HELIUM25 - Helium burning and perspectives for underground labs

Dresden, July 21, 2025

Helium burning and its role in the synthesis of key heavy elements in rotating massive stars

Lorenzo Roberti, INFN – Laboratori Nazionali del Sud, Catania, Italy

Main collaborations:

Pandora + AsFiN

Budapest group: M. Pignatari, M. Lugaro

Rome + Berkeley group: M. Limongi, A. Chieffi, A. Falla, L. Boccioli

NuGriD collaboration

Helium burning in massive stars

- Leading reactions: 3α and $^{12}C(\alpha,\gamma)^{16}O$;
- Efficient $^{12}C(\alpha,\gamma)^{16}O$: C/O<1;
- $^{12}C(\alpha,\gamma)^{16}O$ determines the advanced evolution: compactness, explodability, black hole formation, shell interactions (C-O shell merger);
- Main site of weak s-process at ~solar metallicity via the activation of $^{22}Ne(\alpha,n)^{25}Mg$ (in competition with $^{22}Ne(\alpha,\gamma)^{26}Mg$).

The s-process during central He burning

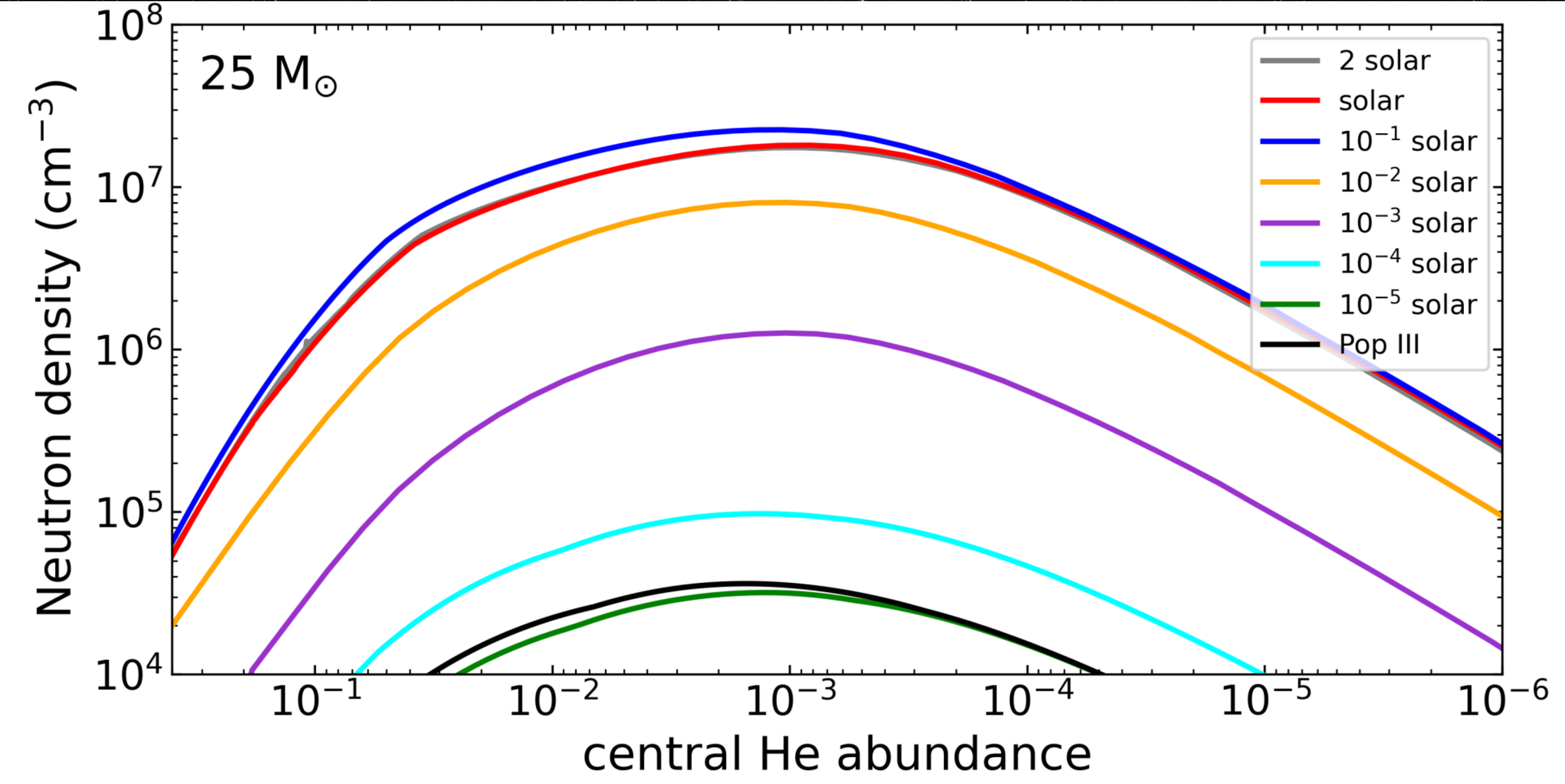
- $^{14}N(\alpha, \gamma)^{18}F(\beta^+)^{18}O(\alpha, \gamma)^{22}Ne$ at Tc~200 MK, followed by $^{22}Ne(\alpha,n)^{25}Mg$ at Tc~300 MK;

- Efficiency scales with the initial metallicity → depends on ^{14}N left by CNO cycle;

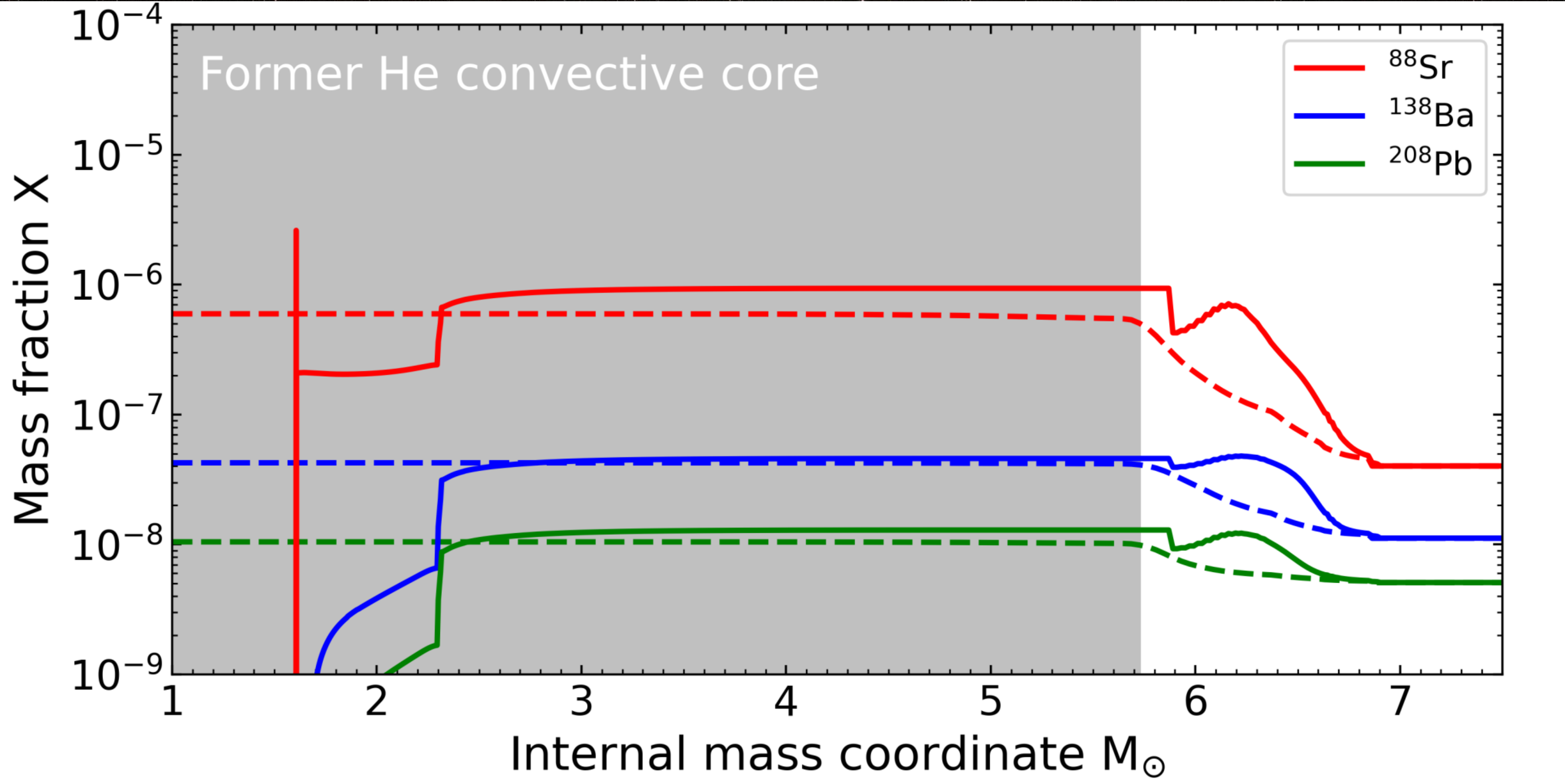
- Limited by the metallicity and low neutron-to-seed ratio: only able to produce weak s-process component (Sr, Y, Zr);

- The bulk of the s-process yields ejected after the CCSN is produced in central He burning; marginal contribution from the He and C burning shells.

