Multiple stellar populations in star clusters: an observational (incomplete) overview

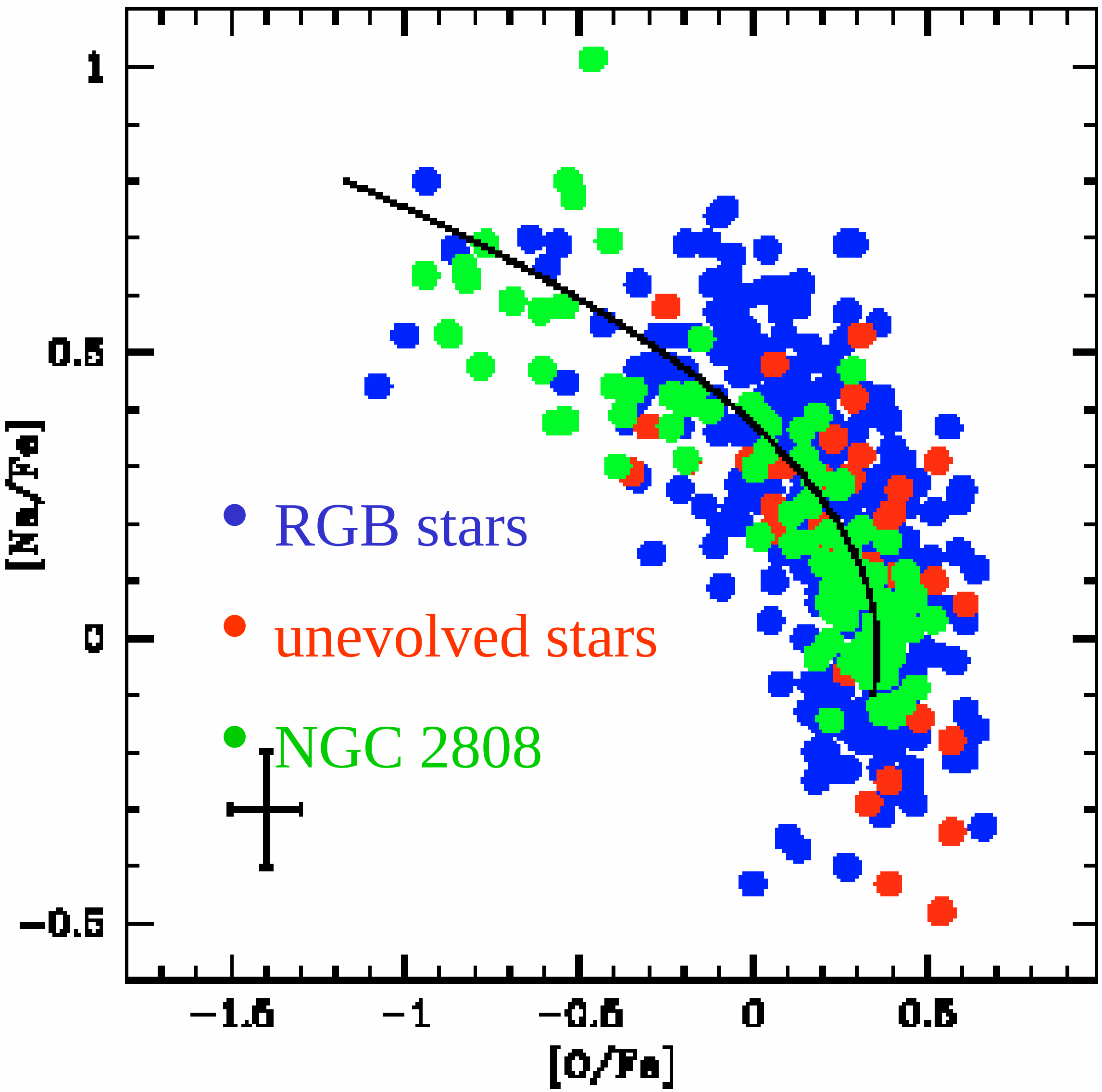
Giampaolo Piotto
Dipartimento di Astronomia
Universita' di Padova

Collaborators: J. Anderson, L.R. Bedin, I.R. King, **A. Milone, S. Cassisi, S. Villanova, A. Bellini, A. Marino, A. Moretti, Y. Momany, A. Renzini, and A. Sarajedini**
+ the HST GC Treasury Project team

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



(from Carretta et al. 2006)

See next talk by Raffaele Gratton

We do have a long standing problem, i.e. the **large spread in abundances for some light elements, like C,N,O, Na, Mg, Al, s-process elements** inside the same cluster.

Some of these spreads indeed result in well defined patterns like the **NaO anticorrelation**, or the **MgAl anticorrelation.**

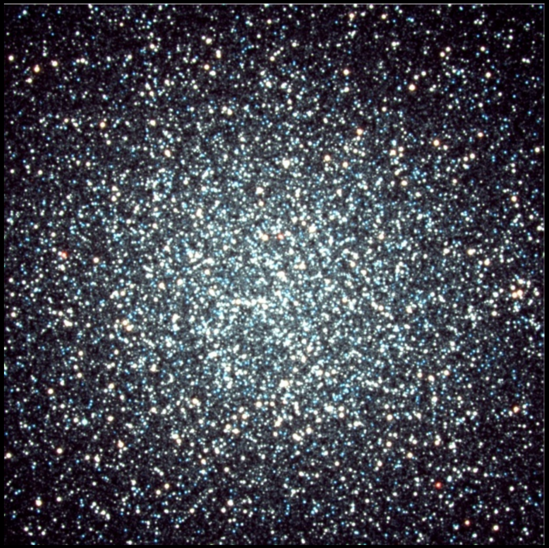
Both anticorrelations indicate the presence of proton capture processes, which transform Ne into Na, and Mg into Al.

These processes are possible only at **temperatures** of a few 10 million degrees, in the complete CNO cycle **not reached in present day GC MS and and RGB stars.**

Some abundace spread must be primordial.

Multipopulations in globular clusters: The smoking guns

The "bad guy": NGC 6388

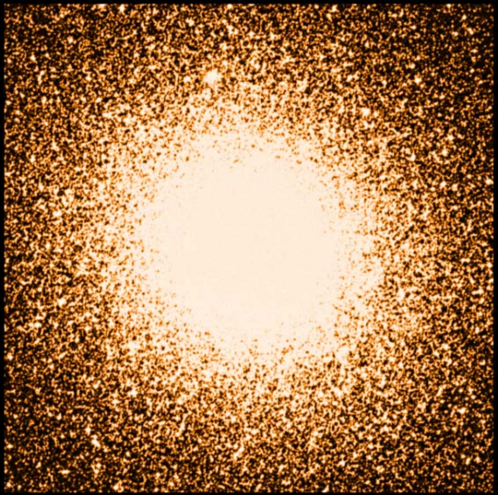


The "puzzling" ω Cen

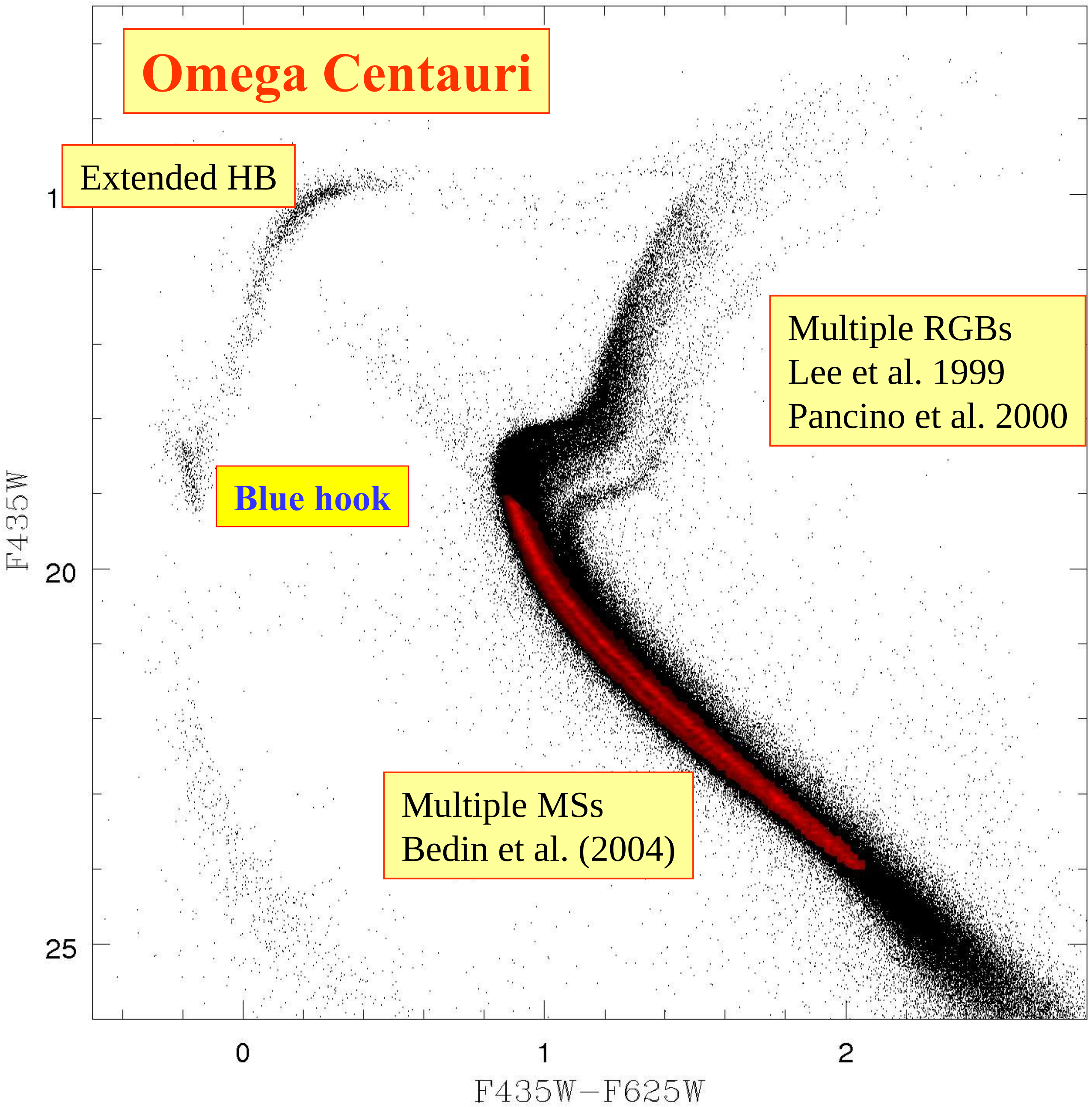
The" complex" M54

The "debated" M22

The "incredible" NGC 2808



And what about 47Tuc….?

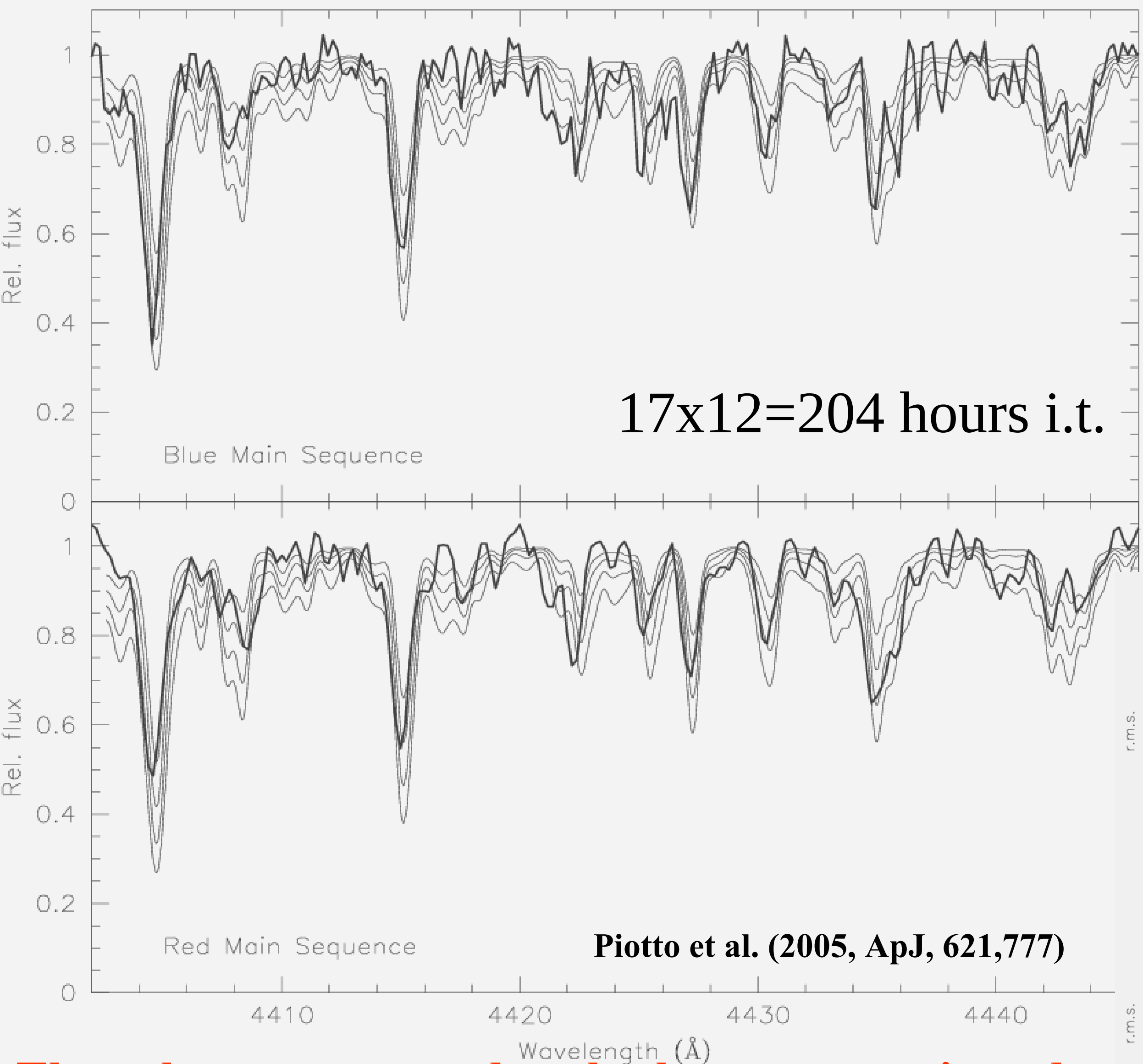


The beginning:
Omega Centauri

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

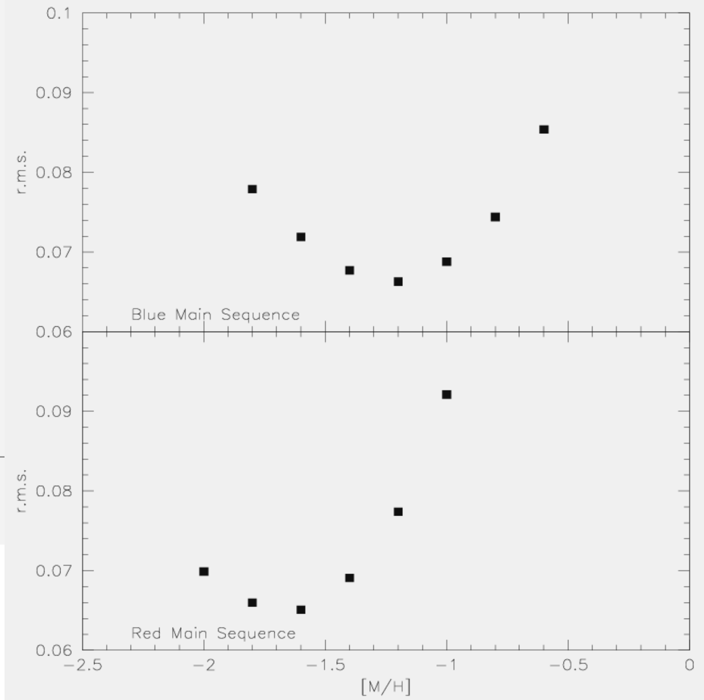
Well known (since the ’70s) spread in metallicity among RGB stars.

The double main sequence in Omega Centauri



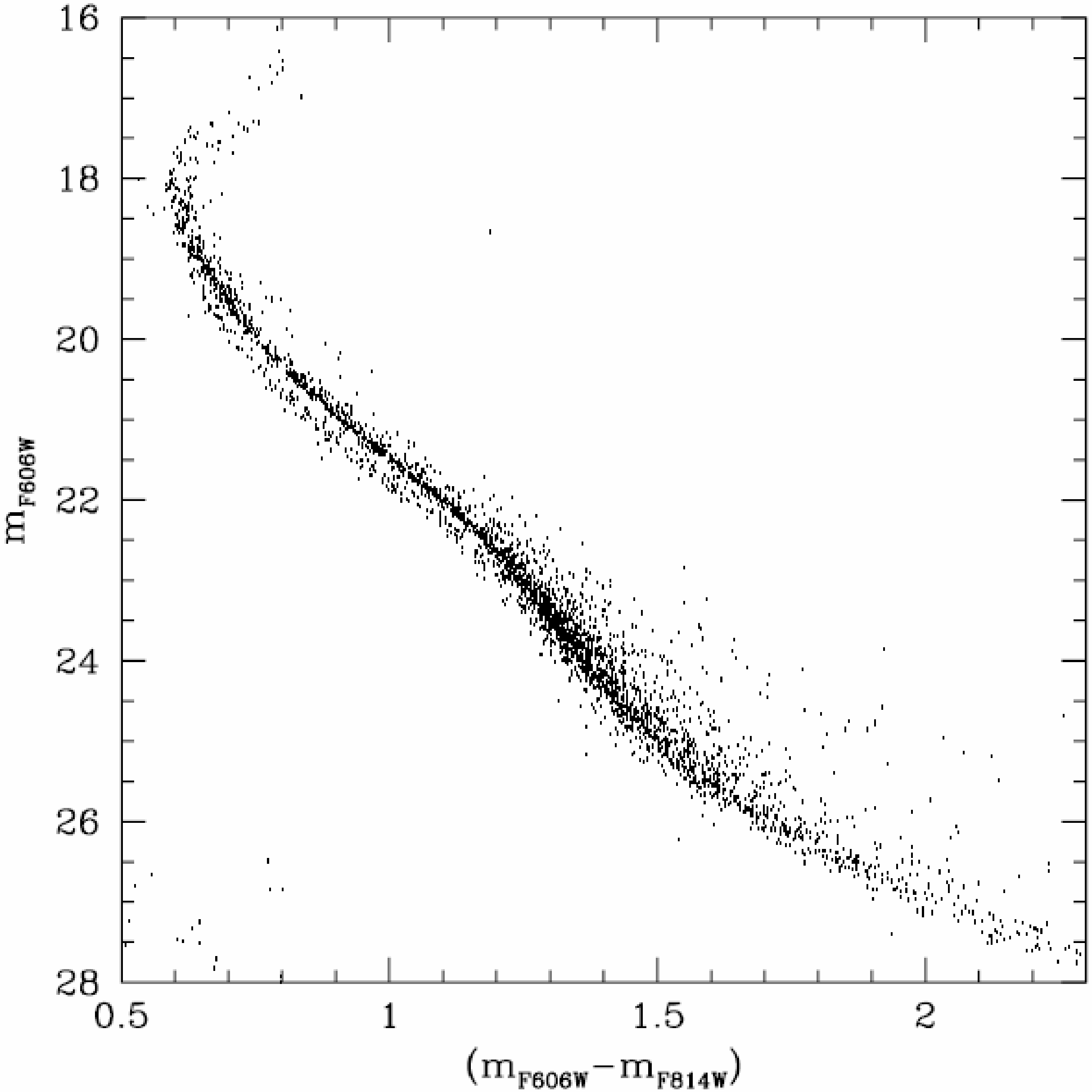
RedMS:
Rad. Vel.: 235+-11km/s
[Fe/H]=-1.56

BlueMS:
Rad. Vel.: 232+-6km/s
[Fe/H]=-1.27
It is more metal rich!



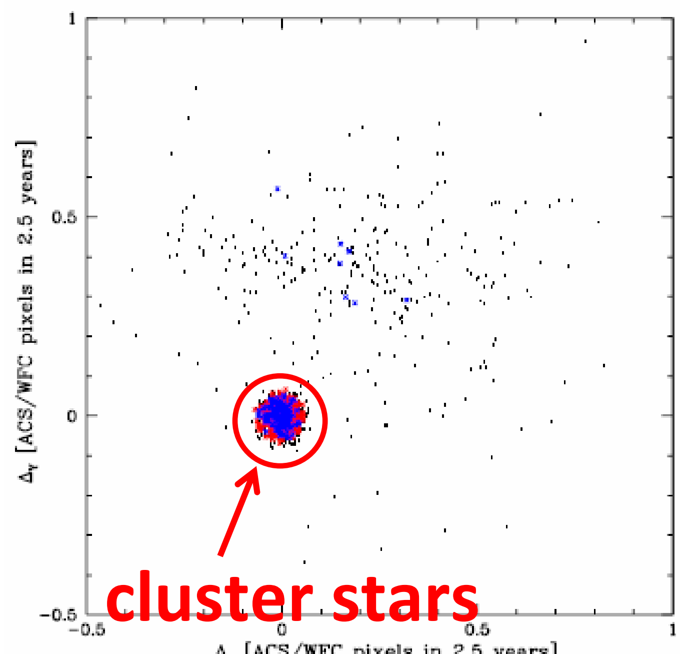
The only way to reproduce both spectroscopic and photometric properties of the MS, is to assume that the blue MS is strongly He enhanced, up to Y~0.40.

Omega Centauri

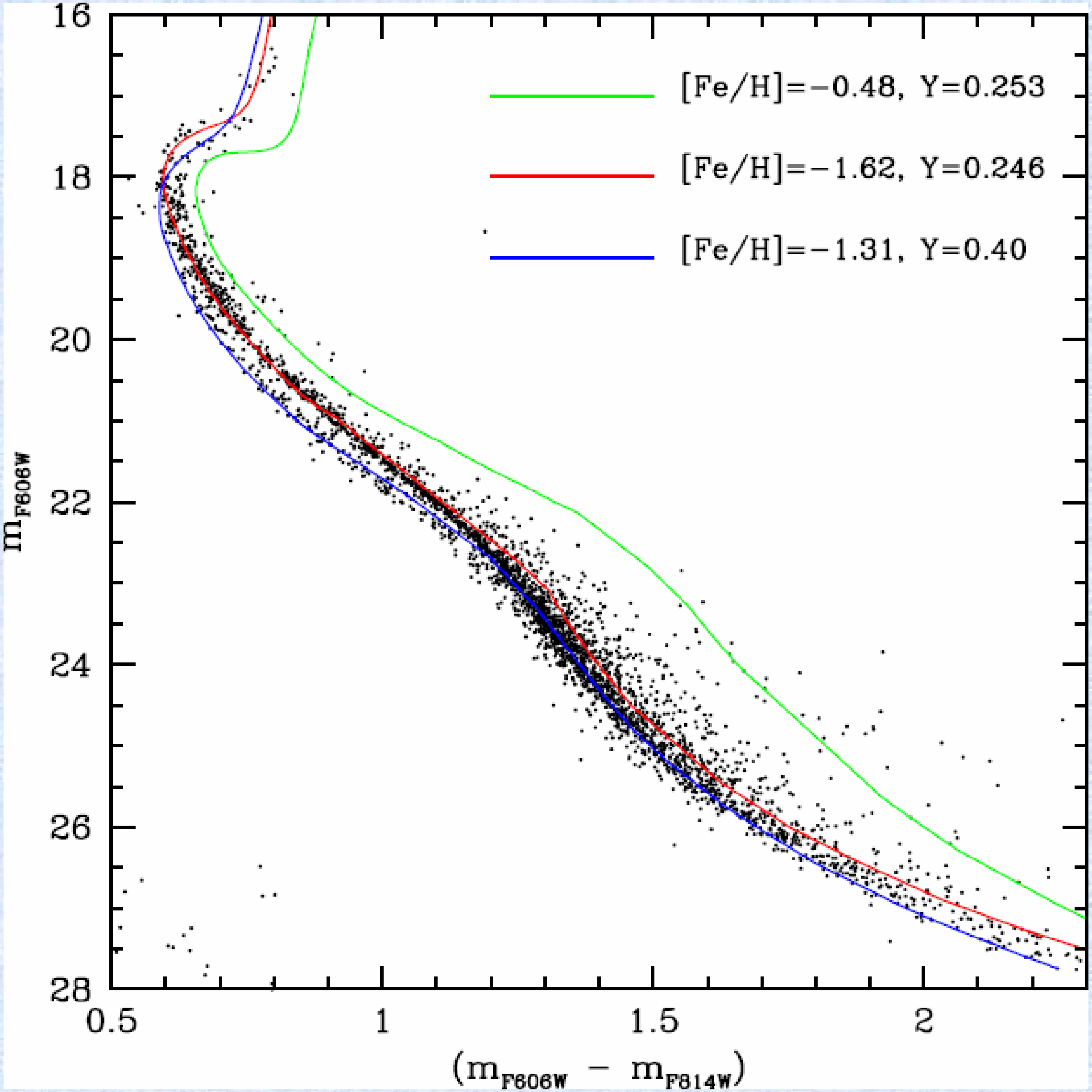


Bedin et al. in preparation

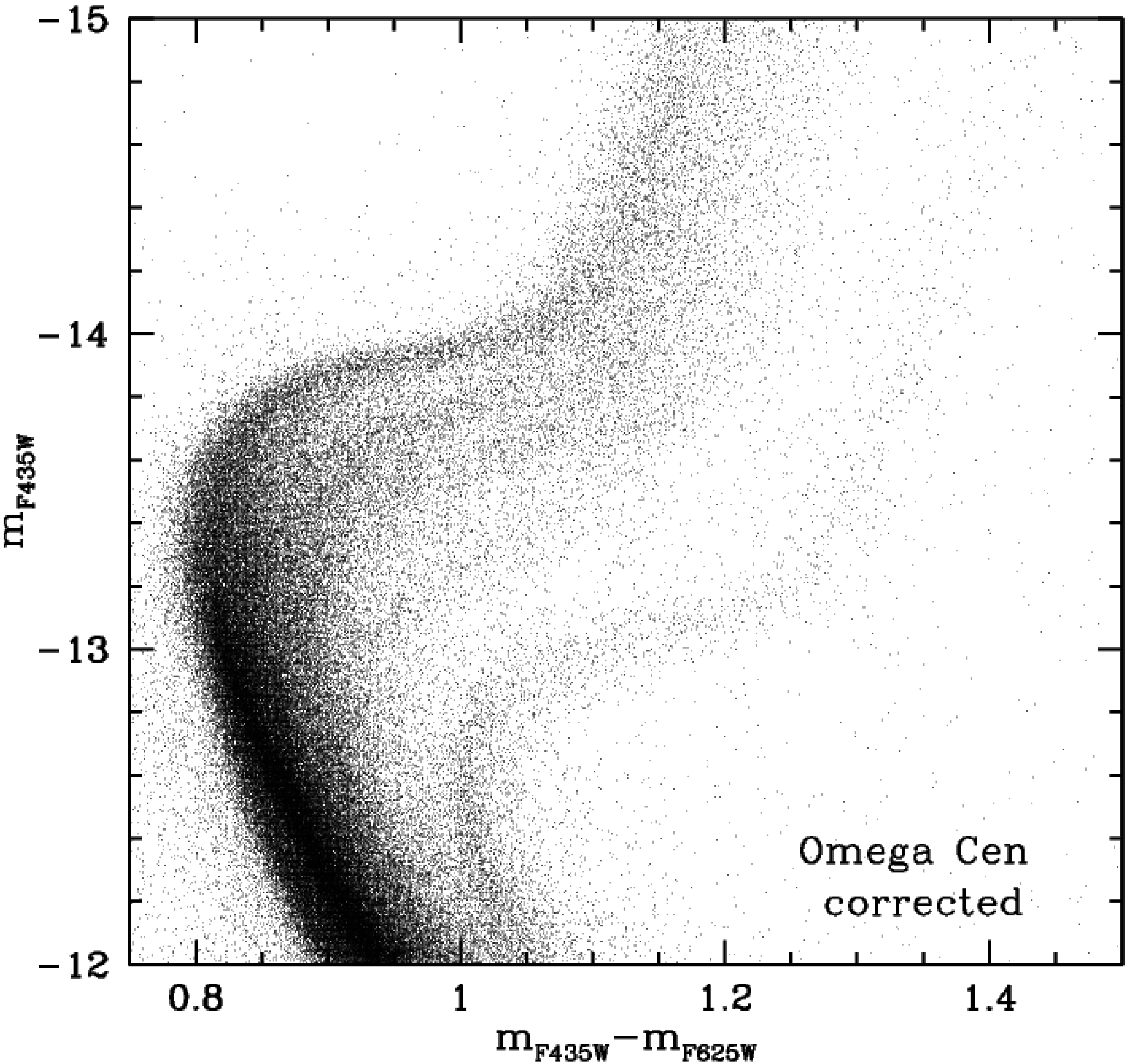
Triple MS from ACS multi-epoch data. Cluster members selected by proper motions.



