An empirical clock to measure the dynamical age of stellar systems

FRANCESCO R. FERRARO

Physics & Astronomy Department – University of Bologna (Italy)

Conception, Chile, March 4, 2015

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)

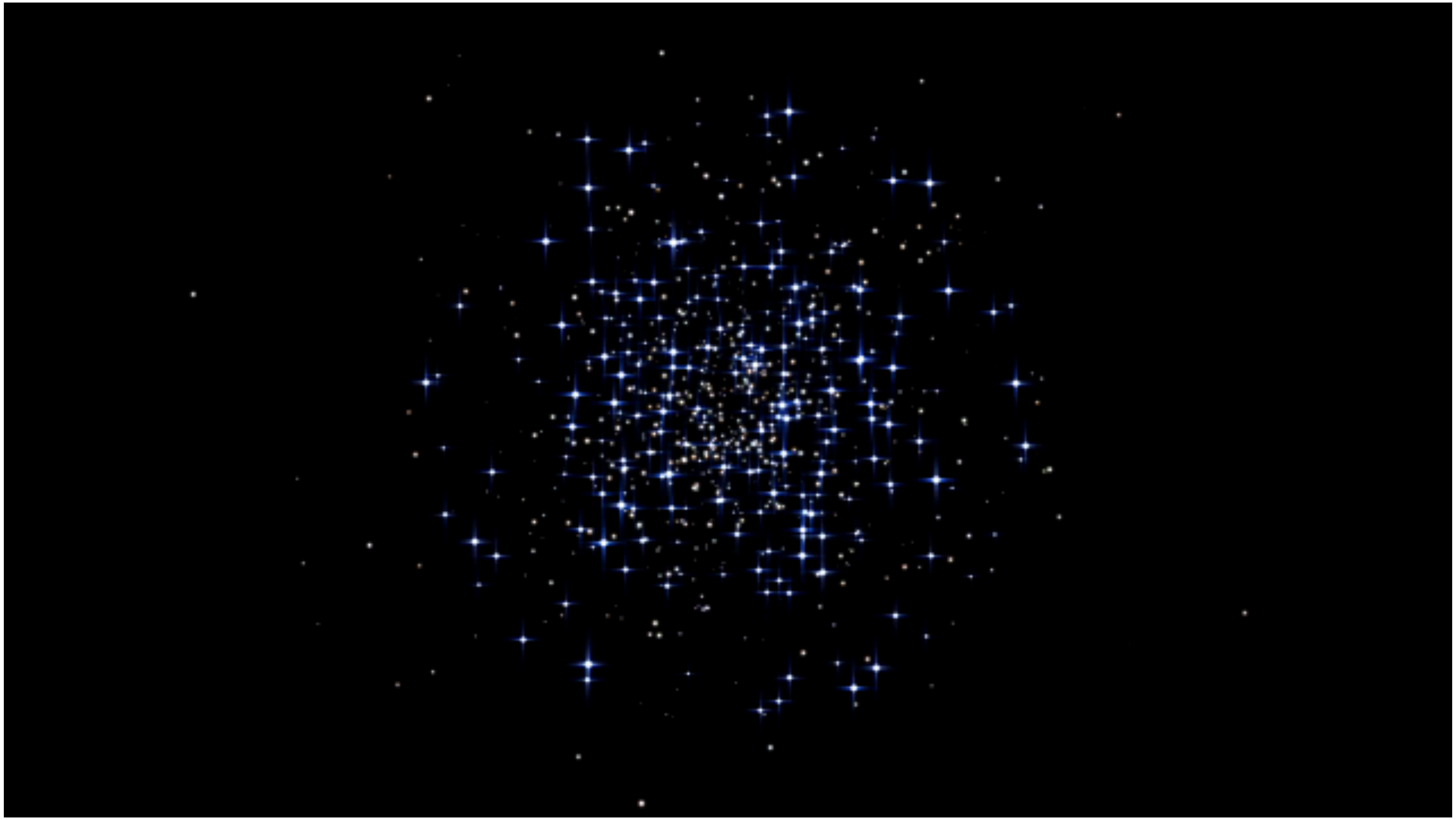
✦ AIM: **to understand the complex interplay between dynamics & stellar evolution**

✦ HOW: using **globular clusters** as cosmic laboratories and

Blue Straggler Stars
Millisecond Pulsars
Intermediate-mass Black Holes

} as probe-particles

WHY GCs?

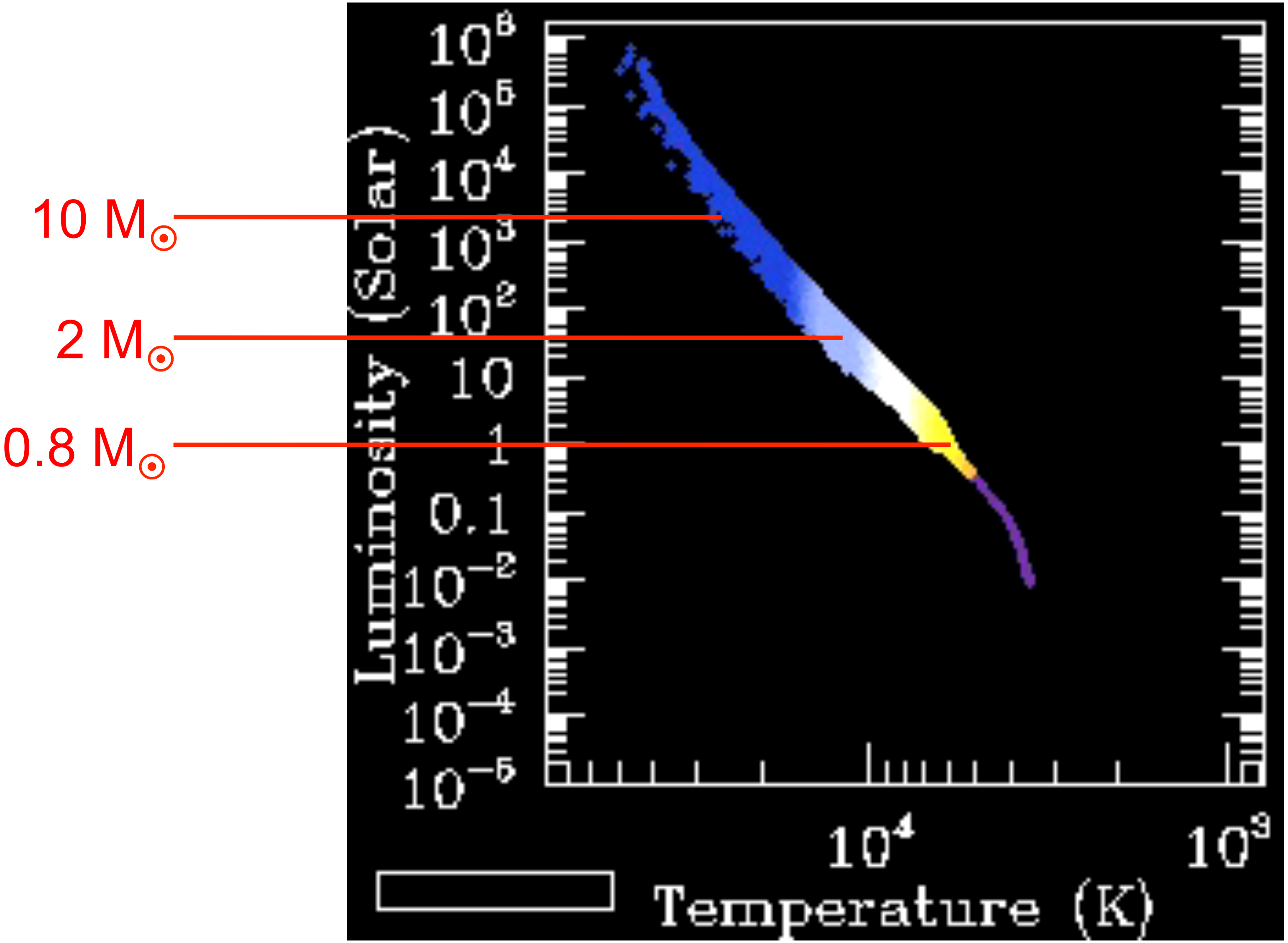


GC are the only stellar systems able to undergo nearly all the physical processes known in stellar dynamics over a time scale significantly shorter than the Hubble time.

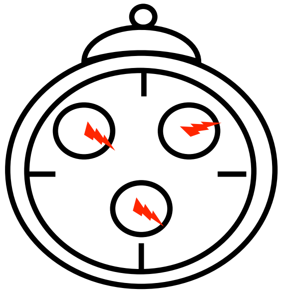
This dynamical activity can generate **exotica**

CHRONOLOGICAL & DYNAMICAL CLOCKS

The chronological clock



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

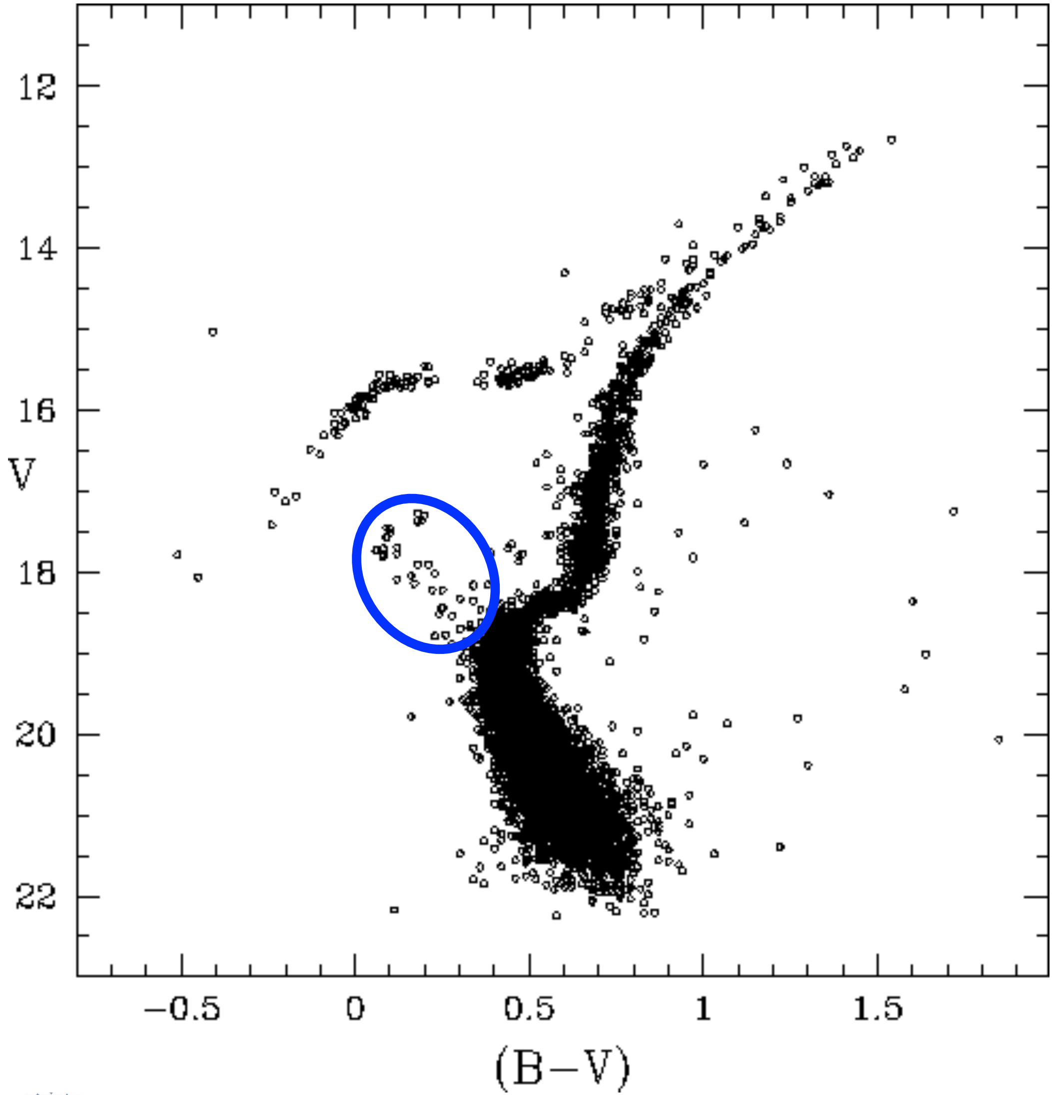


but stellar systems with the same chronological age can have reached quite different stage of dynamical evolution (they have different DYNAMICAL AGE)

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

Blue Straggler Stars (BSS)

