Globular Cluster observations with HST

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Jay Anderson courtesy

HST has wonderful astrometric capabilities

On well exposed stars, astrometric precision on single images is of ~0.01 pixels, which implies:

WFPC2	: 1.00 milliarcsec (mas)
PC	: 0.50 mas
HRC/ACS	: 0.25 mas
WFC3	: 0.30 mas

But you can use many images, and reach higher precision in relative stellar positions, with local transformations (J. Anderson great idea!)

HST high astrometric precision implies high precision proper motions

1) **Bulk motions:**
membership: fast evolving stars, WDs, binaries, exotics like CVs, blue stragglers, etc.

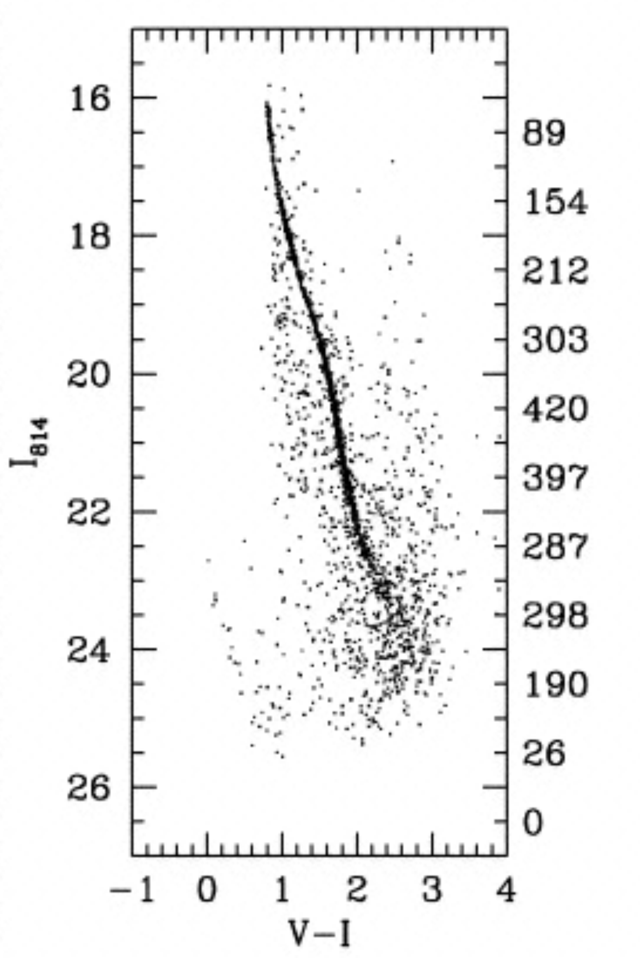
2) **Absolute motions:**
clusters, field stars, rotations

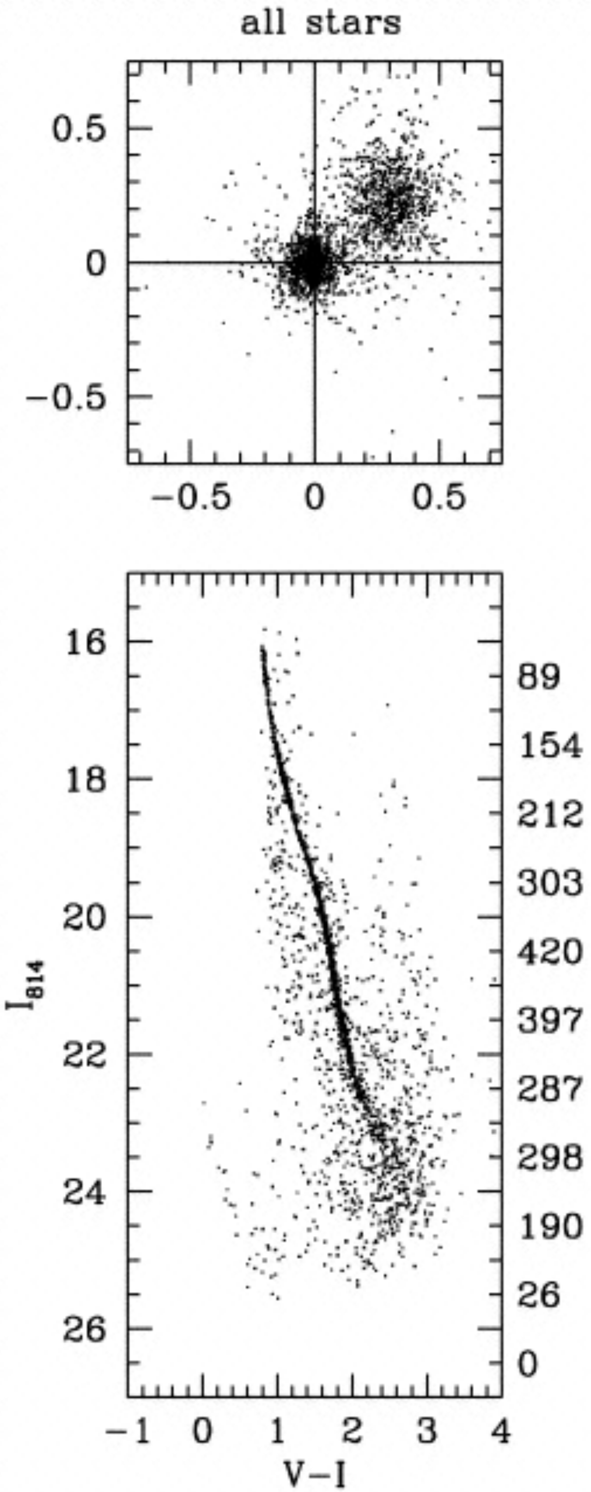
3) **Internal motions:**
Internal dynamics, IMBH?, absolute distances

Ivan King and the faint stars in NGC 6397

- End of sequence lost in field stars
- How to identify the members?

Proper motions!!




all stars
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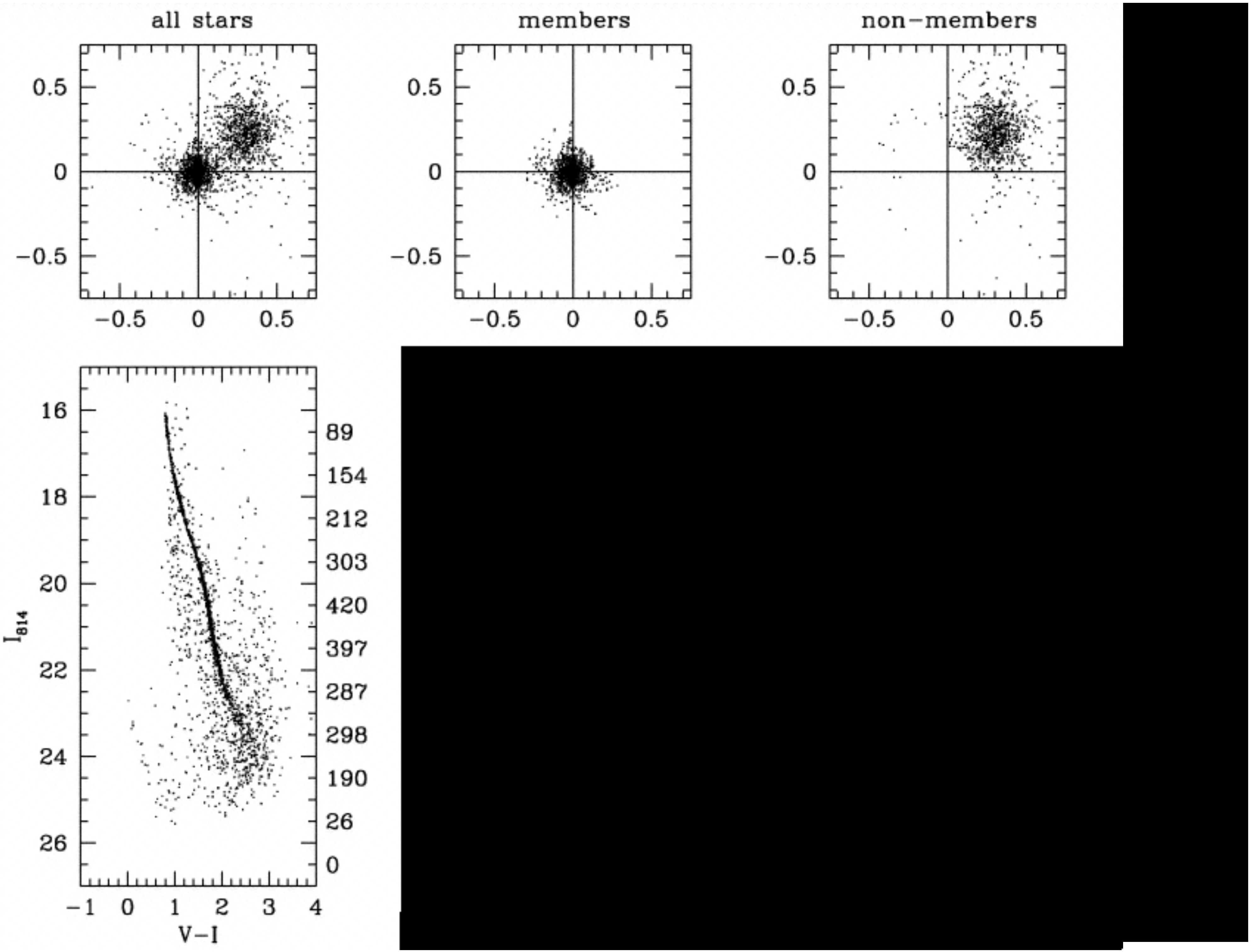
all stars
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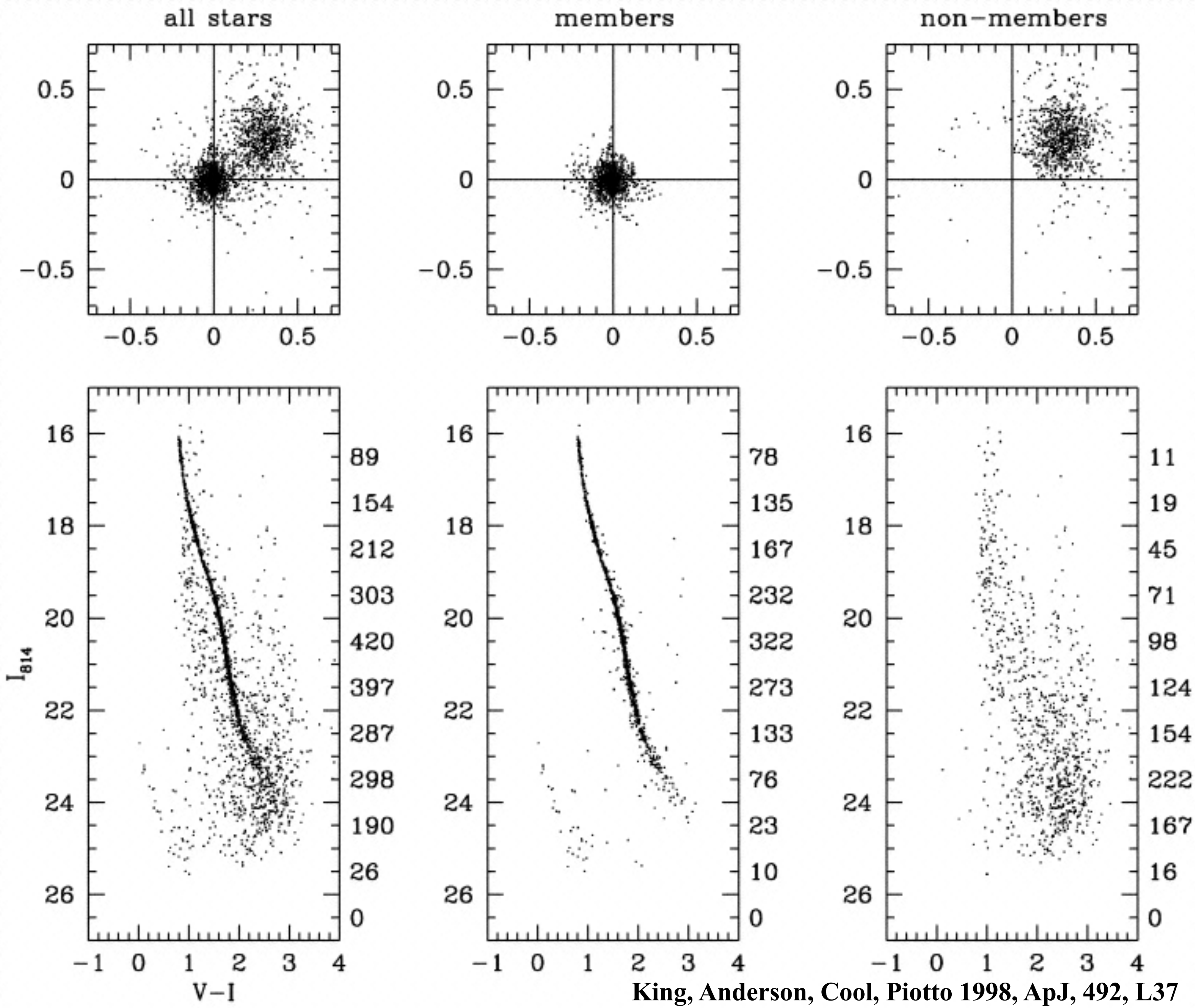
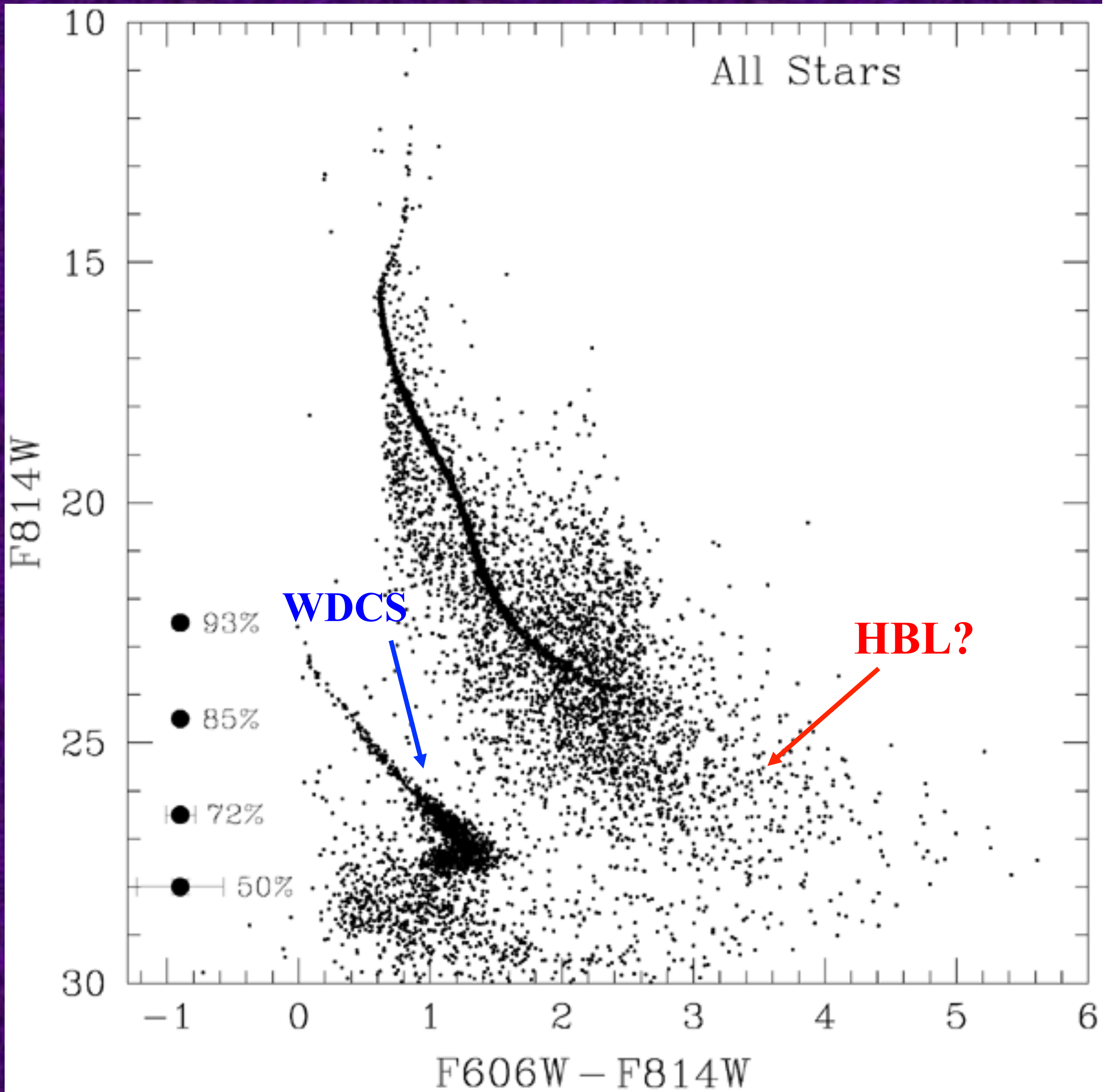


King, Anderson, Cool, Piotto 1998, ApJ, 492, L37

NGC6397 II: pushing HST to the limits

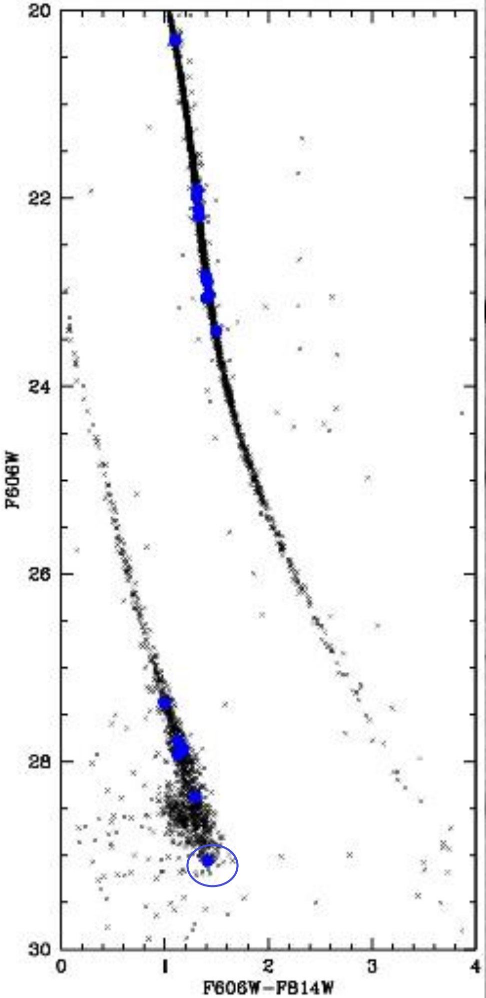
- Richer et al. (2005) observed NGC6397 with **126 orbits**
  - Discoveries
    - End of WD cooling sequence
    - Blue hook at the WDCS bottom!
    - End of MS?
  - Again: limitations: field stars and galaxies!