The fit (by S. Cassisi)

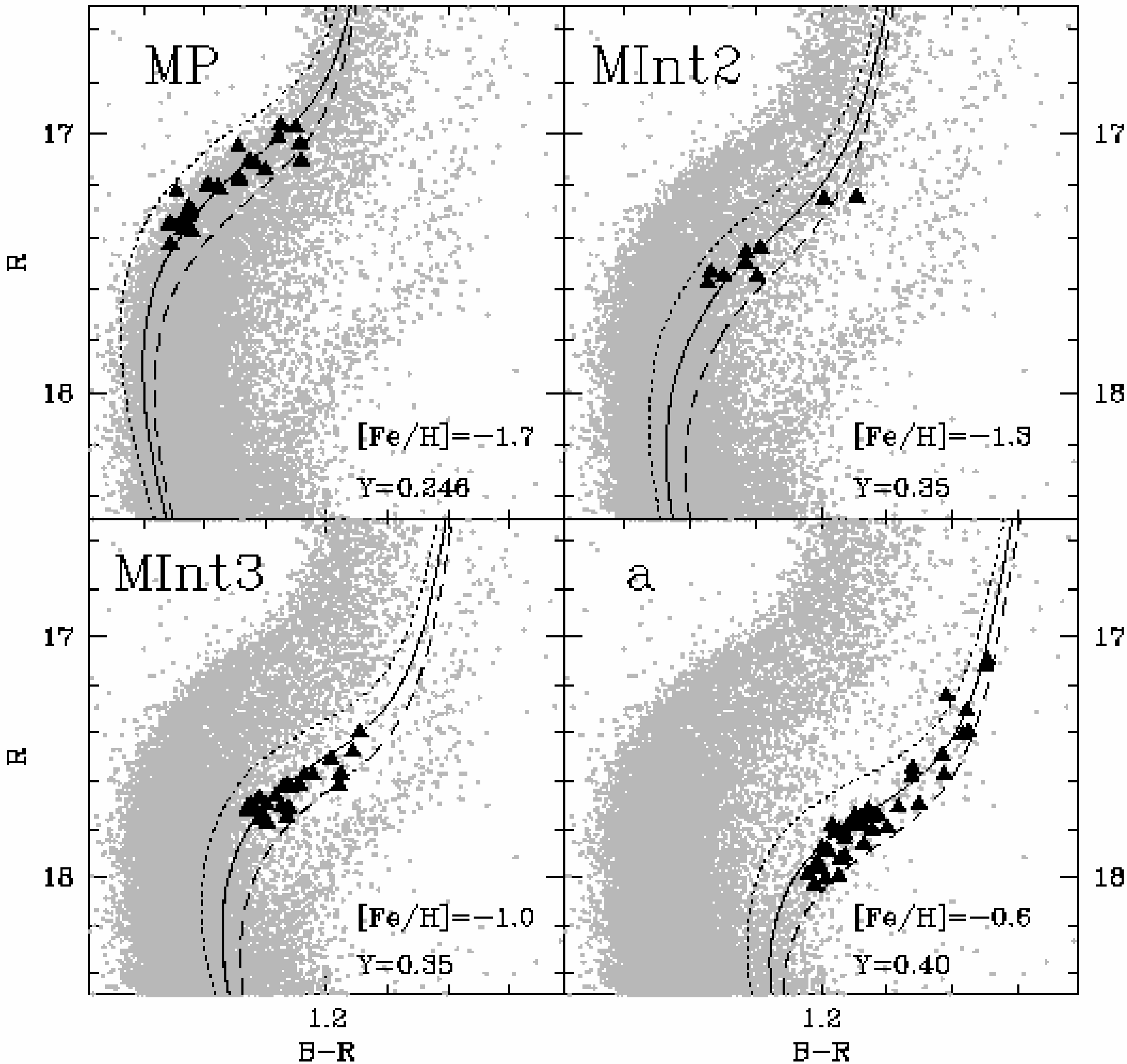


Y~0.40 Confirmed!

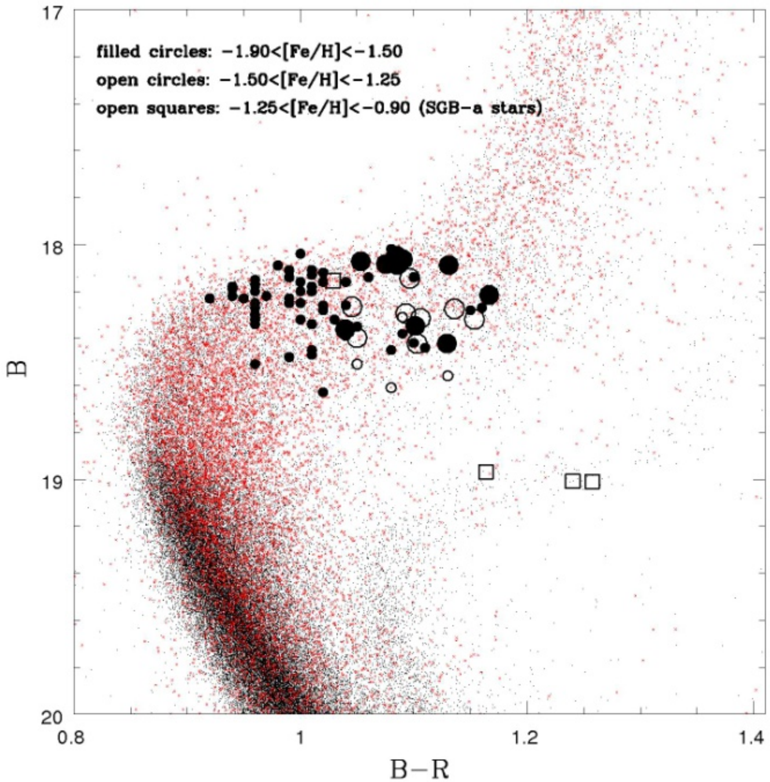


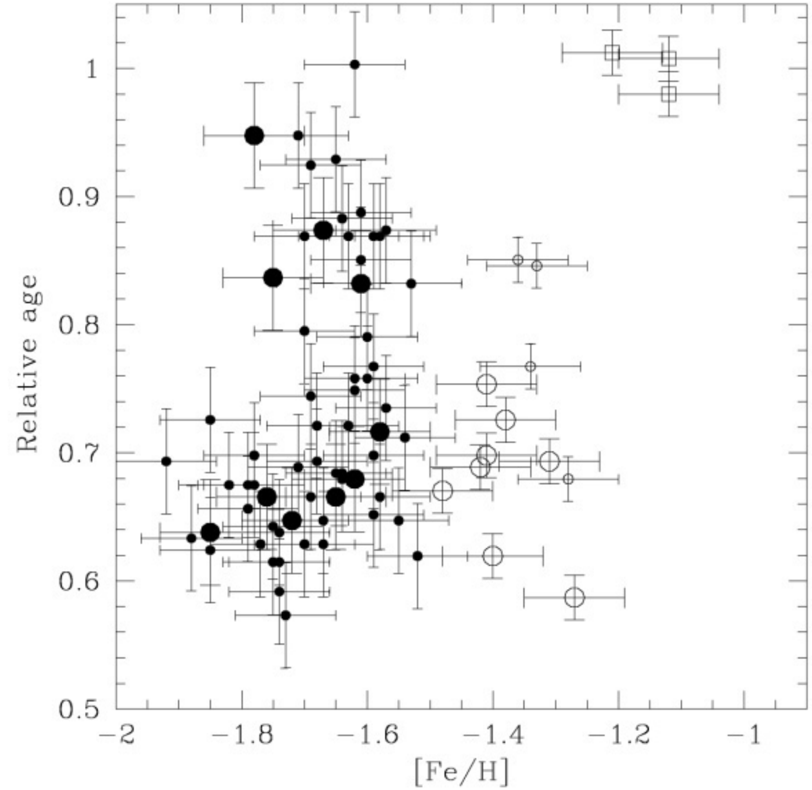
Omega Centauri: the multiple sub-giant branch and the multiple age problem

Villanova et al. (2007)



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





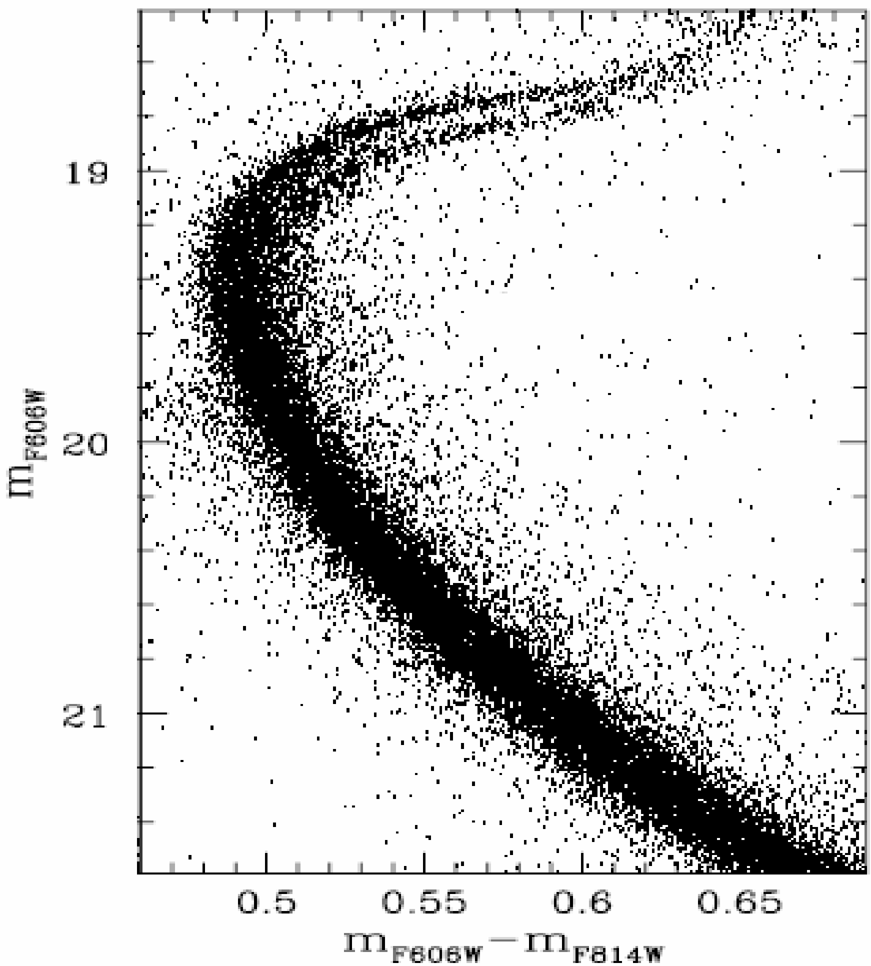
Note how stars with similar metallicity have a large magnitude spread along the SGB.

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 ~4Gyr, with a complex star formation history.

With different assumption on the metal abundances and He, Sollima et al. (2007) concluded that the age dispersion in < 2 Gyr.

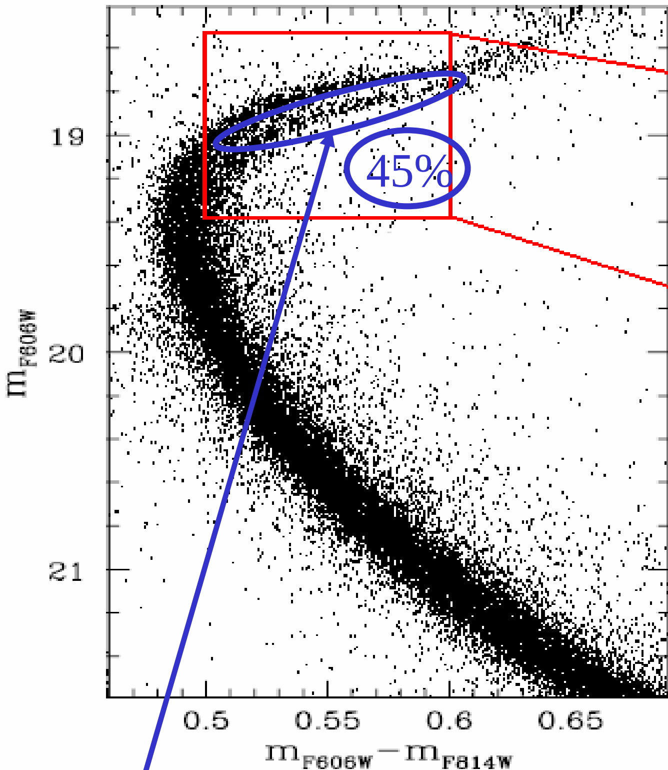
The Double Subgiant Branch of NGC 1851

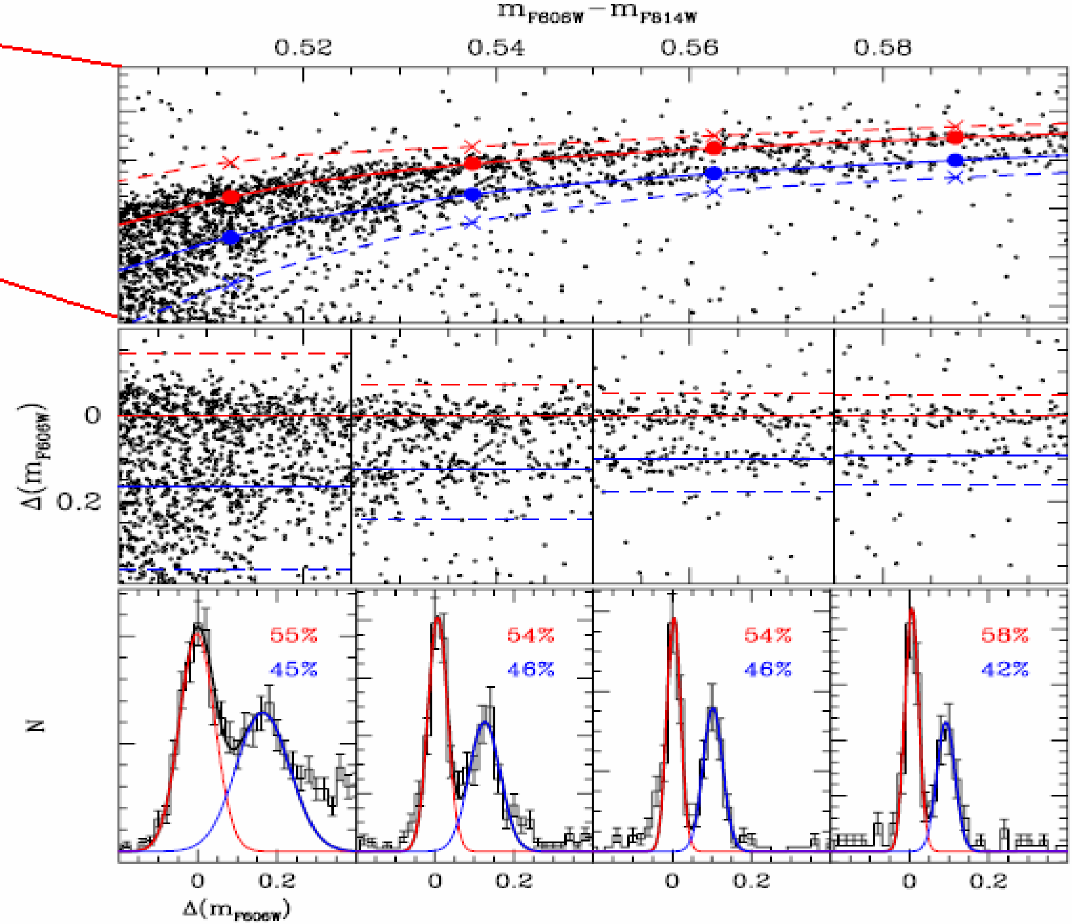
Milone et al. 2008, ApJ, 673, 241

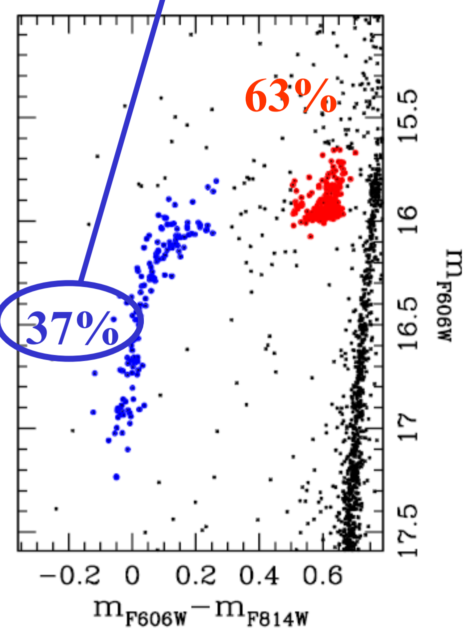


The SGB of NGC 1851 splits into two well defined sequences.

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

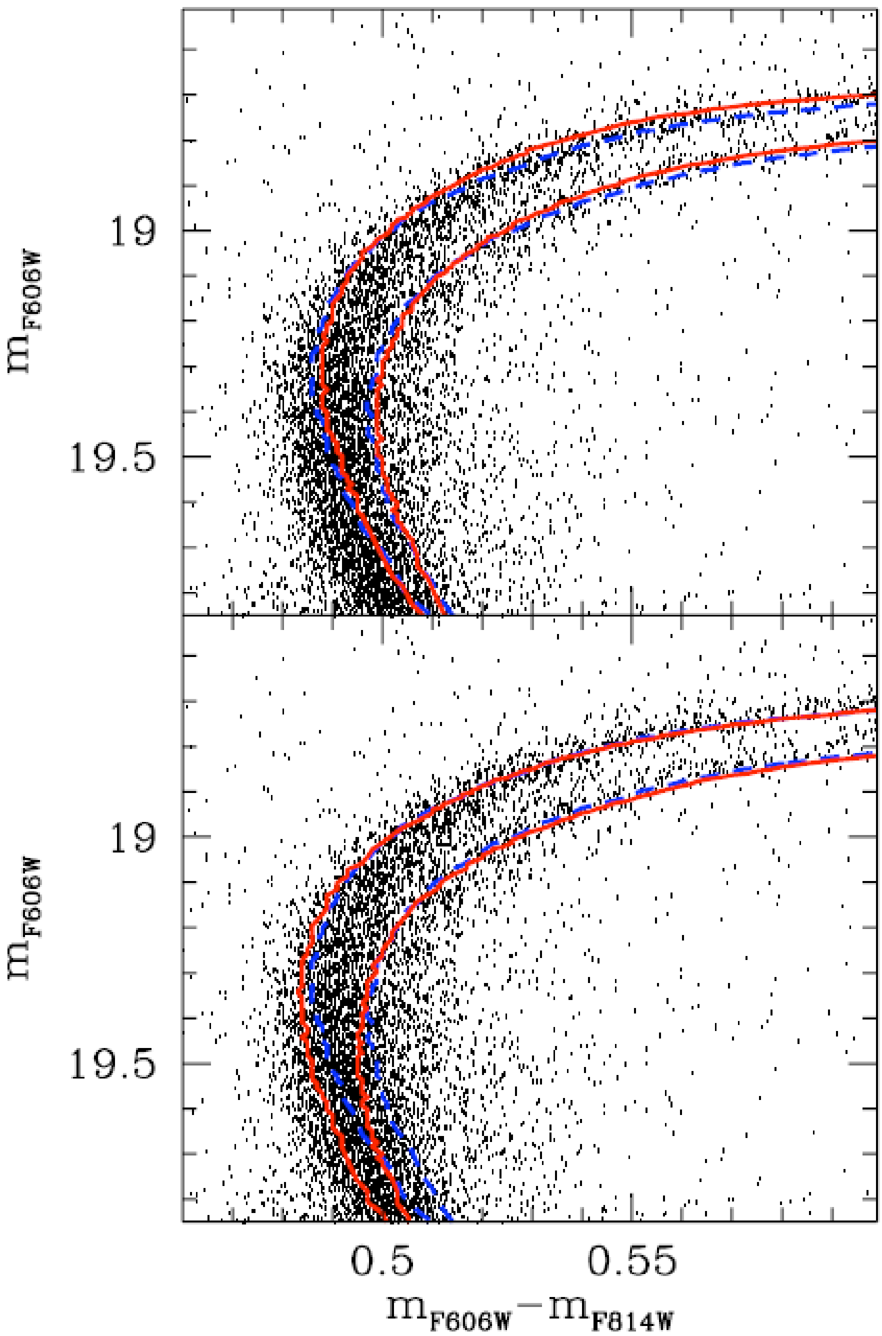






45% of the stars are in the lower SGB; 37% in the blue HB: are the two SGB groups and the two HB branches related with each other?

IMPORTANT OBSERVATIONAL INPUT: from Yong and Grundahl (2008) we know that 40% of the stars are CN-strong and s-process element enhanced. (Already suggested by Hesser et al. 1983)

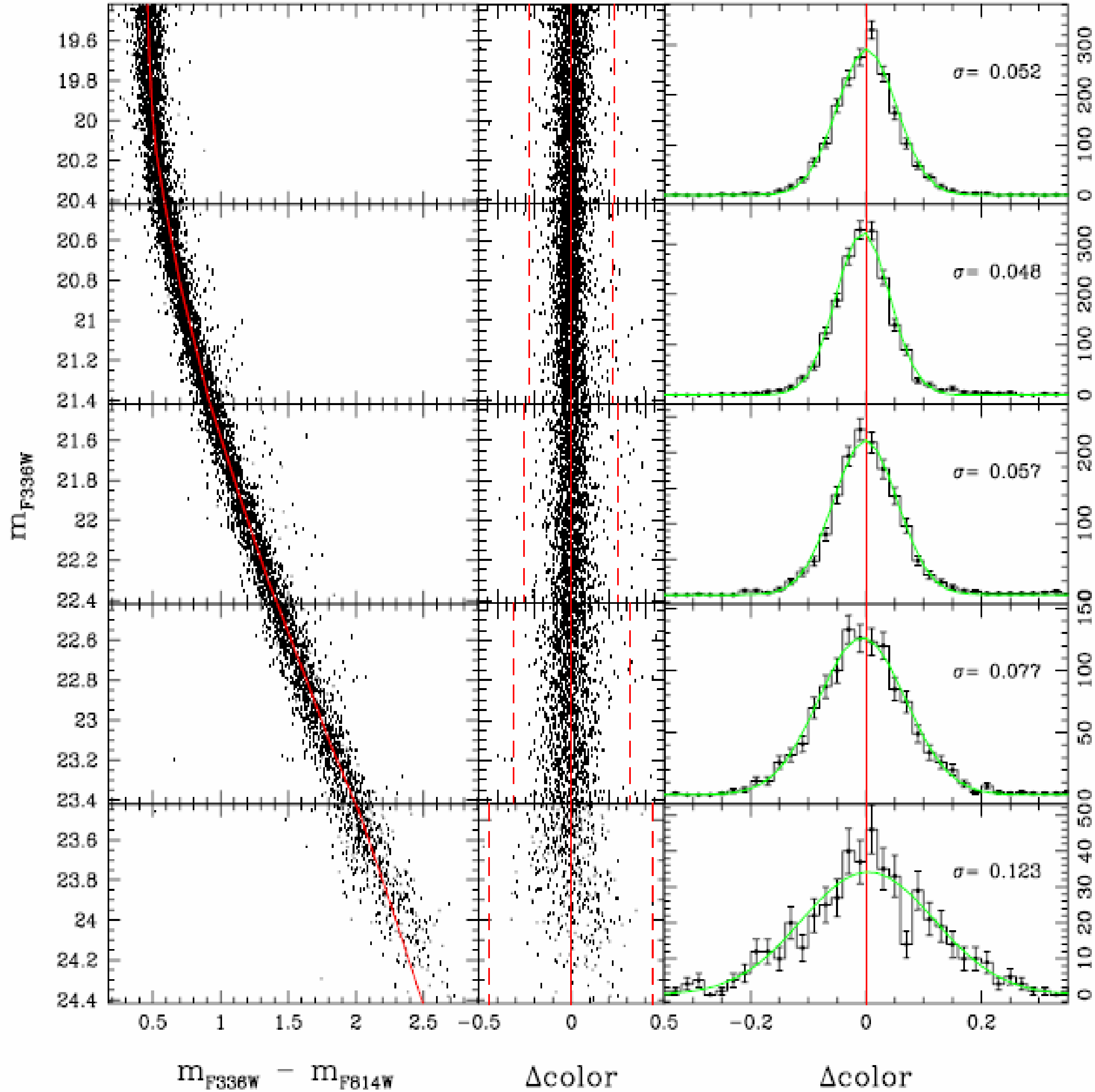


Very recently, Cassisi et al. (2007, ApJ, 672, 115) showed that the two SGBs and the double HB can be reproduced by **assuming that the fainter SGB is populated by a strongly CNNa enhanced population,** which evolve into the blue HB, while the brighter SGB contains normal composition stars.

