The interplay between neutron captures and β-decays at unstable isotopes

Diego Vescovi[1,2,3], Maurizio Busso[4,2], Sara Palmerini[4,2,], and Sergio Cristallo[3,2]

1. Gran Sasso Science Institute (GSSI), L'Aquila, Italia
2. INFN – Sezione di Perugia, Perugia, Italia
3. INAF – Osservatorio Astronomico d'Abruzzo, Teramo, Italia
4. Università degli Studi di Perugia, Perugia, Italia

Meeting Pandora
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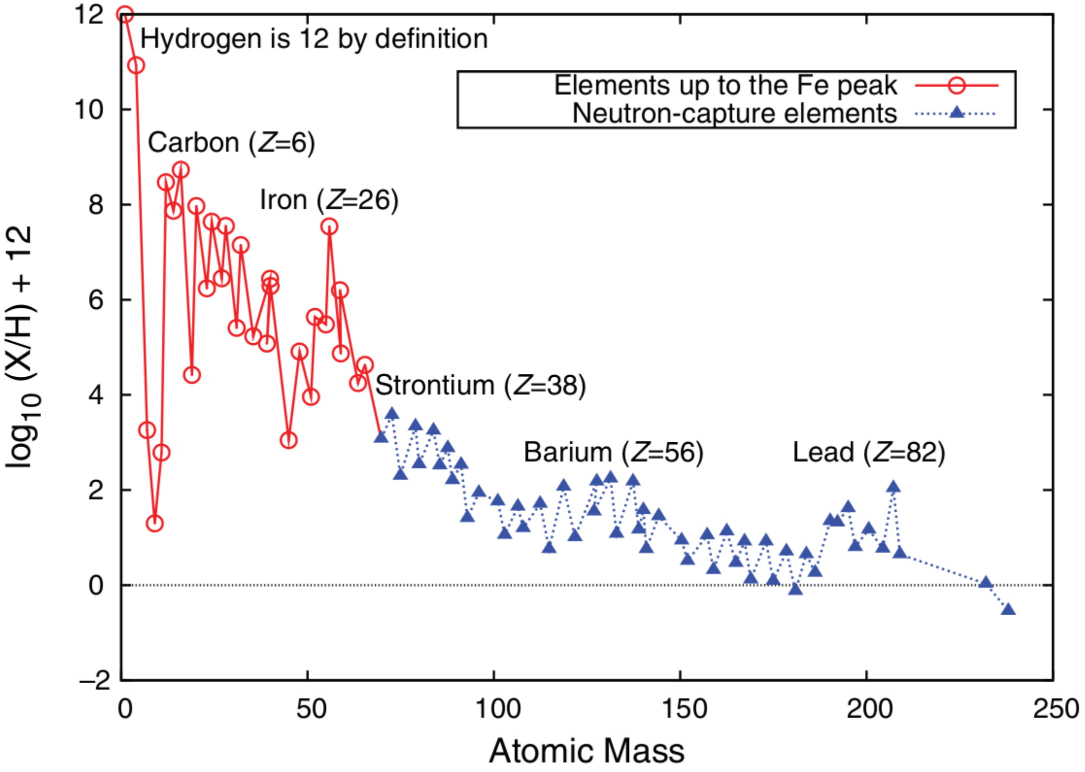
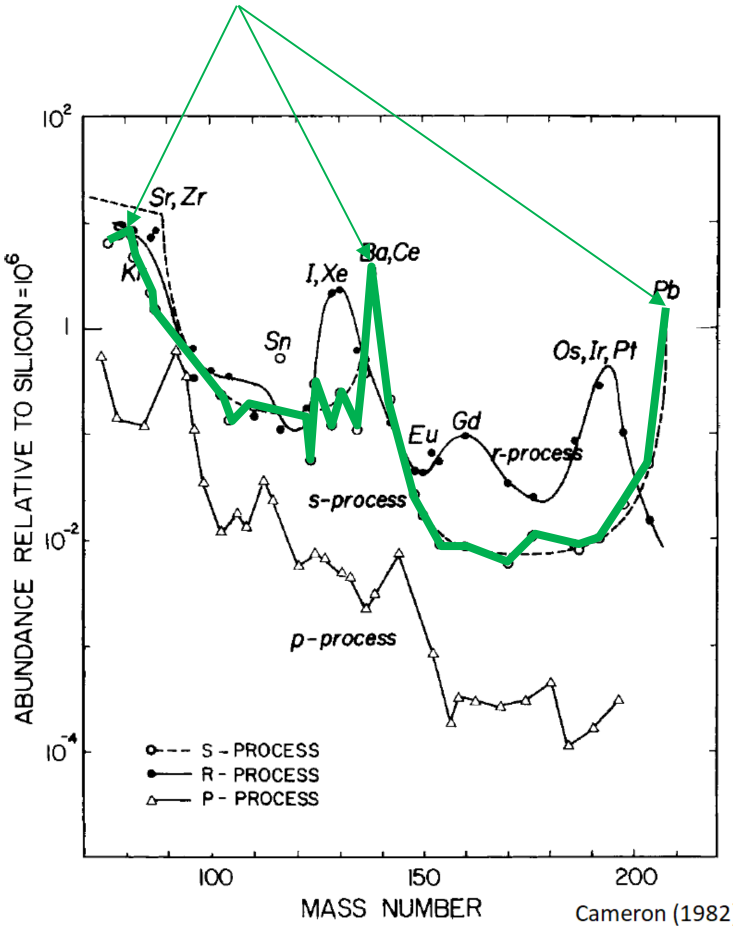
The origin of heavy elements in the Solar System



Location of peaks indicates *n*-capture process along valley of stability ➡ *s*-process



Cameron (1982)

