An empirical clock to measure the dynamical age of stellar systems

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Napoli, May 7, 2014

THE PROJECT

✦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 Sciences of the Universe (3%)

the only Italian project approved in Sciences of the Universe

✦ 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***

Cosmic-Lab

✦ 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

} exotic objects as probe-particles

THE PROJECT

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

PI + WP Coordinator

WP1-STELLAR PHOTOMETRY

WP2-STELLAR SPECTROSCOPY

WP3 - SIMULATIONS

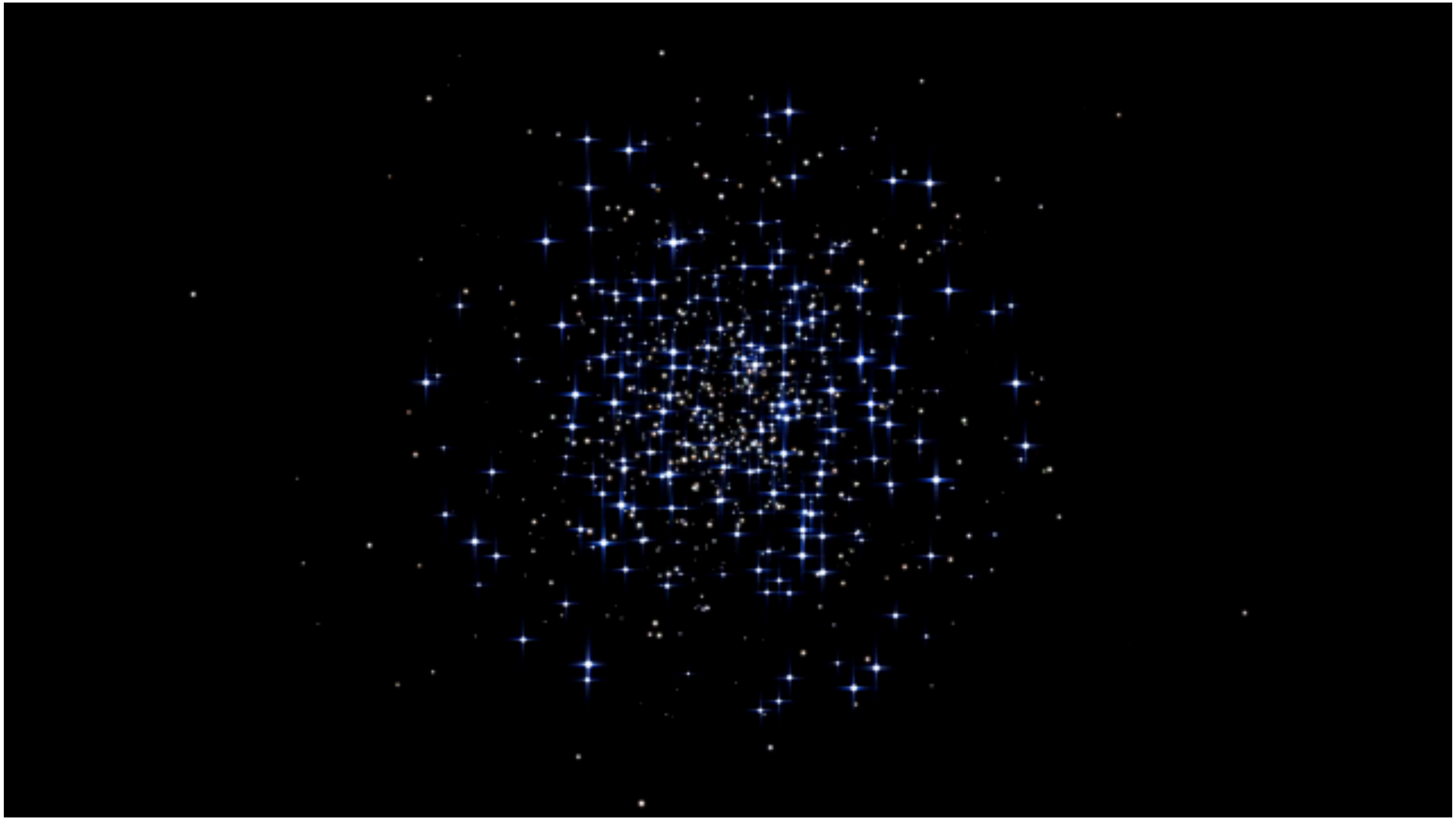
The **COSMIC-LAB team** currently counts 12 researchers (the PI + 1RTI + 2RTD + 4 Post-Docs +4 PhDs)

THE PROJECT

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

We have created a web-page, 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?



GC 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**

THE PROBE PARTICLES

Intermediate-mass Black Holes (IMBH)

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

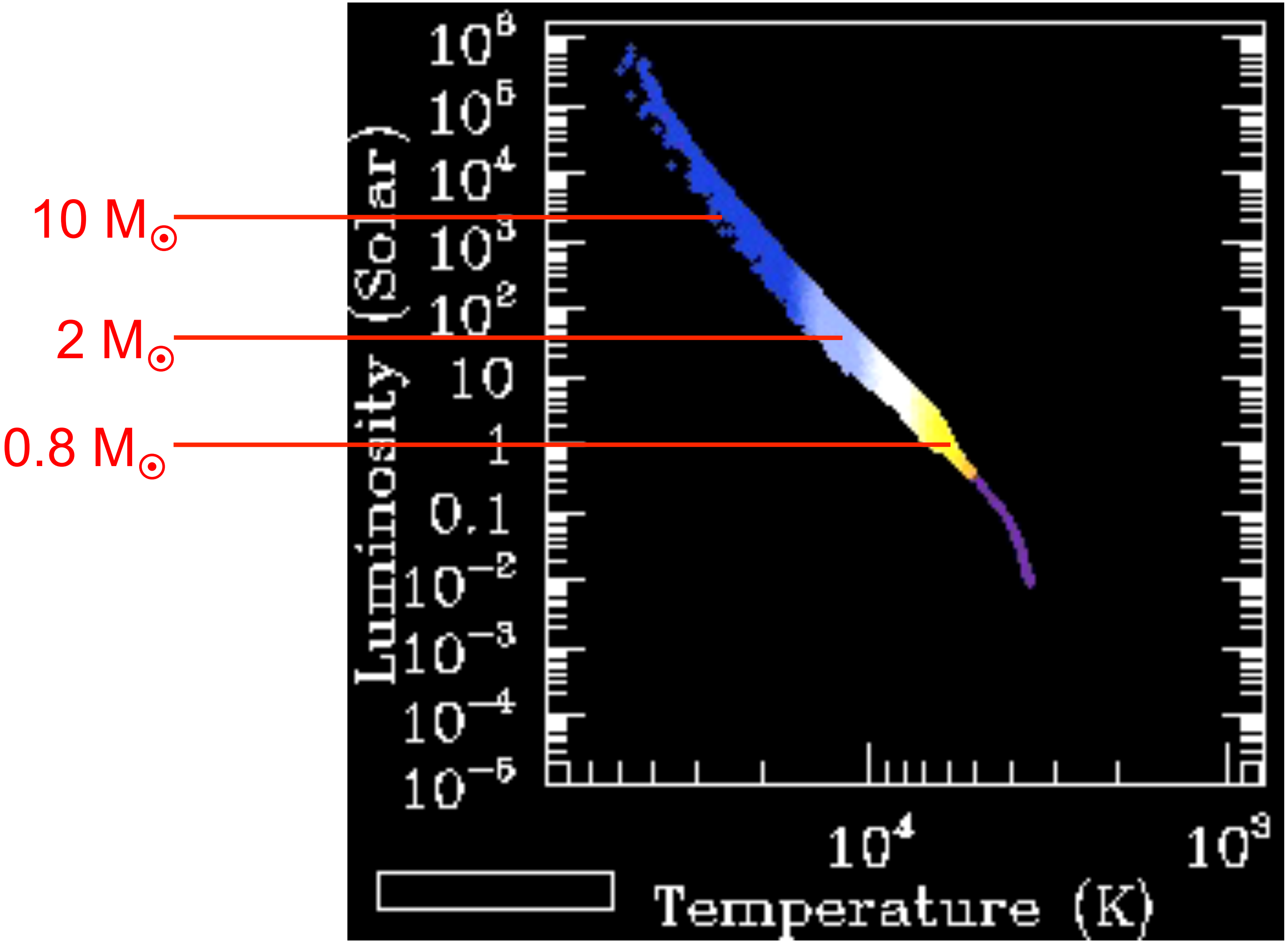
Blue Stragglers (BSS)

Millisecond pulsars (MSP)

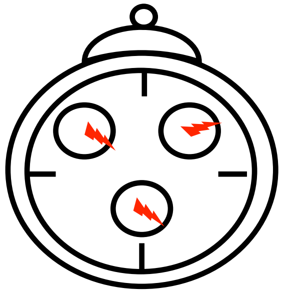
Examples of stellar-rejuvenation processes (possibly induced by dynamics)

.. Some preliminary considerations on the evolution of stellar populations …..

13 Gyr evolution in one minute



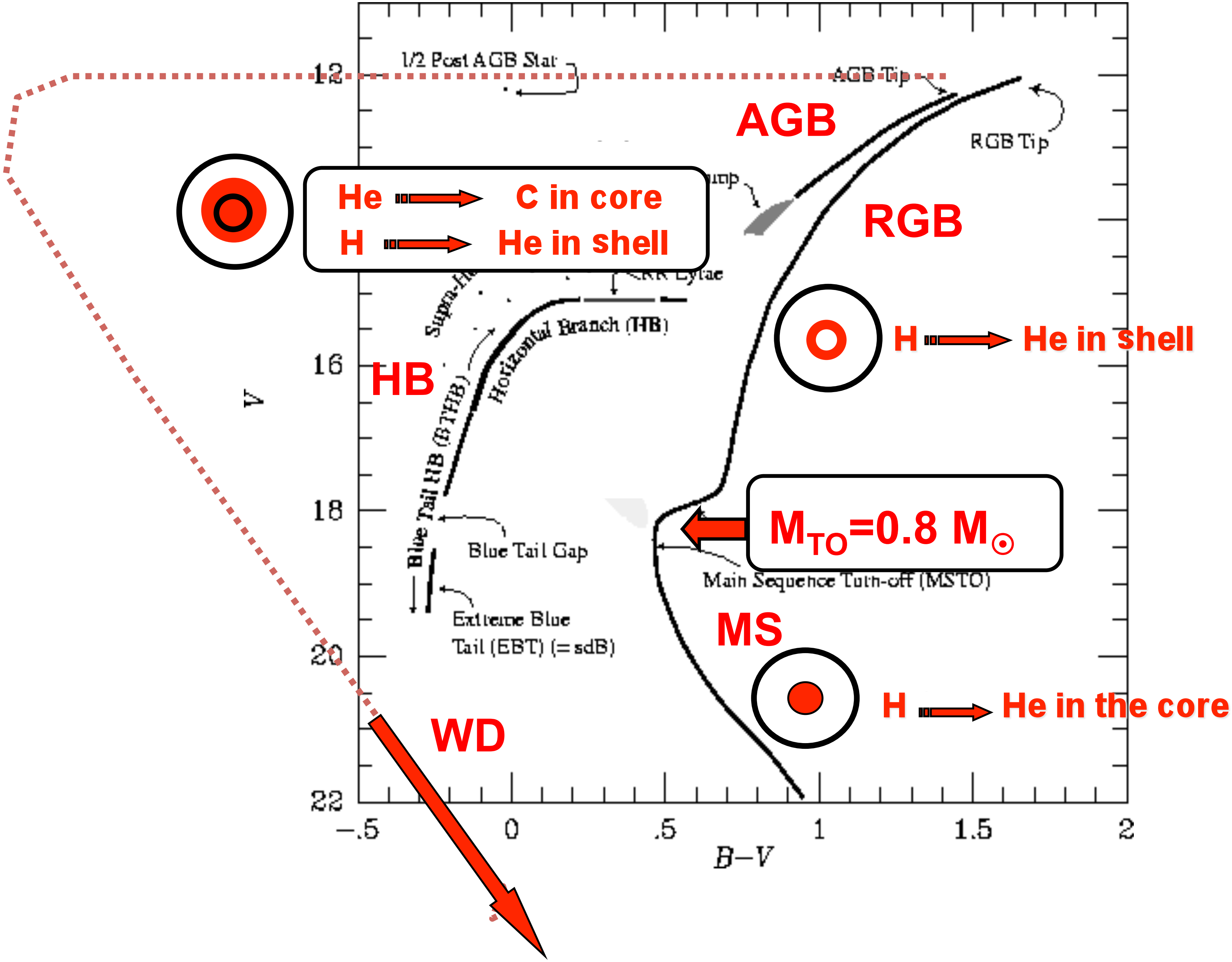
The mass at the TO level sets the CHRONOLOGICAL AGE of a Stellar Population…



but stellar systems with the same chronological age can have reached quite different stage of dynamical evolution (they have different DYNAMICAL AGE)

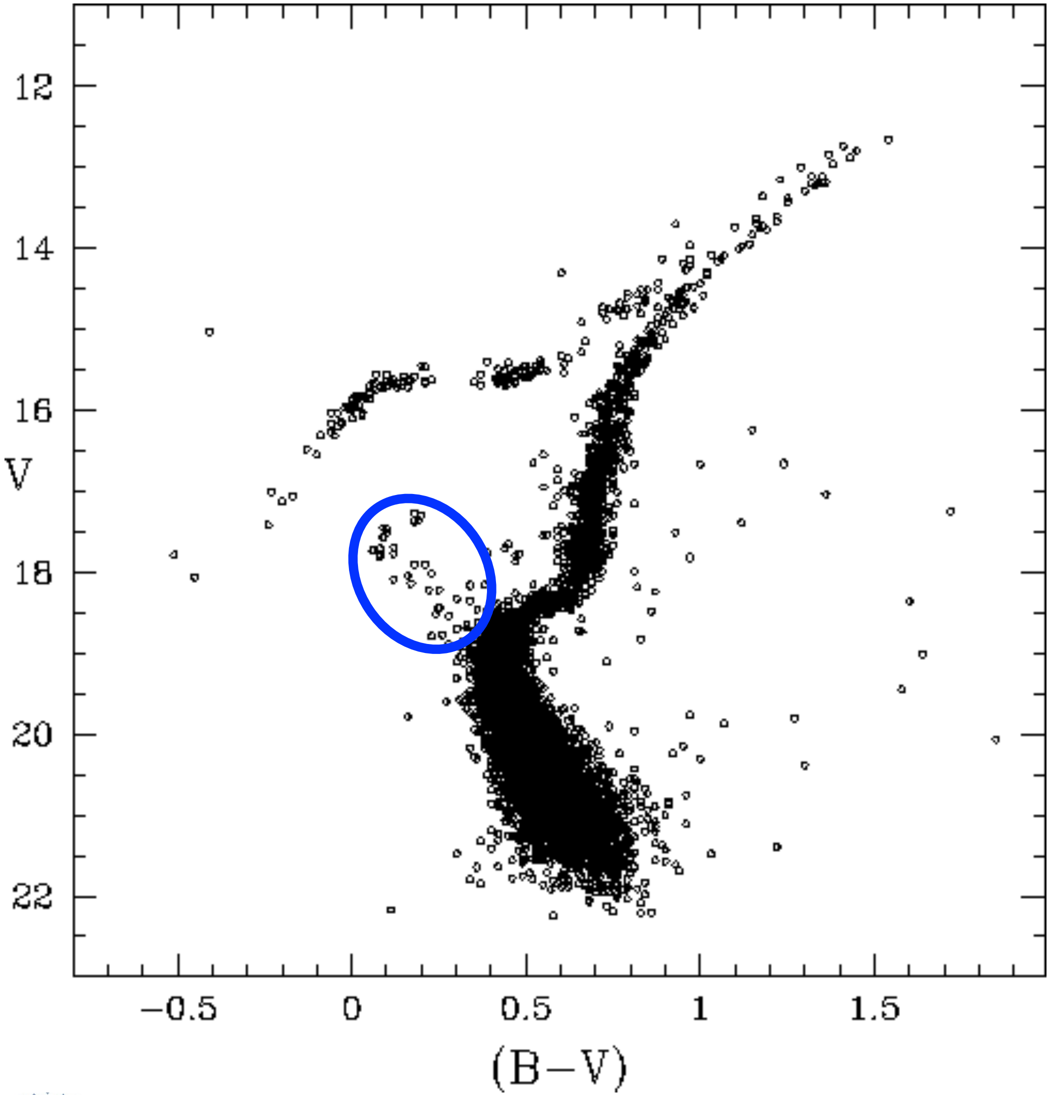
In order to properly characterize a SP we need to know both: the CHRONOLOGICAL & the DYNAMICAL ages

The CMD : A powerfull Tool



Blue Straggler Stars (BSS)

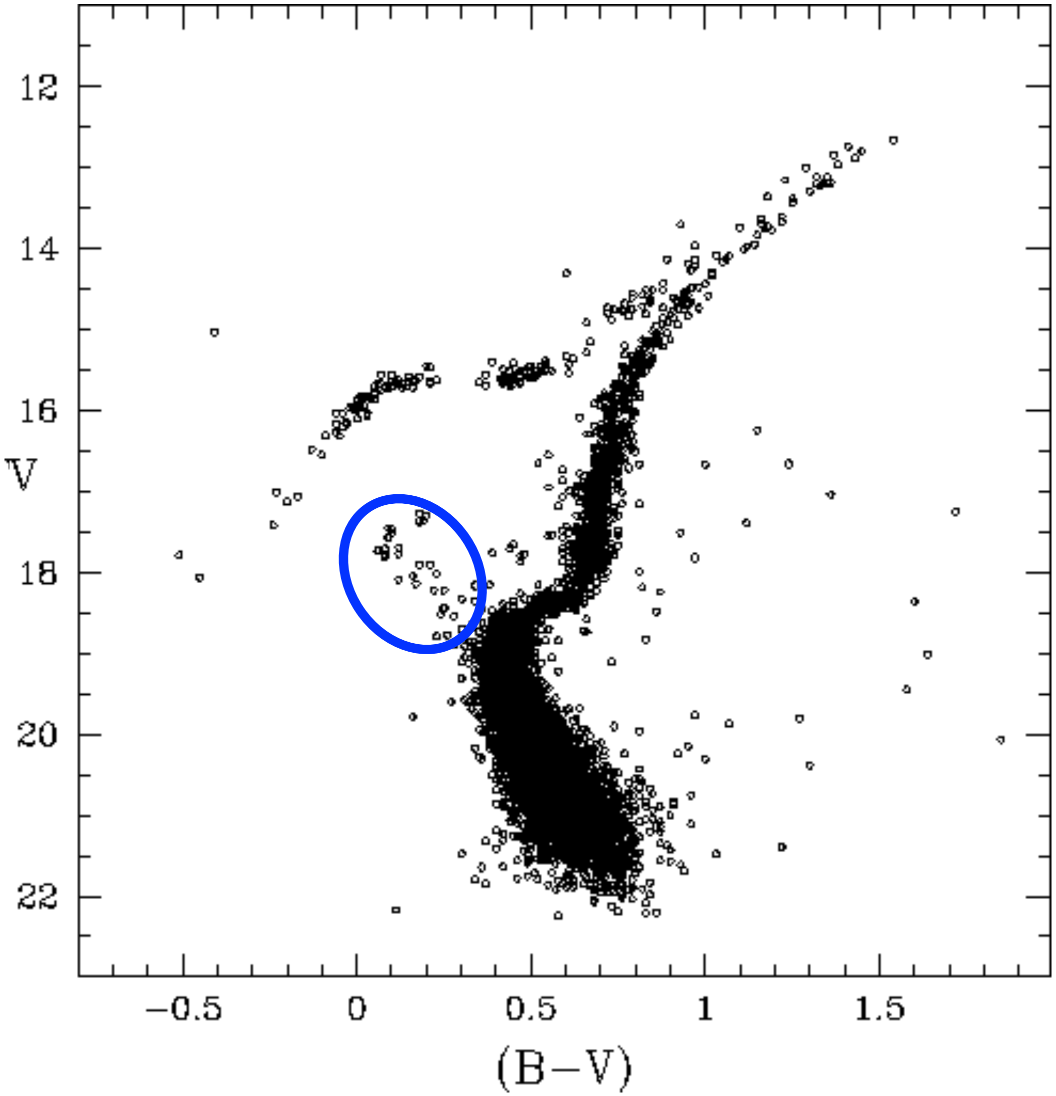
A PECULIAR stellar population



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

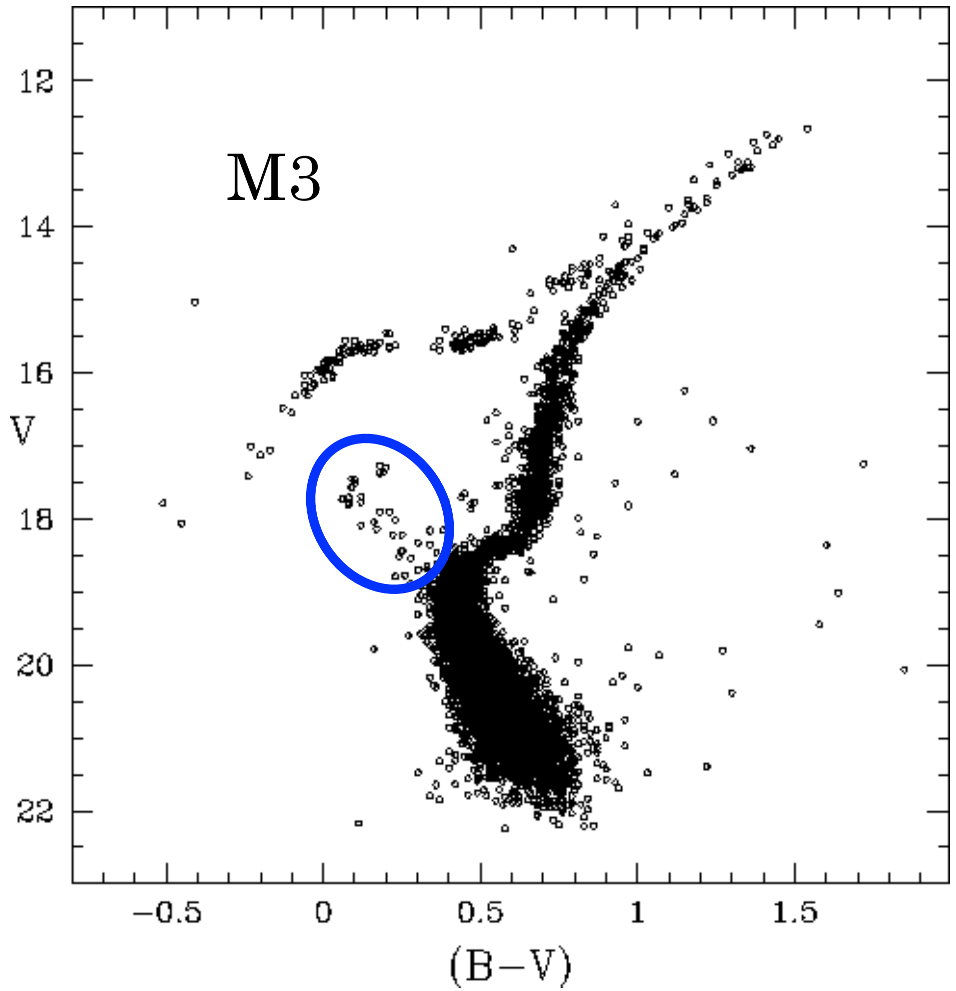
BSS appear as a bunch
of "apparently" younger
blue stars

Blue Straggler Stars (BSS)

What are they doing there???

