Osservatorio Astronomico di Bologna
Istituto Nazionale di Astrofisica

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

DIPARTIMENTO
FISICA E ASTRONOMIA - DIFA

COSMIC-LAB:
project overview and results

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Bologna, Jan 30, 2014

THE PROJECT

Cosmic-Lab

- 5-year project funded by the European Research Council (ERC) with a grant of 1.9 MEuro

- *Advanced Research Grant* (2010 call)
  270 projects funded out of 2000 evaluated (13.8%),
  21 Italian project approved (7%)
  9 in Universe Sciences (3%)
  the only Italian project approved in Universe Sciences

- PI: Francesco R. Ferraro (Dip. of Physics & Astronomy – Bologna)

Cosmic-Lab

ERC Call	Applications received	Of which		
		Evaluated*	Funded	Success rates (%)**
Advanced Grant 2008	2,167	2,034	282	13.9
Advanced Grant 2009	1,584	1,526	245	16.1
Advanced Grant 2010	2,009	1,967	271	13.8
Advanced Grant 2011	2,284	2,245	301	13.4
Advanced Grant 2012	2,304	2,269	319	14.1
Advanced Grant 2013	2,408	2,363	284	12.0
Advanced Grant total	12,756	12,404	1,702	13.9***

✦ 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

MID-TERM REPORT OF THE COSMIC-LAB SCIENTIFIC ACTIVITY

The project started on May 1st 2011 and it will end on April 30th 2016

After 30 months of activity (May 1st 2011 – October 30th 2013)
a mid-term report of the project scientific activity is due to ERC for evaluation and approval

The report has been submitted and approved in November 2013

MID-TERM REPORT

Consolidation of the research group:

- 2 3-year RTD positions
- 20 1-year Post-Doc positions
- 3(+2) 3-year PhD positions

The COSMIC-LAB team currently counts 12 researchers
(the PI + 1RTI + 2RTD + 4 Post-Docs +4 PhDs)

THE PROJECT STRUCTURE & TEAM

PI

+

THE WORK PACKAGE COORDINATOR

Barbara Lanzoni

WP1-STELLAR PHOTOMETRY

Emanuele Dalessandro

WP2-STELLAR SPECTROSCOPY

Alessio Mucciarelli

WP3 - SIMULATIONS

Barbara Lanzoni

THE POST-DOCs

Paolo Miocchi (Dynamical models & N-body simulations)

WP3

Loredana Lovisi (Spectroscopy of Blue Straggler Stars)

WP2

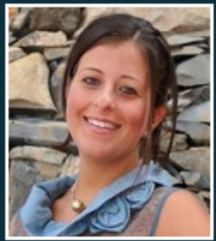
Edoardo Lagioia (Stellar photometry)

WP1

Giuliana Fiorentino (Stellar photometry & variability)

WP1

THE PhD STUDENTS



Cristina Pallanca (Cycle XXVI: starting date Jan. 2010)

Cosmic-Lab: Search for Millisecond Pulsar companions

WP1

Davide Massari (Cycle XXVII: starting date Oct. 2011)

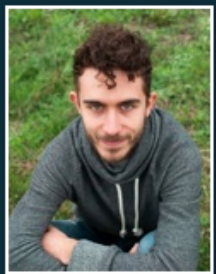
Cosmic-Lab: Search for fossil remnants of the Galactic bulge

WP1-WP2

Emilio Lapenna (Cycle XXVIII: starting date Oct. 2012)

Cosmic-Lab: Internal dynamics of Globular Clusters

WP2



Emiliano Alessandrini (Cycle XXIX: starting date Oct. 2013)

Cosmic-Lab: Globular Cluster internal dynamics through direct N-body simulations

WP3

MID-TERM REPORT

Telescope time assigned to the project:

The scientific activity of the project is deeply connected with the access to the major astronomical observational facilities (telescopes and satellites).
In 30 months: more than 200 orbits with HST and 500 hours at the 8-10 m – class telescope have been assigned to project dealing with COSMIC-LAB

- HST: Cycle 19 = 39 orbits
  Cycle 20 = 28 orbits
  Cycle 21 = 15+131 orbits
- ESO-VLT : Period 87= 6 nights + 15 hours
  Period 89= 3 nights + 3 hours
  Period 90= 5 nights + 21 hours
  Period 91= 2 nights + 24.5 hours
  Period 92= 3 nights + 33 hours
  Period 93= **225 hours !!!!!!** ← **Large Programme**
- GEMINI: 7.5 hours
- KECK: 10 hours

MID-TERM REPORT

Published papers:

24 papers have been published in peer-reviewed journals.
This corresponds to a rate of 0.8 paper/month (over 30 months of activity)

- 15 in the *Astrophysical Journal*
- 3 in the *Astrophysical Journal Letters*
- 3 in *MNRAS*
- 2 in the *Astronomical Journal*
- **1 in *Nature***

Invited/contributed talks:

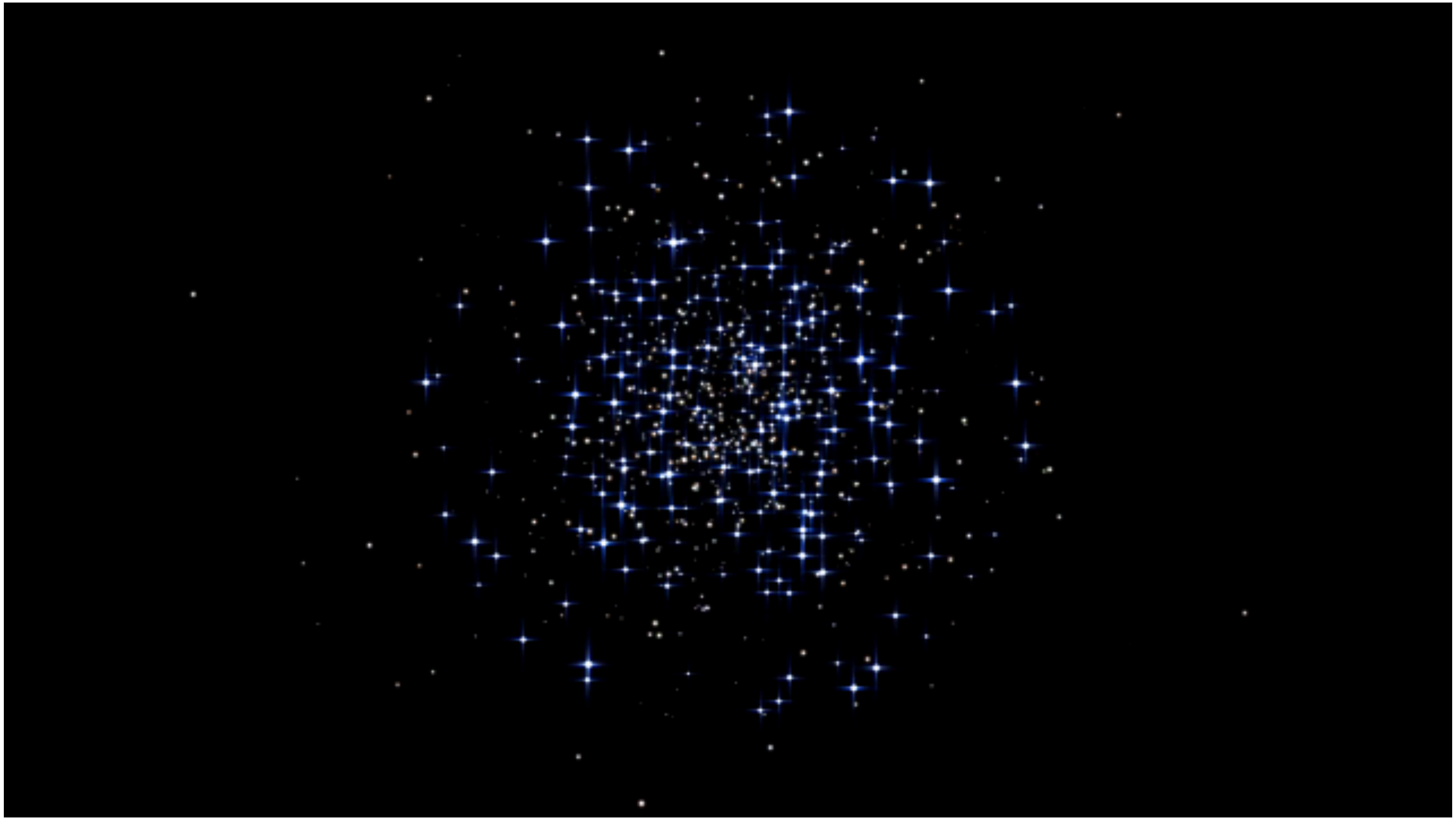
- 23 invited/contributed talks have been given at international conferences and/or at the major science institute over the world.

MID-TERM REPORT

The project web-page: http://www.cosmic-lab.eu/

We have created a web-page of the project, where the entire scientific activity of the project (in terms of scientific results, products and tools, amount of awarded telescope time, press releases, freely downloadable images and videos and job opportunities) is constantly updated and can be monitored

WHY GCs?



In these dynamically active stellar systems phenomena like stellar collisions, mass exchanges and migration of different class of stars are frequent. This activity can generate **exotica**

THE PROBE PARTICLES

Intermediate-mass Black Holes (IMBH)

Dark objects which can dominate the dynamics of GC very central regions

Blue Stragglers (BSS)
Millisecond pulsars (MSP)

Examples of stellar-rejuvenation processes (possibly induced by dynamics)

THE FIRST CLASS OF PROBE PARTICLES

Intermediate-mass Black Holes (IMBH)

Dark objects which can dominate the dynamics of GC very central regions

People involved: Ferraro, Lanzoni, Dalessandro, Mucciarelli, Miocchi, Lapenna,

Origlia (INAF), Bellazzini (INAF) Valenti (ESO), Vesperini (USA)

IMBH

✓ They are expected in GCs

• **Extrapolation of the "Magorrian relation" to GC mass scales**

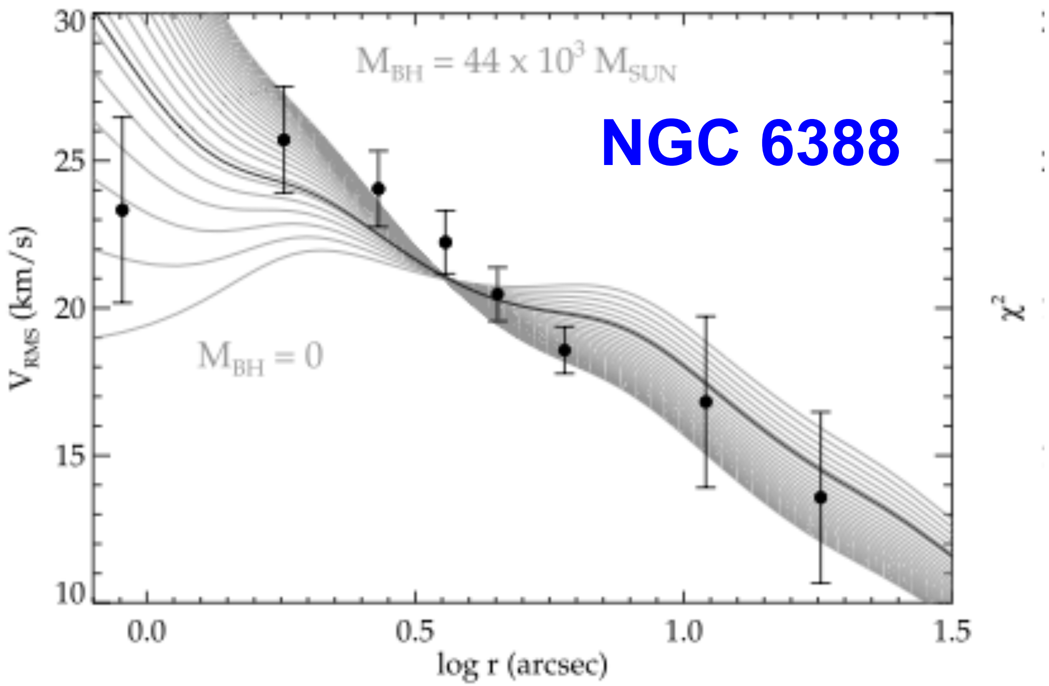
✓ IMBH FINGERPRINTS in GCs

(e.g., Baumgardt +05; Miocchi 2007; Heggie +07; Trenti +07, +10; Dukier & Bailyn +03; Maccarone 2004; Gill +08; Vesperini & Trenti 2010; Umbreti+12)

1) **Shallow cusp in the star density profile**
2) **cuspy velocity dispersion profile**
3) presence of **high-velocity stars** (even *v* ~ 100 km/s)
4) **quenching of mass segregation**
5) **X-ray and radio emission** from accreting gas

IMBH signature: velocity dispersion profile

Recent claims of the detection of IMBH signatures in a number of GGCs have been published by Lutzgendorf et al. on the basis of cuspy velocity dispersion profiles obtained from the line broadening of integrated light spectra

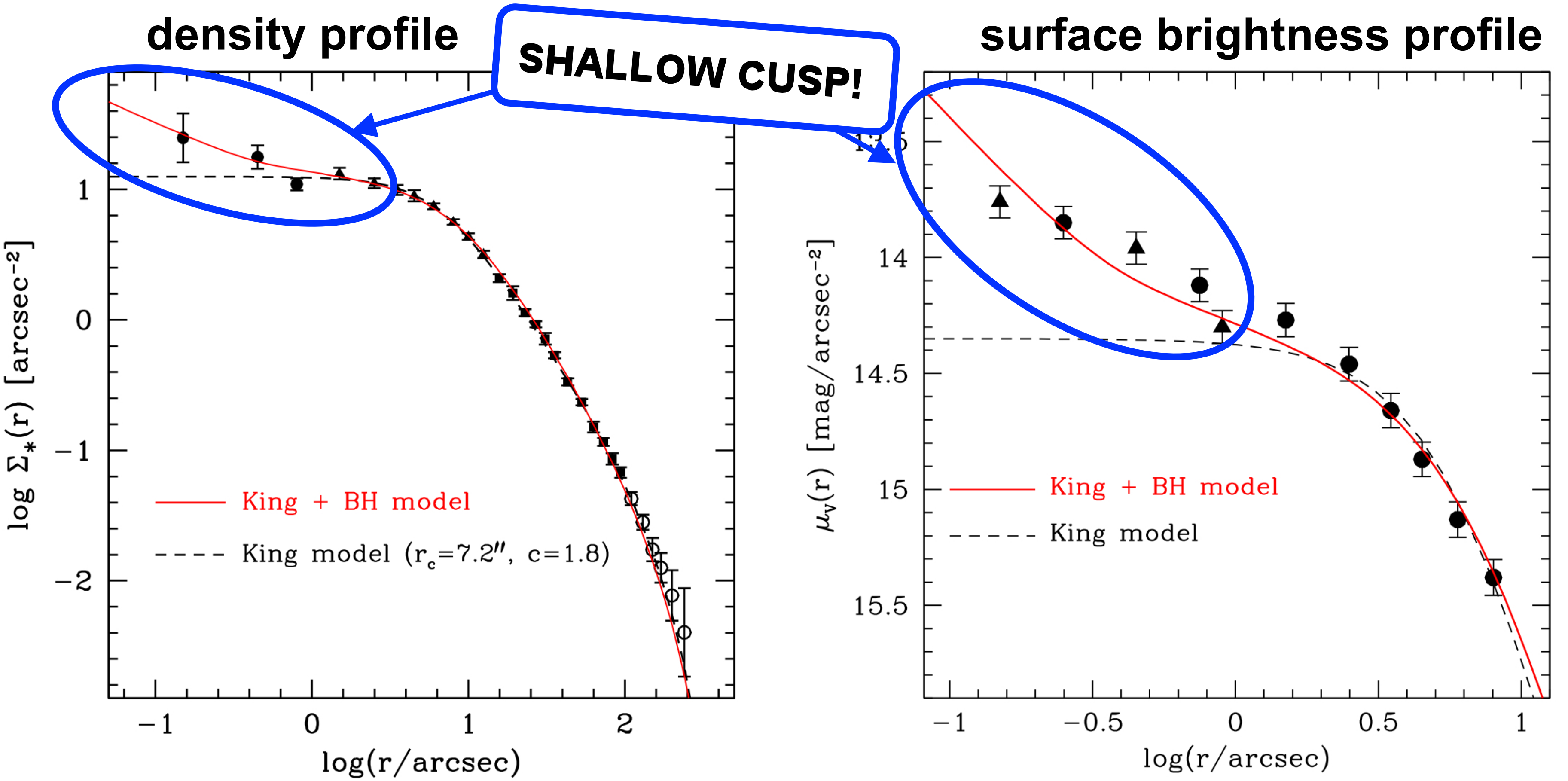


NGC6388: (4.4 ± 0.9) x 10^4 $M_\odot$ (Lutzgendorf et al. 2011)

NGC1904: (3 ± 1) x 10^3 $M_\odot$ (Lutzgendorf et al. 2012)

NGC6266: (2 ± 1) x 10^3 $M_\odot$ (Lutzgendorf et al. 2012)

IMBH signature: star density profile



+ self-consistent, multi-mass, King models with central BH

➔ IMBH of ~ 6000 $M_\odot$ (**Lanzoni et al. 2007, ApJ 668, L139**)

Velocity dispersion from the **radial velocities of individual stars**

(Lanzoni et al. 2013, ApJ 769, 107)

- **ESO-VLT/SINFONI:** AO-assisted IFU spectrograph, R=4000, K-band grating (1.95-2.45 μm), spatial resolution=0.1”, FoV=3.2”x3.2”

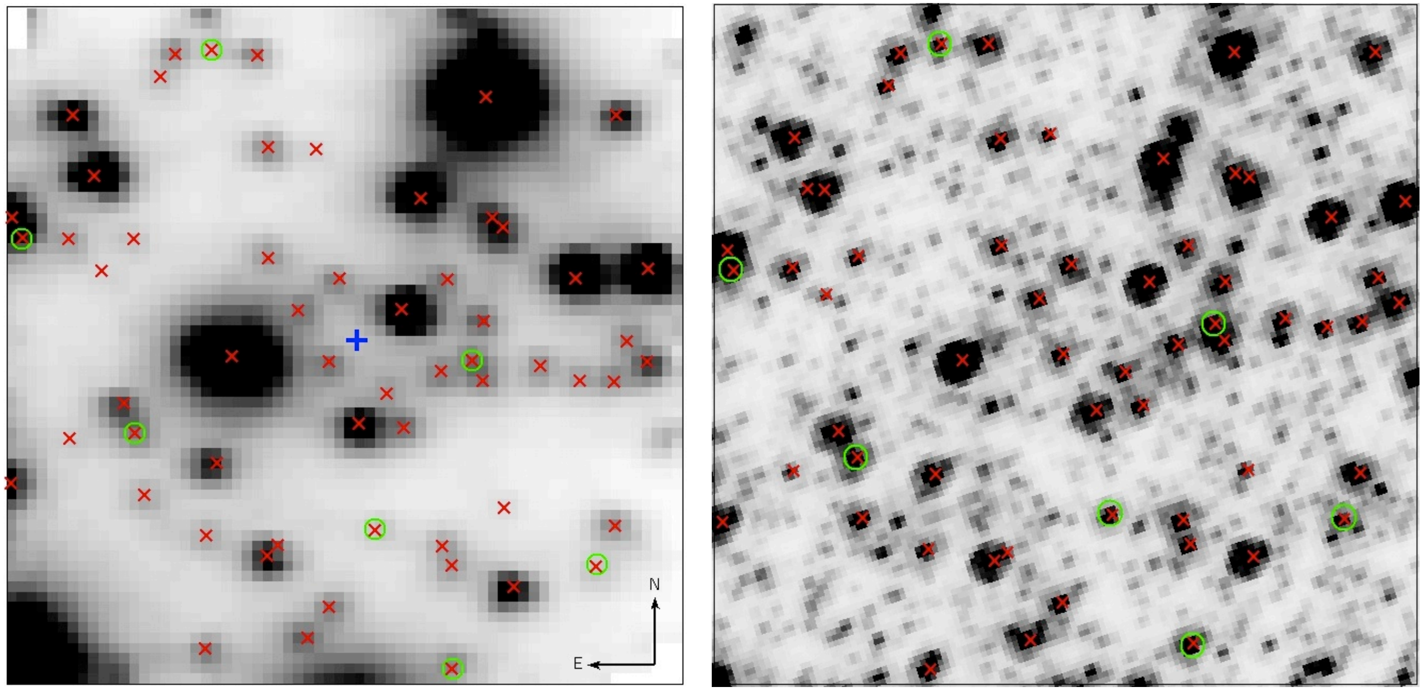
  → **central σ(r)**

- **ESO-VLT/FLAMES-GIRAFFE in MEDUSA mode:** multi-object spectrograph (132 fibres), high spectral resolution (R>10,000), optical (Ca triplet, Fe, ..), FoV of 25’ in diameter

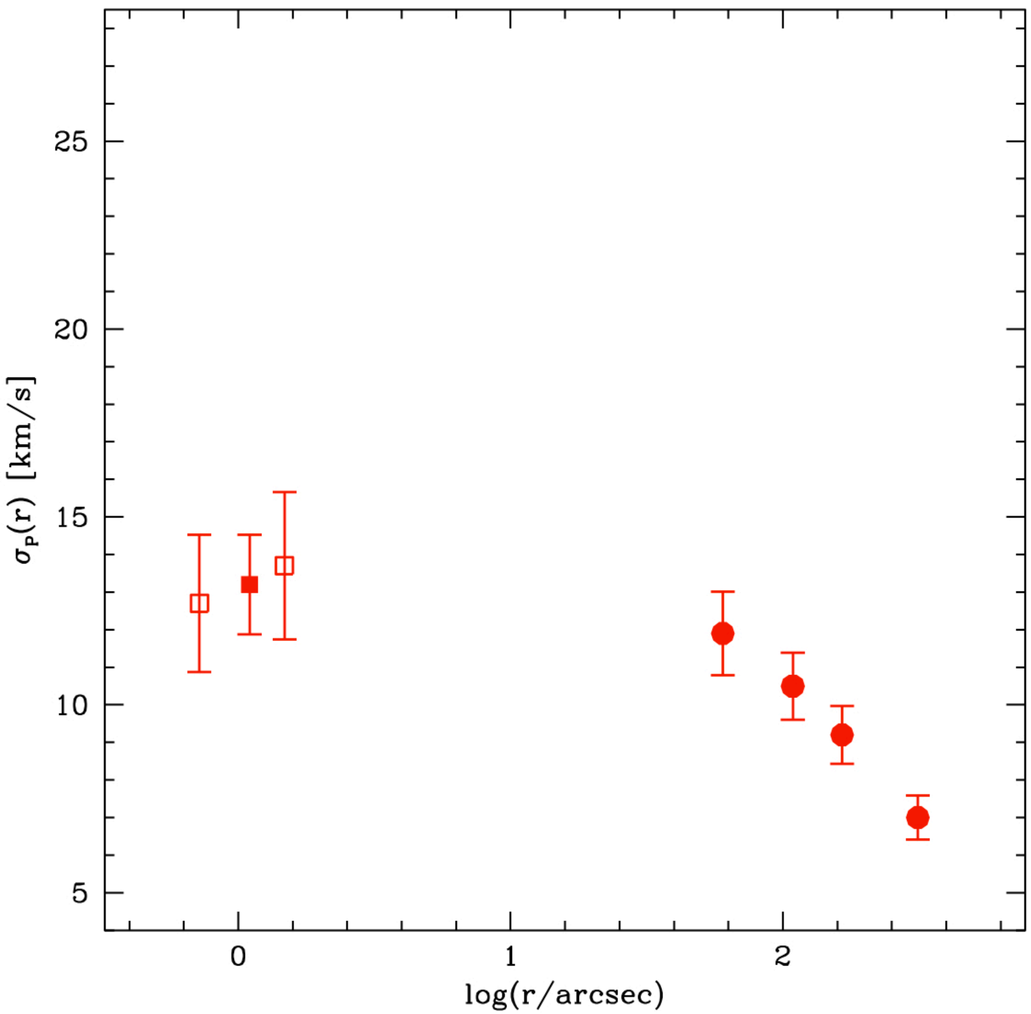
  → **external σ(r)**

SINFONI (central) sample

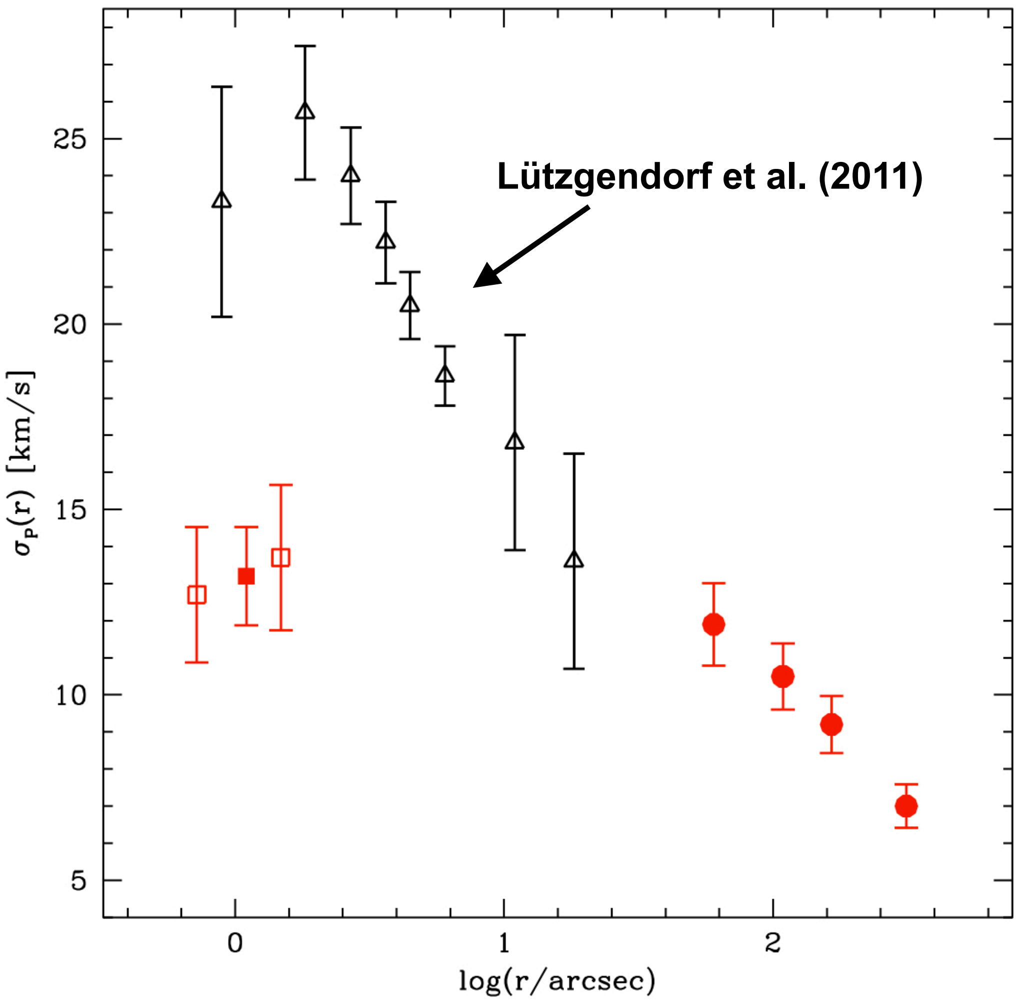
SINFONI HST/HRC



→ V_r for 52 individual stars with r<2”



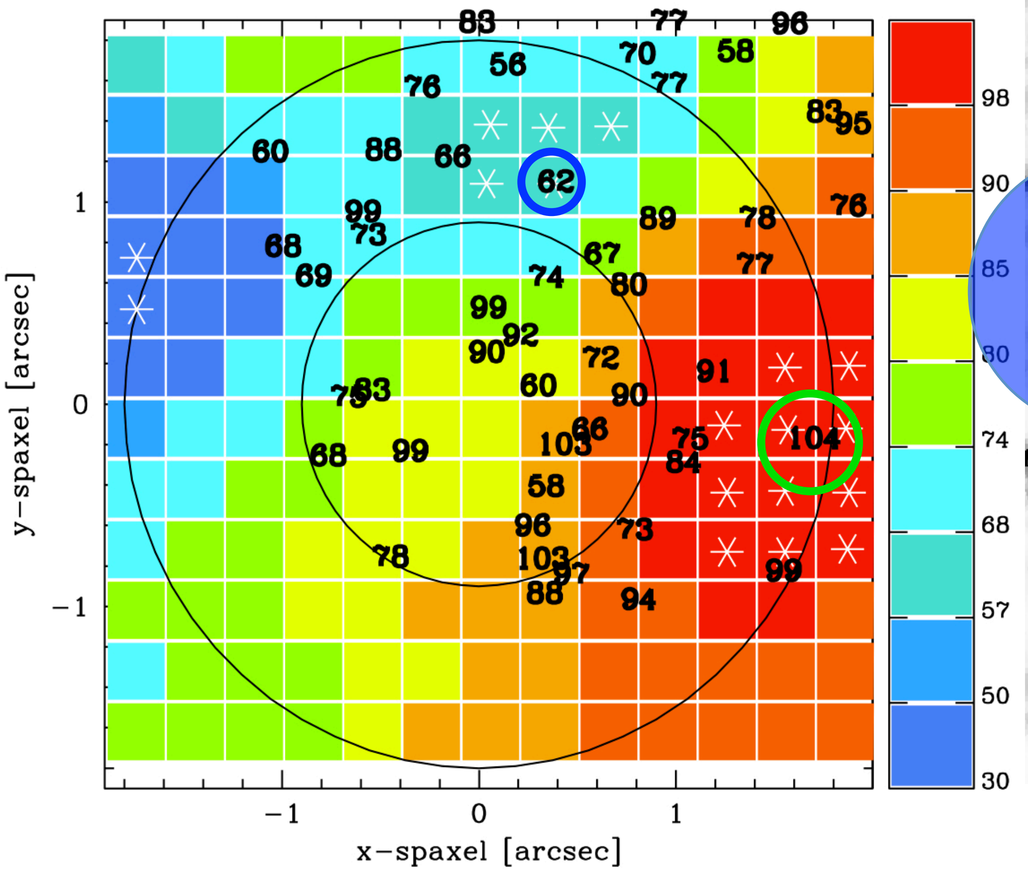
$\sigma(r)$ from individual V_r ($\sigma_0 \sim$ 13-14 km/s)



