# MULTIPLE STELLAR POPULATIONS IN GLOBULAR CLUSTERS


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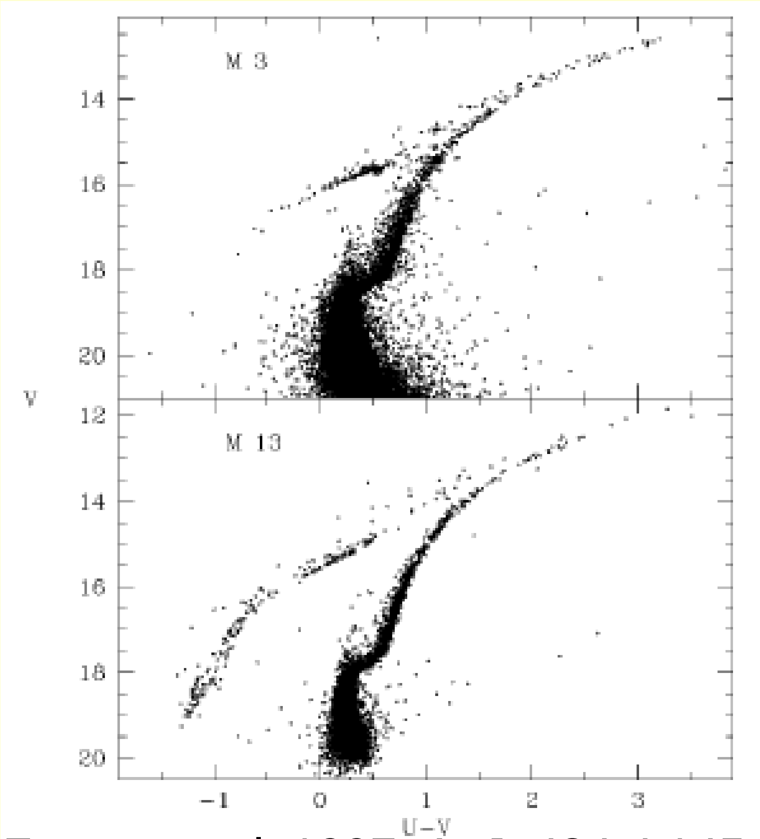
# Simple Stellar Populations

"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)**

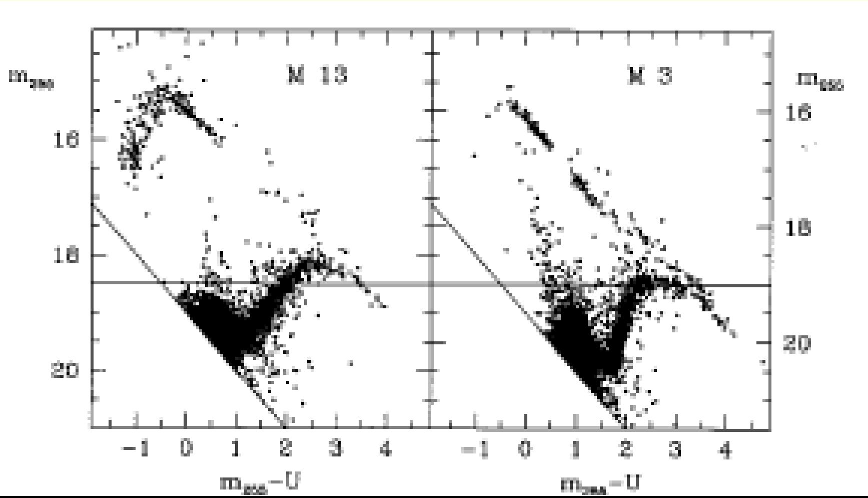
**For this reason, star clusters have been – so far - a fundamental benchmark for testing stellar evolution models and for Population Synthesis Models**

However, we do have a number of problems which have been there, unsolved, for too many years. For example, we never really understood the general behaviour of He core burning sequences.

The classical second parameter problem, i.e. the fact that GCs with the same metallicity have horizontal branches with quite different morphologies still lacks a comprehensive explanation.

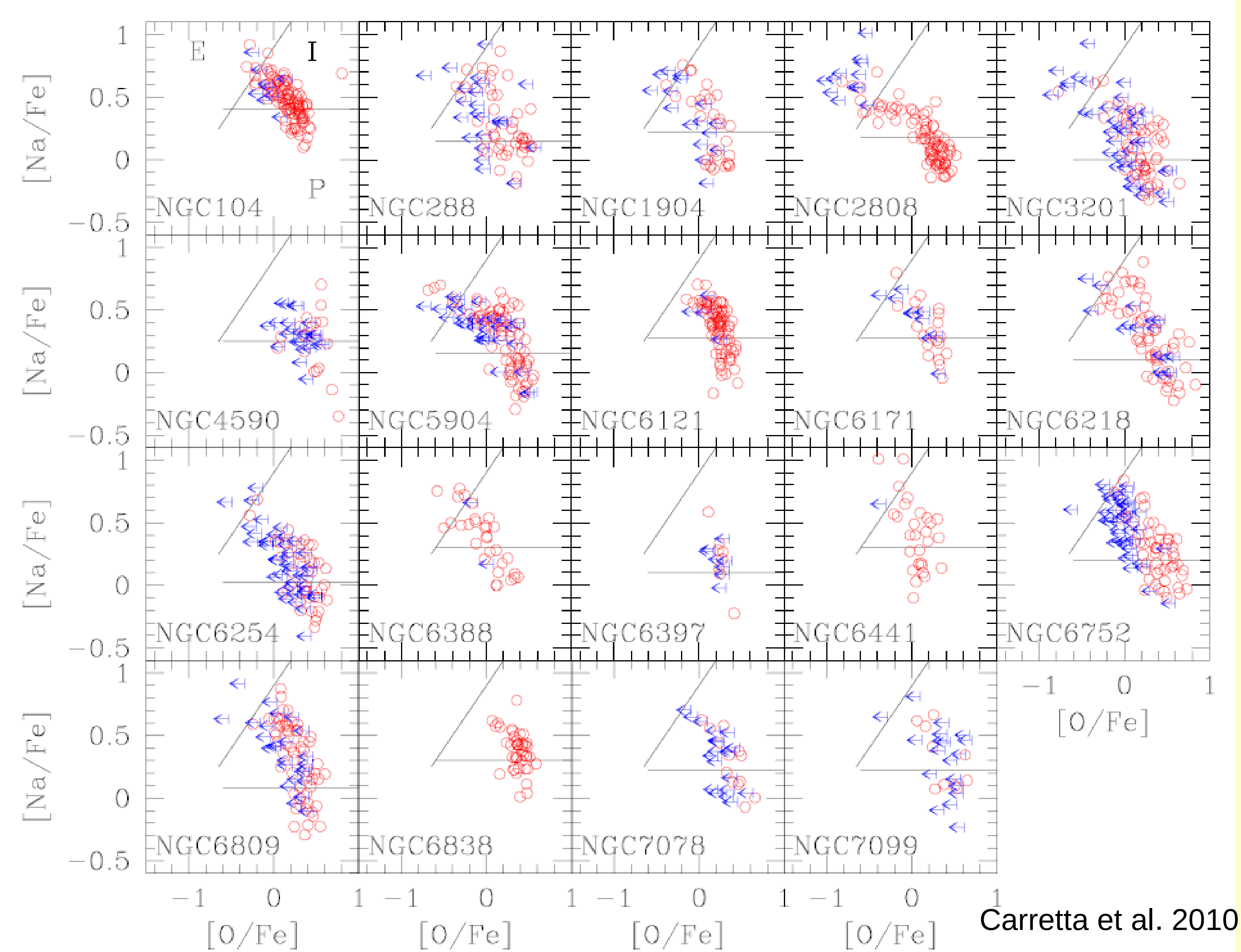



Ferraro et al. 1997, ApJ, 484, L145




| Parameter | M3 | M13 | Reference |
|---|---|---|---|
| $(m-M)_V$ | 15.05 | 14.35 | 1 |
| $E(B-V)$ | 0.01 | 0.02 | 1 |
| [Fe/H] | −1.47 ± 0.01 | −1.51 ± 0.01 | 2 |
| $(15-V)_0$ | 3.41 | 1.63 | 3 |
| $c$ | 1.85 | 1.5 | 4 |
| $\log \rho_0$ | 3.5 | 3.4 | 4 |
| $\log (M/M_\odot)$ | 5.8 | 5.8 | 4 |
| $e$ | 0.04 | 0.11 | 5 |

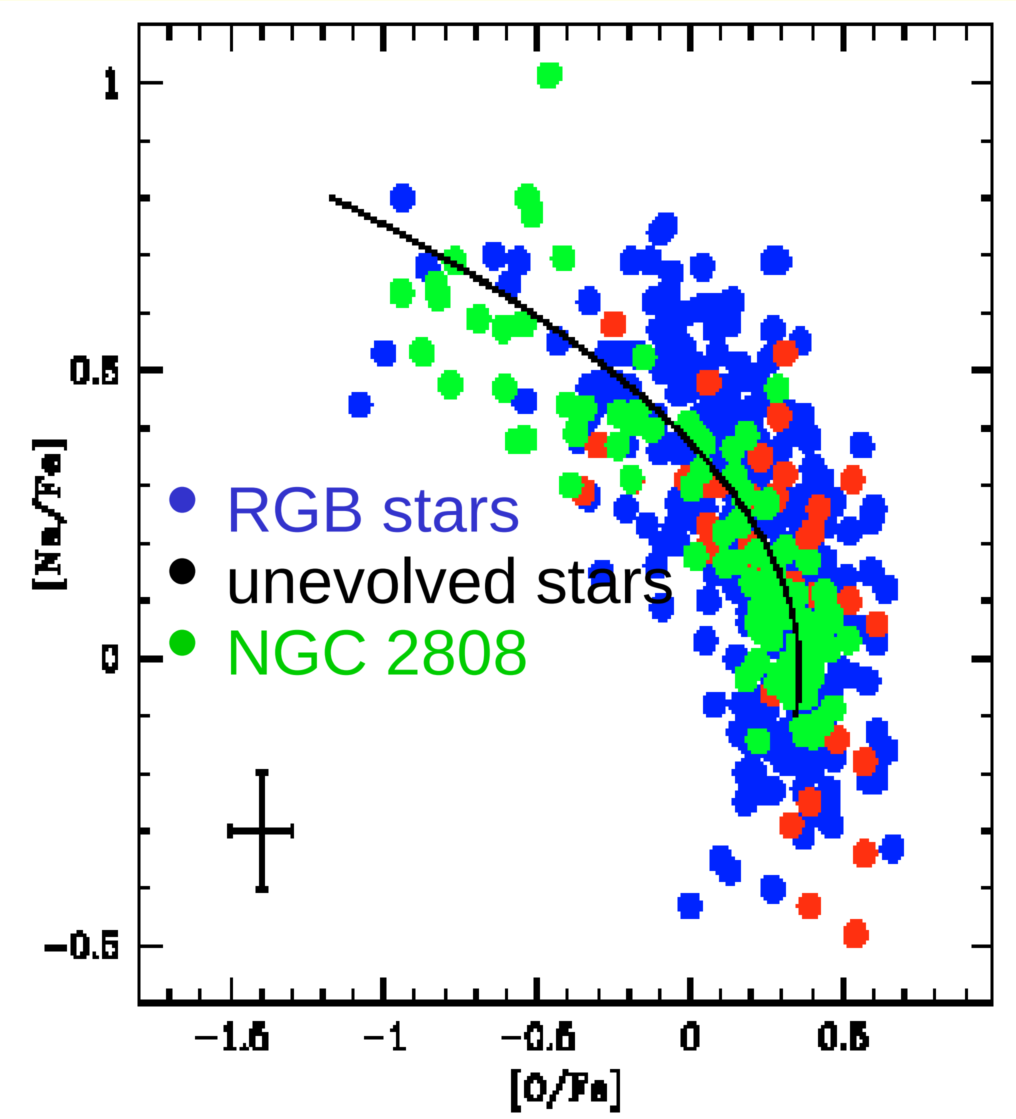
We do have another long standing problem: the large abundance spread for some light elements like C, N, O, Na, Al, Mg within the same cluster




Carretta et al. 2010

Some elements define correlations like the NaO and the Mg-Al anticorrelations

Na-O anticorrelation is observed in all the G Cs studied so far



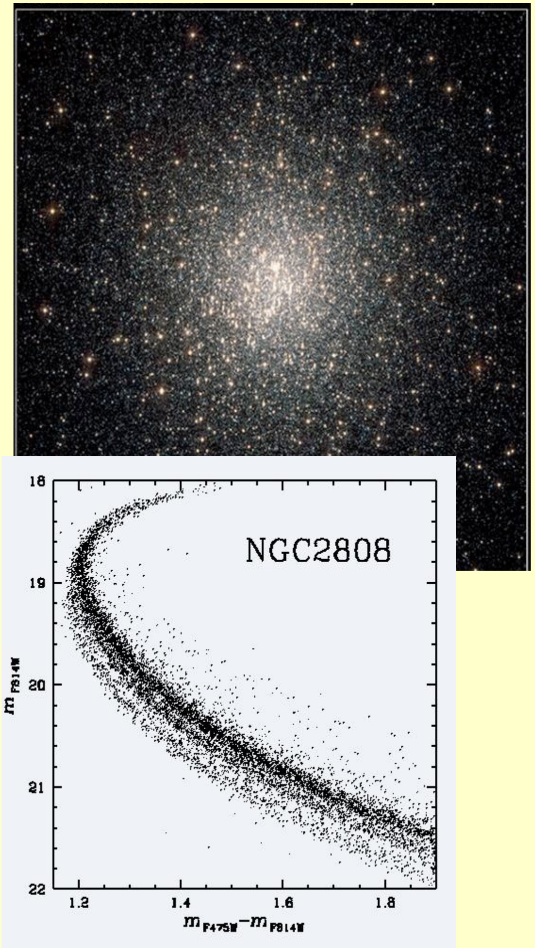

(from Carretta et al. 2006)

NaO anticorrelation has been observed also among unevolved stars stars

Proton capture processes responsible for these anticorrelations are possible only at temperatures of a few 10 million degrees, in the complete CNO cycle (which implies also an O depletion) not reached in present day globular cluster main sequence and red giant stars.

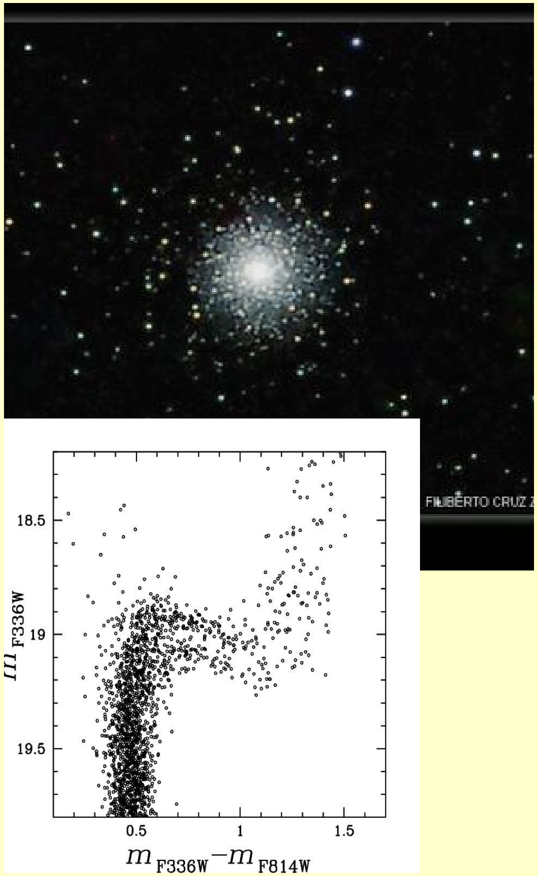
Note that the CNO cycle transforms into helium

# Photometric evidence of multipopulations



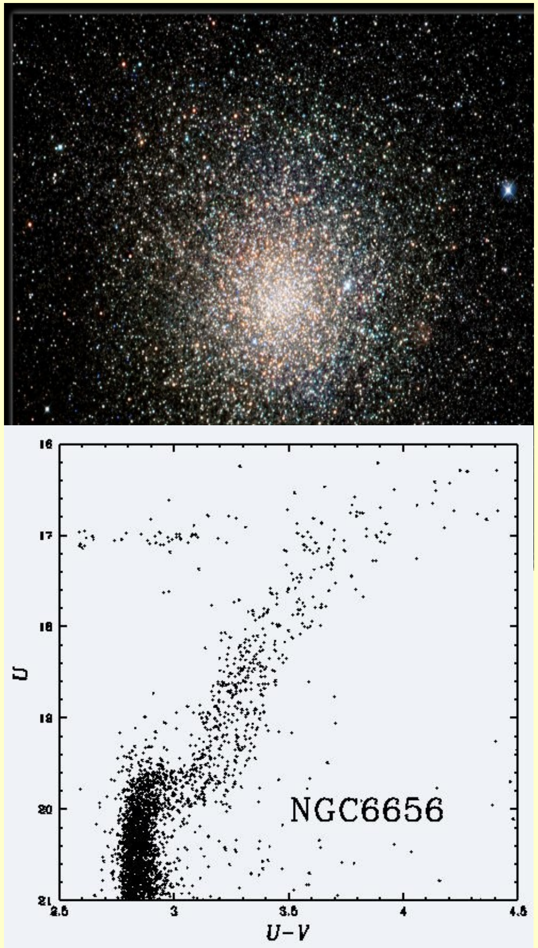

**MULTIPLE/SPREAD MAIN-SEQUENCE**

**NGC2808, NGC6205, NGC6752, NGC 104**



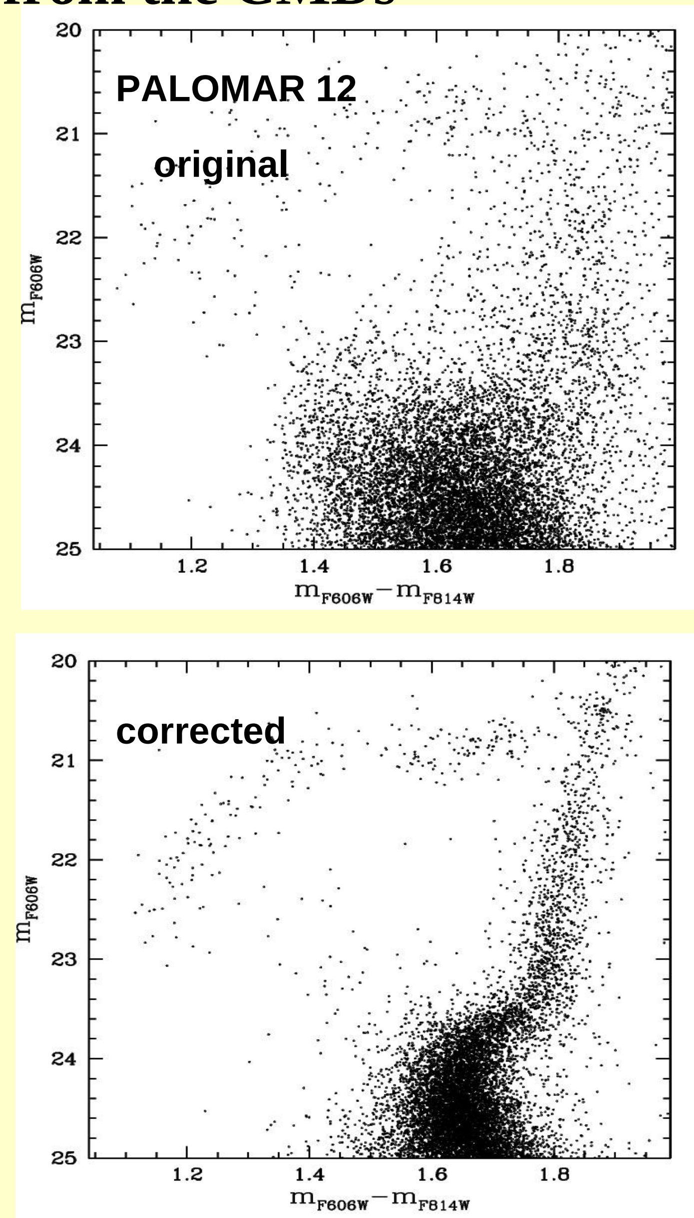

**SPLIT SUB GIANT BRANCH**

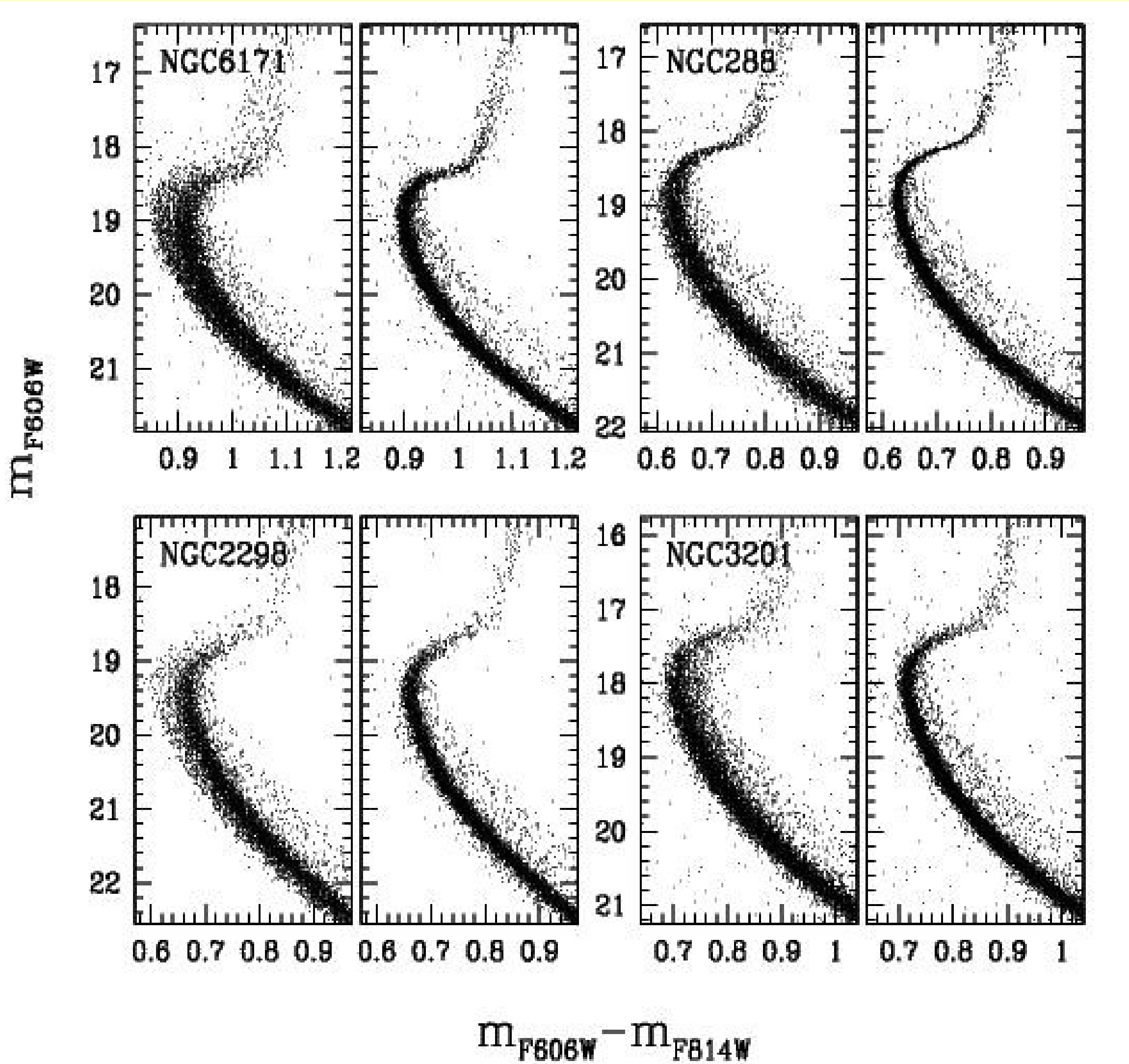
**NGC104, NGC362, NGC1851, NGC5286, NGC6388, NGC6656, NGC6715, NGC7089**




**MULTIPLE/SPREAD RED GIANT BRANCH**

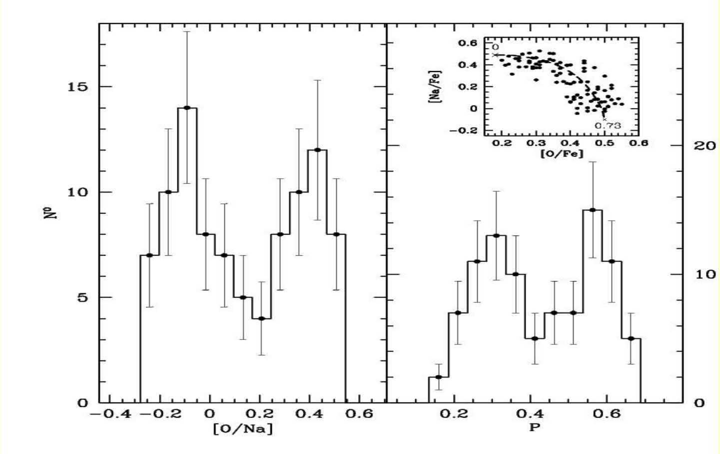
**In many CMDs cluster sequences are spreaded by differential reddening. We developed a procedure to correct the effect of differential reddening from the CMDs**

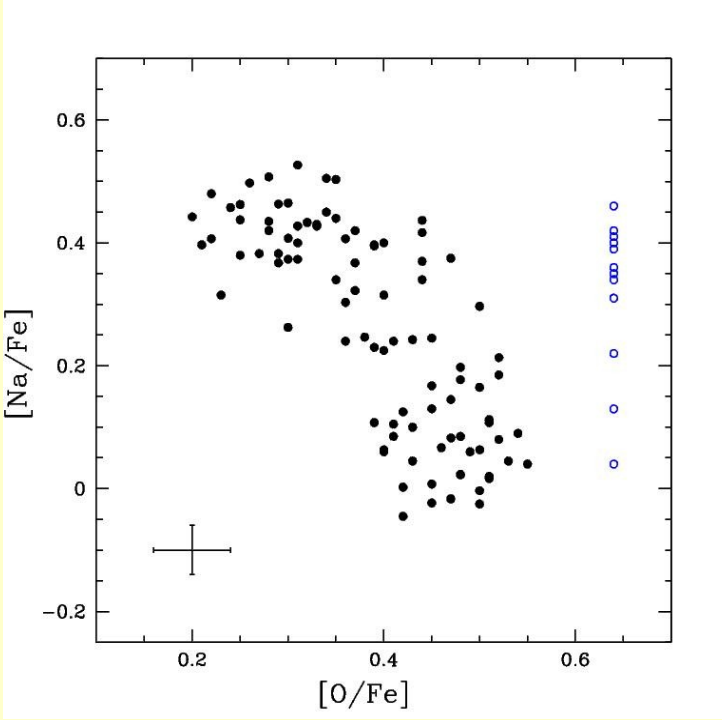


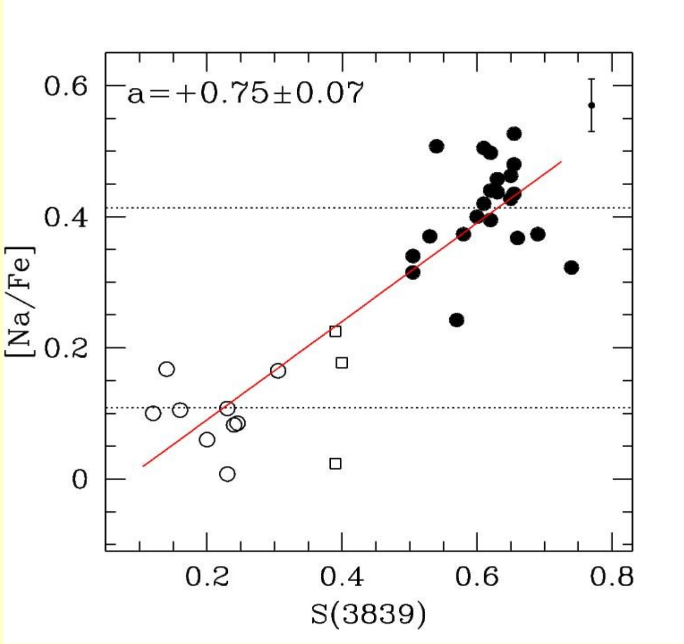
# NGC 6121 (M4)

