An ESO Workshop on

THE IMPACT OF BINARIES ON STELLAR EVOLUTION

03 – 07 July 2017 I ESO HQ, Garching, Germany

The physics of BSS: defining a "dynamical clock" for stellar systems

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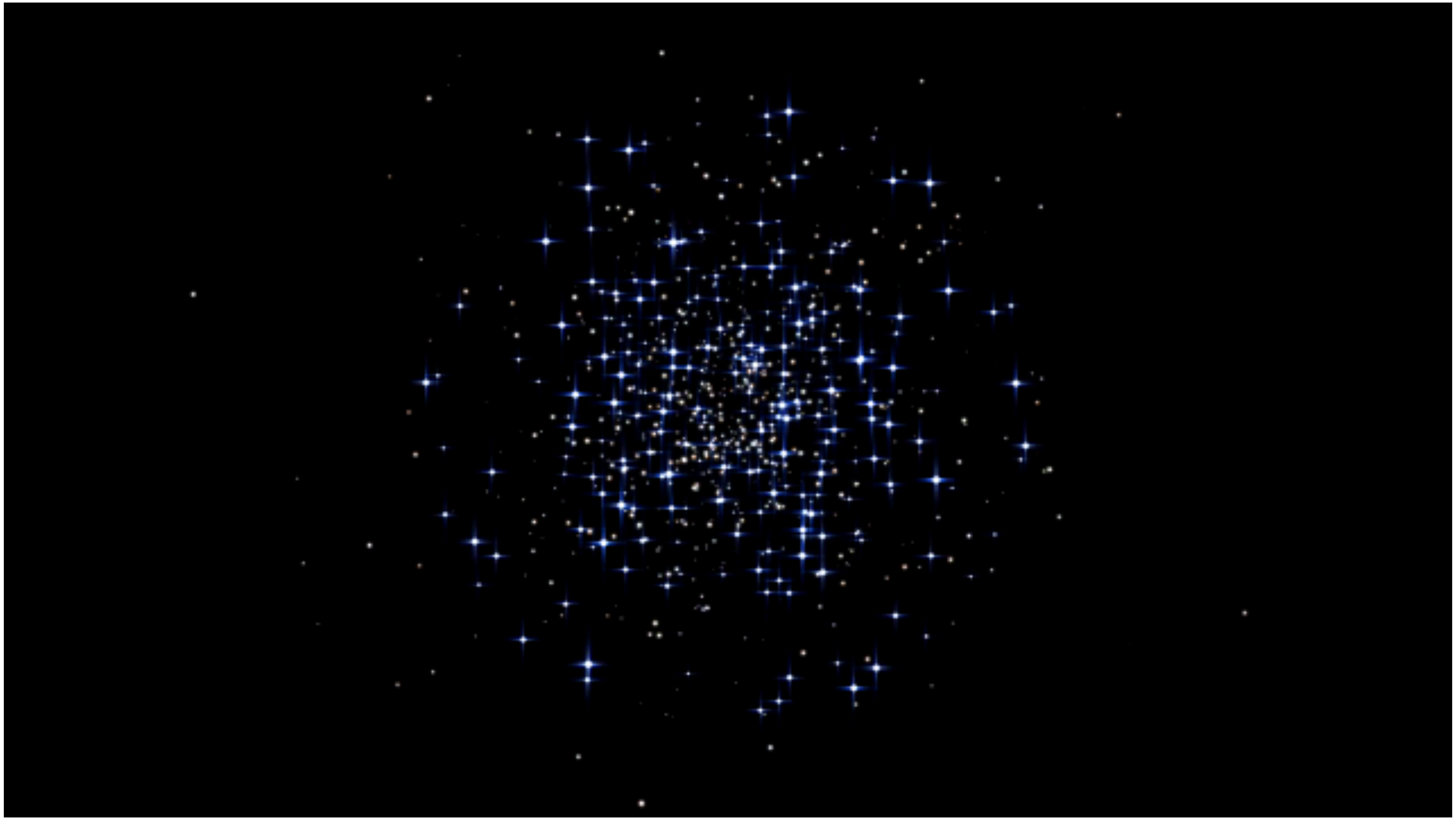
ESO-Garching, July 4, 2017

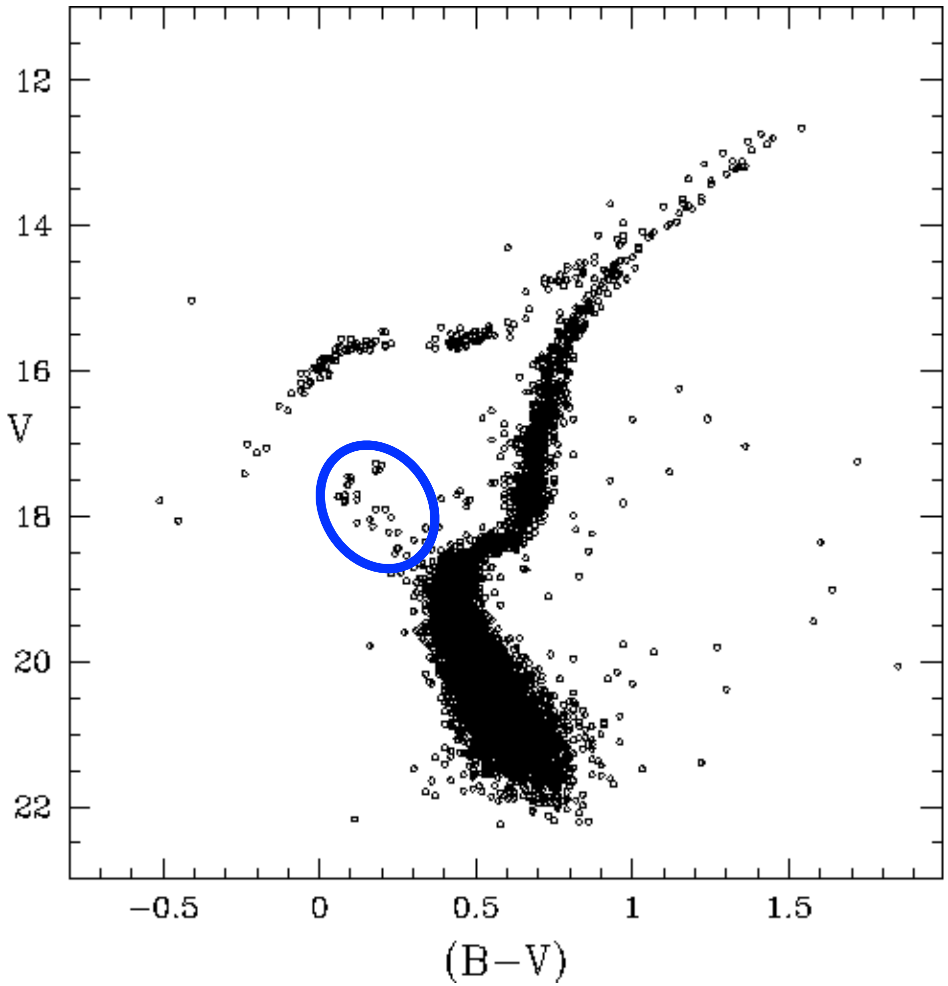
WHY GCs?



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**

Extotic populations in the CMD

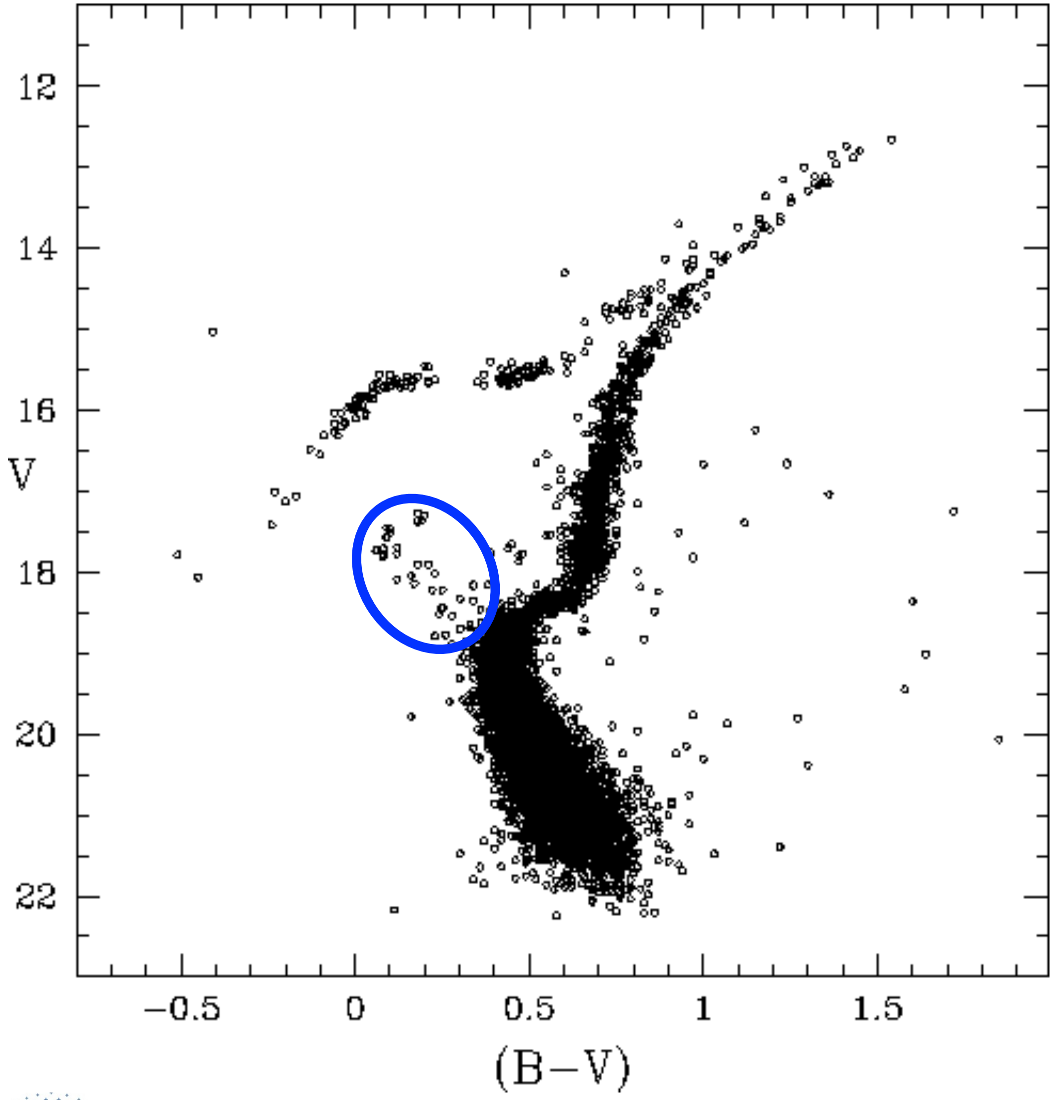


BSS represent the first evidence of binaries in GCs

(Sandage 1953)

Blue Straggler Stars (BSS)

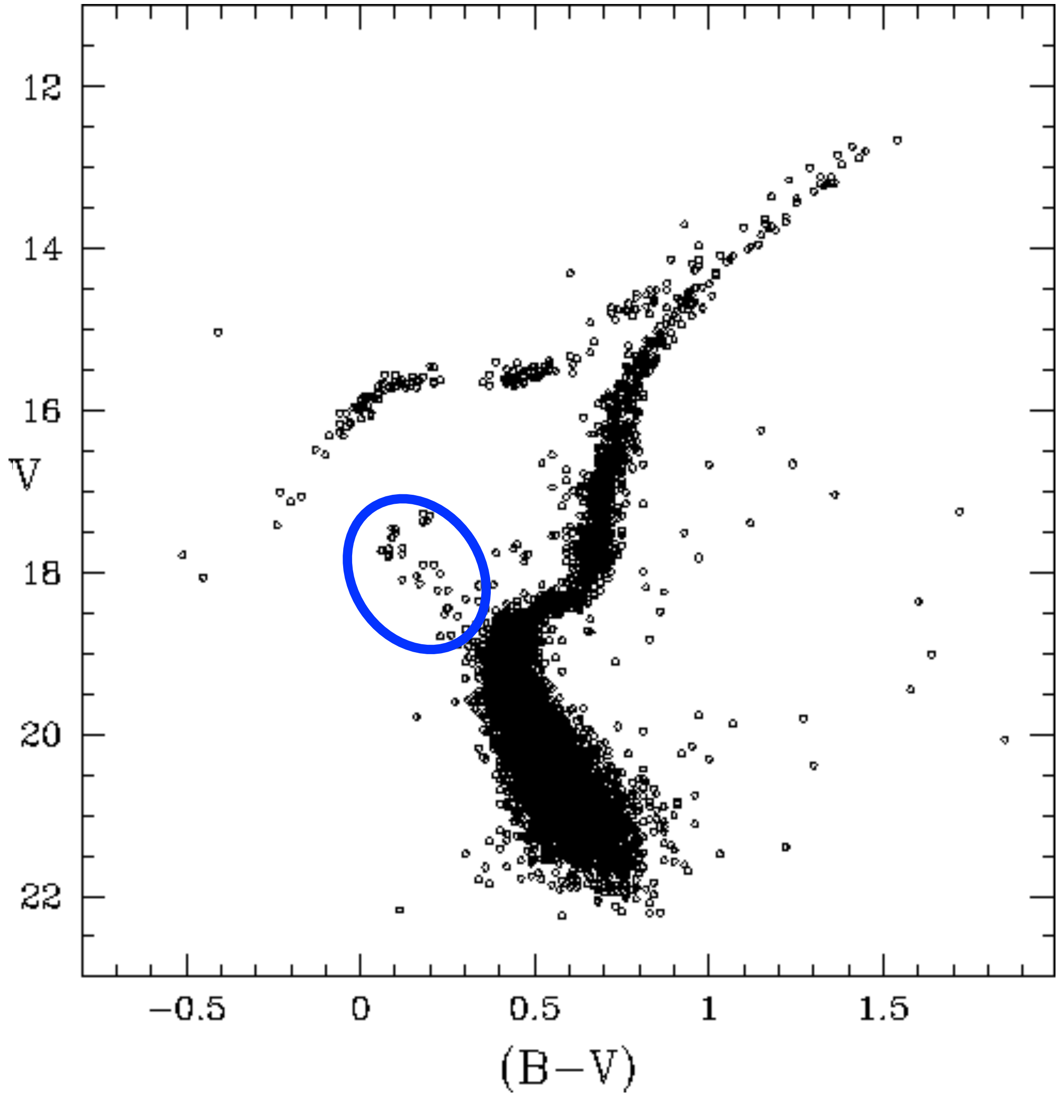
..was considered a PECULIAR stellar population



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)



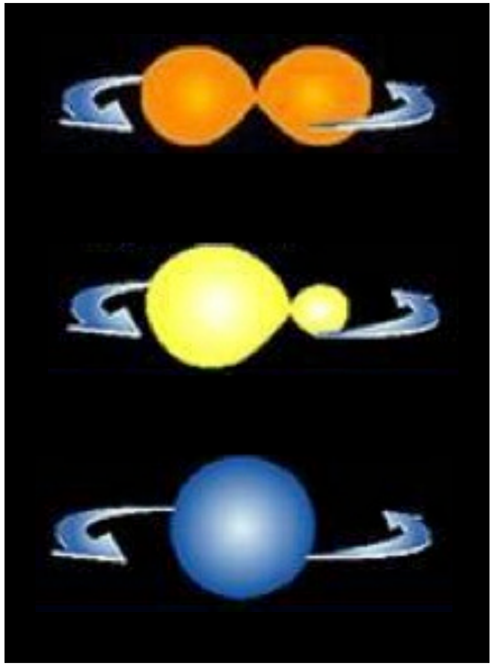
..while
old "normal" stars follow the flock of evolved stars getting progressively redder

BSS appear as a bunch of HEAVY blue stars

Merger of two low-mass stars

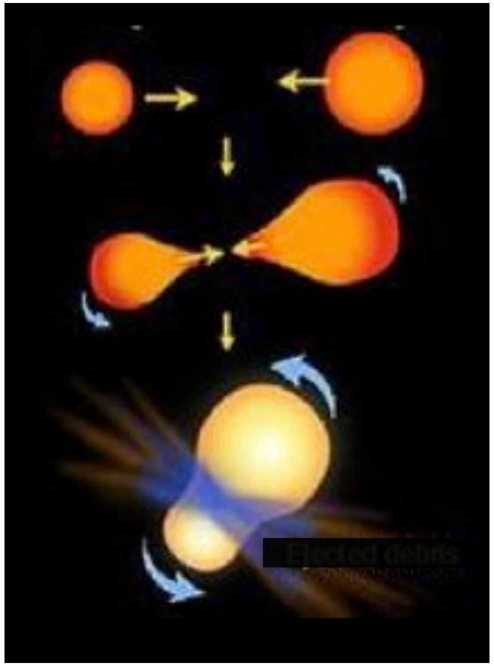
The formation mechanisms

MASS-TRANSFER



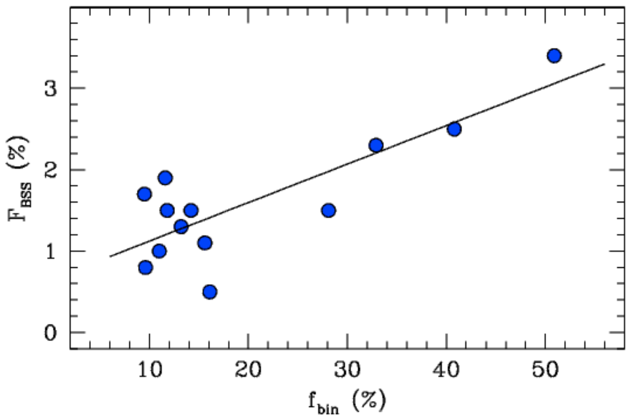
depend on shrinking of binaries
due to **dynamical interactions**
and stellar evolution (McCrea 1964)

COLLISIONS

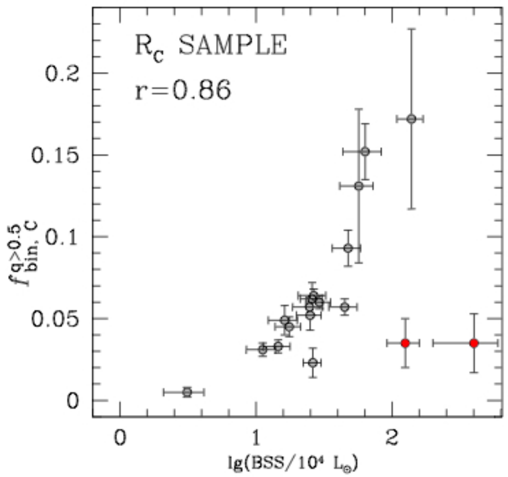


depend on **collision** rate
(Hills & Day 1976)

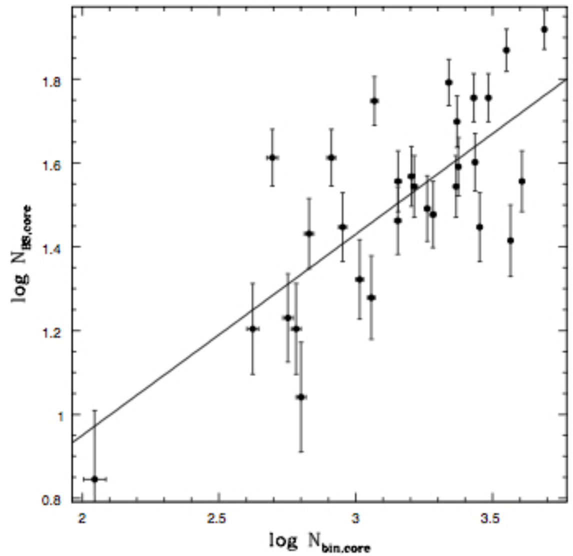
The BSS-binary fraction correlation



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



Milone et al (2012, A&A, 481,701)



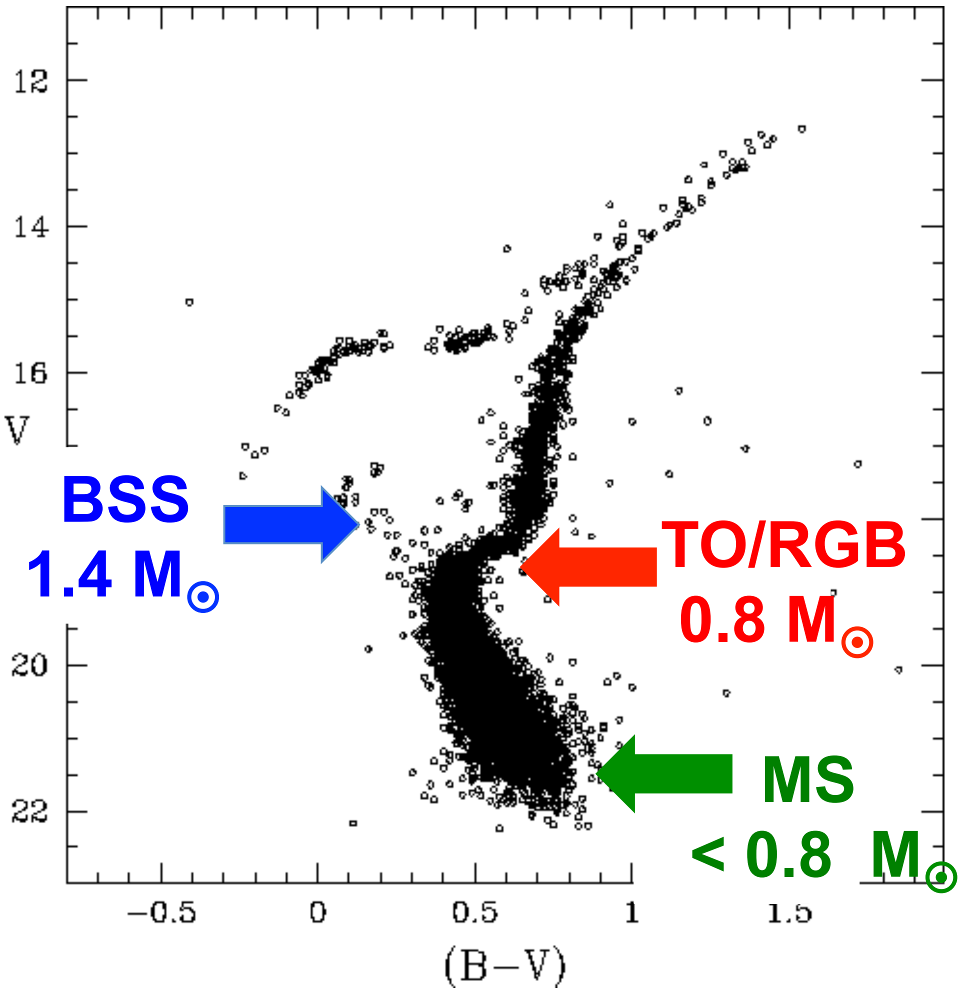
Leigh et al (2013, MNRAS, 428, 897)

These relations confirm the strong BSS-binaries link +
suggest that the MT channel is the dominant BSS formation channel

However the BSS observed in the core:

1. Did NOT form all there (probably a significant part of them form outside the core and then migrate there)
2. Some of them have been originated by Collisions

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 a "sea" of "normal" light stars (M_{mean} = 0.4 $M_{\odot}$): they are subject to **Dynamical Friction (DF)** that progressively makes them sink toward the cluster center

