

Nuclei in the cosmos

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# S-process nucleosynthesis

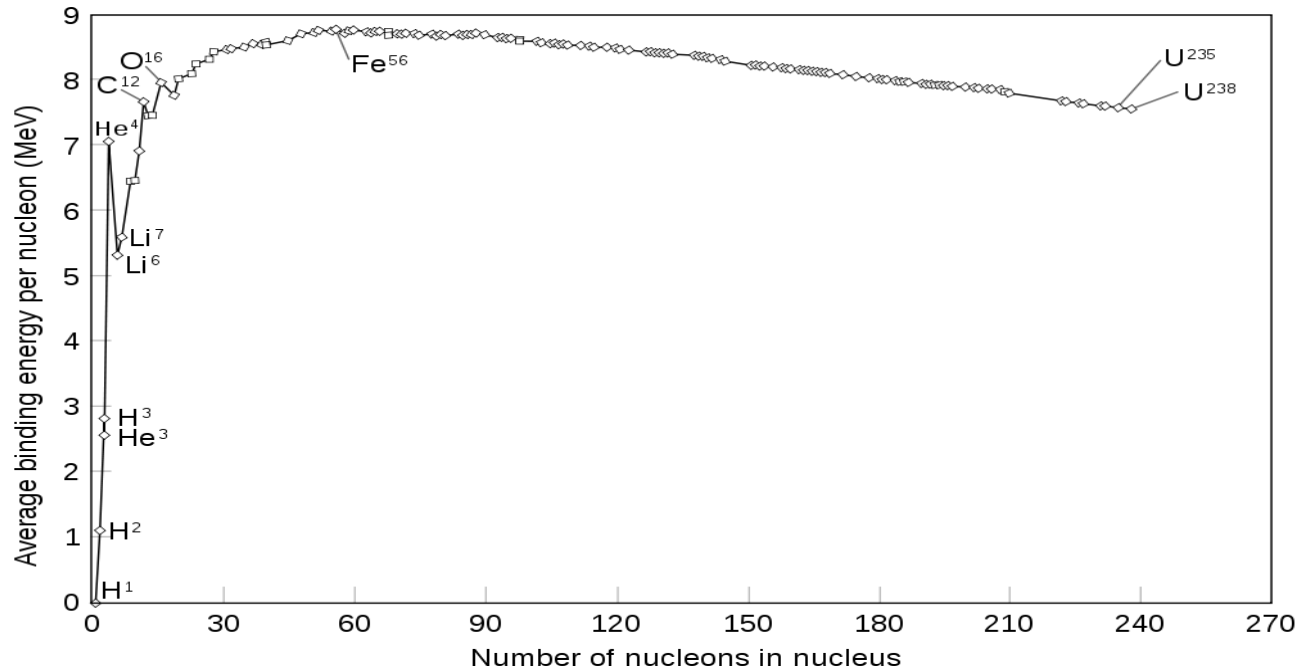
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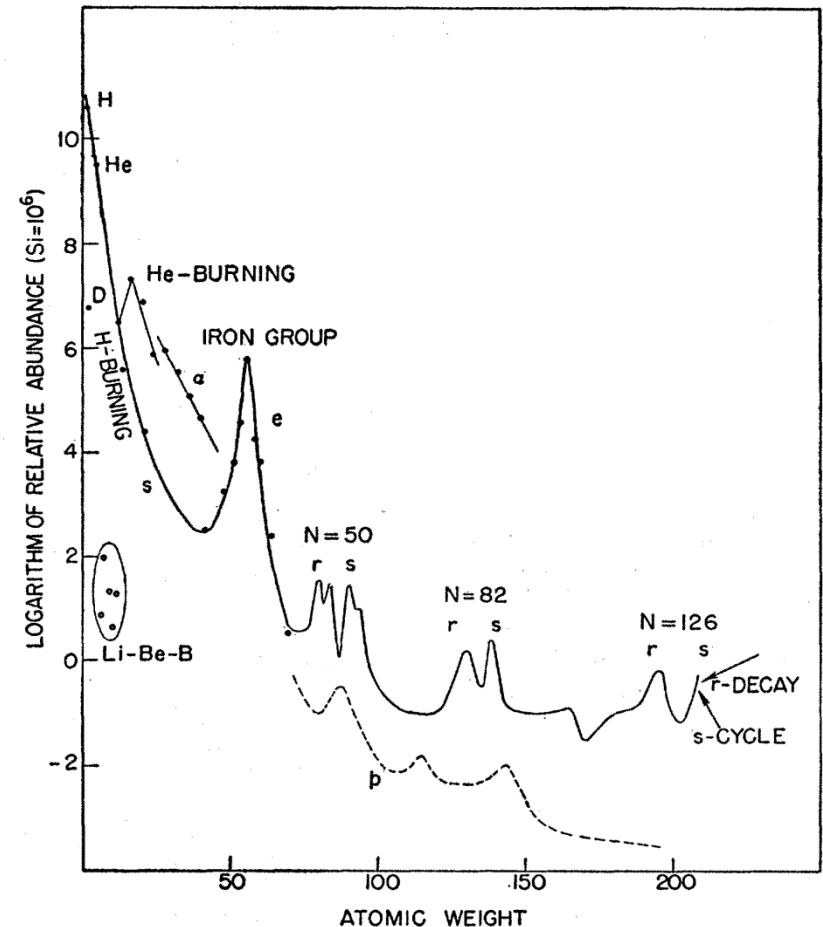
# Recap: Basics of nucleosynthesis past Fe



- For elements heavier than iron, creation through fusion is an endothermic process
- The coulomb repulsion becomes more and more significant with growing  $Z$
- This impedes heavy element creation through primary burning or charged particle reactions

