Multiple populations in Globular Clusters: the role of AGB and super-AGB stars

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thanks to my coworkers

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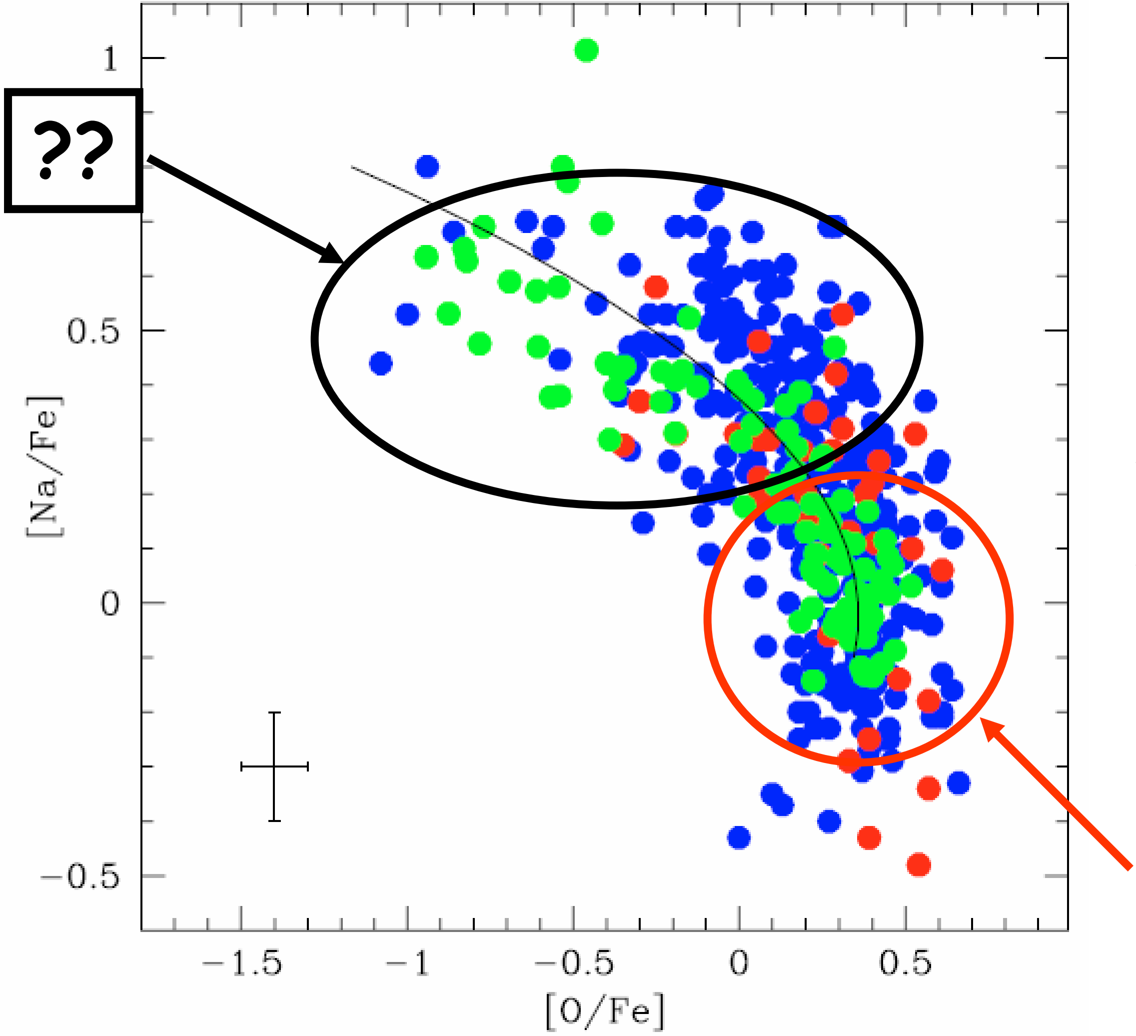
Presented by **R. Gratton** at the KITP Conference **‘Formation and Evolution of Globular Clusters’** meeting, Jan. 12-17, 2009, Santa Barbara

Hot CNO: O depletion and Na formation



Carretta et al. 2006 A&A 450, 523

Global Na-O anticorrelation (solid black line) superimposed on a collection of stars in about 20 globular clusters. Blue points are RGB stars from literature studies; red points are scarcely evolved stars (turnoff or subgiant stars) from Gratton et al. (2001) and Carretta et al. (2004); green points are RGB stars in NGC 2808 from the present study.

this is the range of abundances in low metallicity field stars

OUTLINE

1. The AGB –super-AGB model for the chemistry of “anomalous” stars in GCs

I concentrate on * Oxygen and Sodium and * Helium

*** DILUTION IS NECESSARY! BUT NO DILUTION EXPLAINS NICELY THE VERY HIGH HELIUM BLUE-MS

2. The IMF and dynamical problem

- evidence for a high percentage of anomalous stars
- super-AGBs and AGBs as appropriate candidates in a dynamical model

A summary of the problem

Any good model for GC formation must explain:

1) constant 'metallicity' for all the stars
**Gratton et al. ARAA → no spread >~0.04dex;

2) 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)

3) photometric direct (MS splitting) or indirect (Horizontal Branch morphology) evidence for helium enhancement in SG stars

4) the very high percentage (30-100%) of SG!!!

The “model”: after a first generation (FG) is born, a second star formation event, based on matter processed within FG stars (same Z!) gives origin to the chemically anomalous SG stars.

Are AGBs and super-AGBs good candidates for what concerns the site of nucleosynthesis?

1. constant Z → OK
2. Hot CNO products (O depleted, Na enhanced…) → OK
3. No (scarce?) He-burning products (constant or slightly varied C+N+O) ???

(no time to discuss, but slides available → OK)

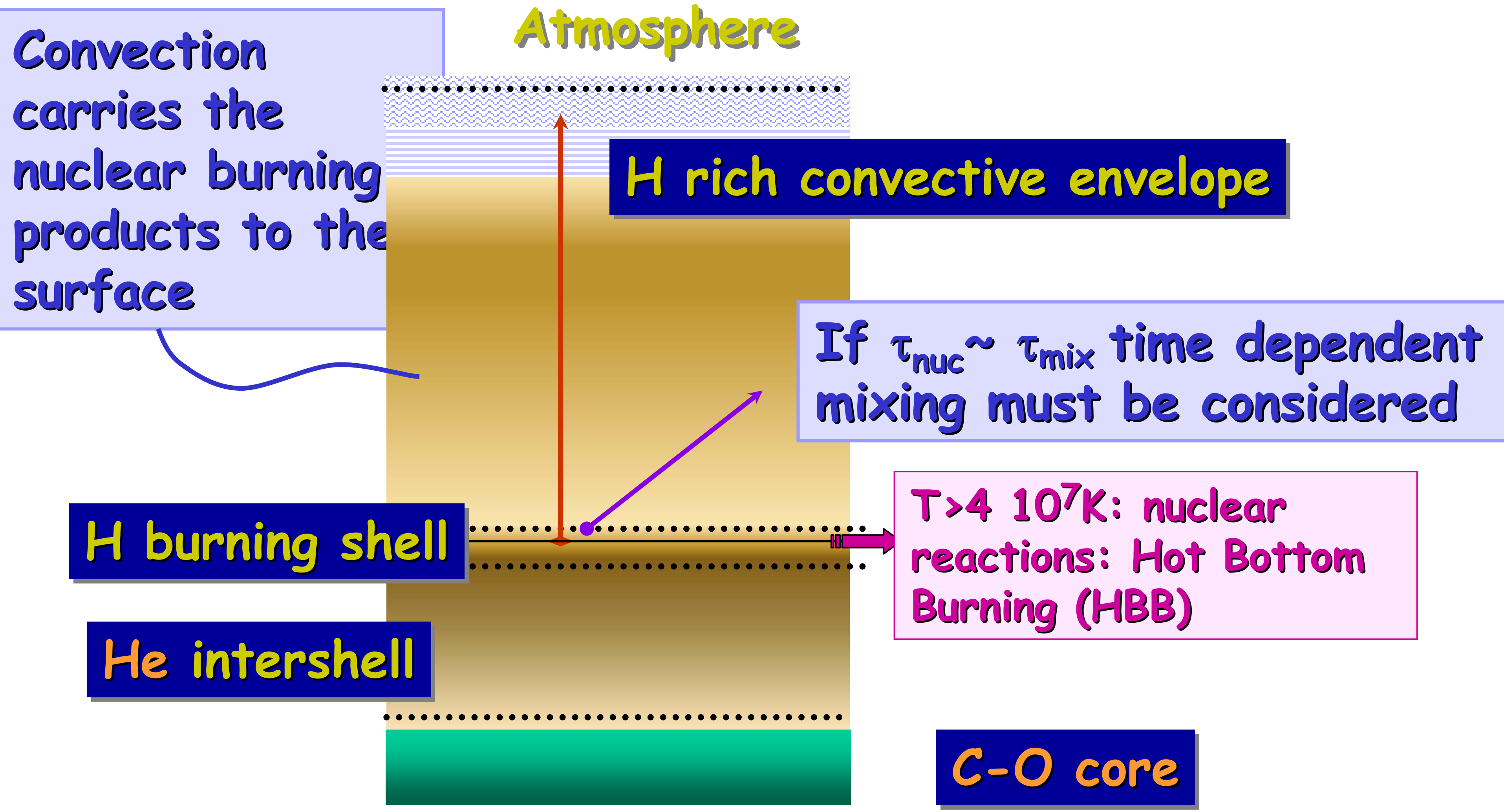
massive AGBs

Can we build AGB models whose ejecta show the "right" chemical composition (i.e. He-rich, Al,Na enhanced, Mg,F and O depleted, ~ constant C+N+O) ??

no!, according to several recent investigations
Problems are (were):

* can we get enough O depletion?
* there should be an overproduction of CNO and Na, or Na burning concomitant to O depletion
* can we get extreme He abundances in AGBs?

