Solar Abundances for nuclei beyond Sr: s, i or r element nucleosynthesis?

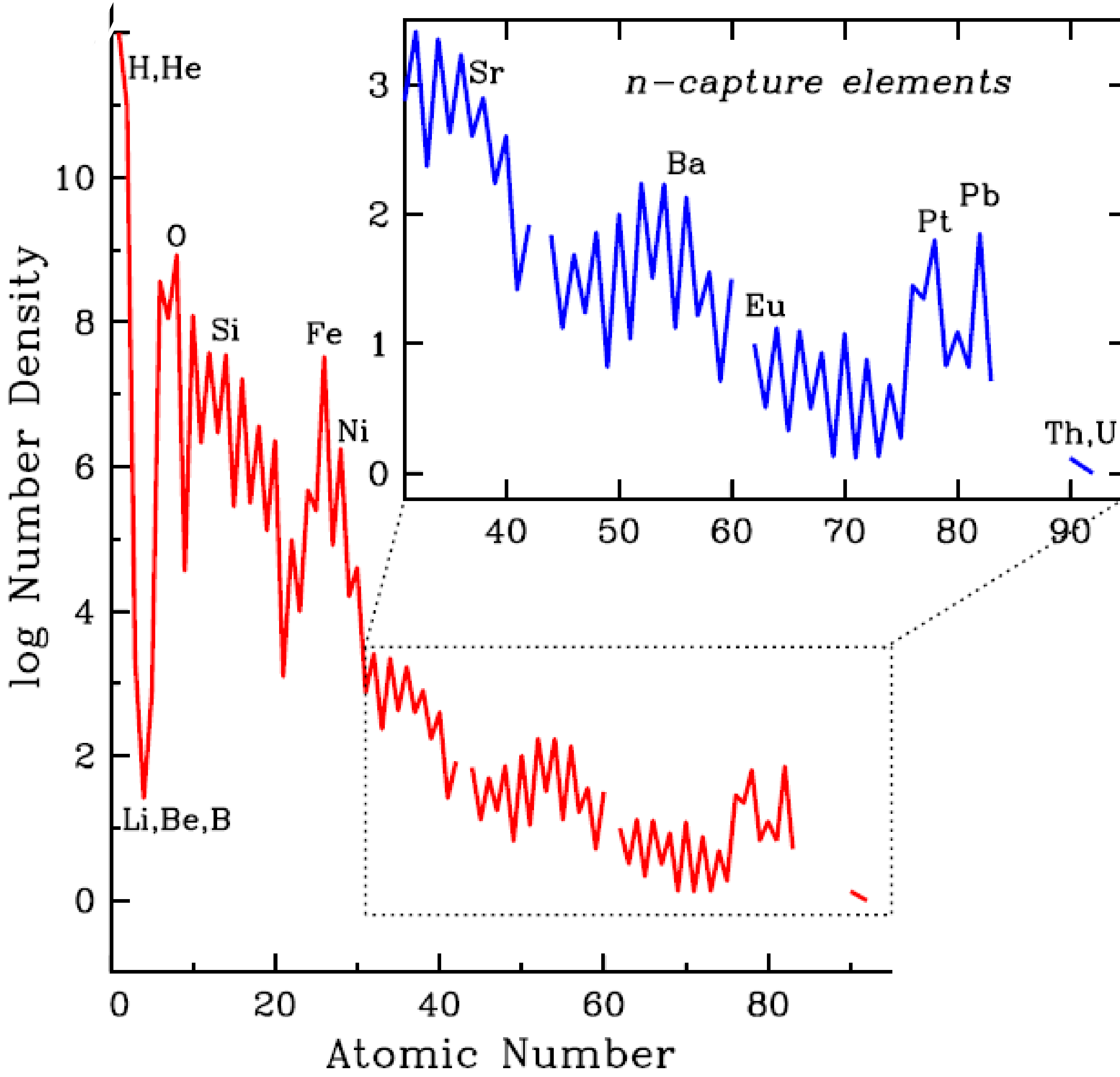
S. Palmerini and M. Busso

Solar System Abundances

s + r = 1

or

s + r + i = 1



r-process: the classical waiting-point approach

- It documents the importance of the N = 50, 82, and 126 bottlenecks of the r-matter flow
- It shows the general patterns of the different r-process scenarios

- It is completely site-independent
- It assumes:
  - chemical equilibrium between fast (n, γ) and (γ, n) within isotopic chains
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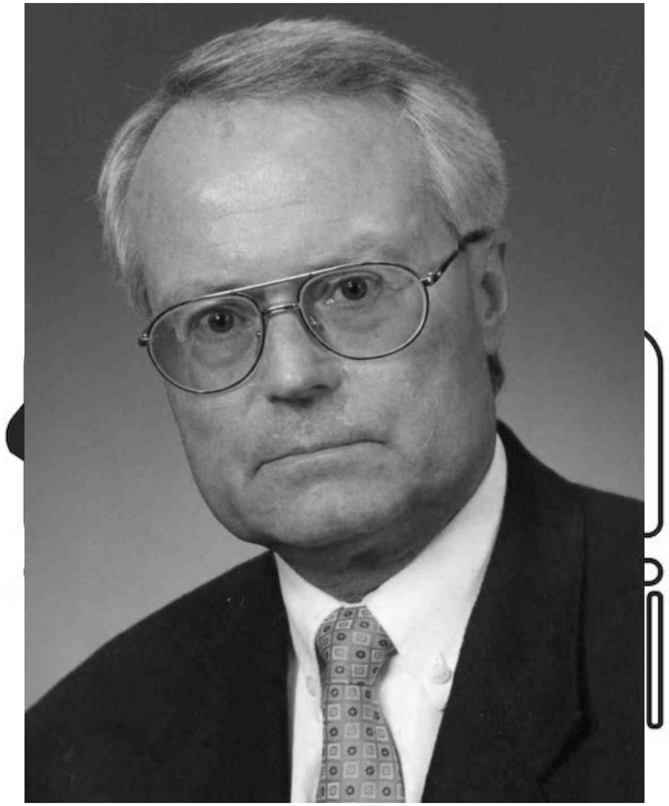

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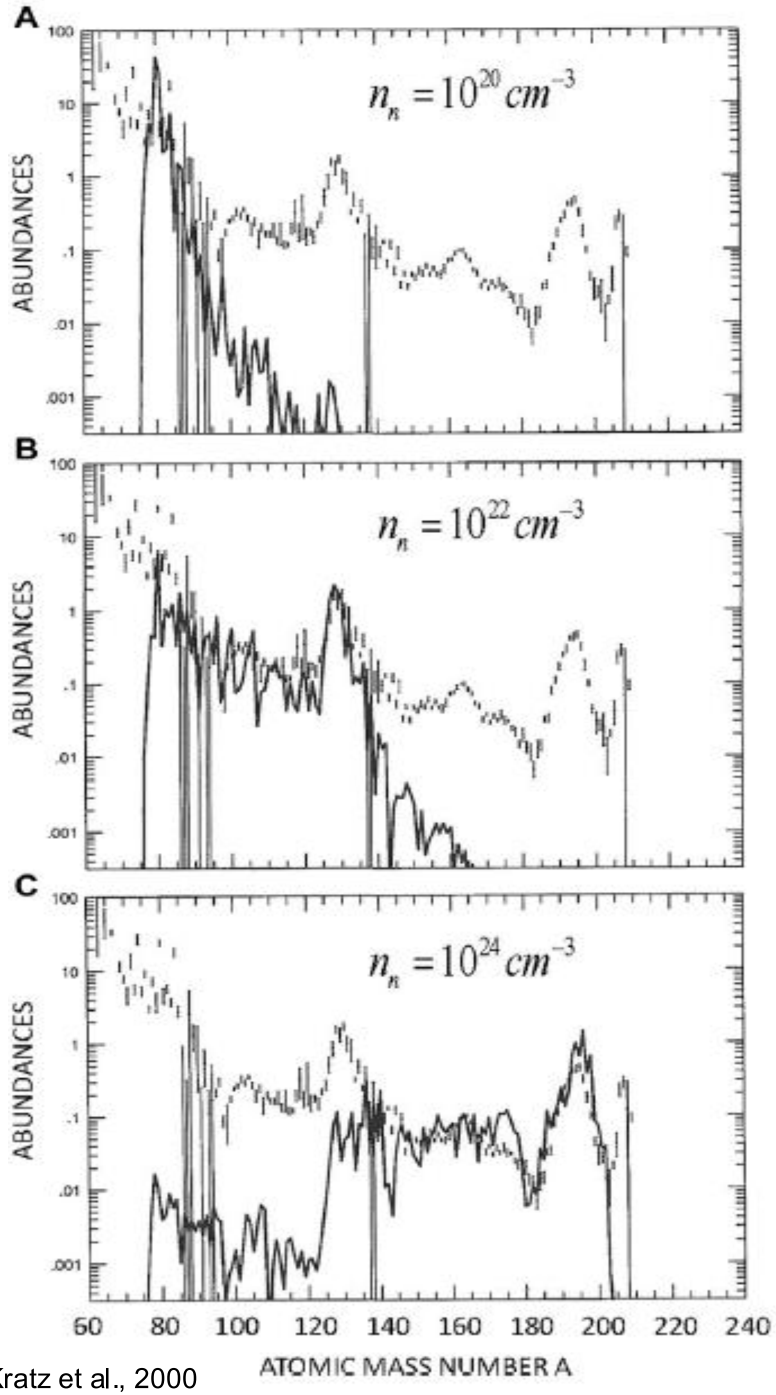


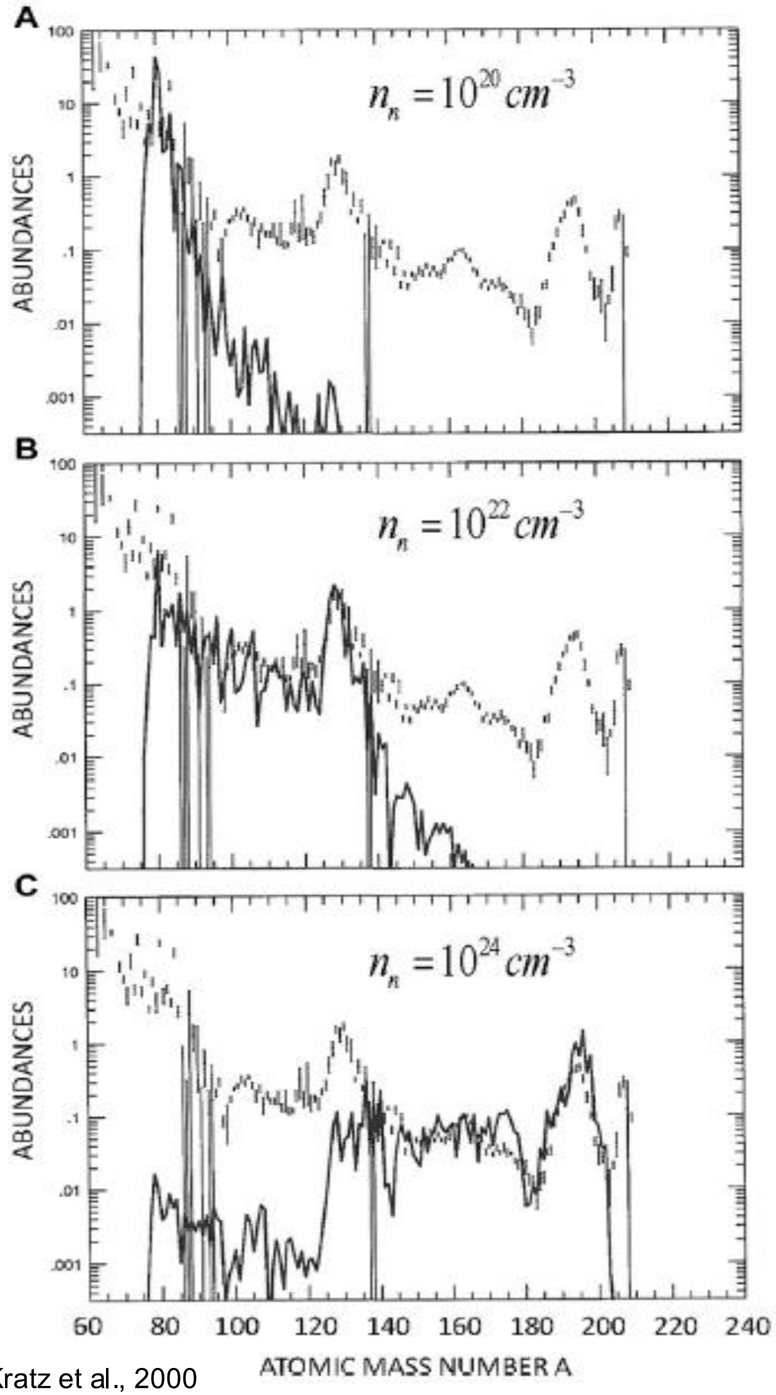
Kratz et al., 2000

r-process yields from the classical waiting-point approach and the SS abundance:

A. $n_n = 10^{20}$ cm^{-3} and $\tau_r = 1.2$ s
   - a "best fit" of the A ≃ 80 r-process peak from N ≃ 50
   - It mimics the isotopic distributions of Sr, Zr, Mo, and Ru in type X presolar SiC grains (ccSNe)

B. $n_n = 10^{22}$ cm^{-3} and $\tau_r = 1.7$ s
   - It covers the r-region up to the A ≃ 130 peak, from Er (Z = 68) to Yb (Z = 70).
   - It mimics the distribution of metal-poor, r-poor, or stars with [Eu/Fe] ≲ 0.2 (weak r-proccss)

C. $n_n = 10^{24}$ cm^{-3} and $\tau_r = 2.1$ s
   - it covers the R.E.E. reagion and the third r-process peak at A ≃ 195, up to the actinides.
   - It "mimics" the elemental abundances of the so-called r-enriched metal-poor halo stars with [Eu/Fe] ≥ + 0.8 (the main or strong r-process patter)



