Osservatorio Astronomico di Bologna
Istituto Nazionale di Astrofisica

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

DIPARTIMENTO
FISICA E ASTRONOMIA - DIFA

Clocks and Scales to understand Globular Cluster and BSS physics

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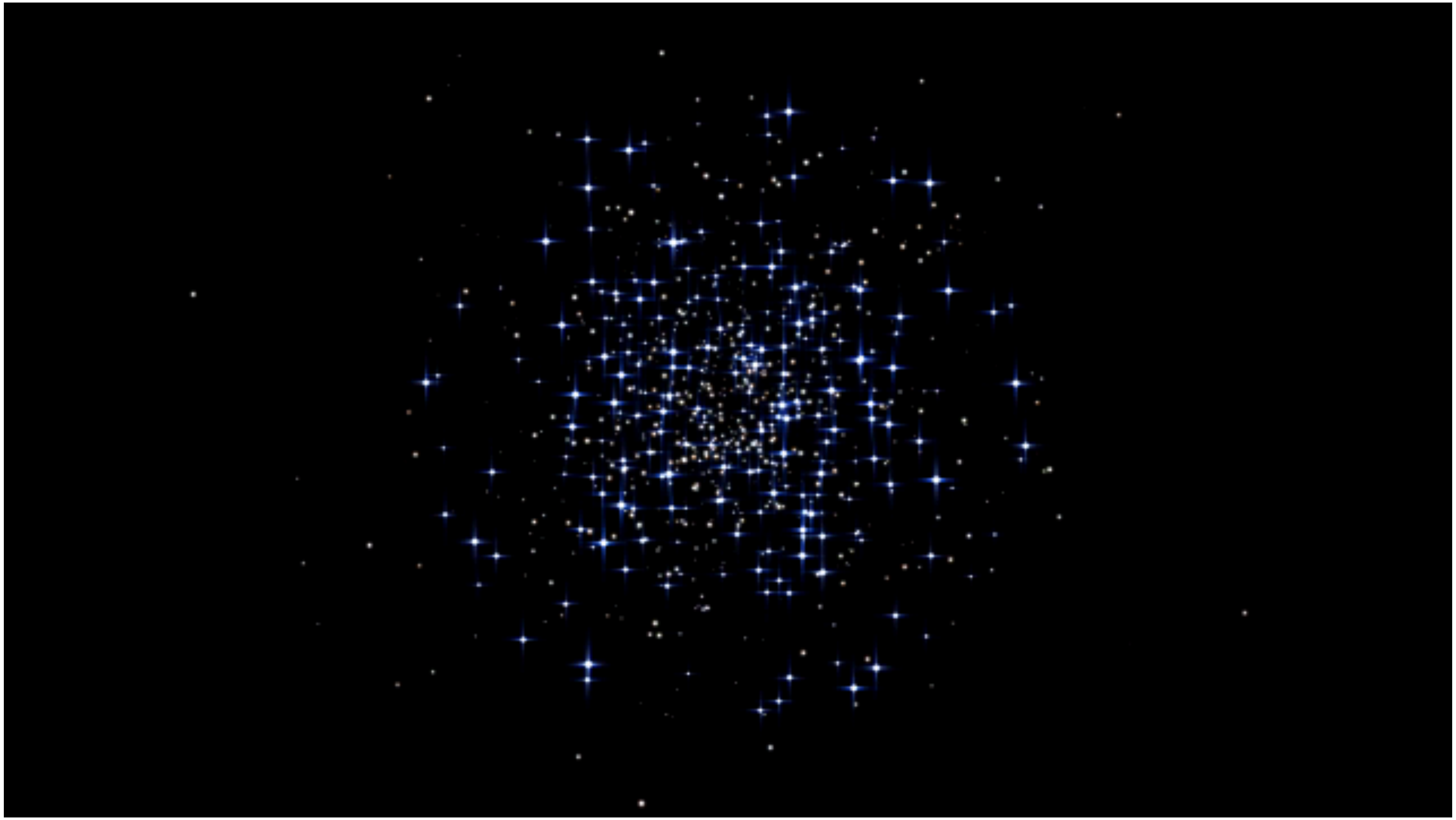
Today I'll talk about CLOCKS and SCALES in the context of understanding the physics of Blue Straggler Stars in GCs

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

$\left.\begin{array}{l}\textbf{Blue Straggler Stars}\\ \textbf{Millisecond Pulsars}\\ \textbf{Intermediate-mass Black Holes}\end{array}\right\}$ as probe-particles

WHY GCs?



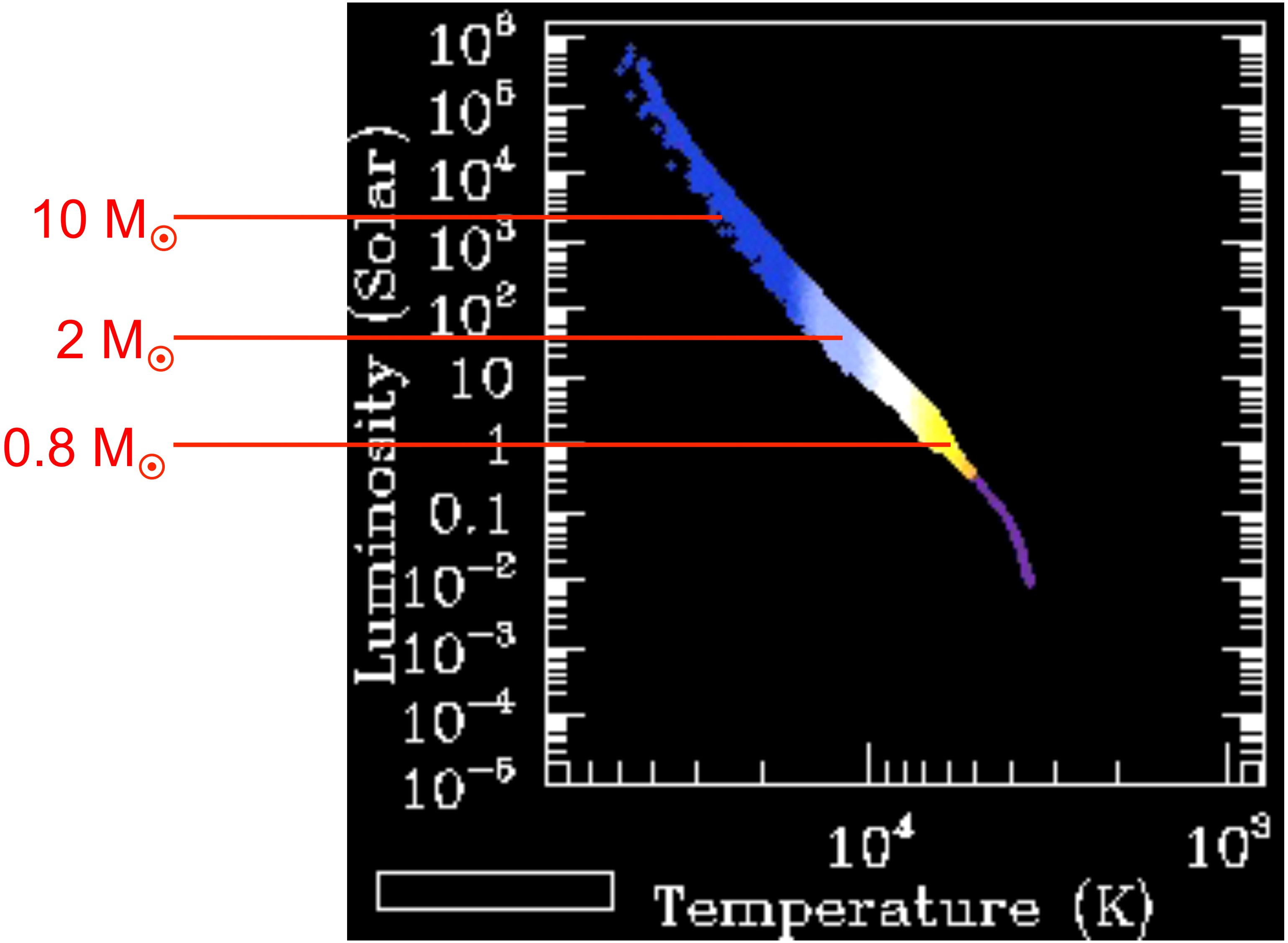
GCs are the only stellar systems able to undergo nearly all the physical processes known in stellar dynamics over a time scale significantly shorter than the Hubble time.

This dynamical activity can generate **exotica**

CLOCKS

for measuring “chronological” and “dynamical” ages

The stellar clock: measuring the "chronological" age



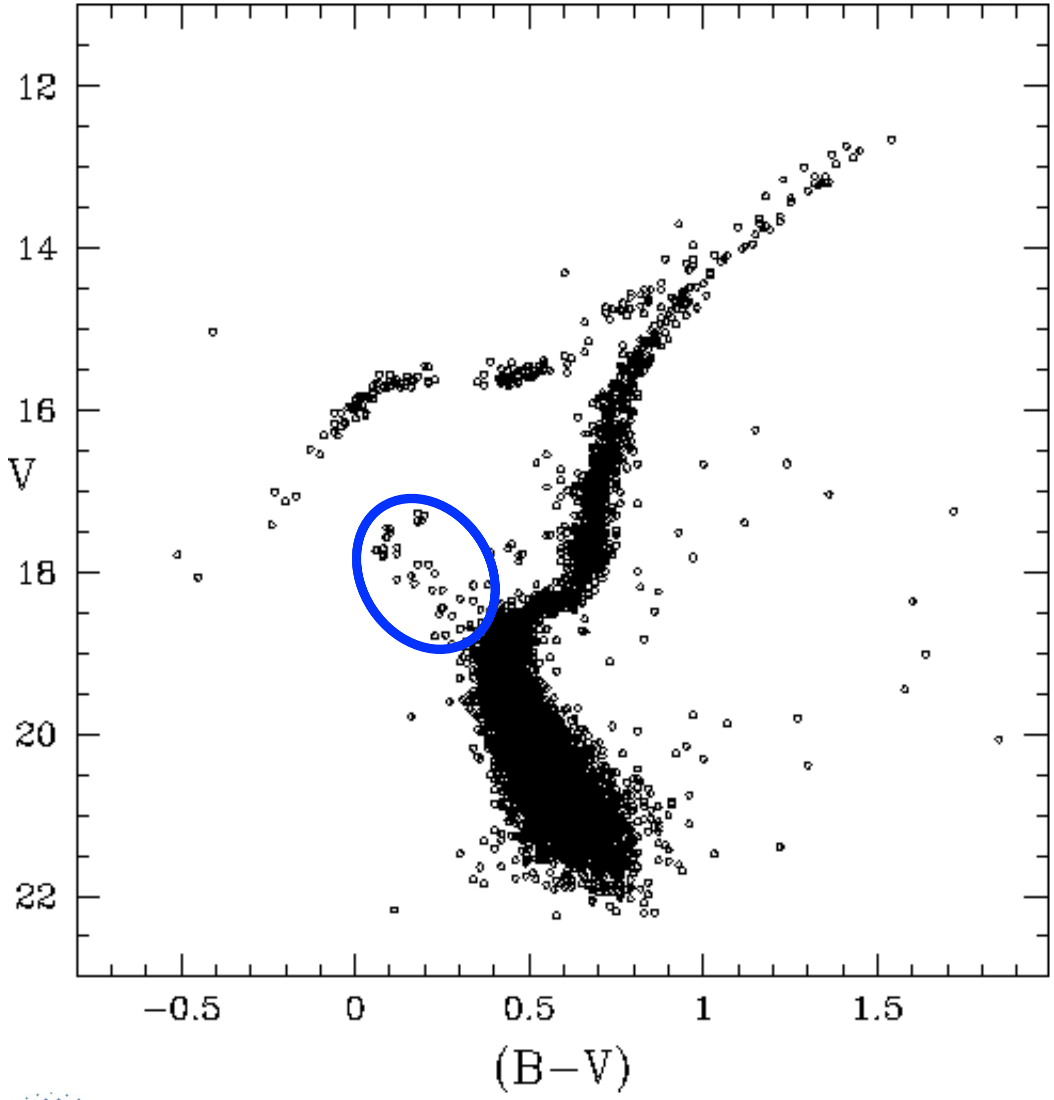
The **luminosity/mass at the TO level** sets the **CHRONOLOGICAL AGE** of a Stellar Population (SP)…

but stellar systems with the same **chronological age** can have reached different stages of dynamical evolution (i.e. they have **different DYNAMICAL AGES**)

In order to properly characterize a SP we need to know both: the **CHRONOLOGICAL**
& the **DYNAMICAL** ages

Blue Straggler Stars (BSS)

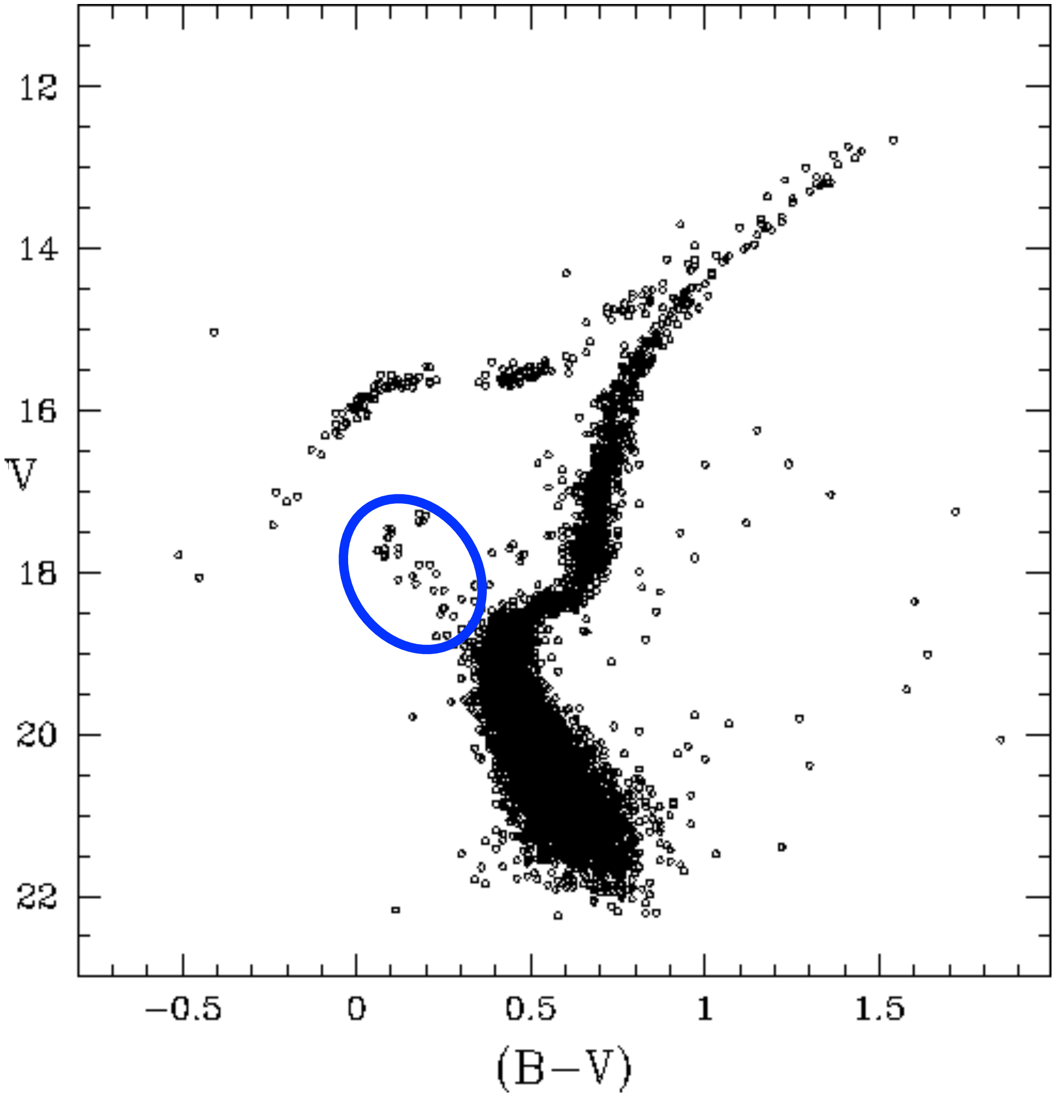
A PECULIAR stellar population



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

Their existence CANNOT be interpreted in terms of the evolution of a “normal” single star

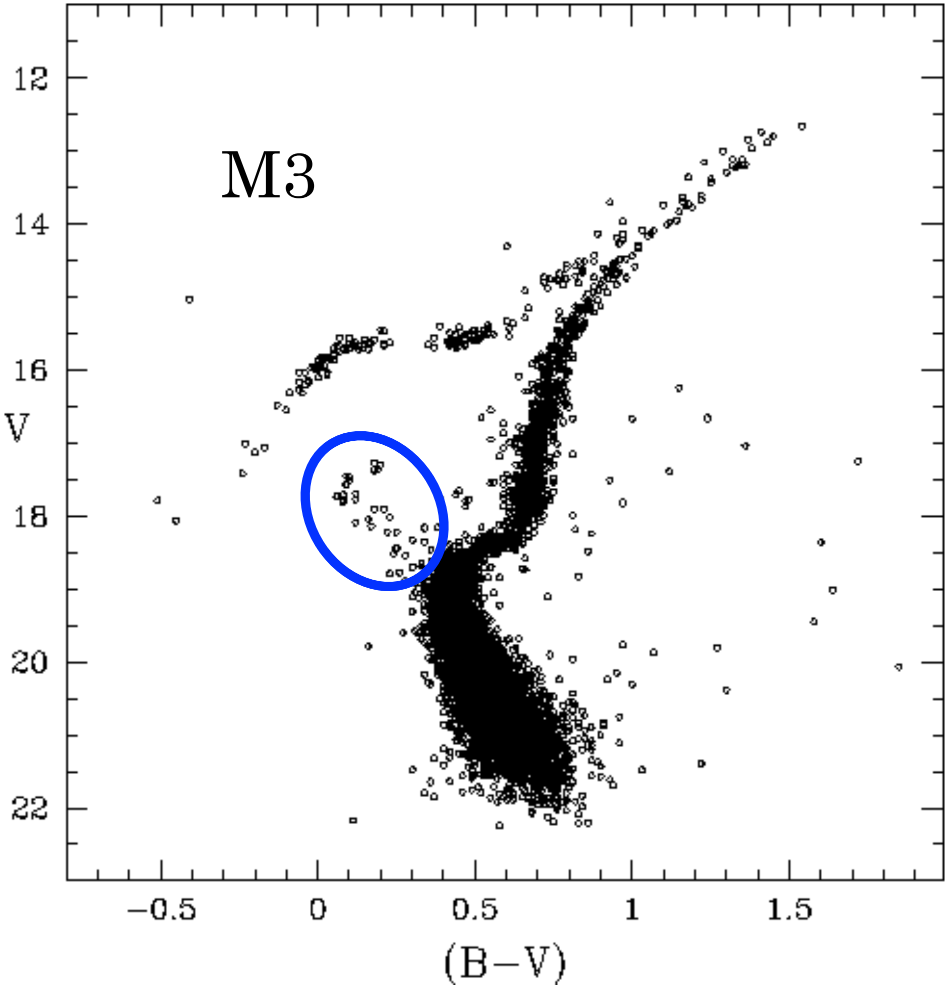
Blue Straggler Stars (BSS)



..while
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)

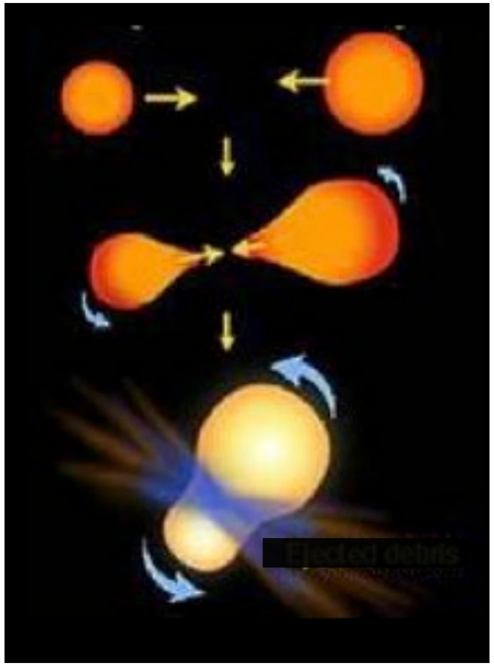


They LOOK younger but they are OLD stars rejuvenated by dynamical processes

Merger of two (old) low-mass stars

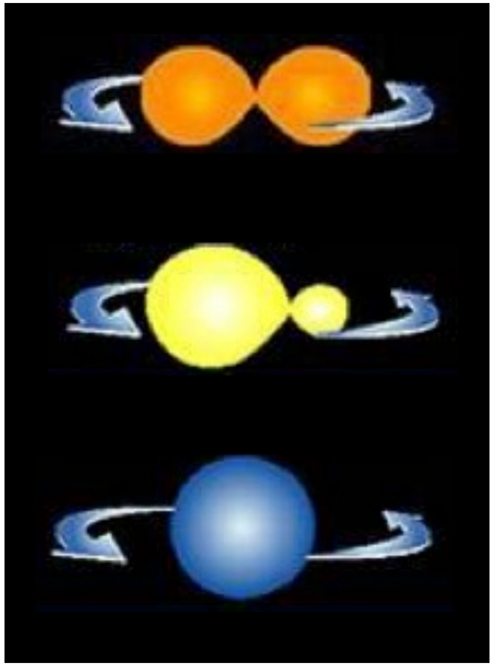
The formation mechanisms

COLLISIONS



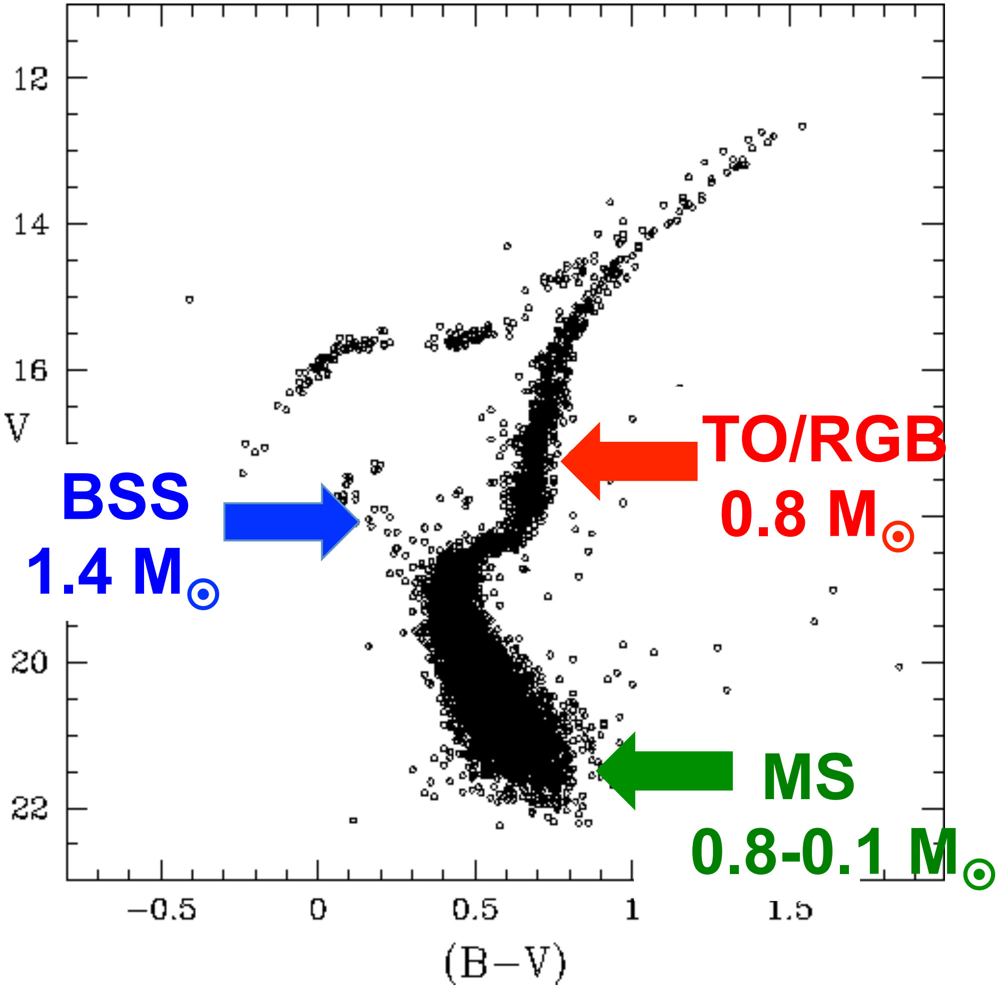
depend on **collision** rate
(Hills & Day 1976)

MASS-TRANSFER



depend on **binary fraction + 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 ($M_{BSS} = 1.2\text{-}1.4\ M_\odot$) orbiting 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

The **df** time-scale depends on:

