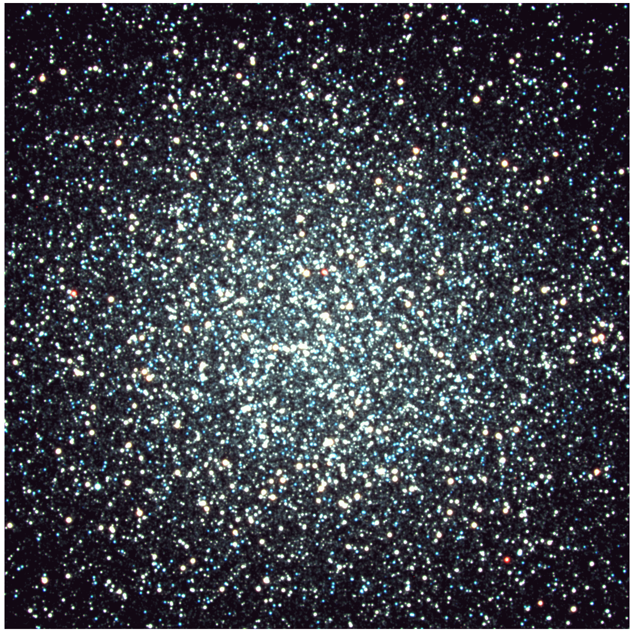
MAX PLANCK INSTITUTE
FOR RADIO ASTRONOMY

Terzan 5: the remnant of a pristine fragment of the Galactic bulge?

FRANCESCO R. FERRARO

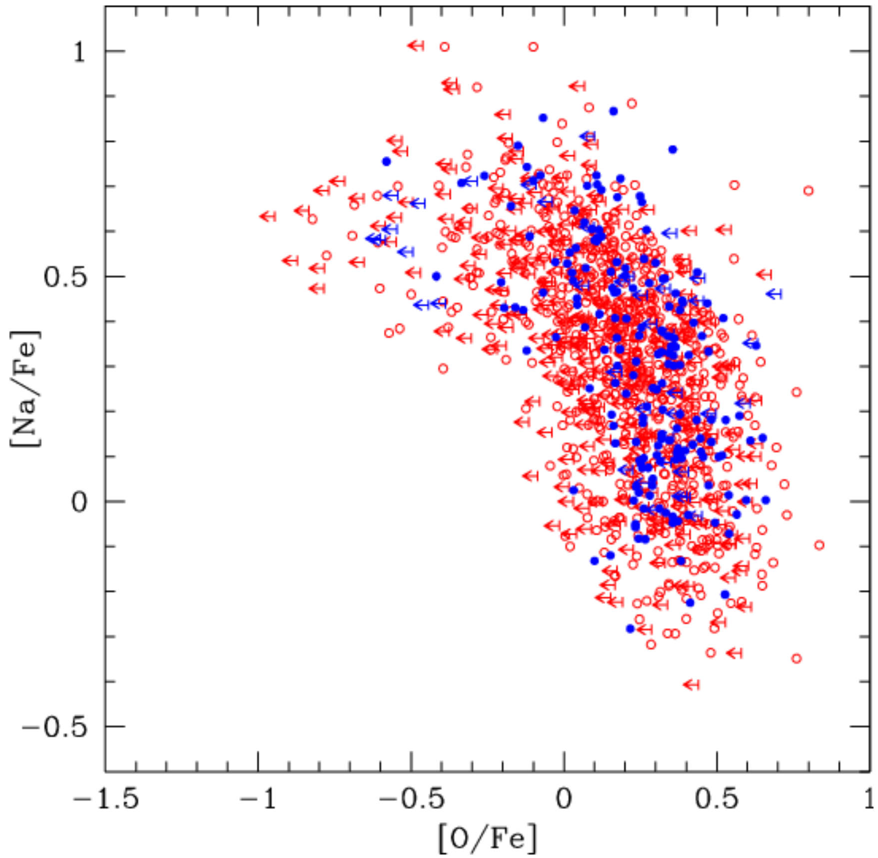
Physics & Astronomy Department – University of Bologna (Italy)

Bonn, March 14, 2014



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

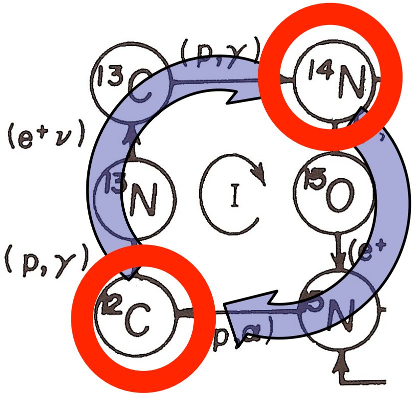
STARS IN GGCs ARE NOT CHEMICALLY HOMOGENEOUS IN LIGHT ELEMENTS



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

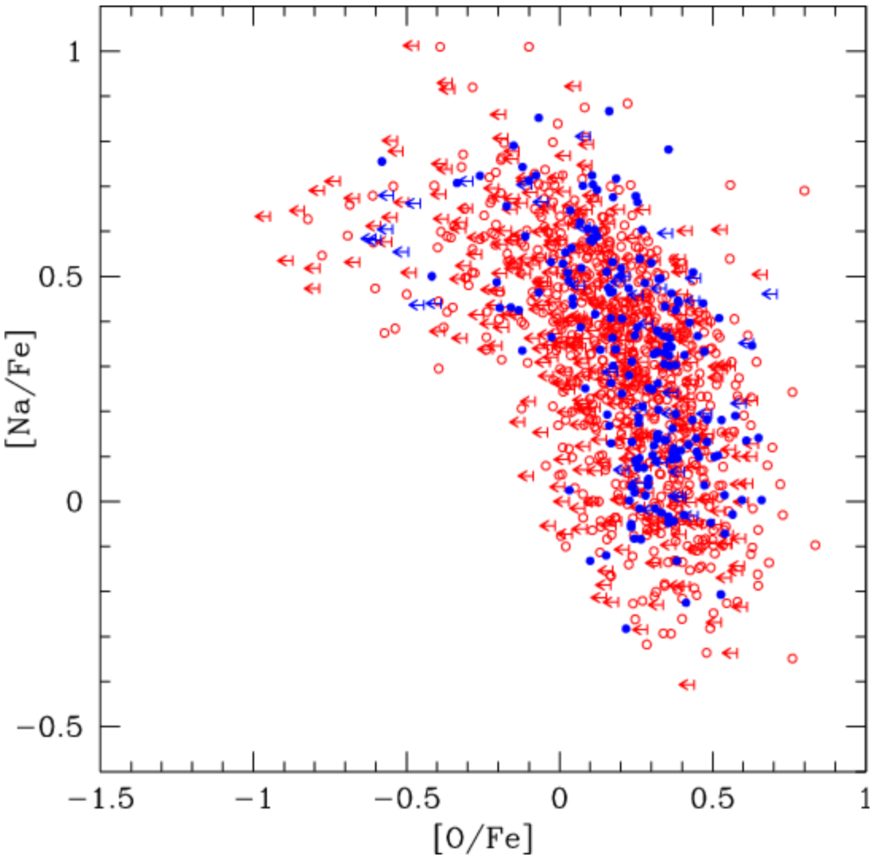


At 20M°K
C-N

At 40M°K
Na-O

At 70M°K
Al-O

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)

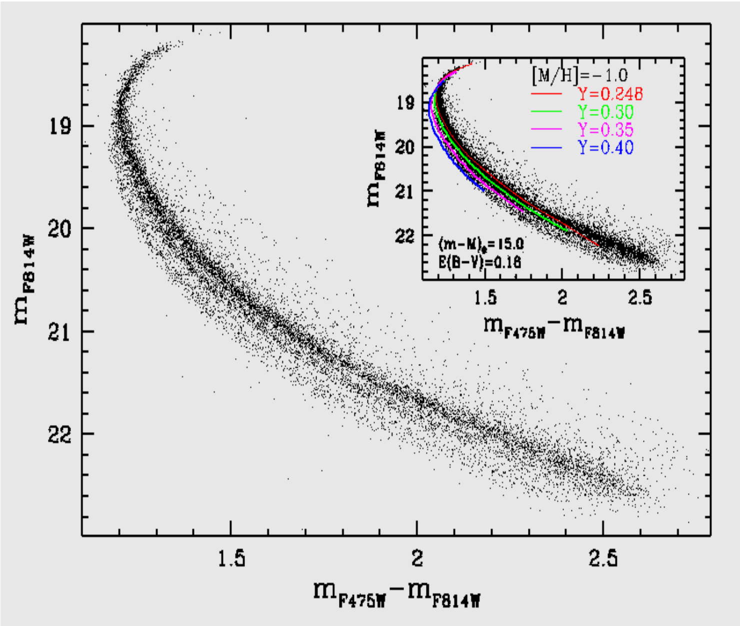
p-processes produce Helium

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)

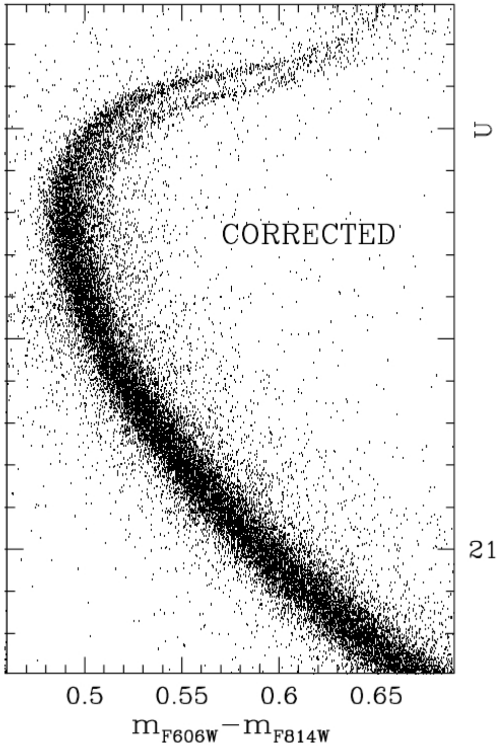
NGC2808



Piotto et al. 2007, ApJ, 661, L35

He

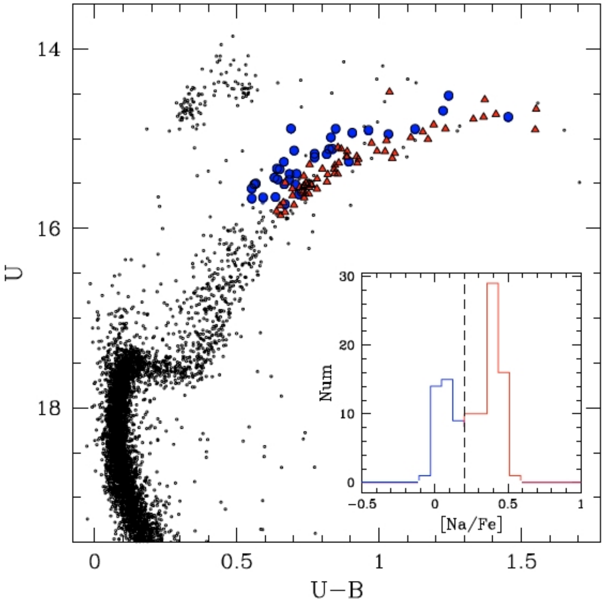
NGC1851



Milone et al. 2008, ApJ 673, 241

CNO Na

M4



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

Na O

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

There are ONLY 2 major exceptions known within the GALAXY with quite large iron difference (Δ[Fe/H]~ 1 dex) :

Omega Cen in the Halo
Terzan 5 in the Bulge

POTENTIAL WELL OF THE ORIGINAL STELLAR SYSTEM

"GENUINE GC" DID NOT RETAIN THE SNe EJECTA

GENUINE GLOBULAR CLUSTERS

Anticorrelations +
Δ [He,C,…/H] $\neq$ 0

Δ [Fe/H] = 0

Enrichment Timescale: 10^8 yr

THEY RETAINED THE SNe EJECTA

ω Cen

Terzan 5

Multi- [Fe/H] populations

Enrichment Timescale: 10^9 yr

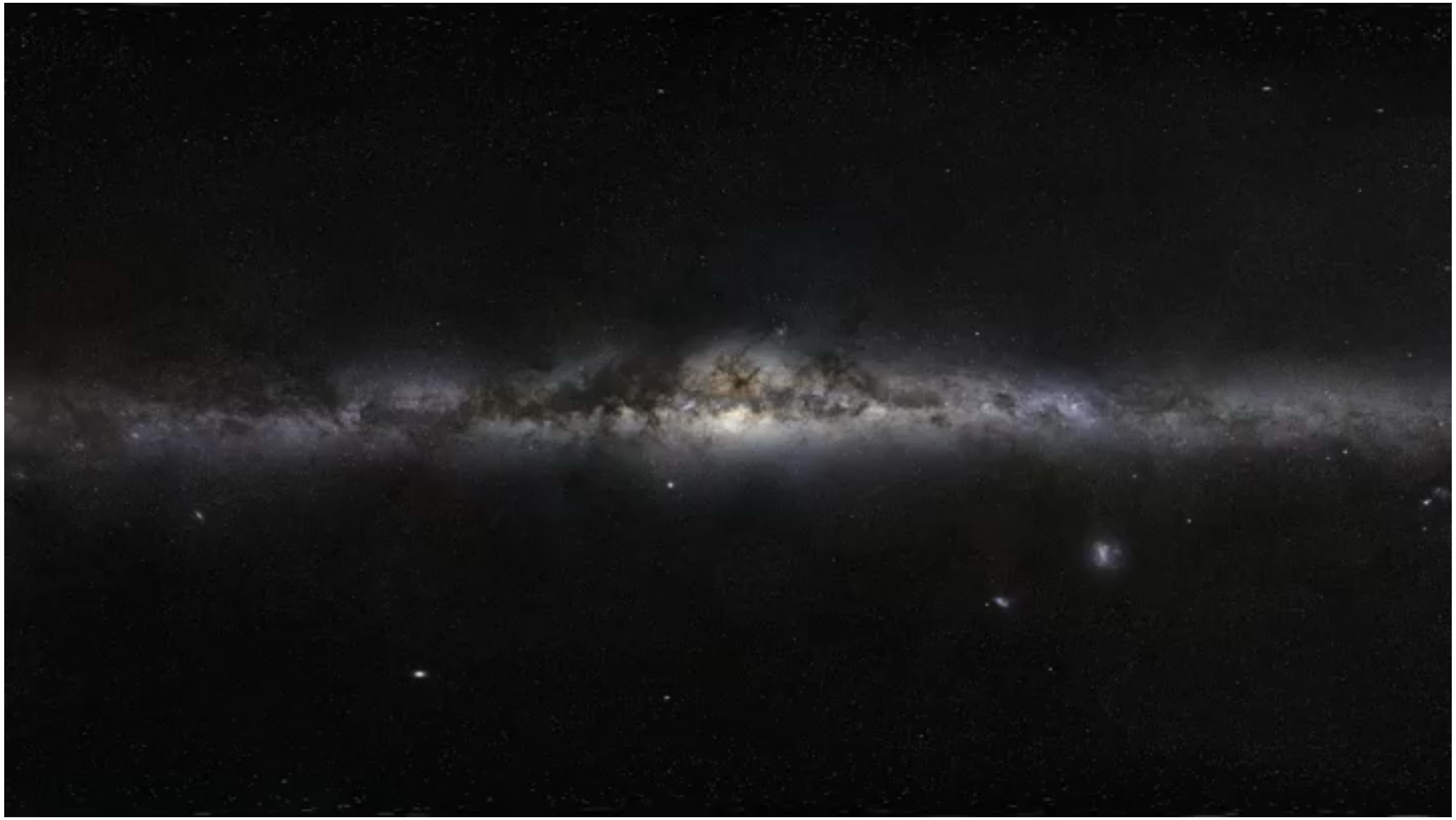
TERZAN 5 :

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

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

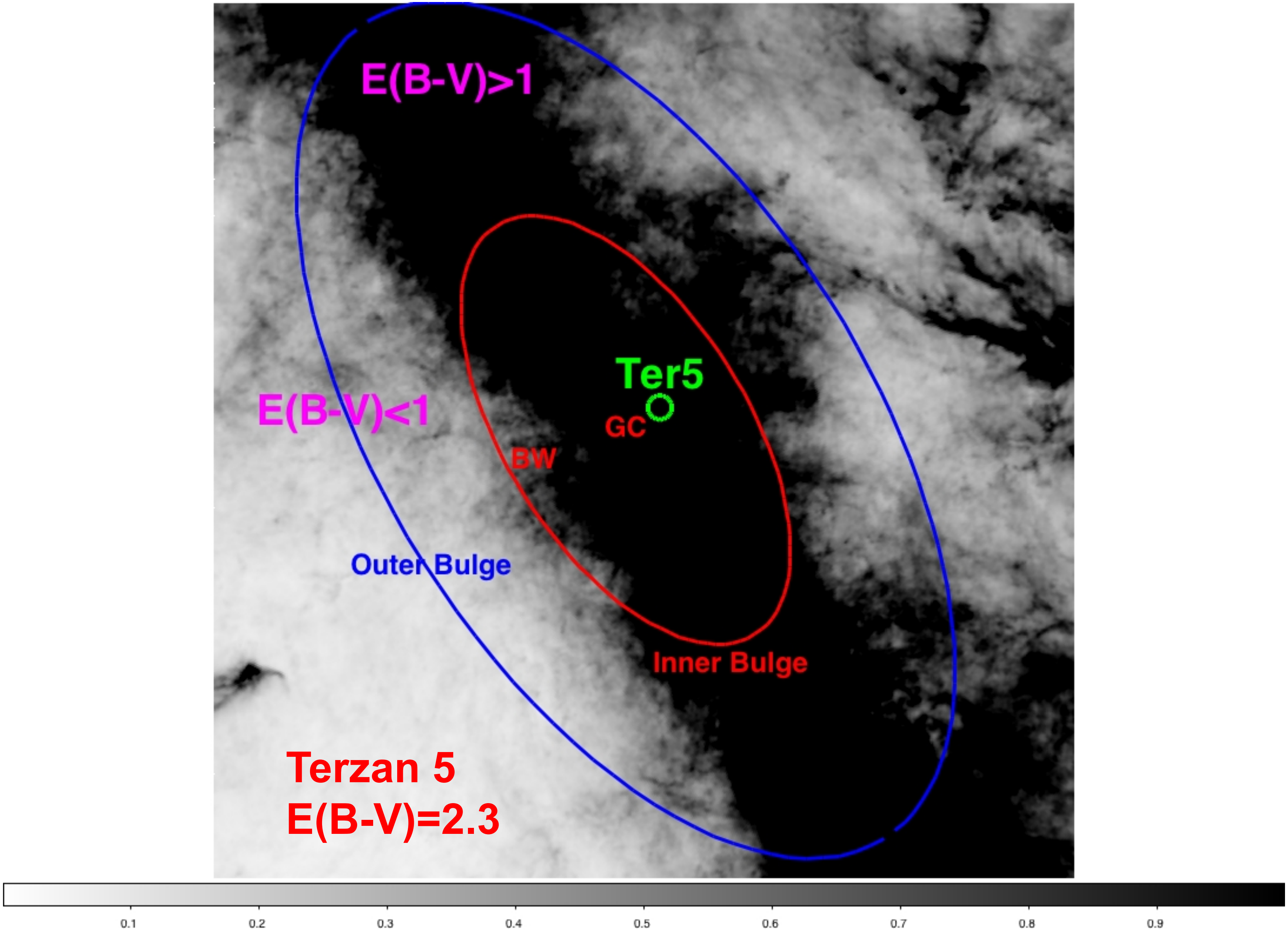
The aim of COSMIC-LAB is to explore the complex interplay between stellar evolution and the dynamical evolution of stellar systems by using exotic objects as BSS and MSP as probe particles.

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

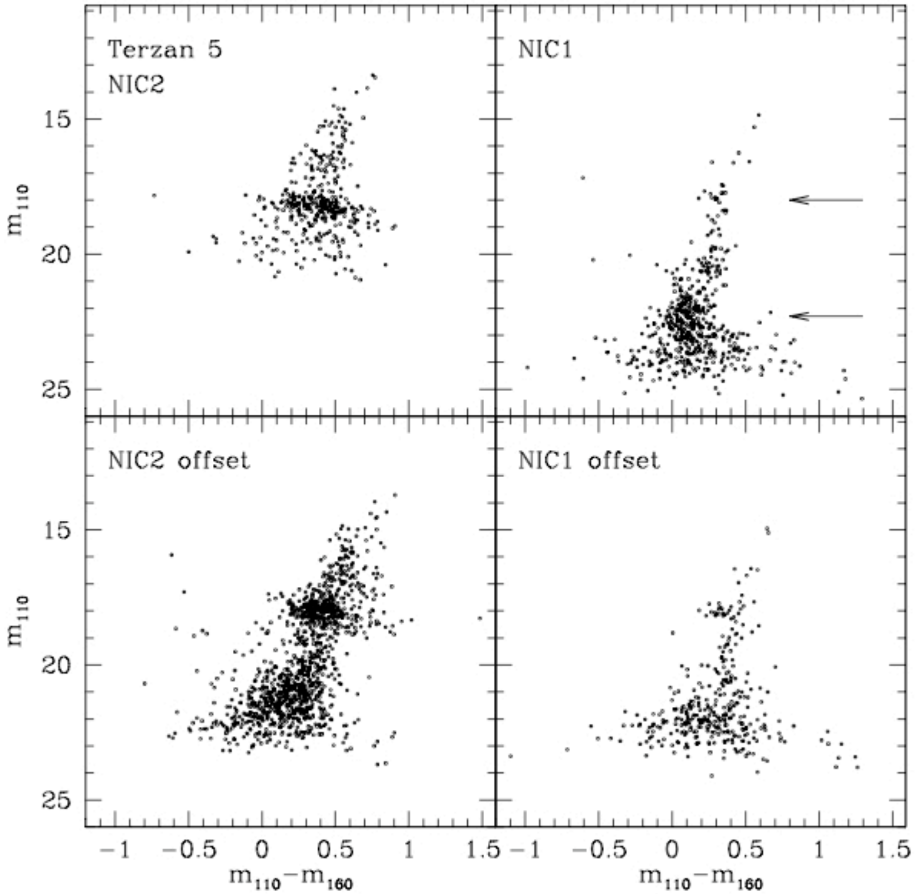


E(B-V)=2.3; d = 6Kpc; d_{GC}=2.1 kpc (Valenti et al 2007) i.e. in the outskirts of the inner Bulge. Suspected to have the largest collision rate of the entire GC system (Verbunt & Hut 1987, Lanzoni et al 2010)

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

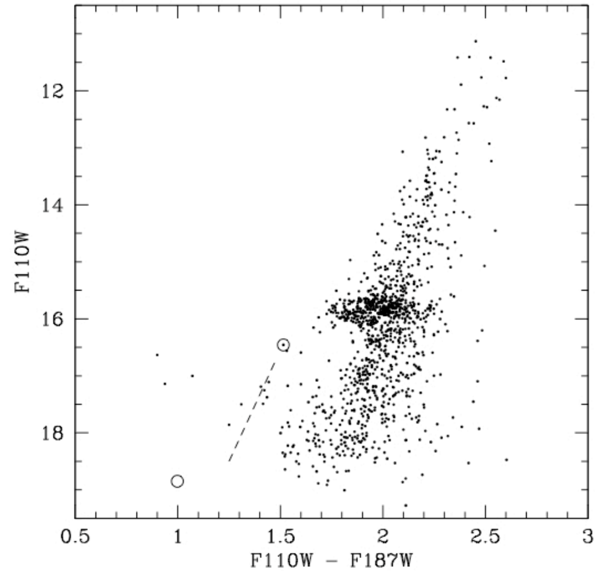

E(B-V)>1
Ter5
E(B-V)<1
GC
BW
Outer Bulge
Inner Bulge
Terzan 5
E(B-V)=2.3
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

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

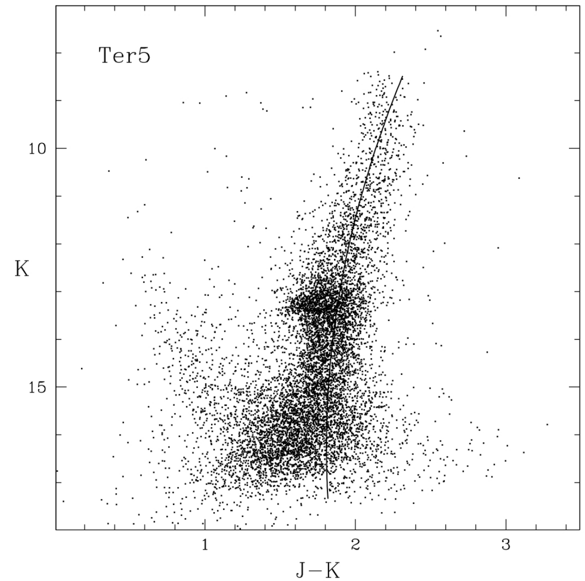


Ortolani et al (2001,A&A,376,878)

NIC2@HST- FoV:19''X19''