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

Blue Straggler Stars (BSS)

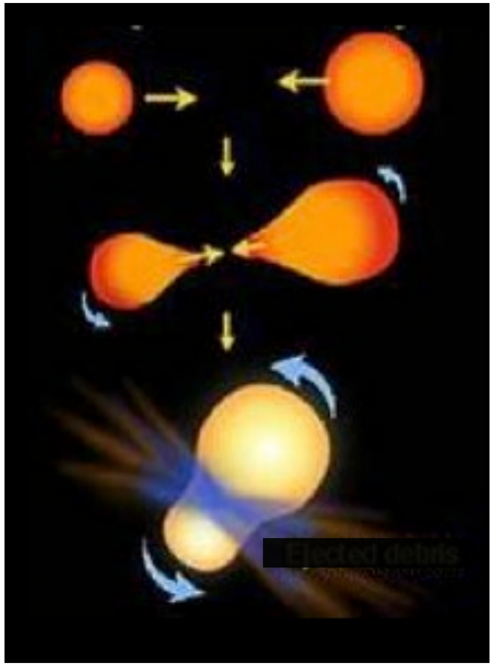


They LOOK younger but they are OLD stars rejuvenated by dynamical processes

Merger of two low-mass stars

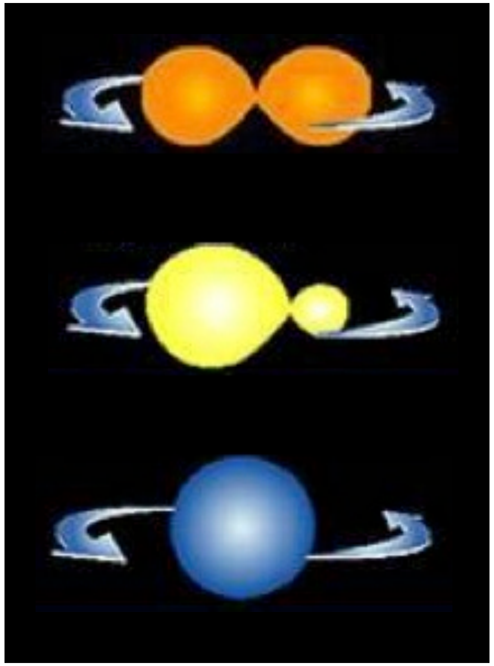
The formation mechanisms

COLLISIONS



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

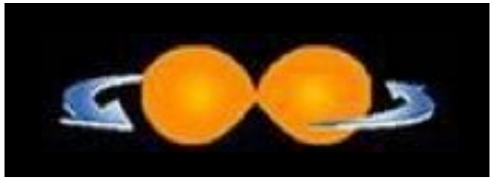
MASS-TRANSFER



depend on **binary fraction + dynamical interactions**
and stellar evolution (McCrea 1964)

The formation mechanisms

MASS-TRANSFER



In OPEN CLUSTER:

Large fraction of BSS in binary systems (Mathieu & Geller 2009, Nature, 462, 1032)

Detection of a WD companion in a few BSS (Gosnell et al 2014, ApJ,783, L8)

In GLOBULAR CLUSTERS:

Chemical signatures of MT in 47 Tuc (Ferraro et al 2006, ApJ, 467, L56)

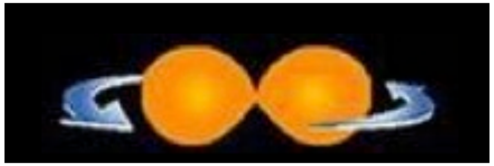
Correlation of N_{BSS} with the core mass (Knigge et al 2009,Nature, 457,288)

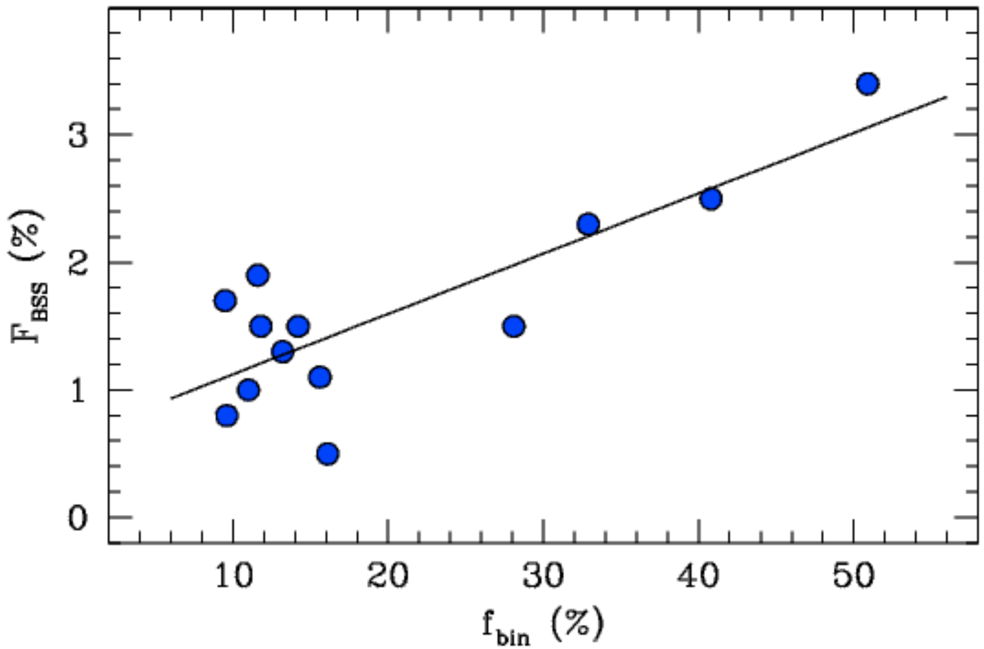
Correlation between BSS and binary fraction in low density clusters

(Sollima et al. 2008, A&A,481,701)

The formation mechanisms

MASS-TRANSFER

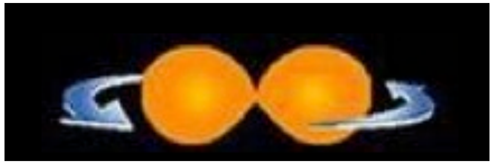


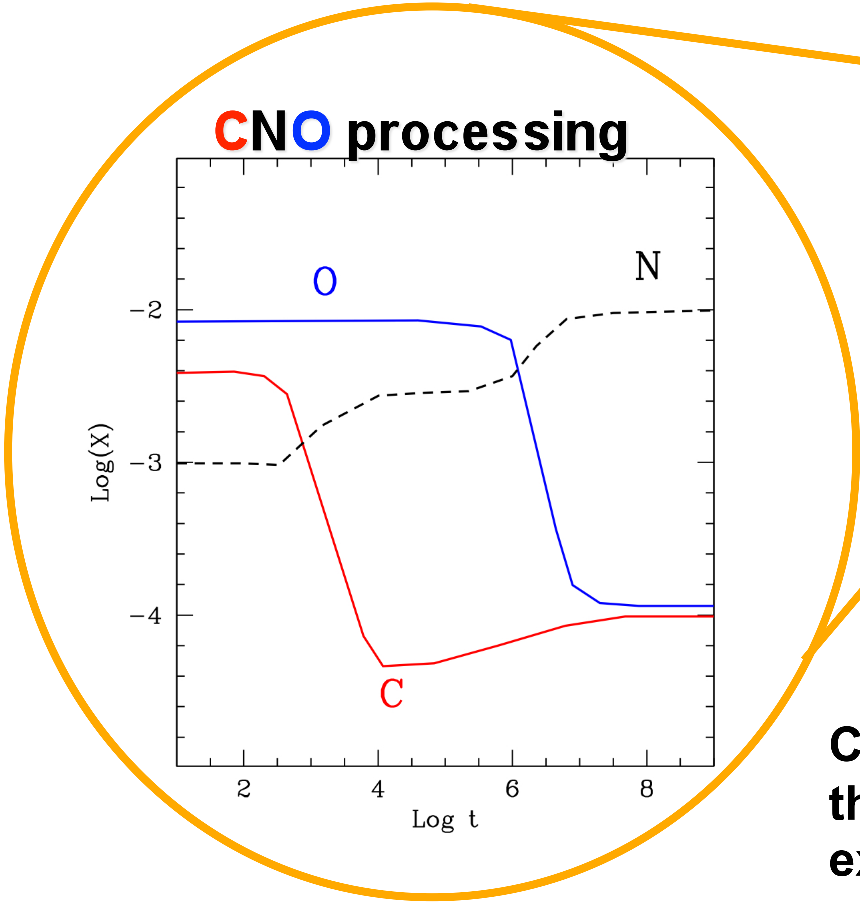


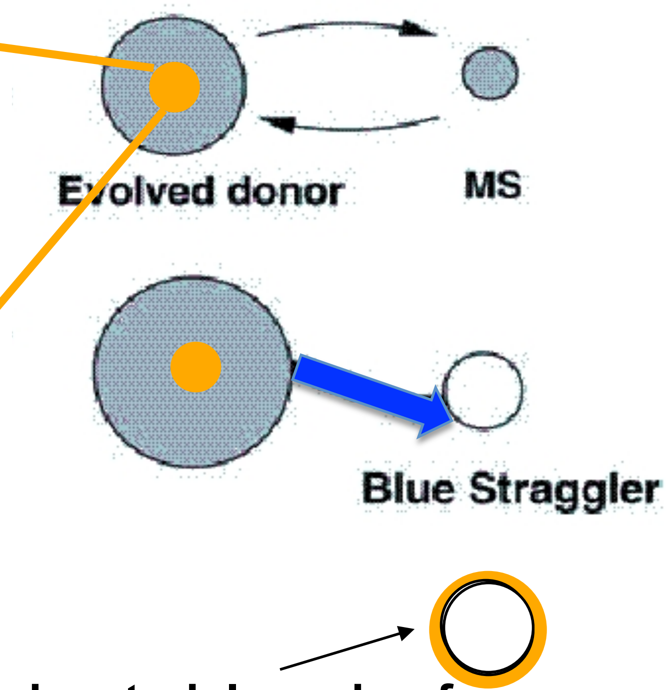
A correlation between BSS and binary fraction found in 13 low-density (Log ρ <2.5) GCs (Sollima et al 2008, A&A,481, 701)

The formation mechanisms

MASS-TRANSFER



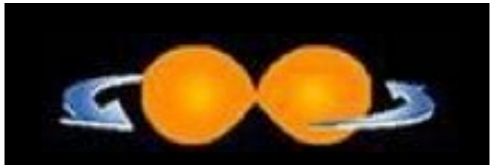


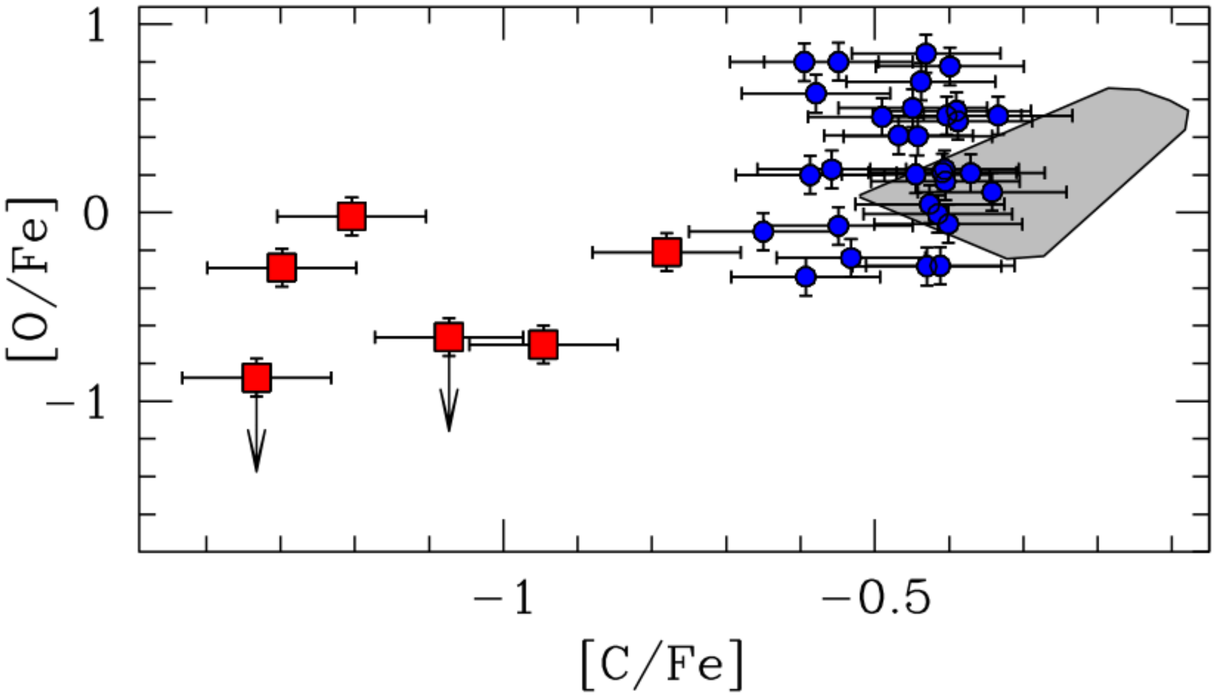


CO depleted material coming from the inner regions of the donor is expected on the BSS surface

The formation mechanisms

MASS-TRANSFER

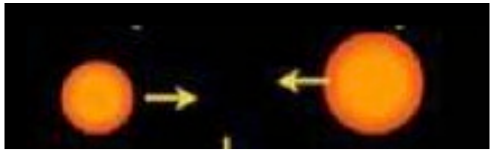




The chemical “signature” of the MT formation process: A sub-population of CO depleted BSS has been found in 47 Tuc (Ferraro et al 2006, ApJ,467, L56)

The formation mechanisms

COLLISIONS

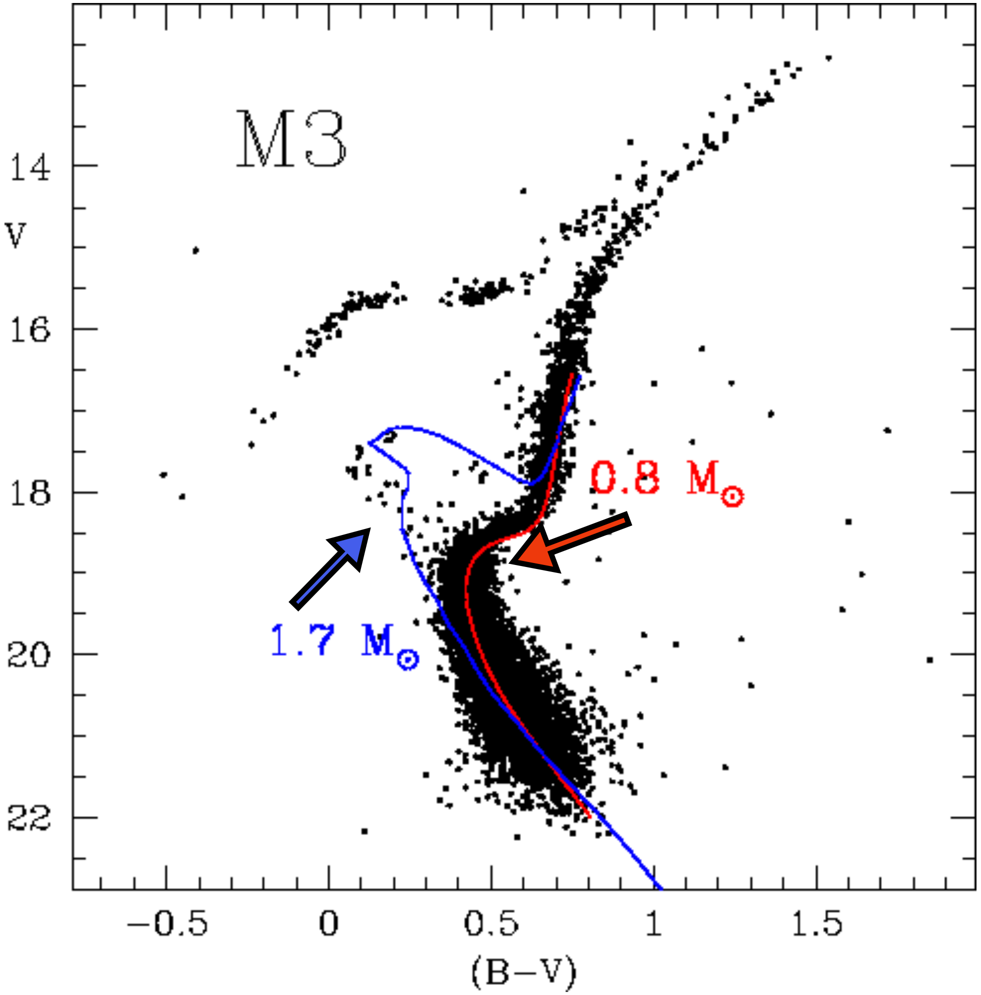


?

In **GLOBULAR CLUSTERS**:

A sequence of Collisional BSS in M30 and in other high density clusters (Ferraro et al 2009, Nature, 462, 1028)

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

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

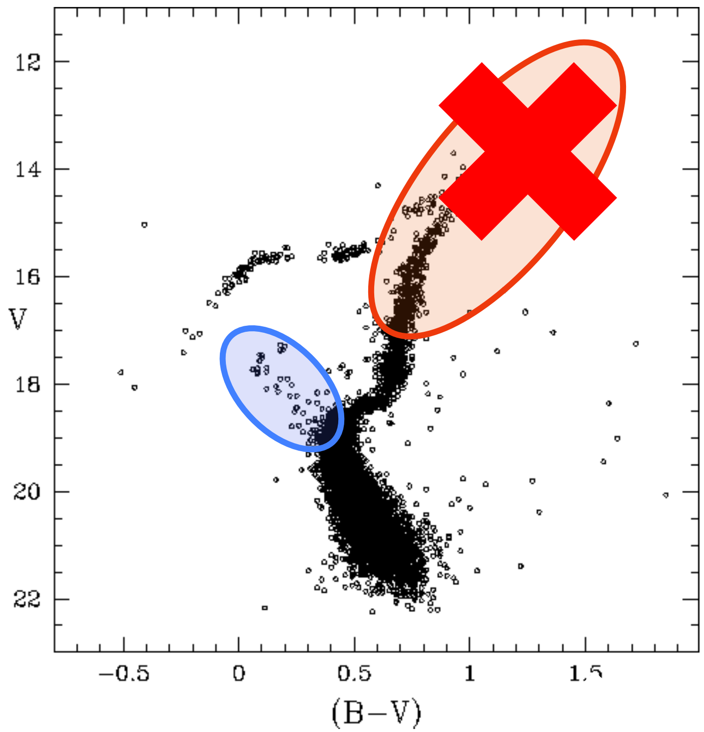
Because of the sensitivity of the **df** time-scale to the cluster local density, **df** is expected to affect first the most internal BSS and then BSS progressively **at larger and larger distances,** as function of time

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

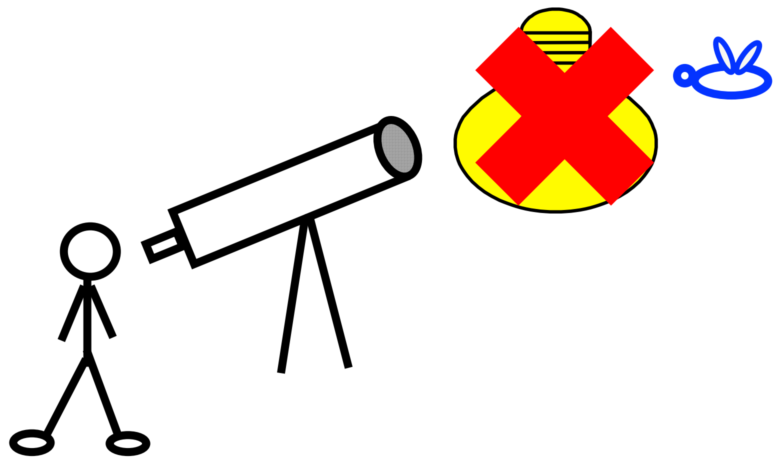
Observations of Blue Stragglers in Globular Clusters: really NOT an easy task !!