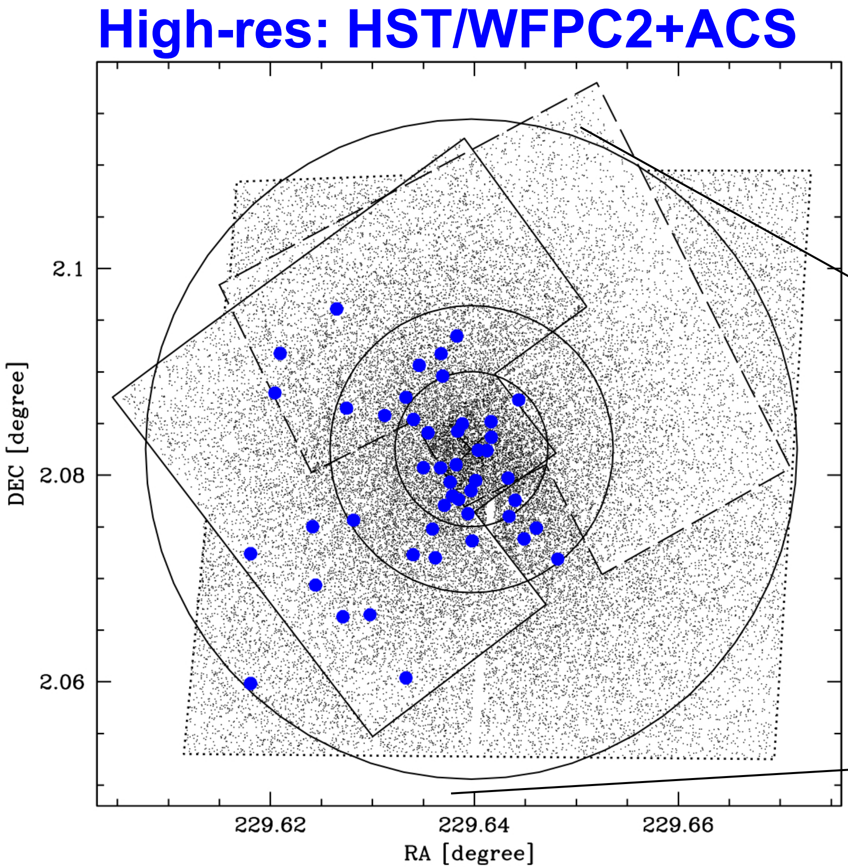
The **DF** time-scale depends on:

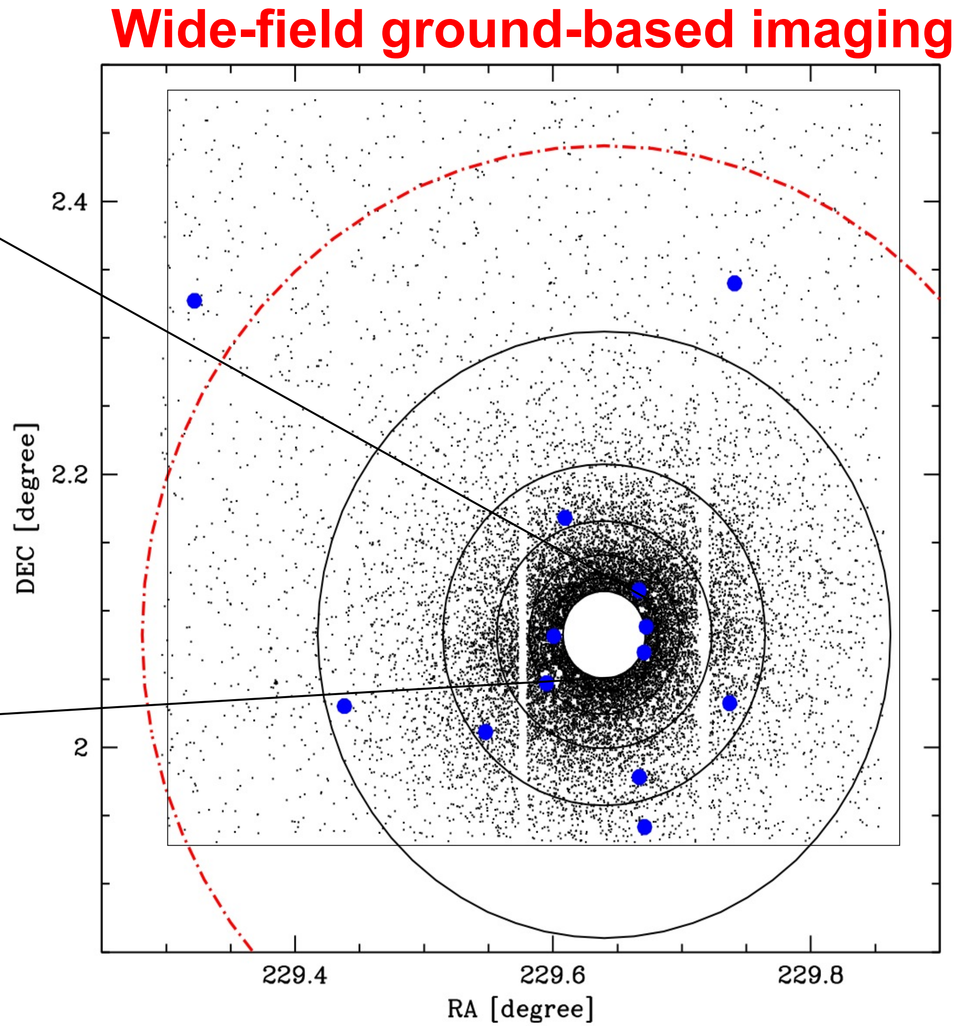
(1) Star mass **(2) Local cluster density**

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

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

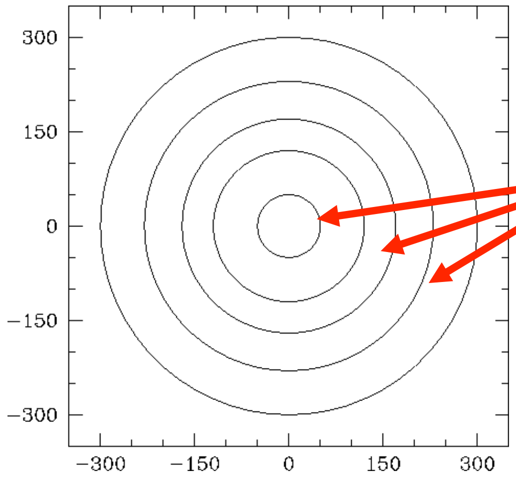
What we need to know is the radial distribution of these heavy objects along the entire cluster extension





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**

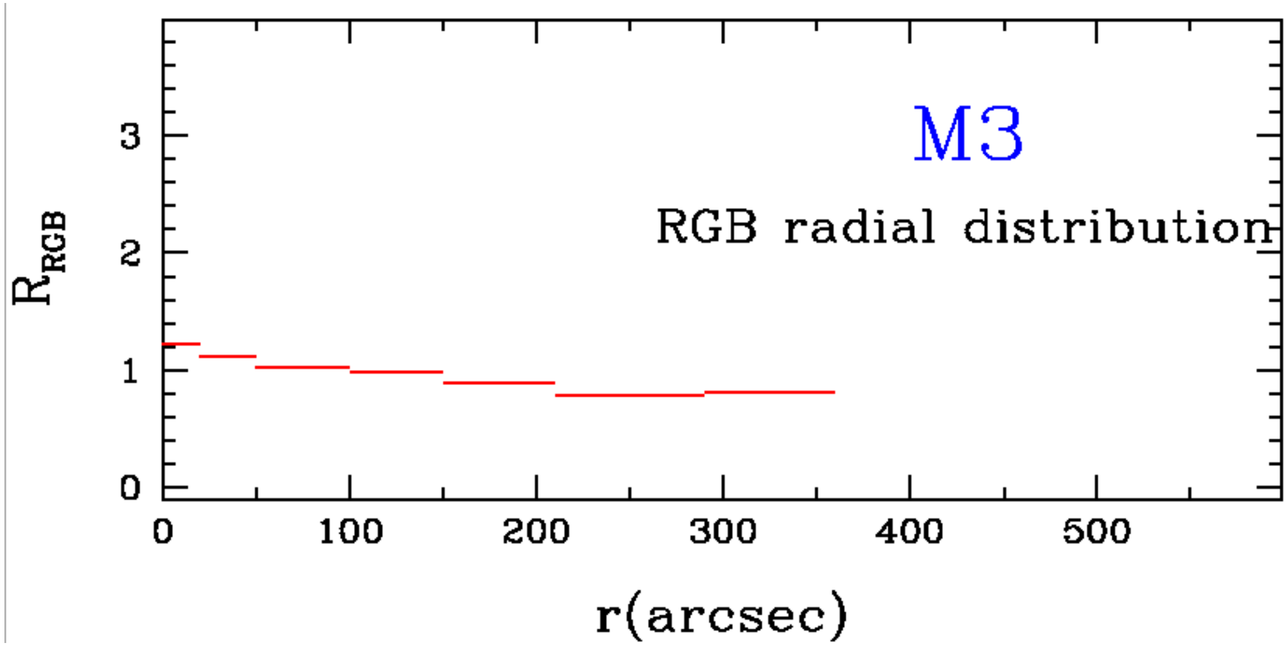
THE “normalized” BSS RADIAL DISTRIBUTION



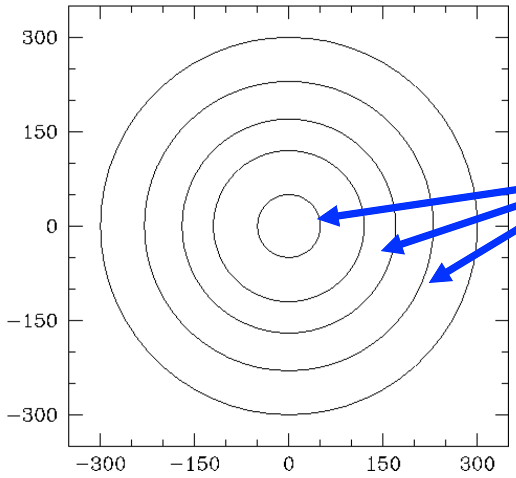
$$R_{RGB} = \frac{N_{RGB}/N_{RGB,TOT}}{L_{samp}/L_{TOT}}$$

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

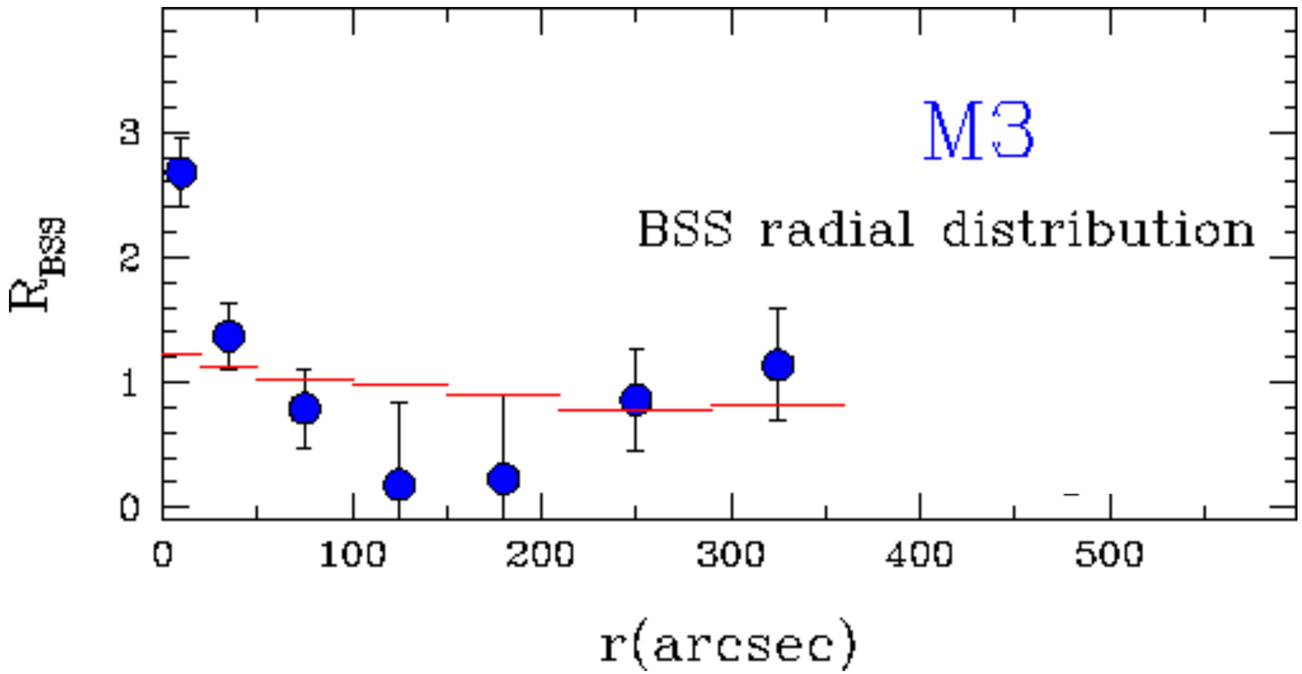
Note that *a flat distribution* in this plot means that *“the number of stars in each annulus exactly scales with the cluster light sampled by each annulus”*



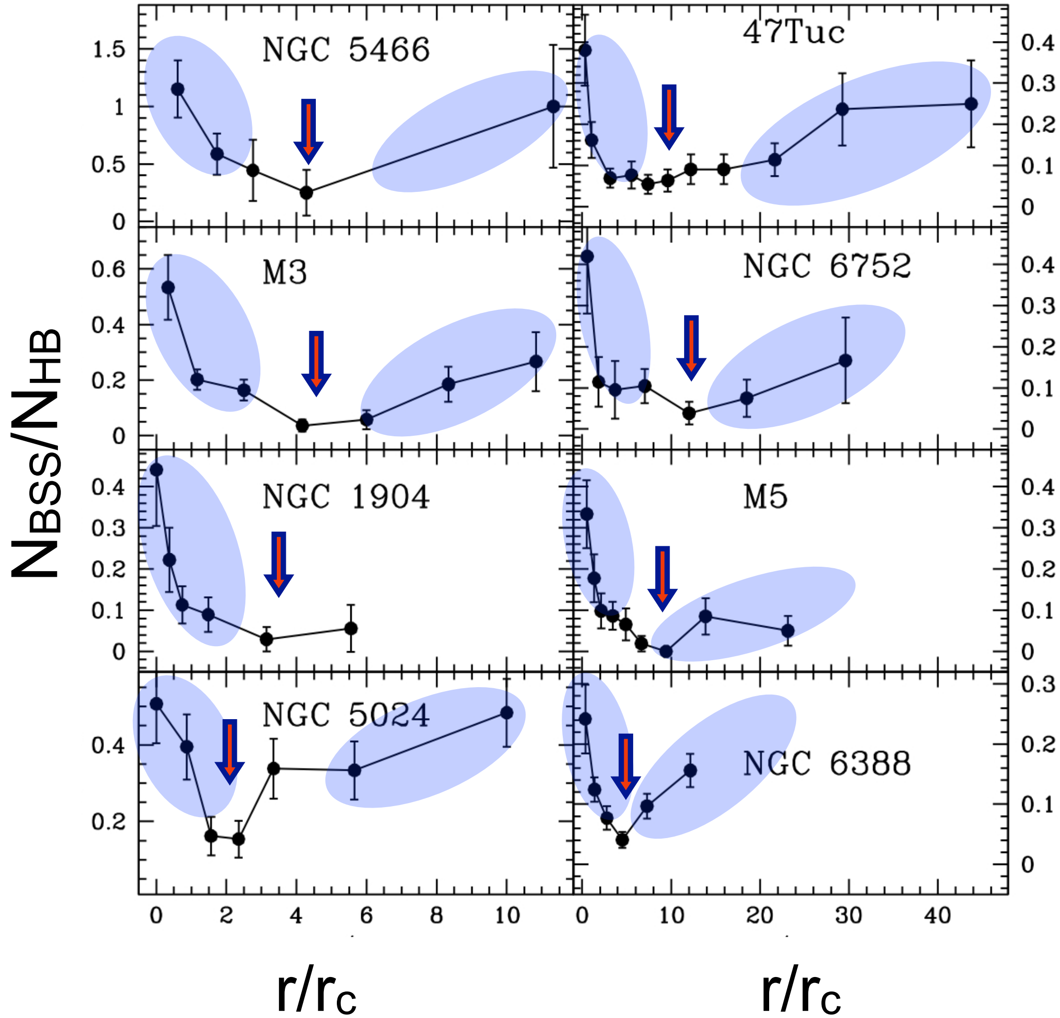
THE "normalized" BSS RADIAL DISTRIBUTION

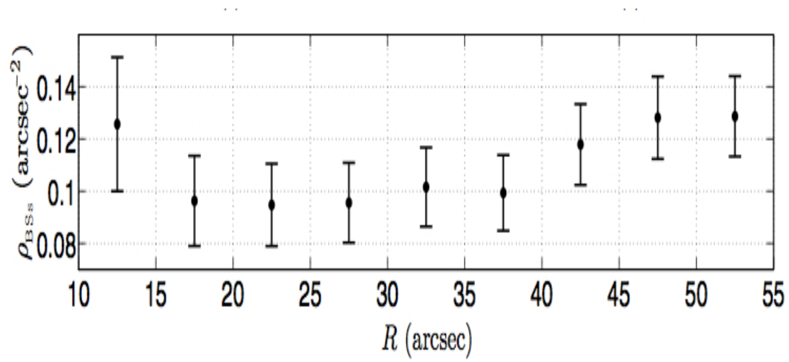


$$R_{BSS} = \frac{N_{BSS}/N_{BSS,TOT}}{L_{samp}/L_{TOT}}$$



Bimodal BSS radial distribution





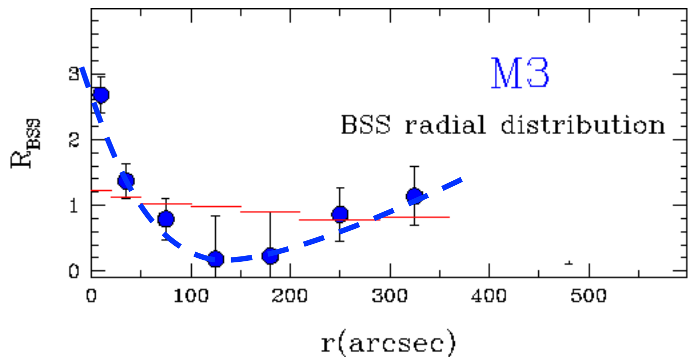
Hodge 11 –LMC

Li et al (2013)

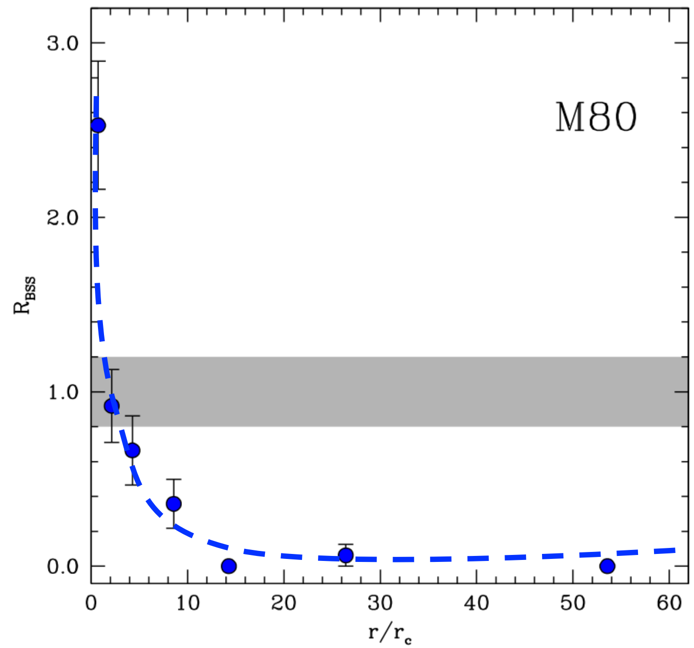
“normalized” BSS radial distribution

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

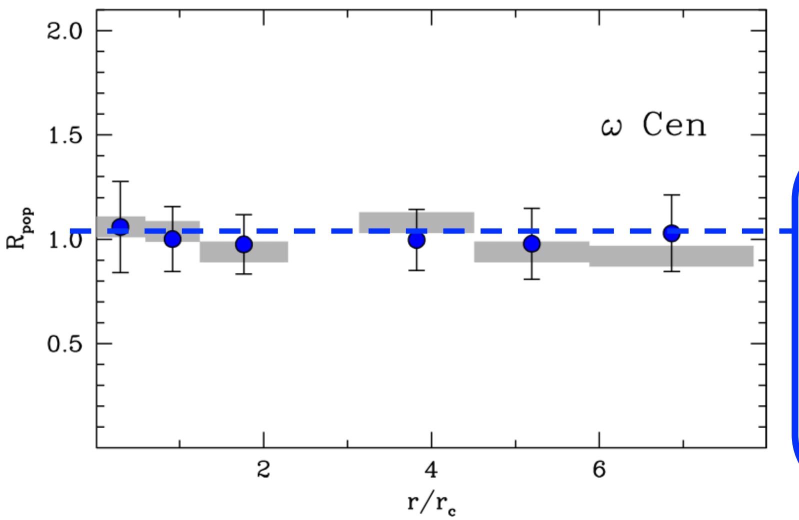
“bimodal”



“Unimodal” (single-peak)



“Flat”



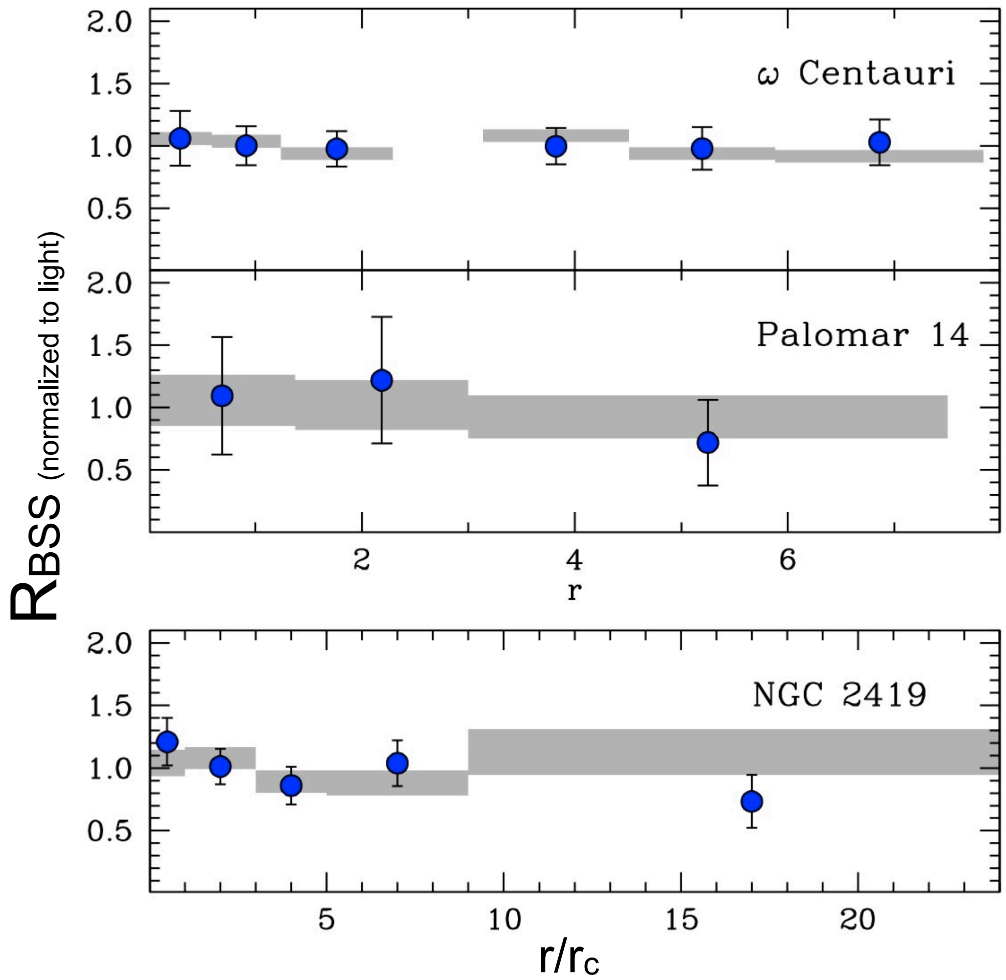
The BSS radial distribution is shaped by dynamical friction, which progressively segregates BSS toward the cluster center

….. THE DYNAMICAL CLOCK…..