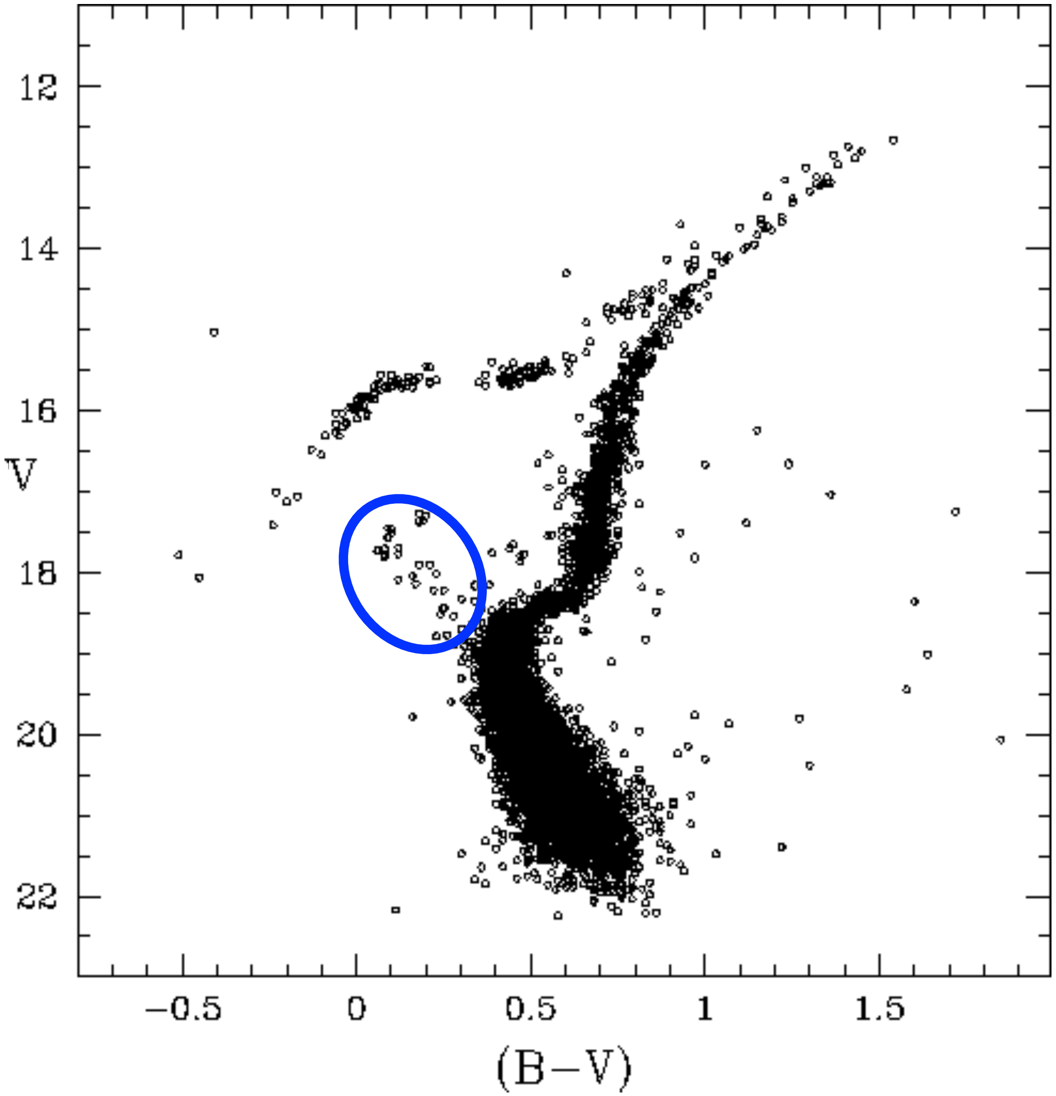
A PECULIAR stellar population



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)

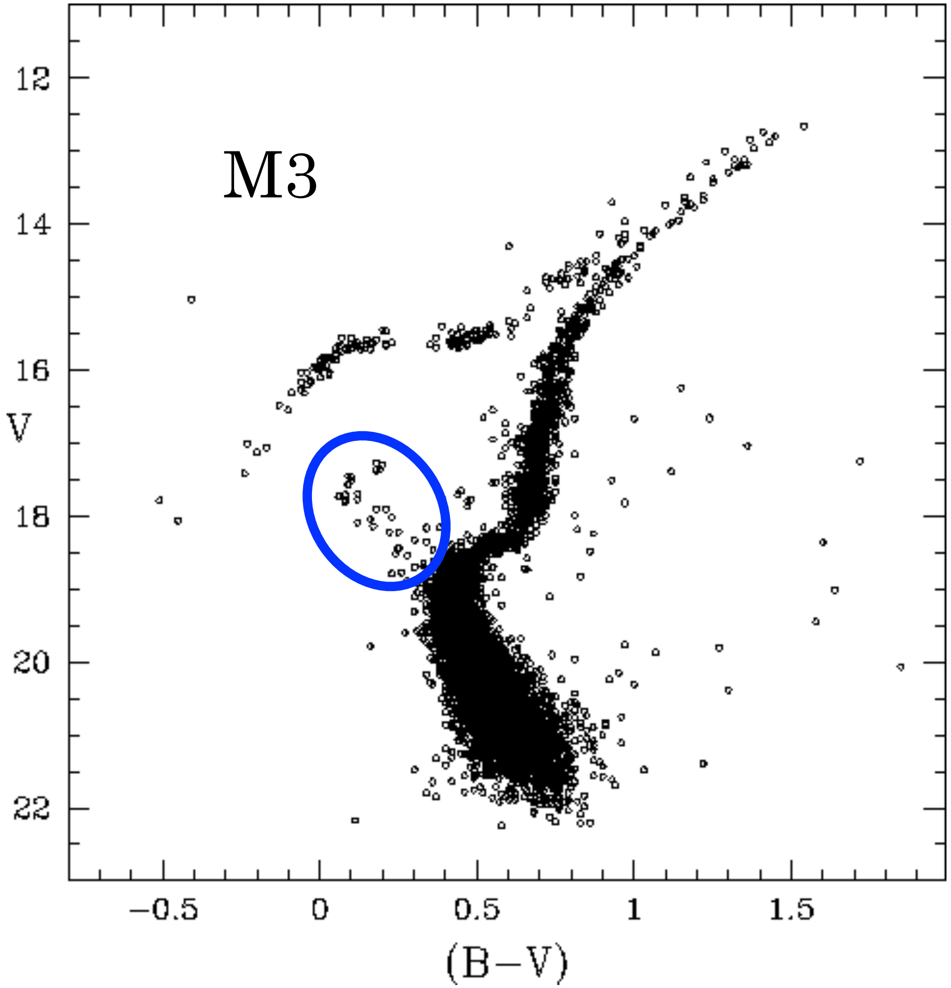


..while
old “normal” stars define
a sort of flock of tired stars
getting progressively
redder

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

Blue Straggler Stars (BSS)

Blue Straggler Stars (BSS)



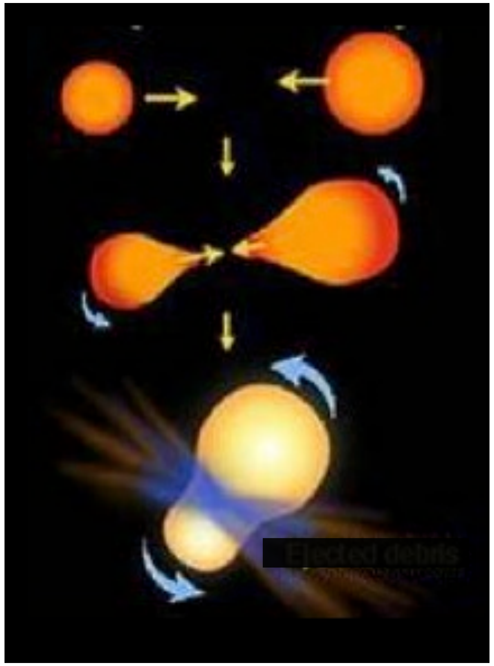
They LOOK younger but they are OLD stars rejuvenated by dynamical processes

↓

Merger of two low-mass stars

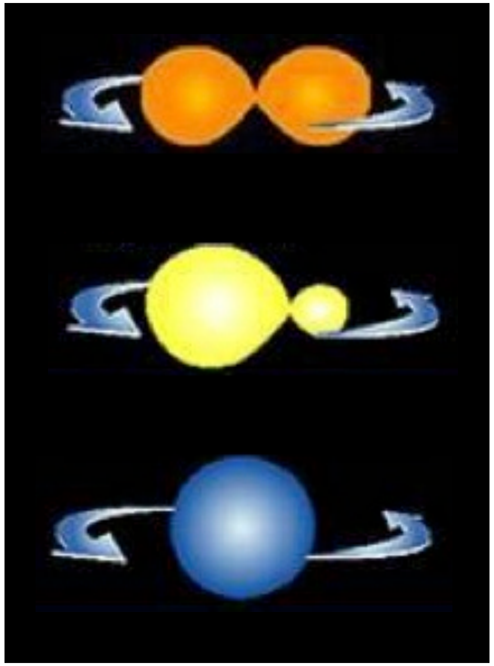
The formation mechanisms

COLLISIONS



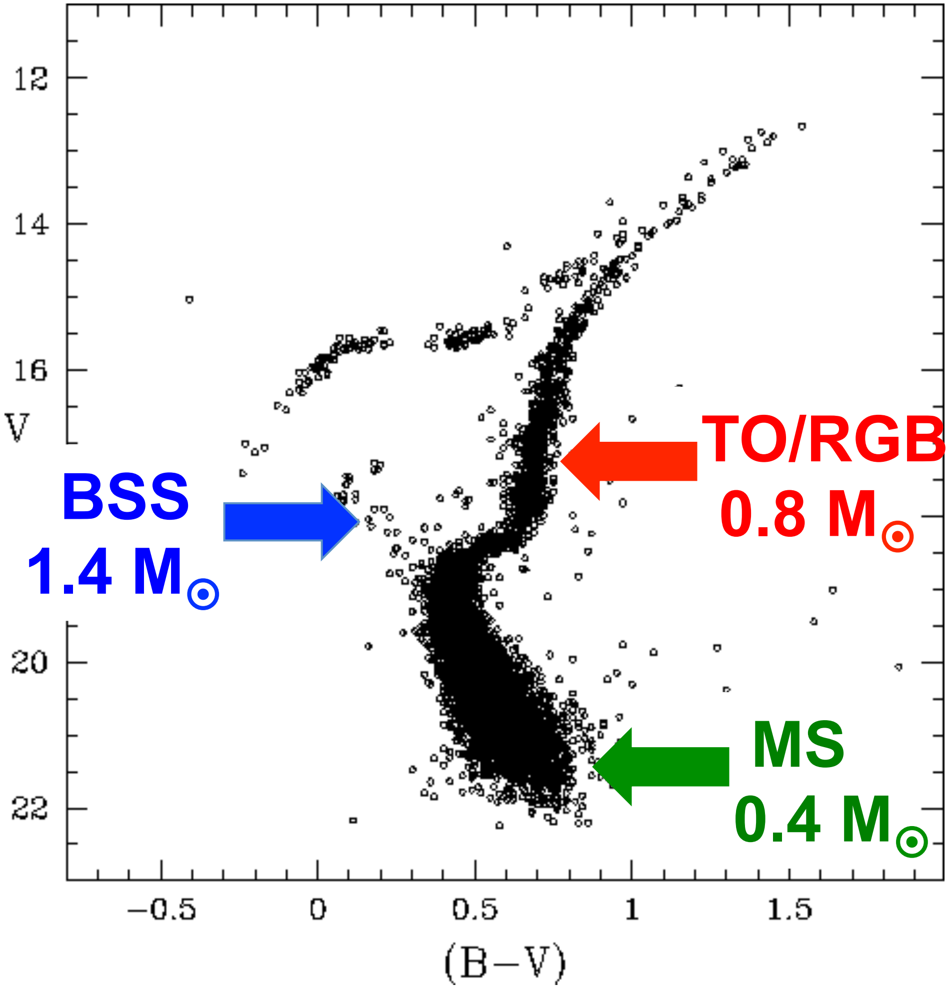
depend on **collision** rate
(Hills & Day 1976)

MASS-TRANSFER



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

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

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

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

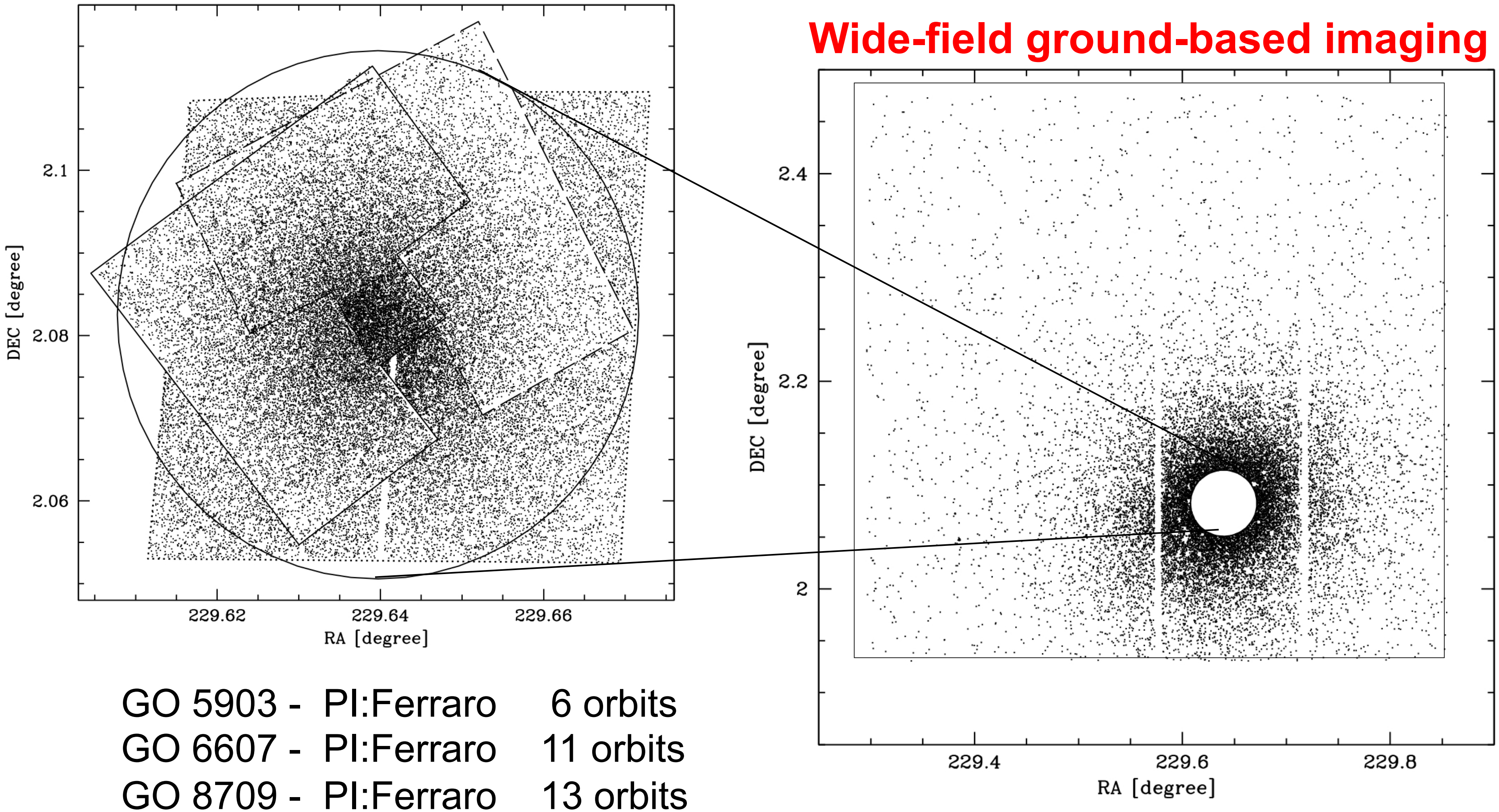
$$t_{df} \approx \frac{1}{M_{BSS}\,\rho(r)}$$