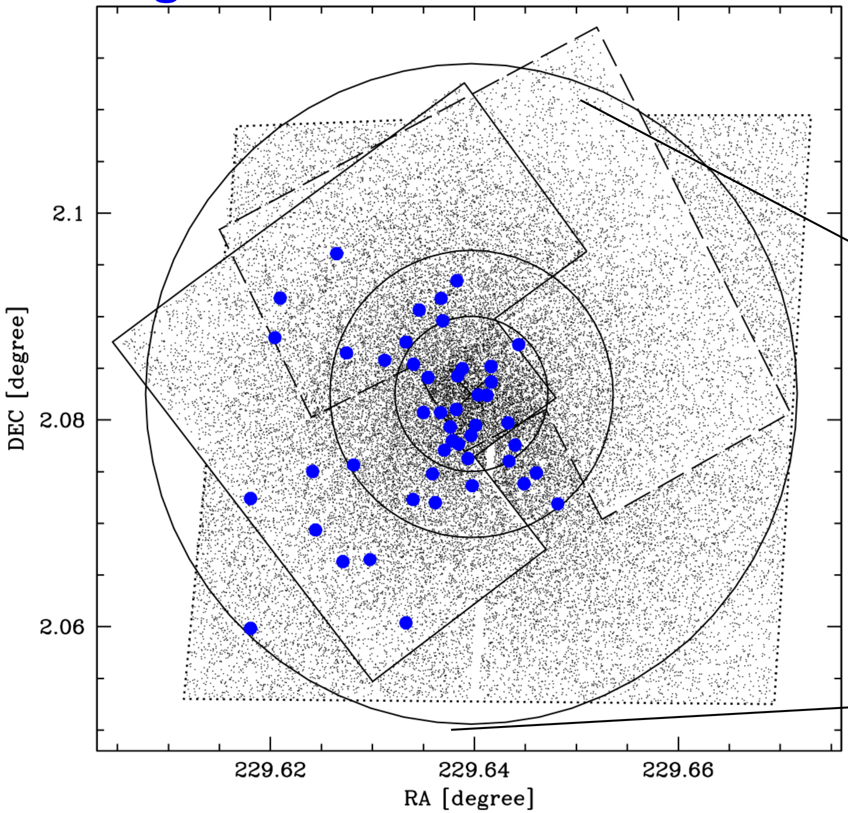
(1) Star mass **(2) Local cluster density**

$$t_{df} \approx \frac{1}{M_{BSS}\,\rho(r)}$$

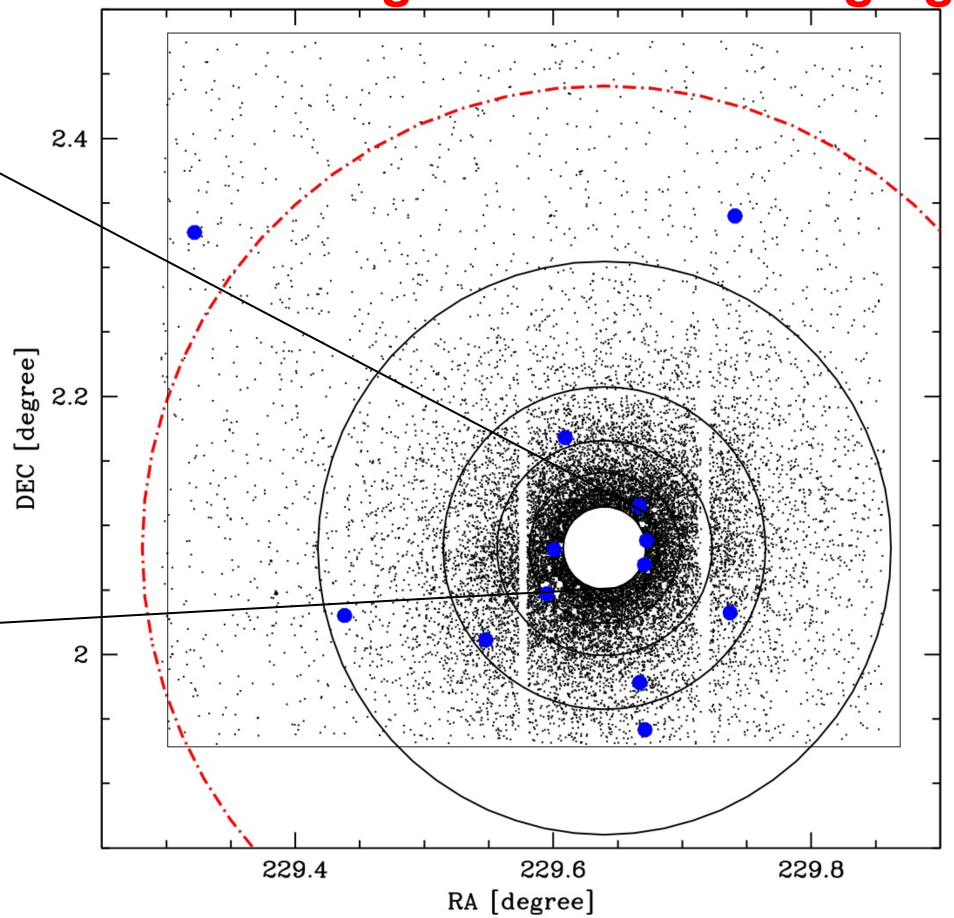
Because of this, **df** is expected to affect, first, the most internal BSS and then BSS at progressively **larger distances from the center,** as function of time

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

High-res: HST/WFPC2+ACS

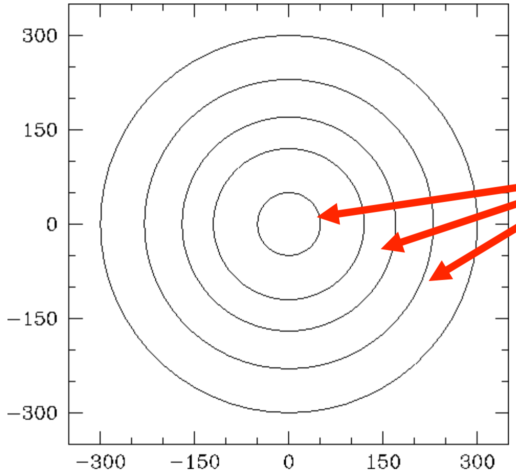


Wide-field ground-based imaging



GO 5903 -	PI:Ferraro	6 orbits
GO 6607 -	PI:Ferraro	11 orbits
GO 8709 -	PI:Ferraro	13 orbits
GO10524 -	PI:Ferraro	11 orbits
GO11975 -	PI:Ferraro	177 orbits
GO12516 -	PI:Ferraro	21 orbits
	Grandtotal	**239 orbits**

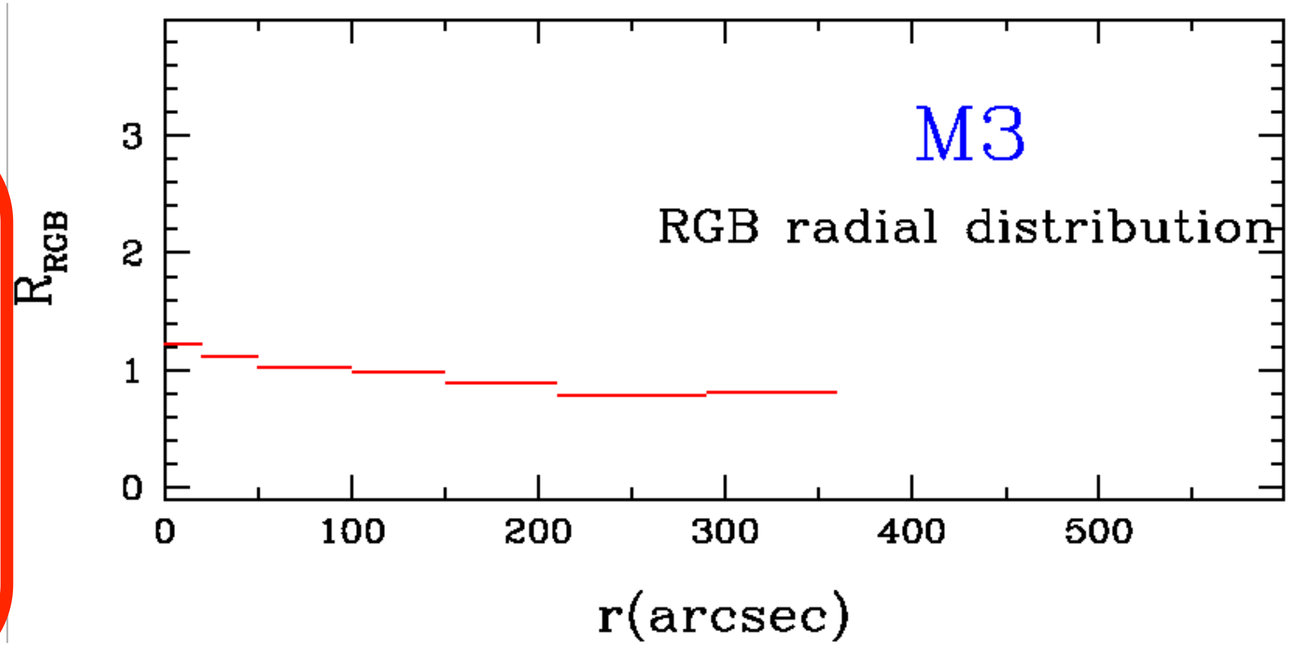
THE BSS RADIAL DISTRIBUTION



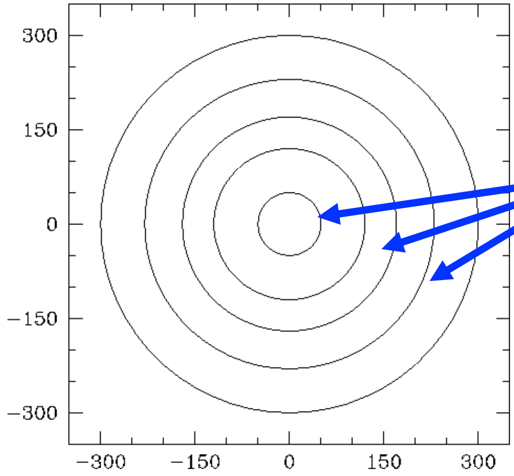
$$R_{RGB} = \frac{N_{RGB}/N_{RGB,TOT}}{L_{samp}/L_{TOT}}$$

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

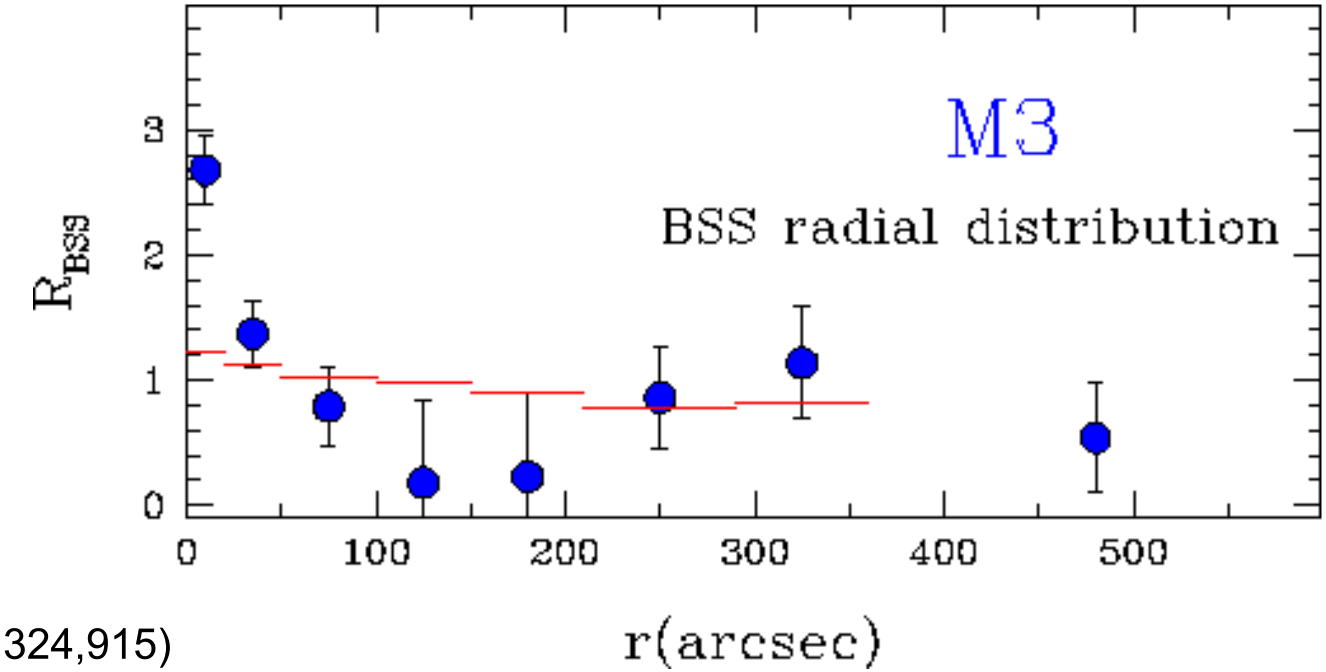
Note that ***a flat distribution*** in this plot means that ***"the number of stars in each annulus exactly scales with the cluster light sampled by each annulus"***



THE BSS RADIAL DISTRIBUTION



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

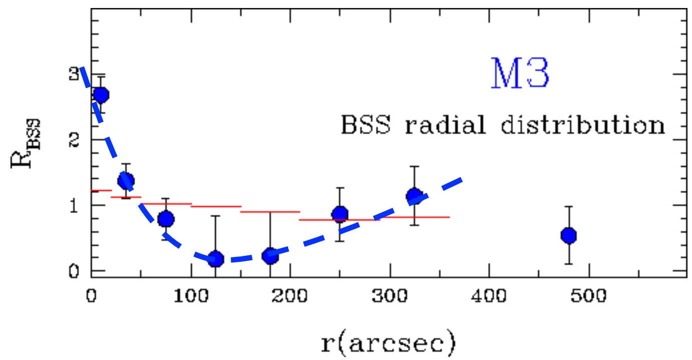


Ferraro et al (1997,A&A,324,915)

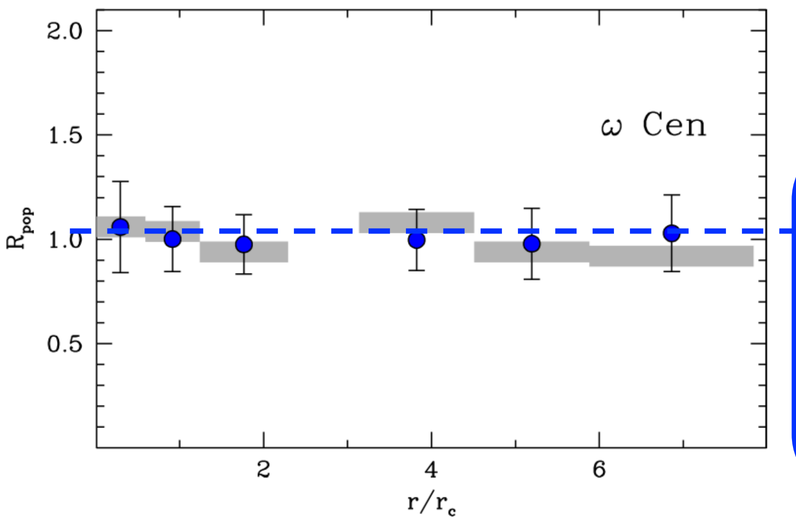
BSS radial distribution

Over the last 20 years we studied the BSS radial distribution over the entire cluster extension in more than 25 stellar systems, finding a variety of cases

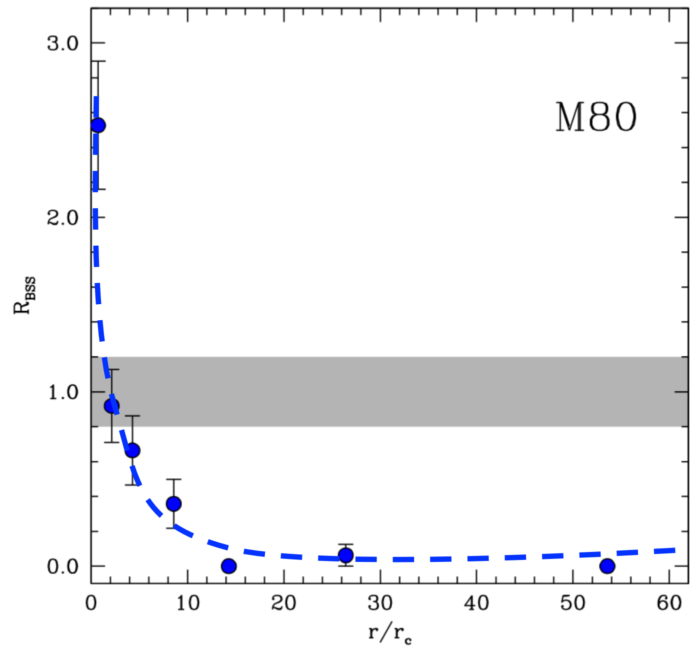
"bimodal"



"Flat"



"Unimodal" (single-peak)



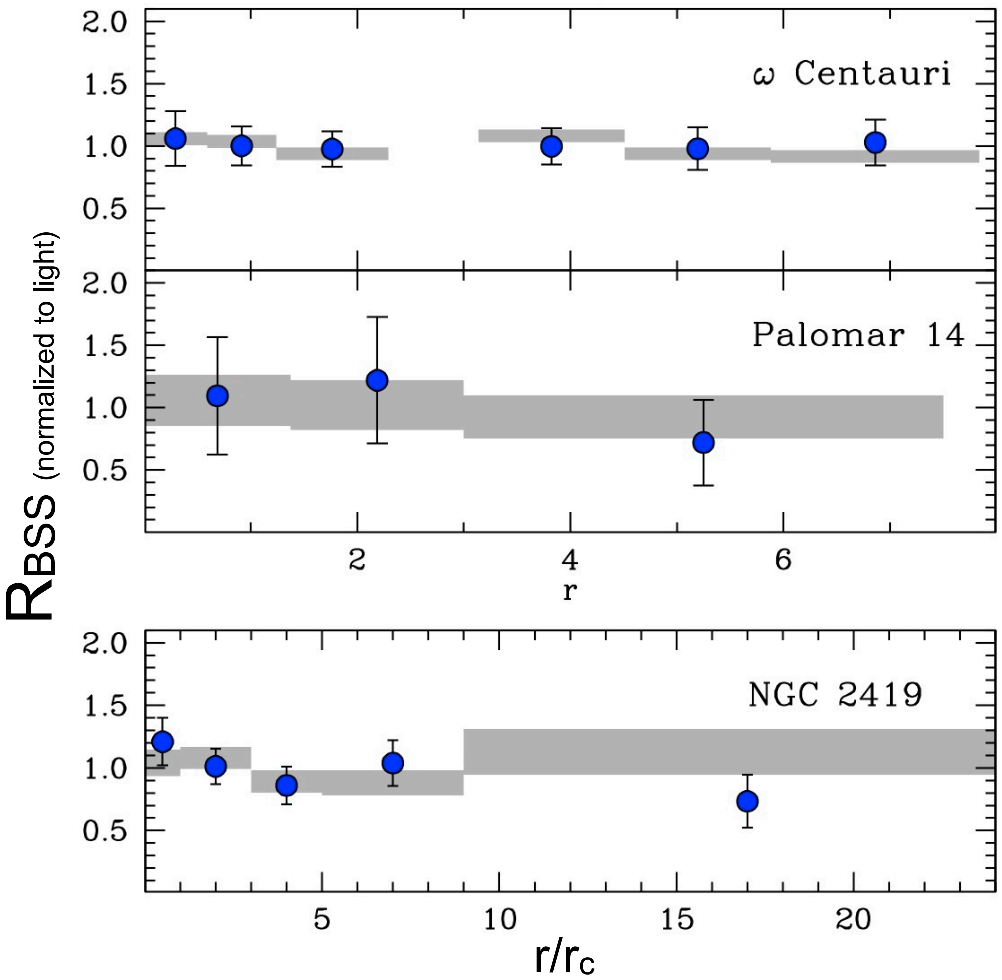
The BSS radial distribution is shaped by dynamical friction, which progressively segregates BSS at larger and larger radii

….. THE DYNAMICAL CLOCK…..

The dynamical clock

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

Family I : FLAT BSS radial distribution



The BSS distribution is **flat** in full agreement with that of “normal stars”

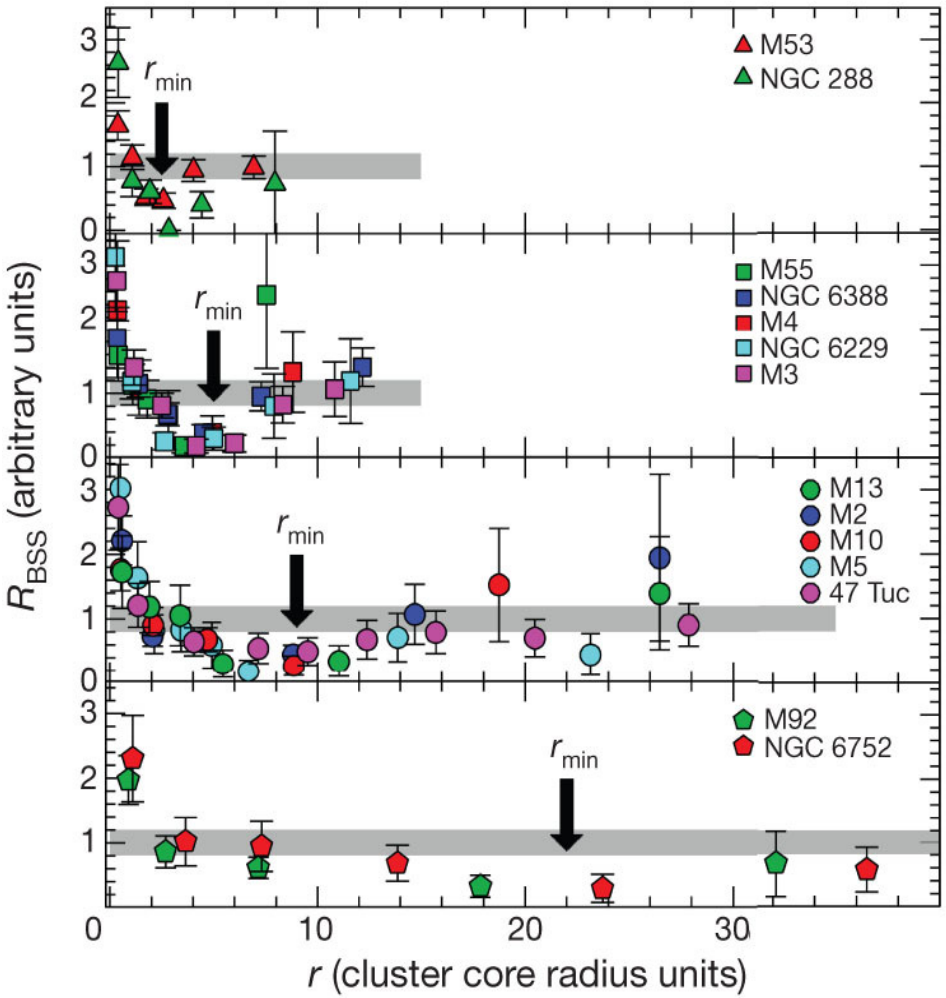
dynamical friction has not affected the BSS distribution yet, not EVEN in the cluster center

Family I: the dynamically YOUNG clusters

The dynamical clock

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

Family II: bimodal BSS radial distribution



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

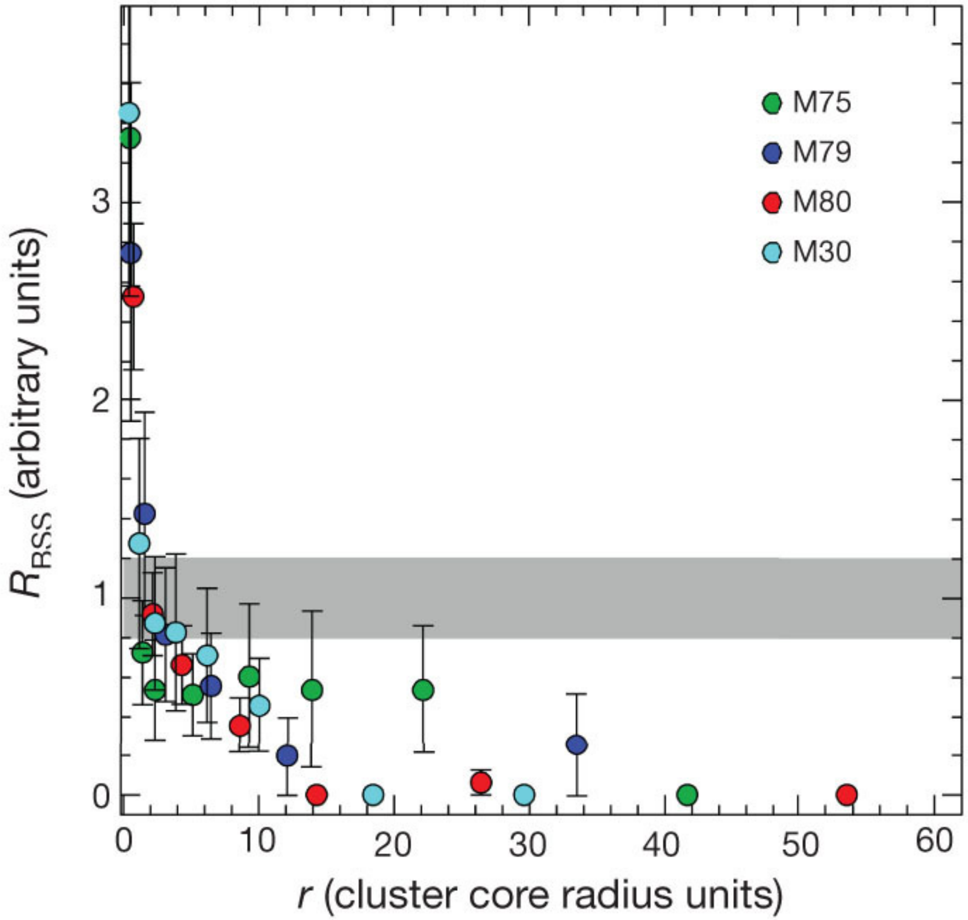
The action of **df** extends progressively at larger distances from the cluster center = the minimum is moving progressively outward

Family II: the dynamically INTERMEDIATE-age clusters

The dynamical clock

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

Family III: unimodal BSS radial distribution



The BSS distribution is **unimodal** with a well defined peak at the cluster center but no rising branch

