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Tracing the dynamical evolution of Galactic Globular Clusters with Exotic stellar populations

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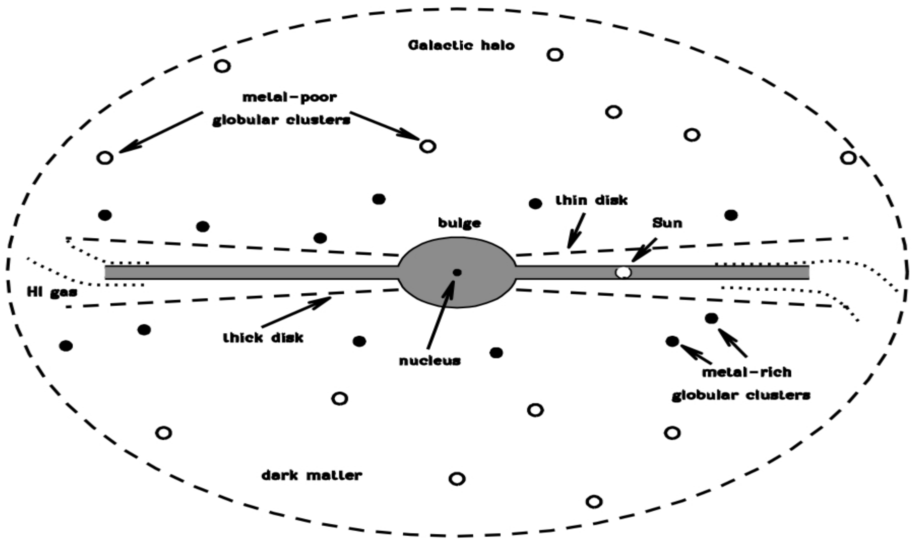
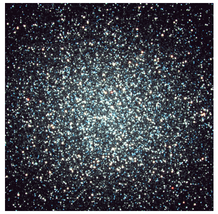
Galactic Globular Clusters

Populous and dense stellar aggregates including up to millions stars.





AGE - Mostly old (12-13 Gyr): formed at the epoch of the Galaxy formation

METALLICITY- Wide range: from Solar to 1/100 Solar

POPULATION- harbour many stars, up to several milions

CENTRAL DENSITIES

$$\rho_0 = 10\text{-}10^6\ M_s/pc^3$$

stellar clusters: cosmic laboratories

Simple Stellar Populations…

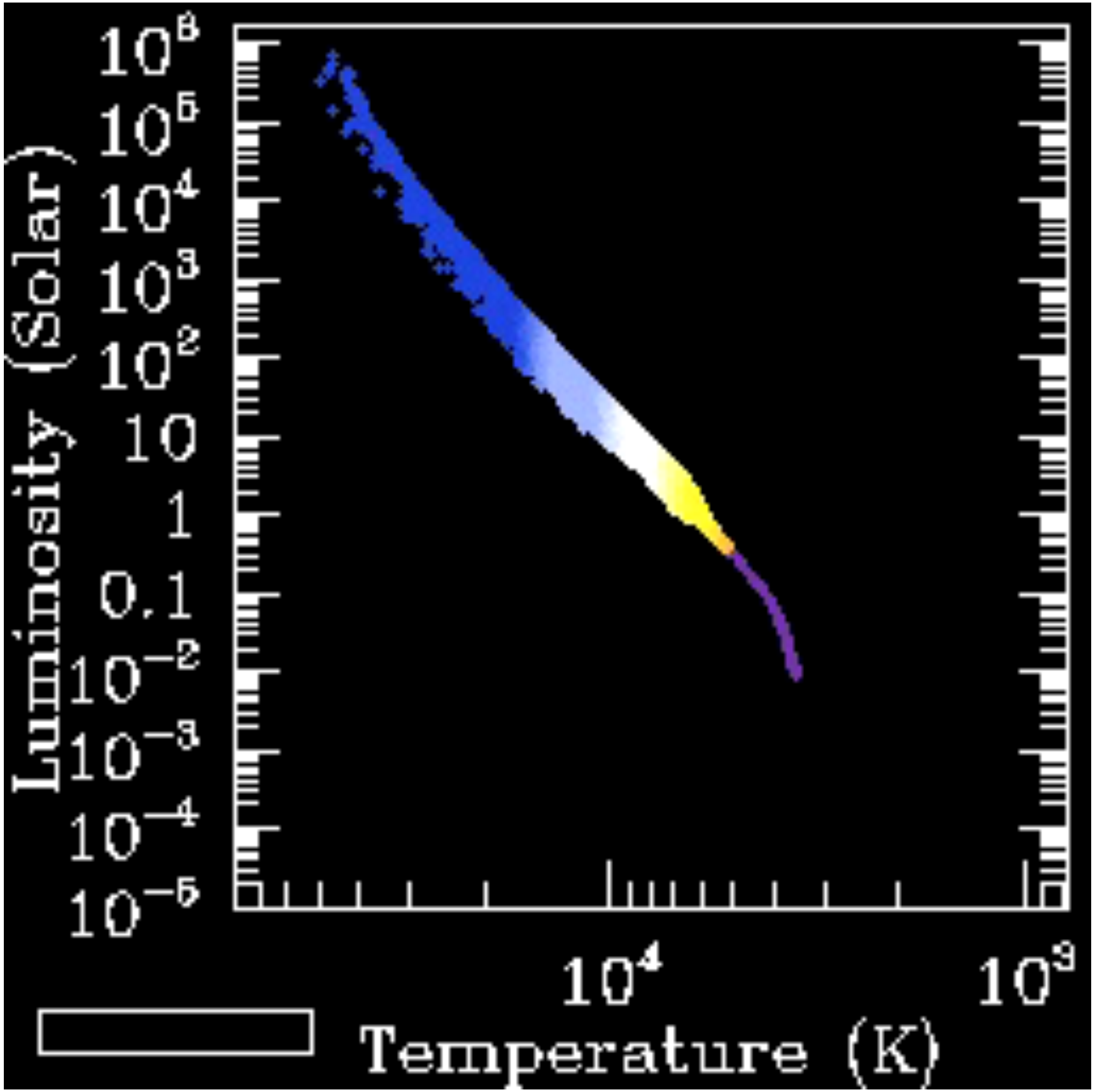
A "Simple Stellar Population" (SSP) is an assembly of stars ....

1) with the same age
ONLY ONE FORMATION BURST

2) with the same initial chemical composition

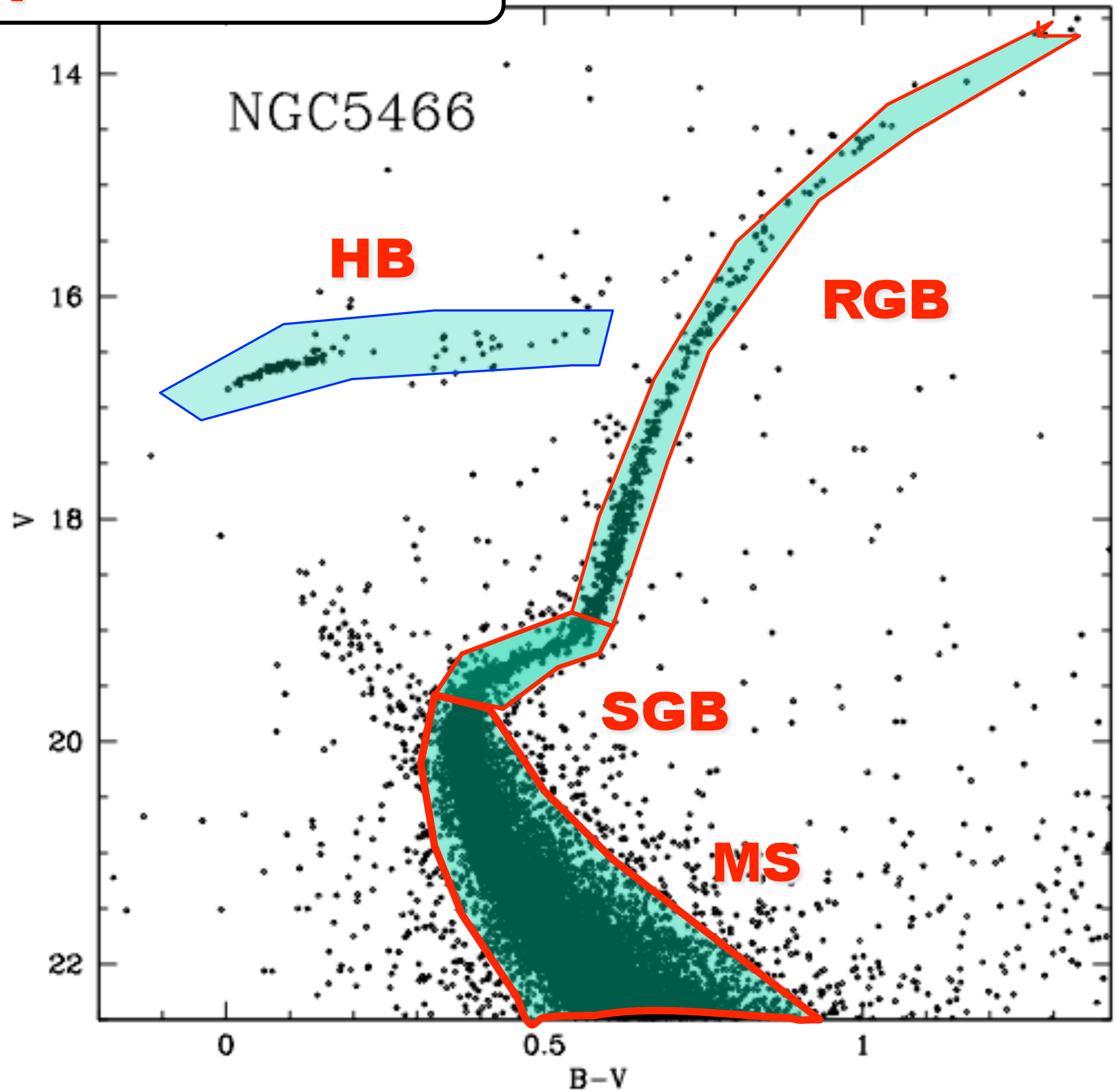
3) single (not located in binary systems)

... and described by 4 parameters:
age, metallicity (Y,Z), IMF

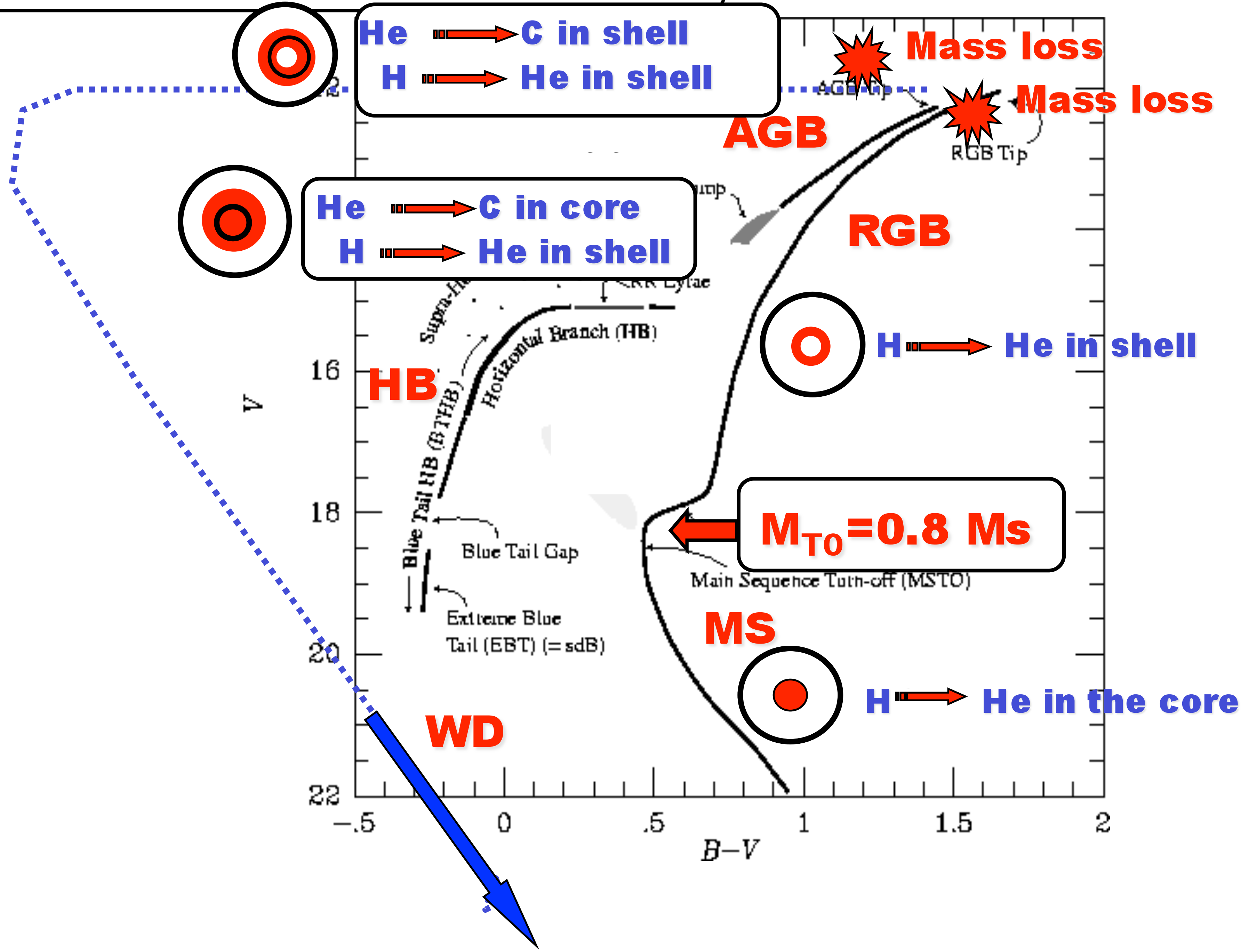


Luminosity (Solar)
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{4}
10^{3}
Temperature (K)

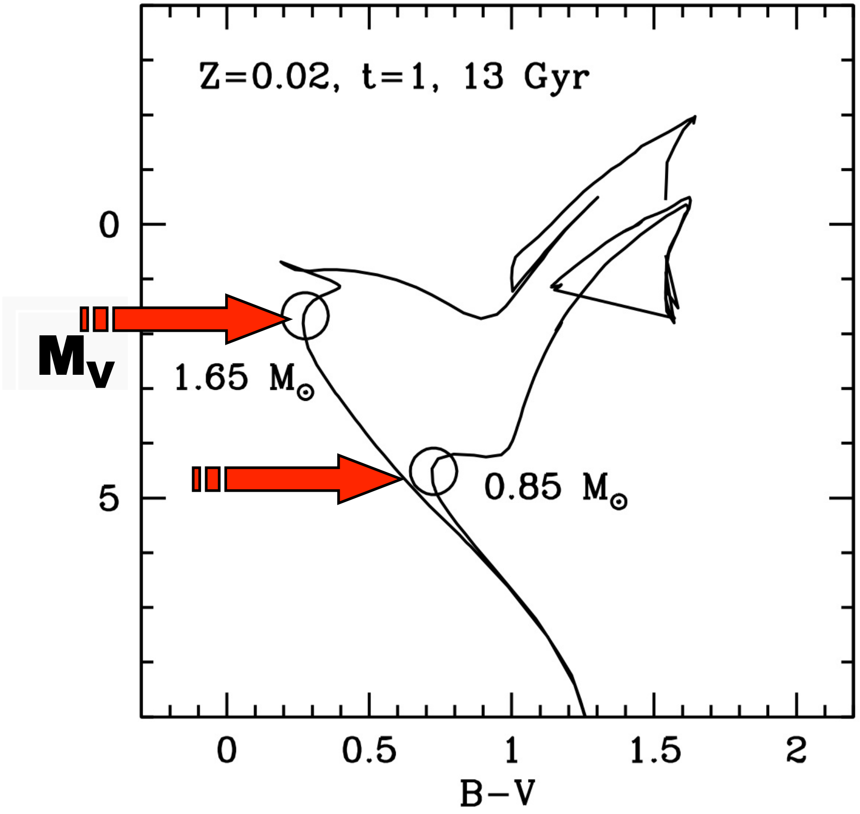
The CMD : A powerfull Tool



The CMD : A powerfull Tool

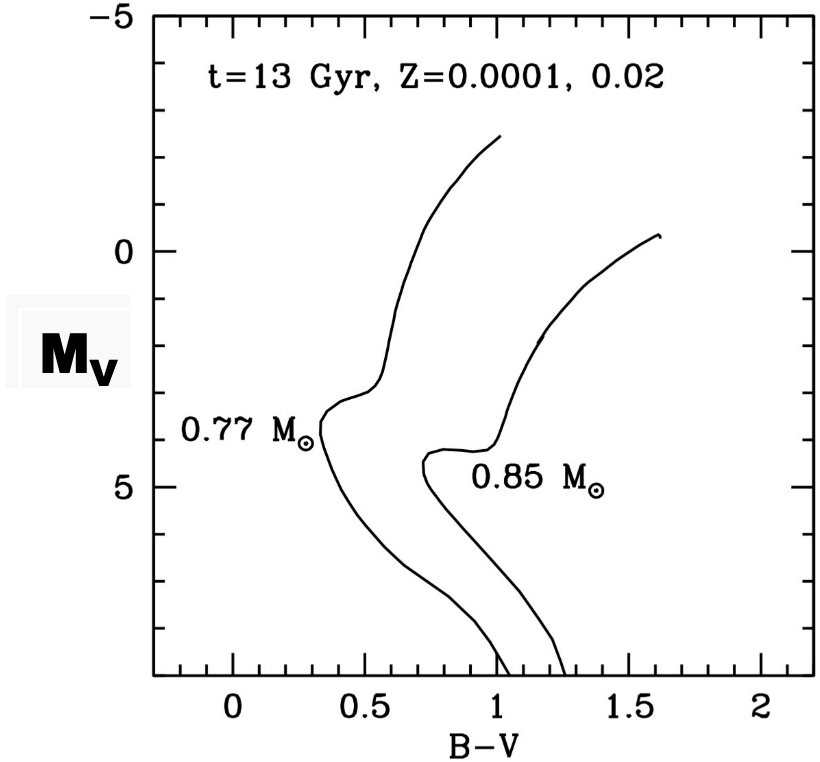


AGE changes the magnitude and mass at the MS-TO



Same metallicity, but different ages

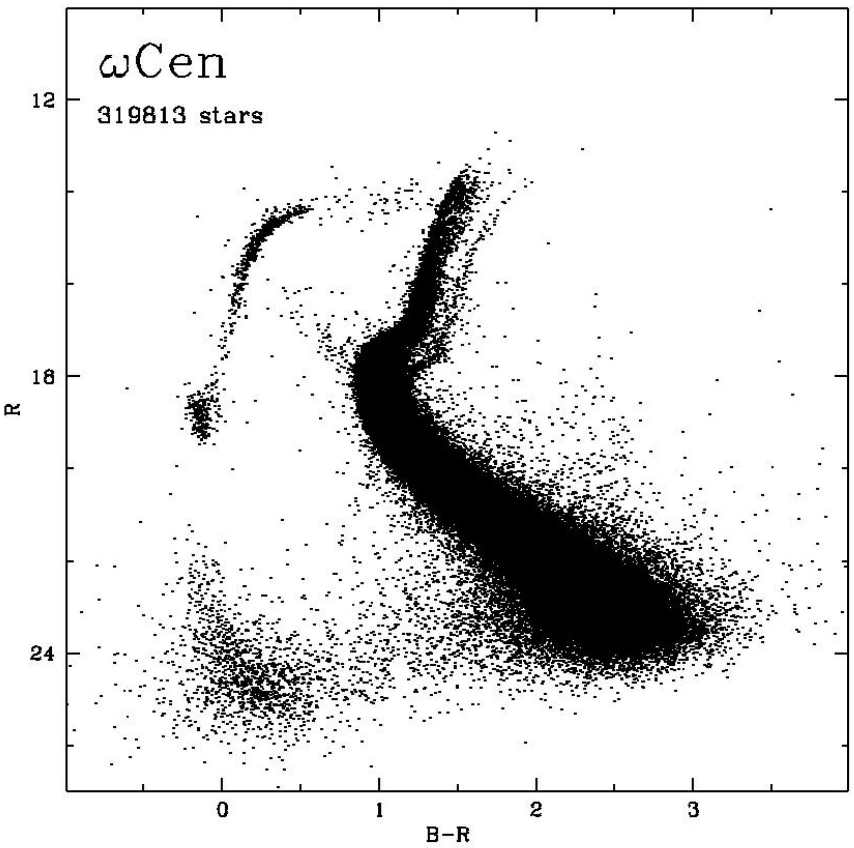
CHEMICAL COMPOSITION changes the position of the isochrone

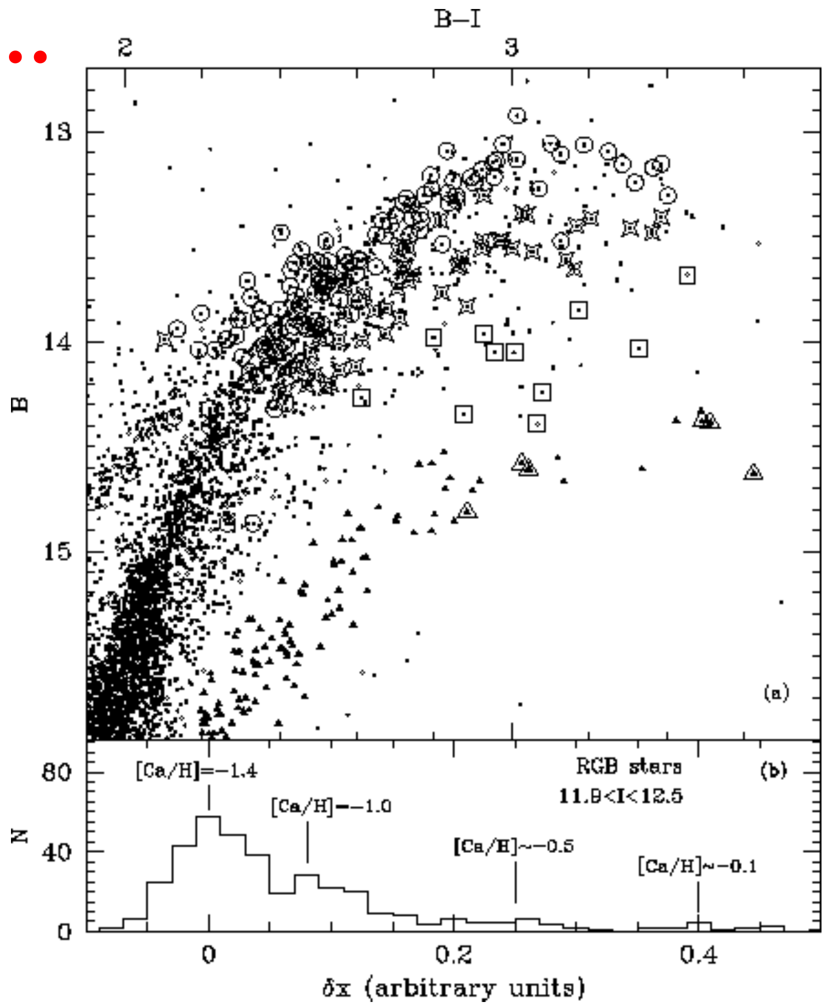


Same age, but different metallicities

Complex Stellar Populations…

Galaxies are not SSPs, since they include stellar populations with different ages and chemical compositions