massive AGBs



Atmosphere

H rich convective envelope

Convection carries the nuclear burning products to the surface

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

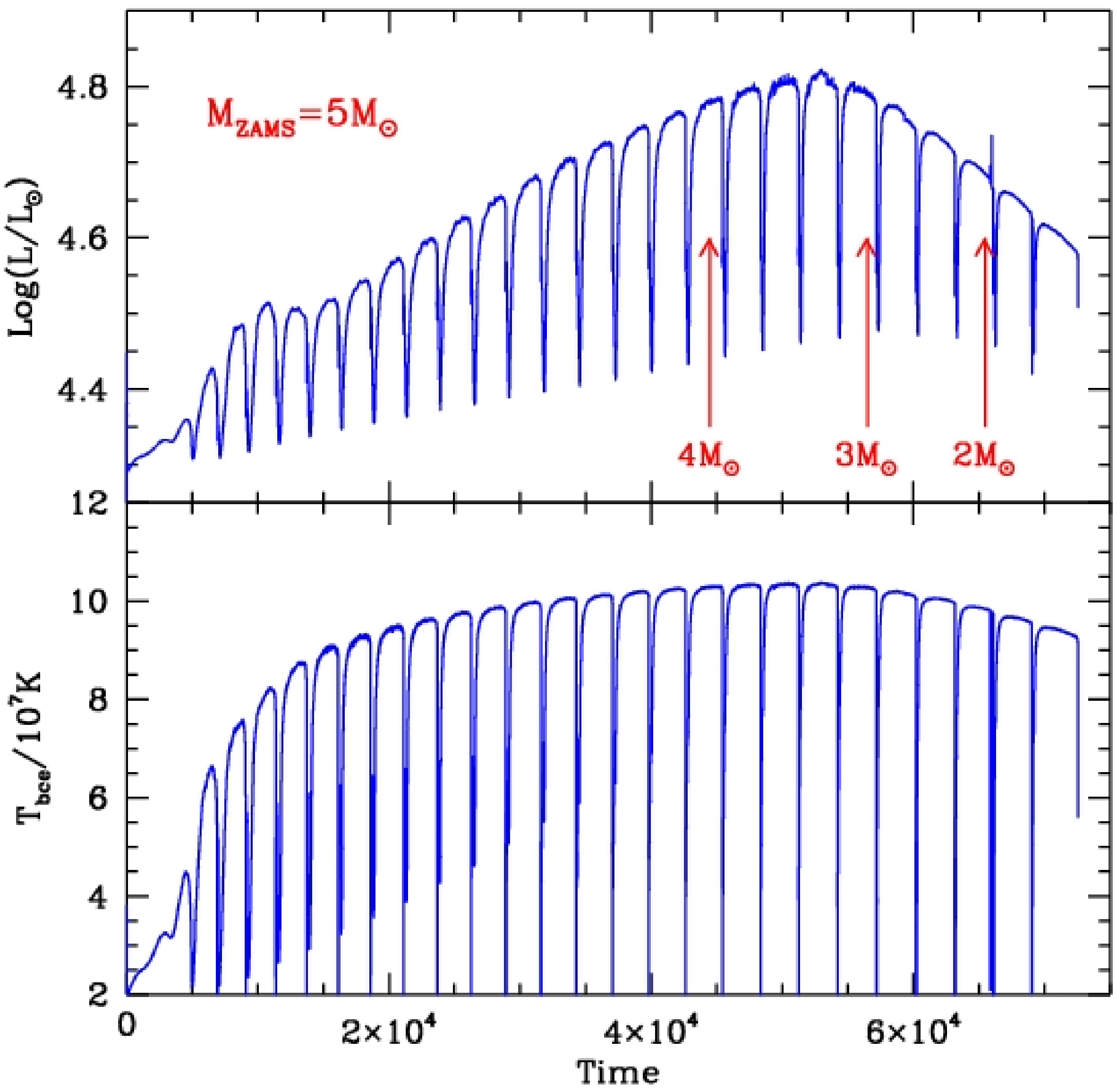
H burning shell

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

He intershell

C-O core

The AGB phase goes on: 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



Hot Bottom Burning

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

$T > 4 \times 10^{7}$ K

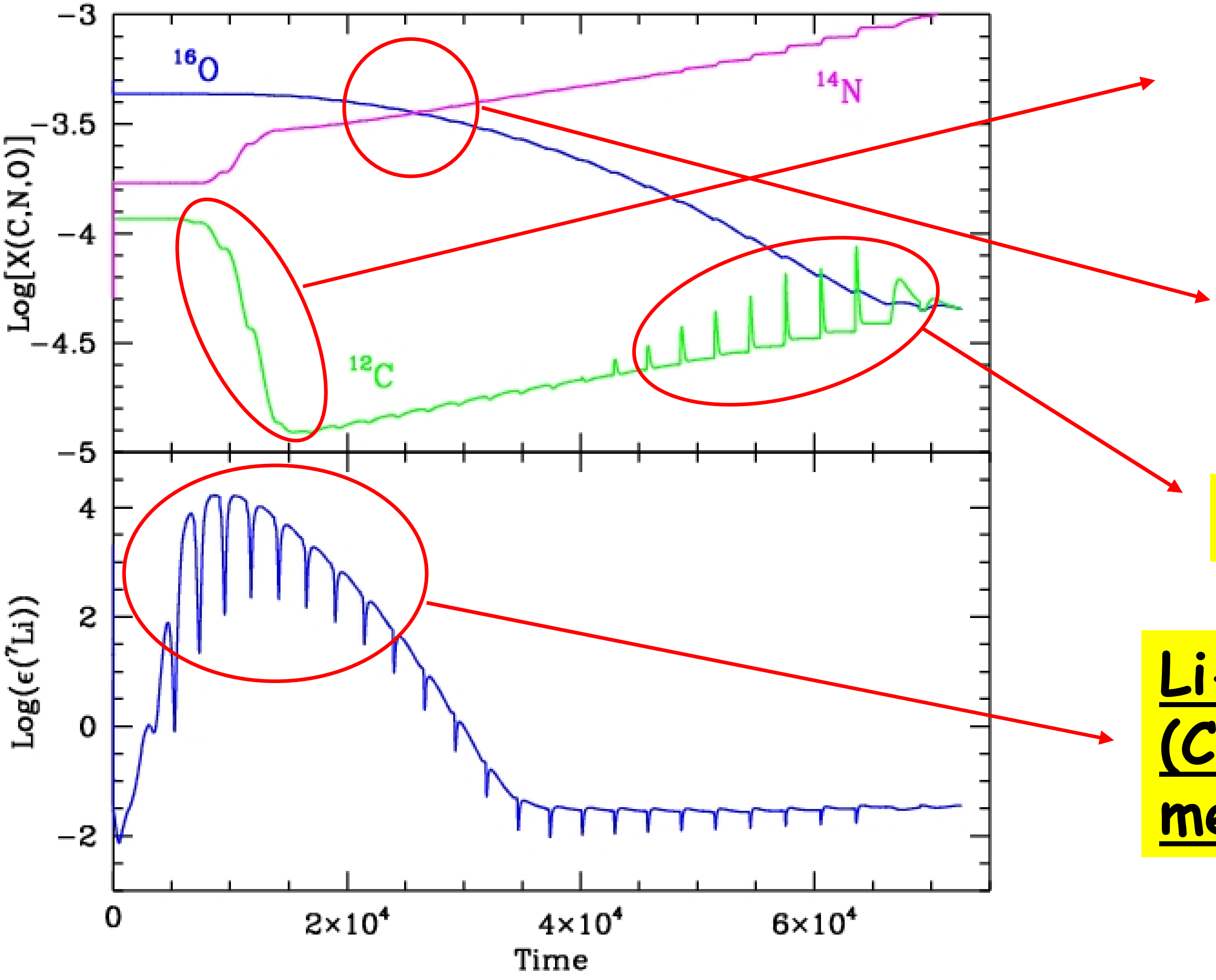
$^{12}C \rightarrow ^{14}N$

$T > 6.5 \times 10^{7}$ K

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

$T > 8 \times 10^{7}$ K

Changes of the surface chemistry



CN burning

ON cycle

III dredge-up

Li-rich phase
(Cameron-Fowler
mechanism)

Summary

- ✓ During most of the AGB evolution the only active nuclear source is the CNO burning shell
- ✓ Periodically, 3α burning is activated in thermally unstable conditions
- ✓ The bottom of the convective envelope becomes hotter and hotter, until mass loss reduces significantly the mass of the envelope

Two possibilities for changing the surface chemistry

Hot Bottom Burning ($M>4M_{sun}$)

3rd dredge-up

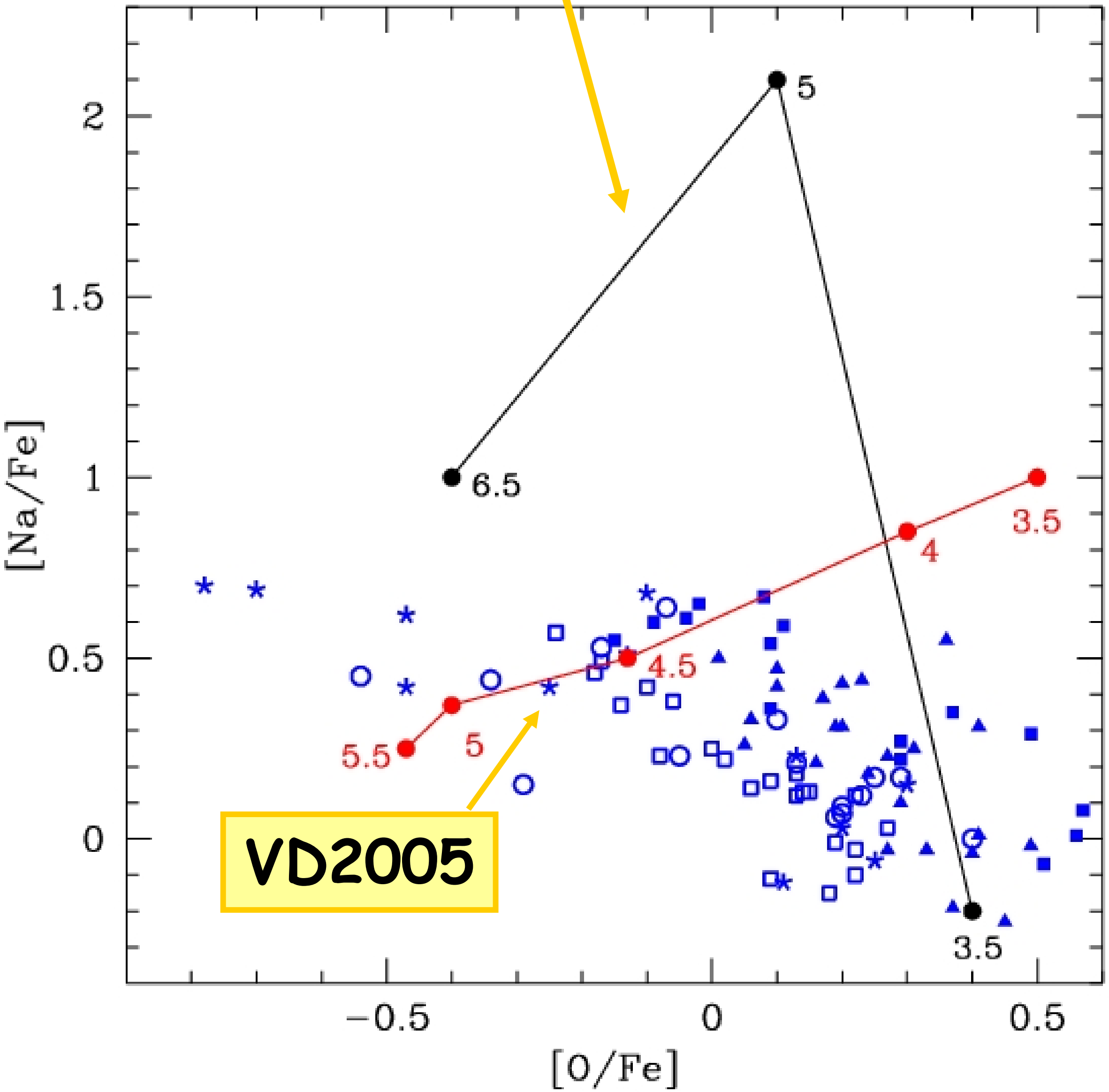
Results are model dependent

✓ Not all models achieve the same T_{HBB} for the same mass, chemistry and evolutionary stage: this mostly depend on convection efficiency. High efficiency of convection provides more intense HBB, higher L and mass loss rate, faster evolution and smaller influence of 3rd dredge up (Ventura & D'Antona 2005)

This justifies the difference in the yields of different models (e.g. Karakas & Lattanzio vs. Ventura)

✓ Inability to provide a good chemical evolution model may depend –first of all– on the inability of some evolutionary models to provide yields in the range required by observations →

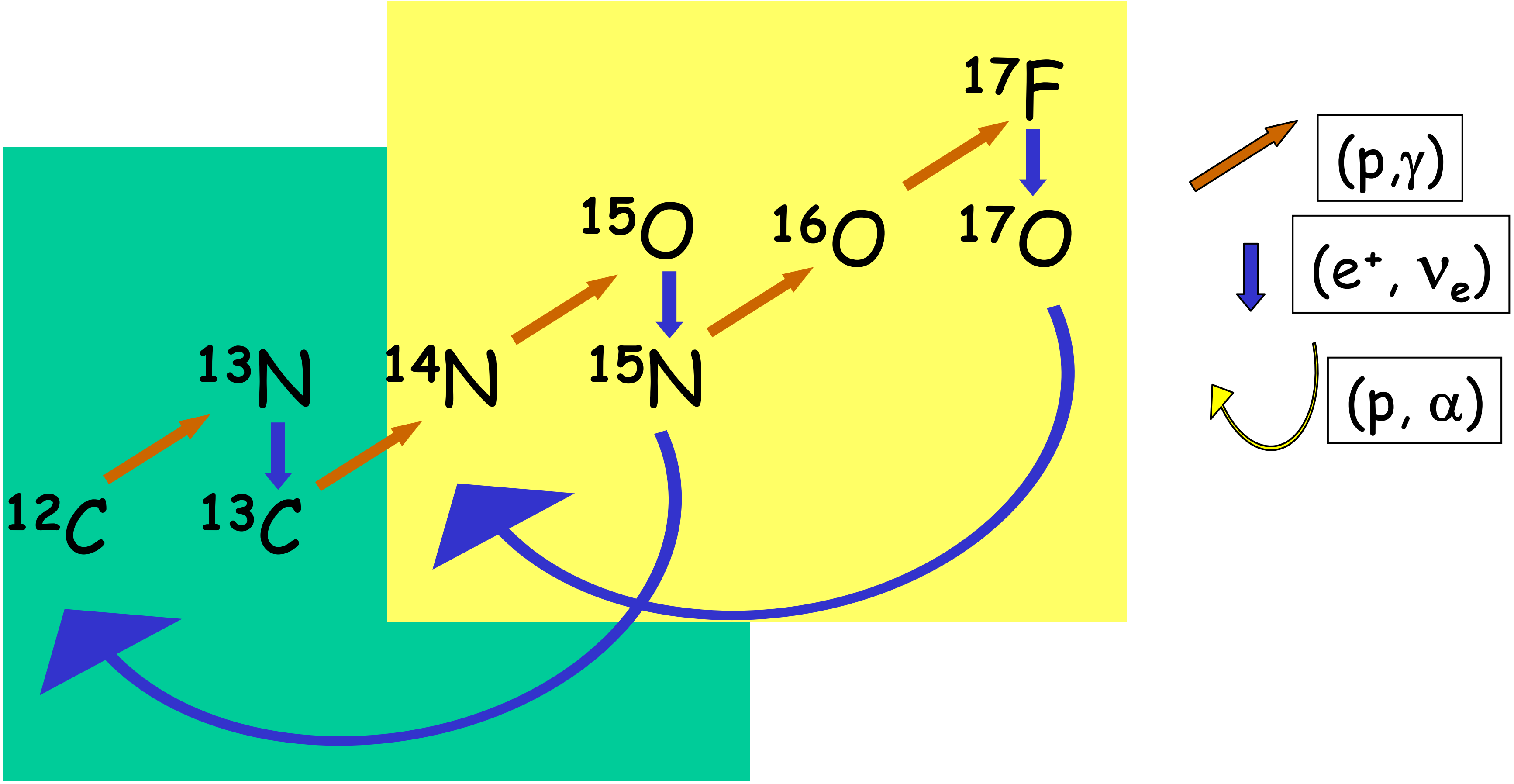
Fenner et al. 2004 (Karakas & Lattanzio 07)



VD2005

HBB nucleosynthesis depends a lot on the convection model adopted: low efficiency: lower T_{bce}, smaller O depletion; lower L: smaller mass loss rate, larger number of 3rd dredge up episodes → Ne22 (from primary N14!) is dredged up and enhances the Na23 production

