The s-process enrichment of M4 and M22

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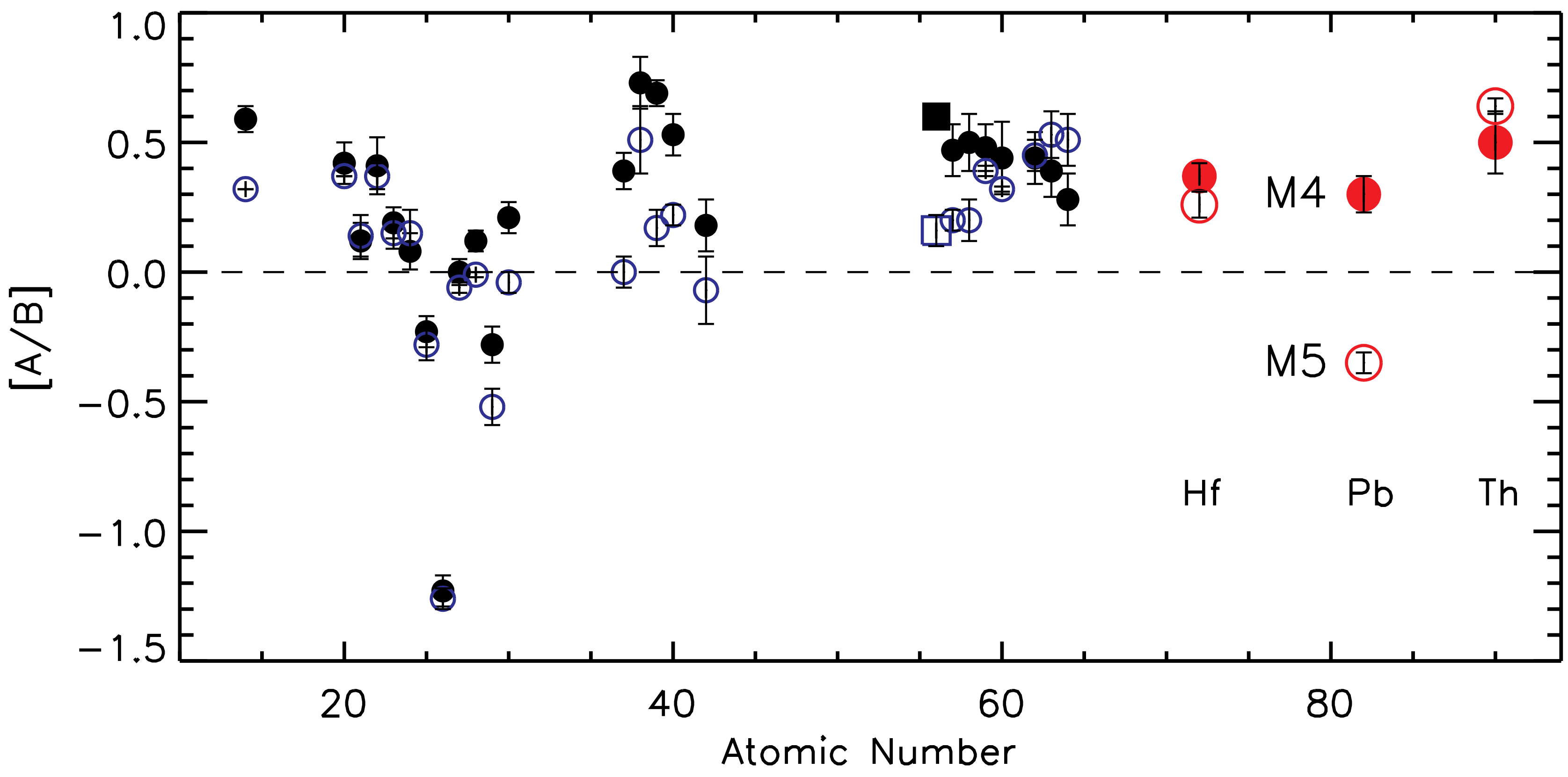
ASA

Globular clusters

Are very old (>10 Gyr) star clusters that are found mostly in the Halo of our Galaxy.

We want to explain the heavy elements (Z>30), which are typically constant within a single globular cluster, although there is a cluster-to-cluster spread at fixed [Fe/H] (e.g., M4 and M5 at [Fe/H]=-1.2).



Yong et al. (2008)

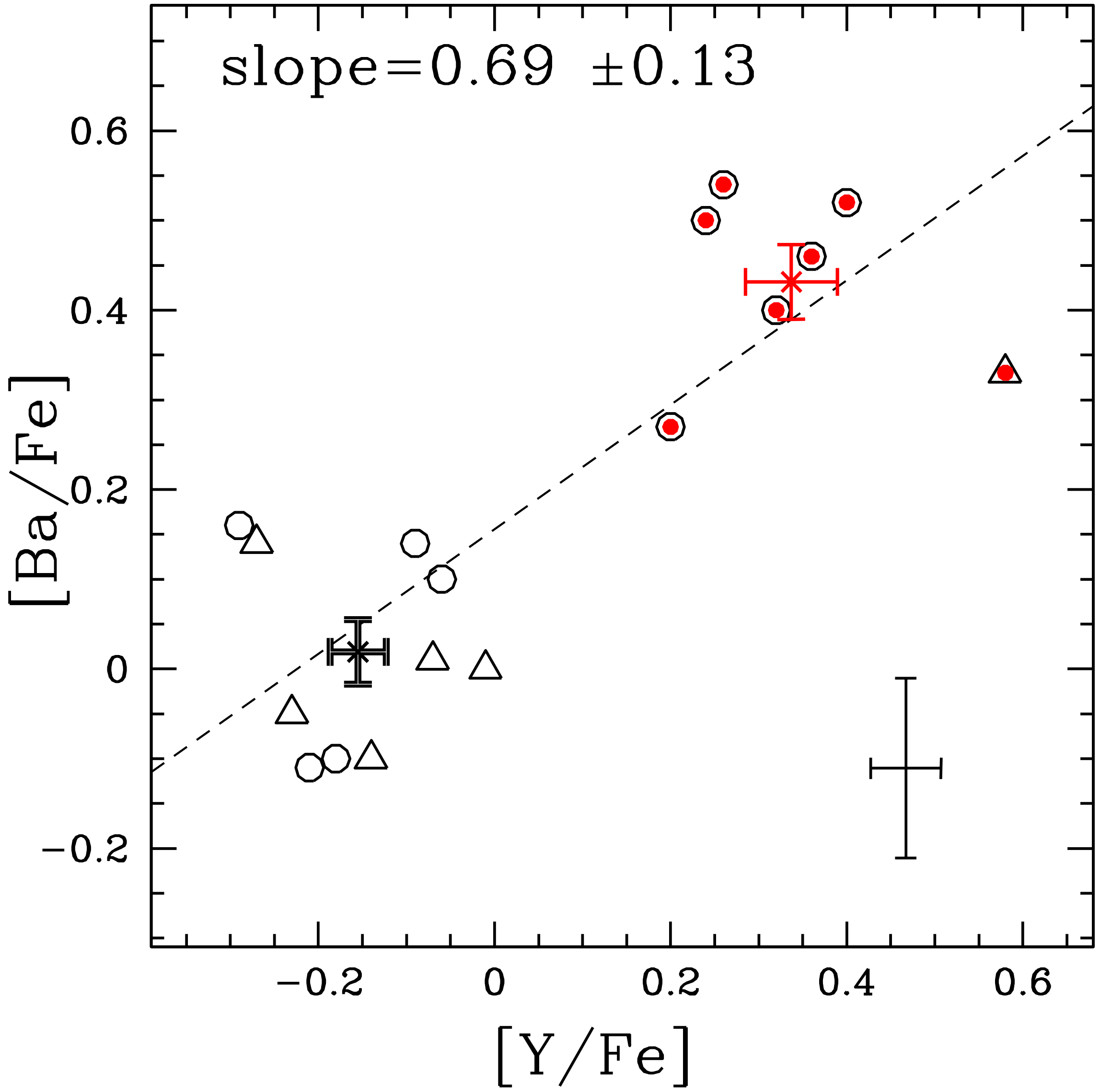
Globular clusters with s-process variation

Some GCs also have spreads in Fe and heavy elements produced by the s-process (e.g., Sr, Y, Ba, Pb).