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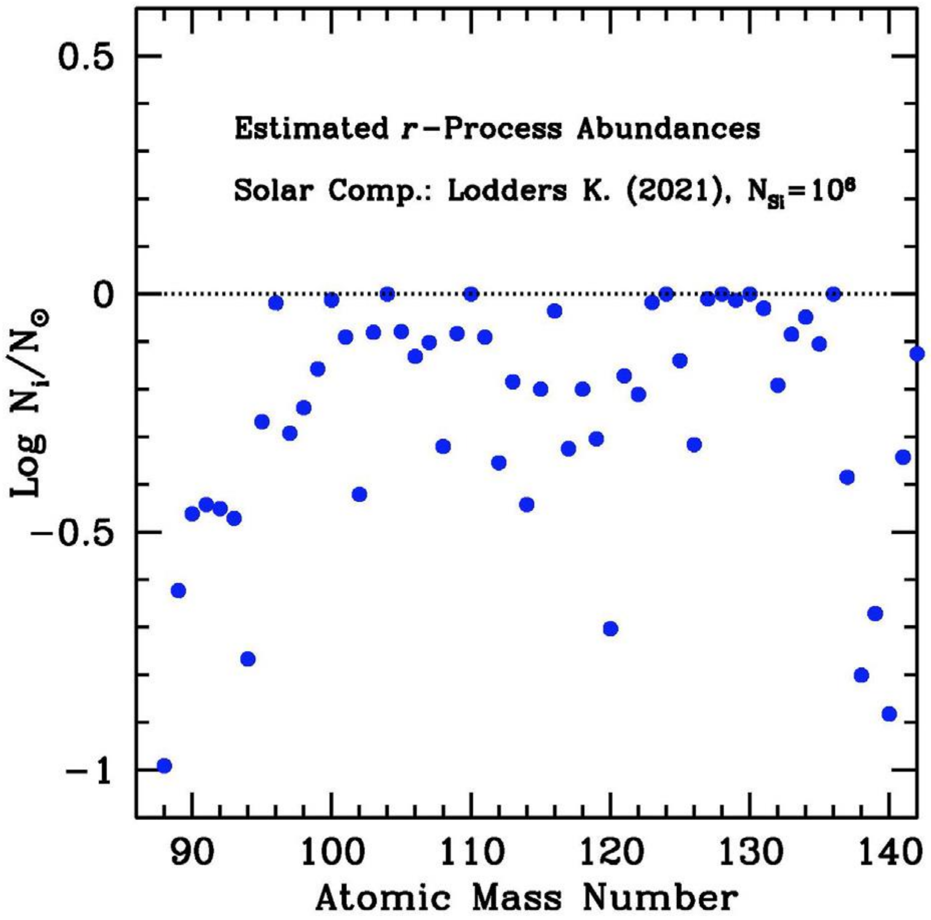
Replace n_n with Y_e to find the proper nucleosynthesis r-process environments

r-process yields from the classical waiting-point approach and the SS abundance:

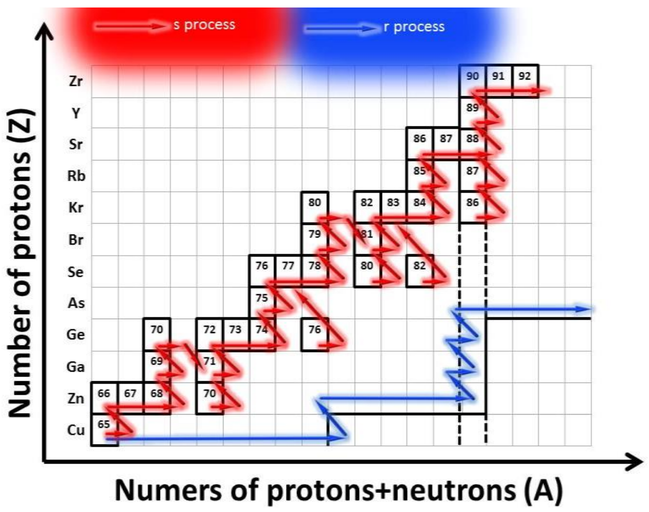


- Distribution of r-process fractional abundances as estimated by the waiting-point approximation
- the second r-peak was normalized to ^{128}Te and ^{130}Te, assumed to be r-only (by our models, their s-fractions are predicted to be ≤1%)
- The third r-peak was normalized to been normalized to the top of the peak with its r-only isotopes of Os, Ir, and Pt,

(Main) s-process ingredients

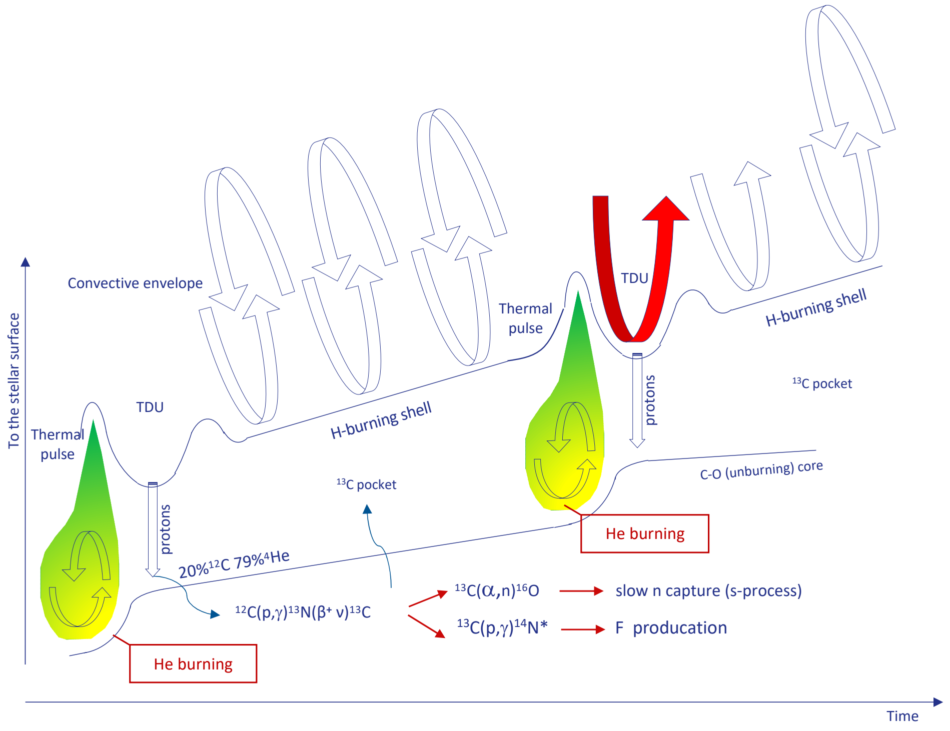
Nuclear Physics

- MACS (stellar cross sections for neutron captures)
- β-decay rates… in stellar conditions



Astrophysics

- ….
- Mixing process in stars

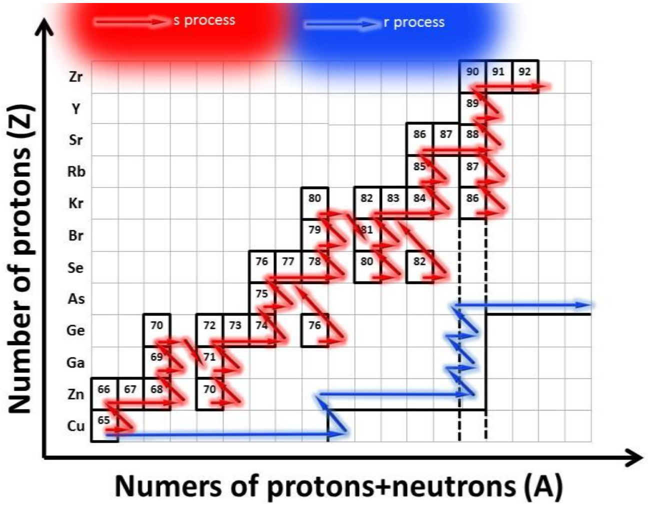


(Main) s-process ingredients

Nuclear Physics

MACs from ASTRAL and Kadonis 0.3 database

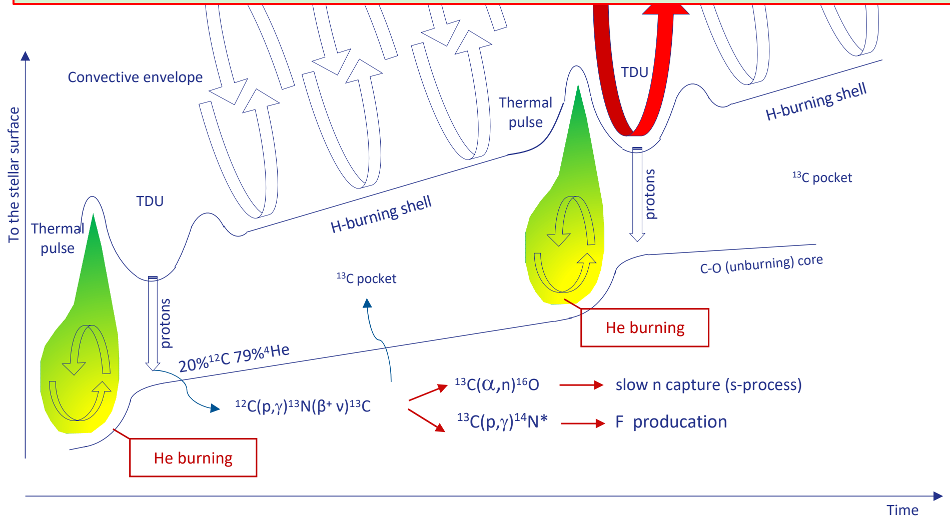
β± decays and e.c. from Takahashi and Yokoi (1987) if not by Taioli et al.



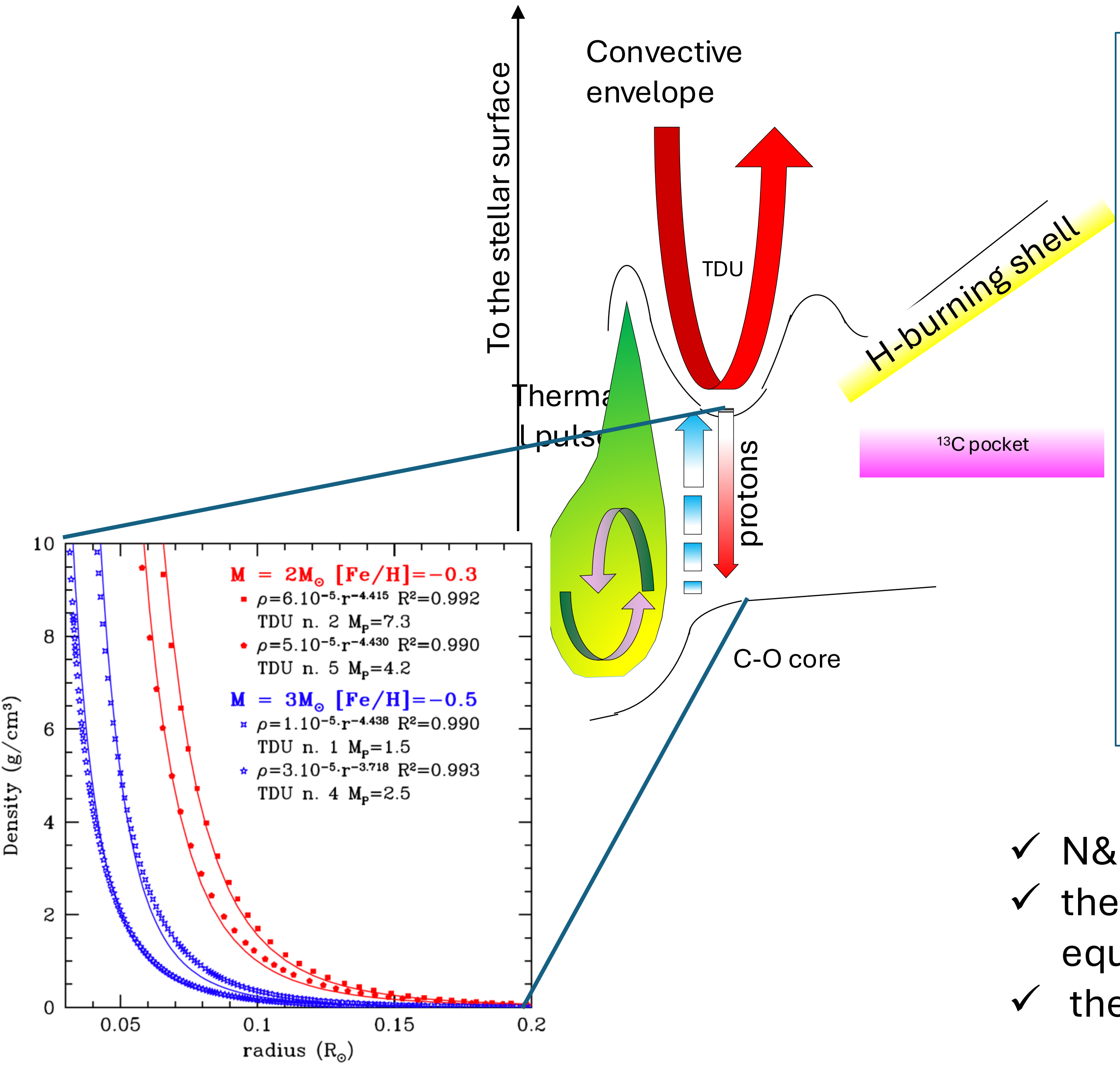
Stellar Physics

Magneto-hydrodynamic mechanism for the formation of the ^{13}C+pocket based on the 3D solutions of MHD equations.

