# GLOBULAR CLUSTERS IN THE HIGH ANGULAR RESOLUTION ERA

## SOME RESULTS AND SOME IDEAS FOR MAD-MAX

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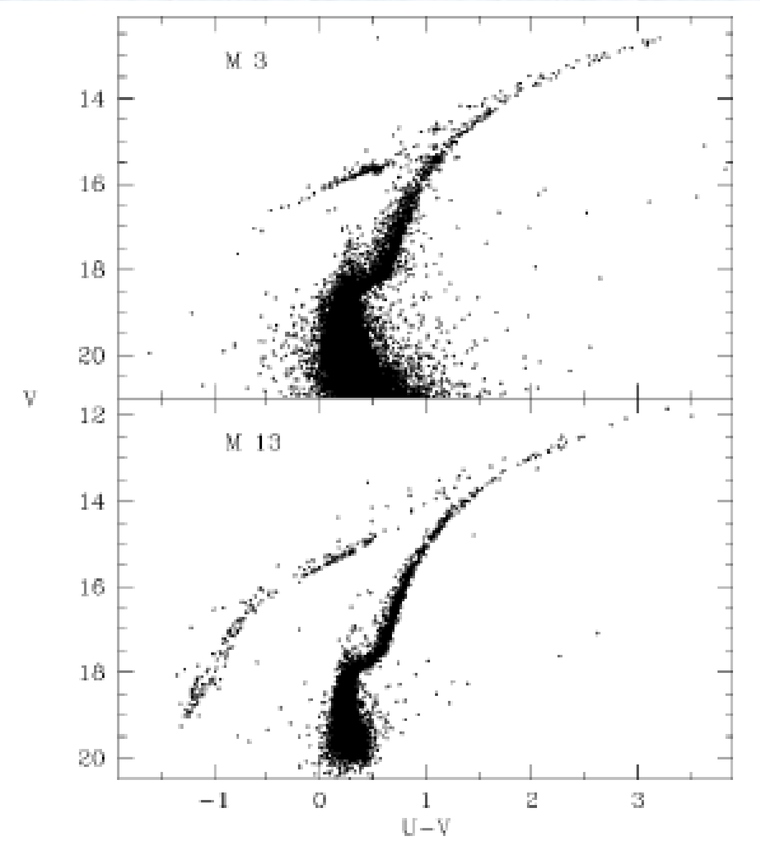
# Simple Stellar Populations

"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)

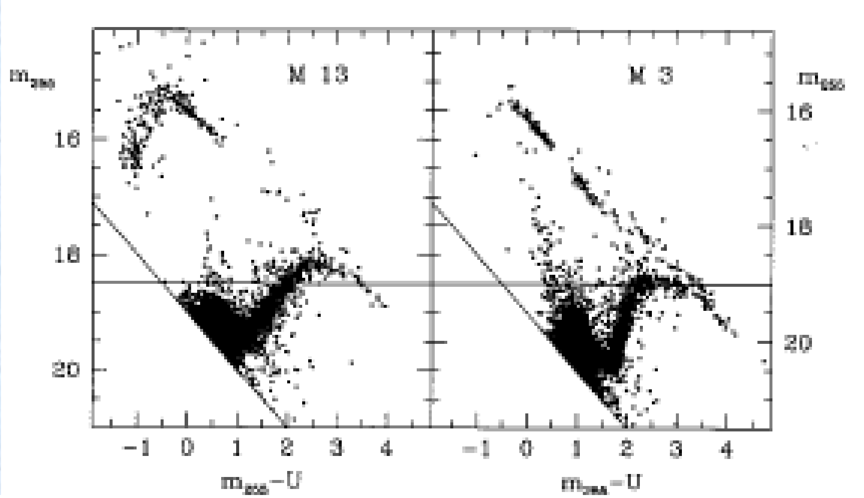
For this reason, star clusters have been – so far - a fundamental benchmark for testing stellar evolution models and for Population Synthesis Models

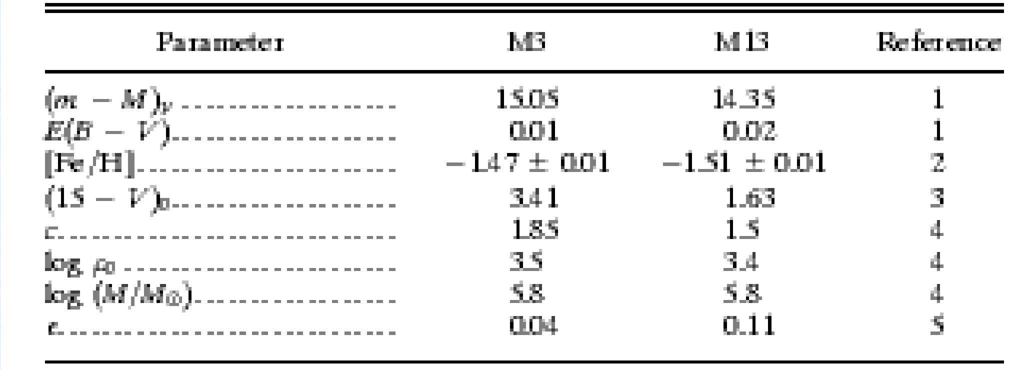
However, we do have a number of problems which have been there, unsolved, for too many years. For example, we never really understood the general behaviour of He core burning sequences.

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.

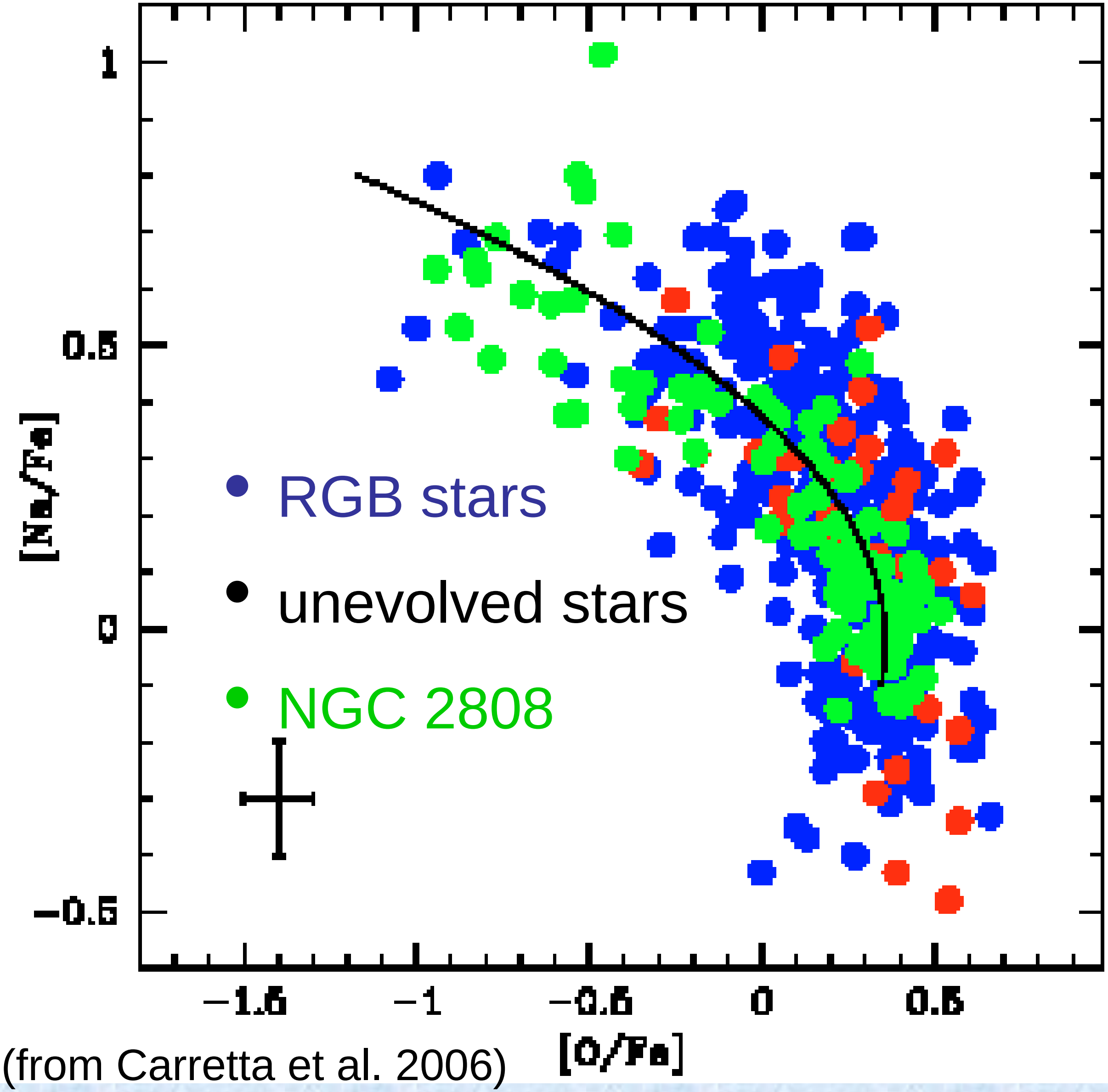


Ferraro et al. (1997)





| 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 |
| $\epsilon$ | 0.04 | 0.11 | 5 |



(from Carretta et al. 2006)

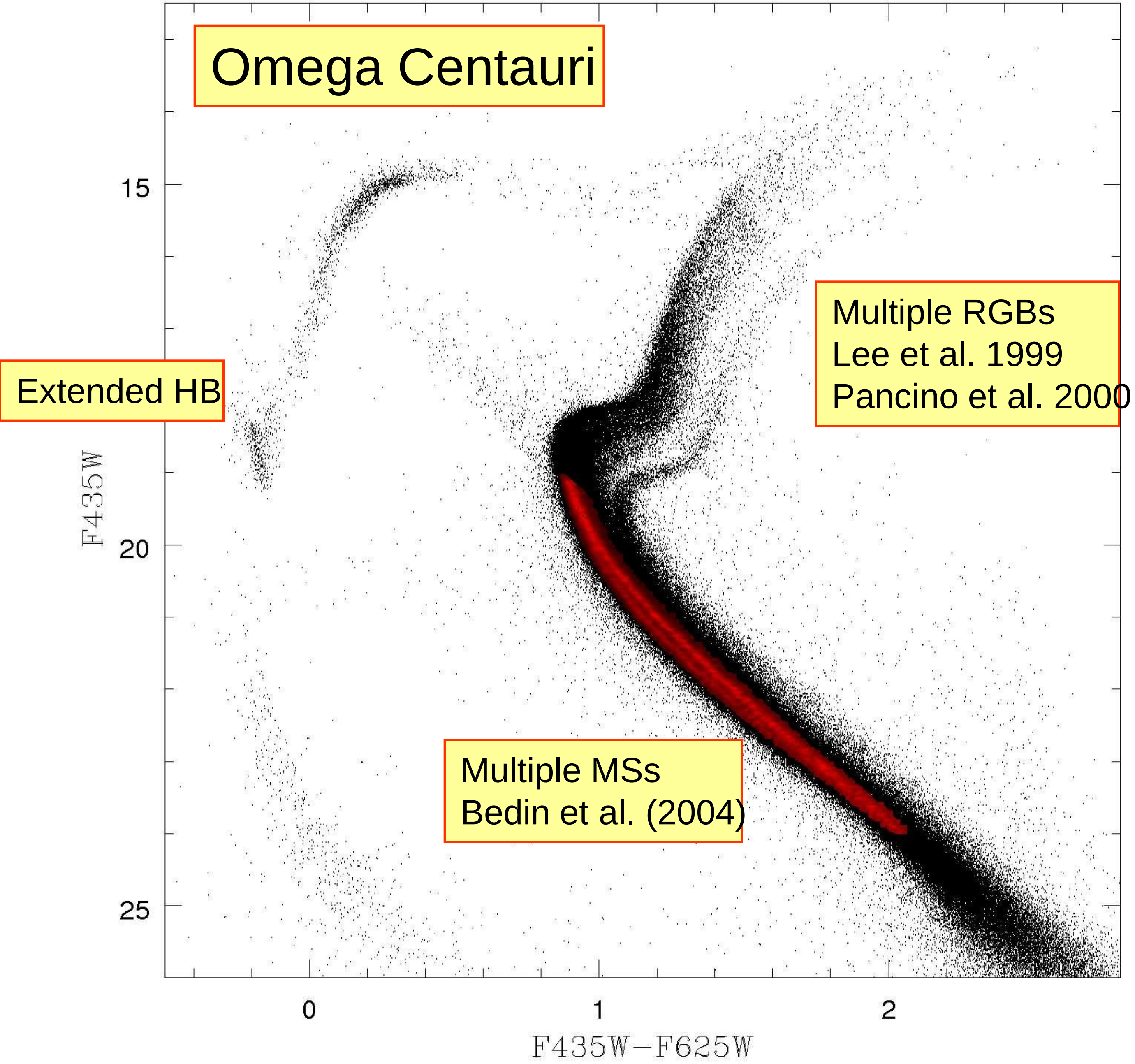
Star to star light element abundance variations, which sometimes result in well defined patterns like the NaO anticorrelation, or the MgAl anticorrelation.

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 (which implies also an O depletion) not reached in present day globular cluster main sequence and red giant stars.

Are globular clusters NOT simple stellar population?

# My favorite "special" case: Omega Centauri



Omega Centauri

Extended HB

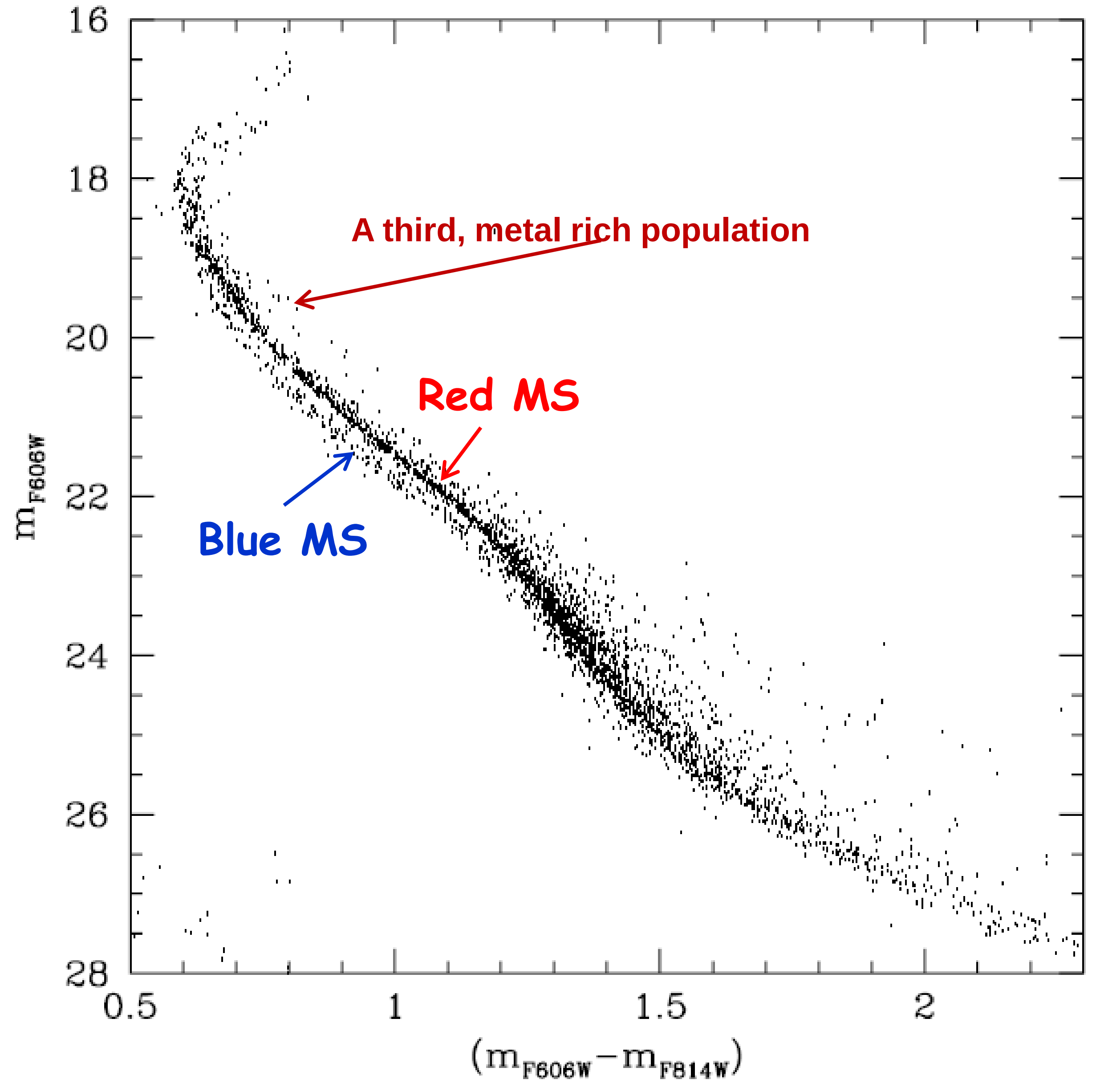
Multiple RGBs
Lee et al. 1999
Pancino et al. 2000

Multiple MSs
Bedin et al. (2004)