Examples include ω Centauri, M22, M2, NGC 1851, M15.

A relatively simple well-studied cluster is M22, which has two groups with different [Fe/H] and s-process abundances (Marino et al. 2009).

M22

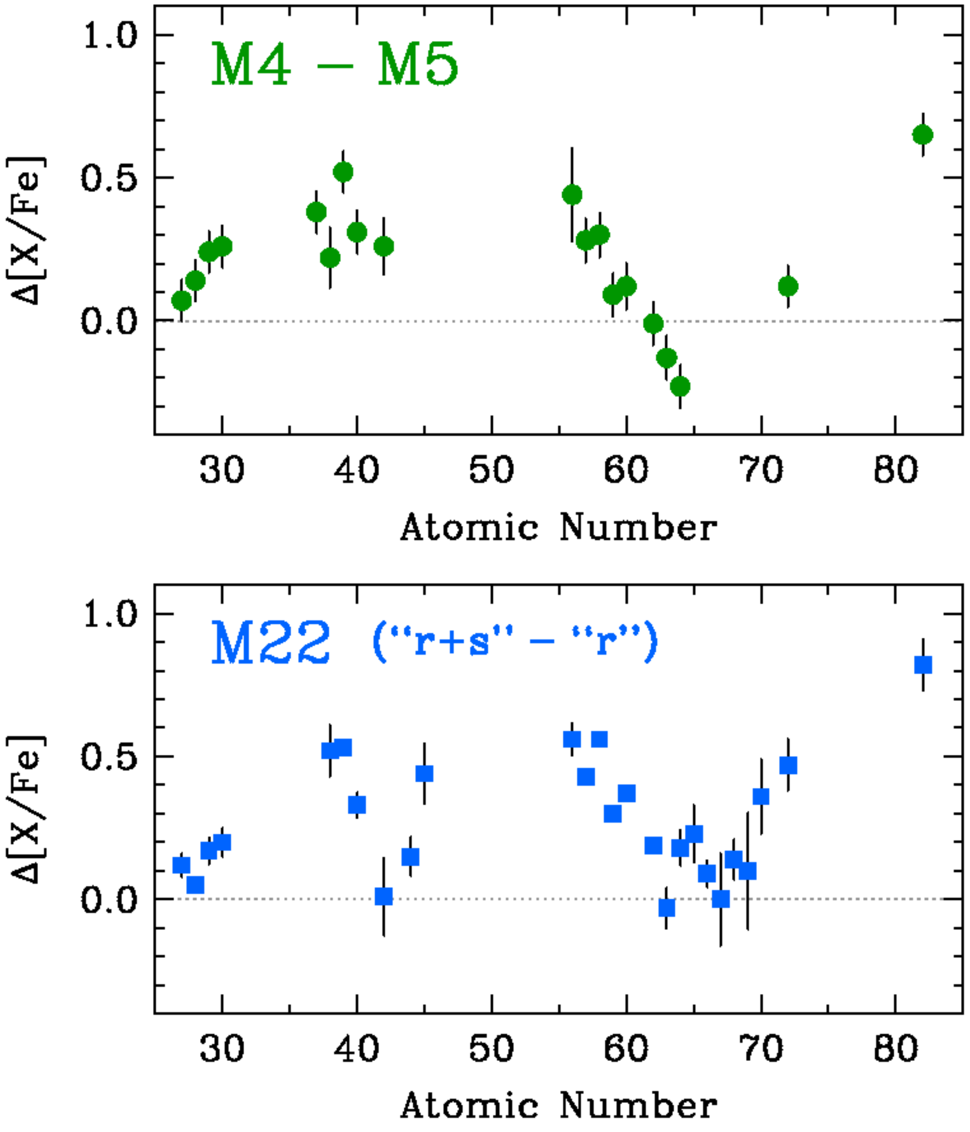


Marino et al. (2009)

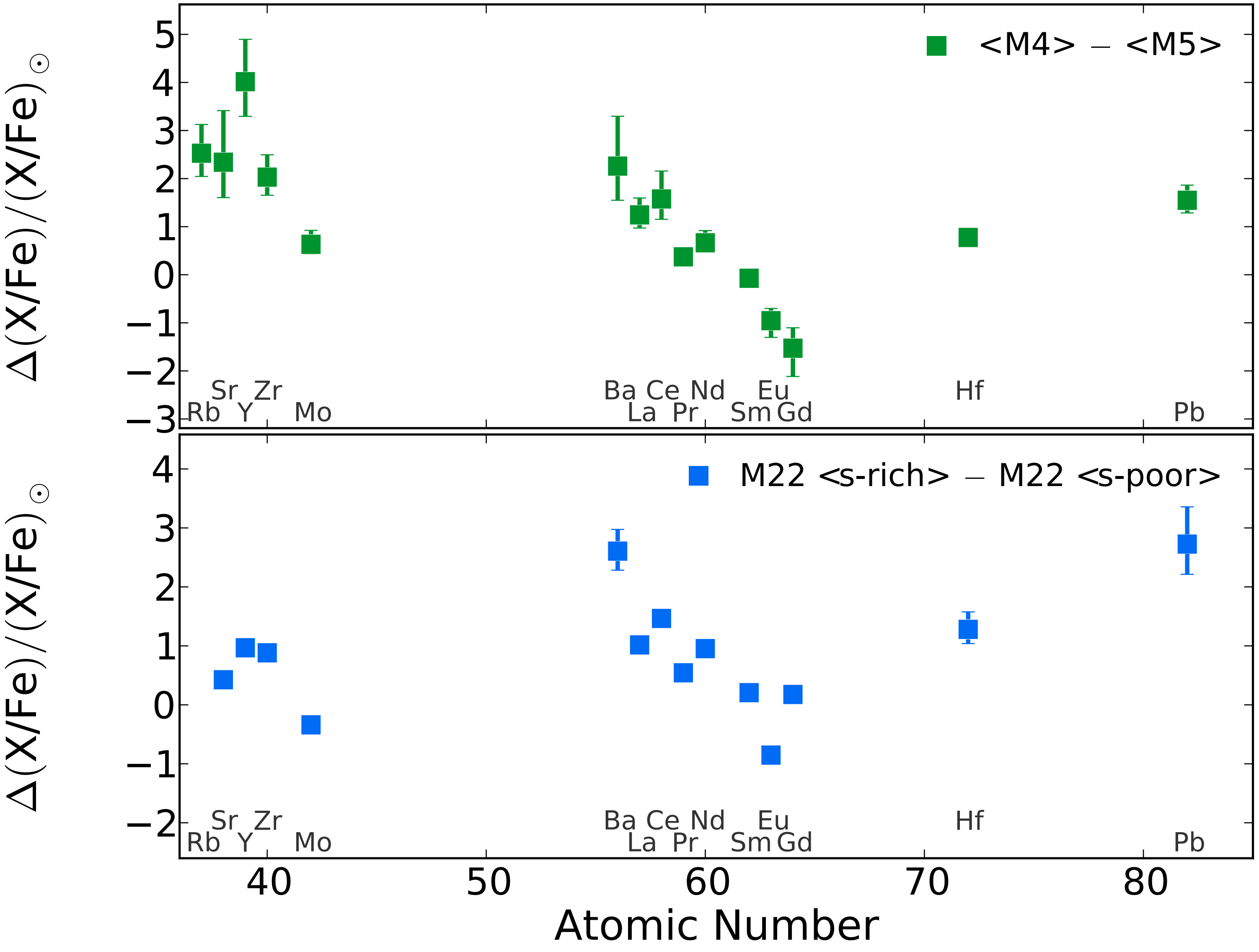
s-poor [Fe/H] = -1.82

s-rich [Fe/H] = -1.68

Subtracting s-poor from s-rich abundances gives an empirical s-process distribution



Roederer et al. (2011)