**- Present day mass:**
**$8x10^4$ MSUN**
**i.e. ~2% the mass of Omega Centauri**




**Marino et al., 2008 A&A 490, 625**

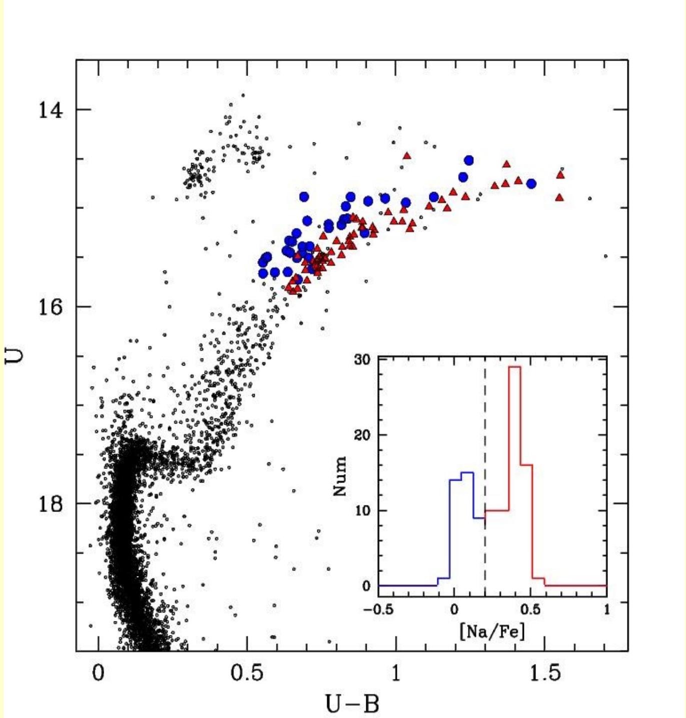


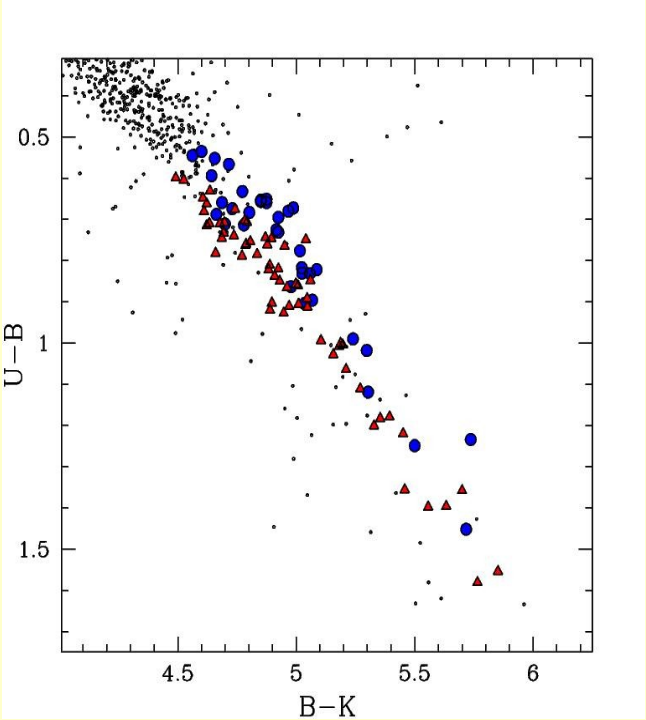

**Two distinct groups of Na rich/poor stars:**

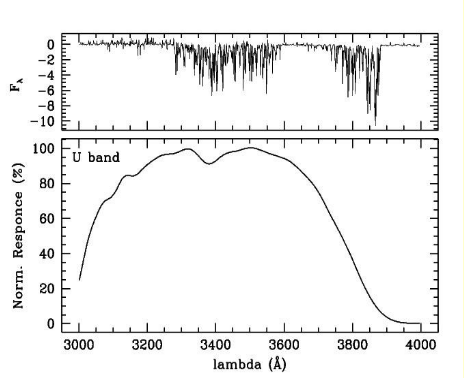
**- Na rich, O poor stars are CN strong**

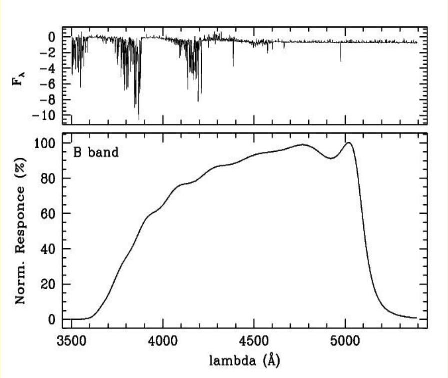
**- Na poor, O-rich stars are CN weak**

The two stellar groups are well distinguishable also in the color-magnitude and two color diagrams:



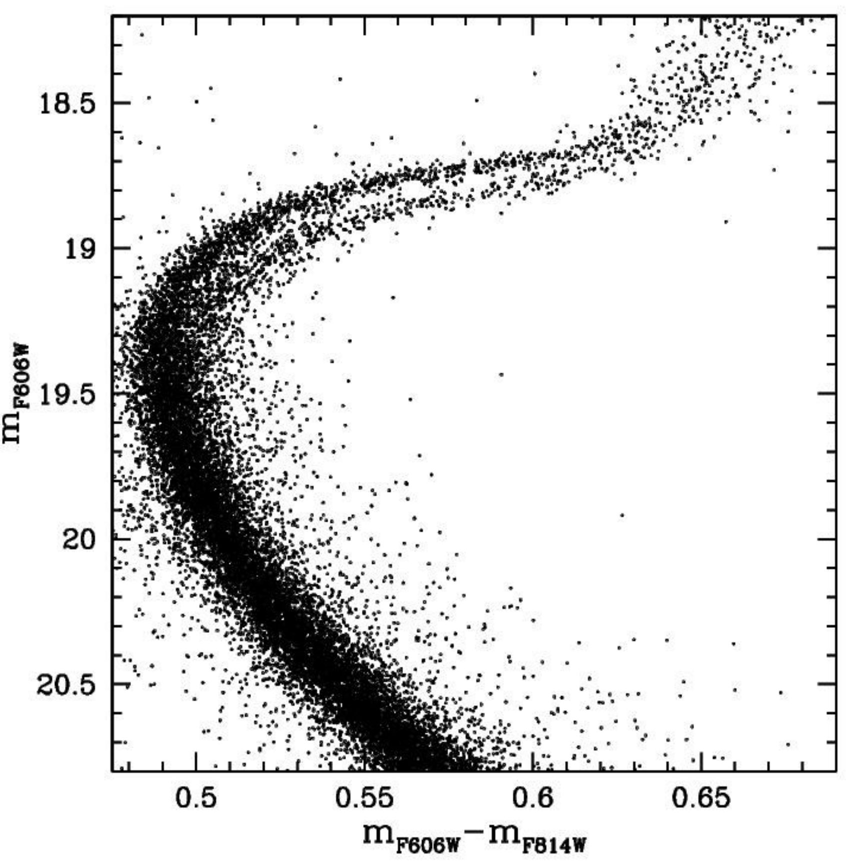




Marino et al., 2008 A&A 490, 625

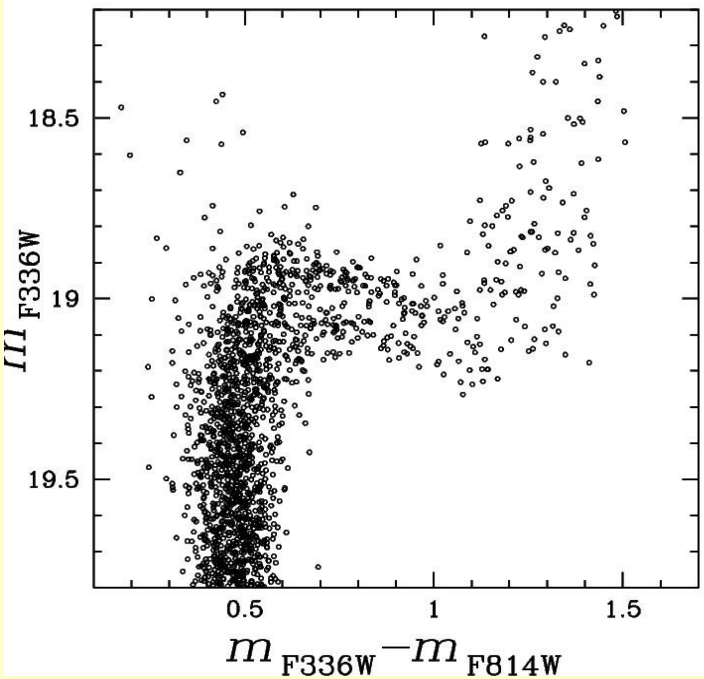
The RGB split in M4 is very likely a C, N, O effect on the atmosphere.

# NGC 1851

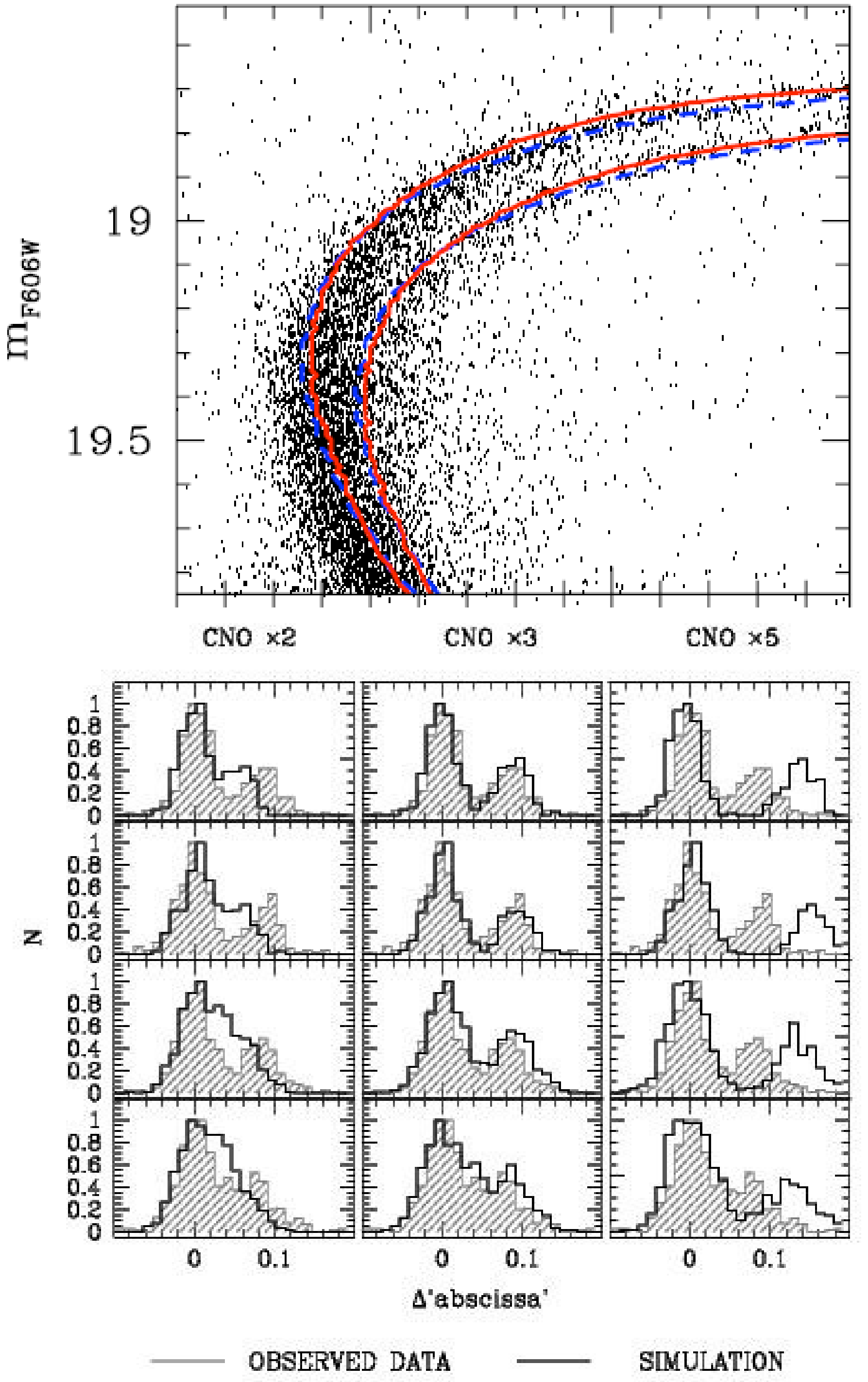



Accurate HST's ACS photometry reveals that **the SGB of NGC 1851 splits into two well defined branches**

The split may be due to a large age spread (1 Gyr) or to a combination of abundance anomalies and a much smaller age spread



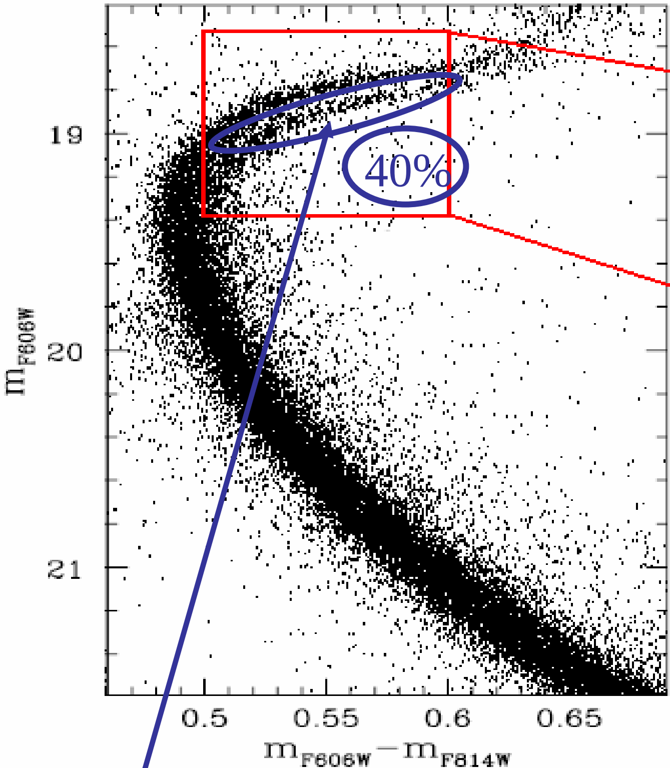

Milone et al., 2008 ApJ, 673, 241

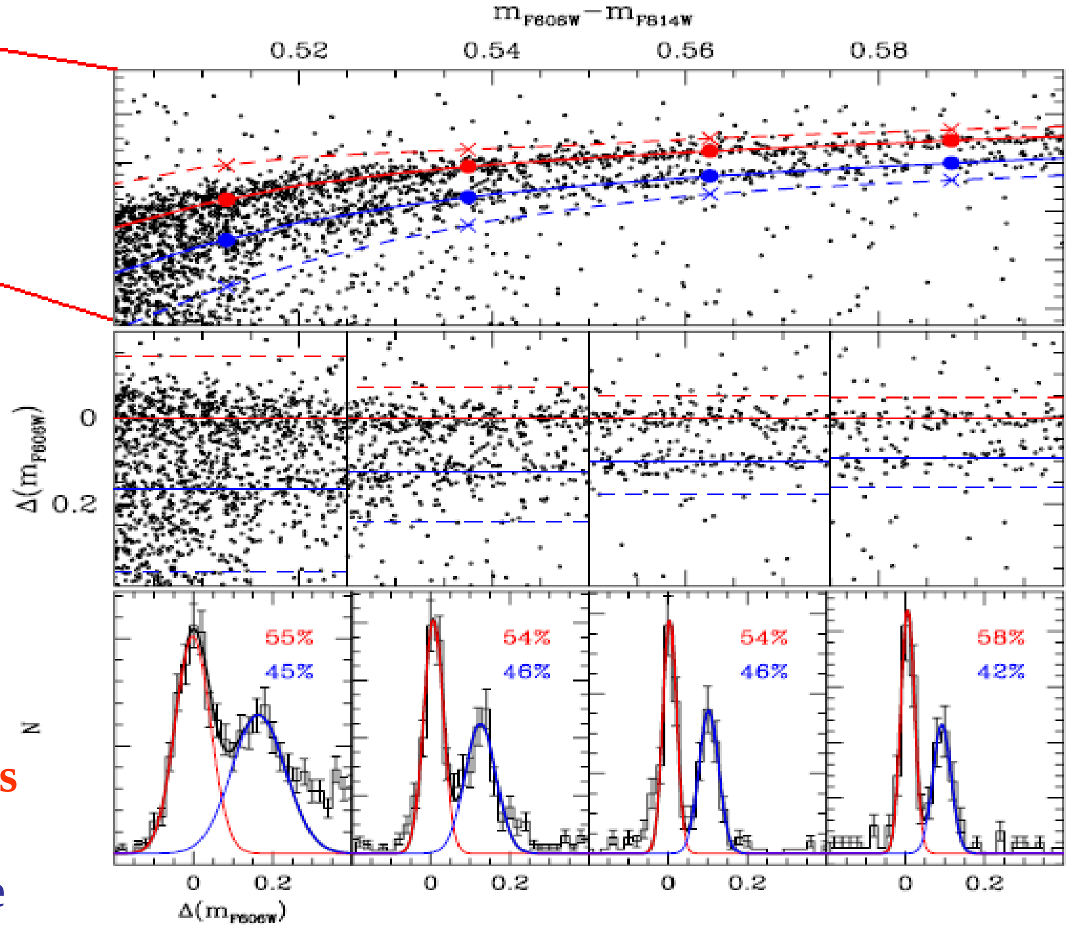


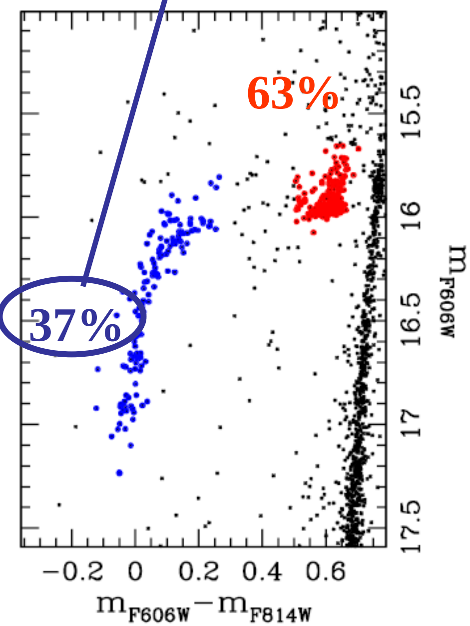

Cassisi et al. (2008) and Ventura et al (2009) showed that the split SGB is due to the presence of two stellar populations:
a normal alpha-enhanced component, and one with a total CNO abundance increased by a factor of ~3.

Yong et al. (2009) found that indeed the sum C+N+O exihibits a range of 0.6 dex, a factor 4.

**In such a case, the age difference between the two groups may be very small  ($10^7$-$10^8$ years).**



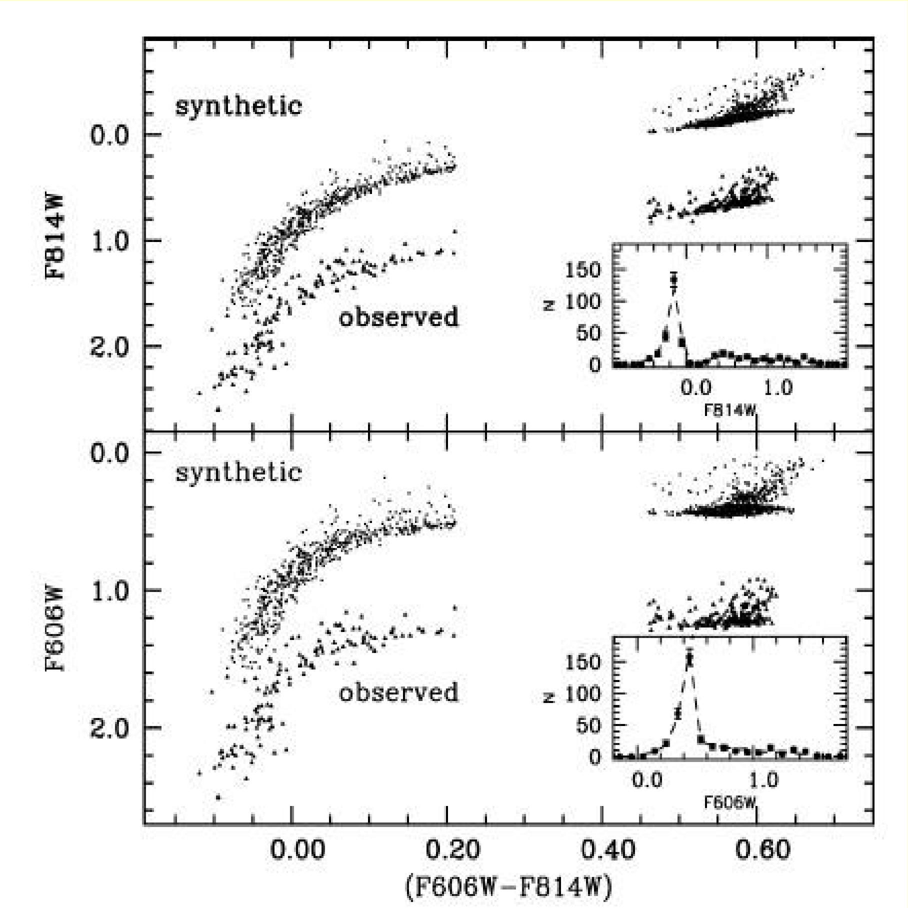




**~40% of the stars are in the lower SGB; 37% in the blue HB.**

**From Yong and Grundahl (2008) we know that 40% of the stars are CN-strong and s-process element enhanced.**

Are the SGB stars related to the blue HB,

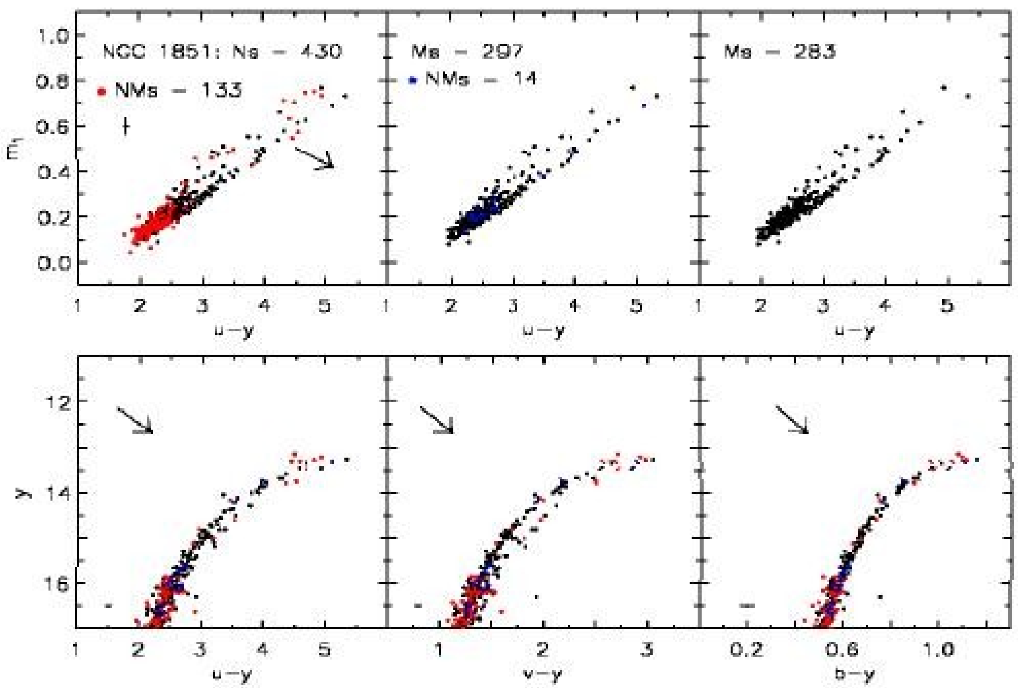
And to the CN-strong, s-process element enhanced subpopulation??_




**Salaris et al. (2008, ApJ, 678, L25) showed that the two stellar populations are distributed in different regions of the HB:**

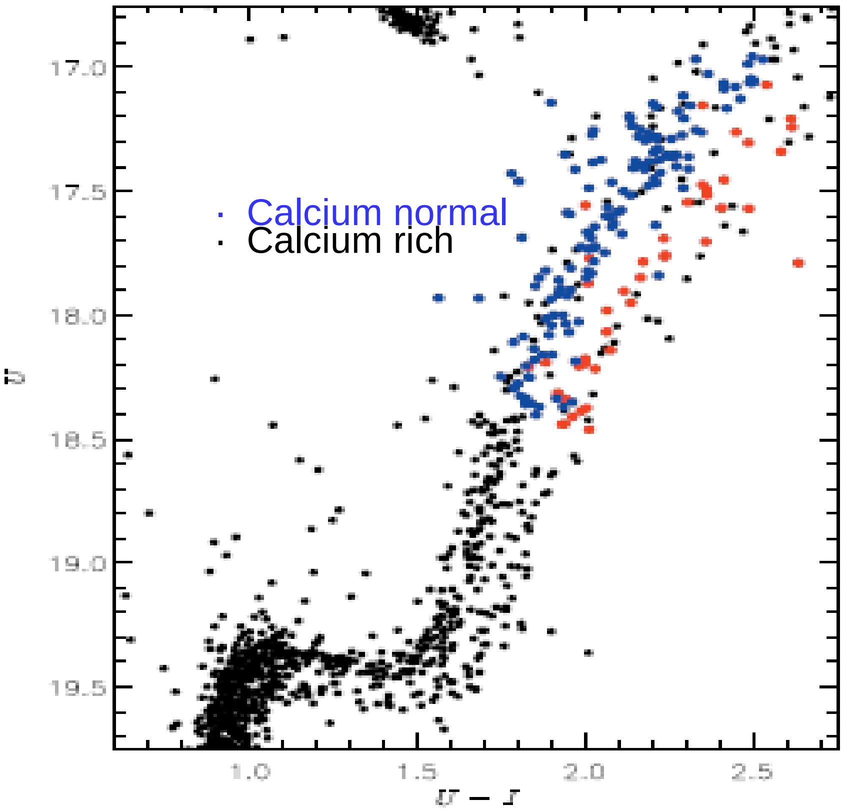
**The evolved stars belonging to the bSGB component are confined to the red HB**