From Nucci & Busso 2004 to Palmerini et al 2021



(MHD) ^{13}C-POCKET FORMATION:



The **density of envelope** material injected (downflow mass) into the He-layers will vary as:

$$d\rho_d/\rho_d = +\alpha dr$$

corresponding to an **exponential profile**:

$$\rho_d(r) = \rho_{d,0} e^{-\alpha(r_e - r)}$$

We multiplied for the infinitesimal **element of volume**:

$$dM_d(r) = 4\pi r^2 \rho_e e^{-\alpha(r_e - r)} dr.$$

After **integration** between envelope border and the innest layer, we obtain:

$$\Delta M_d^H \simeq 0.714 \frac{4\pi\rho_E}{\alpha} \left\{ \left[r_e^2 - \frac{2}{\alpha} r_e + \frac{2}{\alpha^2} \right] - \left[r_p^2 - \frac{2}{\alpha} r_p + \frac{2}{\alpha^2} \right] e^{-\alpha(r_e - r_p)} \right\}$$

Comparing this result with the **mass transported** by magnetic buoyancy

$$M_{up} = \dot{M} \cdot \Delta t = 4\pi r_e^2 \rho_e v_e f_1 f_2 \Delta t$$

we obtain the **amount of proton injested** in the He-rich region for the formation of the ^{13}C-pocket

- ✓ N&B conditions are satisfied;
- ✓ the exact analytical solutions of the MHD equations are held;
- ✓ the formation of ^{13}C-pocket is allowed

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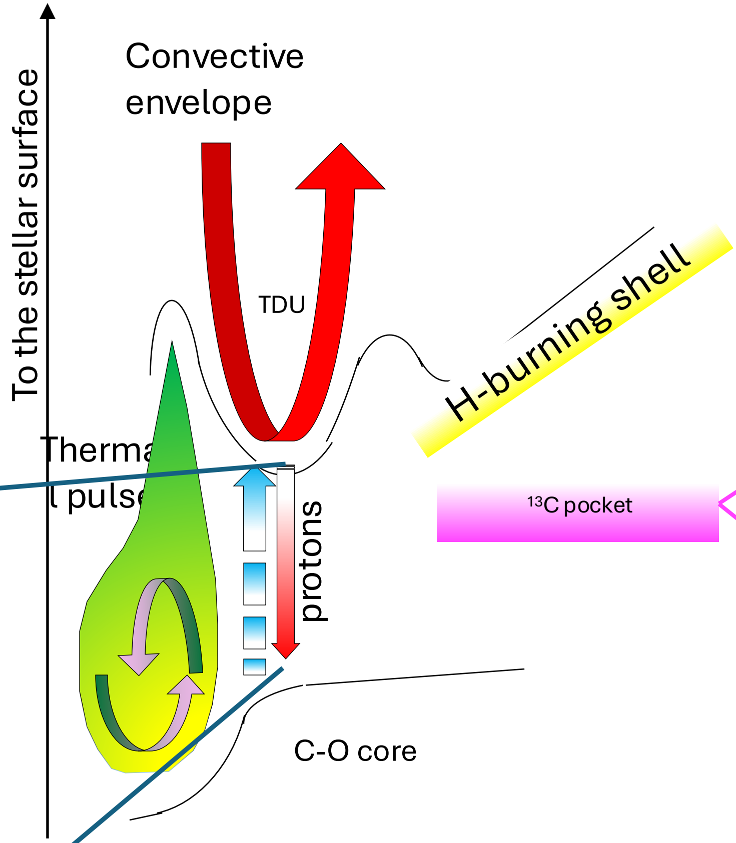
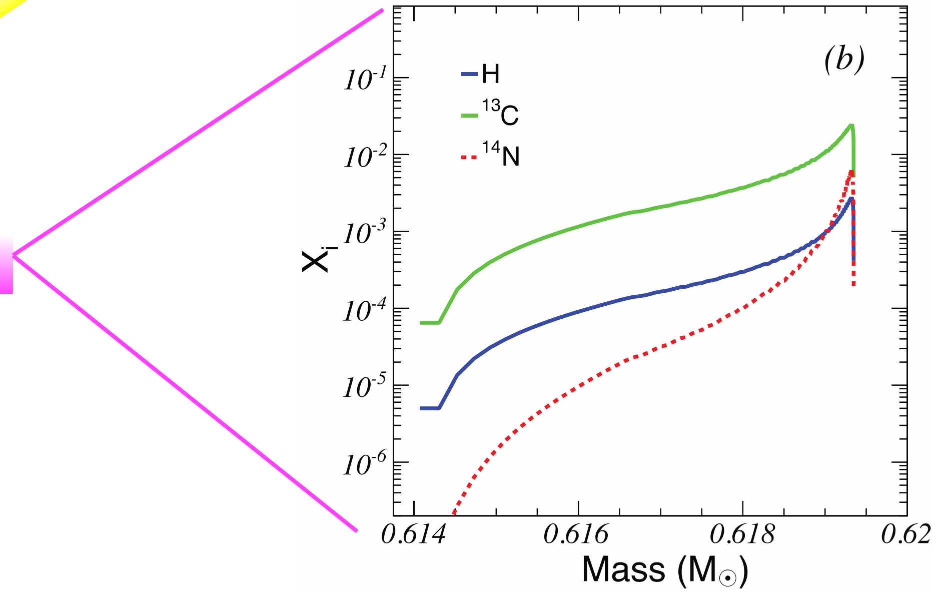
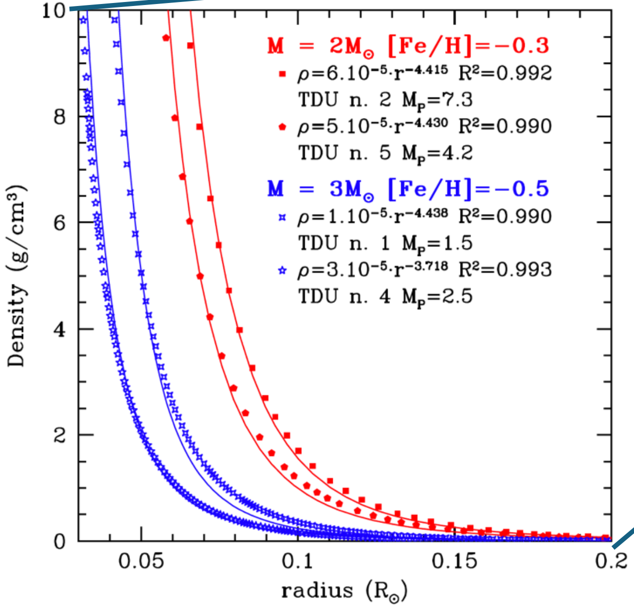


the ^{13}C-reservoir formed is an almost "flat" pocket of about
$5 \times 10^{-3}\ M_\odot$





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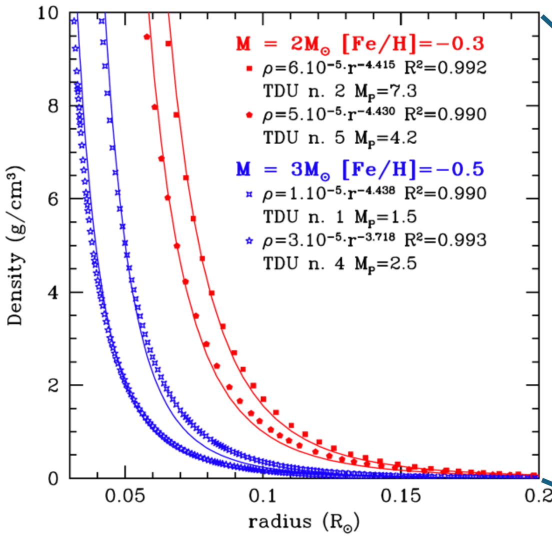

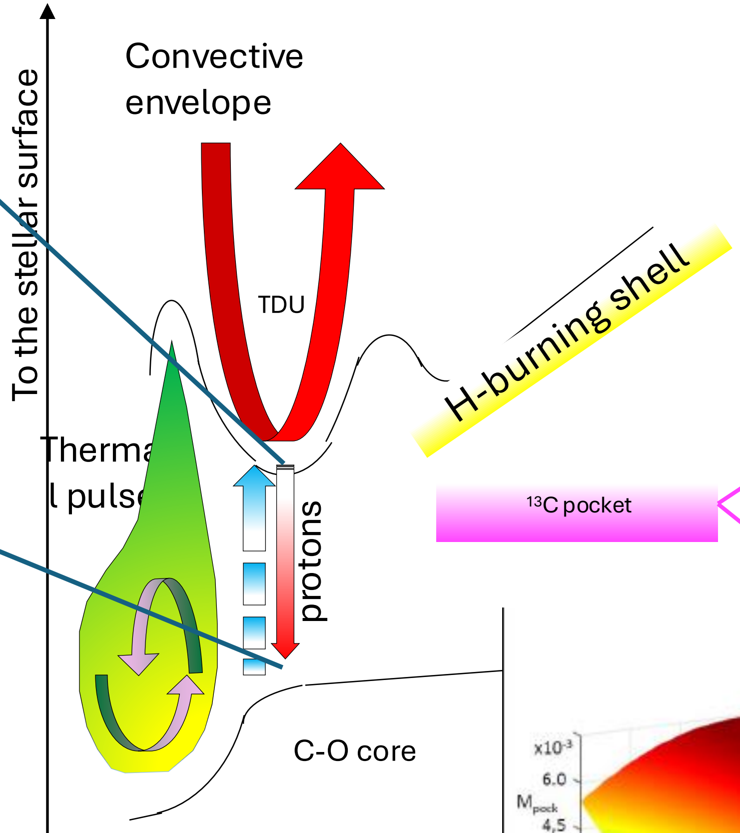

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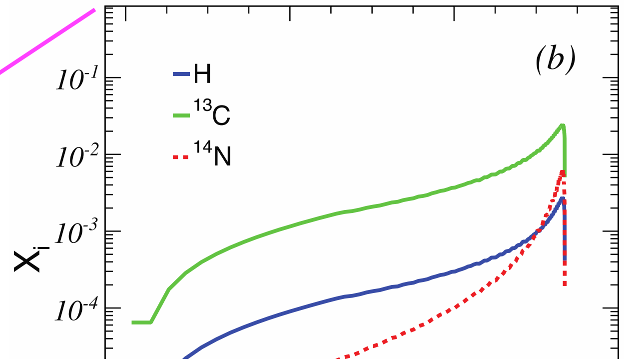
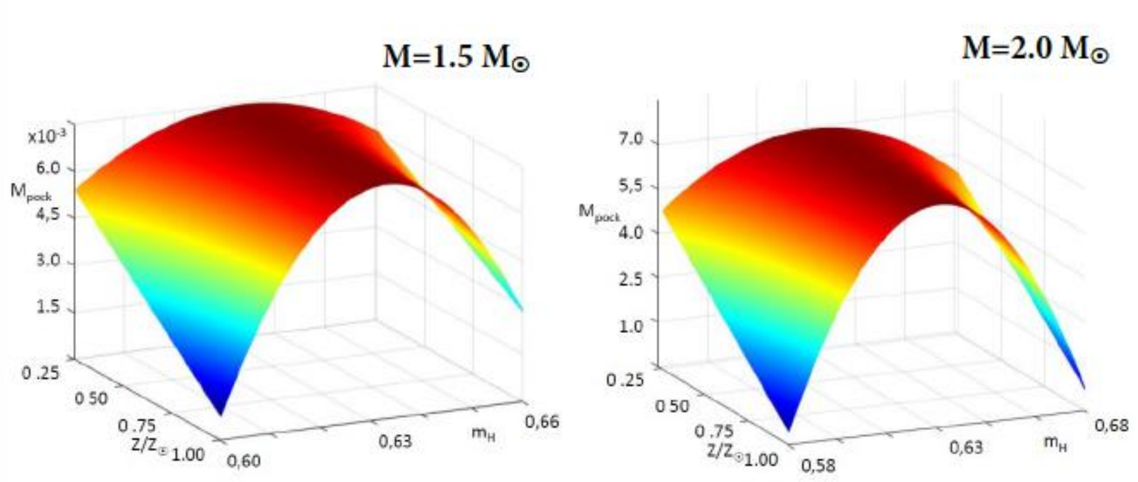


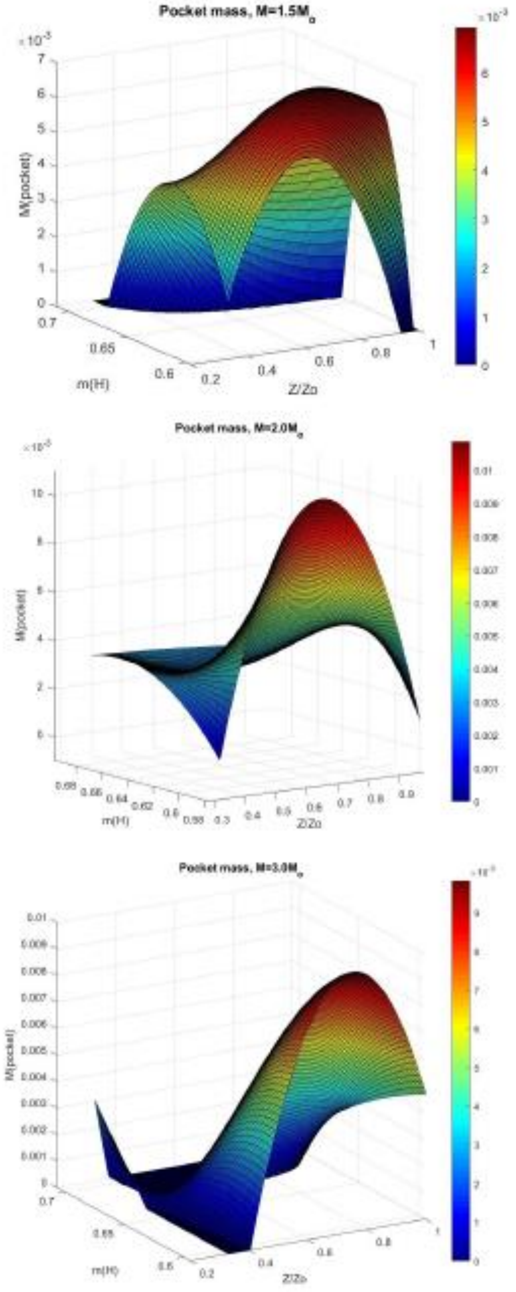


Busso et al. ApJ 908, 55 (2020)

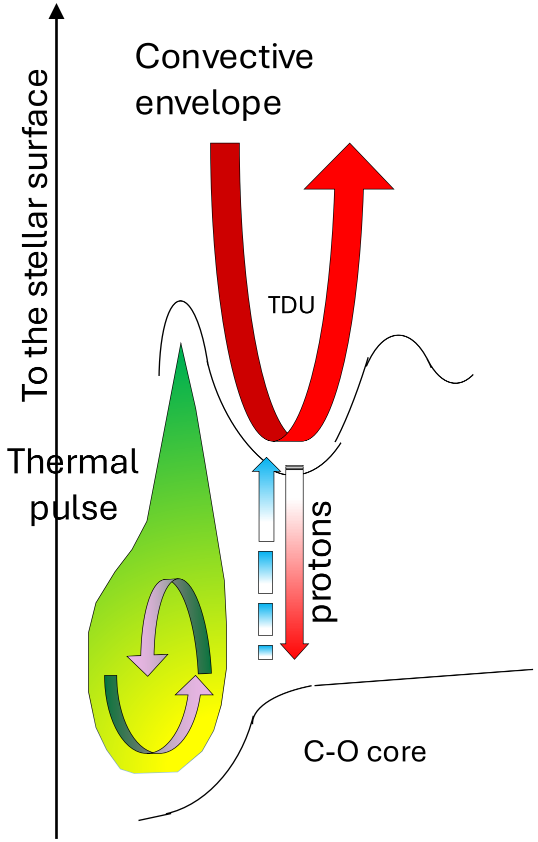
Table 2. General characteristics of the TDU phases where the conditions for forming ^{13}C pockets are found, according to the criteria exposed in the text.