Because of this, **df** is expected to affect first the most internal BSS and then BSS 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

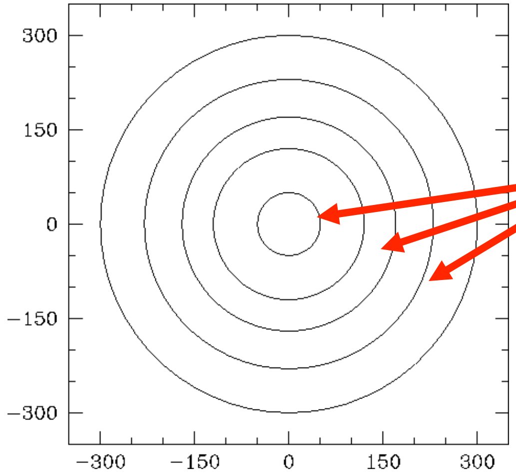
High-res: HST/WFPC2+ACS

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**

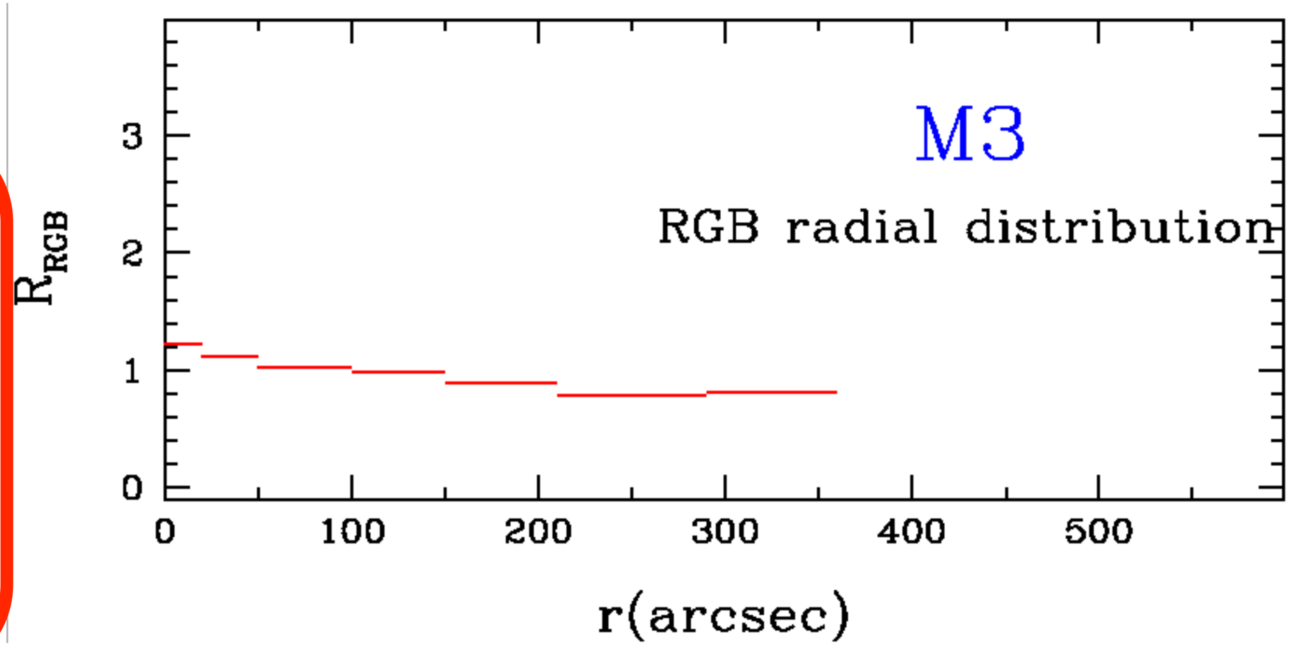
THE BSS RADIAL DISTRIBUTION



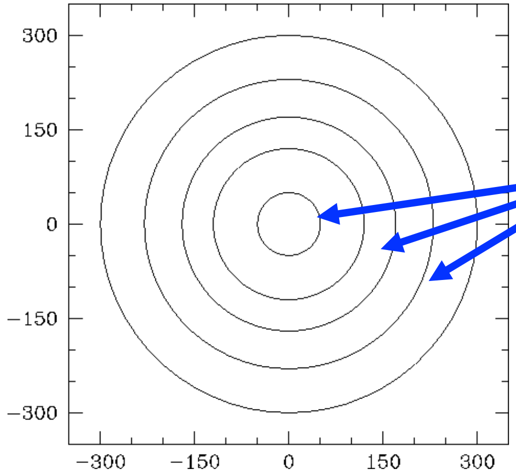
$$R_{RGB} = \frac{N_{RGB}/N_{RGB,TOT}}{L_{samp}/L_{TOT}}$$

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

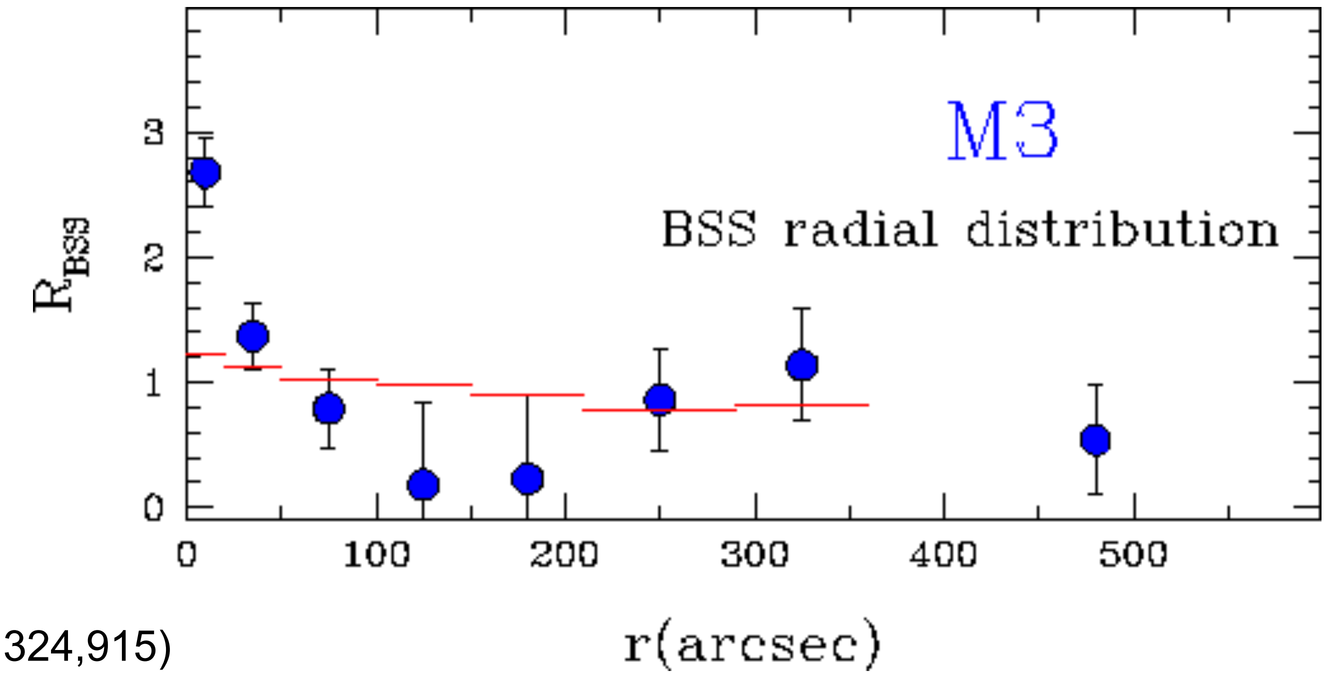
Note that ***a flat distribution*** in this plot means that ***"the number of stars in each annulus exactly scales with the cluster light sampled by each annulus"***



THE BSS RADIAL DISTRIBUTION



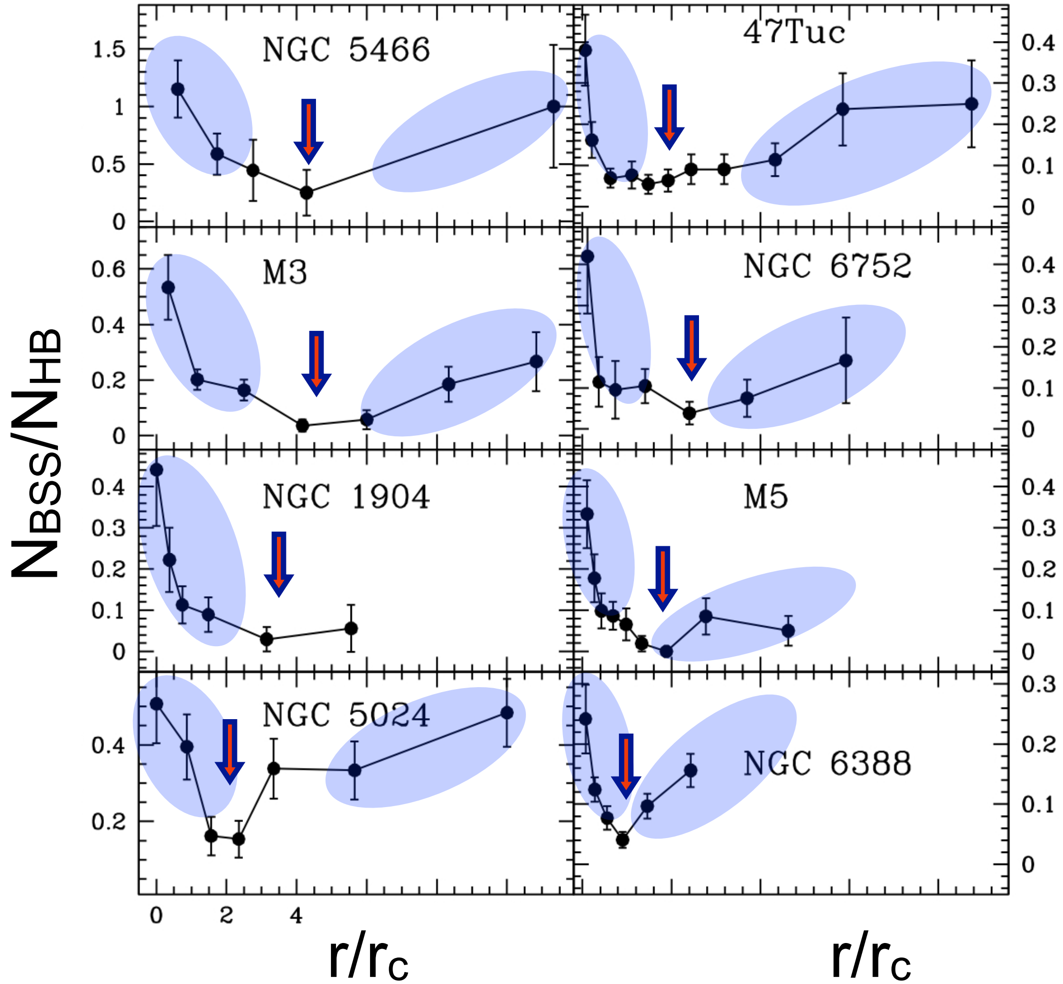
$$R_{BSS} = \frac{N_{BSS}/N_{BSS,TOT}}{L_{samp}/L_{TOT}}$$

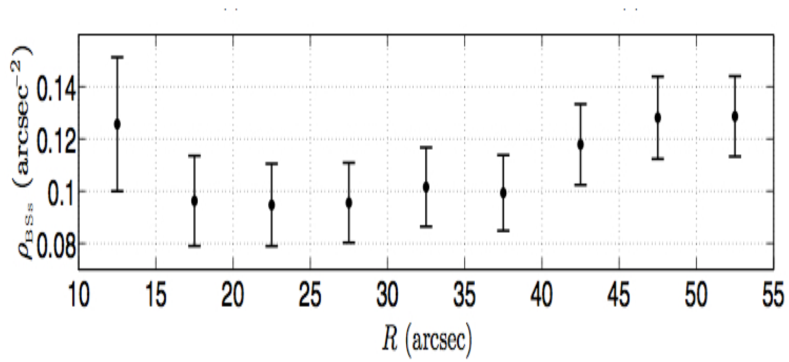


Ferraro et al (1997,A&A,324,915)