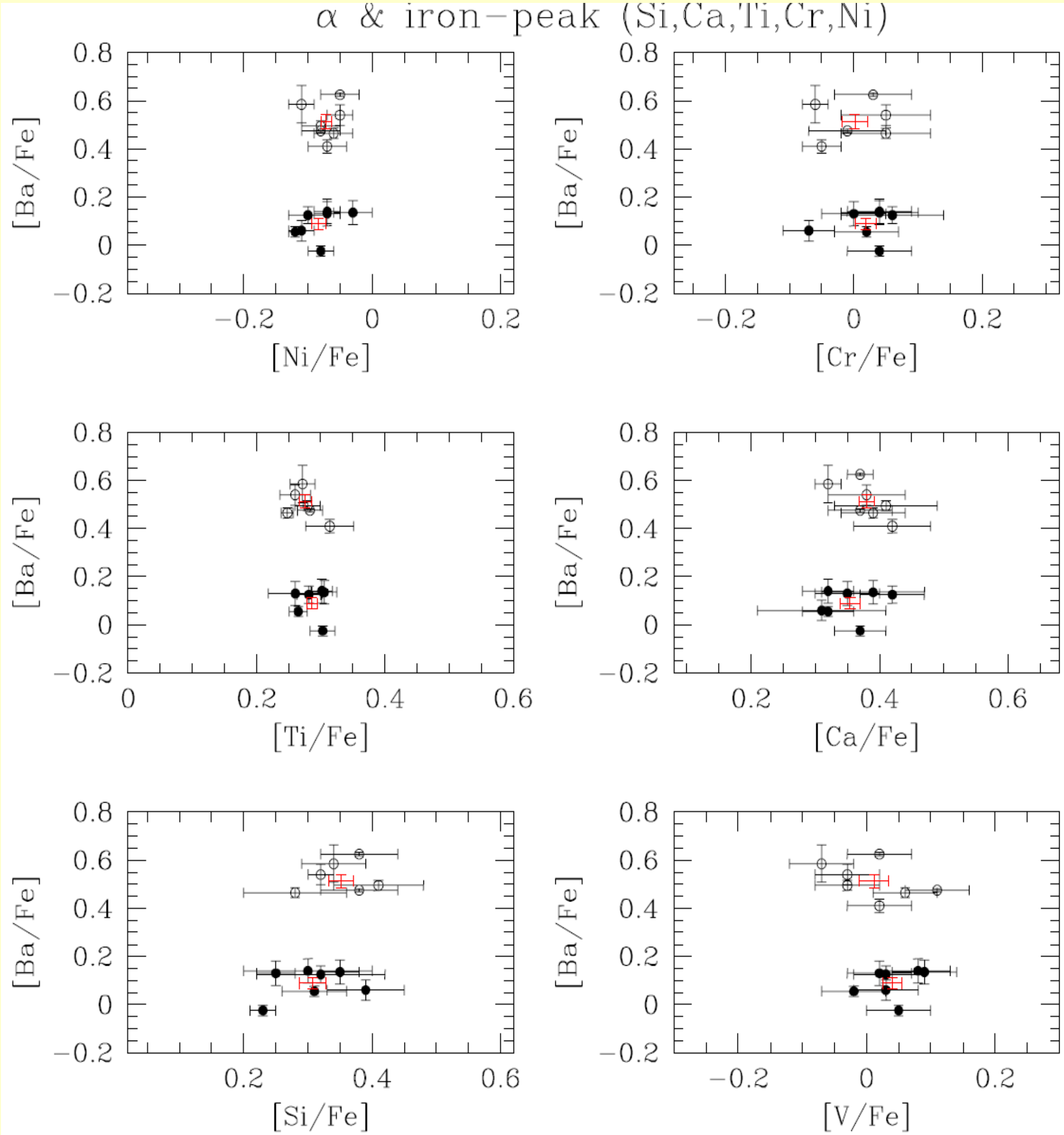
**The ones belonging to the faint SGB are distributed from the red to the blue. populating also the RRLirae instability strip**




**After a careful selection of the best measured RGB stars, Calamida et al. (2007) and Hut et al (2009) find that the RGB of NGC1851 is split in two sequences.**

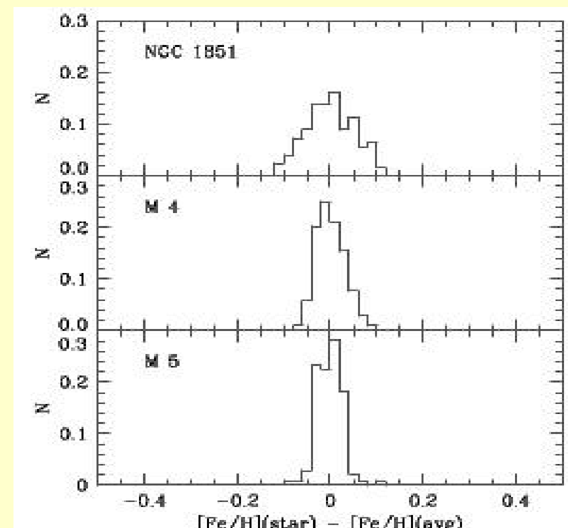
**Lee et al. (2009) suggest that the SGB/RGB is due to two stellar populations with different calcium abundance**





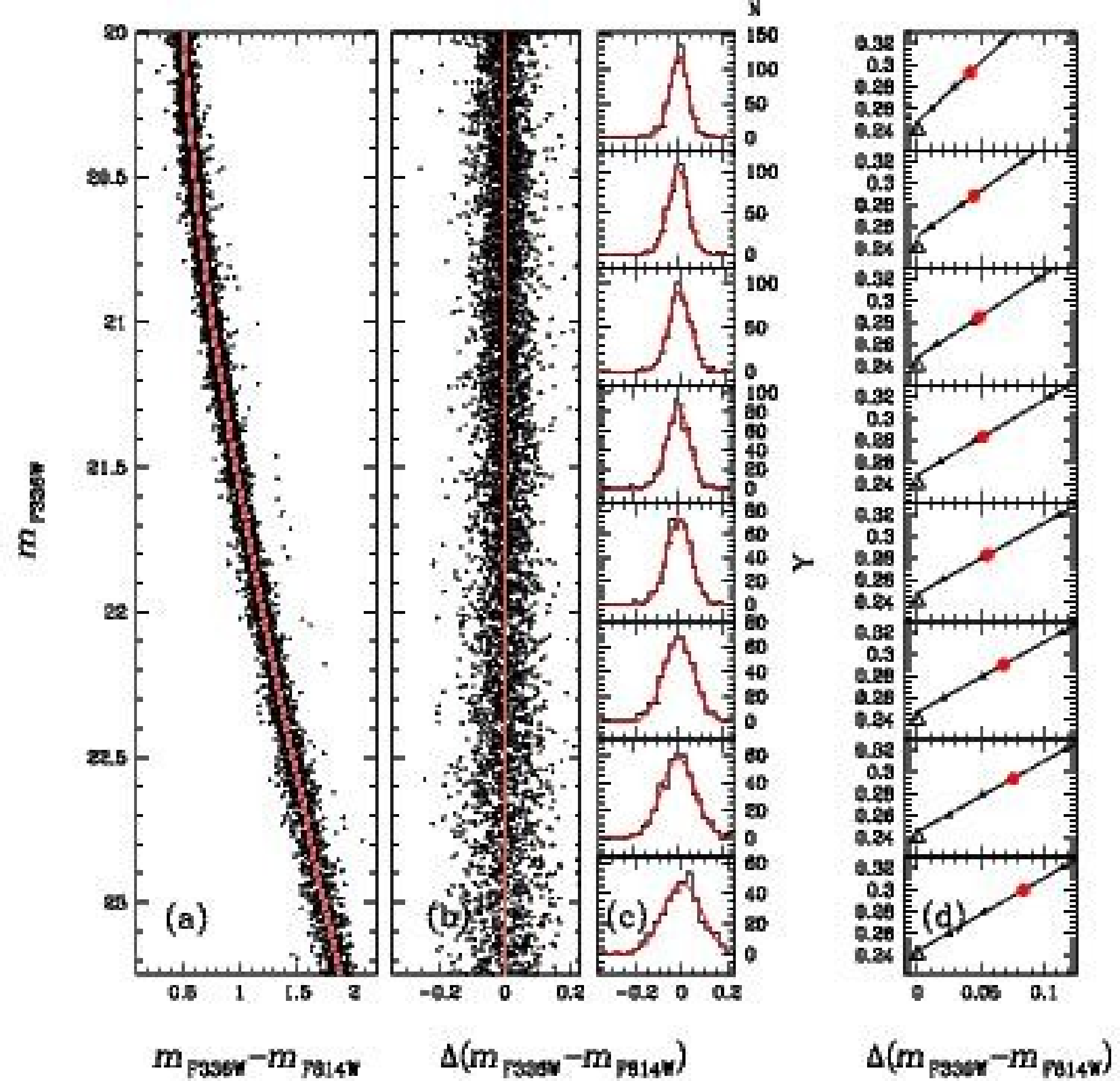

(Villanova et al. (2010)

Villanova et al. detected a clear dichotomy in s-elements abundance but no difference in Calcium and iron.




Carretta et al. (2010)

Carretta et al (2010) detected a spread in Fe/FH




Ventura et al., 2009

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

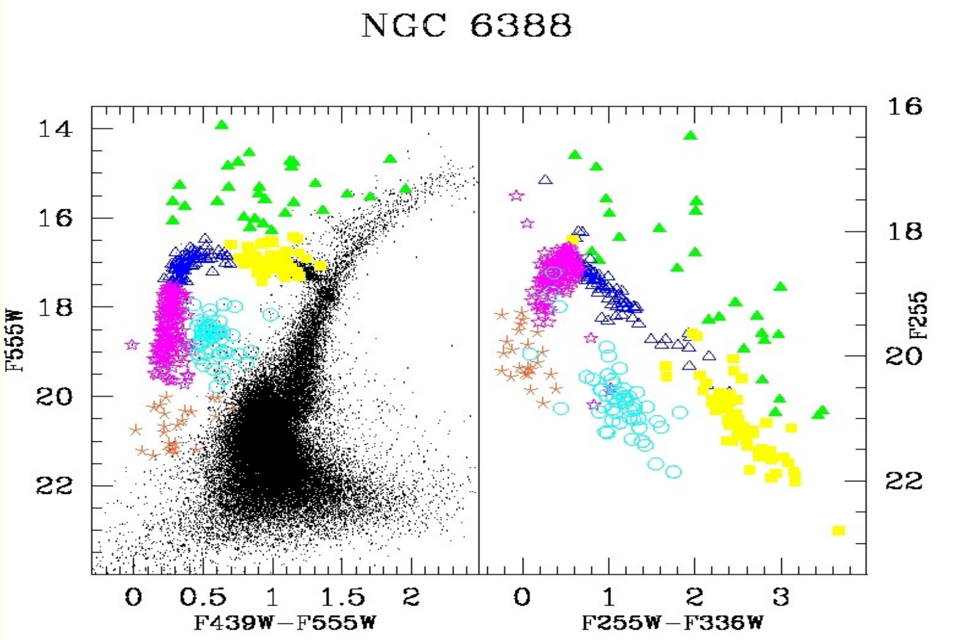
**We set an upper limit to the He spread in**

**NGC 1851 of:**

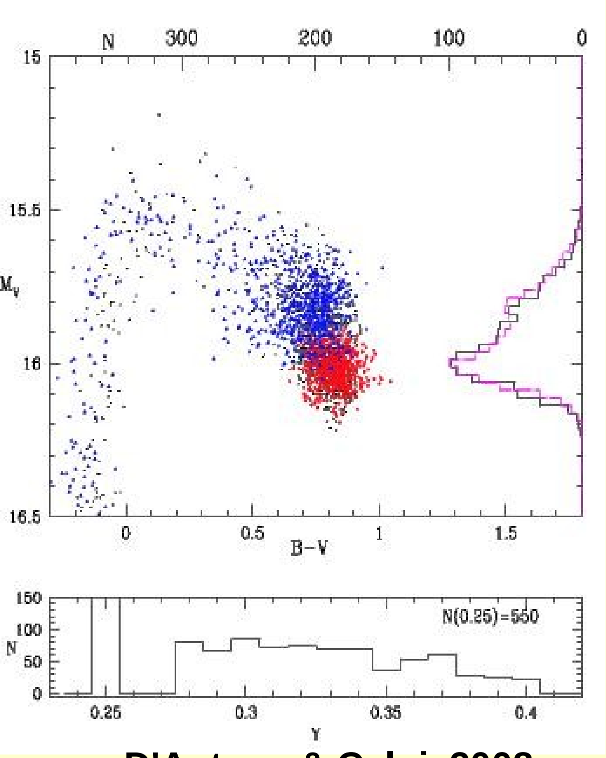
**Delta Y ~ 0.03**

# NGC6388

Since Rich et al. (1997, ApJ, 484, L25) it is known that this cluster has an **anomalous HB.** demonstrating that the **second parameter is at work also in old metal-rich globulars**




Busso et al., 2007



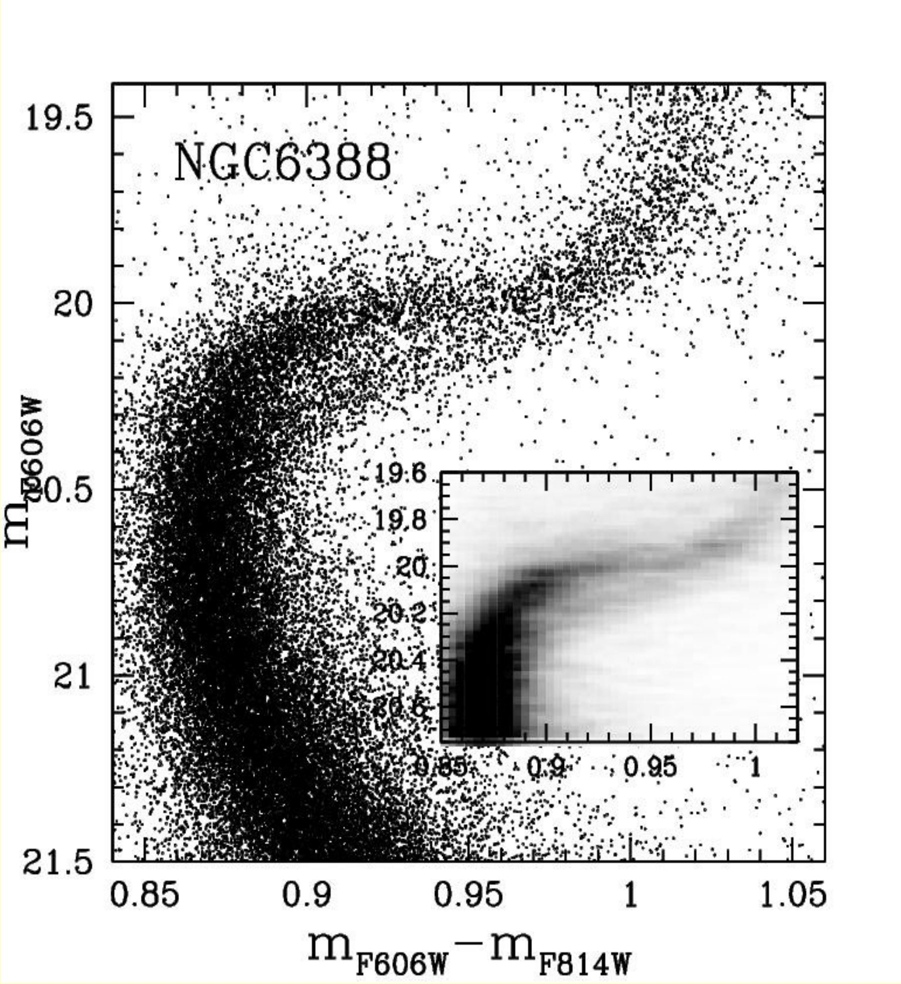

D'Antona & Caloi, 2008

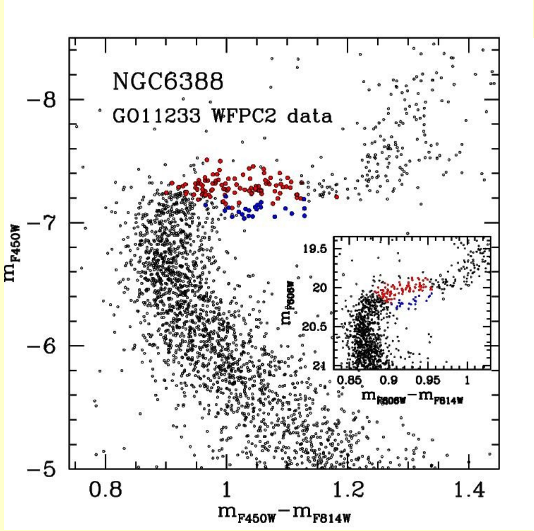
D'Antona & Caloi (2008) show that the HB morphology is consistent with the presence of three stellar population with:

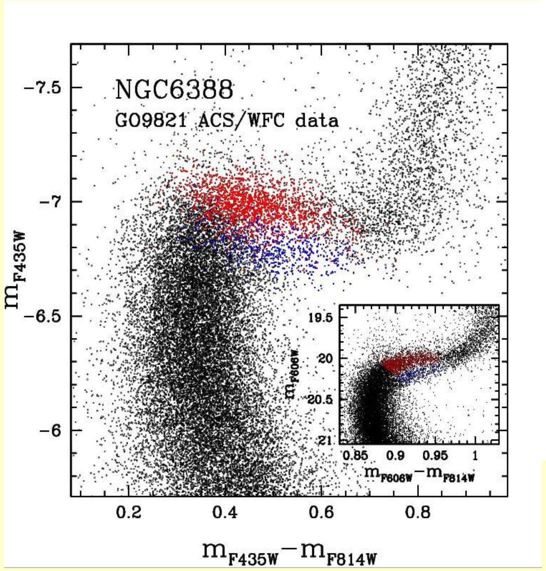
Y=0.25 (39% of the total number of HB stars)

Y=0.27-0.35 (41%), and Y>0.35 (20%)

# HST photometry shows that NGC6388 has a split SGB

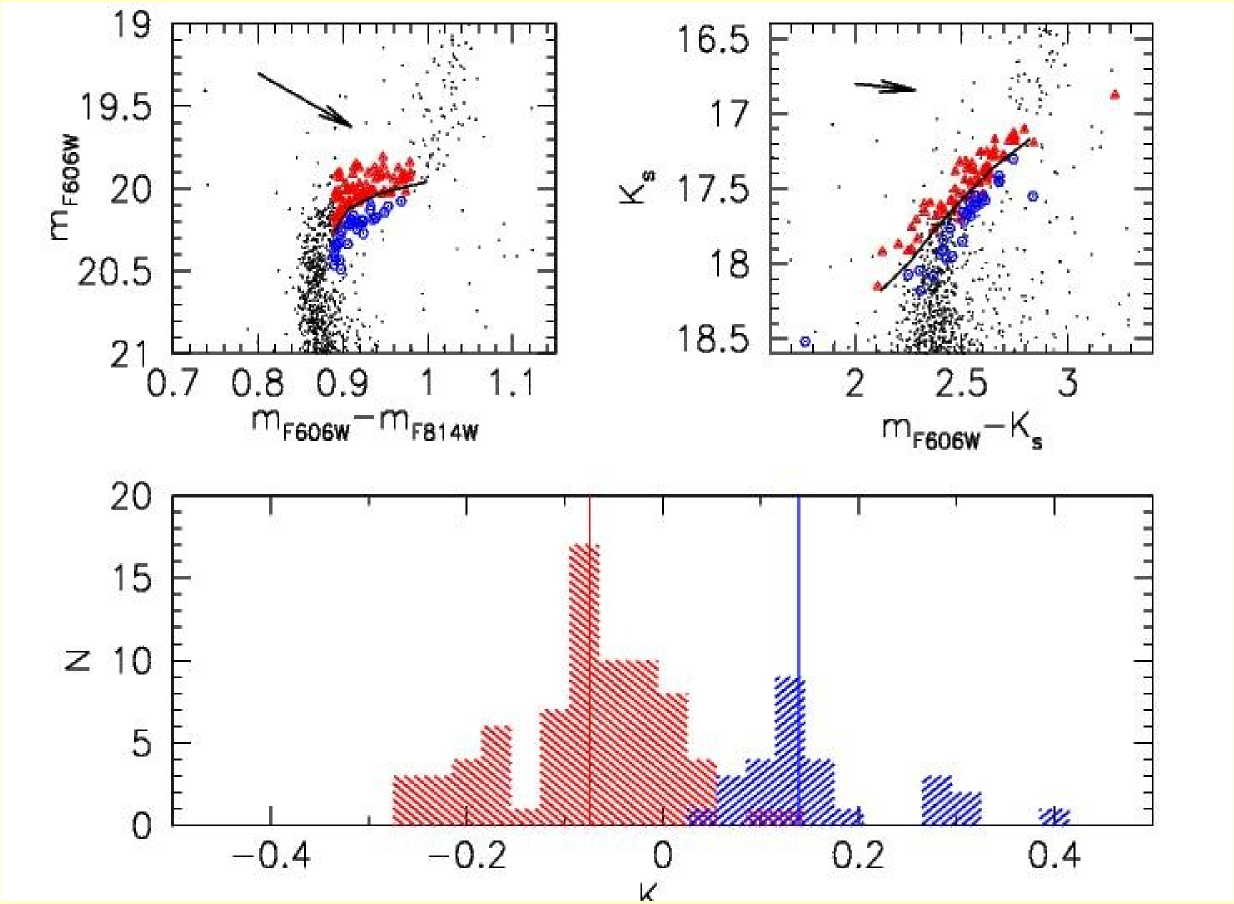



**The fraction of blue over red HB stars is similar to the fraction of faint over bright SGB stars.**

**Piotto et al., (2010) in preparation**

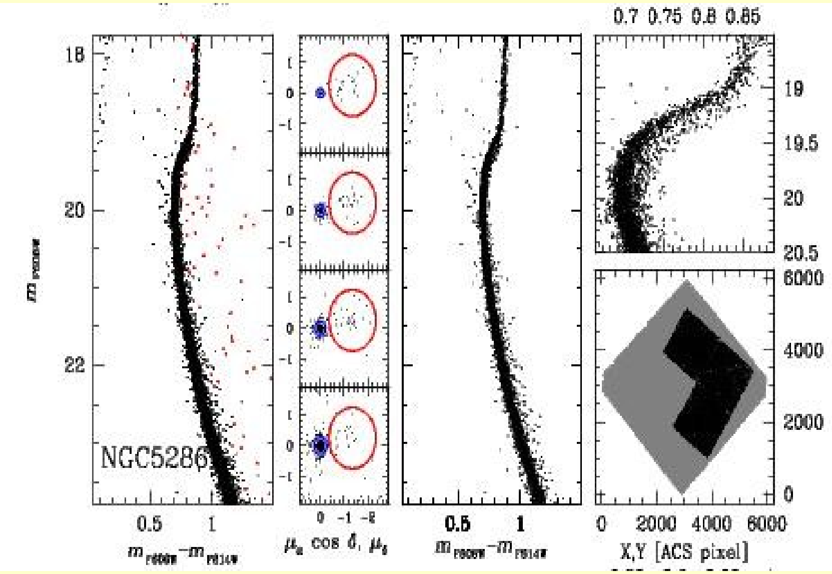


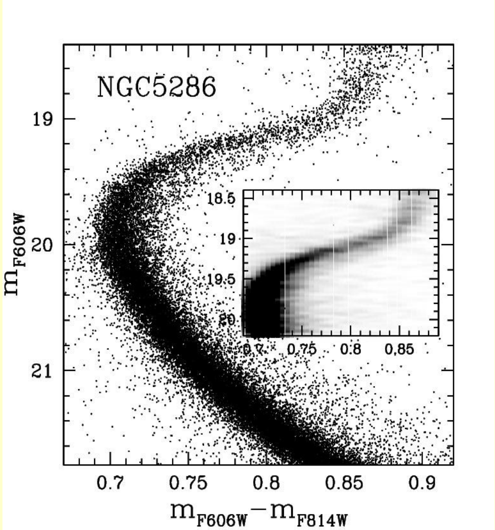

Moretti et al., 2008

# We confirm the SGB split also in IR:

**The bimodal distribution of SGB is present also in the K-band, where the (differential) absorption effects are ~13% of the absorption in F606W band.**

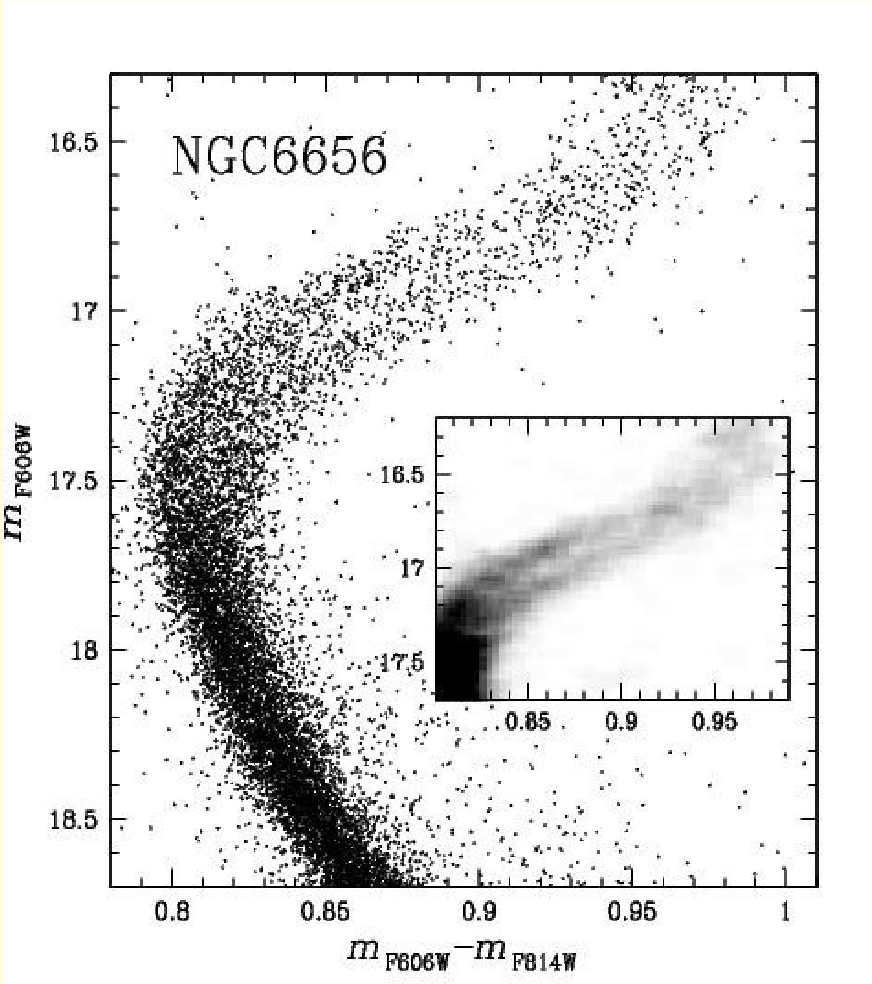
# Other clusters with a double/spread SGB

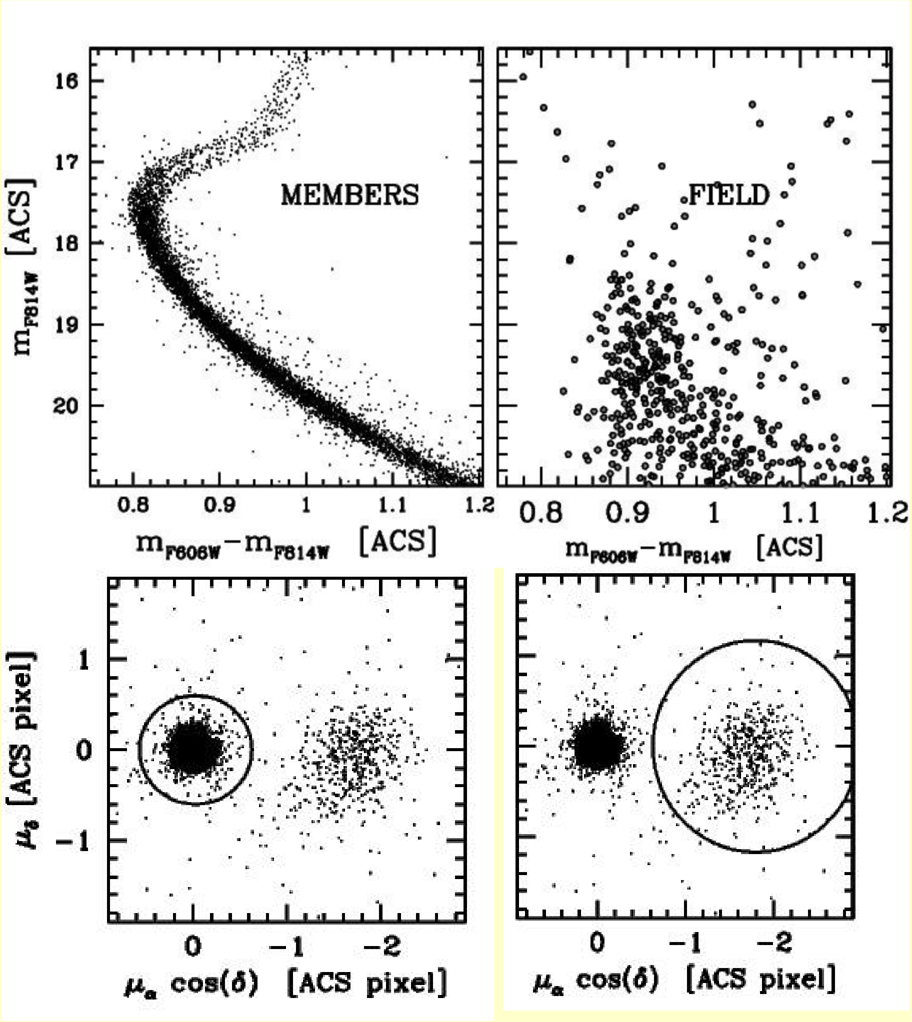



**NGC362, NGC7089, NGC6715, NGC 5286, NGC104 (47 Tucanae)...**

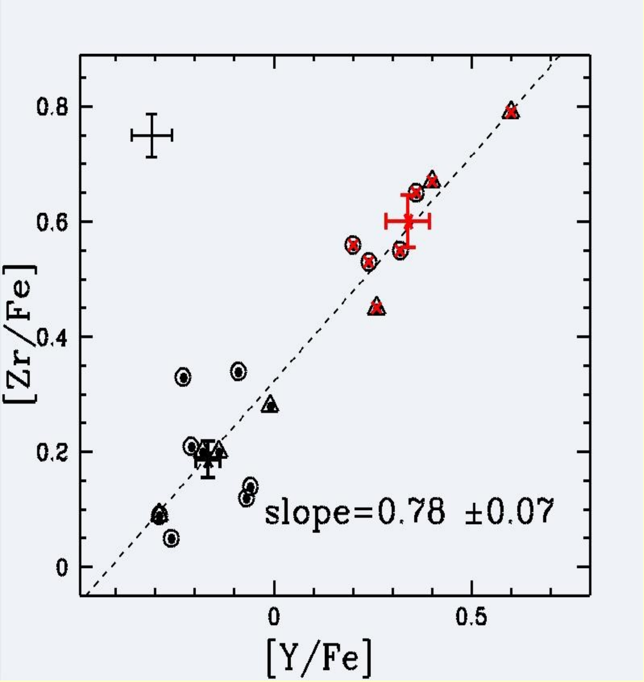
# ... and NGC6656 (M22)



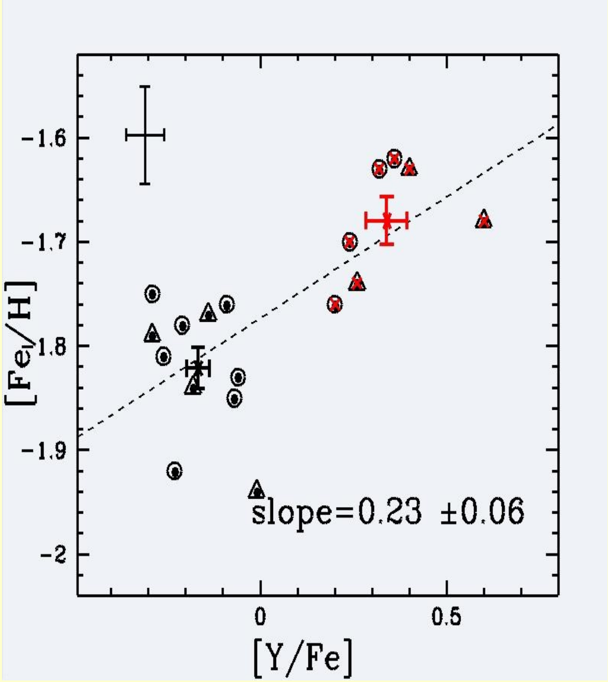



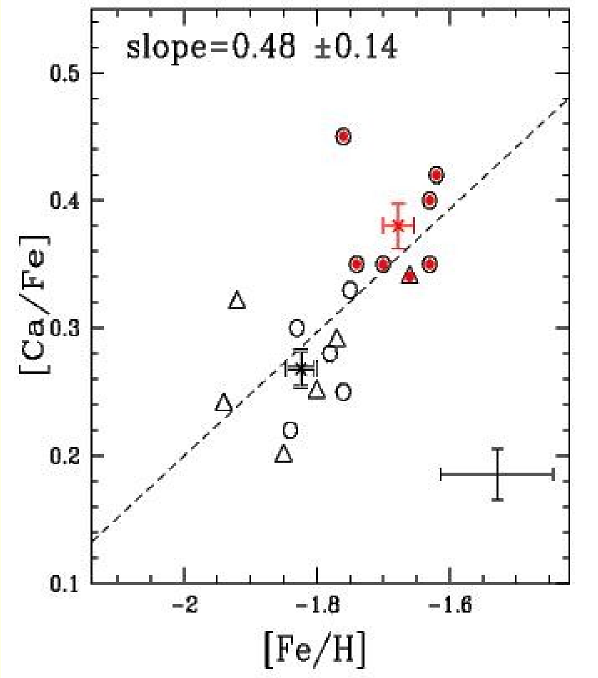

Piotto et al., (2010) in preparation

We discovered two distinct stellar groups: one with enhanced s-element abundance, and one with low s- abundance.