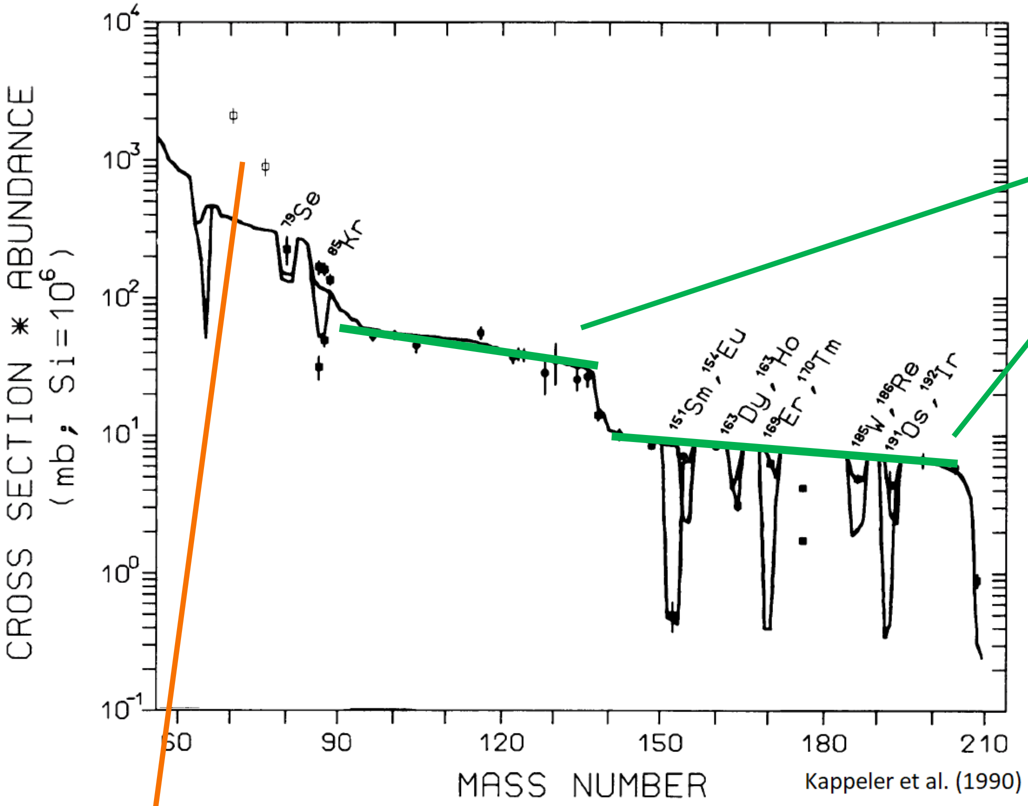
Neutron captures processes :

s-process	*r*-process
• $\tau_\beta << \tau_n$ • Unstable nucleus decays before capturing another neutron	• $\tau_\beta >> \tau_n$ • Unstable nucleus captures another neutron before decaying

Astrophysical sites of the s-process

main s-process (component)

^{13}C-burning and He-flashes
in low mass TP-AGB stars



Kappeler et al. (1990)

steady flow approximation
$\sigma_A \cdot N_A \approx \sigma_{A-1} \cdot N_{A-1} \approx$ cost.

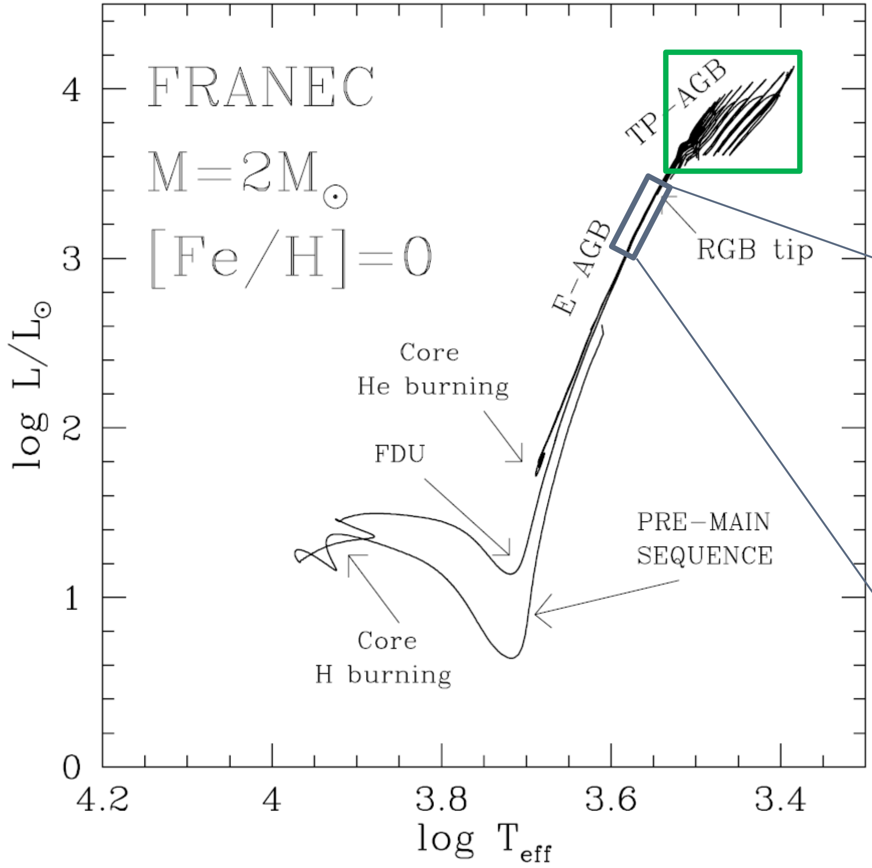
↓

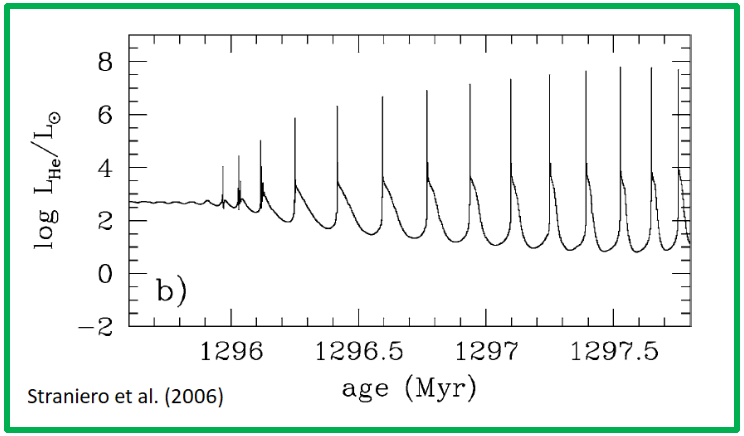
can easily interpolate
s-contribution for s-nuclei
if neutron capture cross sections are known

weak s-process (component)

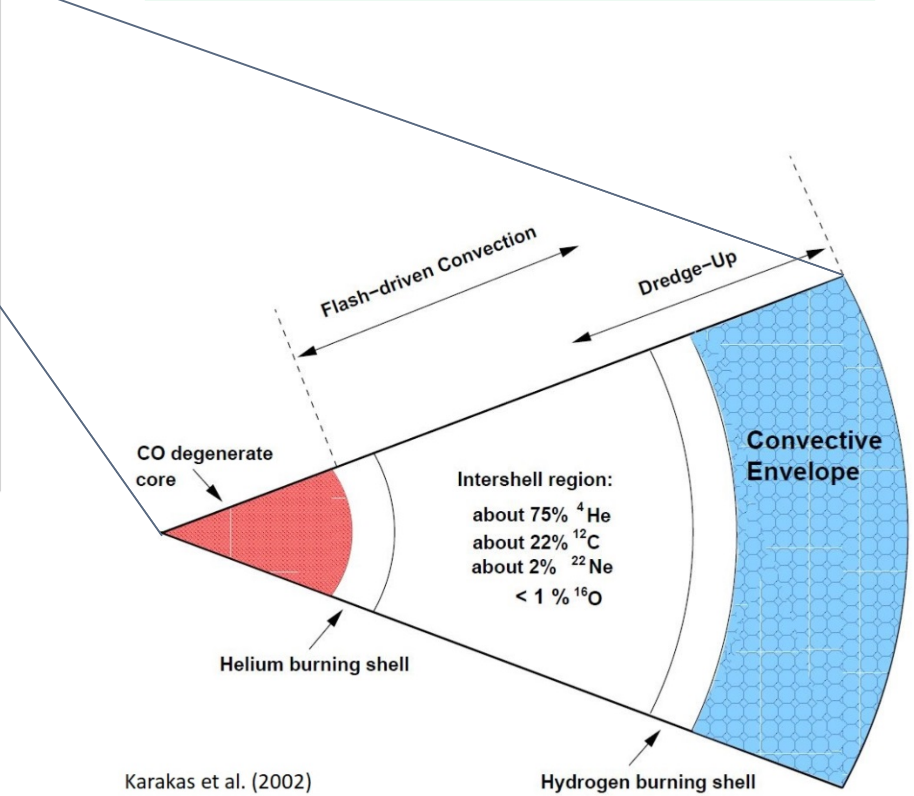
core-He/ shell-C burning in massive stars