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

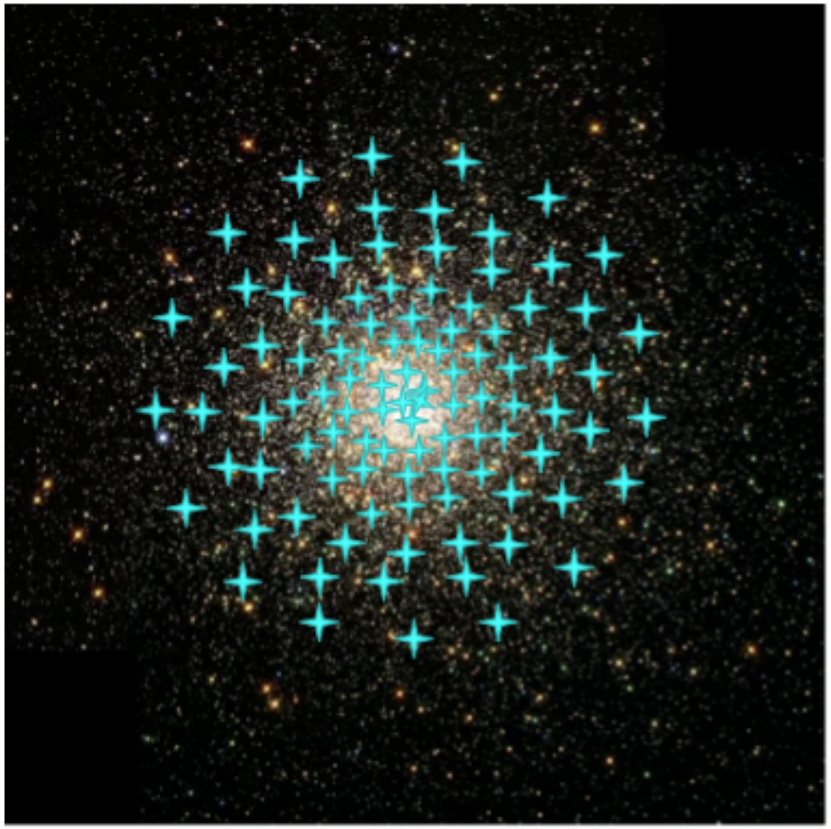
The action of **df** extended out to the cluster tidal radius

Family III: the dynamically OLD clusters

Cosmic-Lab

The dynamical clock

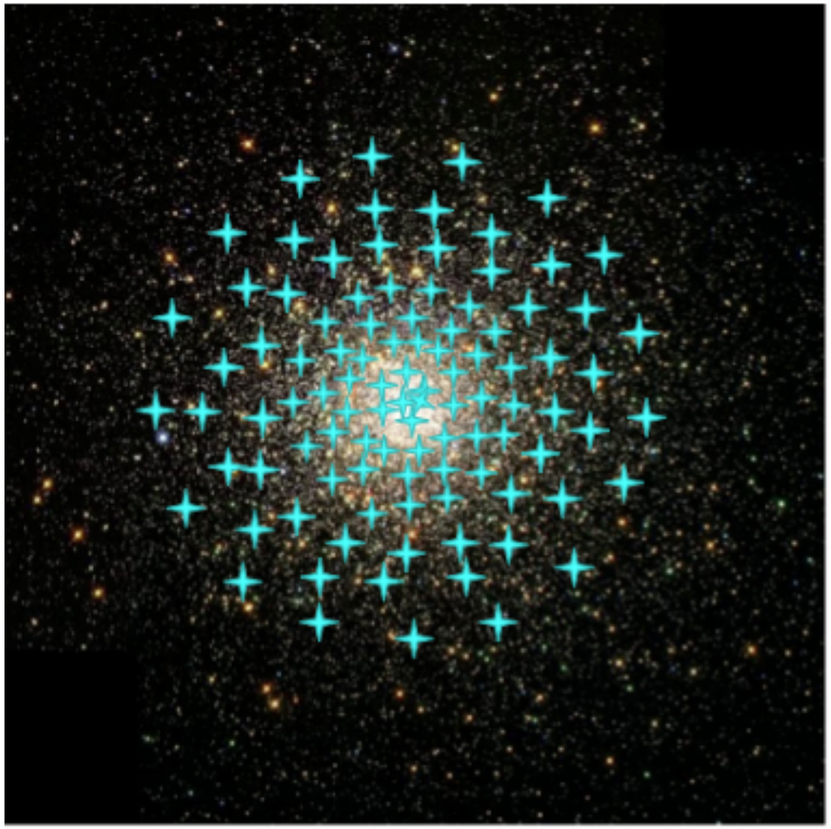
Ferraro et al (2012,Nature,492,393)



The cartoon illustrates the action of **df** that progressively segregates the BSS toward the cluster center producing a dip in the radial distribution that propagates toward the external region with time.

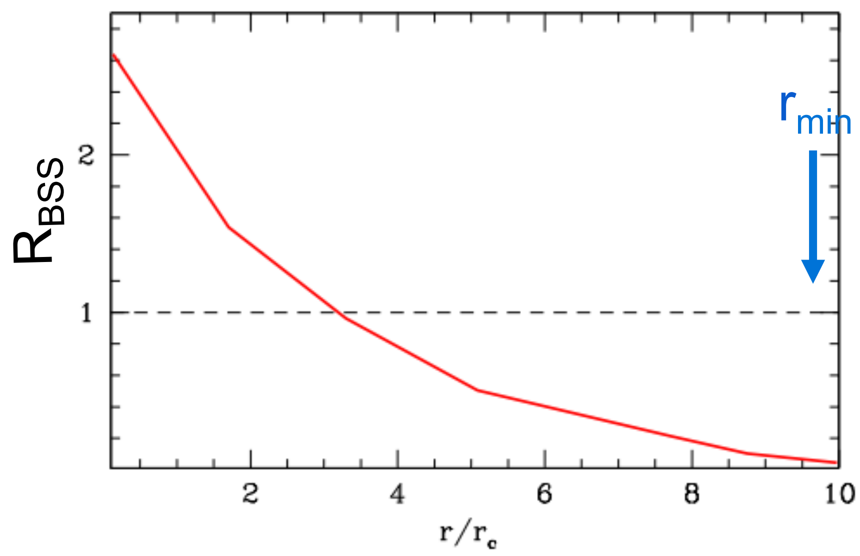
The dynamical clock

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



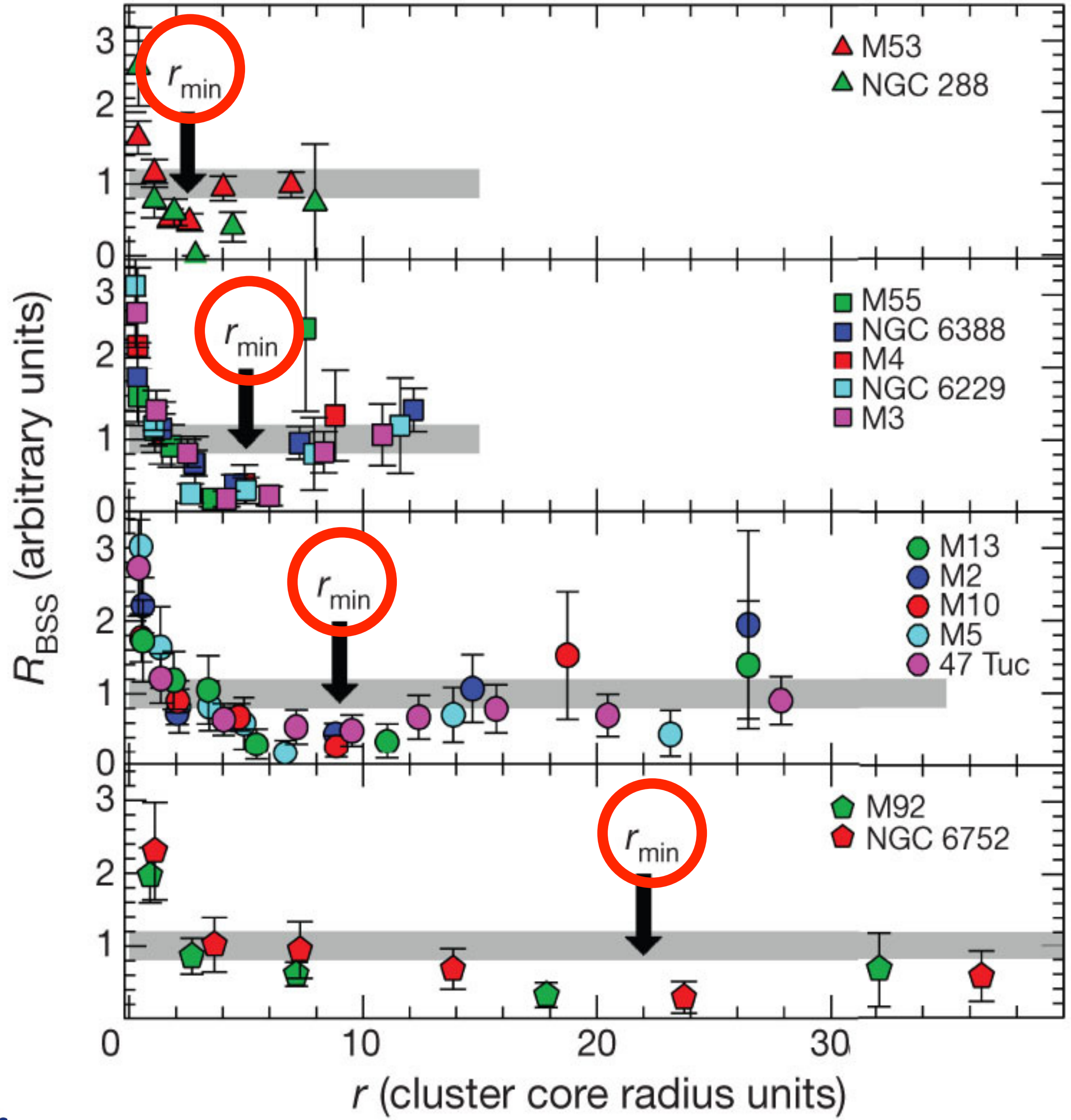
The cartoon illustrates the action of **df** that progressively segregates the BSS toward the cluster center producing a dip in the radial distribution that propagates toward the external region with time.

The dynamical clock



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 position of the minimum is **THE HAND** of the **DYNAMICAL CLOCK**



Increasing dynamical age

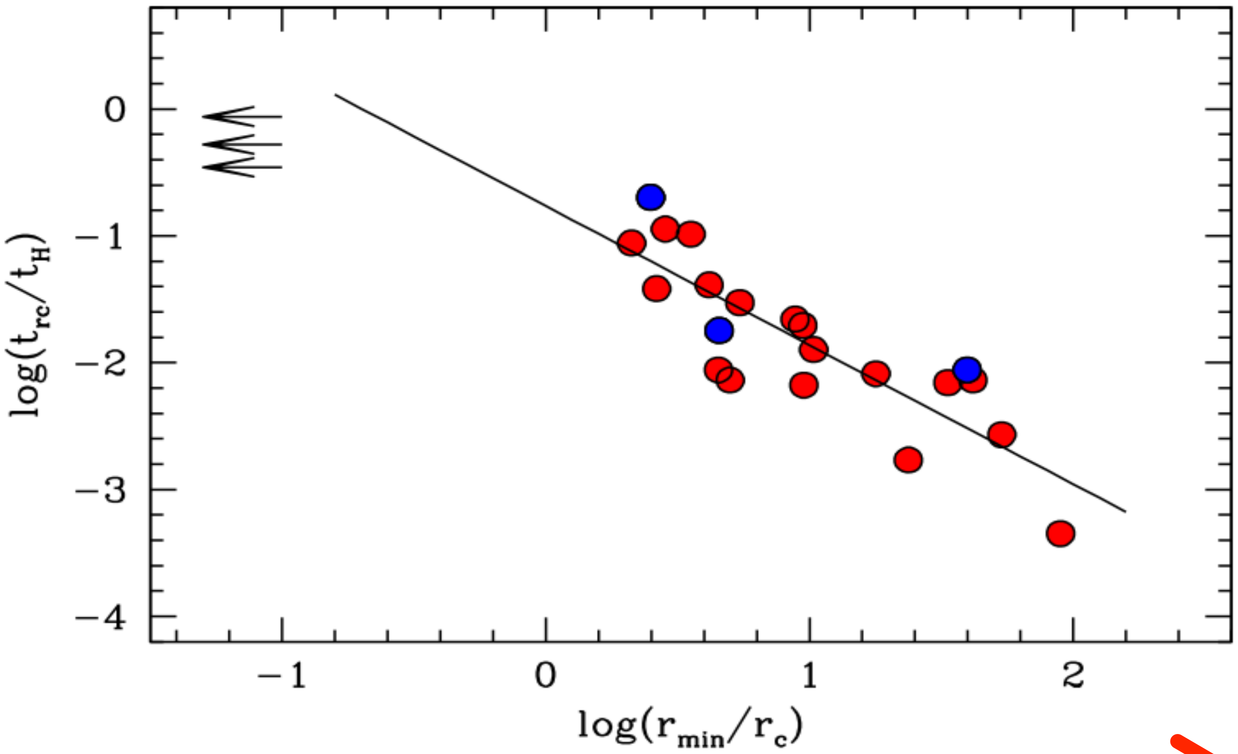
Cosmic-Lab

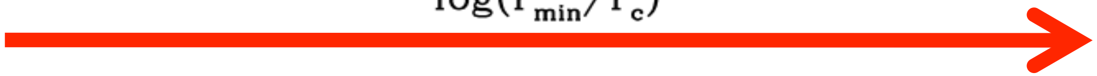
Ferraro et al 2012, Nature,492,393

The dynamical clock

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

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



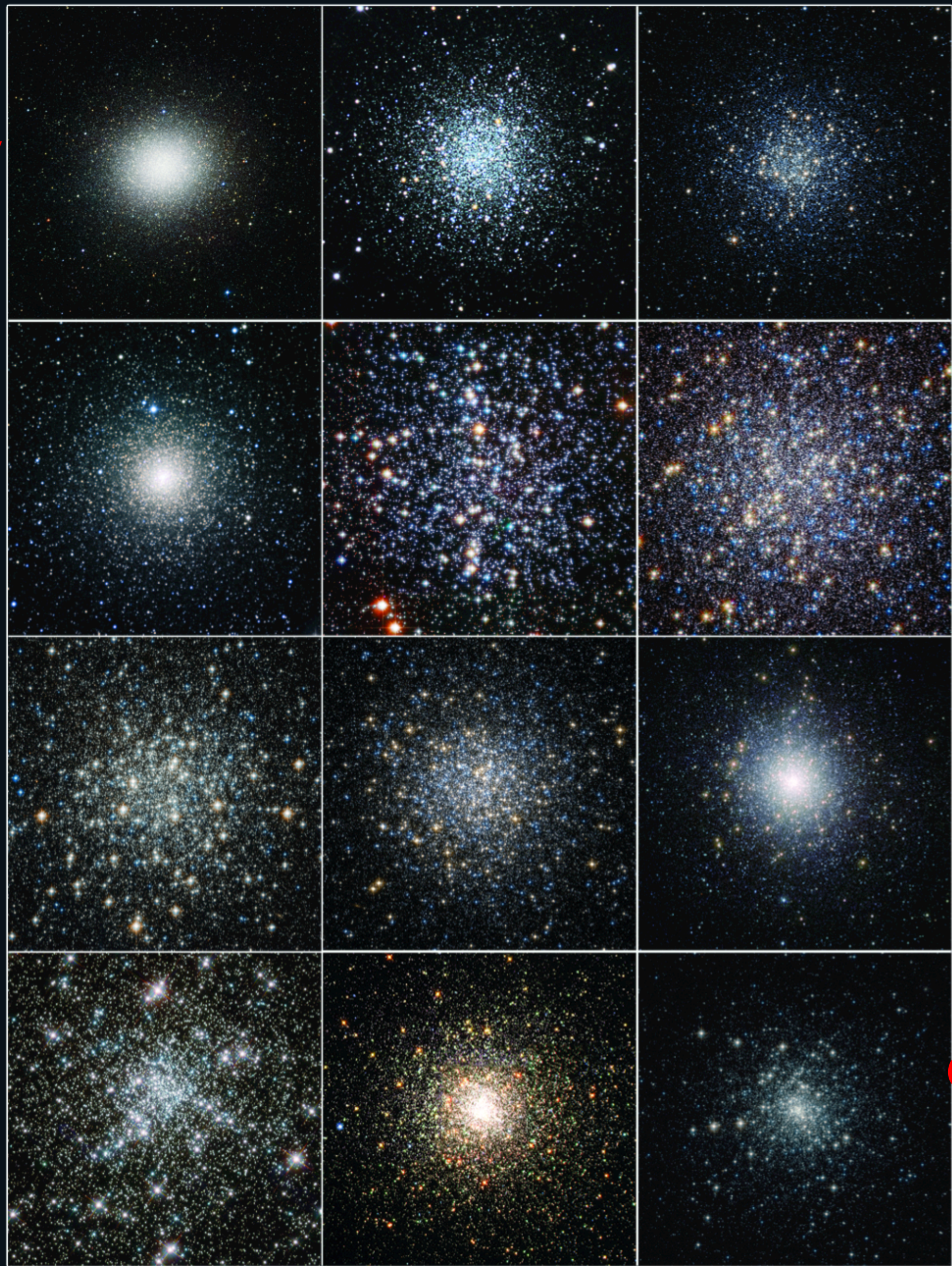


Increasing dynamical age

Cosmic-Lab

THE DYNAMICAL CLOCK

dynamically young

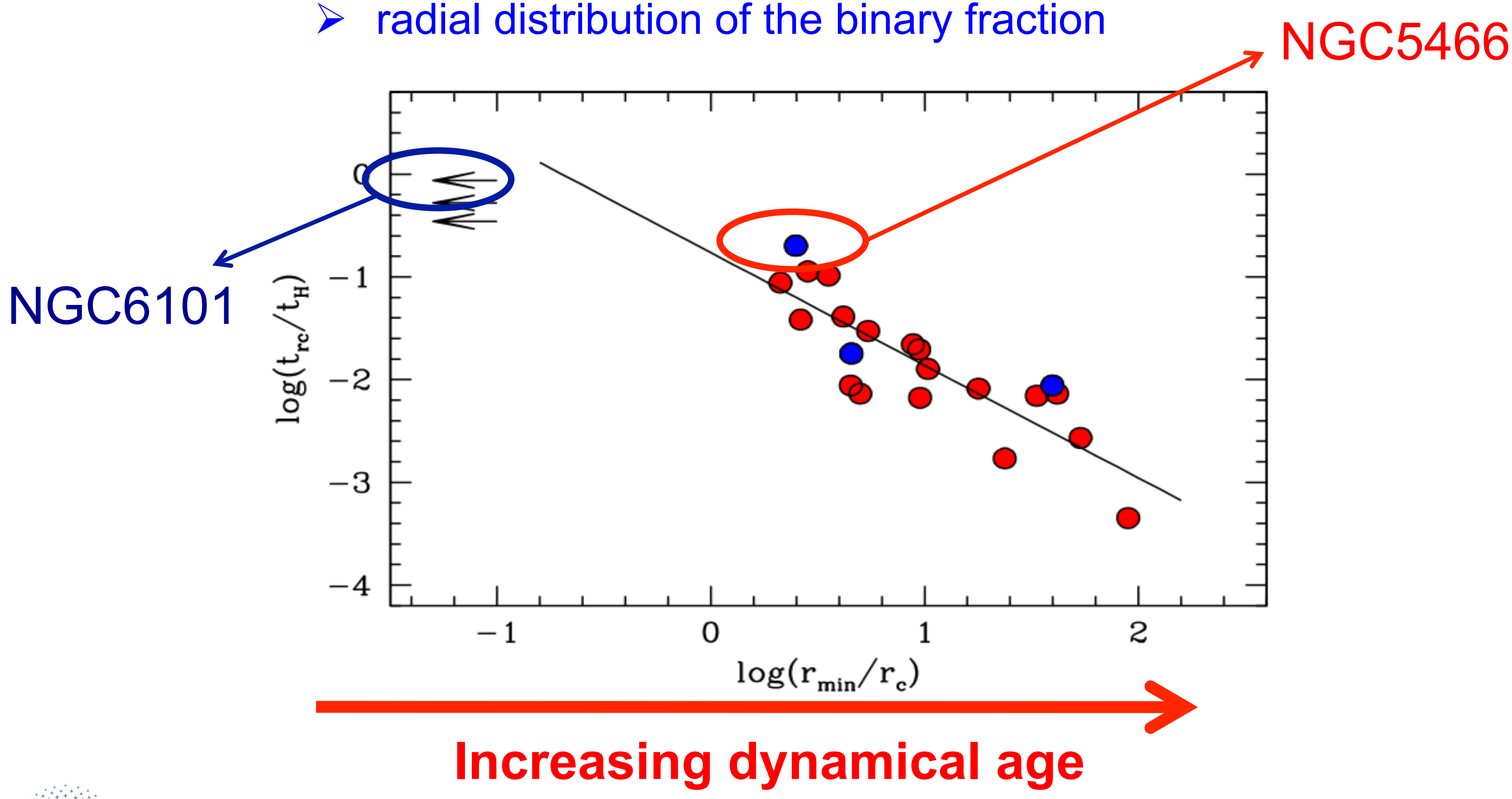


dynamically old

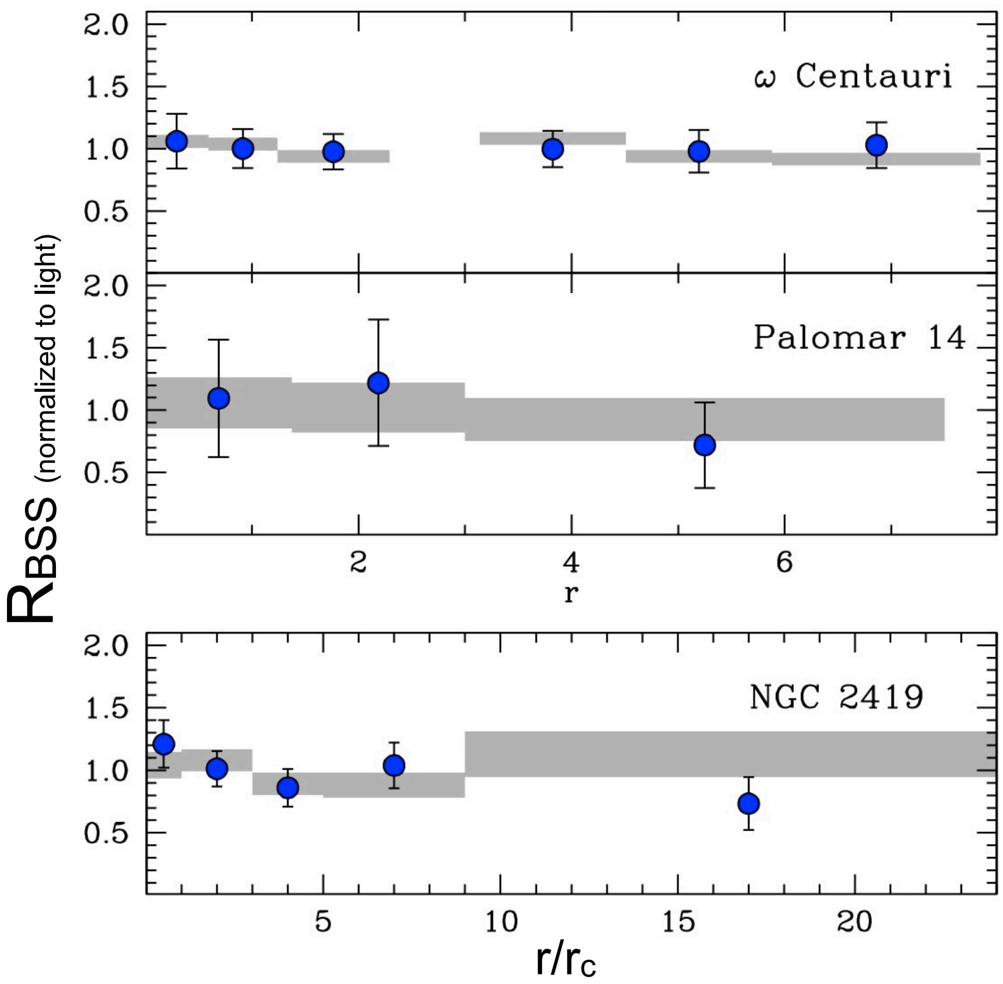
How good the dynamical clock is?

