The impact of ESO facilities on globular cluster research

25 Years of Fascinating Discoveries

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THE ASTRONOMICAL JOURNAL VOLUME 96, NUMBER 6 DECEMBER 1988

COLOR AND POPULATION GRADIENTS IN THE CORE OF THE POSTCOLLAPSE GLOBULAR CLUSTER M30[a]

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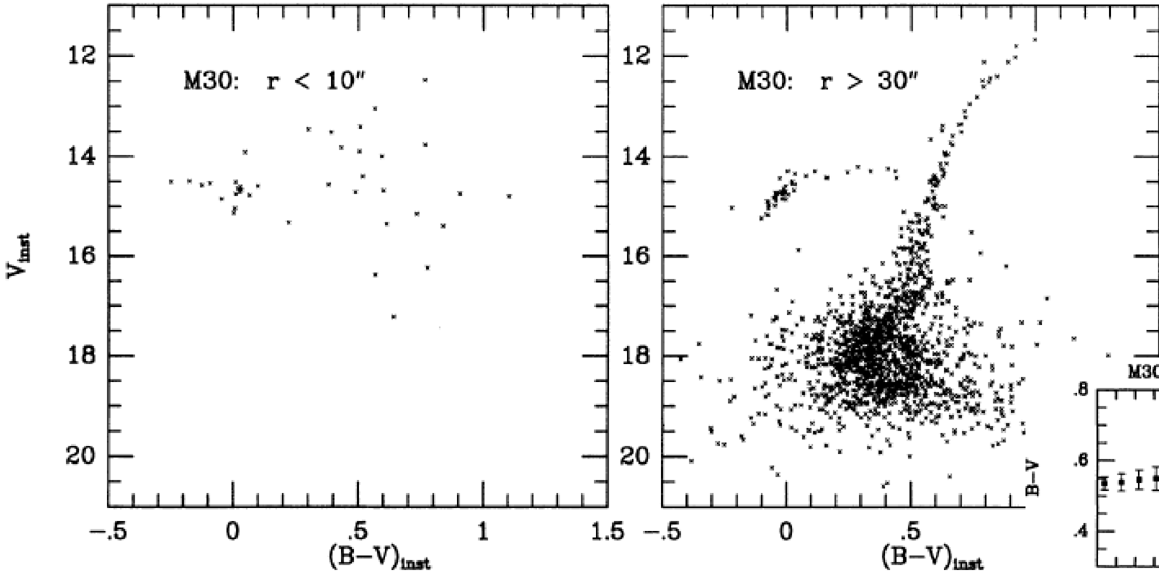
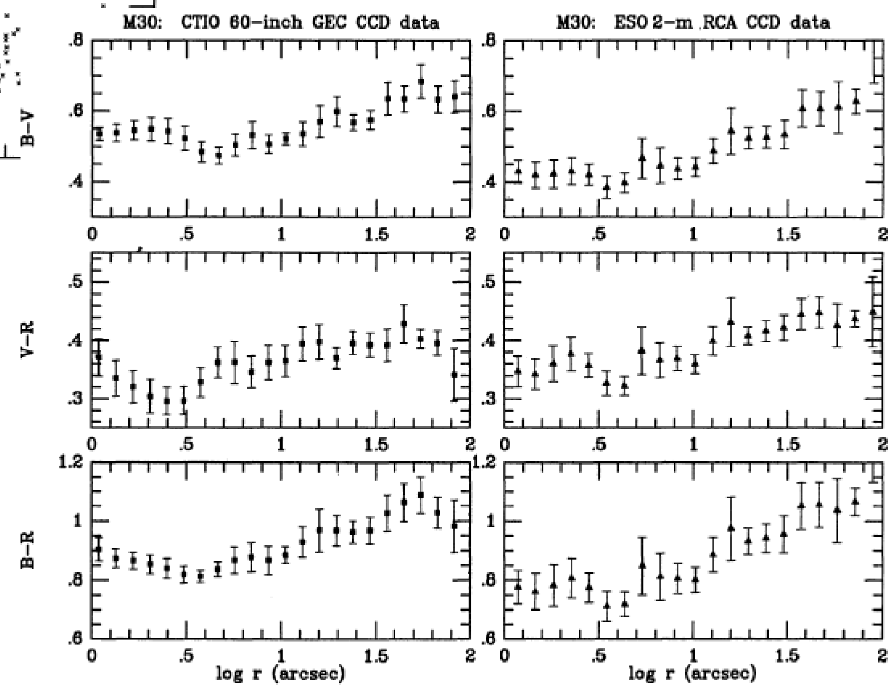
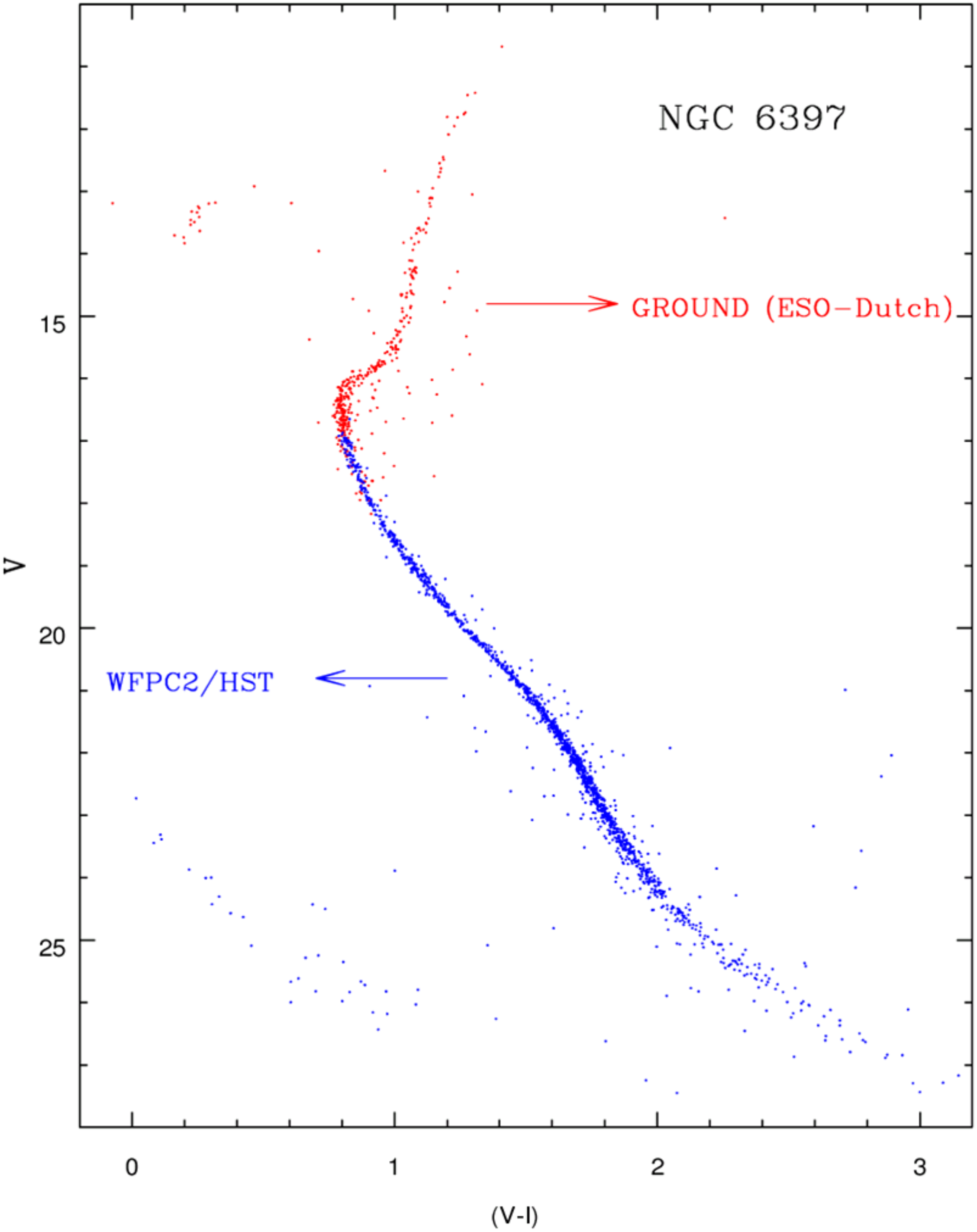


FIG. 4. Color–magnitude arrays of the central part and the outer part of our ESO field.

Discovery of color gradients GCs

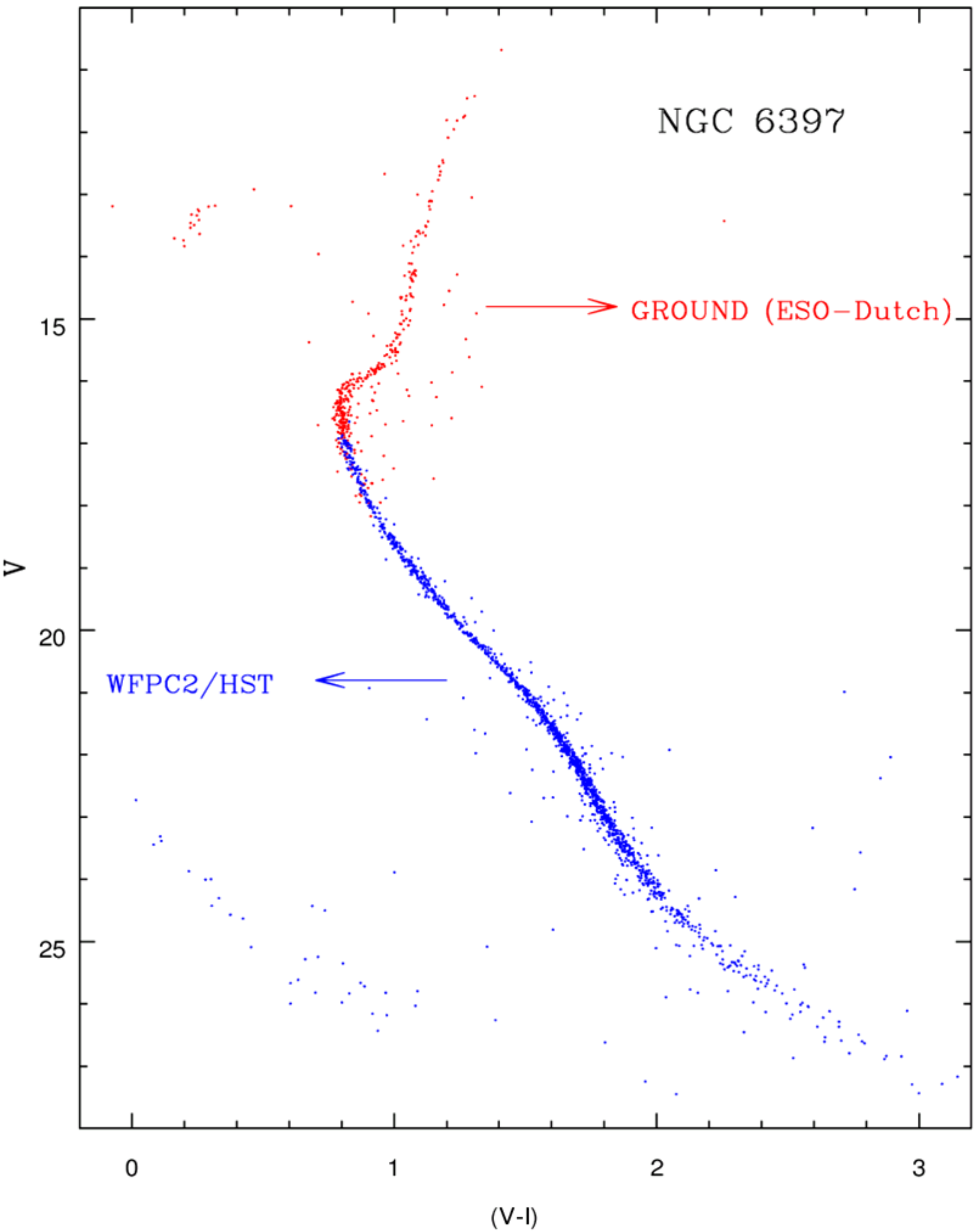


ESO/MPI2.2m CCD data



The typical color-magnitude diagram of a globular cluster all of us wanted to see in the 90's

Optimal example of ground-based and HST sinergy



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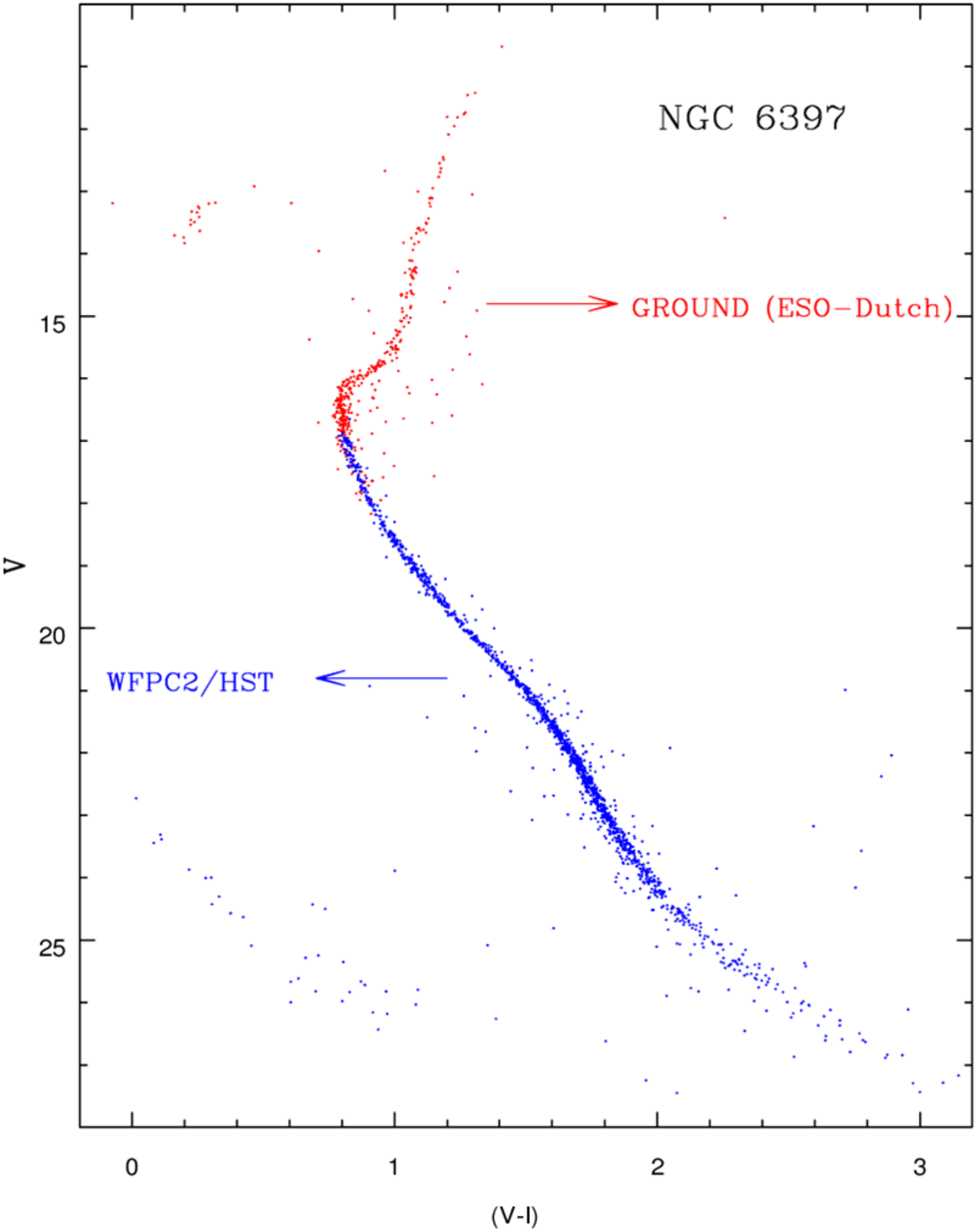
Indeed, the narrowness of the sequences was considered the best possible indicator of a good photometry



The typical color-magnitude diagram of a globular cluster all of us wanted to see in the 90's

Optimal example of ground-based and HST sinergy

Indeed, the narrowness of the sequences was considered the best possible indicator of a good photometry, as we had in mind the **"simple stellar population"** concept, a paradigma for stellar population of star clusters

But real changes on our knowledge of the stellar population of GCs arrived at the beginning of the new millennium, thanks to the **new ACS (and then WFC3) camera onboard HST** and **a few ESO instruments** which significantly contributed to the new vision on GCs. Among them:

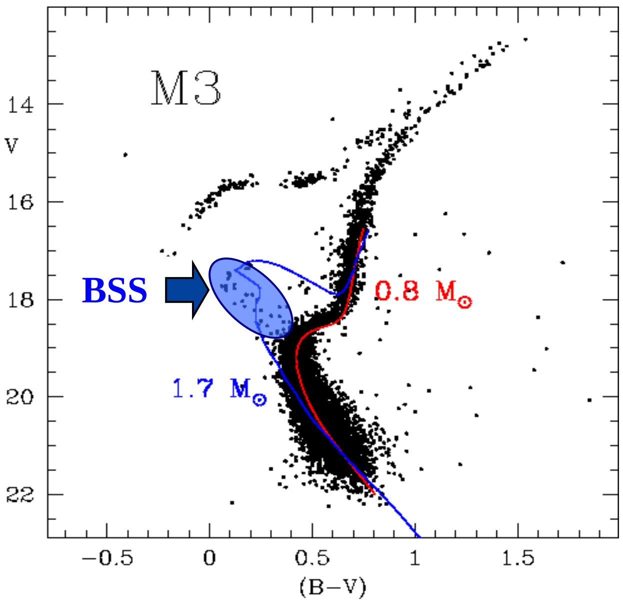
1) **The wide field imager (first one, the WFI@2.2m)**

2) **UVES/GIRAFFE+FLAMES@VLT**

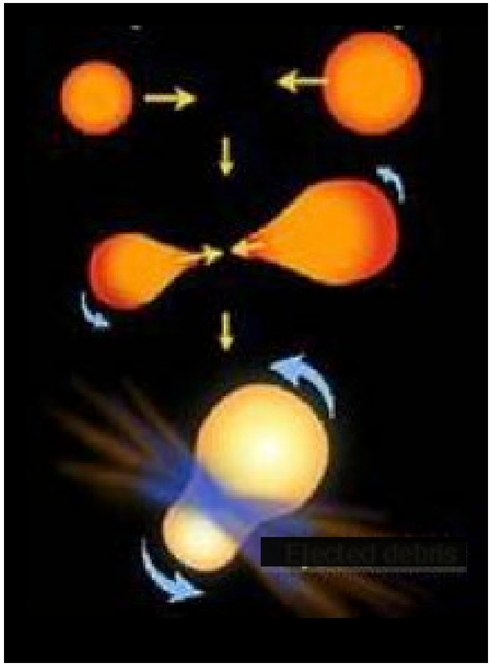
3) **High resolution imagers at VLT**

Blue Straggler Stars (BSS)

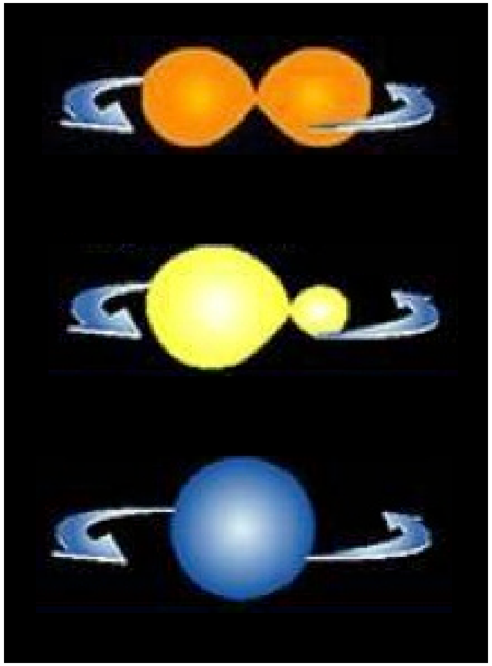
more massive than normal stars (=> dynamical friction)