In such hypothesis, the age difference between the two groups may be very small (10^8 years).

In conclusion, the SGB split may be mainly due to the presence of two groups of stars, with two different metal patterns, small age difference.

We need accurate metallicity for the SGB stars.



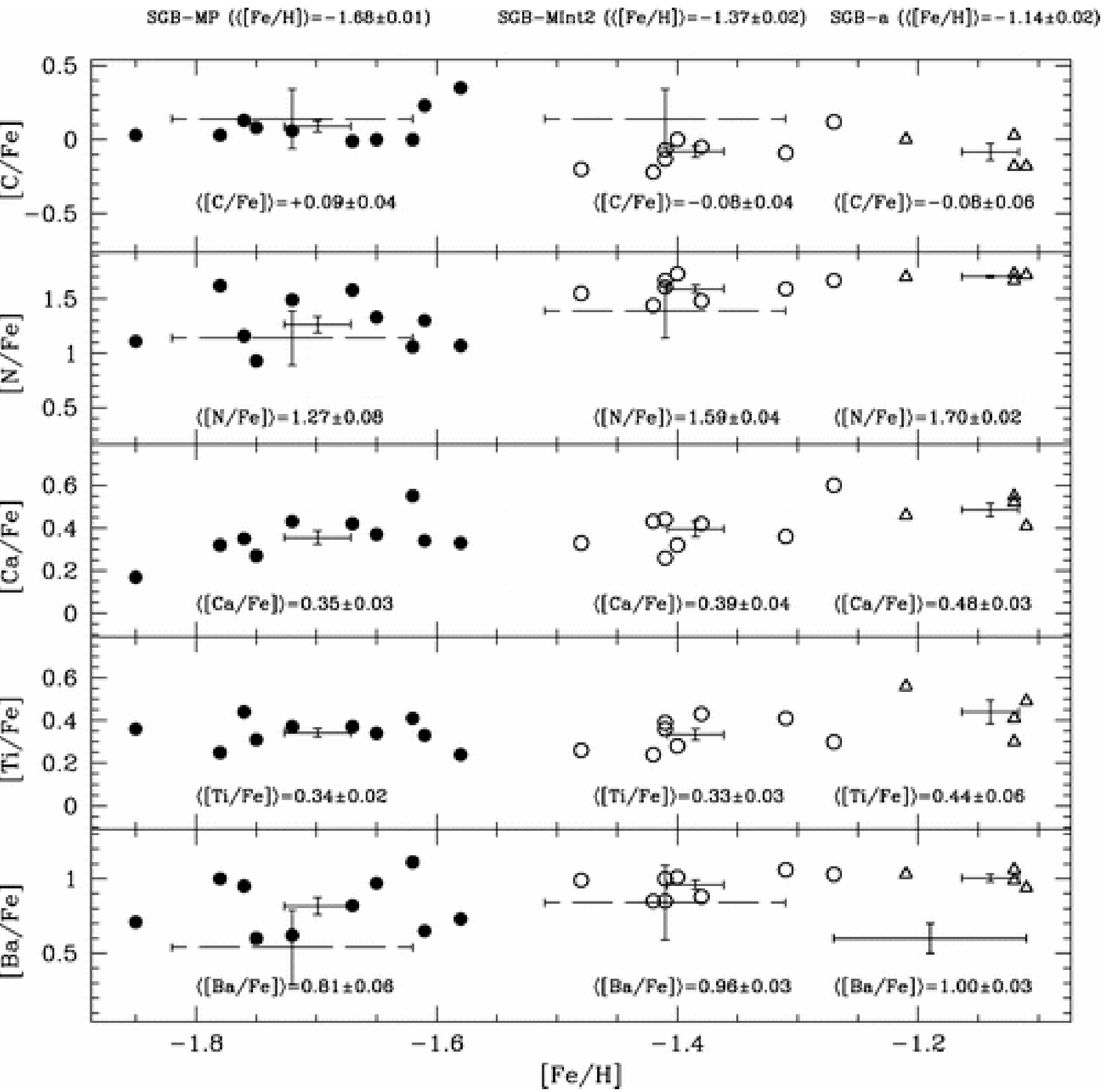
Apparently there is no large He spread among the MS stars.

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)

Sub-giant branch chemistry

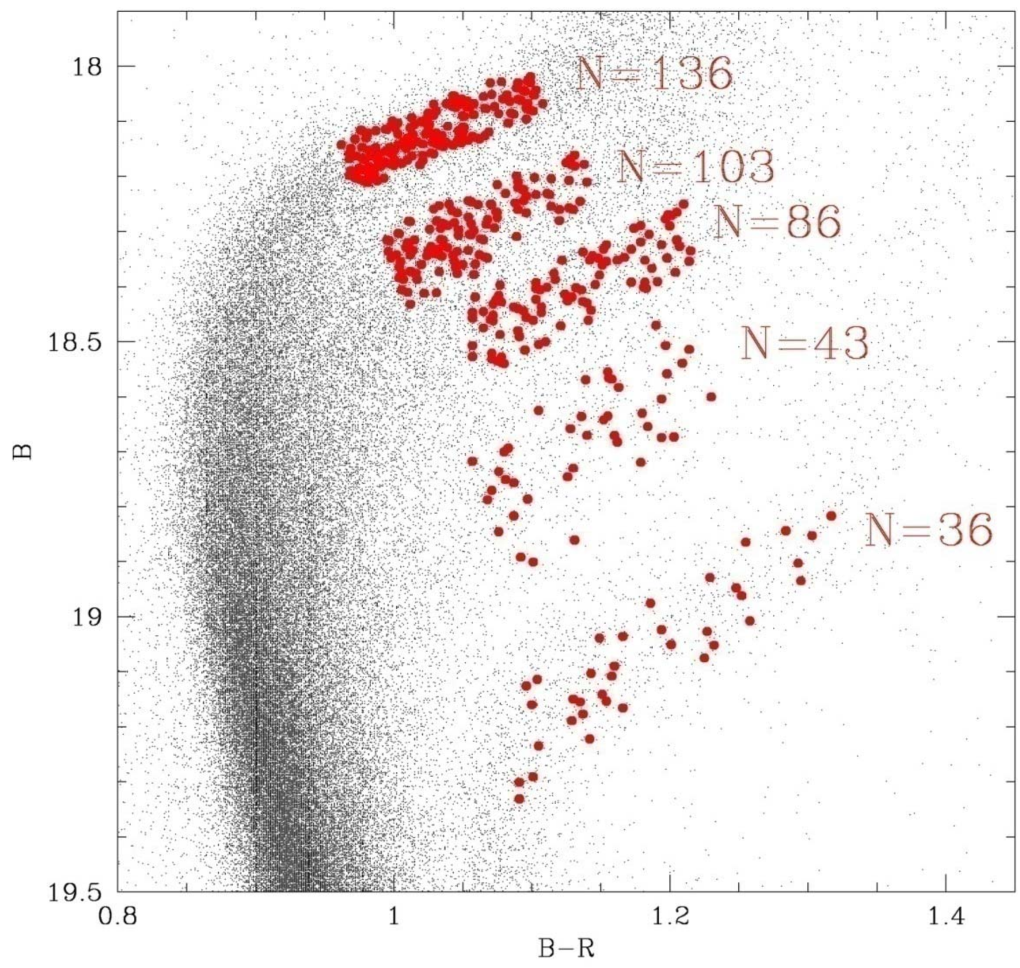


Villanova et al. 2007

- MP stars have a larger (lower) C (N) abundance with respect MInt2 SGB stars;
- There is an hint for an increase of alpha-elements abundance with the metallicity;
- MP stars have a lower Ba abundance.

WARNING: GC age measurement from TO might be a nightmare in the multi-population scenario

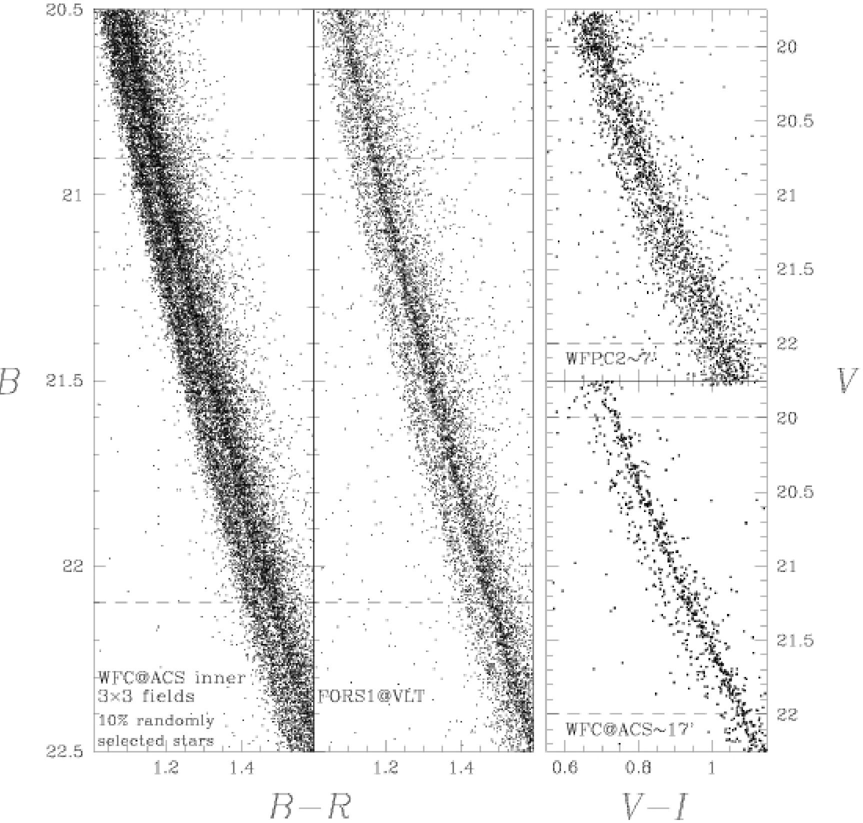
Accurate chemical element abundances are strongly needed to solve the age problem in Omega Centauri and other multipopulation clusters.



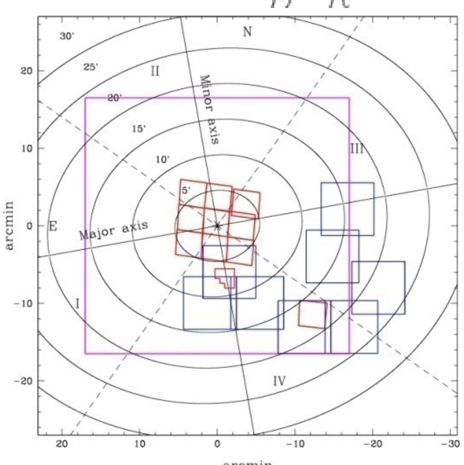
Recently approved FLAMES+GIRAFFE at VLT program for the measurement of the abundances of C, N, O, Na, Mg, Al, Si, Ca, Ti, Fe, Y, Ba for a reliable age estimate (and a better understanding of the chemical evolution of Omega Centauri).

Observations of ~1500 SGB, RGB, and HB stars starting in these days.

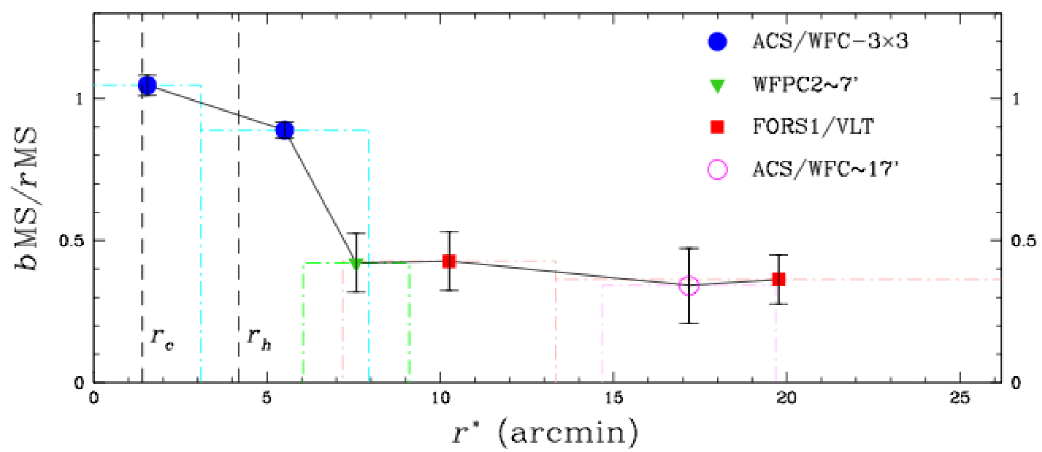
Omega Centauri: Radial distribution of main sequence stars

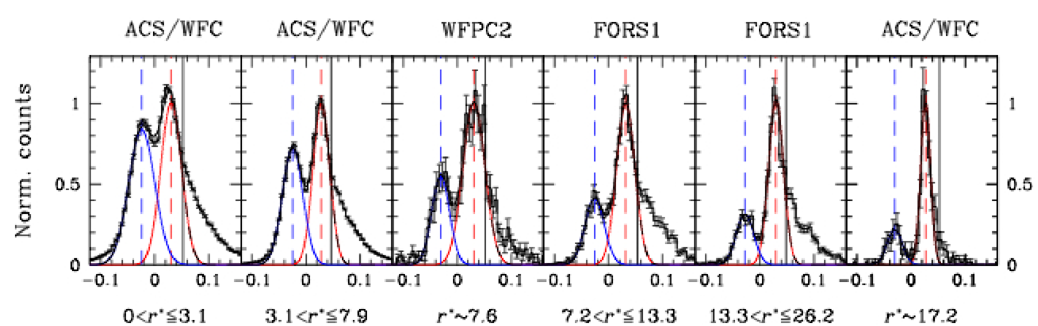


The double
MS is present all over the cluster,
from the inner core to the outer
envelope, but….



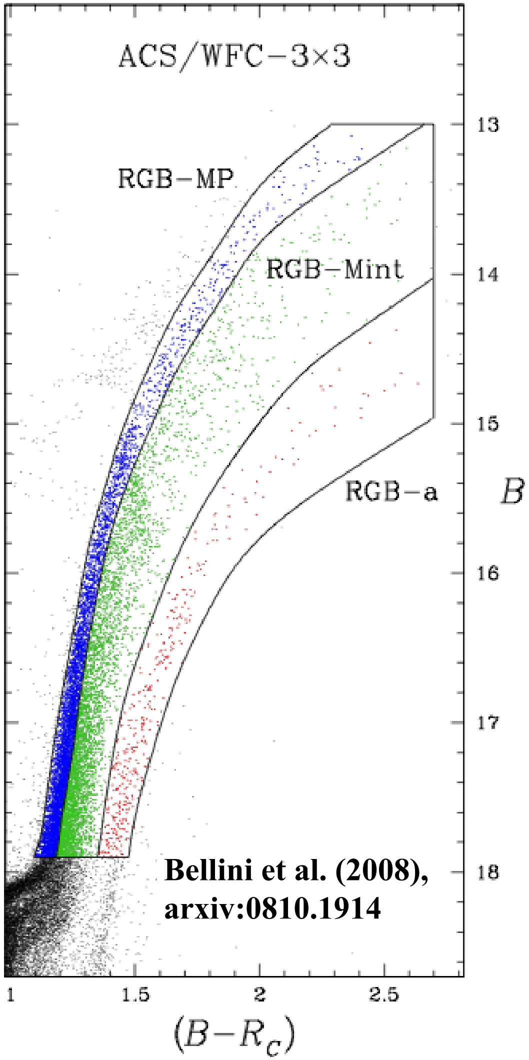
…the two MSs have different radial distributions: the blue, more metal rich MS is more concentrated



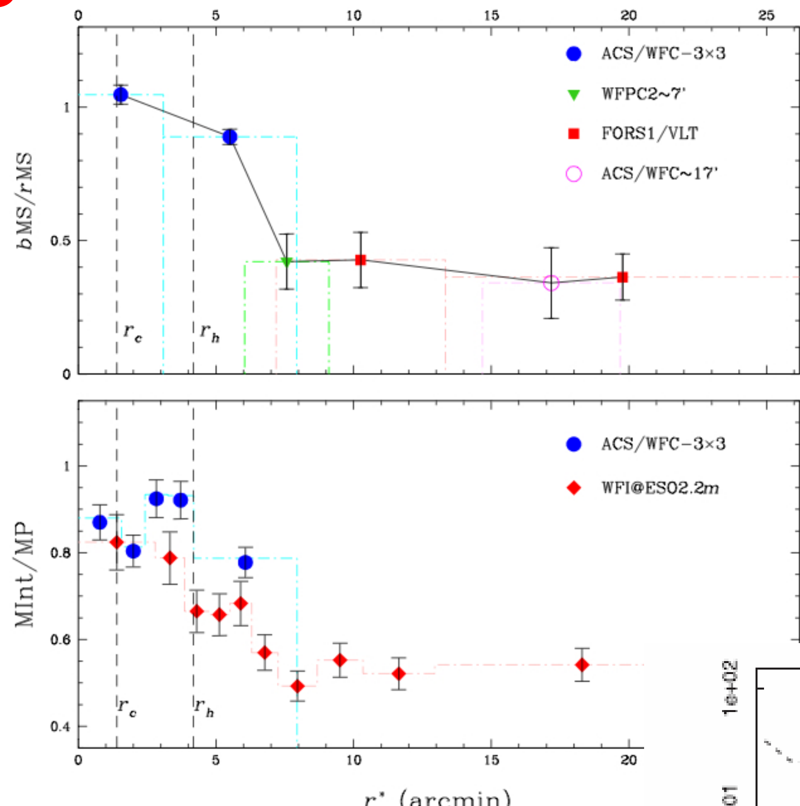


Bellini et al. (2009), in prep

Omega Centauri: radial distribution

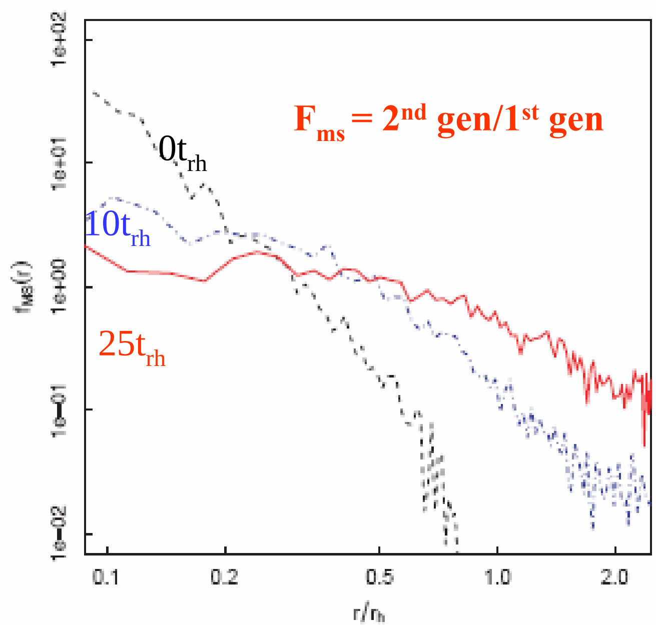


Bellini et al. (2008), arxiv:0810.1914



bMS stars are more concentrated than rMS ones

RGB-Mint more concentrated than RGB-MP

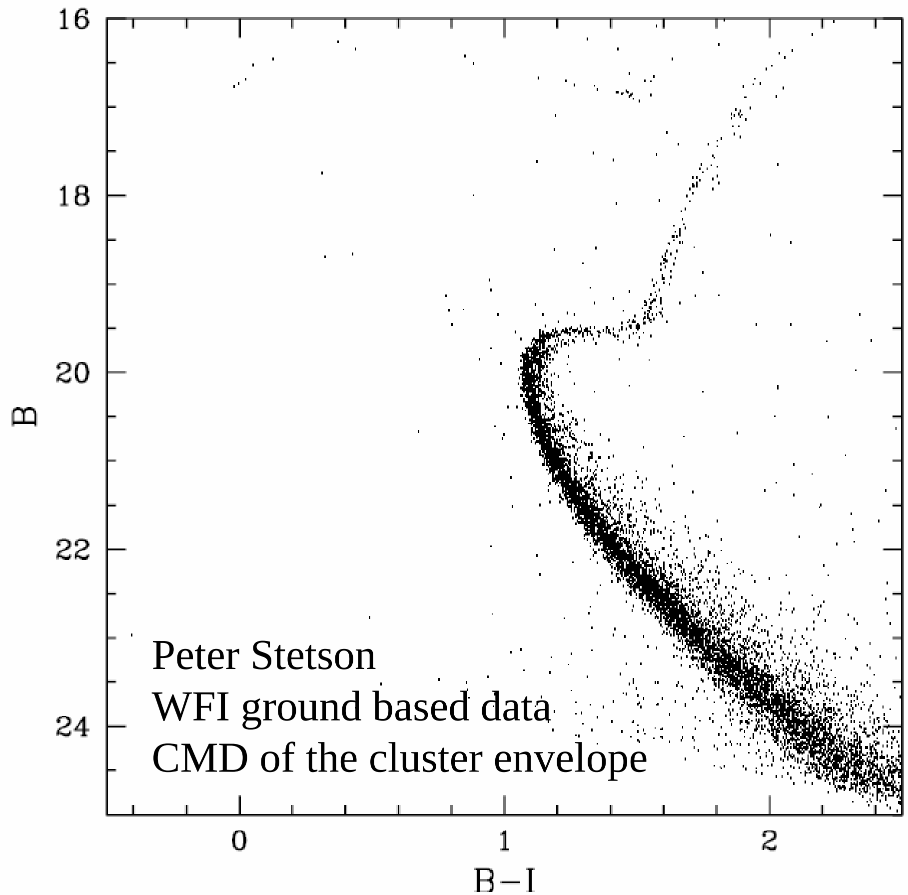


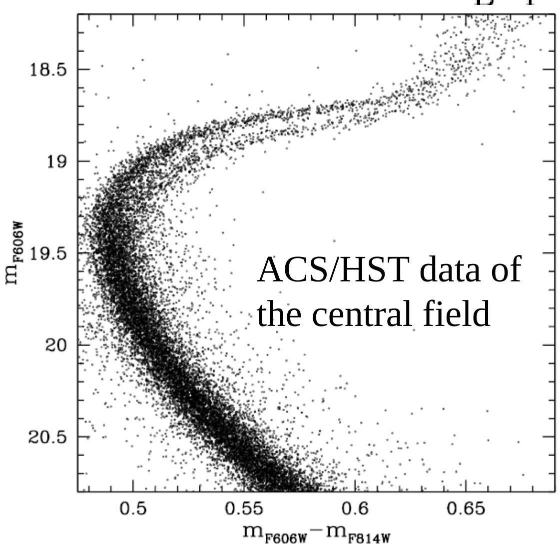
This radial trend is consistent with the radial trend of the ratio between the number of MS stars of the 2nd generation over the 1st one predicted by the models of D'Ercole et al. (2008),MNRAS, 391, 825.

Note: the bMS is related to the RGB-Mint population.