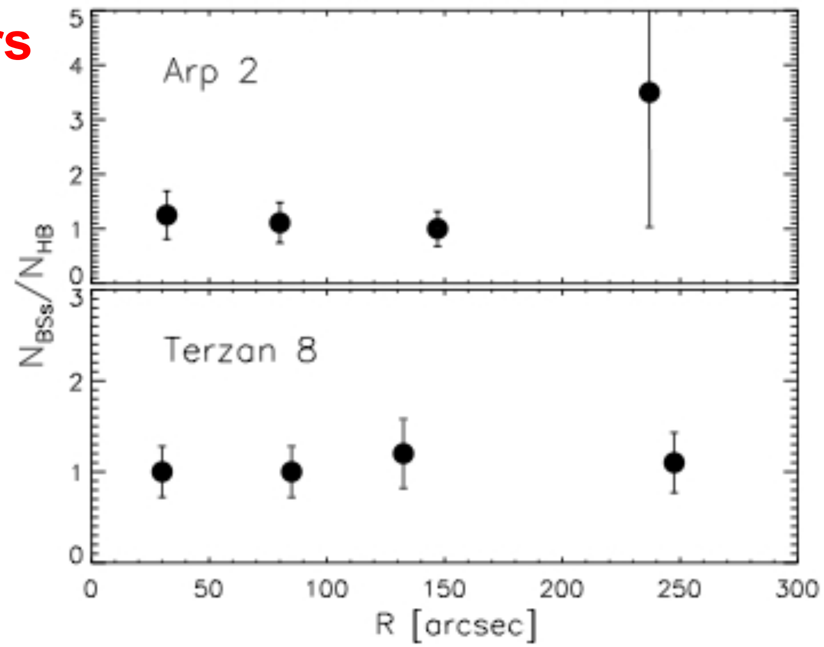
Comparison with other diagnostics of mass segregation:

- radial behaviour of the mass function
- radial distribution of the binary fraction

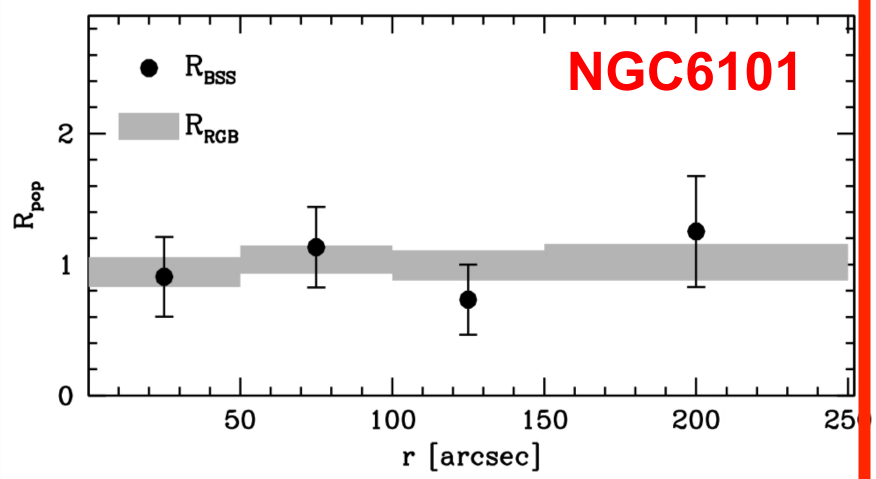


Family I: the dynamically YOUNG clusters



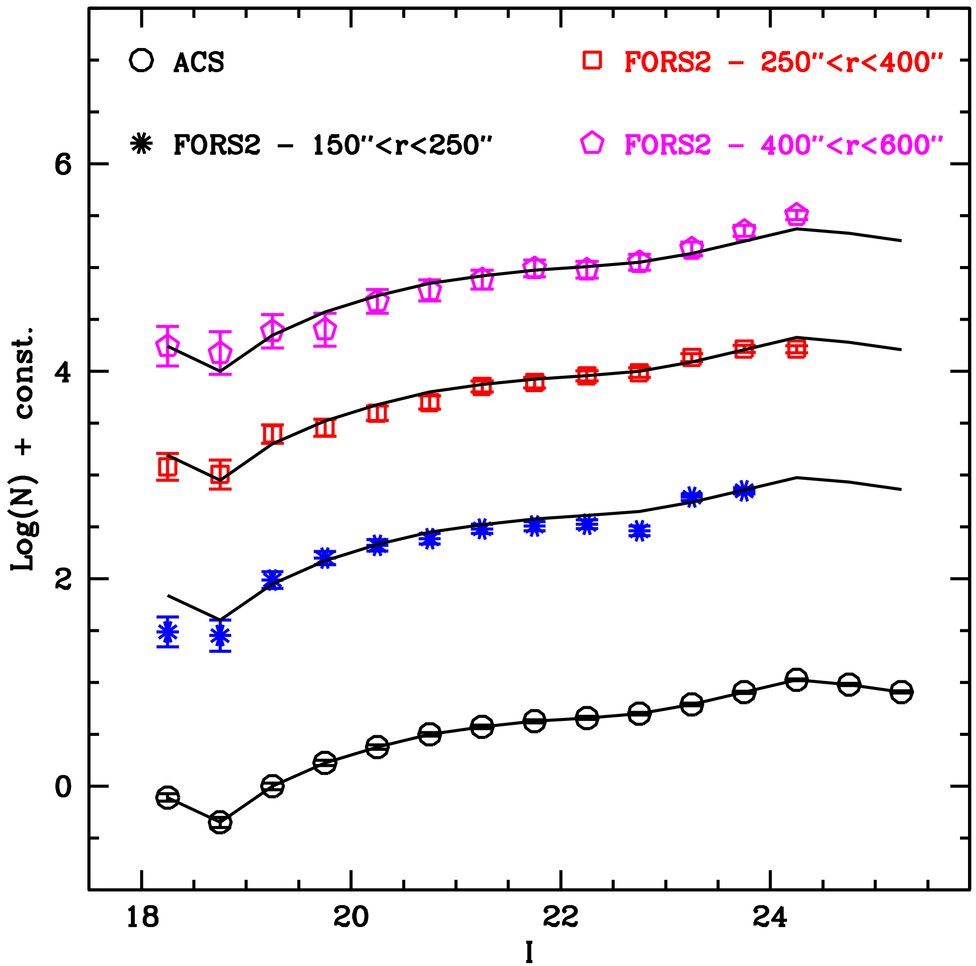


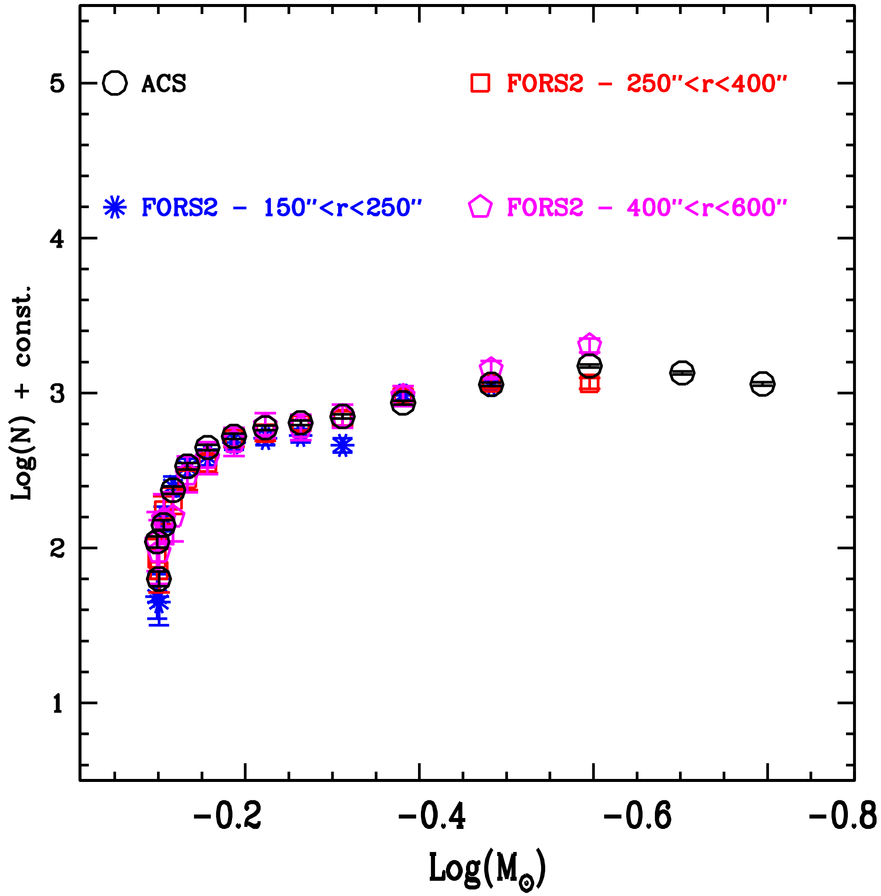
Salinas et al (2012,MNRAS,421,960)



Dalessandro et al (2015, ApJ, 810,40)

The case of NGC6101: the mass function

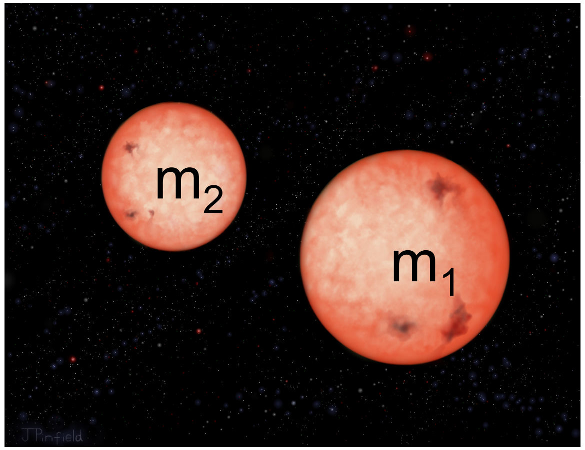


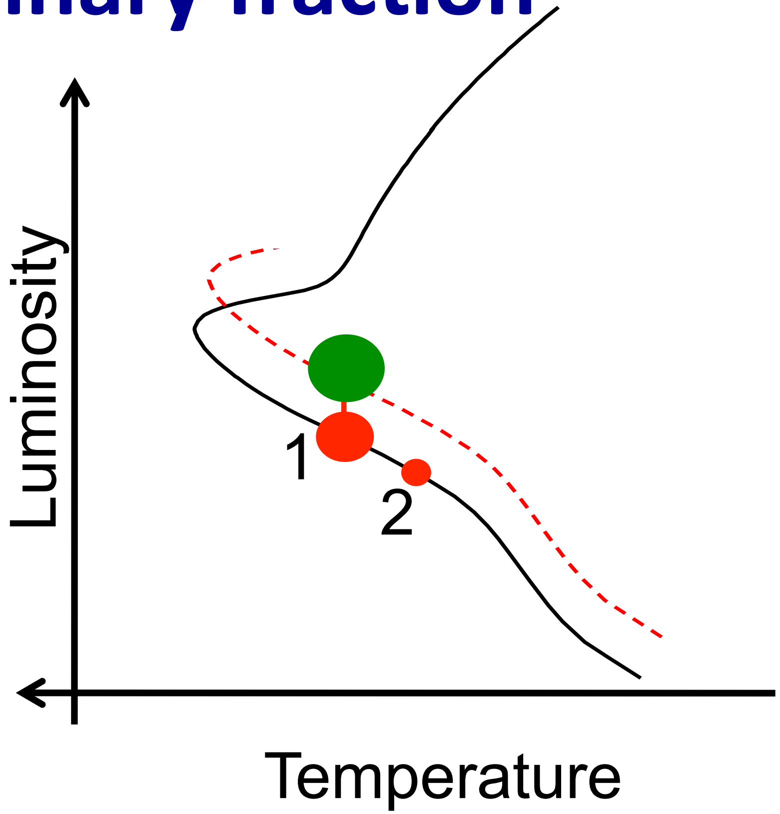


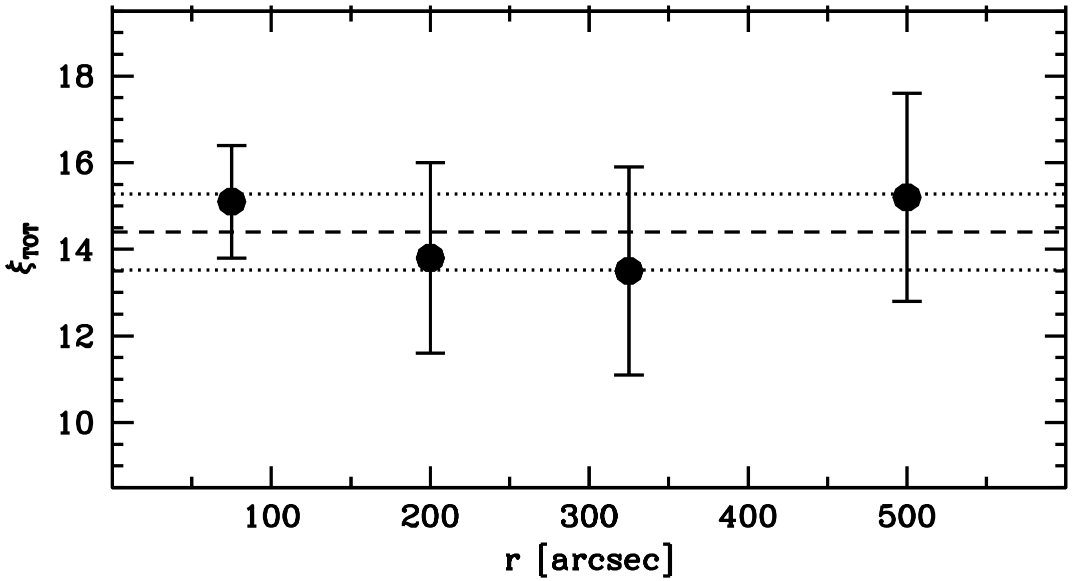
Dalessandro et al (2015, ApJ, 810,40)

NO EVIDENCE OF MASS SEGREGATION

The case of NGC6101: binary fraction







THE MEASURED BINARY FRACTION IS CONSTANT (~14%)

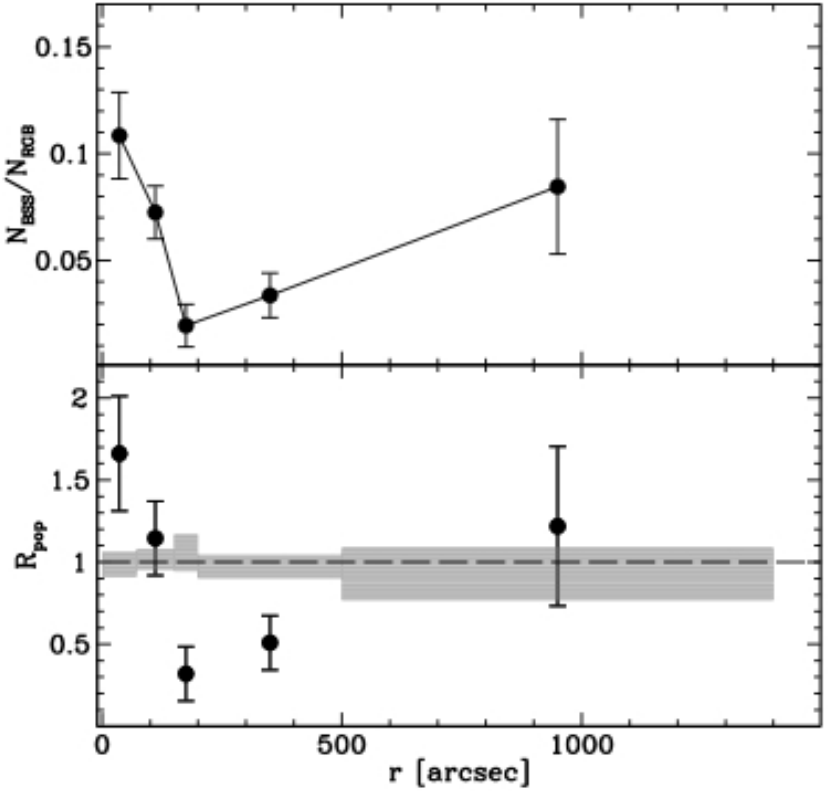
The case of NGC6101

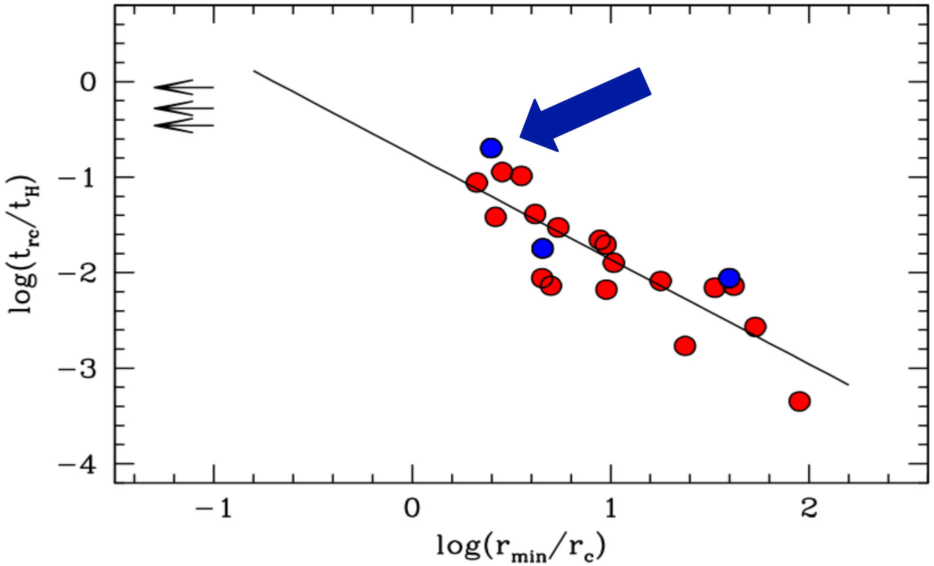
BSS radial distribution	NO Segregation
Mass function (from MS-LF)	NO Segregation
Binary system radial distribution	NO Segregation

Three different diagnostics of mass-segregation yield the same result.

With the clear advantage that BSS are **brighter** than MS stars and the BSS analysis is much **simpler** and **less prone to biases** than the computation of the binary fraction.

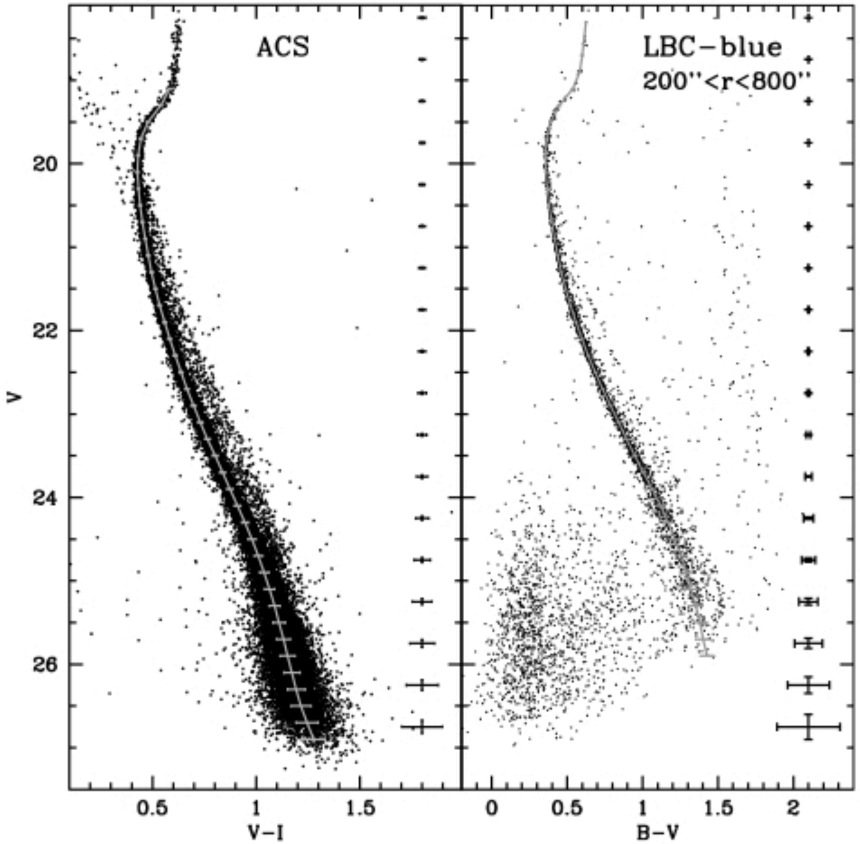
The case of NGC5466: BSS

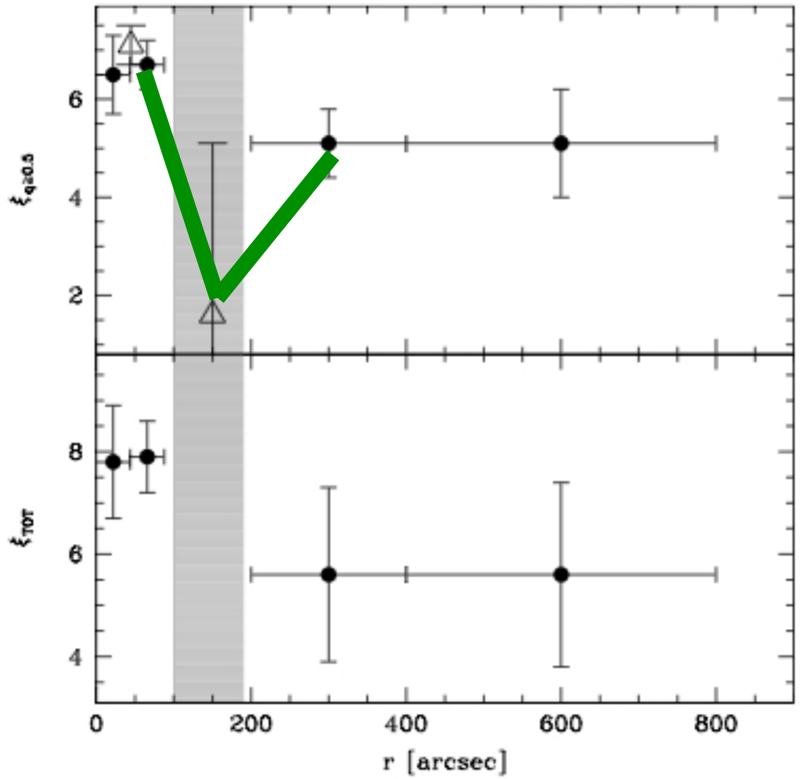




The "dynamical clock" suggested that NGC5466 is an "early Family II cluster" with an intermediate dynamical age

The case of NGC5466: binary fraction





Combining our estimates with the previous measures by Milone et al (2012) the radial distribution of the binary in NGC5466 appears BIMODAL and quite similar to that obtained from the BSS

How good the dynamical clock is?

Different diagnostics of mass-segregation have been found to fully confirm the “dynamical clock” measures.

BSS are brighter than MS/binary stars and the BSS analysis is much simpler and less prone to biases.

The proposed clock appears to be a powerful indicator of the cluster dynamical evolution

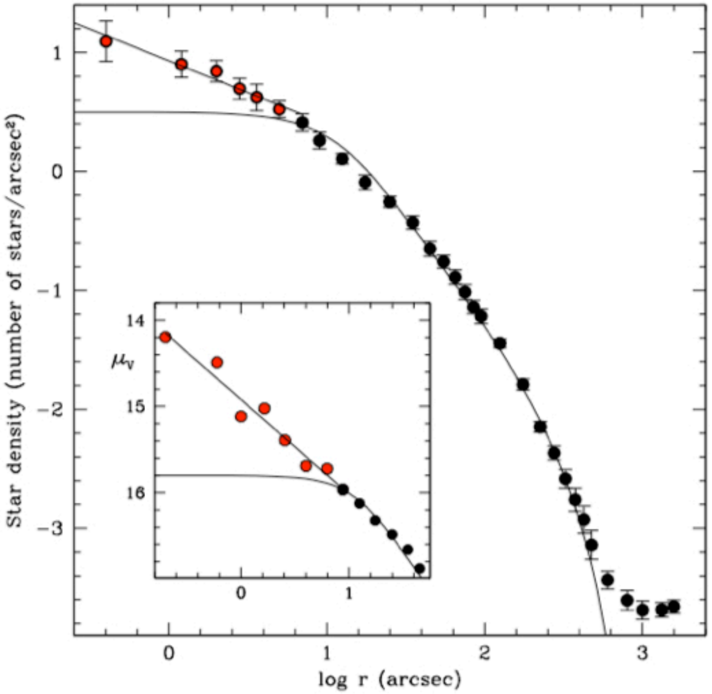
We are now using appropriate N-body simulations to:
(1) explore alternative way to quantify the level of segregation of BSS and
(2) study the impact of different ingredients (dark remnant, binaries, etc) in the segregation process

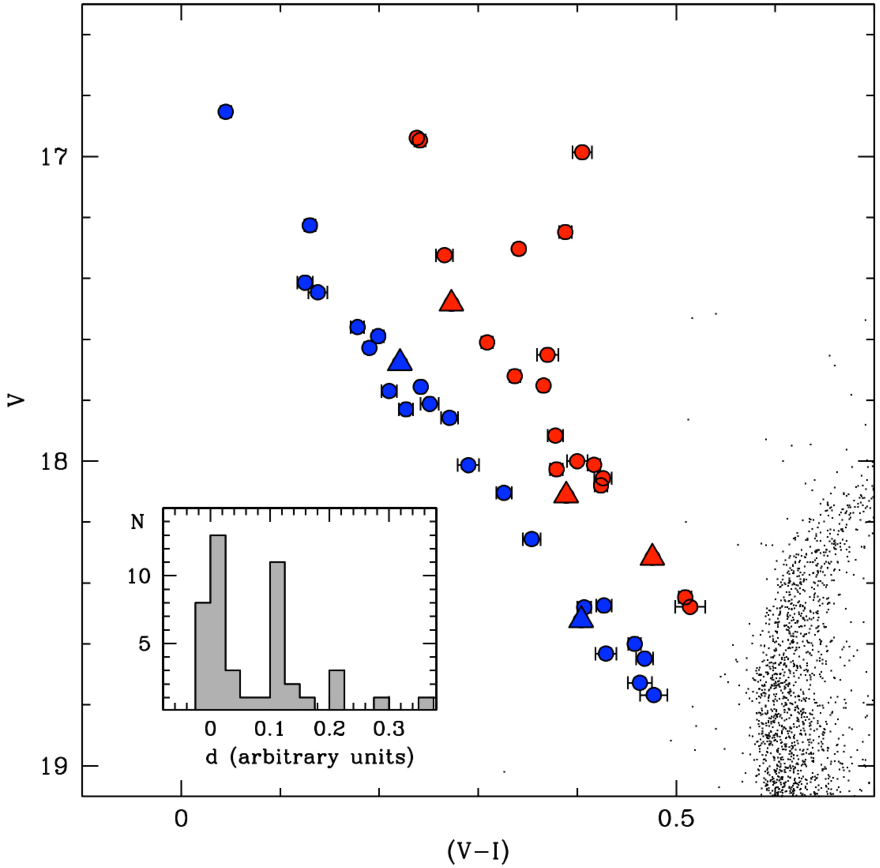
E. Alessandrini PhD Thesis

Indeed we can do even more…..

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

M30 (NGC 7099)





2 distinct sequences of BSS !!