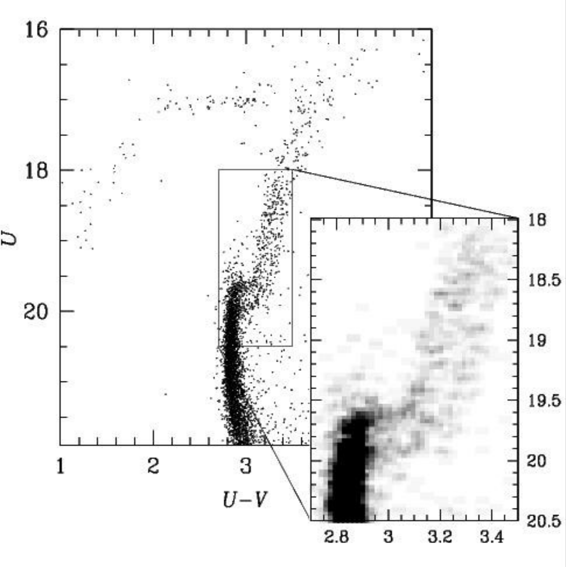

[Fe/H] and [Ca/Fe] are bimodal:
s element rich stars are also iron rich, calcium rich.

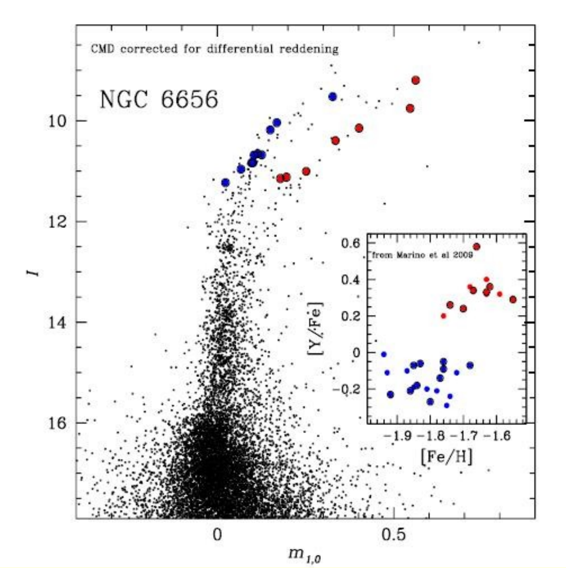


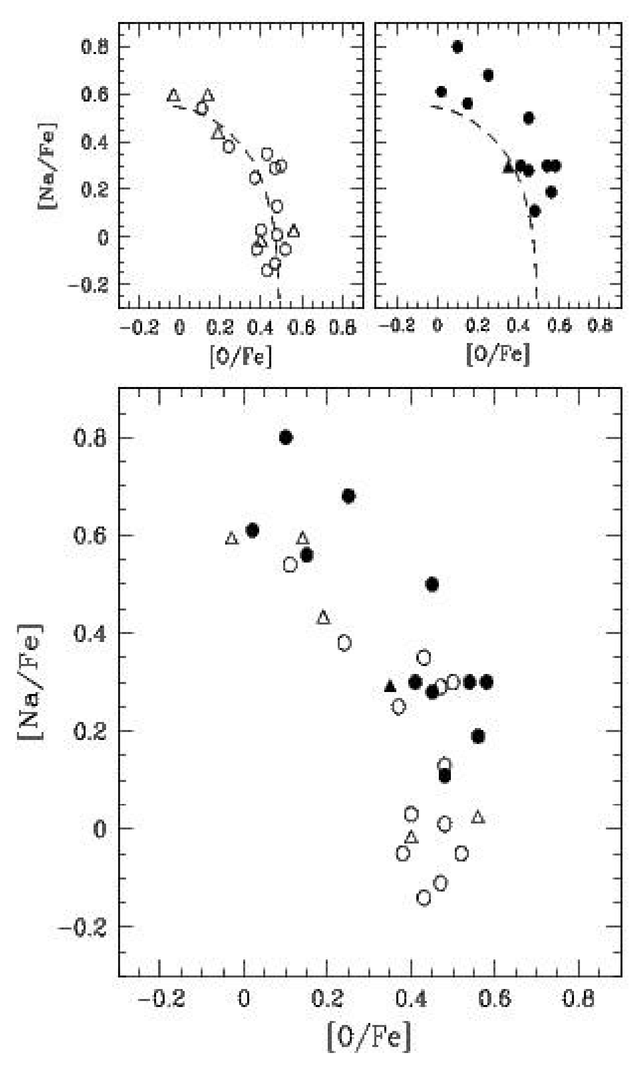




Marino et al. 2009, A&A 505, 1099

# Fainter SGB stars are the progenie of s-elements rich, Iron rich RGB stars



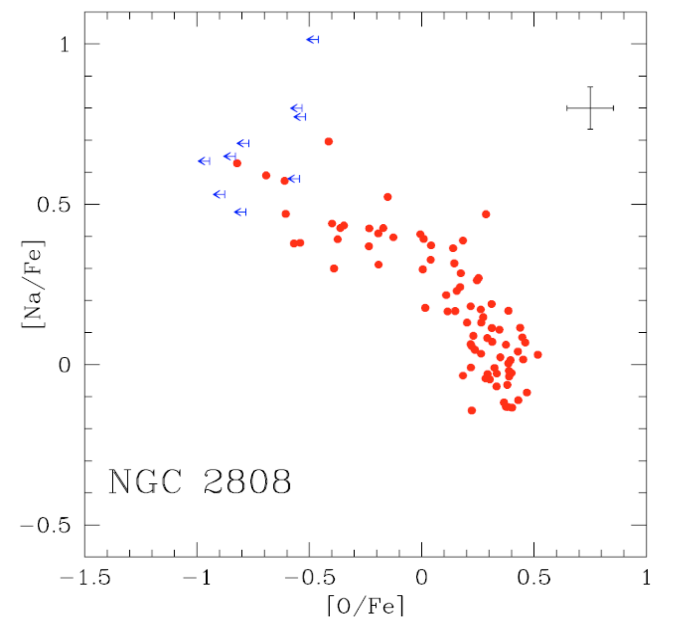



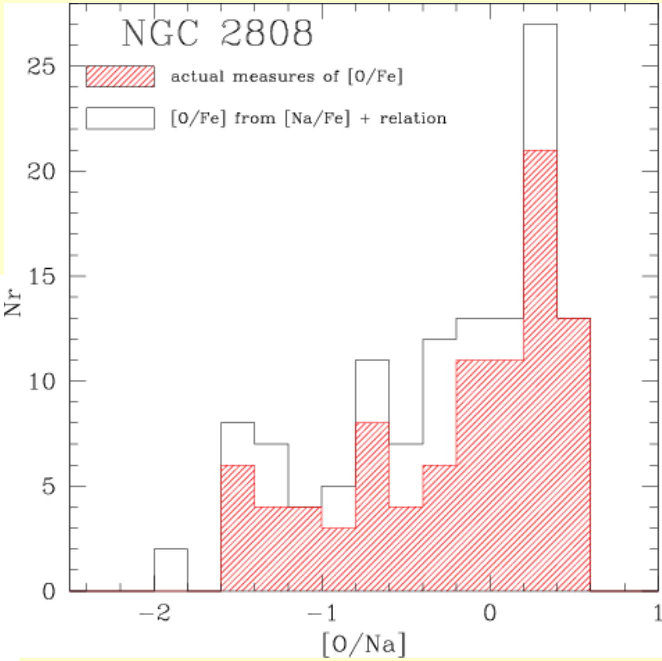

**Both the s-elements/iron rich and the s-elements/iron poor population exhibit a Na-O anticorrelation.**

**The Na-O anticorrelation in the s-elements/iron rich population has higher Na**

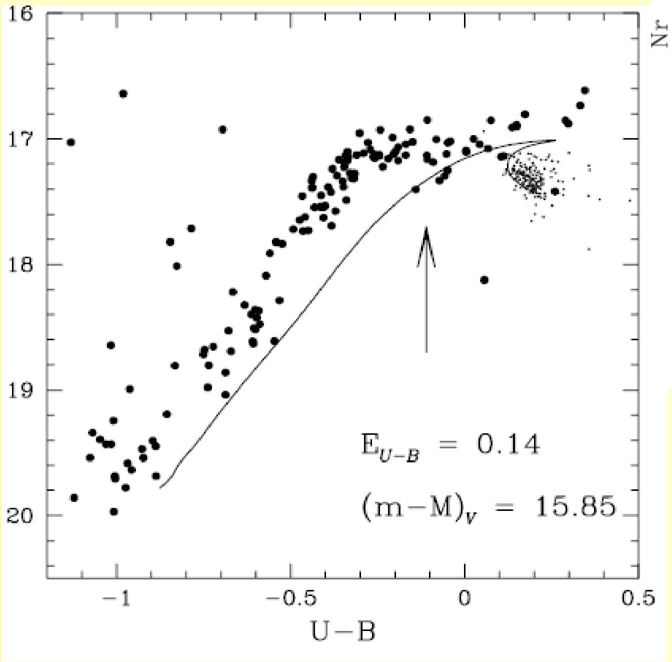
# NGC 2808



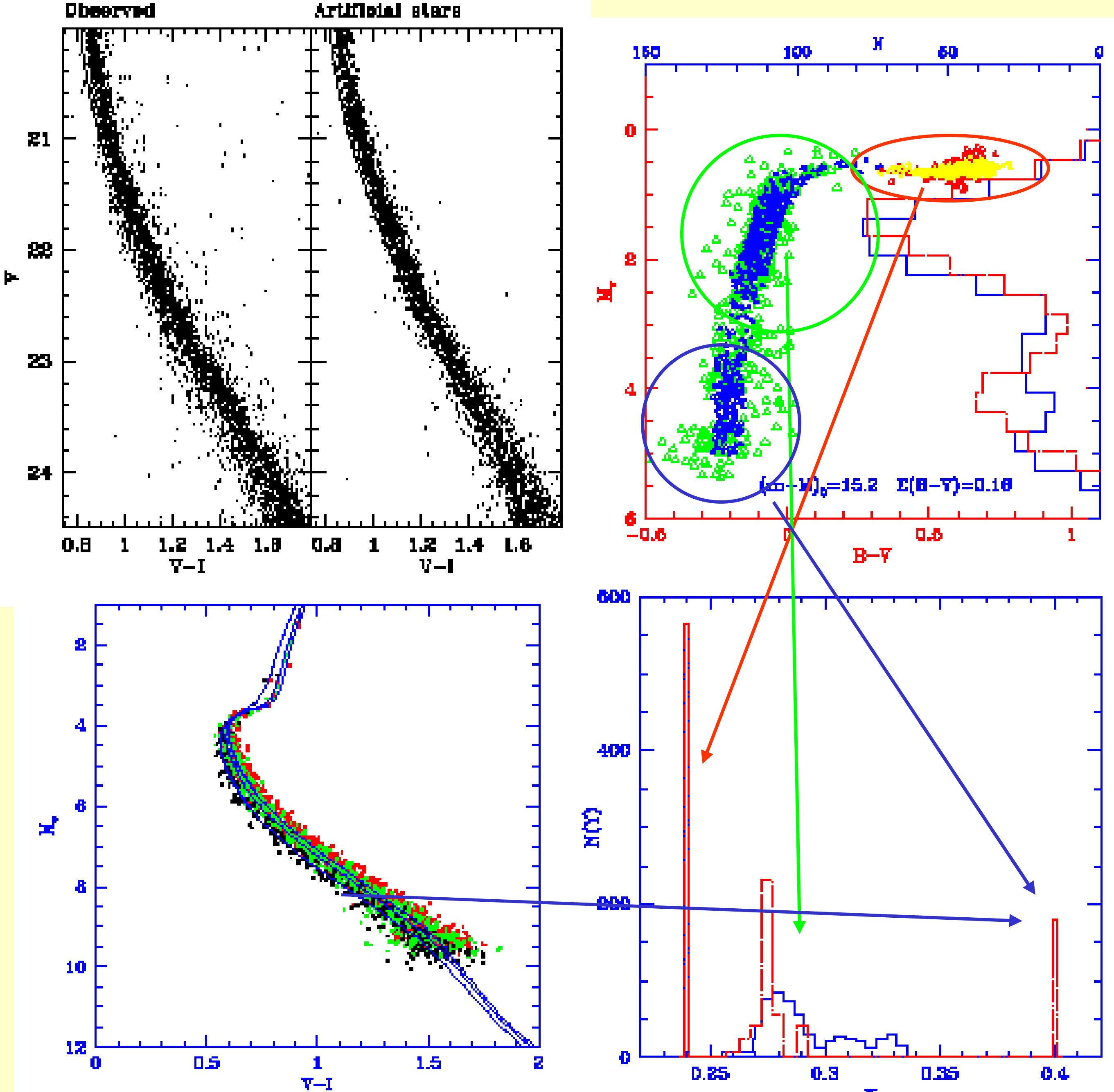

A clear NaO anticorrelation has been identified by Carretta et al. (2006, A&A, 450, 523) in NGC 2808.
Besides a bulk of O-normal stars with the typical composition of field halo stars, NGC2808 seems to host two other groups of O-poor and super O-poor stars




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



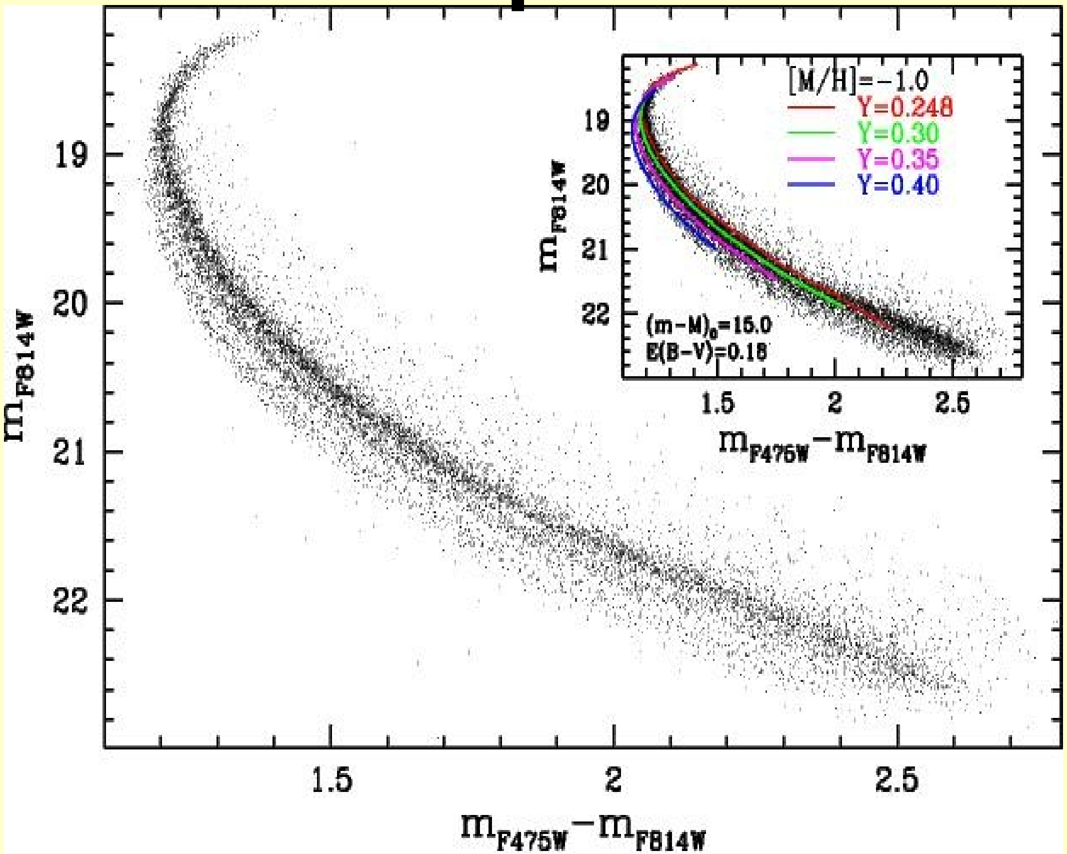

D’Antona et al. 2005, ApJ, 631, 868

D’Antona et al. (2005) detected a MS broadening in NGC2808.

They linked the MS broadening to the HB morphology, and proposed that three stellar populations, with three different He enhancements, could reproduce the complicate HB.

**This result is nicely confirmed by the triple MS observed by Piotto et al (2007)**

# The triple Main Sequence of NGC 2808




Piotto et al., 2007, ApJL, 661, 53

- We tentatively attribute the three branches to successive round of star formation with helium content.
- Overabundances of helium (Y~0.30, Y~0.40) can reproduce the two bluest main sequences.
- The TO-SGB regions are so narrow that any difference in age between the three groups must be significantly smaller than 1 Gyr

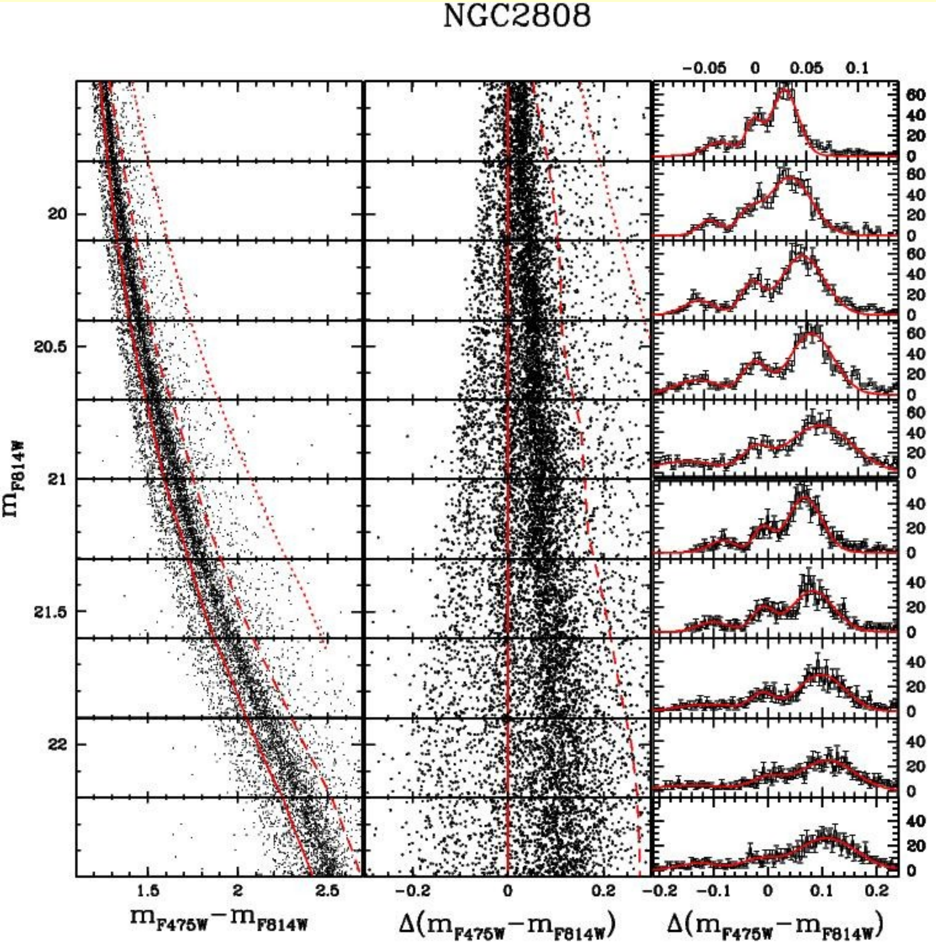
In summary, in NGC 2808,
it is tempting to link together:

**the multiple MS,**

**the multiple HB,**

**and**

**the three oxygen groups.**

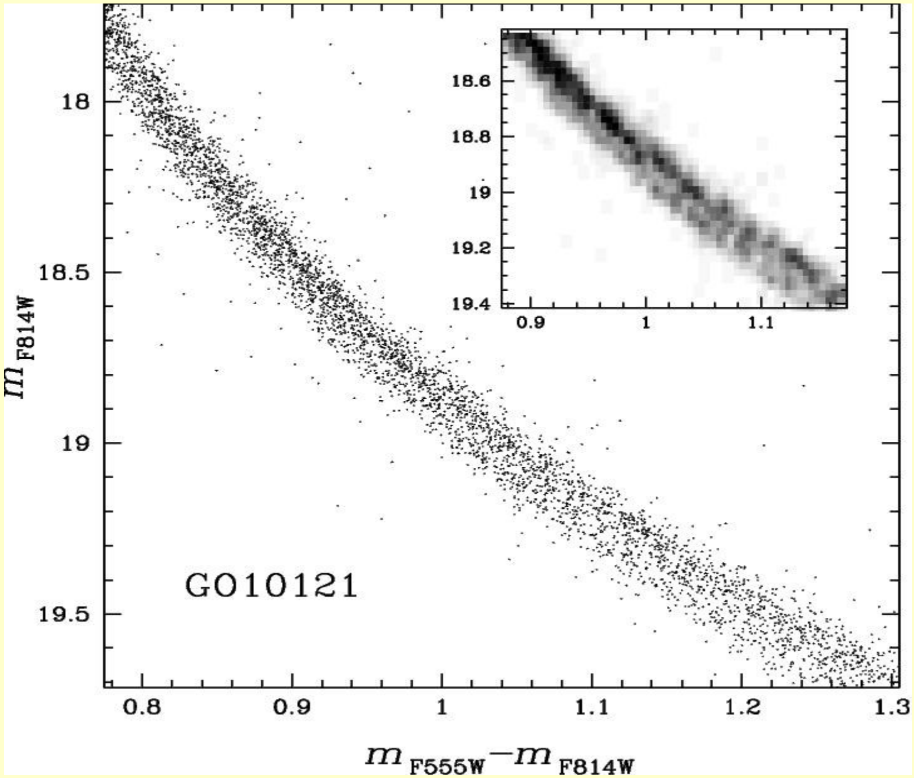


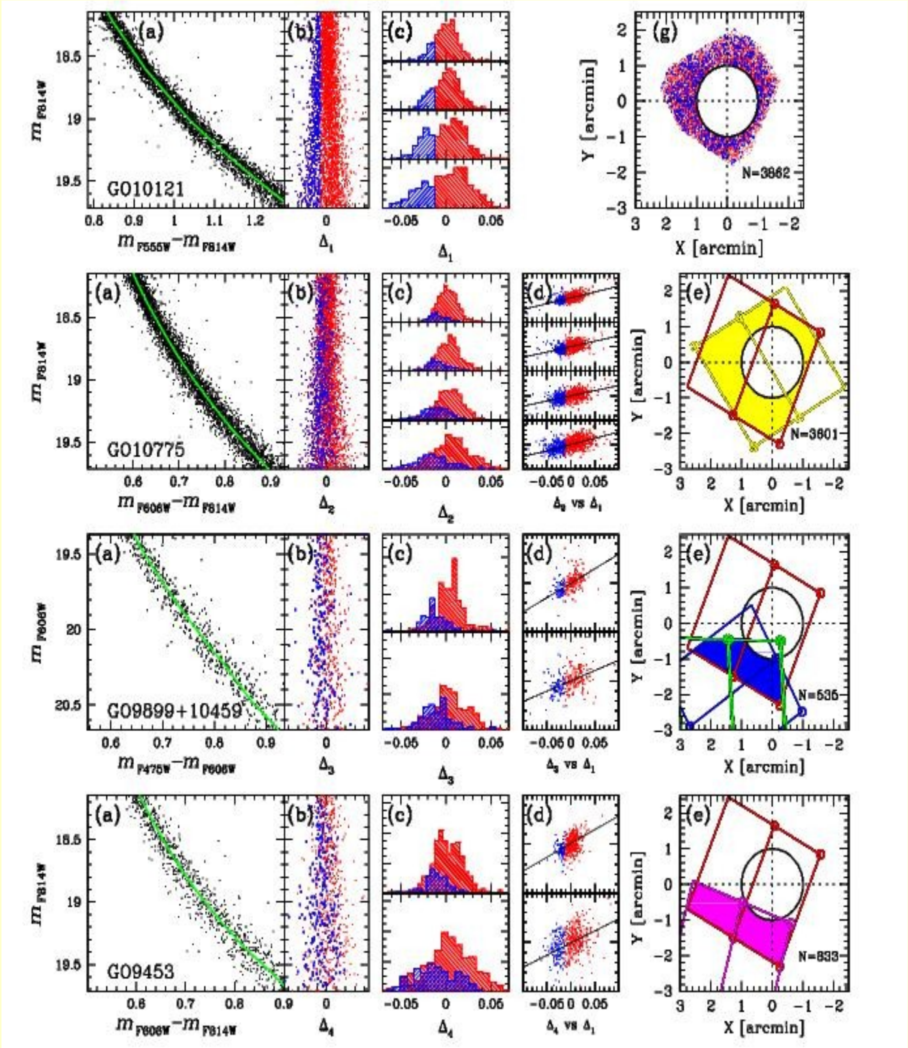

**Piotto et al., 2007, ApJL, 661, 53**

The Population Components of NGC 2808

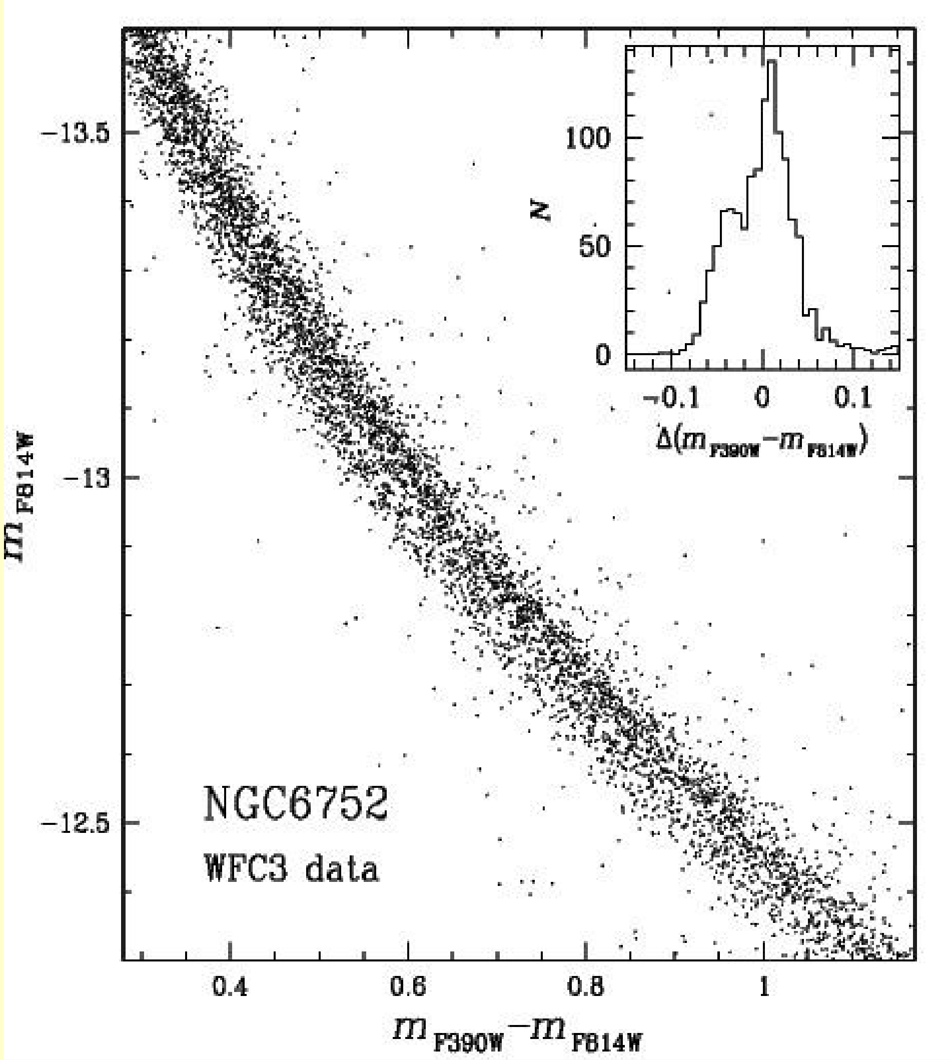
| MS | RGB | HB |
|---|---|---|
| rMS<br>63% ± 5<br>$Y = 0.248$ | O-normal<br>61% ± 7 | Red segment<br>46% ± 10 |
| mMS<br>15% ± 5<br>$Y = 0.30$ | O-poor<br>22% ± 4 | EBT1<br>35% ± 10 |
| bMS<br>13% ± 5<br>$Y = 0.37$ | Super–O-poor<br>17% ± 4 | EBT2<br>10% ± 5 |
| Binaries<br>9% ± 5 | ? | EBT3?<br>9%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

# The spread (double?) Main Sequence of NGC 6752




**Milone et al., (2010 ApJ, 709, 1183)**




**We reduced HST/WFC3 images of NGC6752.**

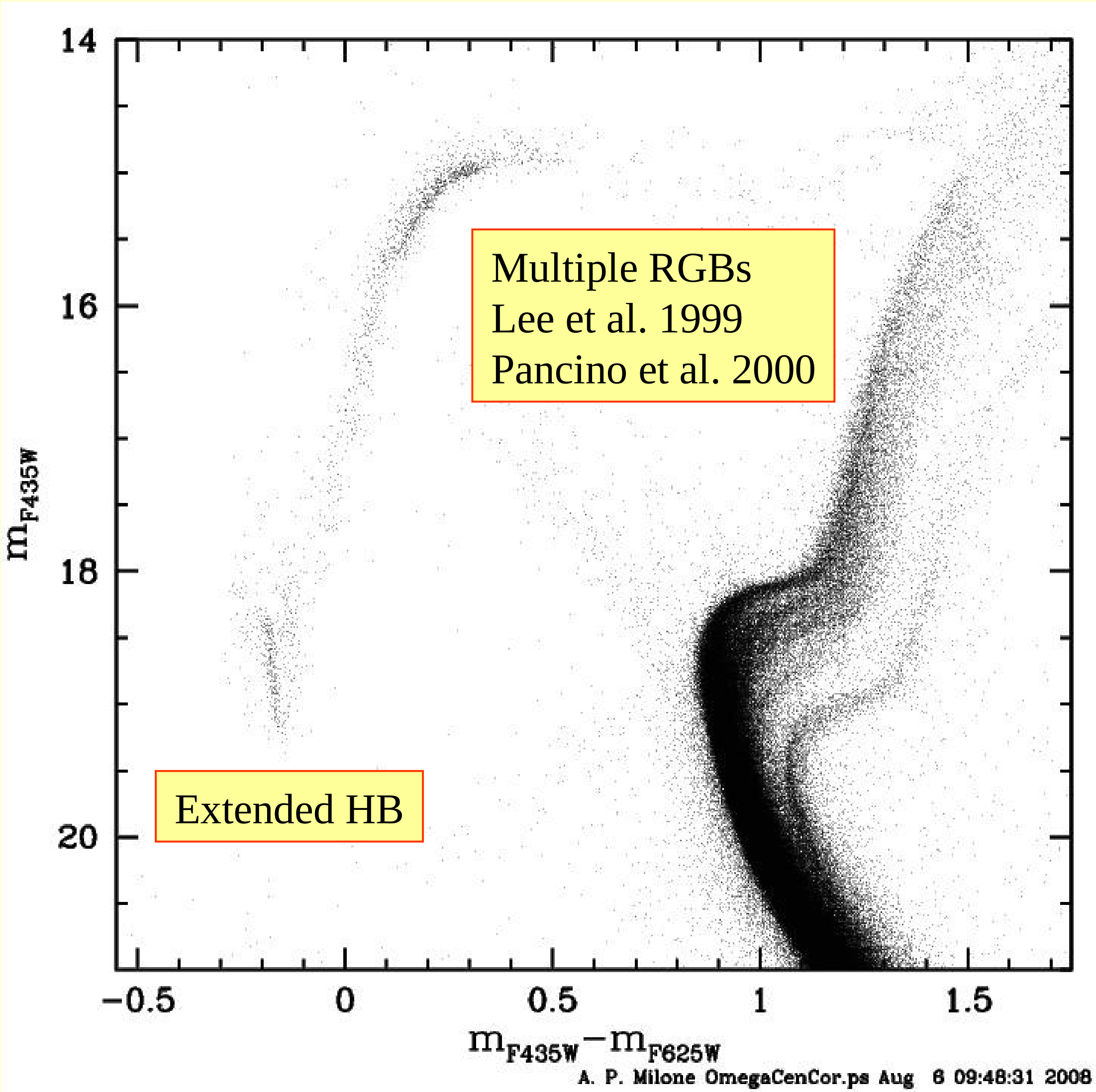
**We confirm the findings by Milone et al. (2010) of a spread in color. The observed CMD is consistent with two MSs formed by stars with the same iron content and different Helium.**

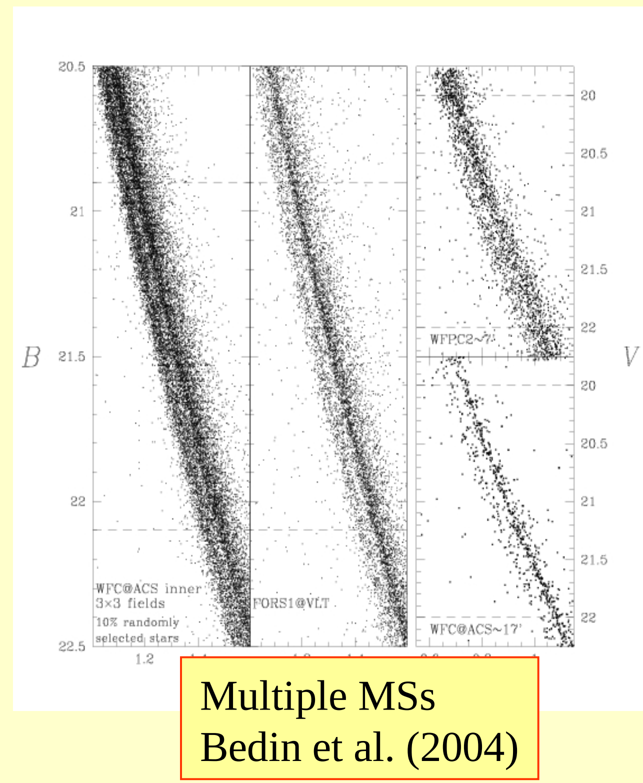
**In this case the blue MS should contain the ~30% of stars and should be He-enriched by ~0.03 dex with respect to the red MS that have nearly primordial Helium**

# Omega Centauri

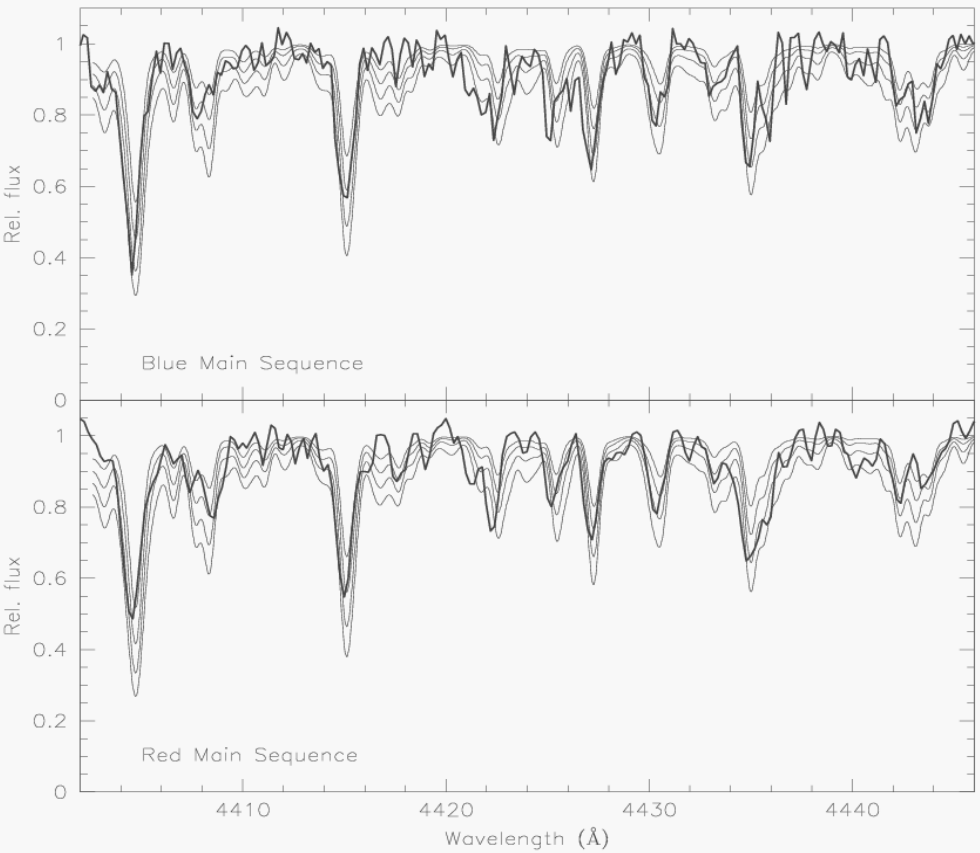
The most massive Galactic "globular cluster"
(present day mass: ~4 million solar masses).

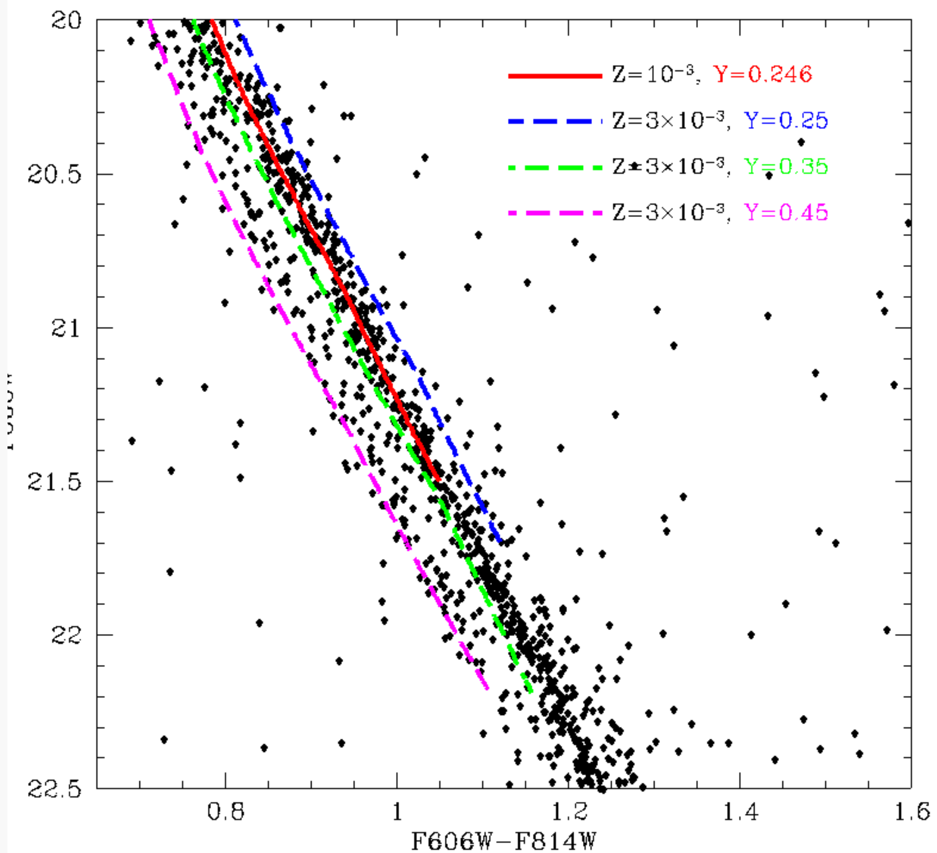
Well known (since the '70s) spread in metallicity among RGB stars.



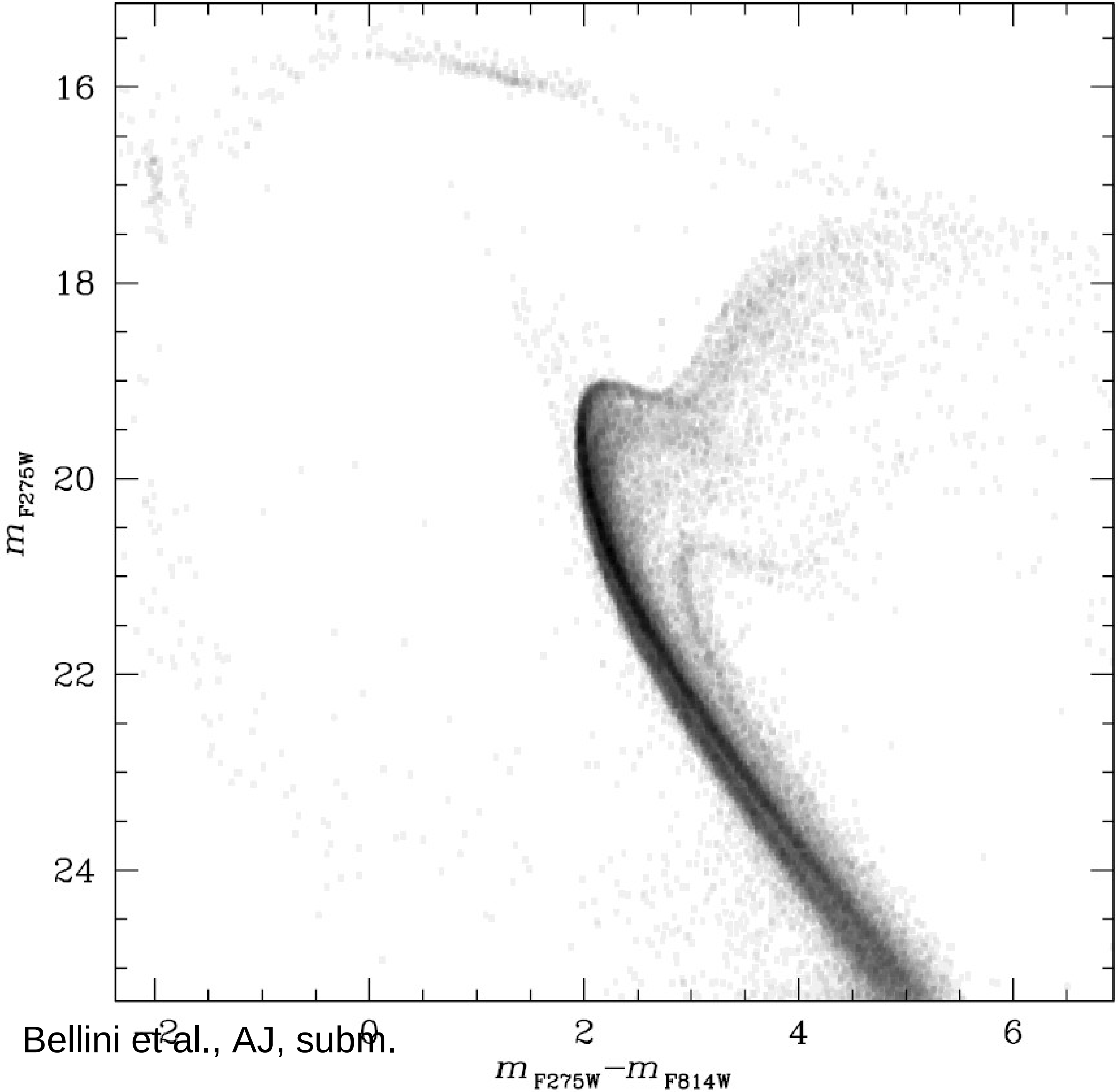




Villanova, Piotto, Anderson et al. (2007, ApJ, 663, 296).




**The most surprising discovery** (Piotto et al. 2005) is that **the bluest main sequence is less metal poor than the redder one: Apparently, only <u>an overabundance of helium (Y~0.40)</u> can reproduce the observed blue main sequence**

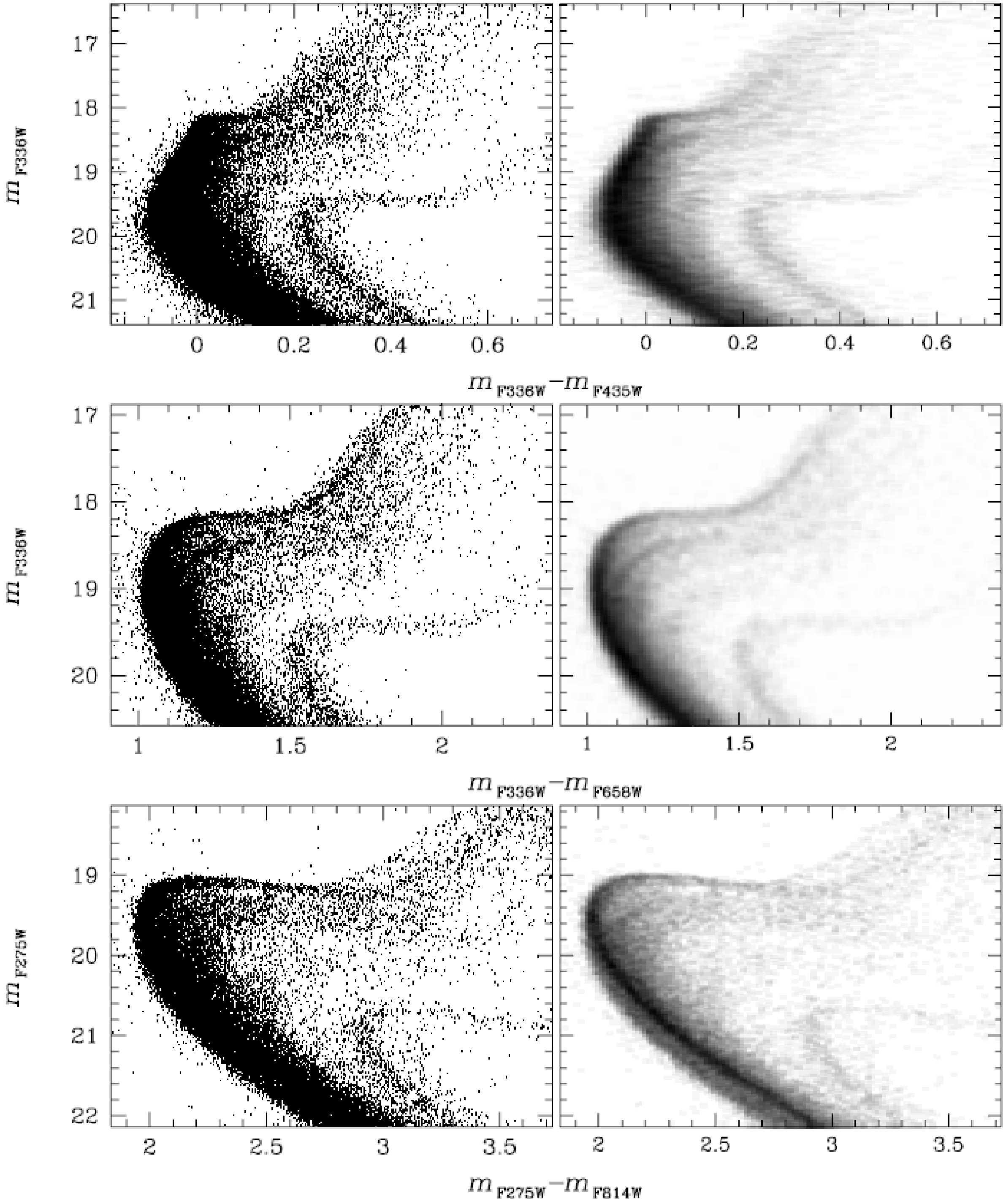



Bellini et al., AJ, subm.

The complexity increases!

New spectacular UV data from the new WFC3 camera onboard HST.

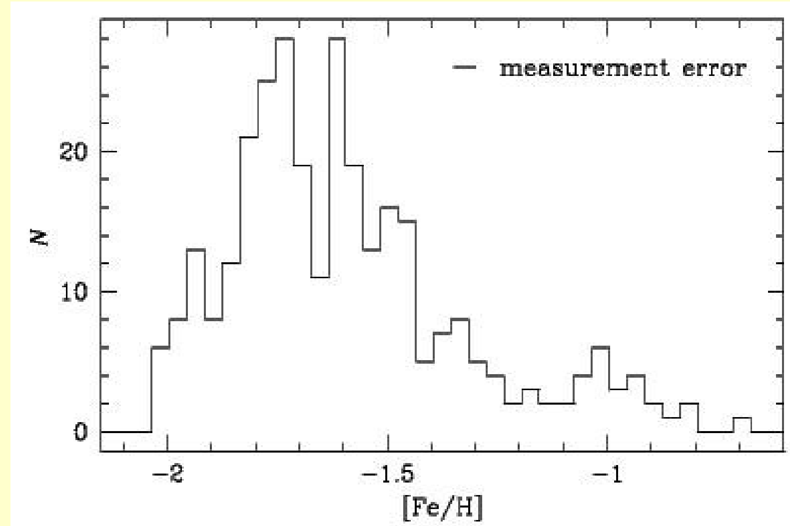
Amazing perspectives with WFC3

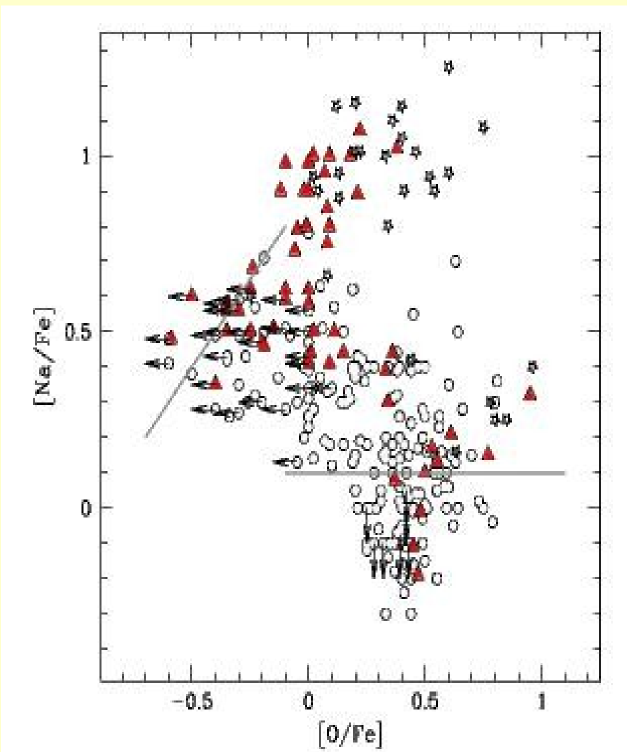



# Again from WFC3

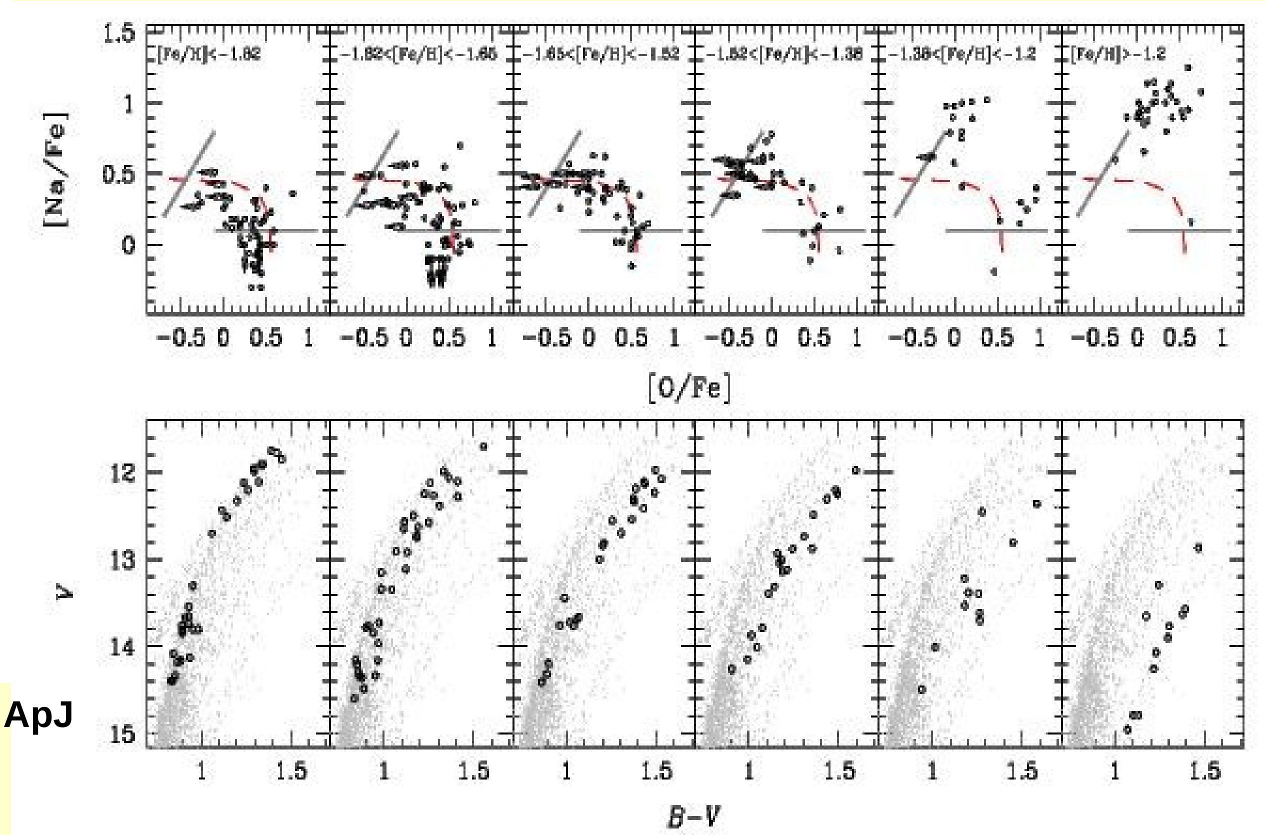
Different colors provide a more complete view of the complexity of Omega Centauri multiple populations

