Hot CNO and p-capture nucleosynthesis in intermediate mass AGB stars

(constraints from Globular Clusters' second generation chemistry)

Francesca D'Antona
INAF-OAR (Monte Porzio, Italy)

GIANTS 2015, Padova, April 28-30

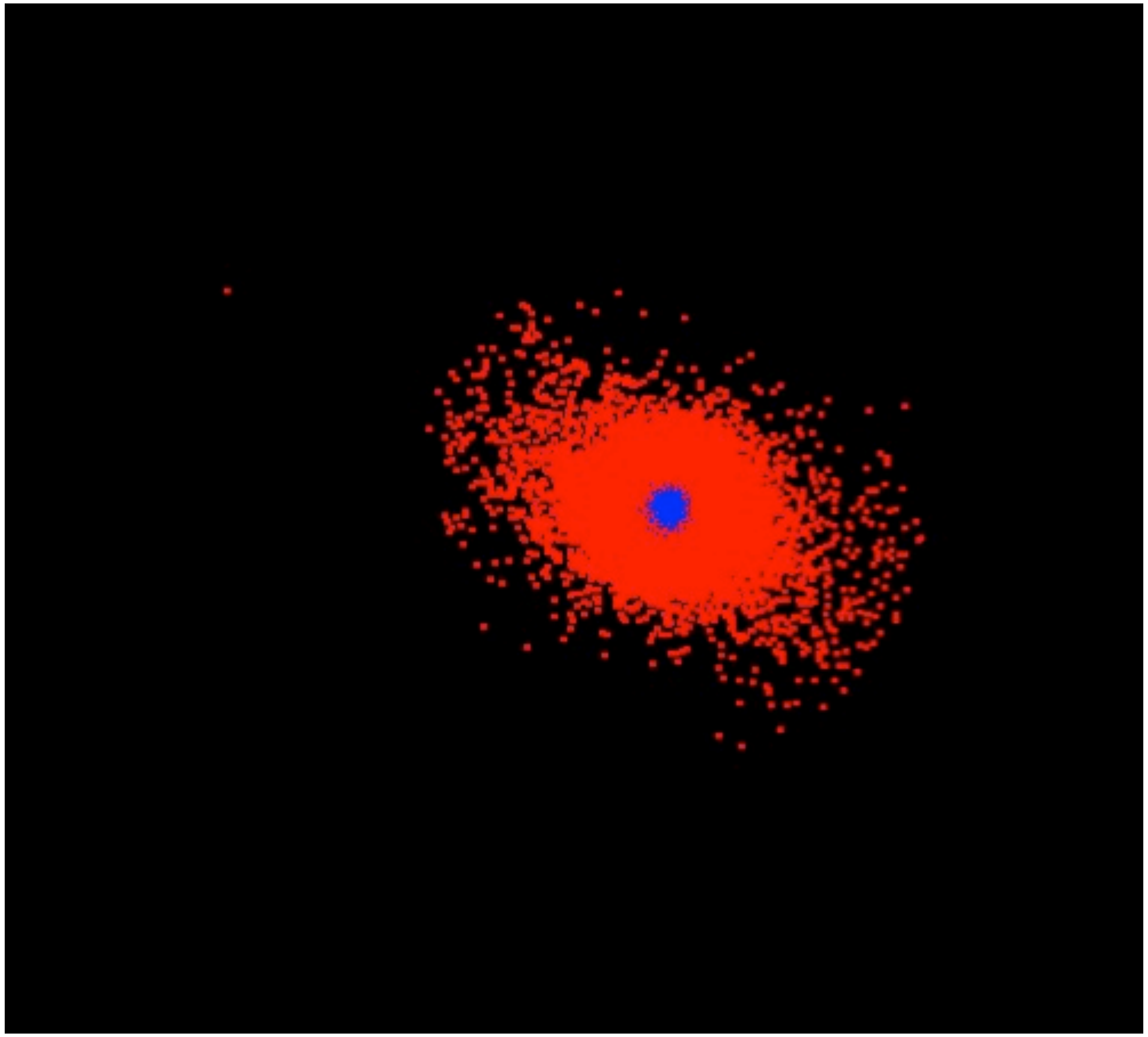
The site of hot CNO cycle

1) The structure of Asymptotic Giant Branch stars evolving above a critical luminosity changes in a dramatic way: the convective boundary touches the H-burning shell, so that the burning products are spread into the envelope, up to the atmosphere

2) As these luminous giants lose mass, the products of nucleosynthsis are recycled into the ISM, and have an important role in the galactic chemical evolution

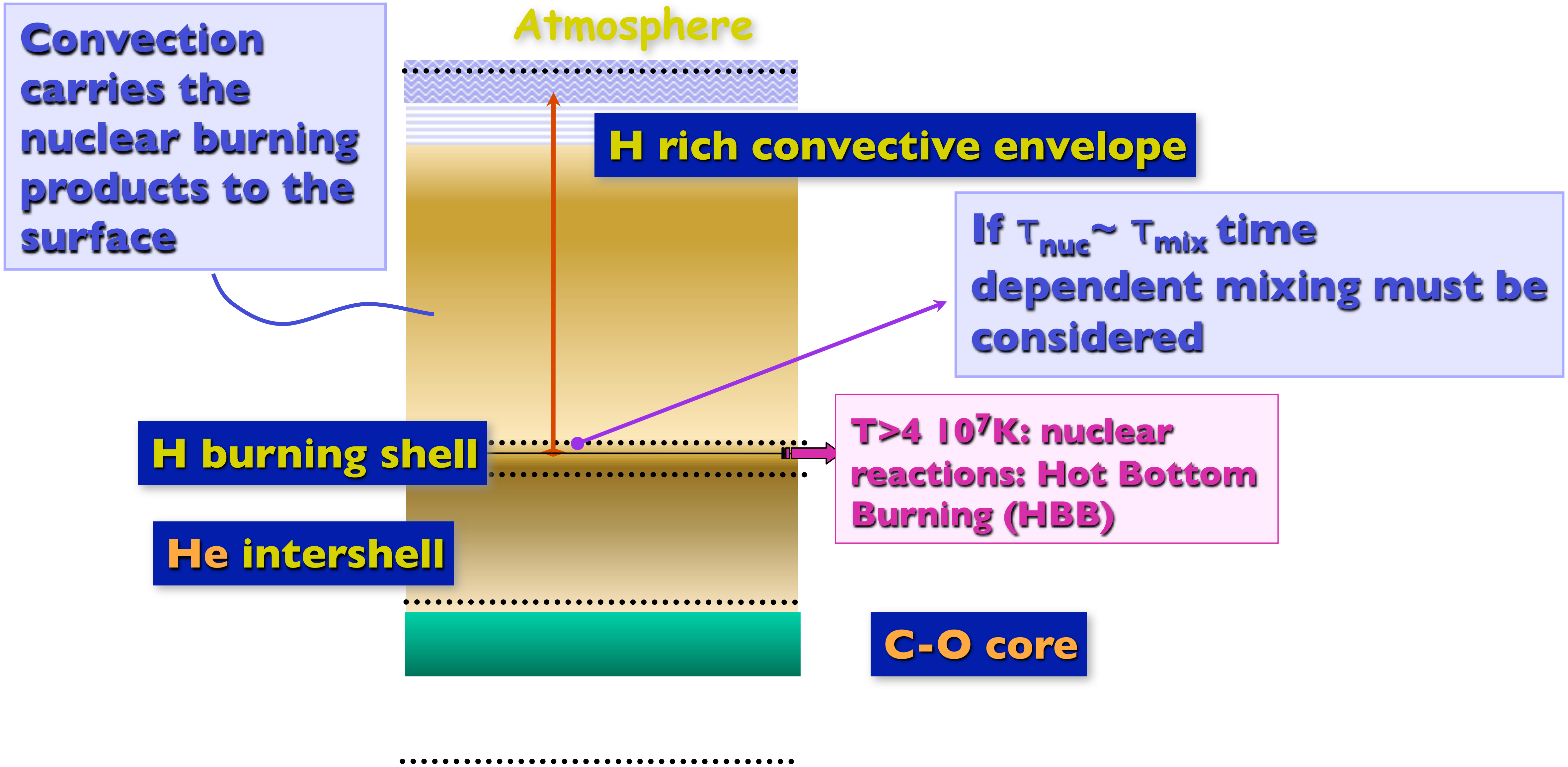
3) This seems to have occurred also in Globular Clusters, where the presence of ubiquitous "multiple populations" showing, inter alia, chemical anomalies due to hot CNO and other p-capture reactions points to pollution by massive AGBs

The "second generation" formation



from D'Ercole et al. 2008 – 25000 stars – blue: initially strongly concentrated SG stars

Structure of massive AGBs



Atmosphere

Convection carries the nuclear burning products to the surface

H rich convective envelope

If $T_{nuc} \sim T_{mix}$ time dependent mixing must be considered

H burning shell

$T > 4\ 10^7$K: nuclear reactions: Hot Bottom Burning (HBB)

He intershell

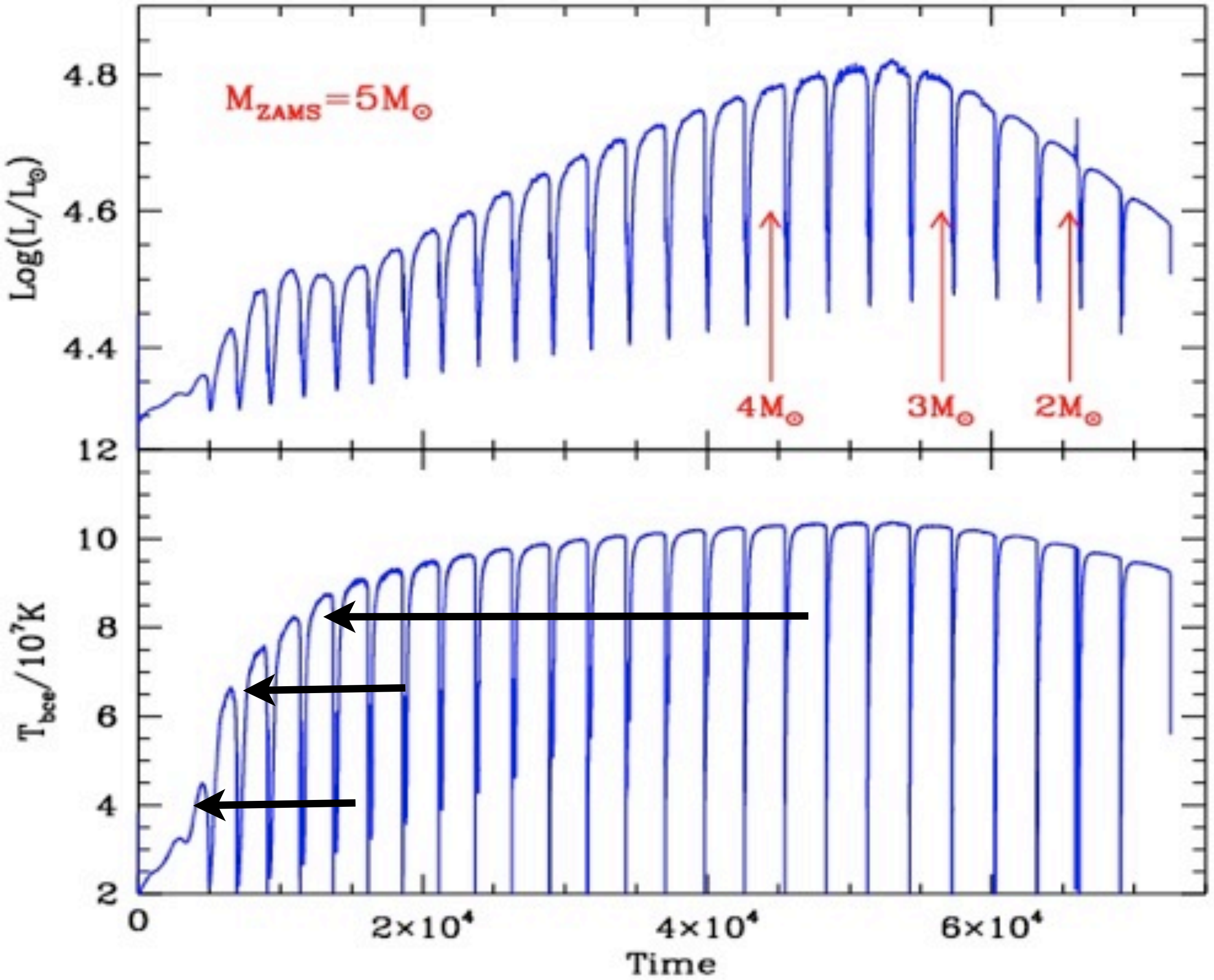
C-O core

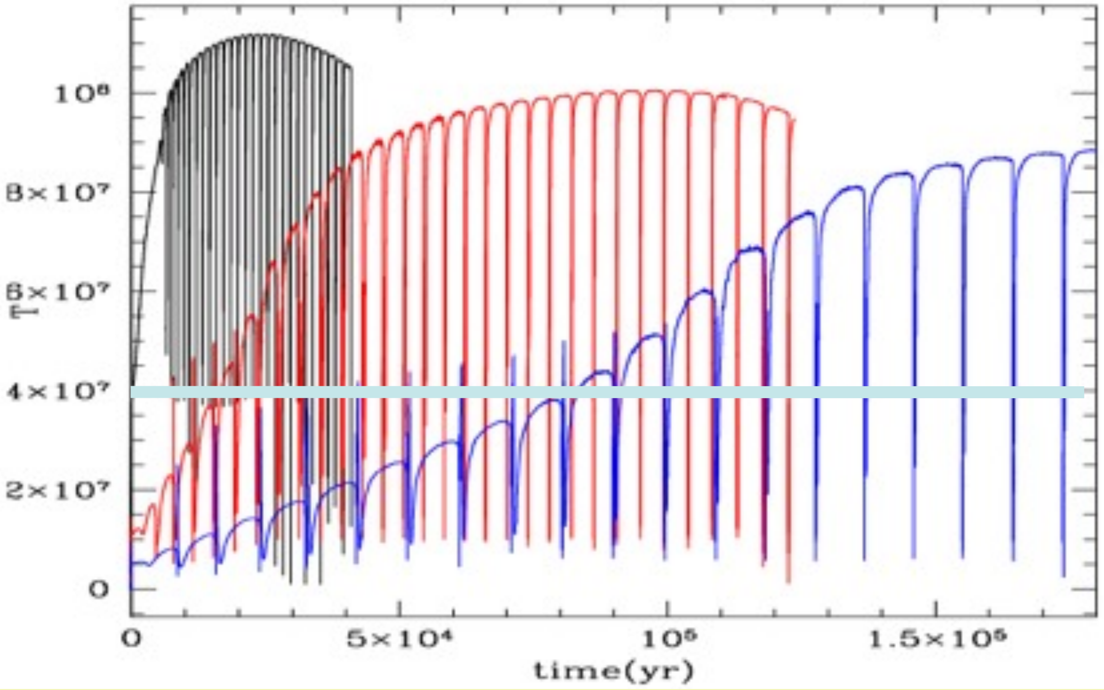
- Quiet wind mass loss: $v_{wind} < v_{escape}$ ⇒ no problem to retain ejecta

- HBB nucleosynthesis: plain convection brings to the surface the elements synthetized ⇒ no fancy mechanism to eject processed matter

Hot Bottom Burning

L increases, thermal pulses (and possibly 3rd dredge up) occur, strong mass loss reduces the stellar mass, while HBB and 3rd dredge up modify the surface (and wind) matter abundances

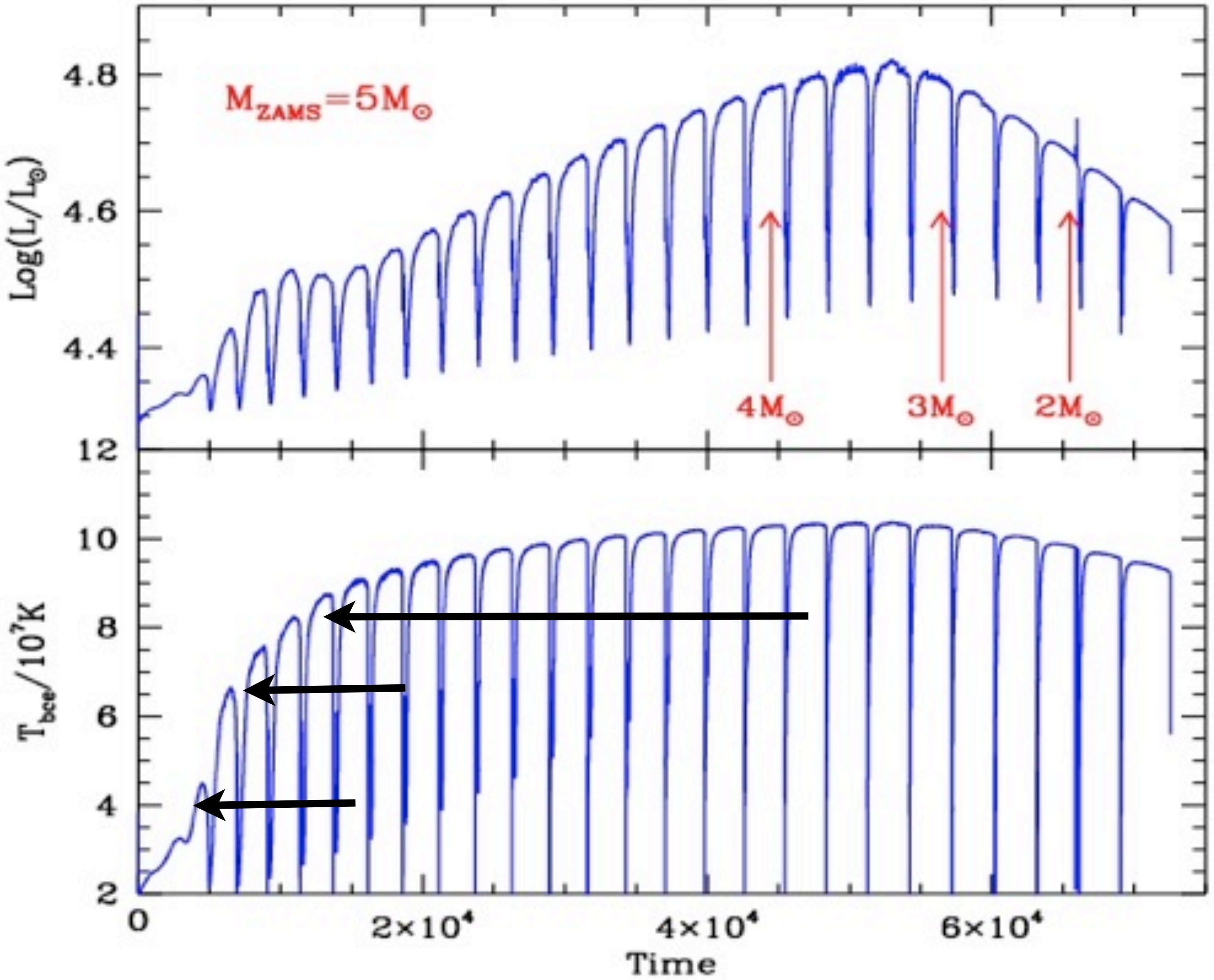


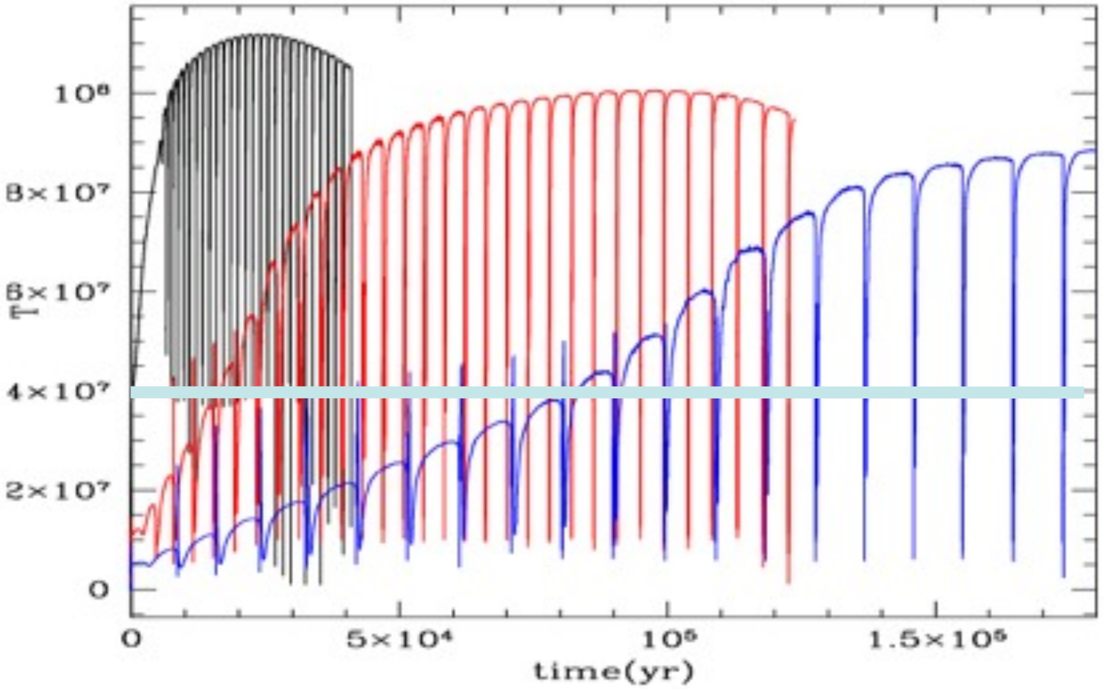


HBB efficiency depends on the convective model! Ejecta composition depend on the rate of mass loss!

Hot Bottom Burning

L increases, thermal pulses (and possibly 3rd dredge up) occur, strong mass loss reduces the stellar mass, while HBB and 3rd dredge up modify the surface (and wind) matter abundances





$^3He + ^4He \rightarrow ^7Be \rightarrow ^7Li$ (Cameron & Fowler 1971)

$T>4 \times 10^7$ K

$^{12}C \rightarrow ^{14}N$

$T>6.5 \times 10^7$ K

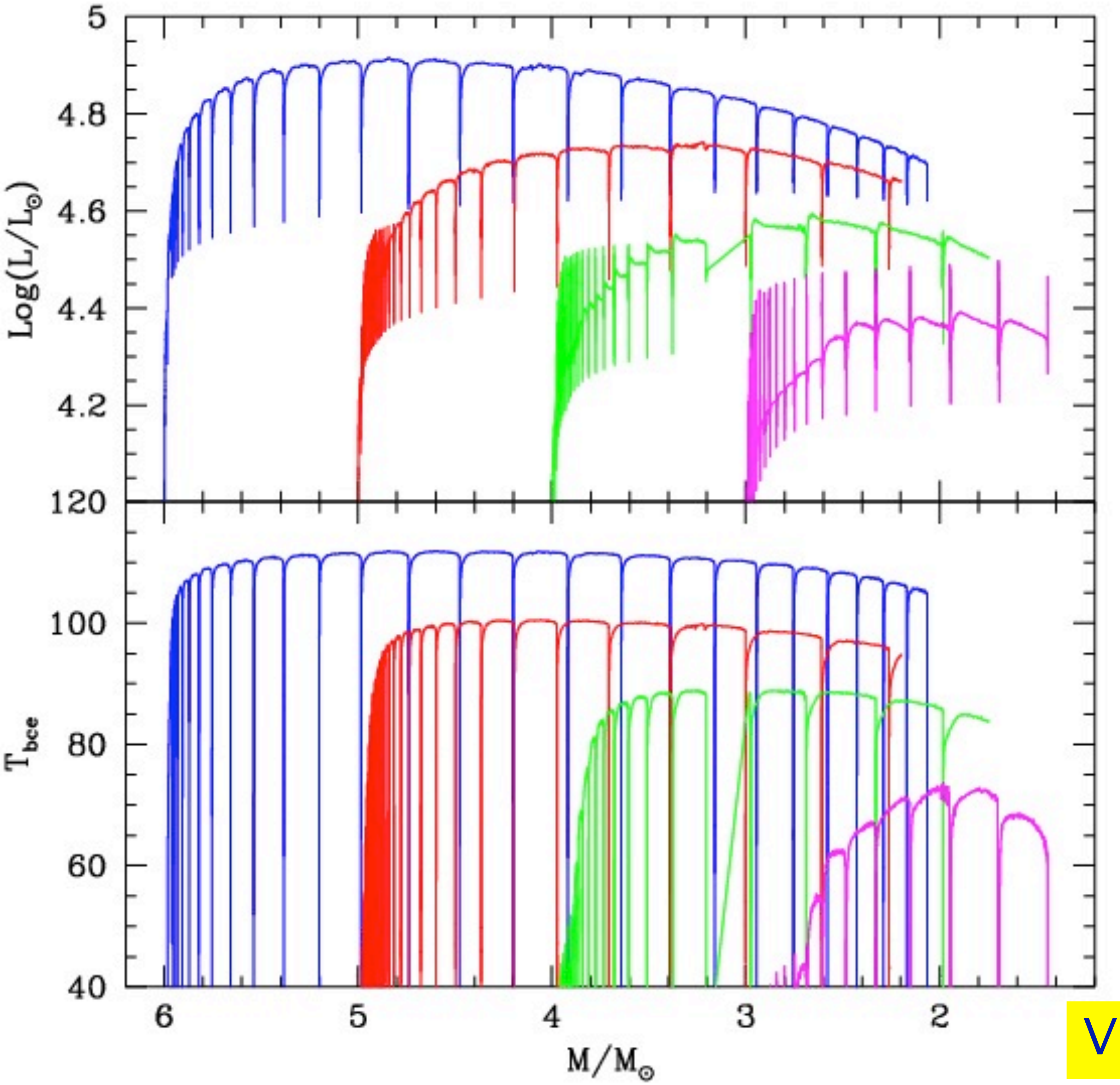
$^{16}O \rightarrow ^{14}N$

$T>8 \times 10^7$ K

HBB efficiency depends on the convective model! Ejecta composition depend on the rate of mass loss!

Nuclear processing at the bottom of the convective envelope in massive AGBs

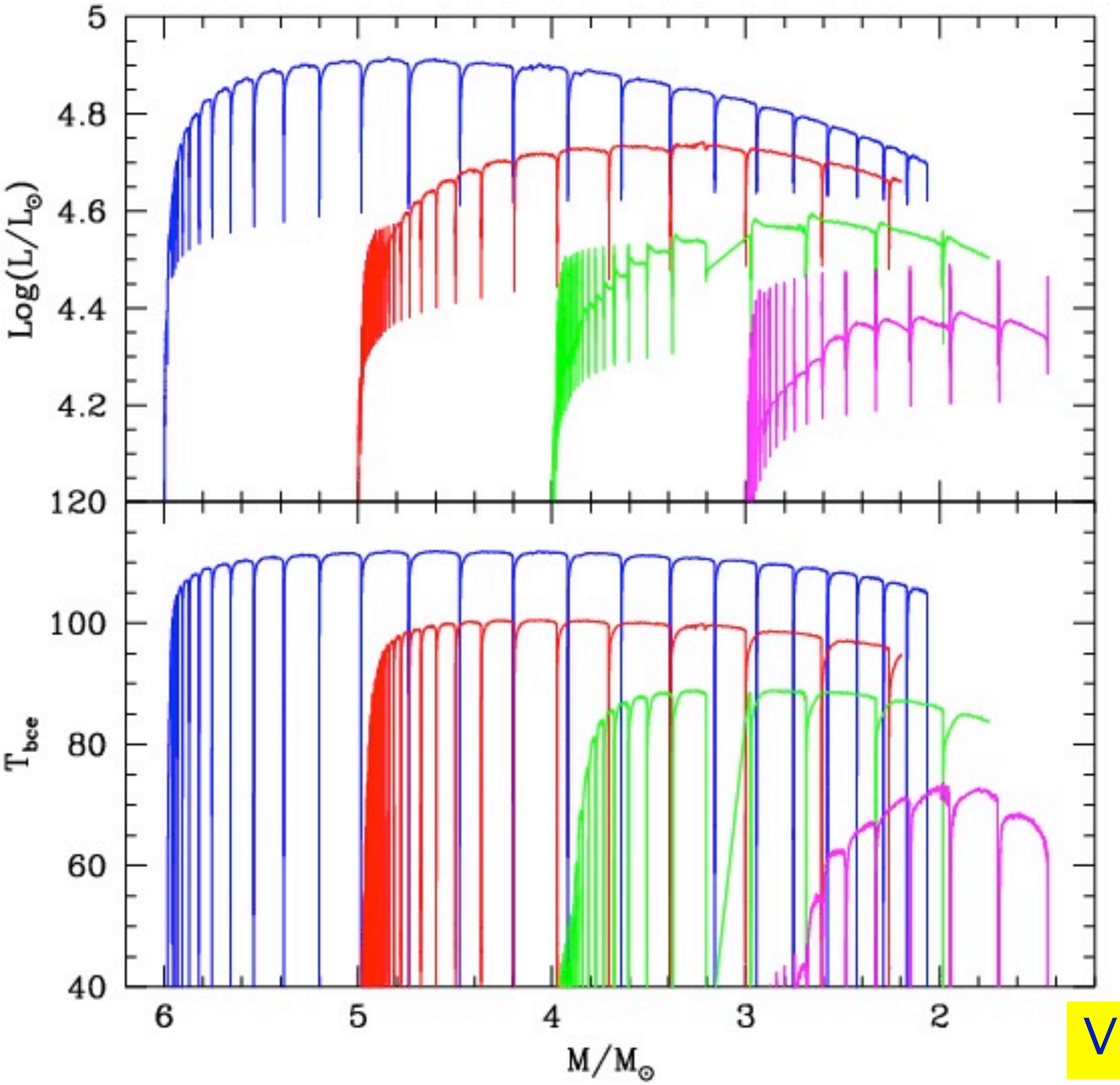
Z=0.001



Ventura & D'Antona (2007)

Nuclear processing at the bottom of the convective envelope in massive AGBs

Z=0.001



Each mass is characterized by a temperature at the bottom of the envelope

More advanced nucleosynthesis for higher masses

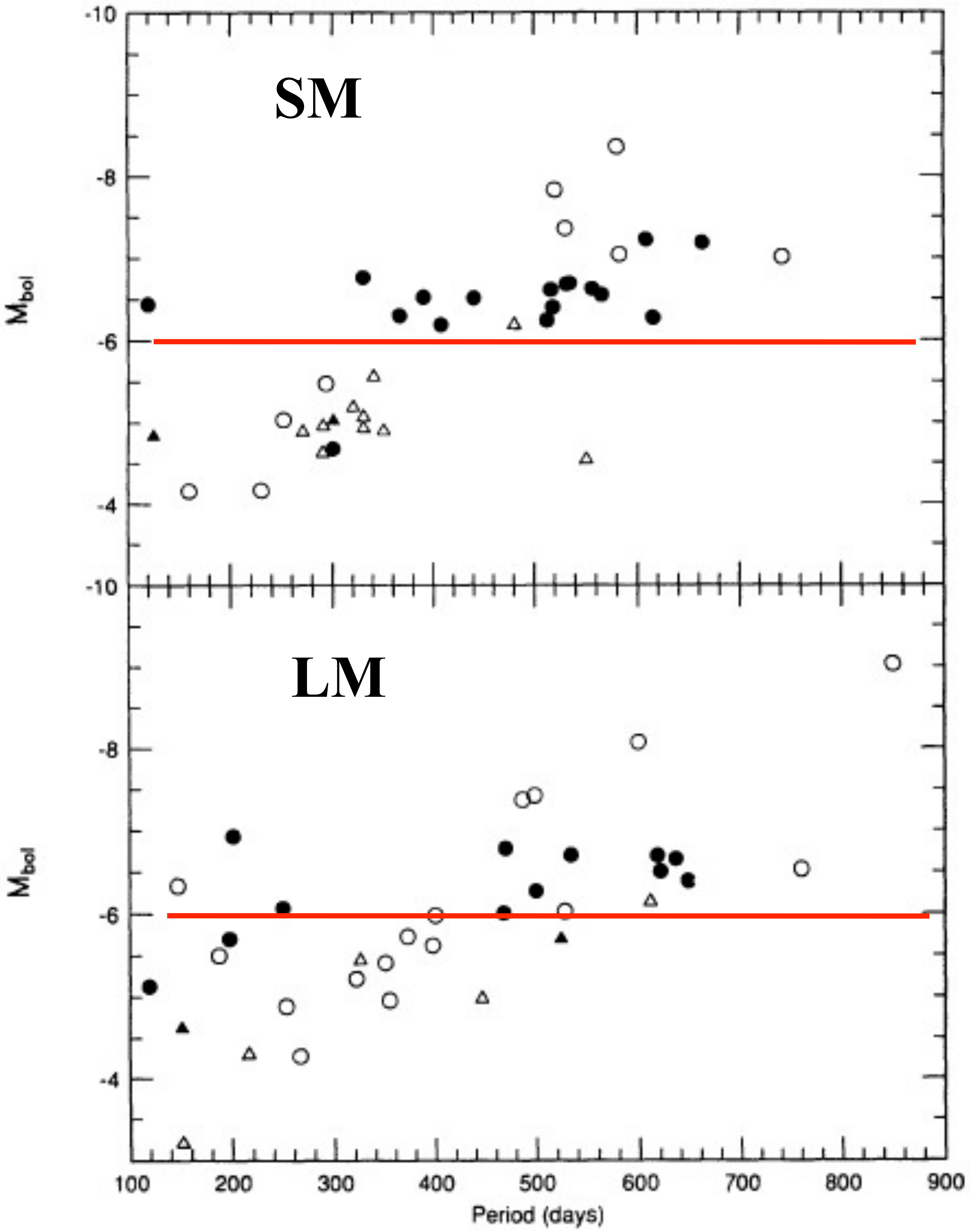
Ventura & D’Antona (2007)

The Cameron-Fowler (1971) model and HBB

◇ Li produced by the chain $\boxed{{}^{3}He(\alpha,\gamma)^{7}Be(e^{-},\nu)^{7}Li}$

in a convective hot region, so that ^{7}Be is transported to cooler regions before it turns into Li. Convective mixing brings Li back to the hot region where it can be burned, but it temporarily survives in the envelope and in the atmosphere. Production of Li is linked to the ^{3}He abundance in the region (remnant of incomplete p-p chain) and lasts until there is ^{3}He

◇ Very luminous AGB stars **T_{HBB} >4 x 10^{7} K:** a hydrostatic, slow process: the bottom of the convective envelope reaches the H-shell burning region and nuclear reaction products are transported to the surface by convection (**Iben 1973, Sackman, Smith & Despain 1974,**
Scalo, Despain & Ulrich 1975 → hot bottom convective envelopes
→ **Hot Bottom Burning (HBB)**



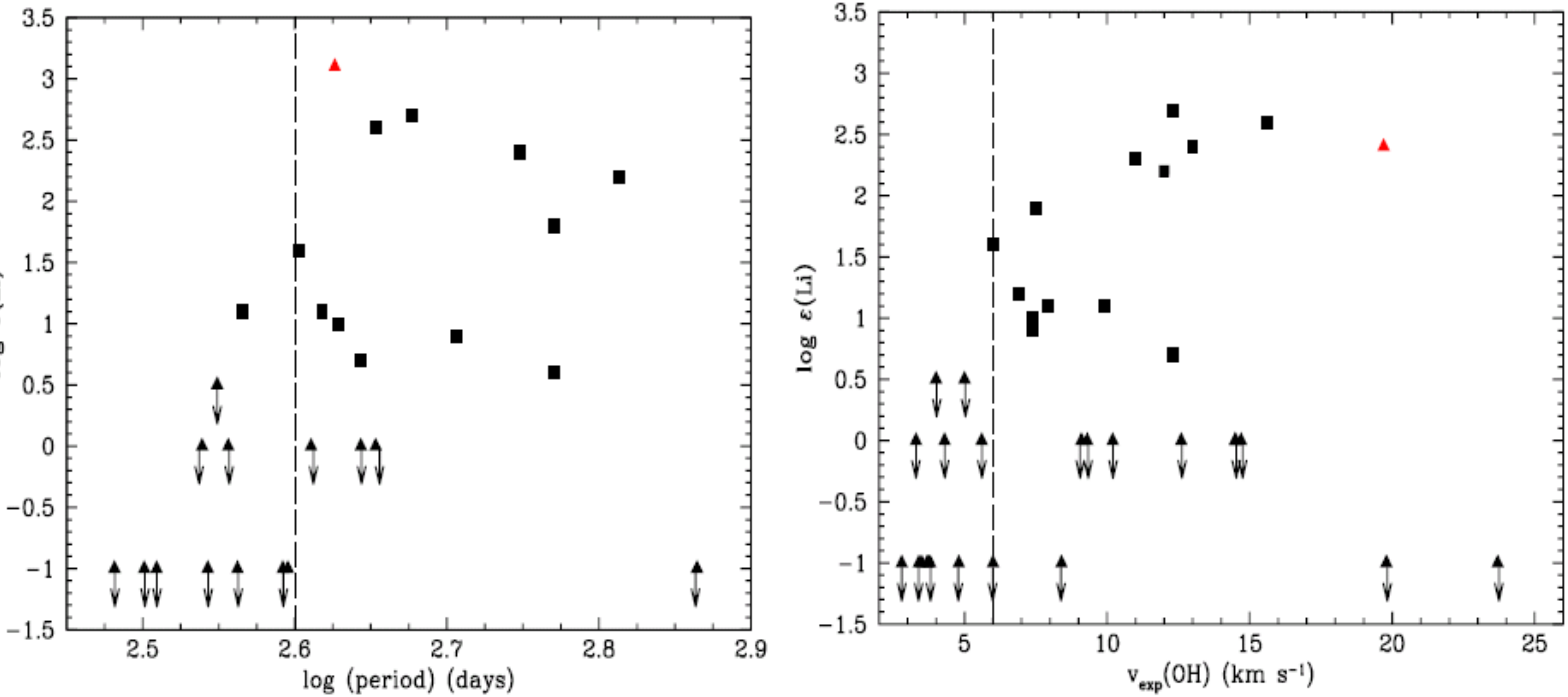
Li rich AGBs in the Magellanic Clouds

Smith & Lambert 1989, 1990. Figure from Smith, Plez & Lambert 1995

At Mbol<-6:
C-stars are no longer present;
practically ALL M-stars show Li7.