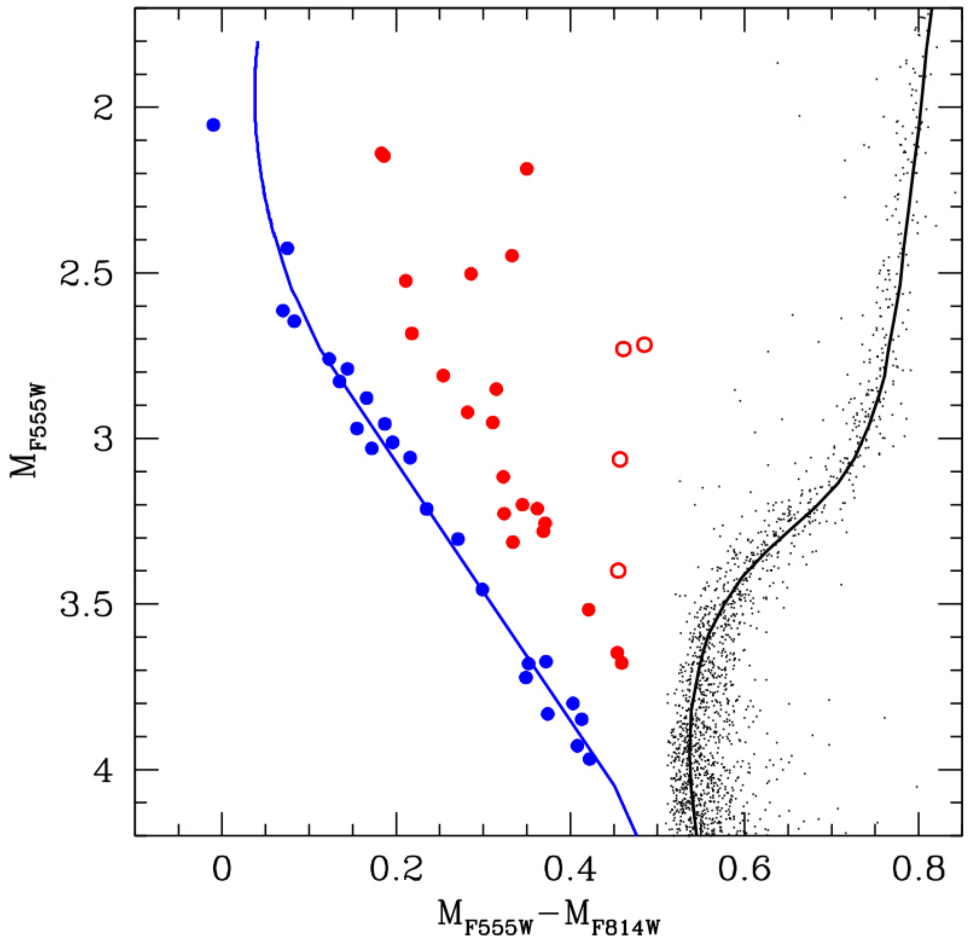
Ferraro et al. (2009, Nature 462, 1028)

Evolutionary models of COLLISSIONAL-BSS (Sills et al. 2009):

- collisions between two MS stars (0.4 - 0.8 $M_{\odot}$)
- $Z = 10^{-4}$ ($Z_{M30} = 2.5\ 10^{-4}$)

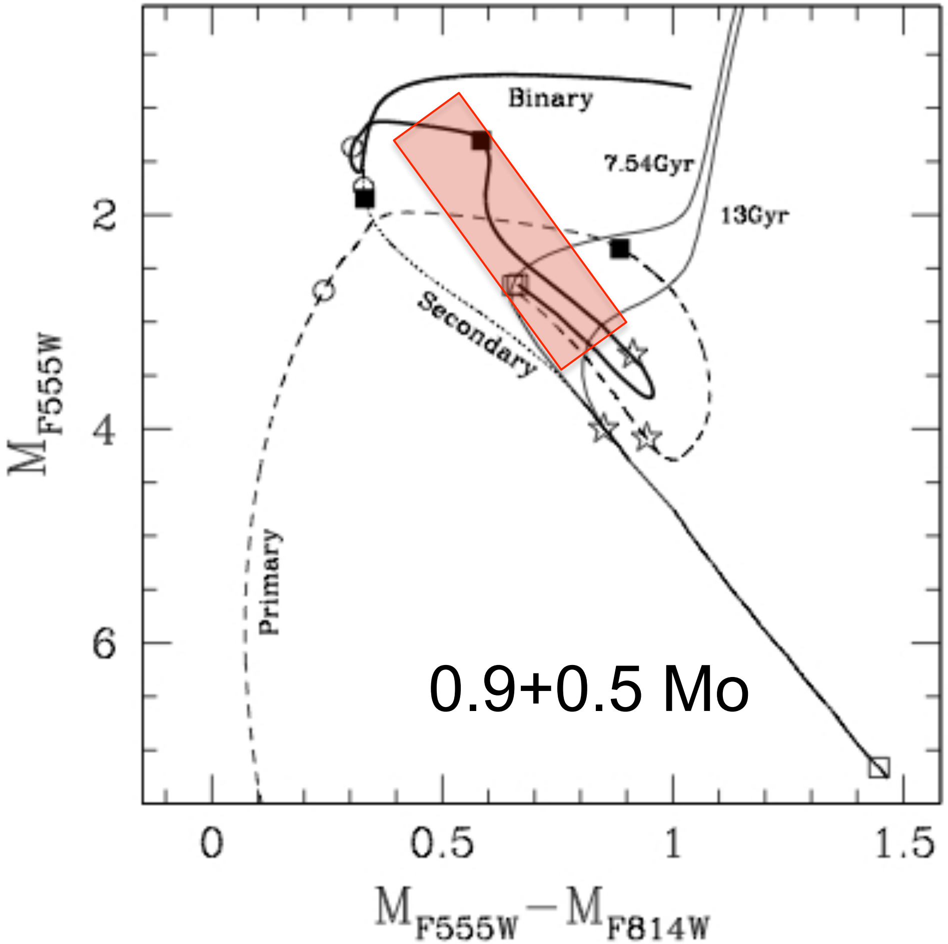
- **blue-BSS sequence well reproduced by collisional isochrones of 1-2 Gyr**

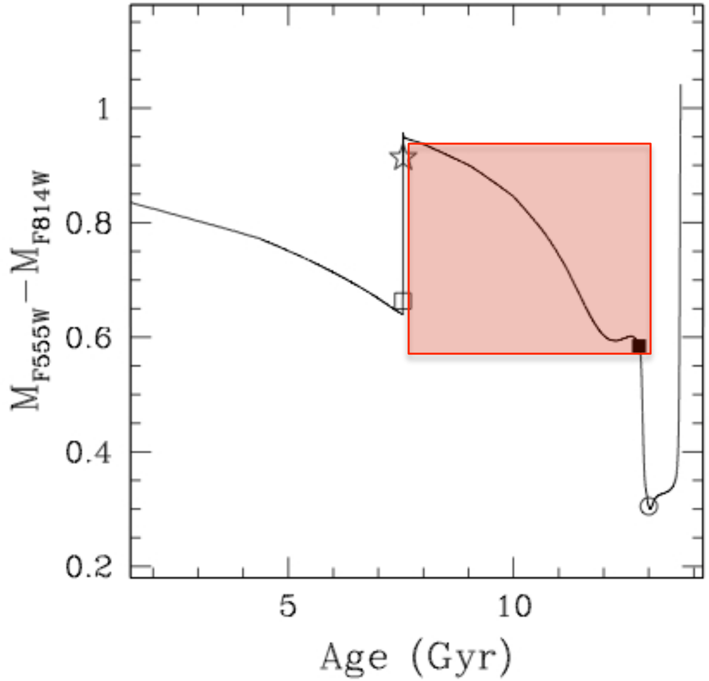
- **red-BSS** sequence **too red** to be reproduced by collisional isochrones of **any** age



In **Xin et al 2015** we followed the evolution of **MT binaries** generated under a variety of initial conditions in terms of mass, mass ratio and orbital separation

..thus, identifying the region in the CMD where each system spends most of the time after the beginning of the MT

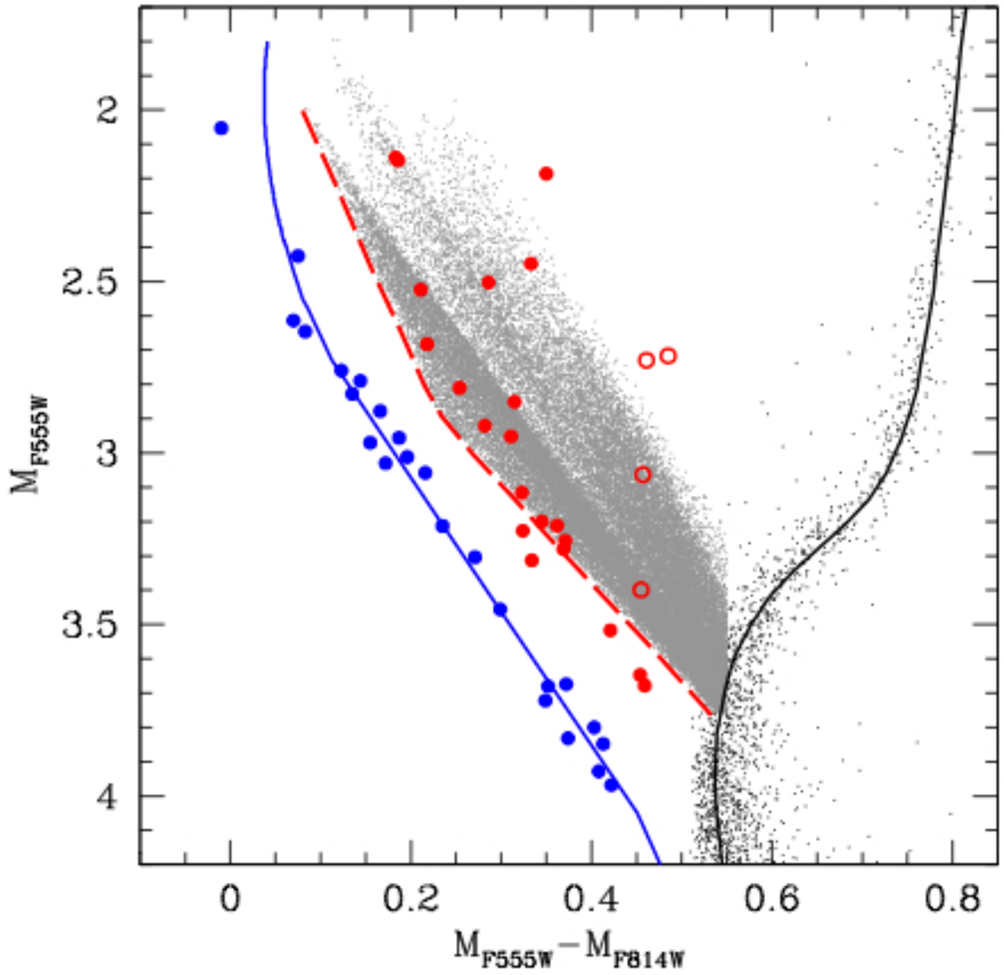




BSS double sequences

- blue-BSS sequence well reproduced by collisional isochrones of 1-2 Gyr

Red-BSS sequence is located in the region where MT binaries are expected (Xin et al 2015)



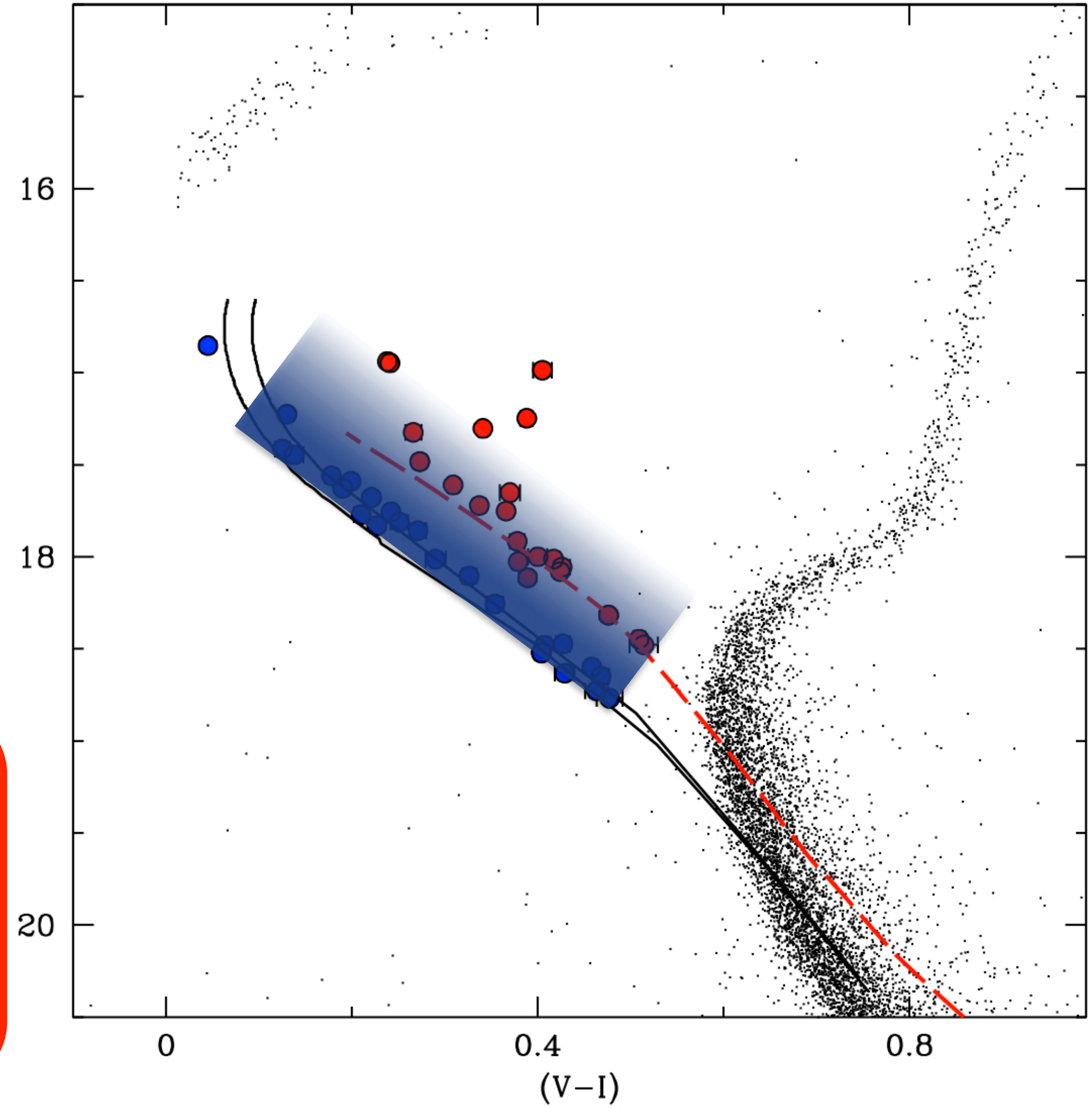
Why the detection of the double-BSS sequence is so RARE ???

• **blue-BSS → collisional** **red-BSS → MT 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 recently 1-2 Gyr ago



This feature can be generated by an event which increases the core collisional activity (the core collapse?)

IS THE DOUBLE BSS SEQUENCE PHENOMENON CONNECTED WITH THE PCC STATUS ?

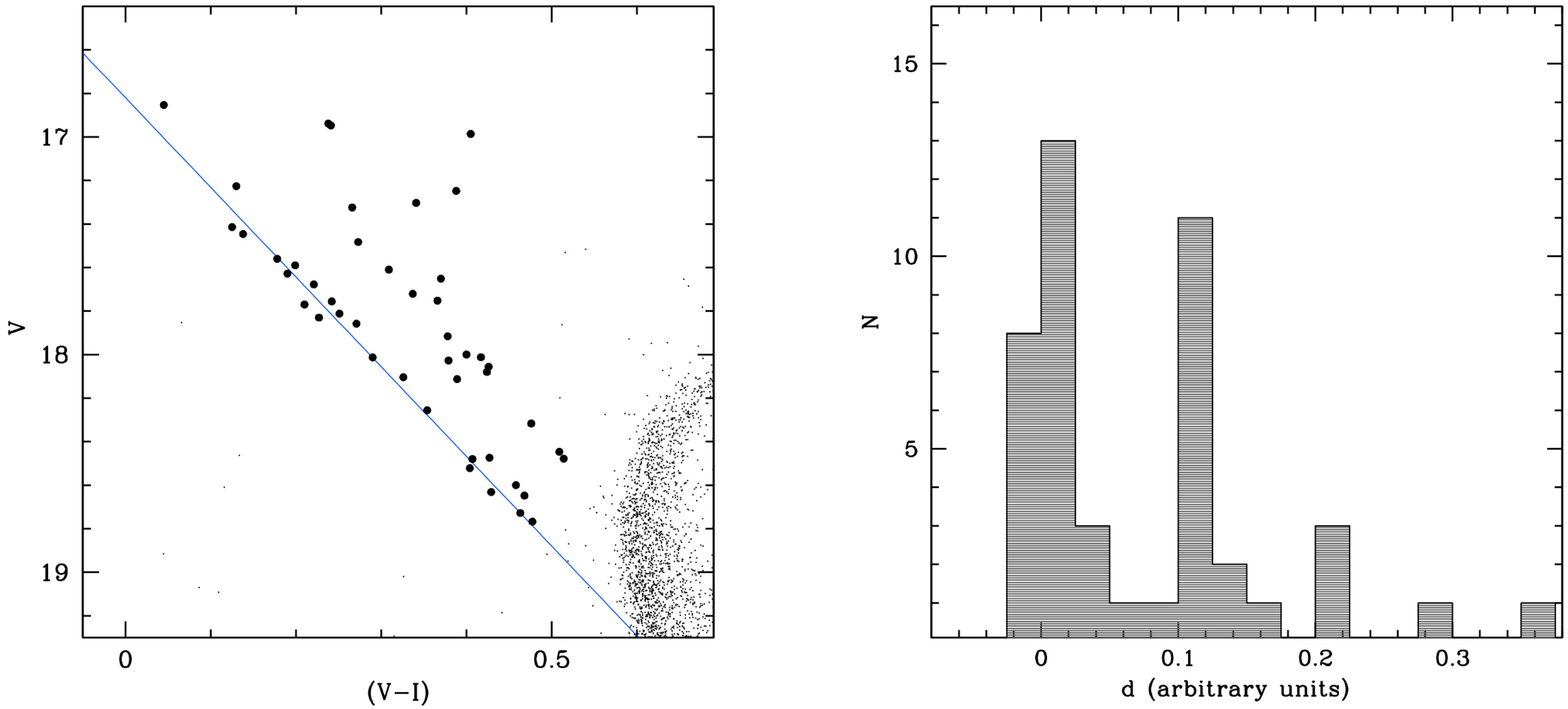
Is there any other PCC with a double BSS sequence?

Classical PCC:
M15
NGC6397

Suspected PCC:
NGC362

BSS double sequence: The case of NGC6397

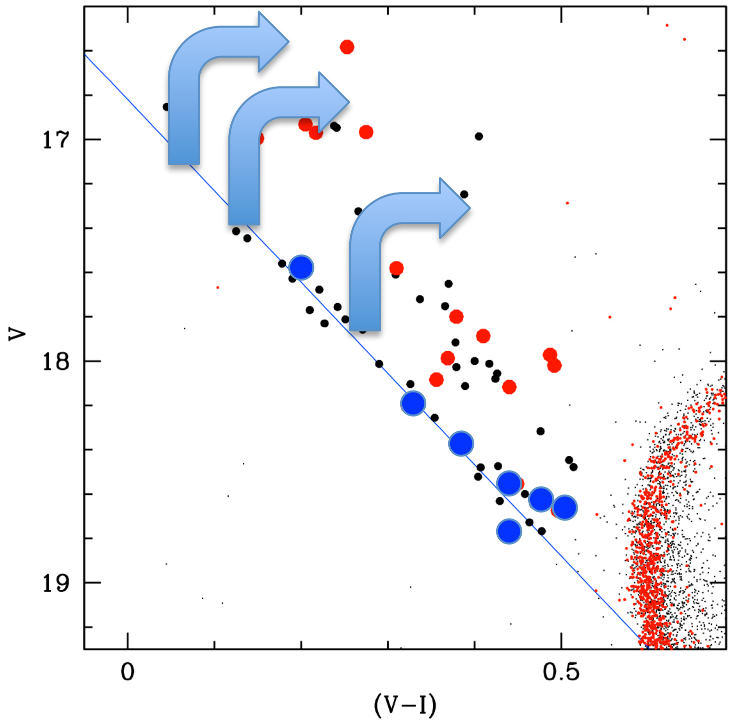
M30 (Ferraro et al. 2009)

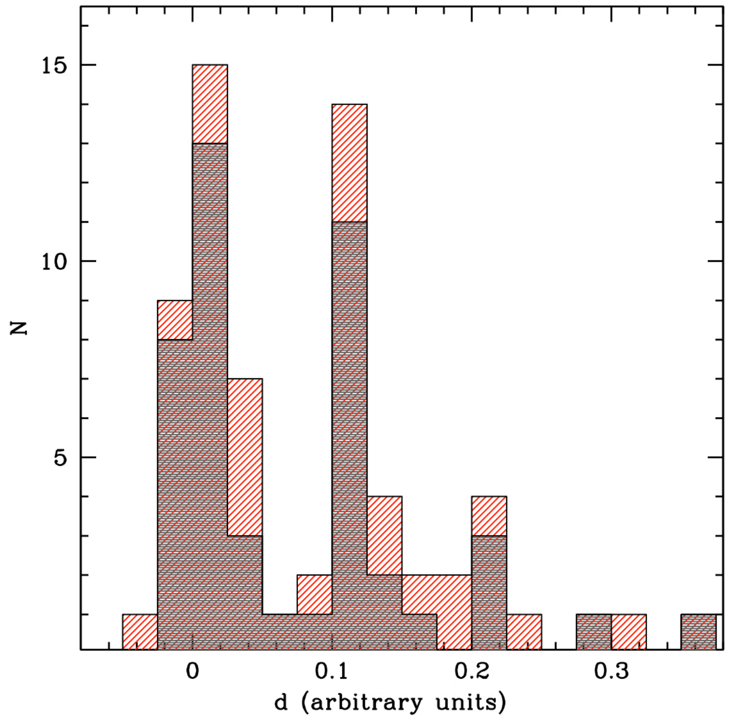


BSS double sequence: The case of NGC6397

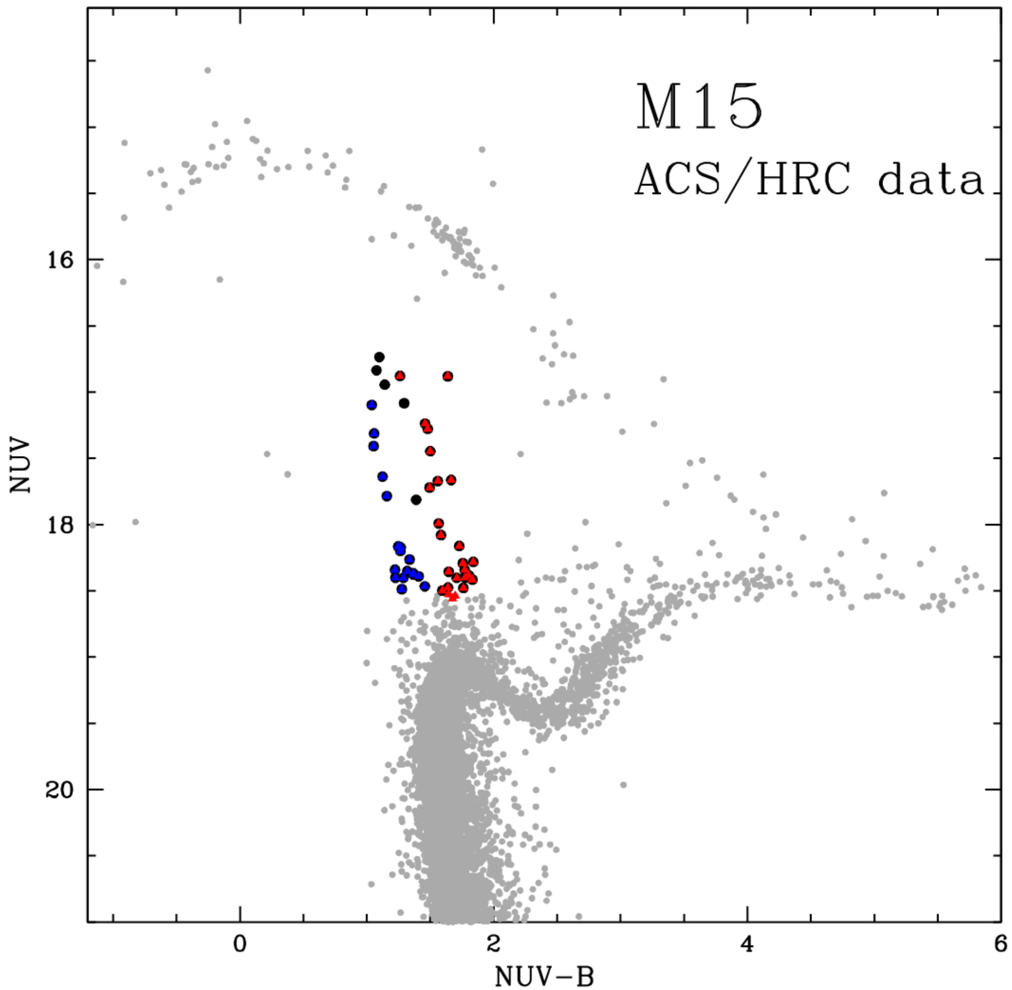
In the case of NGC6397 the **blue-BSS** sequence appears much less populated; thus suggesting that the core collapse in this cluster occurred much **earlier** than M30

NGC 6397 (Contreras et al. 2016, in preparation)