Main s-process





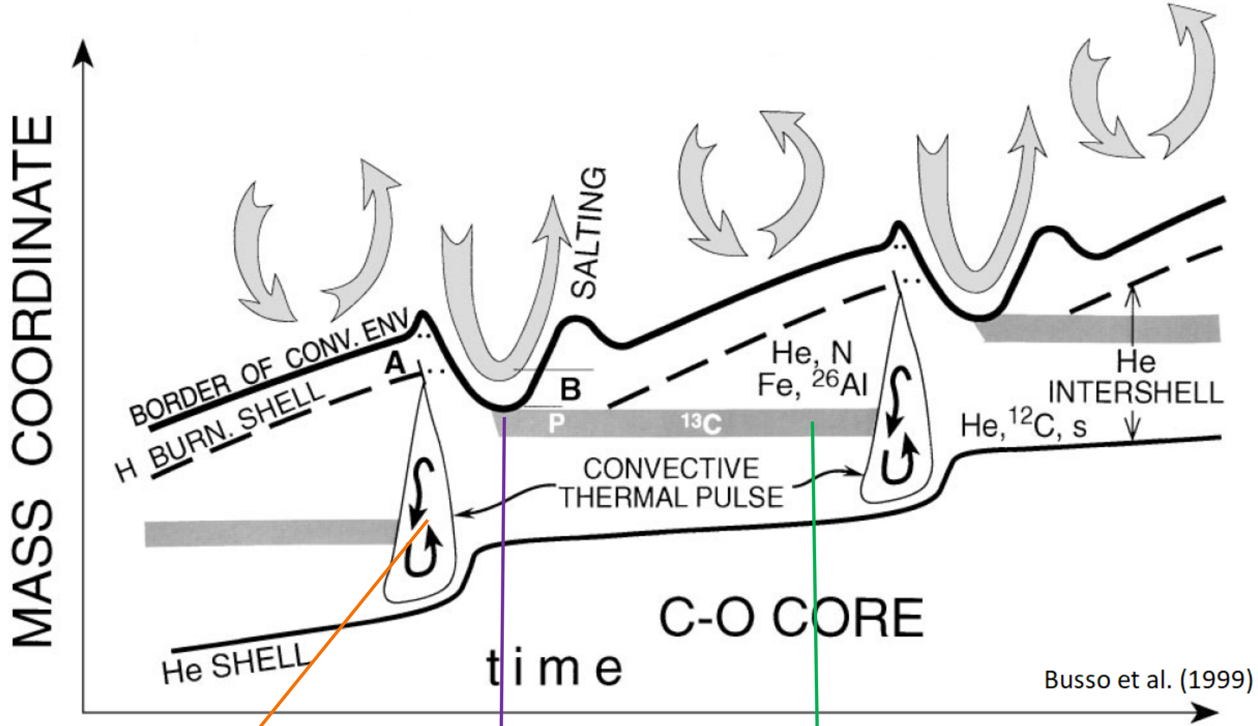
Straniero et al. (2006)



Karakas et al. (2002)

- Thermally Pulsing (TP)
- Asymptotic Giant Branch (AGB)
- Low-Mass Stars (LMS)

H- and He-burning in TP-AGB stars



Busso et al. (1999)

- What?
  Low-Mass Stars
- When?
  Asymptotic Giant Branch (AGB)
- How?
  Thermally Pulsing (TP)

