Multiple populations in Globular Clusers: the puzzling case of the heavy elements

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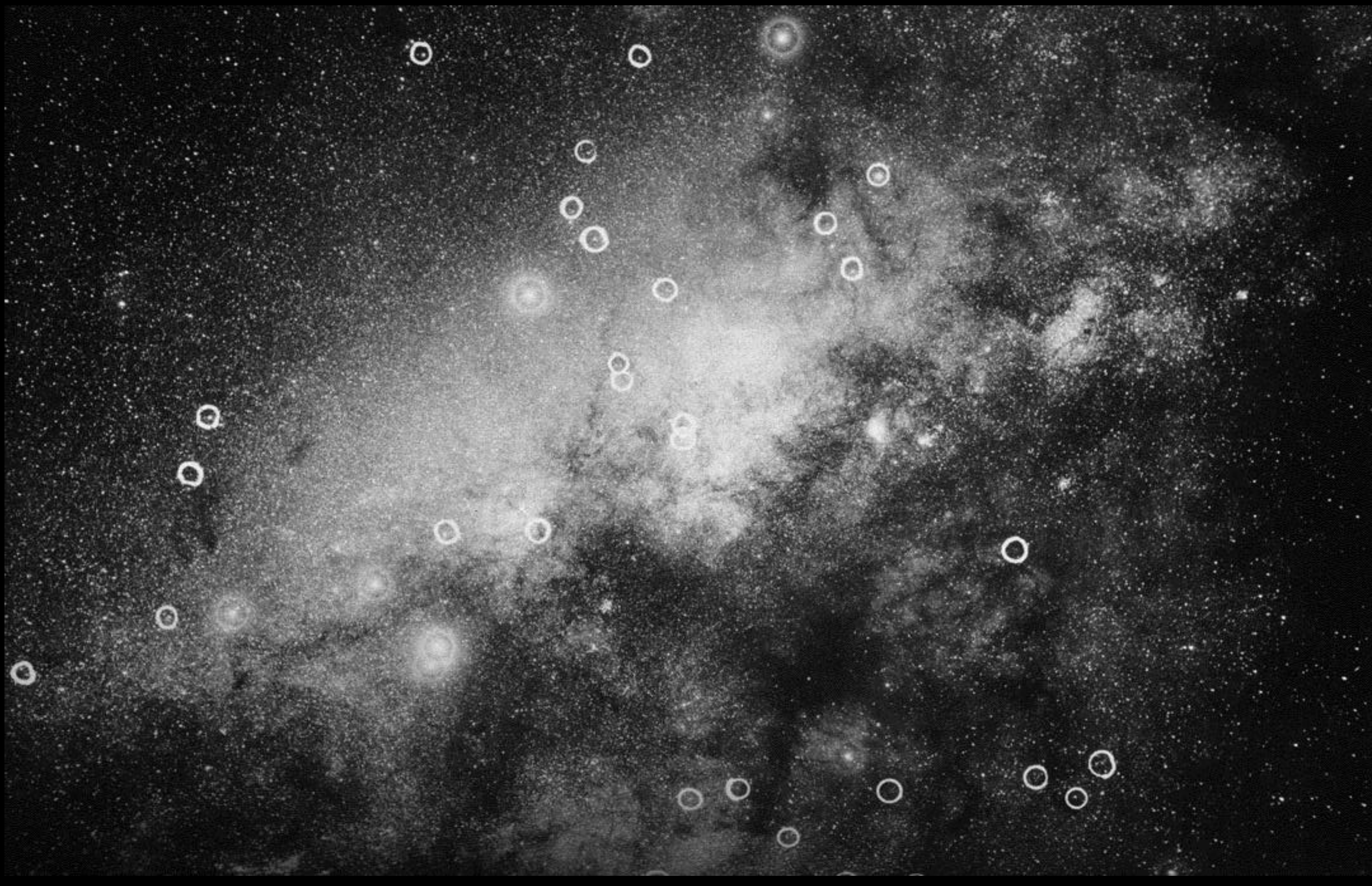
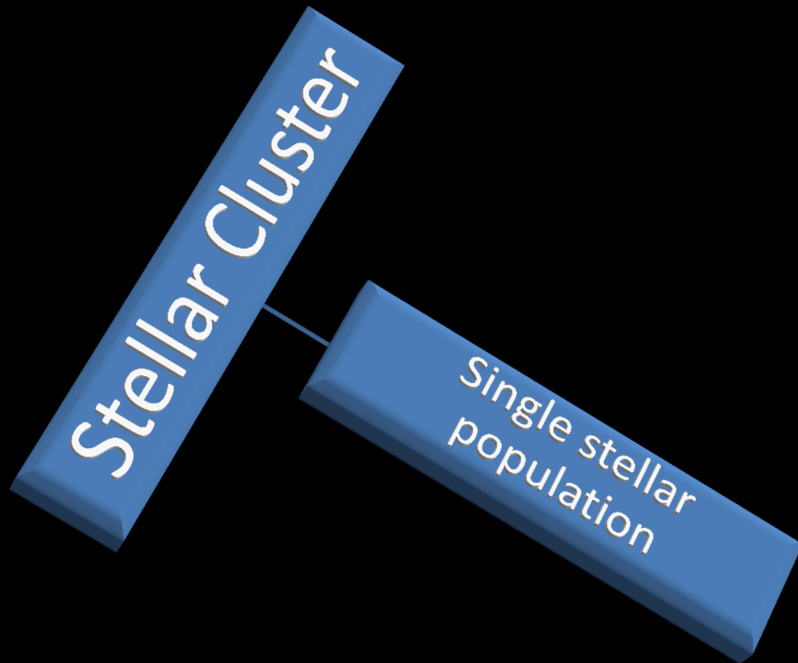
Globular Clusters distribution in the Milky Way

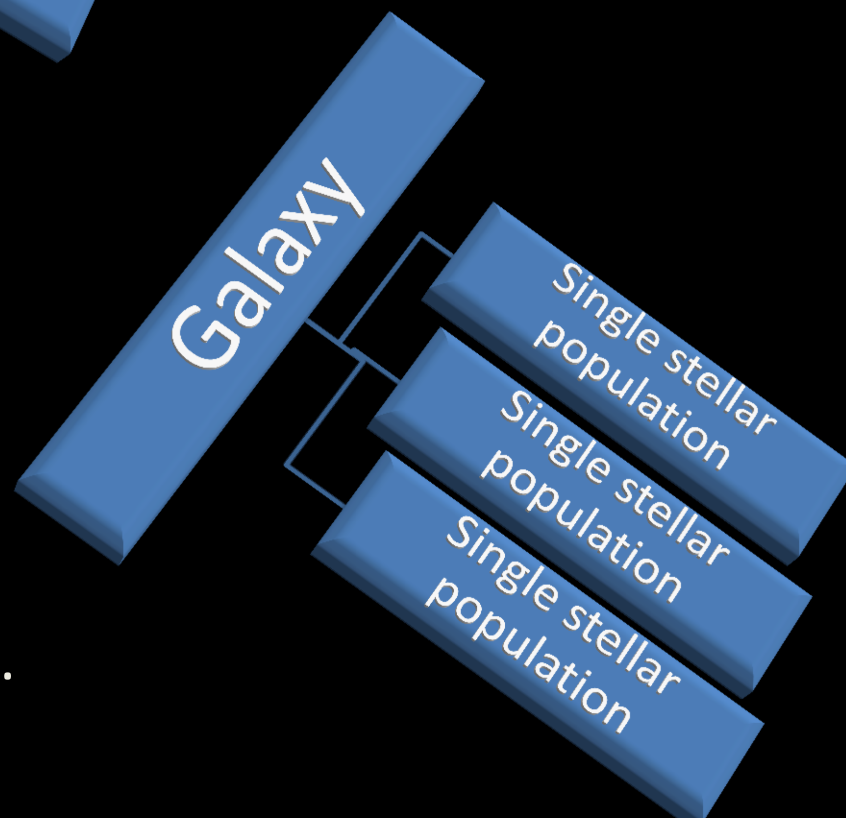


- **GLOBULAR CLUSTERS** populate the halo and the bulge of the Milky Way.
- They are OLD (≈13 Gyr) and metal poor (2.3<[Fe/H]<-0.5), higher Z in the bulge.
- Also found in Milky Way satellites (dwarf spheroidals and LMC/SMC), in the halo of other spiral galaxies (M31) and in giant ellipticals.
- They are made of 10^5 - 10^7 stars .



A single stellar population:

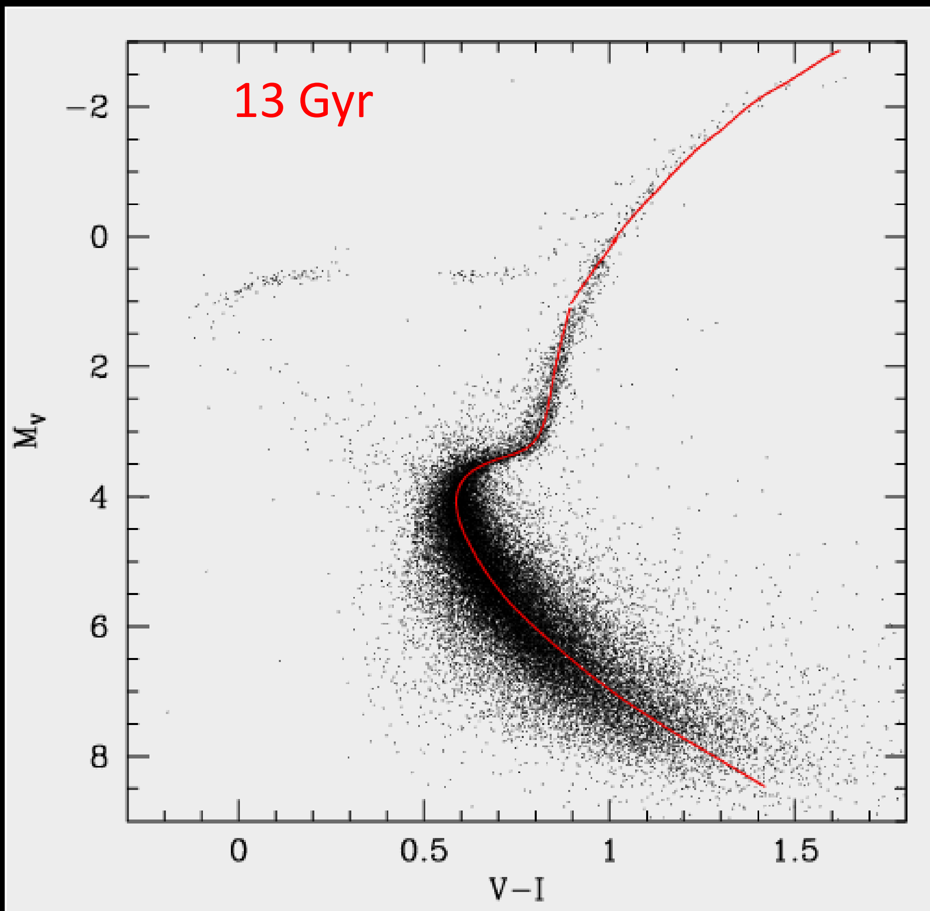
- One composition
- One age
- One variable: the mass