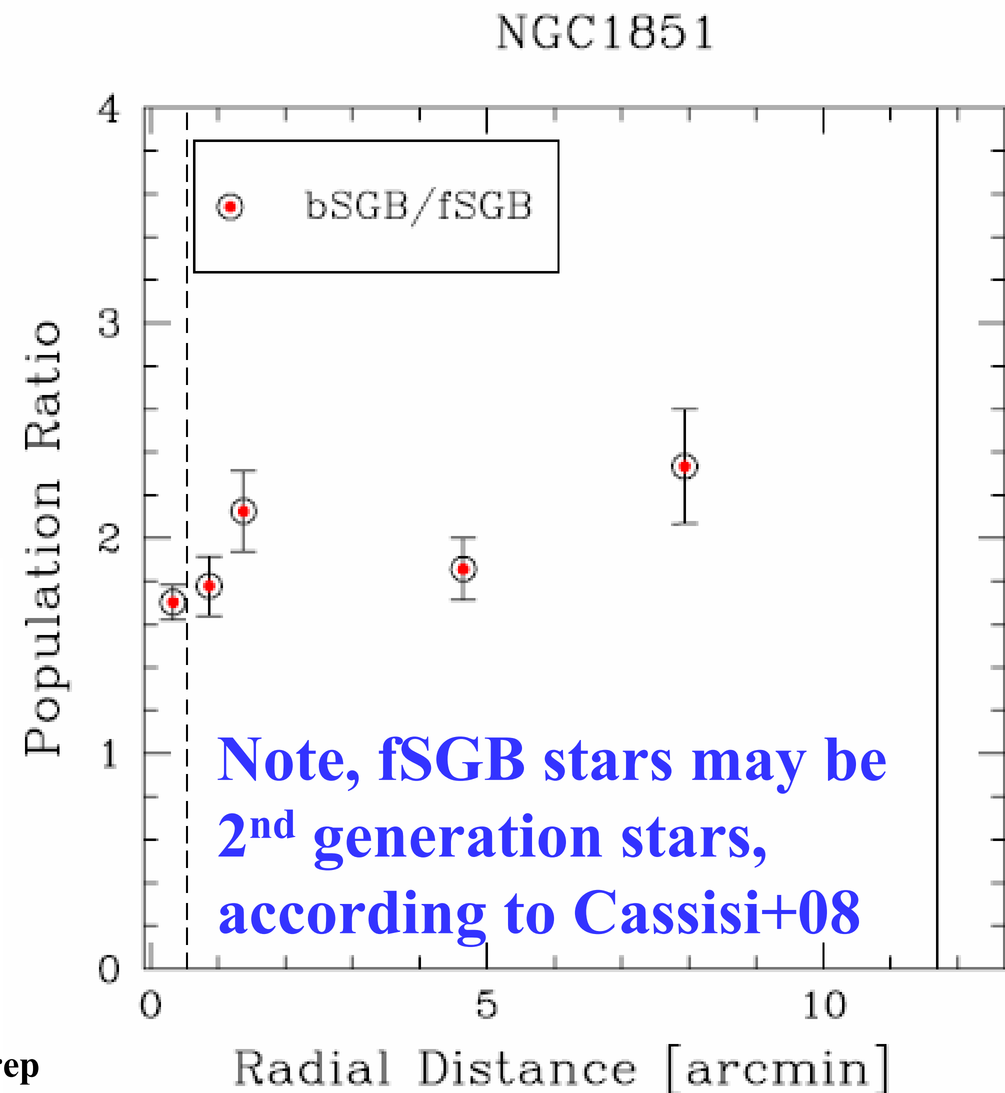
See Enrico Vesperini talk

Radial distribution of the two populations in NGC 1851

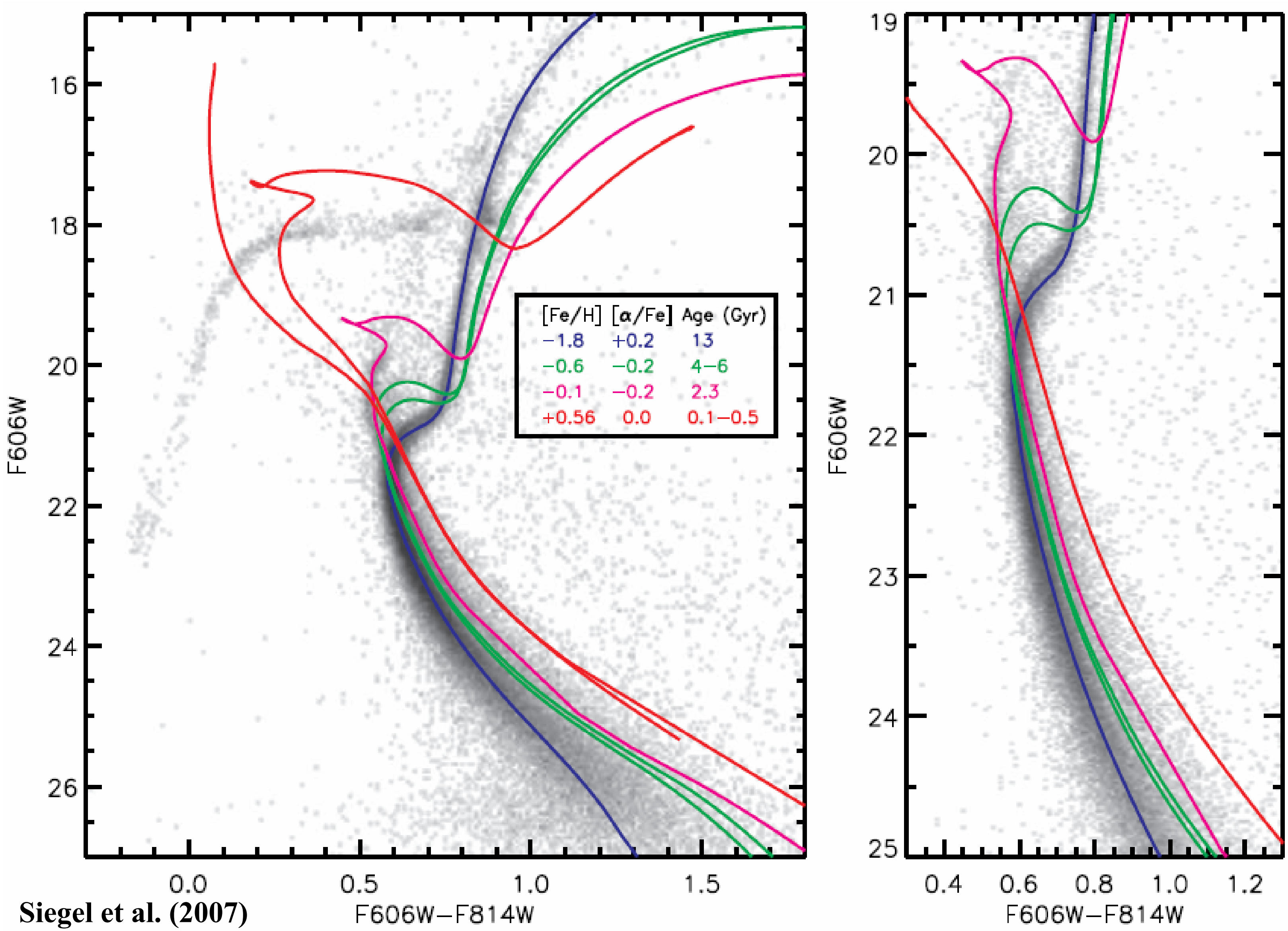




Milone et al. 09, in prep



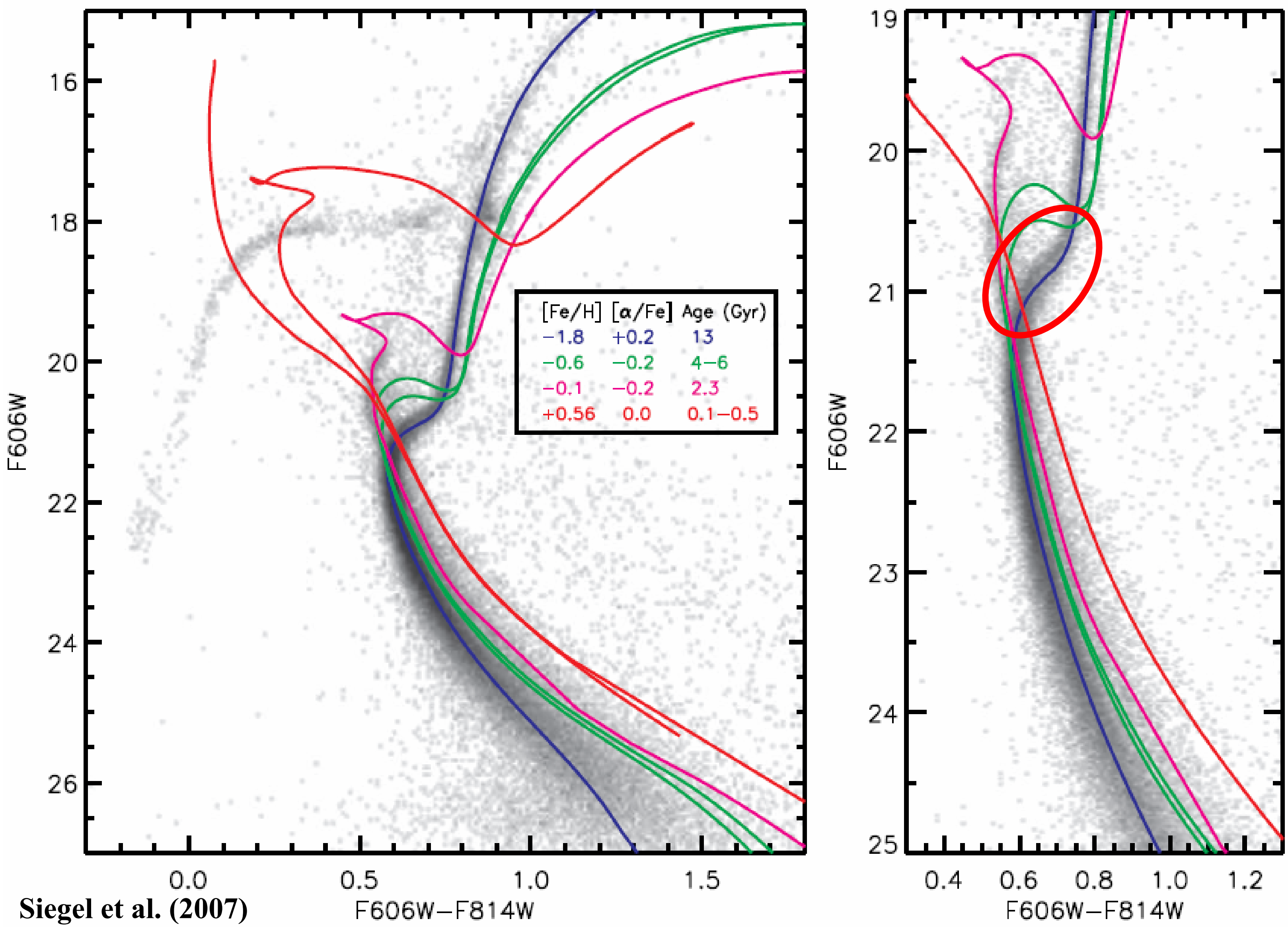
NGC 6715 (M54)



Siegel et al. (2007)

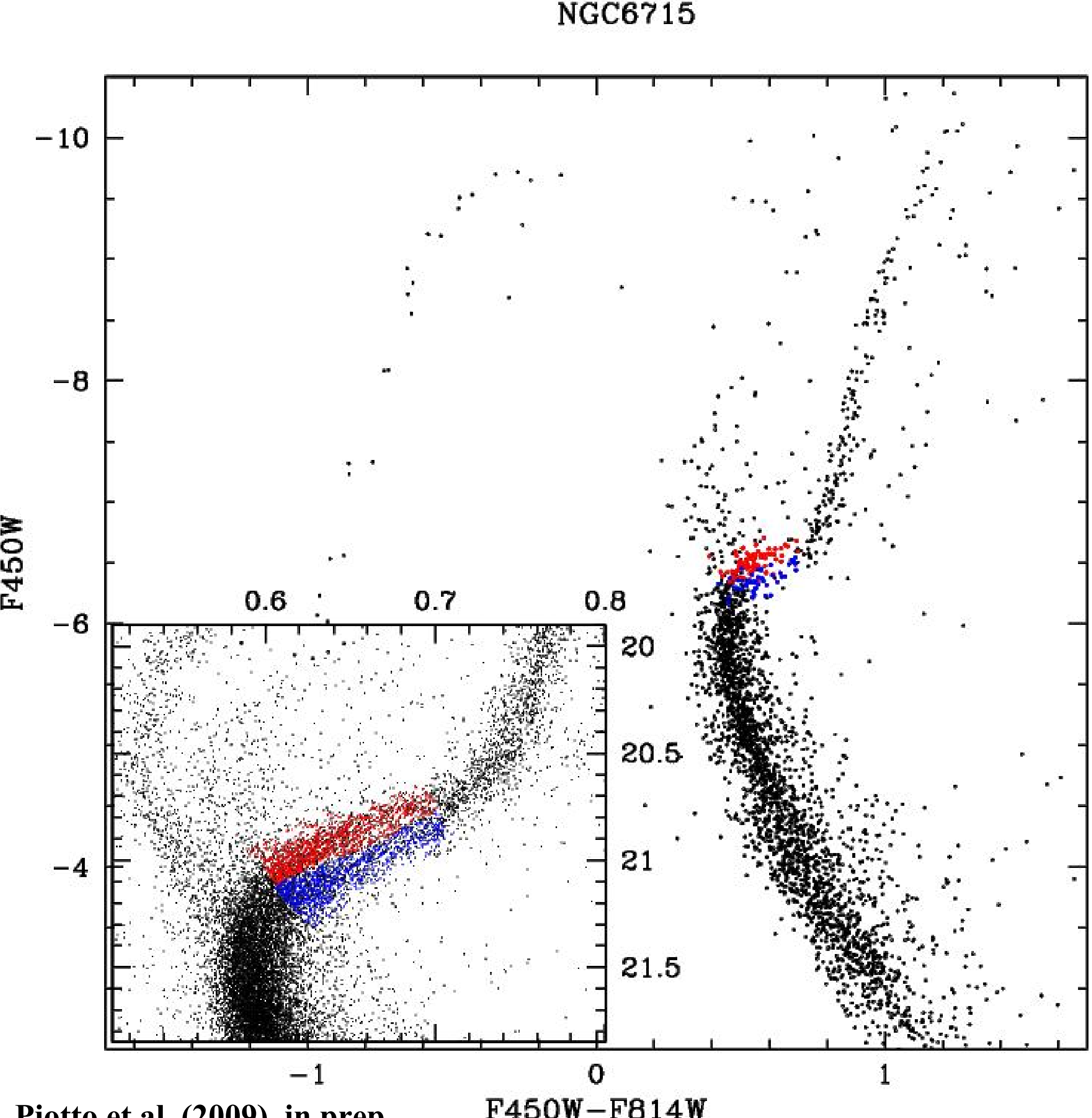
Multiple RGBs, Multiple MSs, ….

NGC 6715 (M54)



Siegel et al. (2007)

Multiple RGBs, Multiple MSs, ….



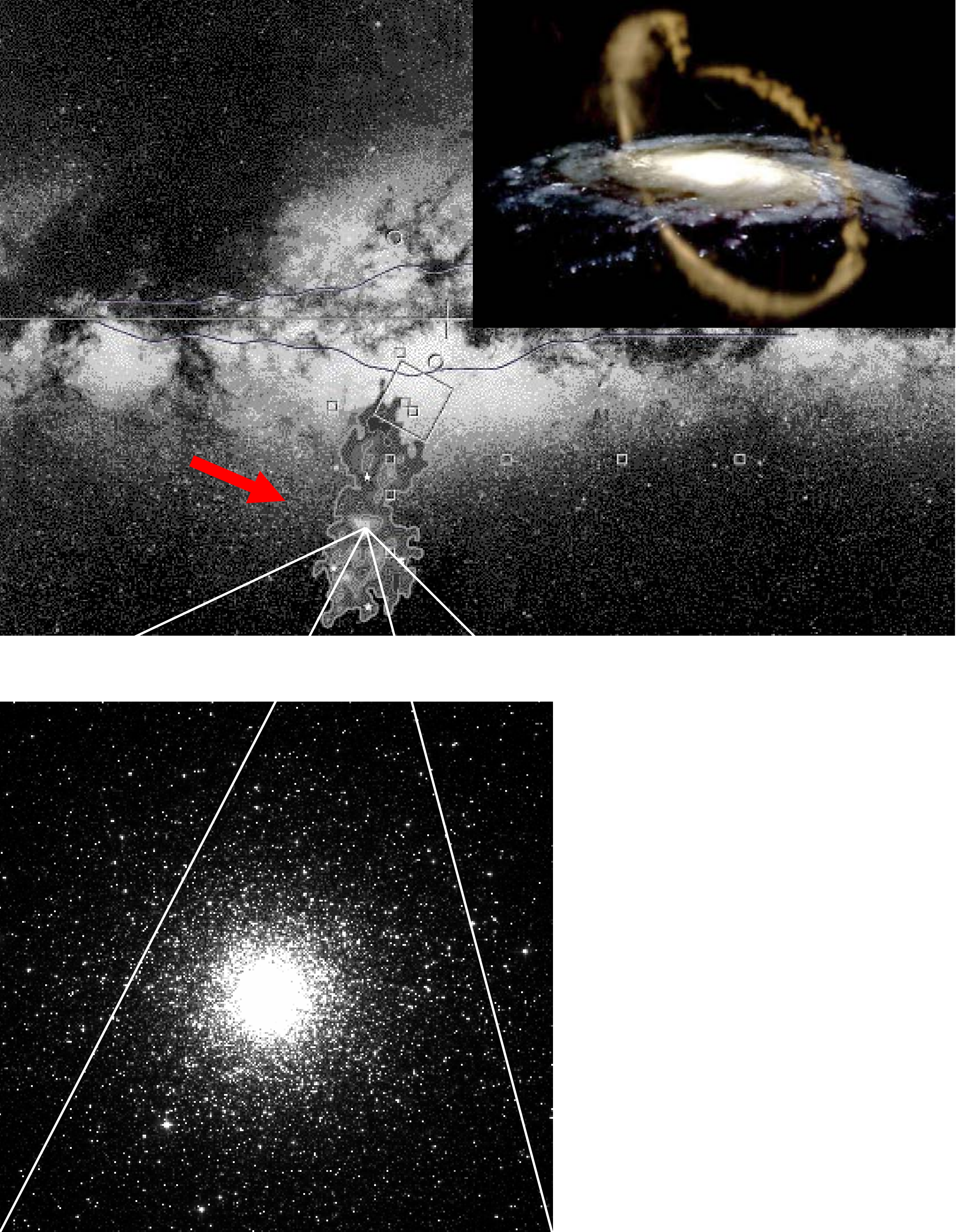
Piotto et al. (2009), in prep.

NGC 6715 (M54)

Multiple SGBs!

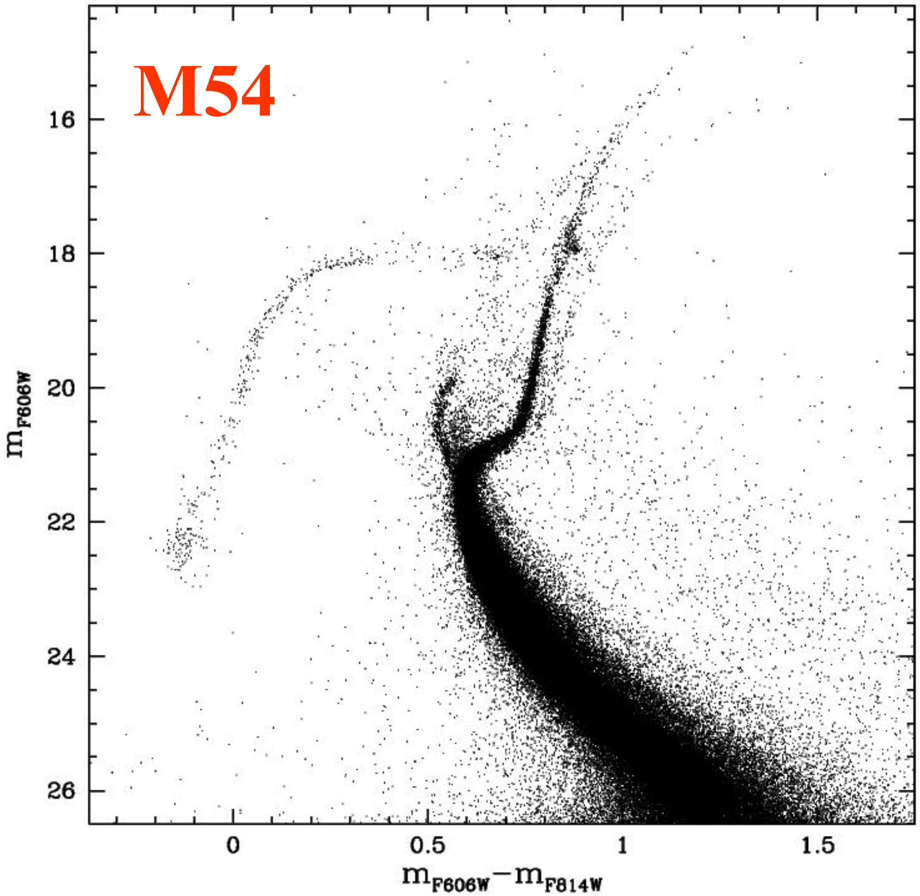
Very, very similar to the cases of the globular clusters Omega Cen, NGC1851… and many others.

Data from the ACS Tresaury and from GO10922,



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.

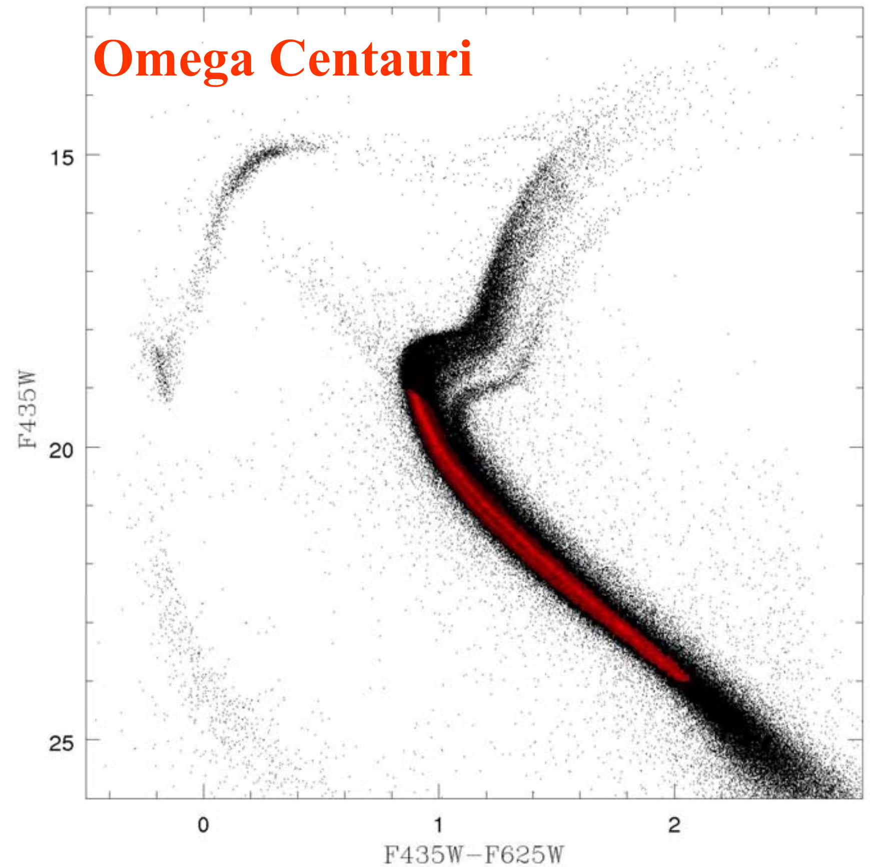


The CMDs of M54 and Omega Centauri are <u>astonishingly similar!</u>

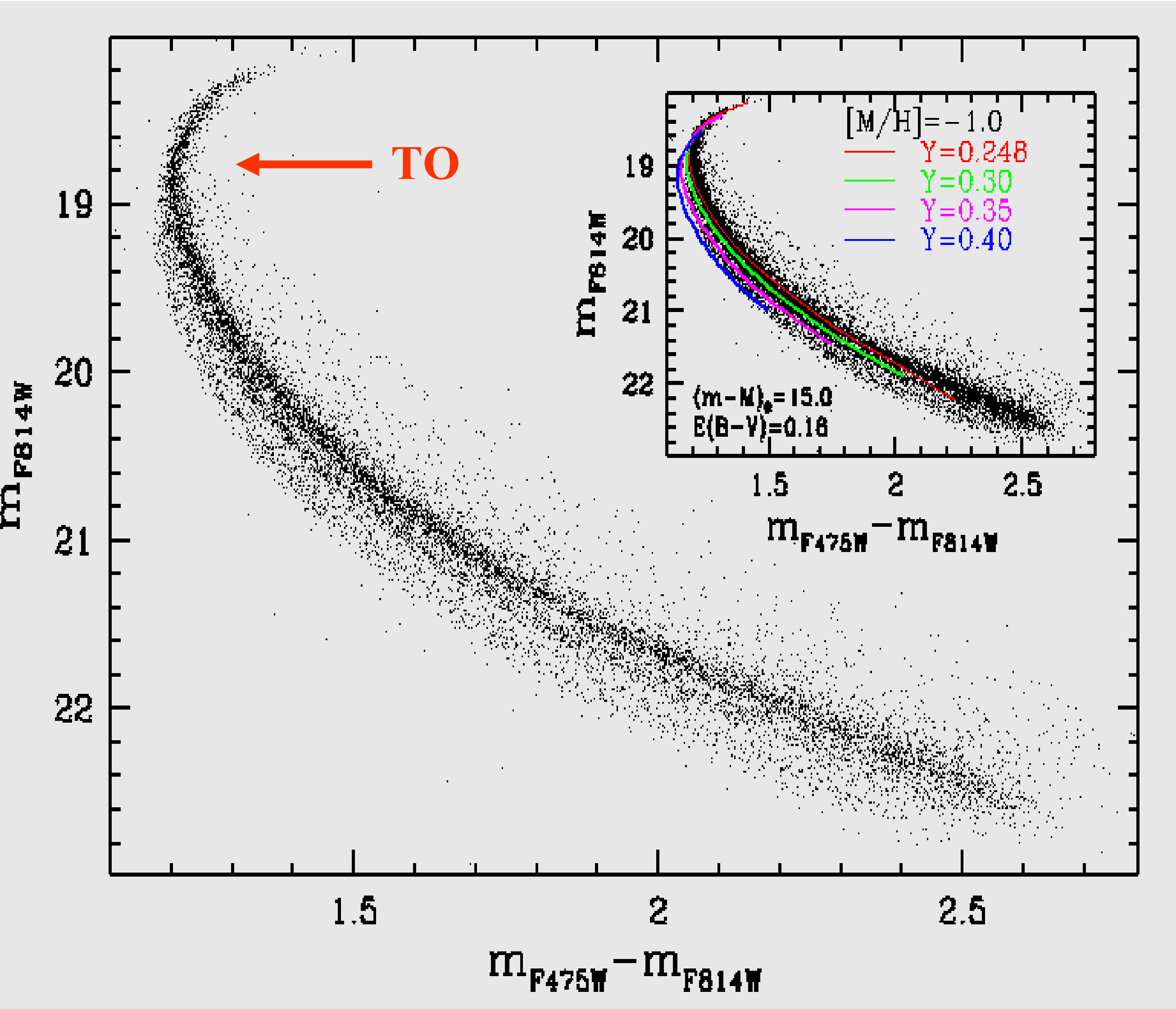
It is very possible that M54 and the Sagittarius nucleus are showing us what Omega Centauri was a few billion years ago: the central part of a dwarf galaxy, now disrupted by the Galactic tidal field.

But, where is the tidal tail of Omega Centauri (see Da Costa et al. 2008)?

Is this true for other GCs?