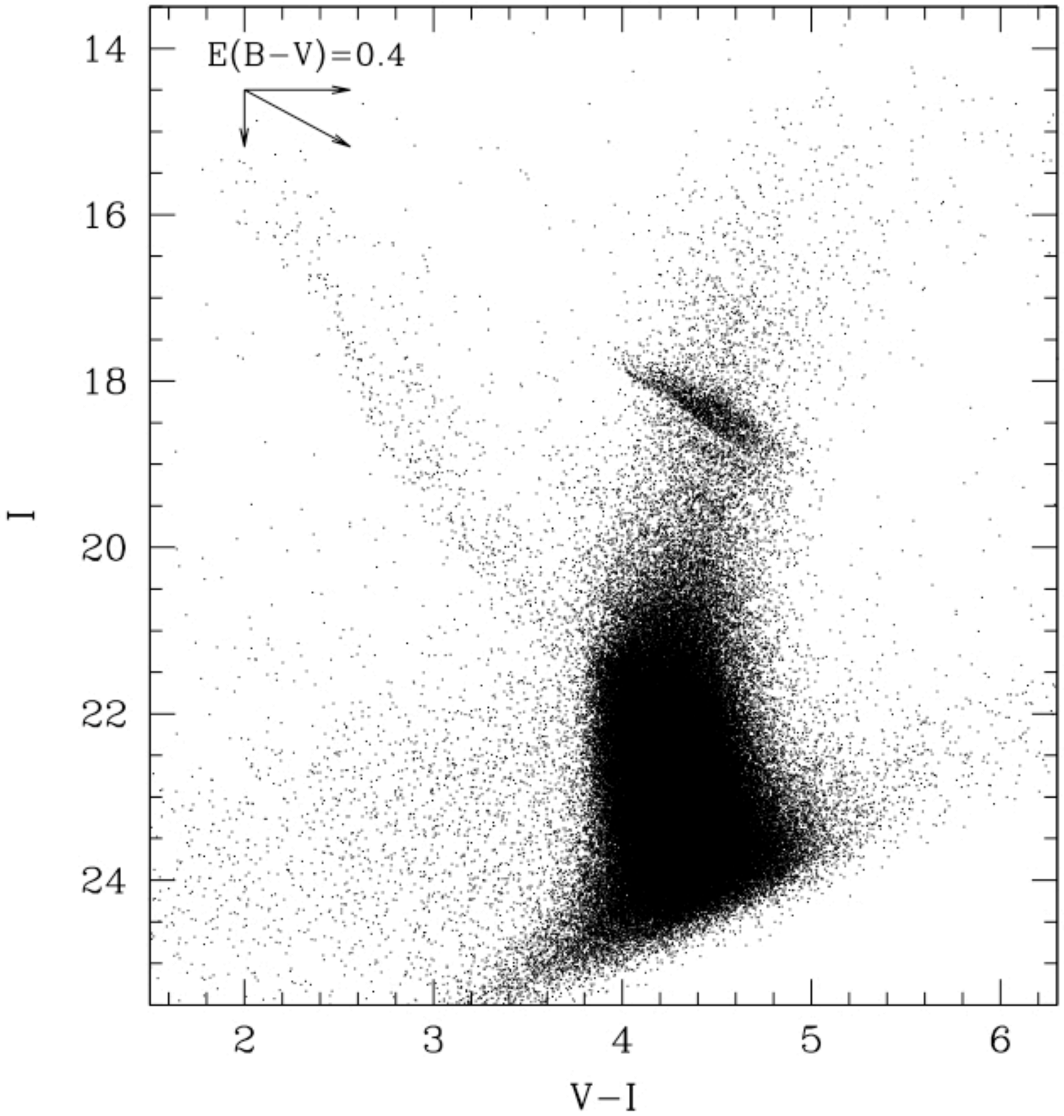
Cohn et al (2002, ApJ, 571, 818)



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

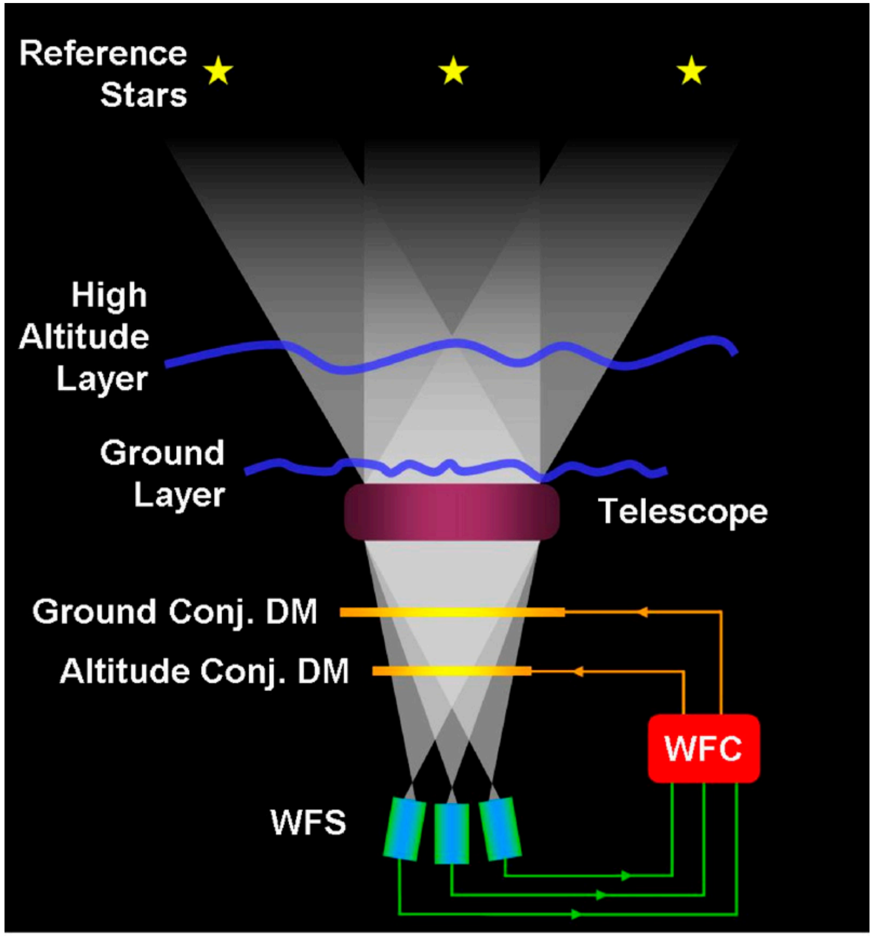
Cosmic-Lab

The deepest optical CMD of Terzan5 from ACS@HST



Main Problem:
Differential reddening

MAD = Multi-conjugate Adaptive Optics Demonstrator

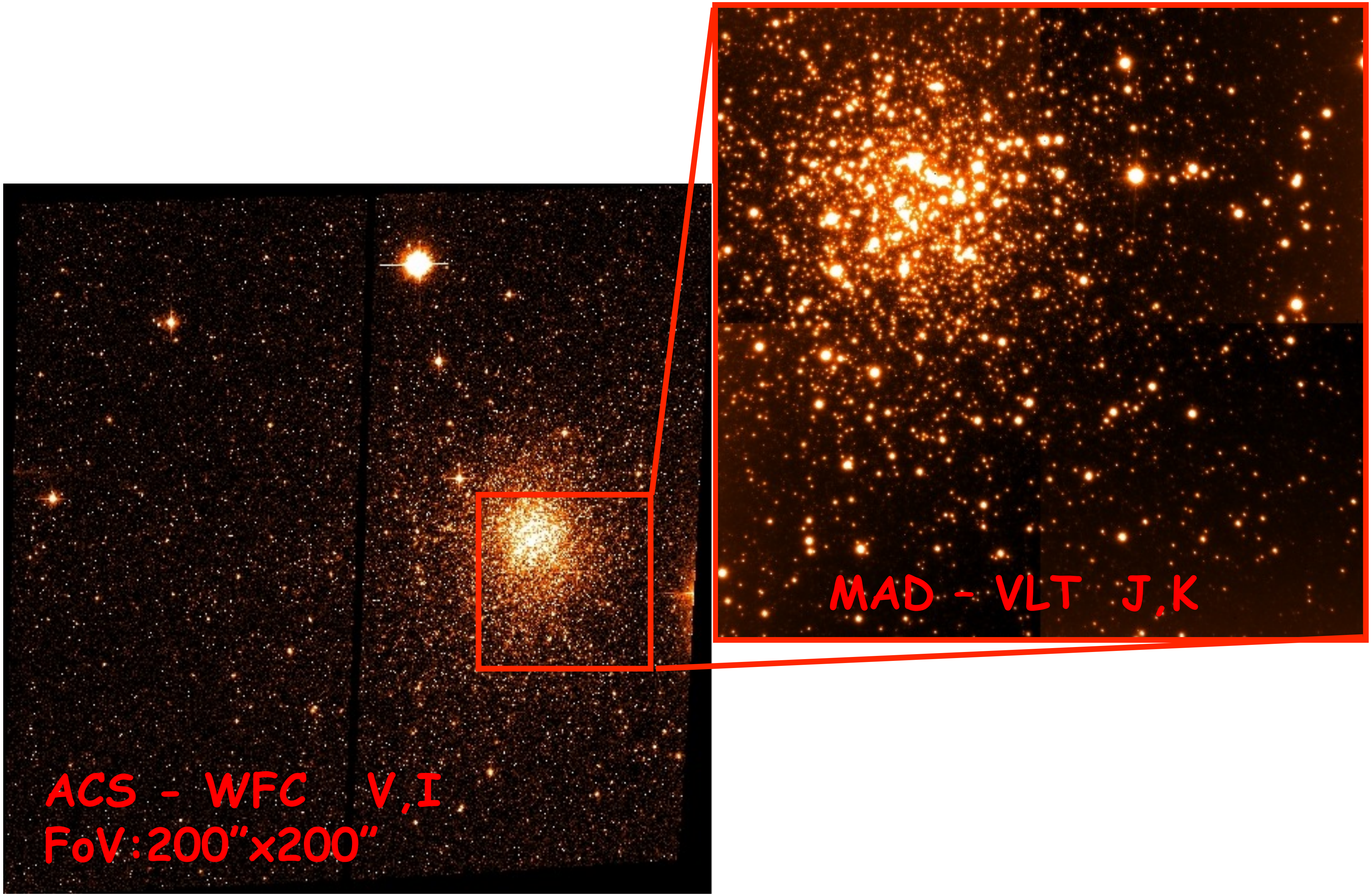


The MCAO Concept

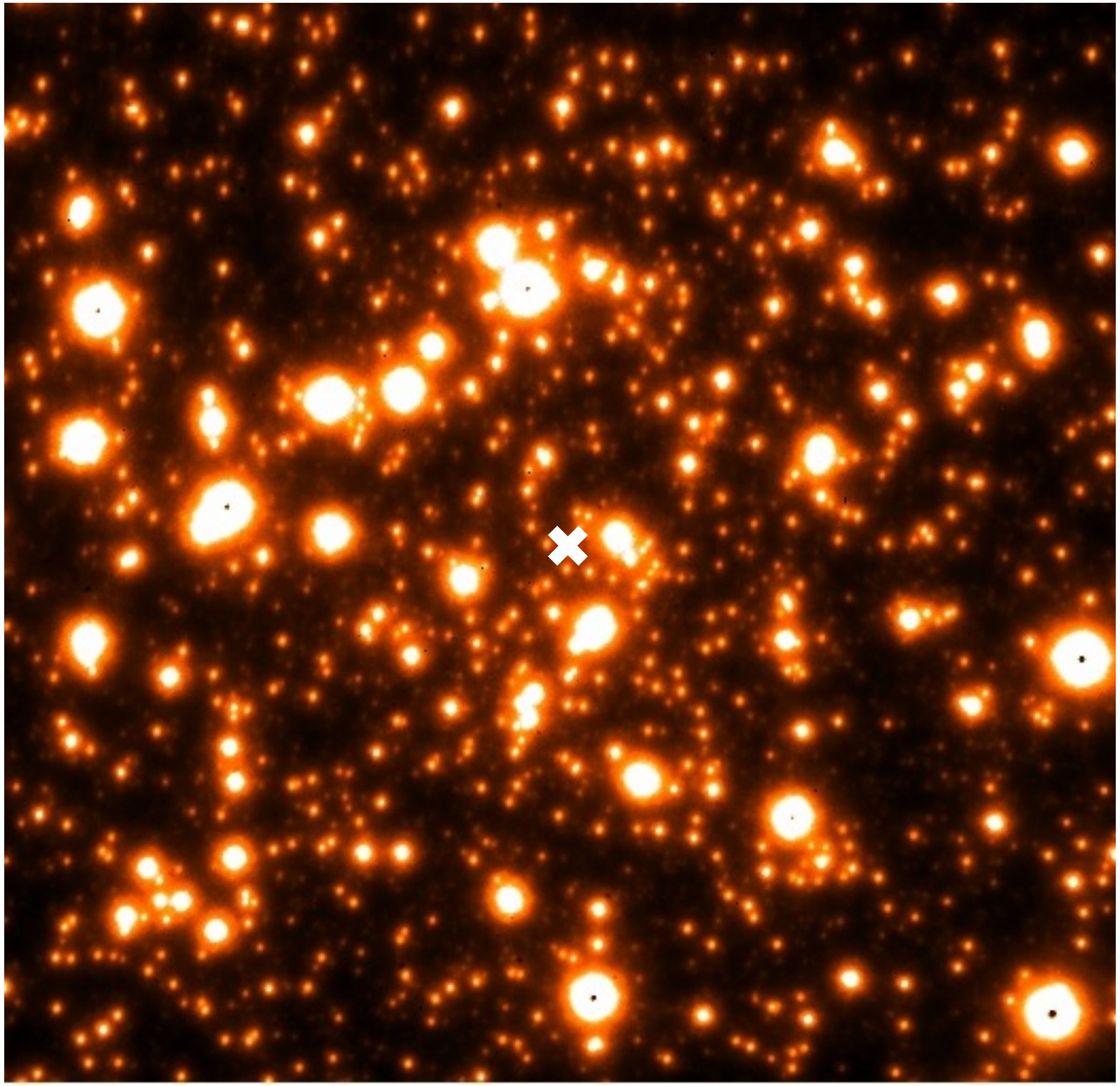
ESO Press Photo 19c/07 (30 March 2007)

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



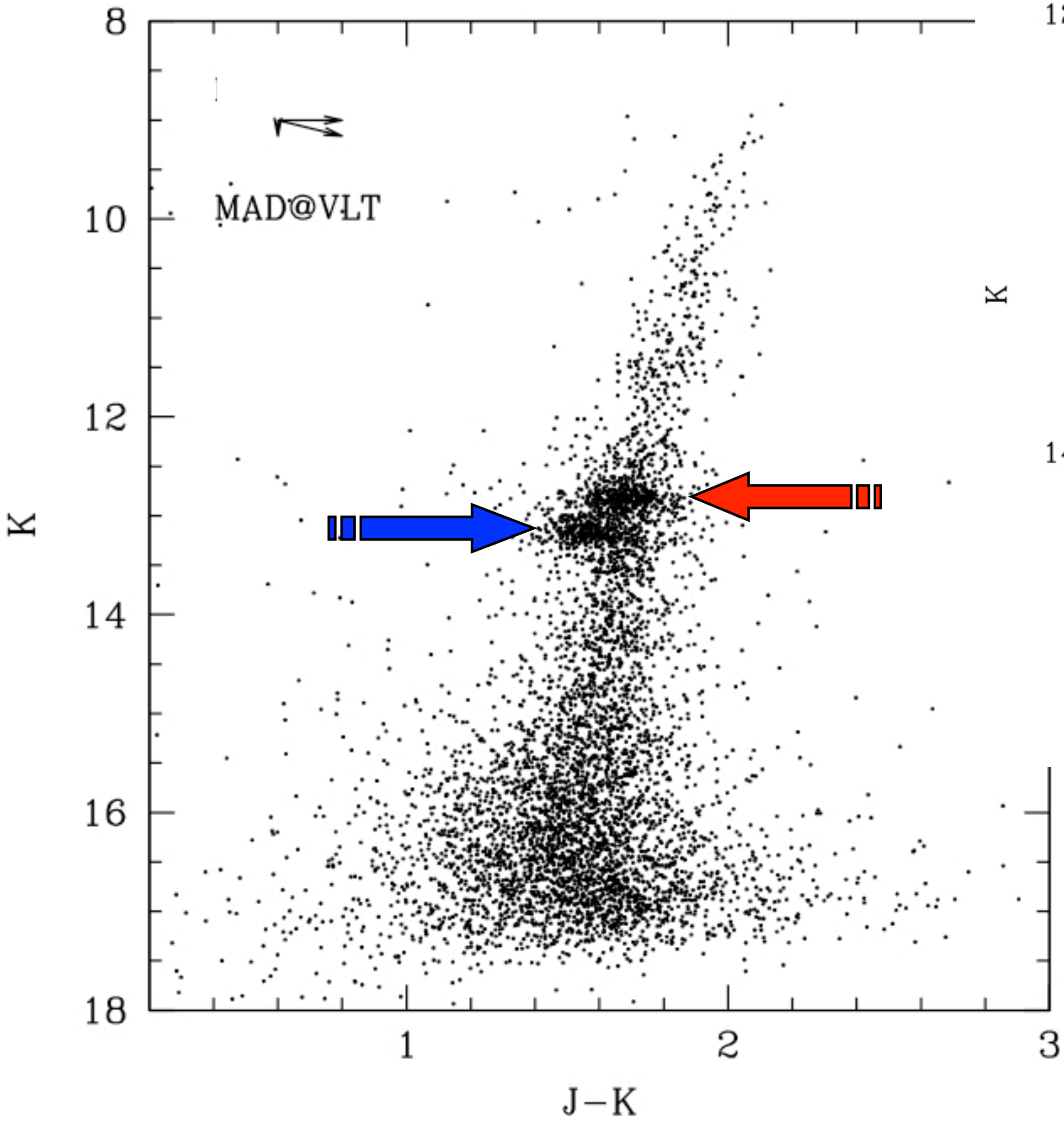
Note the difference between the best K and J image

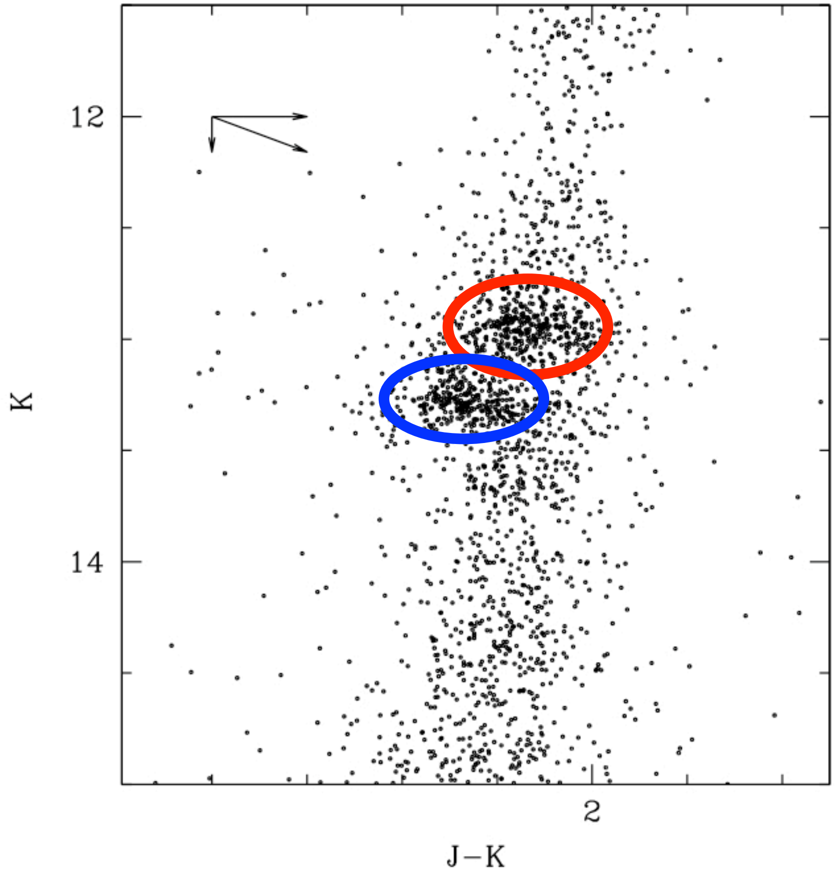


FWHM=100mas
By using
only 2 AOGS !!!!

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

THE MAD CMD OF TERZAN 5

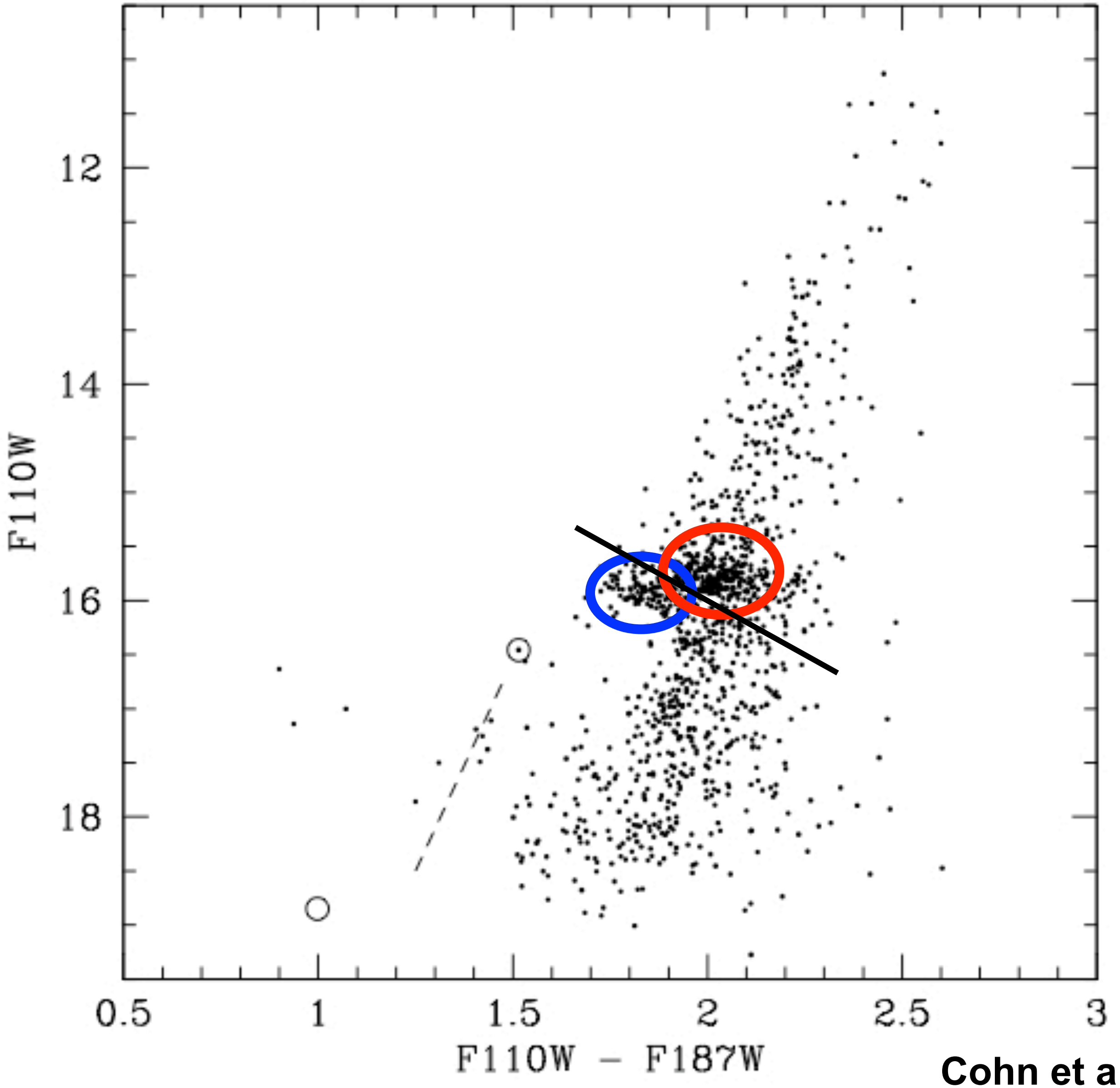




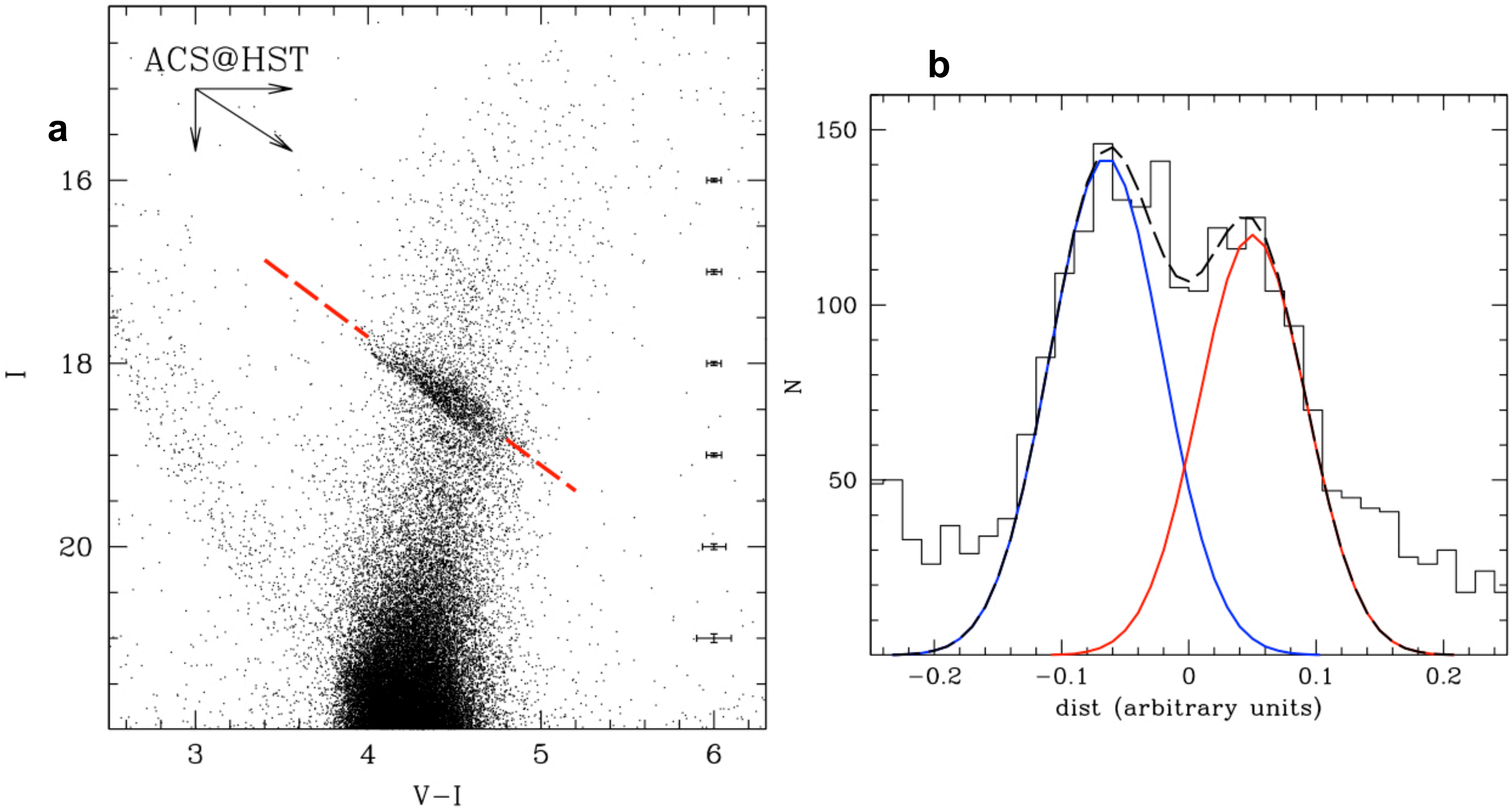
TWO Red Clumps !!!