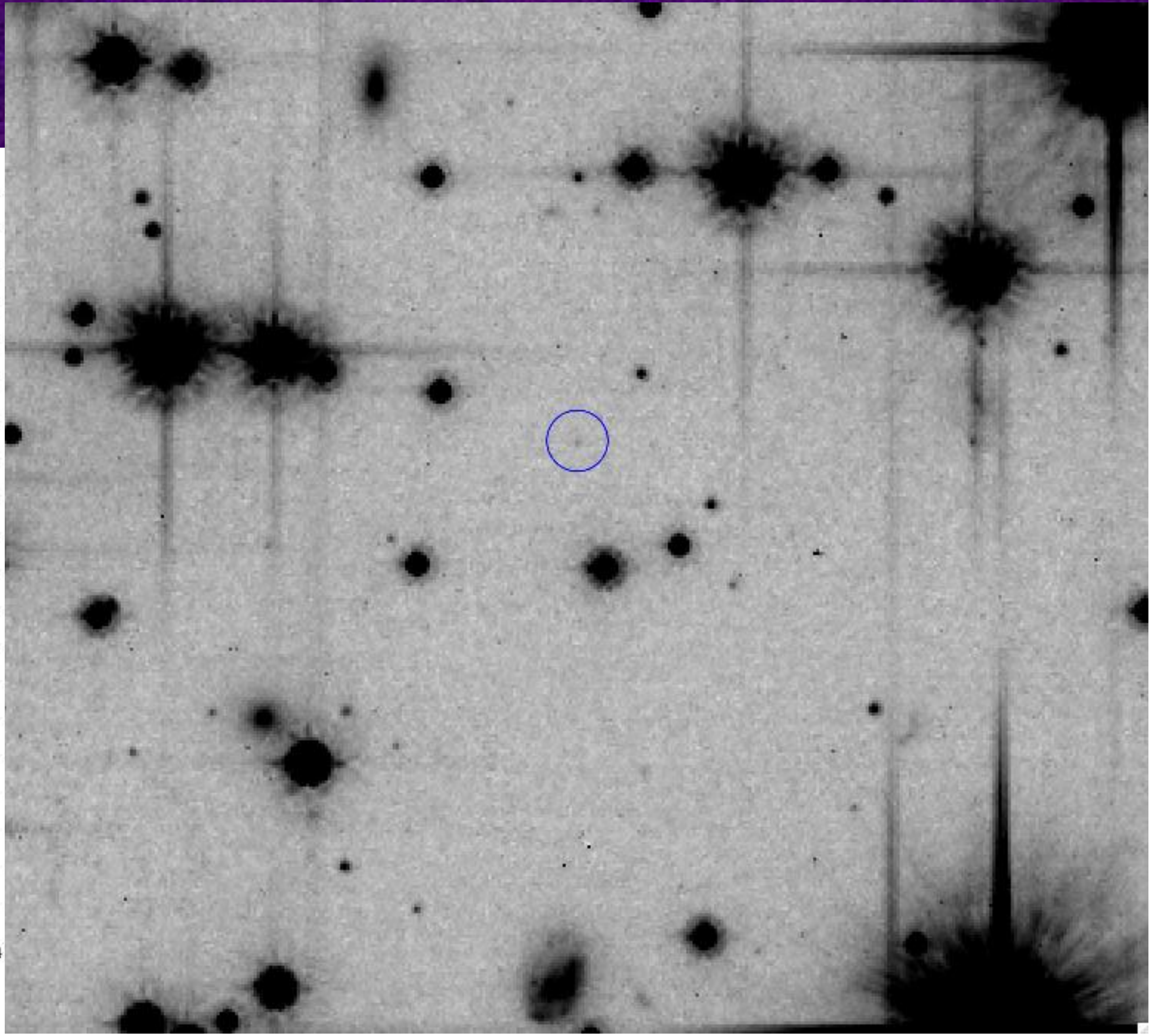


Proper motion cleaning, 5 years baseline

NGC6397

PI-Rich, UCLA

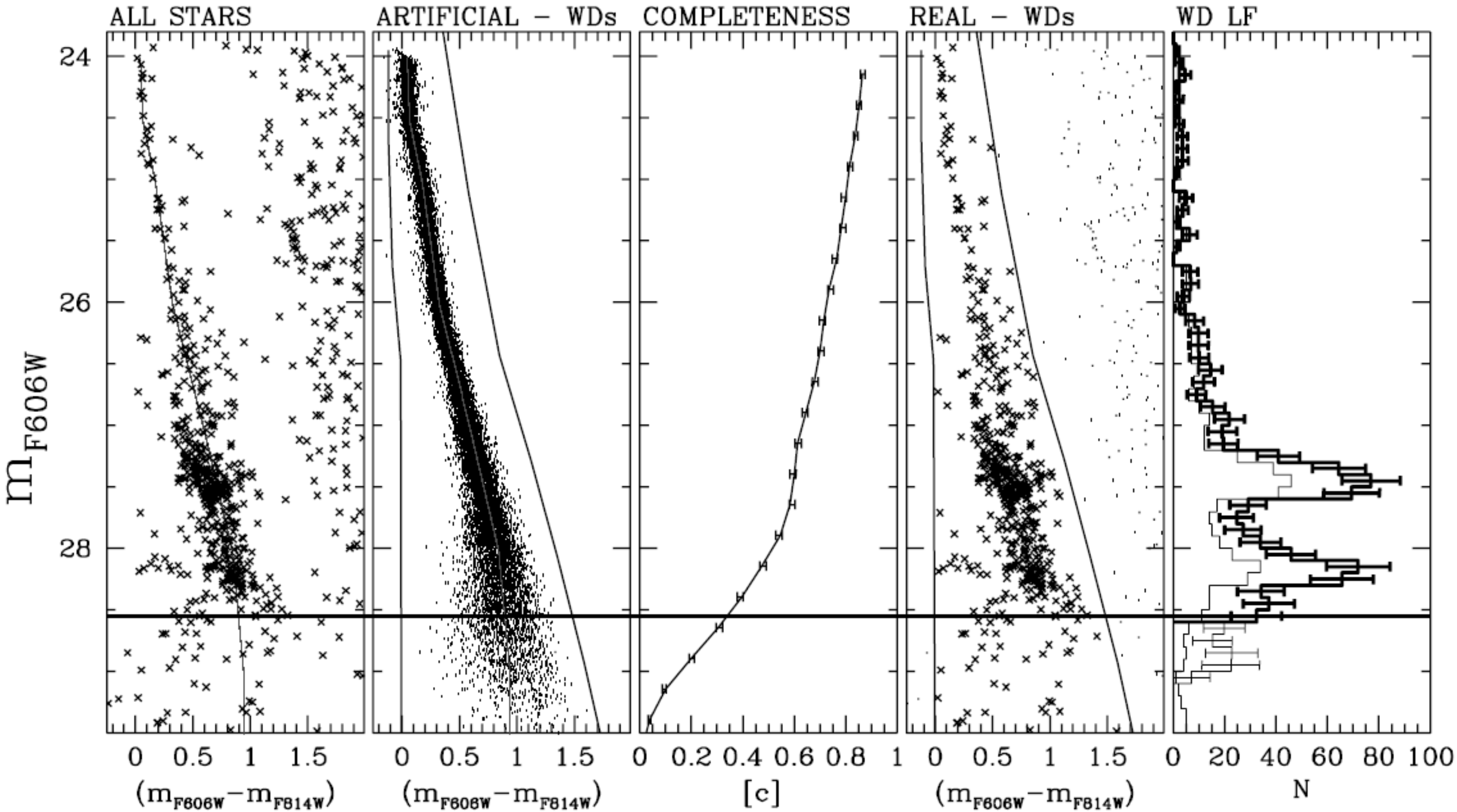




BLINK

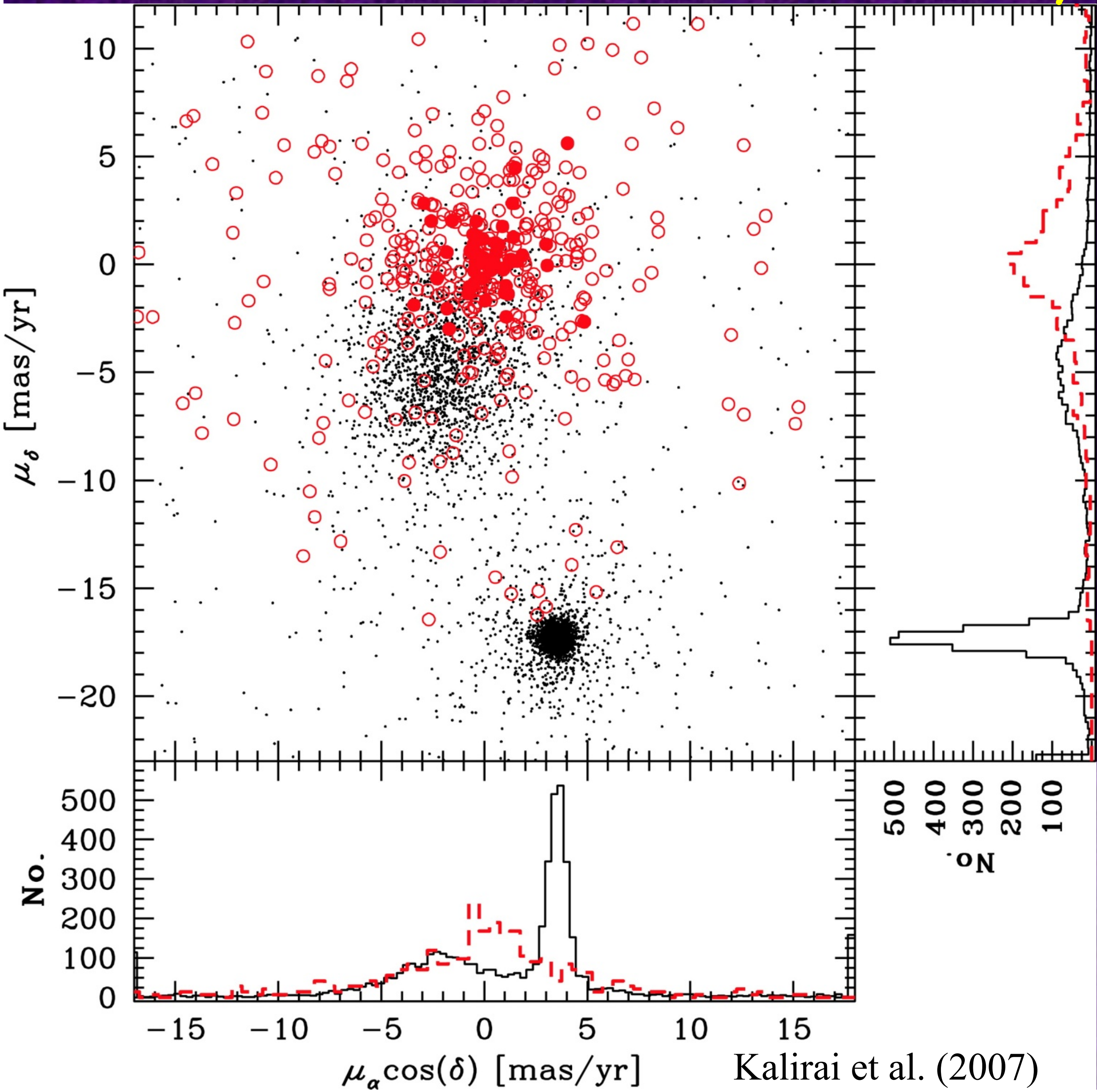
Pushing HST to the limits, sometimes you may get… surprises:

The double peaked WD cooling sequence in NGC 6791



Bedin et al. 2005, 2008a, 2008b

NGC 6397 III: Richer's 126 HST orbits, 398 bk galaxies



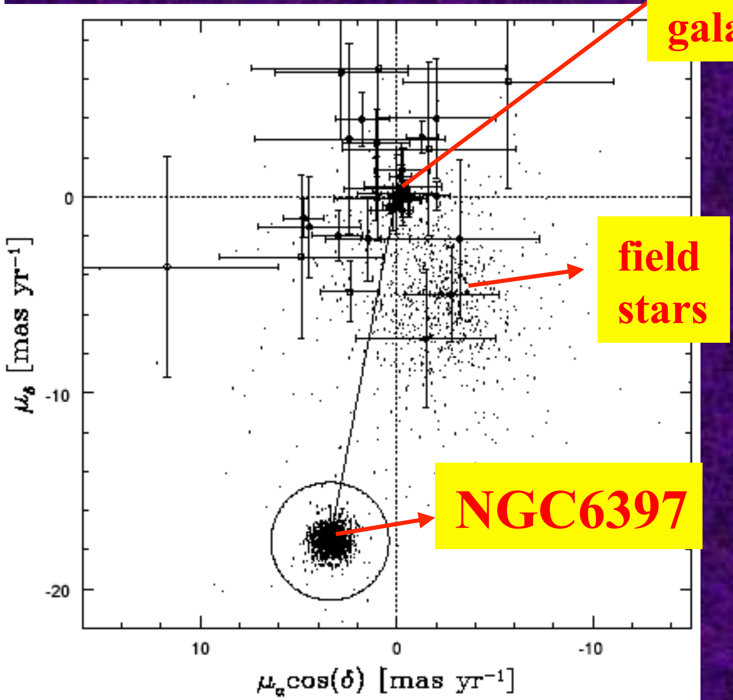
Kalirai et al. (2007)

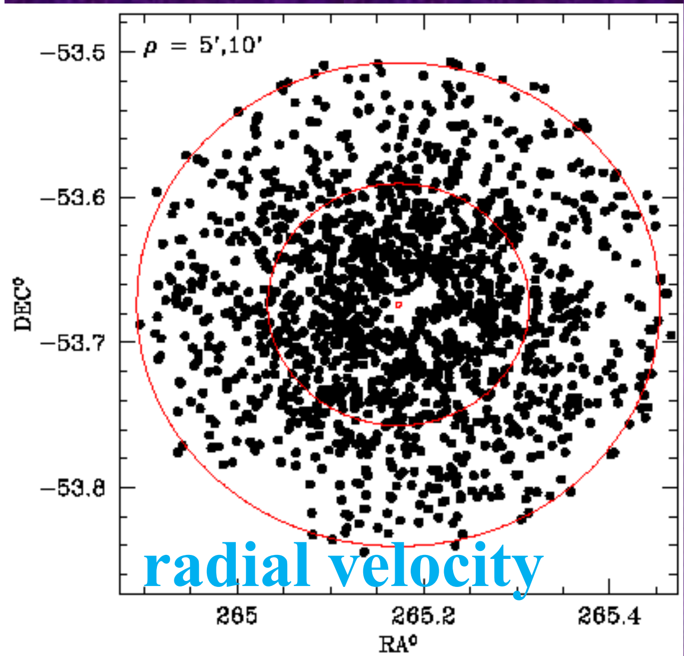
250μas astrometric precision on single brightest galaxies;
10yr baseline, 40μas/yr in absolute proper motion error!

The "problem" with proper motions is that… they become better and better with time!

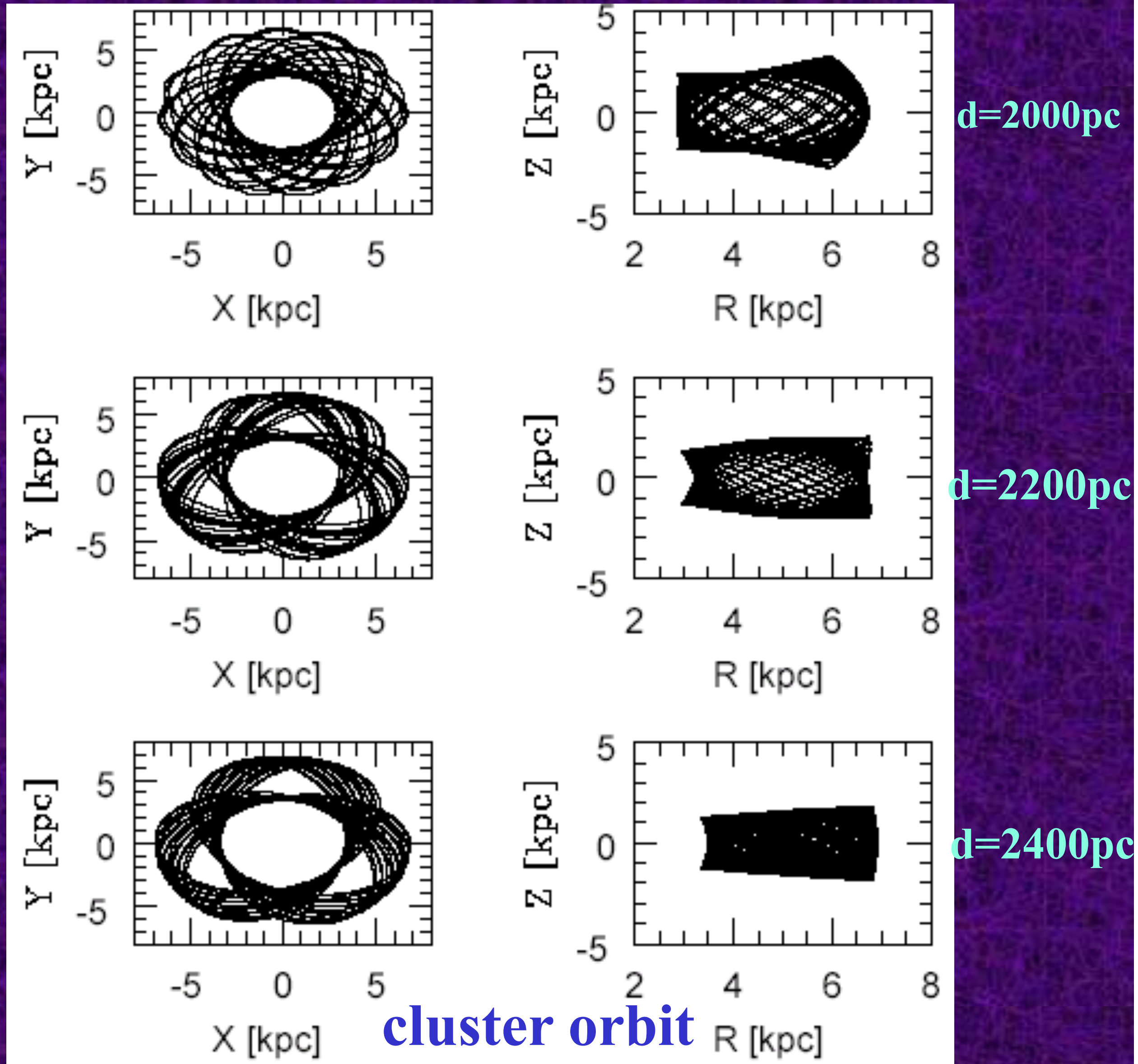
3D absolute motions: the orbits of NGC 6397

proper motion





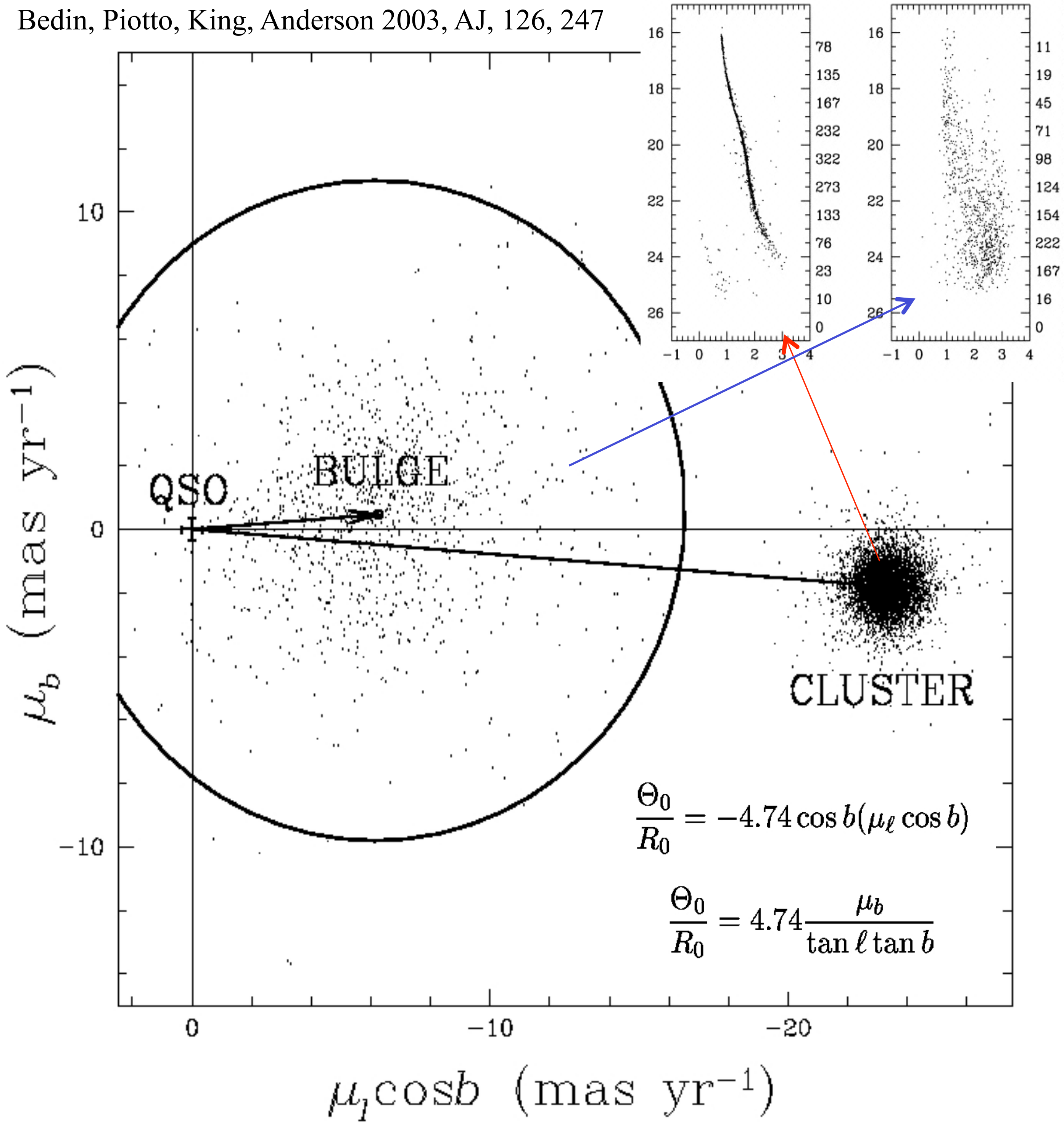
radial velocity



cluster orbit

Milone et al. 2006, A&A 460, L27

Bedin, Piotto, King, Anderson 2003, AJ, 126, 247

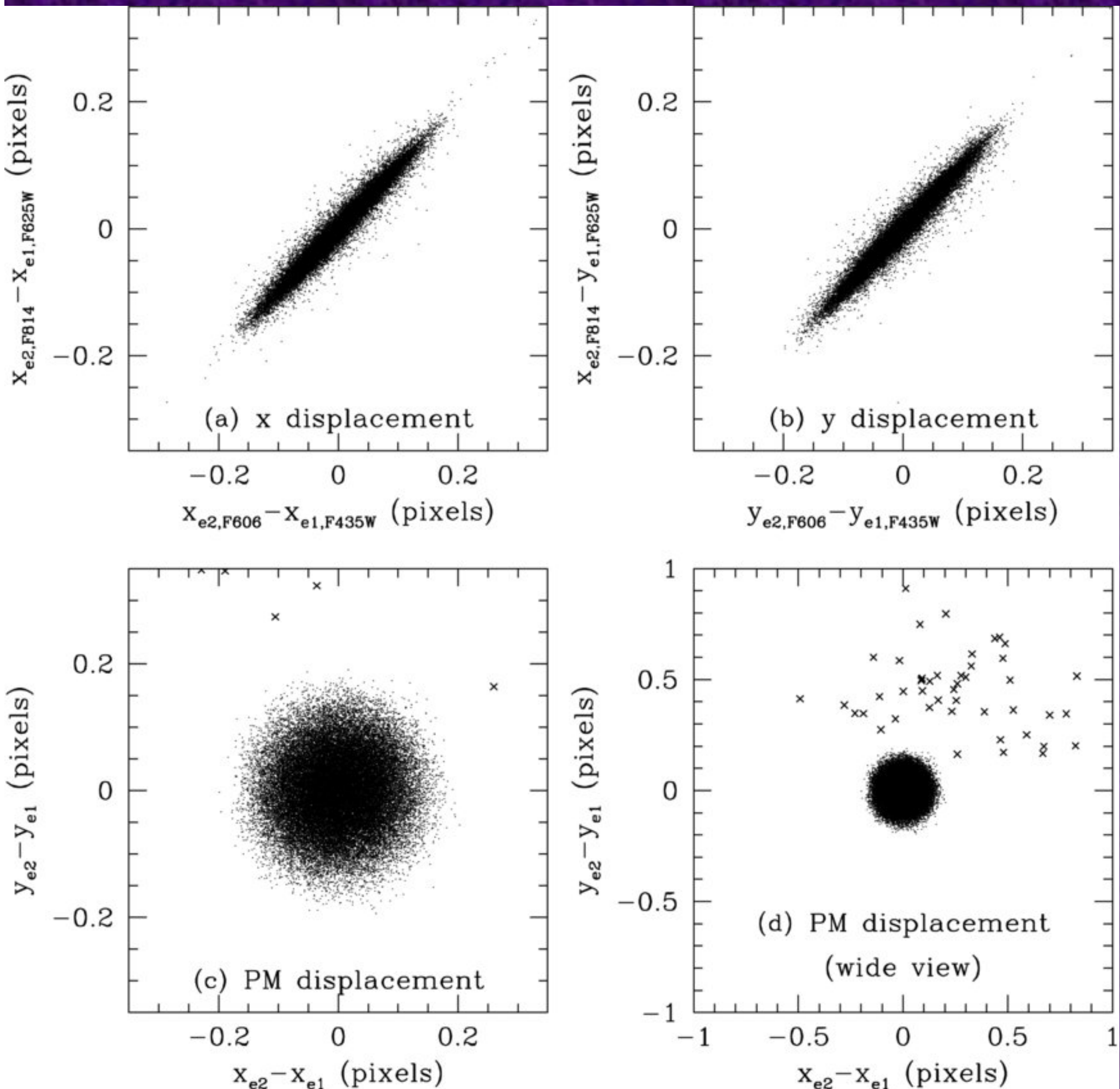


Field stars may be as useful as cluster stars!!!!

Measurement of the Galactic constant:

$(A\text{-}B)_{Oort} = \Theta_0/R_0 =$ 27.6±1.7 km/s/Kpc

Geometrical distance of ωCen



Anderson and van der Marel (2010)
Van der Marel and Andersono (2010)

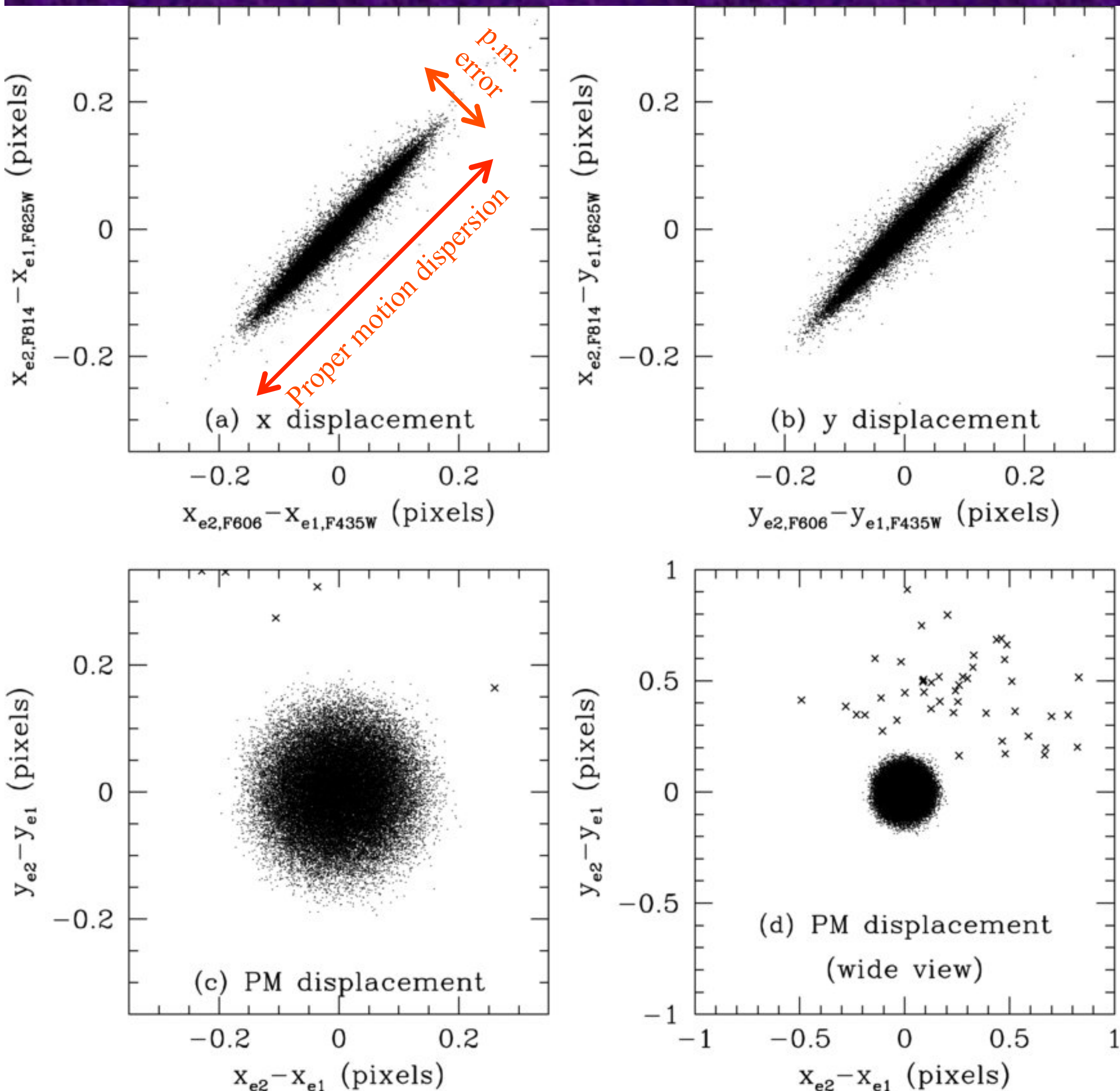
2-dimensional proper motion dispersion:

σ_x = 833 ± 59 μas/yr
σ_y = 835 ± 71 μas/yr

Comparing proper motion dispersion (an angular) quantity with the radial velocity dispersion (a linear quantity), we get the **distance:**

D = 4.70 ± 0.06 kpc

Geometrical distance of ωCen



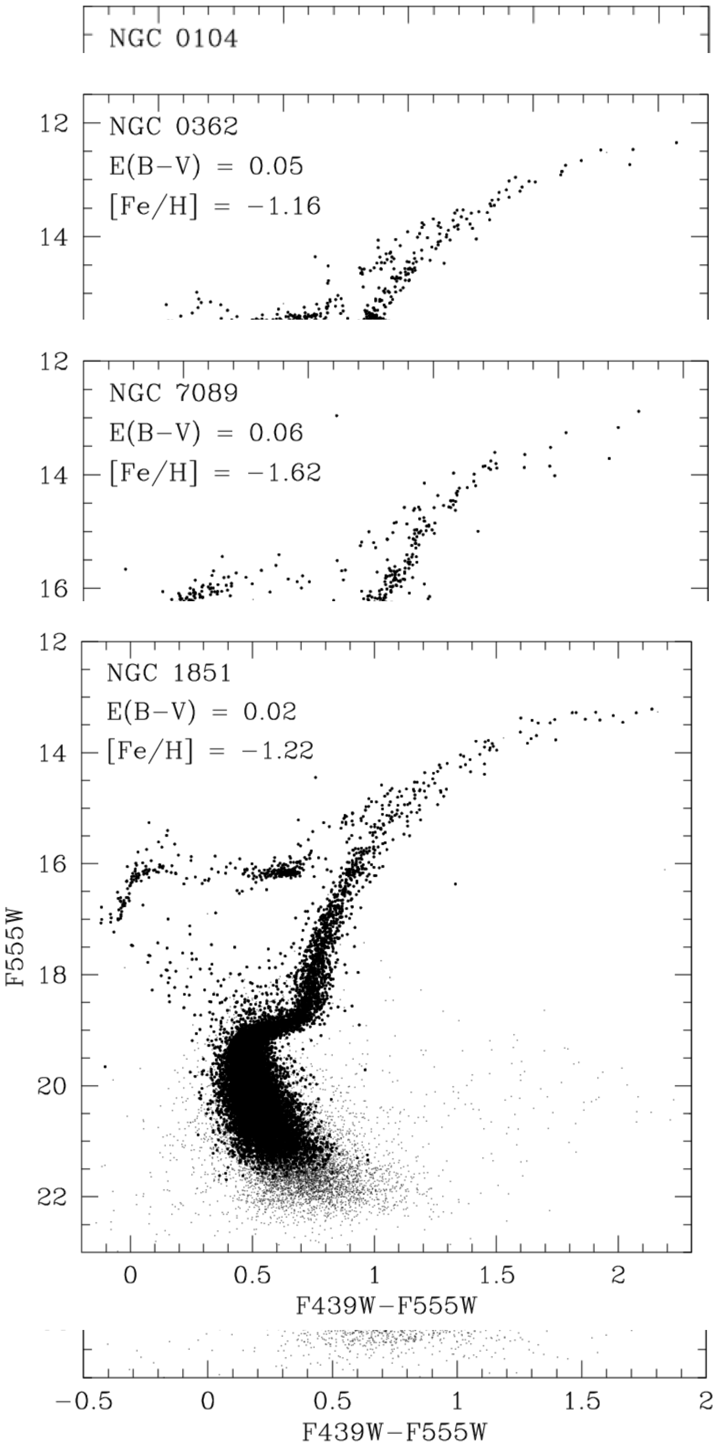
Anderson and van der Marel (2010)
Van der Marel and Andersono (2010)