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





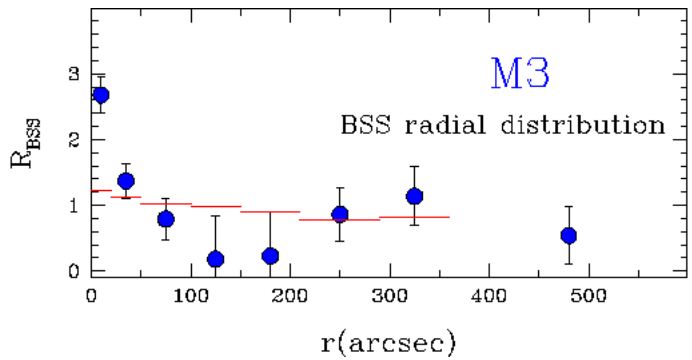
Hodge 11 –LMC

Li et al (2013)

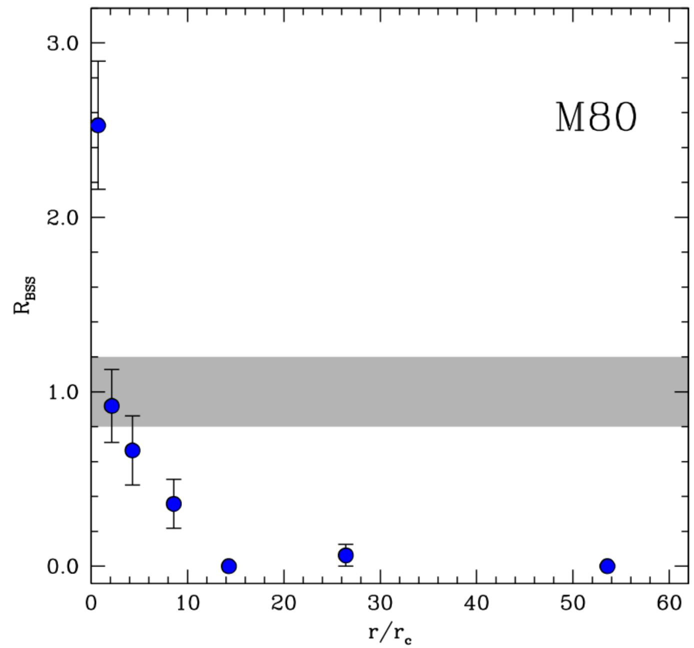
BSS radial distribution

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

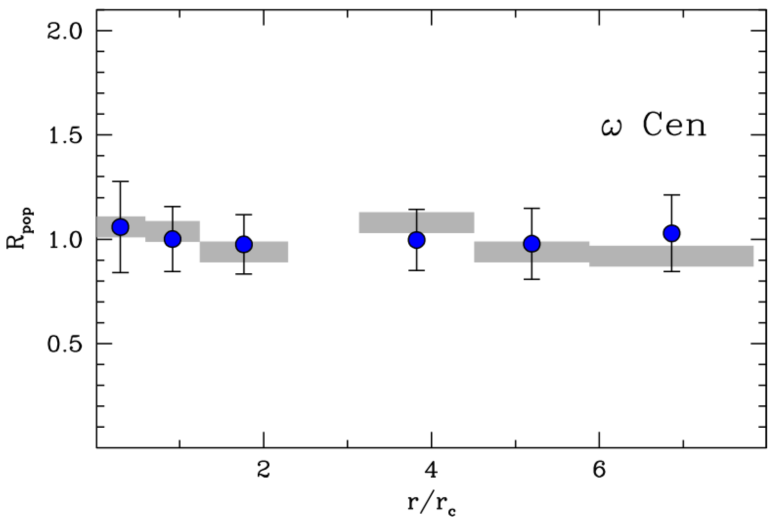
"bimodal"



"Unimodal" (single-peak)



"Flat"



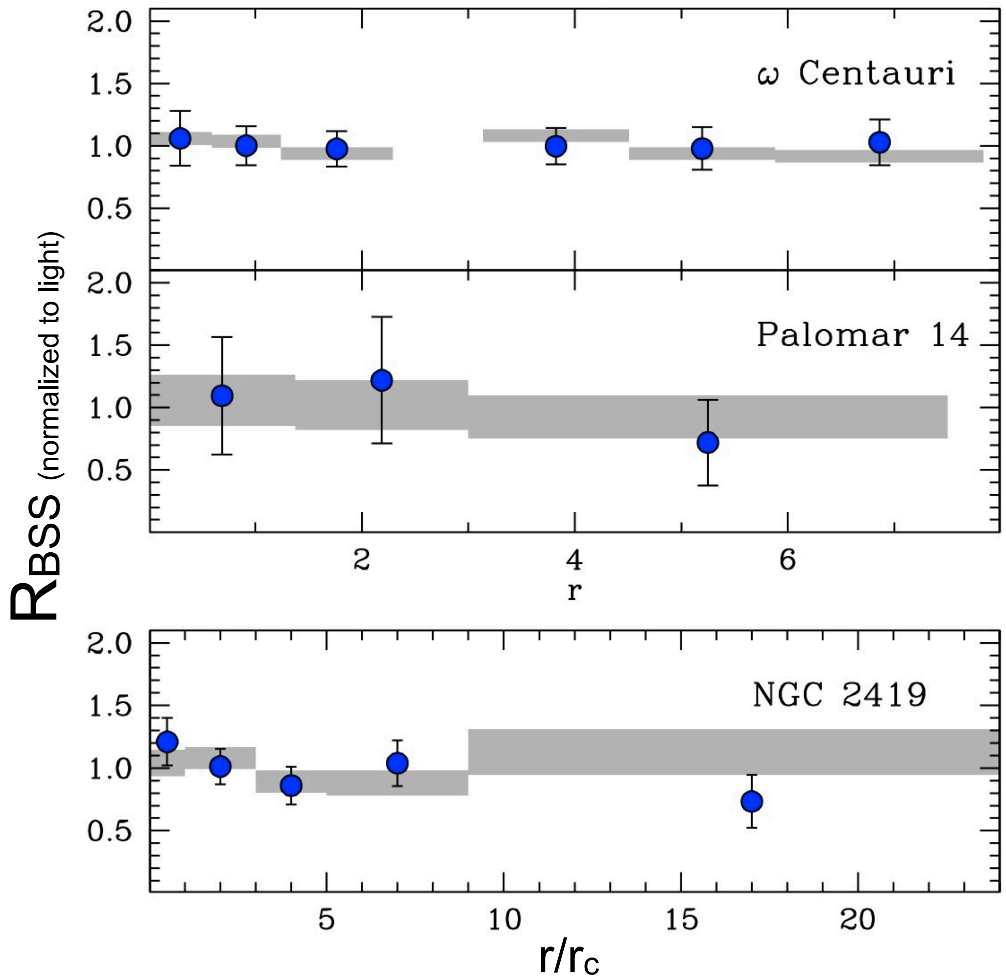
The BSS radial distribution is shaped by dynamical friction, which segregates BSS progressively in time

….. THE DYNAMICAL CLOCK…..

The dynamical clock

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

Family I : FLAT BSS radial distribution

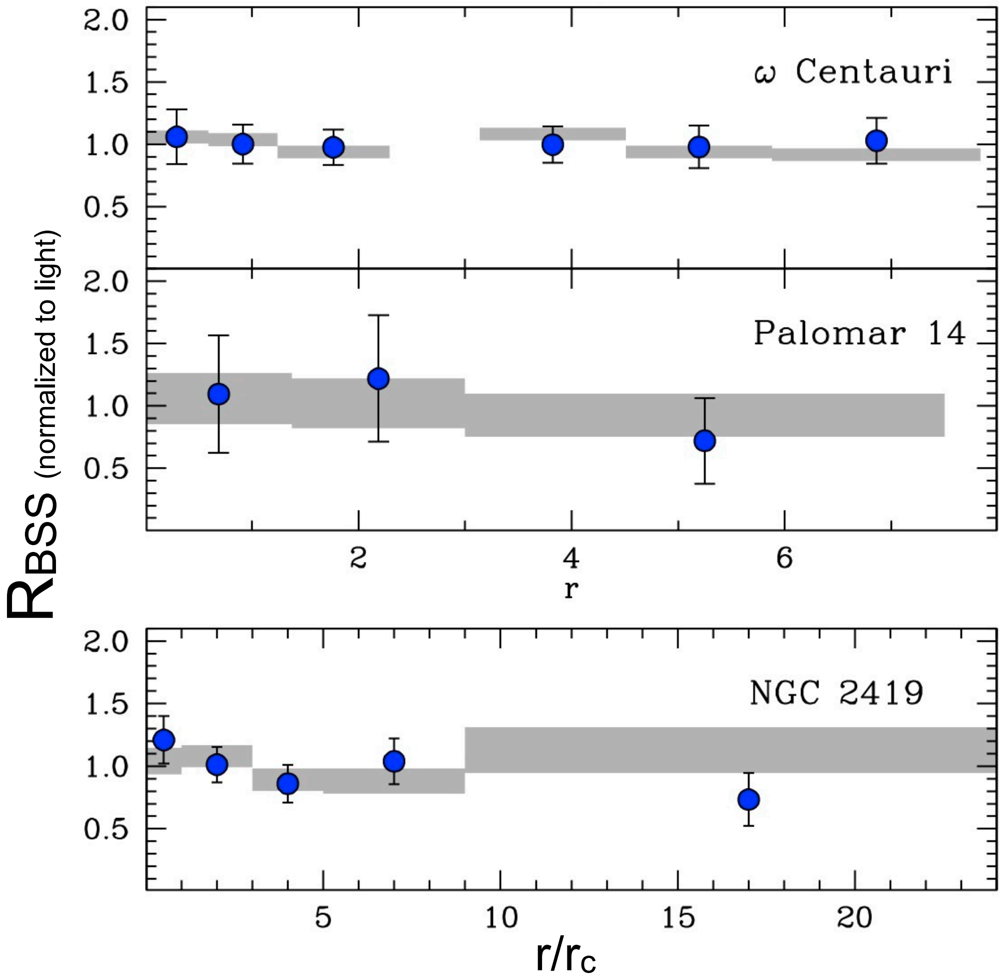


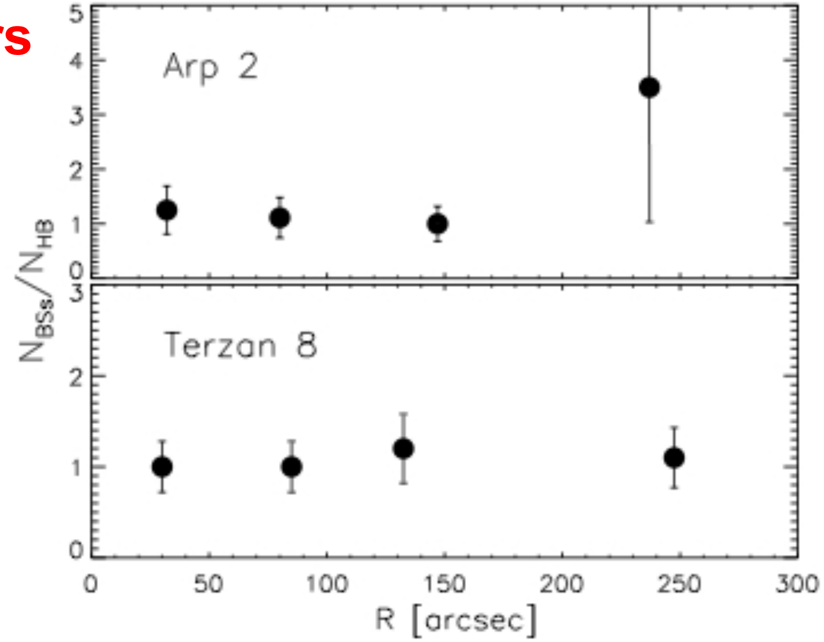
The BSS distribution is **flat** in fully agreement with that of "normal stars"

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

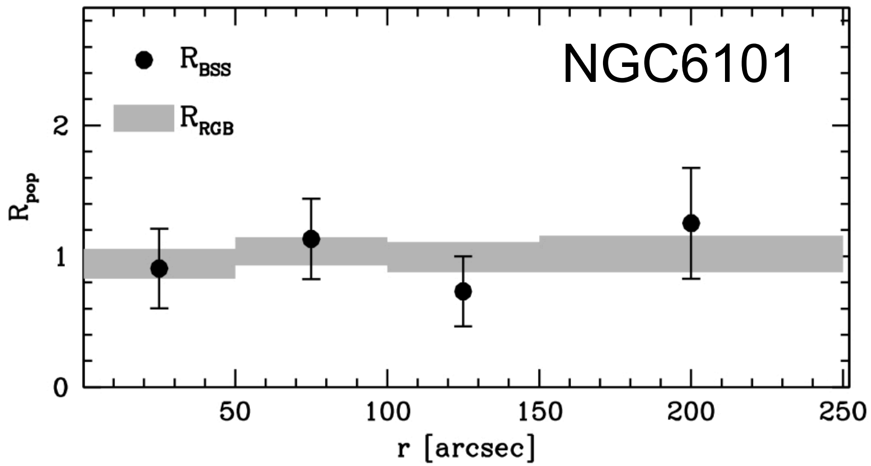
Family I: the dynamically YOUNG clusters