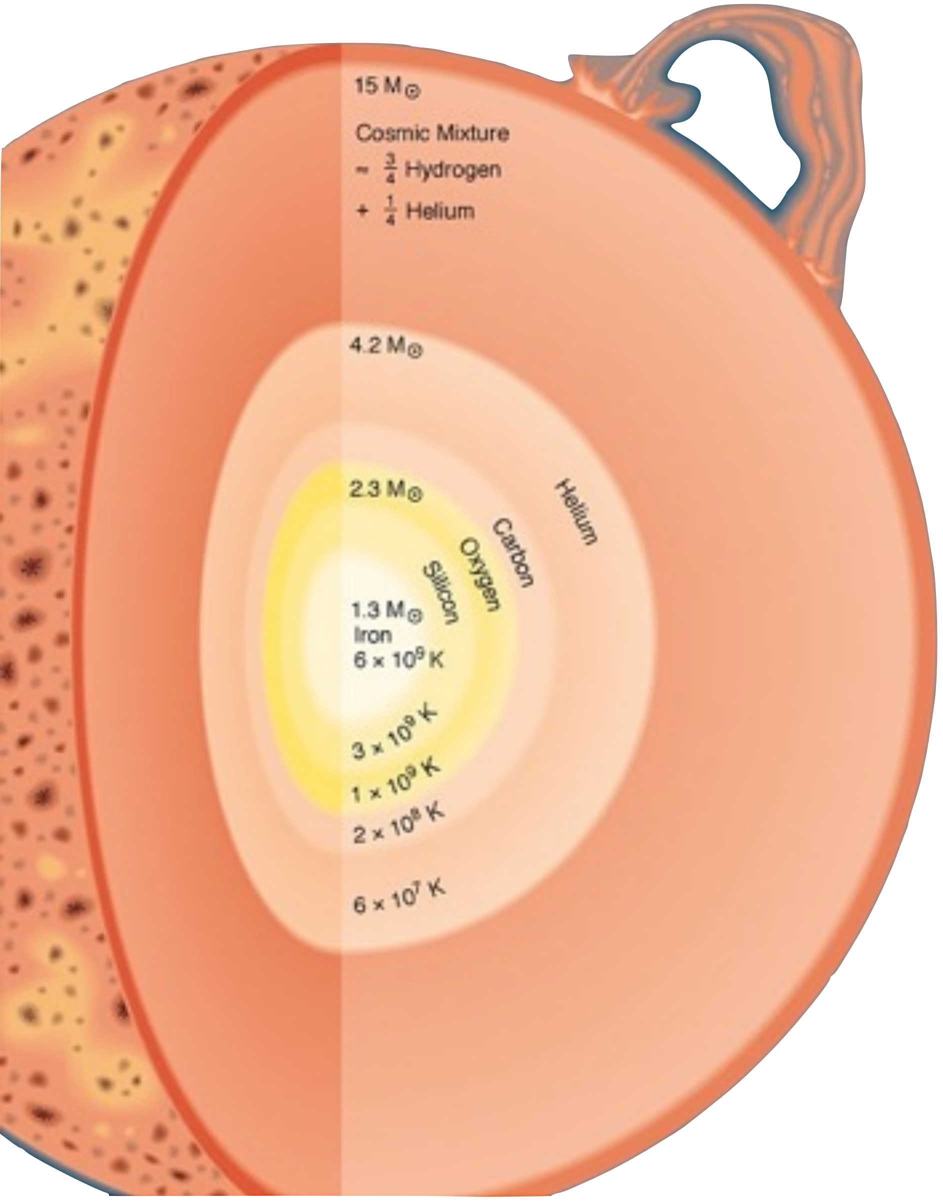


Shingles et al. (2014)

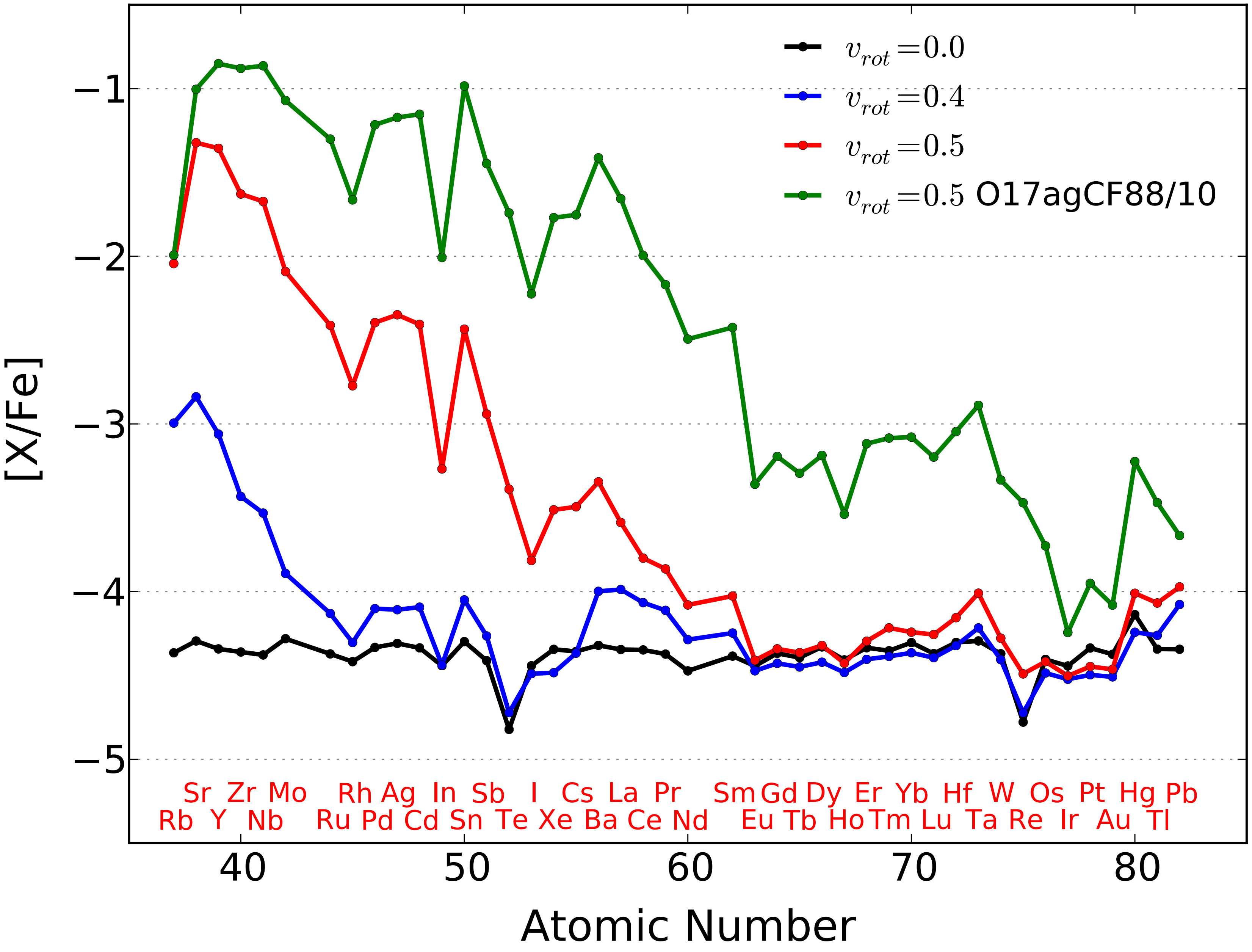
Subtracting the abundances in linear space isolates the net production for comparison with the net yields of nucleosynthesis models.

The s-process in massive stars

- ^{14}N is a product of H burning via the CNO-cycle.
- ^{14}N is converted into ^{22}Ne via two α-captures during core He burning.
- $^{22}Ne(\alpha,n)^{25}Mg$ releases neutrons for s-processing during core He burning and shell He and C burning.
- In rotating massive stars, additional mixing transports ^{12}C and ^{16}O from the He core to the H-shell to make ^{14}N, which is transported back to the He-core.

