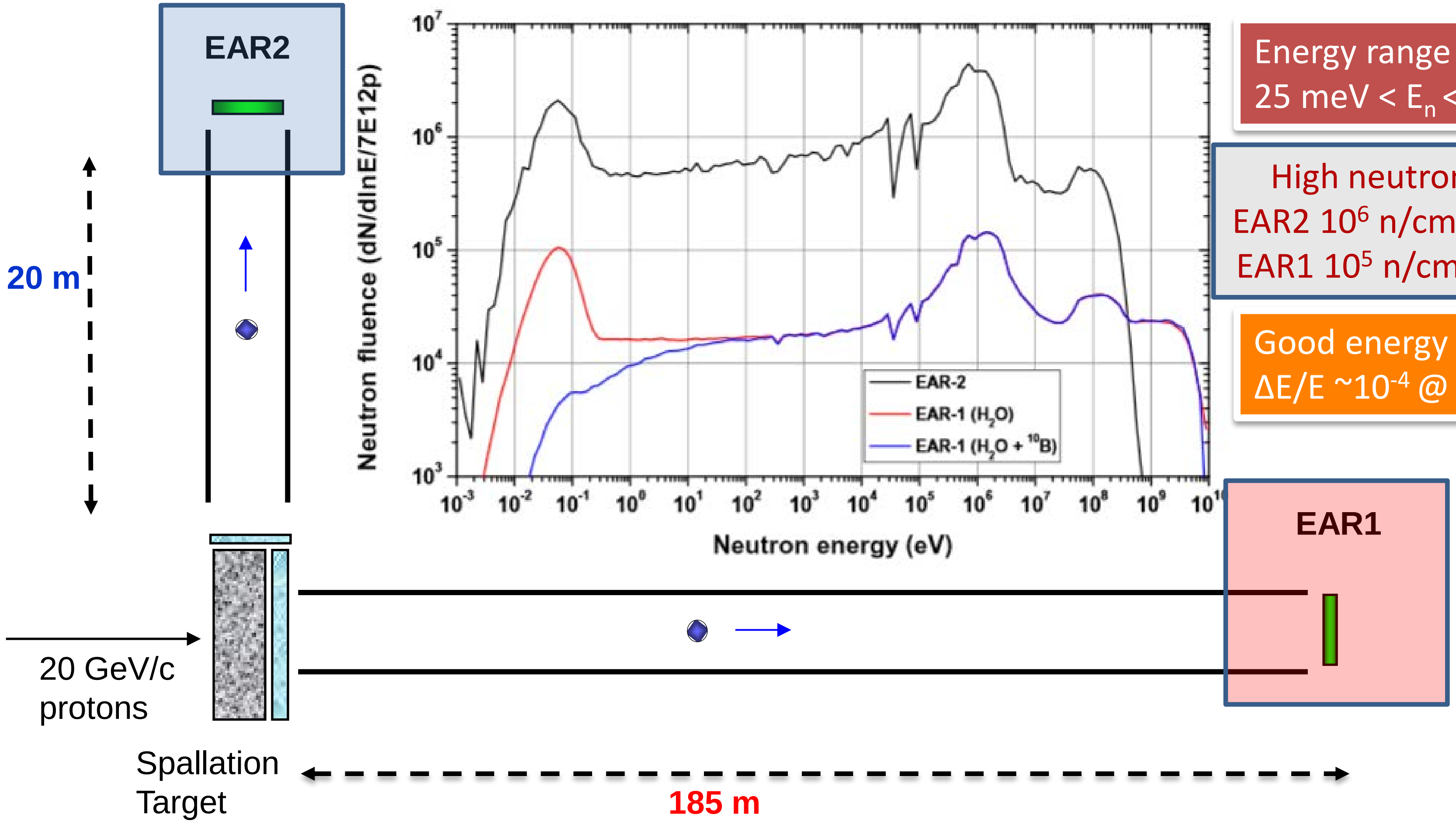
n_TOF al CERN: Spallation source (proposed by C. Rubbia in 1997).
LINE 1 (185 m) since **2000** **LINE 2** (18 m) since **2014**



Neutrons are collimated and guided through a vacuum beam pipe

n_TOF @ CERN

n_TOF al CERN: Spallation source (proposed by C. Rubbia in 1997).
LINE 1 (185 m) since **2000** **LINE 2** (18 m) since **2014**