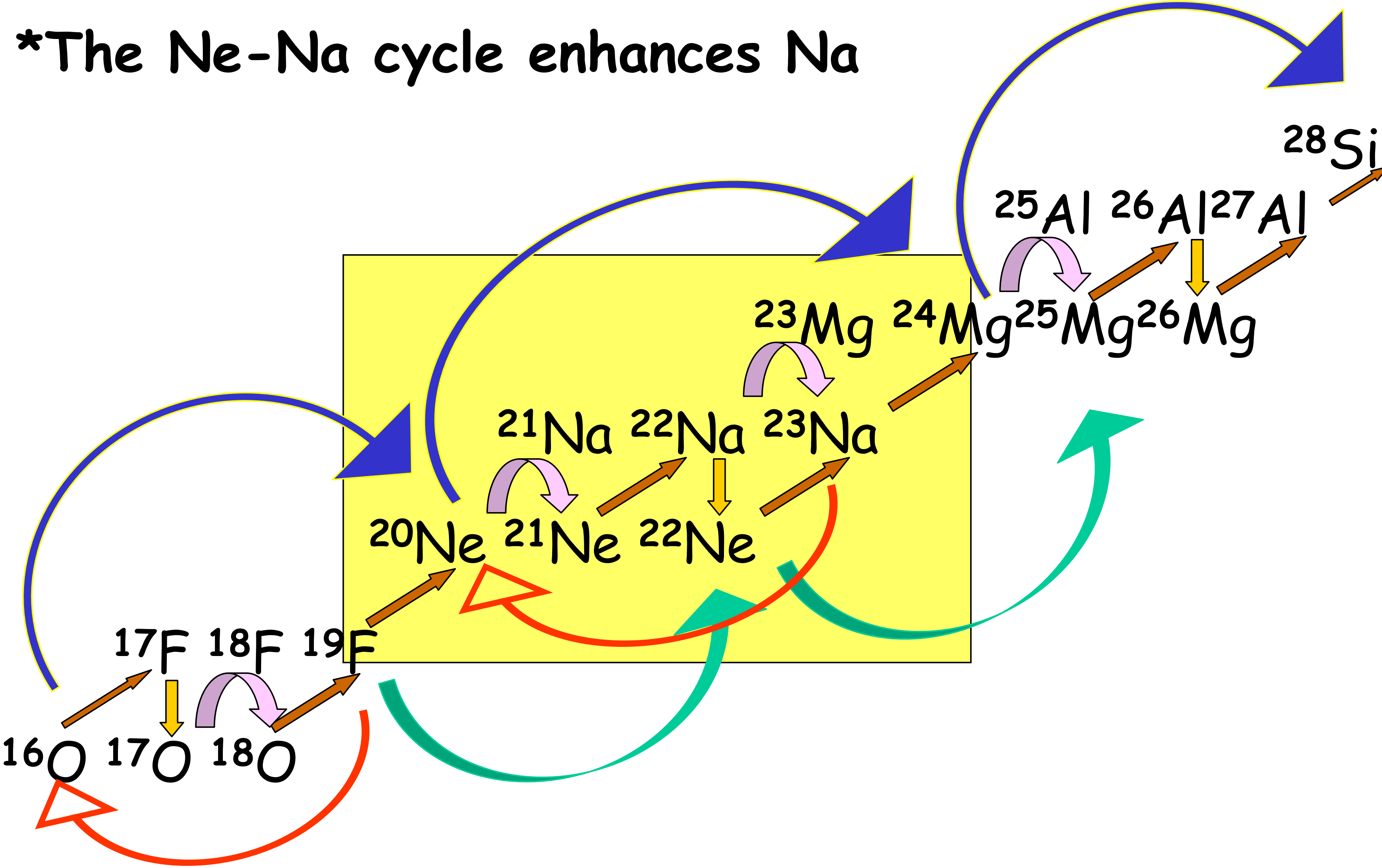
*The ON cycle is the way of reducing O → high T



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

Na high in stars having low O

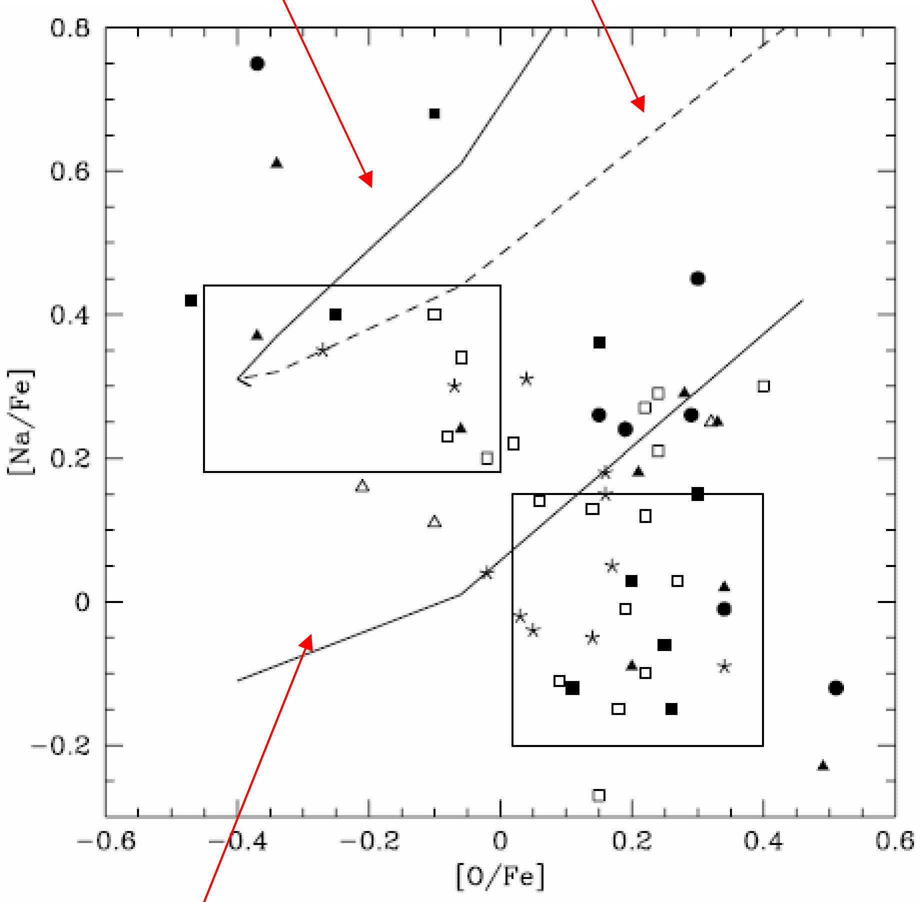
*The Ne-Na cycle enhances Na



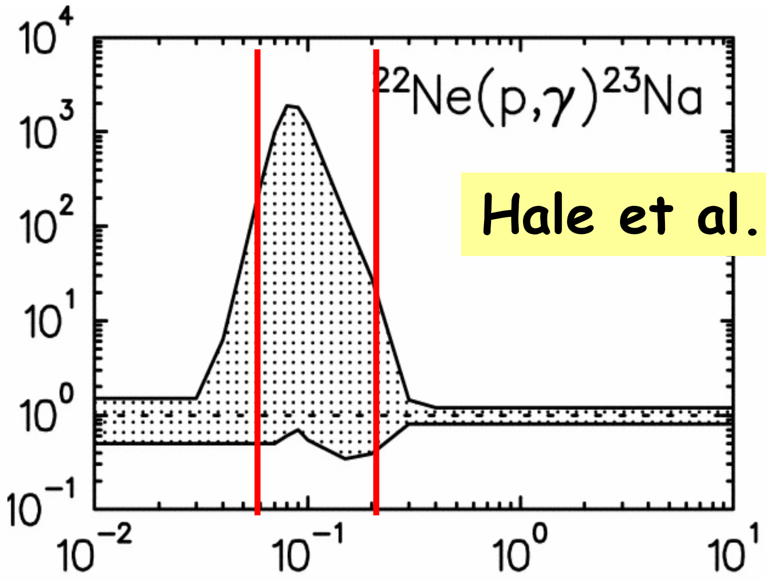
But ^{23}Na production depends on very uncertain cross sections

maximized

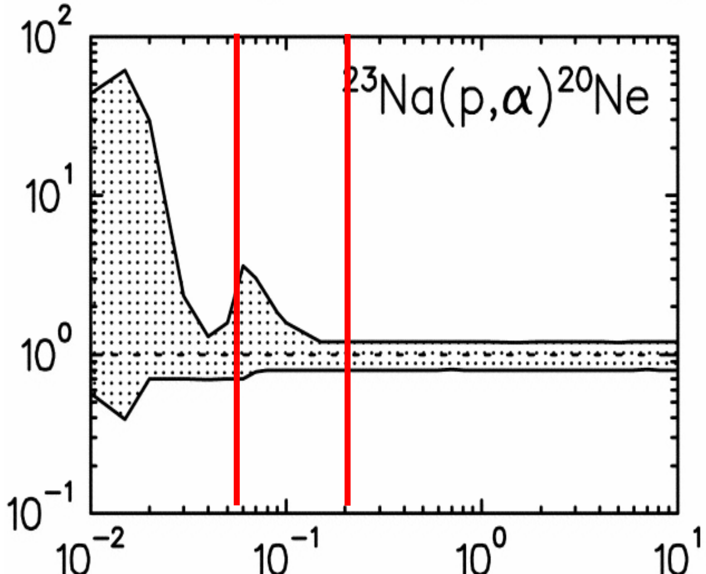
higher Ne22(α,γ)



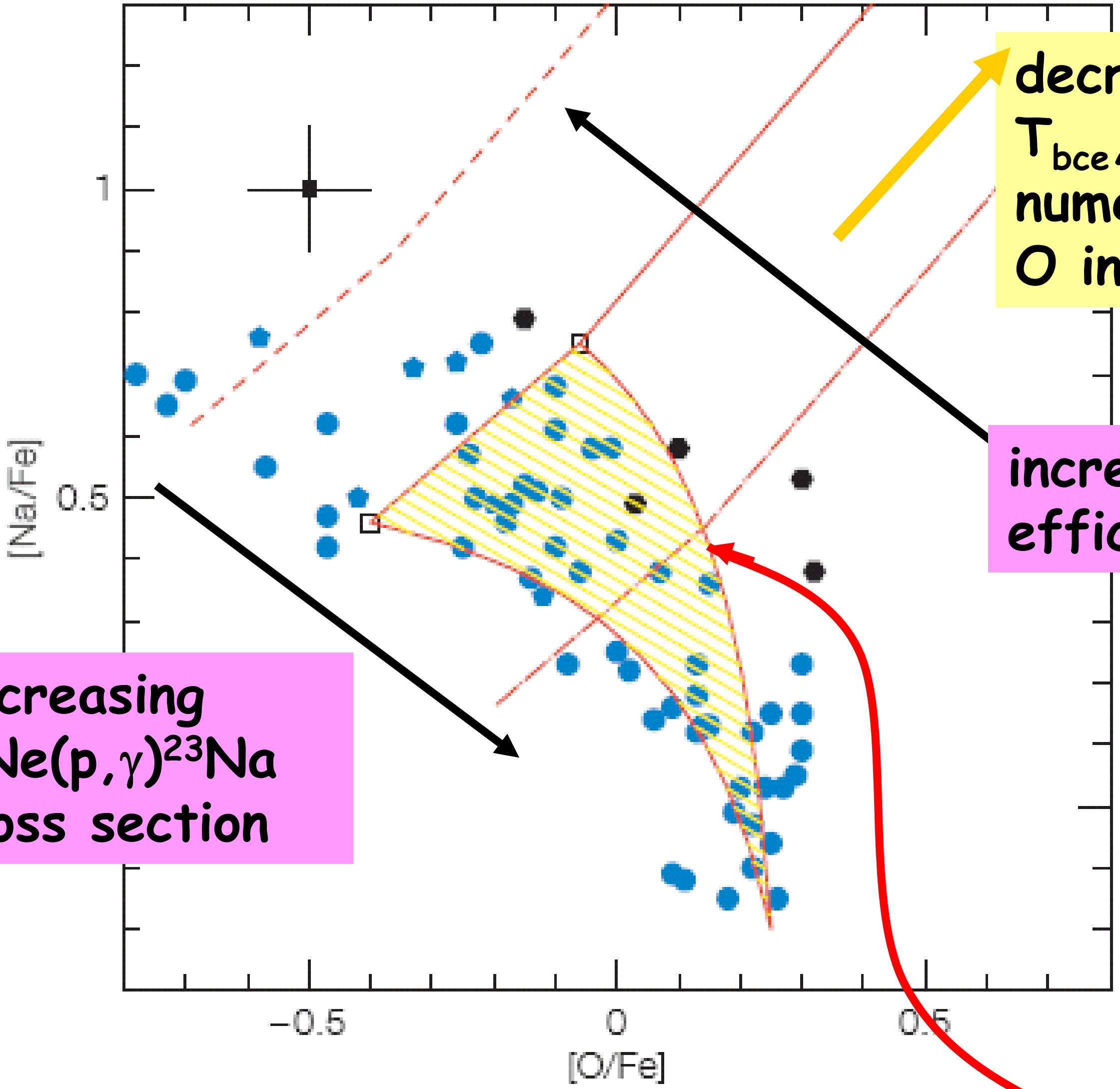
recommended



Hale et al. 2002



Schematically… Na- O yield variation



decreasing mass: lower T_{bce}, lower L, more numerous 3rd DUs, Na and O increase