BSS observations are intrinsically difficult in the optical bands even with HST

Cool giants (RGB/AGB) are much brighter than BSS



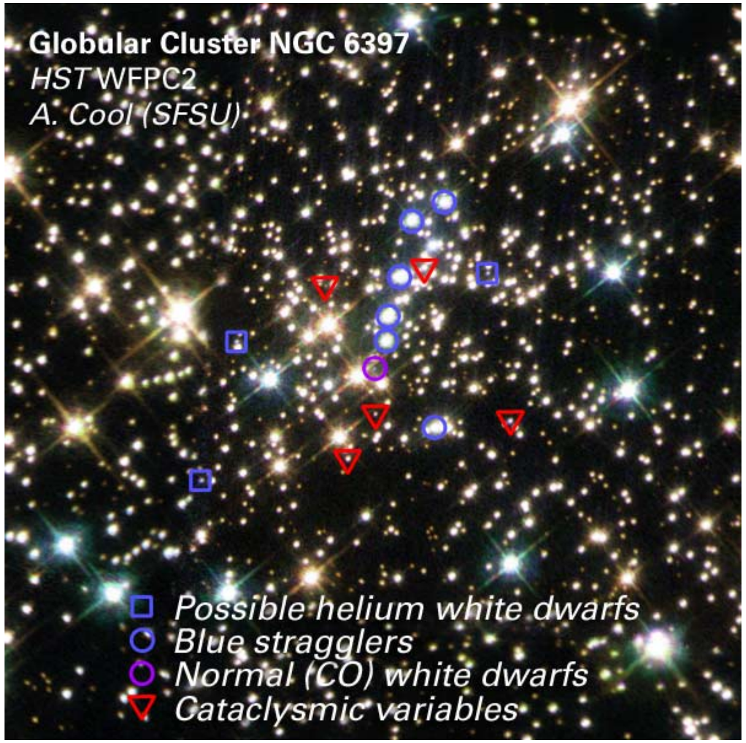
… like trying to distinguish a fire-fly having a HUGE light bulb just in front!



UV observations: switching off the bulbs

Optical

UV



GC images in **UV** are NOT dominated by the red giant light, and therefore are significantly less crowded

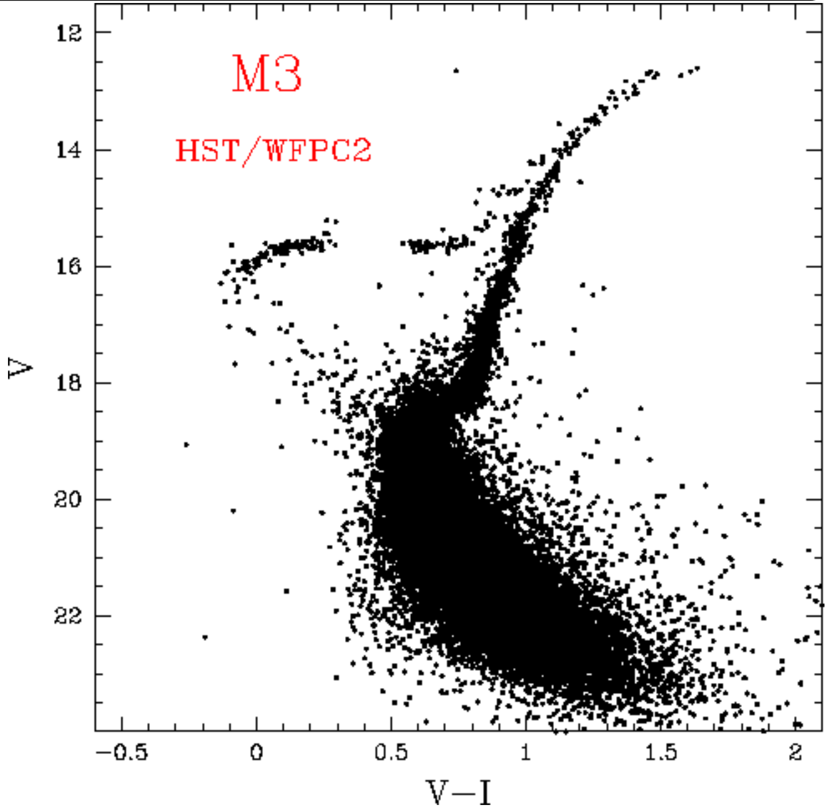
UV

UV sensitivity*, *high resolution

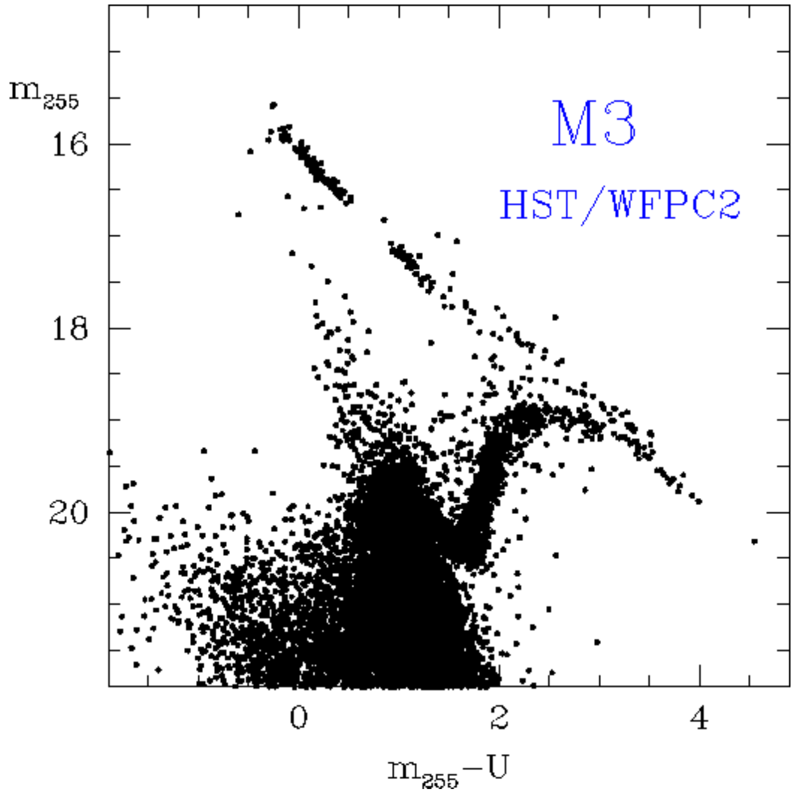
⇓

systematic studies of hot SPs even in the core of high density GGCs

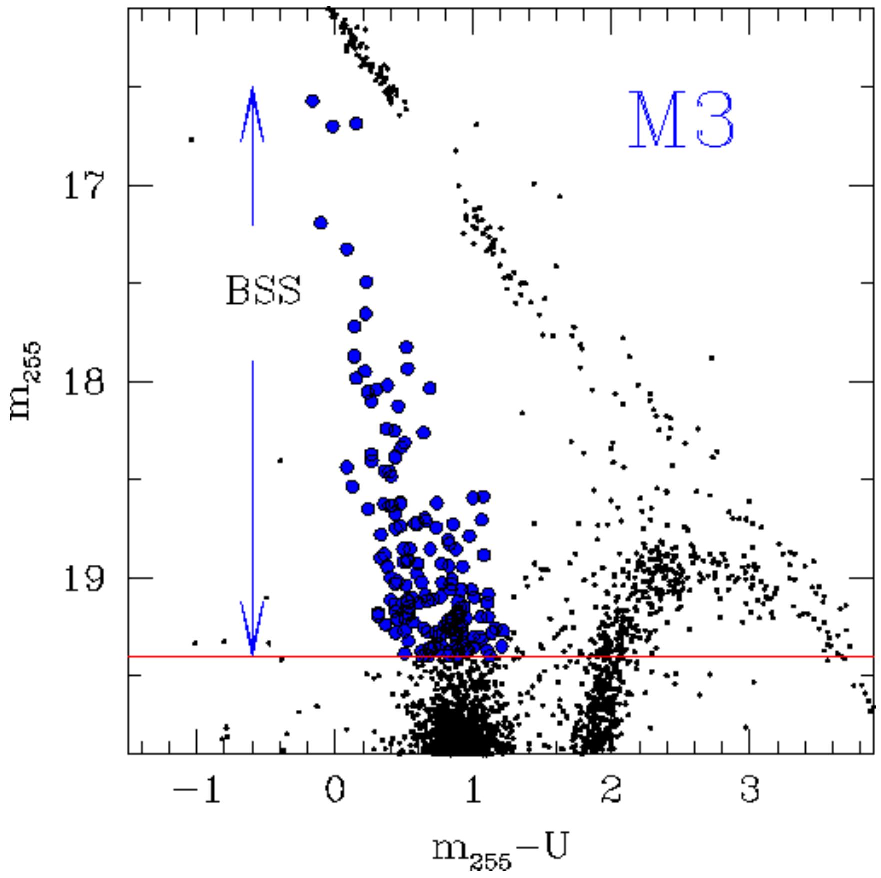
The "classical" plane



The UV plane



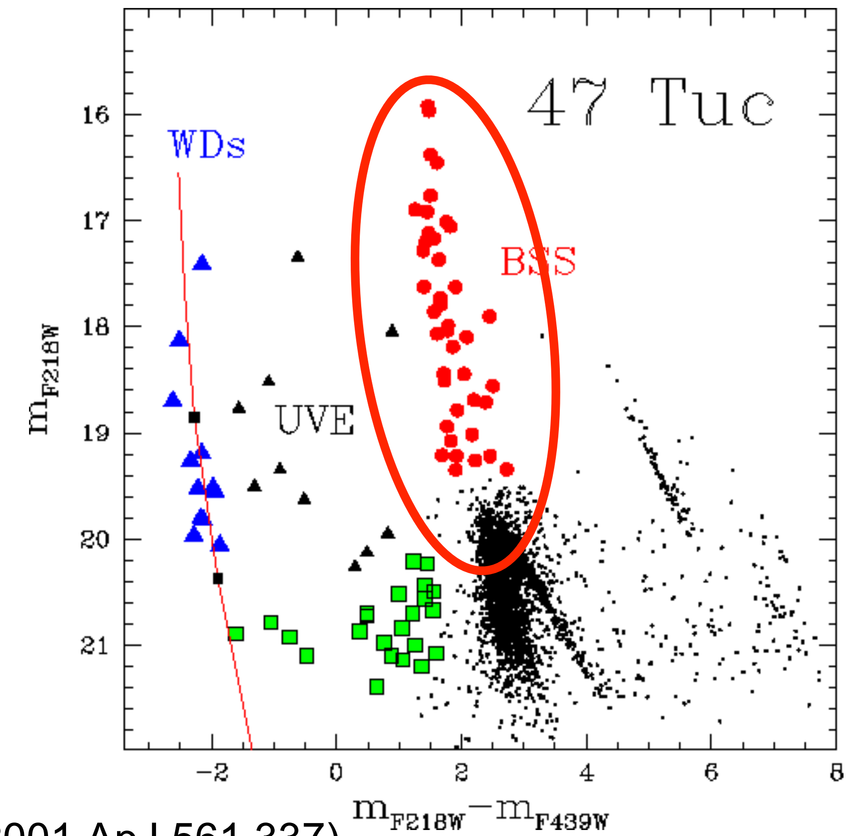
BSS in the UV:



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

UV-plane ideal to study the photometric properties of the *BSS* population:

- **the distribution is almost vertical**
- **span more than 3 magnitudes**

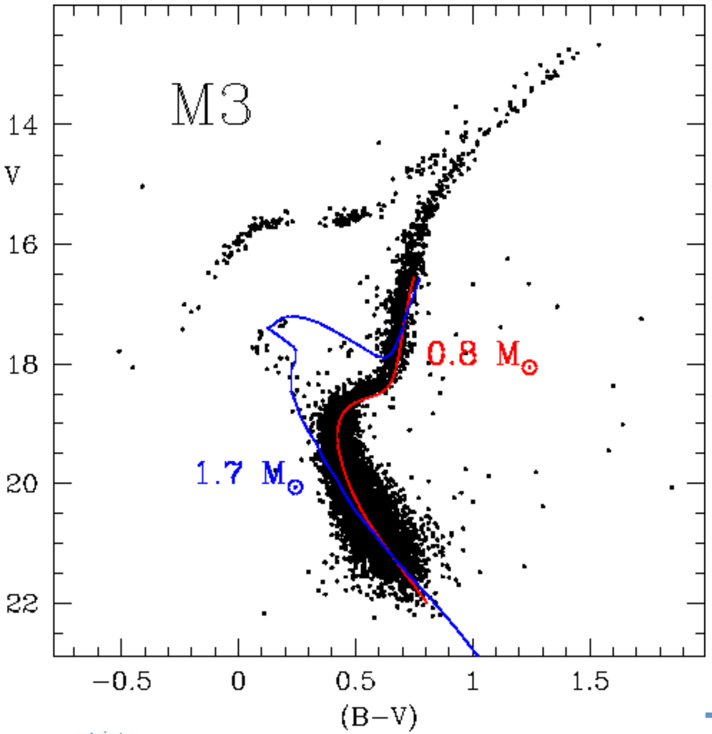


Ferraro et al (2001,ApJ,561,337)

Blue Straggler Stars (BSS)

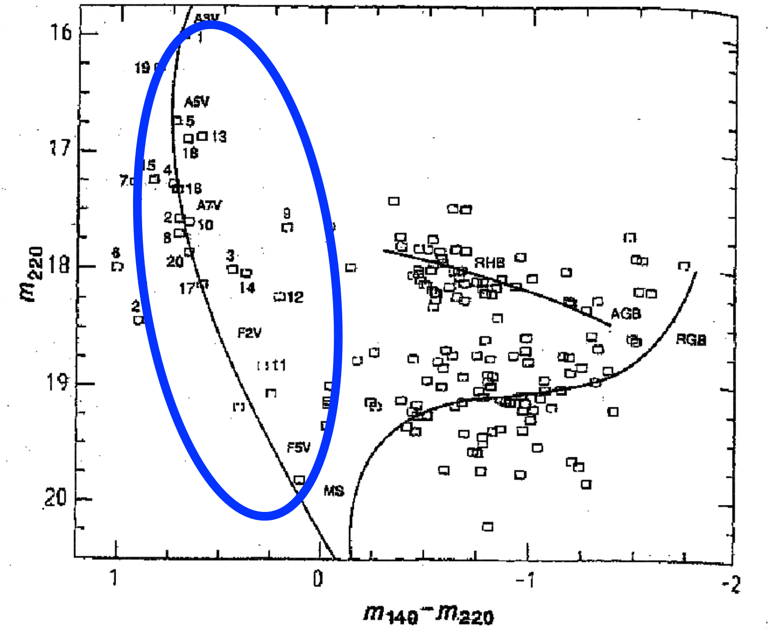
Loose GCs with low c and low ρ → the natural Habitat for BSS

<1990



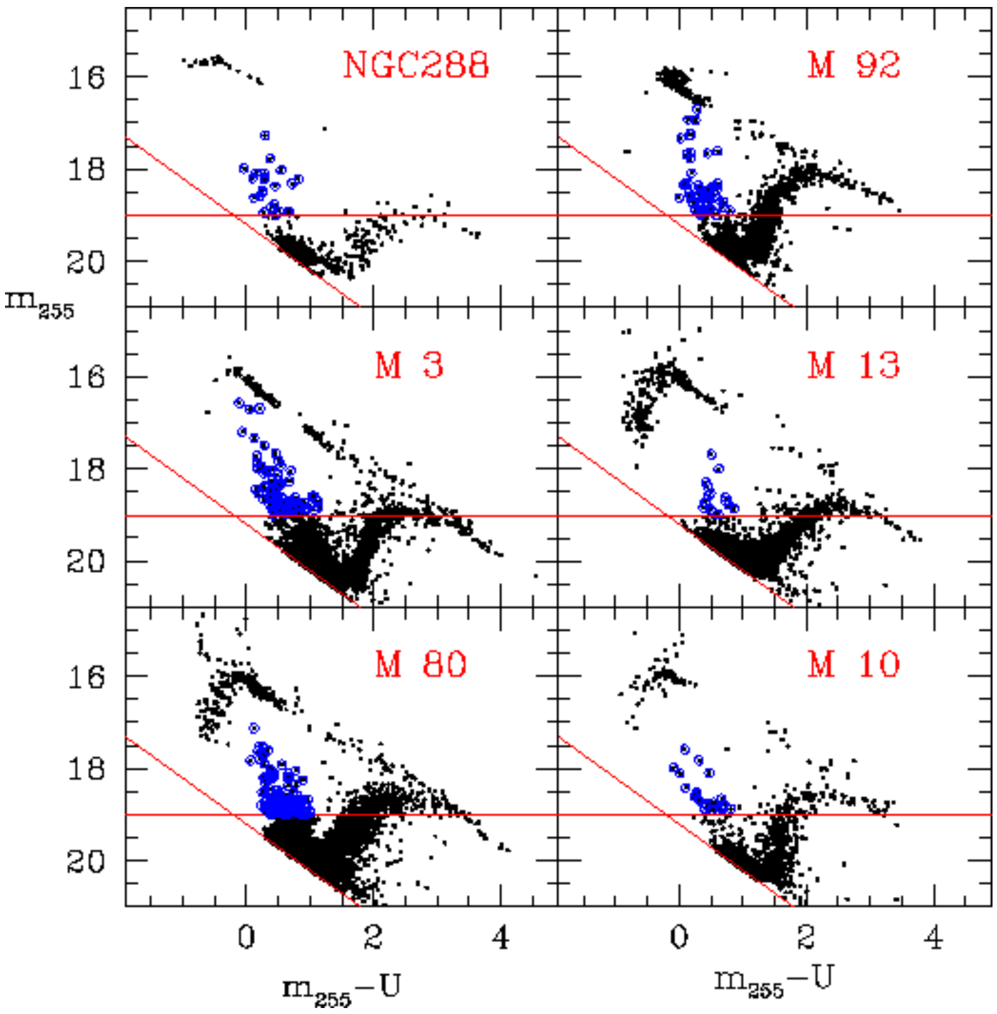
>1990

Paresce et al (1991, Nature, 352, 297)



BSS are common stellar populations found in any stellar system (globulars, open clusters, dwarf spheroidals, galactic field) properly observed

Direct comparison of BSS populations



Ferraro et al (2003, ApJ, 588,464)

Cluster	$[Fe/H]$	$Log\rho_0$ $[M_\odot/pc^3]$	$Mass$ $[Log(M/M_\odot)]$	d $[Kpc]$	σ_0 $[km/s]$
NGC5272(M3)	-1.66	3.5	5.8	10.1	5.6
NGC6205(M13)	-1.65	3.4	5.8	7.7	7.1
NGC6093(M80)	-1.64	5.4	6.0	9.8	12.4
NGC6254(M10)	-1.60	3.8	5.4	4.7	5.6
NGC288	-1.40	2.1	4.9	8.8	2.9
NGC6341(M92)	-2.24	4.4	5.3	9.0	5.9
NGC6752	-1.60	5.2	5.2	4.3	4.5

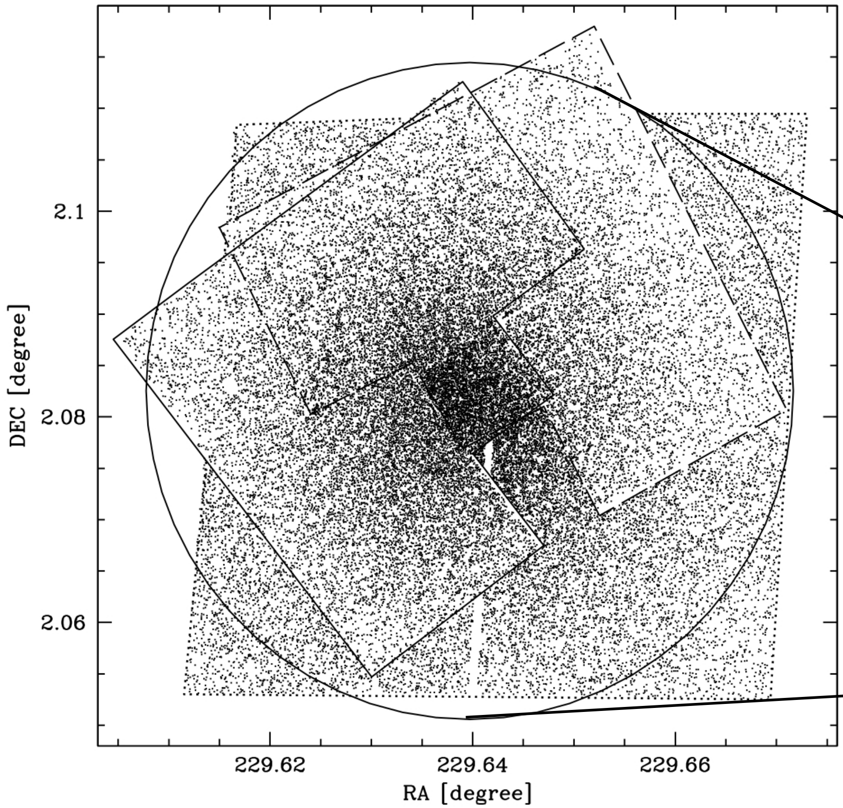
N_{BSS} must be normalized to the cluster population

