Stellar Populations in Globular Clusters: a new era and a new vision

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The context:

The assembly of early stellar populations in galaxies is one of the hottest open issues in modern astronomy.

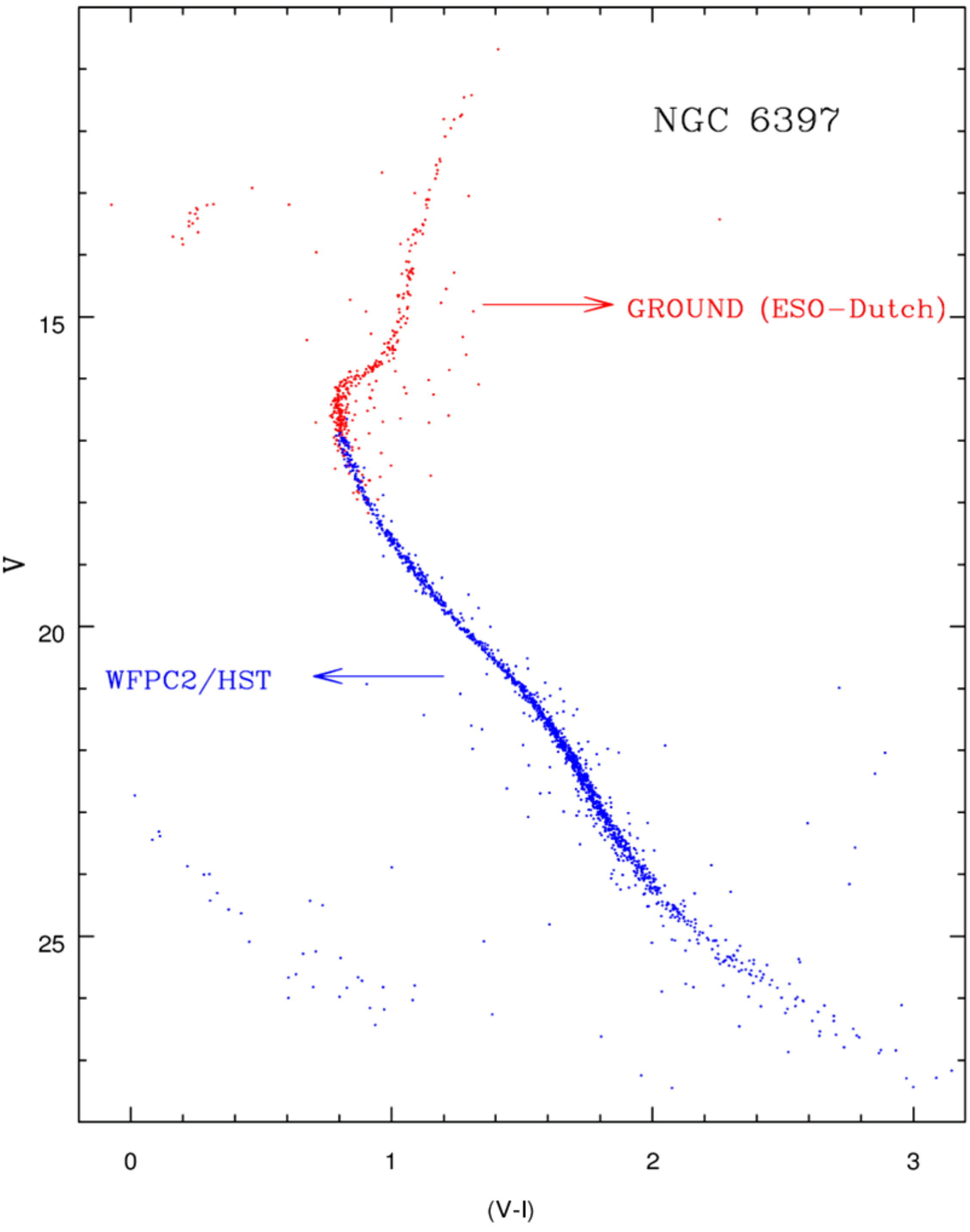
Globular clusters are a major component of these old stellar systems and provide us with a powerful link between external galaxies and local stellar populations.

A clear comprehension of the mechanisms that led to the formation and evolution of globular clusters and the relation existing between globular clusters and field stars is a basic requirement to understand how galaxies assembled.

Globular Clusters as Simple Stellar Populations?

"A Simple Stellar Population (SSP) is defined as an assembly of coeval, initially chemically homogeneous, single stars.
Four main parameters are required to describe a SSP, namely its age, composition (Y, Z) and initial mass function.
In nature, the best examples of SSP's are the **star clusters….**" **Renzini and Buzzoni (1986)**

For this reason, star clusters have been – so far - a fundamental benchmark for testing stellar evolution models and for Population Synthesis Models



Indeed, we have superb examples of globular clusters in which hydrogen burning stars, in the stellar core or in a shell ***typically*** behave as "standard" stellar evolution models predict.

And we have CMDs which (apparently) show that globular clusters are ***typically*** populated by stars with homogeneous composition and born at the same time ***(same age).***

The beginning: GCs are NOT so simple
A complex chemestry

The 1th evidence: Cohen (1978) – Na scatter in RGB stars (M3, M13);

The 2th evidence: Peterson (1980) – 1 order of magnitude scatter in Na abundance in RGB stars (M13);

The 3th evidence: Norris (1981) – Al scatter in RGB stars (NGC6752);

Many GCs show CN bimodality in the RGB;

C and N abundances of GC stars are very different from field stars: the environment must play a role;

Abundance anomalies (?) are present also among MS stars: they must be primordial;

For a complete review see Gratton, Sneden & Carretta 2004, AARA

1990-2000: Big steps in our observing capabilities

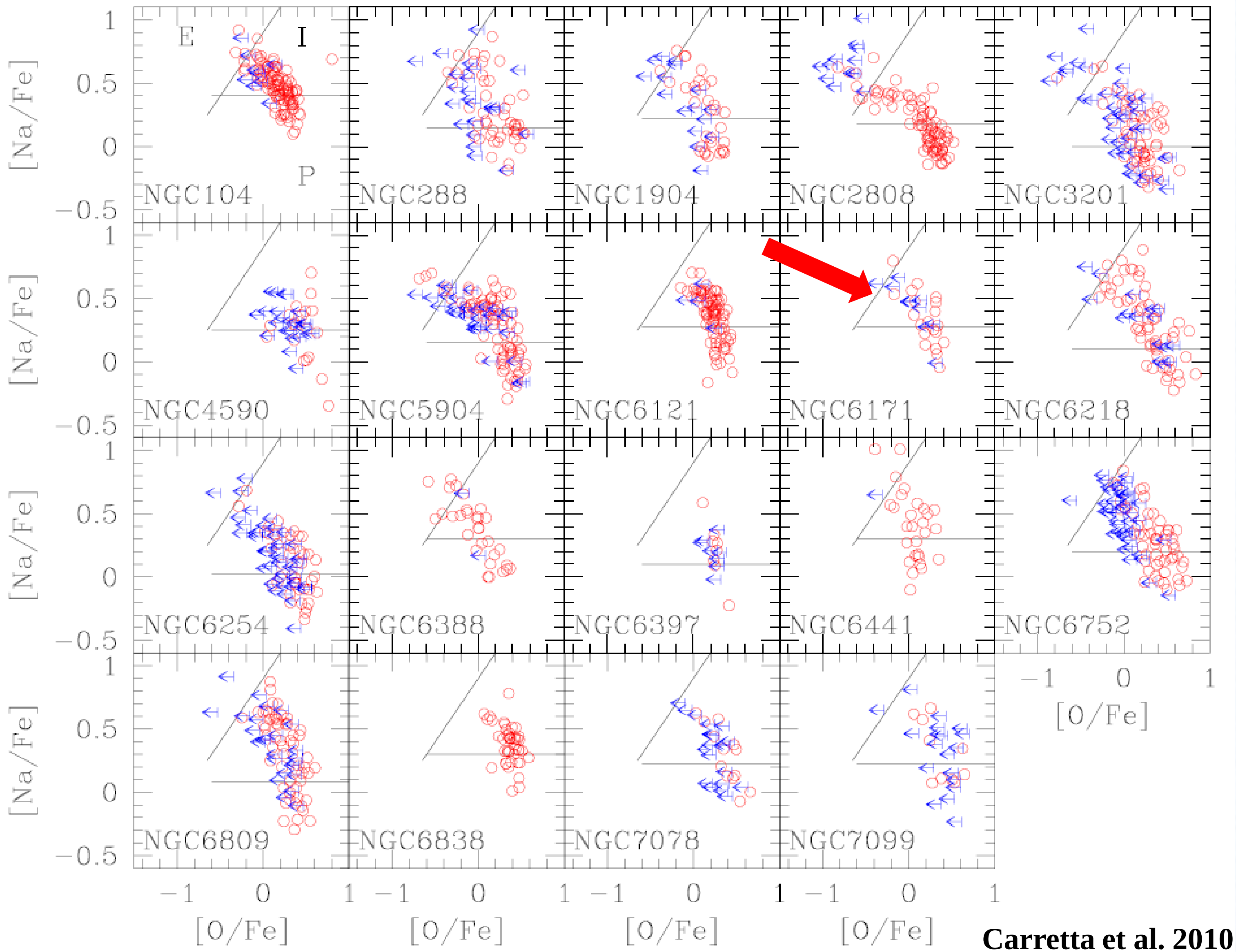
-Wide field imagers

- WFCP2, and then ACS and WFC3 on HST

-Multislit and multifiber high resolution spectrographs on 8-10m class telescopes

→ 1 to 2 orders more photometric, astrometric, and spectroscopic data. Higher precision measurements

A problem: star to star variations of light elements are present in all GCs



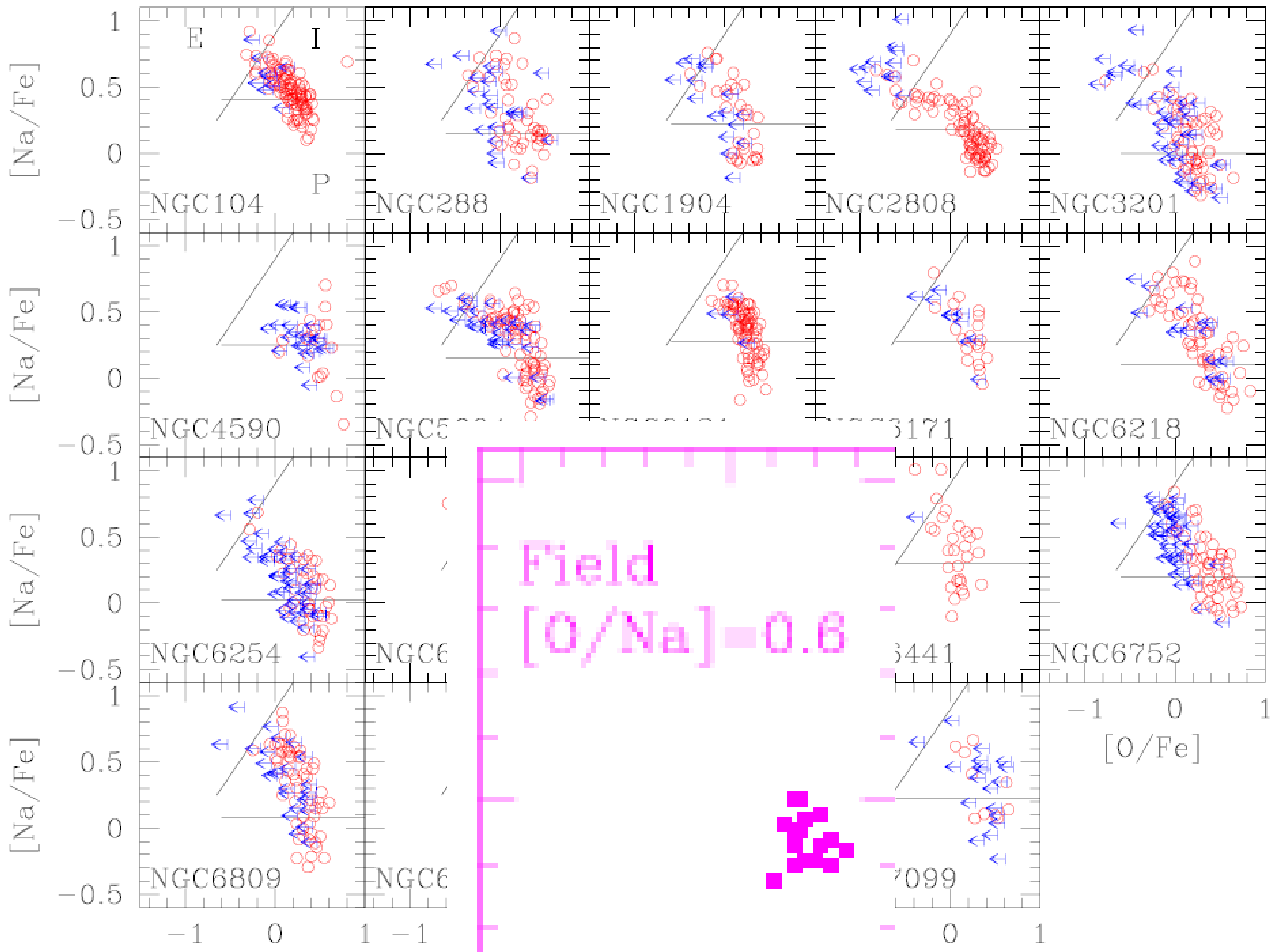
Carretta et al. 2010

Most clusters have constant [Fe/H], but large star to star variations in light elements.

Some elements define correlations like the **NaO anticorrelation**, or the **MgAl anticorrelation.**

These anticorrelations are present in all clusters analyzed so far.

A problem: star to star variations of light elements are present in all GCs

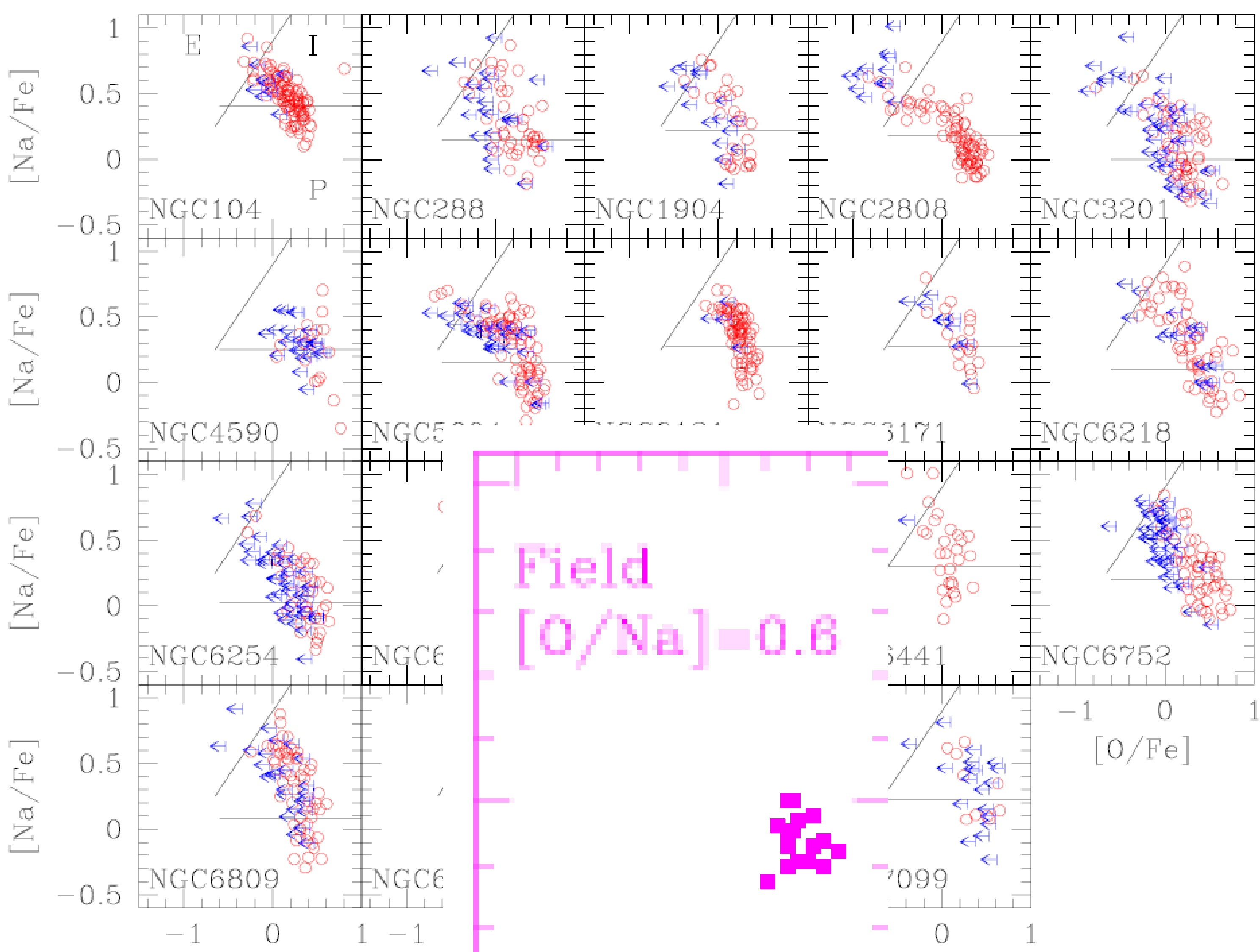


Carretta et al. 2010

However, there is no evidence of NaO anticorrelation in field stars. All of them are O rich and Na poor.

These anticorrelations are present in all clusters so far analyzed.

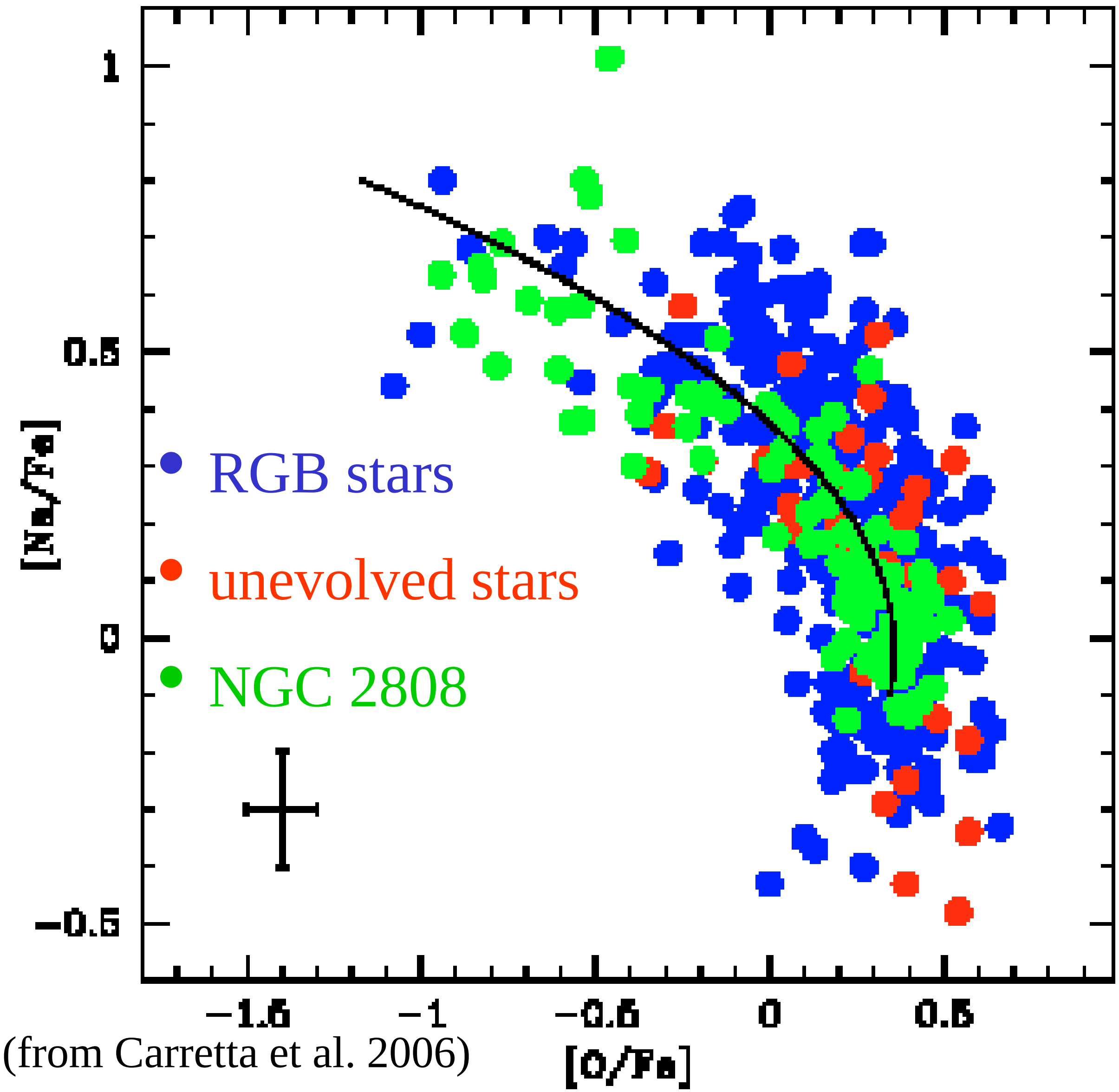
A problem: star to star variations of light elements are present in all GCs



Carretta et al. 2010

Na-O anti-correlation indicates the presence of proton capture processes, which transform Ne into Na, and Mg into Al

These anticorrelations are present in all clusters so far analyzed.



(from Carretta et al. 2006)

Na-O and Mg-Al anti-correlations have been found also among MS stars.

Needs H-burning through CNO cycle at hot temperatures (not reached in present day GC main sequence stars). These anticorrelation can not be due to simple evolutionary effects

Note that the CNO cycle transforms hydrogen into helium

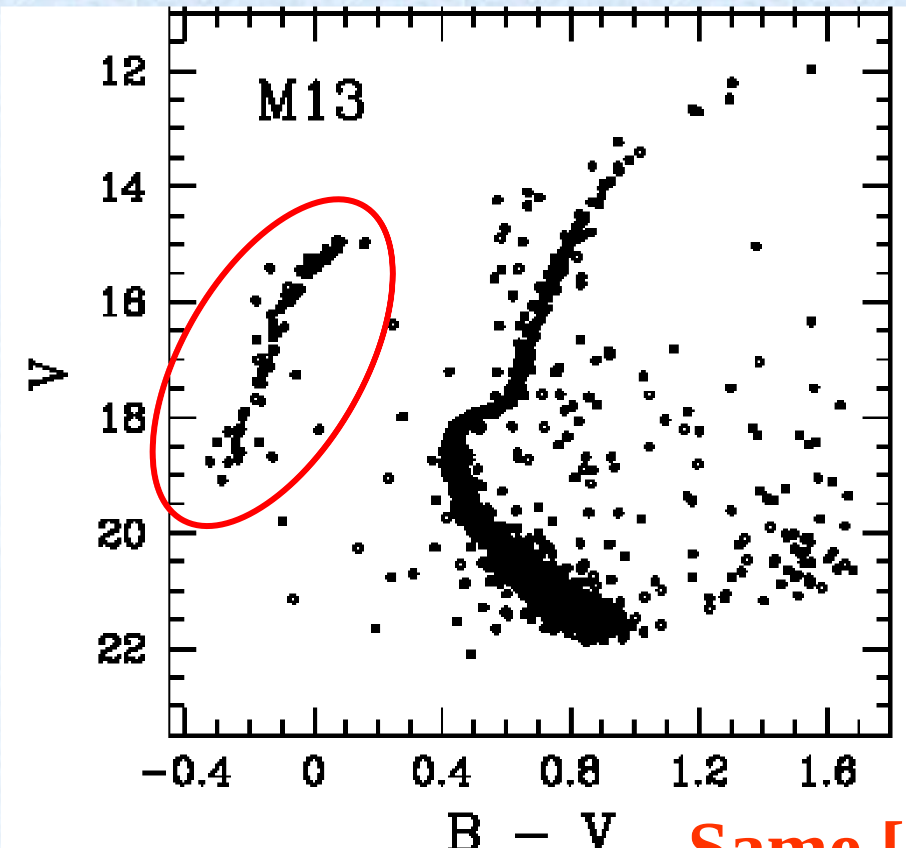
A debate which lasted for decades:

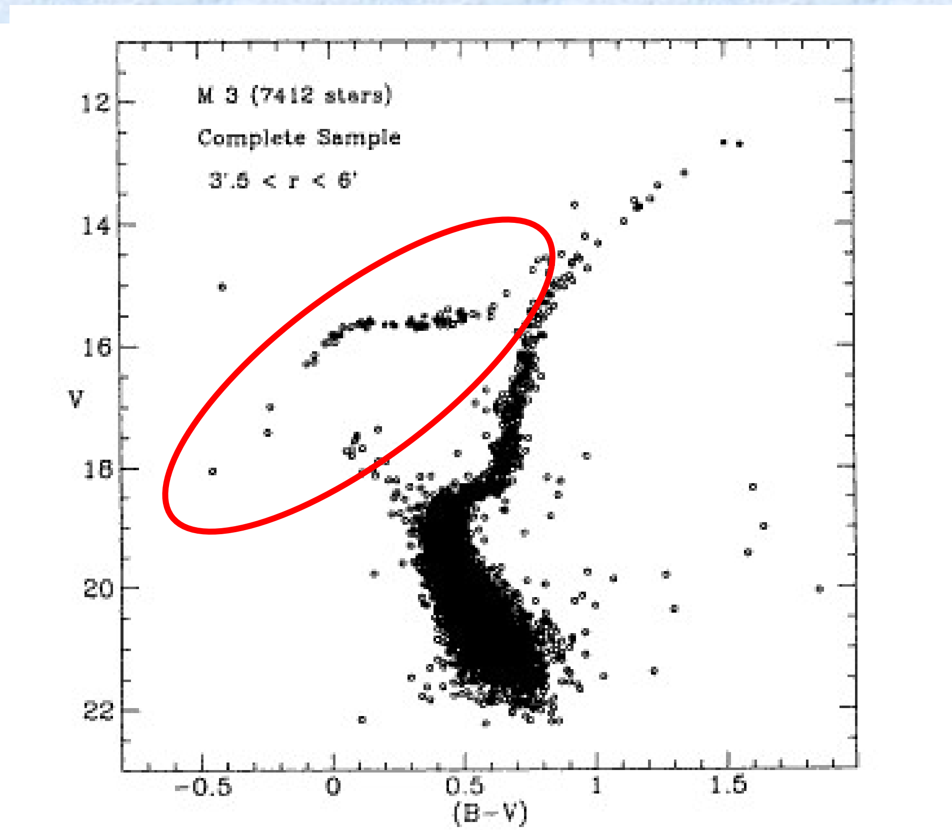
primordial contamination or accretion?

Even older is the problem that we are not able to reproduce all observed properties of the globular clusters horizontal branches

M13: all blue HB (2 RRLyr) and hot blue tail

M3: red clump, RRLyr, and blue side all well populated (no tail)

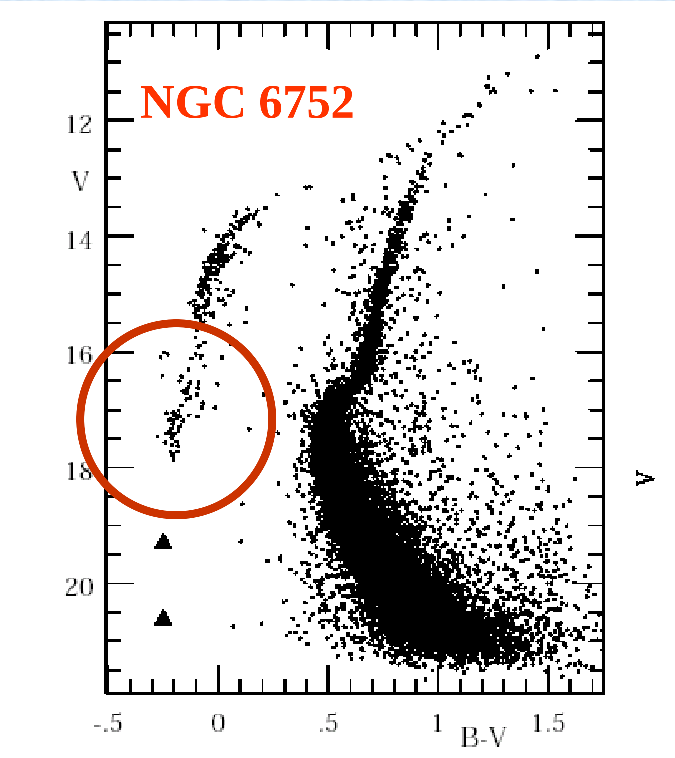




Same [Fe/H] content

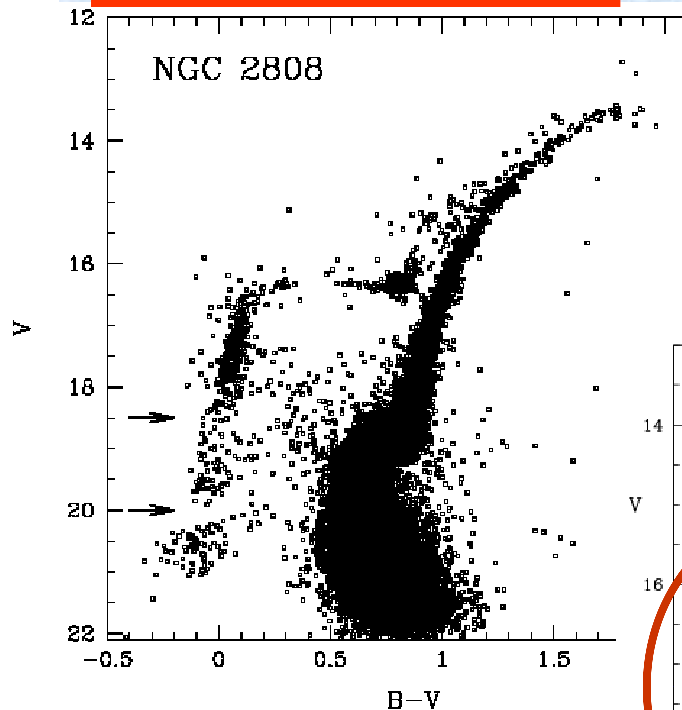
…there are many other problems on the HB

"simple" synthetic models can not easily explain:



EHBs

Bedin et al. 2000

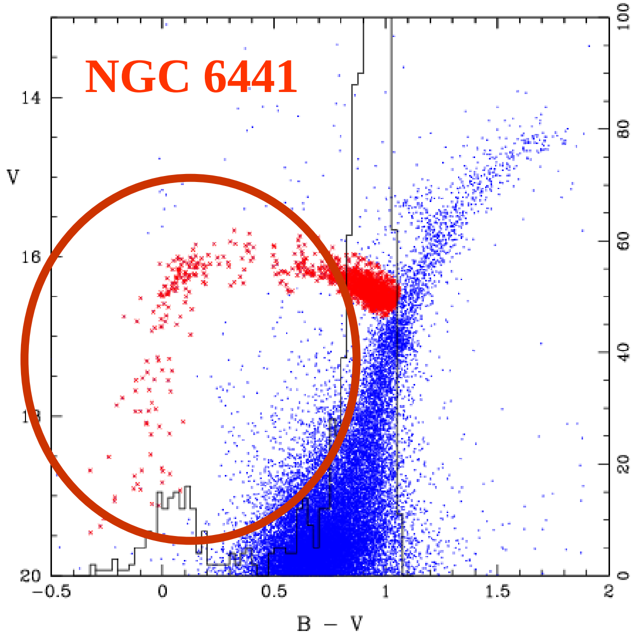


EHB multimodal distribution

anomalous HBs in high Z GCs →

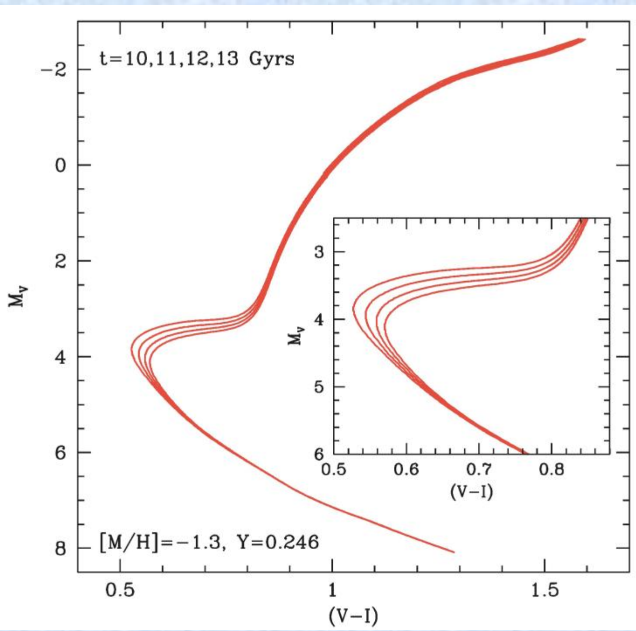
… all clusters showing O-Na anticorrelation

Piotto et al. 2002

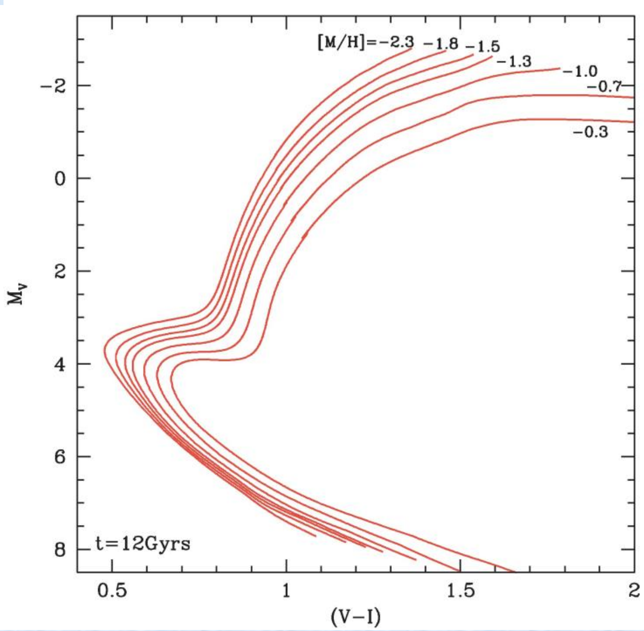


The paradigma starts to be shaked:

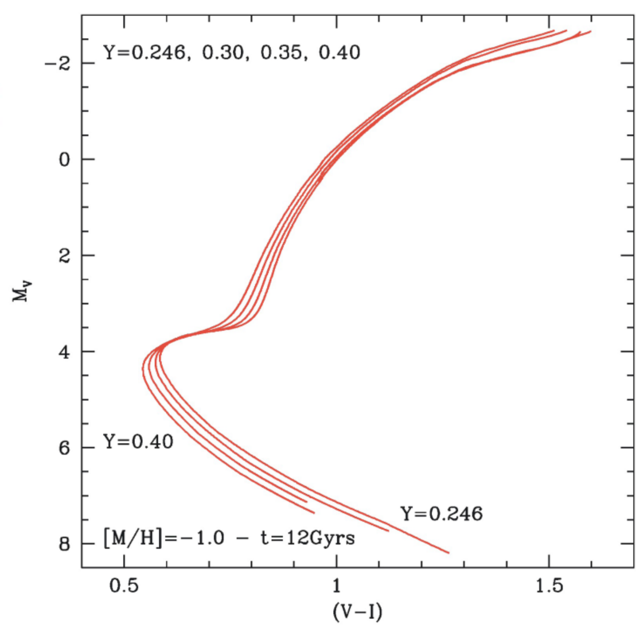
May be GCs are not simple, single stellar populations



Age effect



Metallicity effect



Helium effect

In principle, appropriate observations should allow us to account for all of these effects. But....cluster stellar populations ARE NOT “Simple Stellar Populations”

Multipopulations in globular clusters: The smoking guns

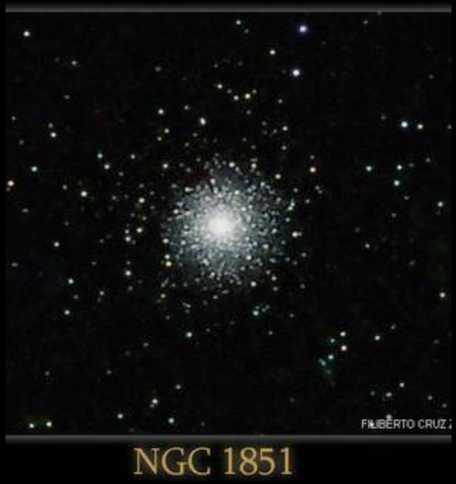
The "bad guy": NGC 6388

The "puzzling" ω Cen

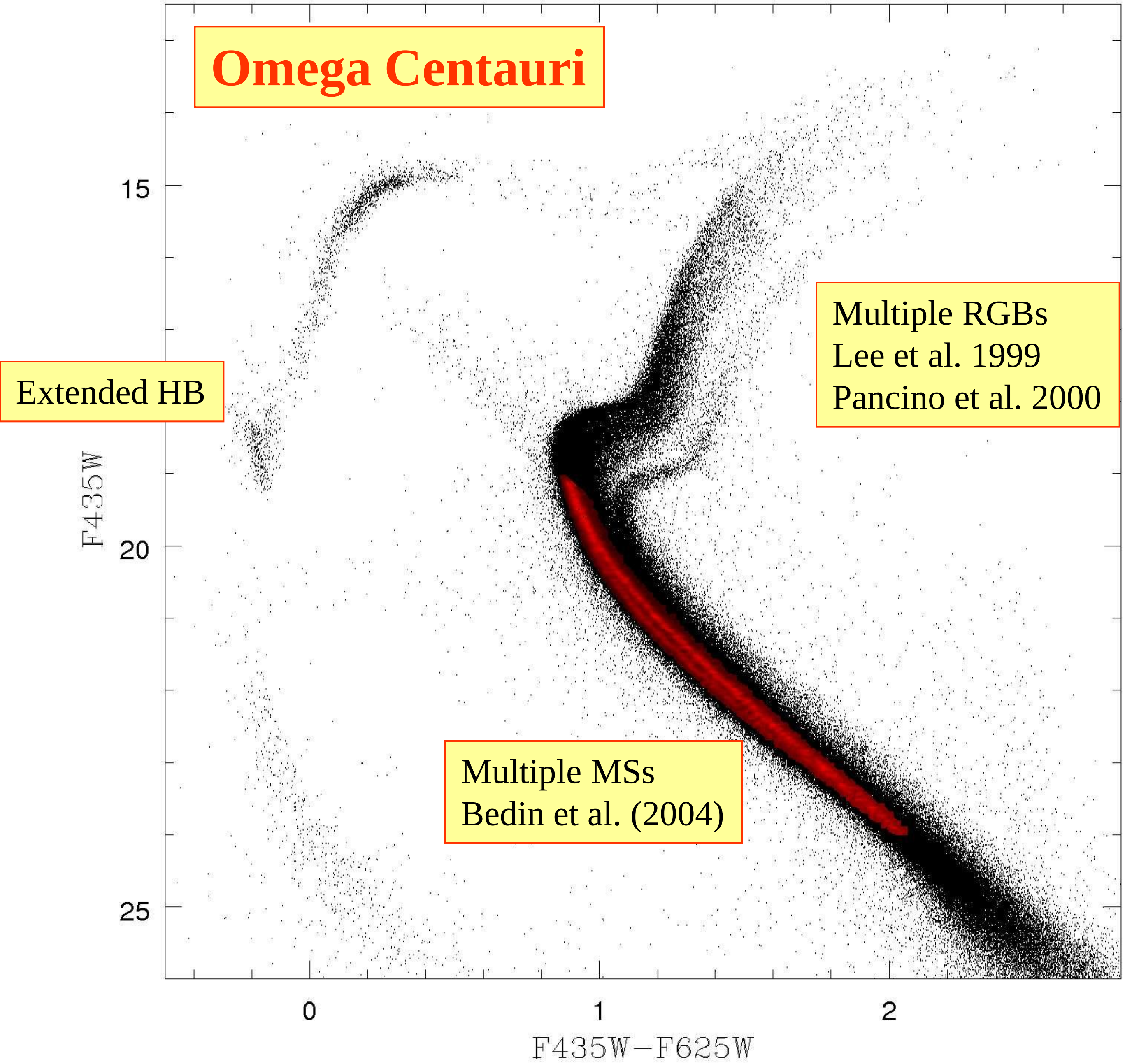
The" complex" M54

The "debated" M22

The "incredible" NGC 2808



The "normal" (?!) NGC1851



The scenario abruptly change. The “special” case: **ω Centauri**

Most massive Galactic “globular cluster” (present day mass ~4 million solar masses).

Well known (since the ’70s) spread in metallicity among RGB stars.

The first evidence for a metallicity spread:

- Freeman & Rodgers (1976) - -1.6 ≤[Ca/H]≤-0.6 from 25 RRLyr
- Butler et al. (1978) - -1.9 ≤[Ca/H]≤-0.9 from 50 RR Lyrae
- … Rey et al. (2000) – confirmed from 131 RR Lyrae

Circumstantial evidence from RGB stars:

•The first hint -Norris & Bessel (1975-77).