Family I: the dynamically YOUNG clusters





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



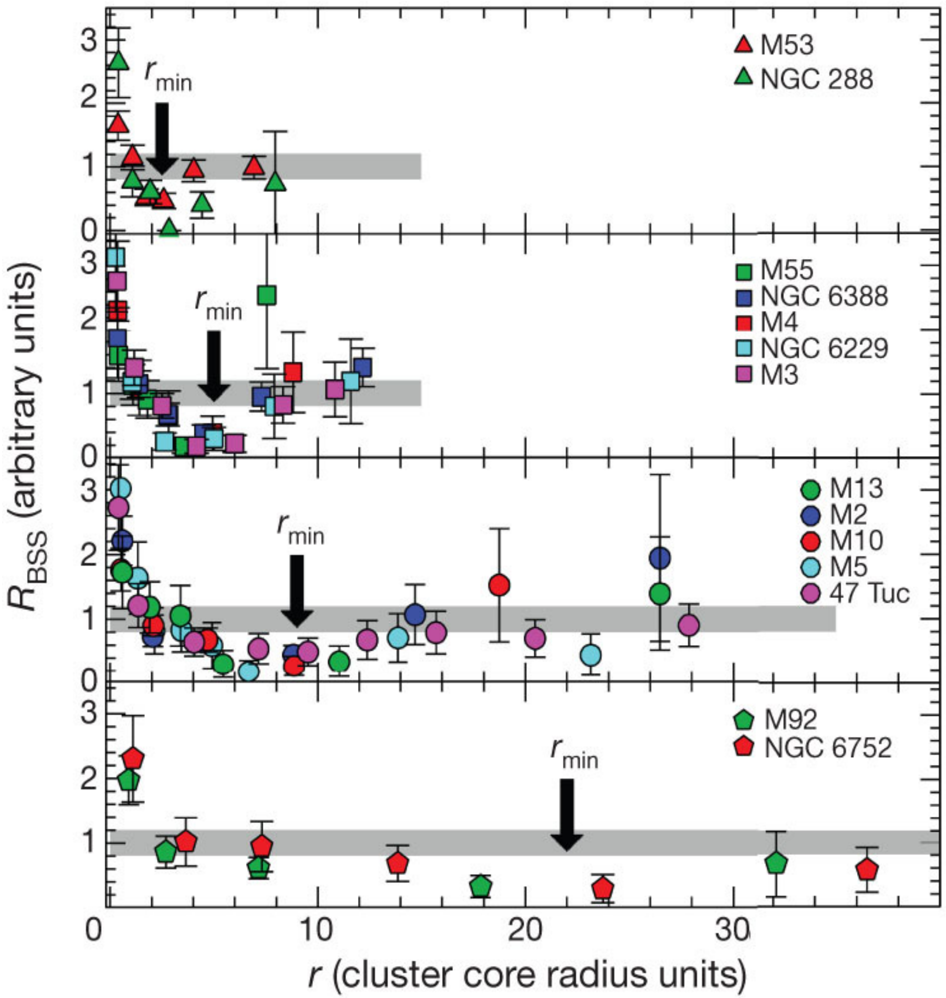
Dalessandro et al (2015, ApJ, submitted)

BSS are the **most powerful indicator** to prove that these stellar systems are not relaxed yet

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

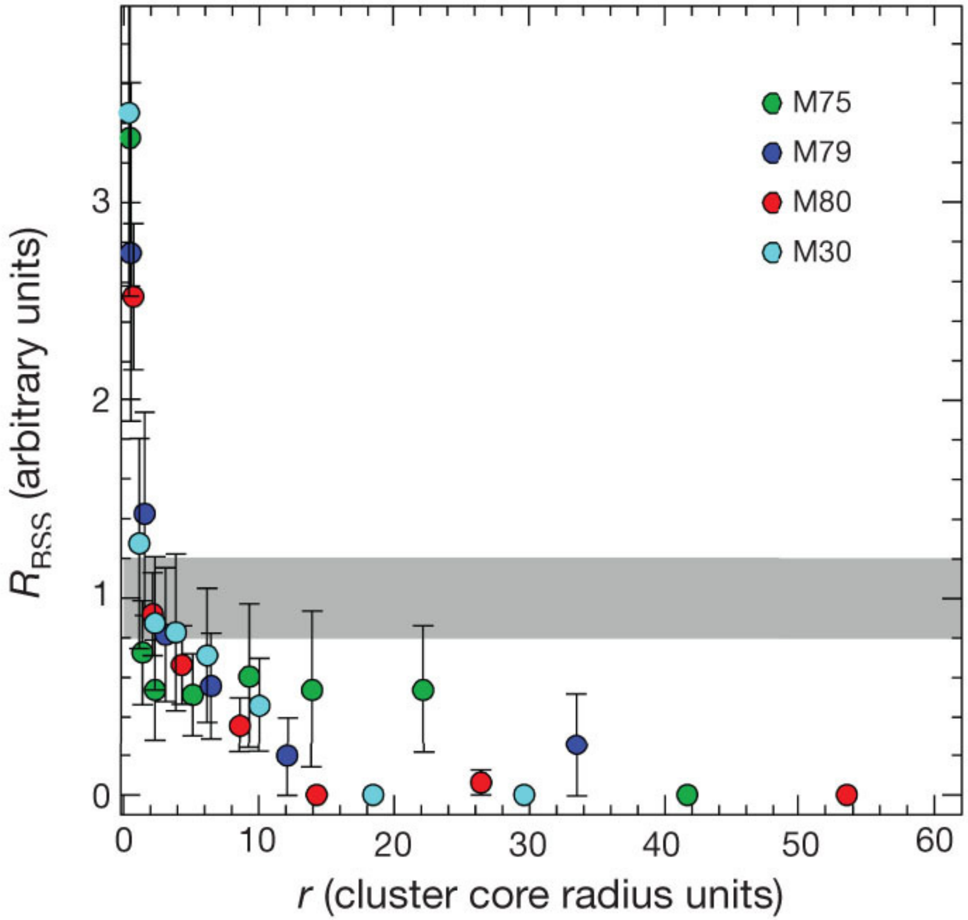
The action of **df** extends progressively at larger distances from the cluster center = the minimum is moving progressively outward

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.

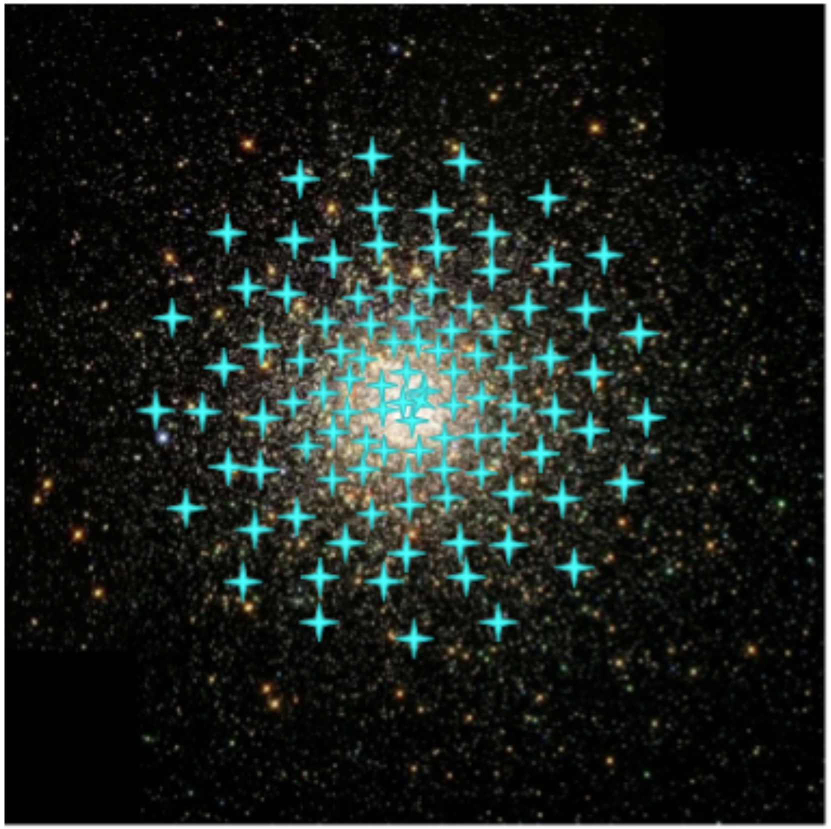
The action of **df** extended out to the cluster tidal radius

Family III: the dynamically OLD clusters

Cosmic-Lab

The dynamical clock

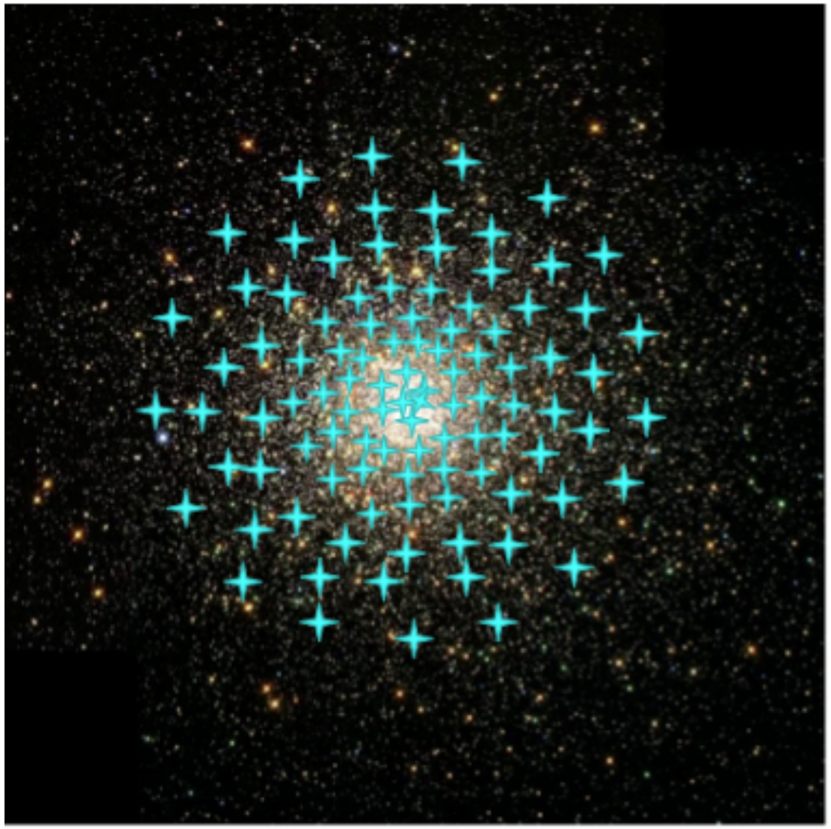
Ferraro et al (2012,Nature,492,393)



The cartoon illustrates the action of 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

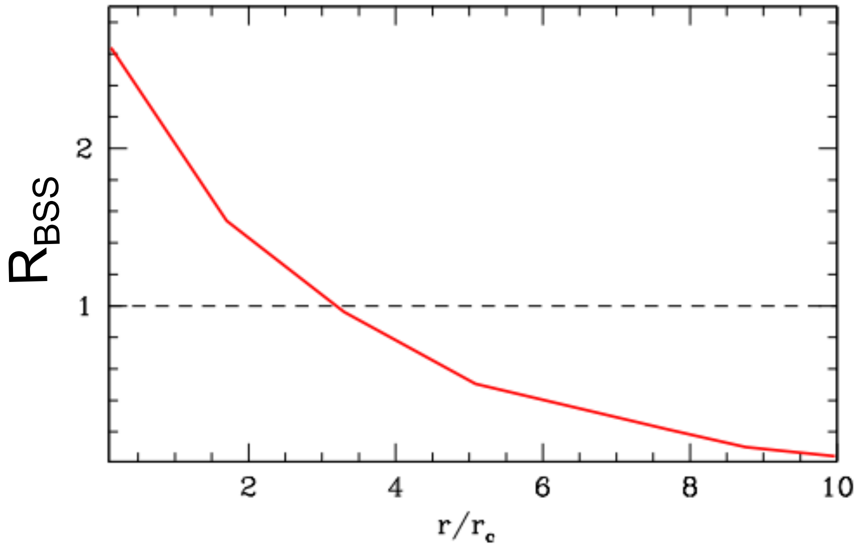
Ferraro et al (2012,Nature,492,393)



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.