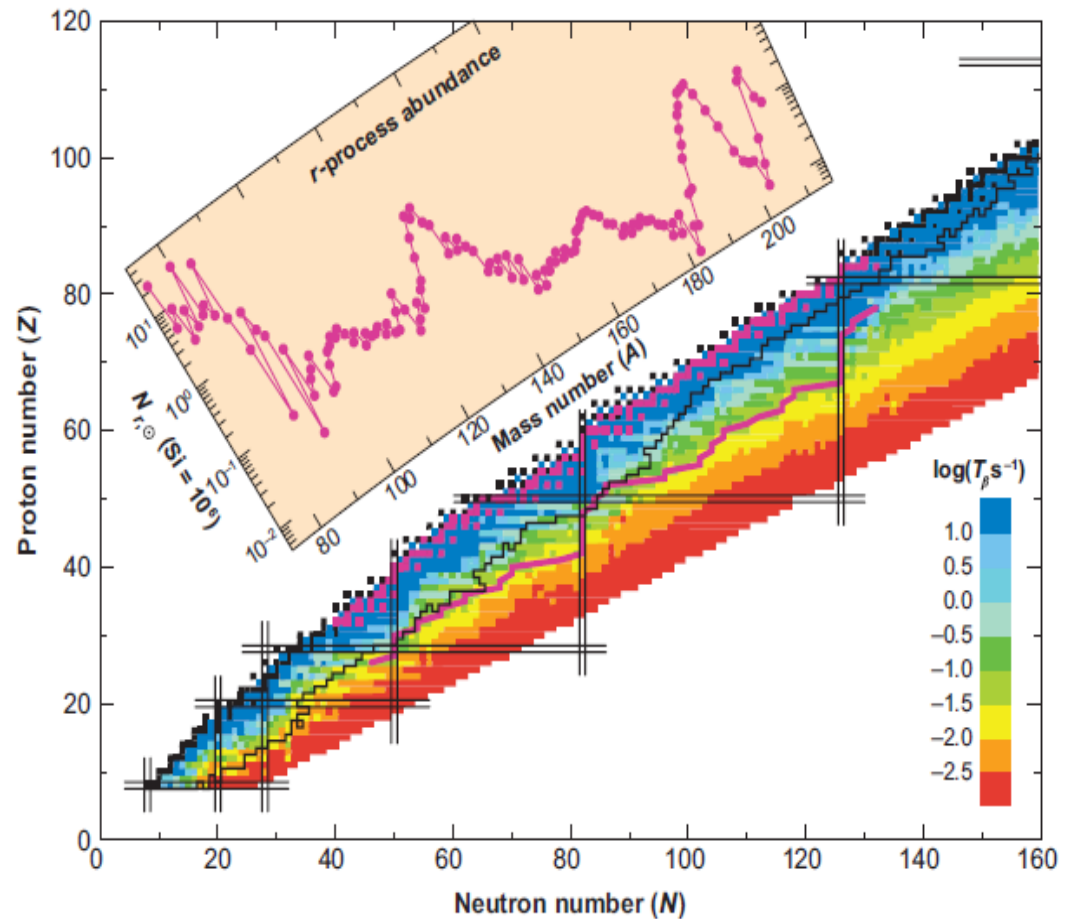
# Recap: Basics of nucleosynthesis past Fe

- Neutron captures are not hindered by coulomb repulsion
- Main mechanism: seed elements encounter an external neutron flux
- 2 primary contributions, r(rapid) and s(slow) processes identified
  - Main difference: neutron density
- Additional p-process: proton capture, insignificant for high Z



# Recap: Basics of nucleosynthesis past Fe

- R-process basics:
  - high neutron densities ( $>10^{20} \text{ cm}^{-3}$ )
  - Very short time scales (seconds)
  - Moves on the neutron rich side of the valley of stability
  - Stable nuclides reached through beta decay chains after the neutron exposure
  - Final abundances very uniform in all stars

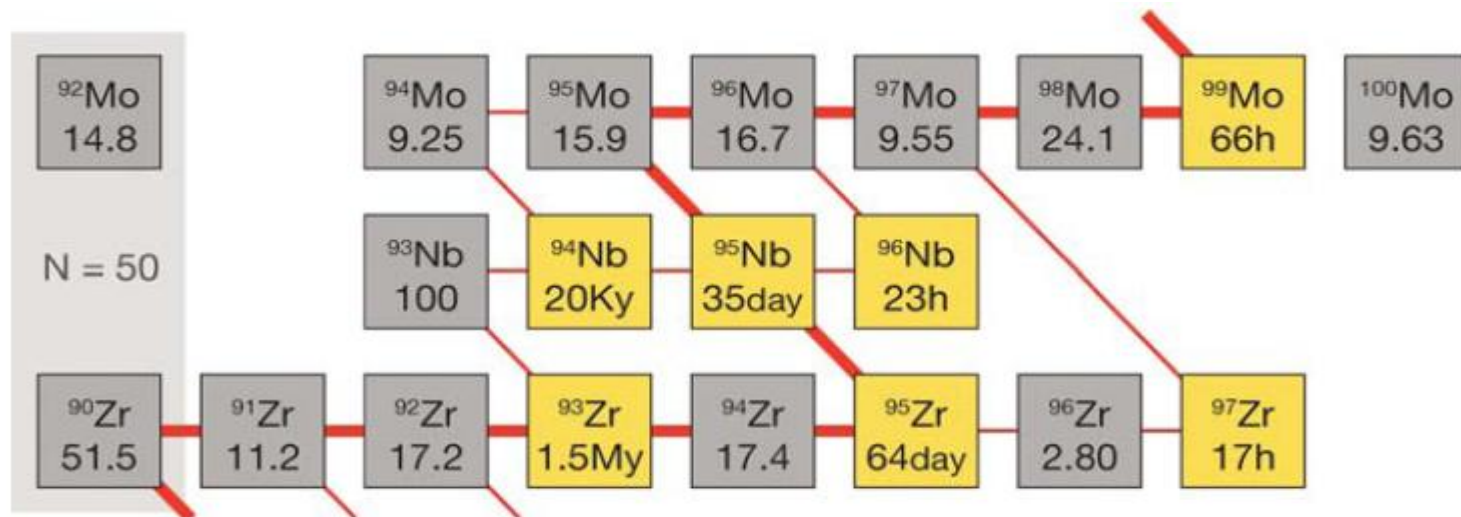


# Nuclear physics of the s-process

- S-process basics:
  - Neutron densities in the order of  $10^6$ - $10^{11}$   $\text{cm}^{-3}$
  - Neutron capture rates much lower than beta decay rates
  - After each neutron capture, the product nucleus has time to decay if it is unstable
  - Moves along the valley of stability
  - Process timescales in the order of years
  - Final abundances depend on the site observed
  - Reaction paths depend on astronomical conditions

# Nuclear physics of the s-process

- Neutron captures increase the mass number through (n, $\gamma$ ) reactions
- The products will beta-decay until a stable (or long-lived) isotope is reached
- Depending on temperature and neutron flux, branchings may be activated when the neutron capture rate reaches the beta decay rate's order of magnitude



# Nuclear physics of the s-process

- Simplified reaction network of the s-process:
  - Assuming the beta decay rates to greatly exceed neutron absorption, we can separate the two processes
  - Neutron captures determine the total abundance of a certain mass number
  - Beta decays determine the elemental composition for a certain mass number
  - Using thermally averaged cross-sections and thermal velocities, we get

$$\begin{aligned}\frac{d}{dt} N_A &= \langle \sigma_{A-1} v \rangle N_{A-1} n_n - \langle \sigma_A v \rangle N_A n_n \\ &= \langle \sigma_{A-1} \rangle v_T N_{A-1} n_n - \langle \sigma_A \rangle v_T N_A n_n\end{aligned}$$

# Nuclear physics of the s-process

- An important quantity used in calculations equations is the neutron exposure  $\tau = \int v_T n_n(t) dt$
- As an estimate for the area between magic neutron numbers, we can set the derivative to zero (equilibrium state). This yields the local approximation:

$$\langle \sigma_{A-1} \rangle N_{A-1} \approx \langle \sigma_A \rangle N_A$$

- Between magic configurations, we expect the abundances to behave inversely to the respective thermally averaged neutron absorption cross-sections