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



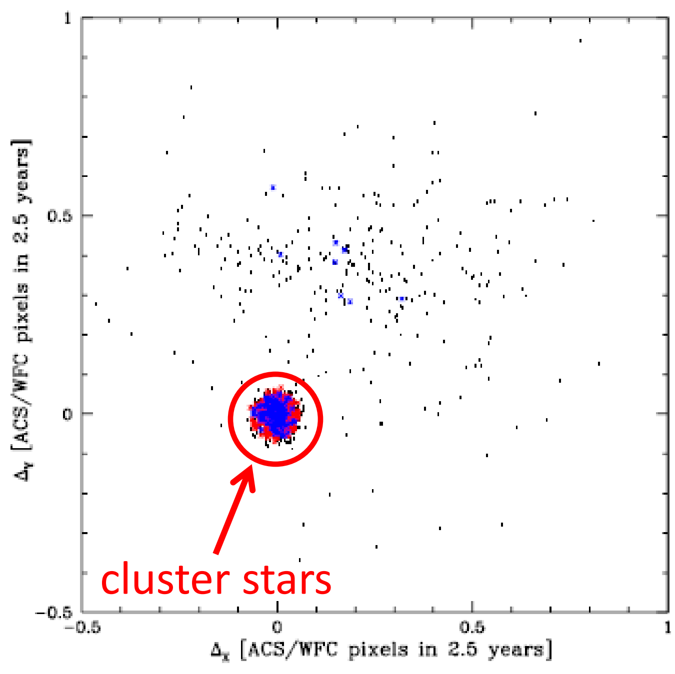
A third, metal rich population

Red MS

Blue MS

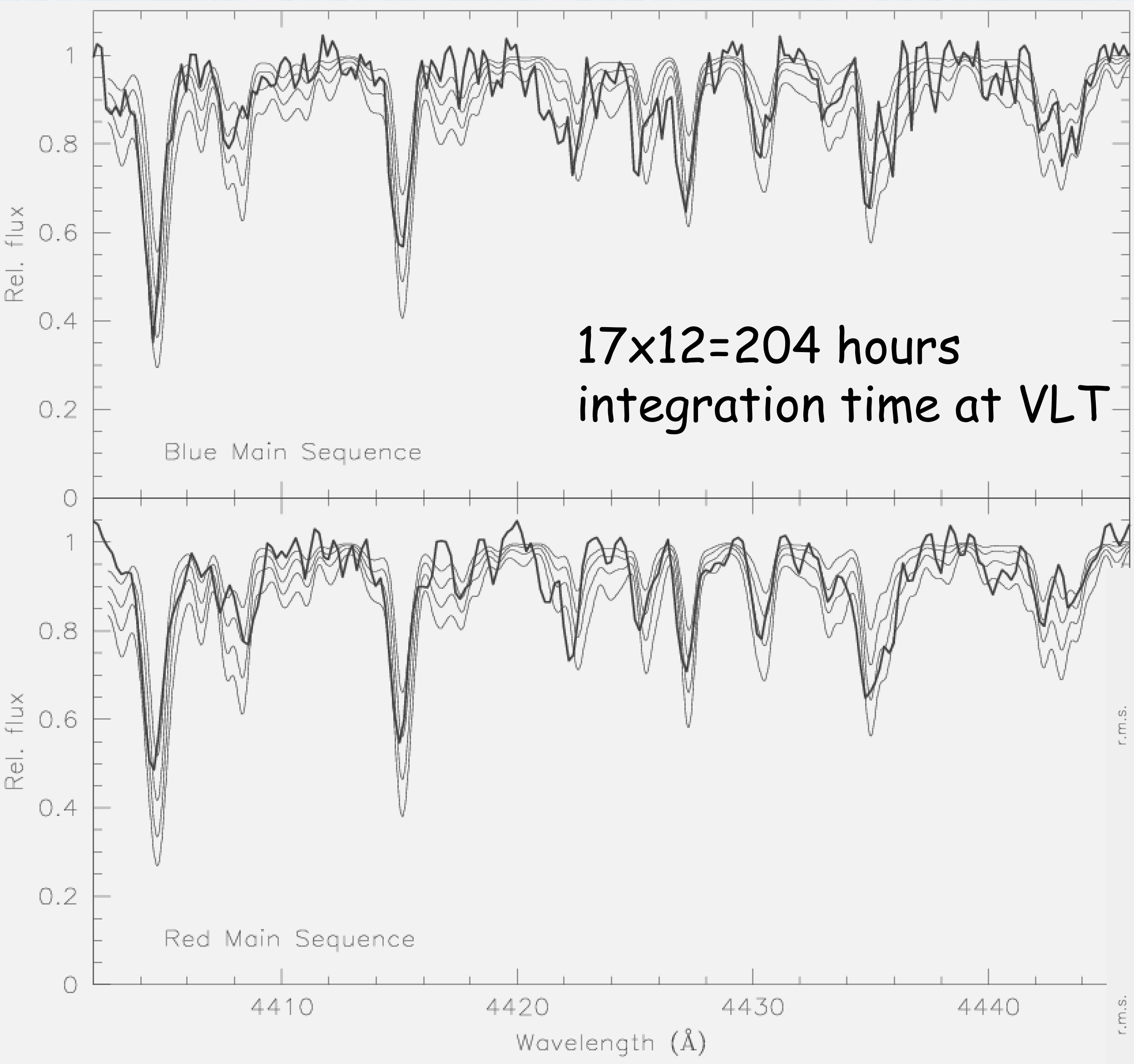
Bedin et al. in preparation

Triple MS from ACS multi-epoch data. Note that **the cluster members have been selected by proper motions.**



cluster stars

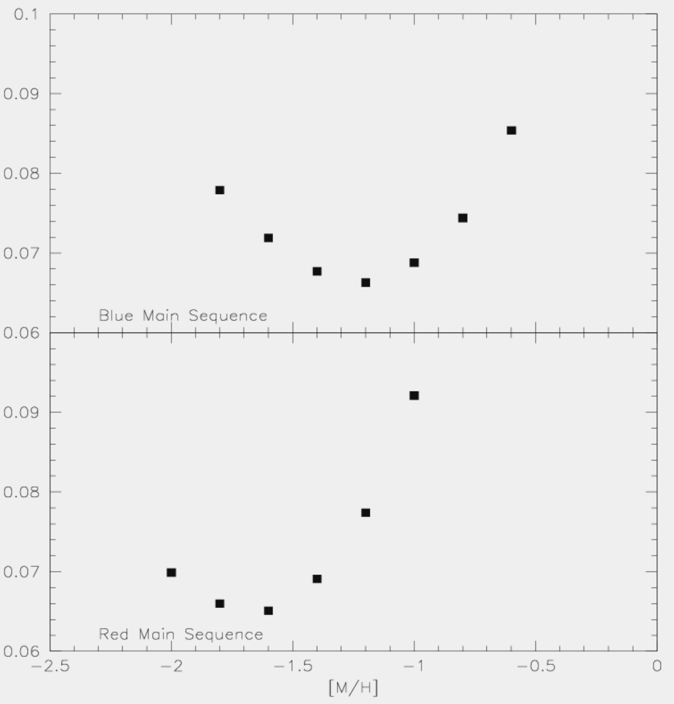
# The double main sequence in Omega Centauri



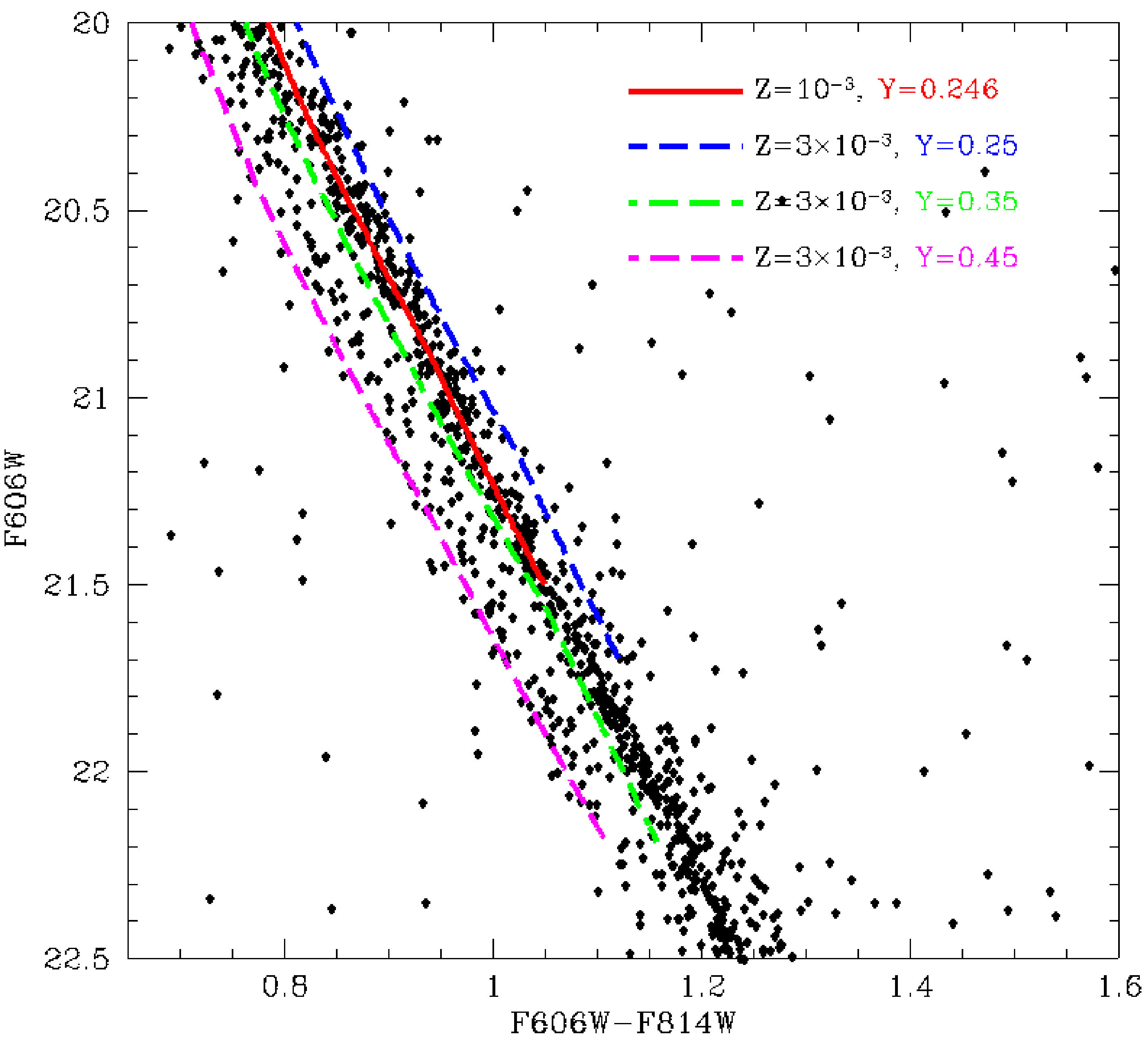
17x12=204 hours
integration time at VLT

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

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

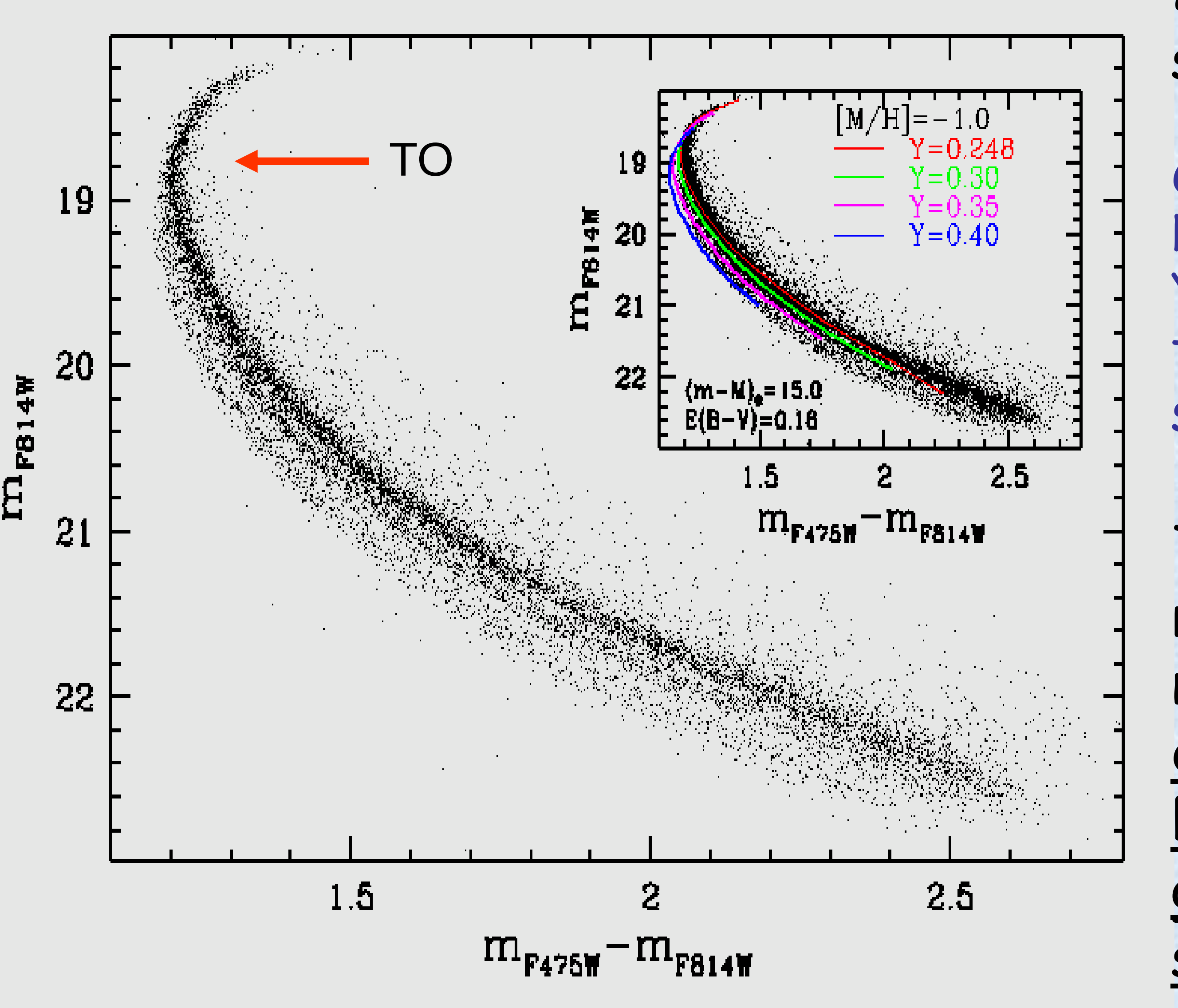


Piotto et al. (2005, ApJ, 621,777)



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

# The triple main sequence in NGC 2808



Piotto et al. 2007, ApJ, 661, L35

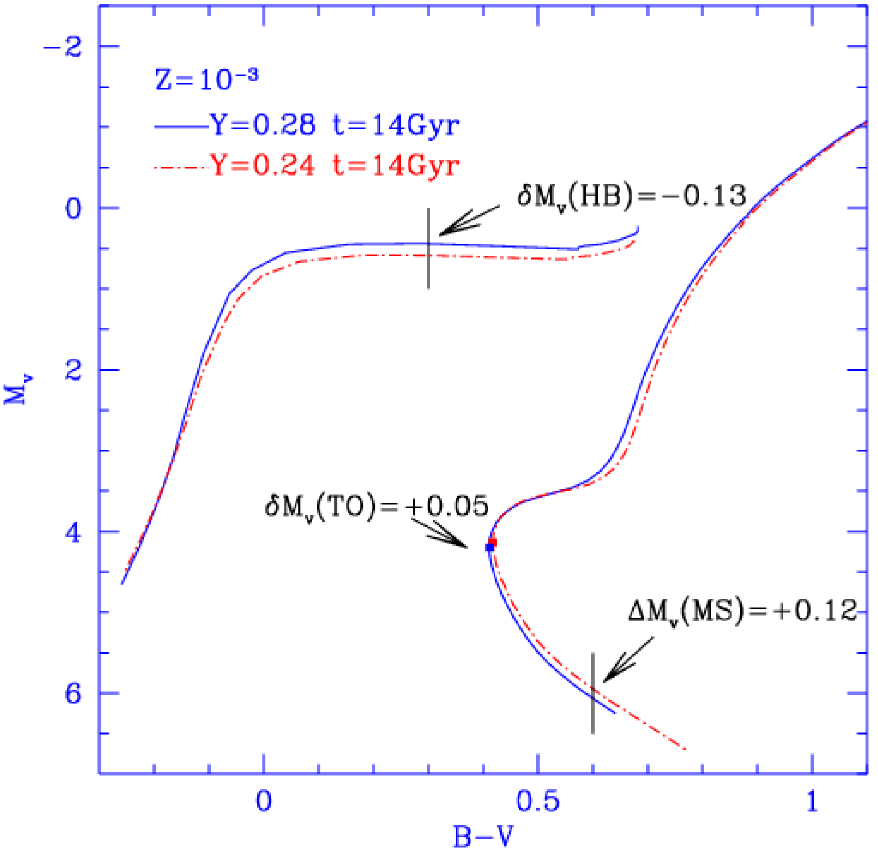
The MS of NGC 2808 splits in three separate branches