2-dimensional proper motion dispersion:

σ_x = 833 ± 59 µas/yr
σ_y = 835 ± 71 µas/yr
4 year time baseline

Comparing proper motion dispersion (an angular) quantity with the radial velocity dispersion (a linear quantity), we get the distance:

D = 4.70 ± 0.06 kpc



High precision astrometry means high precision PSFs and therefore:

High precision photometry

First photometric survey

HST SNAPSHOT PROJECT:

(Piotto et al. 2002, A&A, 391,945)

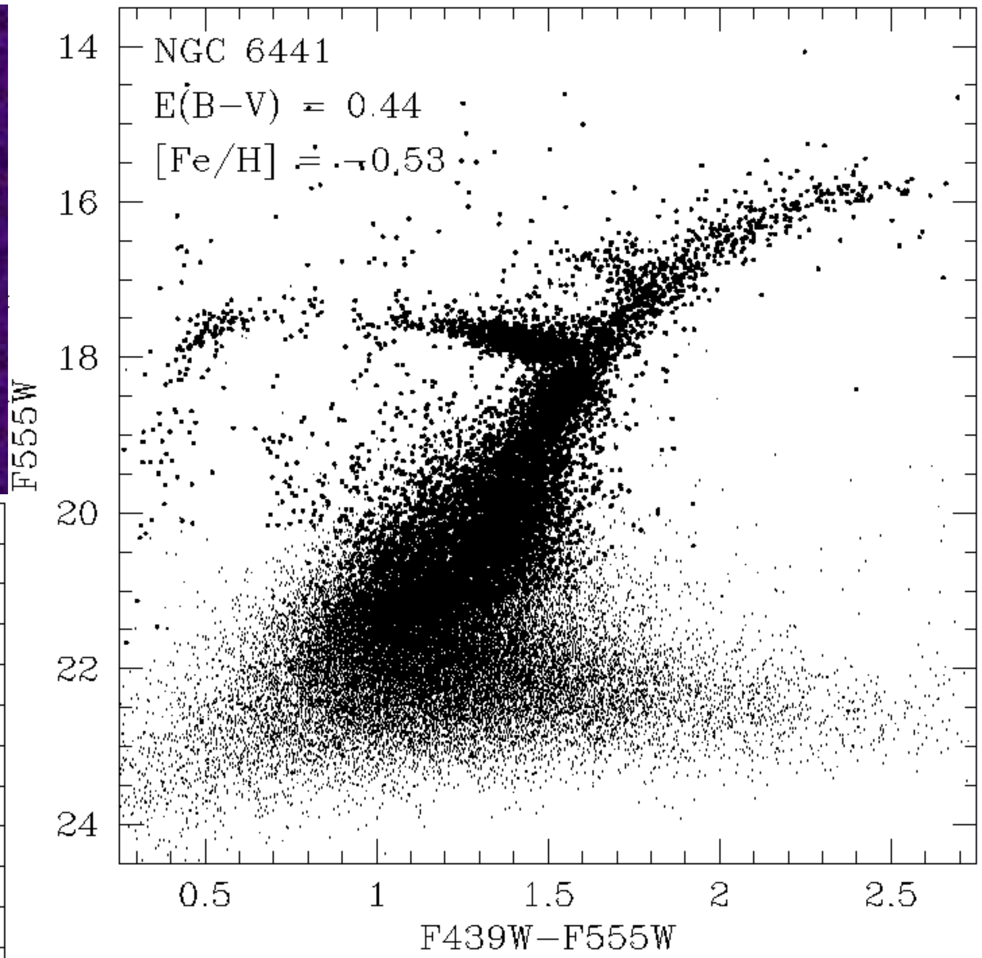
•74 GC cores observed with the WFPC2 in the F439W and F555W band [all clusters with (m-M)B<18];

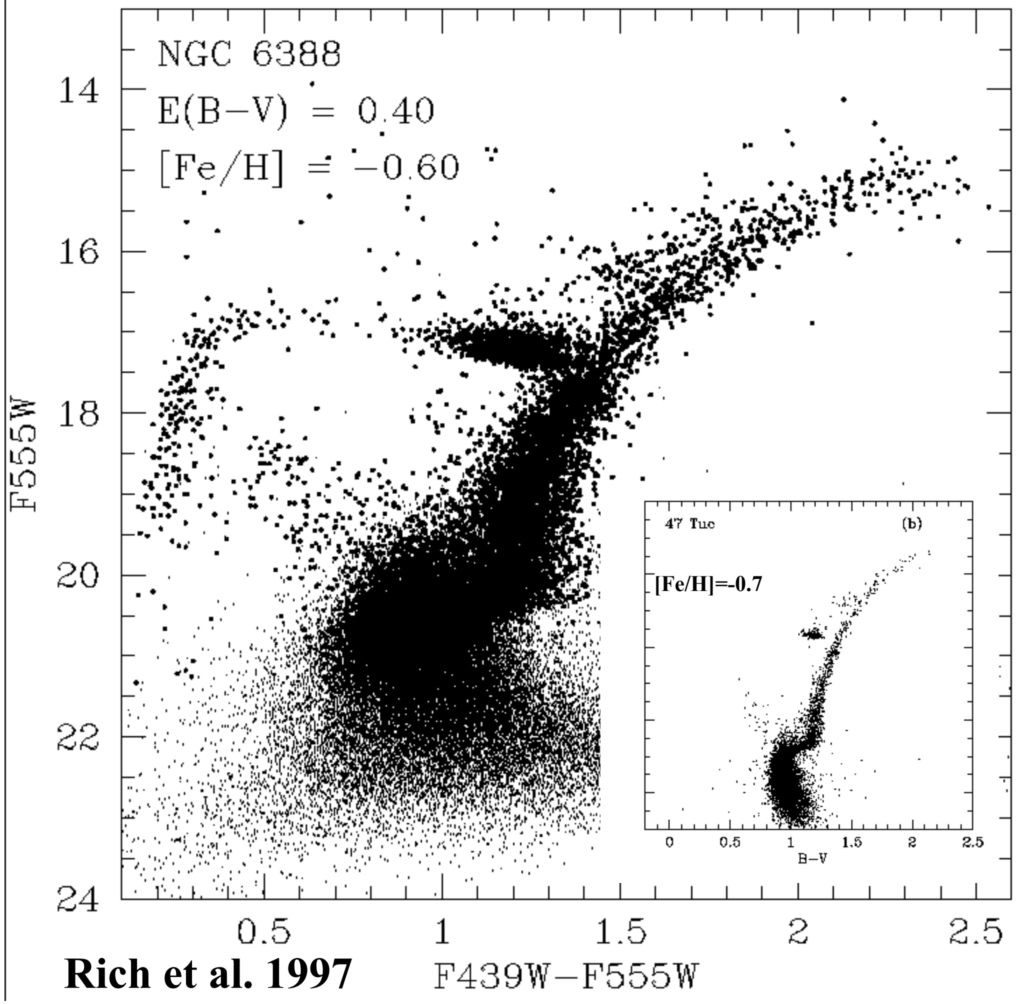
•More than 150 papers based on this data base;

•1st epoch for proper motion measurements;

•Data available on: http://dipastro.pd.astro.it/globulars/databases/snapshot/snapshot.html

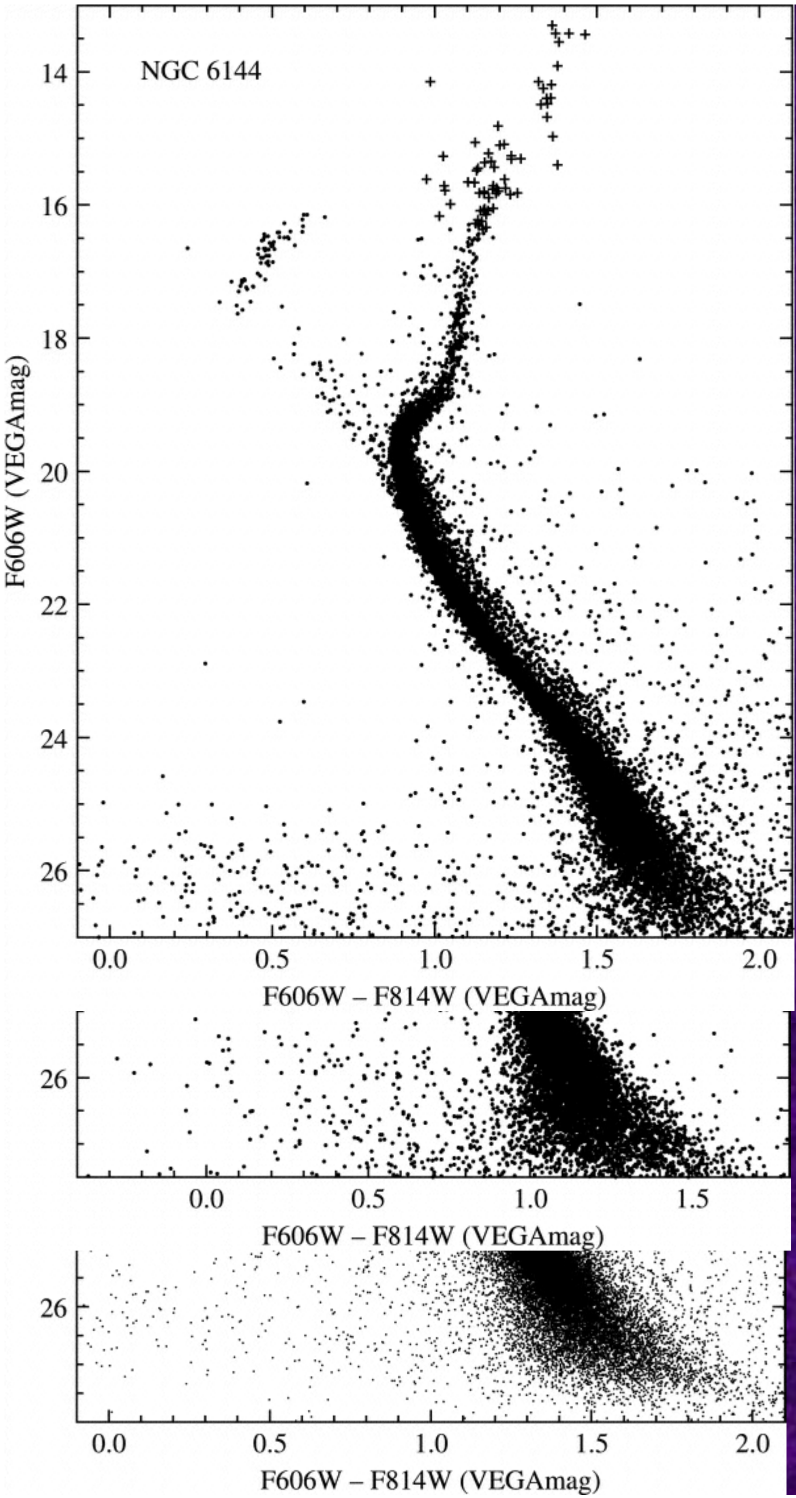
The most surprising discovery from the HST WFPC2 snaposhot survey





Rich et al. 1997

Blue horizontal branches in metal rich globular clusters



Globular Cluster Treasury project PI: A. Sarajedini

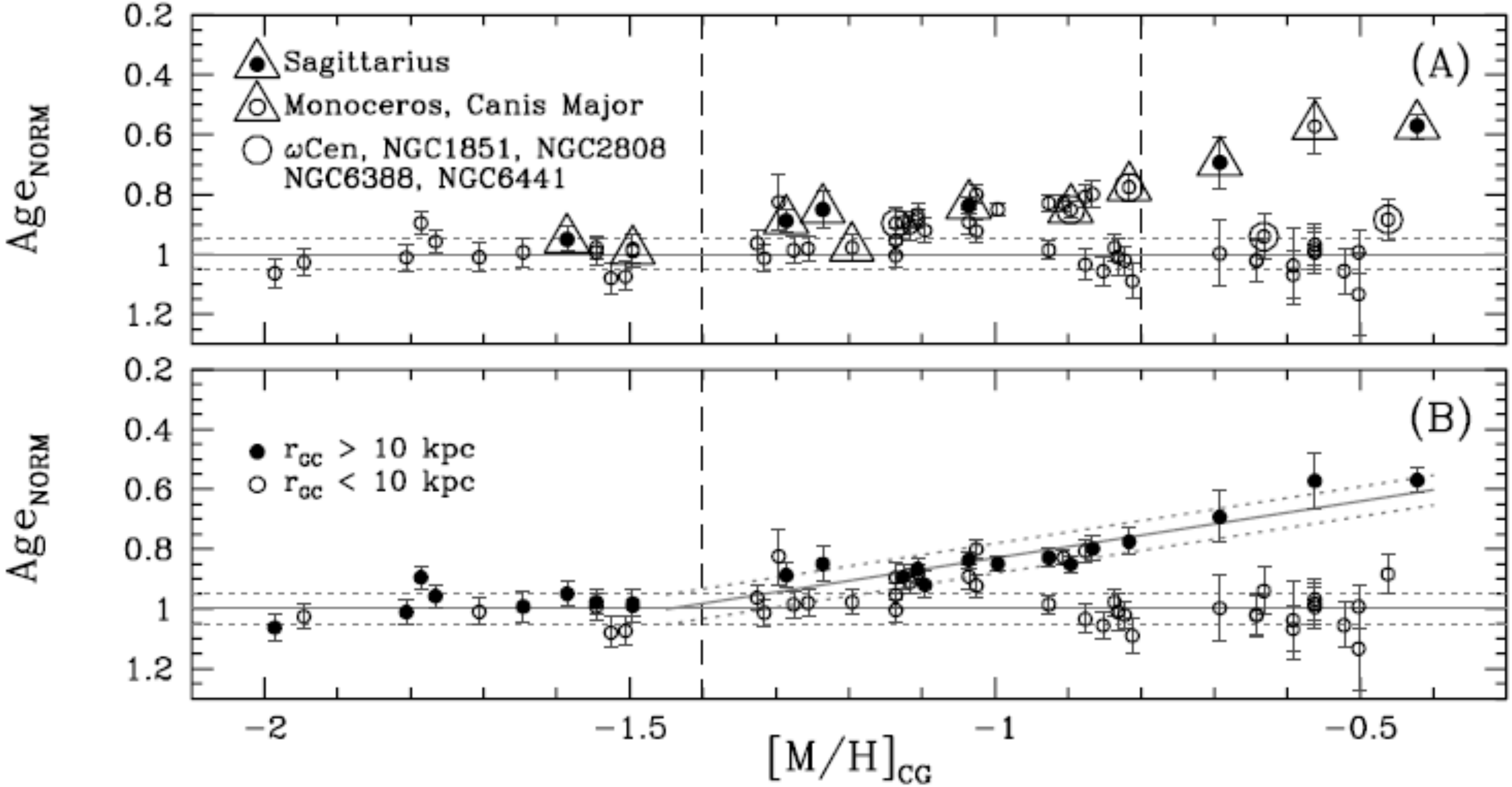
Anderson et al. 2008, AJ, 2008, 135, 2055

ACS/HST survey of 66 Galactic Globular Clusters

Target: down to 0.2 solar masses with S/N>10; highest S/N at the TO

Data available on: http://www.astro.ufl.edu/~ata/public_hstgc/databases.html

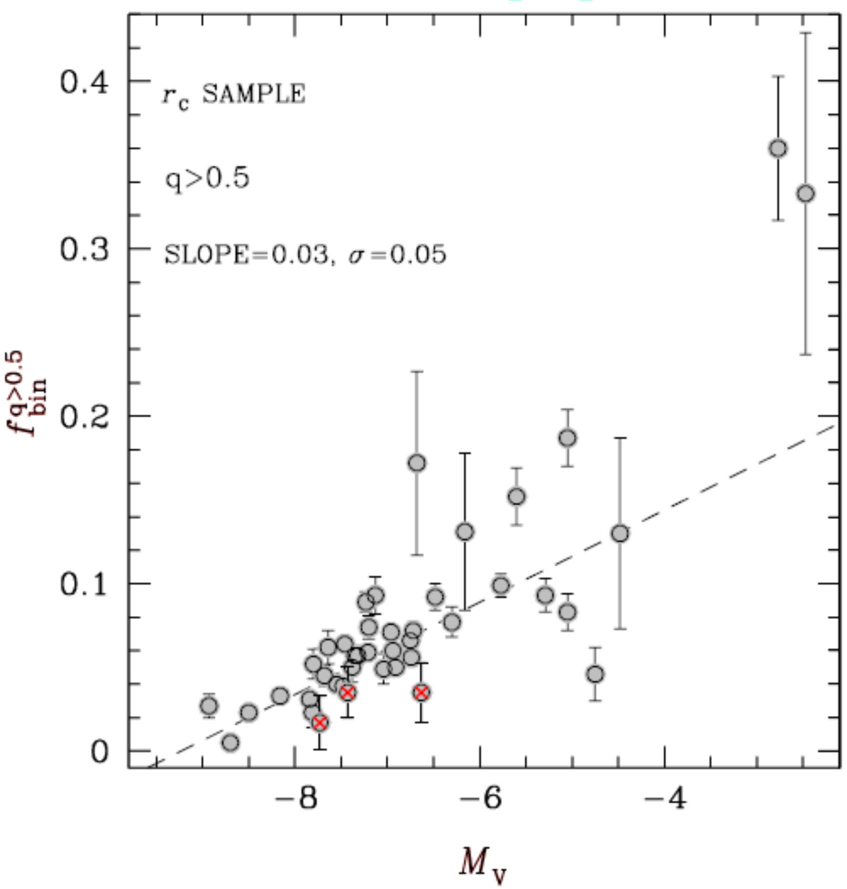
Globular Cluster relative ages

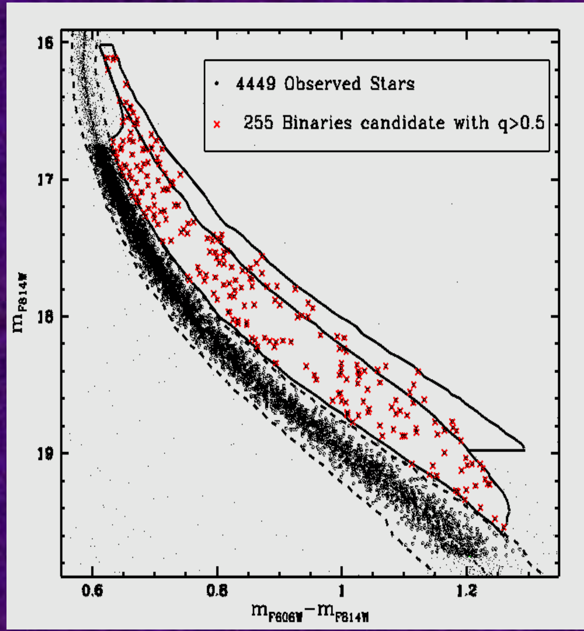


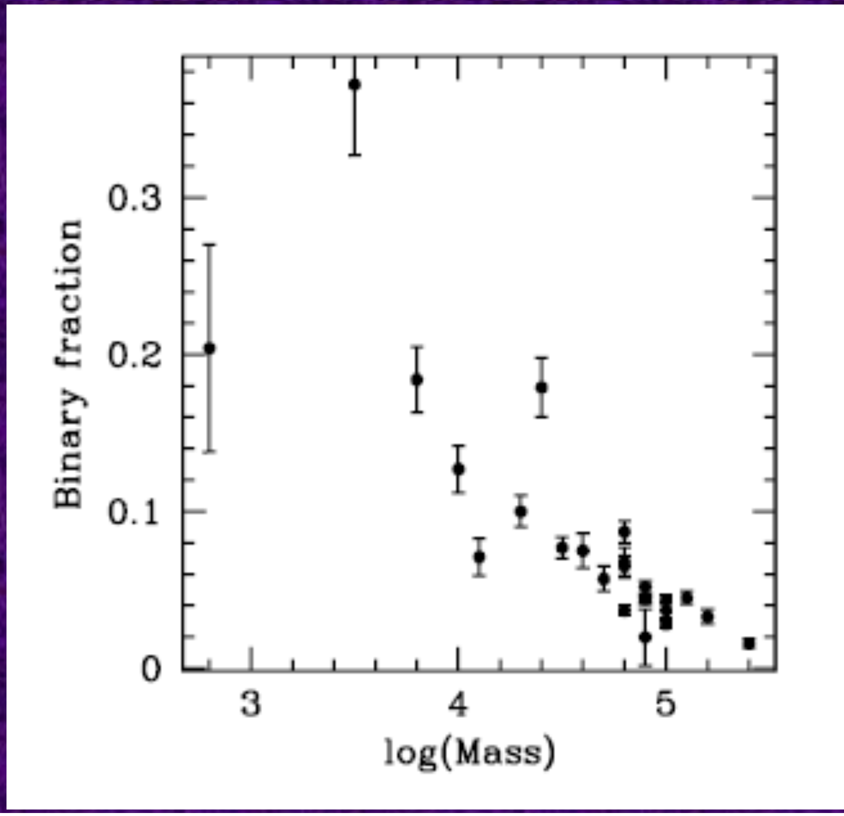
Marin-French et al. 2009

Photometric binaries in 54 Globular Clusters.

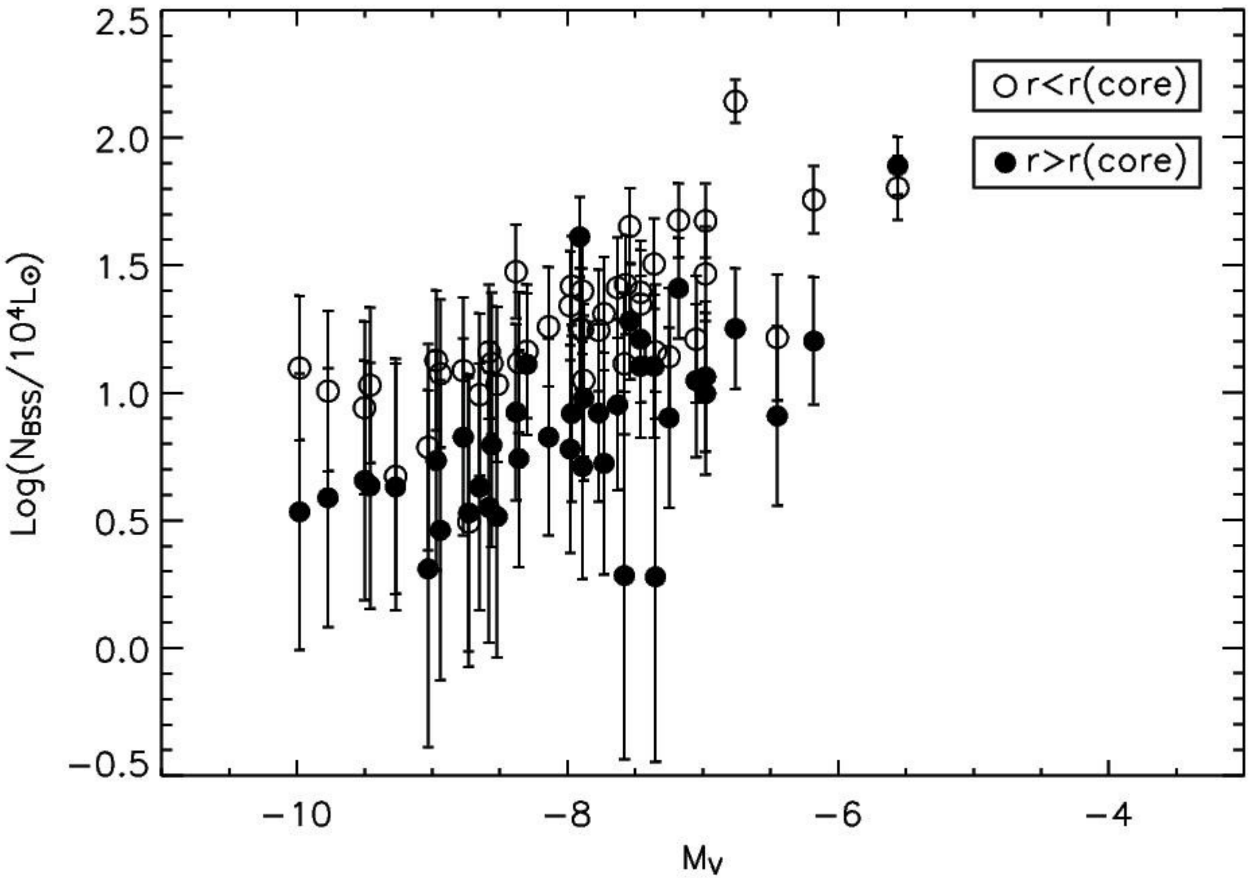
Milone et al. 2010, in prep.