collisional BSS



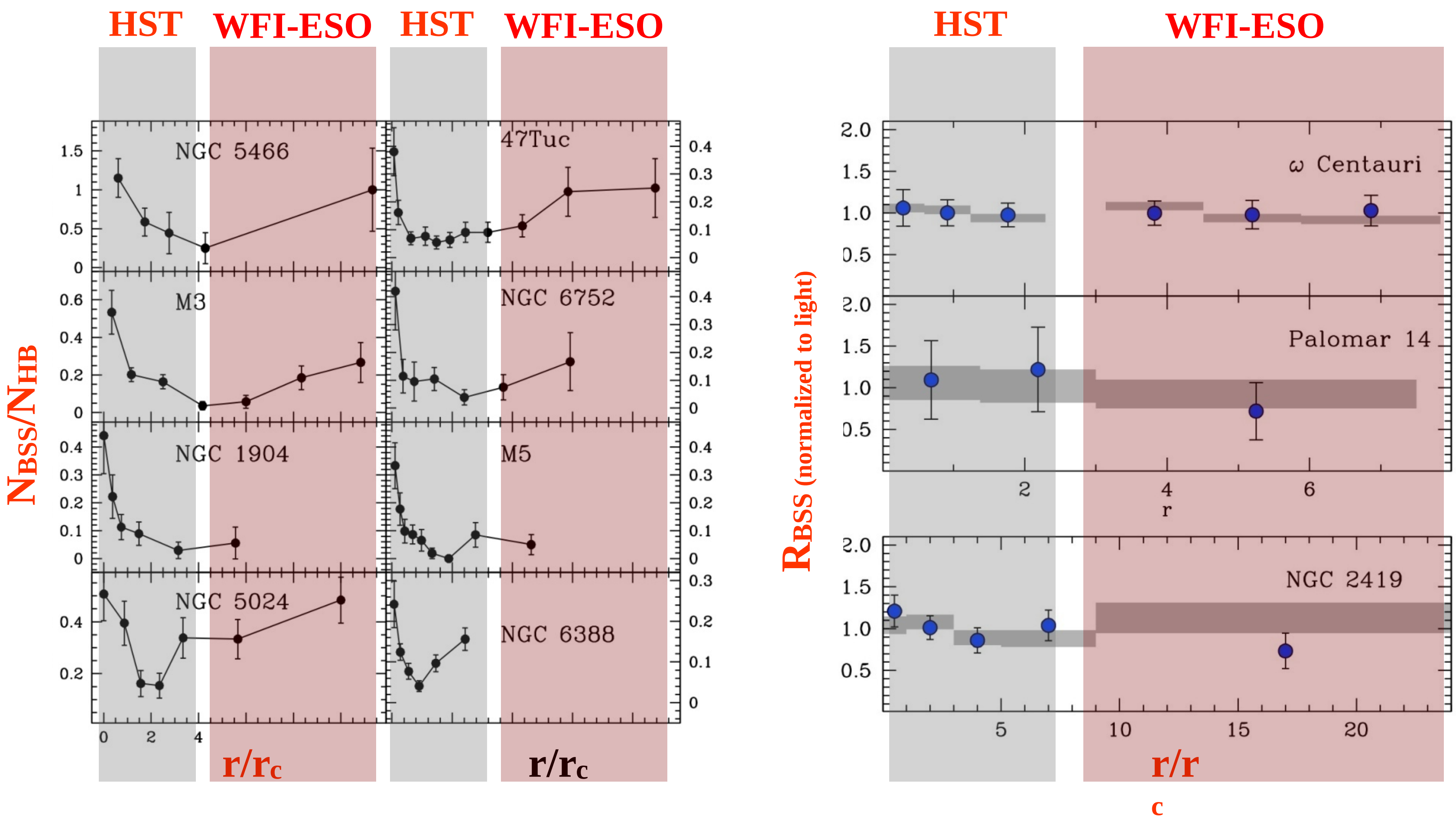
mass-transfer BSS



BSS: crucial probes of

stellar evolution and cluster dynamical evolution

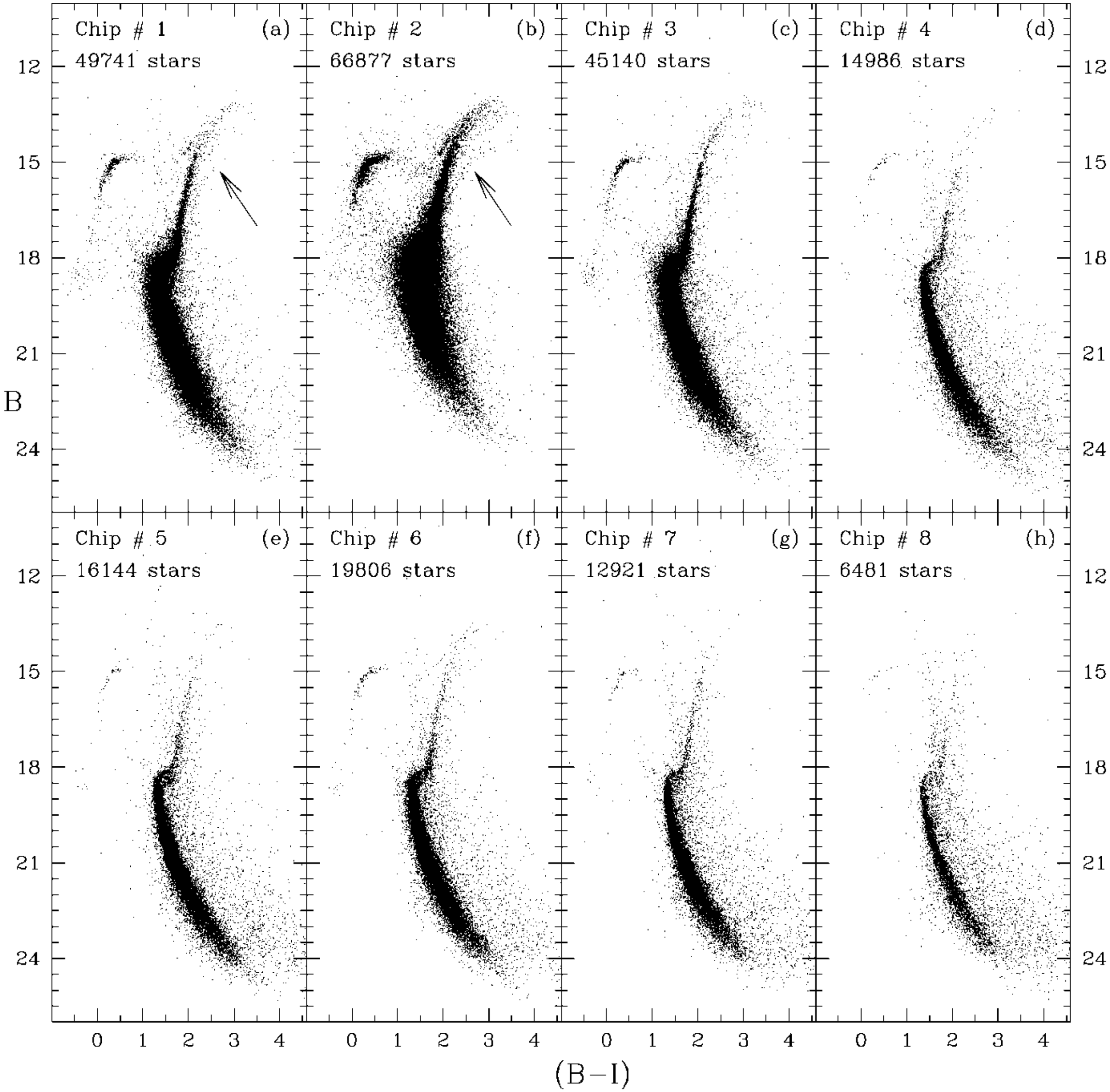
The BSS radial distribution



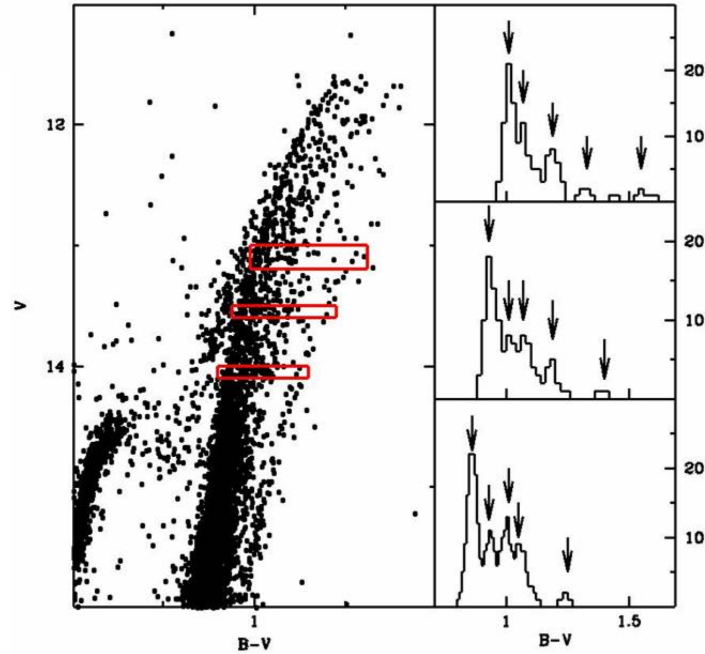
Good example of HST and groundbased complementary data

Ferraro et al. (93, 94, 04); Sabbi et al. (04); Lanzoni et al. (07ab); Dalessandro et al. (08); Beccari et al. (08, 09, 11); Contreras Ramos et al. (12); ...

First results from WFI@2.2m

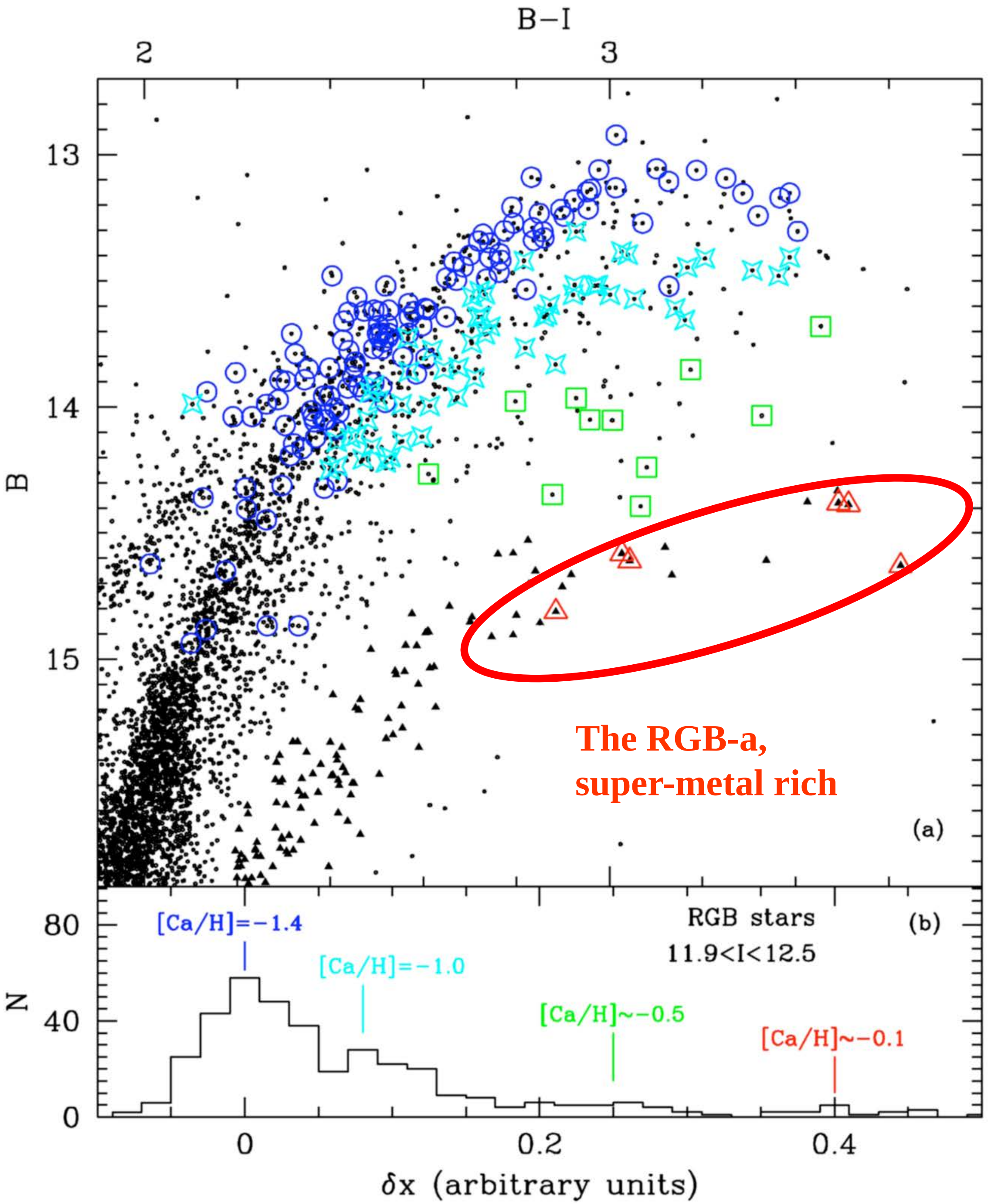


Pancino et al, 2000, ApJ, 534, L83



(More recent data from FORS@VLT data by Sollima et al. 2005)

ωCen has a complex RGB

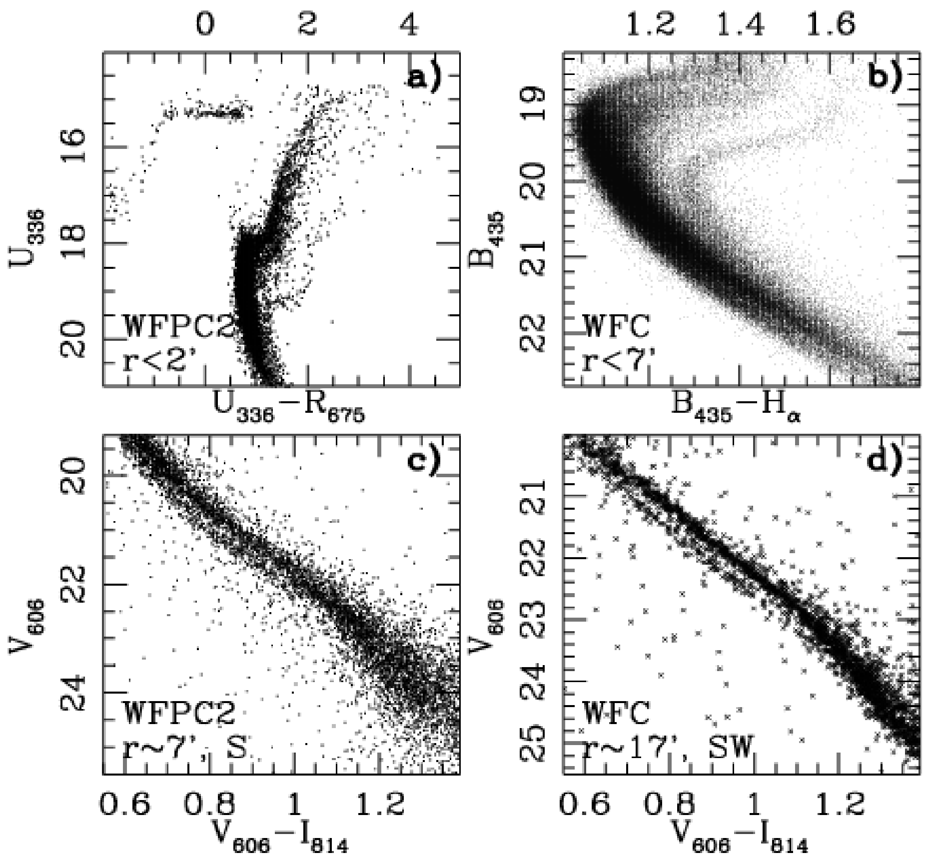


First results from accurate, wide field photometry:

The multiple RGB of ωCen, following the complex metallicity distribution

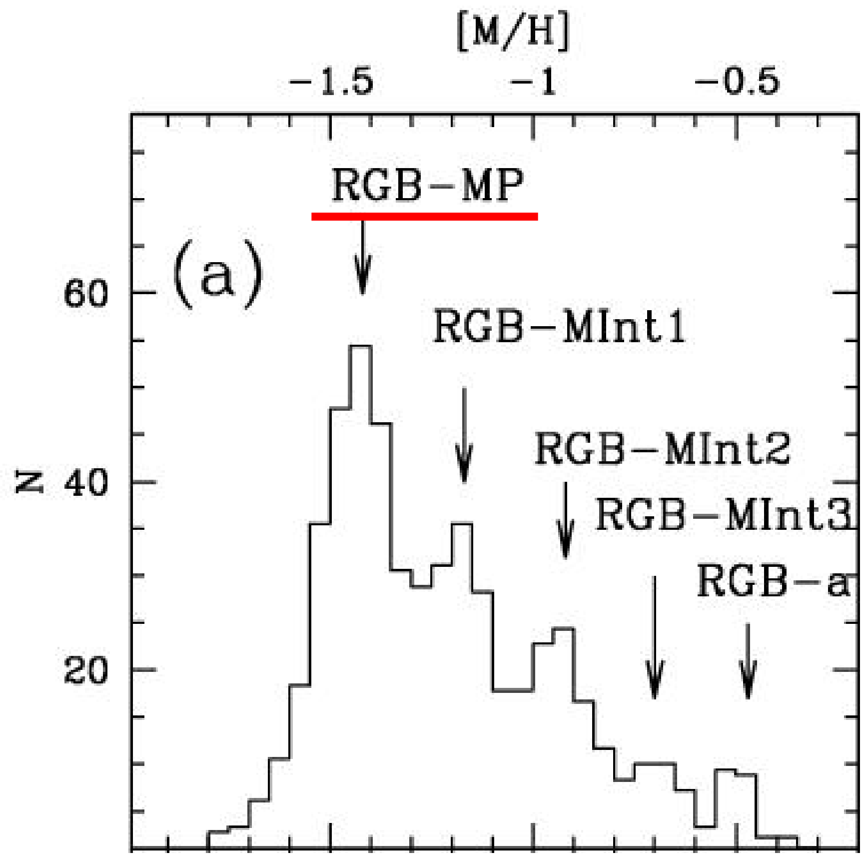
Pancino et al, 2000, ApJ, 534, L83

The double main sequence of ωCentauri



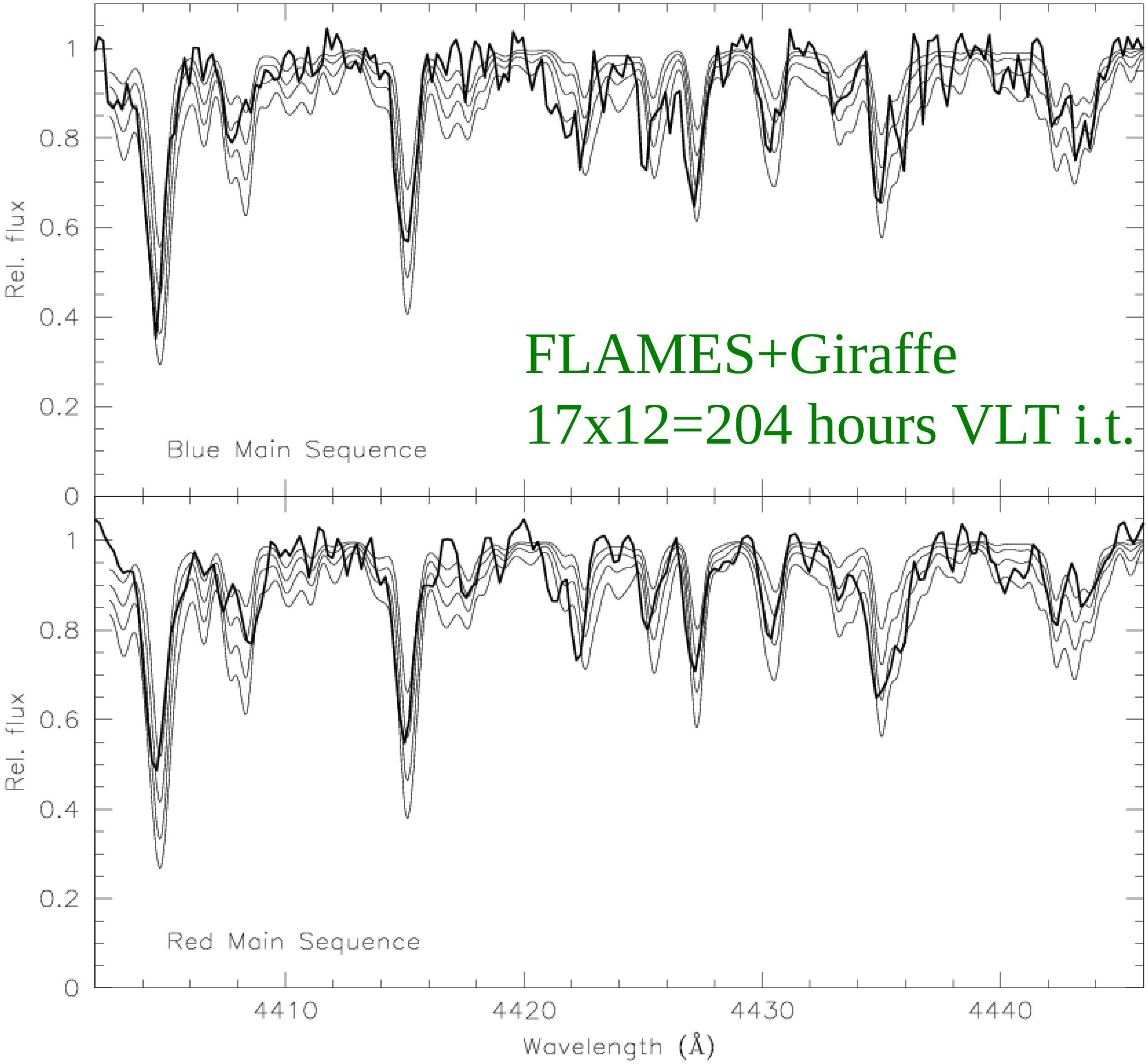
Anderson 1997, PhD thesis

Bedin et al. 2004, ApJL, 605, L125



Something anomalous must be going on…..most populous sequence is also the reddest one, at odds with cluster metallicity distribution

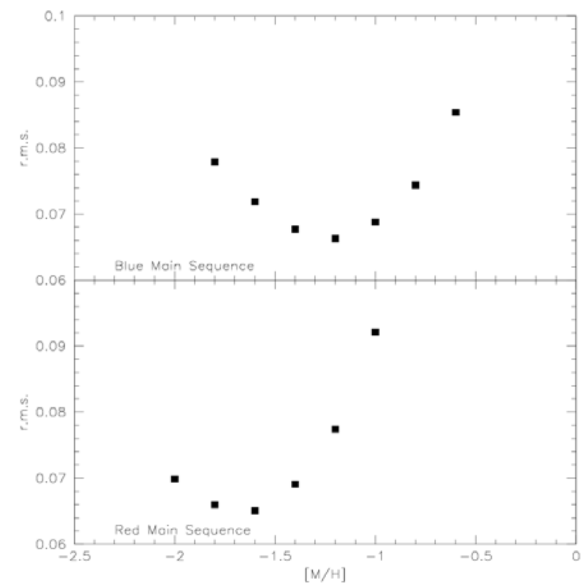
The most surprising discovery: ESO DDT



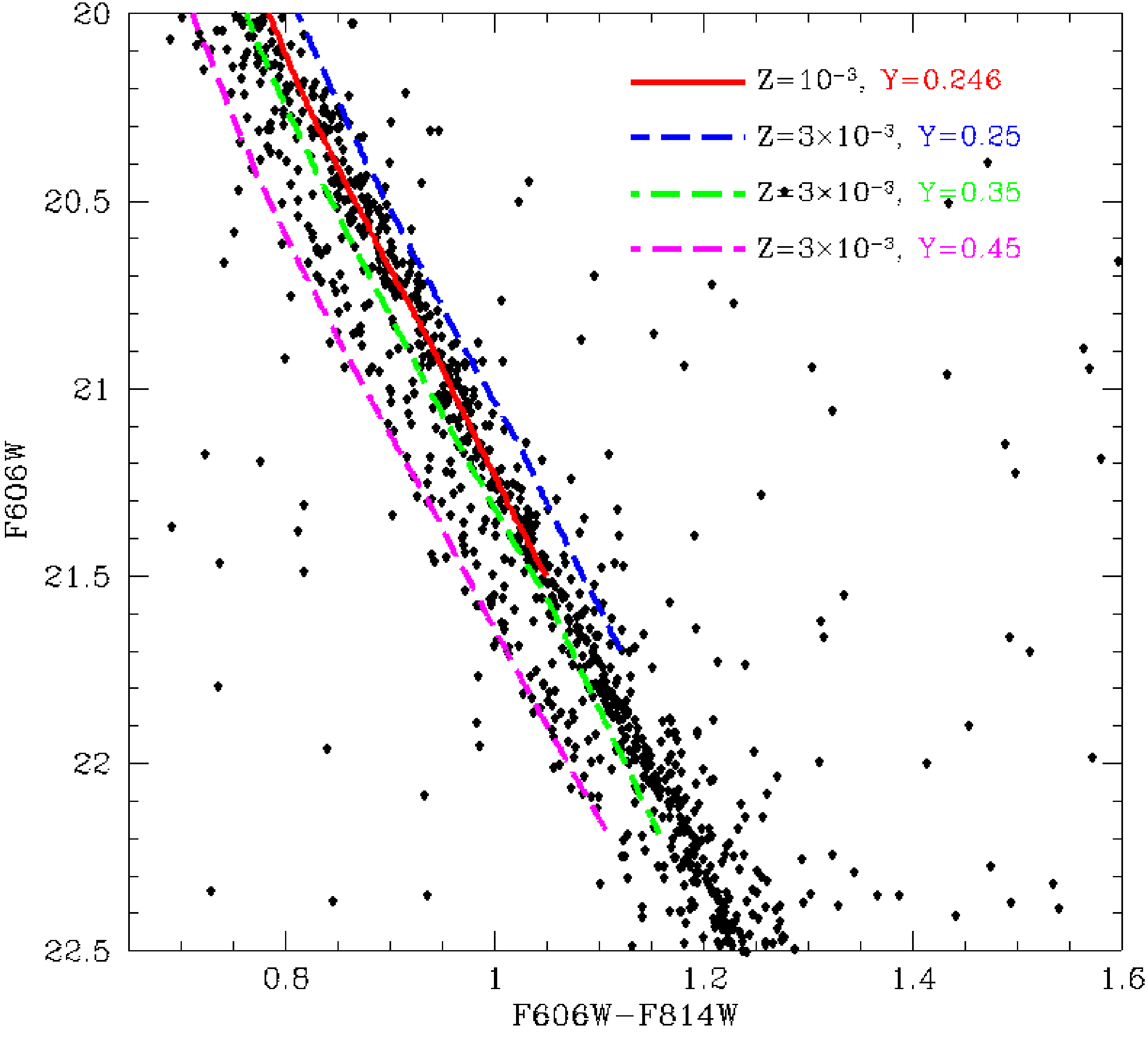
FLAMES+Giraffe
17x12=204 hours VLT i.t.