The most spectacular case: the triple main sequence in NGC 2808

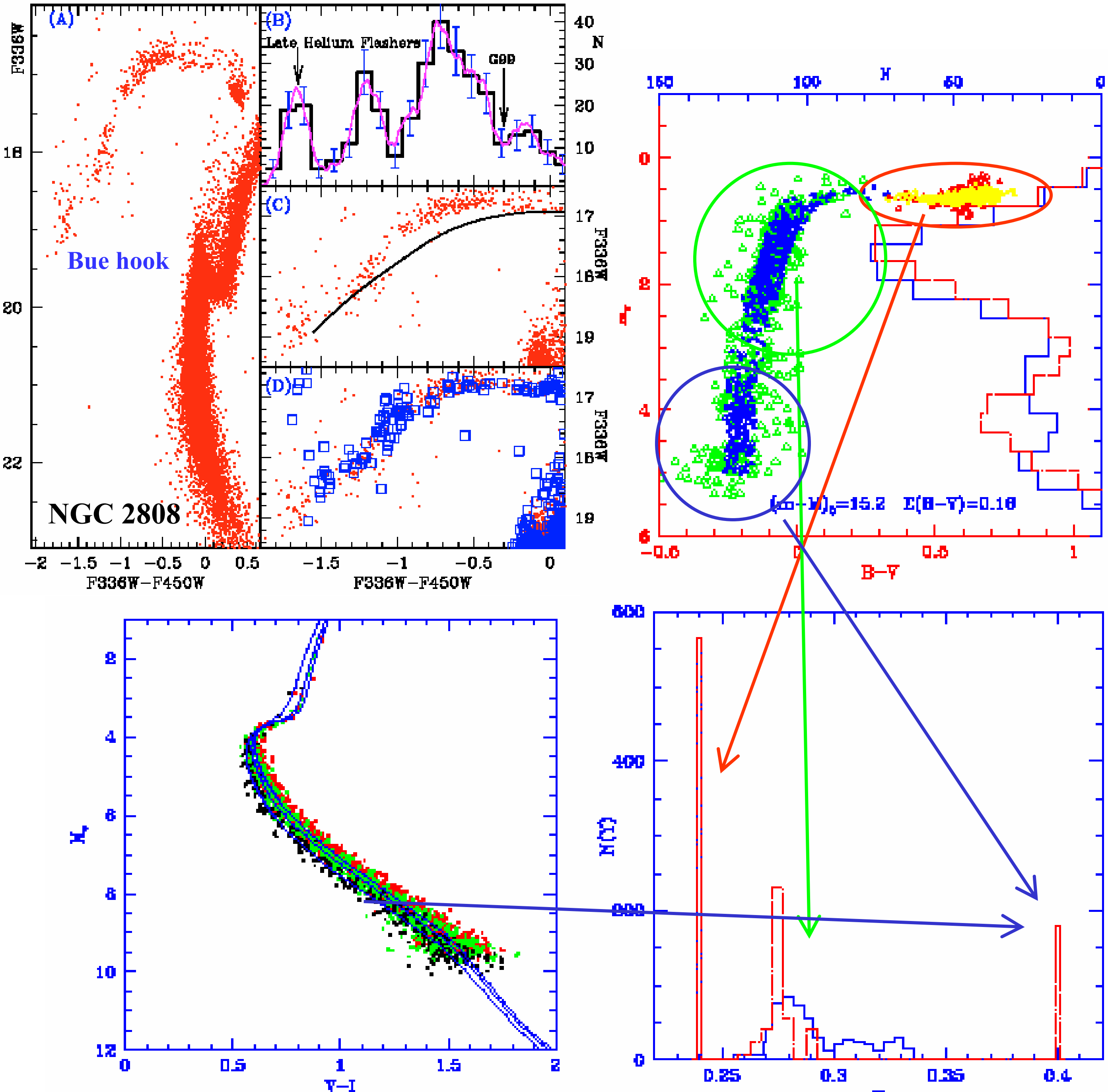


Piotto et al. 2007, ApJ, 661, L35

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>



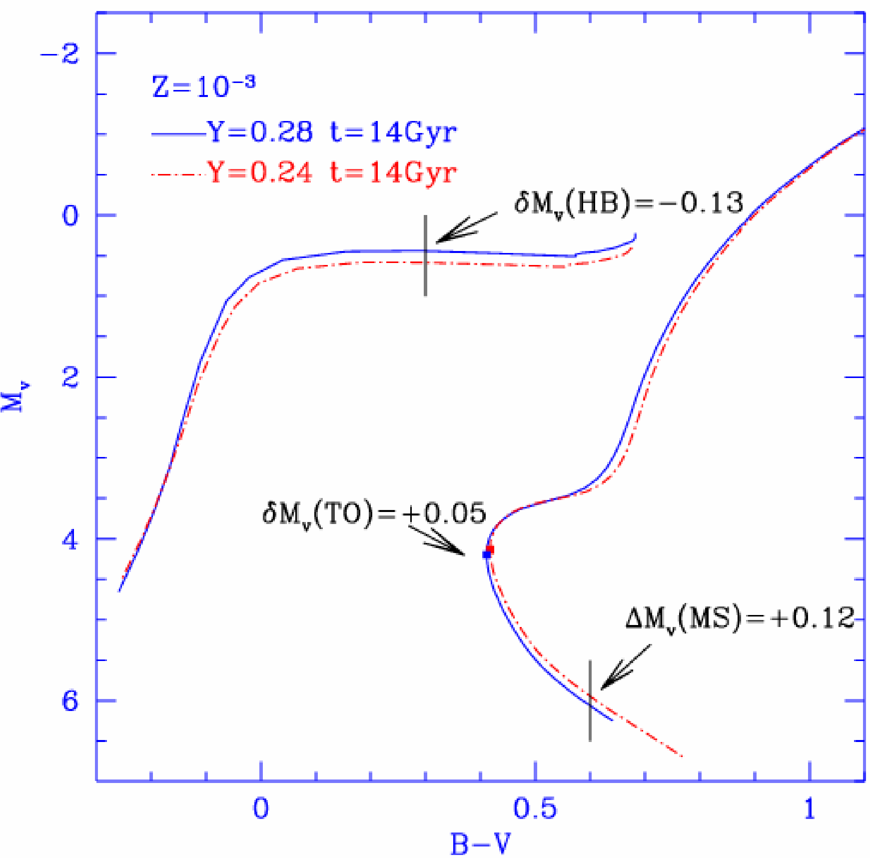
A MS broadening in NGC2808 was already seen by D'Antona et al. (2005).

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!!!

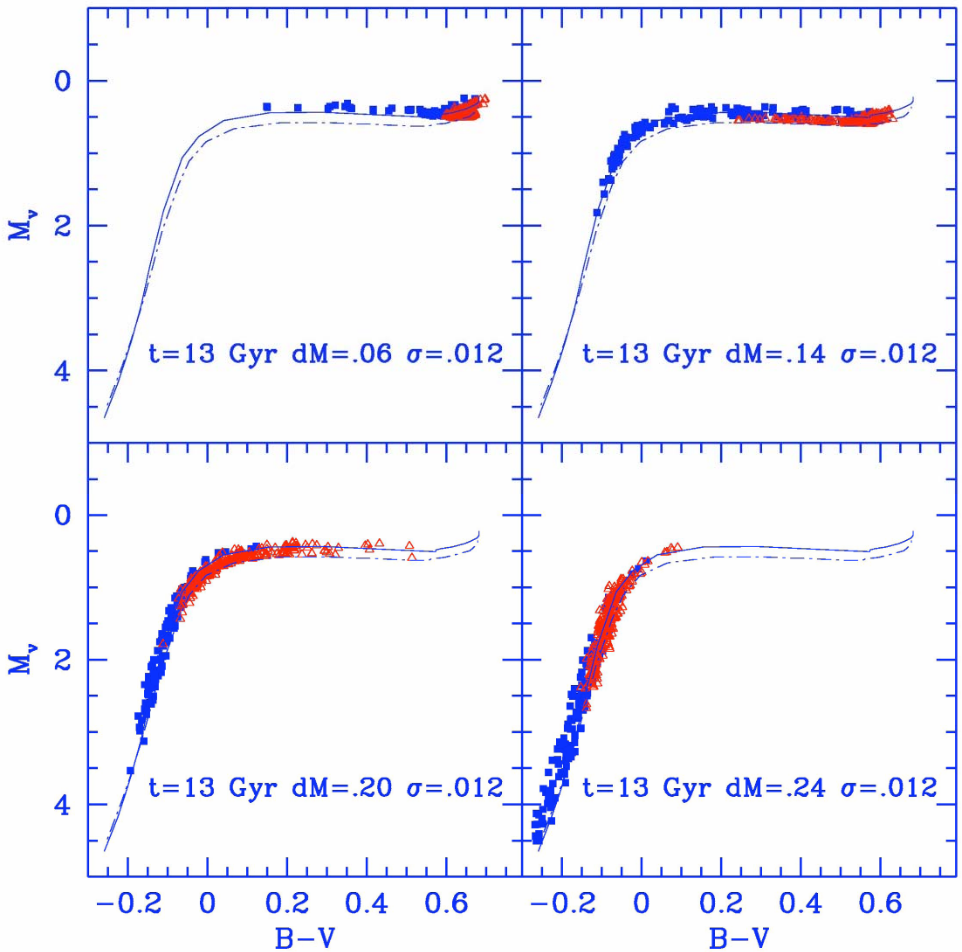
D'Antona et al. 2005, ApJ, 631, 868

Helium enrichment: model predictions



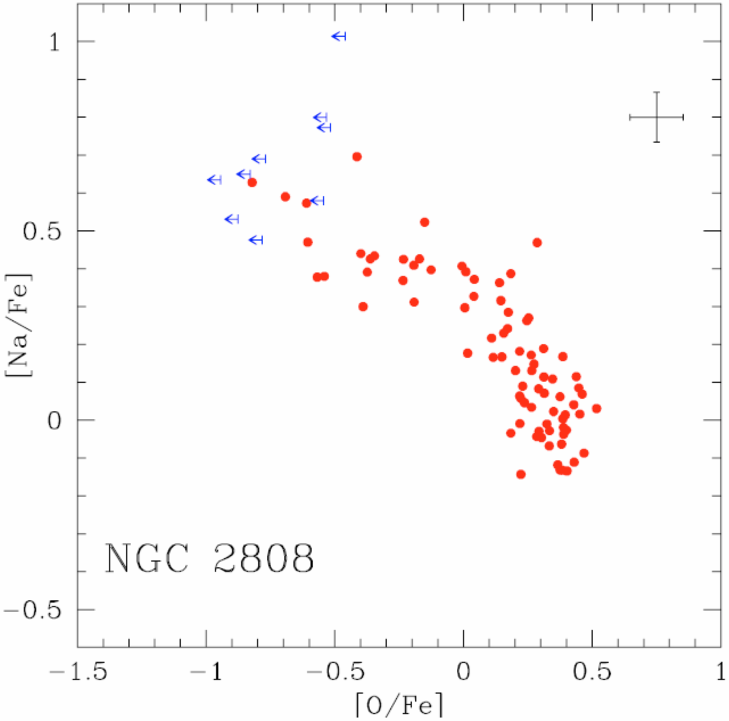
D'Antona et al. (2002)

→ **Higher Y → brighter HB**

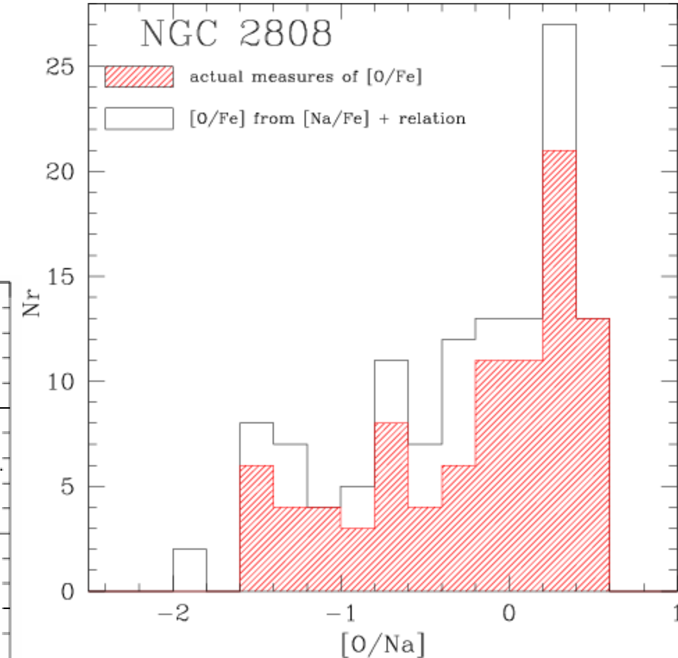


Higher Y → bluer HB ←

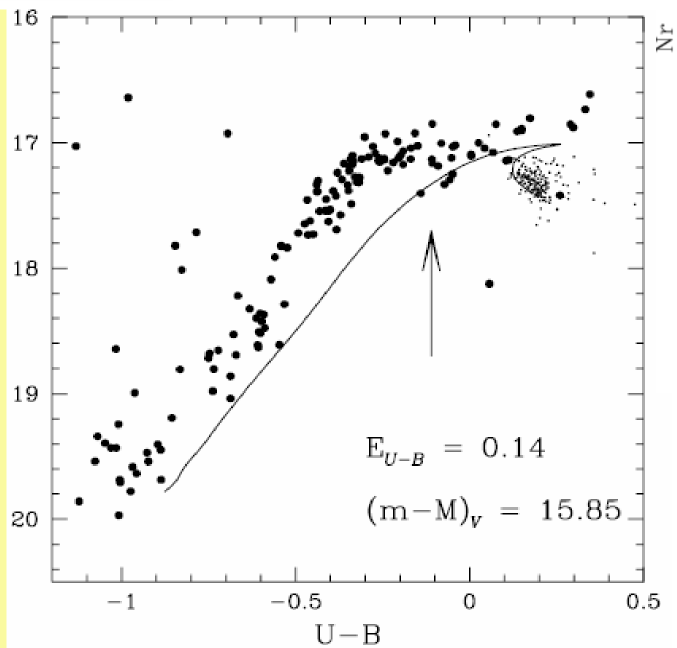
(but we need also higher mass loss along the RGB)



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



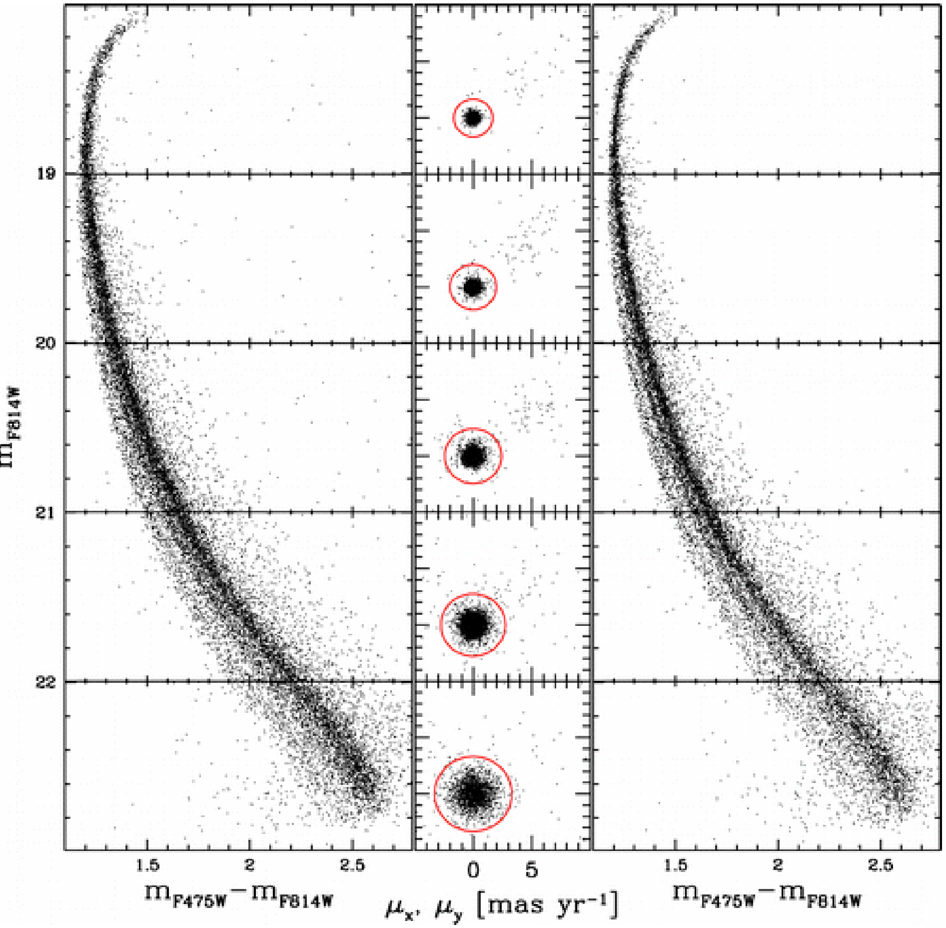
NGC2808 has a very complex and very extended HB (as ω Cen). The distribution of stars along the HB is multimodal, with at least three significant gaps and four HB groups (Sosin et al 1997, Bedin et al 2000)



Observations properly fit the intermediate mass AGB pollution scenario

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

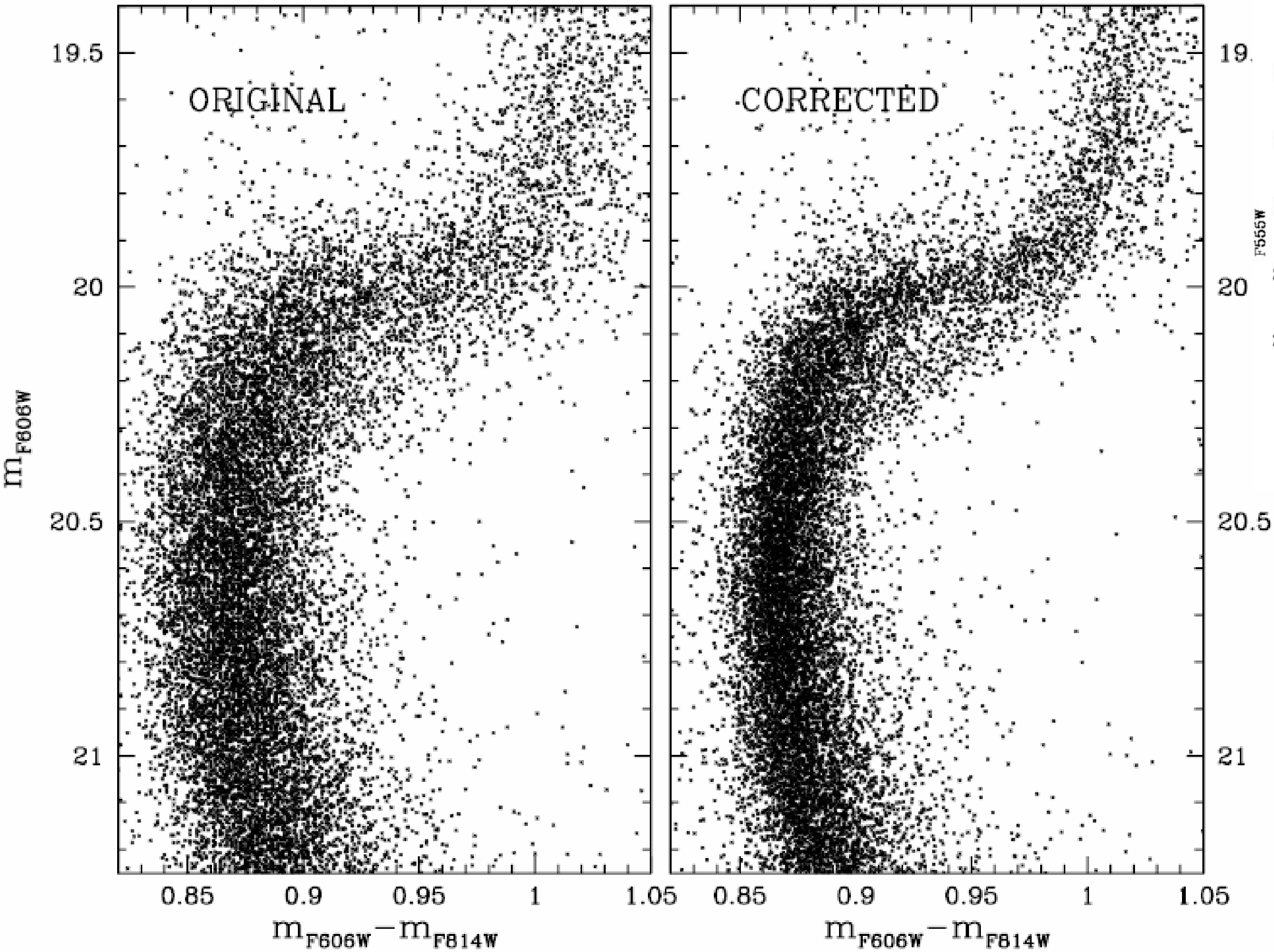
MS	RGB	HB
rMS 63% ± 5 Y = 0.248	O-normal 61% ± 7	Red segment 46% ± 10
mMS 15% ± 5 Y = 0.30	O-poor 22% ± 4	EBT1 35% ± 10
bMS 13% ± 5 Y = 0.37	Super–O-poor 17% ± 4	EBT2 10% ± 5
Binaries 9% ± 5	?	EBT3? 9% ± 5

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

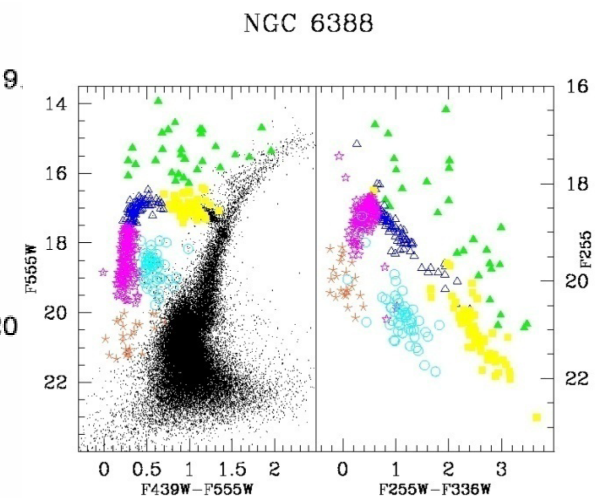
...continuing...

Multiple Stellar Populations in Globular Clusters. IV.

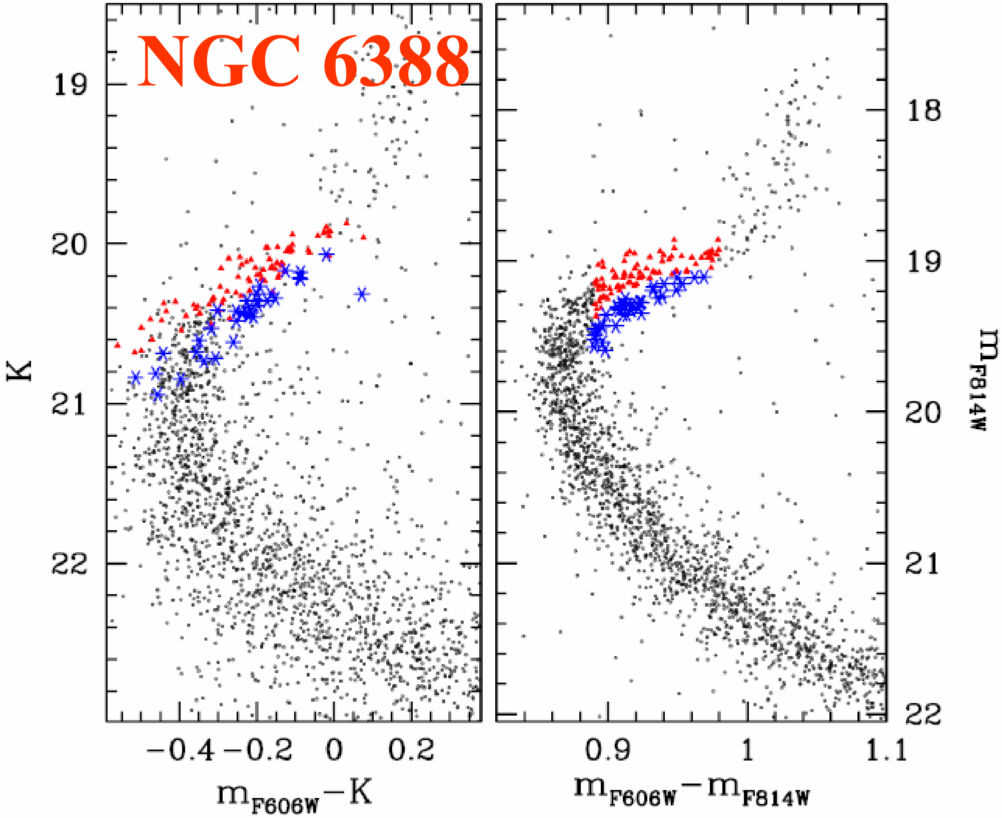
NGC 6388!



Piotto (2008, arXiv0801.3177): GC ACS/HST Tresaury data



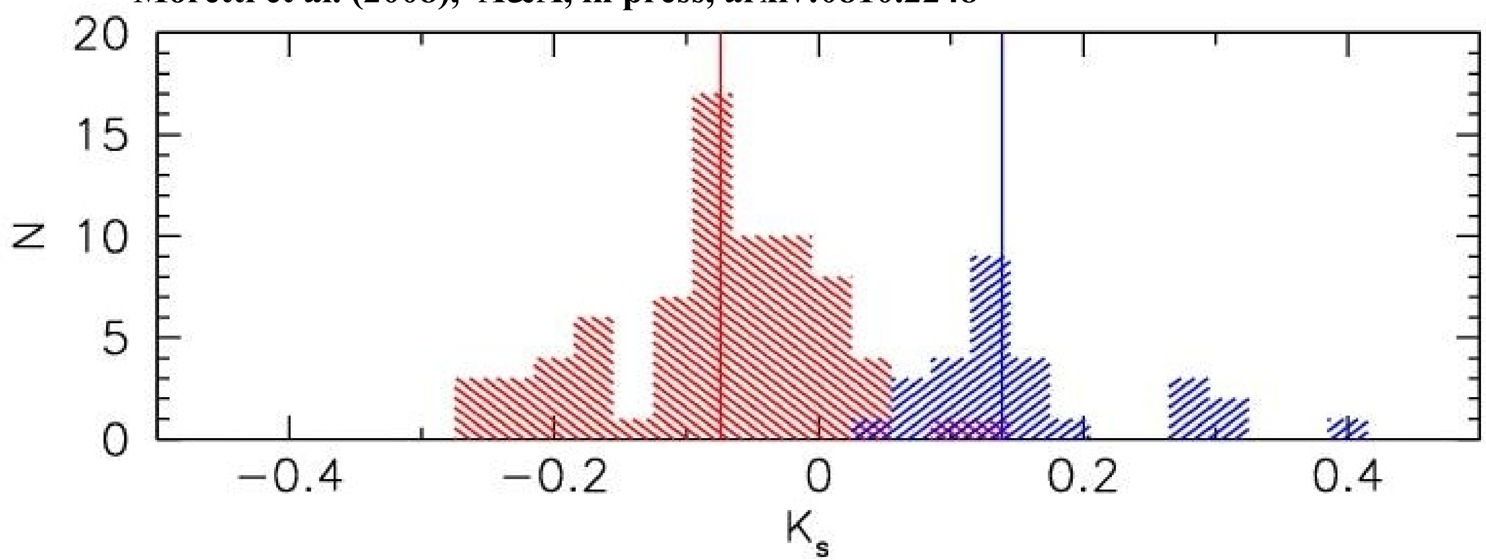
Very anomalous HB (as we know since Rich+97 WFPC2 observations), extended up to the blue hook despite its very high metallicity [Fe/H]~ -0.5



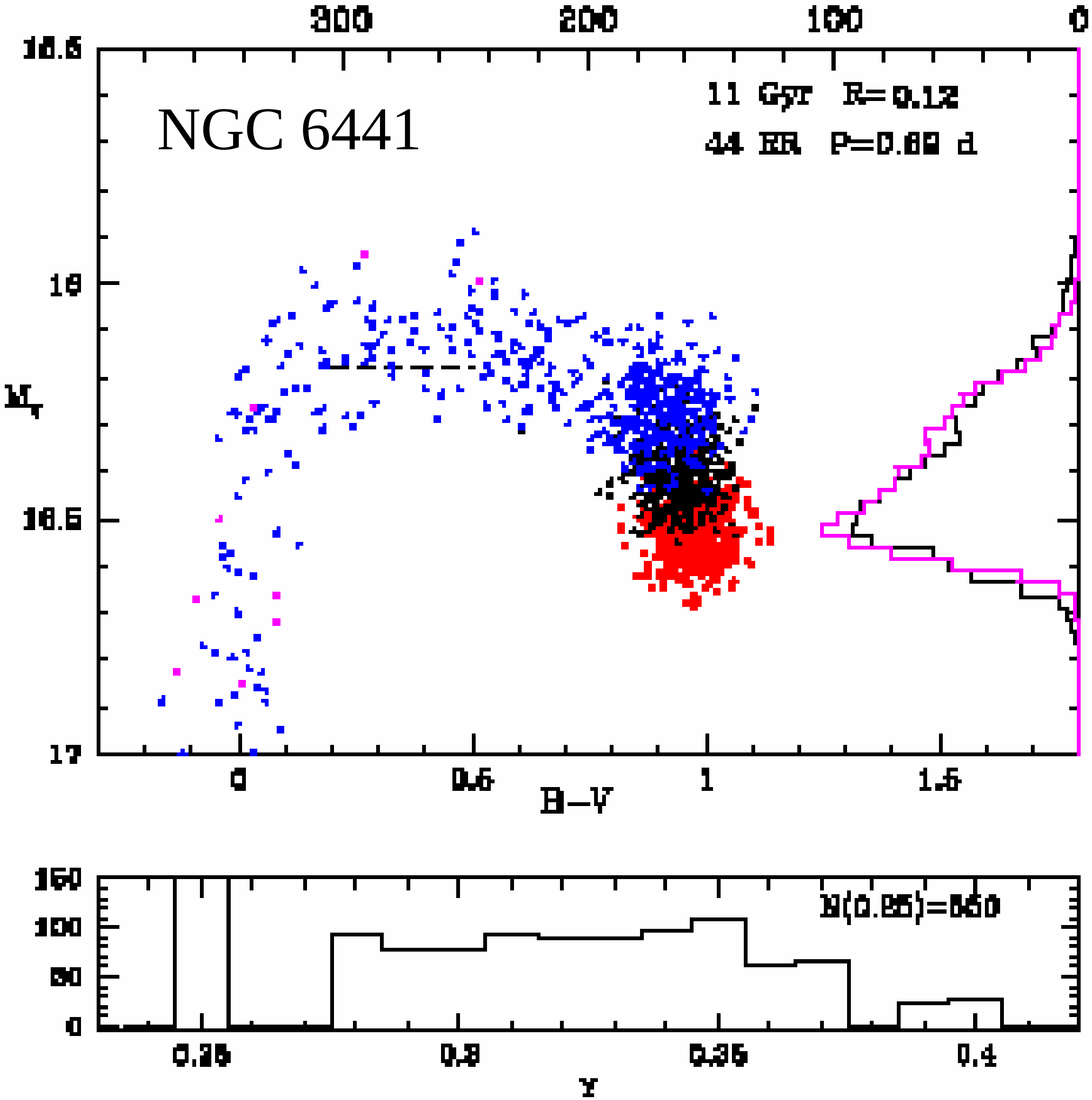
…also in the optical-nearIR diagram

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.