increasing convection efficiency

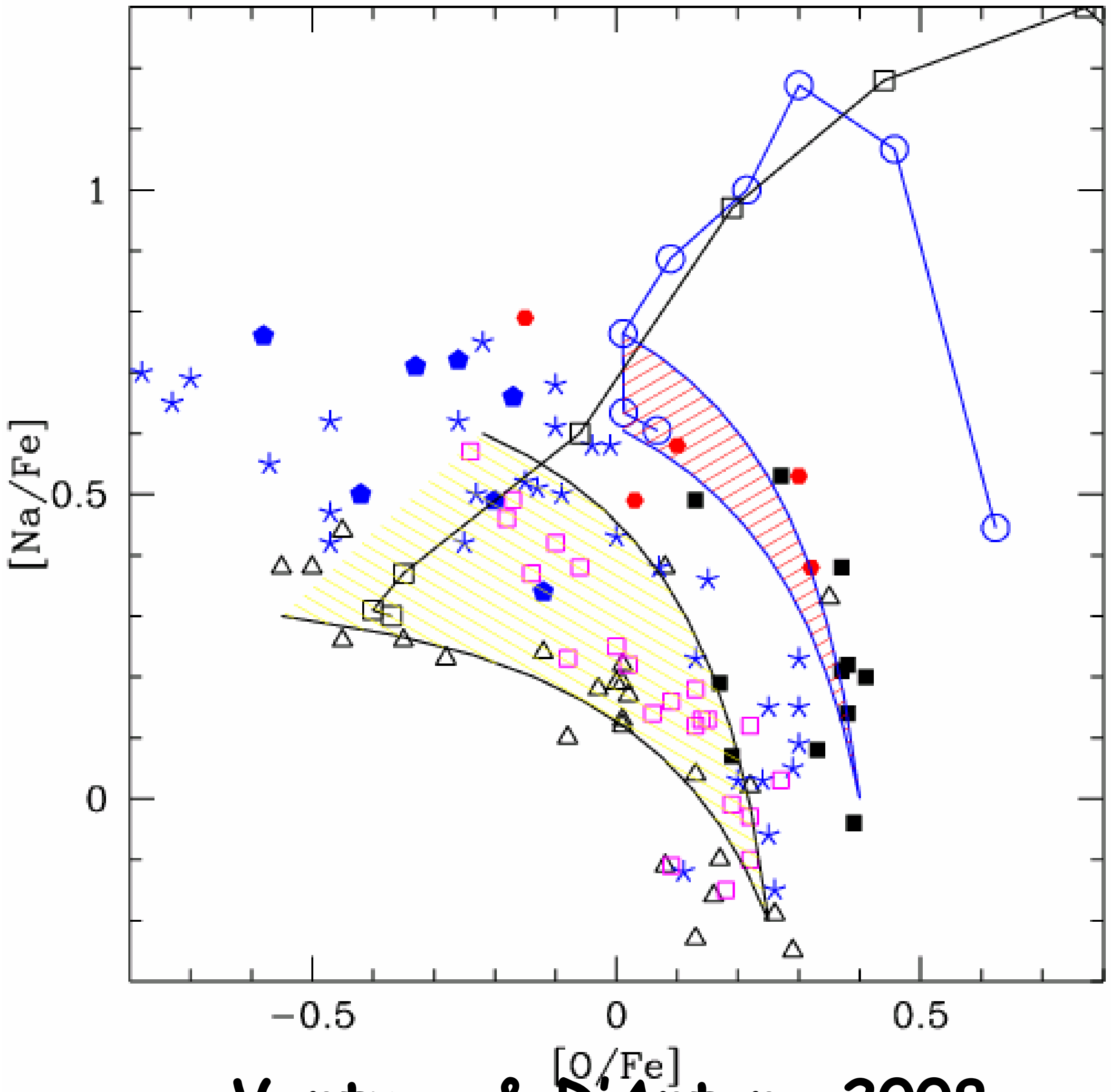
decreasing $^{22}Ne(p,\gamma)^{23}Na$ cross section

In ALL models, Na is correlated with O → a "dilution" model is necessary in order to obtain the observed anticorrelation

Examples of dilution

Interpreting the O-Na data requires mixing of polluted and pristine matter

yields:
open circles: Z=0.004
open squares: Z=0.001



Ventura & D'Antona 2008

THE PROBLEM OF HELIUM

1) Evidence from the HB morphology

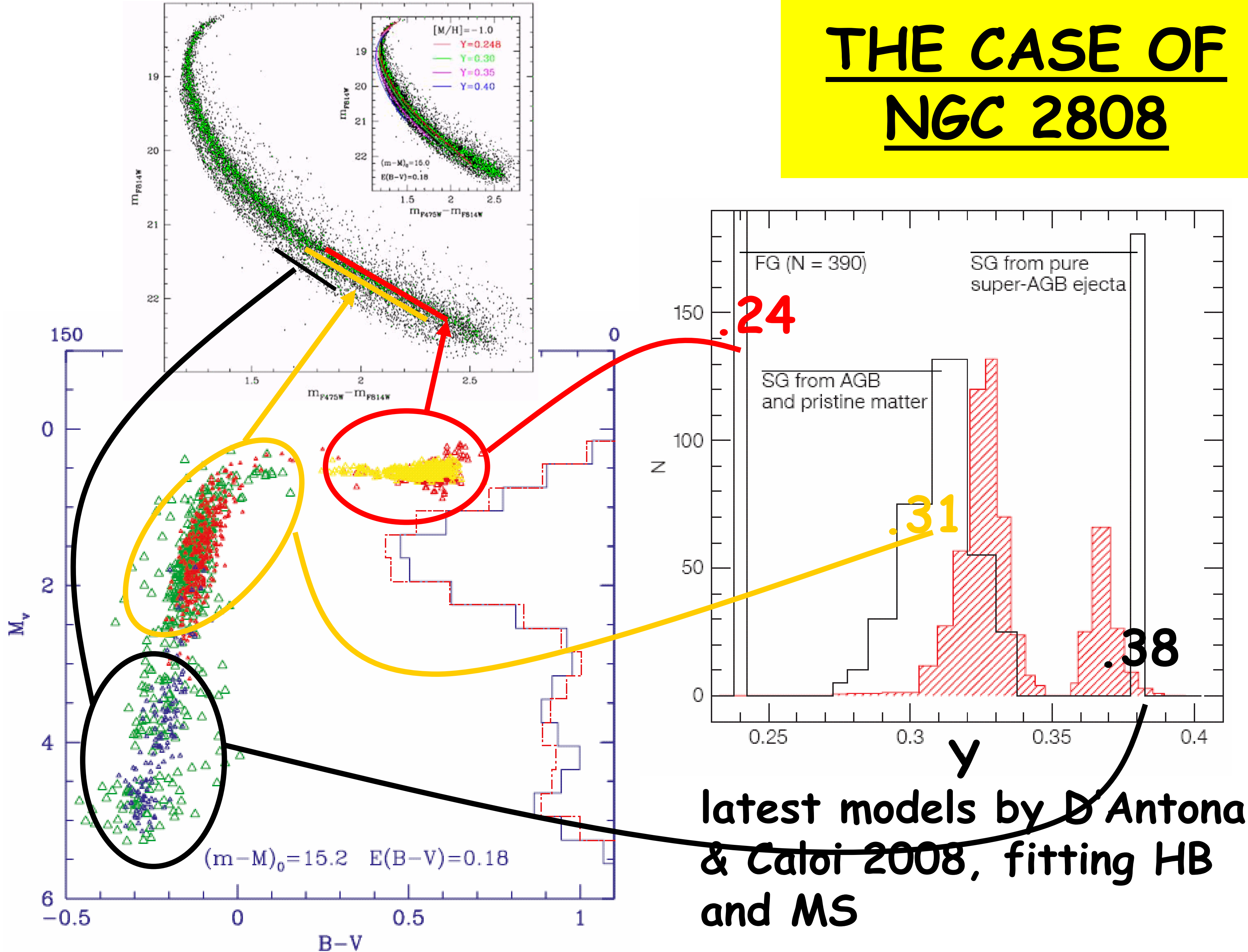
2) Evidence from the main sequence splitting(s)

Notice: MS splitting very evident if:

- ✓ the helium content Y is much larger than the "standard" (probably =Big Bang Y) one
- ✓ the multiple populations are well distinct in Y, like in NGC 2808

There is a variety of other possibilities: these can be put into evidence only from the HB – interpreted in terms of multiple Y populations

THE CASE OF NGC 2808



latest models by D'Antona & Caloi 2008, fitting HB and MS

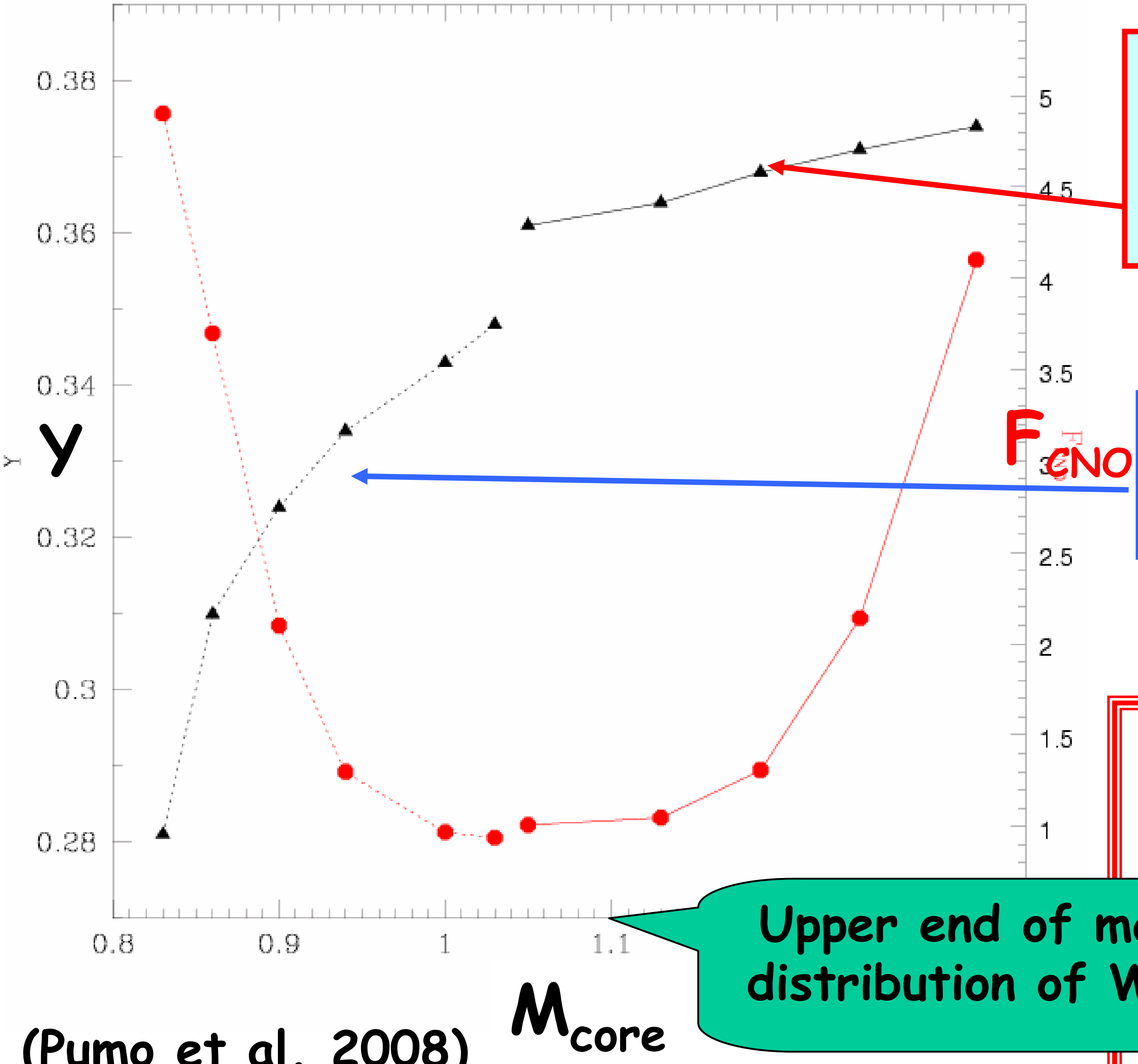
Clusters with a very high Y population (Y>0.35)

the helium content Y is much larger than the "standard" one

✓ NGC 2808	(blue tail in HB and blue MS)
✓ ωCen	(" " " " ")
✓ NGC 6441	(very long RR Lyr periods for
✓NGC 6388	high Z, and blue tails)

Can AGB models provide very high Y yields?

Helium yields from super-AGBs can!