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

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

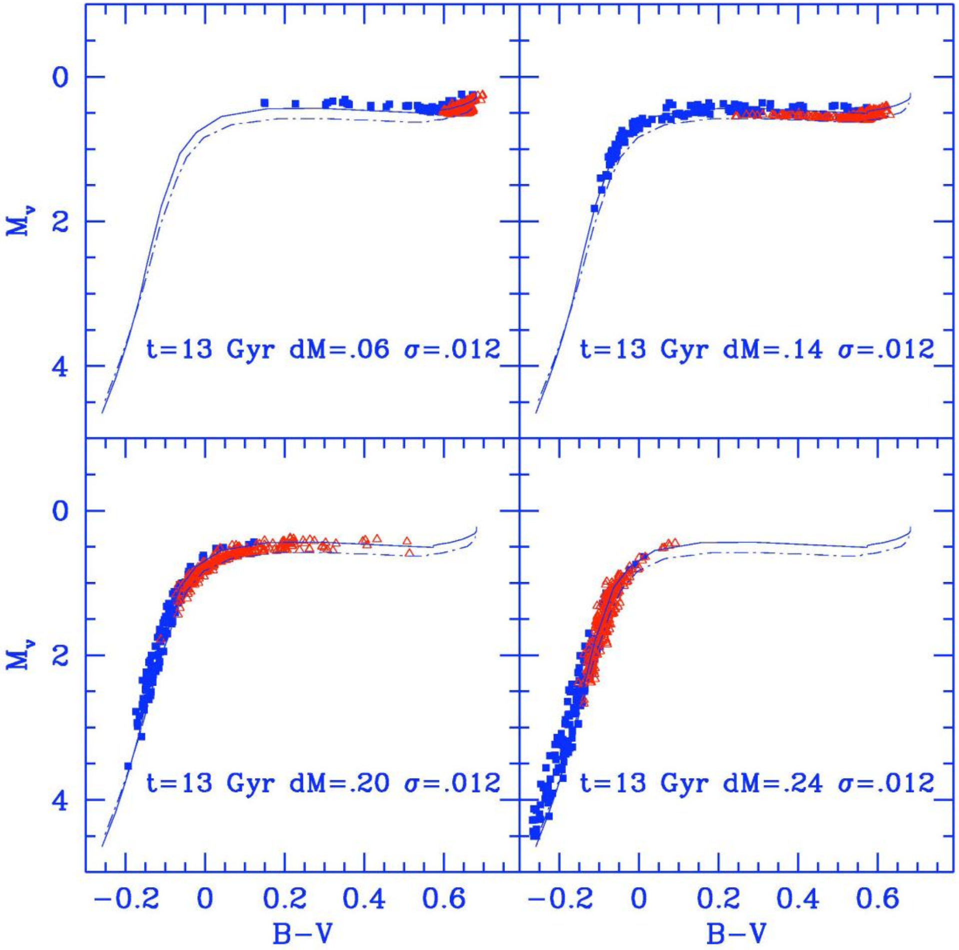
# Helium enrichment: model predictions

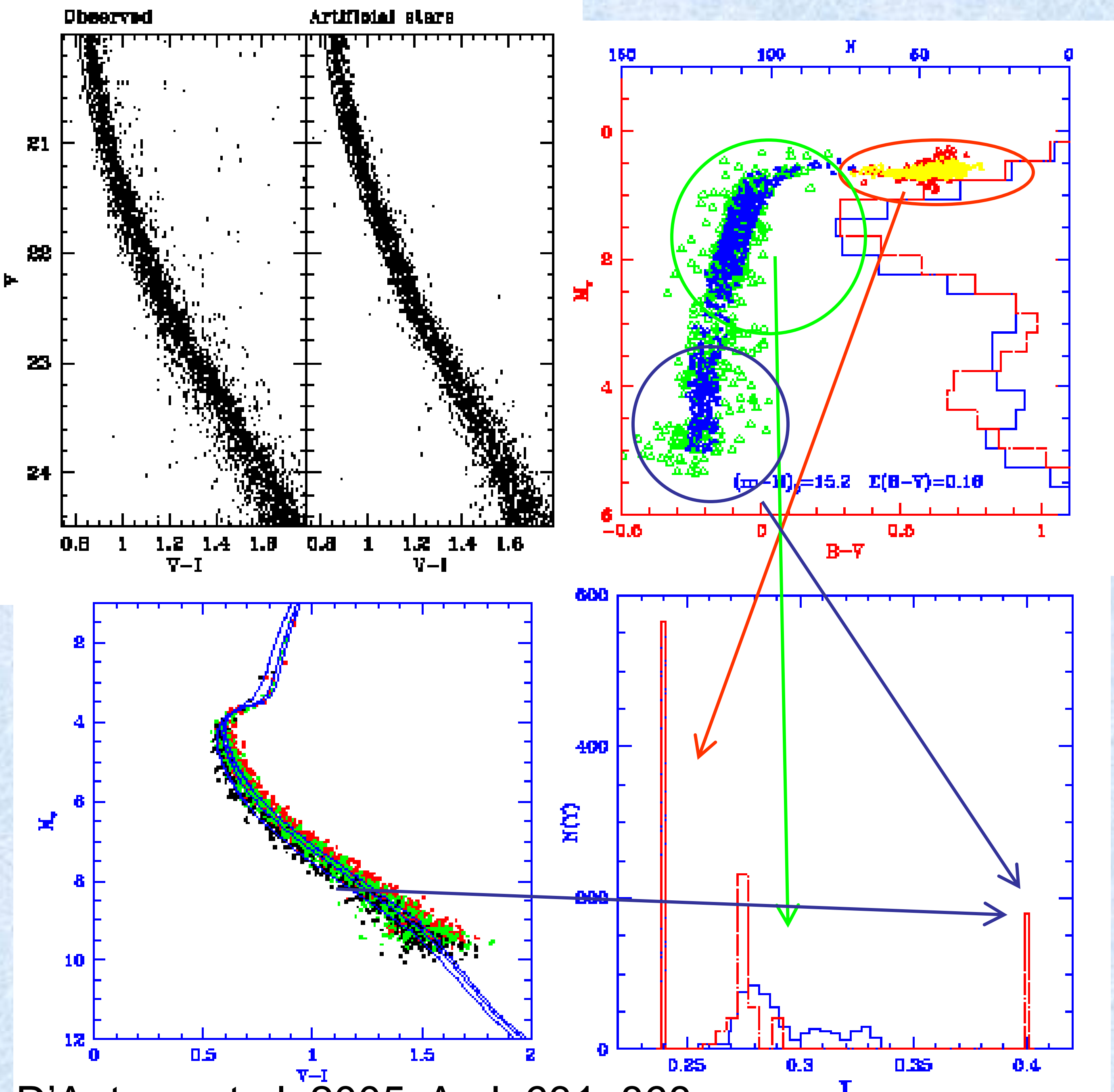
→ Higher Y → brighter HB



D'Antona et al. (2002)

Higher Y → bluer HB ←
(but need also higher mass loss along the RGB





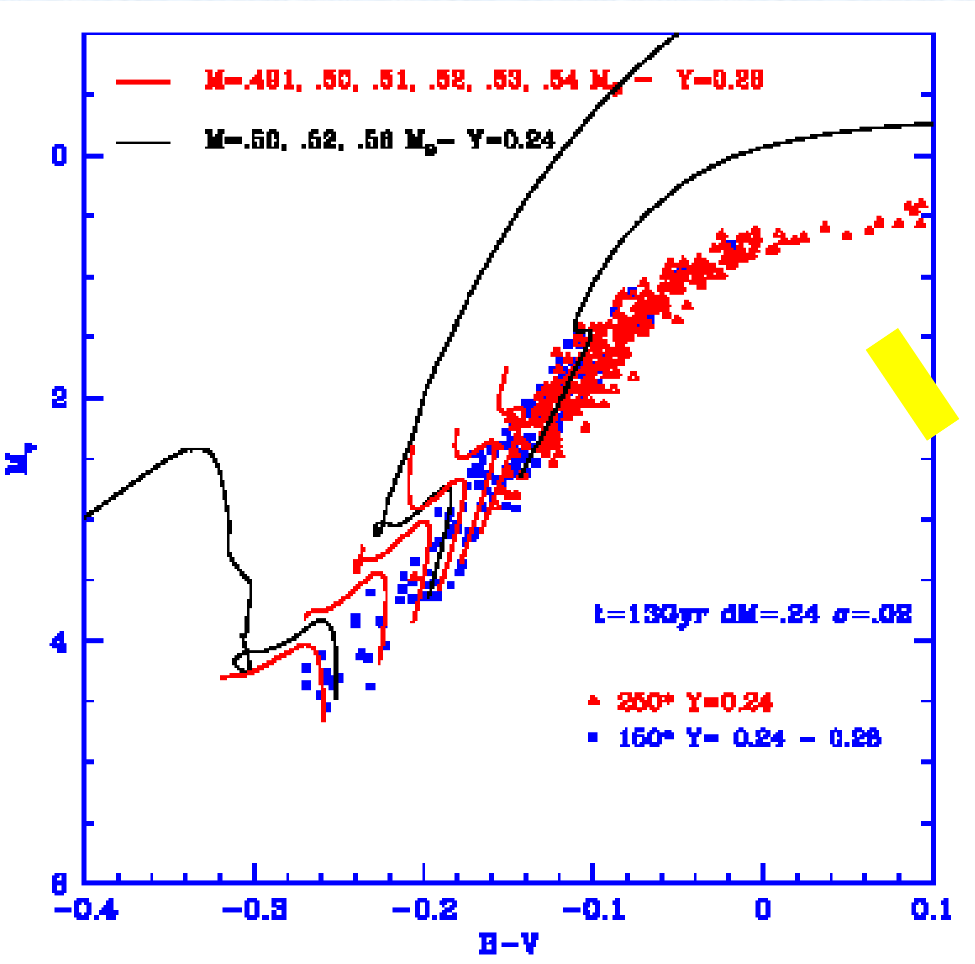
D’Antona et al. 2005, ApJ, 631, 868

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

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

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

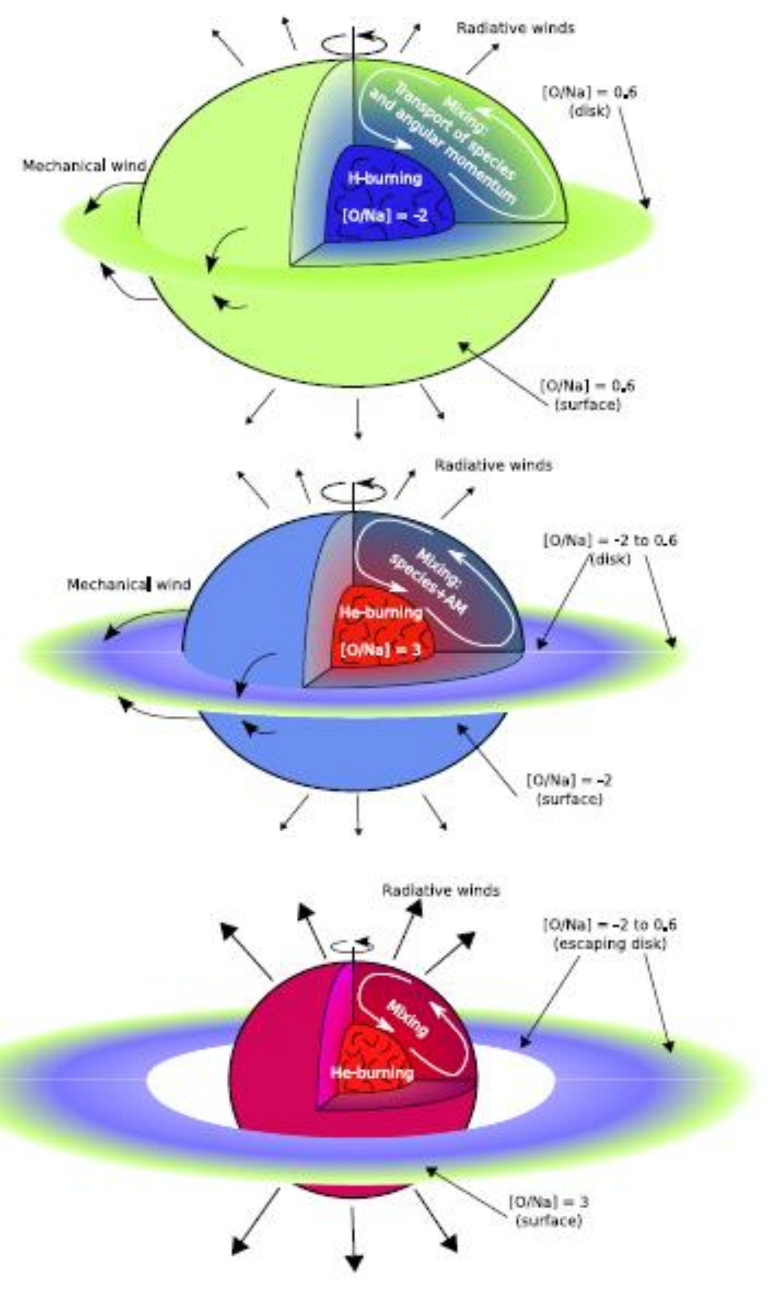
# Proposed scenario (1)



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)



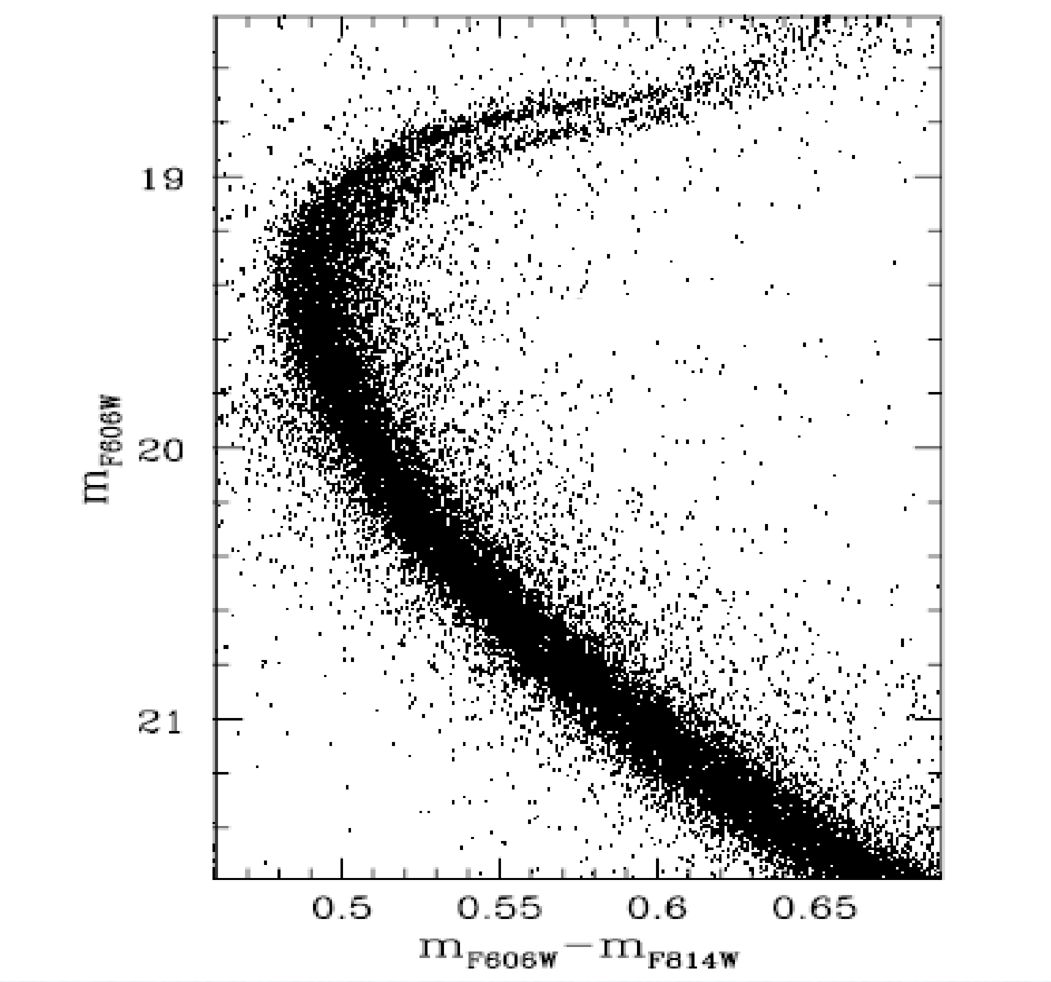
Pollution from fast rotating massive stars (Decressin et al. 2007, A&A, 475, 859).

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 Double Subgiant Branch of NGC 1851

Milone et al. 2008, ApJ, 673, 241

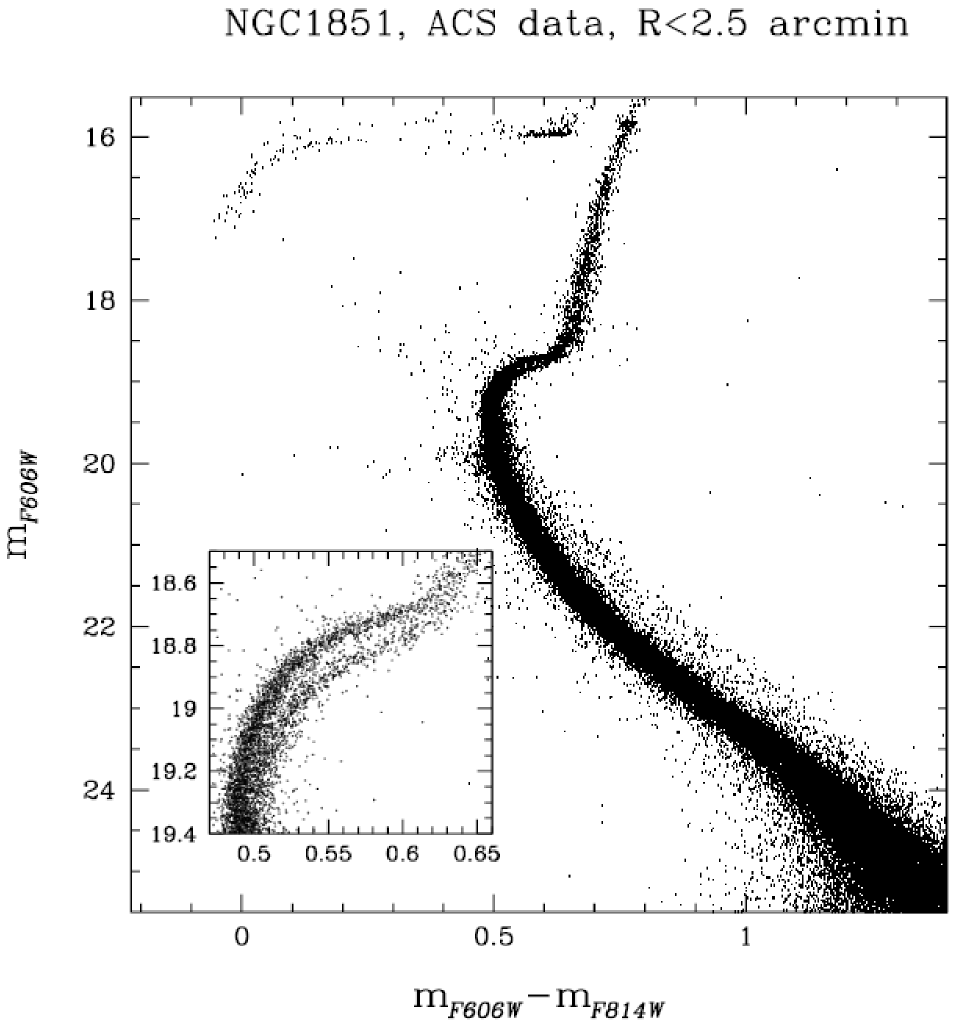


The SGB of NGC 1851 splits into two well defined sequences.

