Lorentz center

Steps Towards a New Generation of Stellar Models

Workshop: 1 – 5 July 2013, Leiden, the Netherlands

Stellar models for clusters and individual stars: an observational perspective

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Cosmic-Lab

www.cosmic-lab.eu

erc

Globular clusters: cosmic laboratories?

ASTRO-ARCHEOLOGY

TRACERS
of the structure & history of the Galaxy

ASTRO-TIMING

LABORATORIES
for theoretical models of stellar evolution

ASTRO-DYNAMICS

LABORATORIES
for interplay between stellar evolution & dynamics

Simple Stellar Populations… ?

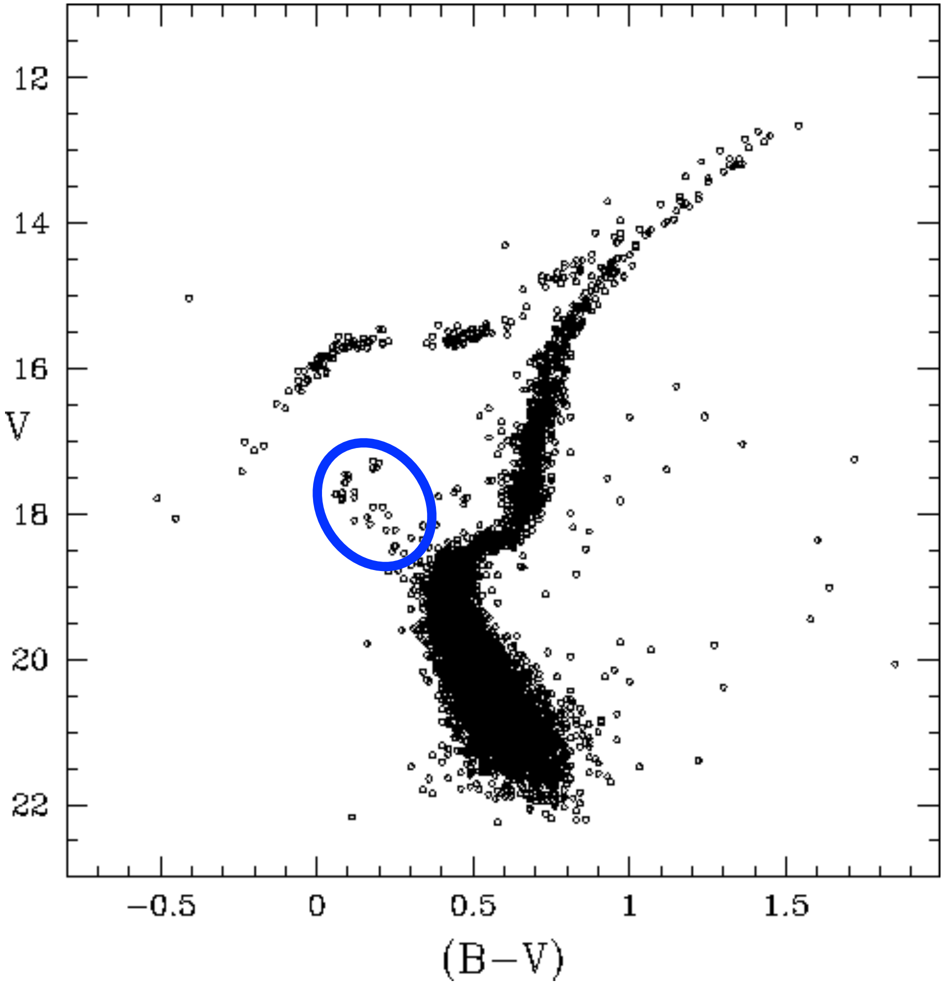
A "Simple Stellar Population" (SSP) is an assembly of stars ….

1) single
(not located in binary systems)

2) with the same initial chemical
composition

3) with the same age
(only one formation burst)

Simple Stellar Populations… ?



Binaries are there!!!
This is known since 1953

Simple Stellar Populations… ?

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There are binaries!!!

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Simple Stellar Populations… ?

A "Simple Stellar Population" (SSP) is an assembly of stars ….

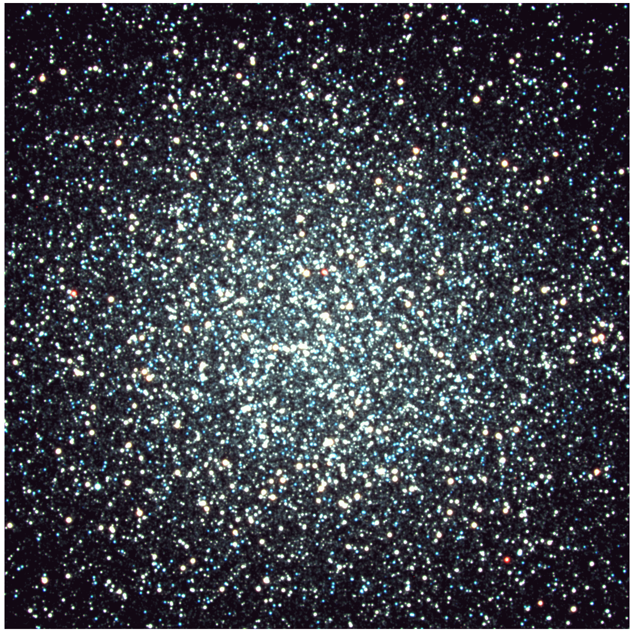
1) single
(not located in binary systems)

There are binaries!!!

2) with the same initial chemical composition

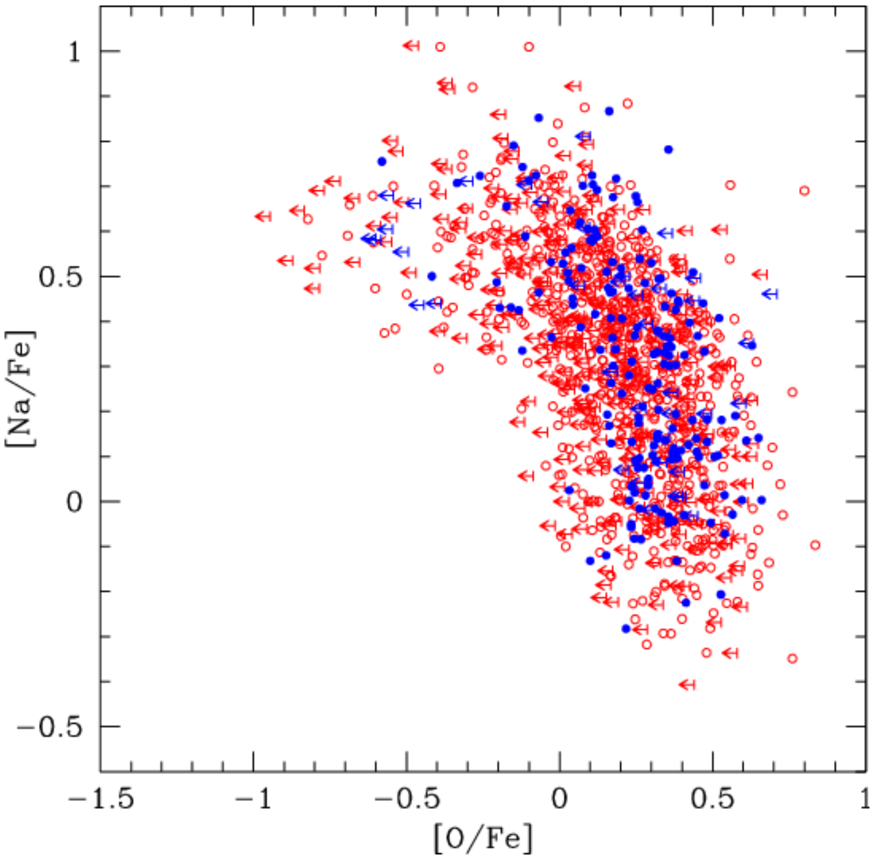
Chemical inhomogeneities
Osborn 1971,
Kraft 1979, etc

3) with the same age
(only one formation burst)



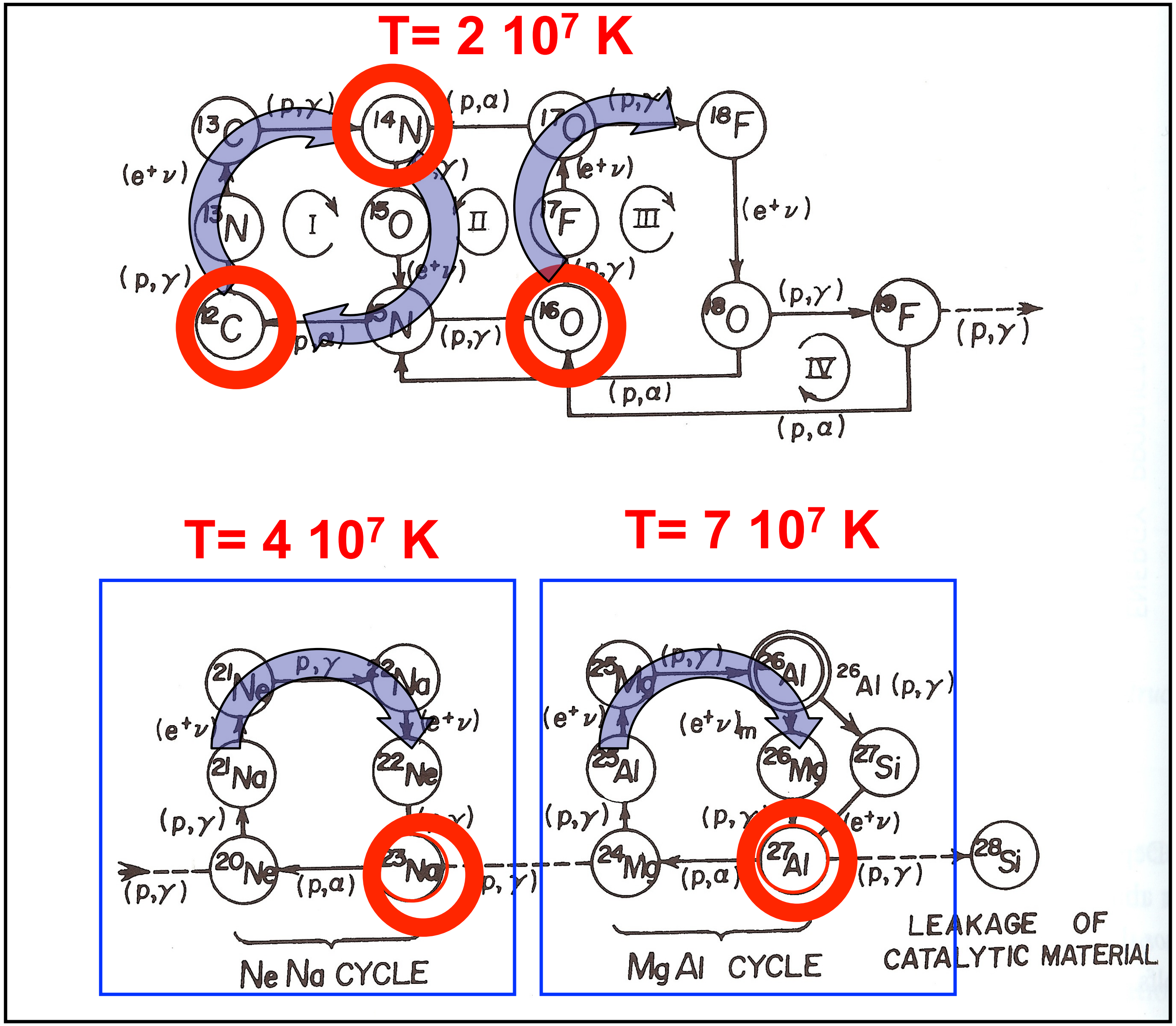
… a few general considerations about the complex (confusing?) scenario emerging from the observations of genuine GC properties

STARS IN GGCs ARE NOT CHEMICALLY HOMOGENEOUS IN LIGHT ELEMENTS



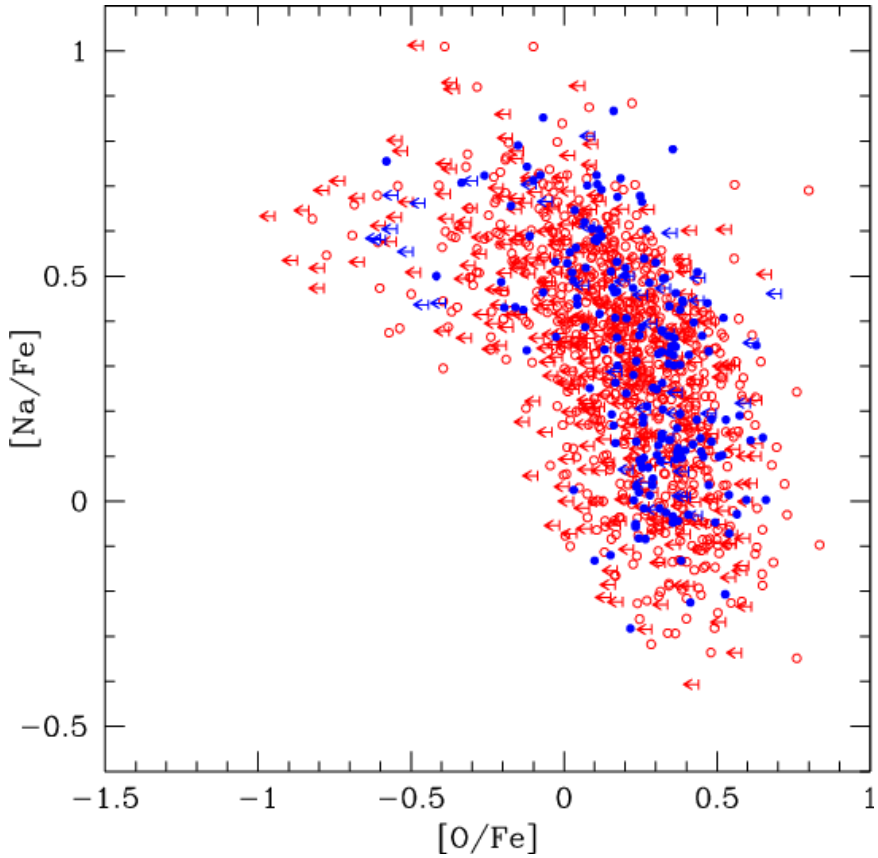
Cumulative behaviour of [Na/Fe] as a function of [O/Fe] for 19 GGCs (Carretta et al. 2009)

Gas enriched by p-capture processes (high-temperature extension of the CNO cycle)



T= 2 10^7 K
T= 4 10^7 K
T= 7 10^7 K
(p,γ)
(p,α)
(e⁺ν)
I
II
III
IV
Ne Na CYCLE
Mg Al CYCLE
LEAKAGE OF
CATALYTIC MATERIAL

STARS IN GGCs ARE NOT CHEMICALLY HOMOGENEOUS IN LIGHT ELEMENTS



Cumulative behaviour of [Na/Fe] as a function of [O/Fe] for 19 GGCs (Carretta et al. 2009)

Gas enriched by p-capture processes (high-temperature extension of the CNO cycle)

These processes occur at 40-70 x 10^6K: a temperature NOT reached in present day GC main sequence and red giant stars.

GC formed from gas enriched by a first-generation of massive (4-6Mo) AGB stars over a quite short time-scale (10^8 yr)

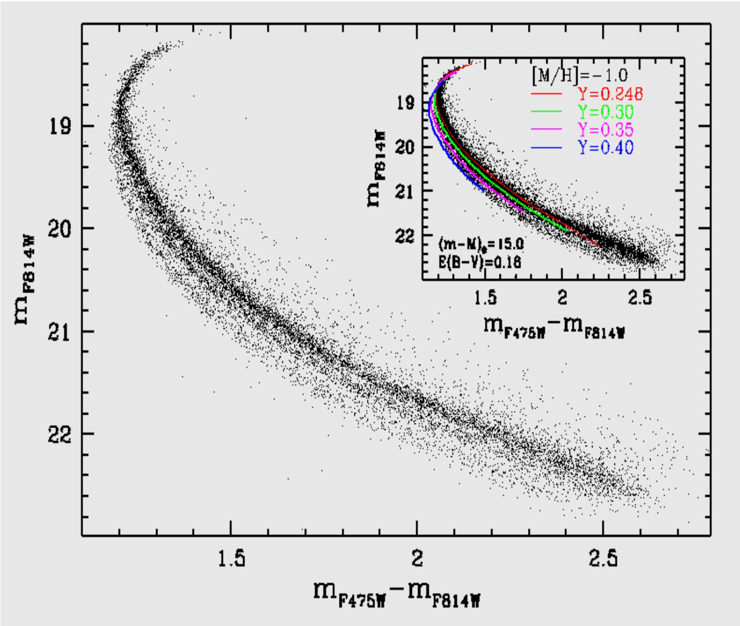
P-processes produce Helium

STARS IN GGCs ARE NOT CHEMICALLY HOMOGENEOUS IN LIGHT ELEMENTS (Na, C, etc) and POSSIBLY HELIUM

The multiple sequences observed in the CMD of several massive clusters are the photometric manifestation of these inhomogeneities.

ALL the multiple sequences observed in the CMD of genuine massive clusters are the photometric manifestation of these inhomogeneities (in terms of He or light elements)

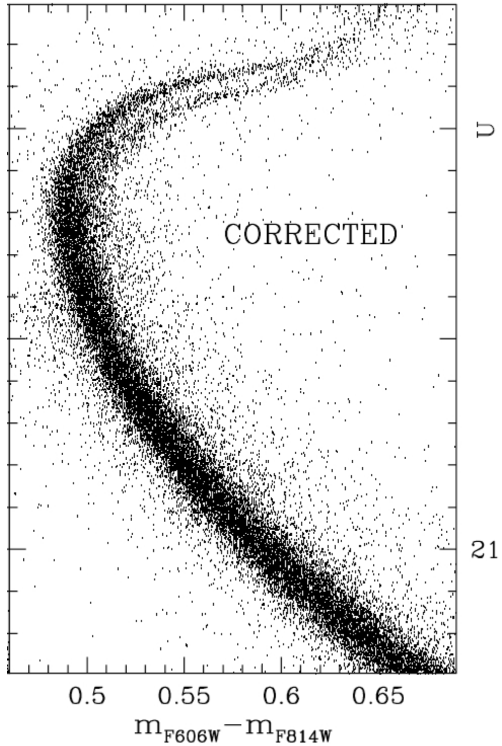
NGC2808



Piotto et al. 2007, ApJ, 661, L35

He

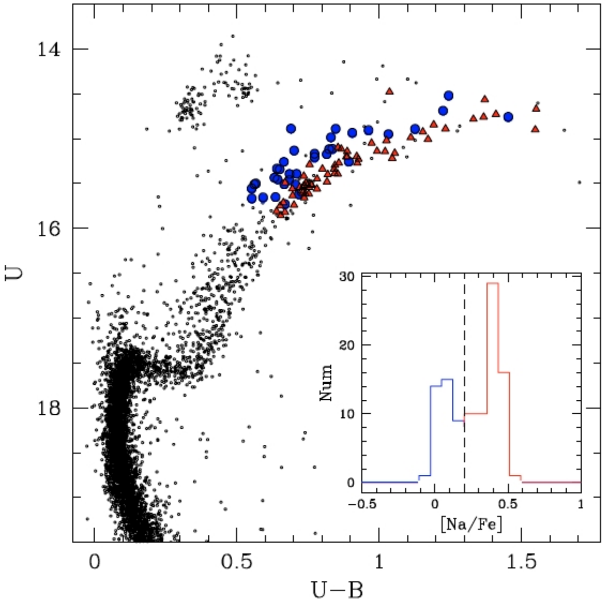
NGC1851



Milone et al. 2008, ApJ 673, 241

CNO Na

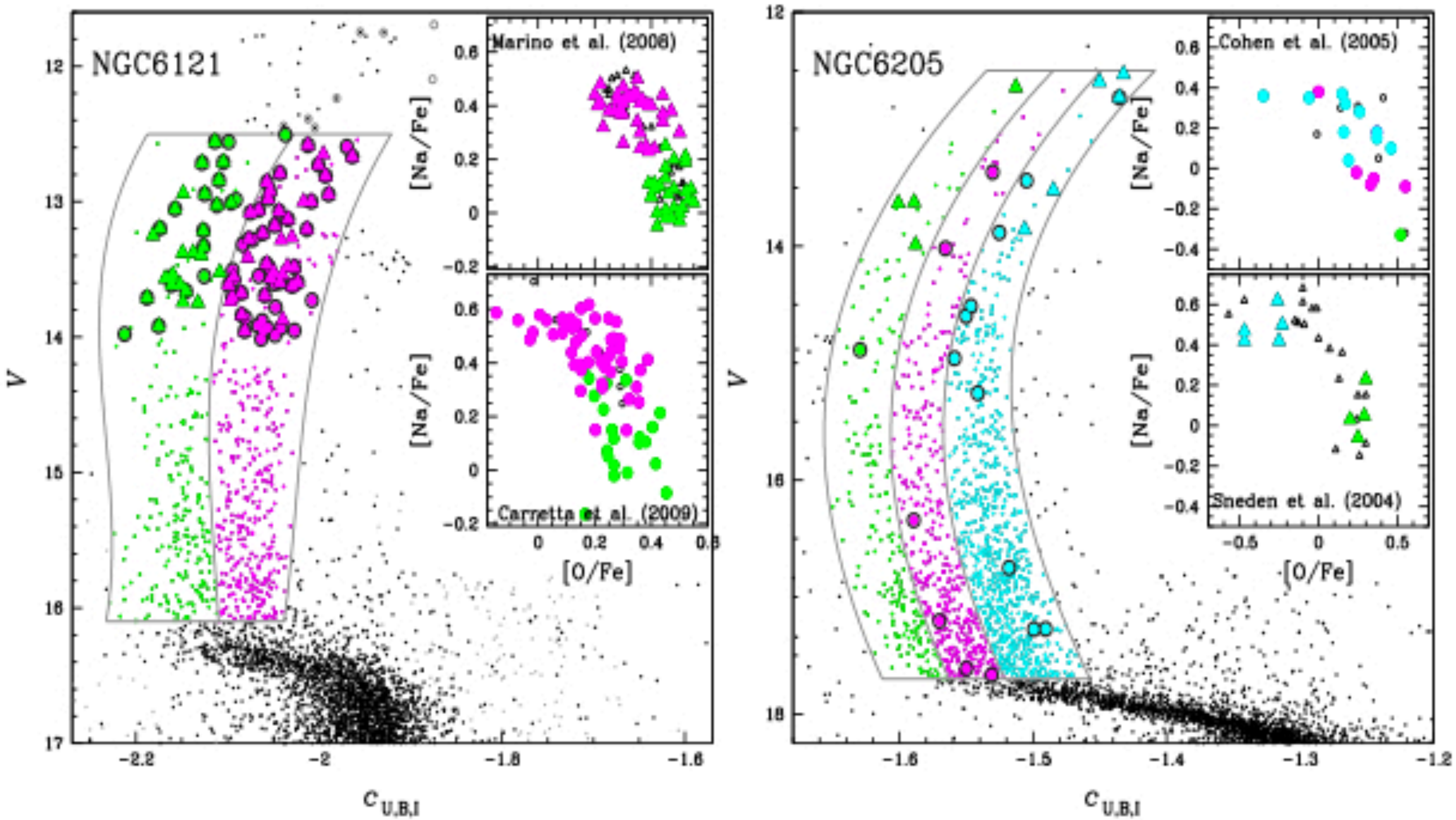
M4



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

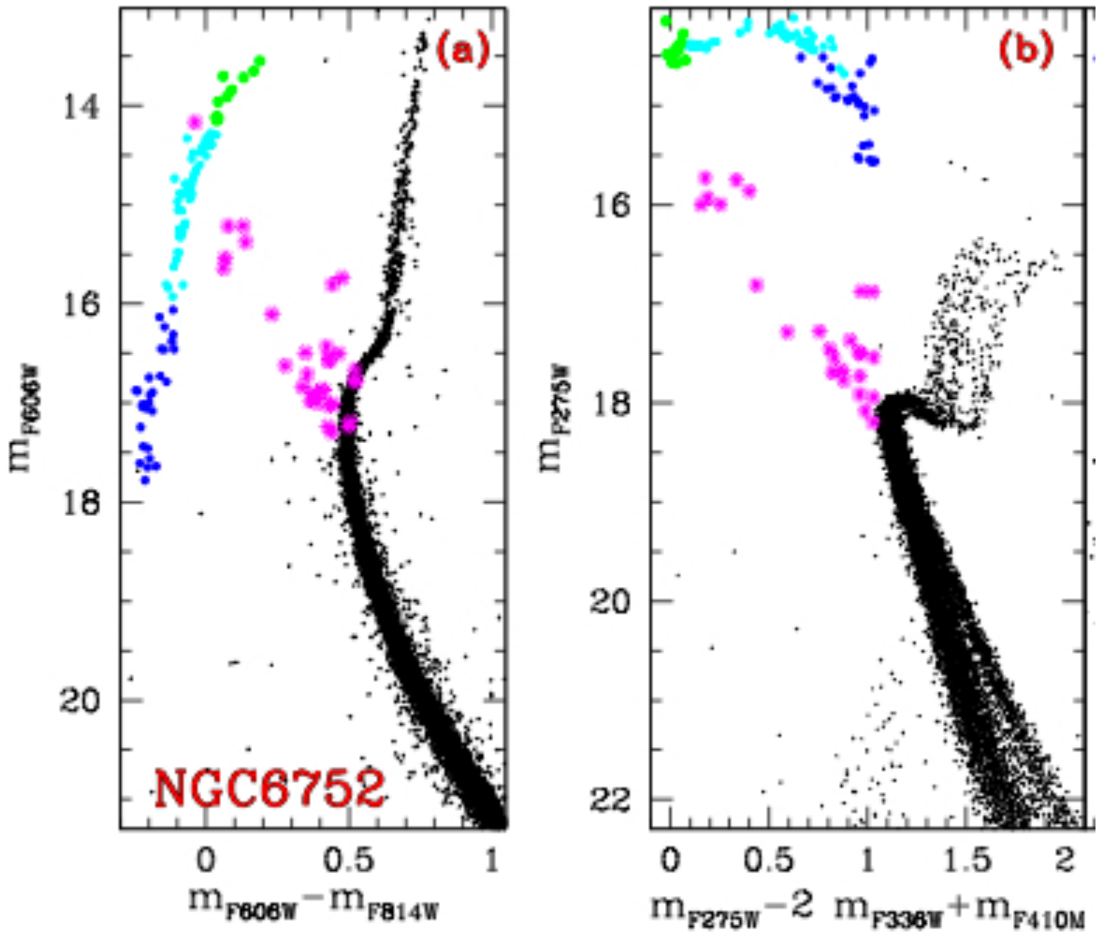
Na O

Appropriate combination of filters are now under investigation in order to better distinguish different sub-populations in clusters



Appropriate combination of filters are now under investigation in order to better distinguish different sub-populations in clusters

F275W === OH bands
F336W === NH band
F435W === CN & CH bands



An UV HST survey for 48 GC is starting in Cycle 21

The new generation of models needs to take into account variation of abundances for all the chemical elements involved in the extended CNO cycle + large Helium abundances in order to properly interpret the CMDs.