•Accurate spectroscopic survey from:

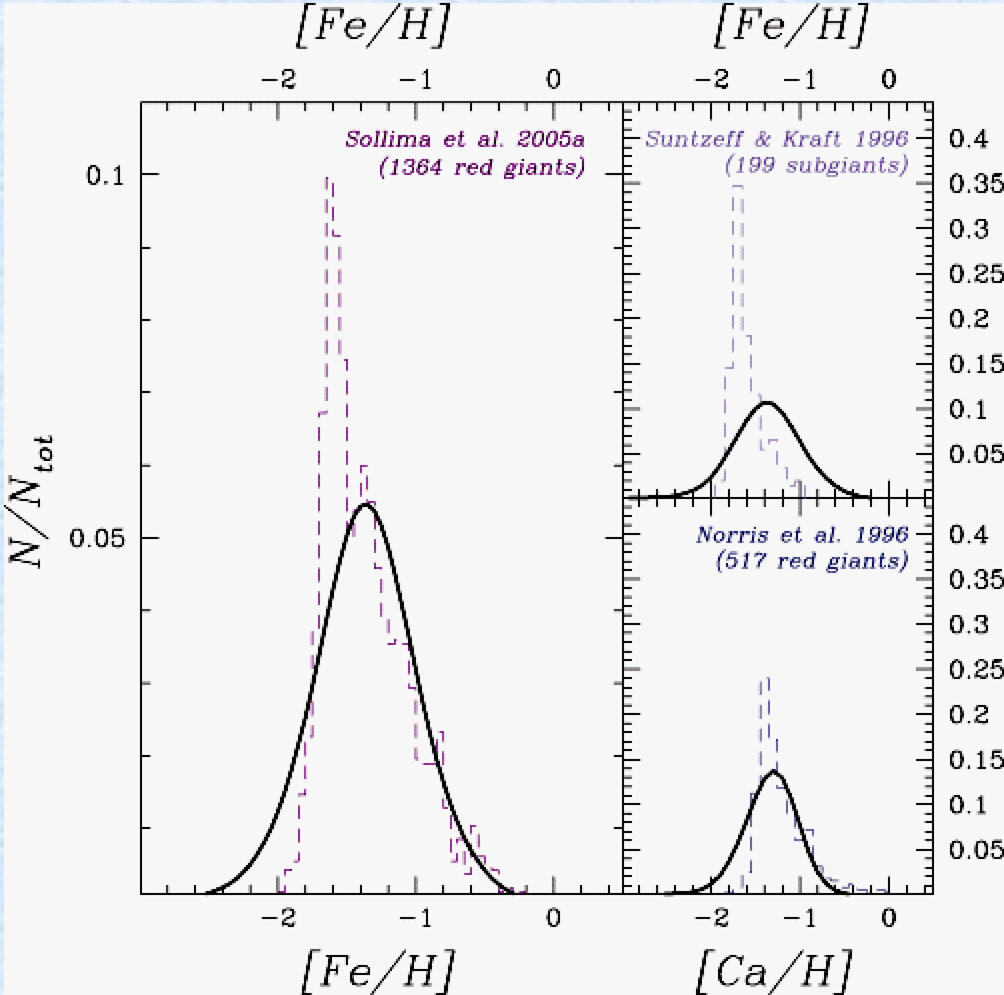
• Suntzeff & Kraft (1996)

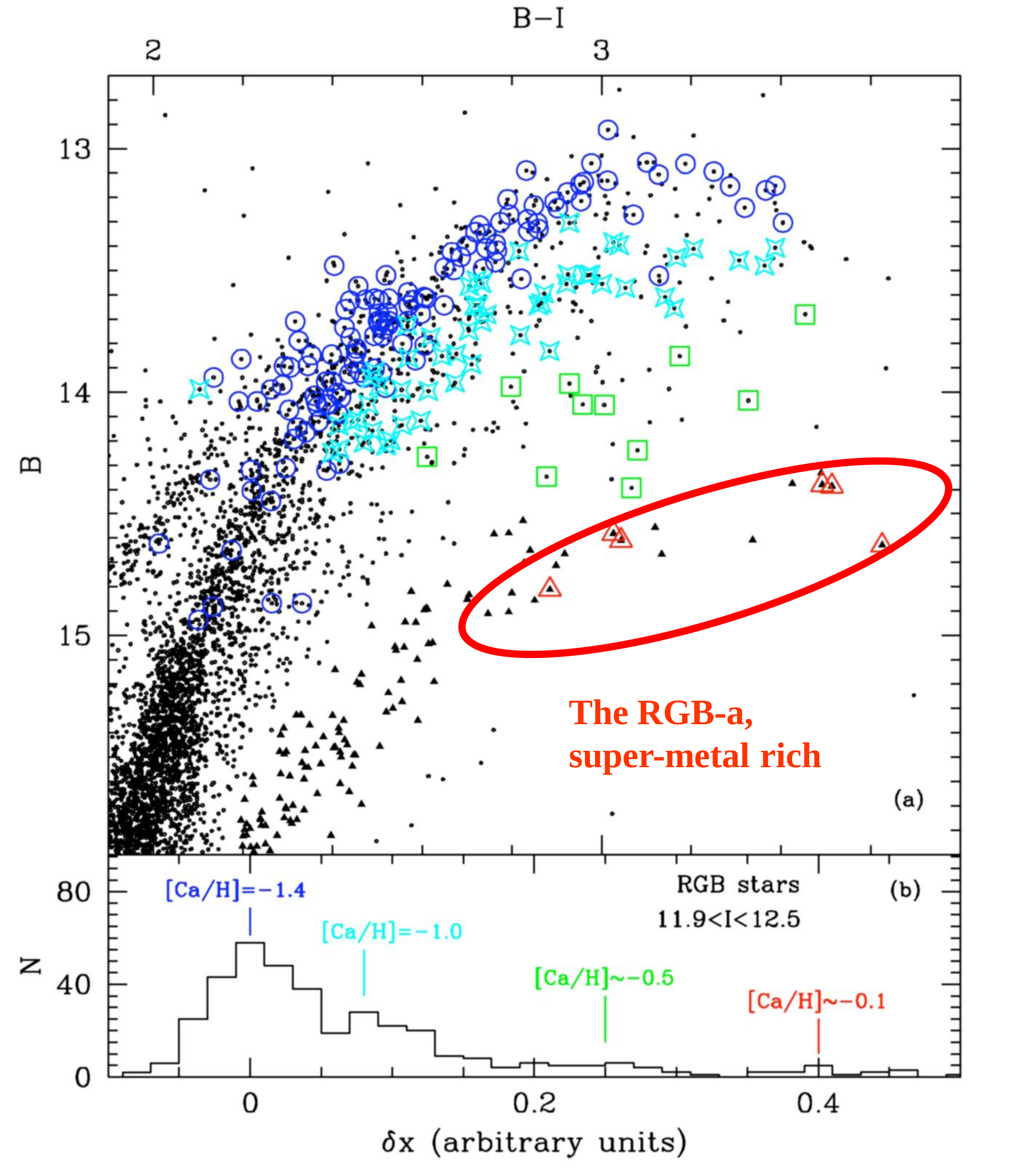
• Norris et al (1997) results:

✓no very metal-poor stars

✓a sharp peak at [Fe/H]≈-1.6

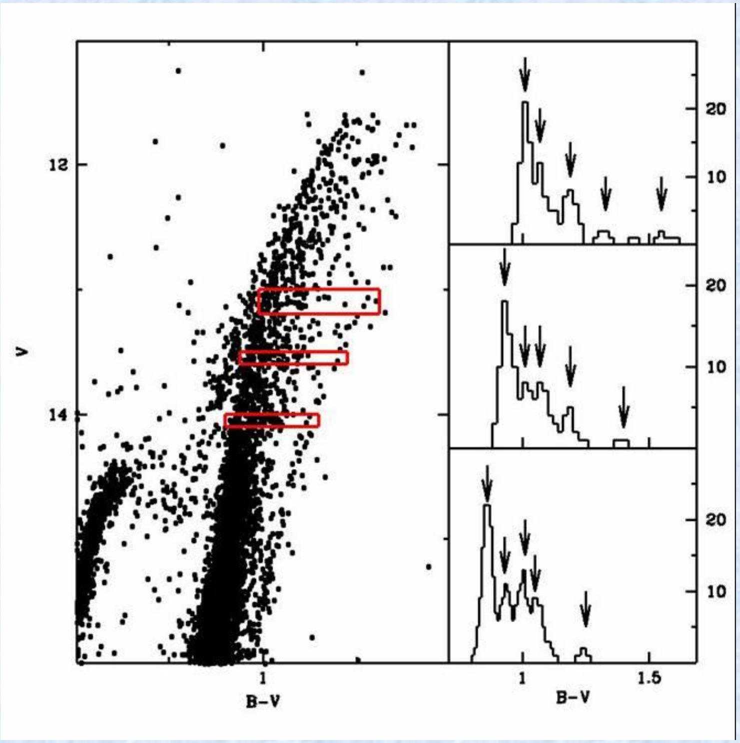
✓a wide tail extending to high metallicity



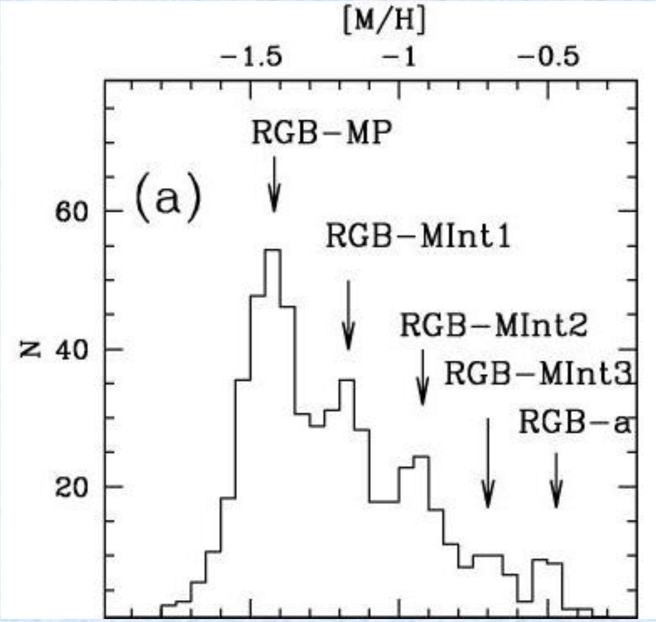


First results from accurate, wide field photometry:

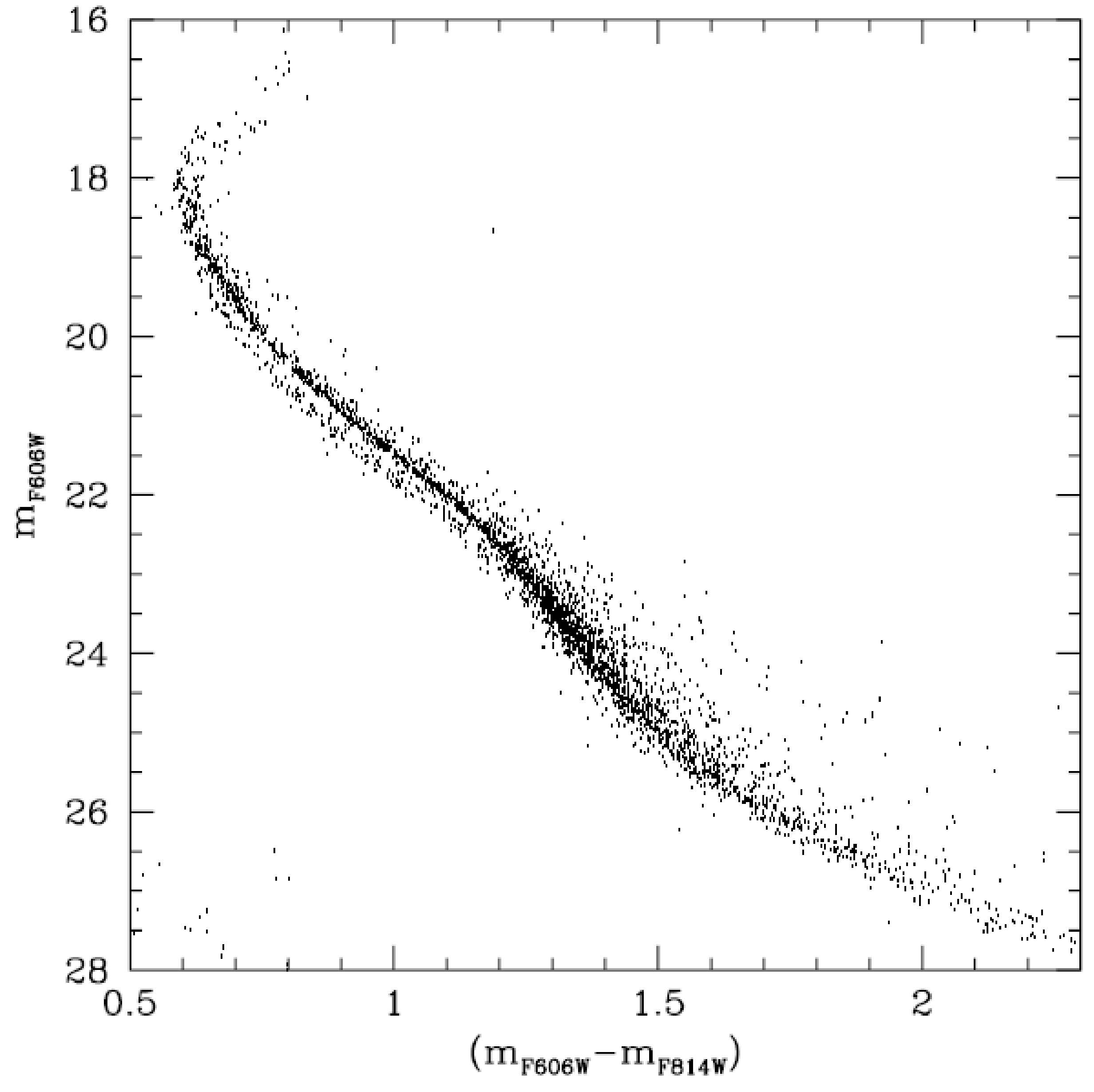
The multiple RGB (Lee et al. 1999. Pancino et al. 2000), following the complex metallicity distribution



VLT@ESO data: Sollima et al. (2005)



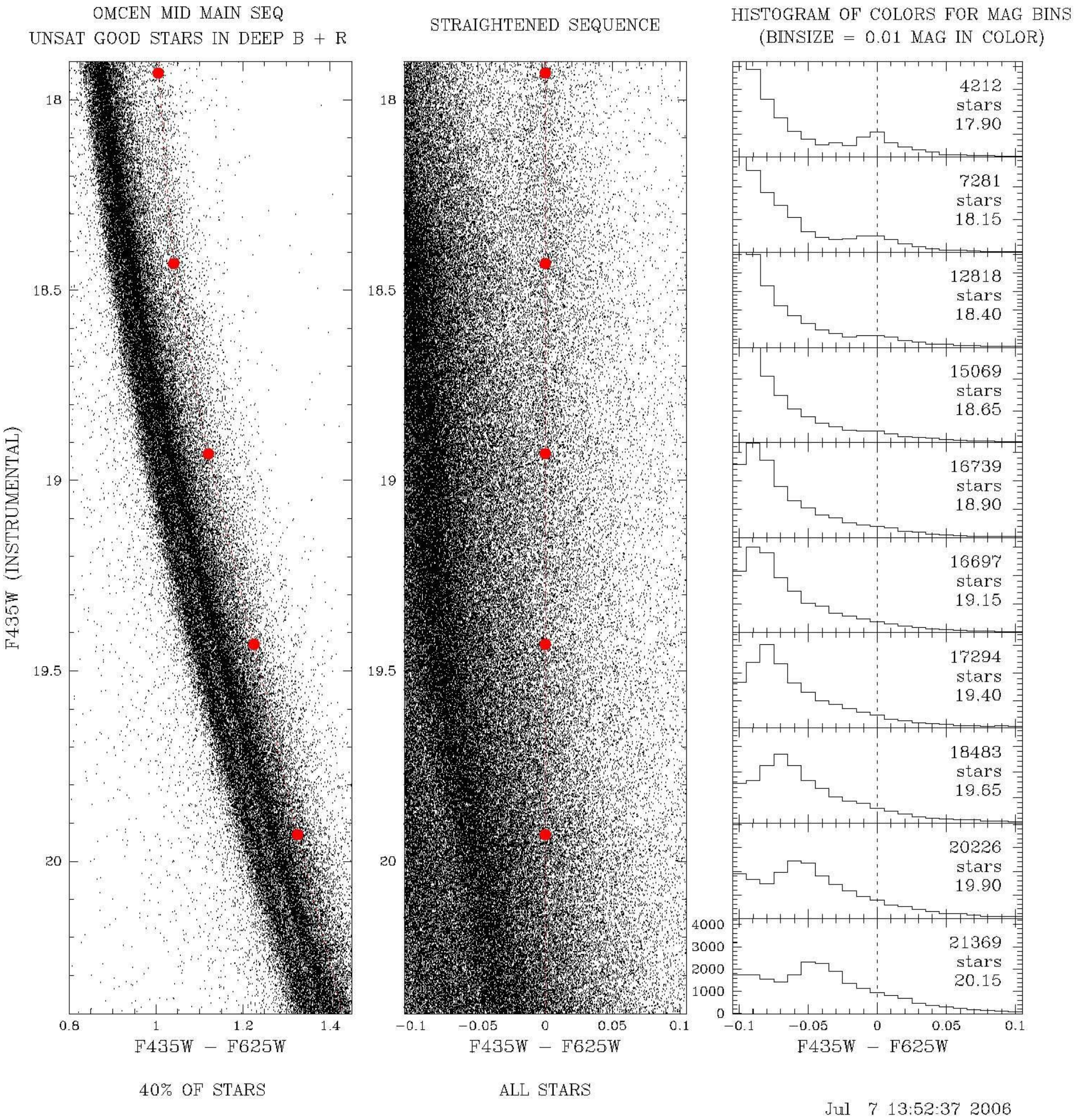
sub-population	<[M/H]>	%
RGB-MP	-1.4	42
RGB-Mint 1	-1.2	28
RGB-Mint 2	-0.9	17
RGB-Mint 3	-0.7	8
RGB-a	-0.5	5



But with HST….

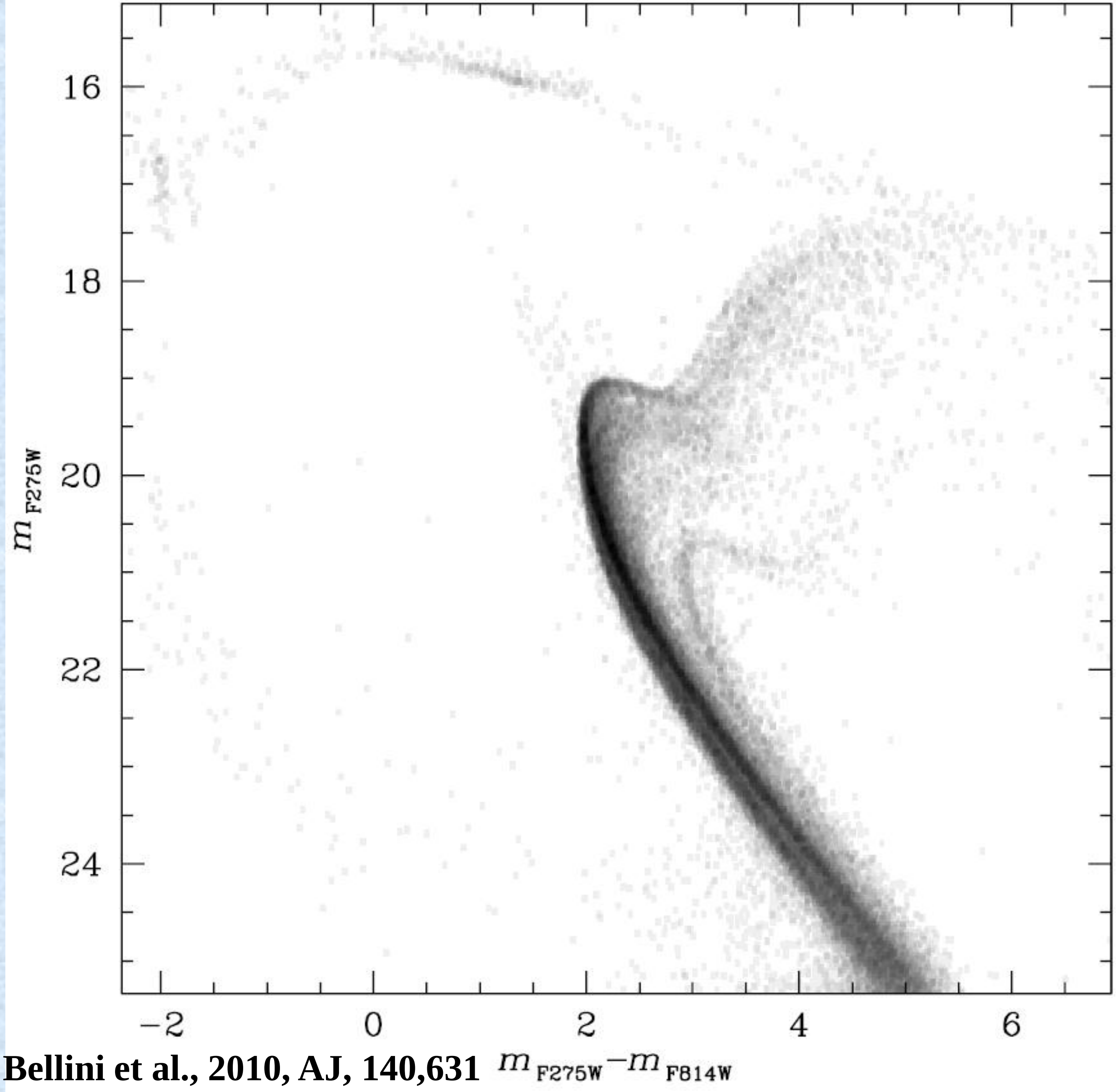
The main sequence of Omega Centauri is splitted into two "main" main sequences (Anderson, 1997, PhD thesis, Bedin et al. 2004, ApJ, 605, L125).

This is the first ***direct***, photometic evidence ever found of multiple stellar populations in globular clusters.



Indeed, also a third main sequence is clearly visible

Villanova, Piotto, Anderson et al. (2007, ApJ, 663, 296).

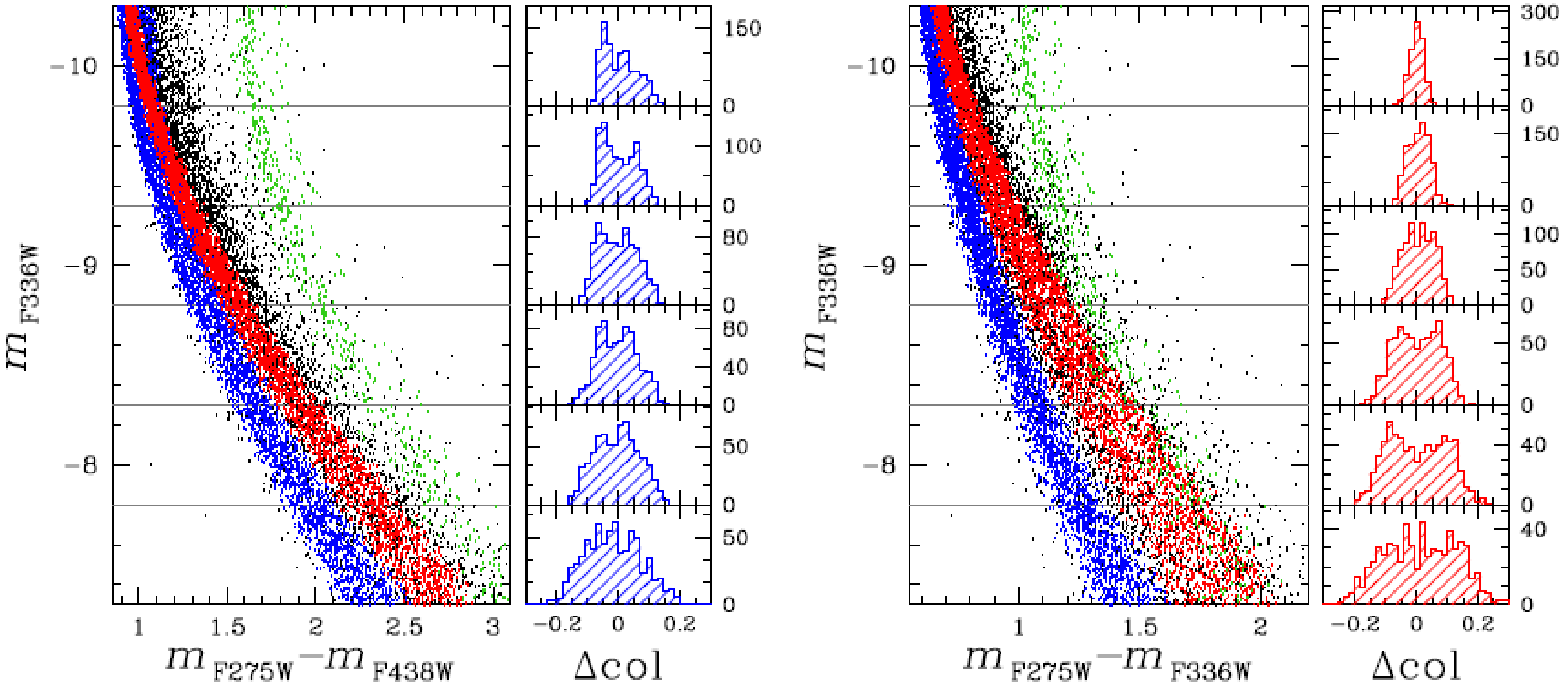


Bellini et al., 2010, AJ, 140,631

New spectacular UV data from the new WFC3 camera onboard HST. Try to count the single SGBs. We see at least 11 SGBs!

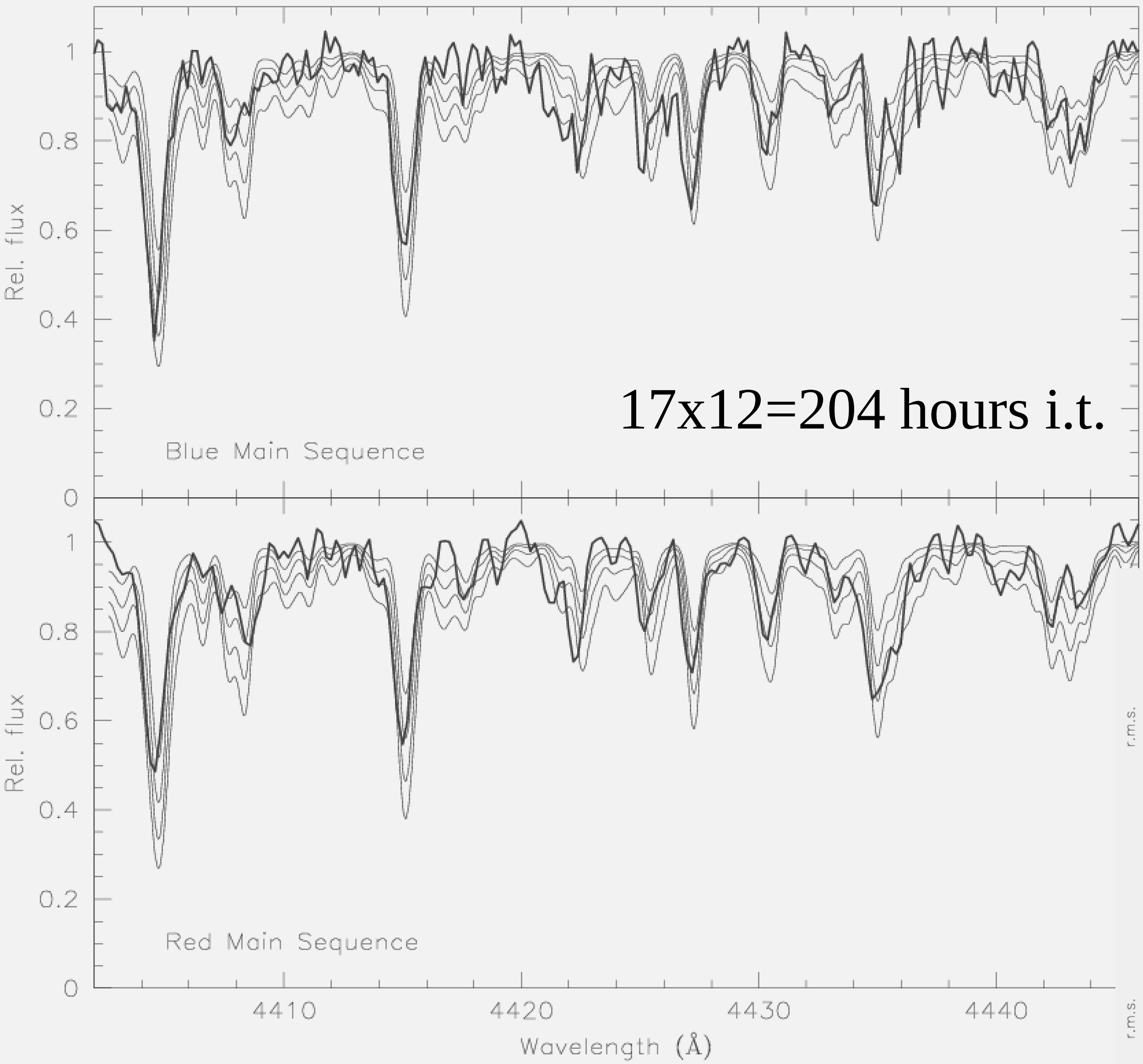
Amazing perspectives with WFC3

Even more complex!!!!! (WFC3/HST multiband photometry)



Bellini et al. 2011, in preparation

The most surprising discovery

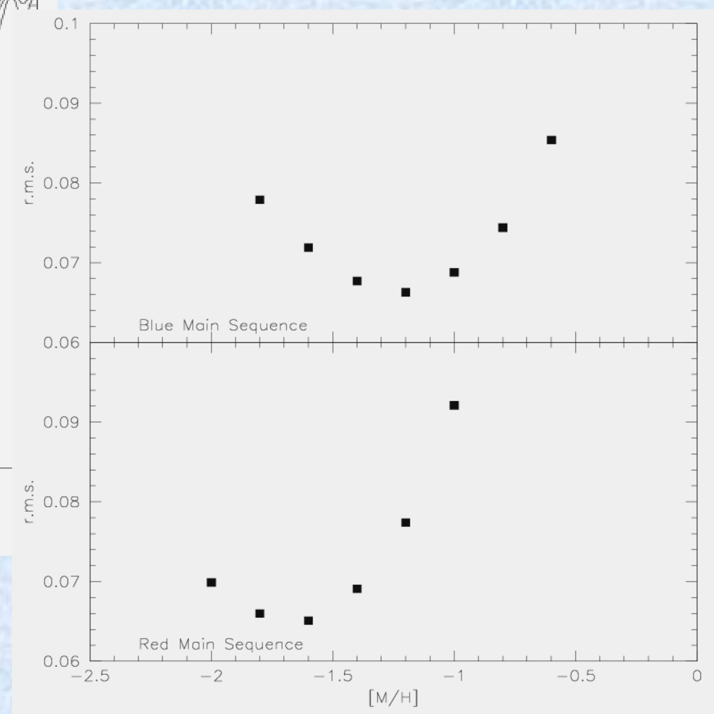


17x12=204 hours i.t.

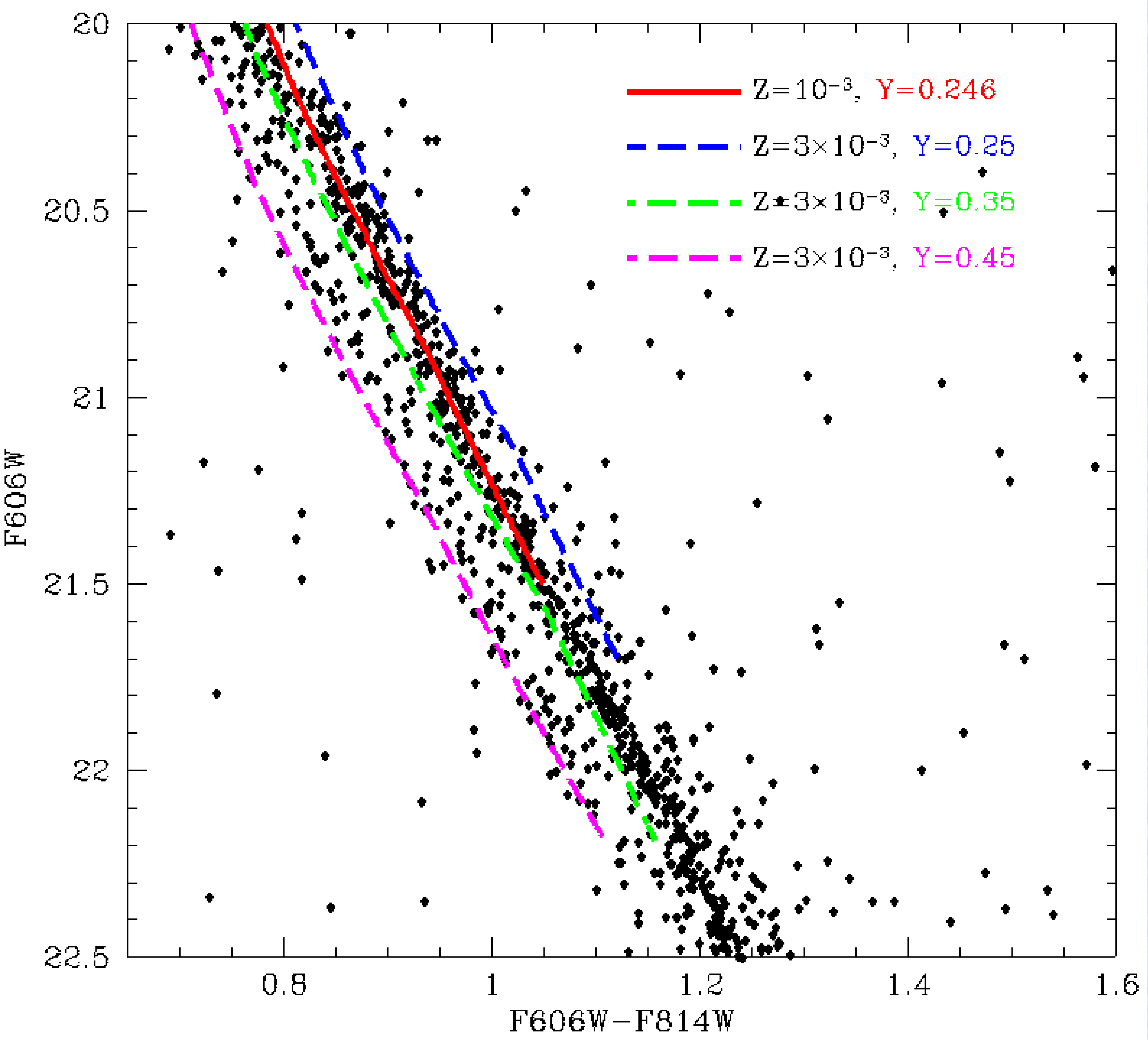
RedMS:
Rad. Vel.: 235+-11km/s
[Fe/H]=-1.56

BlueMS:
Rad. Vel.: 232+-6km/s
[Fe/H]=-1.27

It is more metal rich!



Piotto et al. (2005, ApJ, 621,777)

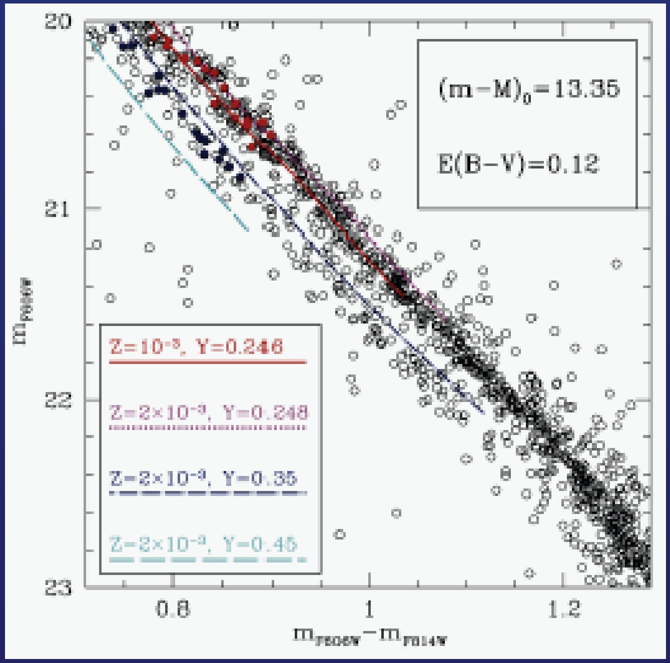


Helium!

Apparently, only **an overabundance of helium (Y~0.40)** can reproduce the observed blue main sequence

Piotto et al. (2005, ApJ, 621,777)

A query for … more Helium…



Some problems:

- **Who is responsible for this huge Helium production?**
- **In order to increase Y from 0.24 to ~0.38, one has to assume that most, if not all!, of the material from which the bMS stars formed is formed by the ejecta of the first stellar generation (Initial Mass Function…?);**
- **these ejecta (a big amount in view of the size of the bMS population) must have been well homogenized in their metal content before the bMS stars formed;**

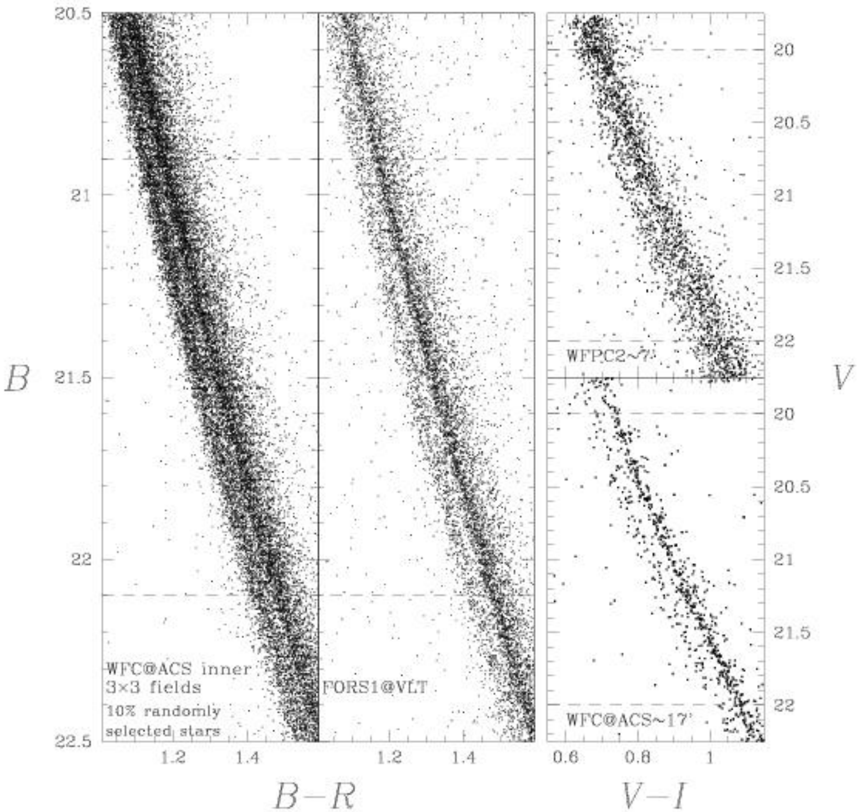
The blue Main Sequence can be reproduced only by adopting 0.35<Y<0.40

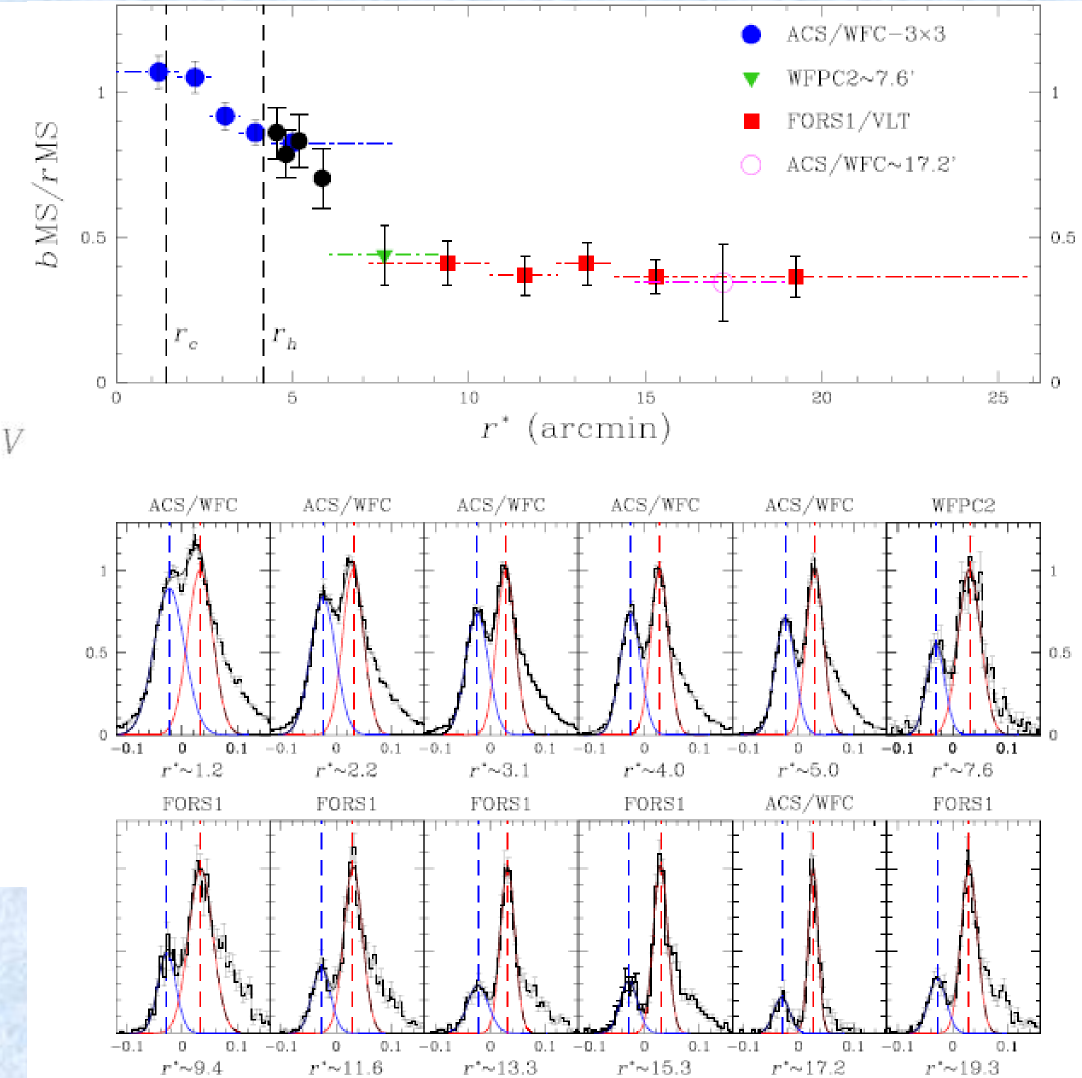
→ $\Delta Y/\Delta Z > 70$!!!

…but see Romano et al. (2007)… "No Way!!!"

Omega Centauri: Radial distribution of main sequence stars

Bellini et al. 2009, A&A, 507, 1393





The double MS is present all over the cluster, from the inner core to the outer envelope, but….

…the two MSs have different radial distributions: the blue, more metal rich MS is more concentrated

Stellar Populations in Globular Clusters: a new era and a new vision. II

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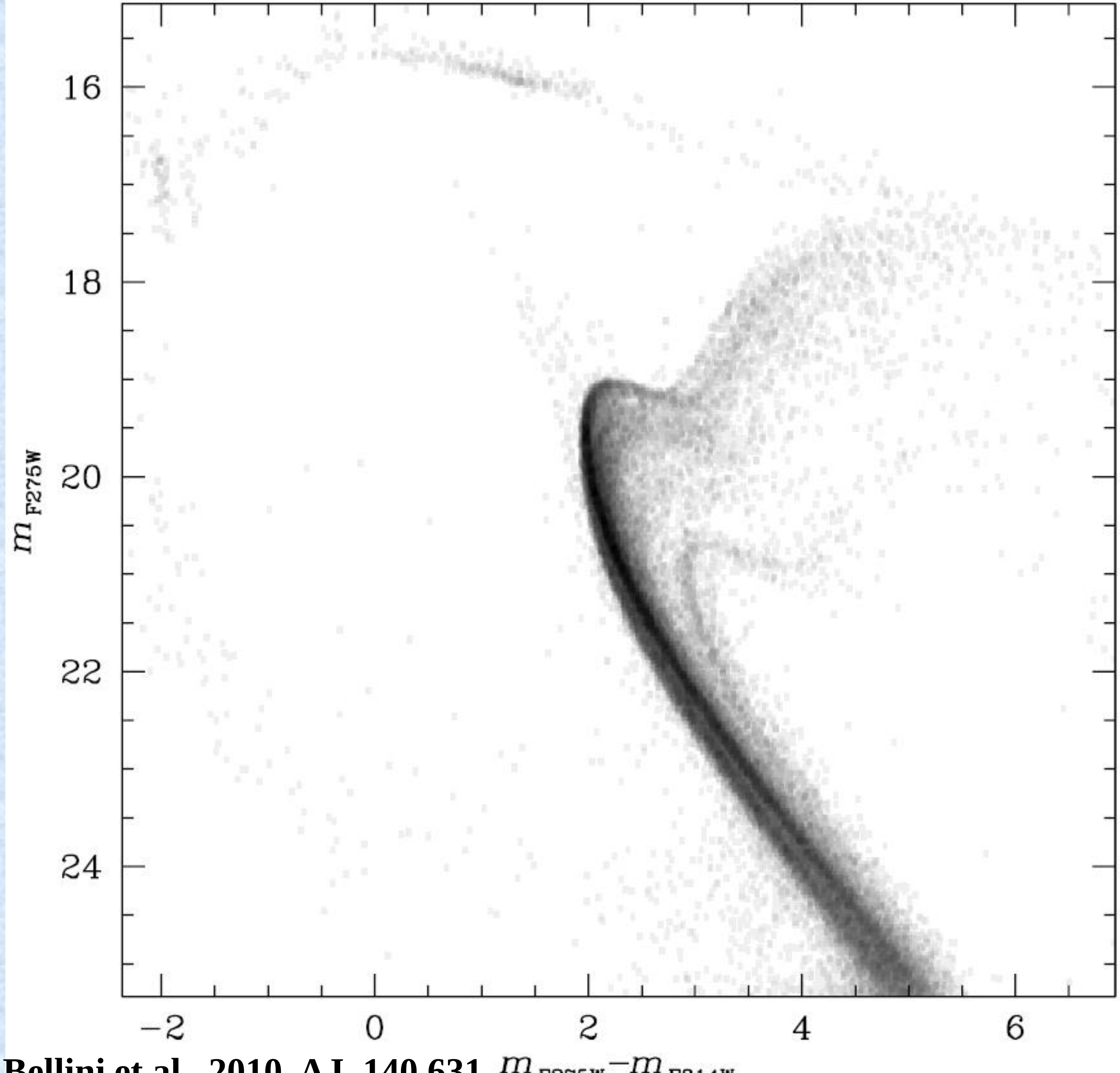

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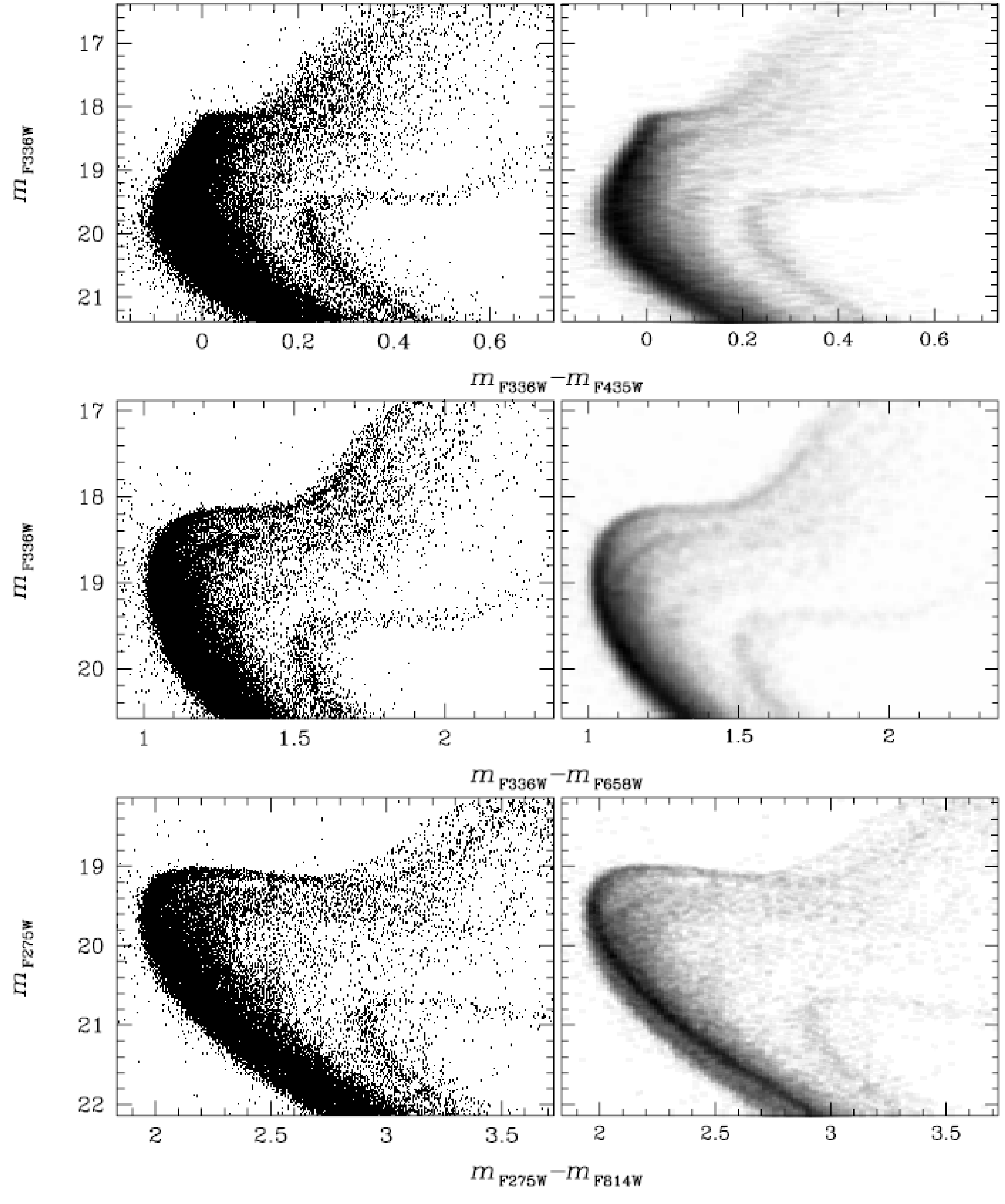
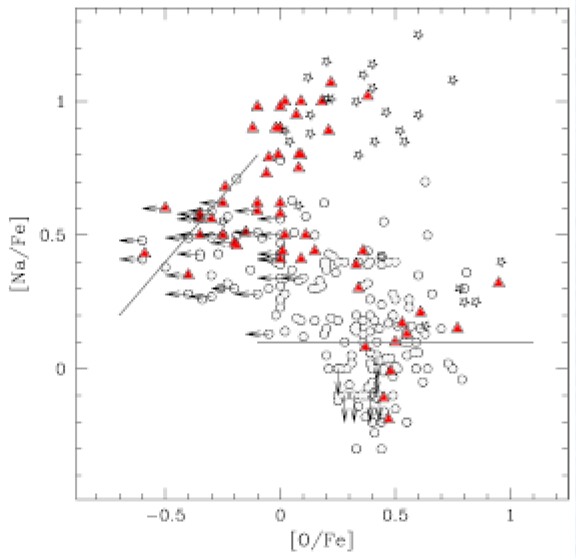


Again from WFC3

Different color baselines give a more complete view of the complexity of Omega Centauri stellar populations

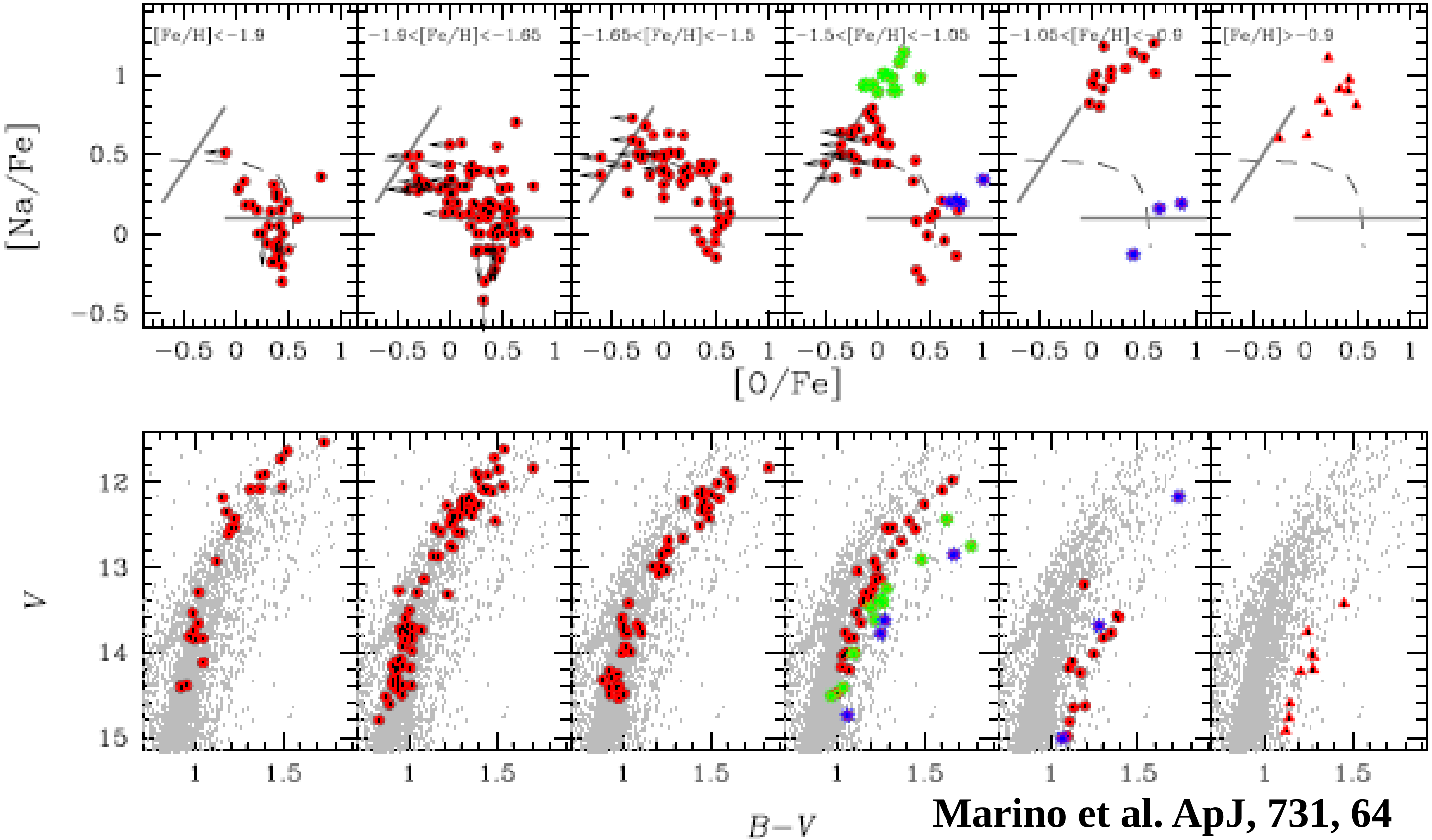


Stellar groups with different [Fe/H] have their own NaO anticorrelation.