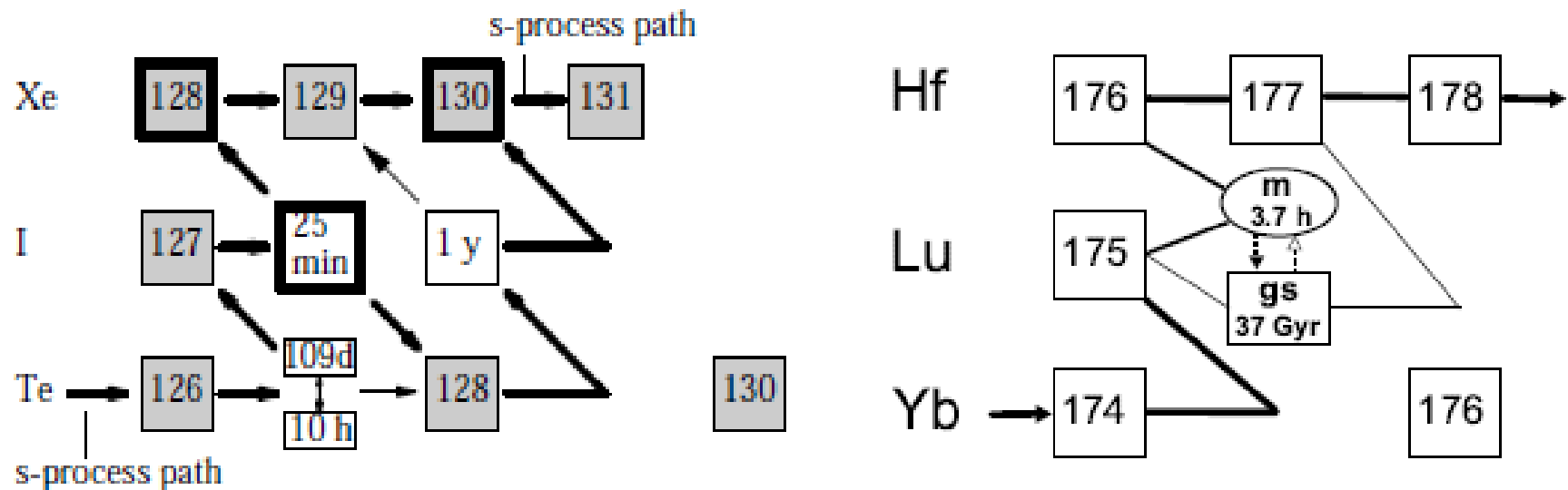
# Nuclear physics of the s-process

- To decrease complexity, the starting point of the s-process network may be set to iron, as the contributions from lighter, less abundant elements can be neglected
- The s-process network goes up to  $^{209}\text{Bi}$ . As there are no stable nuclei with  $A > 209$ , neutron capture will lead back to the previous s-process elements by alpha decay of the capture products
- Magic neutron numbers produce three major peaks in the abundance distribution.
  - $N=50$  (Sr/Y/Zr): "ls" (light-s) peak
  - $N=82$  (Ba/La/Ce/Pr/Nd): "hs" (heavy-s) peak
  - $N=126$  (Pb/Bi) : Pb peak

$^{208}\text{Po}$ 2.898 Y	$^{209}\text{Po}$ 102 Y	$^{210}\text{Po}$ 138.376 D	$^{211}\text{Po}$ 0.516 S
$\alpha$ : 100.00% $\epsilon$ : 4.0E-3%	$\alpha$ : 99.52% $\epsilon$ : 0.48%	$\alpha$ : 100.00%	$\alpha$ : 100.00%
$^{207}\text{Bi}$ 32.9 Y	$^{208}\text{Bi}$ 3.68E+8 Y	$^{209}\text{Bi}$ STABLE 100%	$^{210}\text{Bi}$ 5.012 D
$\epsilon$ : 100.00%	$\epsilon$ : 100.00%		$\beta^-$ : 100.00% $\alpha$ : 1.3E-4%
$^{206}\text{Pb}$ STABLE 24.1%	$^{207}\text{Pb}$ STABLE 22.1%	$^{208}\text{Pb}$ STABLE 52.4%	$^{209}\text{Pb}$ 3.253 H $\beta^-$ : 100.00%

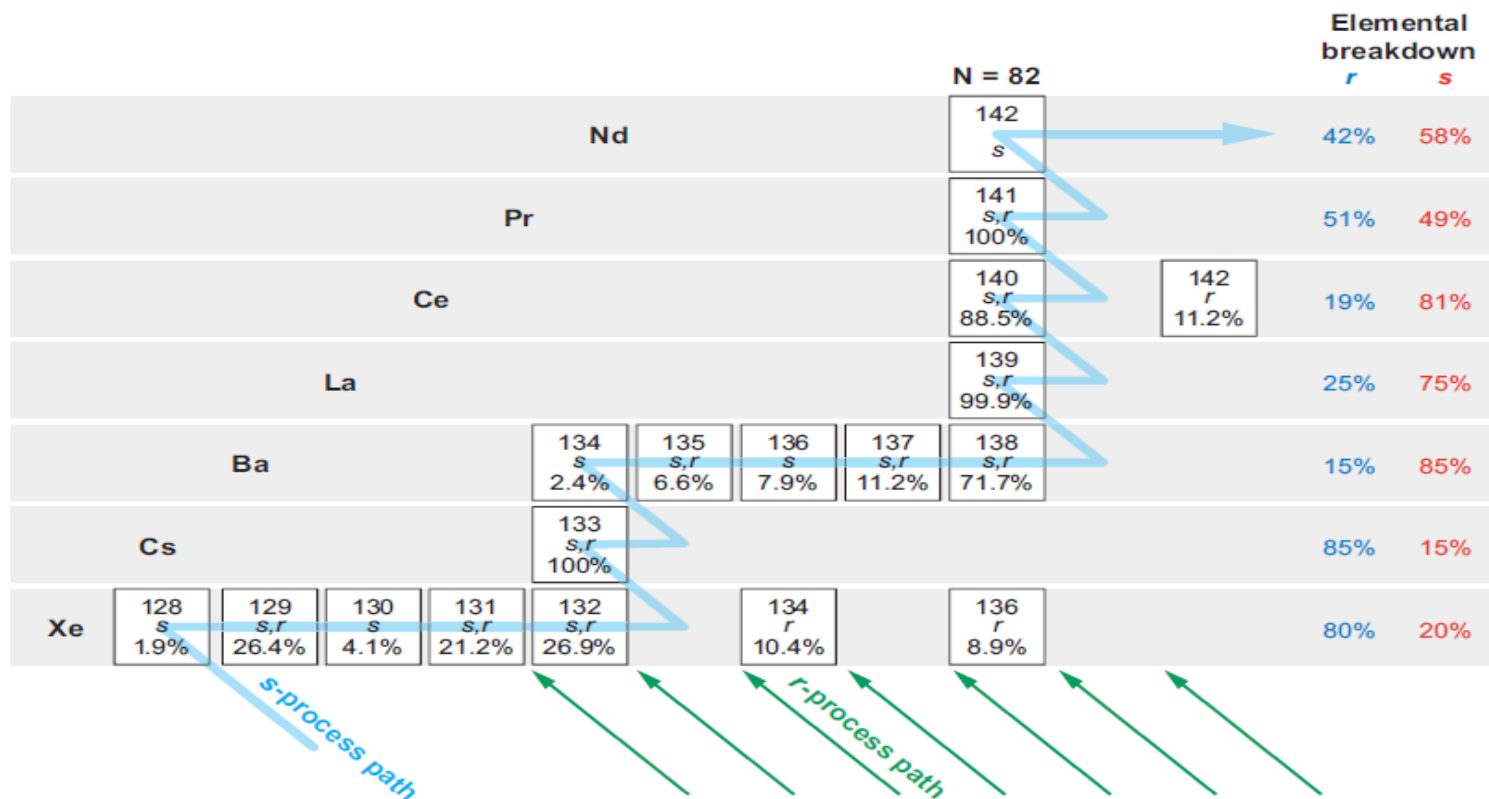
# Nuclear physics of the s-process

- Branchings of the s-process can yield a measure of the conditions at the production site
- Example:  $^{176}\text{Lu}/^{176}\text{Hf}$  branching (T-sensitive),  $^{128}\text{I}$  branching (T, electron density)