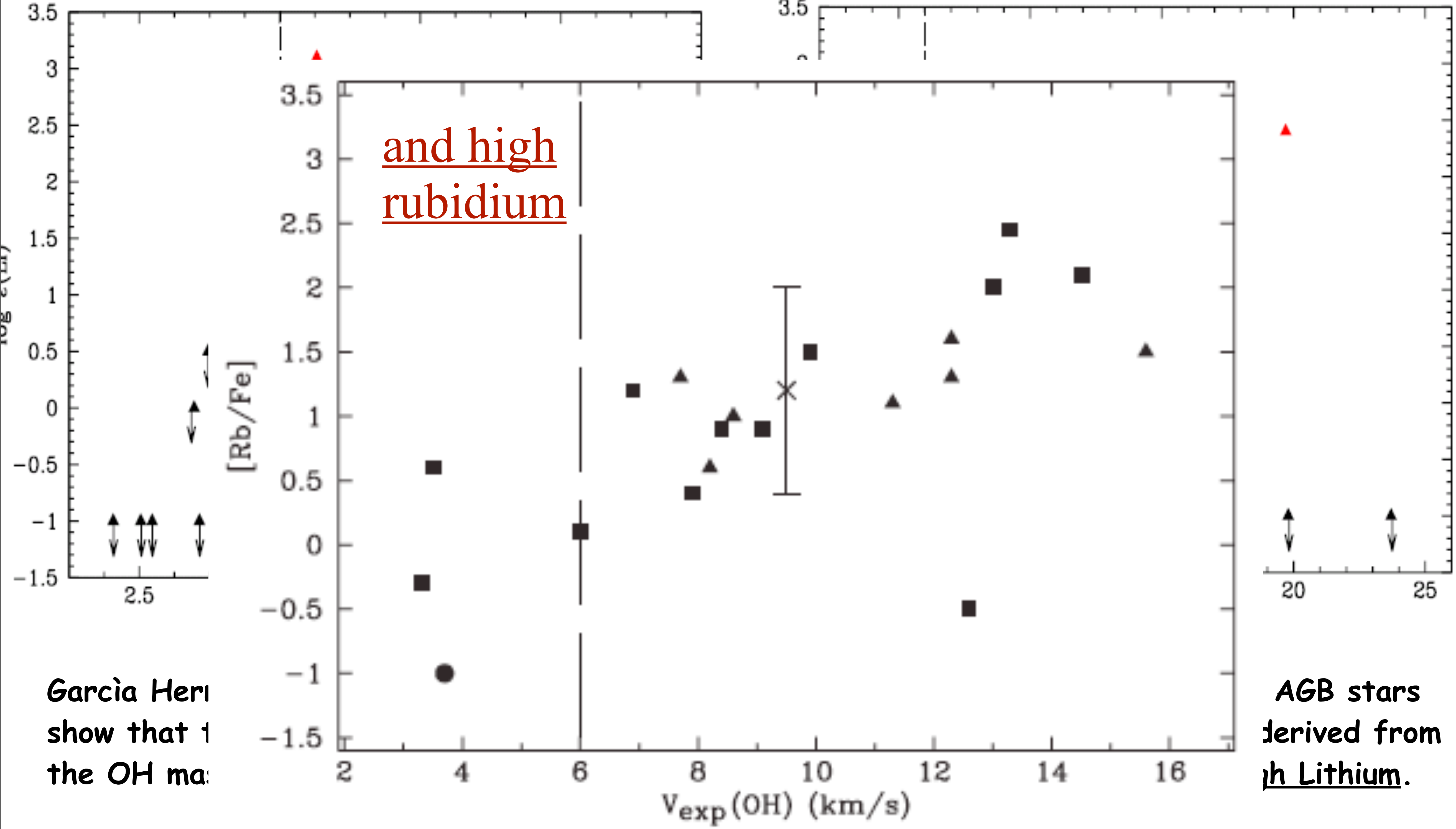
This is imputed to the process of 'Hot Bottom Burning',

Li rich AGBs in the Galaxy



Garcìa Hernandez et al. 2006: examining a large sample of massive Galactic O-rich AGB stars show that the most massive of these objects [those having high expansion velocity derived from the OH maser emission, and the longer periods of variability (P>400days)] <u>have high Lithium</u>.

Li rich AGBs in the Galaxy

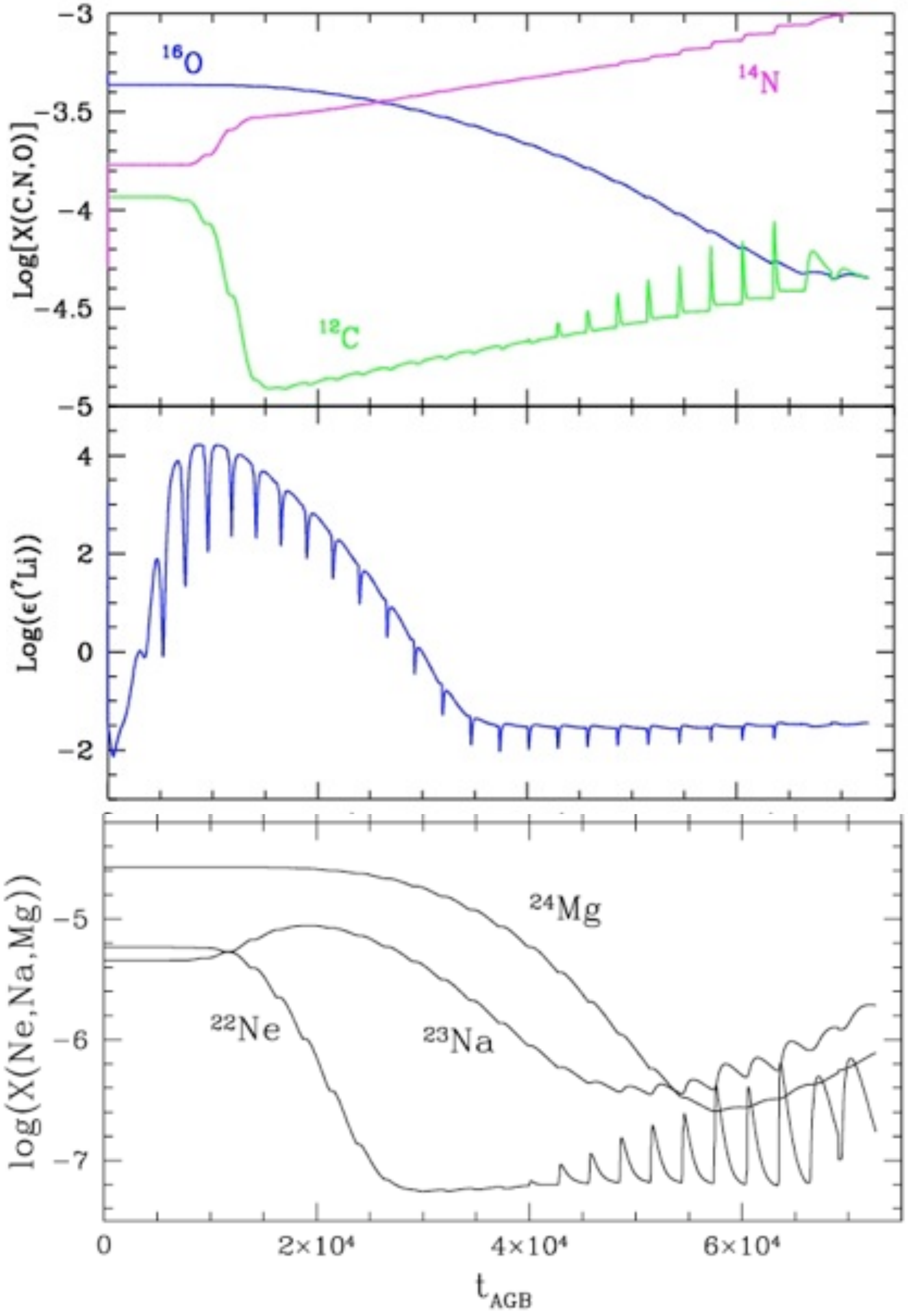


and high rubidium

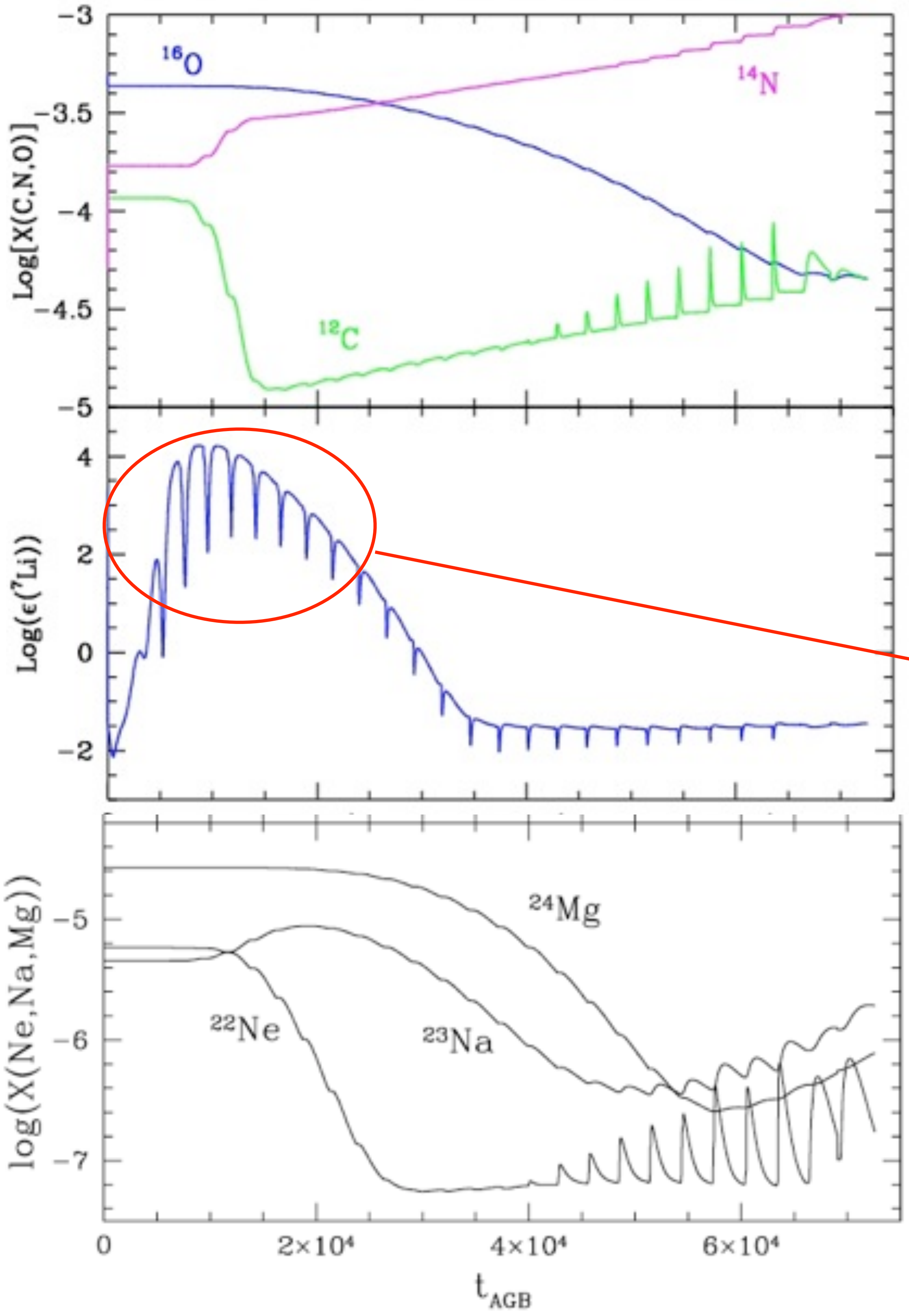
Garcìa Her
show that
the OH ma

AGB stars
derived from
h Lithium.

Changes of the surface chemistry



Changes of the surface chemistry

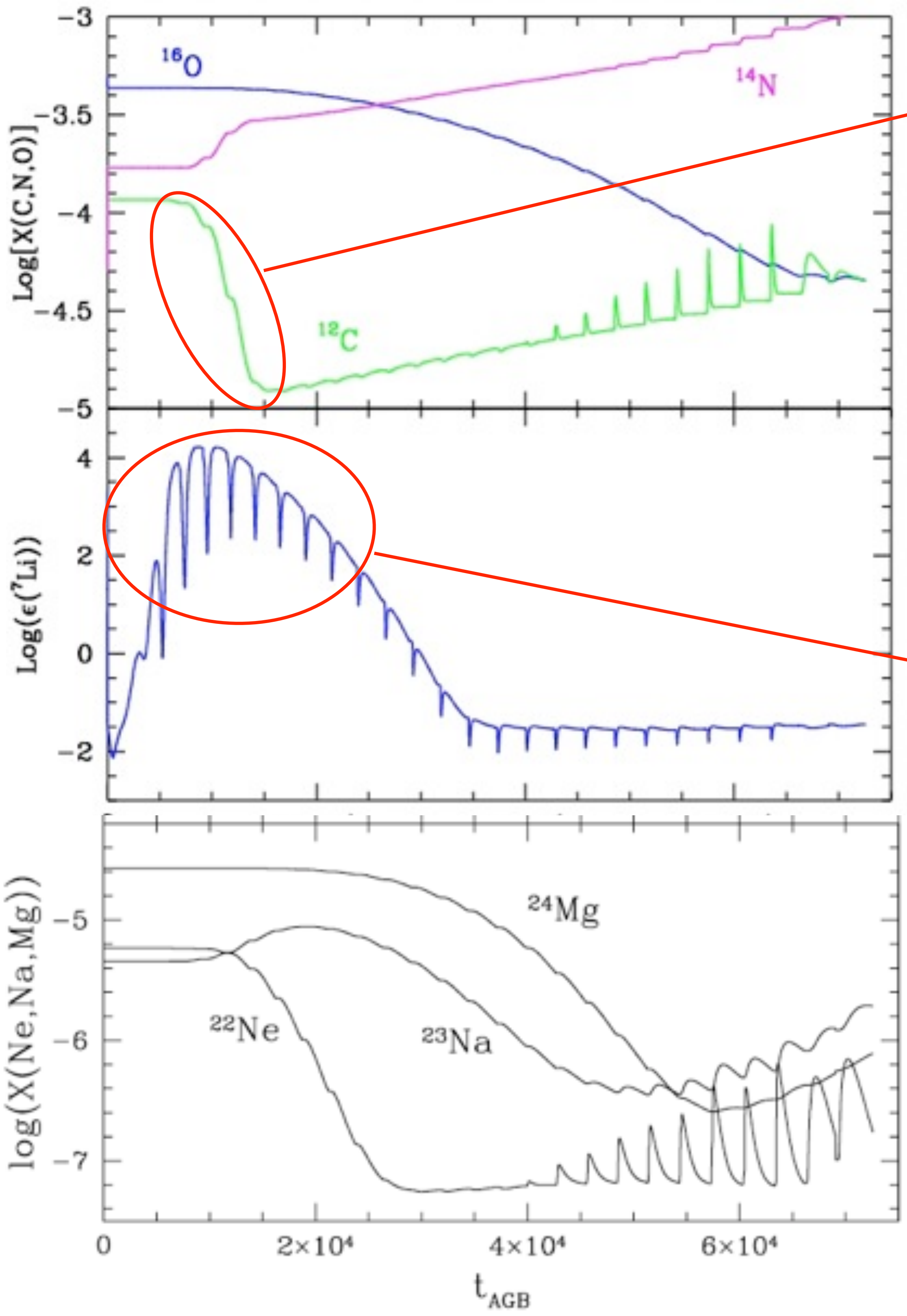


Li-rich phase

^{3}He + ^{4}He → ^{7}Be → ^{7}Li
(Cameron & Fowler 1971)

T>4 x 10^{7} K

Changes of the surface chemistry



^{12}C → ^{14}N

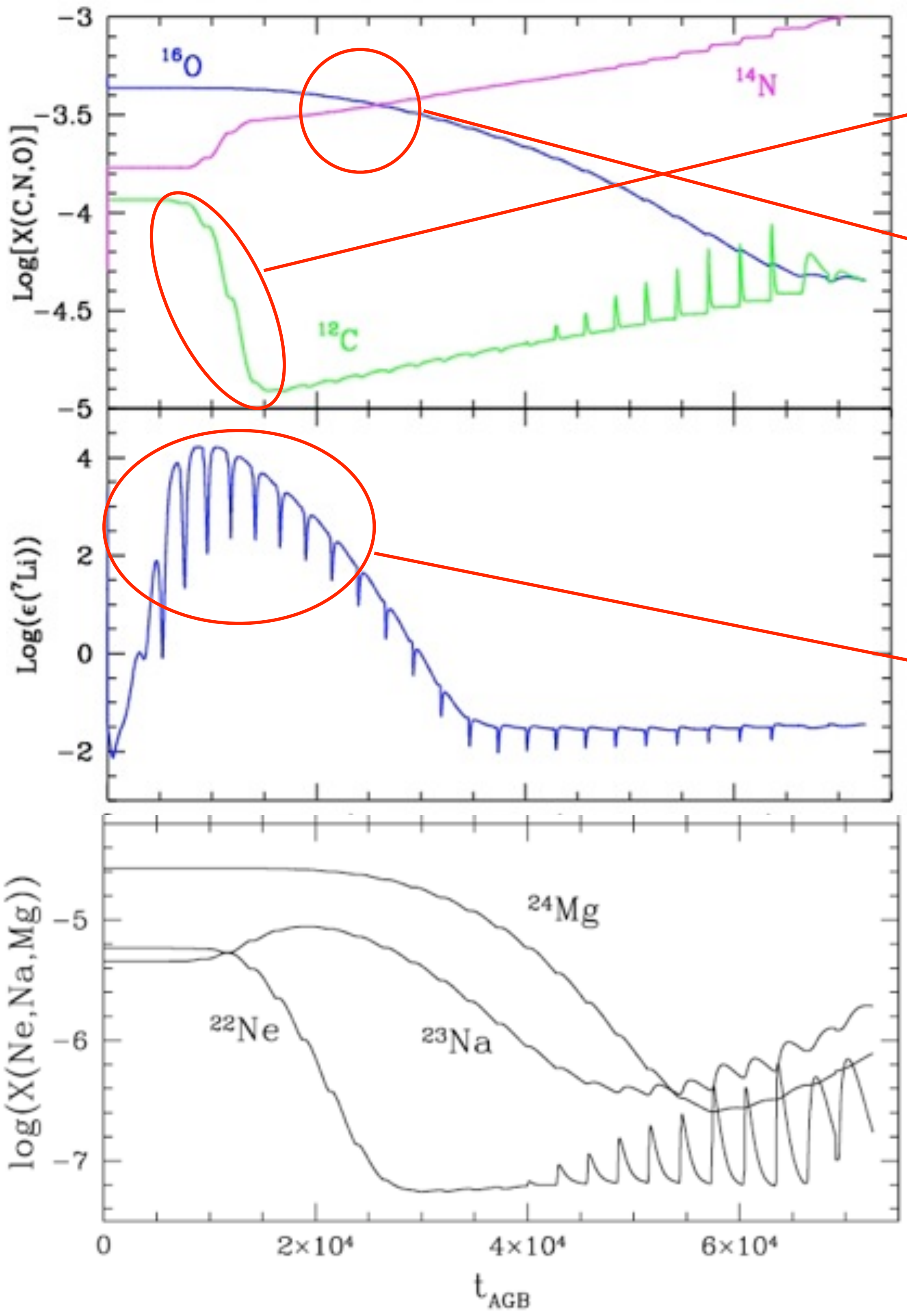
T>6.5 x 10^7 K

Li-rich phase

^{3}He + ^{4}He → ^{7}Be → ^{7}Li
(Cameron & Fowler 1971)

T>4 x 10^7 K

Changes of the surface chemistry



$^{12}C \rightarrow {}^{14}N$ T>6.5 x 10^7 K

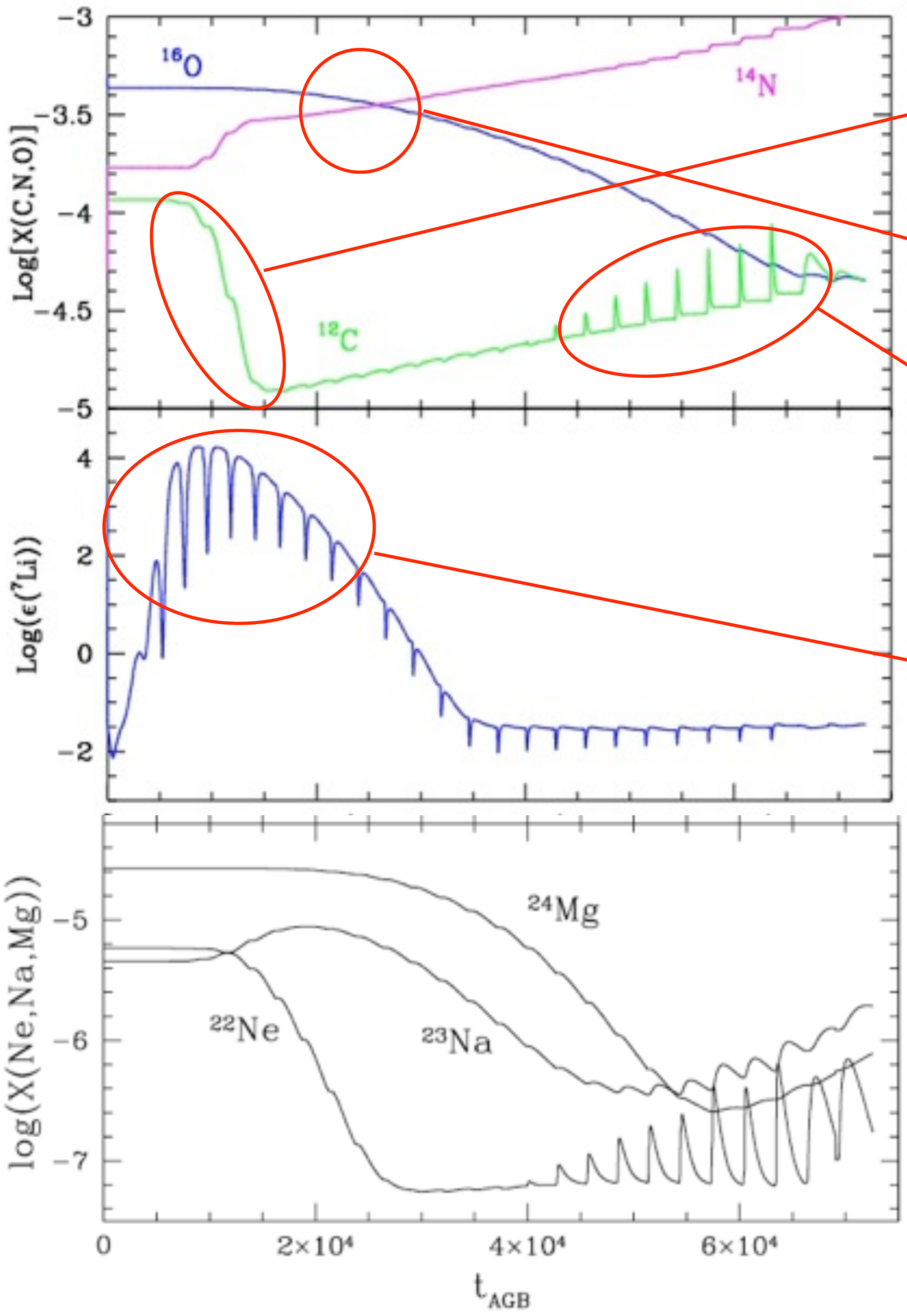
$^{16}O \rightarrow {}^{14}N$ T>8 x 10^7 K

Li-rich phase

$^3He + {}^4He \rightarrow {}^7Be \rightarrow {}^7Li$
(Cameron & Fowler 1971)

T>4 x 10^7 K

Changes of the surface chemistry



^{12}C → ^{14}N

T>6.5 x 10^7 K

^{16}O → ^{14}N

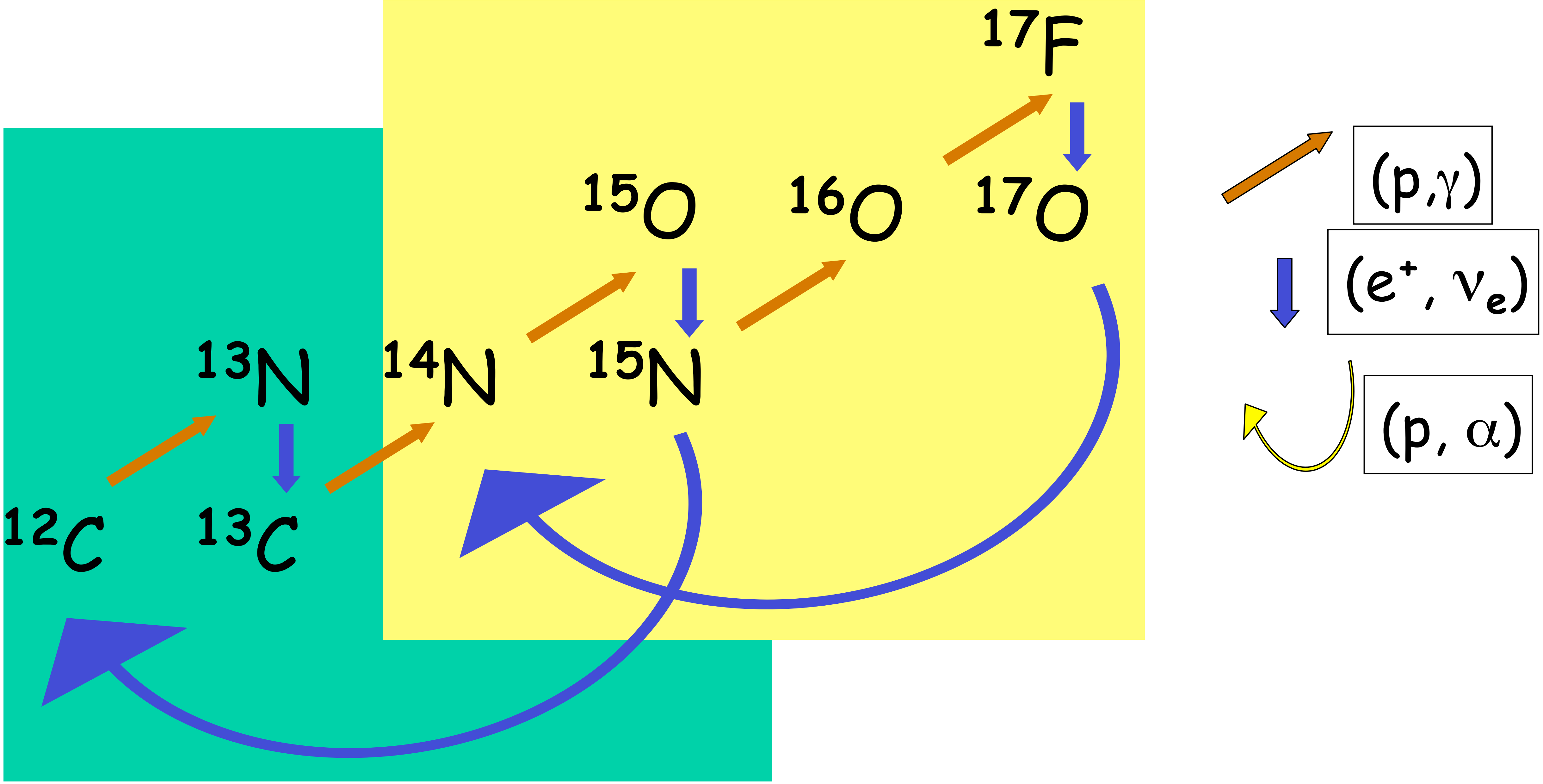
T>8 x 10^7 K

III dredge-up

Li-rich phase

^{3}He + ^{4}He → ^{7}Be → ^{7}Li
(Cameron & Fowler 1971)

T>4 x 10^7 K



^{17}F

^{15}O ^{16}O ^{17}O

^{13}N ^{14}N ^{15}N

^{12}C ^{13}C

(p,γ)

(e^+, ν_e)

(p, α)

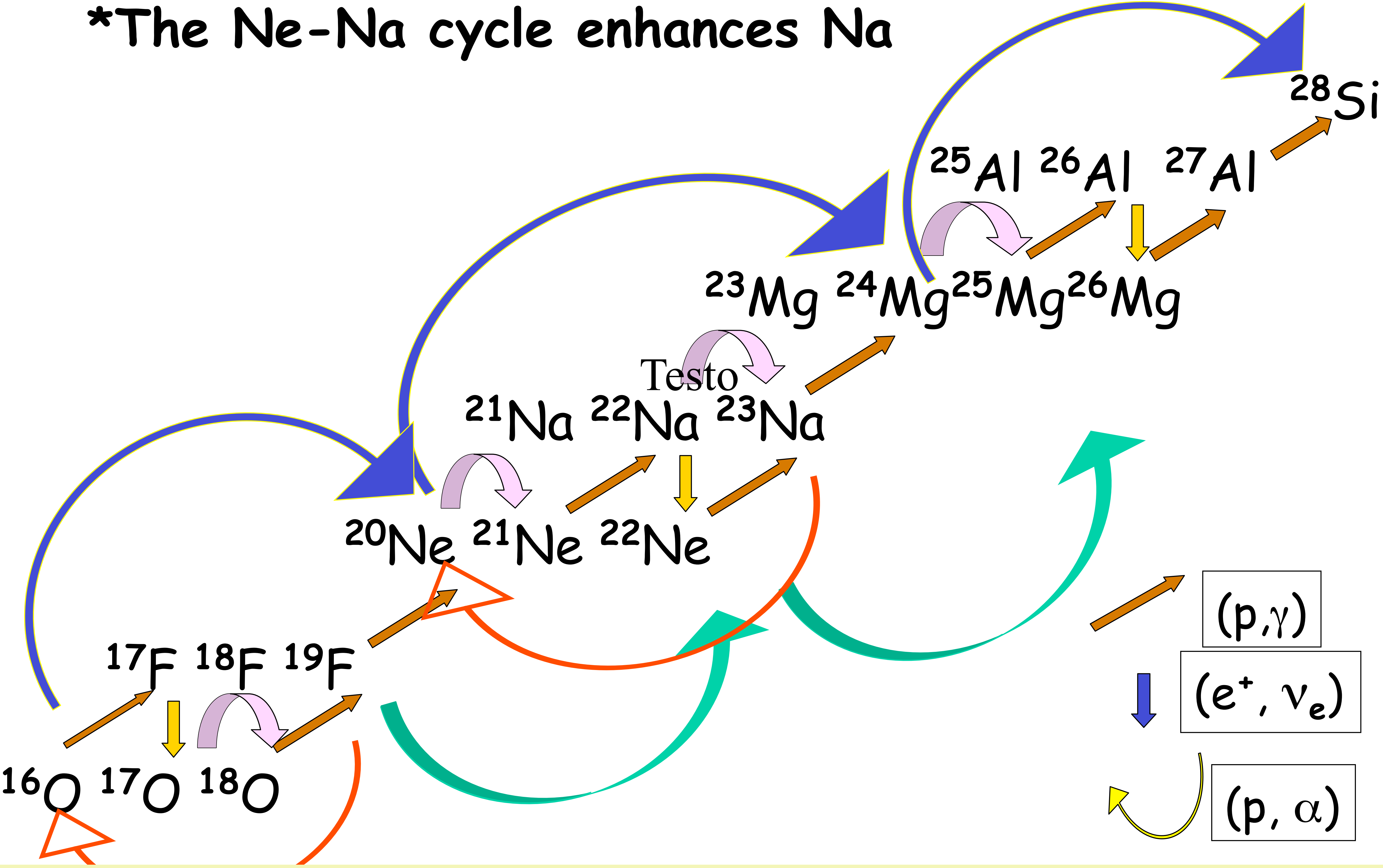
in CNO processed material, C+N+O=cost!!!