The s-process during central He burning



The s-process during central He burning



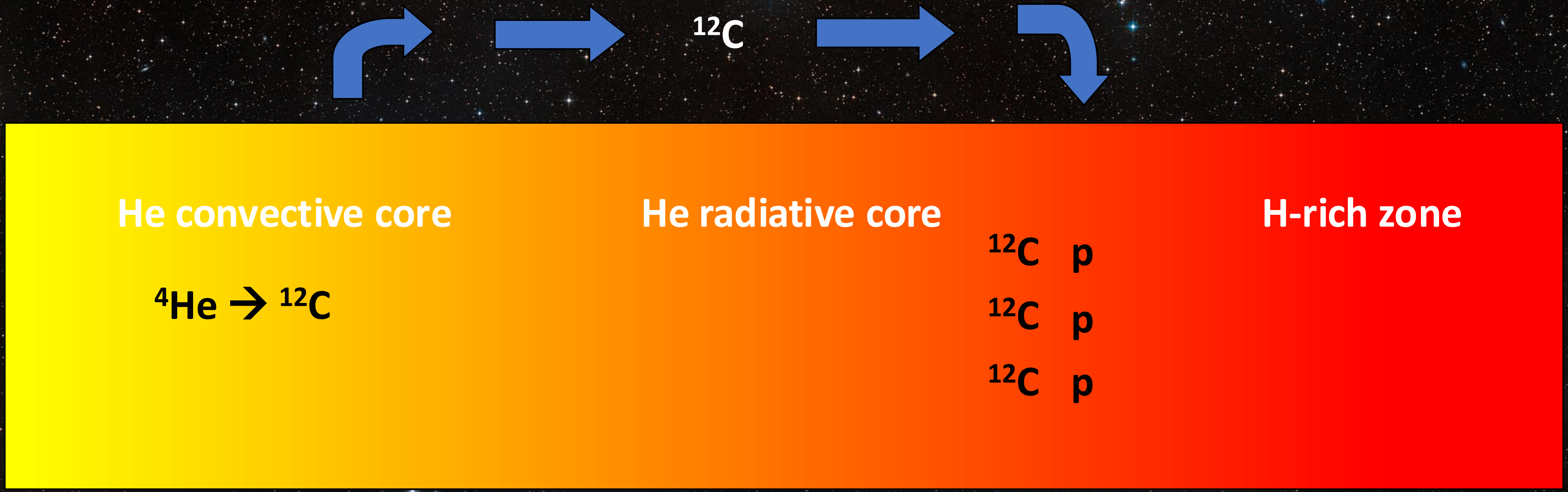
Helium burning in rotating massive stars

- Mixing between convective zones → longer central He burning phase;
- More efficient $^{12}C(\alpha,\gamma)^{16}O$: C/O<<1;
- Important in H and He central burning phases: advanced phases (C, Ne, O, Si burning) too fast compared to secular instabilities;
- Increased efficiency of the s-process (if envelope is not lost): faster rotating stars (more compact structure), higher neutron density, higher neutron-to-seed ratio.