# Nuclear physics of the s-process

- Shielding: some nuclei are inaccessible for the r-process due to  $\beta$ -stable nuclei at the same  $A$  but lower  $Z$
- They can be used to extrapolate the s-process part of the measured abundances

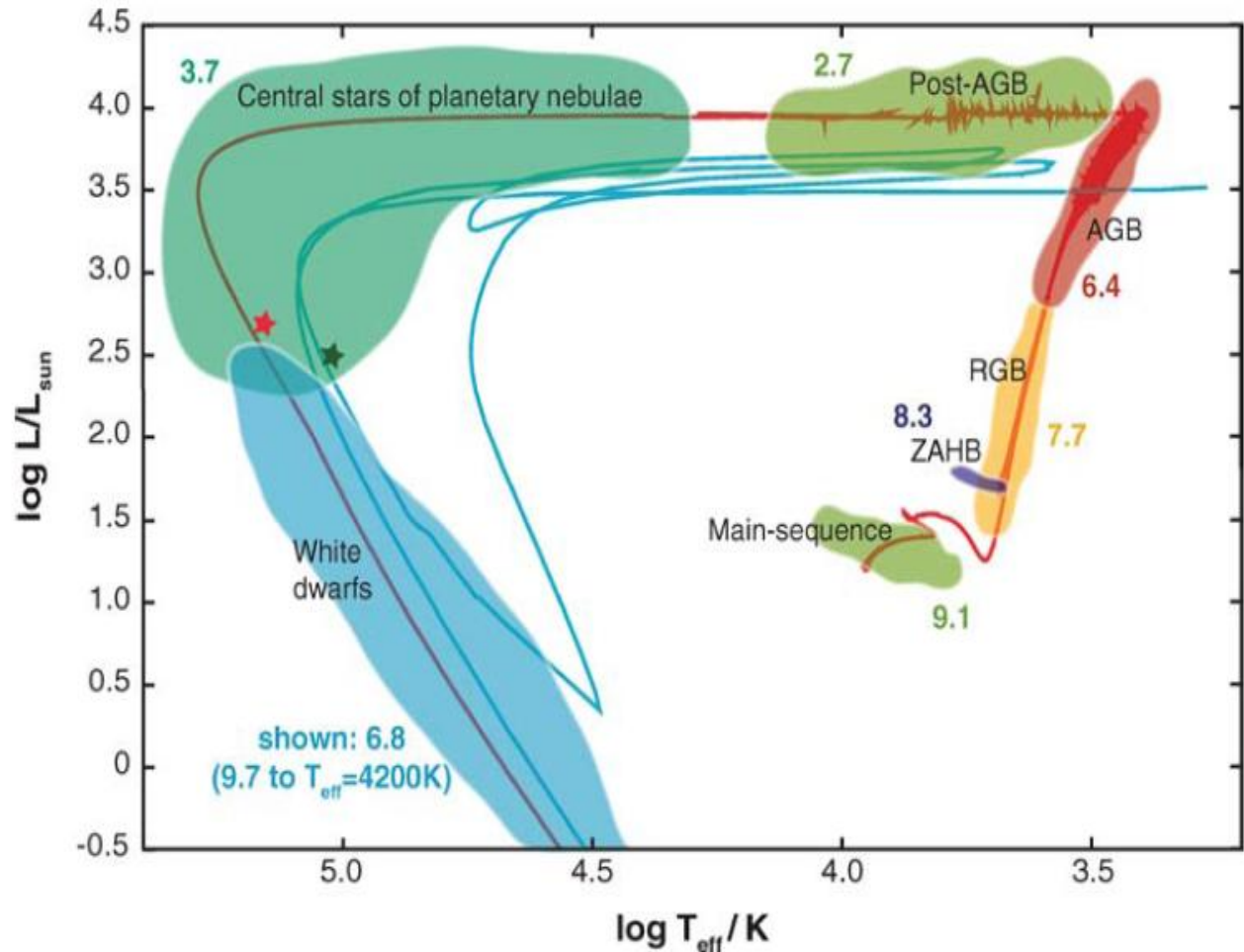


# S-process production sites

- Components of the s-process:
  - Weak component: in massive stars during He/C core burning
    - Neutron source:  $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$
    - Reaches up to  $A < 80$
  - Main component: in thermally pulsing AGB stars
    - Majority of observed abundances
    - Neutron sources:  $^{13}\text{C}(\alpha, n)^{16}\text{O}$ ;  $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$

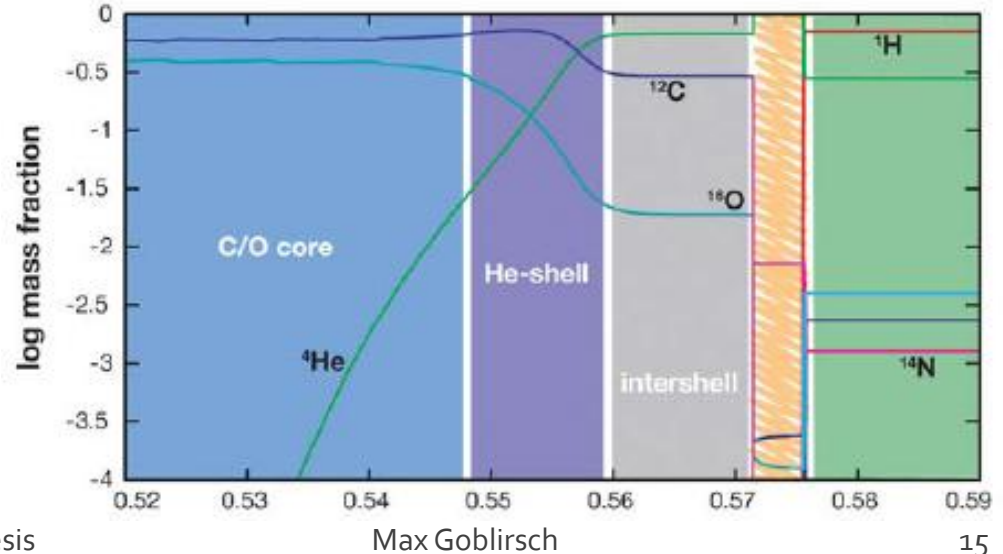
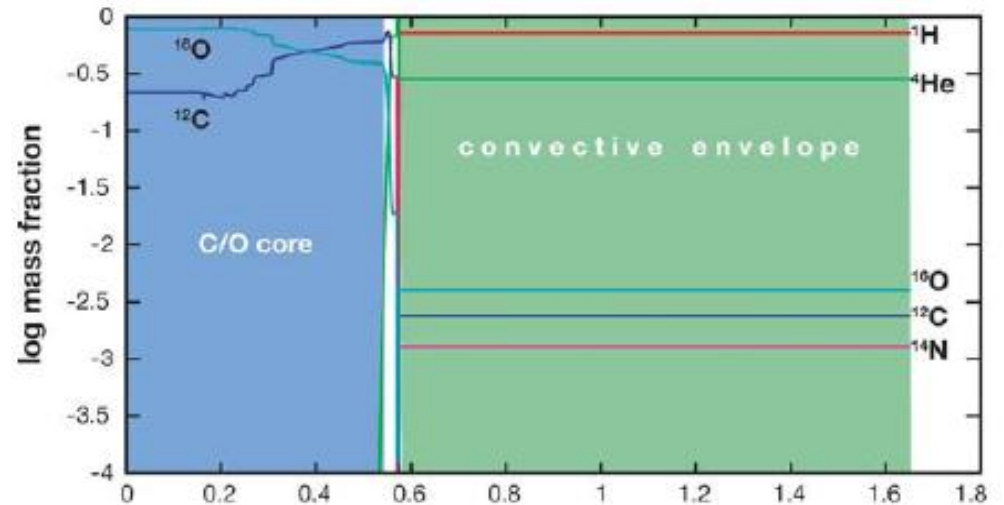
# S-process production sites