He-flash

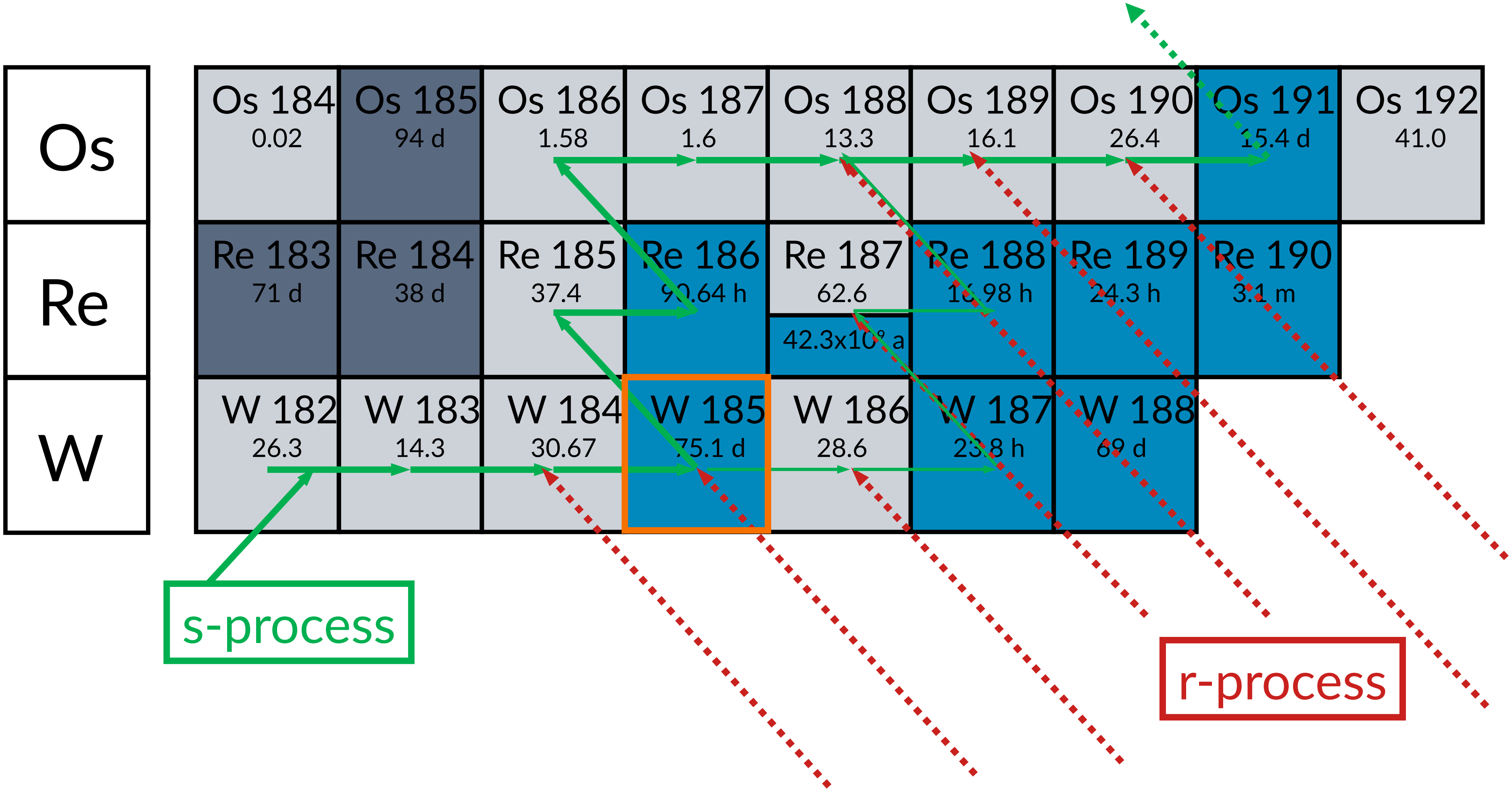
proton penetration

^{13}C-pocket

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

$^{22}Ne(\alpha,n)$ — $^{13}C(\alpha,n)$ → heavy elements!!

How do 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

The main component: uncertainties

- experimental (n, γ) rates have been highly reduced in recent years reaching in some cases a precision smaller than 1 or 2 % (see e.g. Käppeler et al. 2011)
- However, the high s-process temperatures allow the **low-lying excited states to be populated** by the intense and energetic thermal photon bath
- ground state is accessible by experiment ⇒ the effect of neutron captures in excited states has to be evaluated theoretically and suffers from large uncertainties
- β-decay rates of some radioactive isotopes may be **largely affected** by variations of temperature and electron density
- the contribution of thermally populated excited levels and the effects of unknown transitions in a strongly ionized plasma can largely modify the β-decay rates at stellar temperatures.
- **Takahashi & Yokoi (1987)** investigated the β-decay rates of unstable heavy isotopes at temperatures and electron densities typical of stellar interiors ($5 \times 10^7 \leq T \leq 5 \times 10^8$ K; $10^{26} \leq n_e \leq 3 \times 10^{27}$ cm^{-3}), finding large deviations from the terrestrial values
- temperature dependence of branchings is even more complex, if branchigs have isomeric states that are thermalized at high temperatures through transitions via mediating states at higher excitation energy

→ **the abundances of the affected s-only isotopes carry direct information on the physical conditions occurring during the s-process, i.e. neutron density, temperature and density**

The main component: uncertainties of major branches

We distinguish the s-only isotopes in three classes, according to their dependence on reaction branchings:

1) **unbranched s-only isotopes**, with unstable isobars having half-lives shorter than a couple of days (thus forbidding neutron captures during TPs)

   ^{100}Ru, ^{104}Pd, ^{110}Cd, ^{116}Sn, ^{124}Te, ^{150}Sm, ^{160}Dy, ^{198}Hg

2) **s-only isotopes sensitive to neutron density only**, with unstable isobars having half-lives (almost) constant in stellar environments

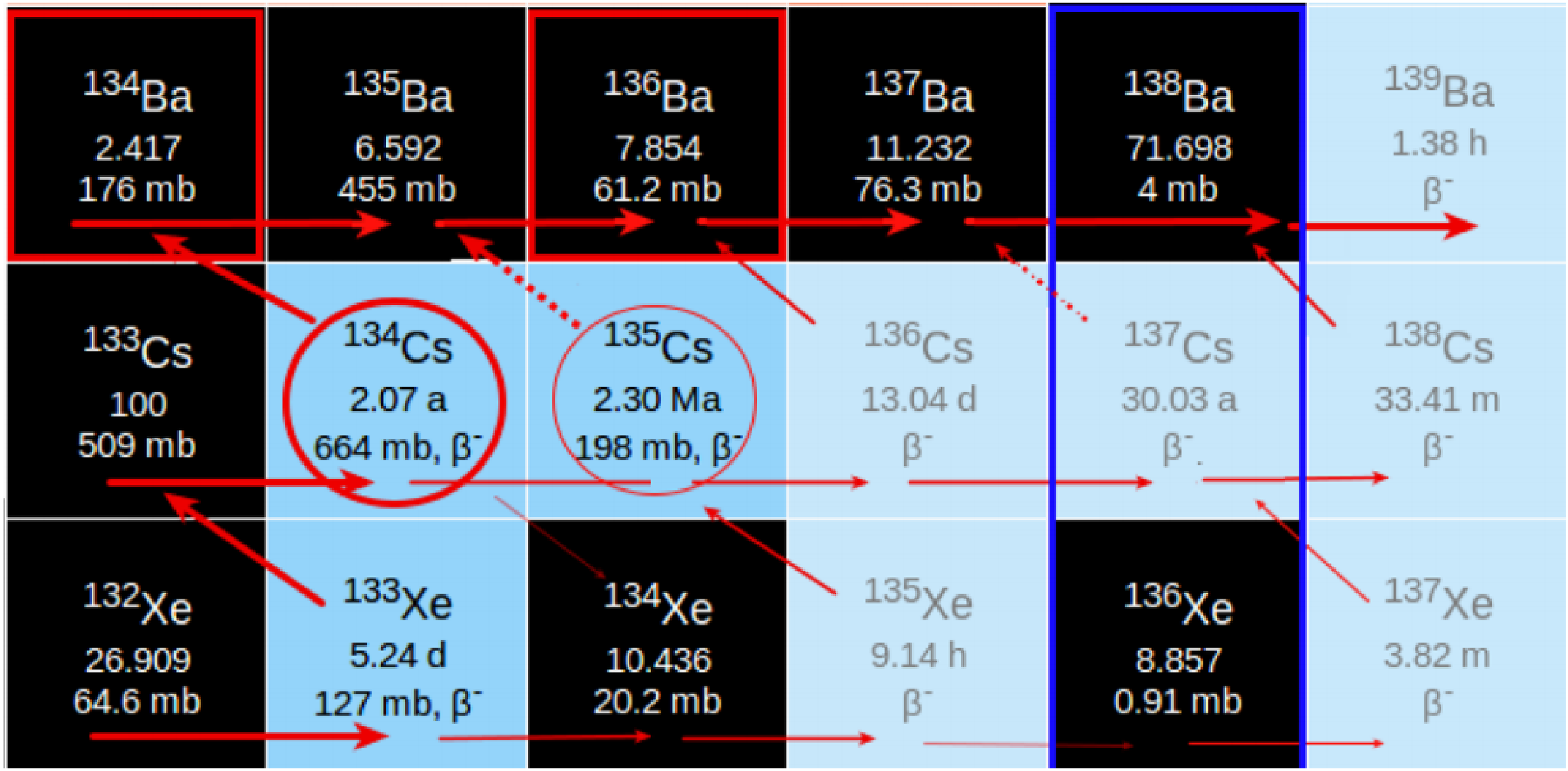
   ^{96}Mo, ^{170}Yb, ^{142}Nd, ^{186}Os, ^{192}Pt