Other p-capture reactions

- ✓ The Ne-Na cycle
- ✓ The Mg-Al chain
- ✓ K production????

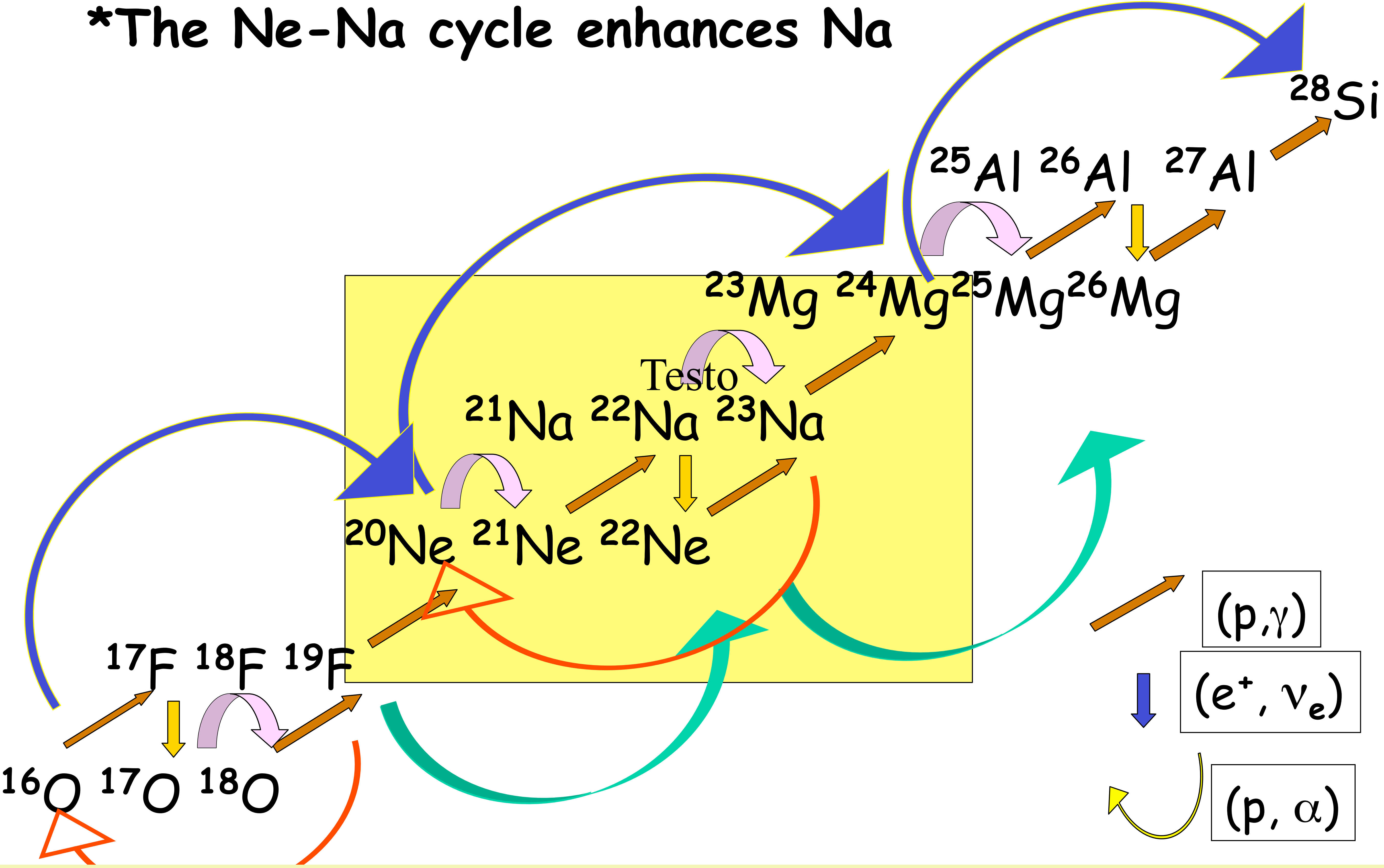
Na high in stars having low O

*The Ne-Na cycle enhances Na



Na high in stars having low O

*The Ne-Na cycle enhances Na



^{28}Si

^{25}Al ^{26}Al ^{27}Al

^{23}Mg ^{24}Mg ^{25}Mg ^{26}Mg

Testo

^{21}Na ^{22}Na ^{23}Na

^{20}Ne ^{21}Ne ^{22}Ne

^{17}F ^{18}F ^{19}F

^{16}O ^{17}O ^{18}O

(p,γ)

(e^+, ν_e)

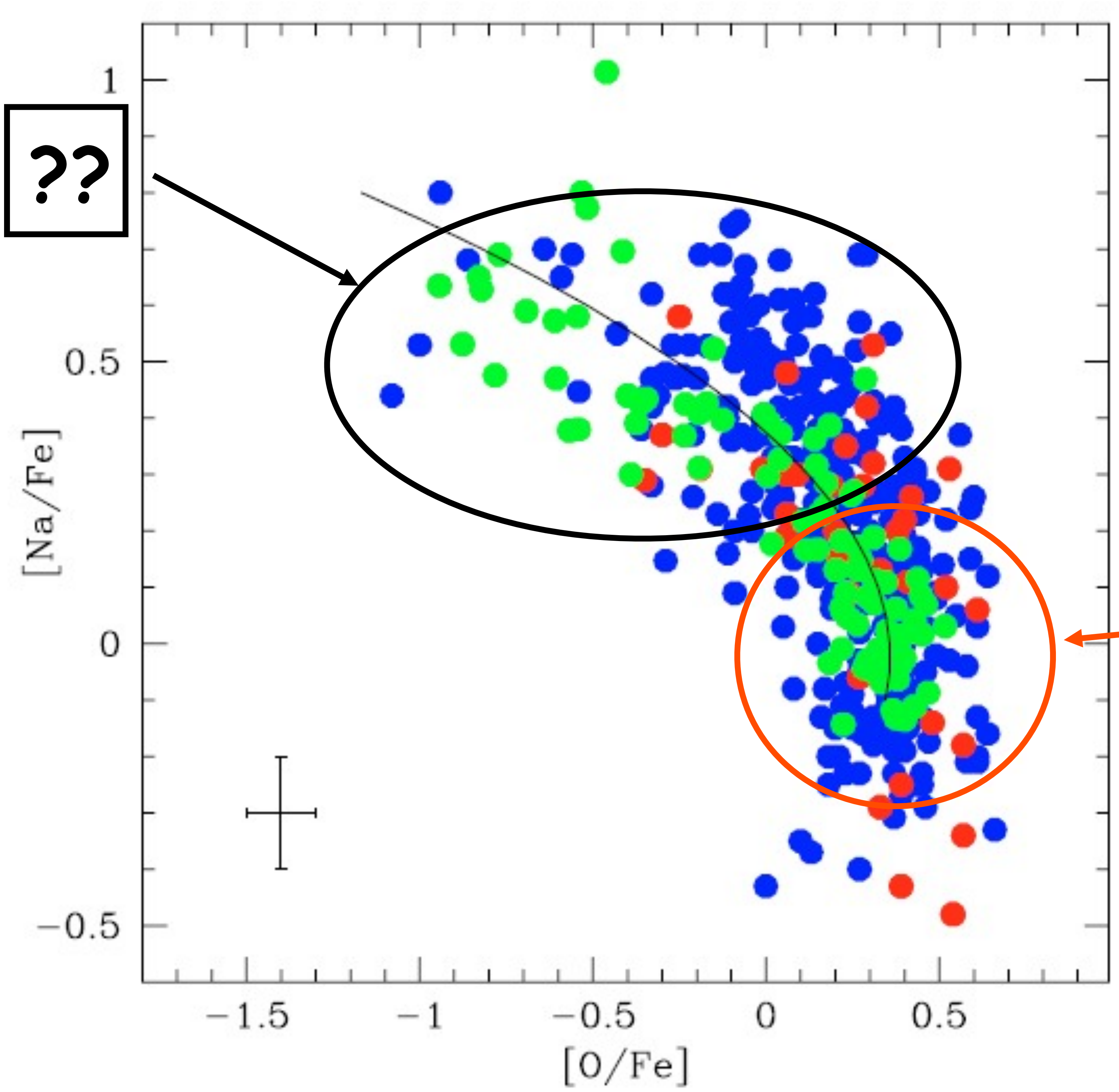
(p, α)

massive AGBs with HBB are the source of "second generation" stars in globular clusters?

spectral evidence for high-T, full CNO and Ne-Na, Mg-Al cycling in the matter forming 'second generation' (SG) stars; constancy of C+N+O (or 'quasi' constancy: NGC 1851)

in a very high percentage (50-70% -or up to 90%) of SG!!!

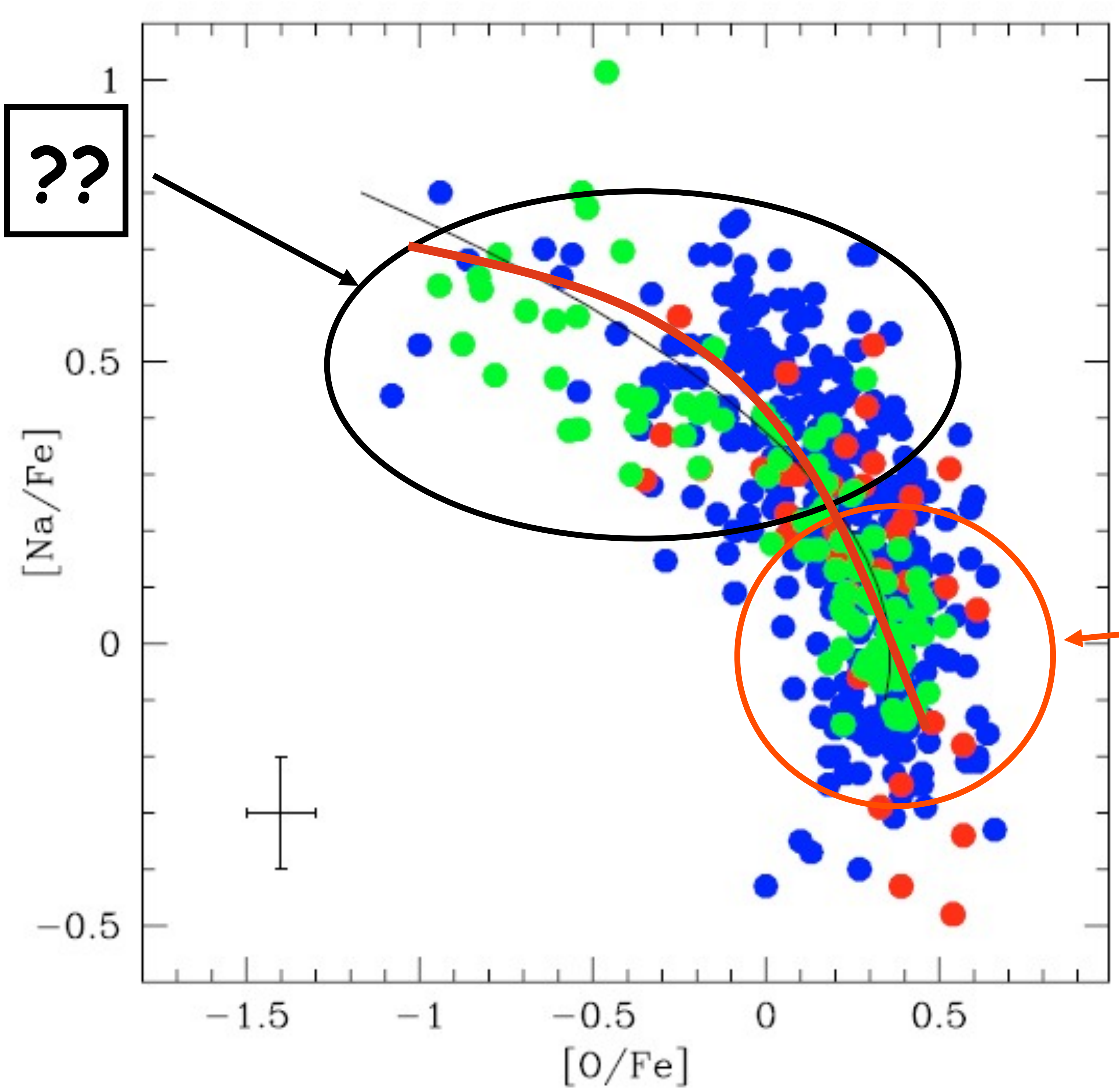
Globular Clusters: Na-O anticorrelation



anticorrelation

this is the range of abundances in low metallicity field stars

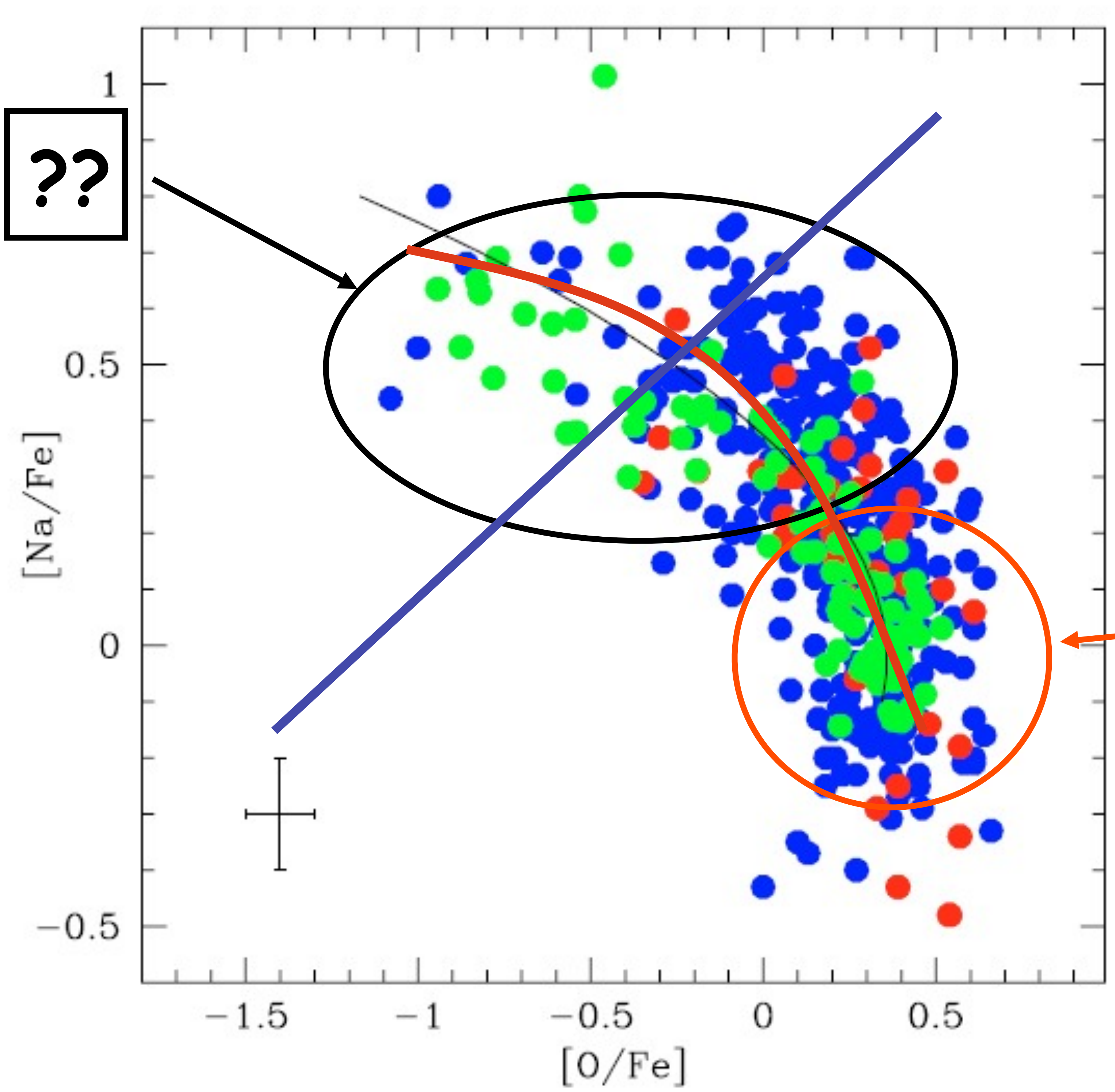
Globular Clusters: Na-O anticorrelation



anticorrelation

this is the range of abundances in low metallicity field stars

Globular Clusters: Na-O anticorrelation

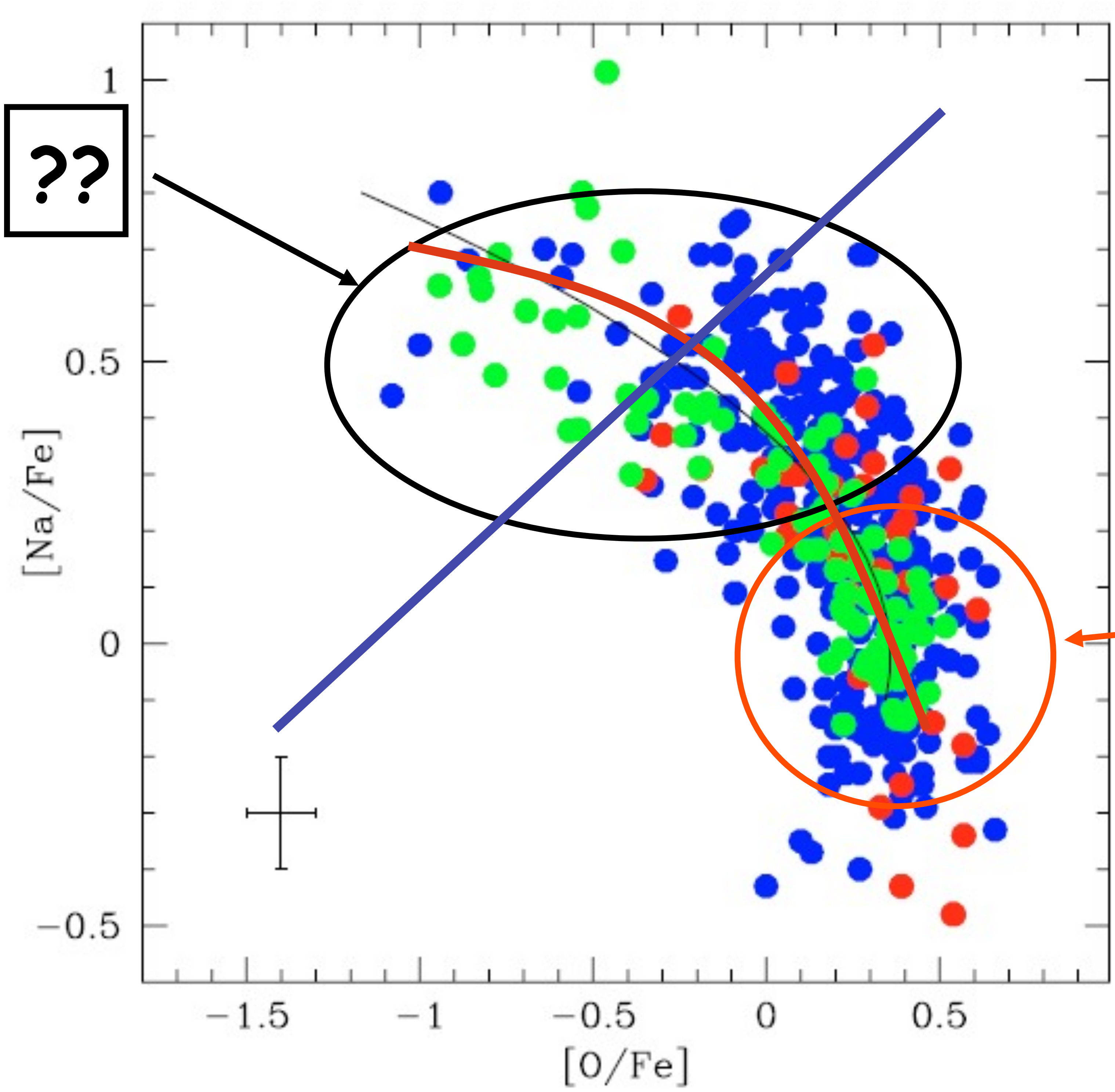


models!!

anticorrelation

this is the range of abundances in low metallicity field stars

Globular Clusters: Na-O anticorrelation



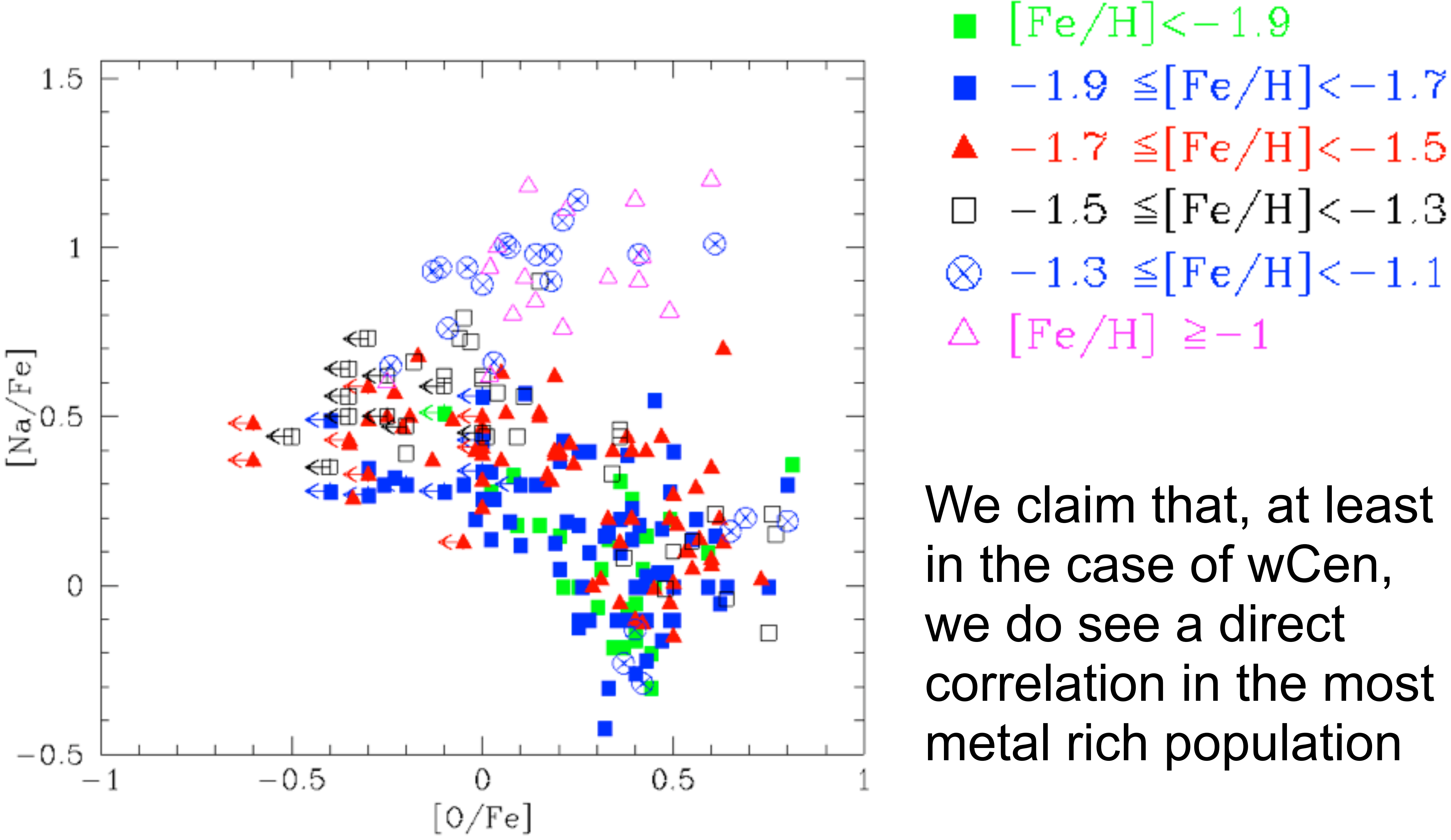
models!!

anticorrelation

this is the range of abundances in low metallicity field stars

we need to add a "dilution" hypothesis: the ejecta hotCNO processed are diluted in different amounts with "pristine" gas

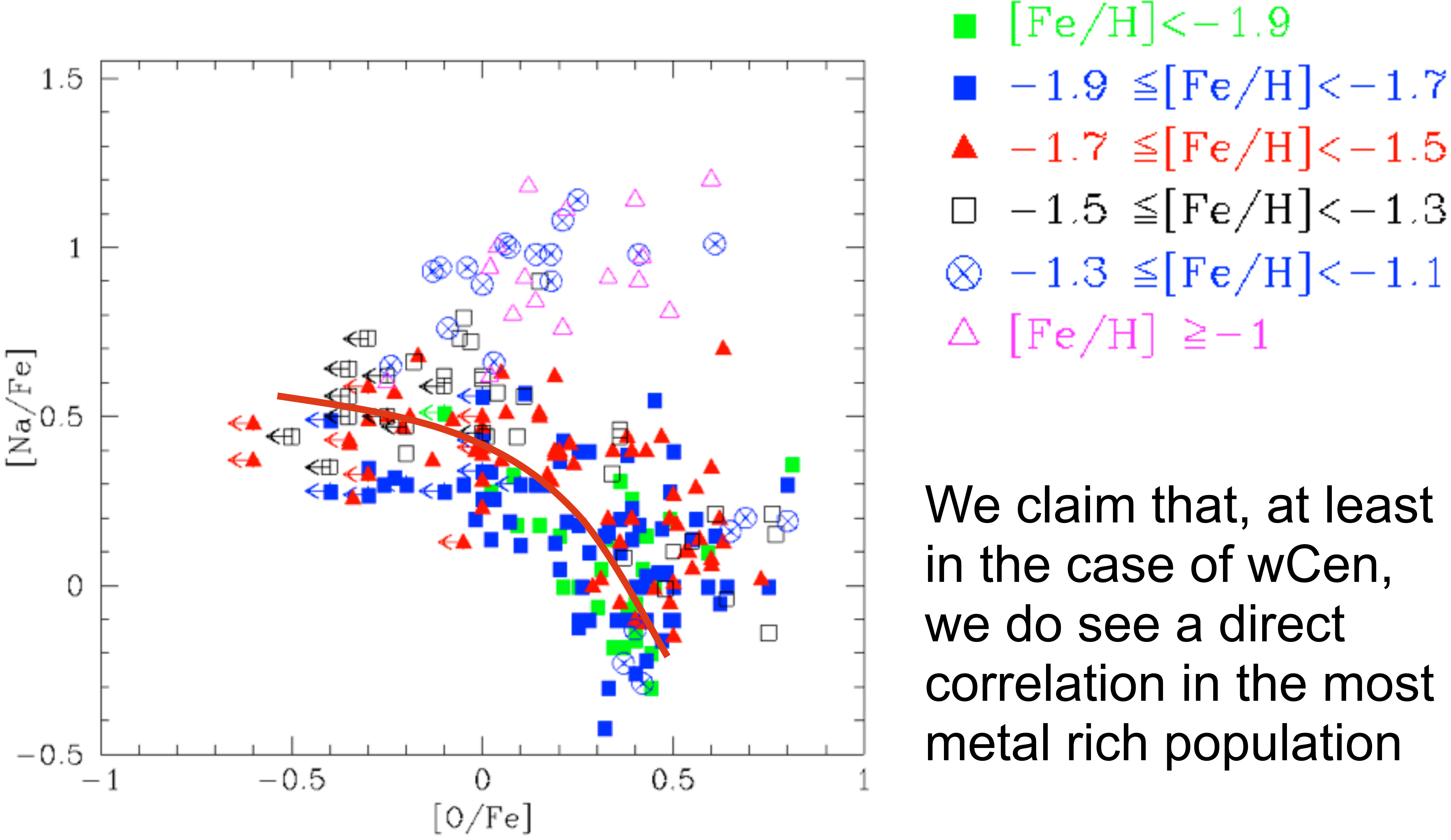
O-Na-Fe distribution in the giants of wCen (Marino et al. 2011)



We claim that, at least in the case of wCen, we do see a direct correlation in the most metal rich population

D'Antona, D'Ercole, Marino, Milone, Ventura, Vesperini 2011

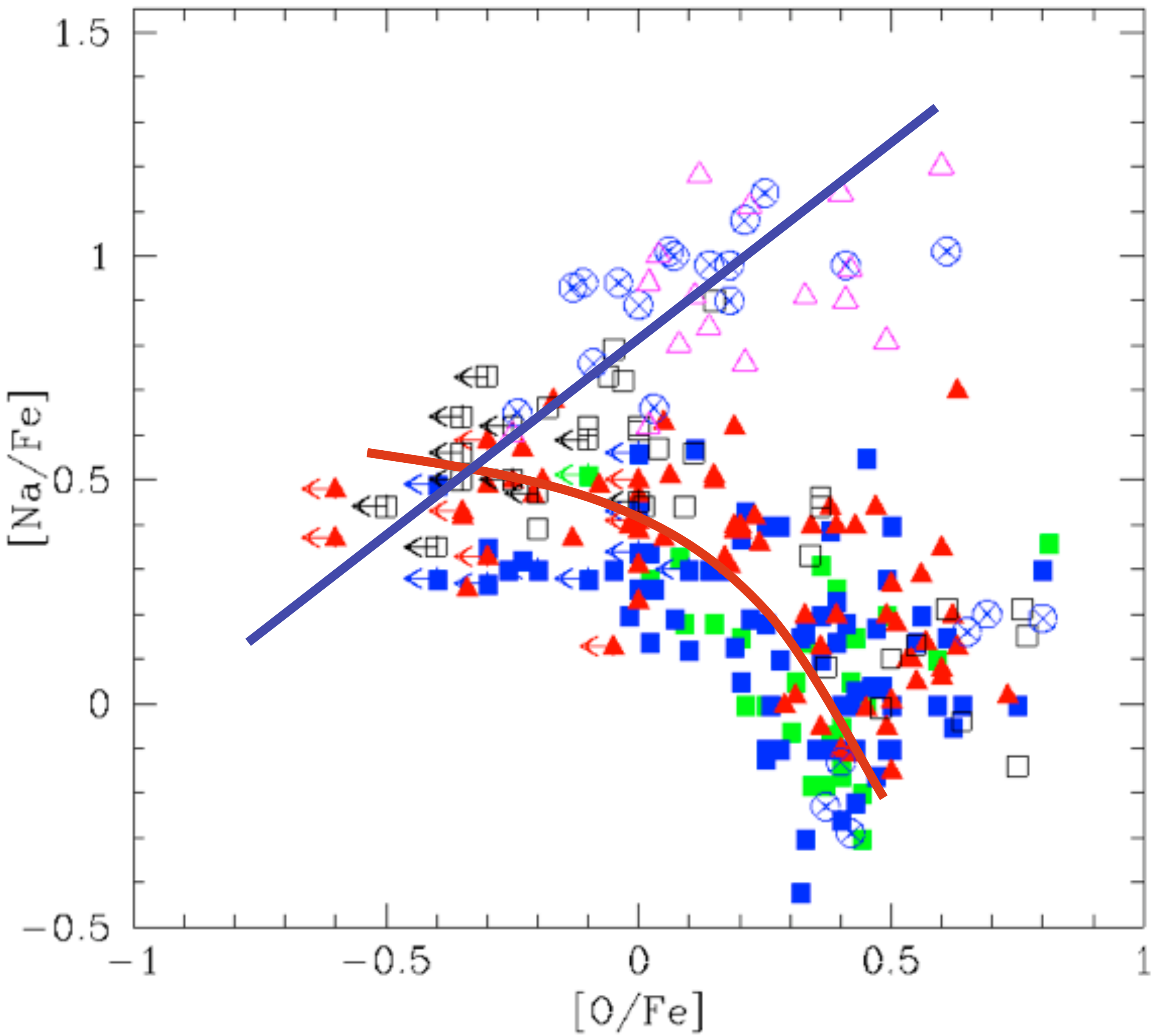
O-Na-Fe distribution in the giants of wCen (Marino et al. 2011)