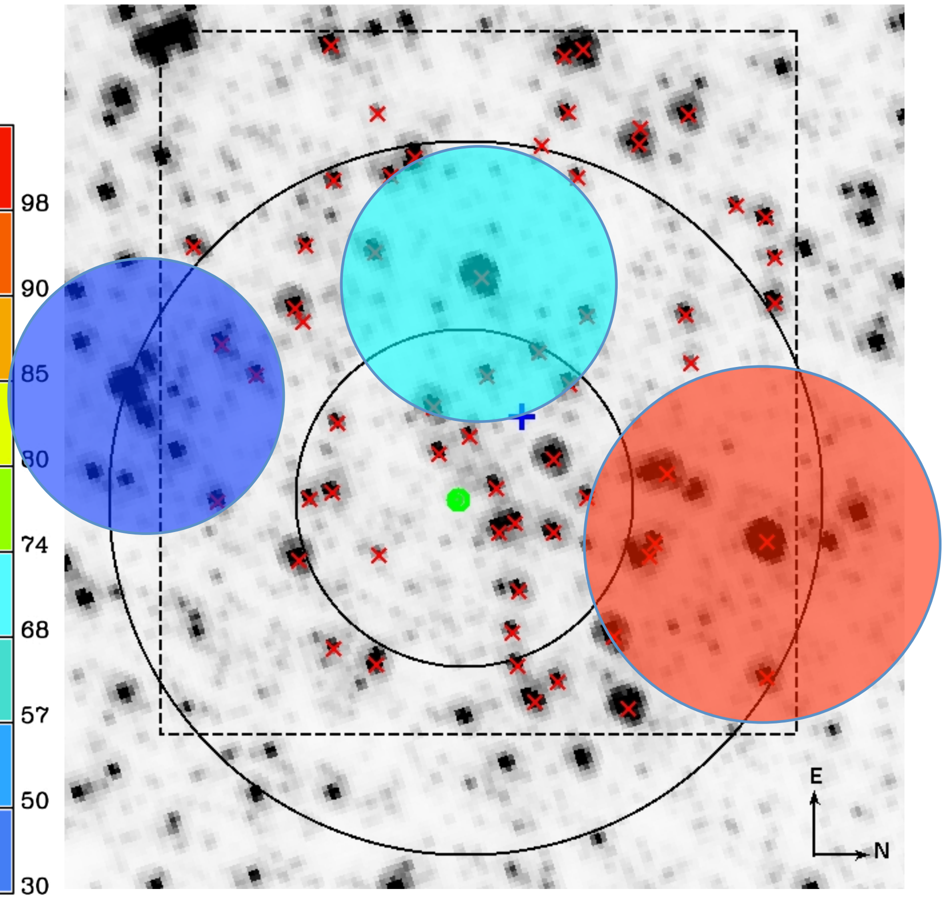
$\sigma(r)$ from individual V_r (σ_0 ~ 13-14 km/s) incompatible with $\sigma(r)$ from the line broadening of integrated-light spectra (σ_0 ~ 23-25 km/s)

Insufficient shot-noise correction

- → **colours**: radial velocity map of L11
- → **white asterisks:** spaxels excluded by L11 for shot noise correction
- → **black values:** our V_r measurements

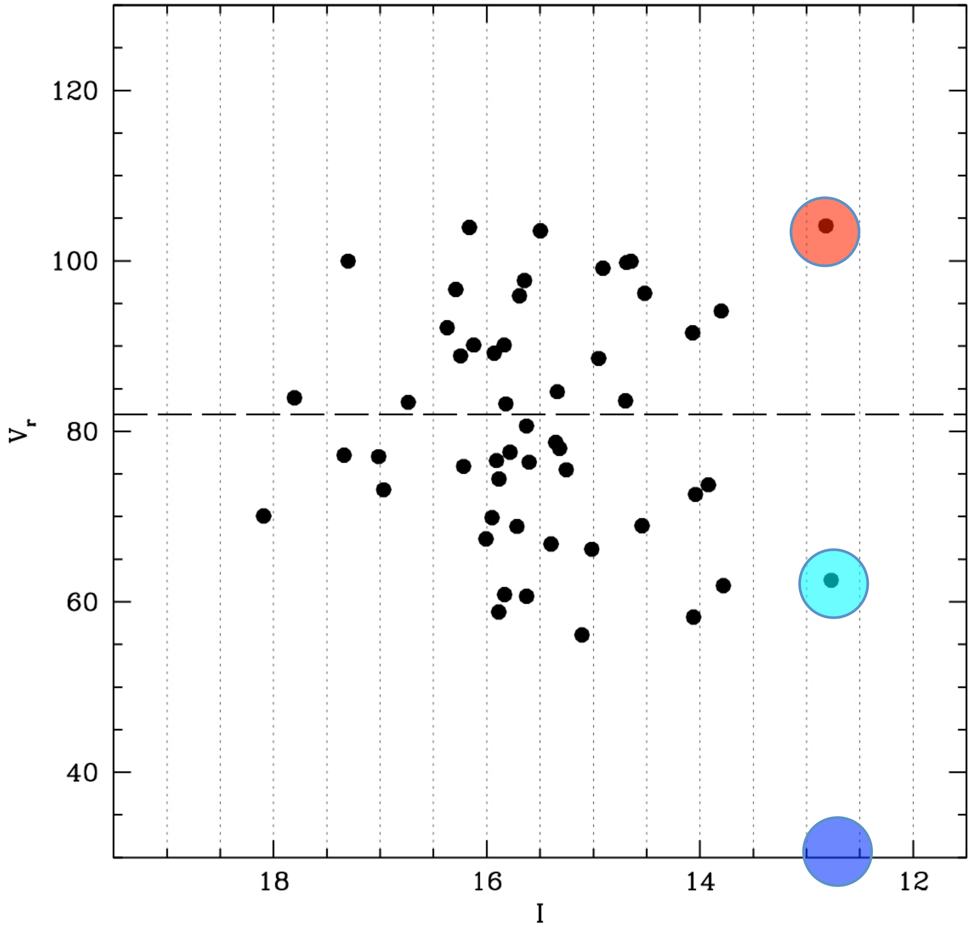


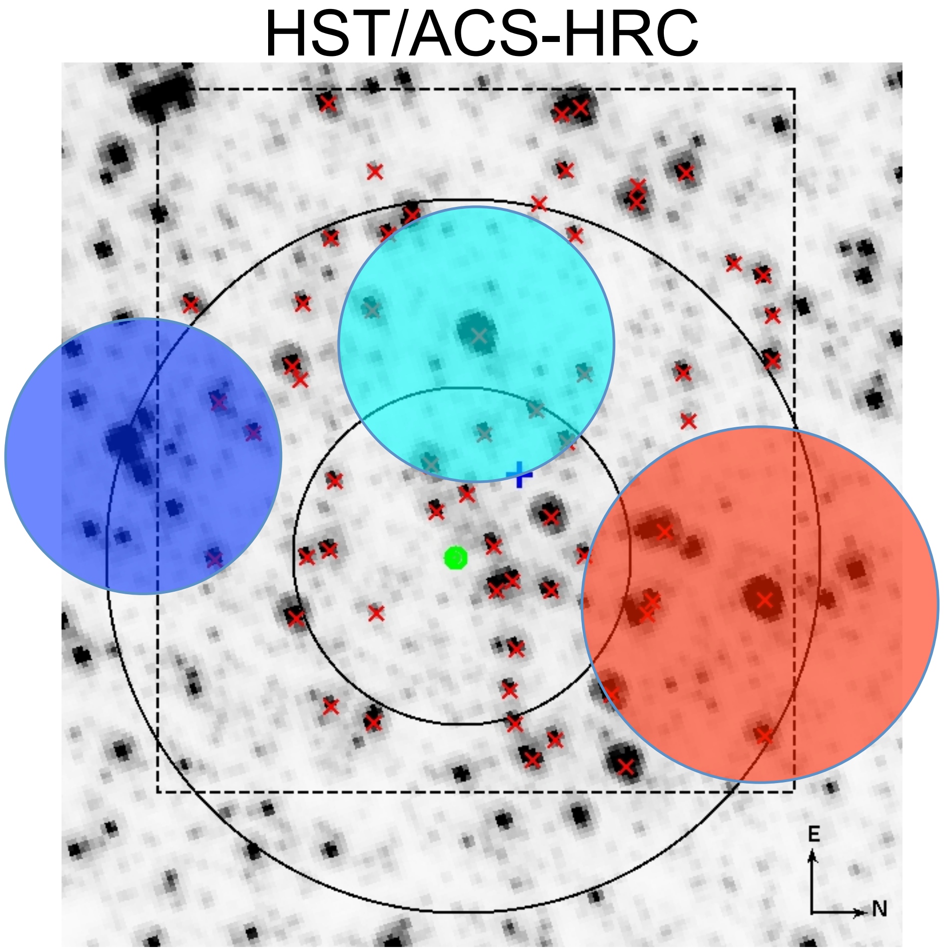
HST/ACS-HRC



Insufficient shot-noise correction

- **integrated light spectra are biased by the dominant contribution of a few bright giants**



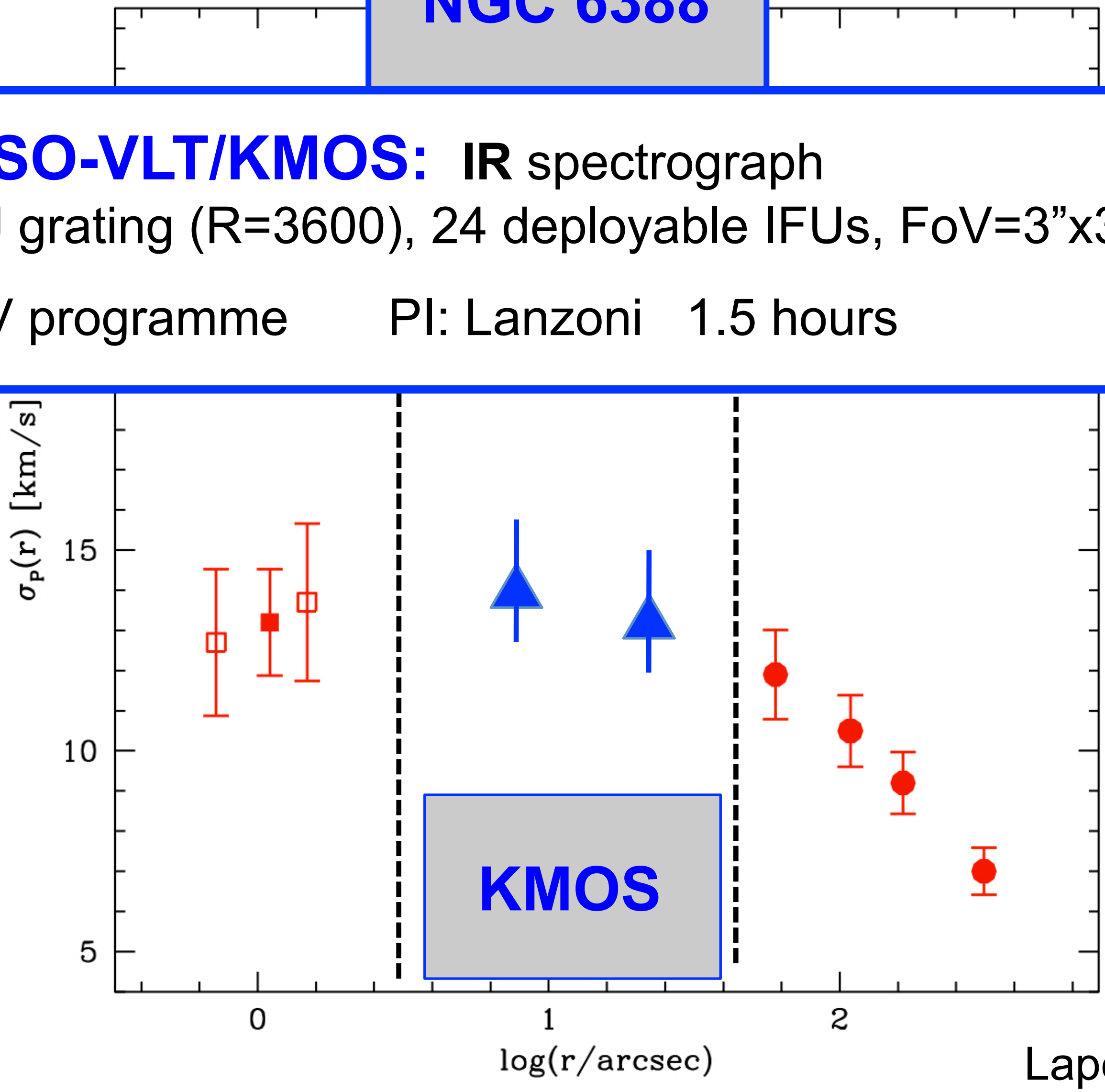


NGC 6388

ESO-VLT/KMOS: **IR** spectrograph

YJ grating (R=3600), 24 deployable IFUs, FoV=3”x3” each

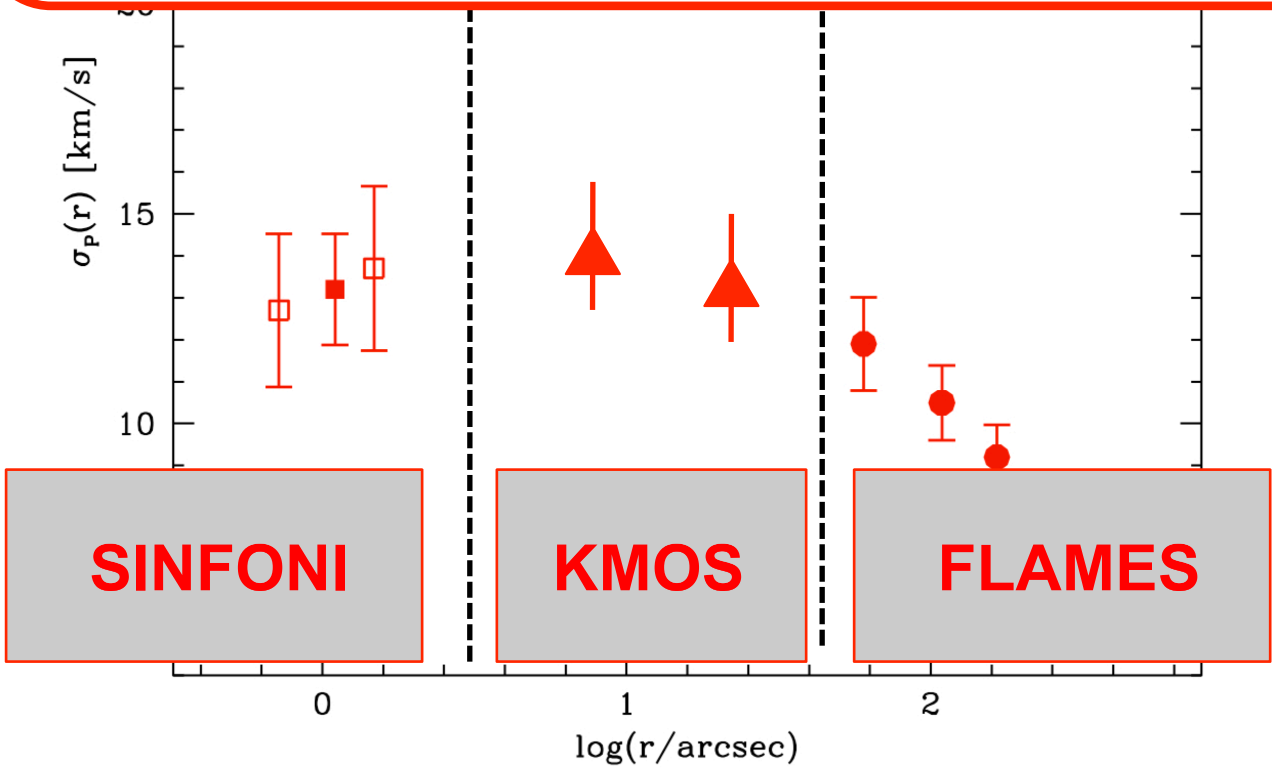
SV programme PI: Lanzoni 1.5 hours



Lapenna et al (2014)

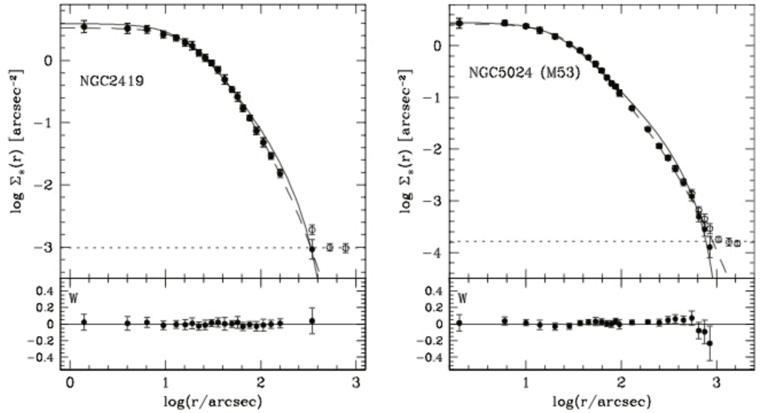
ESO-VLT LARGE PROGRAMME (P93+94+95)

KMOS + FLAMES	PI: Ferraro		194 hours
SINFONI	PI: Lanzoni		31 hours
Grand total		30 GGCs	225 hours



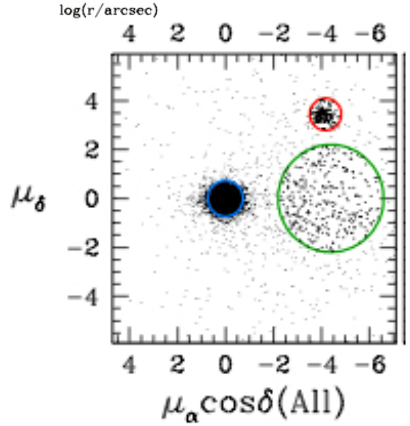
This is the most extensive and complete approach ever attempted to study the internal dynamics of GCs

ESO-VLT LP = The new generation of velocity dispersion profiles (Lanzoni et al. 2013, Lapenna et al 2014)



+ The new generation of Star density profiles of 40 GGCs (Miocchi et al. 2013 + Ferraro et al 2014)

+ internal proper motions from multi-epoch HST observations (see Massari et al 2013)



provide the FIRST 3D velocity map of the cores
+ evidence of any systemic internal rotation
+ evidence of any IMBH
for a significant sample of clusters.

THE SECOND CLASS OF PROBE PARTICLES

Millisecond pulsars (MSP)

Stellar population rejuvenated by dynamical processes

People involved: Ferraro, Lanzoni, Dalessandro, Mucciarelli, Pallanca, Massari

Origlia (INAF), Possenti (INAF), Beccari (ESO), Ransom (USA)

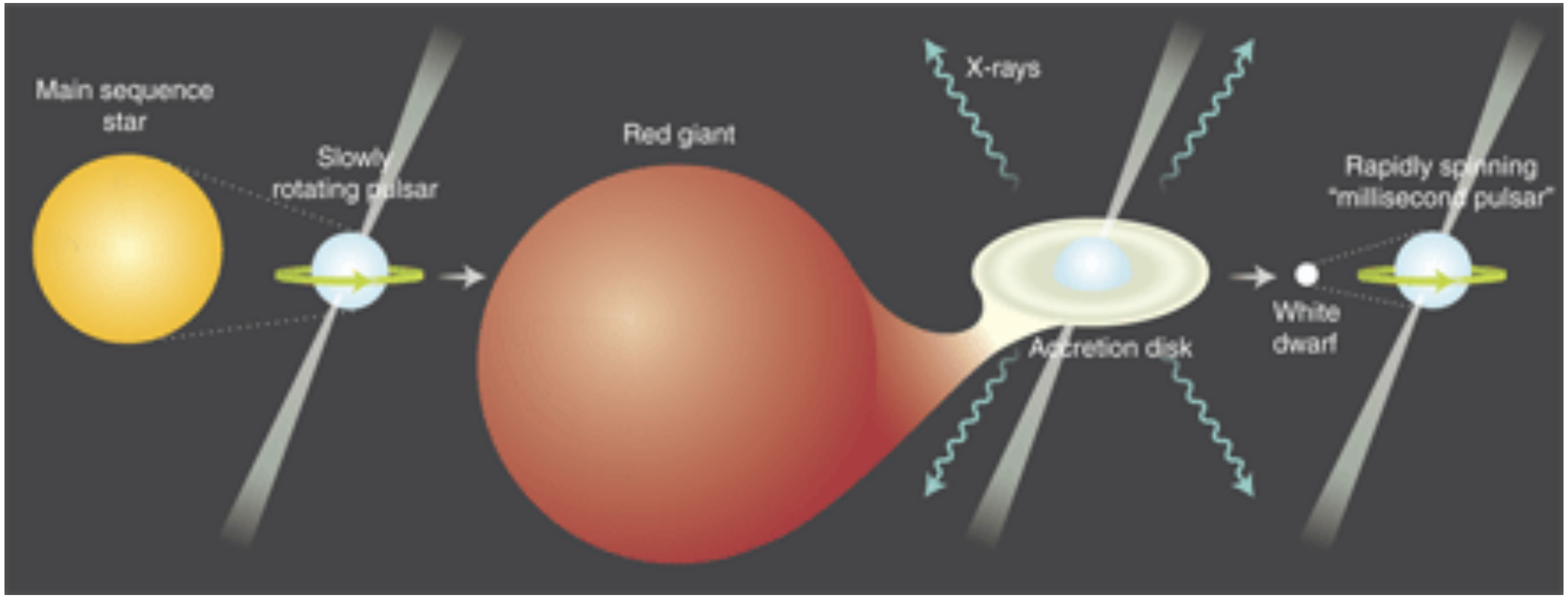
Millisecond pulsars (MSP)

MSP (recycled-pulsars):

pulsars with $dP/dt < 10^{-17}$ (OLD) and $P \sim 10^{-3}$ sec (RE-ACCELERATED)

RE-CYCLING SCENARIO (Bhattacharya et al. 1991):

- binary system: NS + evolving companion
- mass accretion from an evolving companion spin up the pulsar



The MSP population

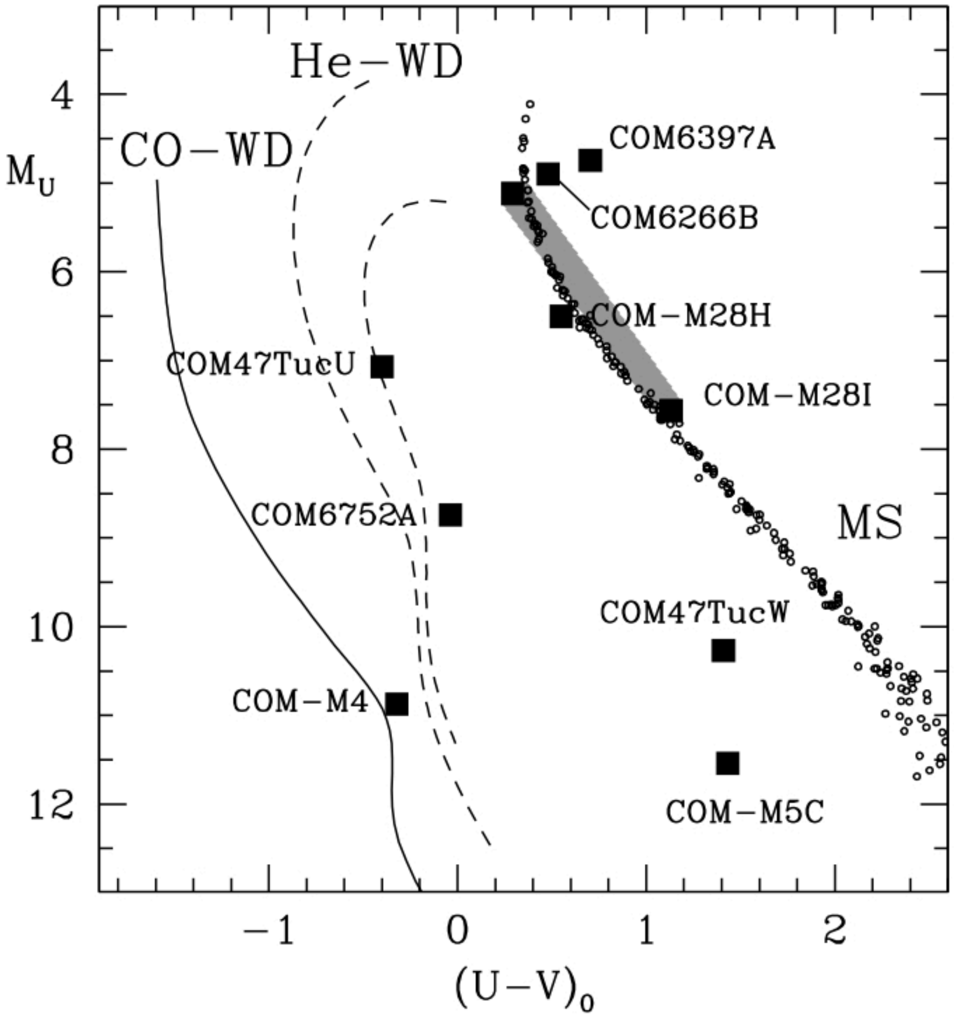
More than 250 MSP are known in the Galaxy.
Although the Galactic disk is 100 times more massive than the GC system, more than 50% of MSP are in GCs

Galactic Field **Globular Clusters**

Evolution of primordial binaries

Dynamical interactions can promote the formation of binaries suitable for recycling NS into MSP

MSP optical companion in GCs



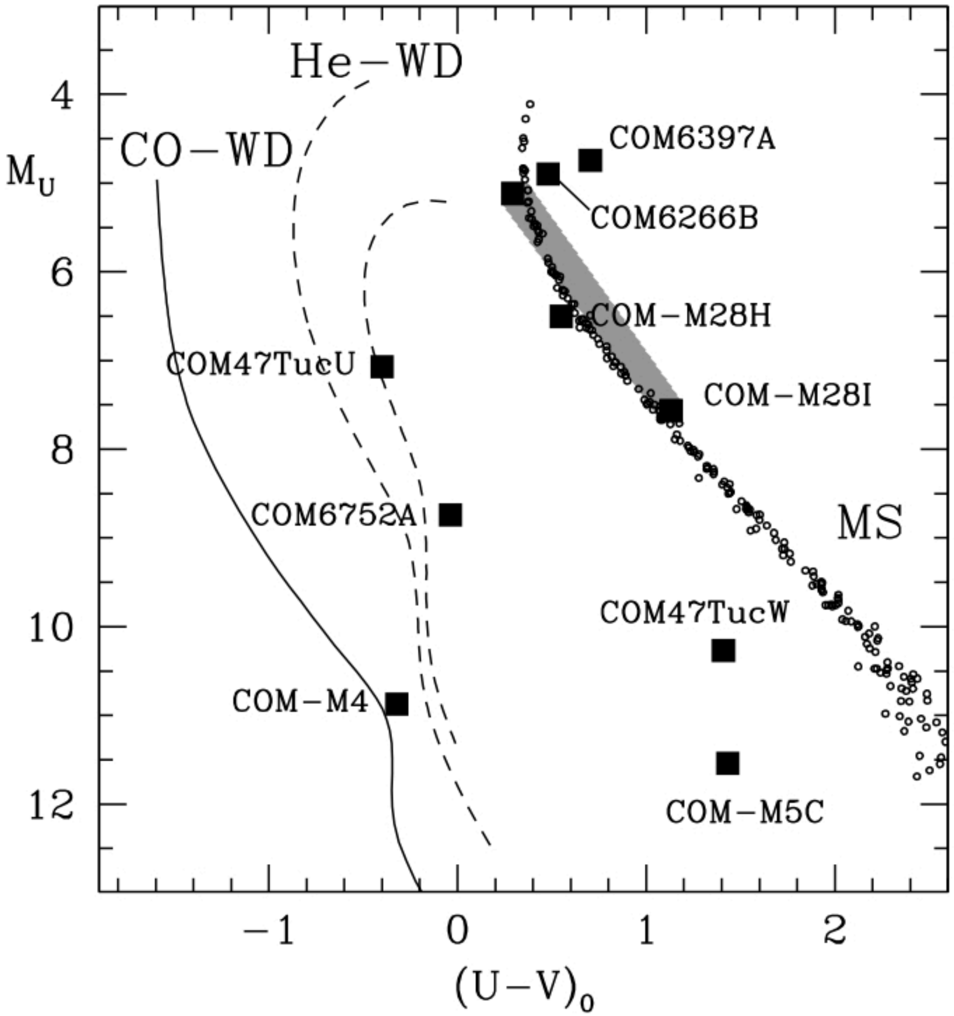
ONLY 9 known MSP companions in 7 GCs
(7 discovered by our group)
See Pallanca PhD thesis

The determination of the mass of the companion allows an estimate of the NS mass.

Maximum NS mass

Equation of state of degenerate matter

MSP optical companion in GCs



Hunting for the MSP companion to PSR-B in NGC6440
The system has a total mass of 2.9 $M_{\odot}$!!!

Maximum NS mass

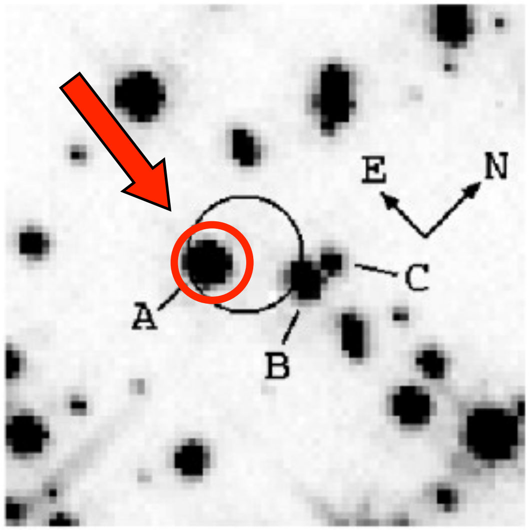
Equation of state of degenerate matter

MSP optical companion in GCs

In order to look for a companion it is mandatory to obtain accurate astrometric solutions.