- AGB: Asymptotic Giant Branch
- Reached by Stars above  $\sim 1.8 M_{\odot}$
- Takes place after H and He core burning are exhausted
- H shell burning and short phases of He shell burning



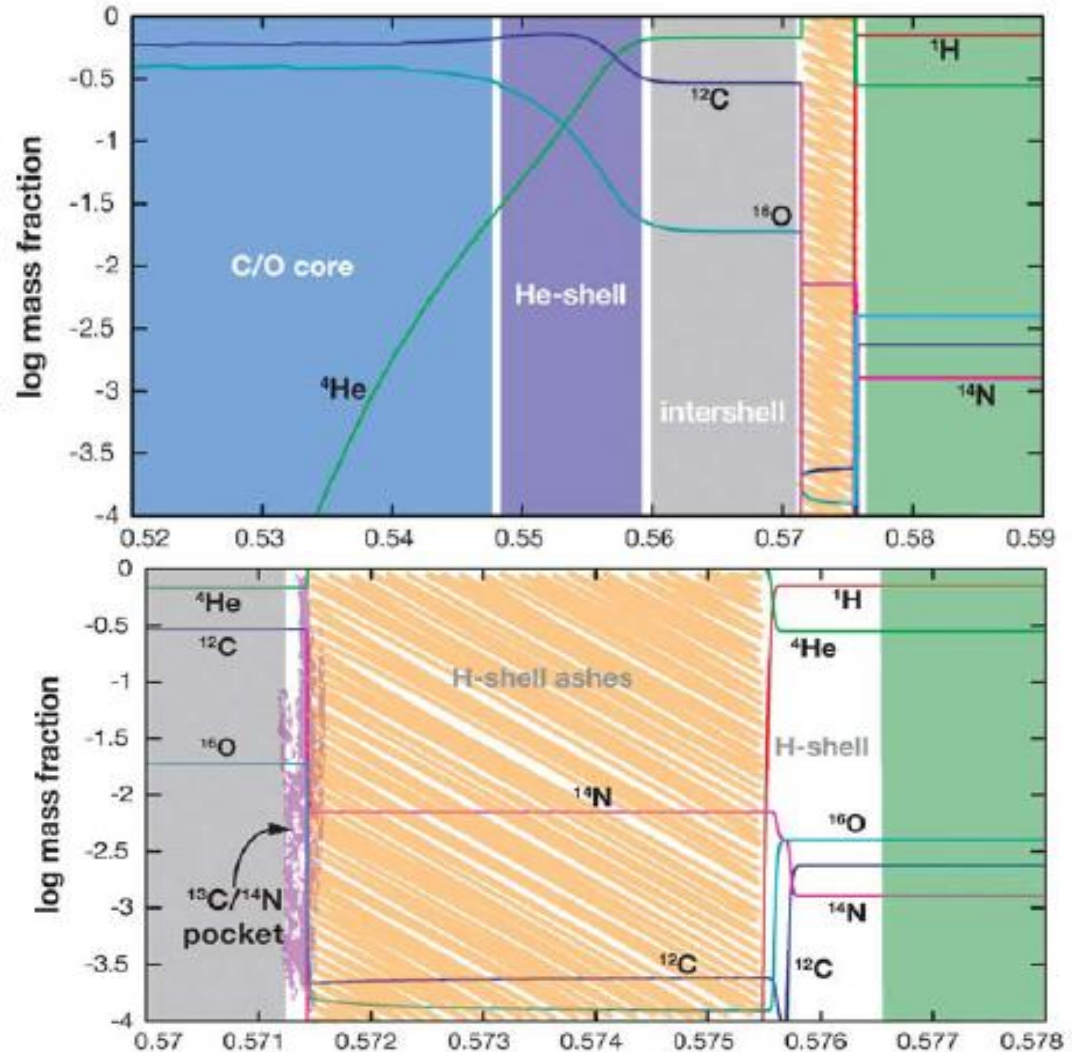
# S-process production sites

- Interior Structure:
  - C/O Core
  - He Shell
  - He Intershell Region (H-burning ashes)
  - H Shell
  - Convective Envelope
  
- In the mass range relevant for the s-process: core does not ignite C burning



# S-process production sites

- Energy production: 2 components
- H shell burning
  - Pure H burning + CNO cycle
  - Duration:  $\sim 10^5$  y per phase
  - Reaction products (He, CNO) accumulate below the H shell in the intershell region