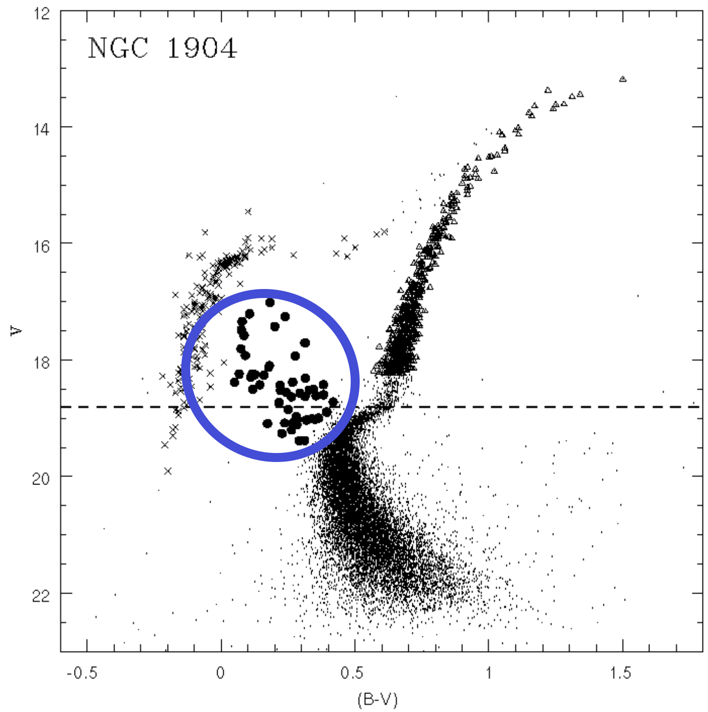






Significant anti-correlation between the fraction of binaries in a cluster and its absolute luminosity (mass)





From HST snapshot survey

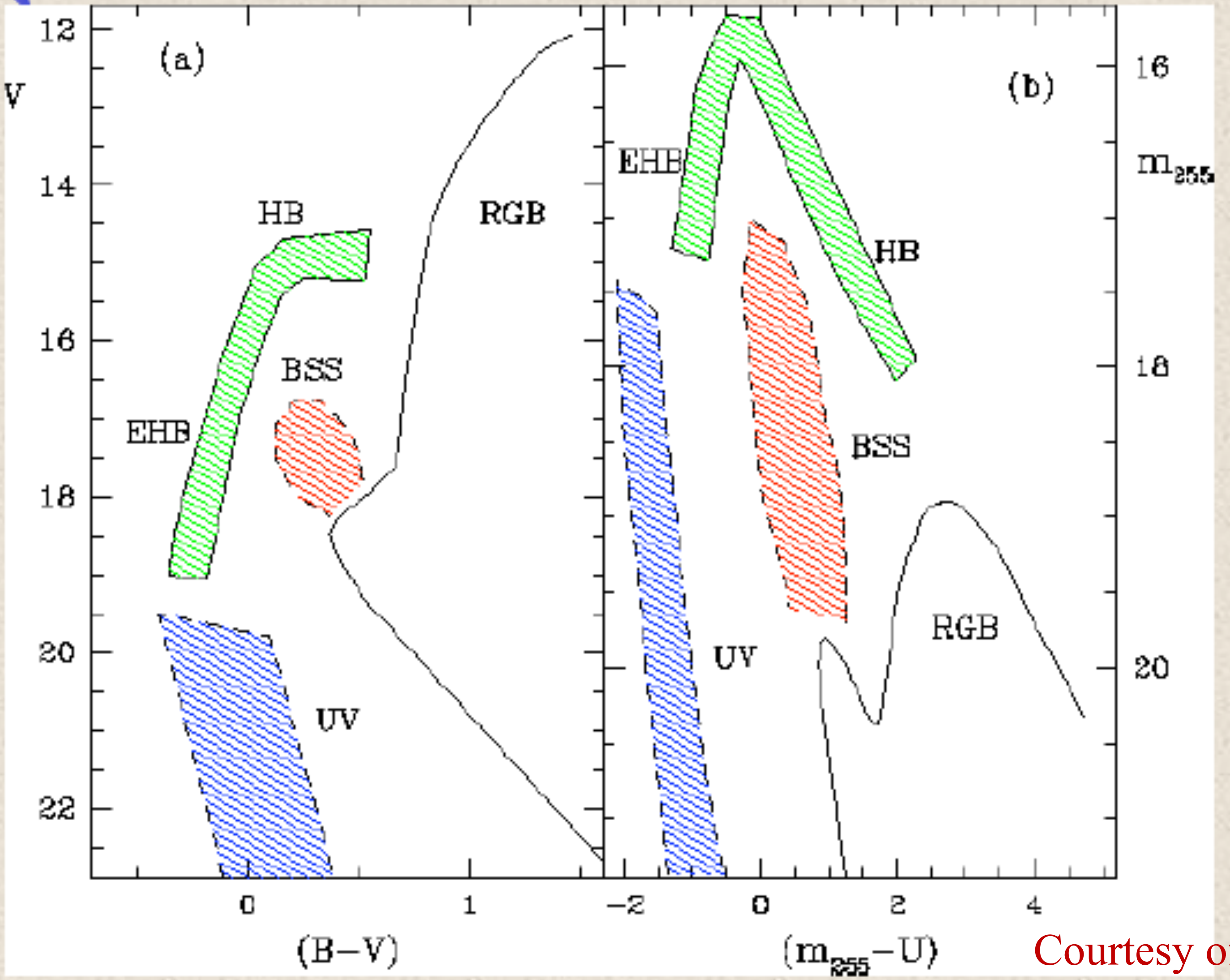
Blue stragglers frequency anticorrelates with cluster total luminosity (total mass). This fact has been interpreted as an evidence of the dynamical evolution of binaries.

Moretti et al. (2008), Davies et al. (2005) Piotto et al. (2004), HST

UV sensitivity , high resolution

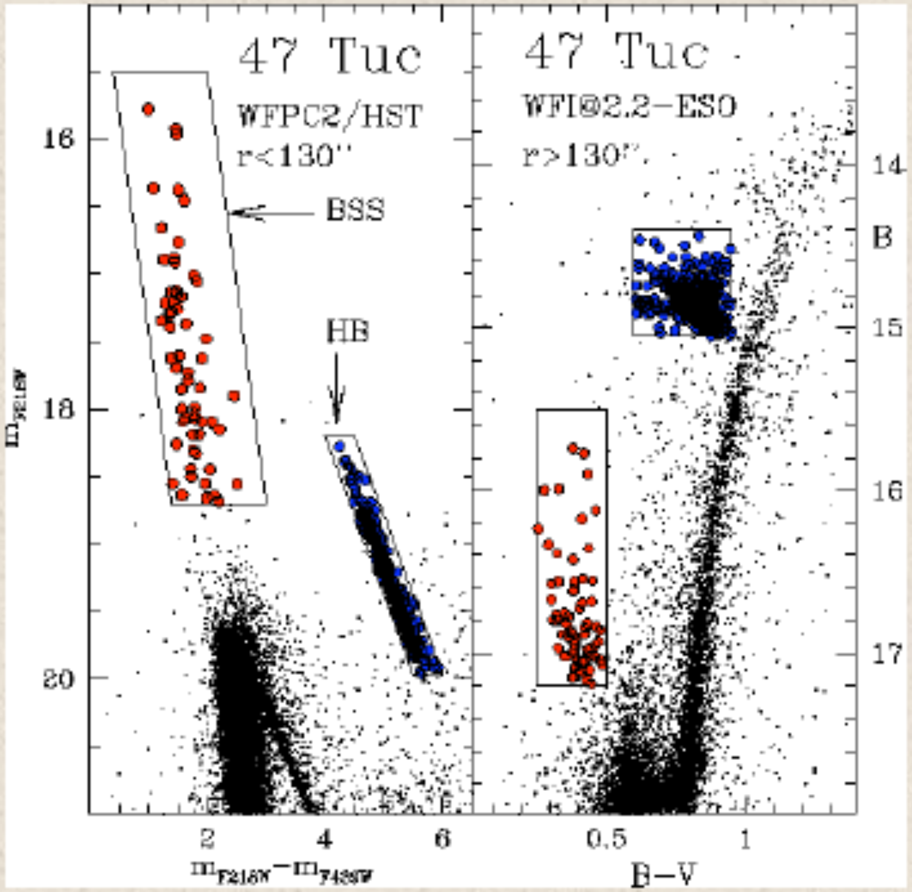
⇓

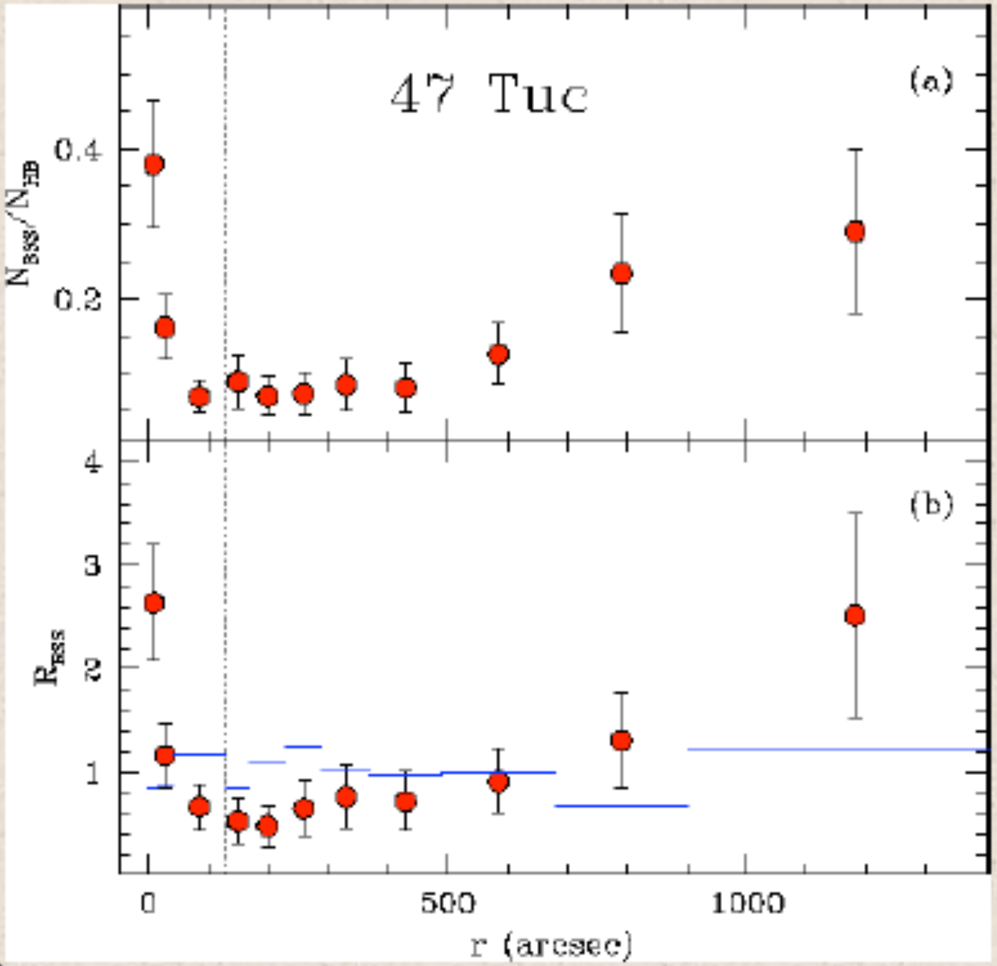
systematic studies of hot SPs in the core of high density GGCs



Courtesy of F. Ferraro

BSS radial distribution: 47 Tuc





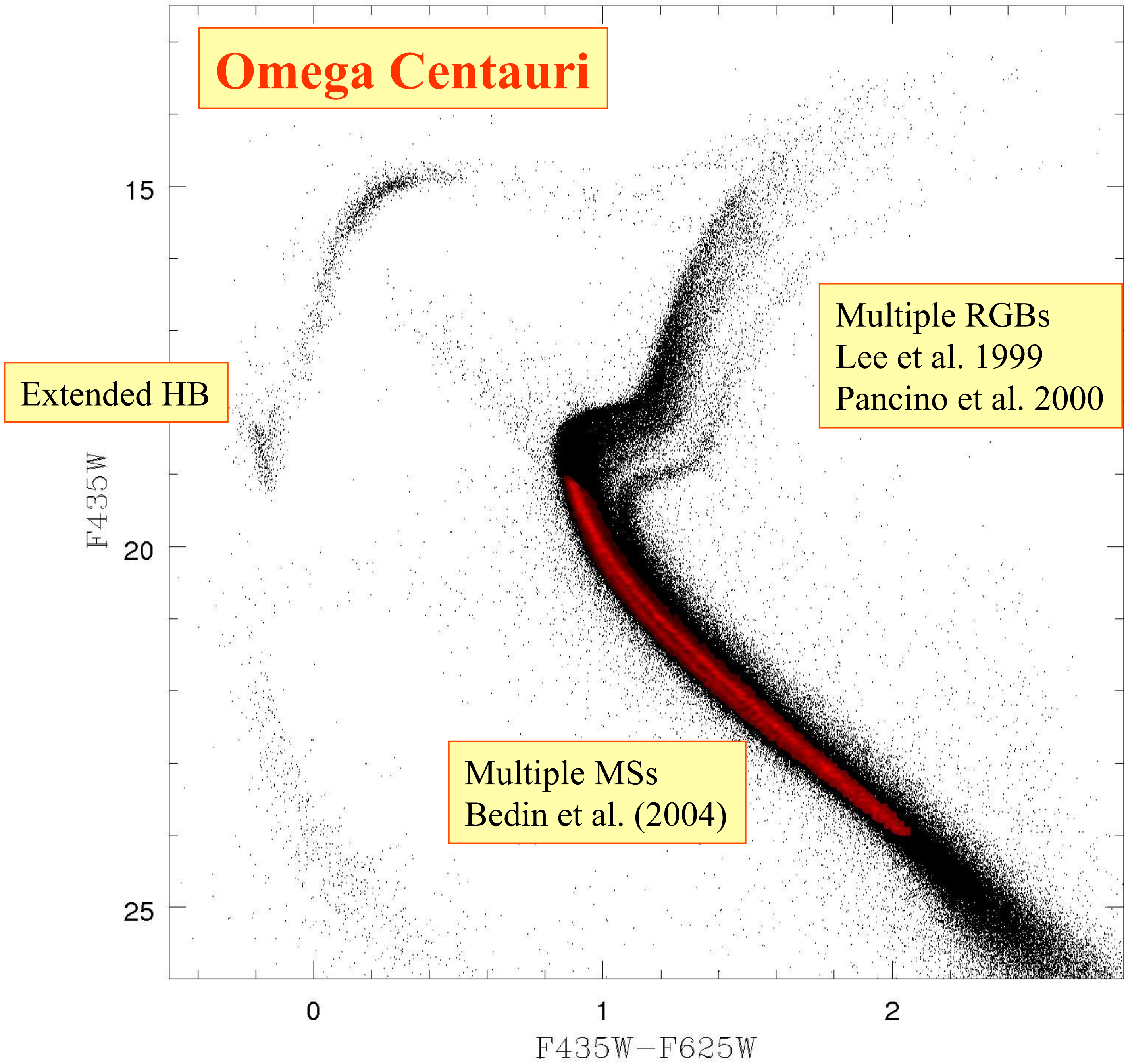
The BSS radial distribution in 47 Tuc is quite similar to that observed in M3

Mapelli et al. (2004)

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

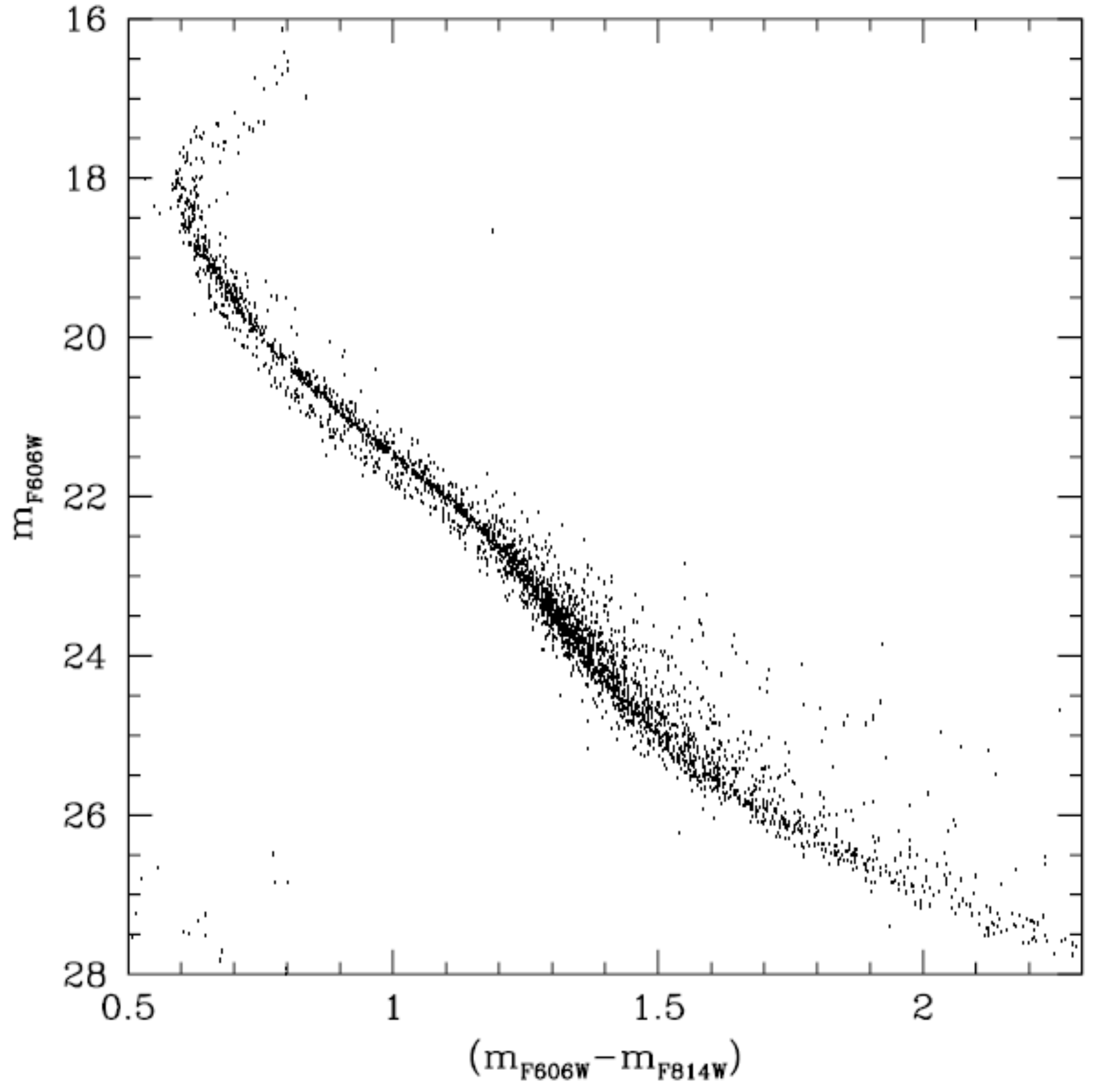


The scenario abruptly changed "special" case: Omega Centauri

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

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

Omega Centauri multiple sequences



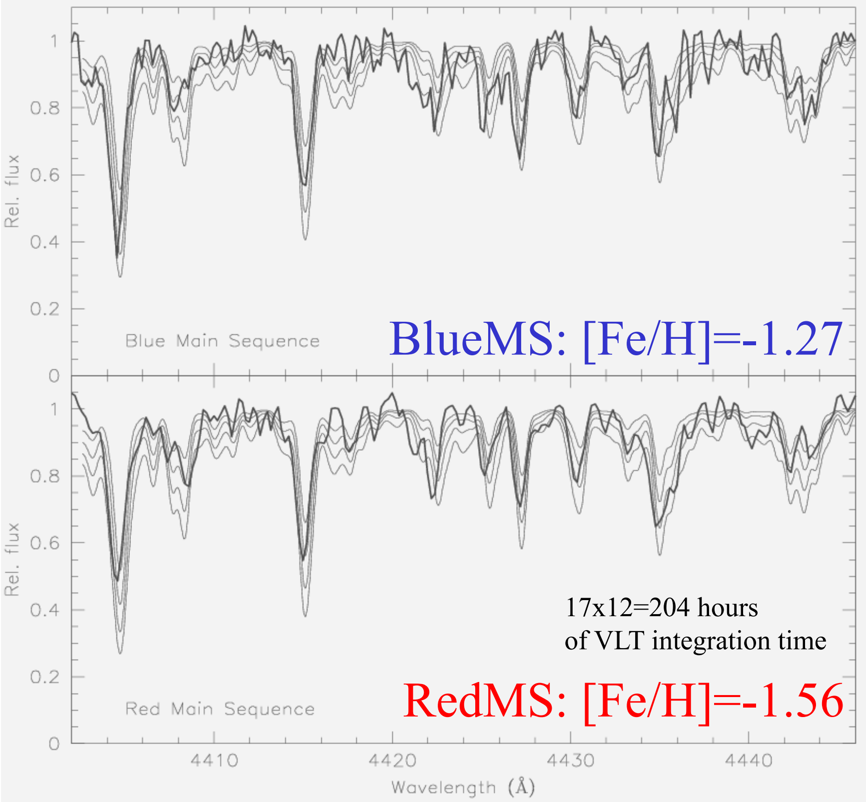
The discussion revitalized thanks to an exceptional HST (WFPC2 and ACS) discovery

The main sequence of Omega Centauri is split into two, distinct "main" main sequences

(Anderson, 1997, PhD thesis, Bedin et al. 2004, ApJ, 605, L125).

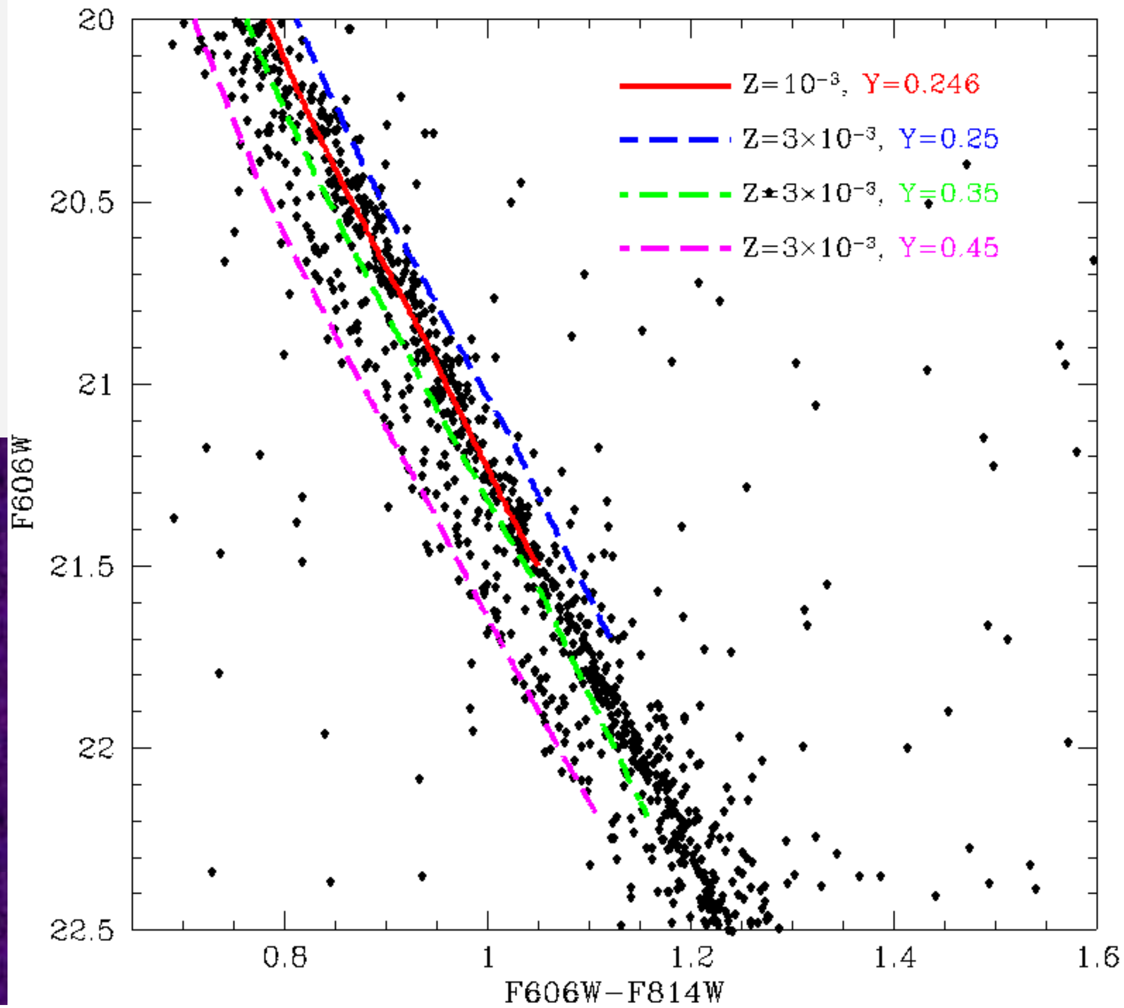
A new era in globular cluster research opened