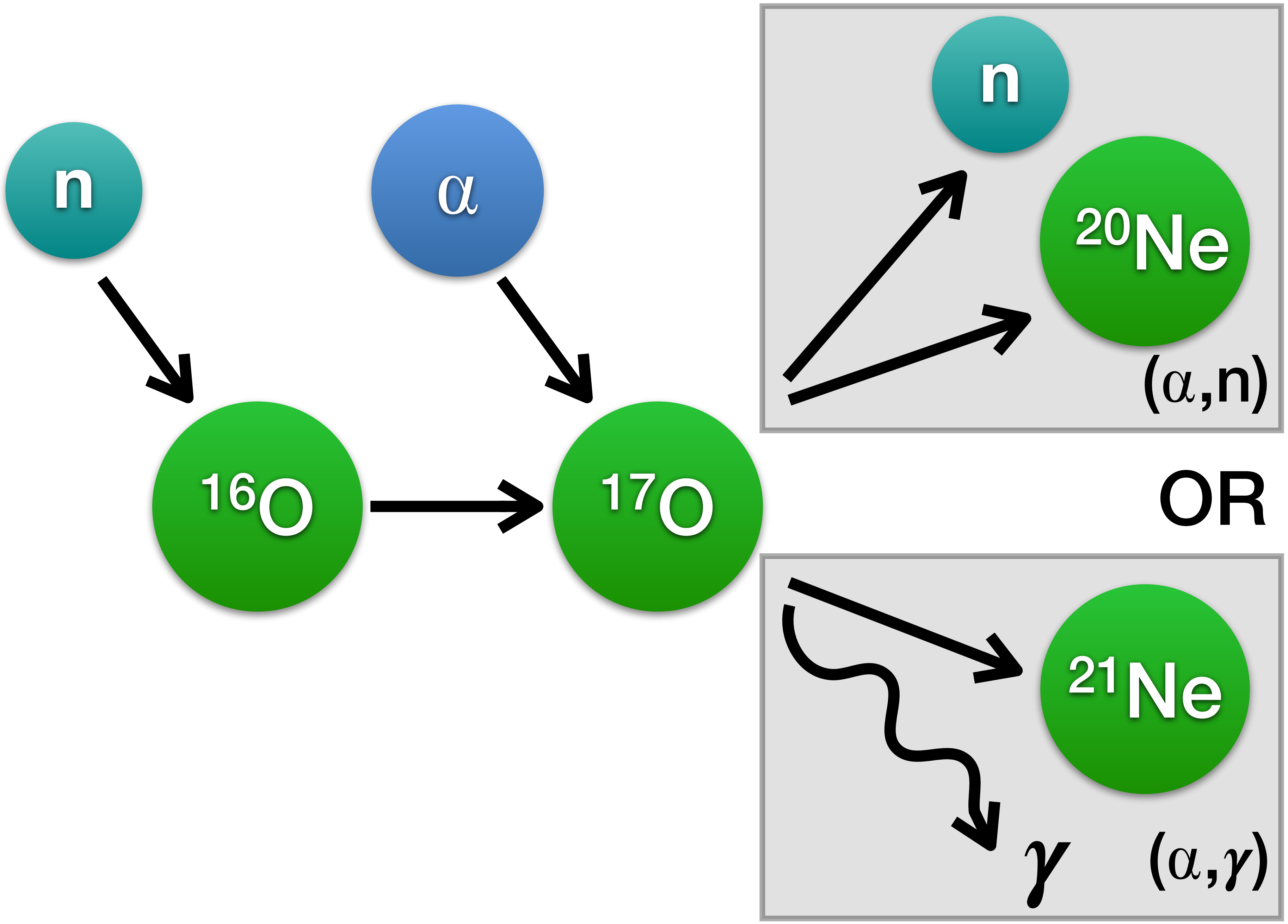


Rotation boosts the s-process yields of massive stars



25 $M_\odot$ pre-supernova yields at [Fe/H] = –3.8 from Frischknecht et al. (2012) with Fe yields from Limongi & Chieffi (2012).

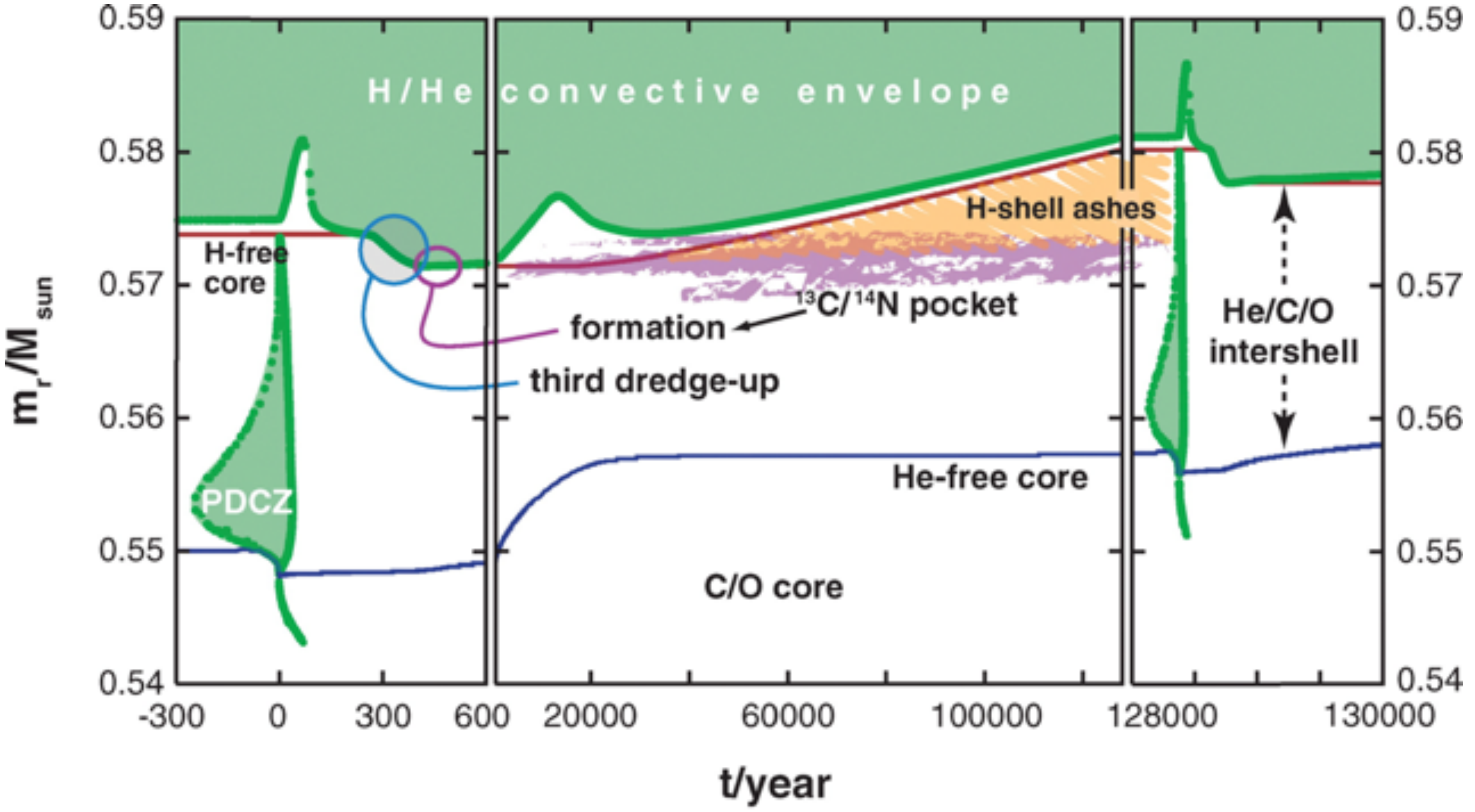
The efficiency of O16 as a neutron poison depends on the ratio of O17(α,n)Ne20 and O17(α,γ)Ne21 reactions