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

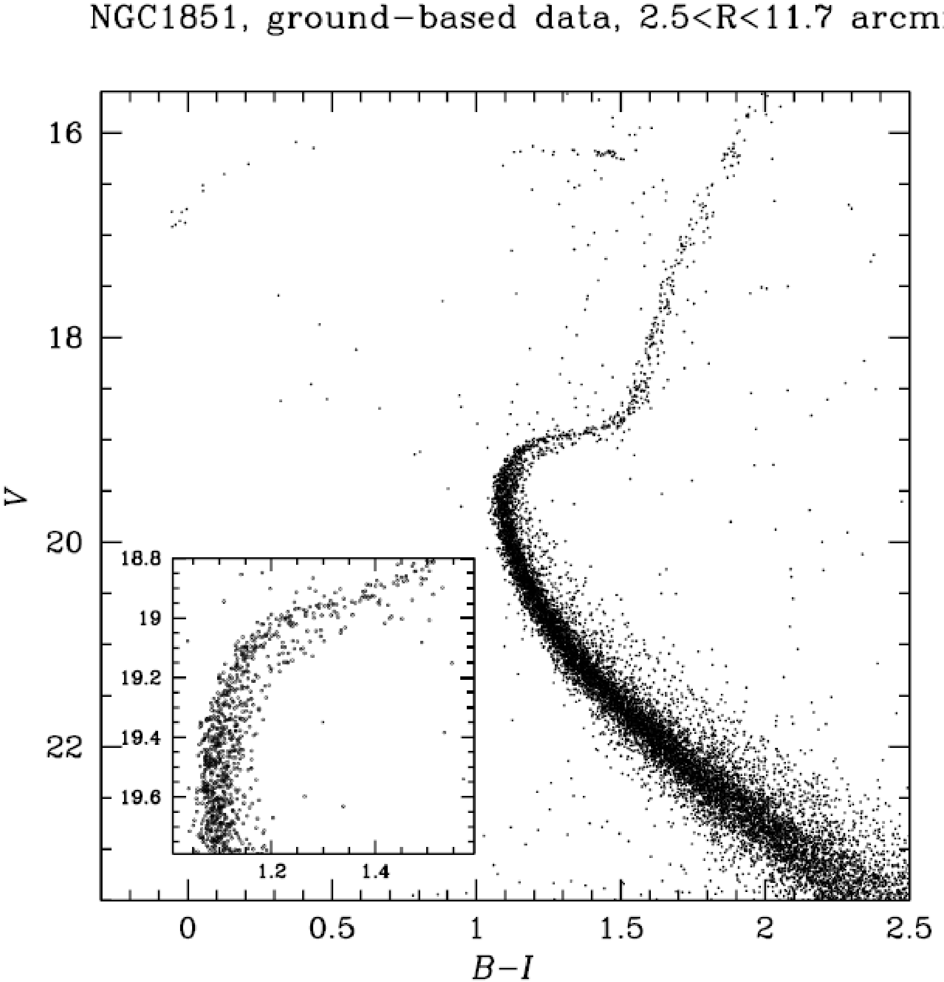
But the split could also be due to two populations with different C+N+O content, as proposed by Cassisi et al. (2008) and found by Yong et al (2009). In this case, the age split could be of the order of $10^8$ years.

**Again, pollution by a first generation stars of the material from which of a second generation formed is the most likely hypothesis.**



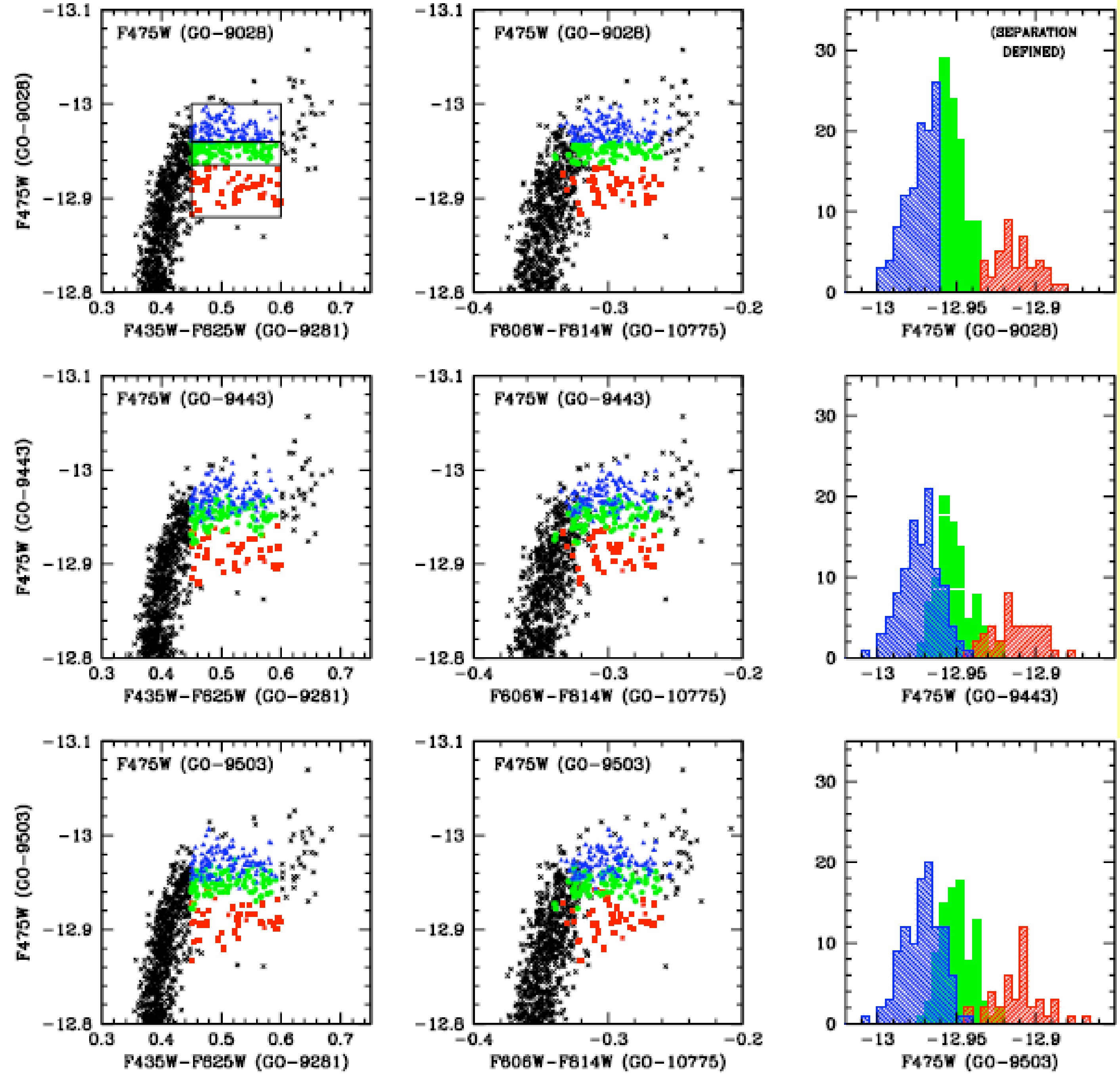
NGC1851, ACS data, R<2.5 arcmin

Sequence split visible also on CMDs from groundbased data (Milone et al. 2009, A&A, in press)



NGC1851, ground−based data, 2.5<R<11.7 arcm

The two sequences follow the same radial distribution and are visible out to the cluster outskirts



# Complex example:

# 47 Tucanae

This globular cluster shows a spreaded SGB, plus a secondary SGB plus…

Anderson et al. (2009, ApJ, 697, 58),

Why MAD-MAX would be important for the multiple population search in star clusters, and for the study of globular clusters in general?

# EXPECTED ASTROMETRIC PRECISION

**Experience with HST** (undersampled images!!)
Astrometric precision *on* ***single high S/N stellar images*** (DL=diffraction limit)

**WFPC2: 2.0mas (0.02 px) ~2.0% DL (@500nm)**
**ACS : 0.5mas (0.01px) ~1.0% DL**

It has been shown that both limits can be **improved by a factor sqrt(N)** from N independent measurements in N independent images (**down to ~0.1mas with well dithered images with ACS**) . Presumably, WFC3 will reach similar performances.

**Groundbased images best astrometric achievements:**

**WFI@2.2m: 7 mas (0.03 px), ~0.75% FWHM (Anderson et al. 2006)**
**NACO@VLT 0.30mas ~0.60% DL (@1.5nm) (Gillesen et al. 2009)**

**With MAD**, and an **appropriate observing strategy**, using local transformations, we can aim to reach **1% FWHM precision** (~1mas) in the best observing conditions, on high S/N images, which lowered by a factor of sqrt(25)=5 (?) with 25 well dithered images. In principle a **0.2-0.3 mas astrometric precision** could be reachable, on a **2x2 arcmin$^2$ field with MAD/MAD-MAX.**
**We need to understand the real astrometric limits reachable with MCAO imagers.**

**Let us suppose we can reach a 0.2 mas precision, by taking also advandage of many, well dithered, high S/N images.**

**This would imply a proper motion precision of 40μas/yr in 5 yrs (20μas/yr in 10 years).**

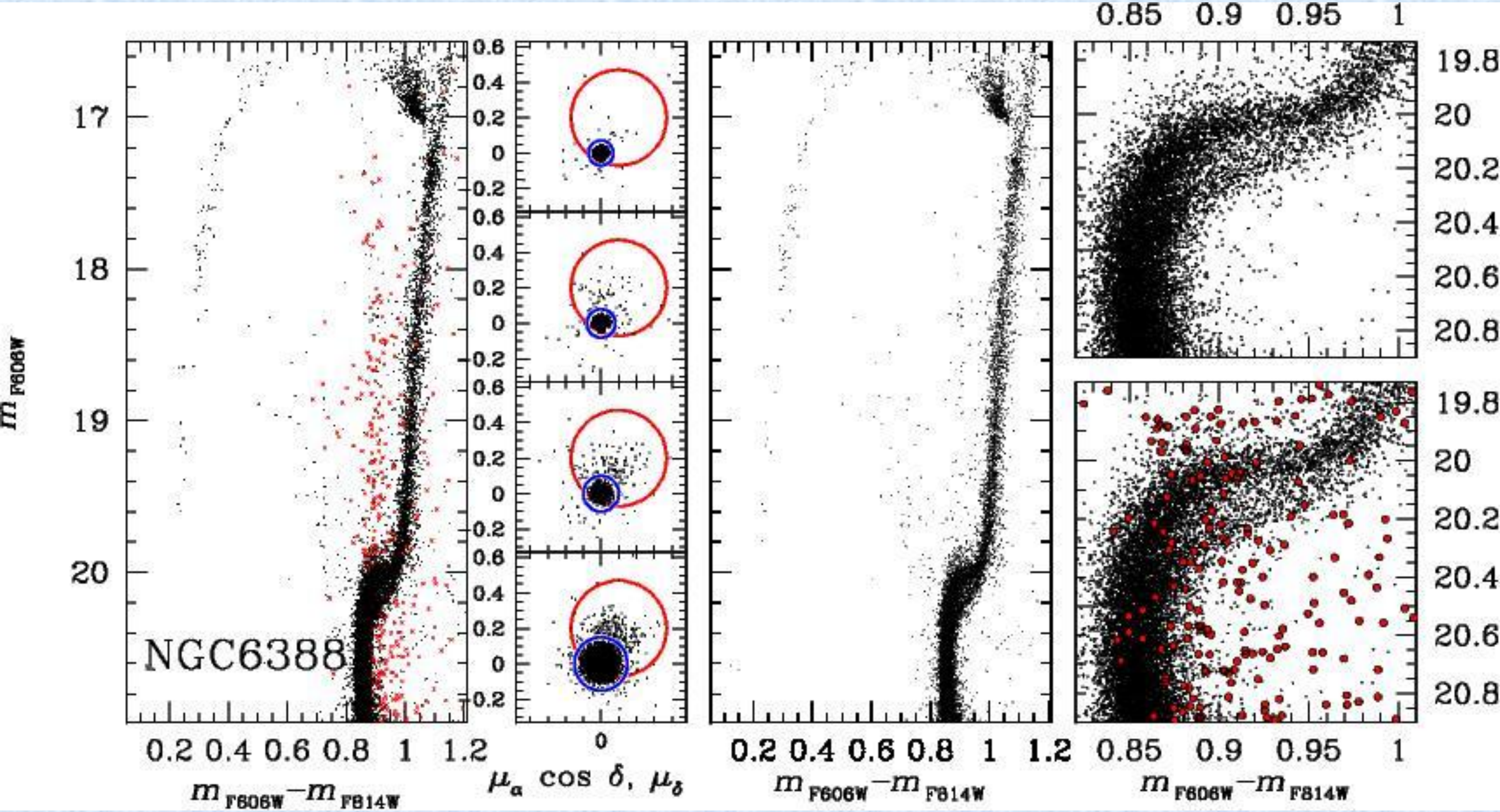
***NOTE 1: in principle, we can think to a >15 yr baseline by using HST archive images, which, in the best cases (ACS) allow us to get an astrometric precision down to ~0.1***

**NOTE 2: for most projects discussed in the following, we do not need such precision (with consequent relaxation of the observing conditions/requirements). A factor of 5 worst (1mas precision) would make many interesting projects on GCs still feasible.** *(see Alessia talk for more details).*

**NOTE 3: Only for the last, most challeging, but "hottest" program, we need to push MAD-MAX at its resolution limits.**

# Importance of the high angular resolution

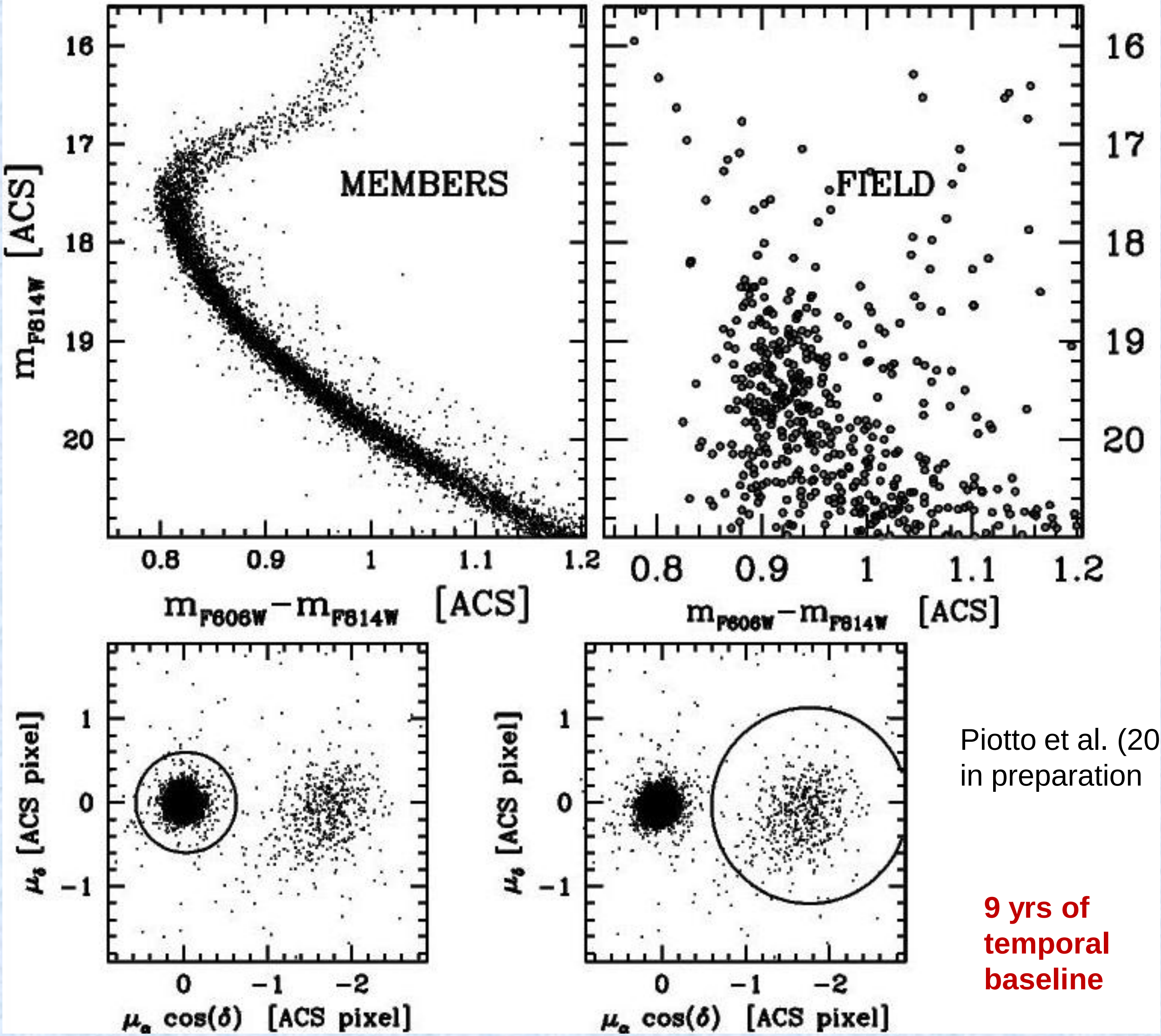
Proper motion membership is very important to clean the CMD, searching for features in the evolving branches. Coupling existing first epoch images from HST with second epoch MAD ones allows us to do a very careful job.