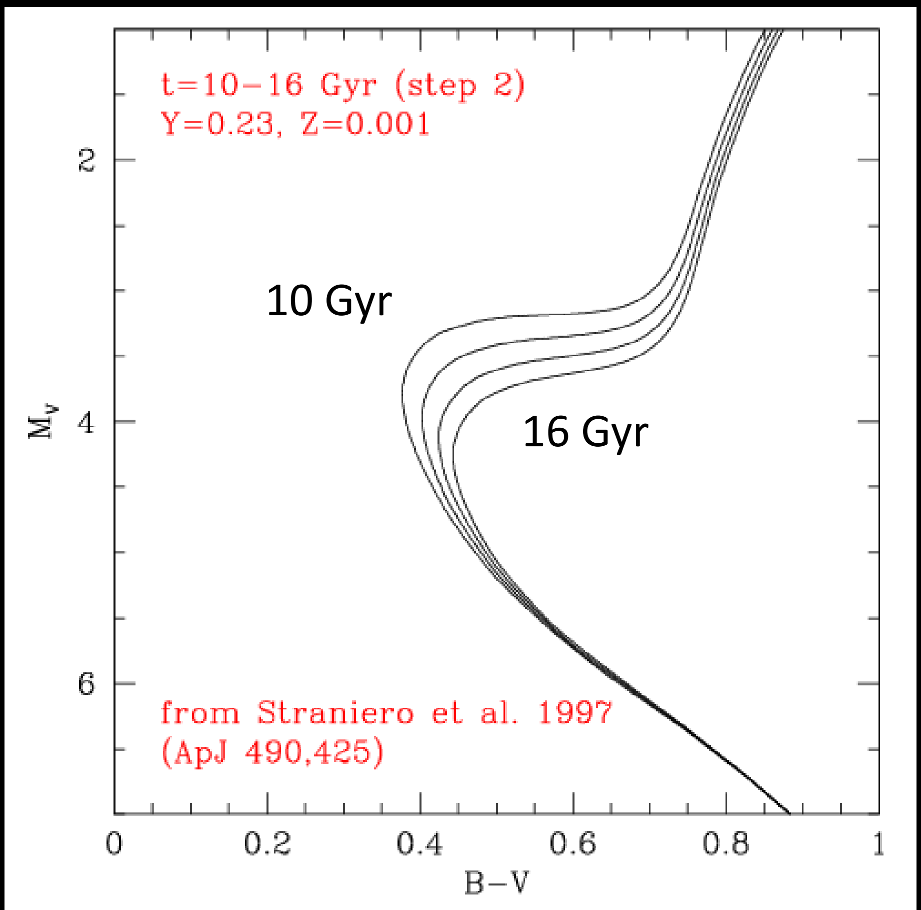


Multiple populations:

- Composition spread
- Age spread
- Many variables: mass, metallicity, helium, age…….

The old fashion: Isochrones fitting



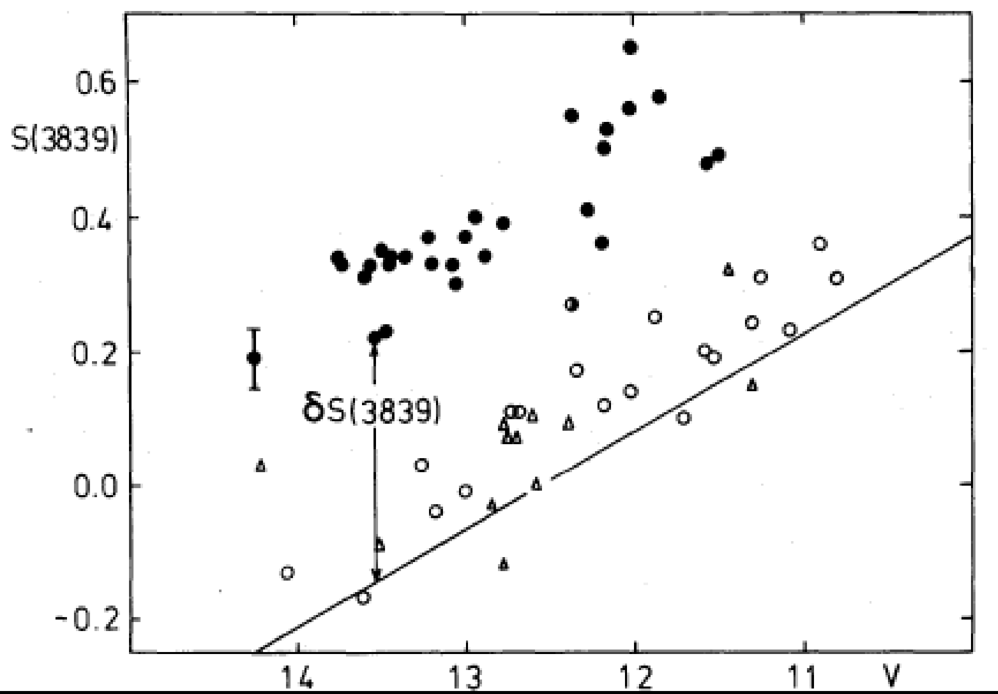


DEVIATIONS FROM SEMPLICITY

Spectroscopic evidence

Star-to-star variations: CN strong & weak

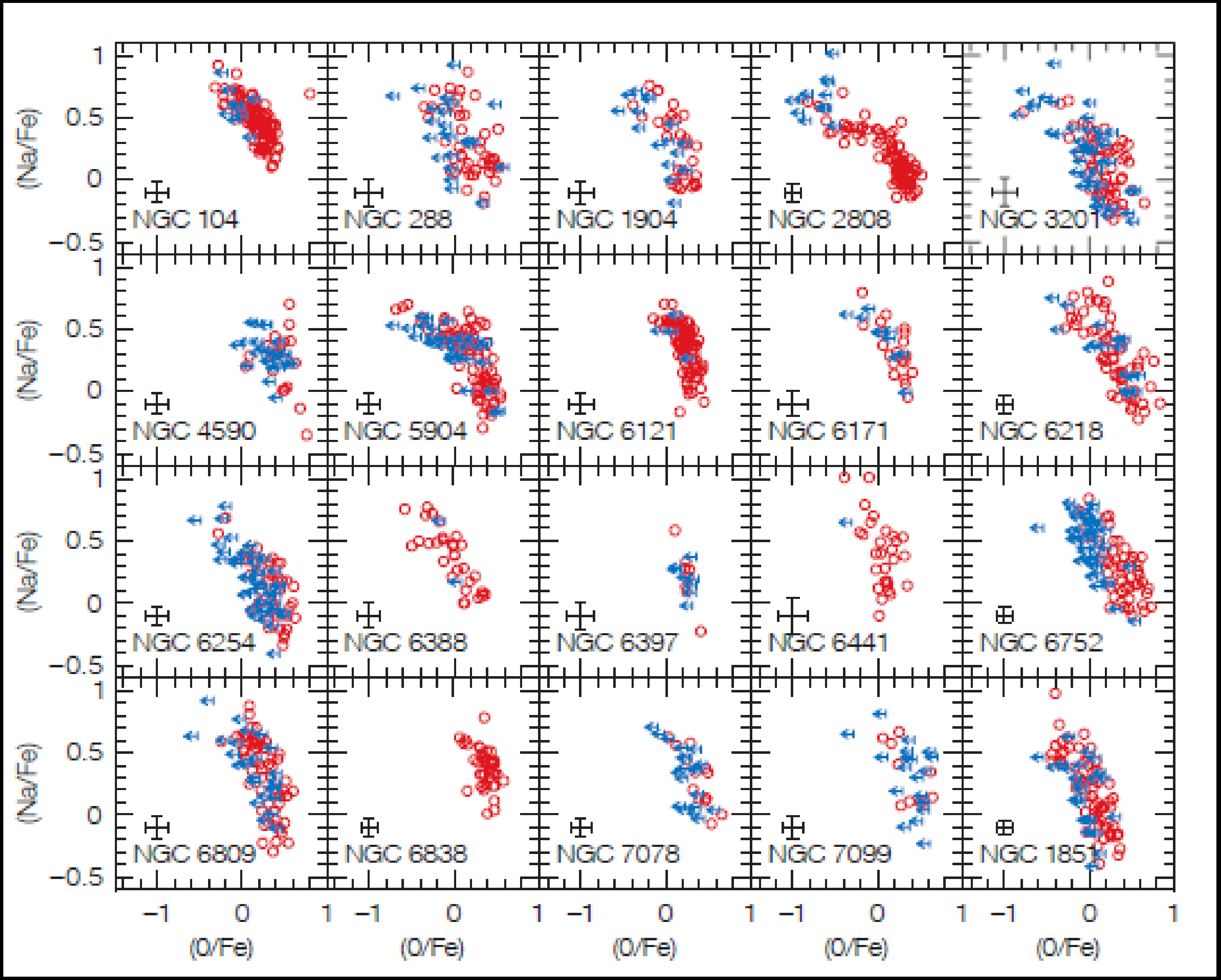
- Some Clusters show stars with variable strength of the CN lines (Cottrell & Da Costa 1981).
- CN and CH strengths are anticorrelated (conversion of C → N ?)
- This is usually ascribed to pollution with material processed by the CN cycle (in-situ or primordial pollution).
- MS, RGB and HB show both type of CN strength, but AGB (CN-weak only).