Rates:
CF88 or
CF88/10 or
~~CF88/1000~~

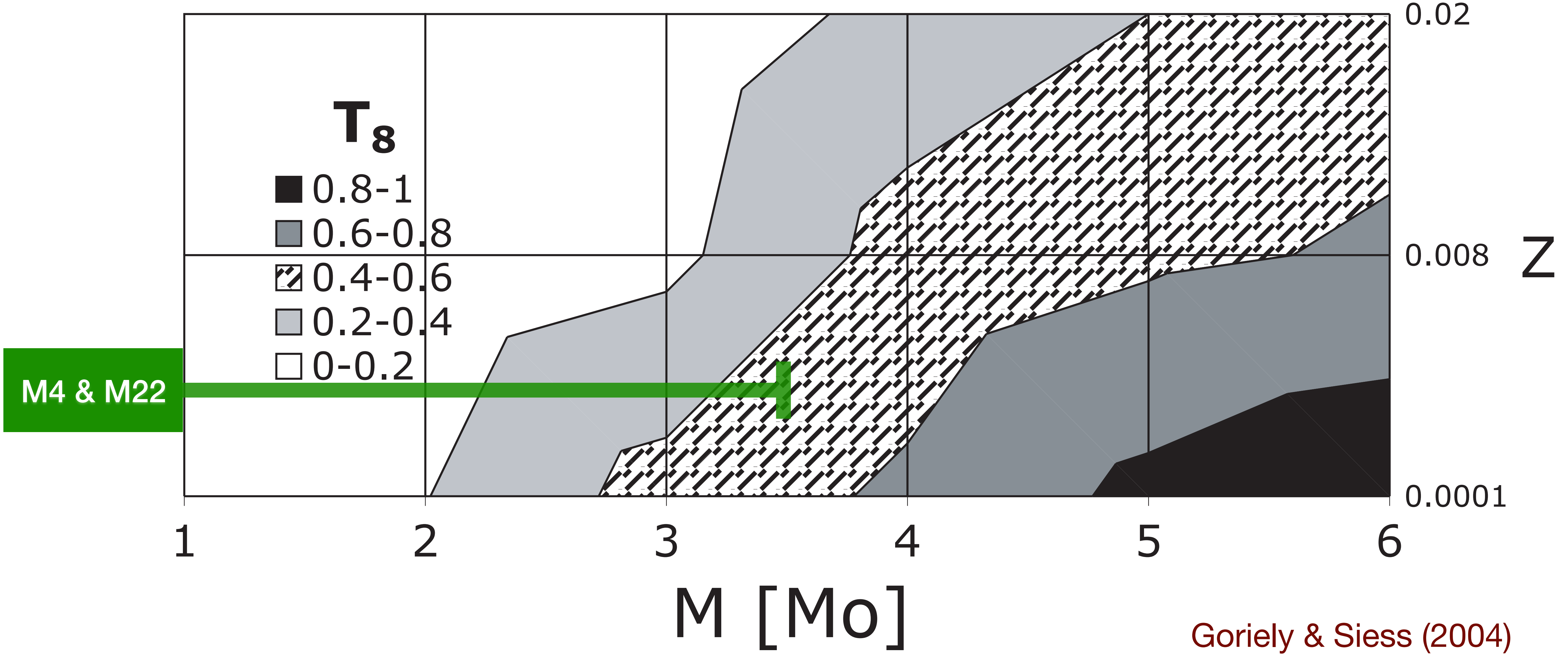
The two neutron sources in AGB stars

- Regime 1: ^{22}Ne(α,n)^{25}Mg reaction at the base of He-shell flash convective zones in intermediate-mass stars (4-8 $M_\odot$), where $T > 300$ megakelvin.
- Regime 2: ^{13}C(α,n)^{16}O in ^{13}C pockets formed during third dredge-up in low-mass stars (<3-4 $M_\odot$).



2.0 $M_\odot$, Z=0.01 model of Herwig (2005). Green shaded regions are convective. PDCZ is the pulse-drive convection zone.

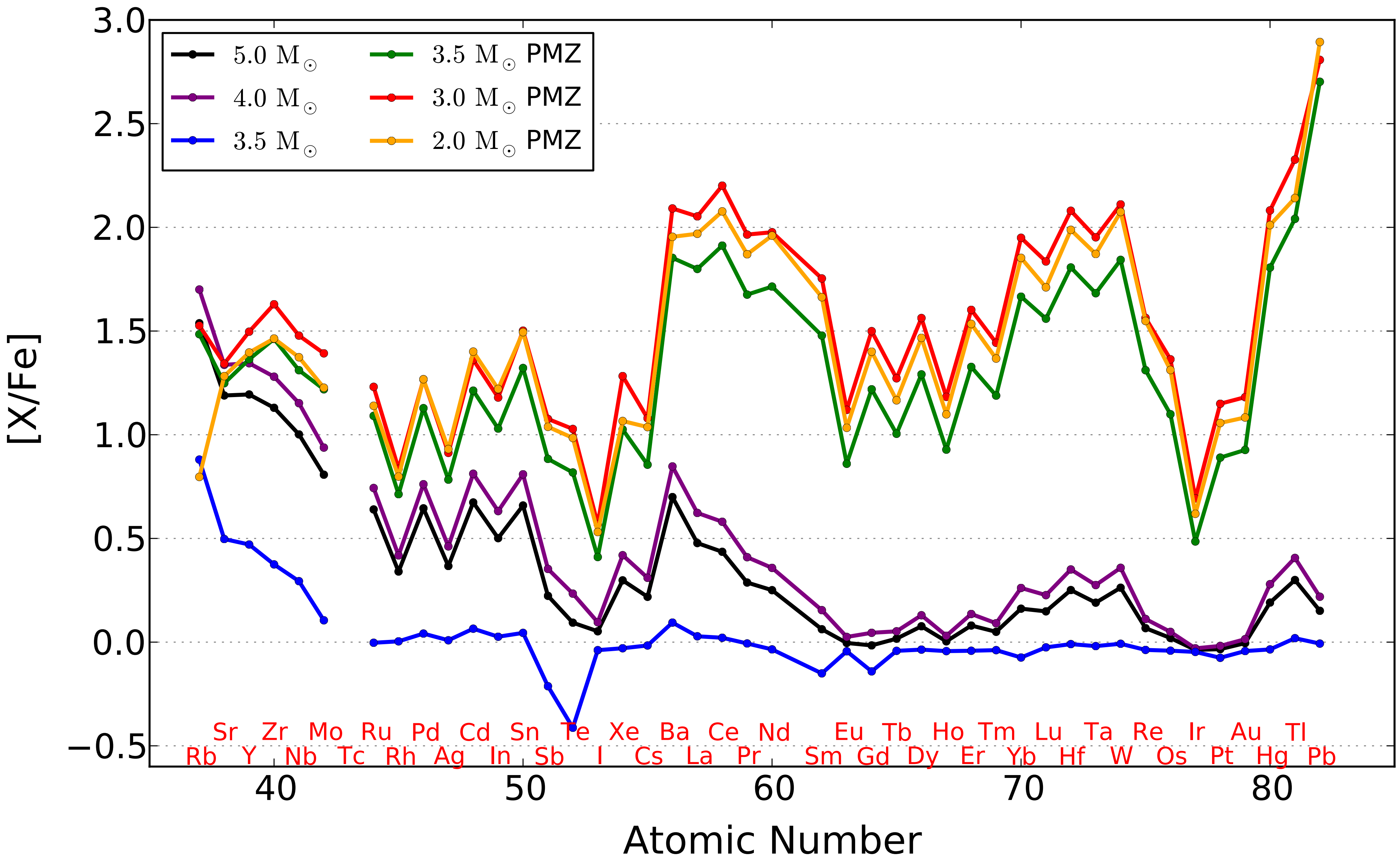
Upper mass limit of ^{13}C-pocket formation



Goriely & Siess (2004)

High temperatures at the base of the convective envelope during third dredge-up can prevent ^{13}C-pocket formation in massive AGB models. (Goriely & Siess 2004, Herwig et al. 2014)

Models with ^{13}C pockets and ^{22}Ne neutron sources produce different abundance patterns



[Fe/H] = —1.2 AGB yields from Fishlock et al. (2014, submitted).

Uncertainties affecting s-process yield predictions

- Convection in 1D models
- Mass loss rates
- Low-temperature opacities
- Rotation rates and numerical treatment
- Unknown physics of ^{13}C-pocket formation
    - Could be due to convective-boundary mixing, rotationally induced mixing or gravity-wave driven mixing.