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

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



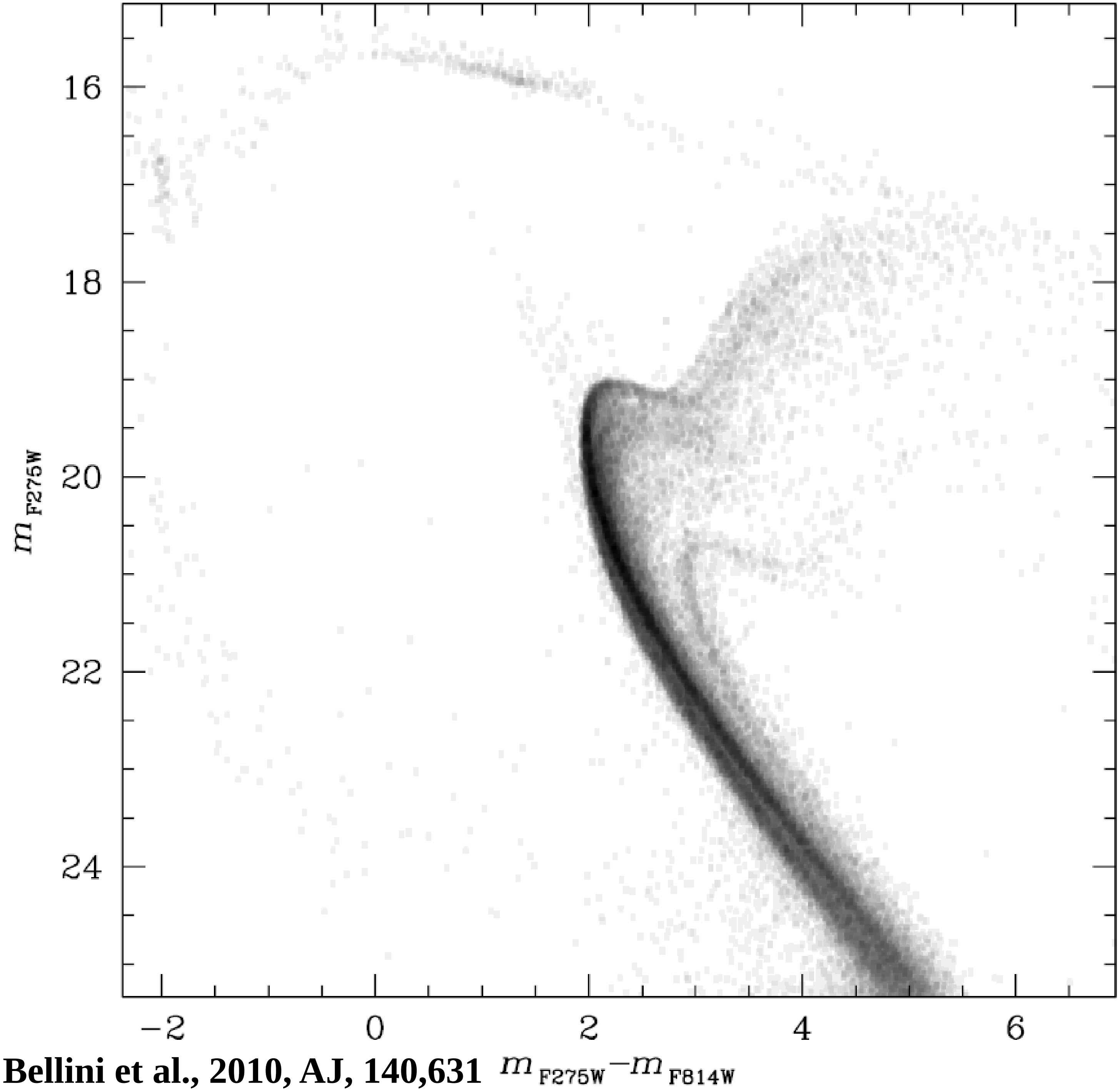
Piotto et al. (2005, ApJ, 621,777)
ESO press release 509, March 15, 2005



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

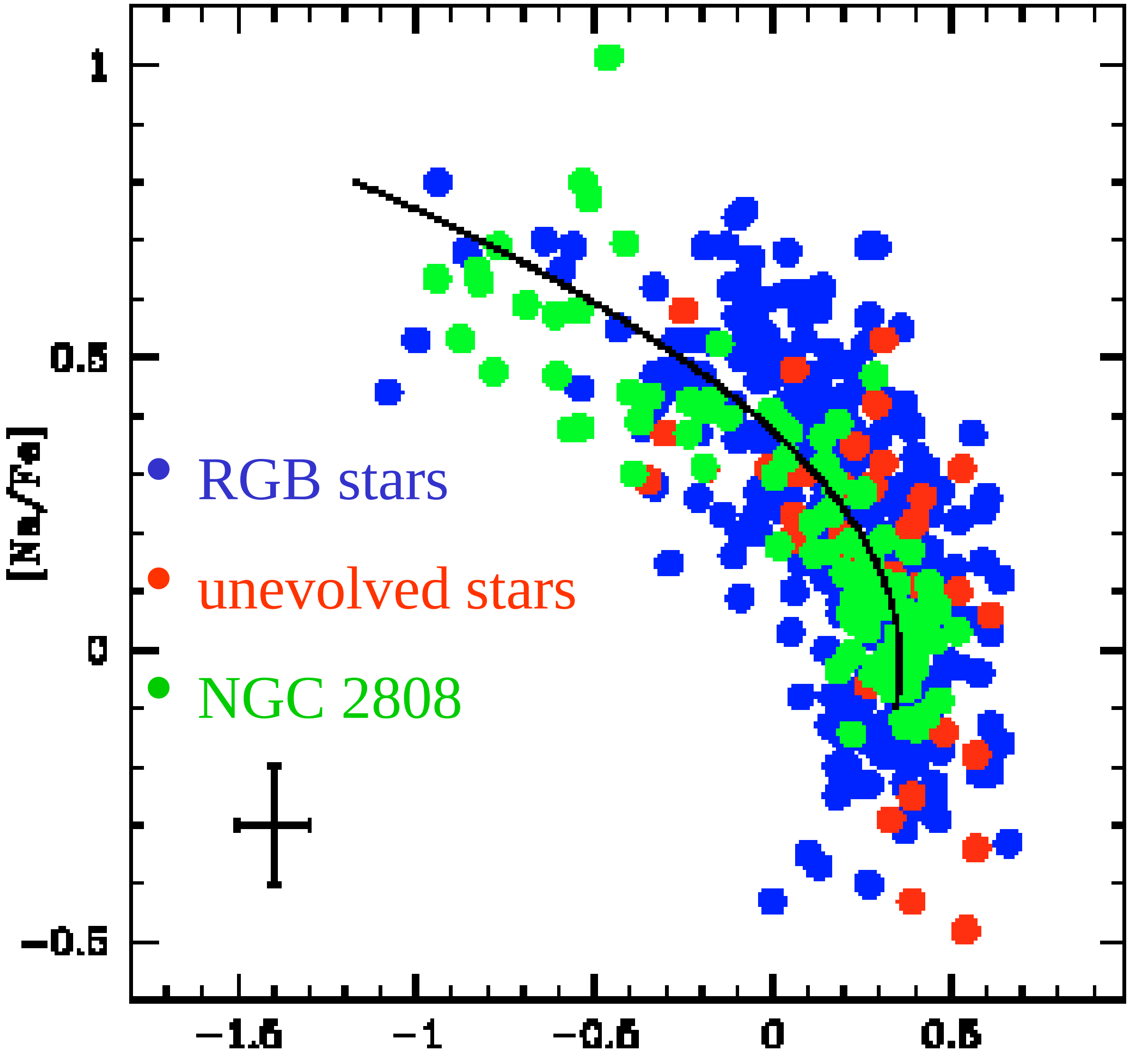
Helium!

Apparently, only <u>an overabundance of helium (Y~0.40)</u> can reproduce the observed blue main sequence



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!



(from Carretta et al. 2006)

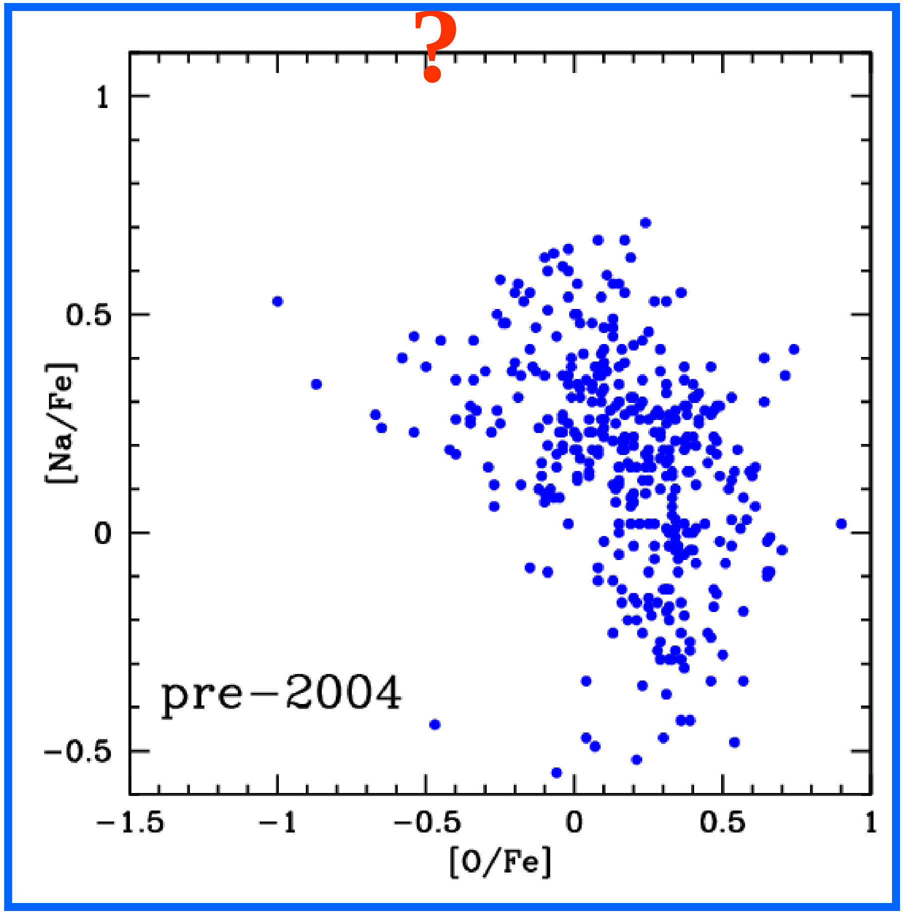
Na-O and Mg-Al anti-correlations have been found also among MS stars (thanks to VLT!).

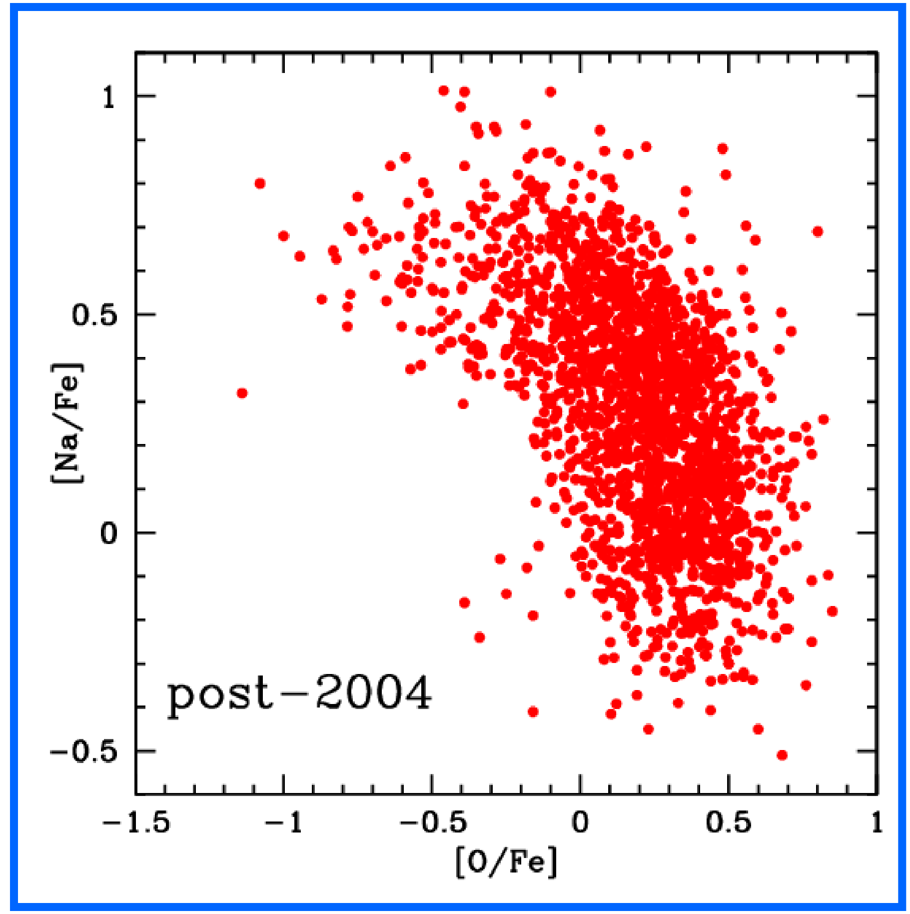
Proton capture processes responsible for these anti-correlations are possible only at **temperatures** of **a few 10 million degrees,** in the complete CNO cycle (which implies also an O depletion) **not reached in present day globular cluster main sequence and red giant stars.**

Note that the CNO cycle transforms hydrogen into <u>helium</u>

Fundamental contribution by VLT and FLAMES/GIRAFFE/UVES

FLAMES: the revolution in high resolution (multiplex) spectroscopy

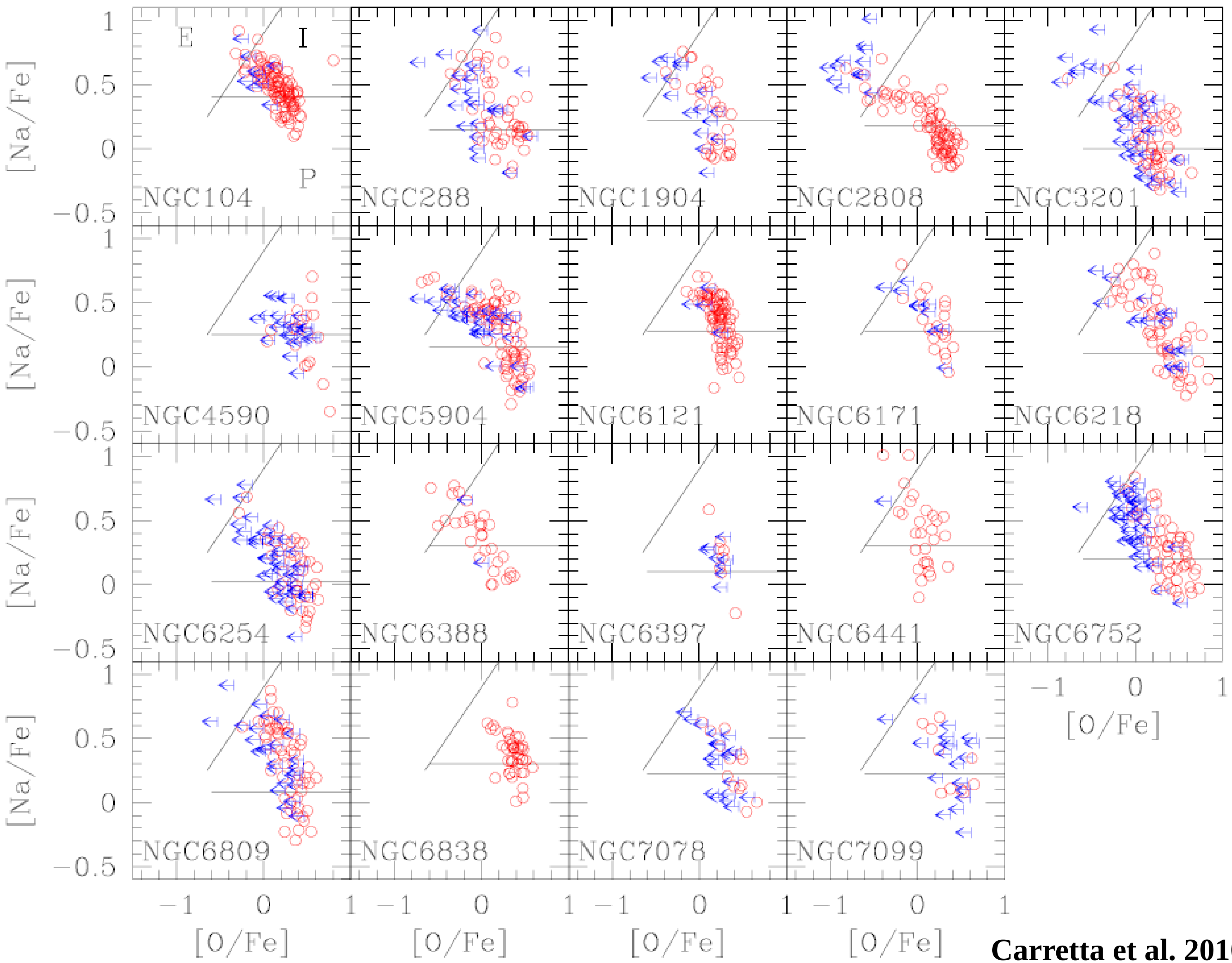




~ 400 stars in 23 GCs

~ 2700 stars in 33 GCs

NaO universal among GCs?



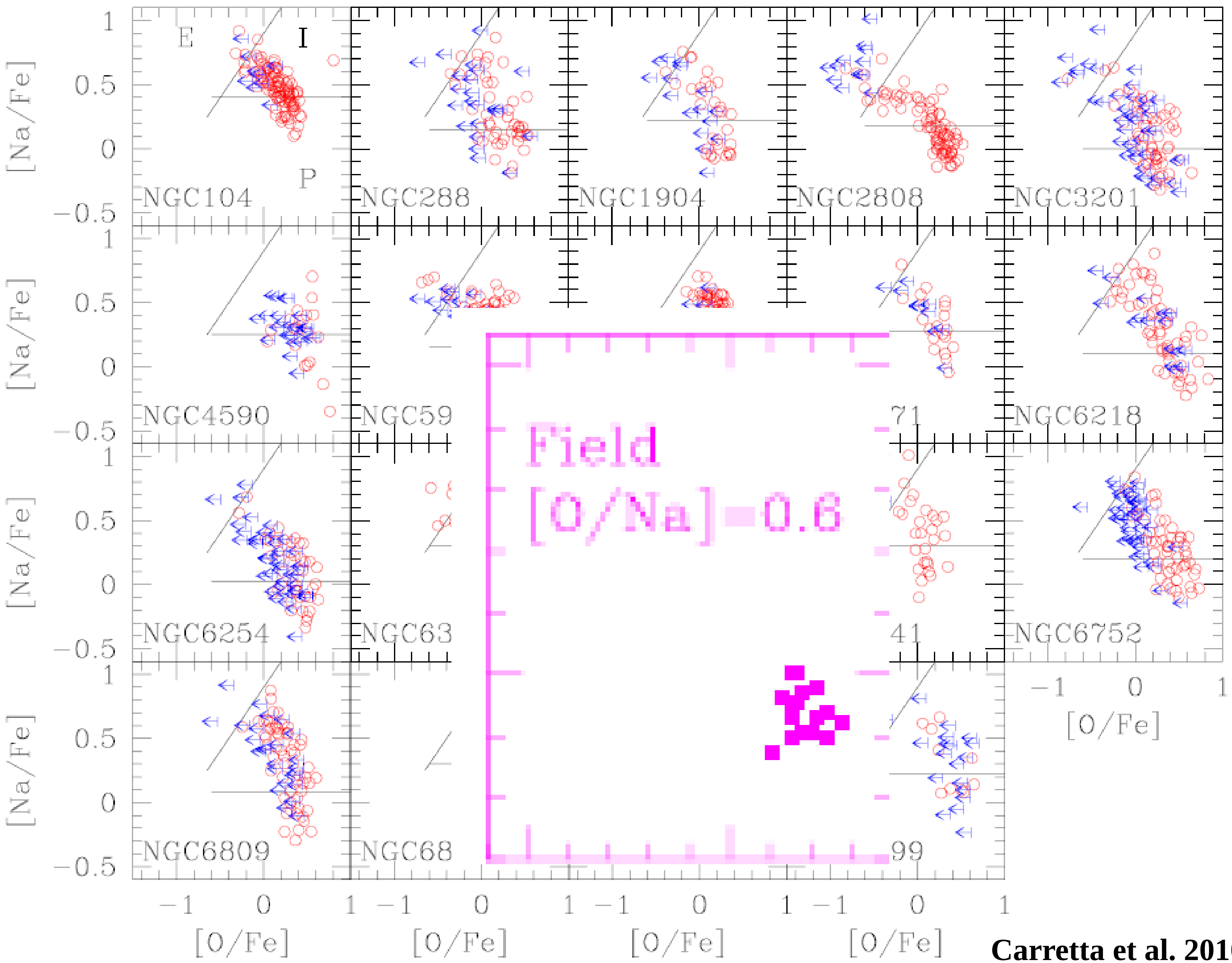
Carretta et al. 2010

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.