Number of TDU episodes and their Maximum/minimum extension in mass									
	M = 1.5M$_\odot$			M = 2.0M$_\odot$			M = 3.0M$_\odot$		
[Fe/H]	N	ΔM_{min}	ΔM_{Max}	N	ΔM_{min}	ΔM_{Max}	N	ΔM_{min}	ΔM_{Max}
-0.50	10	$3.6\cdot10^{-4}$	$1.5\cdot10^{-3}$	11	$1.5\cdot10^{-3}$	$3.6\cdot10^{-3}$	13	$2.4\cdot10^{-4}$	$3.7\cdot10^{-3}$
-0.30	7	$7.2\cdot10^{-4}$	$1.5\cdot10^{-3}$	11	$2.2\cdot10^{-5}$	$1.7\cdot10^{-3}$	12	$1.0\cdot10^{-4}$	$2.2\cdot10^{-3}$
0.00	7	$1.5\cdot10^{-4}$	$7.1\cdot10^{-4}$	9	$3.8\cdot10^{-4}$	$1.6\cdot10^{-3}$	17	$1.0\cdot10^{-4}$	$2.1\cdot10^{-3}$

FINGER-PRINTS OF THE MHD ^{13}C POCKET

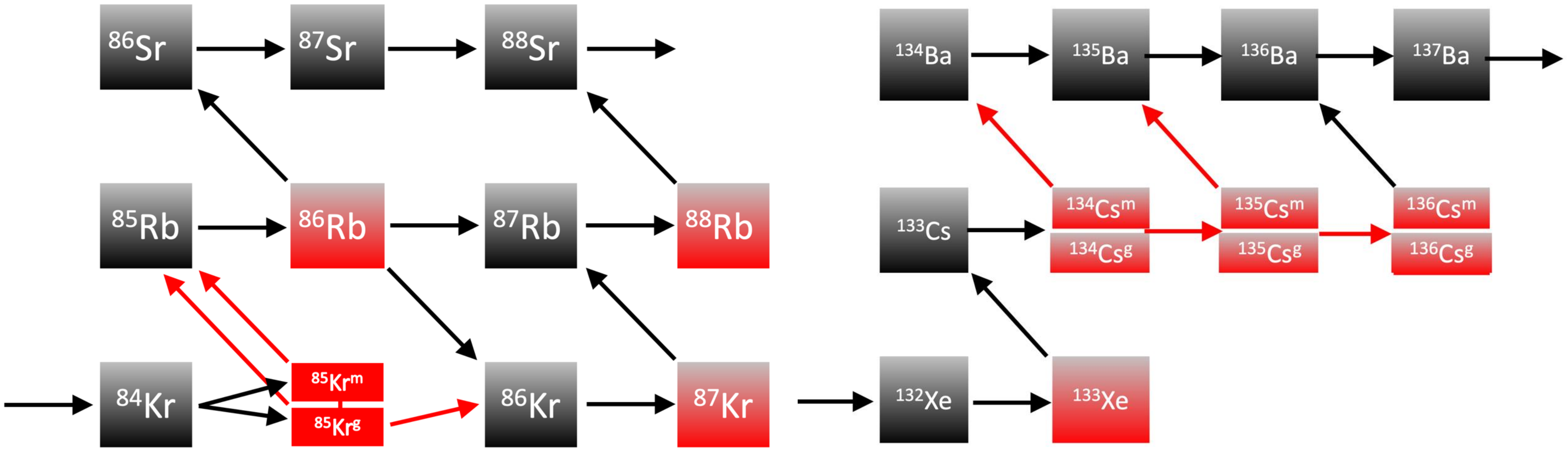


- A stongly reduced synthesis of fresh ^{19}F from nitrogen => F abundances predicted as a function of metallicity in agreement with observations (see Vescovi et al 2021, and the poster by Brady)
- A very limited action of the neutron poisons
- A reduced ^{14}N concentration also implies a reduced formation of ^{22}Ne.



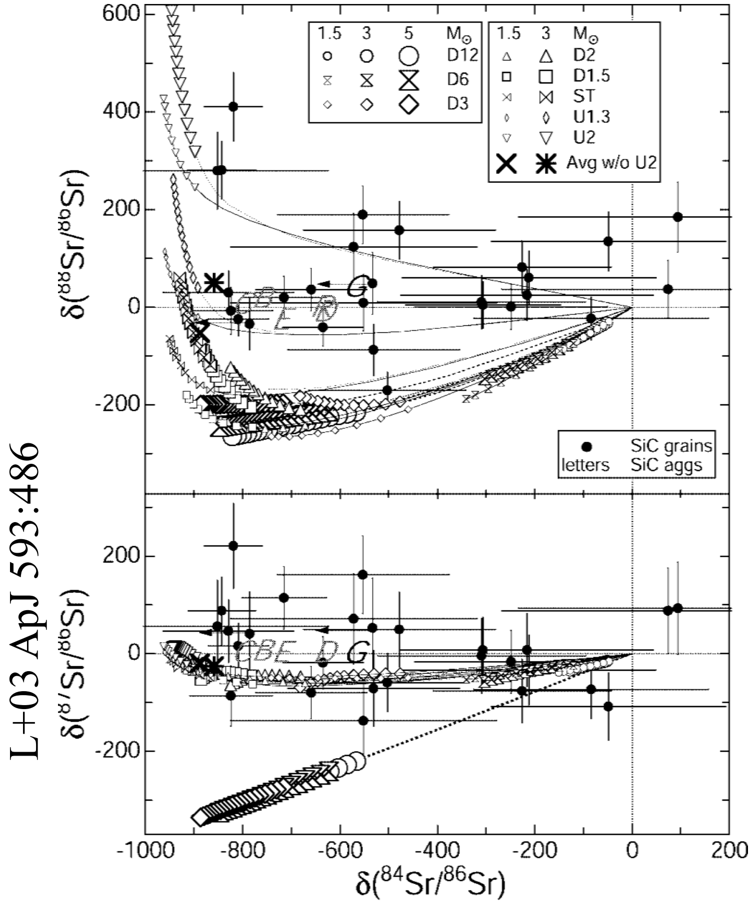
BRANCHING POINTS as BENCHMARCK FOR THE S-PROCESS…IN PRESOLAR GRAINS

…around **N = 50** …. around **N = 82**

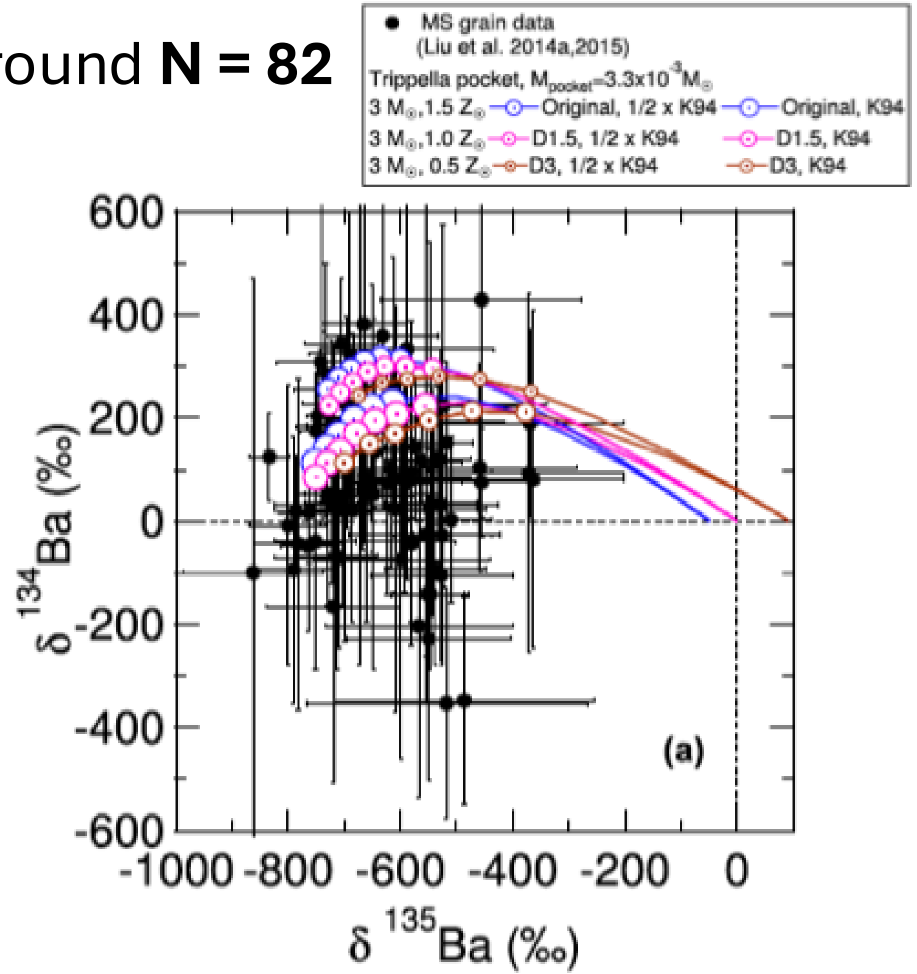


BRANCHING POINTS as BENCHMARCK FOR THE S-PROCESS…IN PRESOLAR GRAINS

…around **N = 50**

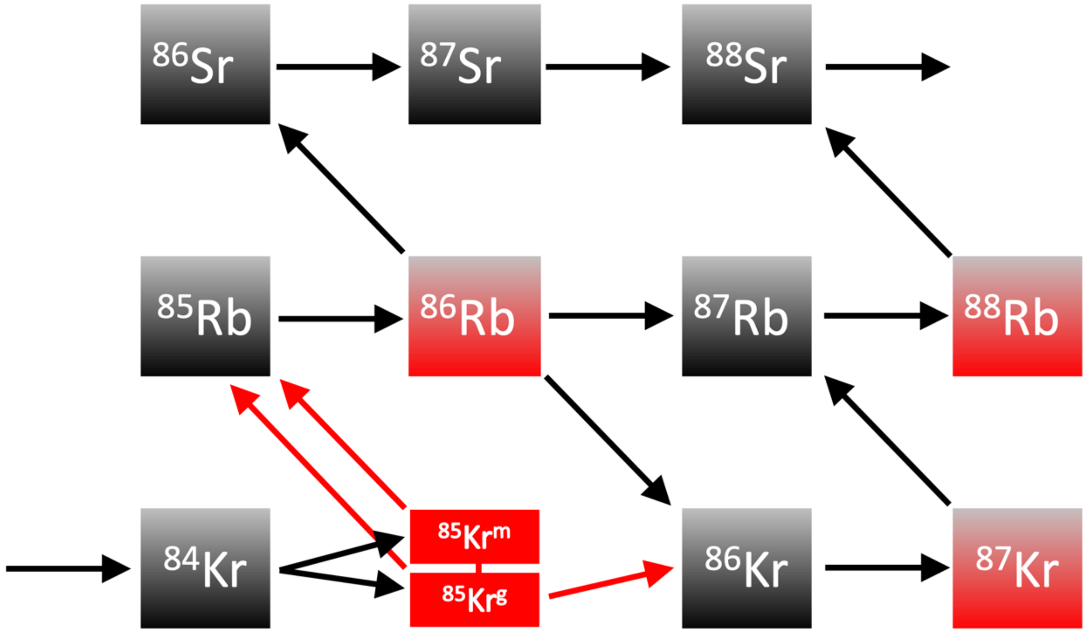


…. around **N = 82**



BRANCHING POINTS as BENCHMARCK FOR THE S-PROCESS…IN PRESOLAR GRAINS

…around **N = 50**; the ^{85}Kr branching is highlighted by the red arrows.



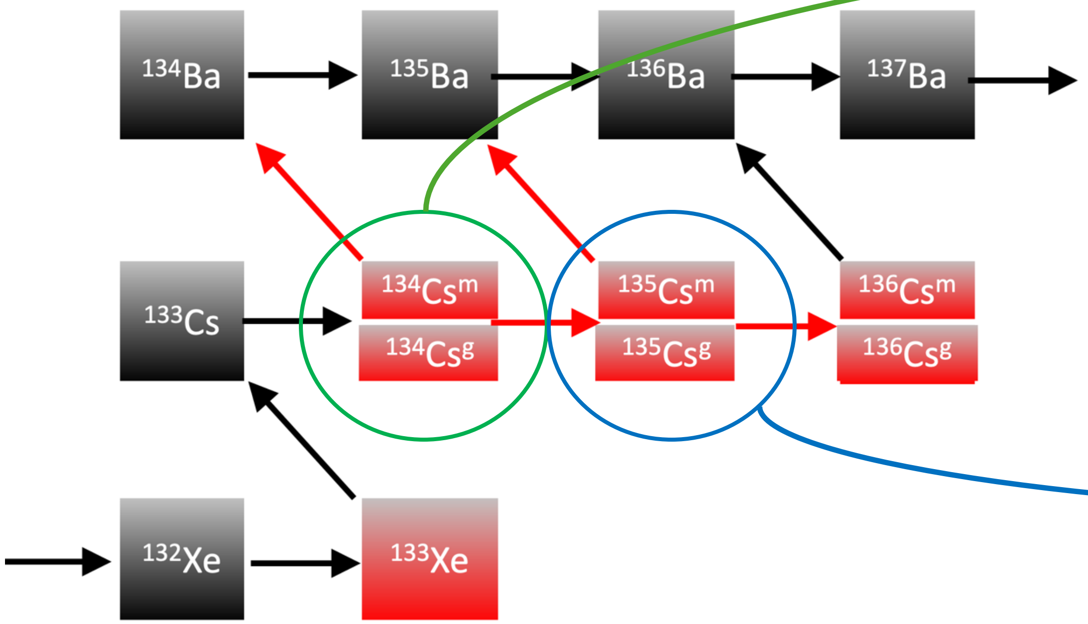
- ^{85}Kr^{m} (305 keV) $t_{1/2} \approx$4.5h
- ^{85}Kr^{g} $t_{1/2} \approx$10.5 yr