We claim that, at least in the case of wCen, we do see a direct correlation in the most metal rich population

D’Antona, D'Ercole, Marino, Milone, Ventura, Vesperini 2011

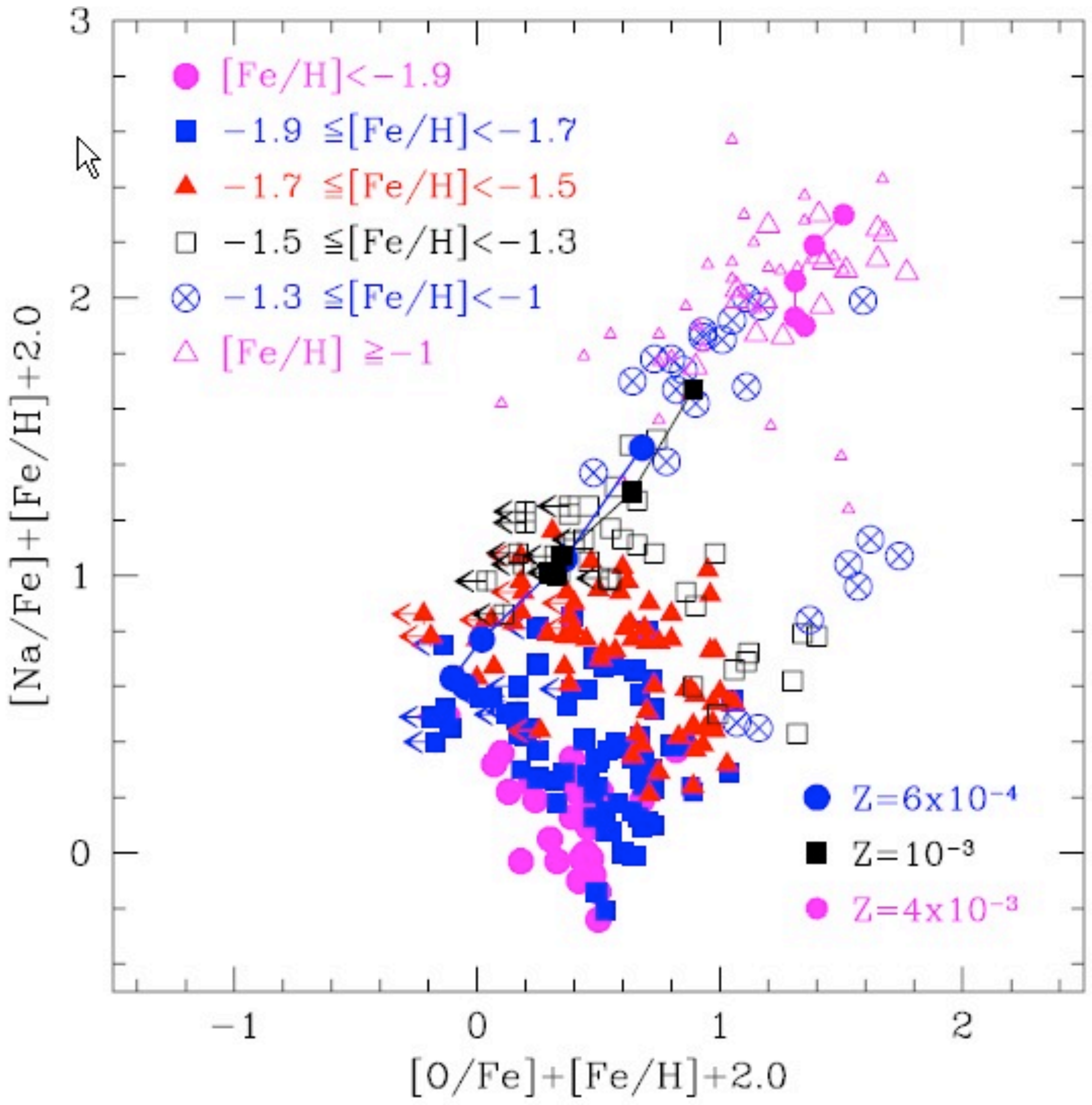
O-Na-Fe distribution in the giants of wCen (Marino et al. 2011)



We claim that, at least in the case of wCen, we do see a direct correlation in the most metal rich population

D'Antona, D'Ercole, Marino, Milone, Ventura, Vesperini 2011

O-Na distribution in abundances not scaled to iron



Nobody is obliged to buy our full model for wCen, but just the suggestion that:

the last event of star formation in wCen is made fully by pure ejecta from metal rich massive AGBs

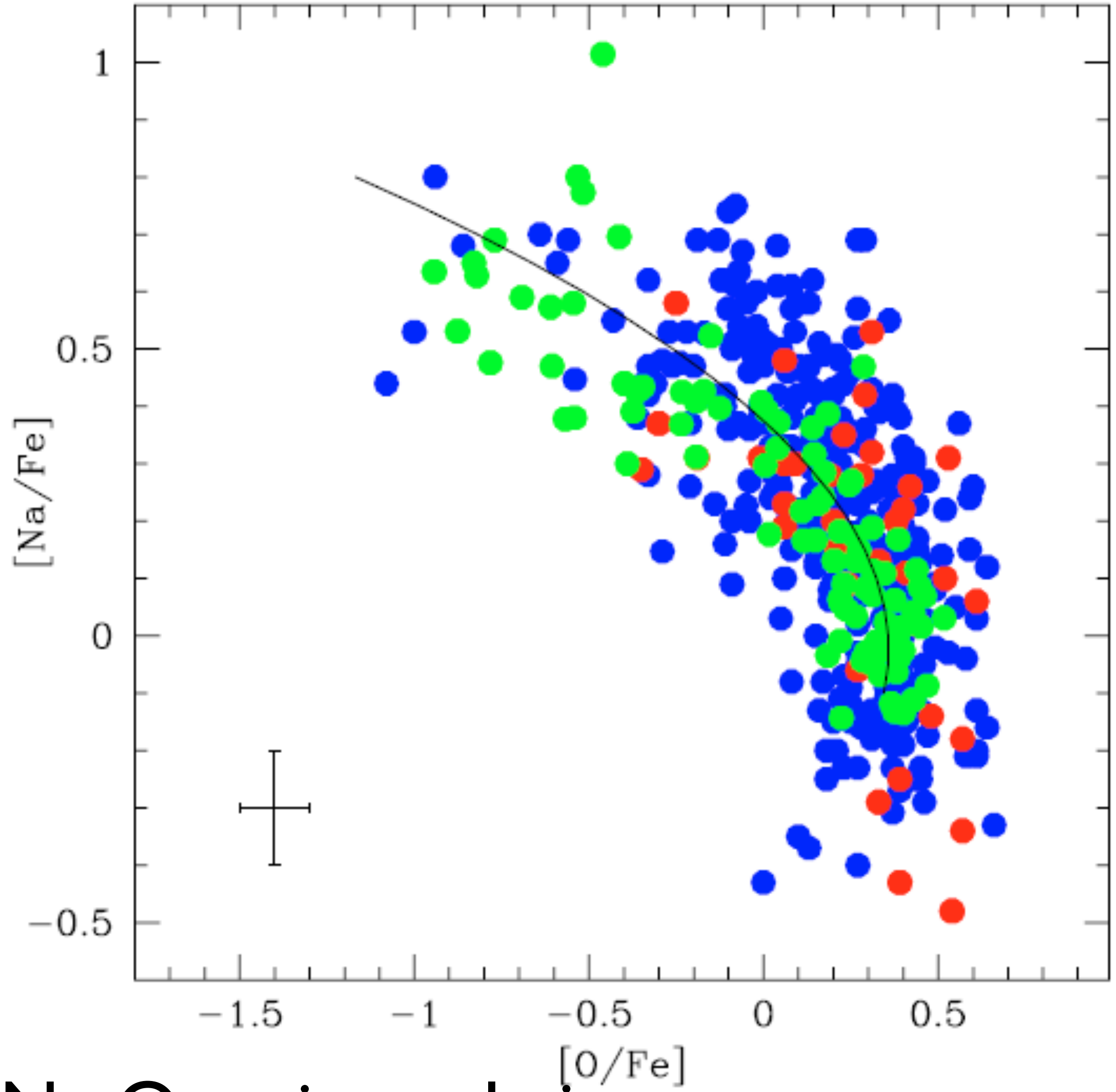
What the AGB scenario explains "naturally" about the chemistry of SG

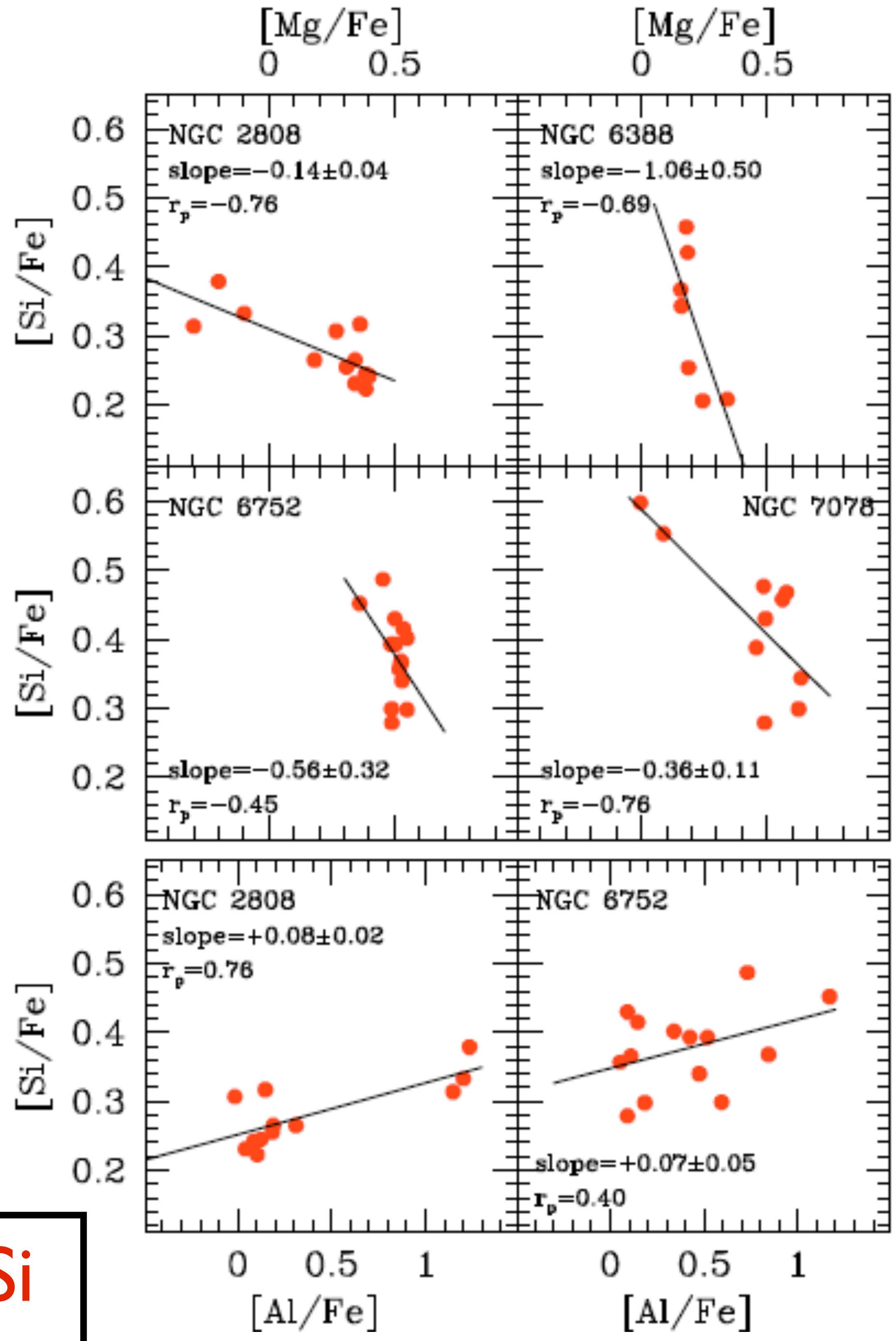
- ✓ Na up, O low (also other models). Mg-Al, Mg-Si - maybe Al-Si anticorrelation also possible
- ✓ Larger anomalies for lower metallicity (for similar degrees of dilution)
- ✓ C+N+O variations are possible in clusters with prolonged star formation history (SN Ia delayed?)
- ✓ C+N+O increase "may" be associated with small iron increase (non destructive effect of the first few Sn Ia?)

What the AGB scenario explains "naturally" about the chemistry of SG

- ✓ Na up, O low (also other models). Mg-Al, Mg-Si - maybe Al-Si anticorrelation also possible
- ✓ Larger anomalies for lower metallicity (for similar degrees of dilution)
- ✓ C+N+O variations are possible in clusters with prolonged star formation history (SN Ia delayed?)
- ✓ C+N+O increase "may" be associated with small iron increase (non destructive effect of the first few Sn Ia?)

Chemical patterns and AGB ejecta



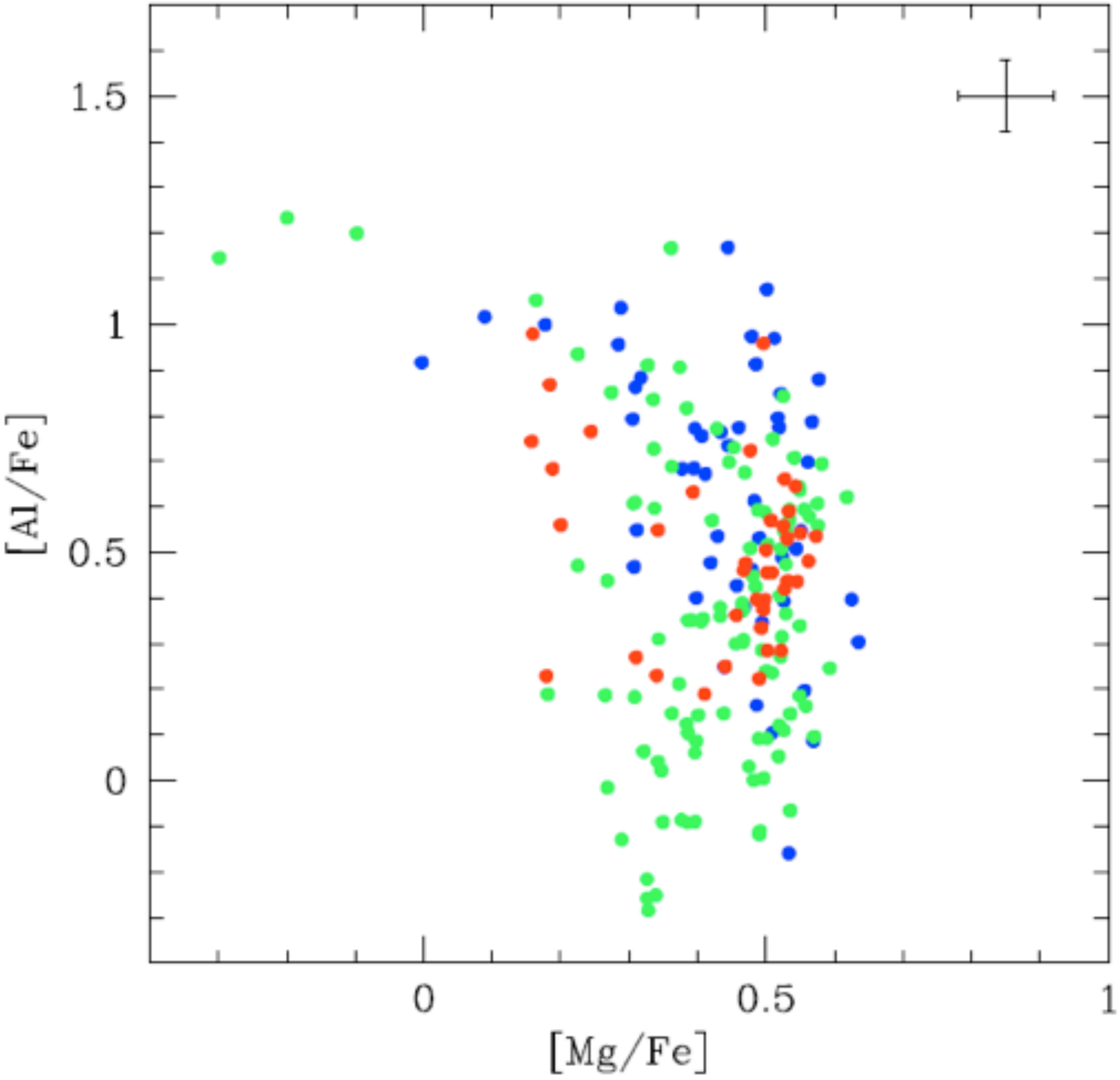


Carretta+ 2009

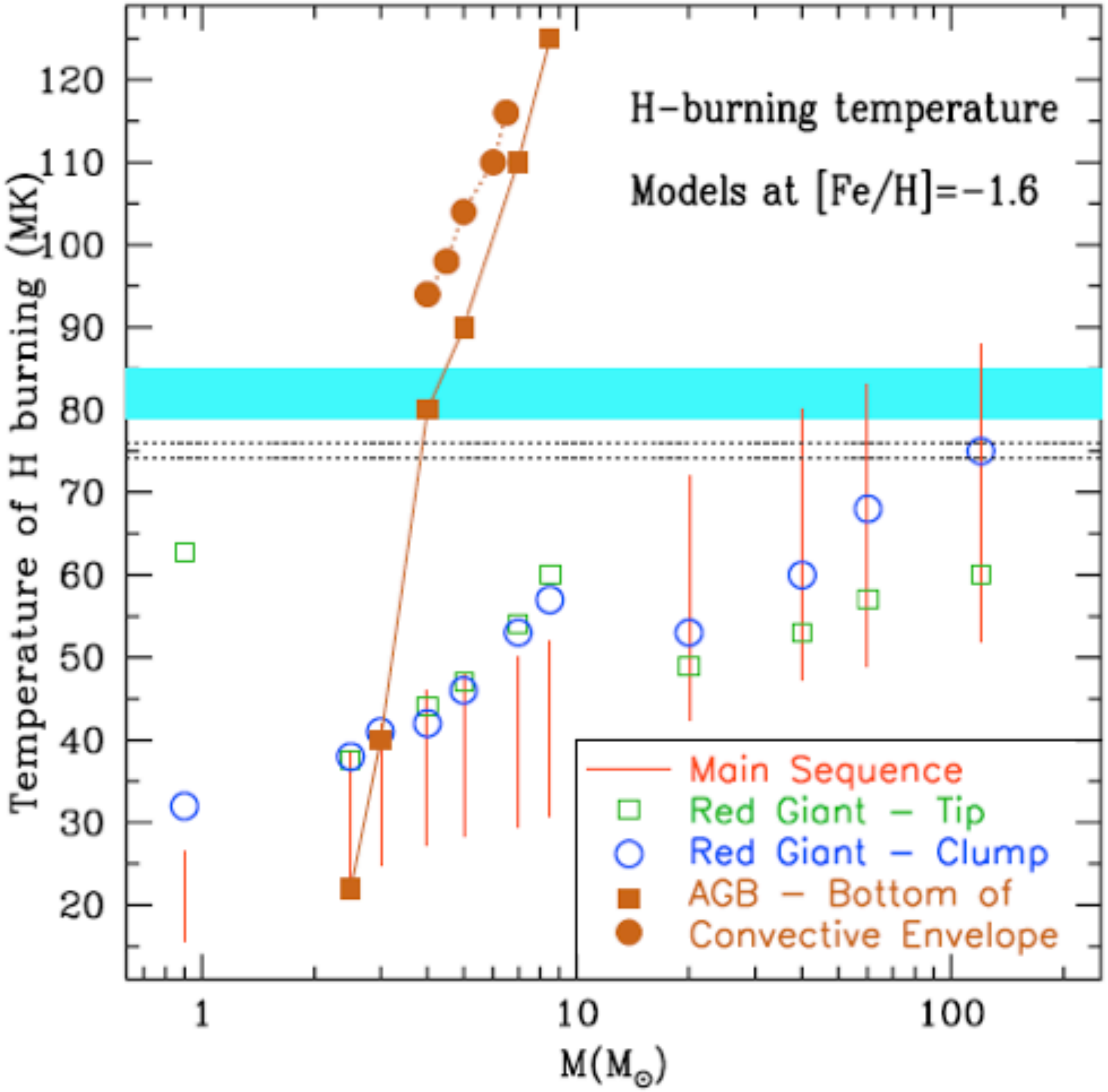
- ✓ Na-O anticorrelation
- ✓ Mg-Al anticorrelation
- ✓ Si-Al correlation!

clusters showing variations in Mg or Si are a limited number

Chemical patterns and AGB ejecta



Carretta et al. 2009 - UVES spectroscopy
red: high Z; green: intermediate Z; blue: low Z clusters

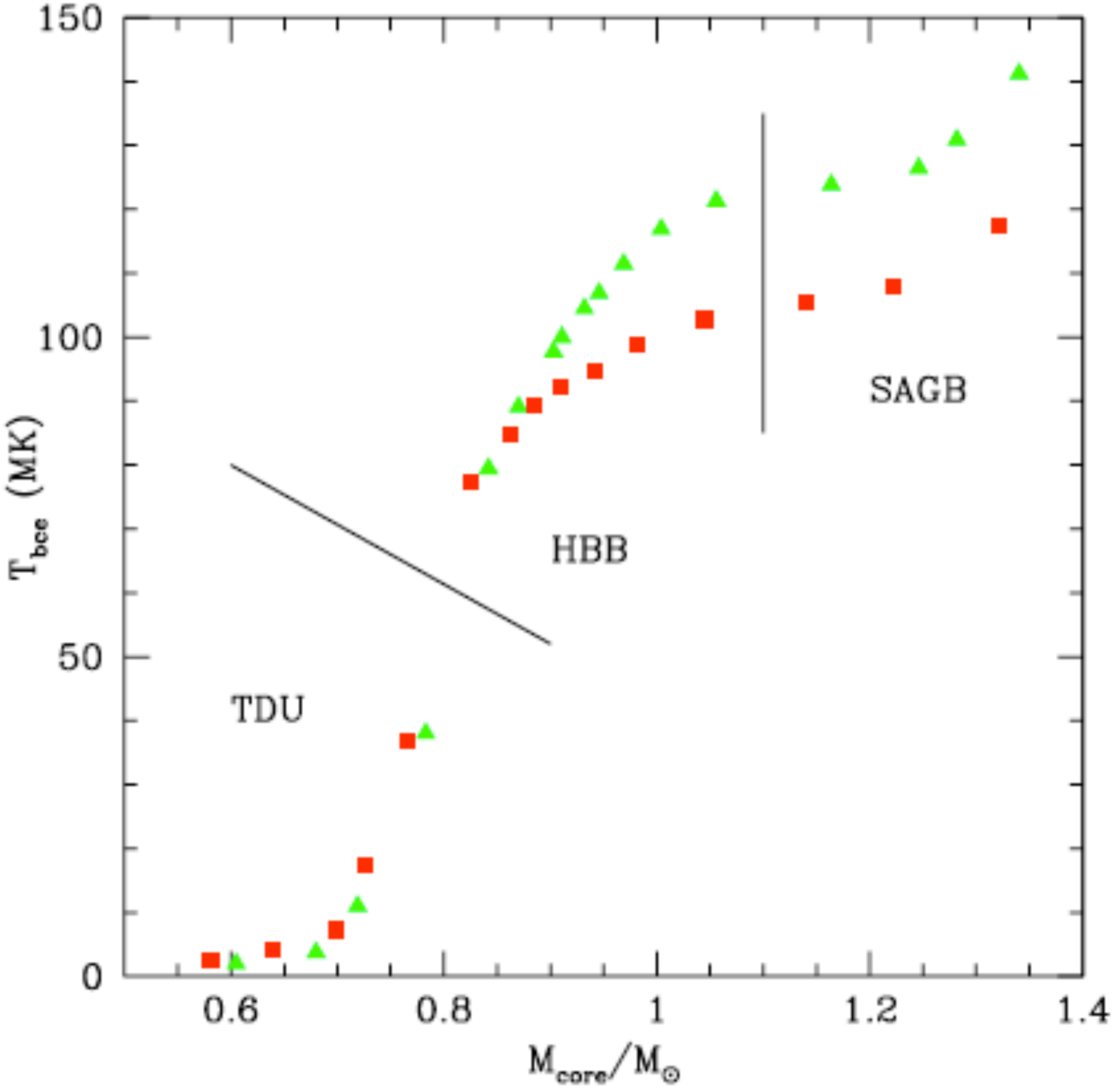


Prantzos, Charbonnel, Iliadis 2007 - one zone model for NGC 6752

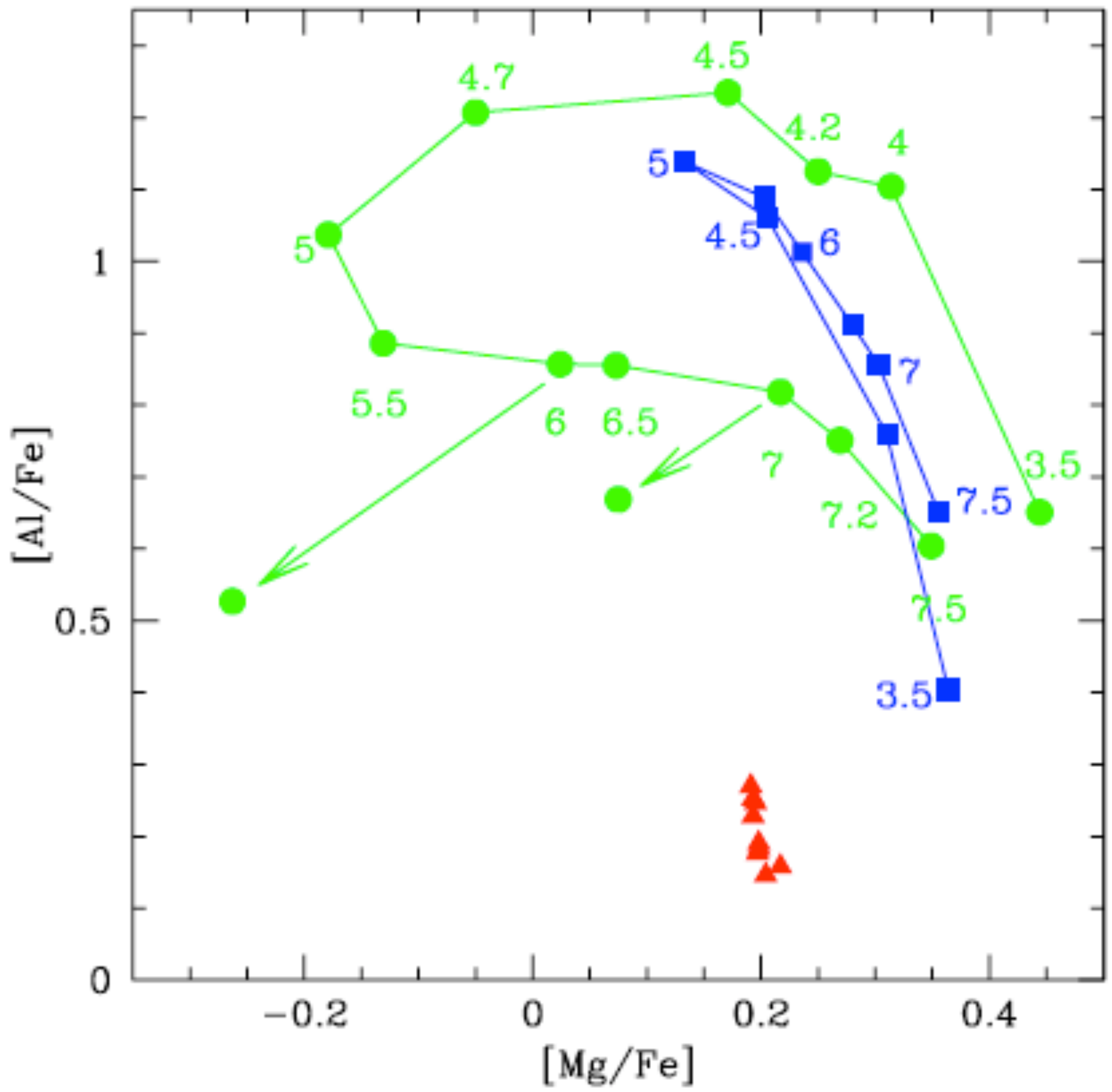
What the AGB scenario explains “naturally” about the chemistry of SG

- ✓ Na up, O low (also other models). Mg-Al, Mg-Si - maybe Al-Si anticorrelation also possible
- ✓ Larger anomalies for lower metallicity (for similar degrees of dilution)
- ✓ C+N+O variations are possible in clusters with prolonged star formation history (SN Ia delayed?)
- ✓ C+N+O increase “may” be associated with small iron increase (non destructive effect of the first few Sn Ia?)