STARS IN GENUINE GGCs ARE NOT CHEMICALLY HOMOGENEOUS IN LIGHT ELEMENTS & HELIUM BUT THEY ARE QUITE HOMOGENEOUS IN IRON !!!

Apart from a few claims (M22, M54..)
of small spread (δ[Fe/H]~0.1 dex)
There are ONLY 2 major exceptions known within the GALAXY with quite large iron difference (Δ[Fe/H]>0.5 dex) :

Omega Cen in the Halo
Terzan 5 in the Bulge

POTENTIAL WELL OF THE ORIGINAL STELLAR SYSTEM

"GENUINE GC" DID NOT RETAIN SNe EJECTA

GENUINE GLOBULAR CLUSTERS

Anticorrelations +
Δ [He,C,…/H] ≠ 0

Δ [Fe/H] = 0

Enrichment Timescale: 10^8 yr

THE SMALLEST STELLAR SYSTEMS ABLE TO RETAIN SNe EJECTA

ω Cen

Terzan 5

Multi- [Fe/H] populations

Enrichment Timescale: 10^9 yr

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GENUINE GLOBULAR CLUSTERS

Anticorrelations +
Δ [He,C,…/H] ≠ 0

Δ [Fe/H] = 0

Enrichment Timescale: 10^8 yr

M 22
M54

Δ [Fe/H] ≠ 0 ?

THEY RETAINED THE SNe EJECTA

ω Cen

Terzan 5

Multi- [Fe/H] populations

Enrichment Timescale: 10^9 yr

Simple Stellar Populations… ?

If the question is
"Are GGCs <u>strictly speaking</u> SSP?"

The answer is NO, but they have NEVER been considered so

Simple Stellar Populations… ?

If the question is

"Are GGCs the simplest SP available in the Universe"

The answer is still YES, whatever complex their formation scenario is

TERZAN 5 :

A new globular cluster-like stellar system with multi-metallicity populations

Cosmic-Lab

- 5-year project (web site at **www.cosmic-lab.eu**)
- *Advanced Research Grant* funded by the European Research Council (ERC)
- PI: Francesco R. Ferraro (Dip. of Physics & Astronomy – Bologna University)
- AIM: **to understand the complex interplay between dynamics & stellar evolution**
- HOW: using **globular clusters** as cosmic laboratories and

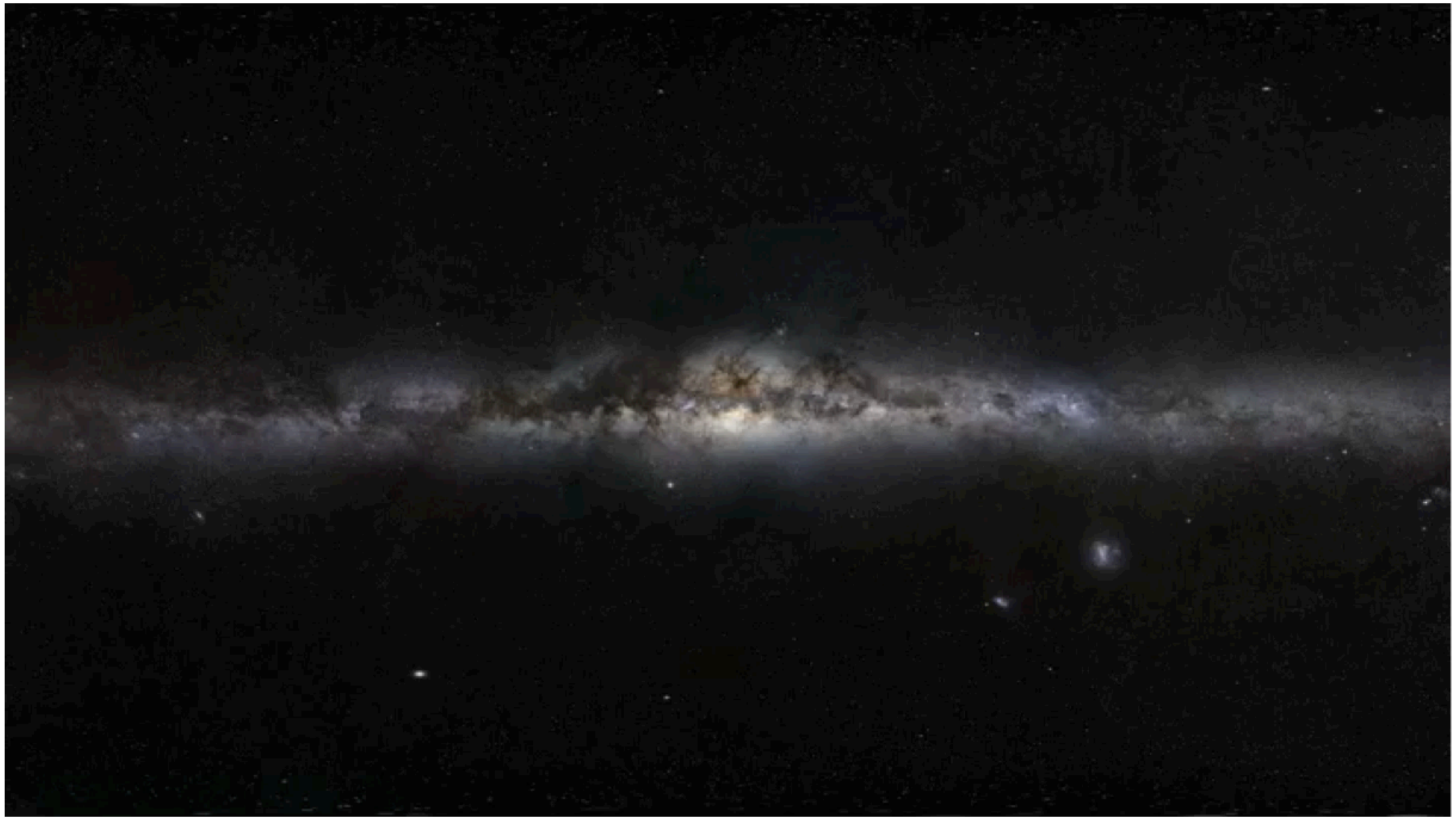
  Blue Straggler Stars
  Millisecond Pulsars
  Intermediate-mass Black Holes

  } as probe-particles

This research is part of the project COSMIC-LAB, a 5-year *Advanced Research Grant* funded by the European Research Council.

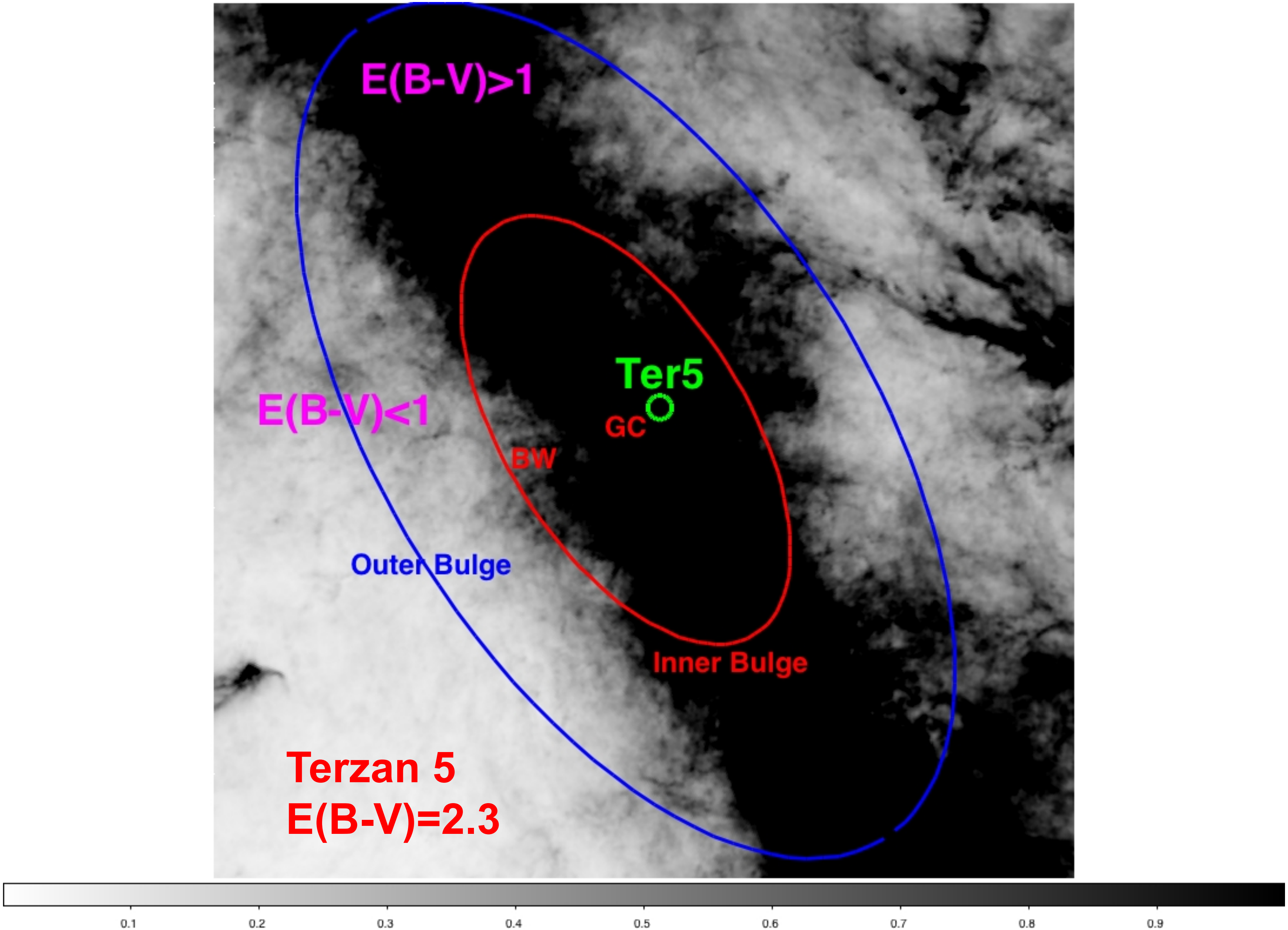
The aim of COSMIC-LAB is to explore the complex interplay between stellar evolution and the dynamical evolution of stellar systems by using exotic objects as BSS and MSP as probe particles.

COSMIC-LAB is led by Francesco Ferraro at the Physics and Astronomy Department of the Bologna University (Italy).

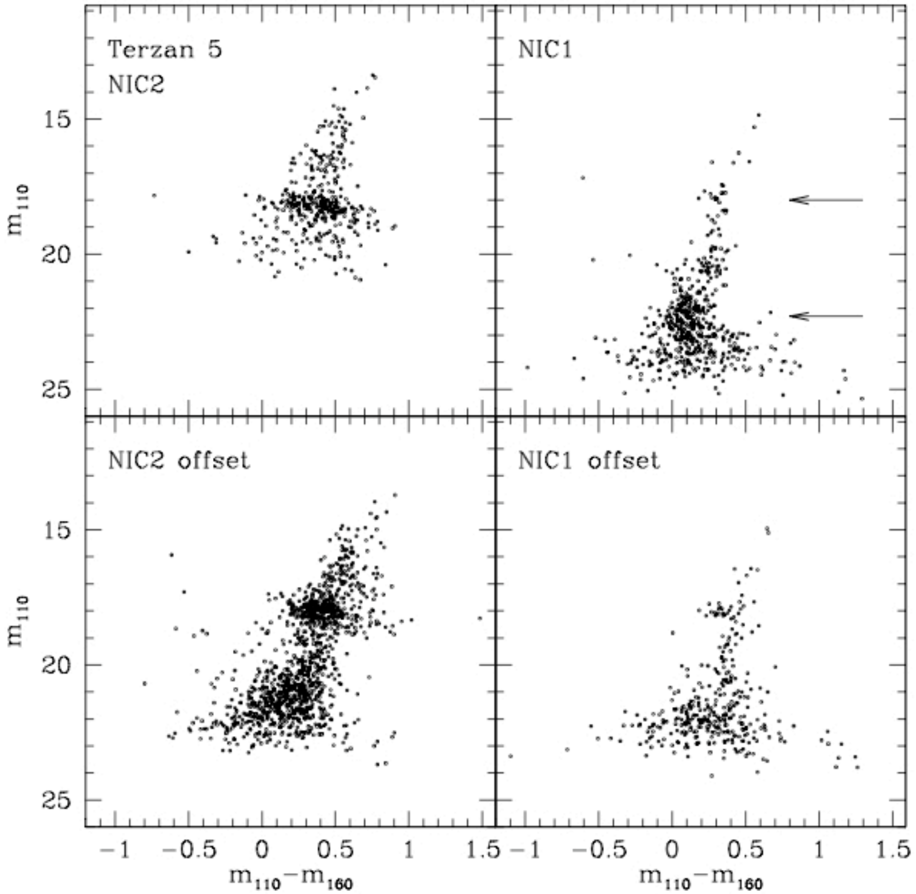


E(B-V)=2.3; d = 6Kpc; d_{GC}=2.1 kpc (Valenti et al 2007) i.e. in the outskirts of the inner Bulge. Suspected to have the largest collision rate of the entire GC system (Verbunt & Hut 1987, Lanzoni et al 2010)

34 MSPs have been discovered in TERZAN 5 to date (see Ransom et al 2004) : this is the largest population of MSP ever detected in a GC

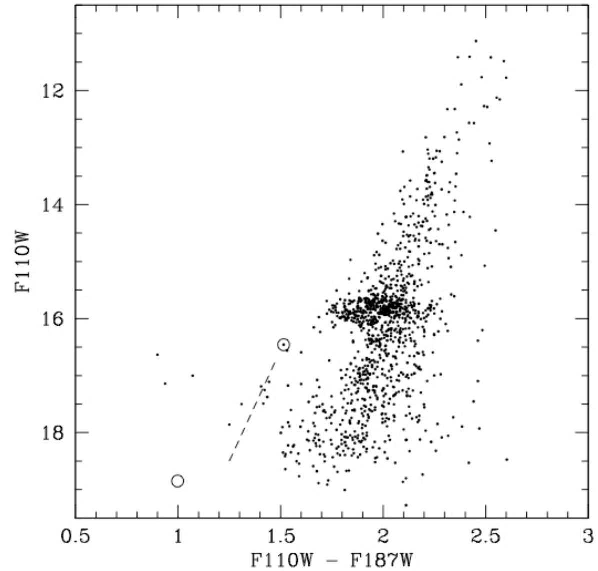

E(B-V)>1
E(B-V)<1
Ter5
GC
BW
Outer Bulge
Inner Bulge
Terzan 5
E(B-V)=2.3
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

NICMOS@HST: First insight into the stellar population of Terzan 5

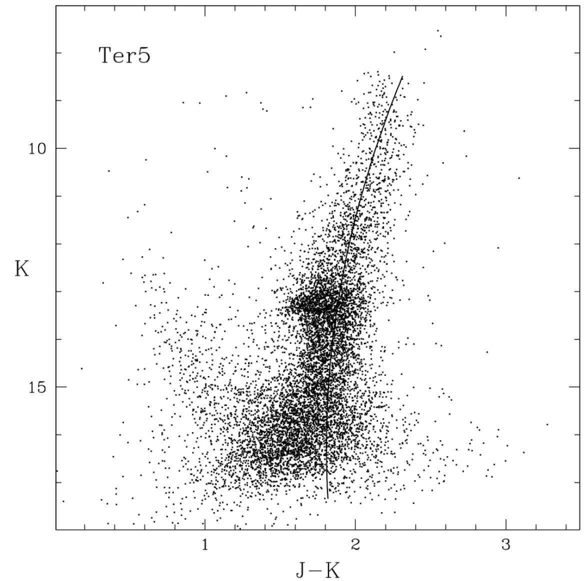


Ortolani et al (2001,A&A,376,878)

NIC2@HST- FoV:19’’X19’’



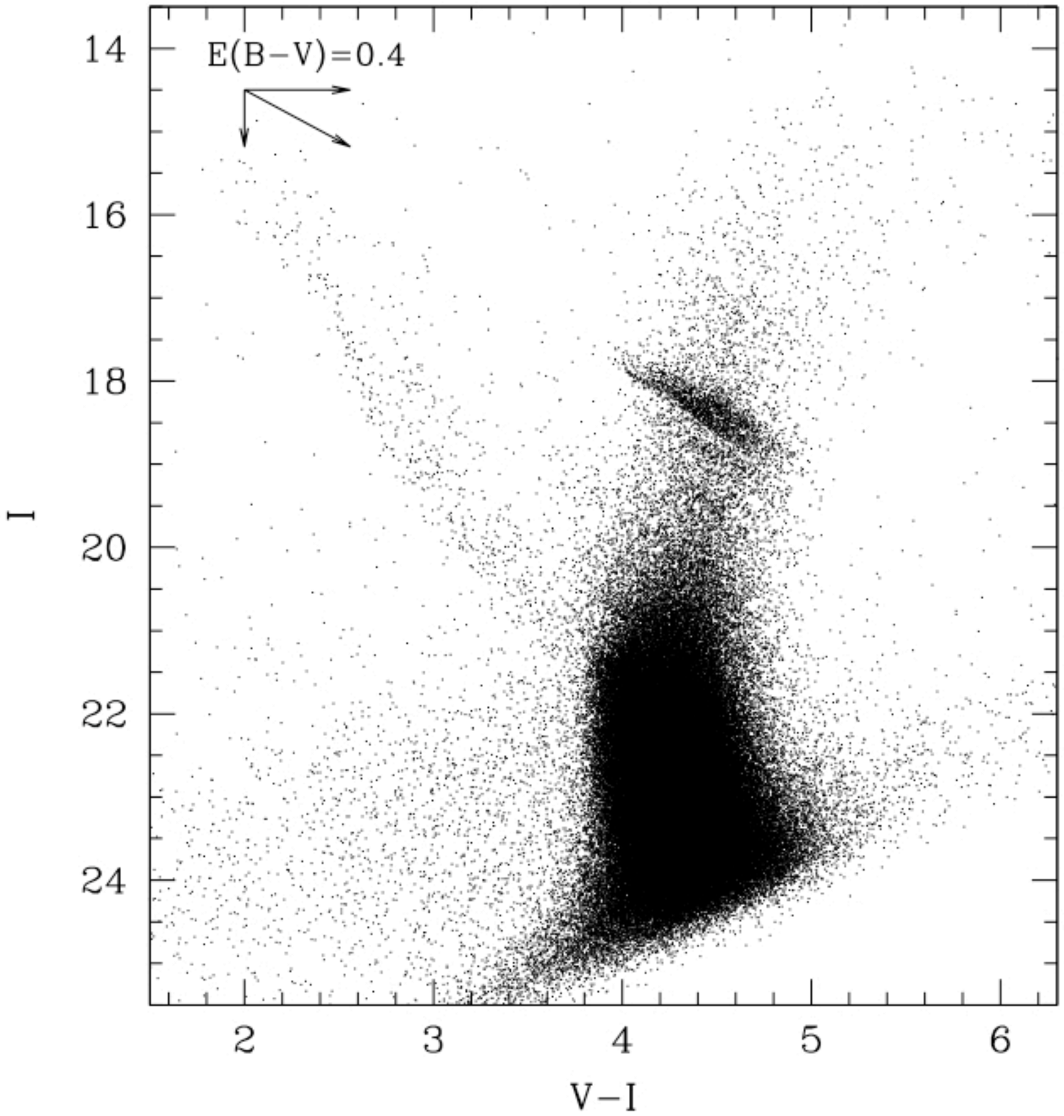
Cohn et al (2002, ApJ, 571, 818)



Valenti et al (2007, AJ, 133, 1287)