NaO anticorrelation becomes more and more extended at increasing metallicity.

Most metal poor stars have close to primordial Na, O

Most metal rich group has strongly Na enhancement, moderate O depletion.

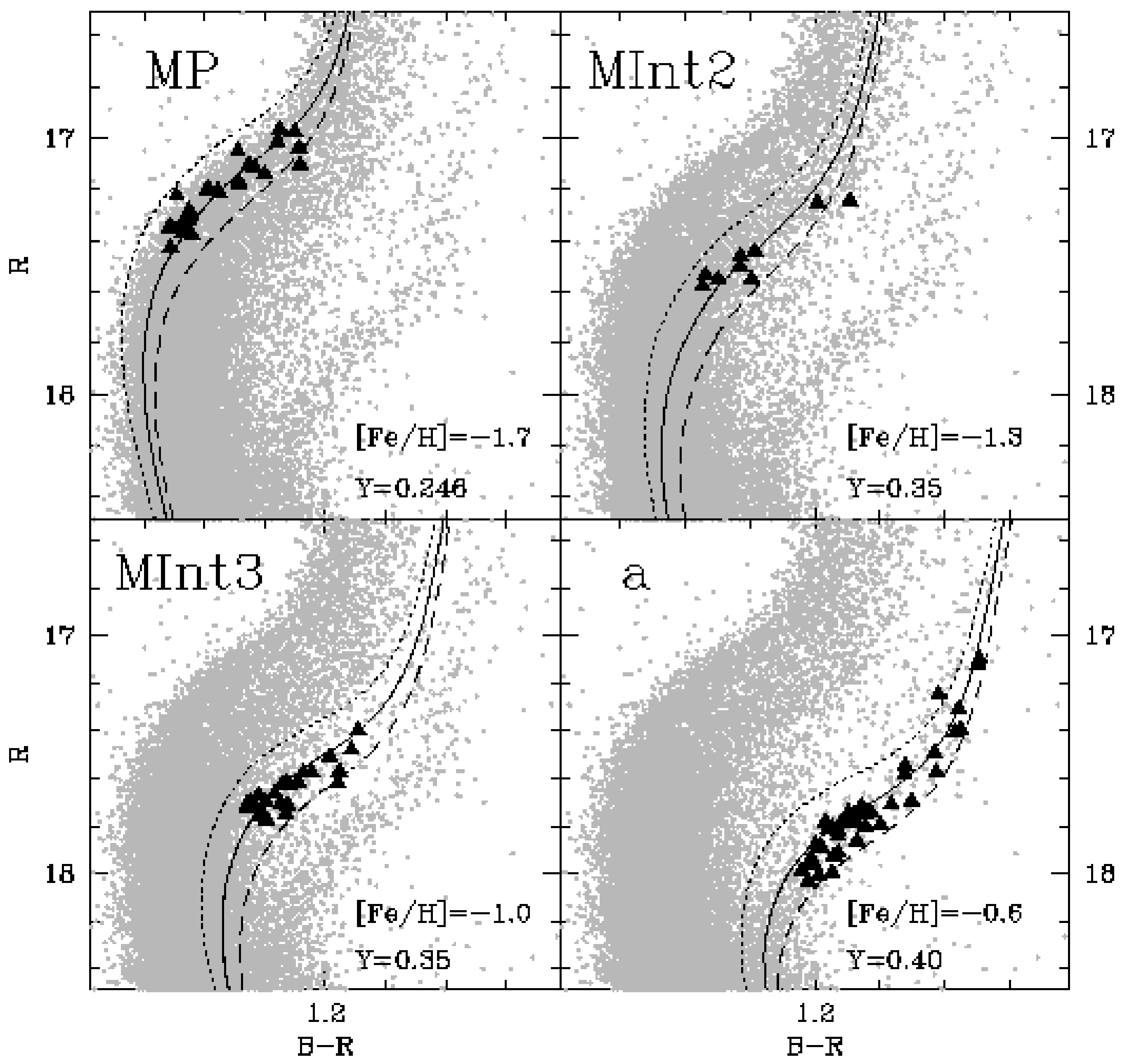


Basic ingredients to reconstruct the formation of Omega Centauri.

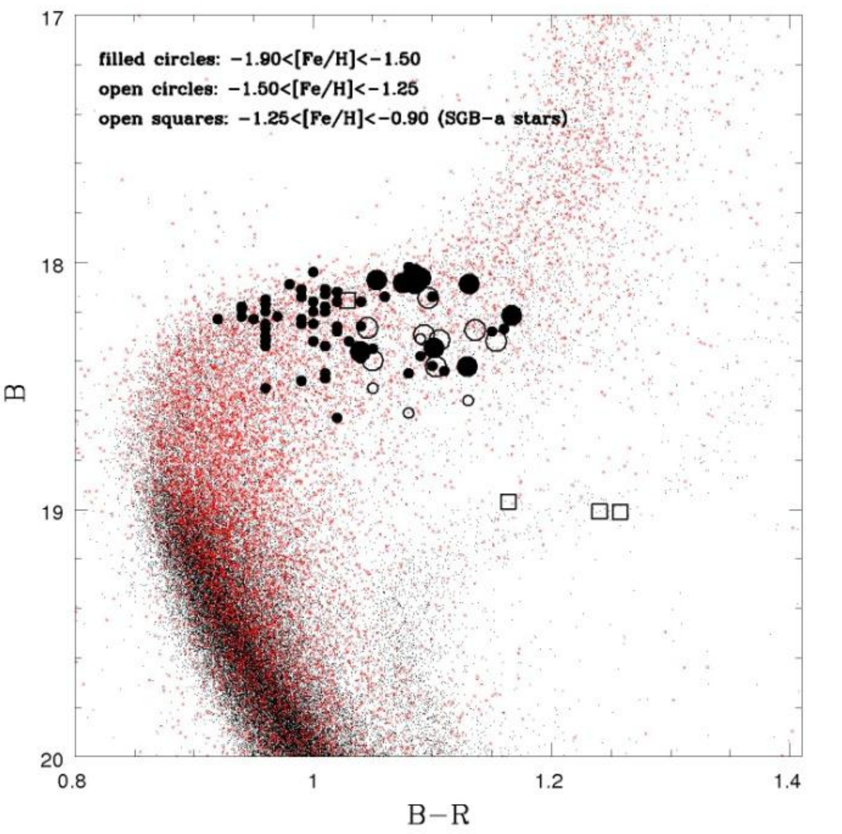
Distinct (in space and time) star formation episodes in a dwarf galaxy?

Marino et al. ApJ, 731, 64

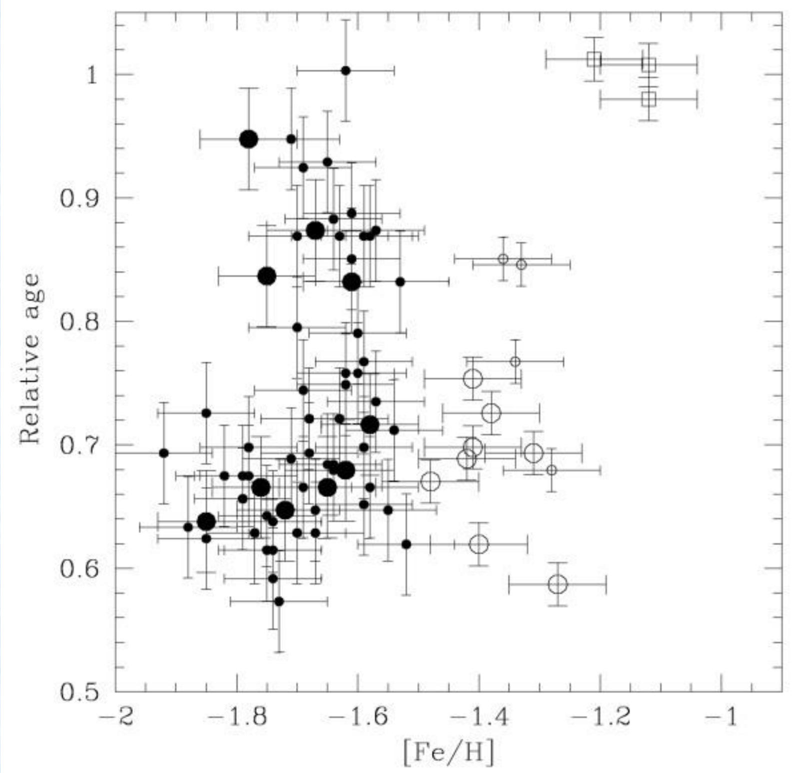
The age problem



Sollima et al (2005): using metallicity from low resolution spectroscopy (Ca triplet) + assumptions on the He content find an age dispersion <u><1.4 Gyr</u>, consistent with null age dispersion.

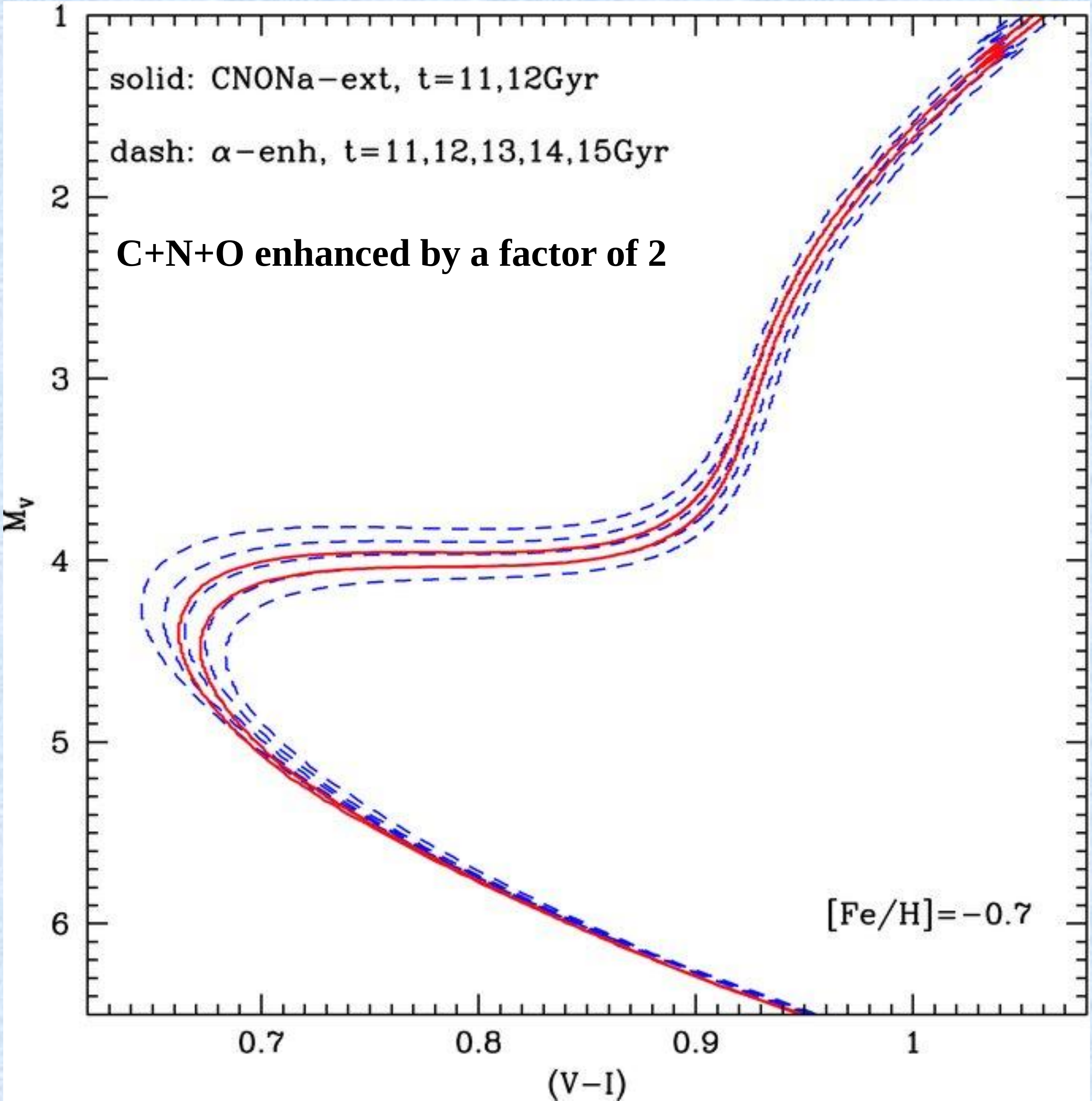


Villanova et al. (2007): [Fe/H] from high resolution spectroscopy. Note how stars with similar metallicity have a large magnitude spread along the SGB



Accounting for the [Fe/H] content and magnitude on the SGB, and assumuing the only the metal intermediate population is He rich, Villanova et al. find **an age dispersion of <u>~4Gyr</u>, with a complex star formation history**

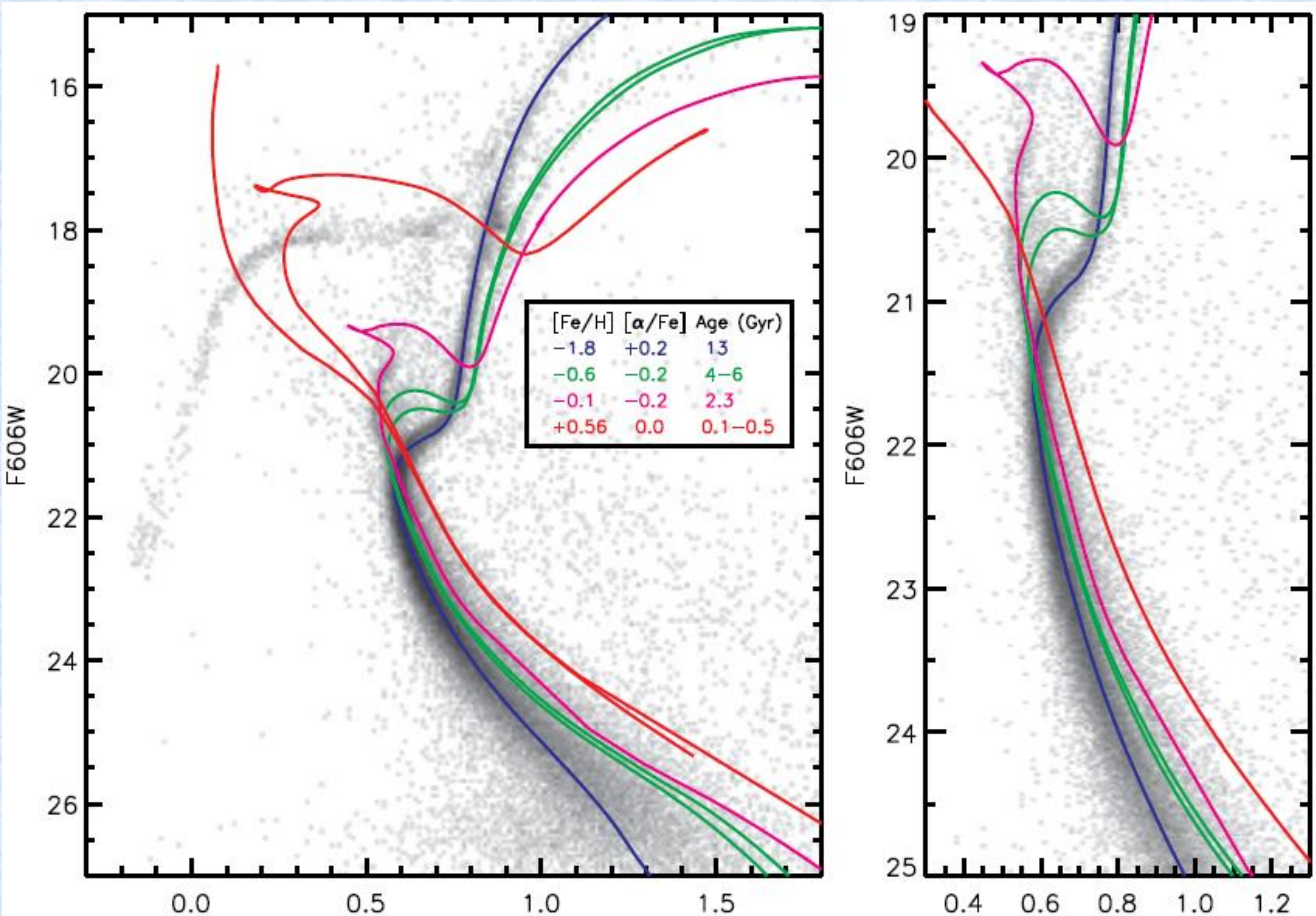
Omega Cen age dispersion remains an open issue



Effect of C+N+O enhancement

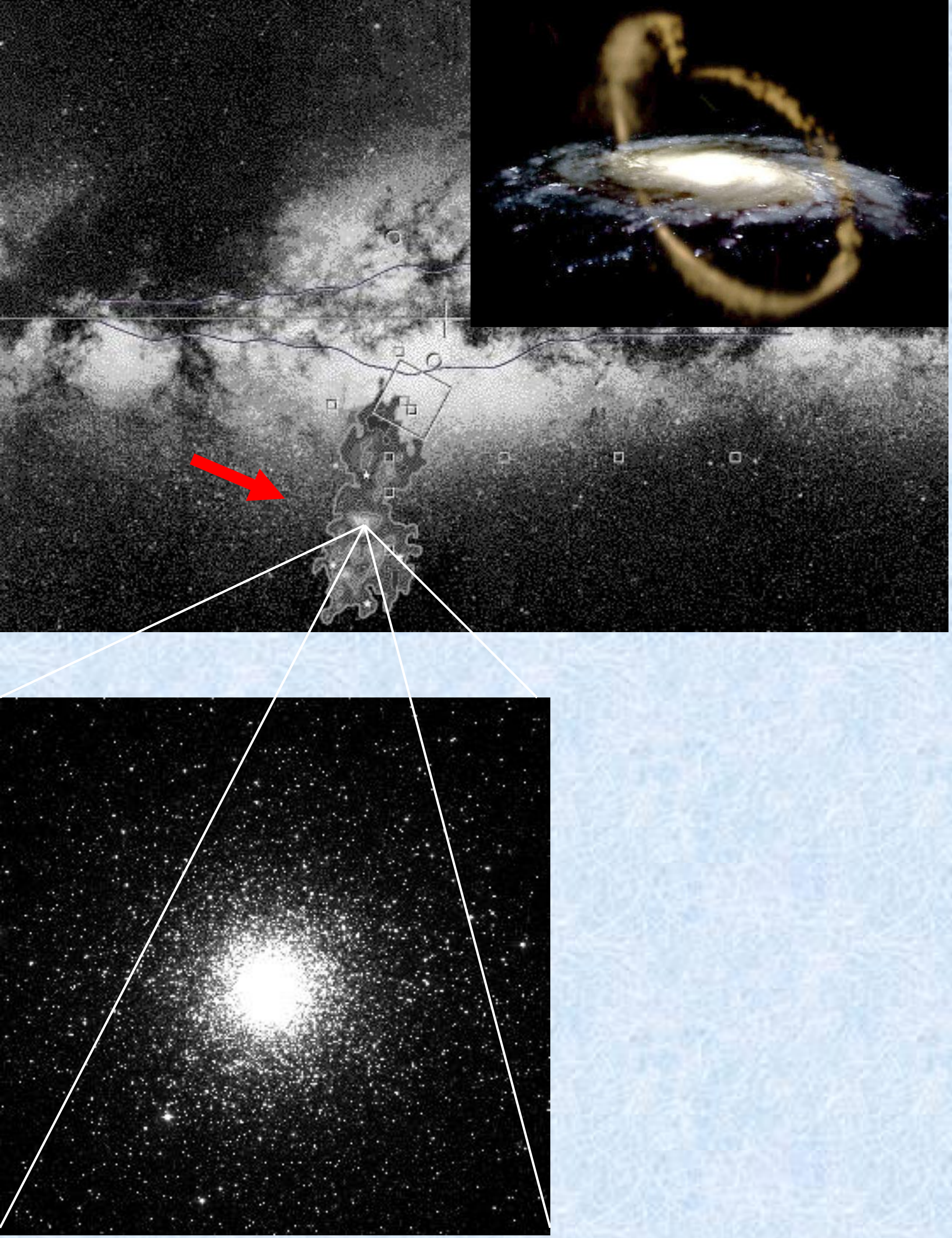
Enhanced CNO isochrones imply larger ages

NGC 6715 (M54)



Siegel et al. (2007)

Multiple MSs, SGBs, RGBs ….

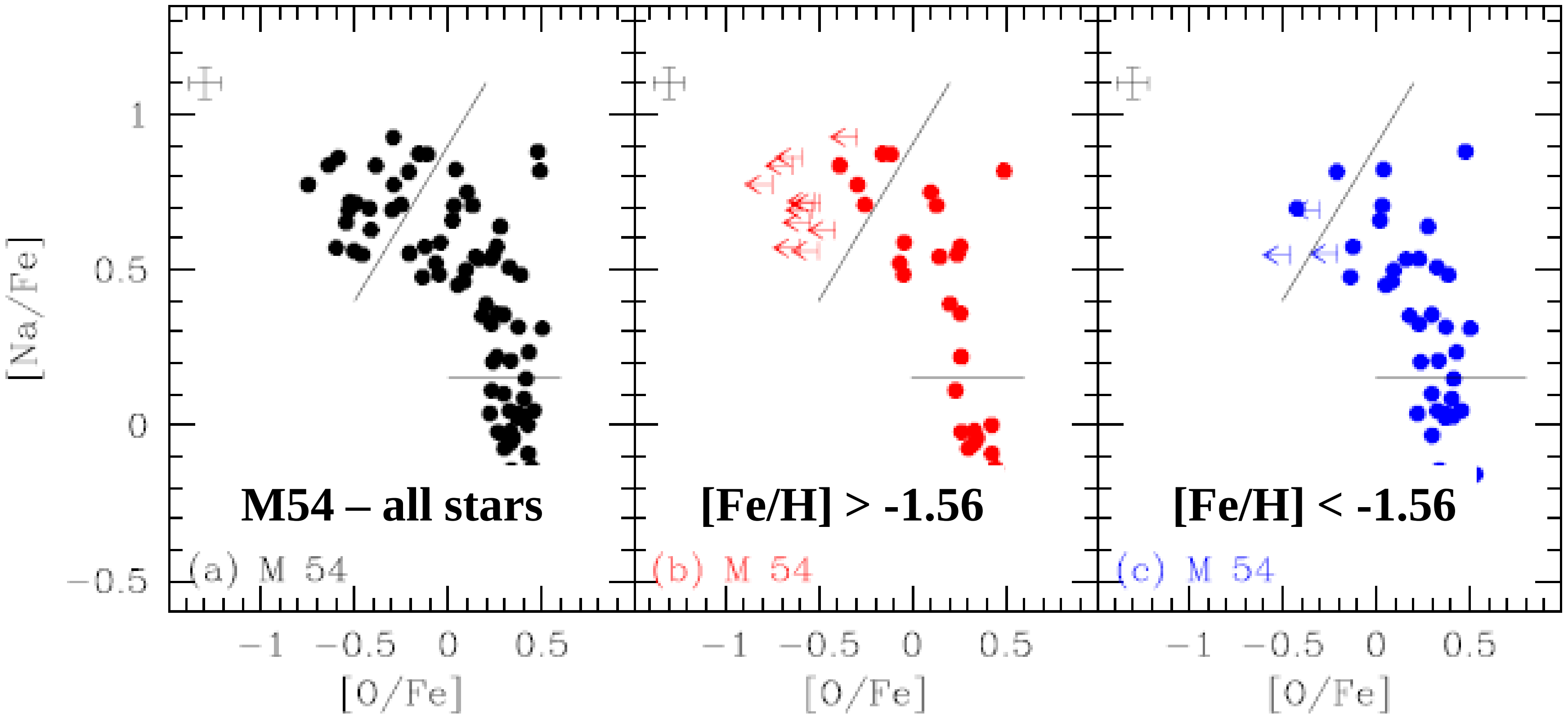


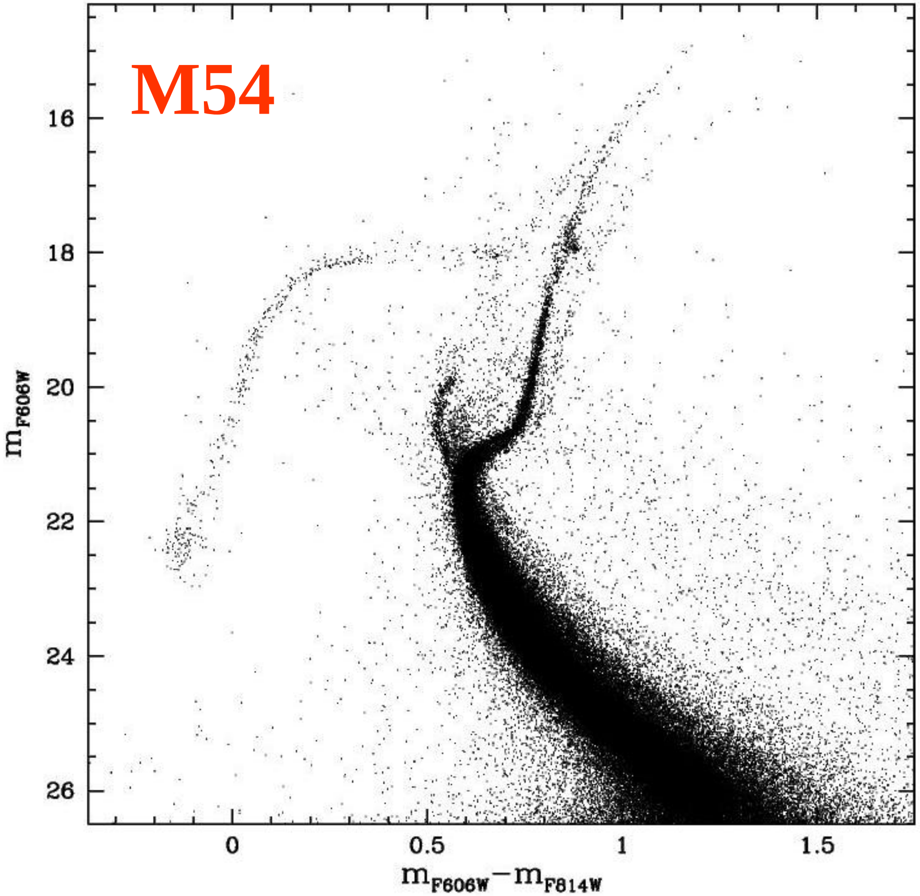
M54 coincides with the nucleus of the Sagittarius dwarf galaxy . It might be born in the nucleus or, more likely, it might be ended into the nucleus via dynamical friction (see, Bellazzini et al. 2008), but the important fact is that, today:

The massive globular cluster M54 is part of the nucleus of a disaggregating dwarf galaxy.

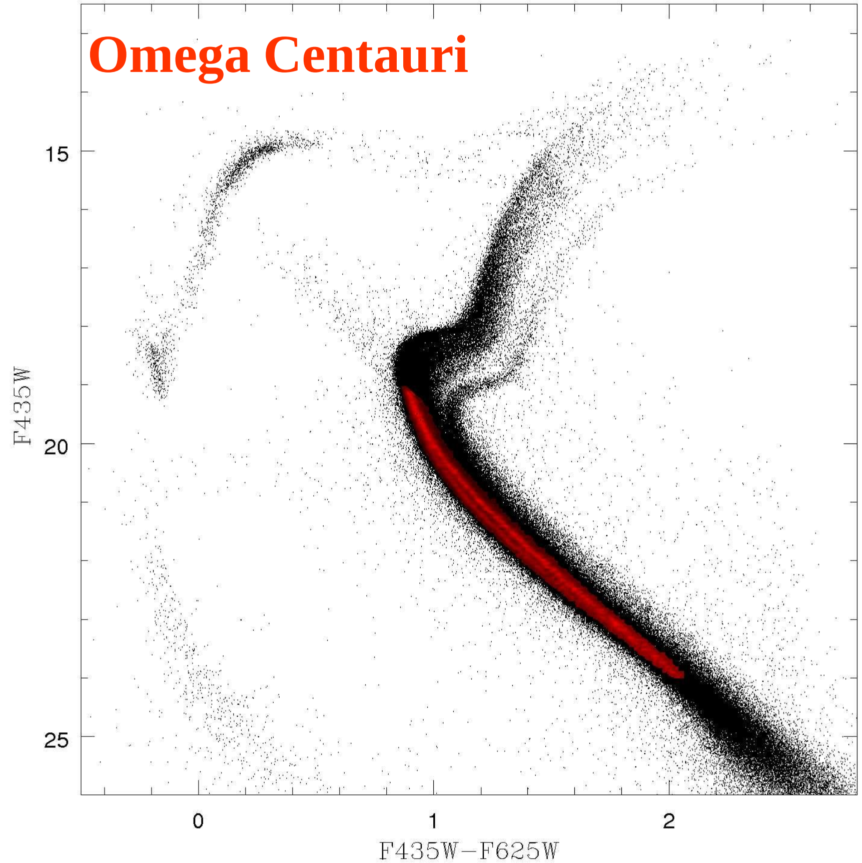
M54 NaO pattern is similar to that of Omega Centauri: More extended in more metal rich stars.

(Carretta et al. 2010, ApJ, 714, L7)





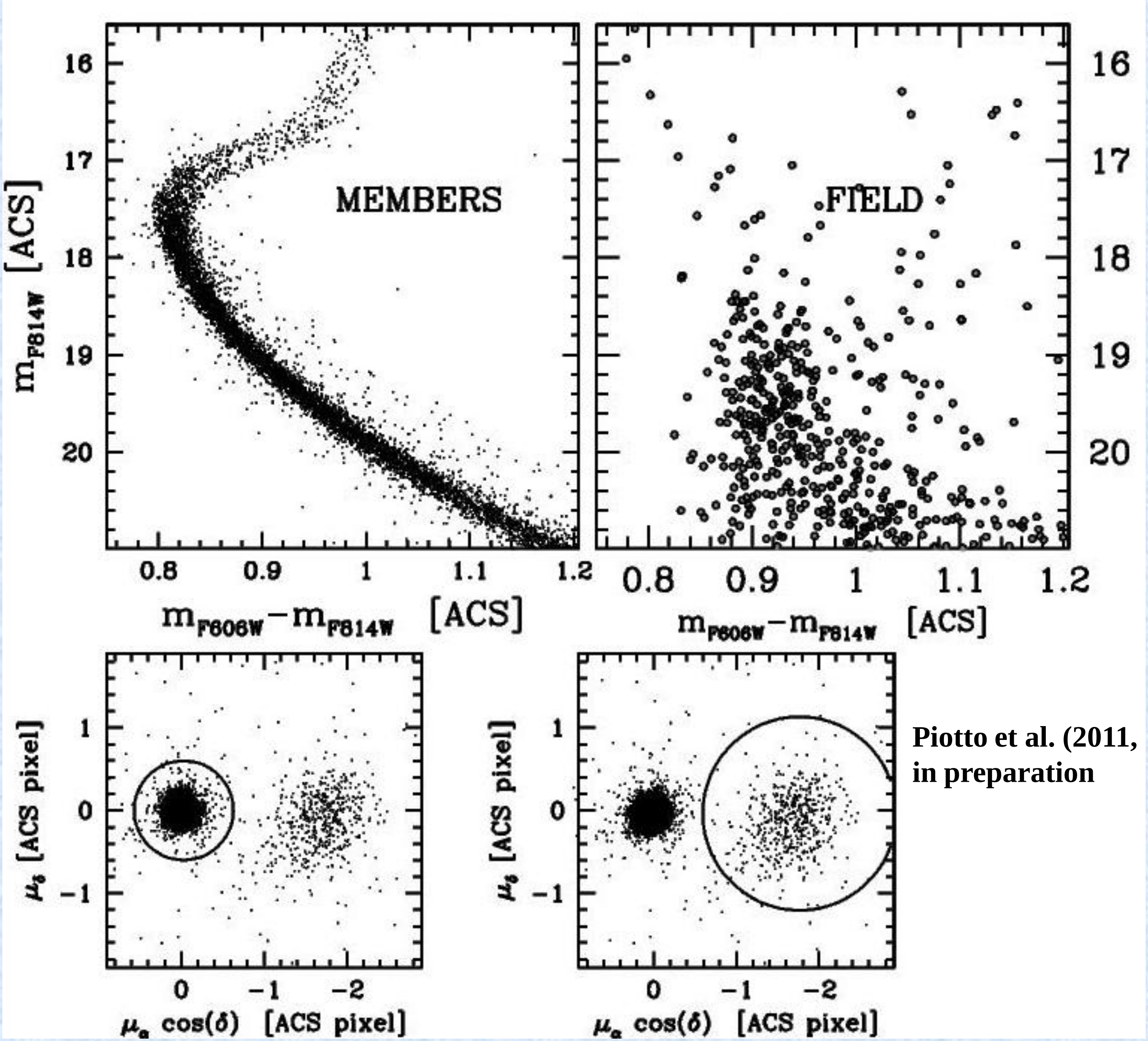
The CMDs of M54 and Omega Centauri are <u>astonishingly similar!</u>



It is very likely that M54 and the Sagittarius nucleus show us what Omega Centauri was a few billion years ago: the central part of a dwarf galaxy, now disrupted by the Galactic tidal field. But, where is the tidal tail of Omega Centauri (see Da Costa et al. 2008)?

Is this true for all globular clusters?

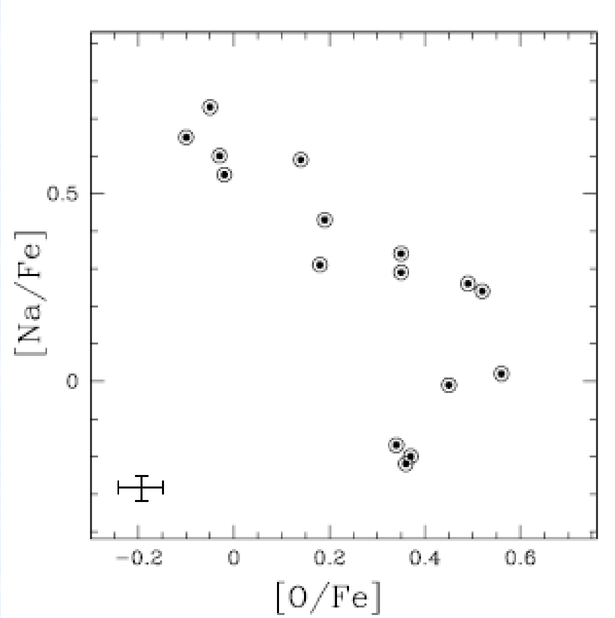
NGC 6656 (M22) double SGB



Piotto et al. (2011, in preparation

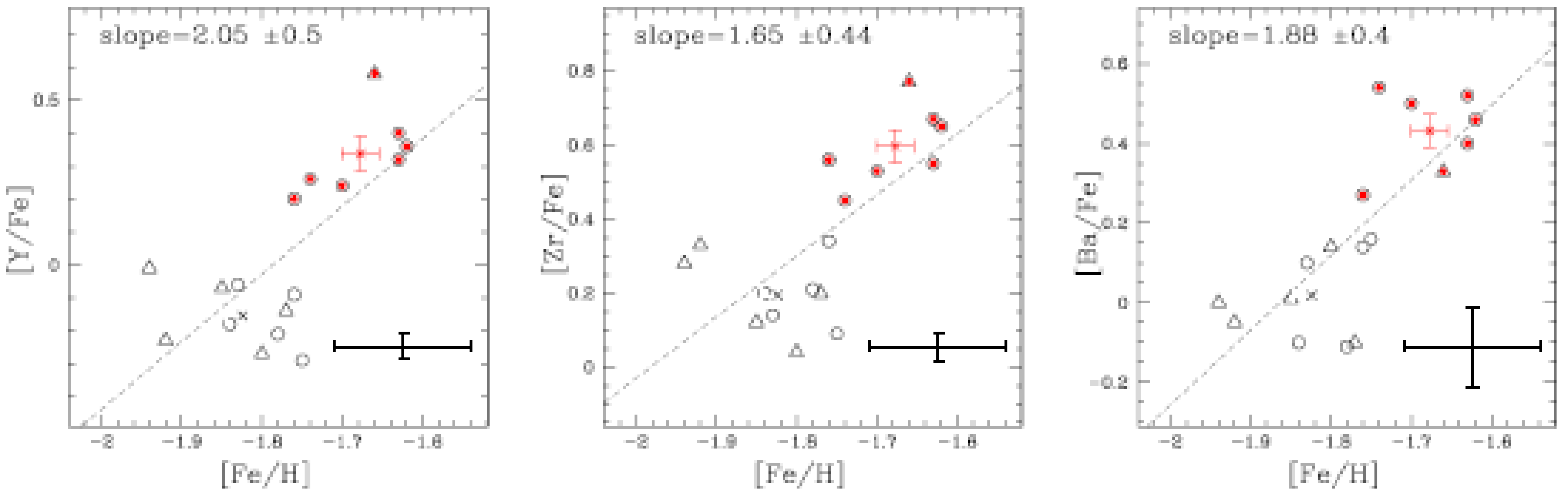
From Marino et al. 2009, A&A, 505, 1099

M22 has a well developed NaO anticorrelation



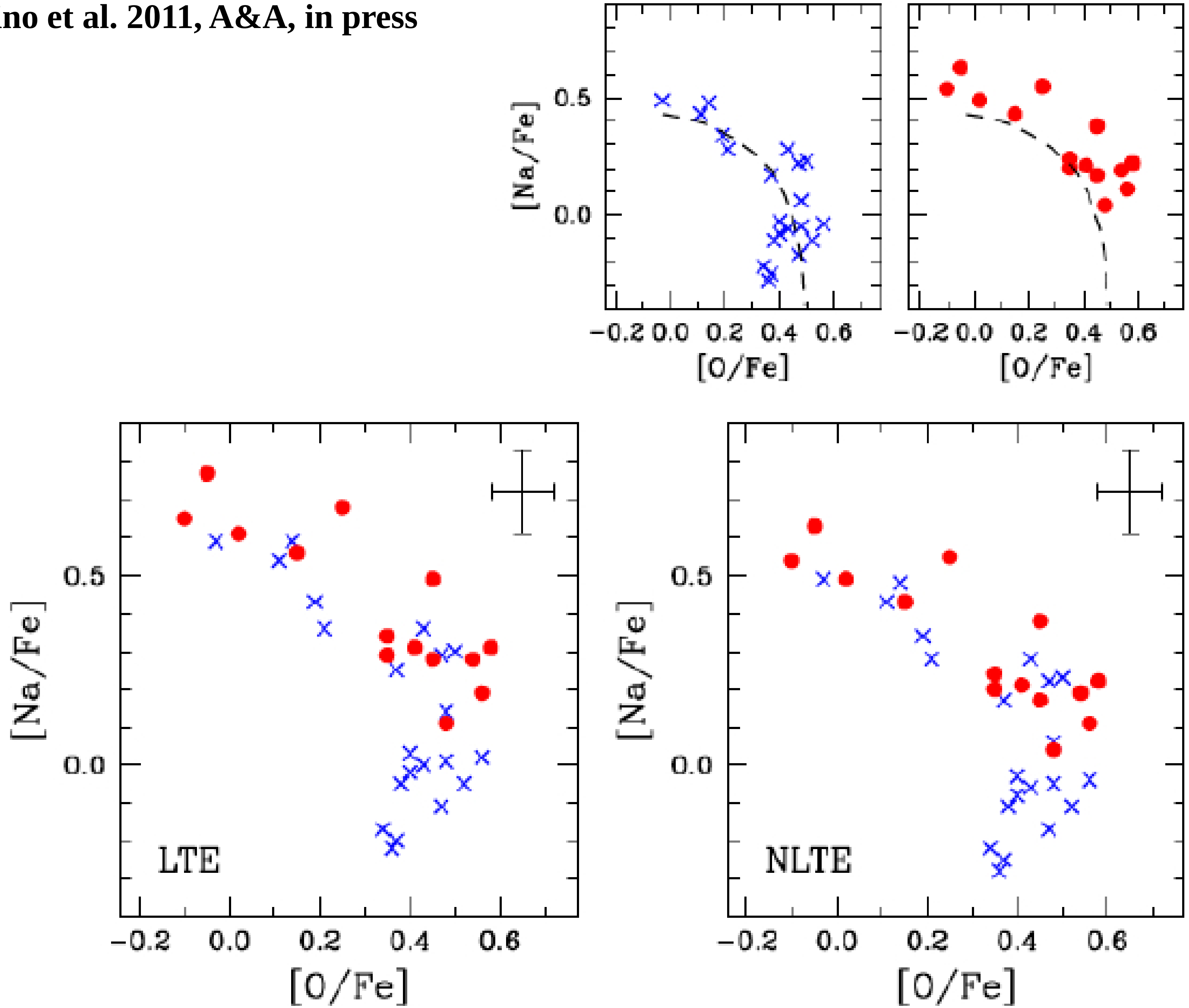
M22 has also a spread in [Fe/H].