Z-dependence model prediction



Red: Z=0.008; Green: Z=0.0002

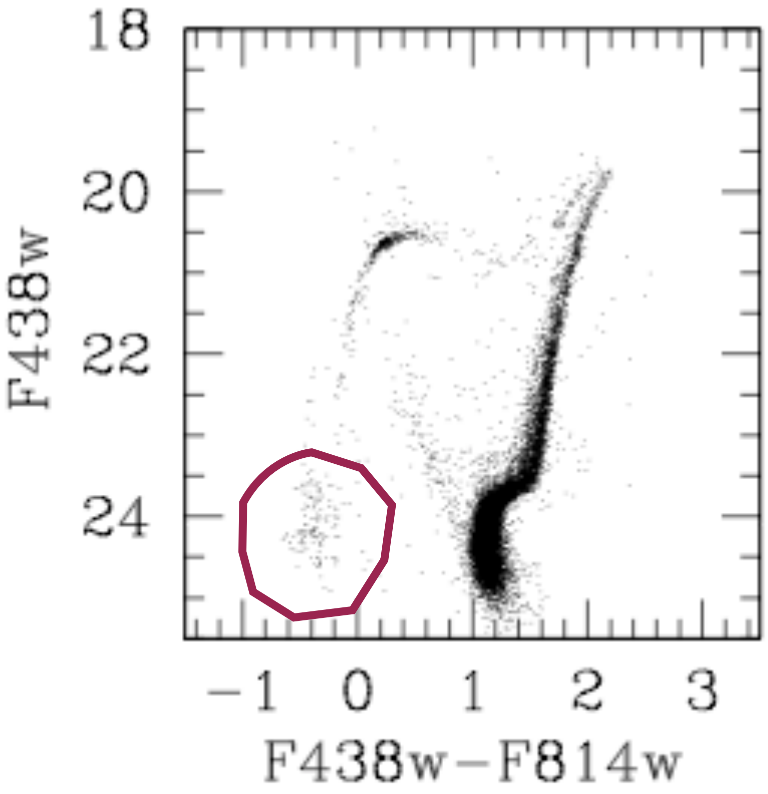


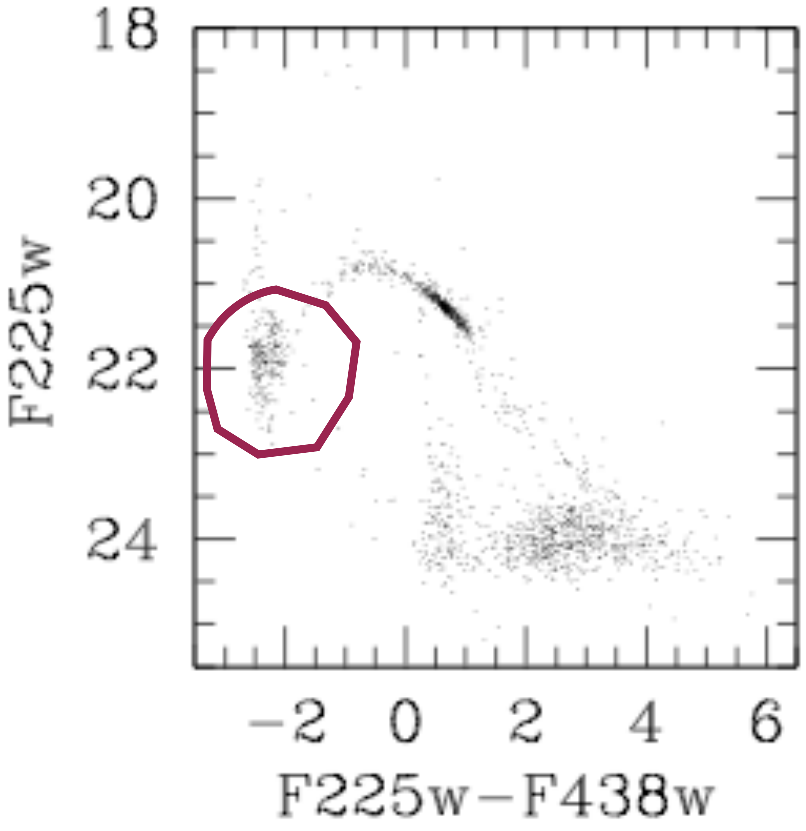
Green: Z=0.0002 Blue= Z=0.001

Ventura+ 2013

NGC 2419: Z=0.0002 and a possibly “pure” SG

We need low metallicity to get larger HBB Temperatures;
We need “no” dilution to enhance the nuclear processing results



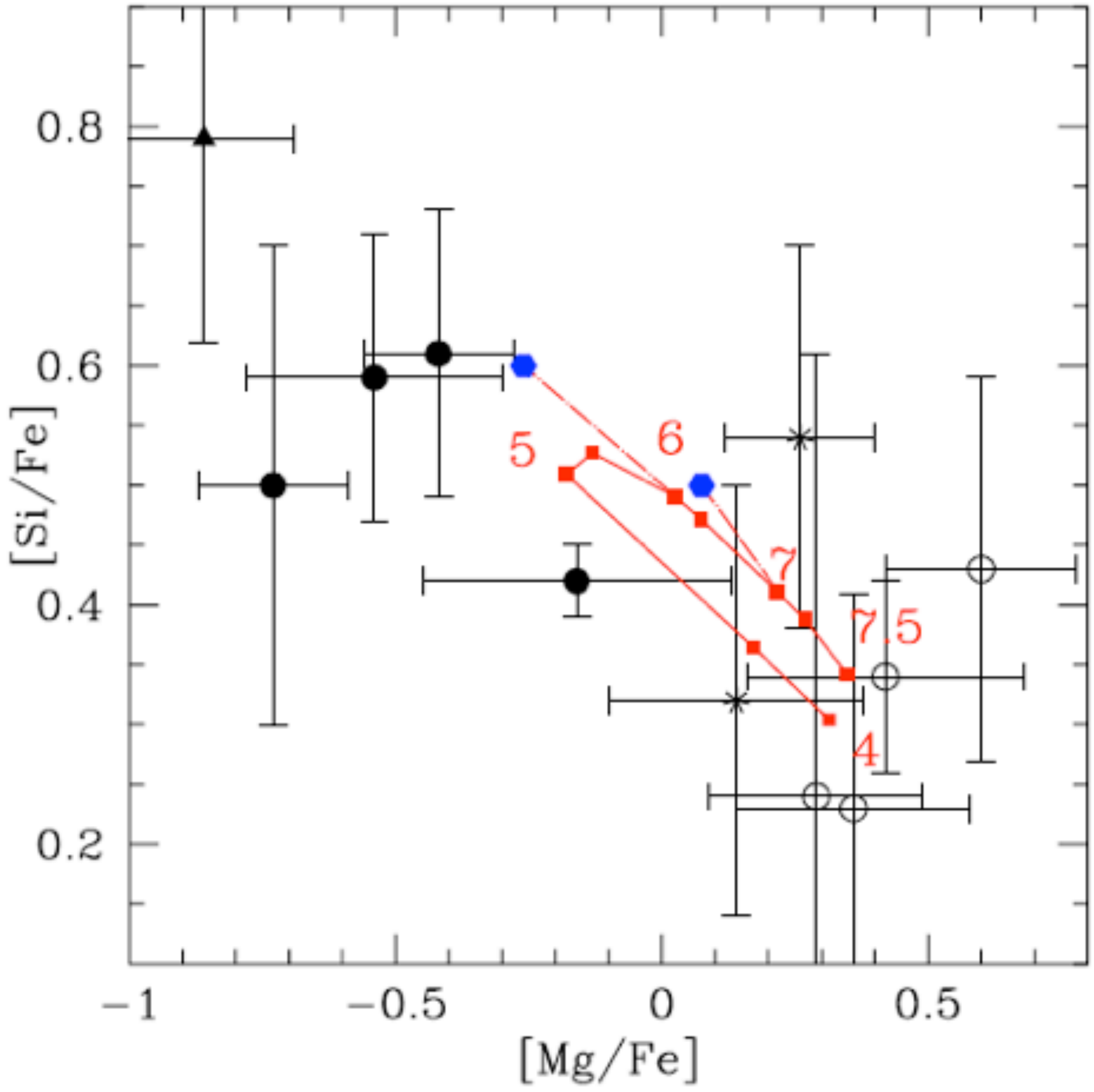


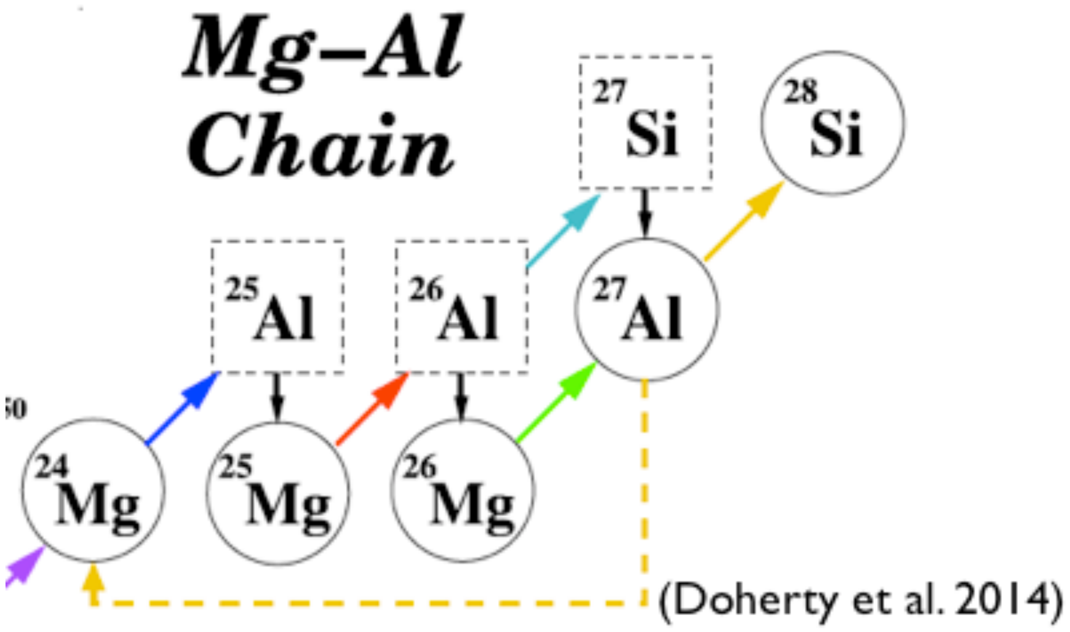
Di Criscienzo+ 2015

FG Y=0.25 - ISG Y=0.25-0.28 - ESG Y=0.36

Chemical patterns and AGB ejecta

NGC 2419: extreme abundance variations!





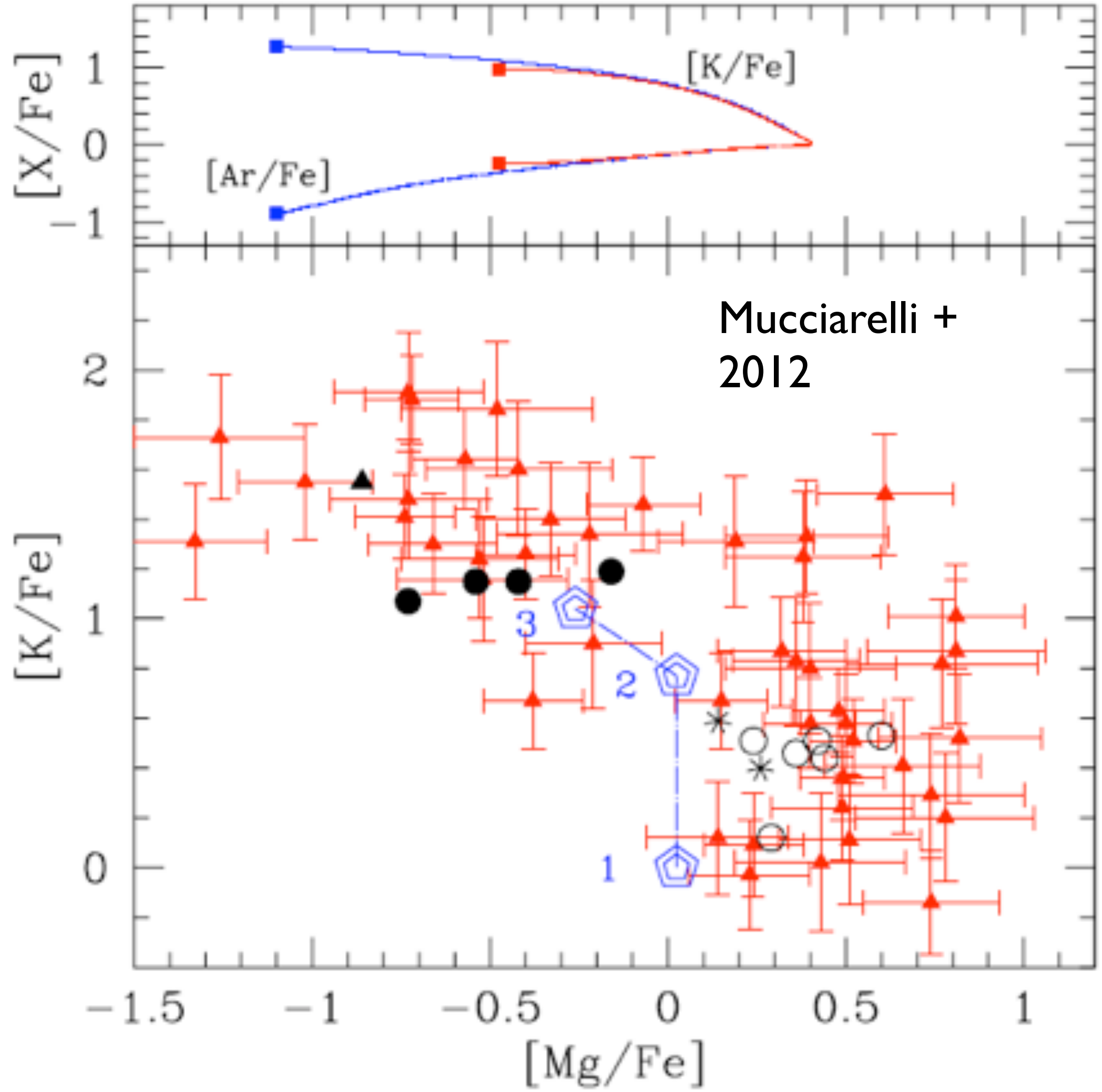
(Doherty et al. 2014)

✓ the Mg-Si and anticorrelation requires a factor two more depletion in Mg than allowed by models

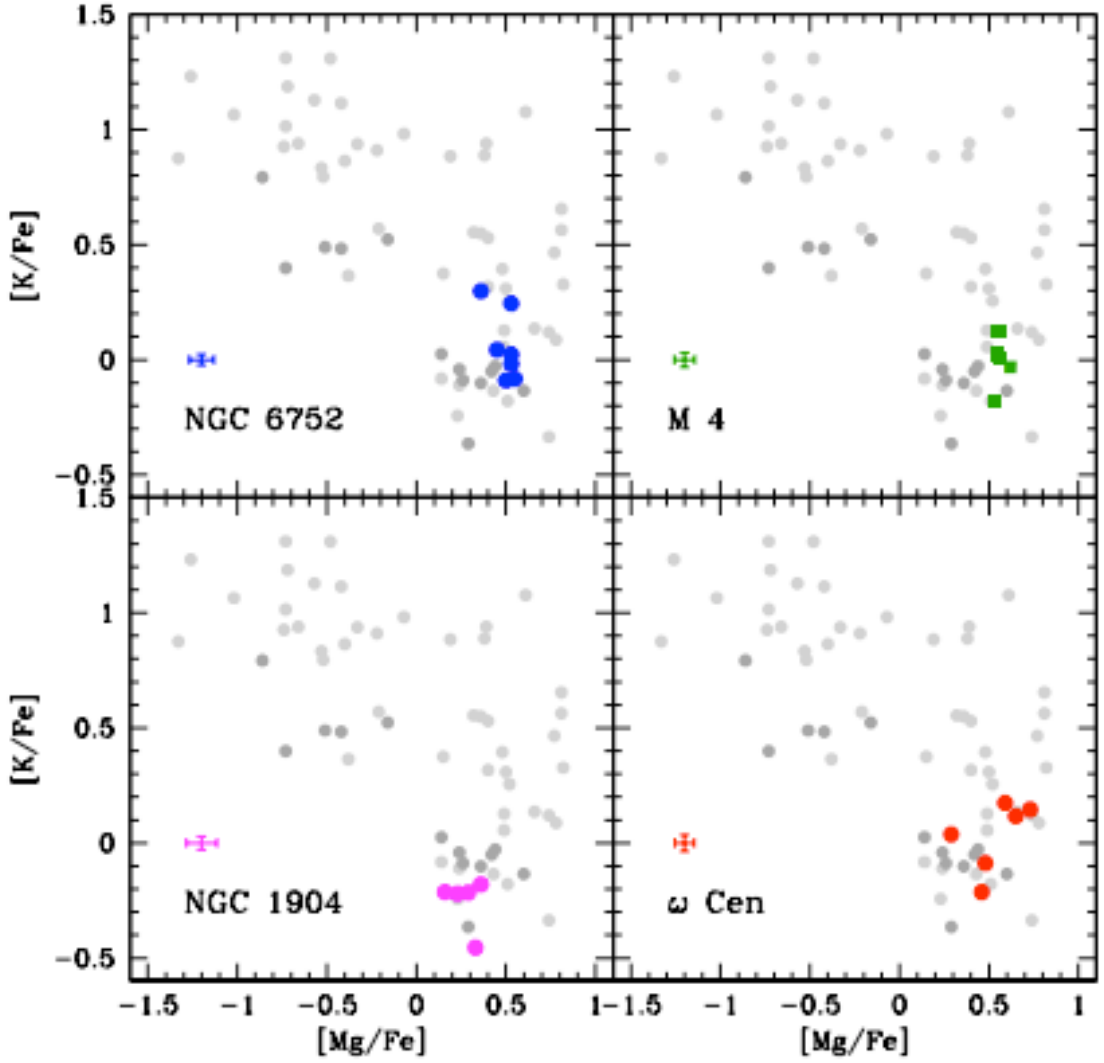
Potassium

NGC 2419 versus other clusters

$$^{36}Ar(p,\gamma)^{37}K(e+,\nu)^{37}Cl(p,\gamma)^{38}Ar(p,\gamma)^{39}K$$



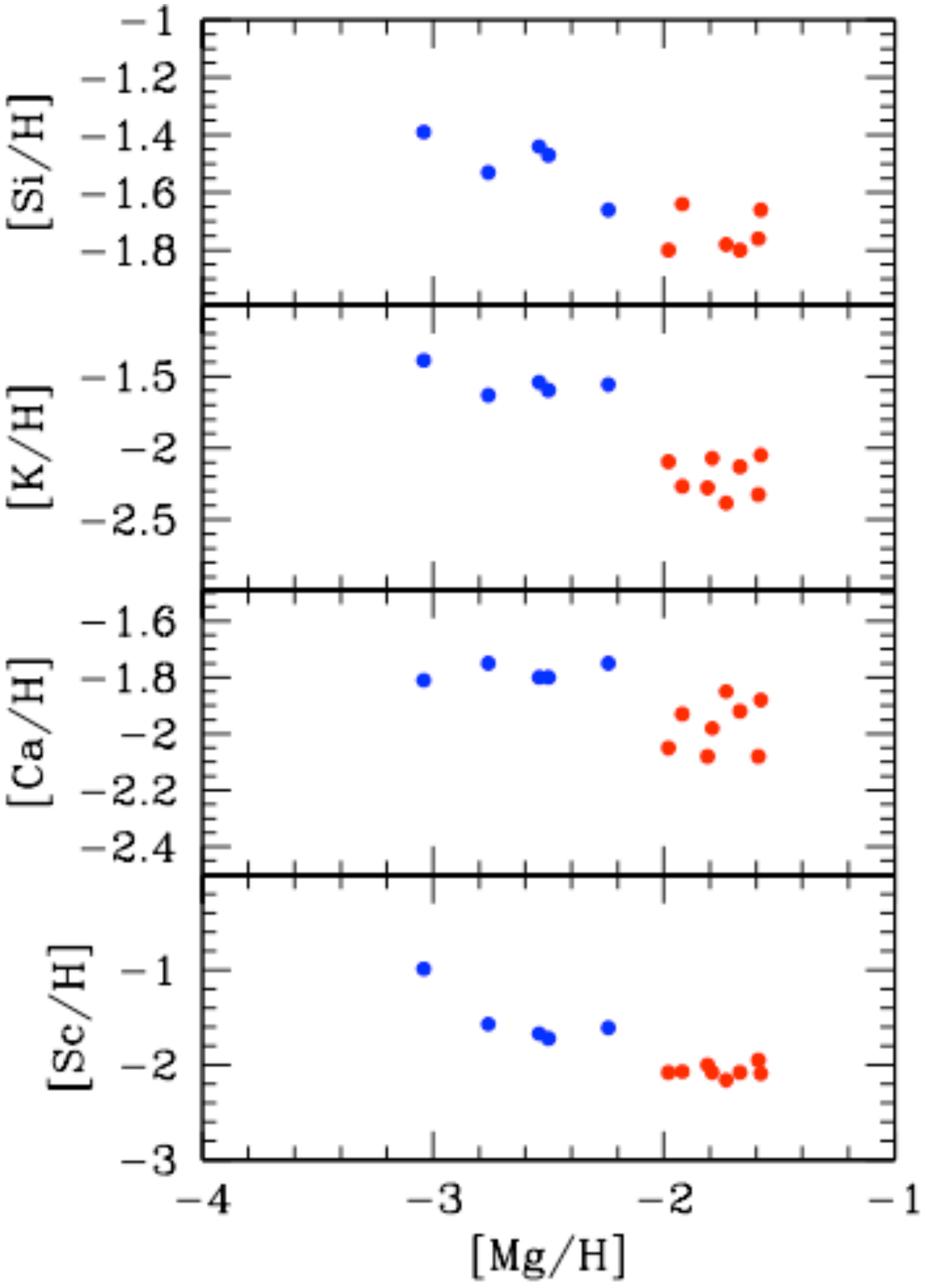
Mucciarelli +
2012



- ✓ Ventura et al. 2012: propose K increase is due to Argon burning!
- ✓ K production not seen in other clusters - Carretta et al. 2013.
- ✓ In NGC 2419 it may be favoured by the low Z

Chemical patterns and AGB ejecta

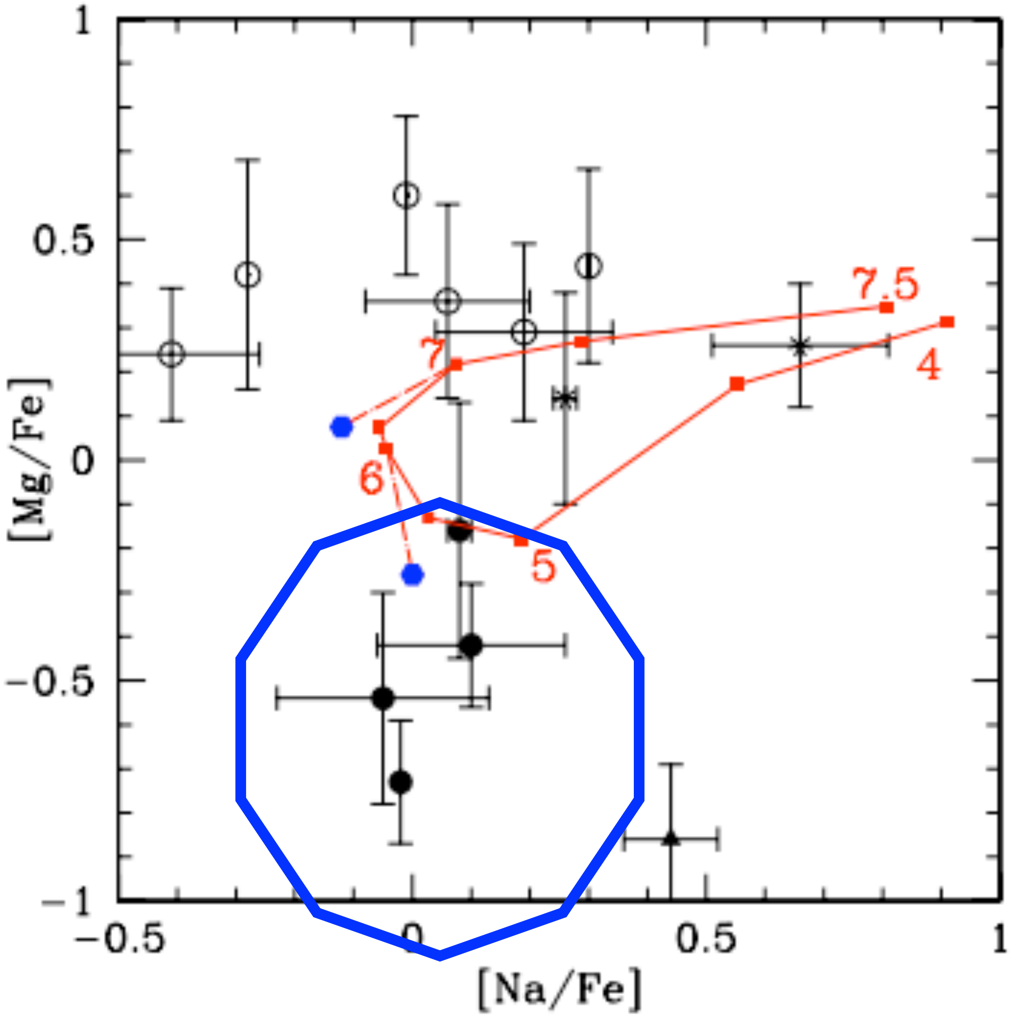
NGC 2419 versus other clusters



- ✓ Mg anticorrelated with Si, K, Ca and Sc! ALL may be obtained by proton capture in NGC 2419 (Carretta et al. 2013). This is seen ONLY in this cluster, it may depend both on low Z AND on the presence of a very extreme second generation

The problem of Na23 abundances

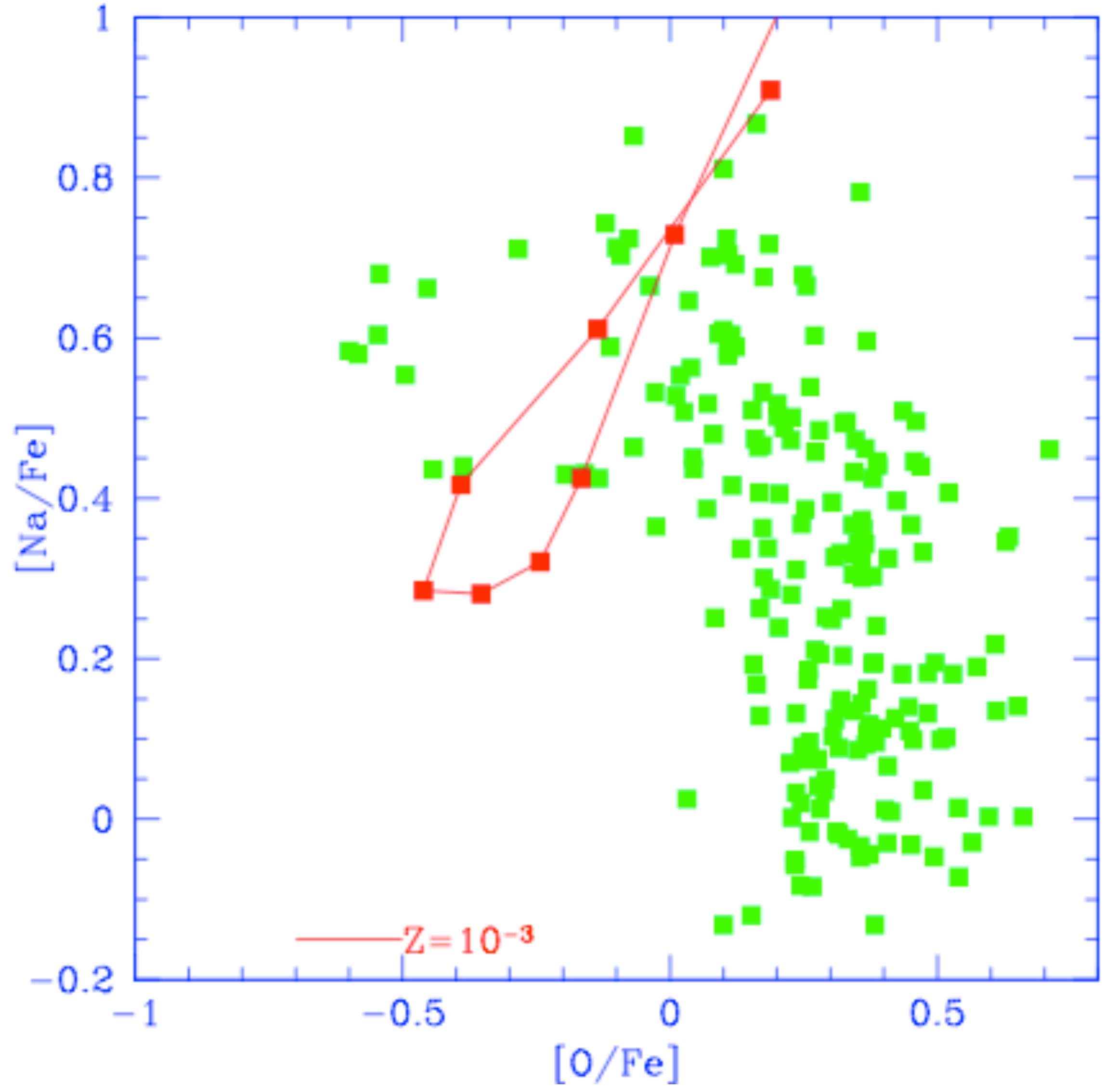
We have seen that extremely advanced HBB nucleosynthesis - requiring T_burning even larger than in our models- are needed to obtain the nucleosynthesis observed in NGC 2419: in these conditions, the Ne-Na cycle destroys Na, for current cross sections



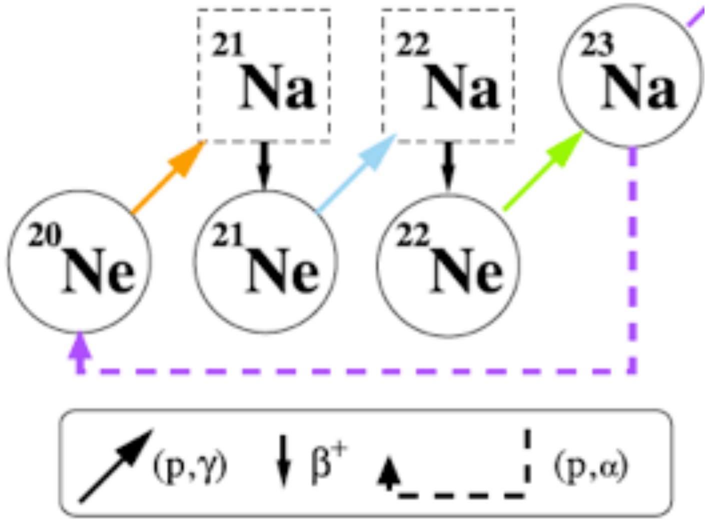
There is enough ambiguity (for now) in NGC 2419 data: Mg poor stars are sodium-normal

...but what happens in other very low Z clusters?

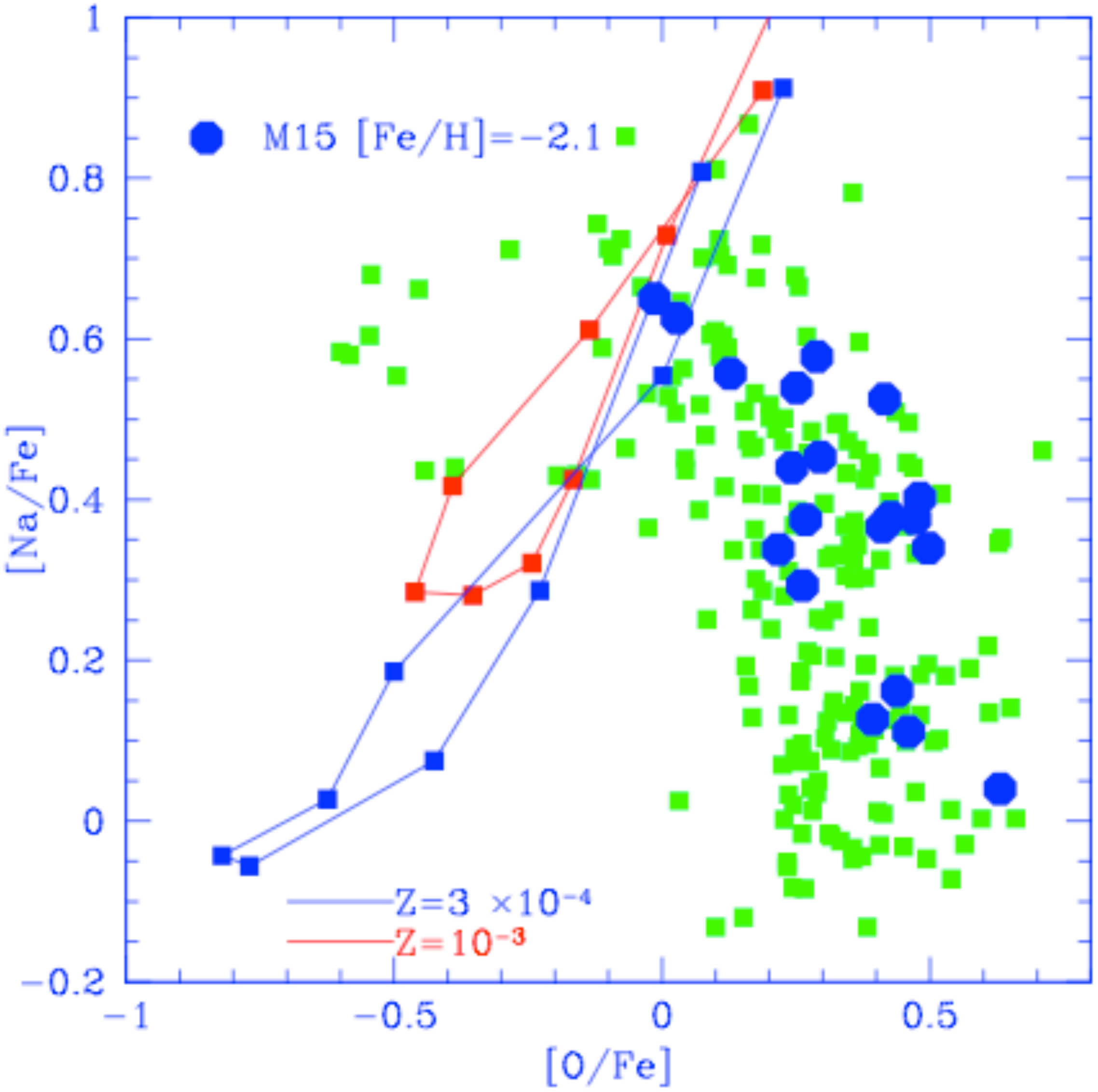
The problem of Na23 abundances in low-Z clusters



For the global O-Na anticorrelation, yields and models do not match perfectly, but adjustments can exist