The dynamical clock

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

Family I: the dynamically YOUNG clusters

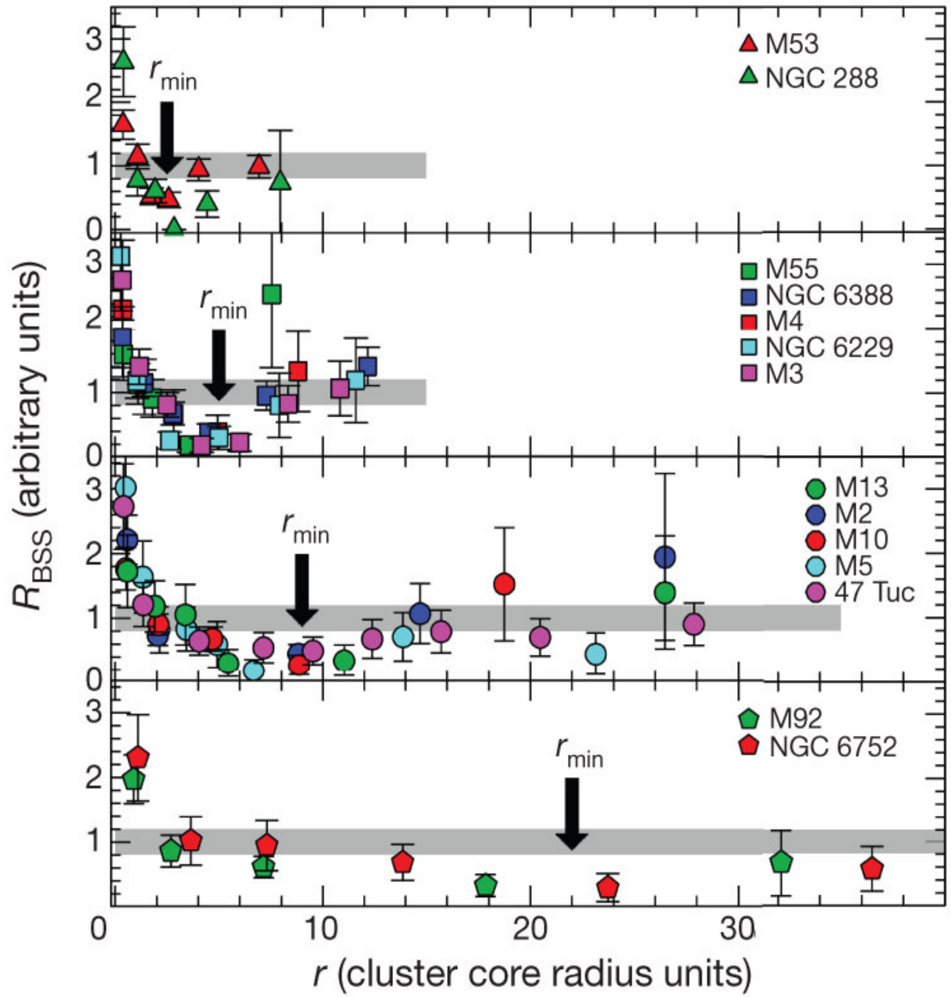


The BSS distribution is **flat** in fully agreement with that of “normal stars”

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

The dynamical clock

Family II: the dynamically INTERMEDIATE-AGE clusters



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

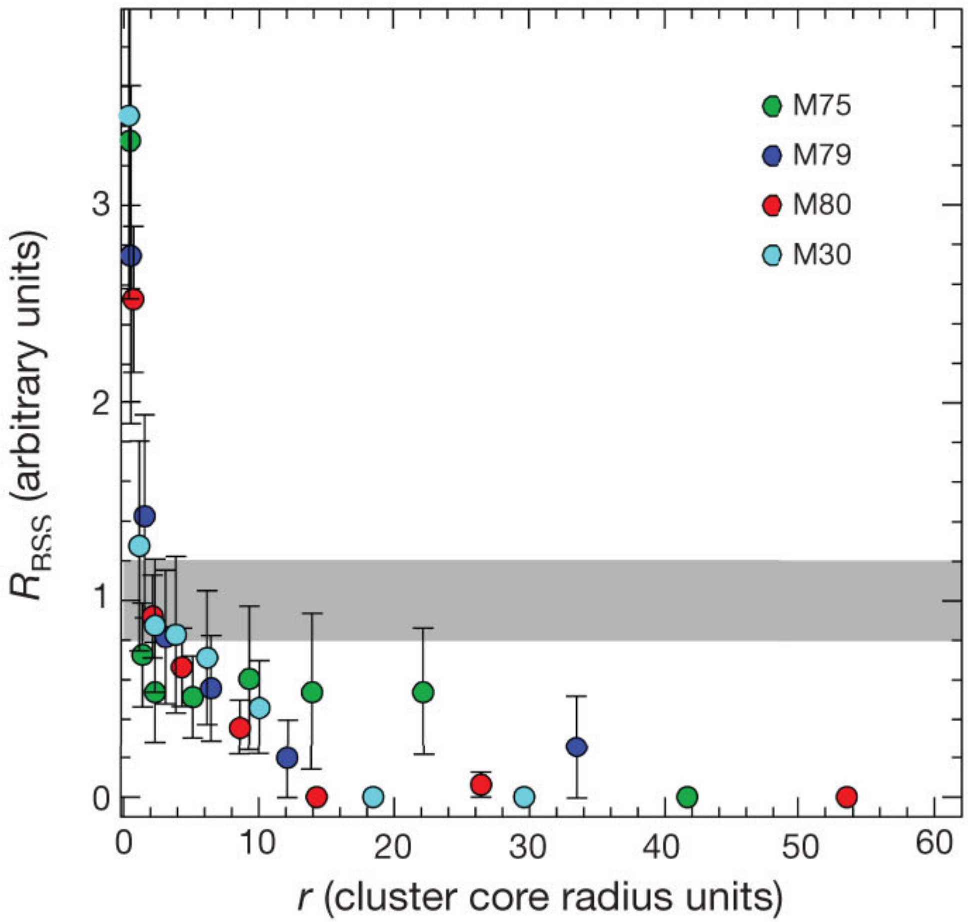
DF is effective in segregating BSS, starting from those at shorter distances from the cluster center

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

Cosmic-Lab

The dynamical clock

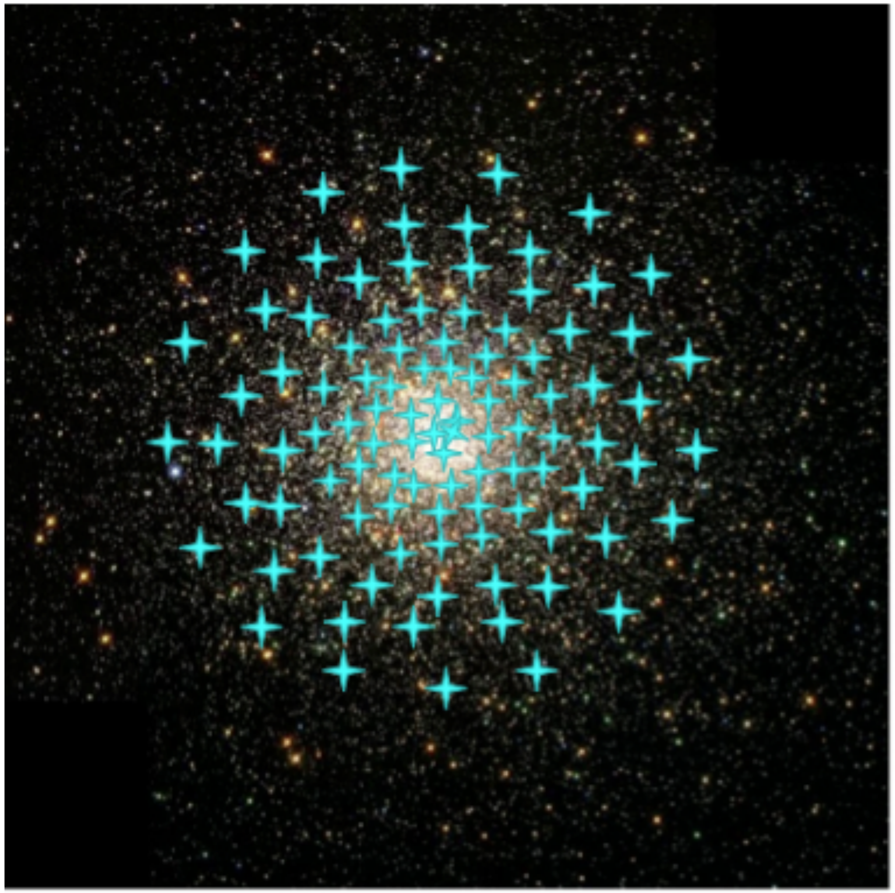
Family III: the dynamically OLD clusters



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

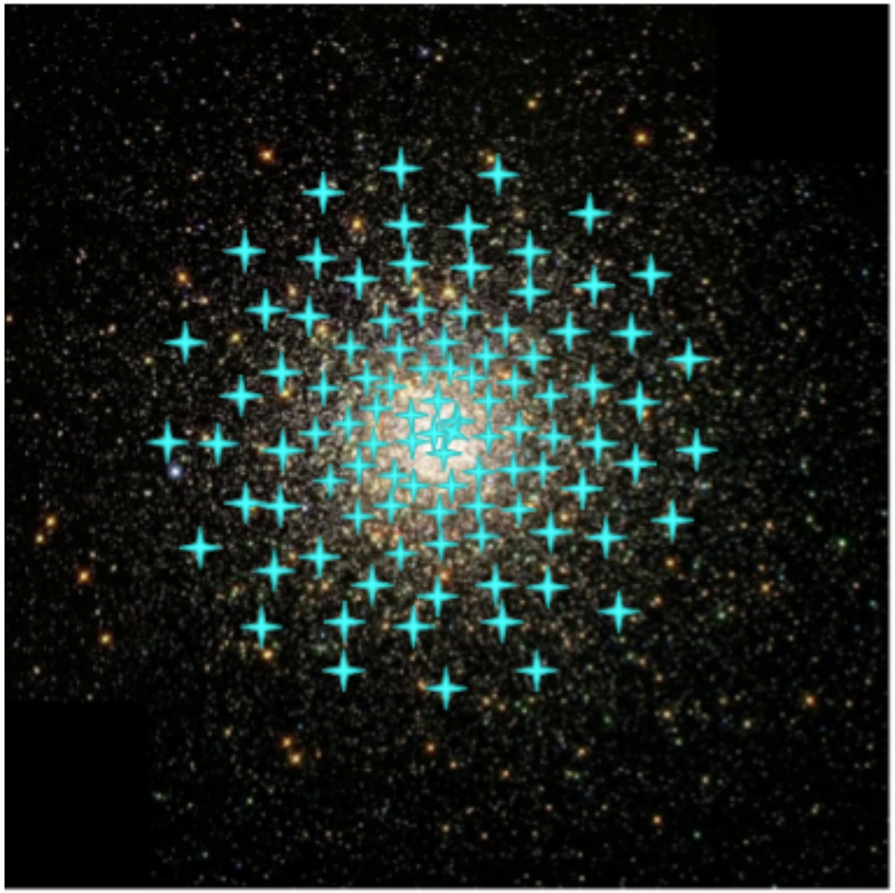
DF has segregated ALL the BSS, even the most remote ones. The external rising branch disappears.

The dynamical clock



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 with time.

The dynamical clock



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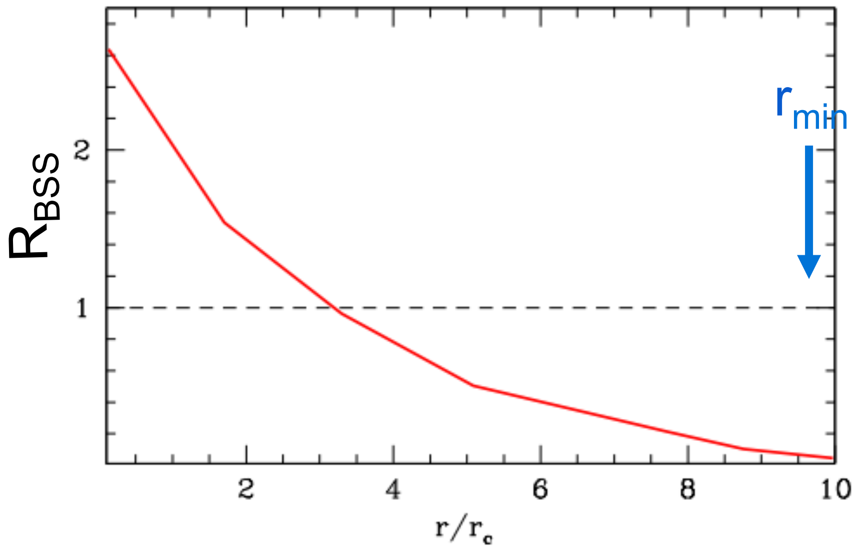
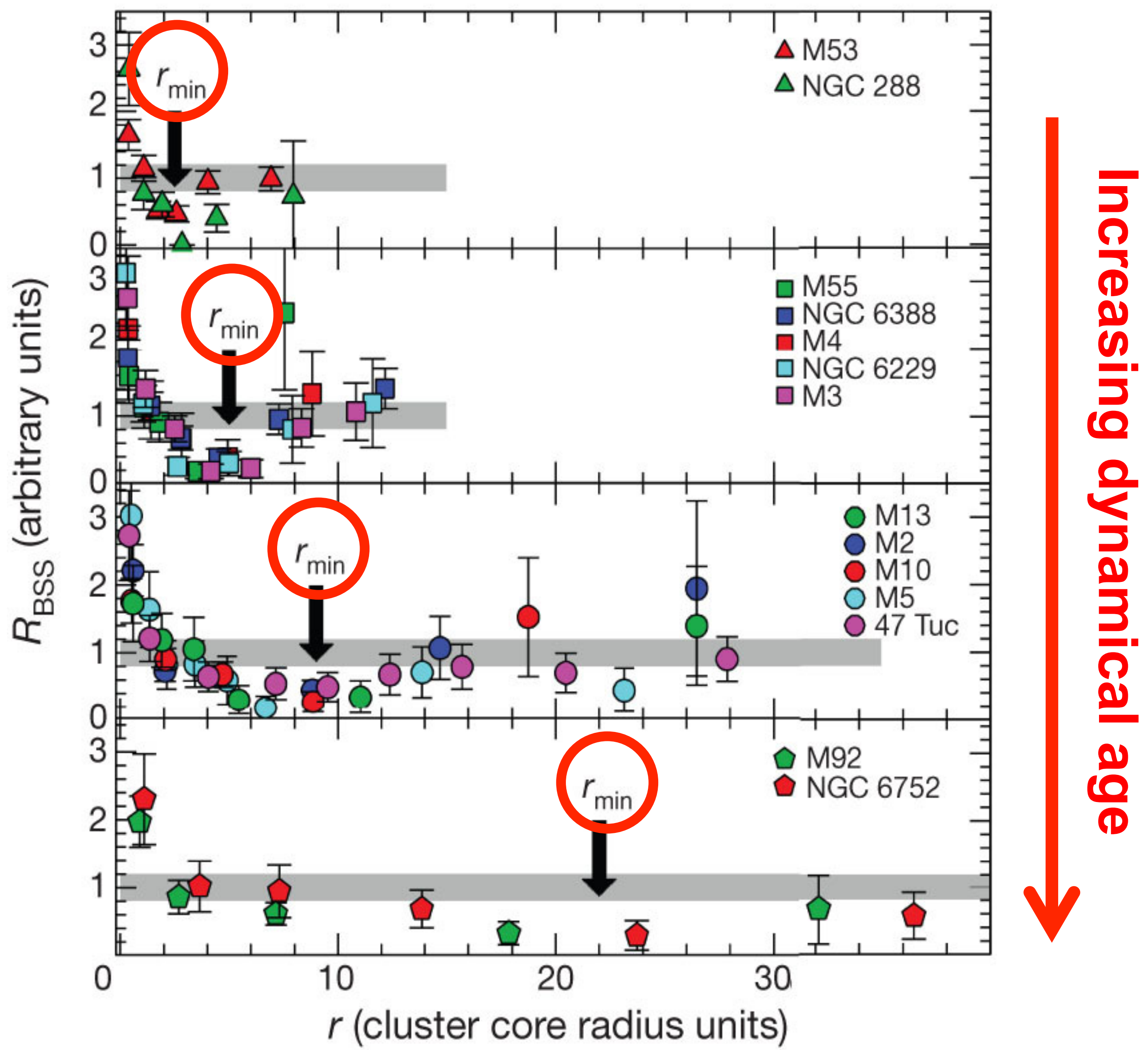
The dynamical clock



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

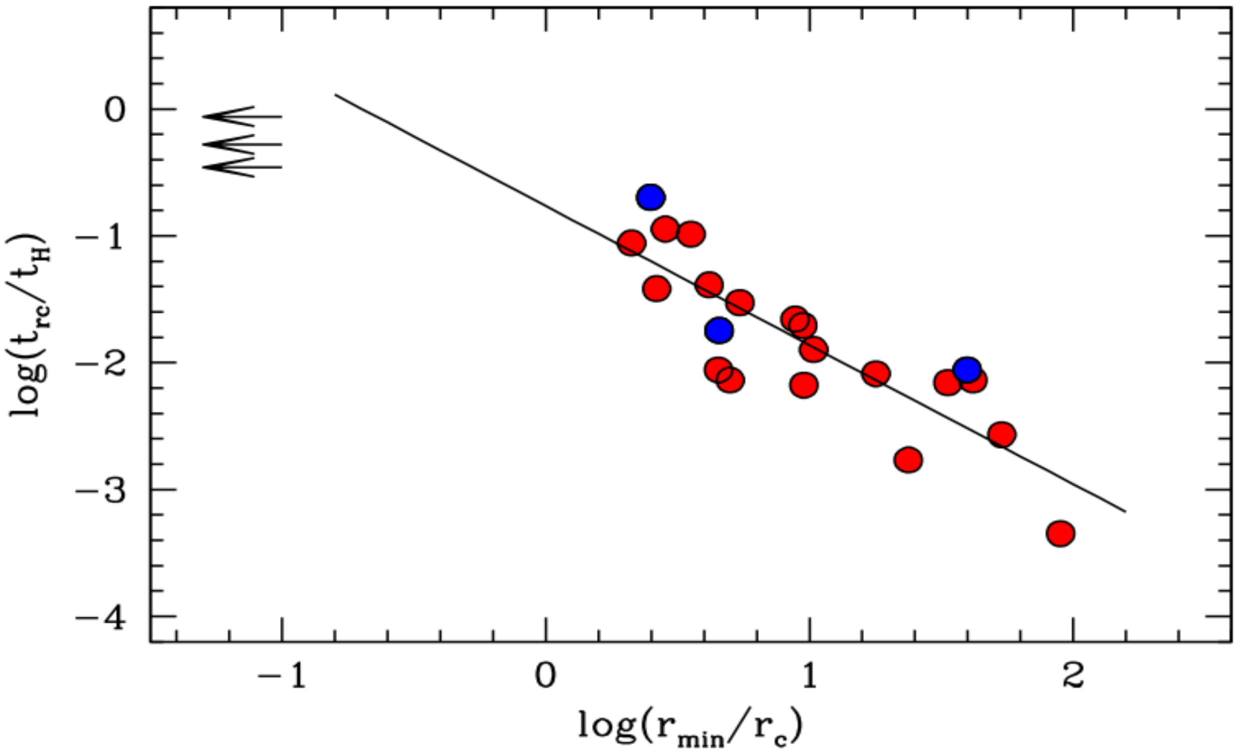


M53
NGC 288
M55
NGC 6388
M4
NGC 6229
M3
M13
M2
M10
M5
47 Tuc
M92
NGC 6752
r_{min}
R_{BSS} (arbitrary units)
r (cluster core radius units)
Increasing dynamical age

The dynamical clock

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

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

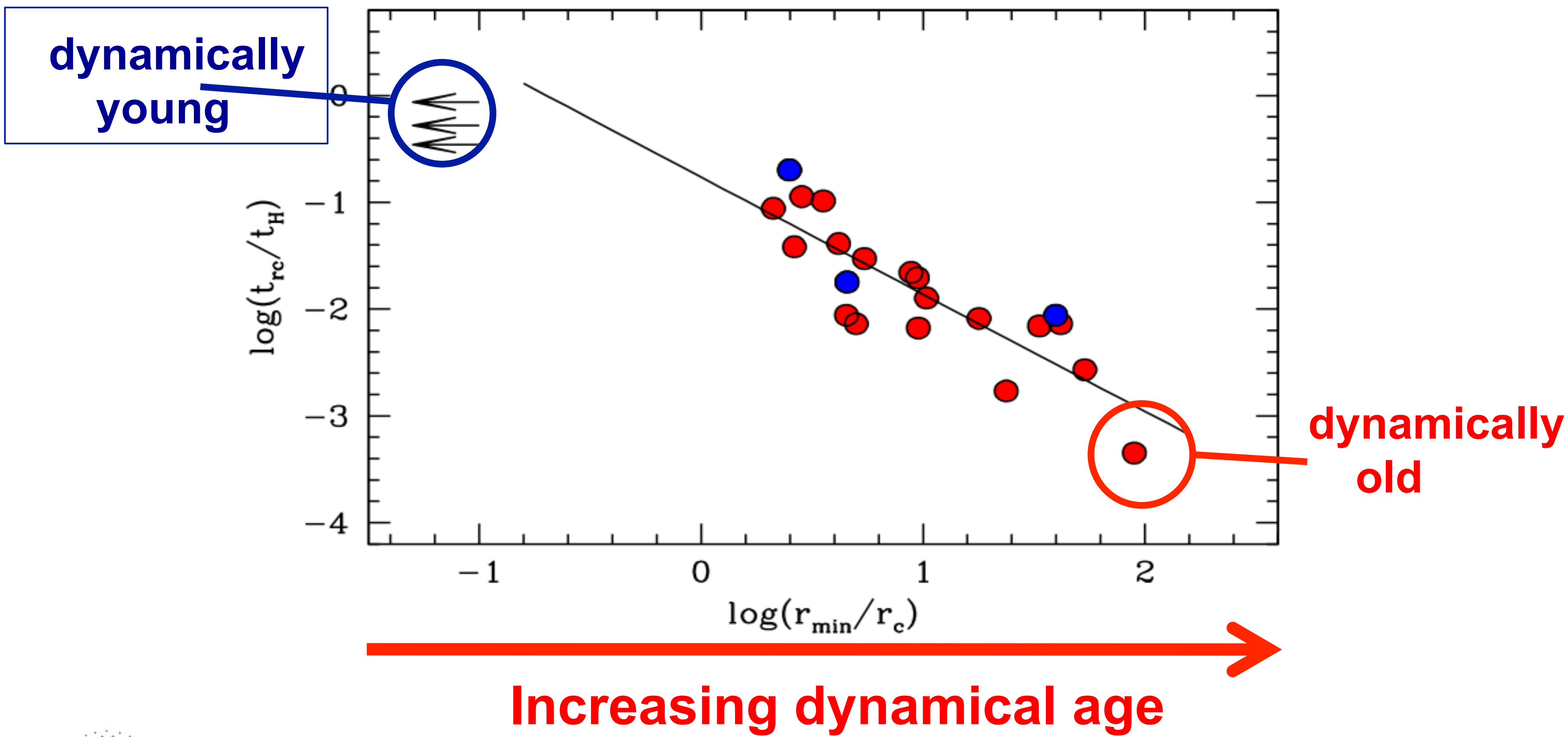


Cosmic-Lab

The dynamical clock

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

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



Cosmic-Lab

12 coeaval GCs

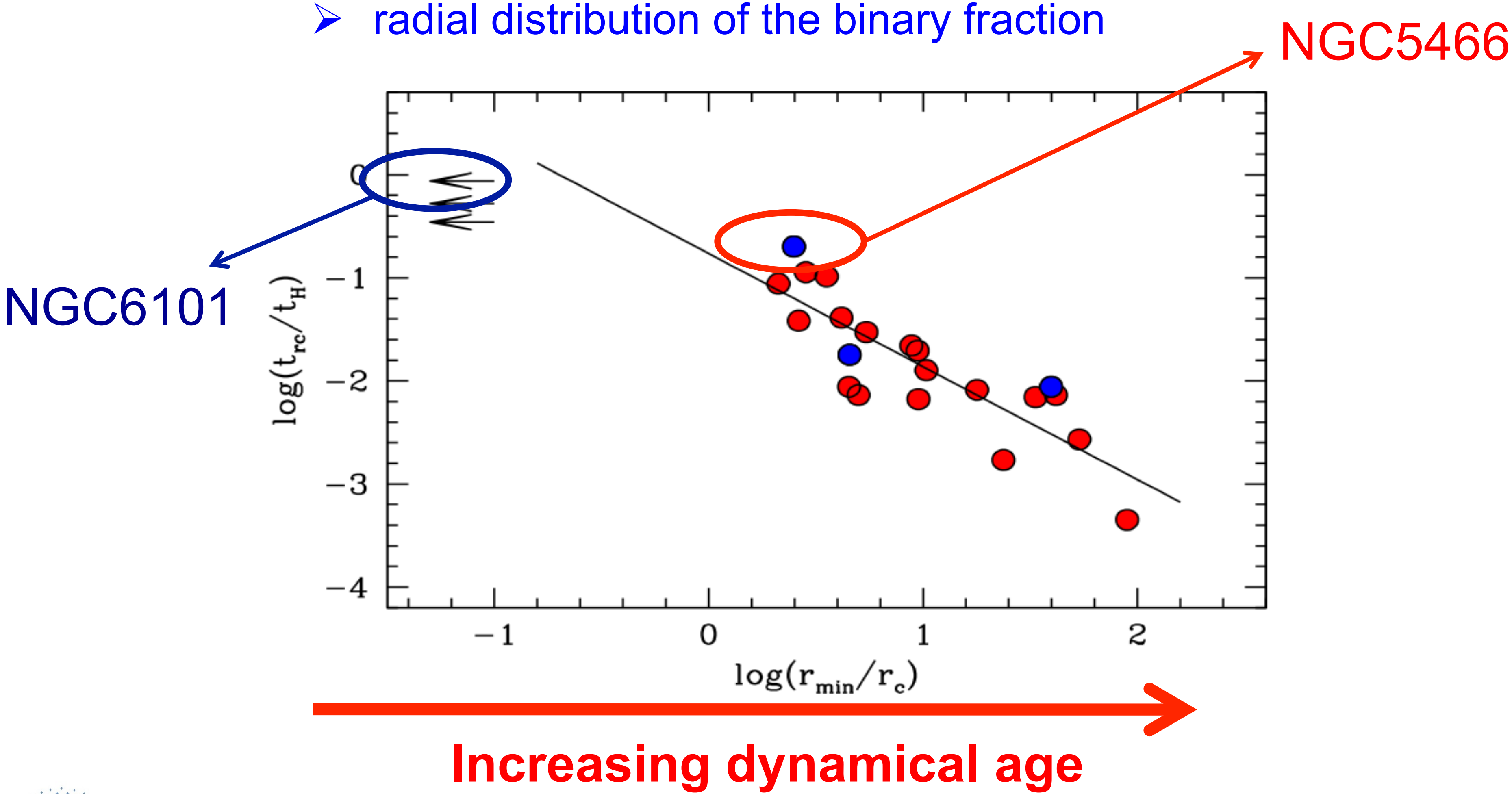
dynamically young

dynamically old

How good the dynamical clock is?