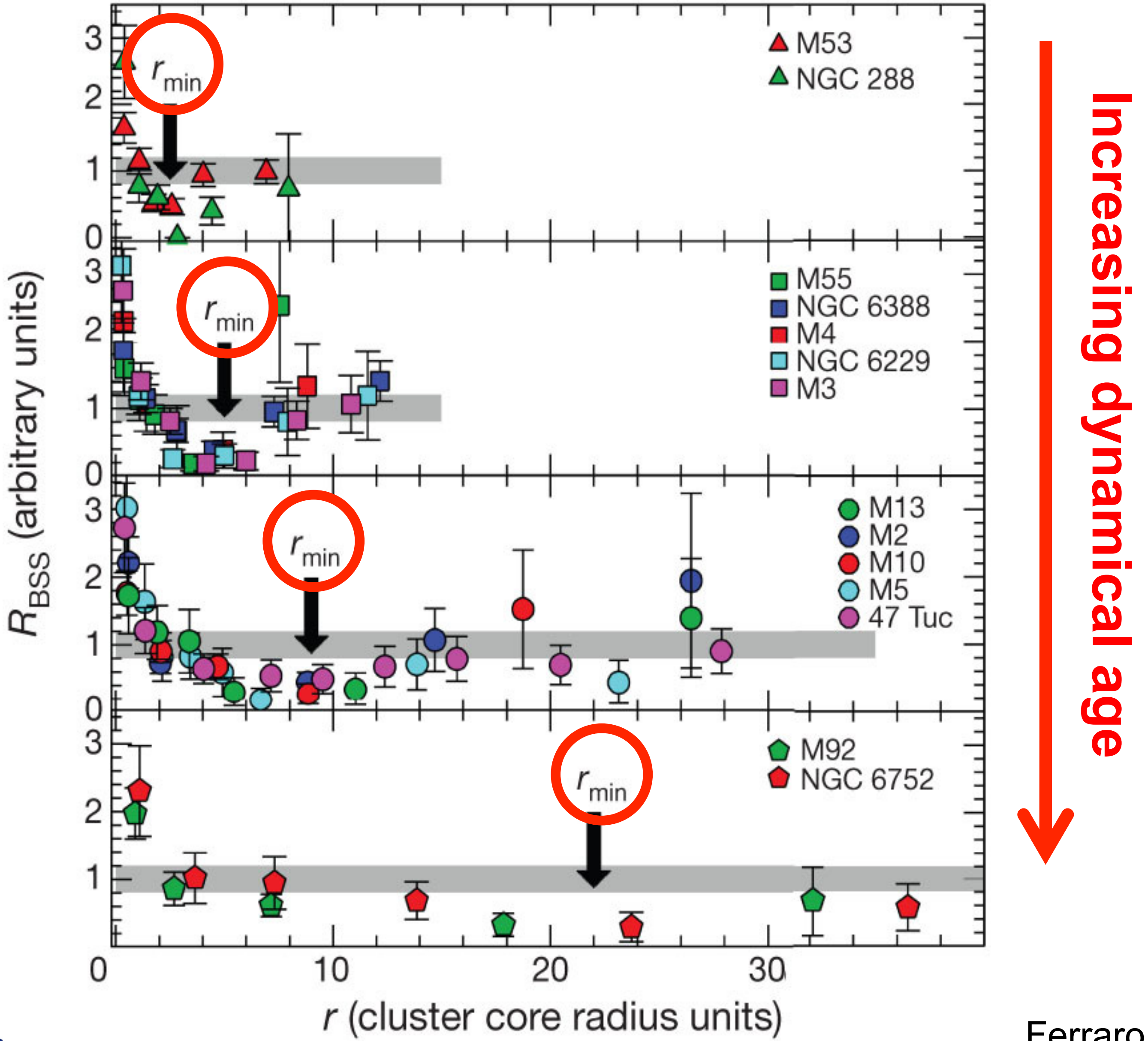
The dynamical clock

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



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**



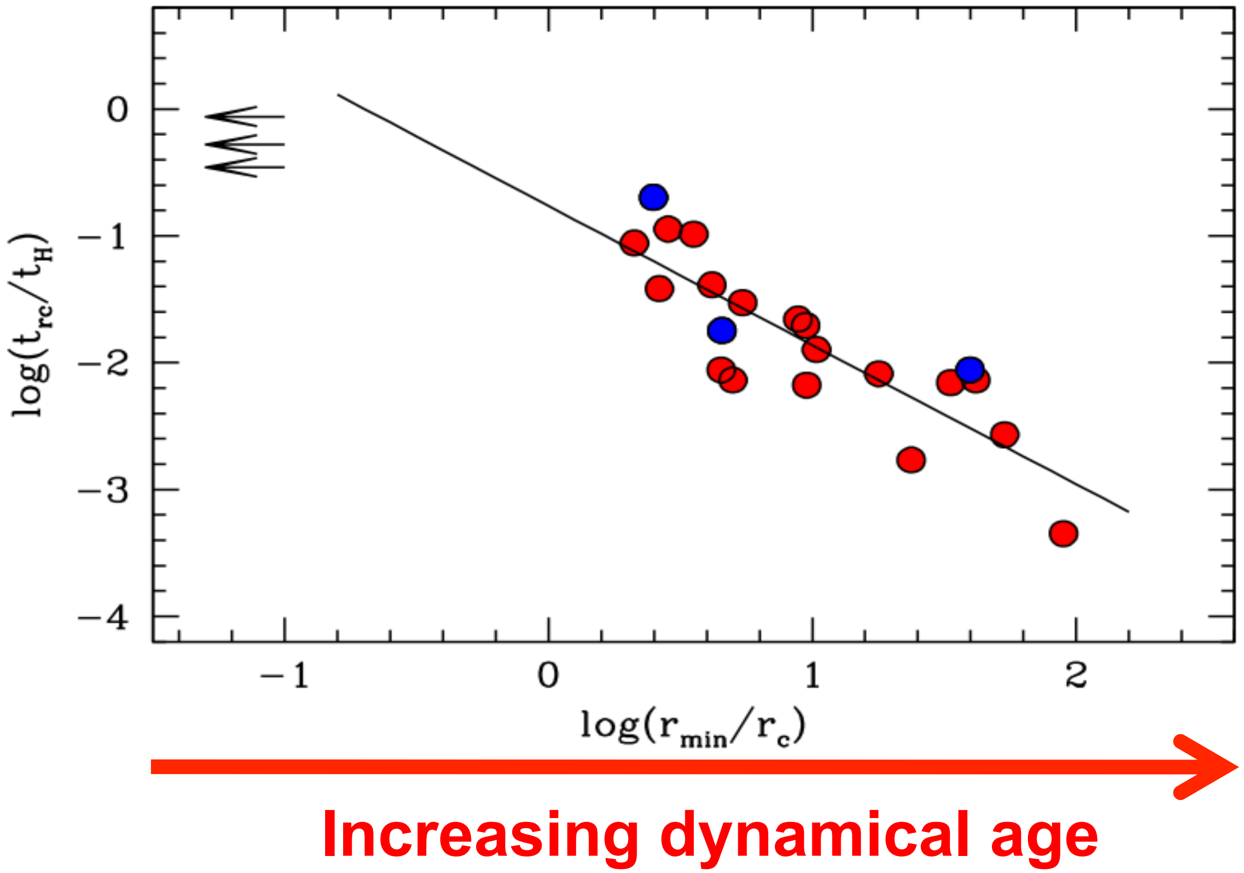
Cosmic-Lab

Ferraro et al 2012, Nature,492,393

The dynamical clock

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

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

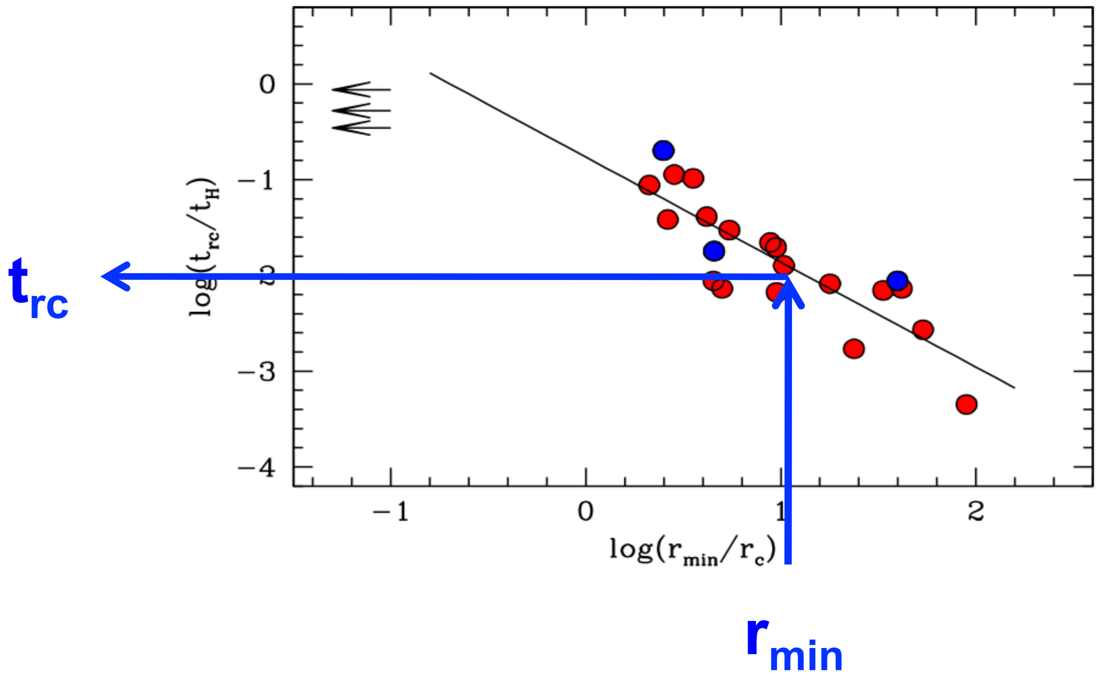


Cosmic-Lab

The dynamical clock

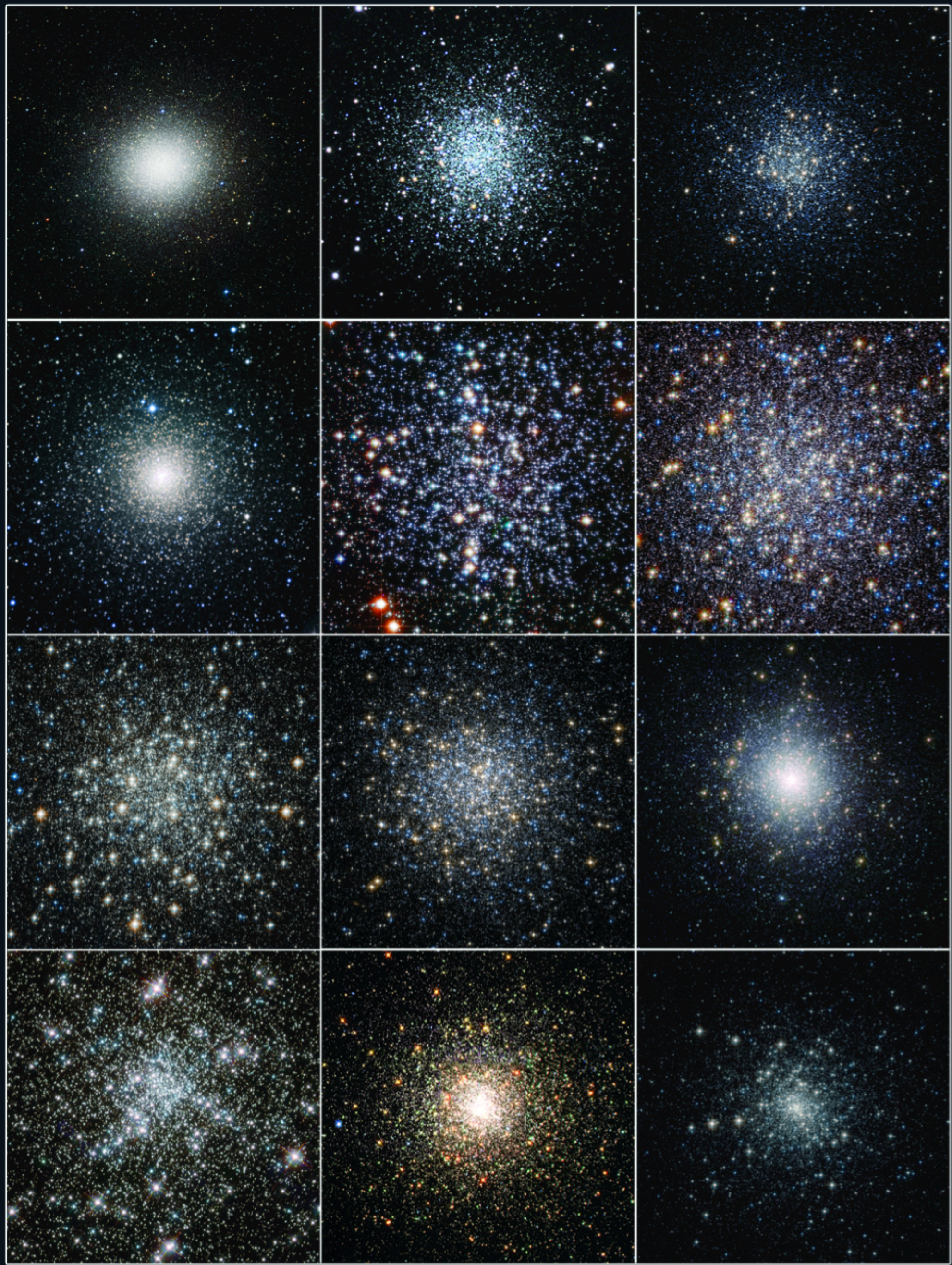
Ferraro et al (2012,Nature,492,393)