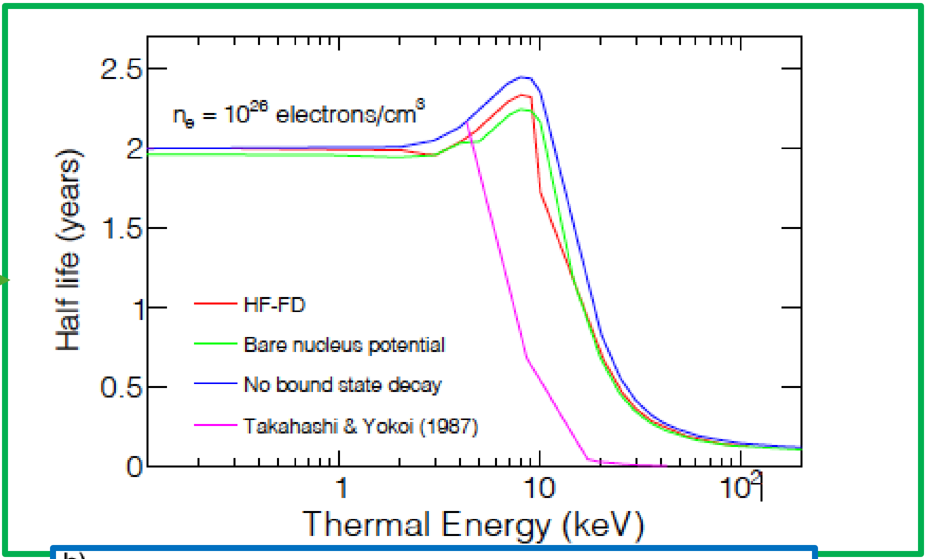
- $\sigma_{(n,\gamma)}$(^{84}Kr) = 33.1 mb @ 30keV
- $\sigma_{(n,\gamma)}$(^{85}Kr) = 73 $\pm$ 34 mb @ 30keV

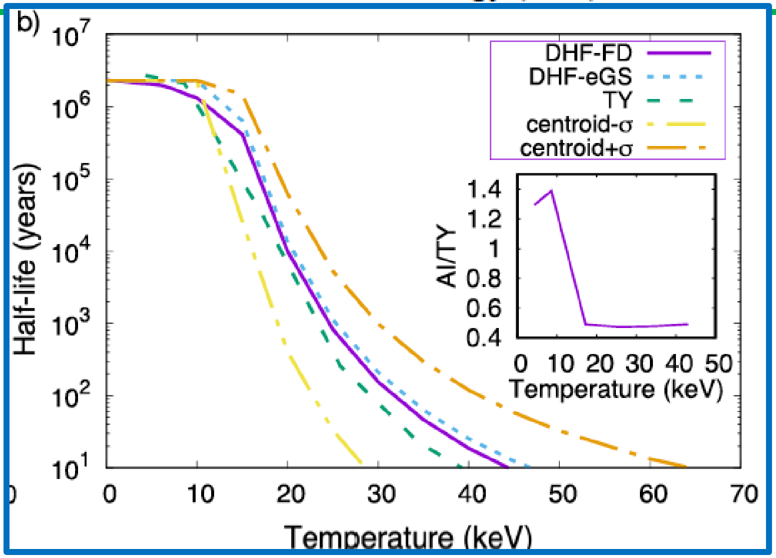
- Kadonis 1:
  - ^{85}Kr b.r. = 0. 6, (60% of the n flux to the ^{85}Kr^{m})
- Kadonis 0.3:
  - ^{85}Kr b.r. = 0.4, (40% of the n flux to the ^{85}Kr^{m}) K0.3 -> more ^{88}Sr
  - Same effect would occur with the ^{84}Kr(n,γ) in K1 and a «new» ^{85}Kr^{m} decay rate

BRANCHING POINTS as BENCHMARCK FOR THE S-PROCESS…

…. around **N = 82**, the ^{134}Cs and ^{135}Cs branching points are highlighted by red arrows.



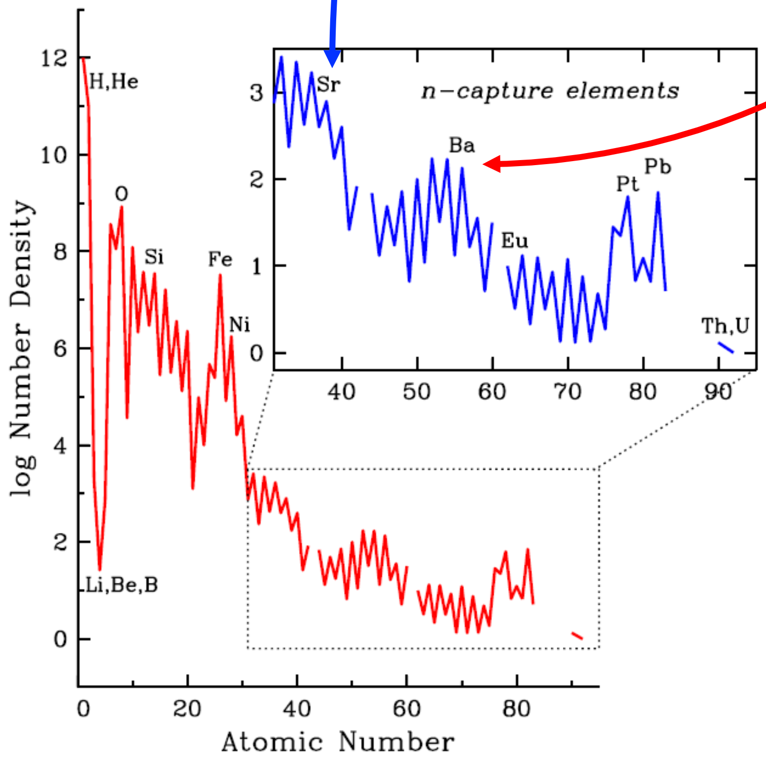




- ^{134}Cs (β^-) $t_{1/2} \approx 2$ yr (lab.)
- @ 3 10^8K the decay rate of ^{134}Cs is enhanced by a factor of about 200. (TY 1987)

from DHF calculations… T+22 ApJ 933:158

LIGHT S AND *HEAVY S* RESULTS



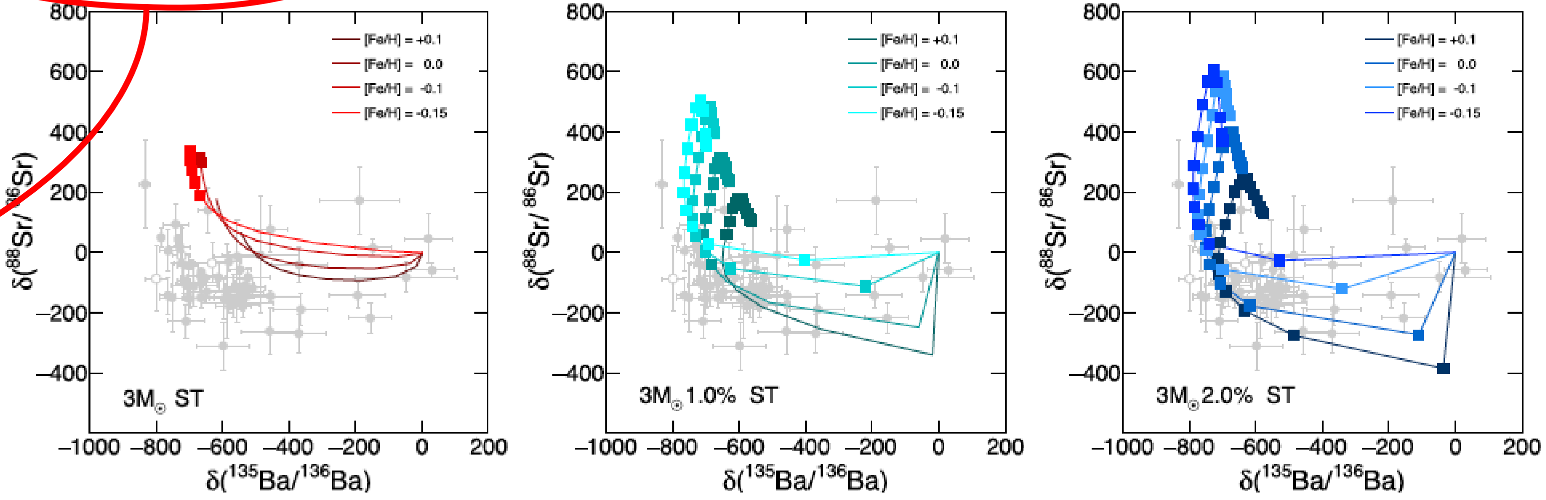


Figure 12. Same as Figure 11, but for models of 3 $M_{\odot}$ stars.

Palmerini et al. ApJ 2021

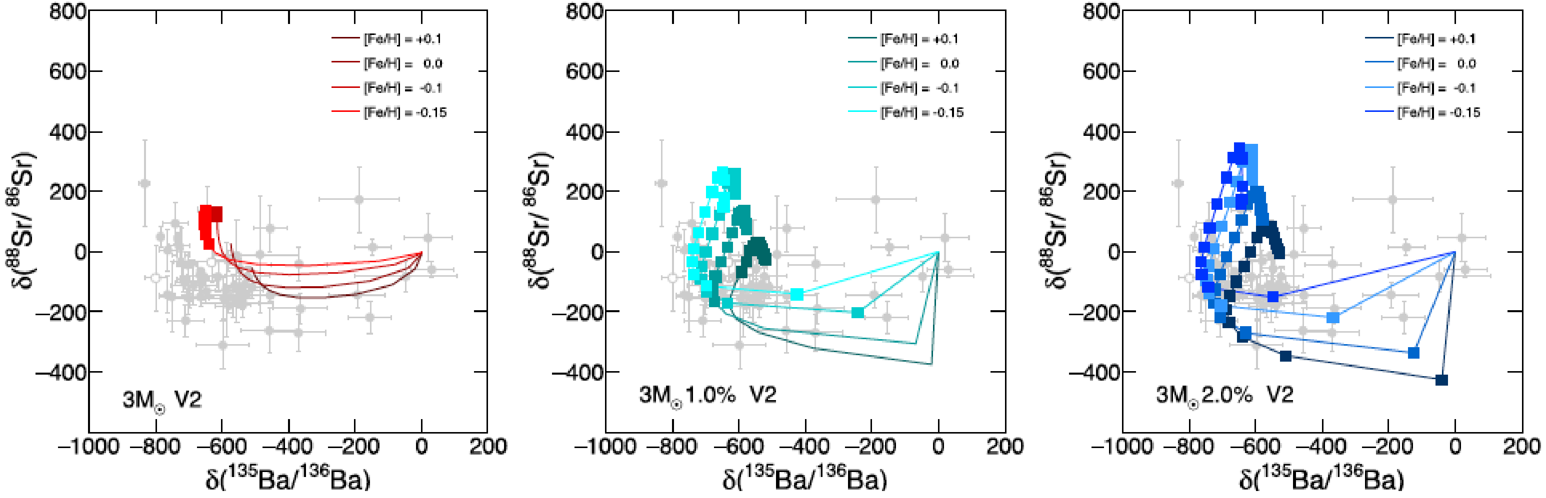
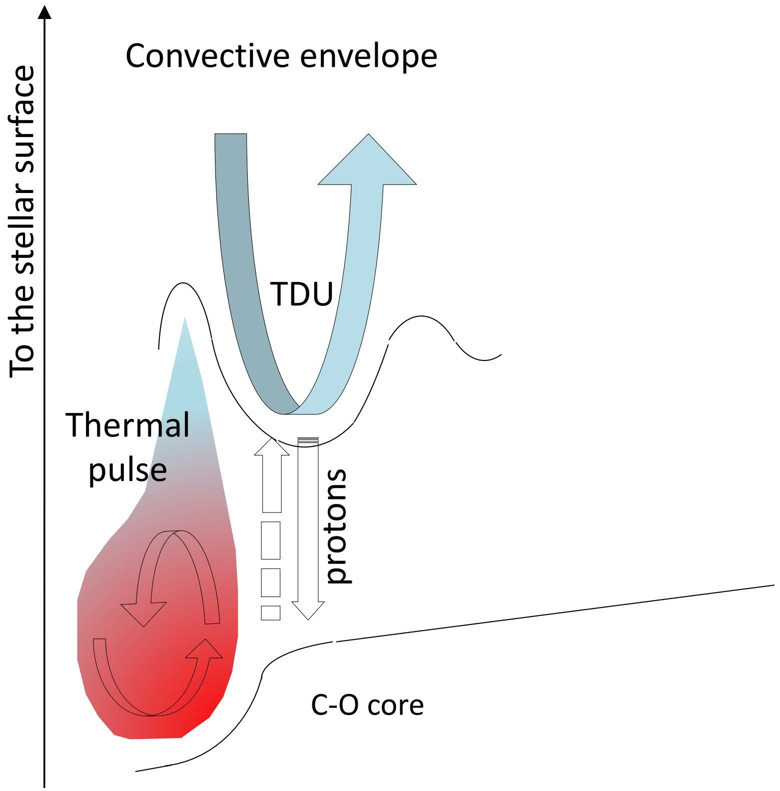
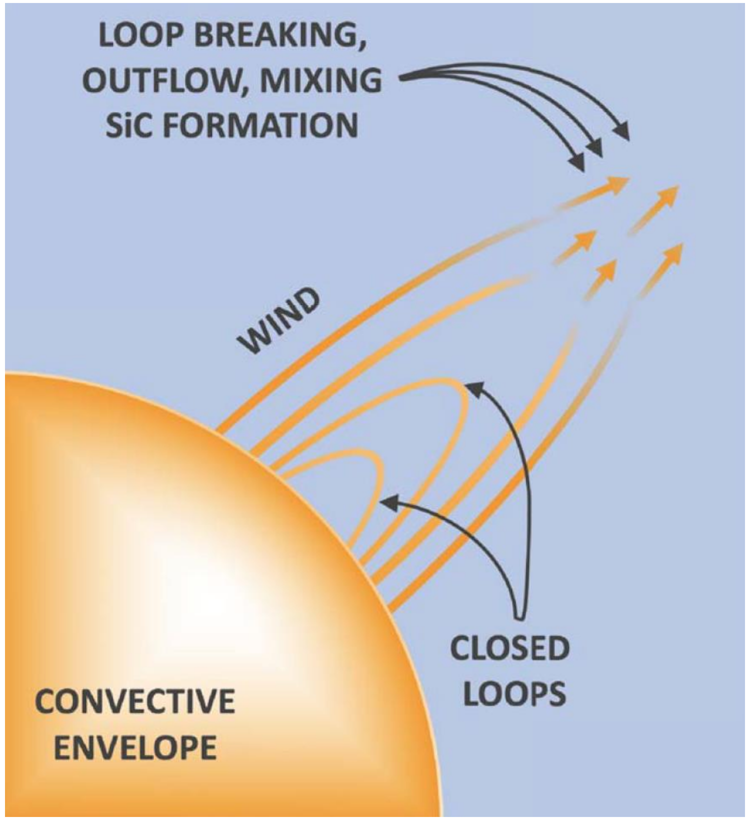


Figure 13. Same as Figure 12, but for the test models V2, with tentatively modified nuclear inputs (see Section 3).