(Pumo et al. 2008)

superAGB models (Siess 2007) at 2nd dredge up

AGB M<6.3Msun (VD 2007)

superAGBs reach the Y values

ded to fit the

MS in ωCen

NGC 2808

Upper end of mass distribution of WDs

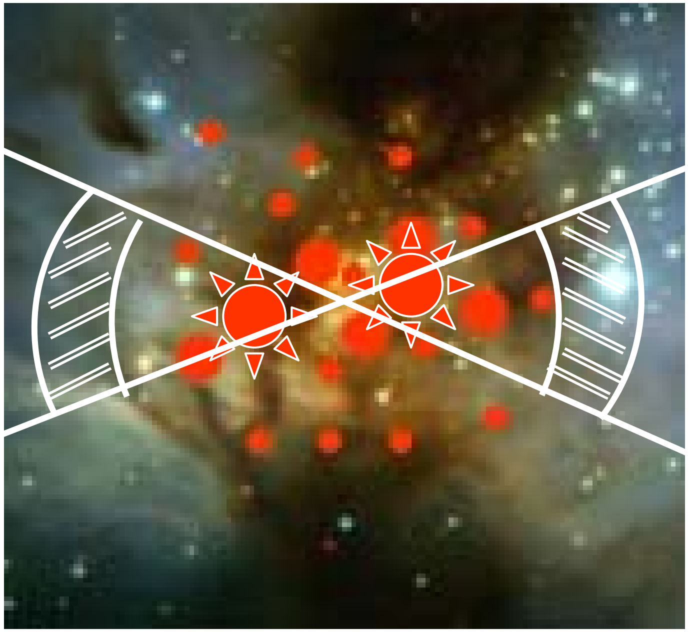
Helium yields

superAGBs reach the Y values needed to fit the blue MS in ωCen and NGC 2808

…if the superAGB winds are UNDILUTED

…on the contrary, we have seen that dilution with pristine matter is necessary to fully explain the O-Na anticorrelation

A possible model



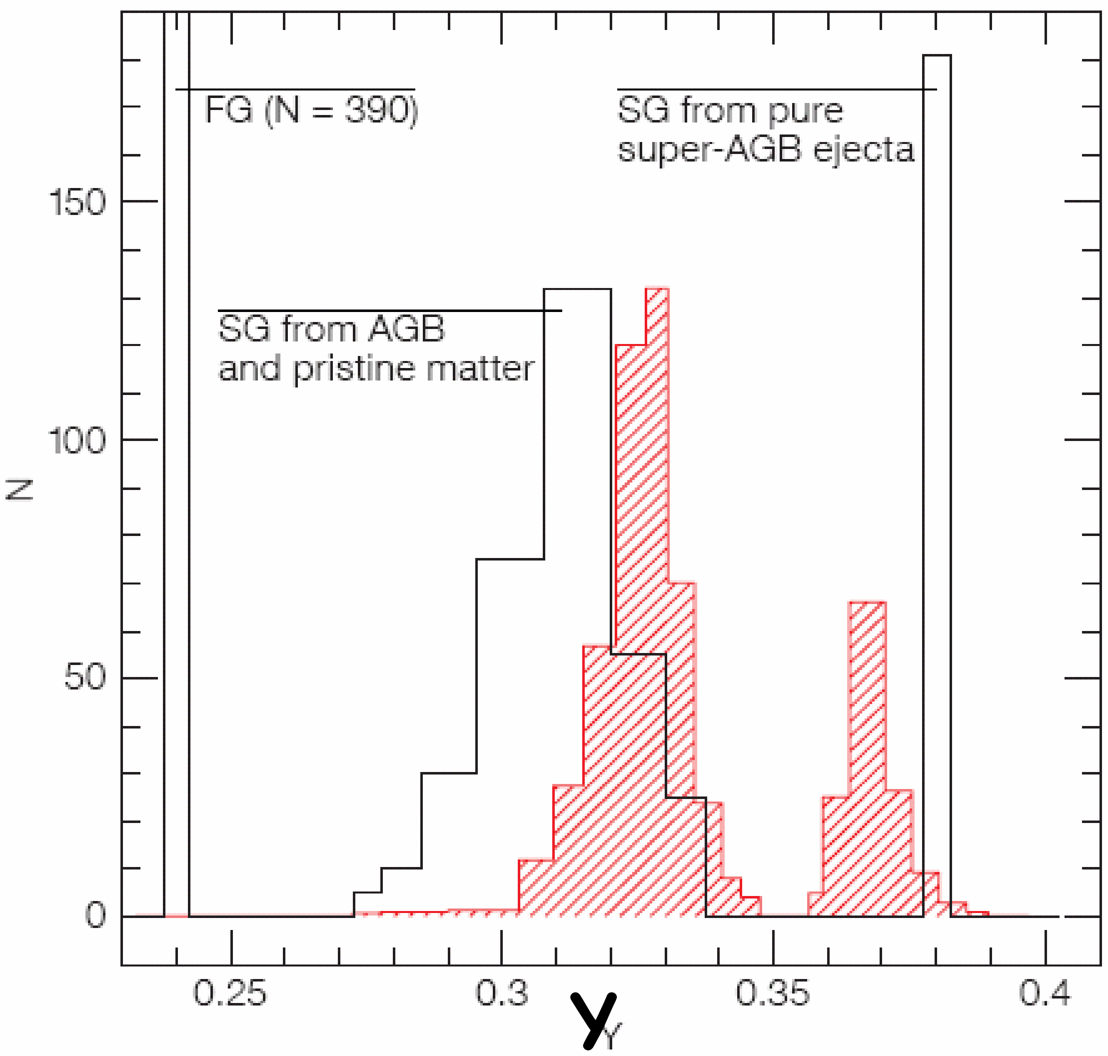
If SN have a preferential direction of ejection, the ejected matter clears out a cone, and leaves a torus of pristine gas in the outskirts of the cluster, within the tidal radius

The super AGB winds collect in the core and form 'pure' second generation stars…

…until the pristine gas falls back into the core regions, mixes with the AGB winds, and forms other stars with diluted ejecta…

D'Ercole et al. 2008

Preliminary result of the hydro simulation

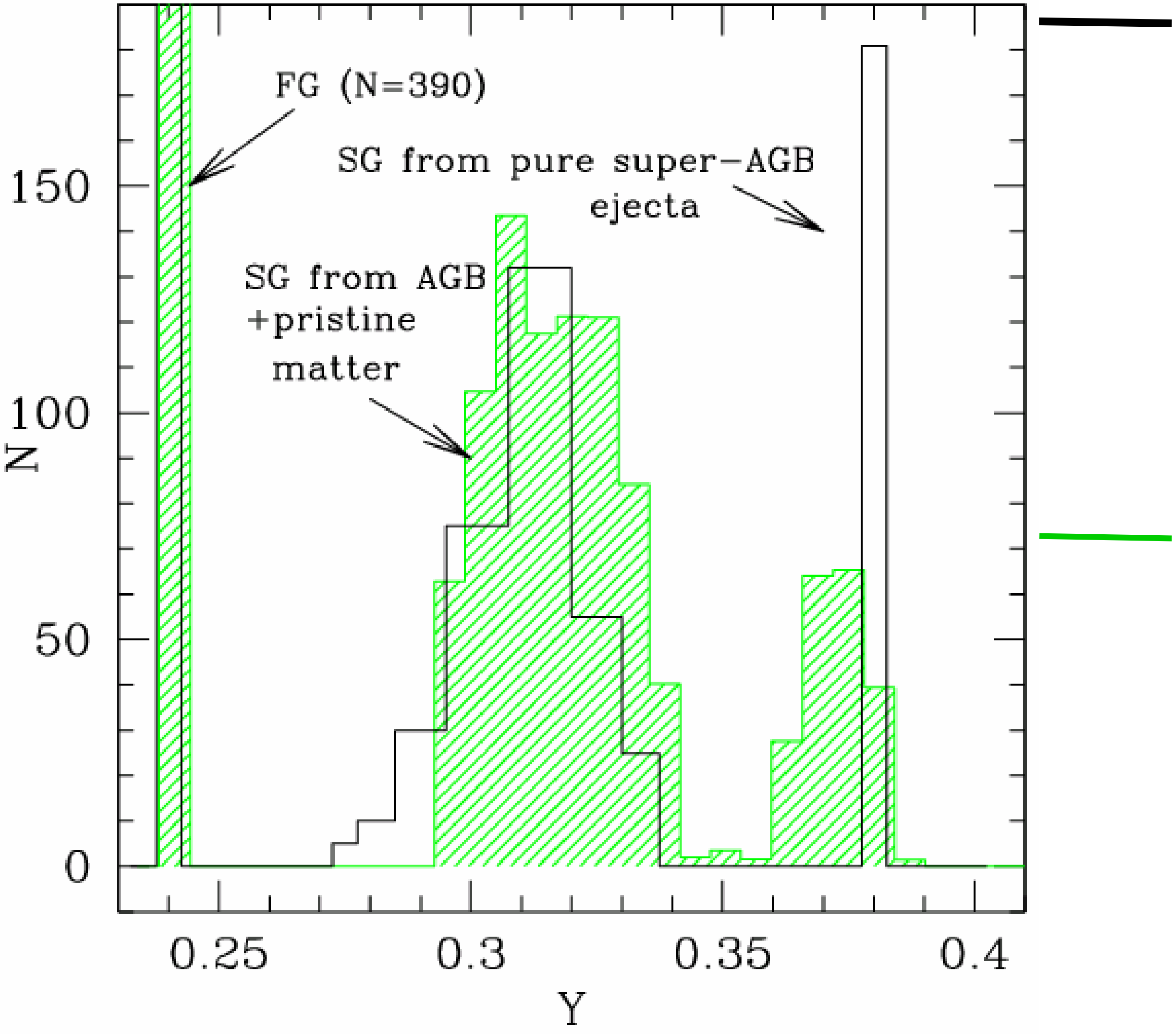


N(Y) distribution necessary to reproduce the blue HB and the intermediate and bMS of NGC2808 (DC2008)

N(Y) distribution obtained in the hydro simulation including infall of pristine matter from a (1D…) torus at the outskirts of the cluster

D'Ercole et al. 2008 MNRAS, no attempt to fit the data

further results



N(Y) distribution necessary to reproduce the blue HB and the intermediate and bMS of NGC2808 (DC2008)

N(Y) distribution obtained in the hydro simulation including infall of pristine matter from a (1D…) torus at the outskirts of the cluster

D’Ercole et al. 2009, more detailed attempt

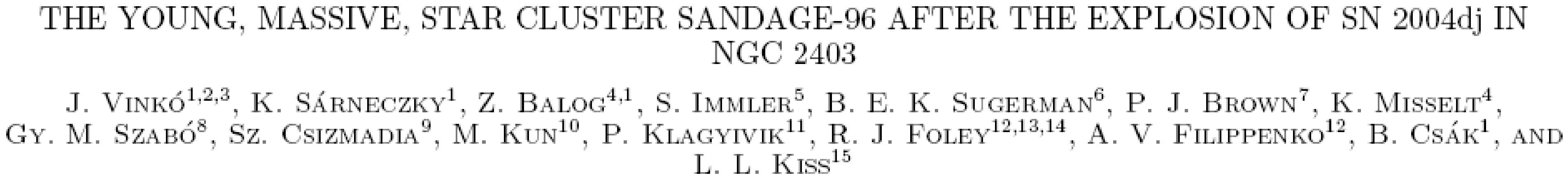
Why the very high helium favours the super-AGB and AGB pollutors

A bonus of the proposed model is the following: the uniformity of Y in the super-AGB ejecta, and the subsequent dilution with the pristine matter, allows to form a “pure” high helium blue MS, well separated from the others, as seen in NGC 2808 and wCen (see also Renzini 2008). In fact, if dilution occurs only after the formation of the high helium stars, both dilution and the smaller Y of the new winds contribute to produce a “gap” between the extreme He stars and the other SG stars (D’Ercole et al. 2008)

New models

To reproduce the blue HB and the intermediate and bMS of NGC2808, we need a long delay (from 32Myr – end of SN epoch- to ~50Myr) before the pristine matter begins to be mixed with the wind matter.
To reproduce the chemical anomalies in less massive clusters (such as M4), the pristine matter must be mixed reasonably sooner, before SG stars are formed, and the efficiency of star formation must be much smaller, so that the final anomalies are less prominent than in the extreme case of the most massive clusters

D'Ercole et al. 2009

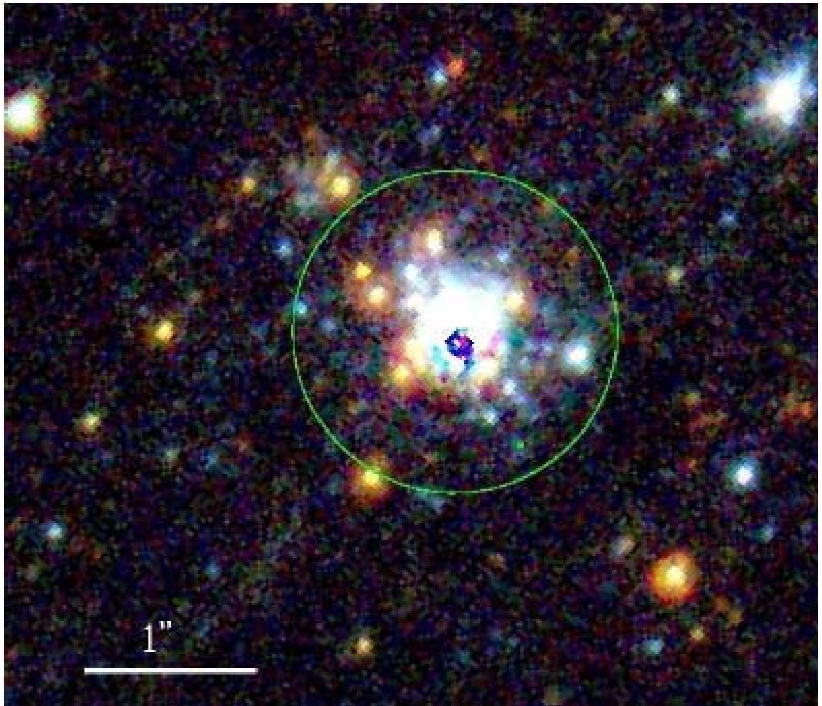


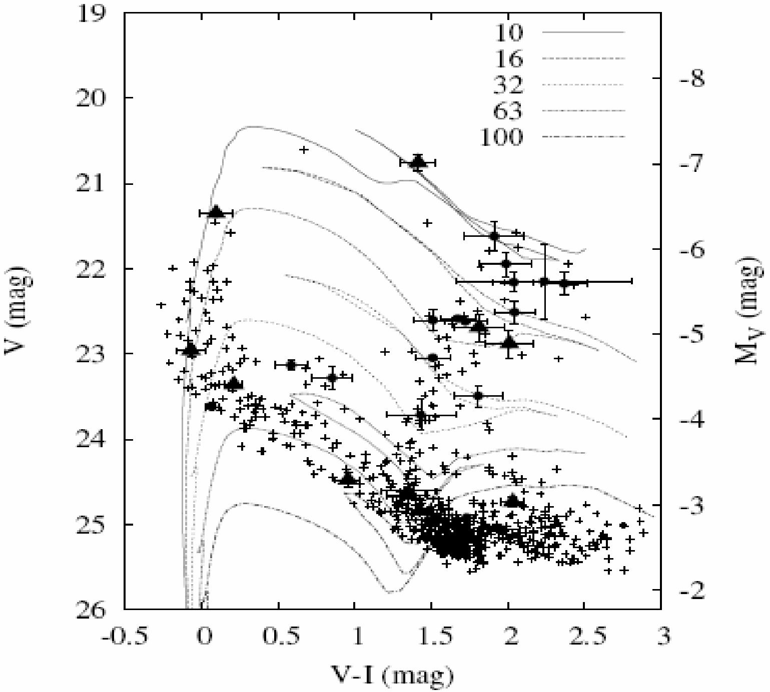
THE YOUNG, MASSIVE, STAR CLUSTER SANDAGE-96 AFTER THE EXPLOSION OF SN 2004dj IN NGC 2403