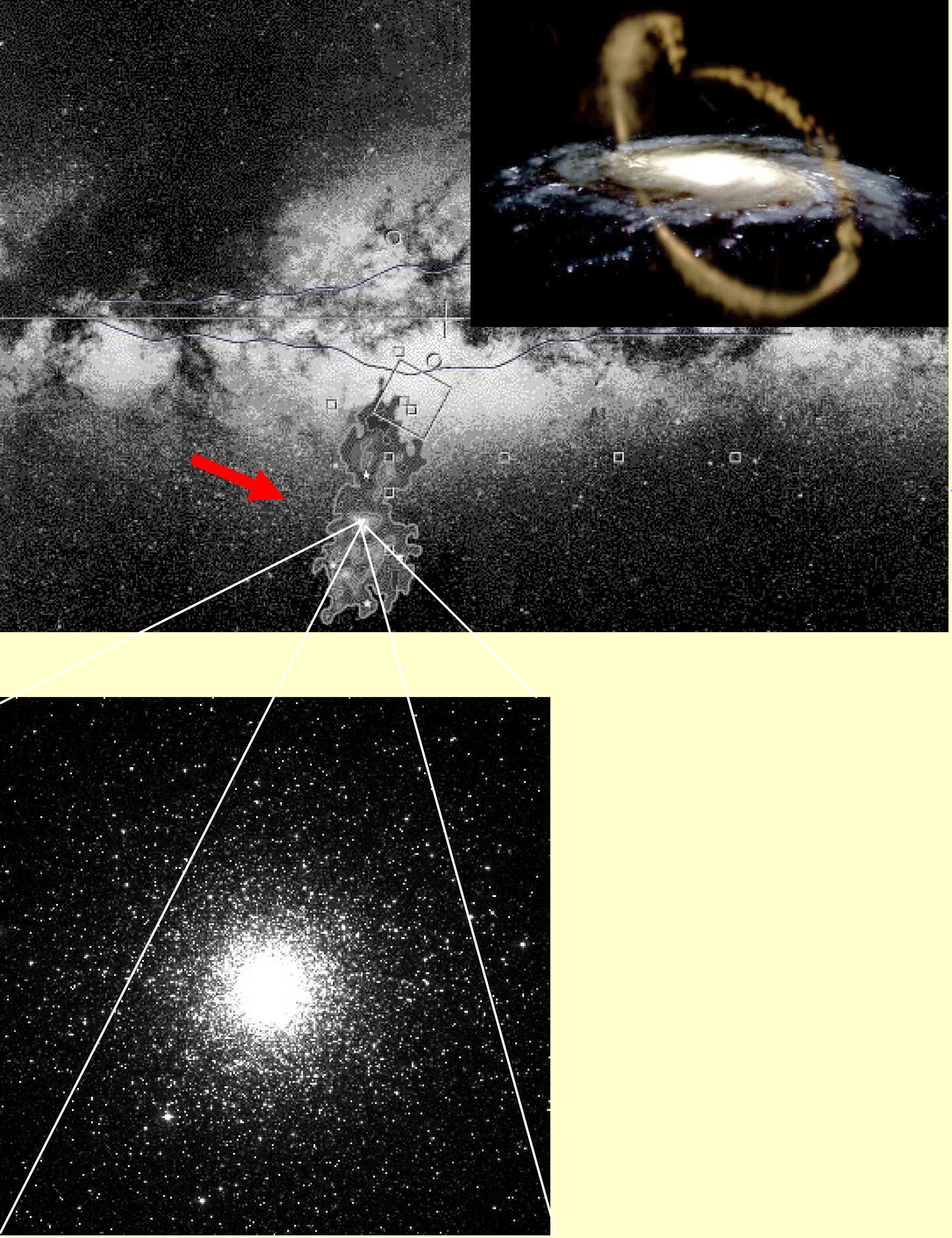
- Multimodal iron distribution
- Complex Na O anticorrelation
- Groups of stars with different Fe/H show the Na-O anticorrelation (like in M22 and M54)




**Marino et al., 2010, submitted to ApJ**

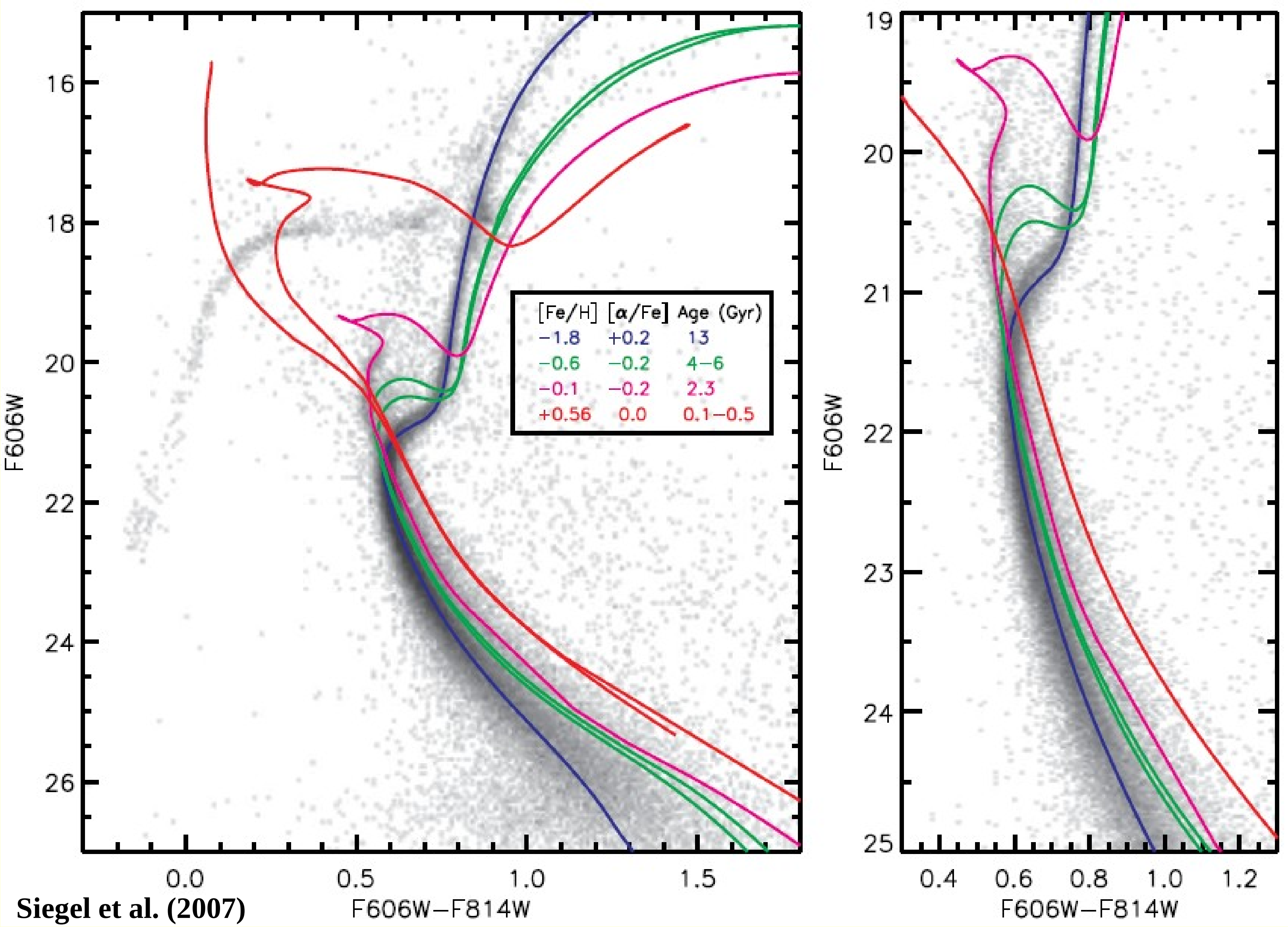




**M54 c**oincides with the nucleus of the Sagittarius dwarf galaxy . It might be born in the nucleus or, more likely, it might be ended into the nucleus via dynamical friction (see, Bellazzini et al. 2008), but the important fact is that, today**:**

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

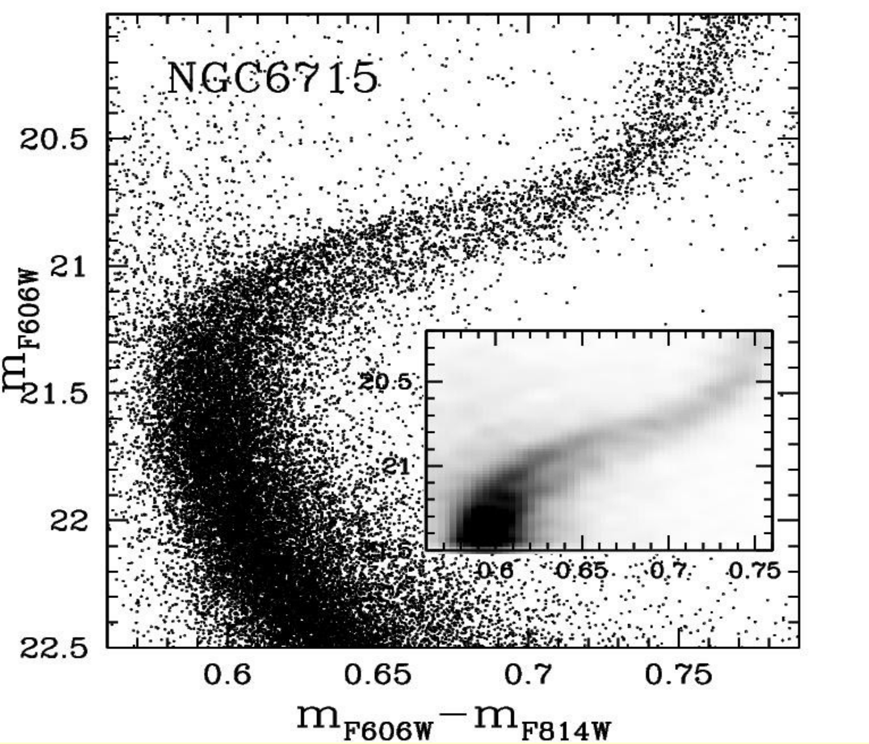
# NGC 6715 (M54)



Siegel et al. (2007)

**Multiple RGBs, Multiple MSs, ….**

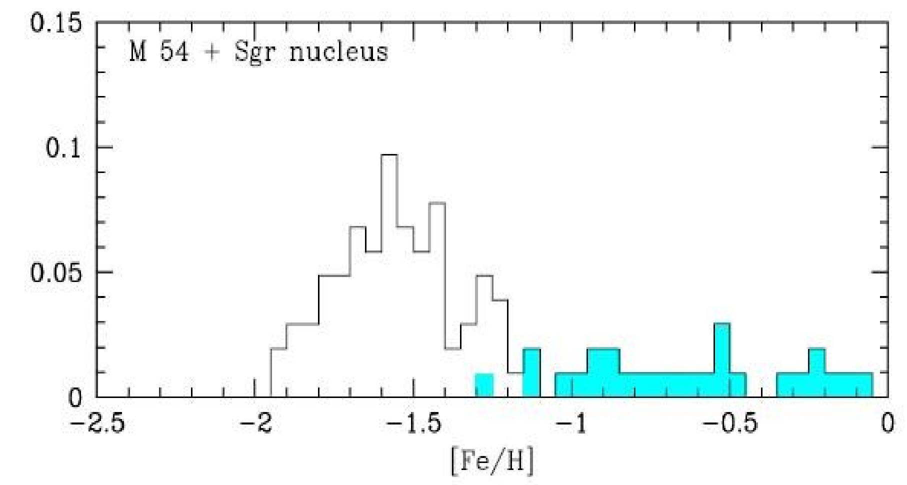
# NGC 6715 (M54)




Piotto et al., (2010) in preparation

**Multiple SGBs!**

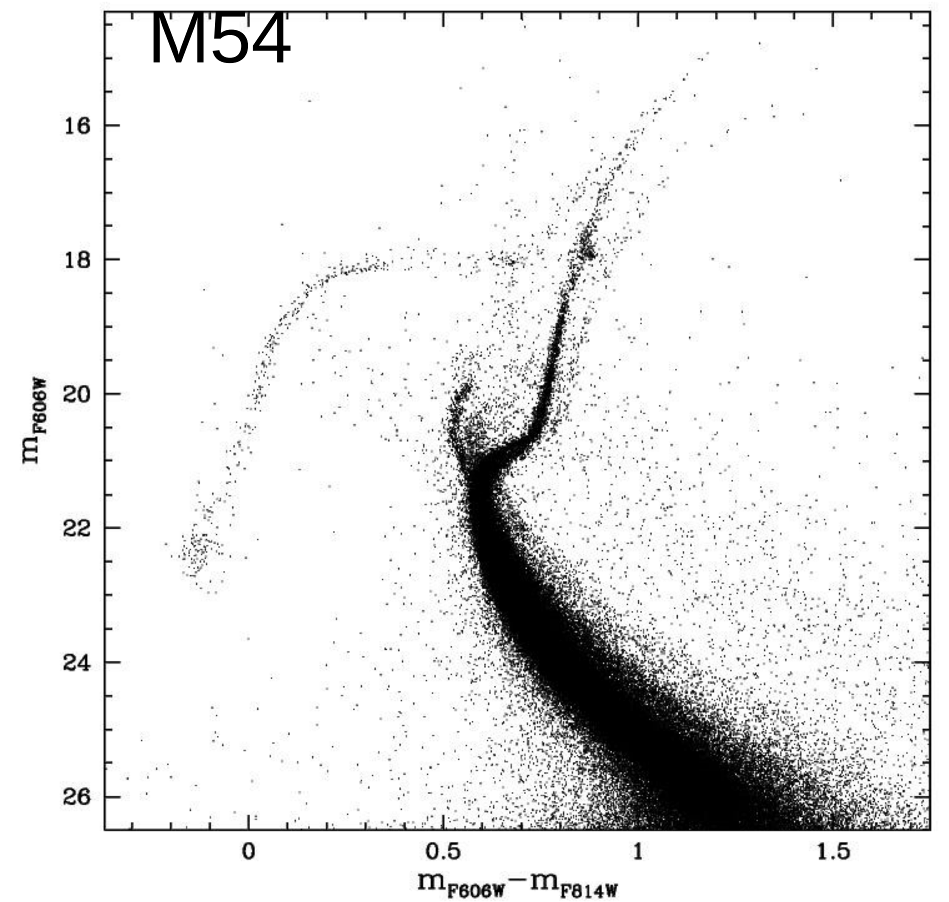
**Very, very similar to the cases of the globular clusters NGC1851, NGC6388, NGC 6656…**



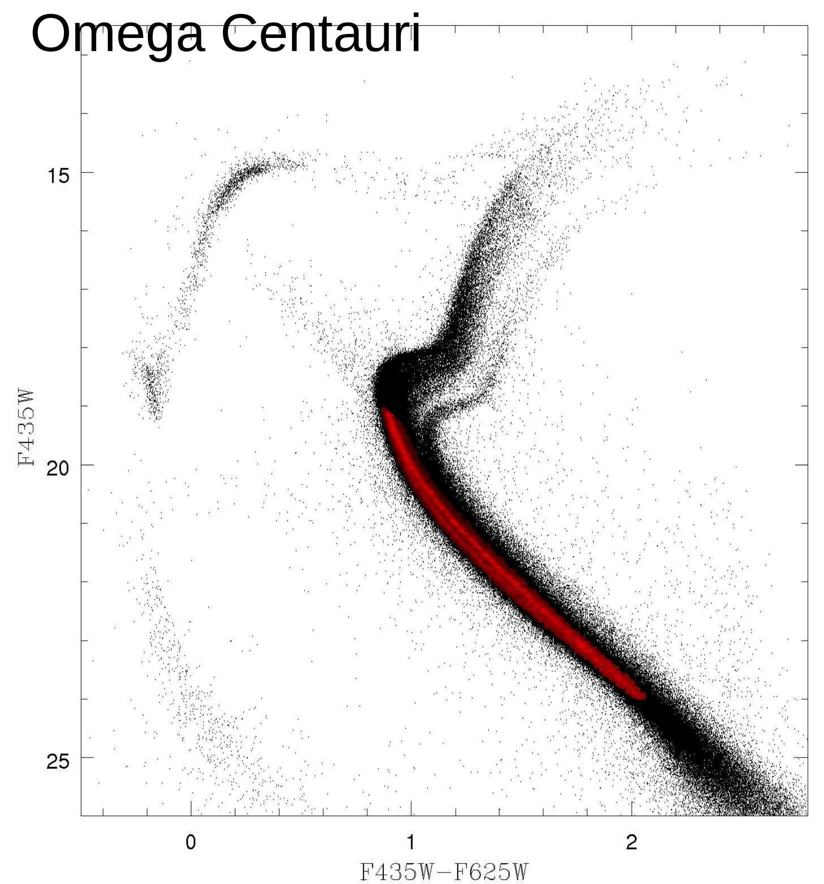

Carretta et al., (2010 ApJ, 714, L7)

**Spread in Fe/H**

**Similar to the cases of the globular clusters NGC6656 (M22), and Omega Centauri**




**The CMDs of M54 and Omega Cen are very similar.**




It is likely that M54 and the Sagittarius nucleus show us what Omega Cen 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 the globular clusters?

# Proposed scenario (1)

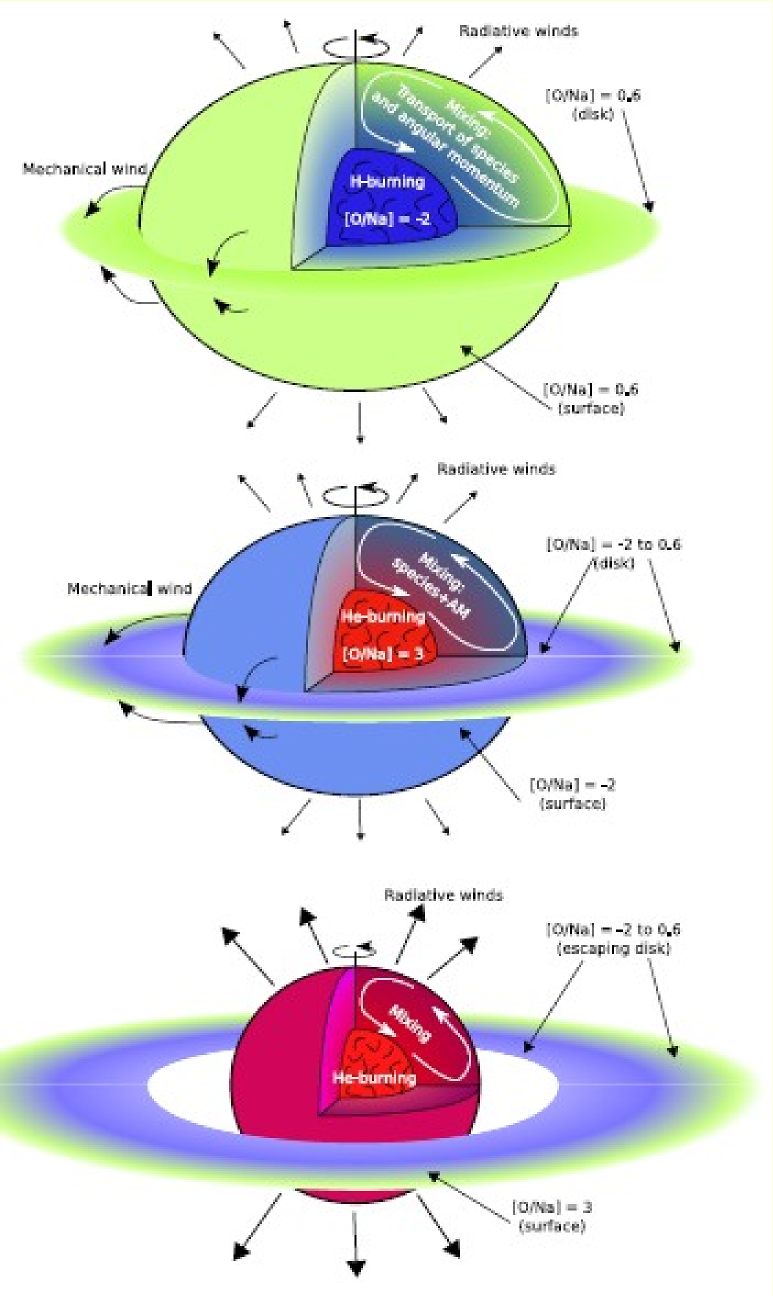
## AGB Stars ejecta

**AGB stars eject large amounts of mass at low velocity (~10-20 Km/sec) which can be retained within the potential well of GCs**

**Among them especially interesting are those in the mass range ~3-8 $M_{SUN}$ because they experienced the 2DU and the HBB processes, therefore are enriched in He and N and present the Na-O Al-O anticorrelations.**

**For the AGB scenario to work they should experience few 3DU events so that there is no an increase of the overall CNO abundance**

# 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 can explain the abundance anomalies**

**2) It is ejected with very low velocity, and therefore can be trapped by the shallow potential well of the cluster**

# Open problems

Open problems

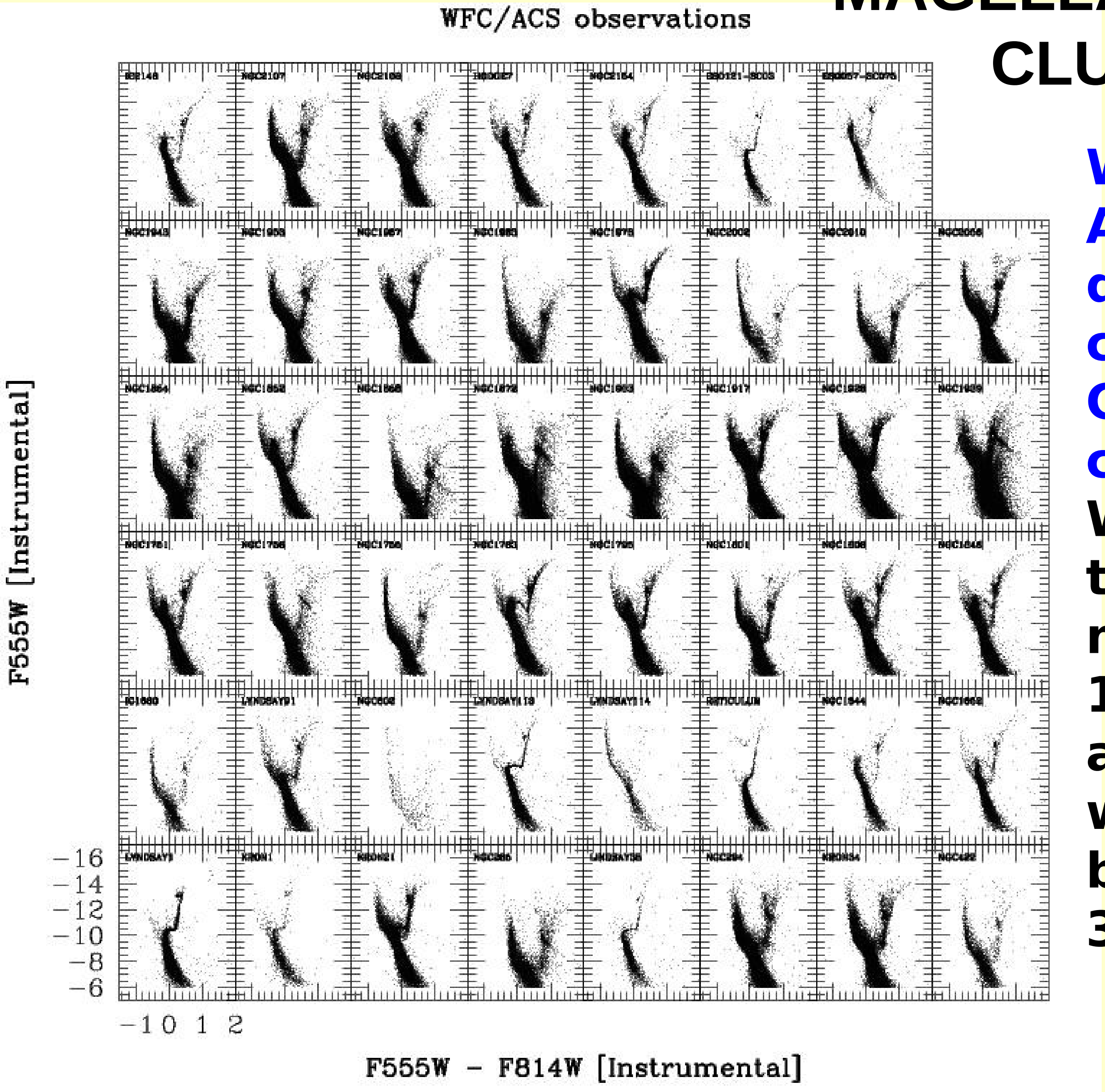
**Both scenarios have a number of problems. Among them:**

**- both scenarios need either an anomalously flat IMF or to assume that the cluster has lost most of its original population**

**-There are serious dynamical problem: how is the gas retained? How is the second stellar population triggered? (But see D'Ercole et al for some possible solution)**