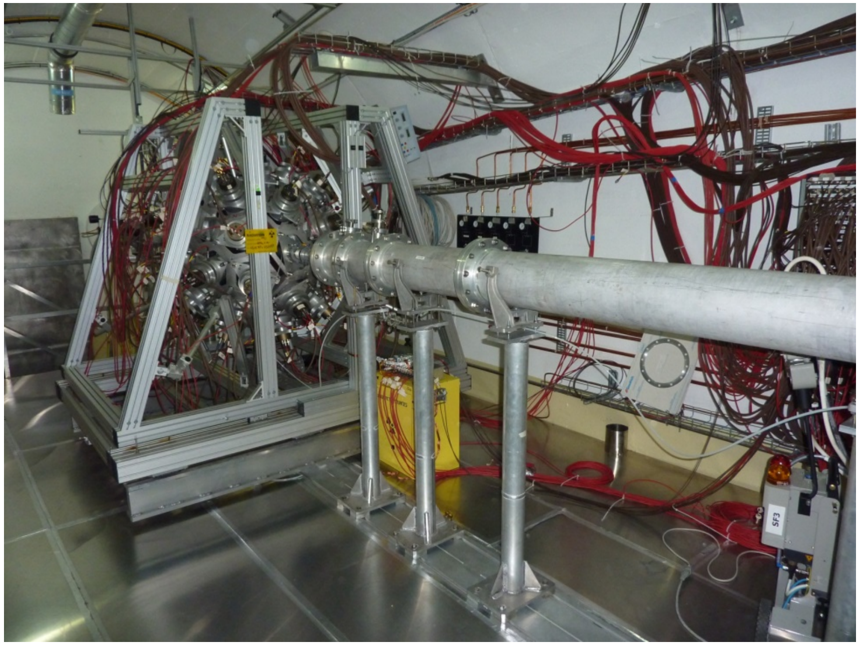
Energy range :
25 meV < E_n < 1 GeV

High neutron flux
EAR2 10^6 n/cm^2/pulse
EAR1 10^5 n/cm^2/pulse

Good energy resolution
$\Delta E/E$ ~10^{-4} @ EAR1


219
219
211


204
38

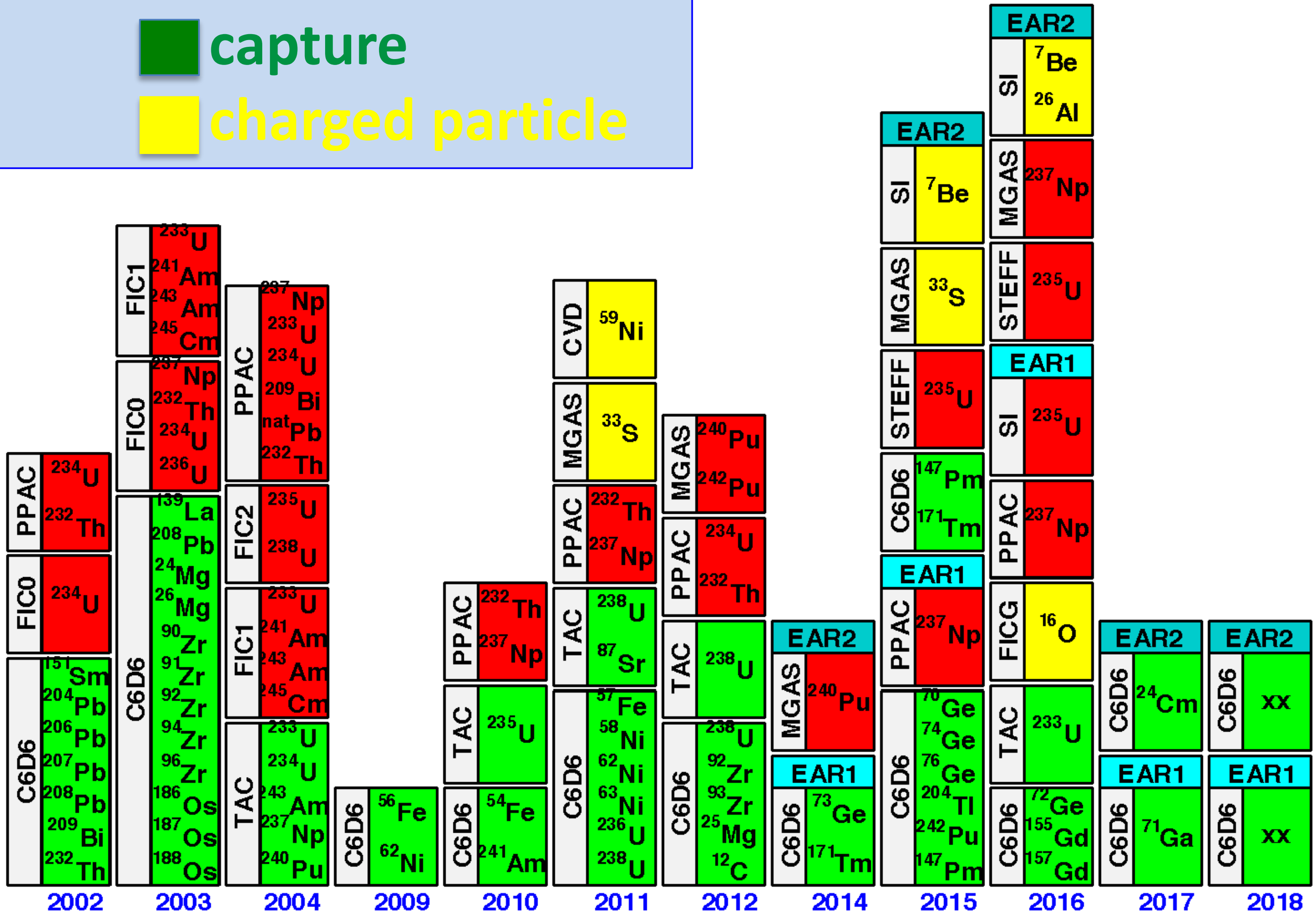

SF3