$\mathcal{F}$ = *BSS* specific frequency

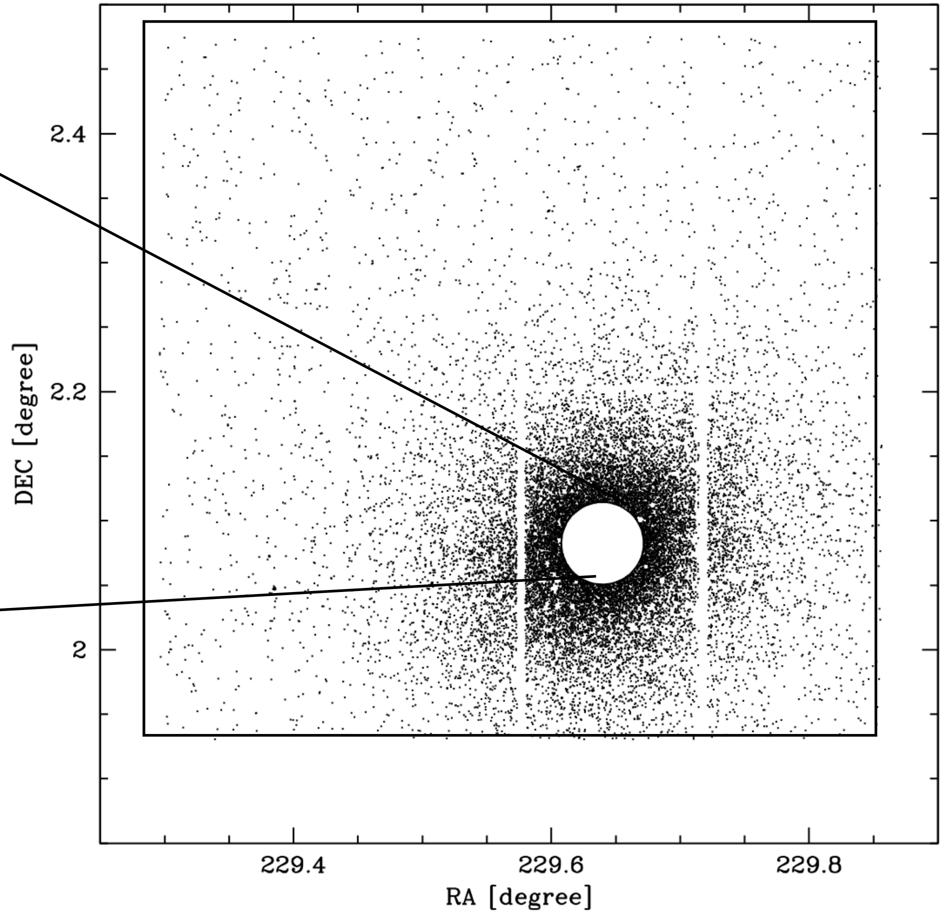
$\mathcal{F} = N_{BSS} / N_{HB}$

Cluster	$[Fe/H]$	$Log\rho_0$ $[M_\odot/pc^3]$	N_{b-BSS}	N_{HB}	F^{HB}_{BSS}
NGC5272(M3)	-1.66	3.5	72	257	0.28
NGC6205(M13)	-1.65	3.4	16	237	0.07
NGC6093(M80)	-1.64	5.4	129	288	0.44
NGC6254(M10)	-1.60	3.8	22	82	0.27
NGC288	-1.40	2.1	24	26	0.92
NGC6341(M92)	-2.24	4.4	53	159	0.33
NGC6752	-1.60	5.2	17	108	0.16

High-res: HST/WFPC2+ACS

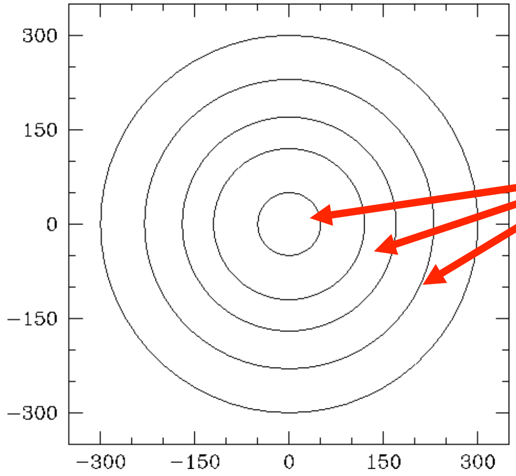


Wide-field ground-based imaging



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**

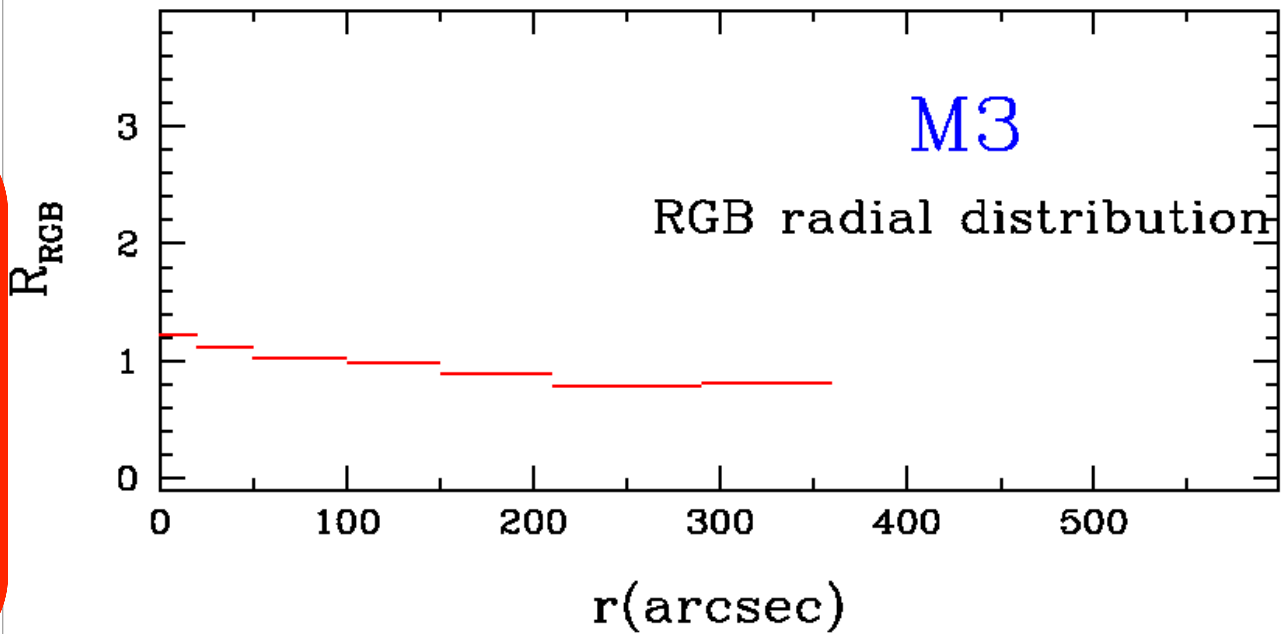
THE BSS RADIAL DISTRIBUTION



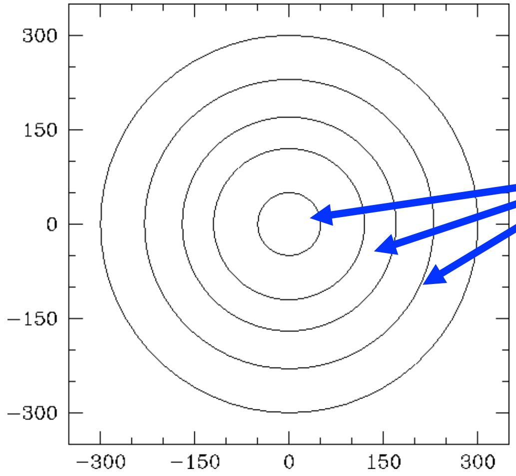
$$R_{RGB} = \frac{N_{RGB}/N_{RGB,TOT}}{L_{samp}/L_{TOT}}$$

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

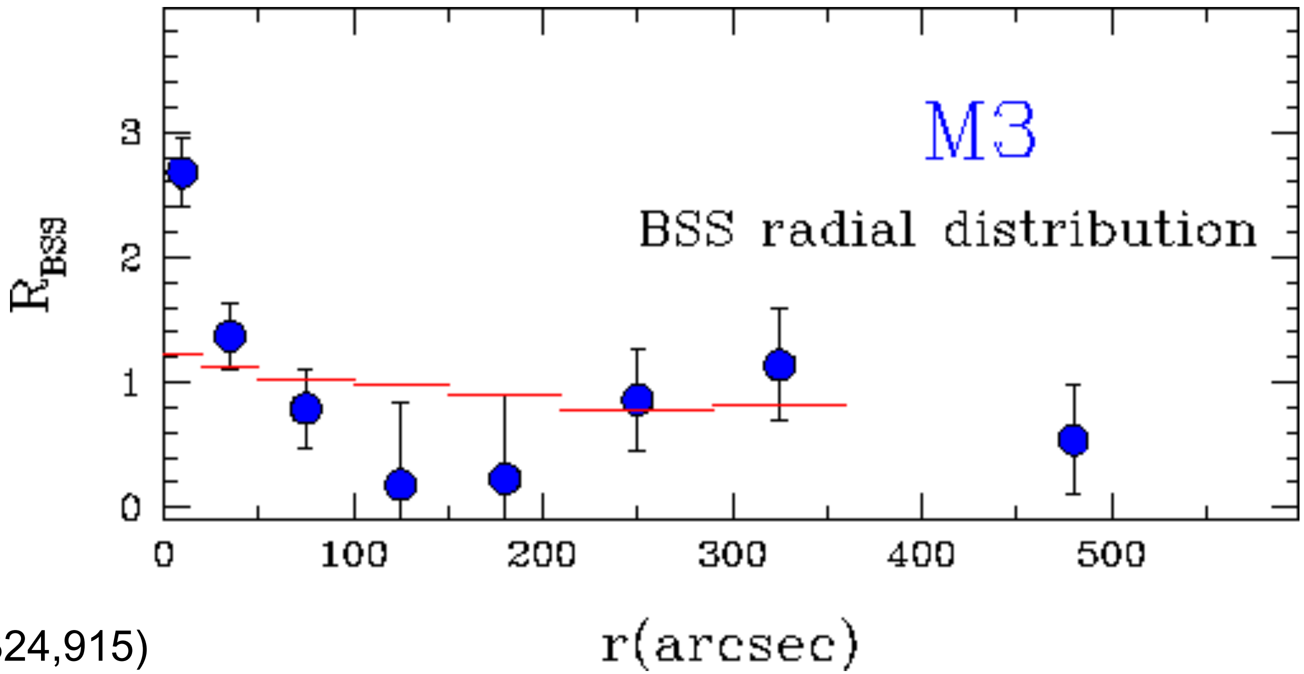
Note that *a flat distribution* in this plot means that *"the number of stars in each annulus exactly scales with the cluster light sampled by each annulus"*



THE BSS RADIAL DISTRIBUTION



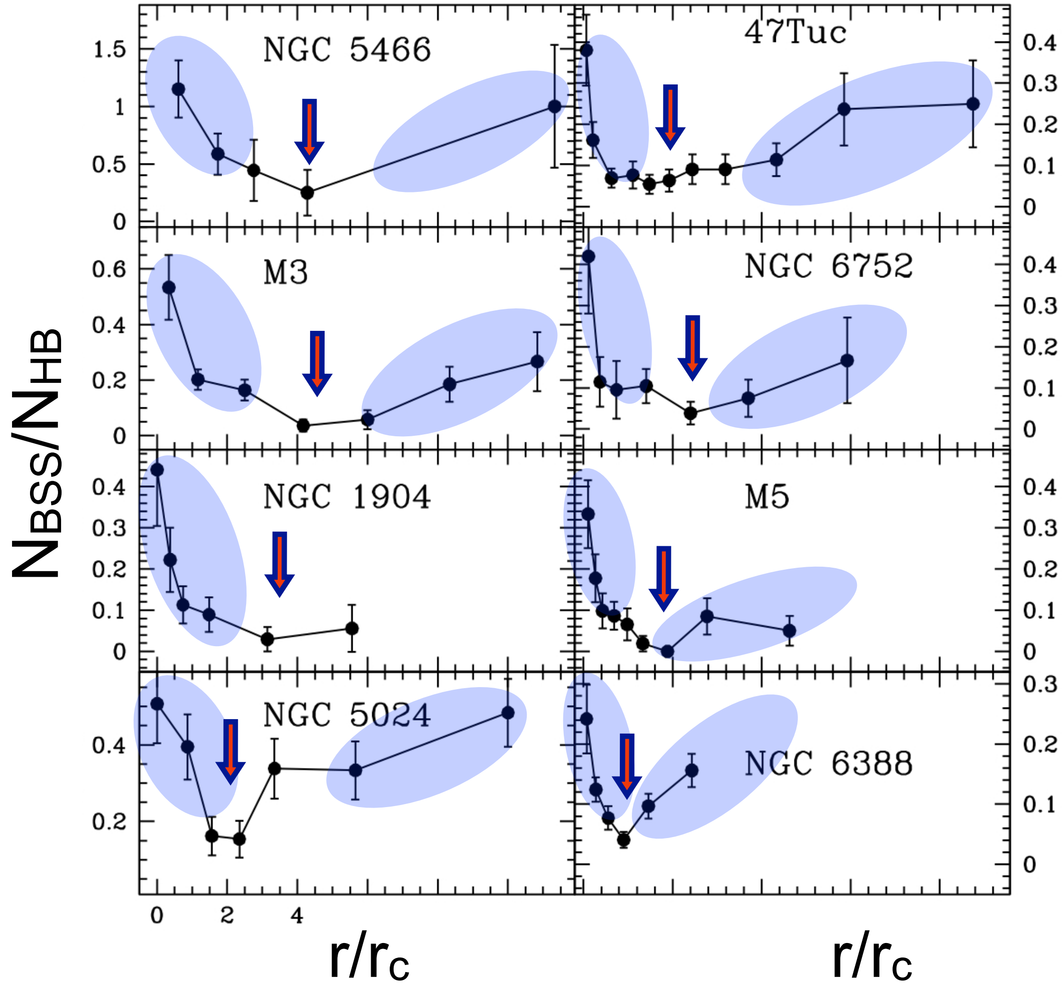
$$R_{BSS} = \frac{N_{BSS}/N_{BSS,TOT}}{L_{samp}/L_{TOT}}$$



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

BSS radial distribution

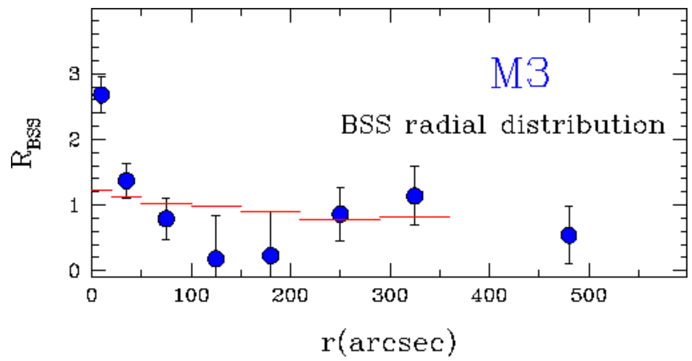
Over the last 15 years we studied the BSS radial distribution over the entire cluster extensions in 25 stellar systems. Finding a variety of cases



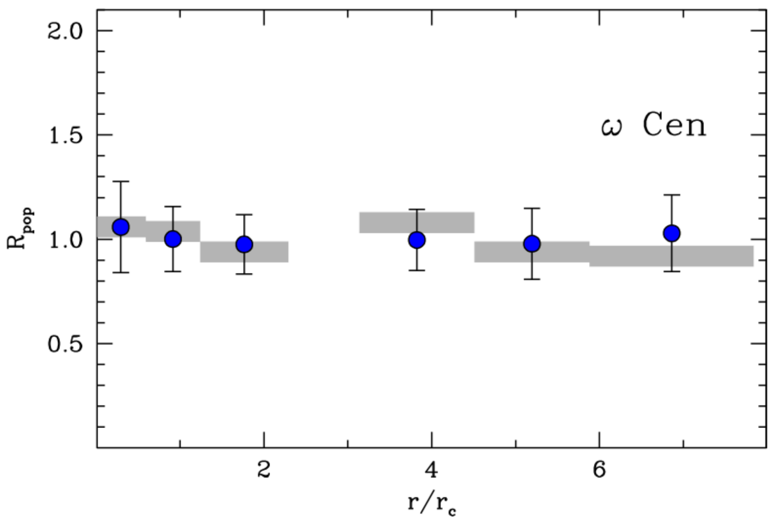
BSS radial distribution

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

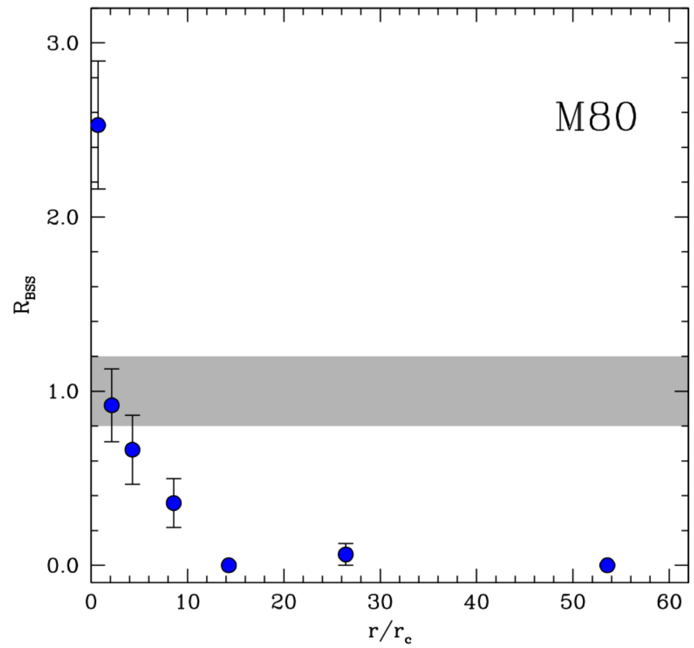
"bimodal"



"Flat"



"Unimodal" (single-peak)



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 progressively **at larger and larger distances,** as function of time

BSS radial distribution

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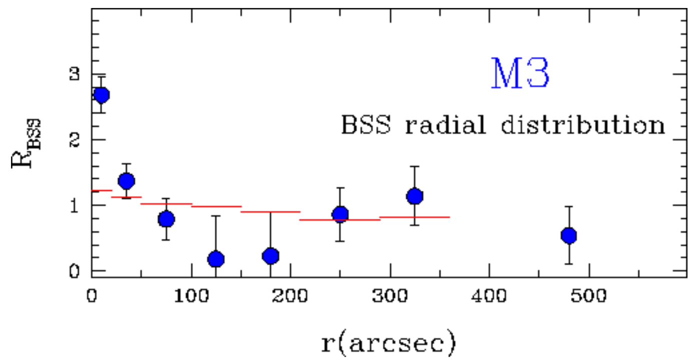
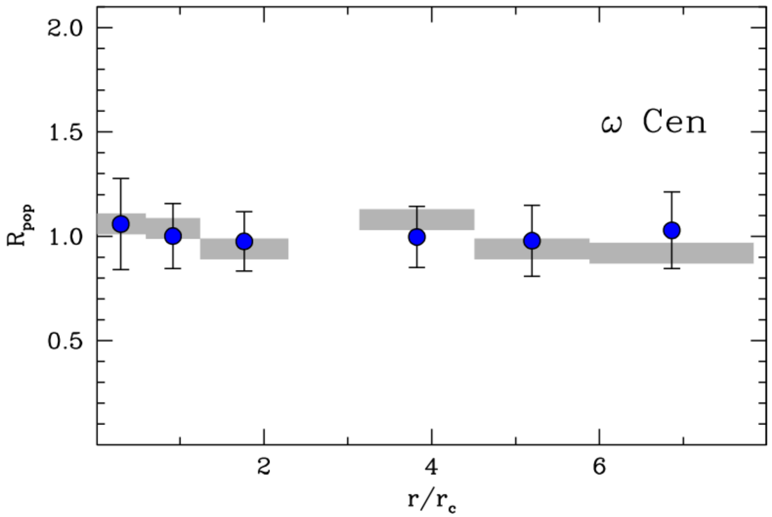
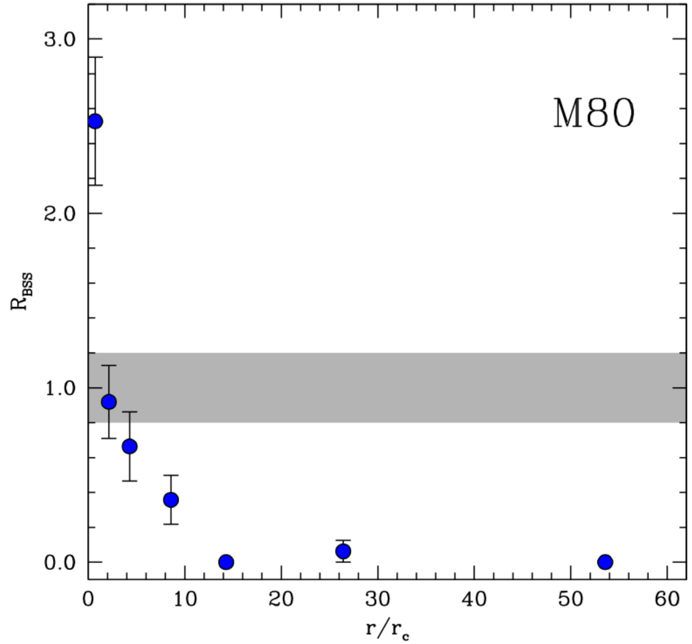
"bimodal"