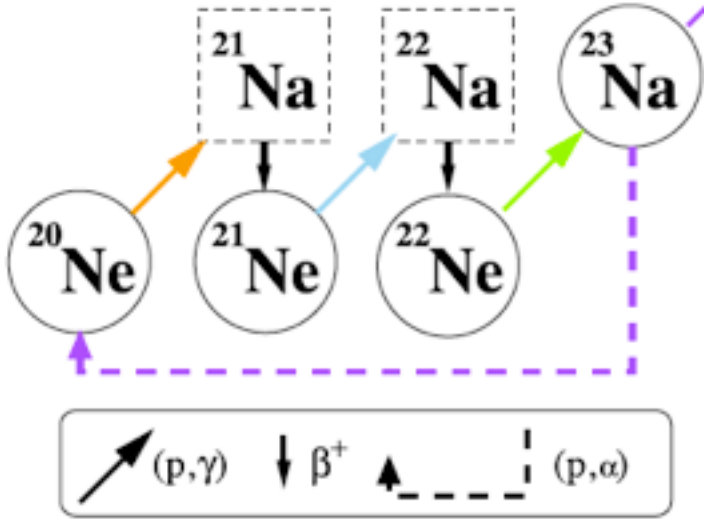


The problem of Na23 abundances in low-Z clusters

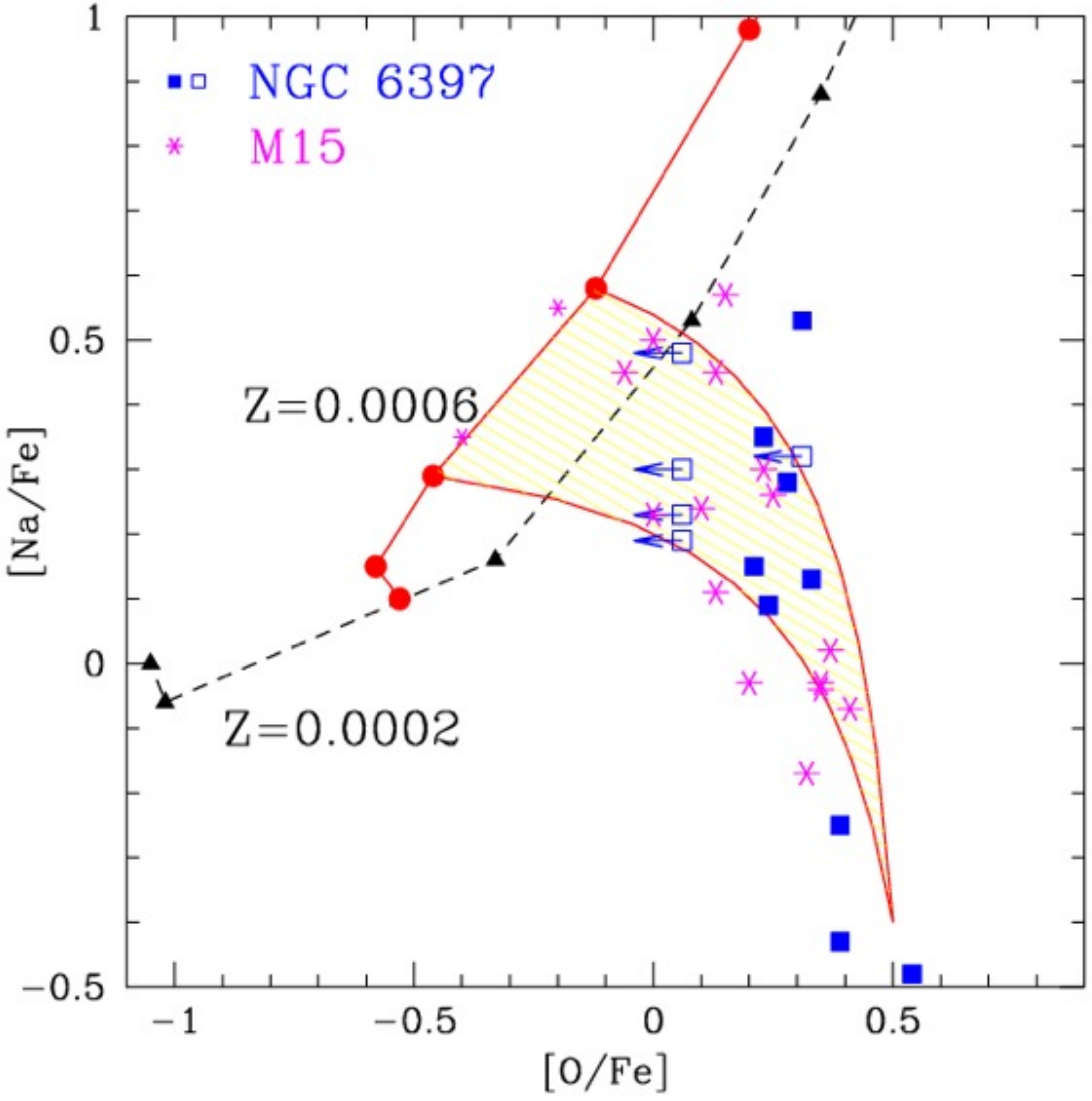


For the global O-Na anticorrelation, yields and models do not match perfectly, but adjustments can exist

but the problem may be very serious for low Z clusters, if their O-Na anticorrelation is similar to others



The dilution model is still possible, if Z of low metallicity clusters were underestimated

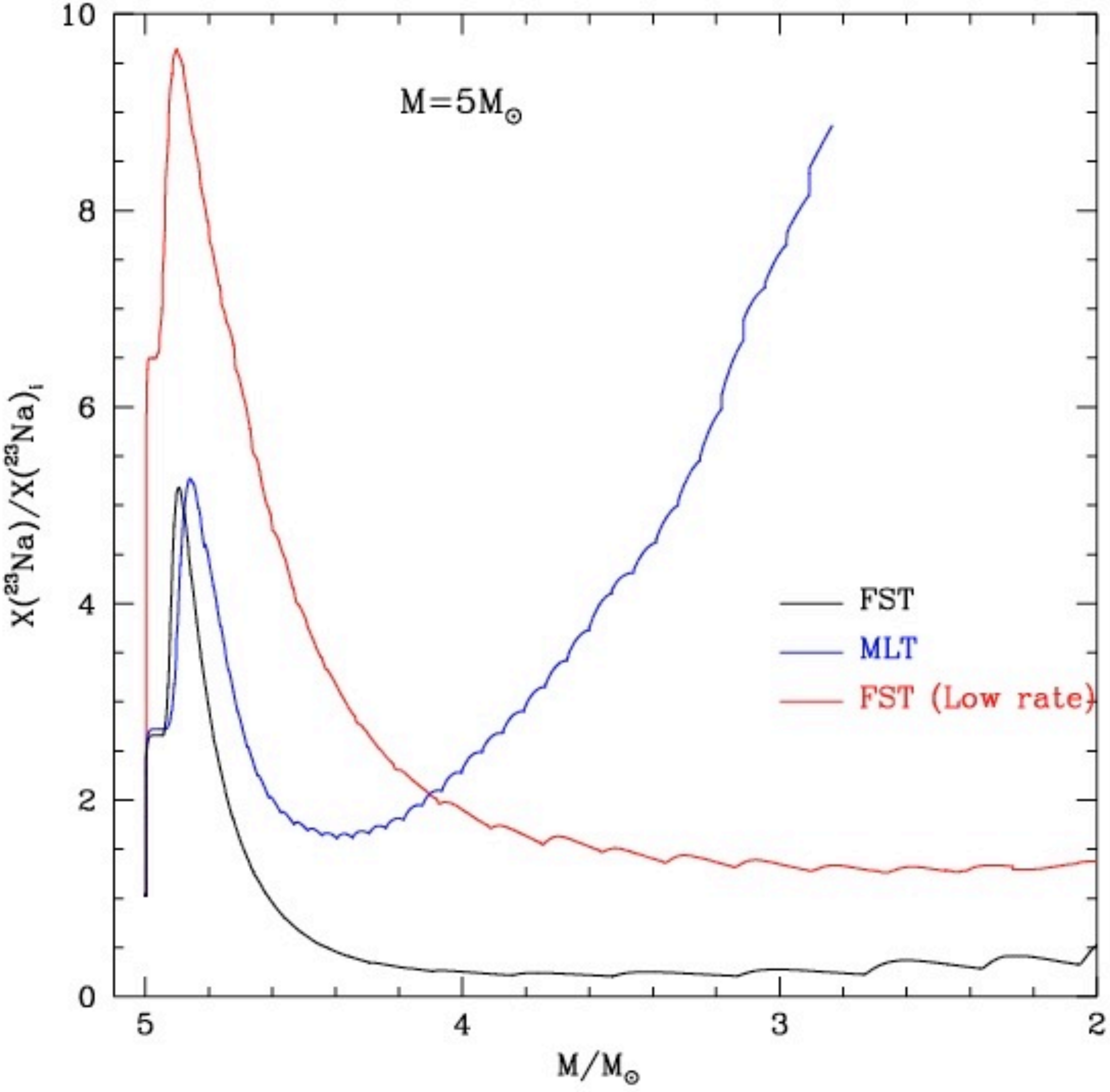


(Ventura & D'Antona 2008)
We attributed Z=6m4 to NGC 6397 and M15 stars

still, we should ask why "dilution" and star formation is effective only at masses ~4.5-5 Msun

But the "low" Z clusters are at 2x10^{-4} or lower Z, according to recent determinations

Na production – destruction in AGB



Na23 first increases due to 2nd dredge up, then through burning of the dredged up Ne22. At large T_{bce} then it is destroyed by p captures

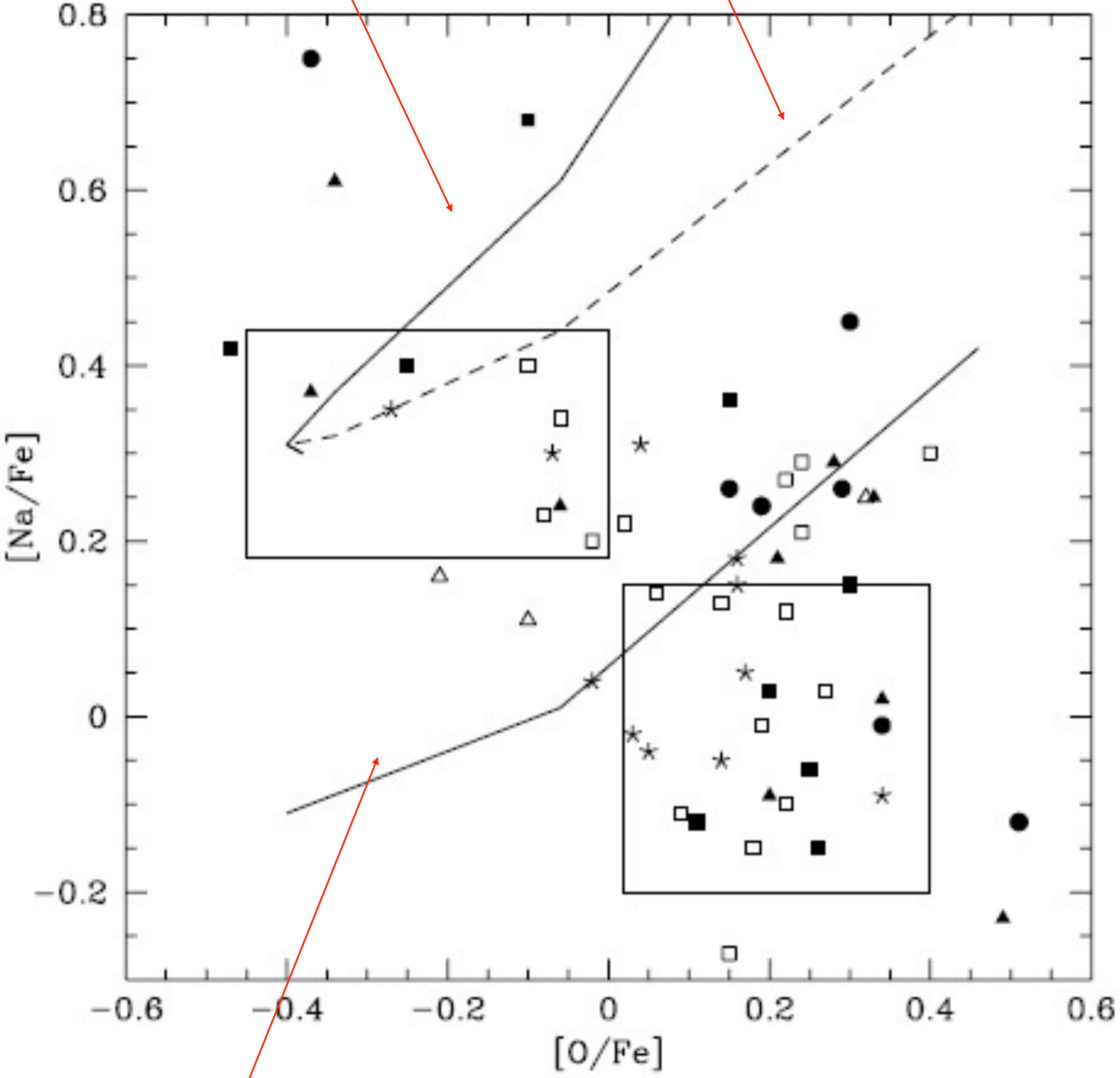
the rate of destruction through the chain Na23(p, α)Ne20 is crucial

(red curve: rate at its lower limit)

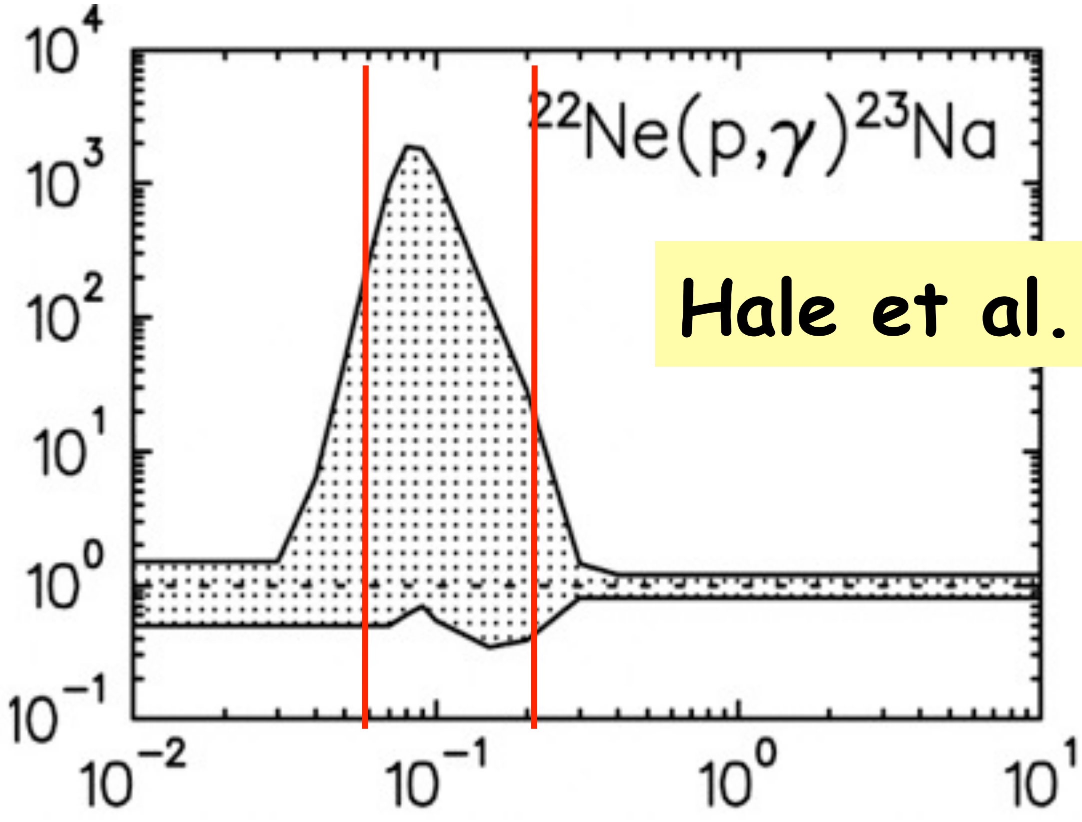
Na23 production depends on uncertain c-sections

maximized

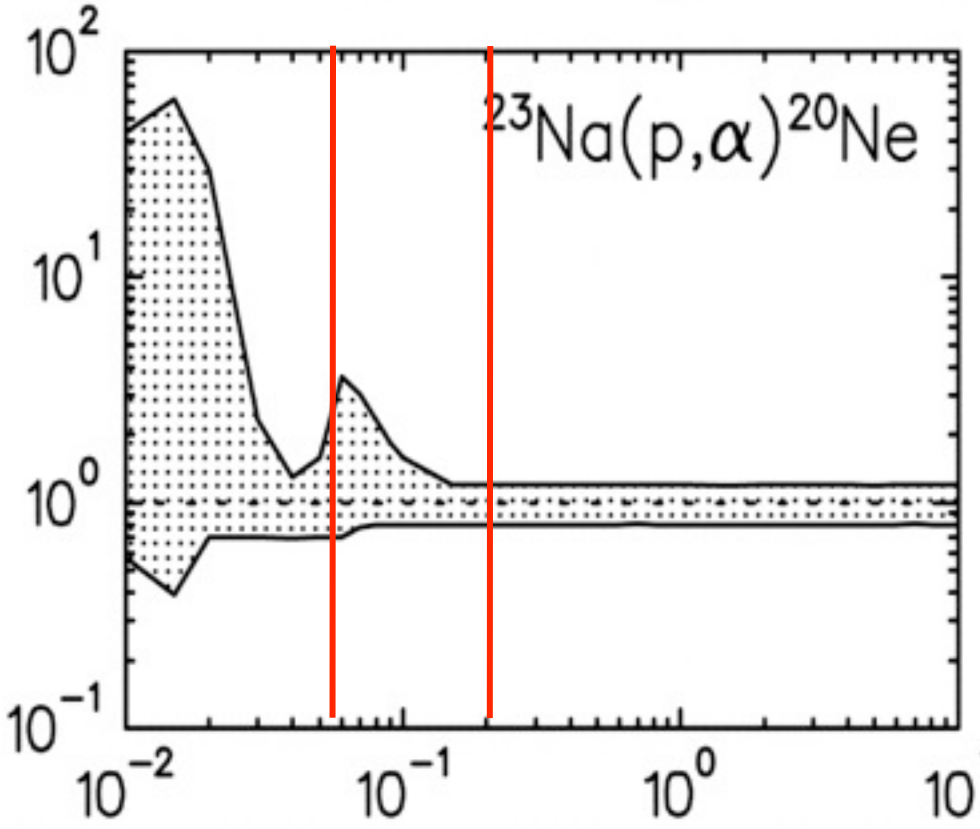
higher Ne22(p,γ)



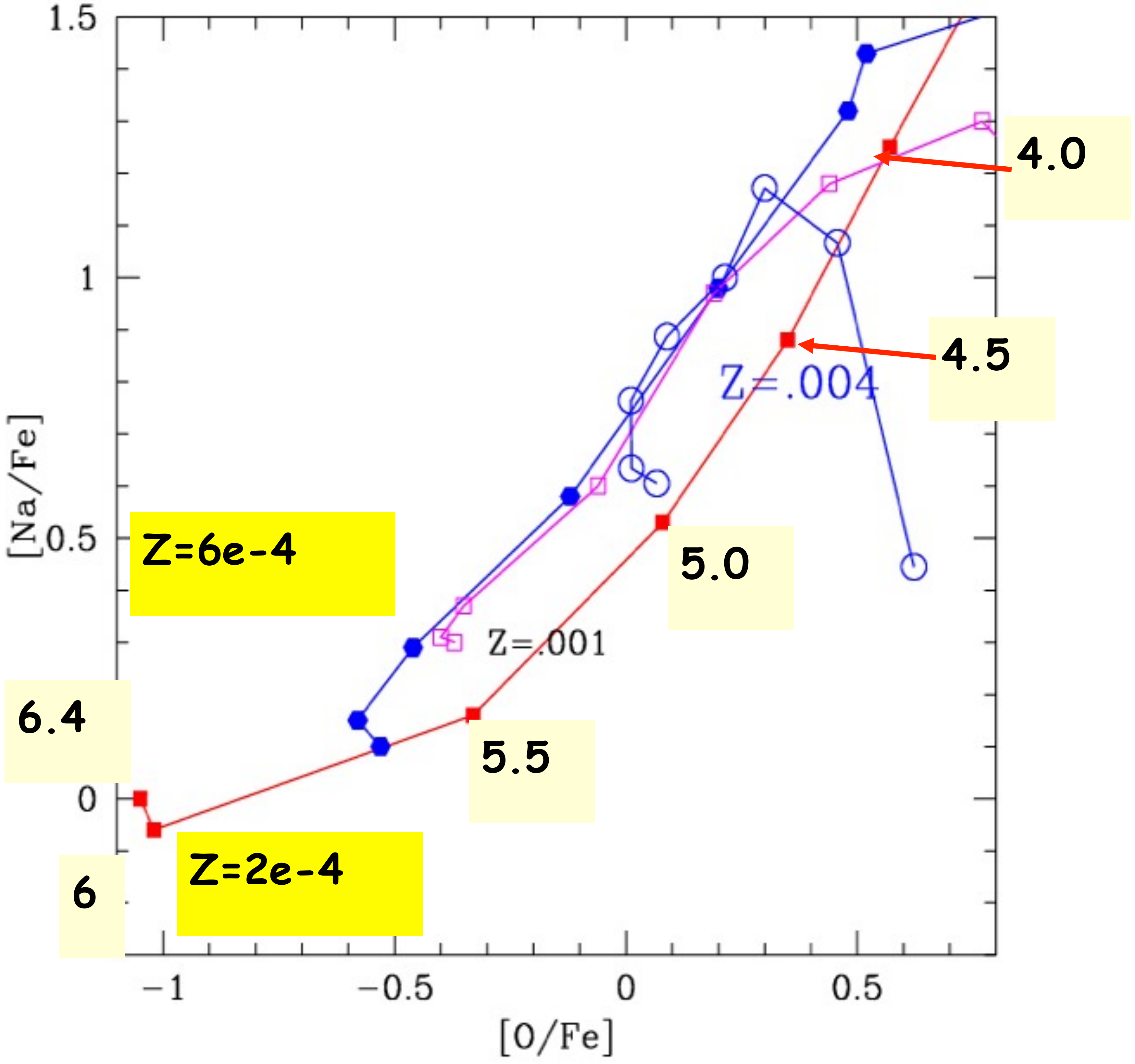
recommended



Hale et al. 2002

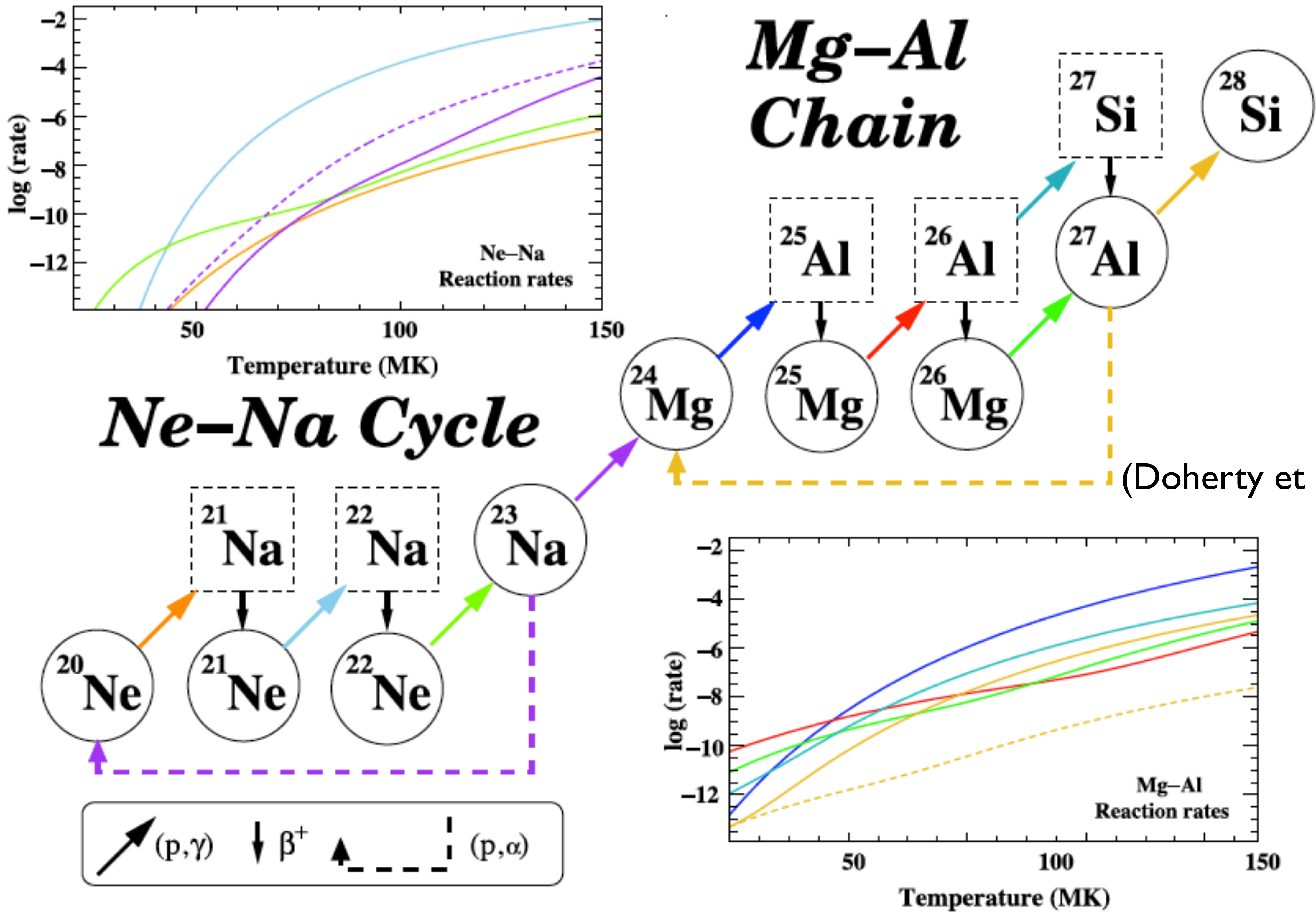


O-Na dependence on Z

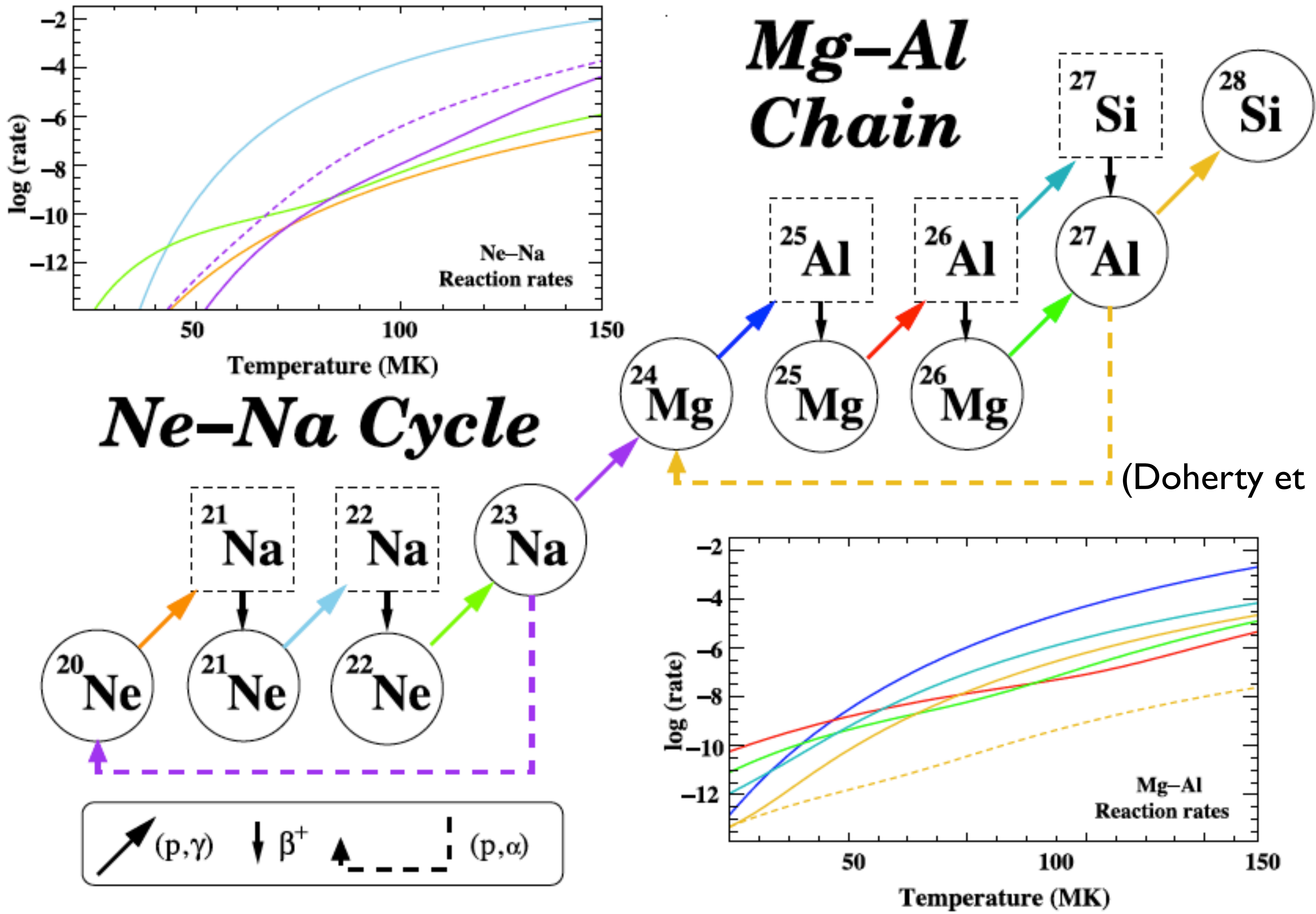


we expect that, for lower Z, the maximum O-depletion increases, and the corresponding Na is smaller

Na however also depends on the initial Neon. What if Ne(Z) anticorrelated?



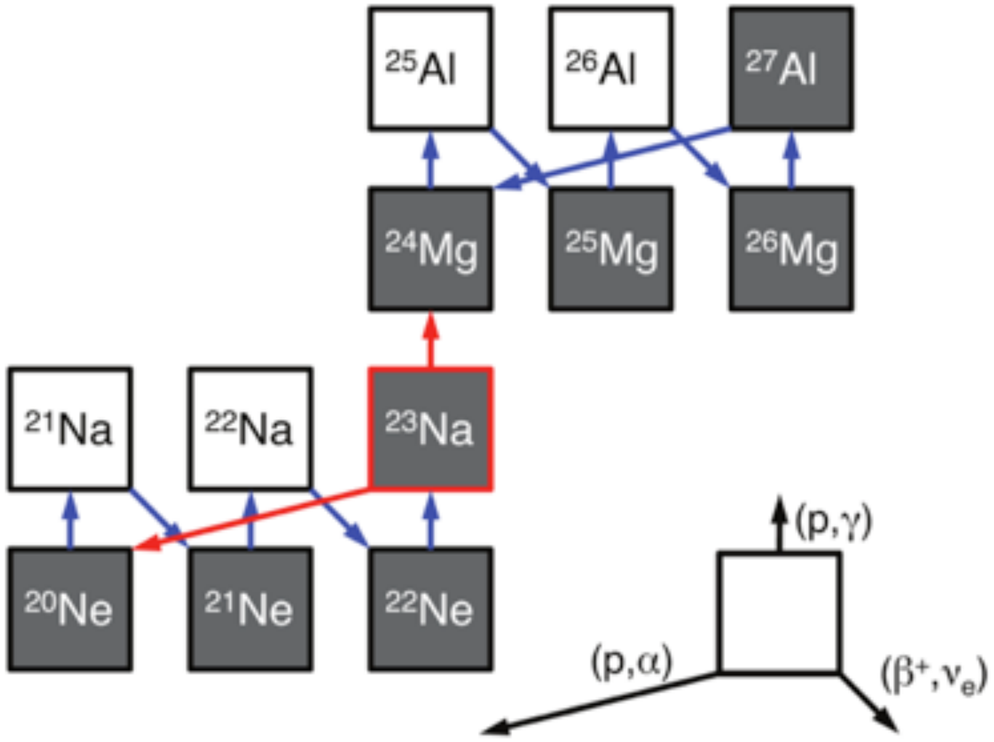
(Doherty et al. 2014)

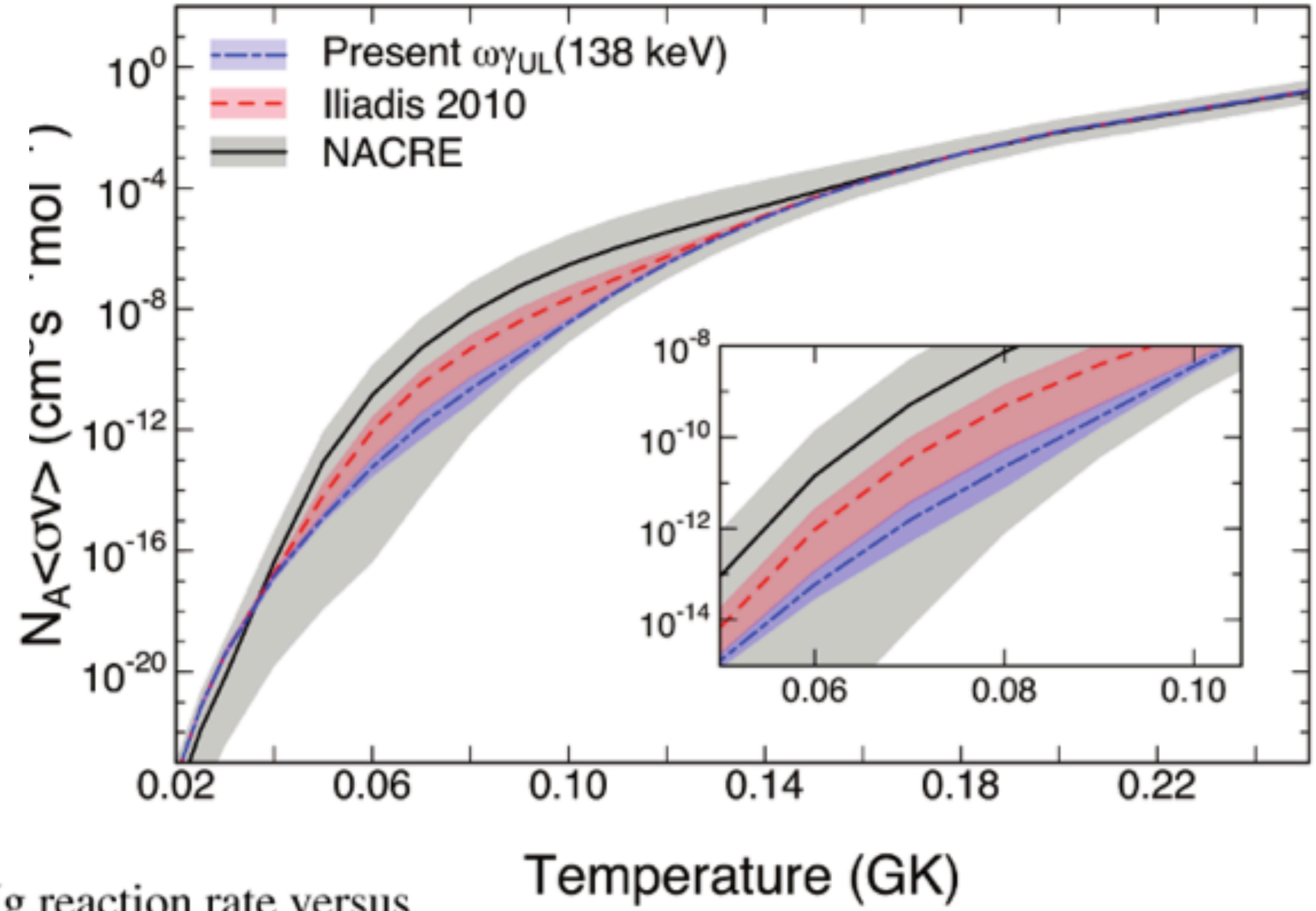


(Doherty et al. 2014)

we need lower reaction rates for Na23 destruction

PHYSICAL REVIEW C **88**, 065806 (2013)





Cesaratto et al. 2014

FIG. 14. (Color online) The ^{23}Na(p,γ)^{24}Mg reaction rate versus temperature. Existing compilations (NACRE [37] in black and Iliadis *et al.* [18] in red) are compared to the present total reaction rate. The blue line corresponds to the new median rate calculated using $\omega\gamma_{\rm UL}$(138 keV) $\leqslant 5.17\times10^{-9}$ eV. The inset of the plot shows an

Measurement of the $E_r^{\rm c.m.} = 138$ keV resonance in the ^{23}Na(p,γ)^{24}Mg reaction and the abundance of sodium in AGB stars

J. M. Cesaratto,* A. E. Champagne, M. Q. Buckner, T. B. Clegg, S. Daigle, C. Howard, C. Iliadis, R. Longland, J. R. Newton, and B. M. Oginni

The problem of Na23 destruction rates

Unfortunately, the reduction of the Na23(p,g)Mg24 rate is not enough to change the models.