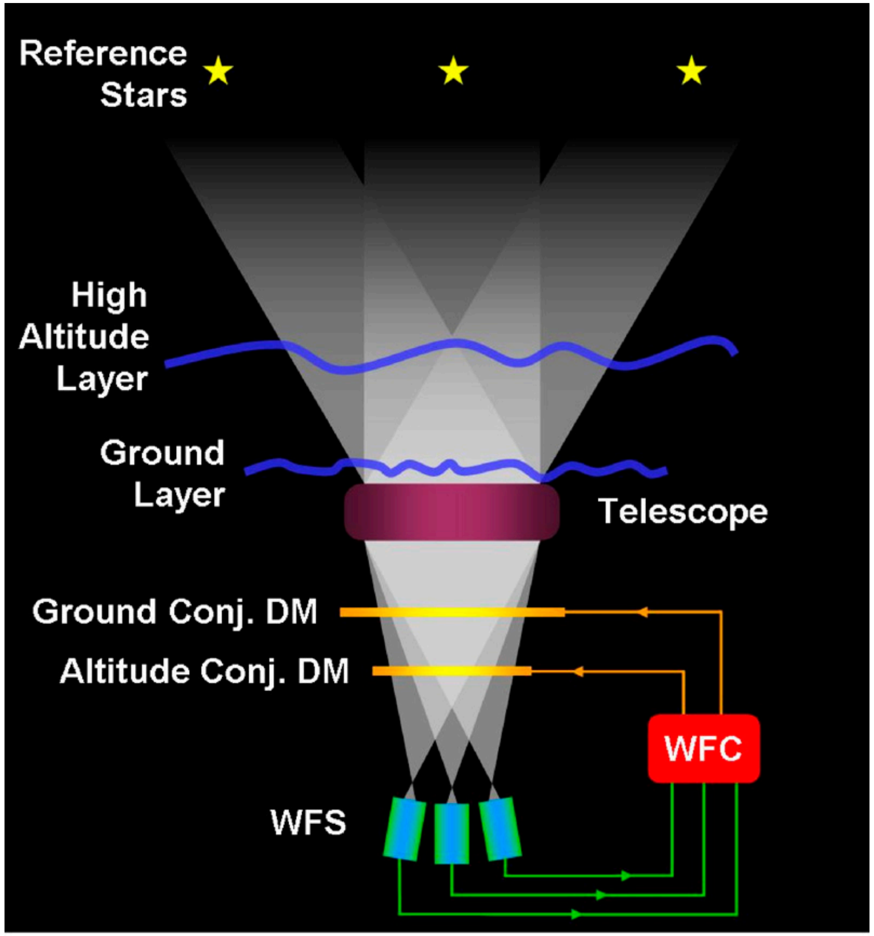
Cosmic-Lab

The deepest optical CMD of Terzan5 from ACS@HST



Main Problem:
Differential reddening

MAD = Multi-conjugate Adaptive Optics Demonstrator

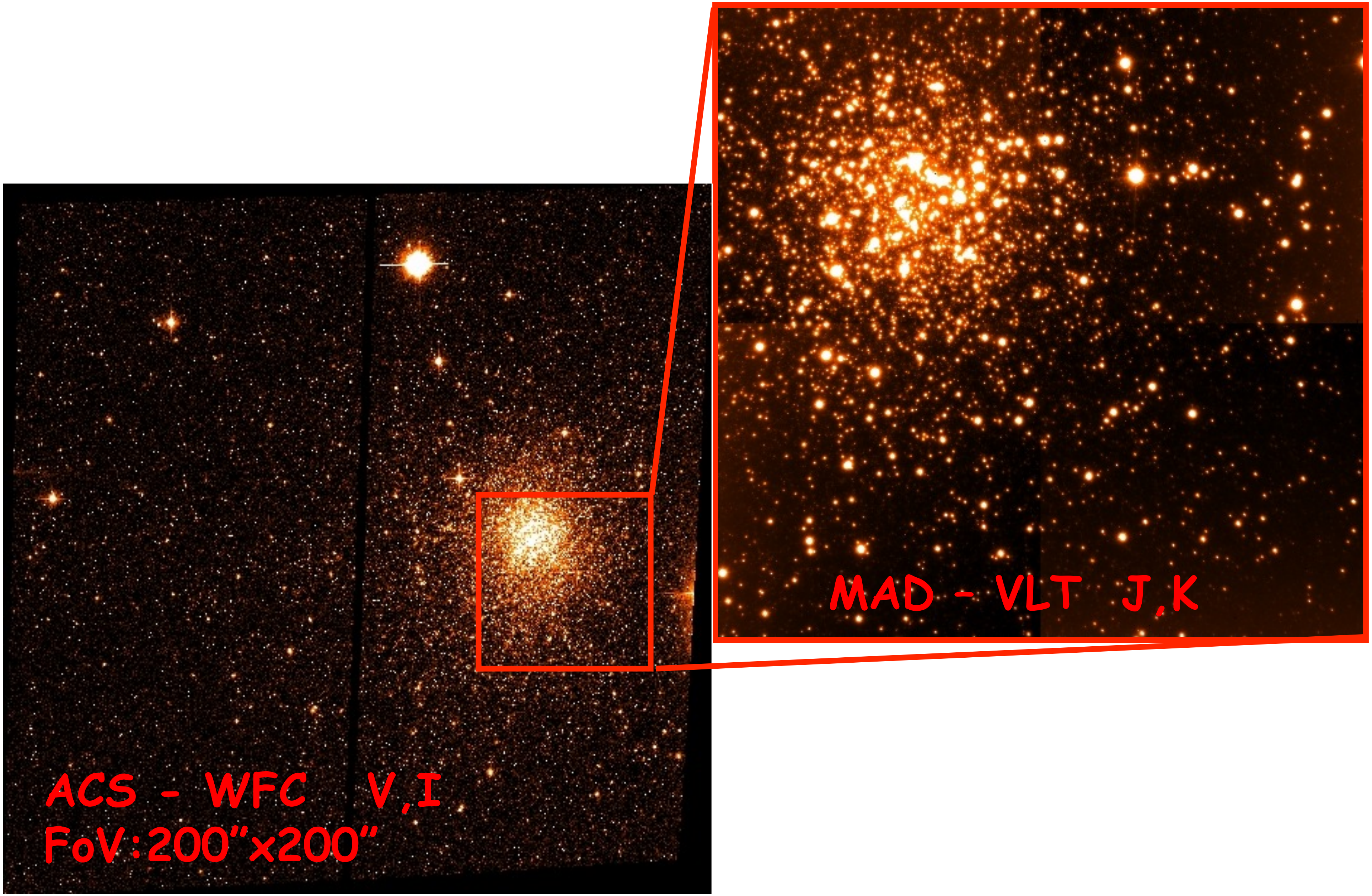


The MCAO Concept

ESO Press Photo 19c/07 (30 March 2007)

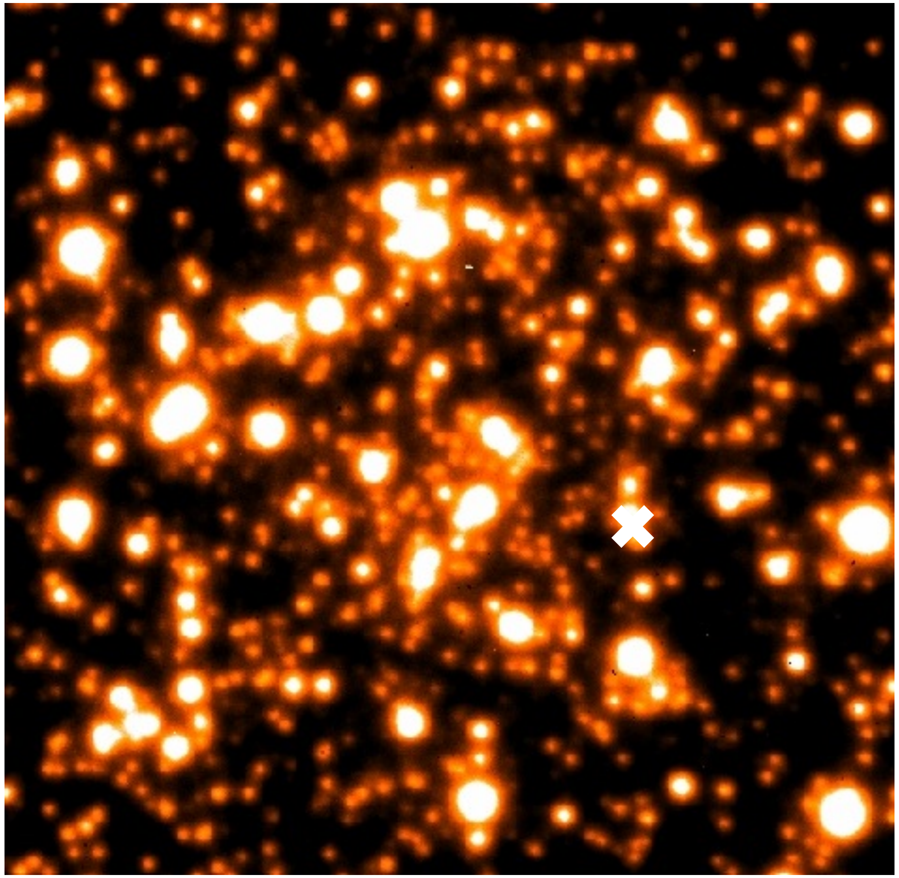
MAD operated in the near-IR
By using up to three Reference stars MAD was able to perform good and uniform AO correction over a large FoV (1` x 1`)
MAD was temporally installed on VLT in summer 2008

The incredibly sharp image in the K band obtained with MAD

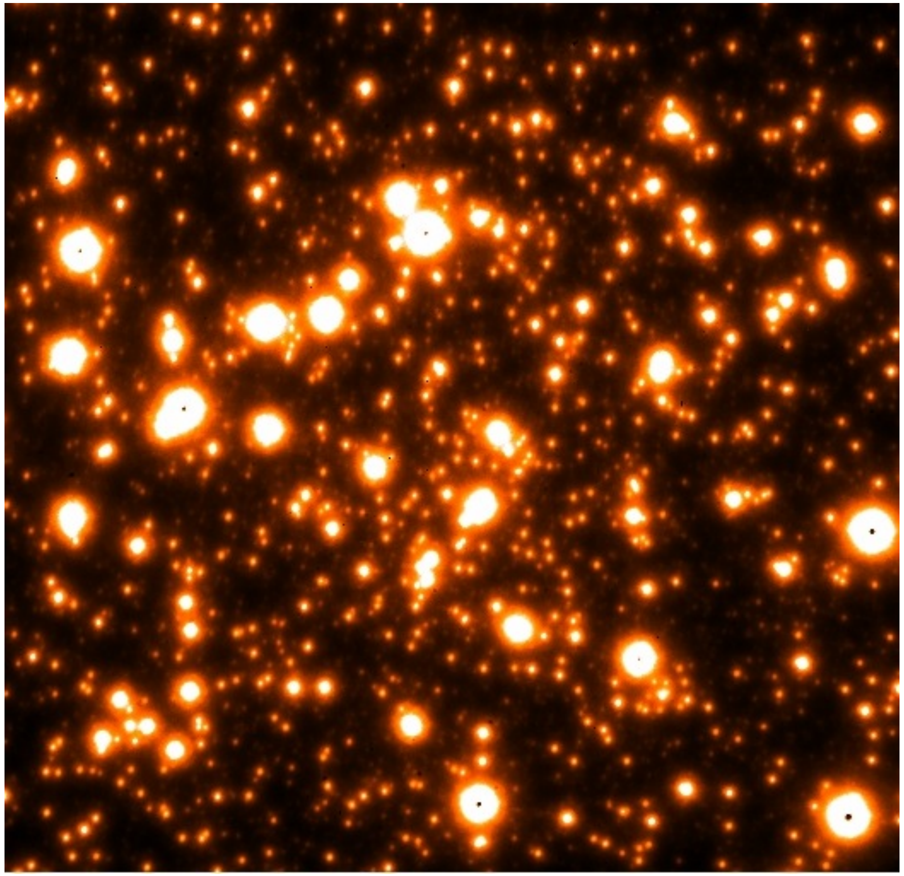


Note the difference between the best K and J image

J band



K band

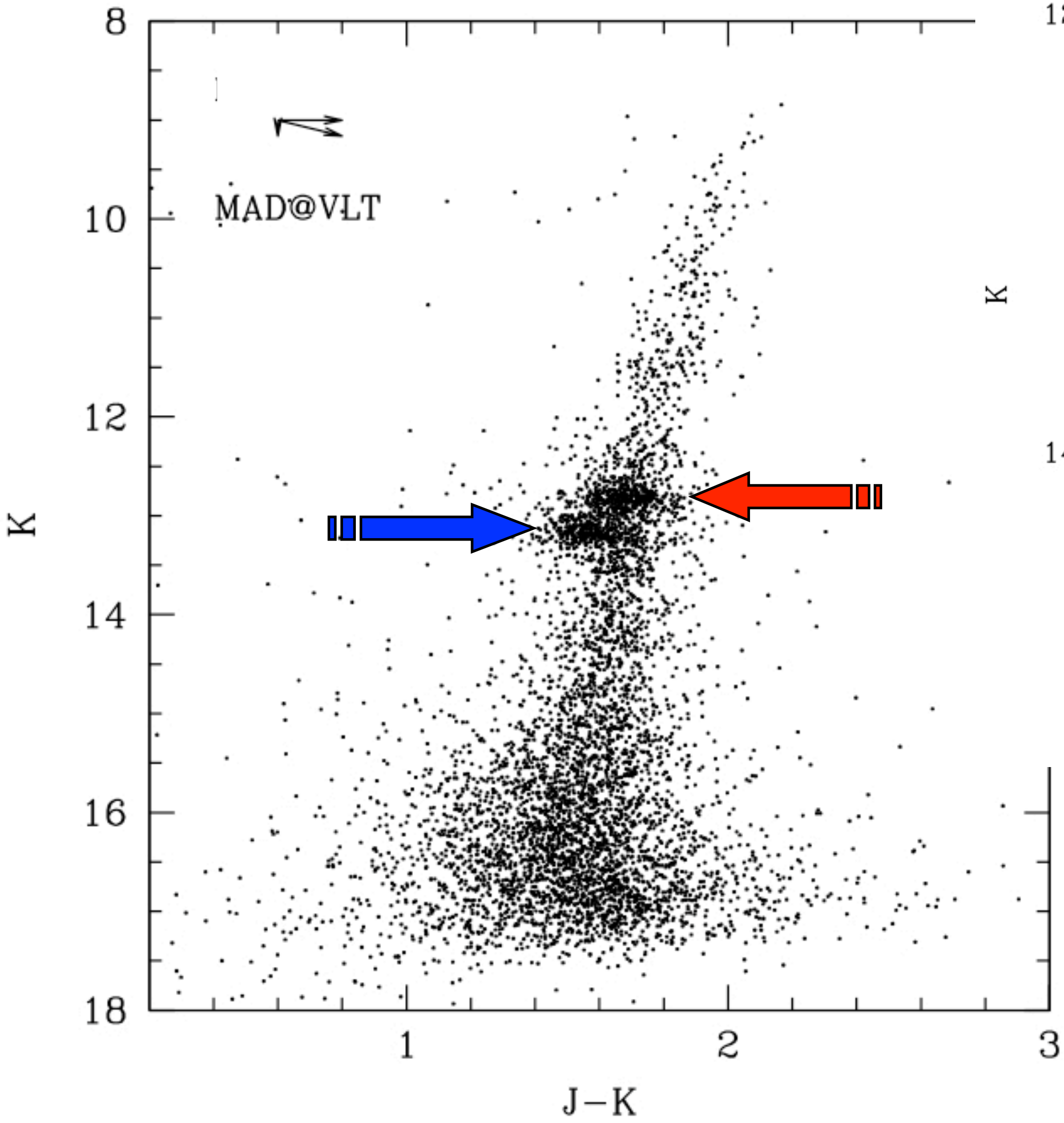


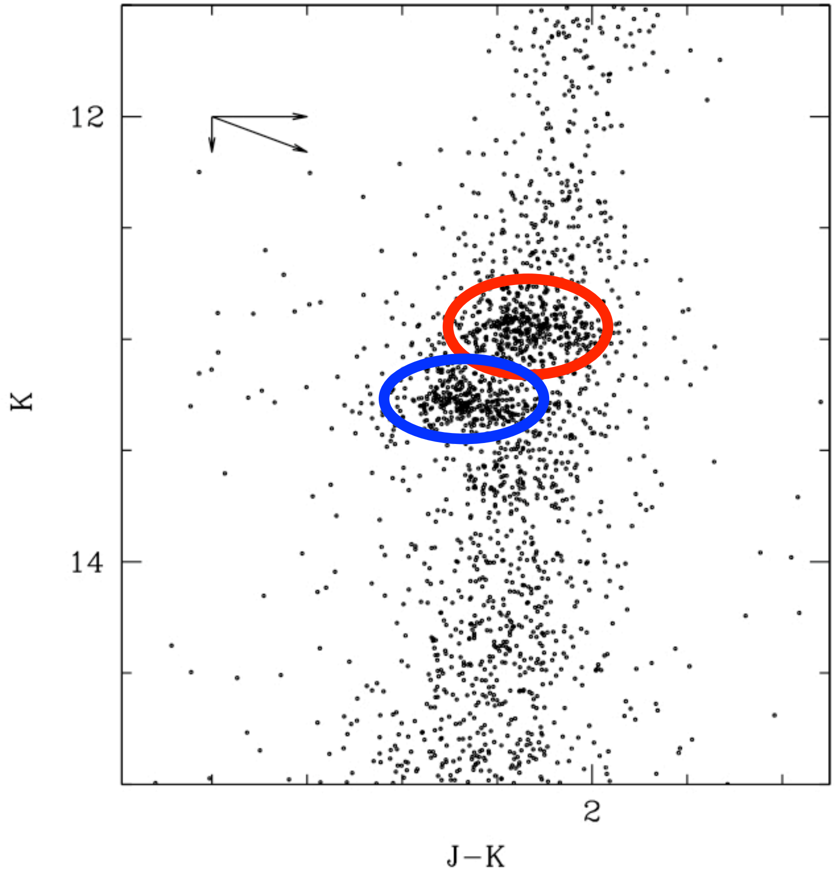
FWHM=100mas

(by using only 2 AOGS !!!)

Thanks to P. Amico & E. Marchetti for the MAD observations

THE MAD CMD OF TERZAN 5

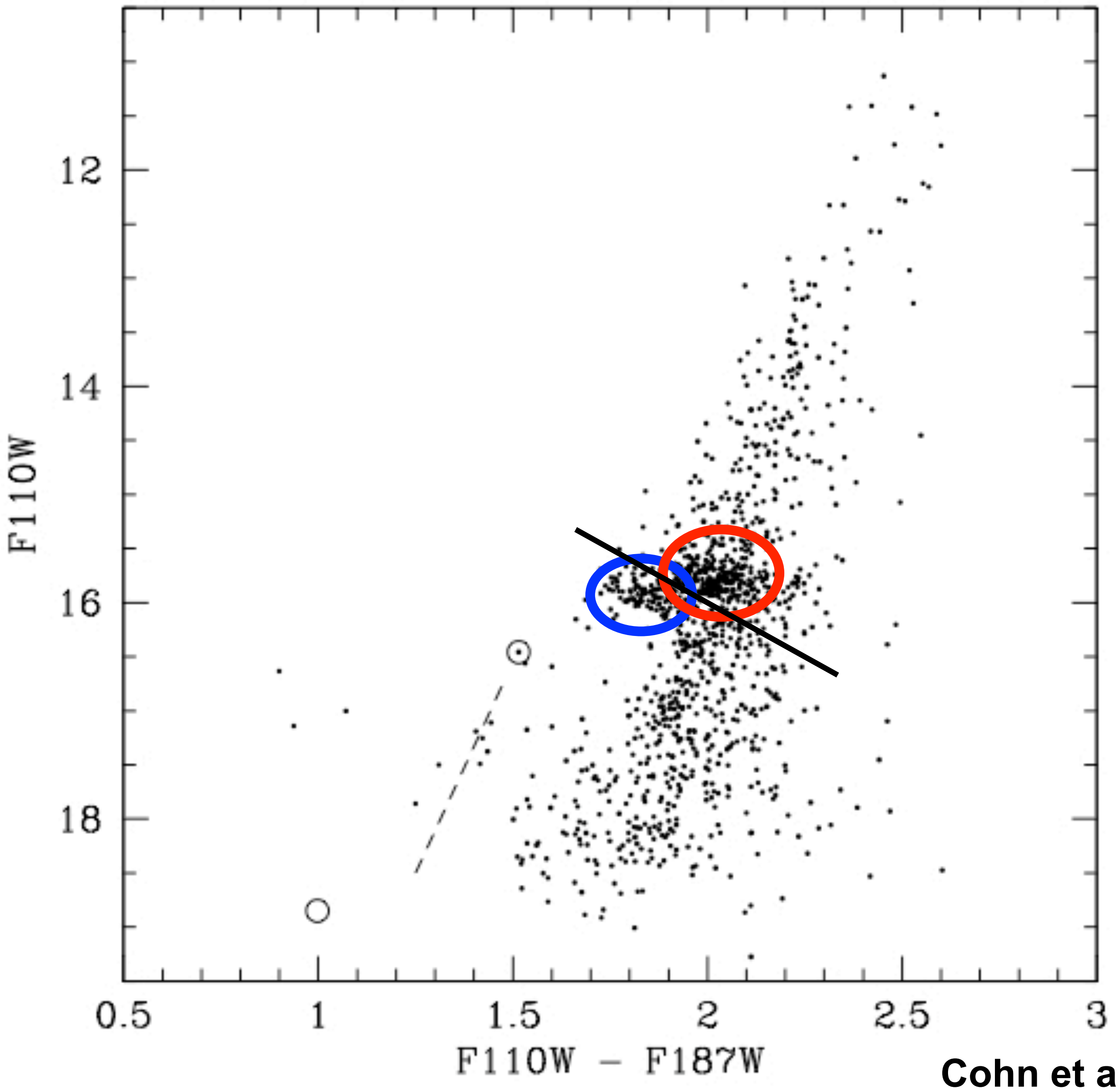




TWO RCs !!!

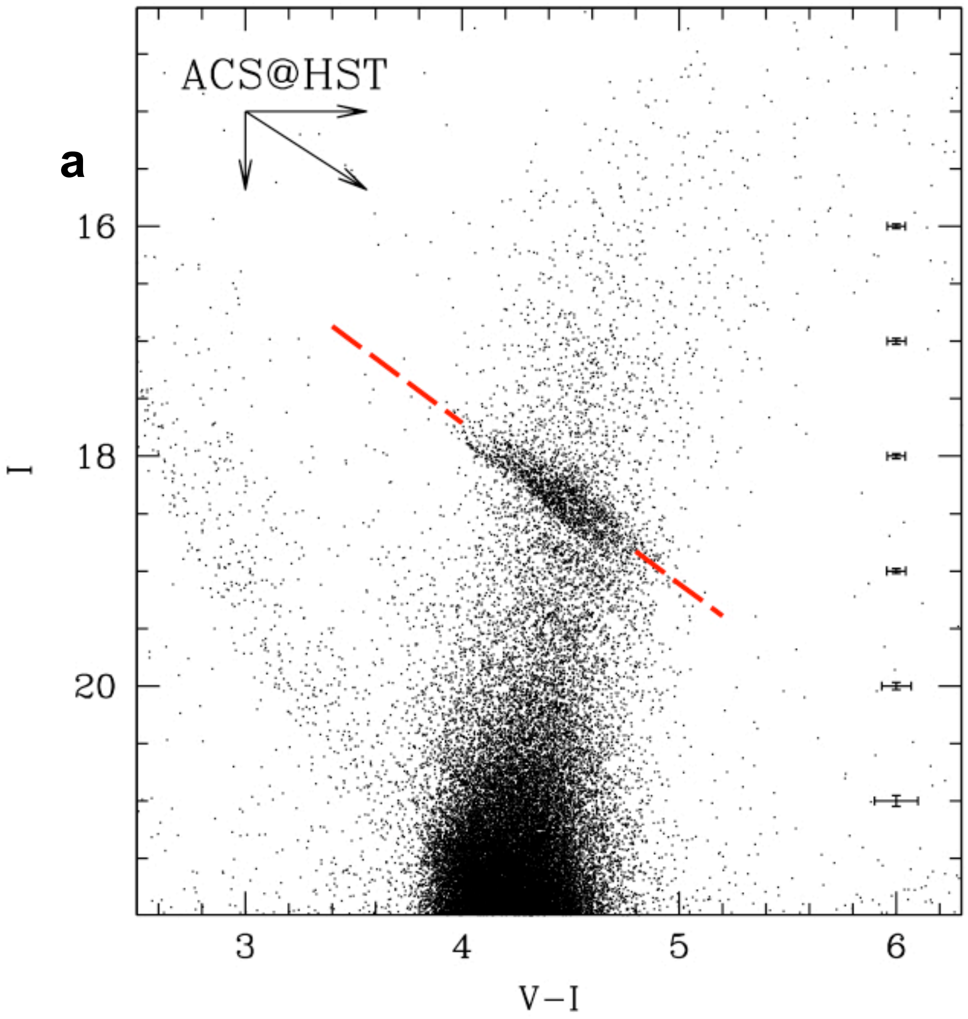
ΔK~0.3 mag
Δ(J-K)~0.2 mag

Ferraro et al (2009, Nature, 462, 483)