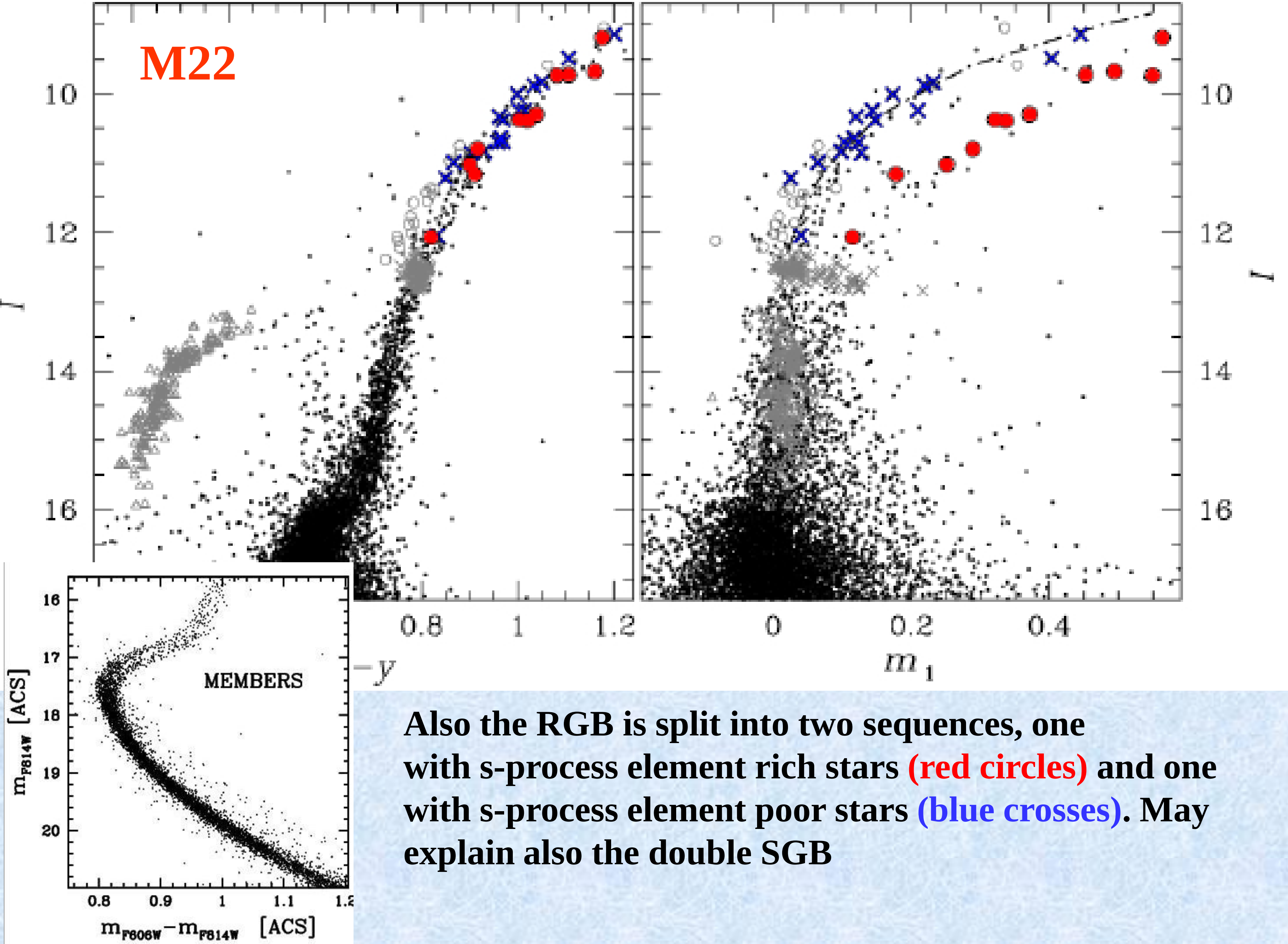
M22 may have same origin as M54 and wCen



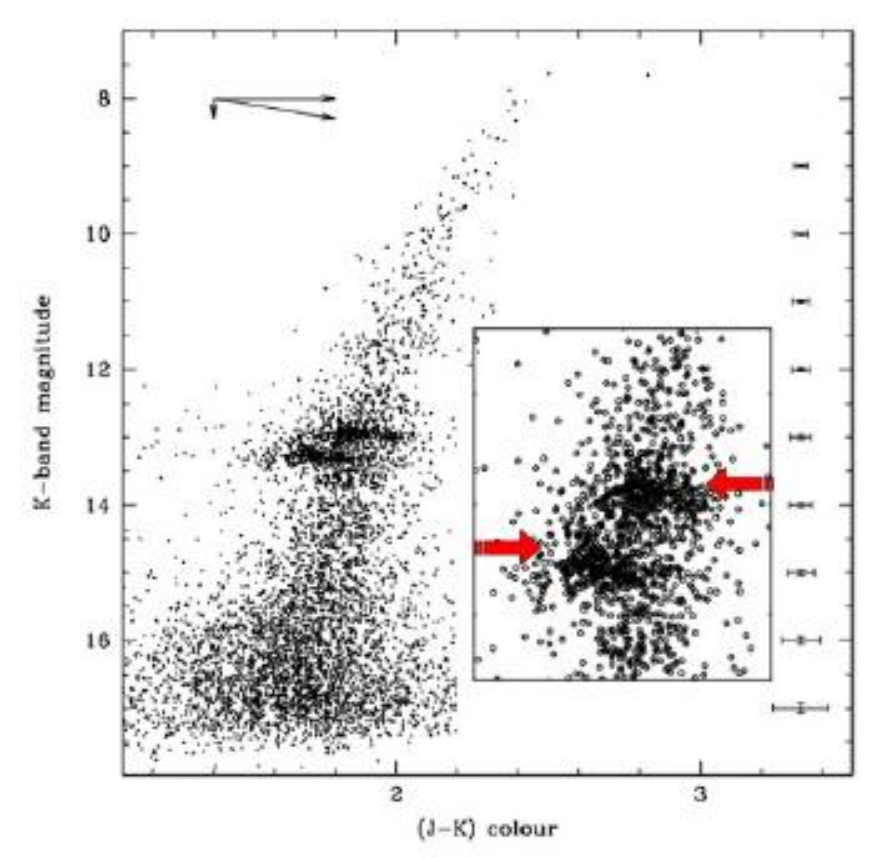
There are two distinct stellar populations, one with enhanced s-process element abundance, and one with low s-process element abundance.

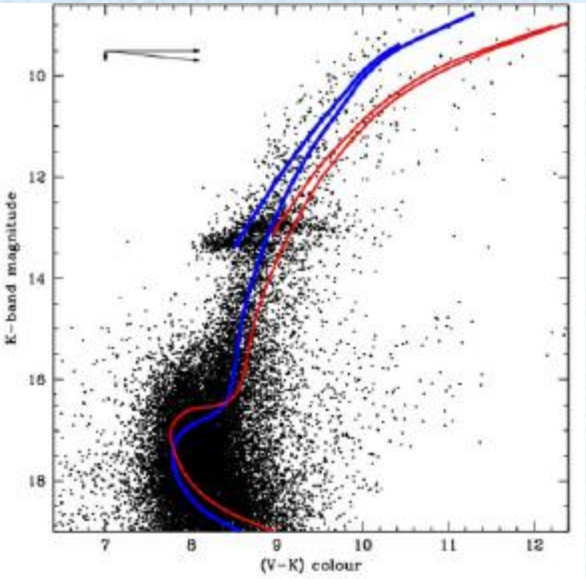
Marino et al. 2011, A&A, in press





Also the RGB is split into two sequences, one with s-process element rich stars (red circles) and one with s-process element poor stars (blue crosses). May explain also the double SGB





Terzan 5

Terzan 5 ($M=2x10^6 m_\odot$ has a double HB and double RGB.

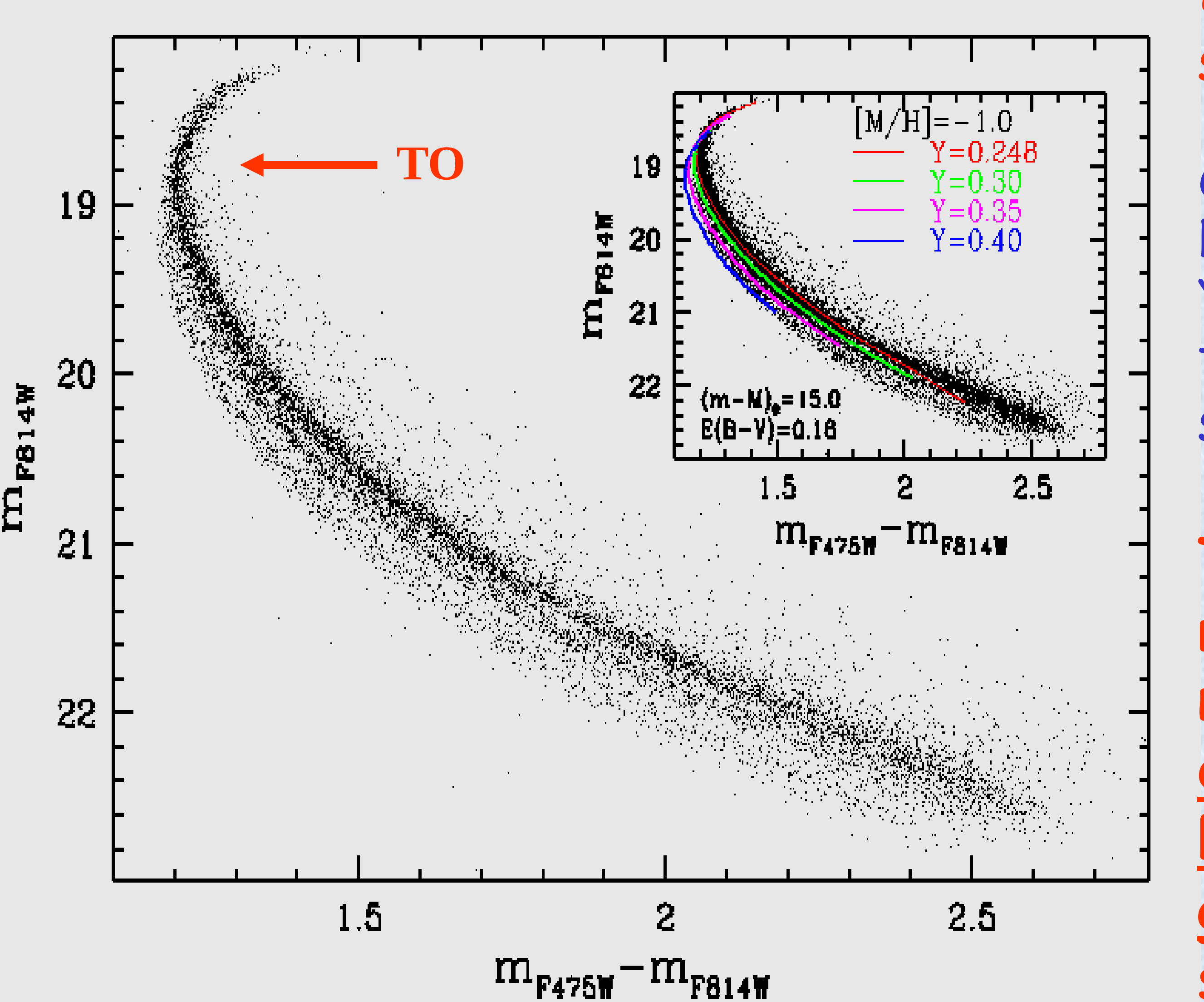
Two stellar populations: 12 and 6 Gyr old.

The bright HB population is younger, more metal rich and more concentrated.

Terzan 5 may be the merge of two globular clusters.

Ferraro et al. 2009, Nature, 462, 483

The triple main sequence in NGC 2808



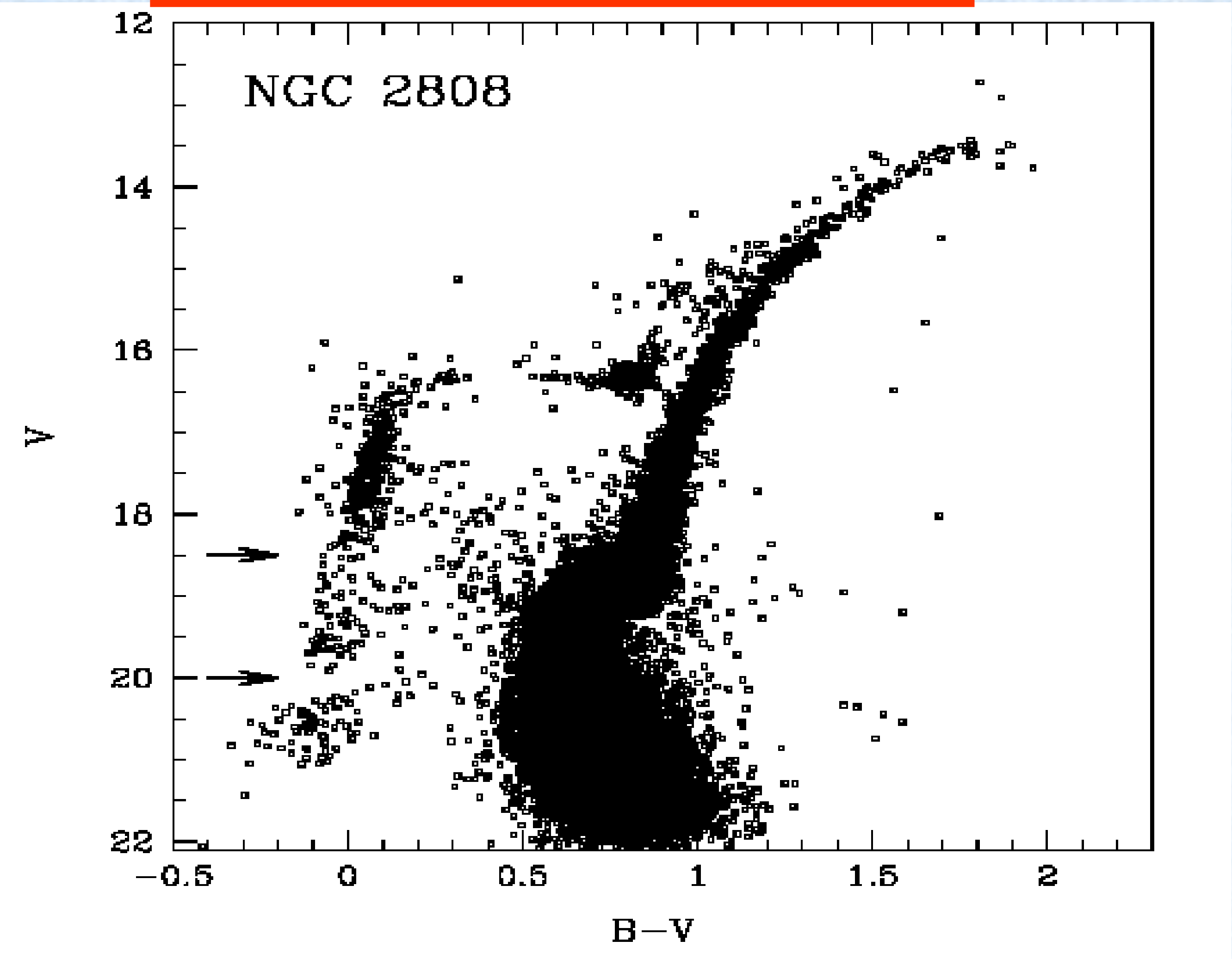
Piotto et al. 2007, ApJ, 661, L35

The MS of NGC 2808 splits in three separate branches

Overabundances of helium (Y~0.30, Y~0.40) can reproduce the two bluest main sequences.

The TO-SGB regions are so narrow that <u>any difference in age between the three groups must be significantly smaller than 1 Gyr</u>

Bedin et al. 2000

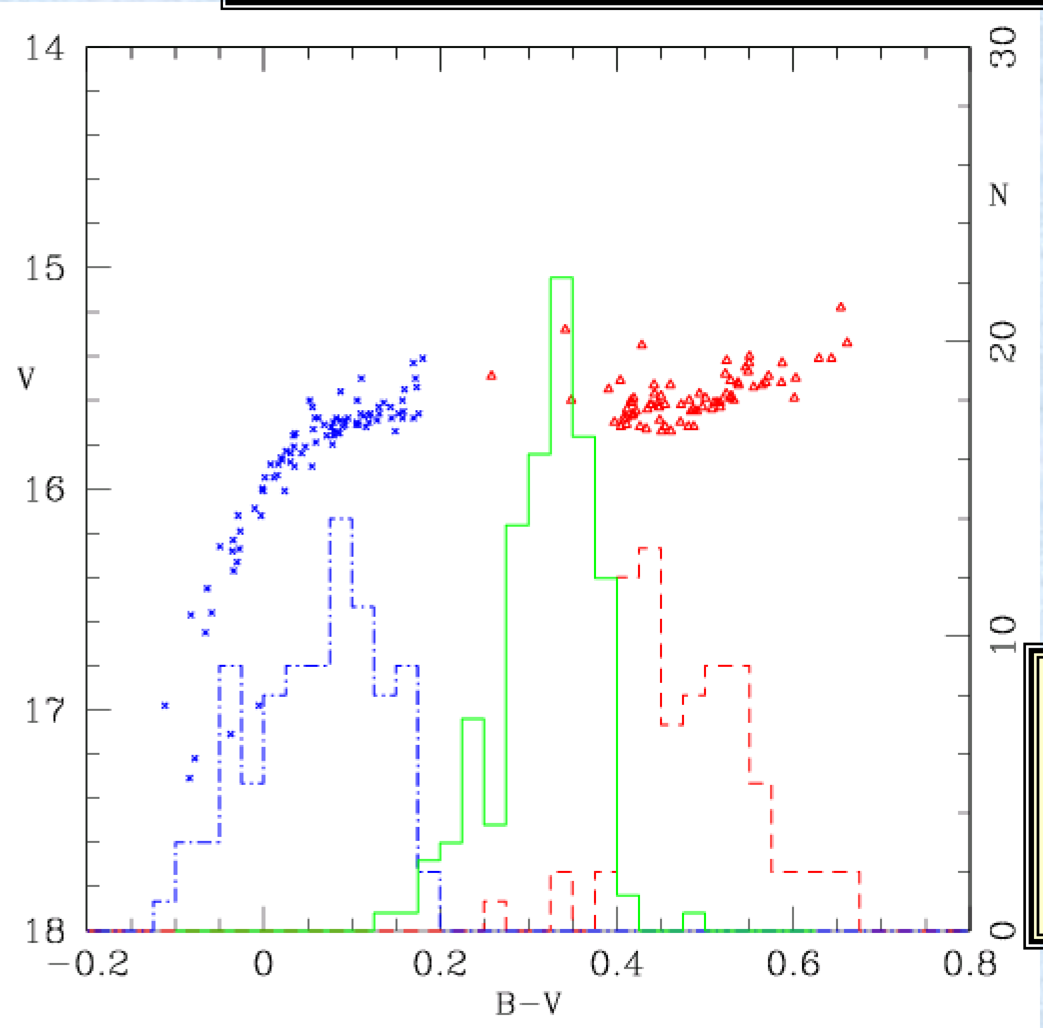


The Horizontal Branch: 40 years of models

Interpretation of the HB as the locus of low mass stars burning Helium in the core and hydrogen in a shell is 40 yr old (Hayashi, Hoshi & Sugimoto 1966, Faulkner 1966, Faulkner & Iben 1967, Iben 1967)

The Horizontal Branch: history of models

A unique track can not explain the Teff extension of the HB



Iben & Rood 1970, ApJ 161, 587

in M3 ΔlogTeff~0.4 (Newell 1970) →→

ΔM~0.1-0.2Msun

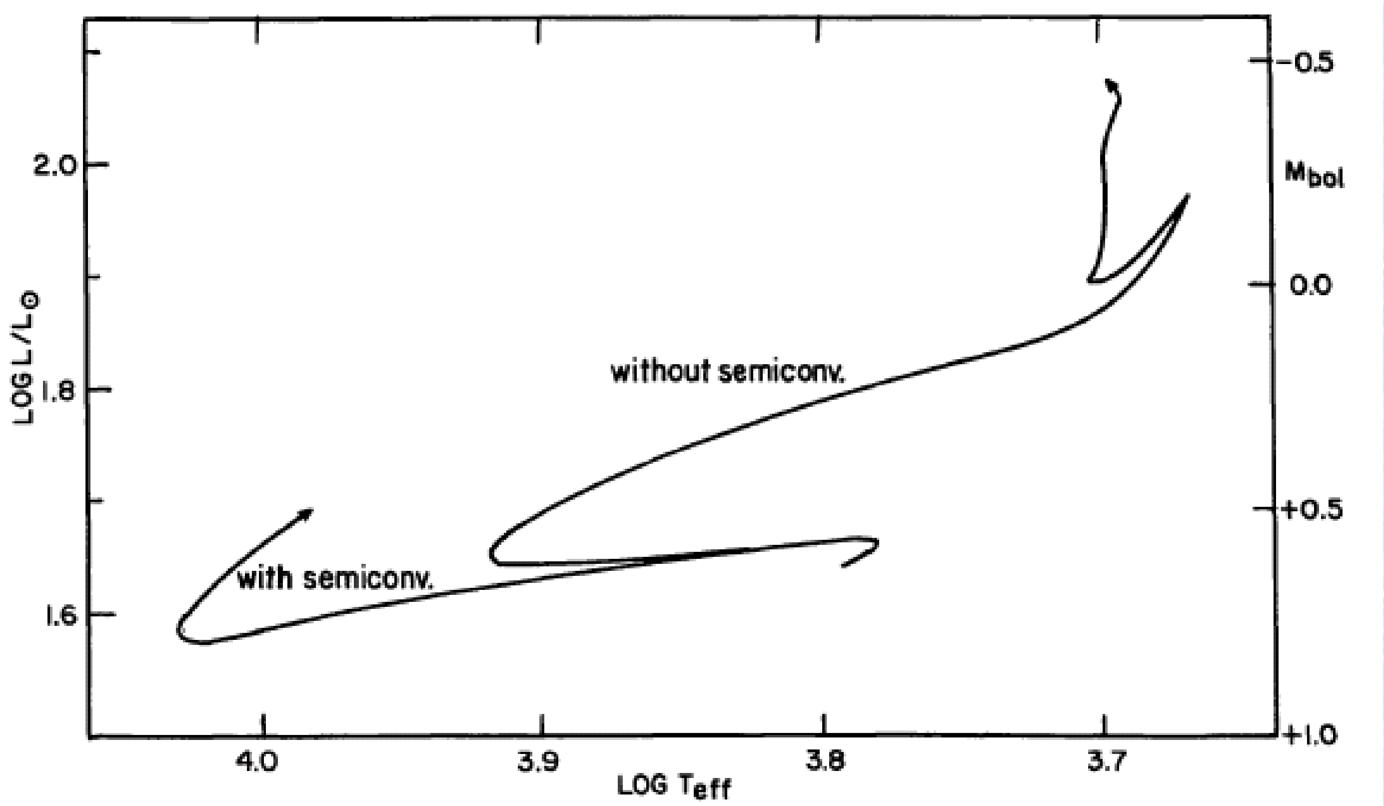
Differential mass loss is necessary to account for the HB extension!

The Horizontal Branch: history of models

Semiconvection and overshooting were described and approached in 1971 (Castellani Giannone Renzini Ap&SS 10,355) Following work assumed maximum extent of overshoot (Sweigart and Demarque 1972, Robertson & Faulkner 1972)

The role of helium sedimentation was explored in the late seventies (Giannone & Rossi 1981)

Semiconvection increases the HB lifetime and the color extension of the tracks



Sweigart & Demarque 1972, A&A 20, 445

An important ingredient: the RR Lyrae

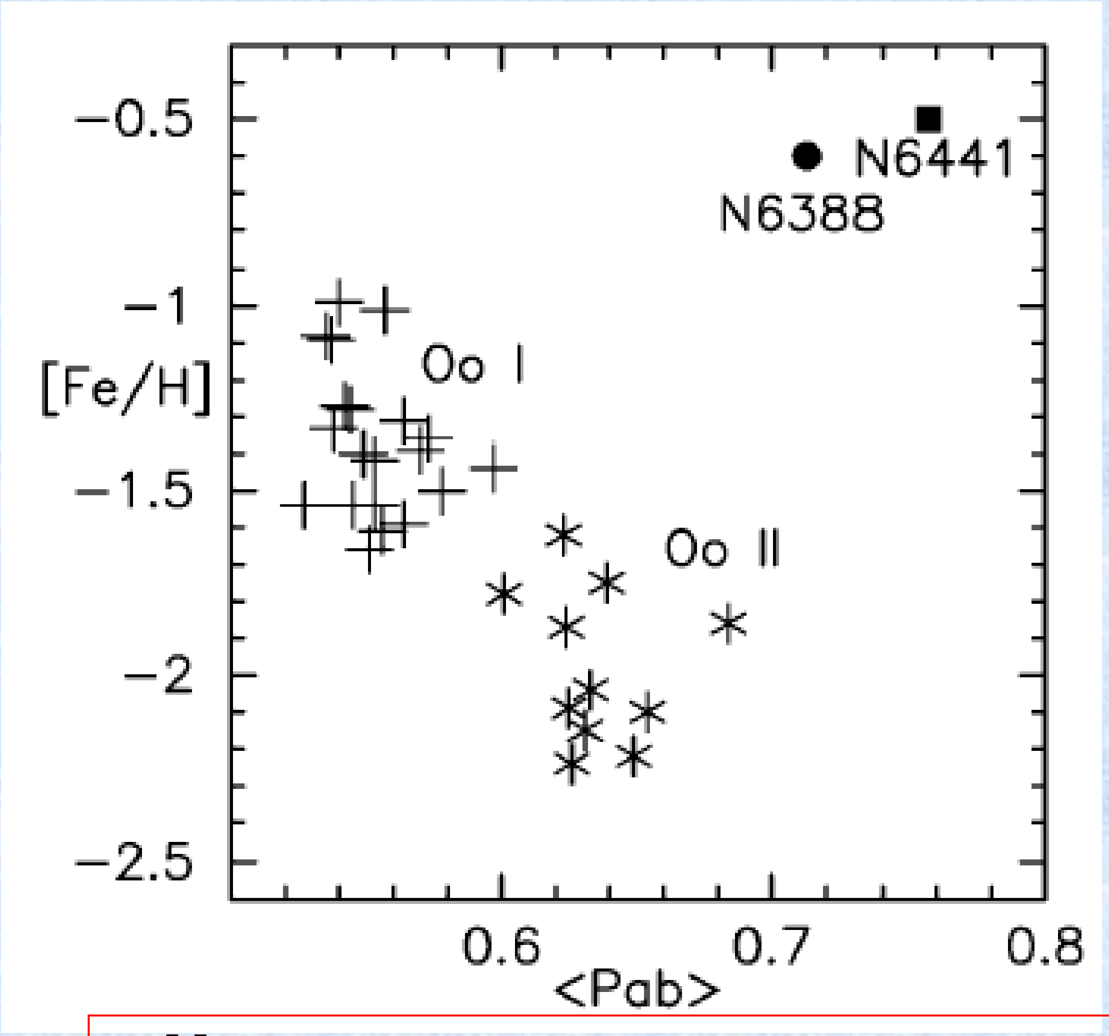
Following the first pulsation models (Baker 1965, Christy 1966, ApJ 164, 108) the relation between RR Lyr period vs. mass, luminosity & T_{eff} was formalized in the early 70s, together with the discussion of the Oosterhoff types I and II (Stobie 1971, ApJ 168, 381; Van Albada & Baker 1971,ApJ169,311)

$$\log P_F = 11.502 + 0.84 \log L / L_\theta - 0.68 \log M - 3.48 \log T_{eff}$$

The periods are a direct signature of absolute luminosity

The Horizontal Branch: RR Lyr periods

The Oosterhoff dichotomy: low-Z clusters: more luminous HB, longer periods: combined effect of L(HB) decreasing with Z and of the progressive cooling of the instability strip dlogTeff/d[Fe/H]=0.012 (Sandage)

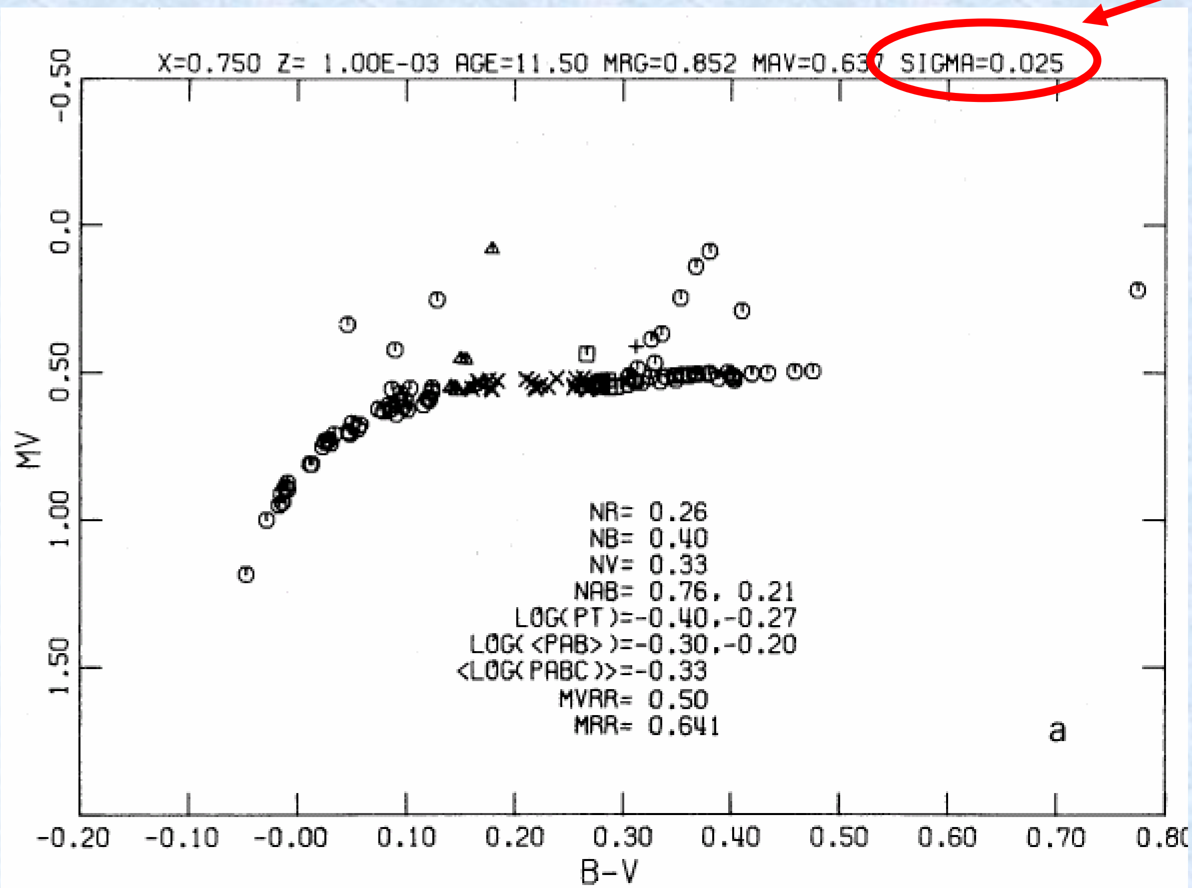


$$\frac{d\log P}{d[Fe/H]} = -0.12 \pm 0.02 \text{ (P in days)}$$

The necessity of differential mass loss

Synthetic HB models were fully developped (Rood 1973, ApJ 184, 815)

σ=0.025Msun

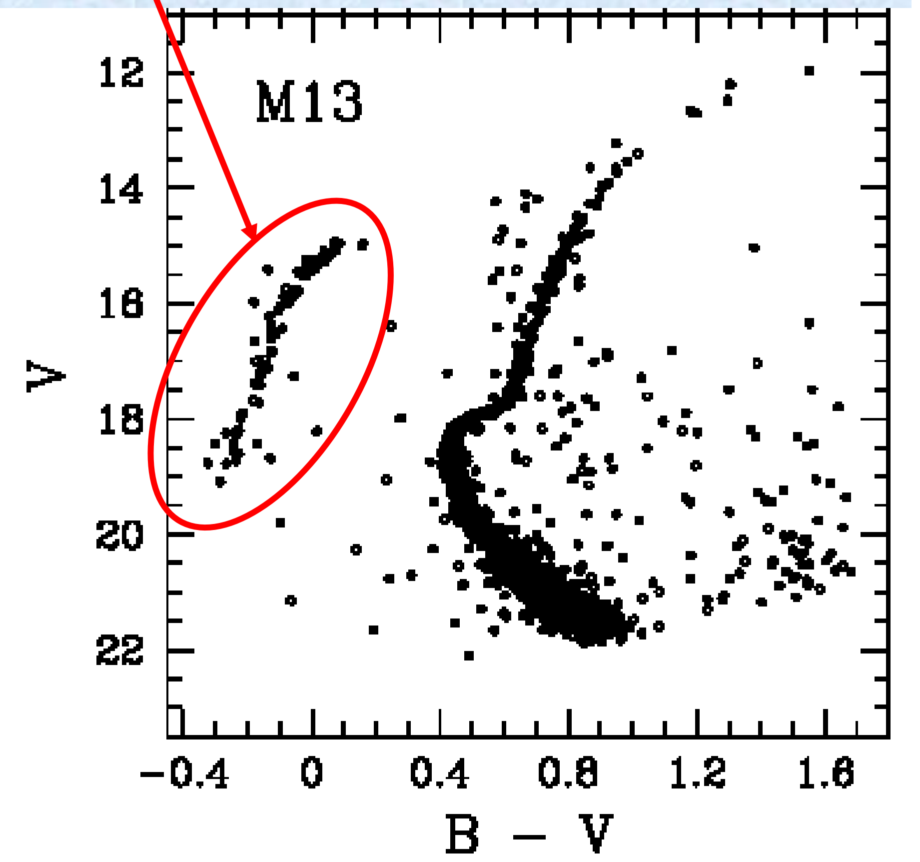


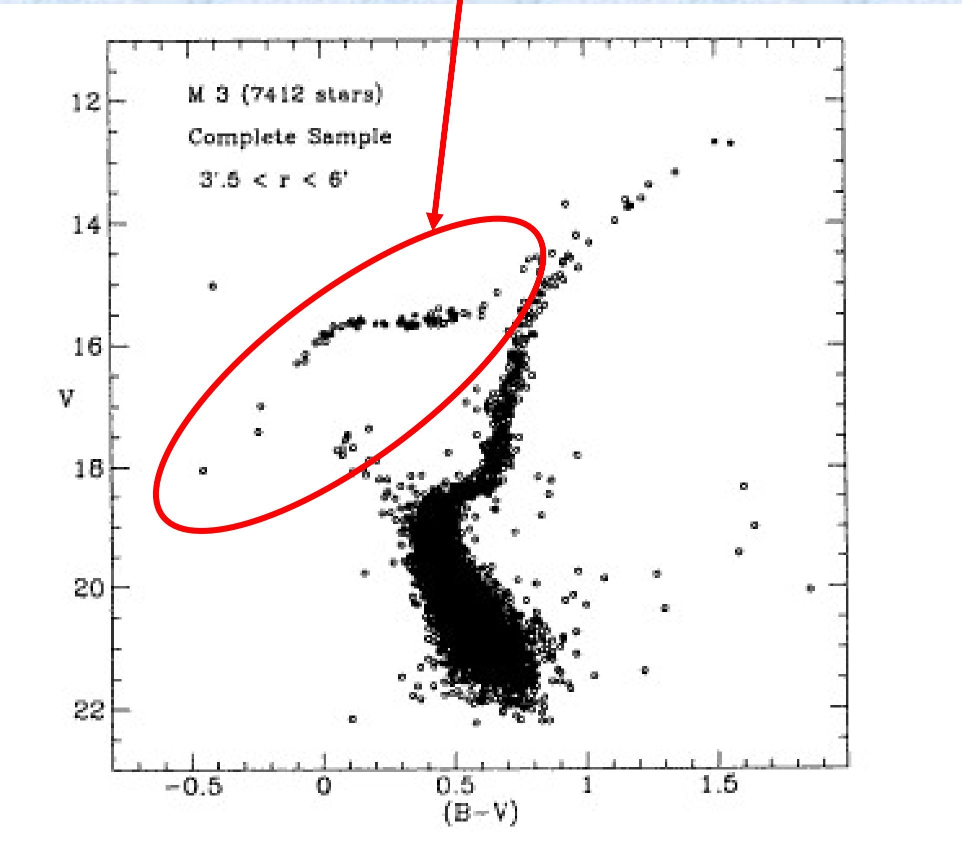
For the first time, the HB is described by setting the age and chemistry, the mass lost on the RGB and spread of mass loss

The second parameter

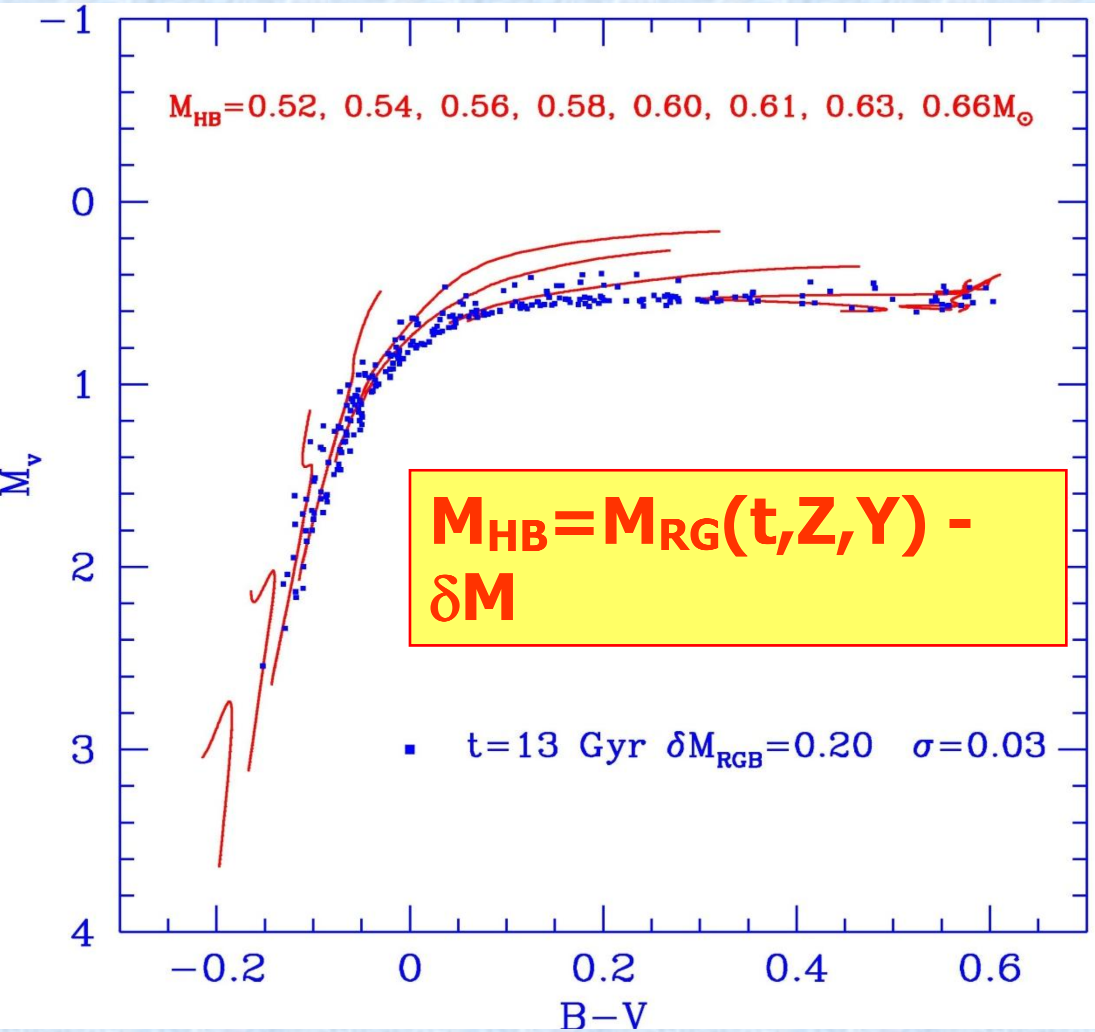
M13: all blue HB (2 RRLyr) and hot blue tail

M3: red clump, RRLyr, and blue side all well populated (no tail)





Synthetic models should solve the problem of the 2nd parameter

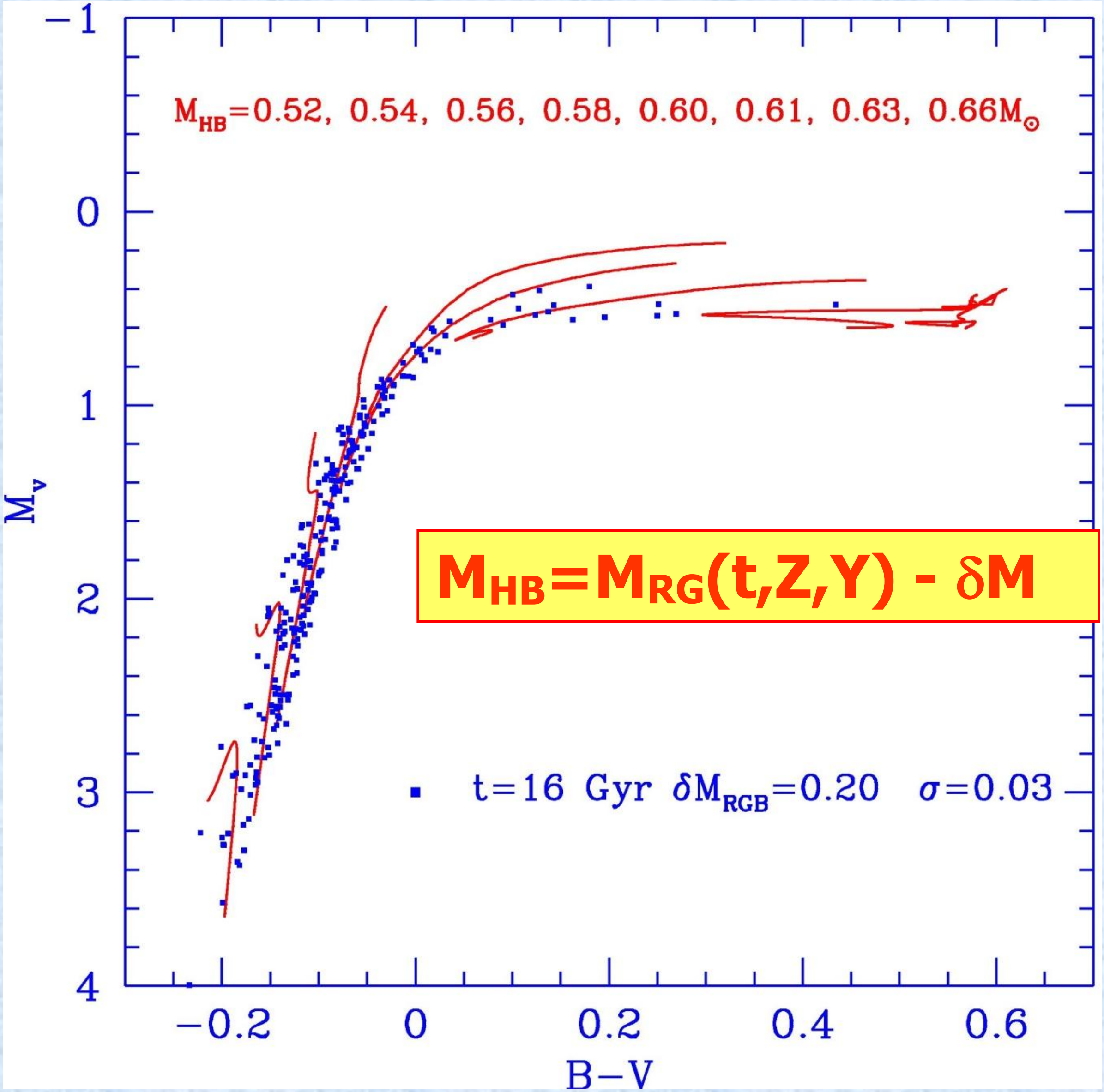


$M_{HB}=M_{RG}(t,Z,Y) - \delta M$

The core mass at the helium flash is *not* dependent on the total mass.