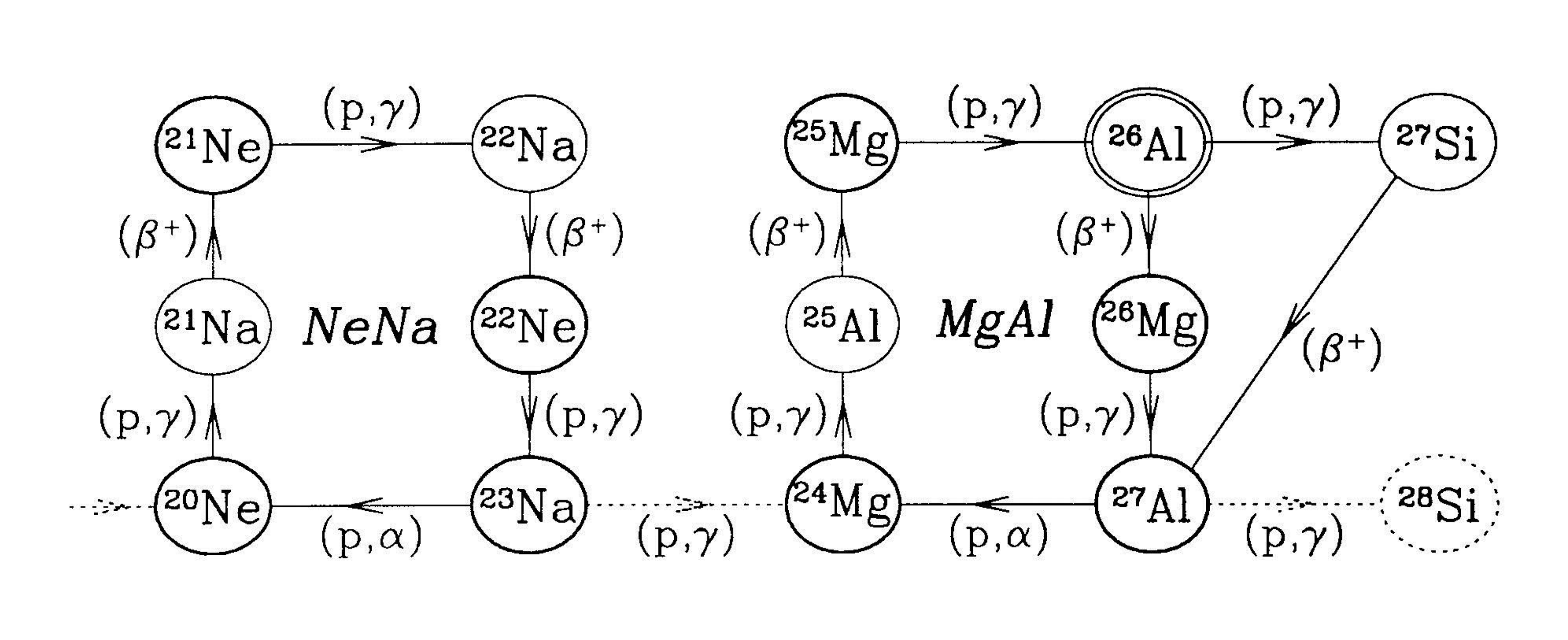
A possible explanation:

- Two stellar populations, different He content.
- He polluters: massive AGB of the first generation. He-rich, because the 2º dredge up, and N-rich, because the Hot Bottom Burning.
- He-richness implies a lower mass for the second generation, so that they skip the AGB (AGB manque).

Star-to-star variations: O-Na and Mg-Al anticorrelations



Ne-Na & Mg-Al Cycles



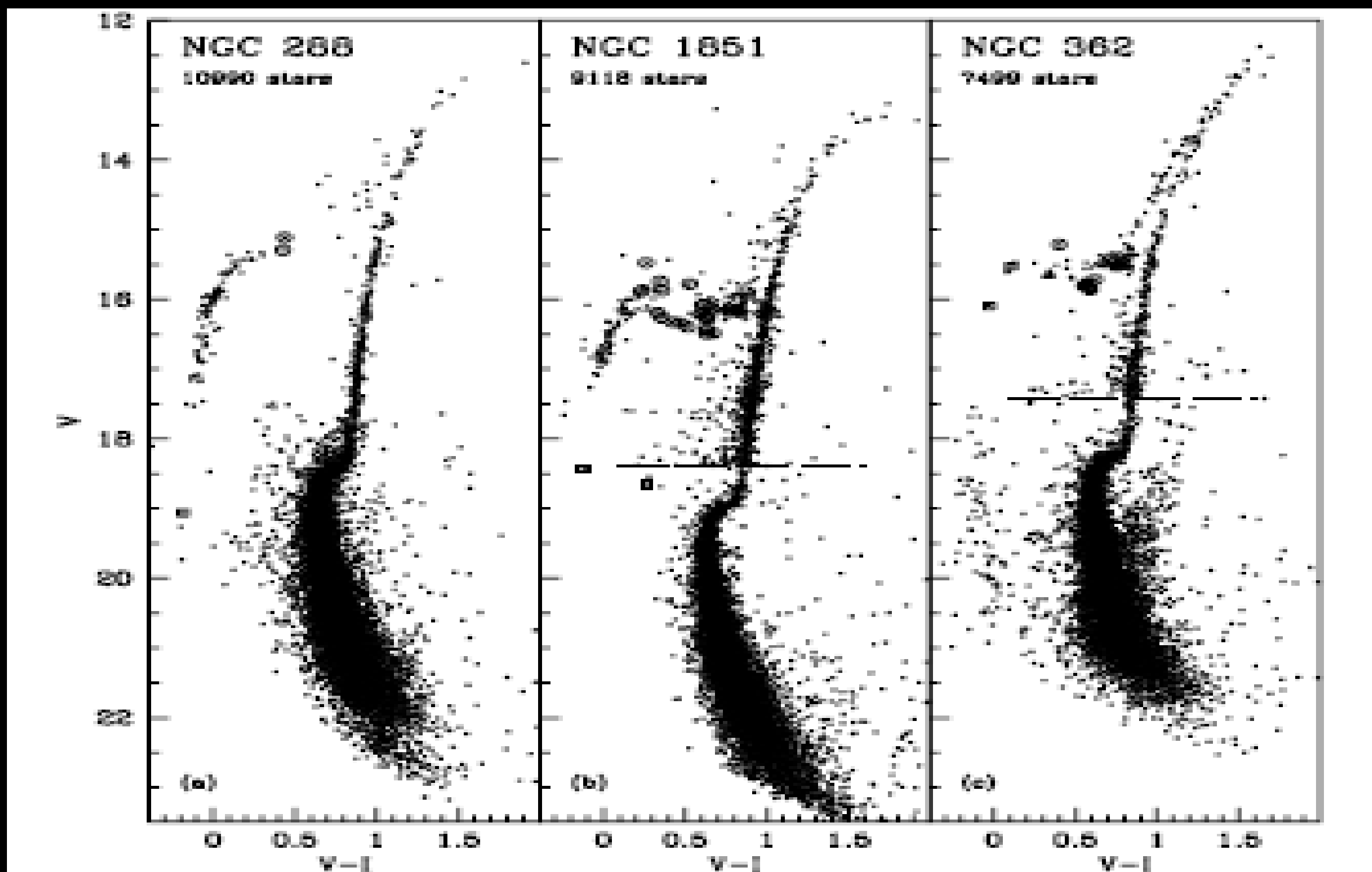
Quite a lot of nuclear astrophysics!!

Photometric evidence

The second parameter Problem.

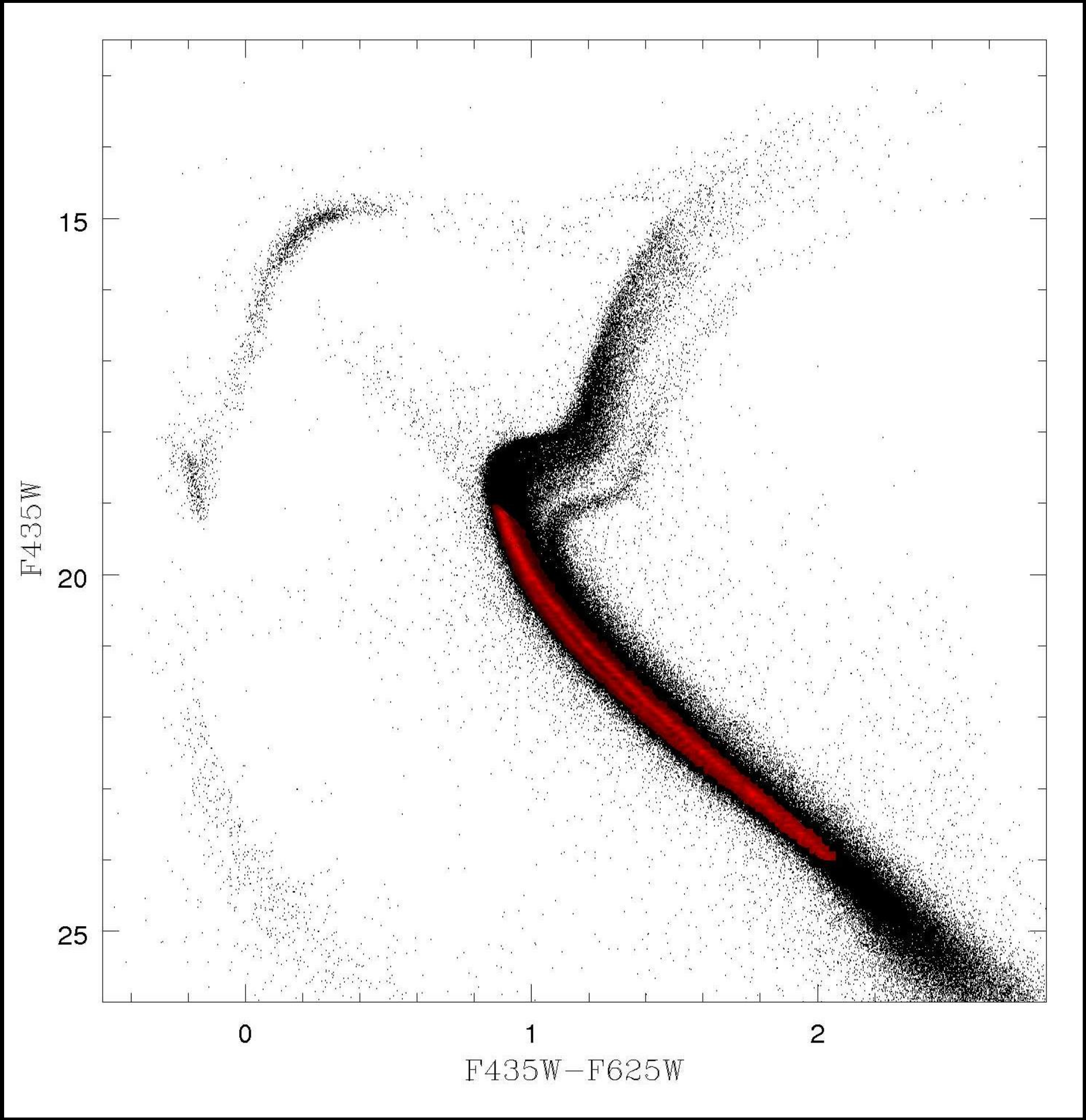
Since the 70’ it was realized that some globular clusters show anomalous horizontal branch (HB). For symple stellar systems, the HB color should depend on the metallicity:

Low Z = blue HB high Z = red HB.



ω Cen

Piotto et al.



The self-pollution scenario

Step 1, about 13 Gy ago, a first stellar generation forms with a typical halo composition, namely: Y≈ 0.245, [α/Fe] ≈ 0.5 and [r/Fe] ≈ 0.5 (NO s process).

Step 2, less than 10 My later, SNe clean up the intracluster region, expelling the residual gas. Star formation stops.

Step 3, a few hundreds My later, fresh gas from low velocity wind of less massive stars refills the cluster area. This gas has been chemically modified by the nucleosynthesis of the first stellar generation. Then, a new stellar generation forms.