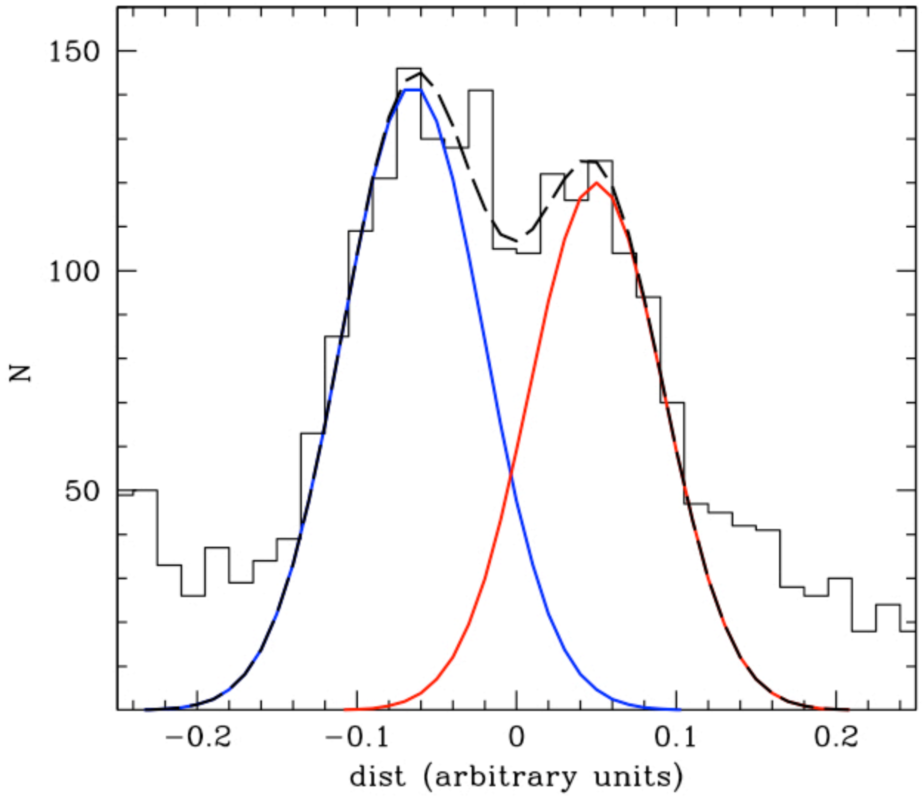


Cohn et al (2002, ApJ, 571, 818)

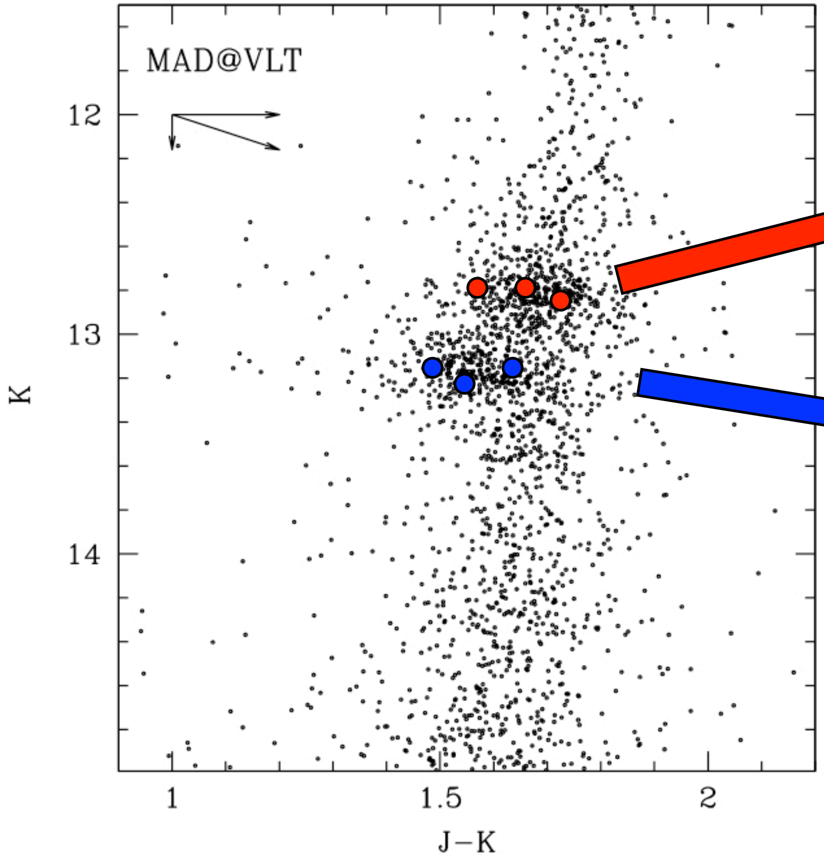
a


ACS@HST
I
16
18
20
3
4
5
6
V−I

b


N
150
100
50
−0.2
−0.1
0
0.1
0.2
dist (arbitrary units)

NIRSPEC @ Keck II observations of HB stars
(in the **bHB** and **fHB**)

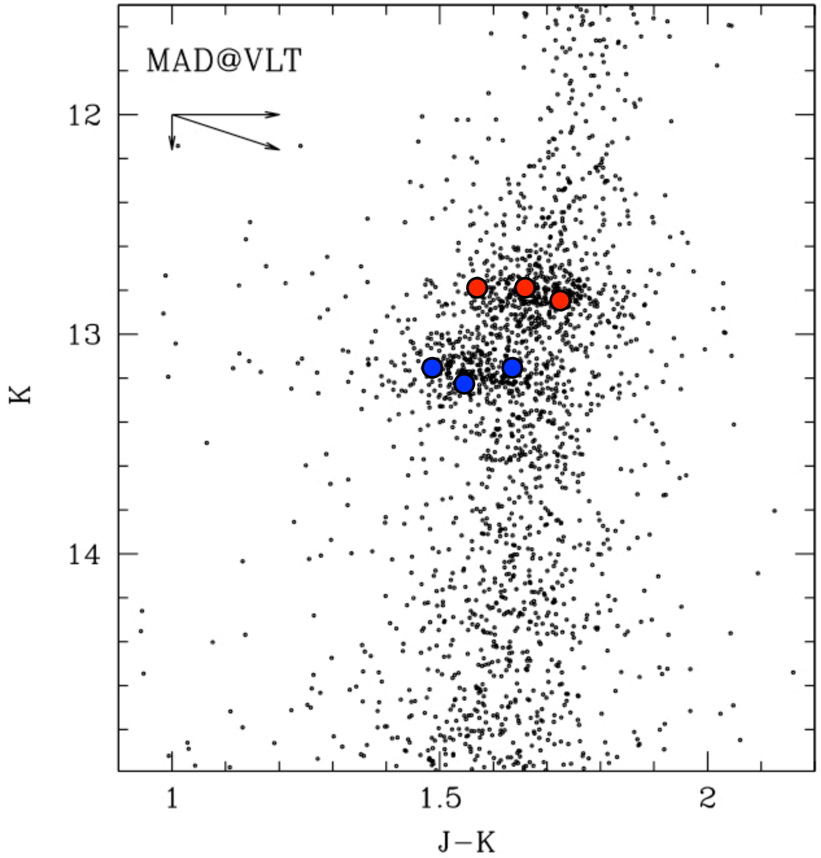


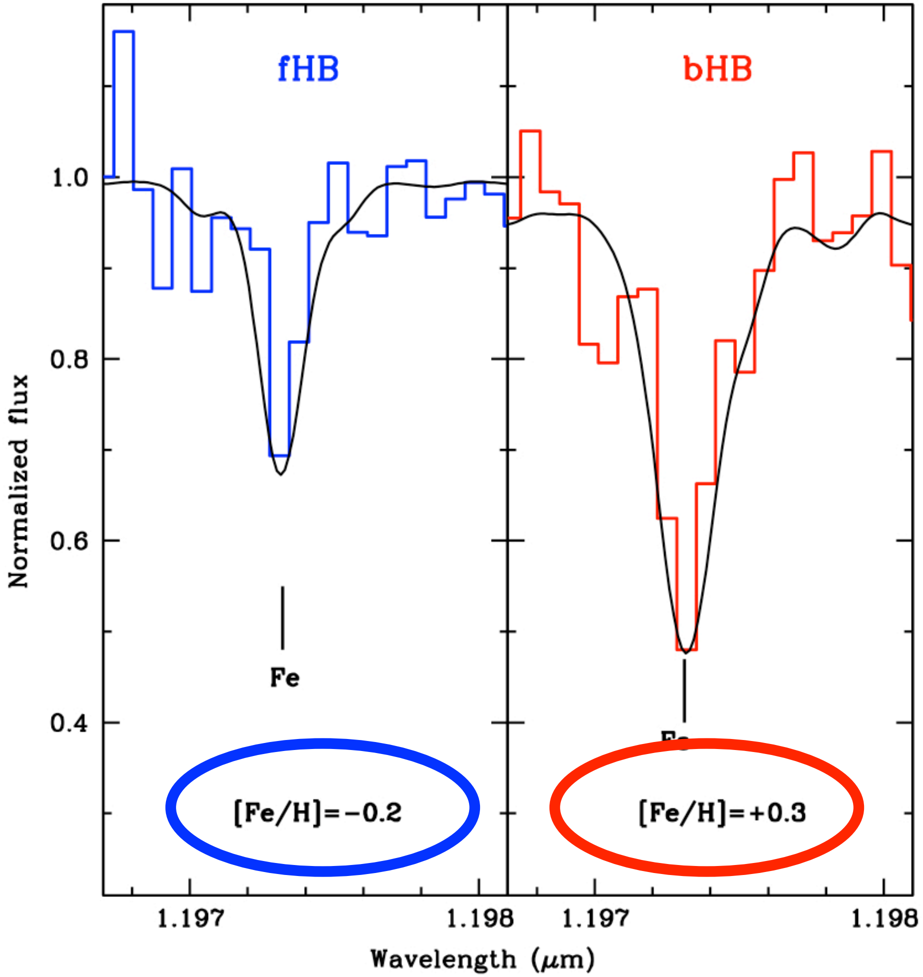
V_{rad} = -85 Km/s

V_{rad} = -85 Km/s

The two populations belong to the same stellar system

NIRSPEC @ Keck II observations of HB stars (in the **bHB** and **fHB**)

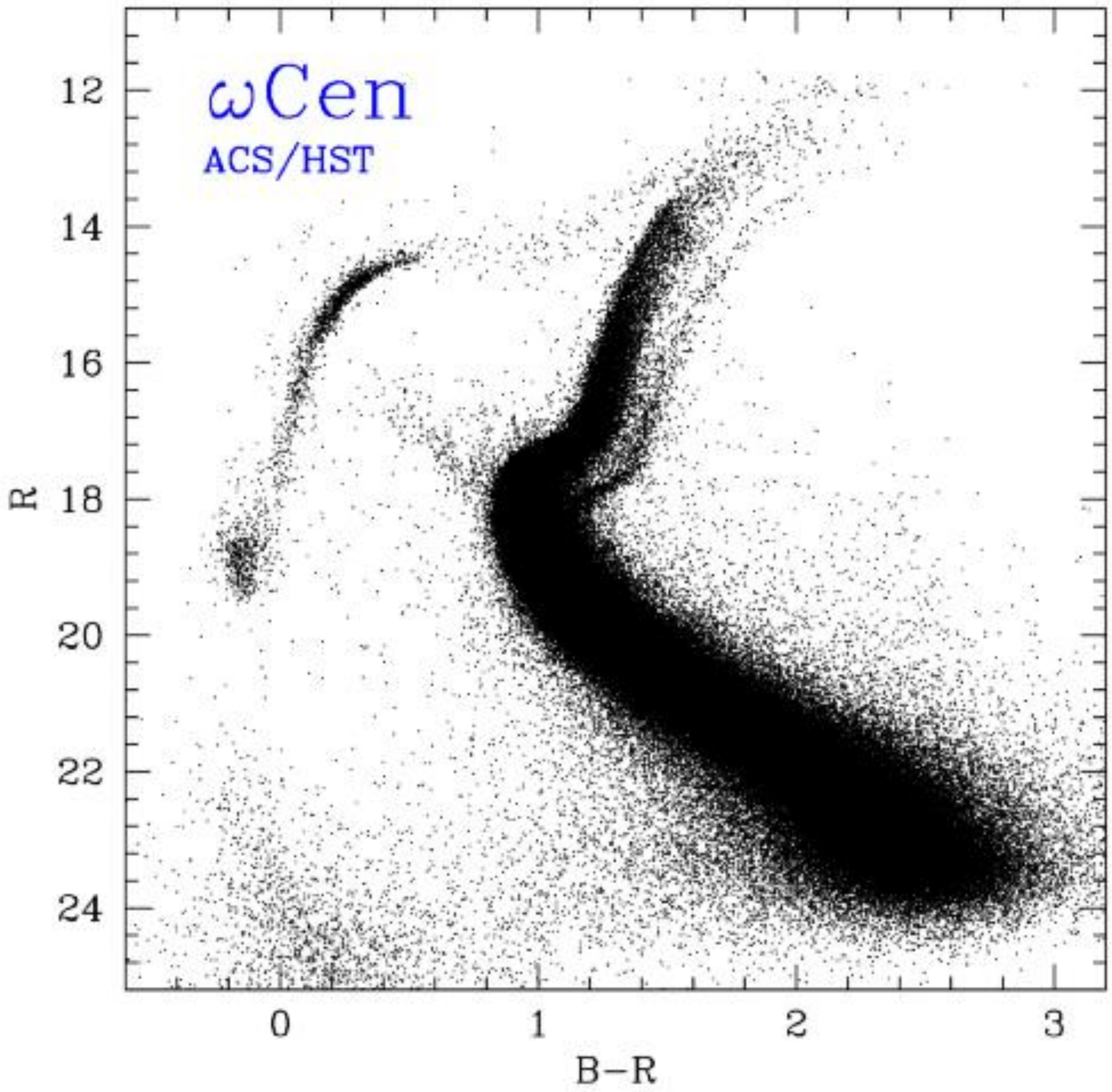




The two populations have different IRON abundance !!!

This is quite exceptional since NO GENUINE cluster has been found to harbor stars with such a large difference (Δ[Fe/H]>0.5 dex) in IRON abundance

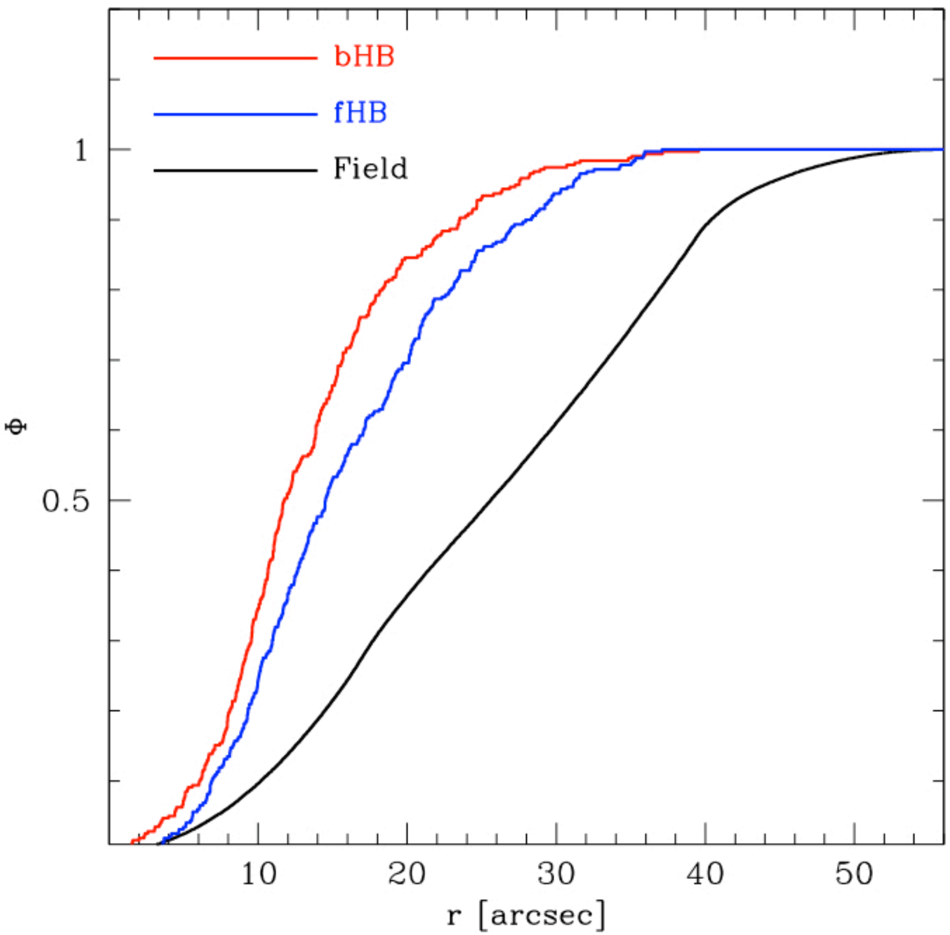
The only known example is OMEGA CENTAURI in the galactic Halo which is considered to be the remnant of a larger structure

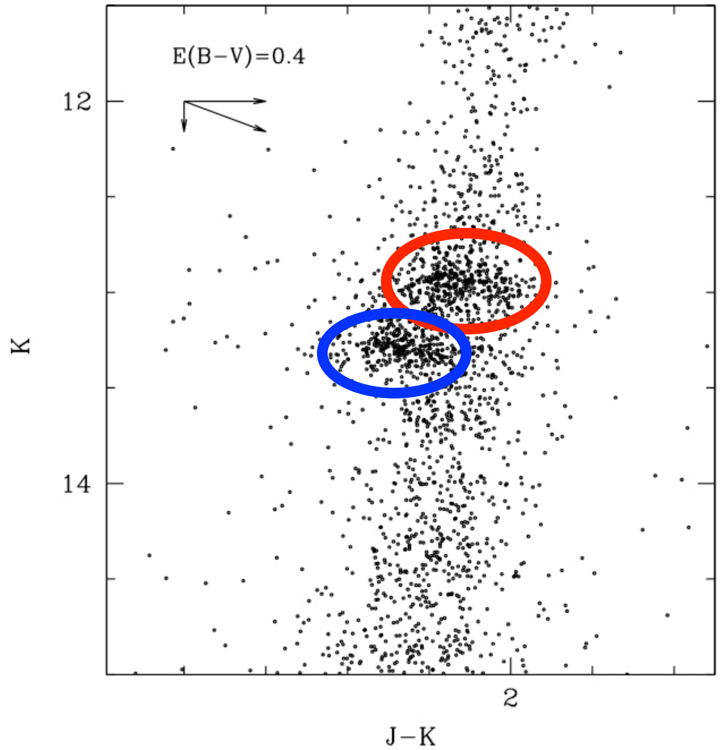


TERZAN 5 IS NOT A GENUINE GC

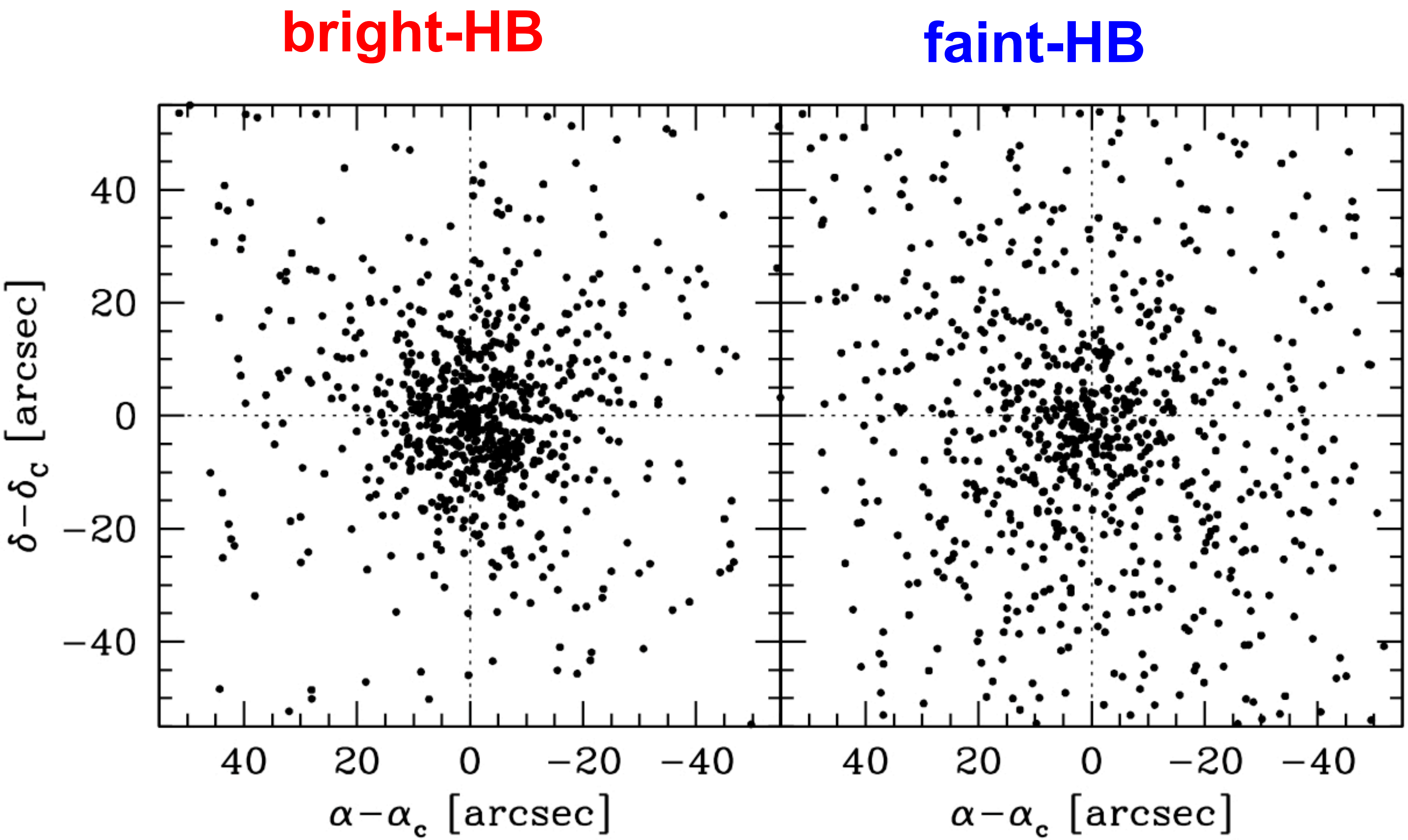
Two populations with different IRON abundance

What about their radial distribution ?