The most surprising discovery



The bluer sequence is MORE METAL RICH

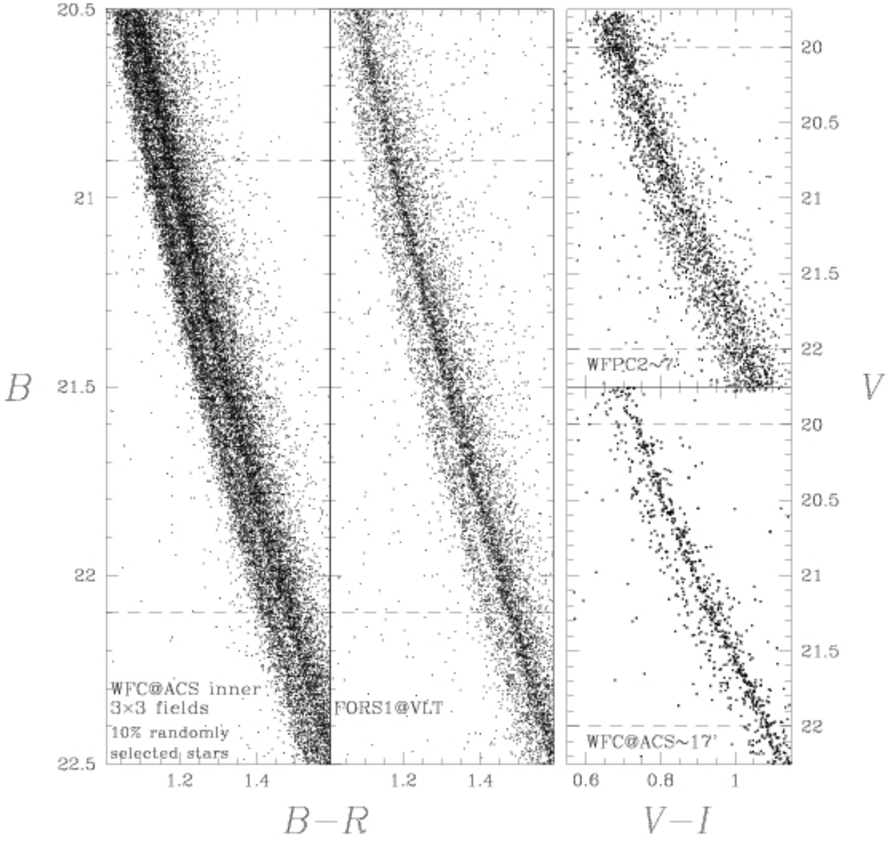
Piotto et al. (2005, ApJ, 621,777)

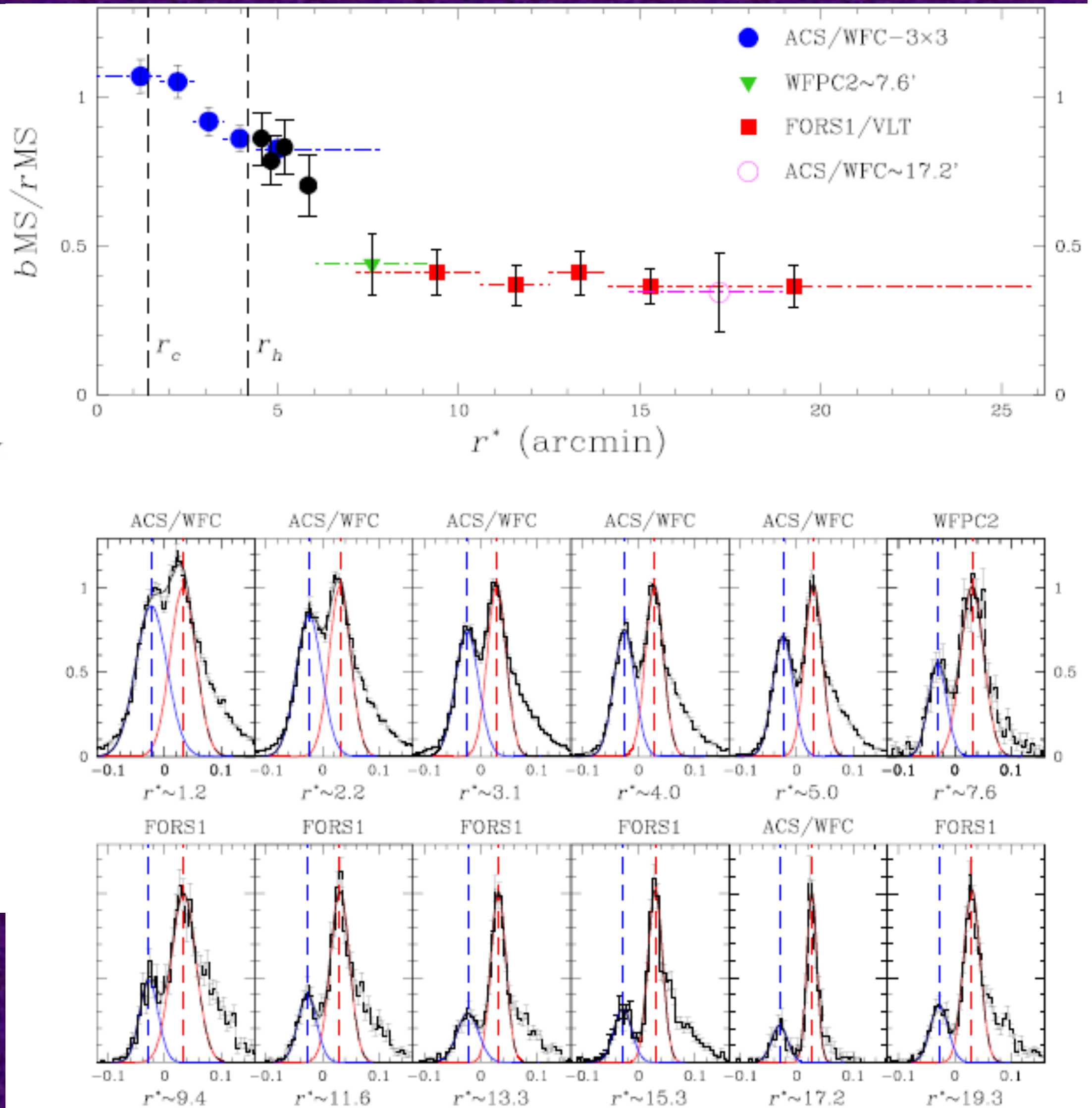


Apparently, only <u>an overabundance of Helium (Y~0.40)</u> can reproduce both the photometric and spectroscopic observations

Omega Centauri: Radial distribution of main sequence stars

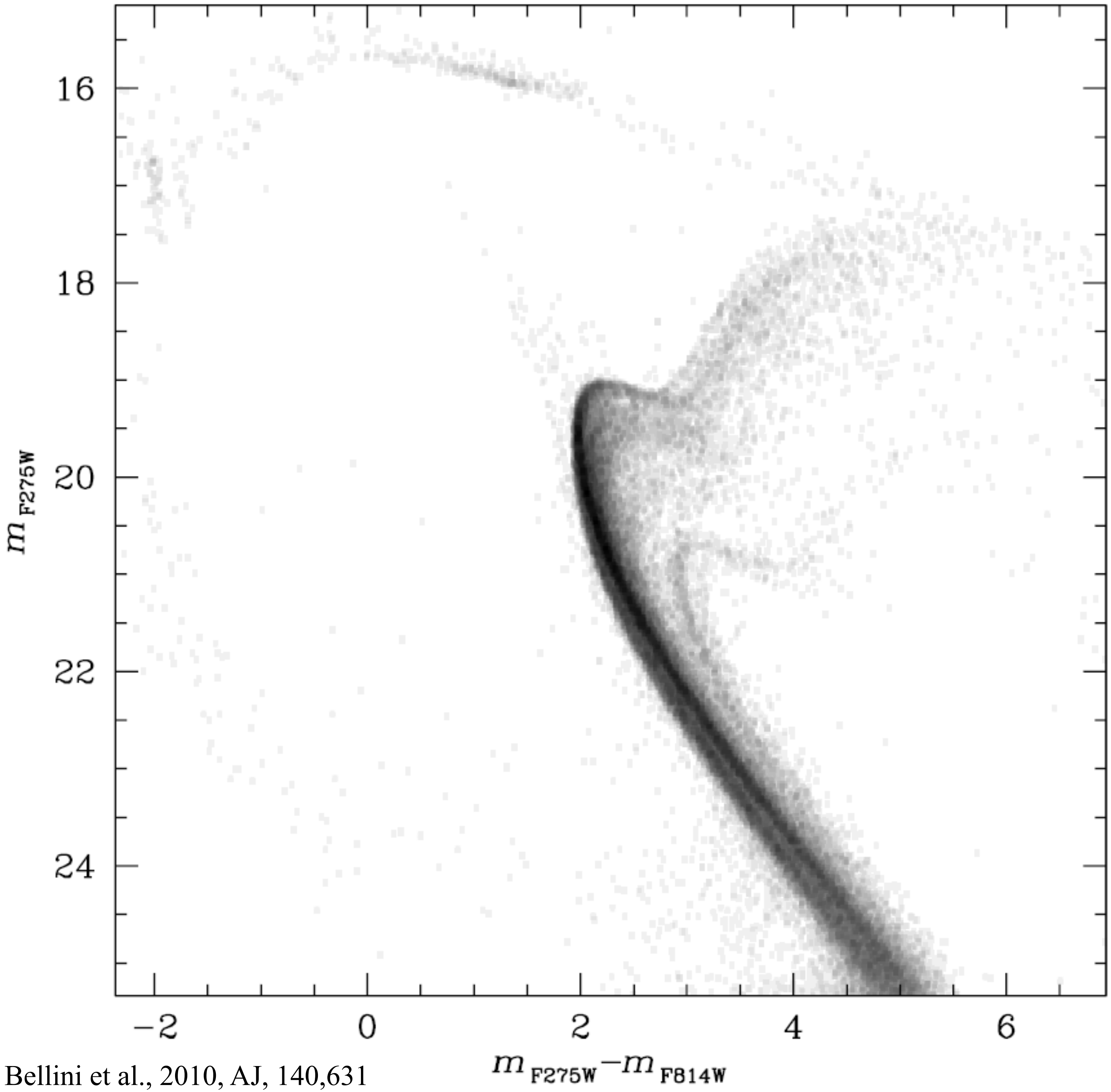
Bellini et al. 2009, A&A, 507, 1393





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



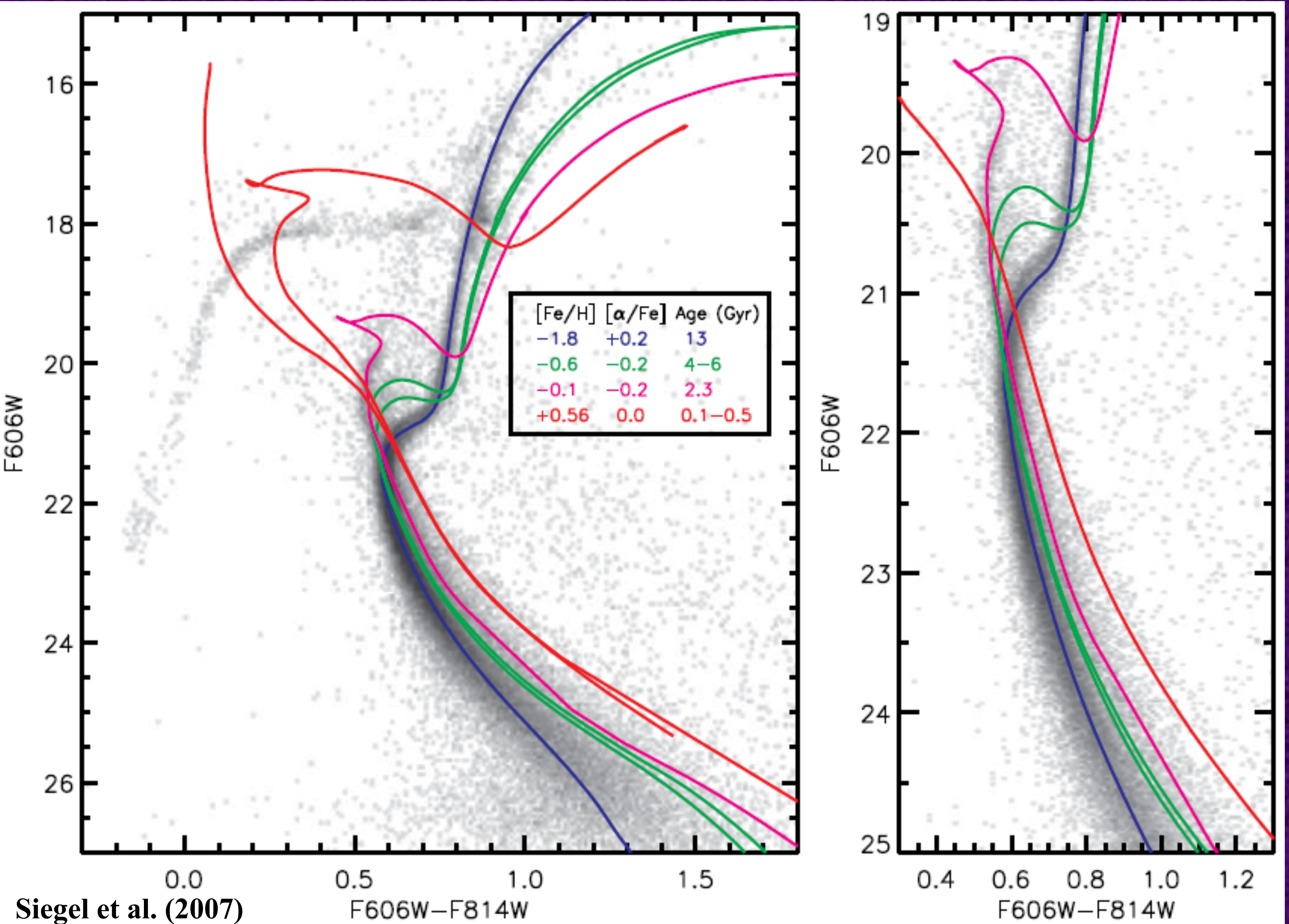
Bellini et al., 2010, AJ, 140,631

The complexity increases!

New spectacular UV data from the new WFC3 camera onboard HST

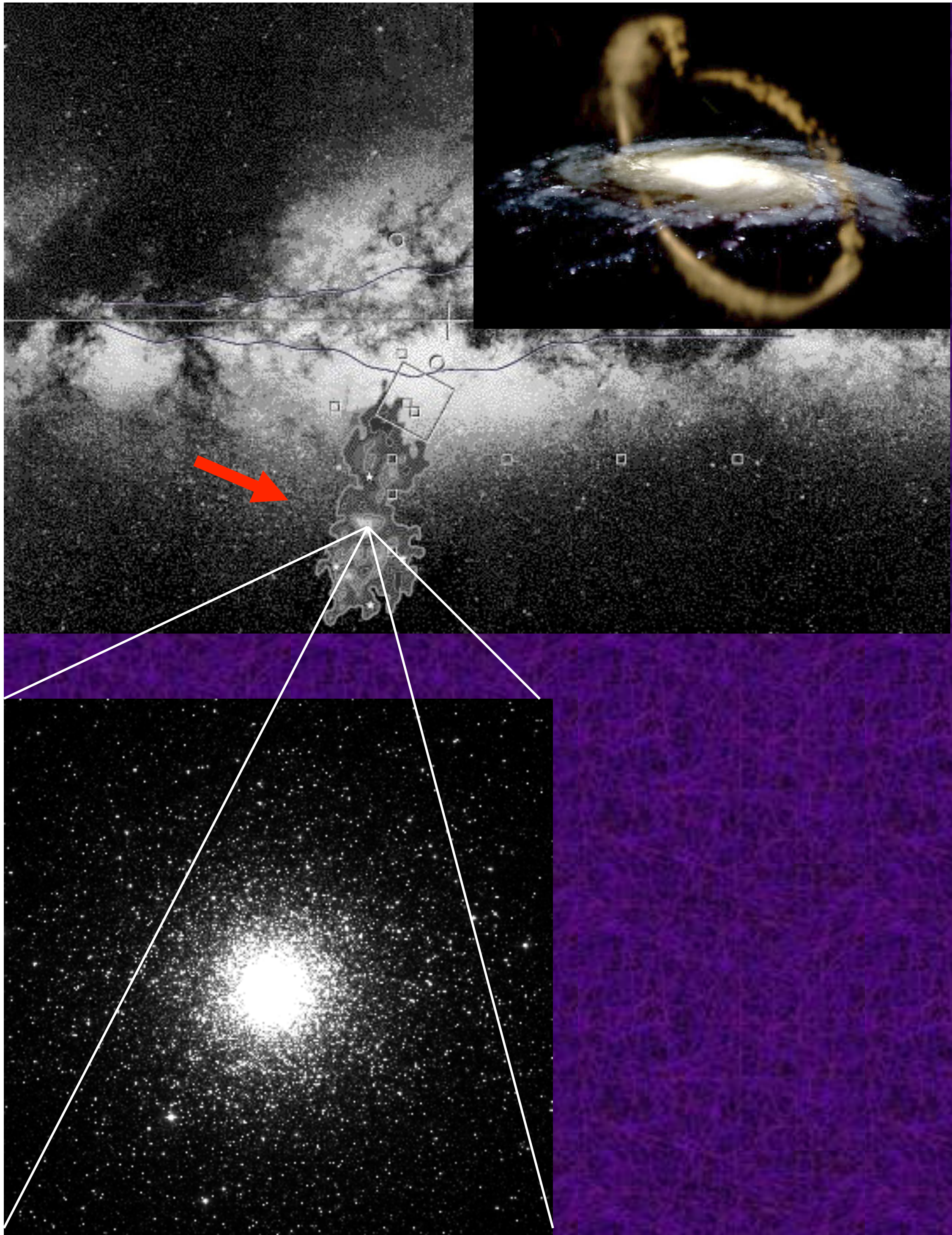
Amazing perspectives with WFC3!!!

NGC 6715 (M54)



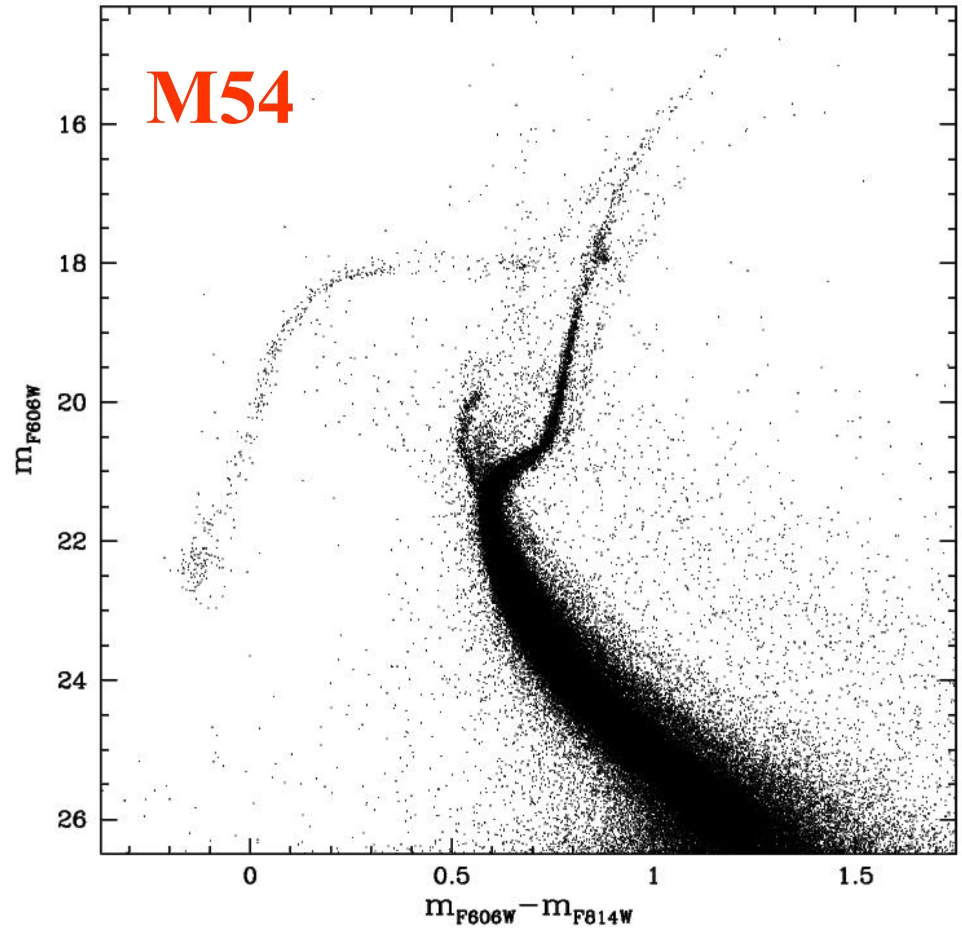
Siegel et al. (2007)

Multiple MSs, SGBs, RGBs ….

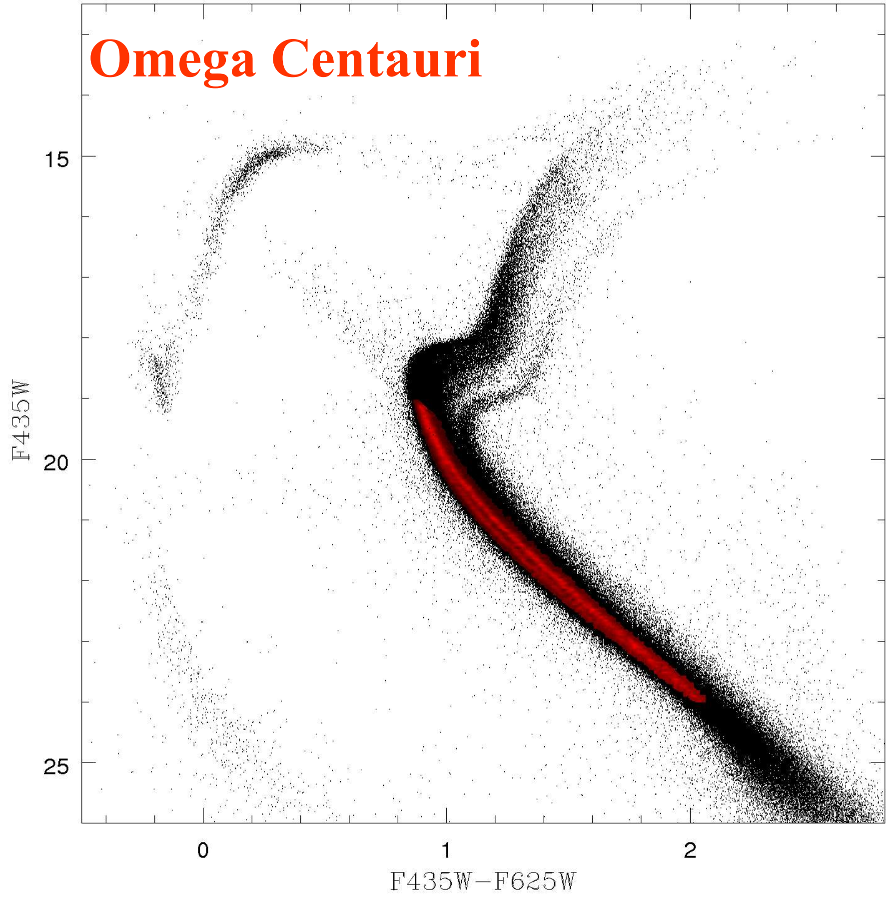


M54 coincides with the nucleus of the Sagittarius dwarf galaxy . It might be born in the nucleus or, more likely, it might be ended into the nucleus via dynamical friction (see, Bellazzini et al. 2008), but the important fact is that, today:

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



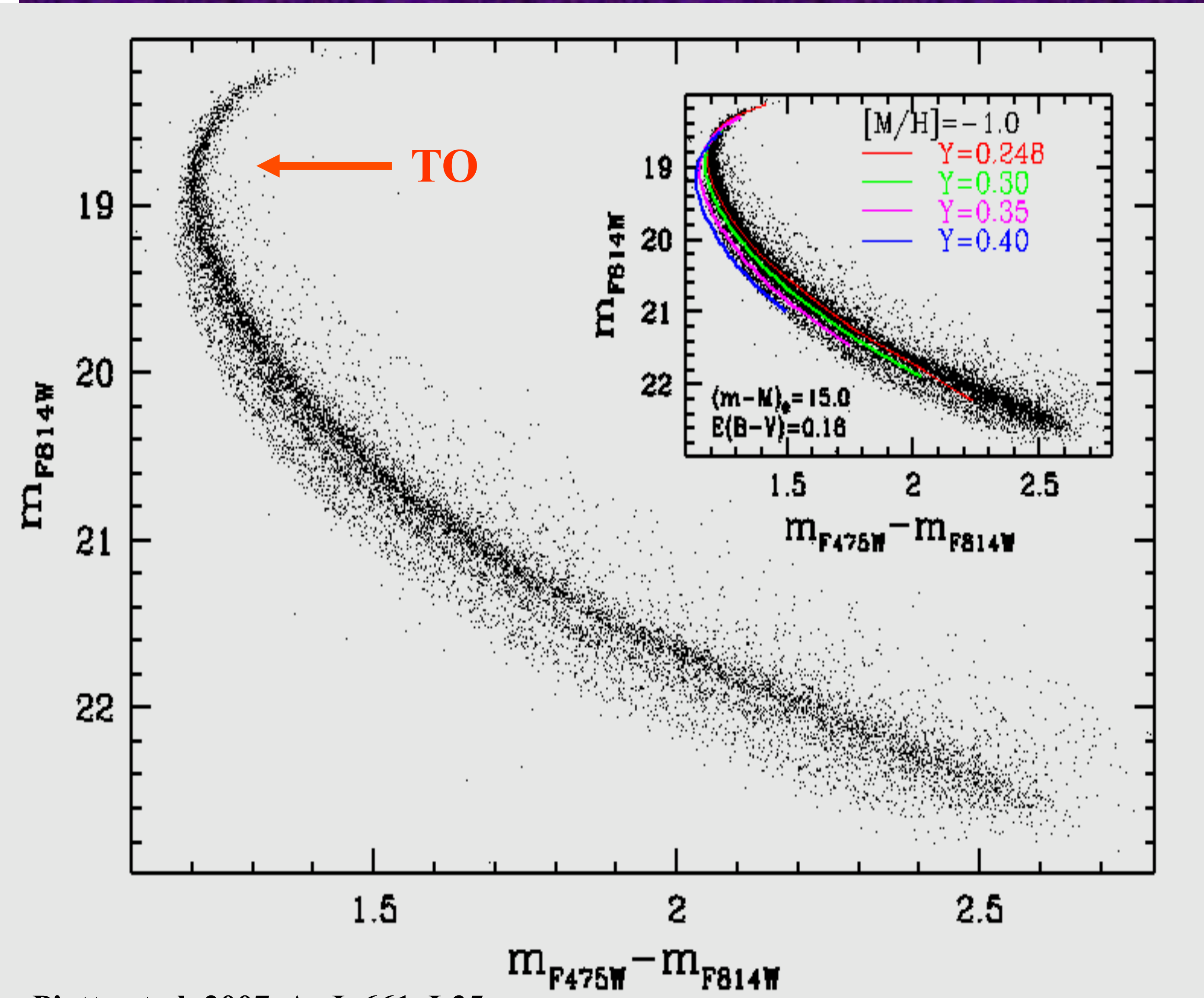
The CMDs of M54 and Omega Centauri are <u>astonishingly similar!</u>



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?