Fixing the age, and chemistry, the mass distribution on HB depends on the average mass lost in RG (δM) and on the mass loss spread σ

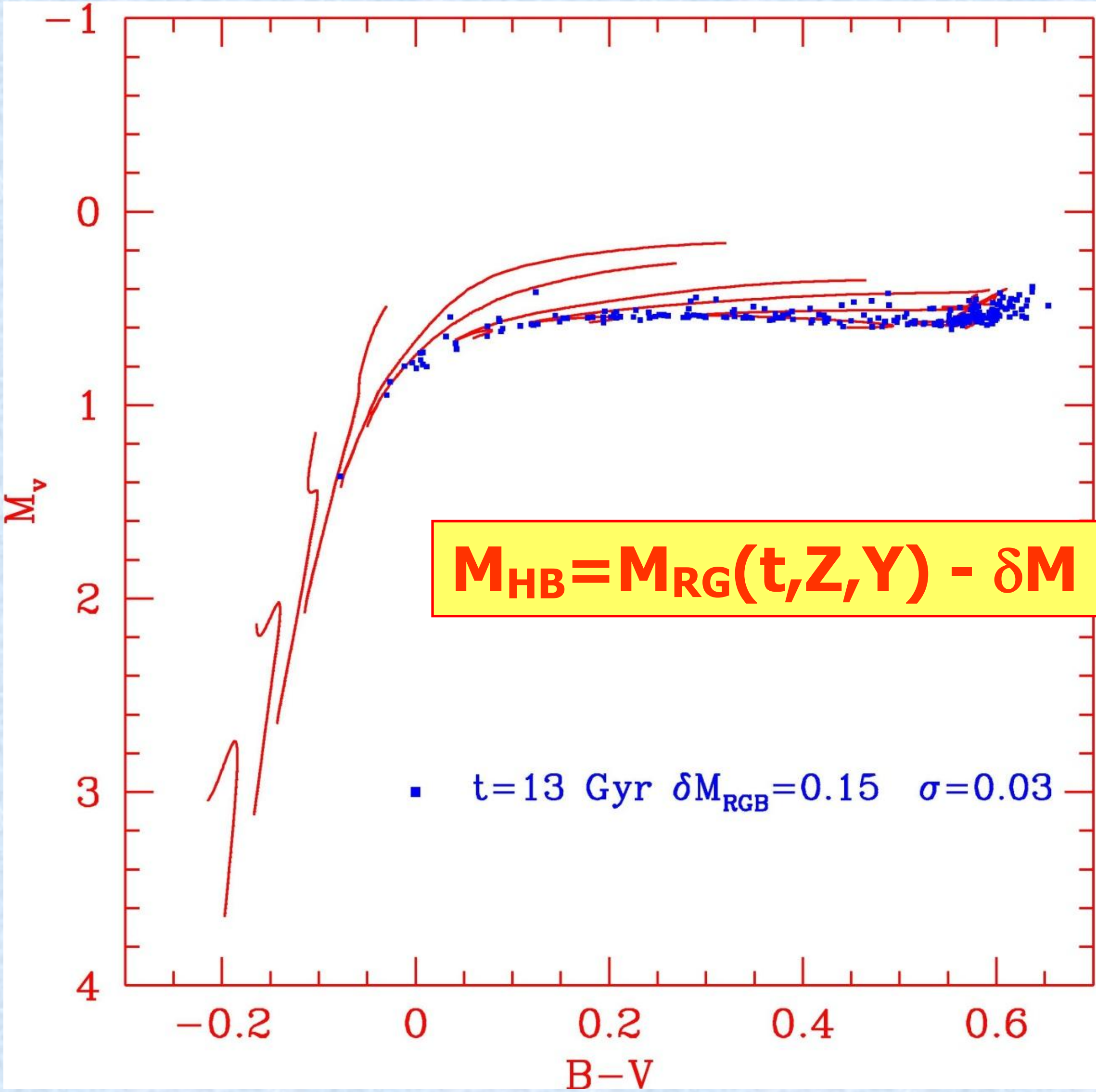
AGE can be the 2nd parameter?



$$M_{HB}=M_{RG}(t,Z,Y) - \delta M$$

Increasing the age (same chemistry, δM and σ) the evolving RG mass decreases, and the mass distribution on HB shifts to the blue

Dependence on mass loss, Z and Y



$M_{HB}=M_{RG}(t,Z,Y) - \delta M$

For a larger δM (same age, chemistry and σ) the mass distribution on HB shifts to the blue

Higher Z → higher M_{RG} → redder HB

Higher Y → smaller evolving M_{RG} → bluer HB

The second parameter

Rood 1973 simulations made quantitatively clear that the "second parameter" problem was not easy to be solved: clusters similar in chemistry and age have very different HB shapes

Rood suggests two possible solutions:
* an age difference of maybe 1Gyr;
* an helium difference $\delta Y \sim 0.03$

Age difference: often reproposed in the following years. On the contrary, the hypothesis of a helium difference was soon dismissed due to R parameter. Reproposed by Caloi & D'Antona 2005 in the context of selfenrichment in GCs

The R parameter

The number ratio R between the number of HB stars and of RG stars above the HB luminosity level was first proposed by Iben and Rood as a way to measure the helium content → at an epoch in which the choice was between Y~0.1 and Y~0.3

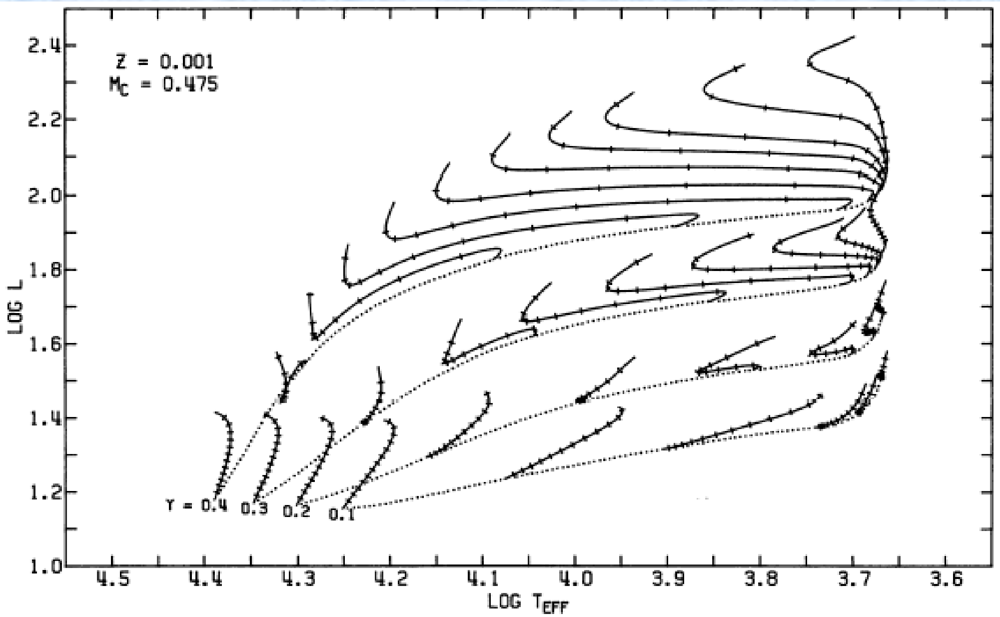


Fig. 4.—Theoretical horizontal-branch tracks with semiconvection for $Z = 0.001$ and $M_c = 0.475\ M_\odot$. The meanings of the dotted curves and tick marks are the same as explained in the legend for Fig. 1. For each Y value tracks are plotted for the following masses: for $Y = 0.10$, $M = 0.50(0.04)0.66$, $0.90\ M_\odot$; for $Y = 0.20$, $M = 0.50(0.04)0.66$, 0.74, $0.90\ M_\odot$; for $Y = 0.30$, $M = 0.50(0.04)0.78$, $0.90\ M_\odot$; for $Y = 0.40$, $M = 0.50(0.04)0.82$, 0.90, $1.02\ M_\odot$.

higher Y → higher μ in the shell → higher T →higher L →

→higher R

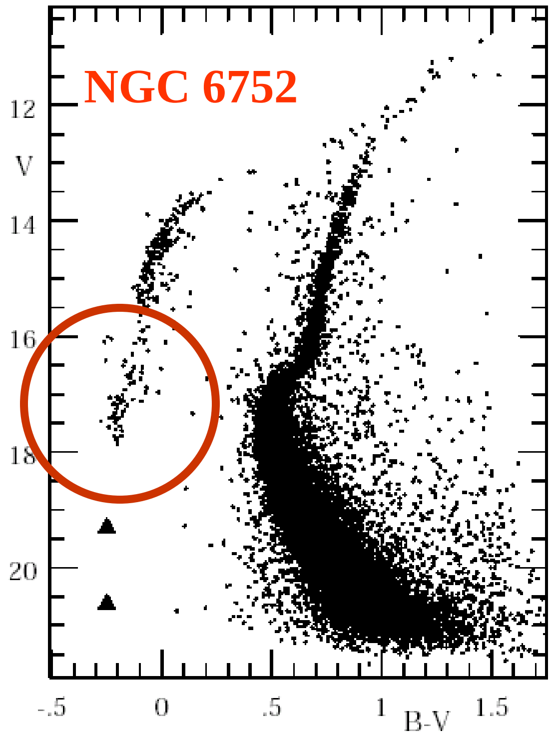
Observed R imply Y~cost for all GCs

The observed R values are consistent with no variation in helium among GCs. Thus the common paradigm became that either age or mass loss were the reason for the 2nd parameter effect

Extreme MASS LOSS, in any case, should have been at the basis of the existence of “blue tails” in some GCs.
A problem in the problem: how can very hot HB stars be formed? Extreme HB stars (Teff>20000K) and “blue hook” stars (Teff>30000K) have such a small H-envelope that the evolving giant would have left the RGB before igniting the He-flash

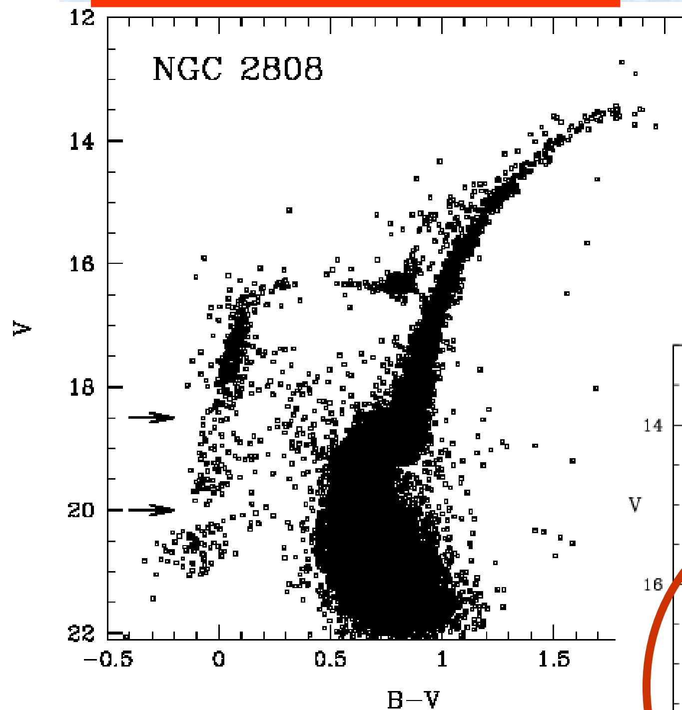
Other problems of HBs

“simple” synthetic models can not easily explain:



blue tails

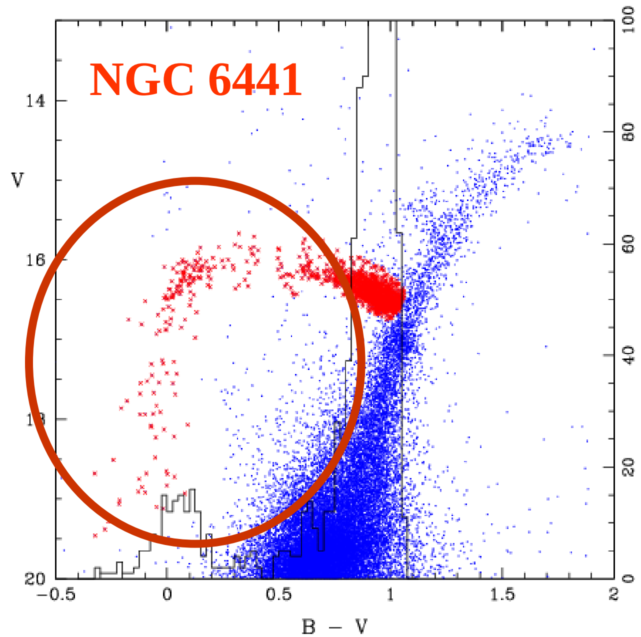
Bedin et al. 2000



gaps!

... all clusters showing O-Na anticorrelation

Piotto et al. 2002



anomalous HBs in high Z GCs →

The paradigm changes: Globular Clusters are no longer simple stellar populations

1. Spectroscopic observations: Na-O and Mg-Al anticorrelations – (There must be a 'second' star formation event in matter contaminated by hot CNO cycle products) Years: 80s → new ~2001
2. Photometric evidence for main sequence or other splittings in some GCs (Bedin 2004, Piotto 2007) (→ >2004)
3. Evidence He enhanced populations in the some clusters (Piotto 2005, 2007)

Also the HB and the RGB mass loss paradigmas change

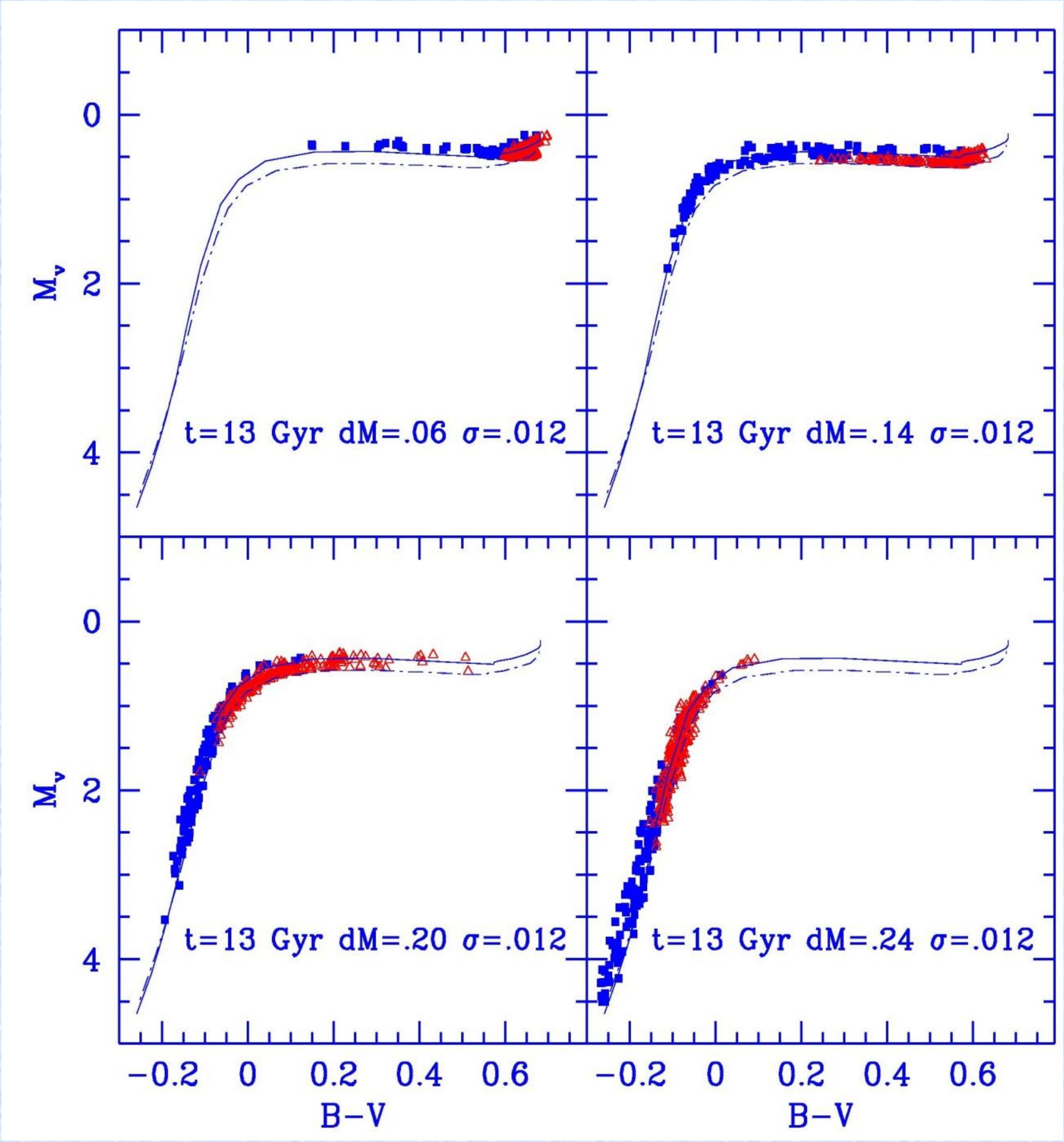
The helium content in the stars with chemical anomalies

→ All models able to explain CNO-Na-Al anomalies provide high helium yields.
Y becomes again a 'powerful' 2nd parameter, able to solve the long standing problems

For a given isochrone, the evolving (turnoff and RG) mass is smaller for larger Y
$\Delta M \approx -1.3\ (Y - 0.24)$

→

the HB mass (=Mass of the RG minus the mass loss in the RGB) is also smaller for larger Y and the star is bluer



adding a population with larger Y extends the HB to the blue (D'Antona et al. 2002)

a smaller spread in mass loss is sufficient to explain an HB morphology broad in color

to explain EHB and blue hook, if Y varies, we do not need that some stars lose an anomalous large amount of mass during the RG phase

standard view: Y=cost=0.24

Mev ~0.80Msun

red HB stars: M~0.66 → δM=0.14Msun

EHB and blue hook stars → M~0.48

→ δM=0.28Msun

Mass loss should be a factor 2 larger!

Y as 2nd parameter even explains the EHB and blue hook stars

For very high Y, the evolving mass becomes smaller and smaller:

If (for a given age and Z)

M_{ev} ~0.80 Msun for Y=0.24

M_{ev} ~0.65 Msun for Y=0.35

If the mass loss does not depend on Y, the smaller evolving masses are the best candidates to become early hot flashers (and then populate the extremely hot section of the HB

the HB of NGC 2808 in the HST ultraviolet

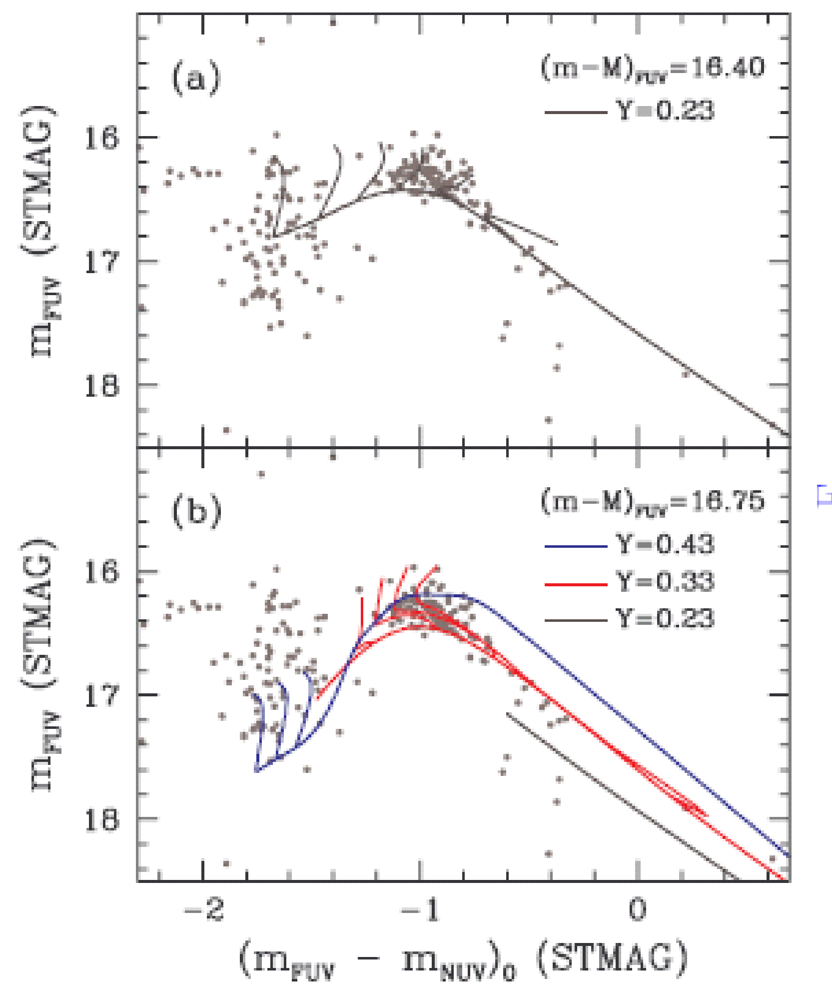
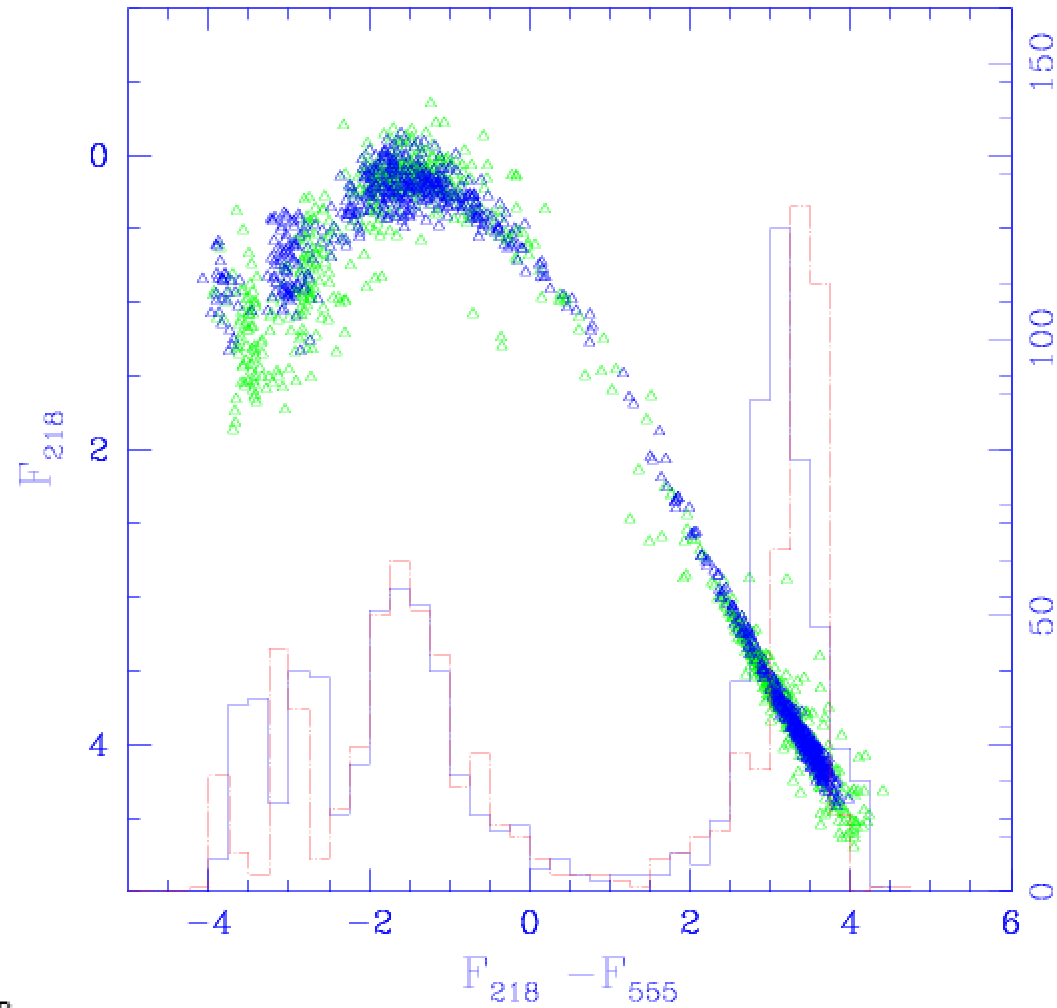


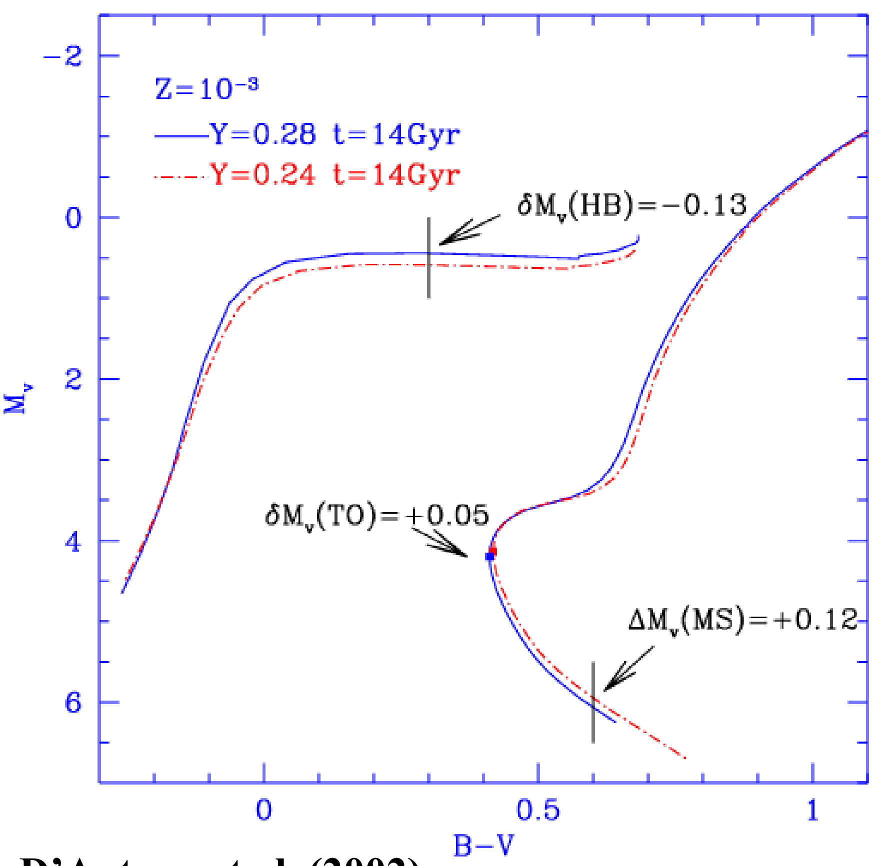
FIG. 4.—Comparison of *HST*/STIS UV CMD of extreme HB and blue HB stars in NGC 2808 (Brown et al. 2001) with the model predictions. Panel *a* is for the case in which all the stars have the same helium abundance of $Y = 0.23$, while panel *b* is for the case of a large range of helium abundance, as in our models in Fig. 3.

Lee et al. 2005



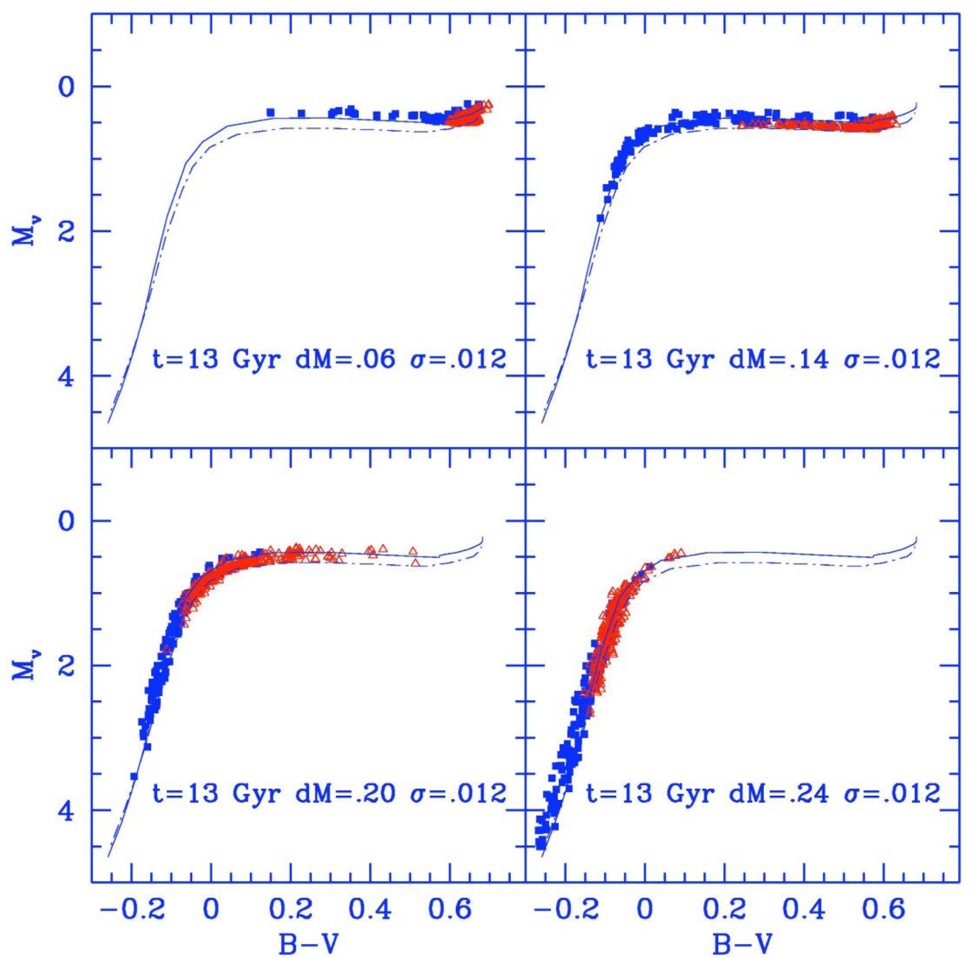
simulation by Caloi & D’Antona 2008

Helium enrichment: model predictions

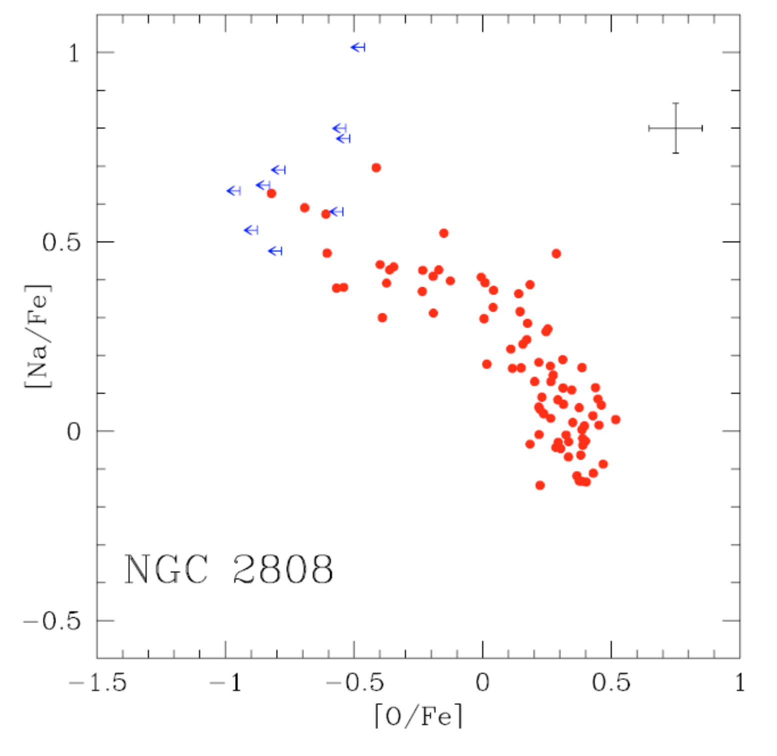


D'Antona et al. (2002)

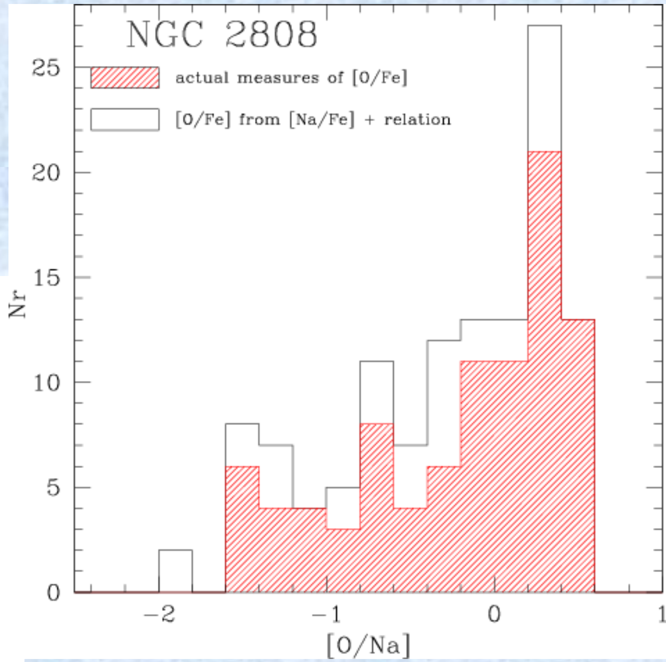
→ Higher Y → brighter HB



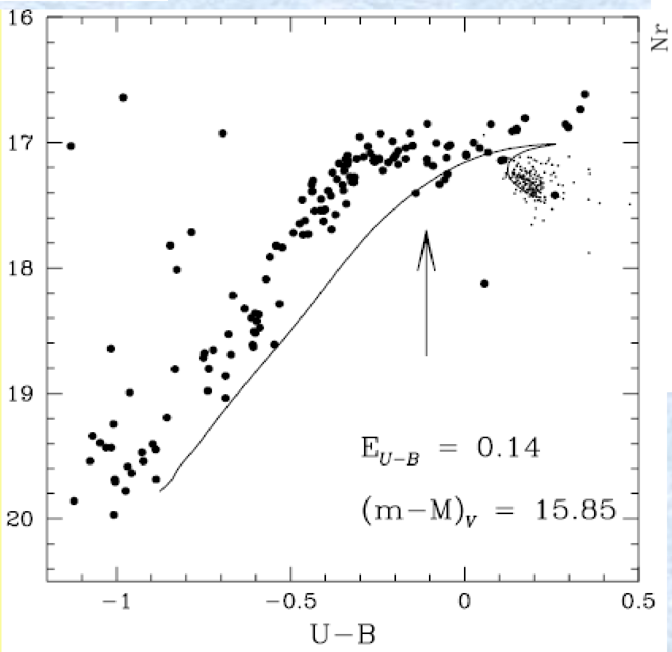
Higher Y → bluer HB ←
(also needs higher mass loss along the RGB, but not as extreme as in the case of primordial He content)



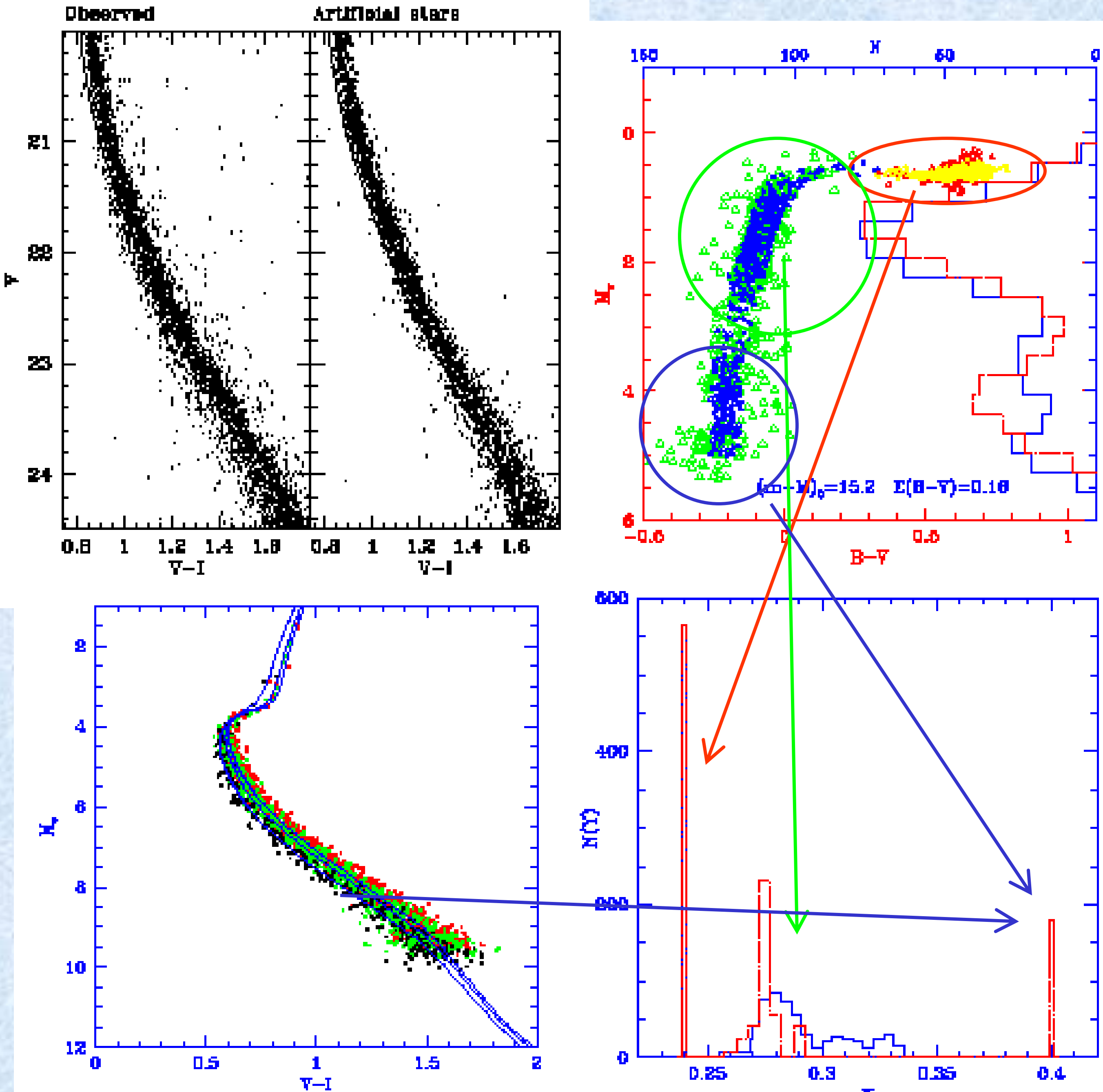
A clear NaO anticorrelation has been identified by Carretta et al. (2006, A&A, 450, 523) in NGC 2808.
Besides a bulk of O-normal stars with the typical composition of field halo stars, NGC2808 seems to host two other groups of O-poor and super O-poor stars



NGC2808 has a very complex and very extended HB (as ω Cen). The distribution of stars along the HB is multimodal, with at least three significant gaps and four HB groups (Sosin et al 1997, Bedin et al 2000)



Observations properly fit the intermediate mass AGB pollution scenario



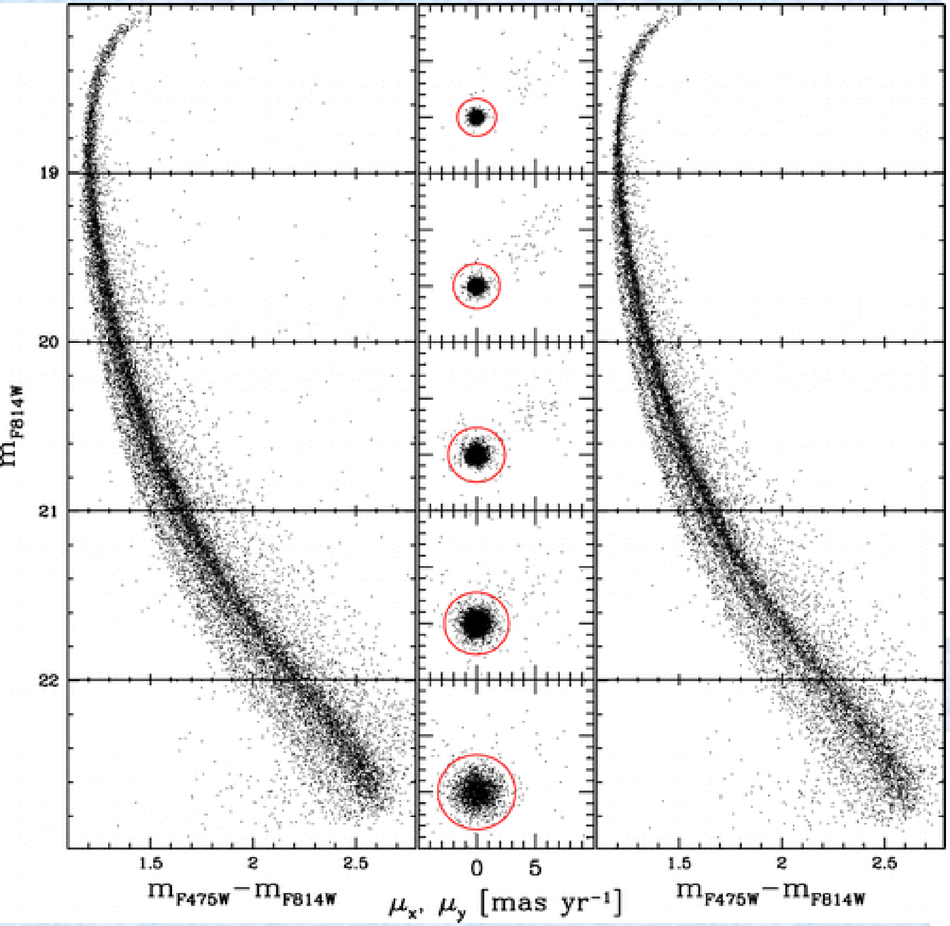
D’Antona et al. 2005, ApJ, 631, 868

A MS broadening in NGC2808 was already seen by D’Antona et al. (2005).

D’Antona et al. (2005) linked the MS broadening to the HB morphology, and proposed that three stellar populations, with three different He enhancements, could reproduce the complicate HB.

We found them in the form of three main sequences!!!

Recently confirmed by Dalessandro et al. arXiv1008.4478



In summary, in NGC 2808,
it is tempting to link together:

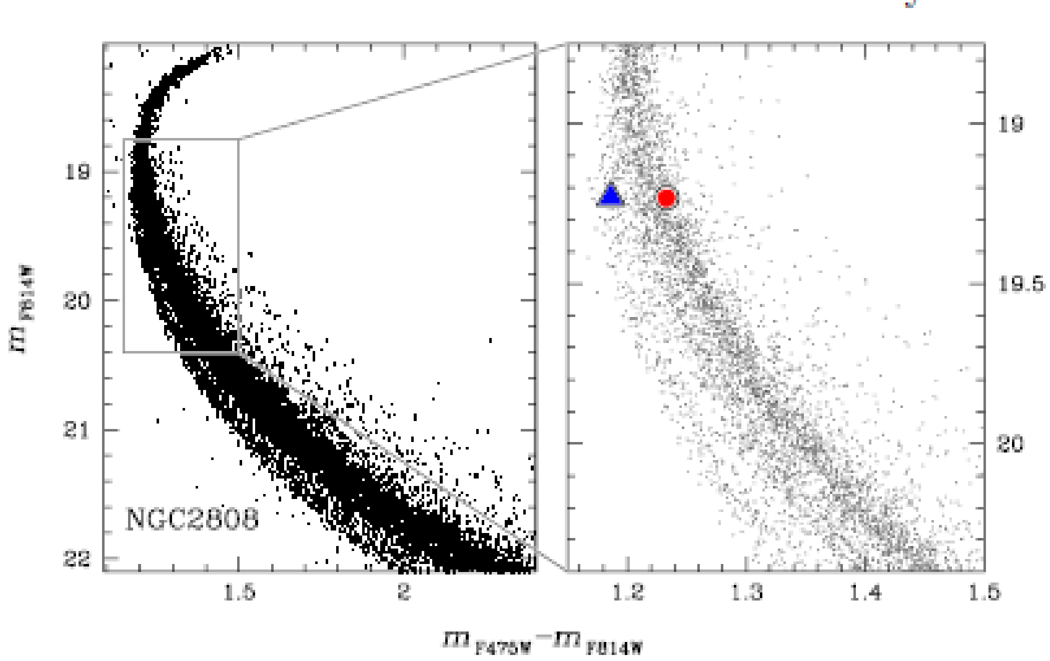
the multiple MS,
the multiple HB,
and the three oxygen groups,
as indicated in the table below
(see Piotto et al. 2007 for details).

THE POPULATION COMPONENTS OF NGC 2808

MS	RGB	HB
rMS 63% ± 5 $Y = 0.248$	O-normal 61% ± 7	Red segment 46% ± 10
mMS 15% ± 5 $Y = 0.30$	O-poor 22% ± 4	EBT1 35% ± 10
bMS 13% ± 5 $Y = 0.37$	Super–O-poor 17% ± 4	EBT2 10% ± 5
Binaries 9% ± 5	?	EBT3? 9% ± 5

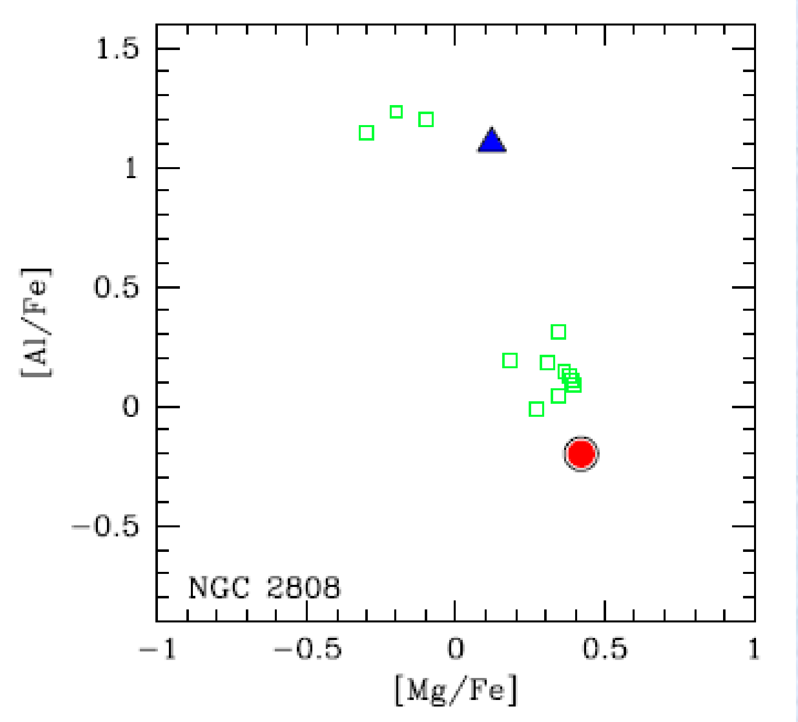
1.4×10^4 and 2.7×10^4 solar masses of fresh Helium are embedded in the 2nd and 3rd generations of stars

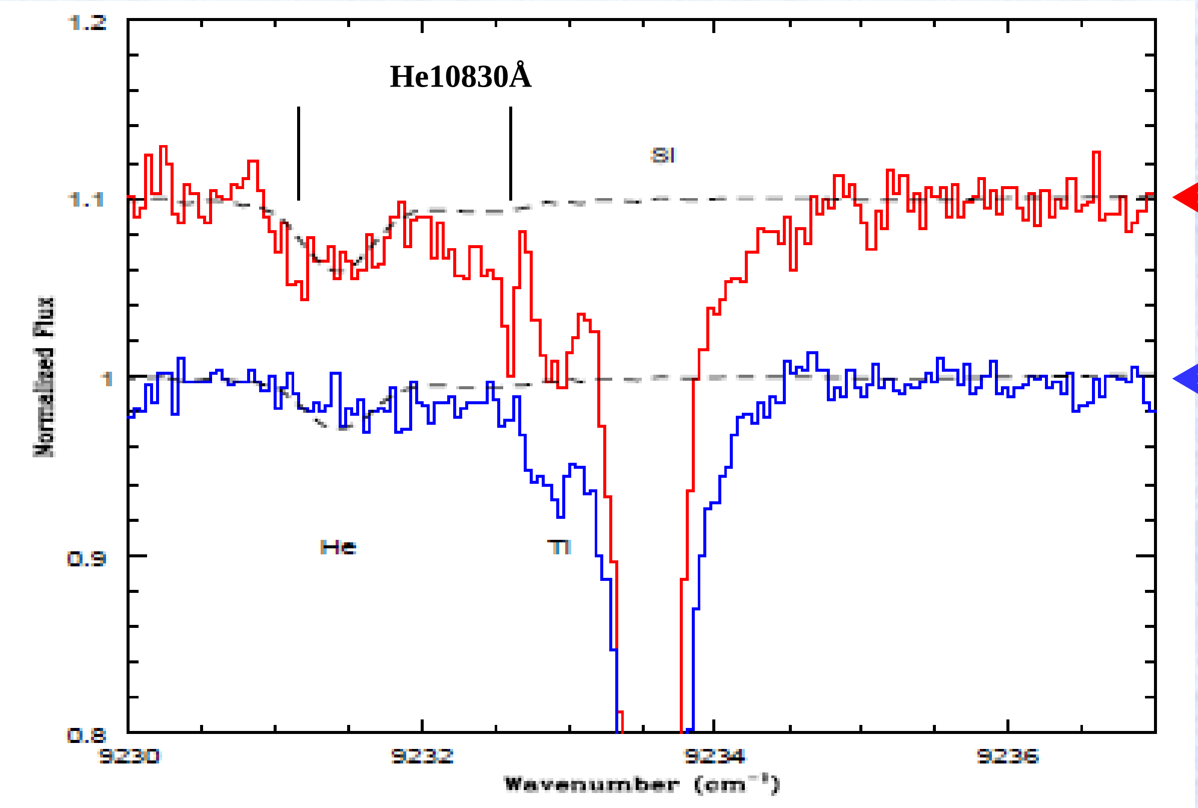
NGC 2808 represents another, direct evidence of multiple stellar populations in a globular cluster.



Bragaglia et al. (2011 ApJ, 720, L41\9 analyzed features of NH, CH, Na, Mg, Al, and Fe. While Fe, Ca, and other elements have the same abundances in the two stars, the bMS star shows a huge enhancement of N, a depletion of C, an enhancement of Na and Al, and small depletion of Mg with respect to the rMS star.

This is exactly what is expected if stars on the bMS formed from the ejecta produced by an earlier stellar generation in the complete CNO and MgAl cycles whose main product is helium.
The elemental abundance pattern differences in these two stars are consistent with the differences in helium content suggested by the color-magnitude diagram positions of the stars.