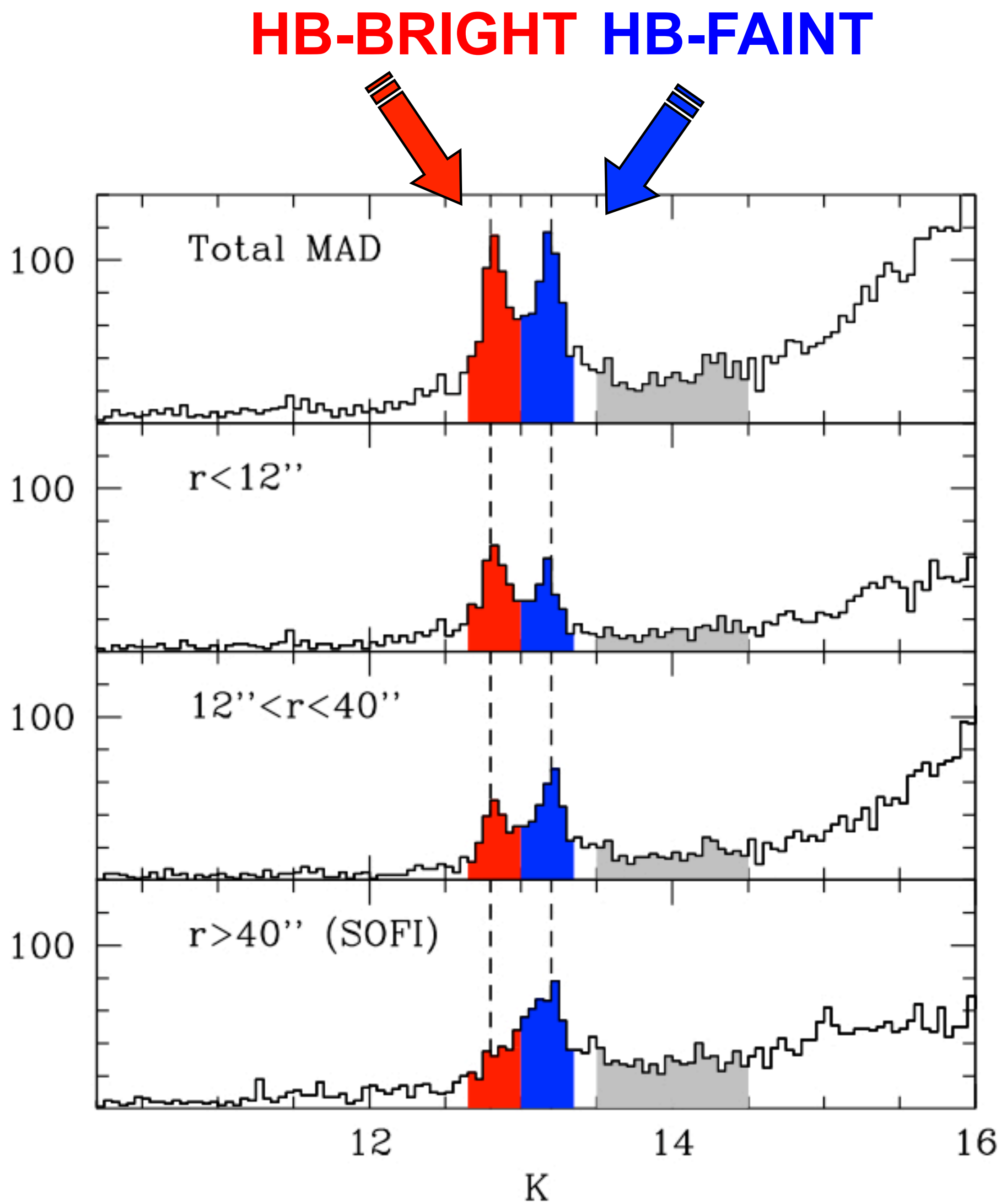




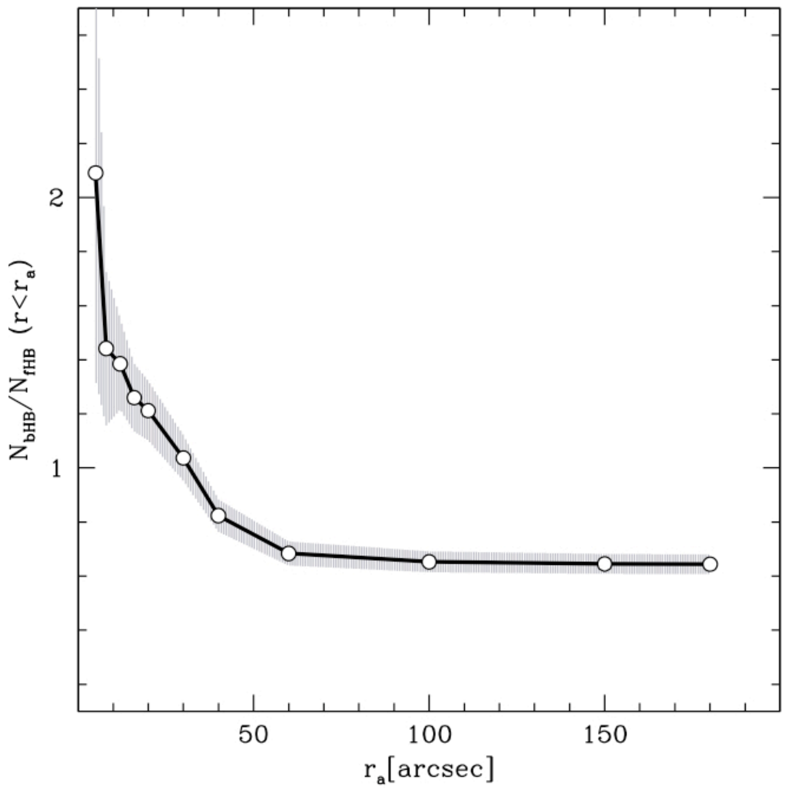
THE bright-HB POPULATION IS MORE CENTRALLY SEGREGATED THAN THE faint-HB ONE



Lanzoni et al. (2010)



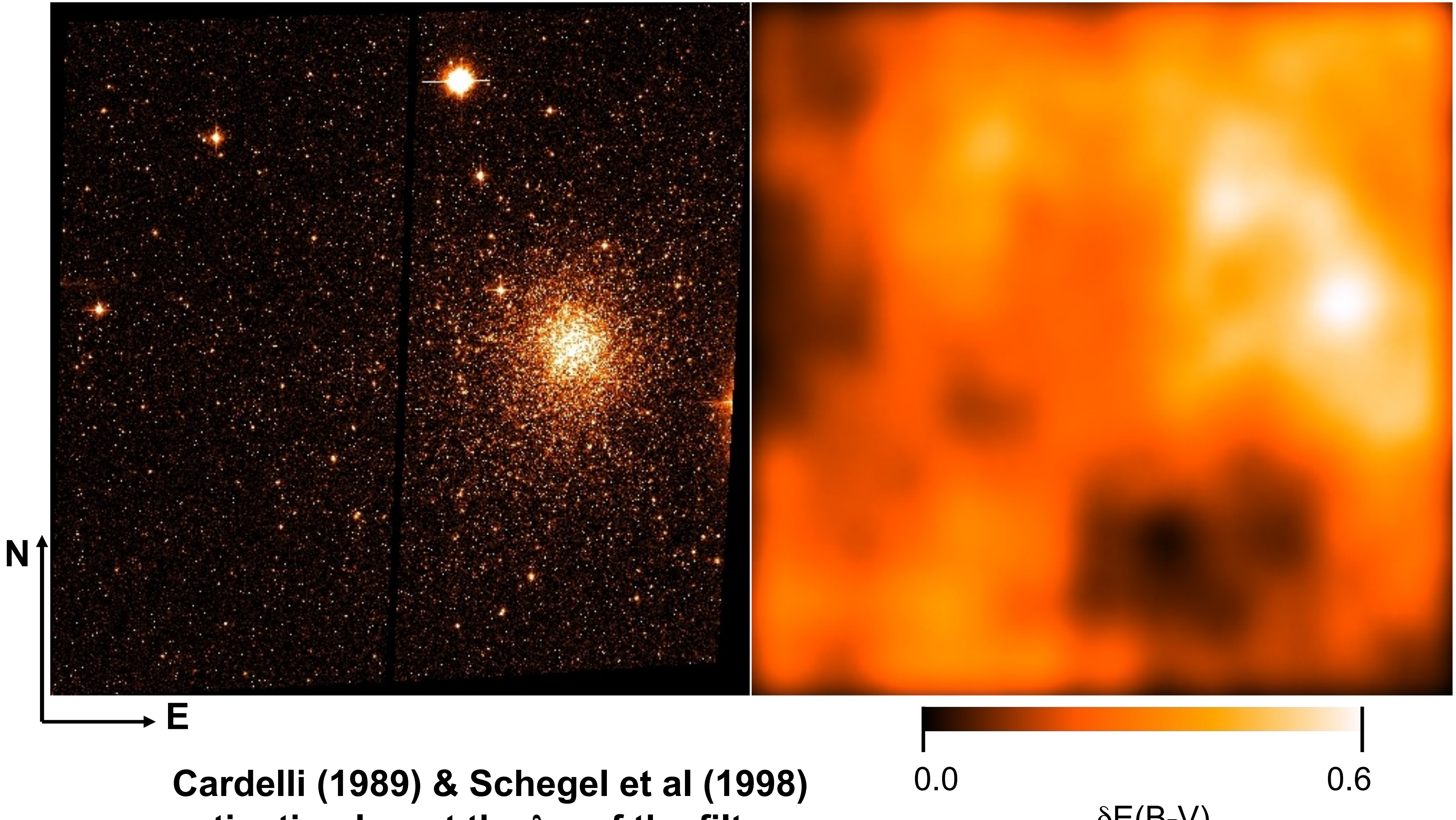
$$R = \frac{N_{BHB}}{N_{FHB}}$$



Two populations with different IRON abundance:

The (b-HB) most metal-rich component is significantly more centrally segregated than the (f-HB) “metal-poor” one

The differential reddening map in the direction of Terzan5



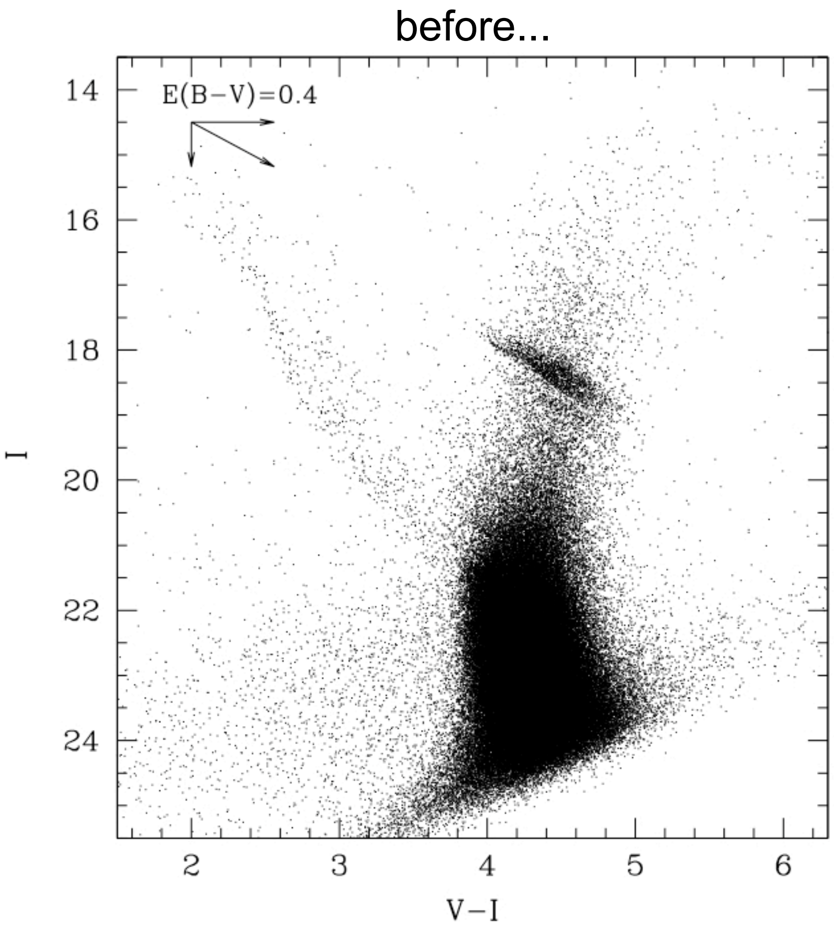
Cardelli (1989) & Schegel et al (1998) extinction law at the λ_{eff} of the filters:

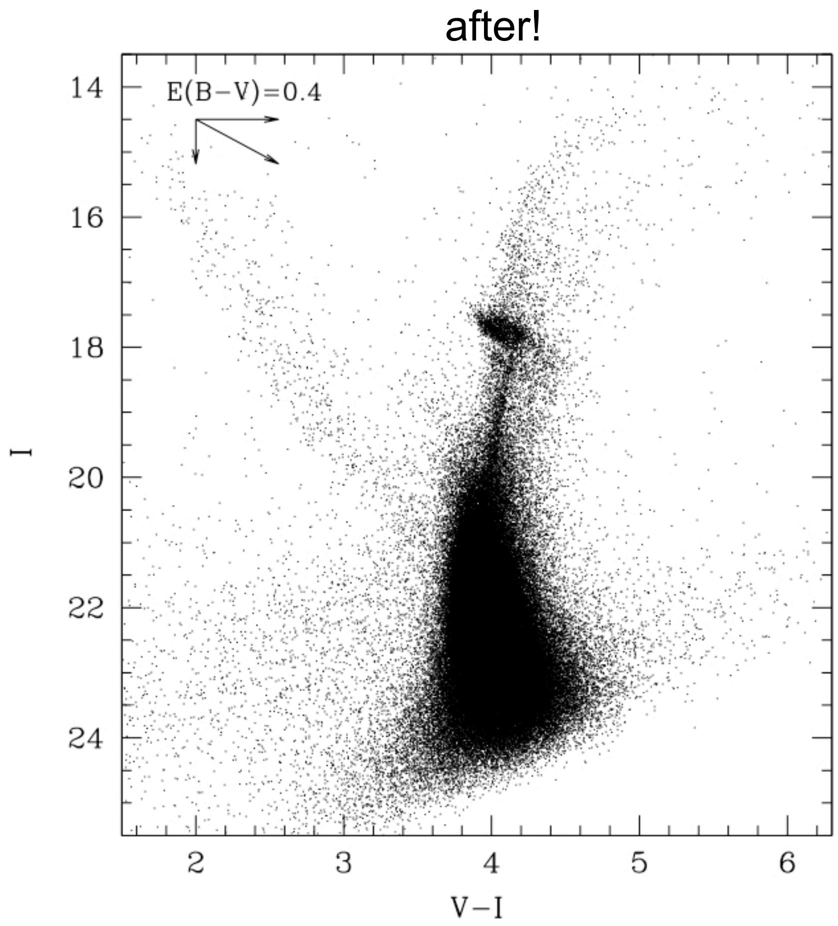
$A_V = 2.83/E(B-V)$

$A_I = 1.82/E(B-V)$

Massari et al (2012, ApJ, 755, L32)

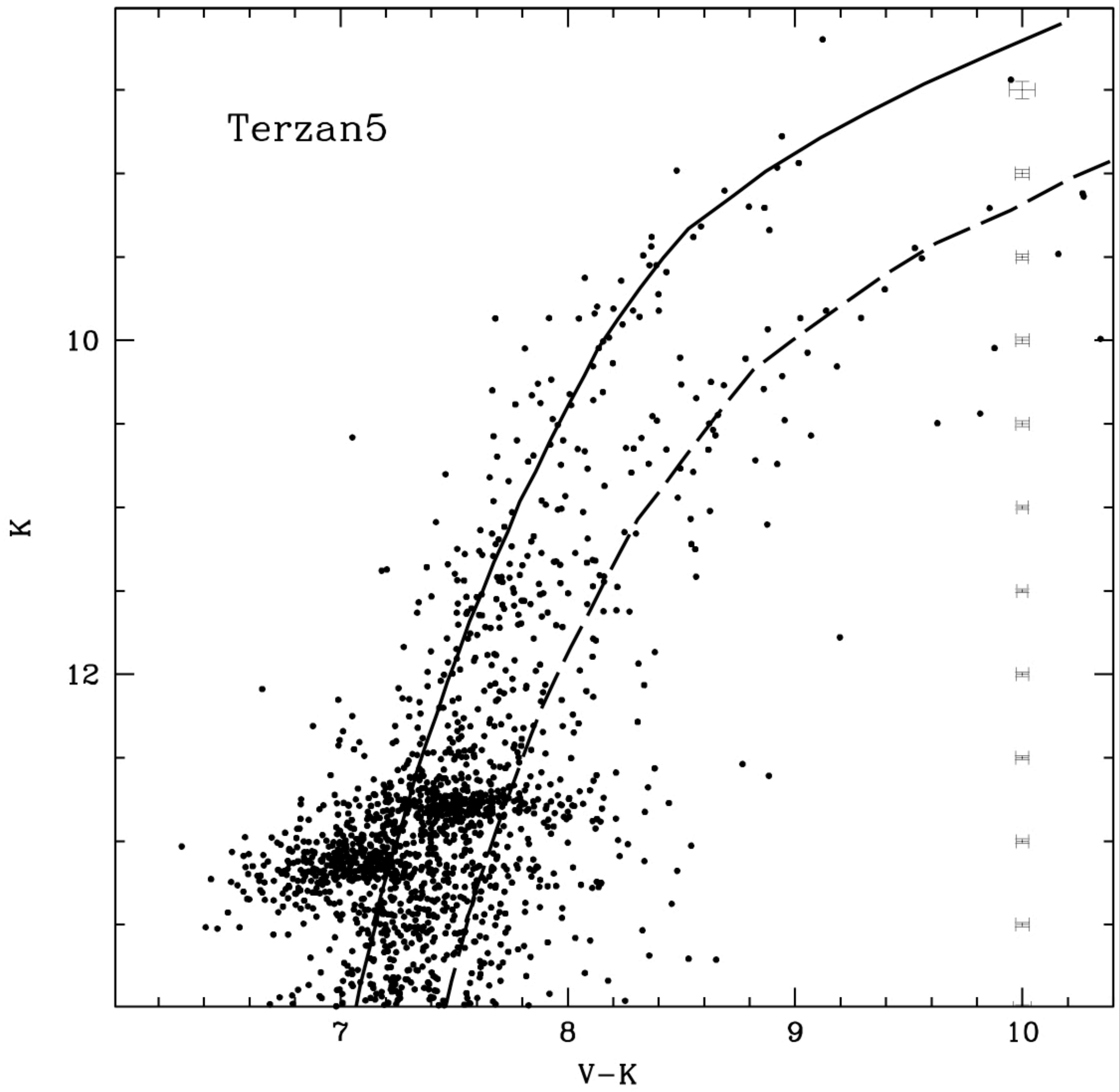
Correcting for differential reddening.





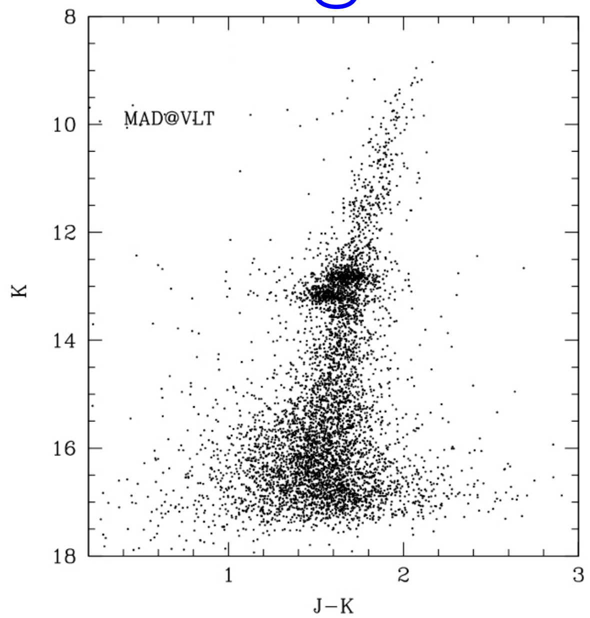
Massari et al (2012, ApJ, 755, L32)

The internal-reddening corrected optical/IR CMD reveals two distinct RGB

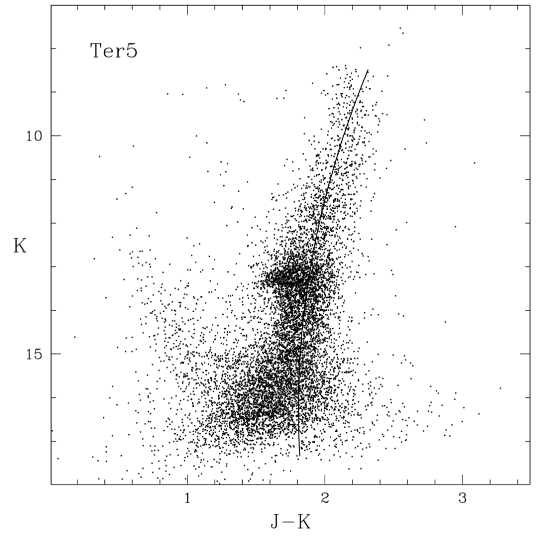


STAR-DENSITY PROFILE & STRUCTURAL PROPERTIES

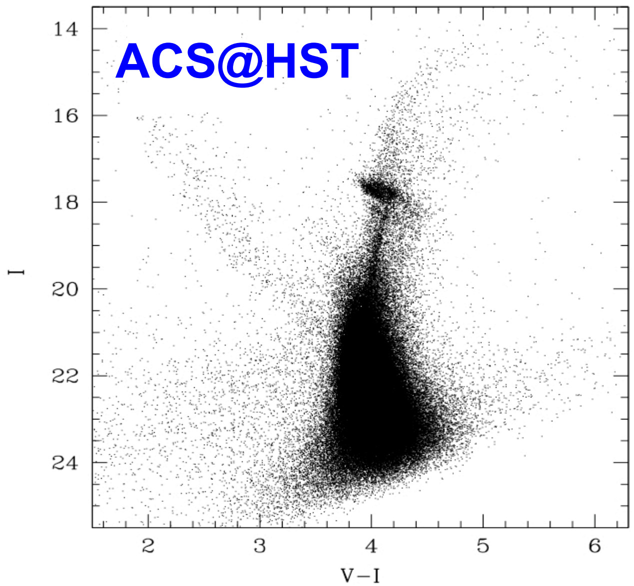
MAD@VLT



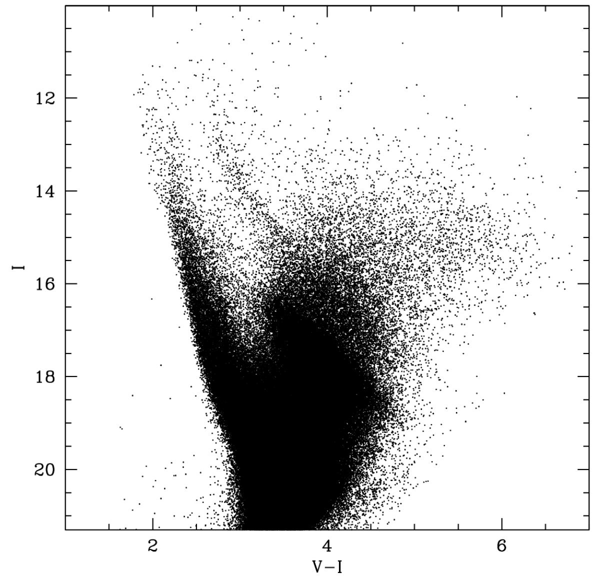
SOFI@NTT



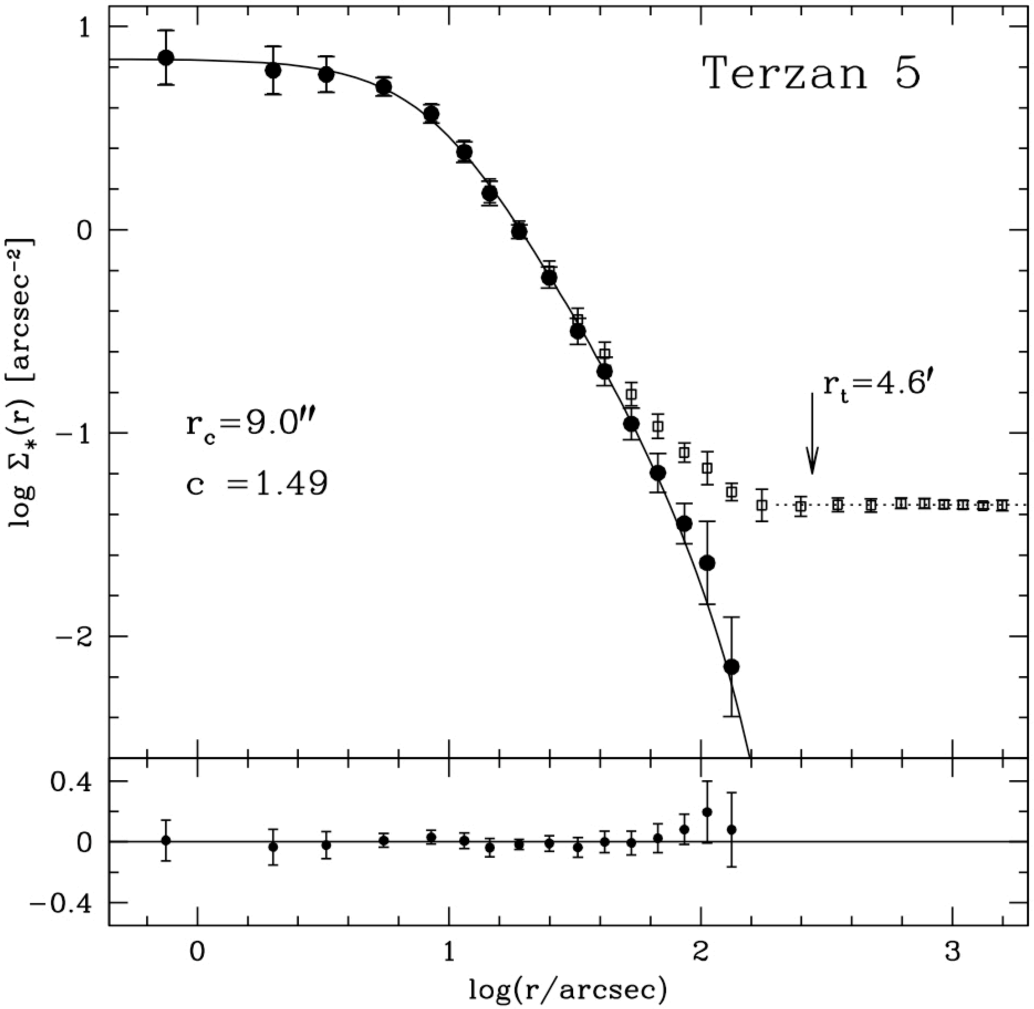
ACS@HST



WFI@2.2m



DENSITY PROFILE & STRUCTURAL PARAMETERS



Lanzoni et al (2010, ApJ, 717, 653)