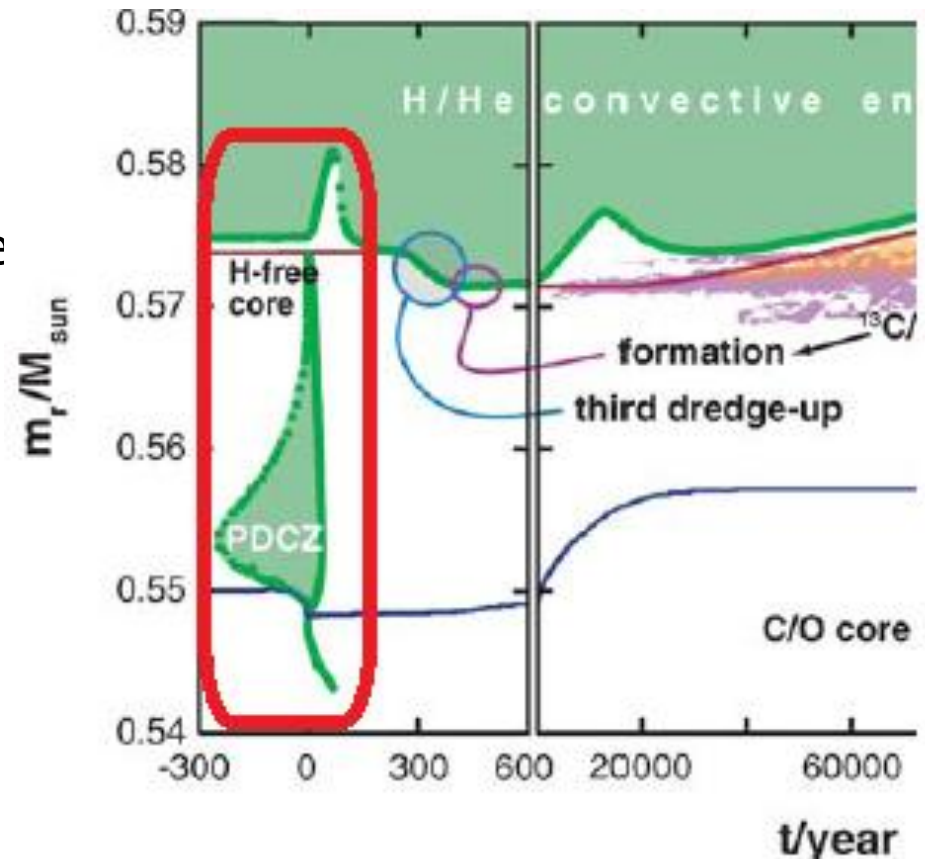


# S-process production sites

- The He shell increases in density, leading to a degenerate electron gas state ( $M < 2.5M_{\odot}$ )
- Thermal pulses (TP): When the He shell reaches sufficient temperature ( $T_8 \approx 1$ ), He burning is ignited
  - Primarily  $3\alpha$  reaction
- The degenerate electron gas state prevents compensation through expansion
  - Thermonuclear runaway, high temperatures ( $T_8 \approx 3$ )
- He burning lasts only short time,  $\sim 10^2$  y

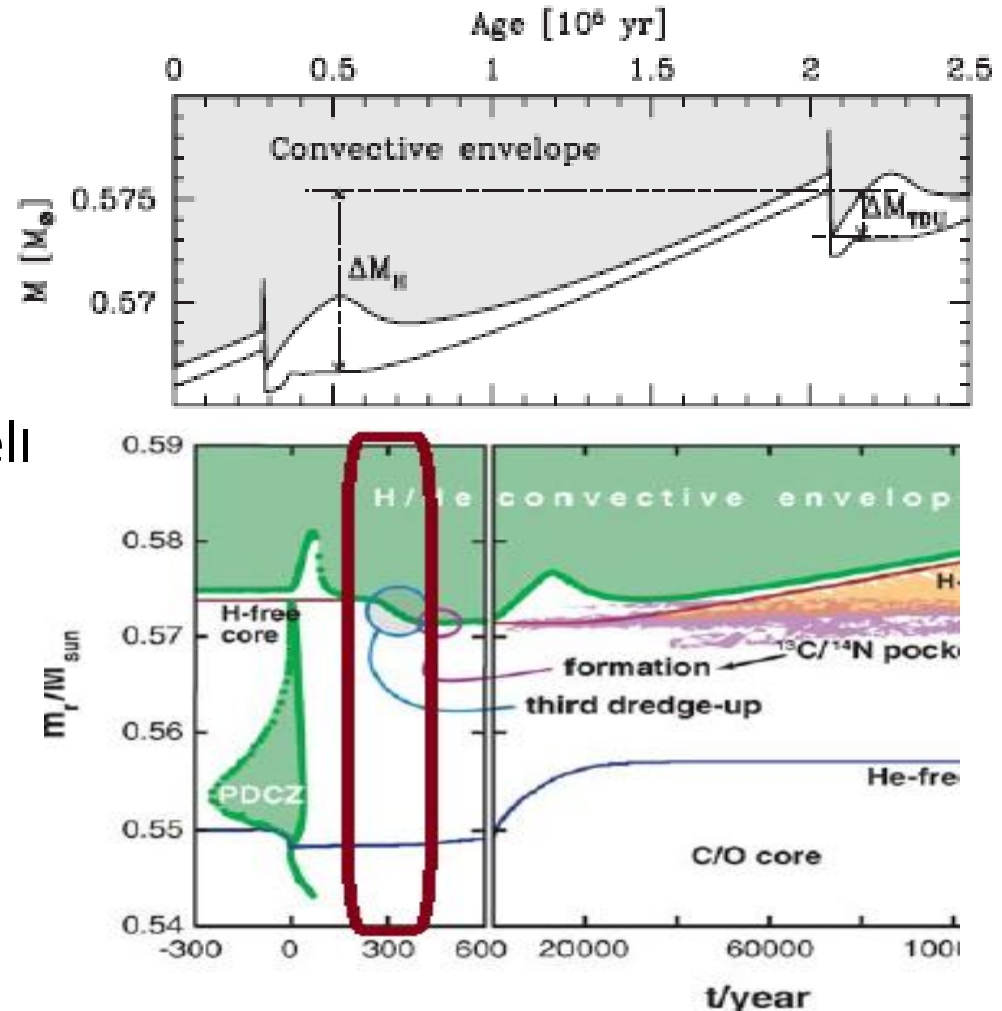
# S-process production sites

- The He shell burning causes convection in the intershell region
- Pulse driven convection Zone (PDCZ)
- High He-burning temperatures found at the bottom of the convection zone
- This mixes He burning products into the intershell
  - Especially important for s-process:  $^{12}\text{C}$