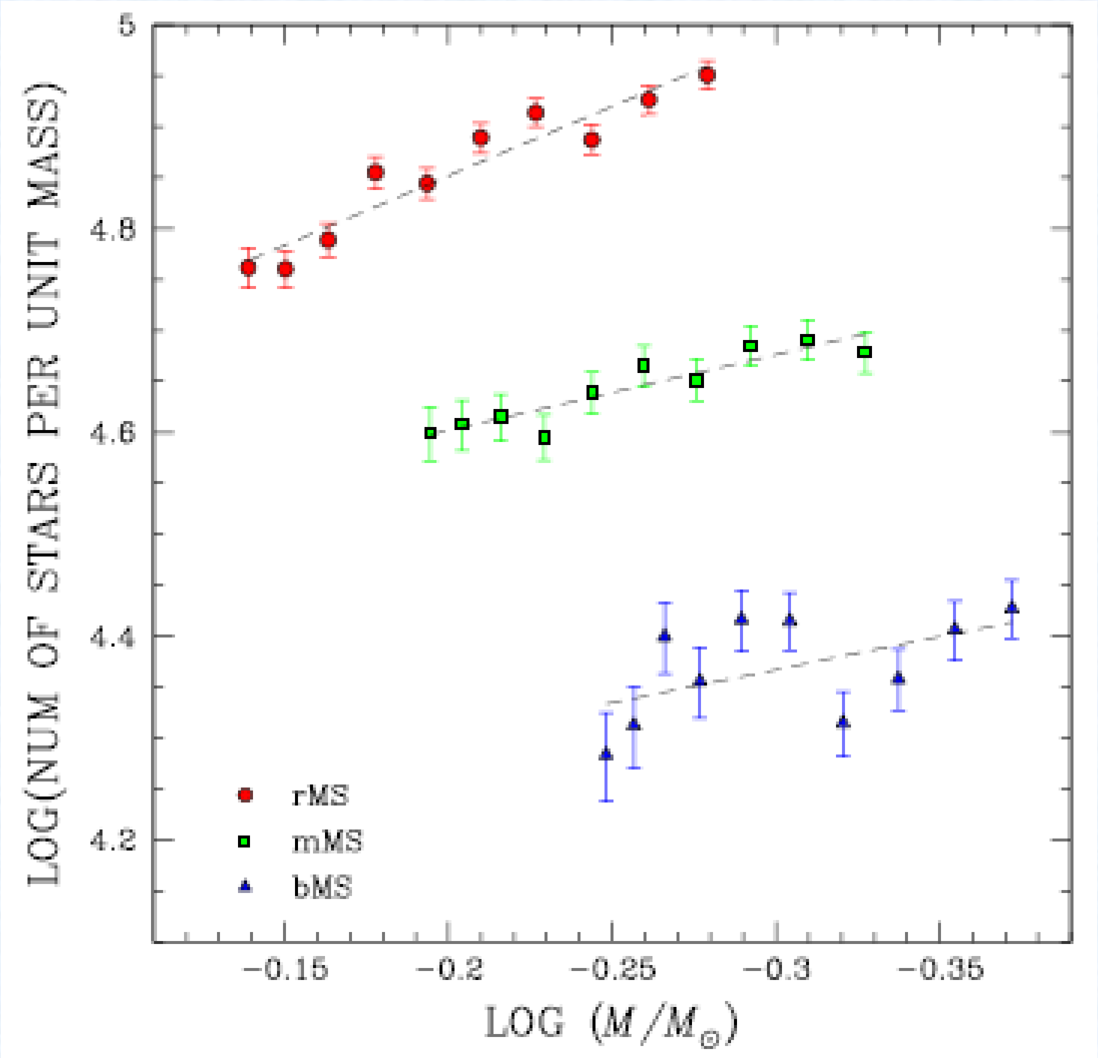




Y=0.39, [Na/Fe]=0.67, [O/Fe]=-0.07

Y=0.22, [Na/Fe]=0.67, [O/Fe]=-0.07

ΔY>0.17 between two RGB stars in NGC 2808 with different Na and O abundances **(Pasquini et al. 2011, arXiv1105.4306)**

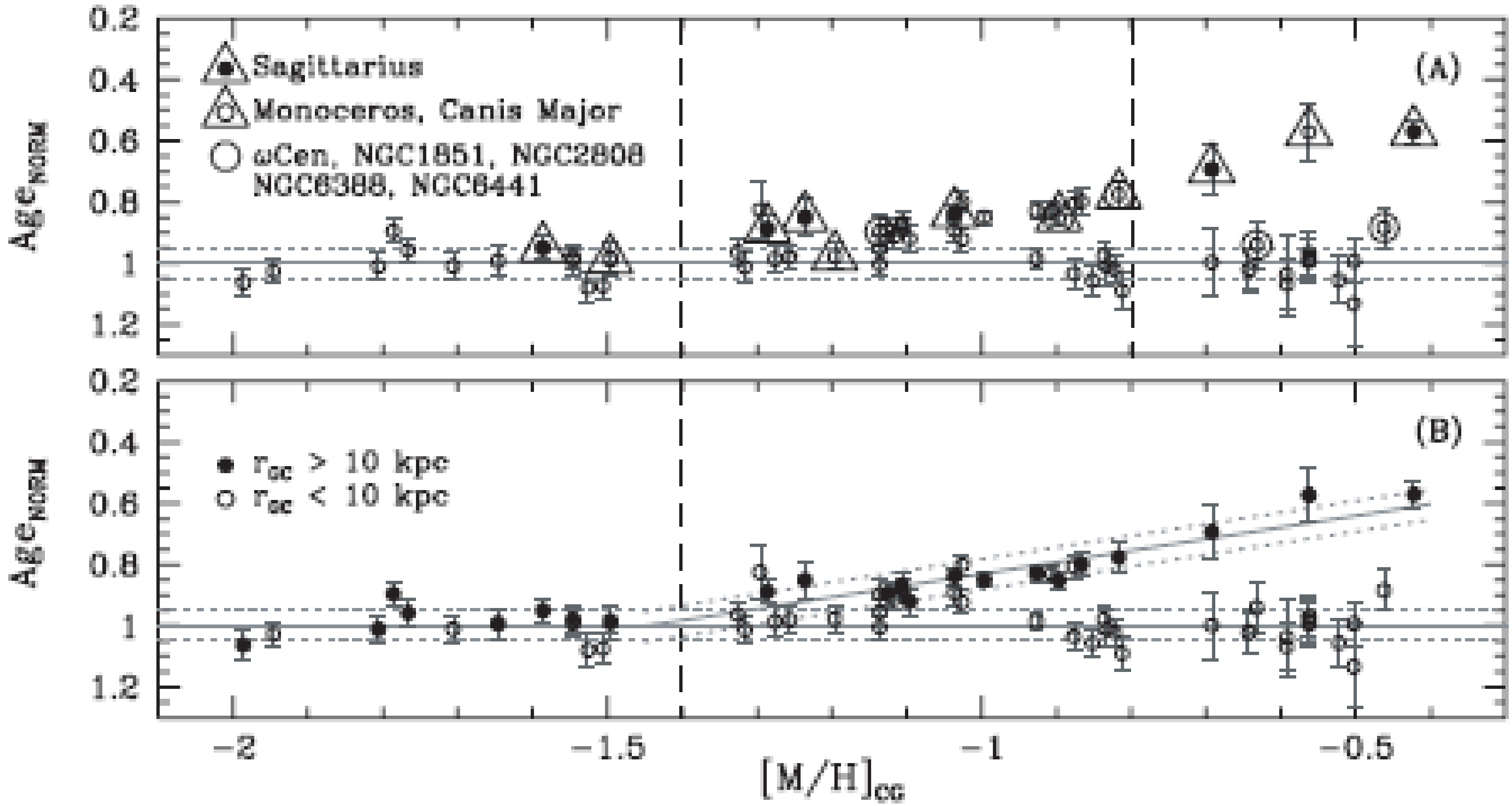


Mass Functions of the 3 main sequences:

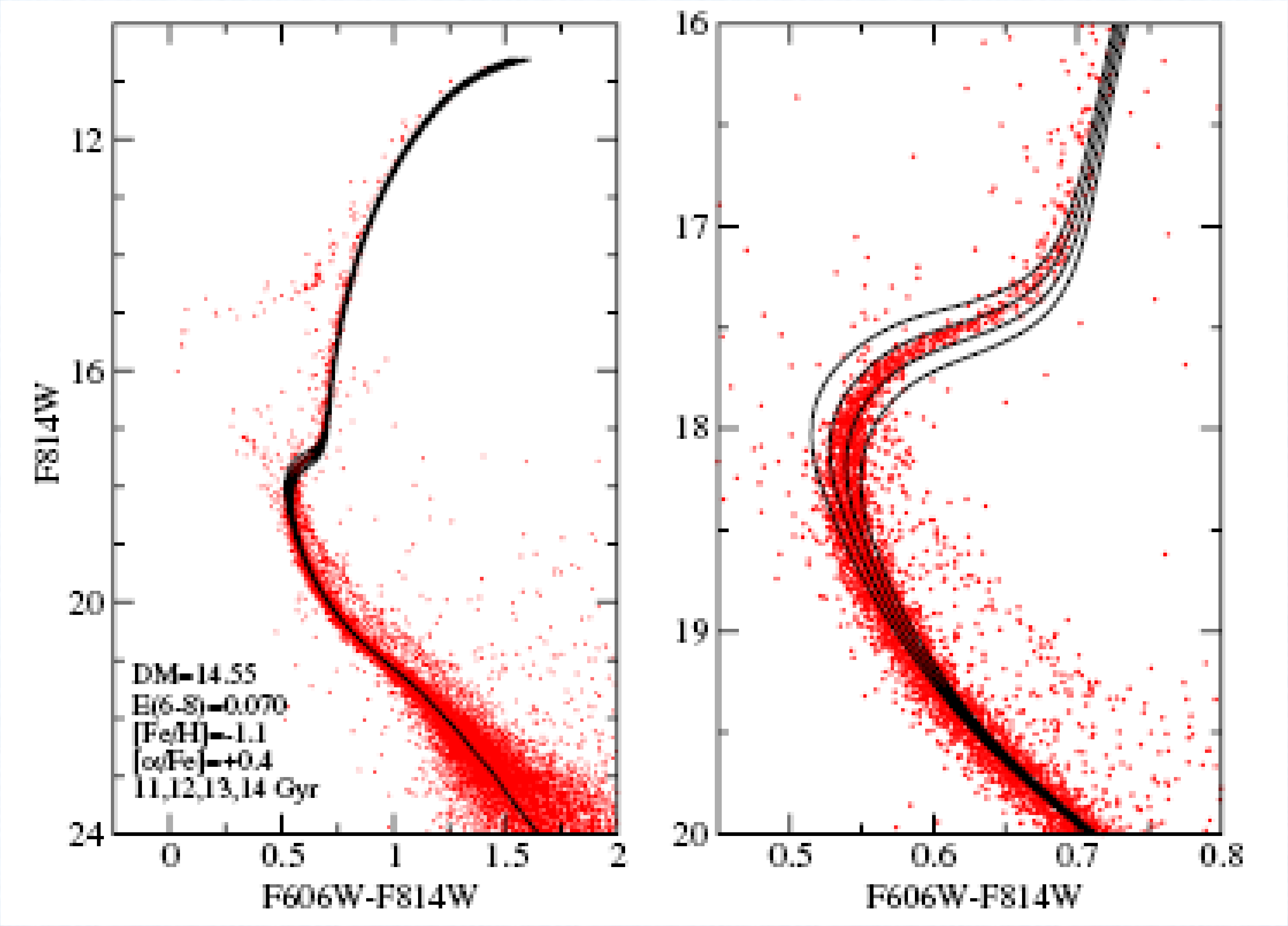
The redder (primordial?) MS has has a (marginally) steeper MF. This makes the production of the material need to form the second generation even more difficult.

The intermediate and blue MS have a similar (flatter) MF slope

Milone et al., A&A, submitted

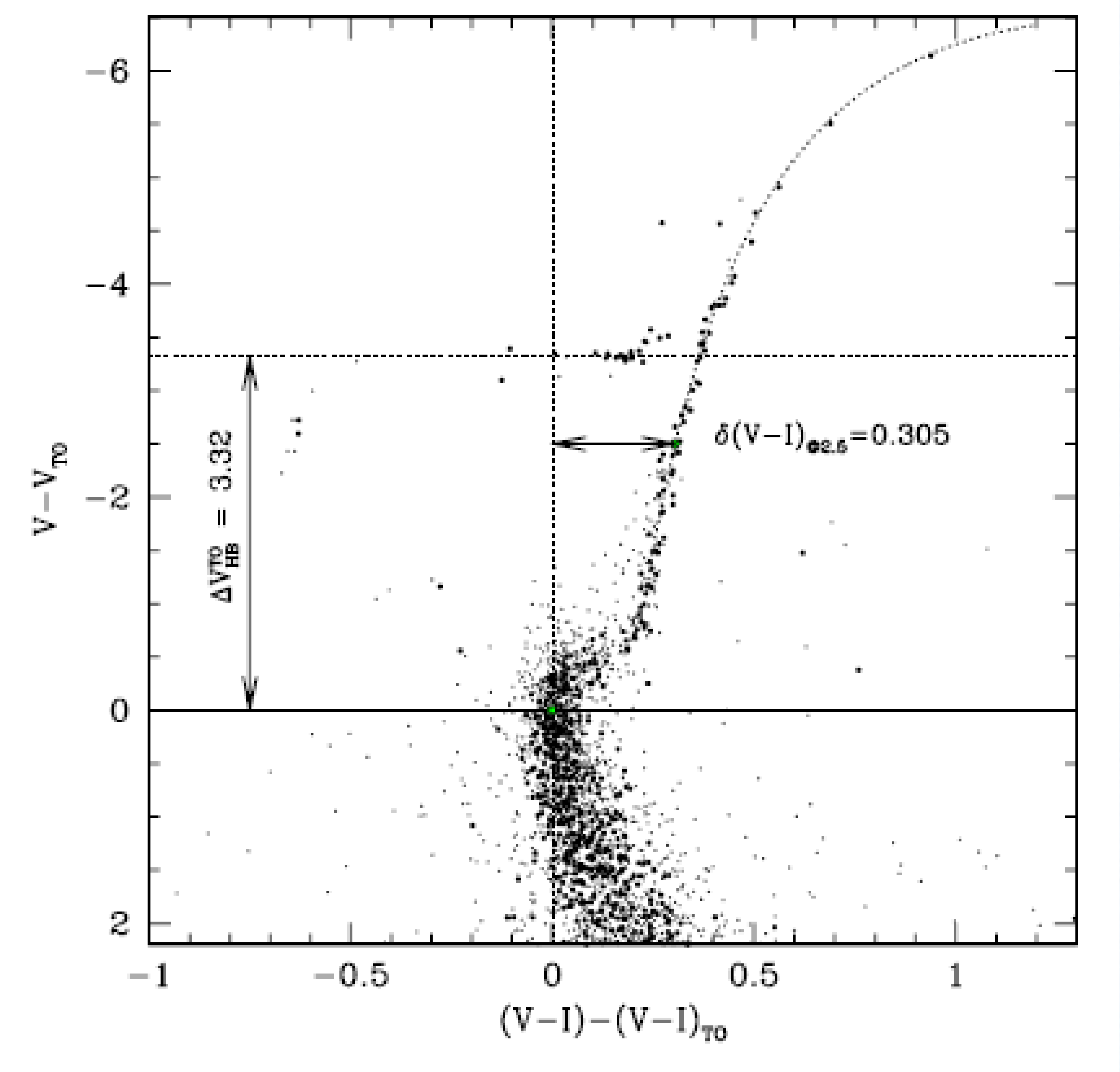


Marin-Franch et al. (2009, ApJ, 694, 1498) find that clusters with multiple populations and clusters related to Galactic streams have younger ages.



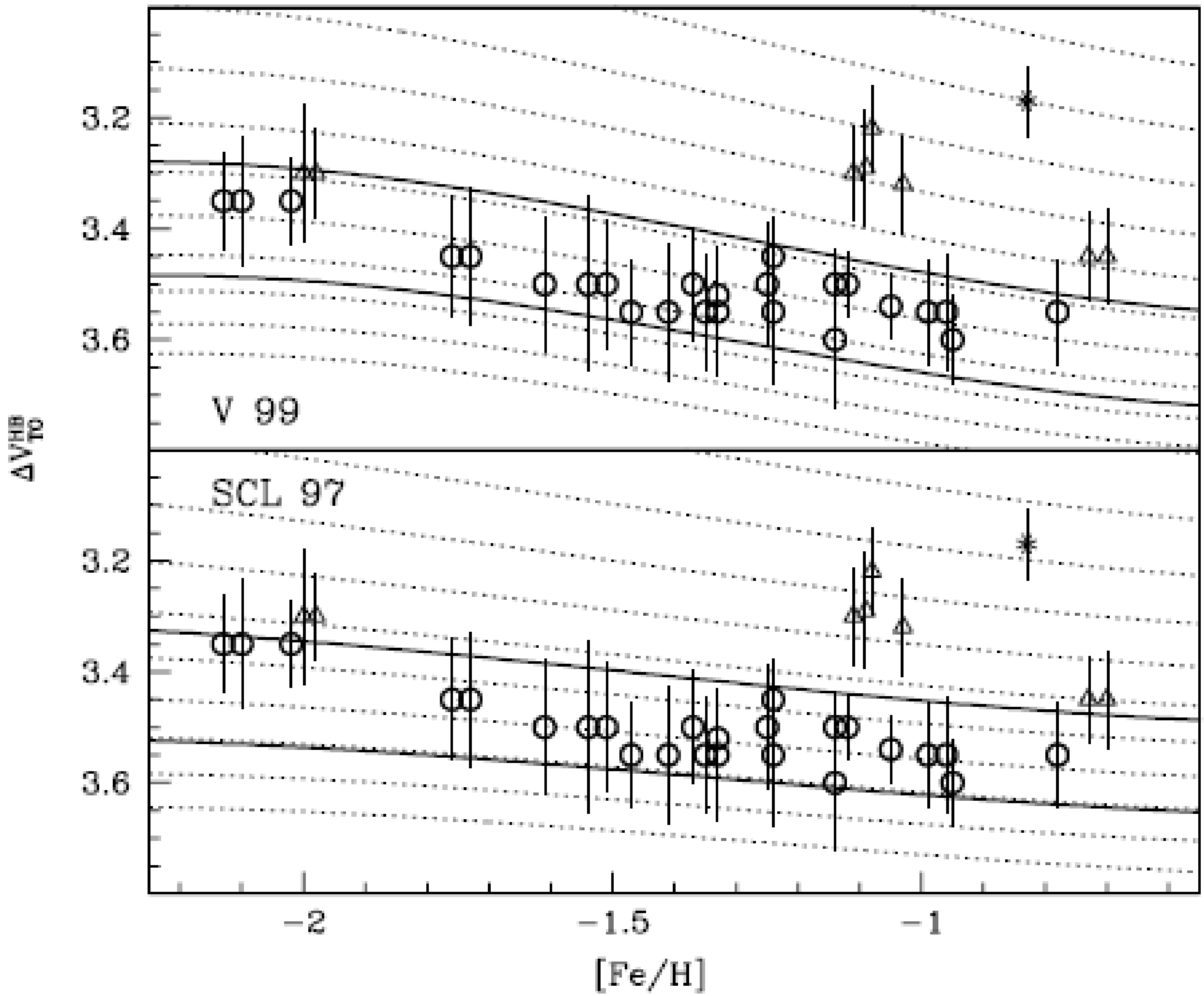
Dotter et al. 2010, ApJ, 708, 698

Da Rosenberg et al. 1999, AJ, 118, 2306

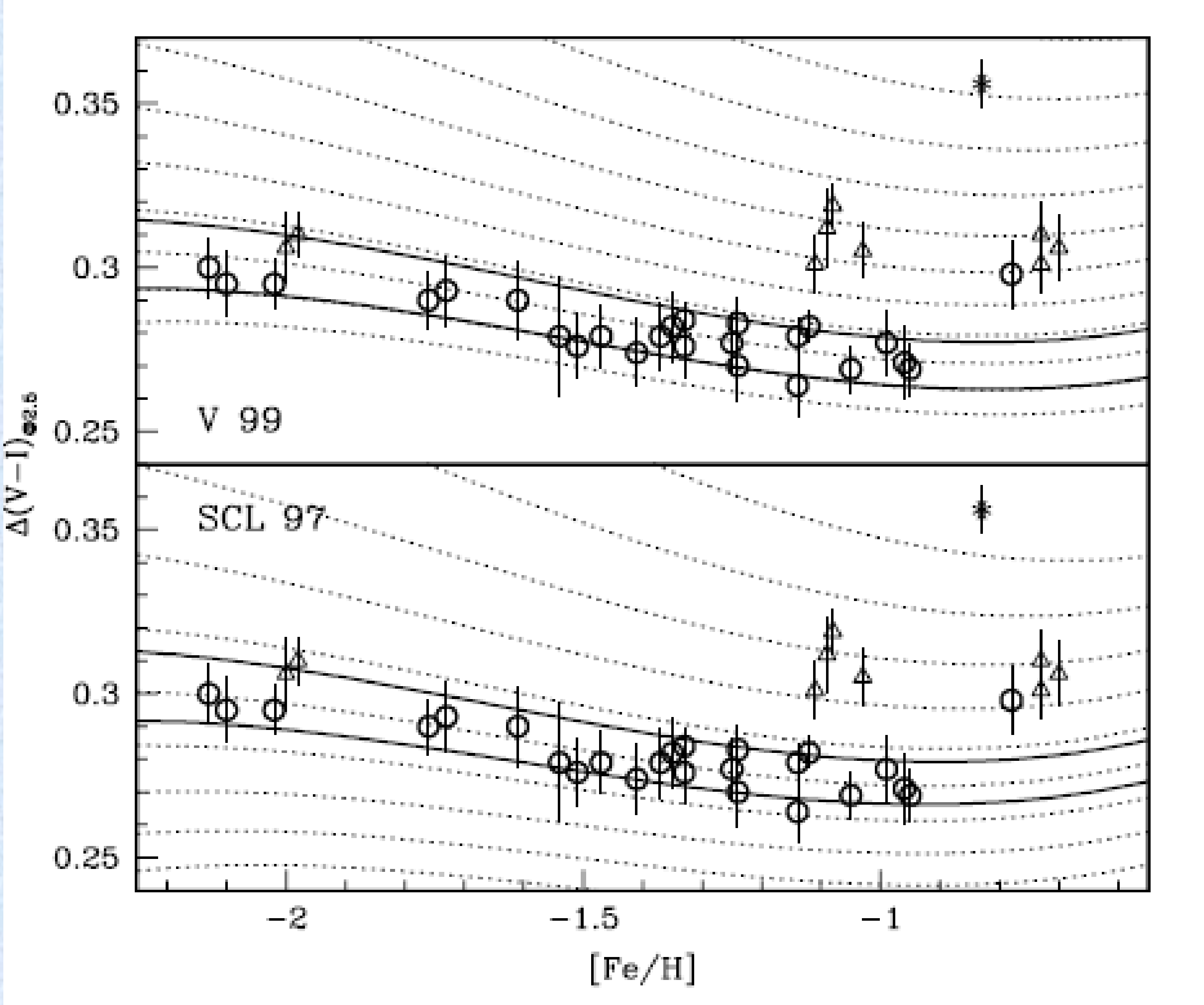


Metodo Verticale

Si veda anche:
De Angeli et al., AJ, 130,116



Metodo Orizzontale



Recent results:

1. Age is the second parameter that account for HB morphology (Dotter et al. 2010)

2. Age is a second parameter, but not sufficent to account for the HB complex morphology. A third parameter is needed, and this is He content (Gratton et al. 2010, A&A, 517, 81)

Stellar Populations in Globular Clusters: a new era and a new vision. III

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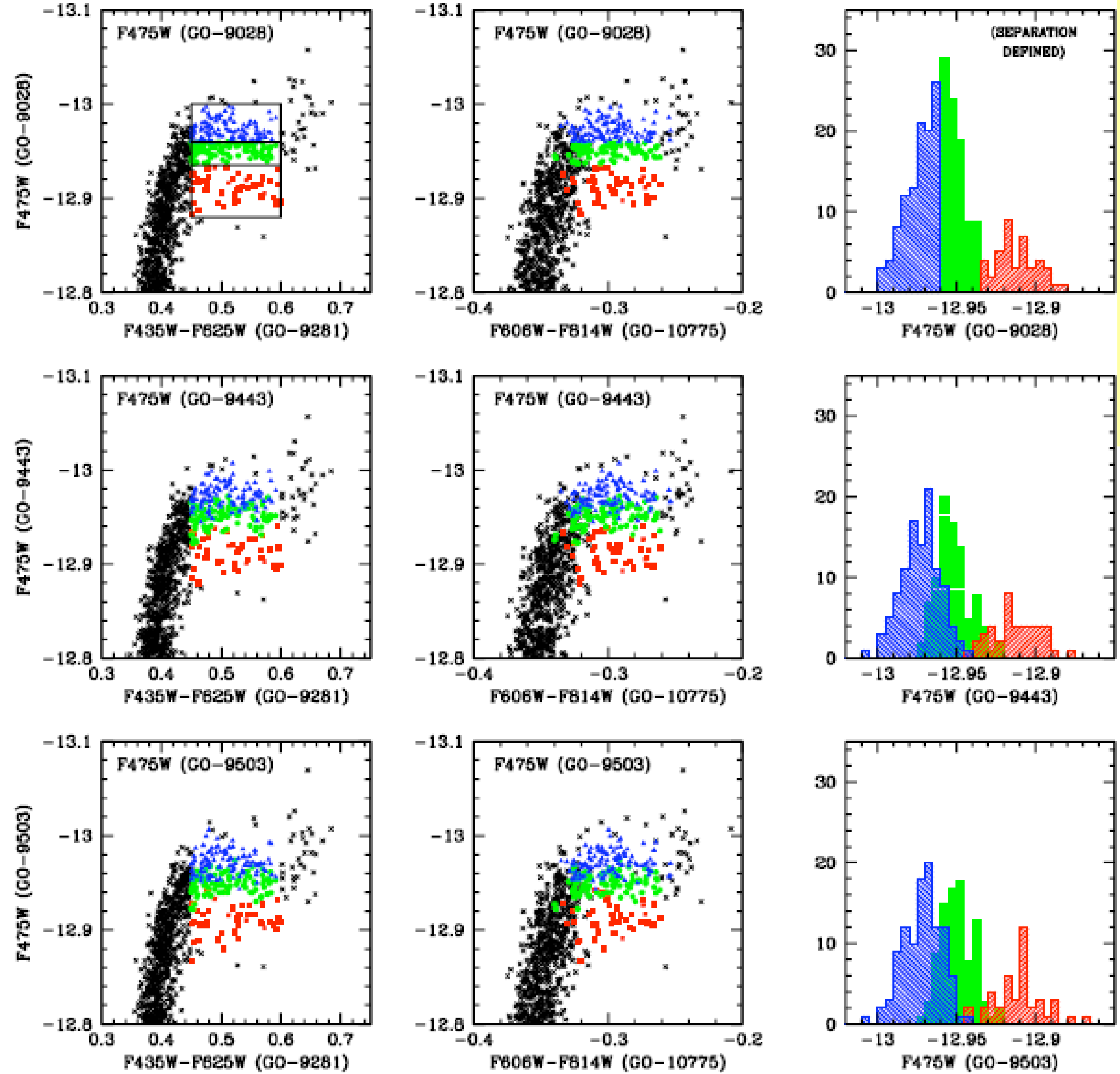
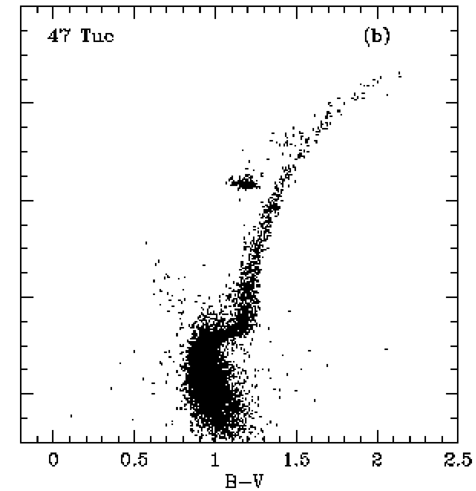
Universita' di Padova

47 Tucanae shows a spreaded SGB, plus a secondary SGB

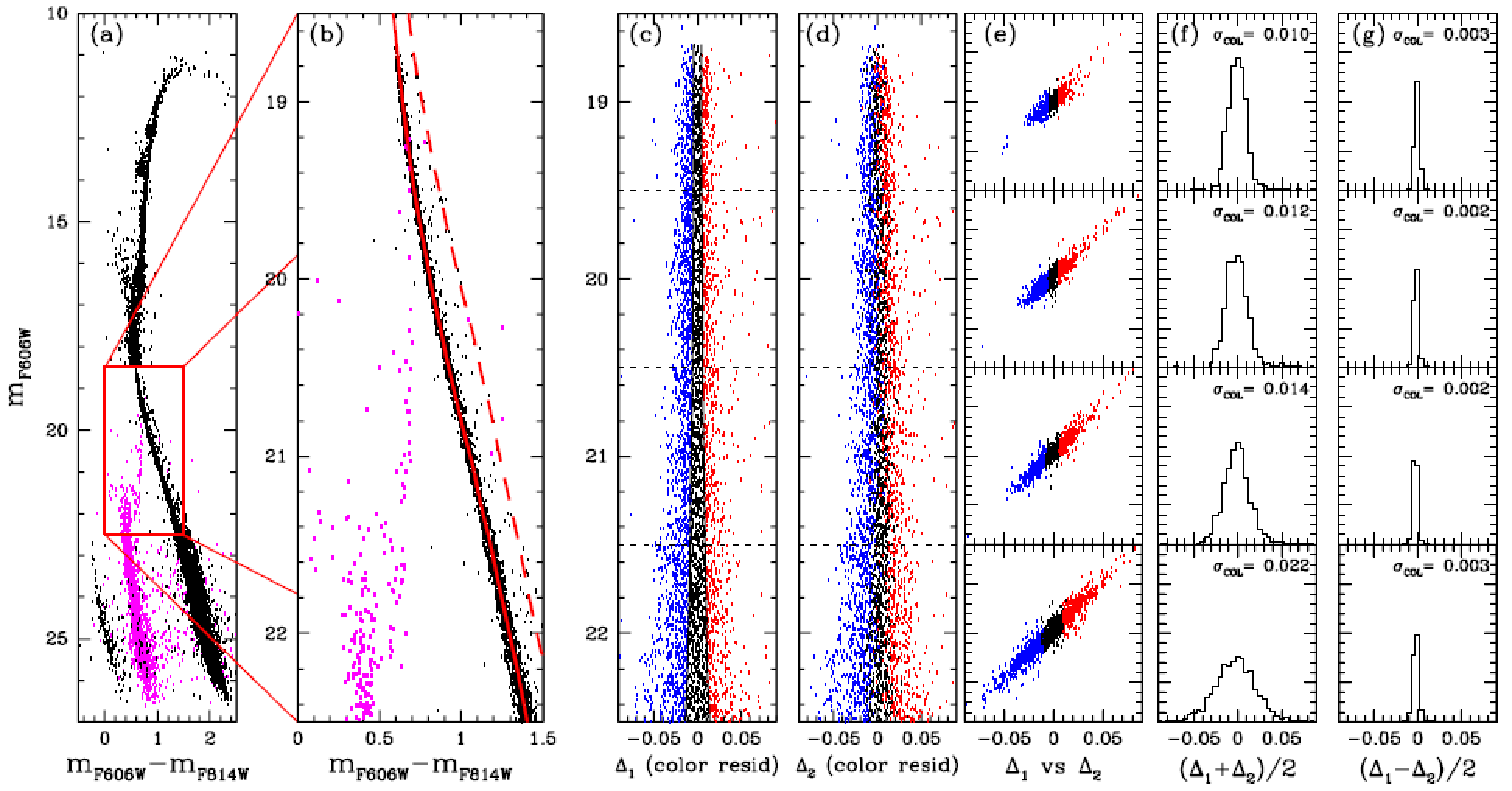


Anderson et al. 2009, ApJ, 697, L58



Example of cluster with not extended HB showing evidence of multiple populations

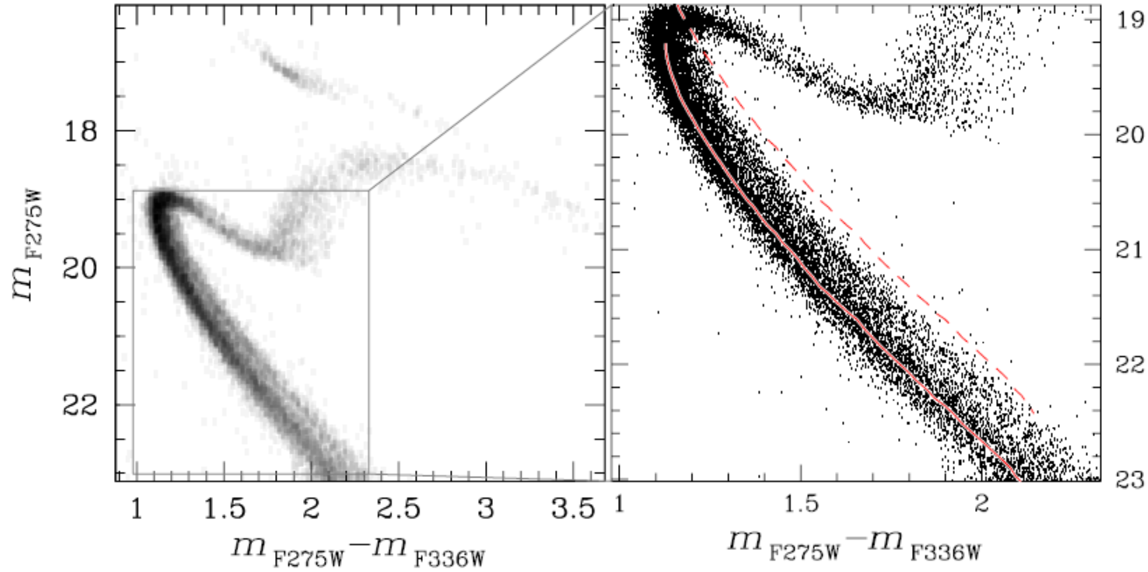
…47Tuc MS is also intrinsically spreaded

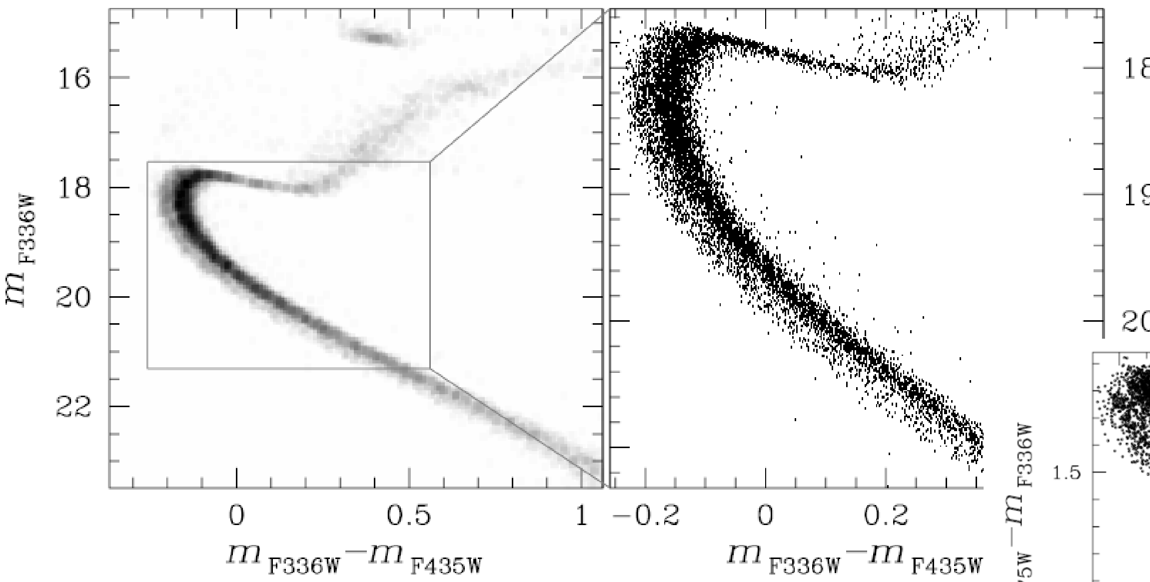


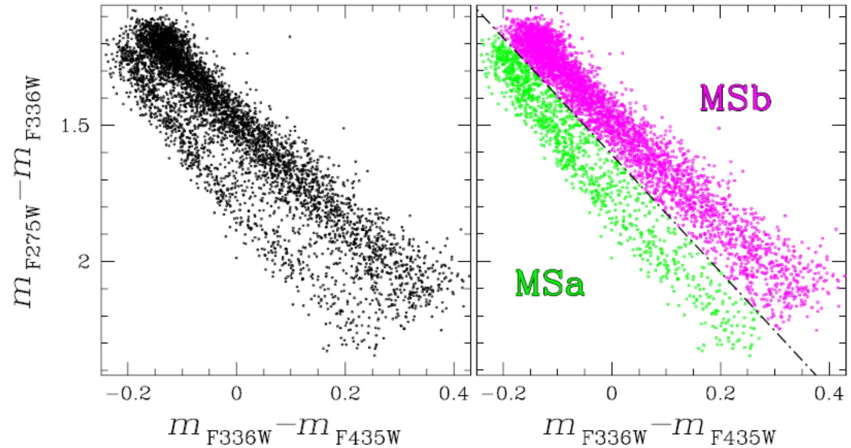
If the spread in color is due to a spread in Fe, it implies a Δ([Fe/H])=0.001; if it is helium, it implies a ΔY=0.03

47Tucanae: new results

WFC3+ACS data
9 photometric bands



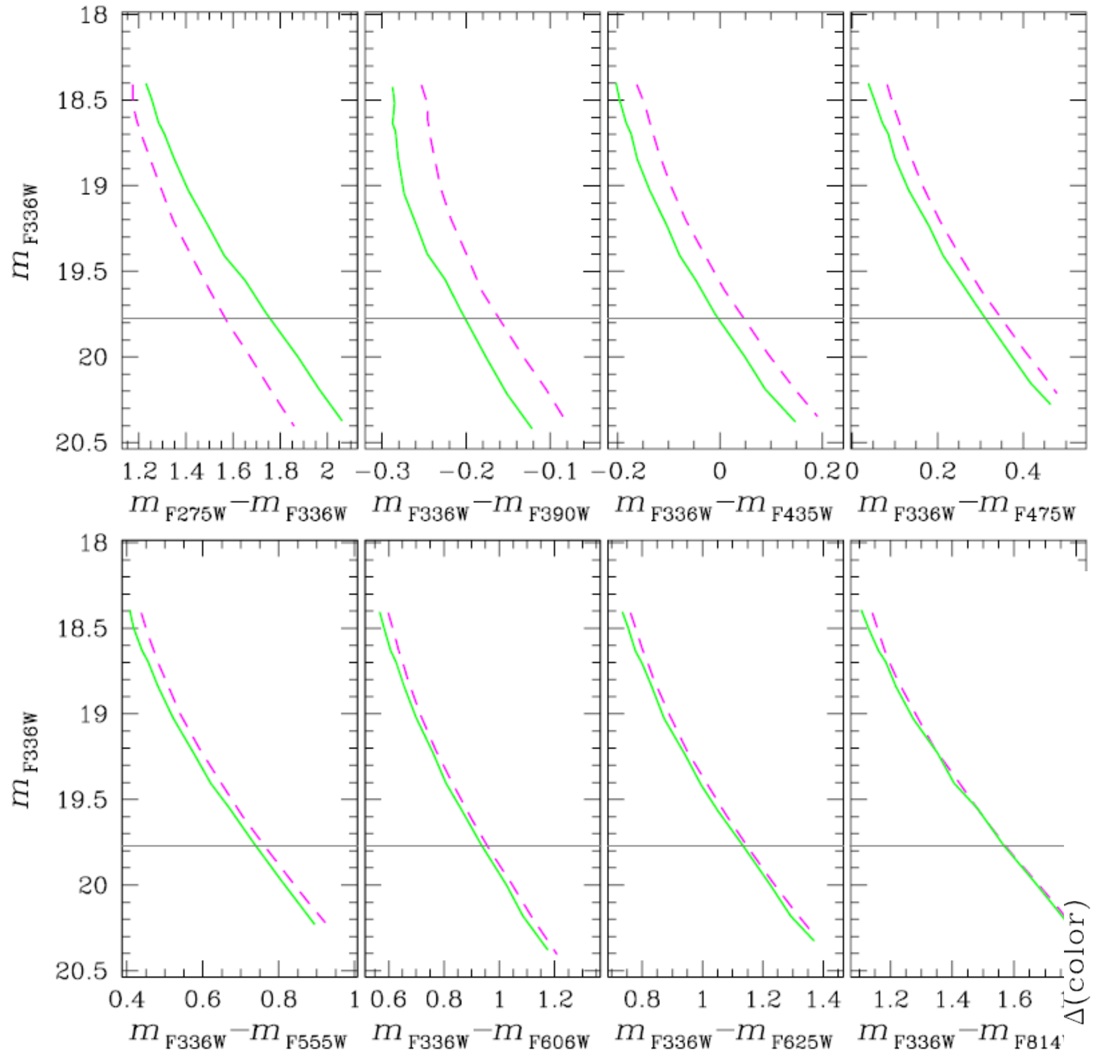


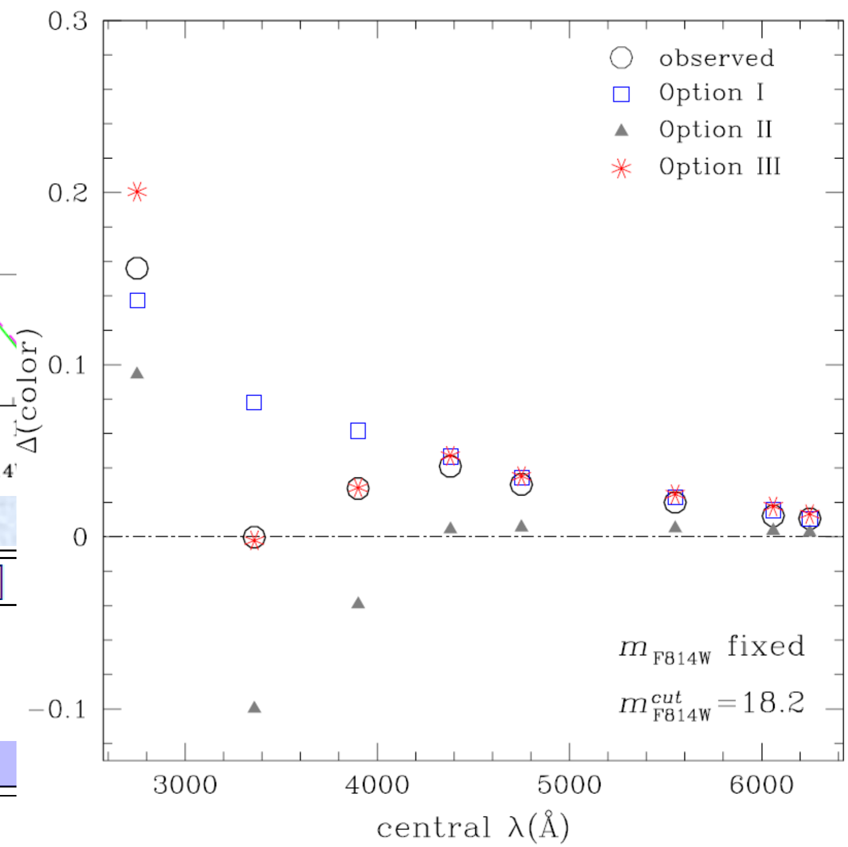


Milone, Piotto et al, 2011, ApJ, subm.

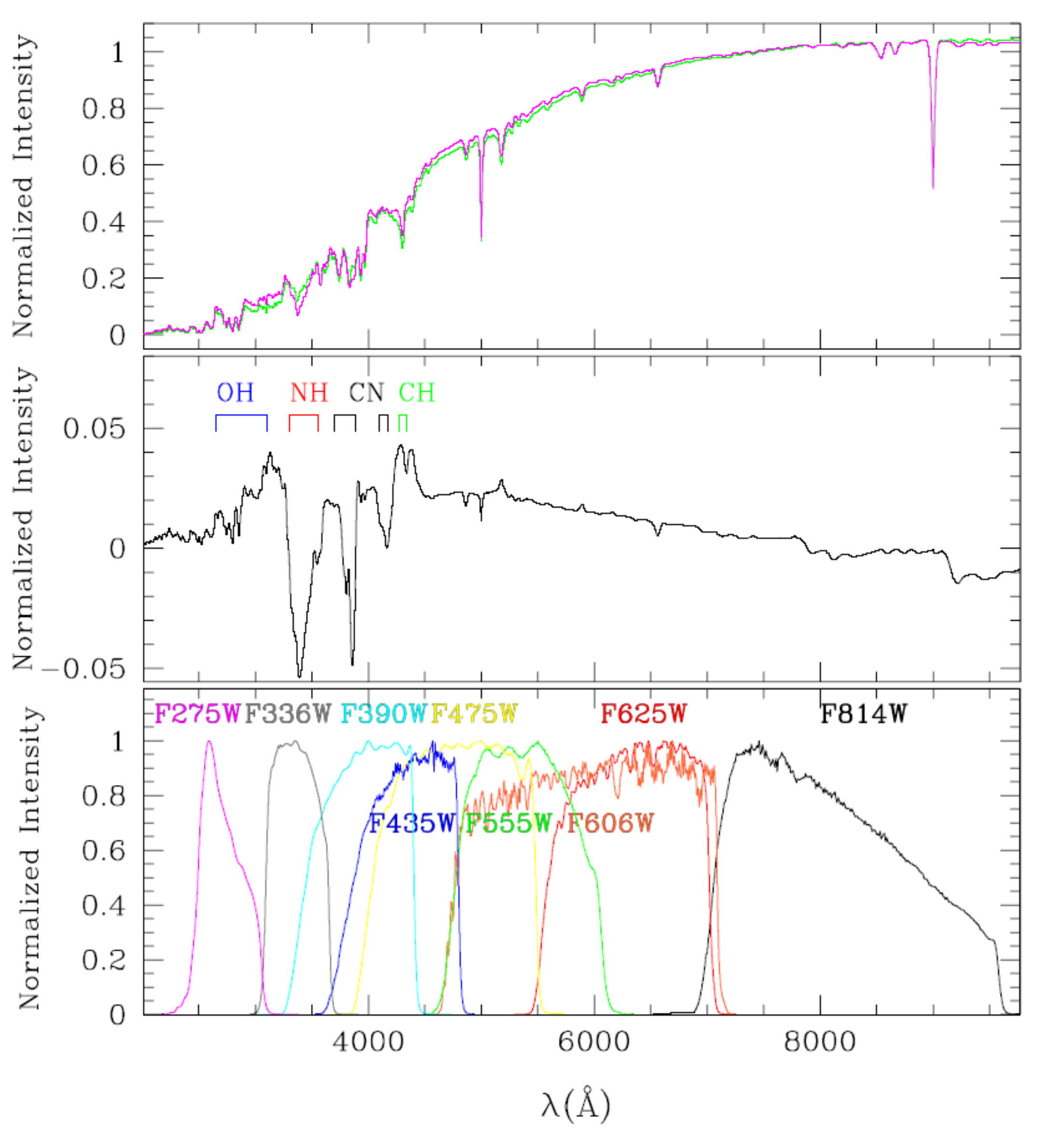
MSa (magenta) corresponds to a first stellar generation, with primordial He, and O-rich/N-poor stars, whereas MSb (green) corresponds to a population that is enriched in He and N but depleted in O.