ΔK~0.3 mag
Δ(J-K)~0.2 mag

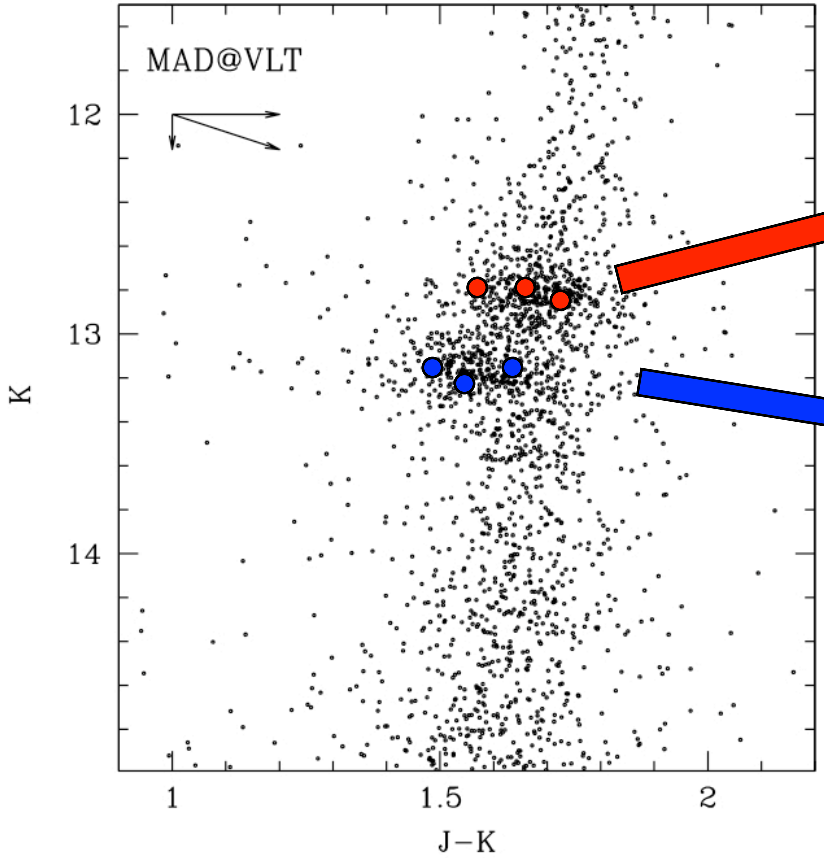
Ferraro et al (2009, Nature, 462, 483)



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


a
ACS@HST
I
16
18
20
V−I
3
4
5
6
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 **bRC** and **fRC**)

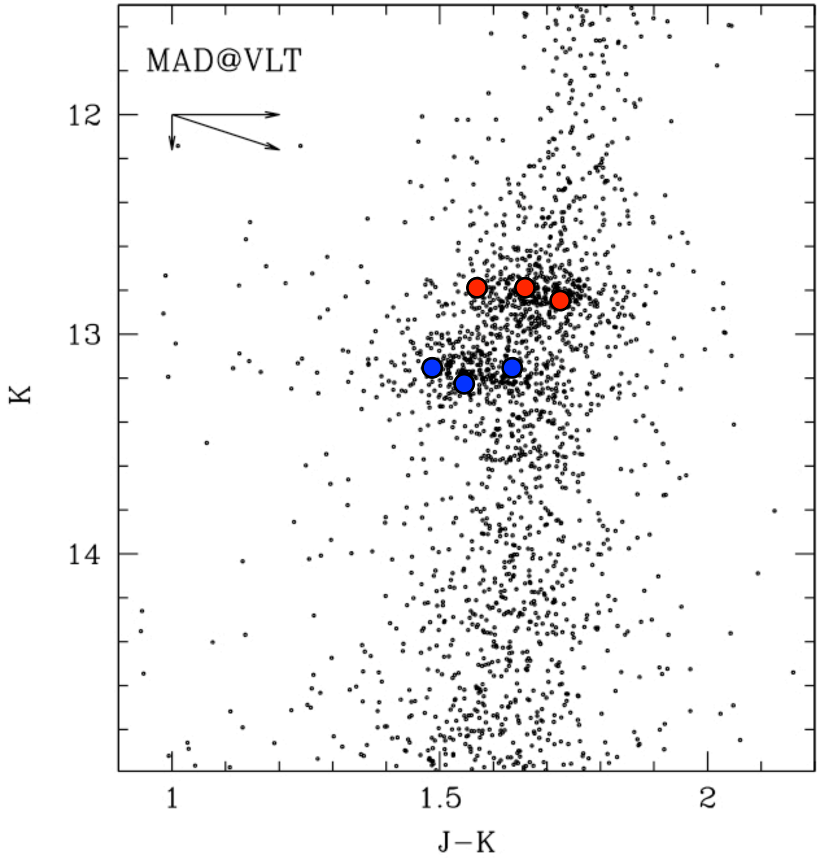


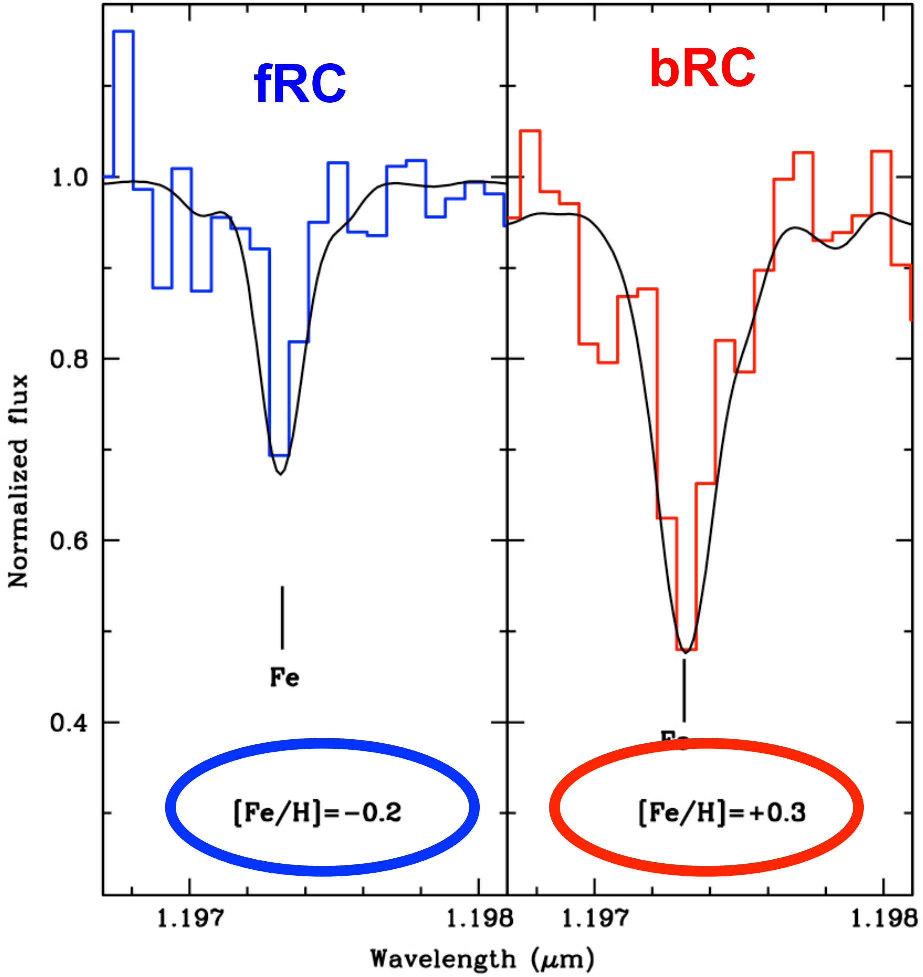
V_{rad} = -85 Km/s

V_{rad} = -85 Km/s

The two populations belong to the same stellar system

NIRSPEC @ Keck II observations of HB stars (in the bRC and fRC)

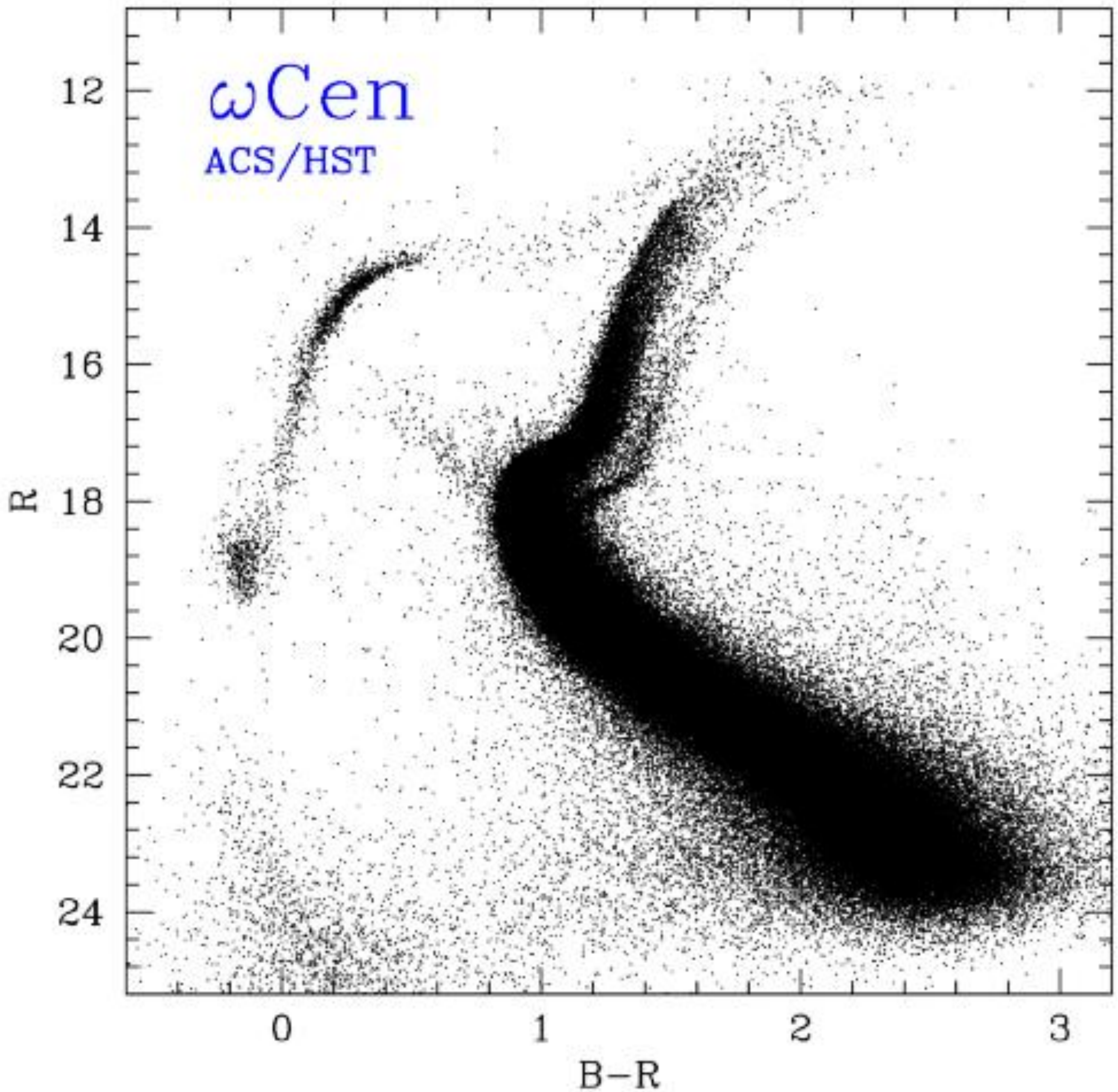




The two populations have different IRON abundance !!!

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

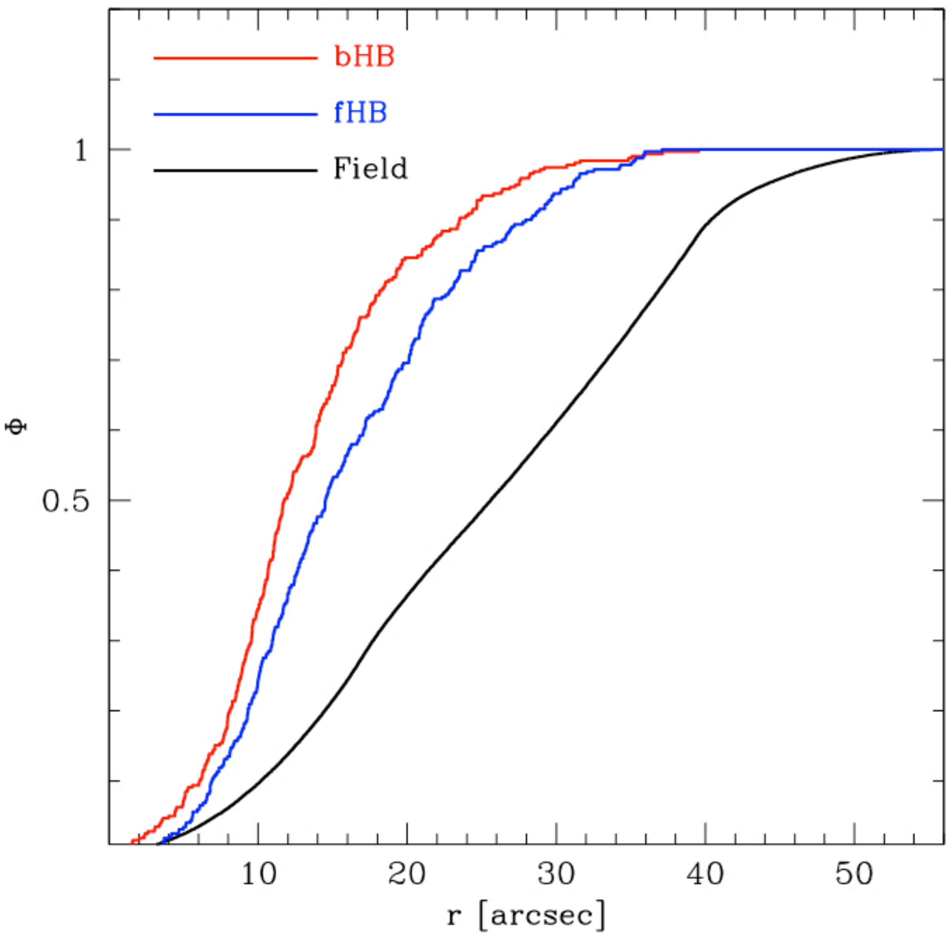
The only known example is OMEGA CENTAURI in the galactic Halo which is considered to be the remnant of a larger structure

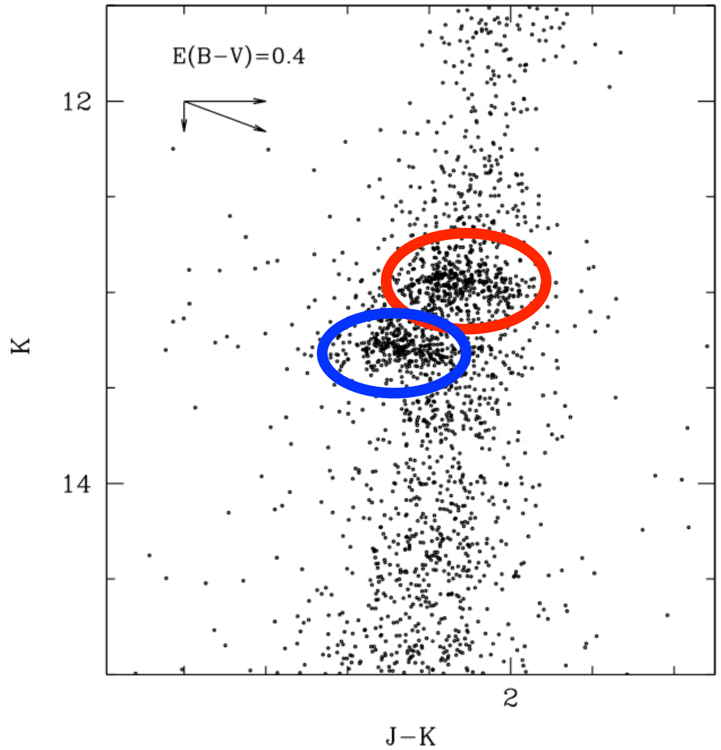


TERZAN 5 IS NOT A GENUINE GC

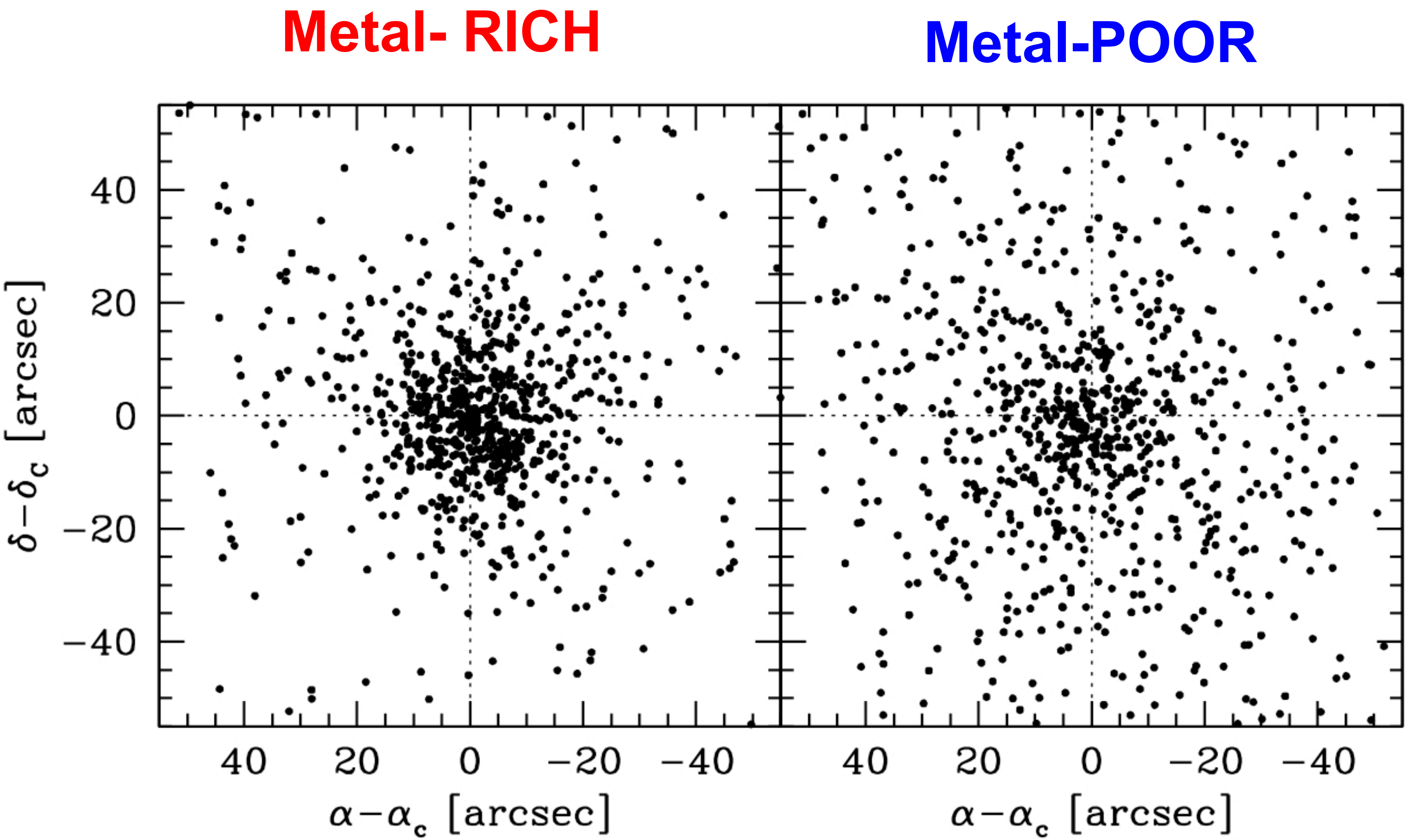
Two populations with different IRON abundance

What about their radial distribution ?

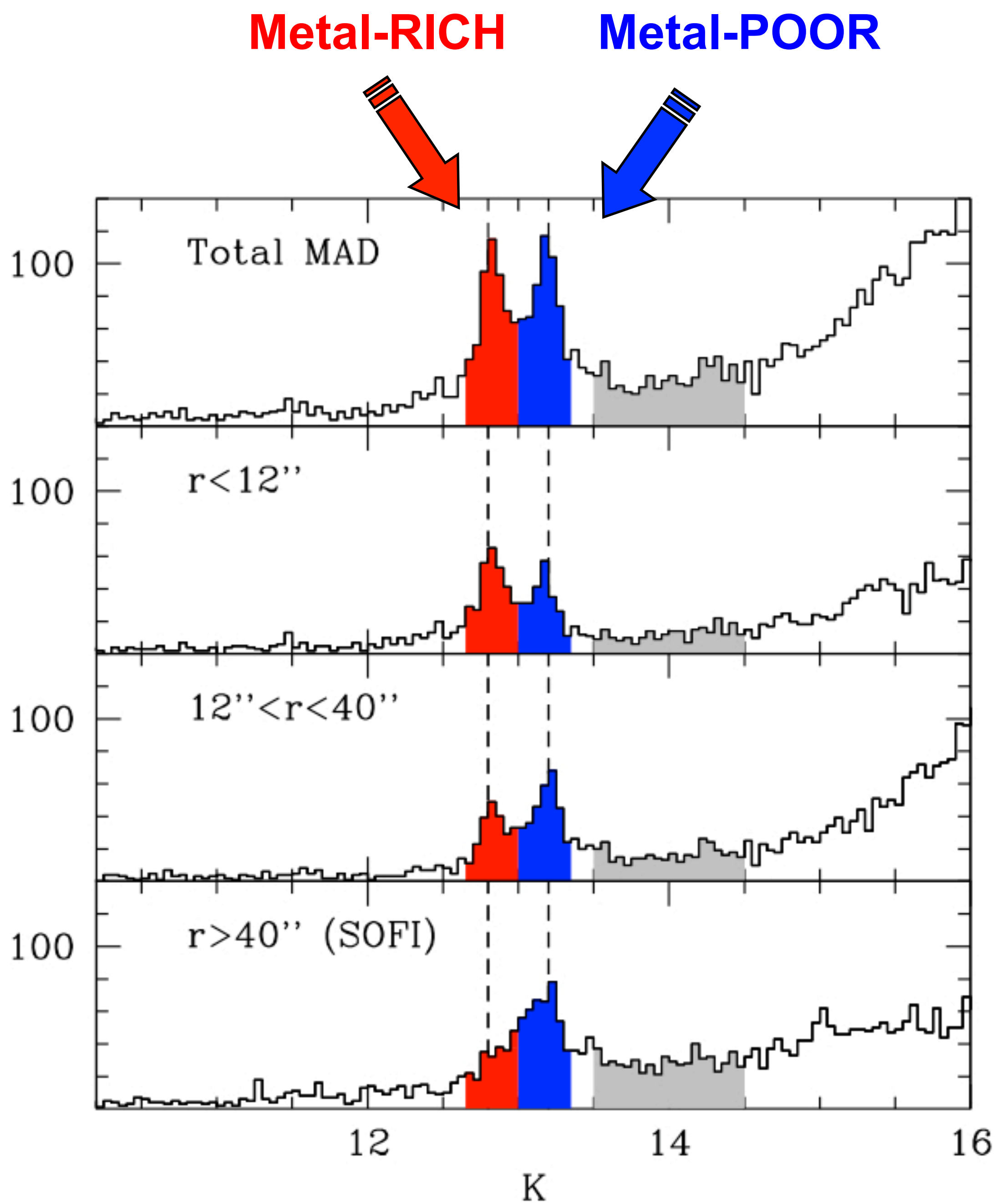




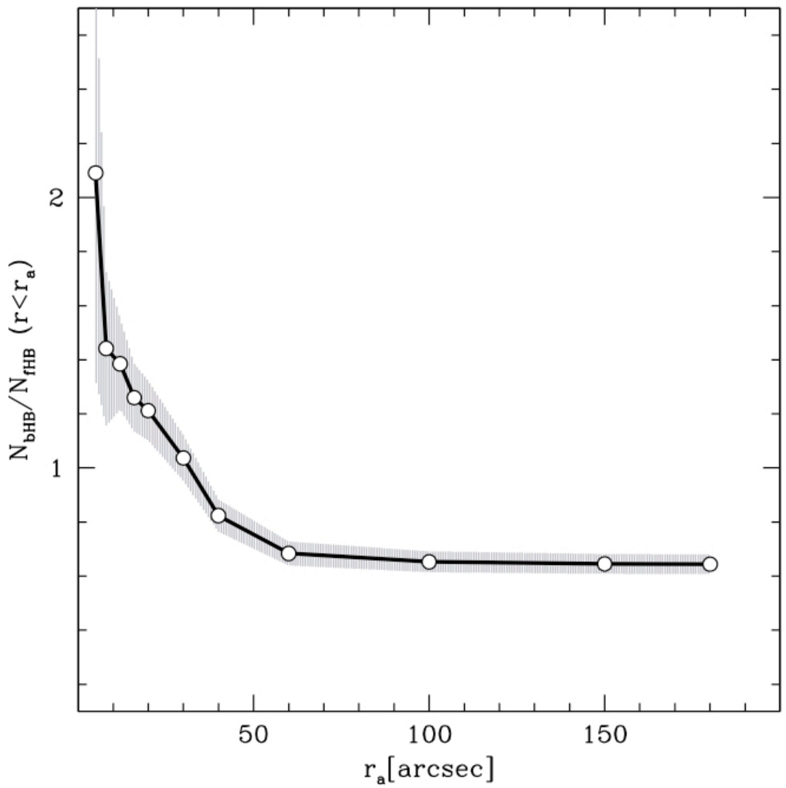
THE METAL RICH (bright-RC) POPULATION IS MORE CENTRALLY SEGREGATED THAN THE METAL POOR (faint-RC) ONE