Moretti et al. (2008), A&A, in press, arxiv:0810.2248



We confirm the SGB split in NGC 6388!

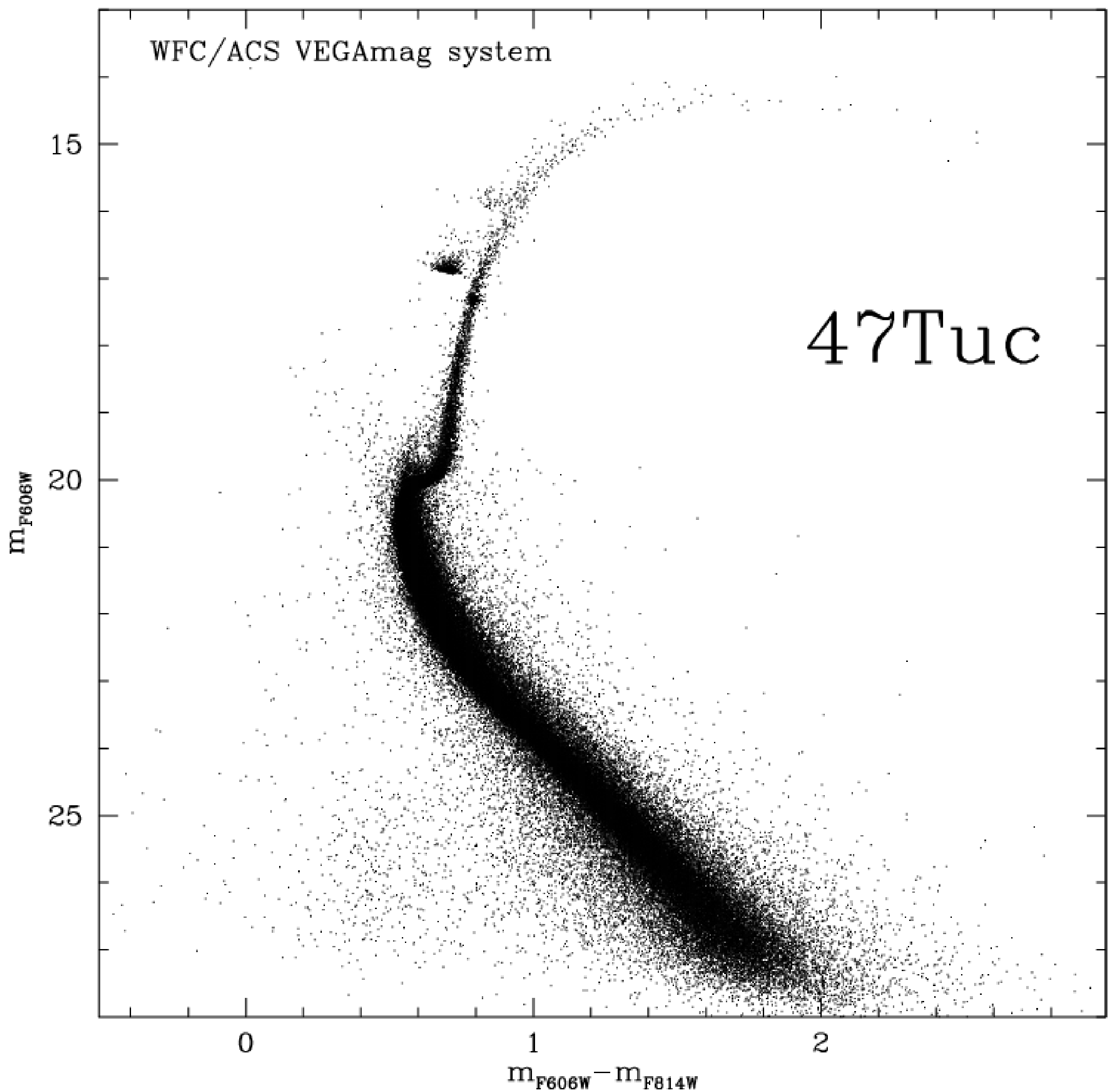


Caloi and D’Antona, 2007, A&A, 463, 949

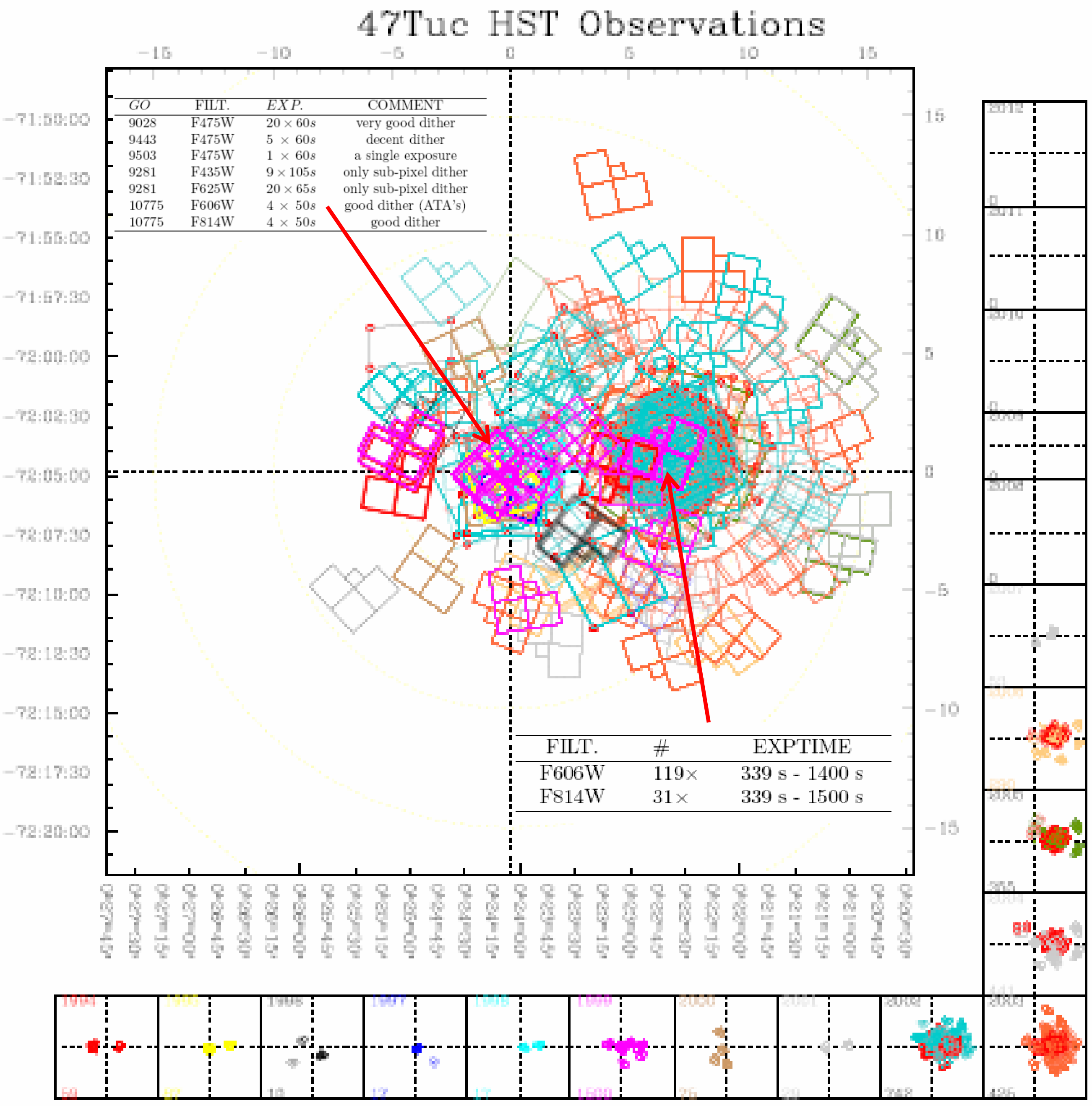
In order to reproduce the anomalous HB of NGC 6388 and NGC 6441, Caloi and D’Antona (2007) propose a complicate scenario with **3 distinct populations:**

1. a normal population (Y~0.25);
2. a polluted pop. (0.27<Y<0.33);
3. A strongly He enhanced pop. (Y>0.35)

Three He populations in NGC 6388 and NGC 6441, as in NGC 2808 and perhaps ωCen?



WFC/ACS VEGAmag system
47Tuc
15
20
25
m_{F606W}
0
1
2
$m_{F606W}-m_{F814W}$

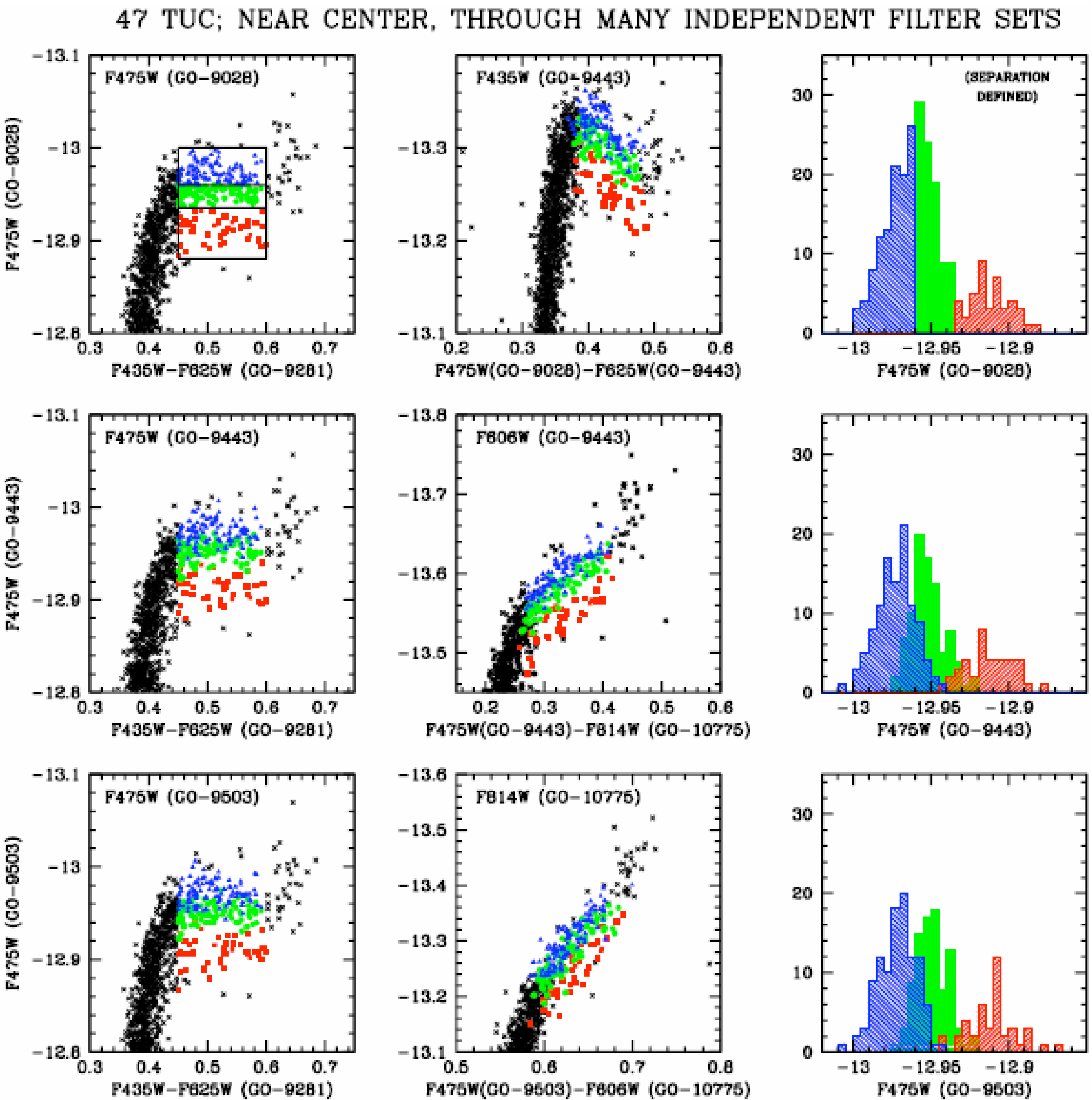


Exceptionally rich data set for an exceptionally accurate photometry

Seven (7!) independent data sets in the center!

150 deep images at 6 arcmin from the center

All data with different rotation angle and shifts.

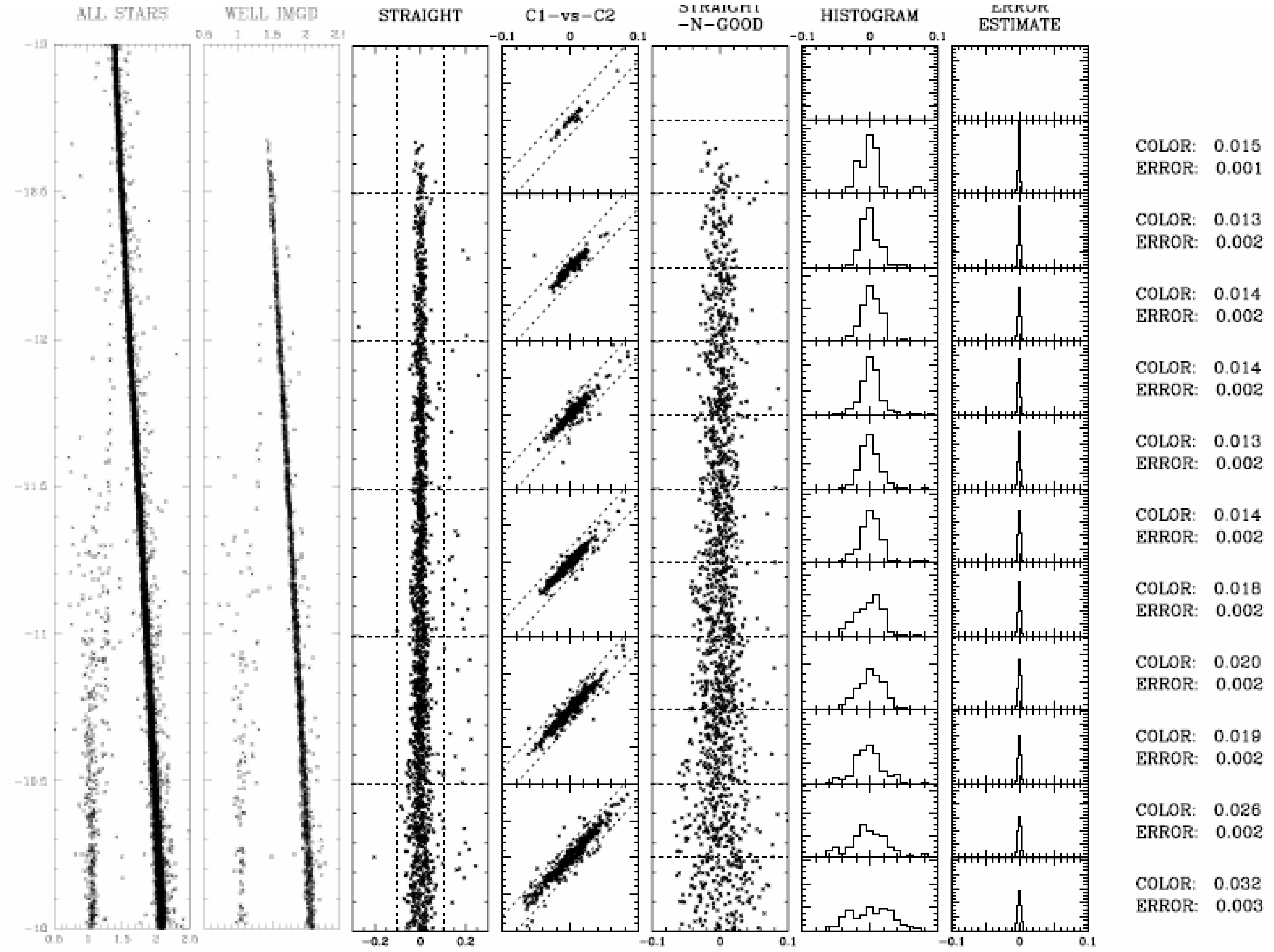


Breaking news:

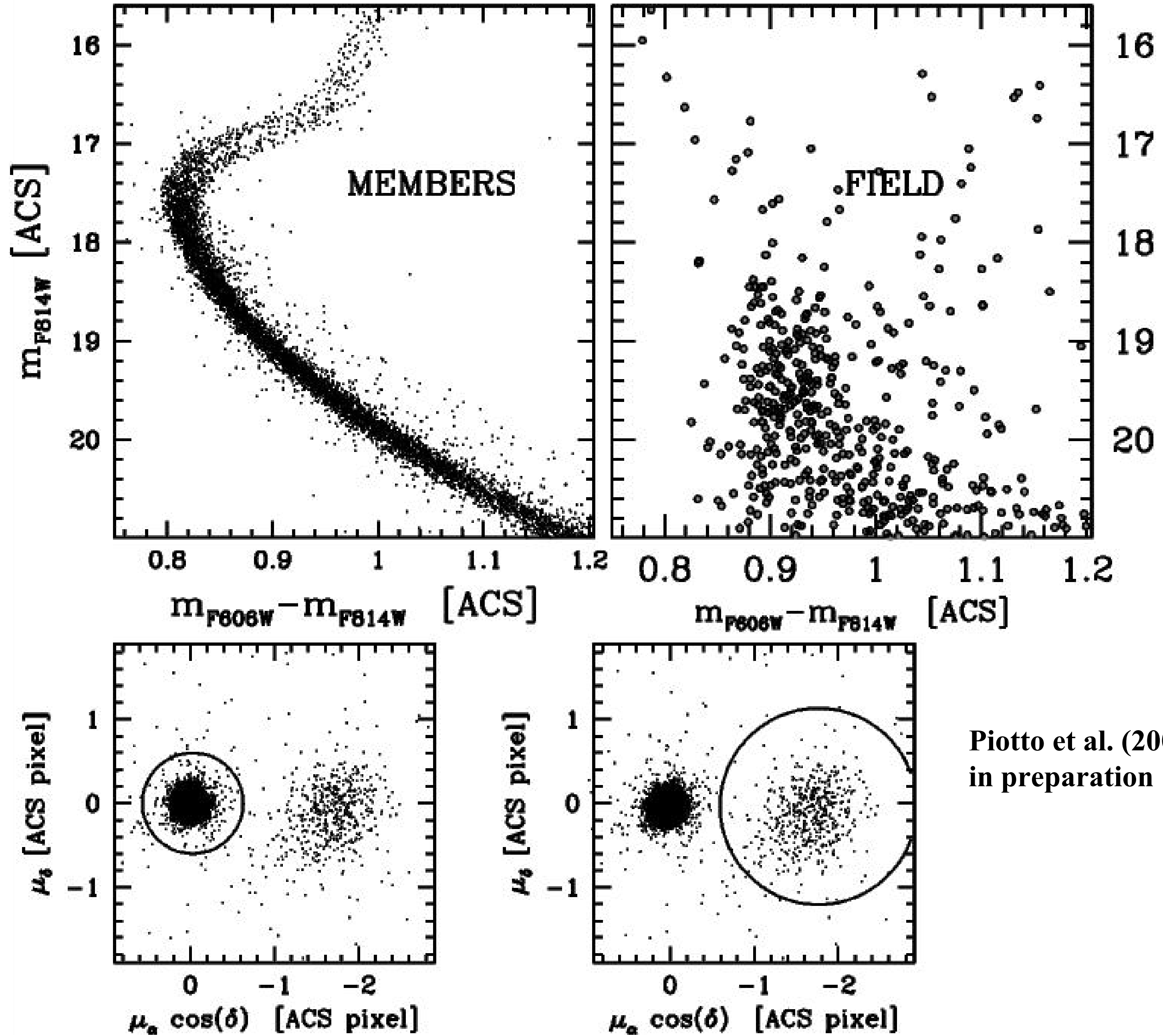
47 Tucanae shows a spreaded SGB, plus a secondary SGB plus…