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



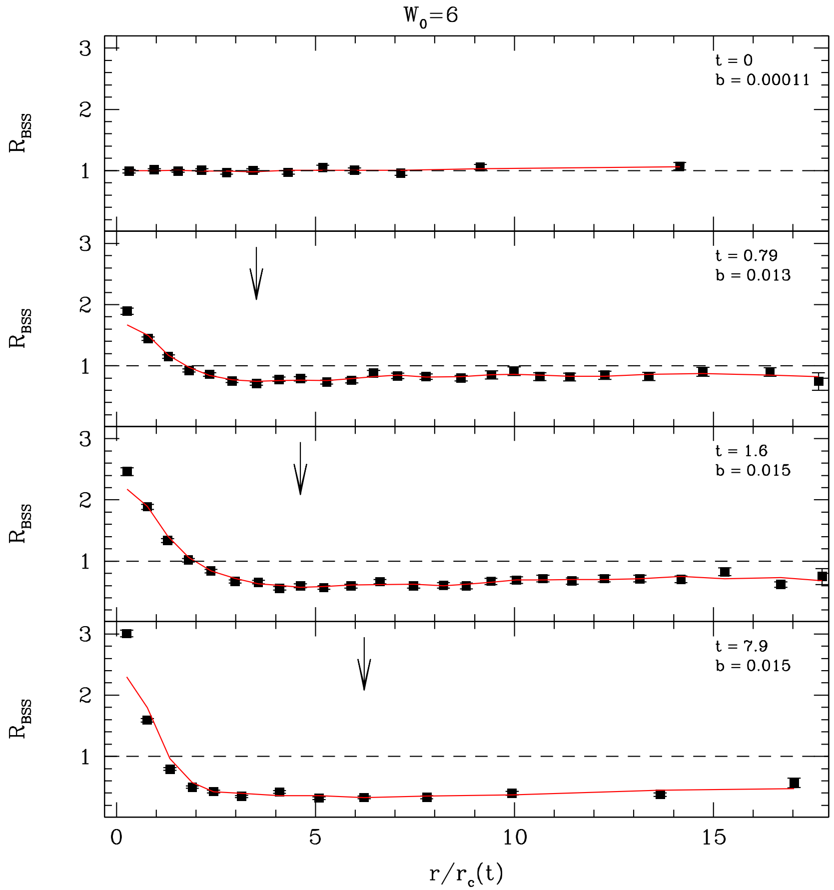
This tool is much more powerful than any previous theoretical estimator of the dynamical time-scale (e.g. the relaxation time-scale at the cluster center) since it simultaneously probe all distances from the cluster center

THE DYNAMICAL CLOCK



N-body simulations

We are now using N-BODY6 for reproducing observations
(first results in Miocchi et al., 2015)



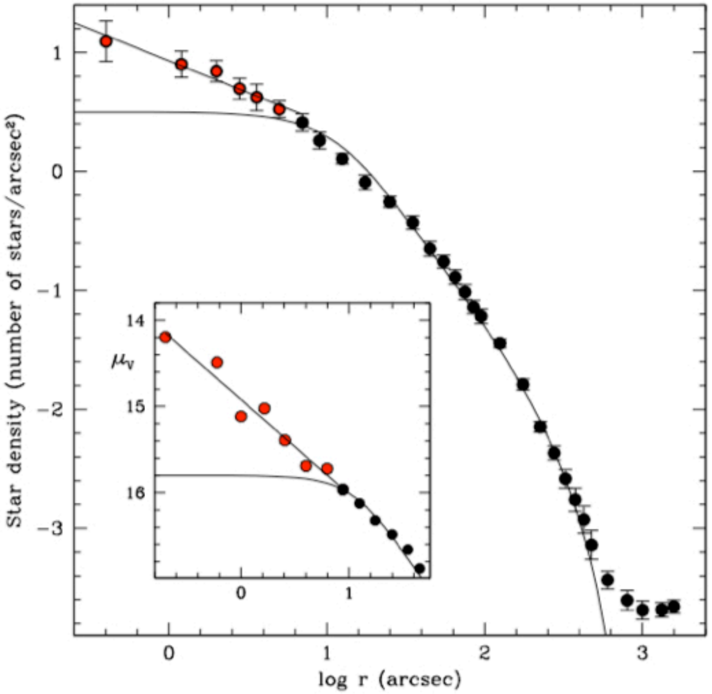
10^4 –particles simulations are still very noisy

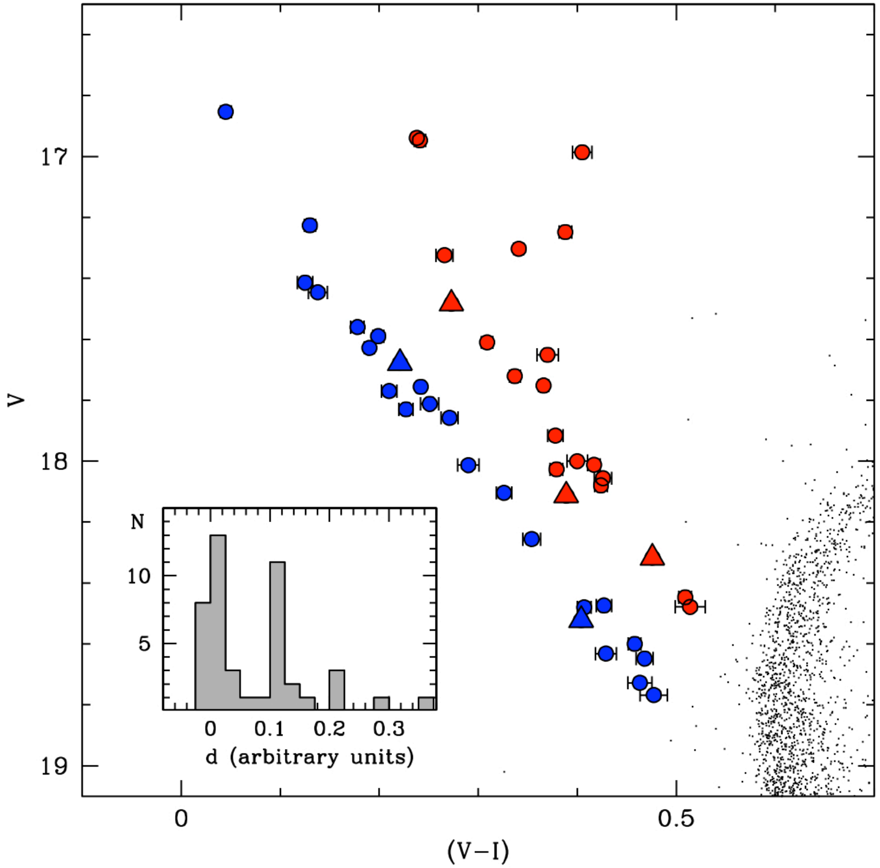
1. **The central peak is a stable feature rapidly forming in ALL the simulations**
2. **the bimodality in the BSS distribution can be distinguished in many snapshots**
3. **the size of the dip increases as fucntion of the evolution**
4. **The most evolved simulations show an unimodal BSS distribution**

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 !!

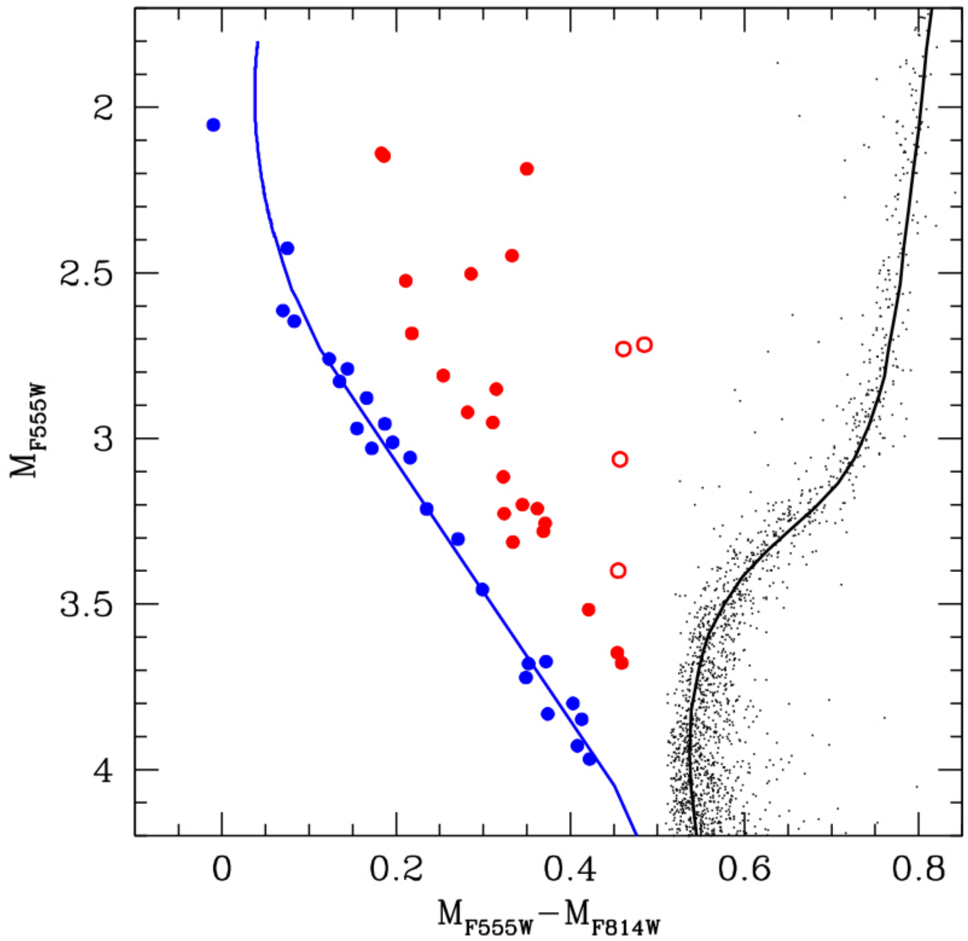
Ferraro et al. (2009, Nature 462, 1028)

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

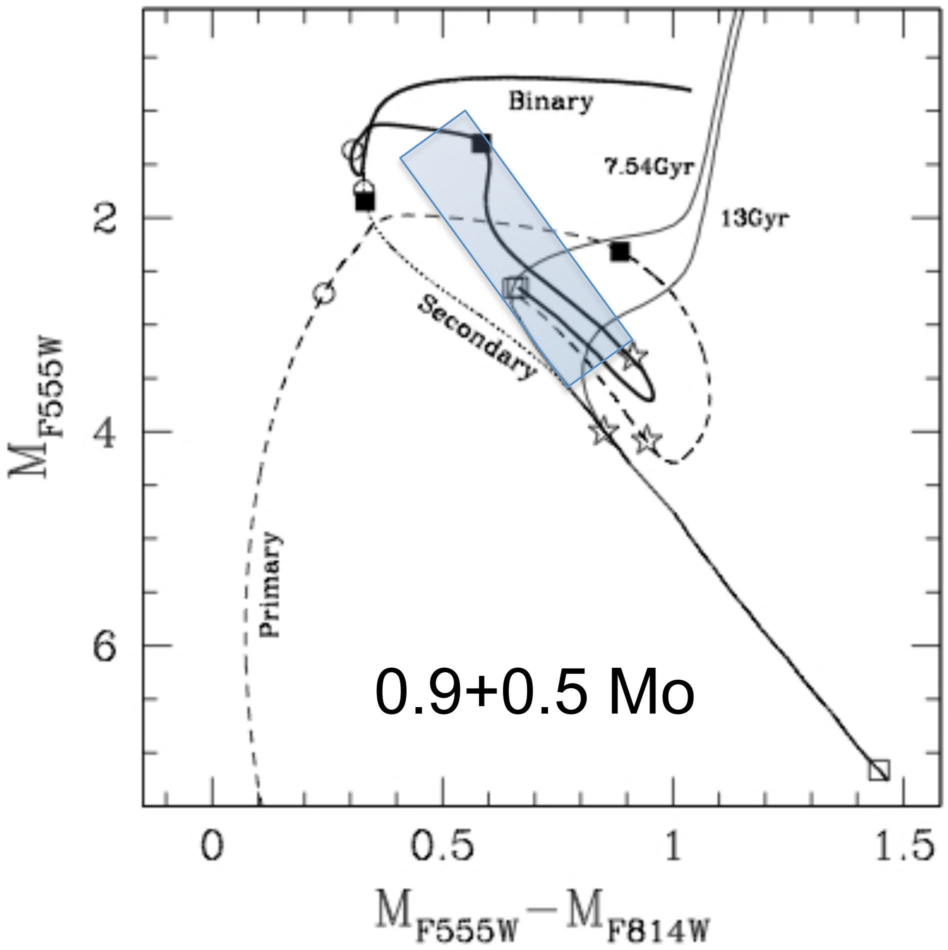
- collisions between two MS stars (0.4 - 0.8 $M_{\odot}$)
- $Z = 10^{-4}$ $(Z_{M30} = 2.5\ 10^{-4})$

- **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



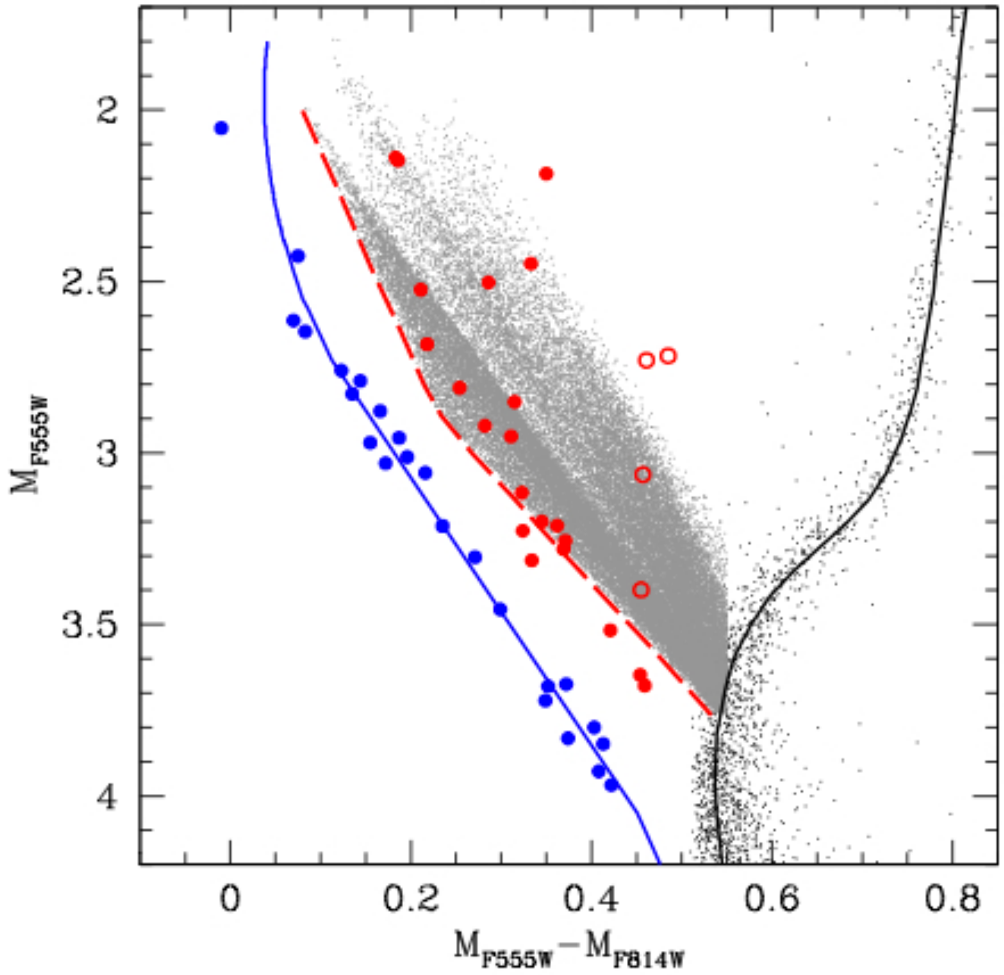
In Xin et al 2015 we followed the evolution of MT binaries generated under a variety of initial conditions in terms of mass, mass ratio and orbital separation



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 ???