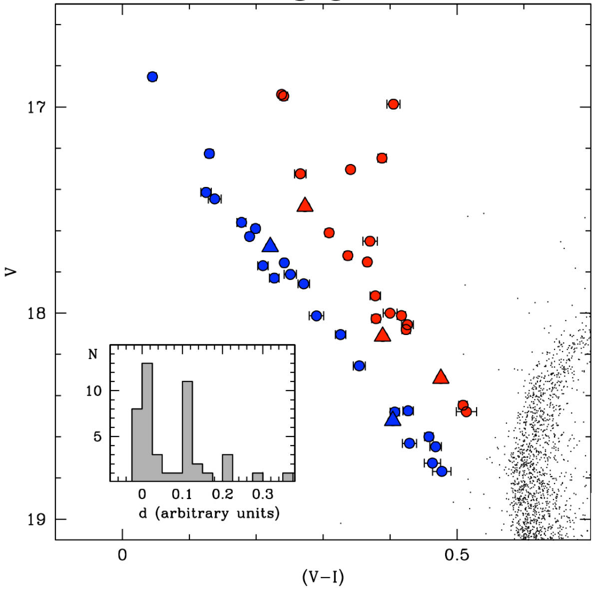
BSS double sequence: The case of M15

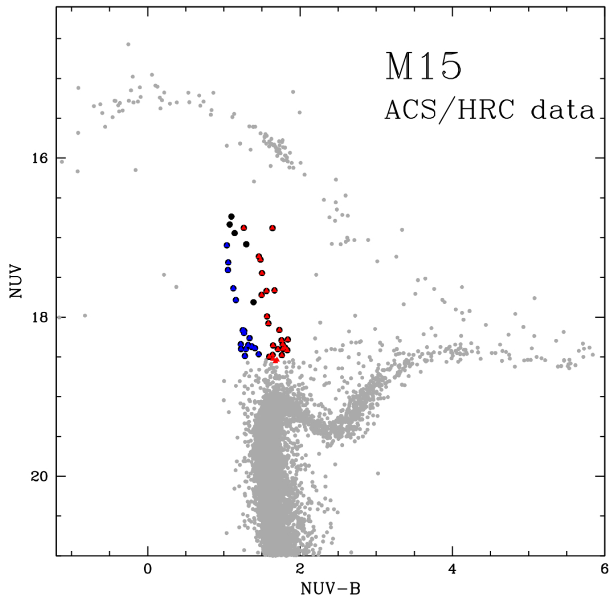


M15

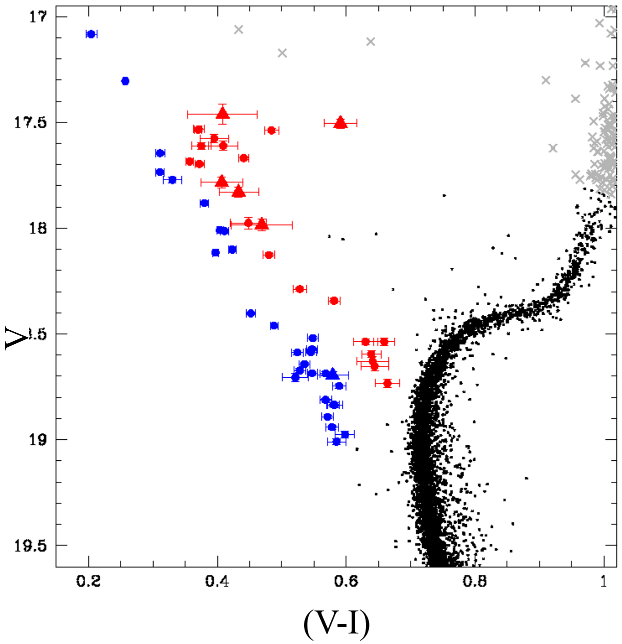
BSS double sequences

M30





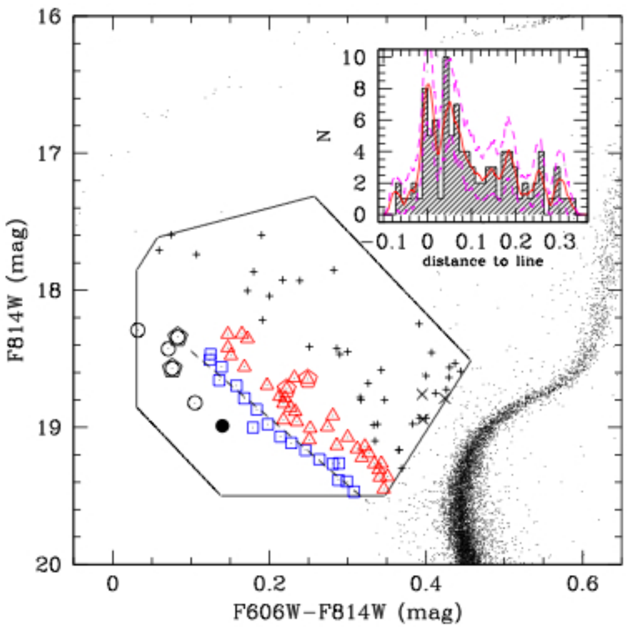
NGC 362



Dalessandro et al. 2013

Collapsing

NGC1261



Simunovic et al. 2014, ApJ, 795, L10

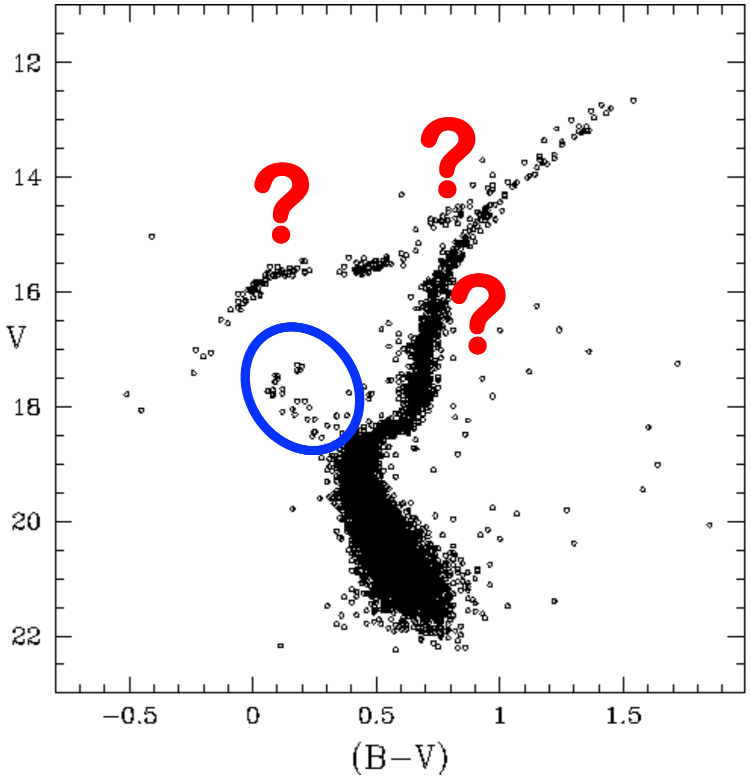
Post PCC Bounce state

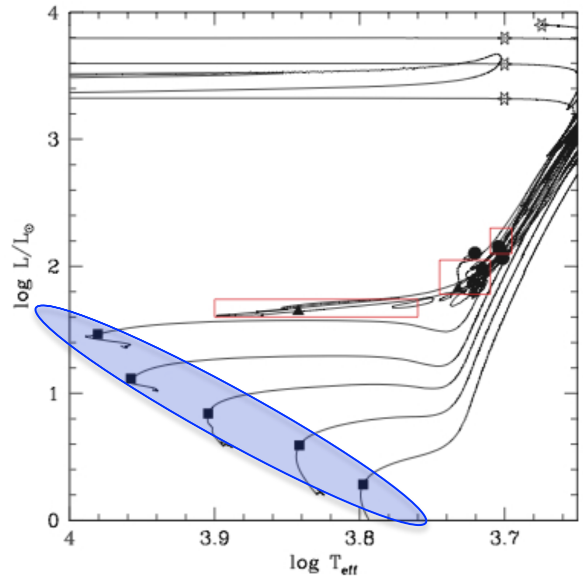
SCALES

to search for Evolved-BSS in GCs

The E-BSS search in GCs

As normal stars, BSS are expected
to evolve outside the MS and to experience
all the post-MS evolutionary phases.

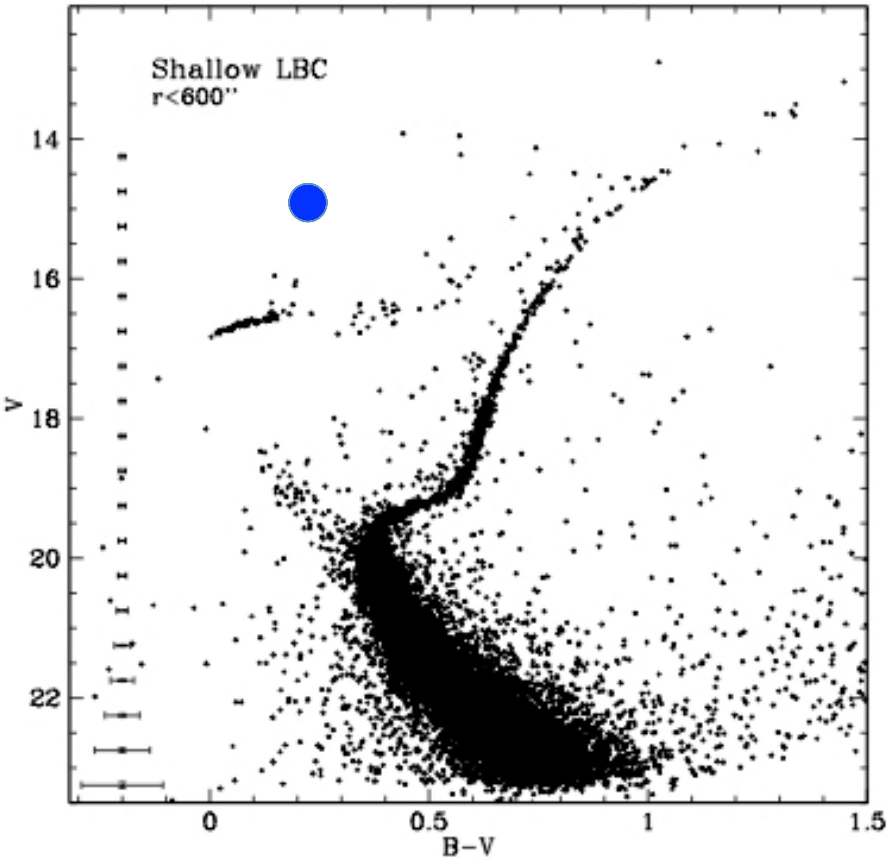




However, while BSS are easily identifiable during the MS stage, E-BSS turns out to be photometrically indistinguishable from the other genuine low-mass stars in the post-MS phases. **This is the reason why, in spite of the long search, clear-cut identifications of E-BSS are still lacking in GCs.**

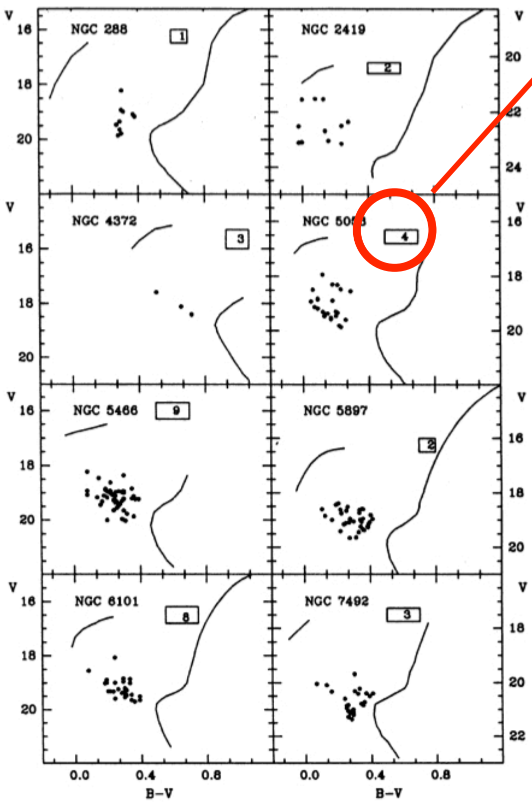
The E-BSS search in GCs

The only EBSS candidate in GCs with an estimated mass is the anomalous Cepheid V19 in NGC5466 (Zinn & Dahn, 1976)
 with an estimated mass of 1.6 $M_{\odot}$ (Zinn & King 1982)

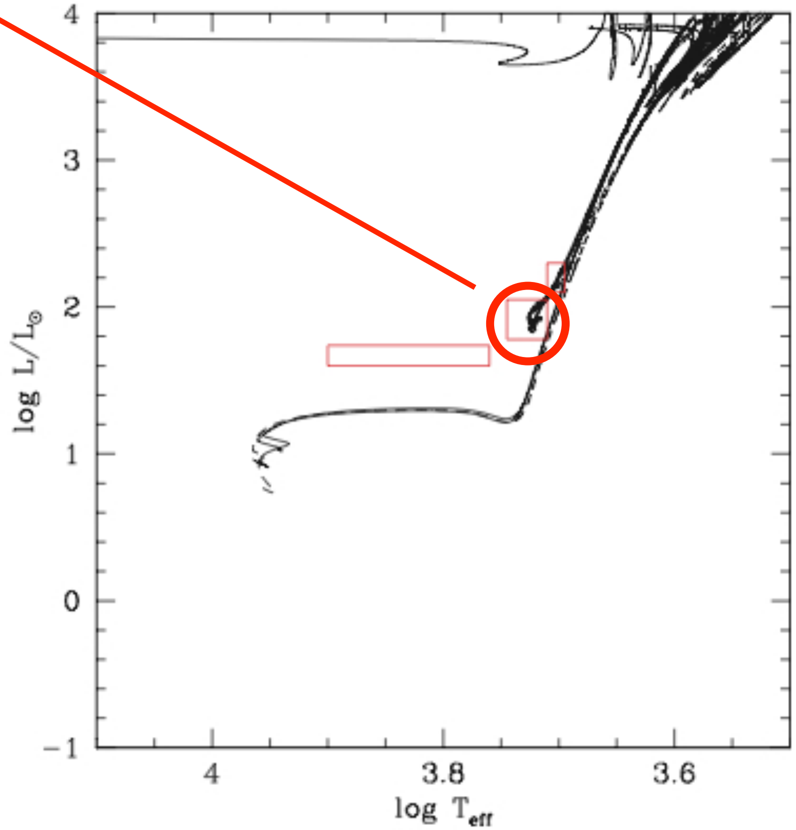


The E-BSS search in GCs

Both observational and theoretical arguments suggest that a **region** located in the CMD between the HB level and the AGB clump is the best place where E-BSS can be identified

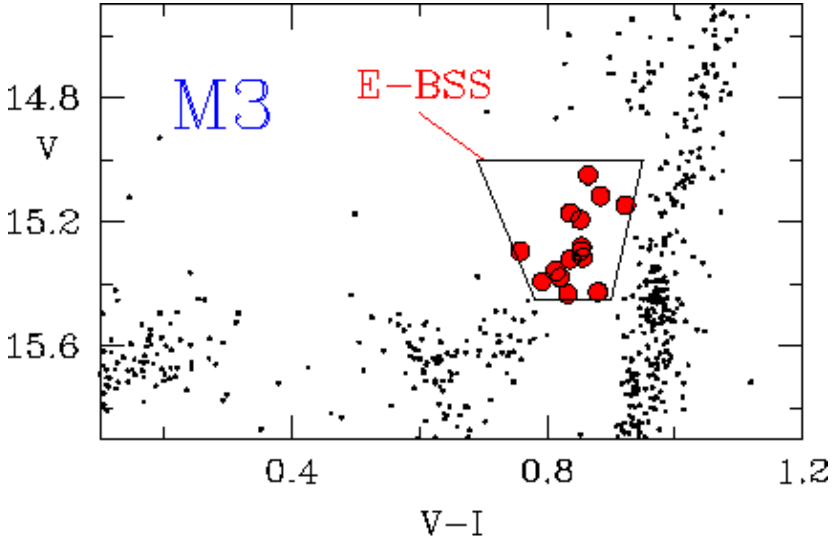


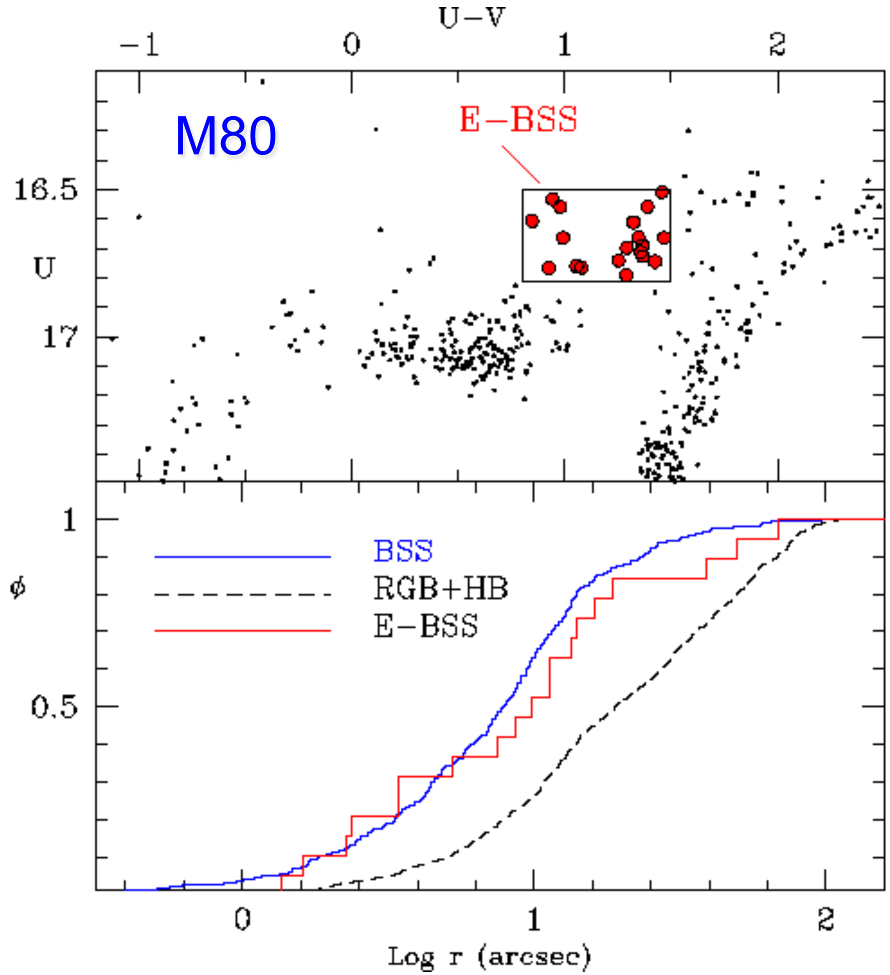
Fusi Pecci et al 1992, AJ,104, 1831



Sills et al 2009, ApJ,692, 1411

The E-BSS search in GCs





19 *E-BSS* candidates

Ferraro et al 1997, A&A, 324, 915
Ferraro et al. 1999, ApJ, 522, 983

A “stellar scale” to search for E-BSS

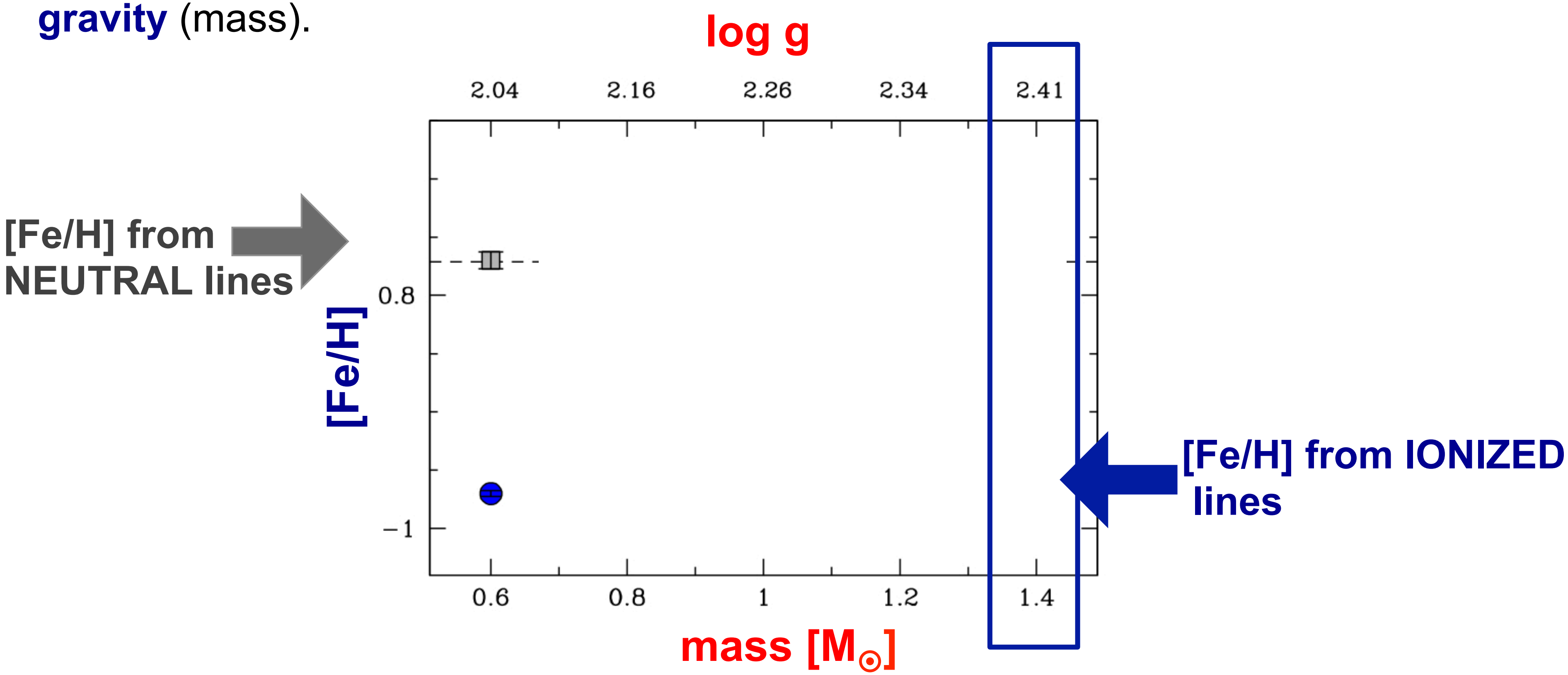
Ferraro et al (2016, ApJ,816,70)

Indeed E-BSS appear photometrically indistinguishable from genuine low-mass cluster stars. Hence a tool able to reveal their different mass is needed: a “stellar scale”.

A "stellar scale" to search for E-BSS

Ferraro et al (2016, ApJ, 816, 70)

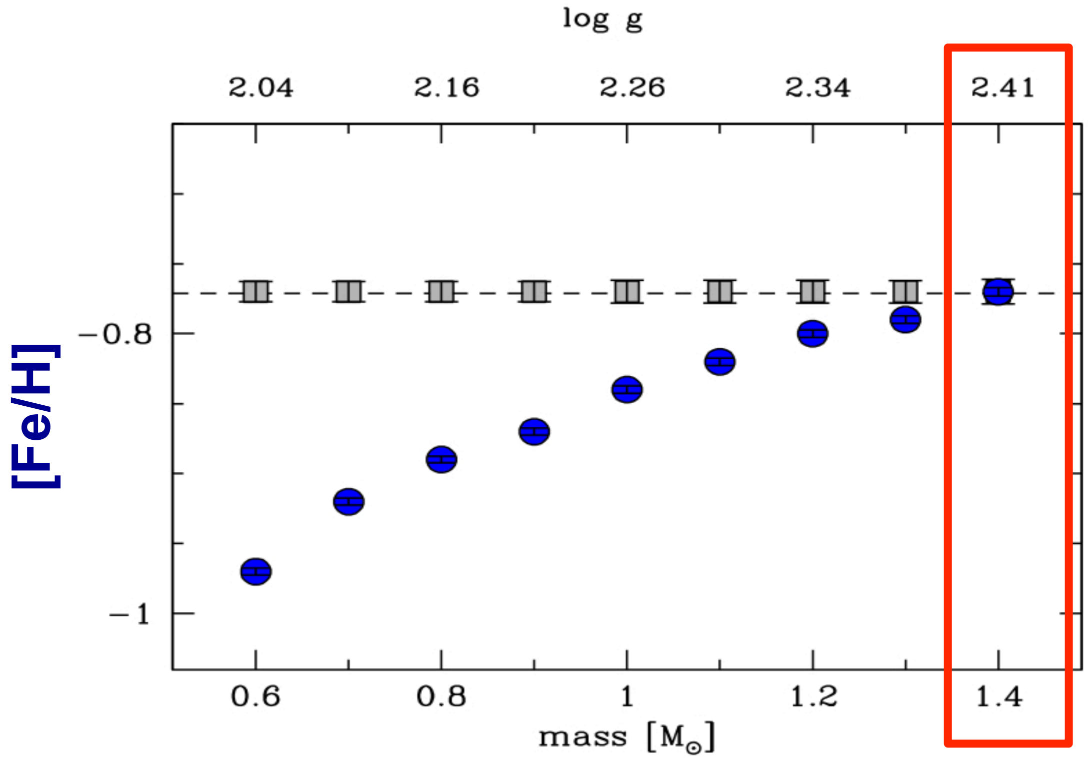
Generally chemical abundances are derived from a combination of neutral and single-ionized absorption lines.
The abundances obtained **from neutral lines are independent of the adopted gravity,** the **abundances from ionized absorption lines are quite sensitive to gravity** (mass).



A “stellar scale” to search for E-BSS

Ferraro et al (2016, ApJ, 816,70)

Hence the BALANCE between the chemical abundances derived from **neutral** and **ionized** absorption lines can be used to determine the correct gravity of the star (hence its MASS !!).