GCs differenct from field stars



Carretta et al. 2010

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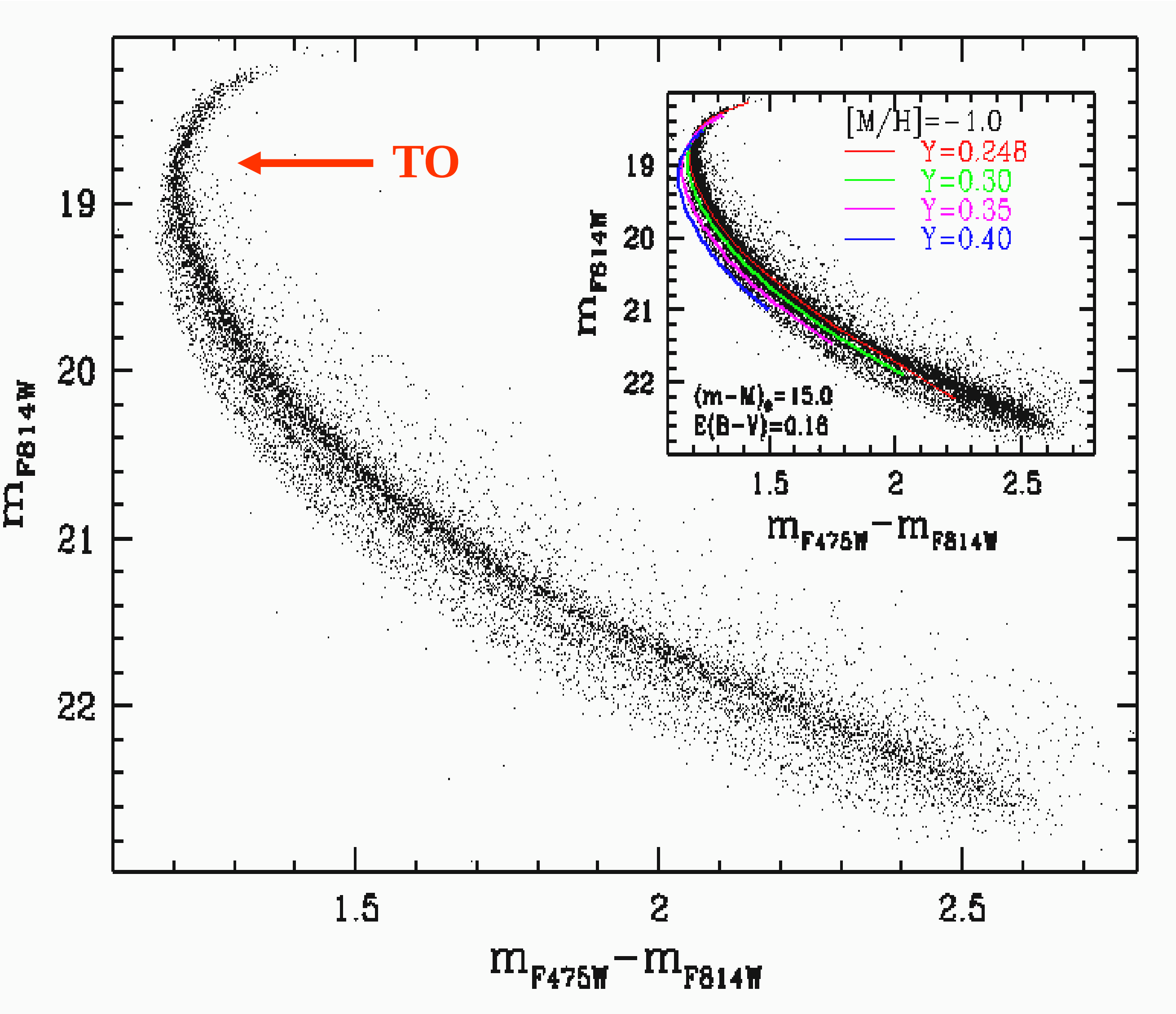
The triple main sequence in NGC 2808



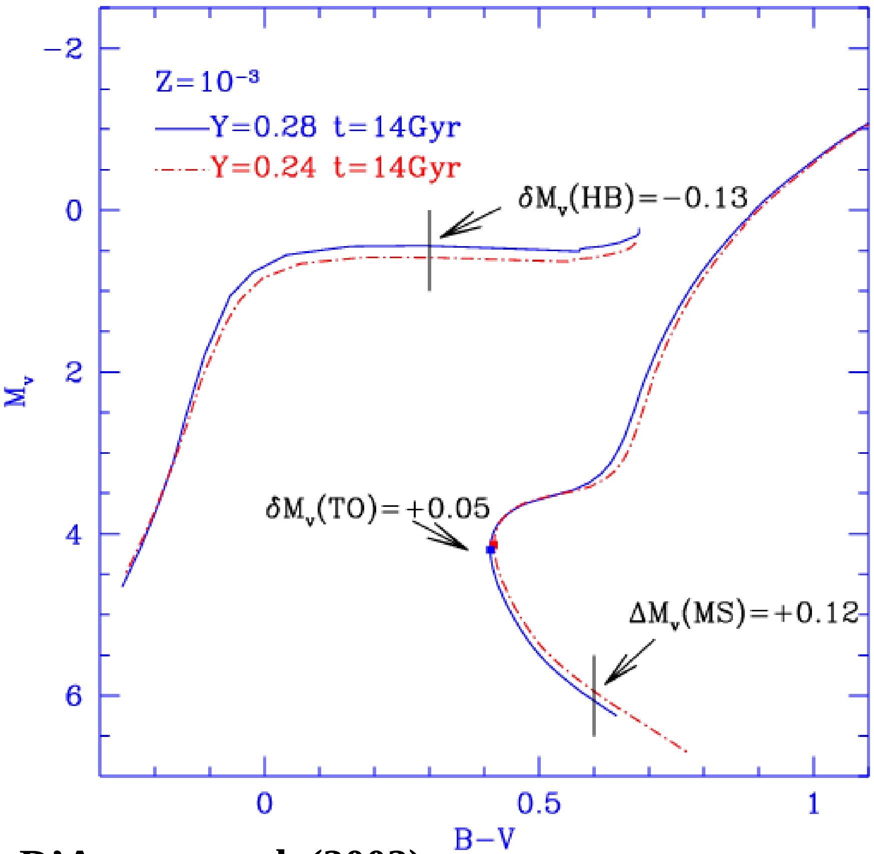
Piotto et al. 2007, ApJ, 661, L35

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.

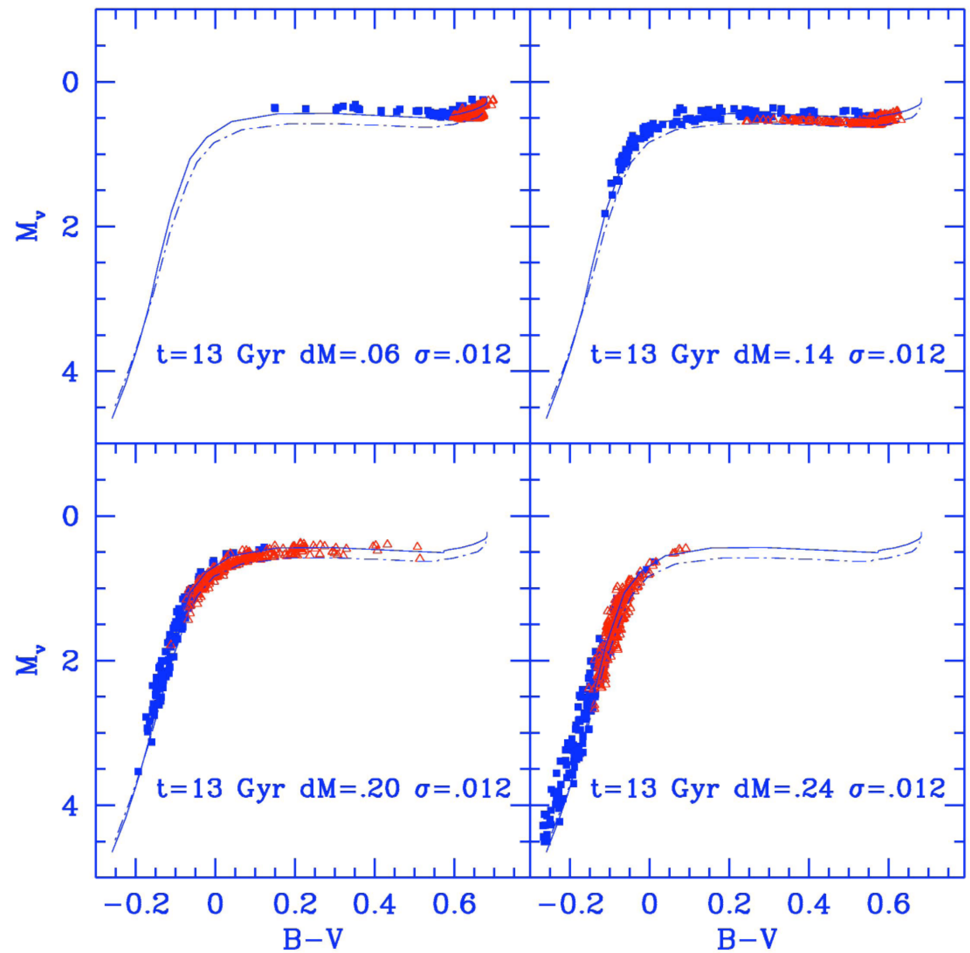
The TO-SGB regions are so narrow that <u>any difference in age between the three groups must be significantly smaller than 1 Gyr</u>

Helium enrichment: model predictions



D'Antona et al. (2002)

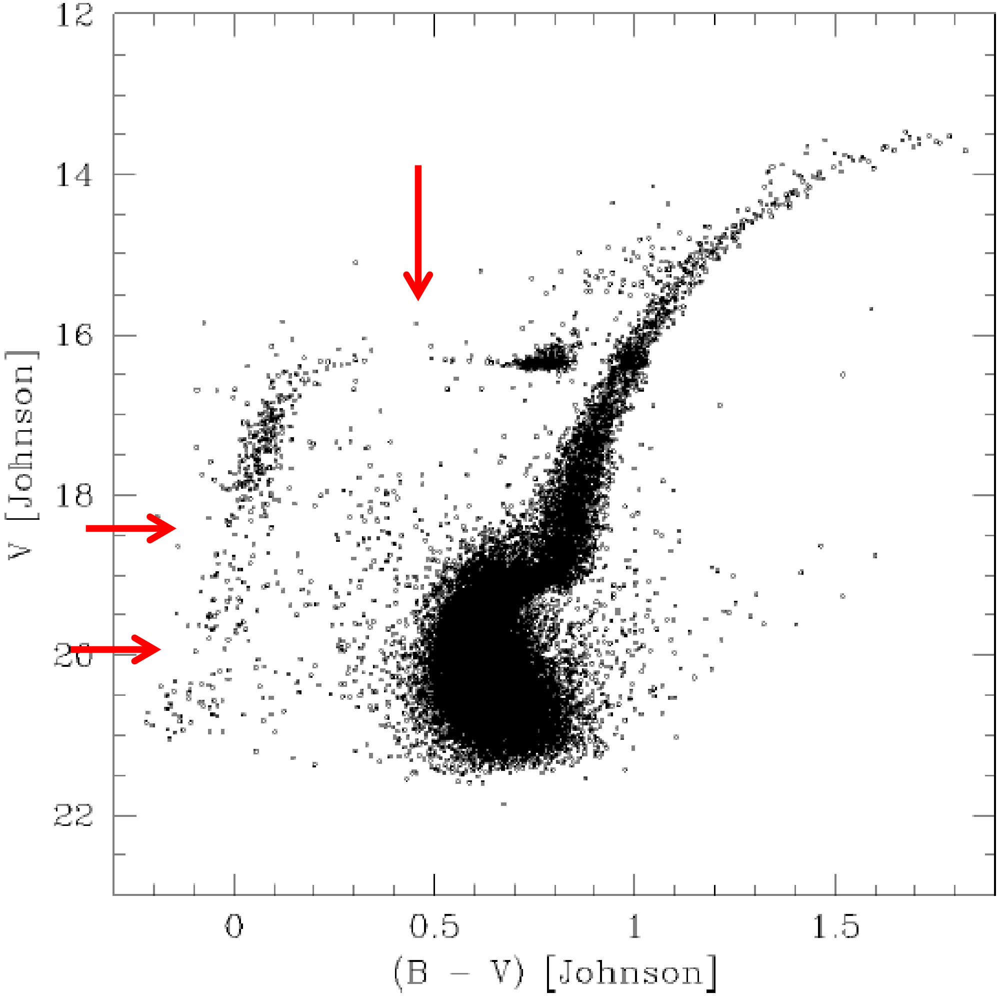
→ Higher Y → brighter HB



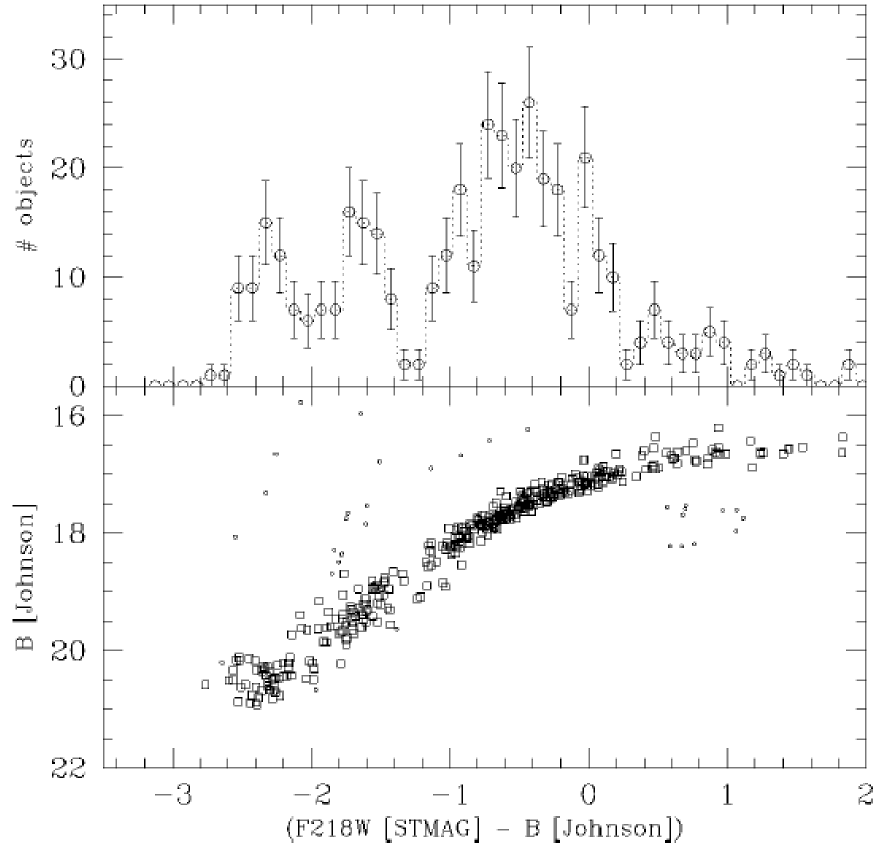
Higher Y → bluer HB ←

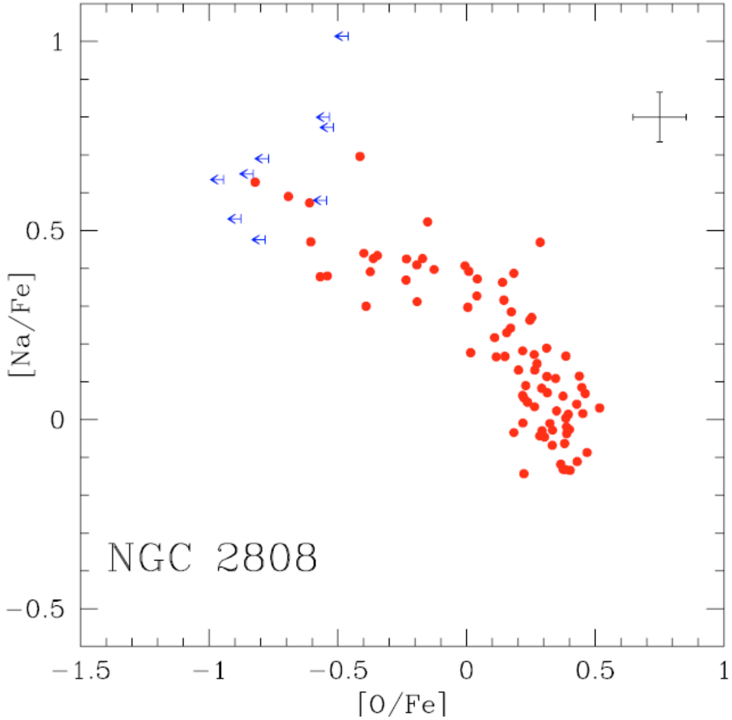
(also needs higher mass loss along the RGB, but not as extreme as in the case of primordial He content)

NGC 2808
Extended horizontal branch, with a multimodal stellar distribution

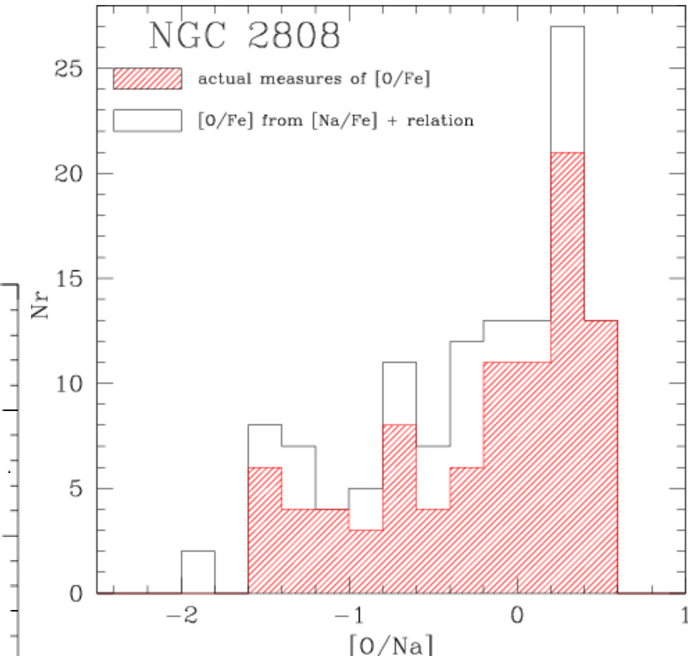


Sosin et al. (1997)

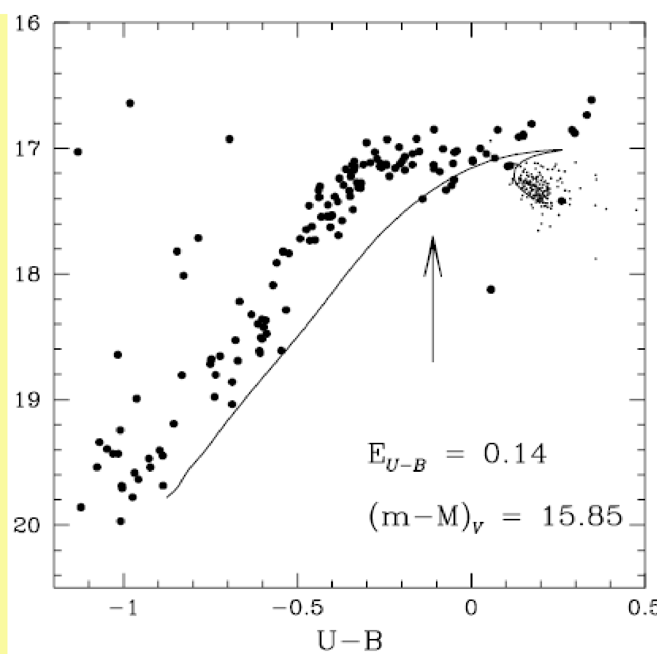




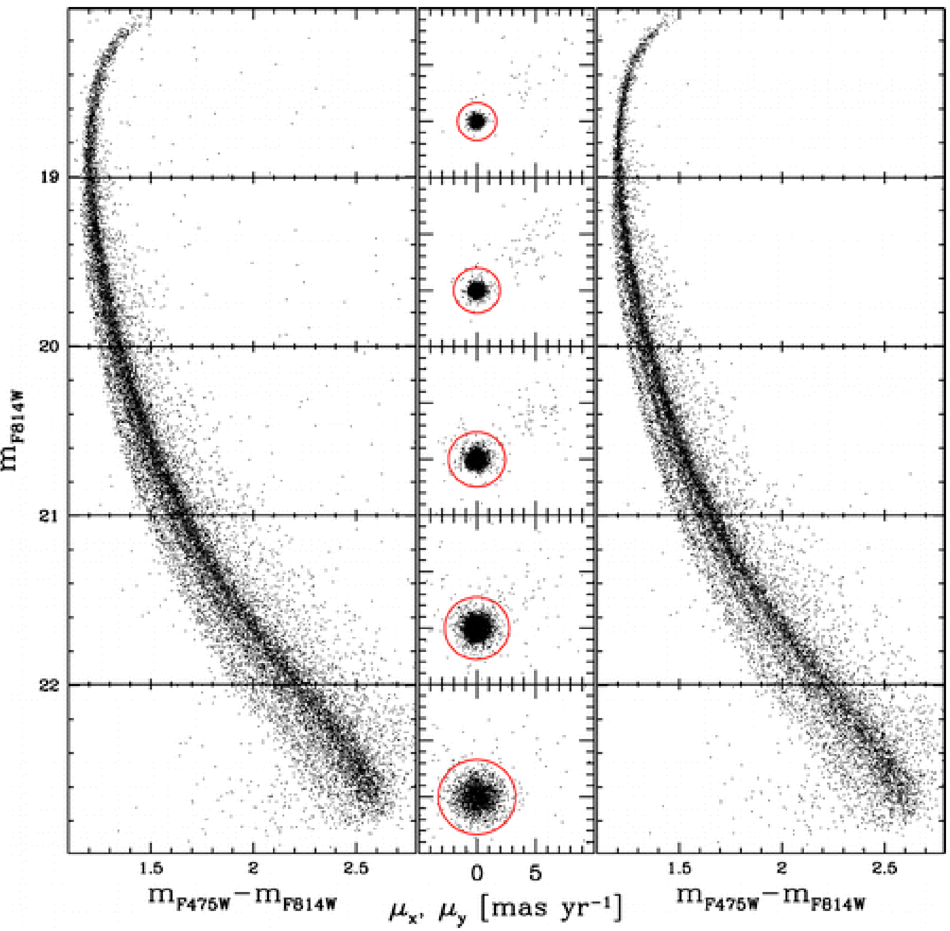
A clear NaO anticorrelation has been identified by Carretta et al. (2006, A&A, 450, 523) in NGC 2808.
Besides a bulk of O-normal stars with the typical composition of field halo stars, NGC2808 seems to host two other groups of O-poor and super O-poor stars



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



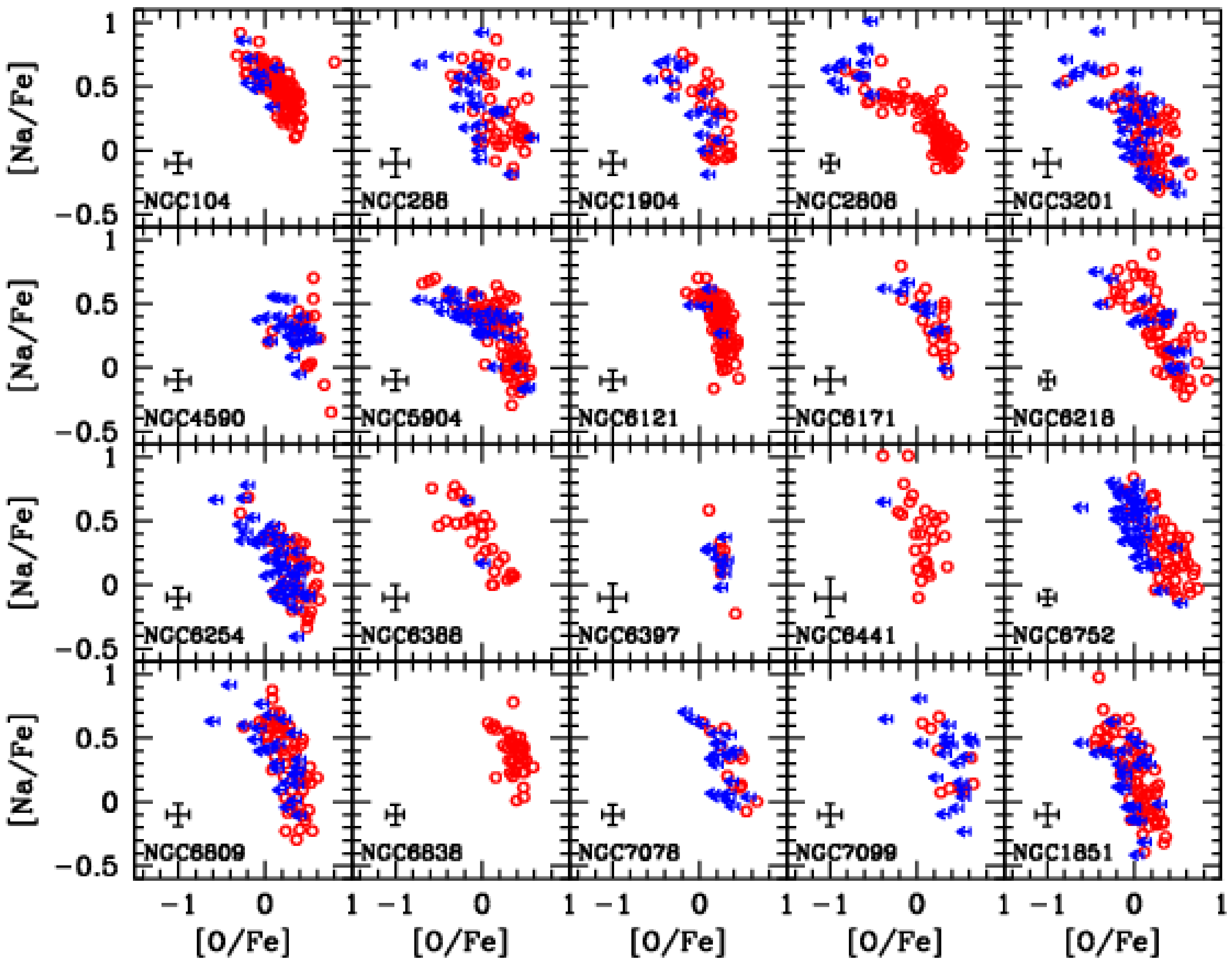
In summary, in NGC 2808,
it is tempting to link together:

the multiple MS,
the multiple HB,
and the three oxygen groups,
as indicated in the table below (see Piotto et al. 2007 for details). May be the solution of the long standing 2nd parameter problem.