Anderson et al. (2009) in preparation

…and an intrisically broad MS

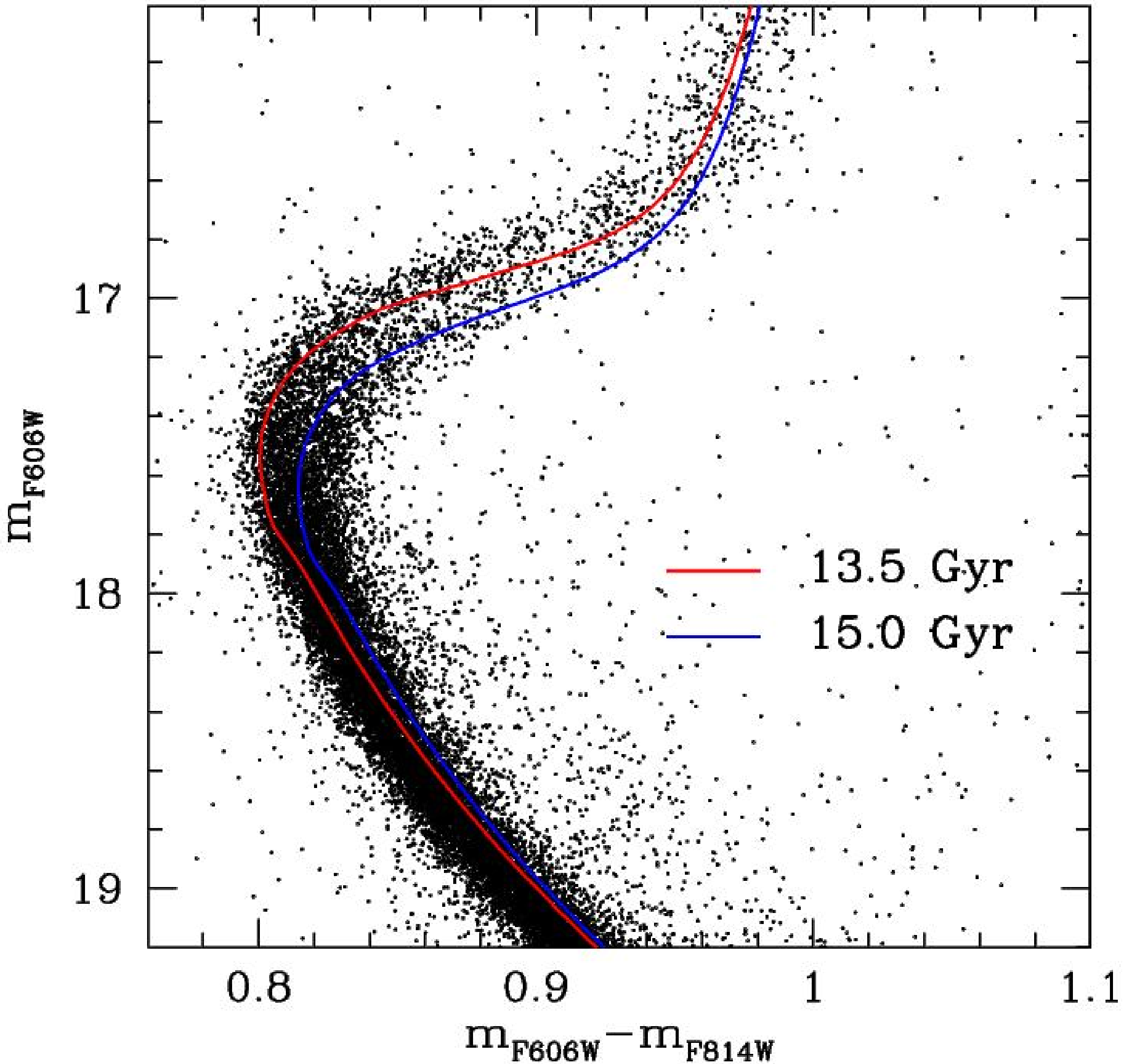


NGC 6656 (M22): another cluster with a double SGB

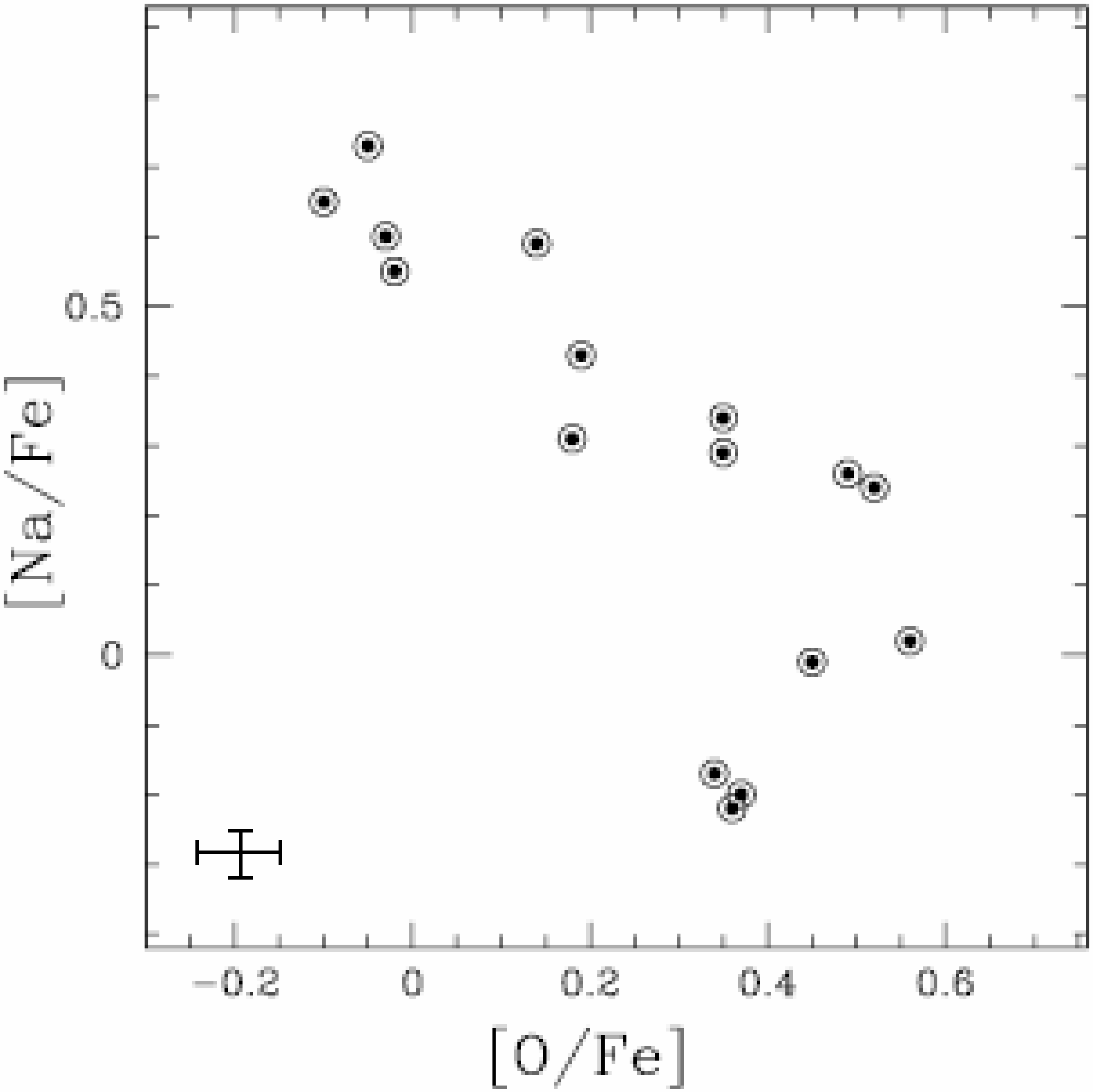


Piotto et al. (2009), in preparation

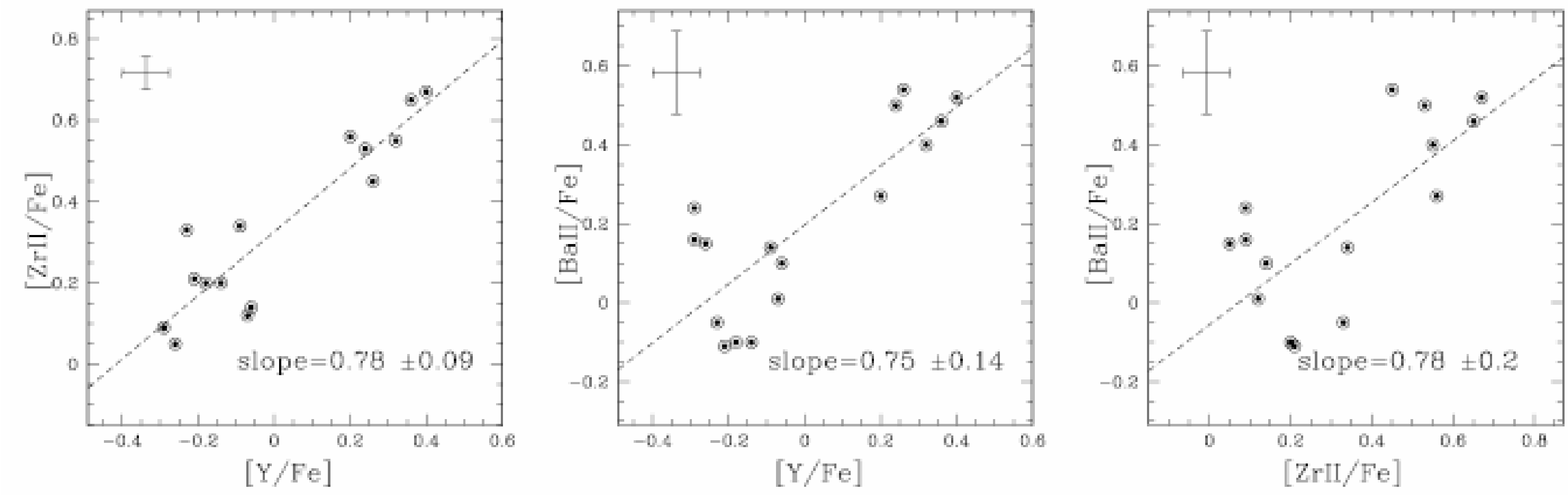
NGC 6656



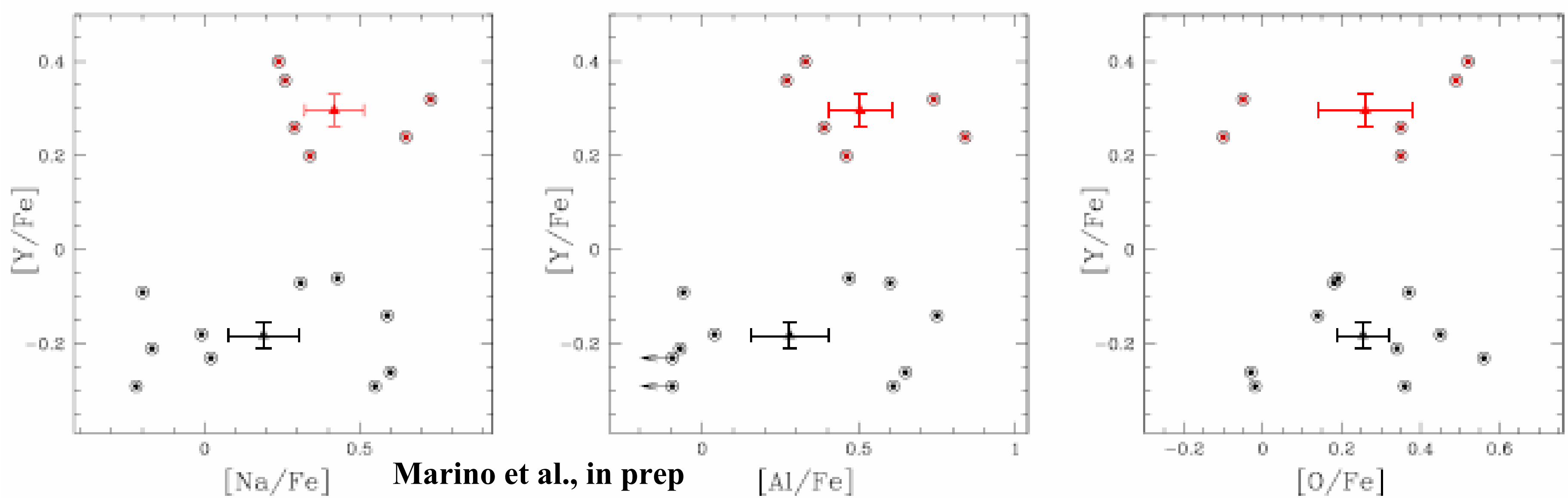
Difficulties to fit the SGB with standard isochrones.
Remember the case of NGC 1851!
We need chemical abundances from high resolution spectroscopy:



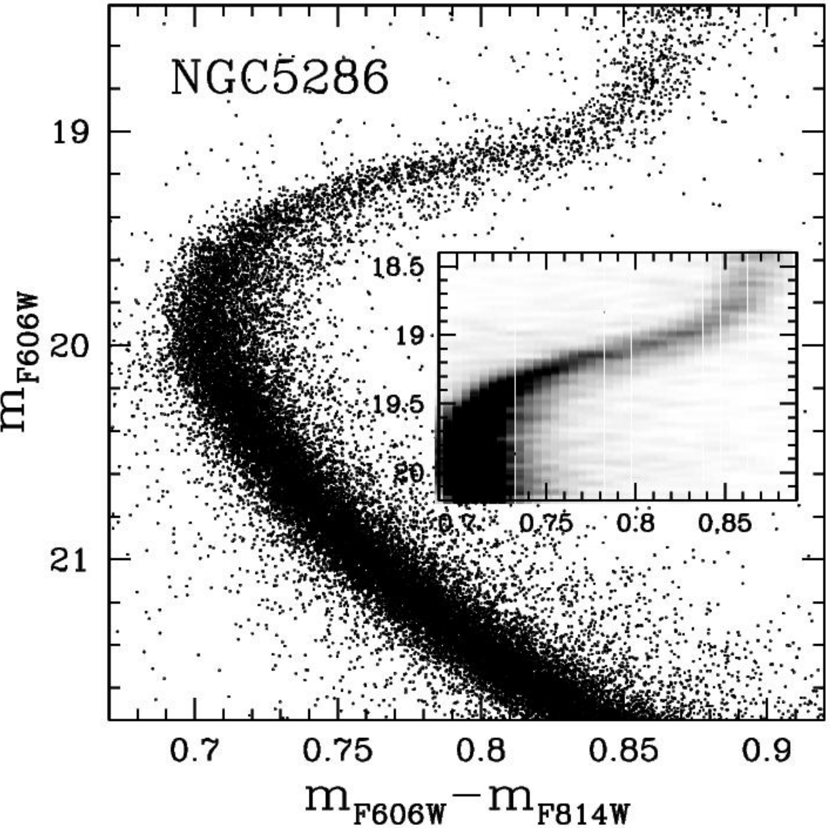
M22 has a well developed NaO anticorrelation



M22 is now the second GCs with a confirmed spread in [Fe/H] and the presence of two distinct stellar population, one with enhanced s-process elemend abundance, and one with low s-process abundance.

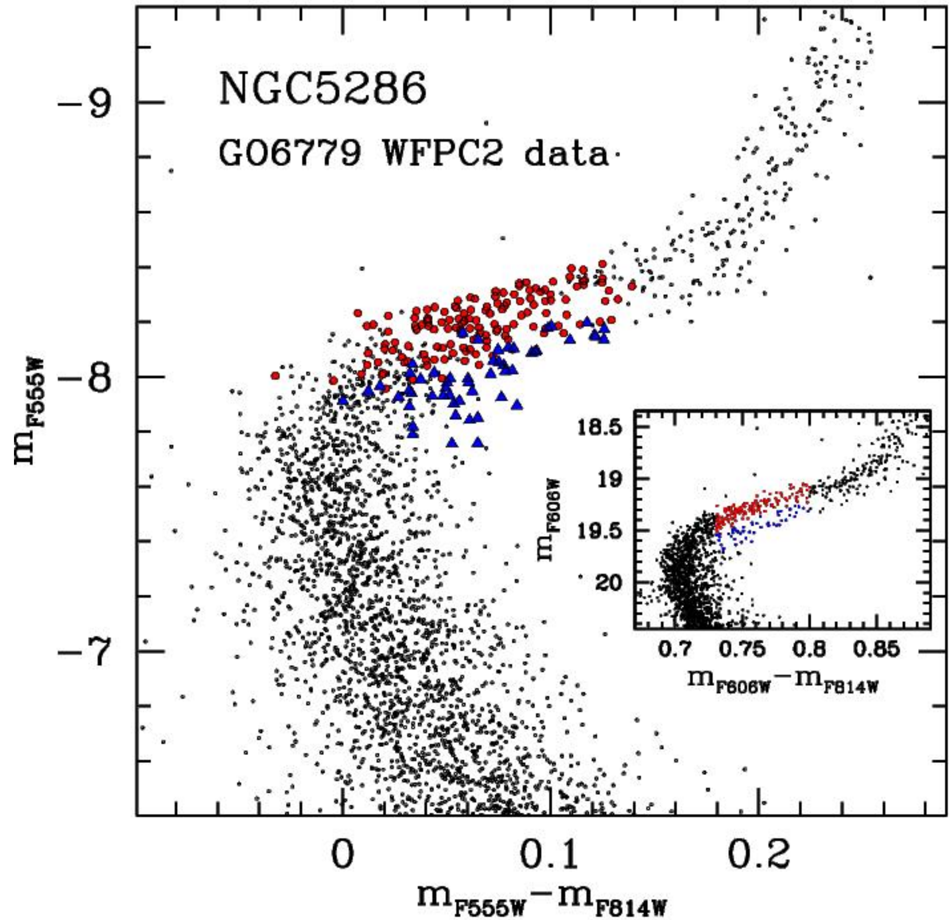


Marino et al., in prep



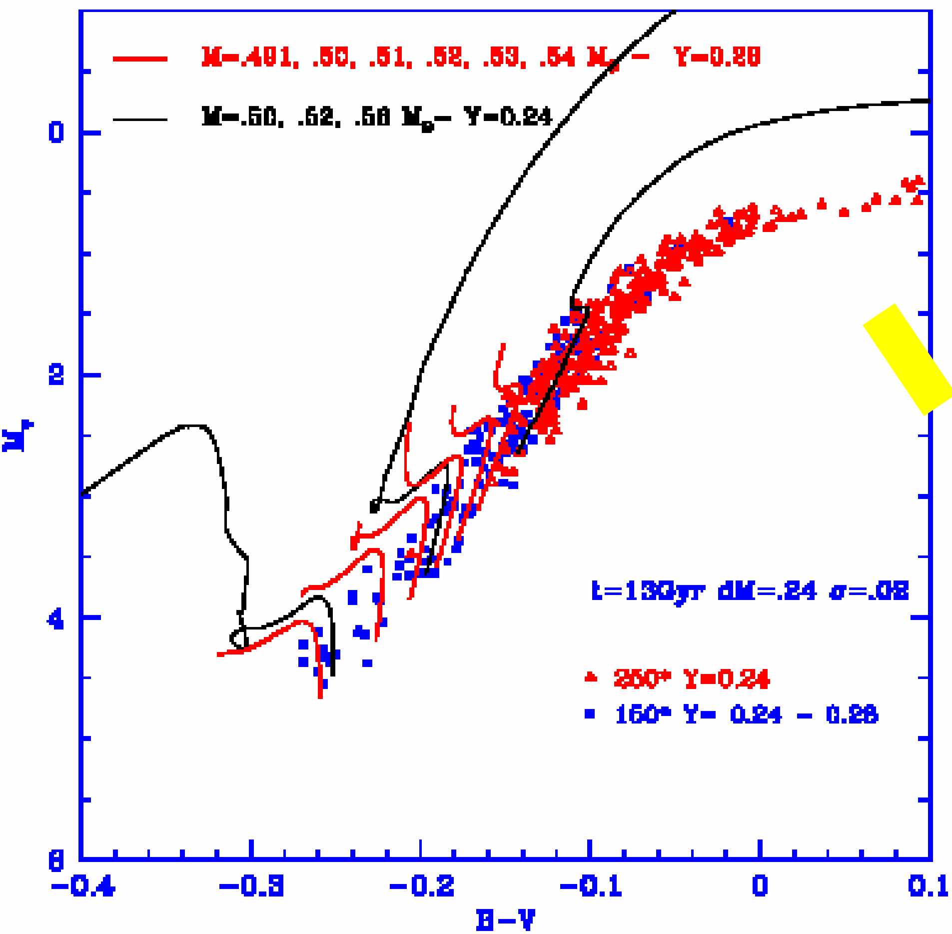
Another one!!!

Piotto et al. (2009), in prep



…and there are more!

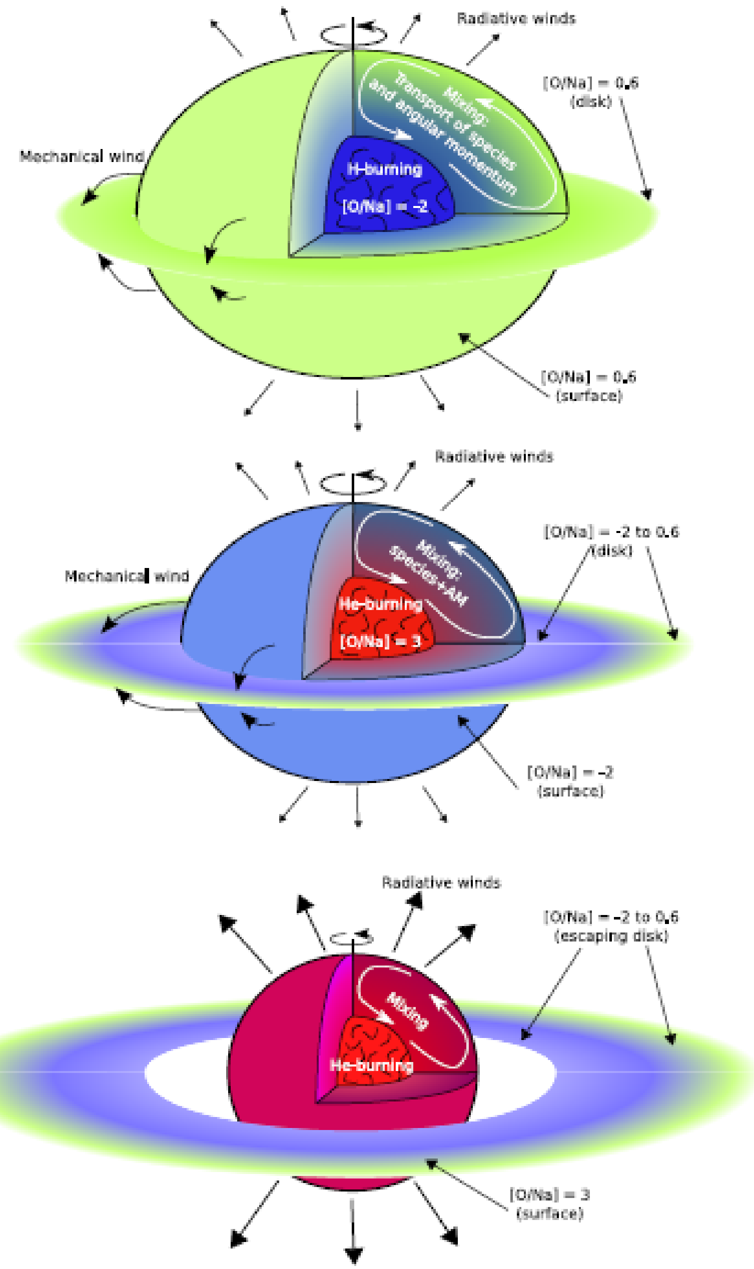
Proposed scenario (1)



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)

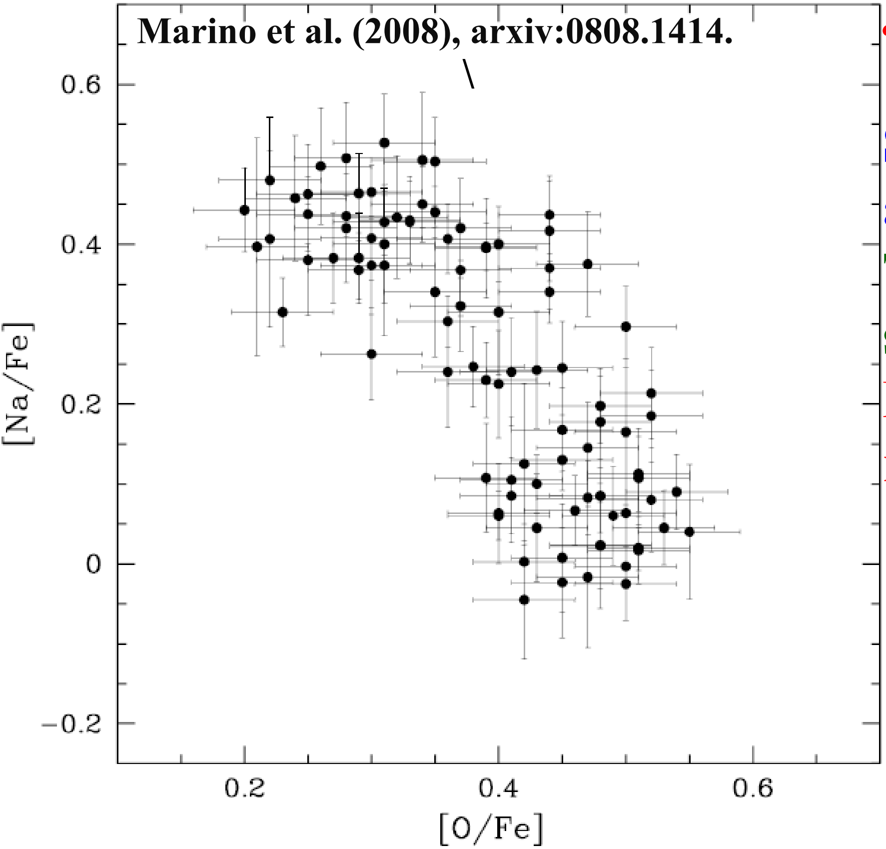


Pollution from fast rotating massive stars (Decressin et al. 2007, A&A, 475, 859).

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.

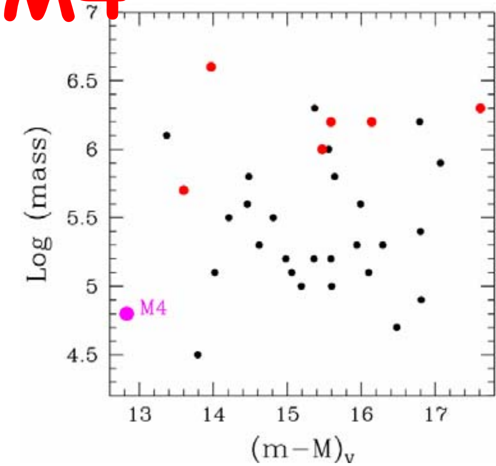
The case of M4

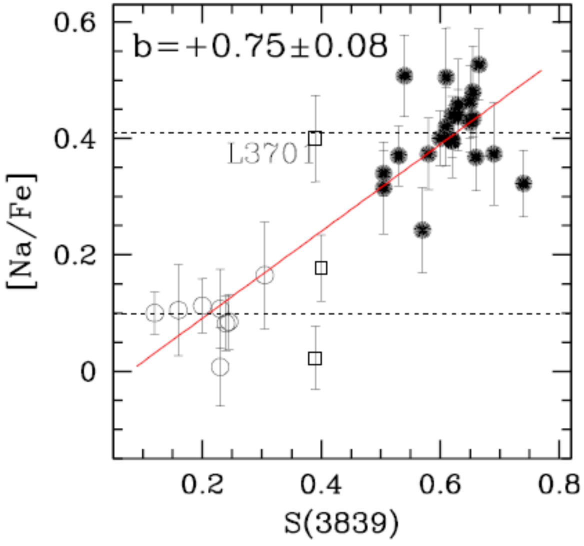


Strong NaO anticorrelation

Two distinct groups of stars

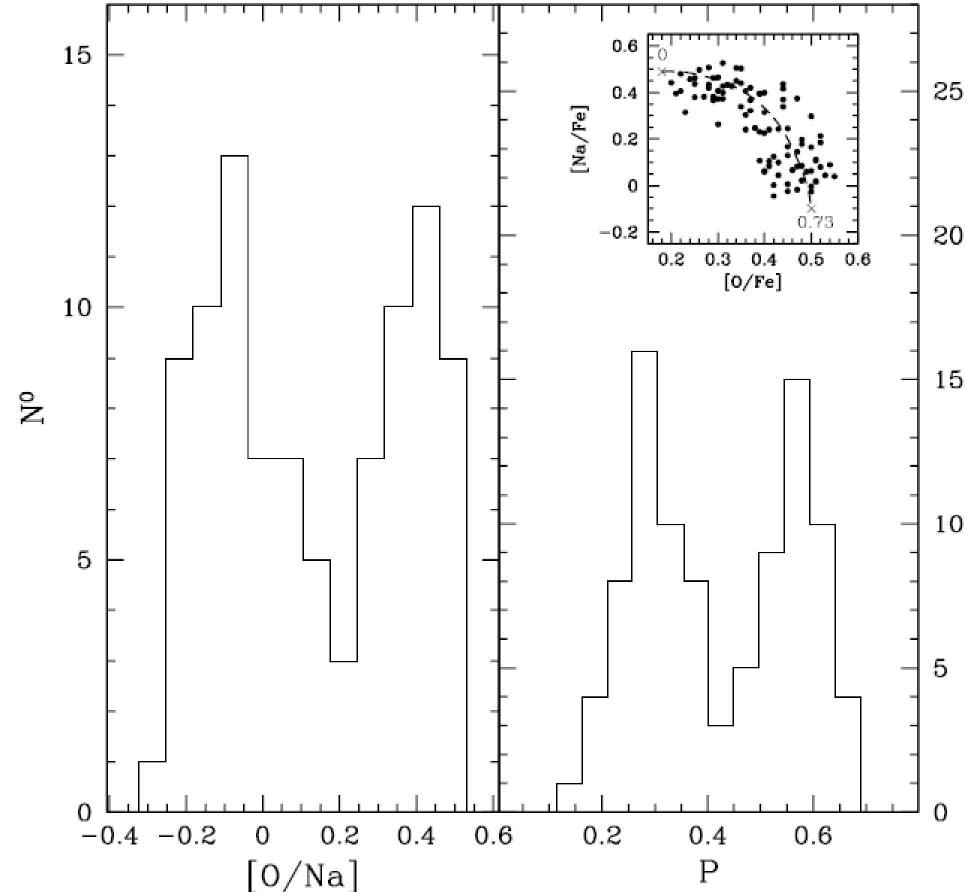
Mass: 8×10^4 solar masses!