"Flat"



"Unimodal" (single-peak)



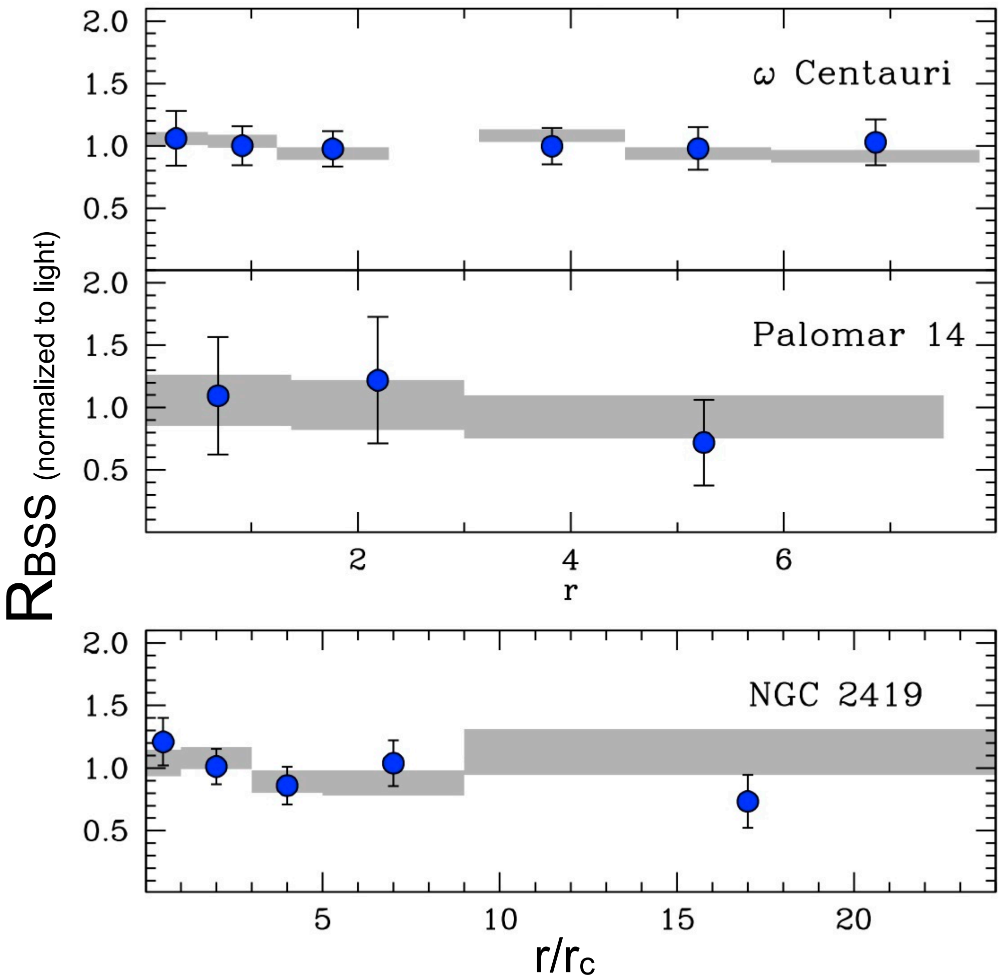
The BSS radial distribution is shaped by dynamical friction, which segregates BSS progressively in time

….. 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 fully agreement with that of "normal stars"

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

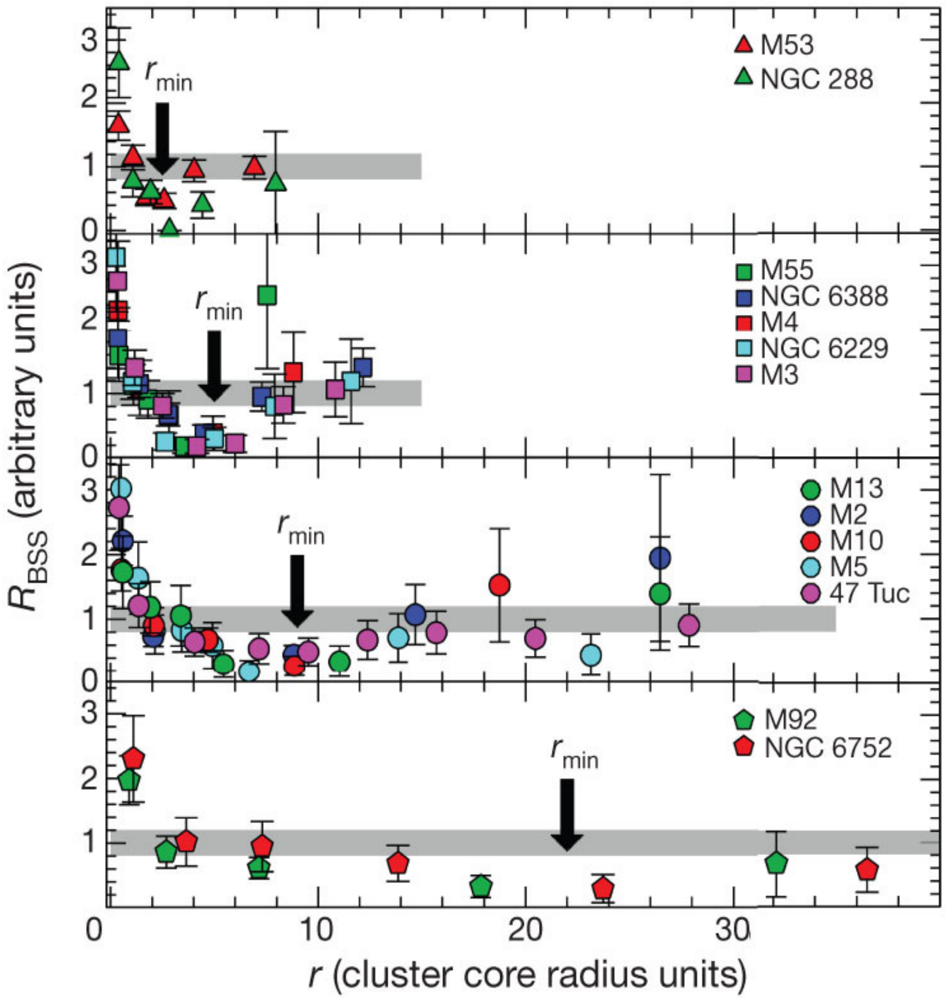
Note that this is the **most efficient way** to prove that these stellar systems are not relaxed yet

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

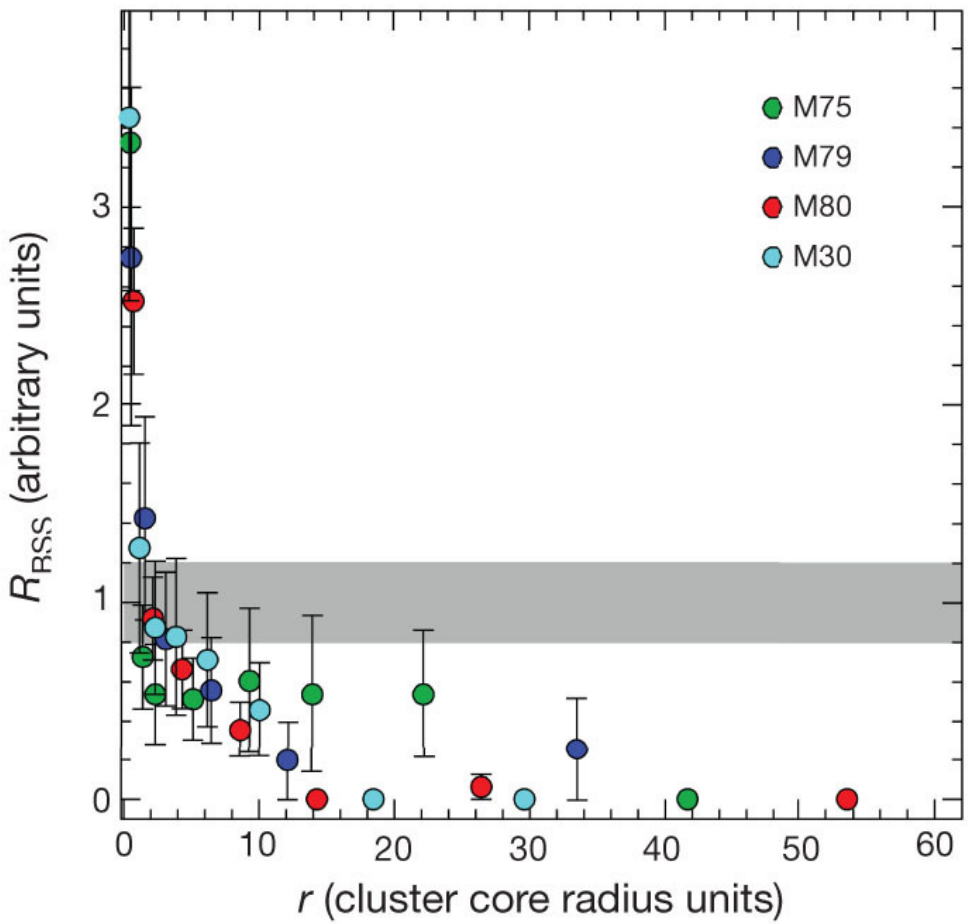
The action of **df** extends progressively at larger distances from the cluster center = the minimum is moving progressively outward

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

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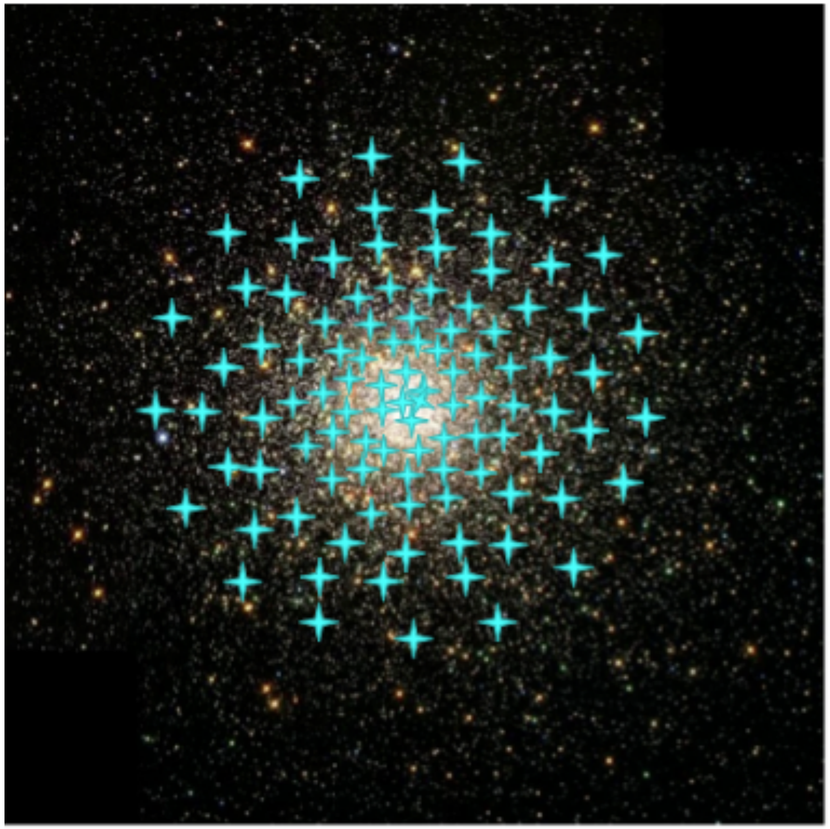
The dynamical clock

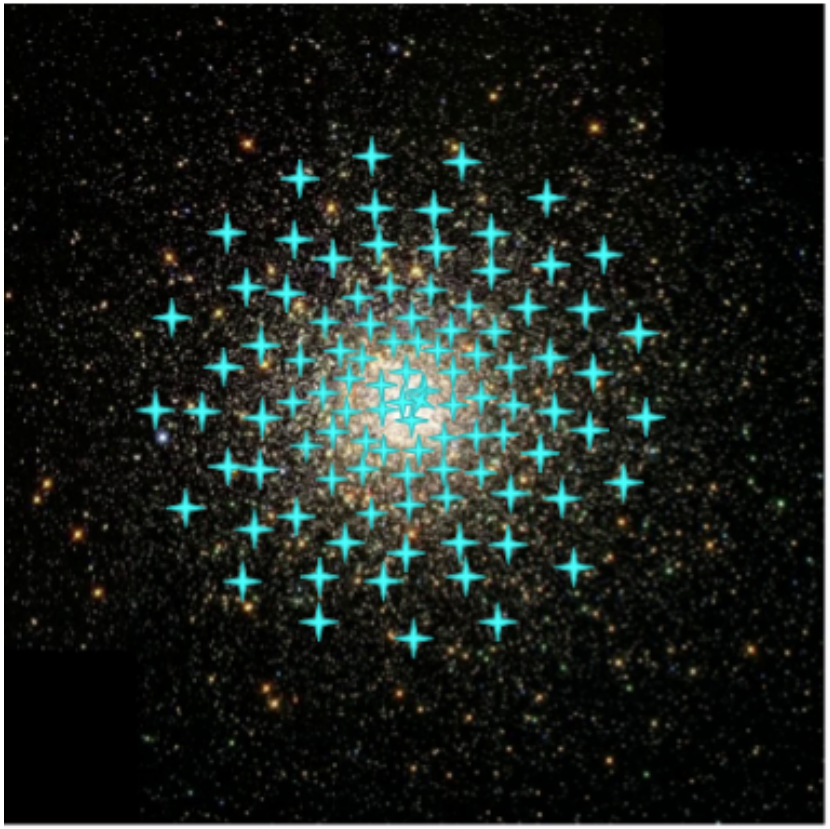
Ferraro et al (2012,Nature,492,393)



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

The dynamical clock

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



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The dynamical clock

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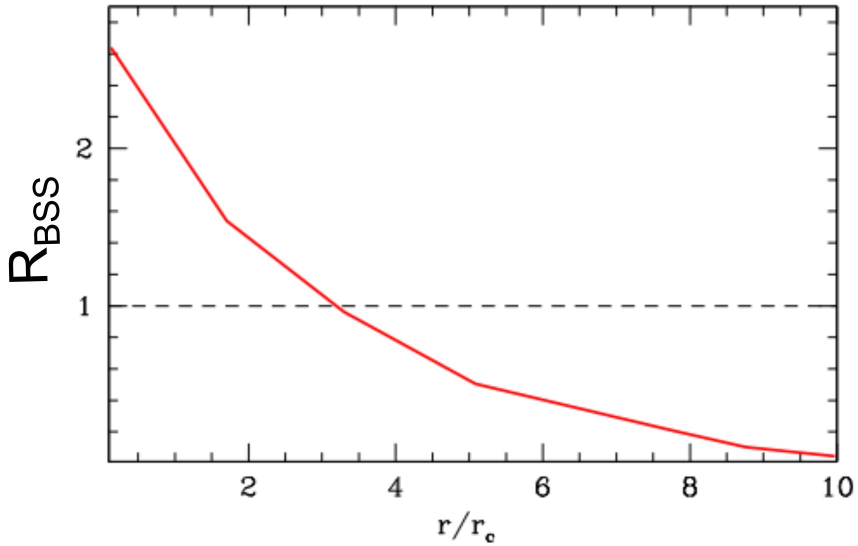
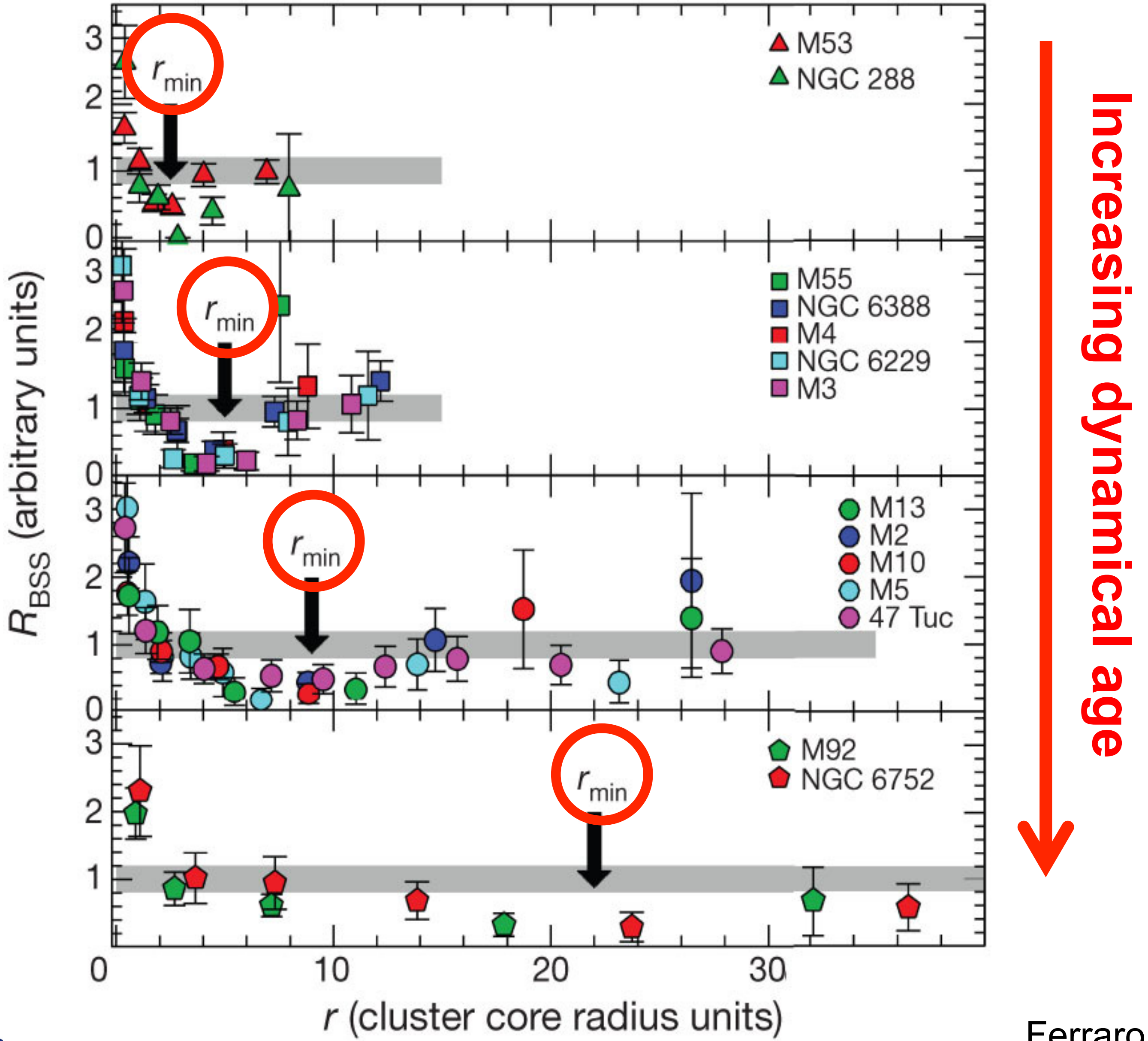


As the engine of a chronometer advances a clock-hand to measure the flow of time, in a similar way dynamical friction moves the minimum outward measuring the dynamical age of a stellar system