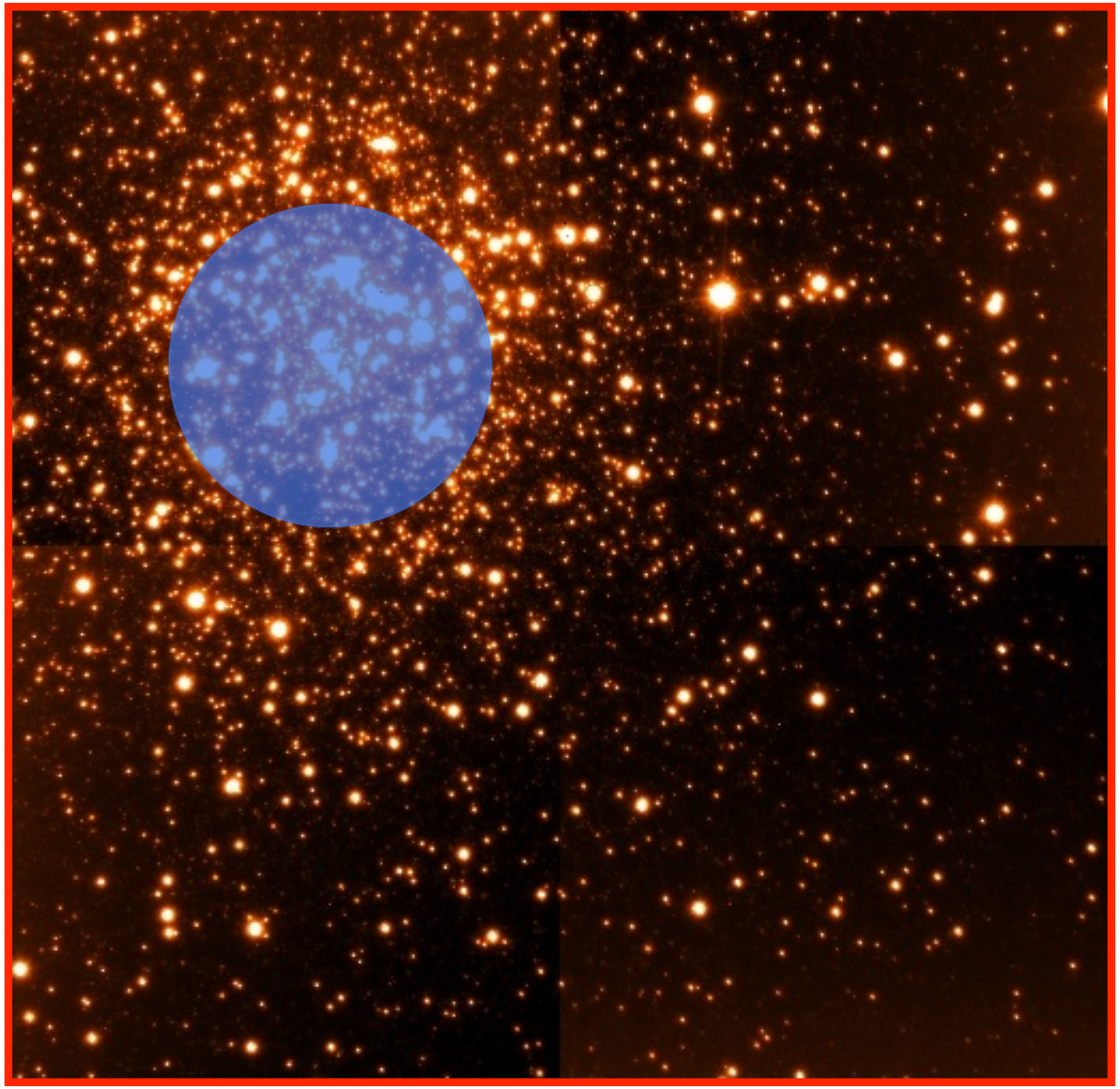
The new profile suggests a core radius larger than previous measures

$$\mathbf{r_c = 9'' = 0.26\ pc}$$

[Cohn et al (2002) found 7.9”]

& an intermediate concentration c=1.5

[Cohn et al (2002) found c=2]



Integrated K-magnitude
of the central region
combined
with the density profile

$\rho_0 \approx 2 \times 10^6\ M_\odot/pc^3$

$L_{bol} \approx 10^6\ L_\odot$

$Mass \approx 2 \times 10^6\ M_\odot$

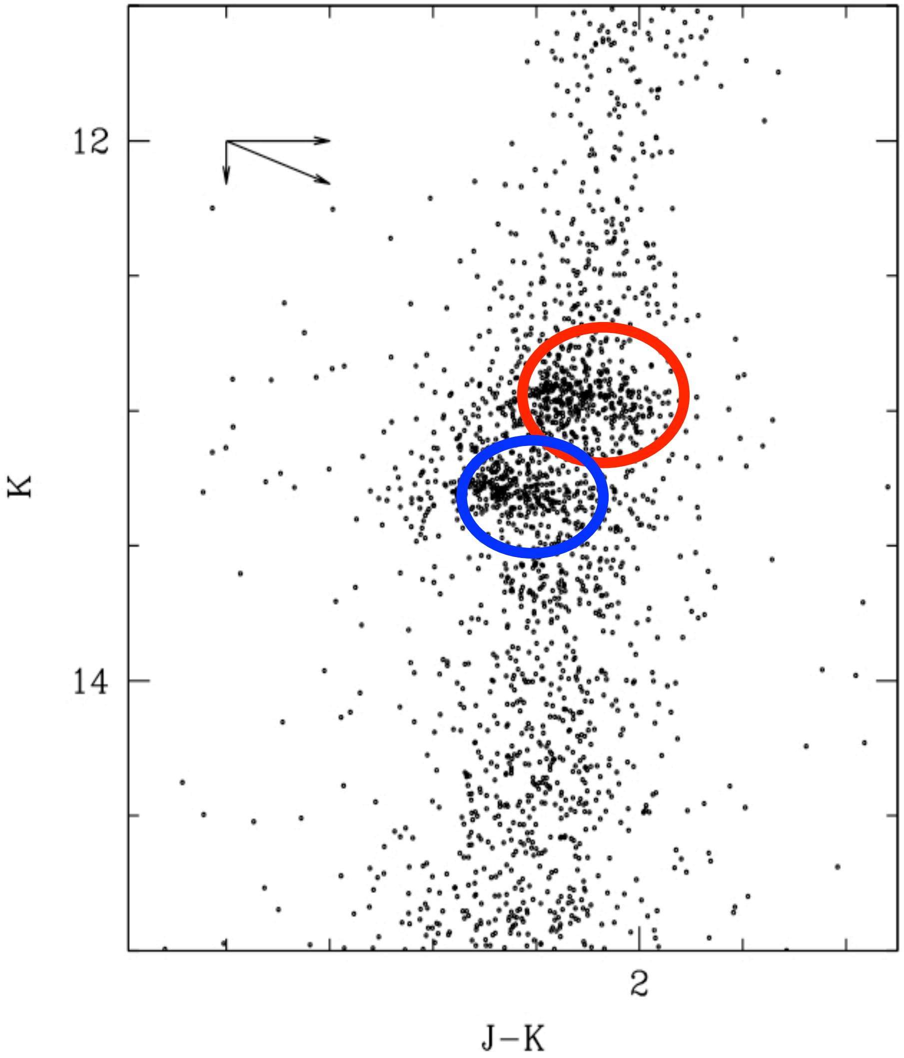
Terzan 5 is a quite massive stellar system

The number of stars counted in the two HBs (corrected for field contamination and sampled luminosity) can be used to derive an independent estimate of the cluster total mass

$$N_j = B \times t_j \times L_T$$

The total number of HB stars in Terzan 5 (N_{HB} = 1300);
$t_{HB} = 10^8$ yr and $B = 2 \times 10^{-11}\ yr^{-1} L_\odot^{-1}$

$$L_T = 6.5 \times 10^5\ L_\odot \quad \text{i.e.} \quad M = 2 \times 10^6\ M_\odot$$



N_{bHB} = 500
M= 7.5 x10^{5} $M_{\odot}$
38%

N_{bHB} = 800
M= 1.2 x10^{6} $M_{\odot}$
62%

Verbunt & Hut (1987) first suggested that Ter 5
has a quite large value of collision rate compared to other GCs.
The collision rate of a King Model stellar system:

$$\Gamma \approx \rho_0^{1.5} \times r_c^2$$

With the increased central mass

($\rho_0 \approx 2 \times 10^6$ Mo/pc^3)

and the new core radius

($r_c \approx 0.26$ pc)

Terzan 5 has the largest collision rate of any stellar aggregate in the Galaxy

Spectroscopic screening of Ter5

NIRSPEC @ Keck II near-IR spectroscopy at R @ 25,000

Chemical abundances for 33 Red Giant Stars

Table 2
Average Abundance Ratios of the Two RGB Populations in Terzan 5

Abundance Ratio	Metal-poor Population	Metal-rich Population
[Fe/H]	-0.25 ± 0.07	$+0.27 \pm 0.04$
[O/Fe]	$+0.34 \pm 0.06$	-0.04 ± 0.04
[Ca/Fe]	$+0.32 \pm 0.05$	$+0.02 \pm 0.03$
[Si/Fe]	$+0.36 \pm 0.08$	$+0.02 \pm 0.10$
[Mg/Fe]	$+0.33 \pm 0.10$	$+0.08 \pm 0.06$
[Ti/Fe]	$+0.34 \pm 0.10$	$+0.06 \pm 0.06$
[Al/Fe]	$+0.52 \pm 0.13$	$+0.13 \pm 0.13$
[C/Fe]	-0.35 ± 0.12	-0.38 ± 0.08

Origlia et al (2010, ApJ, 726, L20)

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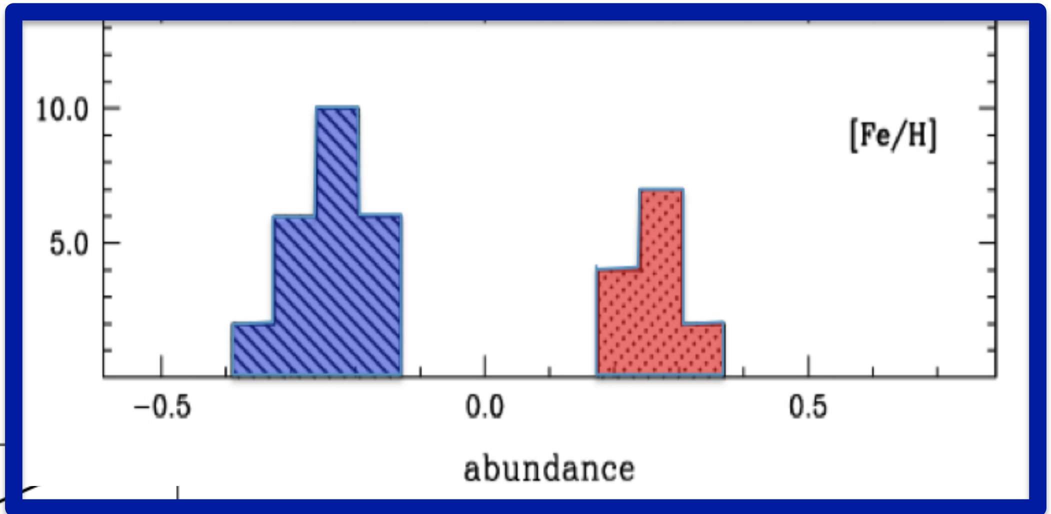
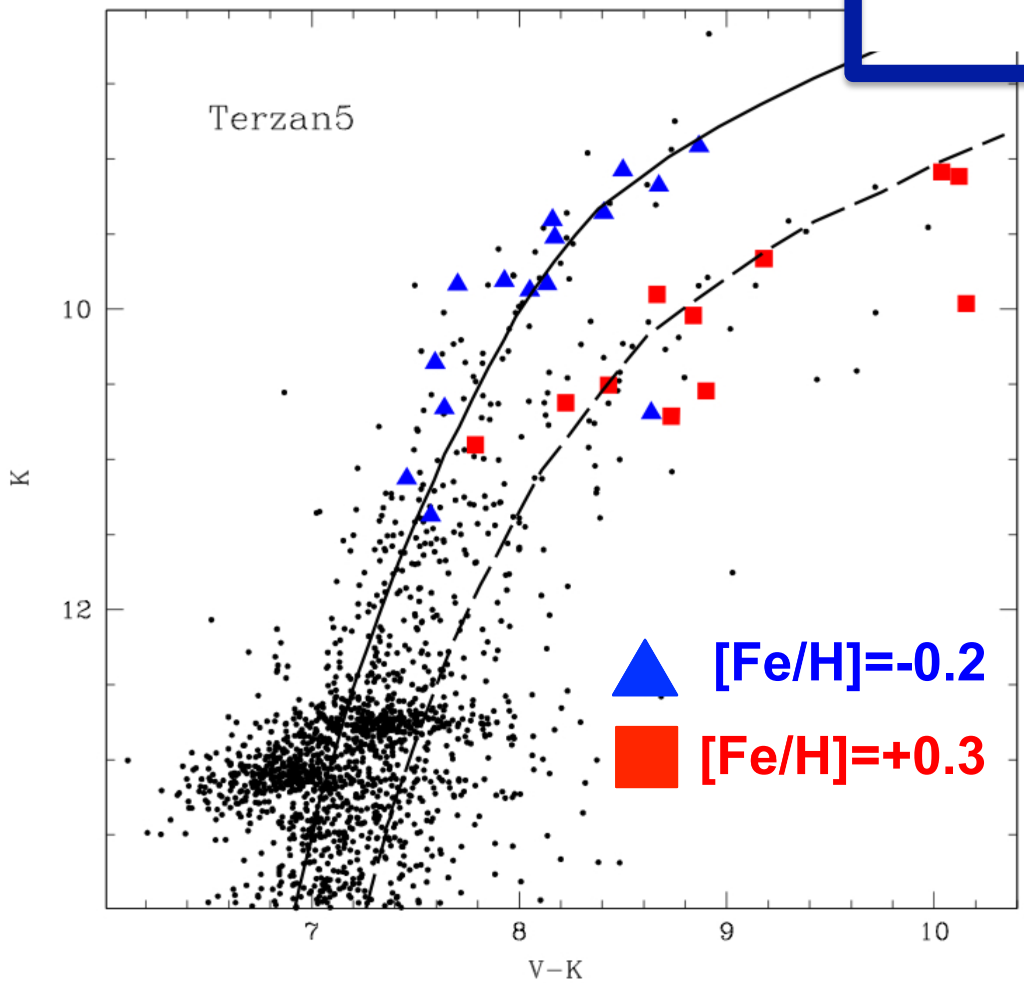
Spectroscopic screening of Ter5: IRON





[Fe/H]:

-0.25 +/- 0.07

+0.27 +/- 0.04

Δ[Fe/H] ≅ 0.5

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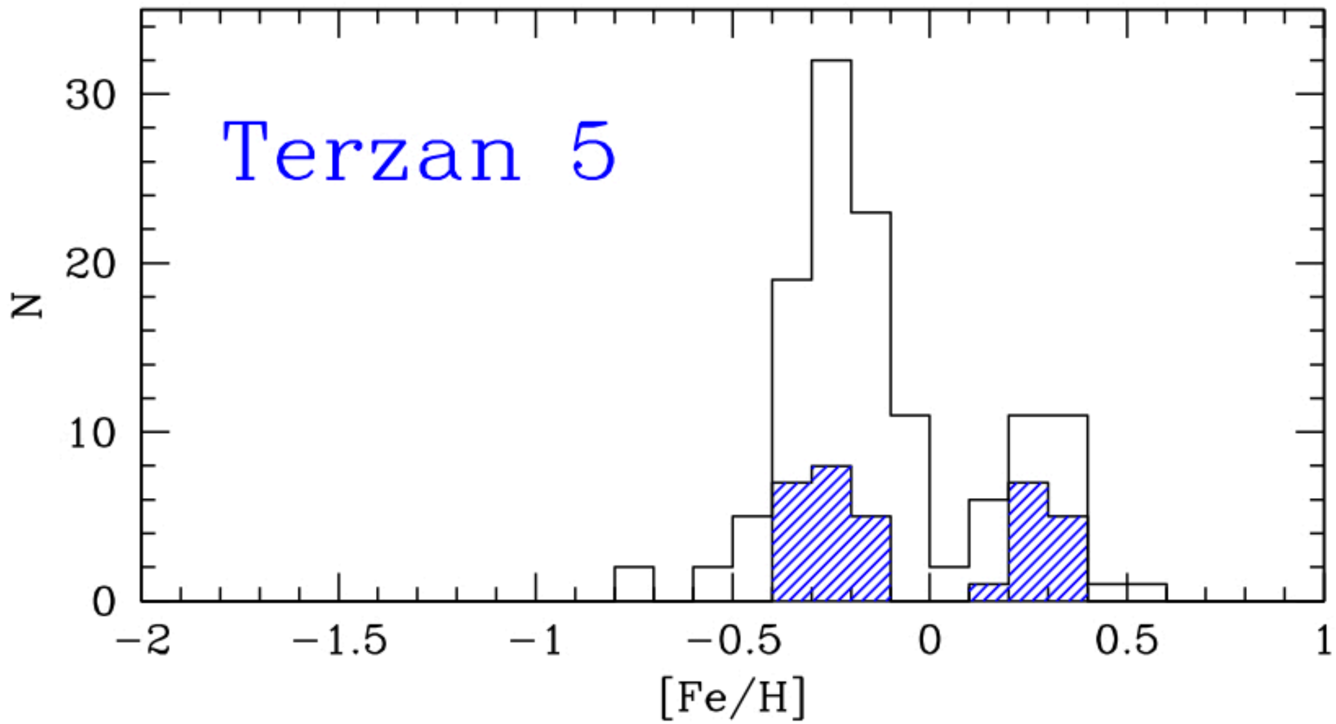
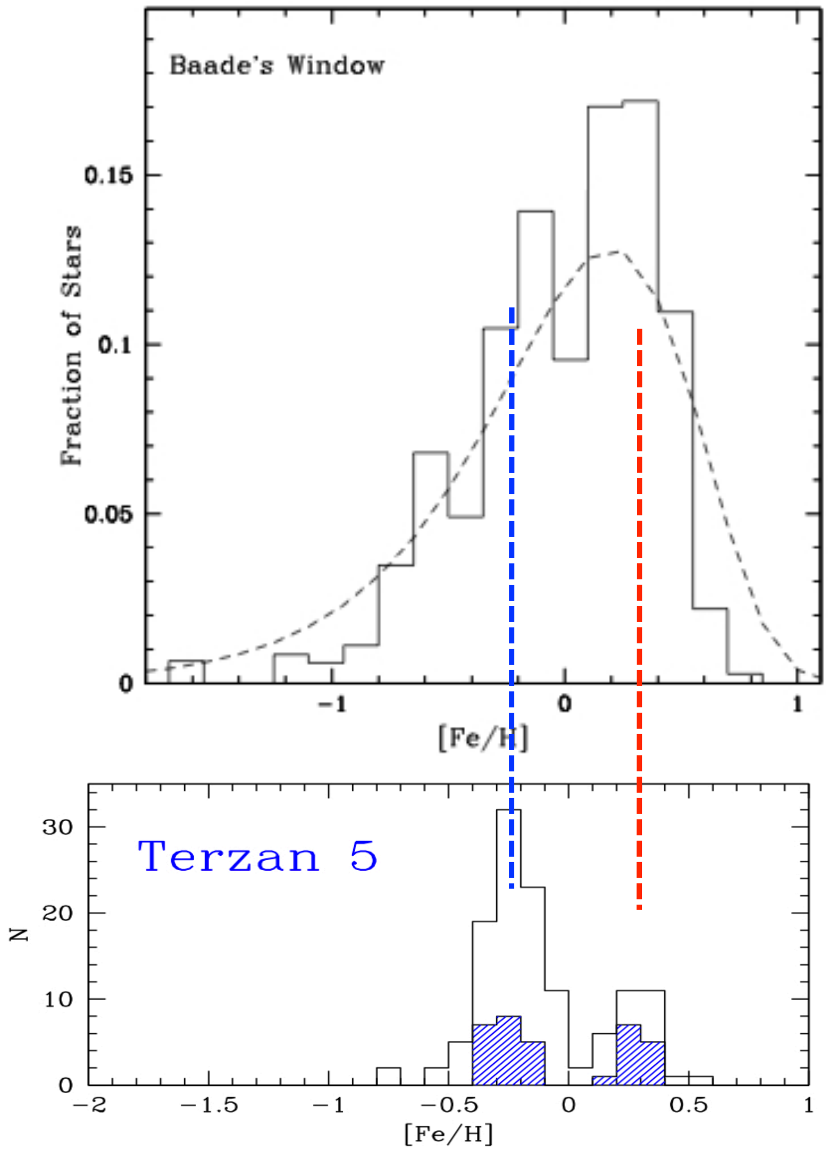
Iron distribution in Terzan 5



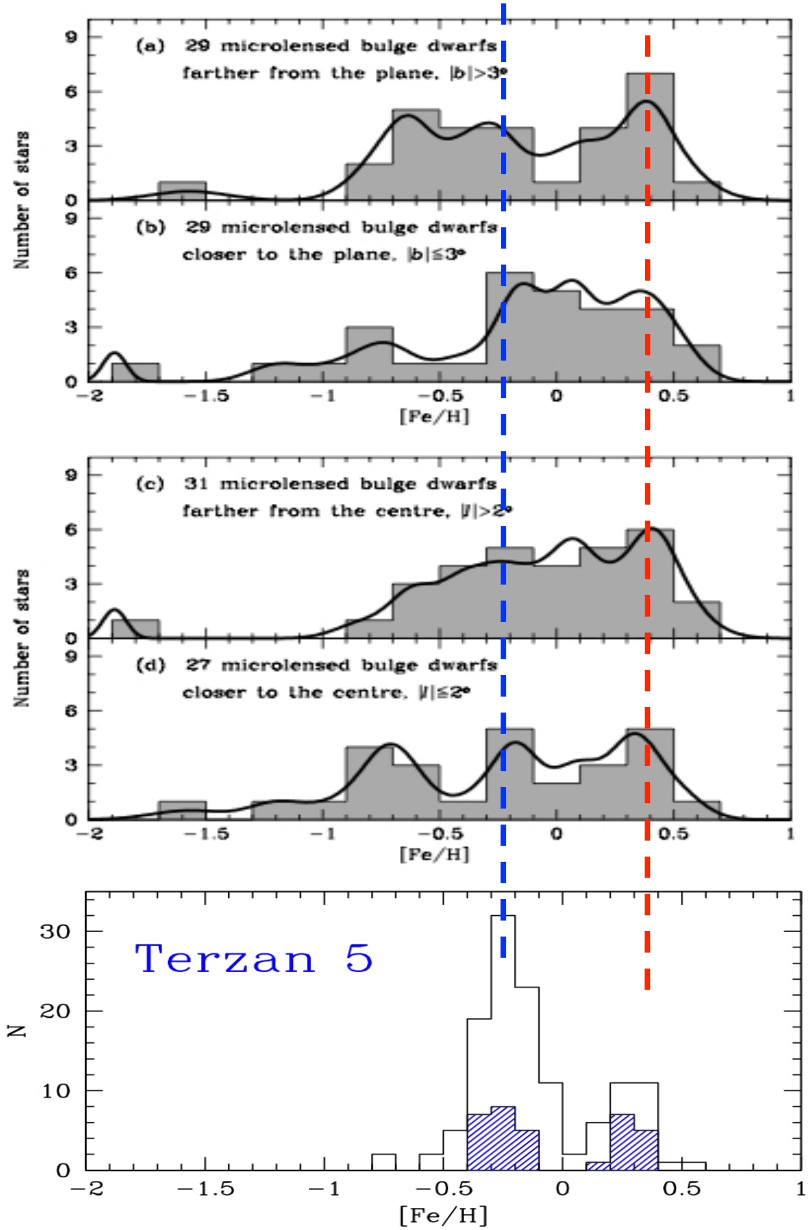
33 giants from Origlia et al (2010) +
93 FLAMES spectra from Massari et al (2013, in prep)