Standard versus non-standard heavy elements composition of halo stars

r-process

The r-process pollution appears very soon in the early Galaxy.

Astrophysical sites. Final fate of massive stars: core-collapse supernovae (II, Ib, Ic) and/or neutron-star mergers.

see lectures by K-L Kratz, O. Korobkin, T. Kajino, S. Shibagaki

s-process standard paradigm

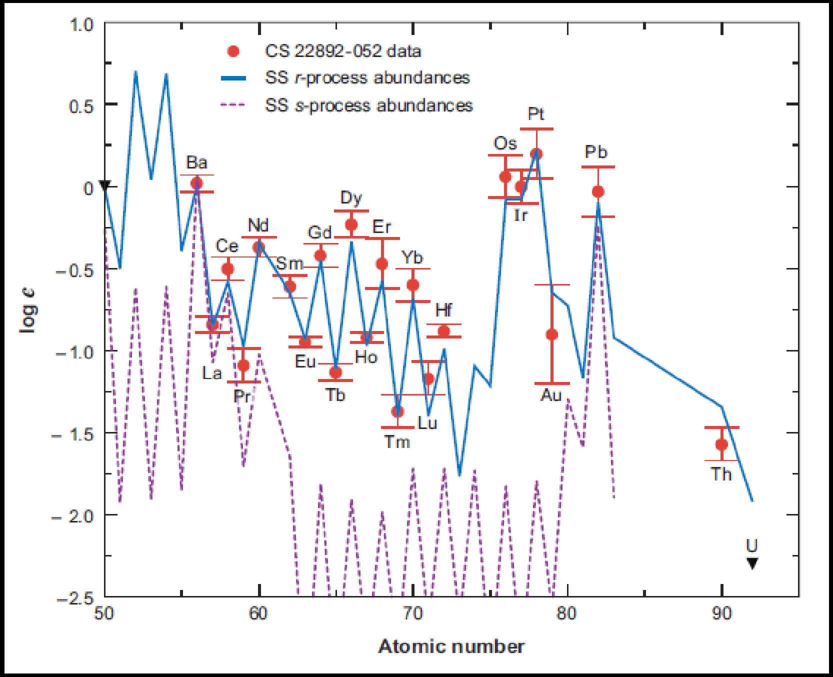
- WEAK (29<Z<40). MASSIVE STARS: Core-He burning (marginal), shell-C burning (dominant). $^{22}Ne(\alpha,n)^{25}Mg$. It does not work at low Z, because the lack of (secondary) ^{22}Ne (but very fast rotators may produce primary ^{22}Ne - see Pignatari 2008).

- MAIN & STRONG (37<Z<84). LOW MASS AGB STARS, 1.3-2.5 $M_{\odot}$: He-rich layer, $^{13}C(\alpha,n)^{16}O$ (main), $^{22}Ne(\alpha,n)^{25}Mg$ (depends on mass and metallicity). Primary ^{22}Ne, because the 3rd dredge up. It could work at low Z (e.g. CEMPs stars), but no contribution to the halo pollution, because the too long lifetime.

The majority of the halo stars (singles) confirm this paradigm.

Only massive polluters, because the too short time scale.

Only r-process, no s-weak, because the lack of neutron sources.



CS 22892-052 (from Sneden, Cowan, Gallino 2008)

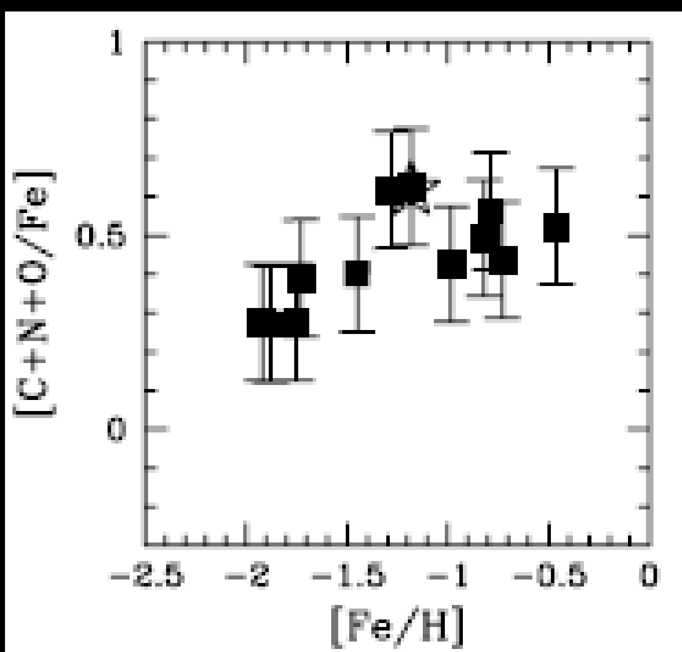
Heavy elements in GC

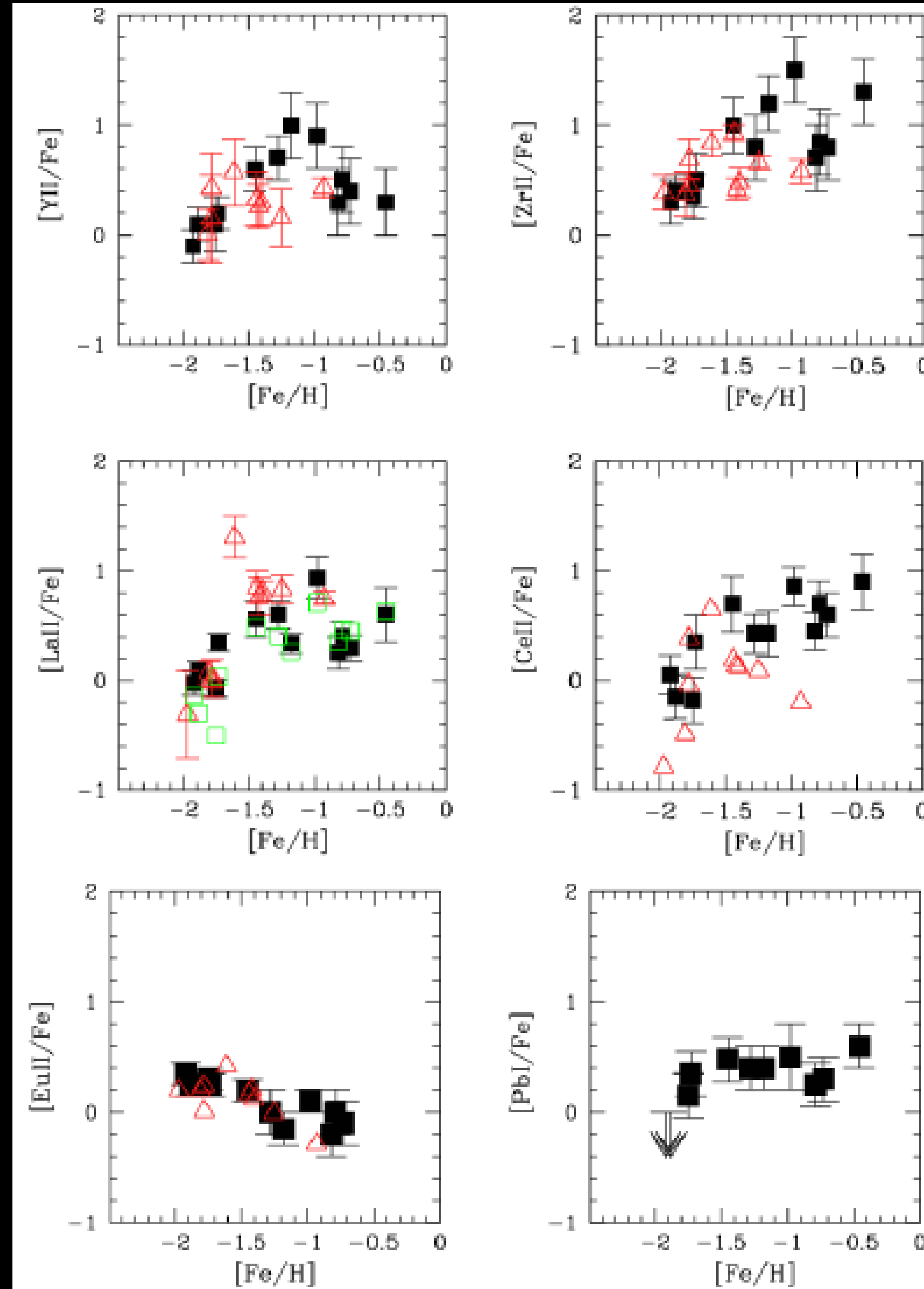
Deviations from standard paradigms

ω Cen

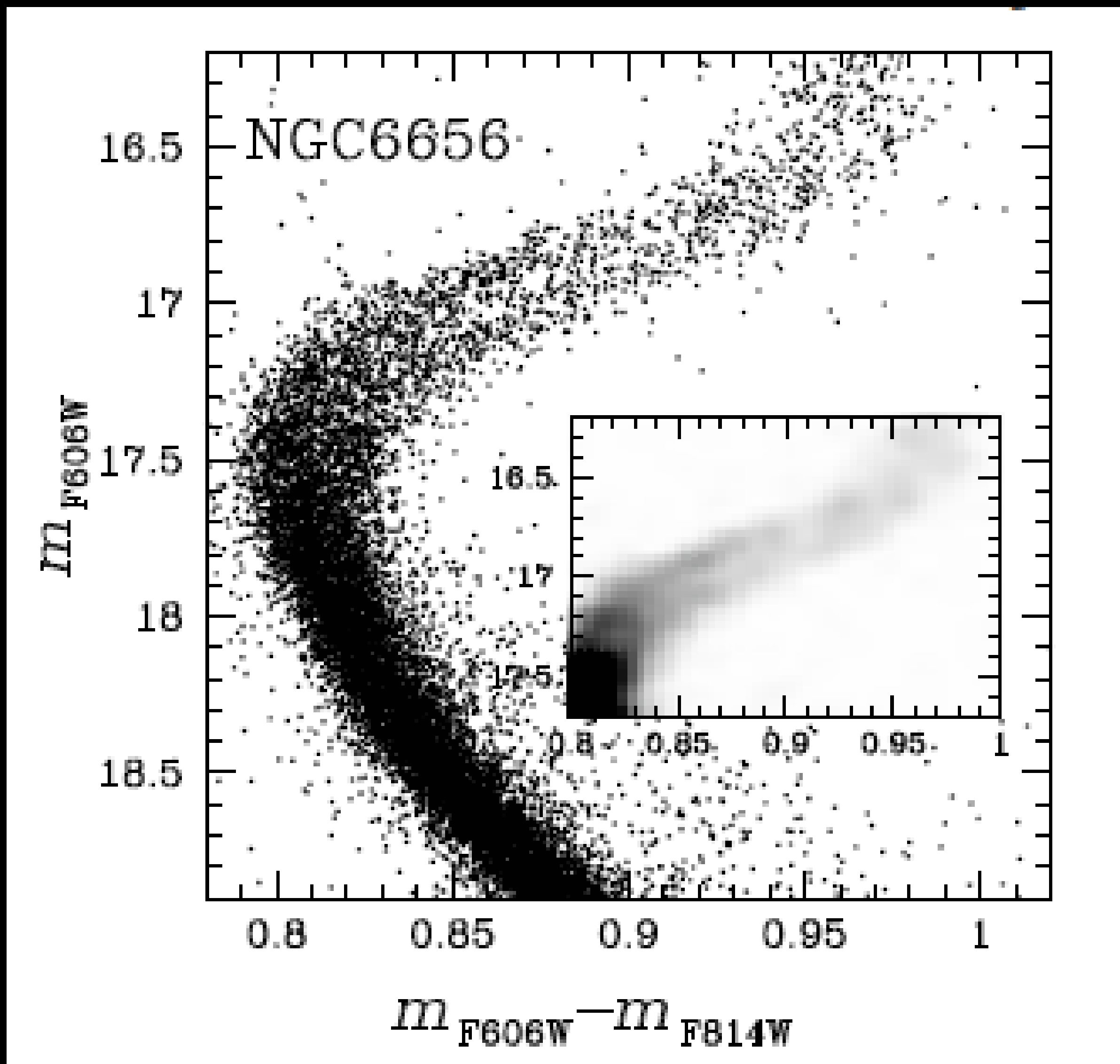
D’Orazi et al. 2011
Smith et al. 2000
Johnson & Pilachowski, 2010