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



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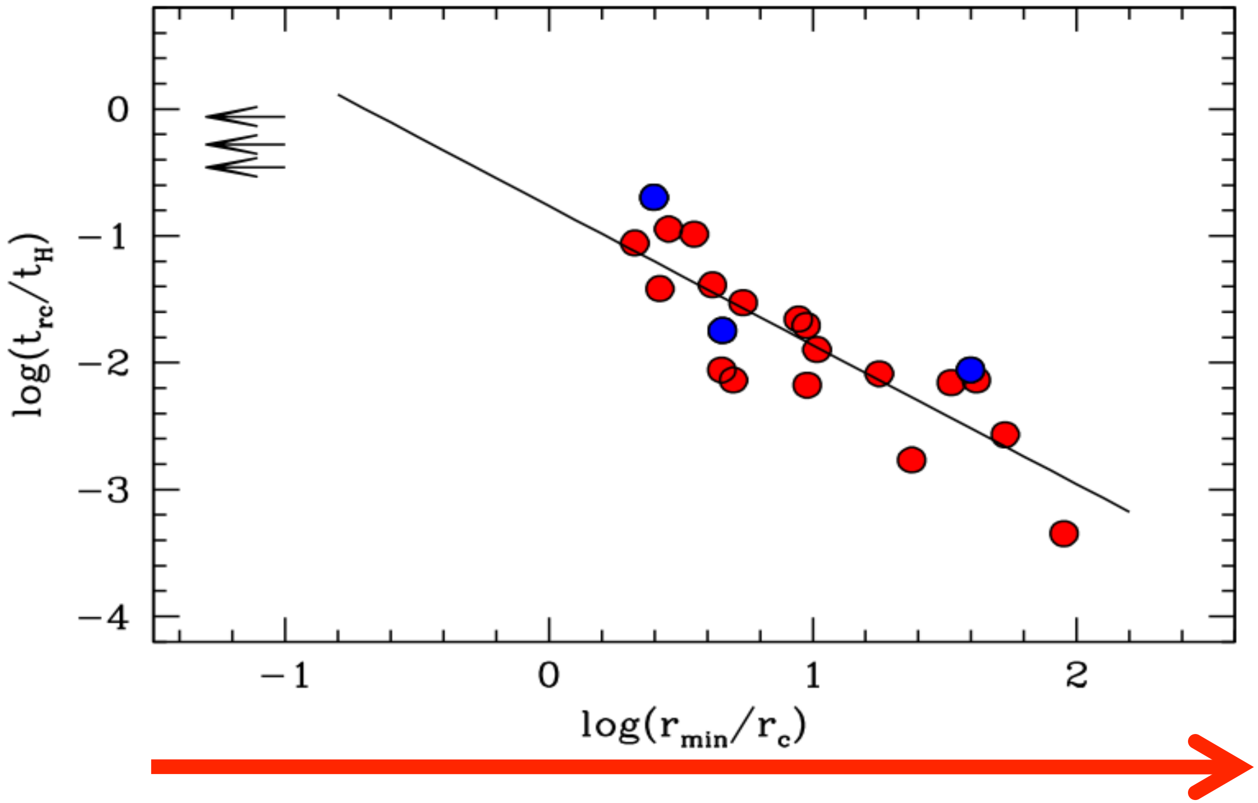
Ferraro et al 2012, Nature,492,393

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. The position of the hand of the clock nicely agrees with theoretical estimates of the central relaxation time (t_{rc})



Increasing dynamical age

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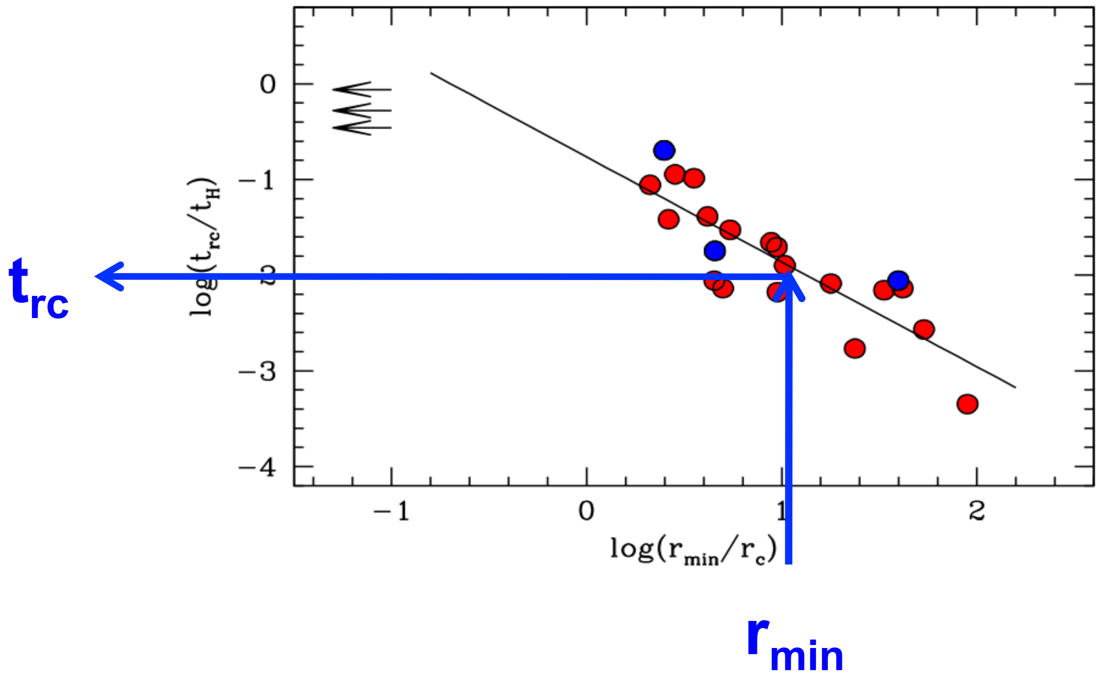
The dynamical clock

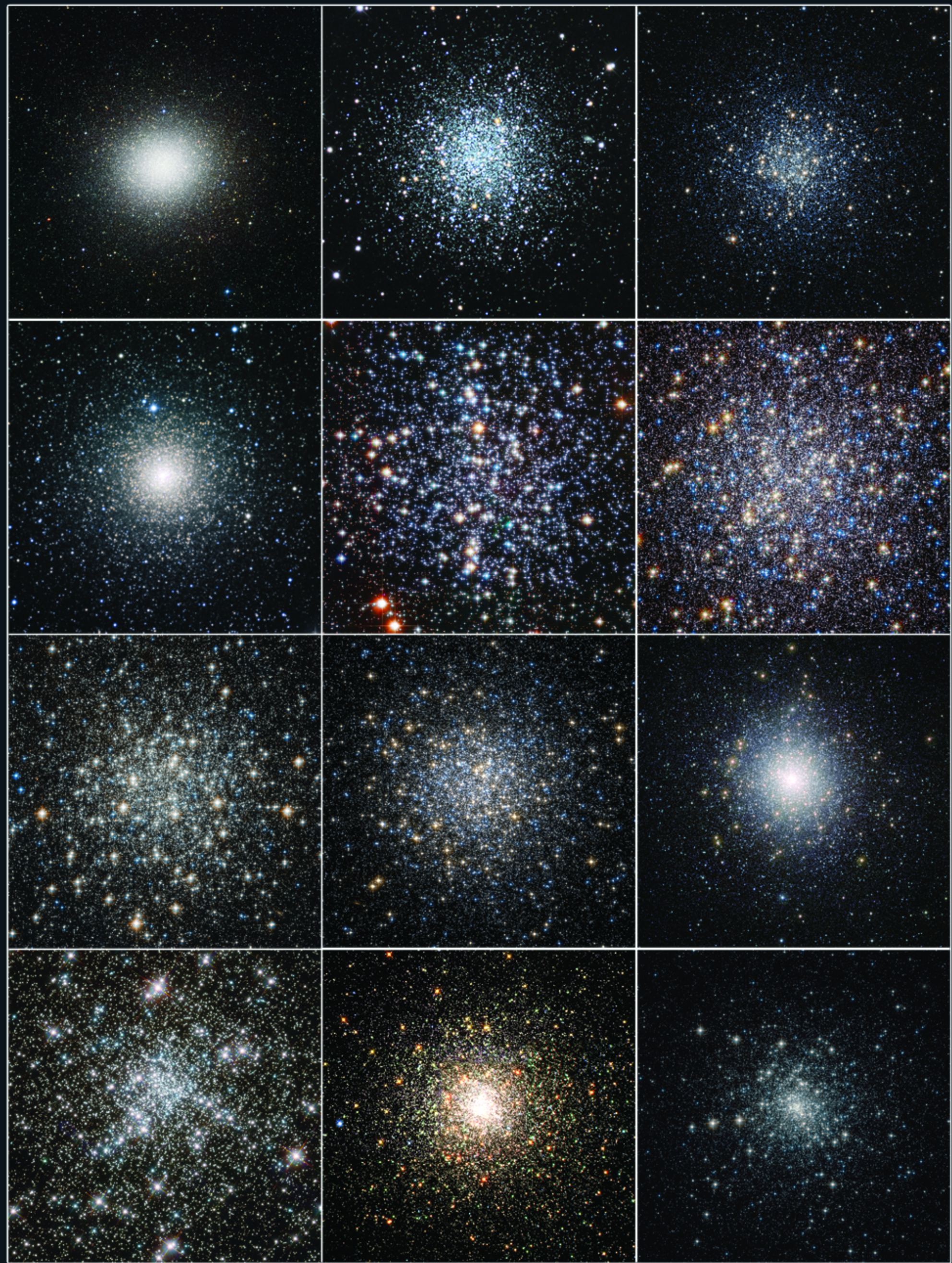
Ferraro et al (2012,Nature,492,393)

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



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

THE DYNAMICAL CLOCK

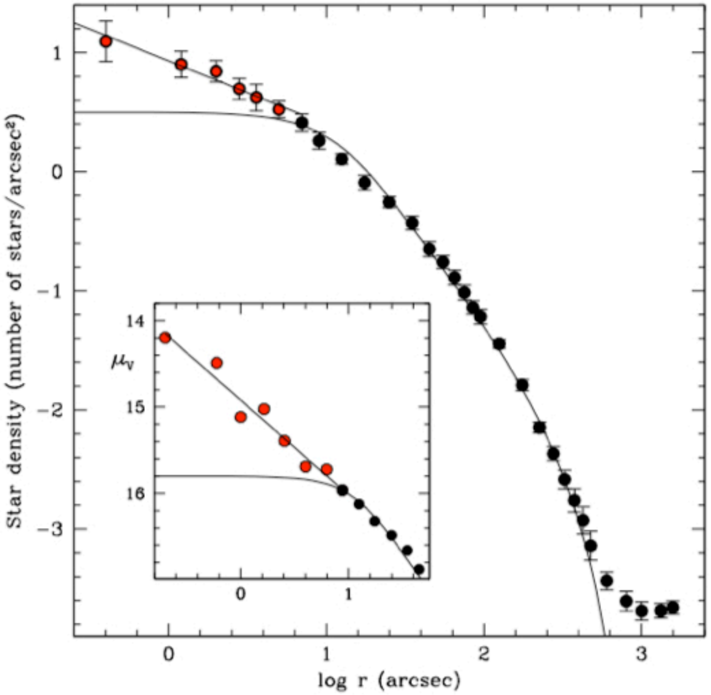


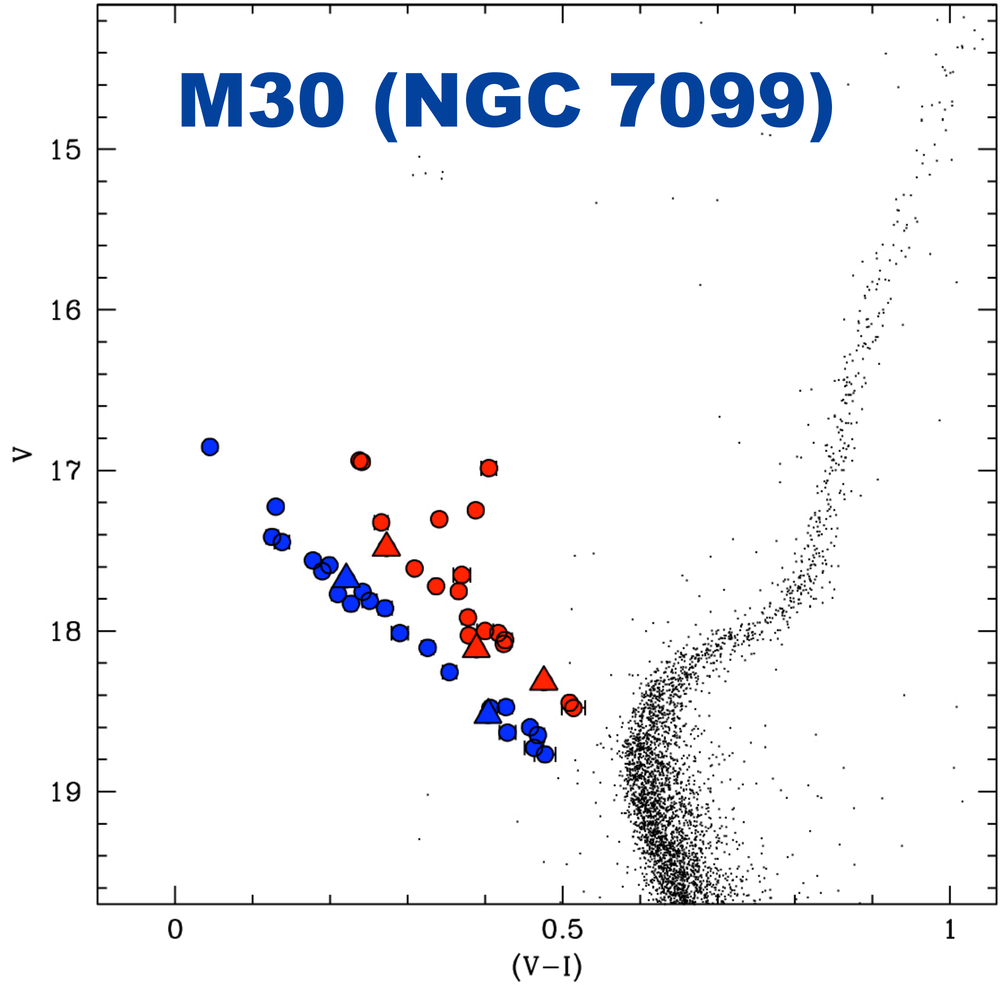
Mosaic of 12 images of Milky Way globular clusters ranked in order of increasing dynamical age, as measured by the "dynamical clock of stellar systems".
From top-left, to bottom-right: omegaCentauri, NGC 288, M55, NGC 6388, M4, M13, M10, M5, 47 Tucanae, NGC 6752, M80, and M30.

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).

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**





2 distinct sequences of BSS !!

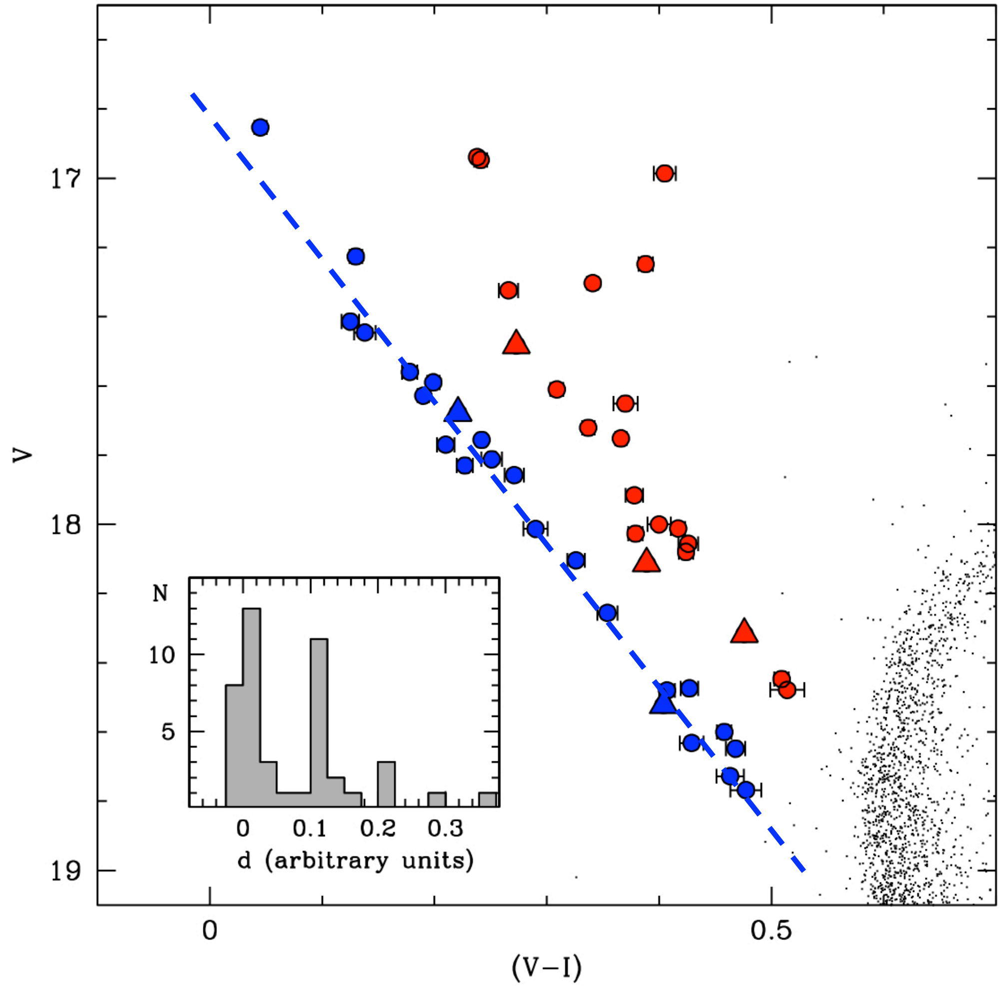
Ferraro et al. (2009, Nature 462, 1028)

2 distinct sequences of BSS !

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

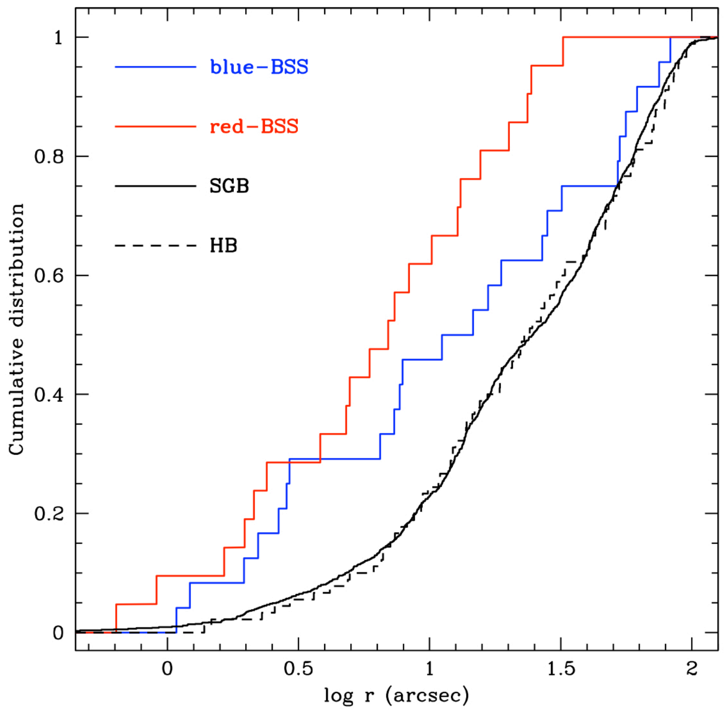
- **similarly populated:**
  24 blue-BSS
  21 red-BSS

- **almost parallel:**
  separated in mag by ΔV ≈ 0.4
  in col by Δ(V-I) ≈ 0.12

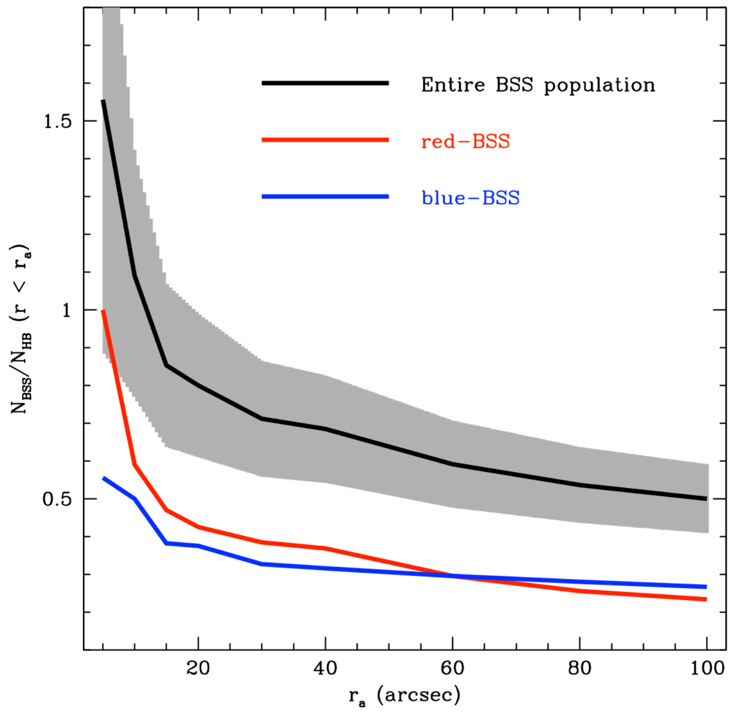


- **centrally segregated:**

cumulative radial distribution



specific frequency N_{BSS}/N_{HB}



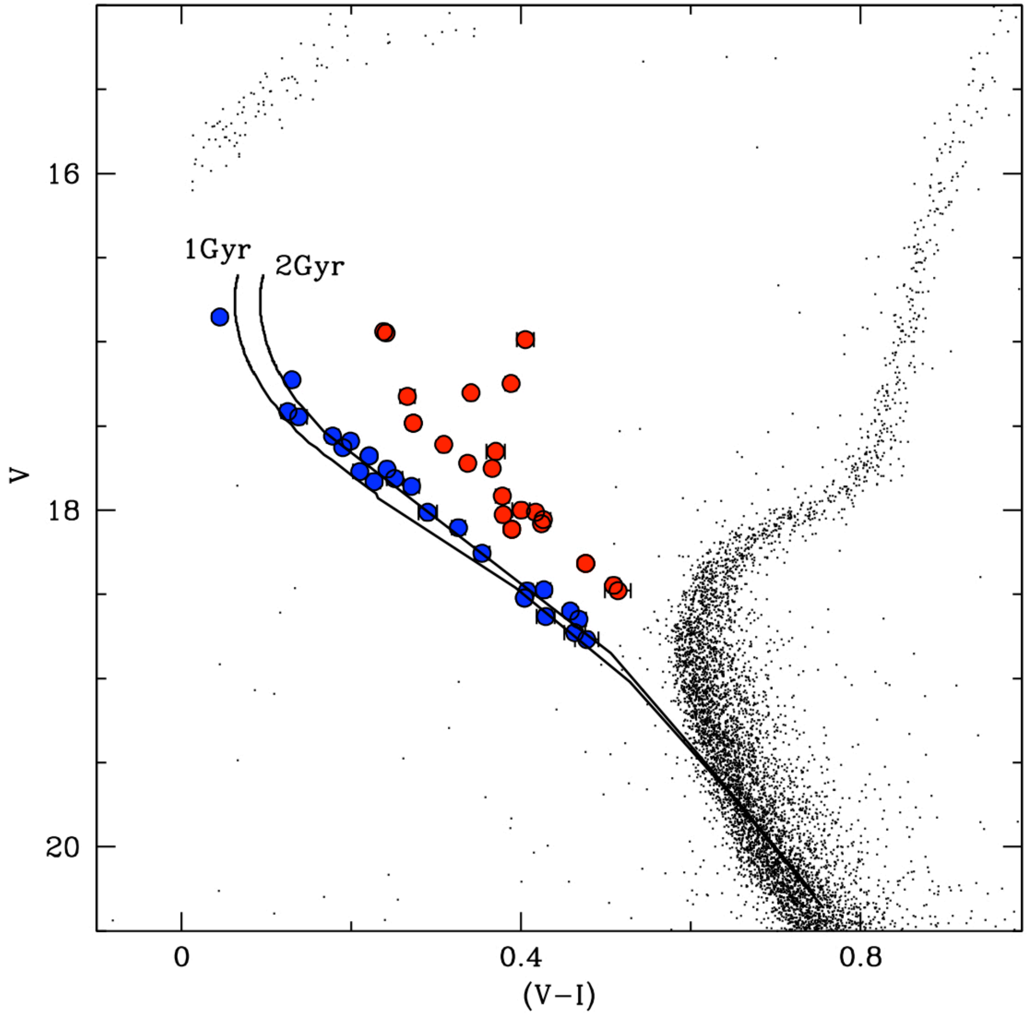
- BSS more centrally concentrated than SGB & HB stars (> 4 σ significance level)
- **red-BSS** more concentrated than **blue-BSS** (~ 1.5 σ significance level)

different formation mechanism for red- and blue-BSS?