**4.7 yr of temporal baseline!**

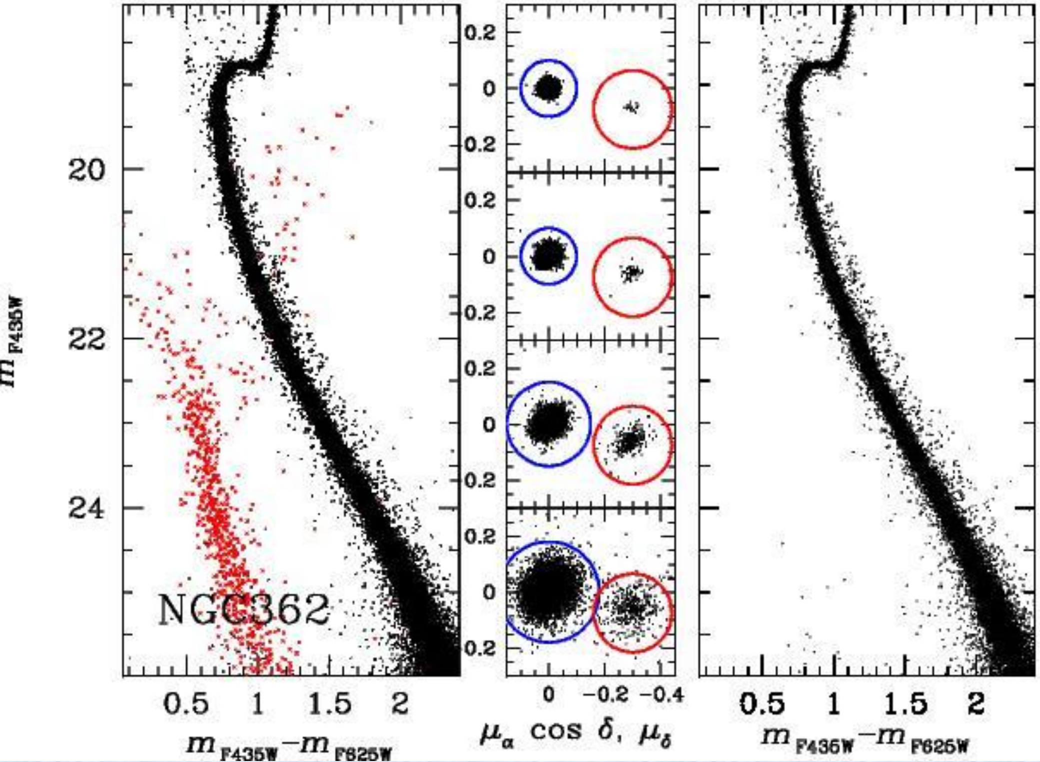
Piotto et al. in preparation

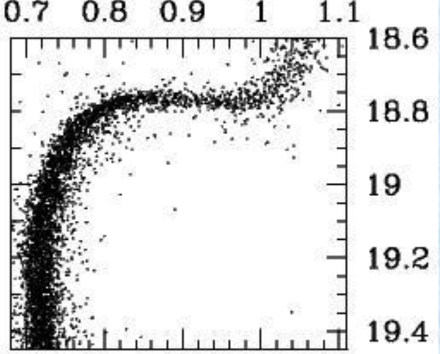
# NGC 6656 (M22): another cluster with a double SGB

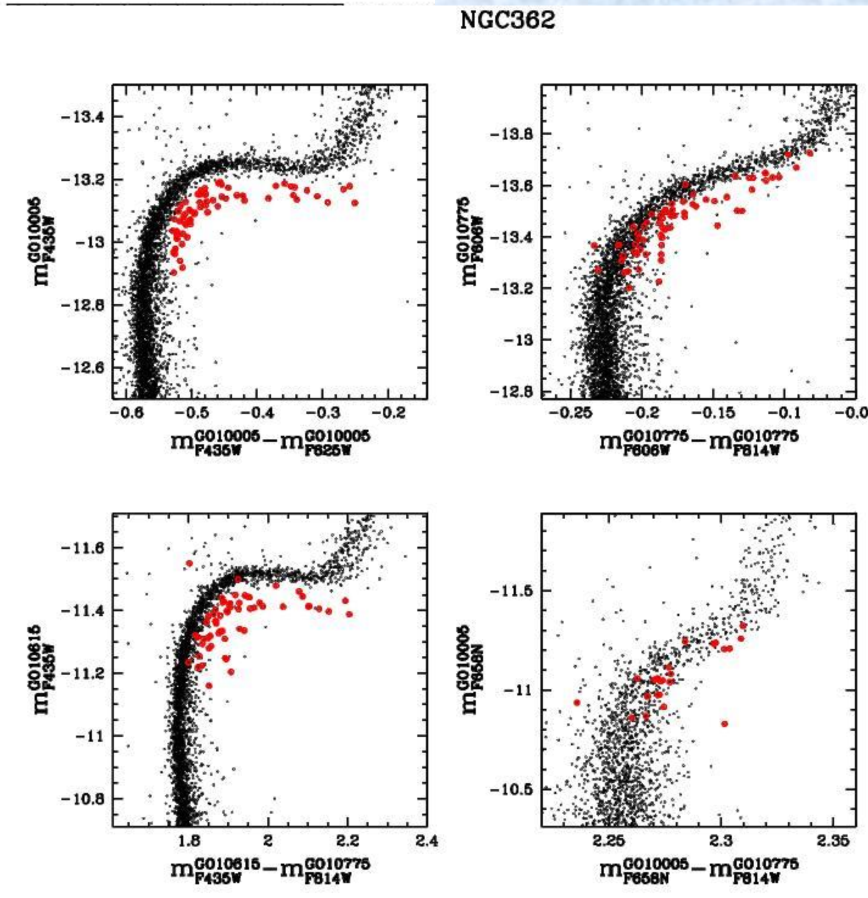


Piotto et al. (2009), in preparation

**9 yrs of temporal baseline**







# Importance of the Statistical Sampling

Sometimes the second generation of stars includes less than 5% of the total population. **High angular resolution images** (for proper motion measurements) in **a large field** (for sampling), **as provided by MAD,** become a unique research tool.

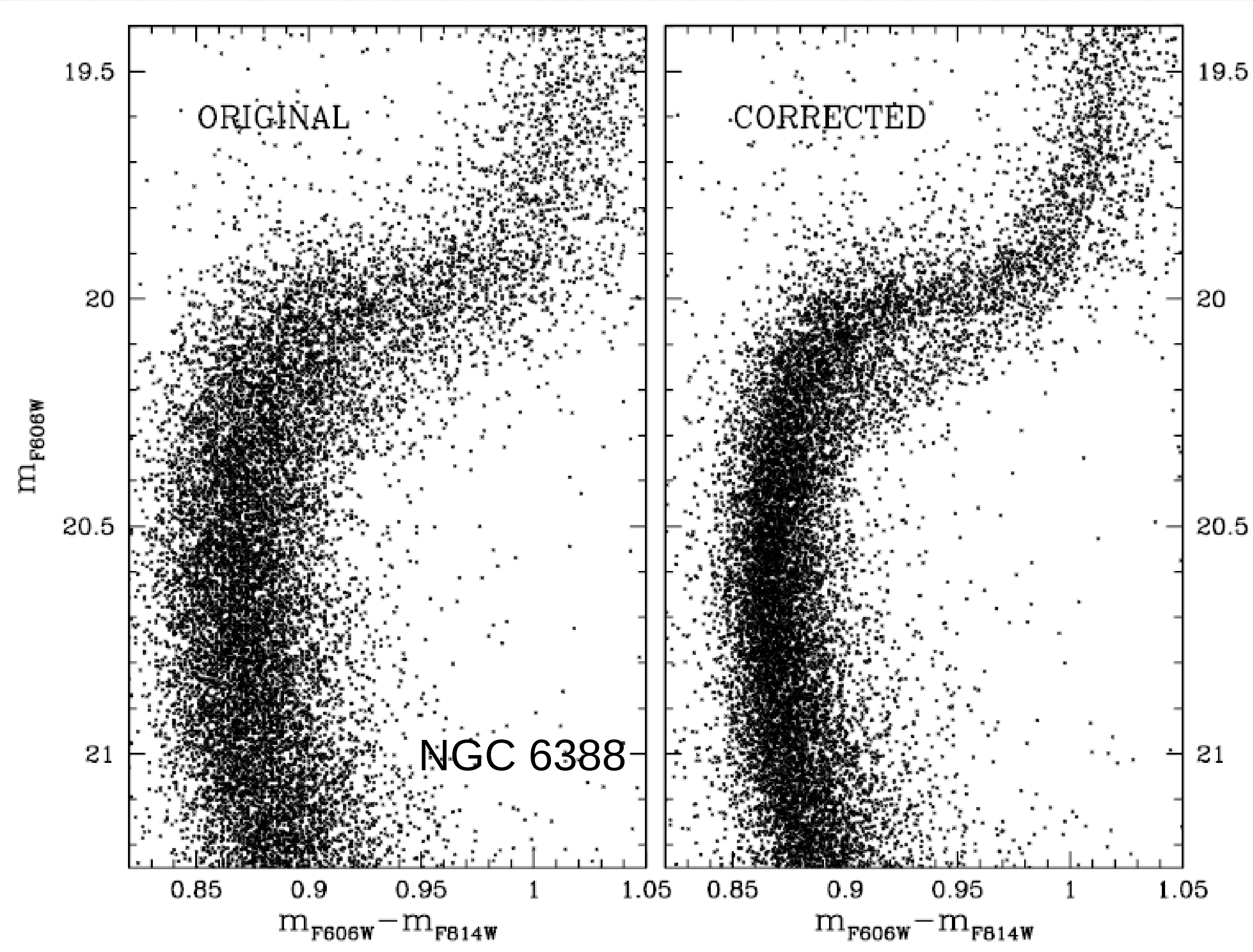
Note MAD field close to ACS and WFC3 fields: again great synergies possible.

**2.2 years of temporal baseline!!**

# Importance of NIR observations (1):

## Smaller absorption and reddening effects

$A_V = 3.252 * E(B-V) = 1.23$
$A_I = 1.948 * E(B-V) = 0.72$
$A_J = 0.902 * E(B-V) = 0.33$
$A_K = 0.367 * E(B-V) = 0.14$



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

$E(V-I)$ 0.51 = 1.37 $E(B-V)$
$E(V-K)$ 1.09 = 2.95 $E(B-V)$
$E(I-K)$ 0.58 = 1.58 $E(B-V)$
$E(J-K)$ 0.20 = 0.54 $E(B-V)$

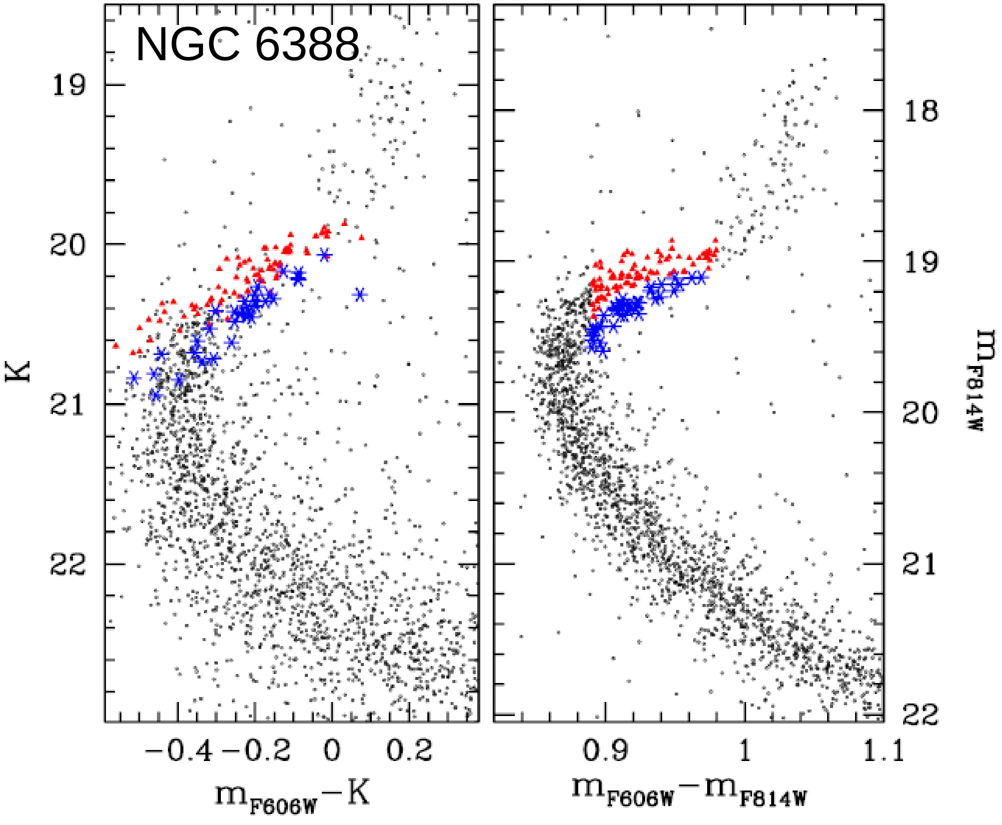
Near-IR observations: very important for highly reddened clusters and clusters affected by differential reddening:

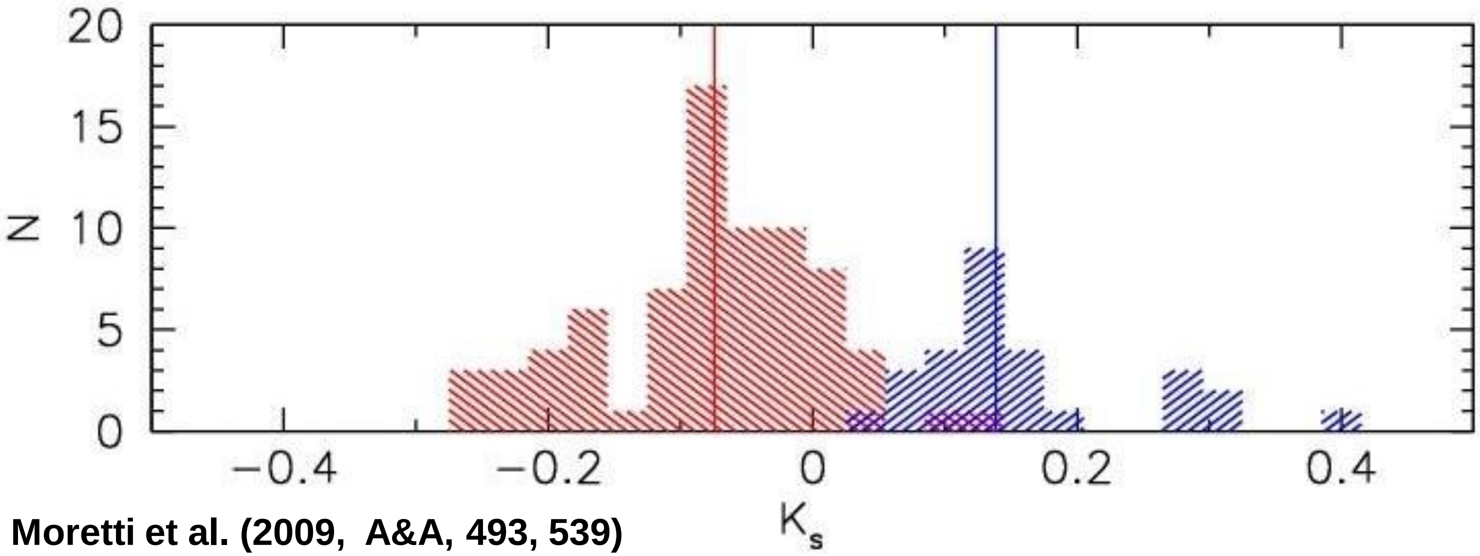
**1) Absorption in K in 11% of the absorption in V (in J it is 27% of the V absorption)**

**2) Reddening in J-K half of the reddening in E(B-V)**

# REAL MAD OBSERVATIONS

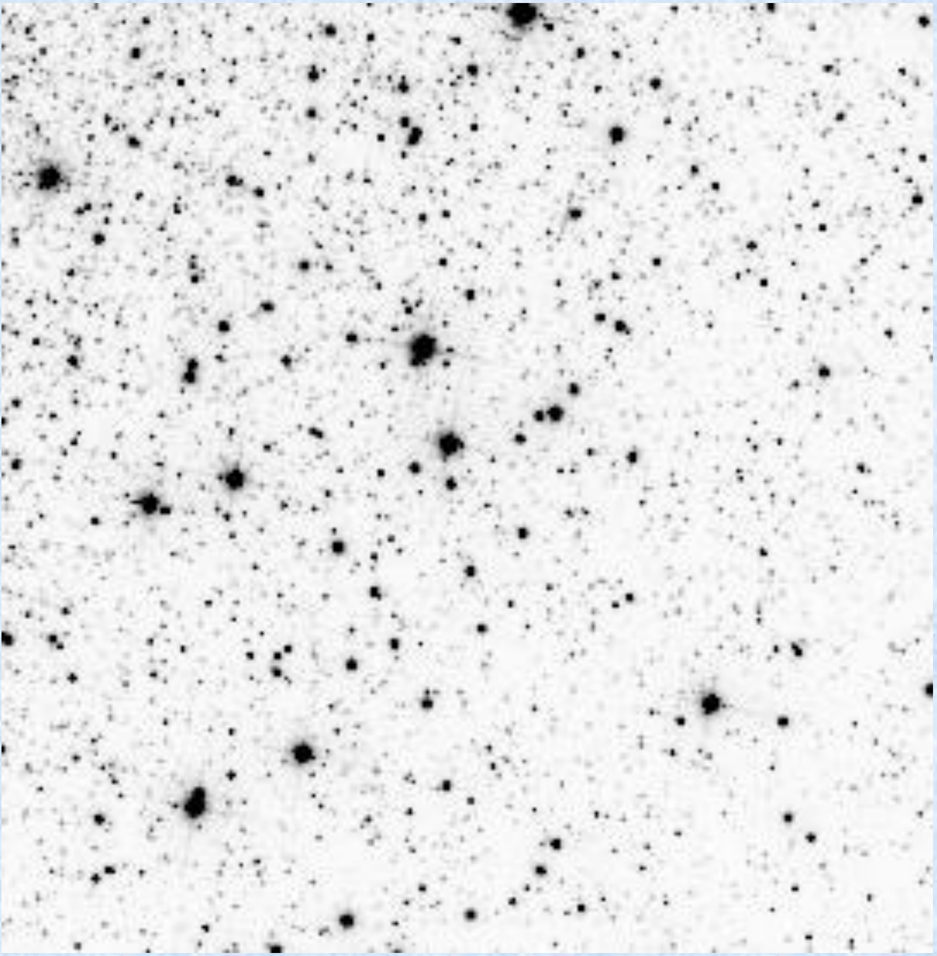
The bimodal distribution of SGB in NGC6388 is present also in the K-band, where the (differential) absorption effects are ~13% of the absorption in F606W band.