Rotation induced mixing

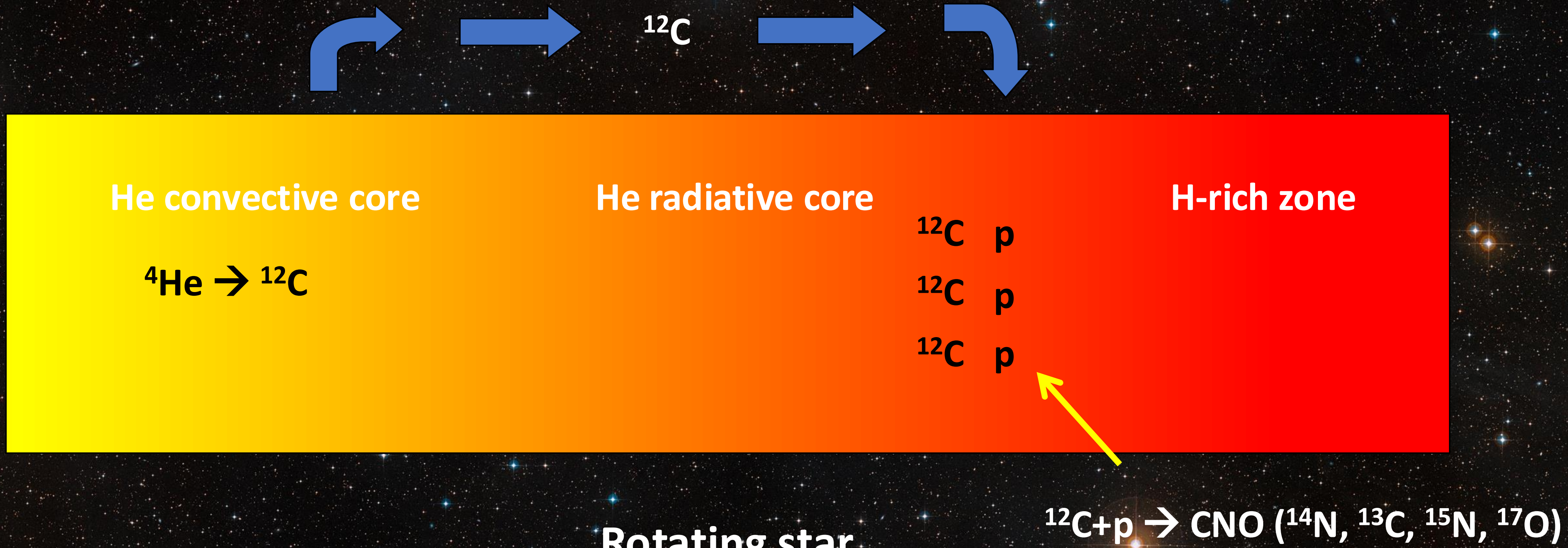
Non rotating star

Rotation induced mixing



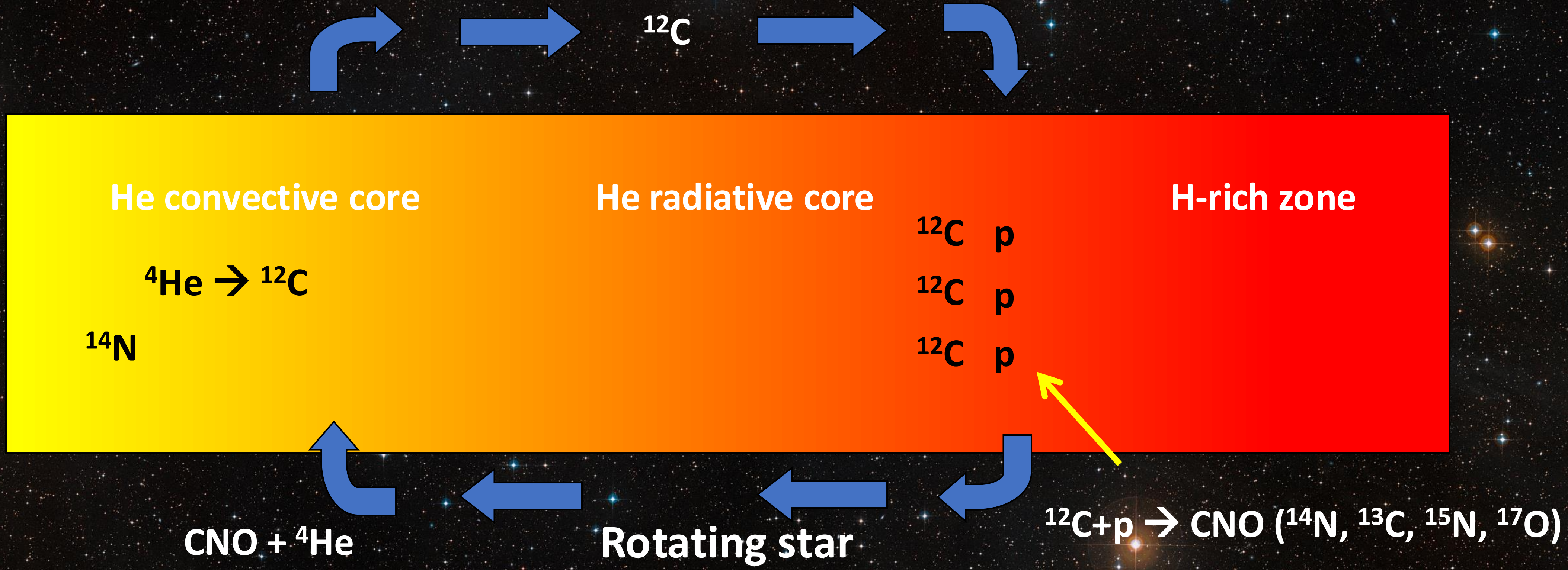
Rotating star

Rotation induced mixing

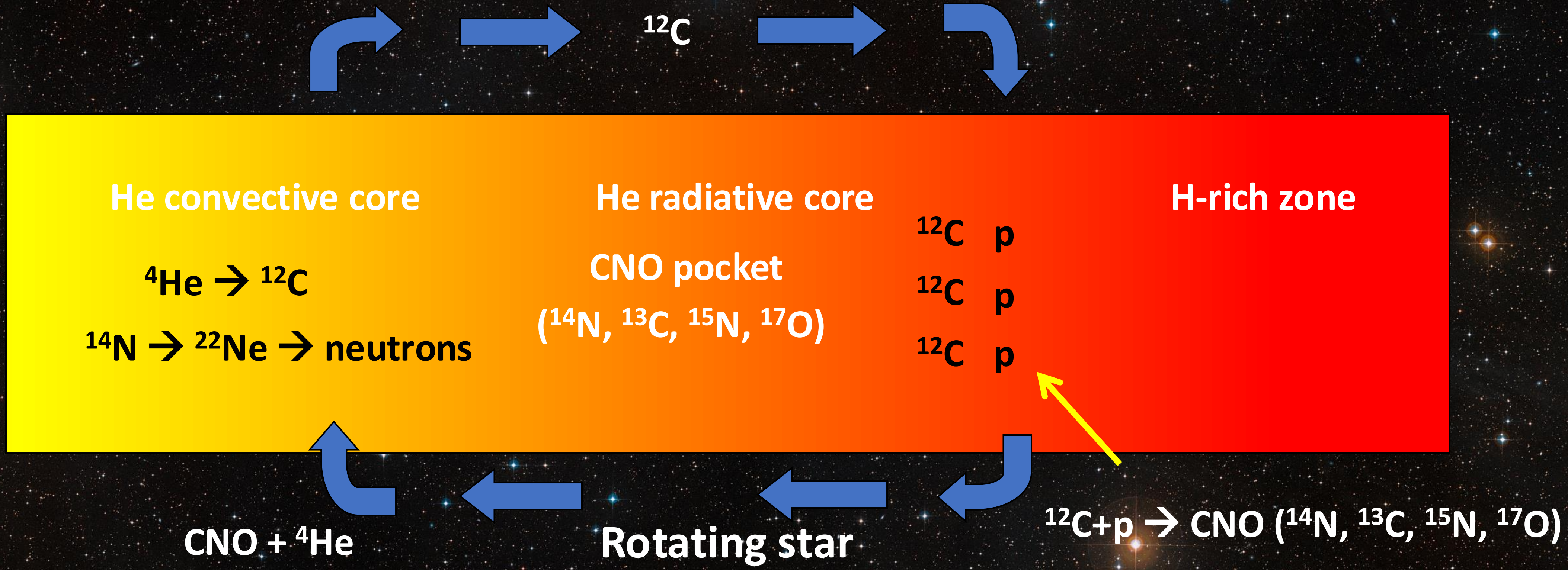


Rotating star

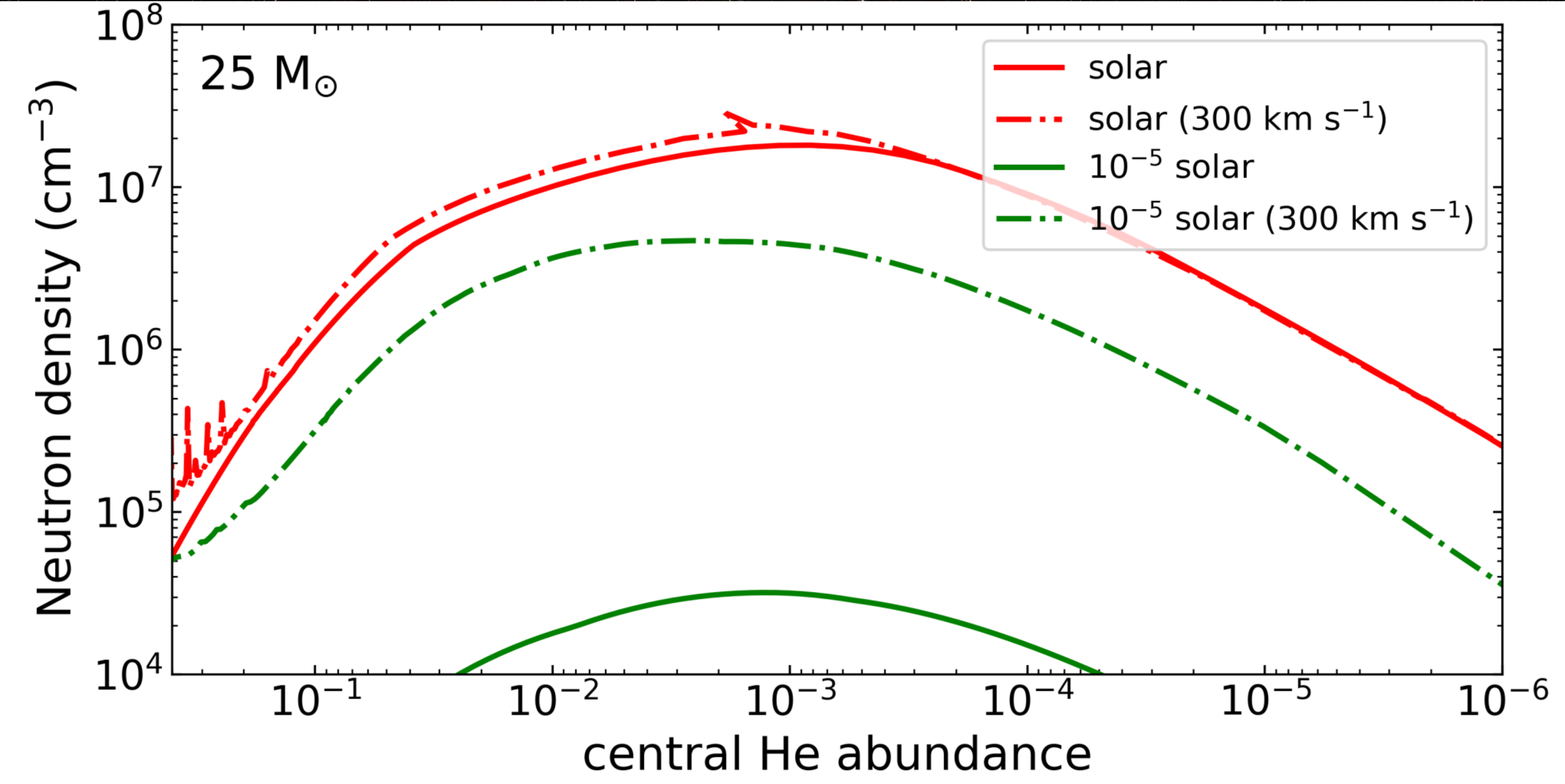
Rotation induced mixing



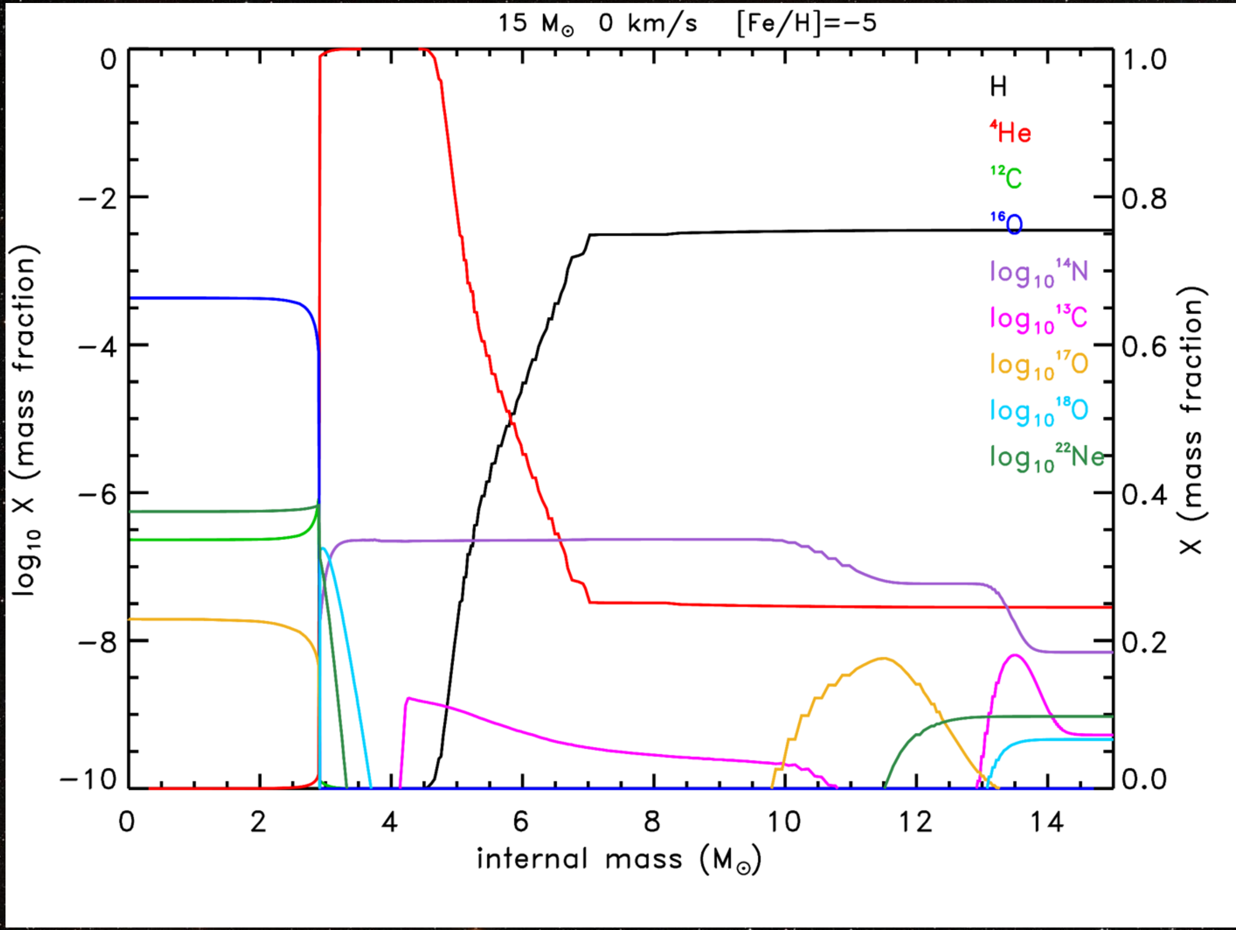
Rotation induced mixing

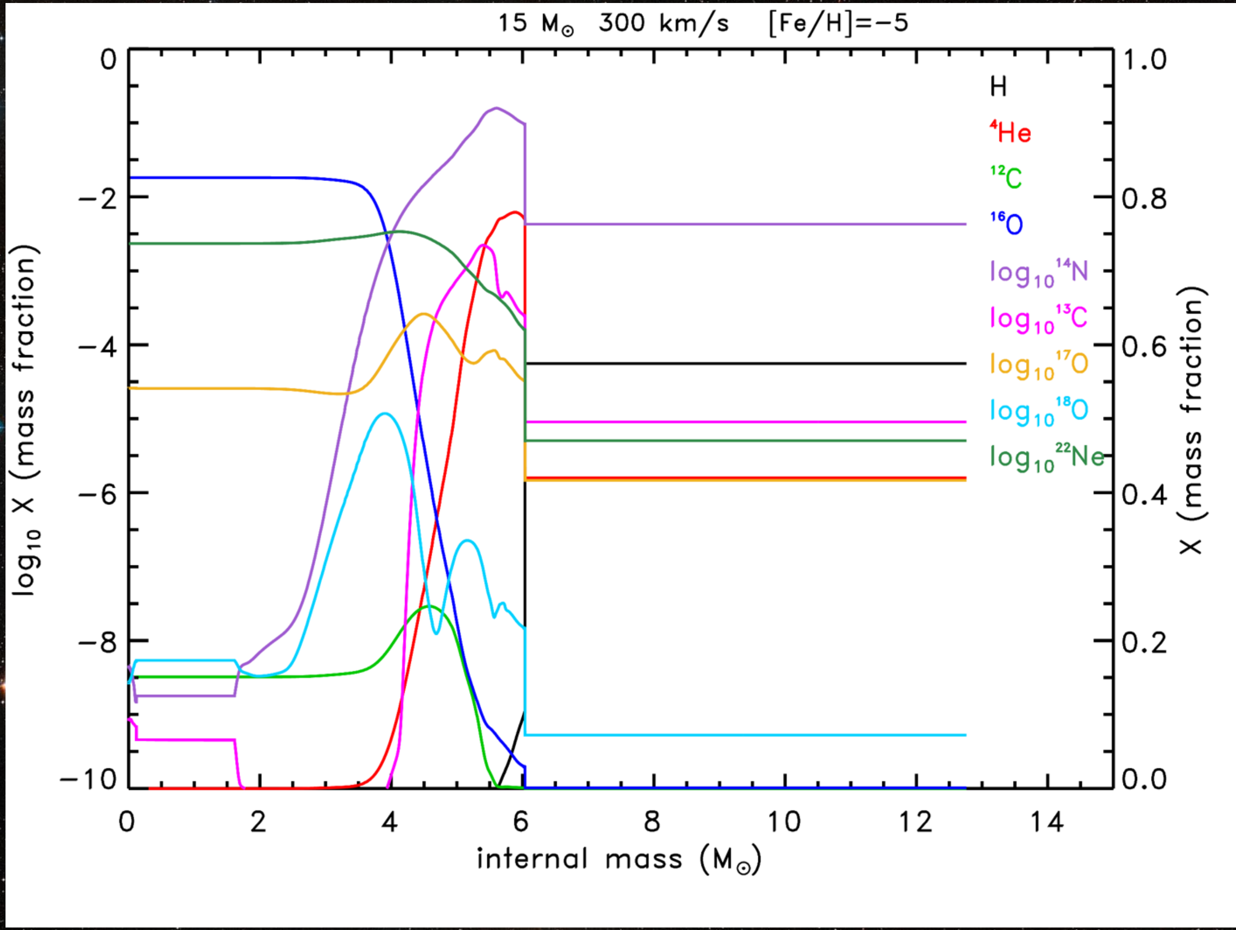