We (would) need a revision of the Na23(p,a)Ne20 !

Increasing the initial Ne20 helps too! (why not?)

The problem of Na23 destruction rates

we need lower reaction rates for Na23 destruction

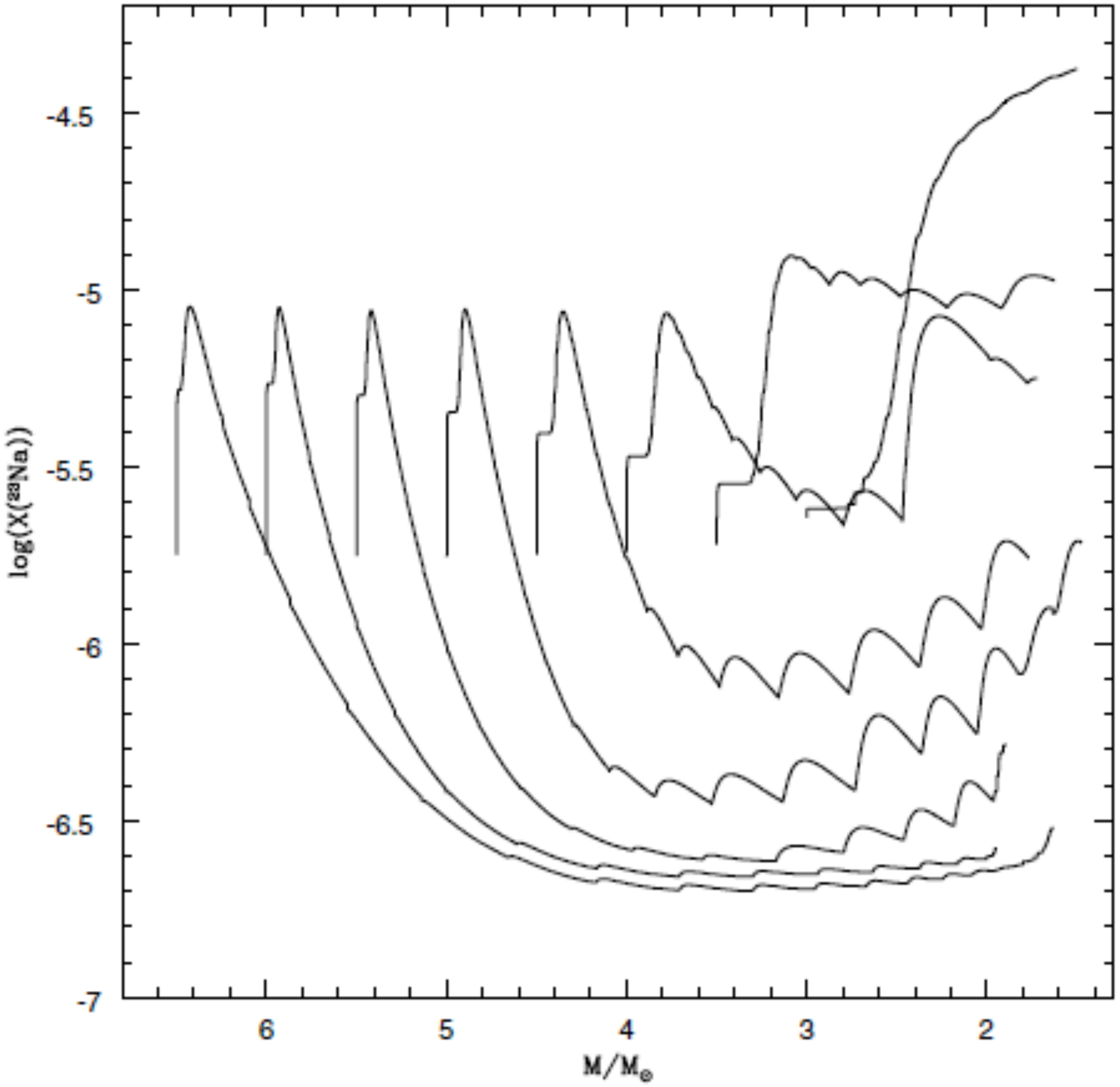
Unfortunately, the reduction of the Na23(p,g)Mg24 rate is not enough to change the models.

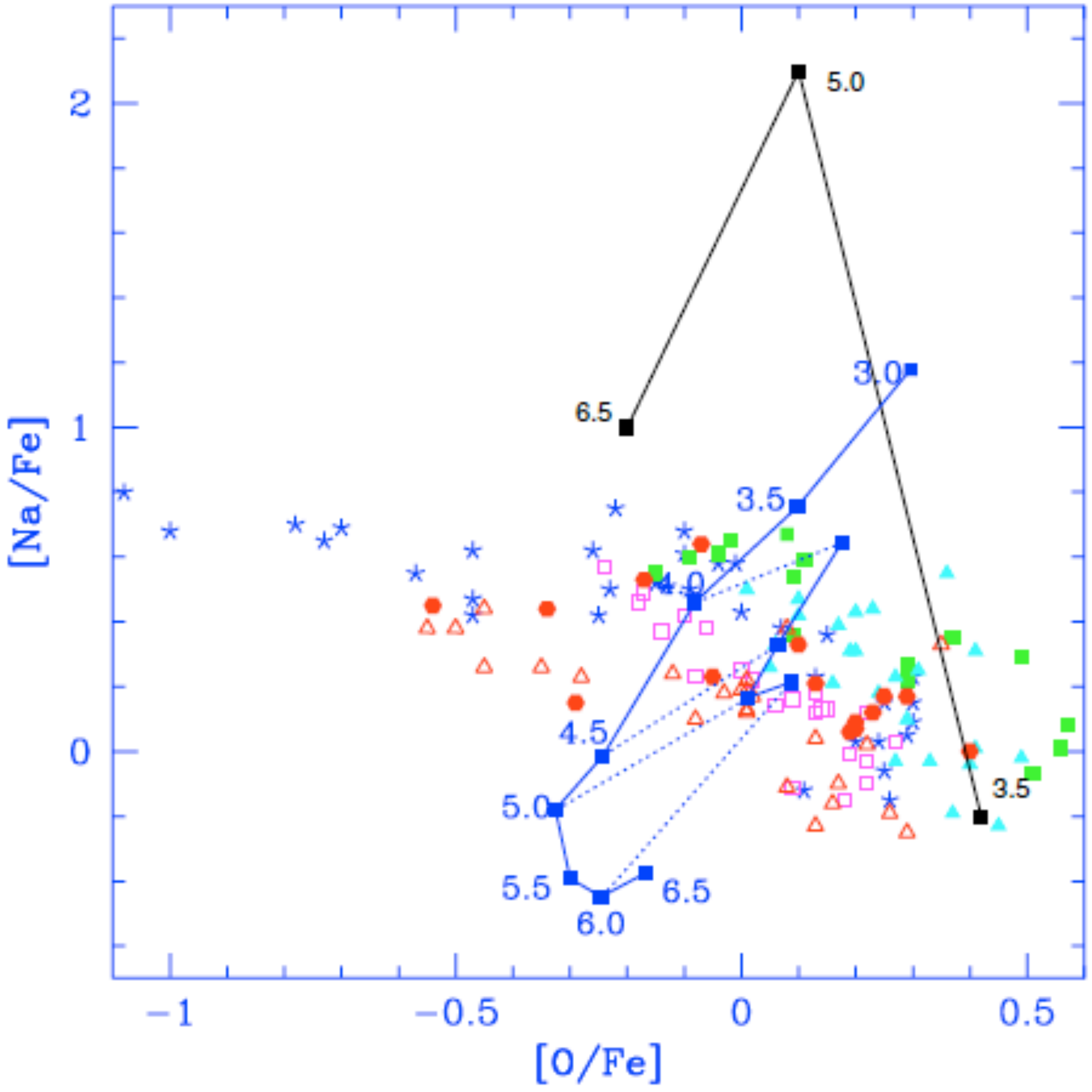
We (would) need a revision of the Na23(p,a)Ne20 !

Increasing the initial Ne20 helps too! (why not?)

Thank you for your patience

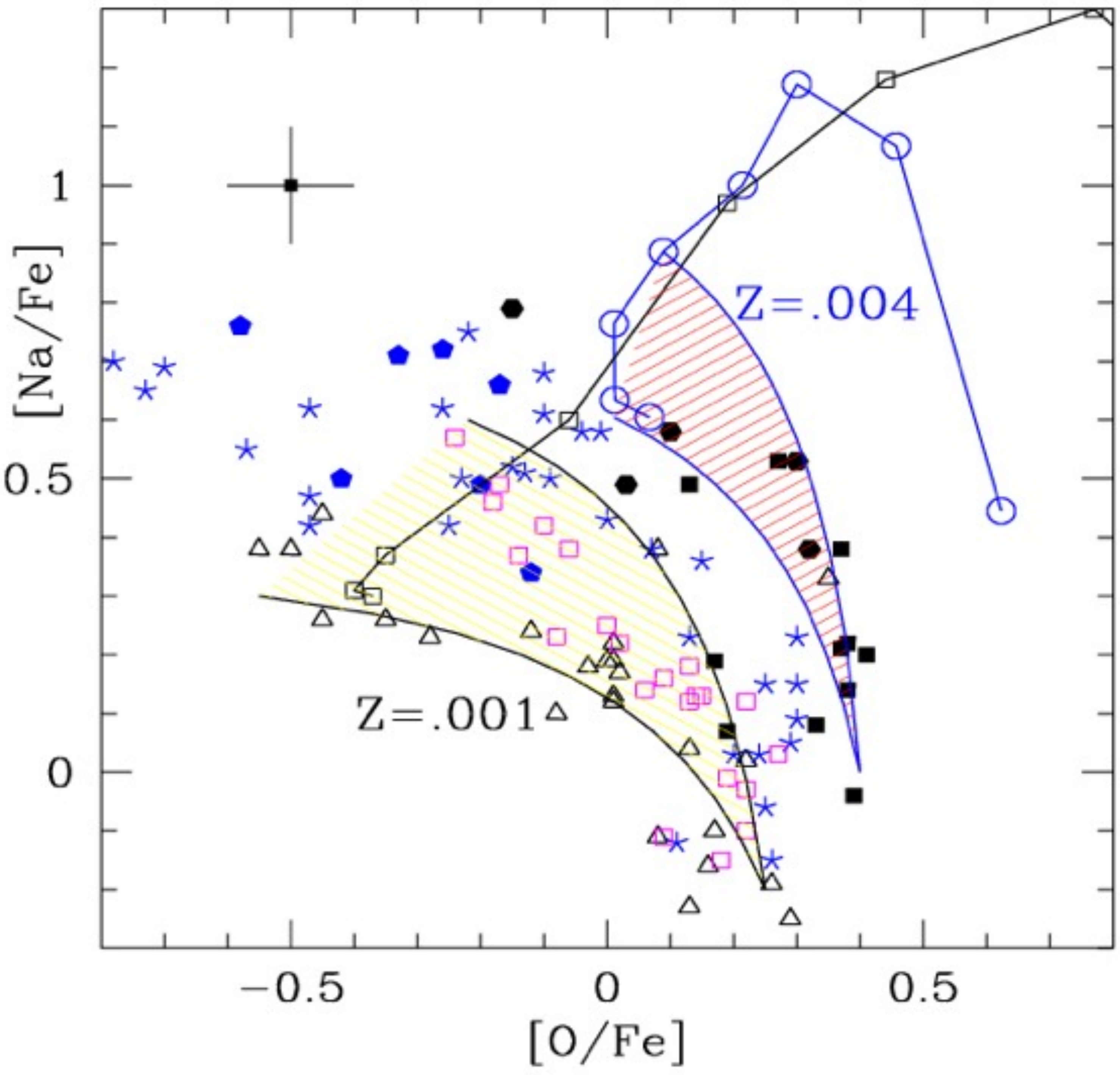
P. Ventura and F. D'Antona: Full computation of massive AGB evolution. II. 1081





Necessity of dilution: the intermediate and high Z clusters

Ventura & D'Antona 2008



The initial Na has a role, as it modulates the dilution

“Strong” and “mild” O-Na anticorrelations

- ✓ successful models should be able to reproduce different cases, as exemplified by NGC 2808 and M4
- ✓ always keep in mind that abundances may not *directly* reflect nucleosynthsis products, because of dilution

E. Carretta et al.: Na-O anticorrelation in 15 globular clusters

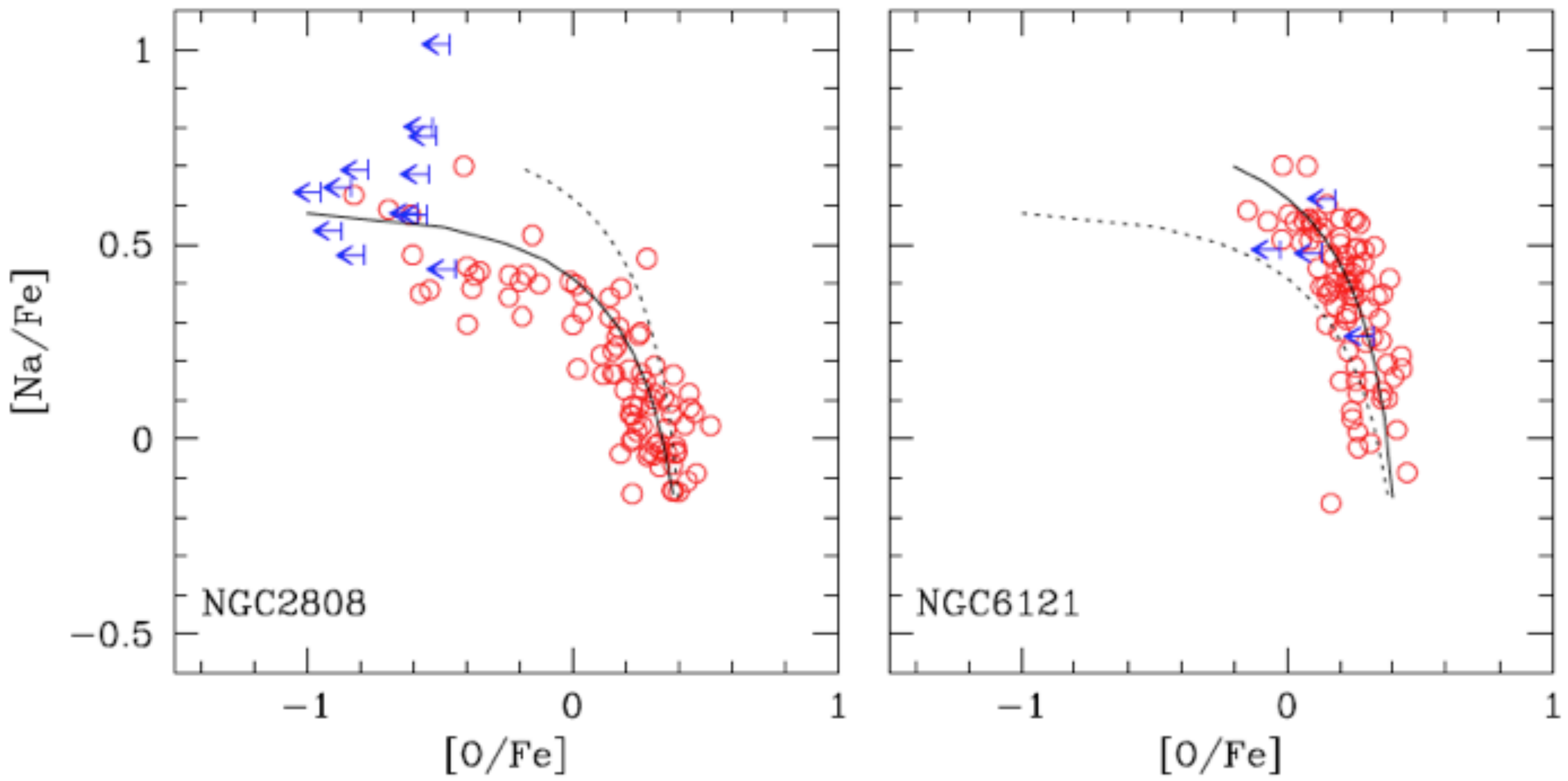
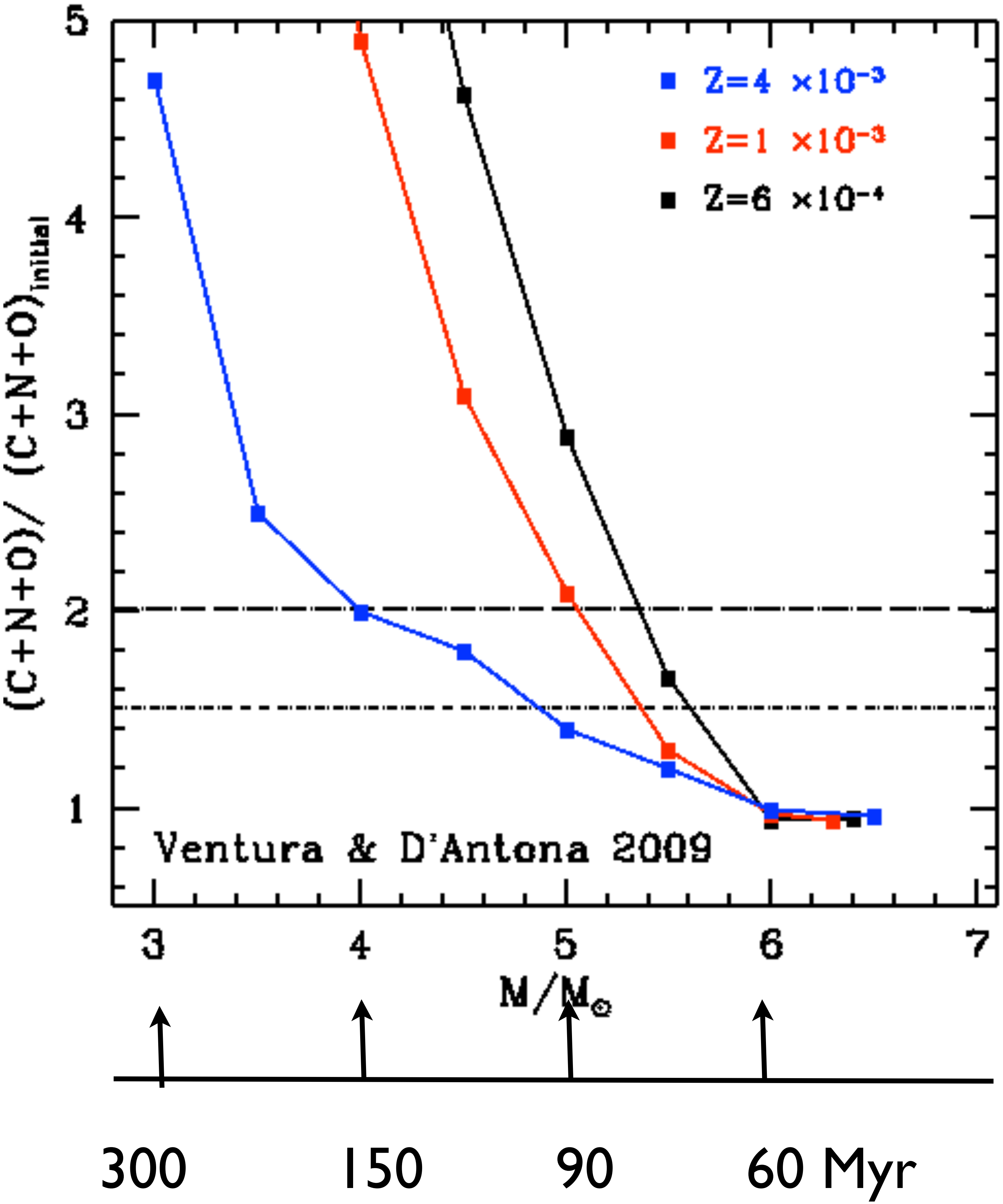


Fig. 18. The O/Na anticorrelation in NGC 2808 (*left panel*) and M 4 (NGC 6121, *right panel*). Red circles represent stars with actual measures of the O abundances, while blue arrows represent those stars for which only upper limits were obtained. Overlying lines are the results of our dilution model for the two clusters, respectively.

What the AGB scenario explains "naturally" about the chemistry of SG

- ✓ Na up, O low (also other models). Mg-Al, Mg-Si - maybe Al-Si anticorrelation also possible
- ✓ Larger anomalies for lower metallicity (for similar degrees of dilution)
- ✓ C+N+O variations are possible in clusters with prolonged star formation history (SN Ia delayed?)
- ✓ C+N+O increase "may" be associated with small iron increase (non destructive effect of the first few Sn Ia?)

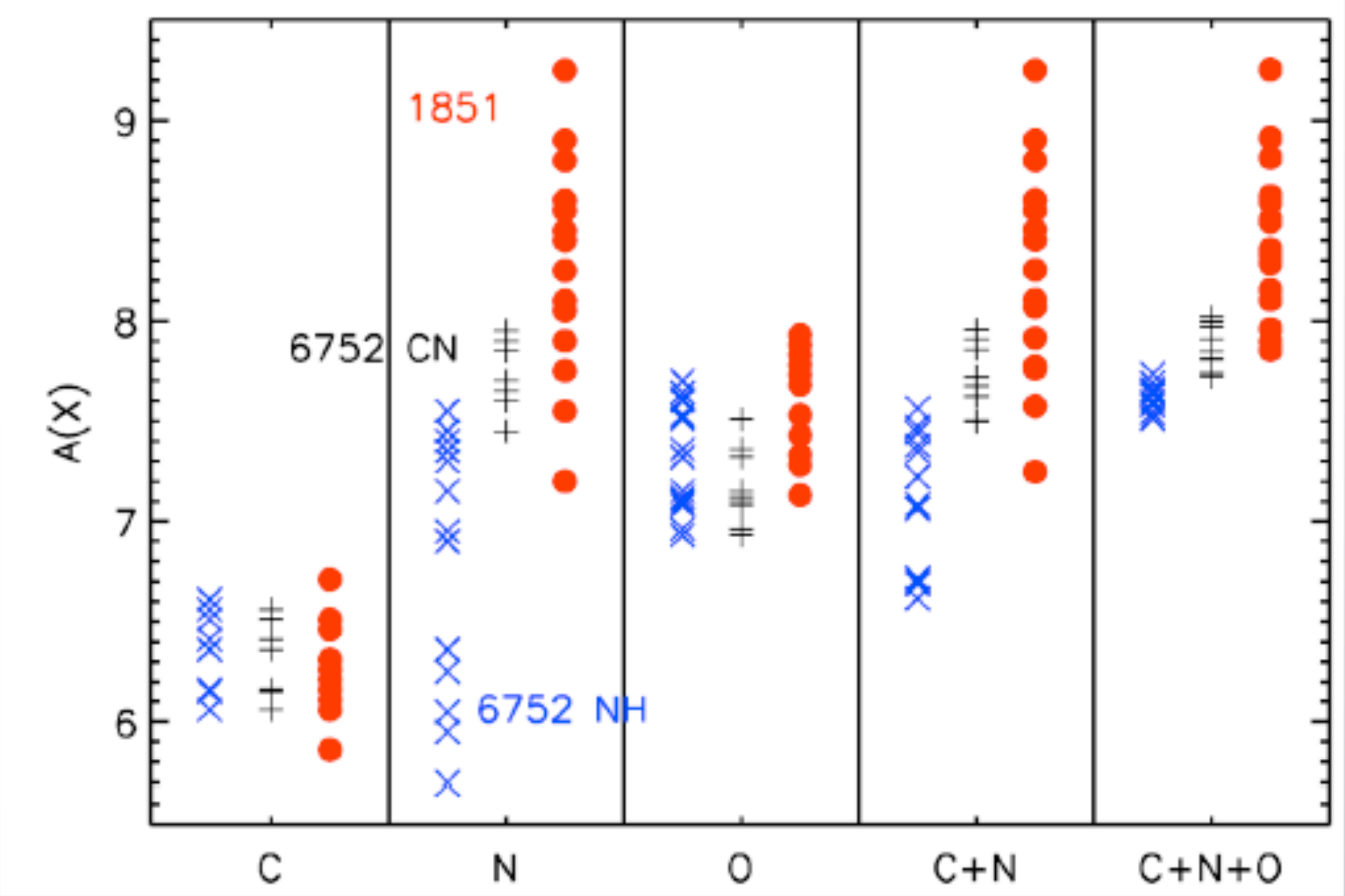


the "standard" model predicts small effect of 3rd Dredge Up until an age of 80-100 Myr

if star formation goes on, the effect of 3rdDU will be seen in total CNO ↑ and s-process ↑

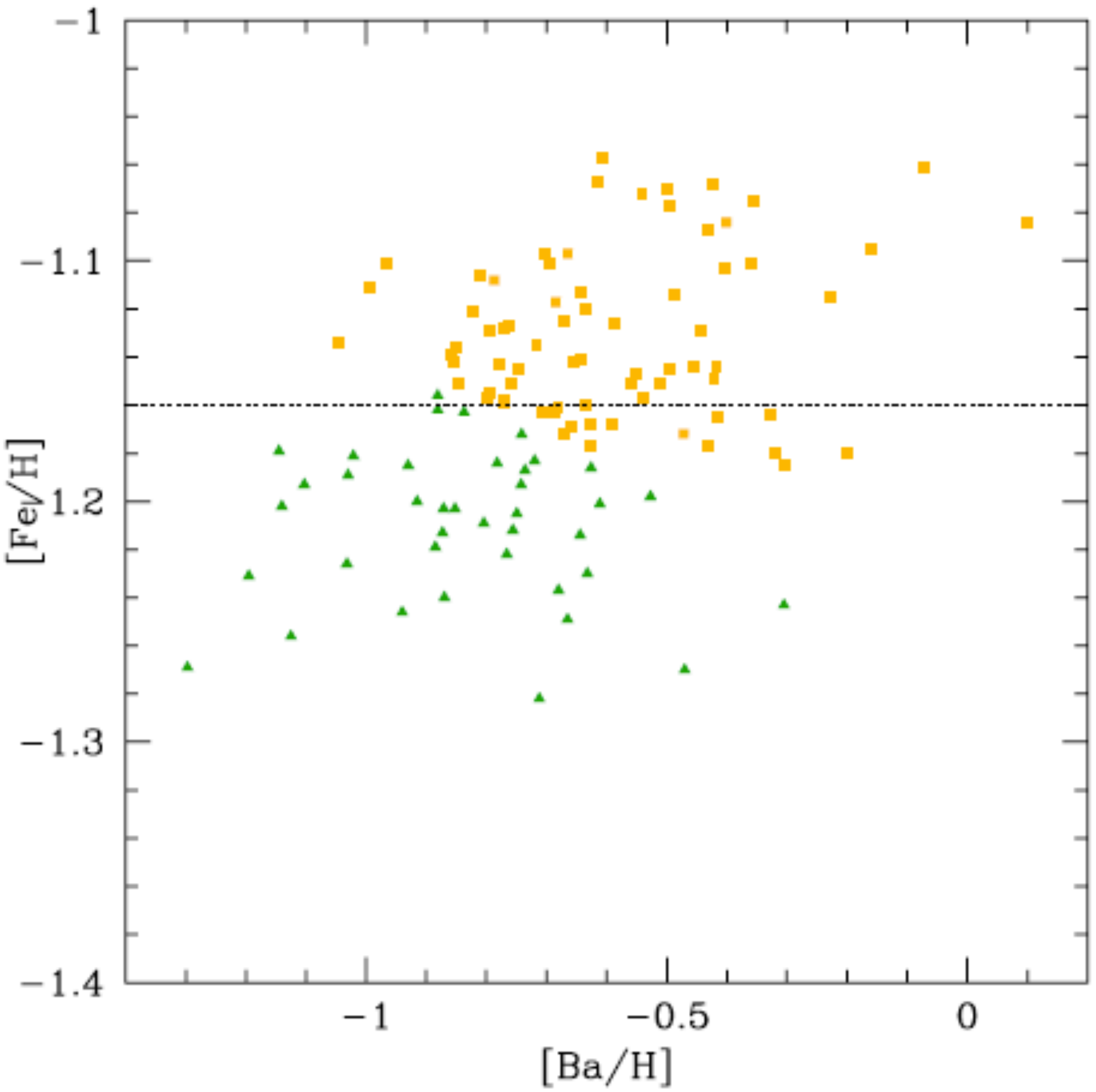
SN Ia begin to explode at ages 50-100Myr …

NGC 1851 vs. 6752: C+N+O

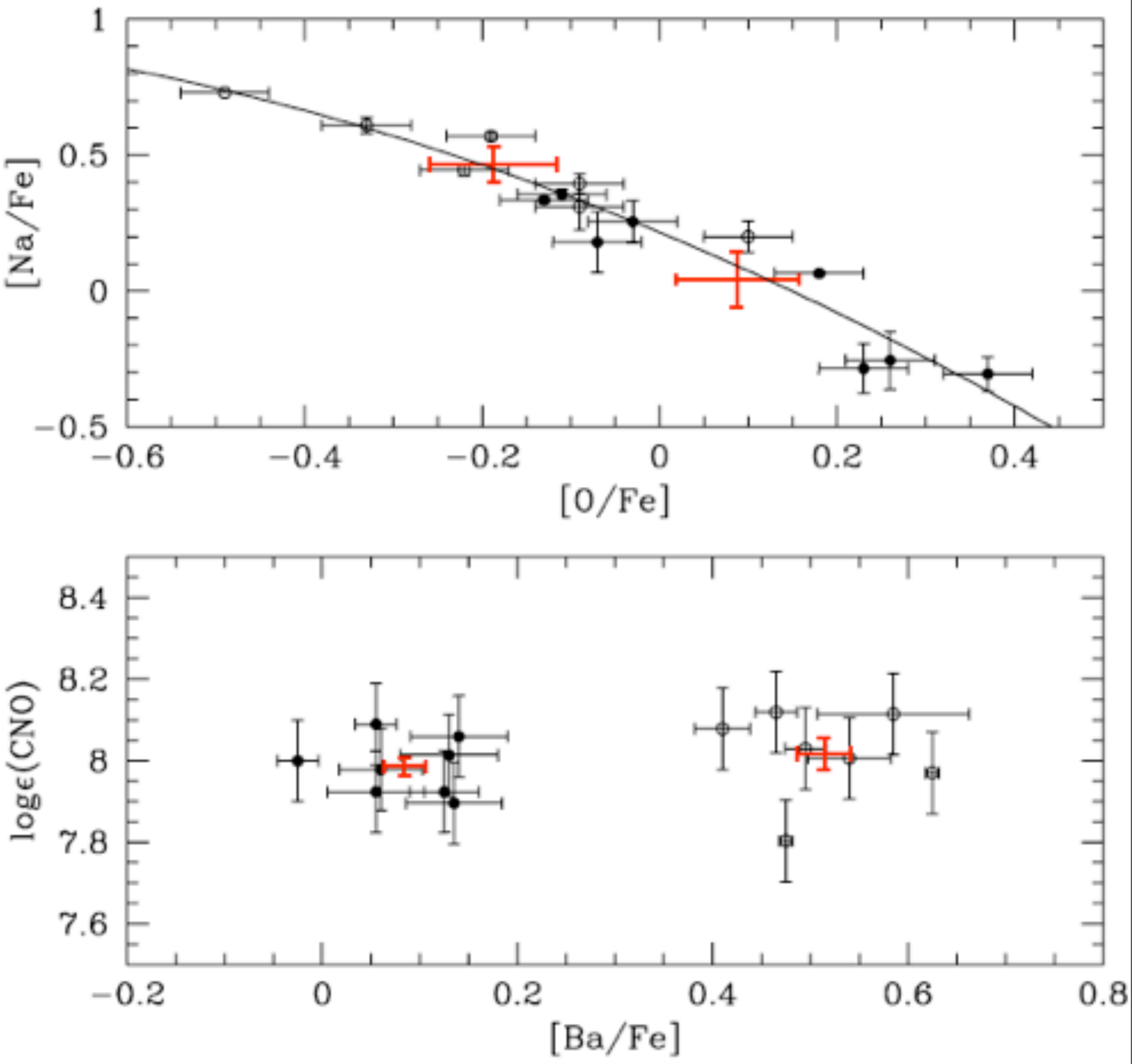


CLEAR DIFFERENCES IN CNO CONTENT

NGC 1851: Ba vs. CNO, and Ba vs Fe!