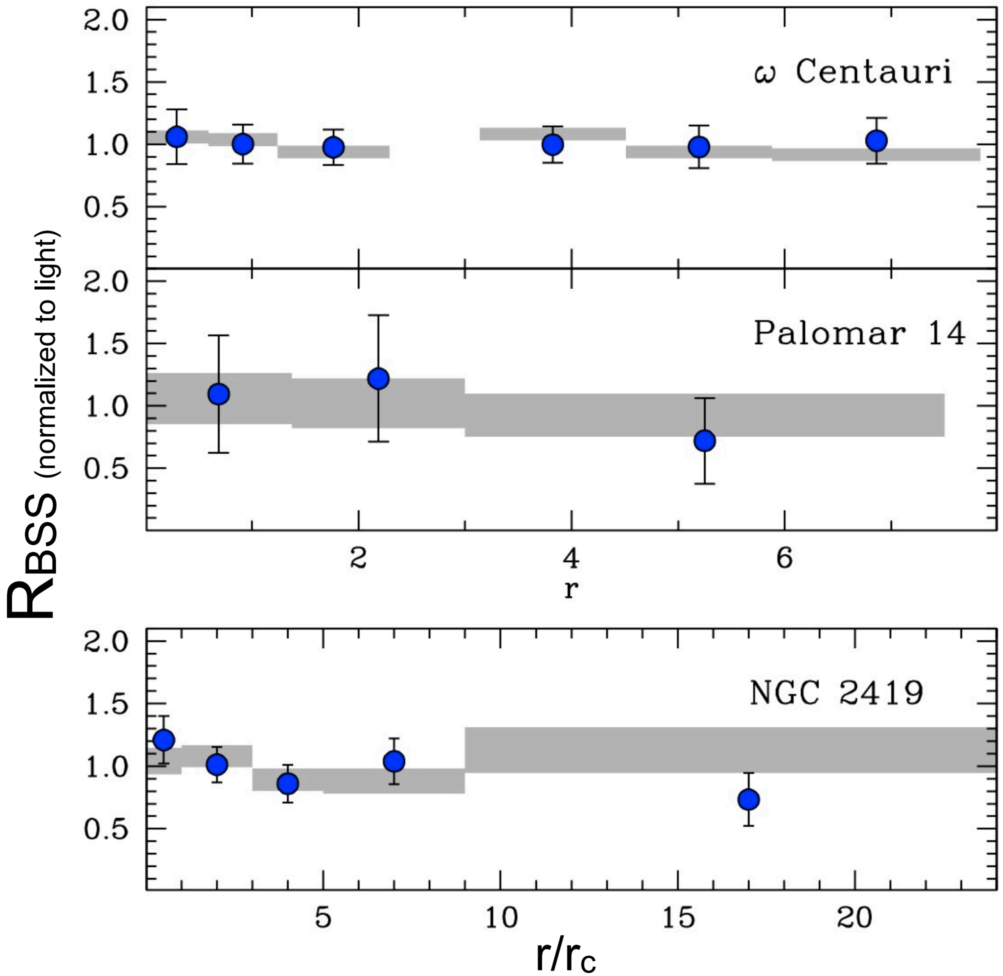
Comparison with other diagnostics of mass segregation:

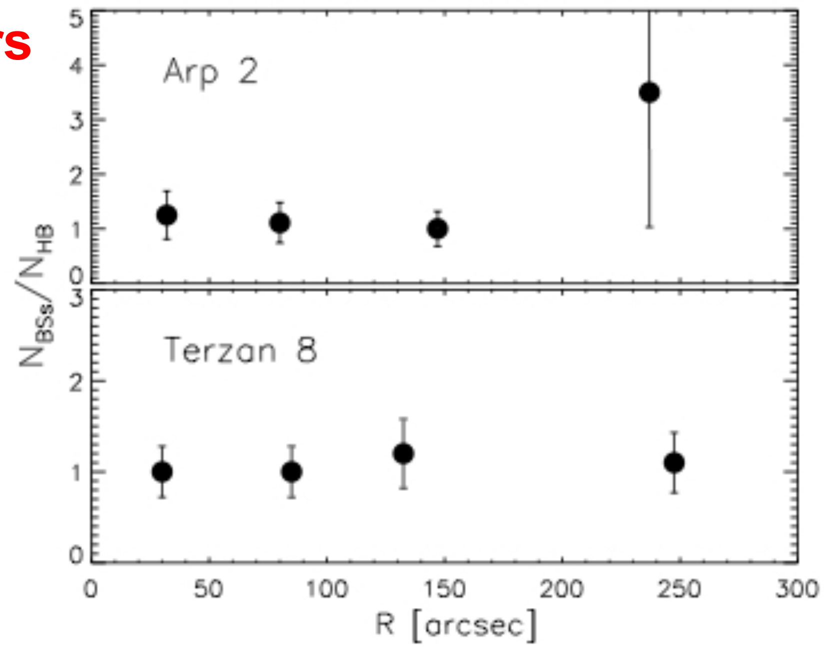
- radial behaviour of the mass function
- radial distribution of the binary fraction



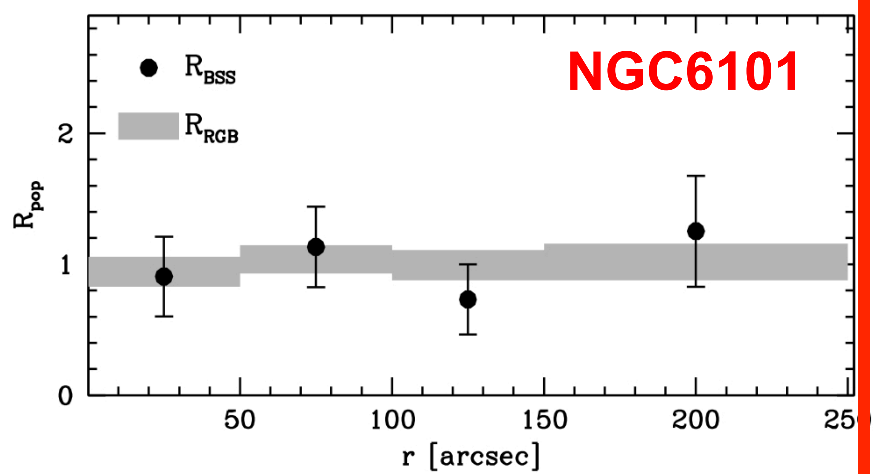
Cosmic-Lab

Family I: the dynamically YOUNG clusters



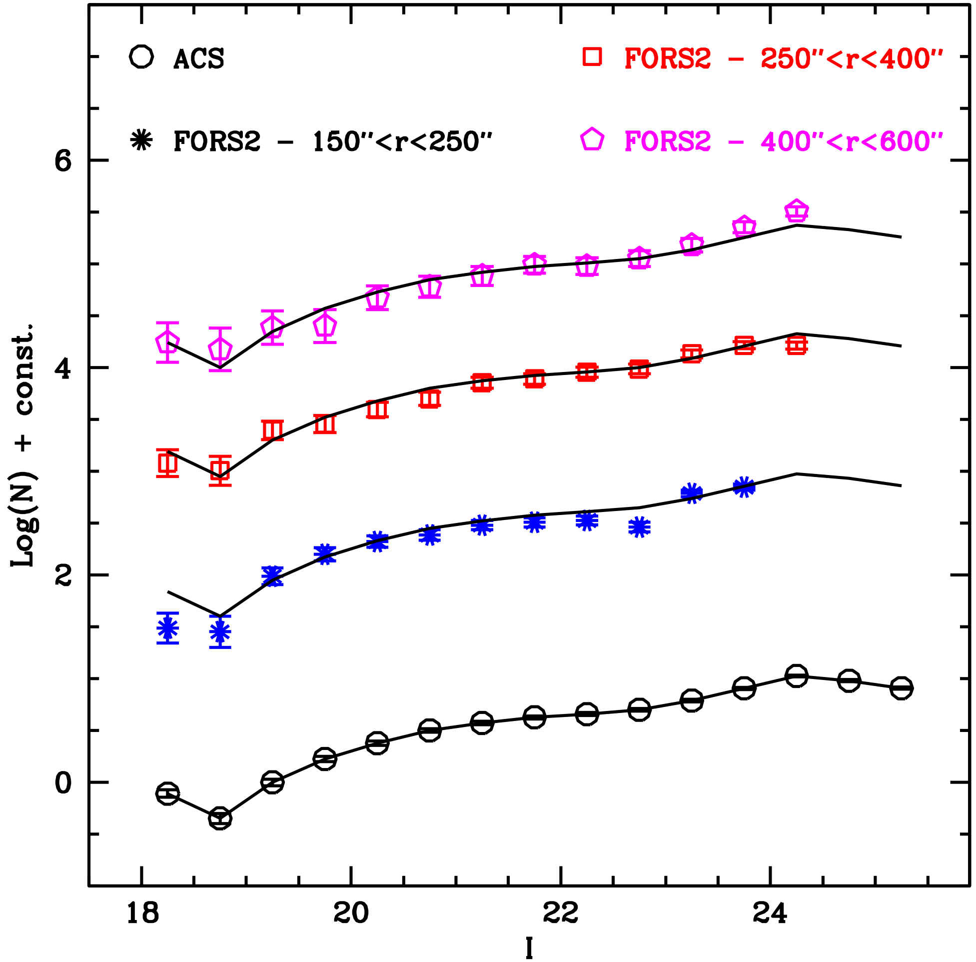


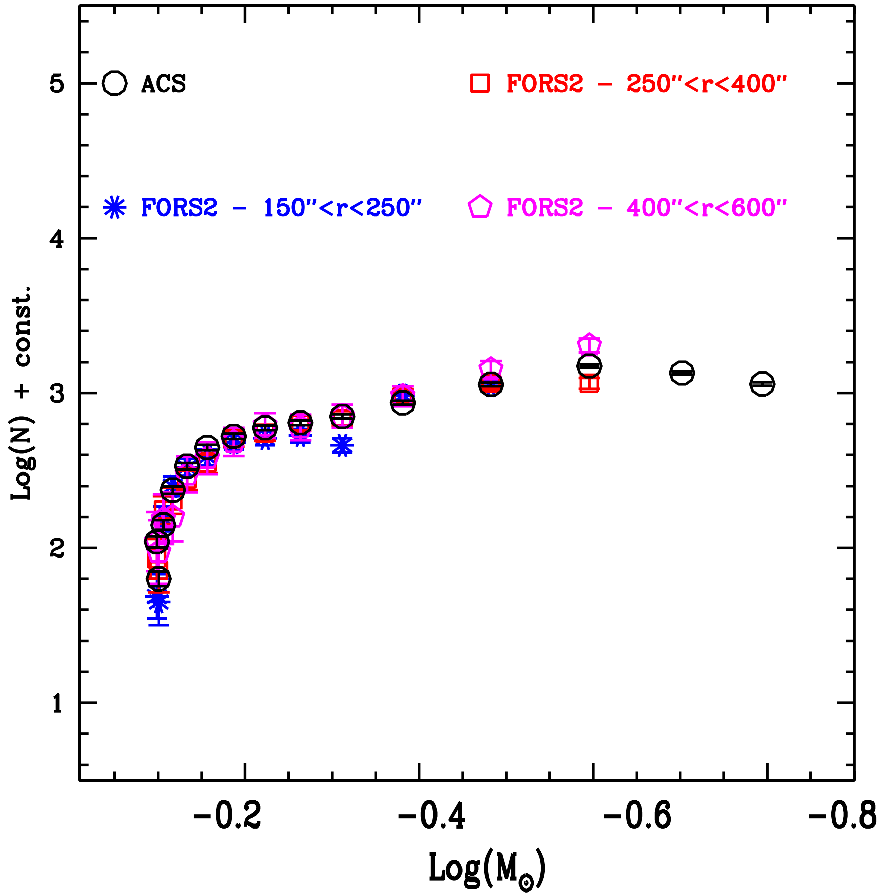
Salinas et al (2012,MNRAS,421,960)



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

The case of NGC6101: the mass function

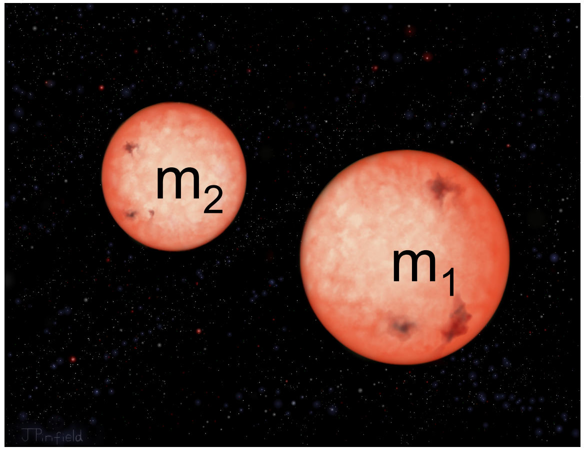


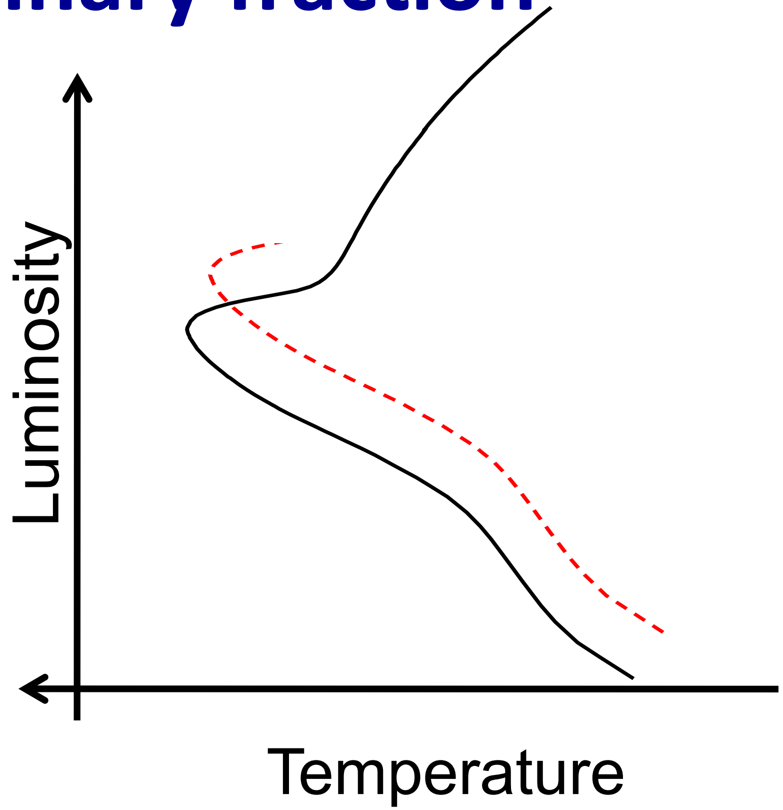


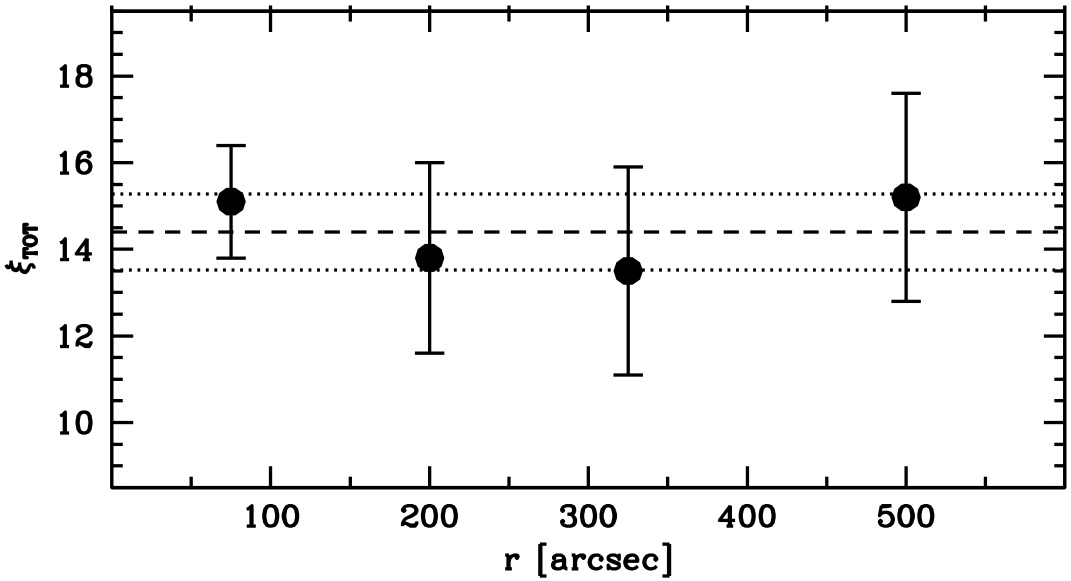
Dalessandro et al (2015, ApJ, 810,40)

NO EVIDENCE OF MASS SEGREGATION

The case of NGC6101: binary fraction







THE MEASURED BINARY FRACTION IS CONSTANT (~14%)

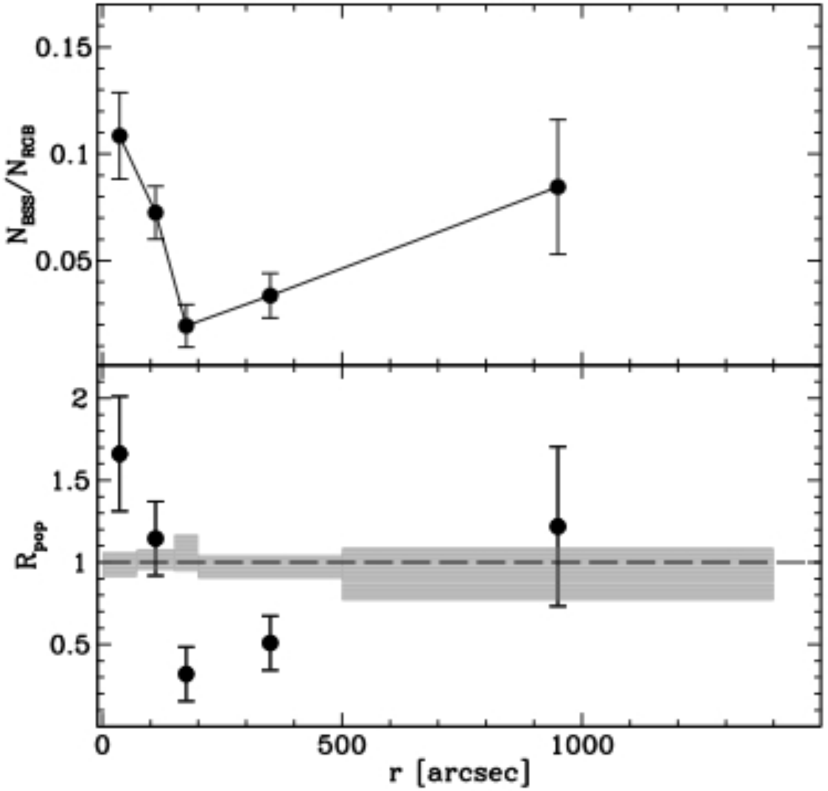
The case of NGC6101

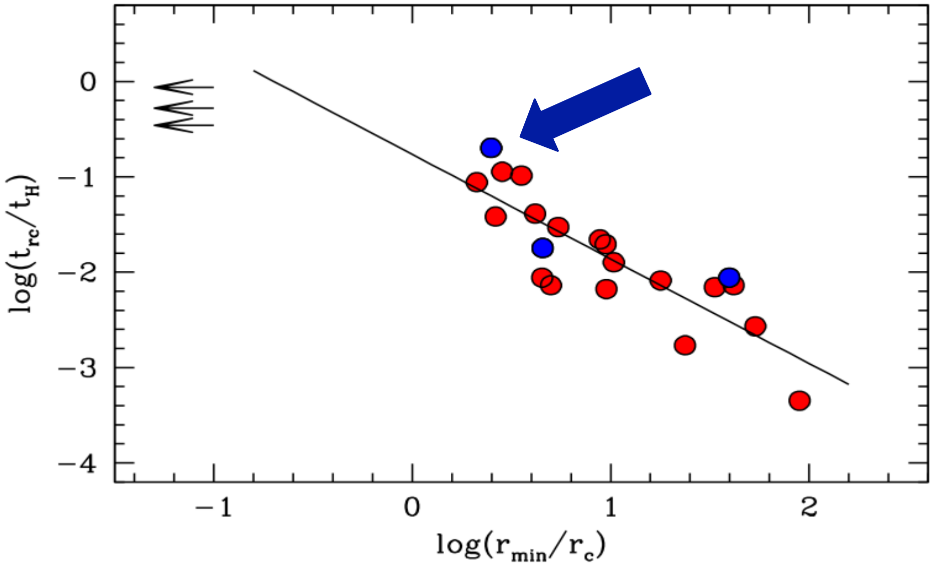
BSS radial distribution	NO Segregation
Mass function (from MS-LF)	NO Segregation
Binary system radial distribution	NO Segregation

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.