The s-process in rotating massive stars

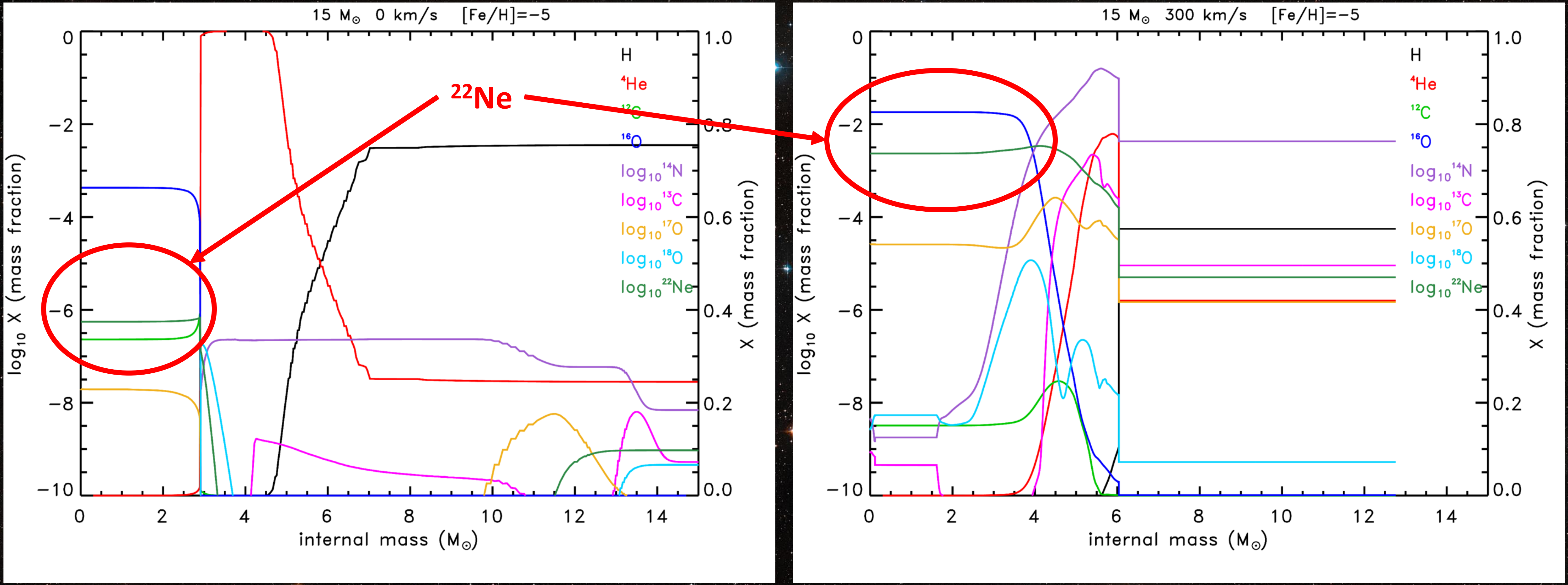


The s-process in rotating massive stars

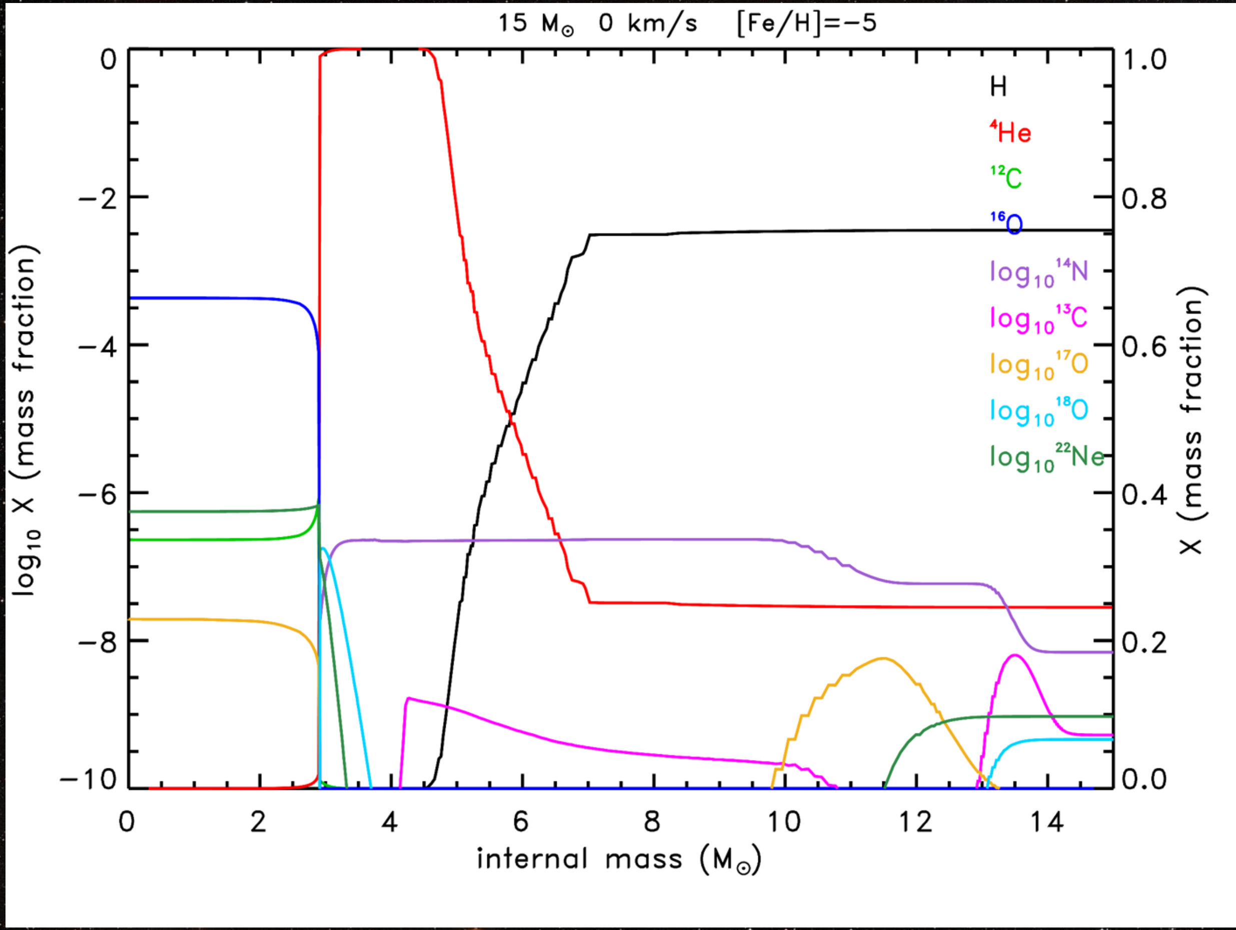


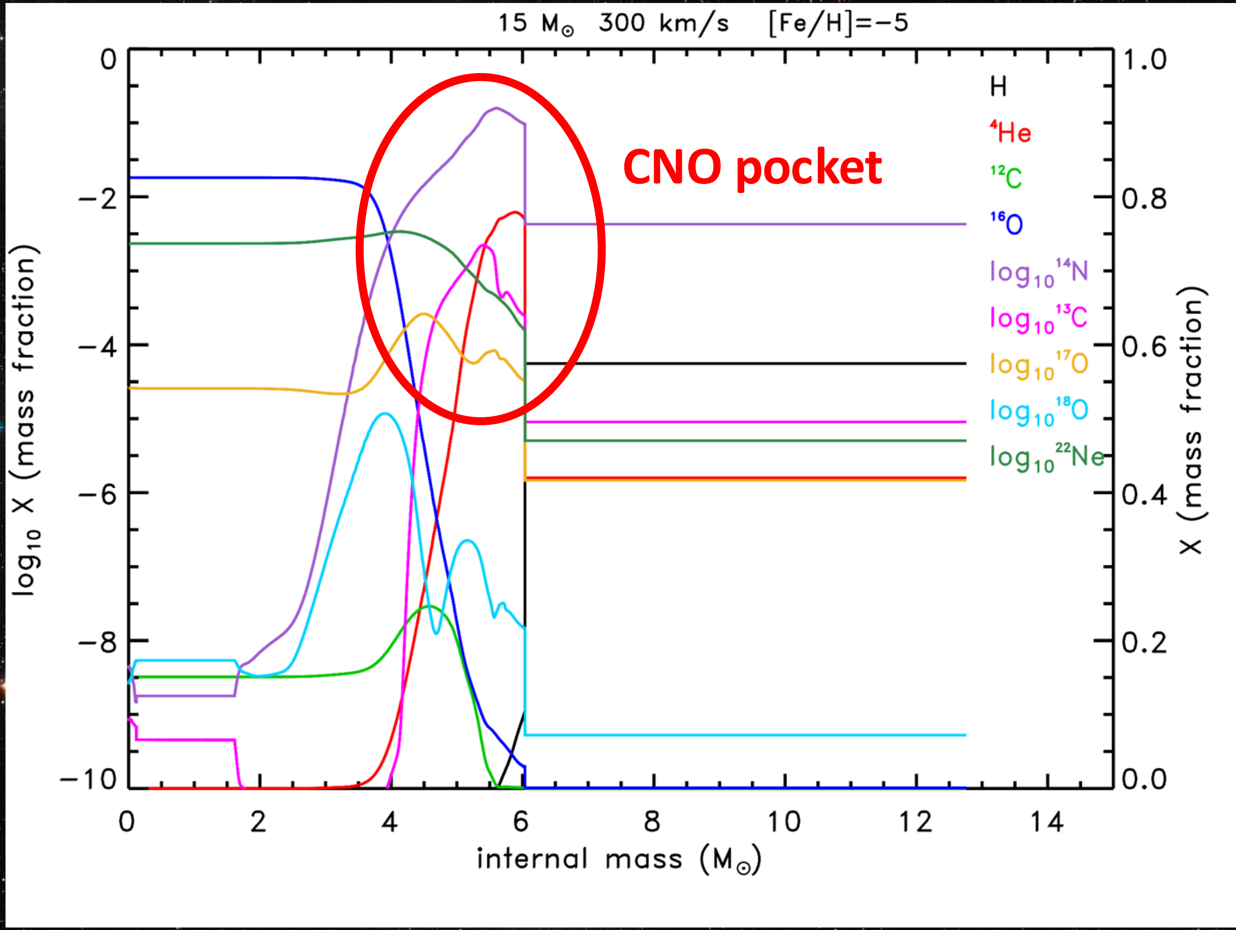


The s-process in rotating massive stars



The s-process in rotating massive stars





^{19}F production in rotating massive stars

- ^{19}F is produced through the chain of reactions:

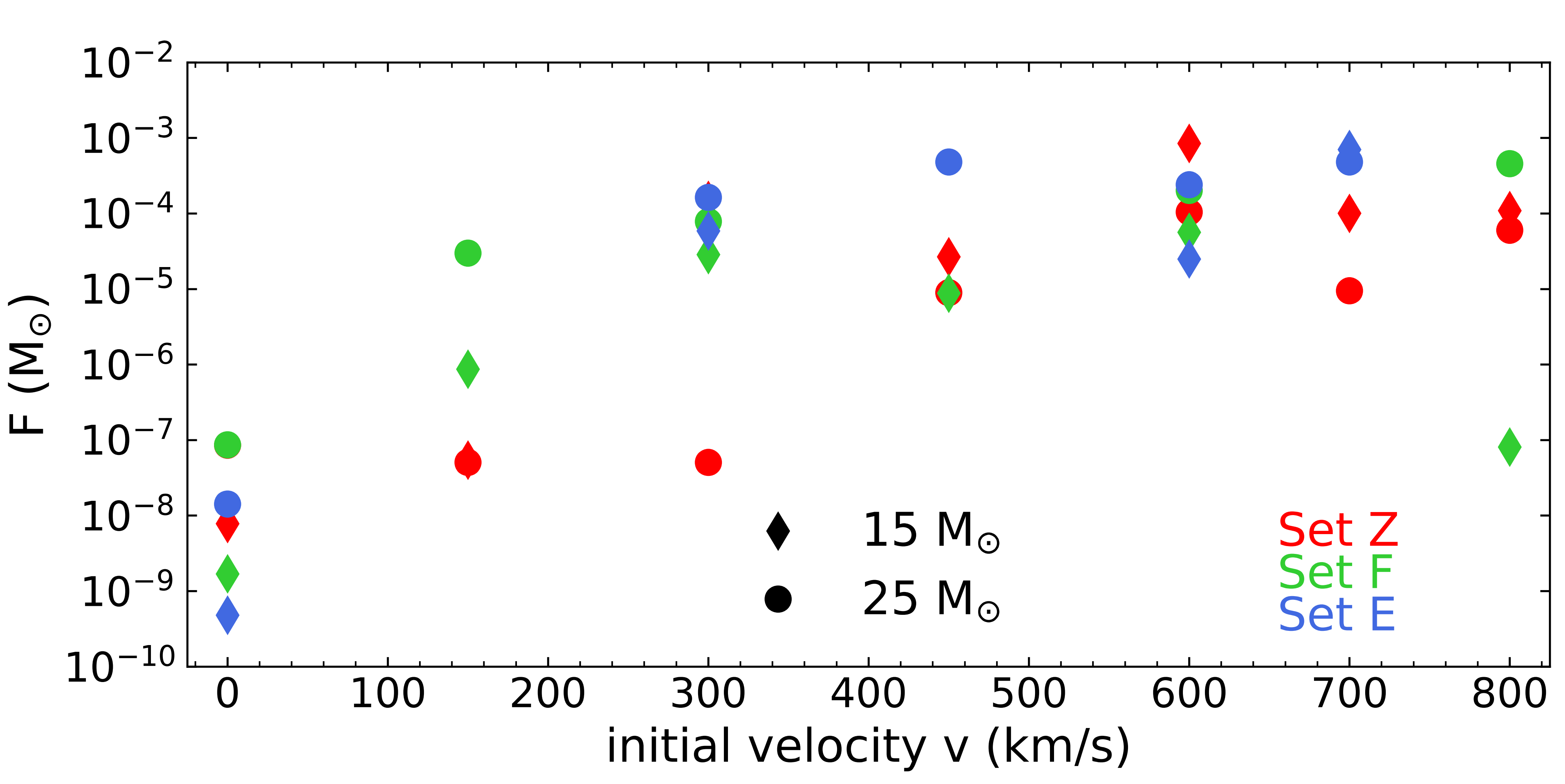
$$^{14}N(\alpha, \gamma)^{18}F(\beta^{+})^{18}O(p,\alpha)15N(\alpha, \gamma)^{19}F$$

- It requires CNO, p, n, and α in the same environment (neutrons are provided by $^{14}N(n,p)^{14}C$);

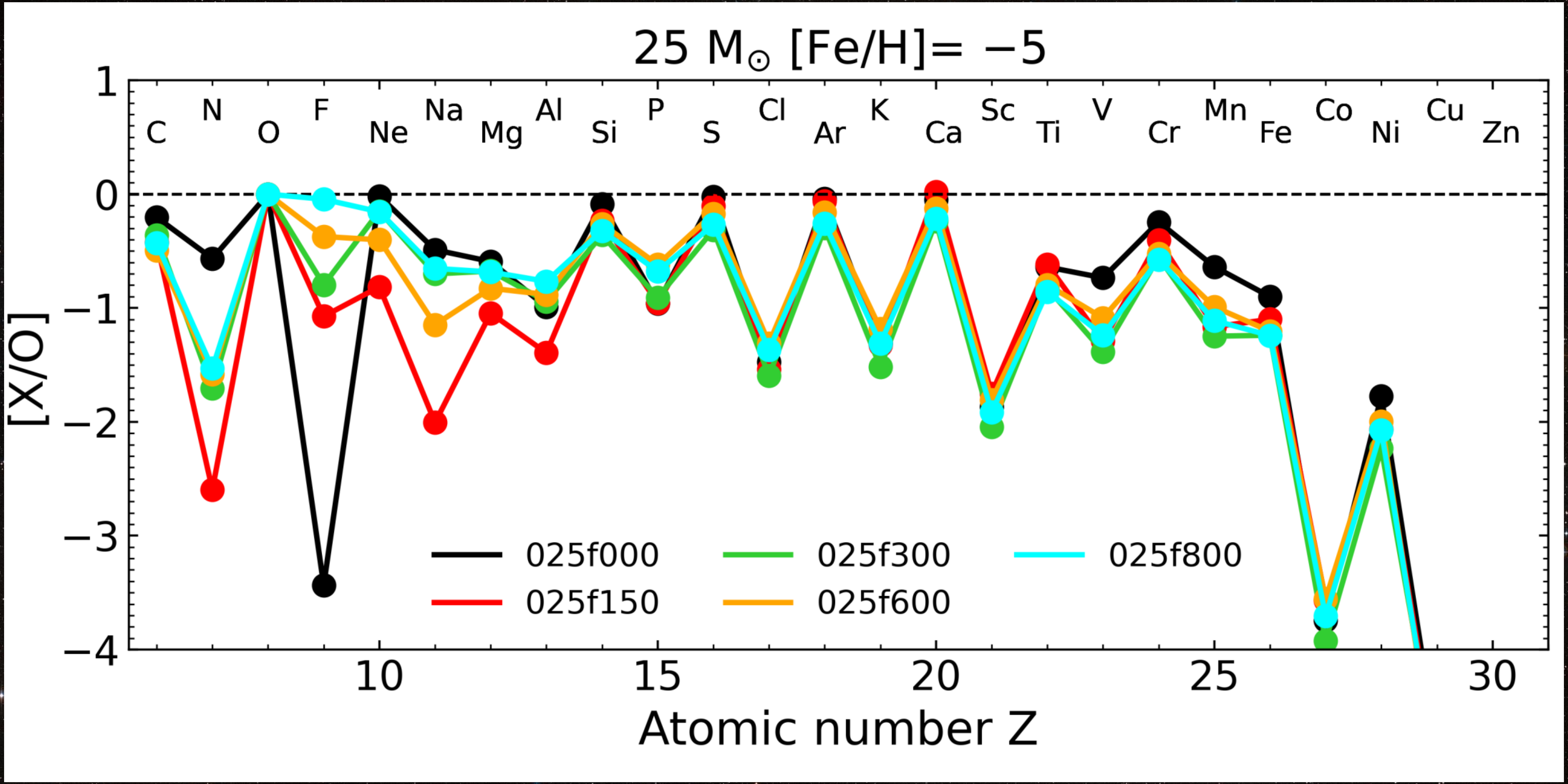
- AGB stars or He burning in shell in rotating massive stars;

- Formation of the convective He shell in the CNO pocket.