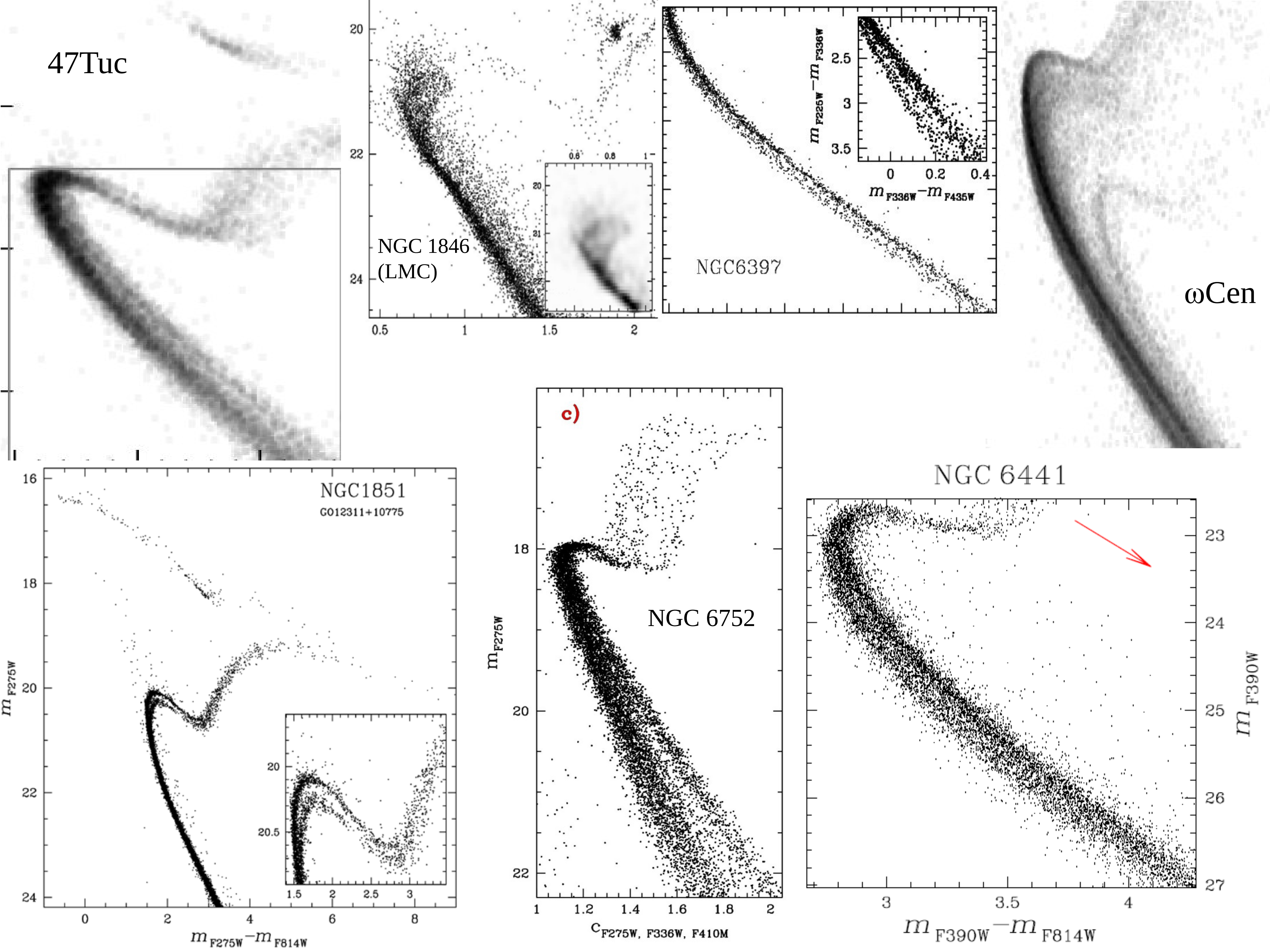
MS	RGB	HB
rMS 63% ± 5 $Y = 0.248$	O-normal 61% ± 7	Red segment 46% ± 10
mMS 15% ± 5 $Y = 0.30$	O-poor 22% ± 4	EBT1 35% ± 10
bMS 13% ± 5 $Y = 0.37$	Super–O-poor 17% ± 4	EBT2 10% ± 5
Binaries 9% ± 5	?	EBT3? 9% ± 5

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

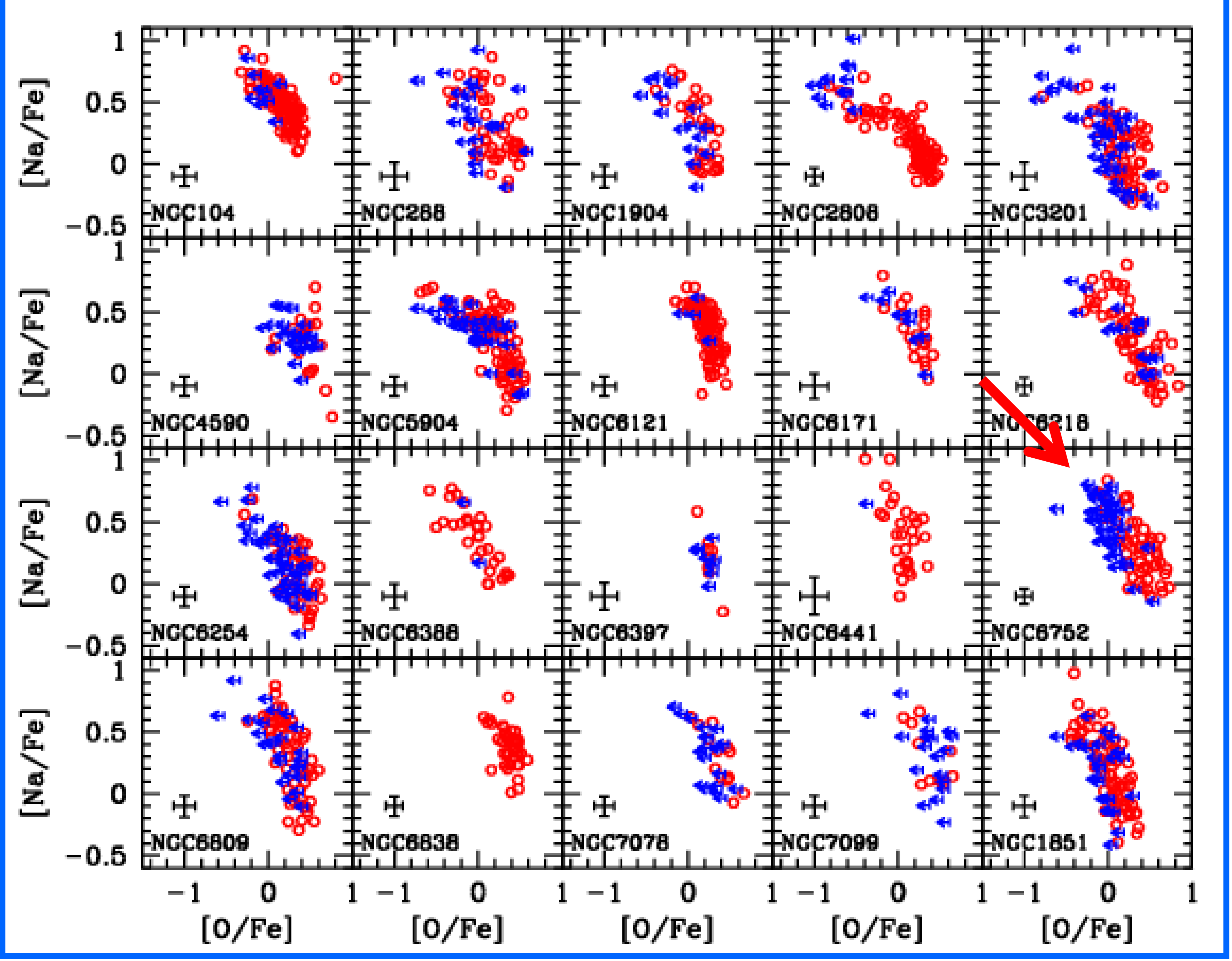
NGC 2808 represents another, direct evidence of multiple stellar populations in a globular cluster.



NGC104
NGC288
NGC1904
NGC2808
NGC3201
NGC4590
NGC5904
NGC6121
NGC6171
NGC6218
NGC6254
NGC6388
NGC6397
NGC6441
NGC6752
NGC6809
NGC6838
NGC7078
NGC7099
NGC1851
[Na/Fe]
[O/Fe]



47Tuc
NGC 1846
(LMC)
NGC6397
$m_{F225W}-m_{F336W}$
$m_{F336W}-m_{F435W}$
ωCen
NGC1851
G012311+10775
m_{F275W}
$m_{F275W}-m_{F814W}$
c)
NGC 6752
m_{F275W}
$c_{F275W,\ F336W,\ F410M}$
NGC 6441
m_{F390W}
$m_{F390W}-m_{F814W}$



[Na/Fe]
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NGC7078
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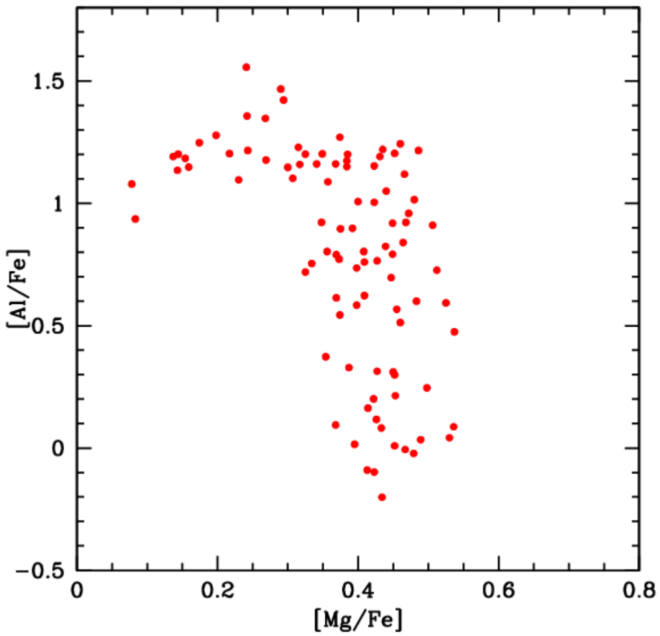
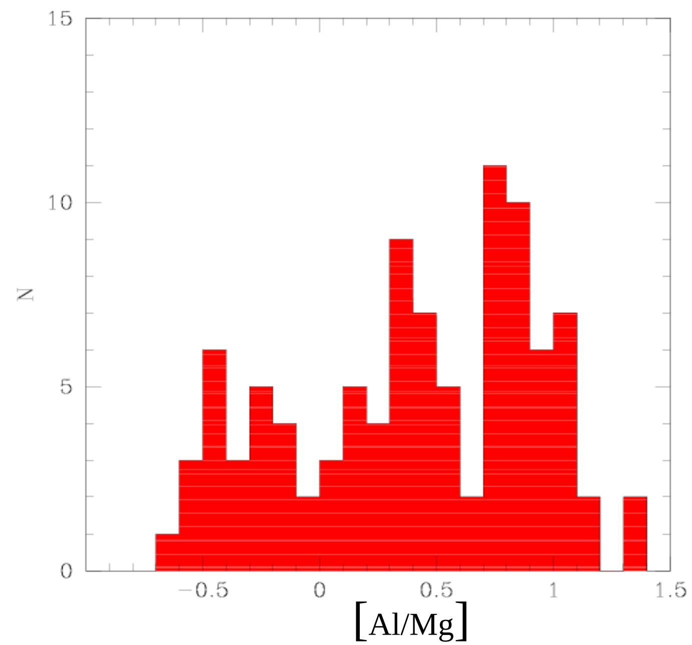
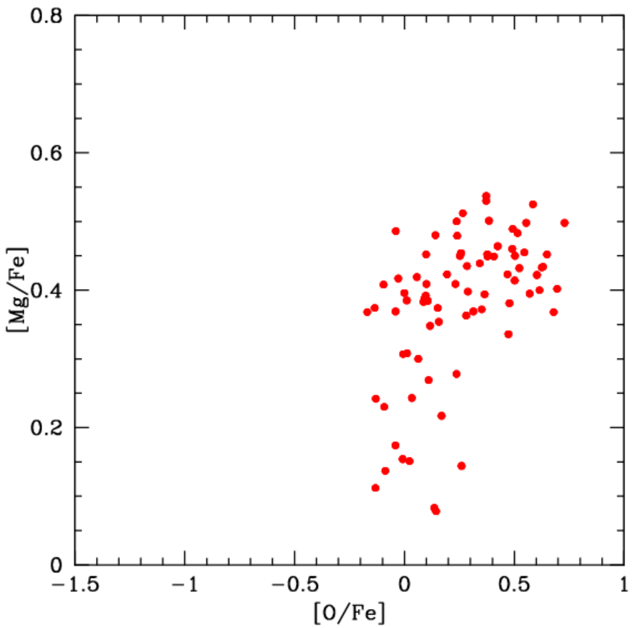
NGC1851

NGC 6752: three discrete groups







GIRAFFE data, 130 red giants!

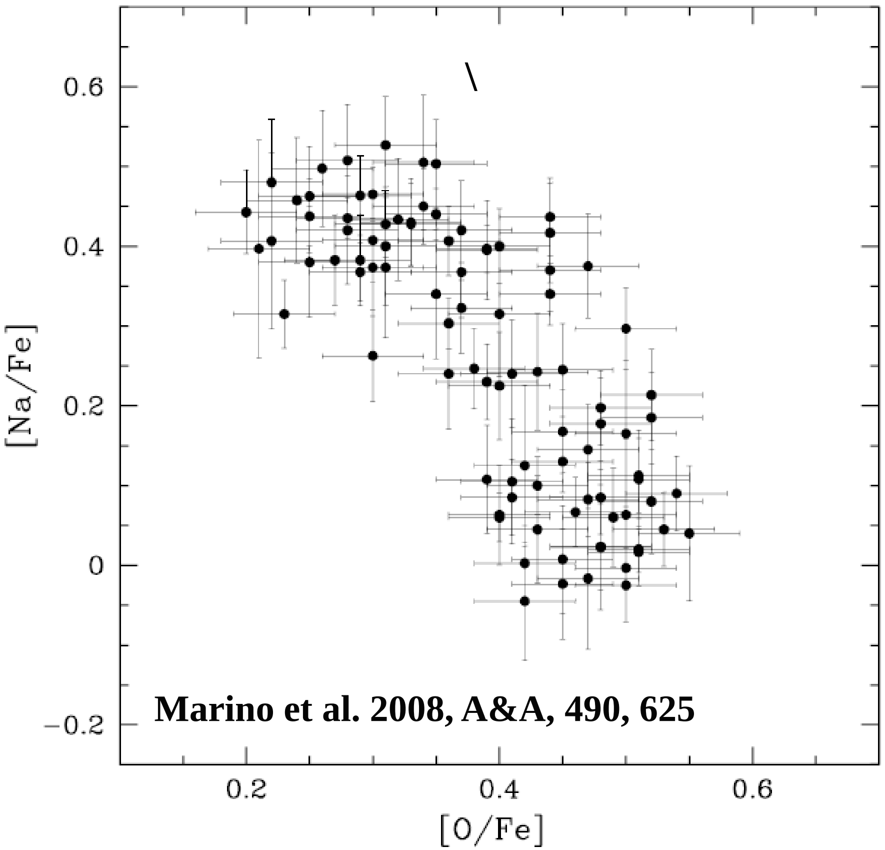
Carretta et al. 2012

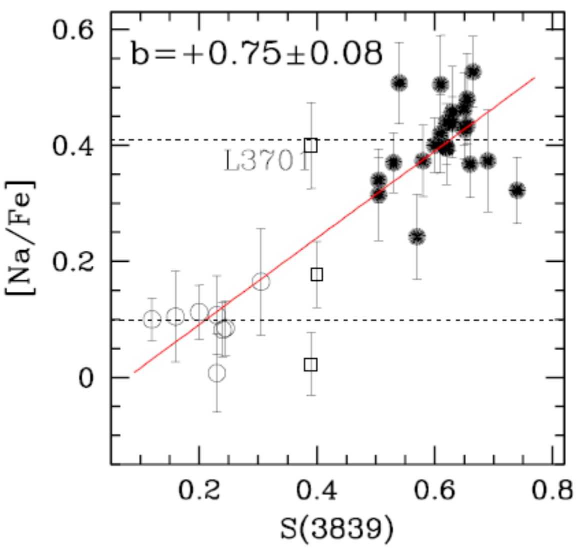
The case of M4

Strong NaO anticorrelation

Two distinct groups of stars

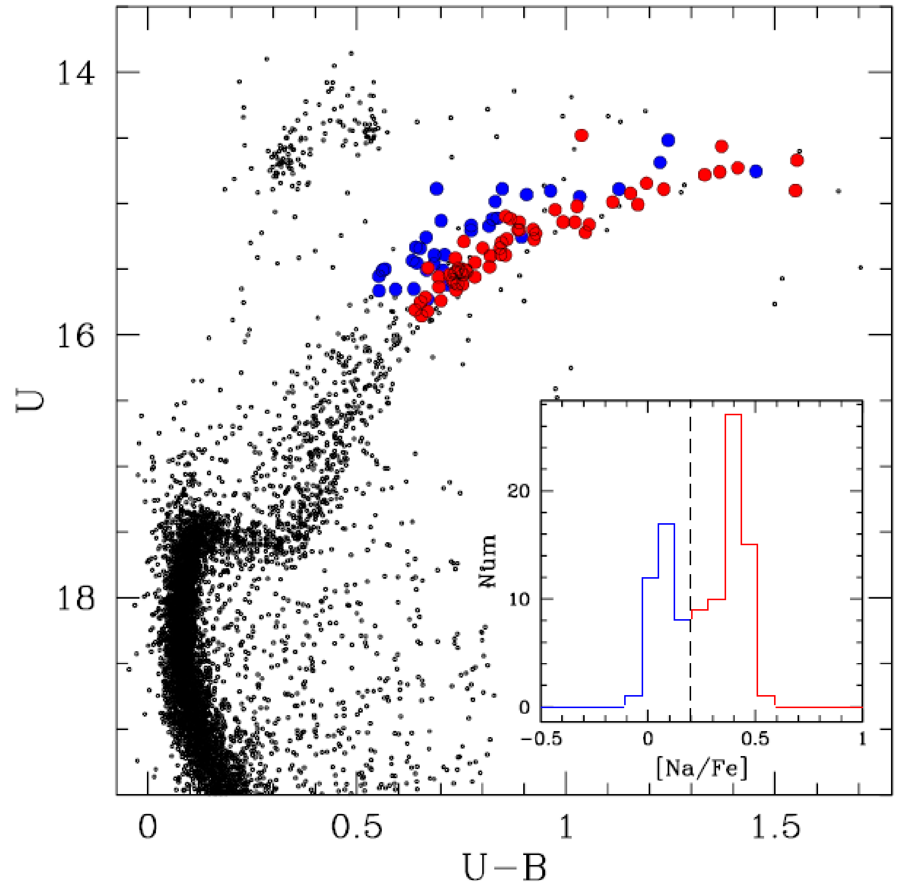
Mass: $8x10^4$ solar masses!