This need for differences in both helium and CNO to account for all the color differences fits quite well with nucleosynthesis expectations, as helium-enriched stellar regions are also inevitably oxygen-depleted and nitrogen-enriched,





MS (Option)	T_{eff}	log g	Y	[C/Fe]	[N/Fe]	[O/Fe]
MSa (all)	5663	5.42	0.248	0.06	0.20	0.40
MSb (I)	5749	5.41	0.280	0.06	0.20	0.40
MSb (II)	5695	5.42	0.248	-0.15	1.05	-0.10
MSb (III)	5749	5.41	0.265	-0.15	1.05	-0.10



MS color is a complex mixuture of effects:

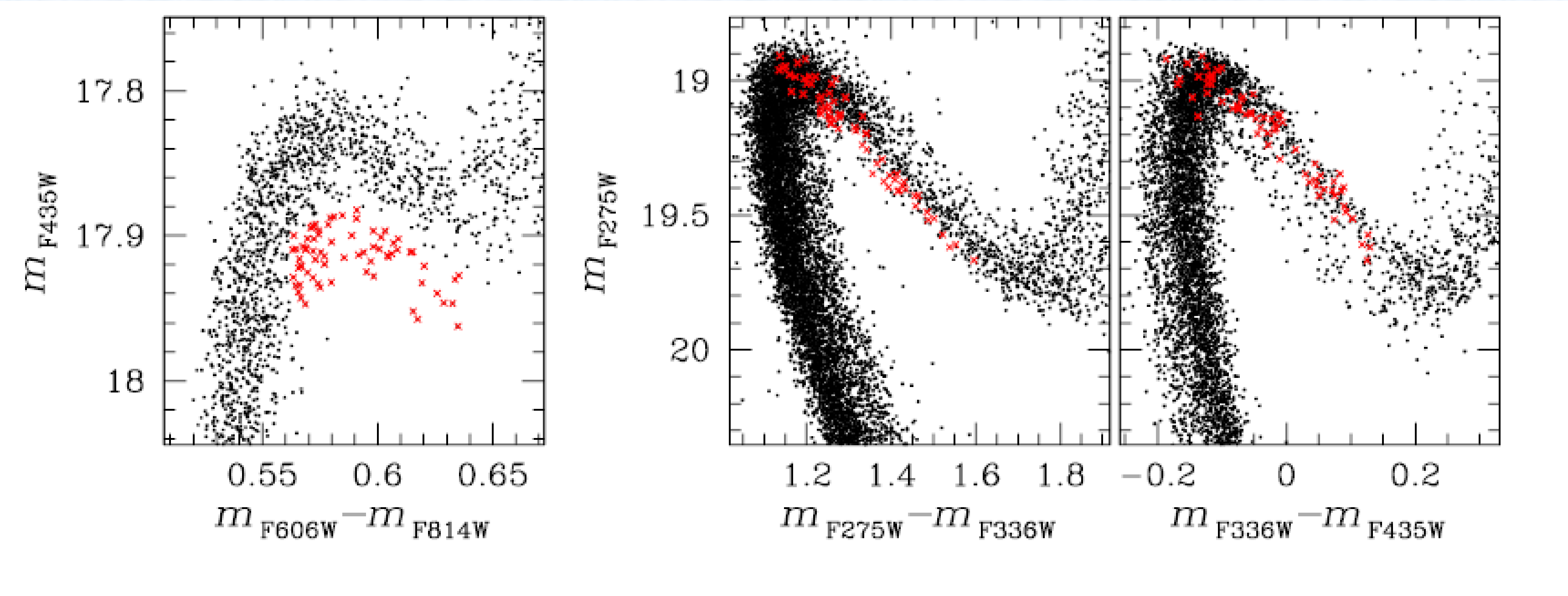
1. Atmospheric spectra:

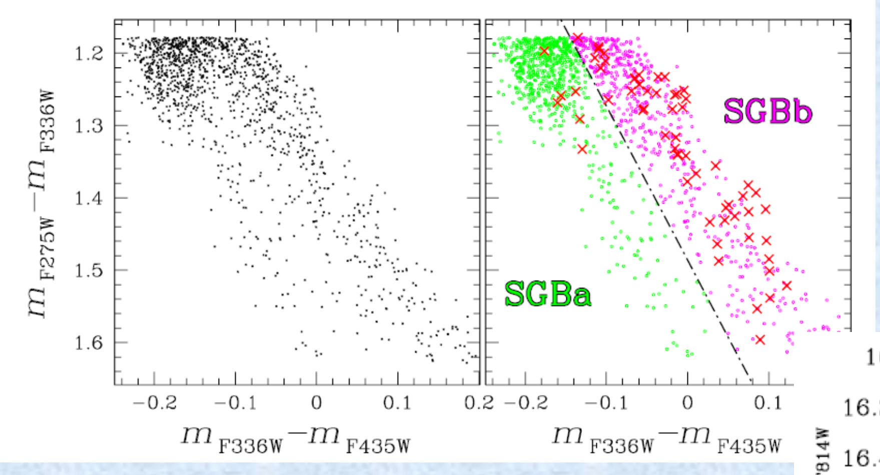
MSa (magenta) corresponds to a first stellar generation, with primordial He, and O-rich/N-poor stars, whereas MSb (green) corresponds to a population that is enriched in He and N but depleted in O.

2. Stellar temperature

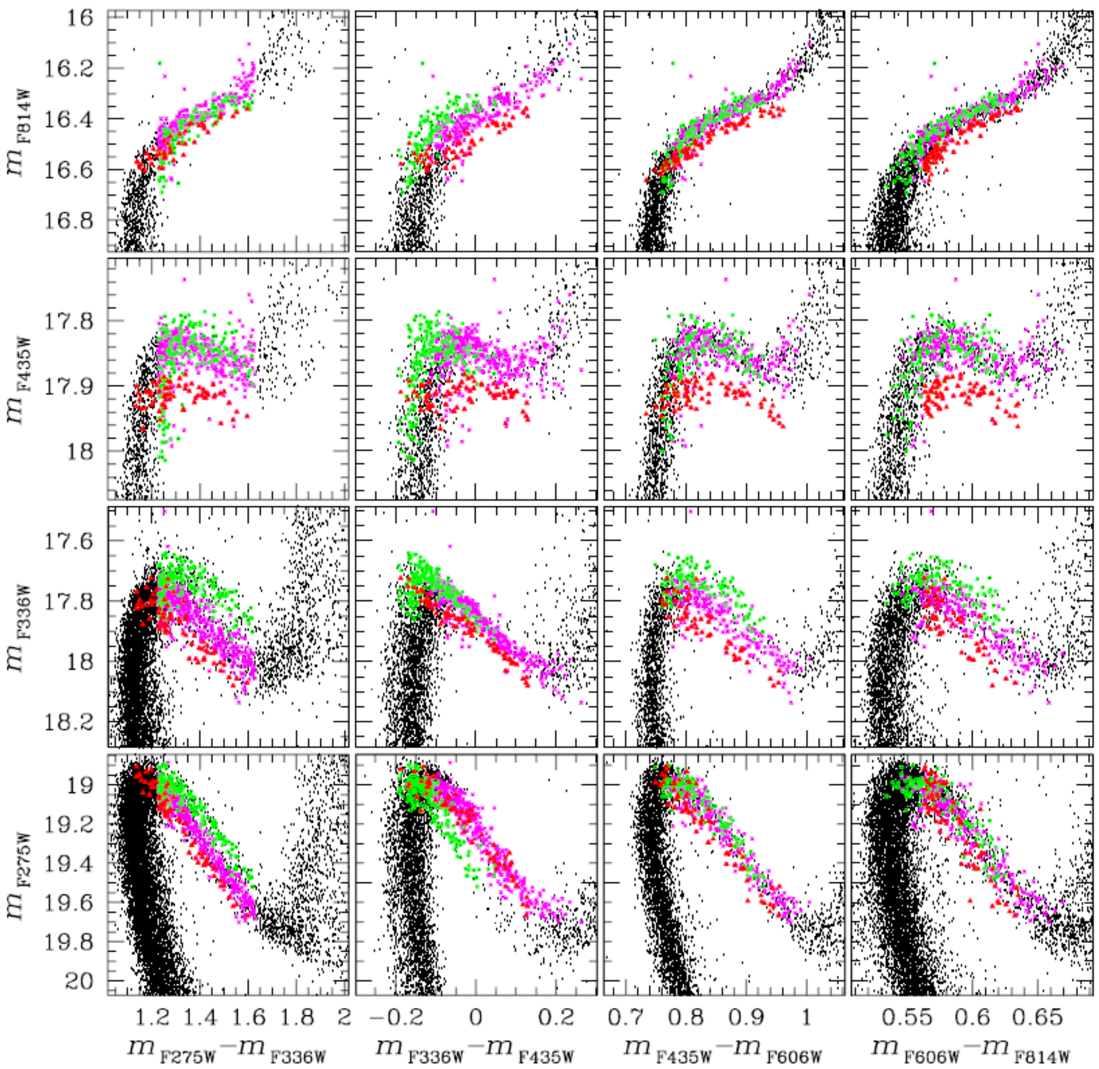
Enhanced He makes temperatures higher.

The complex SGB of 47Tuc

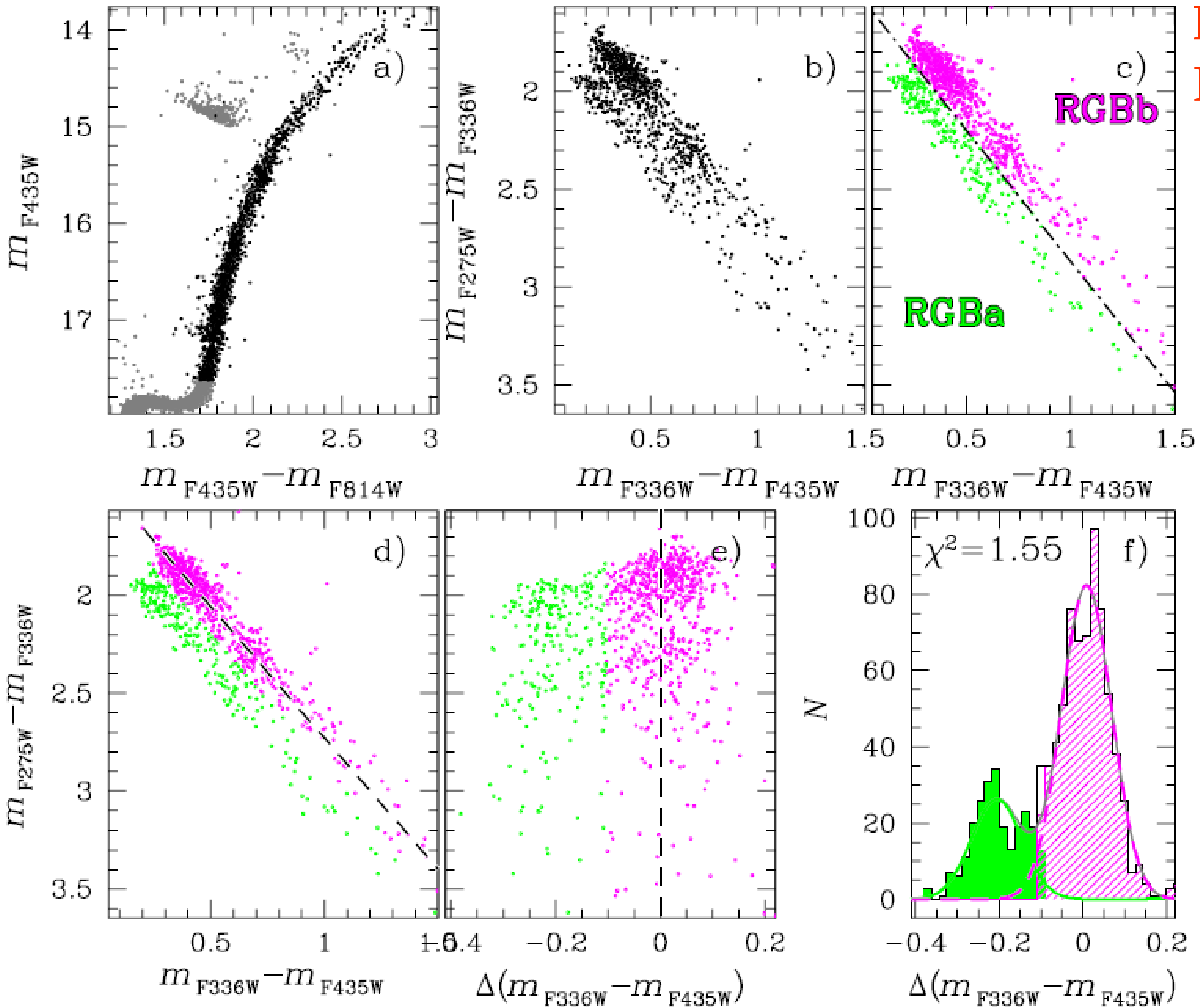


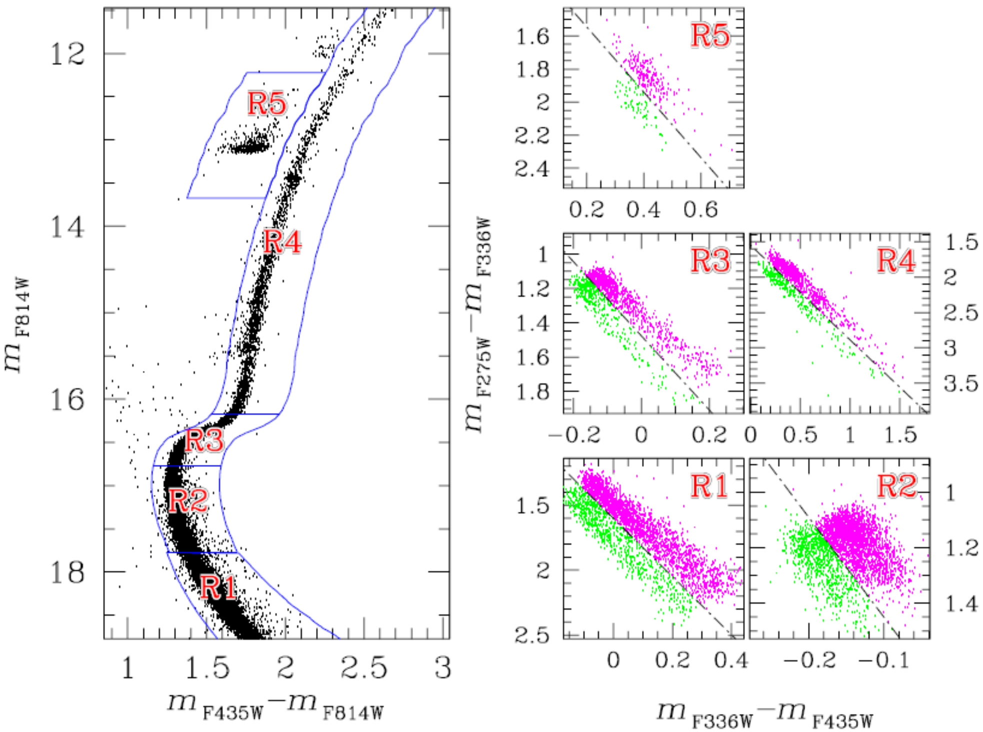


Different photomtric bands provide us with different evidence of population multiplicity

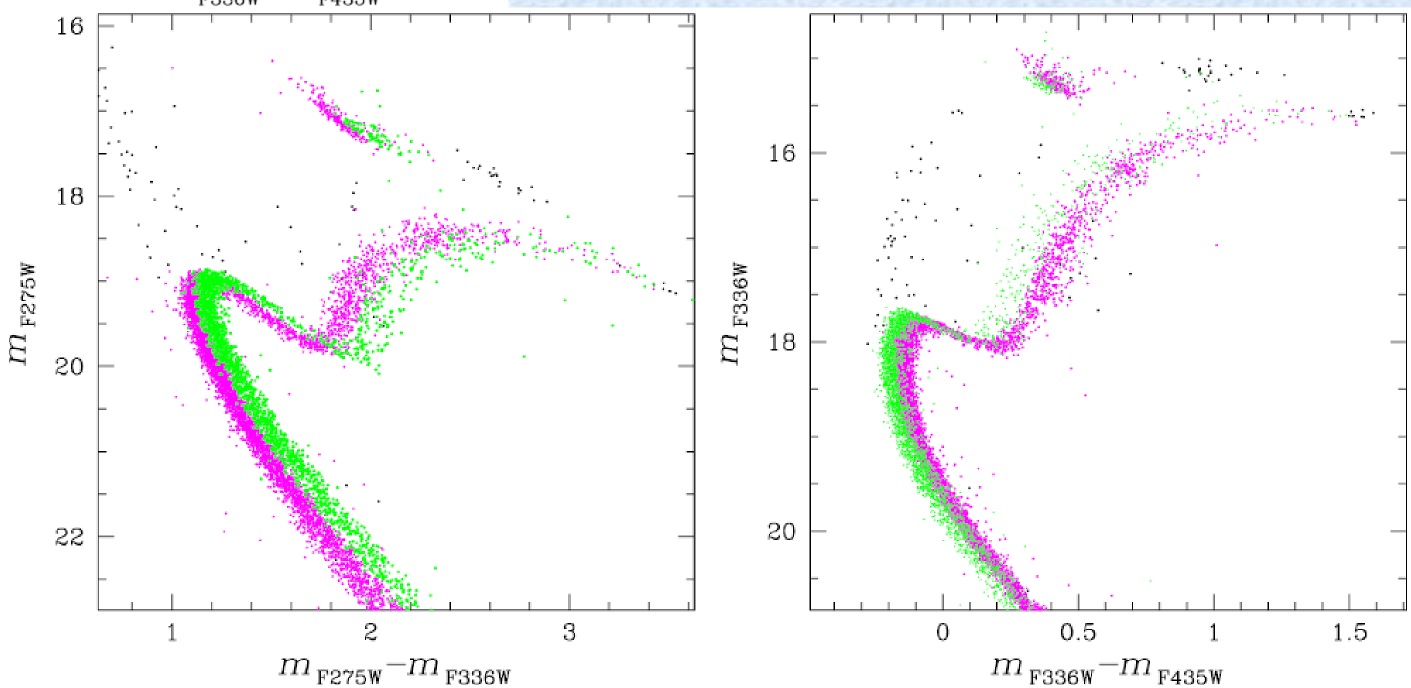


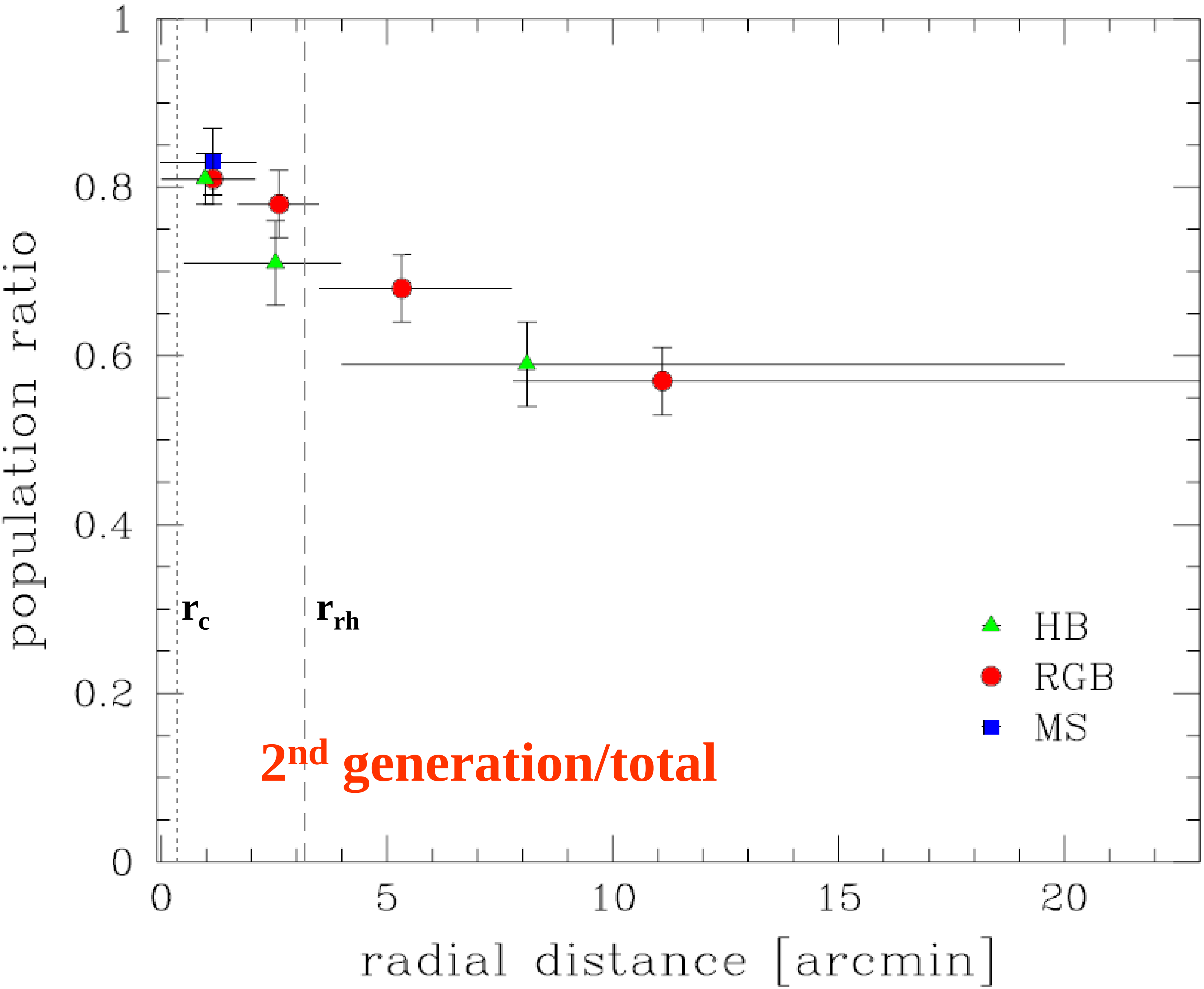
Multiple RGBs In 47Tuc





For the first time, we can Follow the evolutionary path of two stellar generations in the same cluster all along the CMD

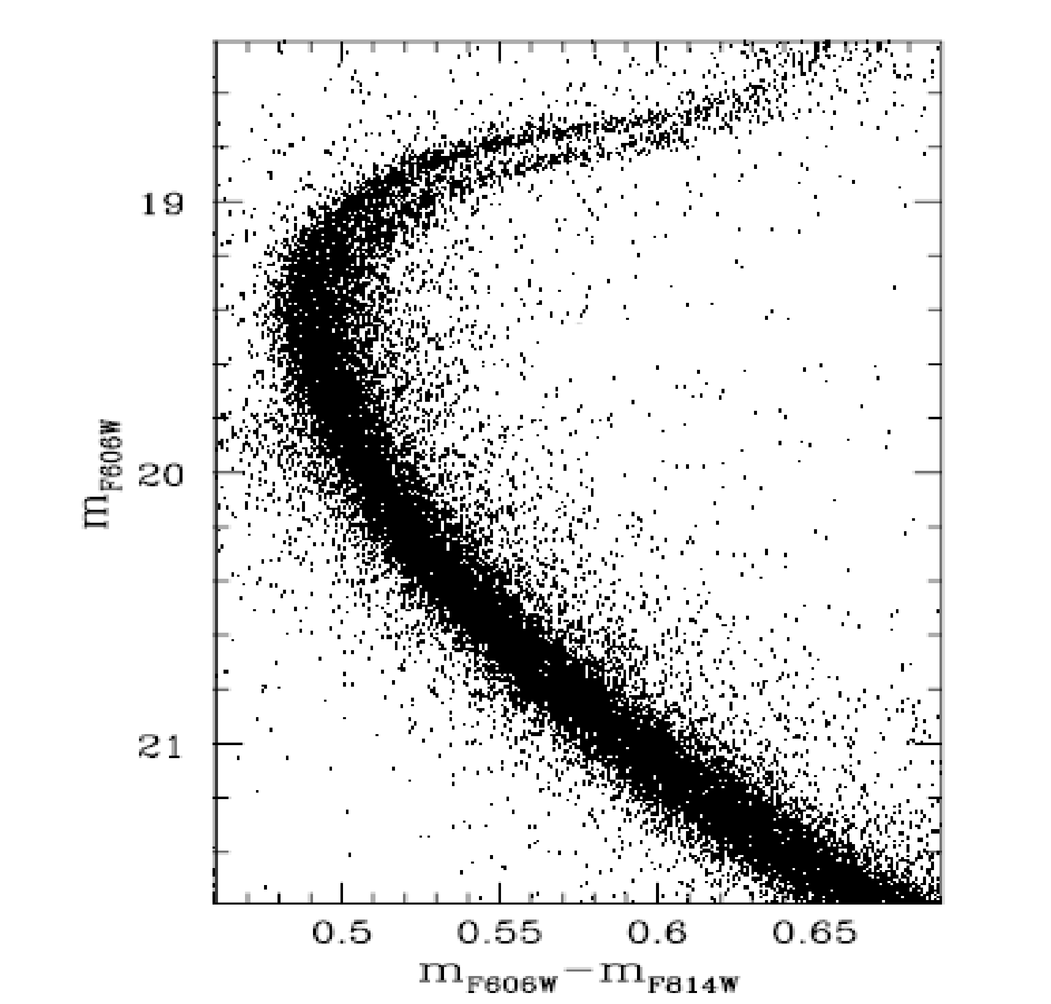




population ratio
radial distance [arcmin]
0
0.2
0.4
0.6
0.8
1
0
5
10
15
20
r_c
r_{rh}
HB
RGB
MS
2nd generation/total

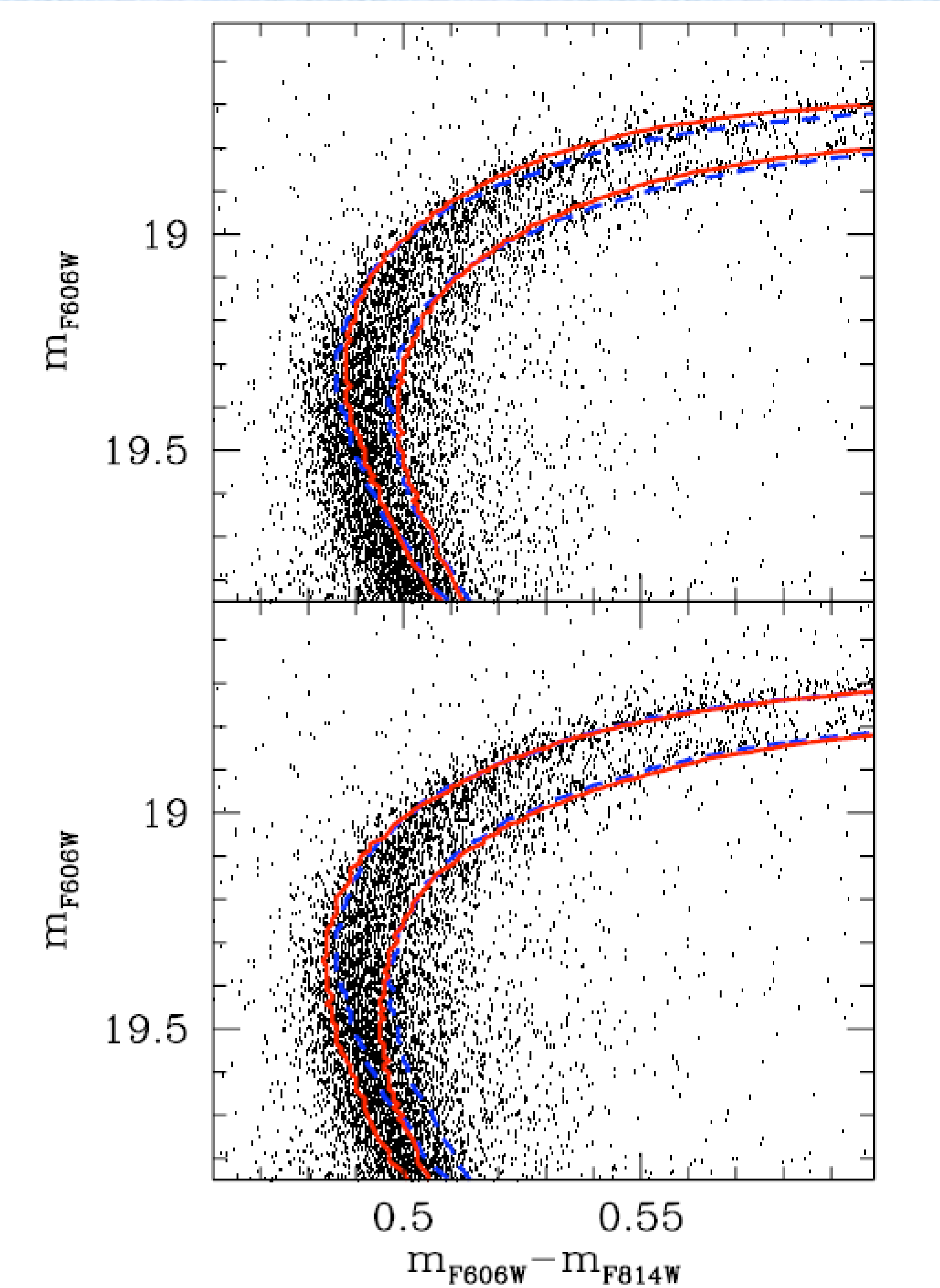
The Double Subgiant Branch of NGC 1851

Milone et al. 2008, ApJ, 673, 241

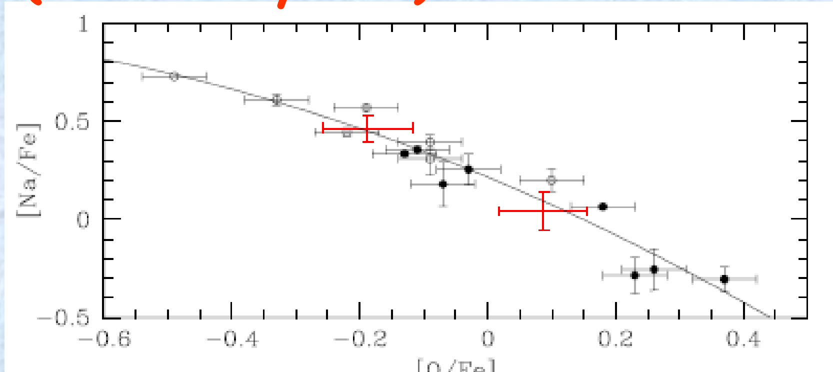


The SGB of NGC 1851 splits into two well defined sequences.

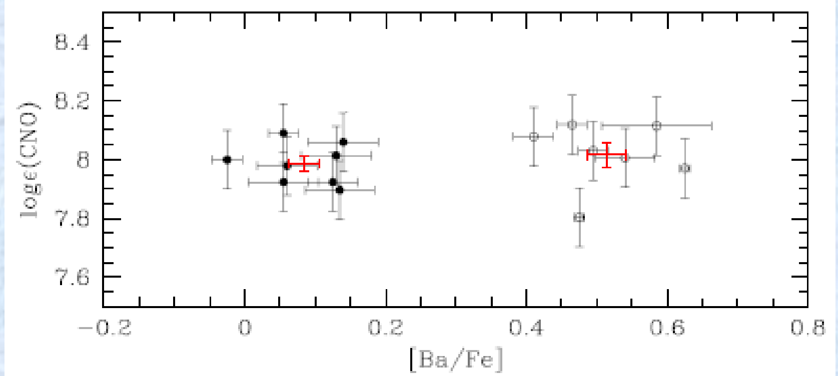
If interpreted only in terms of an age spread, the split implies an age difference of about 1Gyr.

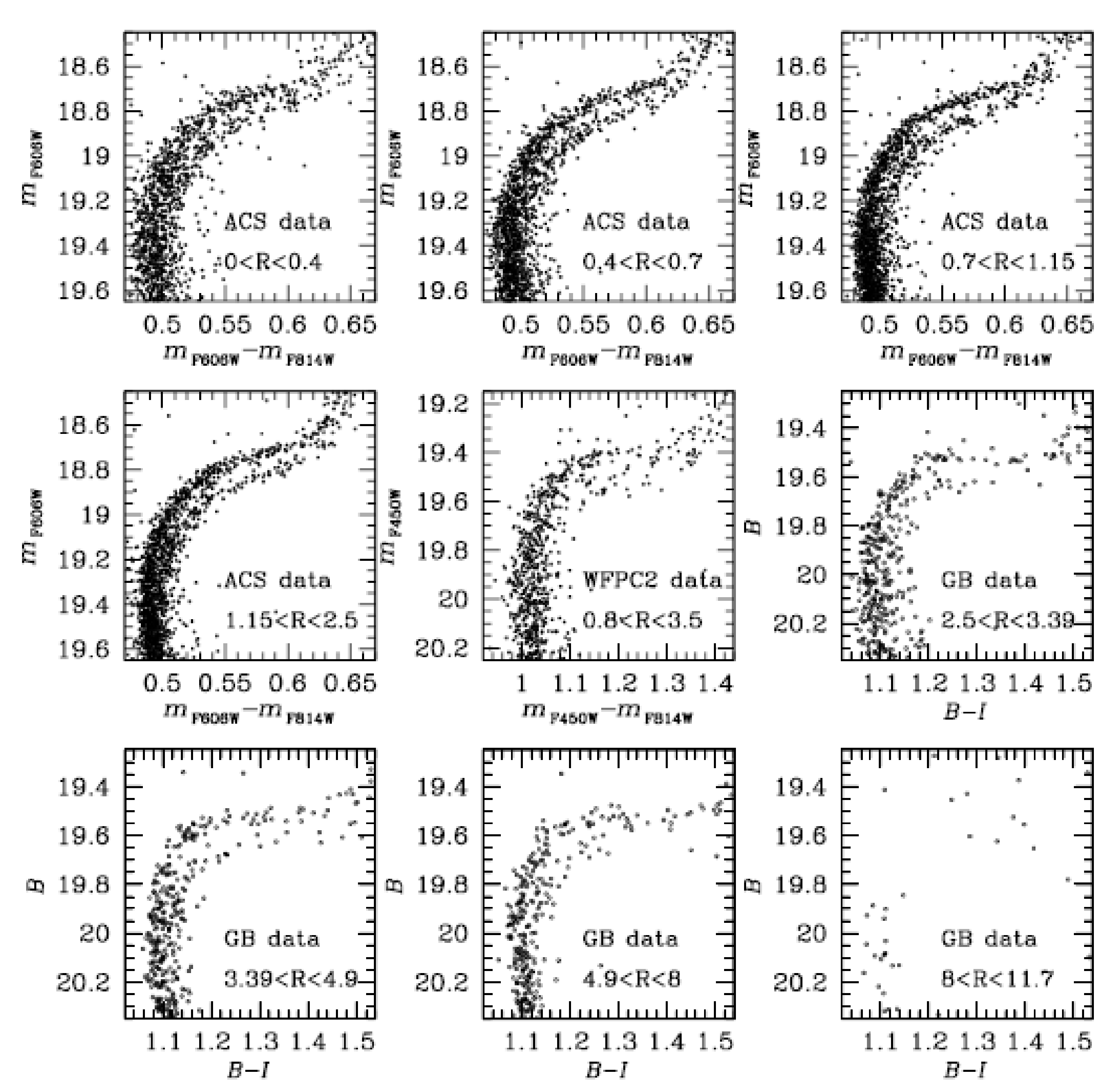


Cassisi et al. (2007, ApJ, 672, 115, Ventura et al. 2009) suggested that the two SGBs can be reproduced by **assuming that the fainter SGB is populated by a strongly CNNa enhanced population,**
In such hypothesis, the age difference between the two groups may be very small (10^7-10^8 years). But….



Villanova et al. 2010, ApJL, in press, arXiv1008.4372





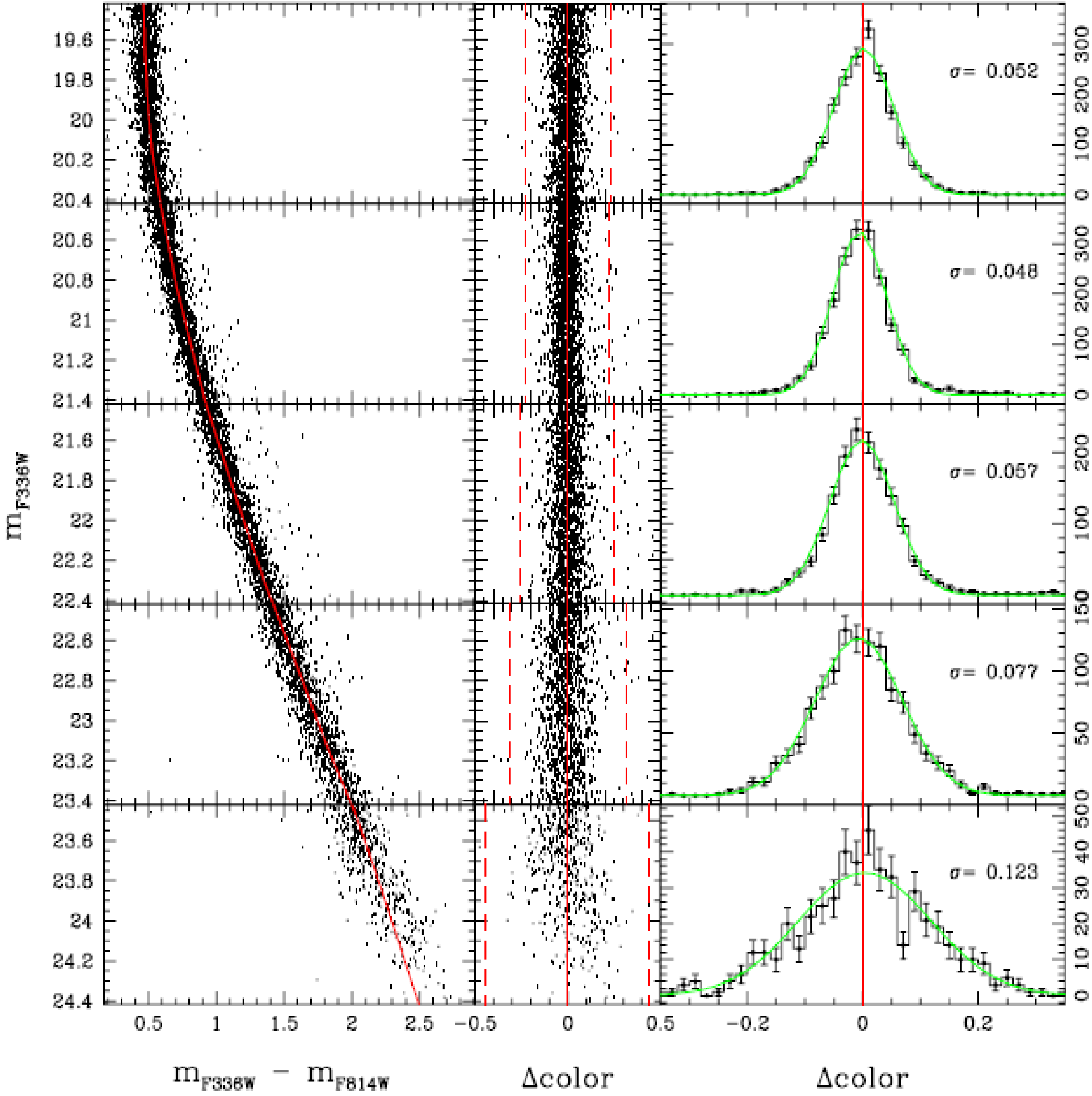
Milone et al. (2009) in prep

Radial distribution of the two SGBs in NGC 1851

The double SGB is present all over the cluster, also in the envelope

There is no radial gradient

Log t_{rh} = 8.9



Apparently there is no large He spread among the MS stars.

A first quick reduction of new HST data from ongoing GO11233 program sets an upper limit to the He spread in NGC 1851 of

Delta Y ~ 0.03

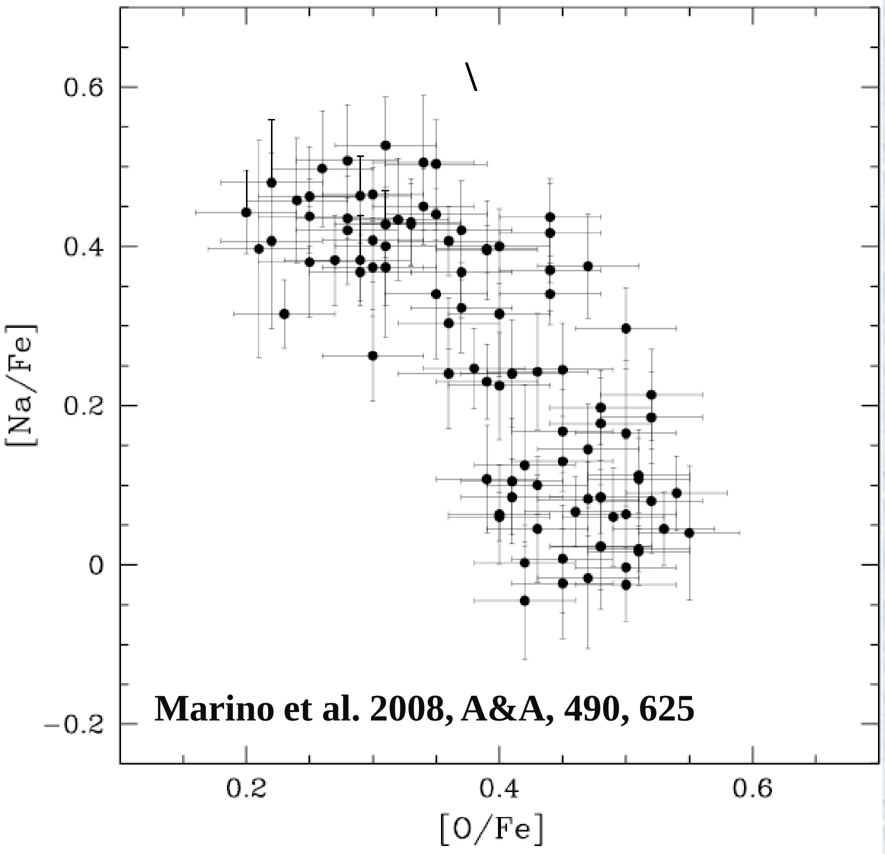
(work in progress)

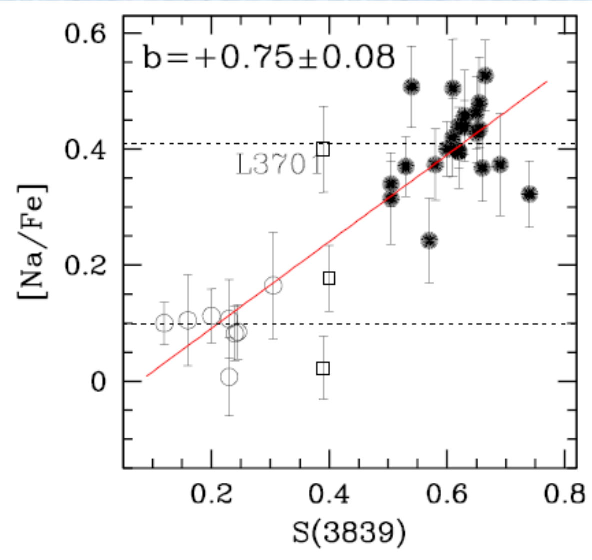
The case of M4

Strong NaO anticorrelation

Two distinct groups of stars

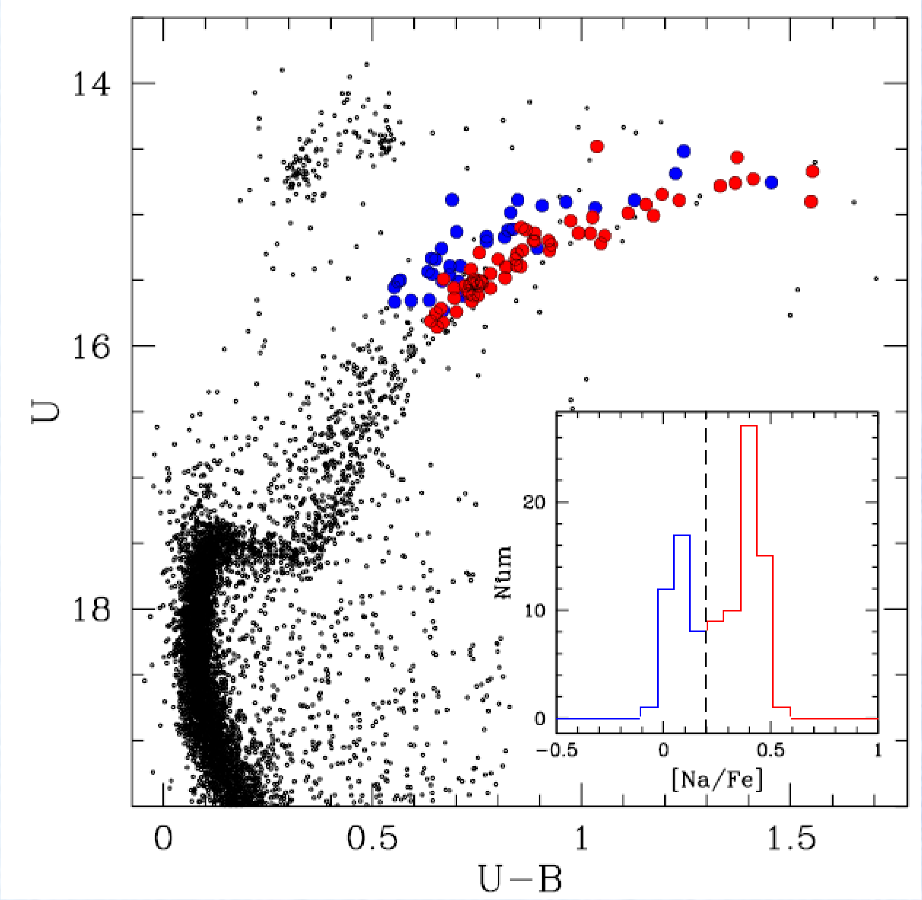
Mass: 8×10^4 solar masses!