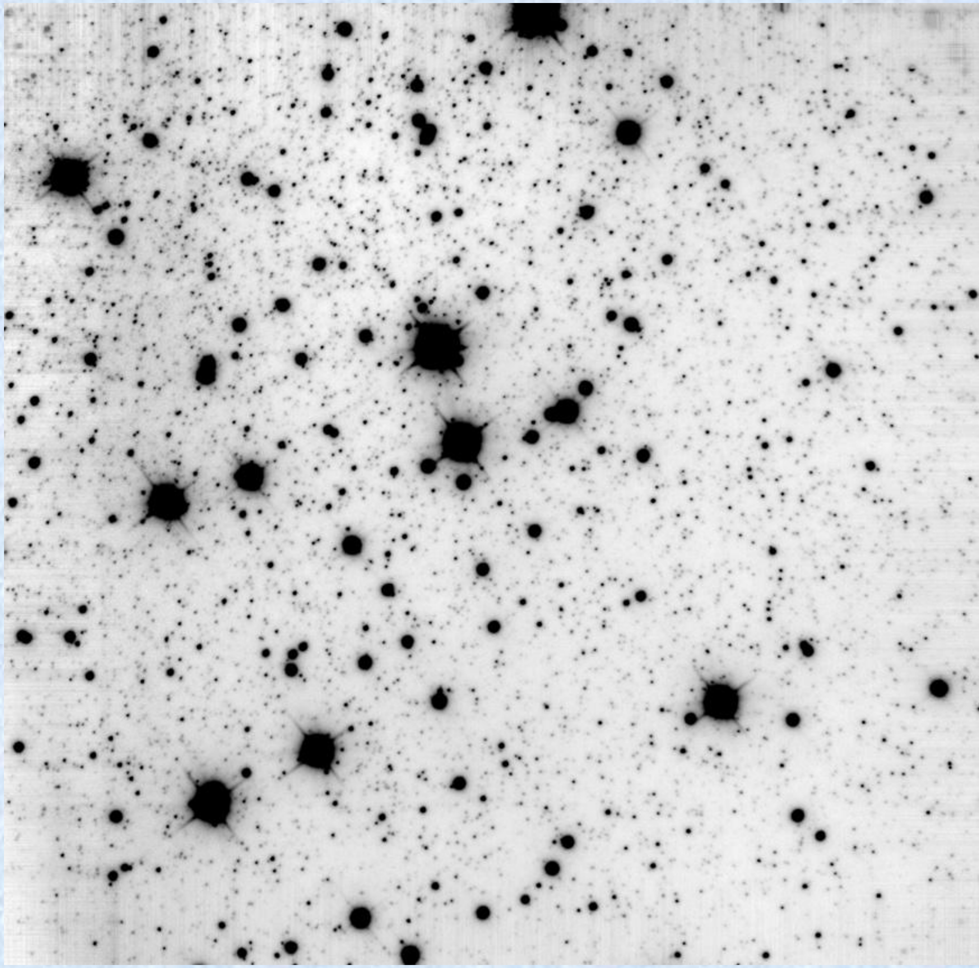


We confirm the SGB split in NGC 6388!

Moretti et al. (2009, A&A, 493, 539)



ACS/WFC@HST, F814W, 1790sec

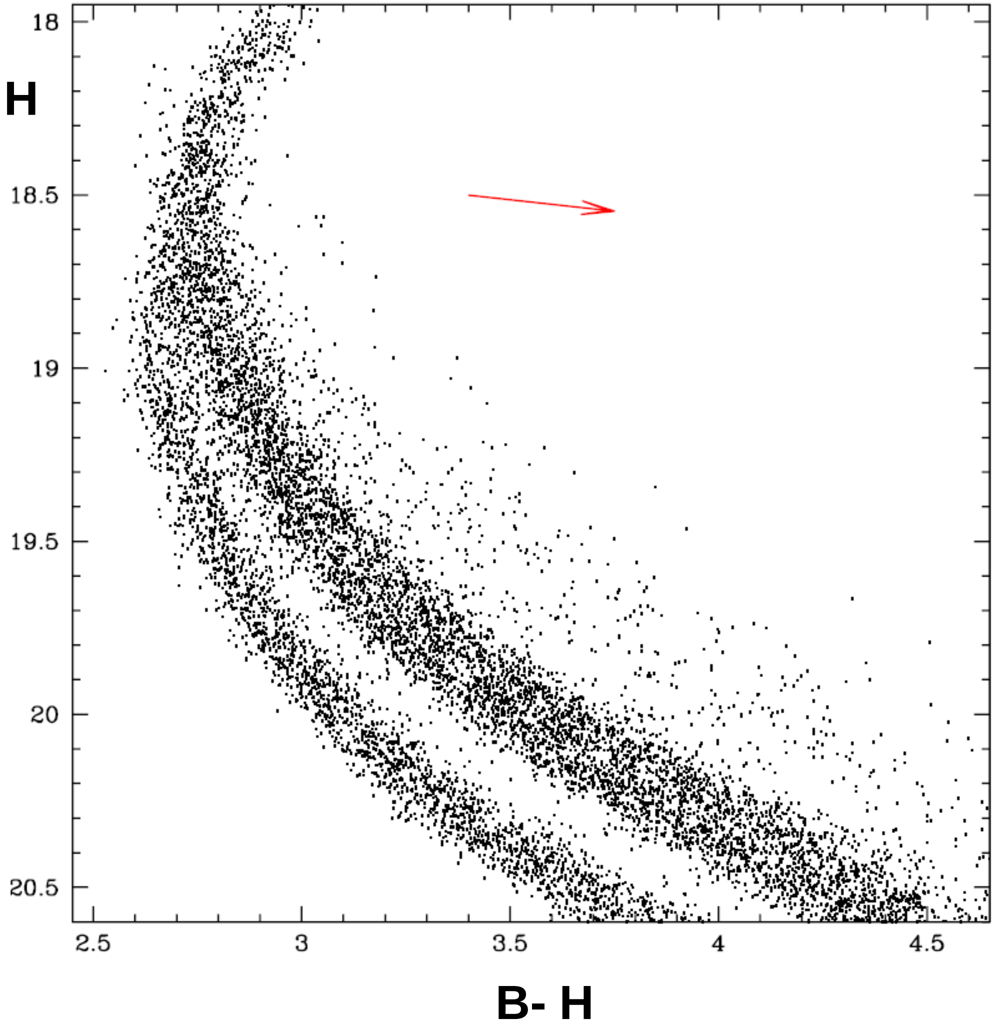


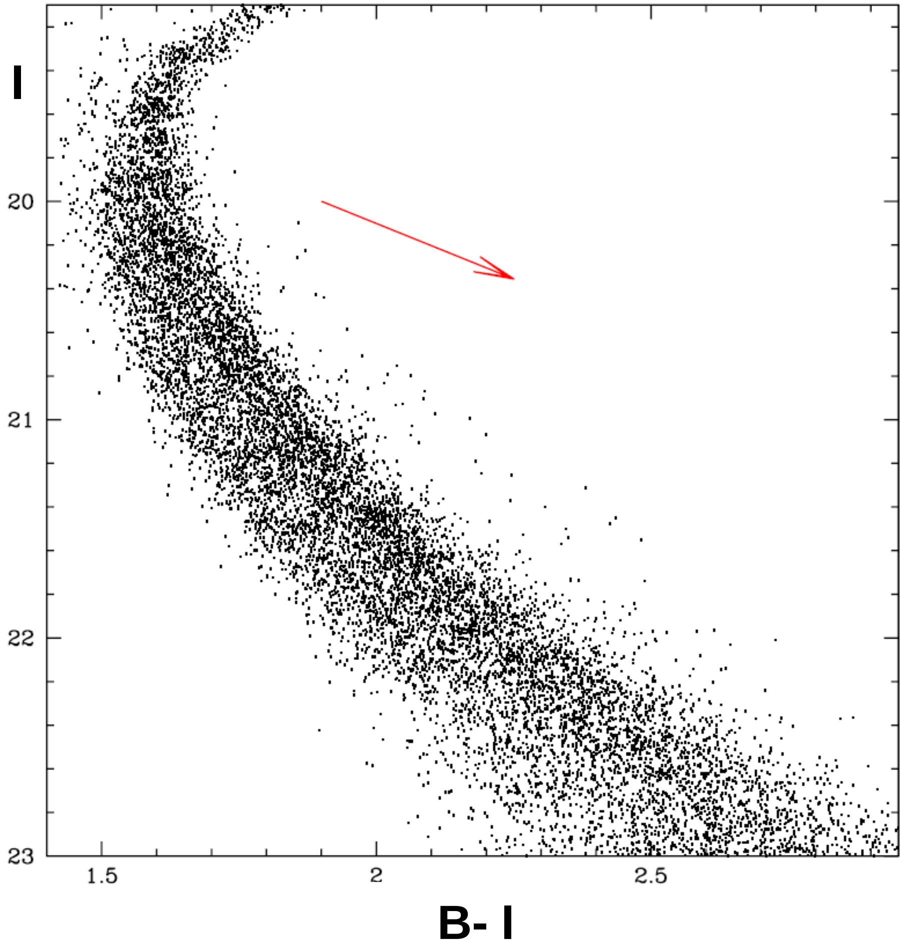
MADLO@VLT, $K_s$, 240sec

NGC 6388

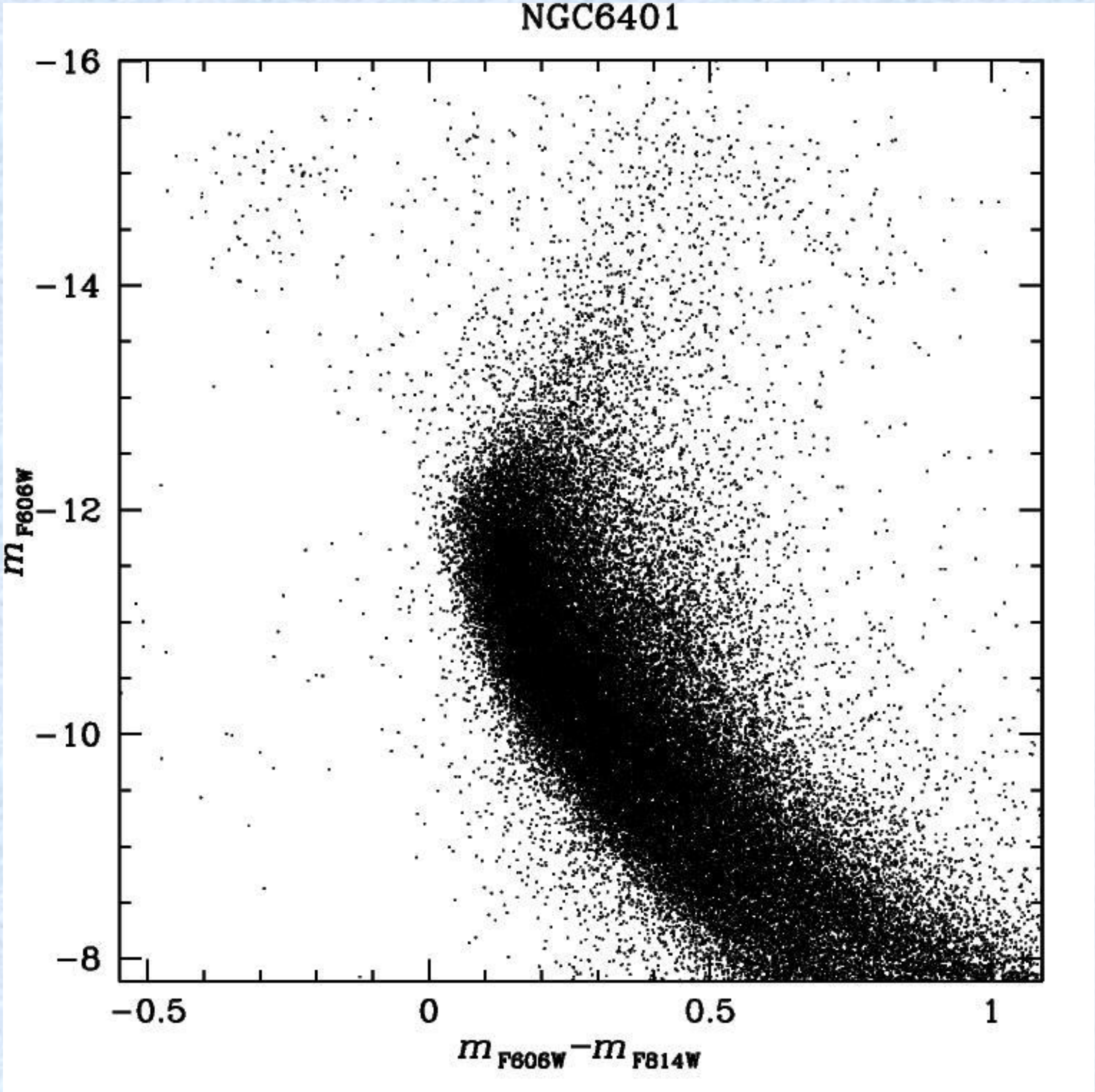
# Importance of NIR observations (2):

**Larger color baseline**





With a larger color baseline,
the sequences are better separated



HST archive is full of **first epoch HST images.**

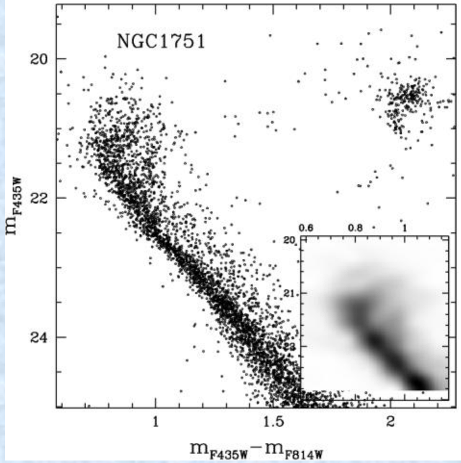
The best, homogeneous sample is represented by the Treasury GC program (GO10775, PI Sarajedini), with F606W + F814W images of cluster cores which allows us for accurate photometry from the tip of the RGB down to $0.2m_{\odot}$.

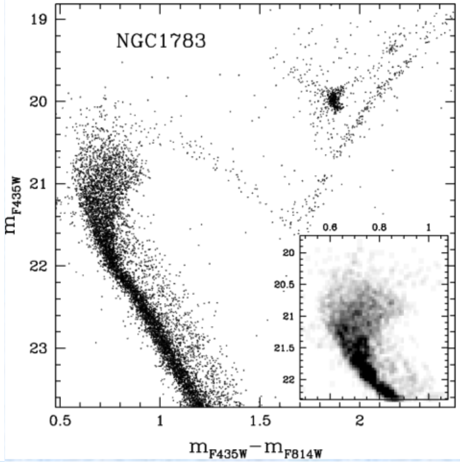
Many heavily reddened, with strong differential reddening, strong field contamination bulge clusters.

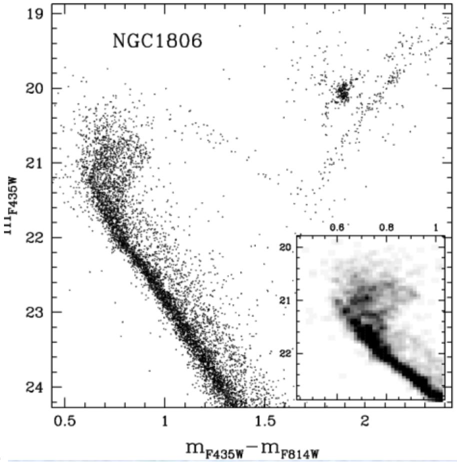
They are just waiting for second epoch NIR, high resolution observations.