104 ISOTOPES MEASURED

🟥 fission

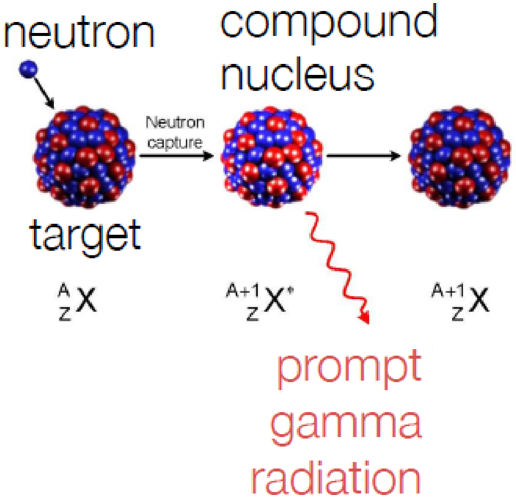
🟩 capture

🟨 charged particle



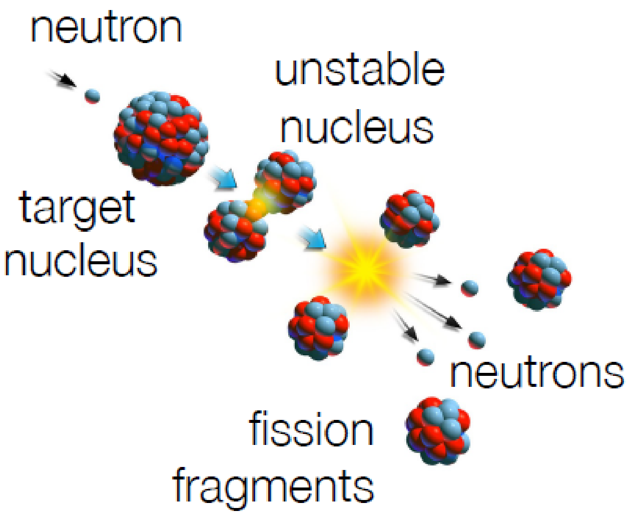
Nuclear AstroPhysics at n_TOF

Radiative capture
(n,γ)



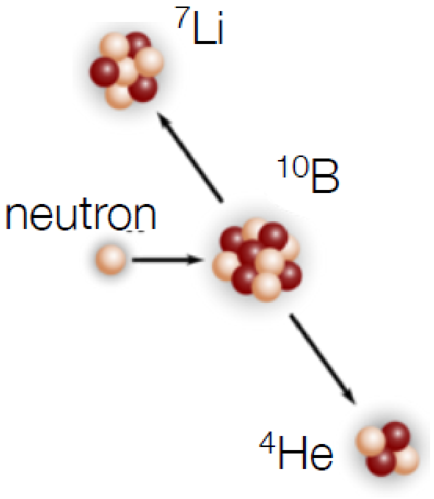
s-process

Fission
(n,f)