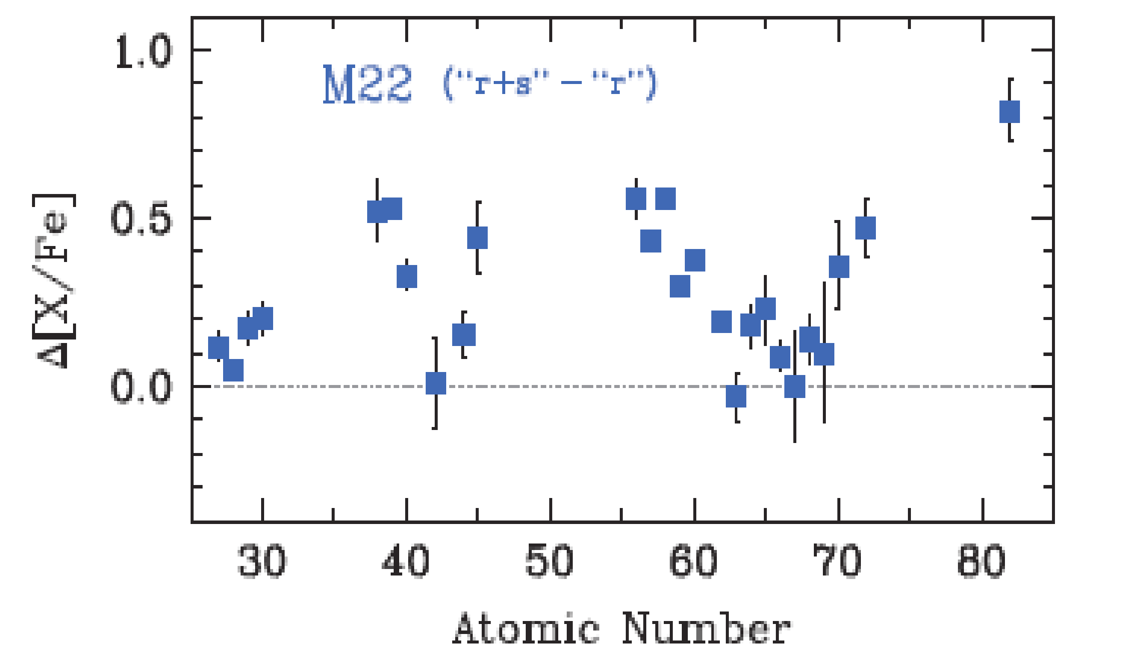
TDU+HBB (or deep mixing)?





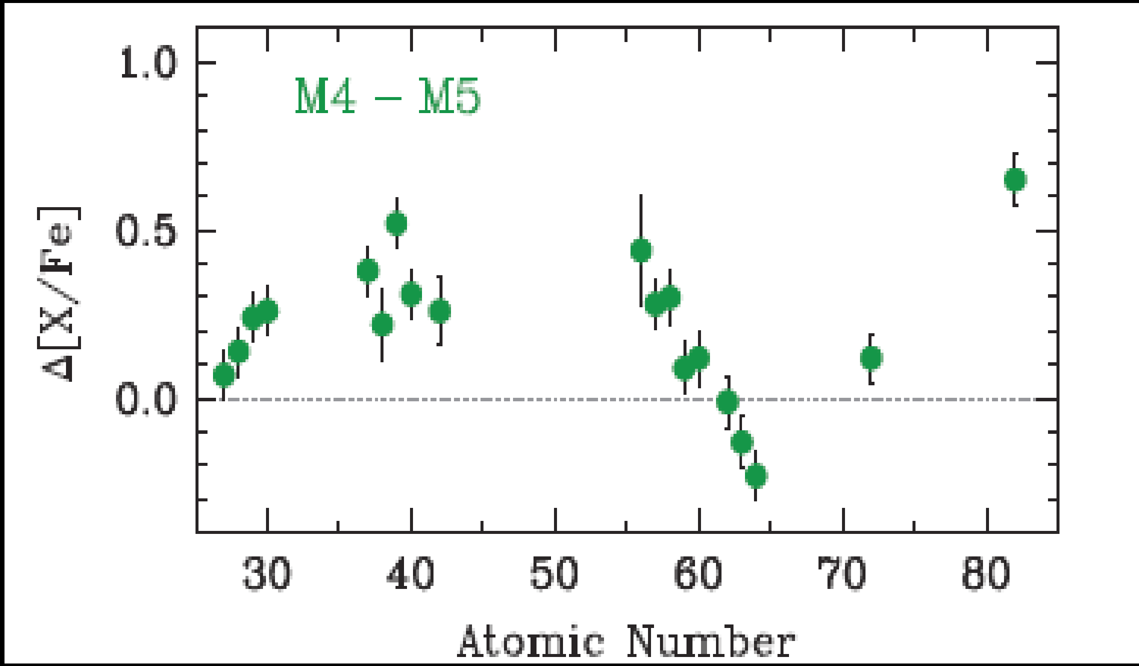
The double sequence of M22.





Double sequences of M22: (r+s) - (r)

Roederer et al. 2012.

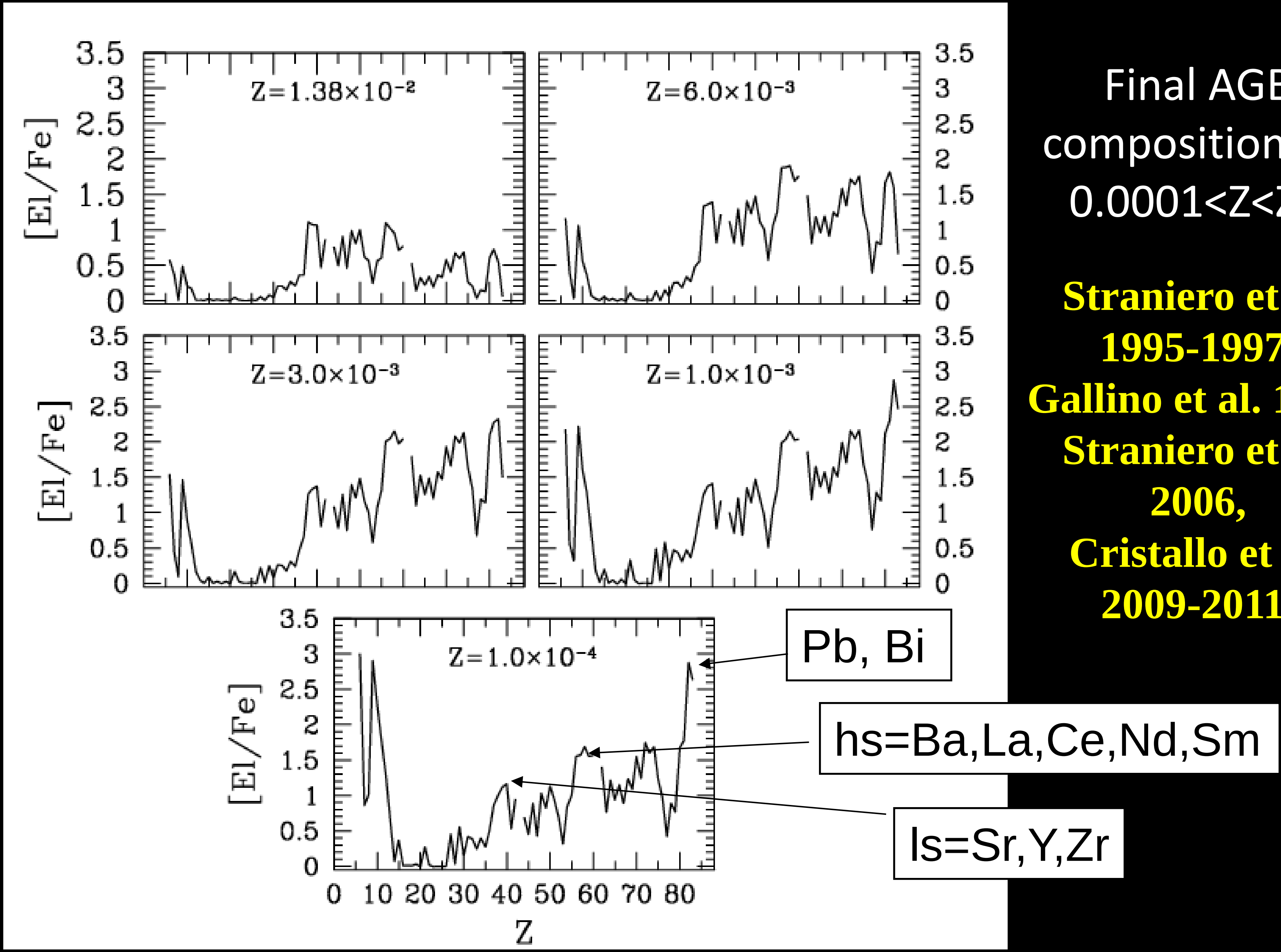


M4(r+s)-M5(r)

Yong et al. 2008
Ivans et al. 2001

Where is the puzzle? Here it is.