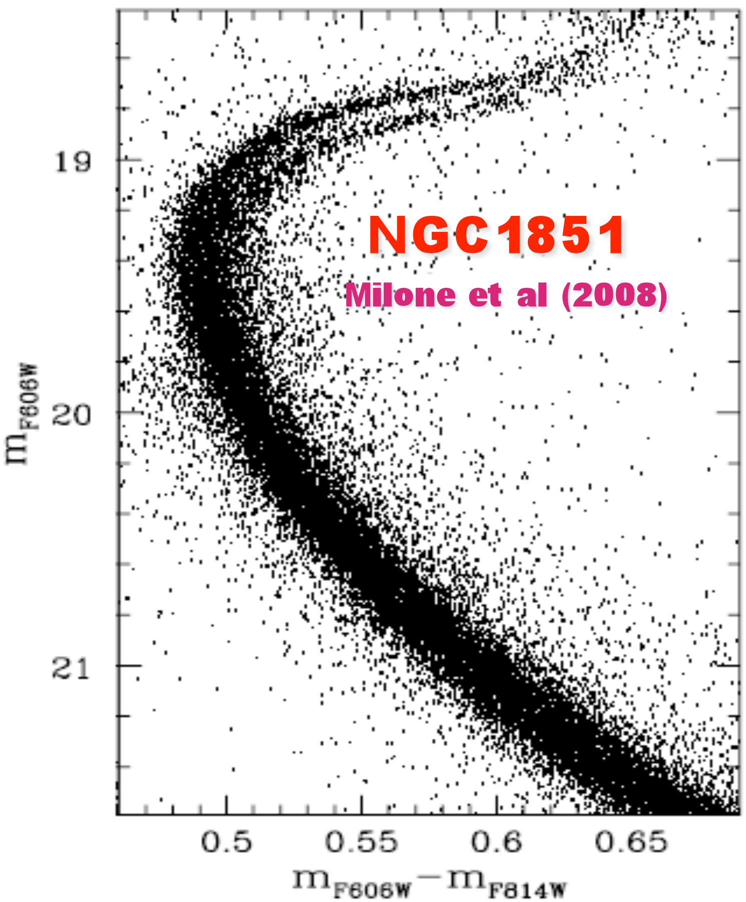


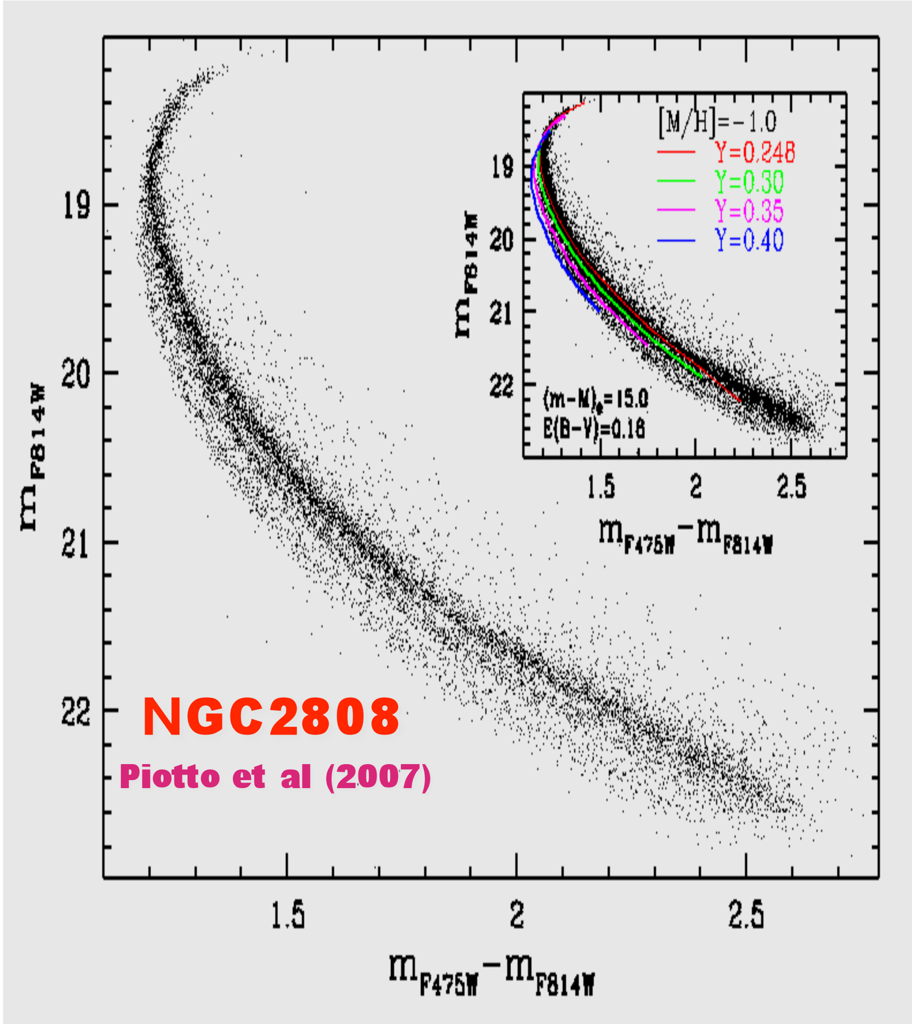


Different Turn-Off: stellar populations with different ages and or metallicities

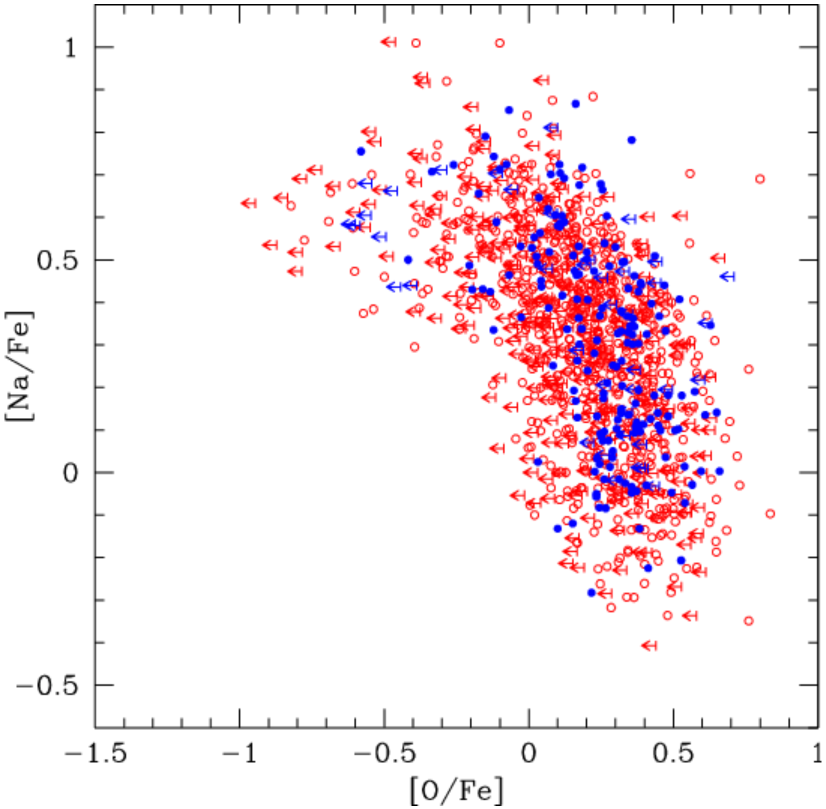
Different RGB: stellar populations with different metallicities

Some GGCs are NOT **TRUE** SSP....



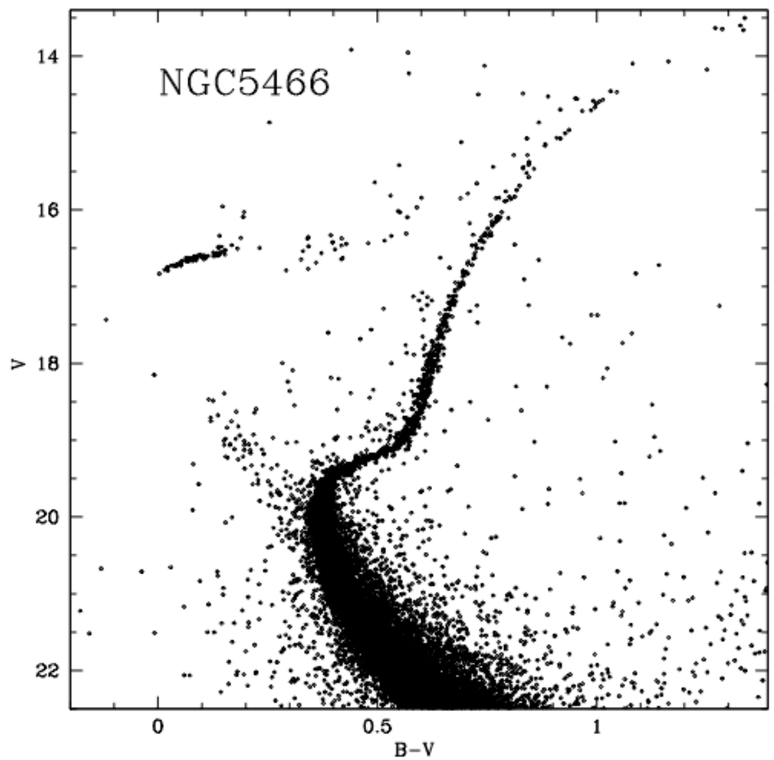


STARS IN GGCs ARE NOT CHEMICALLY HOMOGENEOUS IN LIGHT ELEMENTS



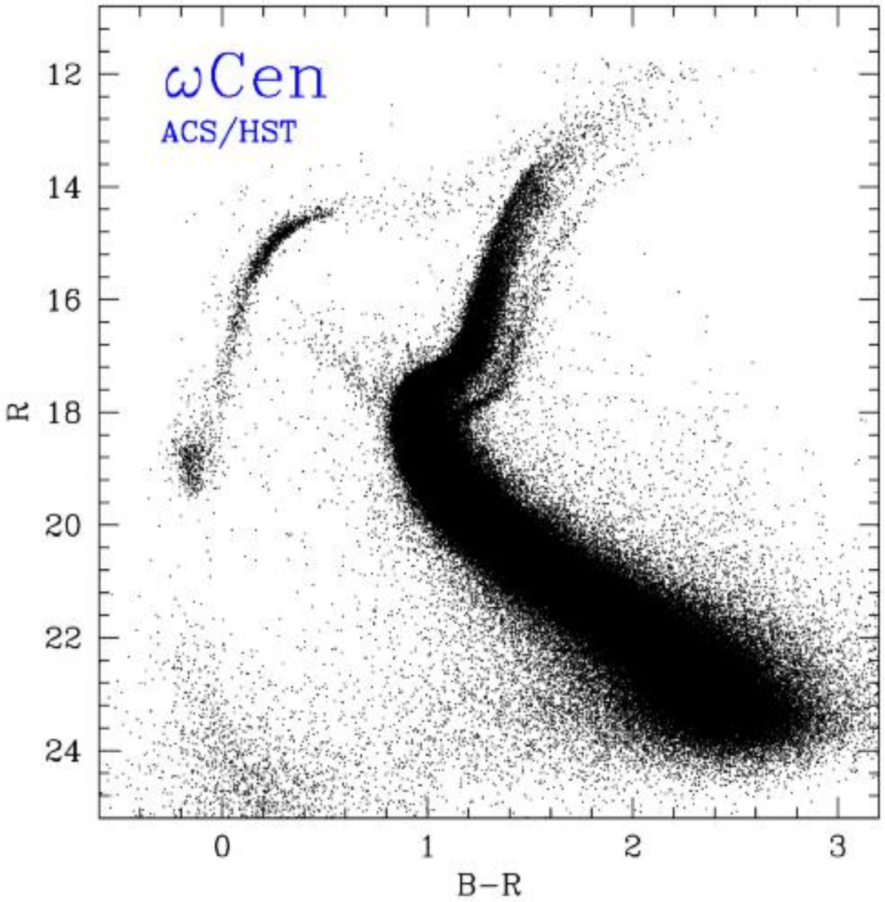
Cumulative behaviour of [Na/Fe] as a function of [O/Fe] for 19 GGCs (Carretta et al. 2009)

BUT Stars are QUITE homogeneous in the IRON content



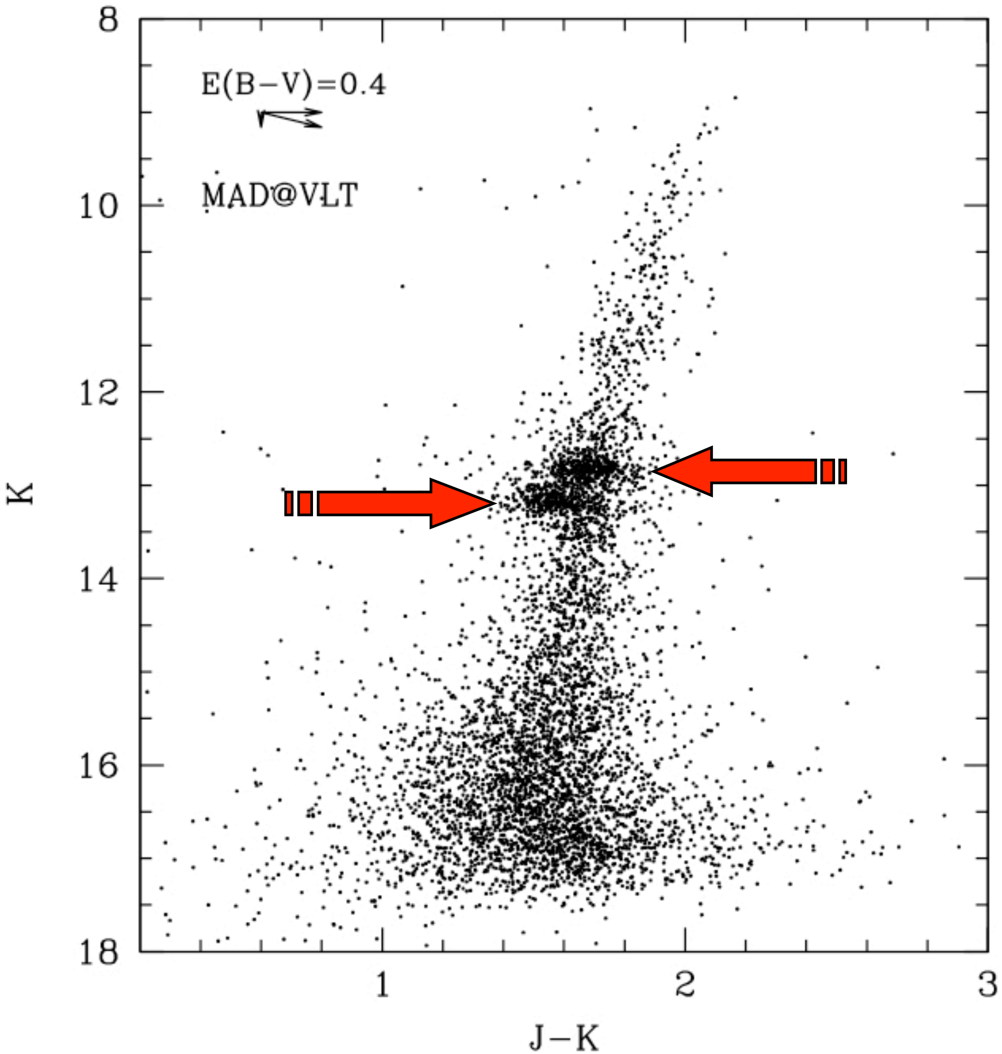
Only TWO exceptions:

OMEGA CEN in the HALO



Ferraro et al., 2004 ApJ, 603, L81

TERZAN 5 in the BULGE



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

Simple Stellar Populations vs GGCs

A "Simple Stellar Population" (SSP) is an assembly of stars ....

1) with the same age

ONLY ONE FORMATION

This could be not strictly true over 10^8 yr - timescale

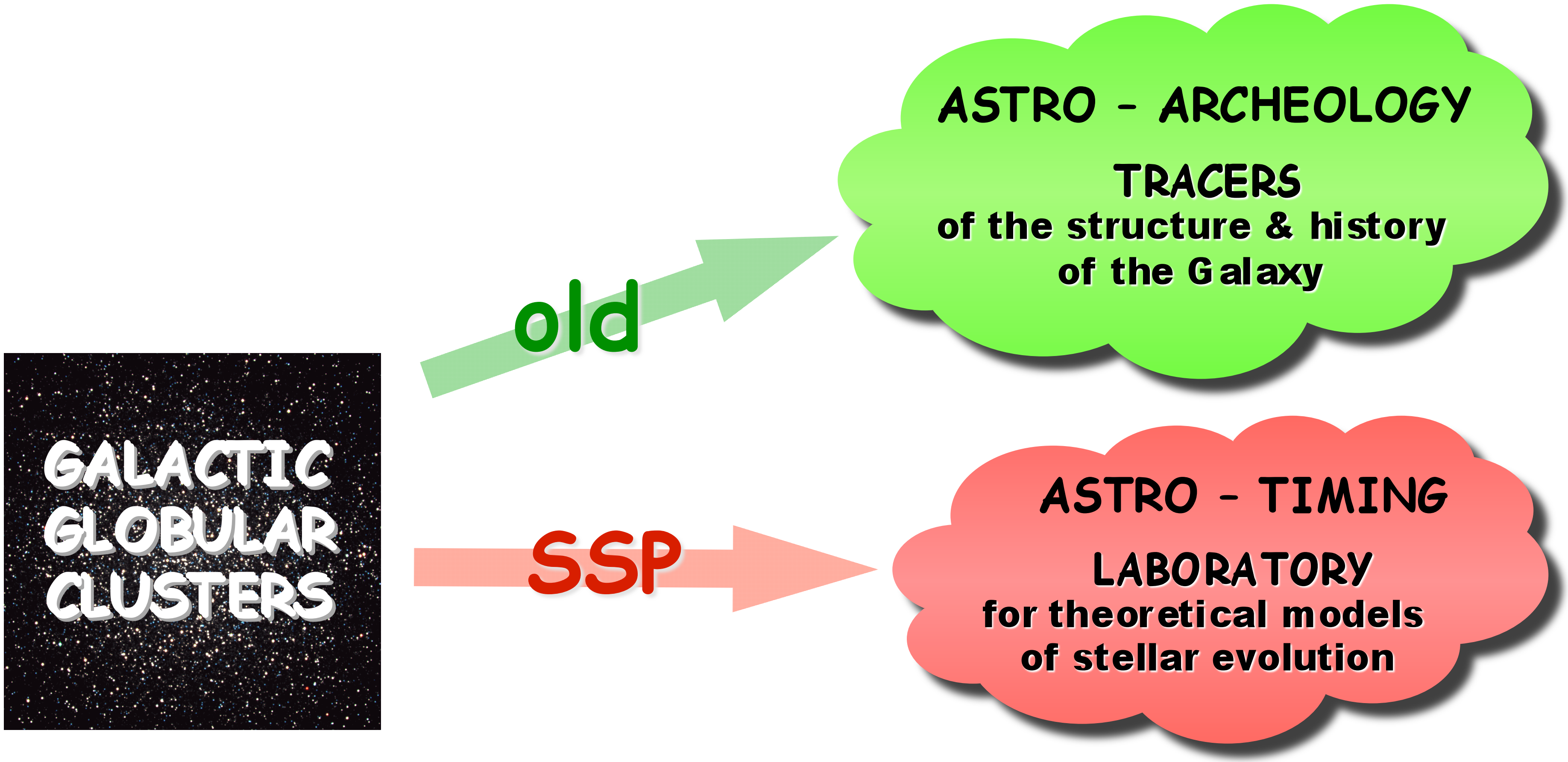
2) with the same initia

Giants show differences in the abundance pattern

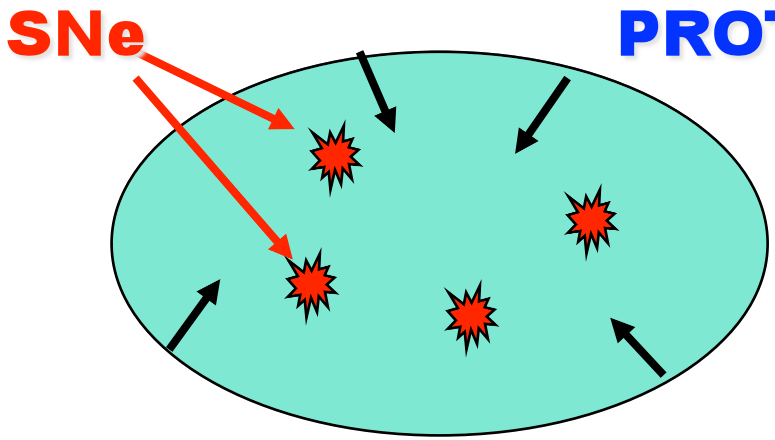
3) single (not located in bina

GGC surely harbour Binaries

... BUT STILL GGCs ARE THE BEST KNOWN APPROXIMATION OF A SSP


GALACTIC GLOBULAR CLUSTERS
old
SSP
ASTRO - ARCHEOLOGY
TRACERS
of the structure & history
of the Galaxy
ASTRO - TIMING
LABORATORY
for theoretical models
of stellar evolution