3) s-only isotopes (^{134,136}Ba, ^{152,154}Gd, ^{176}Hf, ^{204}Pb, ^{180}Ta^{m}, ^{128}Xe) affected by branch points with unstable isobars having β-decay rates quickly changing under stellar conditions:

   - **nuclides sensitive to both neutron density and stellar temperature** (and/or electron density): **^{134}Cs**, ^{151}Sm, ^{154}Eu, **^{176}Lu**, ^{204}Tl

   - **nuclides** less affected by neutron density, but **dominated by stellar temperature and/or electron density gradients during TP:** ^{179}Hf, ^{128}I

The branch at ^{134}Cs I



The **dominant uncertainty** affecting the ^{134}Ba/^{136}Ba ratio **derives from the β-decay rate of ^{134}Cs**

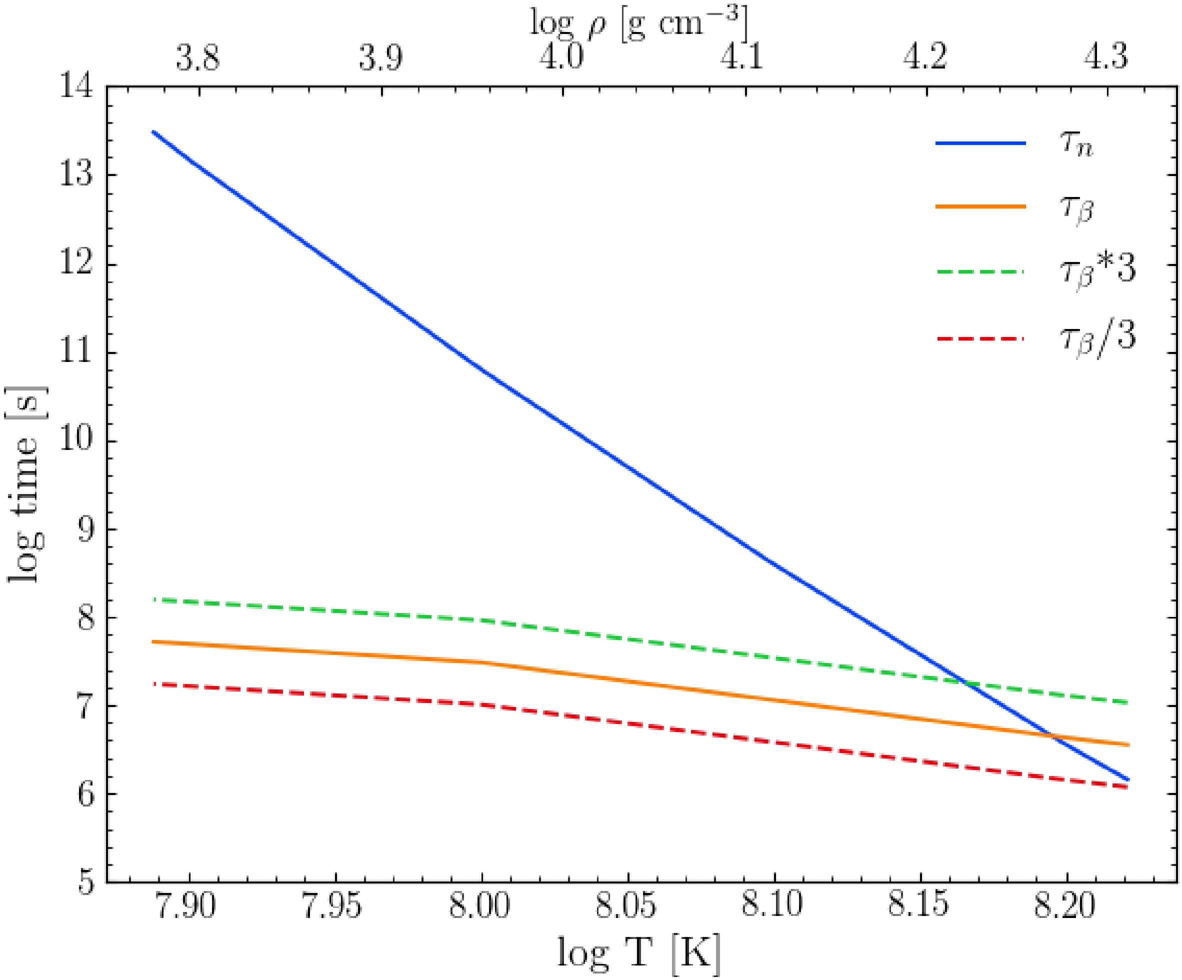
- the terrestrial half-life of 134Cs ($t_{1/2}$= 2.07 yr) is **strongly reduced** under stellar conditions (Takahashi & Yokoi 1987)

The branch at ^{134}Cs II

- $t_{1/2}$ **decreases by a factor of 3** at T = 100 MK (0.67 yr) **and by two orders** of magnitude at T = 300 MK (3.8 d)
- Note that **λ^-(^{134}Cs) does not change with electron (or mass) density**
- a small amount of ^{134}Cs is converted to ^{135}Cs during the peak neutron density at the bottom of the TPs

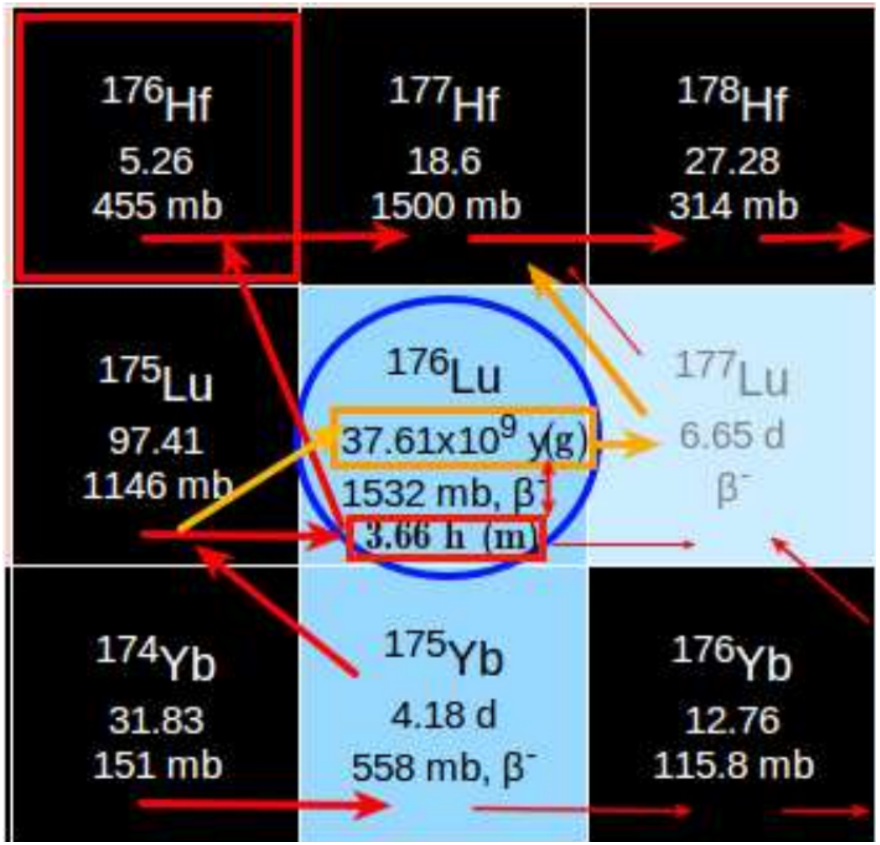
➔ ^{134}Ba is temporarily reduced (by ~30%). The initial amount of ^{134}Ba is almost fully re-established as soon as the neutron density decreases.