Carretta+ 2011



Villanova+ 2010

It is possible that, for peculiarities of some clusters, SG star formation goes on with the (diluted) ejecta of AGBs in which the 3rd Dredge Up effect is seen both in the C+N+O and in the s-process enhancement.

It is plausible that at this epoch the first (isolated) SNIa have already exploded, and were not able to end the cooling flow, but couls slightly enhance the gas metallicity

The initial mass of clusters

- ✓ Yes, we should have $M_{initial} > M_{present}$ ***how much?
- ✓ This applies also to (all?) other models (!)
- ✓ Observations can put constraints!

Quantify M_{in}/M_{now}

- ✓ Factors as large as M_{in}/ M_{now} =100-200 are published
- ✓ Factors below a minimum of 4-6 are untenable for the AGB scenario (in presence of a SG constituting 50%, with dilution not larger than ~70%
- ✓ We "can not" use up more than the ejecta down to ~100Myr (or less): extending to 300Myr + talking about AGB scenario is nonsense
- ✓ Anyway, also talking about a 10% efficiency of star formation, in the context of a cooling flow, does not tell us what happens → matter accumulated is consumed anyway, in a longer time, until deus ex machina stops the event

We now know that the fraction of SG stars is 50-70%!!!

How is it that we see clusters at all?

D'Ercole et al. 2008 show that the survival may be linked to the modalities of formation of the SG (If the SG forms in a cooling flow AFTER the end of the SNII epoch, only the FG stars kinematics "**know**" about the fact that the cluster has lost all the SN II mass: the FG stars will expand out of the tidal radius and be lost, while the SG stars will remain gravitationally bound -and two body encounters will allow some FG stars to remain bound too:
Clusters *need* SG stars to survive (D'Antona & Ventura 2007, D'Antona & Caloi 2009, Conroy 2011)

Dilution with pristine gas is necessary to deal with the anticorrelations. Different environmental conditions are the reason why different patterns O-Na or Na-Al are found in clusters of similar mass and age. Dilution ~**doubles** the mass available for SG formation (for Fornax Clusters, e.g. more than this). How can pristine gas be reaccreted? (*Model requires non spherical symmetry*).

THE BASIS OF D’ERCOLE ET AL. 2008 MODEL

Vesperini, McMillan & Portegies Zwaart (2006, 2009) show that, in a mass-segregated cluster, the effect of early mass loss due to SNII explosions is, in general, more destructive than for an unsegregated cluster with the same density profile, and leads to shorter cluster lifetimes

This, plus also the additional mass loss due to gas expulsion (Baumgardt & Kroupa 2007), by massive stars and triggered by the SN explosions

----> Most clusters should not survive!

THE BASIS OF D'ERCOLE ET AL. 2008 MODEL

Vesperini, McMillan & Portegies Zwaart (2006, 2009) show that, in a mass-segregated cluster, the effect of early mass loss due to SNII explosions is, in general, more destructive than for an unsegregated cluster with the same density profile, and leads to shorter cluster lifetimes

This, plus also the additional mass loss due to gas expulsion (Baumgardt & Kroupa 2007), by massive stars and triggered by the SN explosions

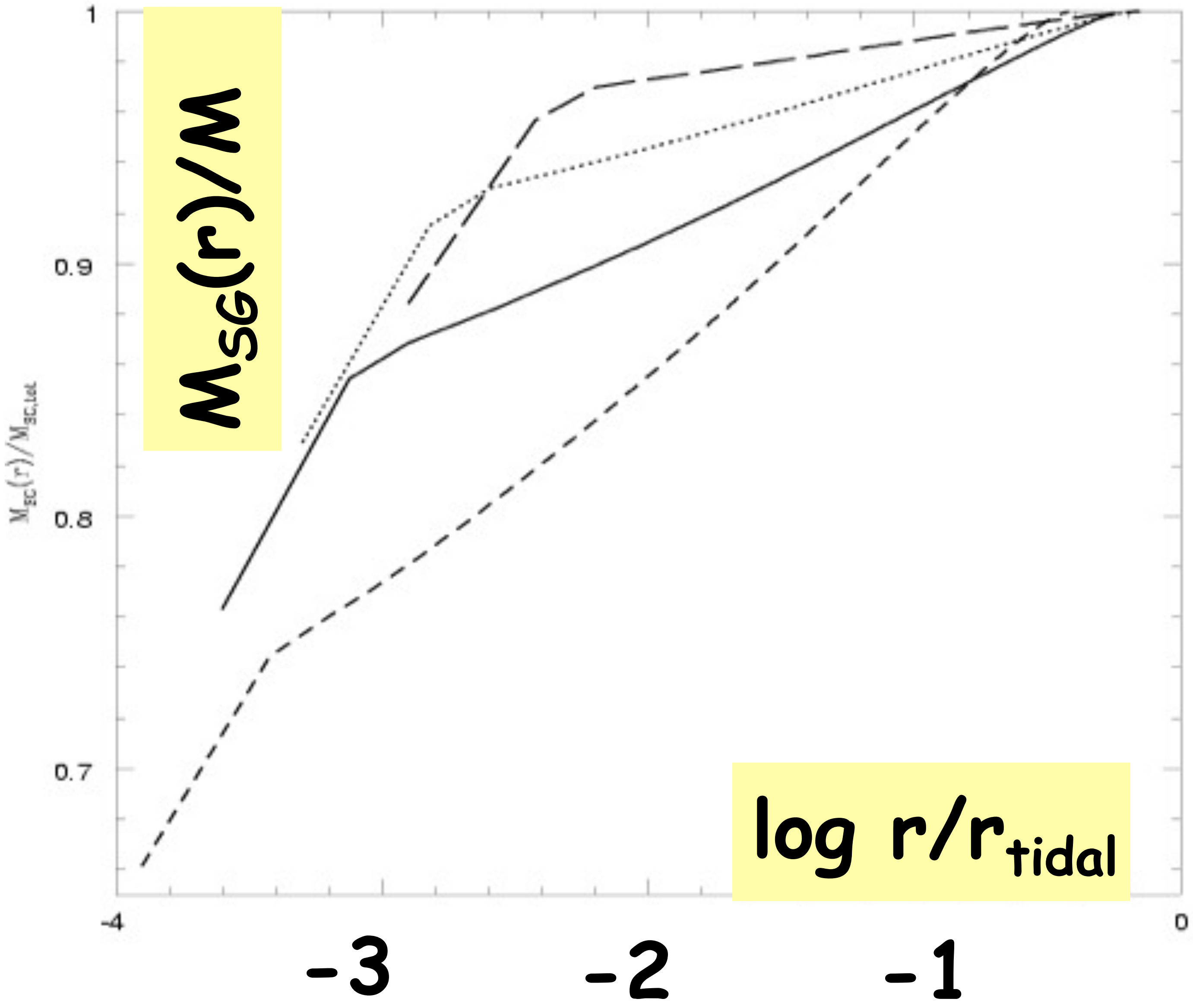
----> Most clusters should not survive!

But what if, when the FG stars begin expanding, the winds of the now evolving stars (super-AGBs, followed by massive AGBs) collect in the core and form a second generation? These new stars do not take part –initially- in the cluster expansion.

a complete (hydrodynamical+N-body) model...

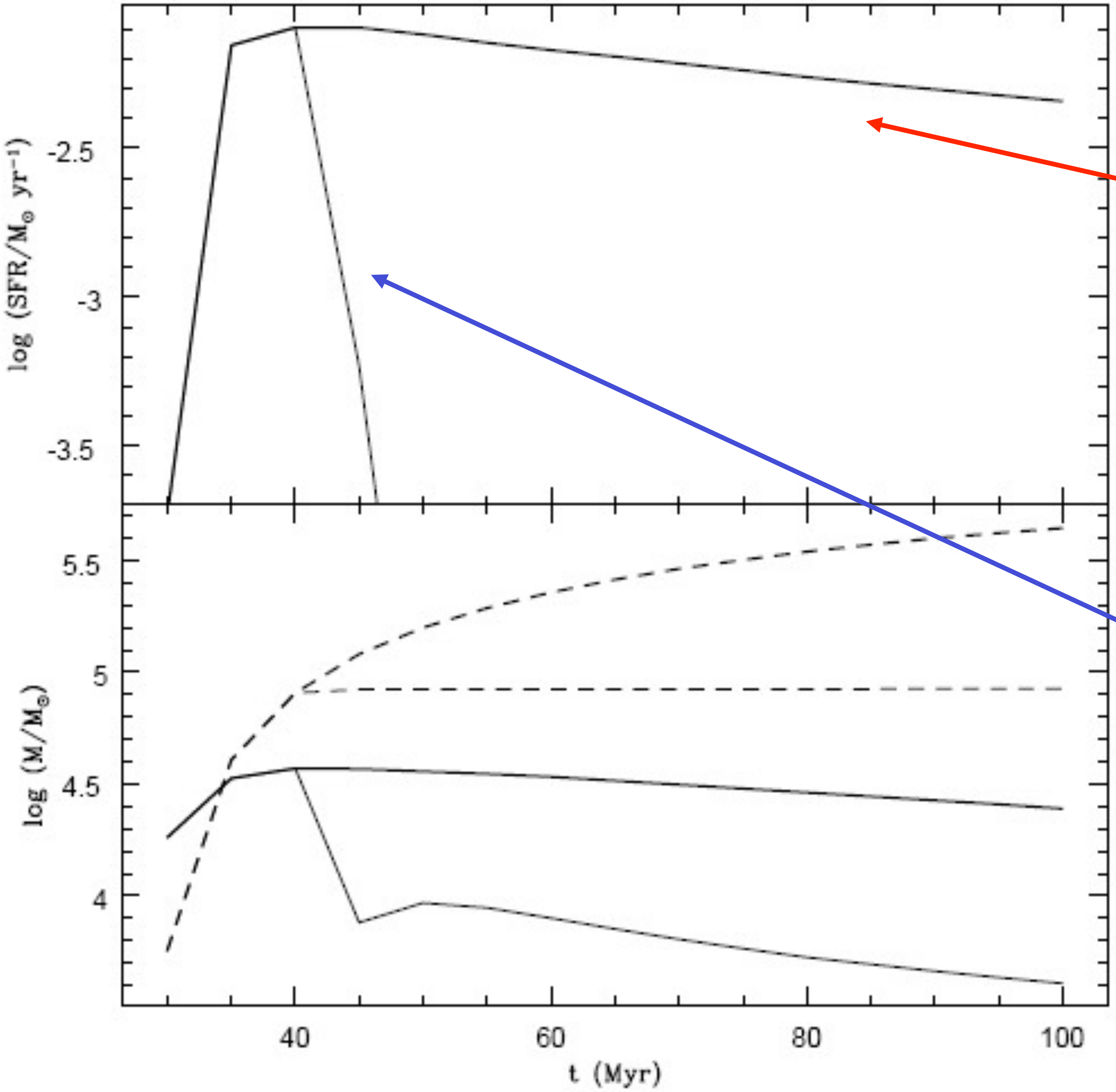
Formation and Dynamical Evolution of Multiple Stellar Generations in Globular Clusters

D'Ercole+ 2008



1) HYDRODYNAMICAL SIMULATIONS:
a cooling flow is established as soon as the SNII phase ends, and the SG star formation occurs mainly in the inner core, largely independent of the FG structural properties. The flow forms even if the FG star system if expanding

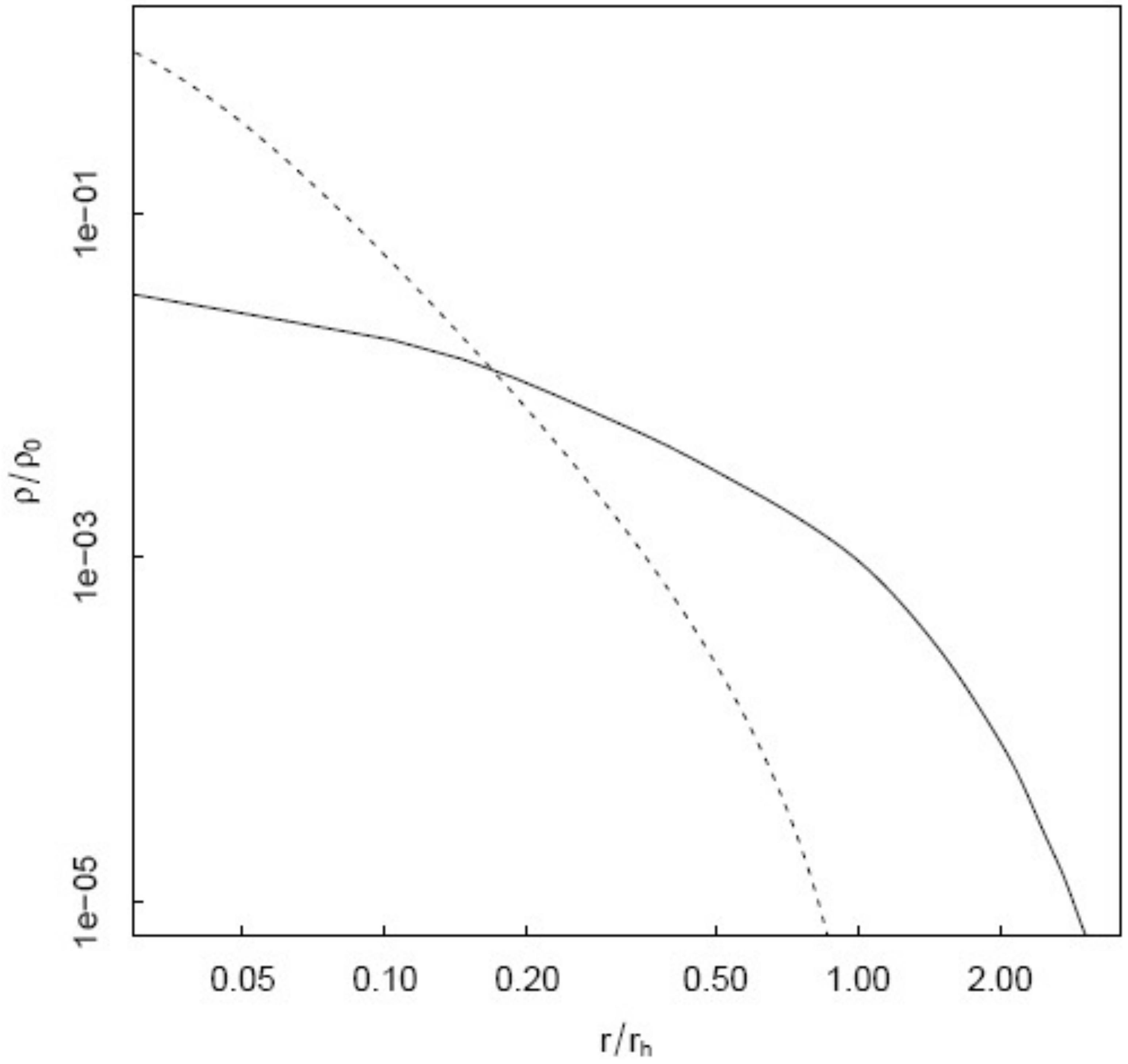
the SG formation ends when SN Ia begin exploding in the cluster. Here we assume that the SNIa epoch begins at 40Myr



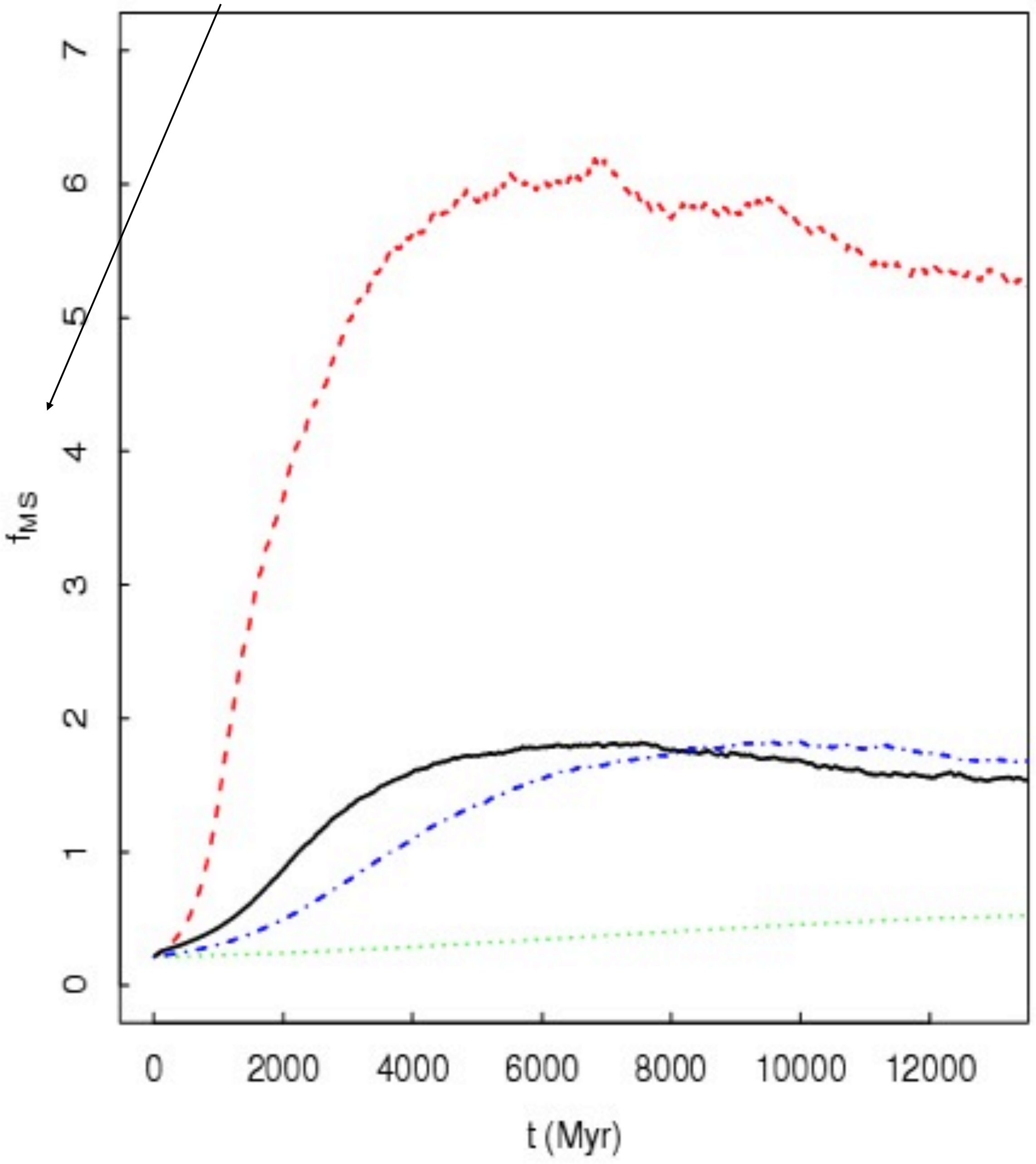
SF goes on, if no energy sources perturb the cooling flow

SF stops due to the cumulative effect of SNIa, the rate is taken to be 1 every 50000yr

each unique SN does not affect the cooling flow the SG is strongly concentrated in the core. But the two populations will interact and evolve dynamically



Dynamical evolution of the two populations


number ratio of SG to FG stars

2) N-BODY SIMULATIONS: starting with two populations differing in concentration

the FG expands, in response to the dynamical heating from the loss of the SNII ejecta. As the cluster expands beyond the tidal radius, its outer parts, largely populated by FG stars, are stripped.

number ratio SG/FG consistent with observational values (~0.5-1.5). Some models produce SG-dominated clusters. The ratio stops increasing when the FG and SG are dynamically mixed.

If the model makes sense, read the consequences

✓ the SG, with its smaller velocity dispersion, allows a part of the FG stars to remain gravitationally bound

✓the mass remaining locked in clusters is 1/10 of the INITIAL cluster mass

✓the other stars –mostly FG- populate the halo: the halo is in part formed by FG stars belonging to clusters (consistent with their "normal" chemistry) ---Vesperini et al. 2010: upper limit to halo SG: ~4%

If the model makes sense, read the consequences

✓ the SG, with its smaller velocity dispersion, allows a part of the FG stars to remain gravitationally bound

✓the mass remaining locked in clusters is 1/10 of the INITIAL cluster mass

✓the other stars –mostly FG- populate the halo: the halo is in part formed by FG stars belonging to clusters (consistent with their "normal" chemistry) ---Vesperini et al. 2010: upper limit to halo SG: ~4%

~~GCs are SSPs~~ →

If the model makes sense, read the consequences

✓ the SG, with its smaller velocity dispersion, allows a part of the FG stars to remain gravitationally bound

✓the mass remaining locked in clusters is 1/10 of the INITIAL cluster mass

✓the other stars –mostly FG- populate the halo: the halo is in part formed by FG stars belonging to clusters (consistent with their "normal" chemistry) ---Vesperini et al. 2010: upper limit to halo SG: ~4%

~~GCs are SSPs~~ →

GCs are the systems in which we see the O-Na anticorrelation (Gratton, Jan 2009)

If the model makes sense, read the consequences

✓ the SG, with its smaller velocity dispersion, allows a part of the FG stars to remain gravitationally bound

✓the mass remaining locked in clusters is 1/10 of the INITIAL cluster mass

✓the other stars –mostly FG- populate the halo: the halo is in part formed by FG stars belonging to clusters (consistent with their "normal" chemistry) ---Vesperini et al. 2010: upper limit to halo SG: ~4%

~~GCs are SSPs~~

→

GCs are the systems in which we see the O-Na anticorrelation (Gratton, Jan 2009)

→

GCs survive thanks to the SG

Where are single-generation clusters?

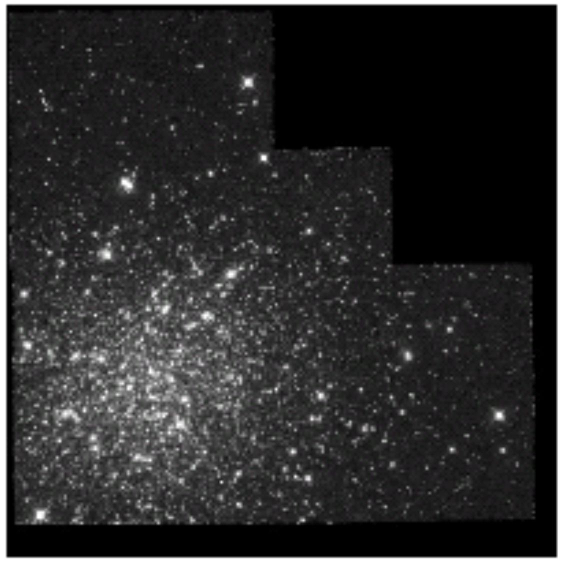
✓ If the cluster IS NOT tidally limited, it may expand into its tidal radius without losing mass! (Vesperini et al. 2009). If the massive stars were initially segregated, it will expand, and have lower core density

✓ its SG will be only a small fraction (few – up to 10 %) of the total mass (closed box evolution!) AND will be mostly concentrated in the core (due to the long relaxation time of the expanded core)

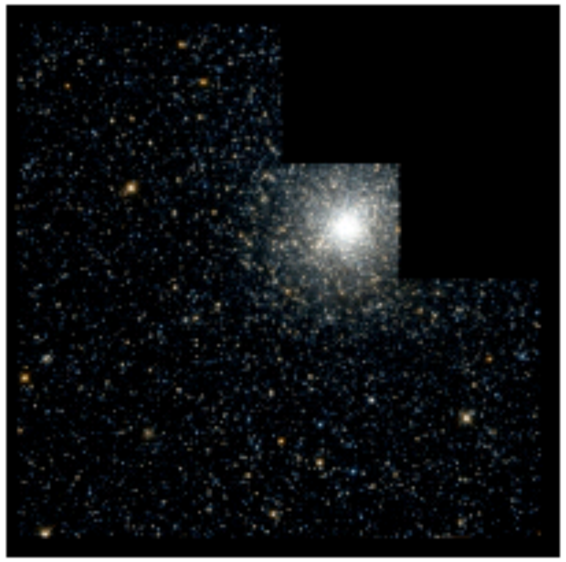
✓ somewhere there "should" be SSP GCs!

ALL young clusters have small core radii. Old clusters may be either core-collapsed or very diffuse! (figures from Davies 2008)

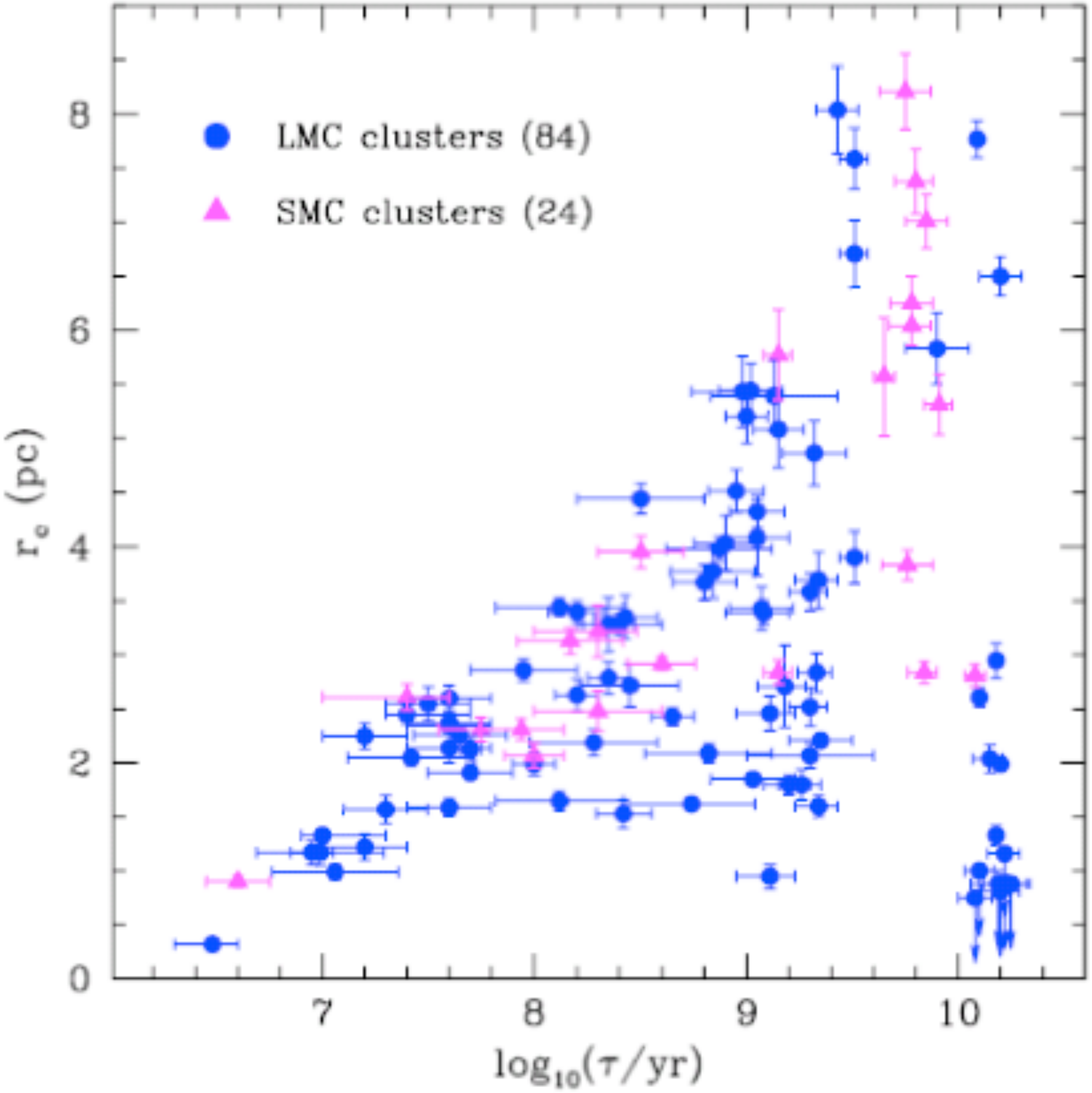
NGC1841 (old/diffuse)



NGC 1818 (young/compact)

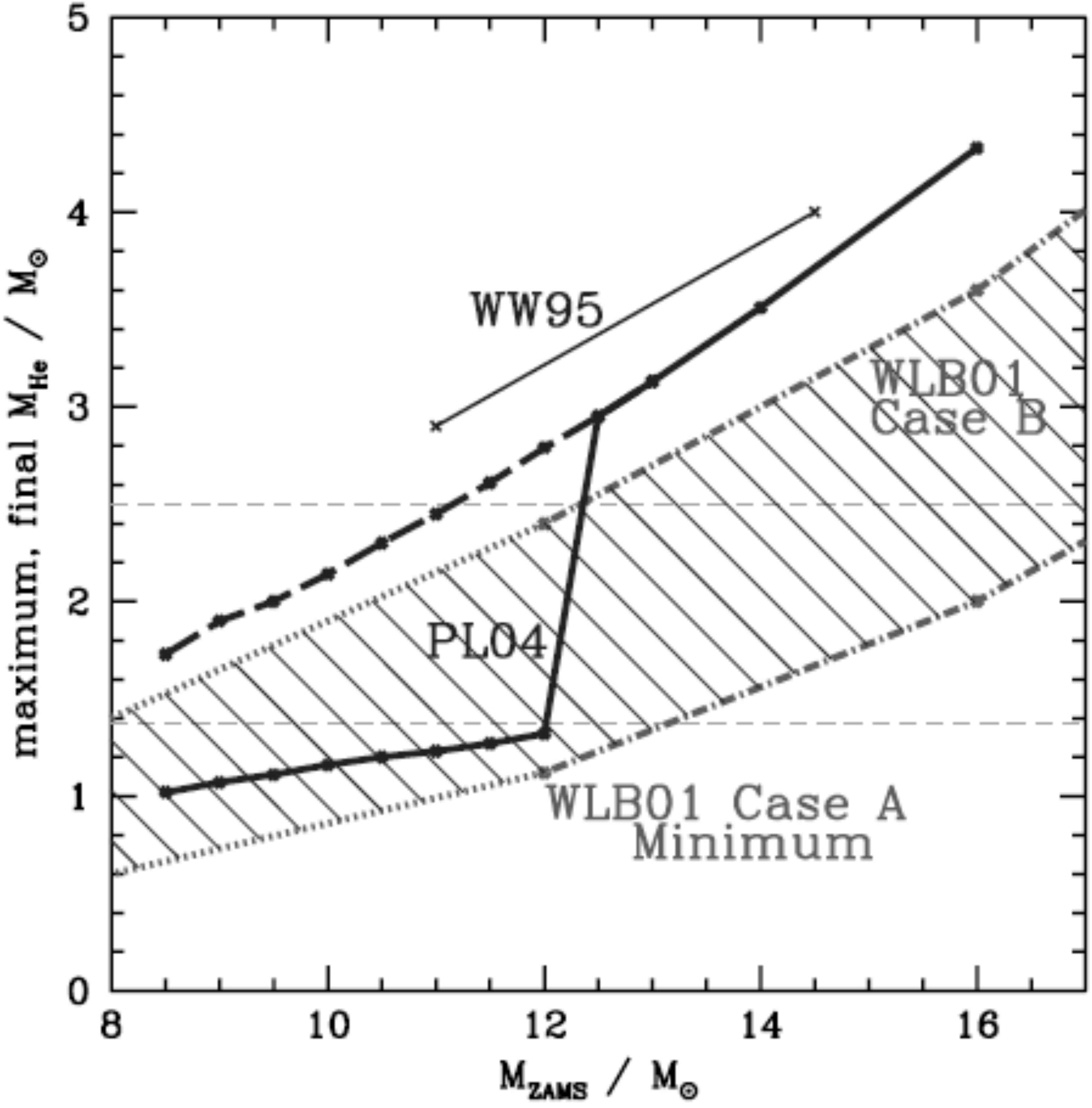


NGC 1916 (old/compact)



long literature on core expansion at later times (location, mass loss, heating from binaries, BHs, finally Richer's WD kicks)

Mackey & Gilmore 2003


maximum, final M_{He} / $M_\odot$
M_{ZAMS} / $M_\odot$
0
1
2
3
4
5
8
10
12
14
16
WW95
WLB01
Case B
PL04
WLB01 Case A
Minimum