Lanzoni et al. (2010)



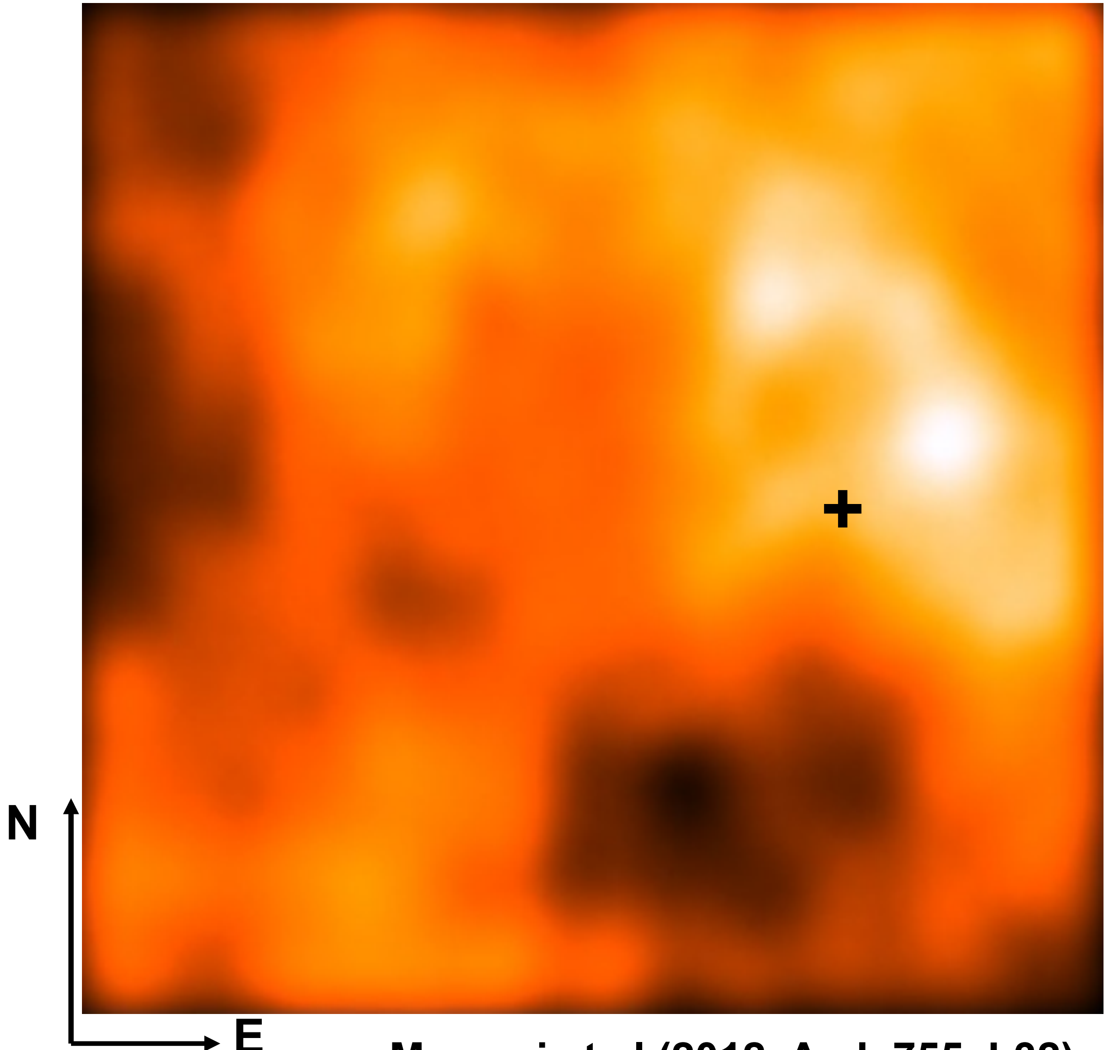
$$R = \frac{N_{bRC}}{N_{fRC}}$$



Two populations with different IRON abundance:

The (b-RC) most metal-rich component is significantly more centrally segregated than the (f-RC) "metal-poor" one

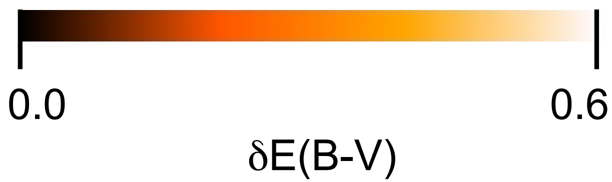
The differential reddening map in the direction of Terzan5



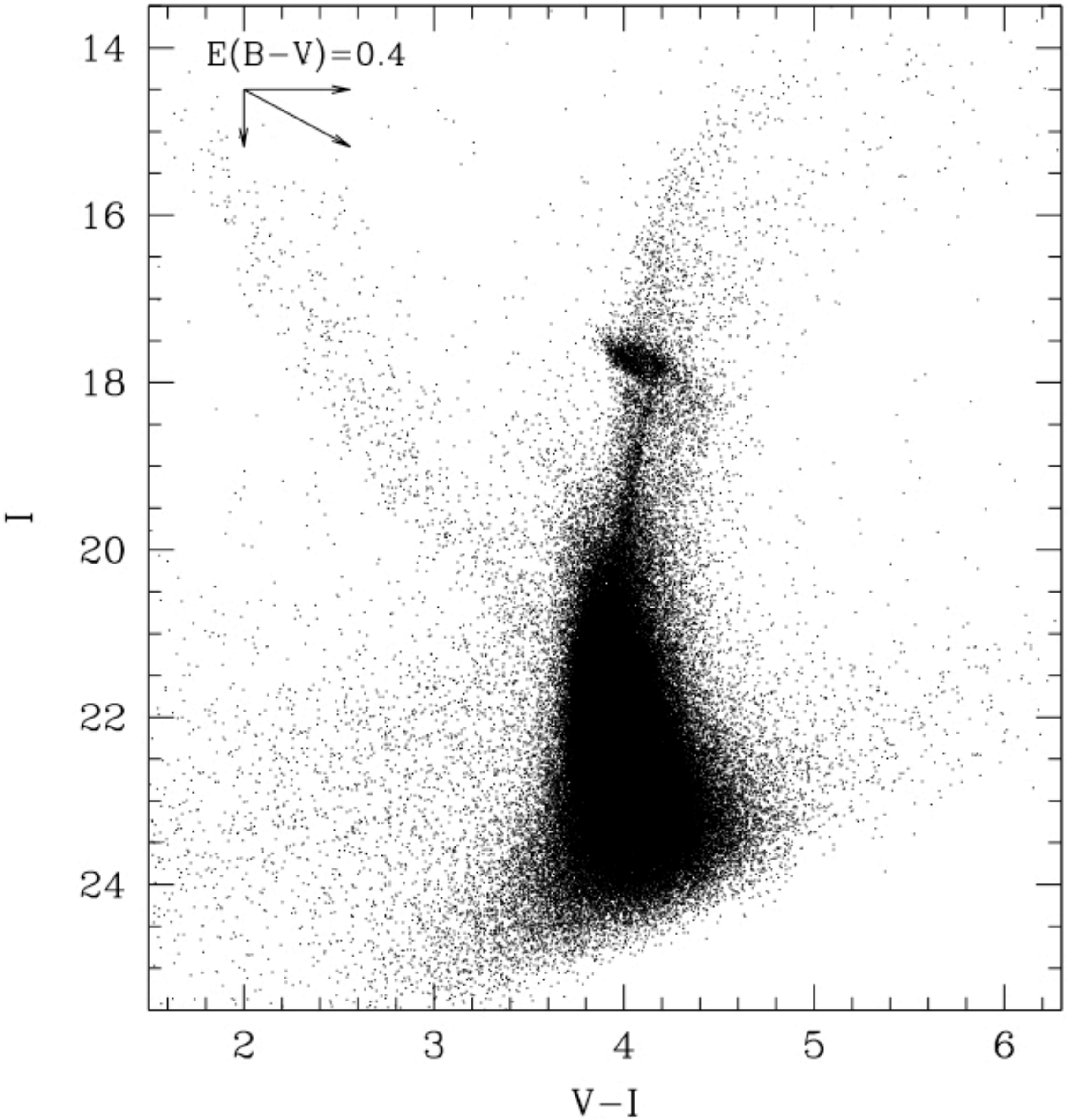
Massari et al (2012, ApJ, 755, L32)

Cardelli (1989)&
Schegel et al (1998)
Extinction law at the λ_{eff}
of the filters has been
used :

$A_V = 2.83/E(B-V)$
$A_I = 1.82/E(B-V)$

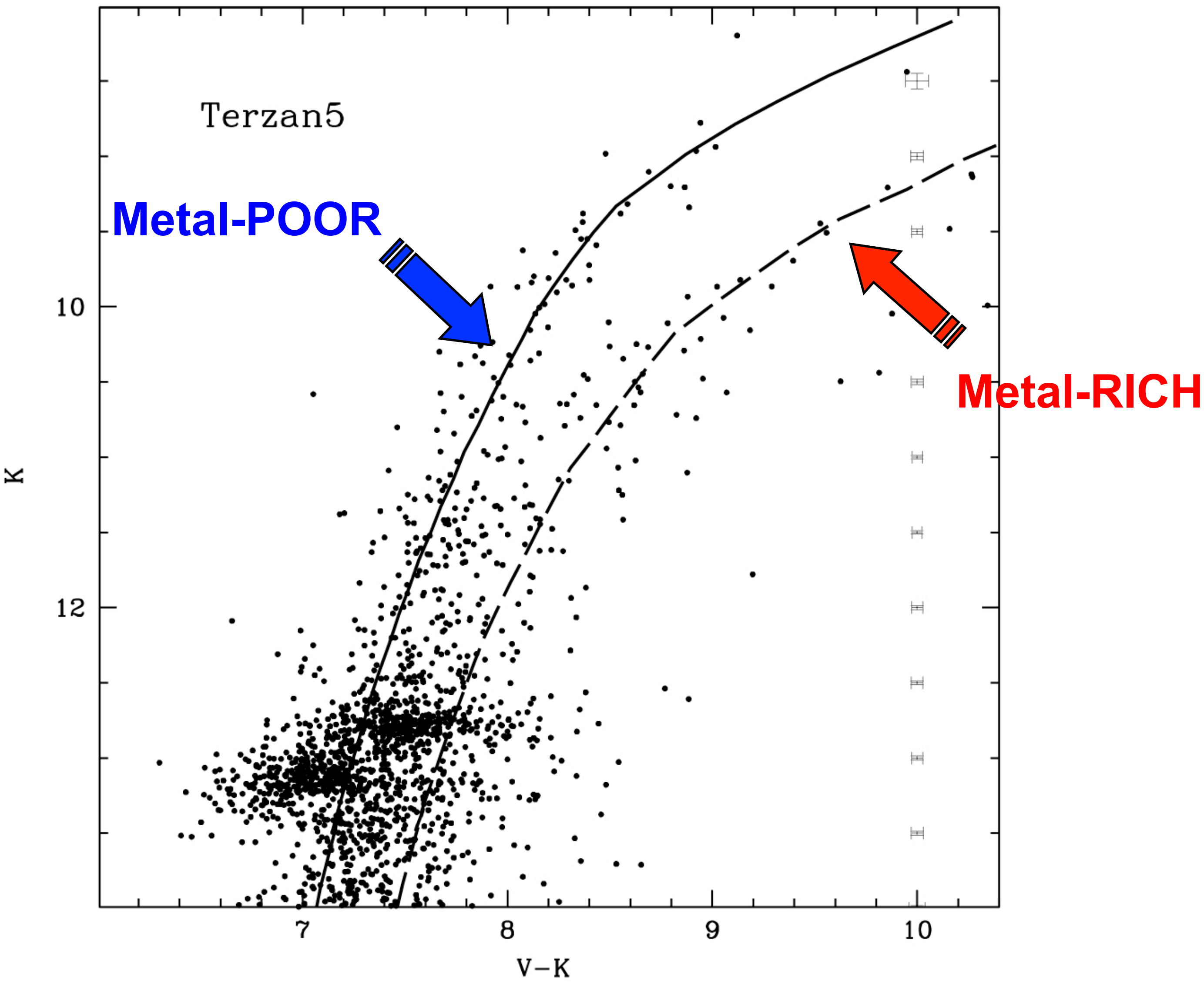


Correcting for differential reddening.



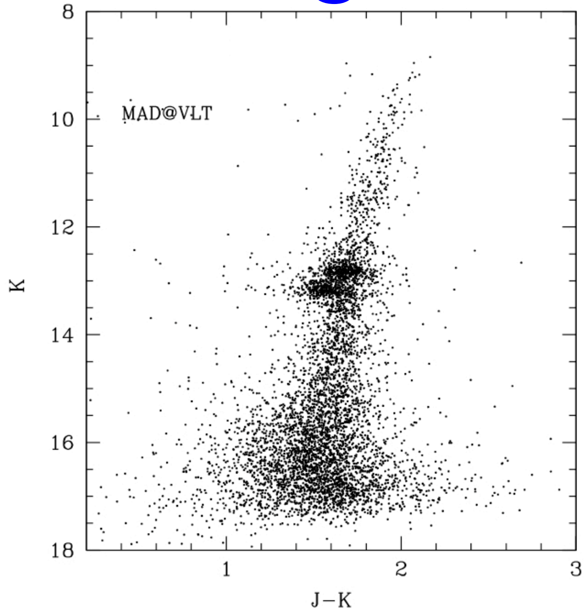
Massari et al (2012, ApJ, 755, L32)

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

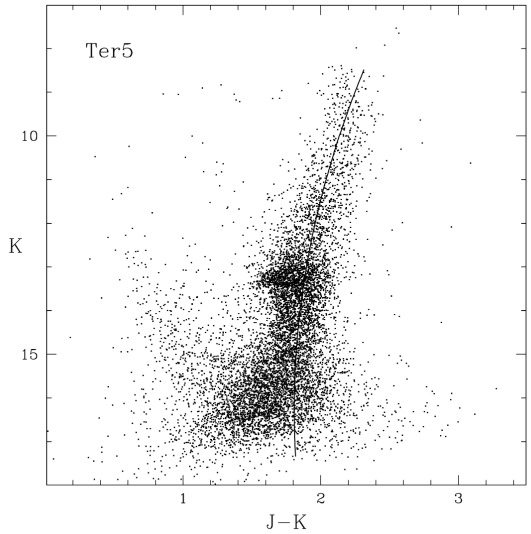


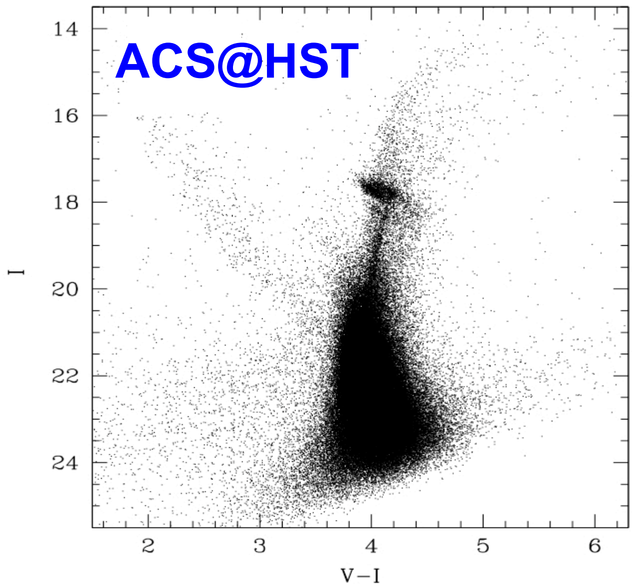
STAR-DENSITY PROFILE & STRUCTURAL PROPERTIES

MAD@VLT

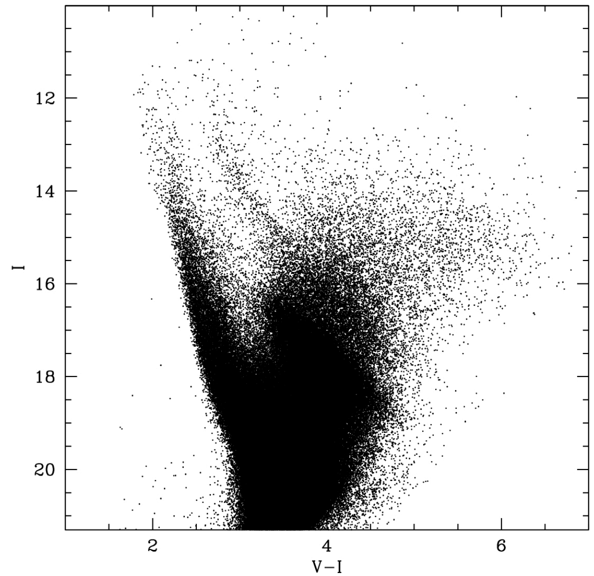


SOFI@NTT

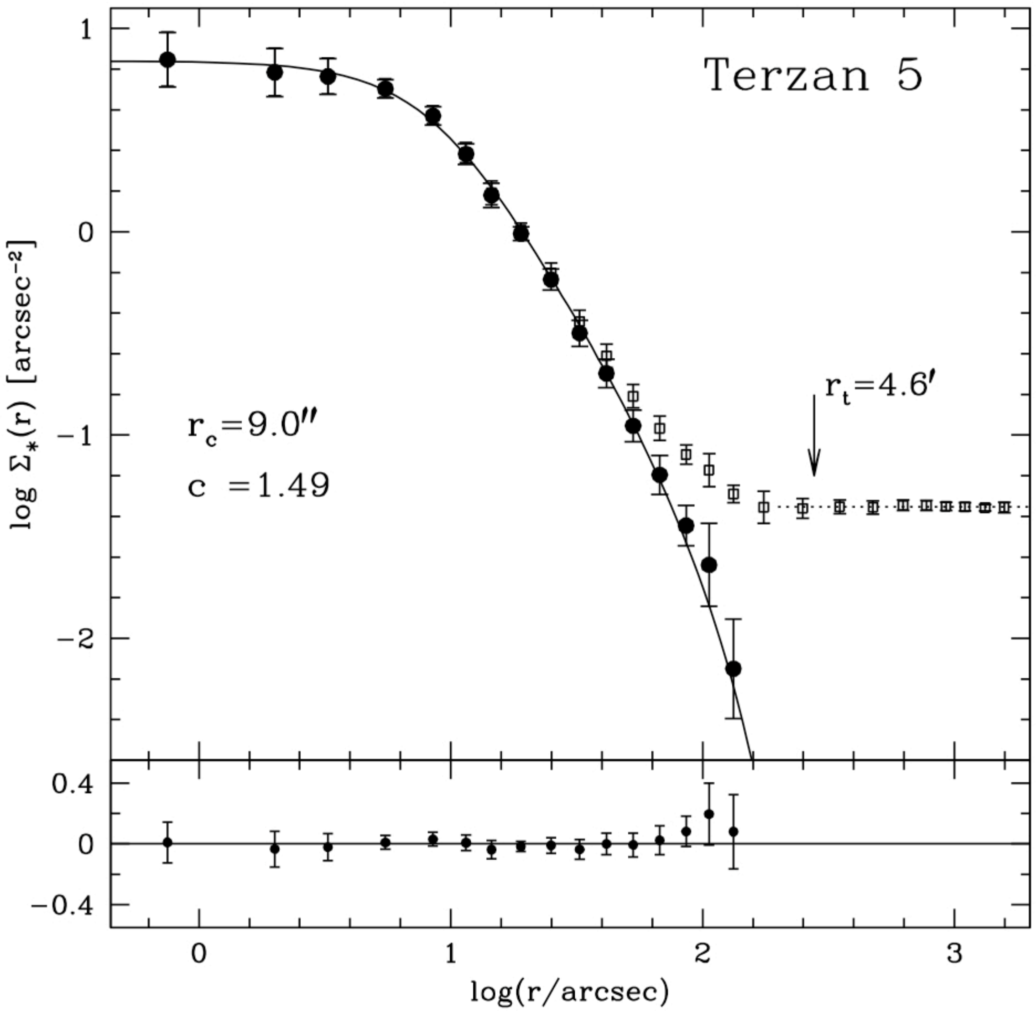




WFI@2.2m



DENSITY PROFILE & STRUCTURAL PARAMETERS



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

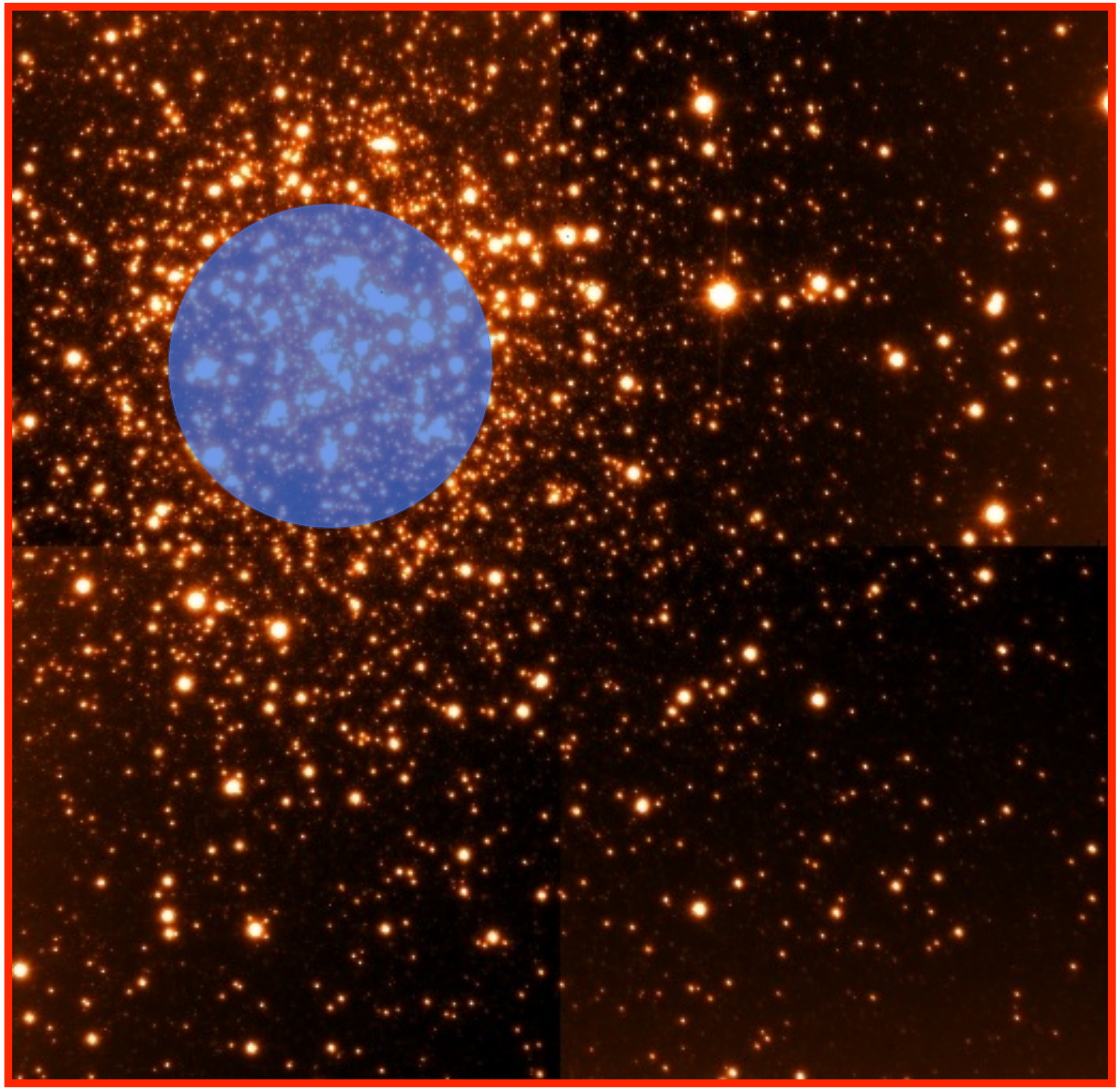
The new profile suggests a core radius larger than previous measures

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

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

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

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

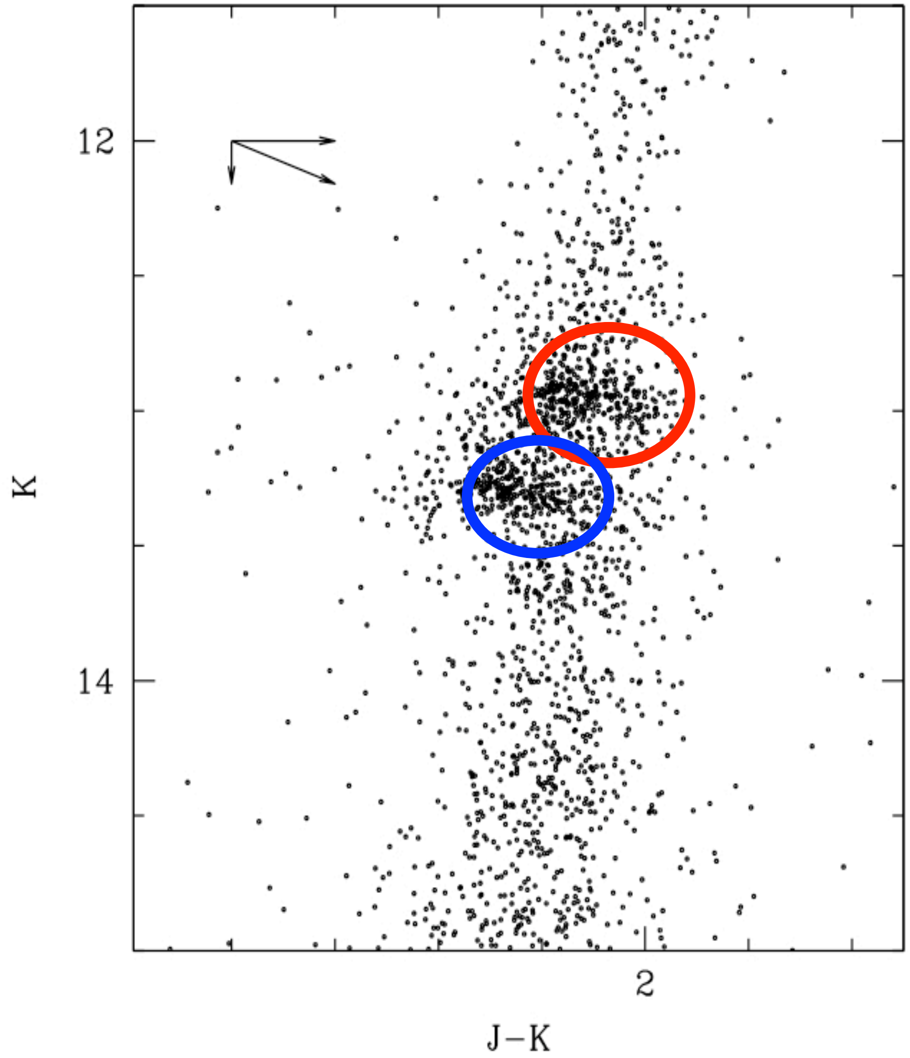
Terzan 5 is a quite massive stellar system