We predict the abundance variation from a combination of polluter stars

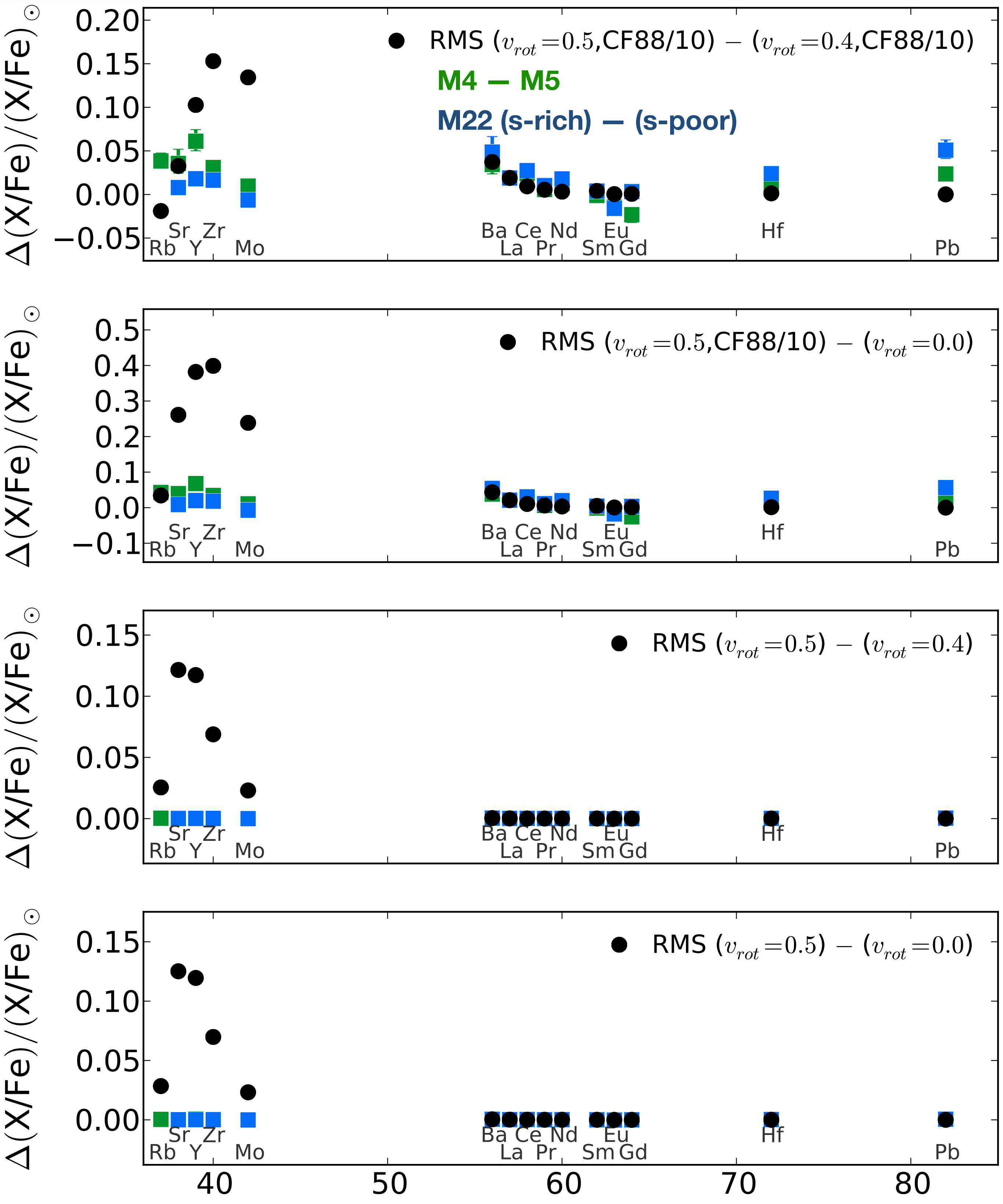
- We use a simple one-zone, closed-box chemical evolution model.
- We subtract the initial abundances from the final abundances of the models (or the final abundances of two models) similar to how we subtract M5 from M4 and s-poor from s-rich in M22.
- Using only the ratios between heavy elements, the results are relatively independent of the uncertain processes of dilution, infall, and cluster wind losses.
- The results allow us to compare various combinations of stellar yields with the observational s-process distributions.

Very low metallicity massive stars as potential s-process polluters

- Perhaps the s-process elements were produced by massive stars that also seeded the clusters with Fe.
- Rotation enhances s-process production in massive stars at low metallicity, especially for elements near the Ba peak and Pb.
- Stochastic star formation might have resulted in different average rotation rates in the polluters of M4 and M5 that led to different s-process abundances.
- M22 could be the result of a merger of two such clusters.

Results with very low metallicity RMS yields

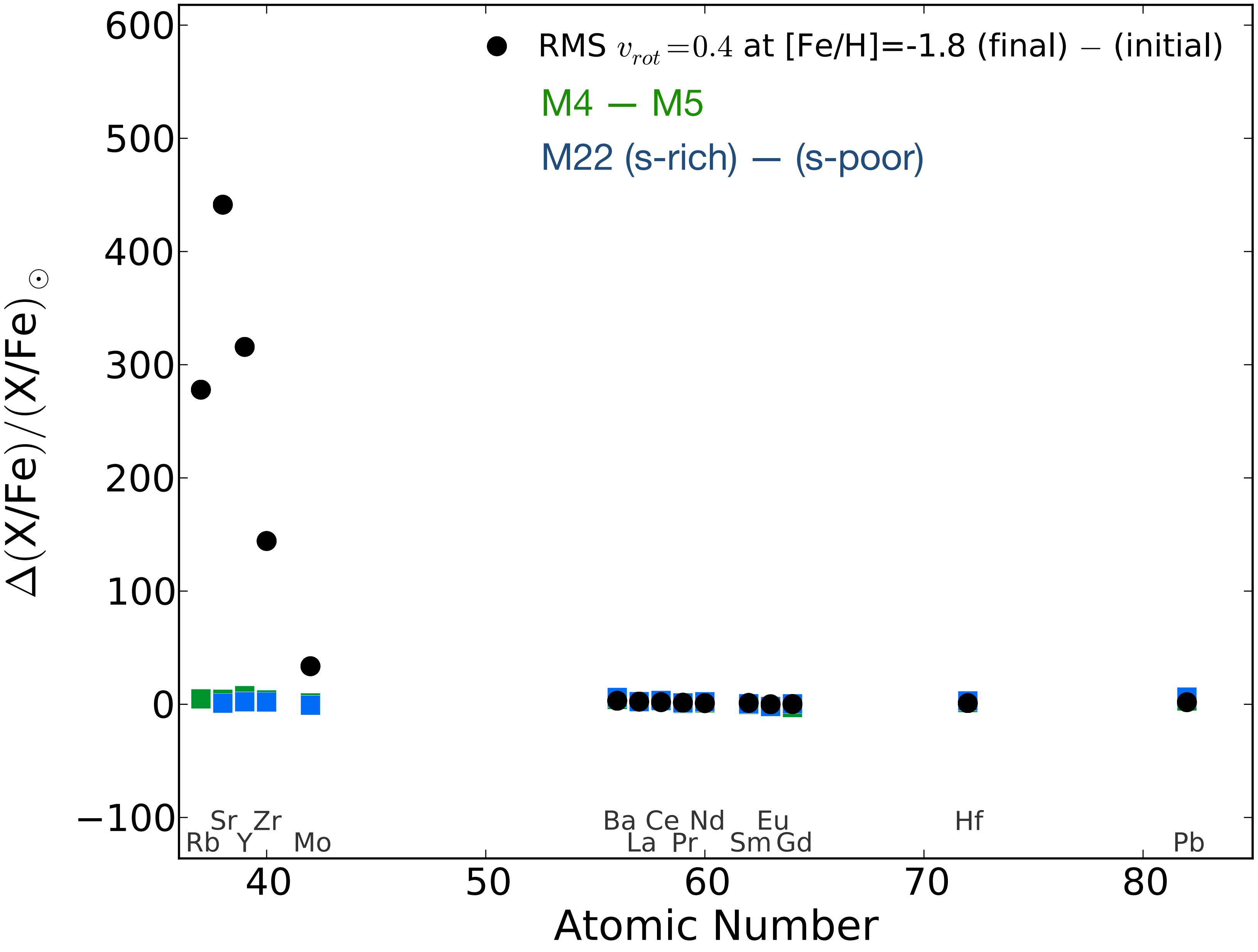
- Start with zero-metallicity gas and pollute with rotating massive star ejecta using 15 to 40 M⊙ pre-supernova yields at [Fe/H]=-3.8 from Frischknecht et al. (2012)
- Abundance differences correspond to a hypothetical average rotation rate difference between stars that polluted M4 and M5.
- Sr peak too high relative to Ba peak in all cases. Not a likely scenario.