PROTO-GALACTIC CLOUD



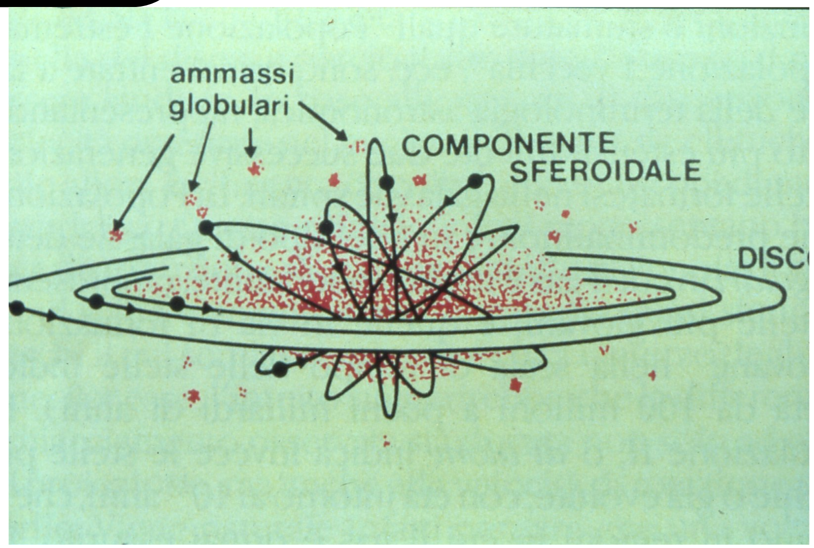
H =76%
He=24%
Z = 0%

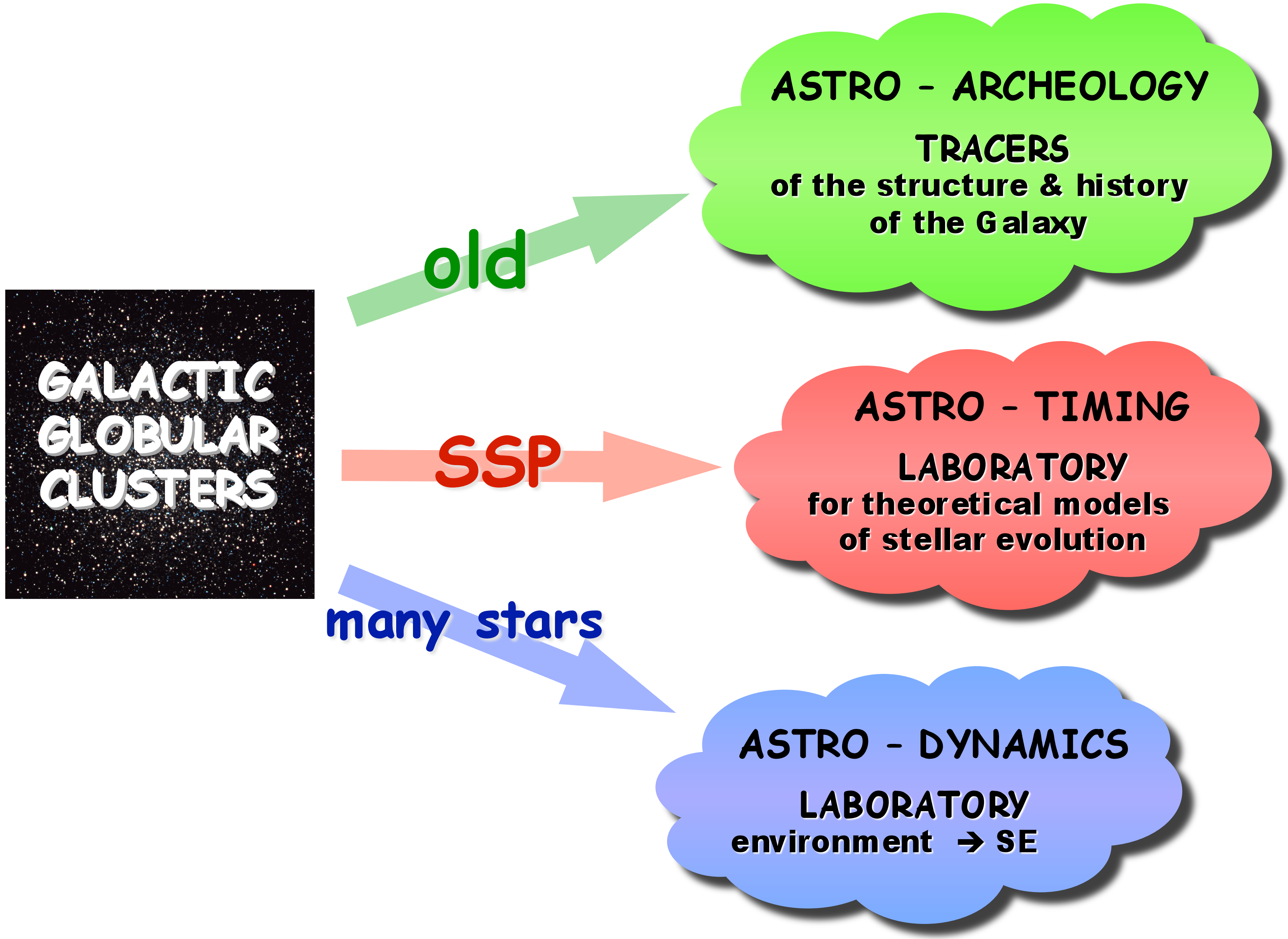
T = 0
POP III

H =76%
He=24%
Z =0.1%

T = 10^8 yr
POP II

Globular clusters



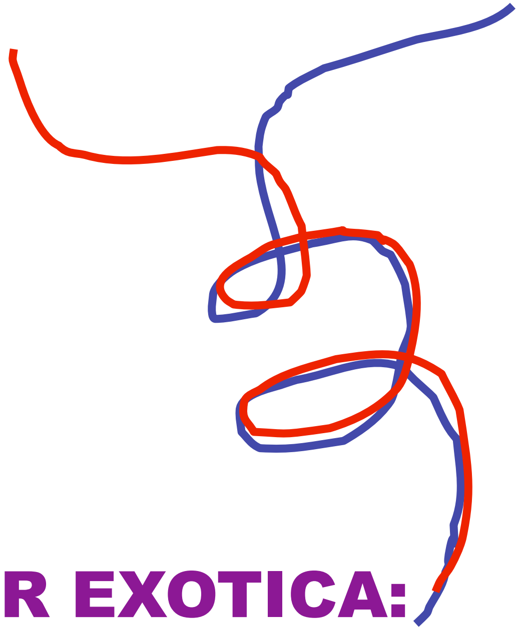

GALACTIC GLOBULAR CLUSTERS
old
SSP
many stars
ASTRO - ARCHEOLOGY
TRACERS
of the structure & history
of the Galaxy
ASTRO - TIMING
LABORATORY
for theoretical models
of stellar evolution
ASTRO - DYNAMICS
LABORATORY
environment → SE

Stellar evolution

- single stars
- old stars
- canonical sequences in the CMD

Stellar dynamics

- collisions
- role of binaries



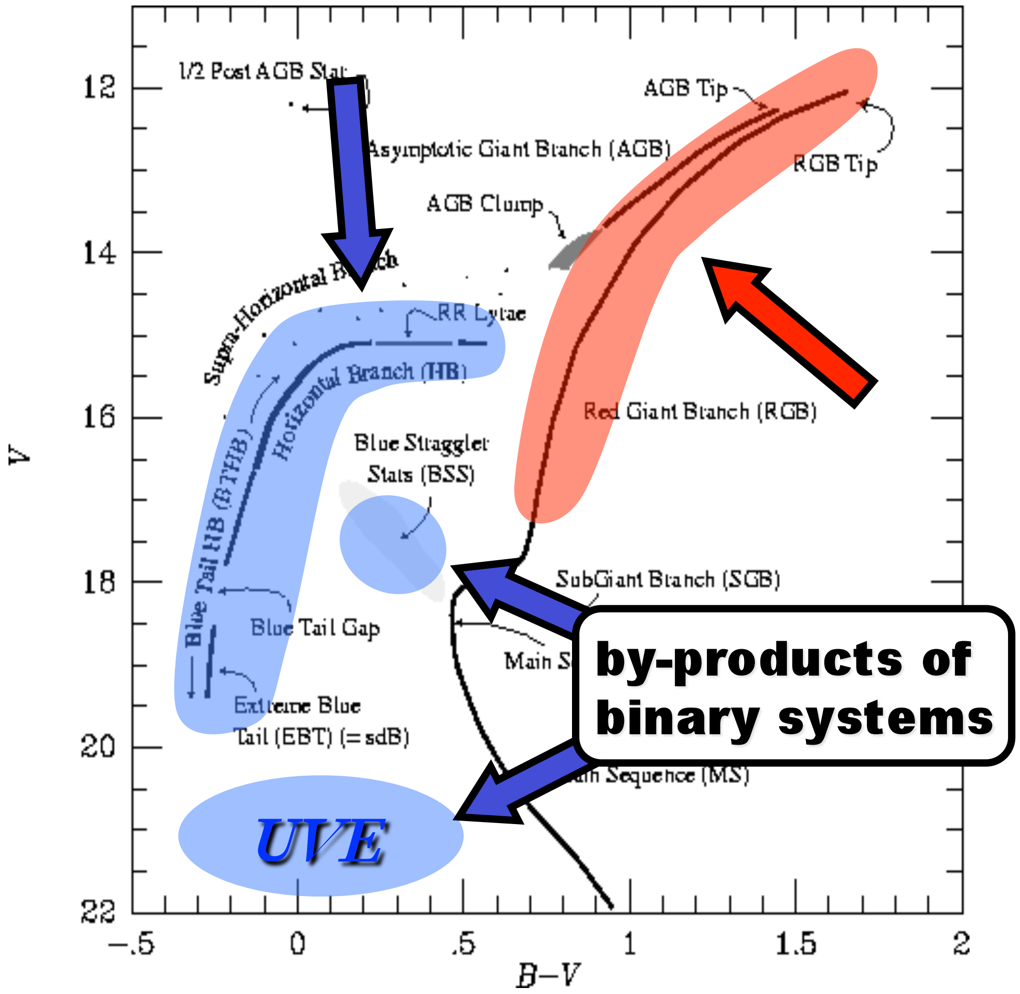
STELLAR EXOTICA:

- Blue Straggler Stars (BSS)
- Millisecond Pulsars (MSP)
- Intermediate-mass black holes (IMBH)
- Cataclysmic variables, Low-mass X-ray binaries…

Exotic populations in the CMD

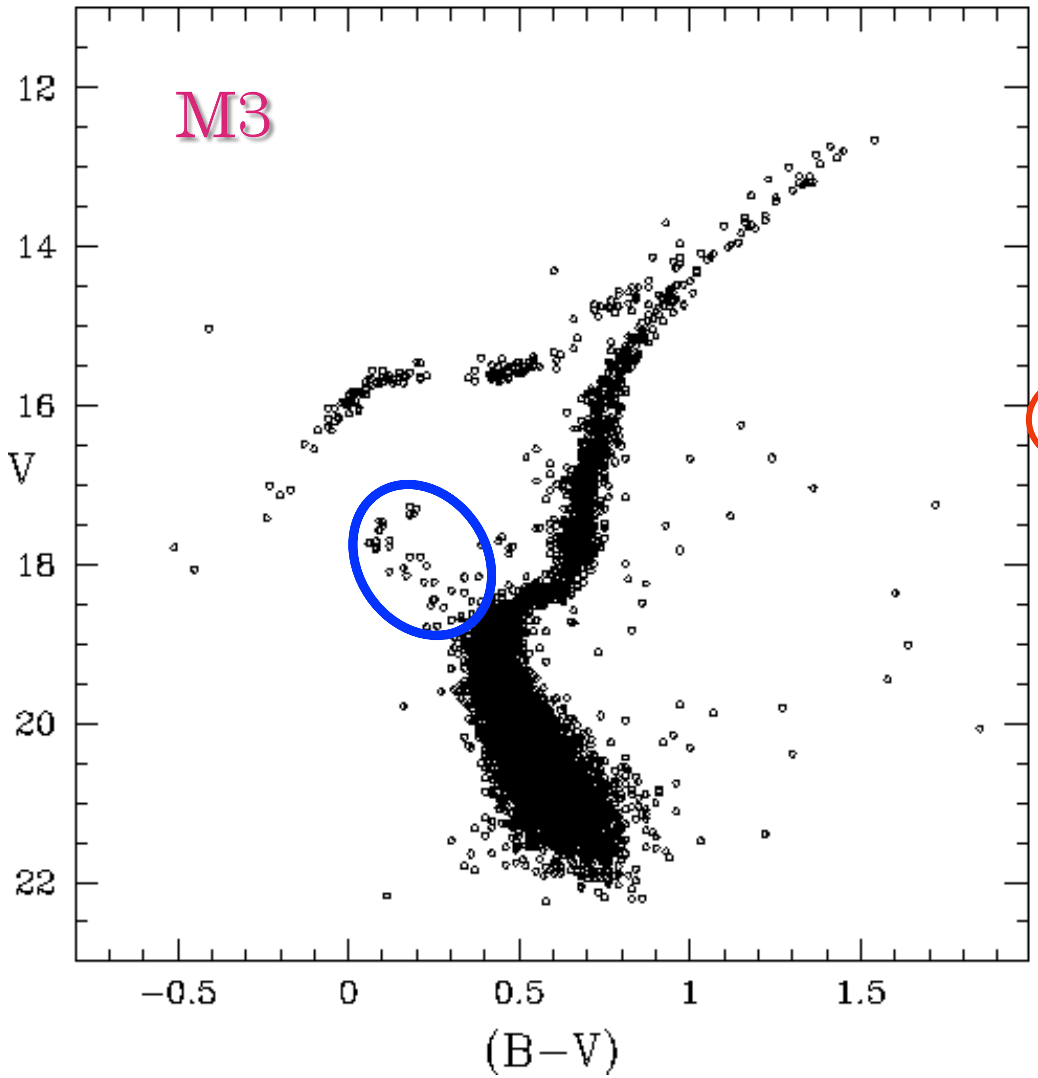
studying "perturbing" effects on "canonical" evolutionary sequences

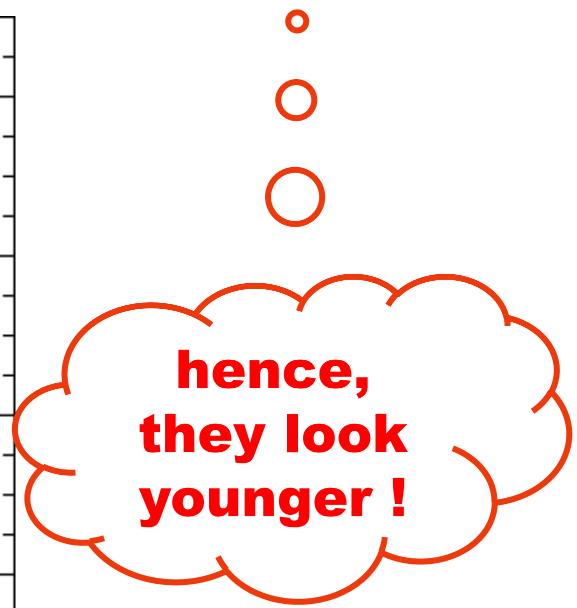
studying ARTIFICIAL sequences as Blue Stragglers Stars and exotic objects



Blue Straggler Stars (BSS)

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



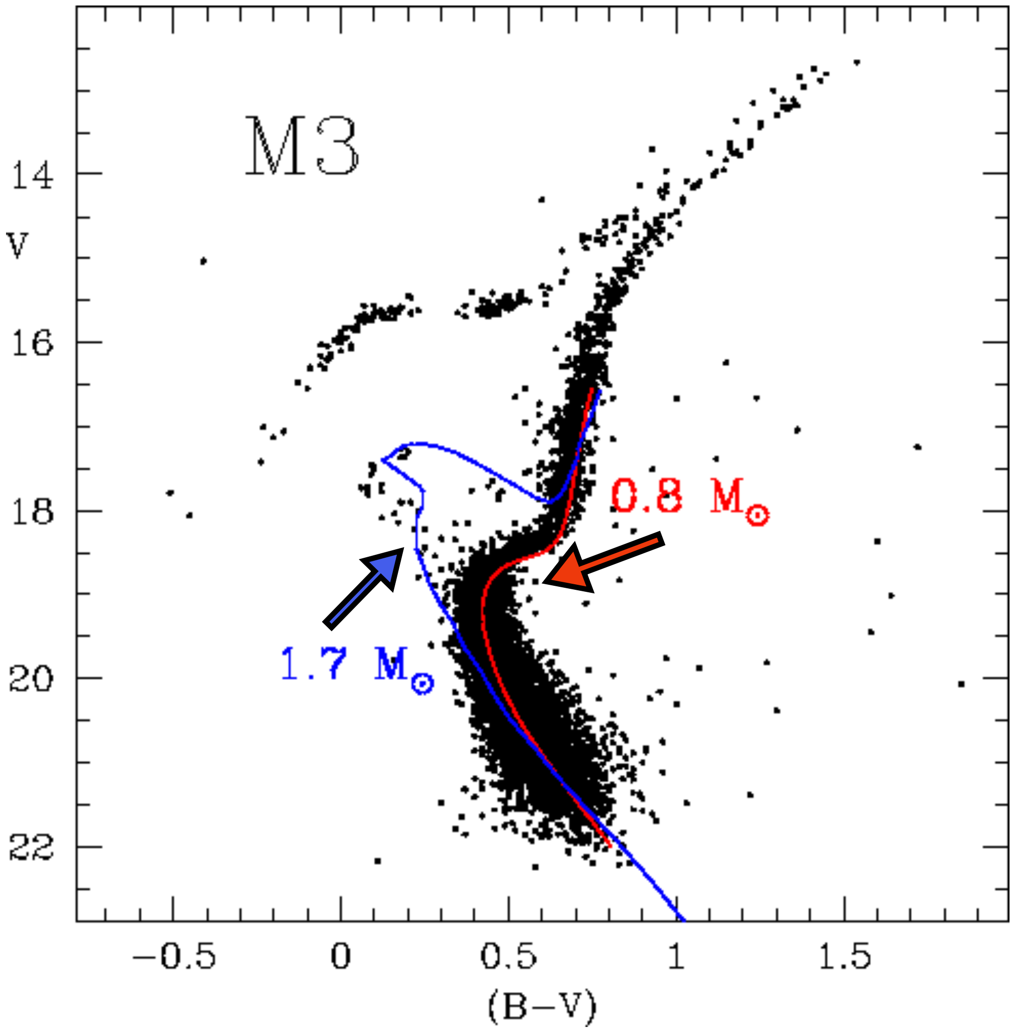


First detected by Sandage (1953) in M3

Blue Straggler Stars (BSS)

like
seeing a
bunch of
young
vigorous
folks
in a
hospice
of
old tired
people..