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

$$\mathbf{N_j = B \times t_j \times L_T}$$

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

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



METAL-RICH

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

METAL-POOR

N_{bRC} = 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 density

($\rho_0 \approx 2 \times 10^6$ 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

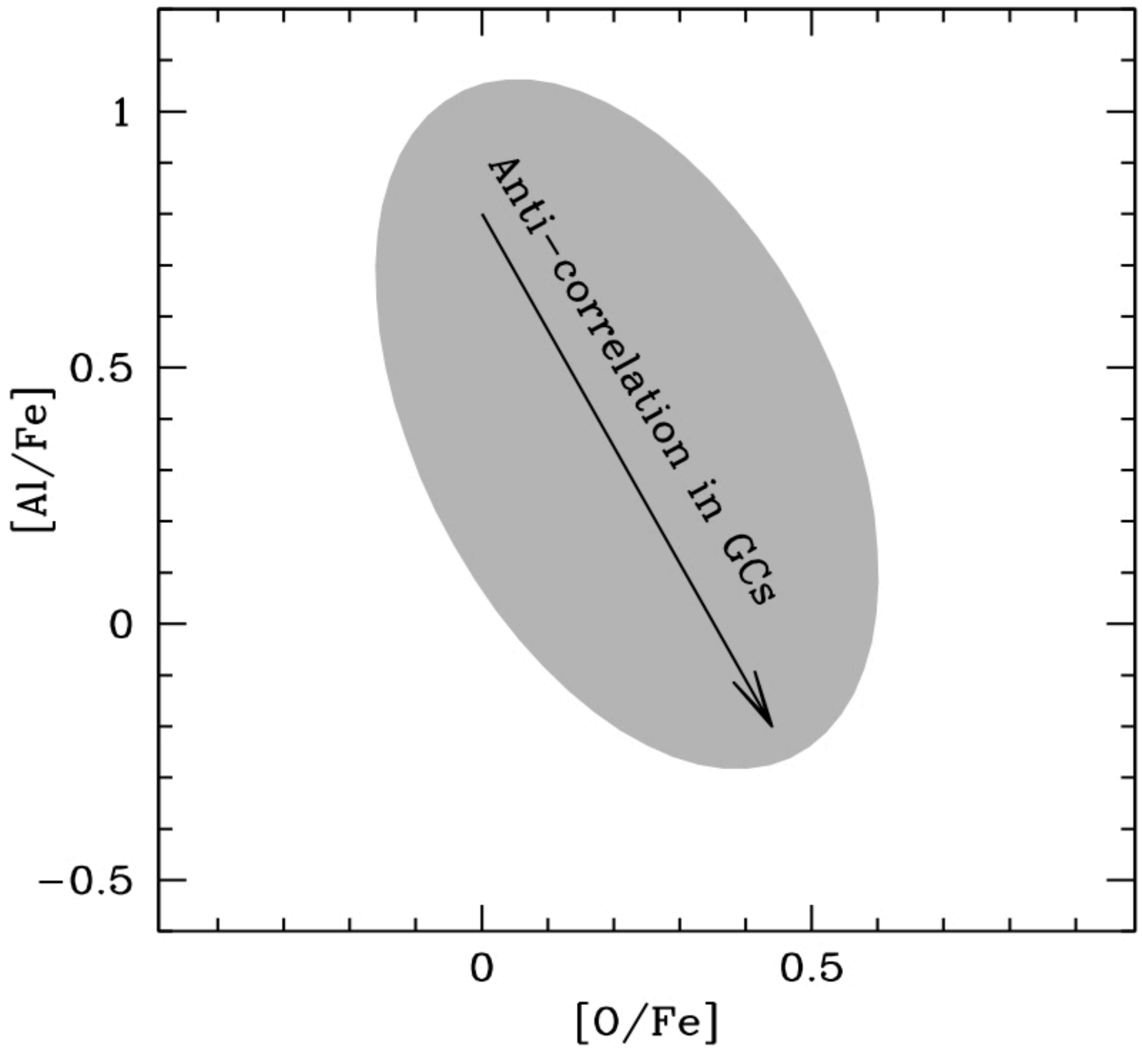
Table 2
Average Abundance Ratios of the Two RGB Populations in Terzan 5

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 (2011, ApJ, 726, L20)

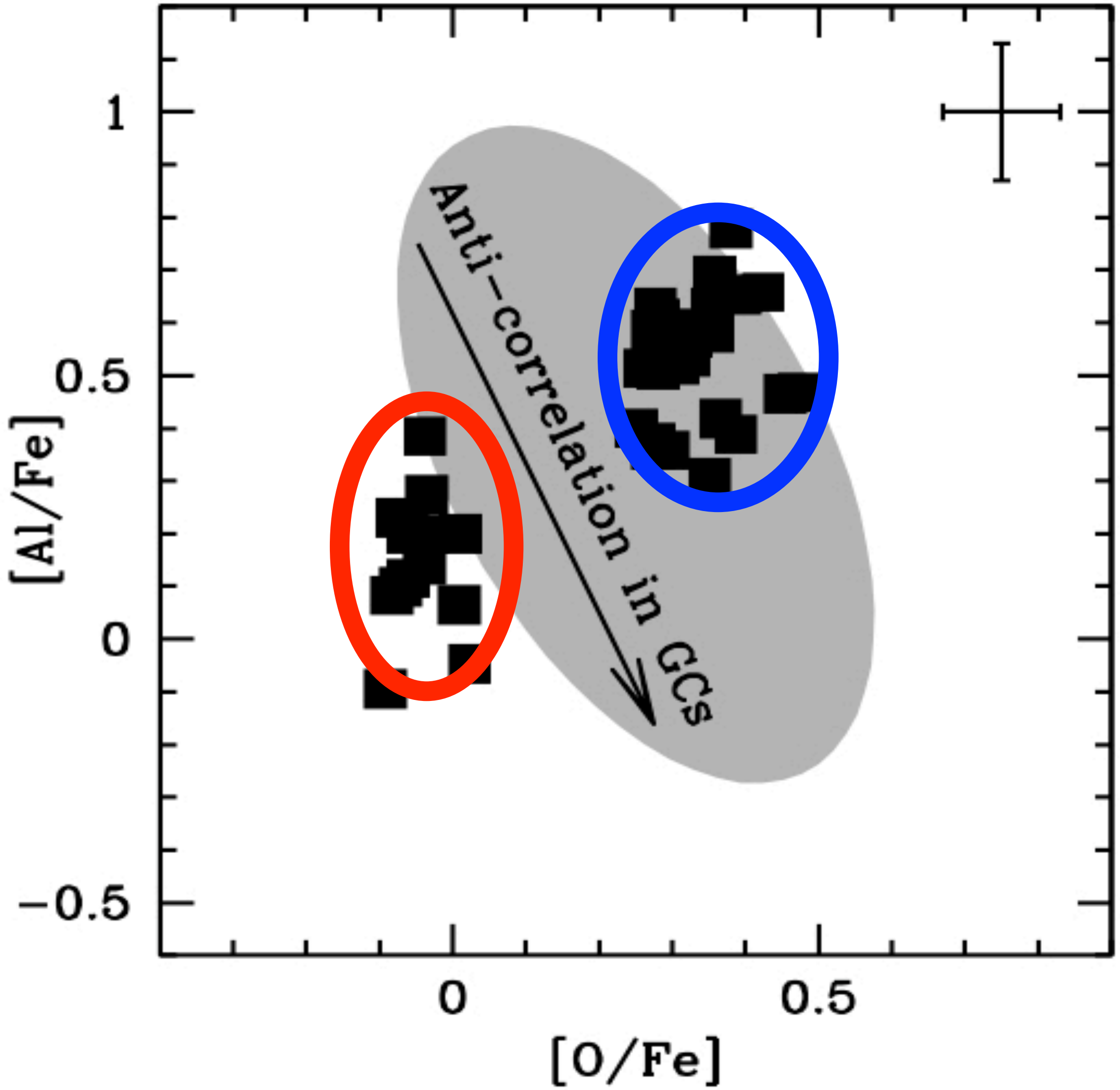
Cosmic-Lab

Spectroscopic screening of Ter5: anti-correlations?



Cosmic-Lab

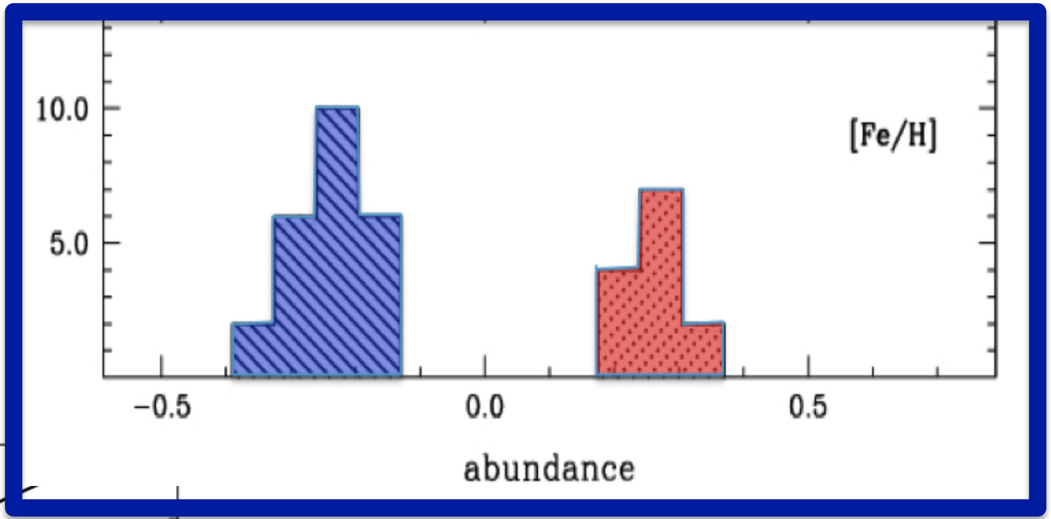
The two populations do **NOT** show any evidence of the Al-O anti-correlation that is typically observed in GCs

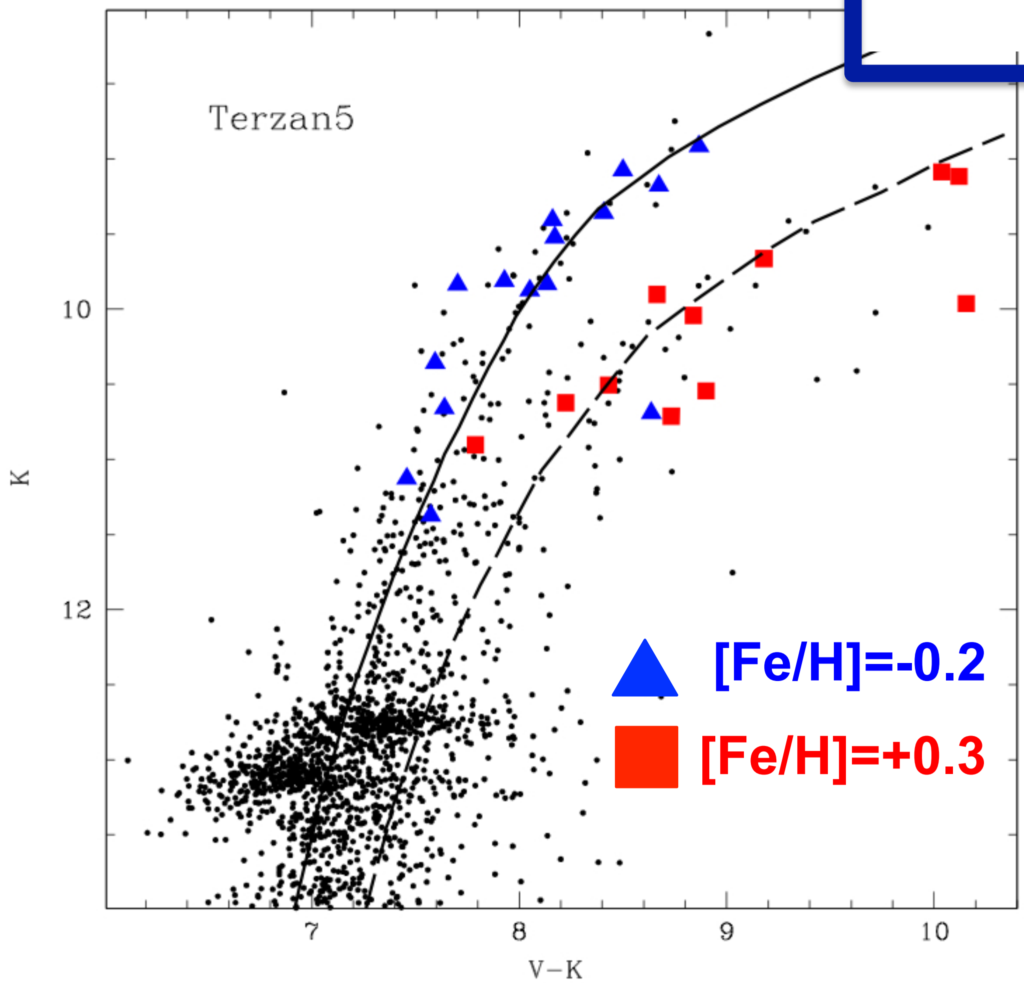


Cosmic-Lab

TERZAN 5 HAD A DIFFERENT ENRICHMENT HISTORY

Spectroscopic screening of Ter5: IRON





[Fe/H]:

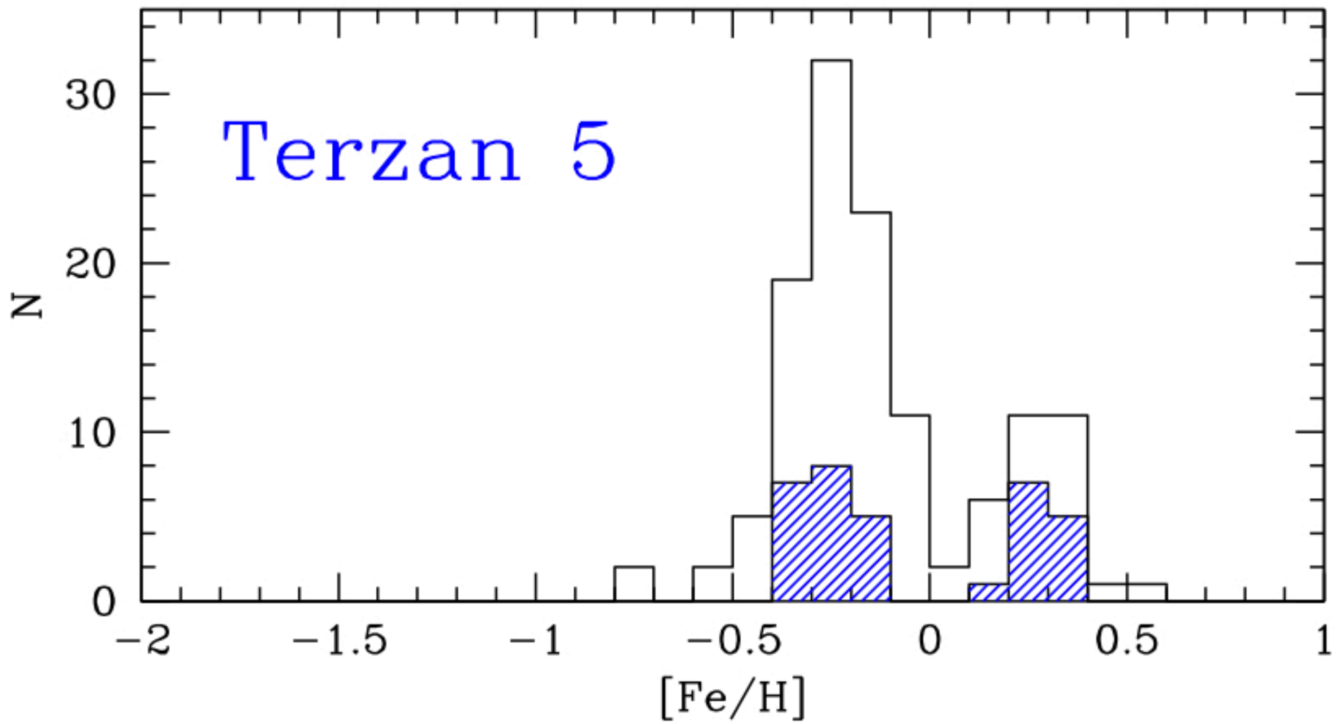
-0.25 +/- 0.07

+0.27 +/- 0.04

Δ[Fe/H] ≅ 0.5

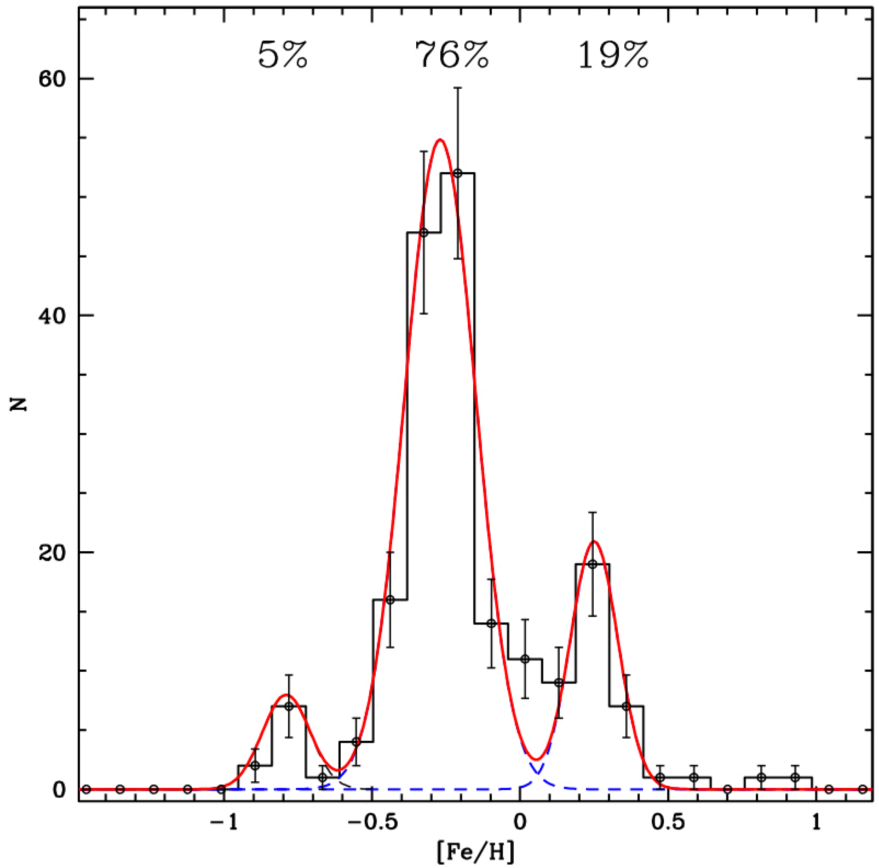
Cosmic-Lab

Iron distribution in Terzan 5



33 giants from Origlia et al (2010) +
160 FLAMES spectra from Massari et al (2014, in prep)

Iron distribution in Terzan 5

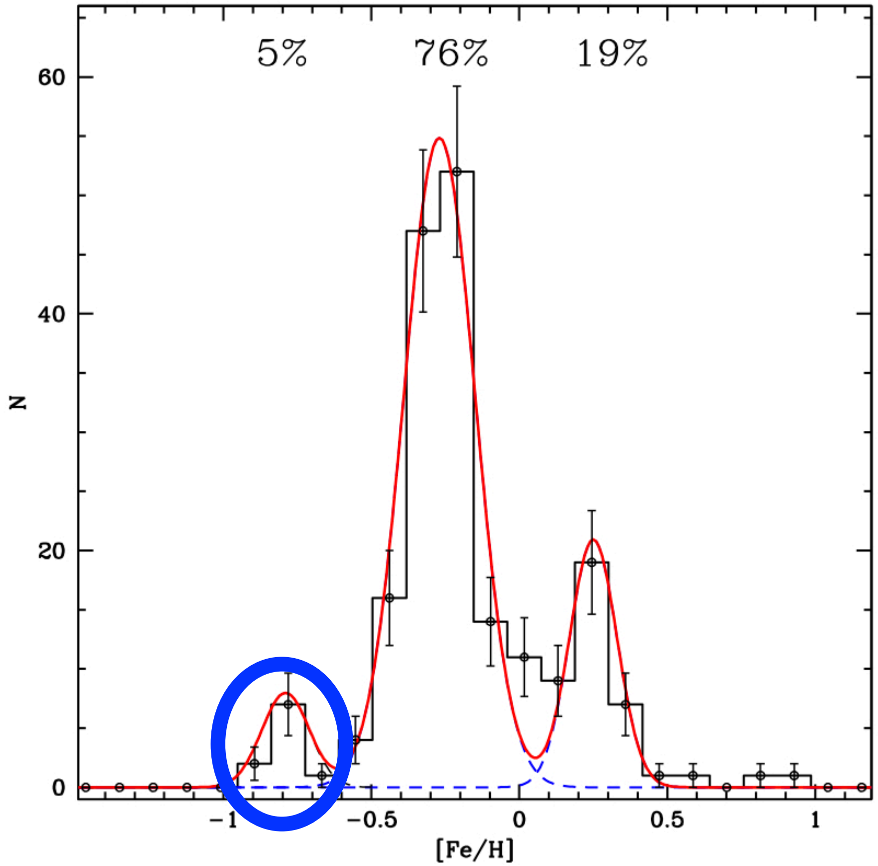


193 Stars

Massari et al (2014, in prep)

TERZAN 5: THE LAST SURPRISE

Discovery of an additional (minor) metal poor component at **[Fe/H]=-0.8**

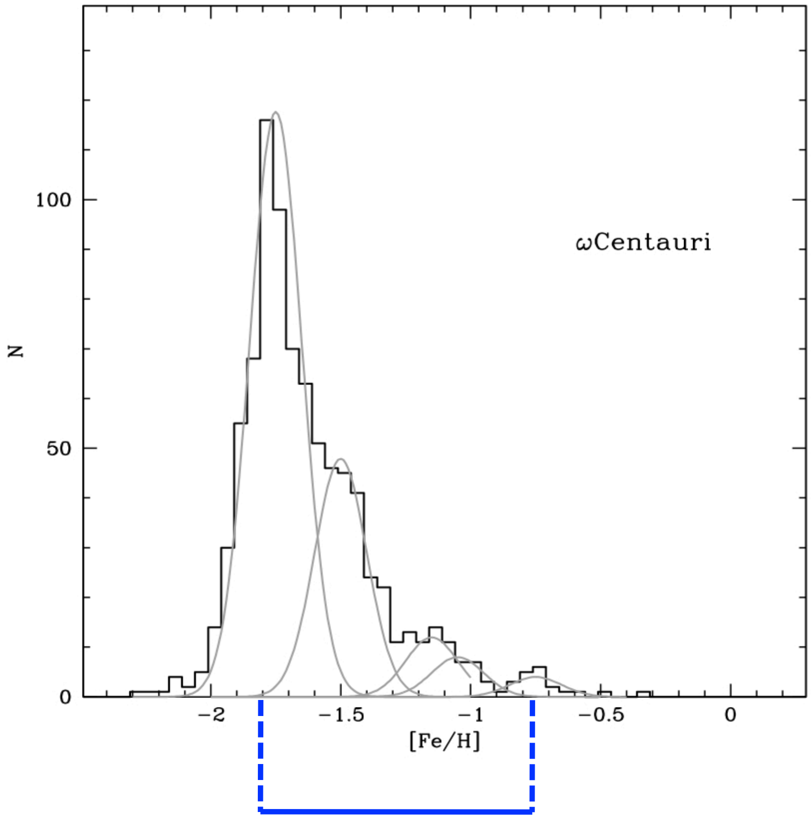


This discovery increases the metallicity range of the Terzan 5 populations to Δ[Fe/H]~ 1 dex !!!