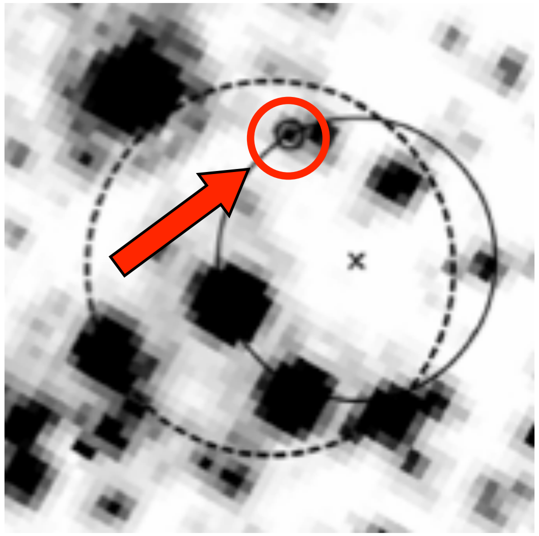
In previous identifications we found an agreement between the radio and the optical positions within 0.3”

COM 6397A



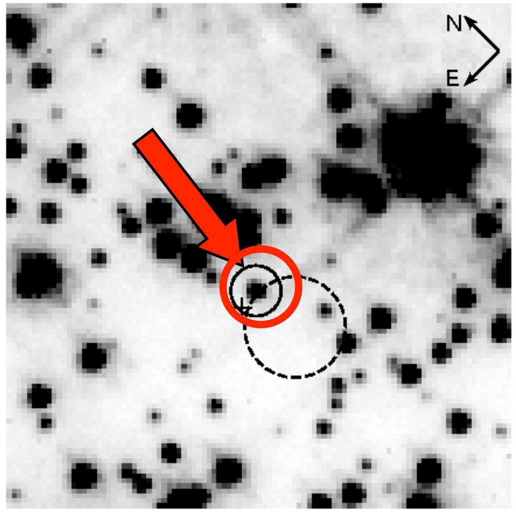
(*Ferraro et al. 2001*)

COM 6266B



(*Cocozza et al. 2008*)

COM-M28H

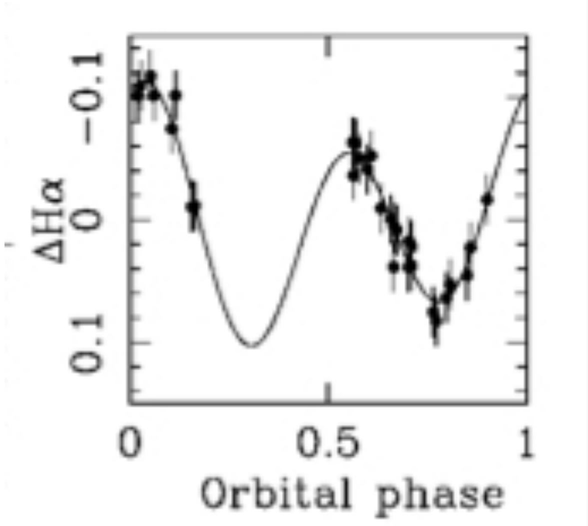


(*Pallanca et al. 2010*)

MSP optical companions in GCs

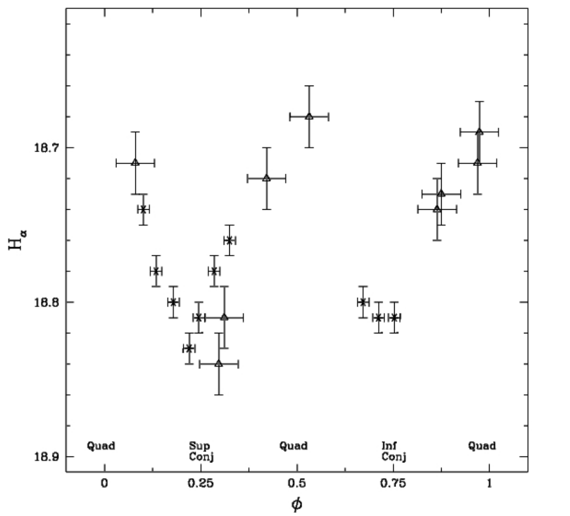
In all the detected companions the optical variability is in full agreement with the orbital period of the binary system

COM 6397A



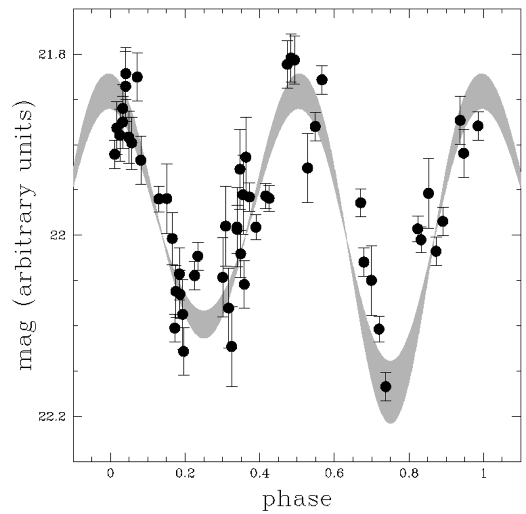
(Ferraro et al. 2001)

COM 6266B



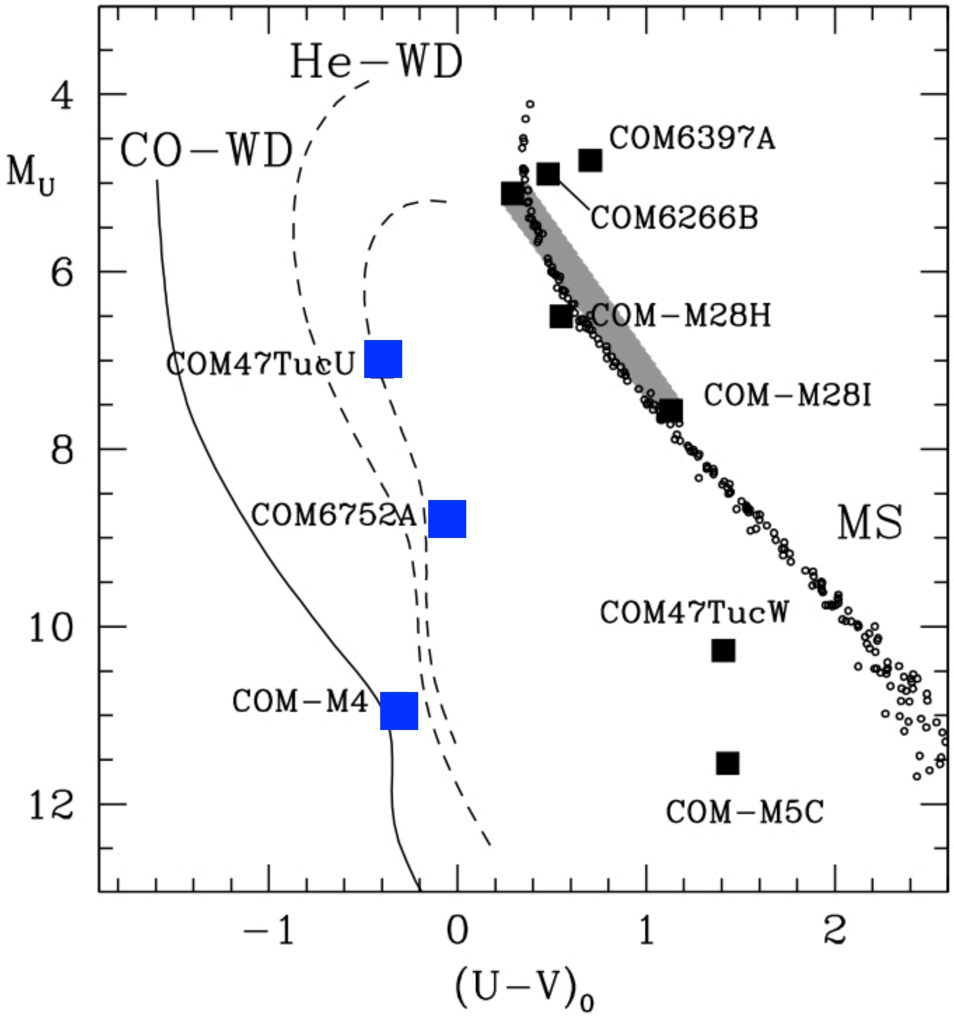
(Cocozza et al. 2008)

COM-M28H



(Pallanca et al. 2010)

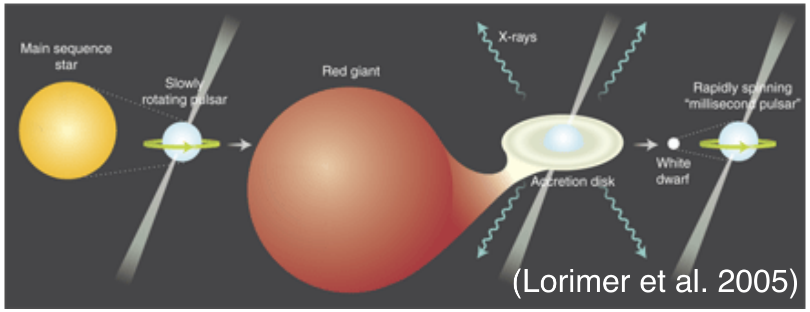
MSP optical companions in GCs



3 He WD
(Edmonds et al. 2001; Ferraro et al. 2003; Sigurdsson et al 2003)

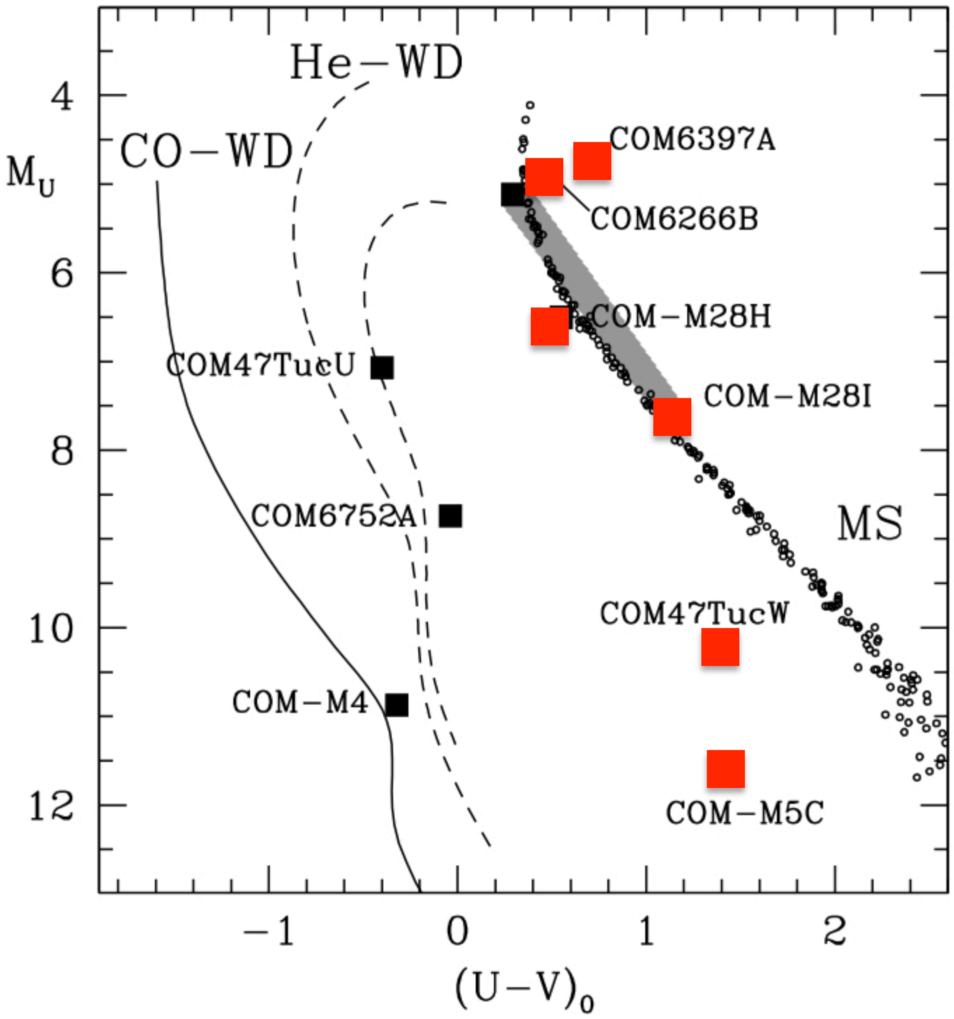
CONFIRMATION OF THE RECYCLING SCENARIO:

low mass He-WD is the “final stage” of the pulsar recycling process

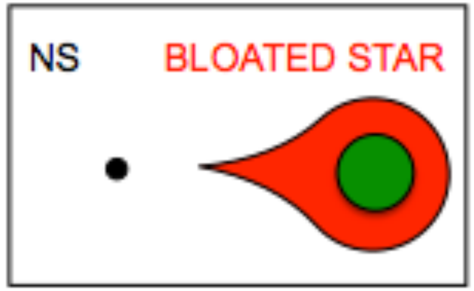


(Lorimer et al. 2005)

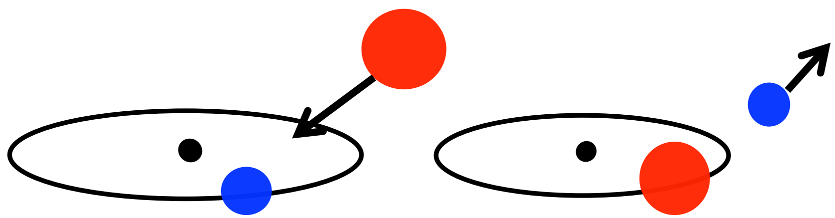
MSP optical companion in GCs



6 NON Degenerate Objects
(Ferraro et al. 2001; Edmonds et al 2002; Cocozza et al 2008; Pallanca et al. 2010, Pallanca et al. 2012,2013, 2014).

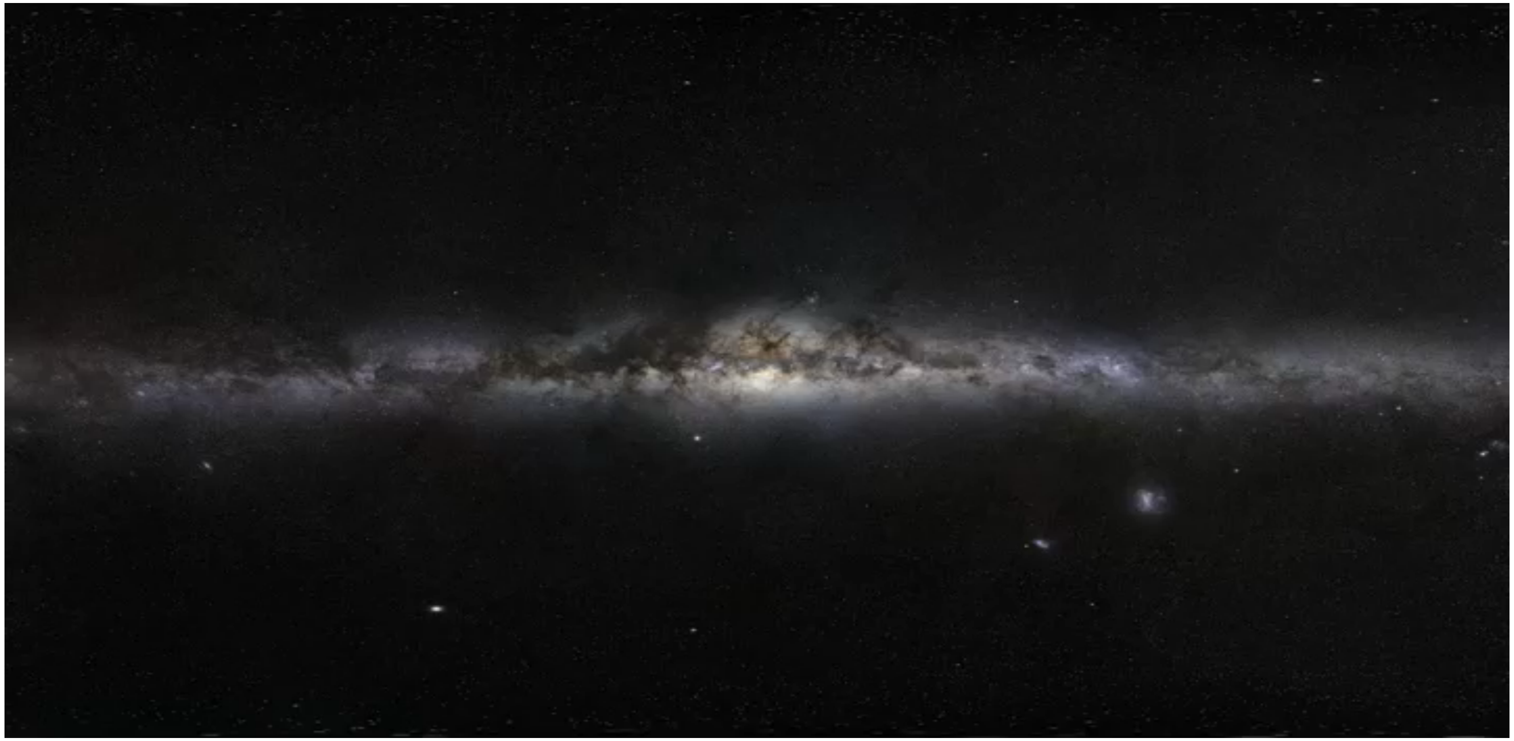


Exchange interactions



THE UNEXPECTED: TERZAN 5

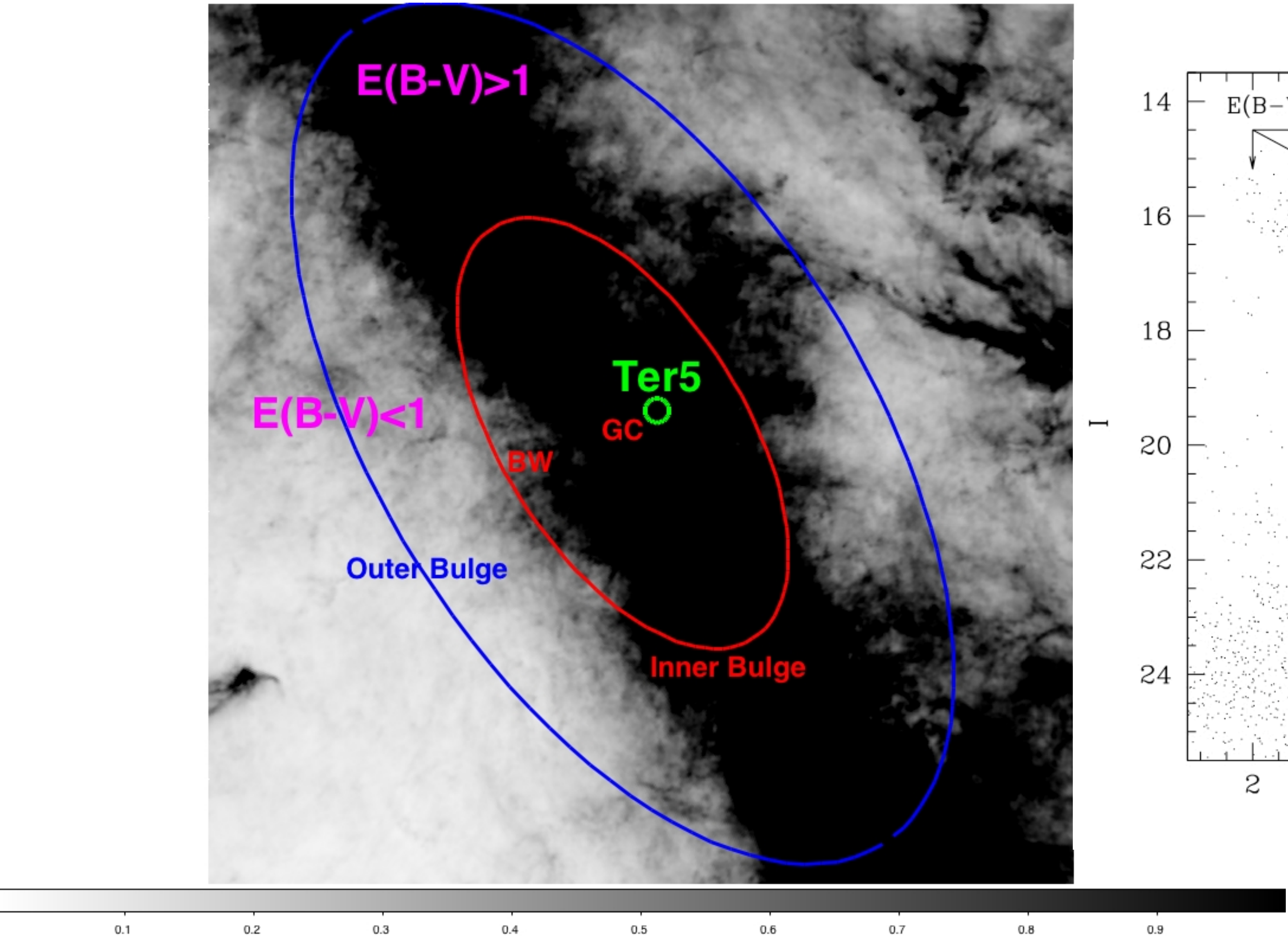
Terzan 5 harbors the largest known population of MSP in the Galaxy:
34 MSP (~25% of the entire MSP population in GCs)

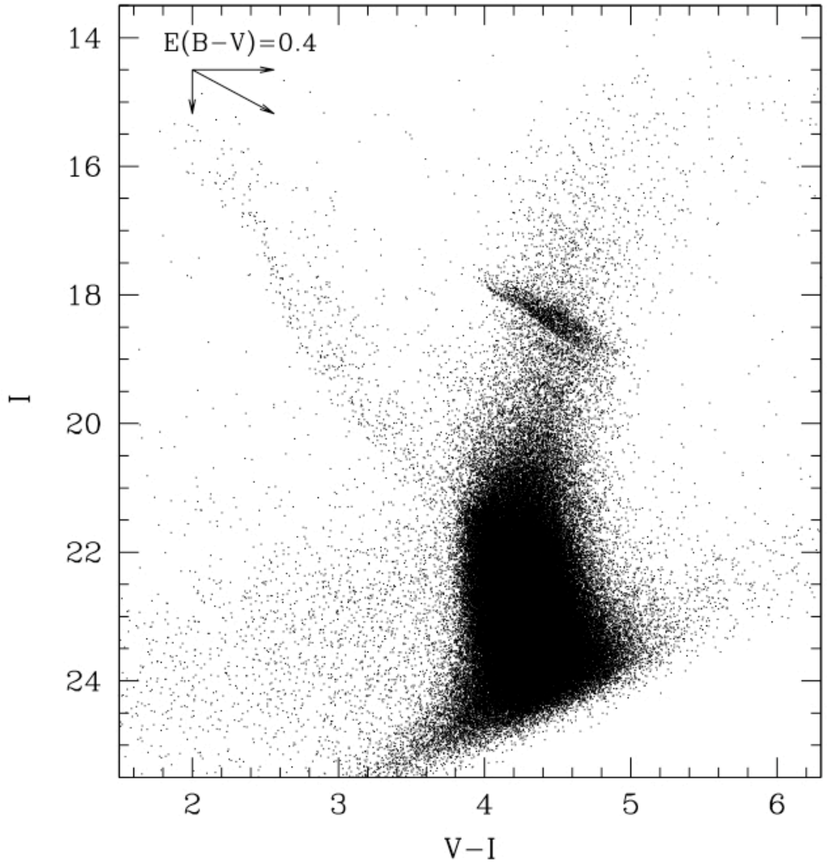


E(B-V)=2.3; d = 6Kpc; d_{GC}=2.1 kpc (Valenti et al 2007) i.e. in the outskirts of the inner Bulge. Suspected to have the largest collision rate of the entire GC system (Verbunt & Hut 1987, Lanzoni et al 2010)

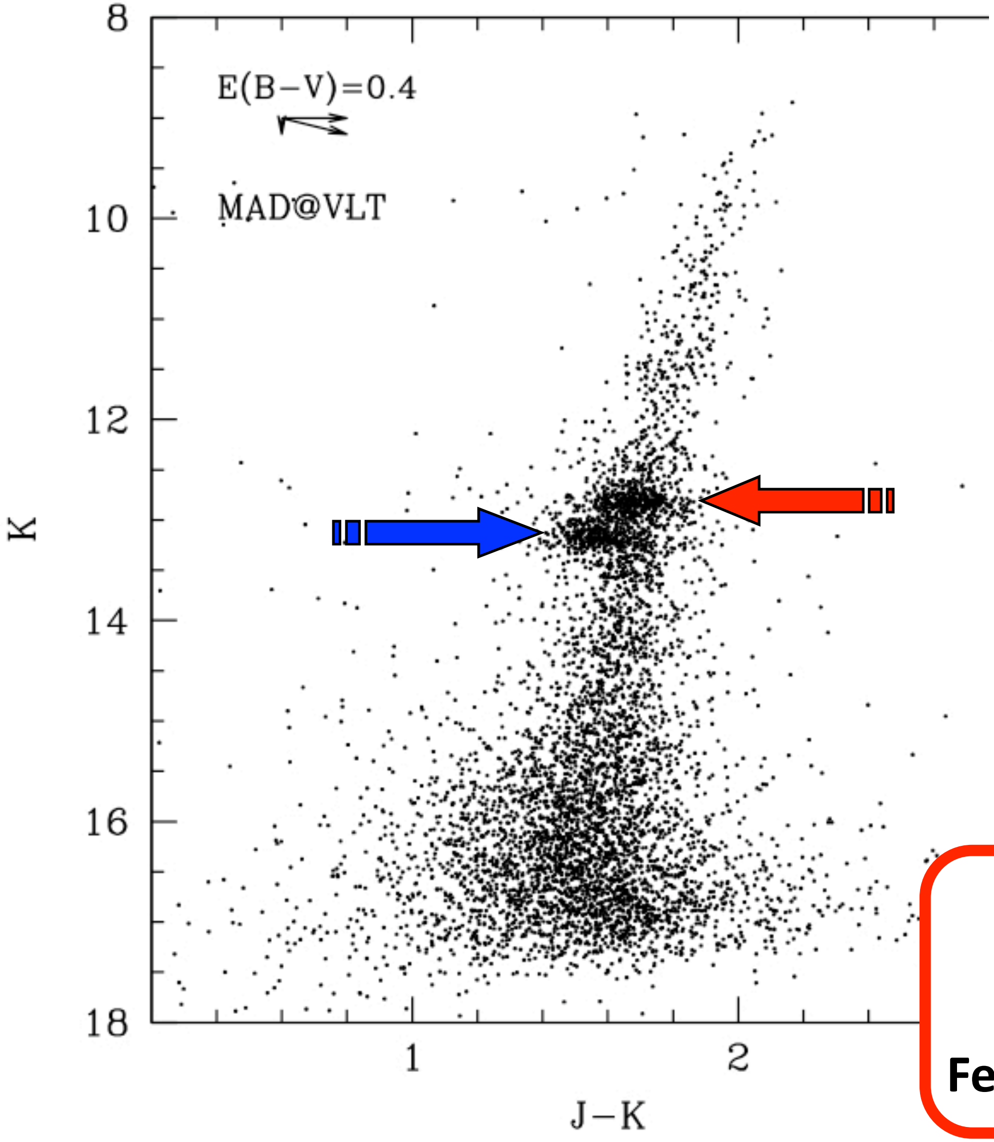
The deepest optical CMD of Terzan5 from ACS@HST

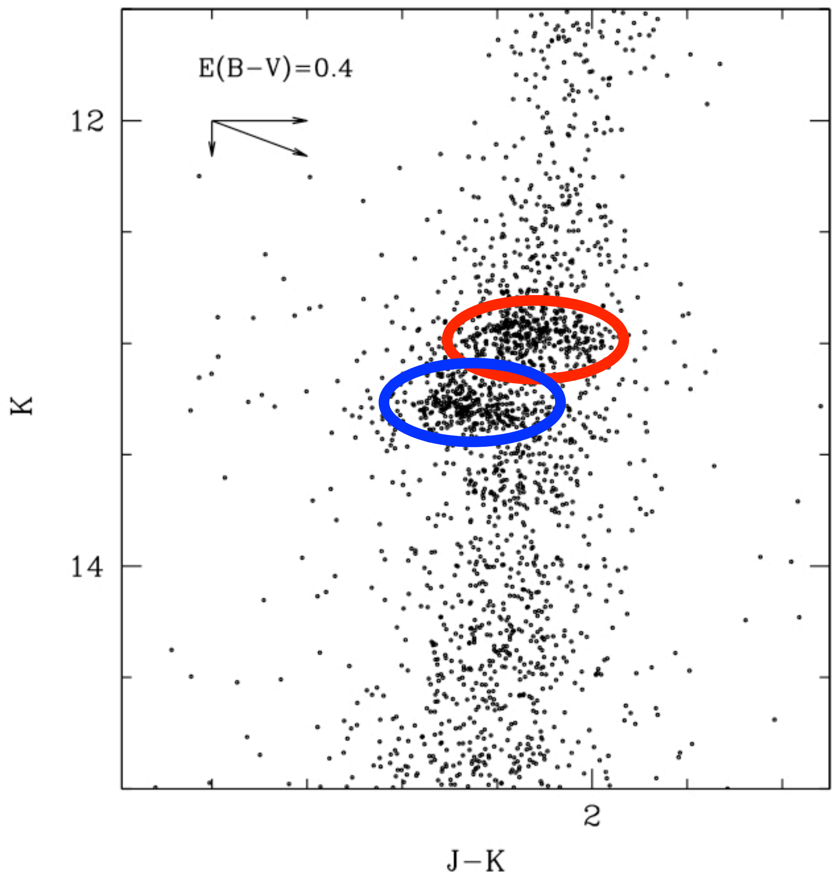
additional Problem:
Differential reddening





THE MAD CMD OF TERZAN 5





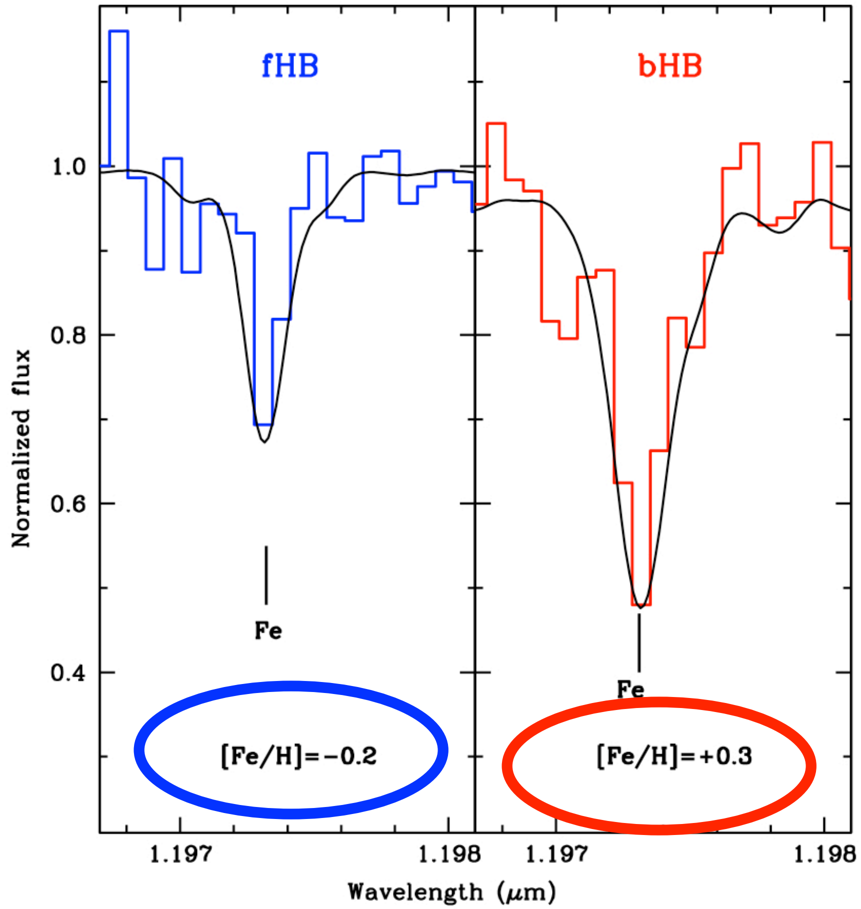
2 distinct Red Clumps !!