The triple main sequence in NGC 2808

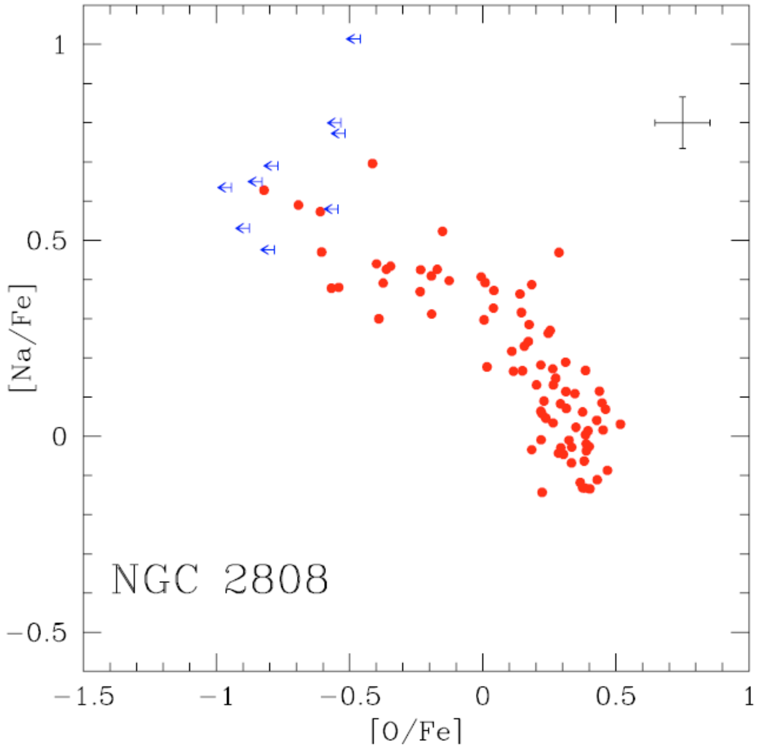


Piotto et al. 2007, ApJ, 661, L35

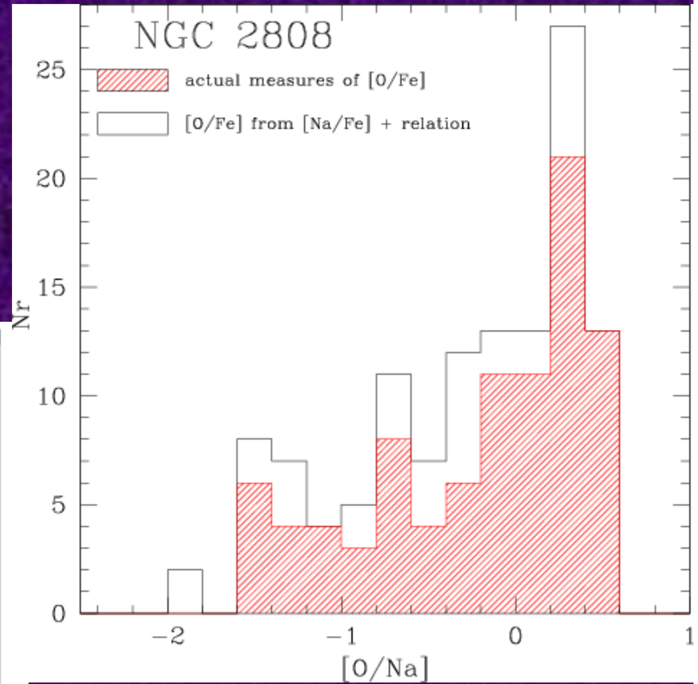
The MS of NGC 2808 splits into three separate branches

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

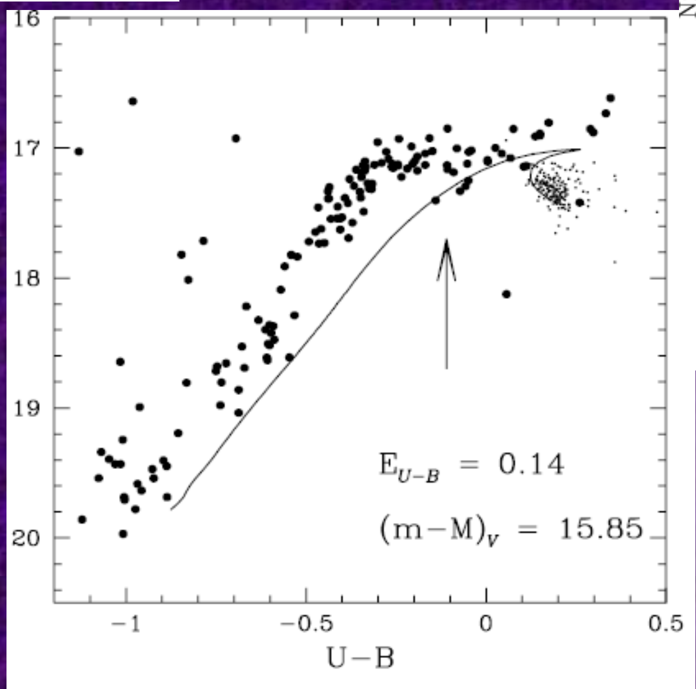
The TO-SGB regions are so narrow that any difference in age between the three groups must be significantly smaller than 1 Gyr

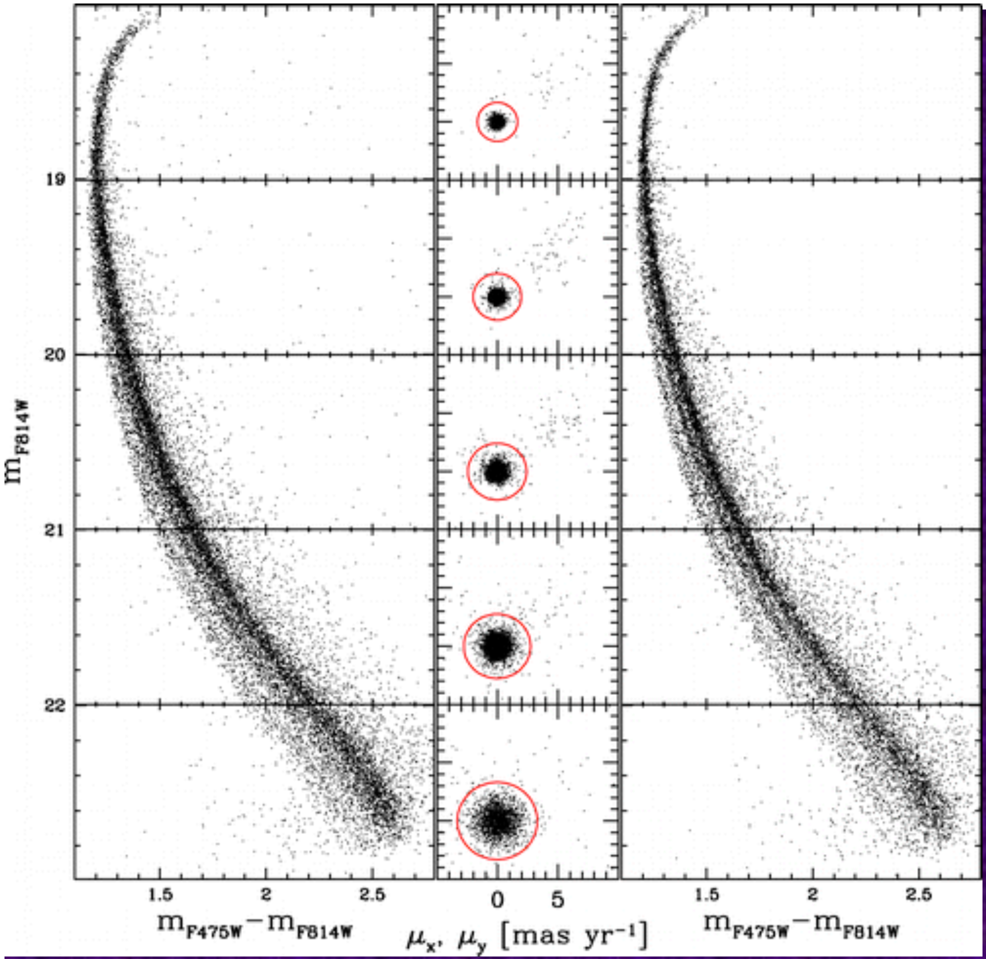


NaO anticorrelation (Carretta et al. 2006)
Besides a bulk of O-normal stars with the typical composition of field halo stars, NGC2808 seems to host two other groups of O-poor and super O-poor stars



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)





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

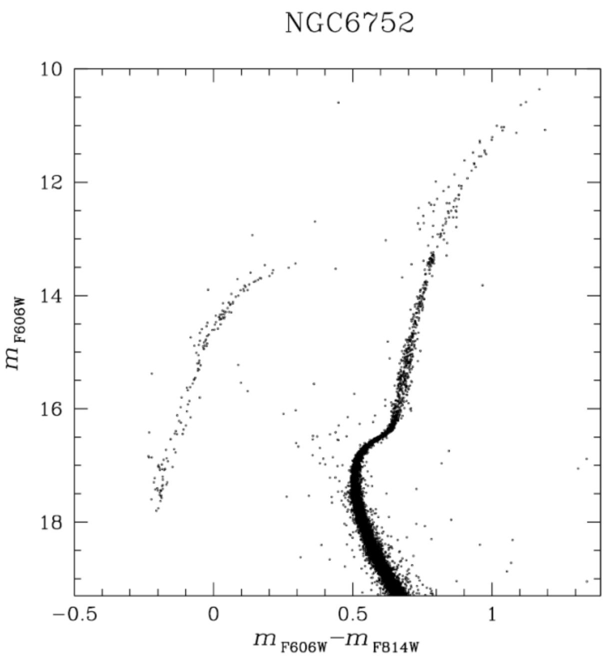
MS	RGB	HB
rMS 63% ± 5 $Y = 0.248$	O-normal 61% ± 7	Red segment 46% ± 10
mMS 15% ± 5 $Y = 0.30$	O-poor 22% ± 4	EBT1 35% ± 10
bMS 13% ± 5 $Y = 0.37$	Super–O-poor 17% ± 4	EBT2 10% ± 5
Binaries 9% ± 5	?	EBT3? 9% ± 5

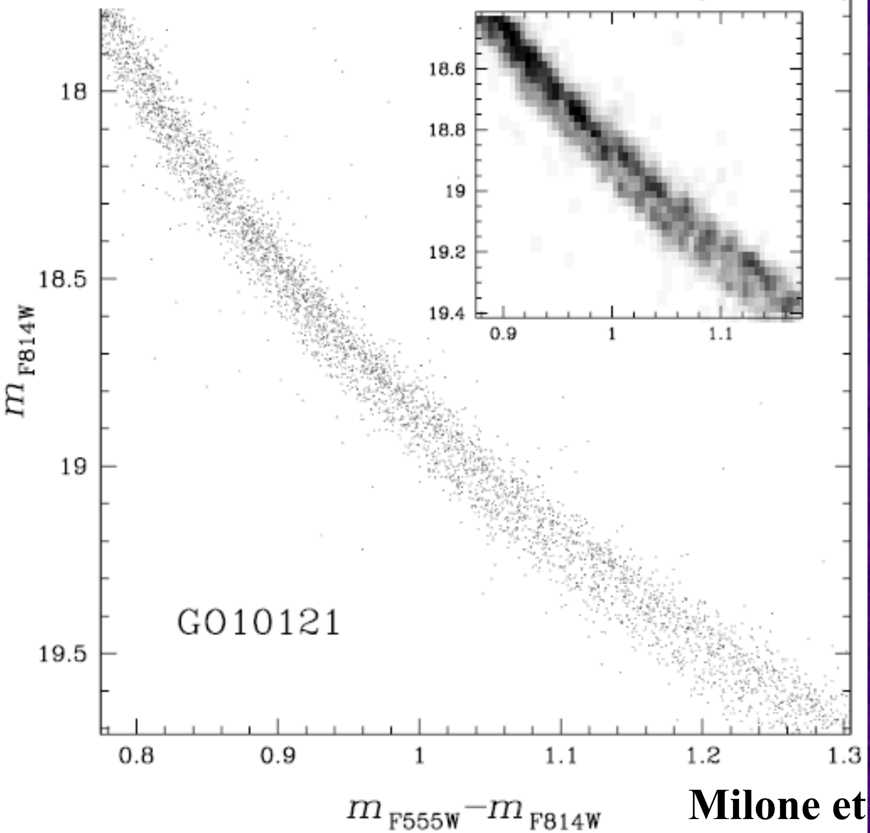
1.4×10^4 and 2.7×10^4 solar masses of fresh Helium are embedded in the 2nd and 3rd generations of stars

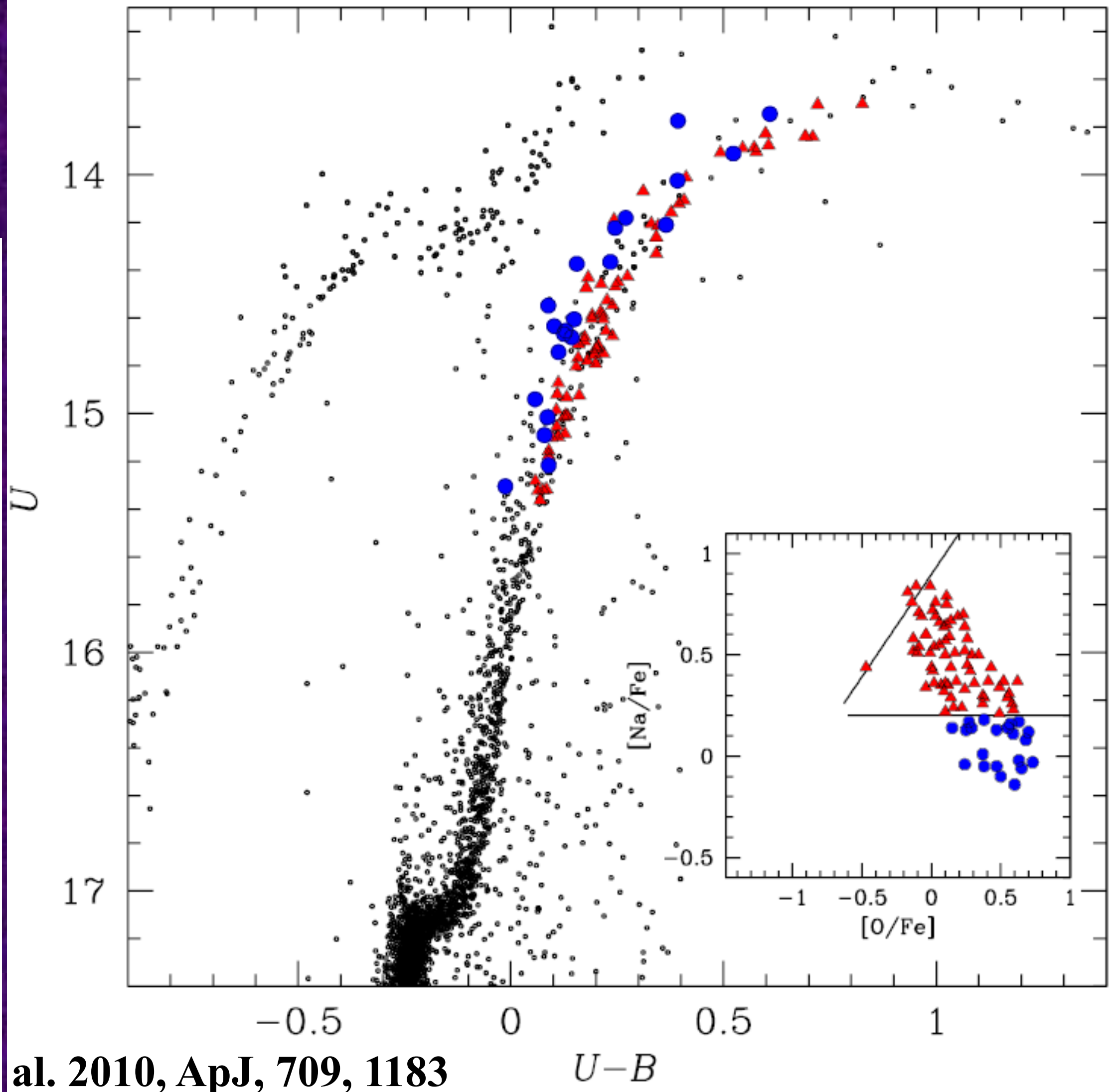
Observations properly fit a scenario in which a 2nd and 3rd stellar generations formed from material polluted by intermediate mass AGB stars of a 1st generation

NGC 6752: very extended EHB, but with a mass of $1.6\times10^5\ M_\odot$

Example of a not massive cluster showing clear evidence of multiple populations

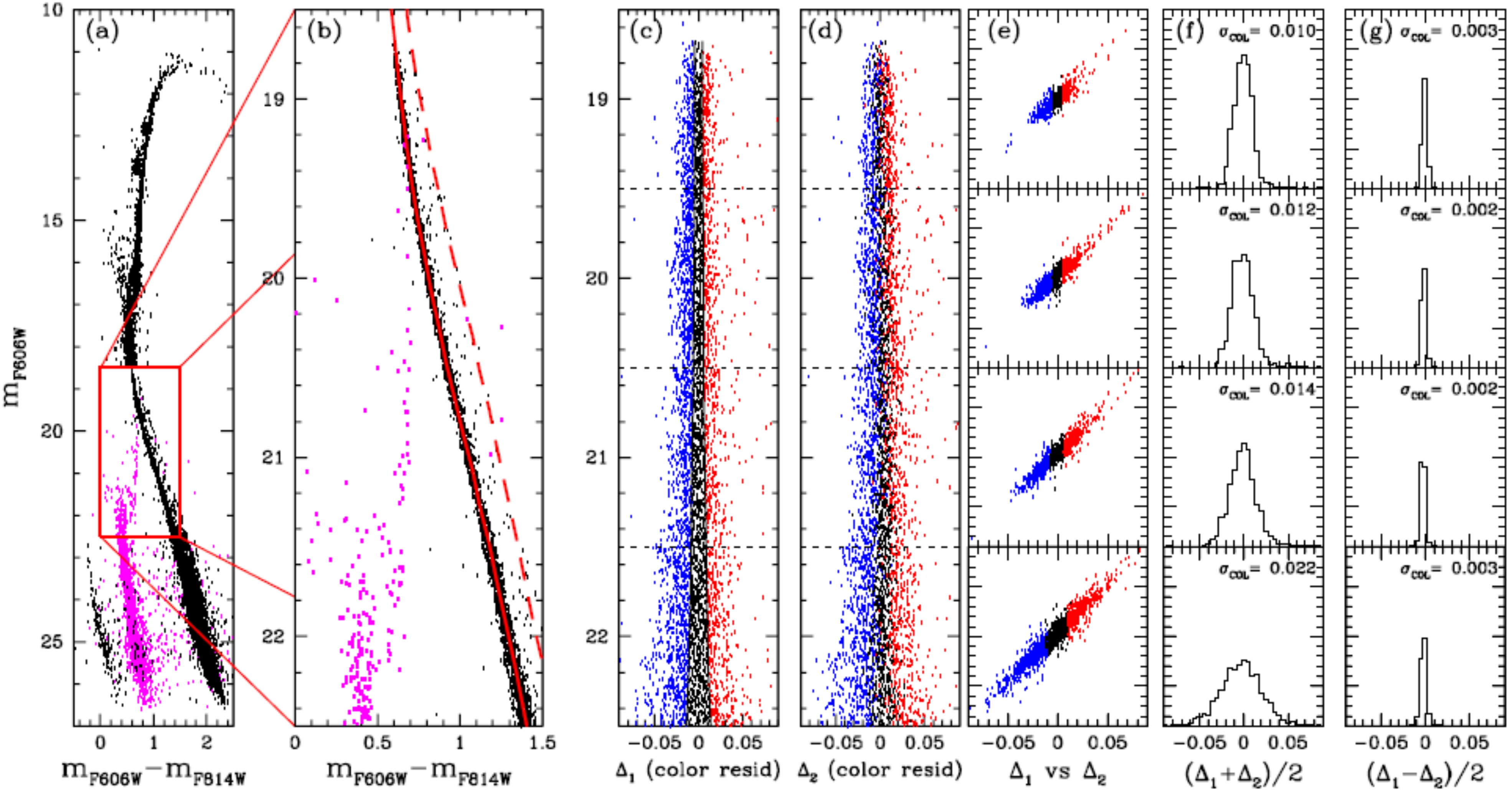






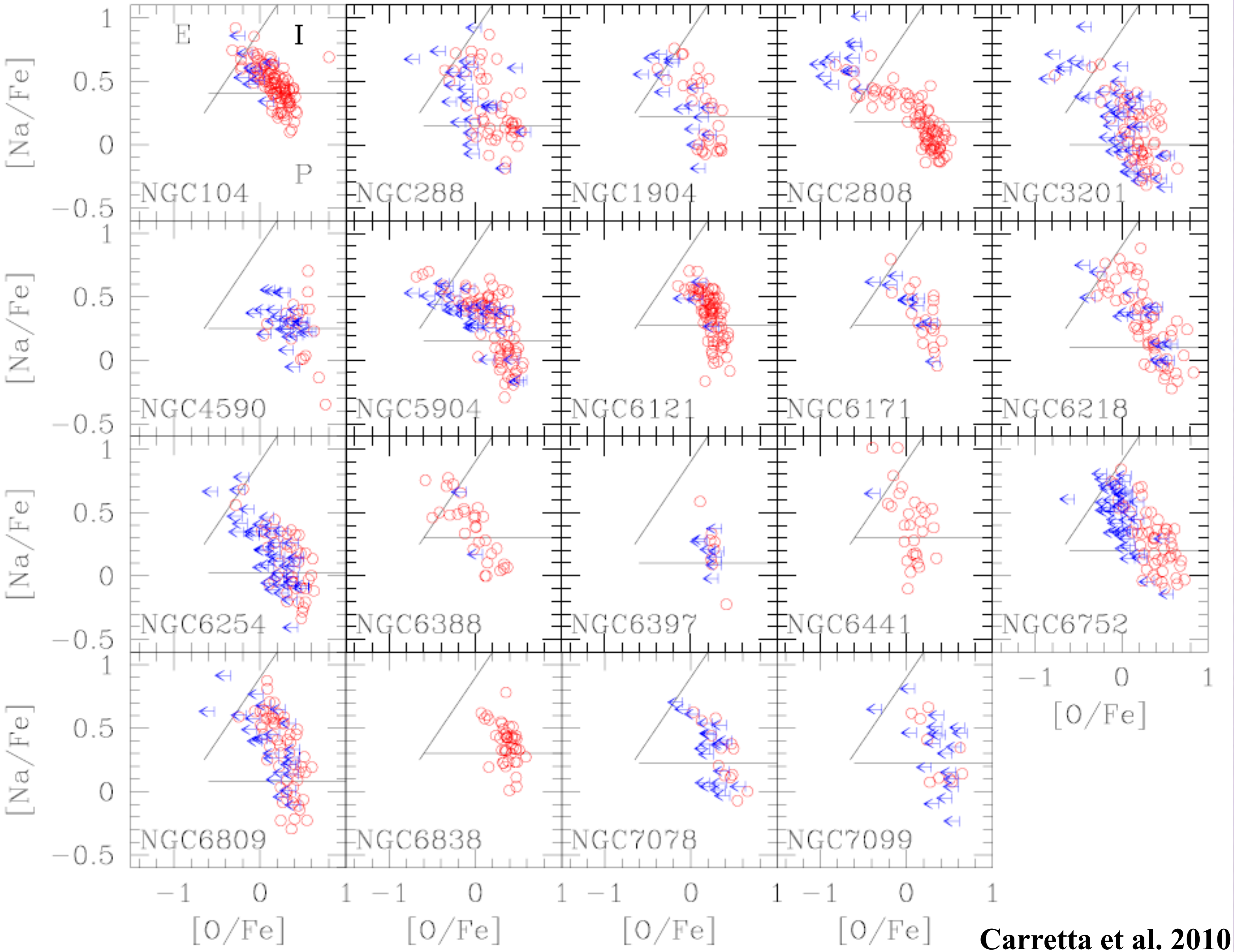
Milone et al. 2010, ApJ, 709, 1183

…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

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



Carretta et al. 2010

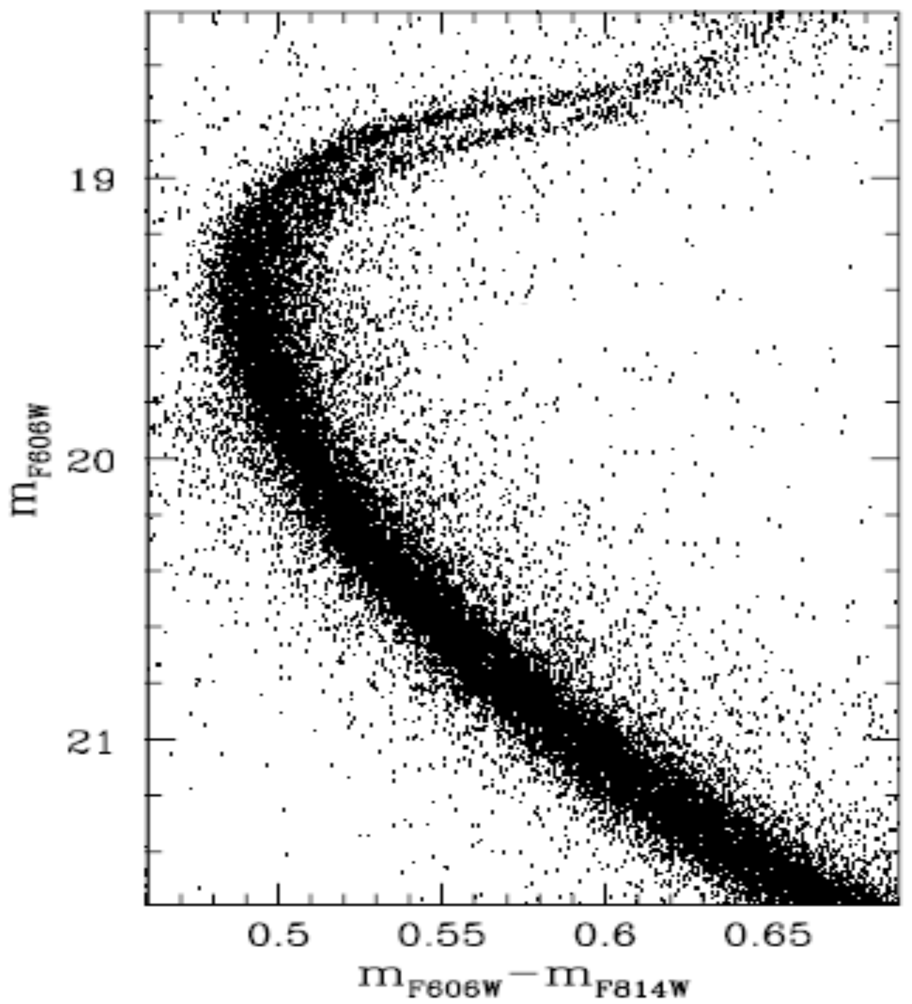
Most clusters have constant [Fe/H], but large star to star variations in light elements.