STARS: younger ⟷ more massive



BSS
more massive
than normal stars

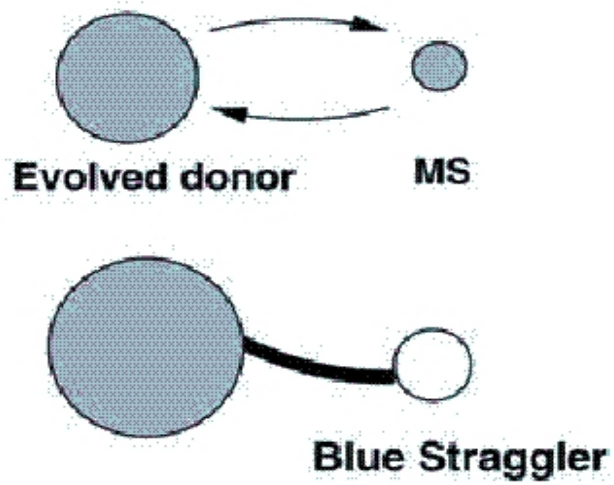
(also from direct measurements by Shara et al. 1997)

merger of
2 low-mass
unevolved stars

merger of 2 low-mass unevolved stars

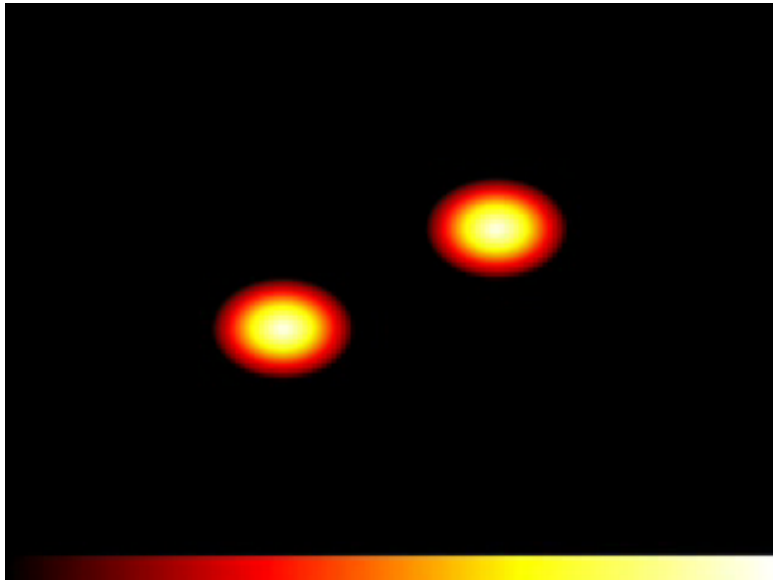
primordial binaries (PB-BSS)

(McCrea 1964; Zinn & Searle 1976)



direct collisions (COL-BSS)

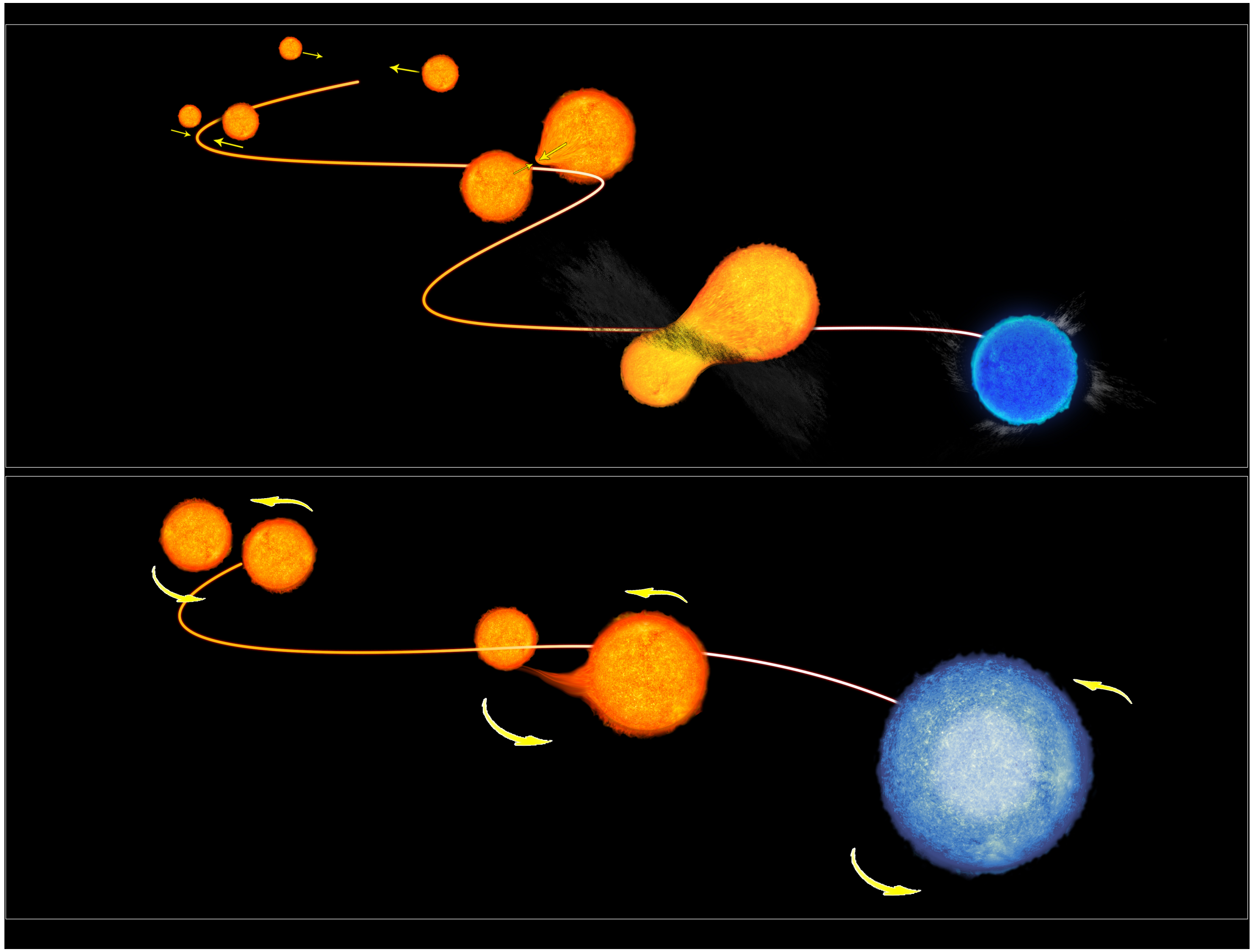
(Hills & Day 1976)



BSS → crucial link between stellar evolution & stellar dynamics

merger of 2 low-mass stars

- **direct collisions (COL-BSS)**
- **mass-transfer in binaries (MT-BSS)**



BSS → **crucial link between**

stellar evolution & stellar dynamics

info about:

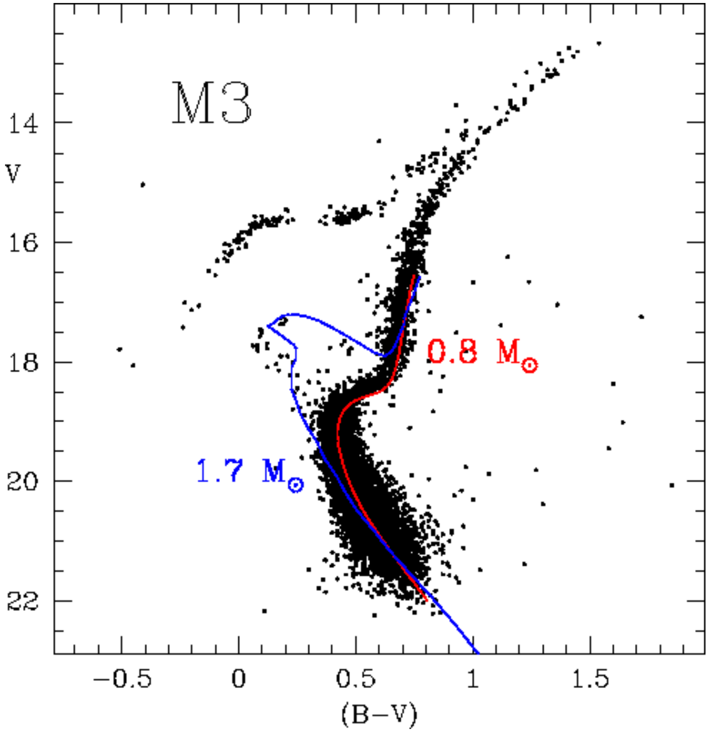
- **the dynamical history of the cluster**
- **the role of dynamics on stellar evolution**
- **the amount of binary systems**
- **the role of binaries in the cluster evolution**

Blue Straggler Stars

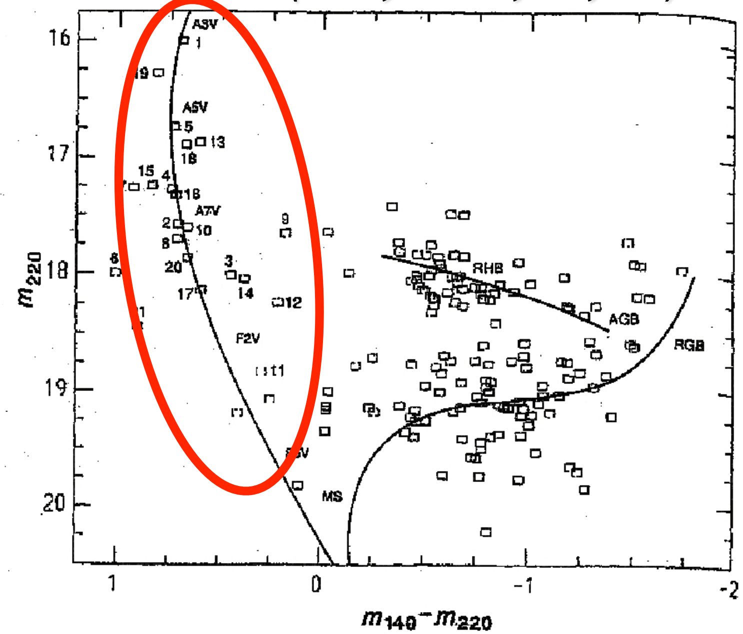
loose GGCs low c, low ρ_0 ⇒ natural habitat for *BSS*

<1990

>1990



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



BSS are a common population of GGCs, found in each cluster when properly observed

some results: optical band

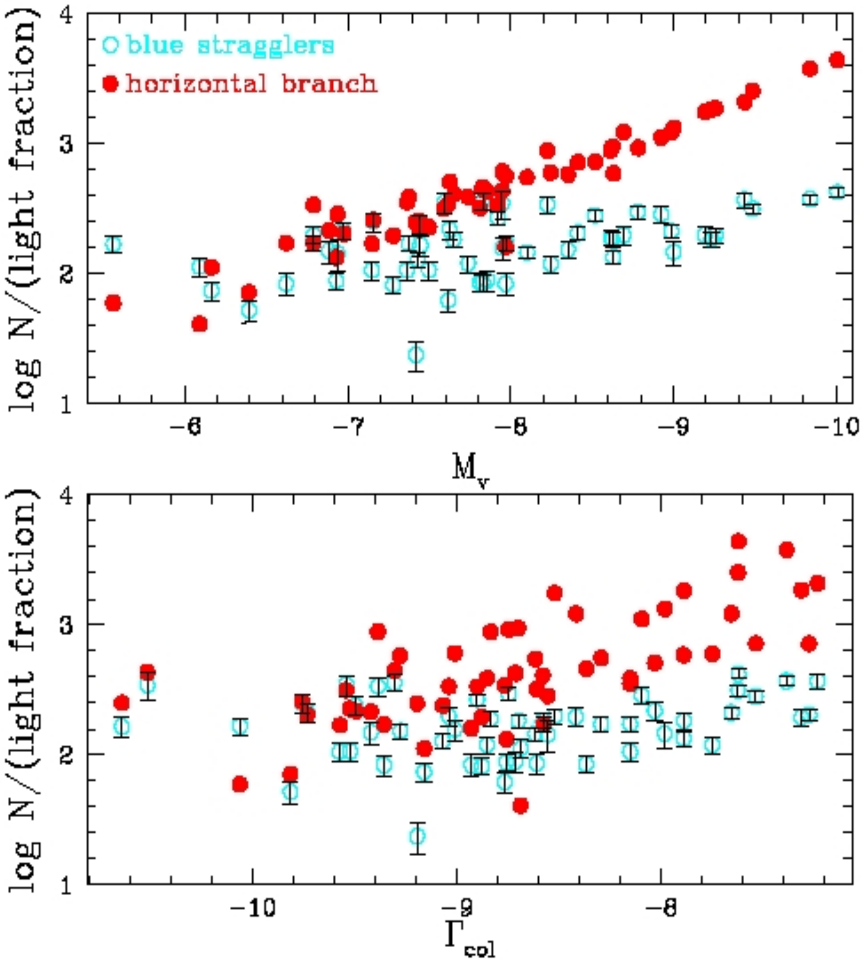
catalog with 3000 BSS in 56 GGCs from HST optical obs

N(BSS)

- **varies by only a factor 10**
- **independent of cluster M**
- **independent of collision rate**

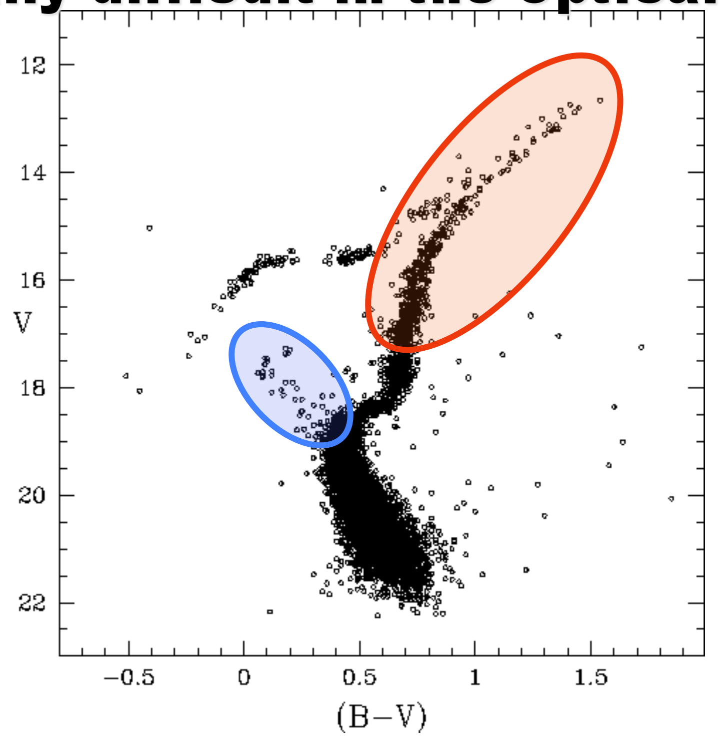
(Piotto et al. 2004; Davies et al. 2004)

BSS are produced by both channels (collisions & binary evolution)



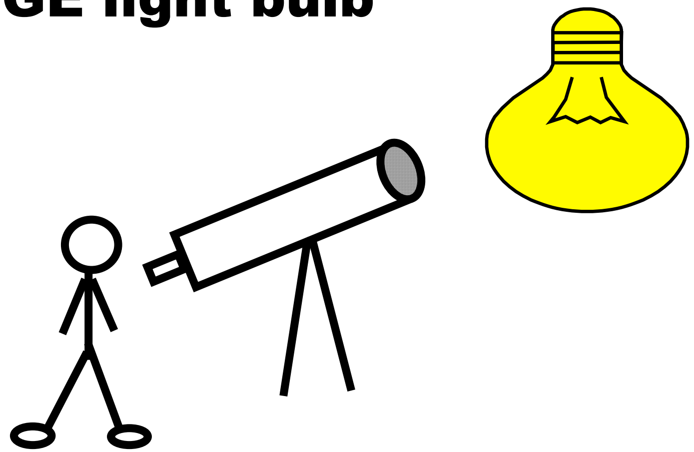
In agreement with previous suggestions by Fusi Pecci et al (1993), Baylin (1995), etc...

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



RGB/AGB much brighter than BSS

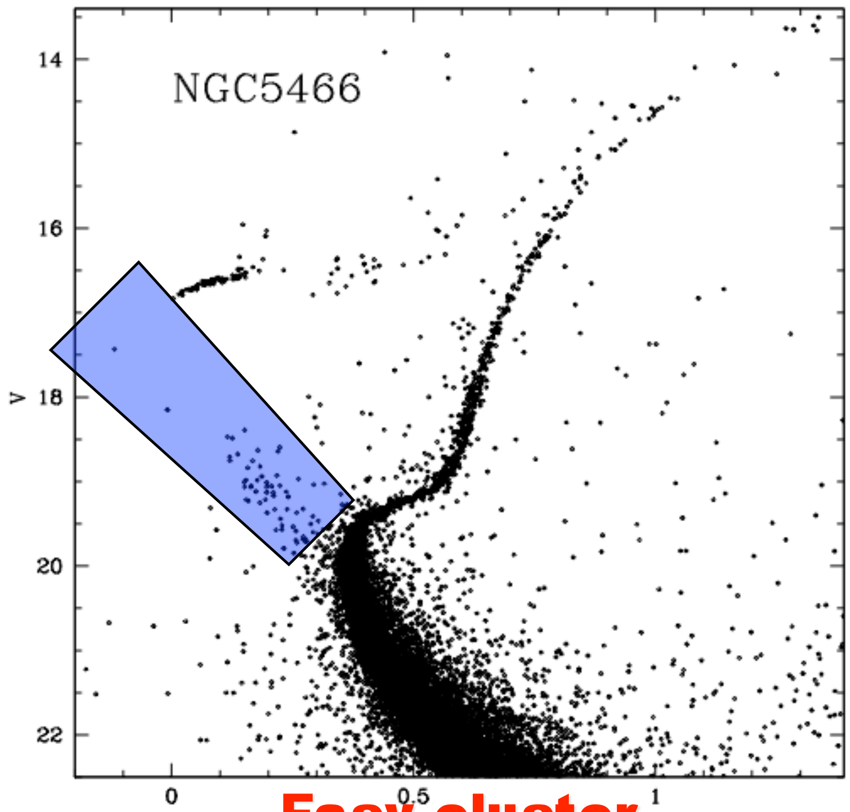
... like trying to distinguish a faint candle here in the Bertinoro night while having a HUGE light bulb just in front of us!



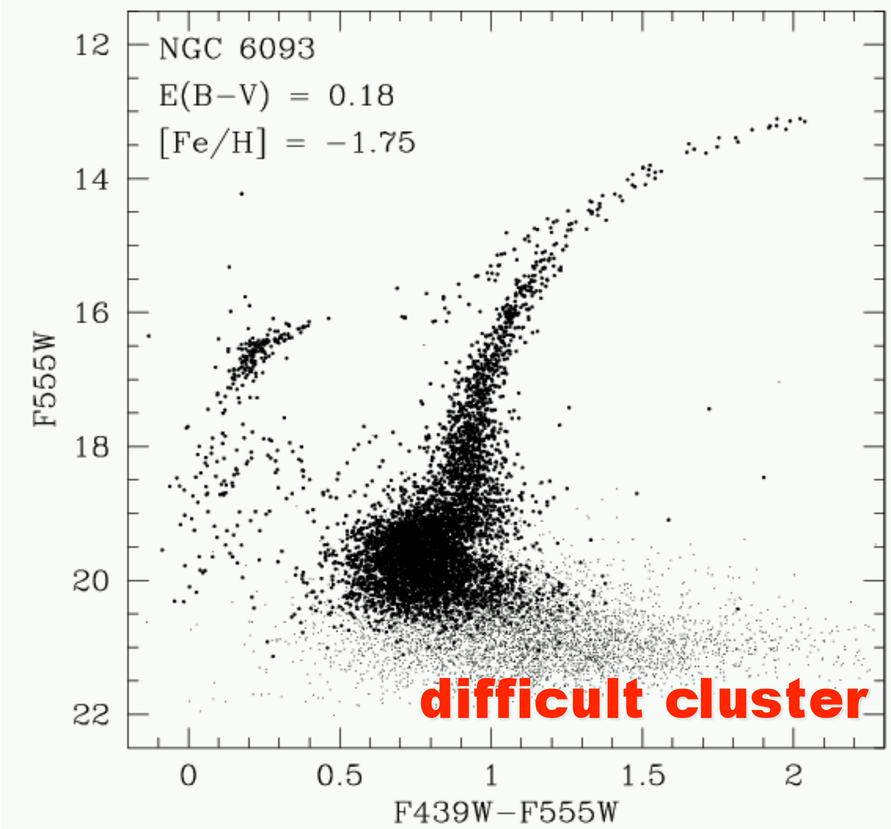
BSS in the optical

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

Definition also depends on the quality of the data



Easy cluster



difficult cluster

HOMOGENEITY & COMPLETENESS are important !!!

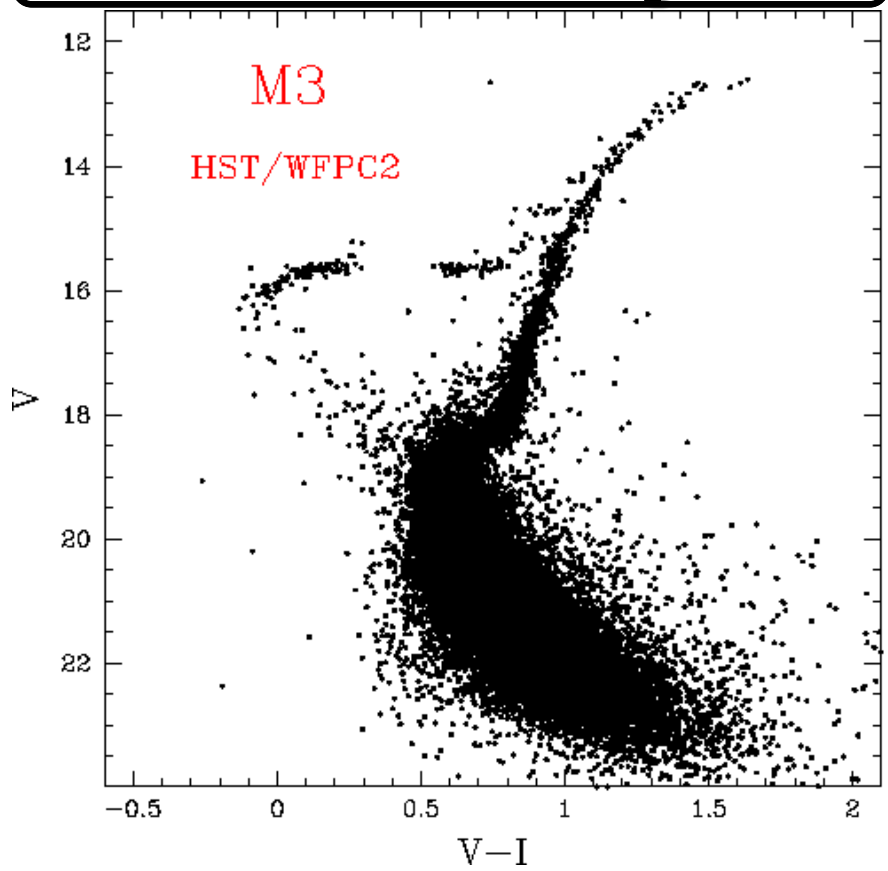
HST

UV sensitivity , *high resolution*

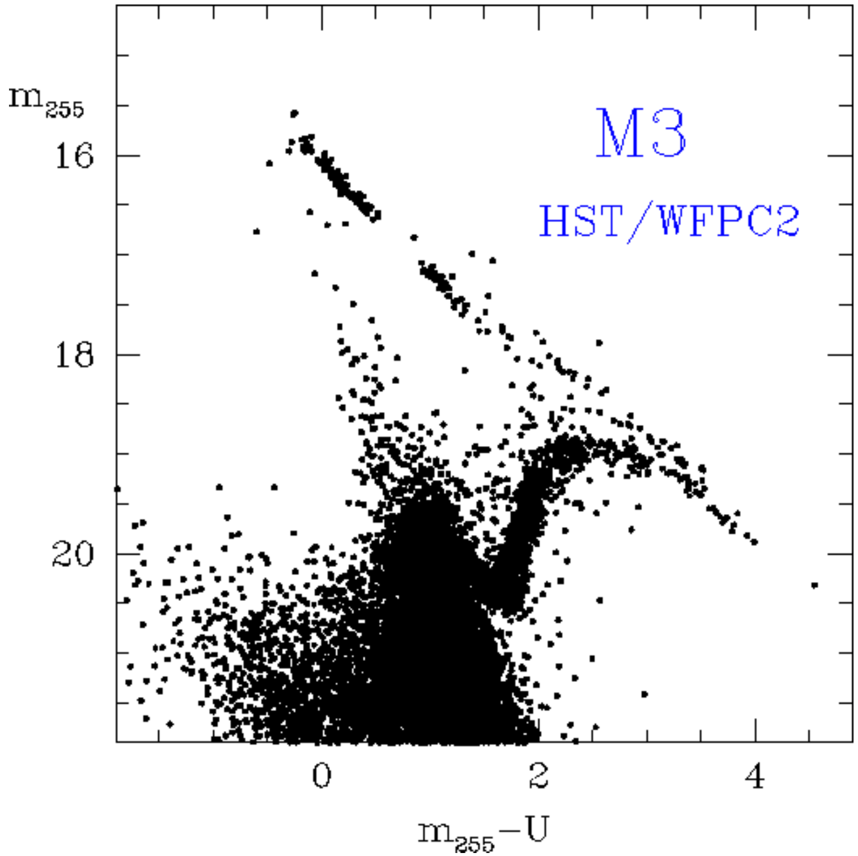
⇩

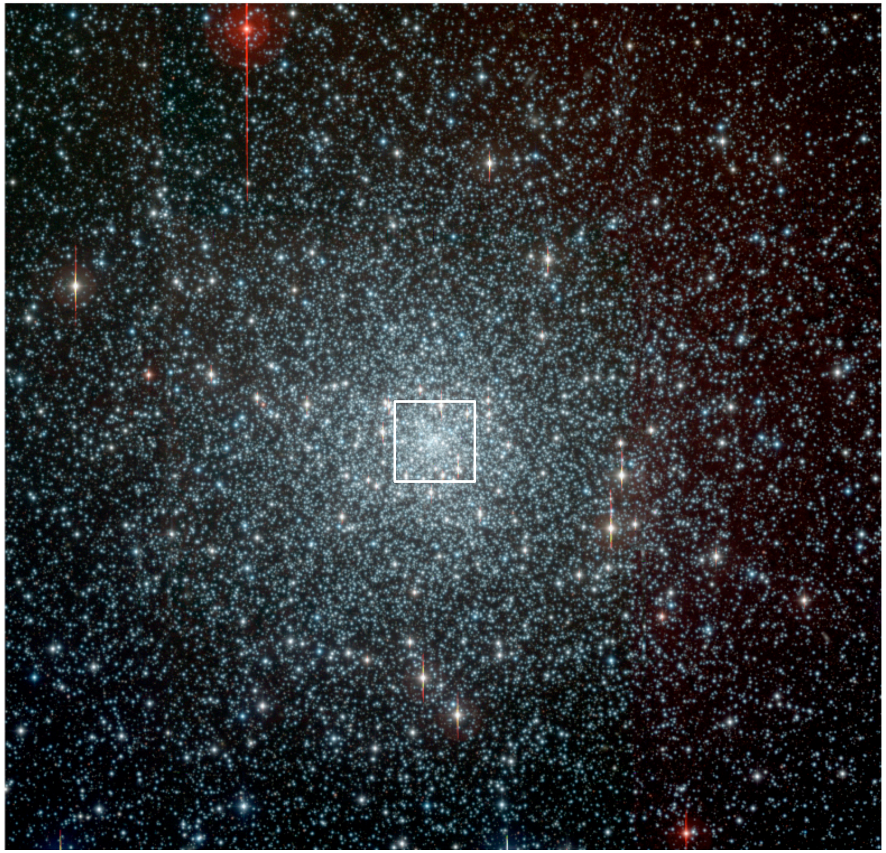
systematic studies of hot SPs even in the core of high density GGCs