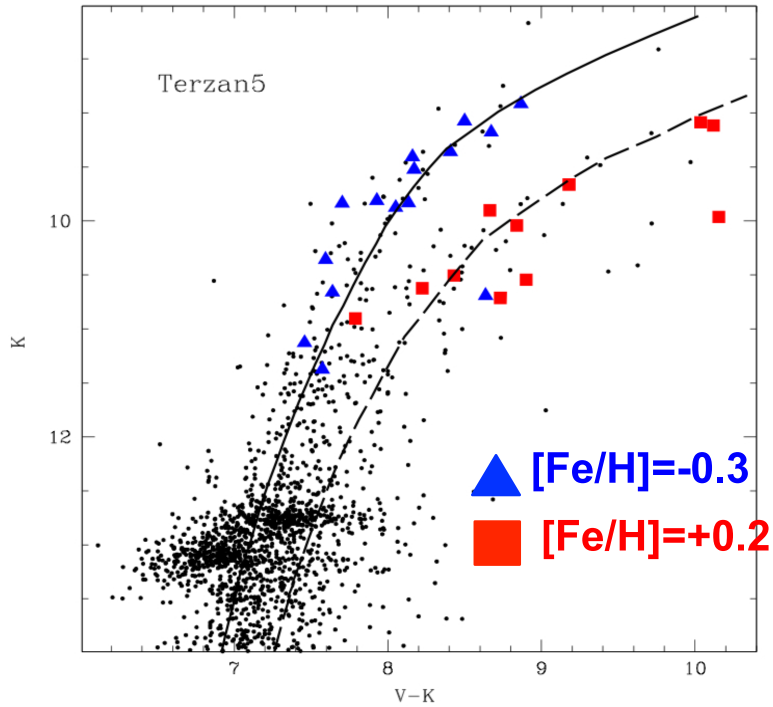
Ferraro et al. (2009, Nature 462, 483)

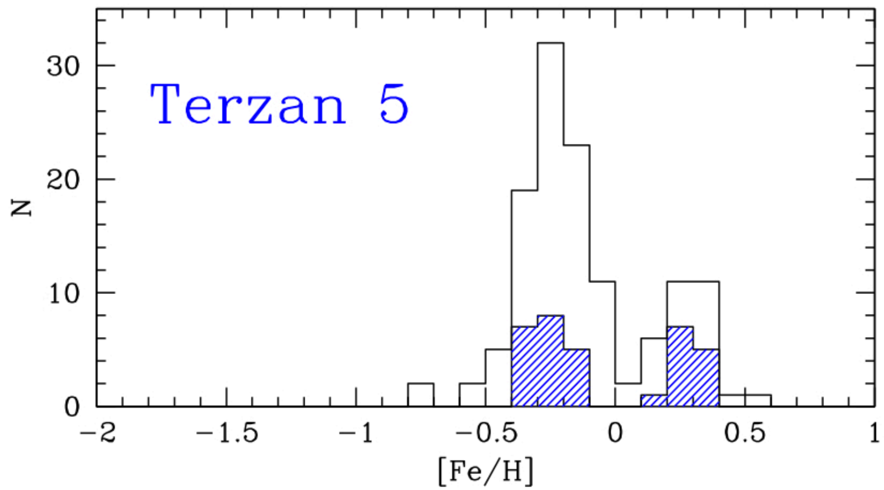
Spectroscopic screening of Ter5

NIRSPEC @ Keck II + ESO-VLT

125 RGB + 6 HB





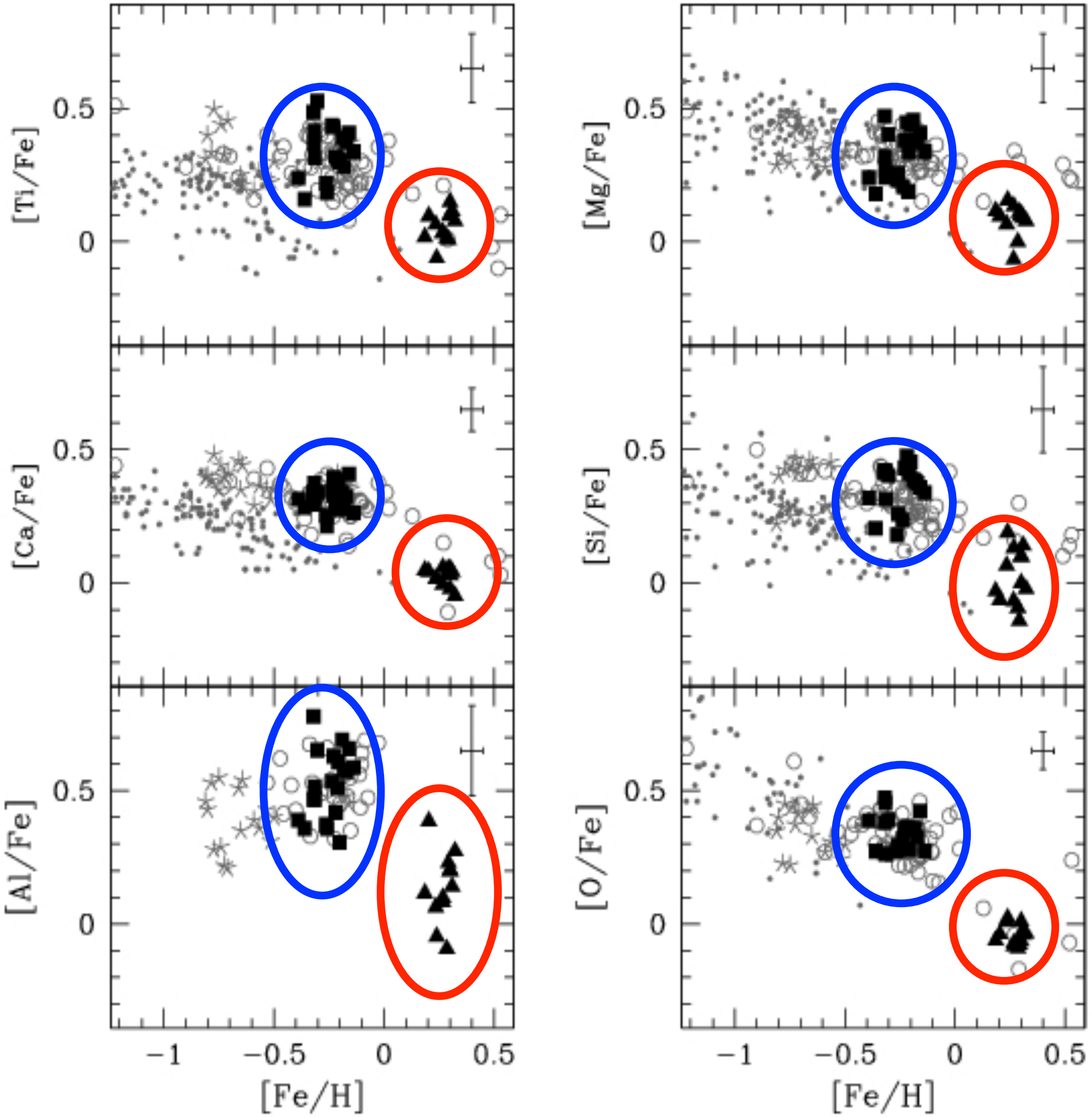


The two populations have different Iron abundance !!!

Origlia et al (2011, ApJ, 726, L20)
Massari et al (2014, in prep)

Cosmic-Lab

Spectroscopic screening of Ter5: α−elements



[α/Fe]:

+0.34 +/- 0.06

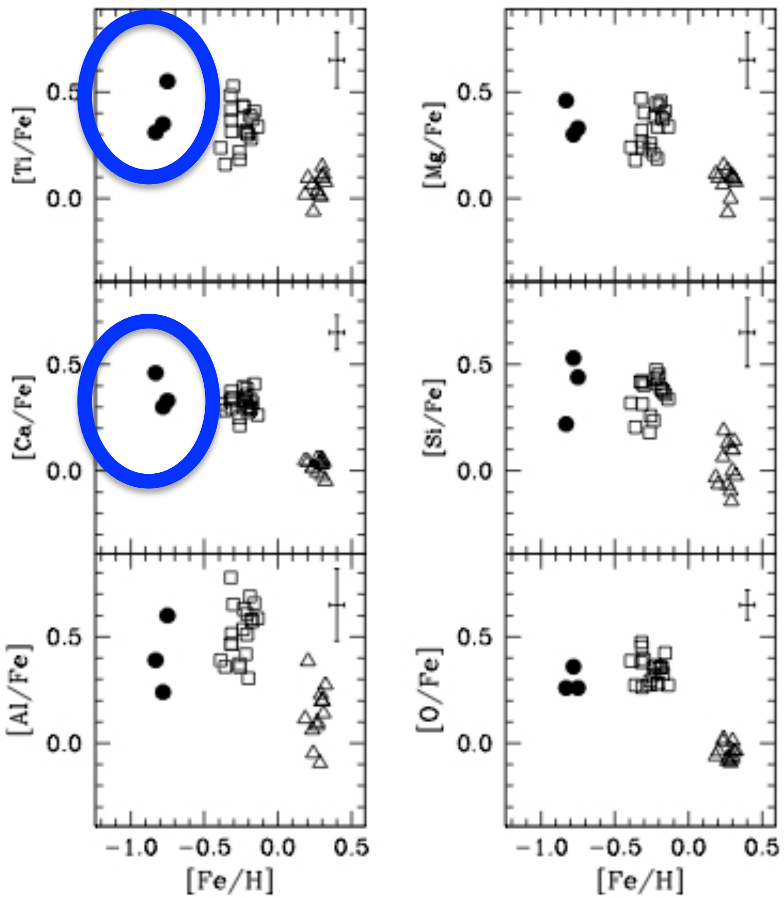
+0.03 +/- 0.04

The metal poor component is α-enhanced

The metal rich one Is solar

TERZAN 5: THE LAST SURPRISE

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

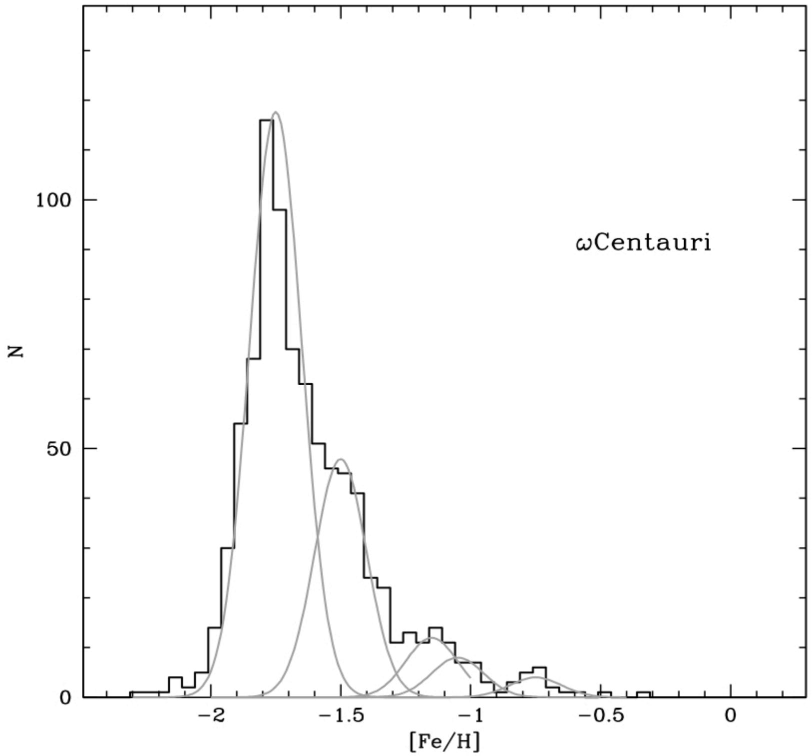


Also the extreme metal poor component is α-enhanced

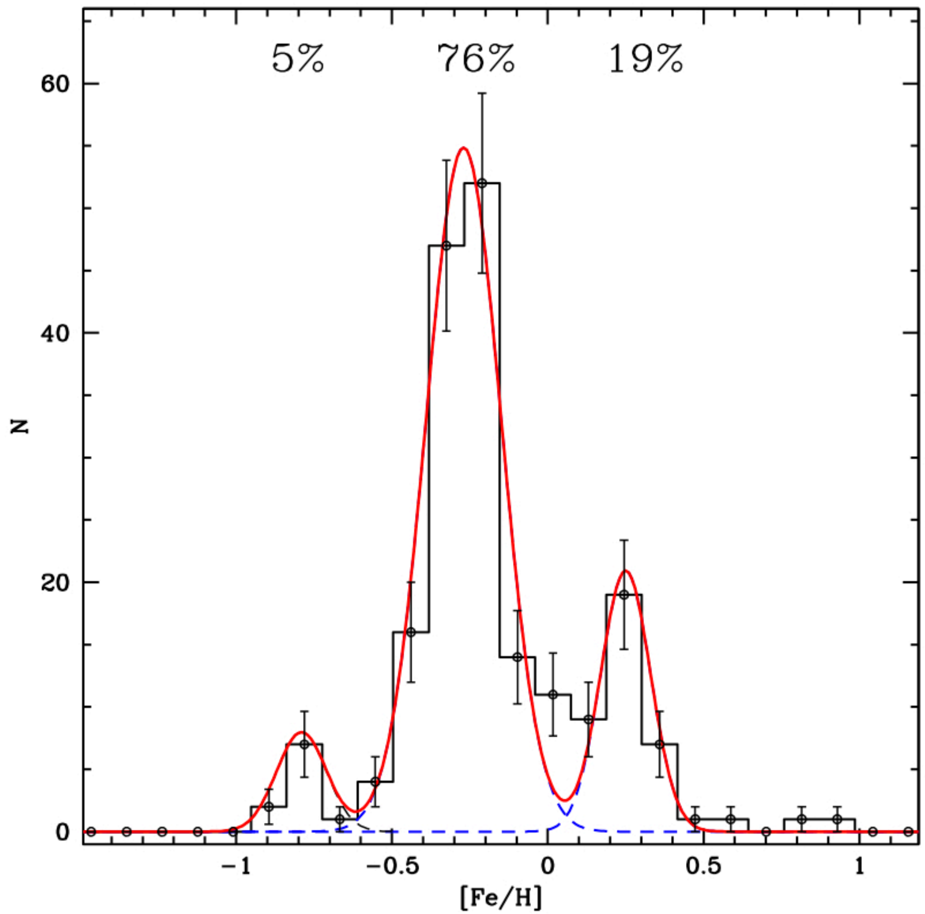
This discovery increases the metallicity range of the Terzan 5 populations to Δ[Fe/H]~ 1 dex !!!

Origlia et al 2013, ApJ, 779, L5

TERZAN 5: THE LAST SURPRISE

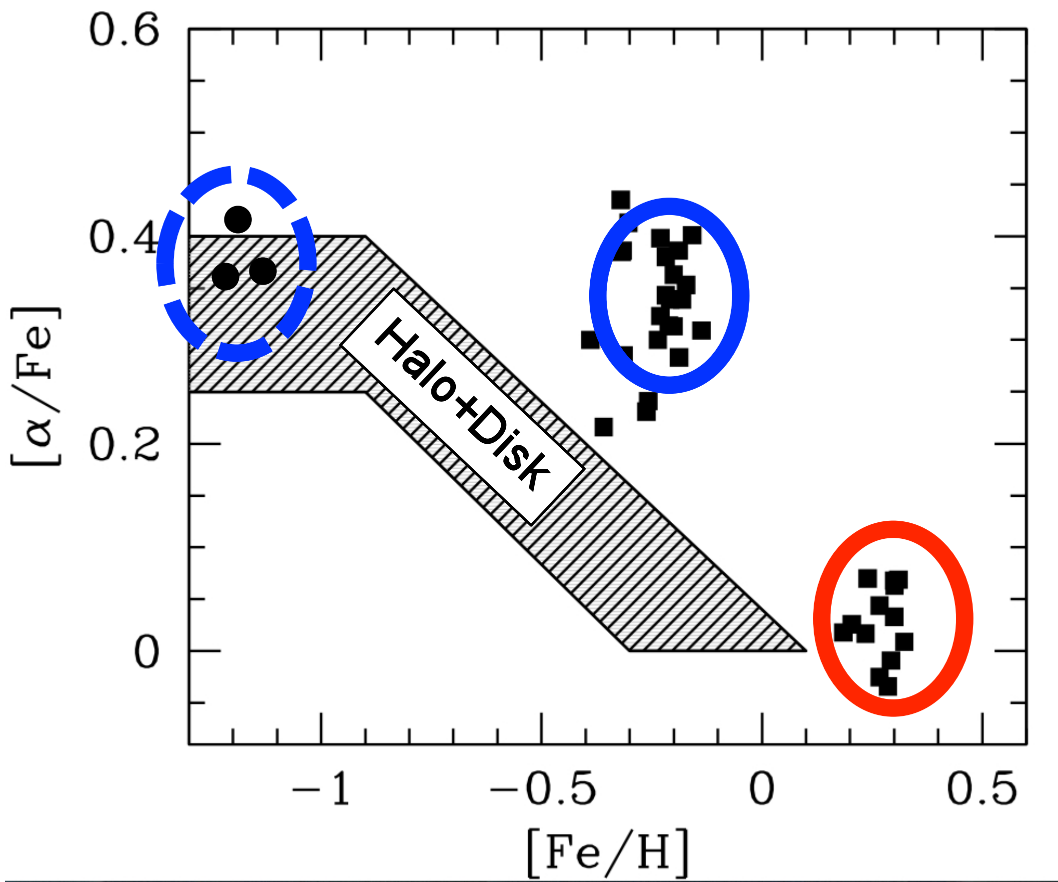


193 stars

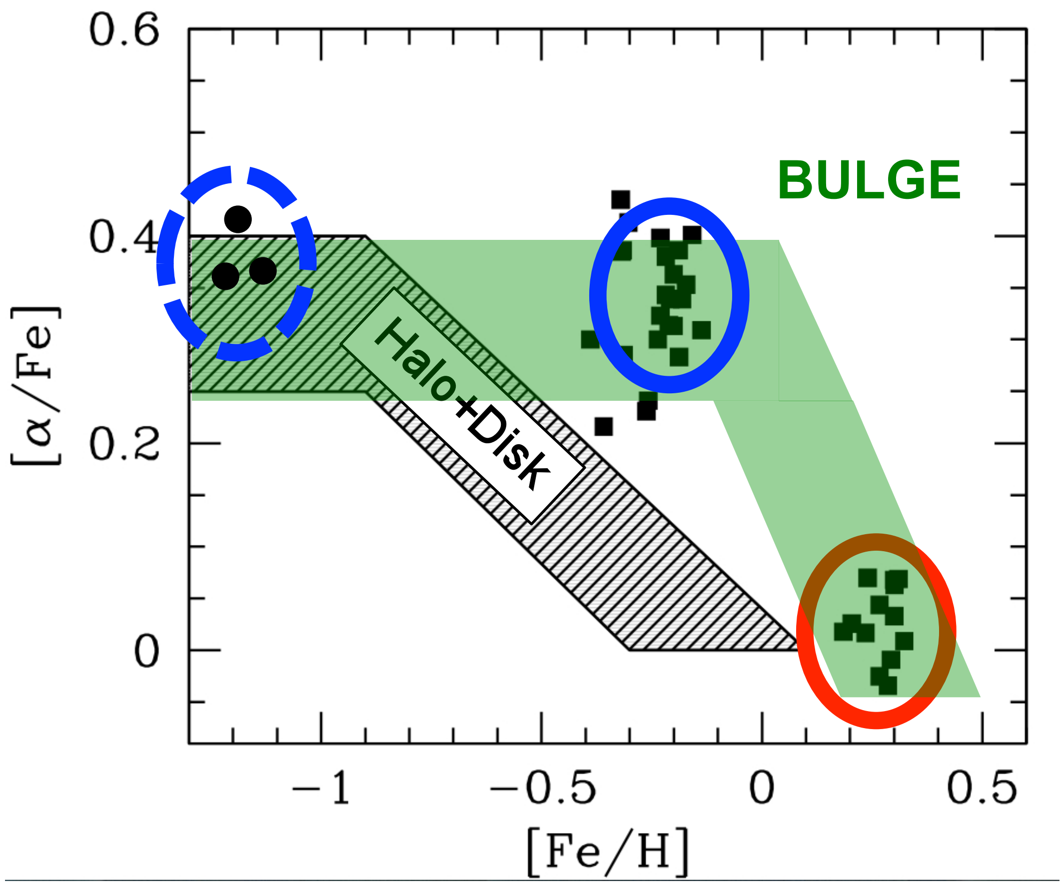


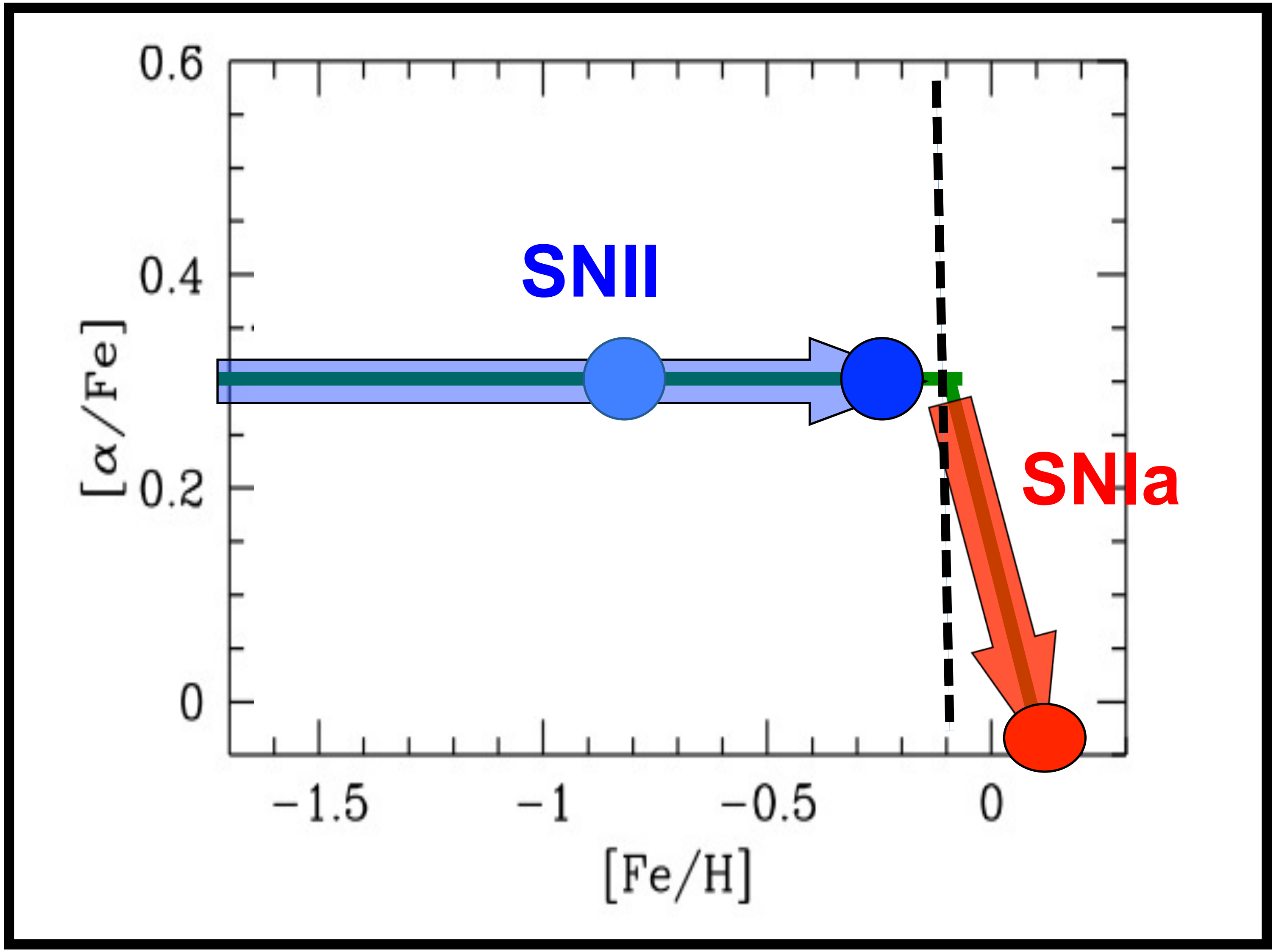
Massari et al 2014, ApJ, in preparation

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

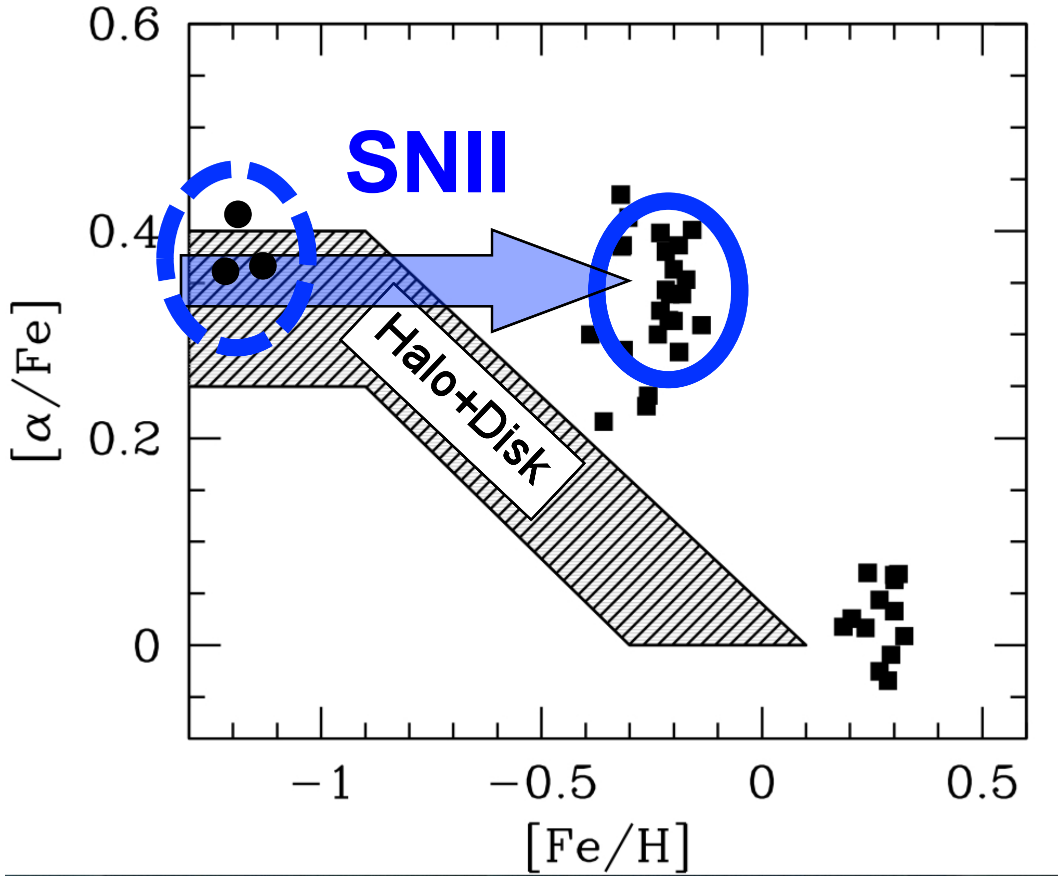


Iron and alpha–elements abundances are similar to those measured in the **Bulge**, thus suggesting **quite similar star formation and chemical enrichment processes**

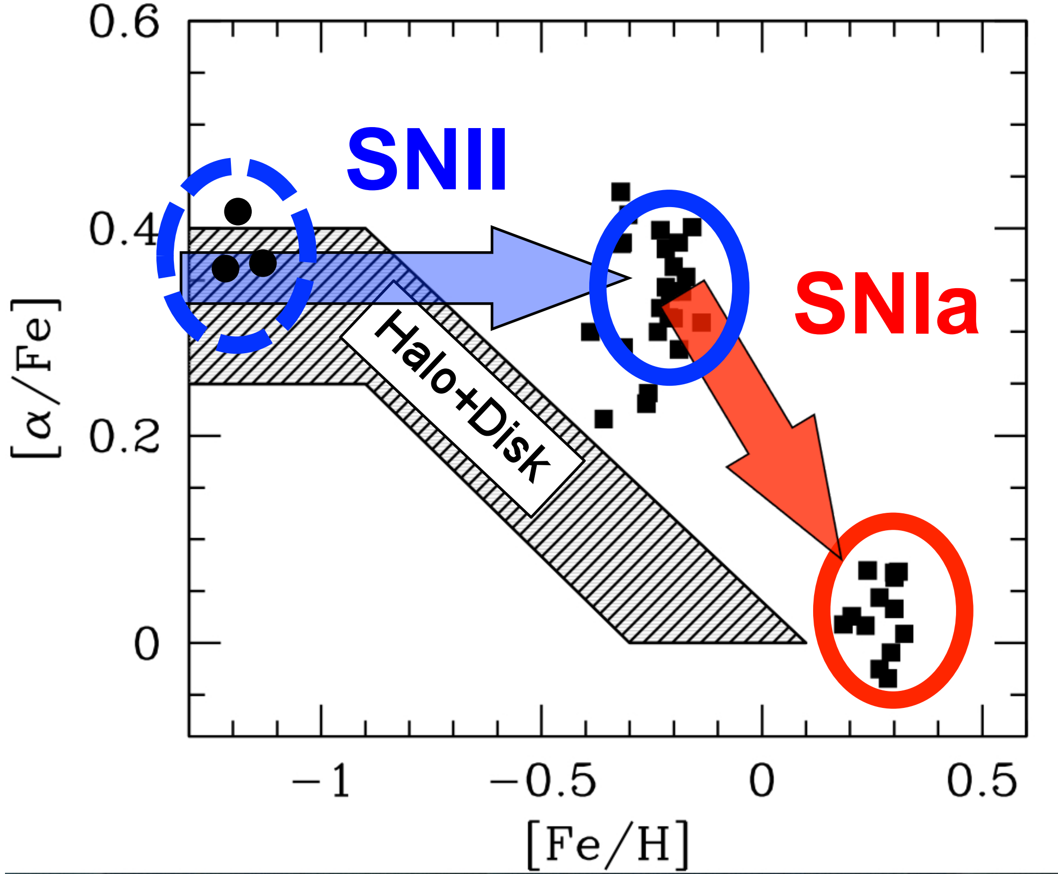



0.6
0.4
0.2
0
[α/Fe]
SNII
SNIa
−1.5
−1
−0.5
0
[Fe/H]