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

These anticorrelations are present in all clusters analyzed so far.

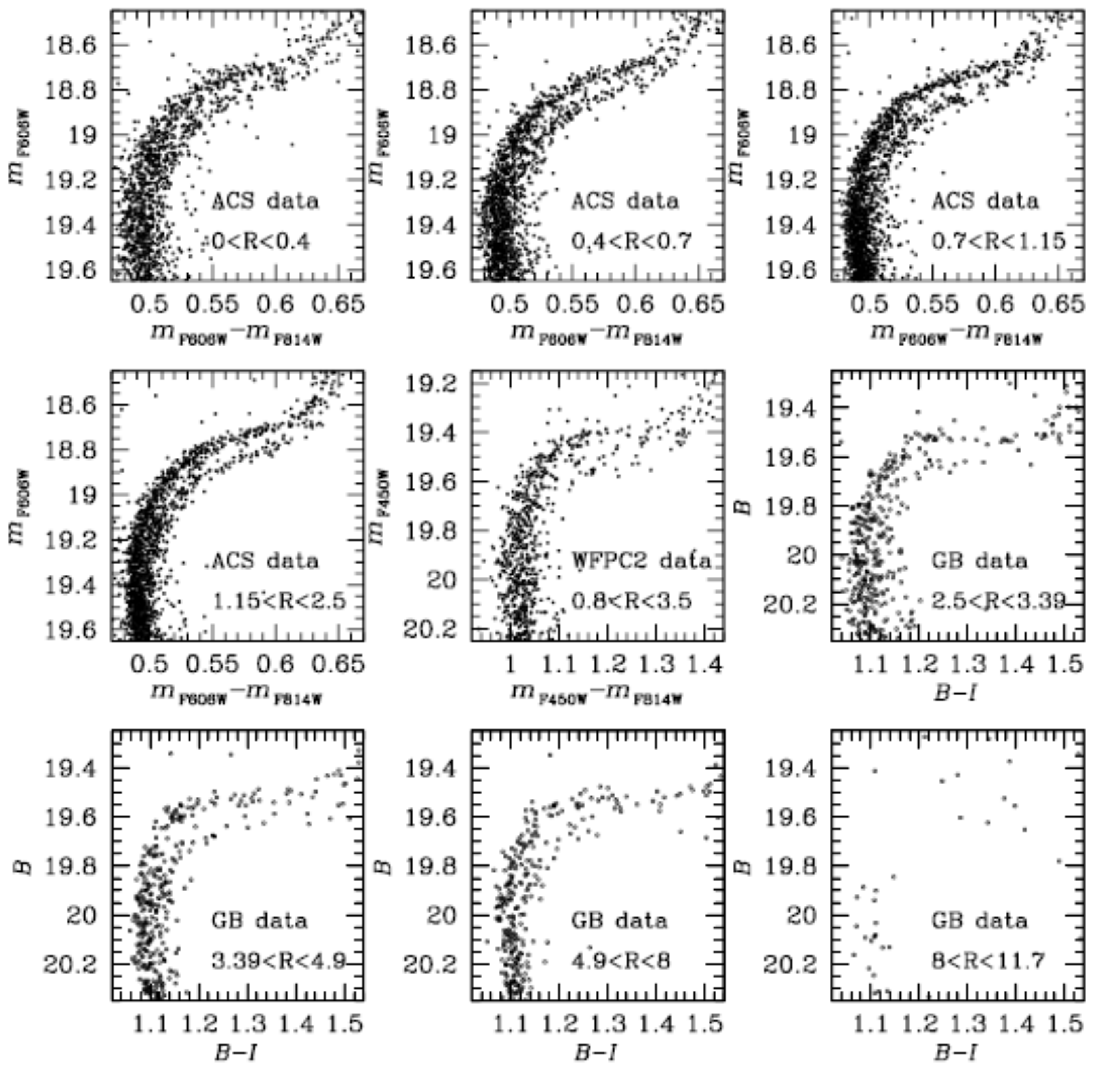
The Double Subgiant Branch of NGC 1851

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.



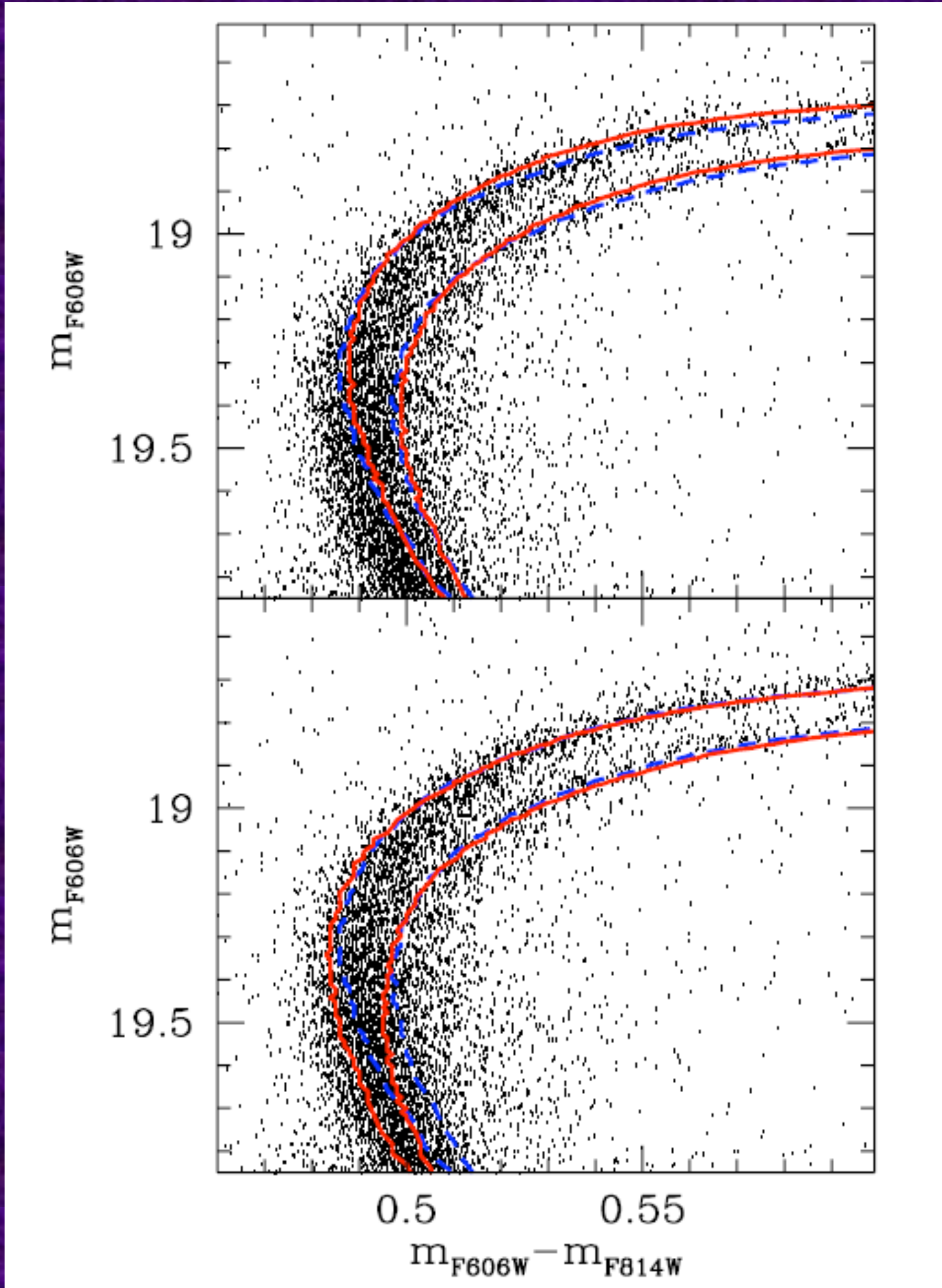
Radial distribution of the two SGBs in NGC 1851

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

There is no radial gradient

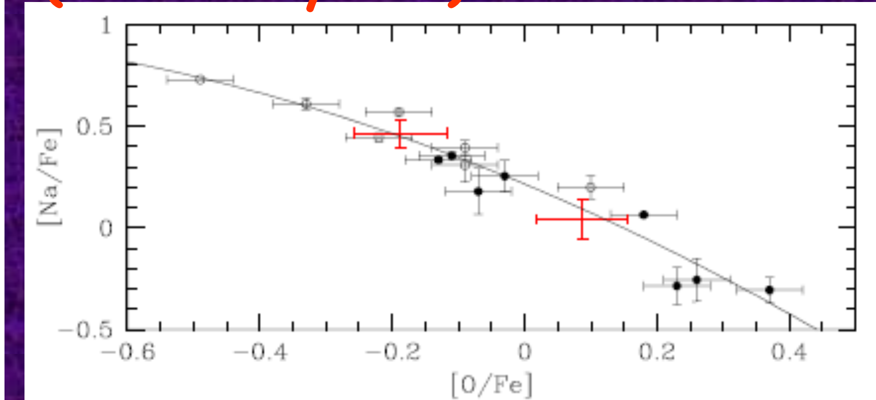
Log t_{rh} = 8.9

Milone et al. (2009) in prep

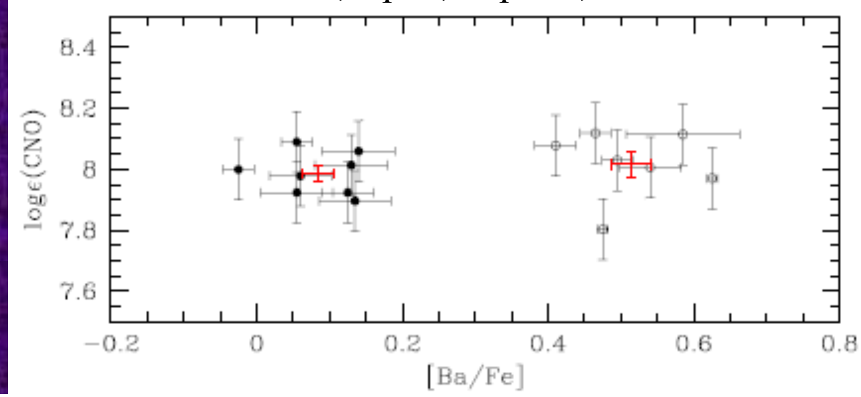


Cassisi et al. (2007, ApJ, 672, 115, Ventura et al. 2009) suggested that the two SGBs can be reproduced by **assuming that the fainter SGB is populated by a strongly CNONa enhanced population.**

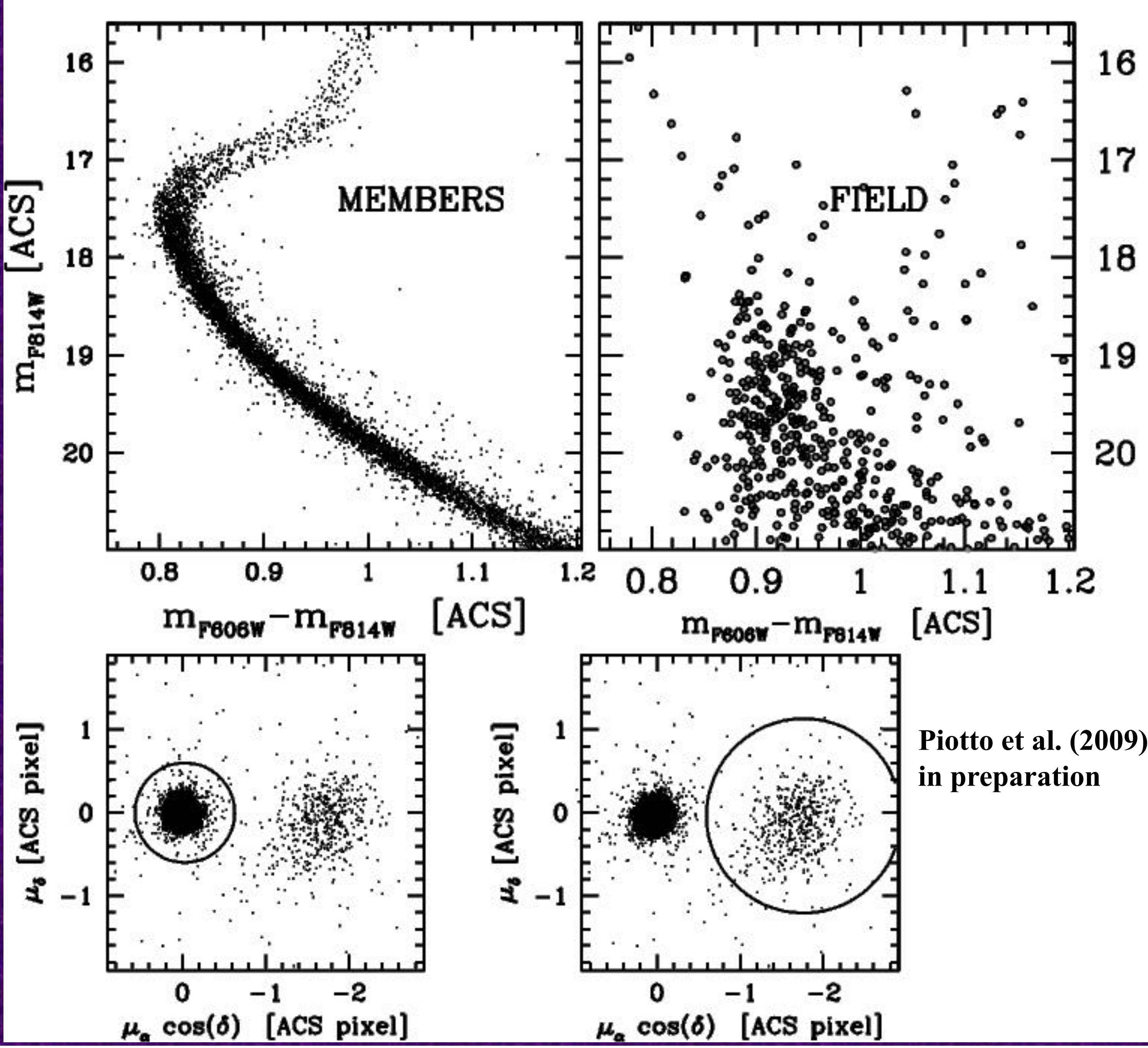
In such hypothesis, the age difference between the two groups may be very small (10^7-10^8 years). **But….**



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

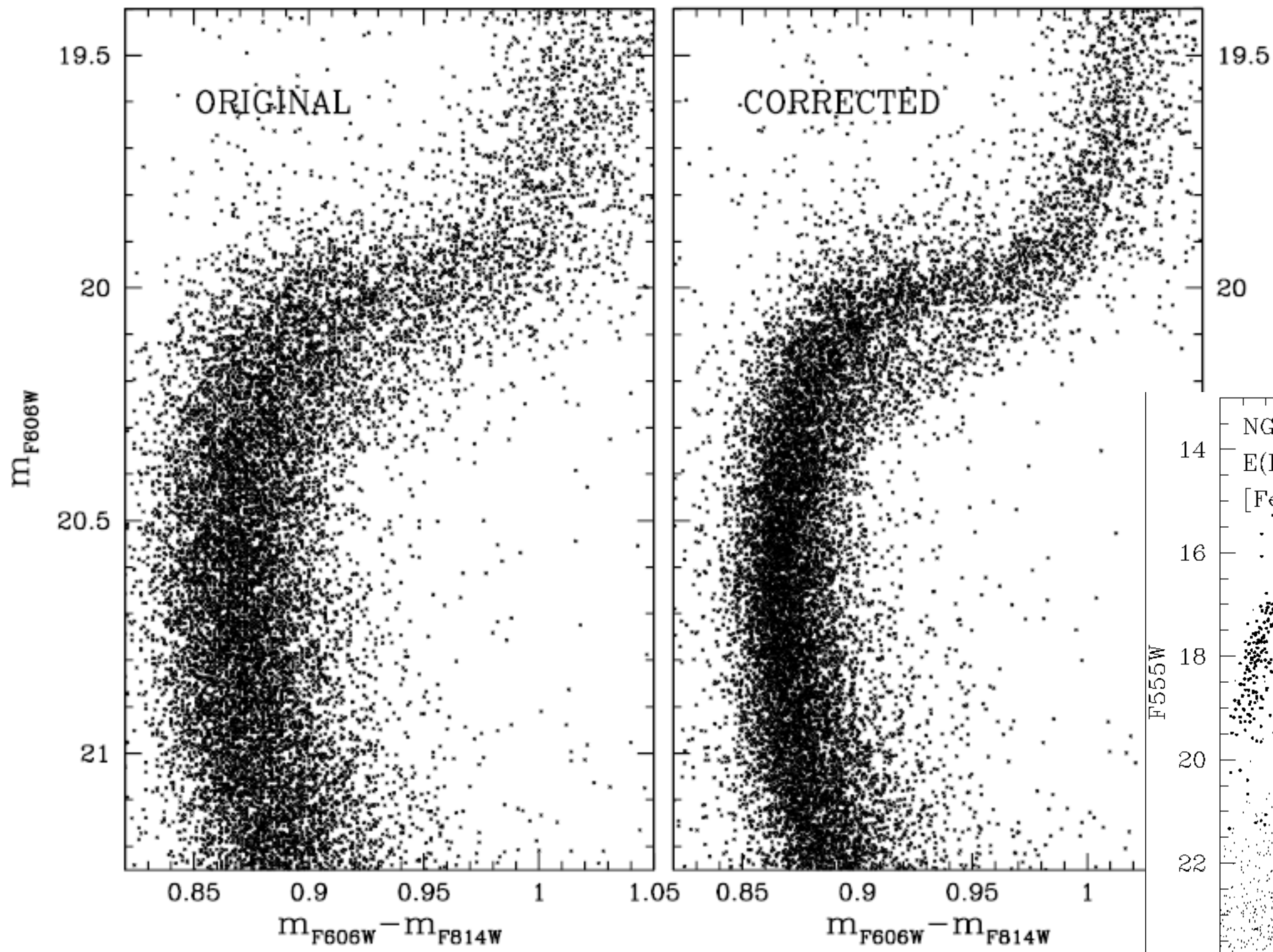


NGC 6656 (M22) double SGB

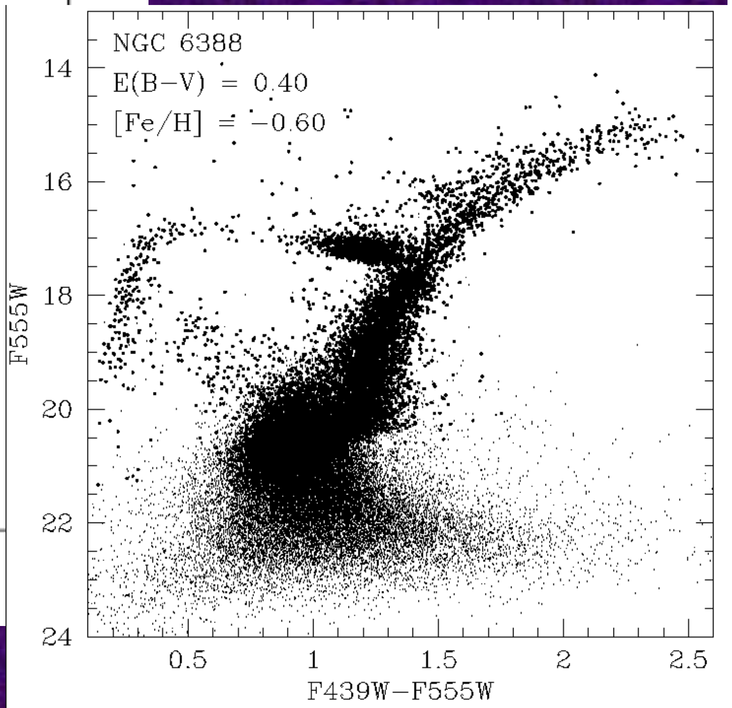


Piotto et al. (2009), in preparation

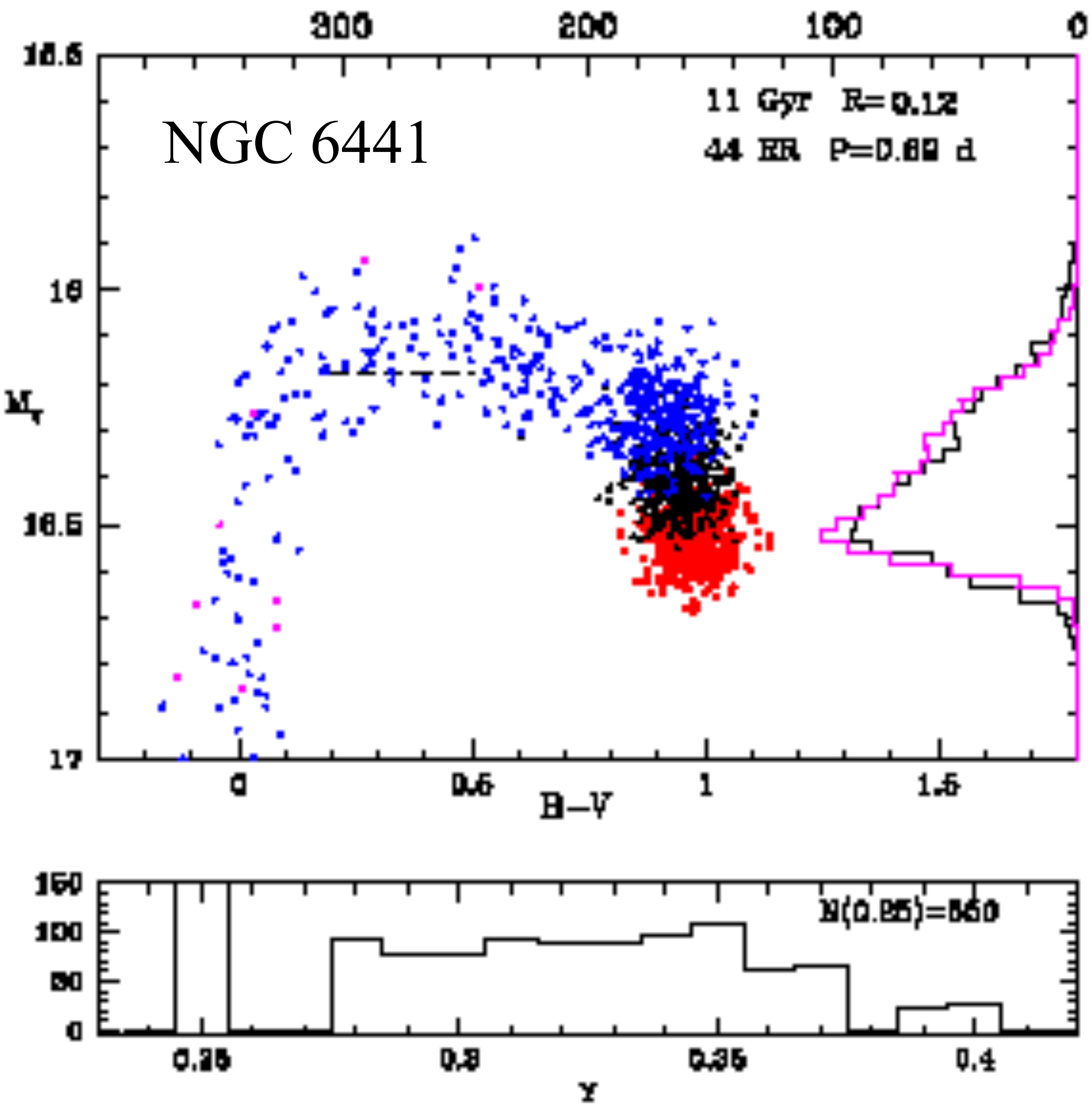
Double SGBs are present in many Globular Clusters: e.g. NGC 6388