- If the polluters were low-mass AGB stars (1.5-2 $M_{\odot}$, as for the solar main component) , we would expect quite large [hs/ls] and a huge amount of lead.
- On the other hand, low-mass stars needs 1-2 Gyr to evolve up to the AGB.
- Observed: [hs/ls] ≈0, a bit more of lead, expected GCs formation timescale less than 500 Myr (with the possible exception of ω Cen)

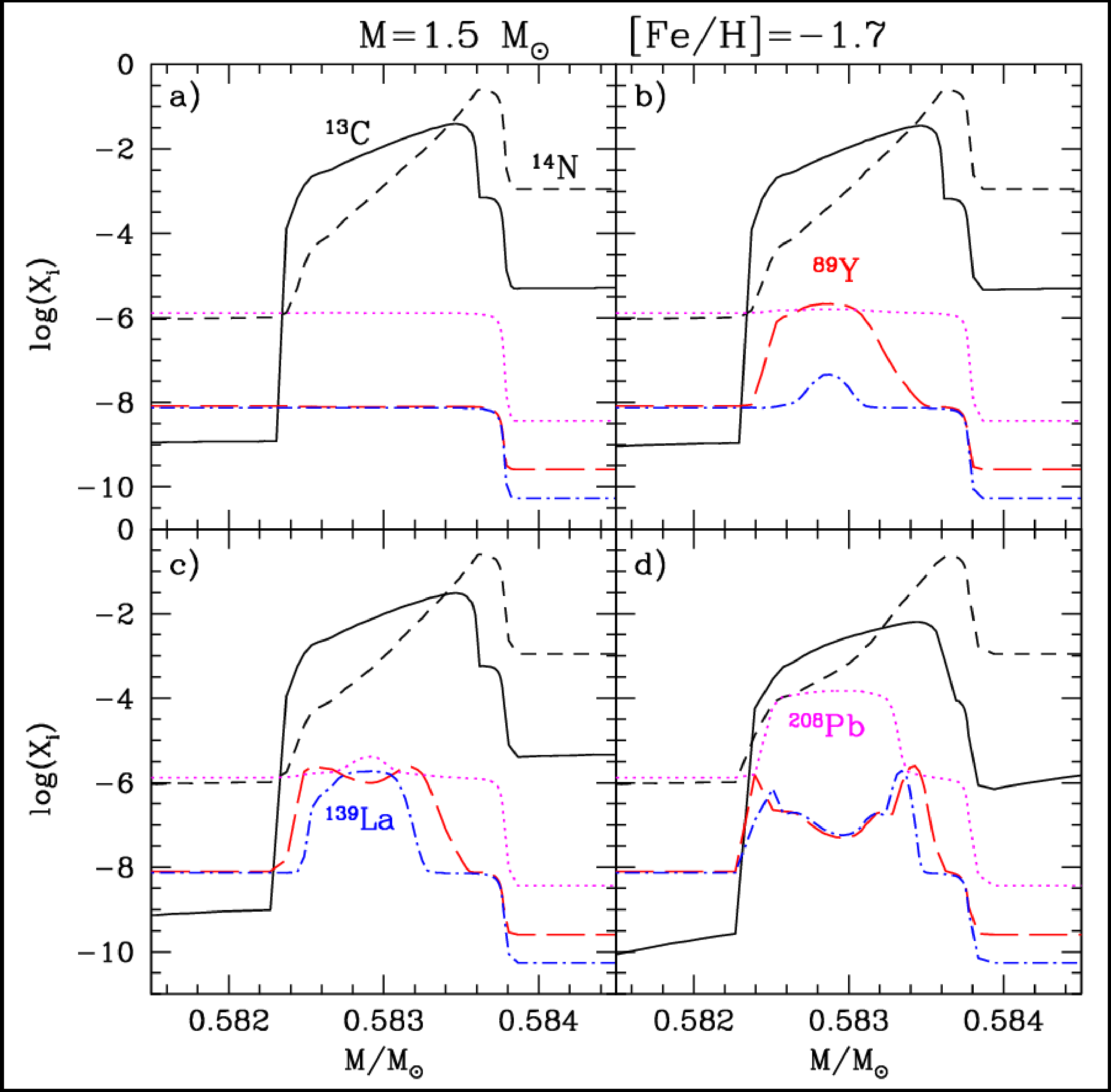


Final AGB composition for $0.0001<Z<Z_{\odot}$

Straniero et al. 1995-1997, Gallino et al. 1998, Straniero et al. 2006, Cristallo et al. 2009-2011,

Radiative ^{13}C burning

at low Z

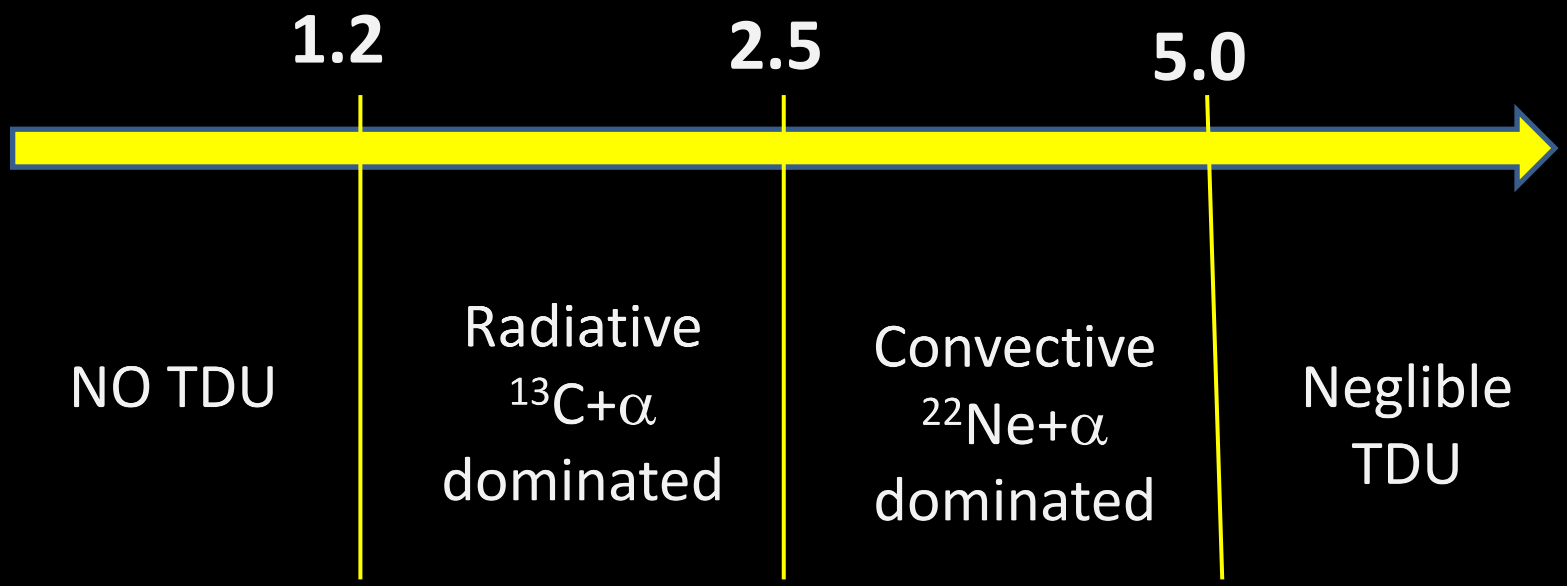


The two neutron bursts

- Radiative ^{13}C burning: long timescale, low neutron density ($<10^7$ neutrons/cm^3). Iron seeds are rapidly consumed to produce light-s. Then, ls become seeds to produce heavy-s. Finally also hs become seeds and lead is accumulated until all the ^{13}C is consumed.
- Convective ^{22}Ne burning: short timescale, high neutron density ($>10^{11}$ neutrons/cm^3). Owing to convection, the initial Fe abundance is continuously restored. Light-s are the main products, while a negligible Pb production is expected.

AGB Types

Very low | low | intermediate | massive (super)