**- Is part of  the ejected material He-rich enough to explain the strongly He-enhanced populations (Y>0.31)?**

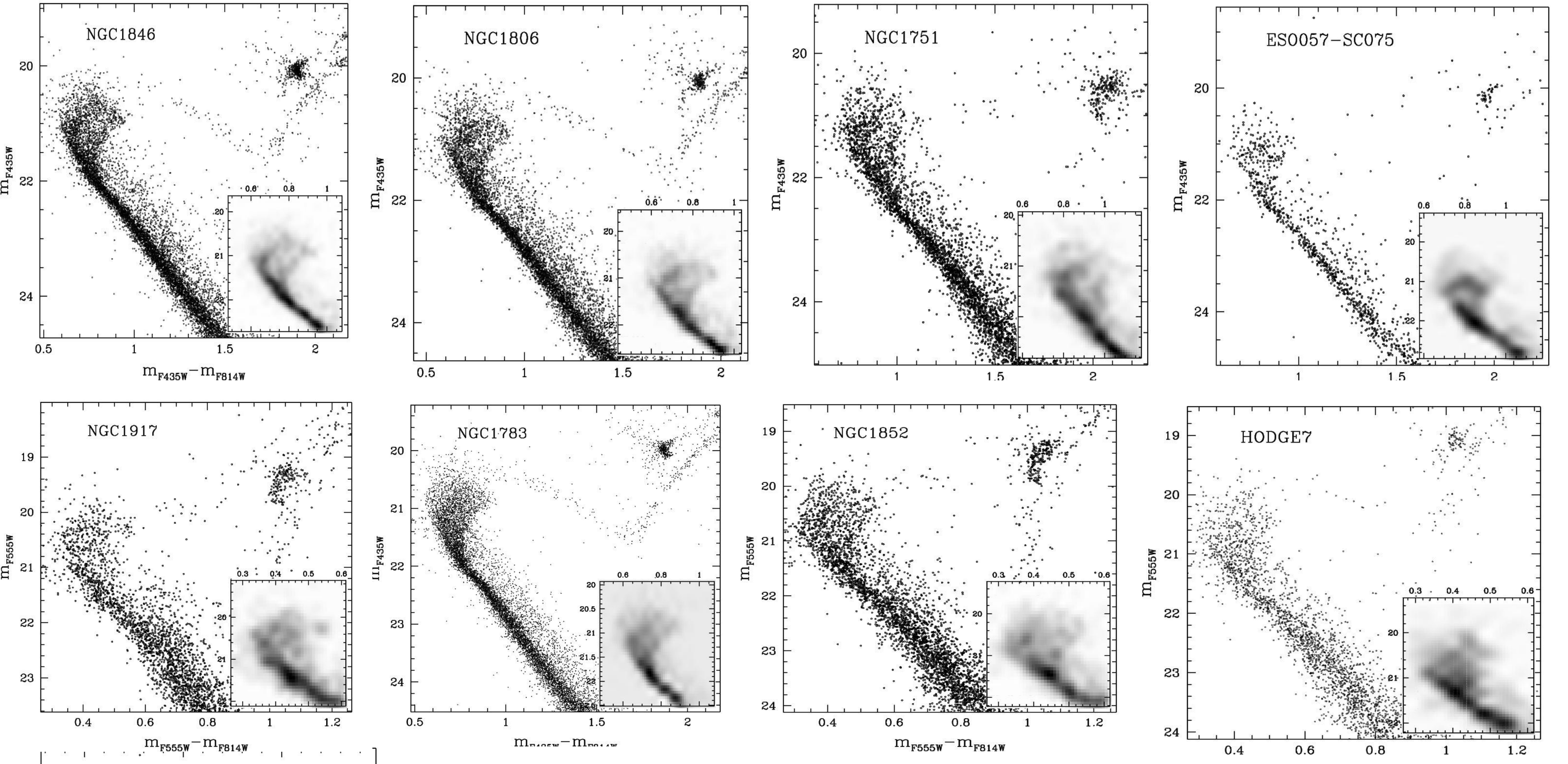
# MAGELLANIC CLOUD CLUSTERS

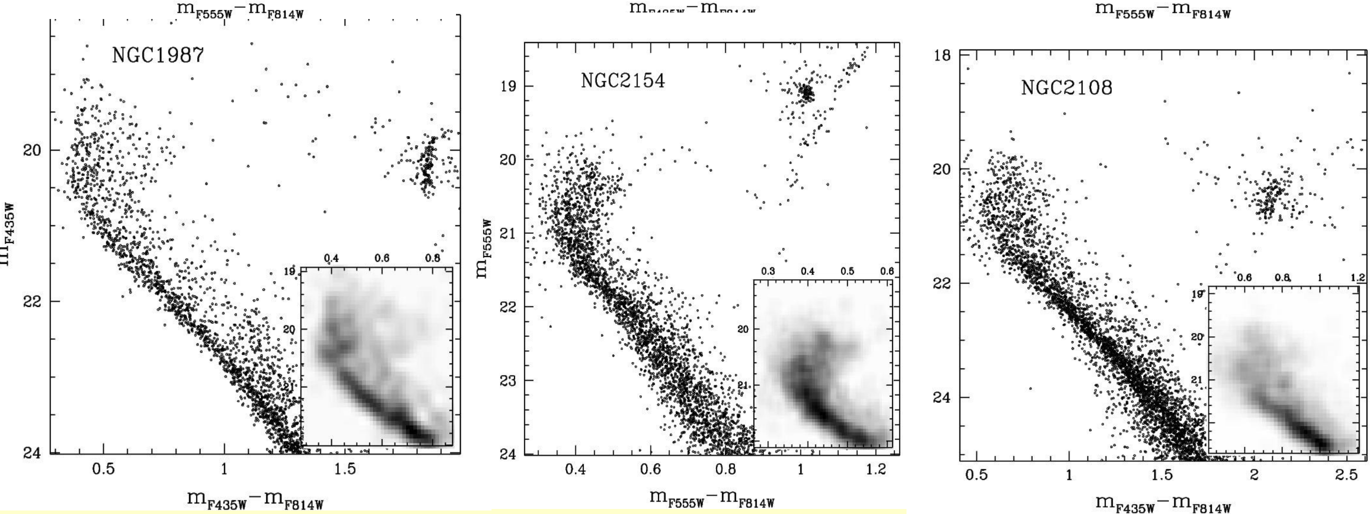



Milone et al., 2009, A&A, 497, 755

**We used ACS/HST archive data to construct the CMDs of 53 MC clusters.**

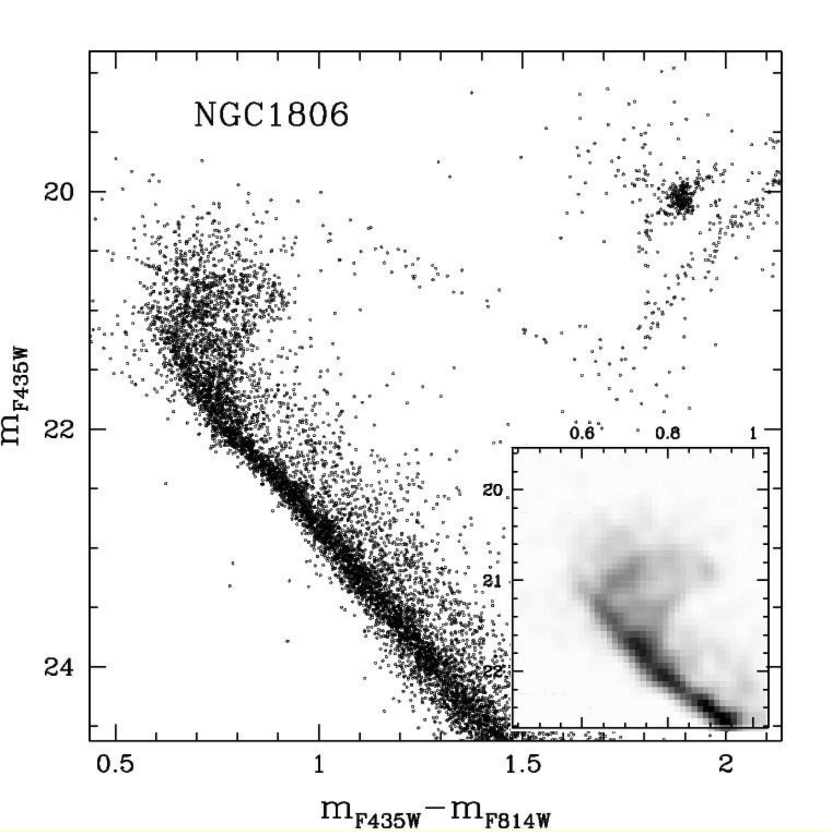
**We investigate the CMD morphology of 16 intermediate age clusters, with ages between 1 and 3 Gyr.**

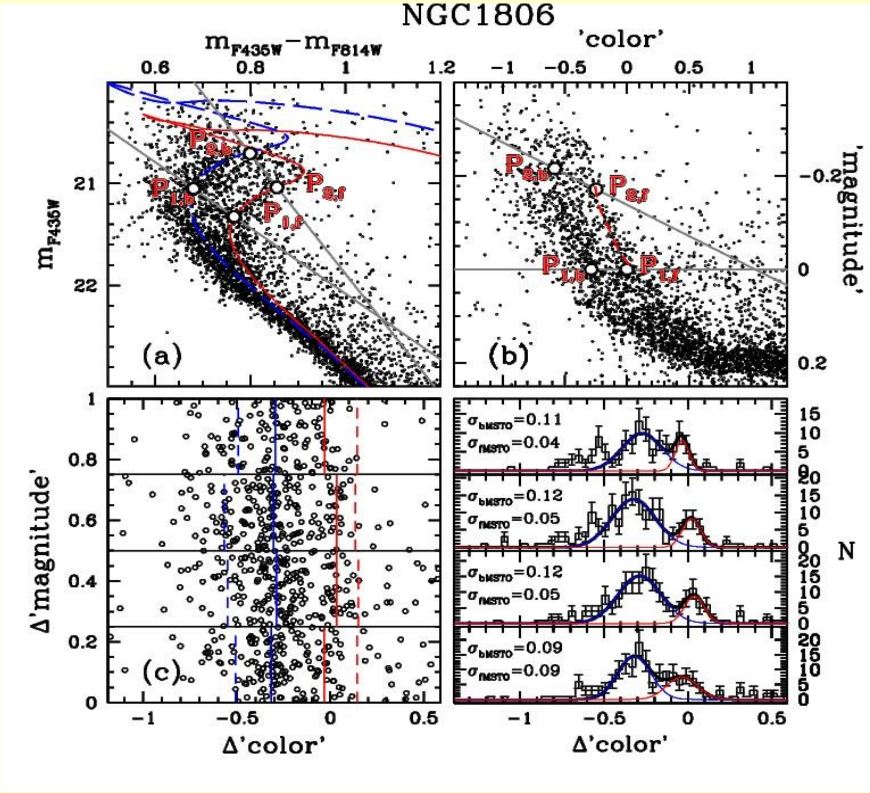


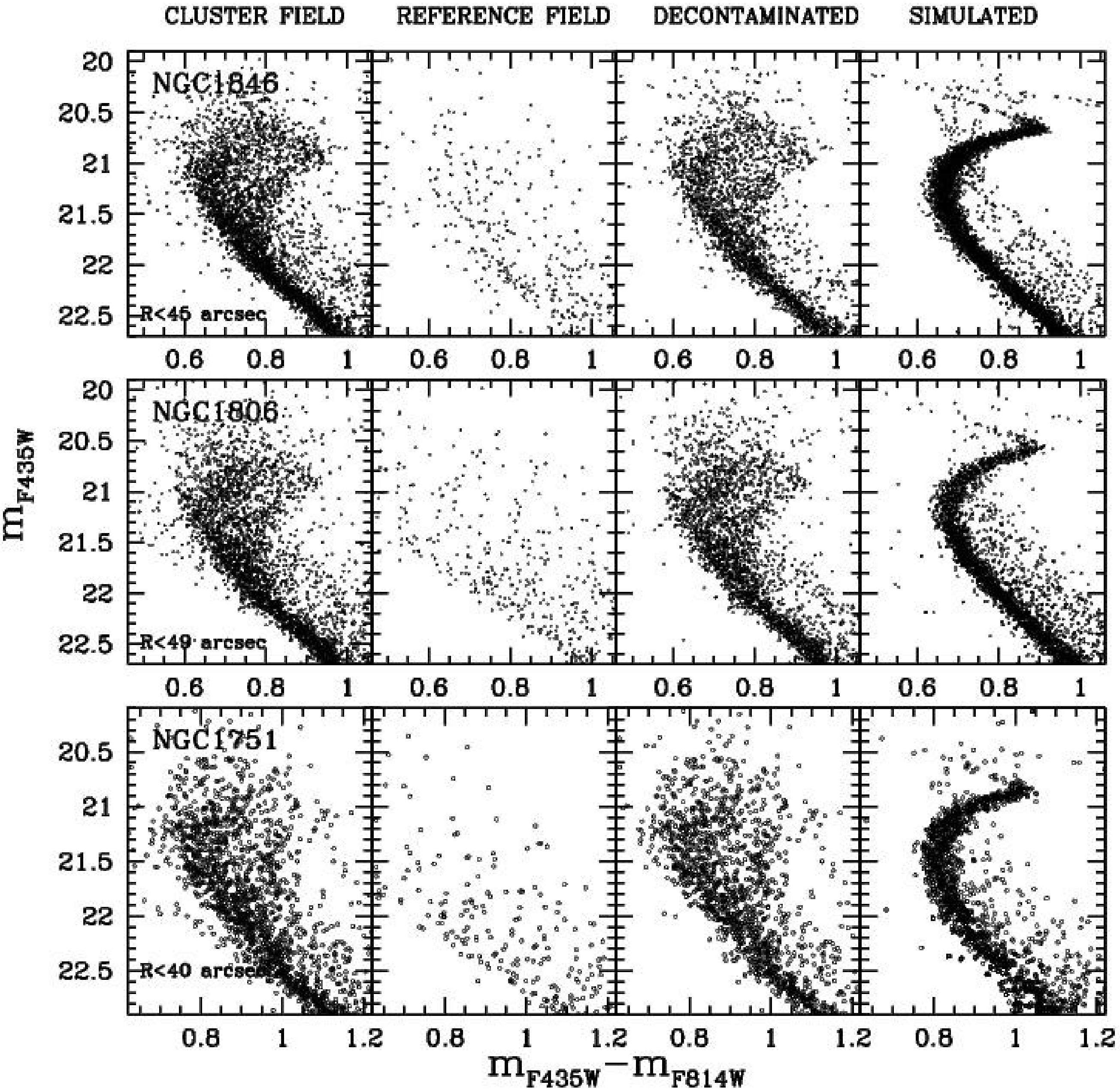

**Eleven out of 16 (~70%) of the intermediate age clusters show either a double or an extended TO!**

In NGC 1846, NGC1806 and NGC1751, ~70% of the stars are part of the brighter (younger?) TO population, and ~30% are part of the fainter (older) TO population.




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

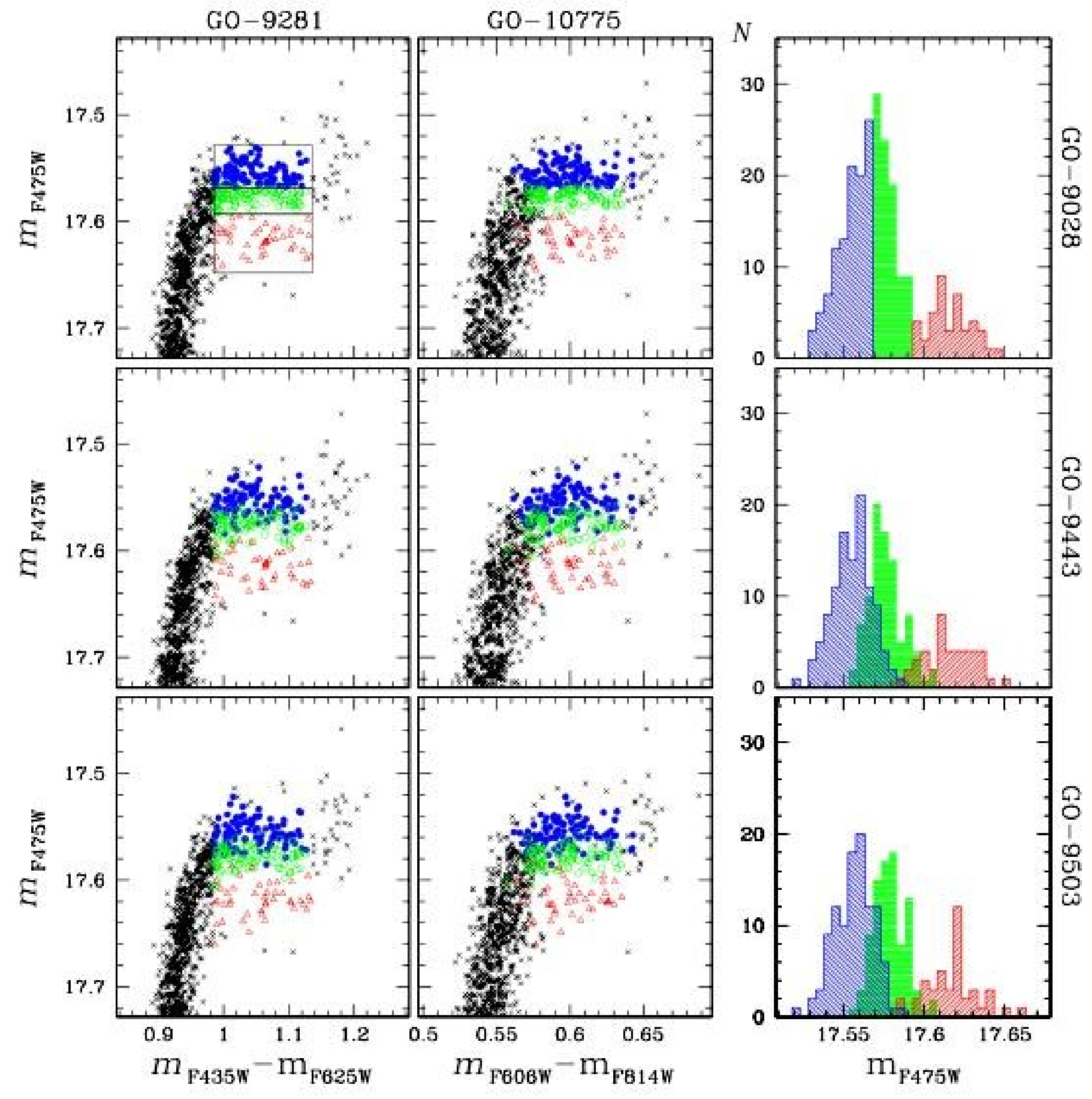



The double or extended TOs are an intrinsic feature of the selected cluster CMDs.

The split spread TO may be due to an age difference of about 2-300 Myr (Mackey et al. 2008, Milone et al 2008)

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

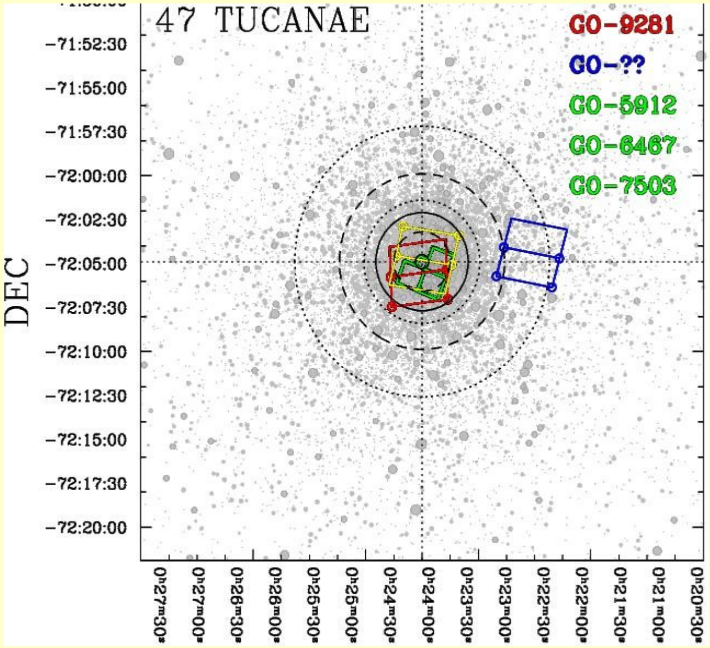
# 1) RADIAL DISTRIBUTION OF MULTIPLE STELLAR POPULATIONS IN 47 TUCANAE



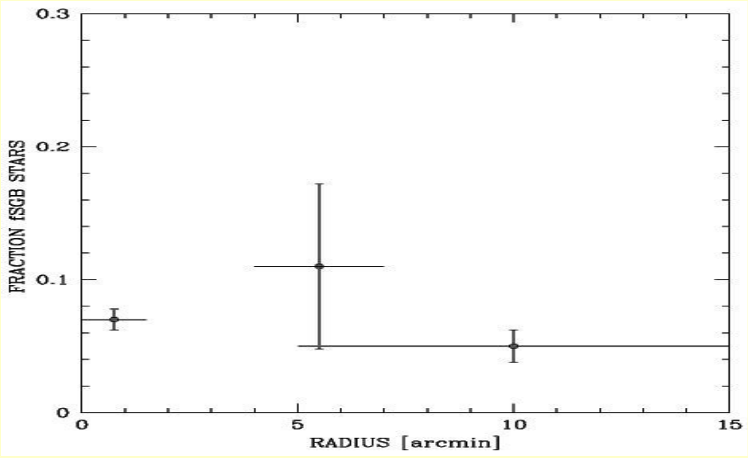

**Anderson et al. (2009, ApJ, 697, L58) found that, in the cluster core the SGB splits into two components:**

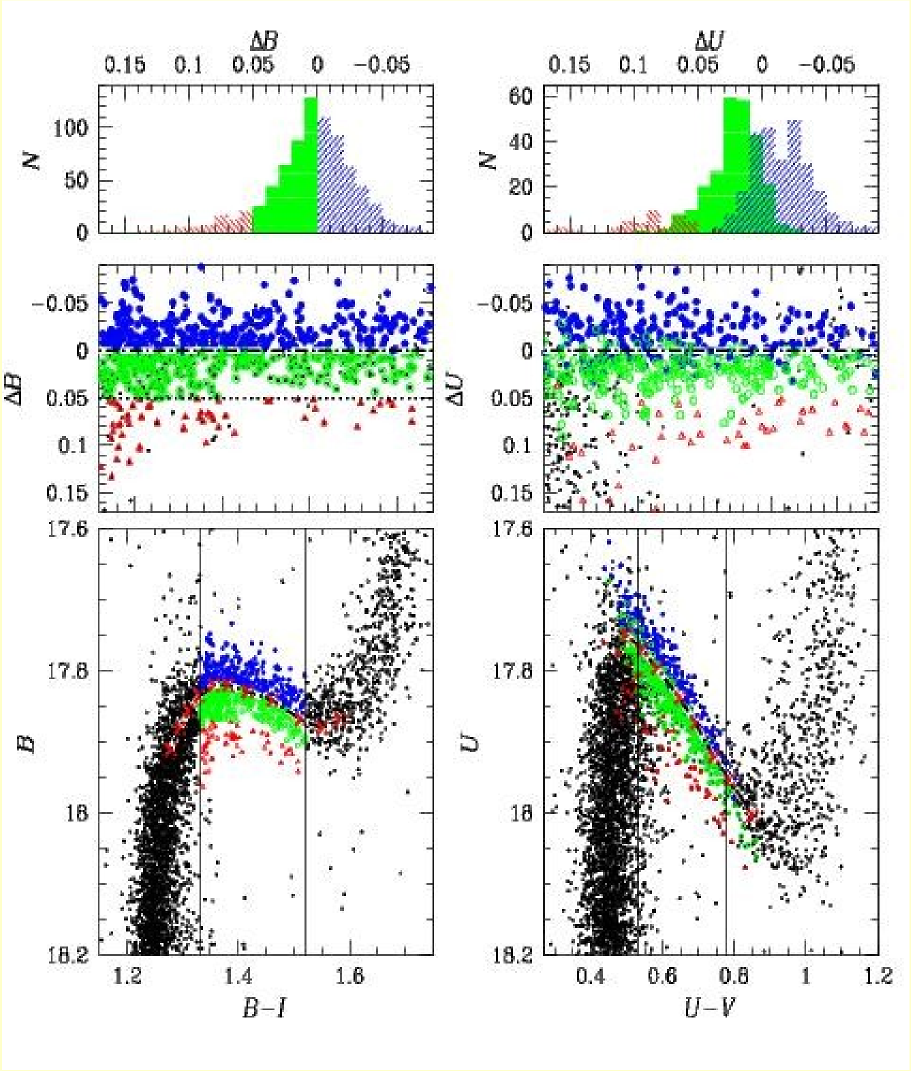
**- a brighter one with a spread that is real but not bimodal**

**-a second one about 0.05 mag fainter, containing a small fraction of stars**



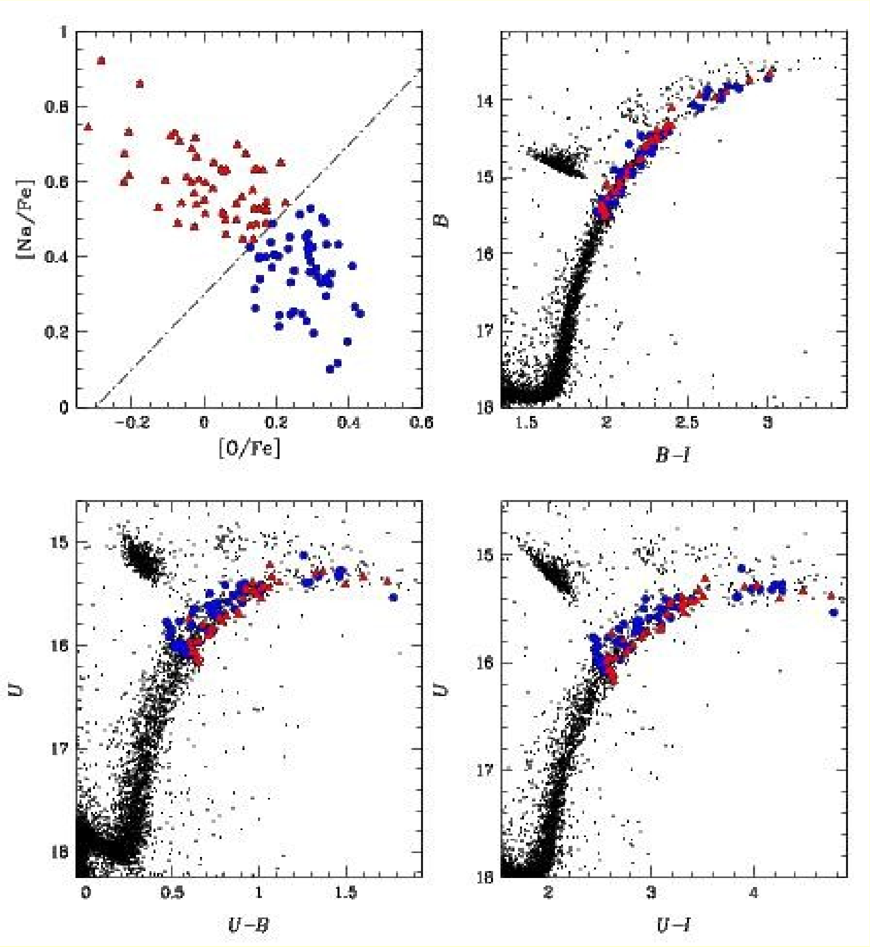

We confirm the findings by Anderson et al. (2009) and detected a similar multimodal SGB at larger radial distances



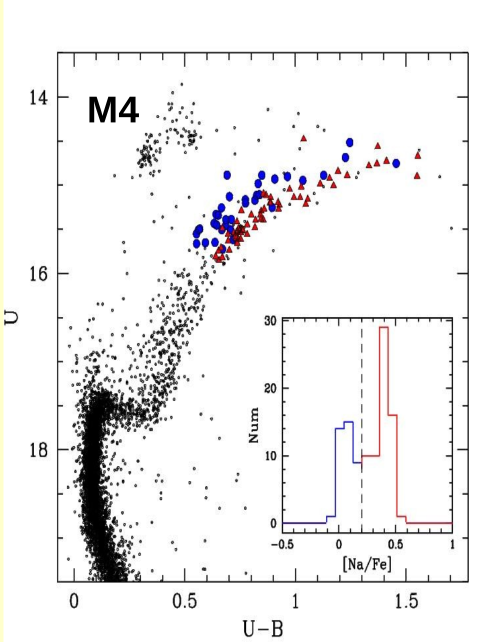



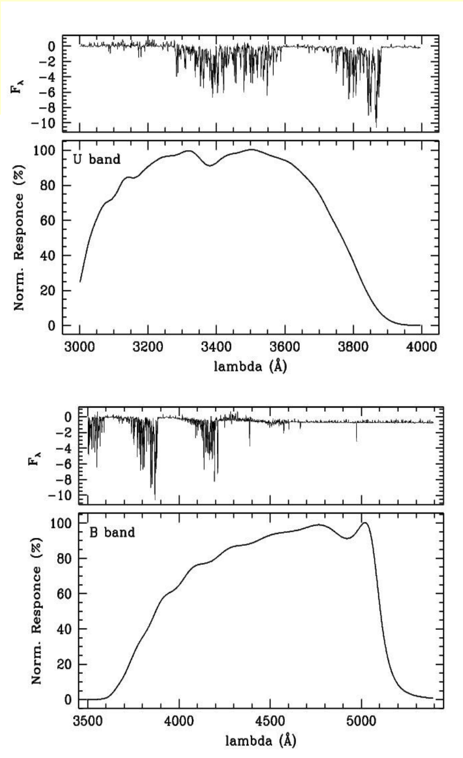

No evidence for significant variations in the fraction of fSGB stars

**A bimodal RGB is distinguishable also in the U vs. U-B and U vs. U-I color-magnitude diagrams. But it is difficult to separate sub-populations from photometry alone**