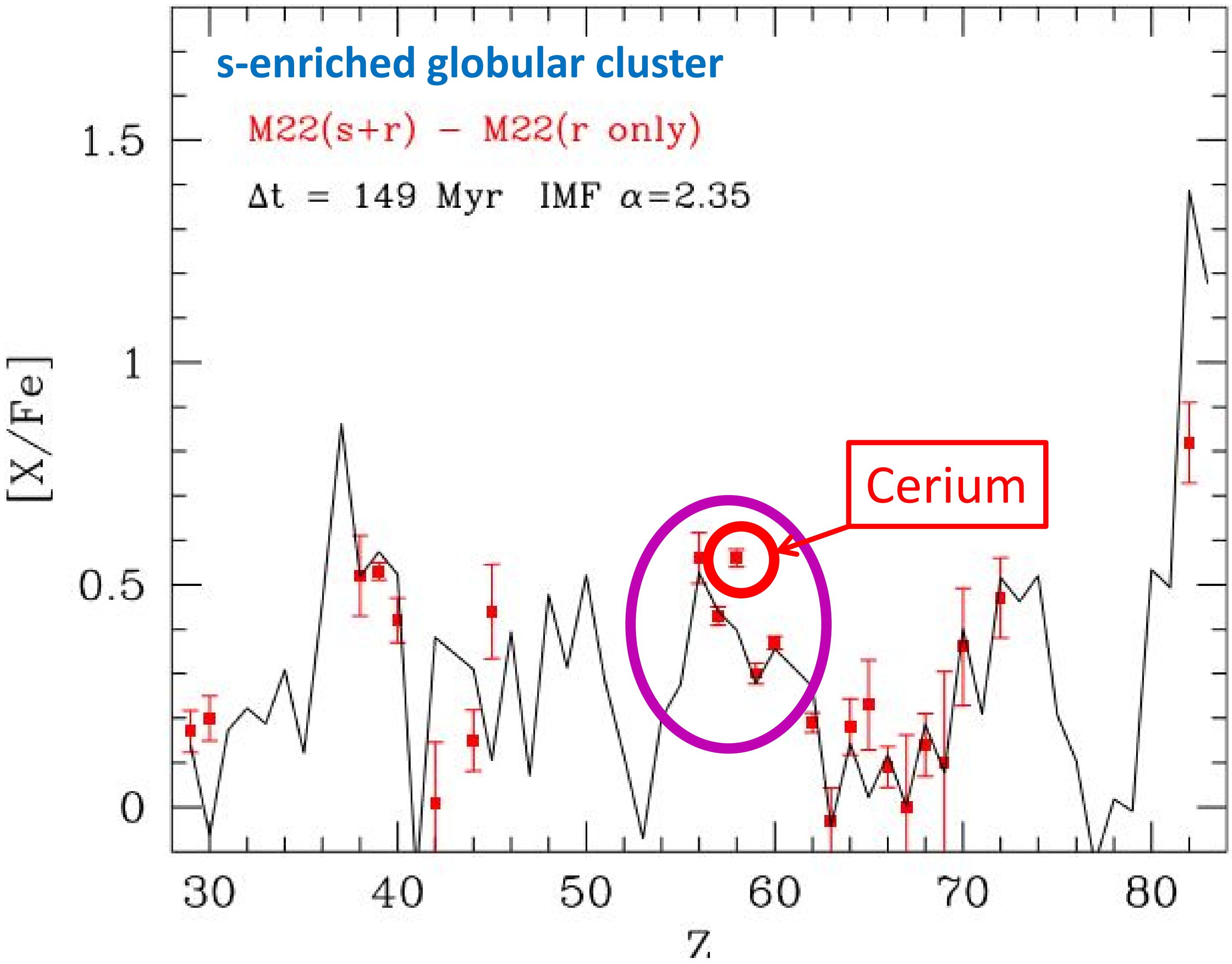
r-process

Charged particle emission
(n,cp)