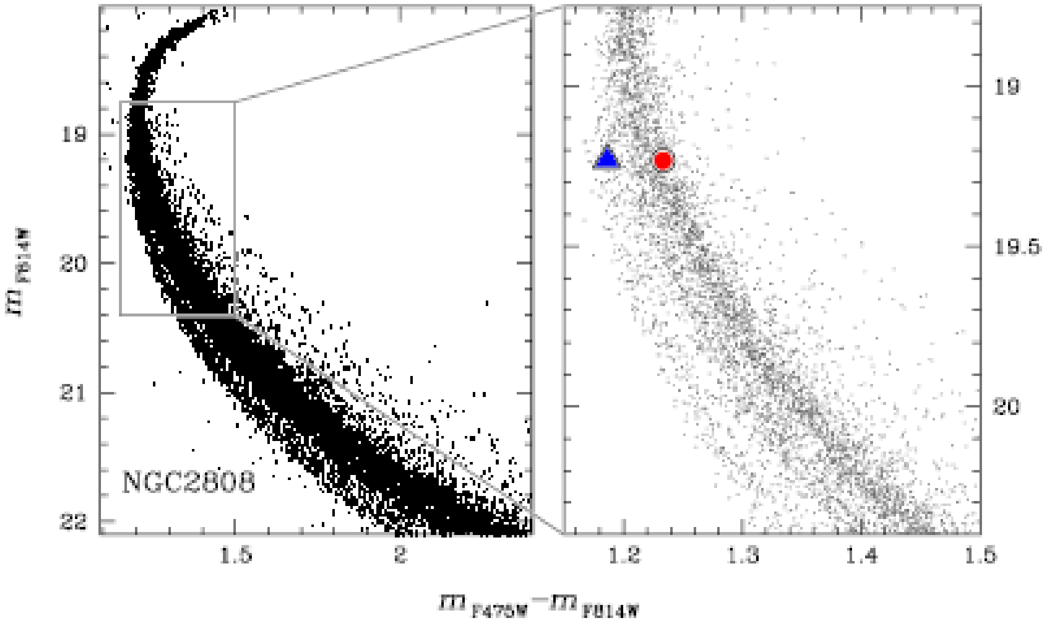




Na rich, O poor stars are CN strong

Na poor, O-rich stars are CN weak

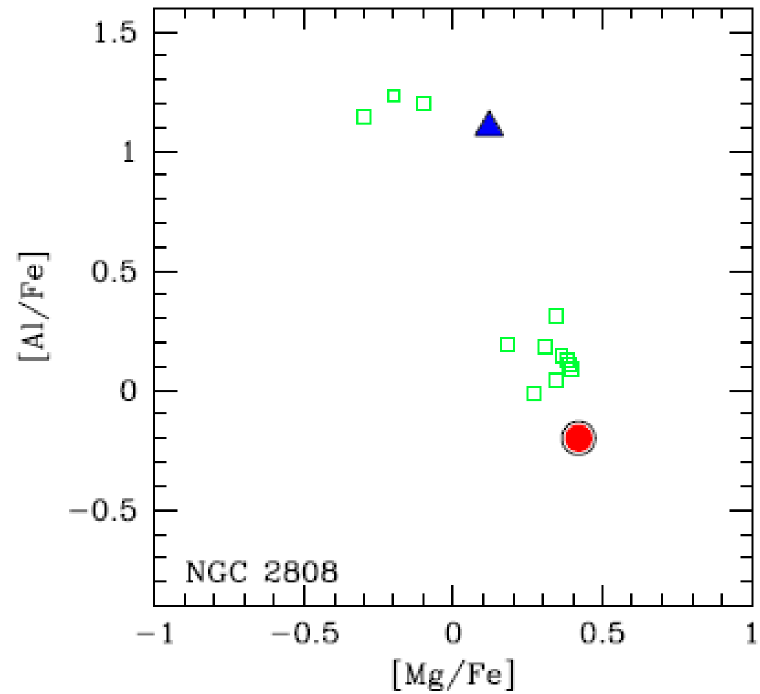




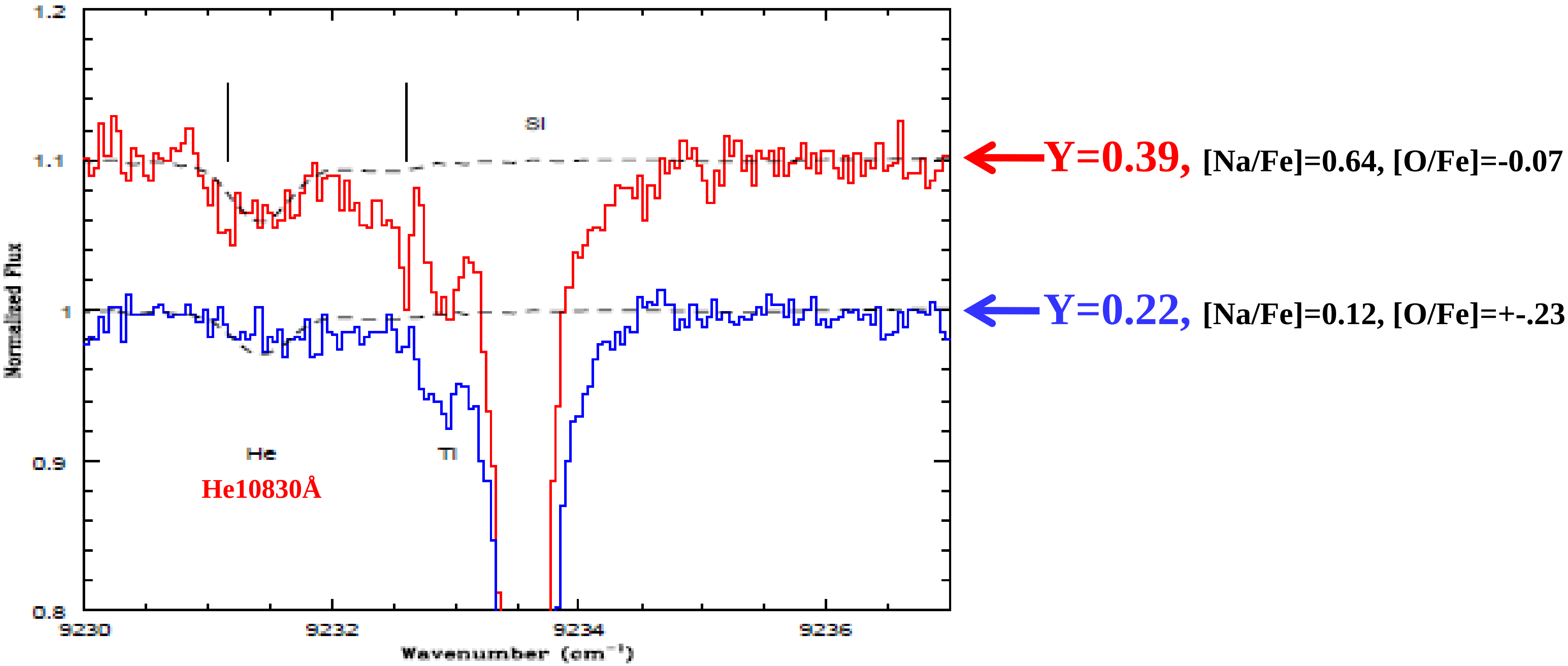
Bragaglia et al. (2011 ApJ, 720, L41\9 analyzed features of NH, CH, Na, Mg, Al, and Fe. While Fe, Ca, and other elements have the same abundances in the two stars, the bMS star shows a huge enhancement of N, a depletion of C, an enhancement of Na and Al, and small depletion of Mg with respect to the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



(X-shooter@VLT)



Pasquini et al. 2011, A&A, 531, 35

ΔY>0.17 between two RGB stars in NGC 2808 with different Na and O abundances

CRIRES@VLT

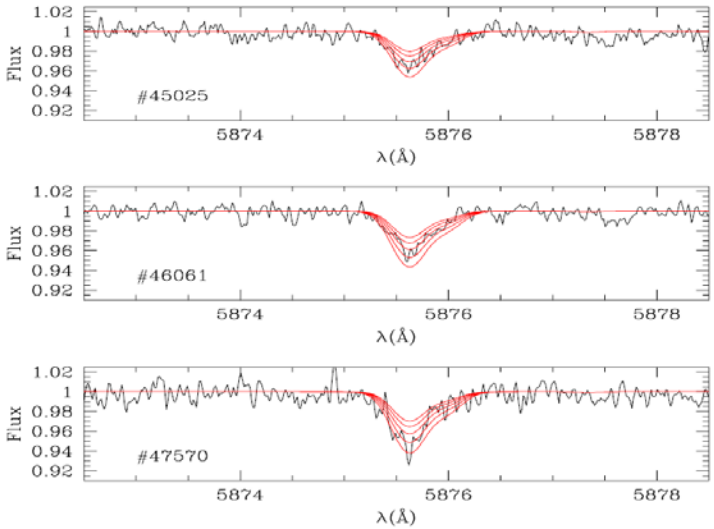
Spectroscopic He abundance determinations

- HB stars

Villanova et al. 2009, A&A, 499, 755

Villanova et al. 2012, ApJ, 748, 62

Gratton et al. 2012, A&A, 539, 19

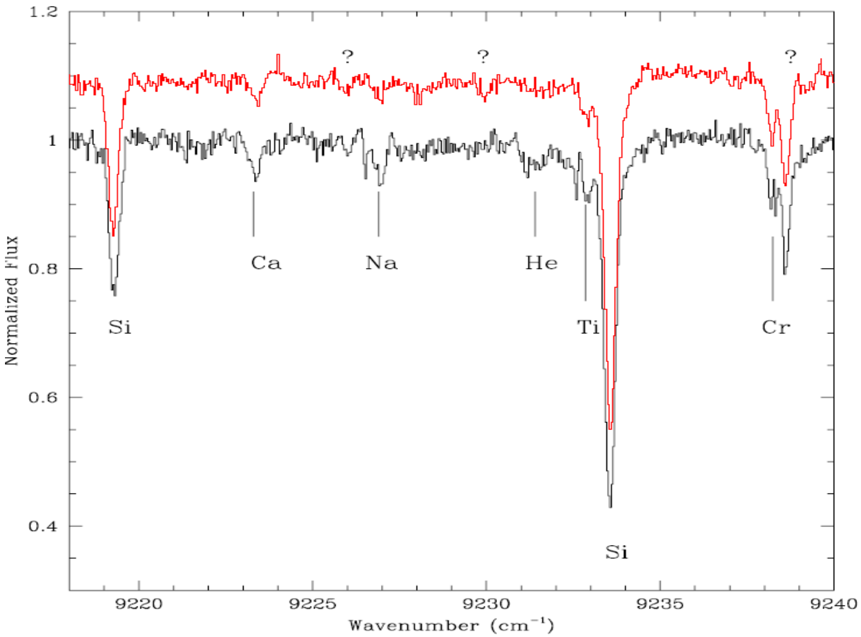


- **Only stars in a restricted range of temperature along the HB**
- **Faint feature ➔ high S/N**

- RGB stars (chromospheric line)

Pasquini et al. 2011, A&A, 531, A35

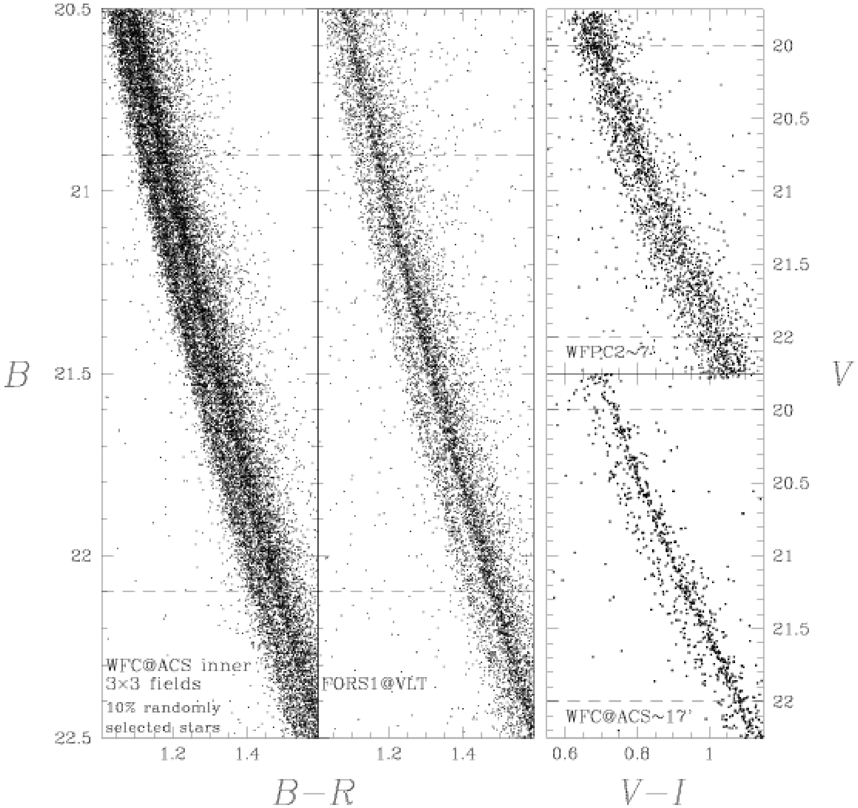
Dupree et al. 2011, ApJ, 728, 155

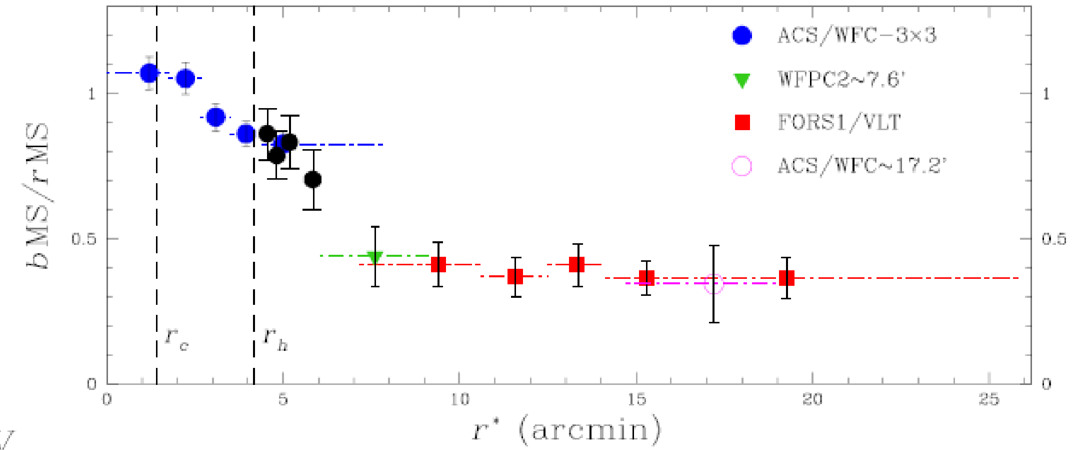


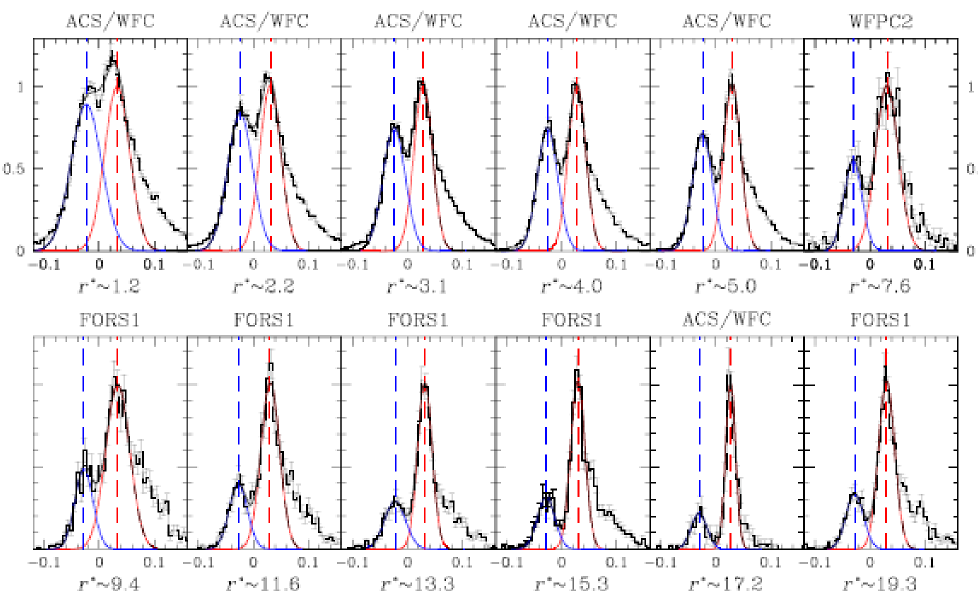
- **Accurate modelling of chromosphere needed**

Omega Centauri: Radial distribution of main sequence stars

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

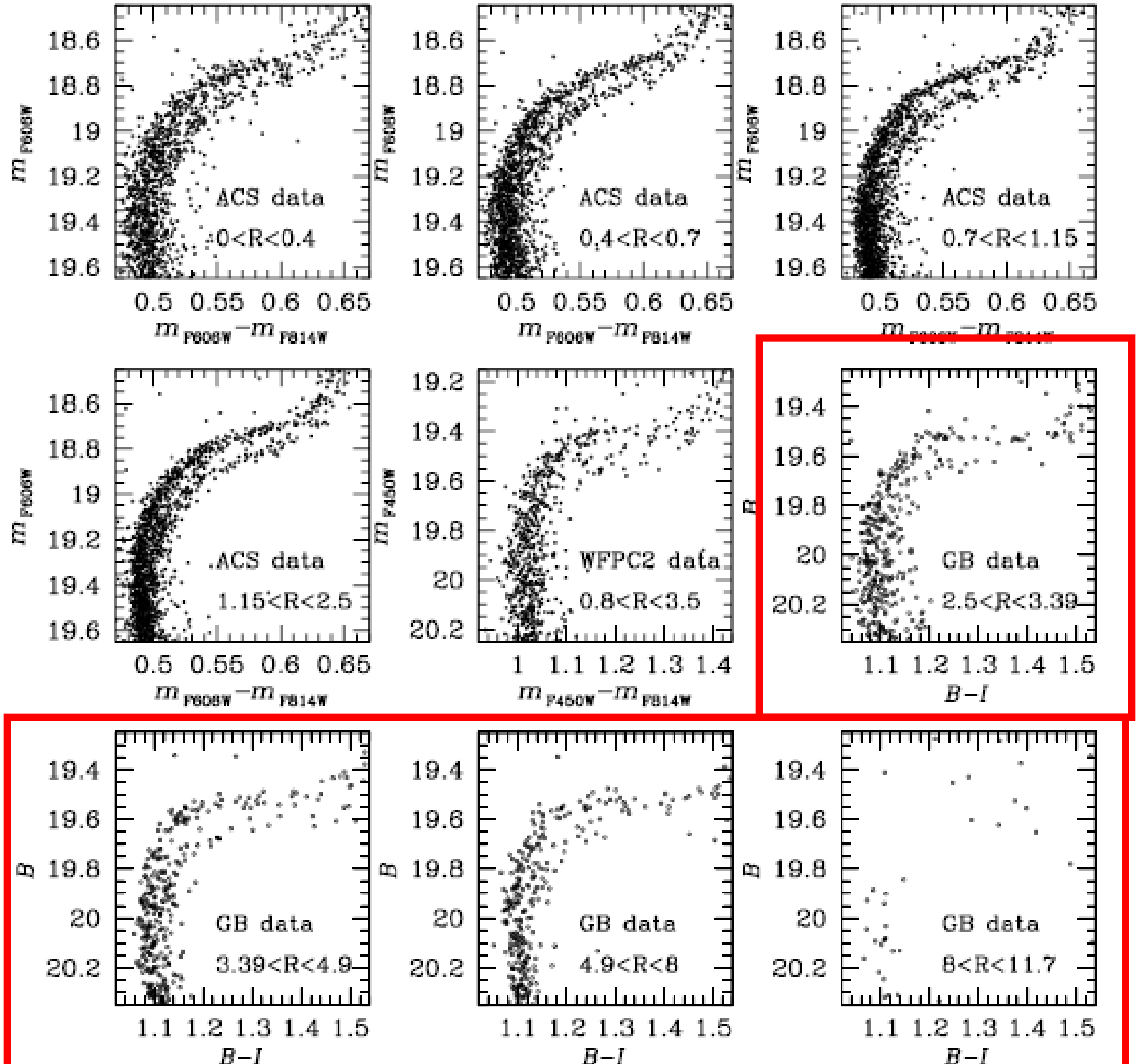






The double MS is present all over the cluster, from the inner core to the outer envelope, but….