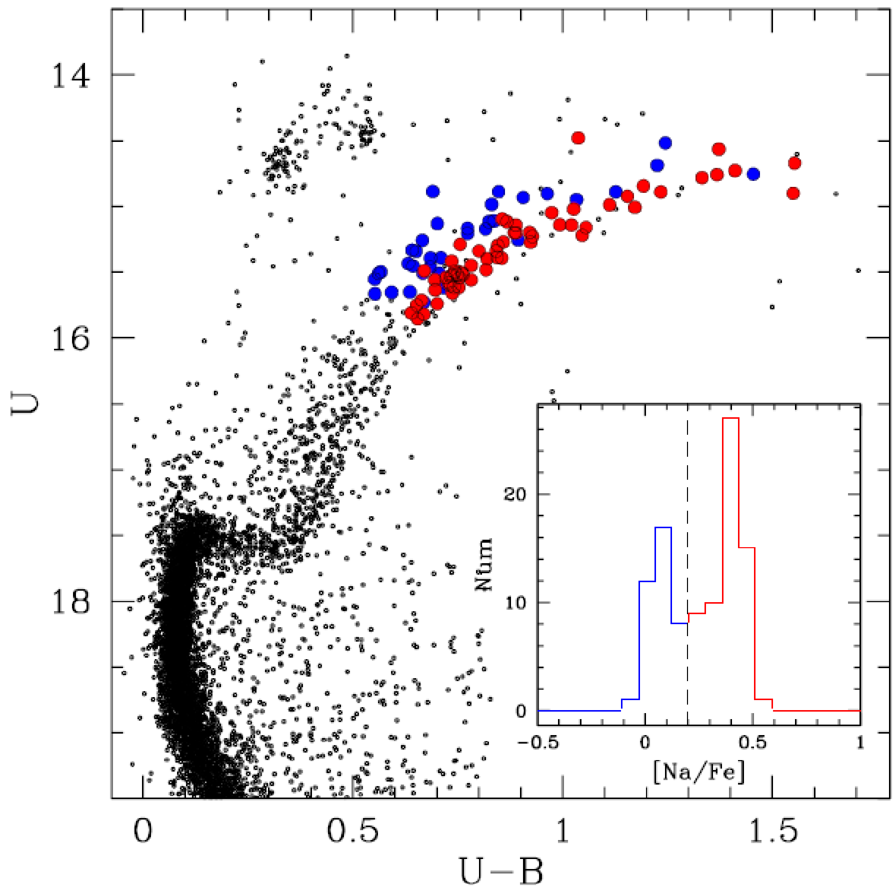


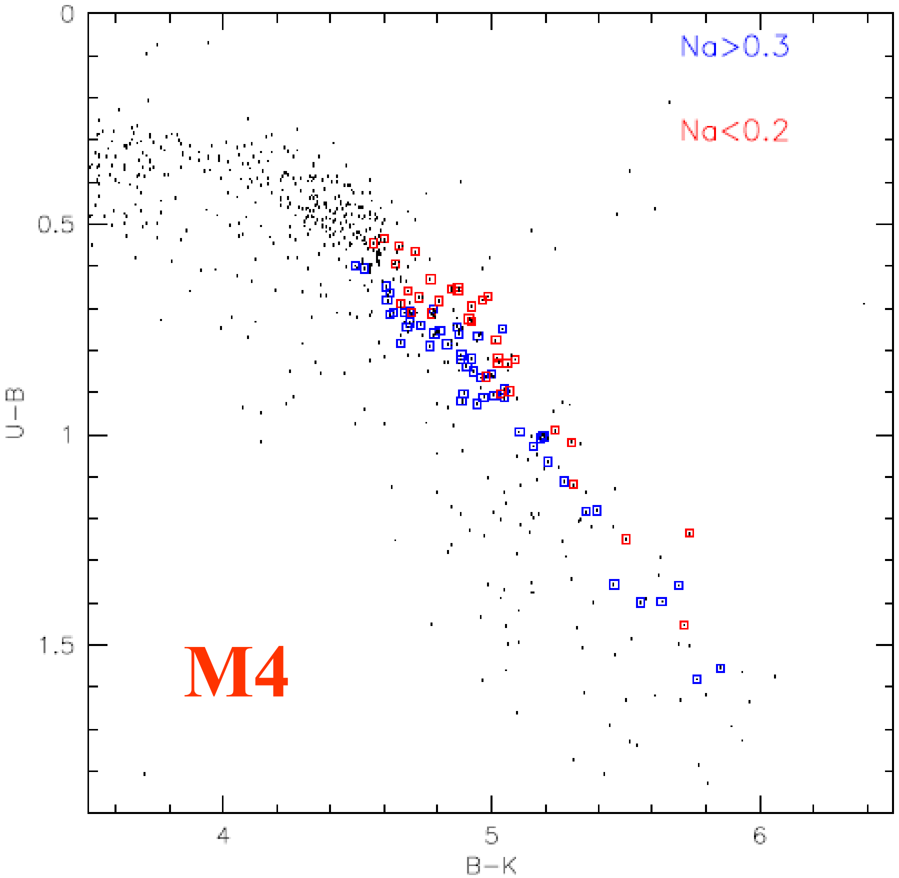
Na rich, O poor stars are CN strong

Na poor, O-rich stars are CN weak



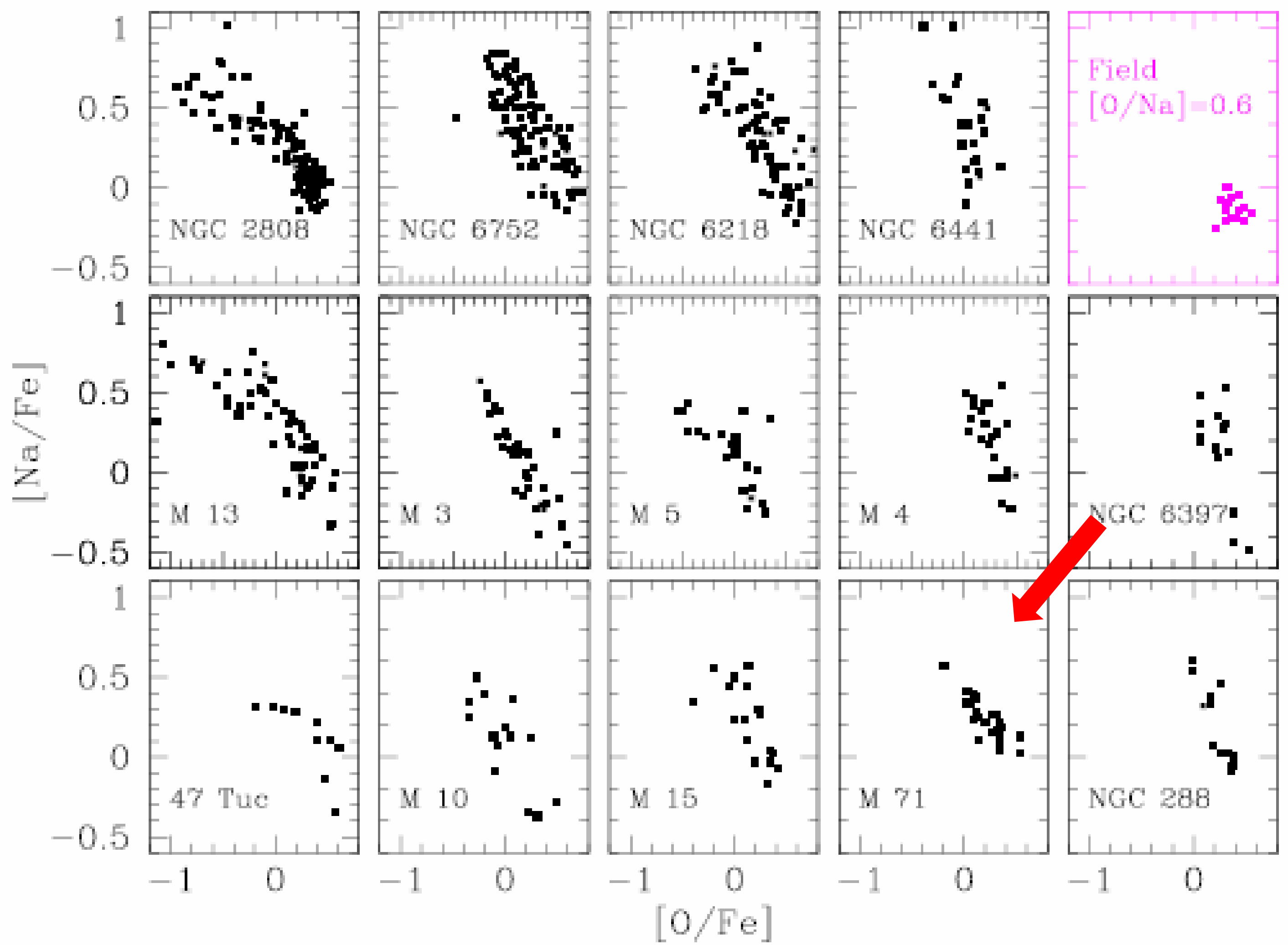
The two stellar groups are well distinguishable also in the color-magnitude and two color diagrams:



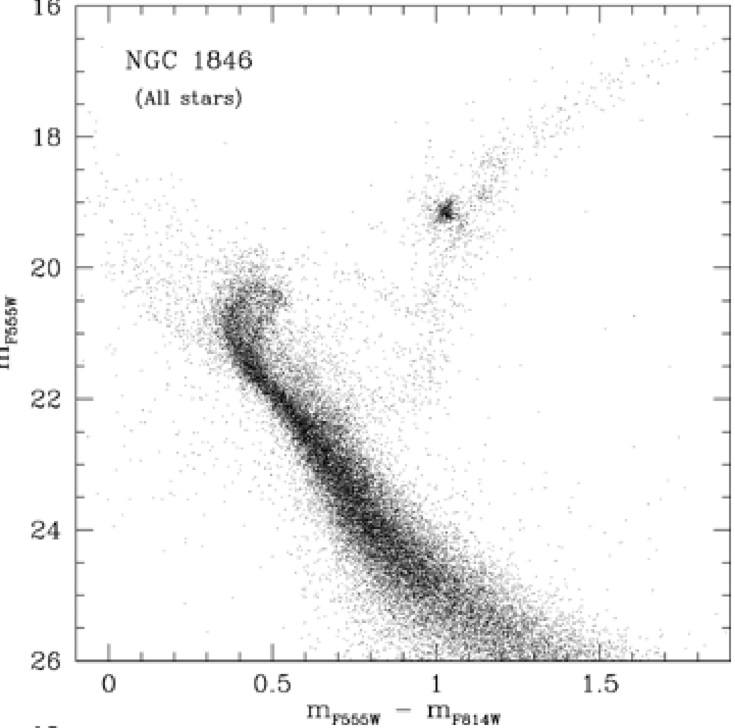


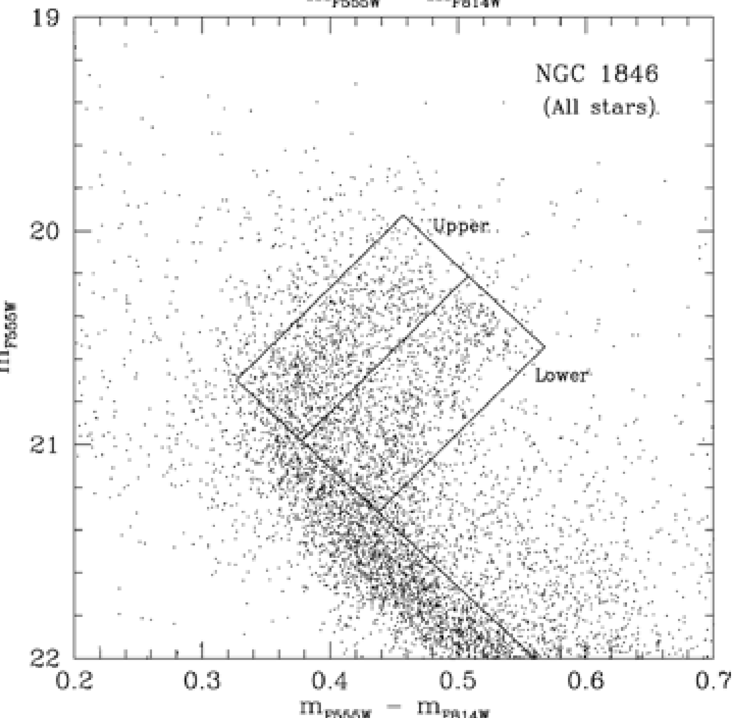
Marino et al. (2008), arxiv:0808.1414.

NaO anticorrelation present also il low mass globular clusters (M71: 3x10^4 solar masses)



Literature data: ∼ 500 stars inside ∼ 20 GCs
from Carretta et al. (2006,2007abc), Gratton et al (2001), Cohen et al (2005), Ivans et al (2001), Kraft et al (1995), Ramirez et al. (2002), Shetrone et al (2000)...

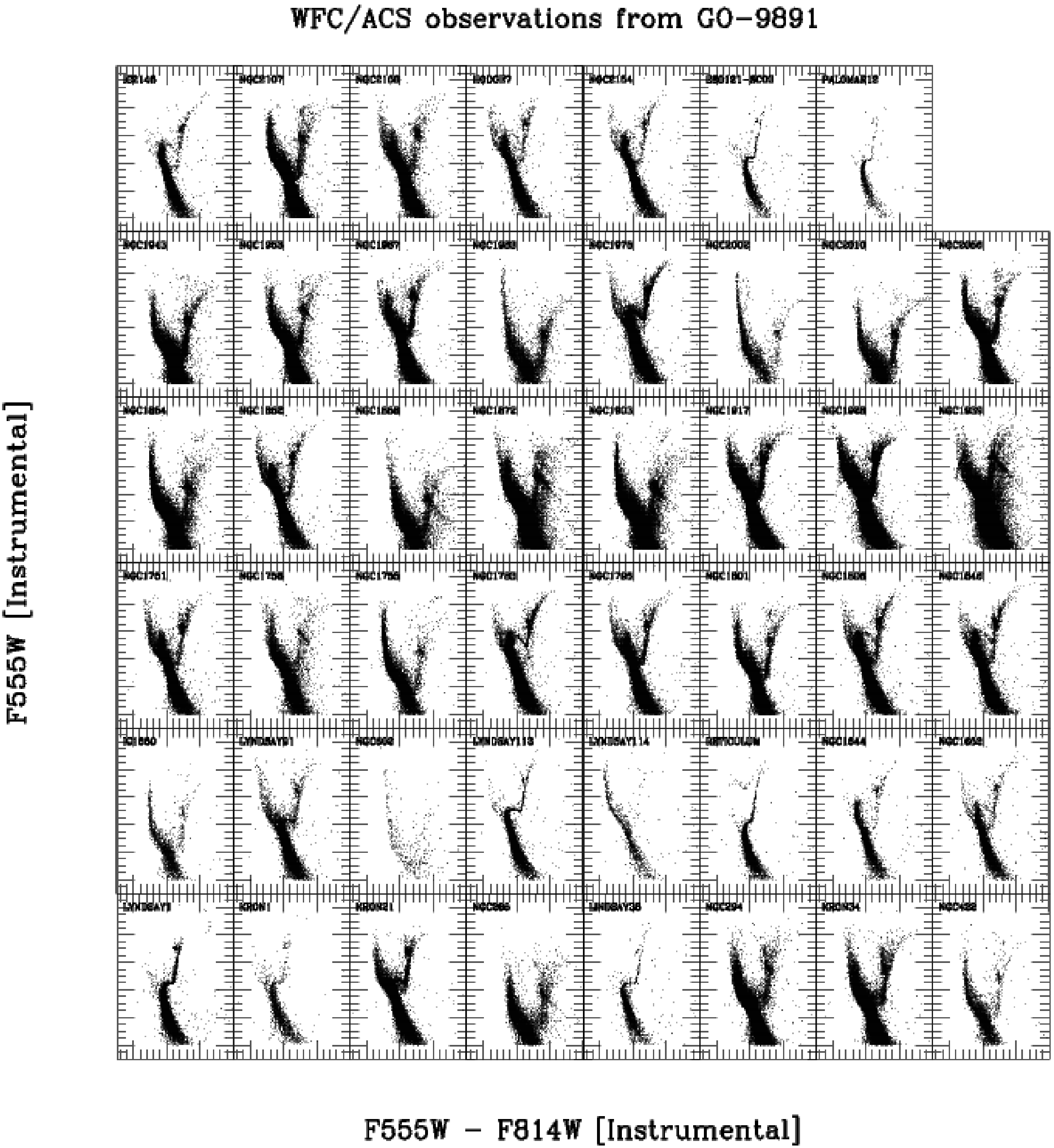




Mackey and Broby-Nielsen (2007, MNRAS, 379,151) suggested the presence of **two populations with an age difference of ~300Myr in the 2Gyr old LMC cluster NGC 1846.**

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).

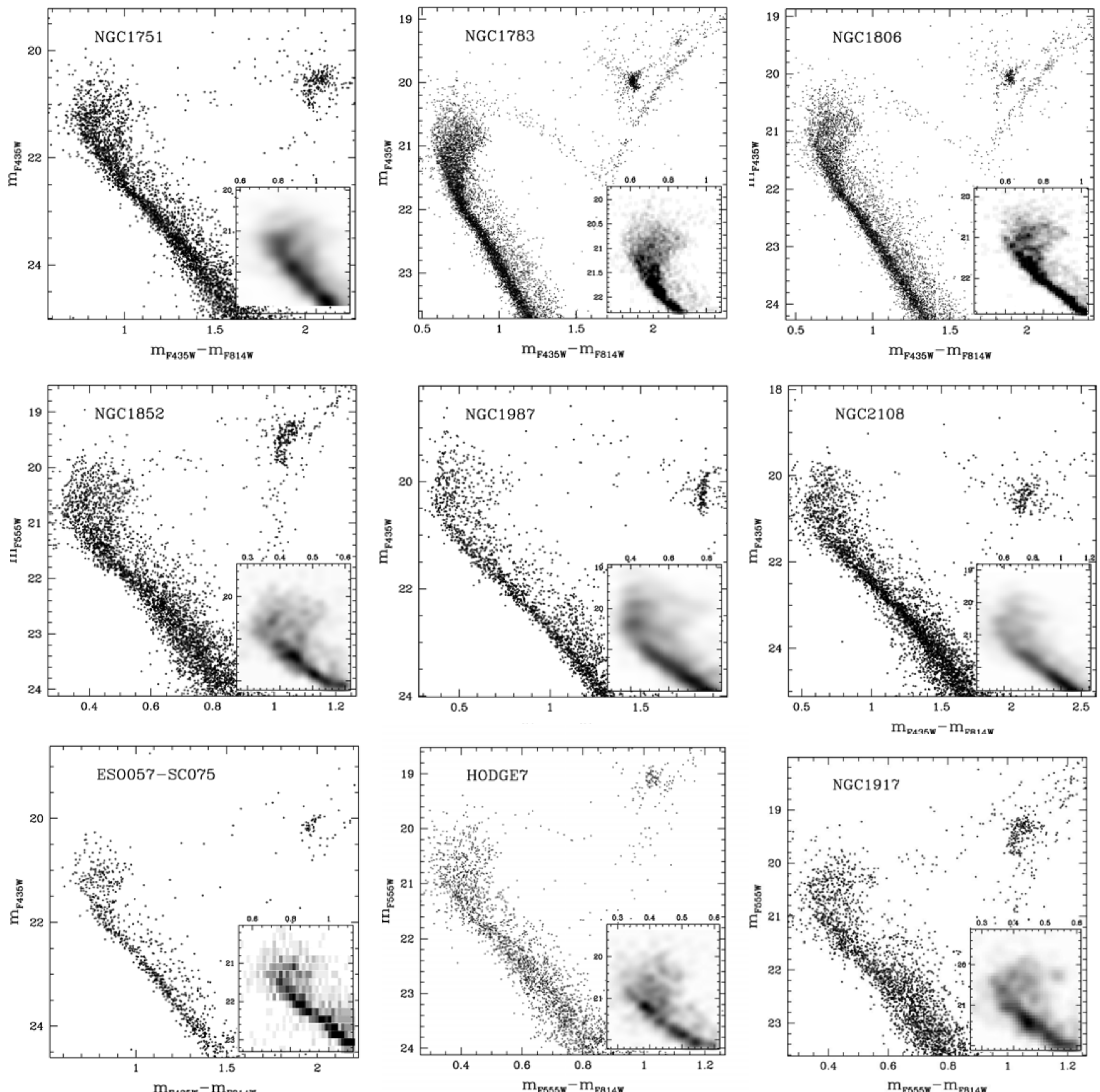


Milone et al. (2008), A&A, in press, arxiv:0810.2558

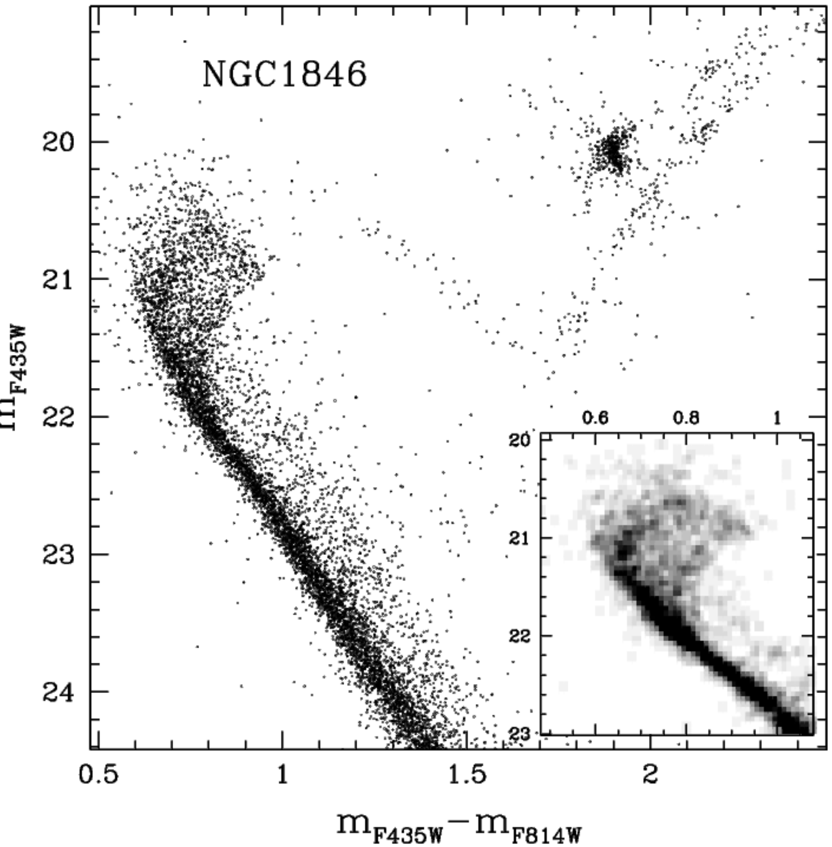
LMC clusters

We used ACS/HST archive data to construct the CMDs of 46 LMC clusters.

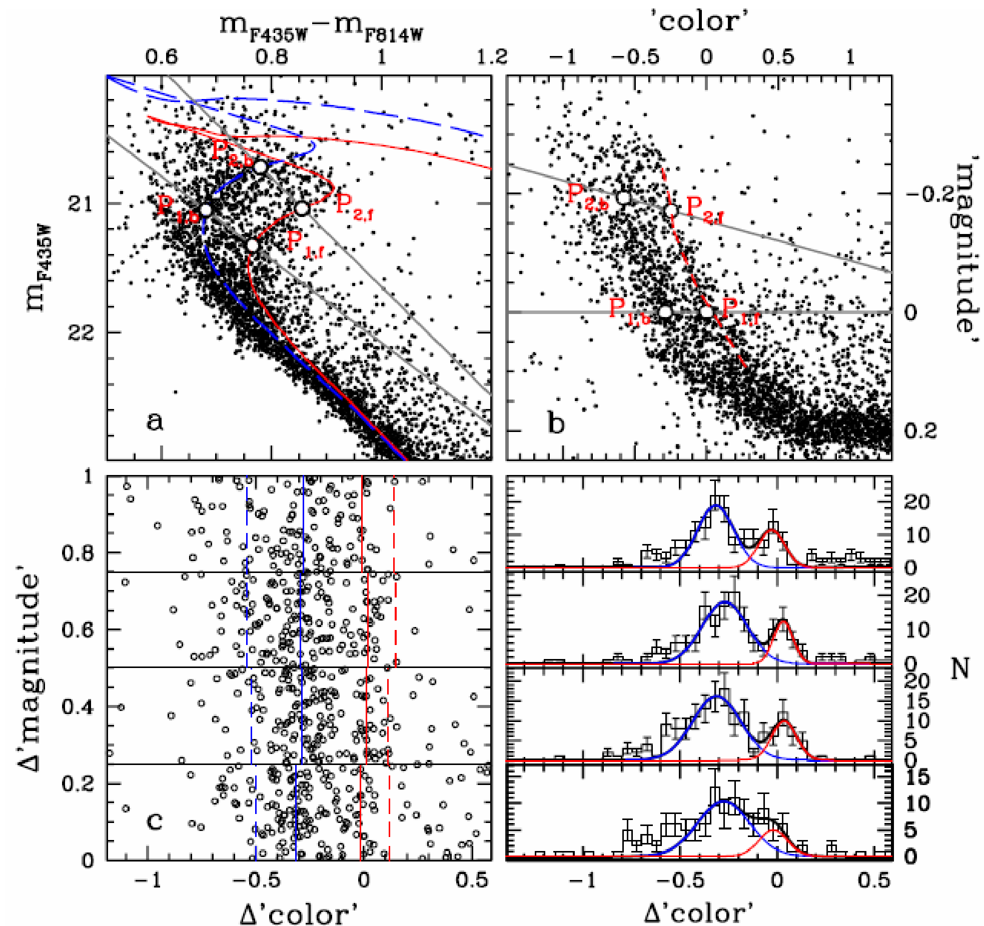
We investigate the CMD morphology of 16 intermediate age clusters, with ages between 1 and 3 Gyr.



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



In NGC 1846, 67±6% of the stars are part of the brighter (younger?) TO population, and 33±6% are part of the fainter (older) TO population.



In NGC 1806, 77±4% of the stars are part of the brighter (younger?) TO population, and 23±6% are part of the fainter (older) TO population.

Conclusions

Thanks to the new results on the multiple populations
we are starting to look 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 HST cameras that will be available after SM4 will play a major role in composing 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 as a nightmare for decades), as well as the newly discovered multiple sequences in the CMD.
3) The new findings on Galactic GCs necessarily imply a radical revision of GC formation and early evolution models, but this is a MODEST problem….