New WFC3 data acquired; reduction in progress



Piotto (2009, IAUS, 258, 233)



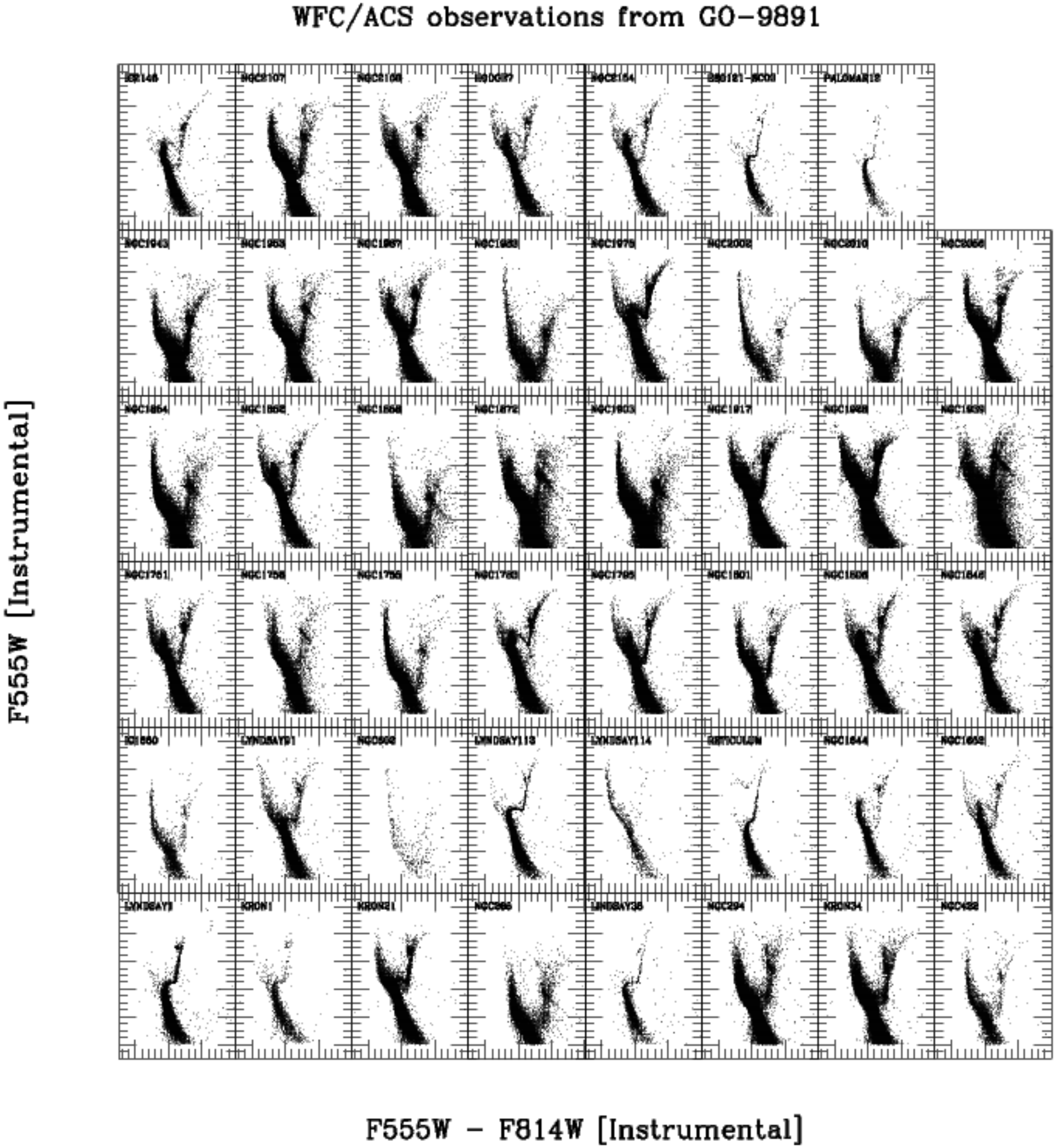
In order to reproduce the anomalous HB, Caloi and D'Antona (2007) propose an even more complicate scenario with **3 distinct populations:**

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

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

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

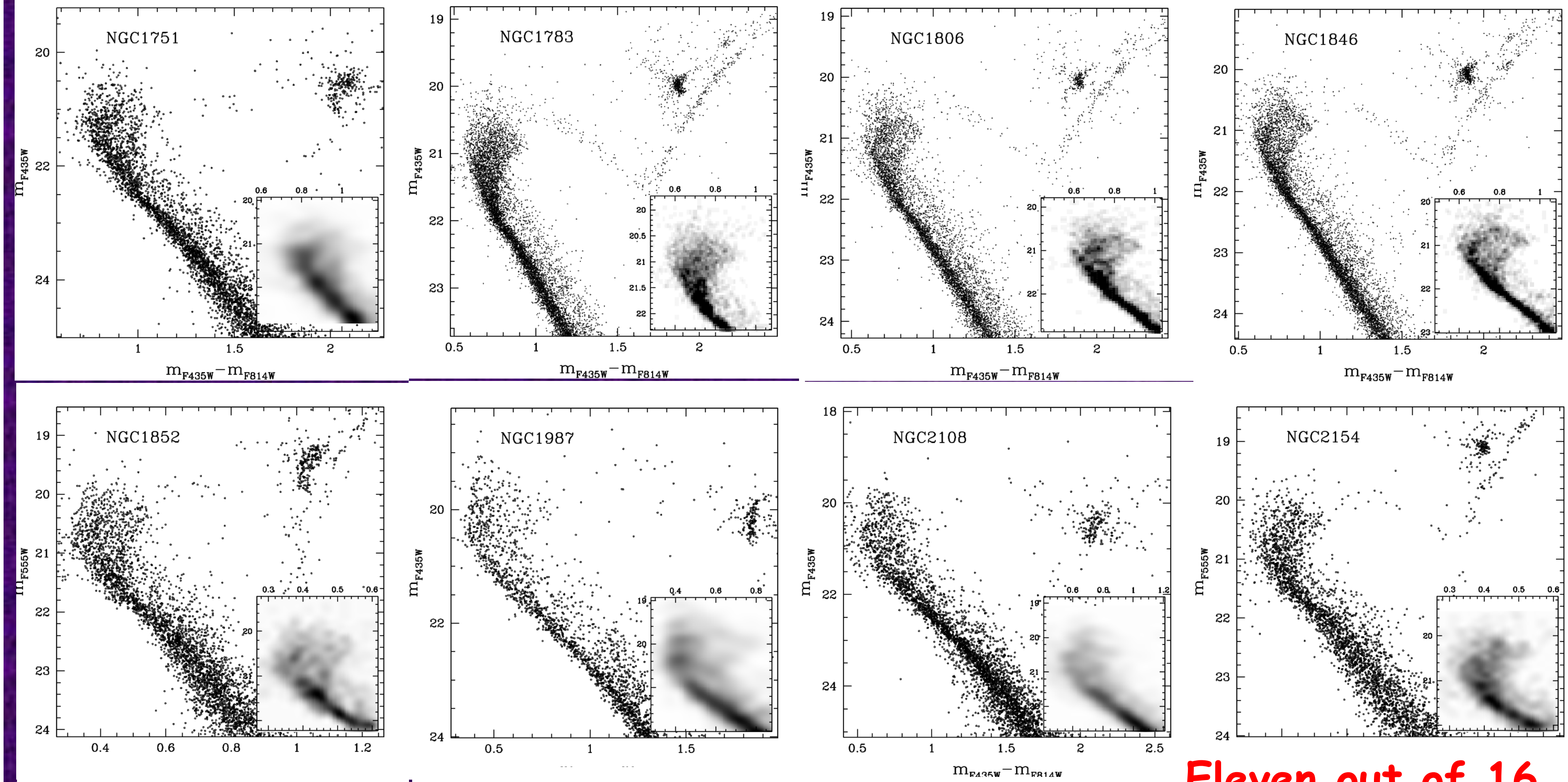
LMC clusters

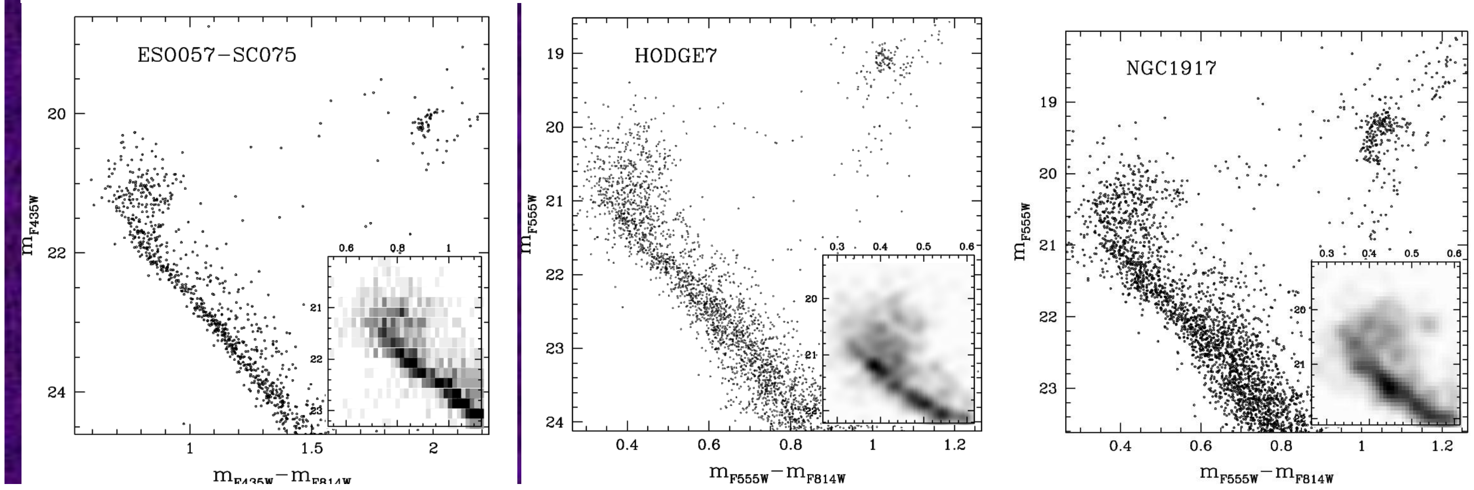


Milone et al. (2008)

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

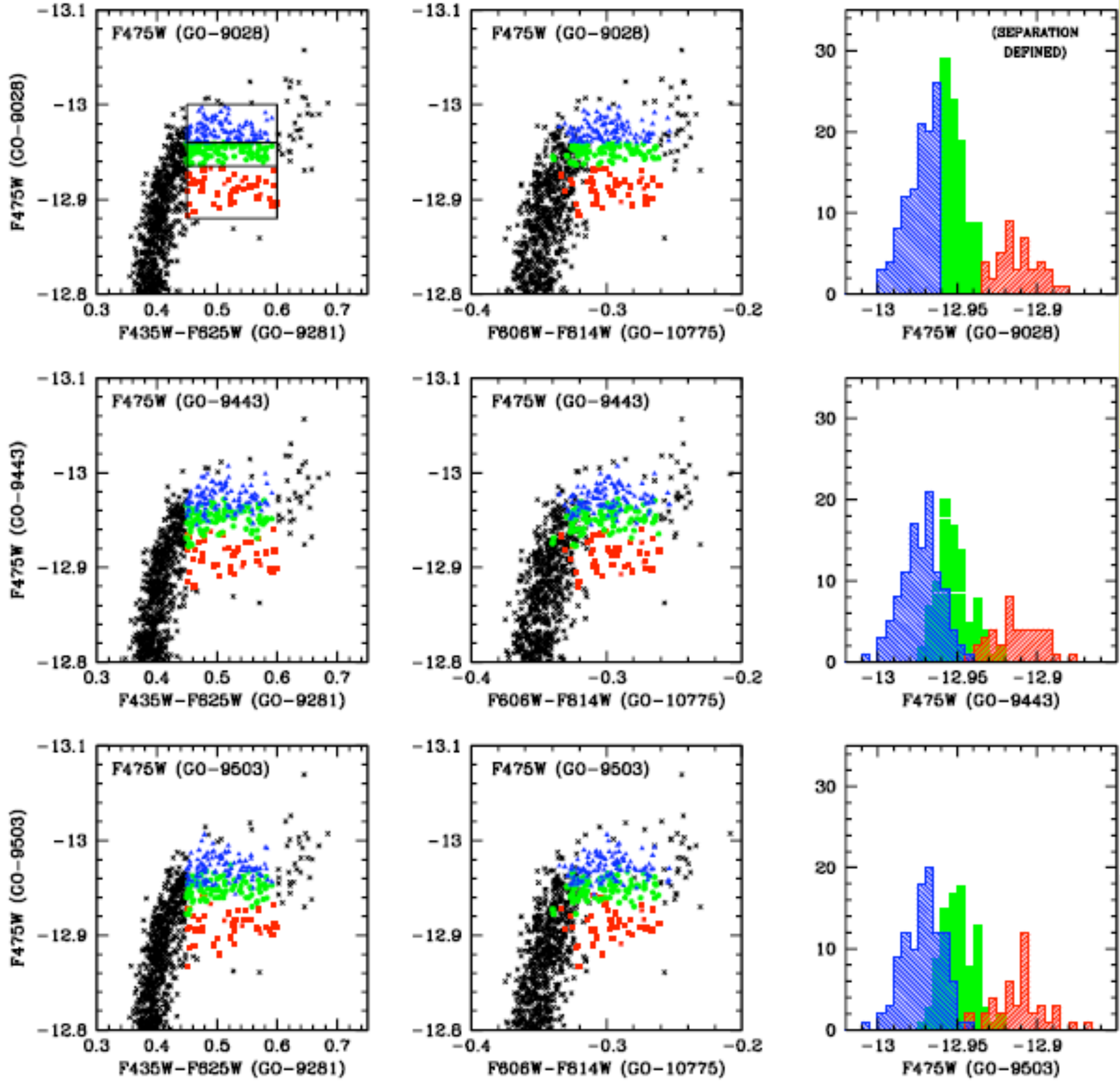
We investigated the CMD morphology of 16 intermediate age clusters, with ages between 1 and 3 Gyr.



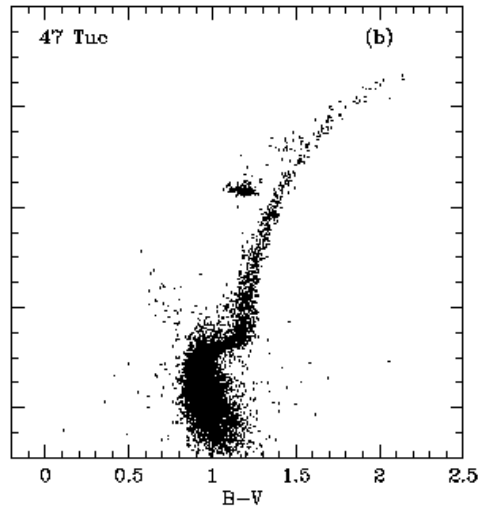


Eleven out of 16 (2/3) of the intermediate age clusters show either a double or an extended TO!

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



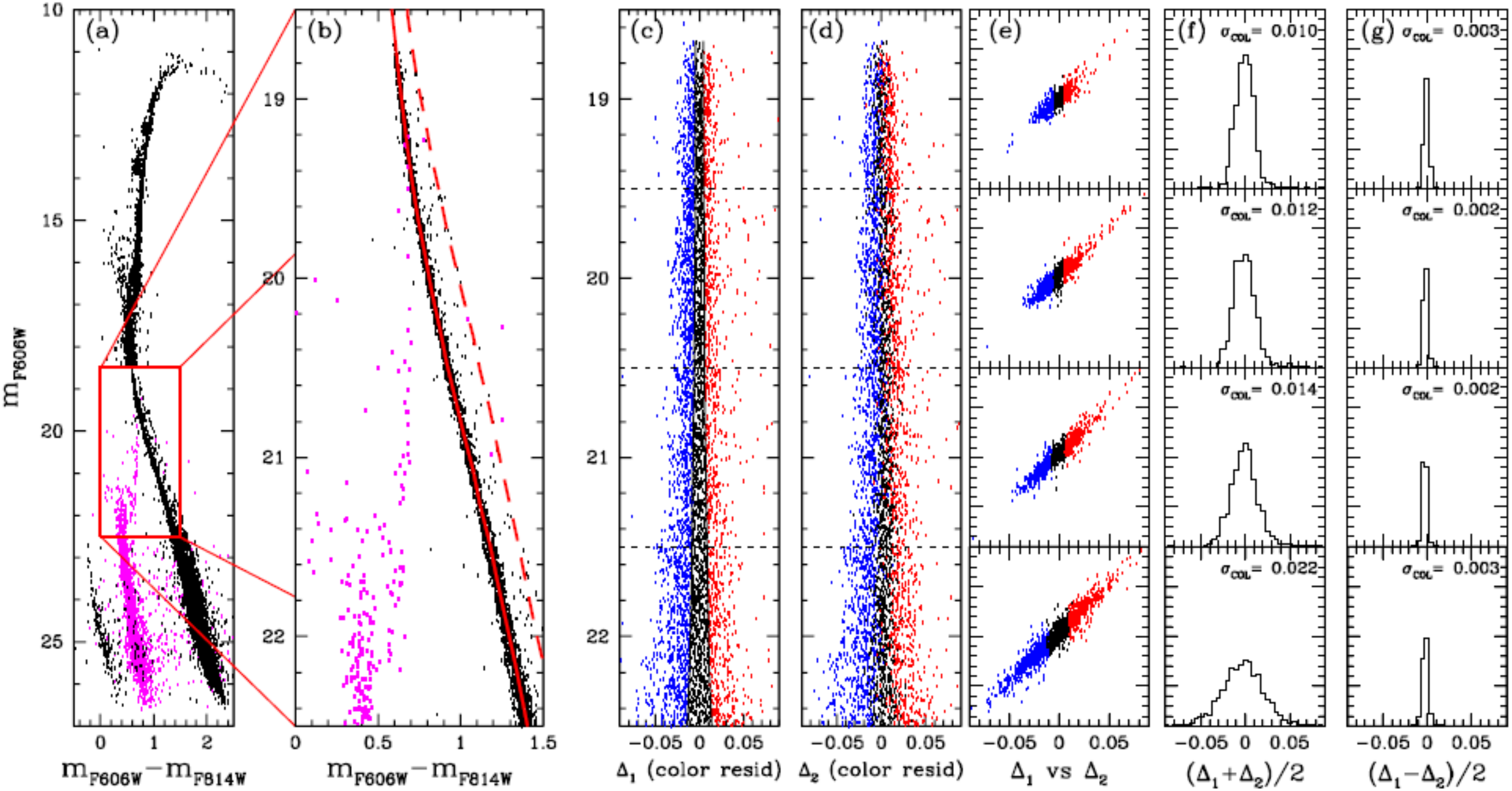
47 Tucanae shows a spreaded SGB, plus a secondary SGB



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

Anderson et al. 2009, ApJ, 697, L58

...47Tuc MS is also intrinsically spreaded



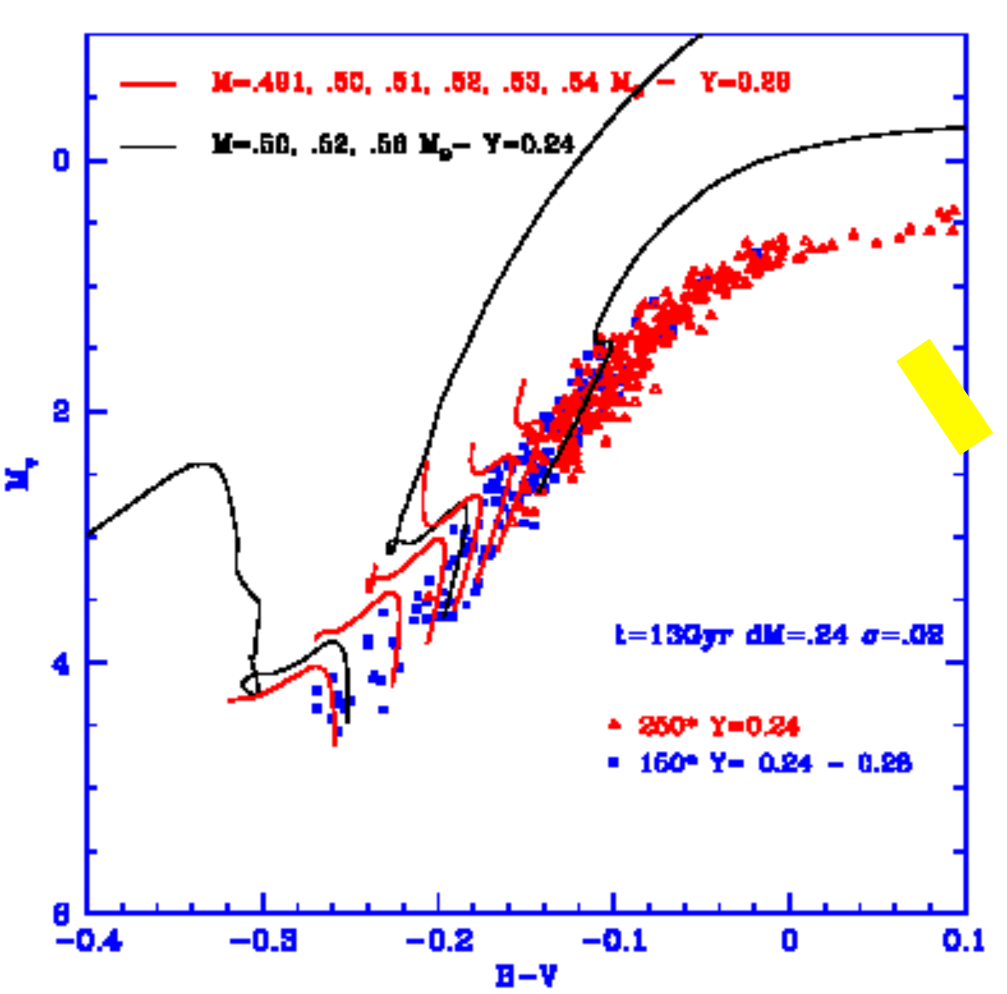
If the spread in color is due to a spread in Fe, it implies a Δ([Fe/H])=0.001; if it is helium, it implies a ΔY=0.03

Multipopulation zoo

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

Are all of them part of the same story?

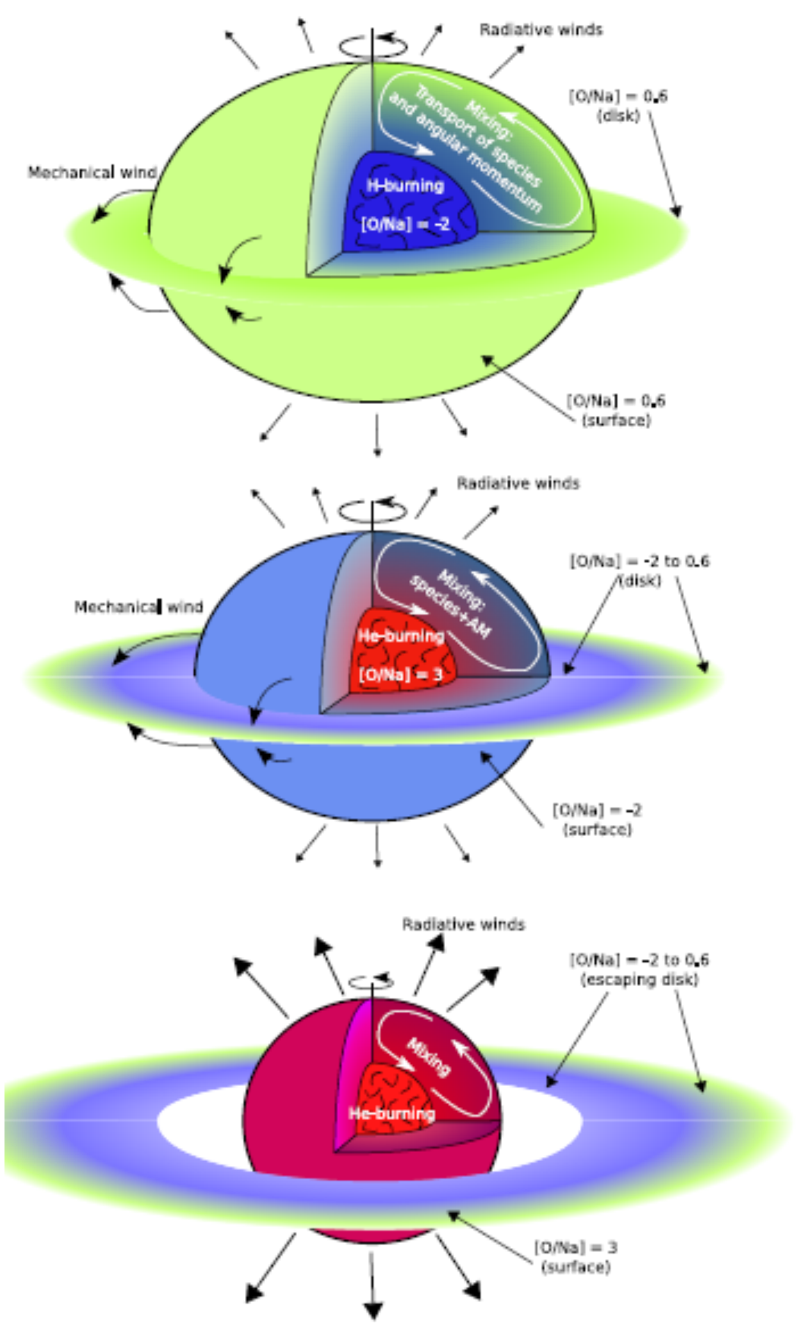
Proposed scenario (1)



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 HST 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) Multiple stellar generations seems ubiquitous. Many serious problems remain unsolved, and we still have a rather incoherent picture. The new WFC3/HST will play a major role. In helping us understanding their origin.
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.