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:

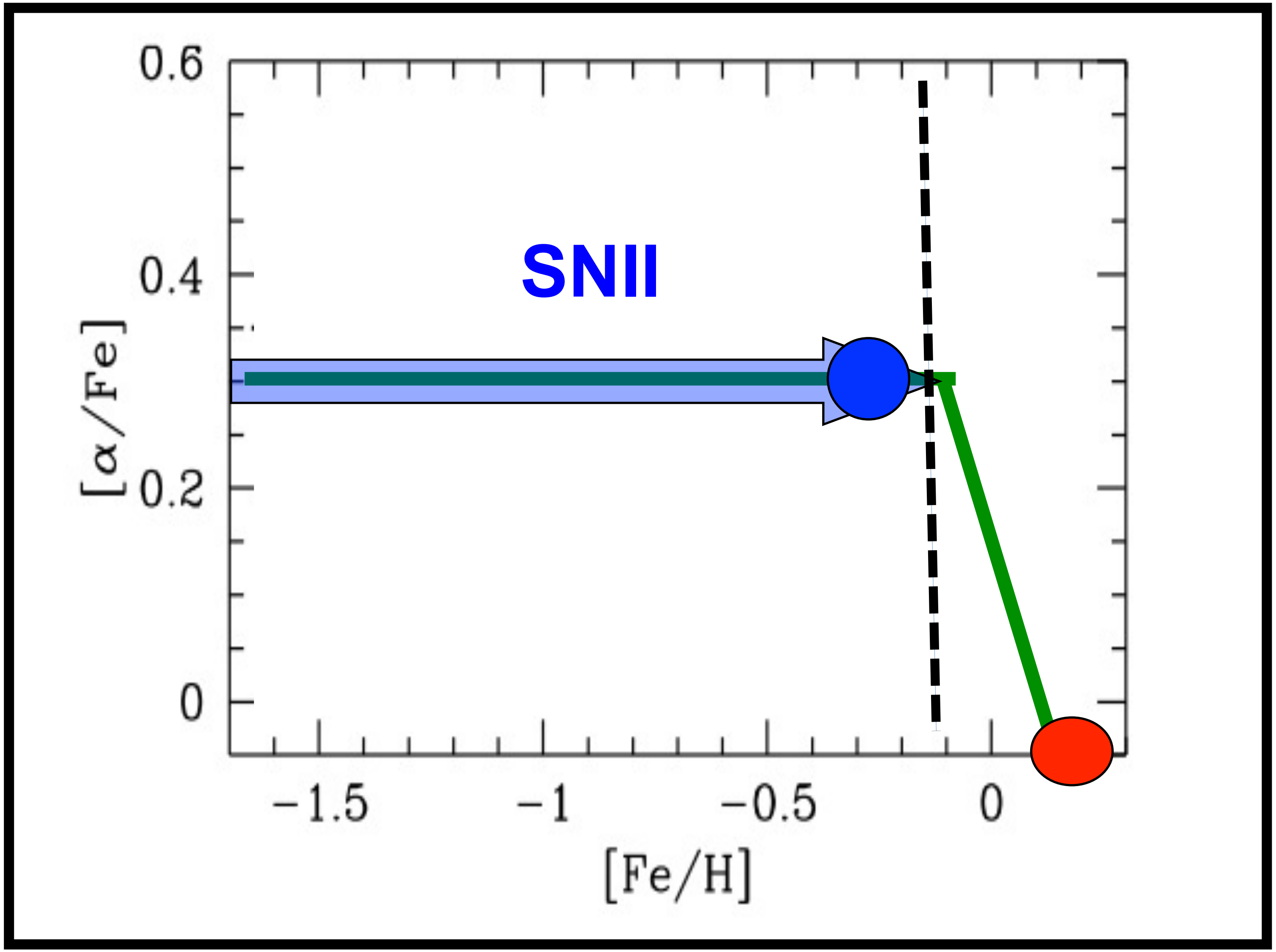
1. IT IS NOT A GENUINE GC

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?**)



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

↓

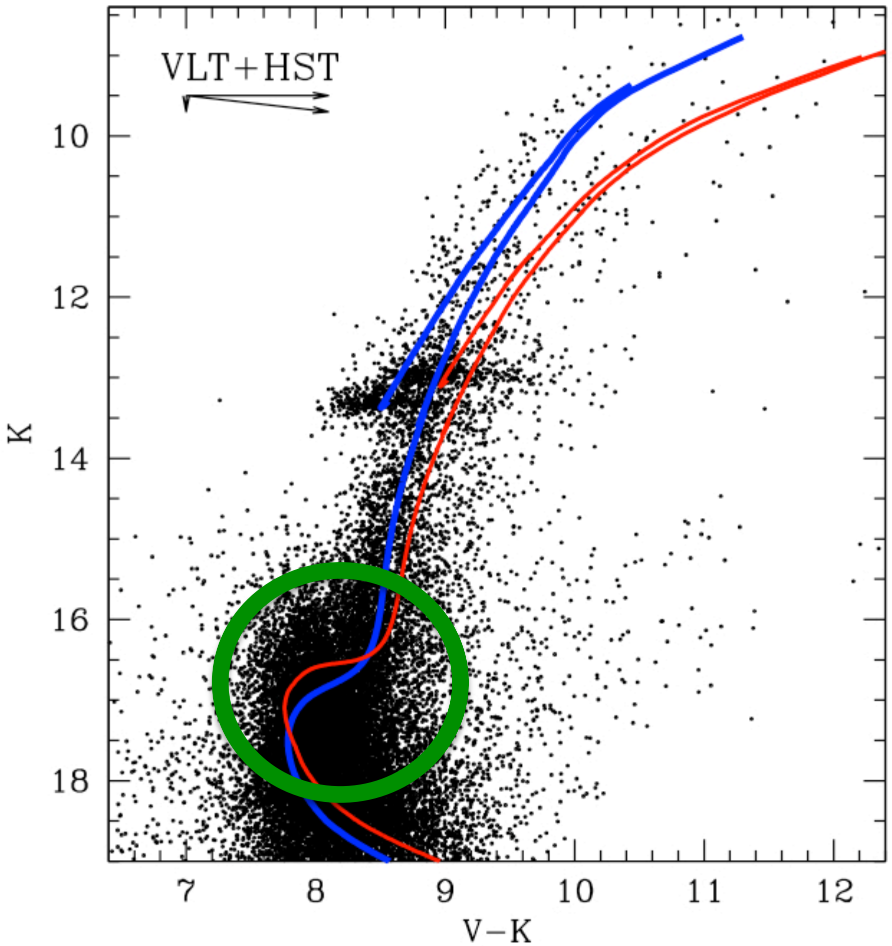
Many MSP

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

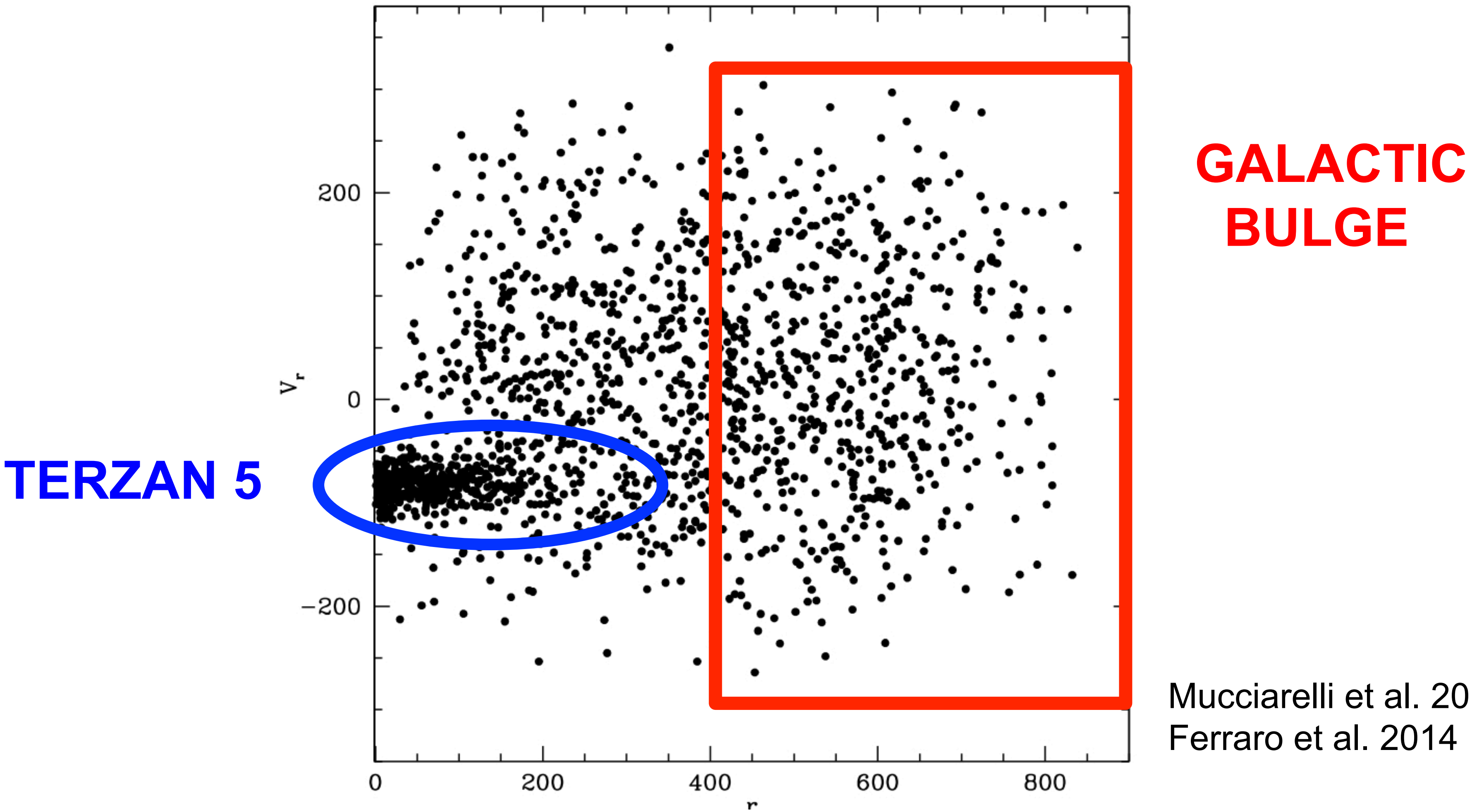


Z=0.01 t=12 Gyr

Z=0.03 t=6?? Gyr

TERZAN 5: KINEMATICS

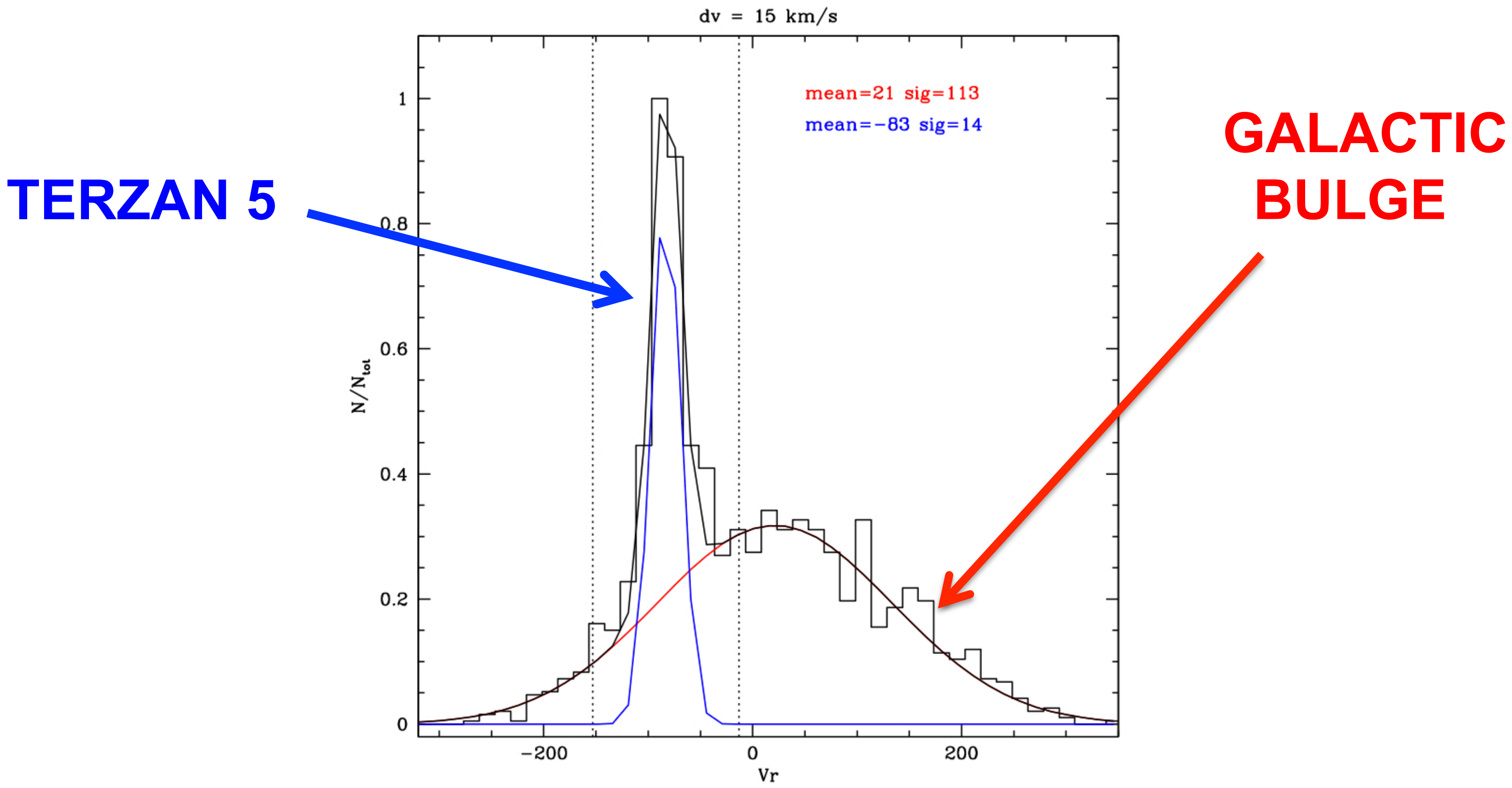
A sample of 1600 stars has been observed with FLAMES and XSHOOTER@ESO-VLT and NIRSPEC and DEIMOS@KECK



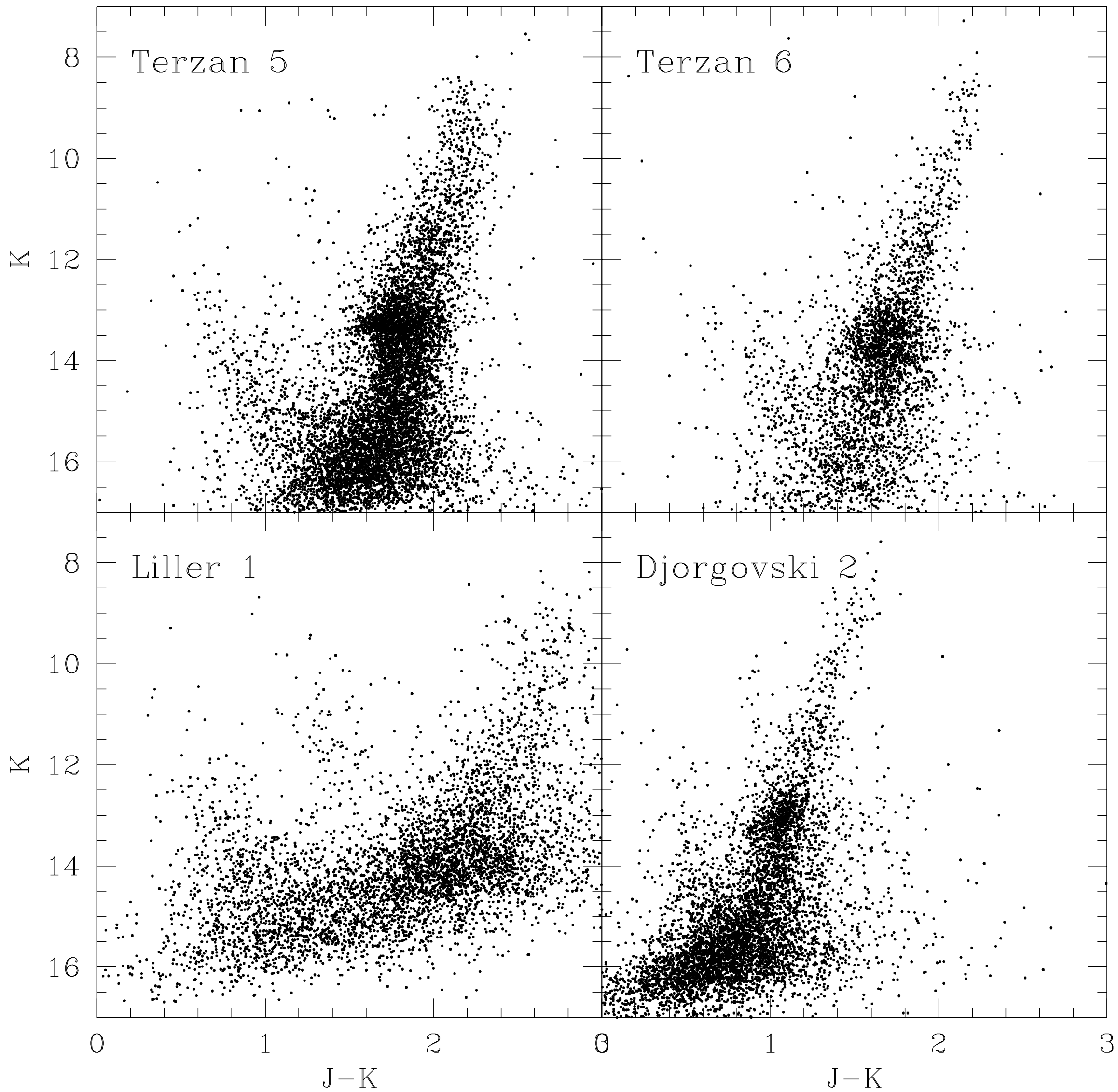
Mucciarelli et al. 2014
Ferraro et al. 2014

TERZAN 5: KINEMATICS

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

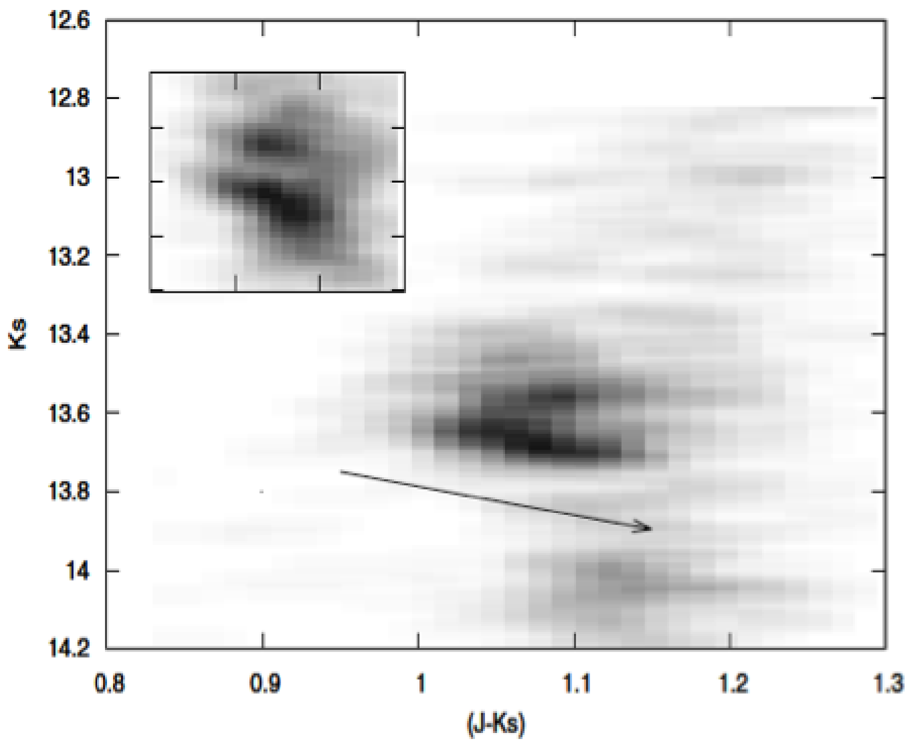


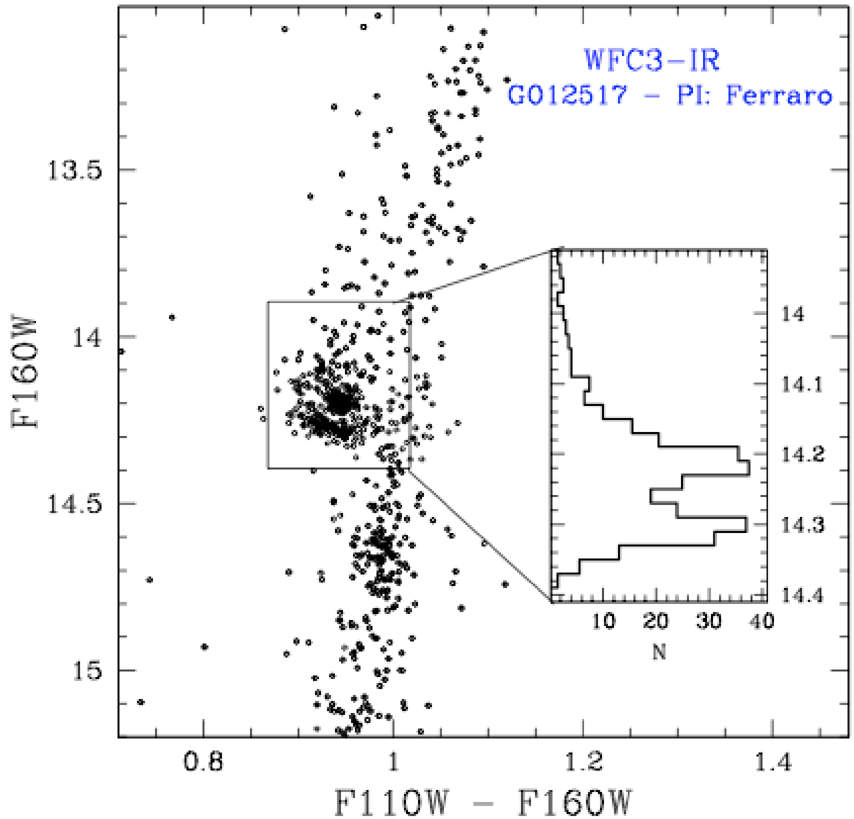
SEARCHING FOR OTHER TERZAN 5-LIKE STELLAR SYSTEMS IN THE BULGE



NGC6440: another Terzan 5?

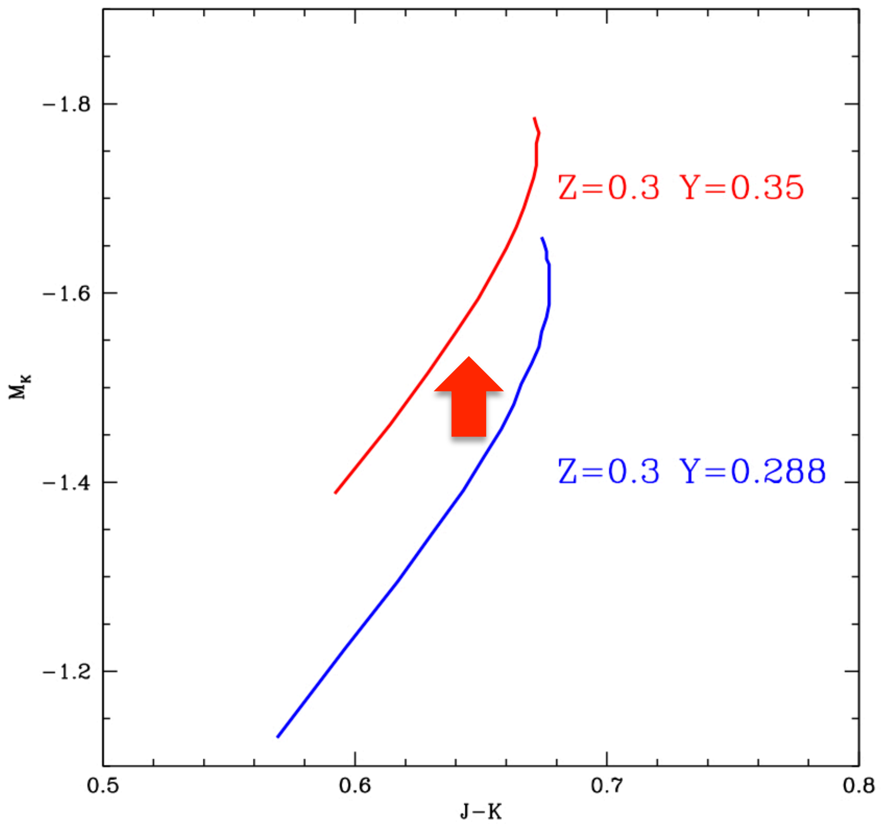
Mauro et al (2012, ApJ, 761, L29)





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

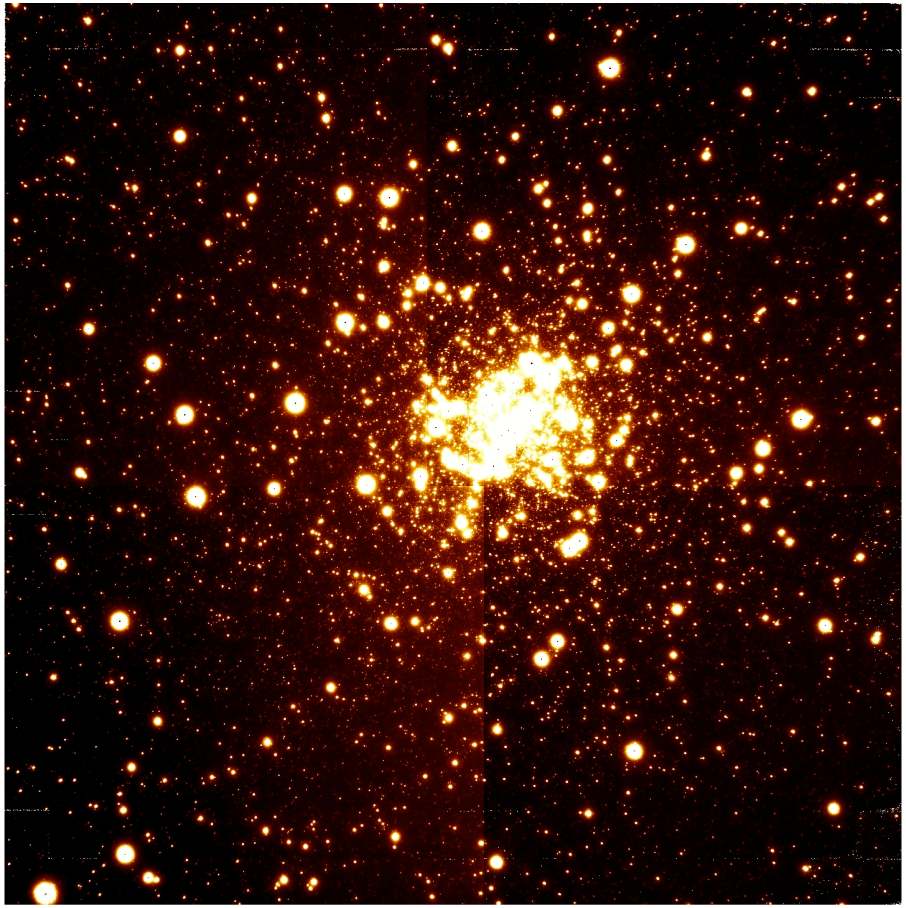
THE HELIUM EFFECT

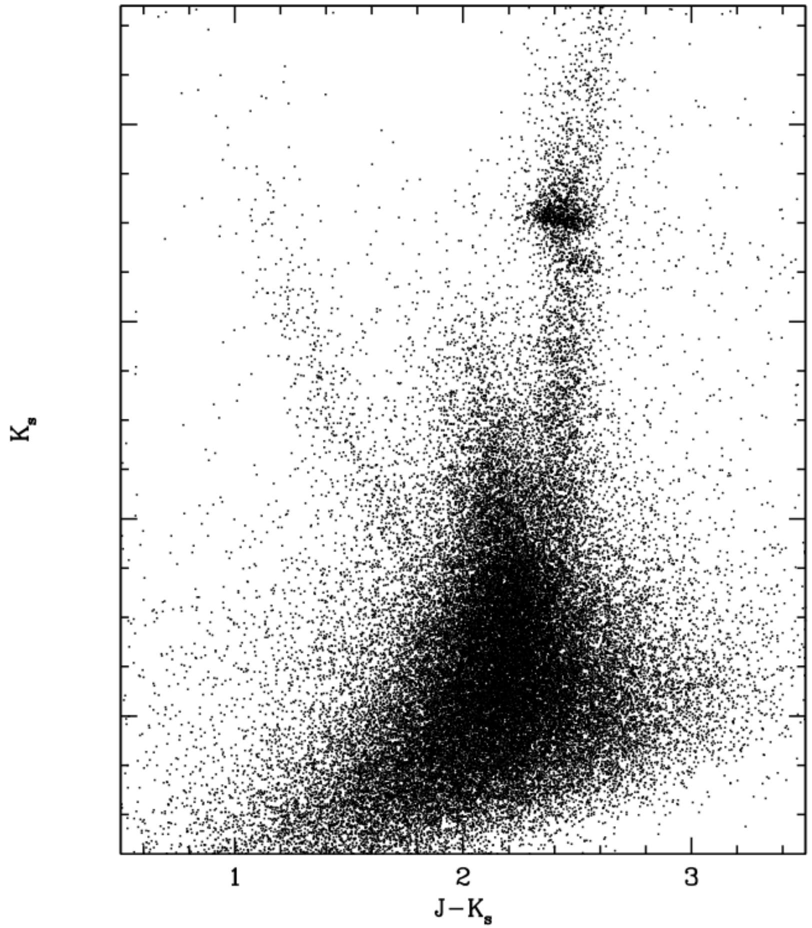


An increase in Helium increases the RC luminosity leaving the color almost unchanged