➔ almost the entire s-flow is directed towards ^{134}Ba, may resulting in a **overestimate of solar ^{134}Ba**



The branch at ^{176}Lu I

- The ^{176}Lu/^{176}Hf ratio is largely affected by the branch at ^{176}Lu, which is strongly sensitive to the temperature during TPs
- ^{176}Lu has a short-lived isomer ($t^m_{1/2}$ = 3.66 h) and an extremely long-lived ground state ($t^g_{1/2}$ = 38 Gyr)
- **internal transitions are highly forbidden** by nuclear selection rules and any coupling can only be provided by states with intermediate quantum numbers and higher excitation energies
- the **low temperatures** during the ^{13}C-pocket phase are not sufficient for that coupling, the s-process flow via both states has been treated independently

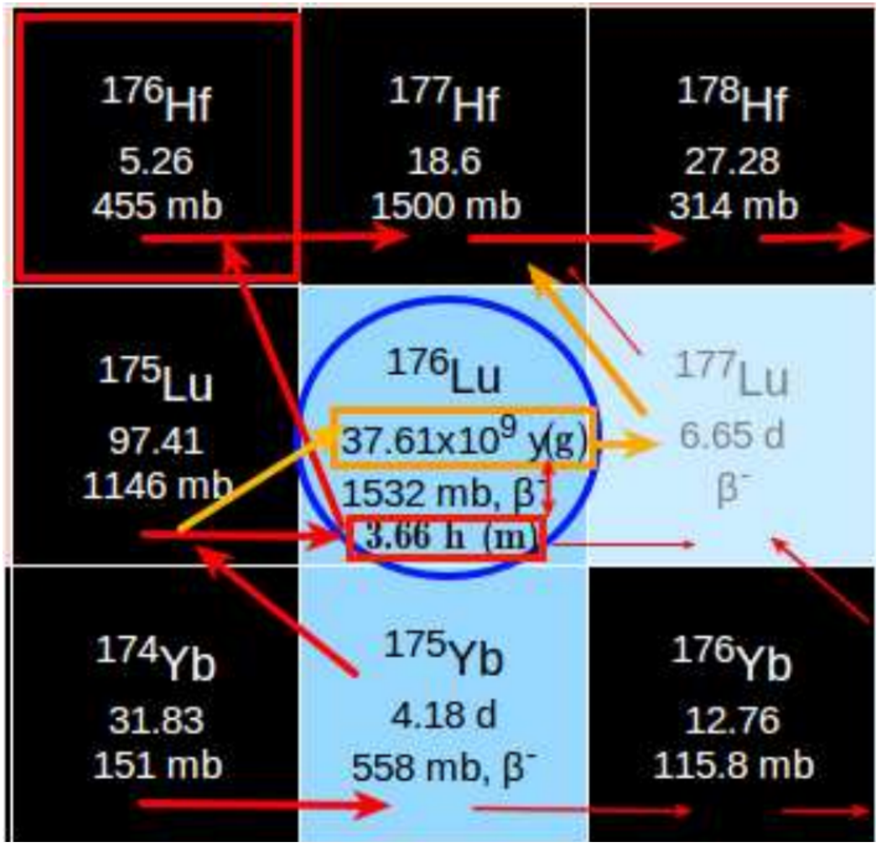


The branch at ^{176}Lu II

- ^{176}Lu^{g} is produced via thermal transitions in the bottom layers of the advanced TPs, where temperatures are T ~ 300 MK

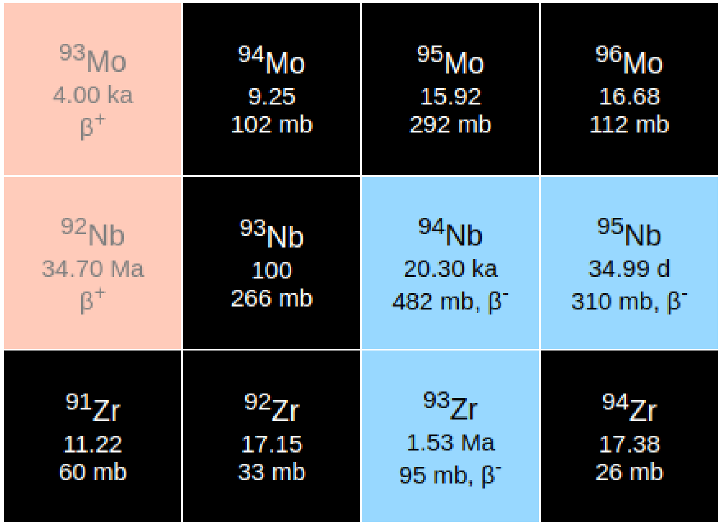
- Once produced, the long-lived ^{176}Lu^{g} survives in the cooler external layers of the convective flashes, outside of the burning zone

- Accordingly, the detailed neutron density and temperature profiles in the TPs have to be considered for the s-process calculations.