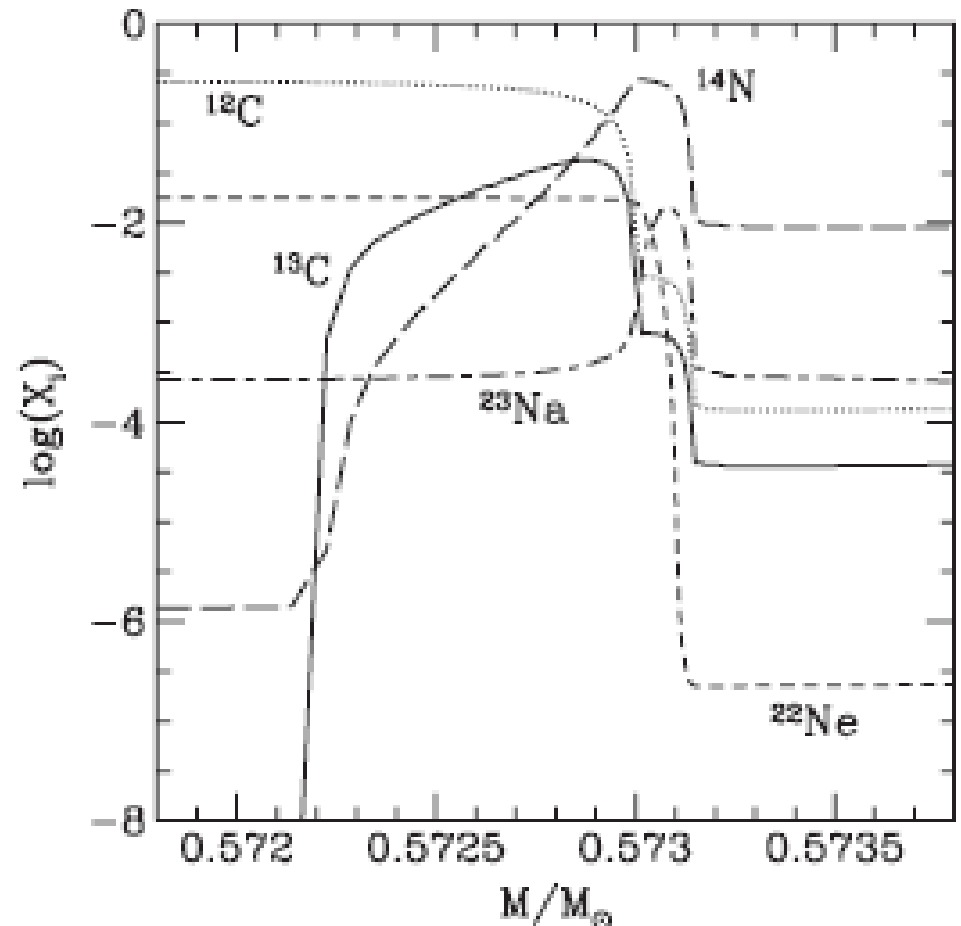
# S-process production sites

- When He burning is exhausted: H shell contracts and reignites
- Pulse-driven convection in the intershell stops
- The contraction of the H shell will lead the convective envelope to penetrate into the intershell region
- This causes mixing of intershell material into the convective envelope and vice-versa



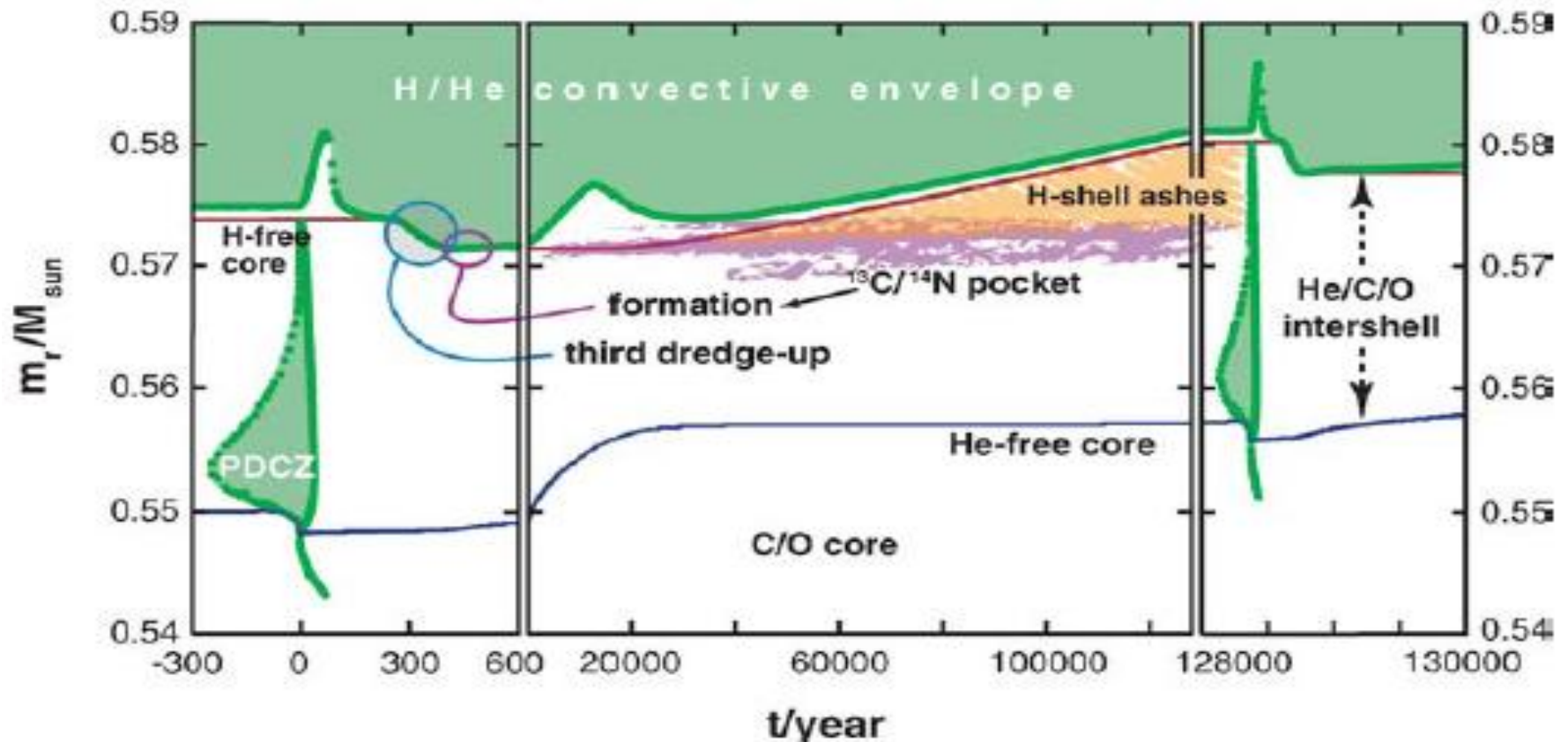
# S-process production sites

- Intershell region after thermal pulse and third dredge-up:
  - Protons from the TDU
  - $^{12}\text{C}$  from the He shell
  - $^{14}\text{N}$  from the TDU
- This allows for proton capture reactions:
  - $^{12}\text{C}(p,\gamma)^{13}\text{N}(\beta^+)^{13}\text{C}$
  - $^{13}\text{C}(p,\gamma)^{14}\text{N}$
- Formation of  $^{13}\text{C}$  and  $^{14}\text{N}$  pockets in the intershell after third dredge-up



# S-process production sites

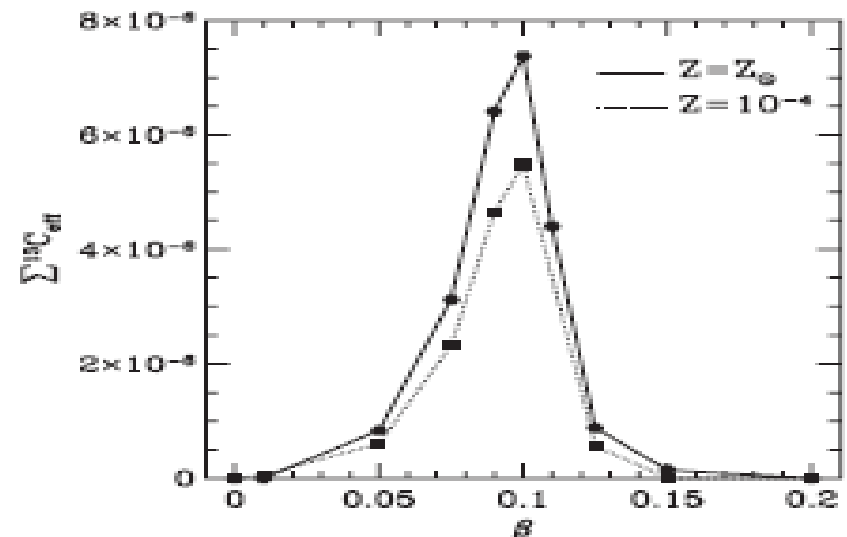
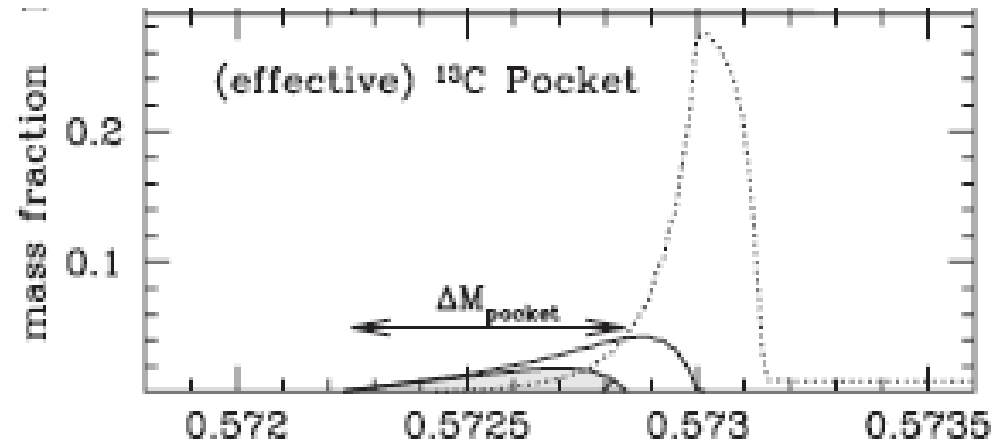
- Overview of the entire process