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

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 THIRD CLASS OF PROBE PARTICLES

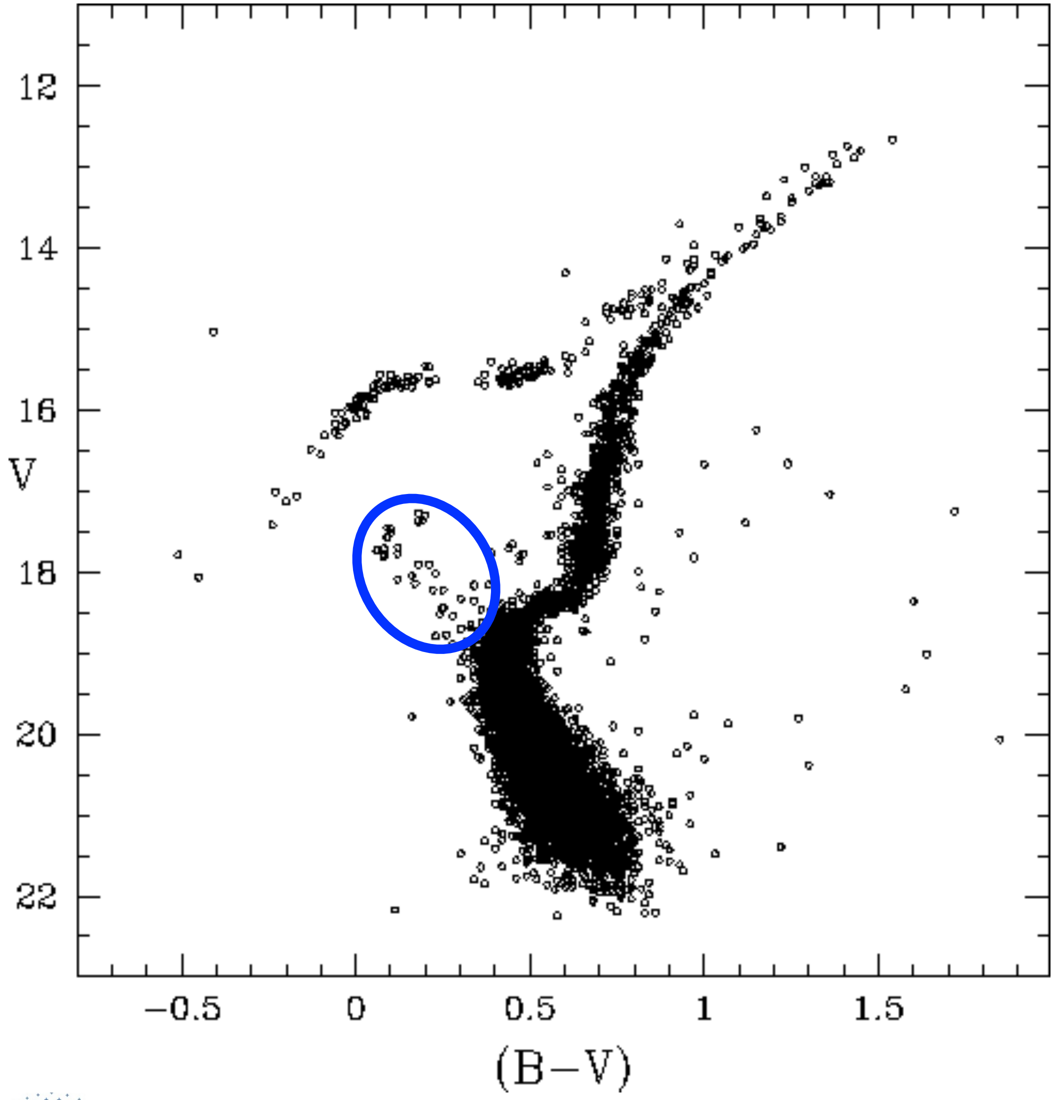
Blue Straggler Stars (BSS)

Stellar population rejuvenated by dynamical processes

People involved: Ferraro, Lanzoni, Dalessandro, Mucciarelli,
Lovisi, Fiorentino, Lagioia, Miocchi, Alessandrini

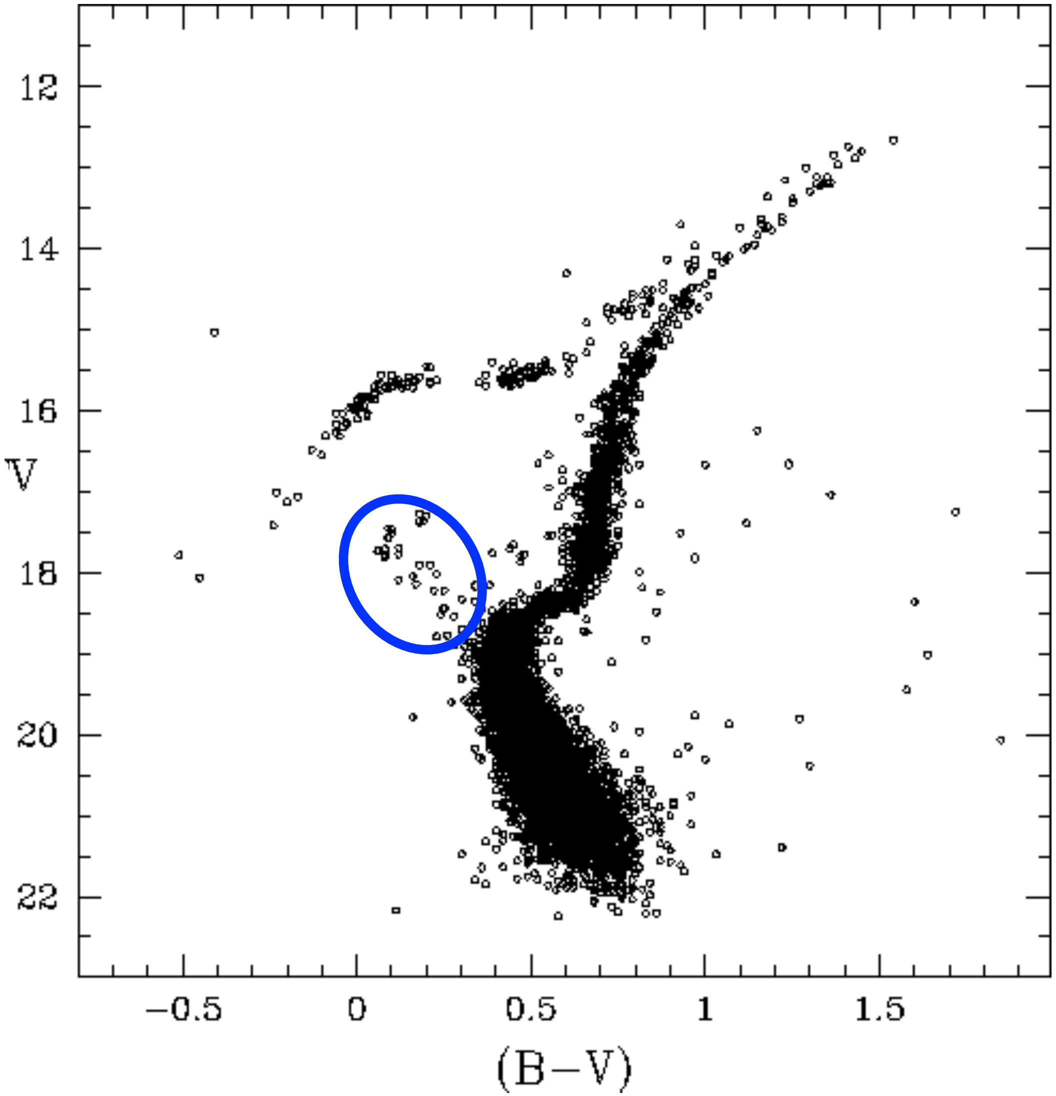
Beccari (ESO), Sills (USA), Pasquato (Corea), Contreras (Chile)

Blue Straggler Stars (BSS)



stars brighter and bluer (hotter) than the cluster MS-TO, along an extension of the main sequence

Blue Straggler Stars (BSS)



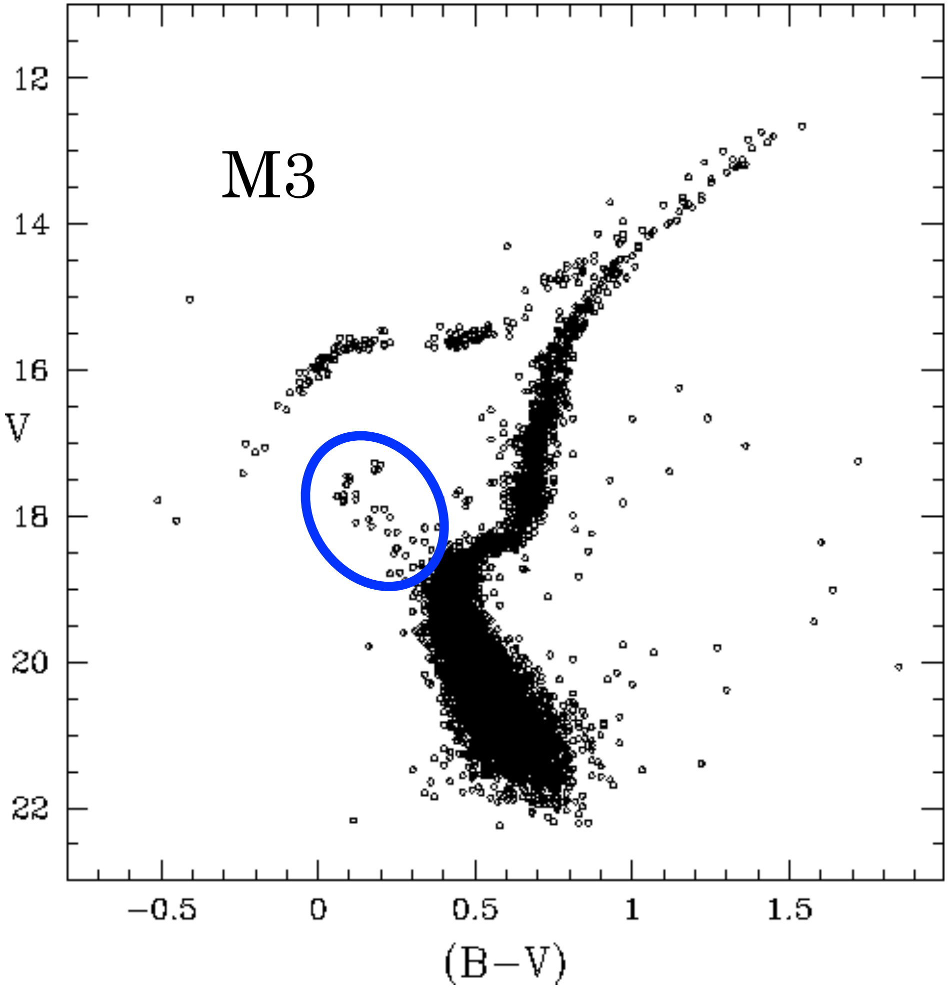
old “normal” stars define a sort of flock of tired stars getting progressively redder

BSS appear as a bunch of “apparently” younger blue stars

Blue Straggler Stars (BSS)

like seeing a bunch of YOUNG folks in a meeting of old tired people..

Blue Straggler Stars (BSS)

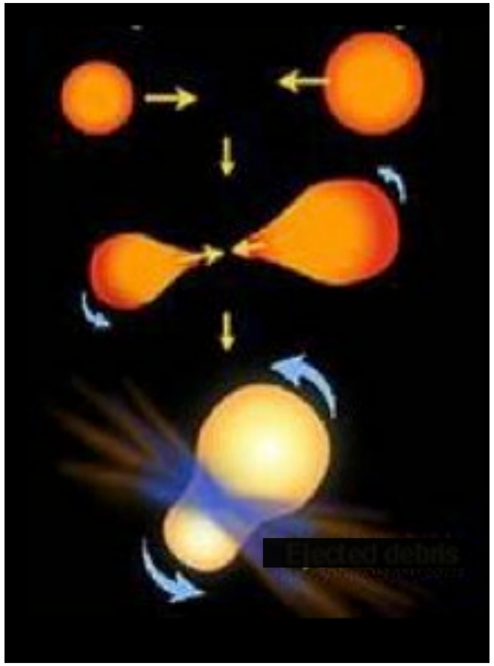


Merger of two low-mass unevolved stars

They LOOK younger but they probably are OLD stars rejuvenated by dynamical processes

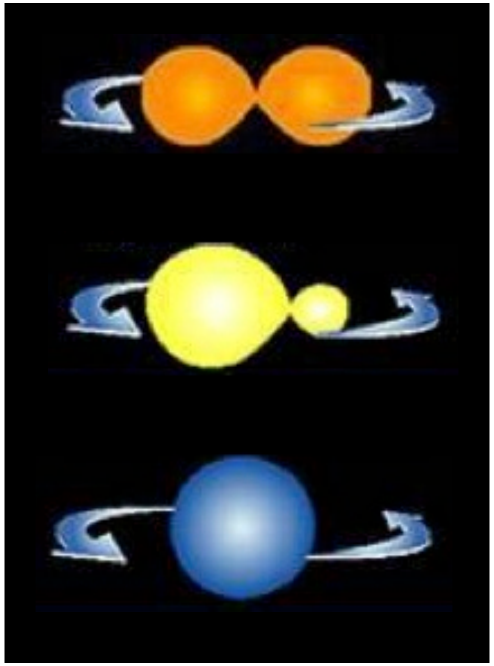
The formation mechanisms

COLLISIONS



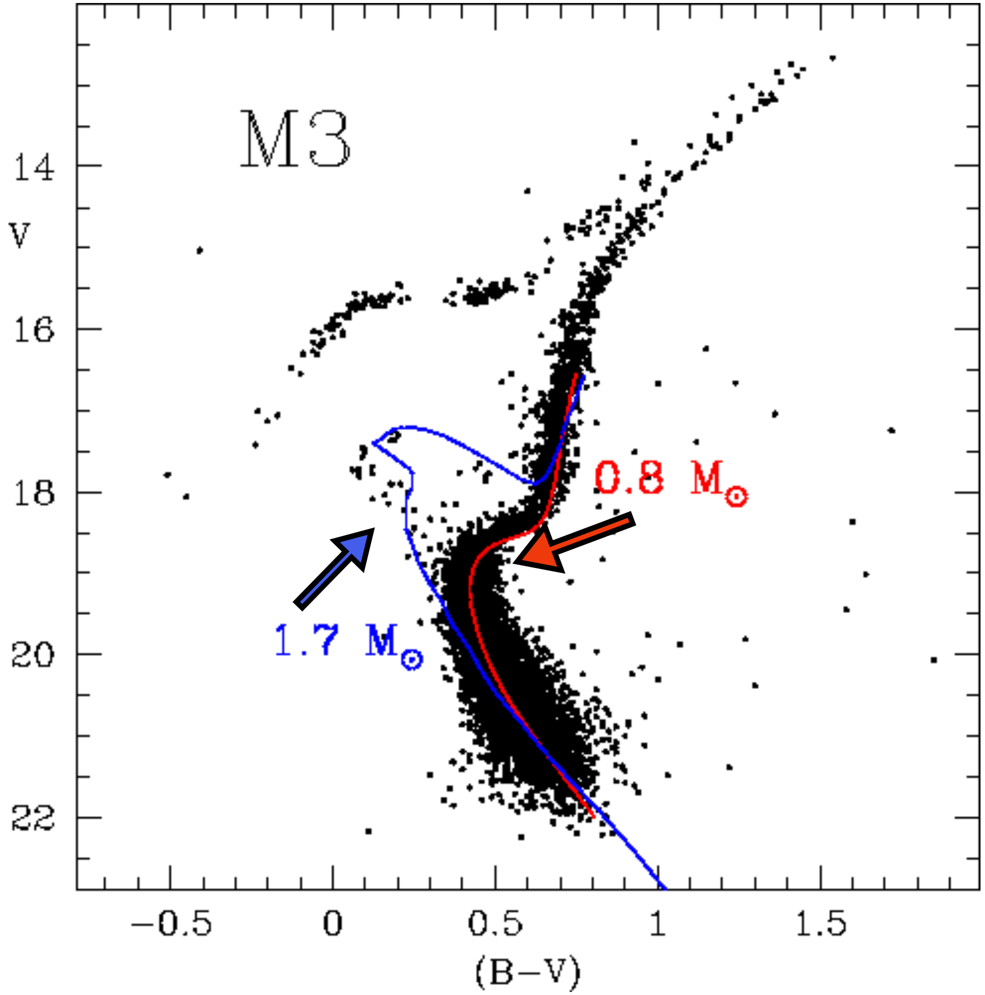
depend on **collision** rate
(Hills & Day 1976)

MASS-TRANSFER



depend on shrinking of binaries
due to **dynamical interactions**
and stellar evolution (McCrea 1964)

Blue Straggler Stars (BSS)



BSS
more massive
than normal stars

(see also Shara et al. 1997, Fiorentino et al 2014)

They are crucial gravitational probe-particles to test GC internal dynamical processes

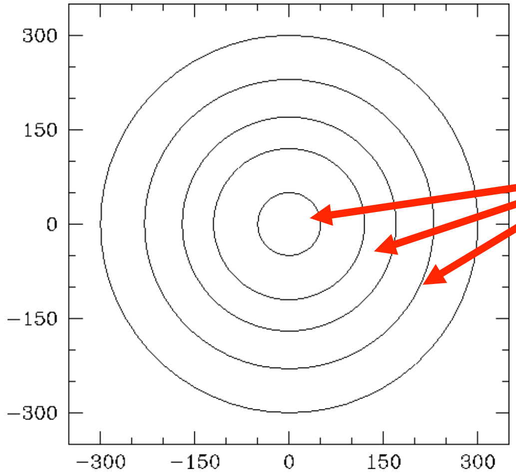
BSS are heavy stars (M_{BSS}=1.2-1.4 $M_{\odot}$) orbiting in a "sea" of "normal" light stars (M_{mean} =0.4 $M_{\odot}$): they are subject to **dynamical friction** that progressively makes them sink toward the cluster center

$$t_{df} = \frac{3\,\sigma^3(r)}{4\,\ln\Lambda\, G^2\, (2\pi)^{1/2}\, M_{BSS}\, \rho(r)}$$

Because of the sensitivity of the **df** time-scale to the cluster local density, **df** is expected to affect first the most internal BSS and then BSS **at larger and larger distances,** as function of time

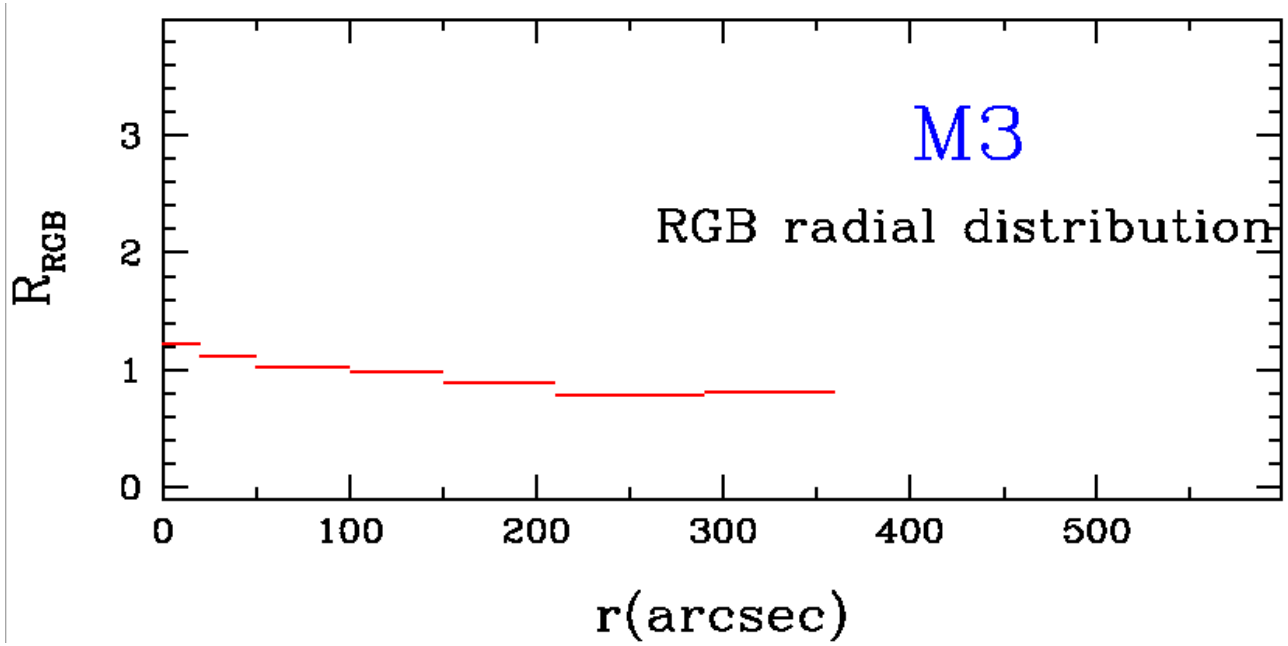
What we need to know is the radial distribution of these heavy objects within the entire cluster extension

THE BSS RADIAL DISTRIBUTION

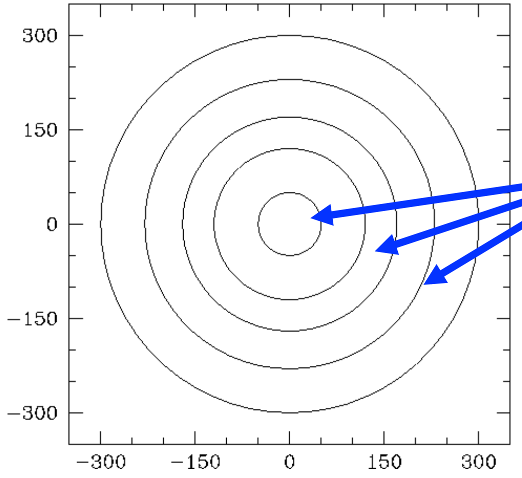


$$R_{RGB} = \frac{N_{RGB}/N_{RGB,TOT}}{L_{samp}/L_{TOT}}$$

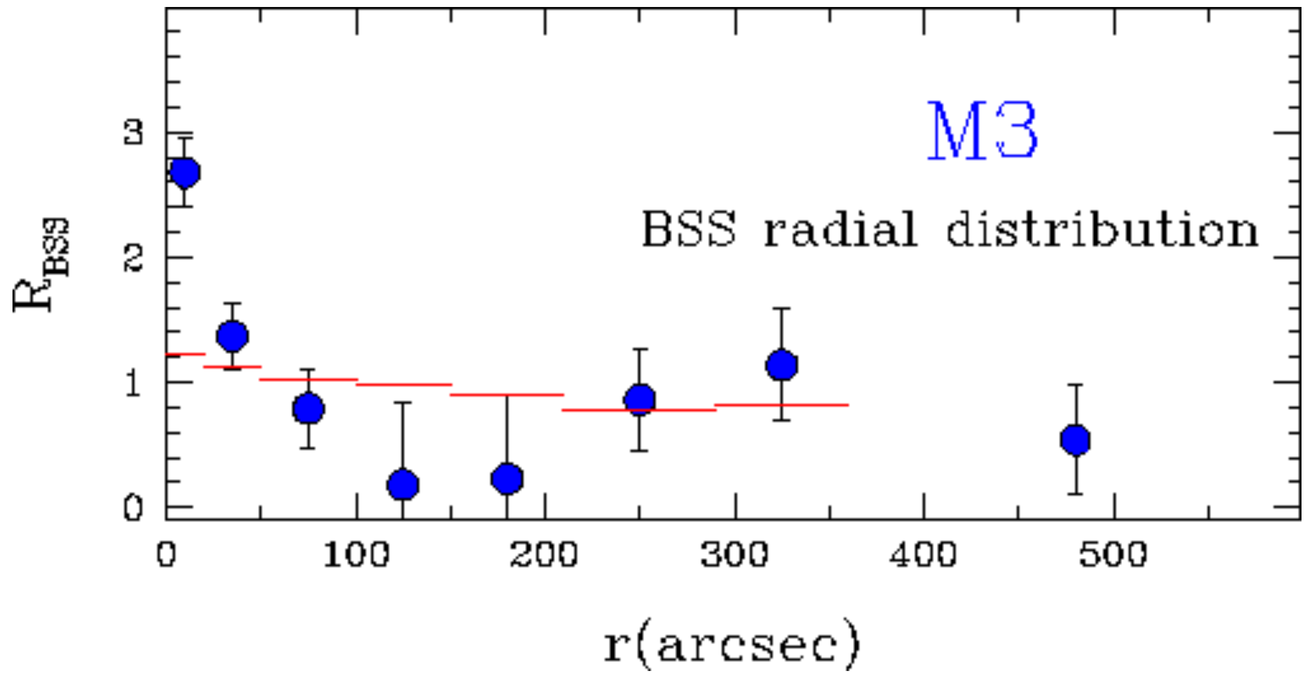
This quantity is expected to be =1 for any not segregated SP



THE BSS RADIAL DISTRIBUTION



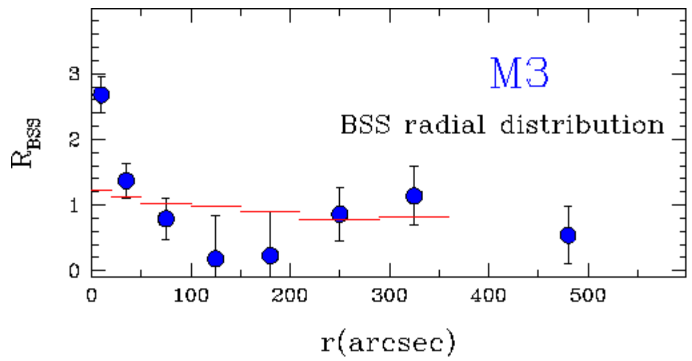
$$R_{BSS} = \frac{N_{BSS}/N_{BSS,TOT}}{L_{samp}/L_{TOT}}$$



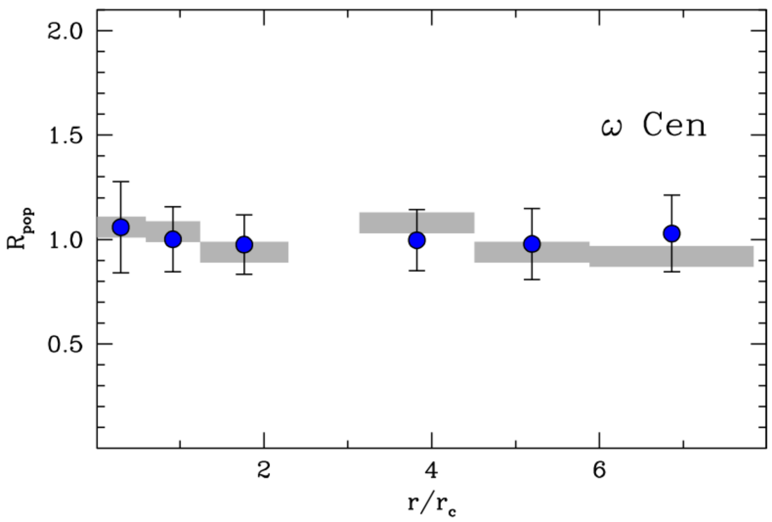
BSS radial distribution

Over the last 15 years we studied the BSS radial distribution over the entire cluster extensions in 25 stellar systems. Finding a variety of cases

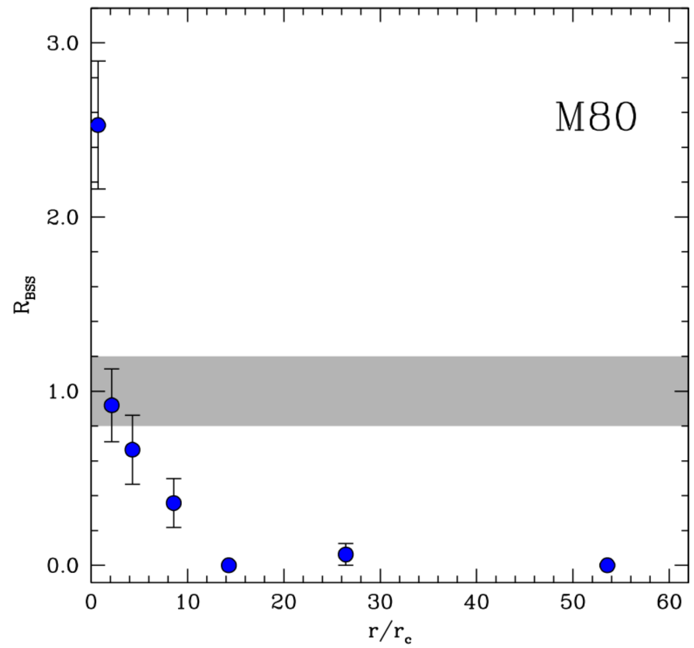
"bimodal"



"Flat"

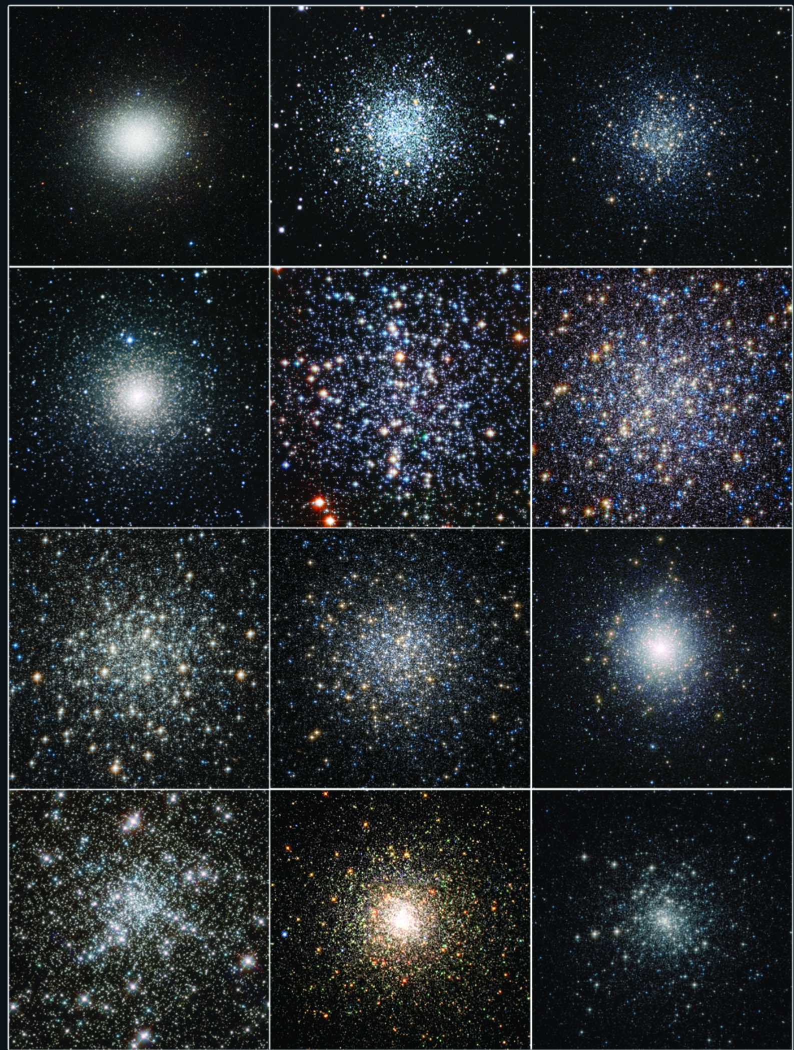


"Unimodal" (single-peak)



The BSS radial distribution is shaped by the effect of dynamical friction, which progressively segregates BSS over the cluster age (~ Hubble time)

THE DYNAMICAL CLOCK



Mosaic of 12 images of Milky Way globular clusters ranked in order of increasing dynamical age, as measured by the "dynamical clock of stellar systems".
From top-left, to bottom-right: omegaCentauri, NGC 288, M55, NGC 6388, M4, M13, M10, M5, 47 Tucanae, NGC 6752, M80, and M30.