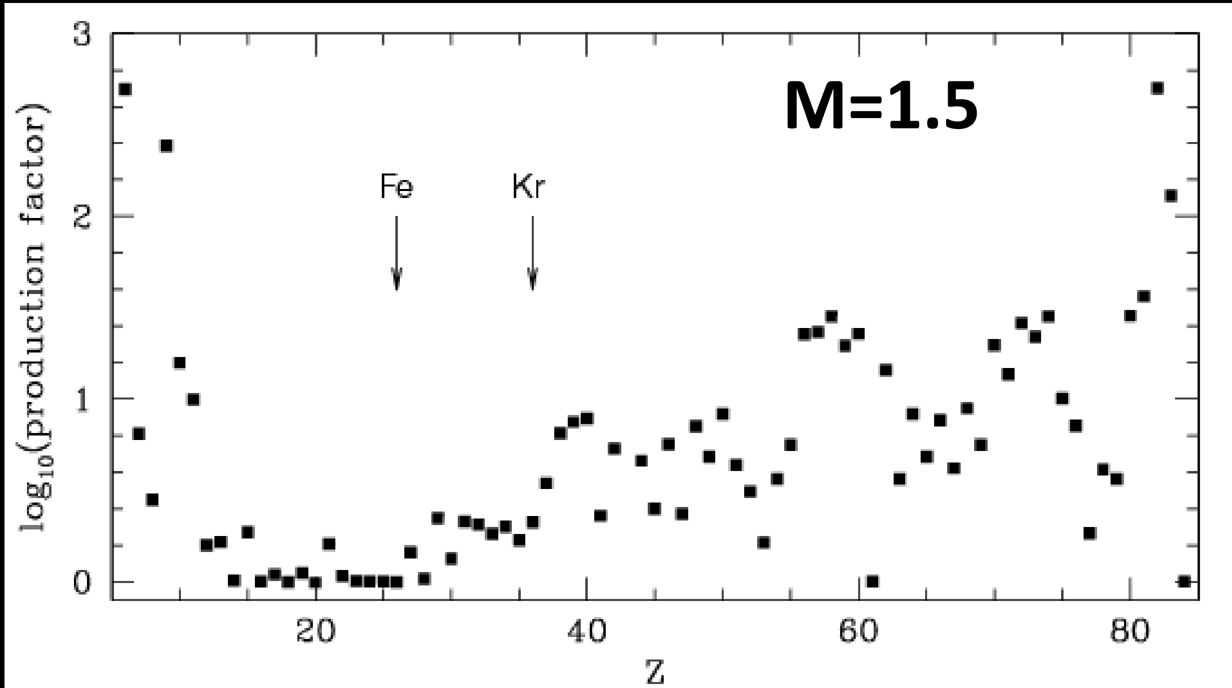


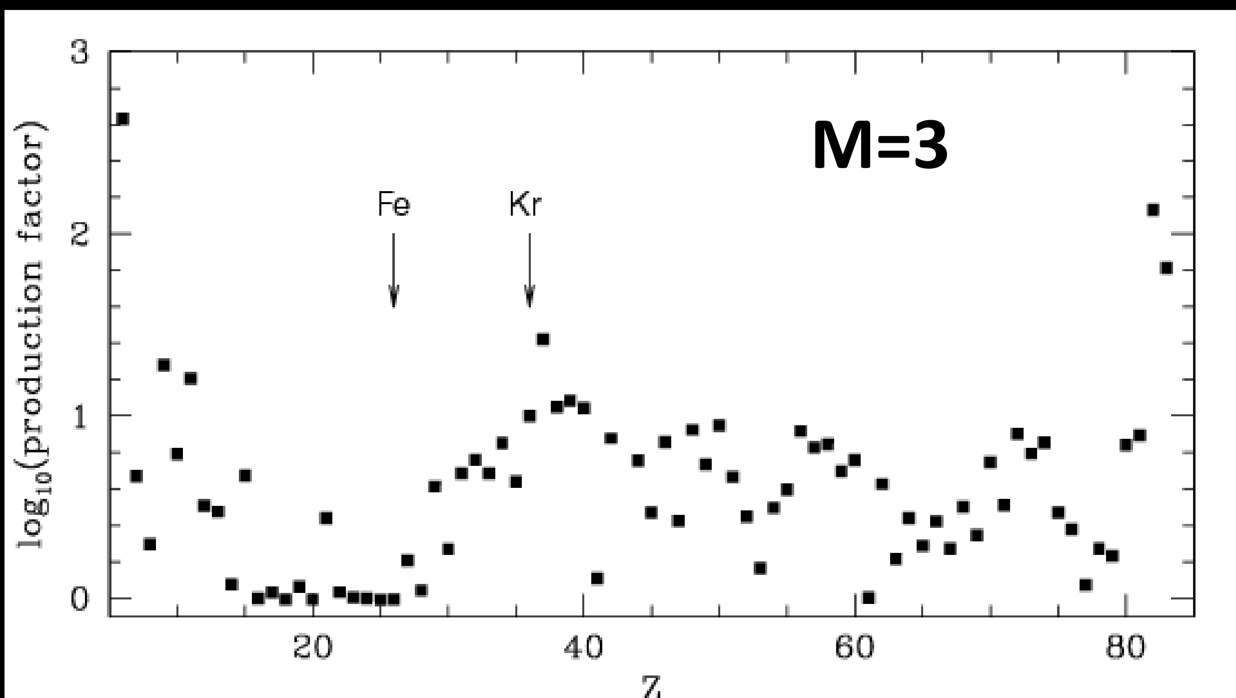
FULL NETWORK STELLAR EVOLUTION (FUNS)

- 500 isotopes (H to U)
- 800 reactions: p, α & n captures, β decays, electron captures
- Rotation (optional)

References: Straniero et al. 2006

Piersanti et al. 2013 (for rotation)