Shingles et al. (2014)

M22: Results with [Fe/H]=-1.8 RMS yields

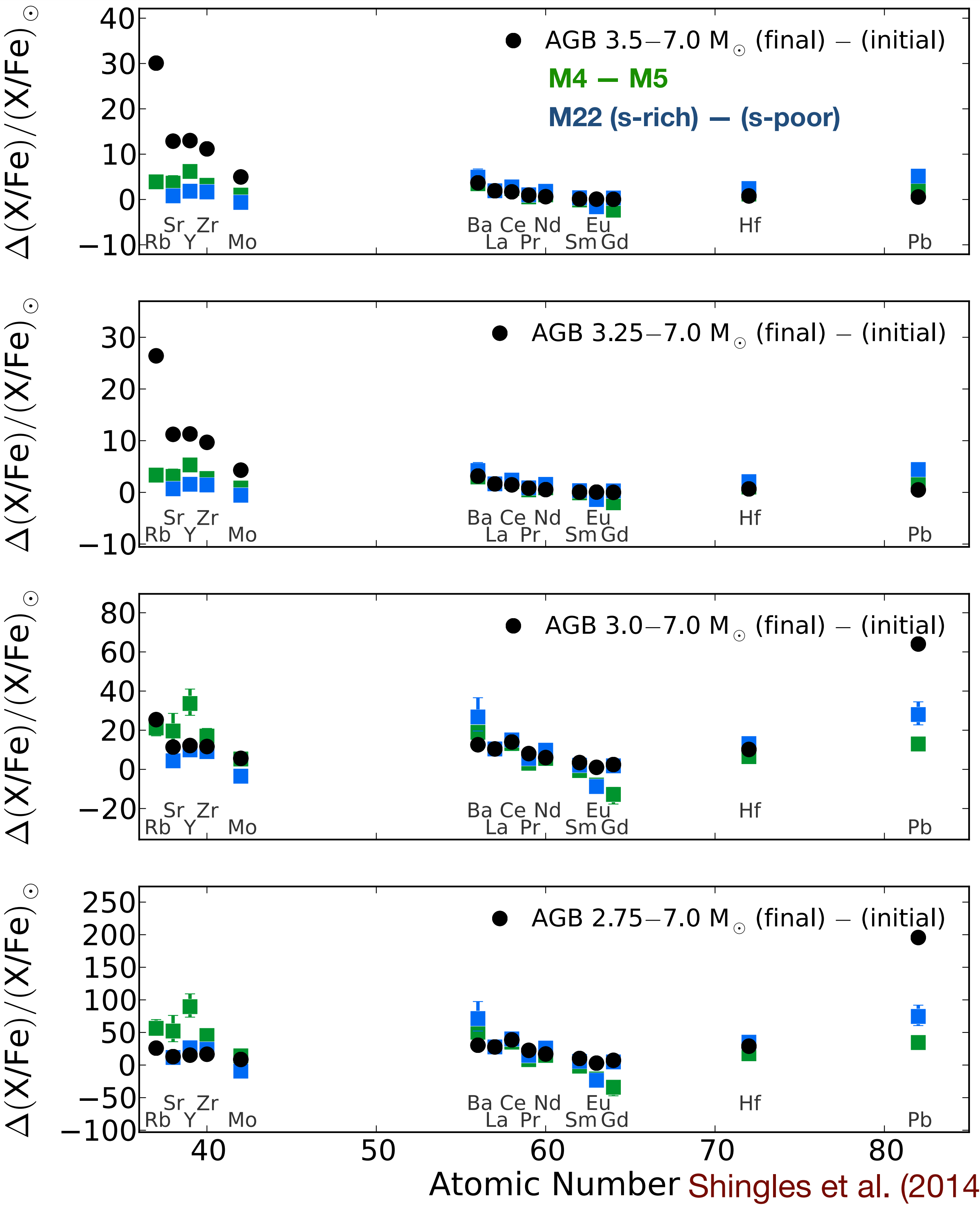
- If we assume the enrichment of the s-rich group of M22 is purely from rotating massive stars in the s-poor group…
- Sr peak far too high relative to Ba peak.
- Not a likely scenario.



Shingles et al. (2014)

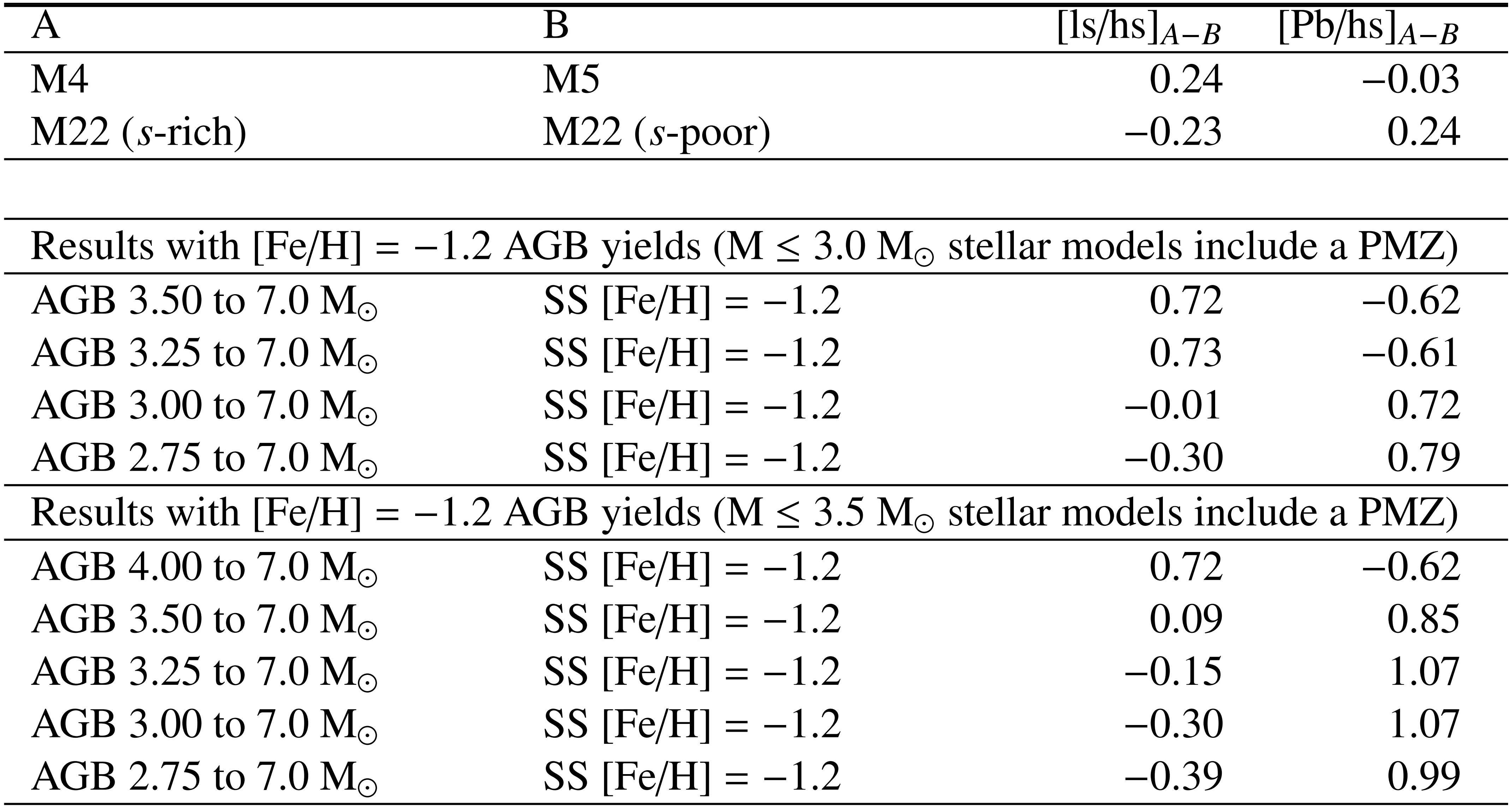
Results with [Fe/H]=-1.2 AGB yields

- A PMZ is included for M ≤ 3.0 M⊙.
- For lower limit masses below 2.75-3.00 M⊙, the light to heavy ratio falls below the value of M4 and M22.
- Finding the best fit will require us to quantify the light to heavy s-element ratio.