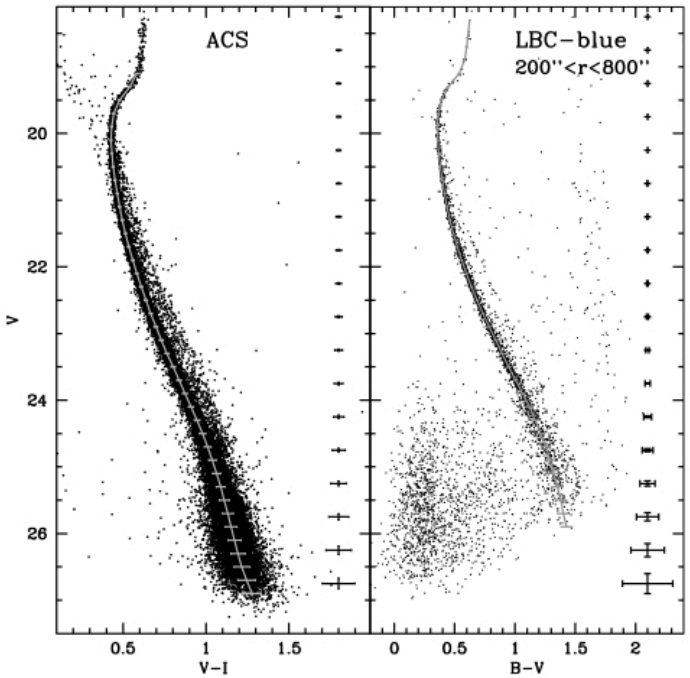
The case of NGC5466: BSS





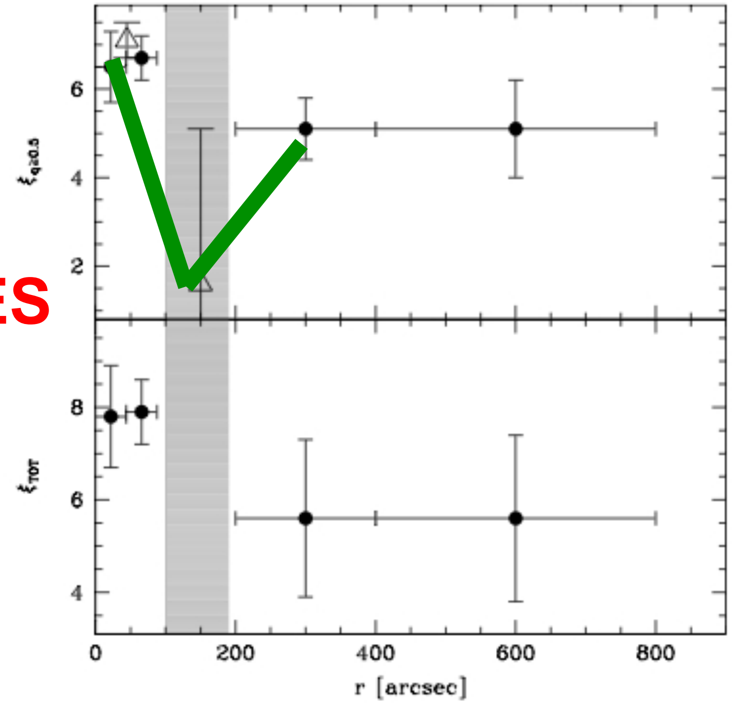
The "dynamical clock" suggested that NGC5466 is an "early Family II cluster" with an intermediate dynamical age

The case of NGC5466: binary fraction

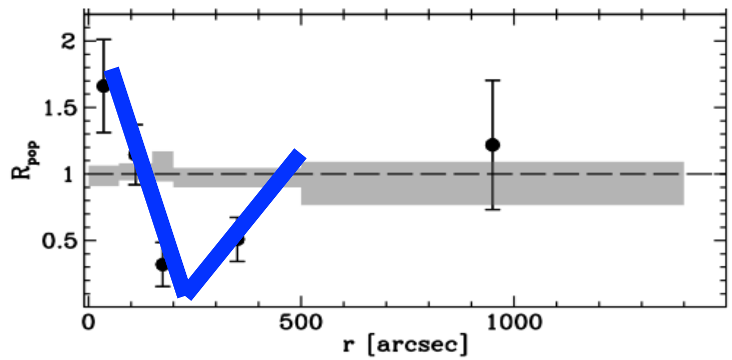


Beccari+13, ApJ,776,60

BINARIES



BSS



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

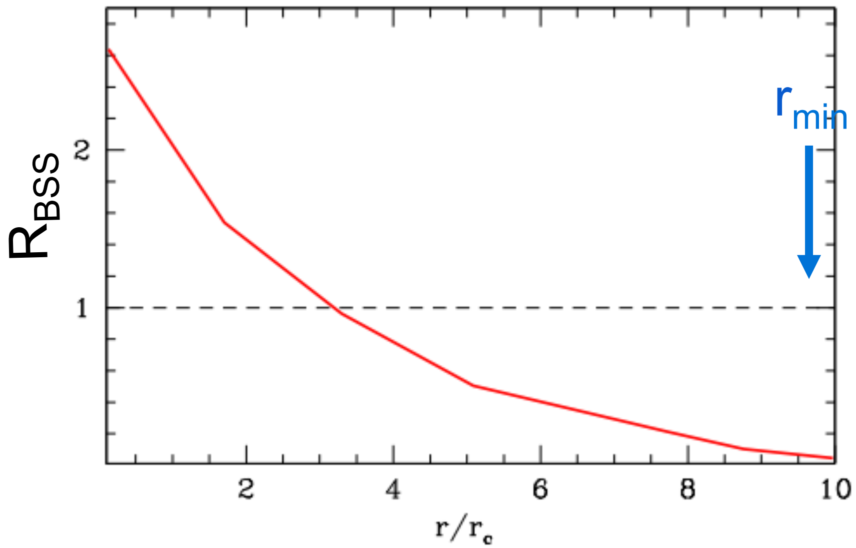
How good the dynamical clock is?

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

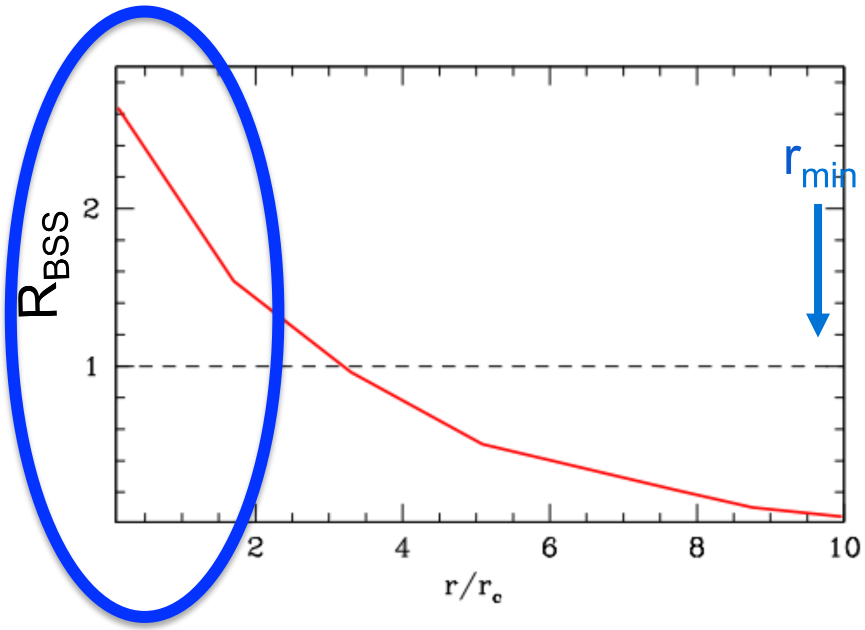
Refining the dynamical clock



r_{min} is a “low-signal” feature

The clock-hand of the dynamical clock as defined in 2012 is the position of the minimum In the radial distribution. But this feature is difficult to be observed especially in the most external region of the cluster.

Refining the dynamical clock

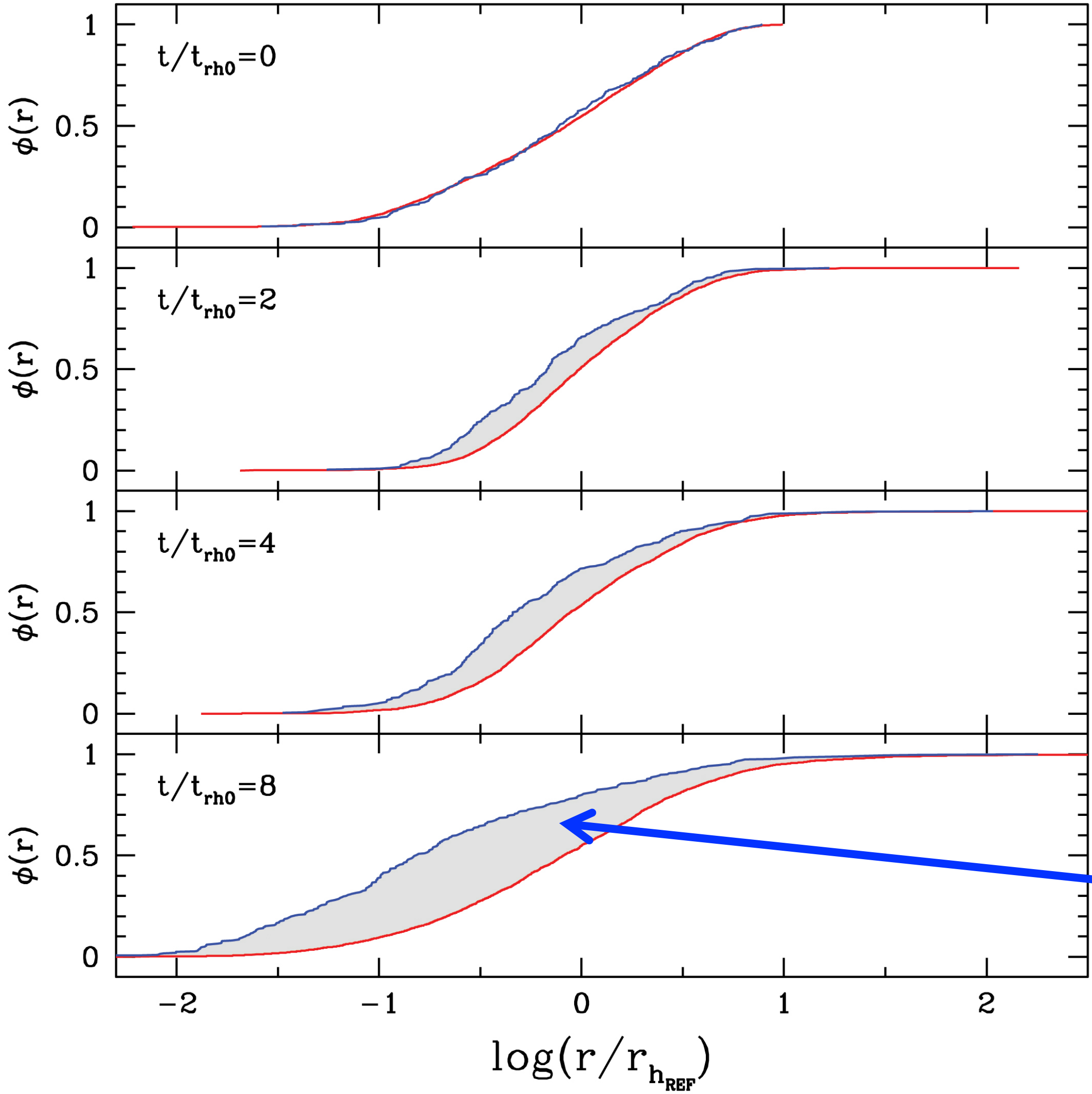


The central peak is a "high-signal" feature

Thus we are now focussing on the central region where the BSS are accumulating.

Refining the dynamical clock

10^5-particles N-body simulations to study the segregation process of BSS as a function of time



Cumulative radial distribution
as a function of time

BSS

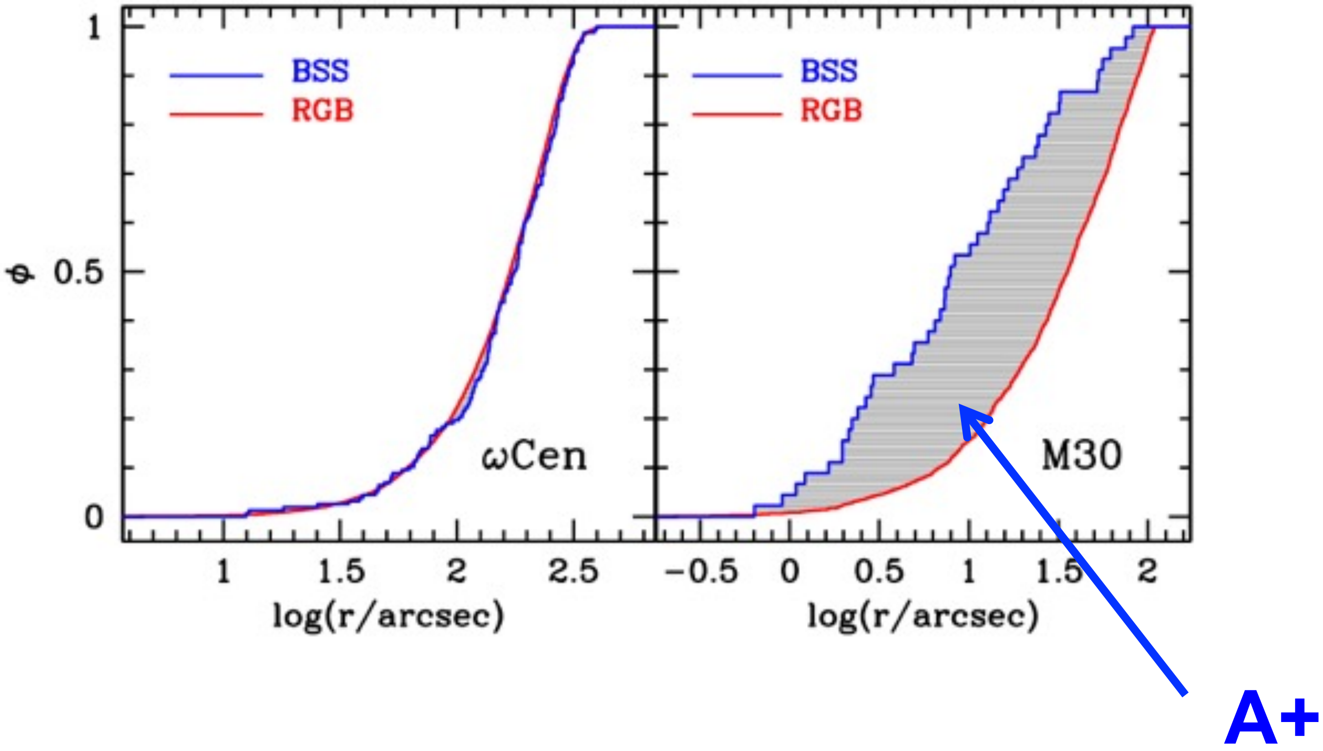
REF population

A+

Alessandrini+16, ApJ, 833,252

Refining the dynamical clock

Indeed also observations GCs show different level of BSS central segregation



A+ provides a measure of the level of BSS central segregation

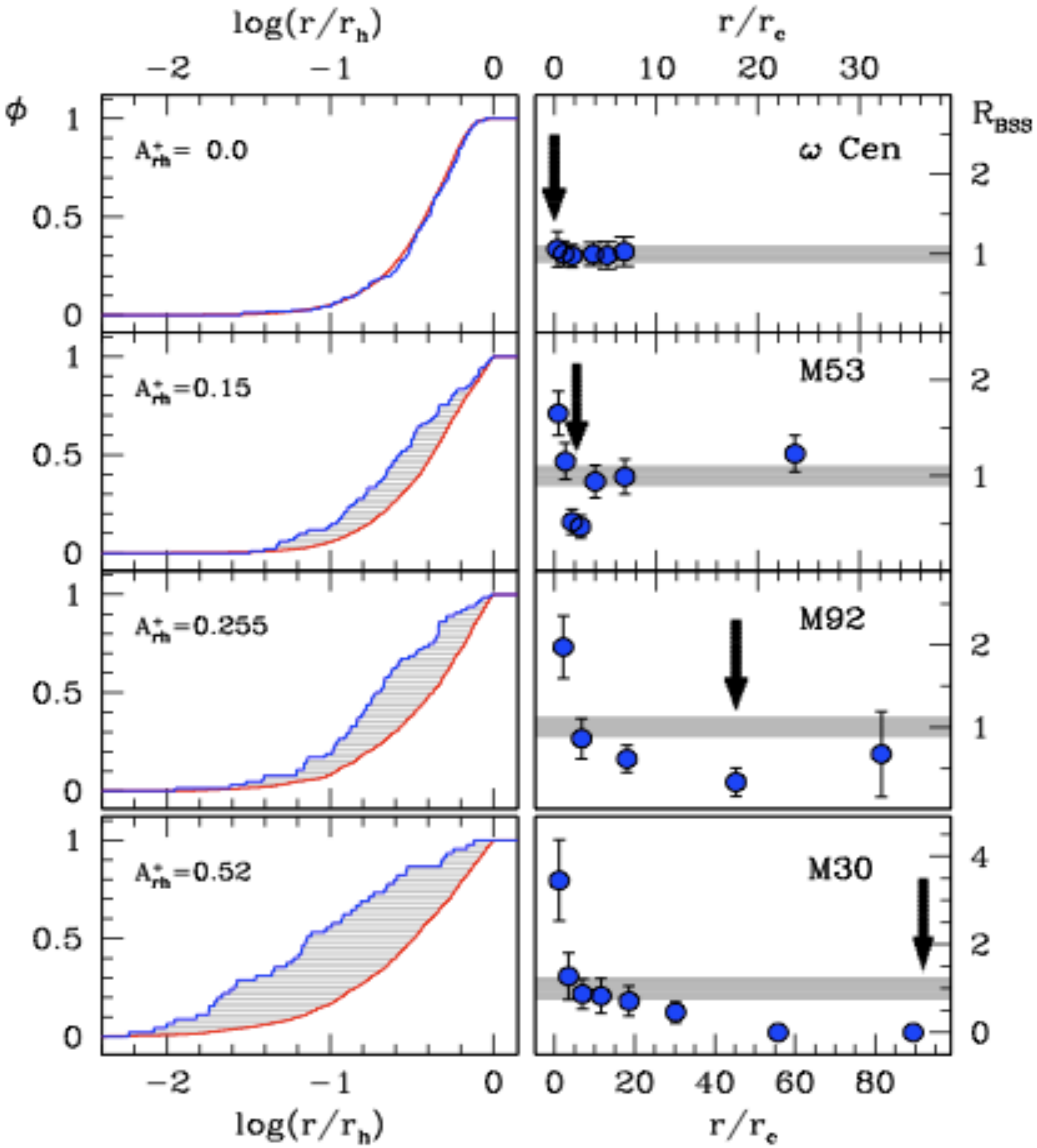
Lanzoni+16, ApJ, 833,L29

Is there any link between r_{min} and A+ ?

r_{min} and A+ are two features which in principle are expected to be fully independent…

but a correlation should be present if they are generated by the same physical phenomenon (the **dynamical friction**)

Refining the dynamical clock

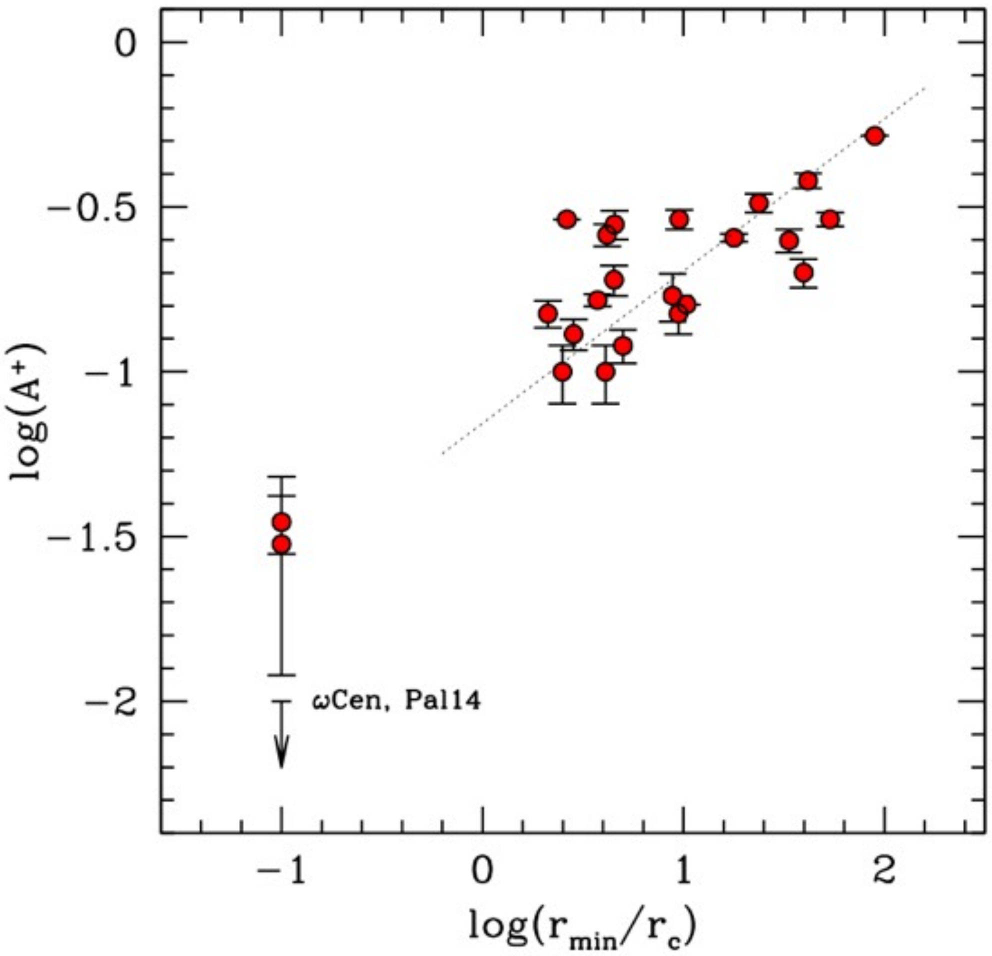


The increases of A+ is correlated to a systematic increase of r_{min} thus confirming that these two parameters are mutually linked, as expected in the case they describe the same phenomenon (**DF**)

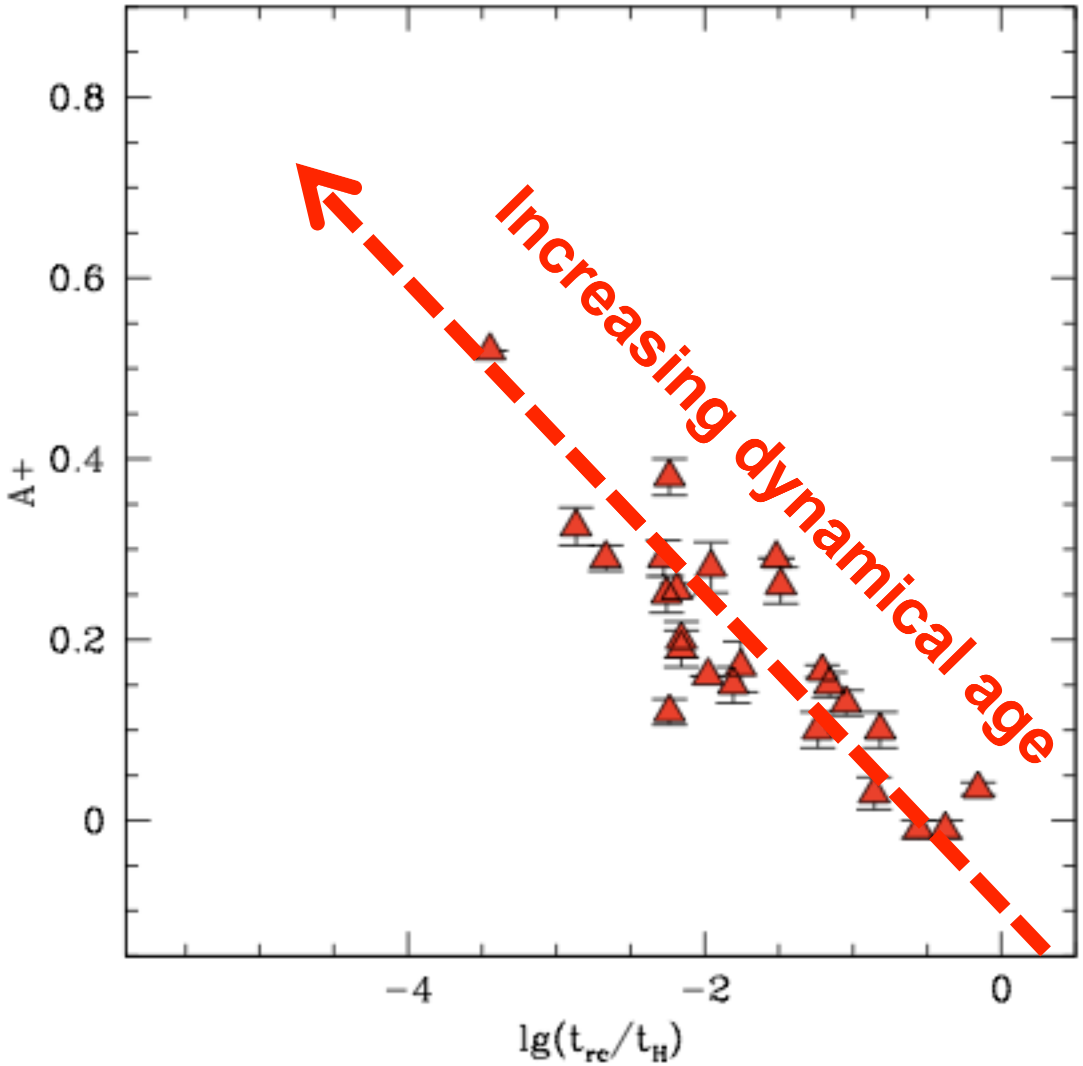
As clusters get dynamically older, **DF** progressively:

1. **removes BSSs** at larger and larger distances from the center (thus **propagating** r_{min})
2. **accumulates BSS** toward the cluster center (thus **increasing A+**) .