^{19}F production in rotating massive stars

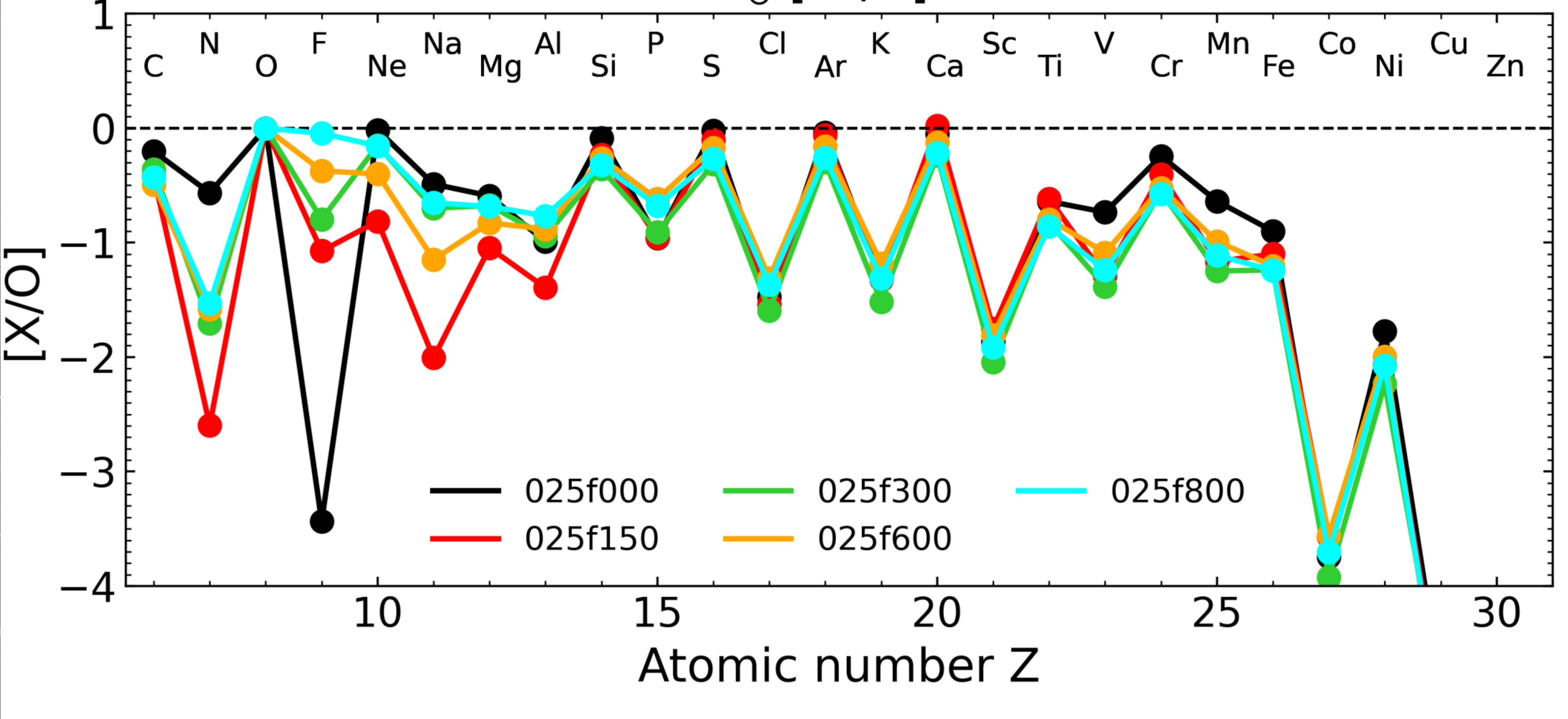


Production factors at low metallicity

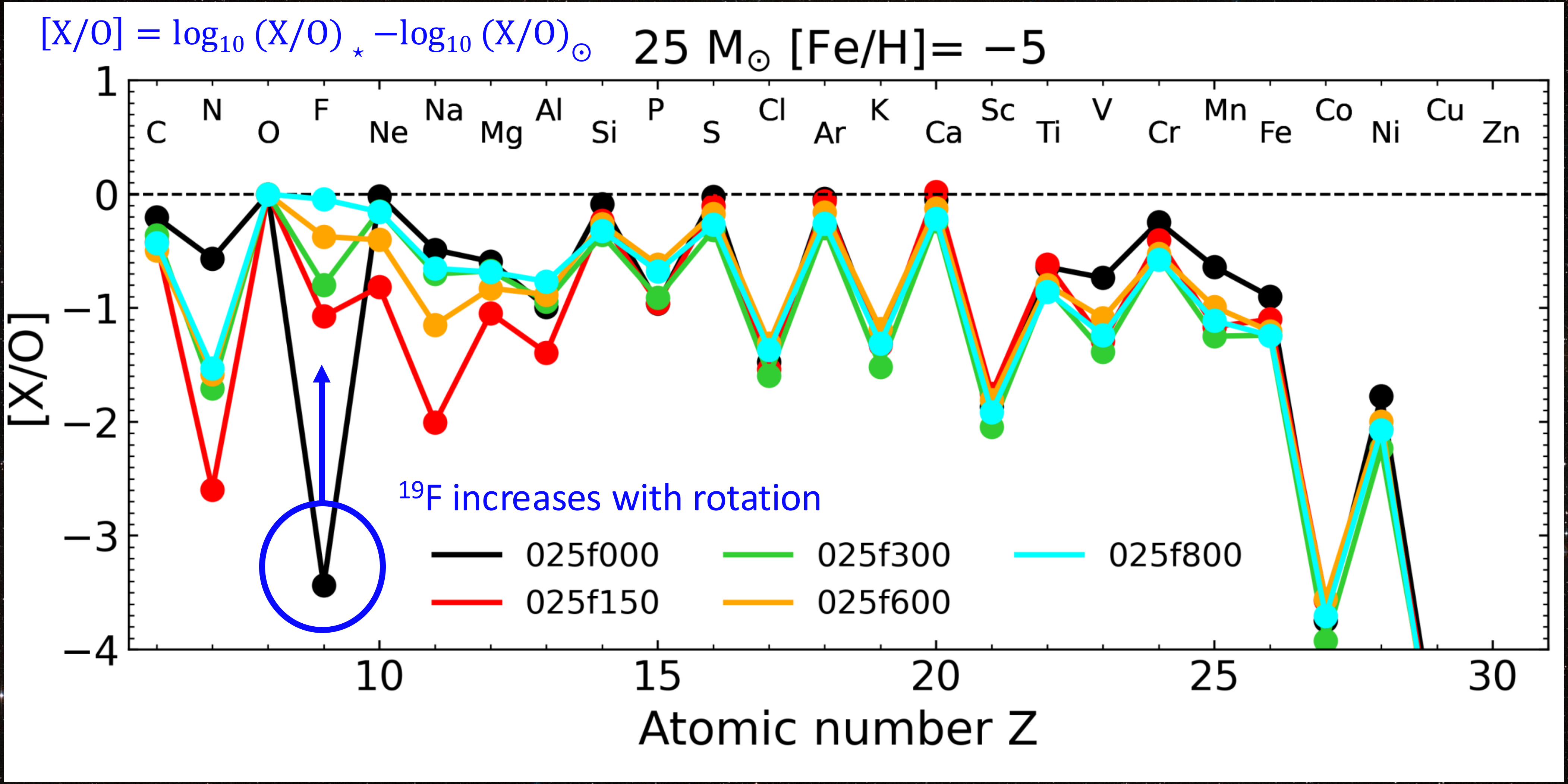


Production factors at low metallicity

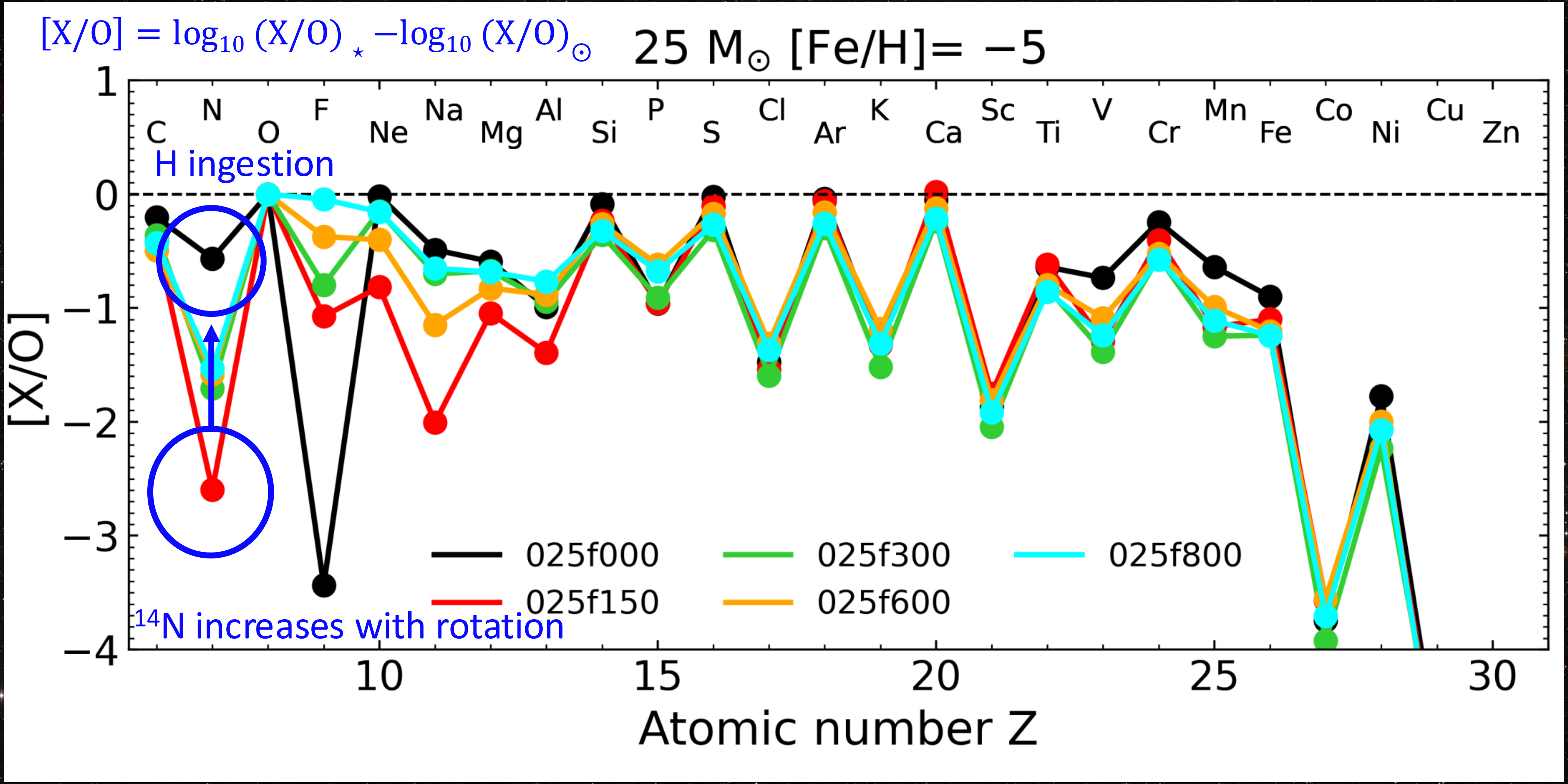
$[X/O] = \log_{10}(X/O)_{\star} - \log_{10}(X/O)_{\odot}$