Shingles et al. (2014)

s-Process Index Results



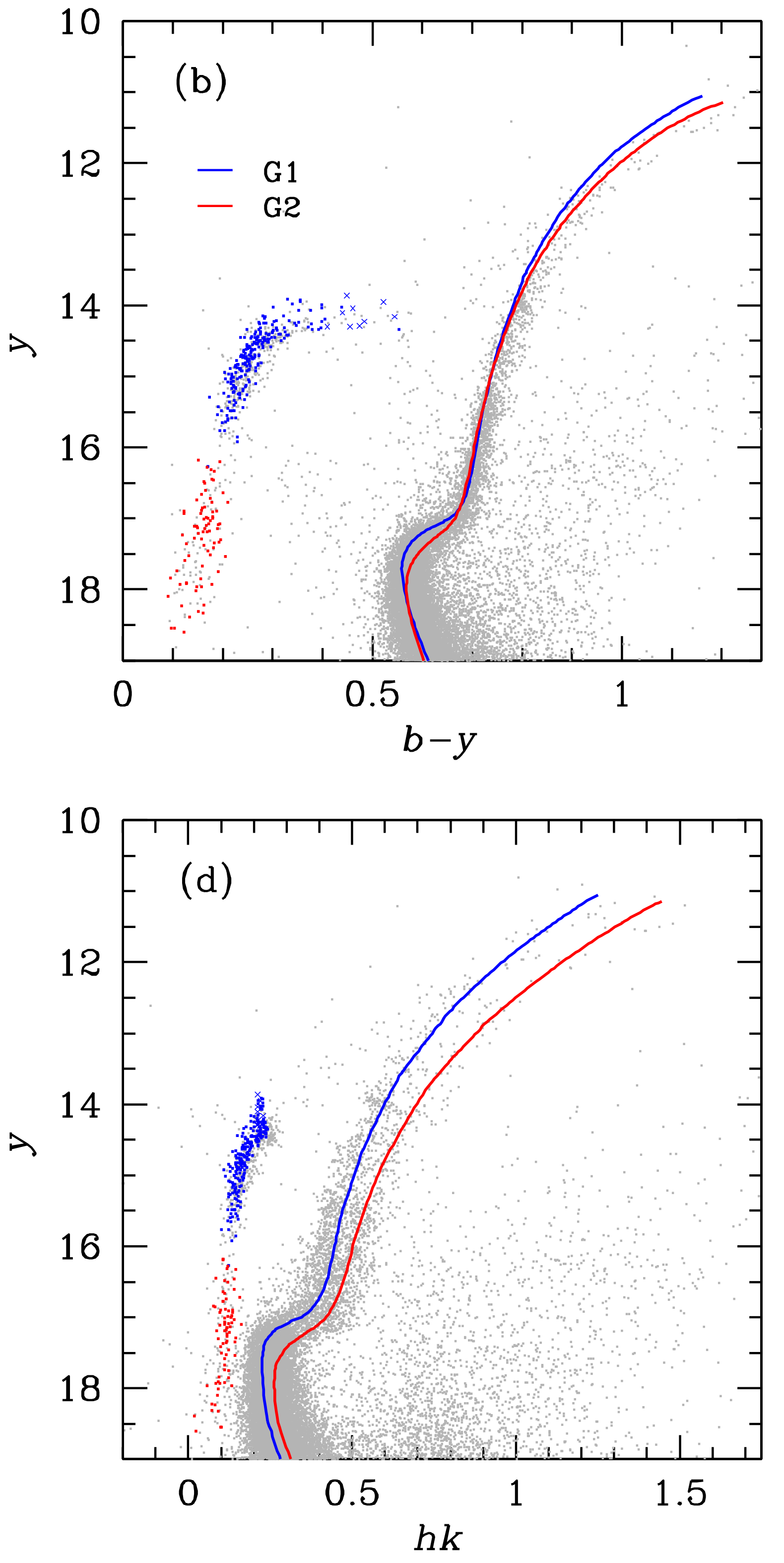
A	B	$[\mathrm{ls/hs}]_{A-B}$	$[\mathrm{Pb/hs}]_{A-B}$
M4	M5	0.24	−0.03
M22 (*s*-rich)	M22 (*s*-poor)	−0.23	0.24
Results with [Fe/H] = −1.2 AGB yields ($M \leq 3.0\ M_\odot$ stellar models include a PMZ)			
AGB 3.50 to 7.0 $M_\odot$	SS [Fe/H] = −1.2	0.72	−0.62
AGB 3.25 to 7.0 $M_\odot$	SS [Fe/H] = −1.2	0.73	−0.61
AGB 3.00 to 7.0 $M_\odot$	SS [Fe/H] = −1.2	−0.01	0.72
AGB 2.75 to 7.0 $M_\odot$	SS [Fe/H] = −1.2	−0.30	0.79
Results with [Fe/H] = −1.2 AGB yields ($M \leq 3.5\ M_\odot$ stellar models include a PMZ)			
AGB 4.00 to 7.0 $M_\odot$	SS [Fe/H] = −1.2	0.72	−0.62
AGB 3.50 to 7.0 $M_\odot$	SS [Fe/H] = −1.2	0.09	0.85
AGB 3.25 to 7.0 $M_\odot$	SS [Fe/H] = −1.2	−0.15	1.07
AGB 3.00 to 7.0 $M_\odot$	SS [Fe/H] = −1.2	−0.30	1.07
AGB 2.75 to 7.0 $M_\odot$	SS [Fe/H] = −1.2	−0.39	0.99

Shingles et al. (2014)

[ls/Fe] = ([Y/Fe] + [Zr/Fe]) / 2
[hs/Fe] = ([Ba/Fe] + [La/Fe] + [Ce/Fe]) / 3
[ls/hs] = [ls/Fe] — [hs/Fe]

M22: Our enrichment timescale versus isochrone age differences

- Assuming the maximum stellar mass for a ^{13}C pocket is between 3 and 3.5 $M_\odot$, we predict a minimum polluter mass between 2.75 and 3.25 $M_\odot$.
- From the stellar lifetimes, this gives a minimum enrichment timescale of 240-360 Myr.
- Marino et al. (2012) fit the subgiant branch region with a 300 Myr age difference.
- Joo & Lee (2013) fit the SGB and horizontal branch and find Δt=0.3 ± 0.4 Gyr.



Joo & Lee (2013)

Comparison with Straniero et al.

- Straniero et al. (2014) perform a similar study on M4 and M22 with AGB models.
- However, they find shorter timescales of 150 ± 50 Myr. Why?
- The presence of ^{13}C pockets in their more massive models increases heavy s-peak production, hence their minimum contributing masses are higher.
- Straniero et al. models are [Fe/H] -1.8, compared to our -1.2. This leads to higher [hs/ls] at a given mass.
- Due to the large uncertainties of isochrone age measurements in M22, both of our results are consistent with the observations.

Conclusions

- With our yields, rotating massive stars or intermediate-mass AGBs alone do not produce enough heavy-s (Ba, La, Ce) and Pb relative to light-s (Sr, Y, Zr) to match the s-process distributions of M4 or M22.
- The dual contribution from stars with a ^{22}Ne source and stars with a ^{13}C pocket are required to match [ls/hs].
- If we assume that ^{13}C pockets stop forming in the range 3-3.5 $M_\odot$ (at $Z=10^{-3}$), we get a simultaneous match to [ls/hs] and the ~300 Myr age difference in M22.
- In M4, a minimum contributing mass of 3-4 $M_\odot$ corresponds to a minimum enrichment timescale of 140-290 Myr.