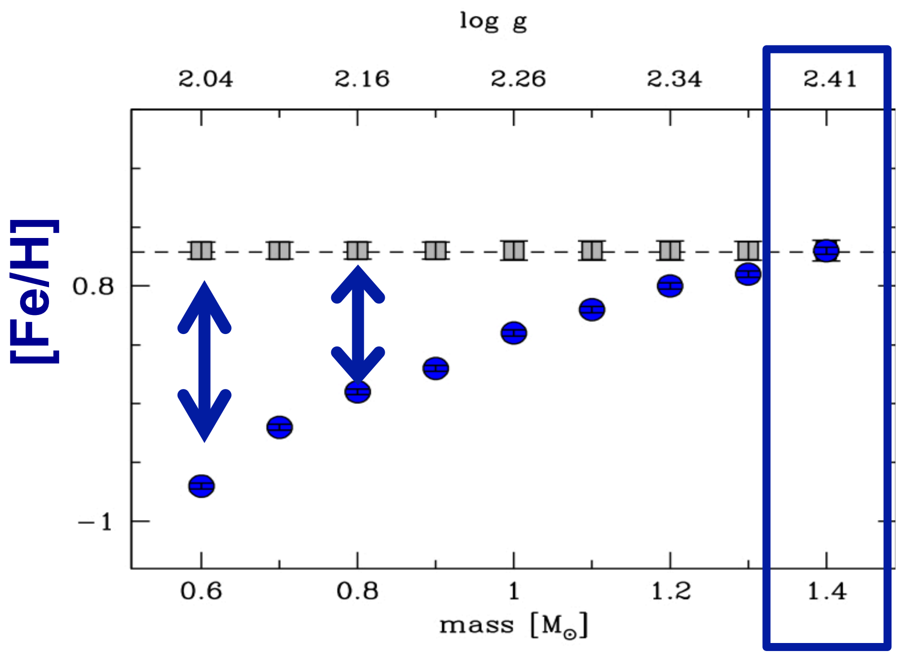


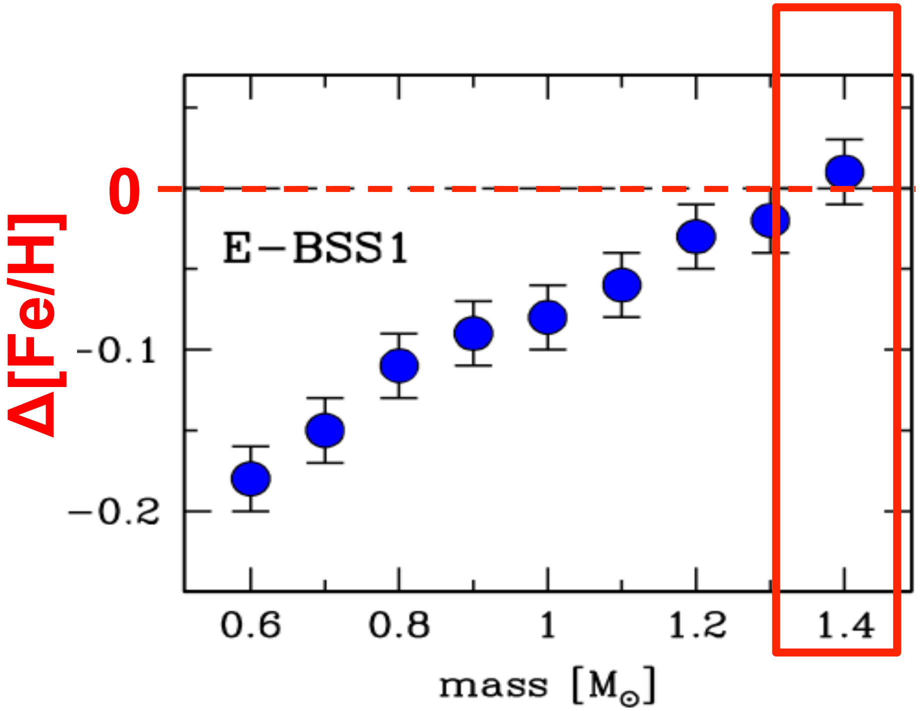
A "stellar scale" to search for E-BSS

Ferraro et al (2016, ApJ, 816,70)

The pointer of the SCALE is the quantity **Δ[Fe/H] = [FeII/H]-[FeI/H].**

When the pointer indicates **Δ[Fe/H] = 0**, then the assumed gravity (mass) is correct

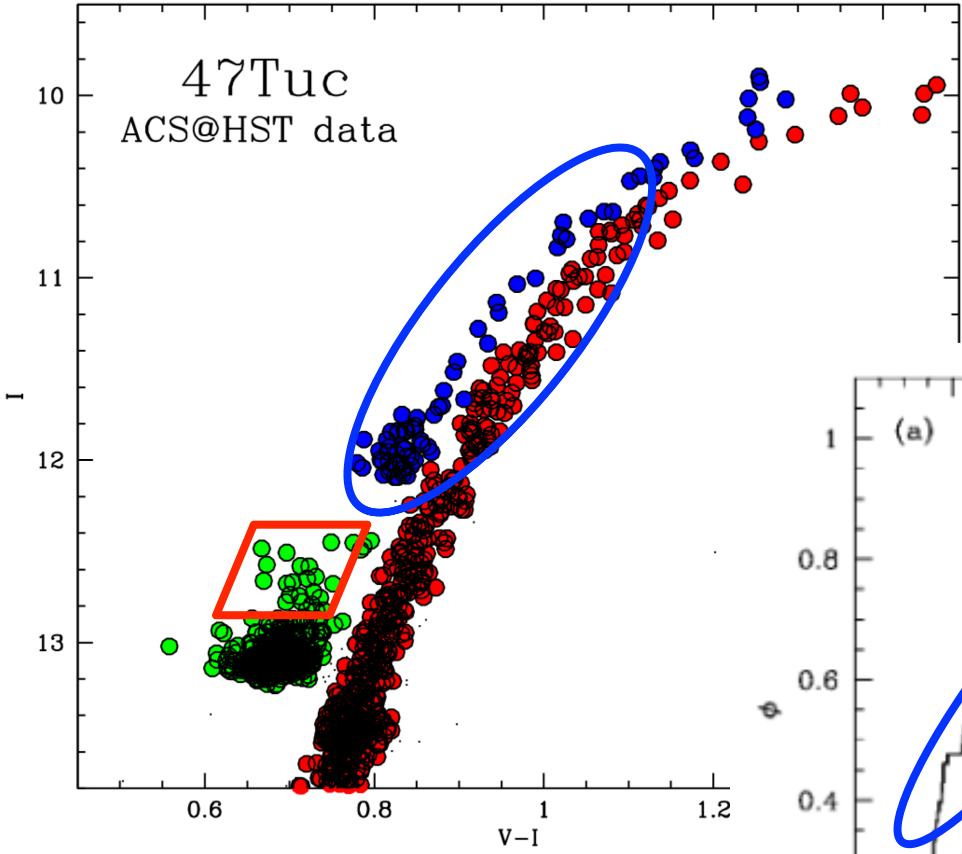




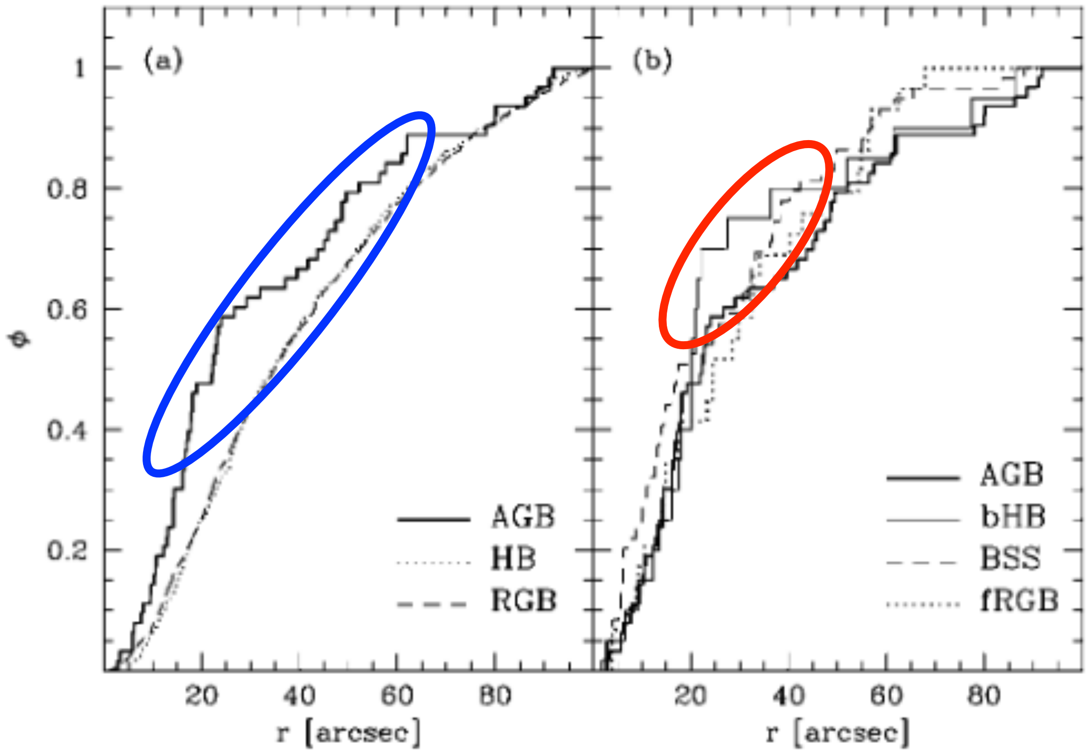
Cosmic-Lab

erc

A "stellar scale" to search for E-BSS

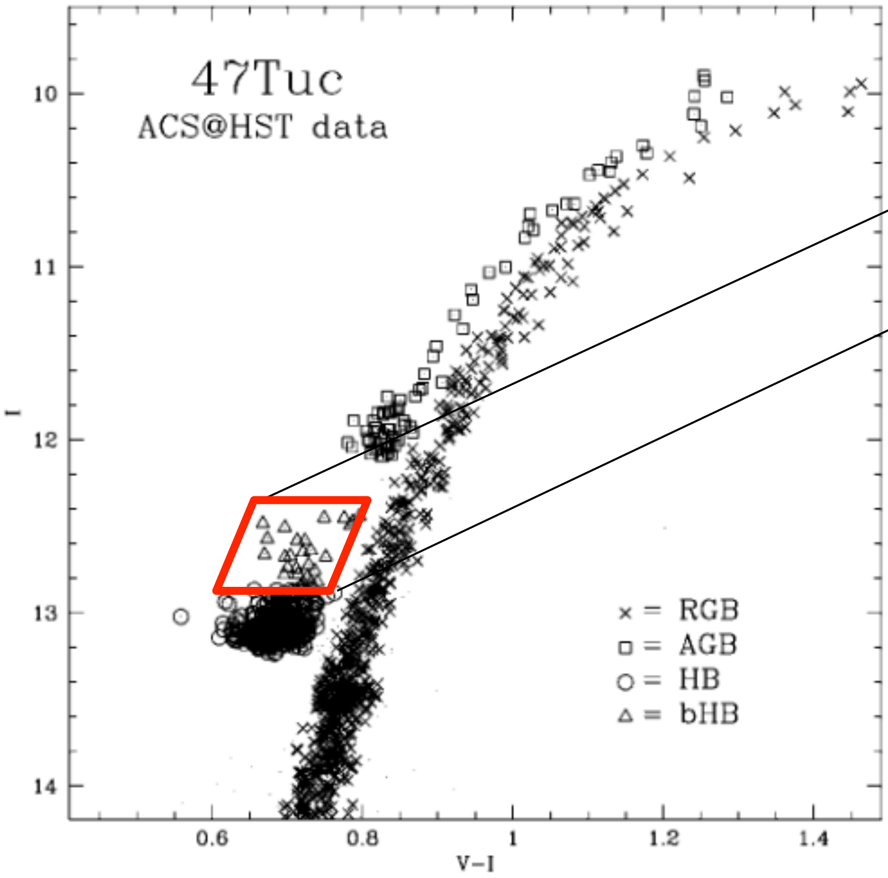


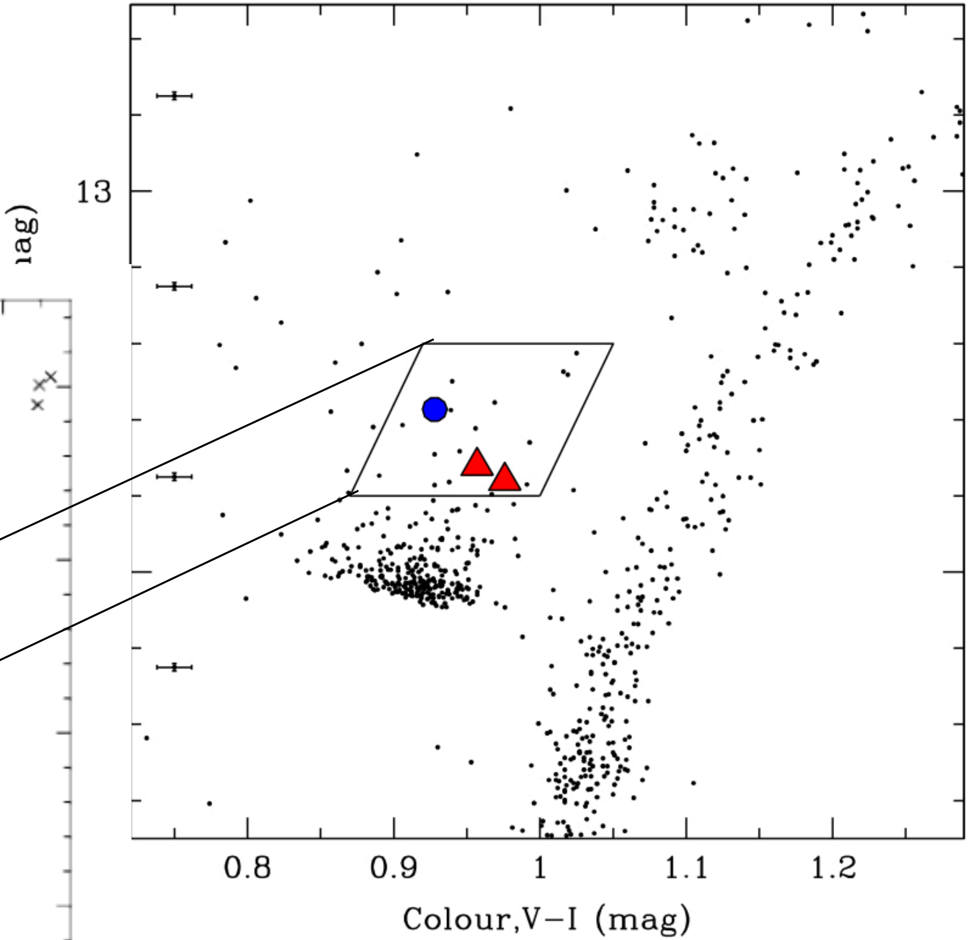
In 47 Tuc anomalous radial distributions of both AGB and bright-HB stars suggest a contamination from high-mass objects



Beccari et al (2006), ApJ, 652, L121

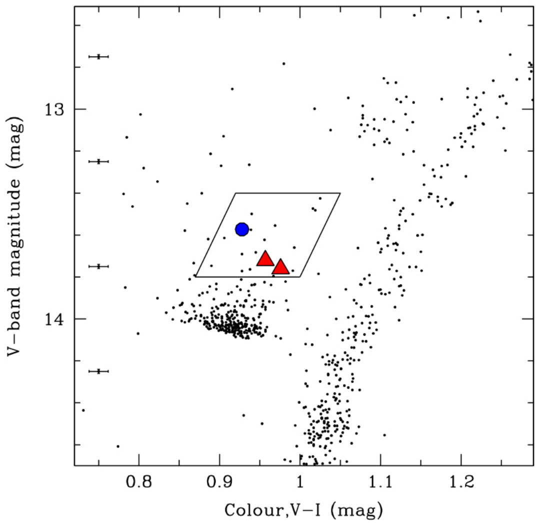
Cosmic-Lab





UVES-FLAMES spectra (**R~40,000**) obtained within a Large Programme at ESO-VLT.

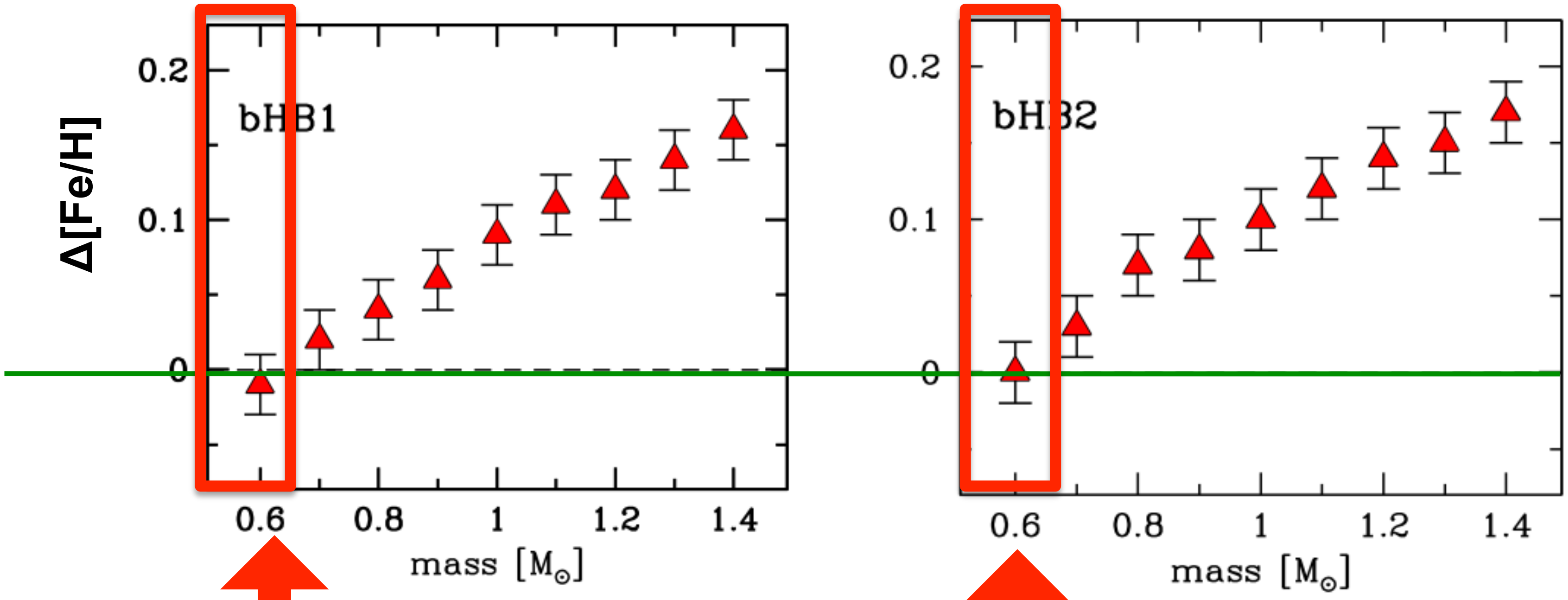
We observed **3 bright-HB** stars selected in the red box.



A "stellar scale" to search for E-BSS

Ferraro et al (2016,ApJ, 618, 70)

For two stars (bHB1 and bHB2) the "stellar scale" yields mass values which are in full agreement with "genuine" HB mass expectations

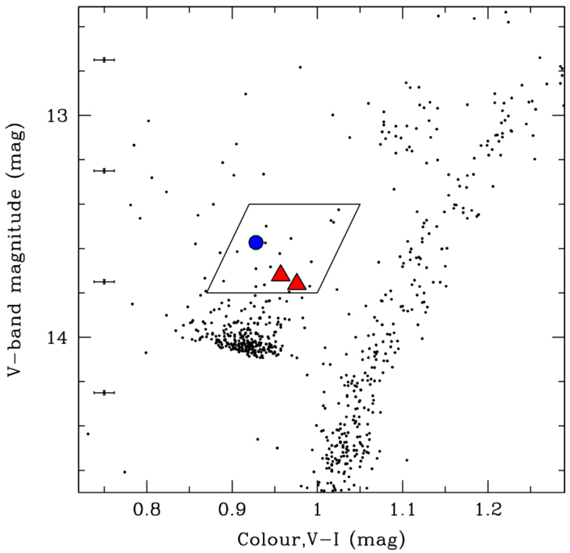


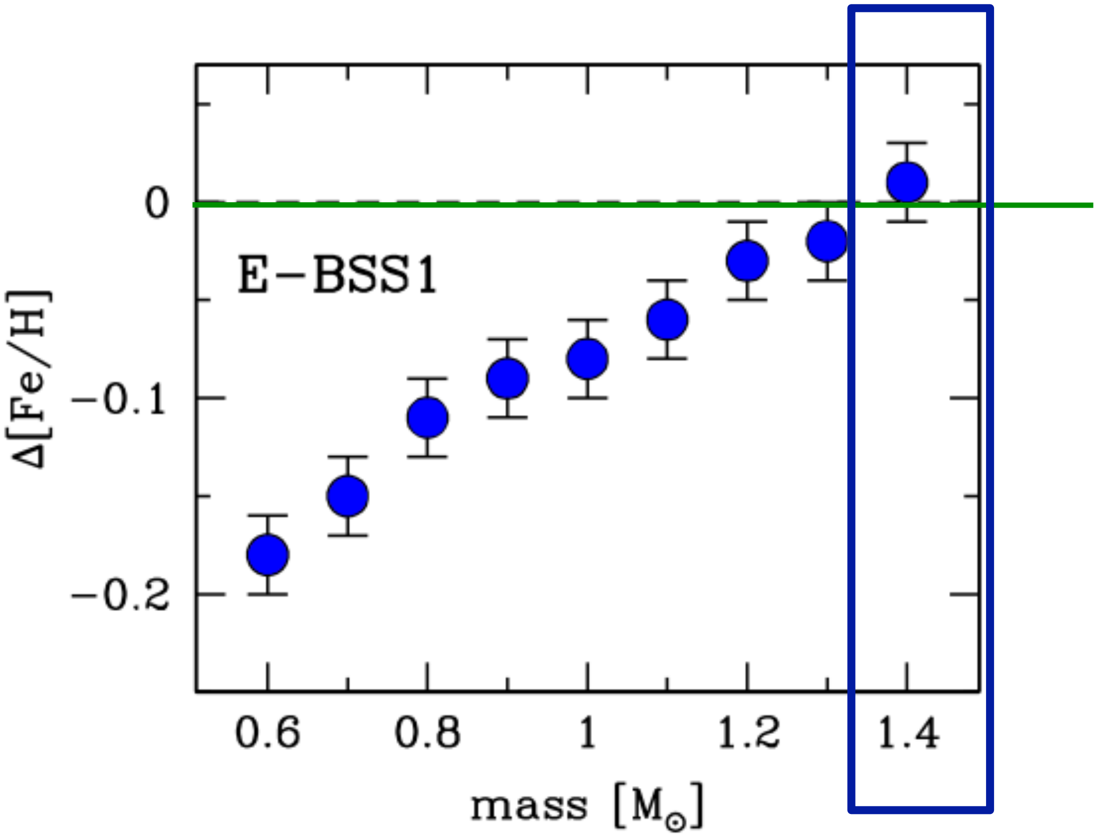
0.6 $M_\odot$

0.6 $M_\odot$

A “stellar scale” to search for E-BSS

Ferraro et al (2016,ApJ, 816,70)

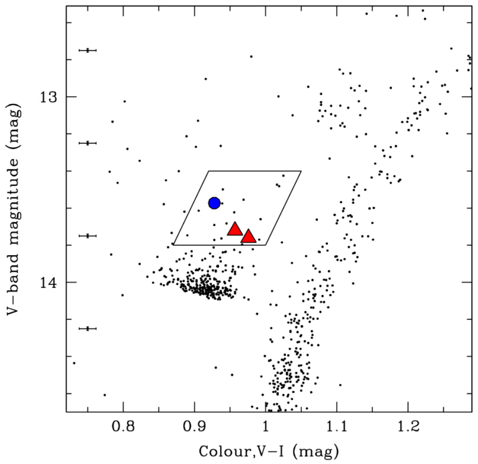




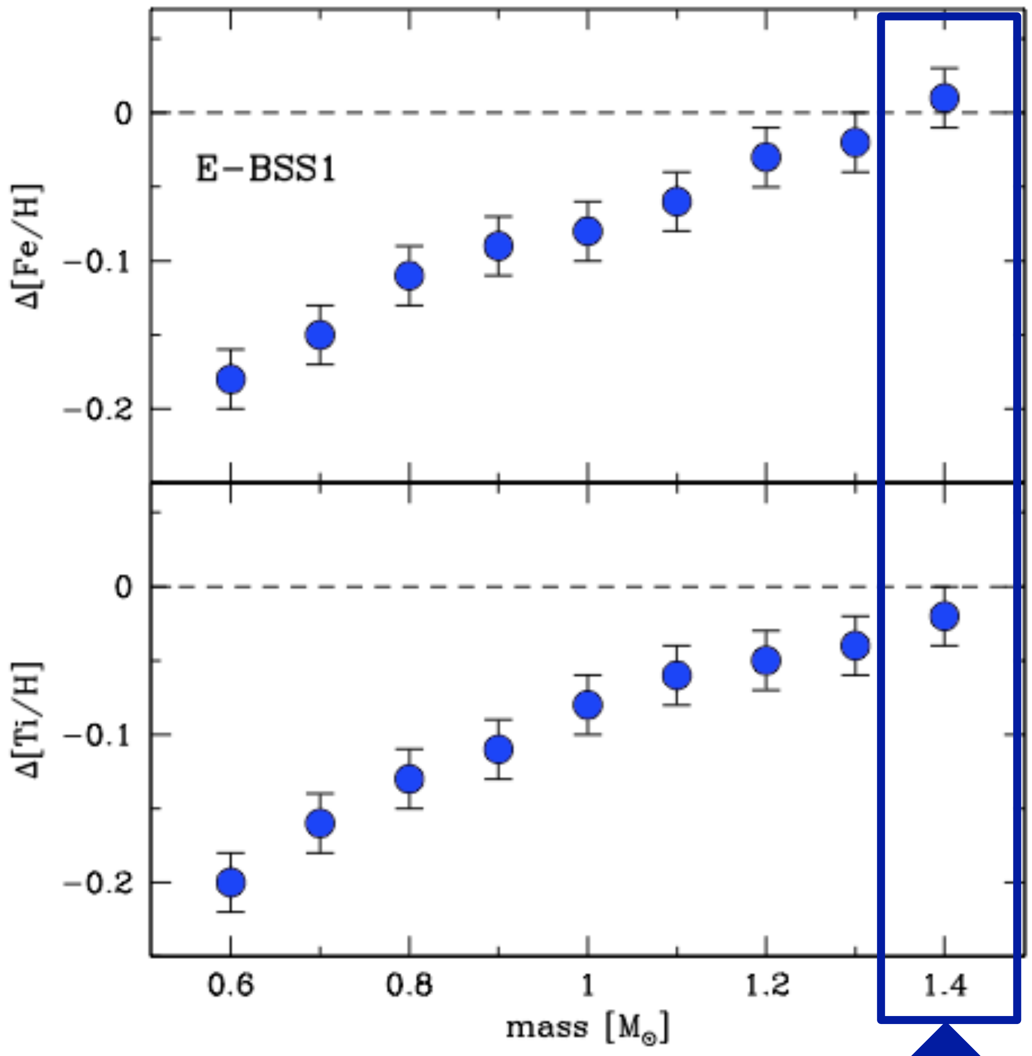
EBSS1 turns out to be significantly more massive than the other two stars and than the TO mass of the cluster

1.4 $M_\odot$!!