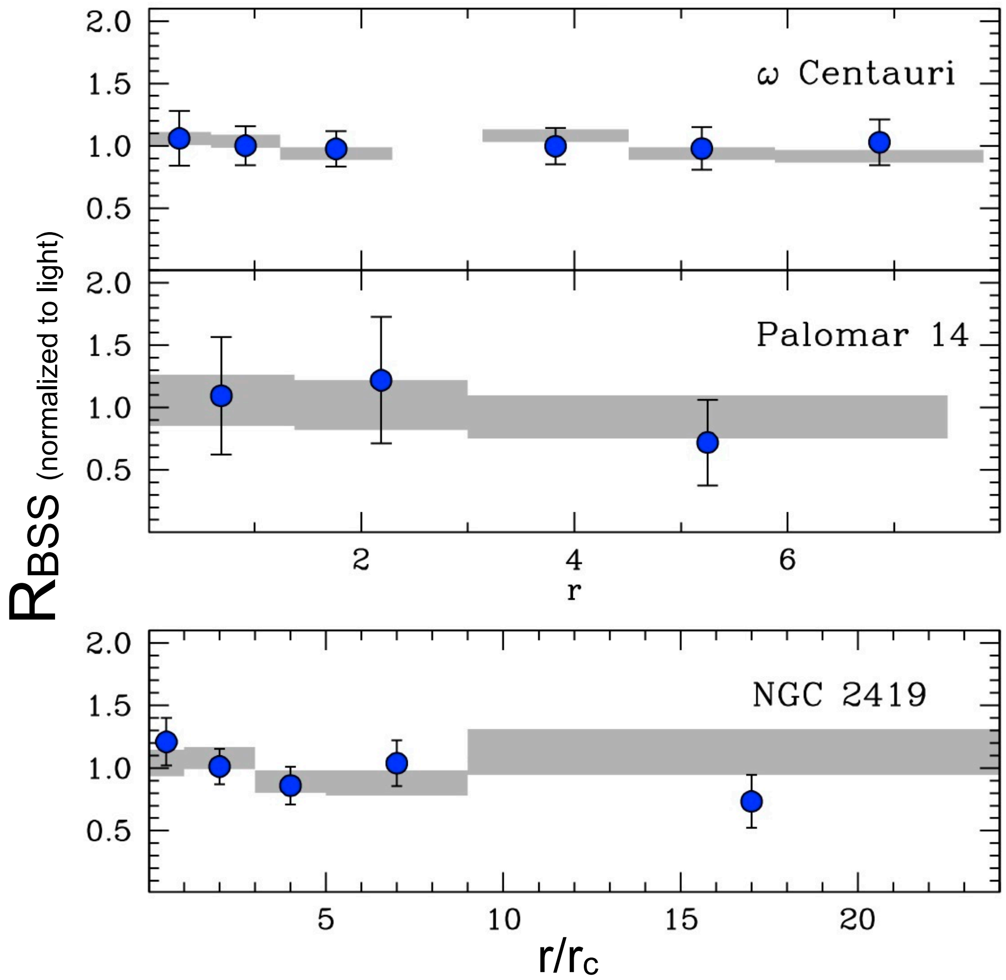
Globular clusters are stellar aggregates counting up to a few million stars. Most of them formed at the same cosmic epoch (12-13 billion years ago, slightly after the Big Bang). Since then, however, they may have evolved rather differently from a dynamical point of view and clusters with the same chronological age may therefore have quite different "dynamical ages". The dynamical evolution is due to a variety of processes that, with efficiencies depending on the internal environment, tend to progressively segregate stars more massive than the average toward the cluster centre. Blue straggler stars are the result of either stellar collisions, or mass-transfer events in binary systems. Because they are among the most massive objects in old clusters, they can be used as gravitational test particles to probe dynamical evolution. By analyzing a sample of globular clusters in our own galaxy, an international team of astronomers has discovered that the observed radial distribution of blue straggler stars can be used as a cosmic clock to measure the dynamical age of stellar systems. The result was obtained within Cosmic-Lab, a five-year project funded by the European Research Council, aimed at probing the complex interplay between dynamics and stellar evolution. The research was led by Francesco Ferraro at the University of Bologna (Italy) and made in collaboration with the National Institute for Astrophysics (INAF), the European Southern Observatory (ESO) and a few institutes in US and Canada. It has been published in the December 20th, 2012 issue of the international science journal Nature (Ferraro et al. 2012, Nature, 492, 393-395).

Cosmic-Lab

The dynamical clock

Ferraro et al (2012,Nature,492,393)

Family I : the dynamically YOUNG clusters



The BSS distribution is **flat** in fully agreement with that of "normal stars"

dynamical friction has not affected the BSS distribution yet, not EVEN in the cluster center

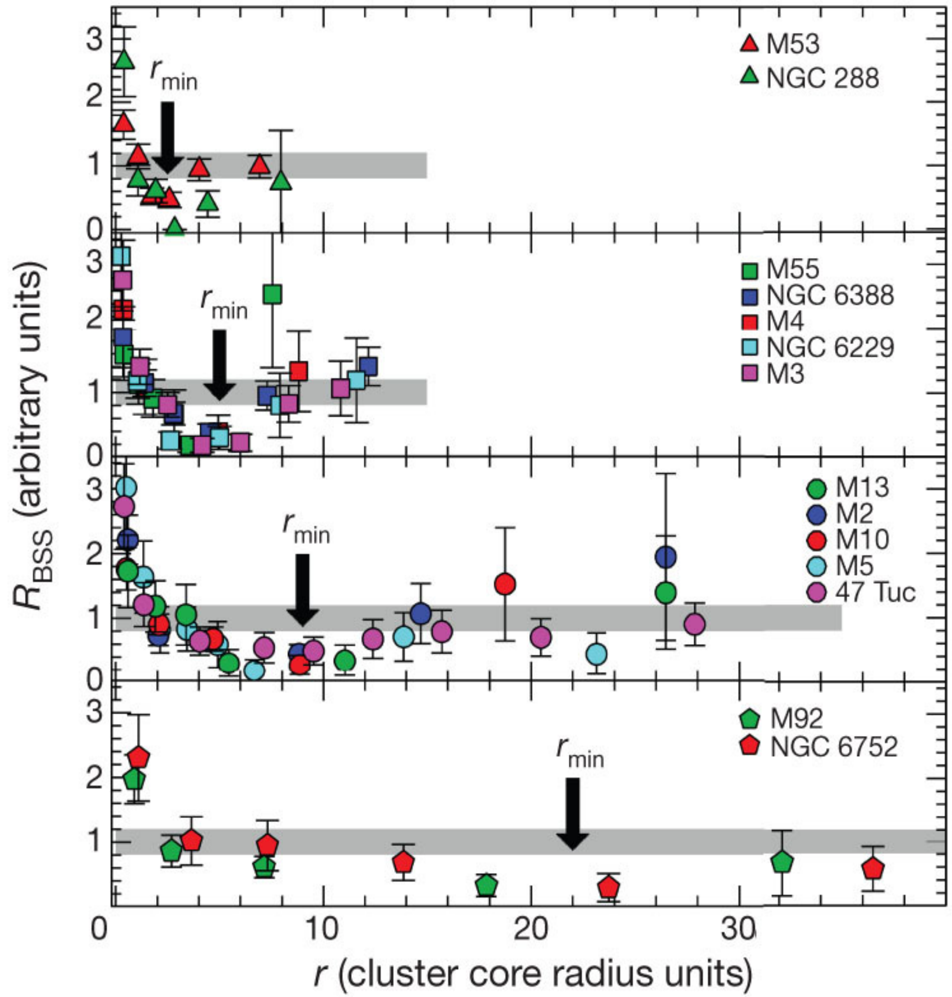
Note that this is the **most efficient way** to prove that these stellar systems are not relaxed yet

Cosmic-Lab

The dynamical clock

Ferraro et al (2012,Nature,492,393)

Family II : the dynamically INTERMEDIATE-age clusters



The BSS distribution is **bimodal** but the minimum is found at different distances from the cluster center

df is effective in segregating BSS, starting from those at shorter distances from the cluster center

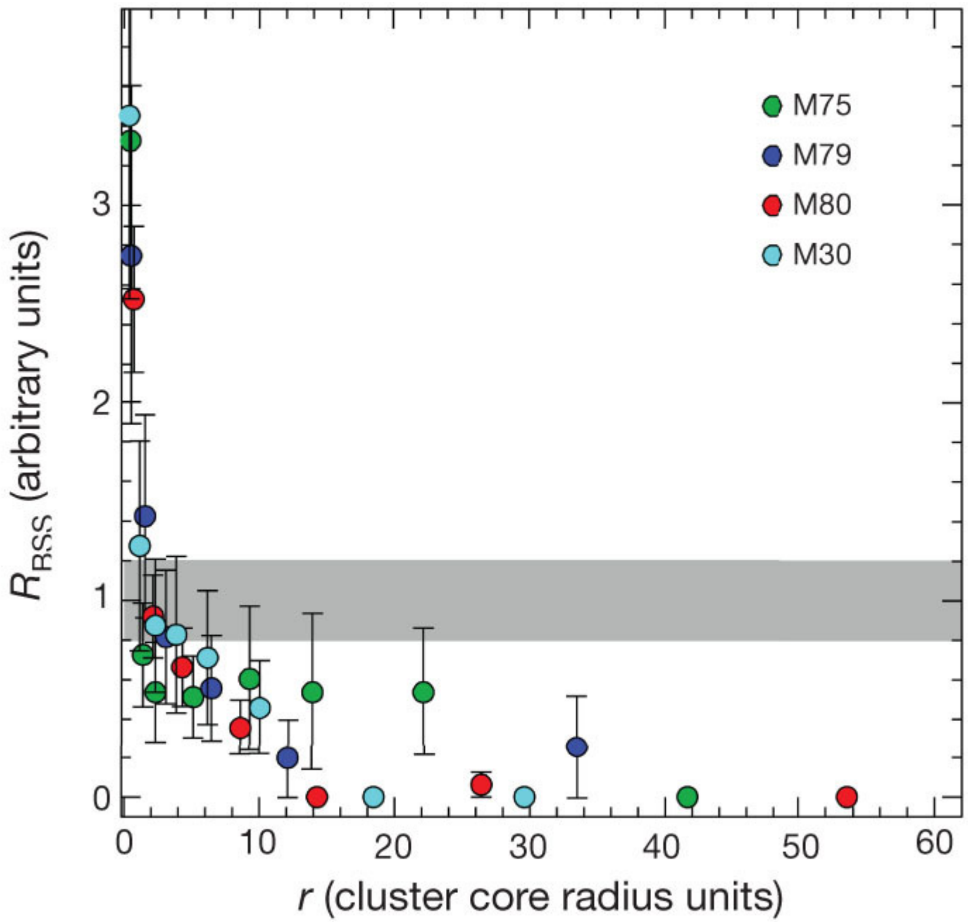
The action of **df** extends progressively at larger distances from the cluster center = the minimum is moving progressively outward

Cosmic-Lab

The dynamical clock

Ferraro et al (2012,Nature,492,393)

Family III: the dynamically OLD clusters



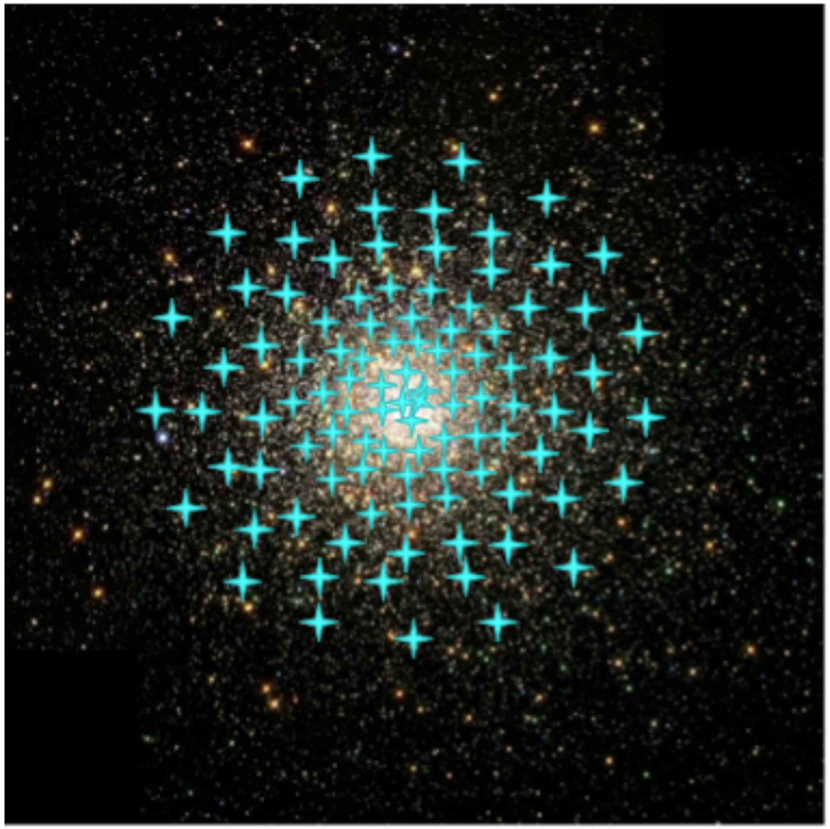
The BSS distribution is **unimodal** with a well defined peak at the cluster center but not rising branch

df has segregated ALL the BSS, even the most remote ones. The external rising branch disappears.

The action of **df** extended out to the cluster tidal radius

The dynamical clock

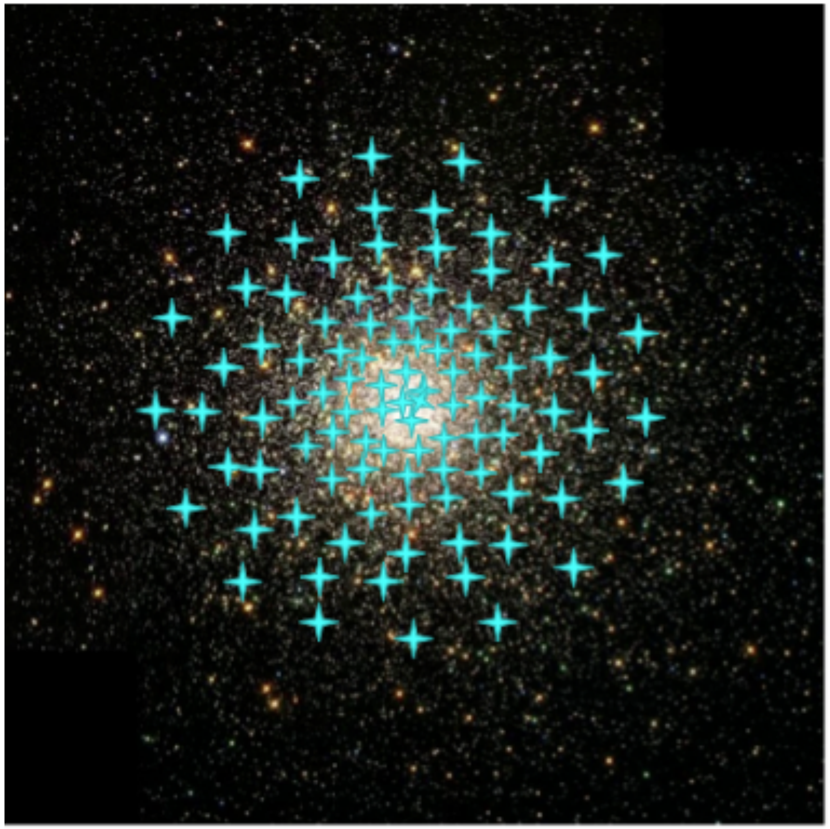
Ferraro et al (2012,Nature,492,393)



As the engine of a chronometer advances a clock-hand to measure the flow of time, in a similar way dynamical friction moves the minimum outward measuring the dynamical age of a stellar system

The dynamical clock

Ferraro et al (2012,Nature,492,393)



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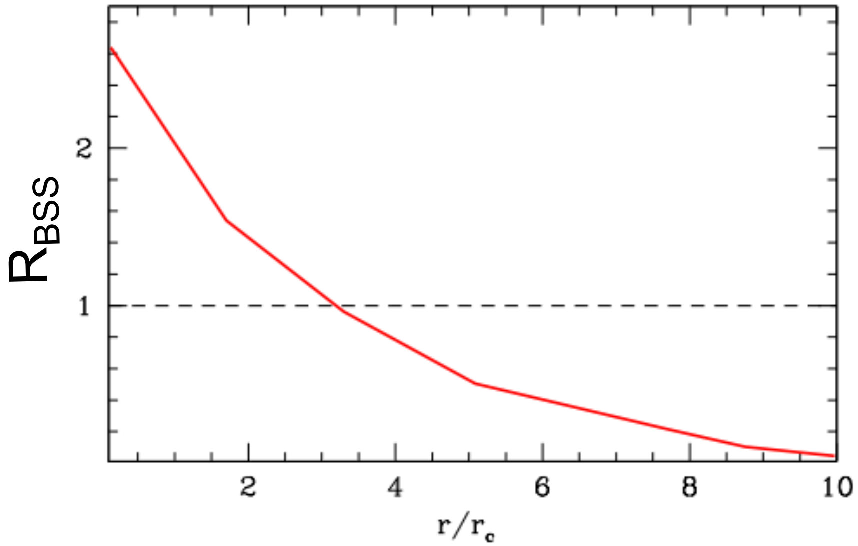
The dynamical clock

Ferraro et al (2012,Nature,492,393)

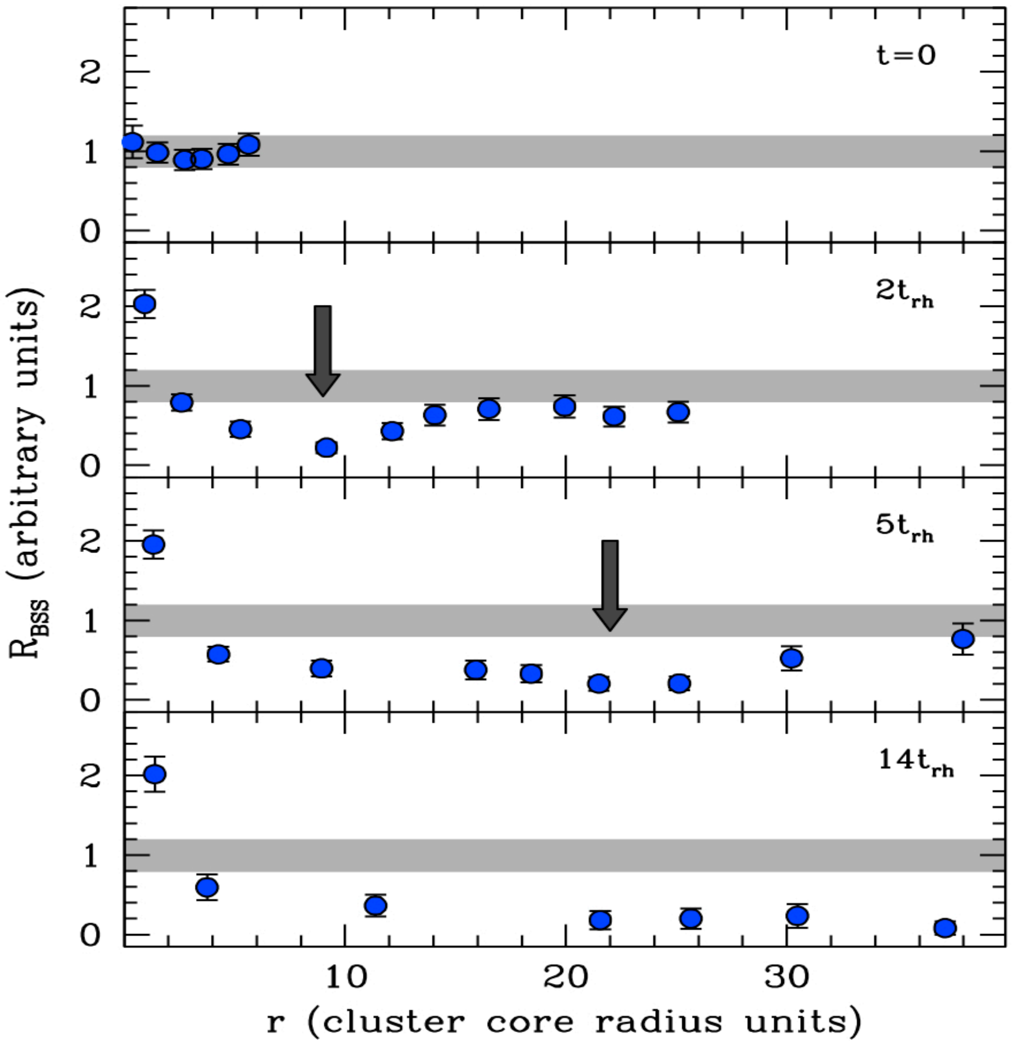


As the engine of a chronometer advances a clock-hand to measure the flow of time, In a similar way dynamical friction moves the minimum outward measuring the dynamical age of a stellar system

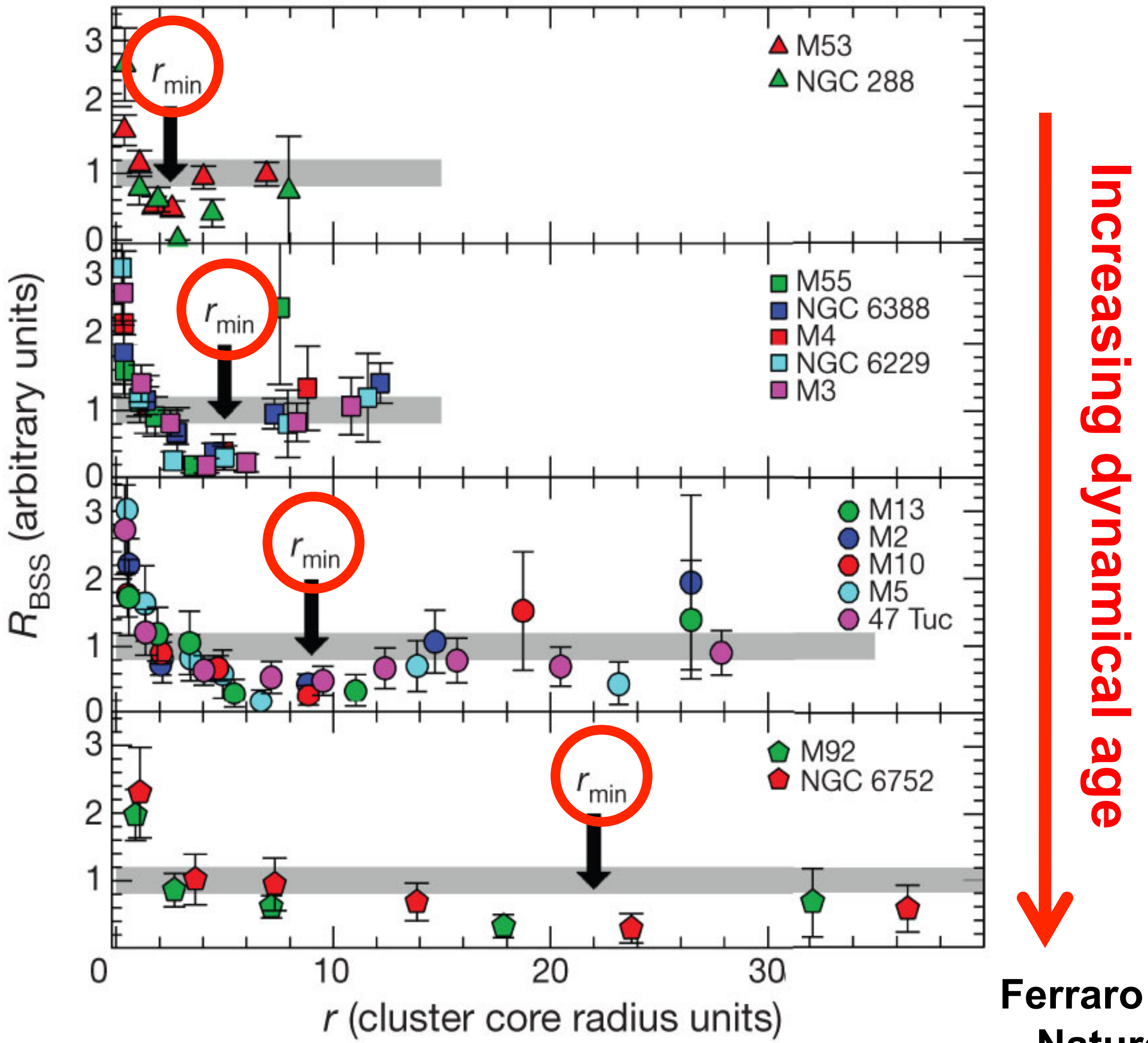
The dynamical clock

Ferraro et al (2012,Nature,492,393)

Preliminary N-body simulations fully confirmed this scenario.
Additional models are now in progress (Lanzoni, Miocchi, Pasquato, Alessandrini)



Cosmic-Lab

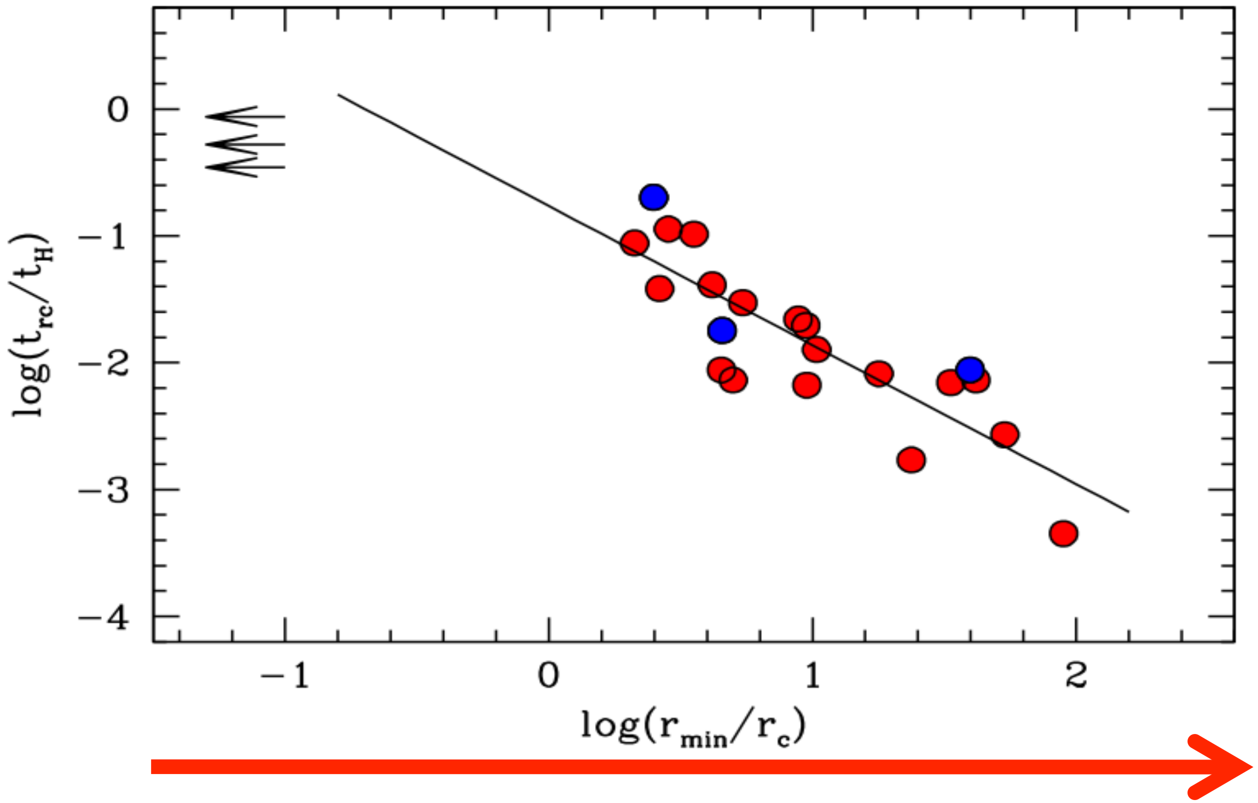


Ferraro et al 2012, Nature,492,393

The dynamical clock

Ferraro et al (2012,Nature,492,393)

A fully empirical tools able to rank stellar systems in terms of their dynamical age. It nicely agrees with theoretical estimates of the central relaxation time (t_{rc})