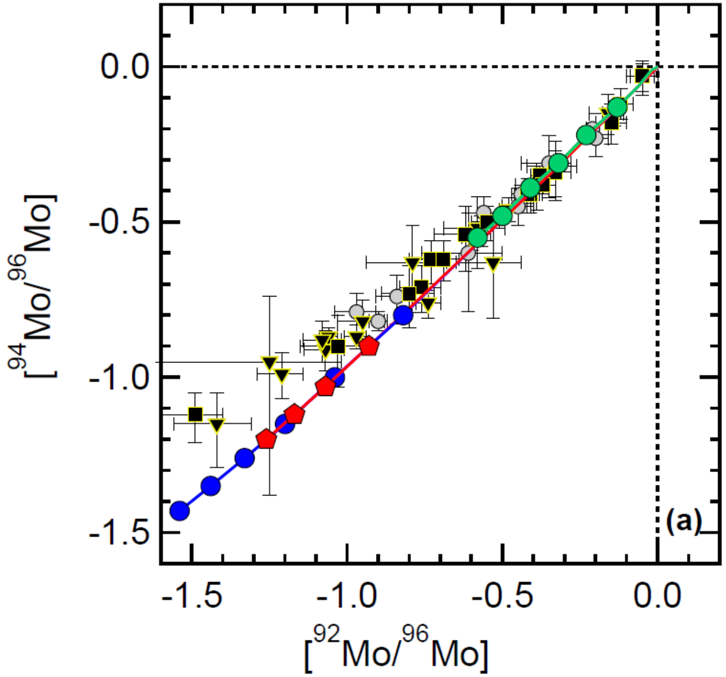


^{94}Nb

- main production channel for ^{94}Mo via ^{93}Nb(n,γ)^{94}Nb(β+ν)
- ^{94}Nb comes indirectly from ^{93}Zr, which actually behave as stable in timescale of TP-AGB stars evolution: its presence, and thus the presence of ^{94}Mo, **should be strongly underabundant**
- In presolar SiC grains this nucleus is overabundant with respect to model's predictions, probably due to lifetime of ^{94}Nb itself
- **β-decay rate of ^{94}Nb has a strong dependence on stellar temperature**
- $t_{1/2}$ reduced from 20,000 yr at room temperature to 0.5 yr at 10^8 K and 9 days at 3×10^8 K

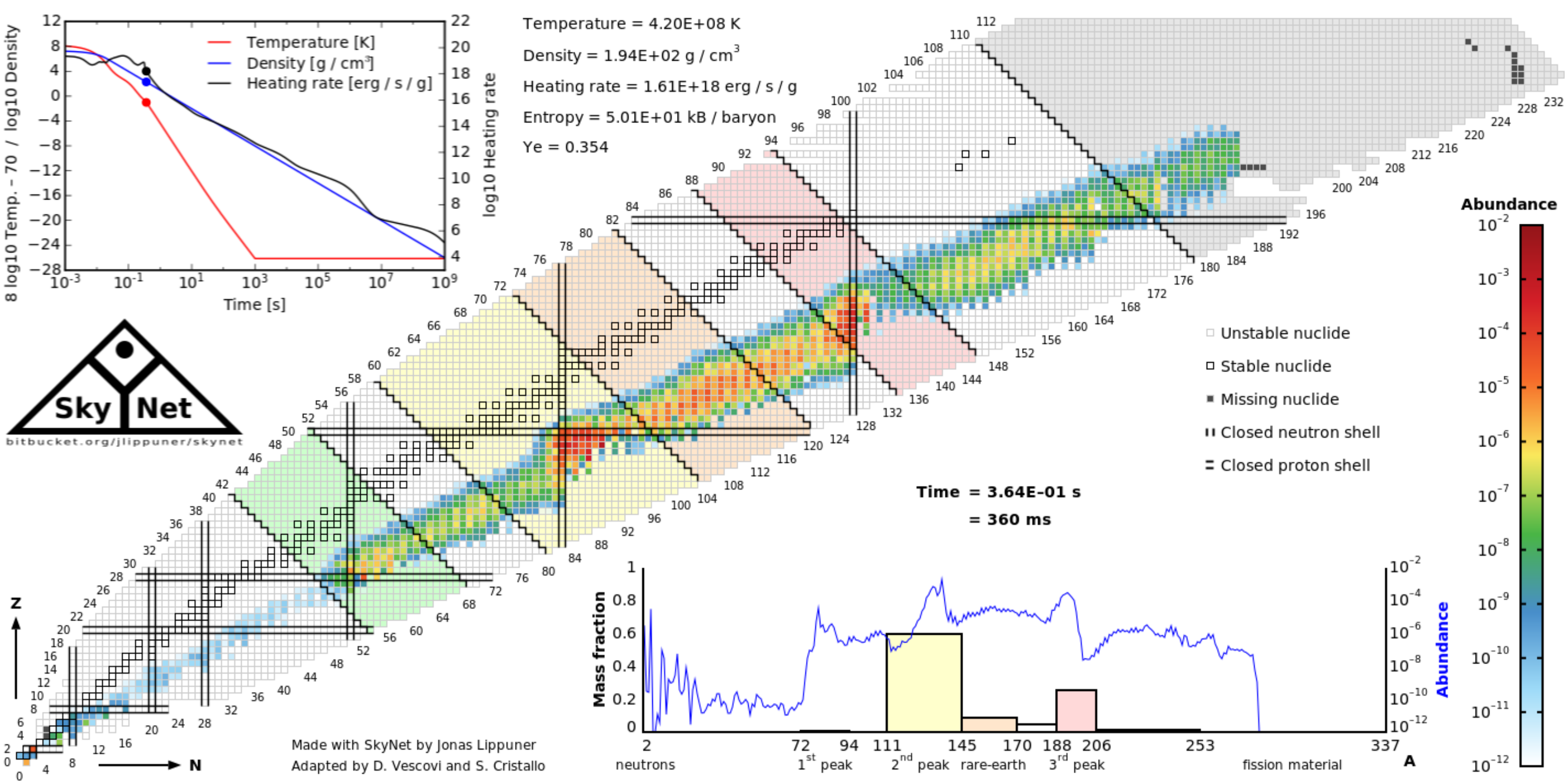


^{93}Mo 4.00 ka β^+	^{94}Mo 9.25 102 mb	^{95}Mo 15.92 292 mb	^{96}Mo 16.68 112 mb
^{92}Nb 34.70 Ma β^+	^{93}Nb 100 266 mb	^{94}Nb 20.30 ka 482 mb, β^-	^{95}Nb 34.99 d 310 mb, β^-
^{91}Zr 11.22 60 mb	^{92}Zr 17.15 33 mb	^{93}Zr 1.53 Ma 95 mb, β^-	^{94}Zr 17.38 26 mb



r-process: basic ideas

- key reactions: $(A, Z) + n \leftrightarrow (A + 1, Z) + \gamma$
- r-process requires initial high n_n and T
  - ➔ high n_n : $\tau_{(n,\gamma)} << \tau_{\beta\text{-}decay}$
  - ➔ high n_n and T: $(n,\gamma) \leftrightarrow (\gamma,n)$ along isotopic chain
  - ➔ steady abundances intra-chain with one dominant nucleus
- β-decay rates of dominant nuclei regulate inter-chain flow
- equilibrium freeze-out: n_n drops and β-decays take over