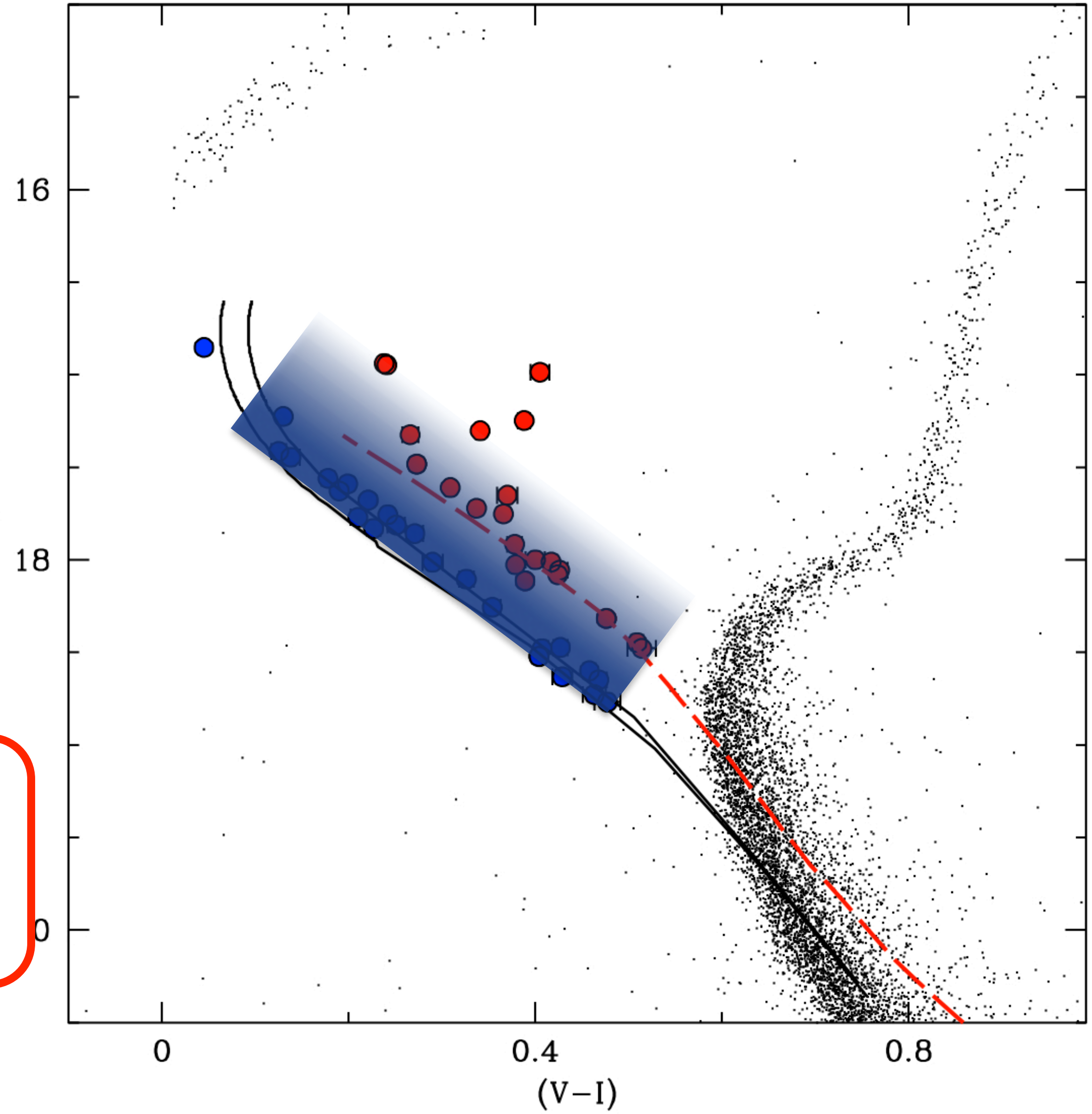
• **blue-BSS → collisional** **red-BSS → MT binaries**

double BSS seq. is NOT a permanent feature

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

⇓

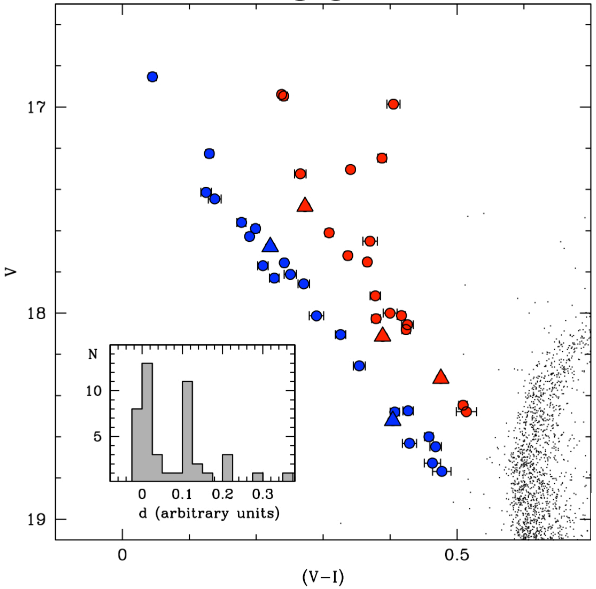
The blue-BSS population must have formed recently 1-2 Gyr ago

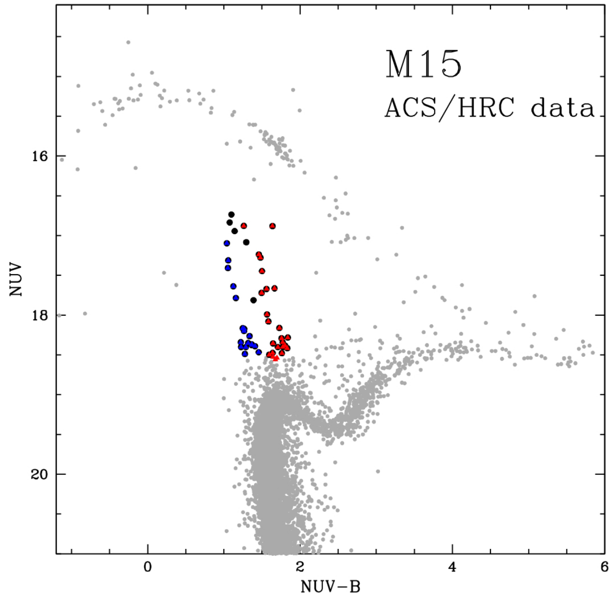


Is this feature connected to the core collapse?

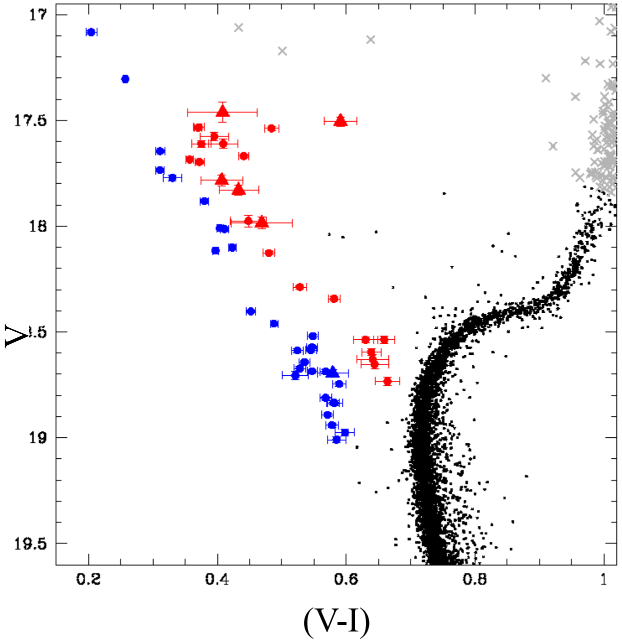
BSS double sequences

M30





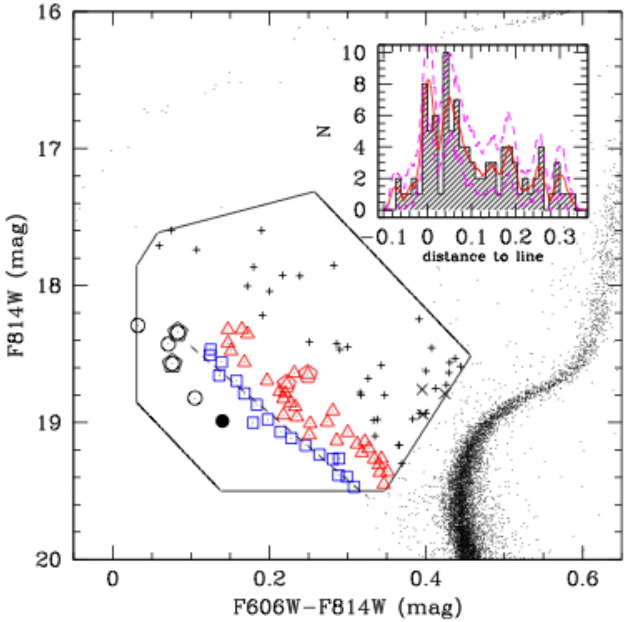
NGC 362



Dalessandro et al. 2013

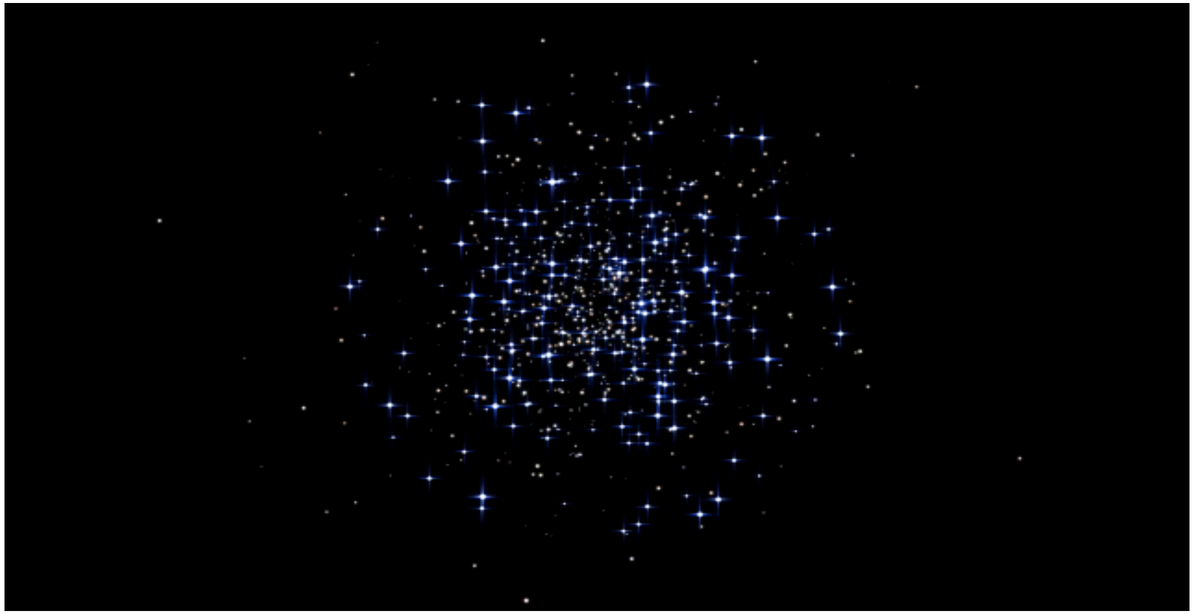
pre Collapse

NGC1261



Simunovic et al. 2014, ApJ, 795, L10

Post PCC
Bounce state



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….

Cosmic-Lab

You can download this presentation from our web-site:
http://www.cosmic-lab.eu/Cosmic-Lab/Presentations.html

The End