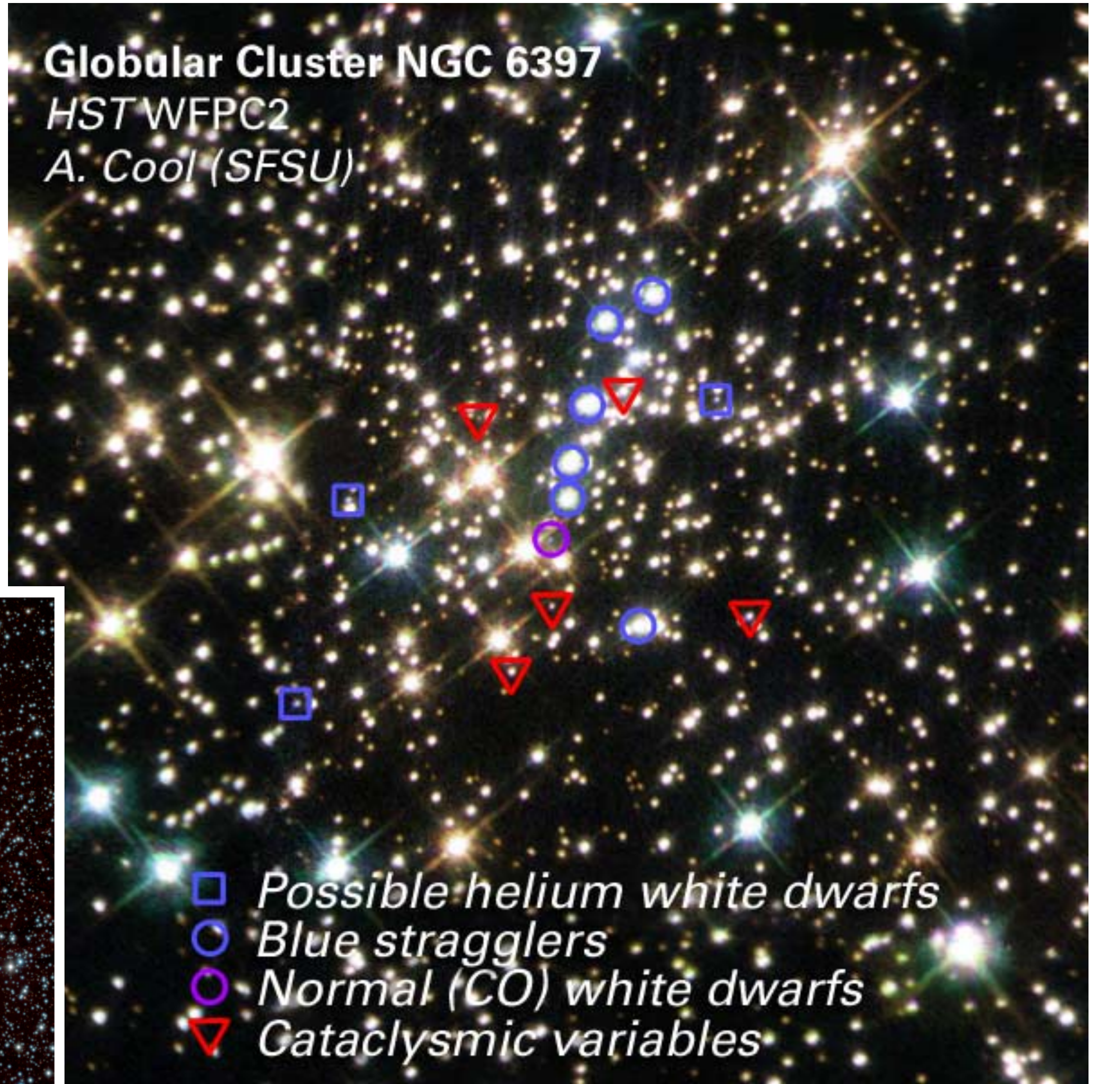
The "classical" plane



The UV plane





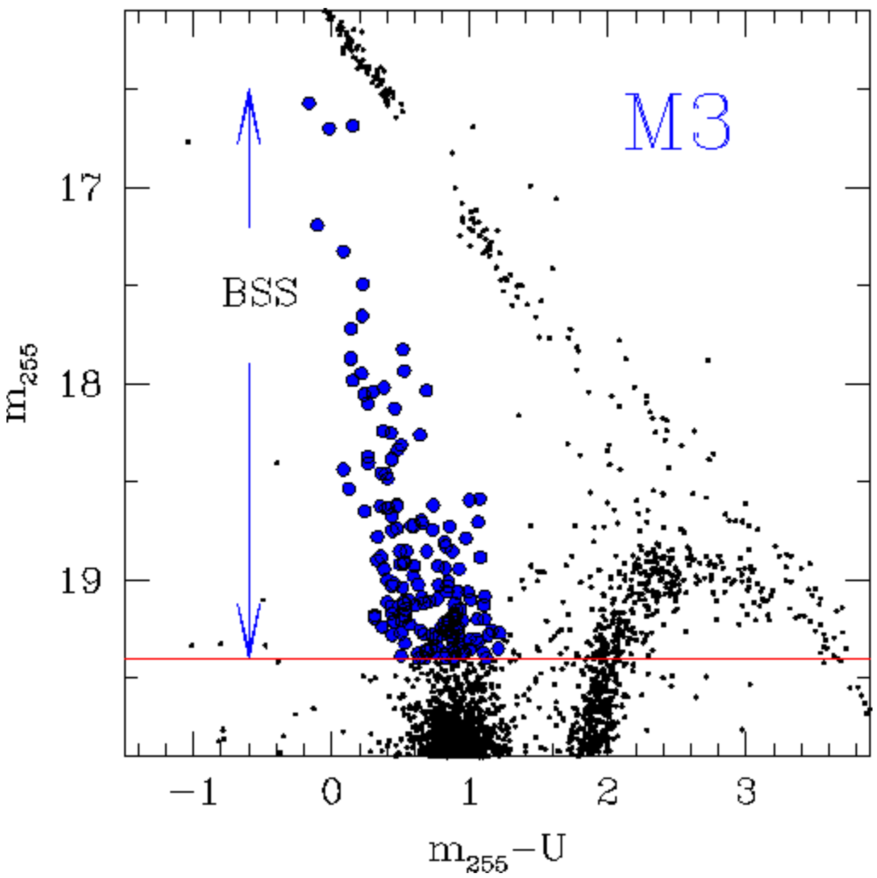


Globular clusters images in UV are not dominated by the red giant light, and therefore are significantly less crowded.

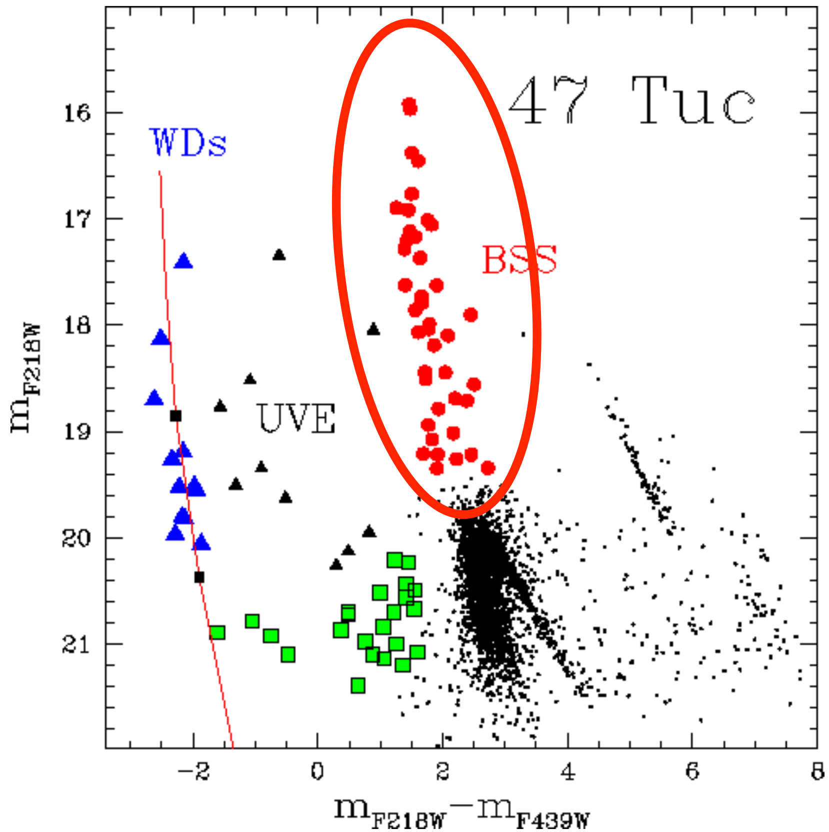
BSS in the UV:

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

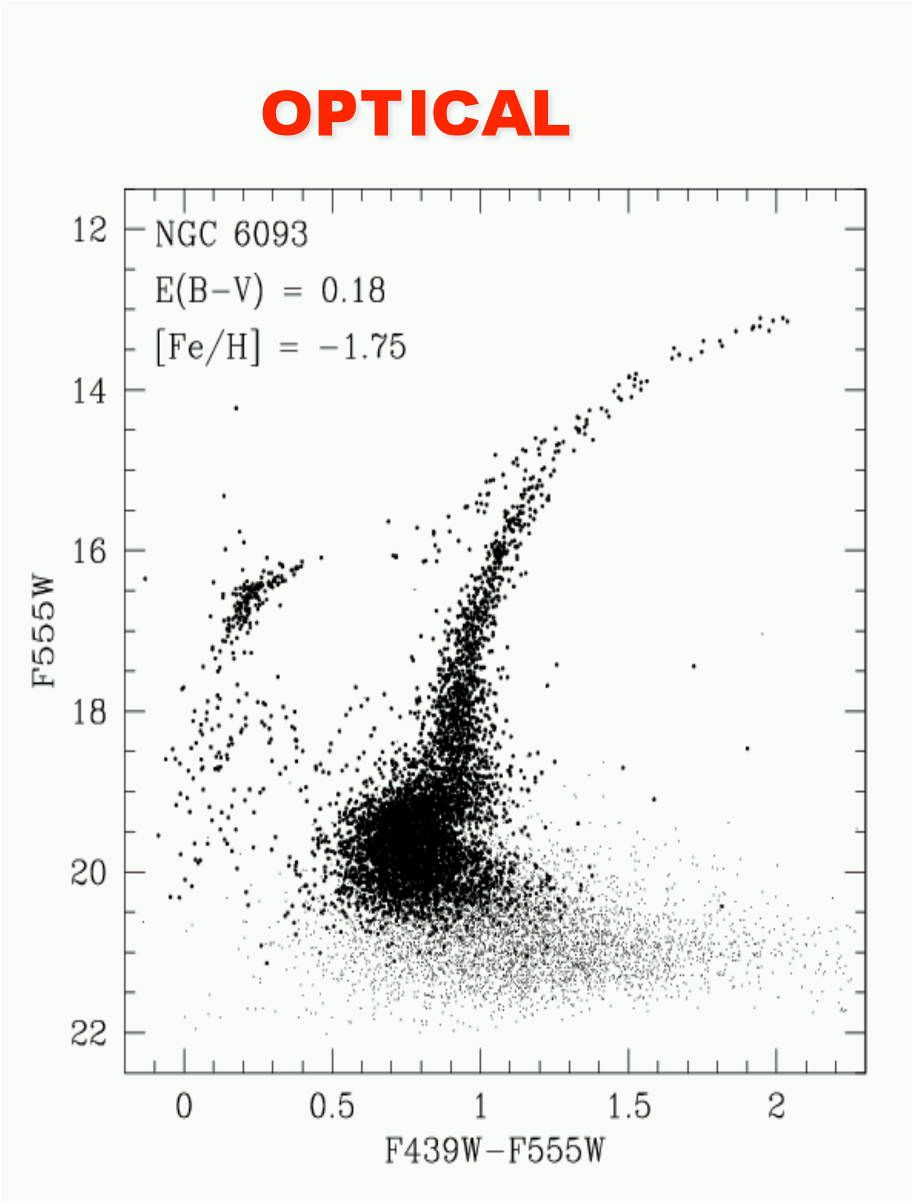
- the distribution is almost vertical
- span more than 3 magnitudes

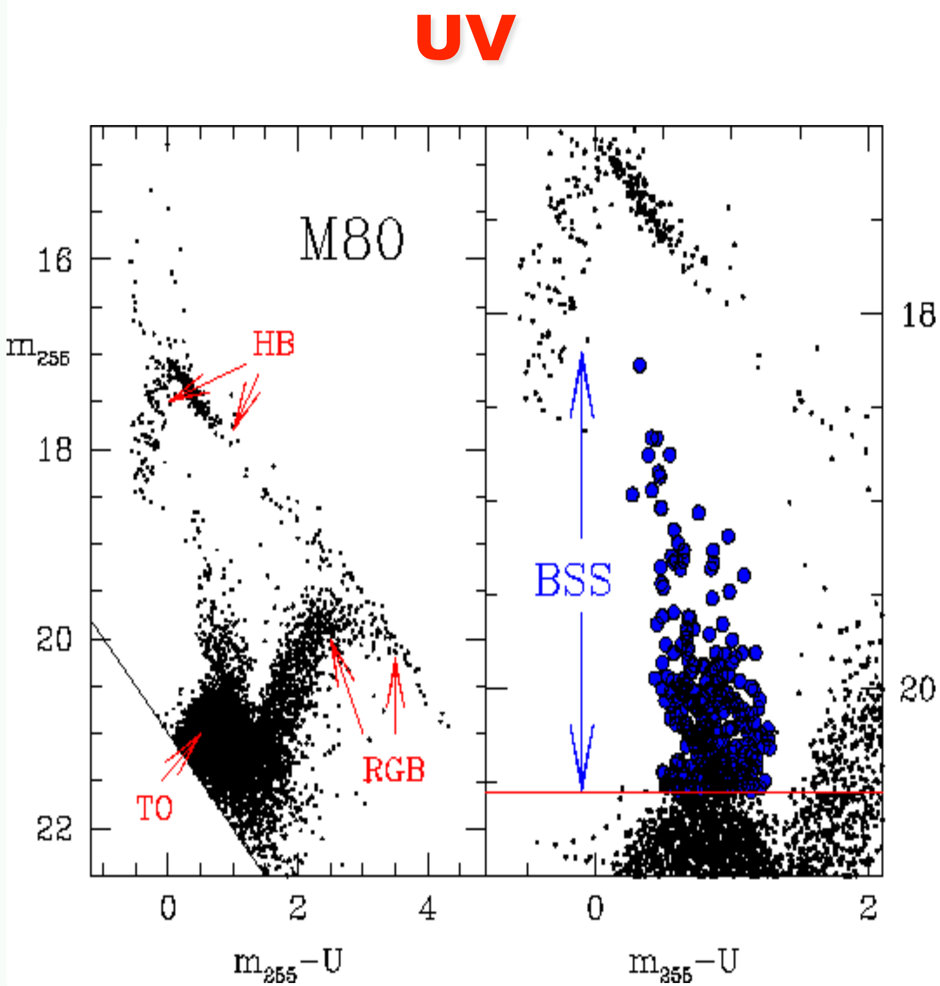


Ferraro et al (1997,A&A,324,915)

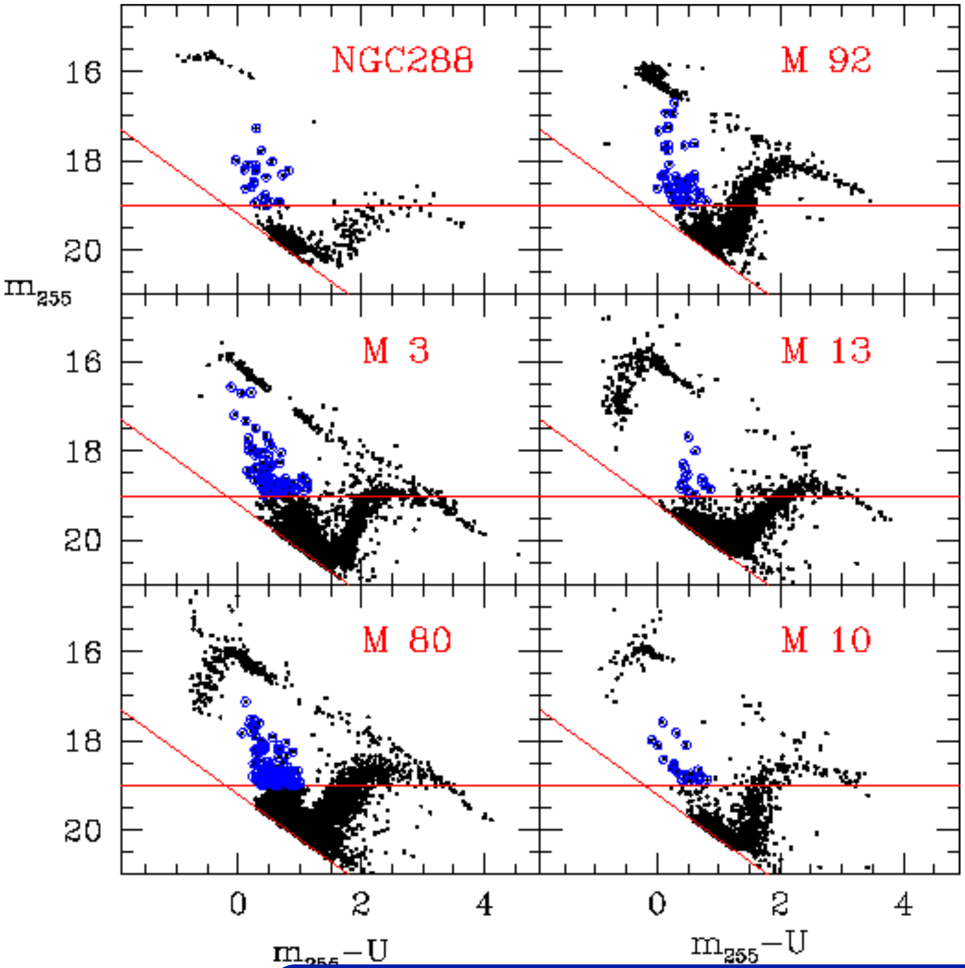


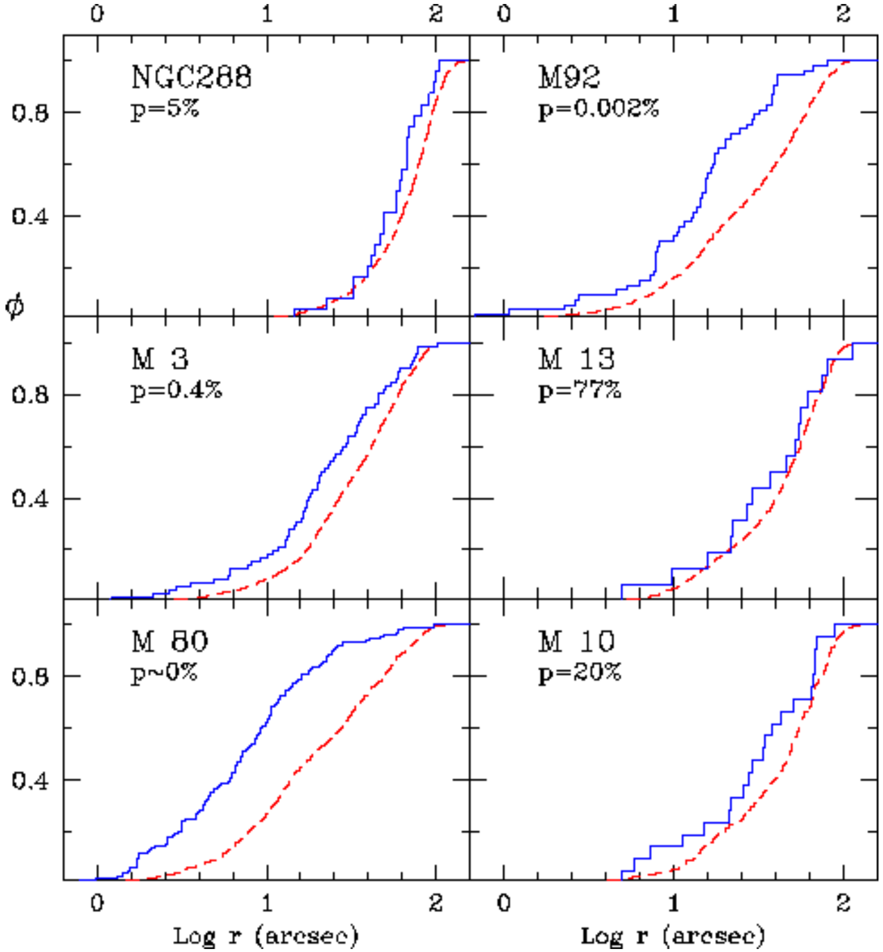
Ferraro et al (2001,ApJ,561,337)