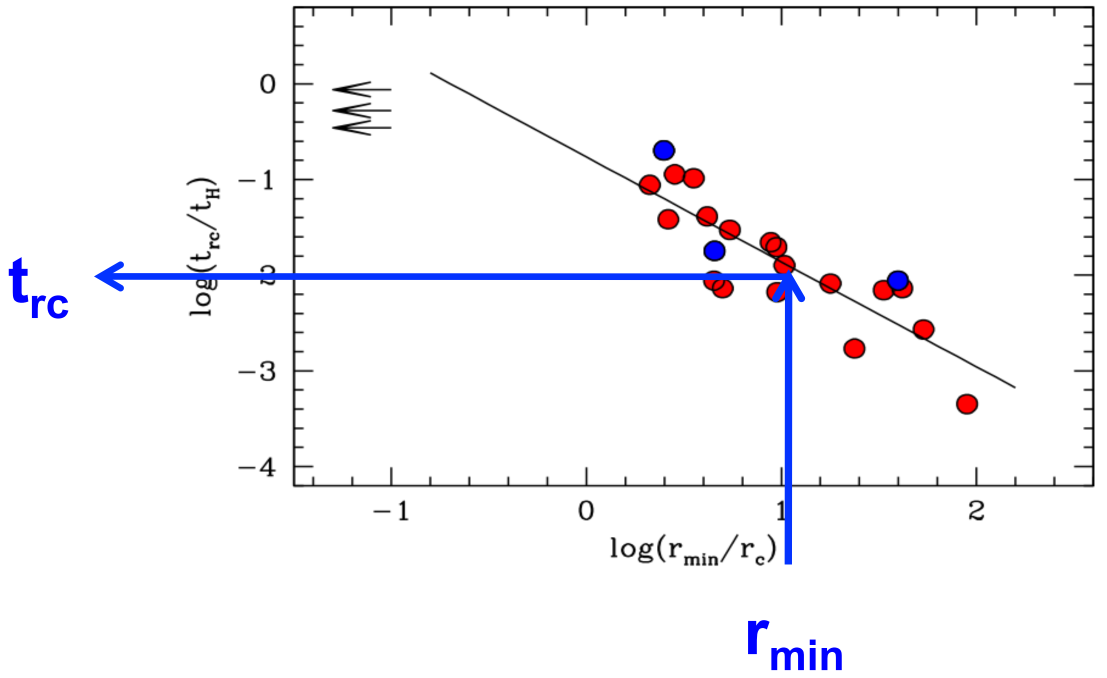
Increasing dynamical age

Cosmic-Lab

The dynamical clock

Ferraro et al (2012,Nature,492,393)

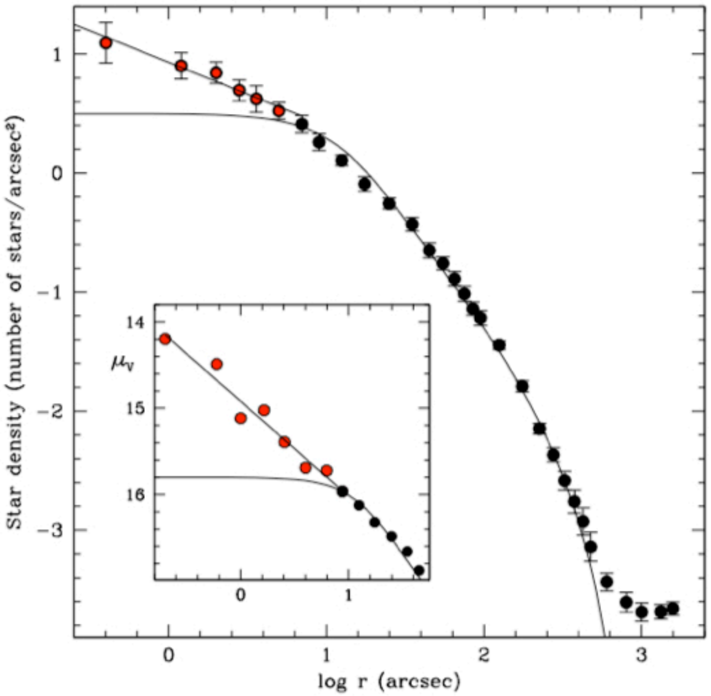
$$Log(t_{rc}/t_H) = -1.11\ log(r_{min}/r_c) - 0.76$$

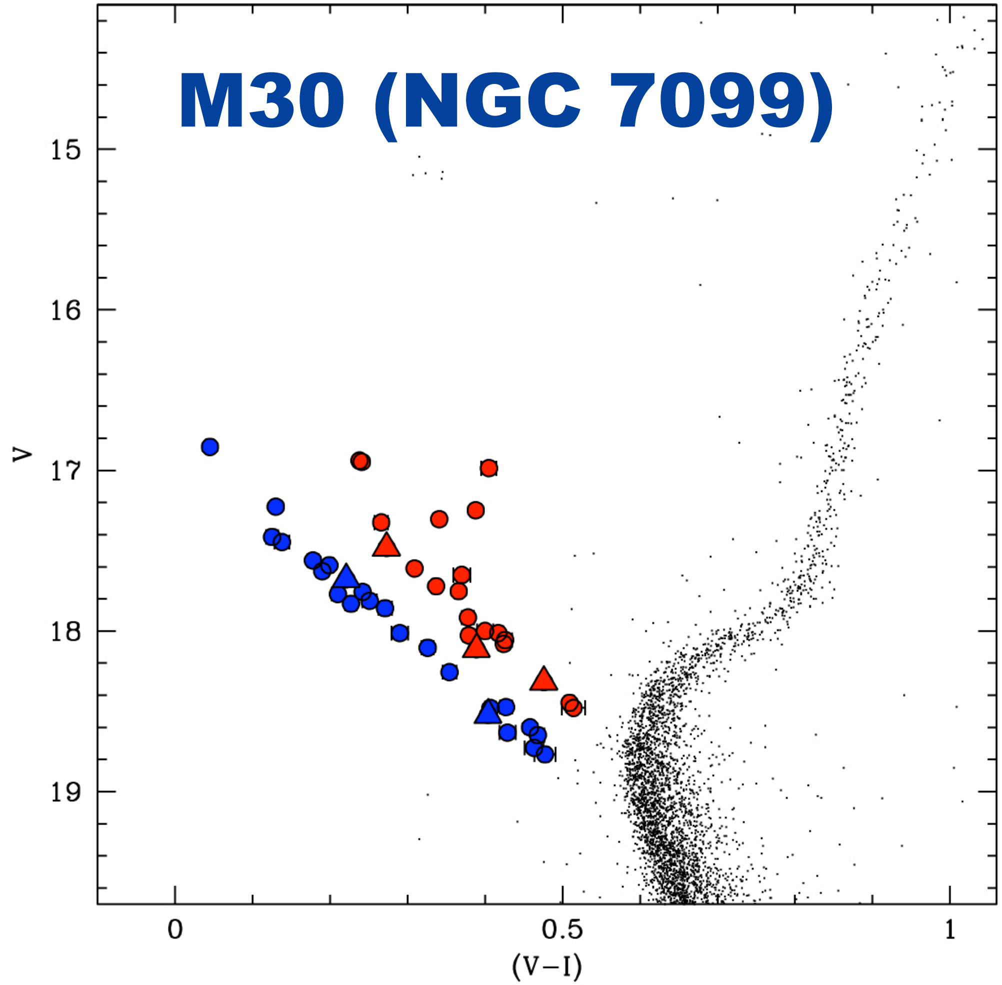


This tool is much more powerful than any previous theoretical estimator of the dynamical time-scale (e.g. the relaxation time-scale at the cluster center) since it simultaneously probe all distances from the cluster center

Indeed we can do even more…..

BSS sequences might provide crucial information about one of the most spectacular dynamical event in the cluster lifetime: **the collapse of the core**





2 distinct sequences of BSS !!

Ferraro et al. (2009, Nature 462, 1028)

- **blue-BSS → collisional**
- **red-BSS → mass-transfer binaries**

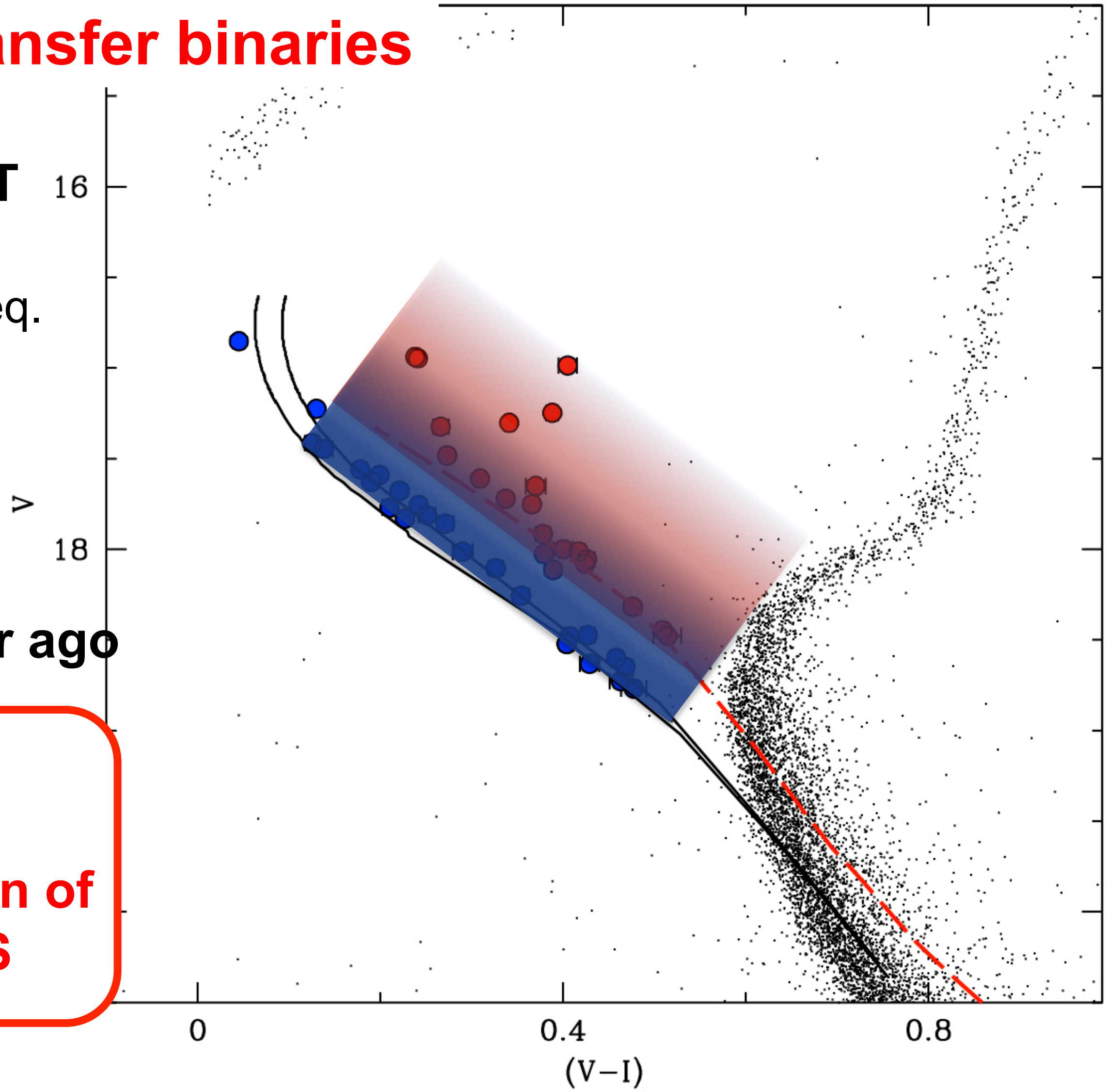
- **double BSS seq. is NOT a permanent feature**

The evolution of the BLUE Seq. will fill the gap in a few Gyr

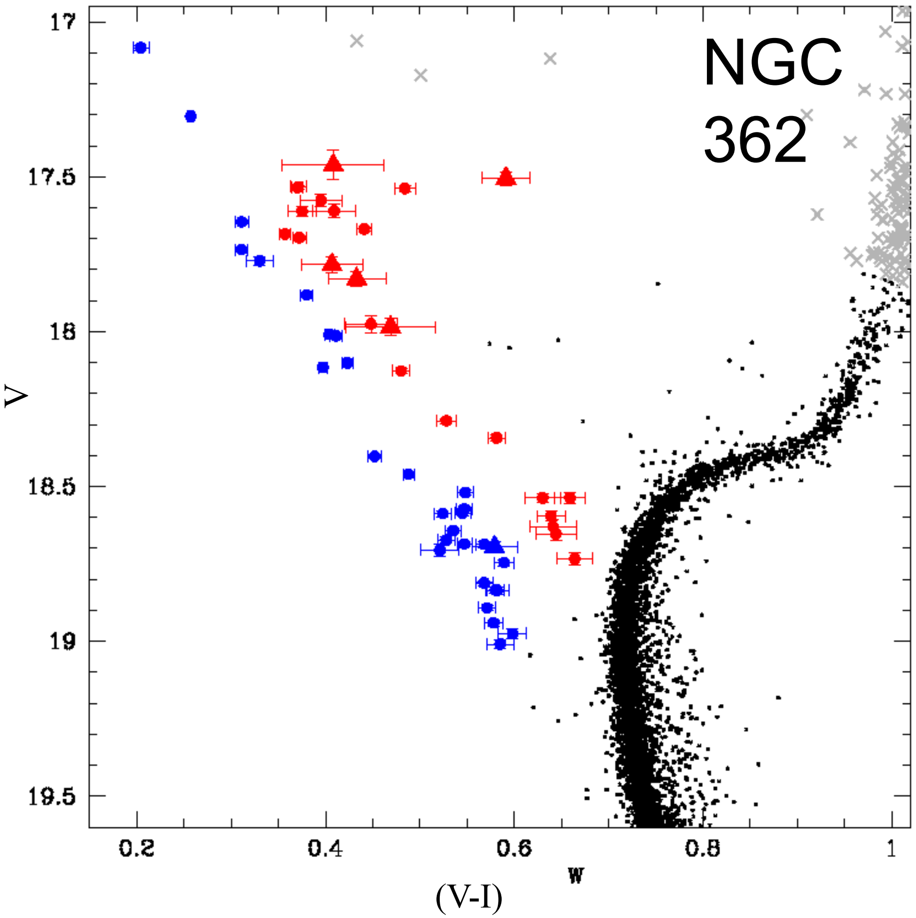
⇩

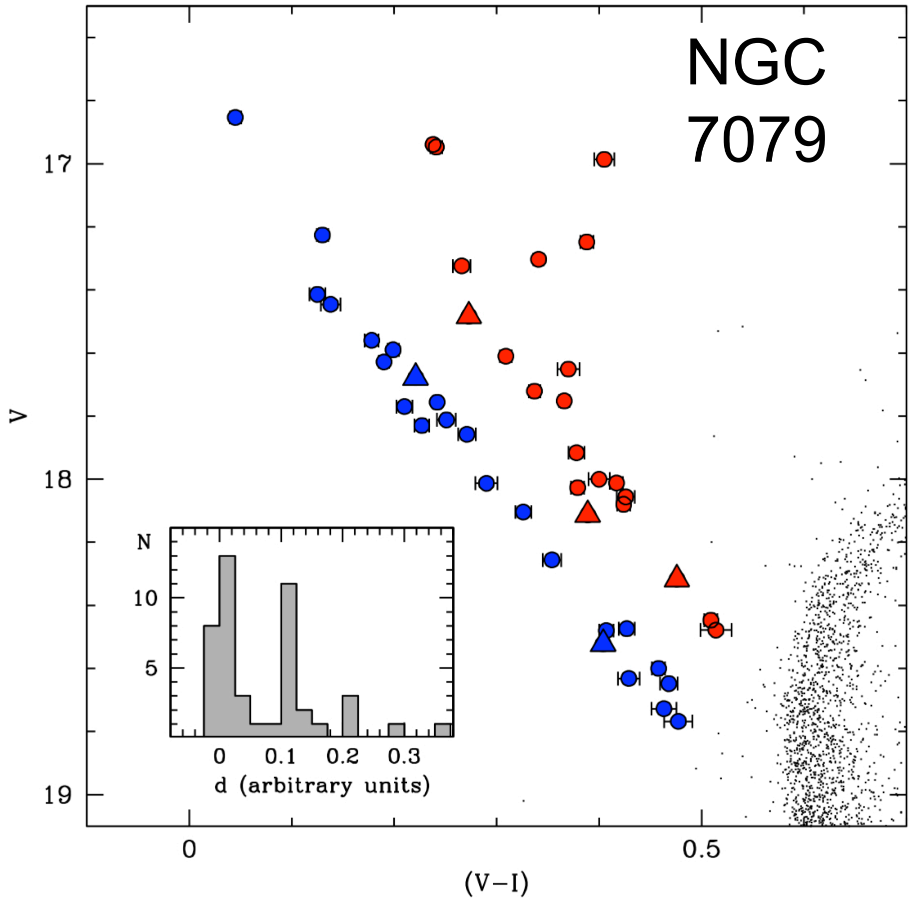
The blue-BSS population must have formed 1-2 Gyr ago

cluster core-collapse occurred 1-2 Gyr ago and boosted the formation of (at least) the COL-BSS



BSS double sequences probe & date the cluster core-collapse

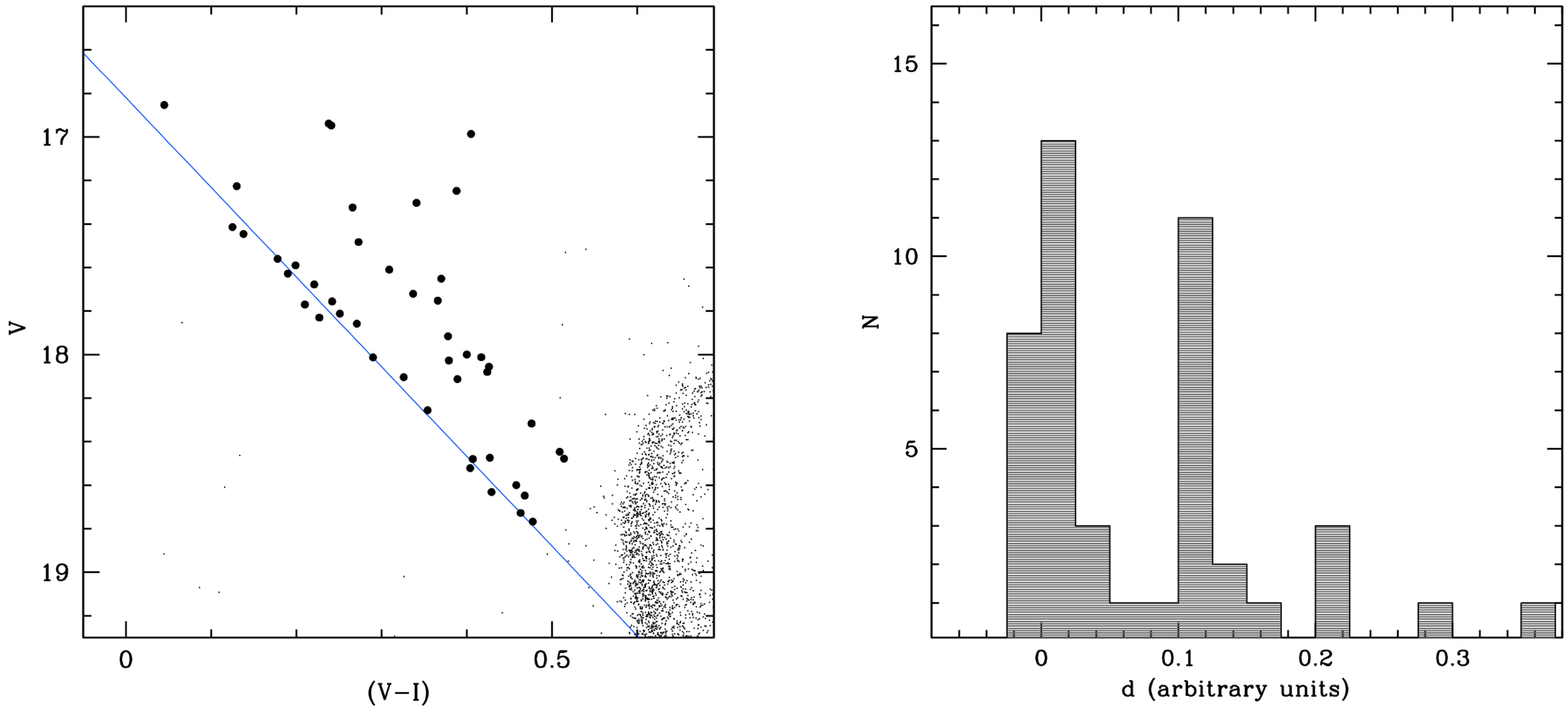




Dalessandro et al. 2013

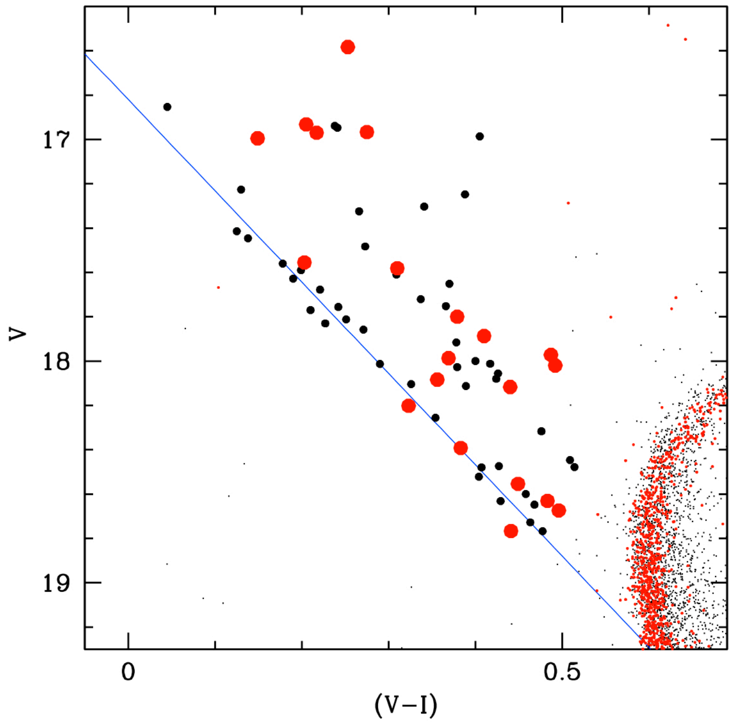
BSS double sequences probe & date the cluster core-collapse

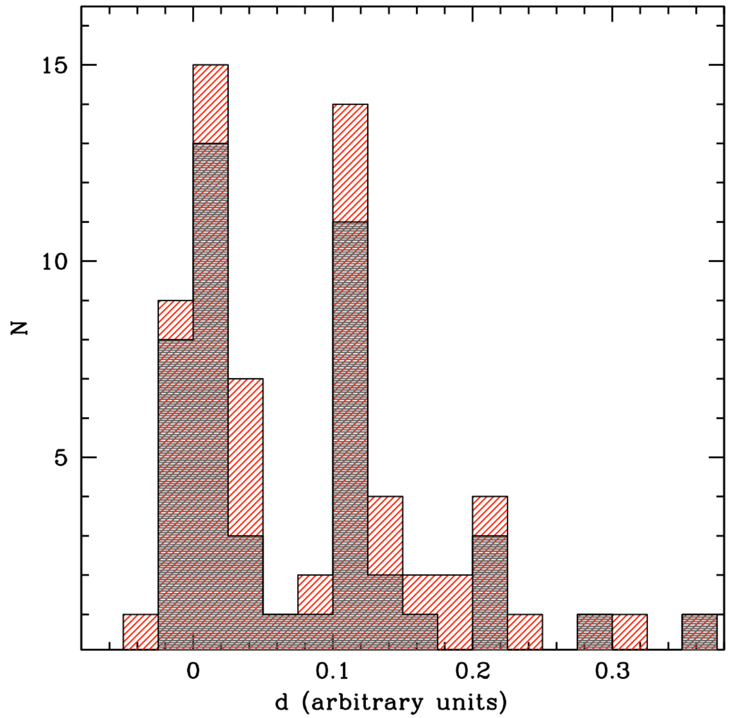
M30 (Ferraro et al. 2009)



BSS double sequences probe & date the cluster core-collapse

NGC 6397 (Contreras Ramos et al. 2014, in preparation)





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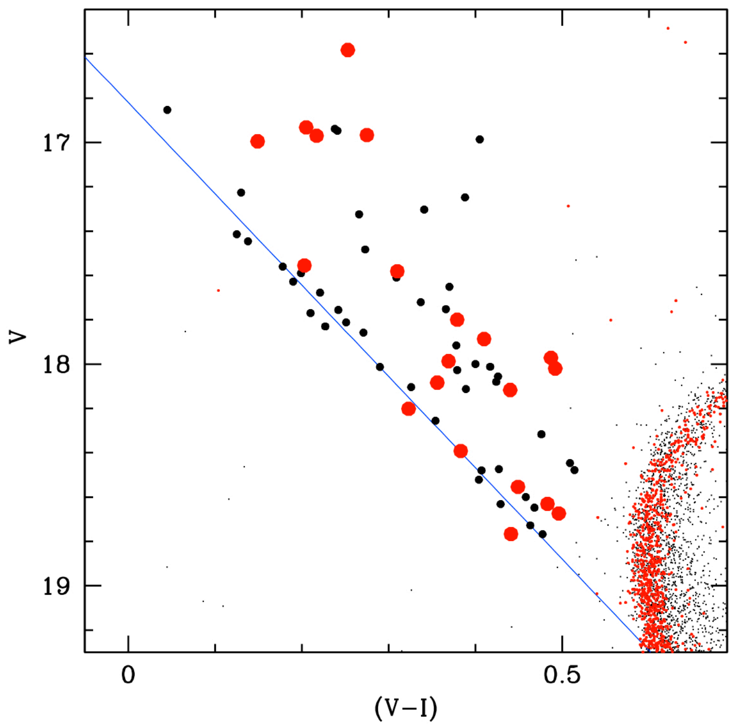
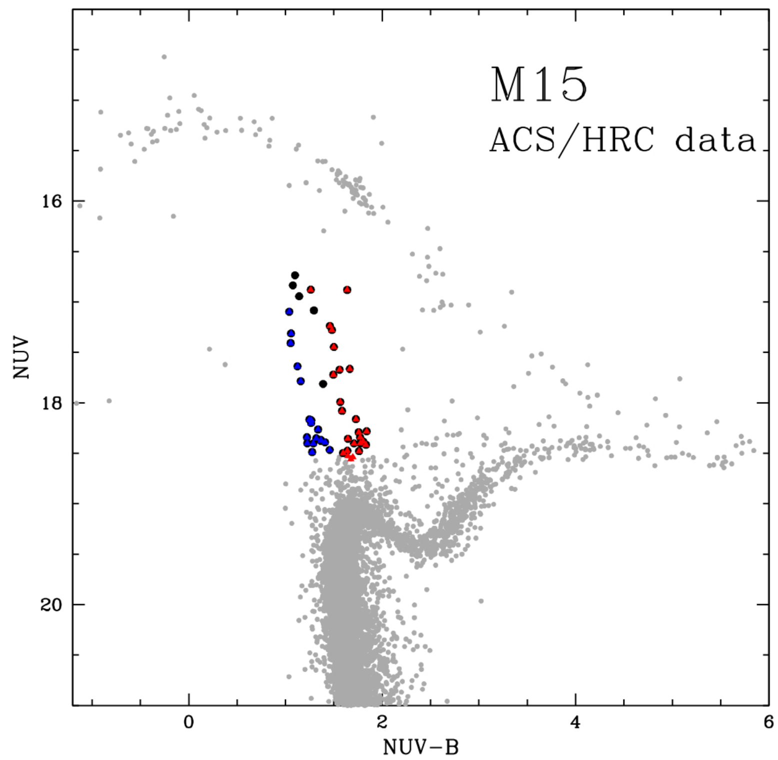
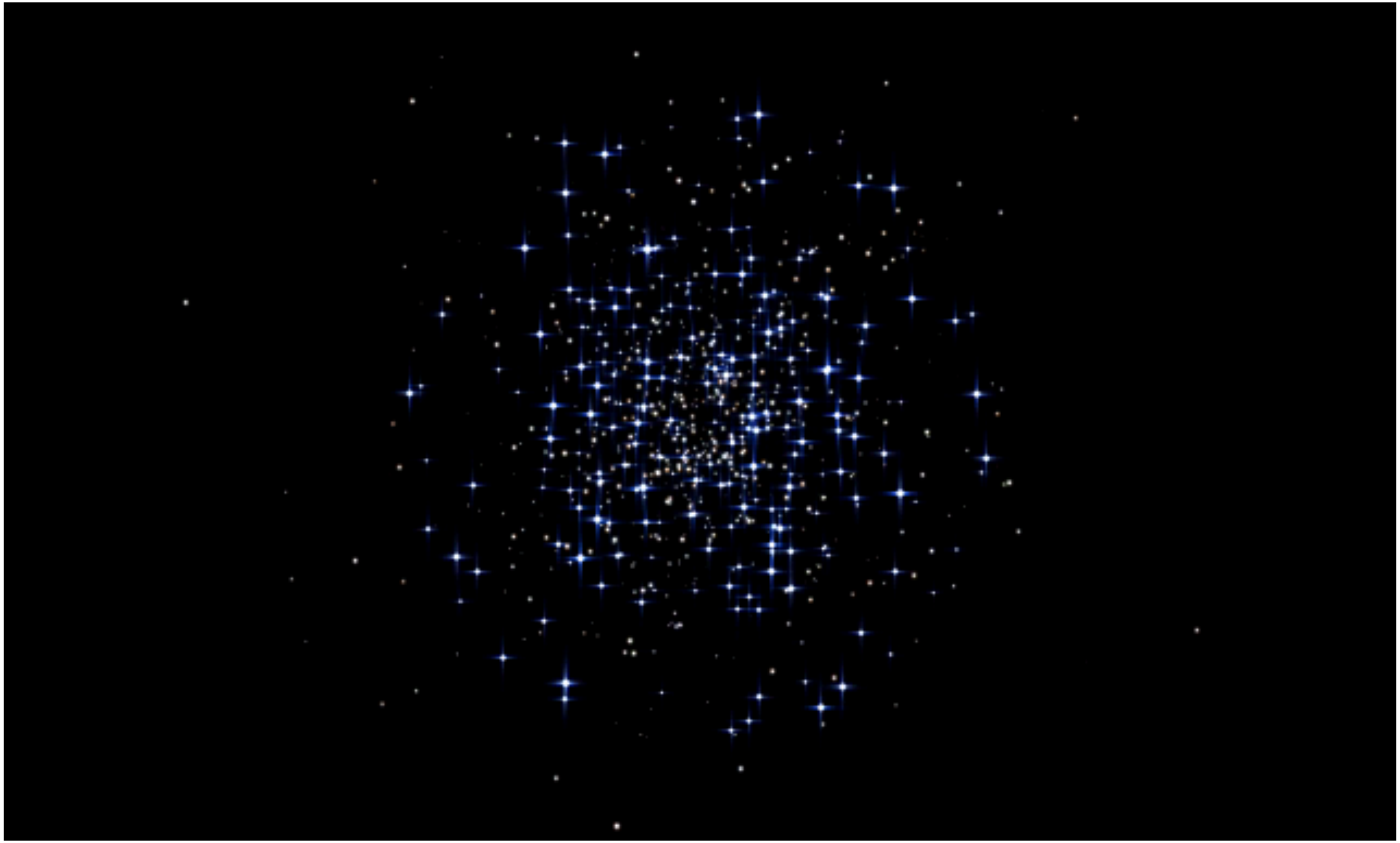


M15
(Beccari et al., in prep.)





Thank you for your attention !!!

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The End