Evolutionary models of COL-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**

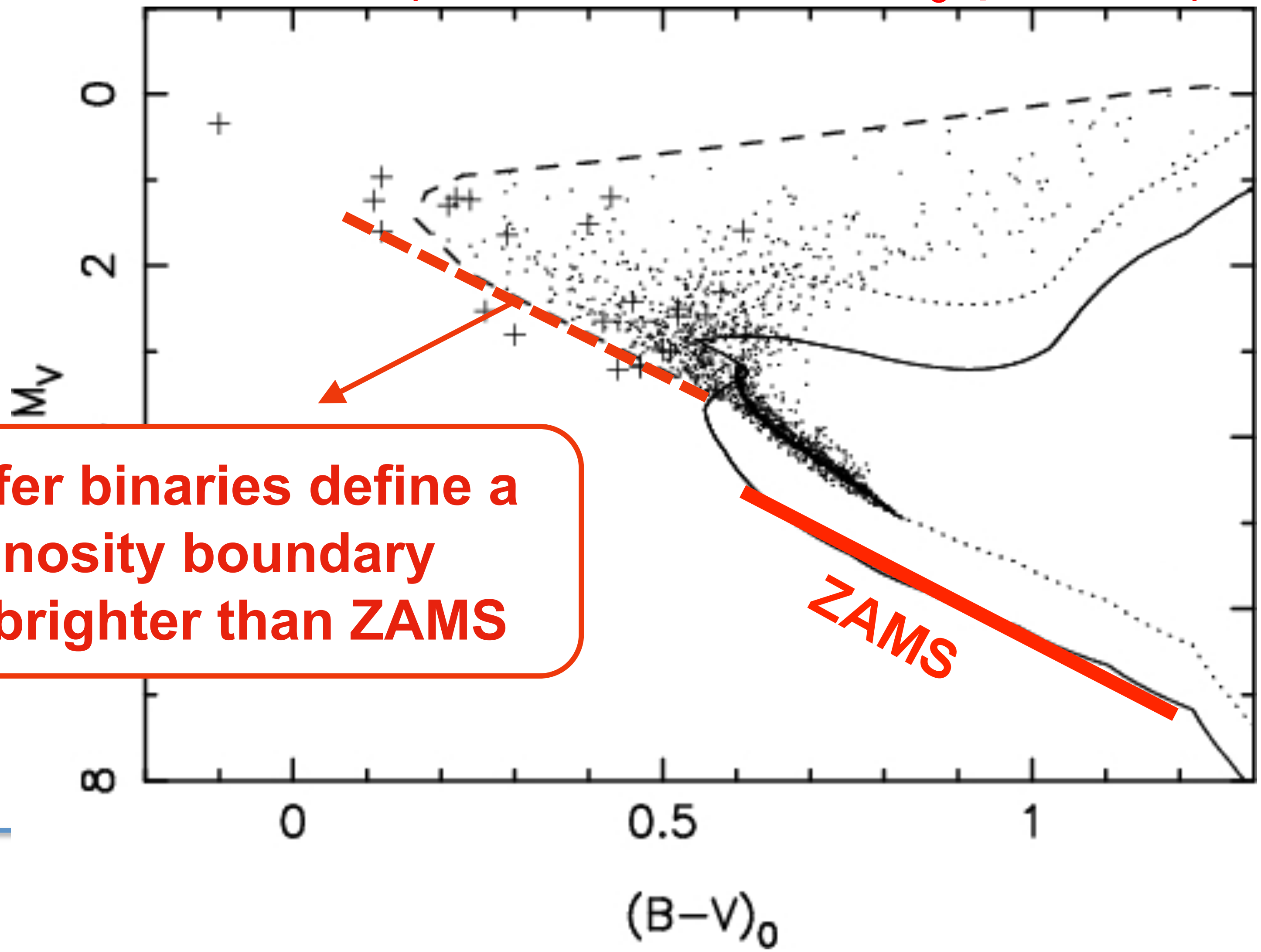


- **red-BSS** sequence **too red** to be reproduced by collisional isochrones of **any** age

Binary evolution models (Tian et al. 2006)

+ : observed BSS in M67 (Deng et al. 1999)

dots: simulated mass-transfer binaries **(2000 PB, donor: 1.2-1.4 $M_{\odot}$,q: 0.35-0.95)**



mass-transfer binaries define a low-luminosity boundary ~0.75 mag brighter than ZAMS

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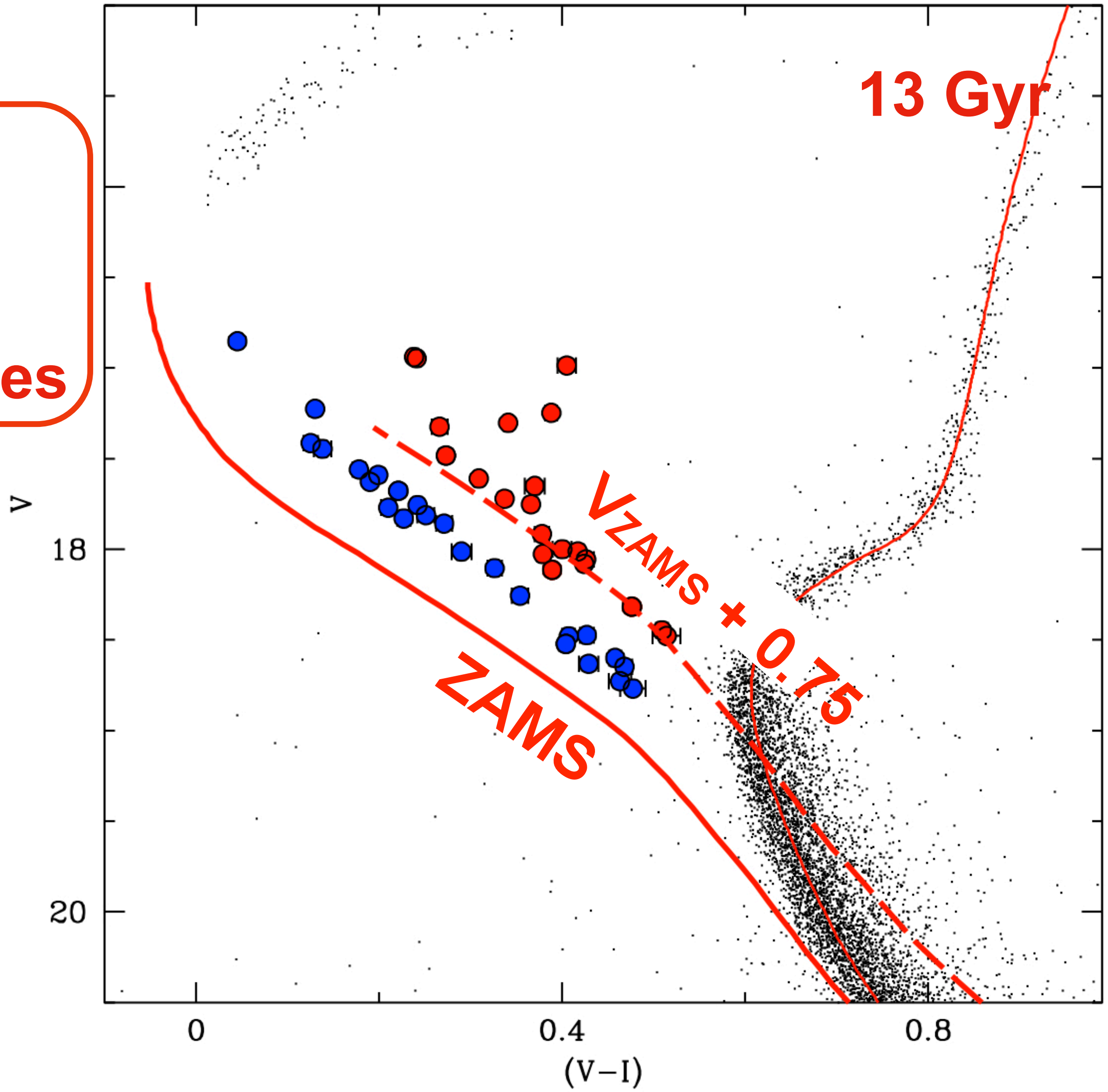
Single star isochrones of $Z = 2\ 10^{-4}$

(Cariulo et al. 2004)

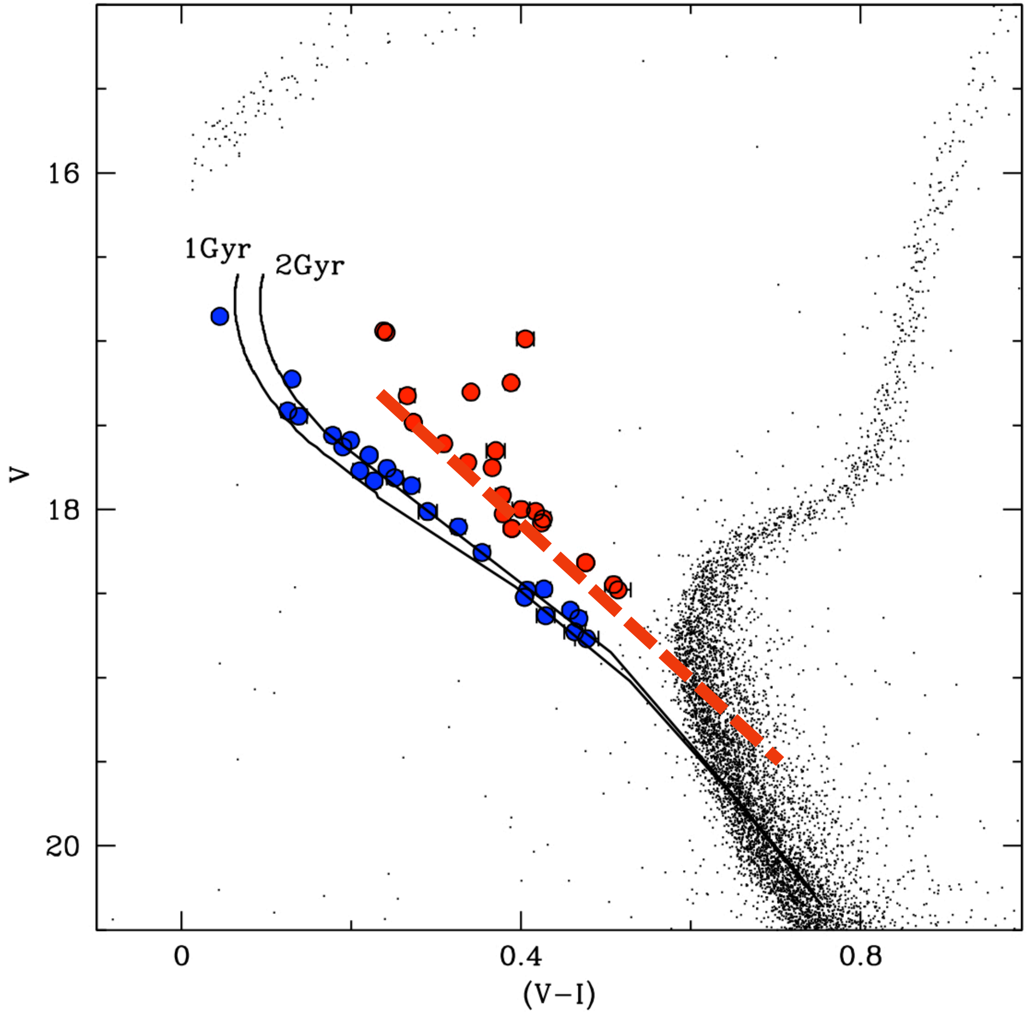
red-BSS sequence well reproduced by models of mass-transfer binaries



BSS double sequences probe & date the cluster core-collapse

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

Red-BSS sequence is located at the low-luminosity boundary defined by MT binaries



Why did we observe the double-BSS sequence ONLY in the PCC M30 ???

• **blue-BSS → collisional** **red-BSS → MT binaries**

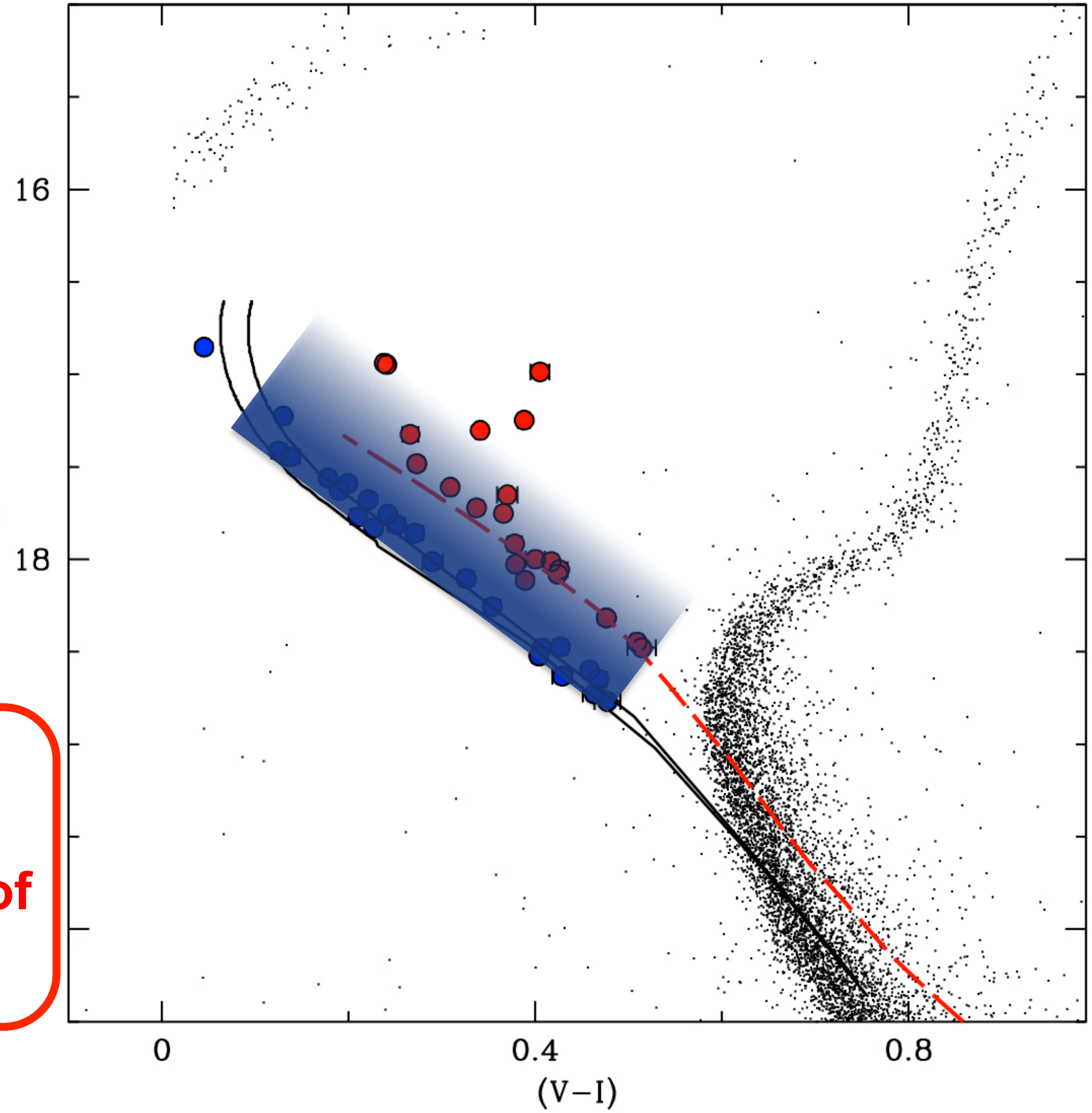
double BSS seq. is NOT a permanent feature

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

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



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

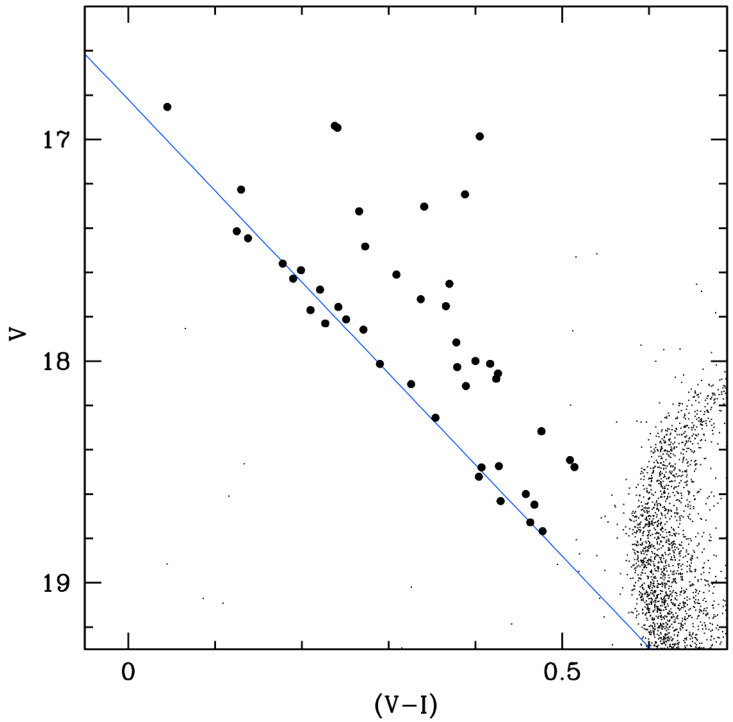
Is there any other PCC with a double BSS sequence?