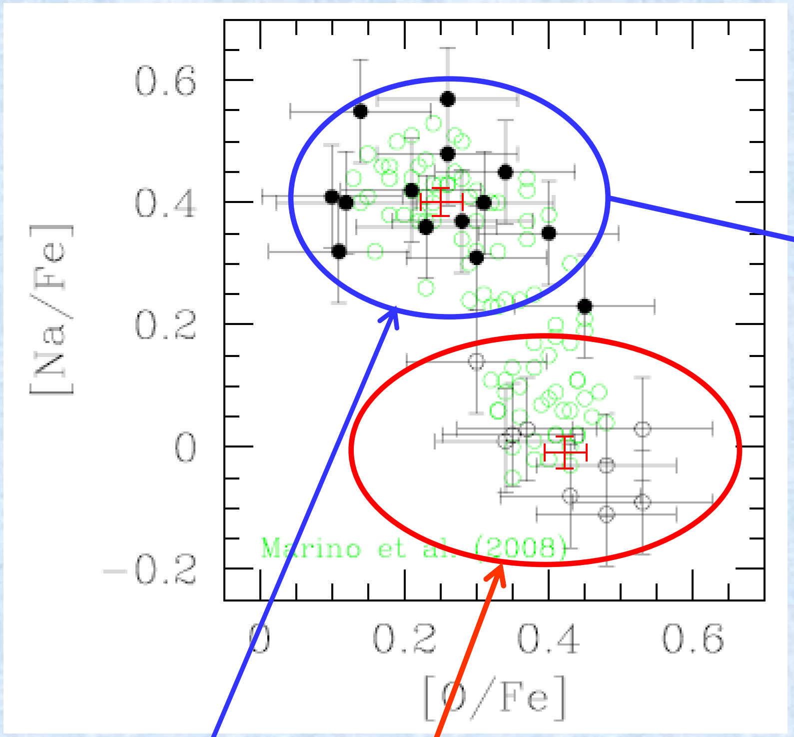


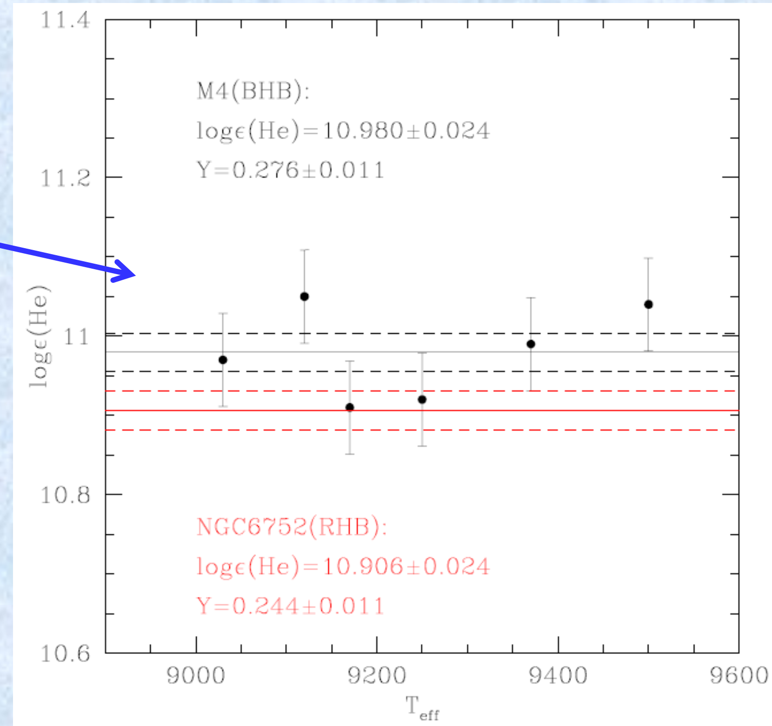


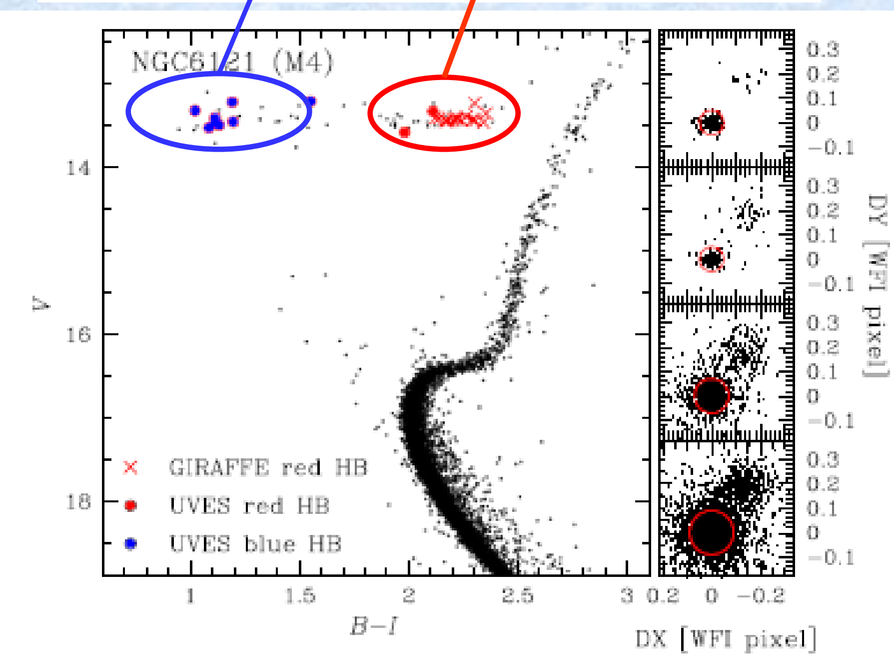
Na rich, O poor stars are CN strong

Na poor, O-rich stars are CN weak



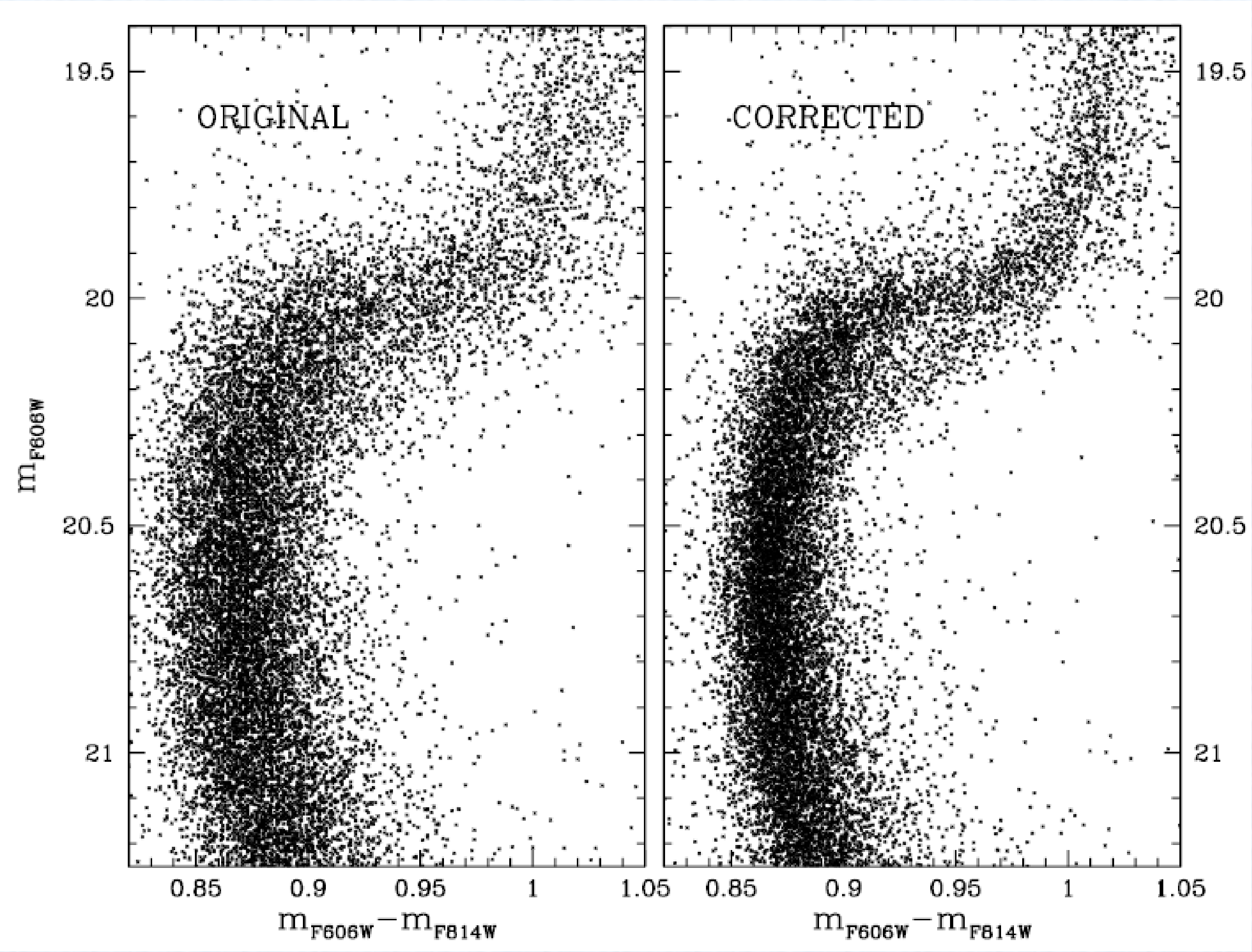




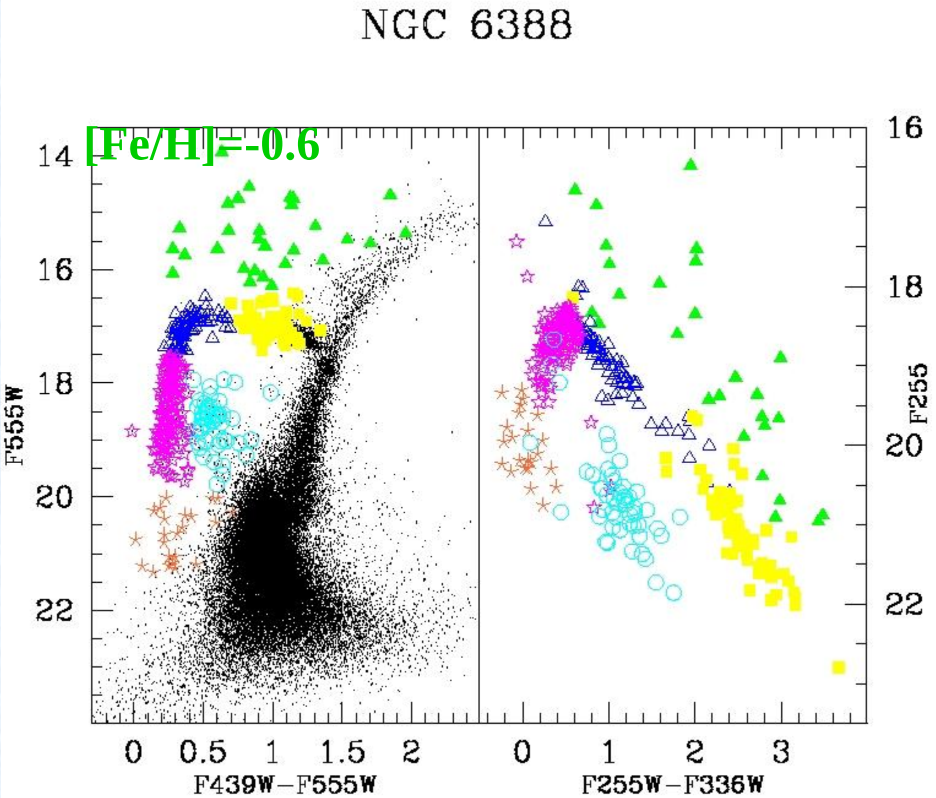


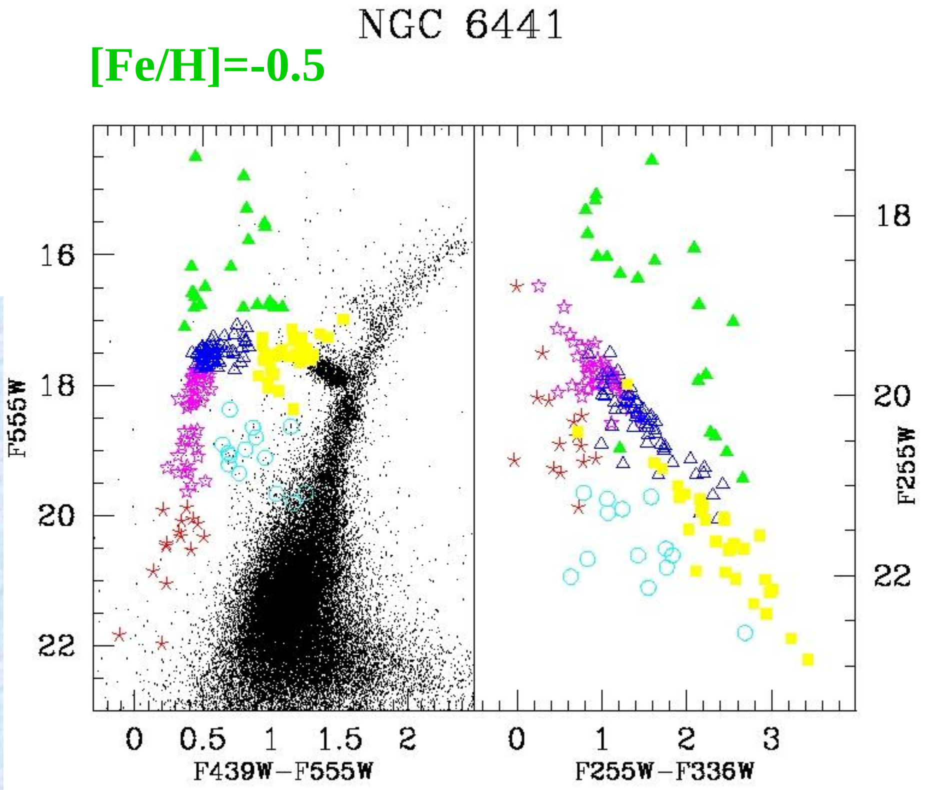
Blue HB stars in M4 are Na-rich, O-poor, He-enriched: they must be second generation stars.

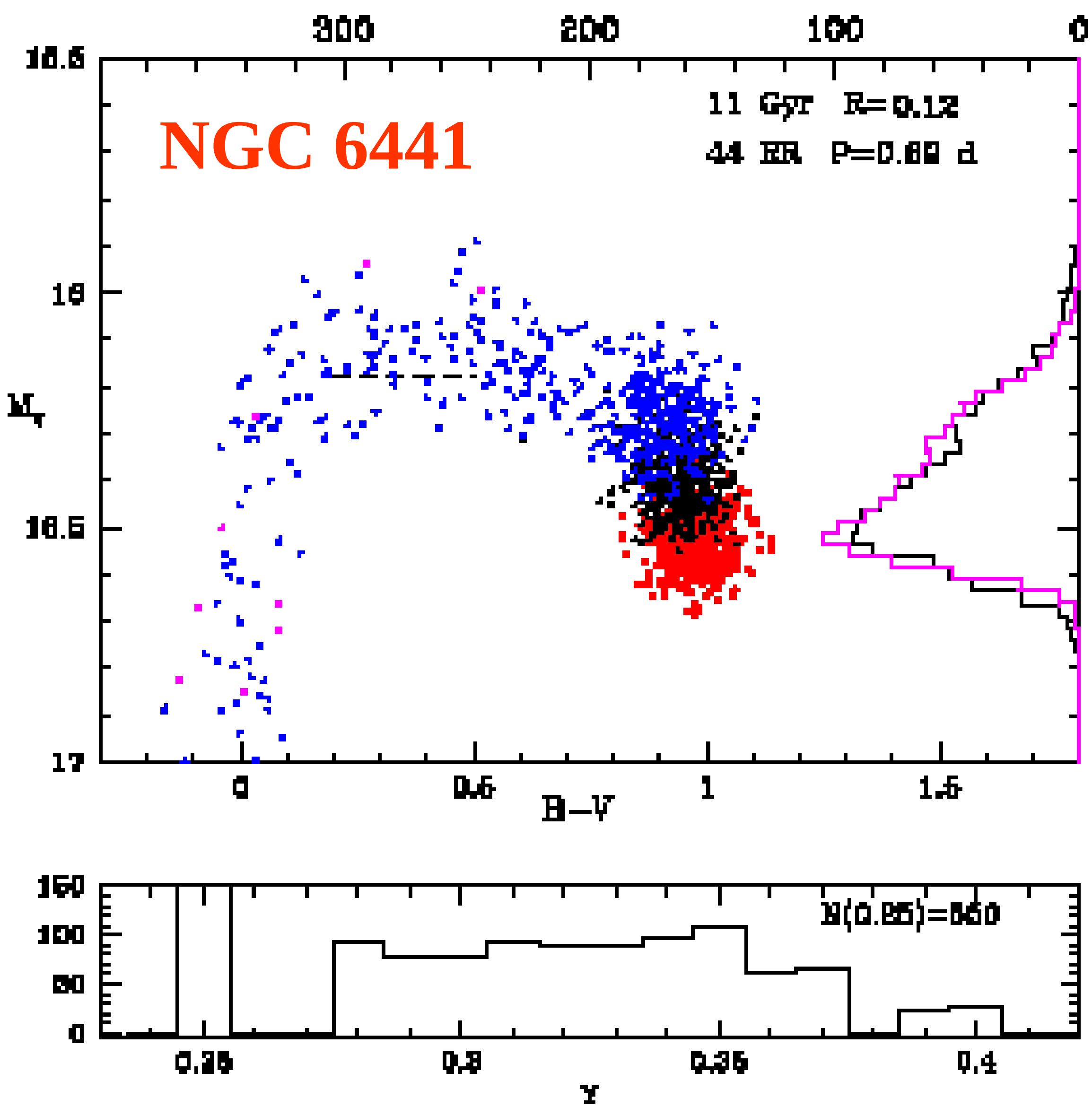
Double SGBs are present in many Globular Clusters: e.g. NGC 6388



Piotto (2009, IAUS, 258, 233)

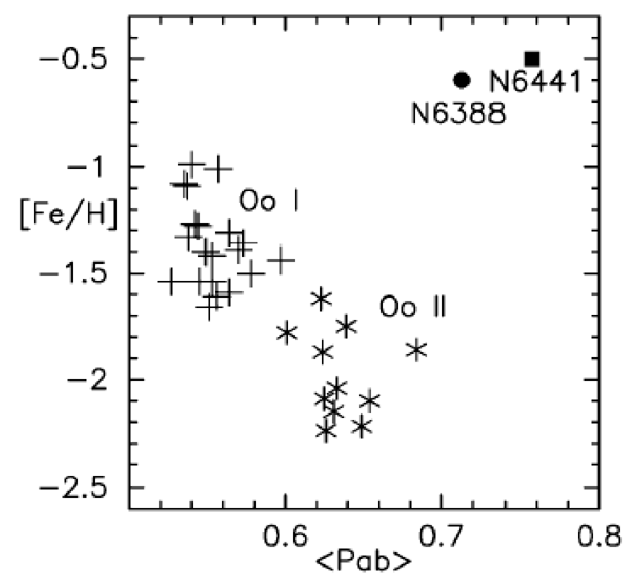

NGC 6388
[Fe/H]=-0.6
F555W
F255
F439W−F555W
F255W−F336W


NGC 6441
[Fe/H]=-0.5
F555W
F255W
F439W−F555W
F255W−F336W

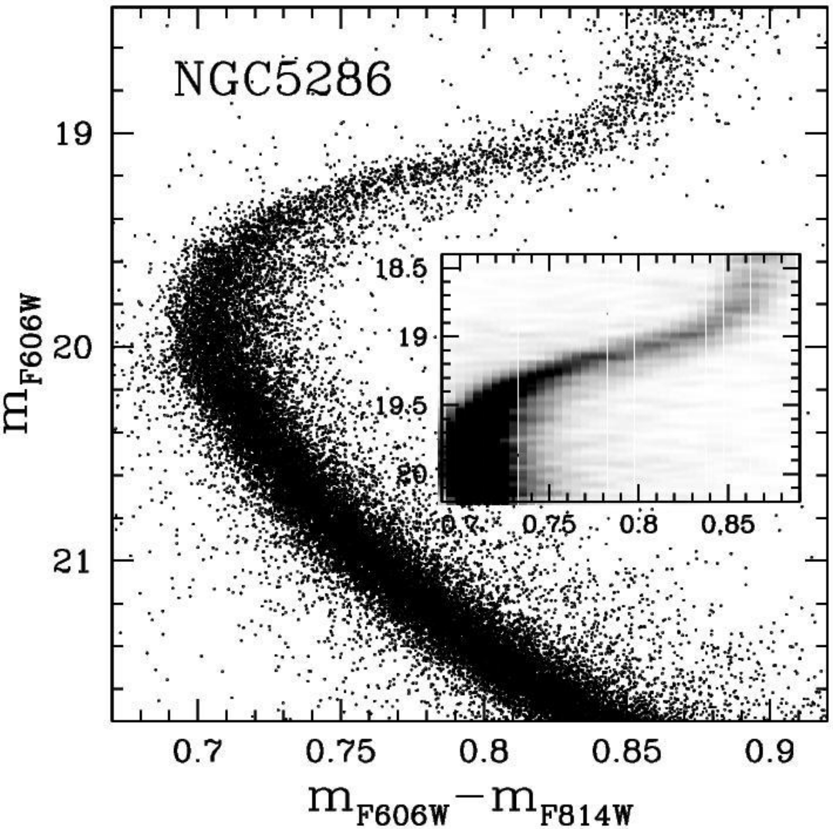


And the real scenario may be even more complicate.
Caloi and D'Antona (2006) propose 3 distinct populations:

1. a normal population (Y~0.25);
2. A first polluted pop. (0.27<Y<0.33);
3. A strongly He enhanced pop. (Y~0.4)

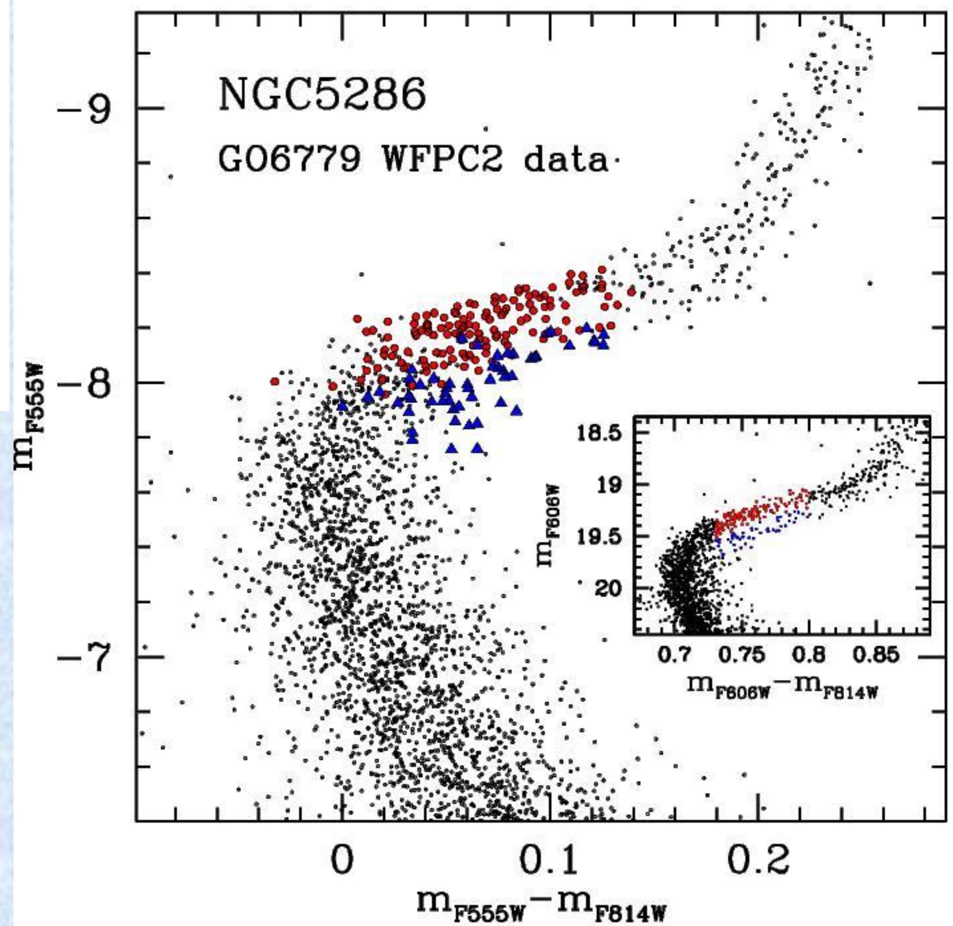


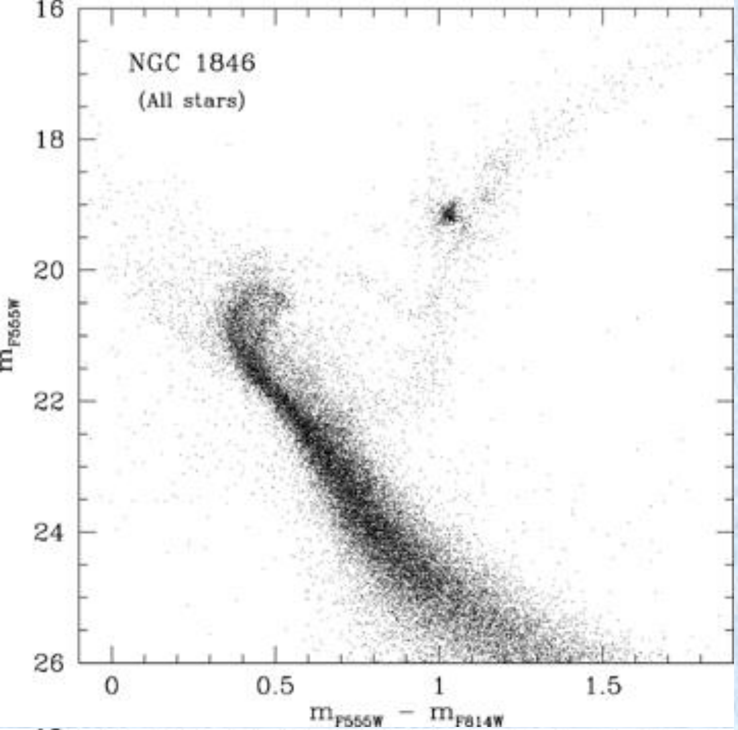
Caloi and D'Antona, 2006, A&A

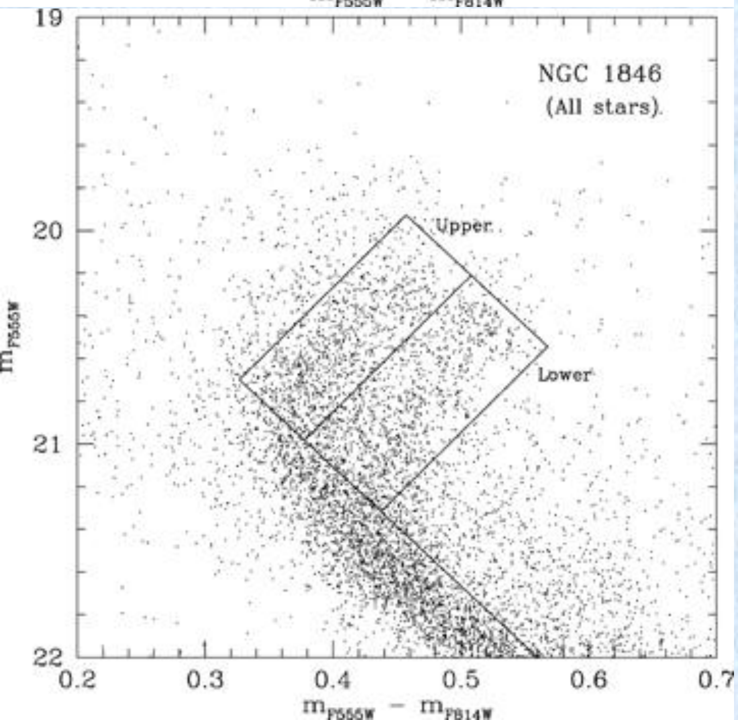


There are many other globular clusters with a SGB split.

Piotto et al., in prep.





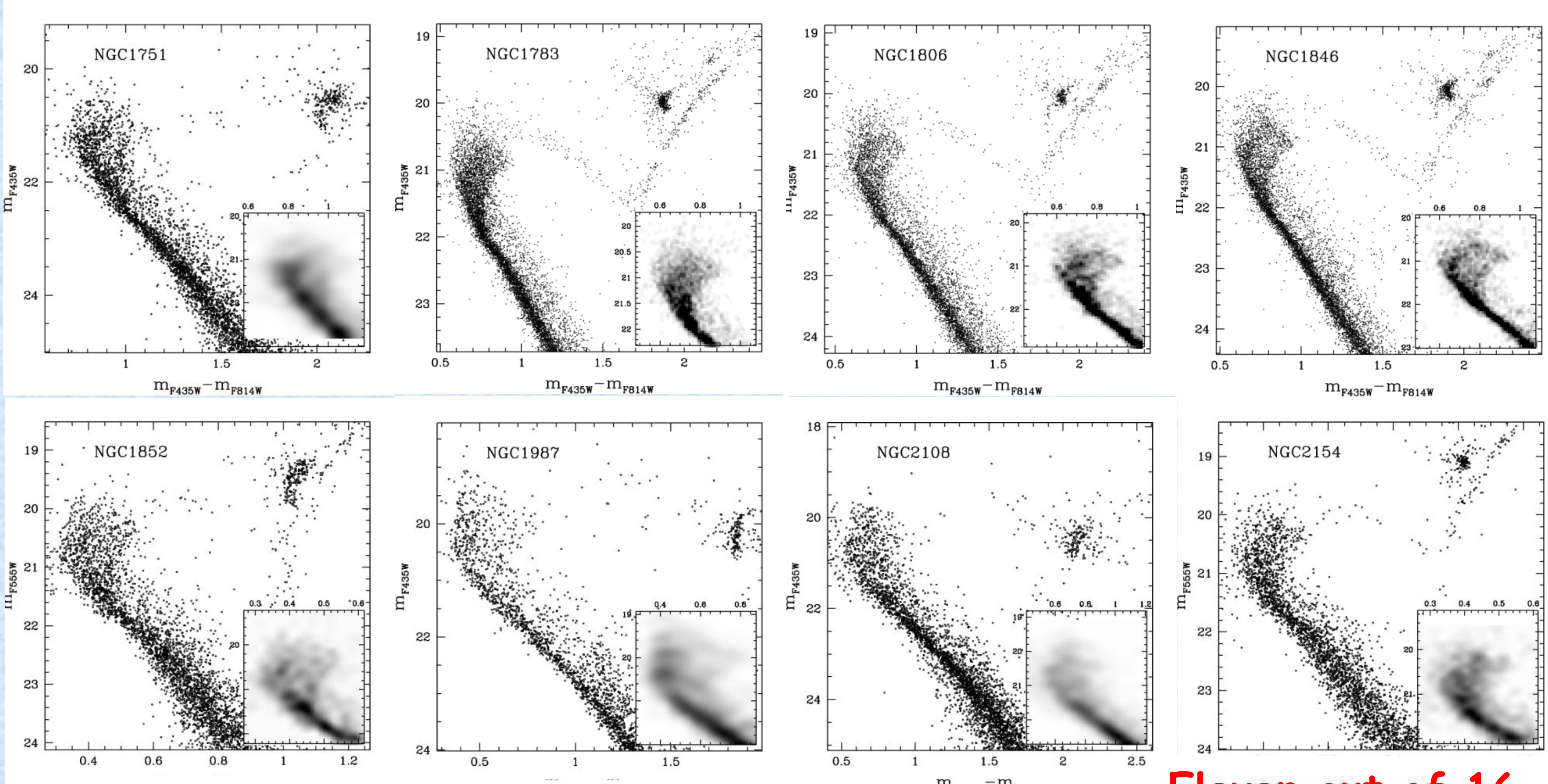


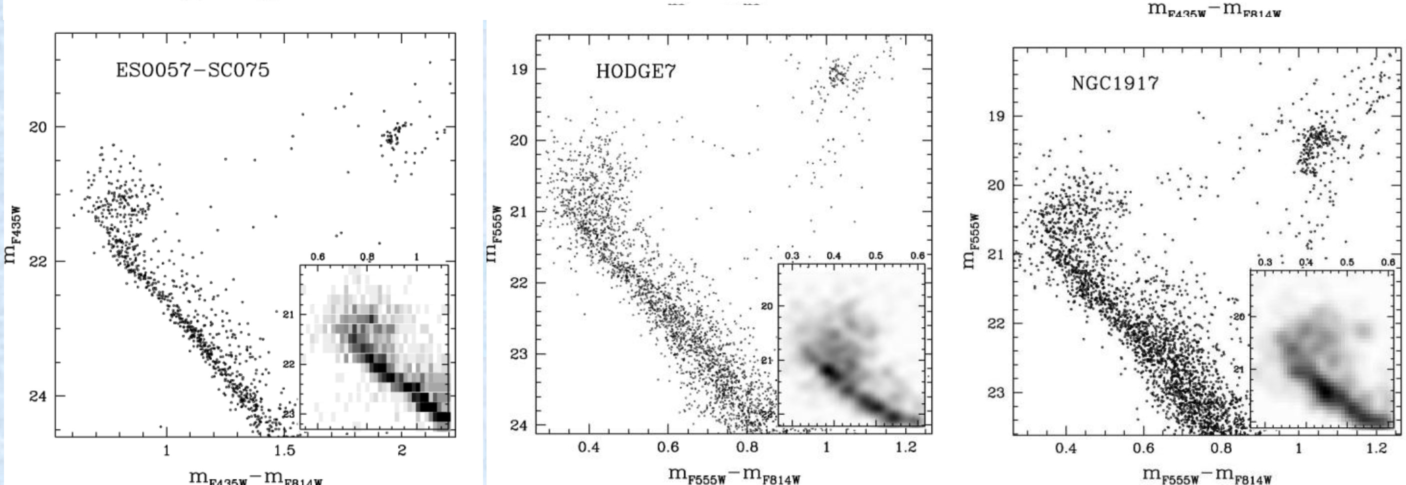
Multiple populations also in Magellanic Cloud intermediate age clusters

Mackey and Broby-Nielsen (2007, MNRAS, 379,151) suggested the presence of **two populations with an age difference of ~300Myr in the 2Gyr old LMC cluster NGC 1846.**

The presence of two populations is inferred by the presence of **two TOs** in the color magnitude diagram of the cluster.

Three additional LMC candidates proposed by Mackey et al. (2008, ApJ, 681, L17).





Eleven out of 16 (2/3) of the intermediate age clusters show either a double or an extended TO!

Milone et al 2009, A&A, 497, 755).

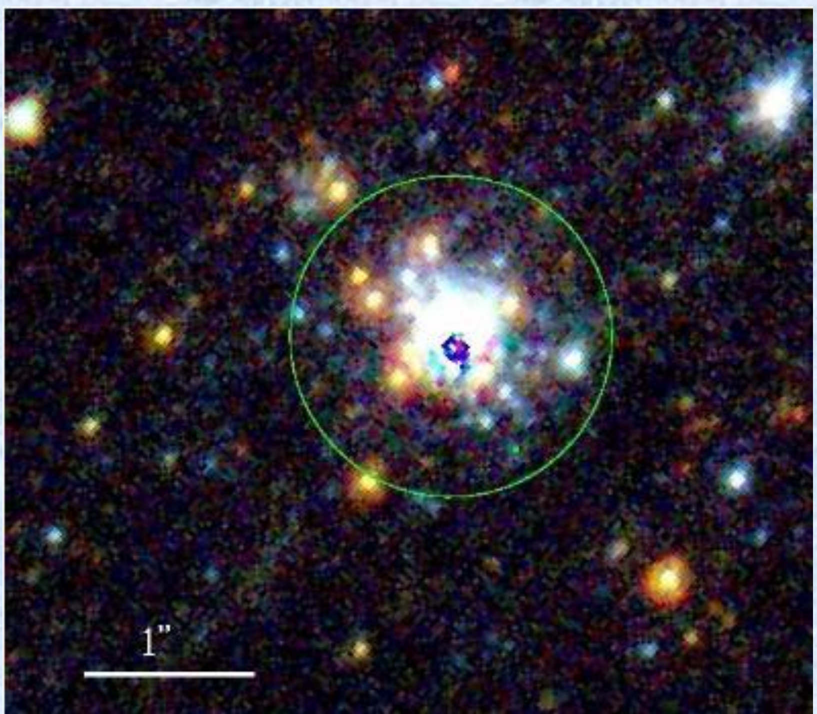
THE YOUNG, MASSIVE, STAR CLUSTER SANDAGE-96 AFTER THE EXPLOSION OF SN 2004dj IN NGC 2403

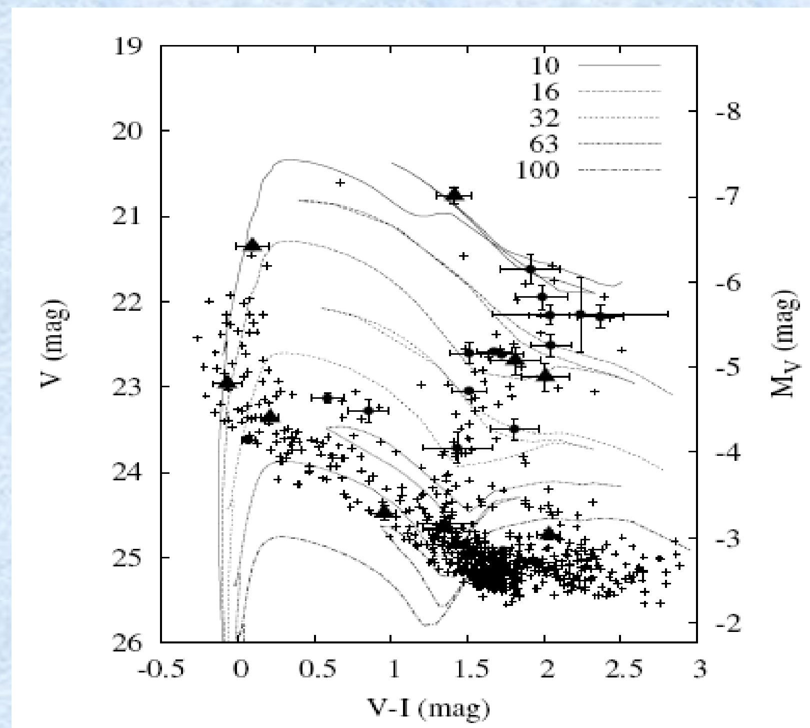
J. Vinkó[1,2,3], K. Sárneczky[1], Z. Balog[4,1], S. Immler[5], B. E. K. Sugerman[6], P. J. Brown[7], K. Misselt[4], Gy. M. Szabó[8], Sz. Csizmadia[9], M. Kun[10], P. Klagyivik[11], R. J. Foley[12,13,14], A. V. Filippenko[12], B. Csák[1], and L. L. Kiss[15]

- 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.

S96 Mass~10^5 Mo

- The older population has an age distribution similar to that of the other nearby field stars (=an association where the cluster is embedded)



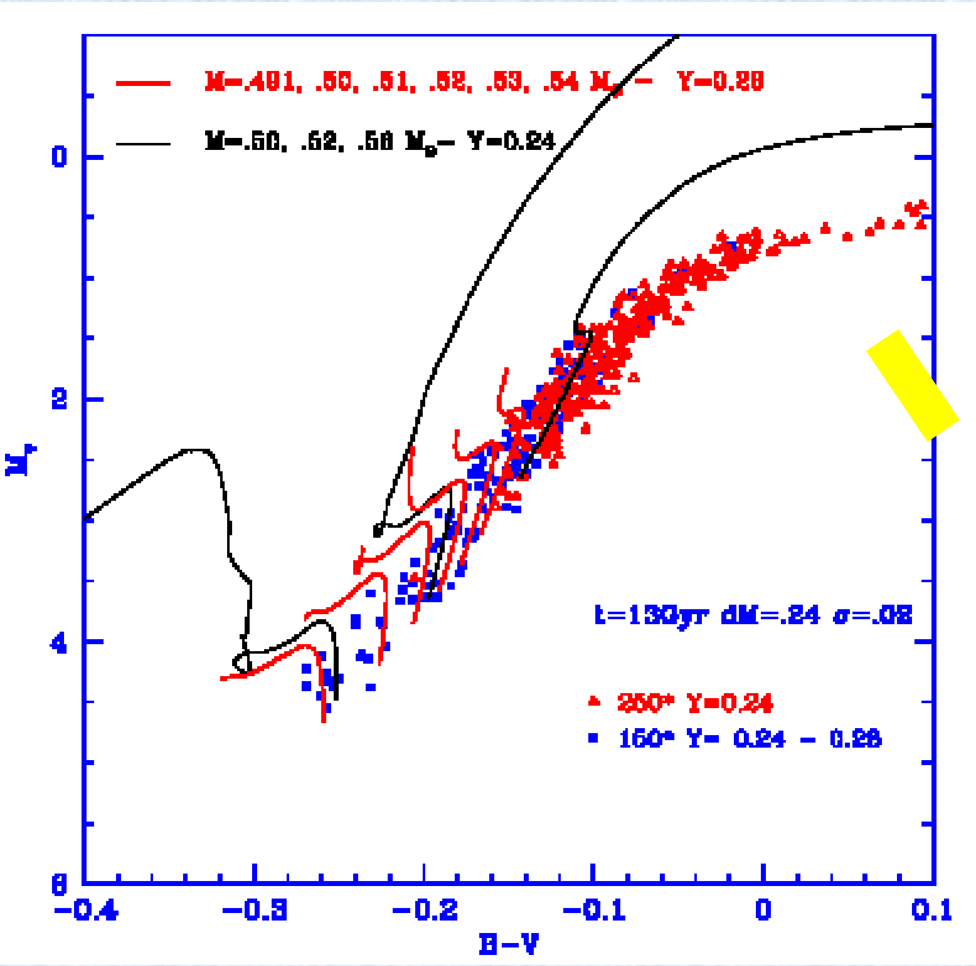


Multipopulation zoo

1. Multipopulations may be ubiquitous: NaO anticorrelation found in all clusters searched so far.
2. Clusters with discrete multiple main sequences, implying He enrichment (47Tuc, NGC6752), and in some cases extreme He enrichment, up to Y=0.40 (e.g., ωCentauri, NGC2808),
3. Complex objects like M22, M54 (= Omega Cen?)
4. Intermediate objects like Ter 5 (=M22, M54, ωCen?)
5. Clusters with double SGB or RGB (e.g., NGC 1851, NGC6388, NGC 5286, M4, and many others)
6. The LMC/SMC intermediate age clusters with double TO/SGB.
7. Young massive clusters in external galaxies.

Are all of them part of the same story?

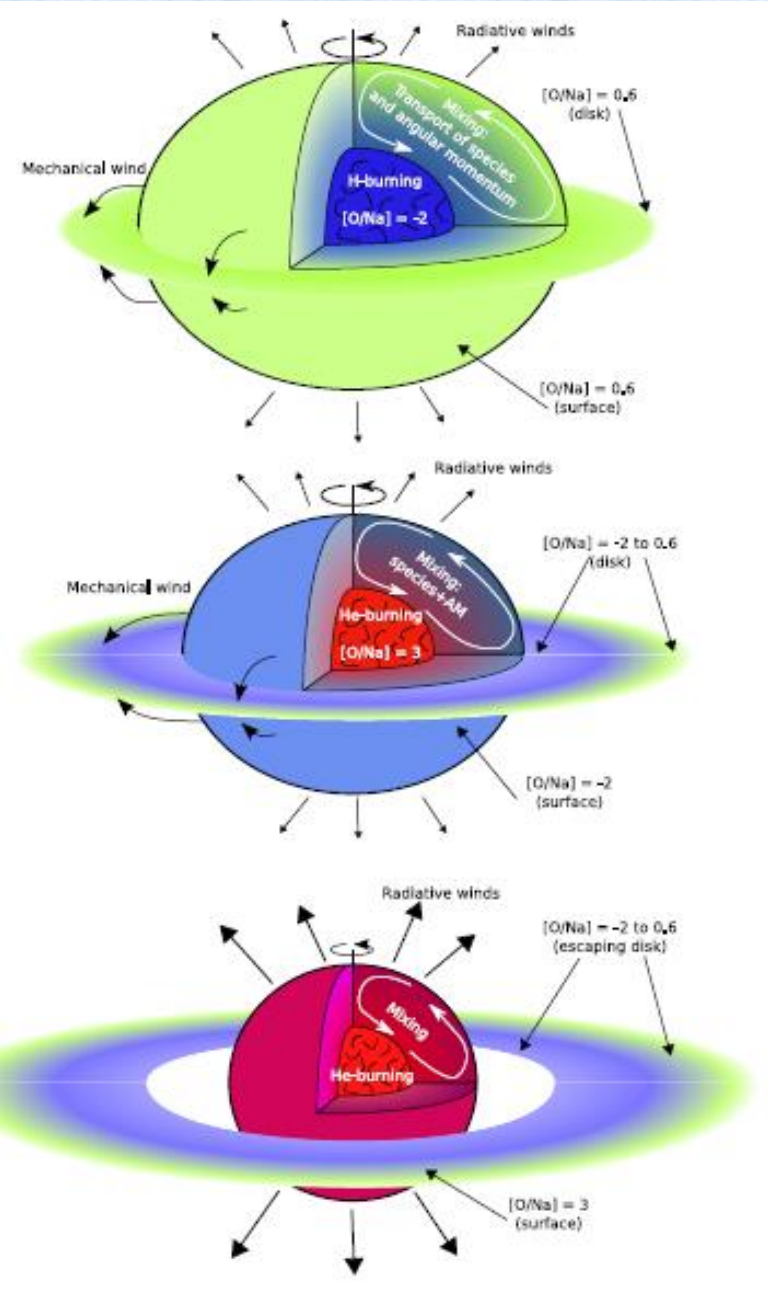
Proposed scenario (1)



Ejecta (10-20 km/s) from intermediate mass AGB stars (4-6 solar masses) could produce the observed abundance spread **(D'Antona et al (2002, A&A, 395, 69).** These ejecta must also be He, Na, CN, Mg) rich, and could explain the NaO and MgAl anticorrelations, the CN anomalies, and the He enhancement.

Globular cluster stars with **He enhancement could help explaining the anomalous multiple MSs, and the extended horizontal branches.**

Alternative explanation (2)



Pollution from fast rotating massive stars (Decressin et al. 2007, A&A, 475, 859).

The material ejected in the disk has two important properties:

1) It is rich in CNO cycle products, transported to the surface by the rotational mixing, and therefore it can explain the abundance anomalies;
2) It is released into the circumstellar environment with a very low velocity, and therefore it can be easily retained by the shallow potential well of the globular clusters.

Conclusions

Thanks to the new results on the multiple populations

we are now looking at globular cluster (and cluster in general) stellar populations with new eyes.

De facto, a new era on globular cluster research is started:

1) Many serious problems remain unsolved, and we still have a rather incoherent picture. The new WFC3/HST will play a major role. But also multi-object spectroscopy is mandatory to compose the puzzle.
2) For the first time, we might have the key to solve a number of problems, like the abundance "anomalies" and possibly the second parameter problem (which have been there for decades), as well as the newly discovered multiple sequences in the CMD.
3) Finally, we should never forget that what we will learn on the origin and on the properties of multiple populations in star clusters has a deep impact on our understanding of the early phases of the photometric and chemical evolution of galaxies.

Old Paradigma

Globular Clusters are a Simple Stellar Population, defined as an assembly of coeval, initially chemically homogeneous, single stars.

(Renzini and Buzzoni 1983)

NewTheorem

Globular clusters are an assembly of stars which exhibit a Sodium-Oxygen anticorrelation

(Gratton, KITP conference, 14/01/2009)