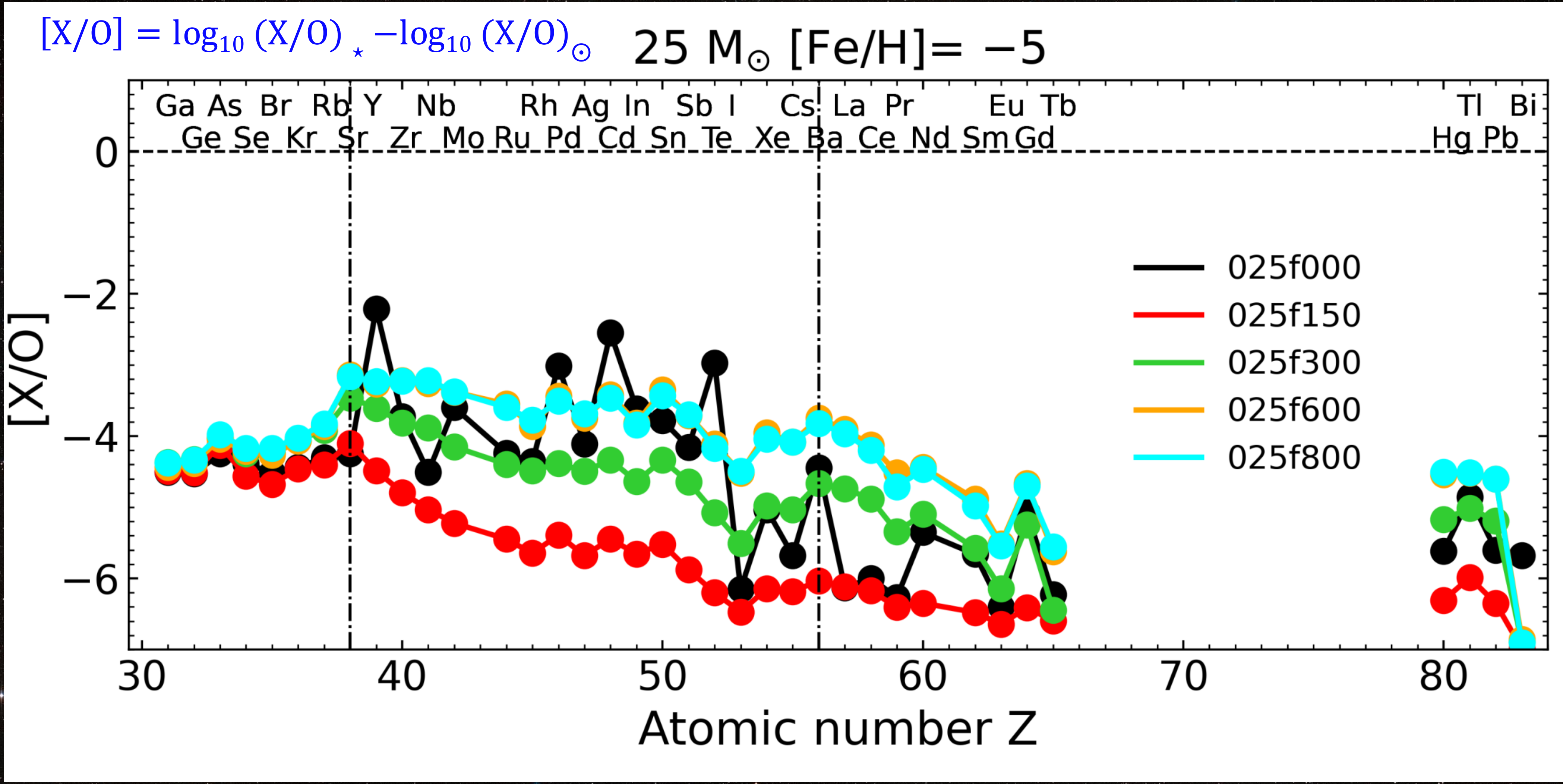
Production factors at low metallicity



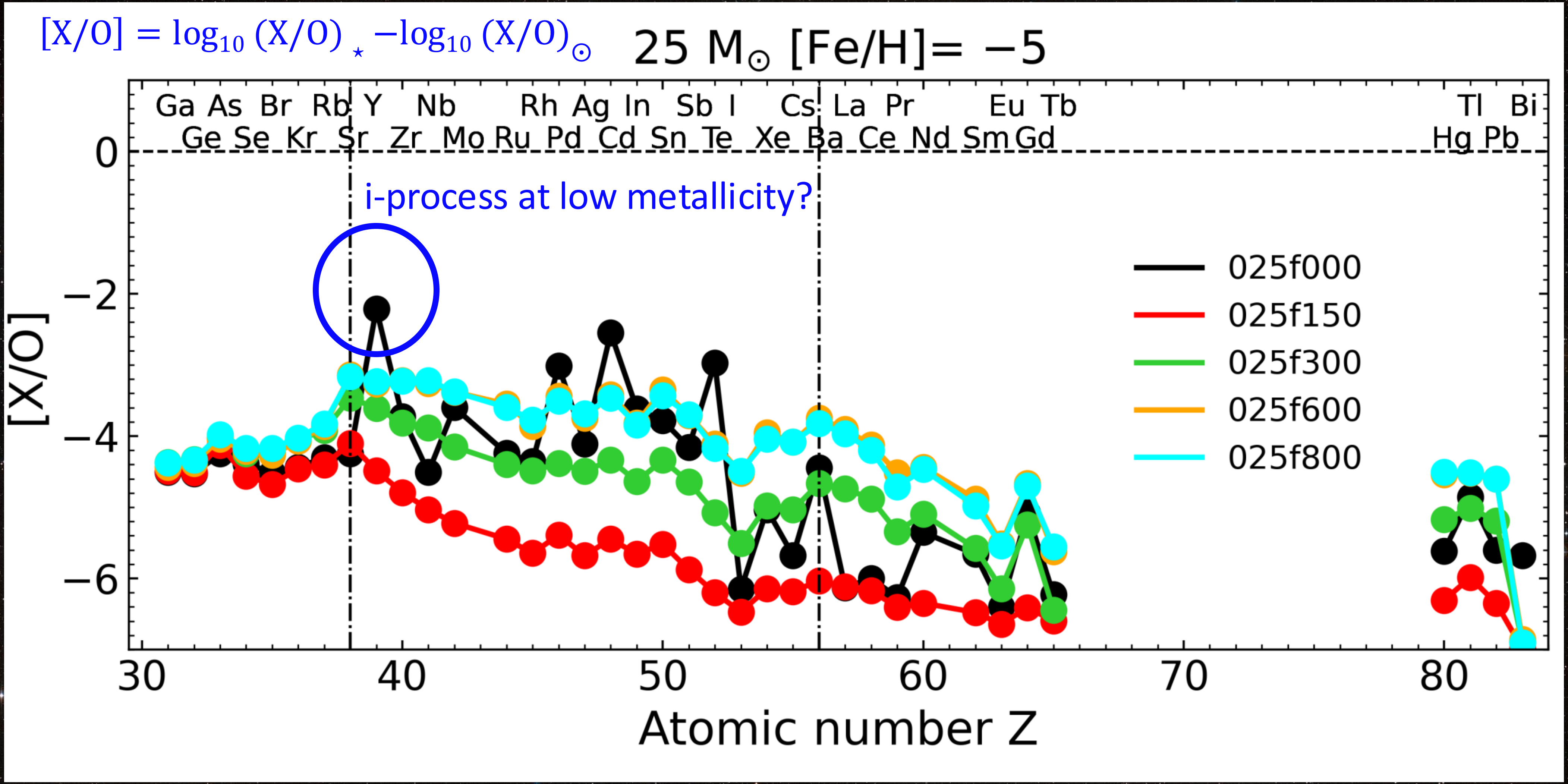
Production factors at low metallicity



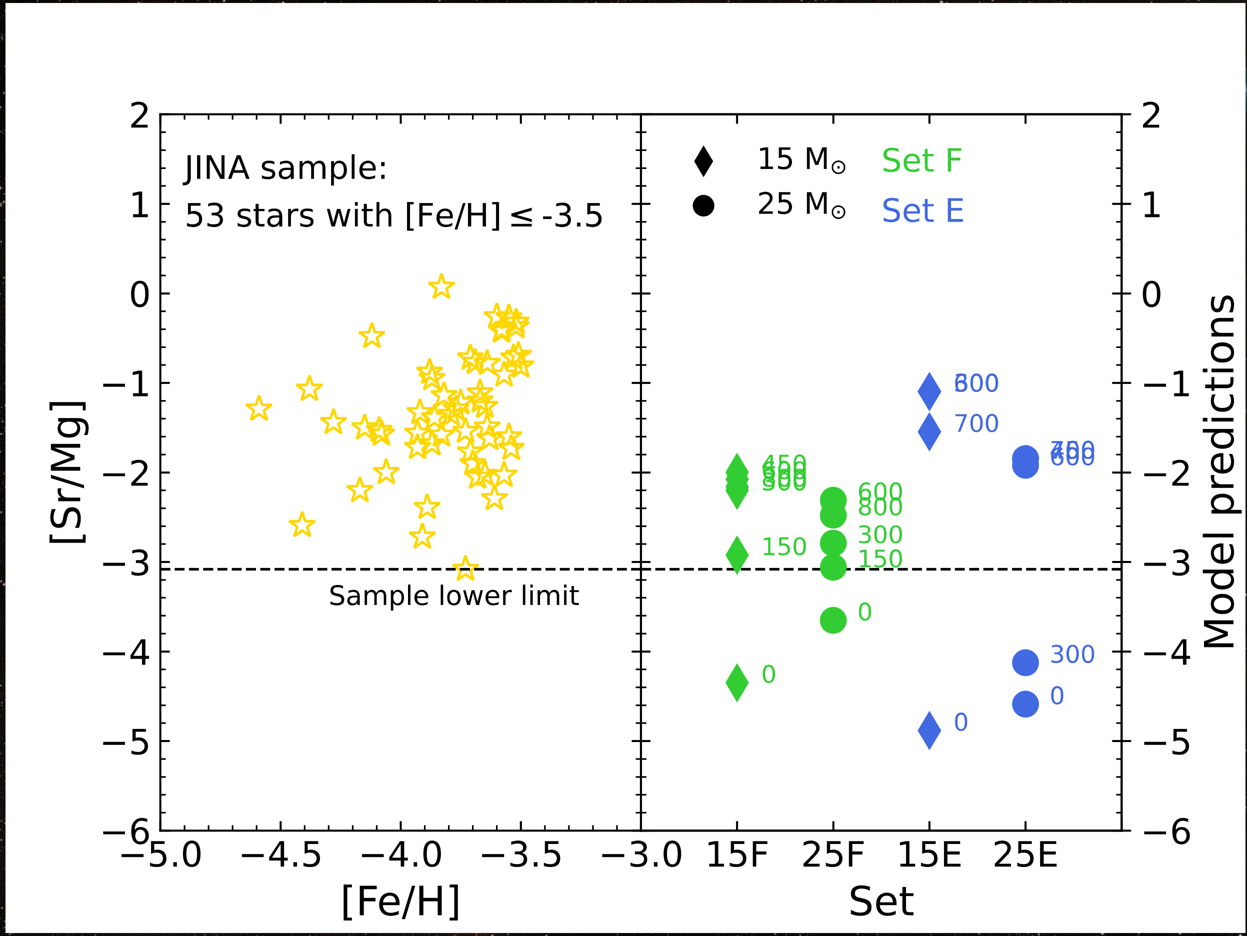
Production factors at low metallicity

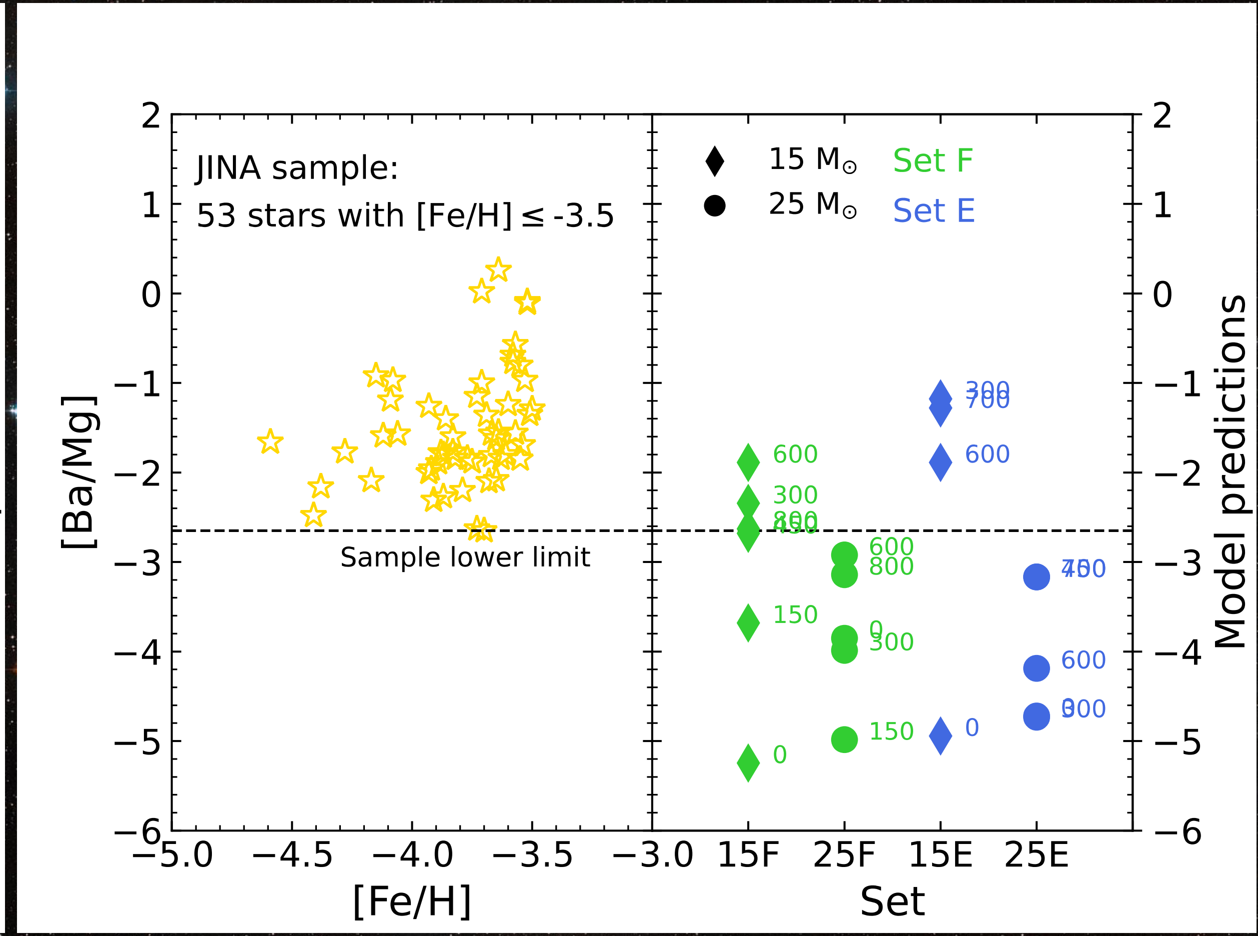


Production factors at low metallicity

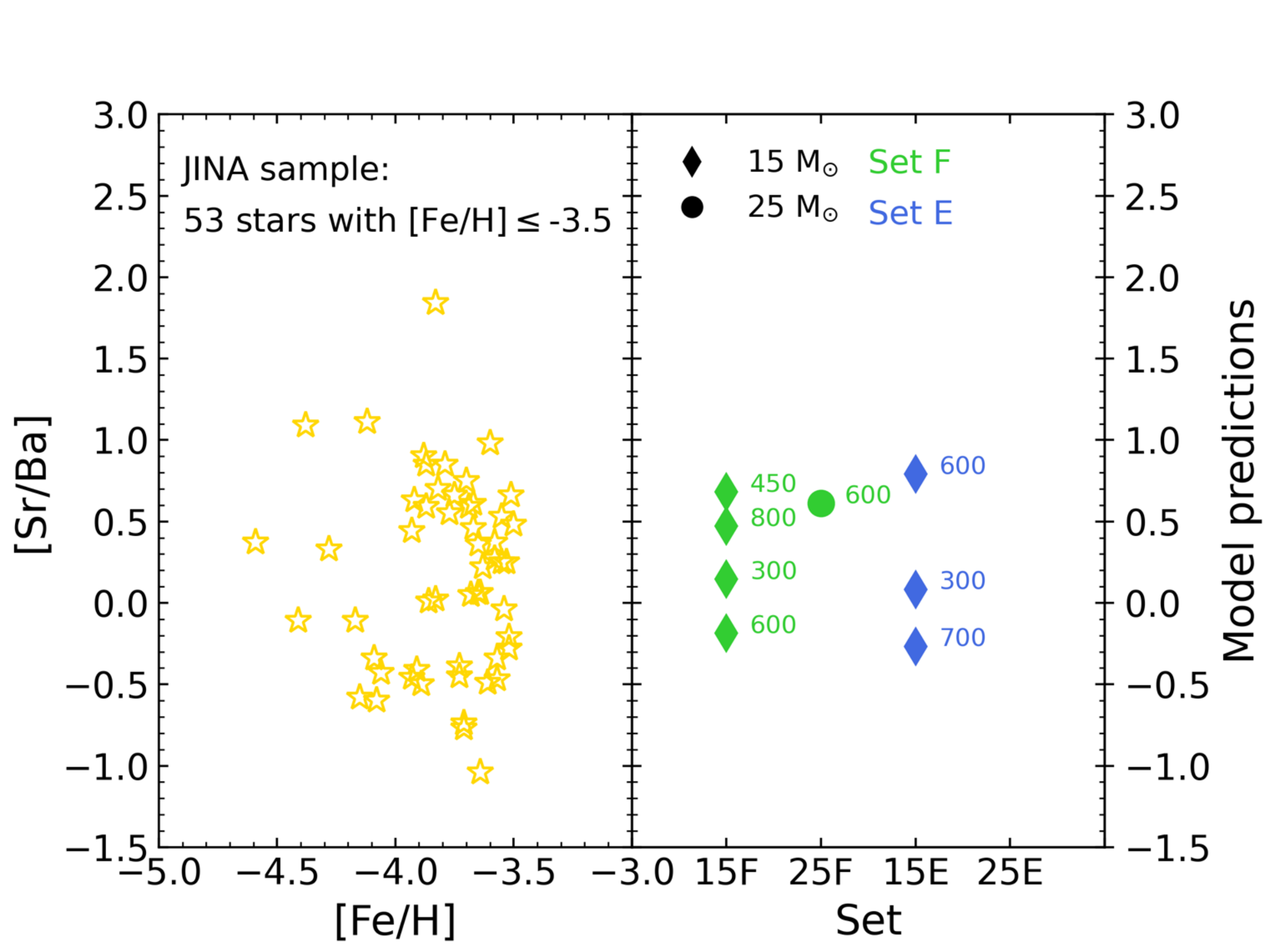


Comparison with observations





Comparison with observations



Summary and conclusions

- He burning phase is fundamental to determine the final fate of a massive star;
- Main site for s-process in massive stars;
- Rotation increases the efficiency of the s-process and ^{19}F nucleosynthesis (CNO pocket) in He burning;
- Very low metallicity rotating massive stars can produce beyond the weak s-process component and match the abundance ratios of the most metal poor stars observed today.