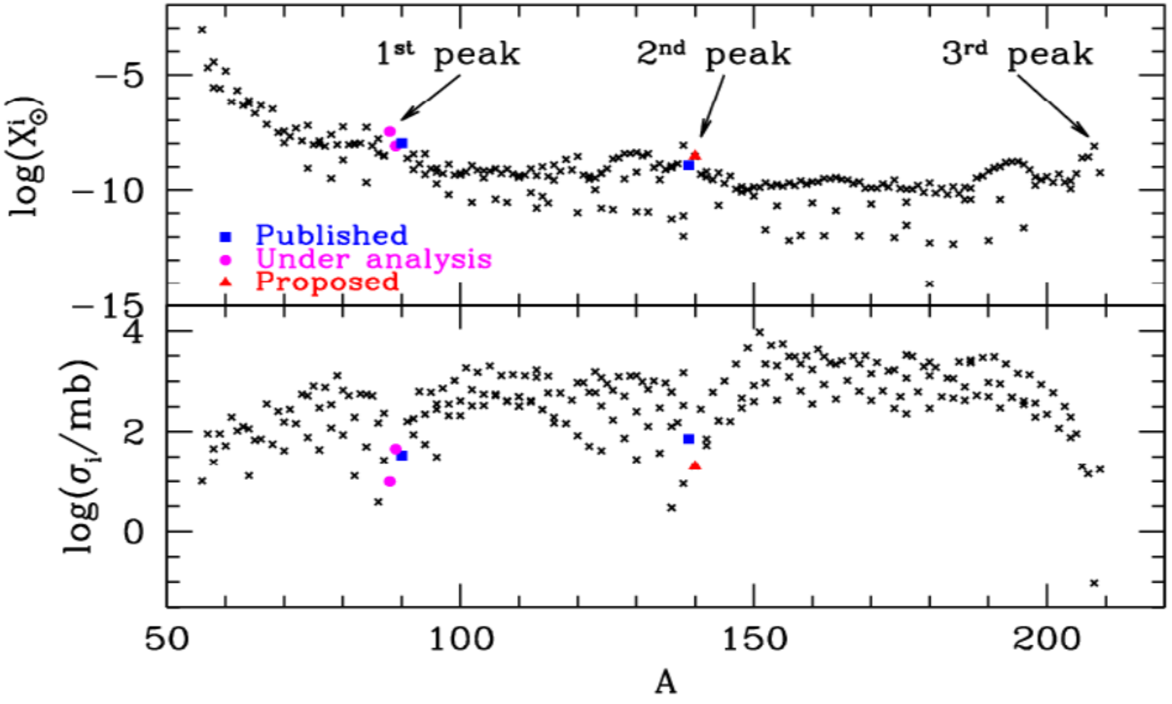
BBN

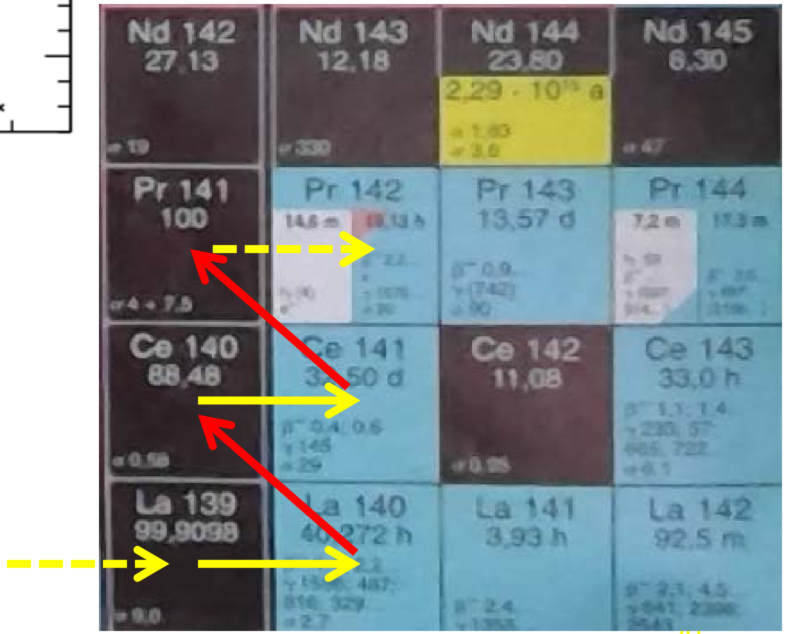
An example: the ^{140}Ce cross section



$$[X/Fe]=\log(N_X/N_{Fe})_{STAR}-\log(N_X/N_{Fe})_{SUN}$$

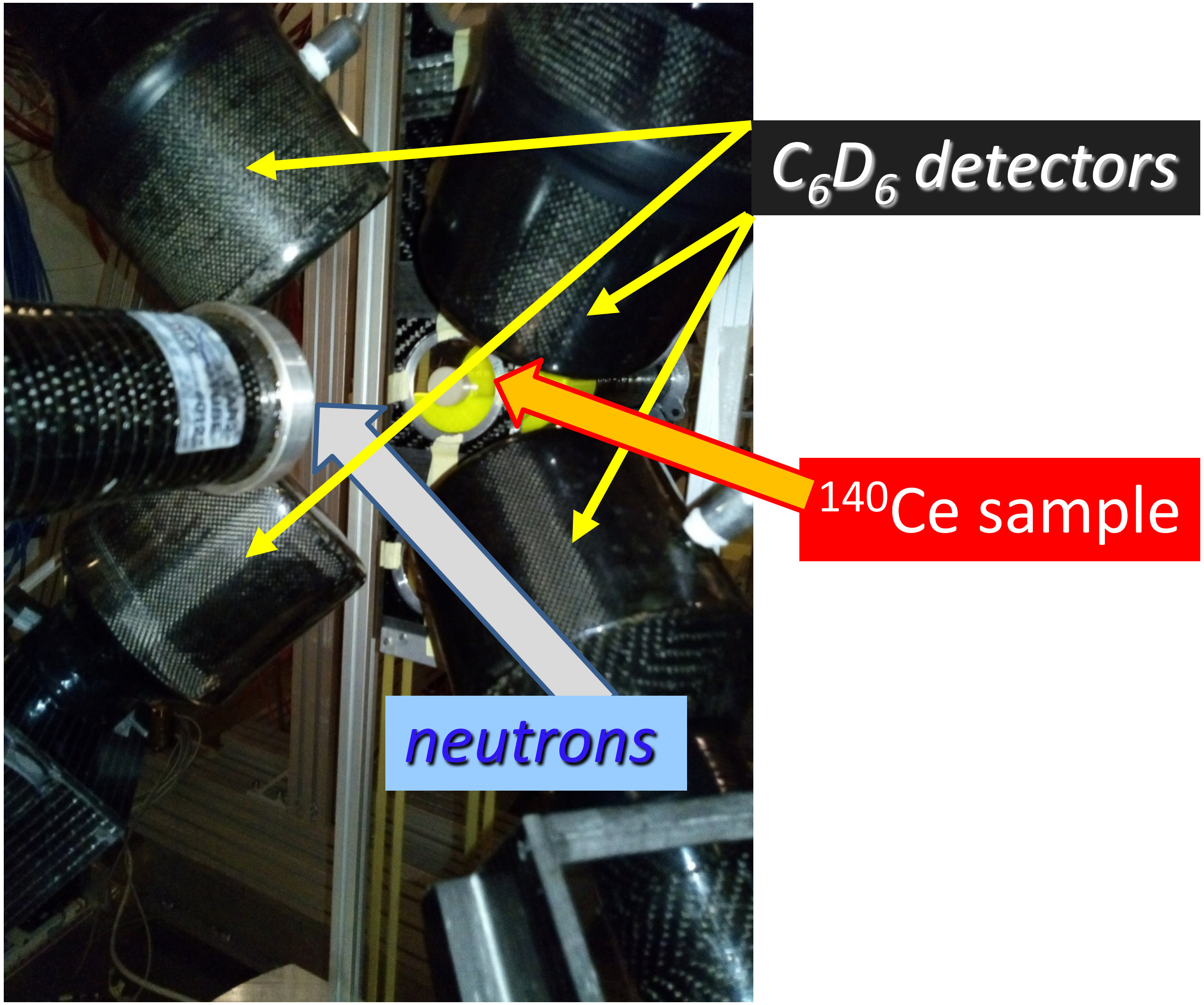
Neutron capture on ^{140}Ce





Experimental (n,γ) set-up

Liquid scintillators: low neutron sensitivity measurements



TAKE HOME MESSAGES

- **Nuclear Astrophysics is an essential ingredient to understand stellar evolution;**

- **Half of the heavy elements in the Universe are synthesized by the r-process**

- **Neutron stars mergers are the ideal site for the r-process. The questions is: are they sufficient to explain observations?**

- **Asymtptic Giant Stars and pre-explosive phases of massive stars evolution provide the other half;**

- **Experiments and theory must proceed together to provide a satisfactory picture of stellar nucleosynthesis.**