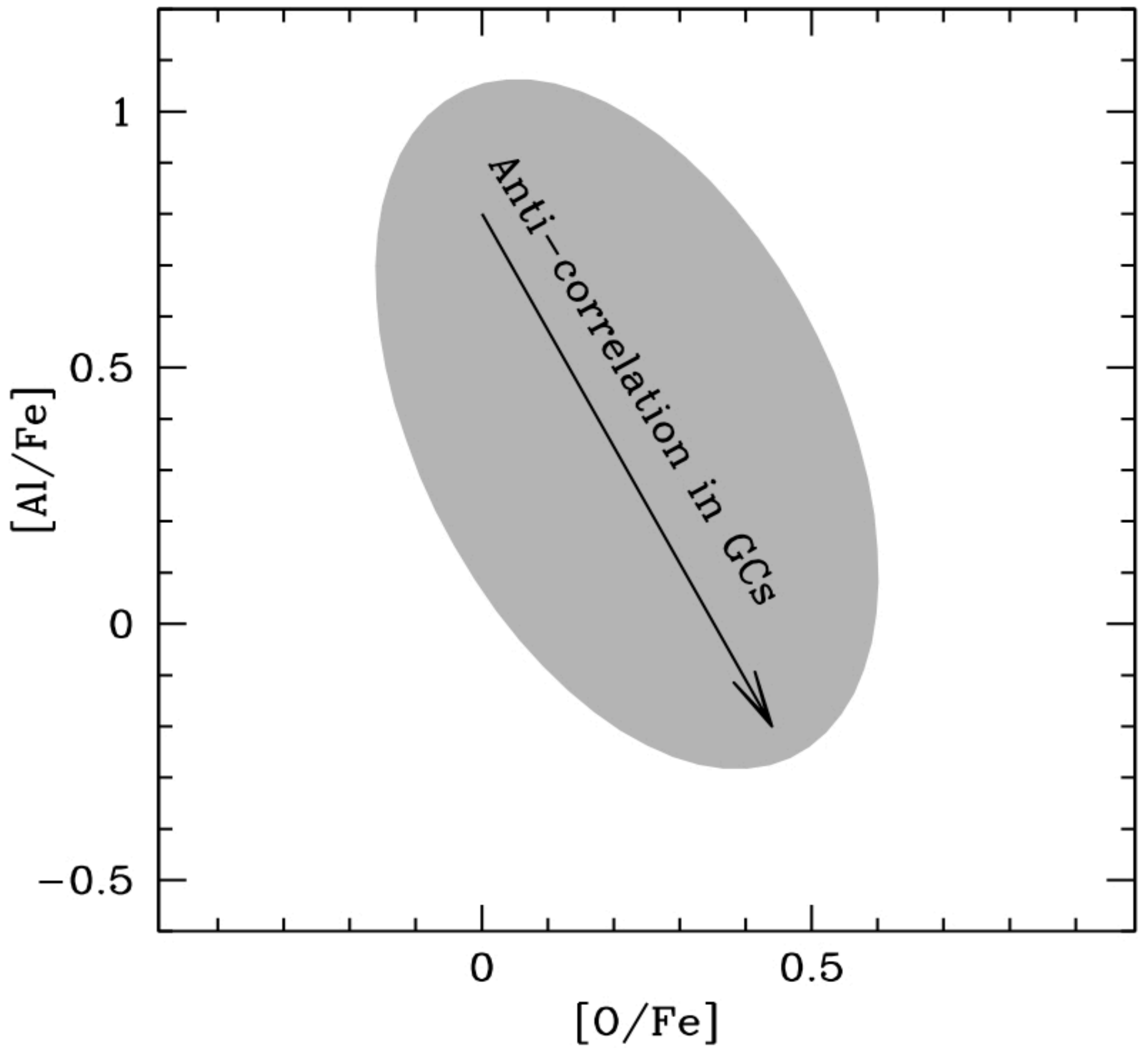
800 Bulge K giants

Zoccali et al 2008, A&A,486,177

Bensby et al 2013, A&A,549,147



Spectroscopic screening of Ter5: anti-correlations?



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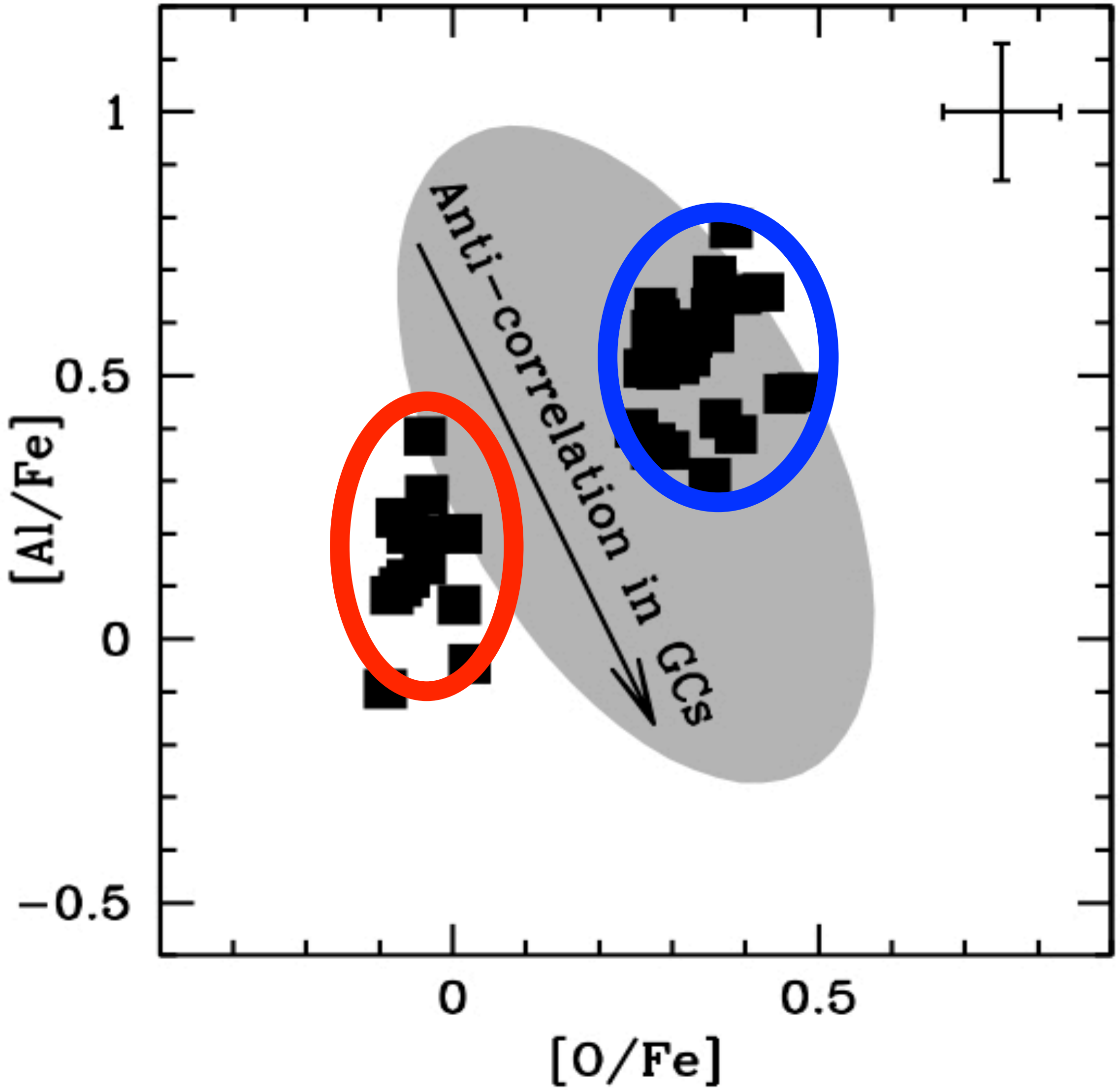
The two populations do **NOT** show any evidence of the Al-O anti-correlation that is typically observed in GCs



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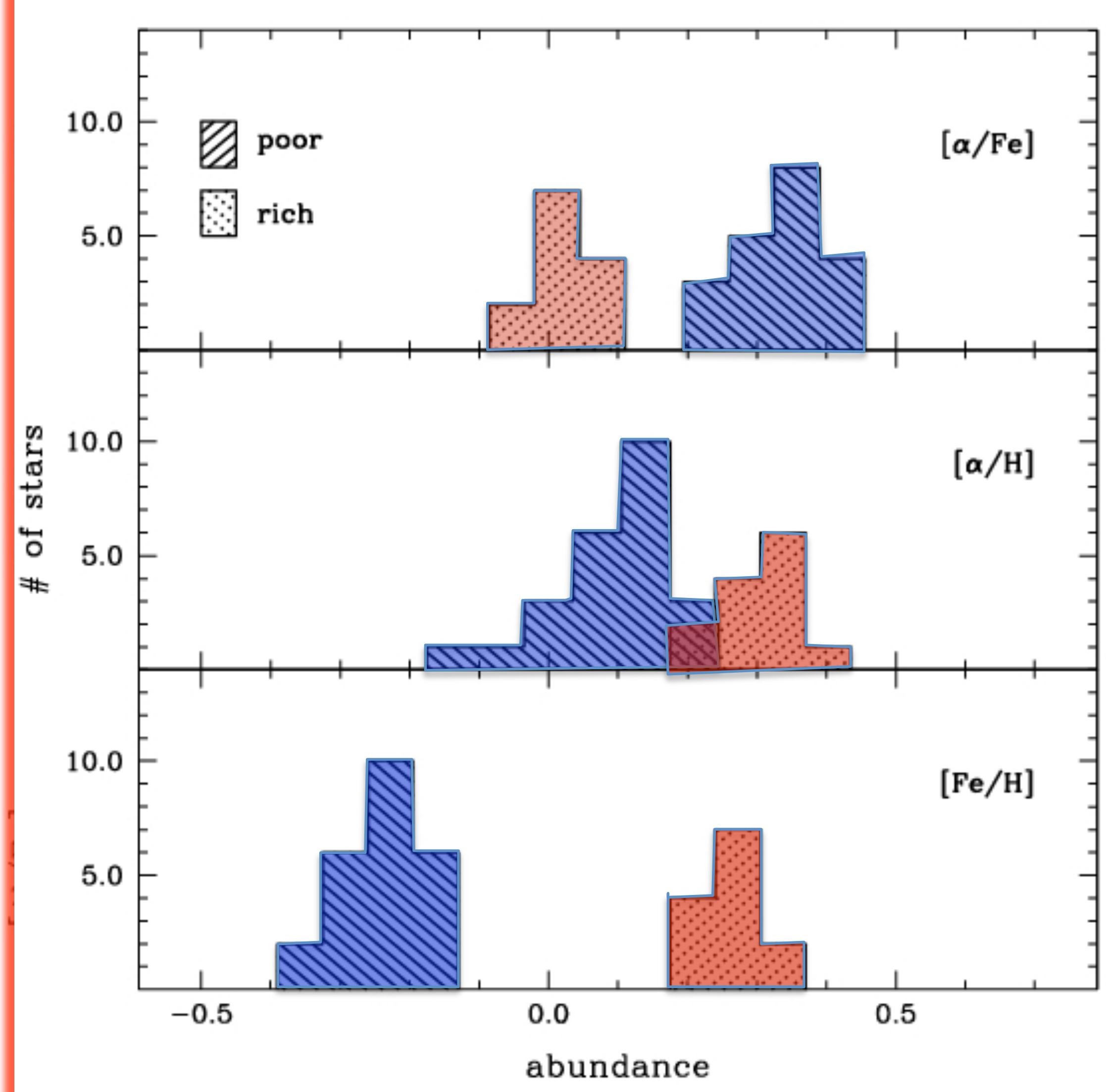
TERZAN 5 HAD A DIFFERENT ENRICHMENT HISTORY

Spectroscopic screening of Ter5: α−elements



[α/Fe]:

+0.34 +/- 0.06

+0.03 +/- 0.04

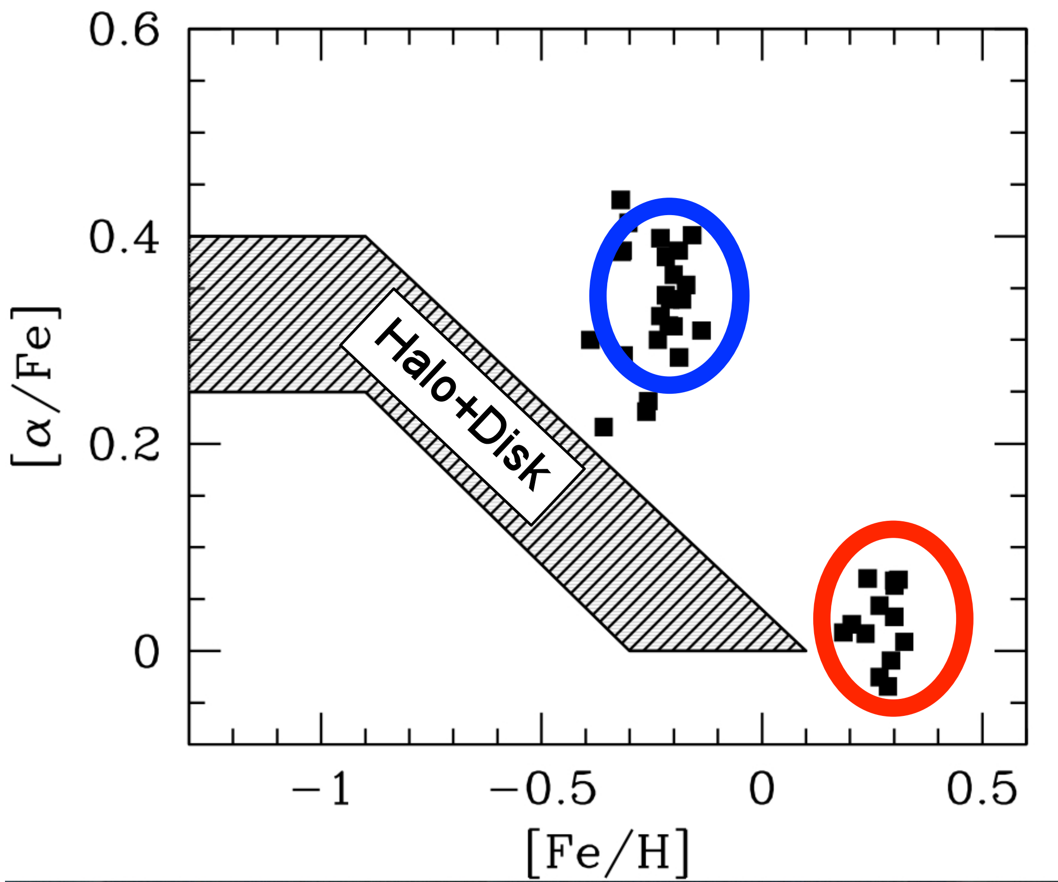
Δ[α/Fe] ≅0.3

Δ[α/H] ≅0.2

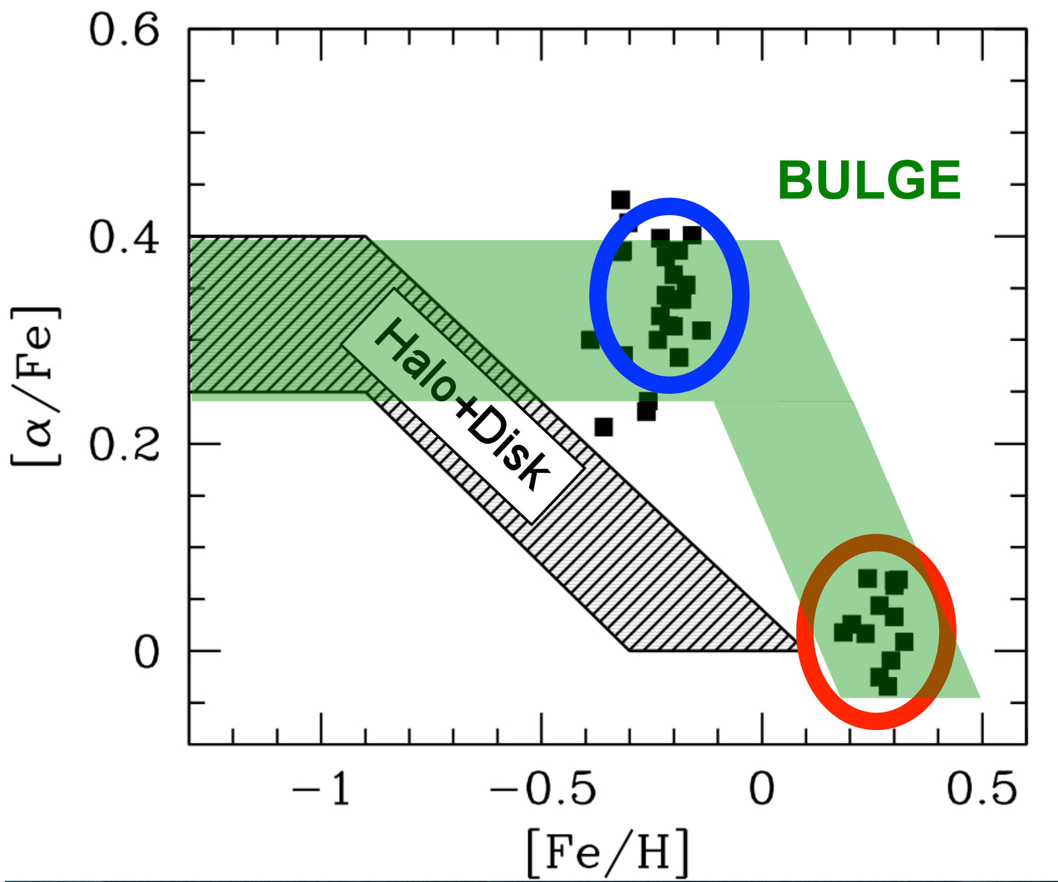
metal poor component is α-enhanced

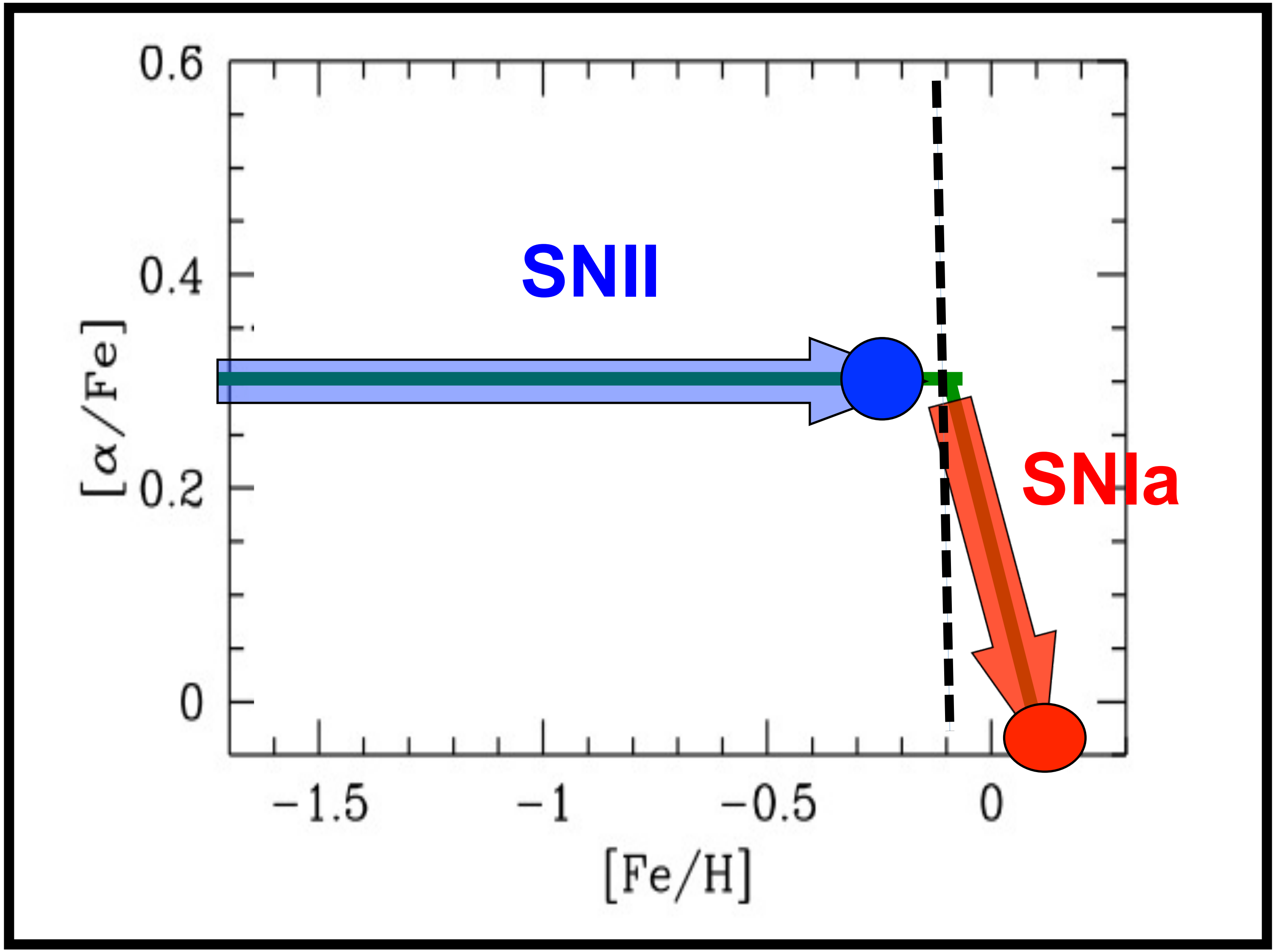
The metal rich one is solar

The chemistry of the two stellar populations in Ter5 is completly different from that observed in the Halo and Disk of the Galaxy

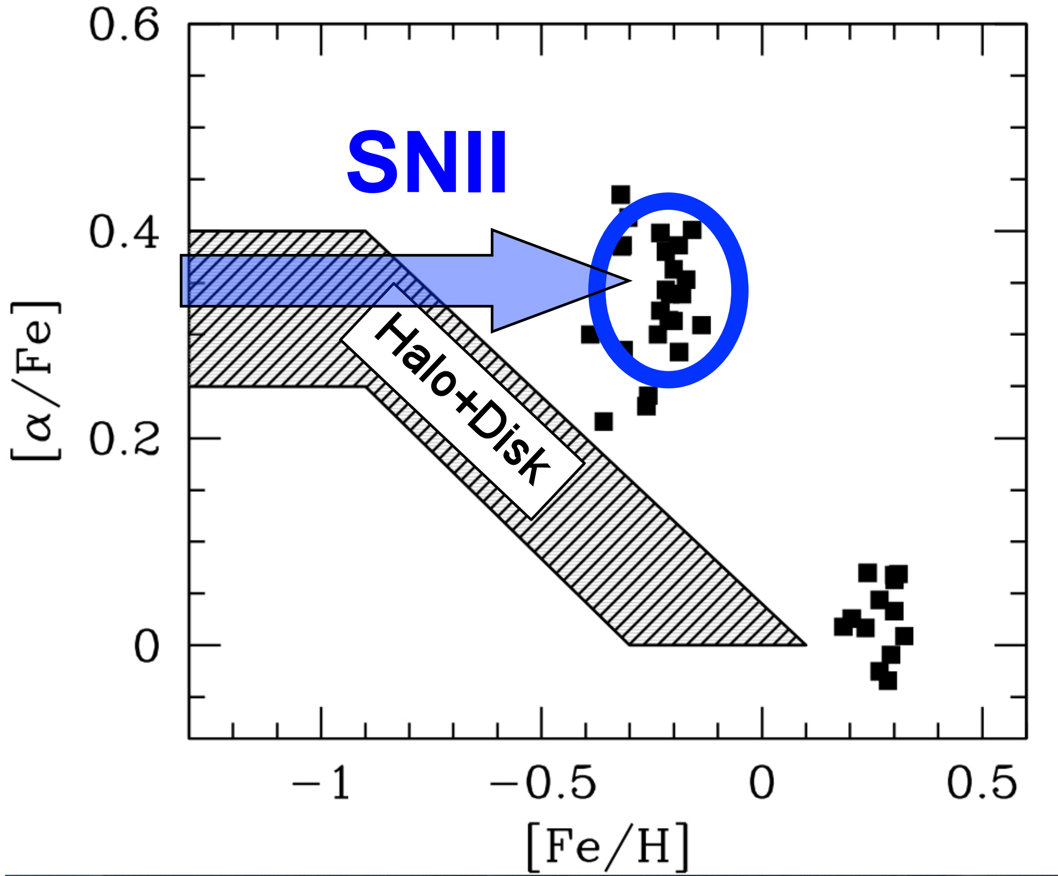


Iron and alpha –elements abundance are similar to those measured in the **Bulge**, thus suggesting **quite similar star formation and chemical enrichment processes**