Lanzoni+16, ApJ, 833,L29

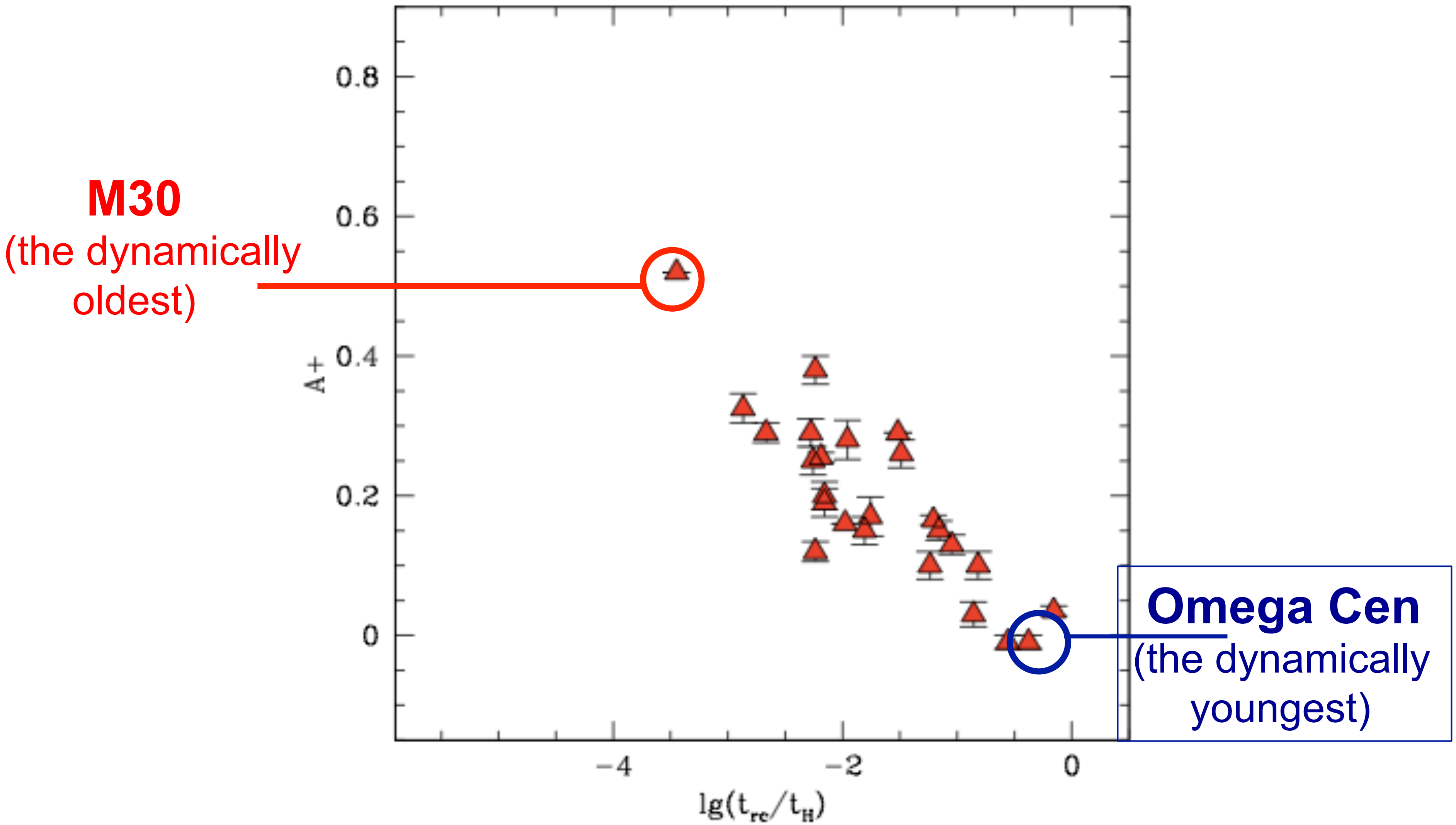


the two parameters are mutually linked through a quite tight correlation. This confirms that they are actually different ways of measuring the same physical process (i.e the dynamical friction), which progressively removes BSSs at increasingly larger distances from the center (thus generating a minimum at increasingly larger values of rmin) and accumulates them toward the cluster center (thus increasing A+).



This new hand of the clock nicely agrees with theoretical estimates of the central relaxation time (t_{rc}), thus providing an efficient tool able to rank stellar systems as a function of their dynamical age.

Lanzoni+16, ApJ, 833,L29



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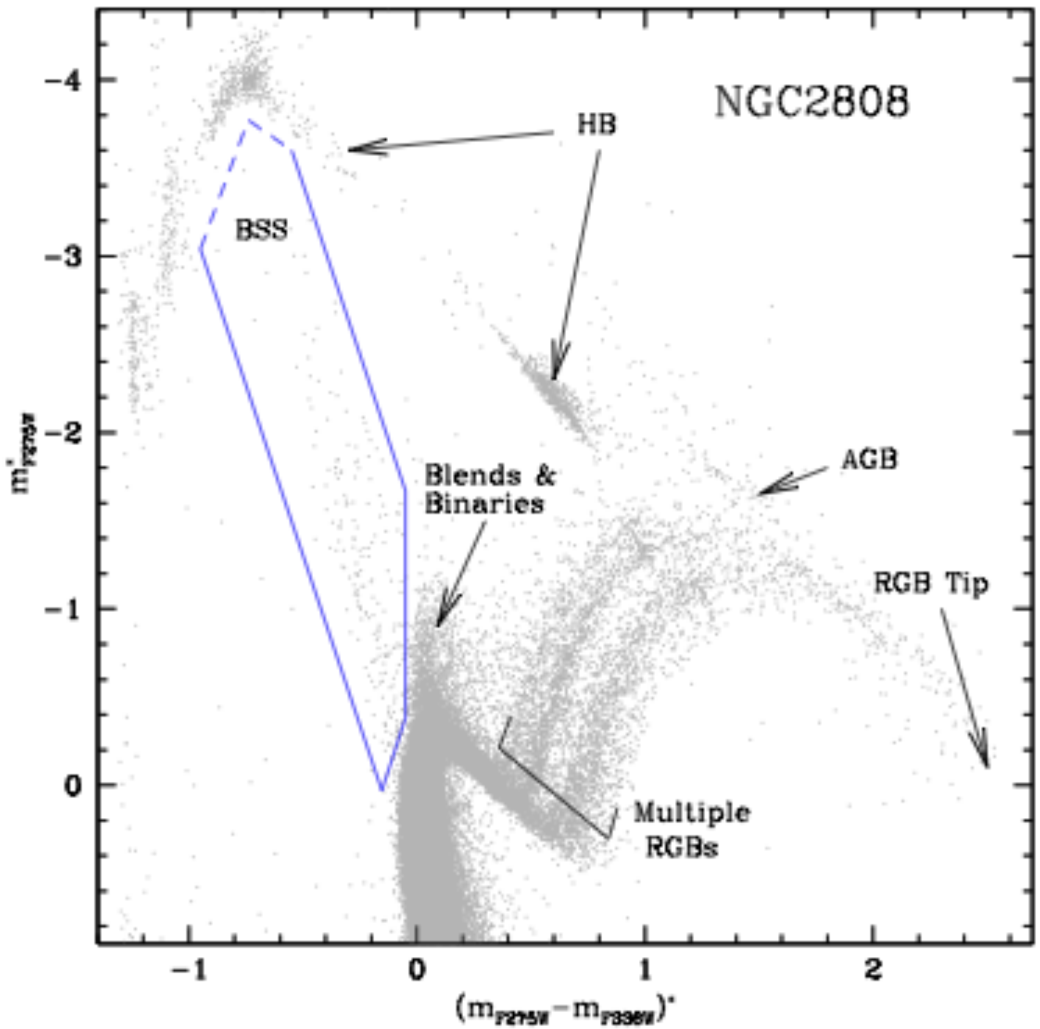
Lanzoni+16, ApJ, 833,L29

Exploiting the HST UV legacy survey of GGCs

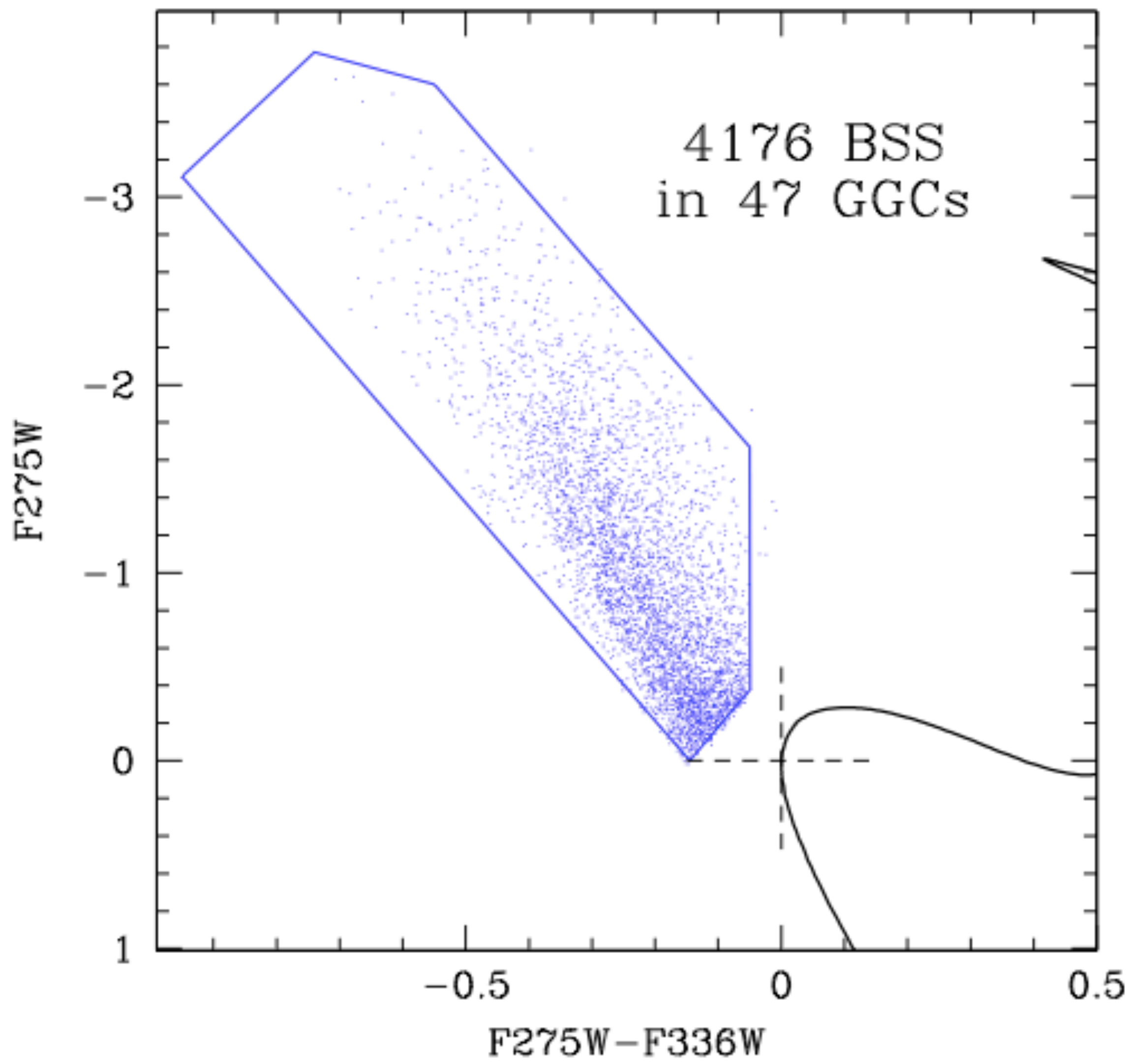
About 54 GGCs have been observed in 3 blue filters (F275W, F336W, F438W)
GO-13297; PI: Piotto



Raso+17, ApJ, 839,64

Exploiting the HST UV legacy survey of GGCs

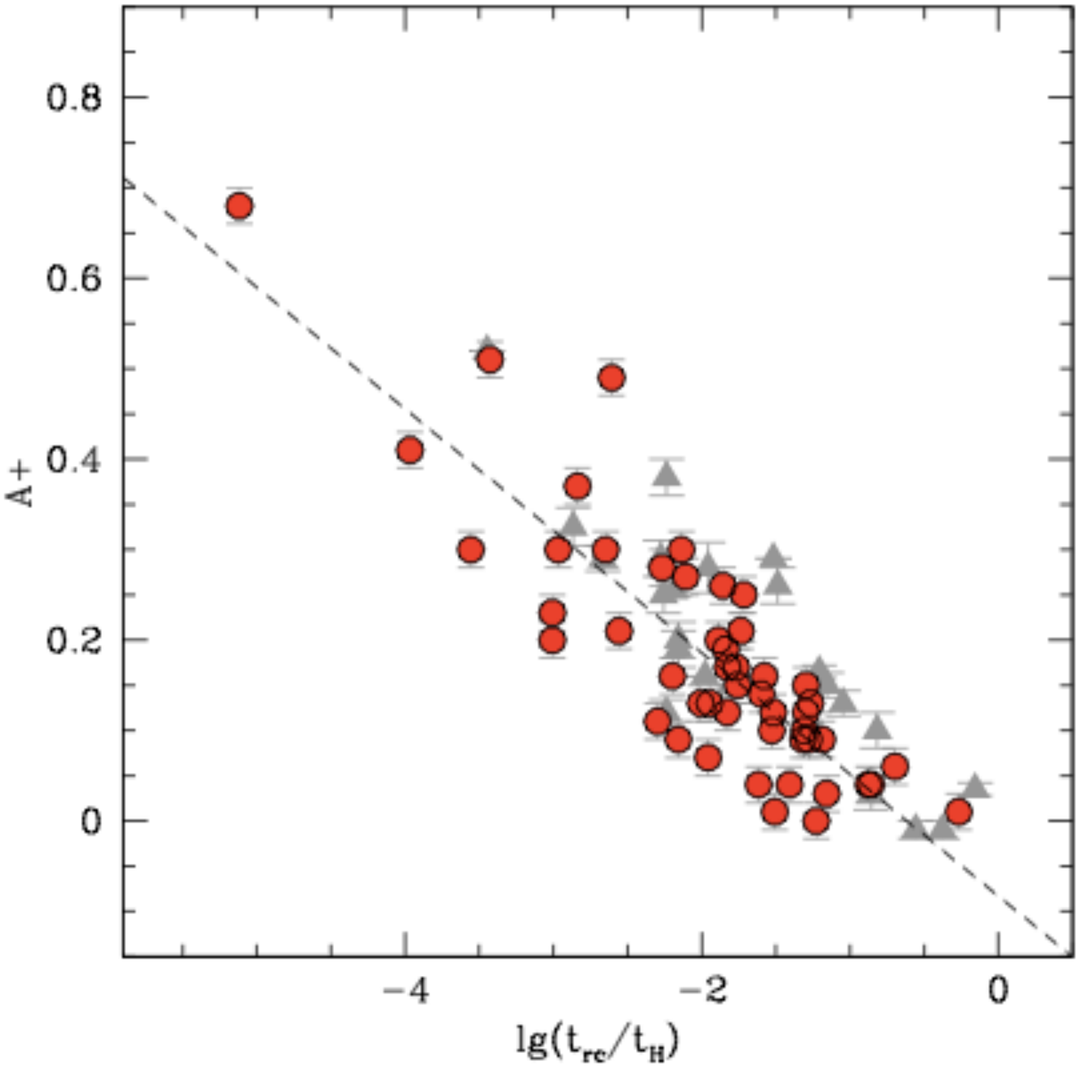
The largest sample of BSS ever published



Ferraro+17, in preparation

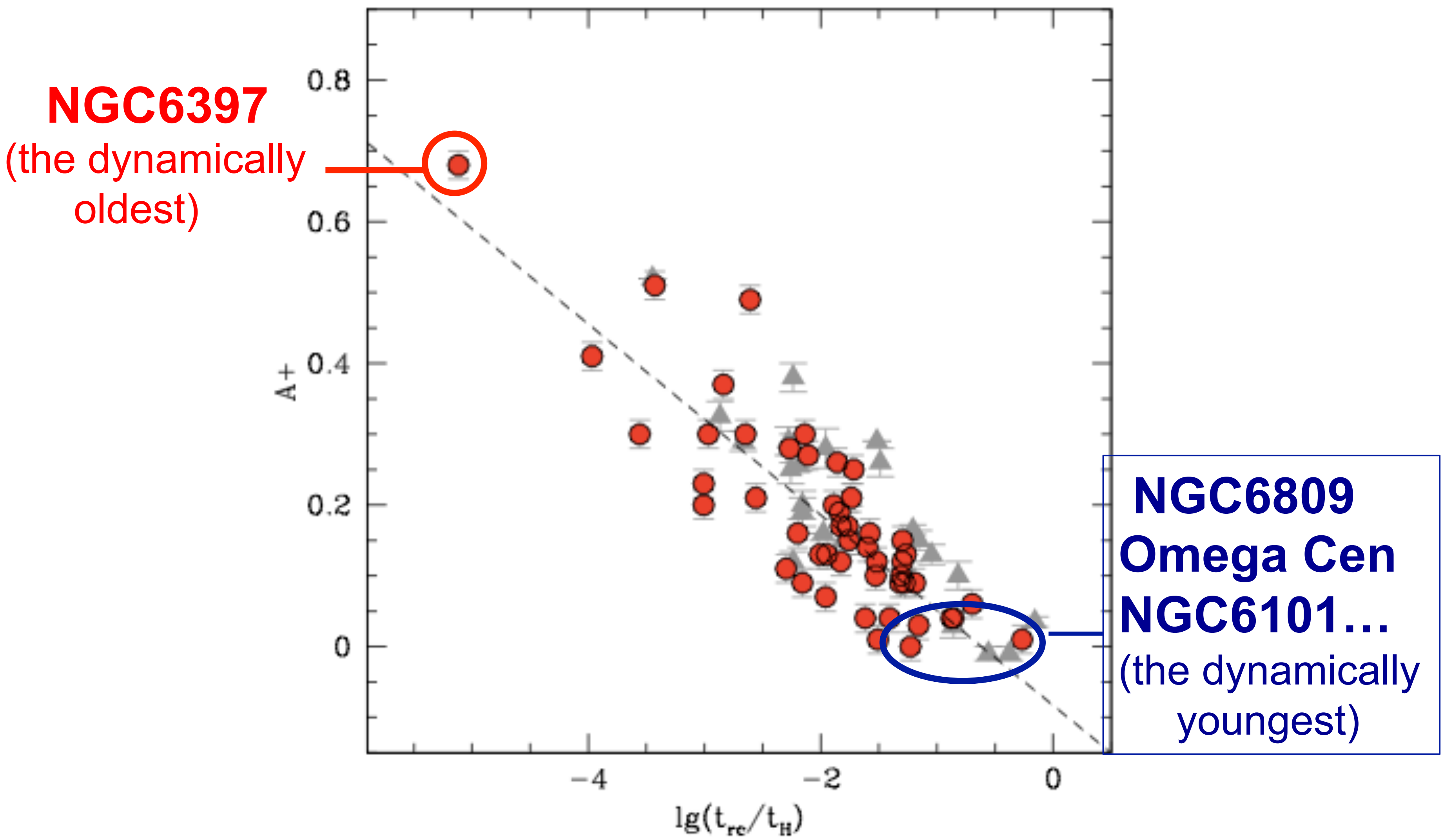
Exploiting the HST UV legacy survey of GGCs

The A+ parameter has been measured in a sample of 70 GGCs



Ferraro+17, in preparation

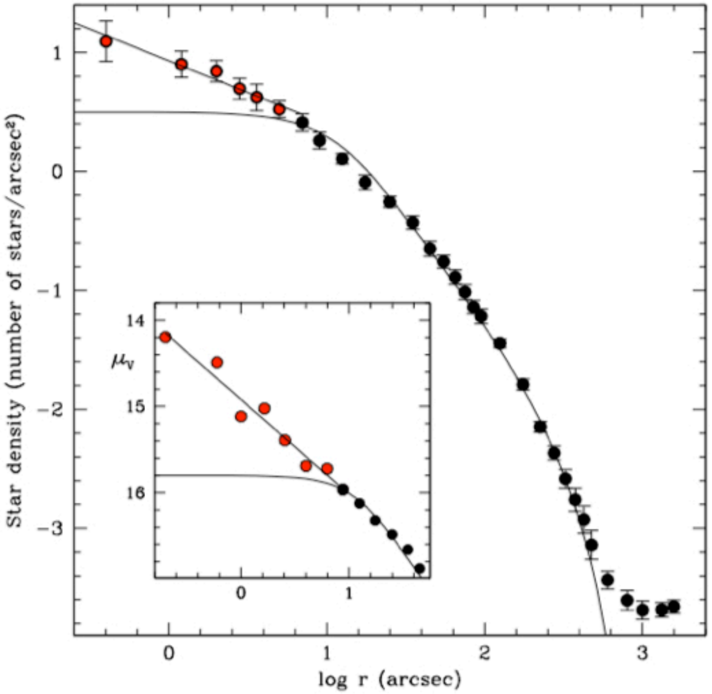
Exploiting the HST UV legacy survey of GGCs

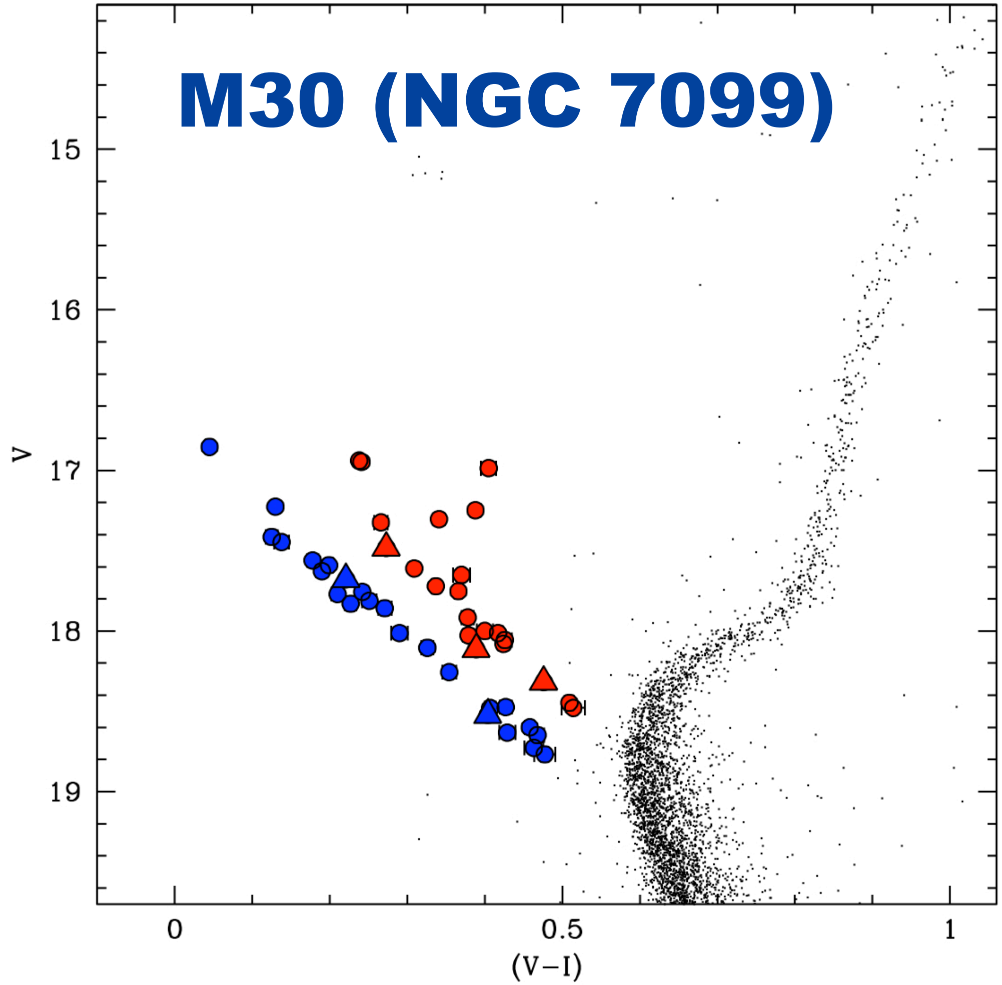


Ferraro+17, in preparation

Indeed we can do even more…..