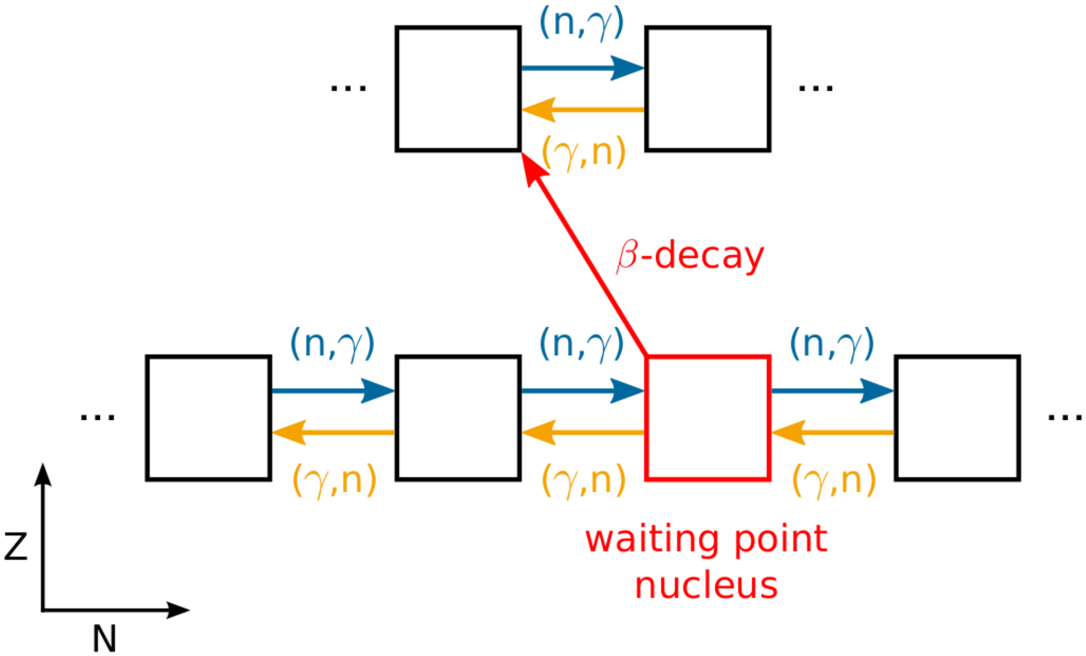
r-process: uncertainties

- constraining the astrophysical site for the r process comes from the challenge and shear number of measurements that must be performed on thousands of short-lived neutron-rich nuclei far from stability that may participate in this process
- For instance, neutron captures in the r process are believed to first exceed and then compete with β decays allowing for the set of most abundant isotopes or “path” to potentially push out to the neutron dripline

➔ **β-decay lifetimes of these nuclei are critical inputs for the r-process**

1) <u>set the timescale for heavy element production</u> if (n,γ)-(γ,n) equilibrium occurs
2) help to <u>shape the final pattern</u> as the path moves back to stability

➔ many studies of β-decay rates most of which have focused on so-called **‘waiting point’** nuclei, for which the abundance flow waits for its decay to proceed



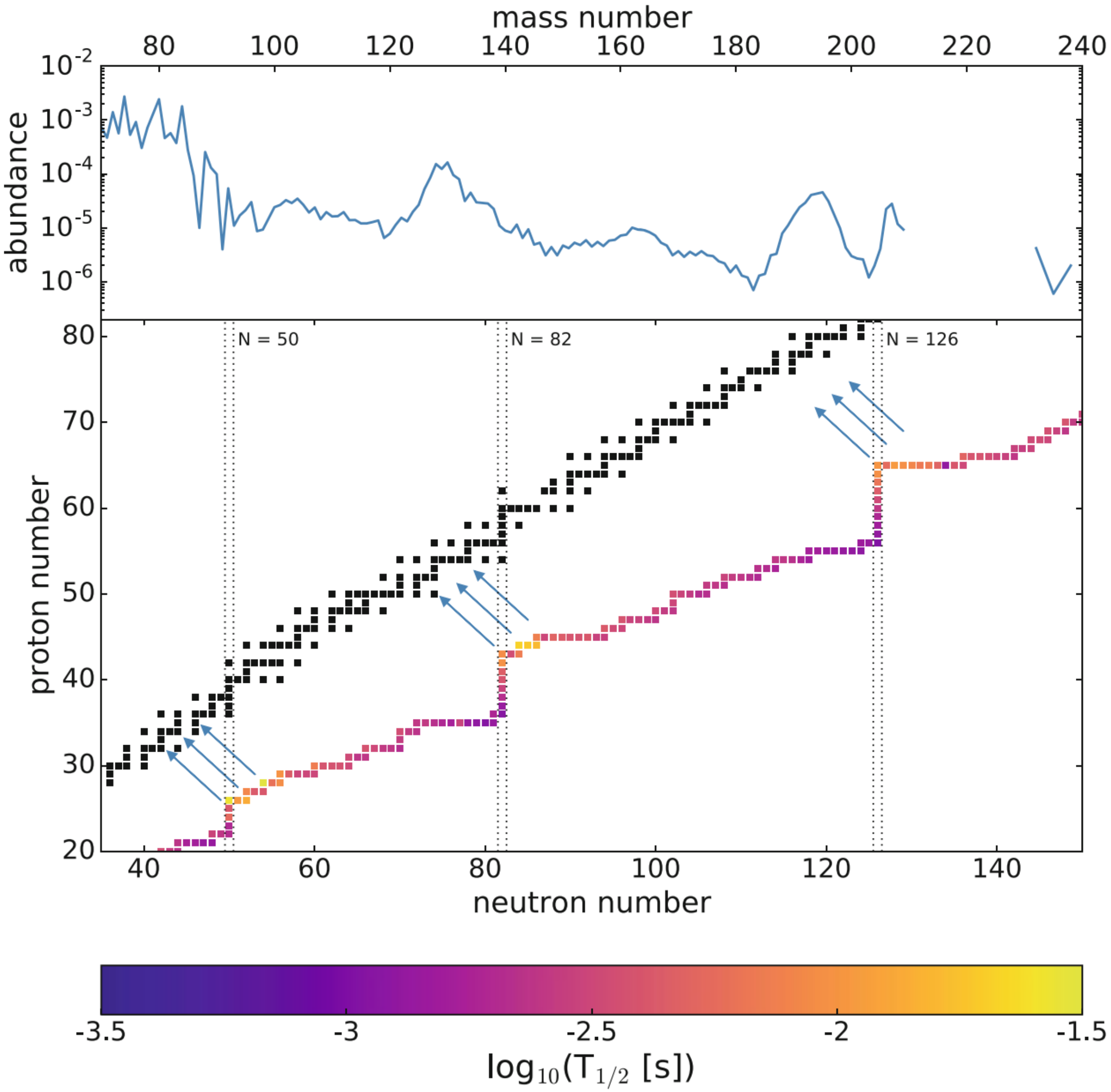
r-process: peaks

- Wherever the path crosses isotopes with a **closed neutron shell**, both the neutron capture cross sections and β-decay rates become significantly **smaller**

  ➔ accumulation of material in these nuclei

- after the supply of free neutrons has ceased, the extremely neutron-rich isotopes undergo a series of β-decays to stability

- the mass numbers where the r-process path crossed the magic neutron numbers can be identified in the final abundance pattern by **characteristic peaks**



r-process: simulation