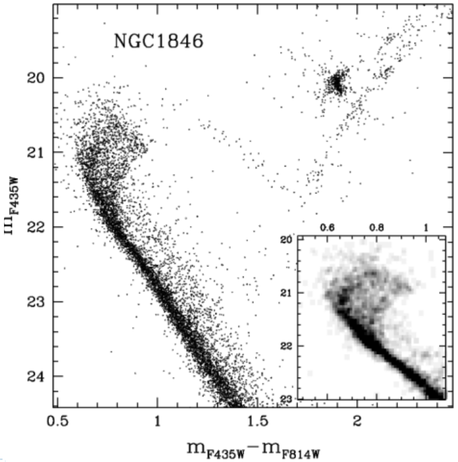
**MAD-MAX would perfectly do the job!**

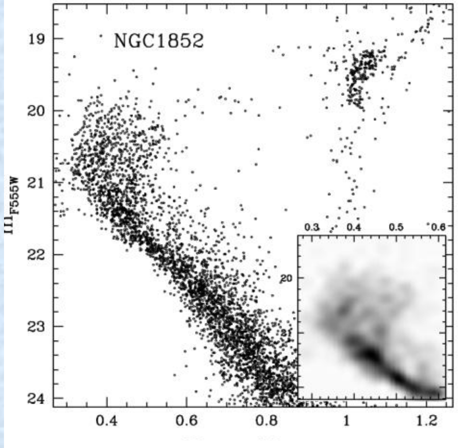
(See Alessia and Sergio talks)

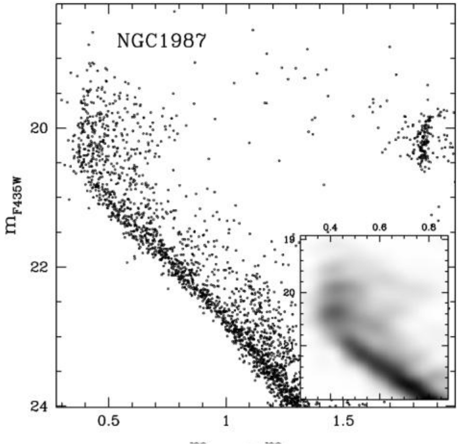


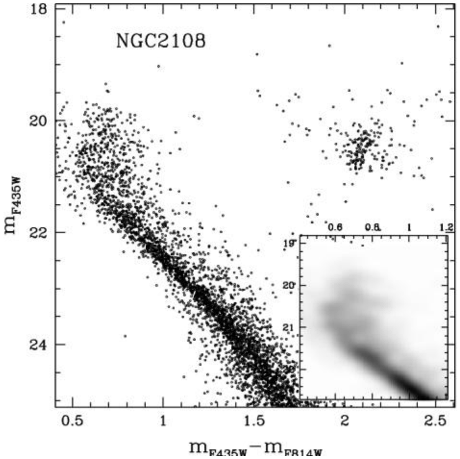


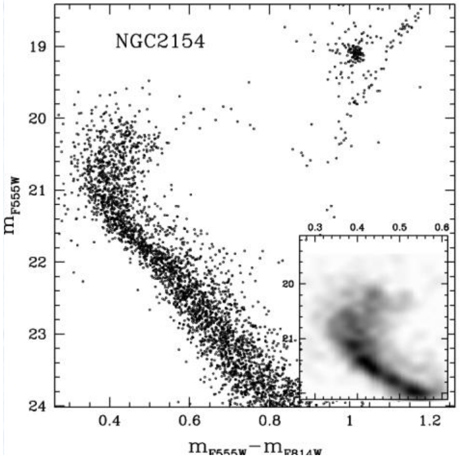


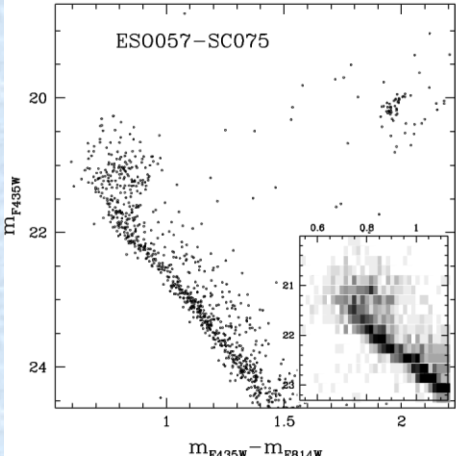


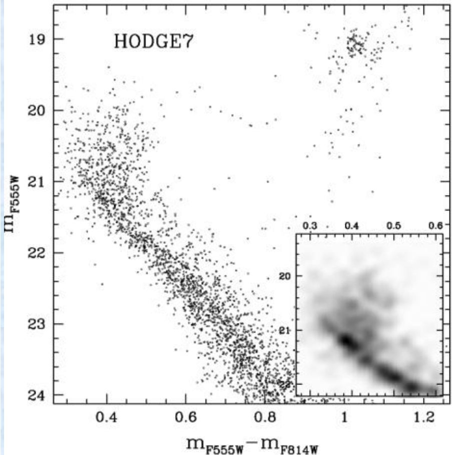


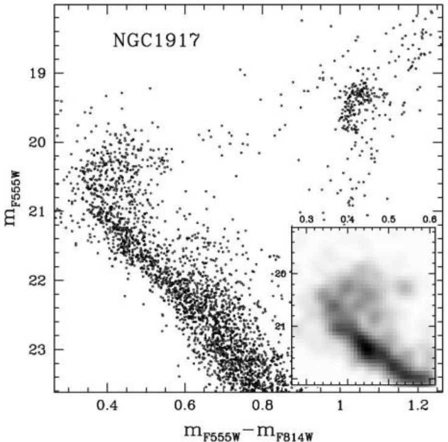






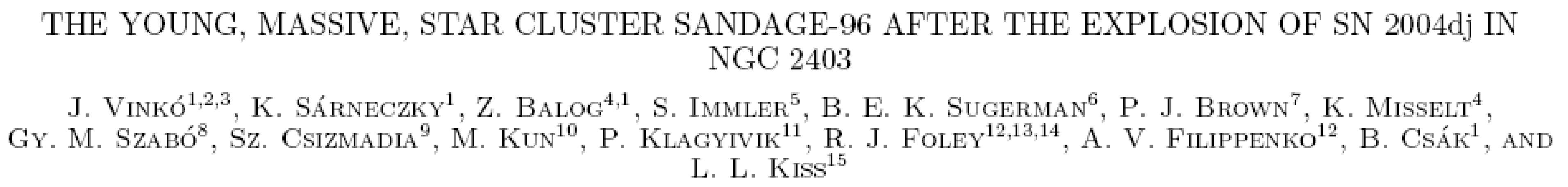






Eleven out of 16 (2/3) of the intermediate age clusters show either a double or an extended TO!

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

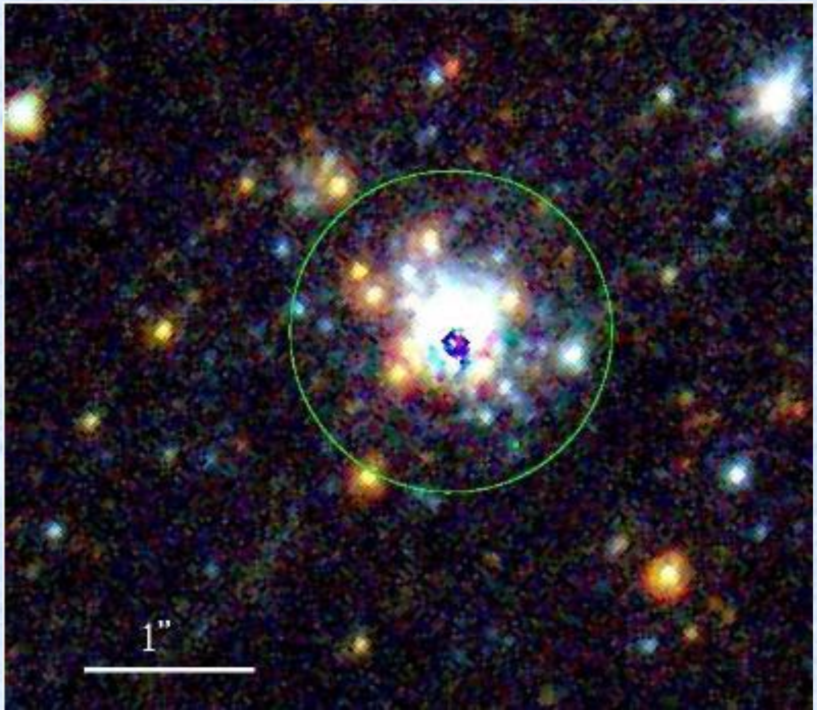


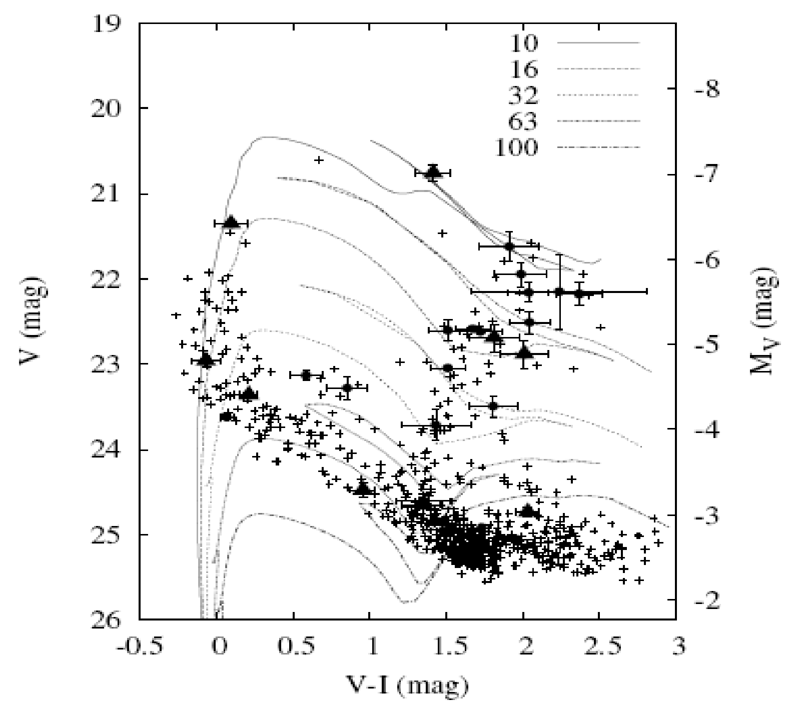
# THE YOUNG, MASSIVE, STAR CLUSTER SANDAGE-96 AFTER THE EXPLOSION OF SN 2004dj IN NGC 2403

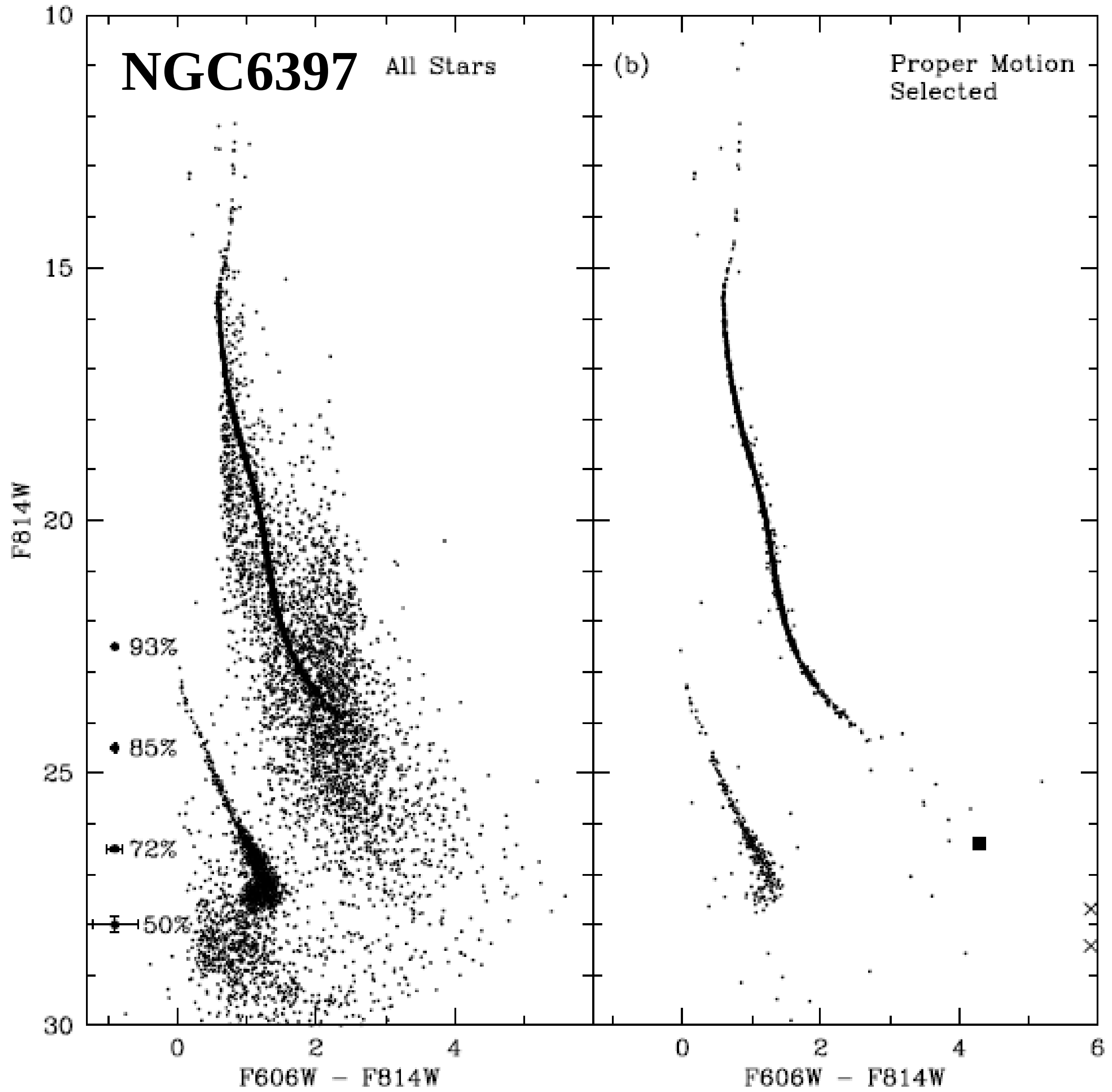
J. Vinkó[1,2,3], K. Sárneczky[1], Z. Balog[4,1], S. Immler[5], B. E. K. Sugerman[6], P. J. Brown[7], K. Misselt[4], Gy. M. Szabó[8], Sz. Csizmadia[9], M. Kun[10], P. Klagyivik[11], R. J. Foley[12,13,14], A. V. Filippenko[12], B. Csák[1], and L. L. Kiss[15]

- The isochrone fitting of the c-m diagrams indicates that the resolved part of the cluster consists of stars having a bimodal age distribution:
  - a younger population at 10–16 Myr
  - an older one at 32–100 Myr.
- The older population has an age distribution similar to that of the other nearby field stars (=an association where the cluster is embedded)

S96 Mass~$10^5$ Mo







Richer et al. (2007)

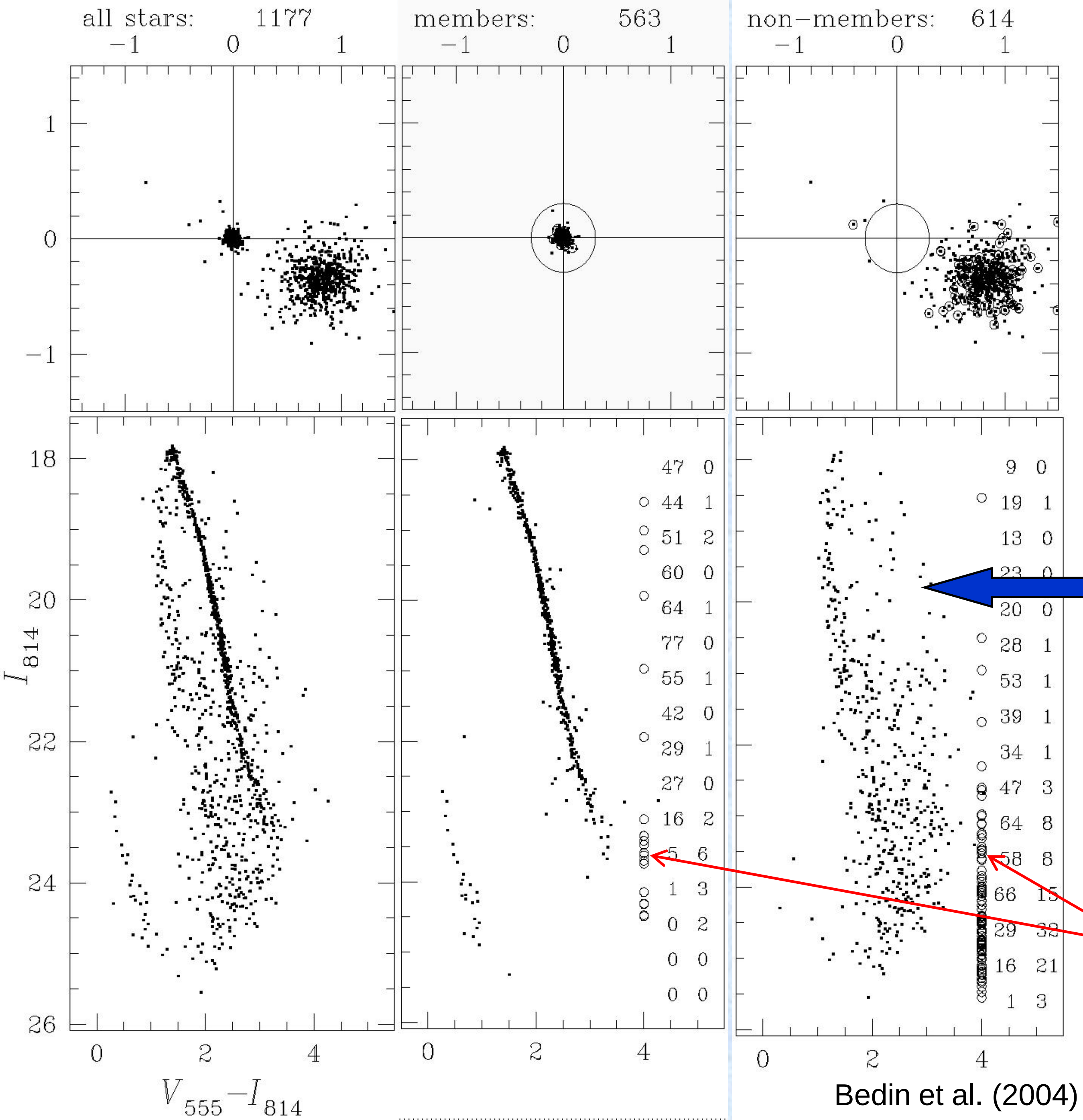
Cleaning of field stars with proper motions: very important when **hunting for the bottom of the main sequence.**

Very cool stars; most of the emission in NIR.