J. Vinkó[1,2,3], K. Sárneczky[1], Z. Balog[4,1], S. Immler[5], B. E. K. Sugerman[6], P. J. Brown[7], K. Misselt[4], Gy. M. Szabó[8], Sz. Csizmadia[9], M. Kun[10], P. Klagyivik[11], R. J. Foley[12,13,14], A. V. Filippenko[12], B. Csák[1], and L. L. Kiss[15]

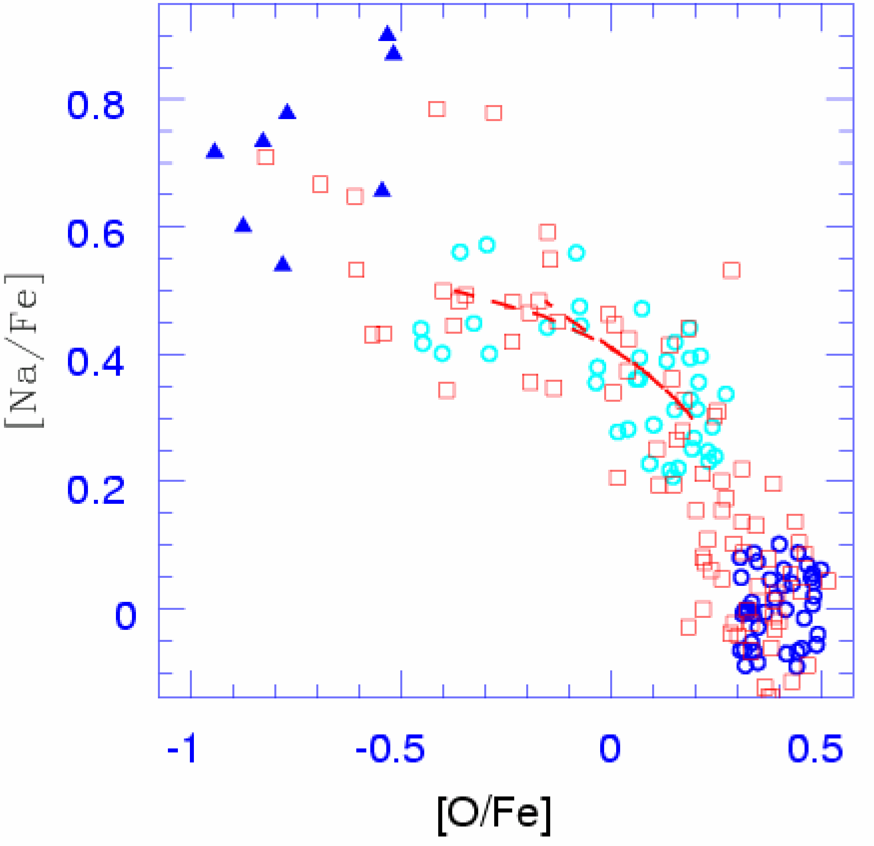
- The isochrone fitting of the c-m diagrams indicates that the resolved part of the cluster consists of stars having a bimodal age distribution:
  - a younger population at 10–16 Myr
  - an older one at 32–100 Myr.
- The older population has an age distribution similar to that of the other nearby field stars (=an association where the cluster is embedded)

S96 Mass~10^5 Mo





Example of new models: NGC 2808



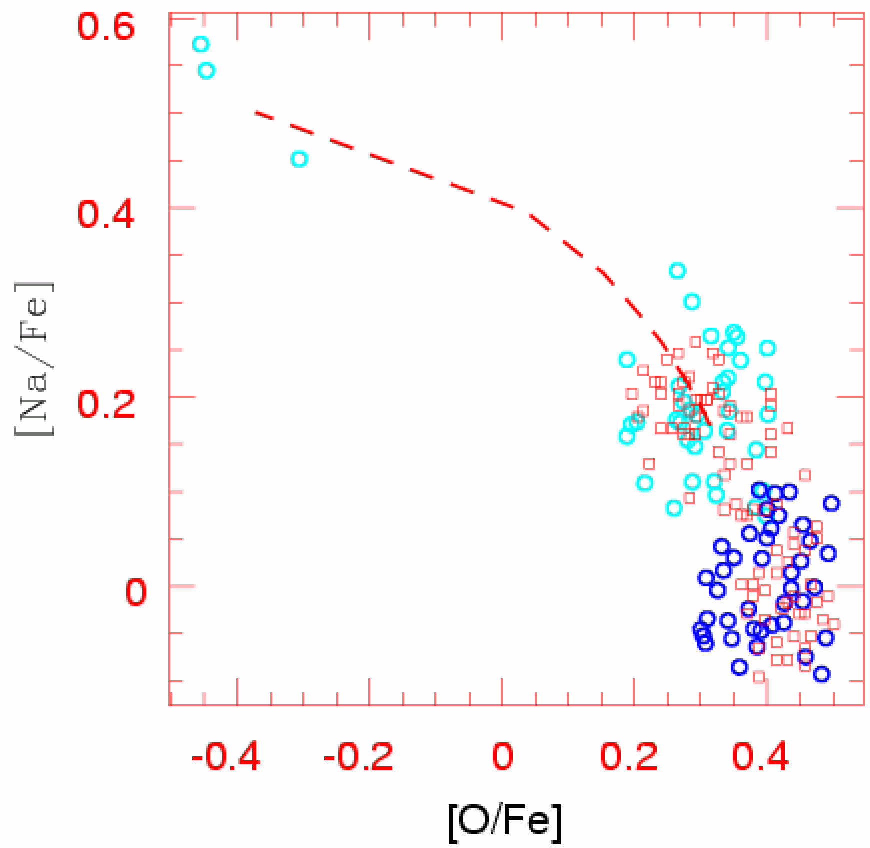
blue dots: simulation of the pristine population; cyan: simulation of the SG

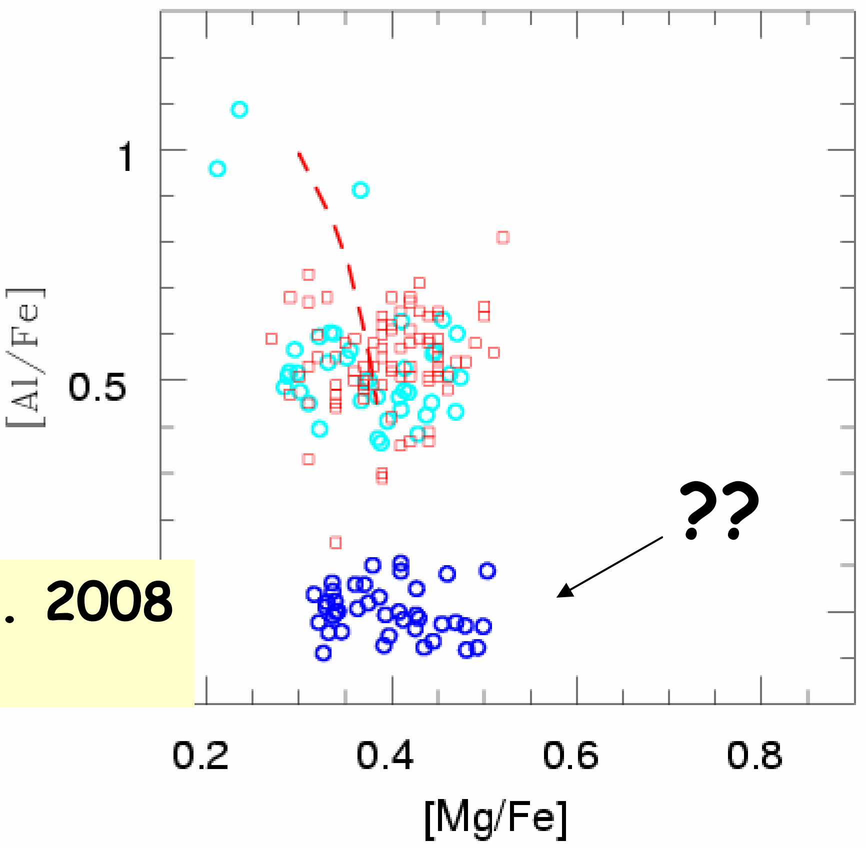
notice: the lower O abundances are not reproduced in the simulation (do we need extramixing?)

red squares: data by Carretta et al. 2006 for NGC 2808
triangles: upper limits

D'Ercole et al. 2009

Examples of new models: M4





red squares: data by Marino et al. 2008 (adjusted by δO=-0.1, δNa=-0.2)

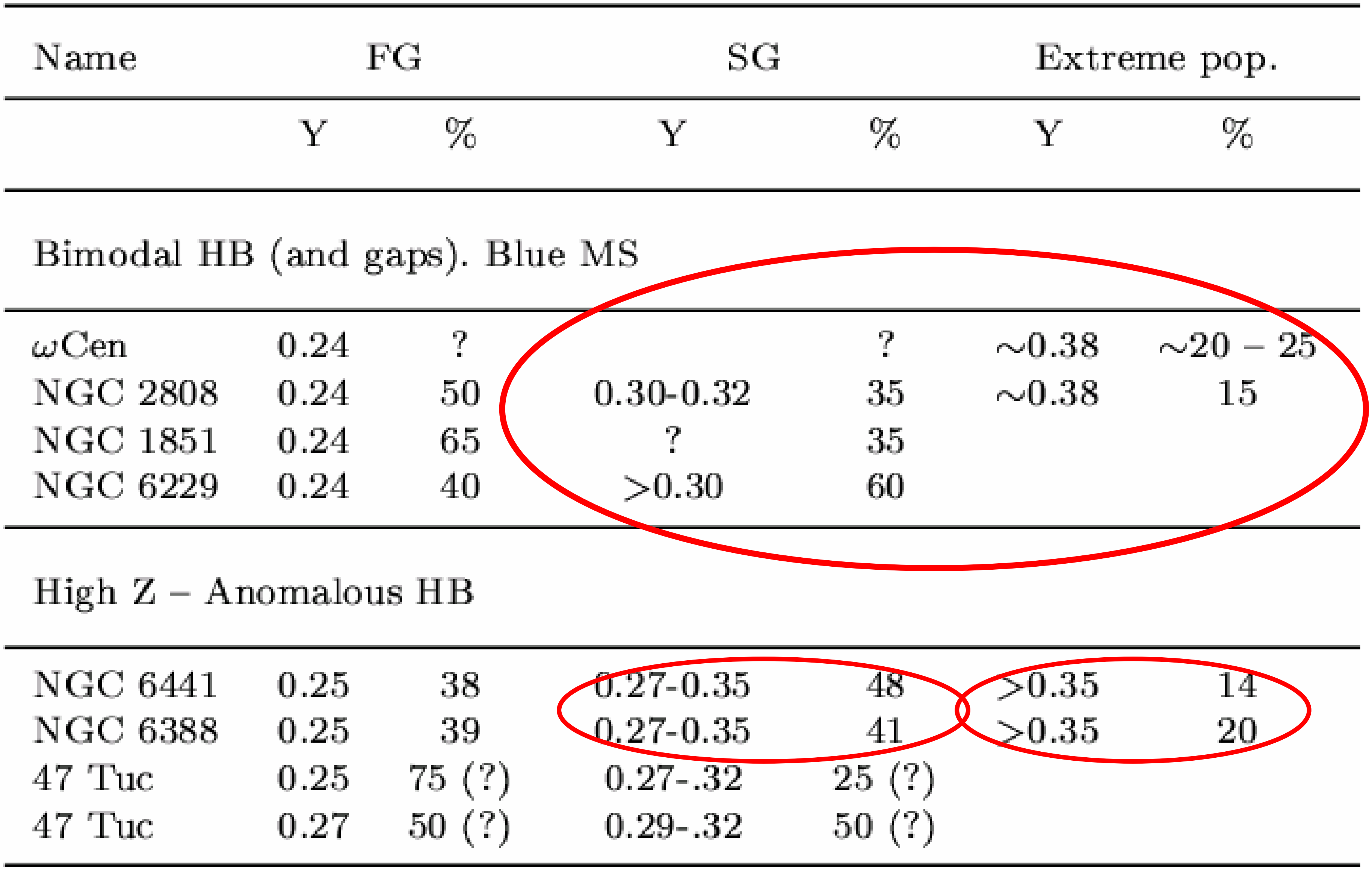
D'Ercole et al. 2009

The problem of the IMF

examining several HB features (gaps, RR Lyr period distribution, peculiar RR Lyr periods, only-blue HB clusters) and interpreting them in terms of helium variations, D'Antona & Caloi 2008 find that ALL examined clusters contain a high % of anomalous stars (30 to 70%). In some cases, we propose that 100% of stars belong to the SG).