OPTICAL
NGC 6093
E(B−V) = 0.18
[Fe/H] = −1.75
F555W
F439W−F555W


UV
M80
HB
TO
RGB
BSS
m255
m255−U
m255−U

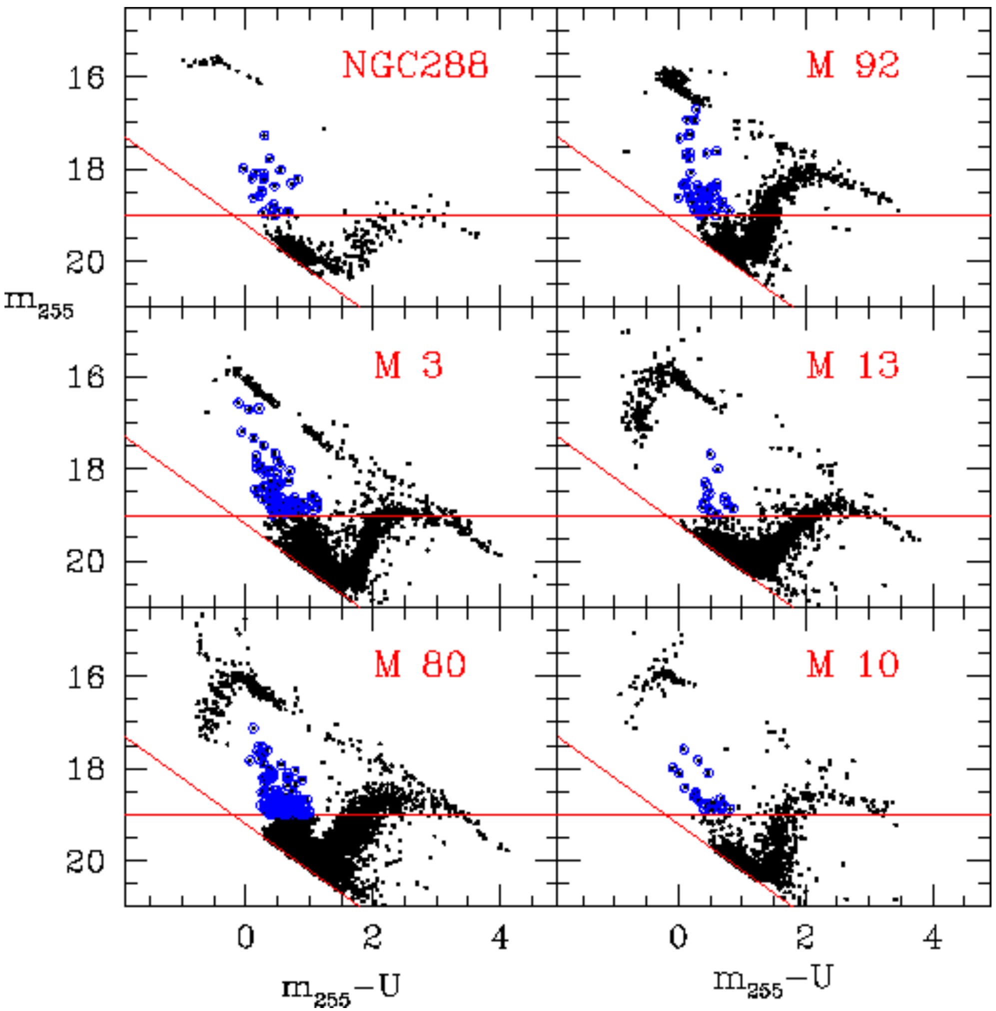
Direct comparison of BSS populations





BSS are centrally segregated

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

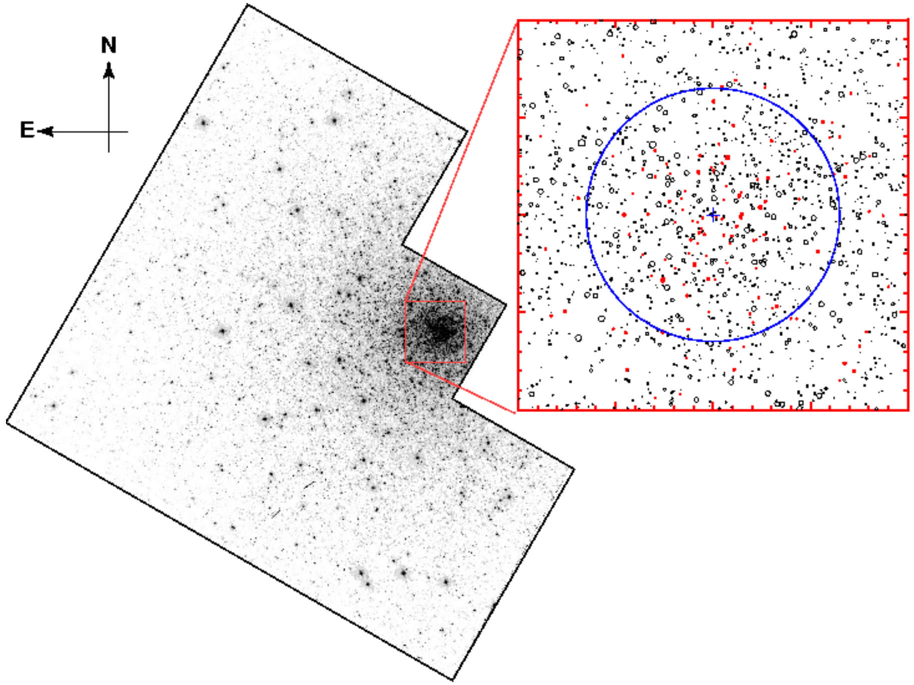
N_{BSS} must be normalized to the cluster population

$\mathcal{F}$ = *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

BSS in the UV:
The large population of BSS in M80

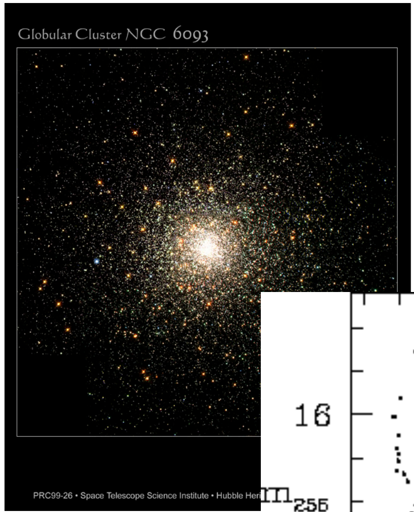


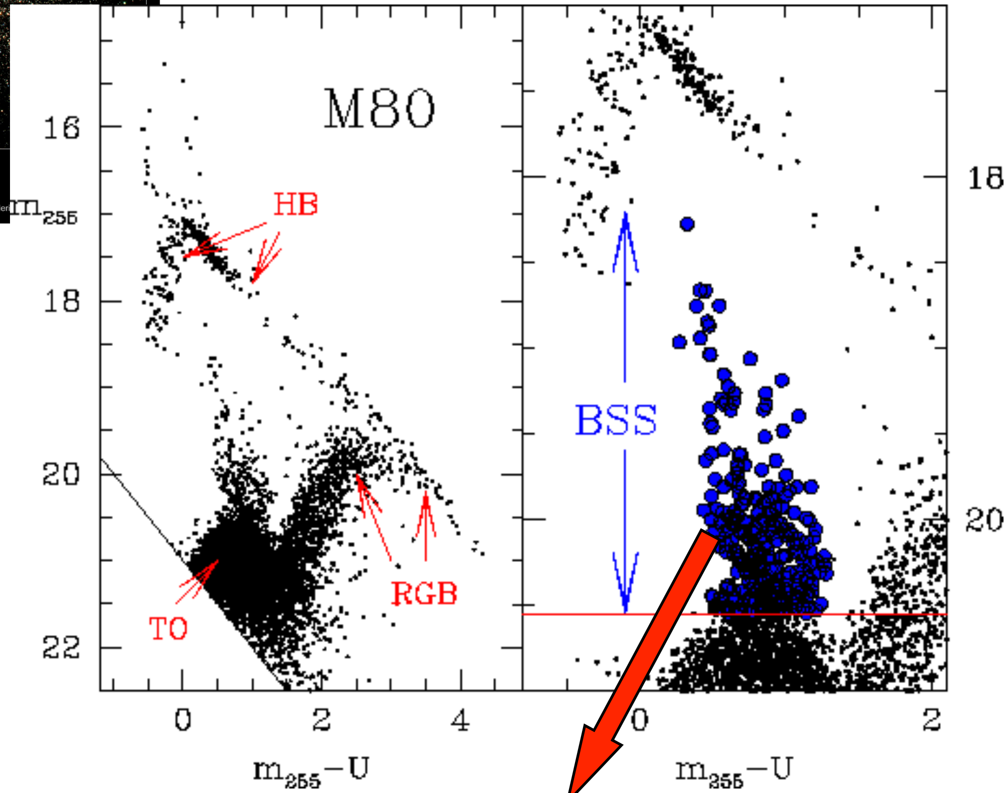
M80 is the densest, not-*PCC* cluster of the Galaxy

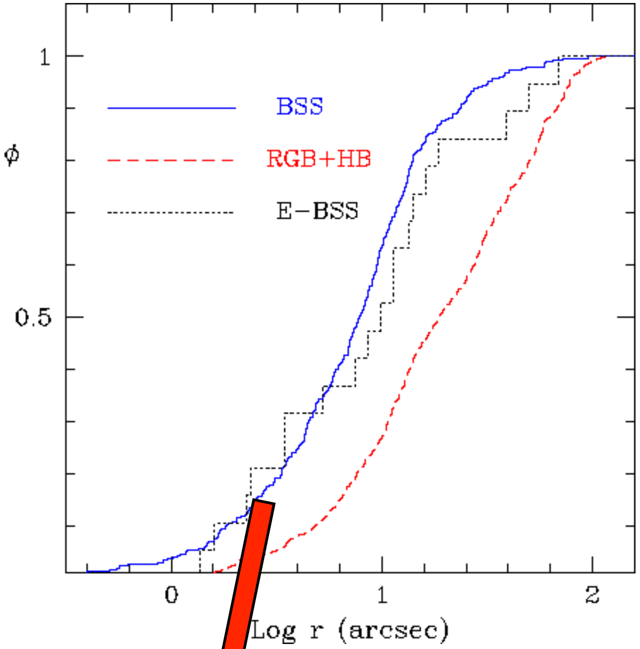
$\textbf{Log}\ \rho_0 = 5.8\ M_s/pc^3$

Ferraro et al (1999, ApJ, 522,983)

The large population of BSS in M80







305 *BSS* !!
The largest population ever observed in a *GGC*

The most concentrated BSS population ever found in a GGC

The large population of BSS in M80

Why M80 has such a huge population of BSS ?

M80 is concentrated
(Log ρ_0 = 5.8 M_s/pc^3)

BUT other clusters with similar concentration like
47 Tuc (Log ρ_0 = 5.1 M_s/pc^3)
NGC2808 (Log ρ_0 = 5.0 M_s/pc^3)
NGC6388 (Log ρ_0 = 5.7 M_s/pc^3)

have many fewer *BSS* (N_{BSS}< *100*)

Could the dynamical evolution of the cluster play a role in the formation of *BSS*?

M80 is not a *PCC*
but it should be !!!!
its dynamical time scale
is much shorter than its age !
BUT
even the *PCC* state cannot explain such a huge BSS population

Are collisions delaying the core collapse and generating *COL-BSS*?

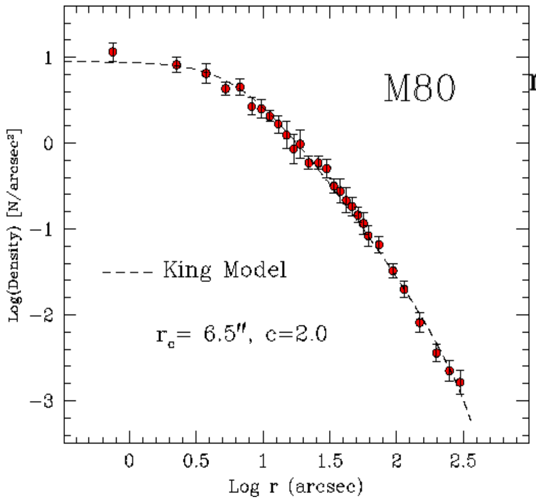
This would be the
<u>first direct evidence</u> !!!

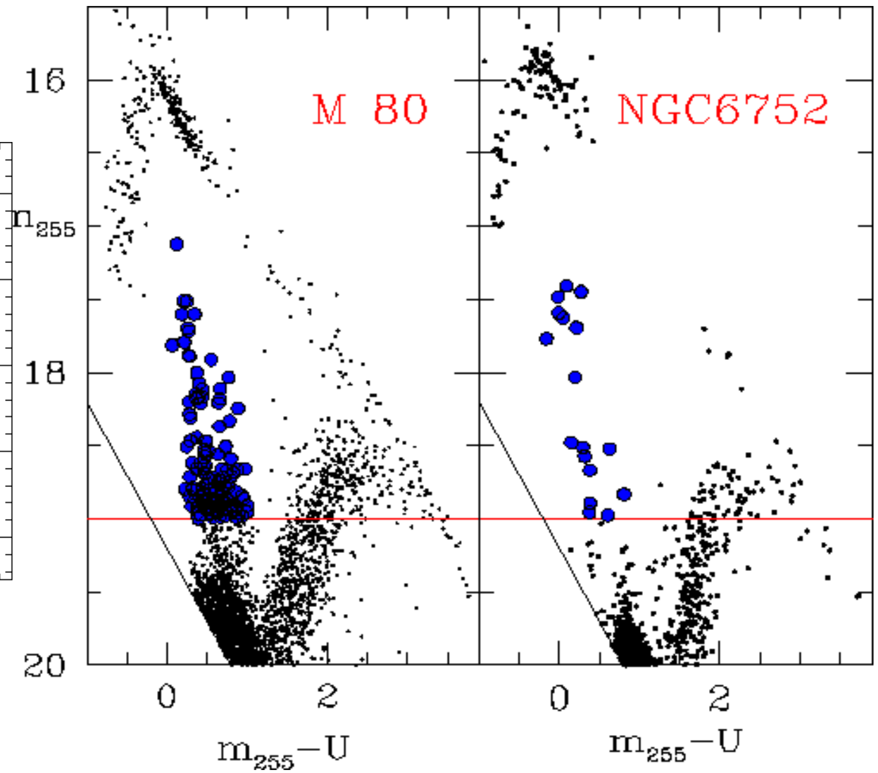
Direct comparison of BSS populations

different dynamical status

M 80

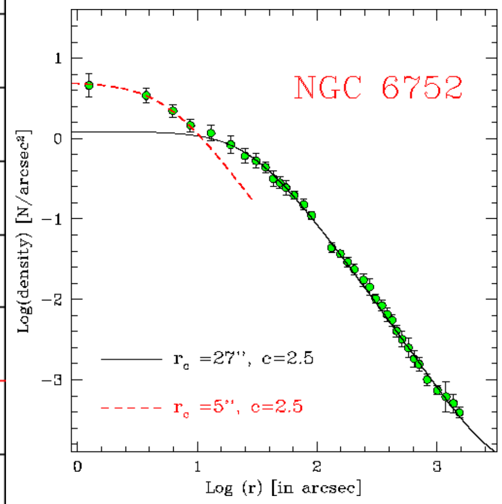
collapsing





NGC 6752

PCC



N_{BSS} = 129

$\mathcal{F}$ = 0.44

N_{BSS} = 17

$\mathcal{F}$ = 0.16

?

are binaries preventing the core collapse ?

are binaries destroyed during the collapse ?

Direct comparison of BSS populations

different ρ_0

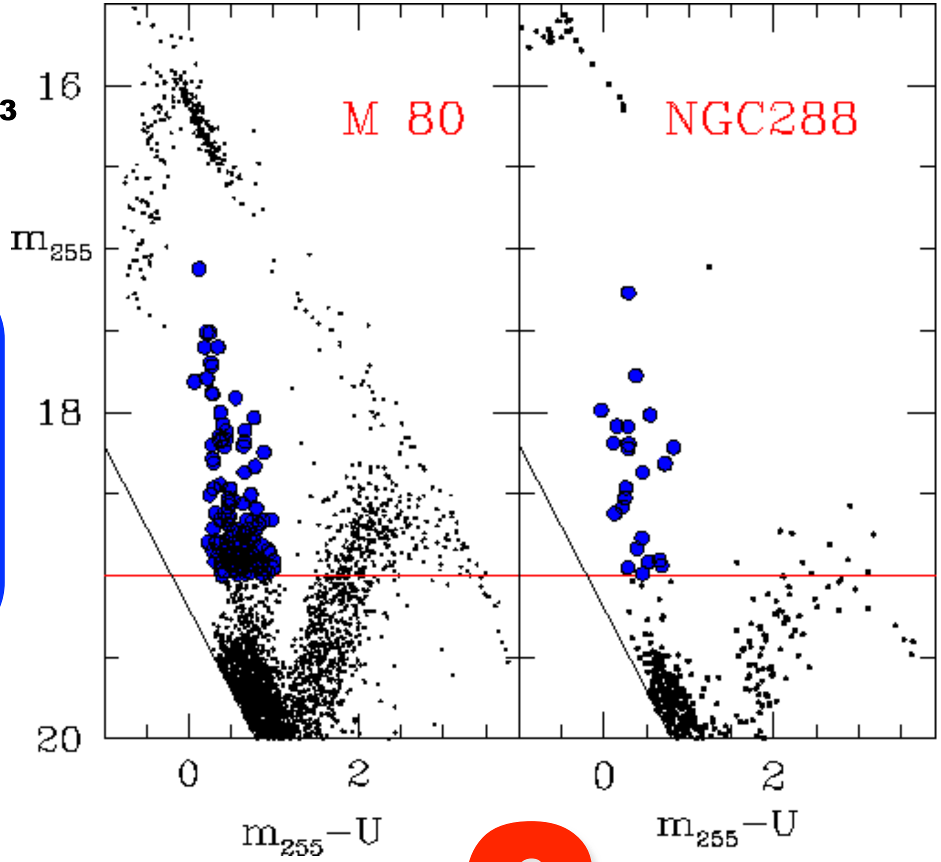
M 80

Log ρ_0 = 5.8 M_s/pc^3

N_{BSS} = 129

$\mathcal{F}$ = 1.0

if only the PC is considered



NGC 288

Log ρ_0 = 2.1 M_s/pc^3

N_{BSS} = 24

$\mathcal{F}$ = 0.92

The largest specific frequency ever observed!
In one of the lowest density clusters…!

COLL-BSS in M80 ⟵ **?** ⟶ **PB-BSS in NGC 288**

comparable efficiency in their respective environment ?

Direct comparison of BSS populations

twin clusters

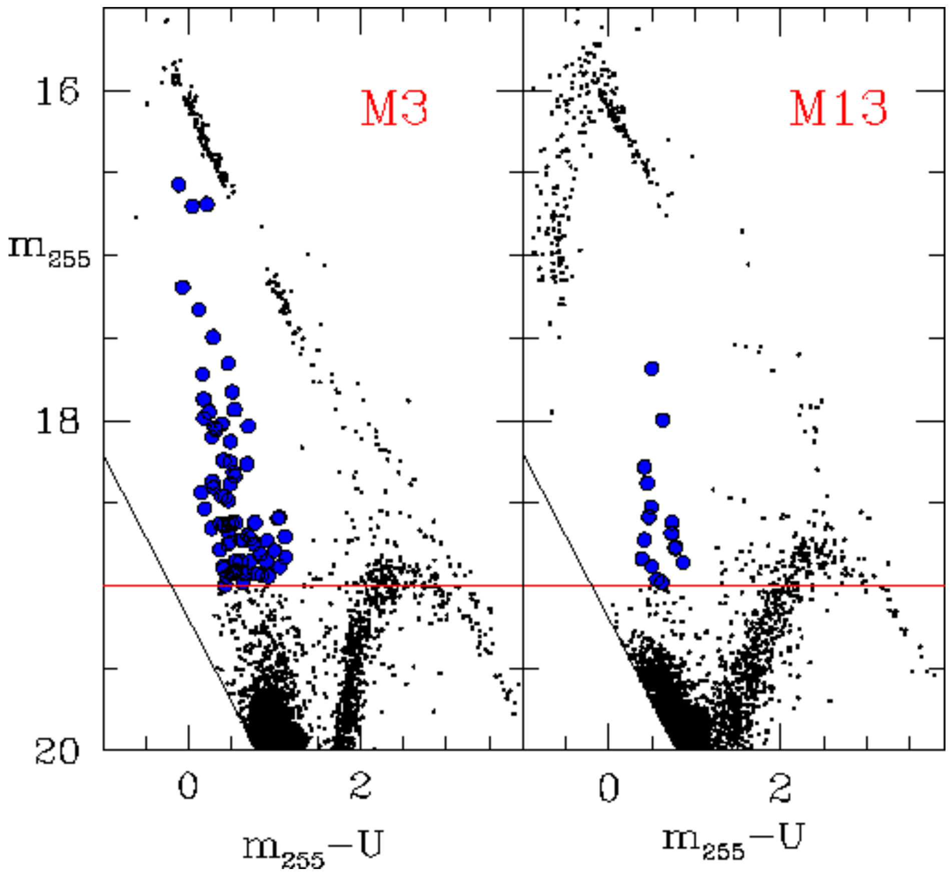
M 3

Log ρ_0 = 3.5 M_s/pc^3

Log M = 5.8 M_s

N_{BSS} = 72

$\mathcal{F}$ = 0.28



M 13

Log ρ_0 = 3.4 M_s/pc^3

Log M = 5.8 M_s

N_{BSS} = 16

$\mathcal{F}$ = 0.07

clusters in different dynamical phases ?