**Very few objects (steepening of the mass-luminosity relation): projects needs removal of field stars and large field of view.**

# NGC6121=M4

Cleaning of field stars with proper motions: feasible



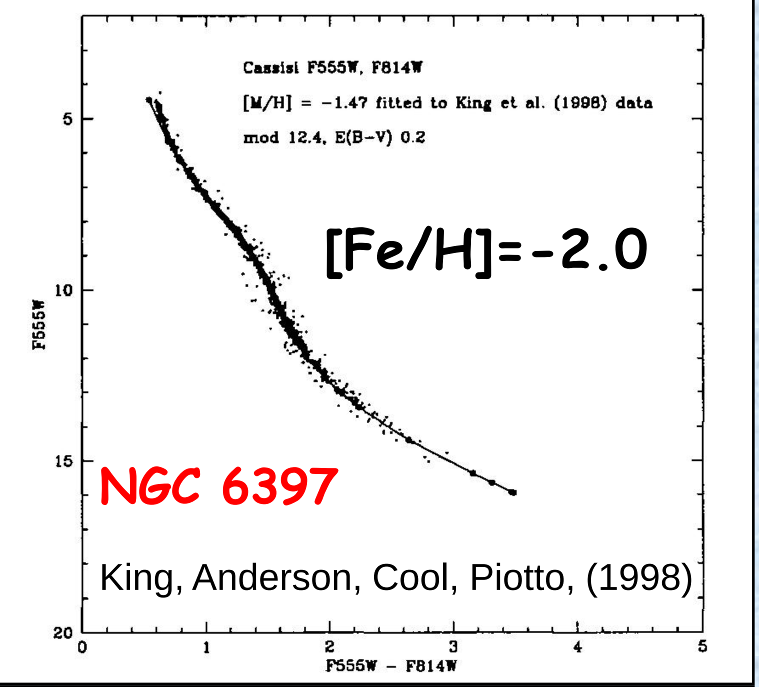
Bedin et al. (2004)

field stars

**Stars with only $I_{814}$ magnitude**

# Luminosity-Radius relation

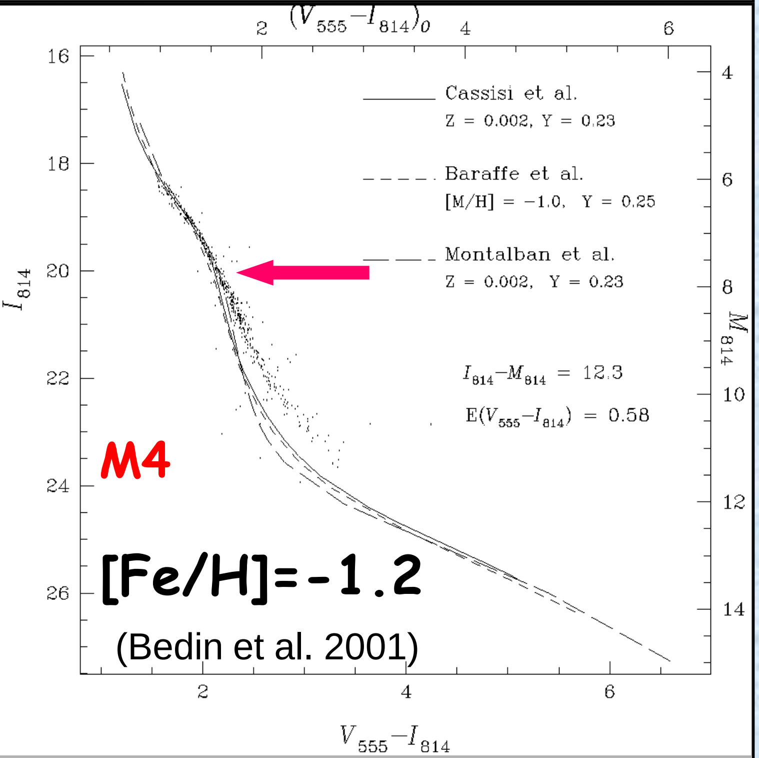
**There are problems, likely with the trasformation from theoretical to observational plane, at intermediate and high metallicities.**



[Fe/H]=-2.0

NGC 6397

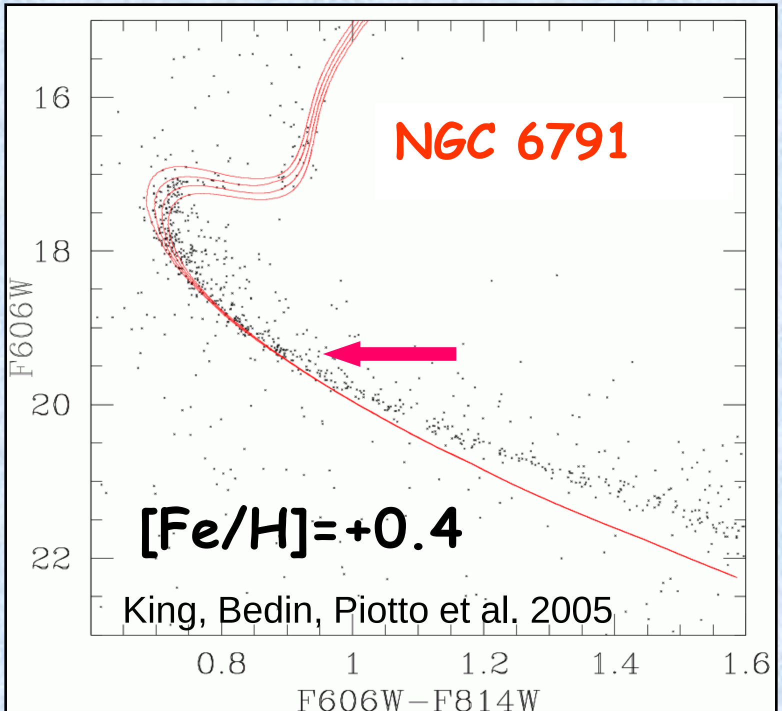
King, Anderson, Cool, Piotto, (1998)



M4

[Fe/H]=-1.2

(Bedin et al. 2001)

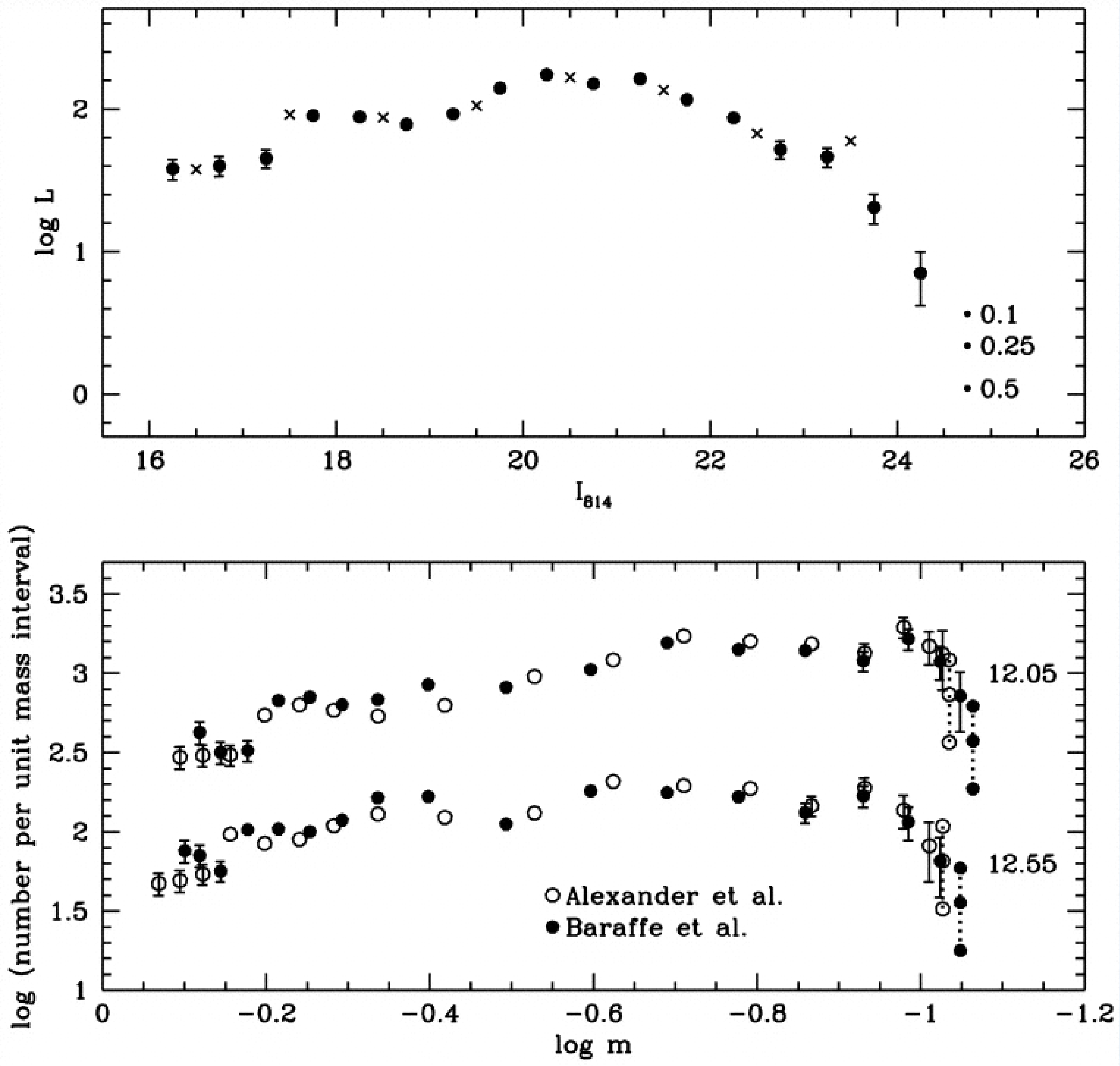


NGC 6791

[Fe/H]=+0.4

King, Bedin, Piotto et al. 2005

# Mass Functions down to the hydrogen burning limit



Mass function of NGC6397 down to ~0.08 m⊙ from King et al. (1998)

# Binaries in globular clusters

1) Binaries in globular clusters are the most important energy source

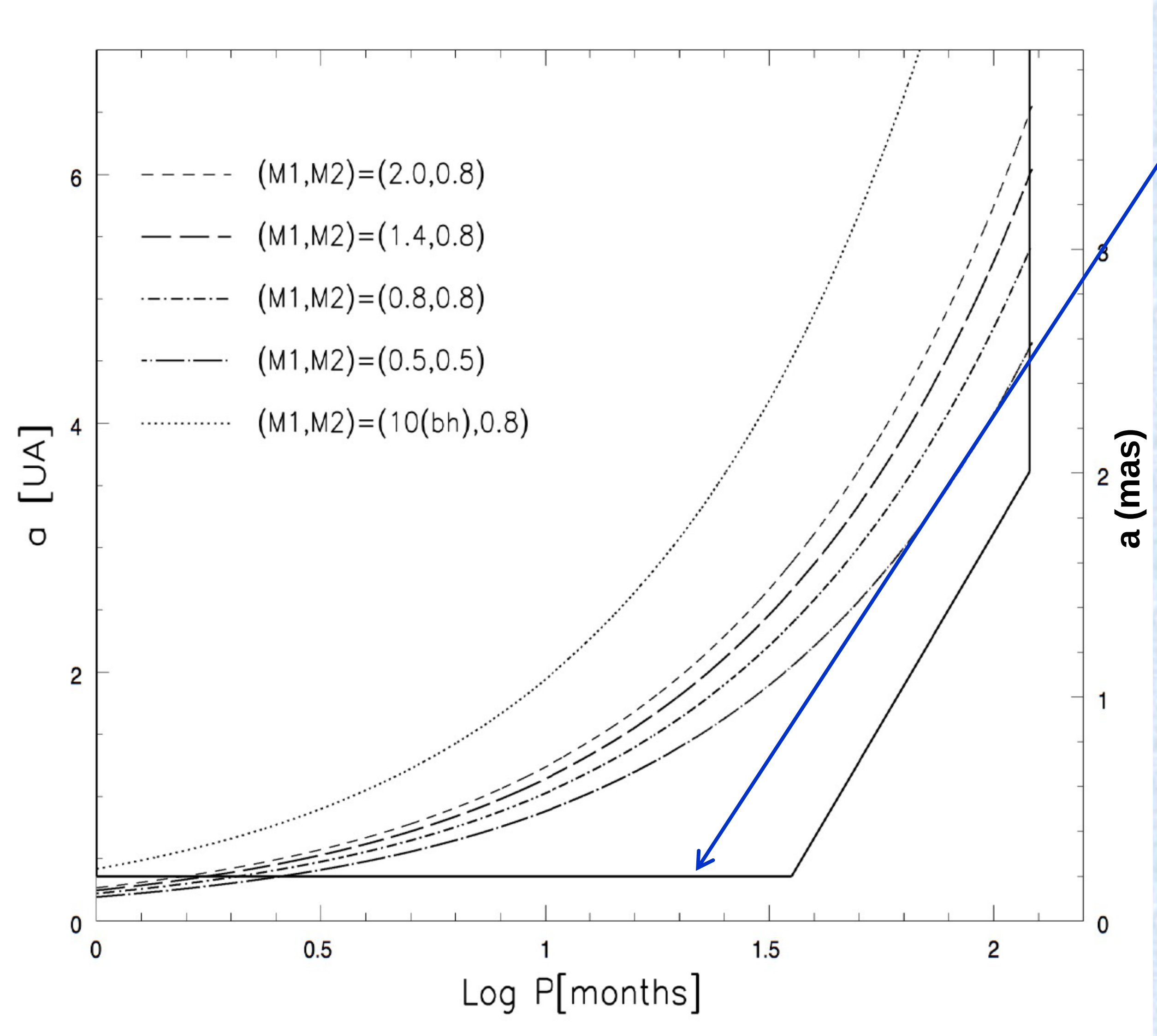
2) Binary fraction and binary properties are a fundamental input for any dynamical model. Dynamical models needed to understand the dynamical evolution of cluster stars

3) Binary fraction is important to interpret the properties of cluster stellar populations

4) Binaries are an important source of a number of exotica populating globular clusters (see Francesco's talk).

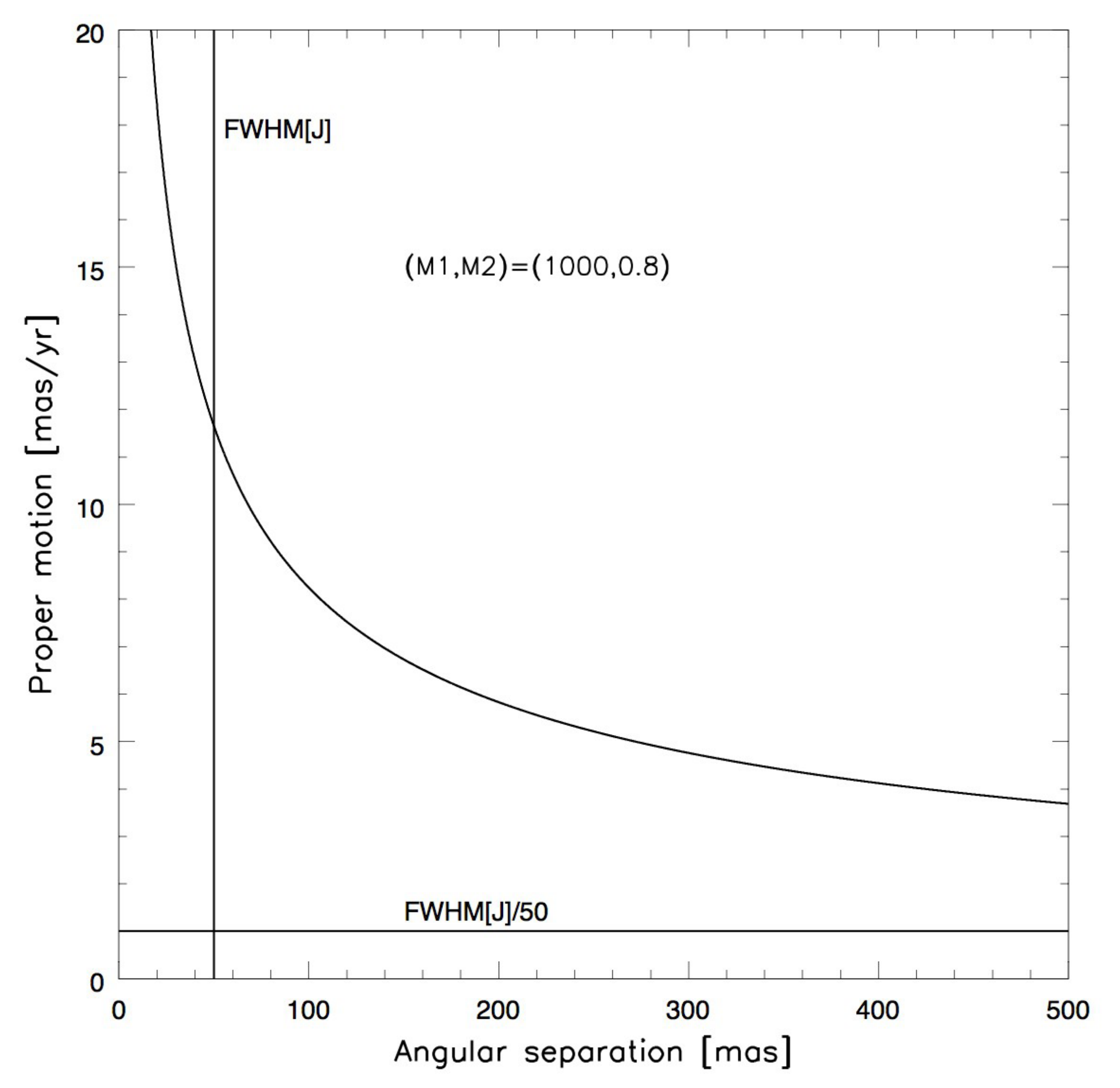
# Pushing MAD-MAX to its limits:

## Astrometric signature of binaries in GC core



**With a 0.2mas astrometric precision** we can measure the wobble of all binaries with dark companion (BH,NS, WD) with periods >1.5 months, and semi-major axes >0.4 AU, corresponding to 0.22mas at the distance of M4 (1800pc; note that the total displacement would be 0.44mas).

# IMBH in Globular Clusters



Proper motion of a main sequence star around a central massive black hole of 1000M as a function of the distance from the black hole (for M4).

The same observations used for the binary wobble allow us to study the proper motion of stars very close to the cluster center, and therefore explore the presence of IMBH (this project is feasible for clusters well beyond 10kpc).

# MAD – MAX (and MCAO imagers in general) should be a MUST for ESO

1) It is an important complement, and in some cases alternative to HST imagers: in general, we should not use the limited HST resources for programs which are feasible on Earth;

2) We need to develop the appropriate reduction and analysis software;

3) We need to learn more about MCAO image limits in terms of astrometric (and photometric) performances before E-ELT era;

4) MAD-MAX allows us to think to really new and challenging projects.