Origlia et al 2013, ApJ, 779, L5

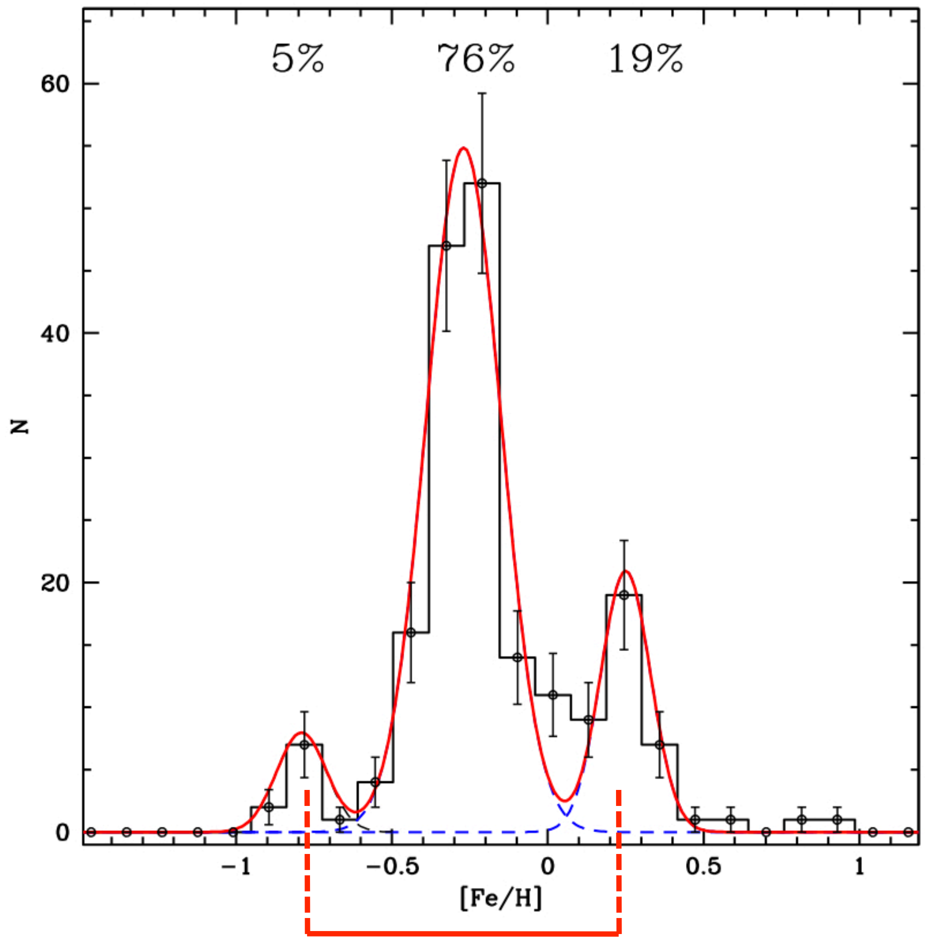
TERZAN 5: THE LAST SURPRISE

Omega Cen

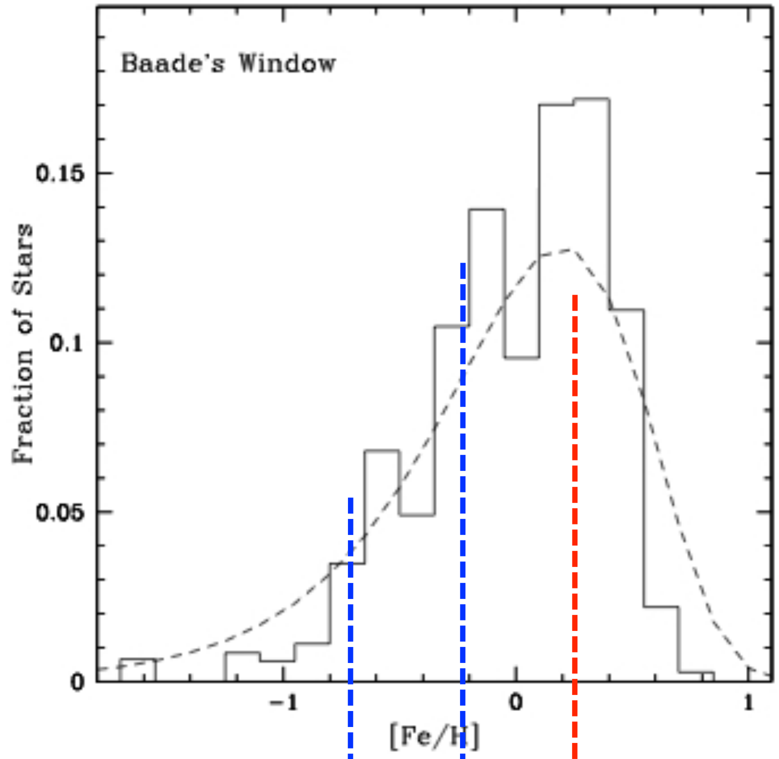


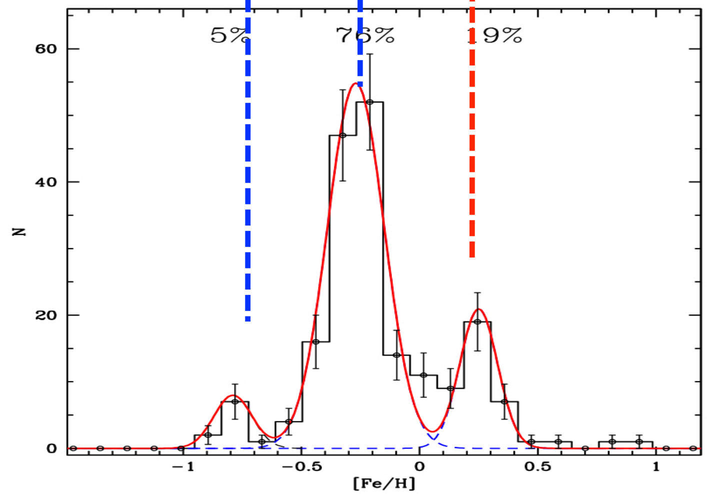
Δ[Fe/H]=1 dex

Terzan 5



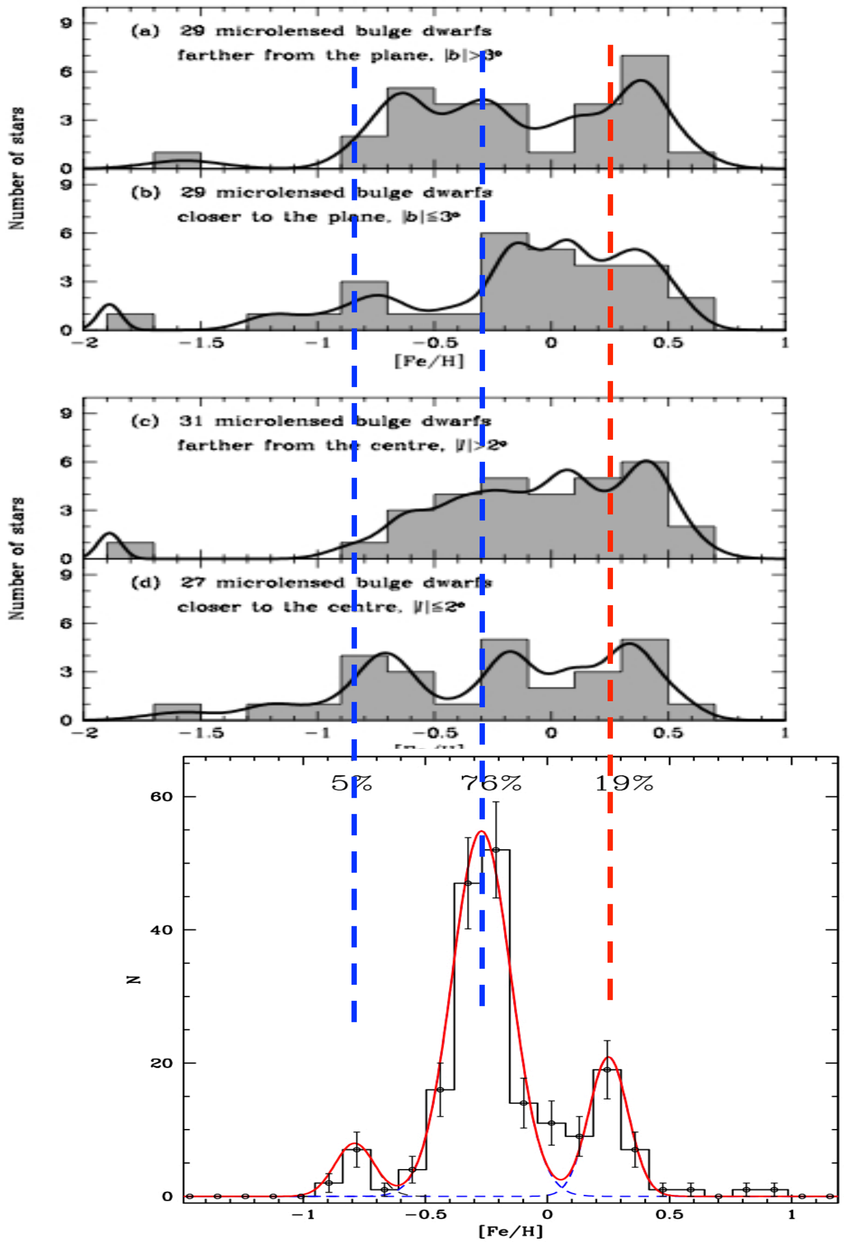
Δ[Fe/H]=1 dex





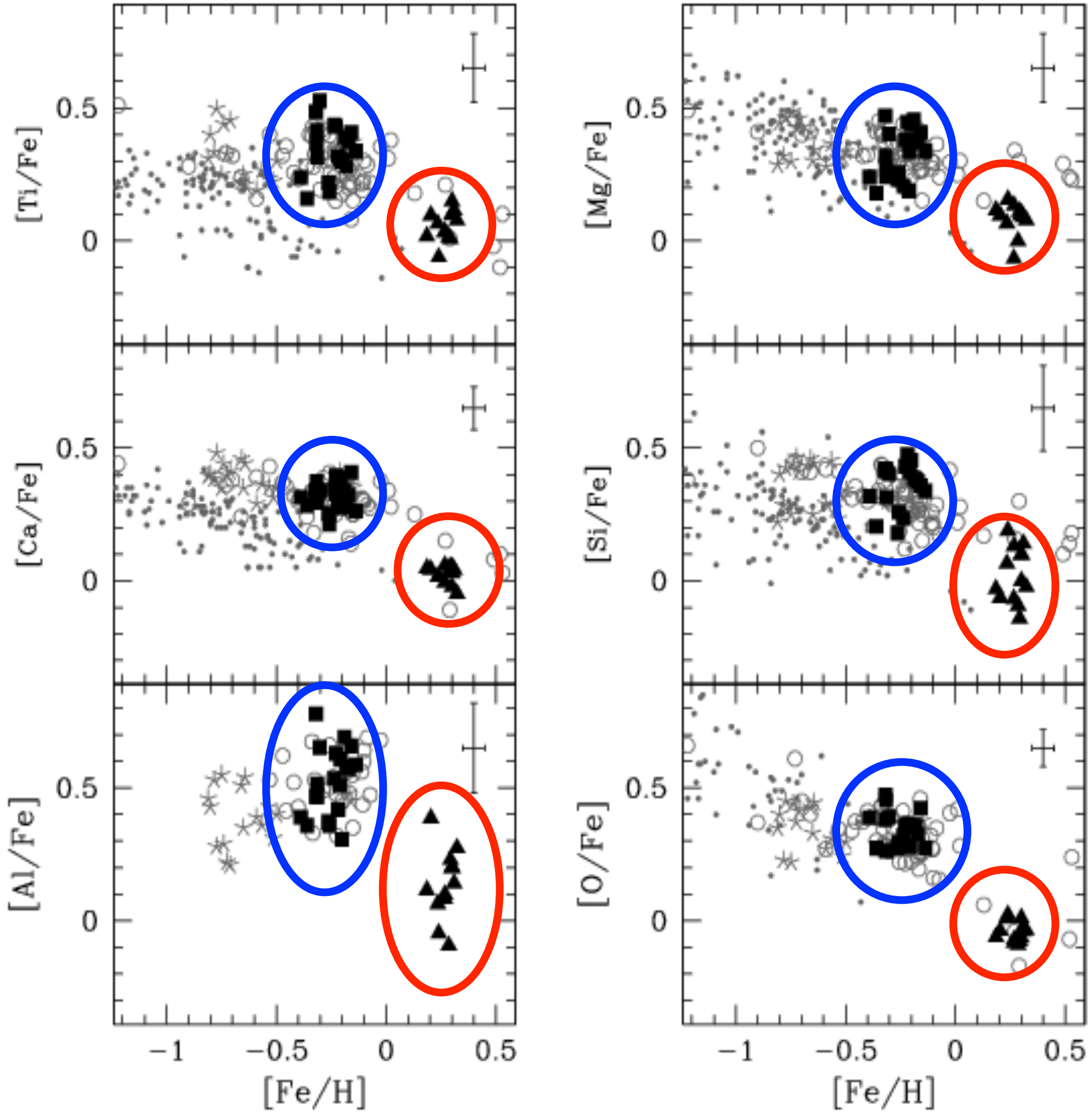
800 Bulge K giants

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



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

Spectroscopic screening of Ter5: α–elements



[α/Fe]:

+0.34 +/- 0.06

+0.03 +/- 0.04

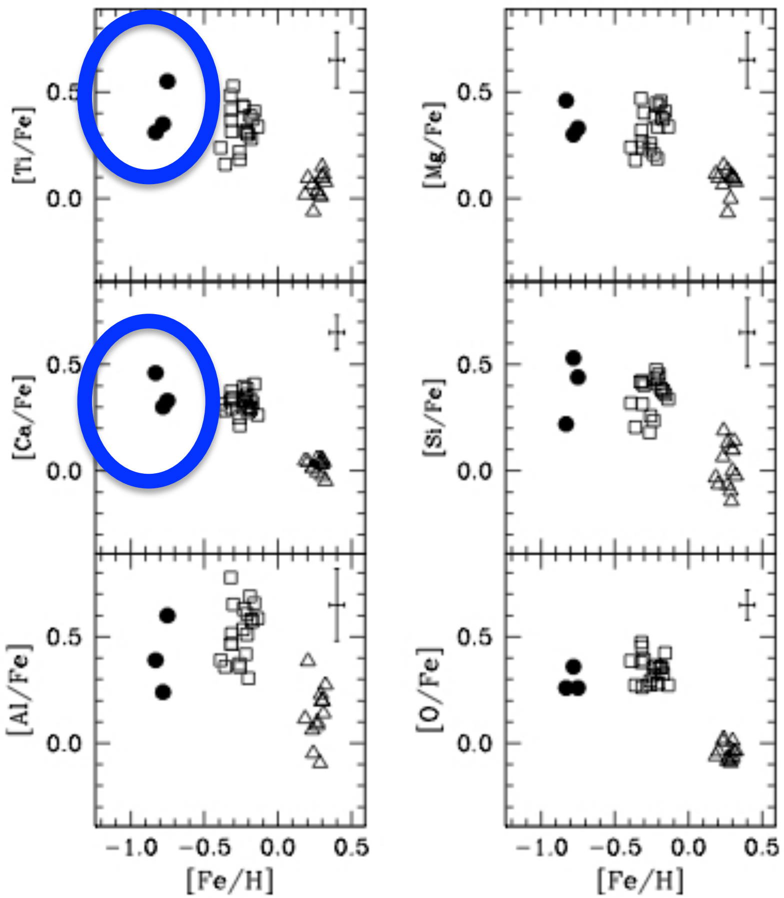
The metal poor component is α-enhanced

The metal rich one is solar

These abundances are quite similar to those observed in the Bulge Field
(grey open circles in the Figure)

TERZAN 5: THE LAST SURPRISE

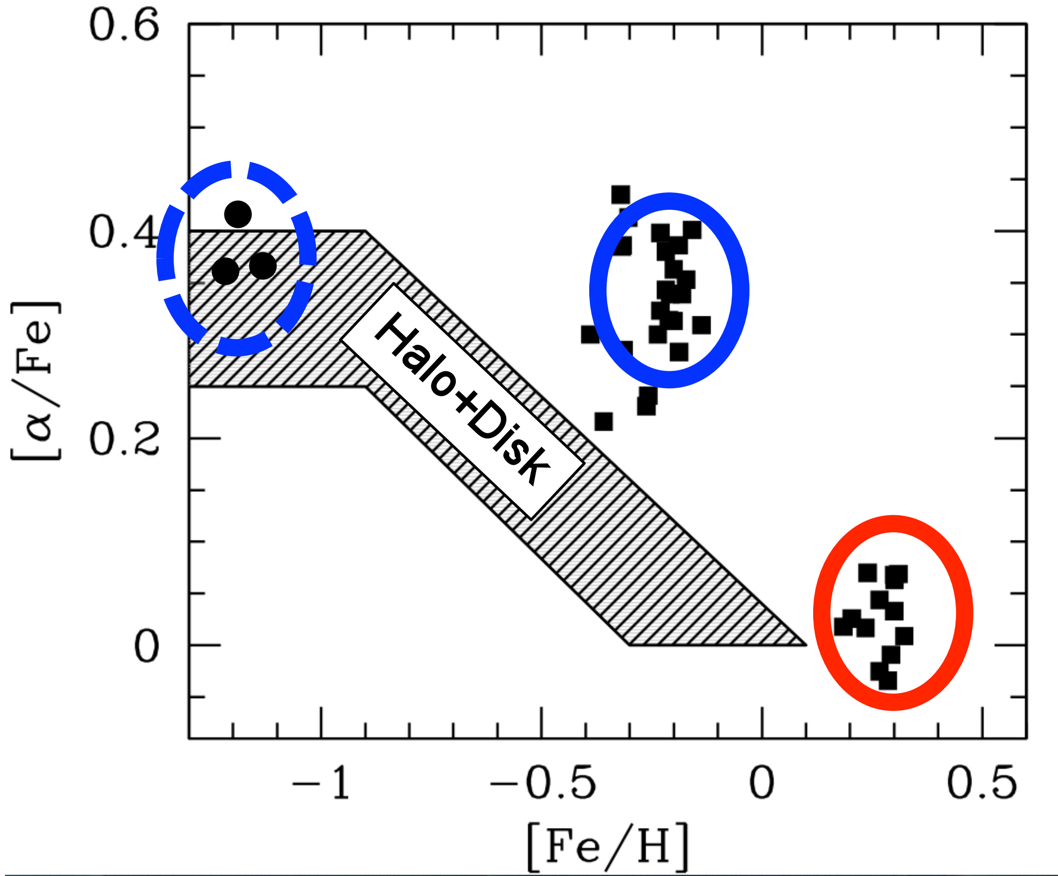
Discovery of an additional (minor) metal poor component at **[Fe/H]=-0.8**



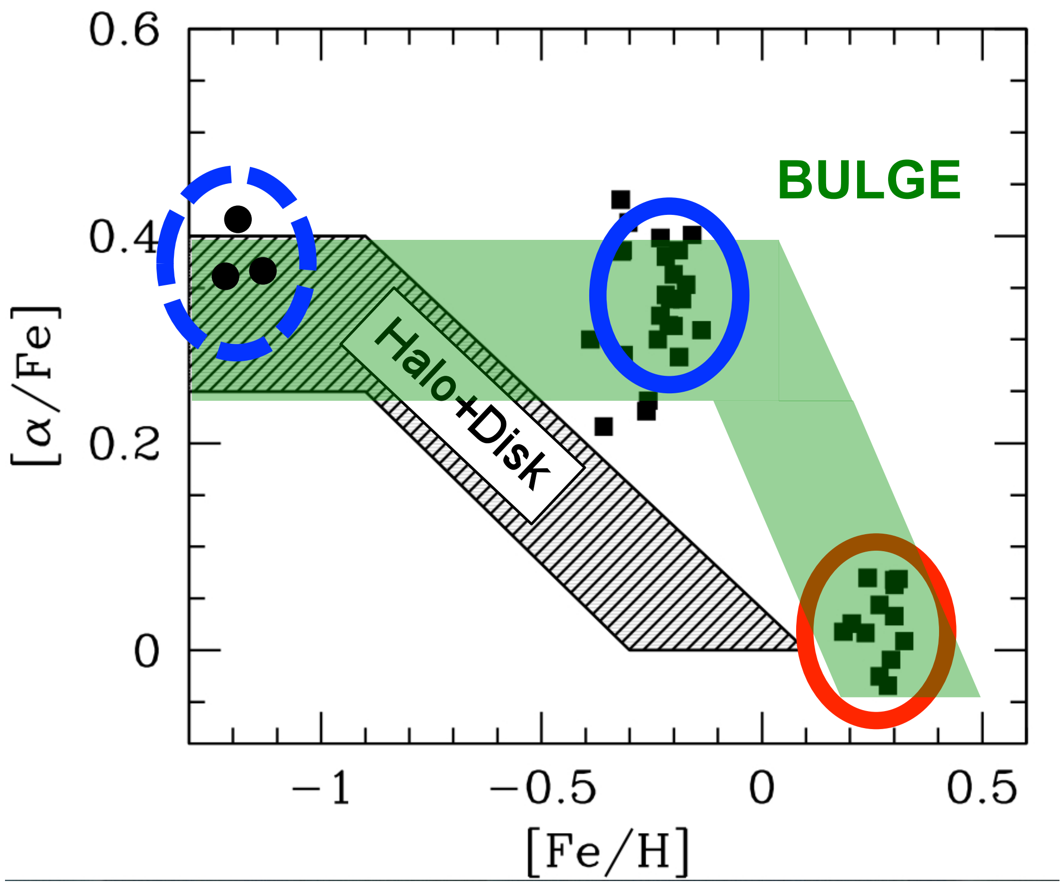
Also the extreme metal poor component is α-enhanced

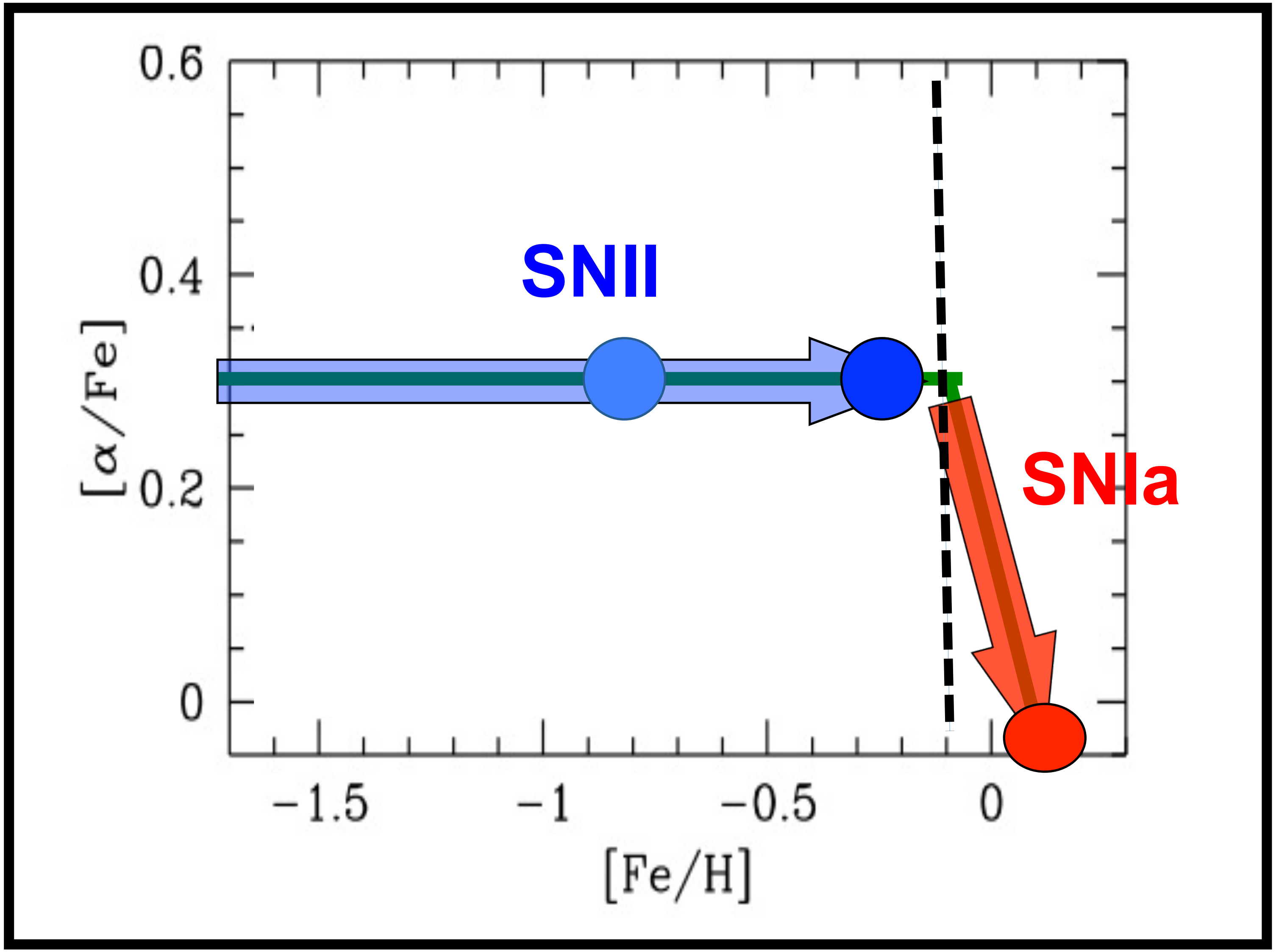
Origlia et al 2013, ApJ, 779, L5

The chemistry of the two most metal rich stellar populations in Ter5
is completely different from that observed in the Halo and Disk of the Galaxy



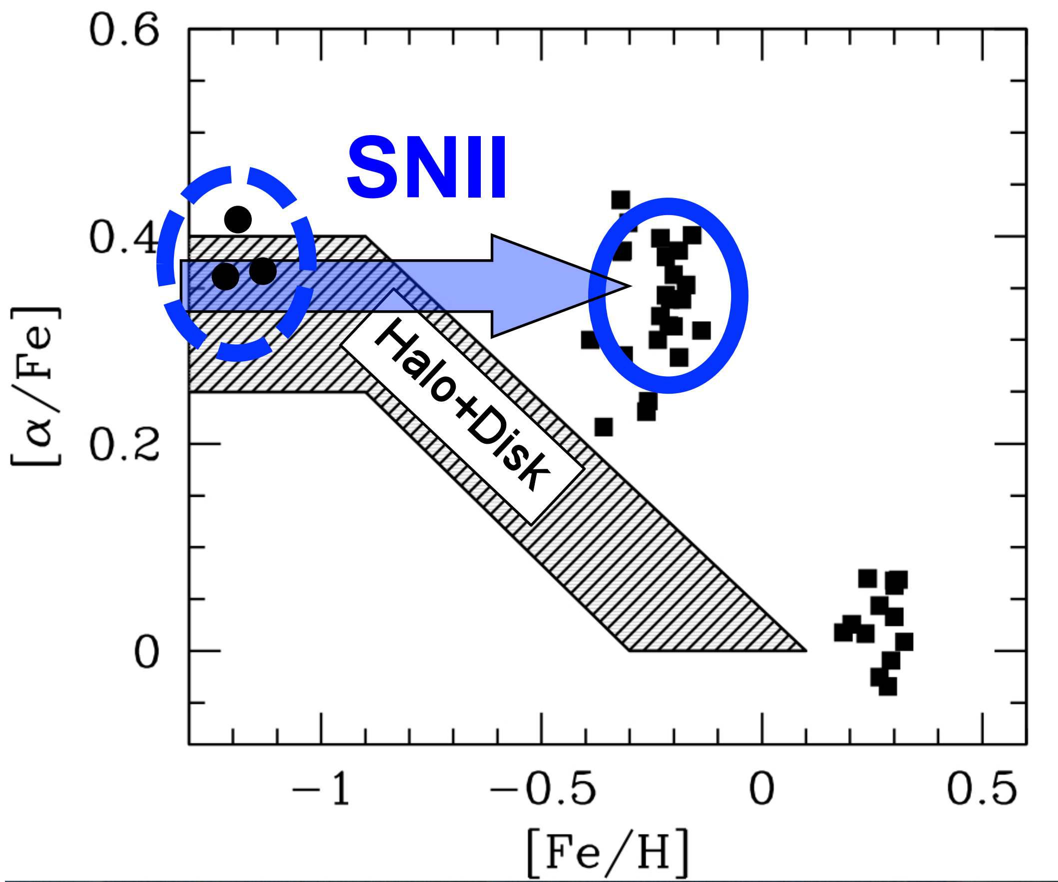
Iron and alpha–elements abundances are similar to those measured in the **Bulge**, thus suggesting **quite similar star formation and chemical enrichment processes**