…but stellar physics can help too

The advection of magnetic bubble in the stellar envelope may allow the existence of C-rich domains, isolated by magnetic tension, even when the average envelop composition is still O-rich.





Busso et al. ApJ 908, 55 (2021)

Is your s-process model a good one?

Test it with:

- Presolar grains
- Solar System Abundances
- Post-AGB spectra

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PLEASE WAIT FOR THE NEWT CONFERENCE

Is your s-process model a good one?

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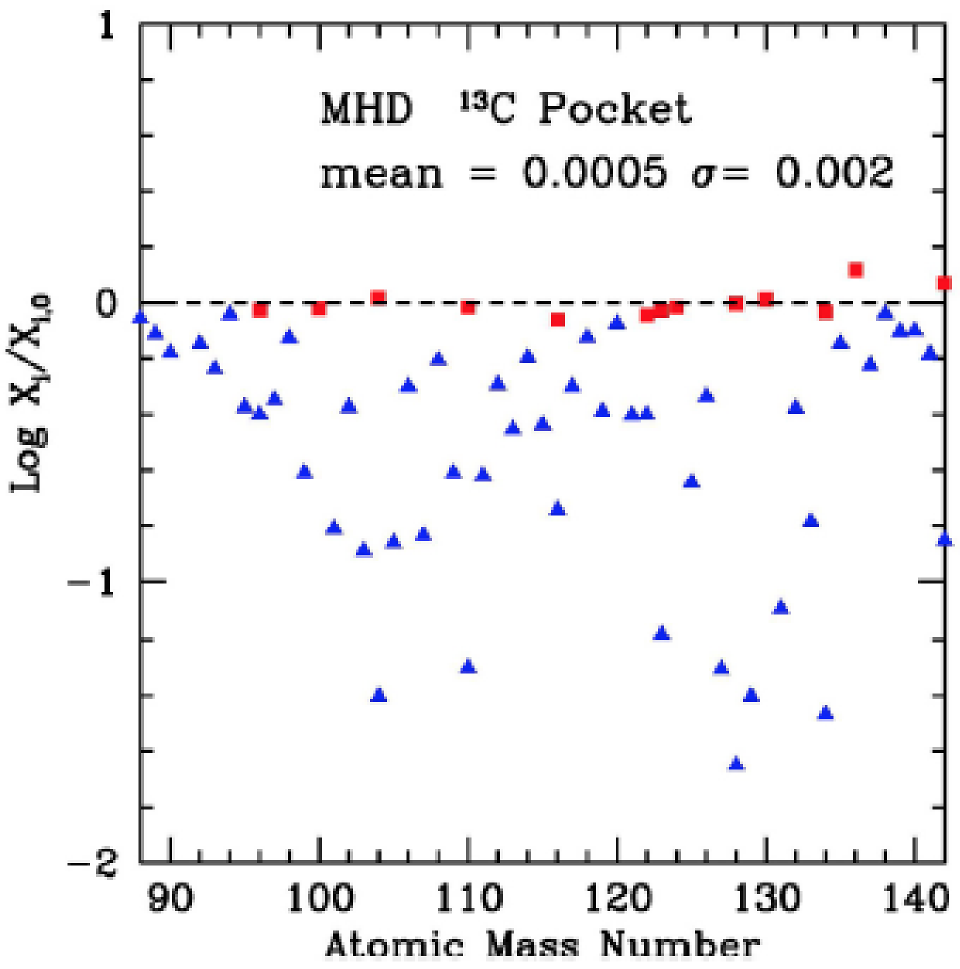
PLEASE WAIT FOR
THE NEWT CONFERENCE

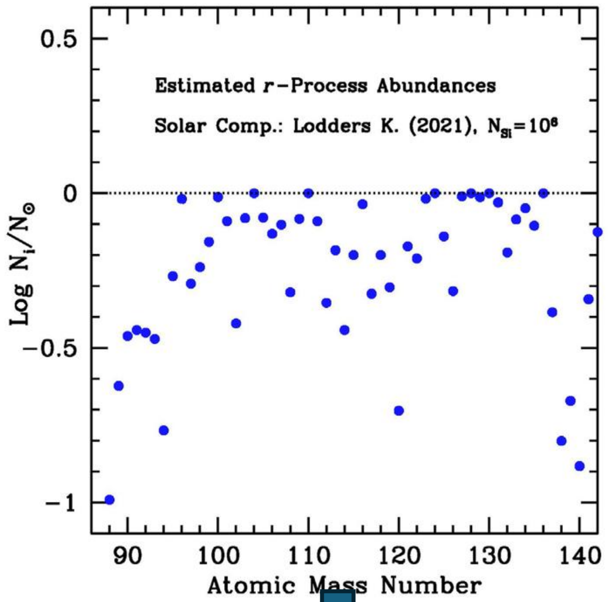
The s-process Solar abundace distribution

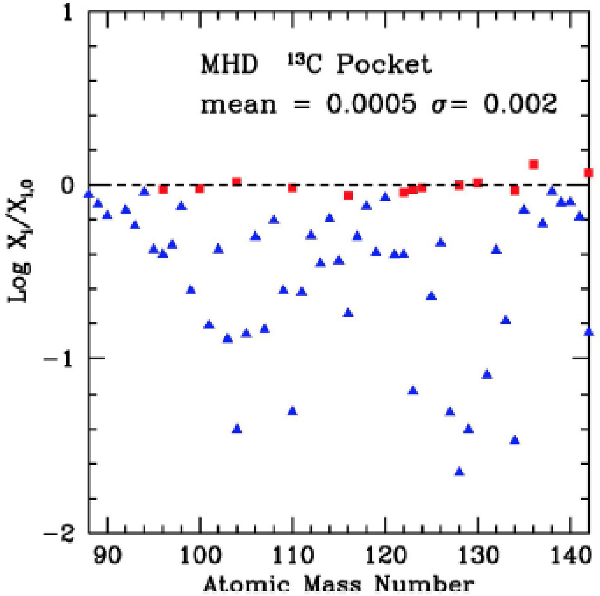
Distribution of s-process abundances in the mass range $88 \lesssim A \lesssim 142$ as obtained with s-process yields from MHD ^{13}C pocket of AGB stars for M = 1.3, 1.5, 2.0, and 3.0 $M_{\odot}$ and $-0.8 \leq [Fe/H] \leq 0.1$ with:

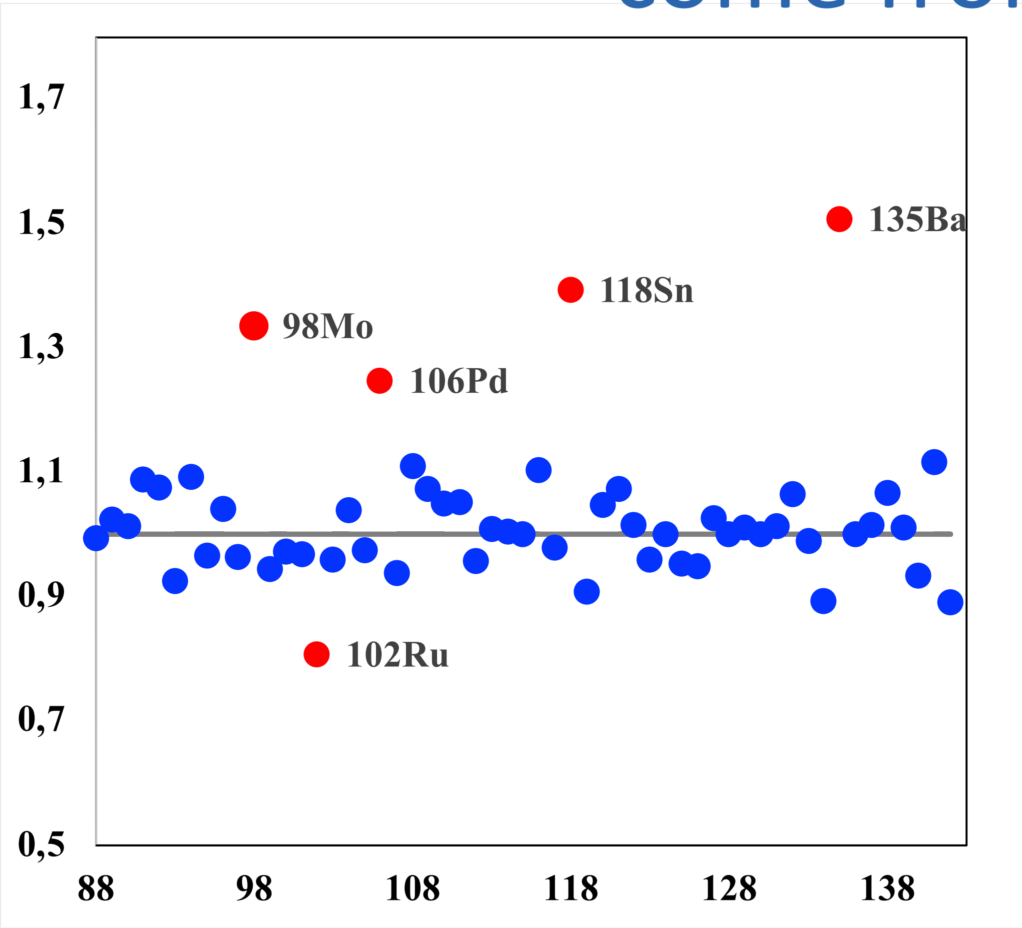
- a dominant contribution from the $^{13}C(\alpha,n)^{16}O$ because of:
  - a moderate temperature in the thermal pulses
  - An extended ^{13}C distributions with little 14N
- the solar abundances are reproduced with an average dispersion around 11% but for:
  - the s-only isotopes (in red) that are predicted close to 100%
  - the isotopes with a large r-process contribution



Where do these 5 anomalies come from?







- s-process
- r-ptocess
- i-process
- nuclear input
- observations
- ???

Where do these 4 anomalies come from?

1-r

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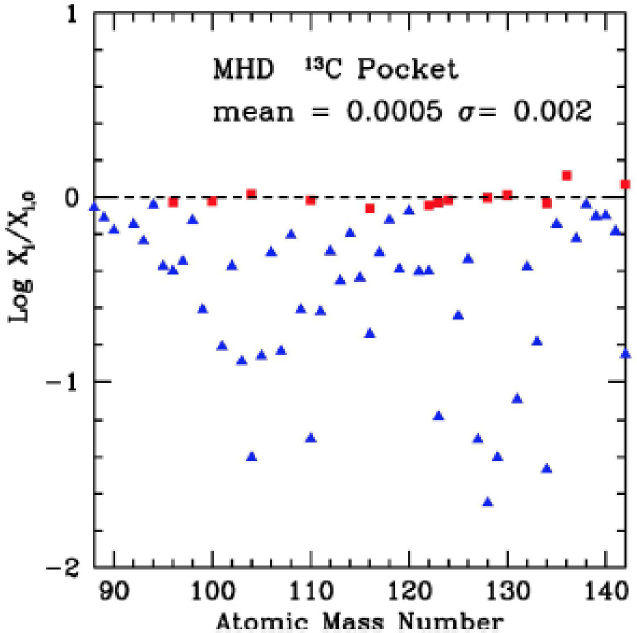

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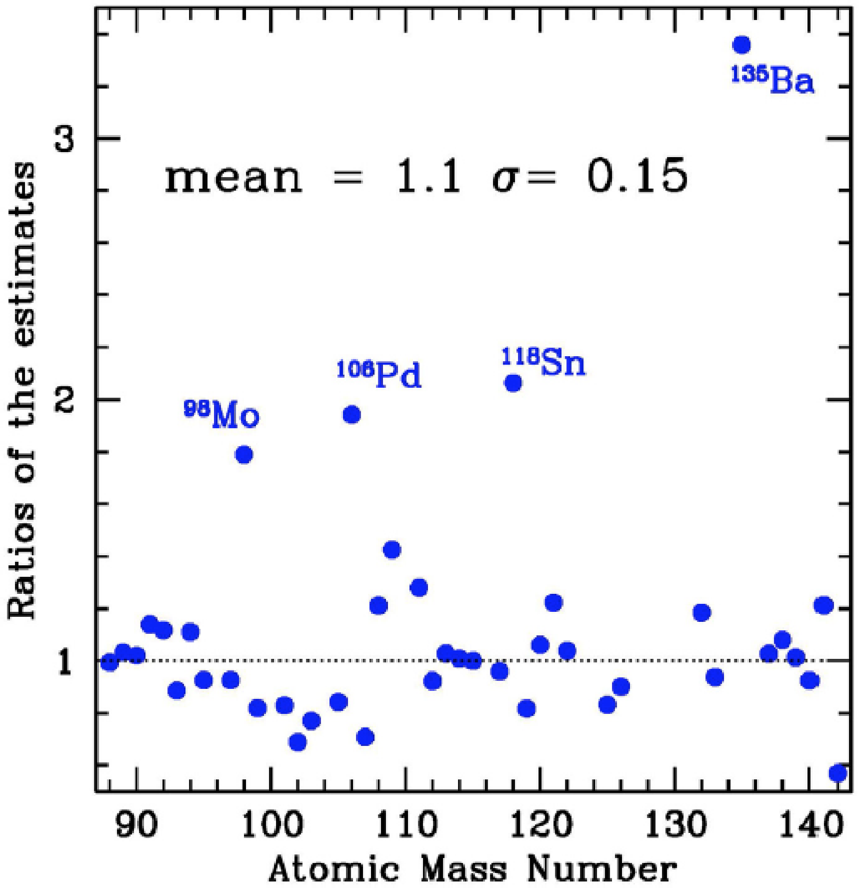