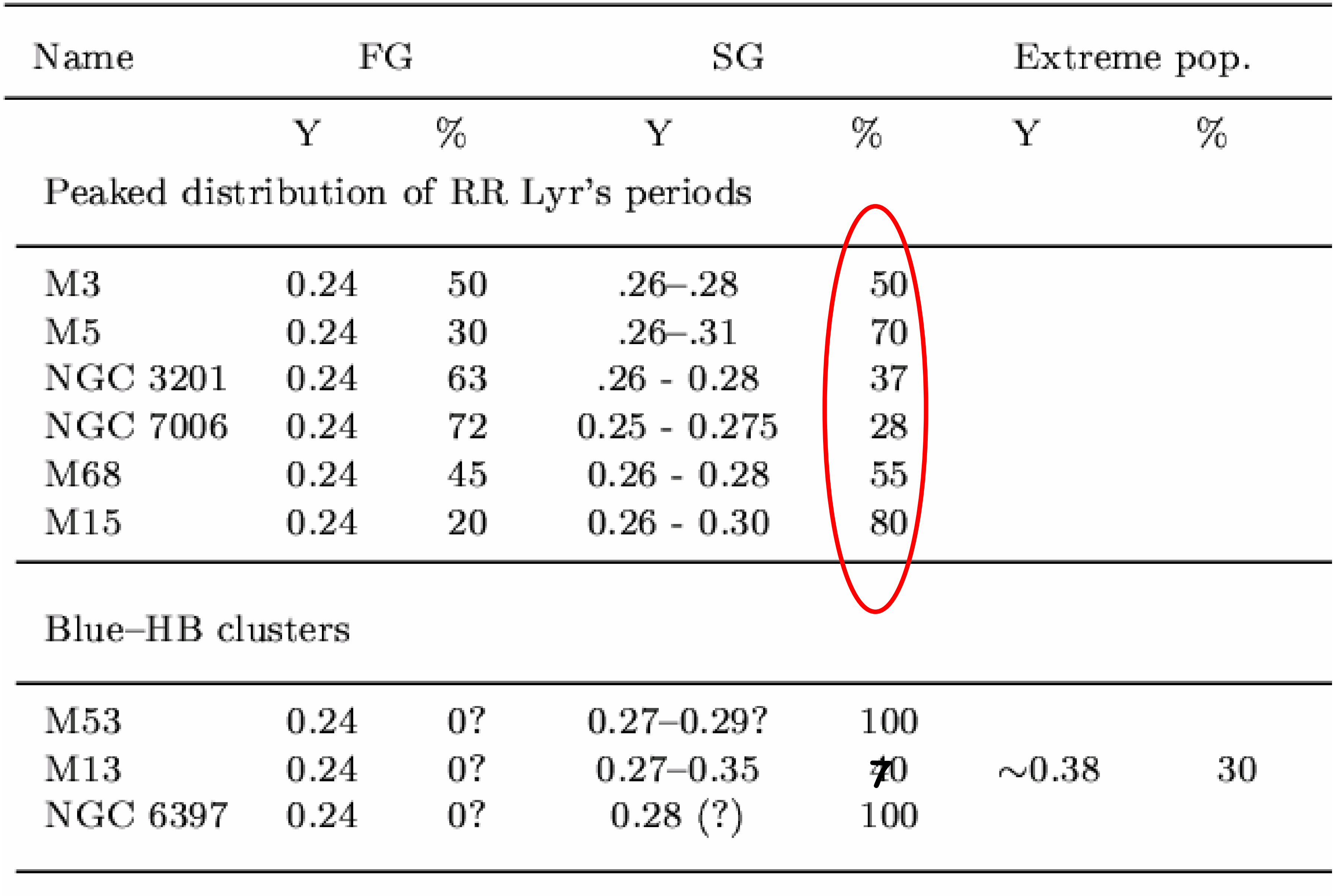
The same result is independently obtained in the new spectroscopic data by Carretta et al. (2008)

…very high % of anomalous stars…



Name	FG		SG		Extreme pop.	
	Y	%	Y	%	Y	%
Bimodal HB (and gaps). Blue MS						
ωCen	0.24	?		?	$\sim$0.38	$\sim$20 – 25
NGC 2808	0.24	50	0.30-0.32	35	$\sim$0.38	15
NGC 1851	0.24	65	?	35		
NGC 6229	0.24	40	>0.30	60		
High Z – Anomalous HB						
NGC 6441	0.25	38	0.27-0.35	48	>0.35	14
NGC 6388	0.25	39	0.27-0.35	41	>0.35	20
47 Tuc	0.25	75 (?)	0.27-.32	25 (?)		
47 Tuc	0.27	50 (?)	0.29-.32	50 (?)		

% of anomalous stars



Name	FG		SG		Extreme pop.	
	Y	%	Y	%	Y	%
Peaked distribution of RR Lyr's periods						
M3	0.24	50	.26–.28	50		
M5	0.24	30	.26–.31	70		
NGC 3201	0.24	63	.26 - 0.28	37		
NGC 7006	0.24	72	0.25 - 0.275	28		
M68	0.24	45	0.26 - 0.28	55		
M15	0.24	20	0.26 - 0.30	80		
Blue–HB clusters						
M53	0.24	0?	0.27–0.29?	100		
M13	0.24	0?	0.27–0.35	~~4~~70	∼0.38	30
NGC 6397	0.24	0?	0.28 (?)	100		

We need to form ~half of today's GC stars (the SG) from matter processed through hot CNO and other p-capture reactions in stars of the FG

the FG must be much more massive (at least 10 times as massive) than today

this favours again the AGB - superAGB model, for dynamical resons, as the winds of these stars take place during the quietest lifetime of the cluster, in between the SN II epoch and the SN Ia epoch

(see D'Ercole et al. 2008, and Vesperini's talk)

Summary

1) Massive AGB can provide yields consistent with the chemical anomalies (Na and O have been discussed, but this is valid also for CNO and the Mg-Al anticorrelation), although the results are very model dependent;

2) The very high helium population of some massive clusters may be produced if "pure" superAGB winds form stars.

3) The less extreme anomalies may be explained by dilution of the AGB winds with pristine gas re-accreted in the core from the outskirts of the cluster

Summary

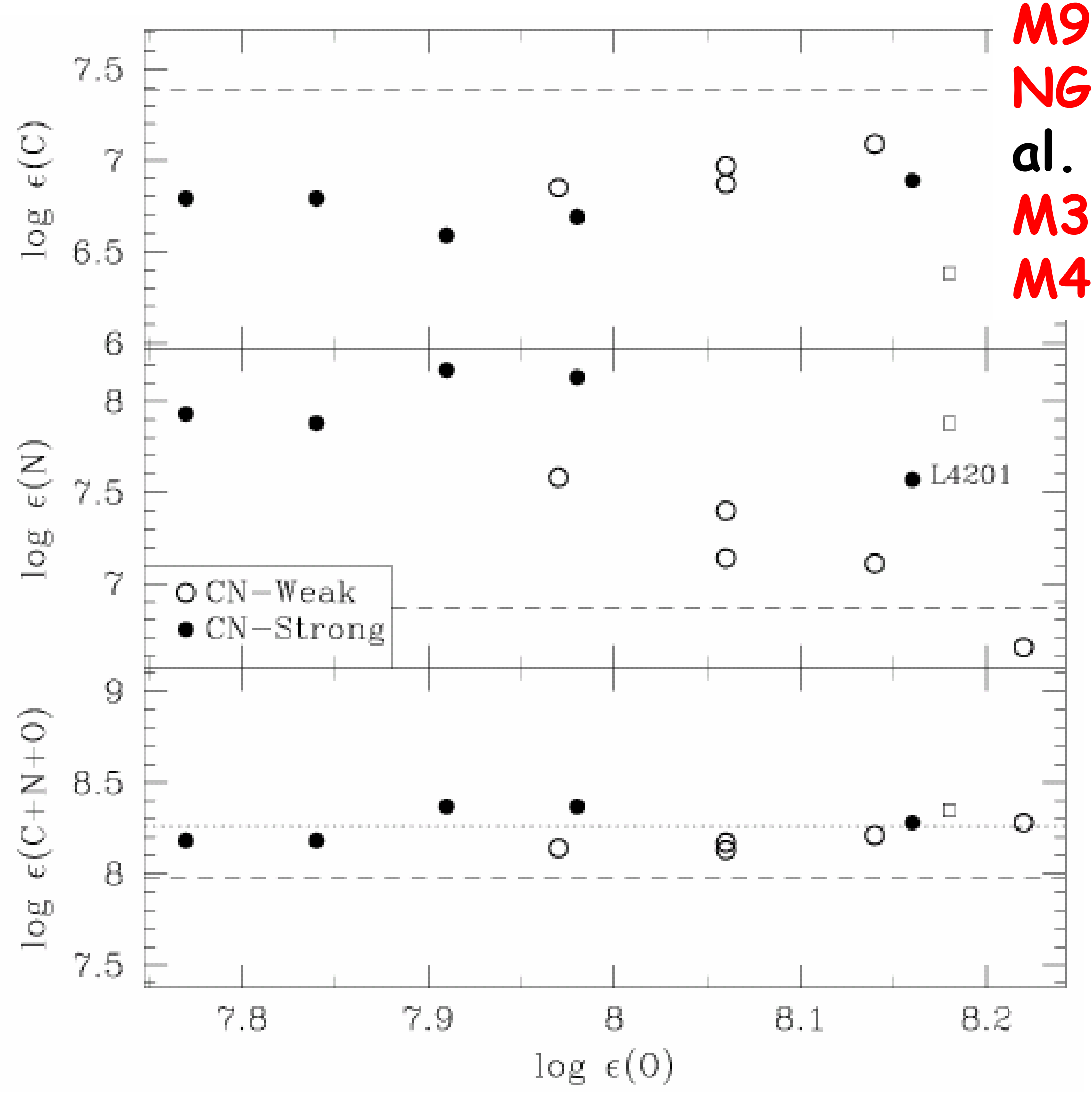
4) Smaller clusters do not show the extreme anomalies. Mixing with pristine gas occurs before the SG begins to be formed.

5) The AGB – superAGB model is dynamically favoured, as the winds of these stars take place during the quiet lifetime of the cluster, in between the SN II epoch and the SN Ia epoch

END → thanks, Raffaele

Corollary on C+N+O variations in GCs

C+N+O is constant in some GCs…



M92: Pilachowski et al. (1988);
NGC 288, NGC 362: Dickens et al. (1991);
M3, M13: Smith et al. (1996);
M4: Ivans et al. (1999)

the 3rd dredge up must have a scarce role (or none? Pure CNO cycling would favour the massive stars pollutors?)

Ivans et al. 1999 - M4

but not in all cases

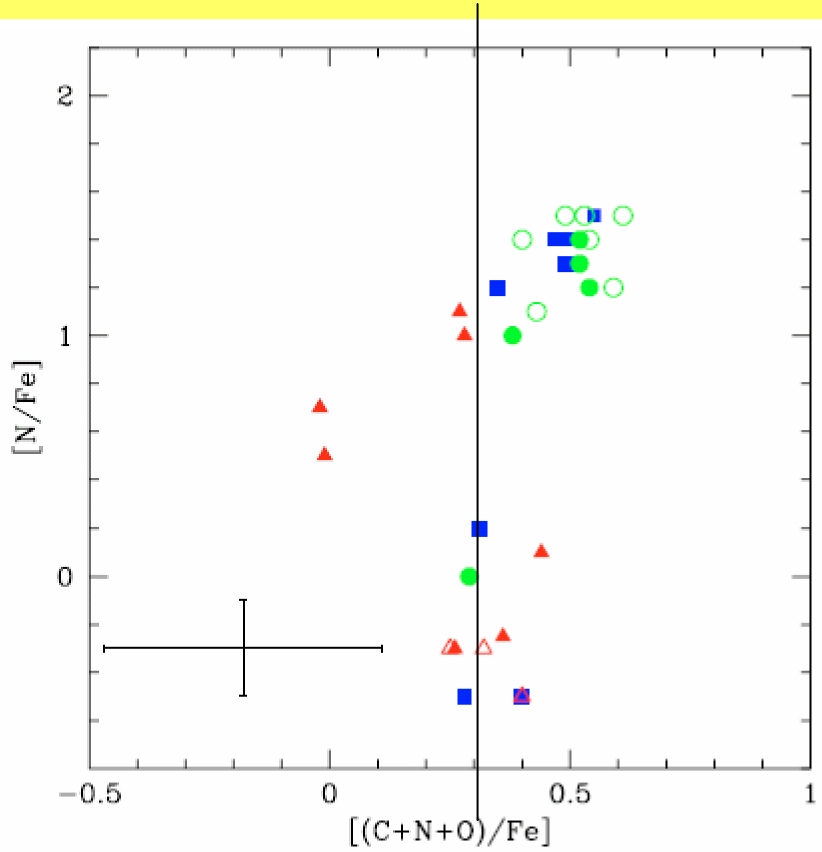
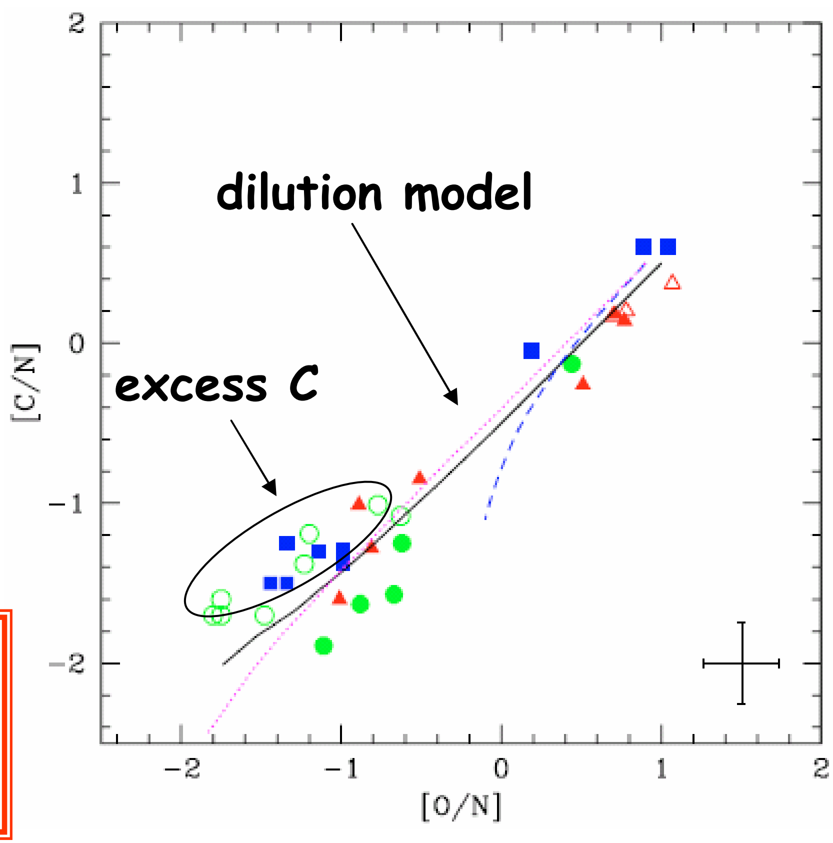


Fig. 17. [N/Fe] ratio as a function of [(C+N+O)/Fe] for our stars in 47 Tuc, NGC 6397 and NGC 6752; symbols are as in Fig. 6.