A “stellar scale” to search for E-BSS



Ferraro et al (2016,ApJ, 816,70)

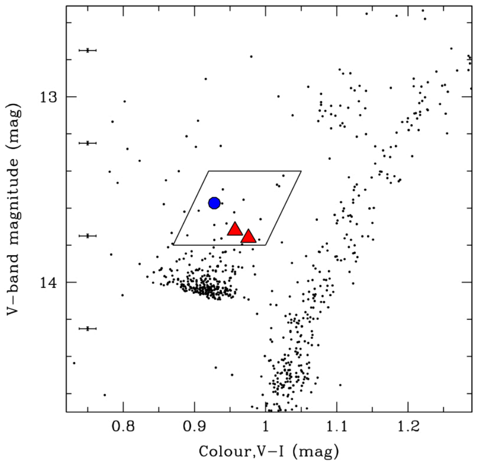


Note that also the analysis of the Titanium lines yields exactly the same result !!!

1.4 $M_\odot$!!

A “stellar scale” to search for E-BSS

Ferraro et al (2016,ApJ, 816,70)



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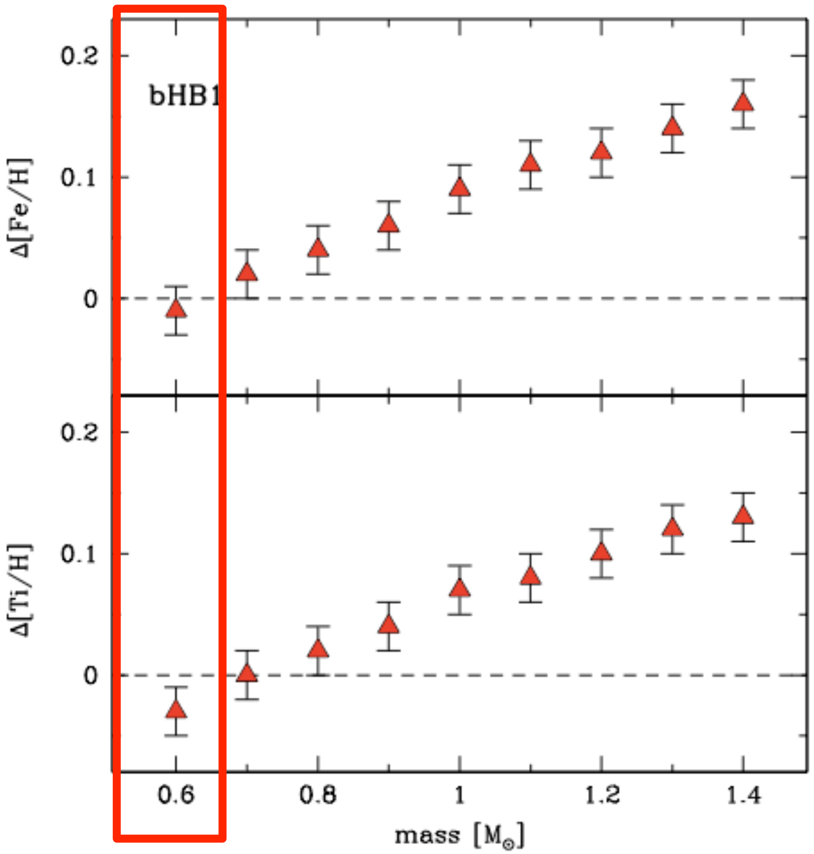
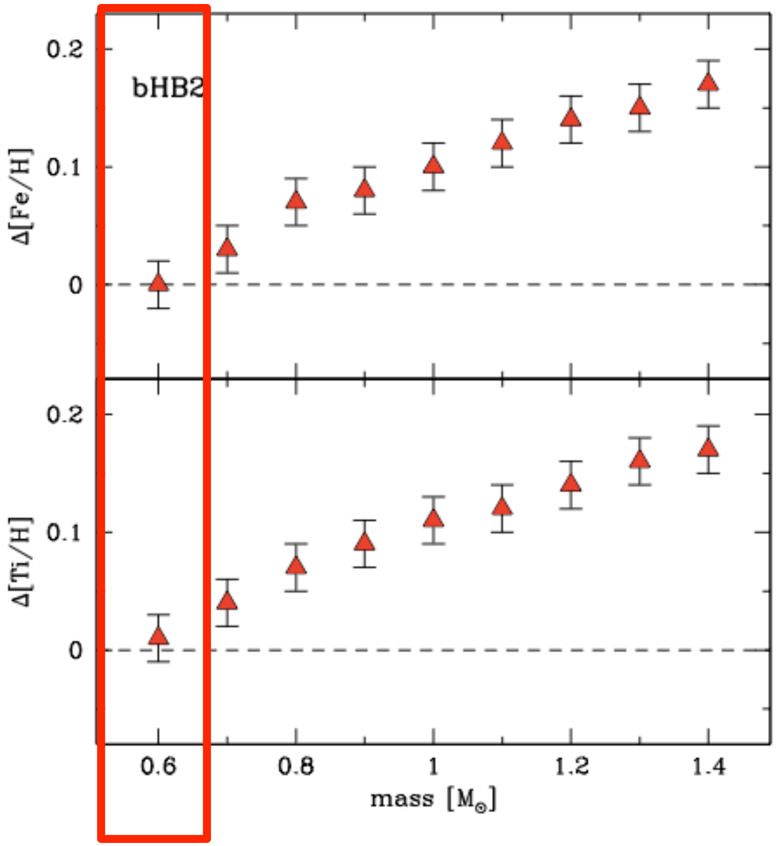
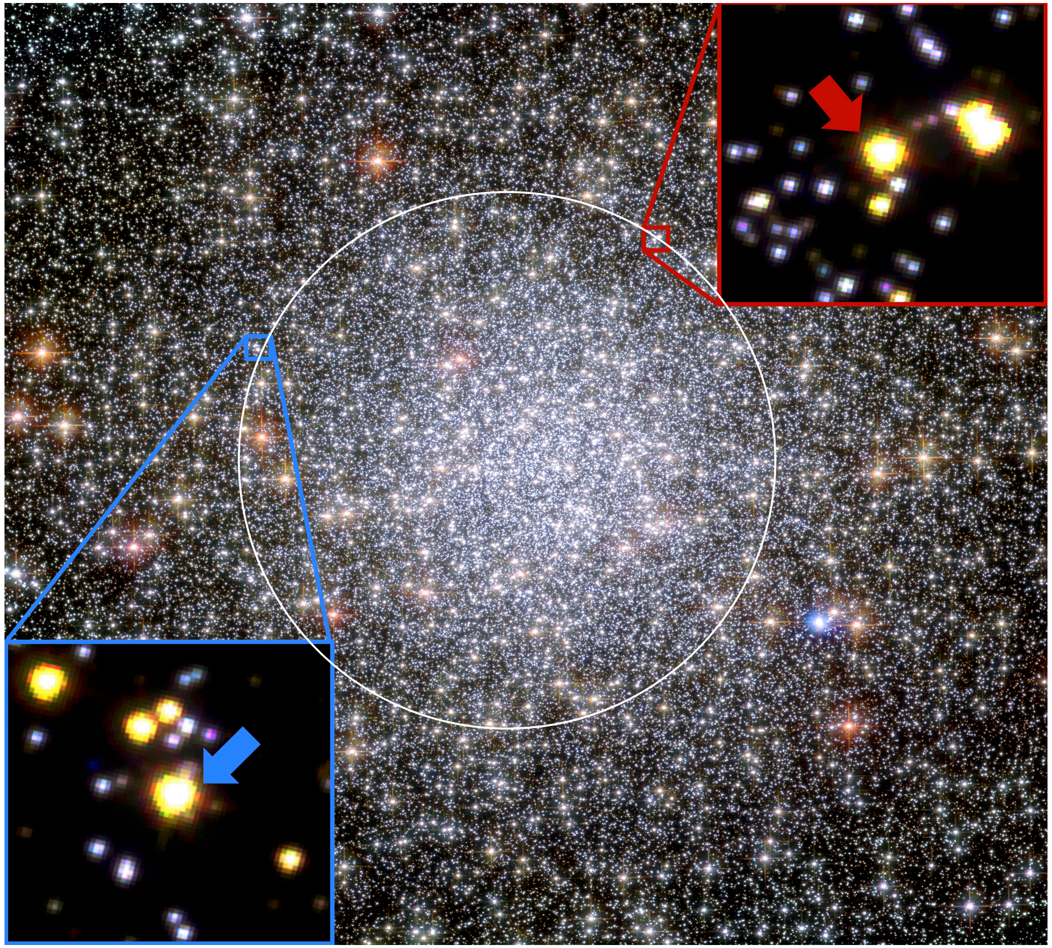
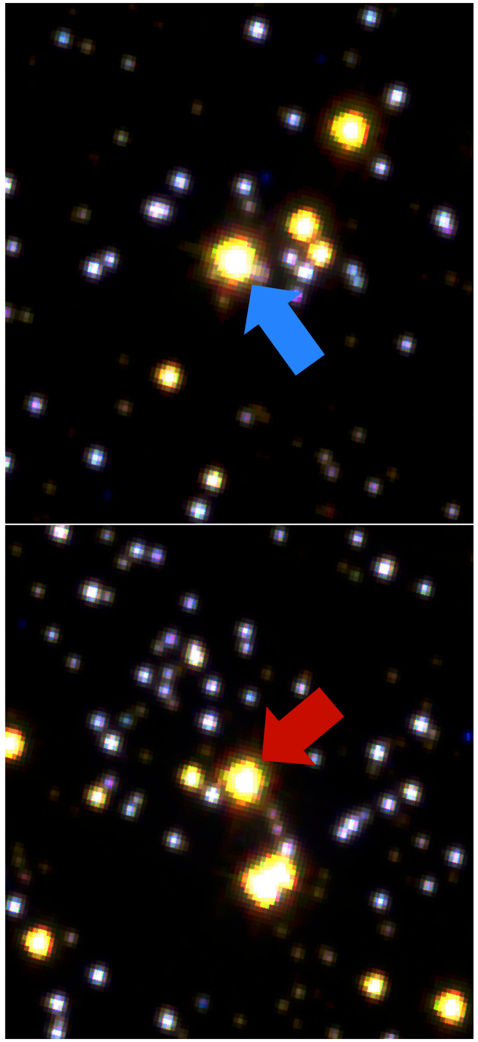




A “stellar scale” to search for E-BSS

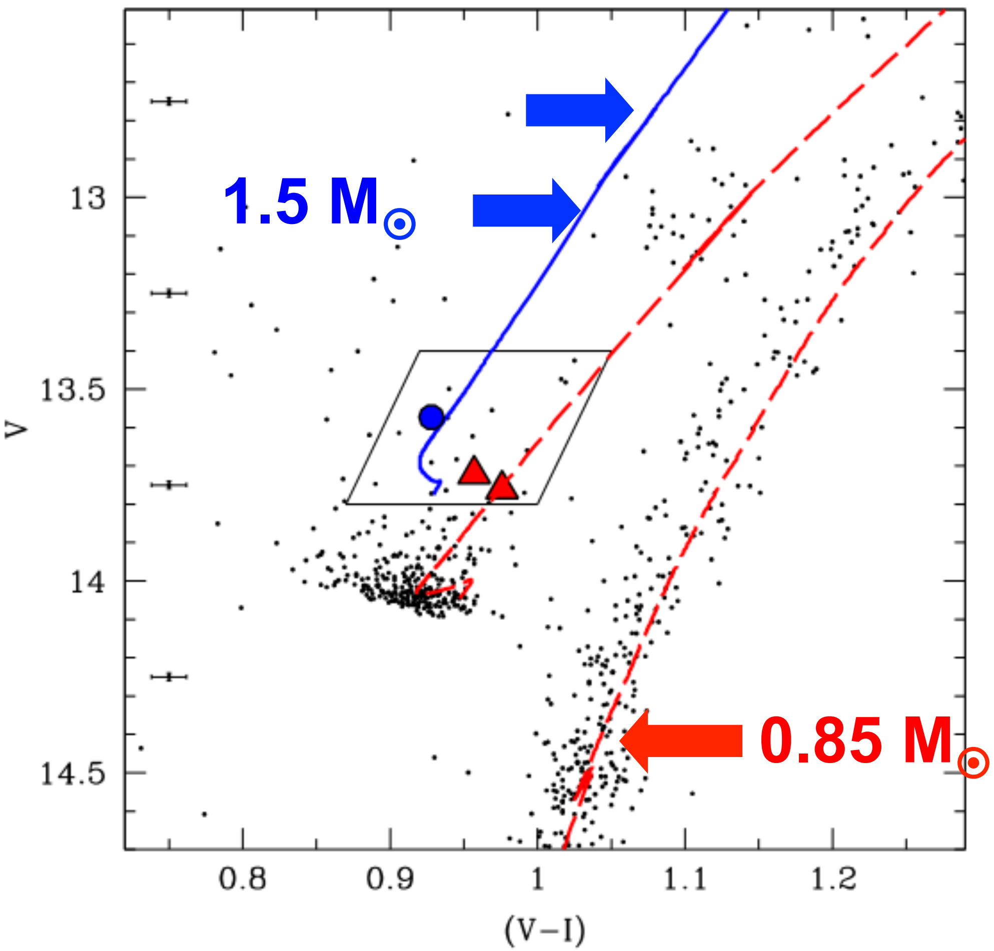
Ferraro et al (2016,ApJ, 816,70)





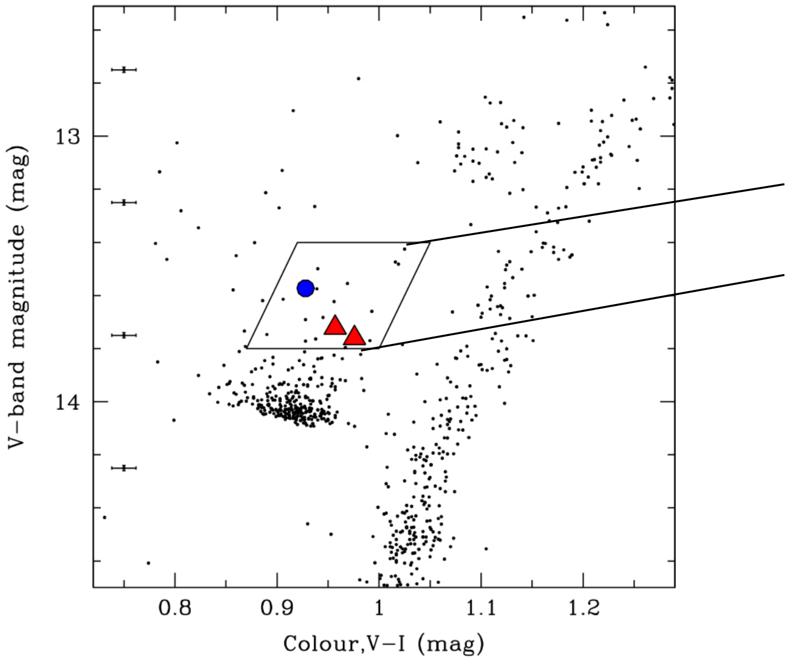
A "stellar scale" to search for E-BSS

Ferraro et al (2016, ApJ, 816,70)



According to its position in the CMD and to the estimated temperature (T = 5000K) and gravity (logg = 2.5 dex), EBSS1 is probably an **evolved Blue Straggler Star caught during its He-burning phase.**

A “stellar scale” to search for E-BSS



Ferraro et al (2016,ApJ,816,70)

How many stars do we observe in the box?

The evolution between the HB and the AGB is quite rapid (3.5 x 10^6 yr):

$N_{HB\text{-}AGB}$ (r<50”) = 11 (expected)

$N_{HB\text{-}AGB}$ (r<50”) = 20 (observed)

A total of 9 EBSS are possibly located into the box !!!!

How many EBSS do we expect in the box?

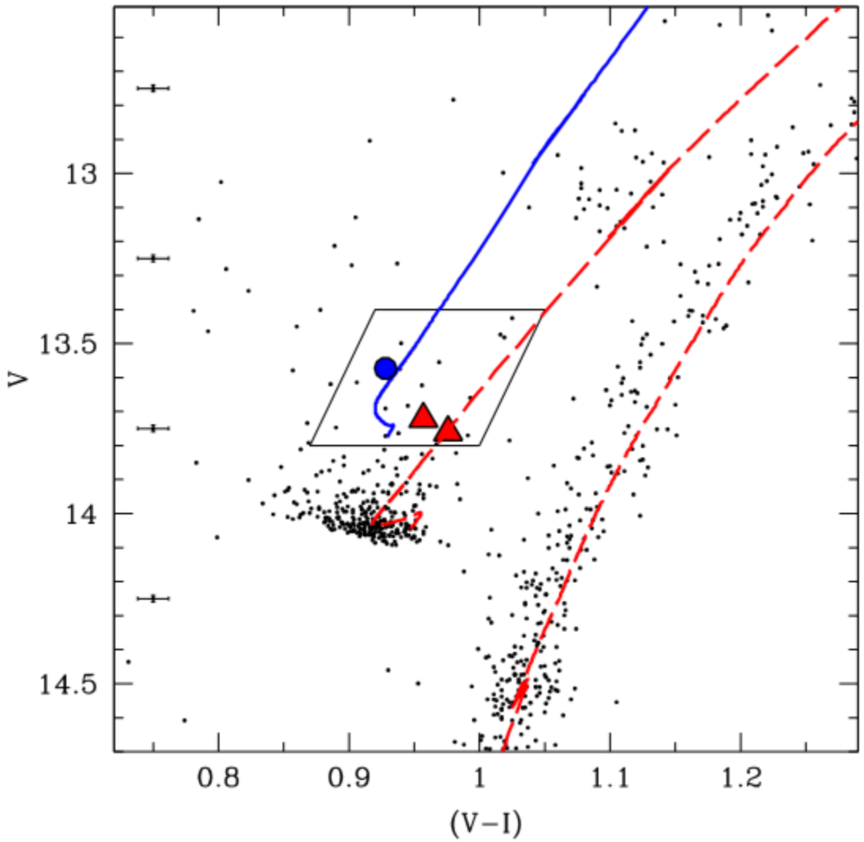
N_{BSS} (r<50”) = 75

N_{BSS}/N_{EBSS} = 8-17 (?)

N_{EBSS}= 4-9 (?)

A “stellar scale” to search for E-BSS

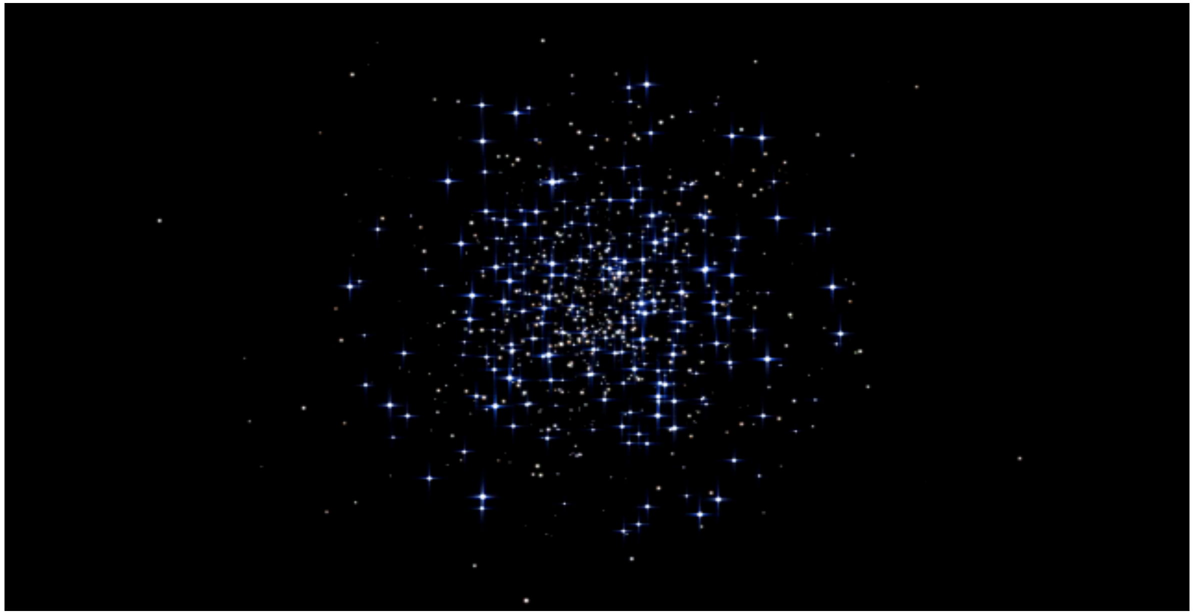
Ferraro et al (2016, ApJ, 816,70)



This identification opens the possibility to start a systematic search of E-BSS in GCs and to determine their chemical/kinematic properties.

Note that in this evolutionary stage EBSS are 20 times more luminous of their BSS progenitors

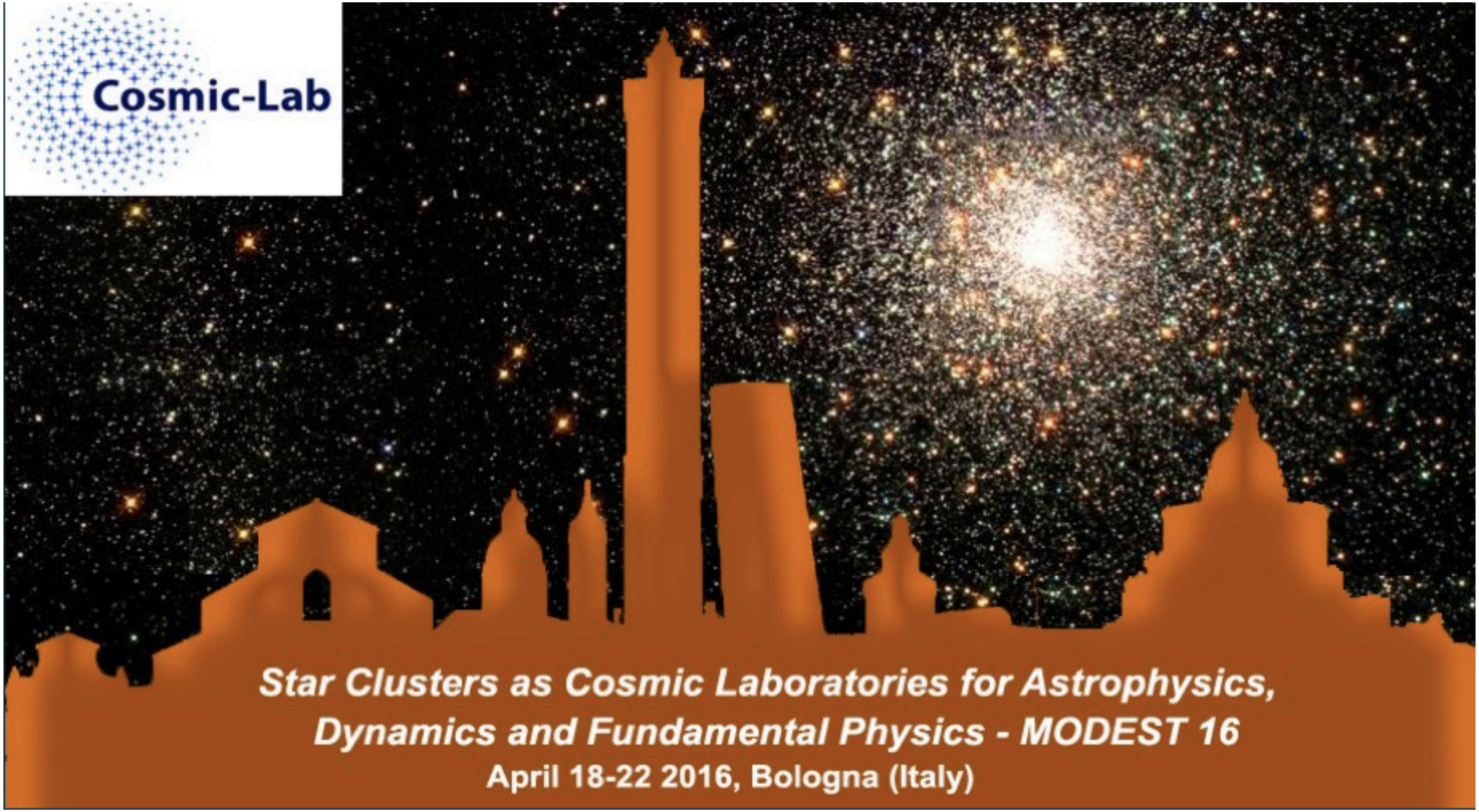
This will provide crucial information about the advanced stages of BSS evolution and possibly on their formation mechanism



BSS are crucial and powerful gravitational test particles.
EBSS are now distinguishable from low-mass sisters

BSS properties (in terms of radial distribution, photometry, etc) trace the past history of the parent clusters
E-BSS can keep memory of their formation mechanism offering us an alternative route to understand the BSS origin…

… we have just started to learn how to read and interpret their properties



TOPICS: **Blue Stragglers Stars** **(Intermediate-mass) Black Holes**
Milli-second pulsars **GC dynamics**

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The End