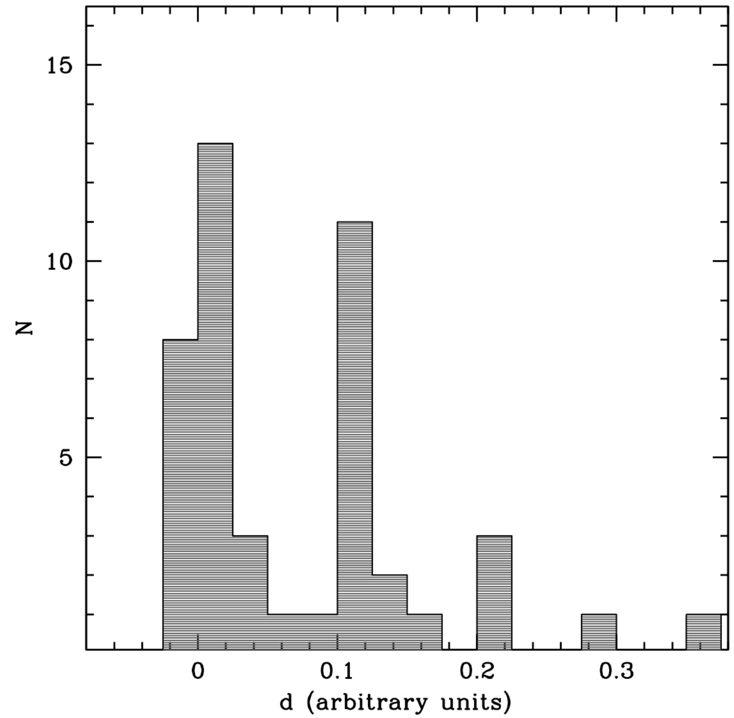
Classical PCC:
M15
NGC6397

Suspected PCC:
NGC362

BSS double sequence: The case of NGC6397

M30 (Ferraro et al. 2009)

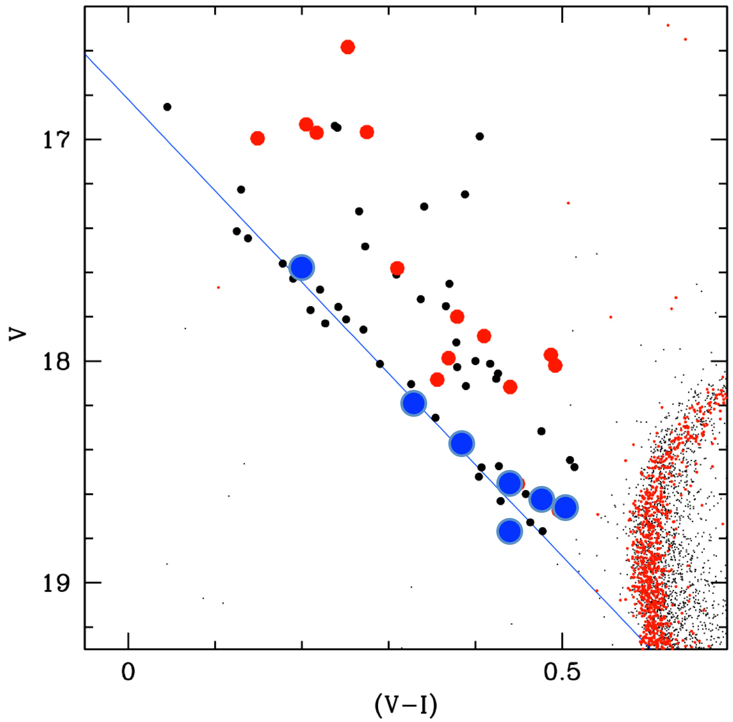


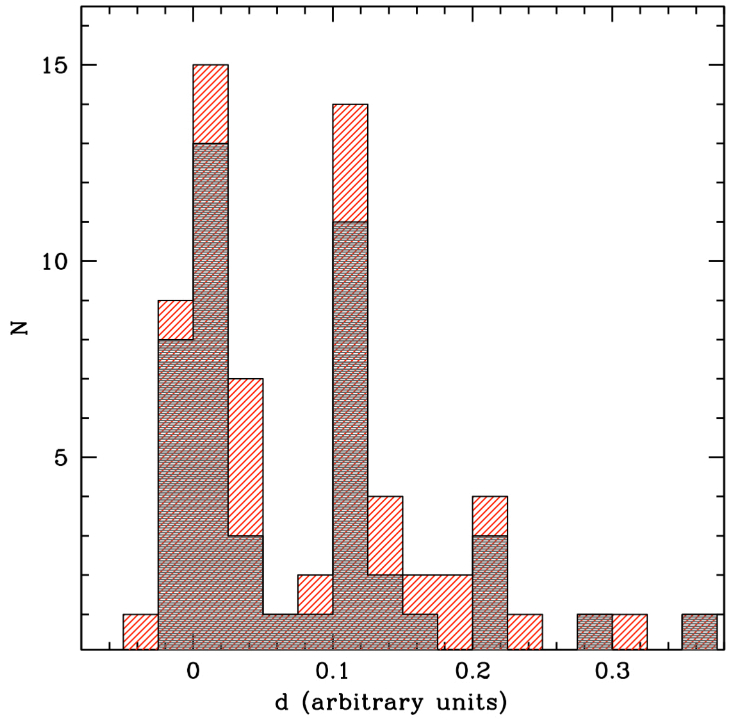


BSS double sequence: The case of NGC6397

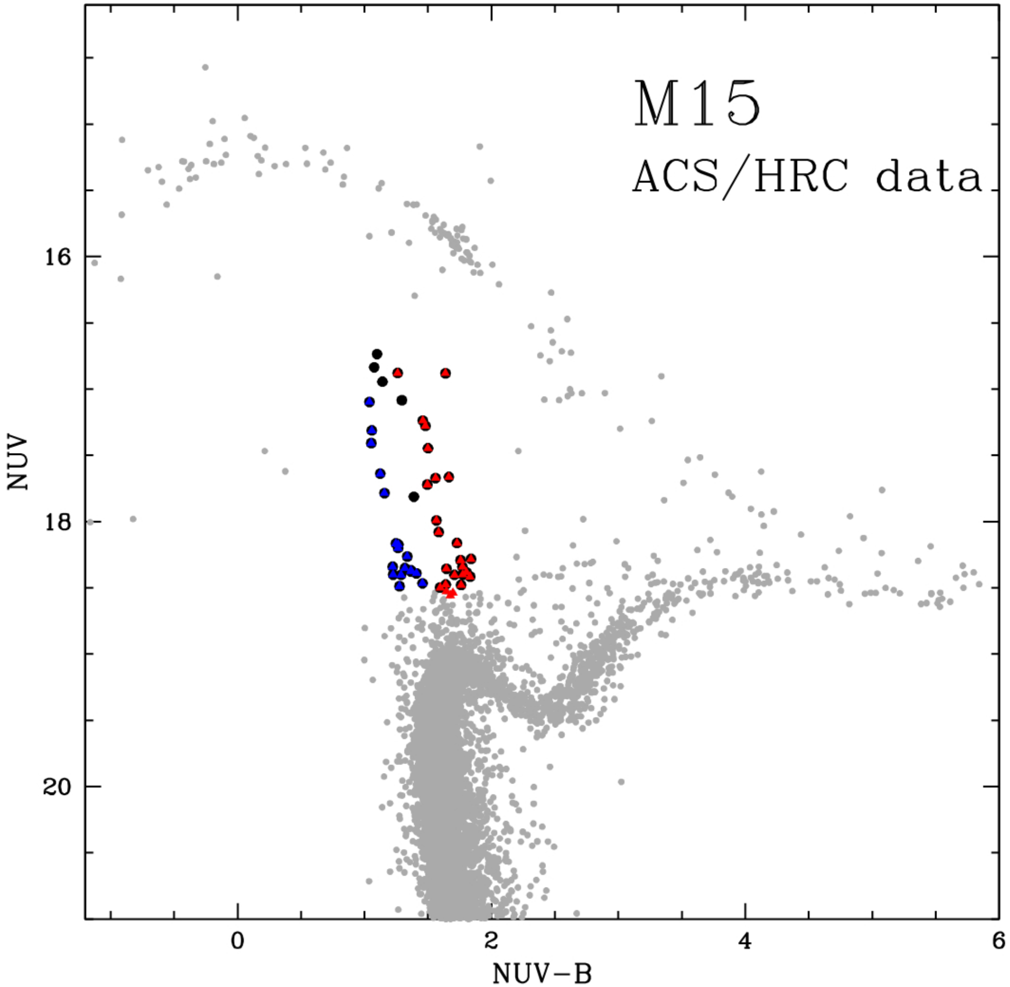
In the case of NGC6397 the **blue-BSS** sequence appear much less populated possibly suggesting that the core collapse in this cluster occurred much **earlier** than M30

NGC 6397 (Lanzoni et al. 2014, in preparation)





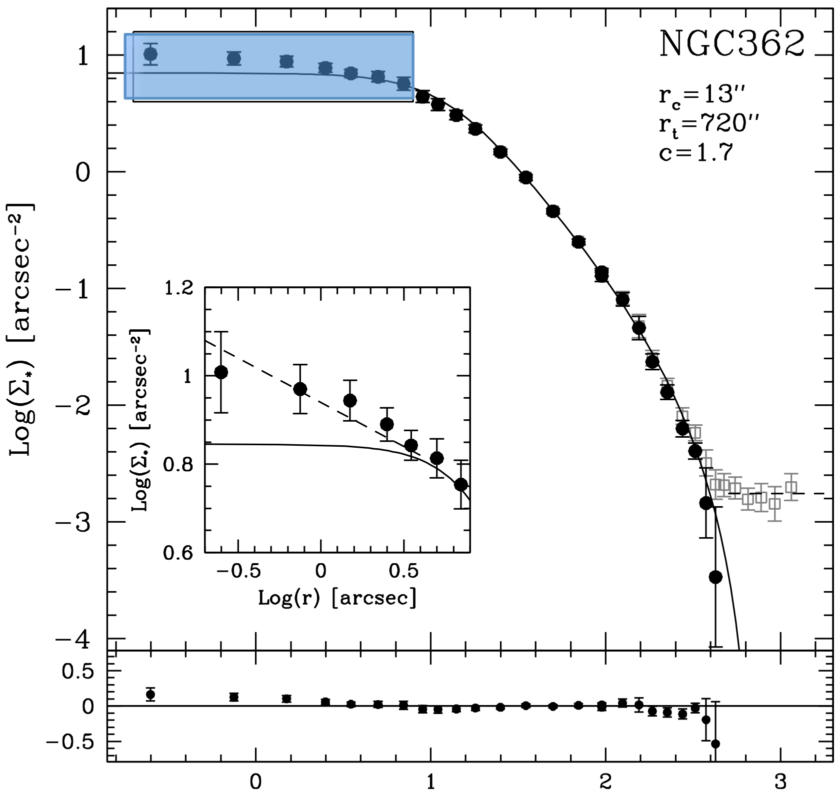
BSS double sequence: The case of M15



M15

(Beccari et al., in prep.)

BSS double sequence: The case of NGC362



The dynamical state of NGC362 is quite uncertain (Fischer et al. 1993, Trager et al. 1995, Harris et al. 2010, McLaughlin & van der Marel 2005)

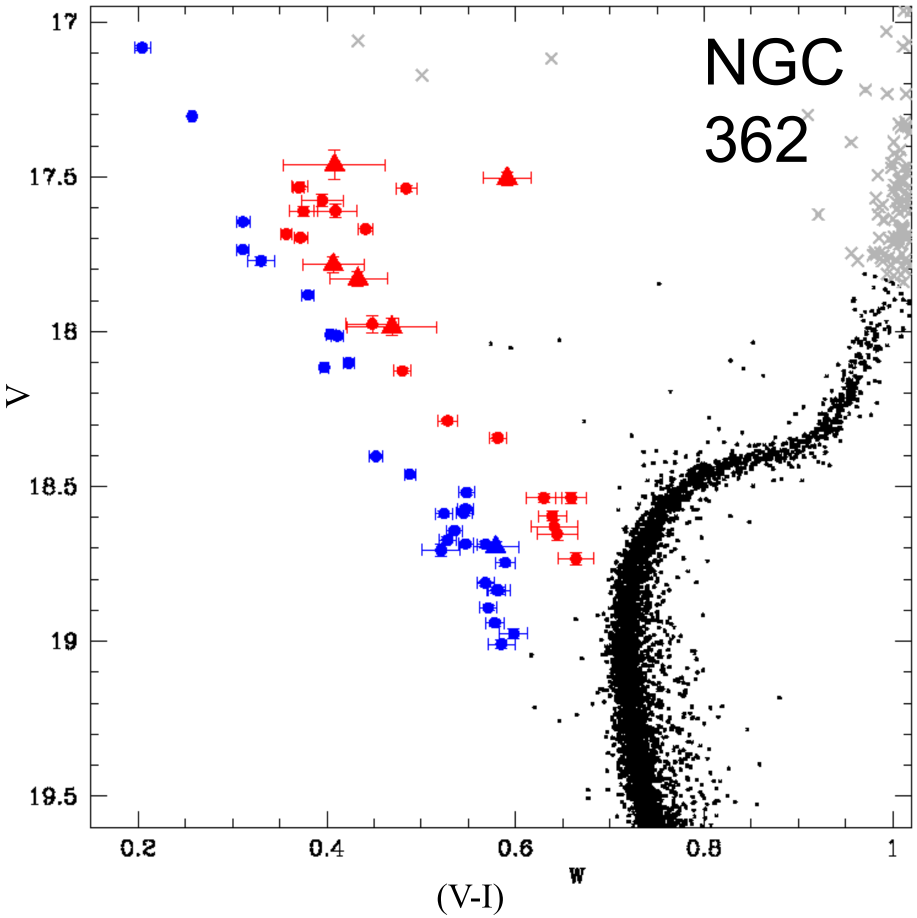
The innermost region (r<4”) is NOT REPRODUCED by a King model

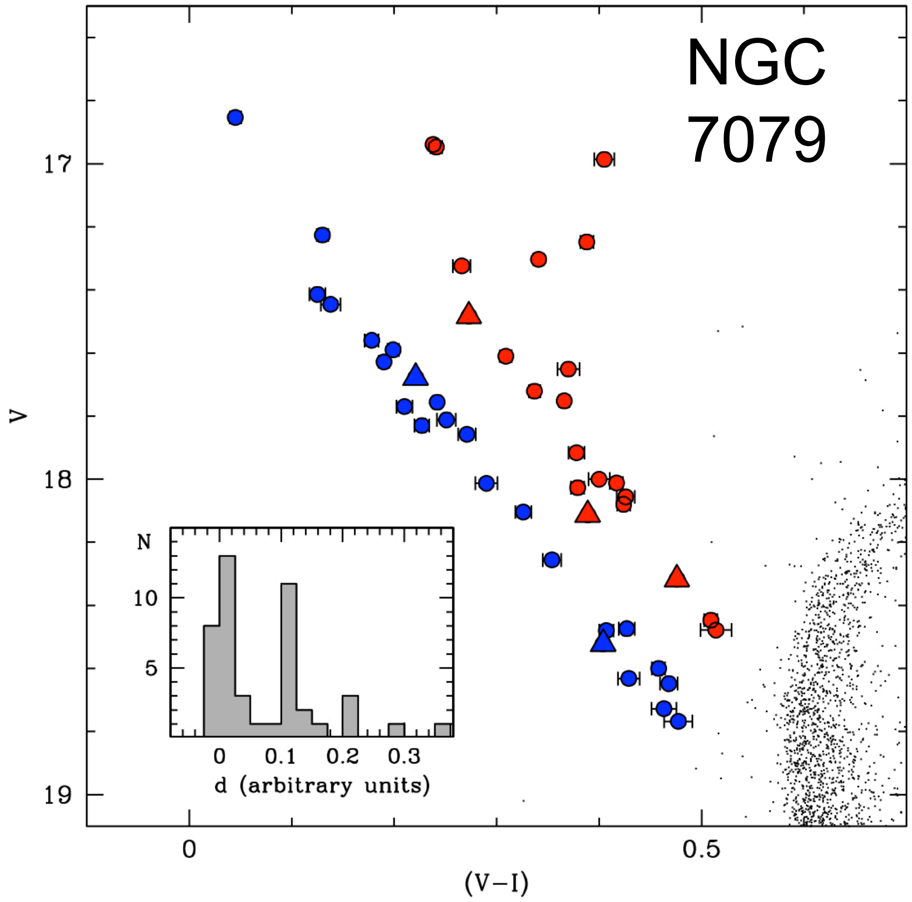
A mild power-law (α=-0.25) is observed

The observed density profile is compatible with that of a collapsed core

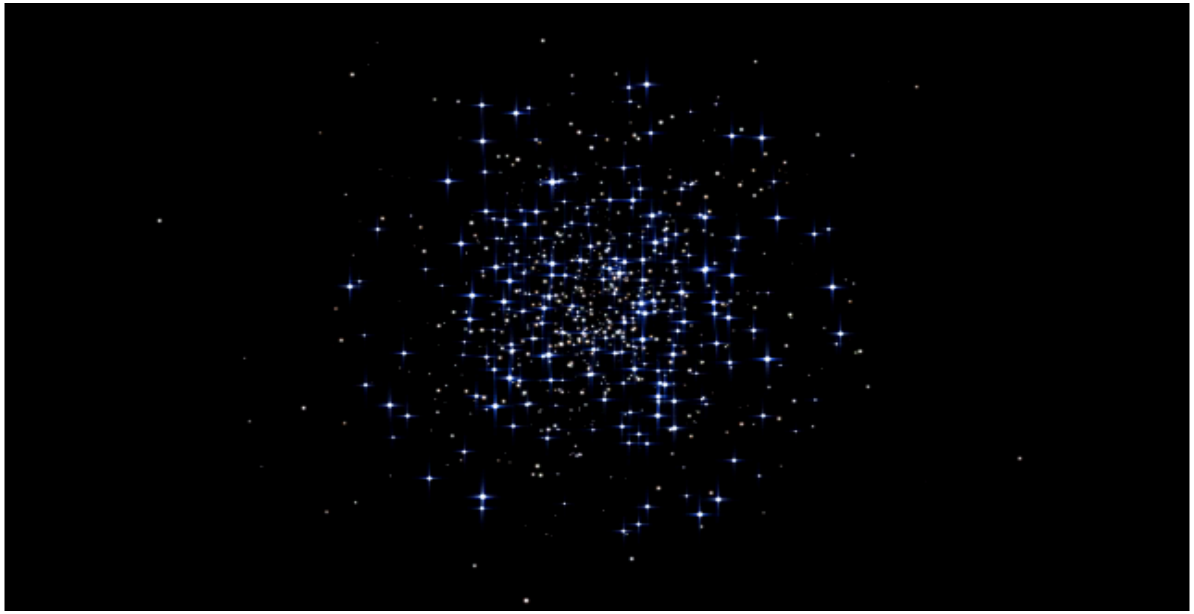
(Vesperini &Trenti 2010)

BSS double sequence: The case of NGC362





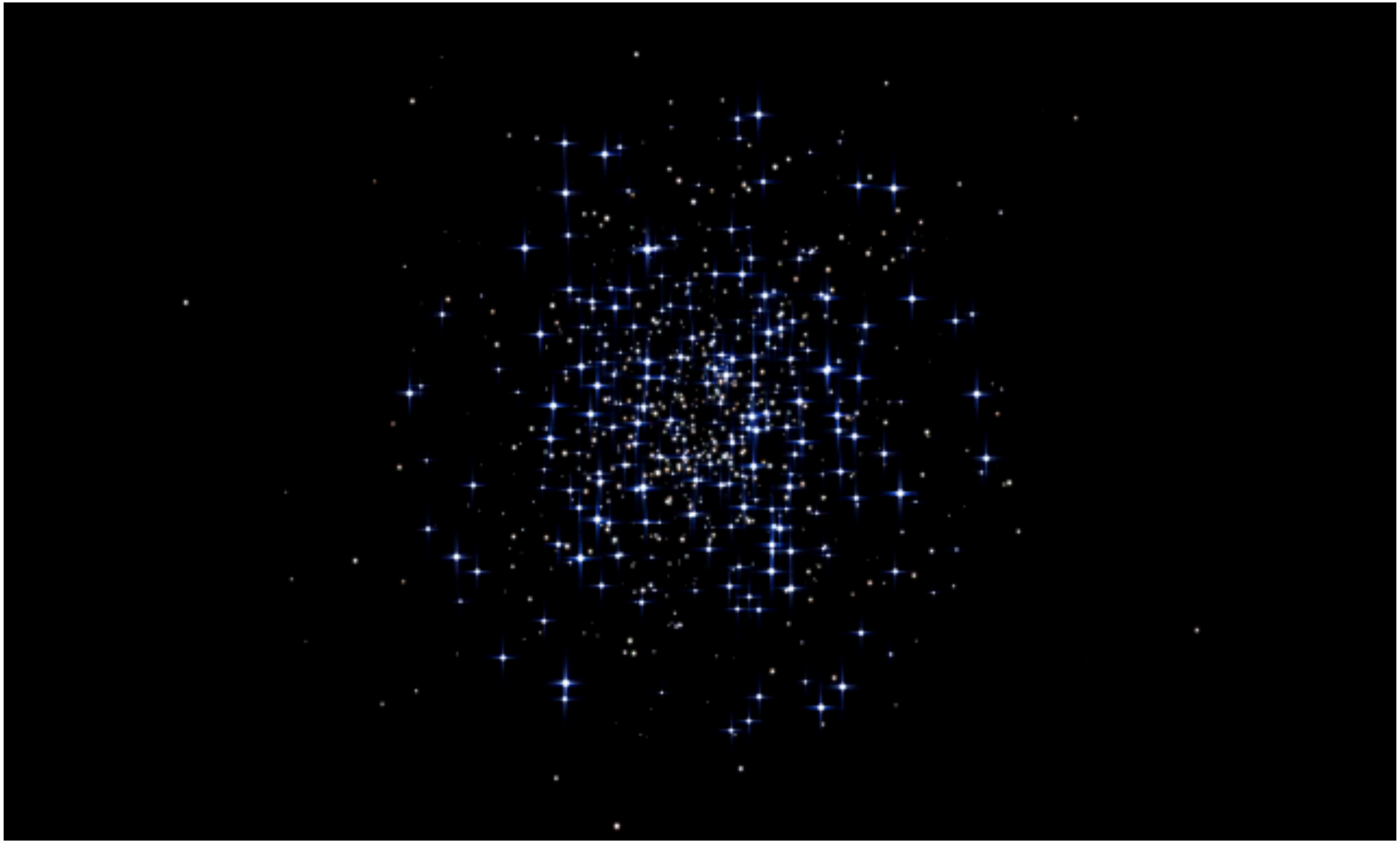
Dalessandro et al. 2013



BSS are crucial and powerful gravitational test particles.

Their properties (in terms of radial distribution, photometry, etc) seem to keep memory of the past history of the parent clusters offering us the possibility of dating their dynamical age and past crucial dynamical event (as the CC)…

…we have just started to learn how to read and interpret them….



Thank you for your attention !!!

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The End