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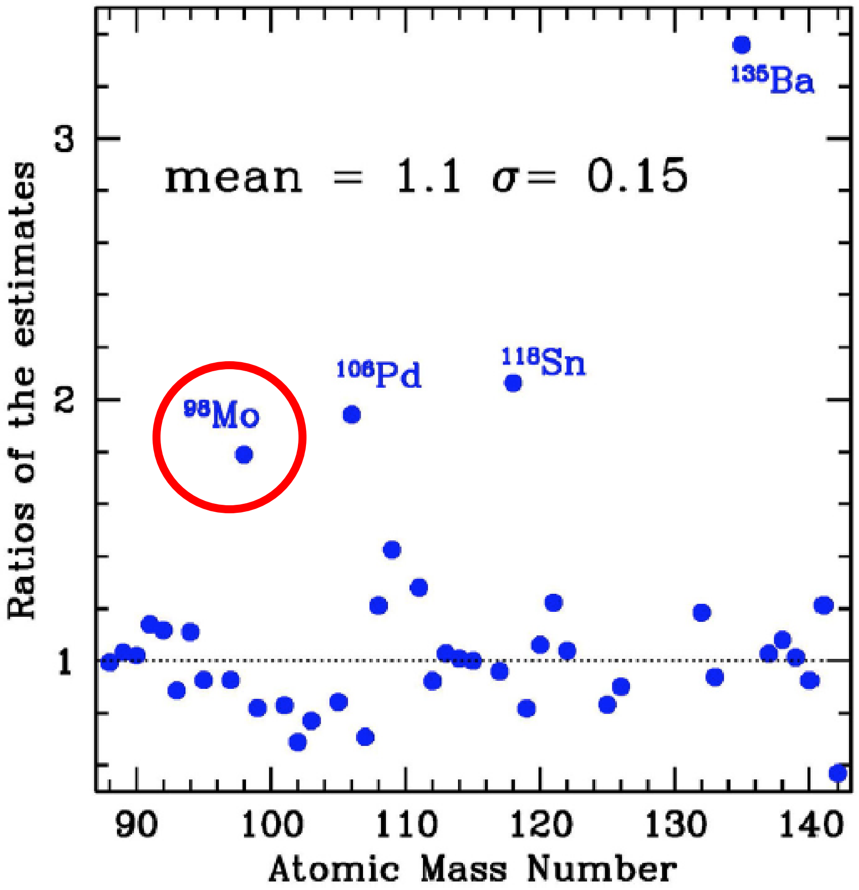
Where do these 4 anomalies come from?

^{98}Mo

- Solar abundance is obtined from presolar SiC grains of AGB origins
- estimate from the waiting-point approch: 75.7%
- yields from AGB models 42.3%



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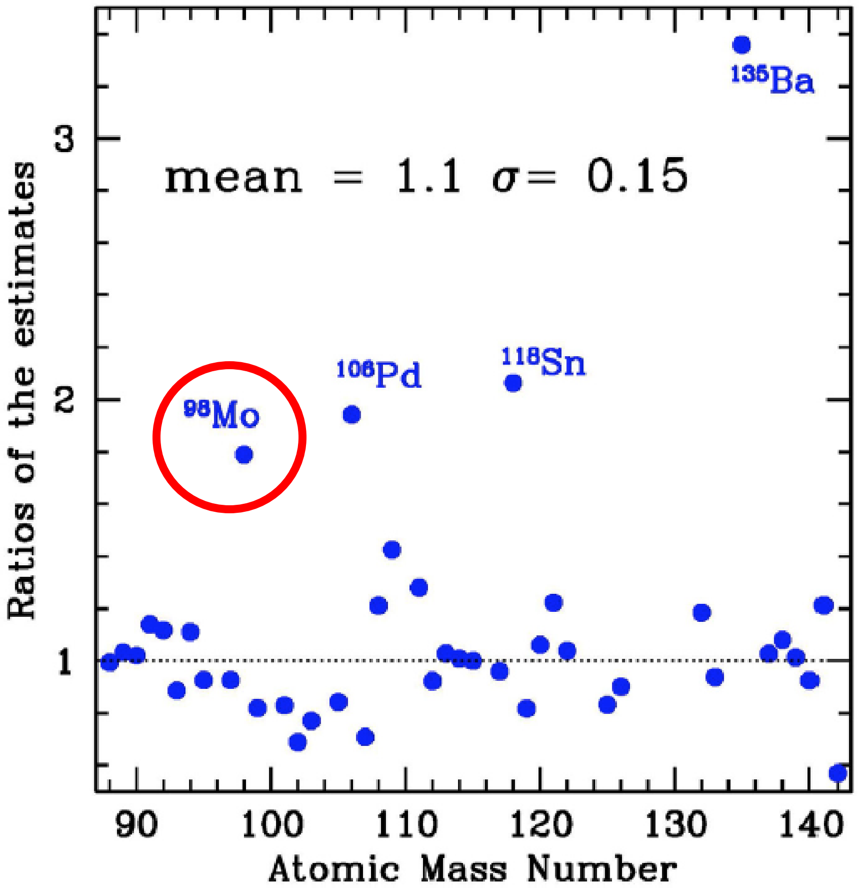
Is this value s+i?



- s-process
- r-ptocess
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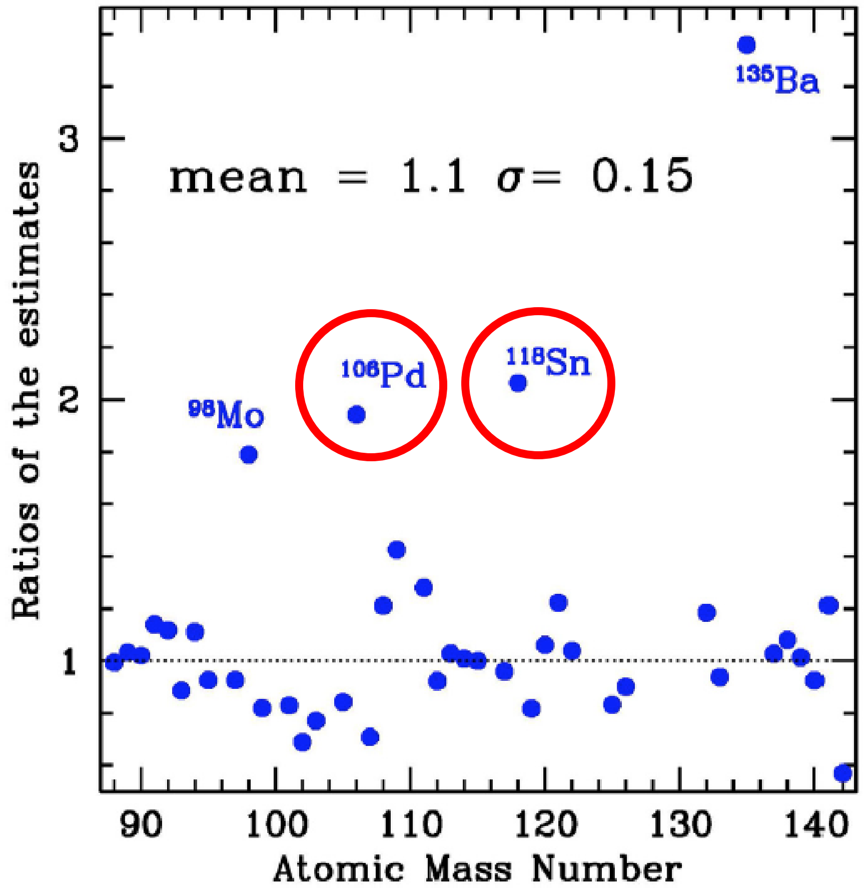
- nuclear input
- observations
- ???

Where do these 4 anomalies come from?

^{106}Pd and ^{118}Sn

- A very complex «nuclear» situation characterizes the region from Pd to Sn



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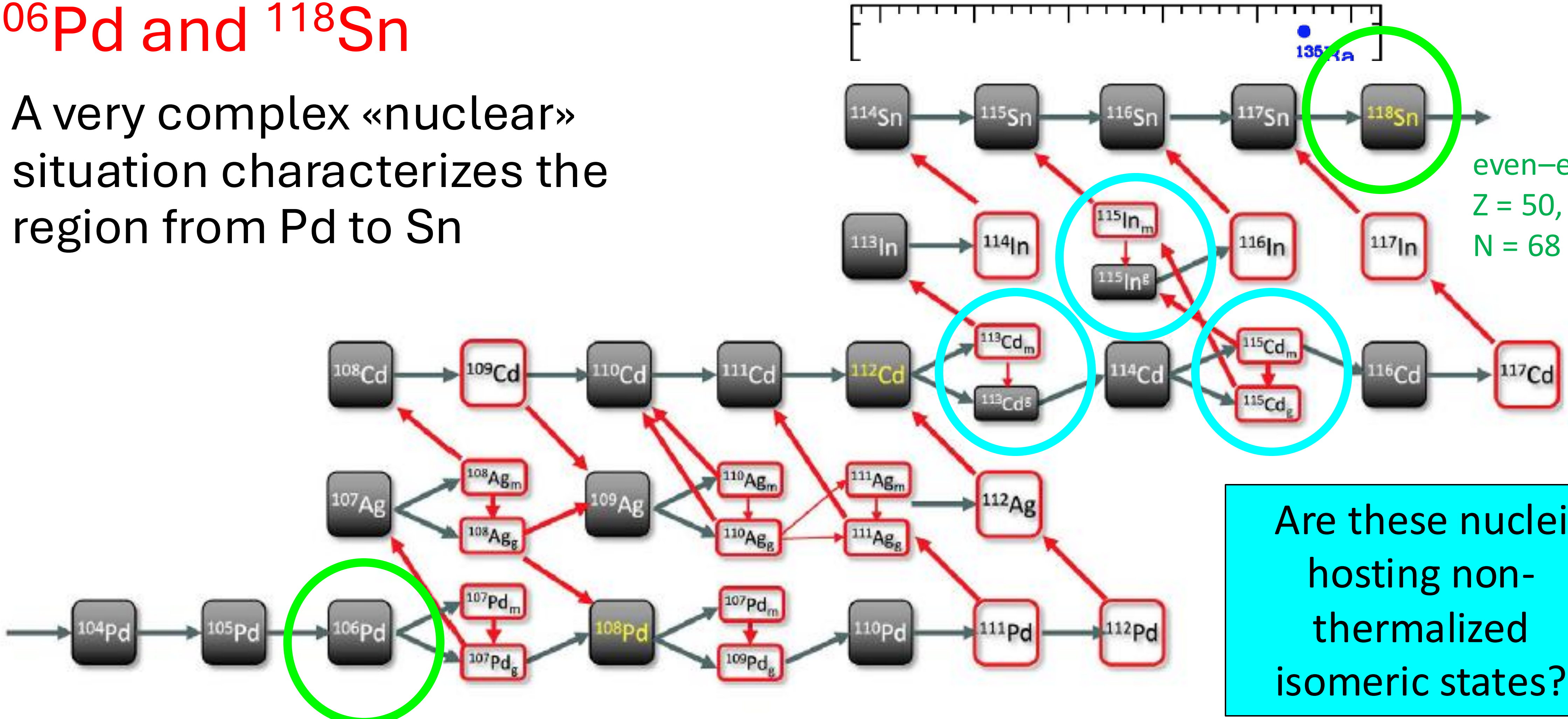


even–even
Z = 50,
N = 68

Are these nuclei hosting non-thermalized isomeric states?

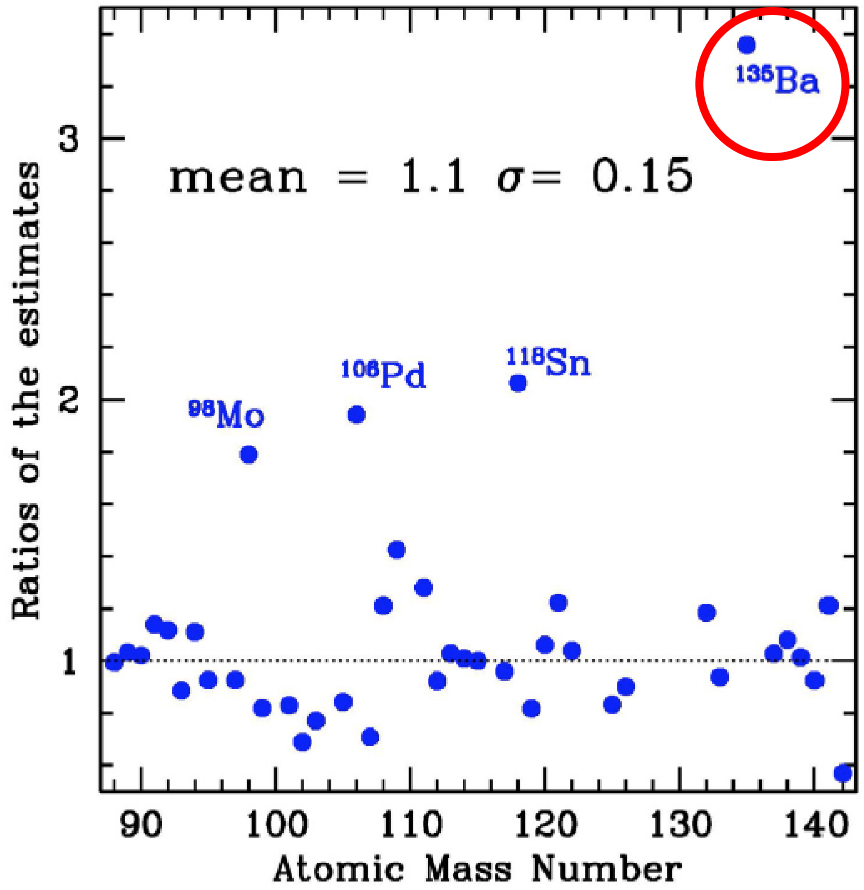
even–even nucleus
r-precursor 106Sr N=66

- i-process
- ???

Where do these 4 anomalies come from?