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



Milone et al. (2009) in prep

Radial distribution of the two SGBs in NGC 1851

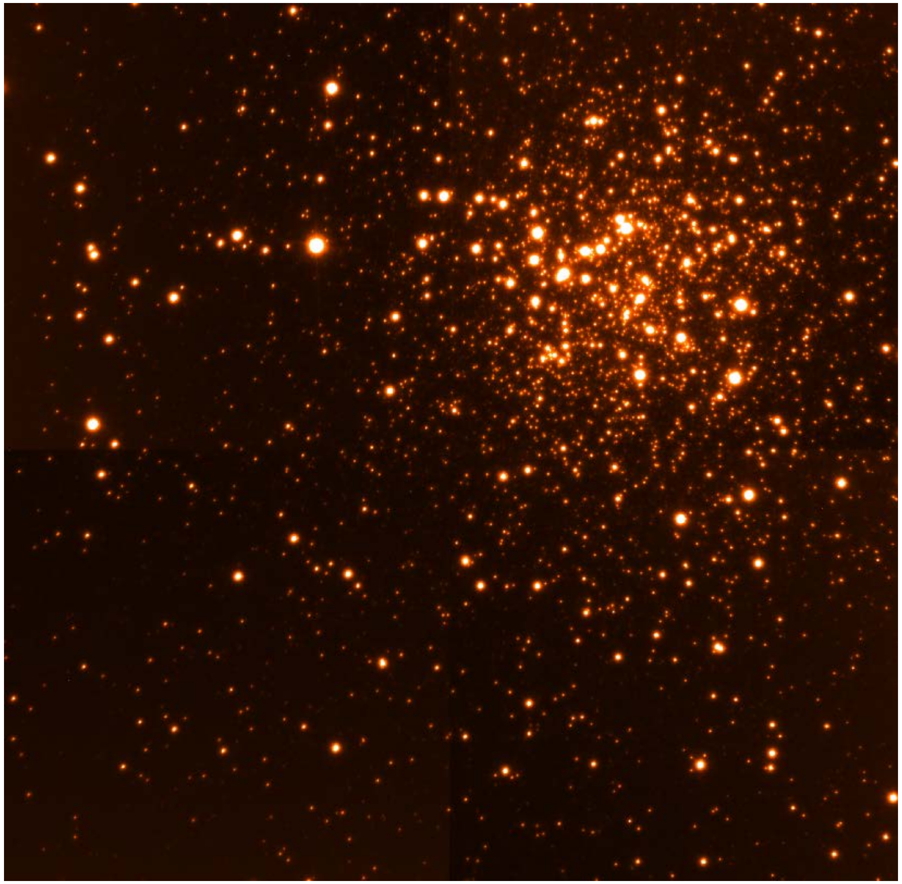
In red, FORS@VLT data

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

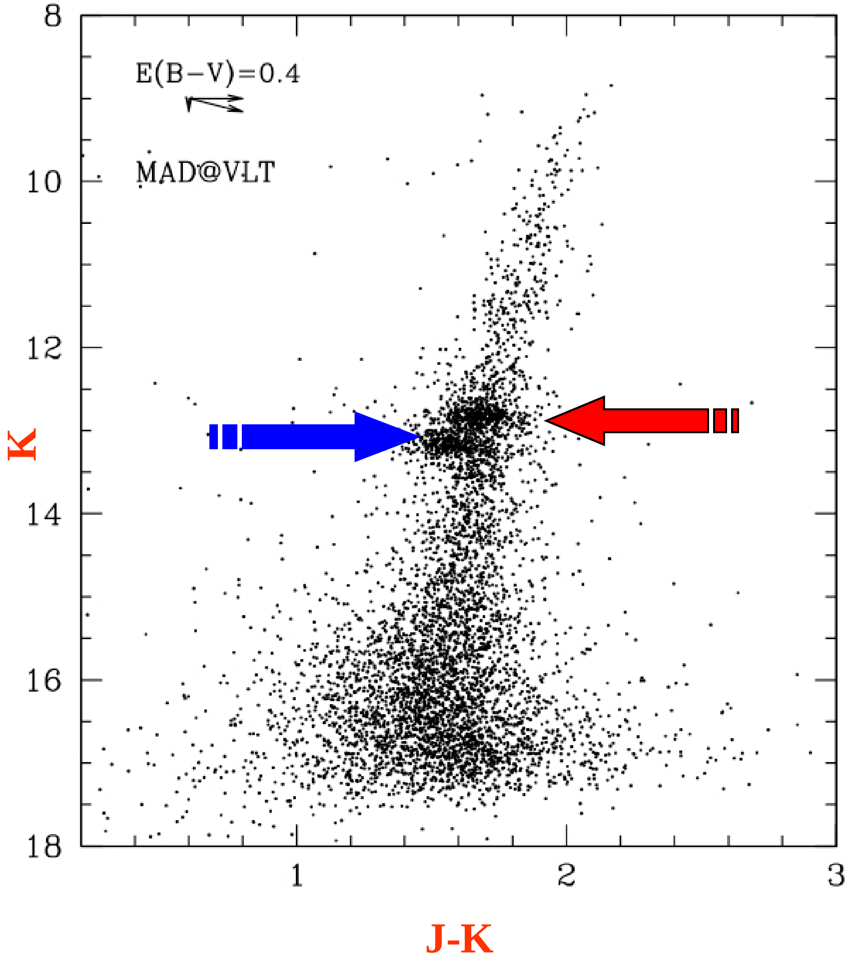
There is no radial gradient

Log t_{rh} = 8.9

Terzan 5 : a pristine fragment of the Galactic Bulge



Incredibly sharp K-band image of Terzan 5 obtained with MAD@VLT (FWHM=100mas over the entire FoV)

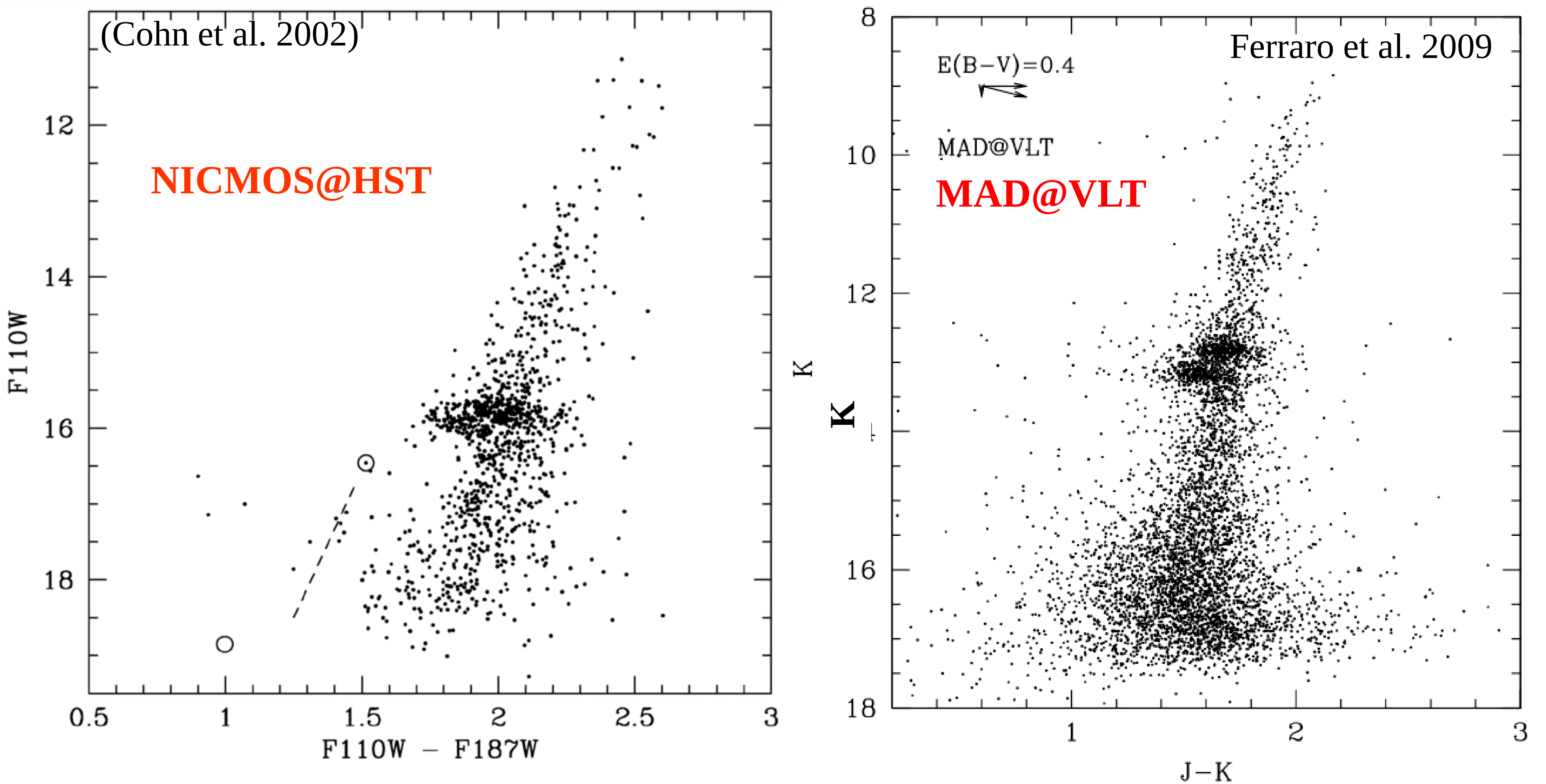


TWO Red Clumps !!!

Ferraro et al. 2009, Nature, 462, 483

ESO press-release, Nov 25, 2009

Terzan 5 : a pristine fragment of the Galactic Bulge



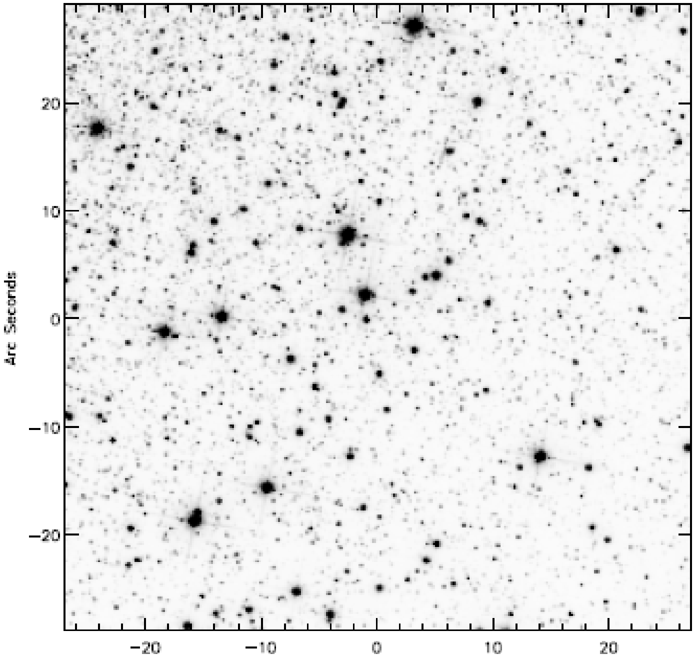
The two populations have different [α/Fe] and [Fe/H] (Δ[Fe/H] =0.5 !!)

Working hypothesis: Ter5 is the remnant of a pristine fragment that contributed to build the Galactic Bulge and that survived the total disruption.

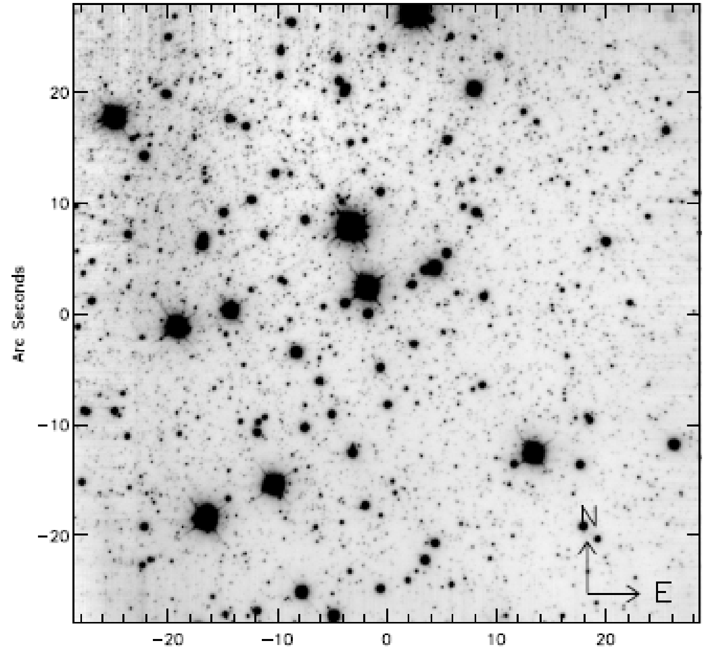
The old, metal poor component may trace the early stages of the Bulge formation

The younger (?) metal-rich component may contain crucial information on the Bulge most recent chemical & dynamical evolution

MCAO/ MAD@VLT

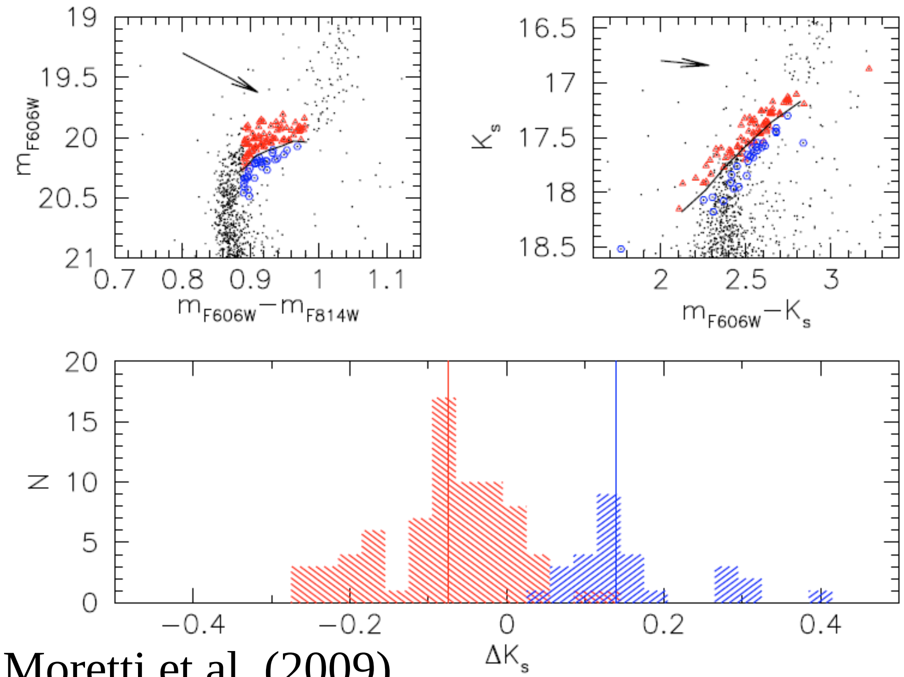


ACS@HST/F814W



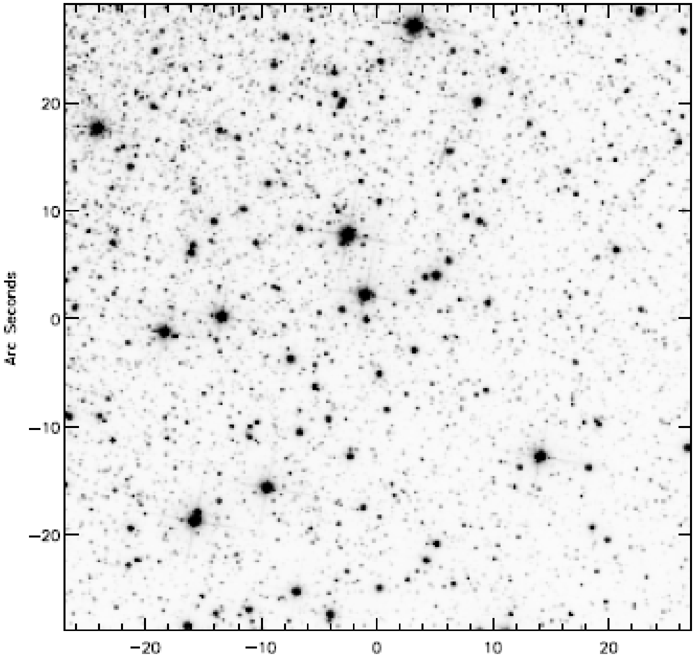
MAD@VLT/Ks

Discovery of a double sub-giant branch in NGC 6388

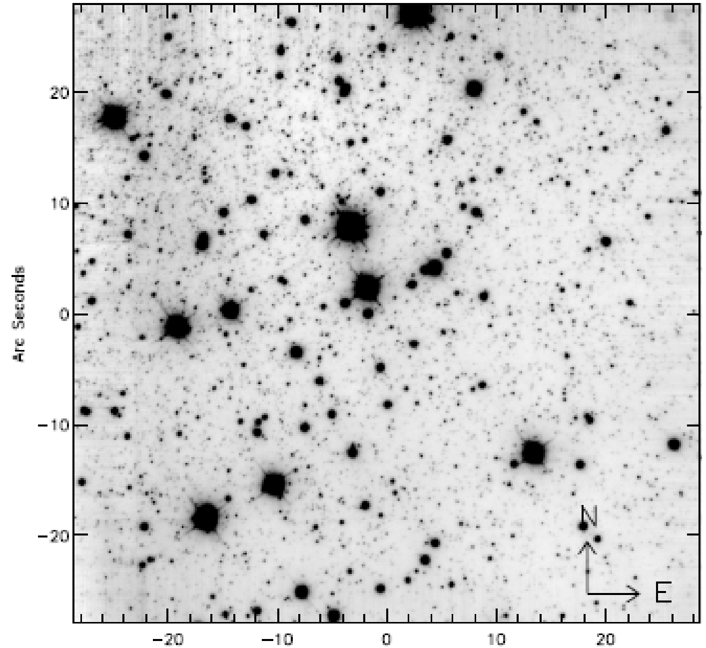


Moretti et al. (2009)

MCAO/ MAD@VLT



ACS@HST/F814W



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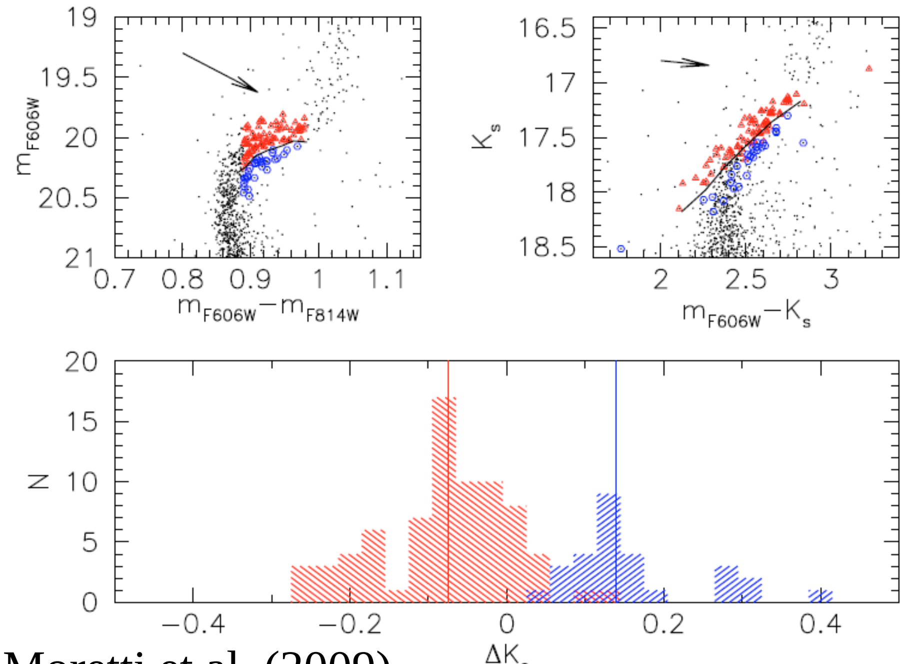

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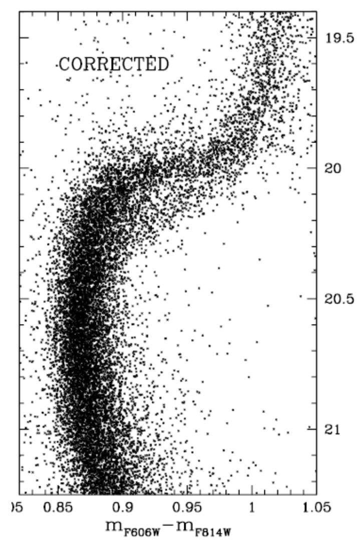
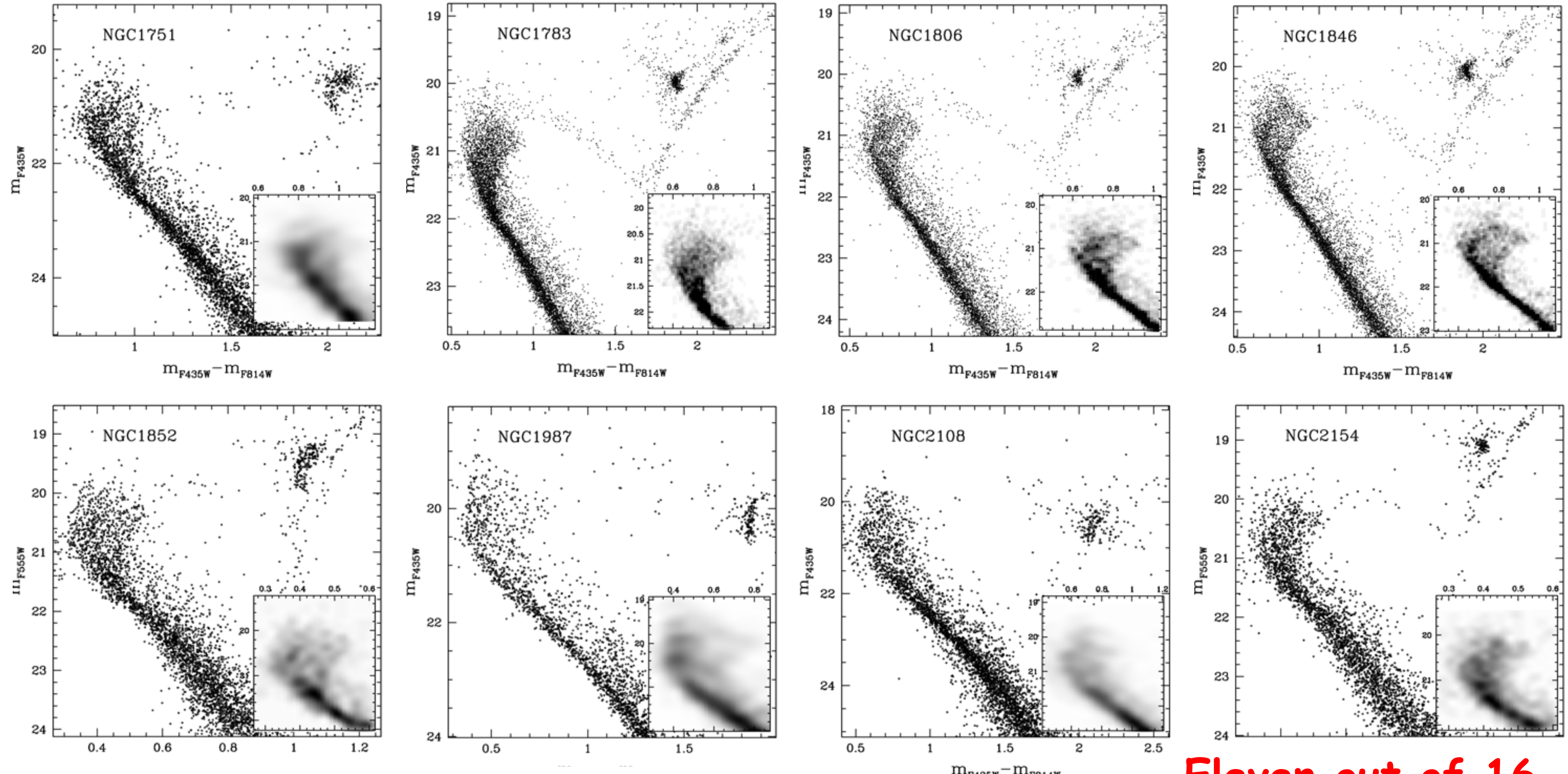
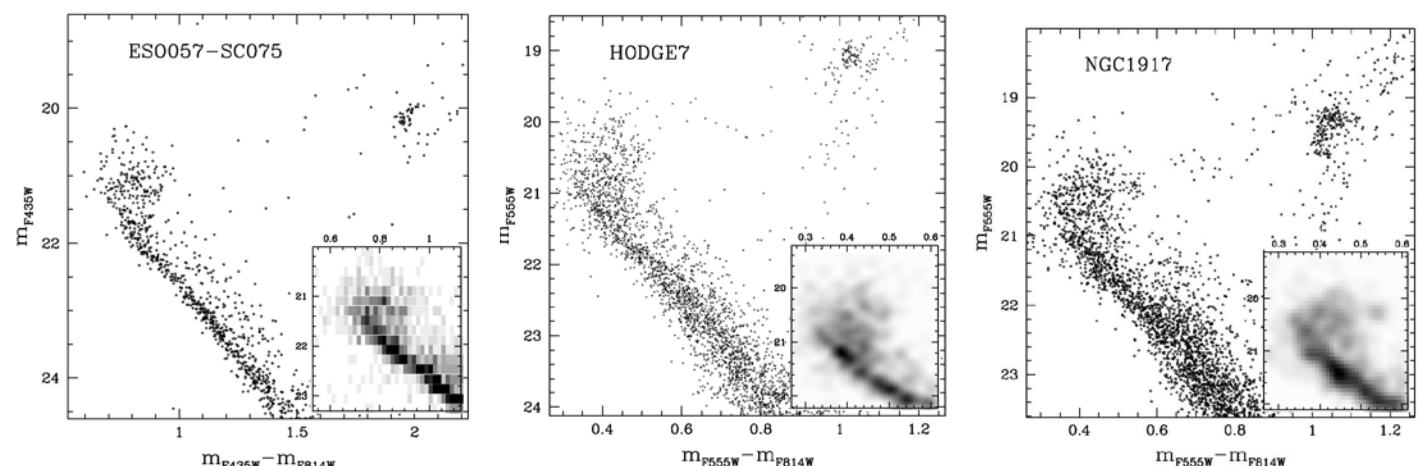


Nicely confirmed by HST.