# S-process production sites

- The  $^{13}\text{C}$  pocket hosts the  $^{13}\text{C}(\alpha, n)^{16}\text{O}$  reaction, delivering neutrons for the s-process
- $^{14}\text{N}$  acts as a neutron poison, absorbing neutrons required for nucleosynthesis
  - $^{14}\text{N}(n, \gamma)^{15}\text{N}$
- Competition between  $^{13}\text{C}$  and  $^{14}\text{N}$  (pockets overlap)
- Effective  $^{13}\text{C}$  mass defined as relevant parameter for the total neutron exposure available to the s-process

$$X^{\text{eff}}(^{13}\text{C}) = X(^{13}\text{C}) - \frac{13}{14} X(^{14}\text{N})$$

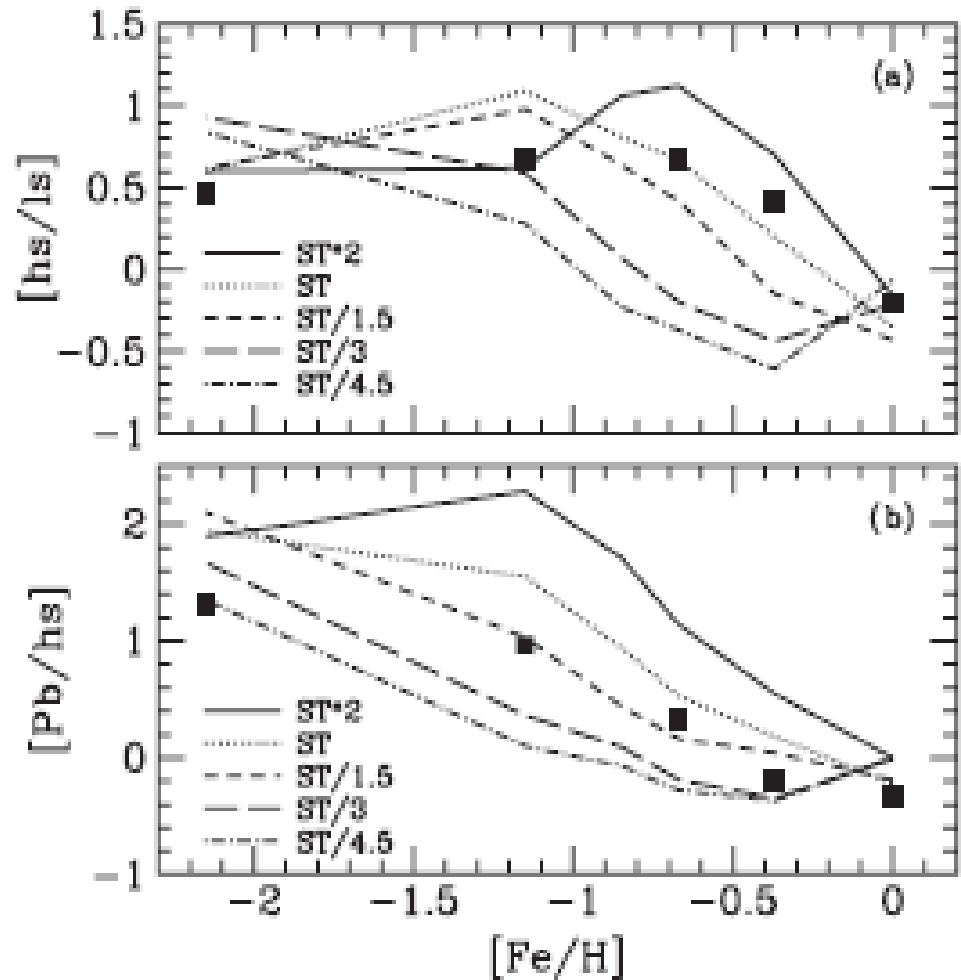


# S-process production sites

- The subsequent thermal pulse will spread the s-process material through the intershell
- During the pulse, the  $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$  reaction may activate at the bottom of the pulse driven convection zone
  - Possible for higher mass stars
  - High neutron densities ( $10^{11}\text{cm}^{-3}$ , compared to  $10^7\text{cm}^{-3}$  from the  $^{13}\text{C}$  source) for short periods
  - PDCZ convection will expose s-process material to these neutrons, enhancing the resulting abundances
  - The different neutron densities and temperatures may activate new branchings
- The next third dredge-up will mix s-process products into the envelope, making them observable through spectroscopy
- This entire cycle will repeat several times until the star moves on in the HRD

# S-process production sites

- The observed abundance distributions and the total amount of material generated depend on metallicity ( $[Fe/H]$ )
- High metallicity: Much seed material, large amounts of products, but bias on  $ls$  elements (more seeds compete for a constant # of neutrons)
- Low metallicity: less total amount, bias on  $hs$  peak (fewer seeds, same amount of  $n$ )
- Very low metallicity: Bias on  $Pb$  peak but only minimal total amounts generated



# S-process production sites

- Open Question: TDU Mechanism
  - Convection only modelled by inaccurate Mixing-Length-Theory
  - MLT alone does not yield required  $^{13}\text{C}$  pocket
    - First approach: Assume a fixed, constant pocket size (“Standard Theory”)
    - Modifications of the MLT model: Exponential overshooting at the edges of the convection zone, shear from rotation, gravity waves
    - Parameters calibrated to fit measurements and theoretical requirements
  - The existence of a TDU is supported by observation: C-star formation
    - C from the intershell is admixed into the envelope, increasing [C/O] ratios and significantly altering opacity and resulting mass loss etc

# Summary

- S-process: slow neutron capture, neutron captures much slower than beta decays
- 3 peaks (ls,hs,Pb) at magic N, local approximation in between
- Site: Thermal pulsing AGB stars
- Neutron sources:  $^{13}\text{C}(\alpha,n)^{16}\text{O}$ ,  $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$
- Observations and results strongly linked to processes in the specific star

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