The BSS photometric properties of BSS can trace the **formation channel** + might provide crucial information about one of the most spectacular dynamical event in the cluster lifetime: **the collapse of the core**





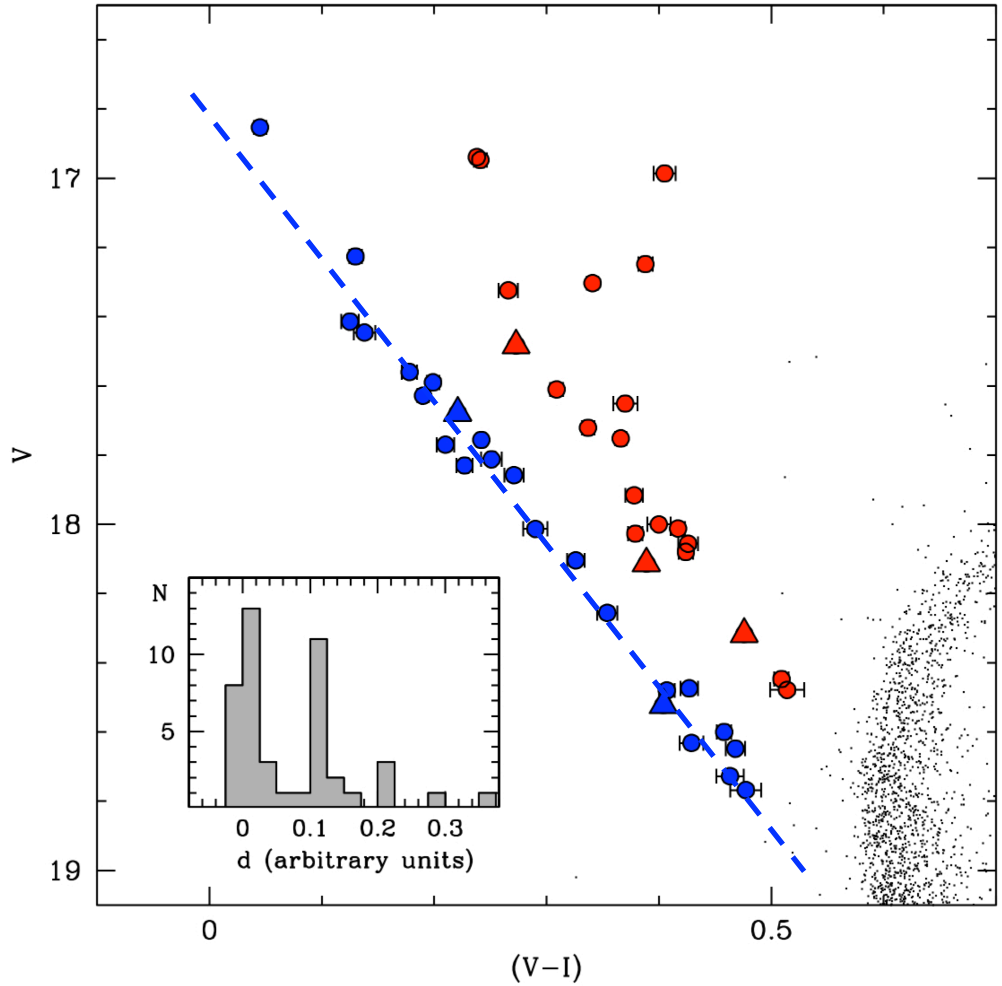
2 distinct sequences of BSS !!

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

2 distinct sequences of BSS in M30

- **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



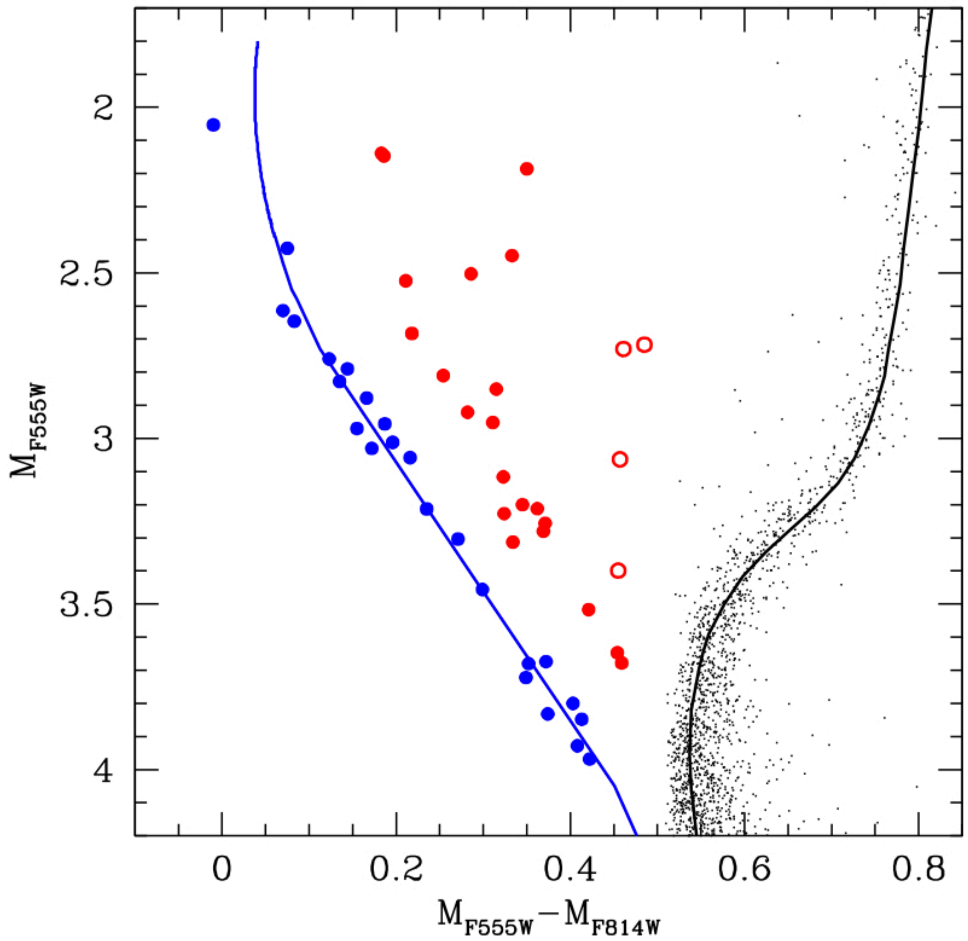
Cosmic-Lab

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

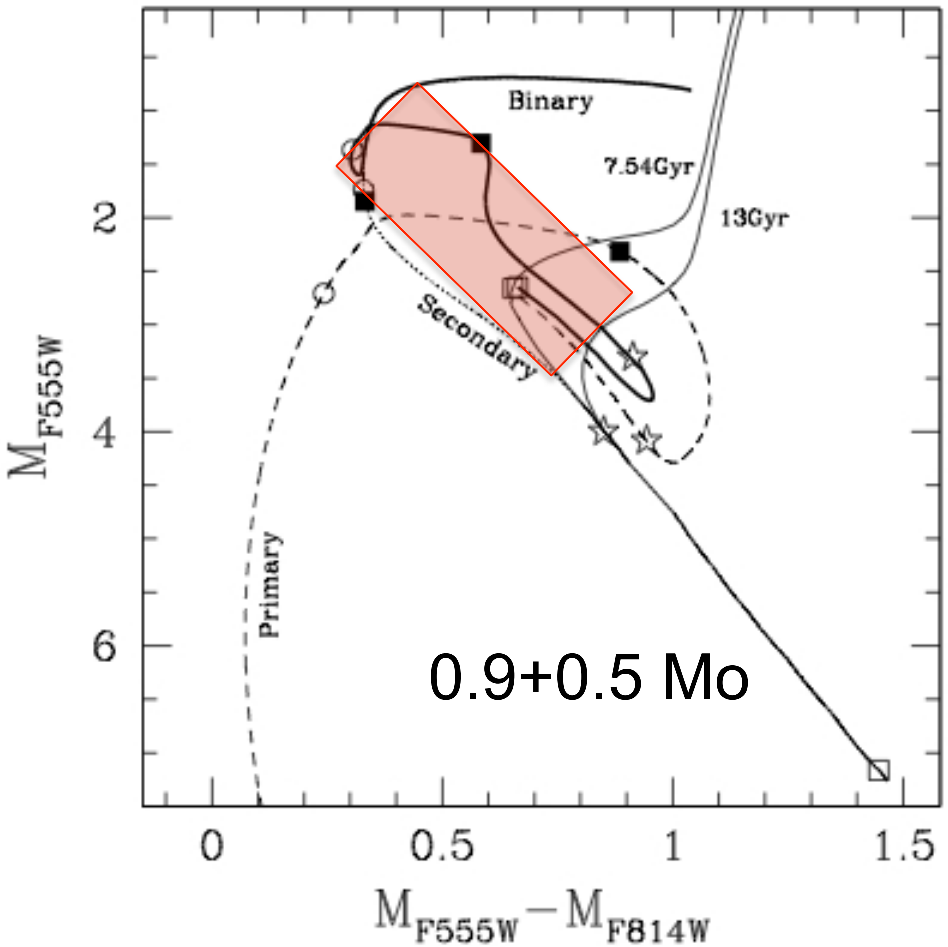
- collisions between two MS stars (0.4 - 0.8 $M_{\odot}$)
- $Z = 10^{-4}$ ($Z_{M30} = 2.5\ 10^{-4}$)

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

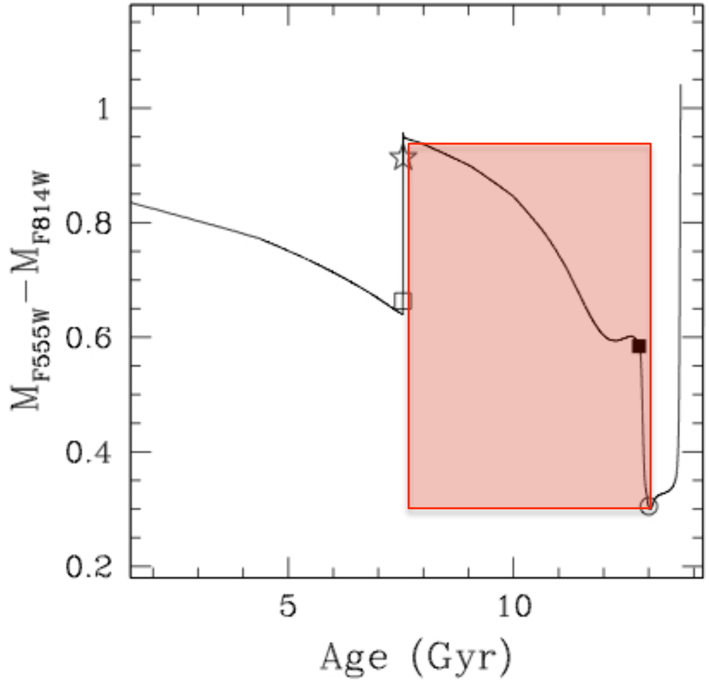
- **red-BSS** sequence **too red** to be reproduced by collisional isochrones of **any** age



Xin et al 2015 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



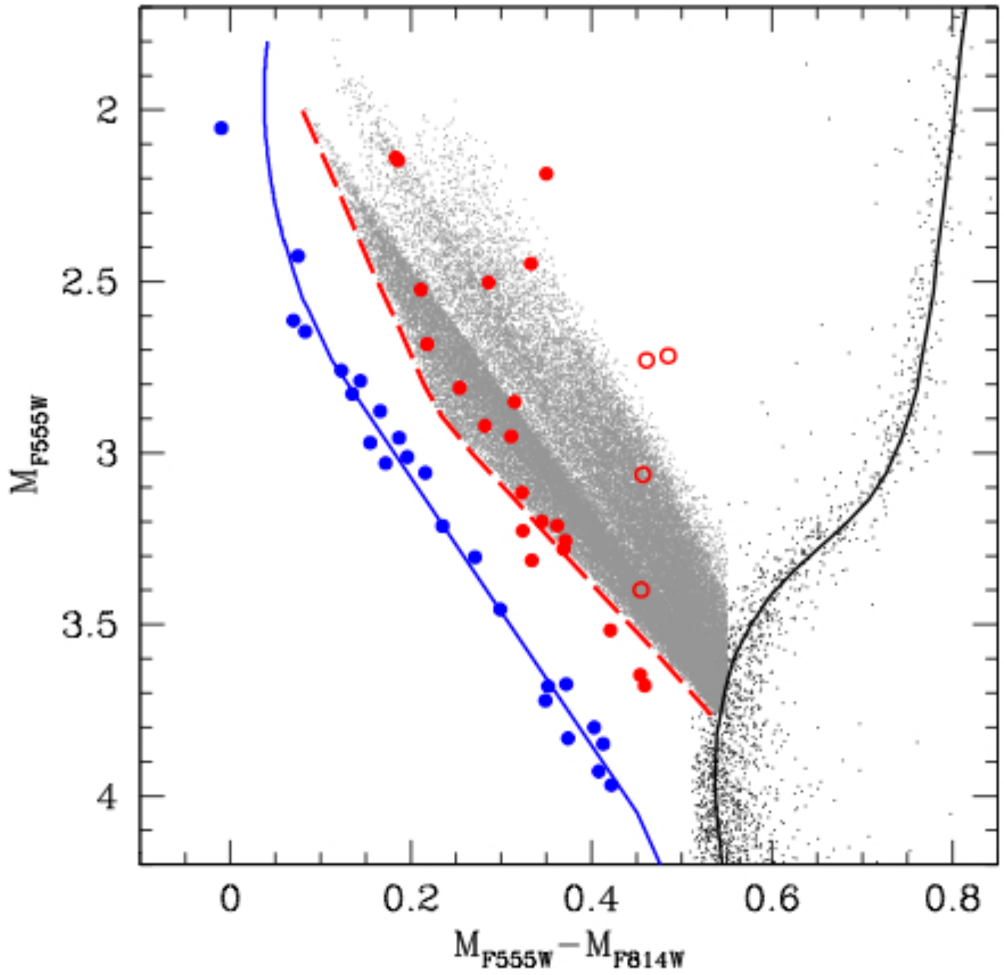
□ =MT starts ■ =MT ends ○ =13 Gyr

Xin+15, ApJ,810,67

BSS double sequences

- blue-BSS sequence well reproduced by collisional isochrones of 1-2 Gyr (Sills+09)

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 ???

Two reasons:

1. **The detection requires a quite large photometric accuracy**
   (44 high-resolution images have been combined for the detection in M30)

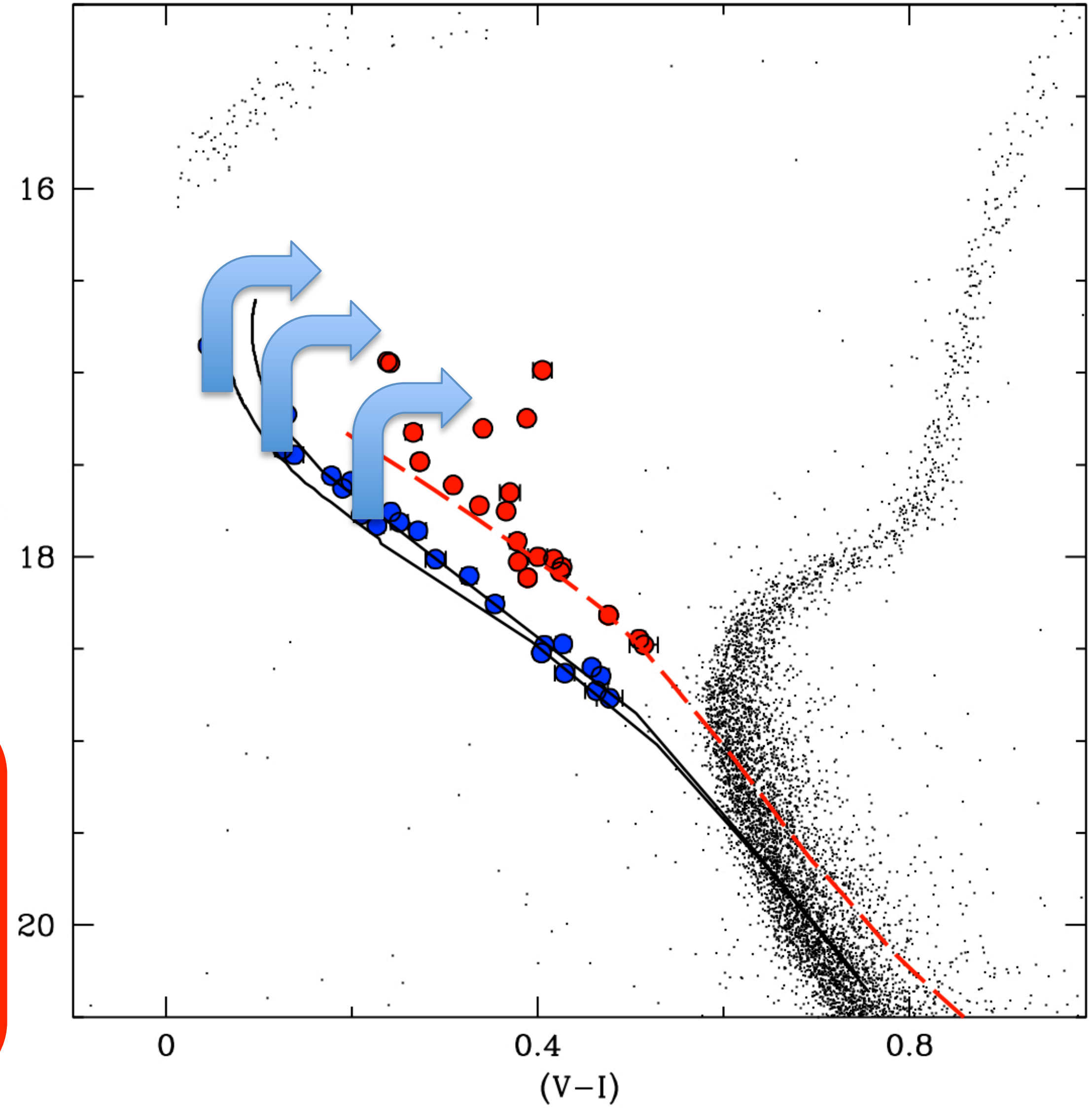
2. **A "physical" motivation:** it is NOT a permanent feature

• **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

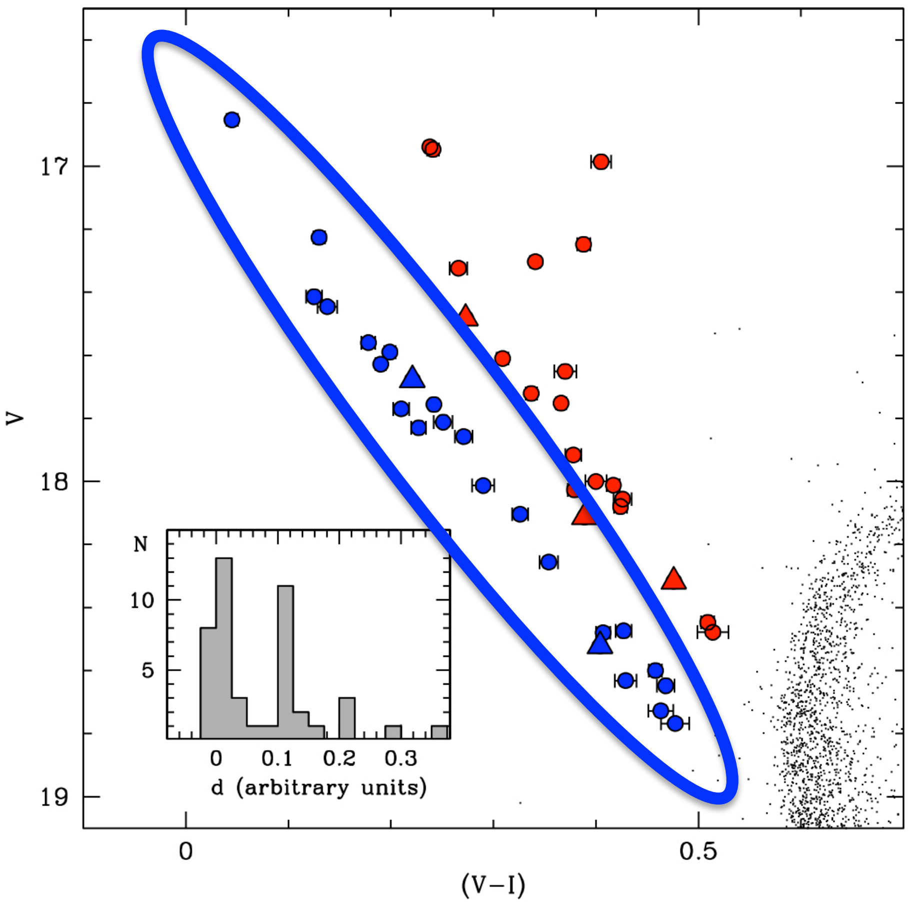
⇓

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?)