Piotto et al. 2012, ApJ in press (arXiv1208.1873)



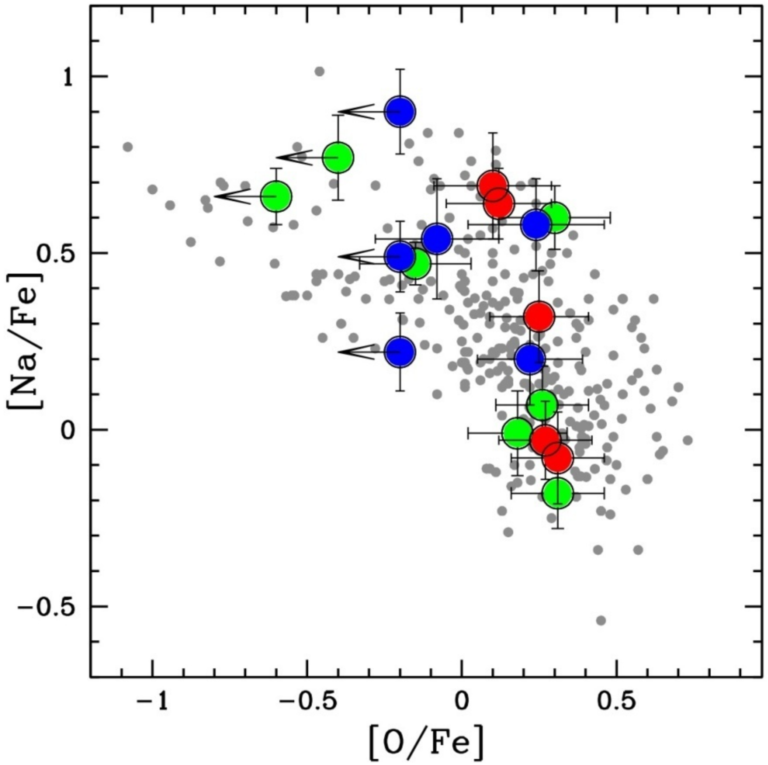


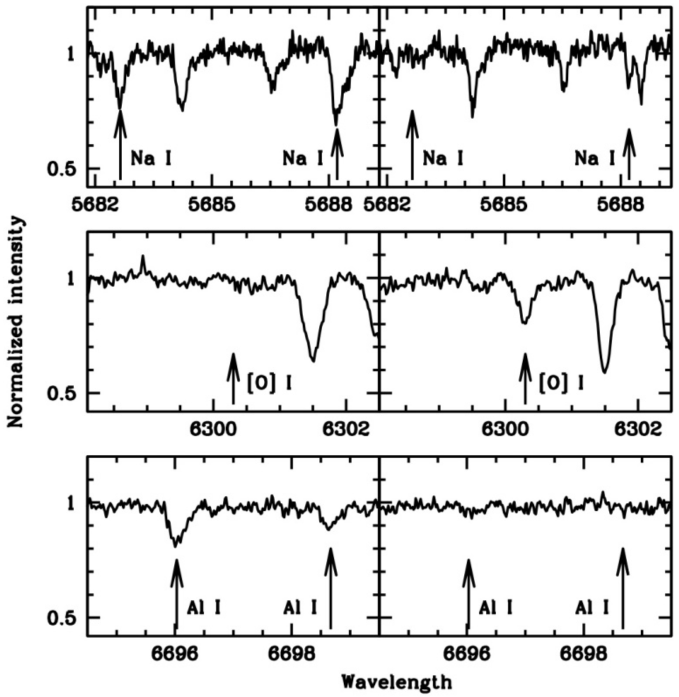
Eleven out of 16 (2/3) of the intermediate age clusters show either a double or an extended TO!

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

The first detection of the Na-O anticorrelation outside our Galaxy

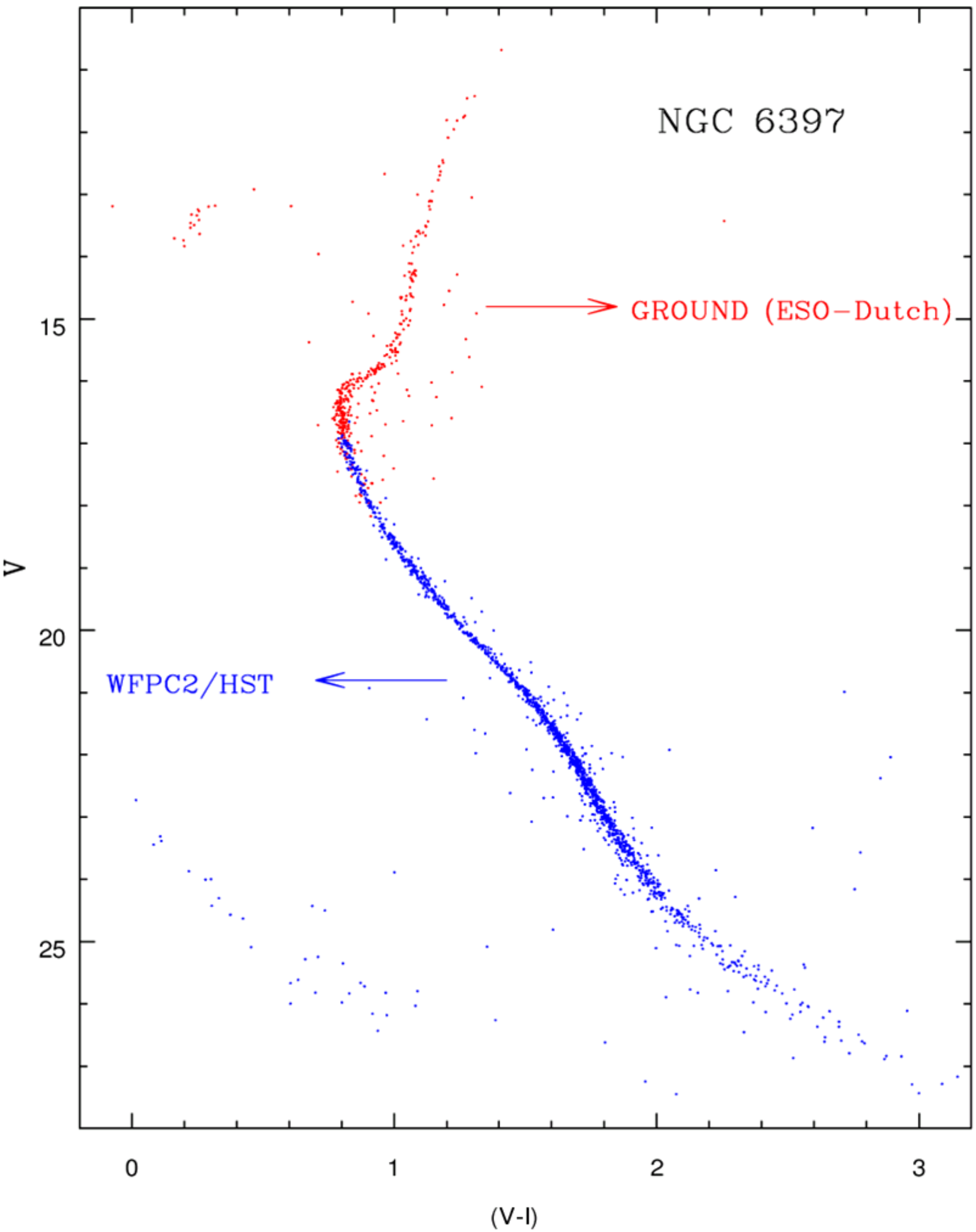
FLAMES+UVES@VLT spectra of giant stars in 3 old LMC GCs





UVES spectra of 2 giants in NGC 1786

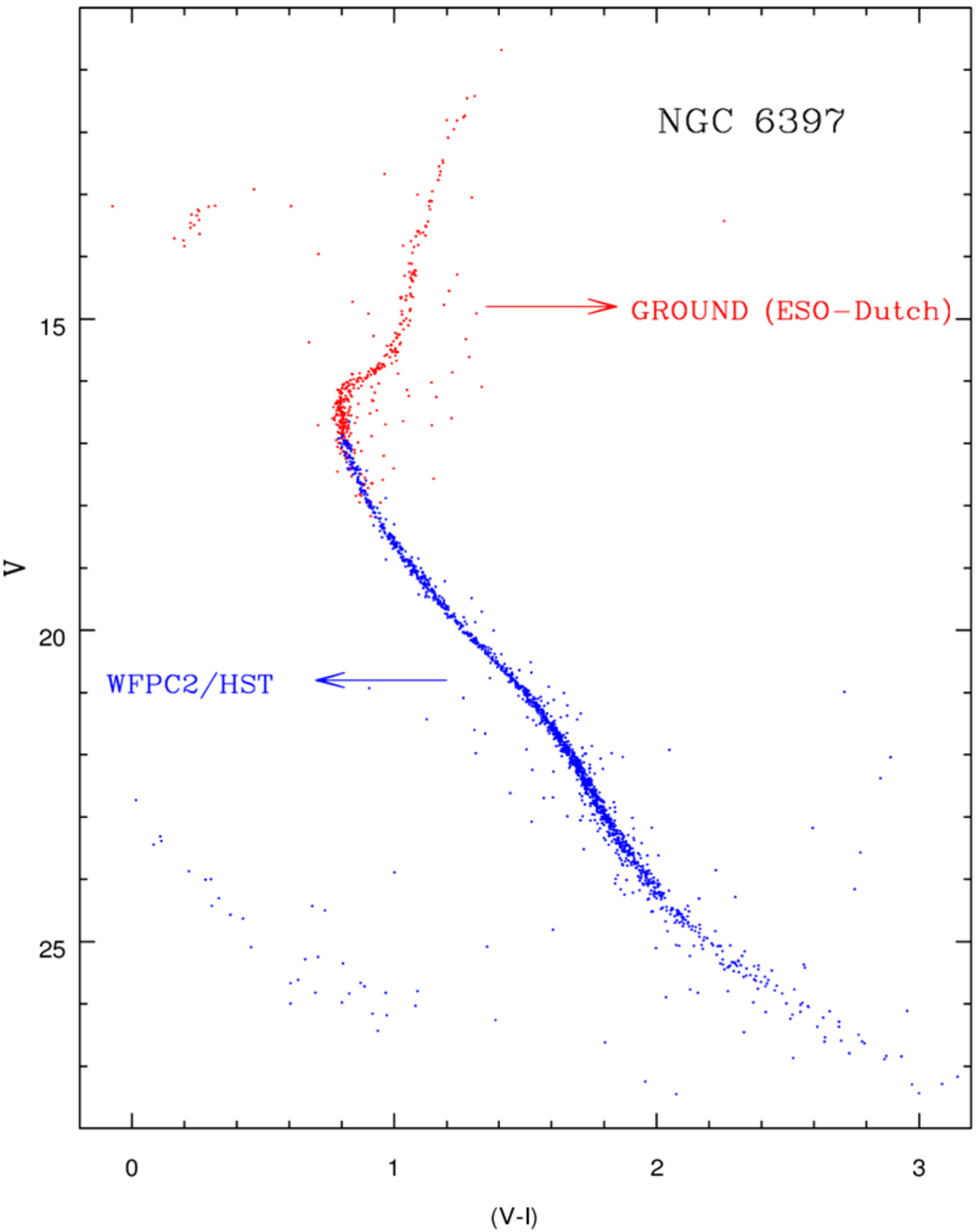
(Mucciarelli et al. 2009, ApJ 695, L134)



Once upon the time….we were thinking that…

*"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 show that globular clusters are **typically** populated by stars with homogeneous composition and born at the same time **(same age)**."*



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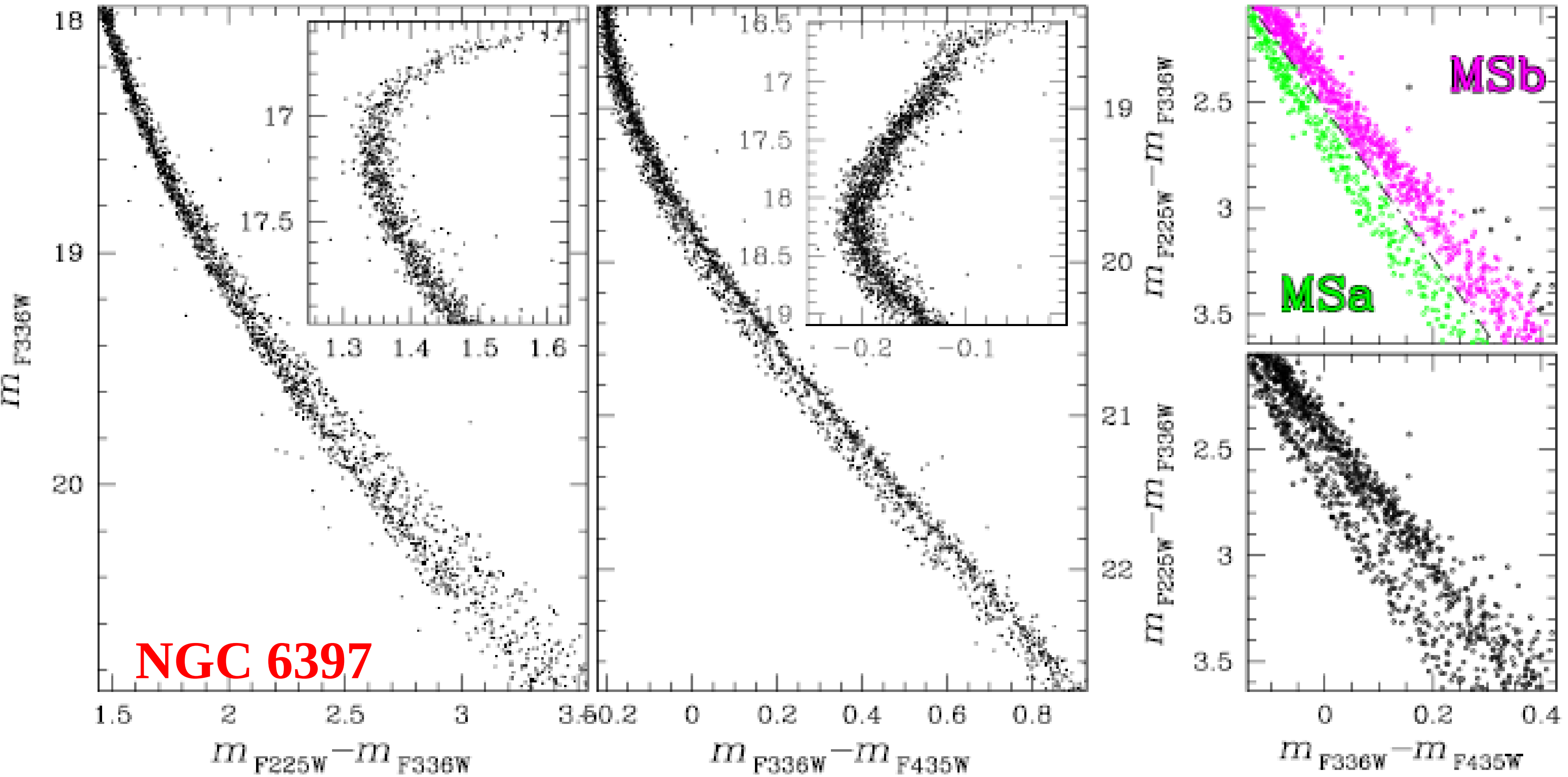
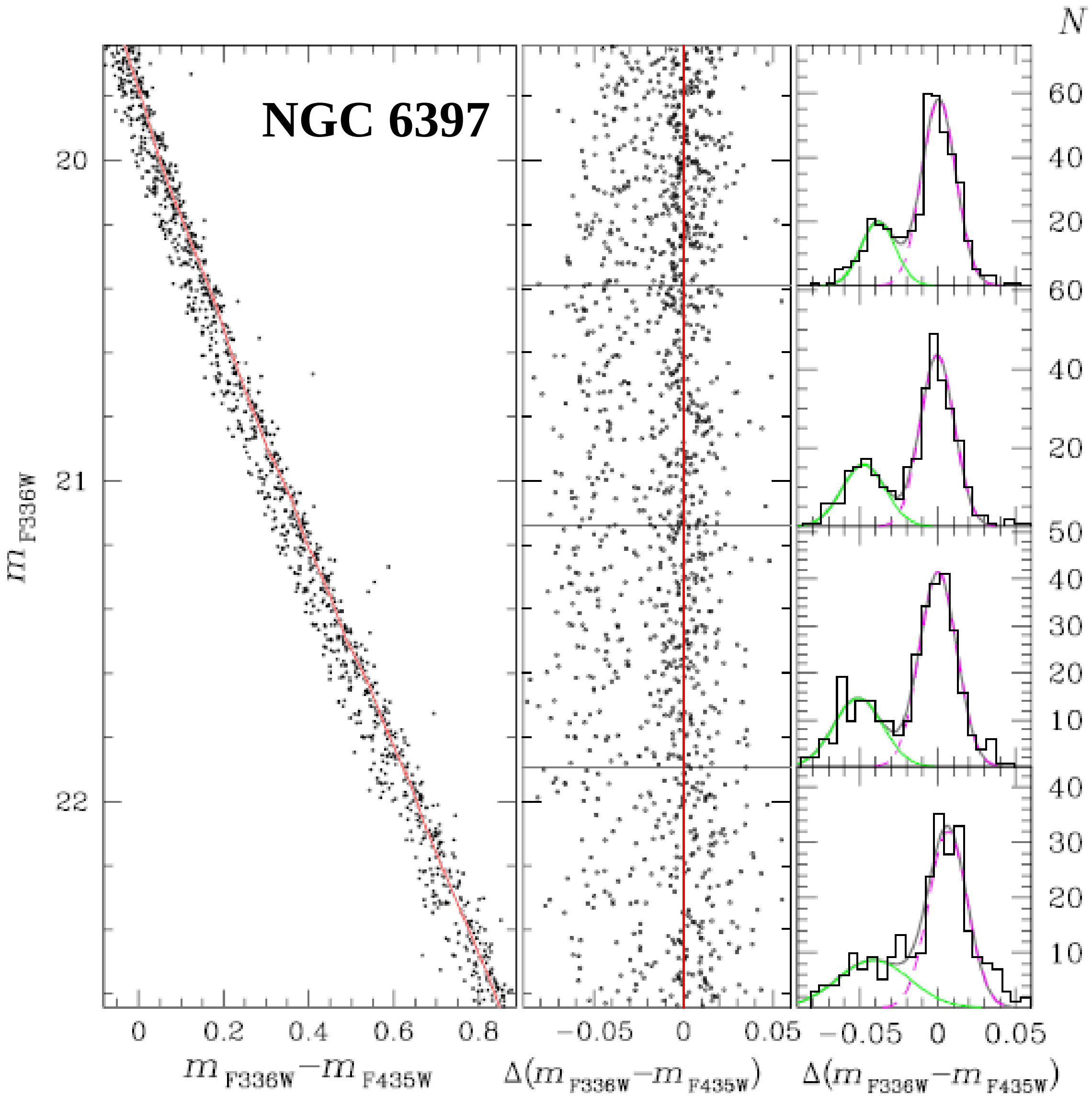
OLD TALE!!!

HST UV photometry shows that:



Milone et al. 2012, ApJ, 745, 27



"I spent most of my life to make color-magnitude diagram sequences as narrow as possible, and now you have shown that all globular clusters have multiple stellar populations…." Peter Stetson, 2010, priv. comm.

Old Paradigma

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

~~(Renzini and Buzzoni 1983)~~

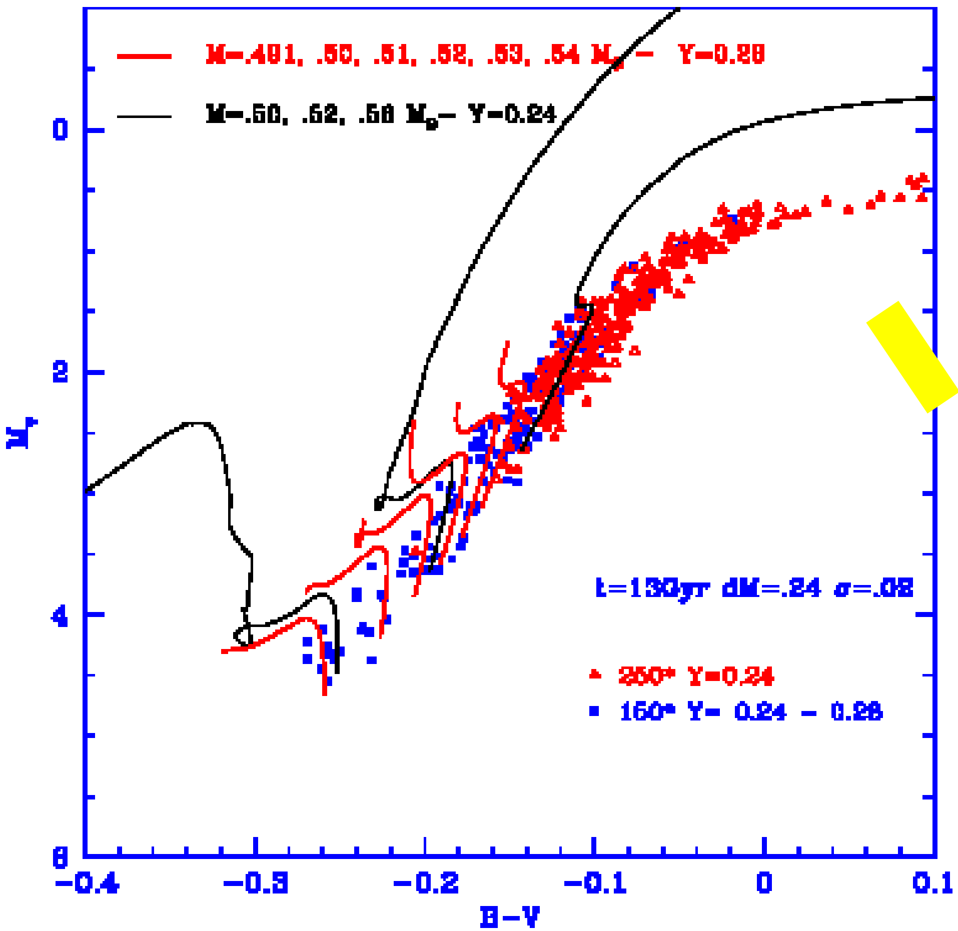
NewTheorem

Globular clusters are an assembly of multiple stellar populations which exhibit a Sodium-Oxygen anticorrelation

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

...and here you can see all the legacy of FLAMES(+UVES/GIRAFFE)@VLT

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.**