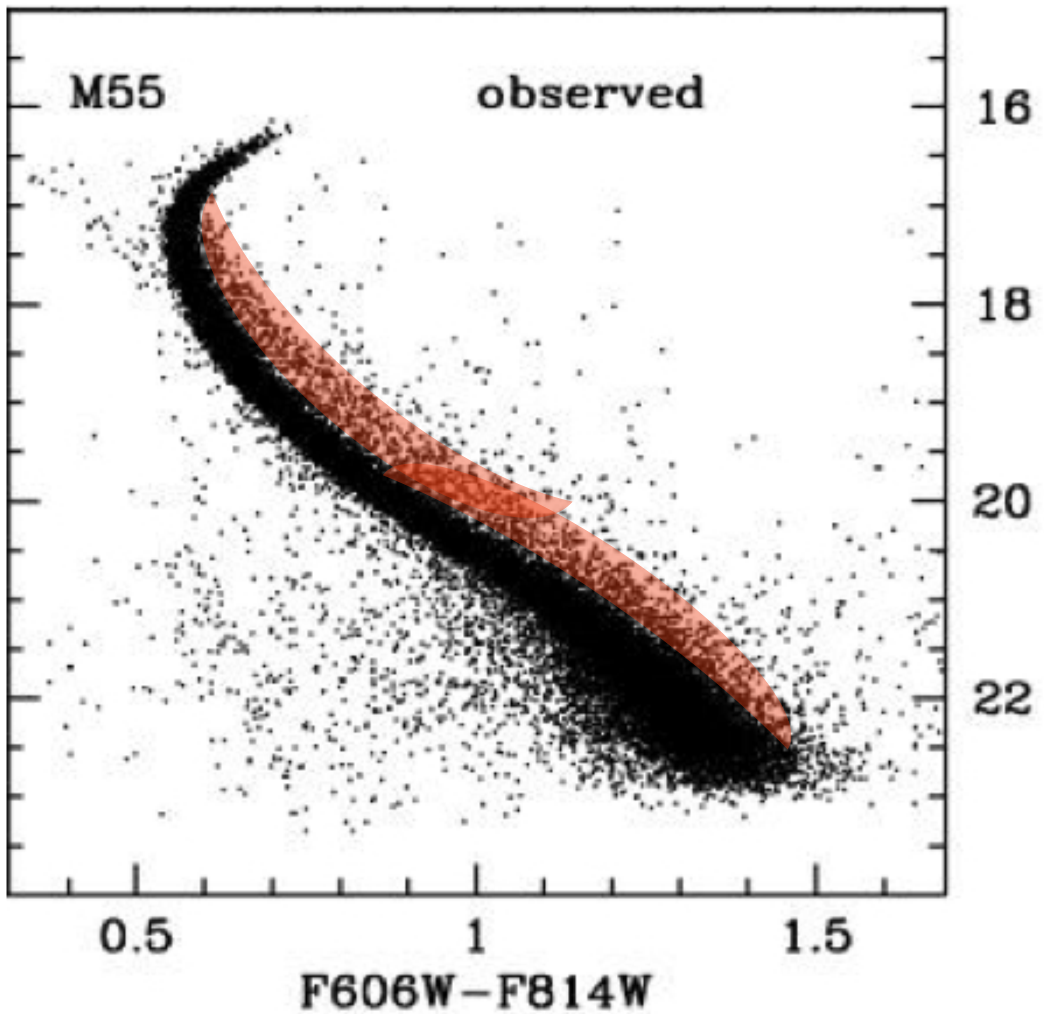
?

different primordial binary populations?

Which is the binary fraction in GGCs ?

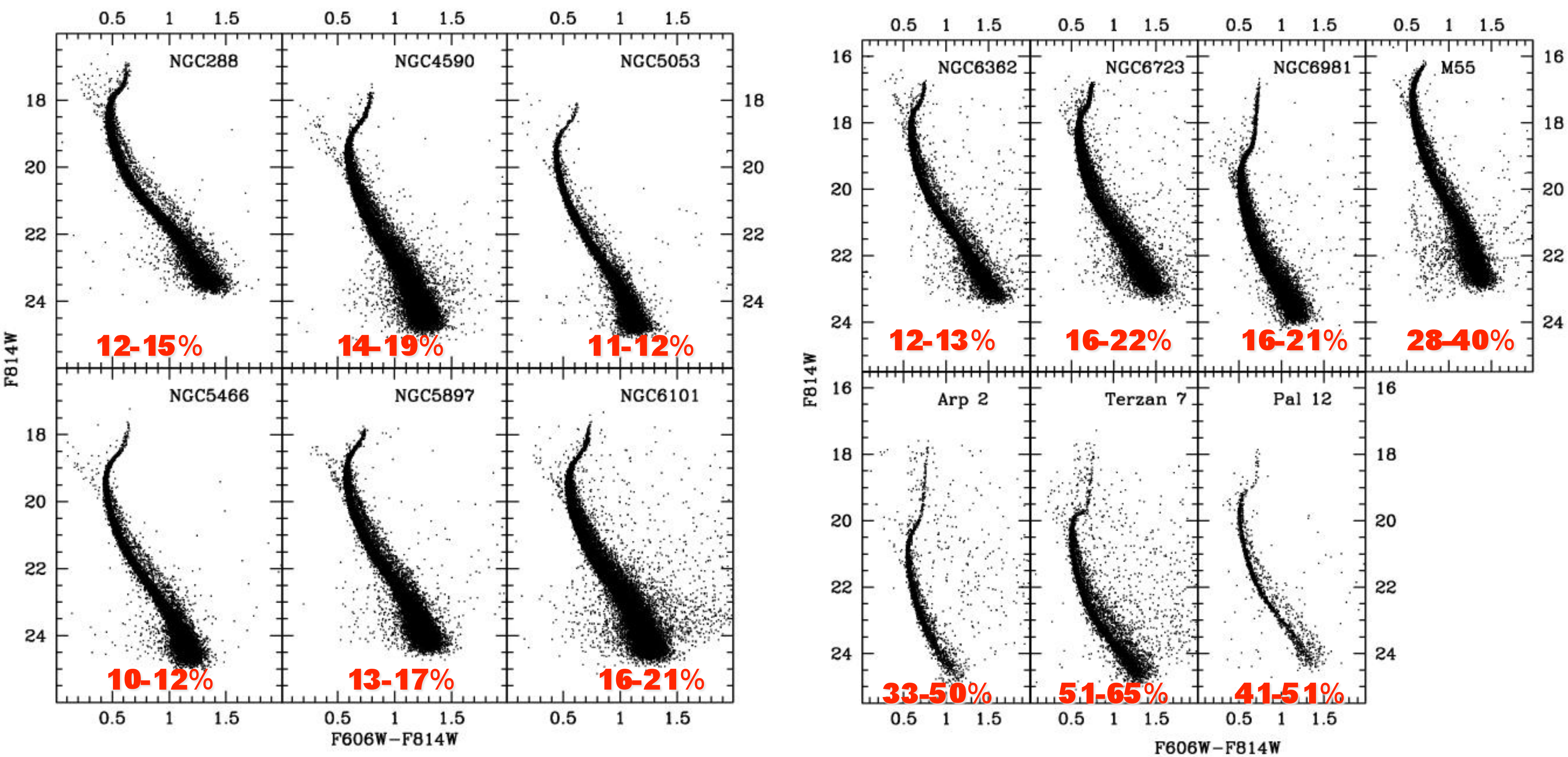
still
LARGELY
unknown...

need <u>very deep</u>
<u>high-accuracy</u>
photometry
(especially for
high-density clusters)



Which is the binary fraction in GGCs ?

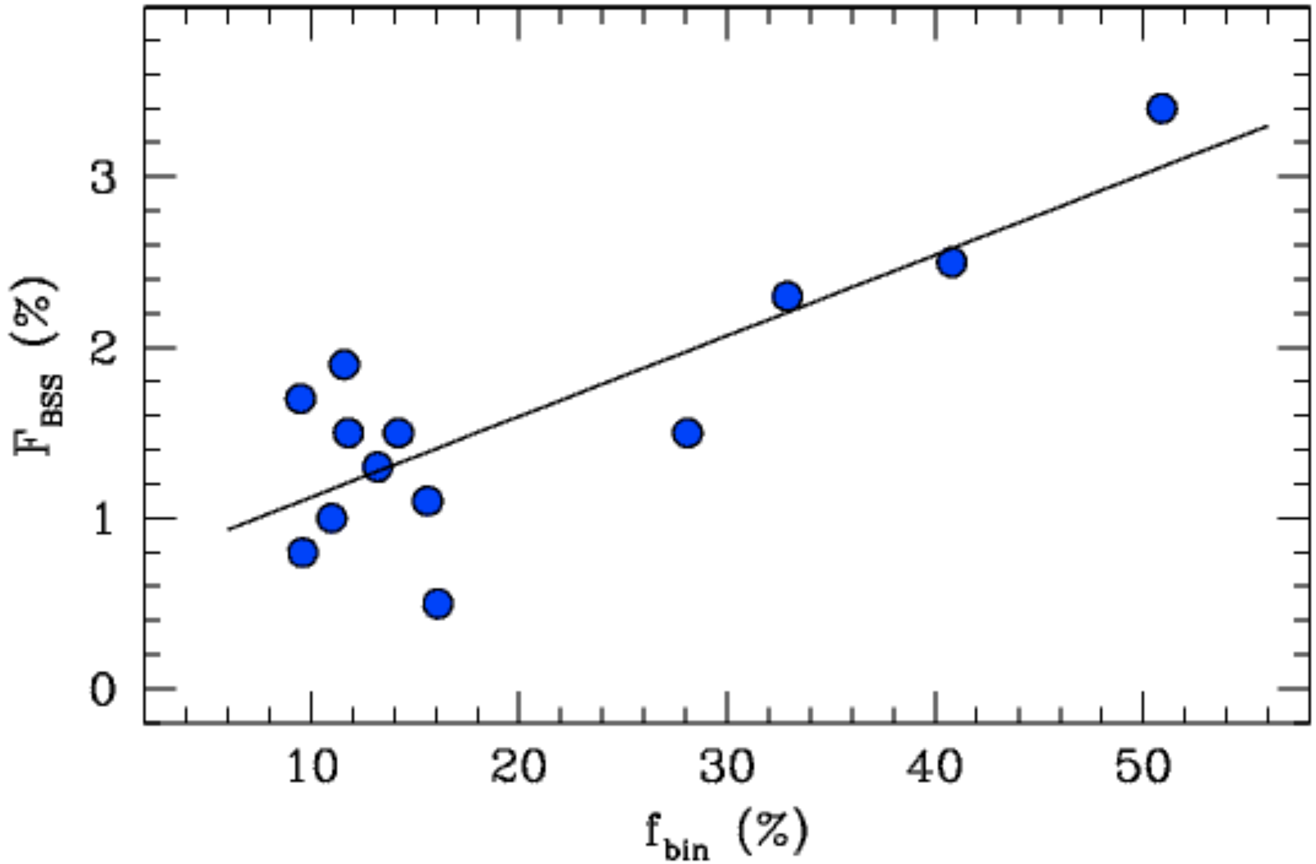
The Binary fraction in 13 low-density clusters from ACS-HST observations



Sollima et al (2007, MNRAS, 380,781)

BSS & binary fraction

A strong correlation between BSS and the binary fraction has been found in 13 low-density (Log ρ <2.5)clusters



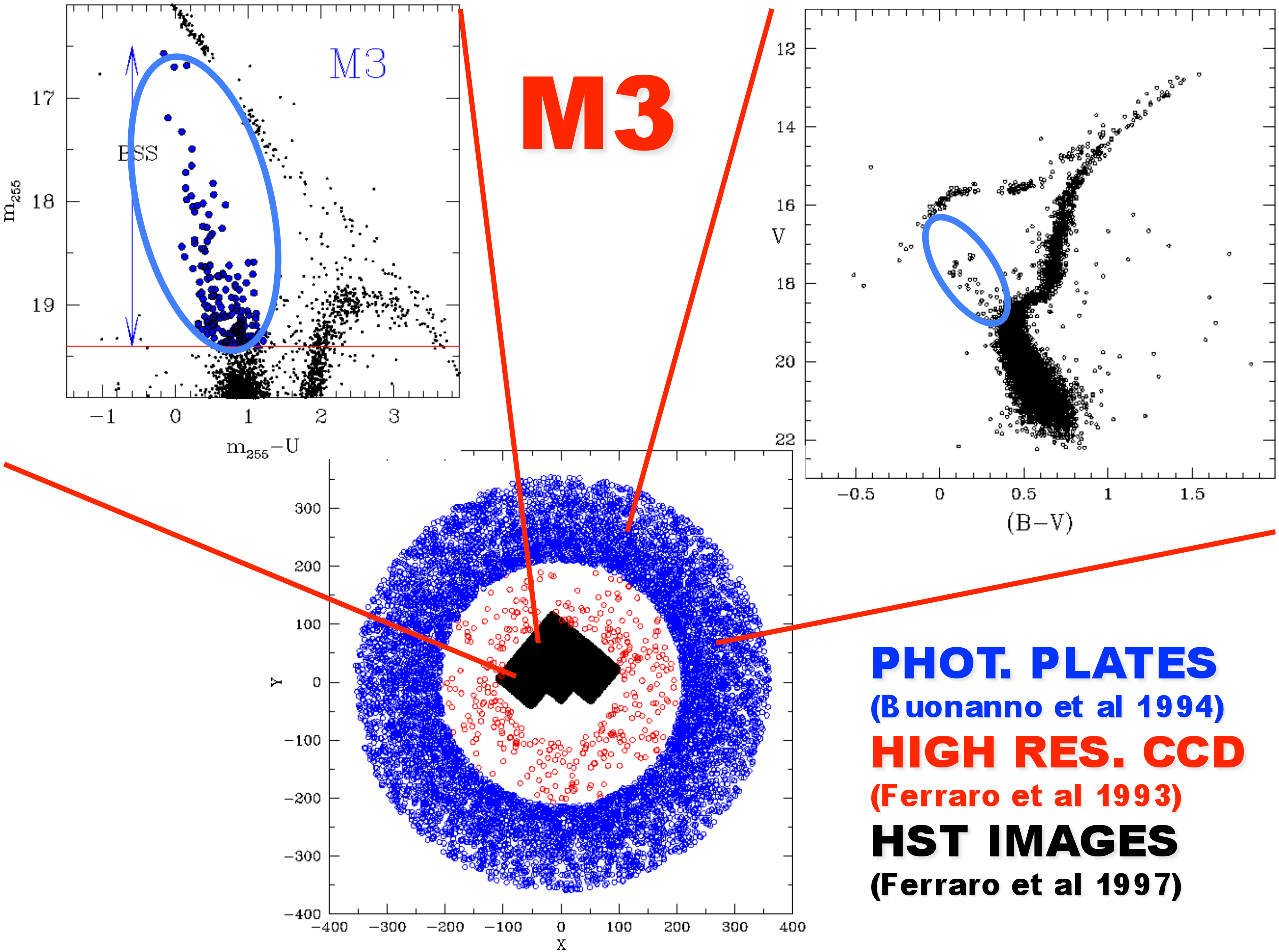
Sollima et al (2008, A&A, 481,701)

Most PB-BSS !!!

The BSS radial distribution

The population of BSS in the <u>central</u> region of clusters is only part of the story: in fact the <u>global</u> BSS radial distribution contains important signatures of the cluster dynamical evolution

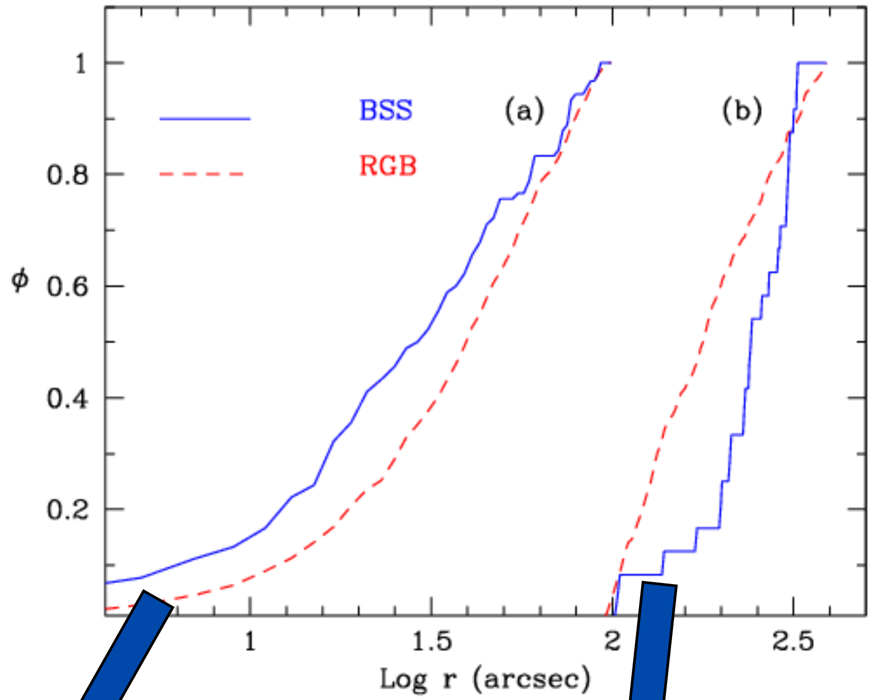
M3



PHOT. PLATES
(Buonanno et al 1994)
HIGH RES. CCD
(Ferraro et al 1993)
HST IMAGES
(Ferraro et al 1997)

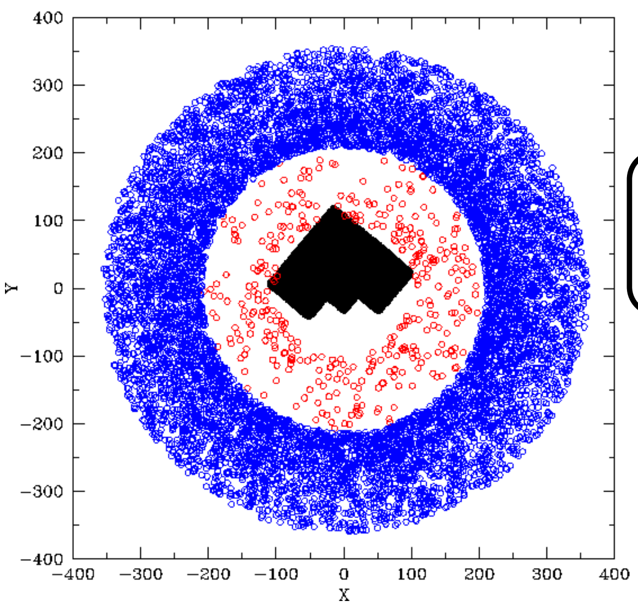
M3 : The first surprise

The first complete coverage of the entire the cluster extension



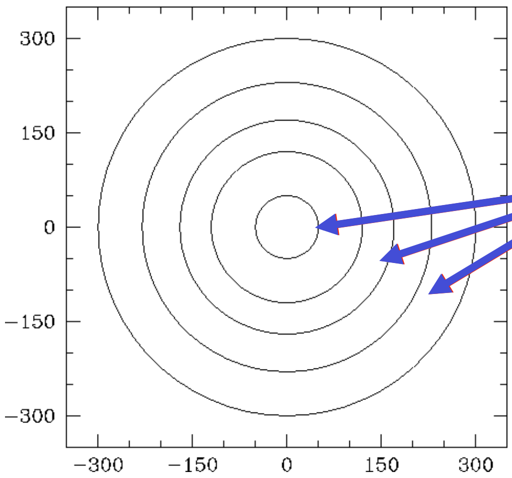
BSS are more concentrated in the central region