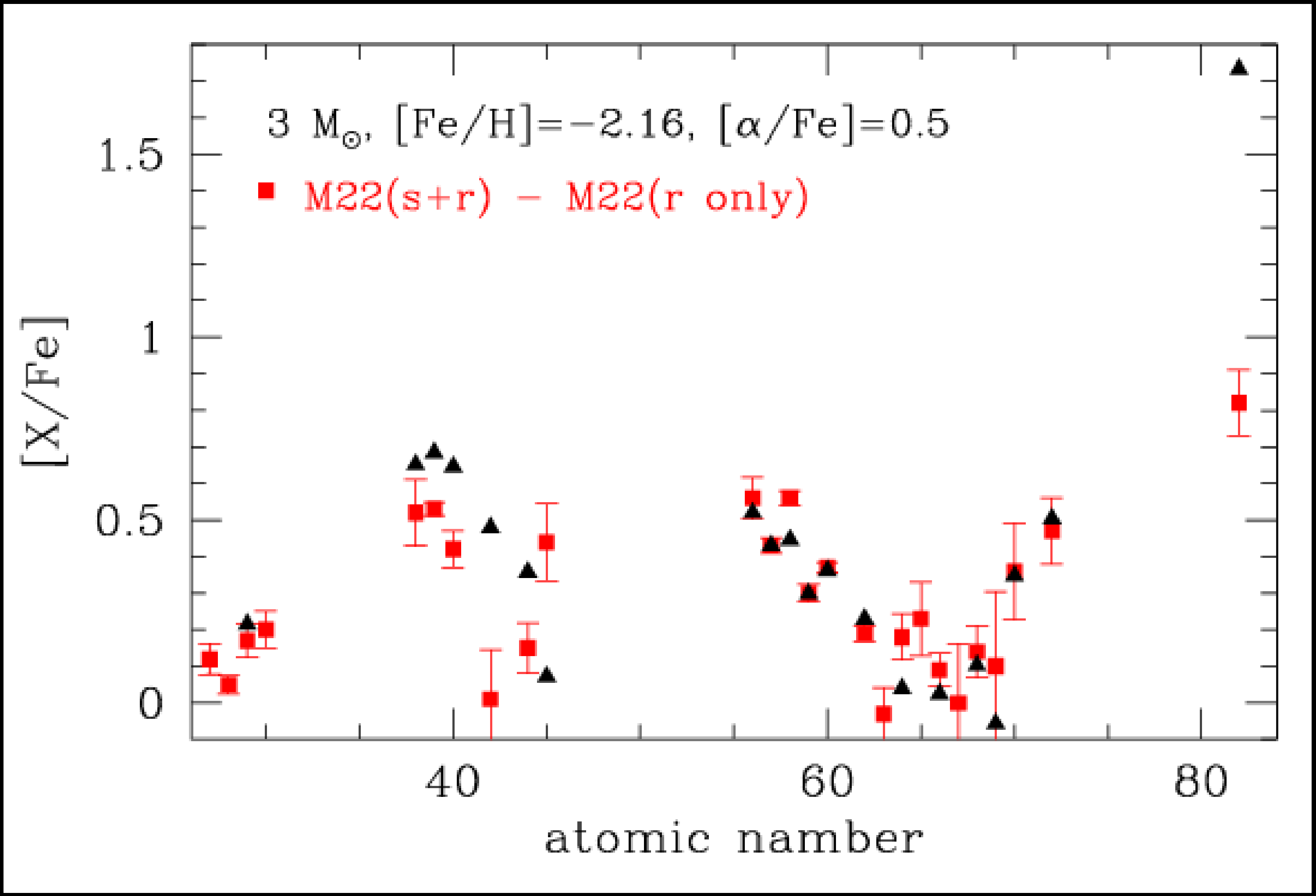




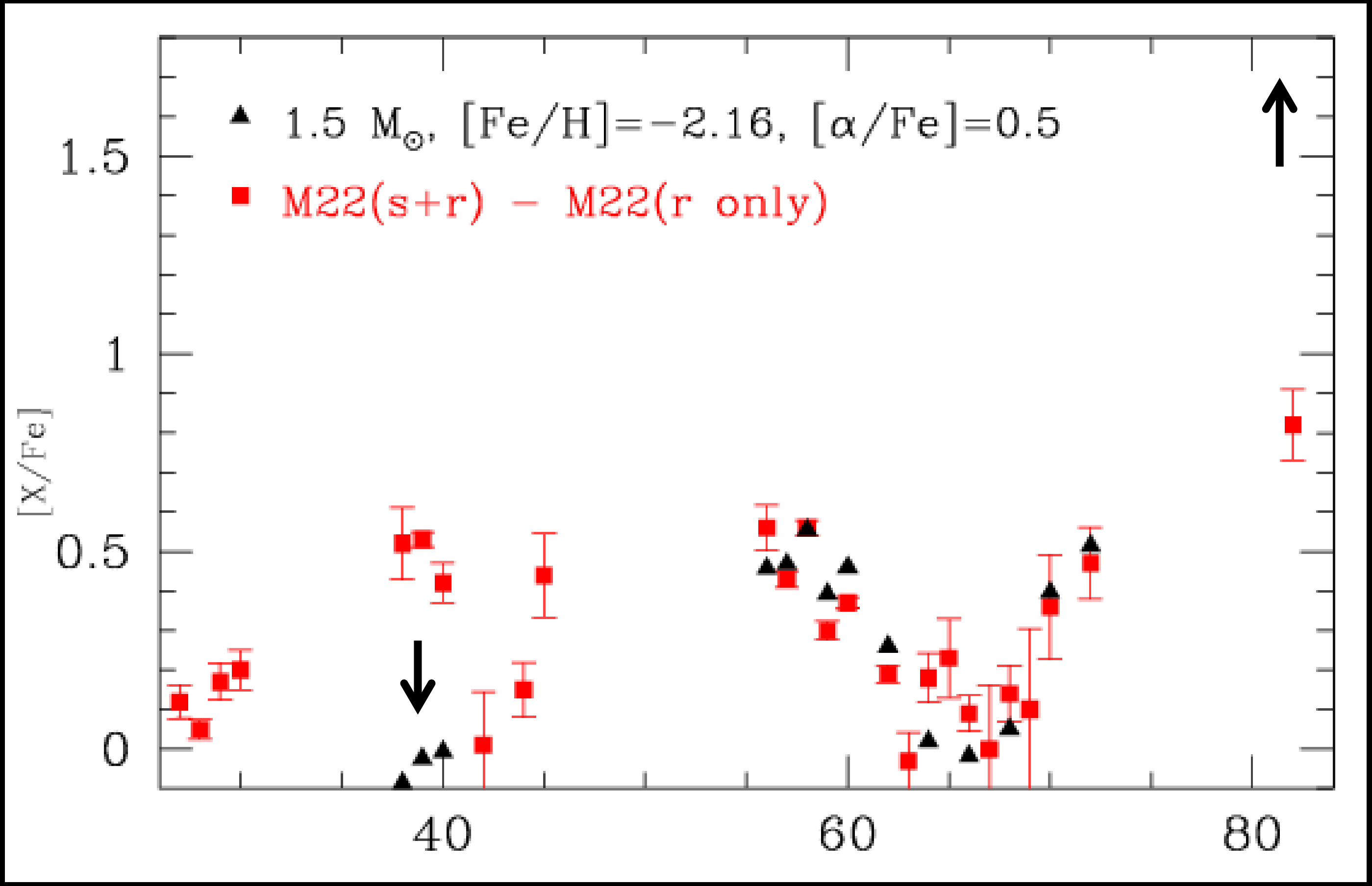
[Fe/H]=-2.16

[α/Fe]=0.5

pf=$X_{final}/X_{initial}$



3 M$_\odot$, [Fe/H]=−2.16, [α/Fe]=0.5
M22(s+r) − M22(r only)
[X/Fe]
1.5
1
0.5
0
40
60
80
atomic namber



1.5 M$_\odot$, [Fe/H]=−2.16, [α/Fe]=0.5
M22(s+r) − M22(r only)
[X/Fe]
0
0.5
1
1.5
40
60
80

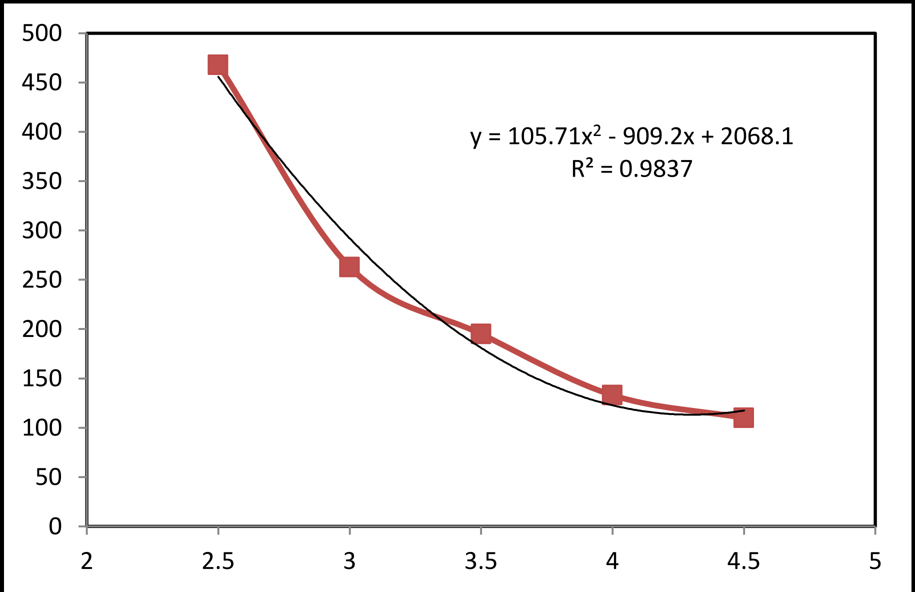
Timescale and chemical pollution

$$Y = \frac{\sum_{j=M\min}^{M\max} p_j Y_j}{\sum_{j=M\min}^{M\max} p_j}$$

$$M_{\min} = f(\Delta t)$$
$$M_{\max} \approx 5\, M_{\otimes}$$

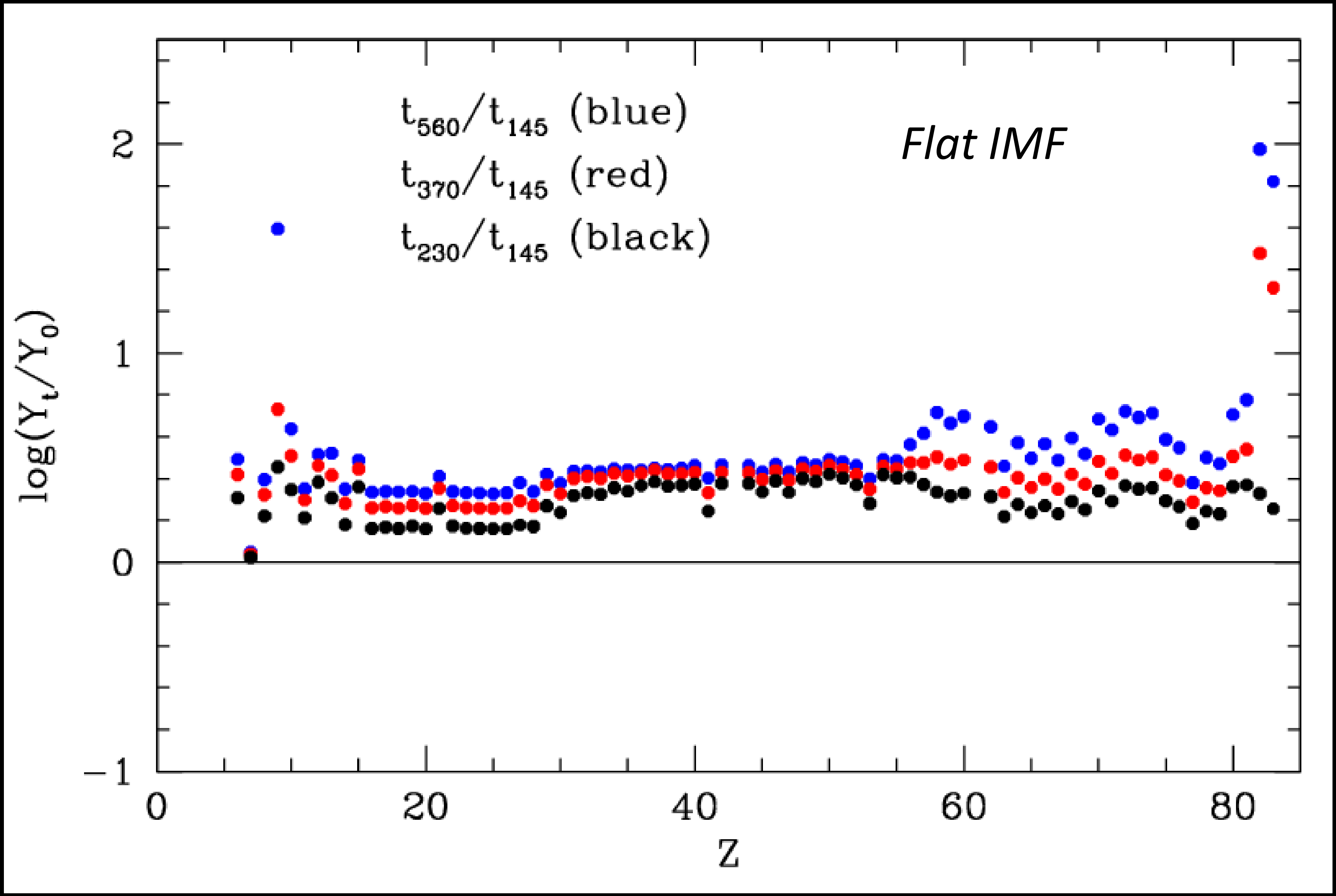
p_j = weight, depends on the mass function

Y = *yield* (solar masses)

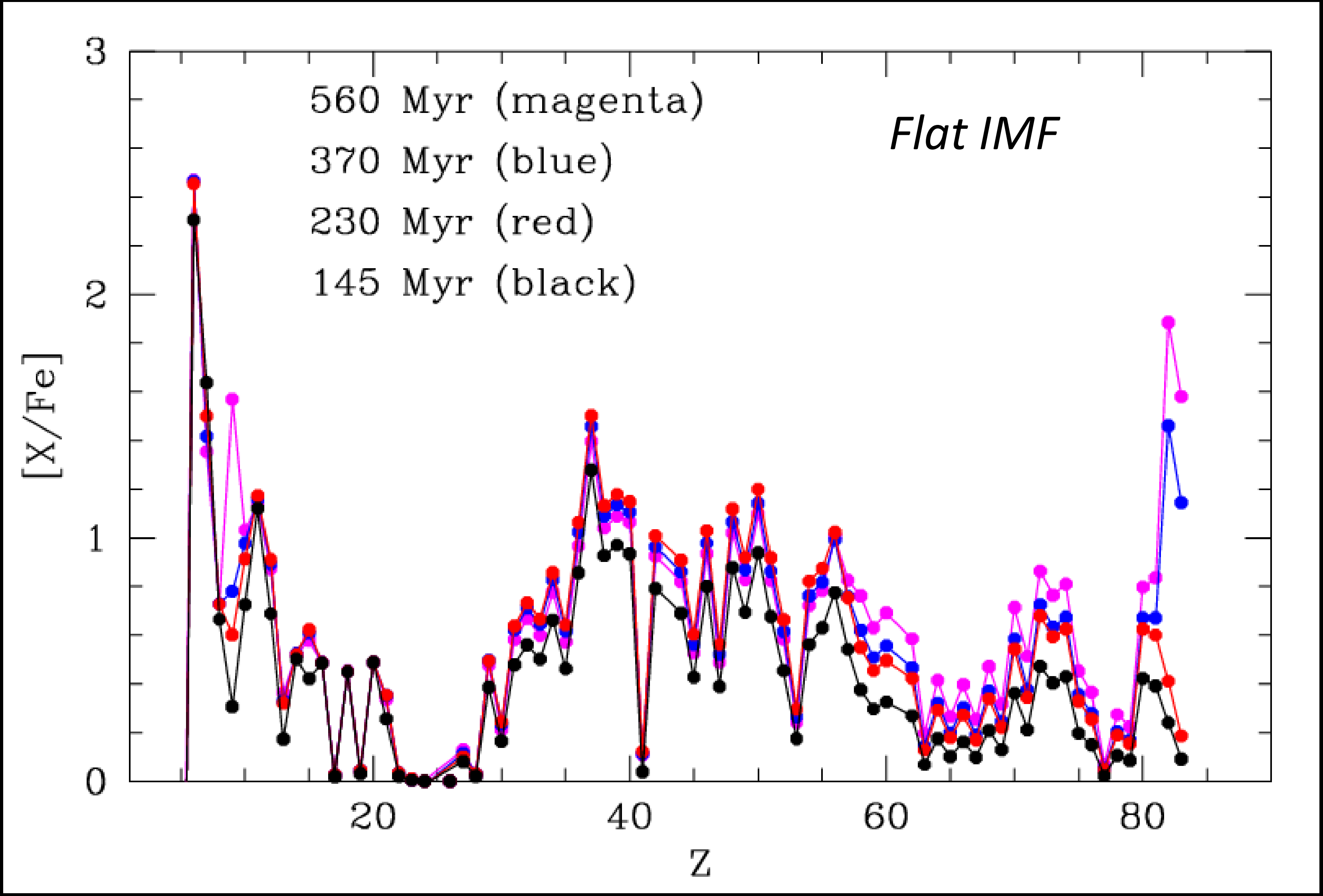


M	*Δt (My)*
2.5	468
3.0	263
3.5	197
4.0	133
4.5	110

2º generation composition vs delay time



2° generation composition vs delay time



Summary of low-Z AGB

- Low-mass AGB (1.2-3), s-process nucleosynthesis dominated by the radiative ^{13}C burning: large amount of Pb and 0 < [hs/ls] ≤ 0.5.
- Intermediate mass (3-5), a mix of ^{13}C and ^{22}Ne burning, low (10^6 n/cm^3) and high (10^{13} n/cm^3) neutron densities, respectively. Larger ls production. due to the second neutron burst: [hs/ls] ≤ 0 . Strong suppression of Pb production.
- Massive and super AGB (M>5): negligible TDU (if any), no heavy elements. Neutron source ($^{13}C+\alpha$) actives at the bottom of the convective envelope. A main revision of the HBB scenario expected . Implications for the O-Na and Mg-Al anticorrelations (?)

CONCLUSIONS

- r-process is observed everywhere in the halo (field and clusters)
- Star-to-star variations of O-Ne (Mg-Al ?) are observed in almost all the GC stellar populations.
- At variance, s-process enrichment is observed in a few GCs only.

A different class of polluters is needed for the s-process.

- Massive and super AGB: NO TDU
- Low mass (?) long timescale and too much Pb.

3-5 $M_\odot$ OK: Δt=100-500 My.