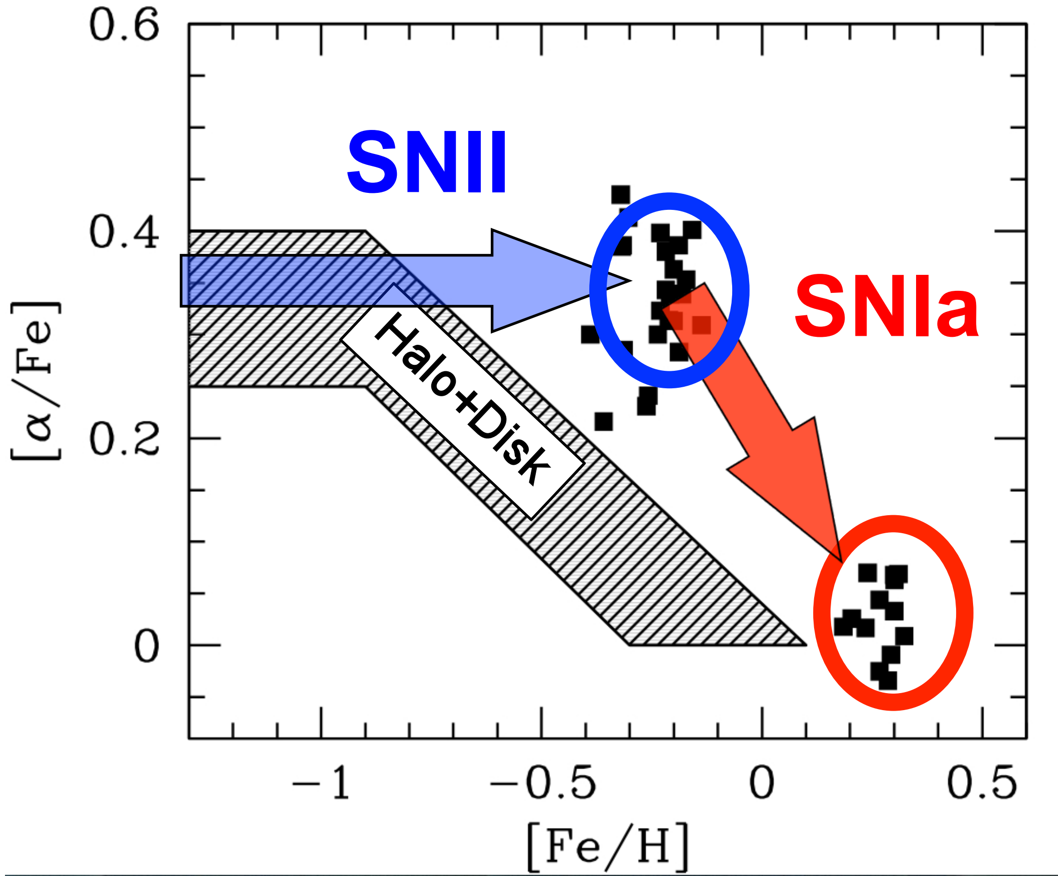



0.6
0.4
0.2
0
[α/Fe]
−1.5
−1
−0.5
0
[Fe/H]
SNII
SNIa

The chemistry of the **"metal-poor"** component of Terzan 5 shows that it formed from a gas which was polluted by **Type II SNe** ejecta



The chemistry of the **metal-rich** component of Terzan 5 shows that it formed from a gas which was (mainly) polluted by **Type Ia SNe** ejecta (over a large time-scale)



The observational facts demonstrate that Terzan 5 has experienced a quite complex formation history:

1. IT IS NOT A GENUINE GC

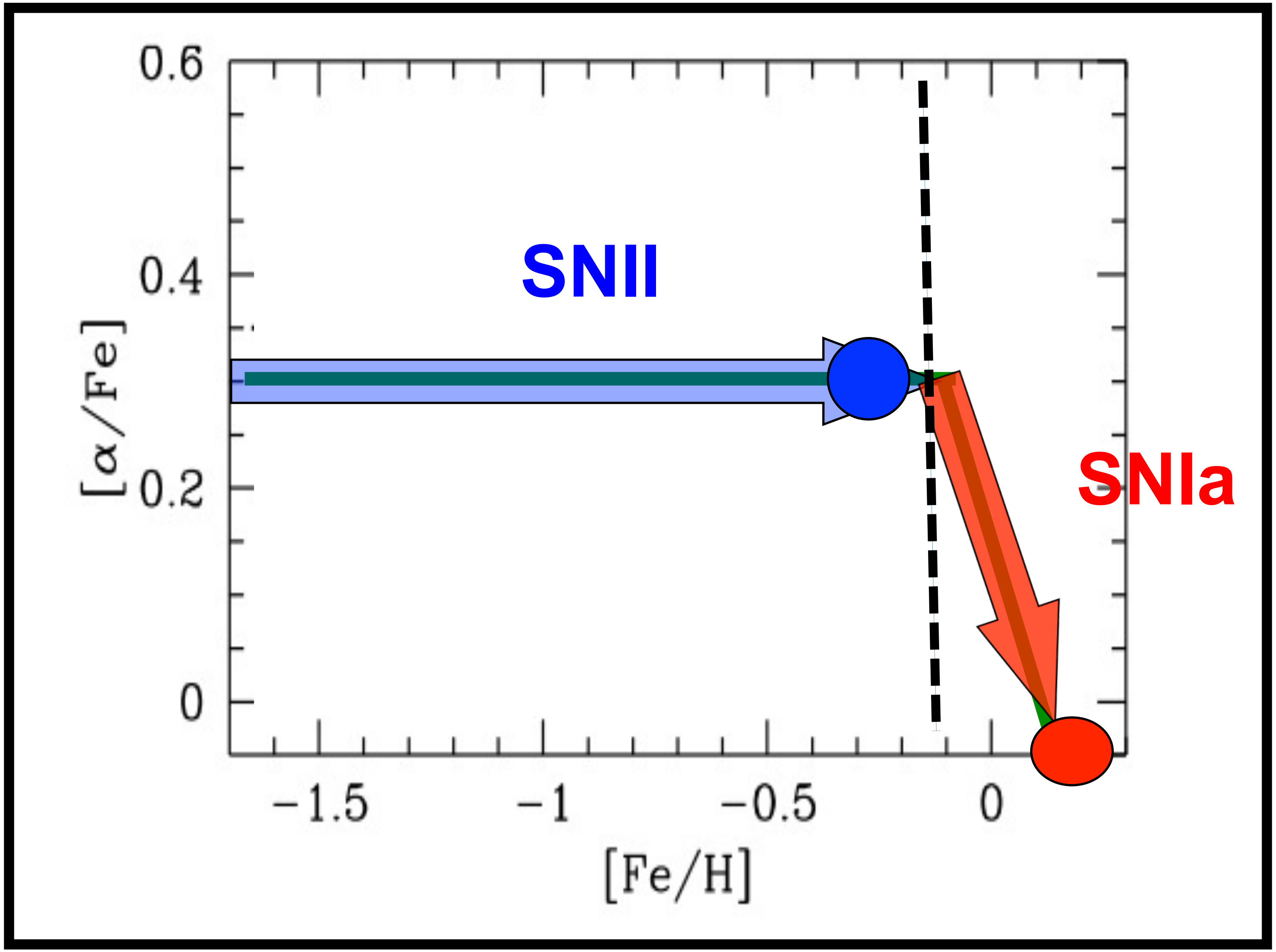
The significant iron abundance (Δ[Fe/H] =0.5 dex) difference measured in the two populations and the light elements abundance patterns (the Al-O CORRELATION!) demonstrate that it has a chemistry **QUITE DIFFERENT** from a genuine globular

2. IT IS A STELLAR SYSTEM SELF-ENRICHED IN IRON.

Observational scenario is compatible to a system self-enriched in Iron (the most metal-rich component is also more centrally segregated). Hence it was likely much **more massive** in the past (in order to retain the SN ejecta) than what observed now.
We estimate that the current mass of Terzan 5 is a few 10^6 Mo i.e. 1-2 order of magnitude lower than the smallest systems (dwarf galaxies) showing self-enrichment in iron.
It is the relic of a large stellar system (like Omega Cen).

3. IT SHARED THE EVOLUTION OF THE GALACTIC BULGE

However it is unlikely that Terzan 5 is a system "accreted" from outside the Galaxy, since the chemical composition of the two Populations are similar to that measured in Bulge stars, thus suggesting a Terzan5-Bulge "common" evolution and possibly origin (**Is Terzan 5 a pristine fragment of the bulge?**)



Chemical evolution models for the Galactic Bulge (e.g. Ballero et al 2007) suggest that this trend can be reproduced by a high SFR and a flat IMF .. i.e. with a large number of SNII !!!

3. IT SHARED THE EVOLUTION OF THE GALACTIC BULGE

However it is unlikely that Terzan 5 is a system "accreted" from outside the Galaxy, since the chemical composition of the two Populations are similar to that measured in Bulge stars, thus suggesting a Terzan5-Bulge "common" evolution and possibly origin (**Is Terzan 5 a pristine fragment of the bulge?**)

4. (1. + 2. +3.) = NATURAL EXPLANATION FOR THE LARGE MSP POP.

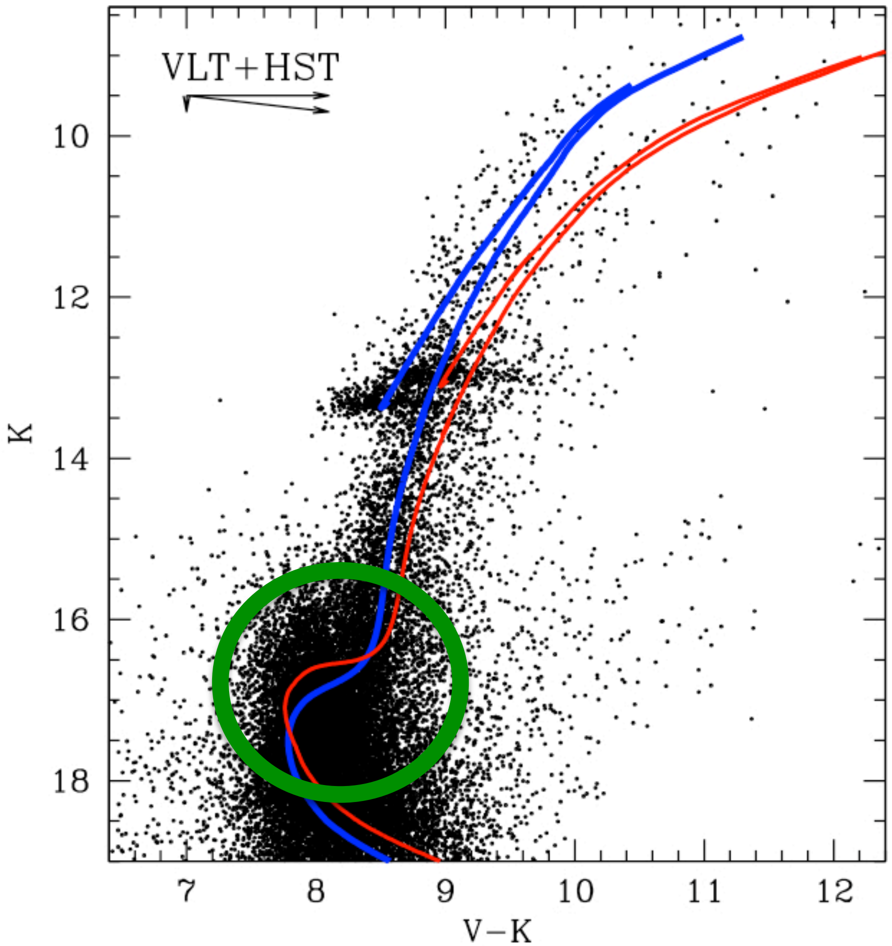
The **large number of SN II** needed to reach the fHB metallicity created a huge number of NS +
The **deep potential well** of the proto-Terzan5 system has retained most of them +
The **high collision rate** has favored the NS recycling
= the **large number of MSP that we observe today**

working hypothesis

If Bulges could form from the evolution and coalescence of giant primordial clumps (Immeli et al 2004, Elmegreen e al 2008) **Ter5 could be the remnant of one of those pristine fragments that survived the total disruption**

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

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



Z=0.01 t=12 *Gyr*

Z=0.03 t=6 *Gyr*

We are now leading a number of projects aimed at:

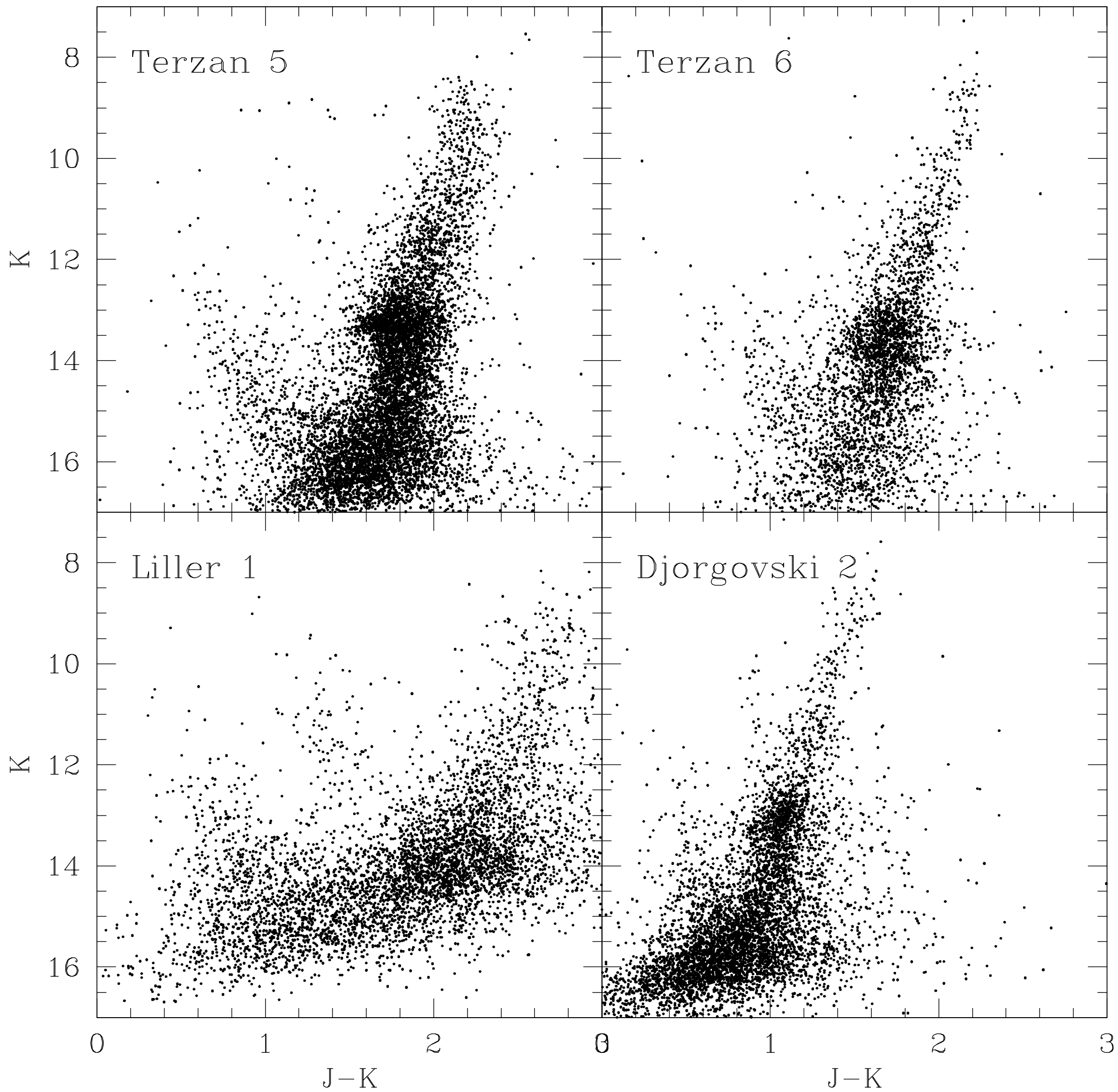
1. **Measuring the ages of the two populations from the MS-TO.** **Ultra-deep IR observations with WFC3-IR channel are planned in Cycle 20 (10 orbits allocated)**

2. **Investigating the radial velocity dispersion profile – We have collected 800 FLAMES spectra covering the entire cluster extension**

3. **Performing proper motion measures to search for kinematical signatures (second epoch ACS planned in HST-Cycle 20)**

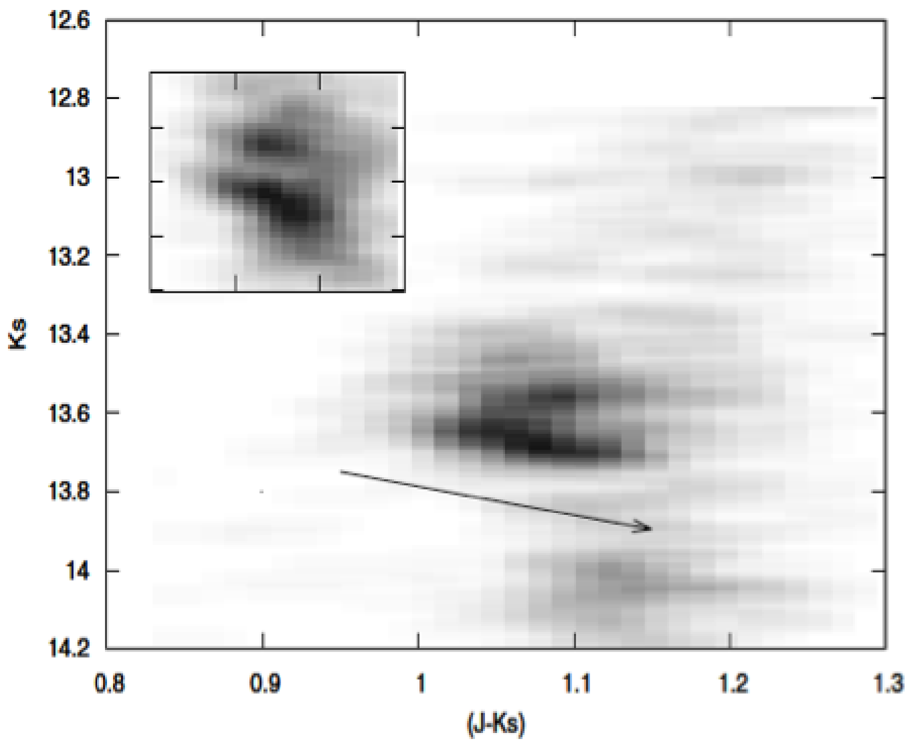
4. **Searching for other Terzan5-like systems in the Galactic Bulge**

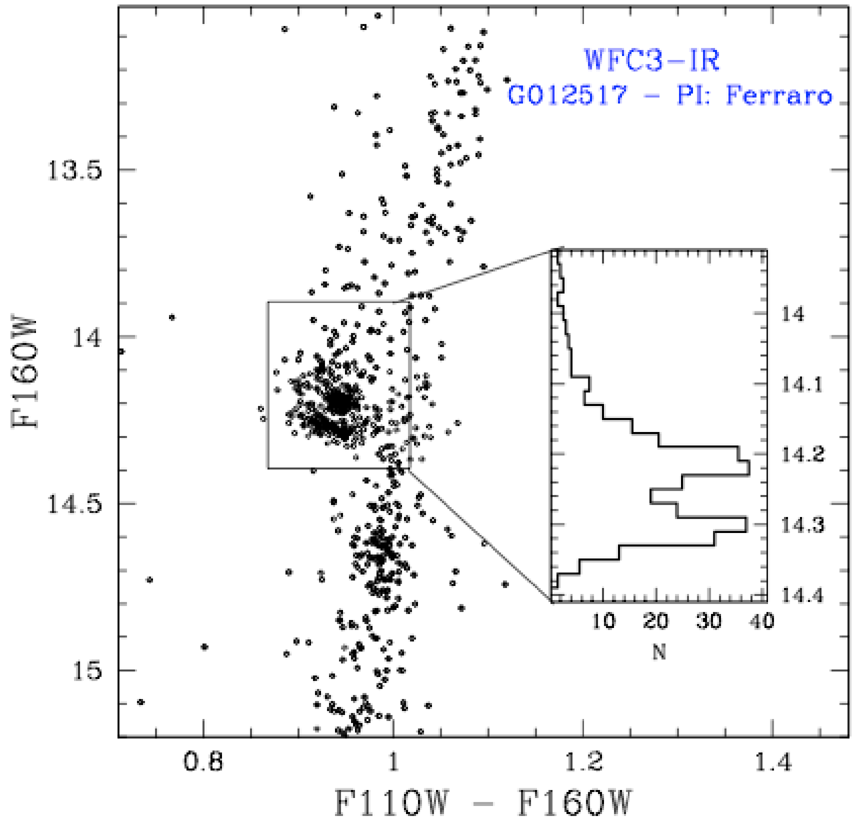
SEARCHING FOR OTHER TERZAN 5-LIKE STELLAR SYSTEMS



NGC6440: another Terzan 5?

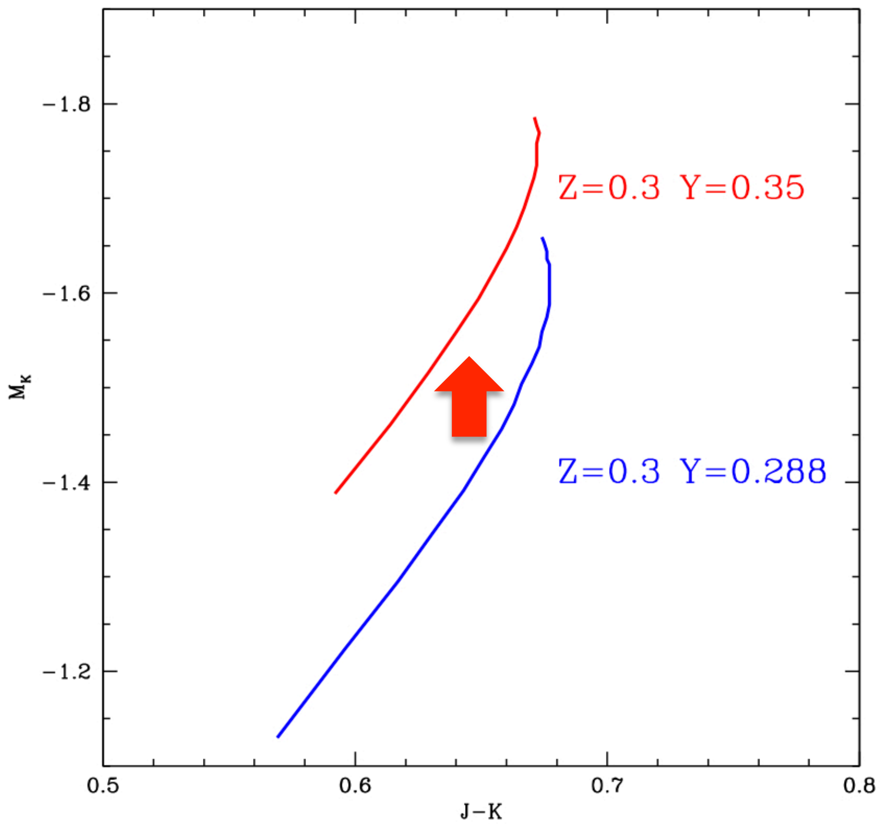
Mauro et al (2012, ApJ, 761, L29)





Spectroscopic measures of giants in this clusters (at the moment) DID NOT provide any evidence of MULTI-IRON populations

THE HELIUM EFFECT



An increase in Helium increases the RC luminosity leaving the color almost unchanged

$$\left(\frac{\Delta M_K}{\Delta Y}\right)_{[Fe/H]} = \frac{0.17}{0.062} = 2.7$$

The Galactic Bulge summary

Chemical composition

The MDF peaks around solar, a long tail down to [Fe/H]~ -1.6 and
a super solar component
[α/Fe]>0 enhancement at least up to solar [Fe/H]

Terzan 5

Age

The bulk is old (>10 Gyr)
A few Gyr younger component (few % ?)

Formation

Bulges could form from the evolution and coalescence of **giant primordial clumps**
(Immeli et al 2004, Elmegreen et al 2008)

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The End