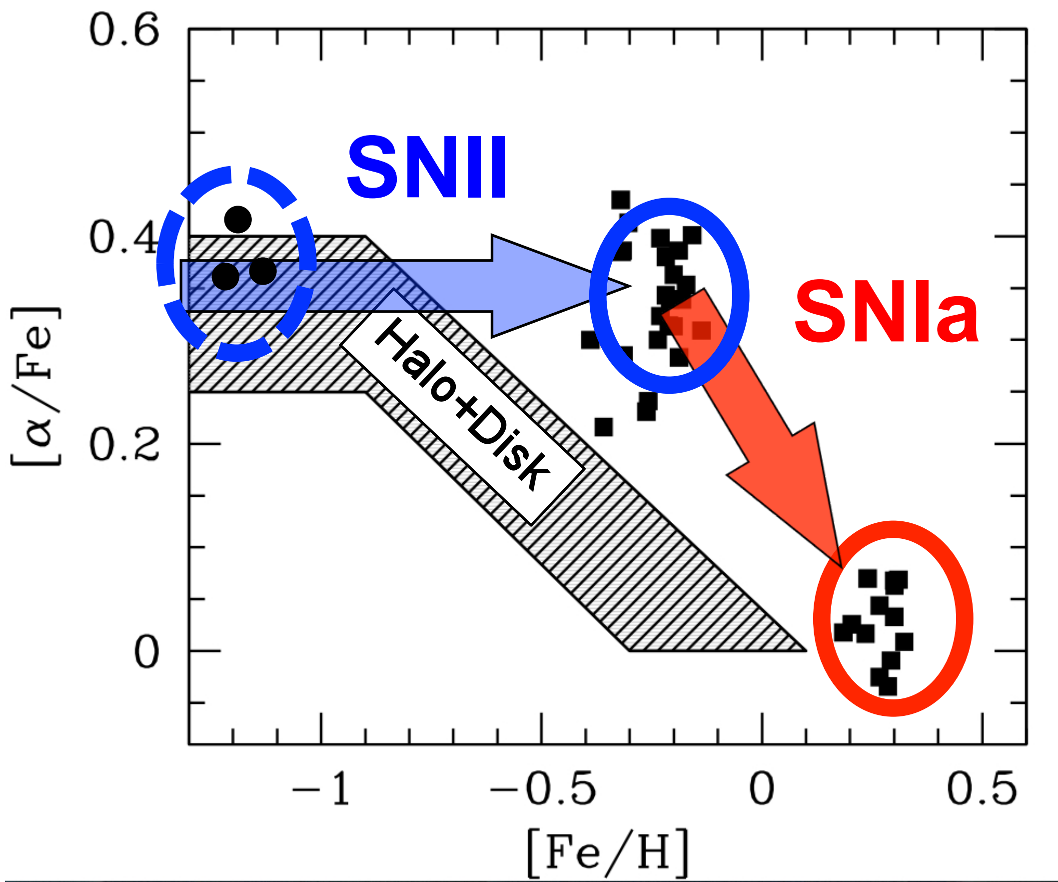


0.6
0.4
0.2
0
[α/Fe]
SNII
SNIa
−1.5
−1
−0.5
0
[Fe/H]

The chemistry of the **"metal-poor"** components of Terzan 5 shows that they 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

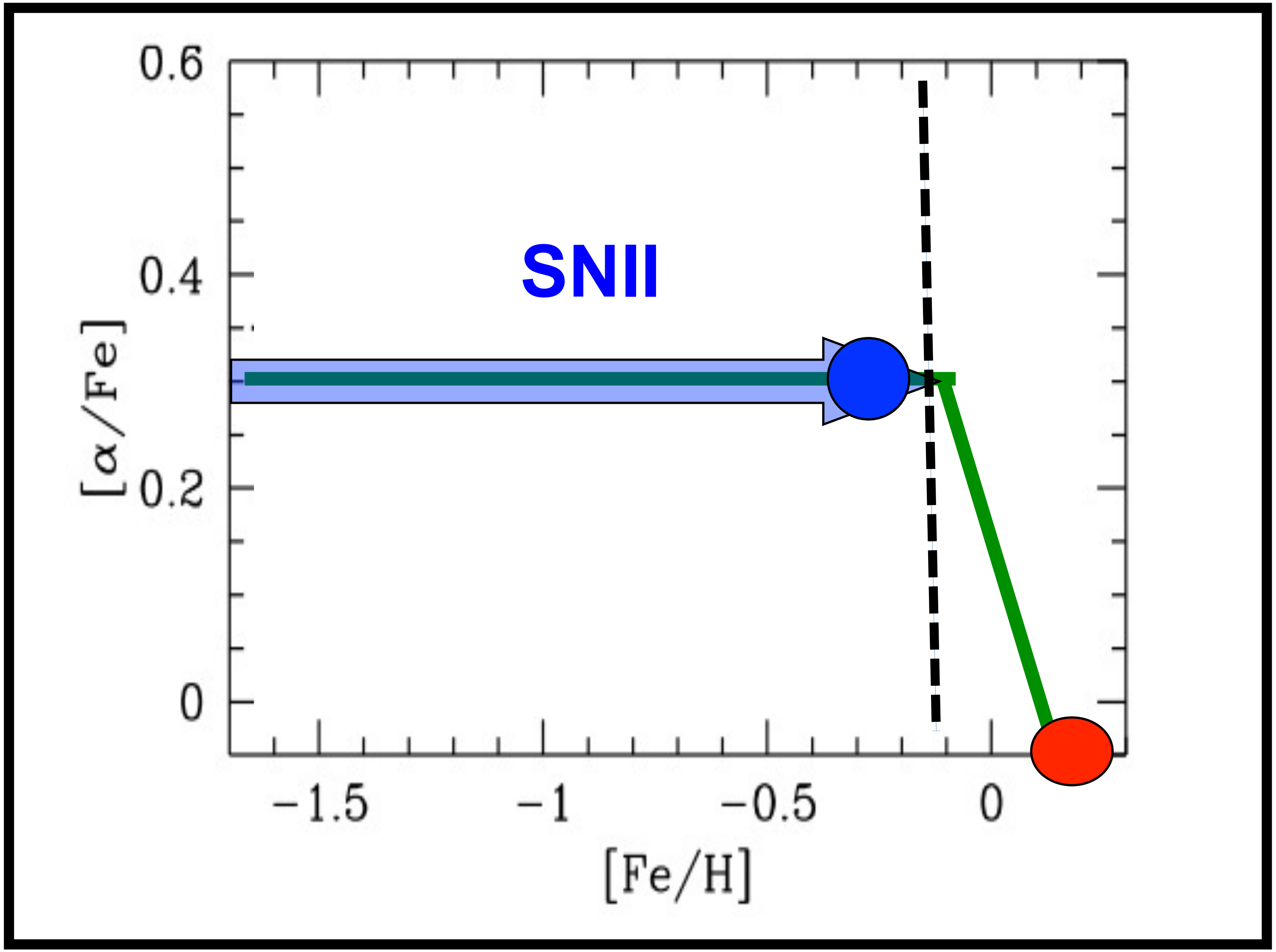
The significant iron abundance (Δ[Fe/H] =1 dex !!) measured in the three populations and the light elements abundance patterns (the Al-O CORRELATION!) demonstrate that it is **NOT** a genuine globular

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

Hence it should have been much more massive in the past than what observed now (in order to retain the SN ejecta). We estimate that the current mass of Terzan 5 is a few 10^6 Mo.
It is the relic of a large stellar system (like Omega Cen).

3. 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
(**Is Terzan 5 a pristine fragment of the bulge?**)

Cosmic-Lab



Chemical evolution models for the Galactic Bulge (i.e.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 !!!

4. **The assumption of a similar scenario for TERZAN5 would naturally explain the large number of MSP**

Many SNII

↓

Many NS (mostly retained within the deep potential well of the proto-Terzan5 system)

+

High collision rate

↓

Many recycled NS

↓

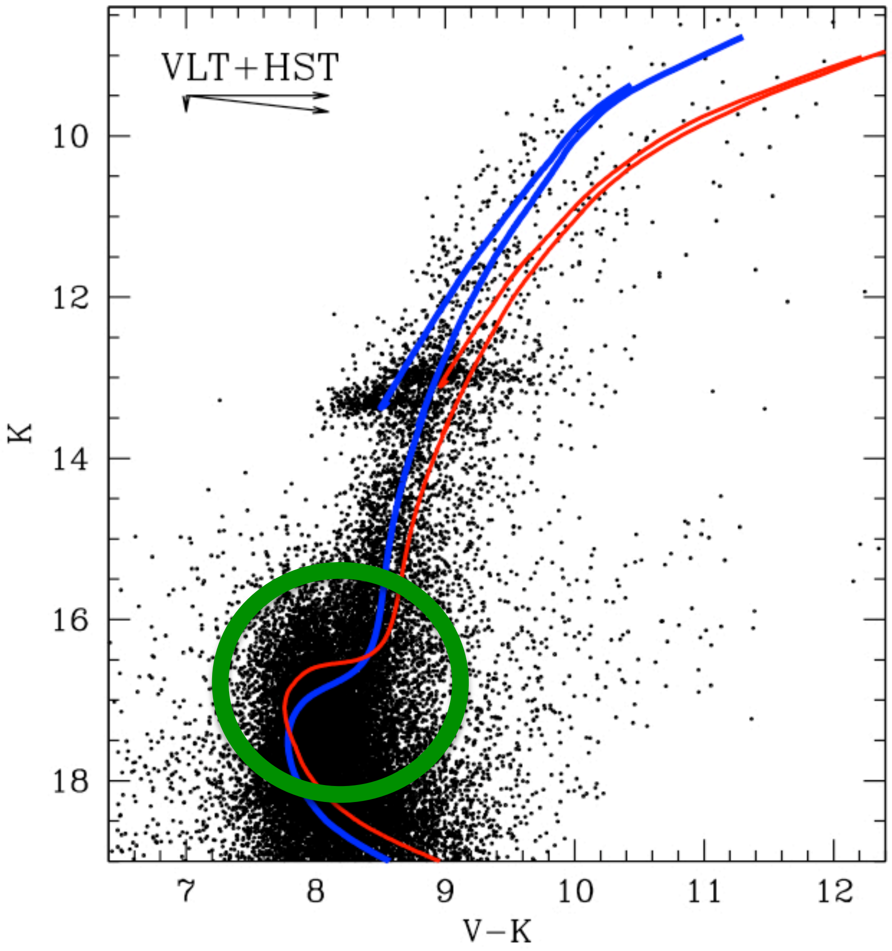
Many MSP

working hypothesis

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

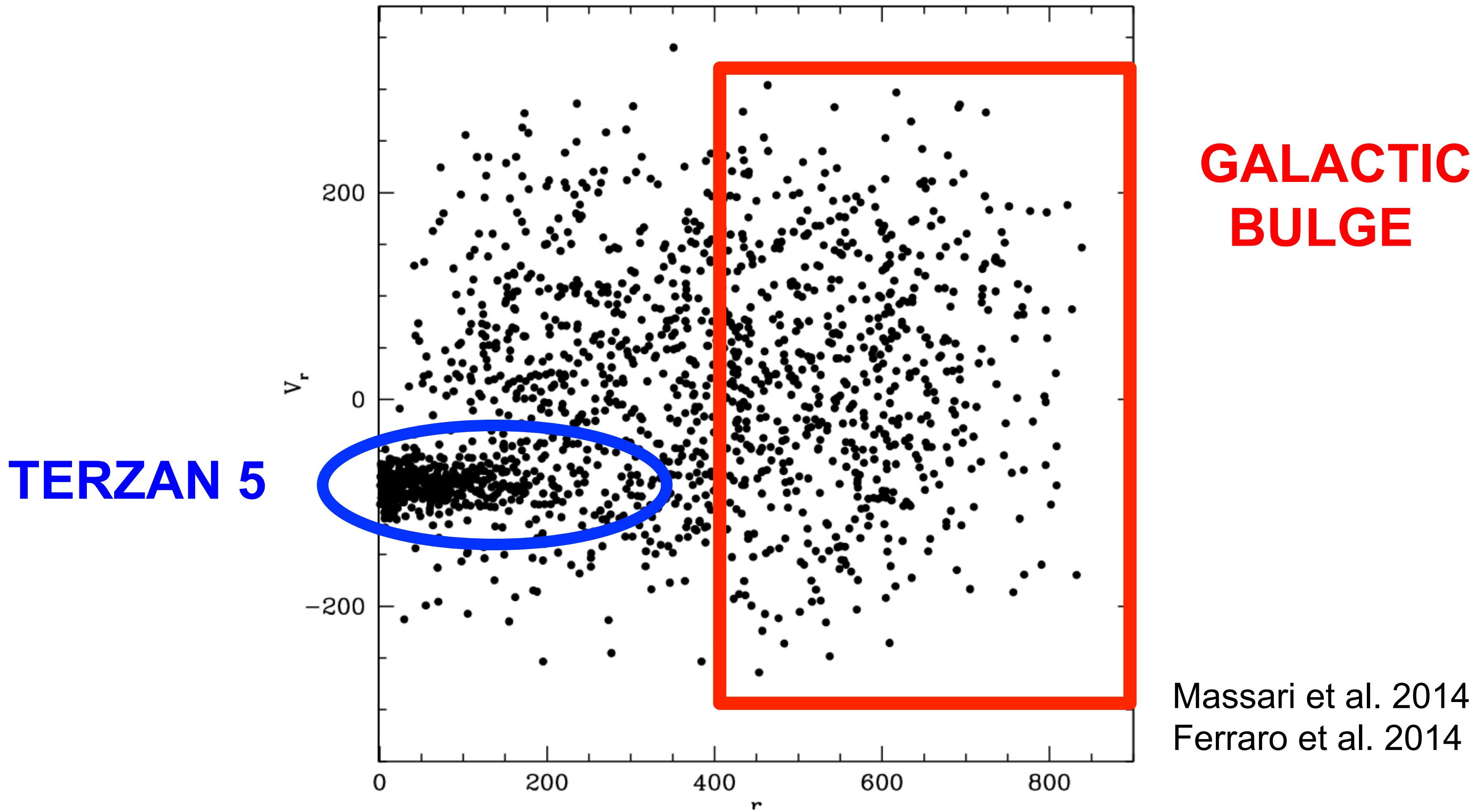
2. Investigating the radial velocity dispersion profile – We have collected 1600 FLAMES spectra covering the entire cluster extension

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

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

TERZAN 5: KINEMATICS

A sample of 1600 stars has been observed with FLAMES and XSHOOTER@ESO-VLT and NIRSPEC and DEIMOS@KECK



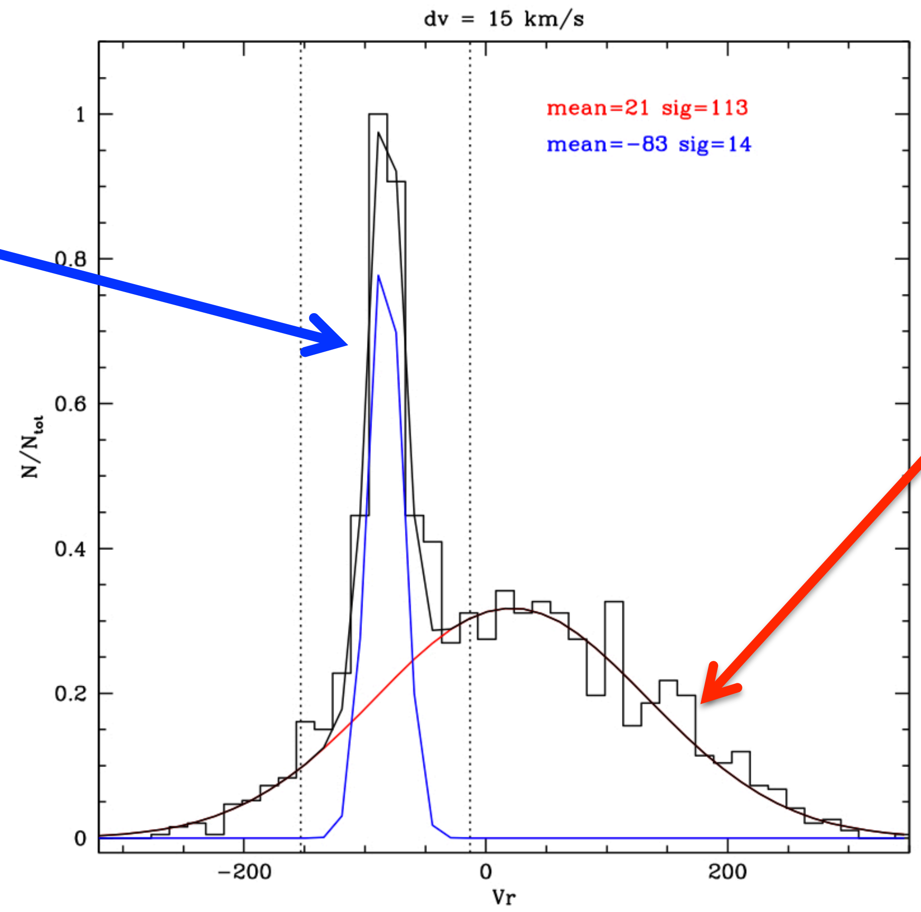
Massari et al. 2014
Ferraro et al. 2014

TERZAN 5: KINEMATICS

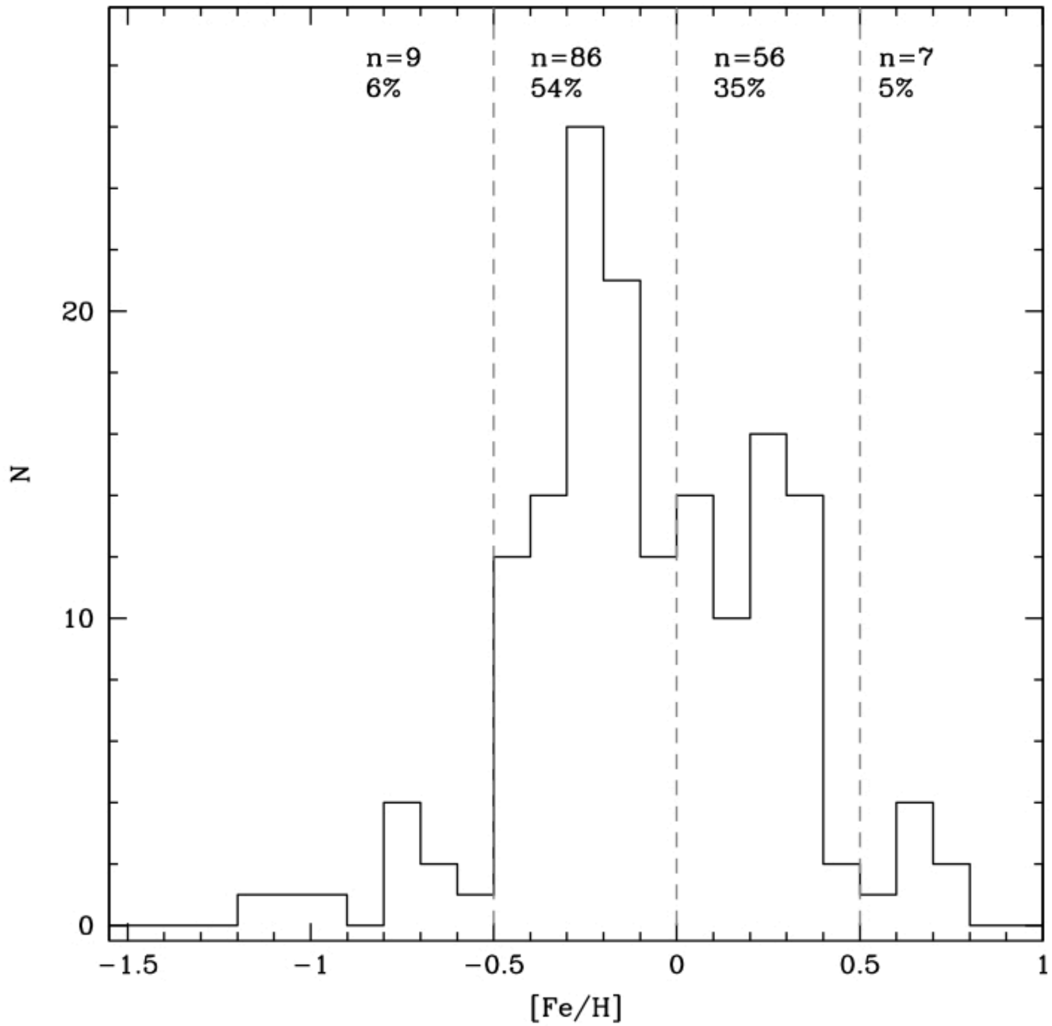
A sample of 1600 stars has been observed with FLAMES and XSHOOTER@ESO-VLT and NIRSPEC and DEIMOS@KECK