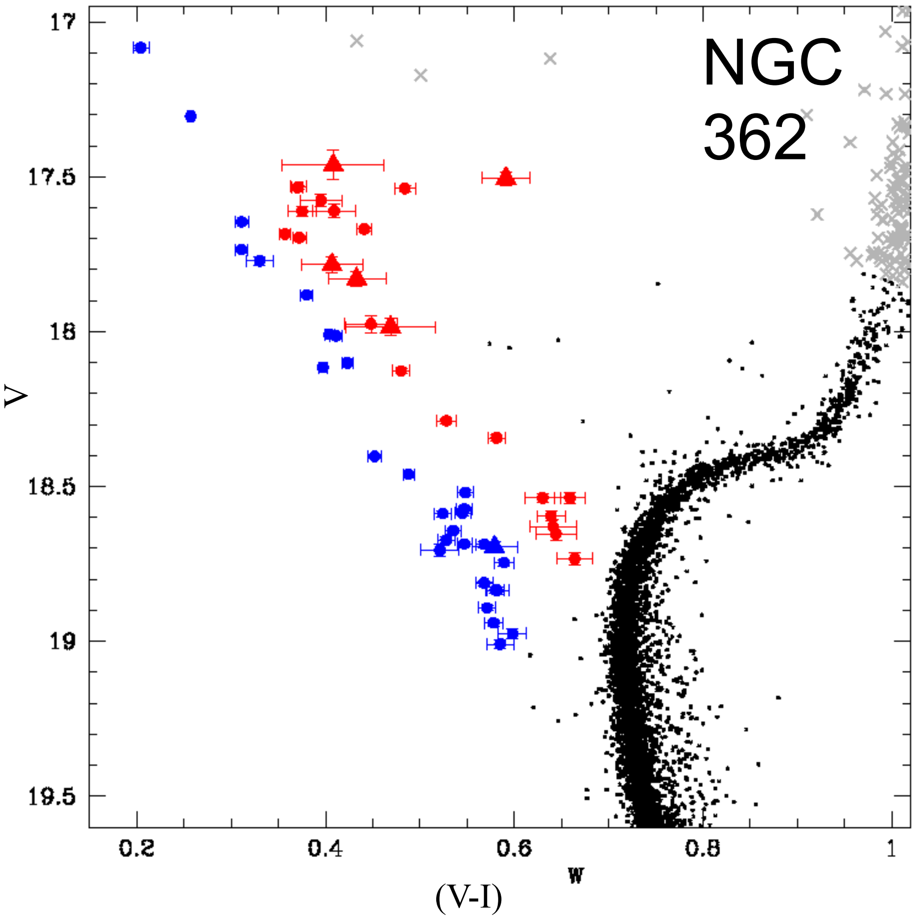
BSS double sequences

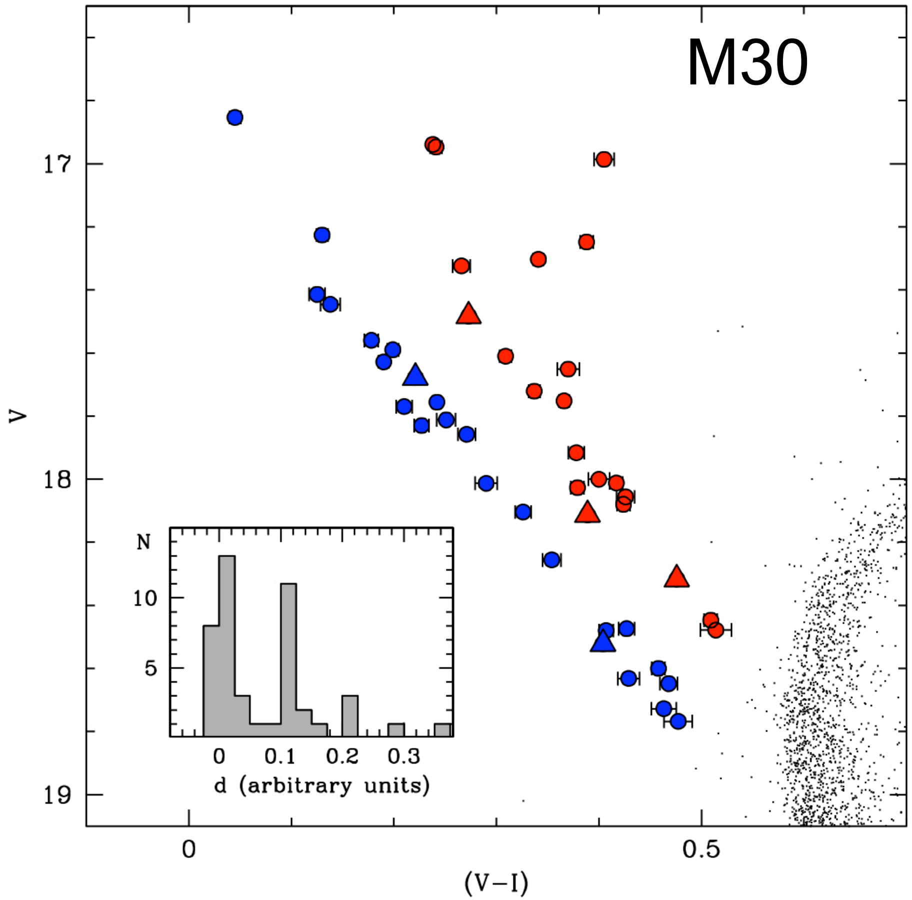


The properties of the **blue sequence** (extension and level of population) can be possibly used to **date the epoch of the Core Collapse**

Is there any other PCC with a double BSS sequence?

BSS double sequences

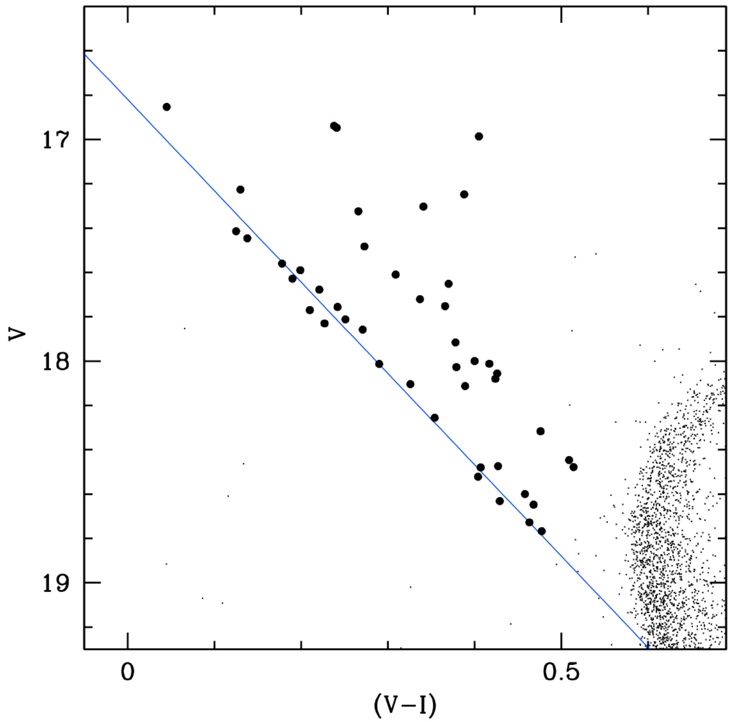


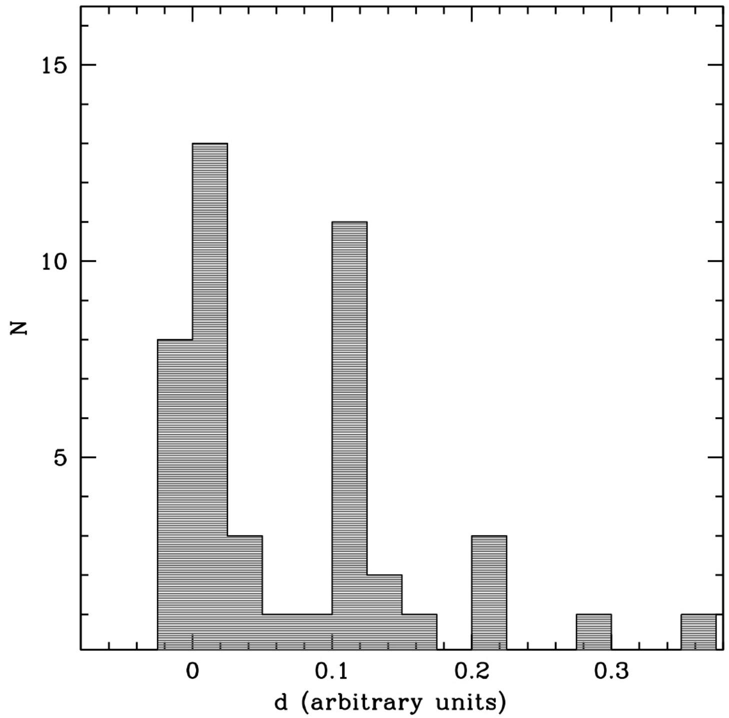


Dalessandro et al. 2013

BSS double sequence: The case of NGC6397

M30 (Ferraro et al. 2009)

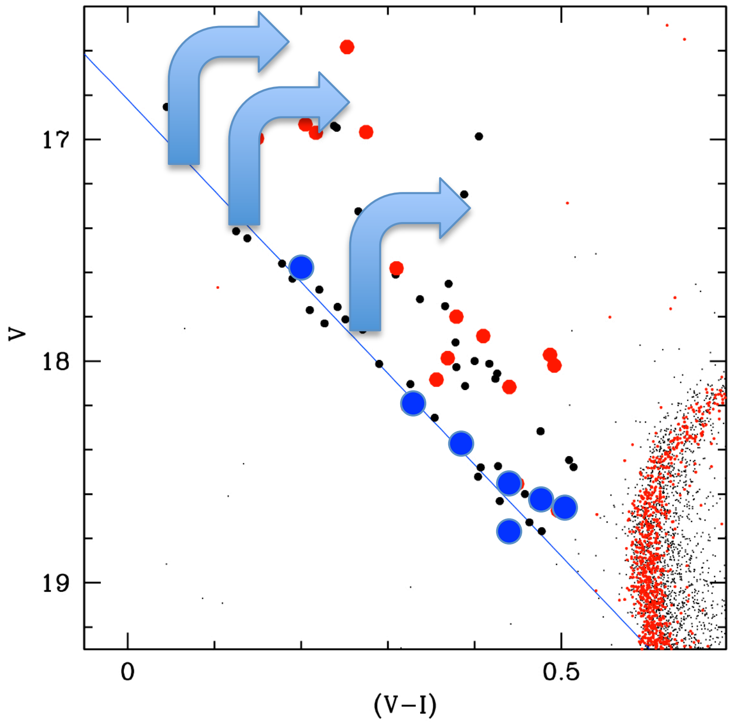


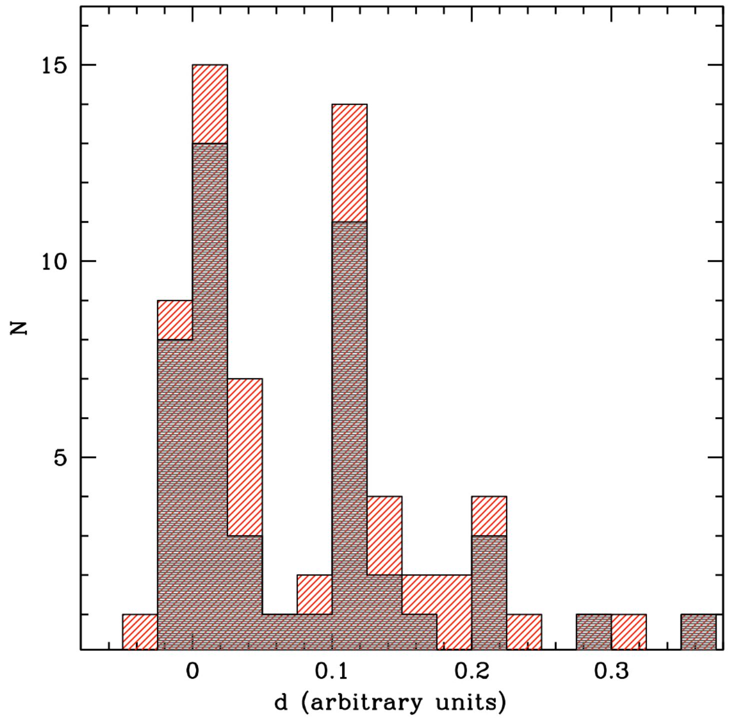


BSS double sequence: The case of NGC6397

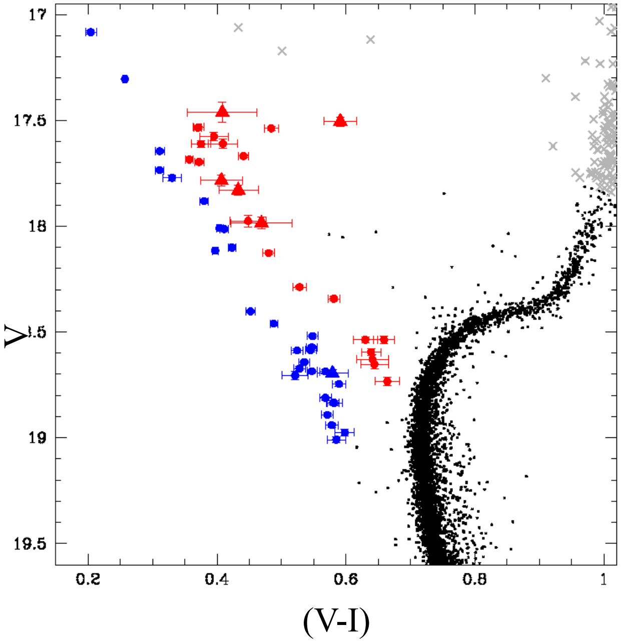
In the case of NGC6397 the **blue-BSS** sequence appears much less populated; thus suggesting that the core collapse in this cluster occurred much **earlier** than M30

NGC 6397 (Ferraro et al. 2017, in preparation)



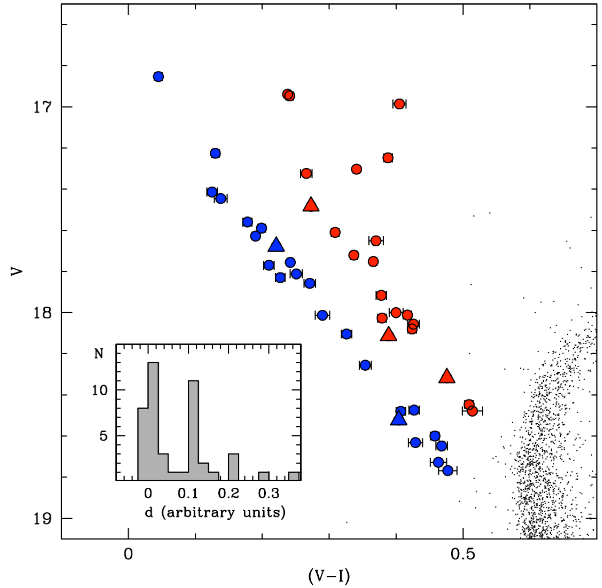


NGC 362

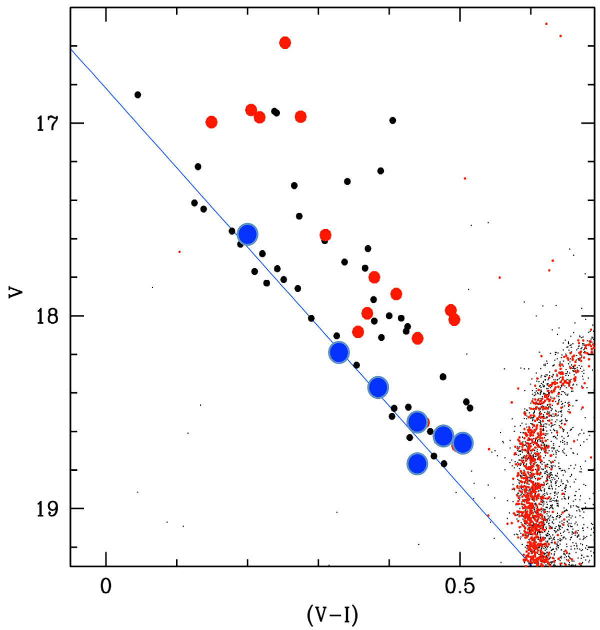


Dalessandro et al. 2013

M30



NGC6397

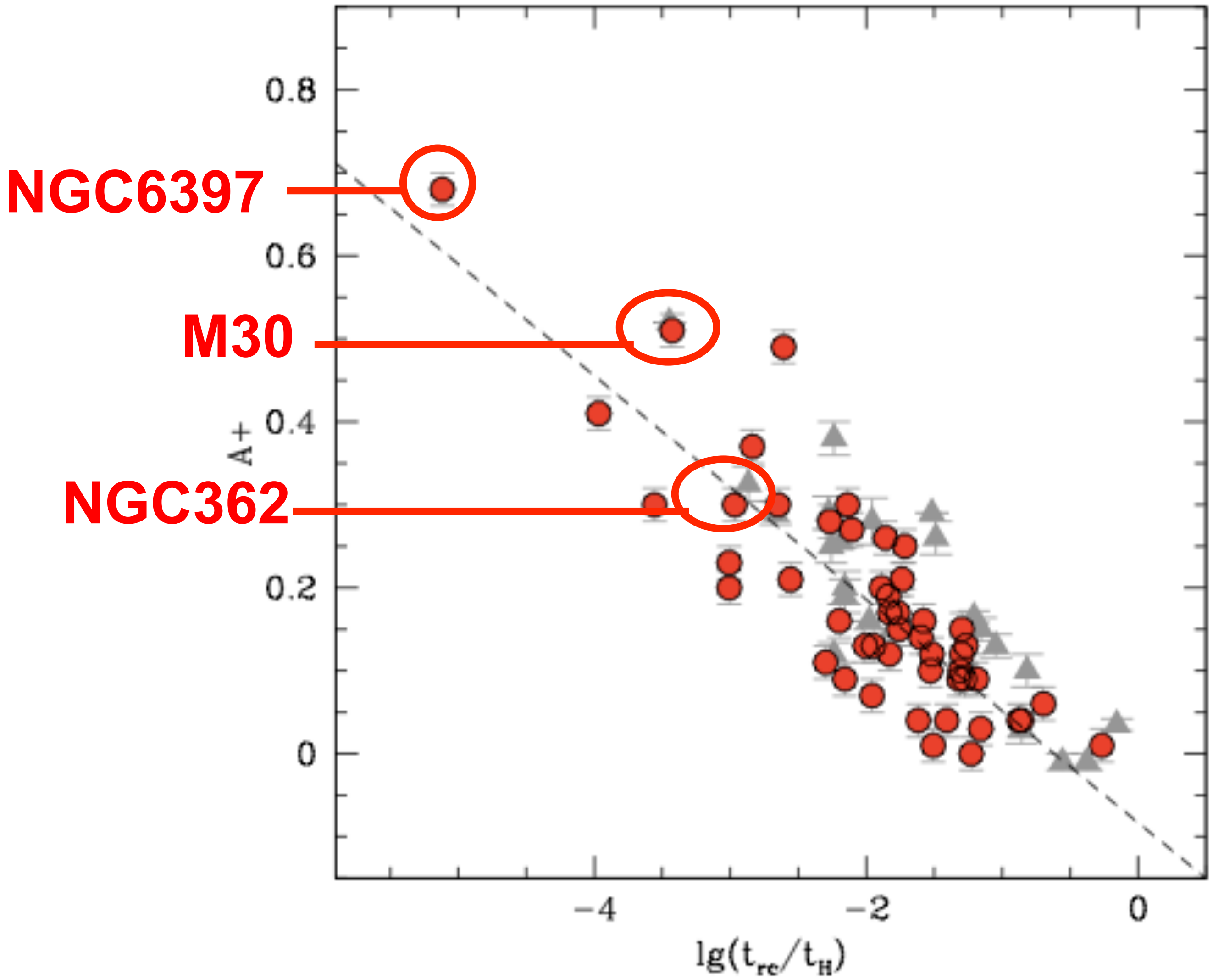


Recent collapse
(1 Gyr ago)

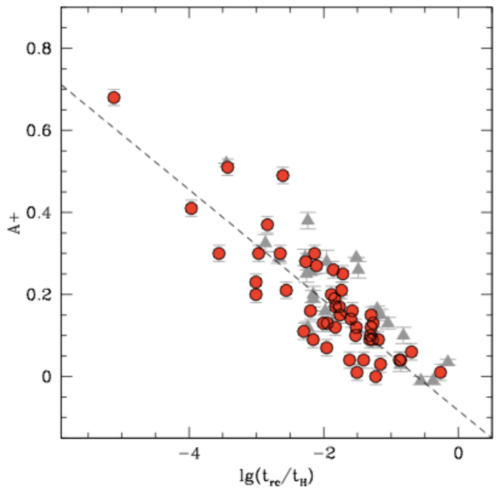
OLD collapse
(Several Gyr ago)

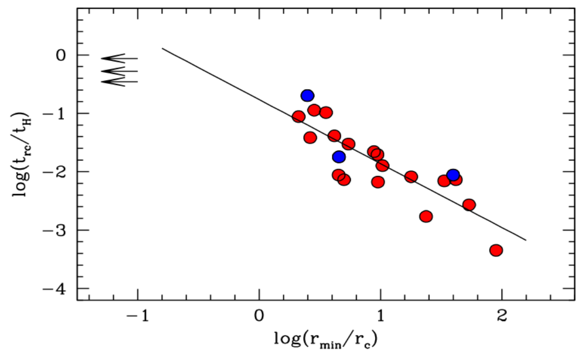
Cosmic-Lab

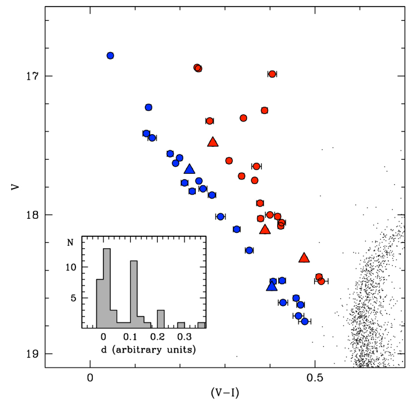
A+ in PCC GCs



Ferraro+17, in preparation



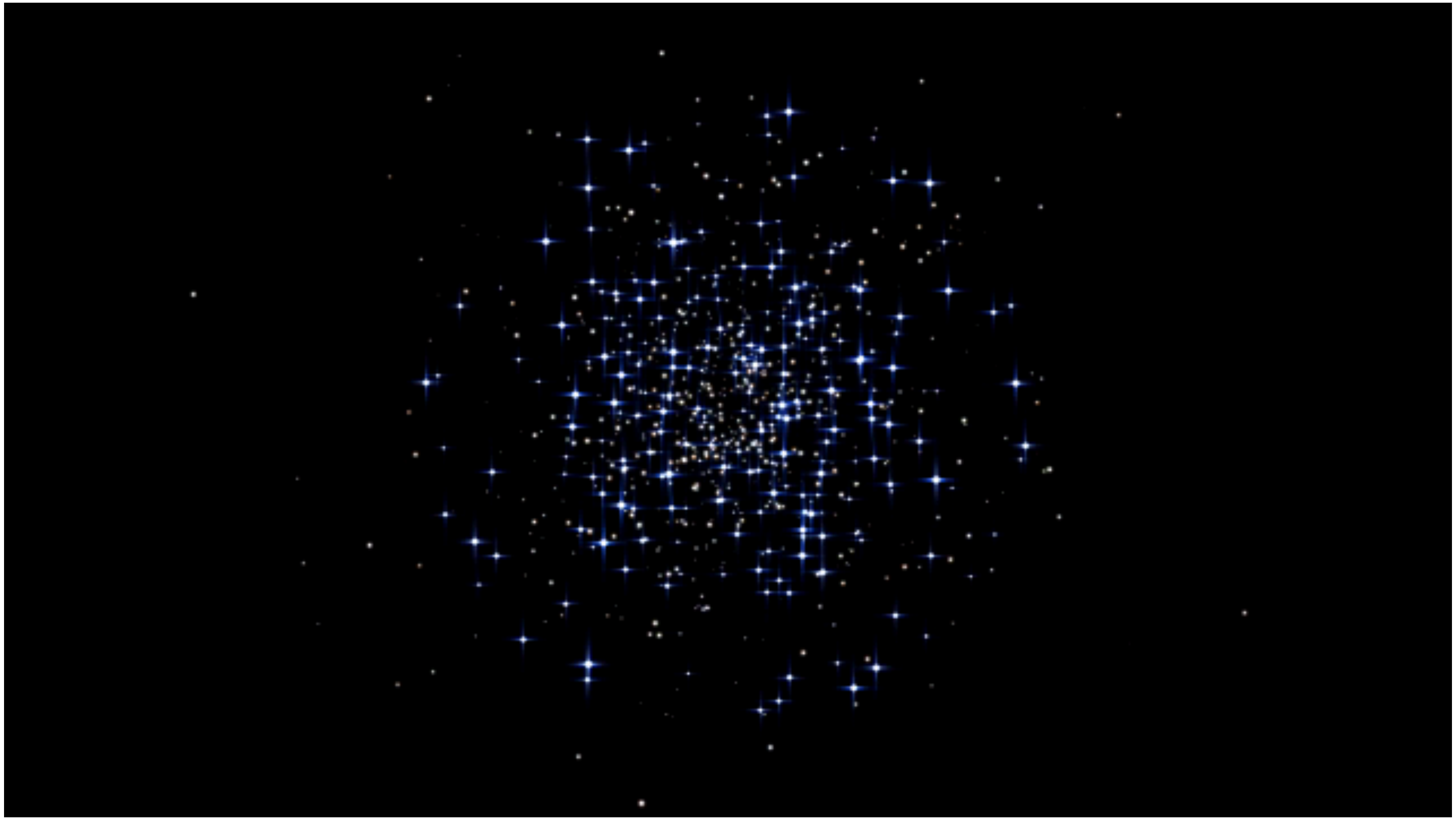




BSS are the most common **by-product of binary evolution.**
They are crucial and powerful **gravitational test particles.**

BSS properties (in terms of radial distribution, photometry, etc)
trace the past history of the parent clusters

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



The End

Thank you for your attention !!!