Carretta et al. 2005
open symbols: dwarfs
red triangles: 47 Tuc
green circels: NGC 6752
blue squares: NGC 6397

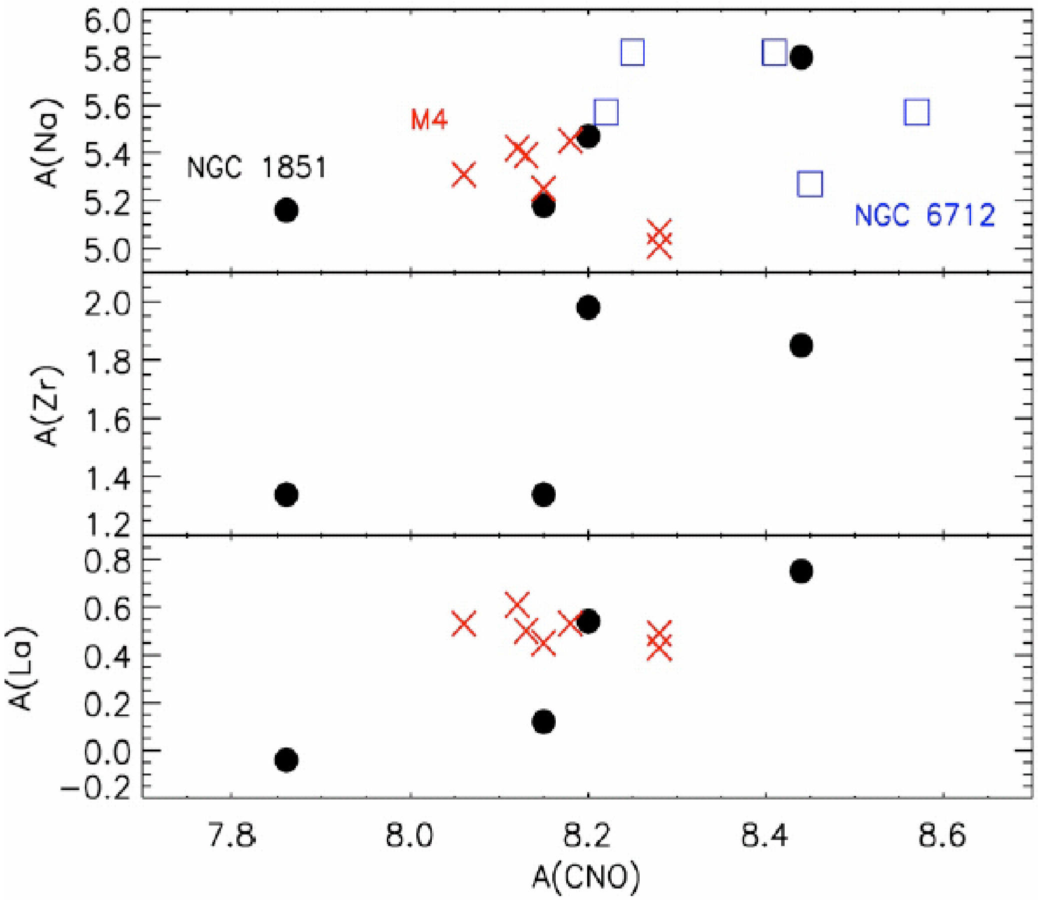


dilution model

excess C

is some CNO coming from 3α processing?

…in particular in NGC 1851

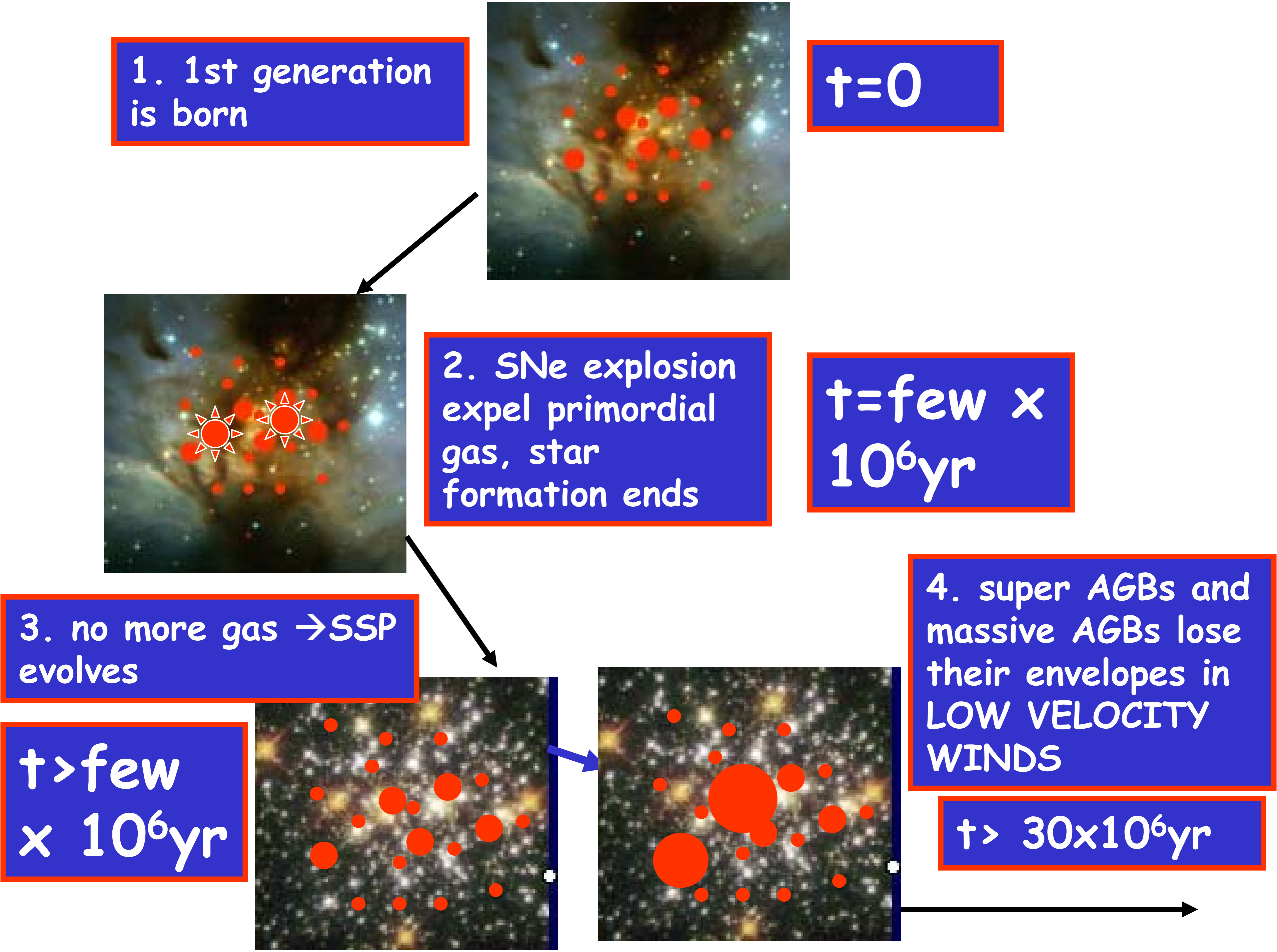


Yong, Grundahl et al. 2009:

C+N+O varying by a factor 4 in NGC 1851 →
and correlated variations in s-process and Na_→
this explains also double subgiant branch in two coeval subpopulations

NGC 1851 is the 'best proof' for AGB pollutors?

The concomitant variation of C+N+O and s-process elements in NGC 1851 probably indicates that the SG was formed including the contribution of winds from AGBs a bit less massive than in the other clusters, AGBs that have suffered a larger number of 3rd dredge up episodes, and so were able to increase both the total CNO abundance, by dredging up carbon (then converted to nitrogen by HBB) and s-process elements. (Yong et al. 2009).



1. 1st generation is born

$t=0$

2. SNe explosion expel primordial gas, star formation ends

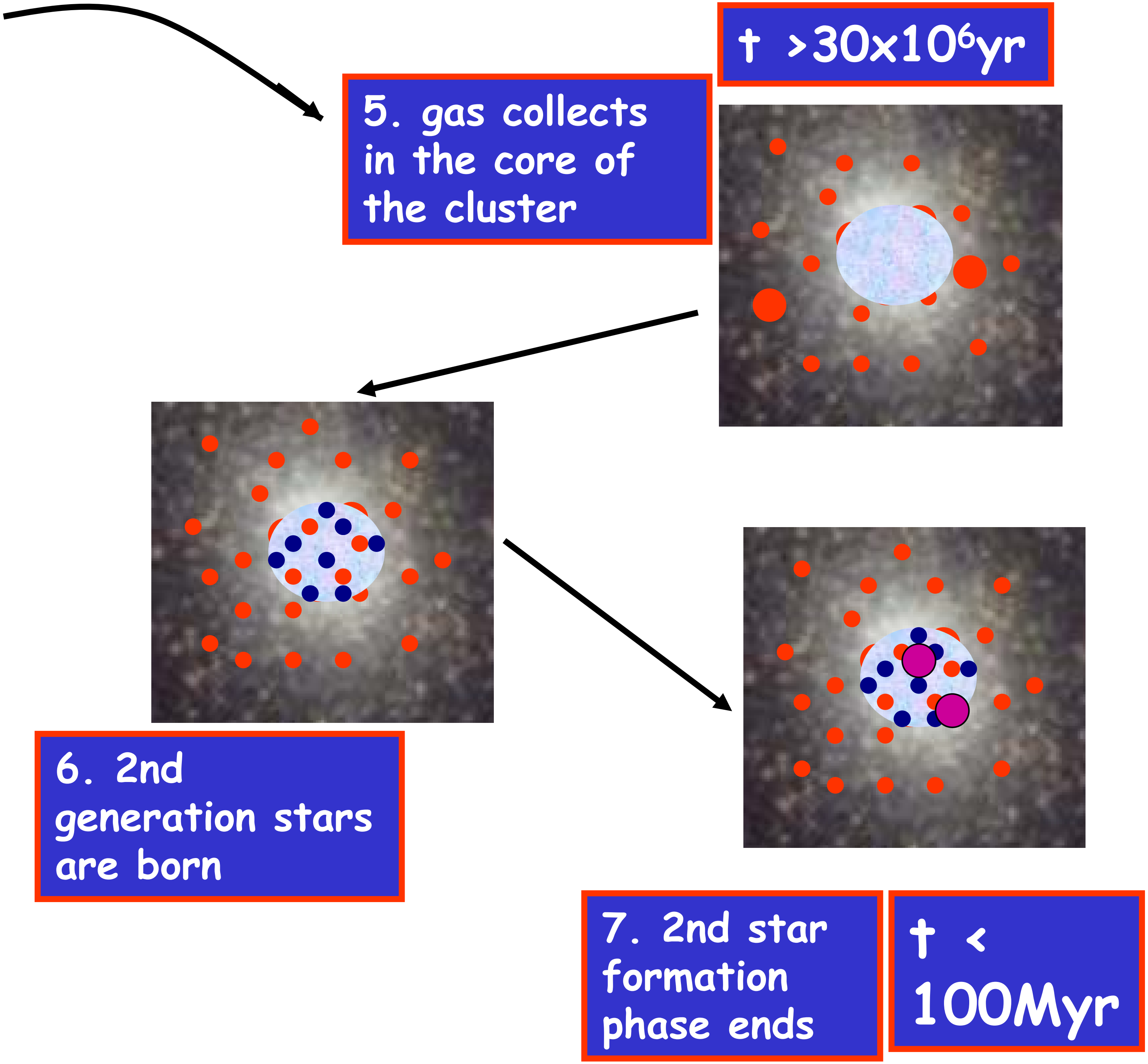
$t=\text{few} \times 10^6\text{yr}$

3. no more gas →SSP evolves

$t>\text{few} \times 10^6\text{yr}$

4. super AGBs and massive AGBs lose their envelopes in LOW VELOCITY WINDS

$t> 30\times10^6\text{yr}$



5. gas collects in the core of the cluster

t $>30\times10^6$yr

6. 2nd generation stars are born

7. 2nd star formation phase ends

t < 100Myr