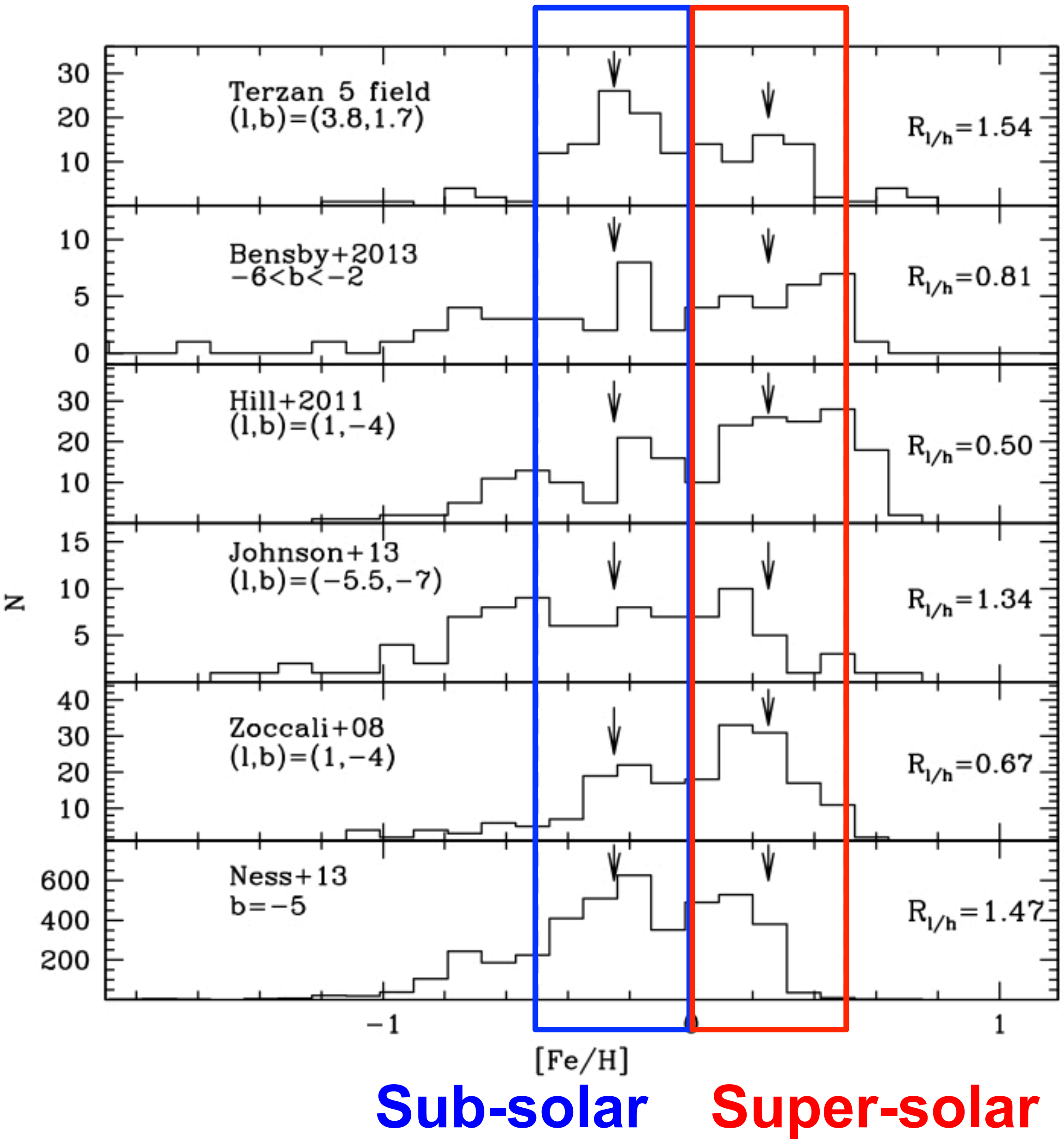
TERZAN 5

GALACTIC BULGE

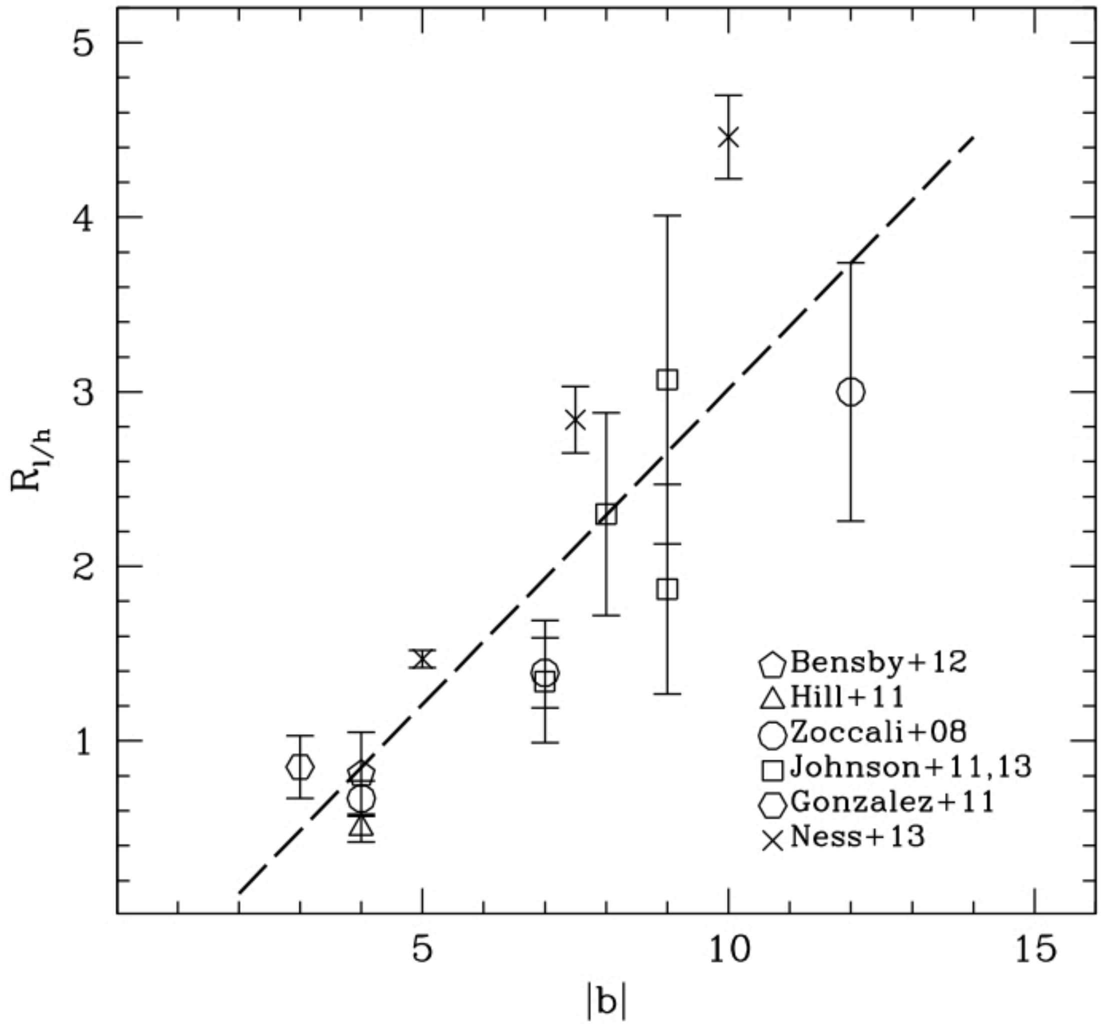


THE BULGE FIELD SURROUNDING TERZAN 5

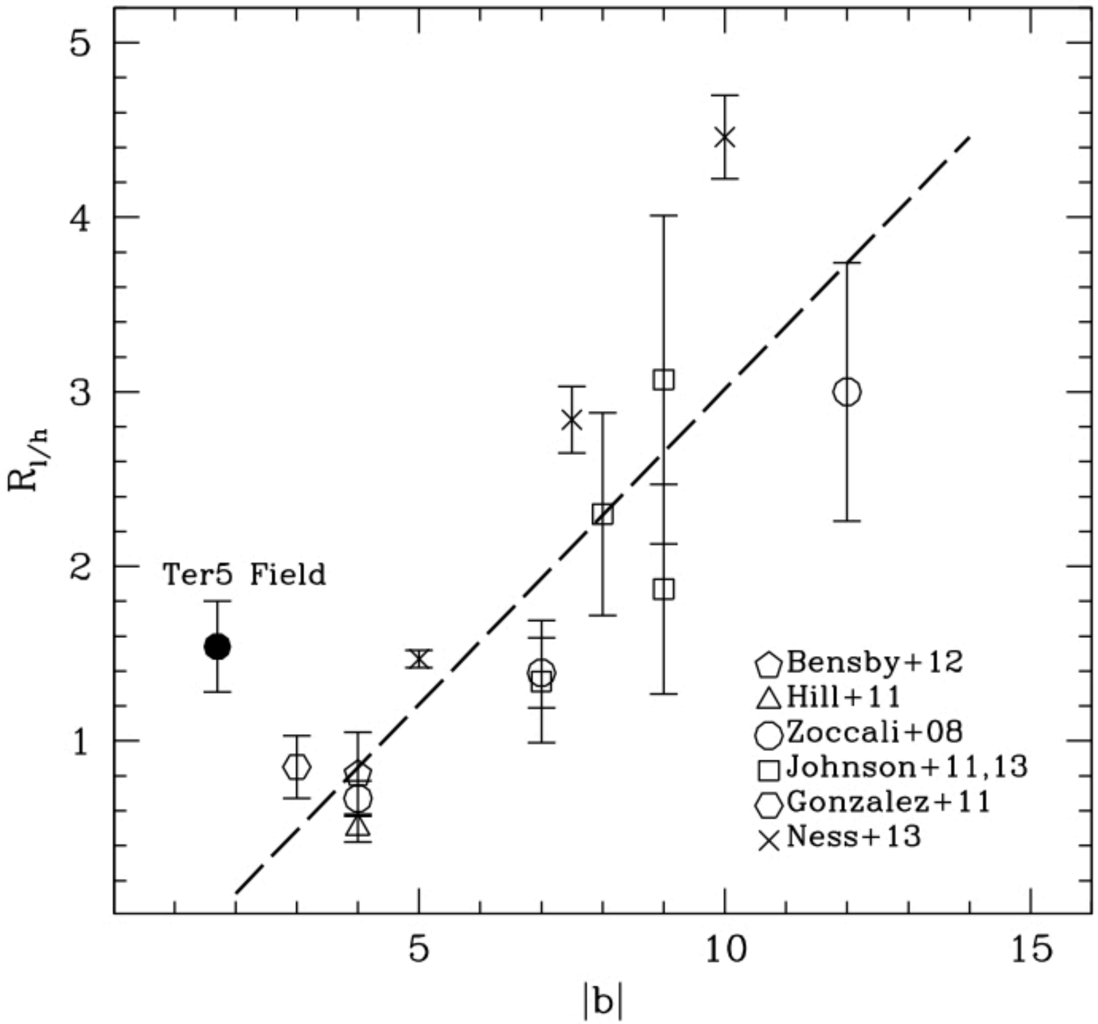



Terzan 5 field
(l,b)=(3.8,1.7)
$R_{l/h}$=1.54
Bensby+2013
−6<b<−2
$R_{l/h}$=0.81
Hill+2011
(l,b)=(1,−4)
$R_{l/h}$=0.50
Johnson+13
(l,b)=(−5.5,−7)
$R_{l/h}$=1.34
Zoccali+08
(l,b)=(1,−4)
$R_{l/h}$=0.67
Ness+13
b=−5
$R_{l/h}$=1.47
N
[Fe/H]
Sub-solar
Super-solar

$$R_{l/h} = N_l/N_h$$

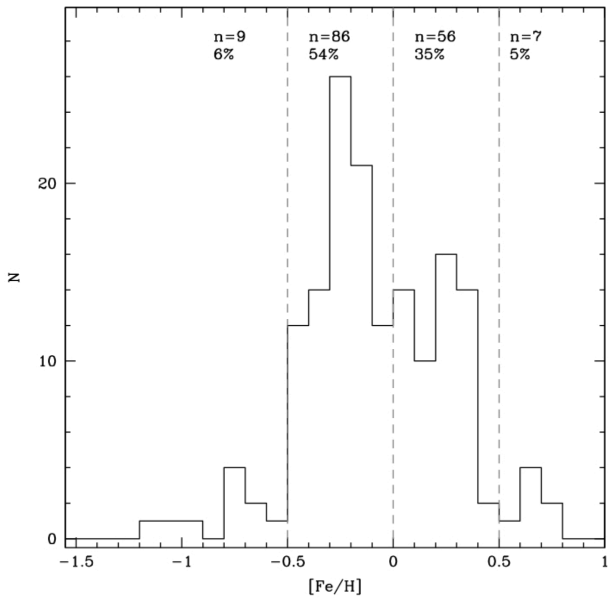


The super-solar component tends to dominate at low latitudes

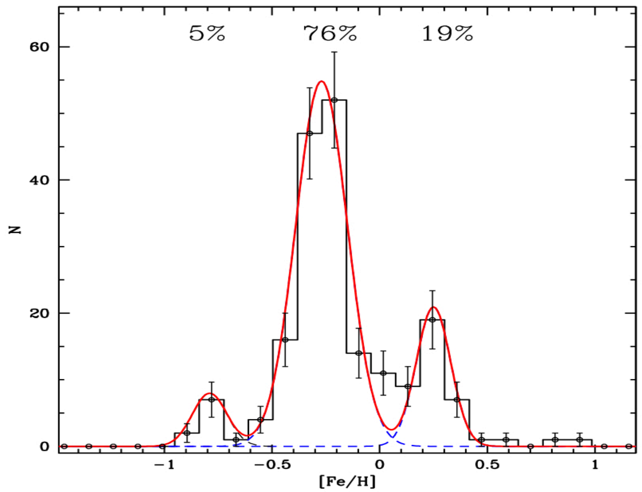


The bulge-field around Terzan5 shows a sub-solar star excess == a possible "contamination" of stars lost by Terzan 5 in the past….

THE BULGE FIELD SURROUNDING TERZAN 5

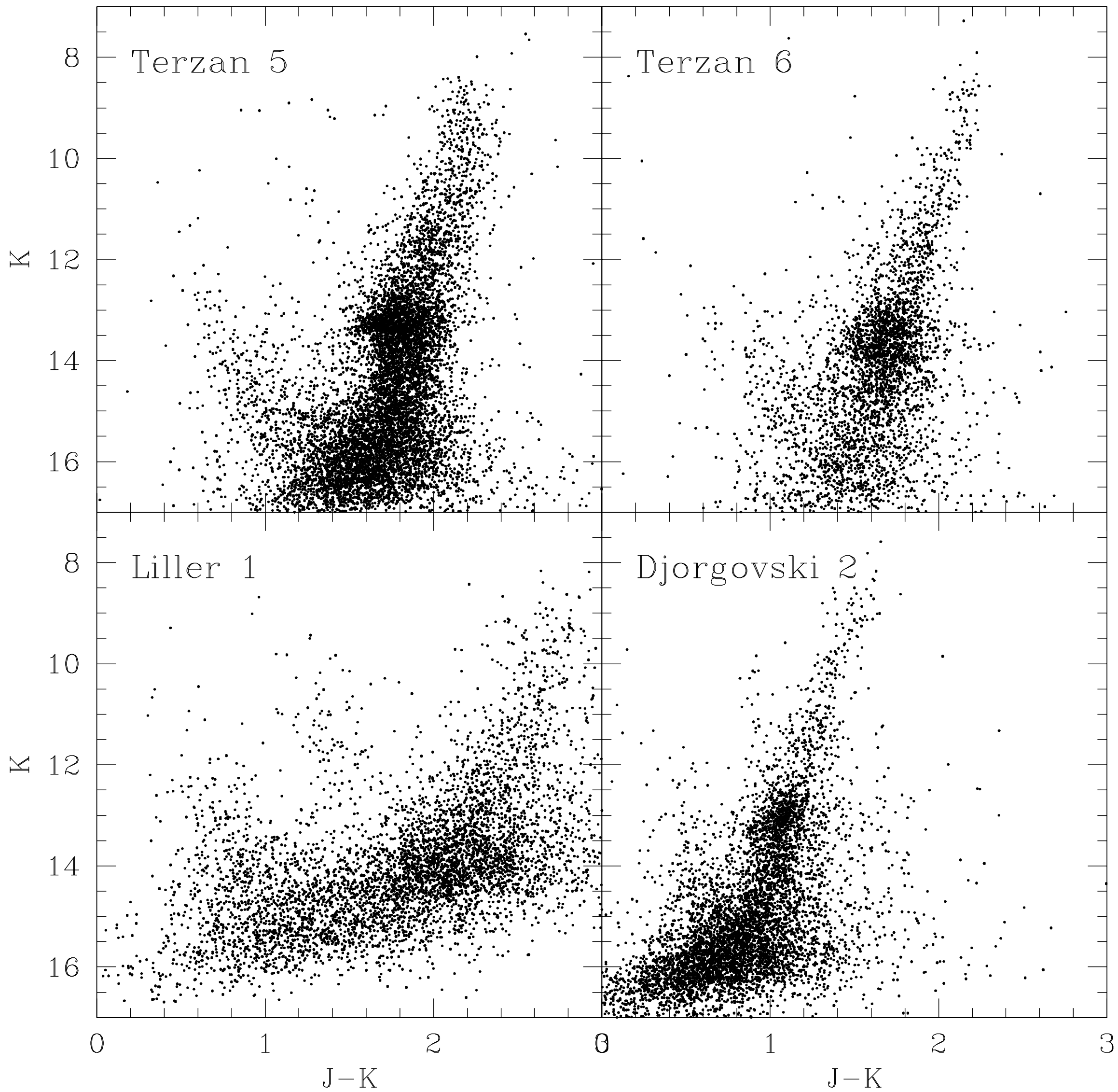


BULGE-FIELD



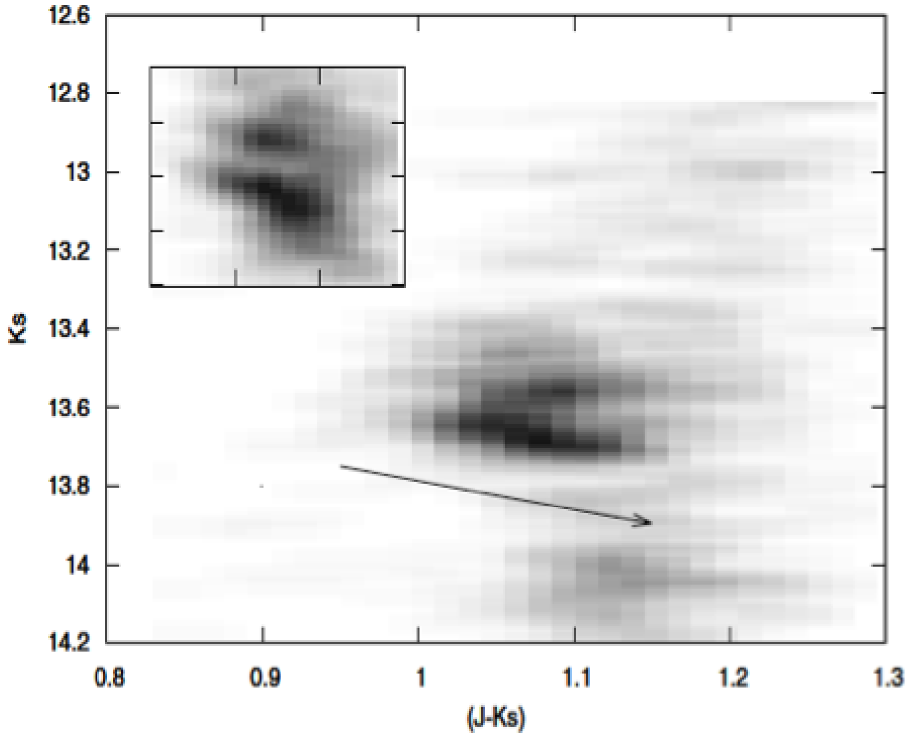
TERZAN 5

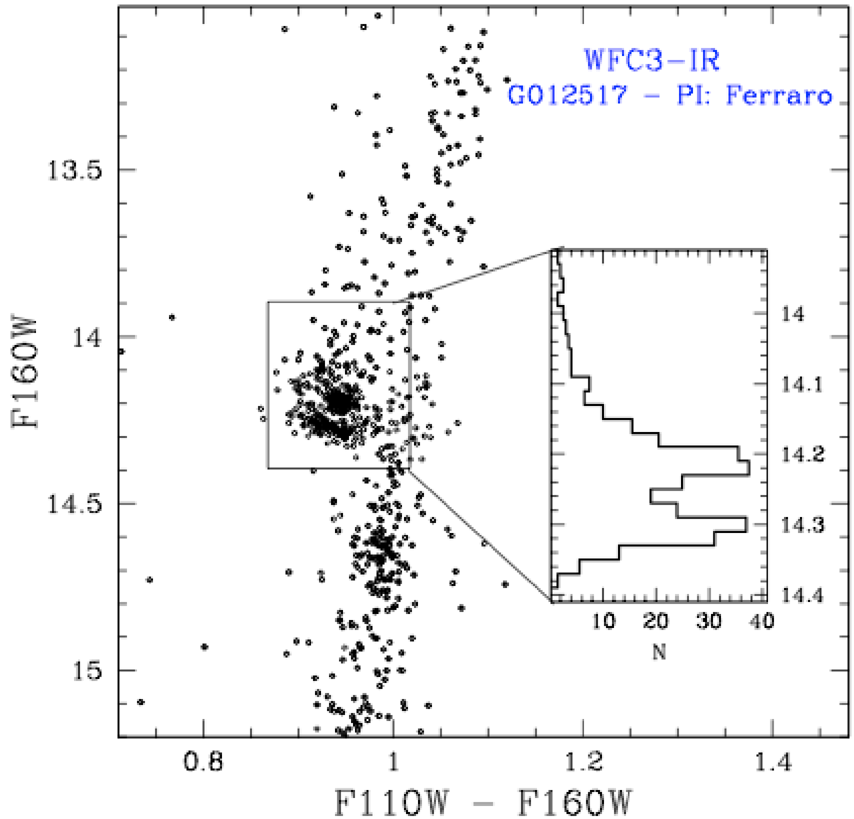
SEARCHING FOR OTHER TERZAN 5-LIKE STELLAR SYSTEMS



NGC6440: another Terzan 5?

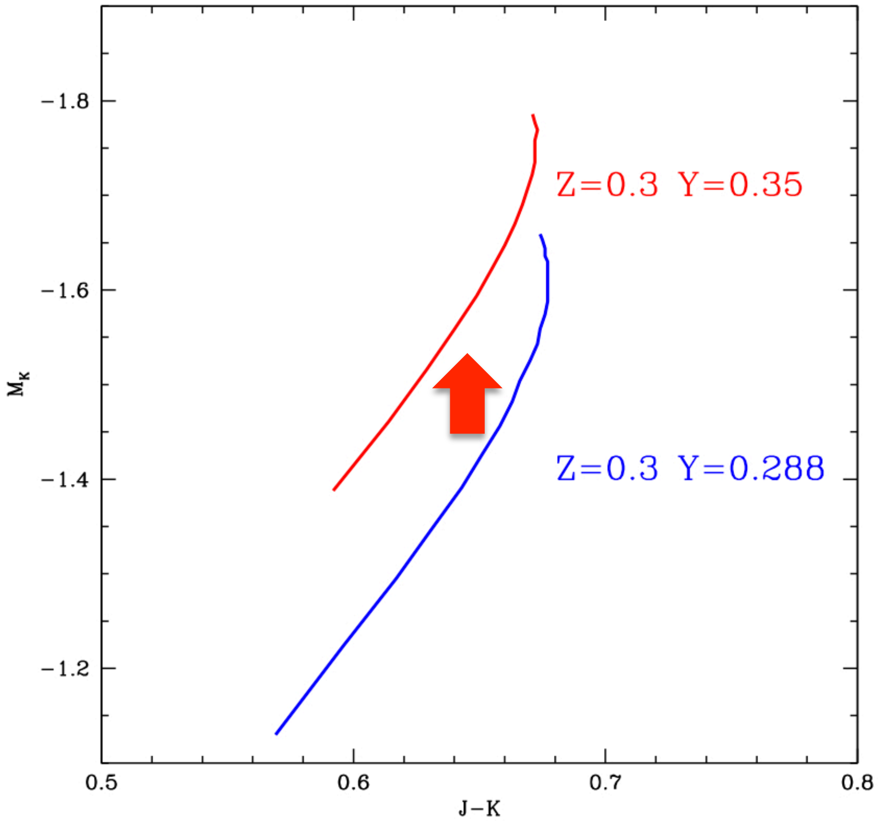
Mauro et al (2012, ApJ, 761, L29)





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

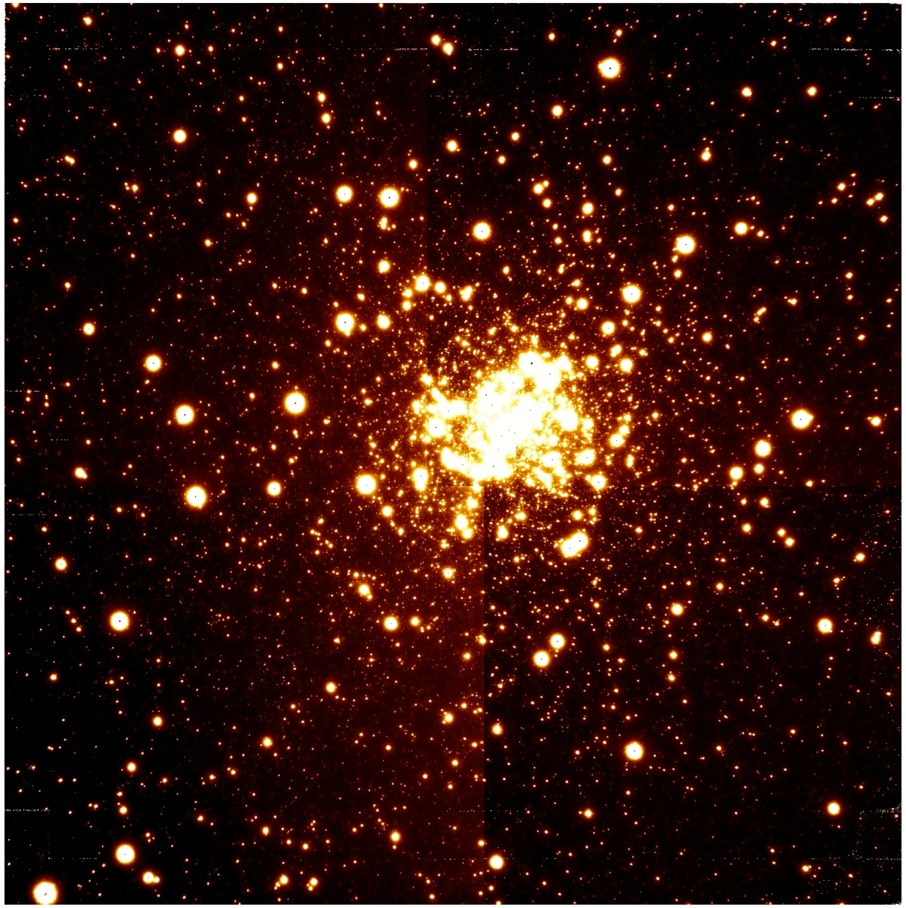
THE HELIUM EFFECT



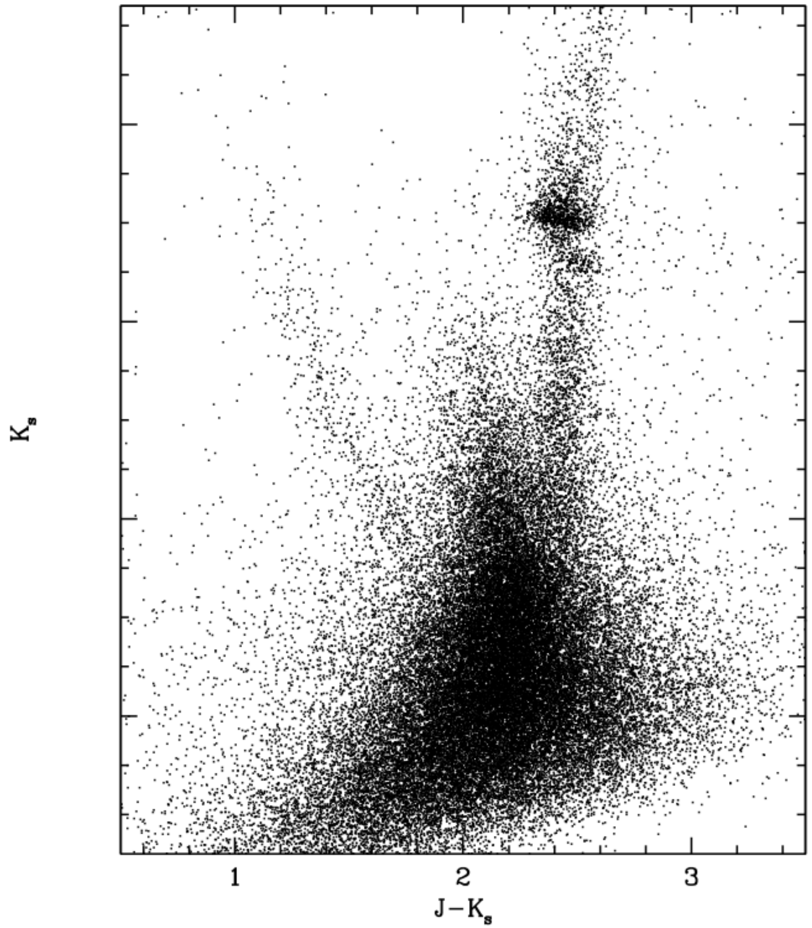
An increase in Helium increases the RC luminosity leaving the color almost unchanged

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

GEMINI observations of Liller1



Mosaic of 2x2 images
(FoV=85”x85”)



GSAOI (high resolution imager assisted by a Multi Conjugate Adaptive Optics system) mounted at GEMINI

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)

Cosmic-Lab

You can download this presentation from our web-site: **www.cosmic-lab.eu**

The End