Na, O from Carretta et al., 2009

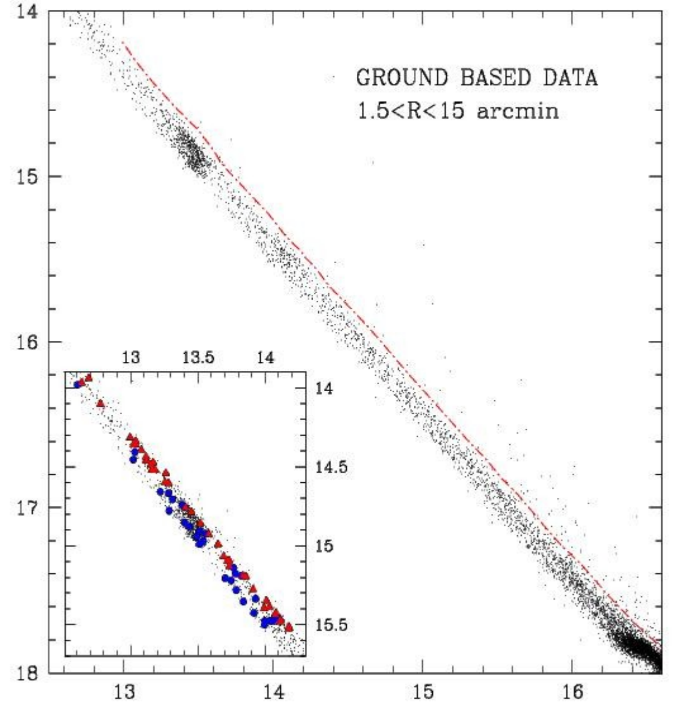


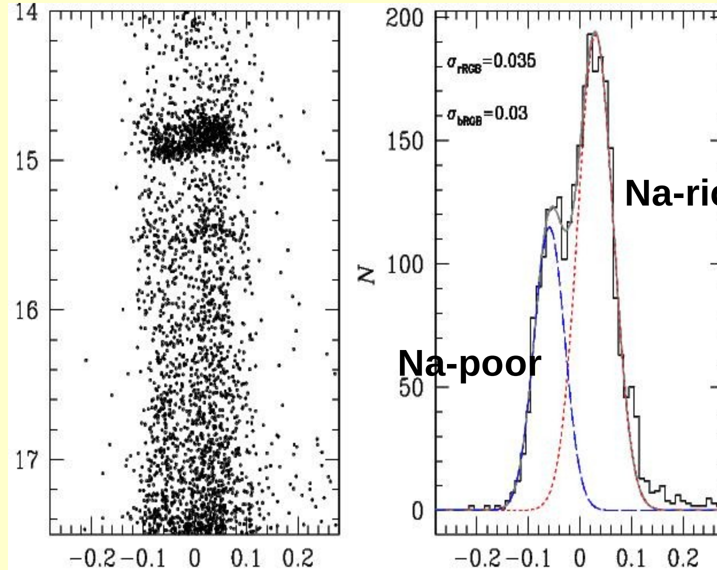

Marino et al., 2008 A&A 490, 625

**Similar RGB splits have been detected also in M4 and other GCs and are likely due to a C, N, O effect on the atmosphere (Marino et al. 2008).**

c2

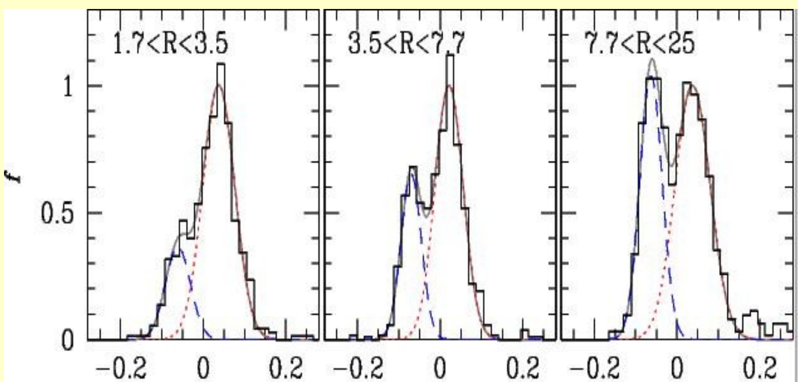



c1




Dc1

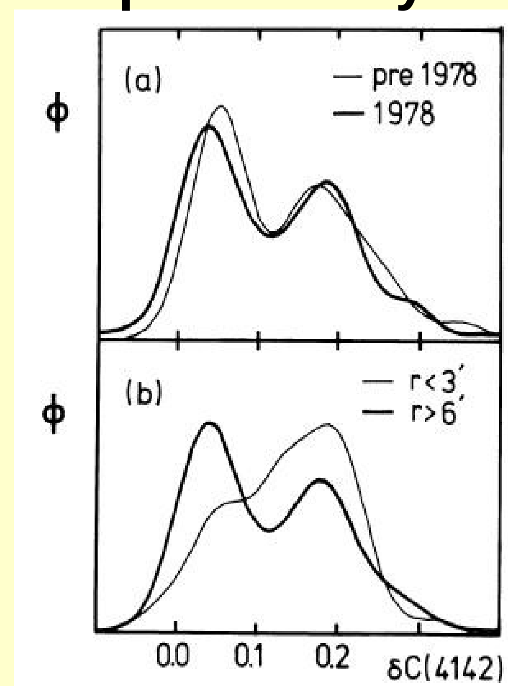
We used linear combinations of magnitudes to better isolate RGB components from photometry




Dc1

Na-rich/O-poor RGB (second generation) is significantly more centrally concentrated.

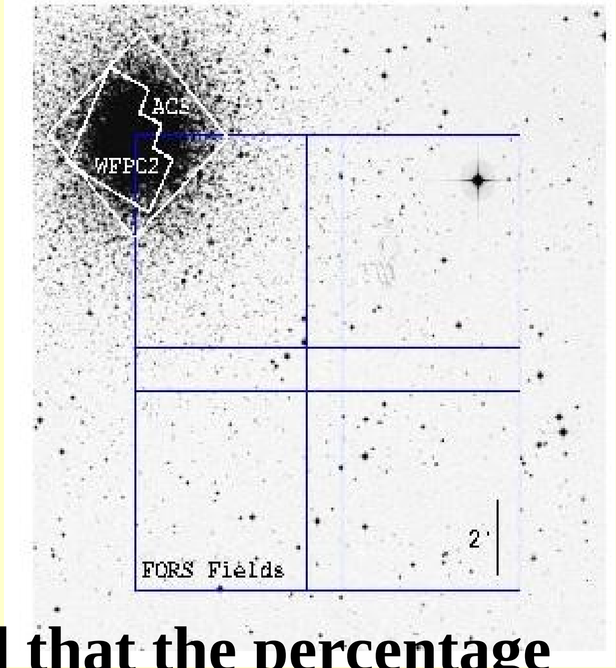
(In agreement with Norris & Freeman 1978)

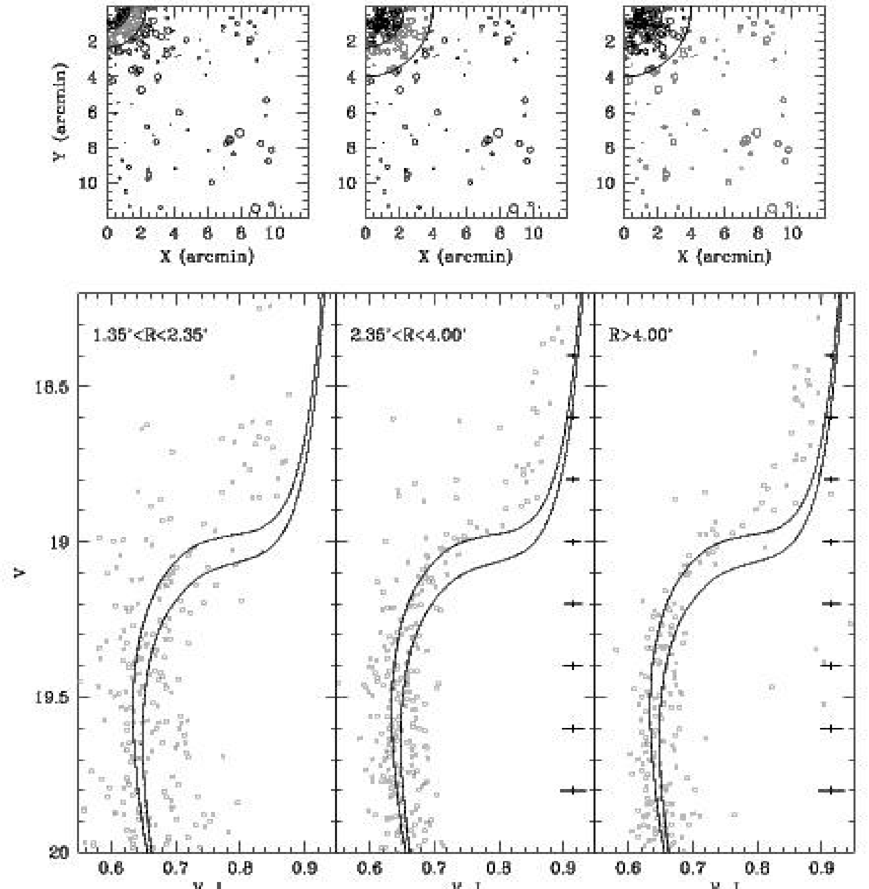



Norris & Freeman (1978)

# RADIAL DISTRIBUTION OF MULTIPLE POPULATIOND IN NGC1851:

**Zoccali et al. (2009) estimated the radial extent of the double SGB from 1.4 to 13 arcmin**



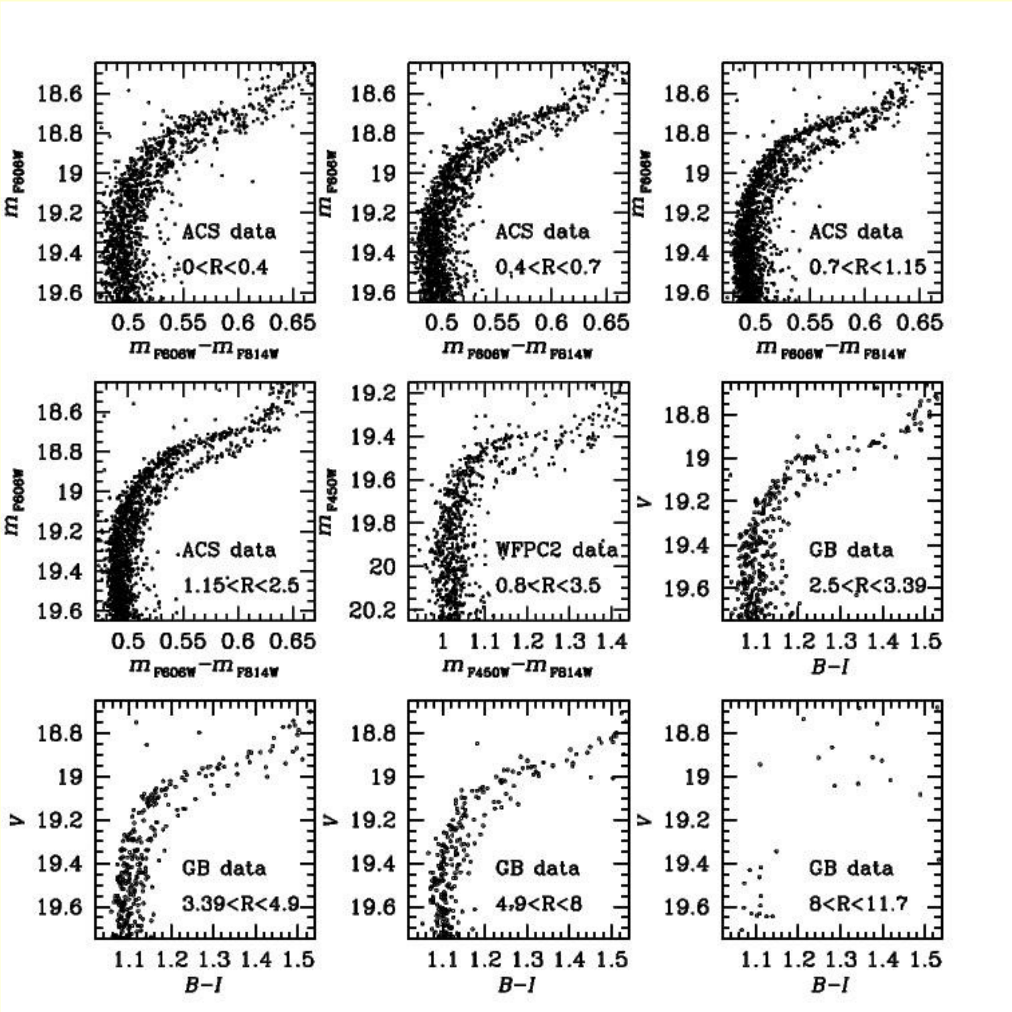




**They find that the percentage of fSGB stars is 45% in the core and drops sharply at ~2.5 arcmin :**

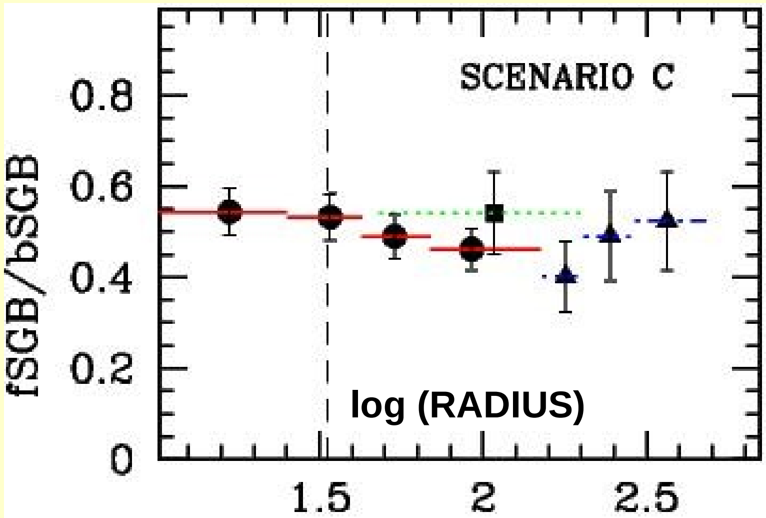
**According to these authors fSGB is more centrally concentrate.**

**BUT...**

# Milone et al. (2009) found that the SGB split can be followed all the way from the center to at least 8 arcmin

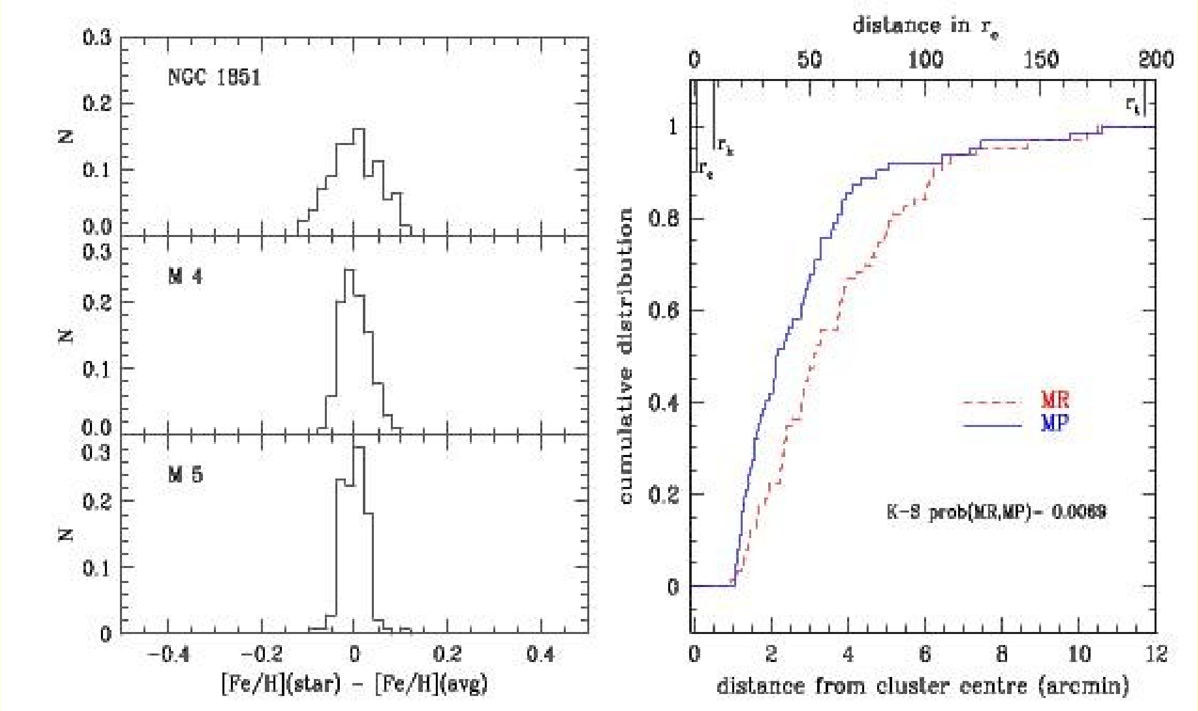



According to this work
the number ratio of the bright SGB to the faint SGB stars shows no significant radial trend.
BUT...



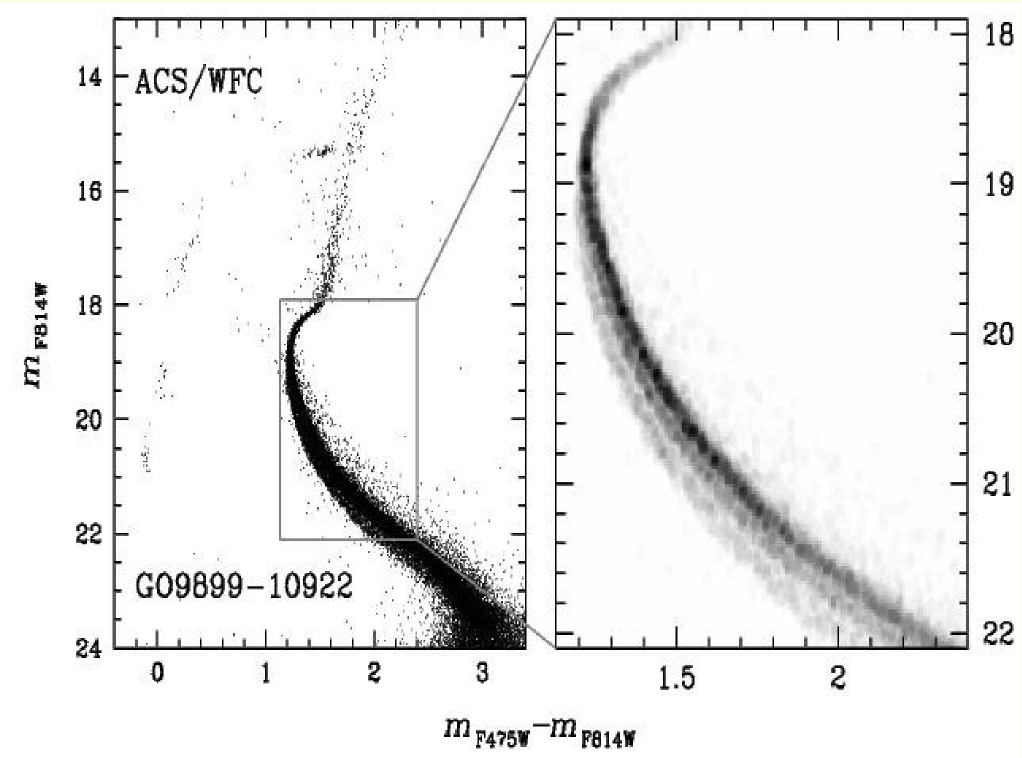

Milone et al., 2009 A&A, 503, 755

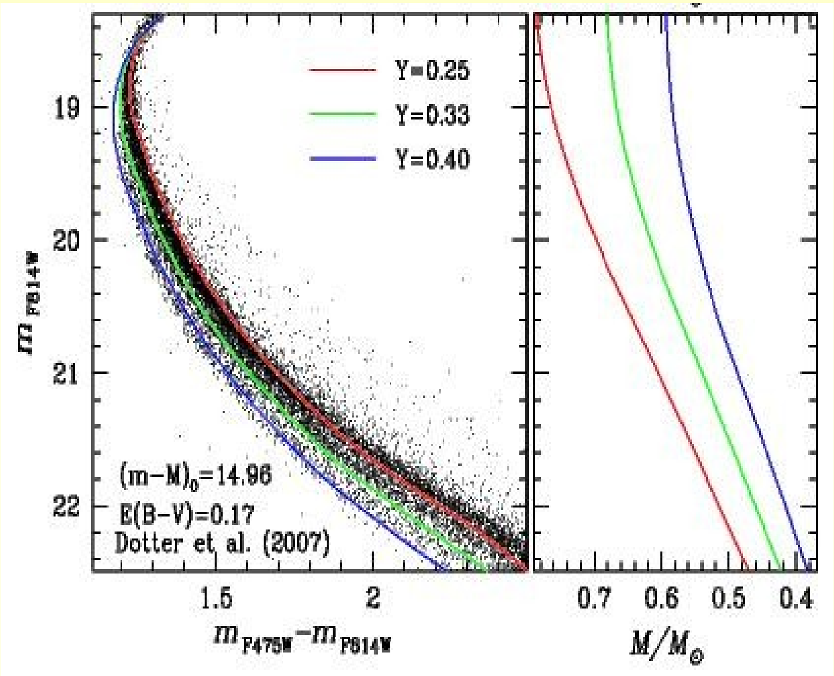
# Carretta et al. (2010) compared the cumulative radial distribution of Fe-rich and Fe-poor in NGC1851




**A K-S test returns a negligible probability that the two come from the same distribution**

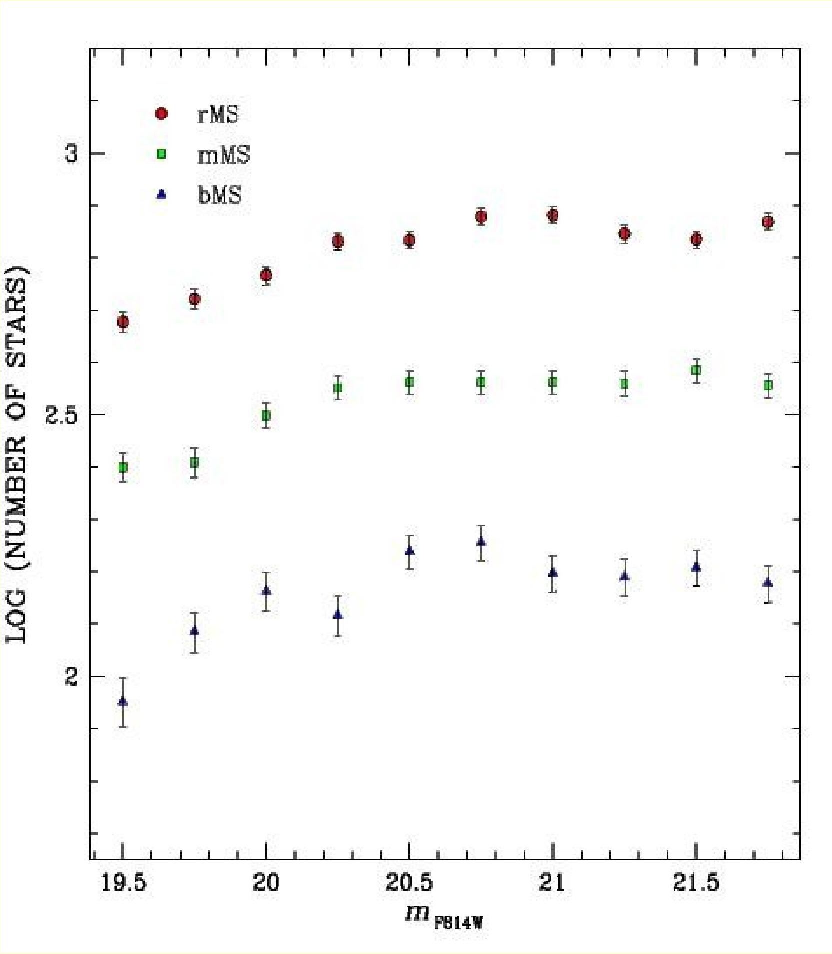
# 2) The luminosity and mass functions of the three Main Sequences of NGC 2808

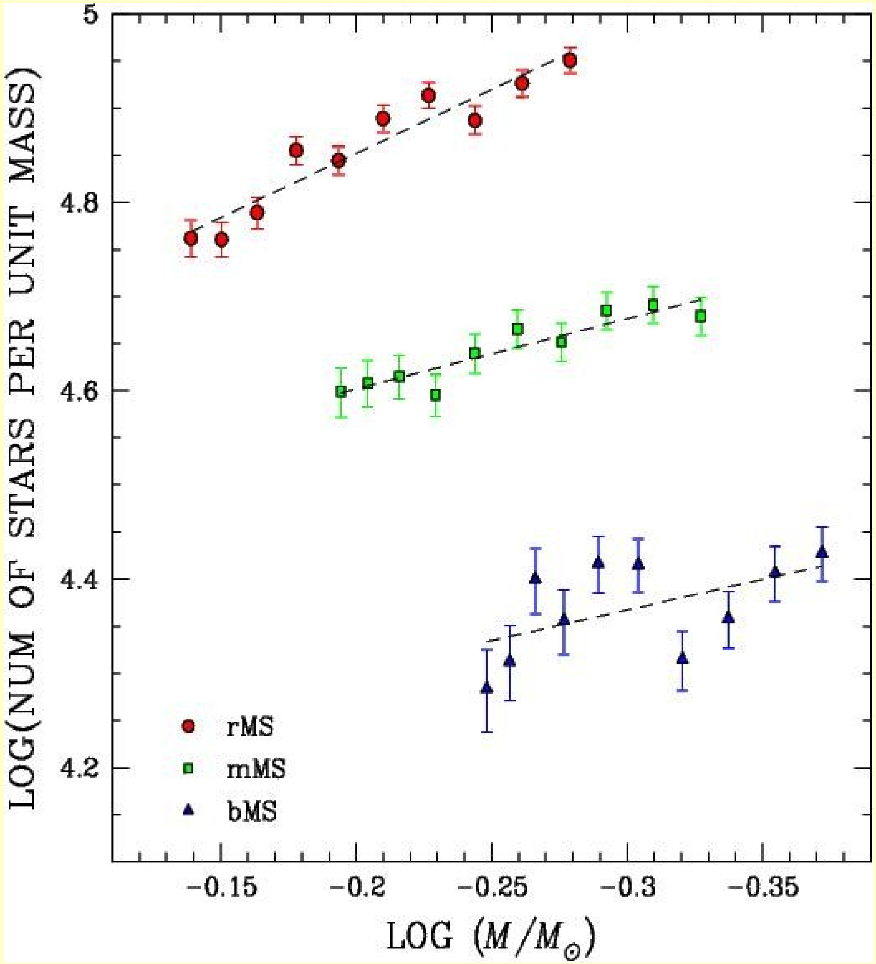



- **NGC 2808 hosts three distinct MSs that are attributed to successive round of star formation with helium content (Piotto et al. 2007, D'Antona et al. 2005).**
- **Overabundances of helium (Y~0.30, Y~0.40) can reproduce the two bluest main sequences.**
- **The TO-SGB regions are so narrow that any difference in age between the three groups must be significantly smaller than 1 Gyr**

**We determined the LFs of the three main sequences and used the mass-luminosity relations from from Pietrinferni et al (2004) to transform the LF into MF.**




**The present-day MFs of the blue and the middle MS have very similar slope s~-0.8 while the red MS is significantly steeper with s~-1.35**

# Multipopulation zoo

- Multipopulations may be ubiquitous: NaO anticorrelation found in all clusters searched so far.
- Clusters with discrete multiple main sequences, apparently implying extreme He enrichment, up to Y=0.40 (e.g., Omega Centauri, NGC2808)
- Clusters with broadened or splitted MS (as NGC6752 and 47Tuc)
- Complex objects like M54 (= Omega Cen?)
- Intermediate objects like M22 (=M54, Omega Cen?)
- Clusters with double SGB or RGB (e.g., NGC 1851, NGC6388, NGC 5286, M4, and many others)
- The LMC/SMC intermediate age clusters with double TO/SGB.

Are all of them part of the same story?

# 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:

- Many serious problems remain unsolved, and we still have a rather incoherent picture. The new HST cameras will play a major role in composing the puzzle.
- 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 as a nightmare for decades), as well as the newly discovered multiple sequences in the CMD.
- 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.