^{135}Ba

- The s-process production remains very uncertain due to the adopted decay rates of Cs isotopes
- The fit to the s-only nuclei ^{134,136}Ba is improved thanks to the new estimates for ^{134,135}Cs half-lives
- The effects of the new Cs isotope decay rates at the temperature of the He-shell in AGB stars (where it can be produced too) have to be tested

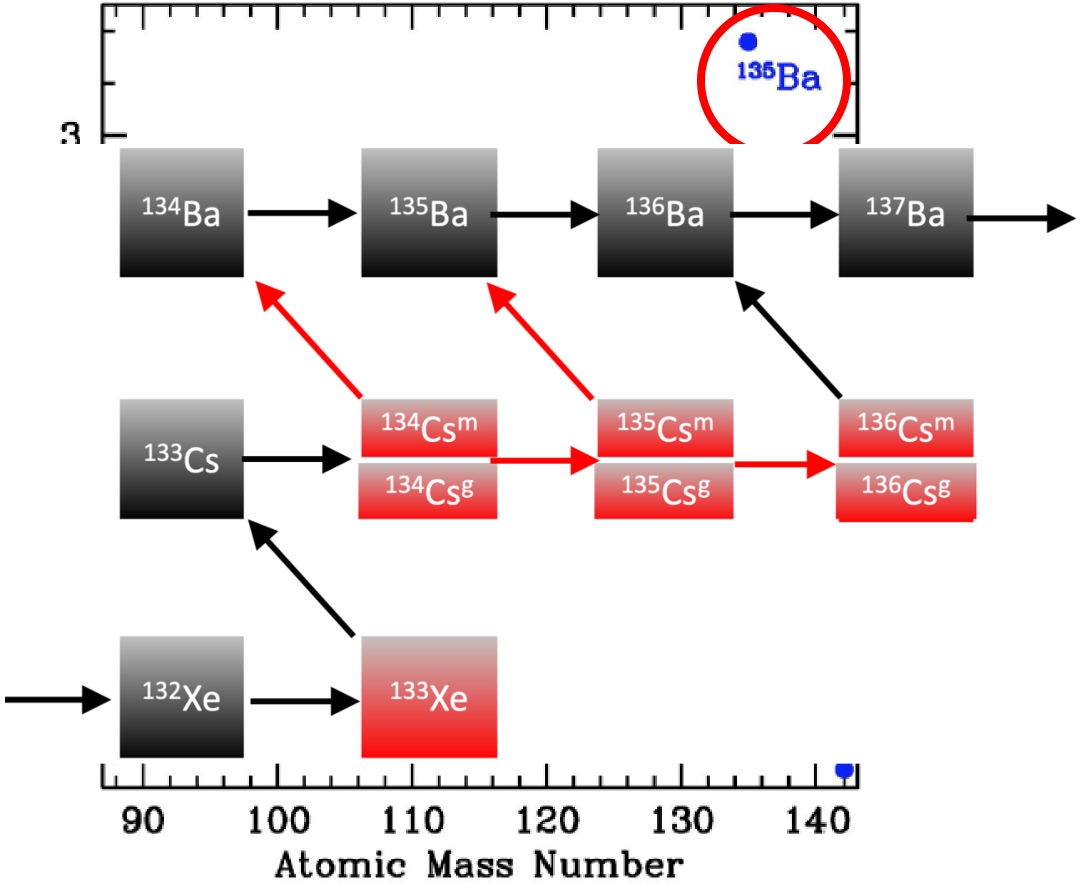


- s-process
- r-process
- i-process
- nuclear input
- observations
- ???

Where do these 4 anomalies come from?

^{135}Ba

- The s-process production remains very uncertain due to the adopted decay rates of Cs isotopes
- The fit to the s-only nuclei $^{134,136}Ba$ is improved thanks to the new estimates for $^{134,135}Cs$ half-lives
- The effects of the new Cs isotope decay rates at the temperature of the He-shell in AGB stars (where it can be produced too) have to be tested

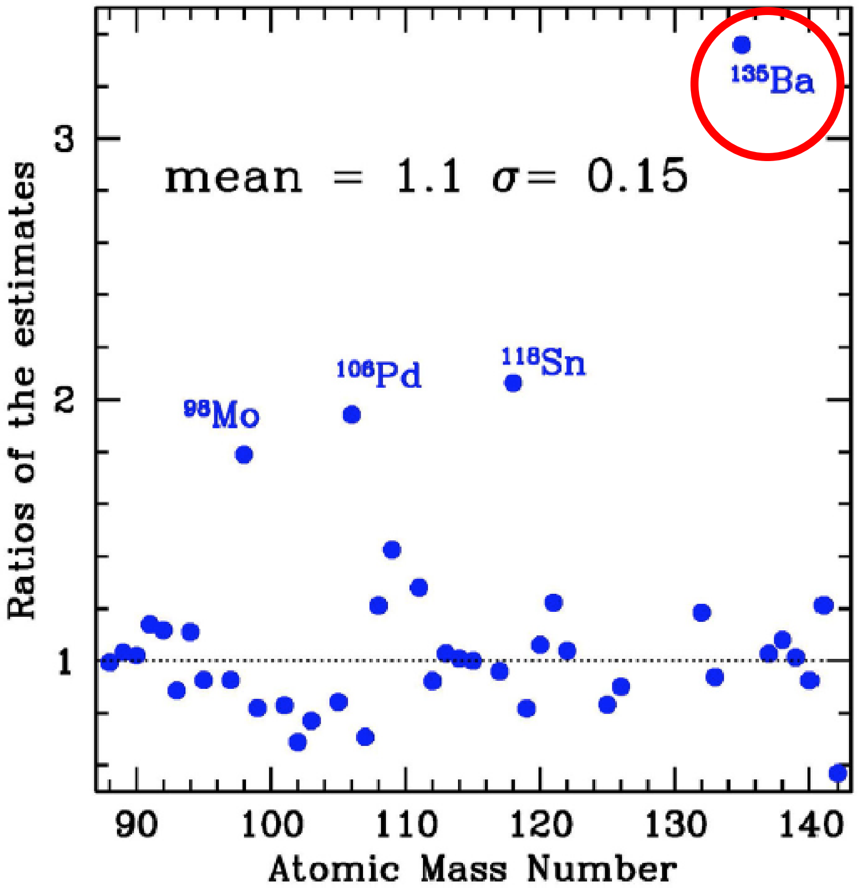


- s-process
- r-process
- i-process
- nuclear input
- observations
- ???

Where do these 4 anomalies come from?

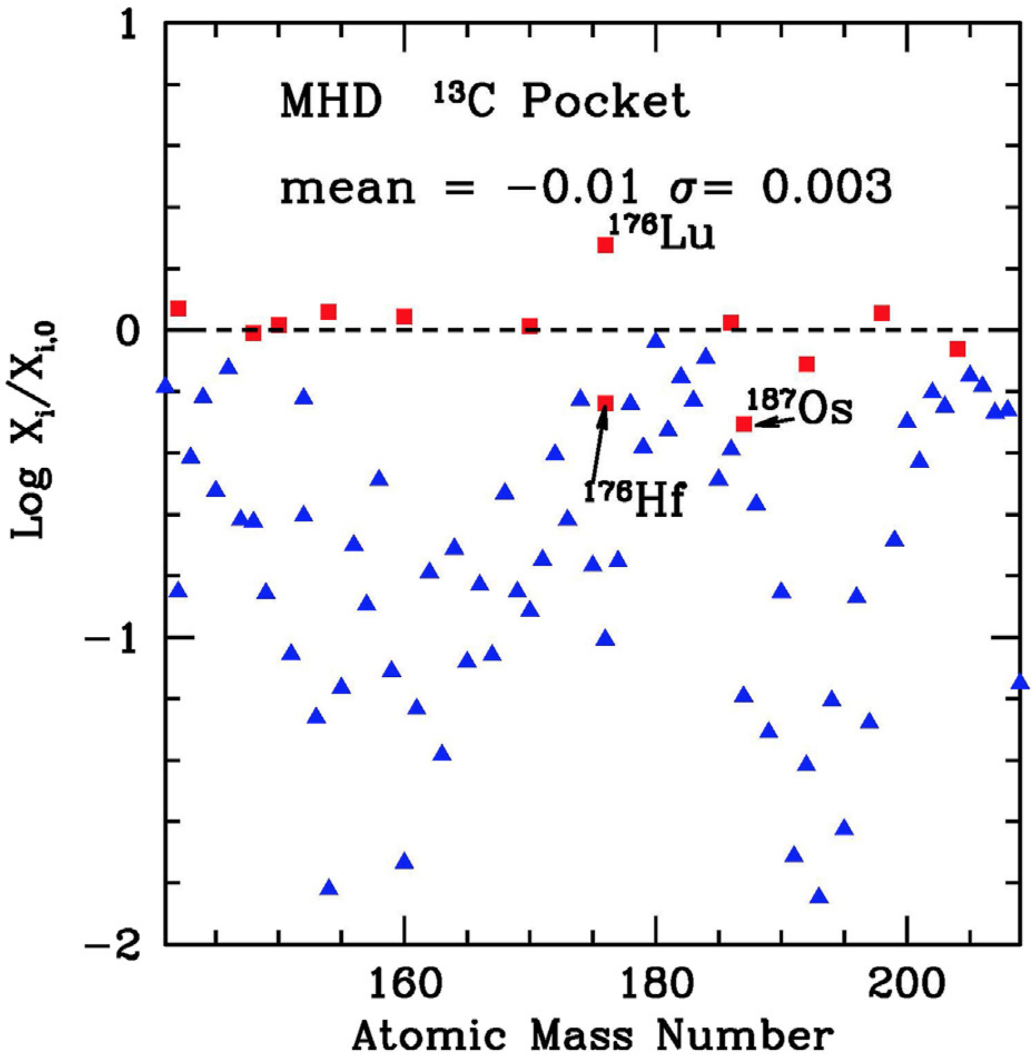
^{135}Ba

- Can the origin of the discrepancy come from the r-process apprach?
  - in the β-delayed neutron-branchings during the decay back to stability only negligible fractions of the initial abundance of ^{135}In and ^{138}Sn reach ^{135}Ba.
  - while the 40% of the initial ^{136}Sn populates ^{135}Ba, but the resulting effect is only a slight reduction in the final S.S. r-fraction of ^{135}Ba (maybe by ≃ 10%).



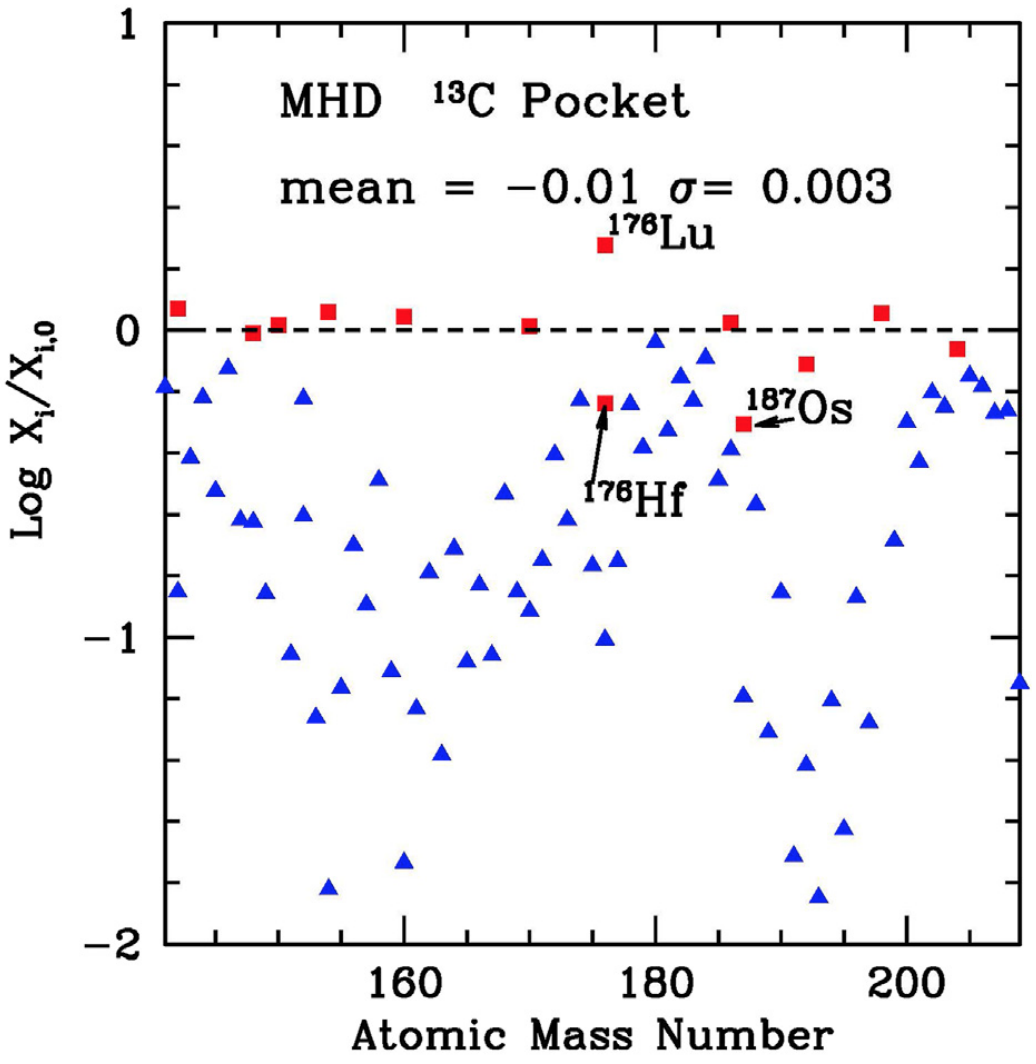
- s-process
- r-process
- i-process
- nuclear input
- observations
- ???

Reproducing the SS distribution above A = 142



- Estimates for S.S. abundances of heavy nuclei (A ≥ 142) from our yields
  - a general good reproduction of the solar abundances for s-only nuclei (red dots
  - three very remarkable outlayers: ^{176}Lu, ^{176}Hf, and ^{187}Os
- nuclear problems known since a long time:
  - ^{176}Hf, ^{176}Lu and ^{187}Re dacay rates should be (exerimentally) verified in stellar plasma conditions
  - isomeric states at ^{175}Yb, ^{176}Lu, and ^{177}Hf are involved in the s-process reaction chain.

Reproducing the SS distribution above A = 142



- Estimates for S.S. abundances of heavy

Lots of uncertainty for the s-process,
lots of uncertainty for the r-process ...
... and lots of space for the i-process