BSS are less concentrated in the external region



BSS in M3

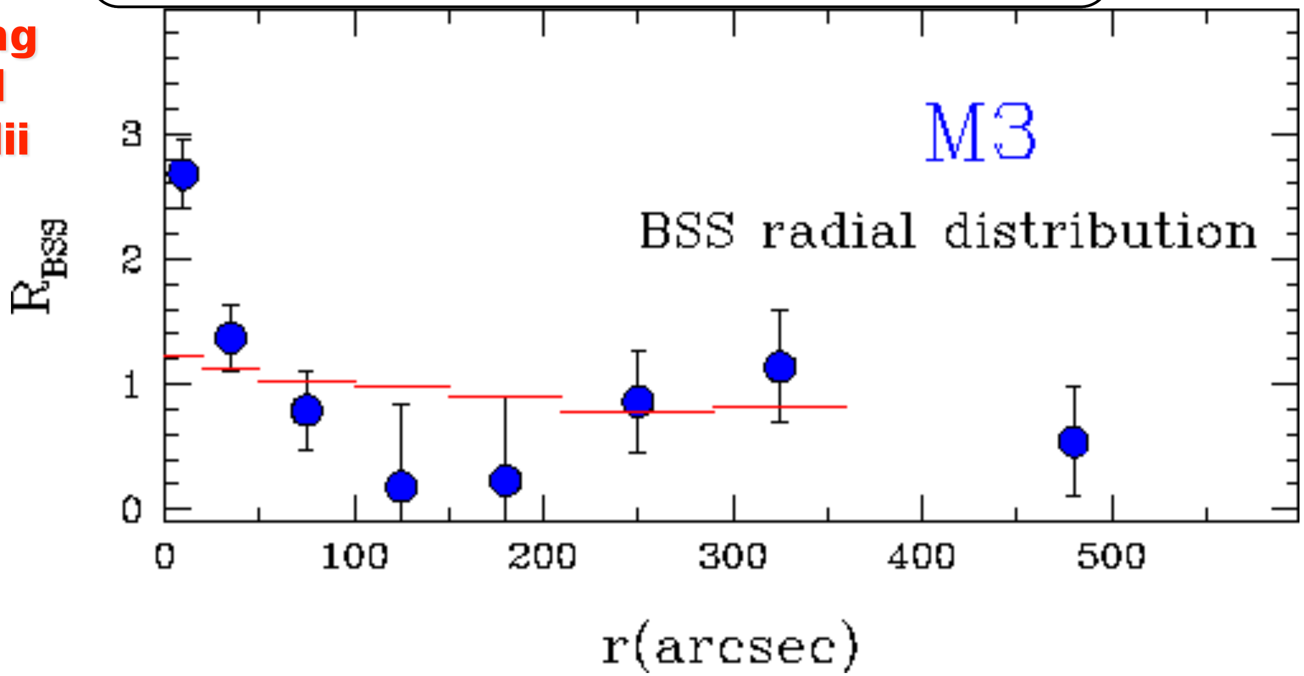
The first complete coverage of the entire cluster extension



$$R_{BSS} = \frac{N_{BSS}/N^{TOT}}{L_S/L_{TOT}}$$

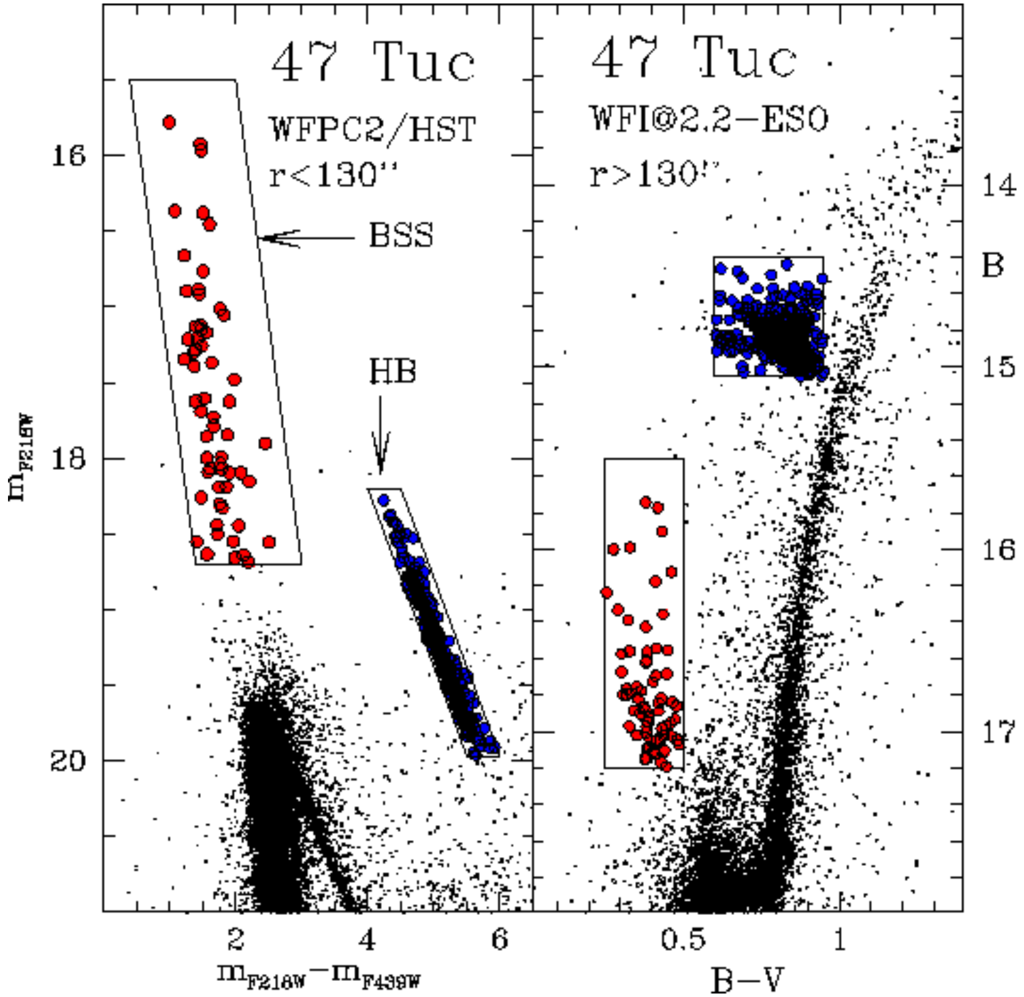
Highly peaked in the center, rapidly decreasing at intermediate radii and rising again at larger radii

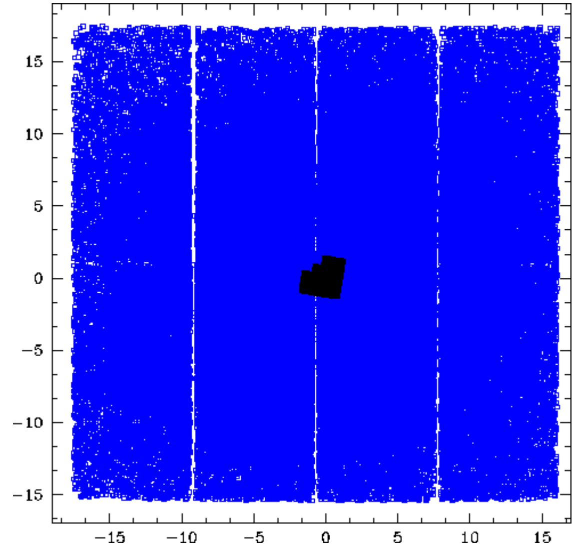
The BSS radial distribution is BIMODAL

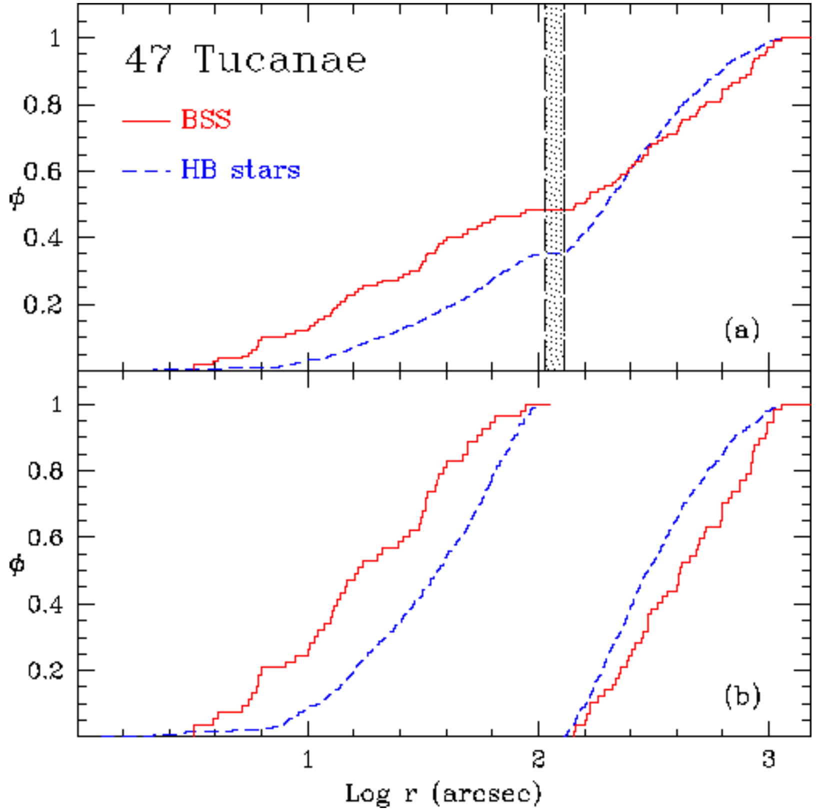


Is this distribution really "peculiar" & unique ?

BSS radial distribution: 47 Tuc

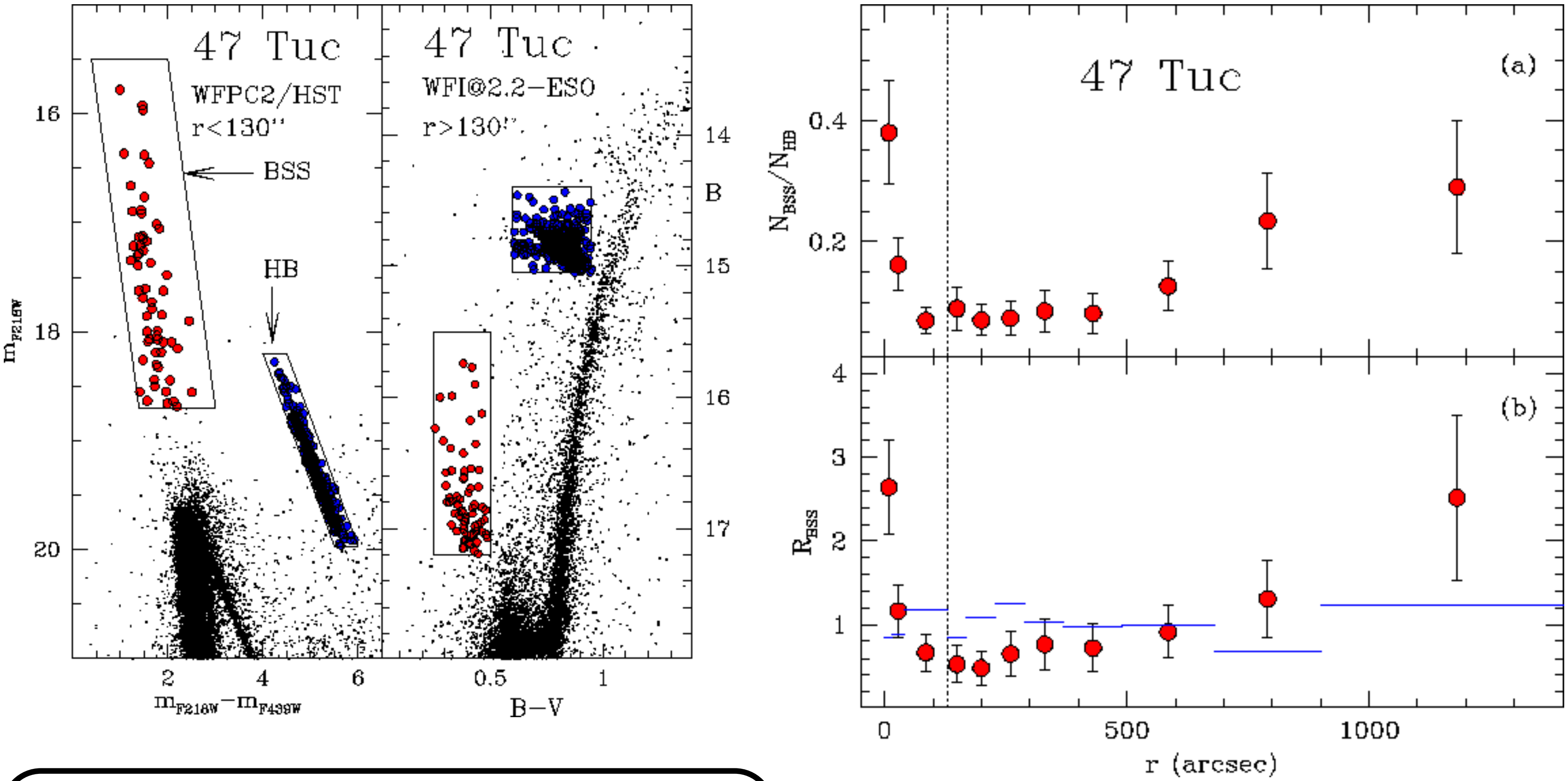






47 Tuc: another surprise!!!!

BSS radial distribution



The BSS radial distribution in 47 Tuc is quite similar to that observed in M3

Is this the "natural" BSS radial distribution?

METHODOLOGY :

HST High-Resolution (UV + optical): cluster central regions

+

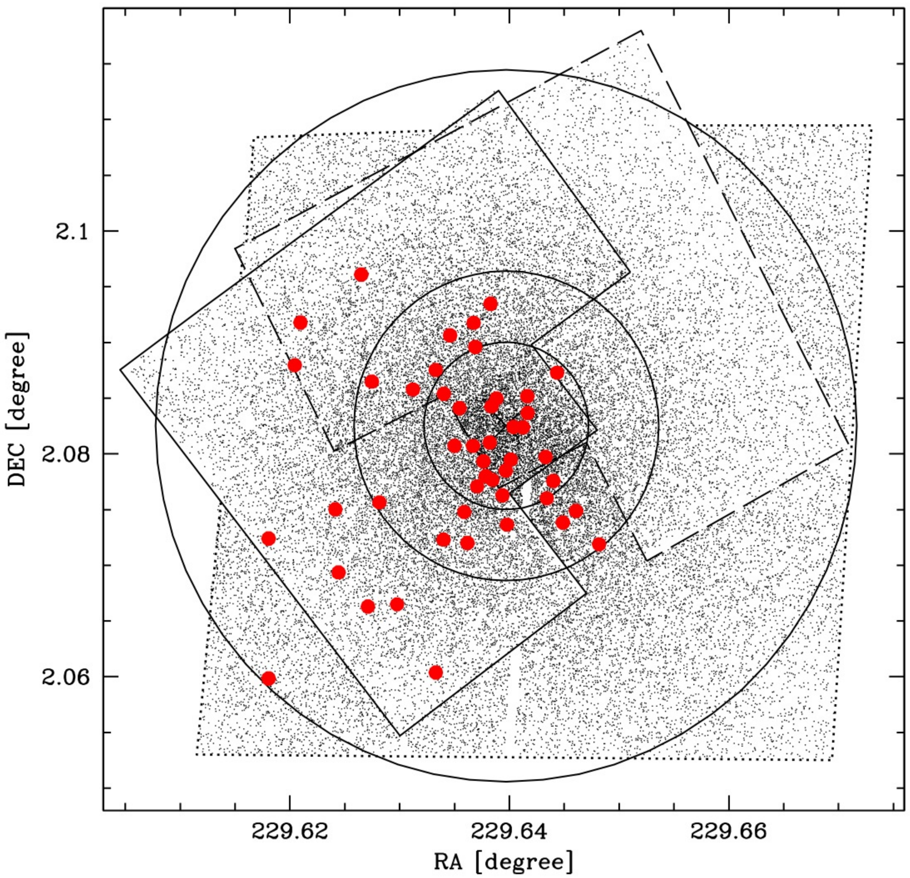
Wide-Field observations: cluster outskirts

- ✓ **ground-based (optical bands)**
- ✓ **GALEX satellite (UV)**

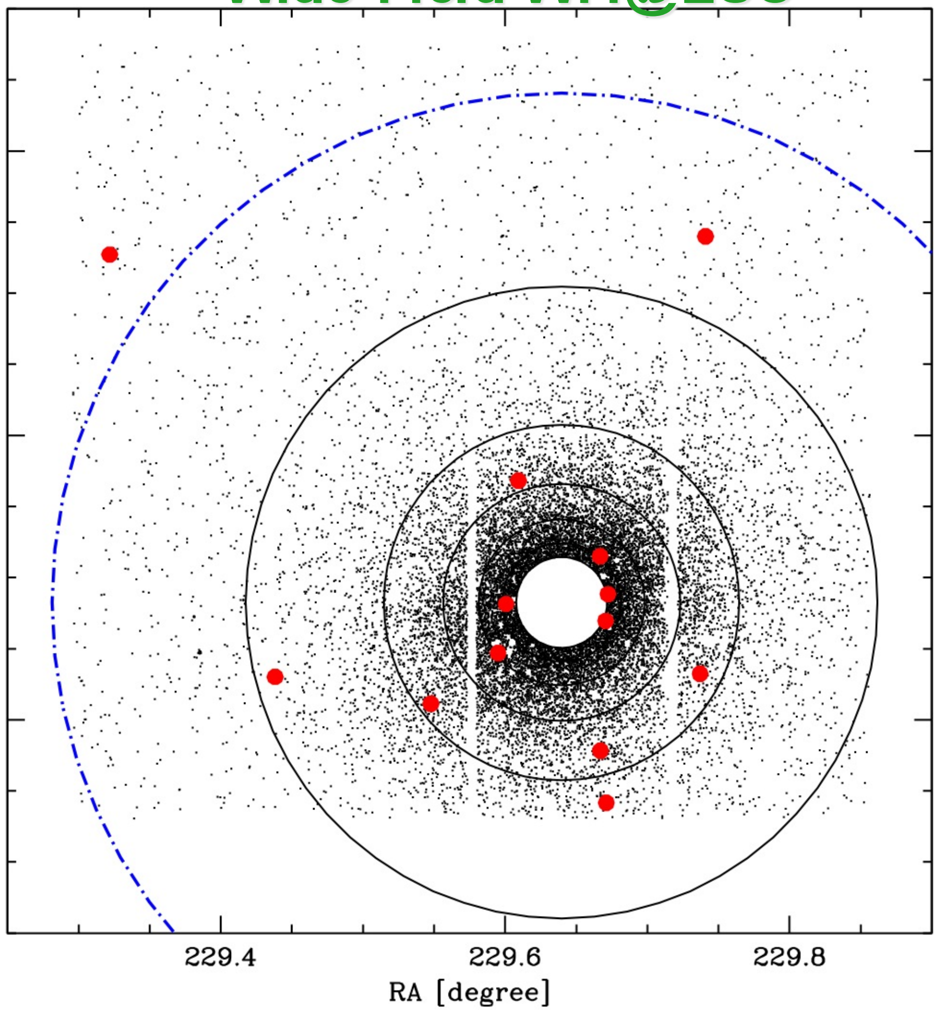
M5 (NGC5904)

BSS radial distribution

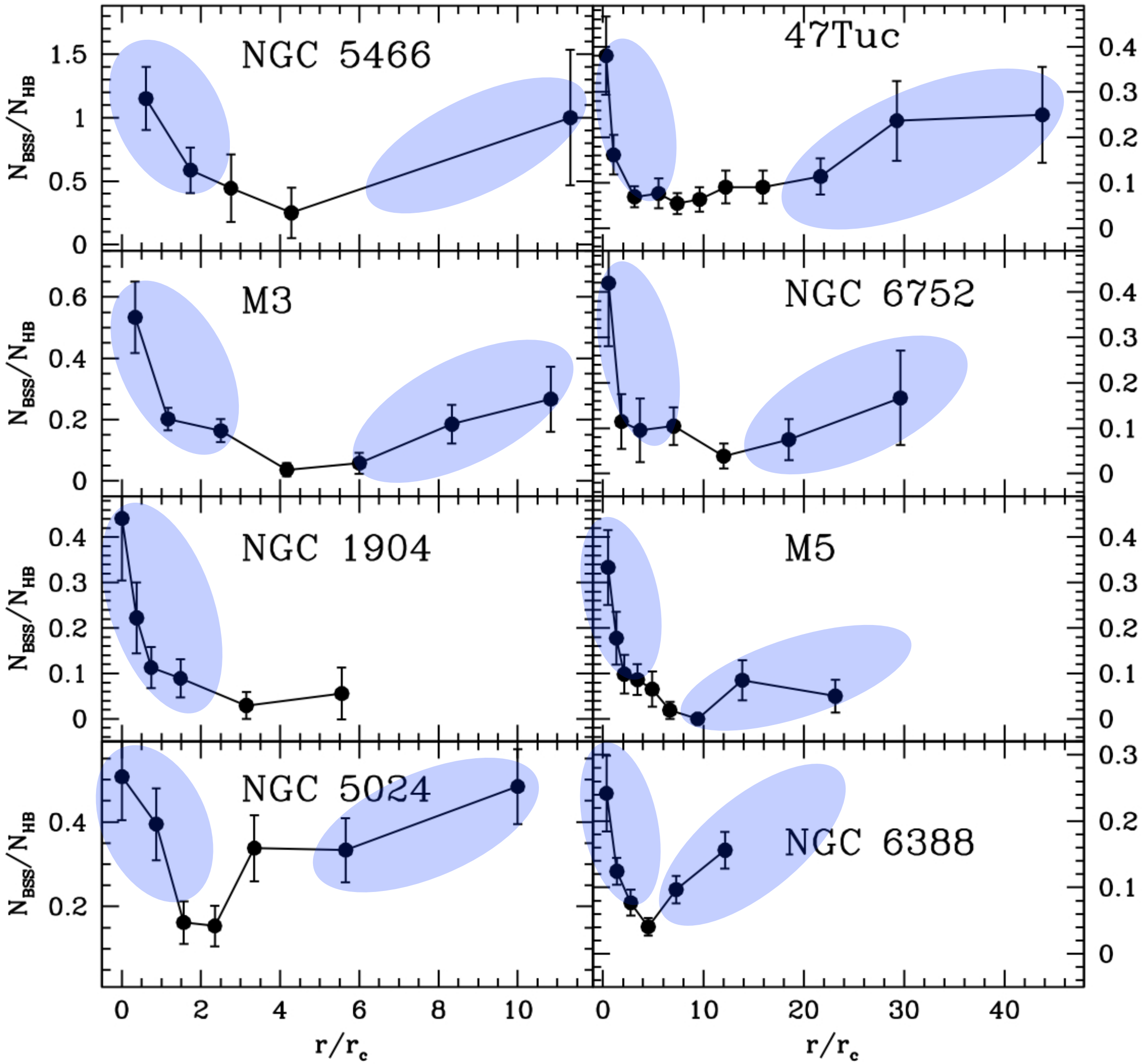
High-Res WFPC2+ACS HST



Wide-Field WFI@ESO

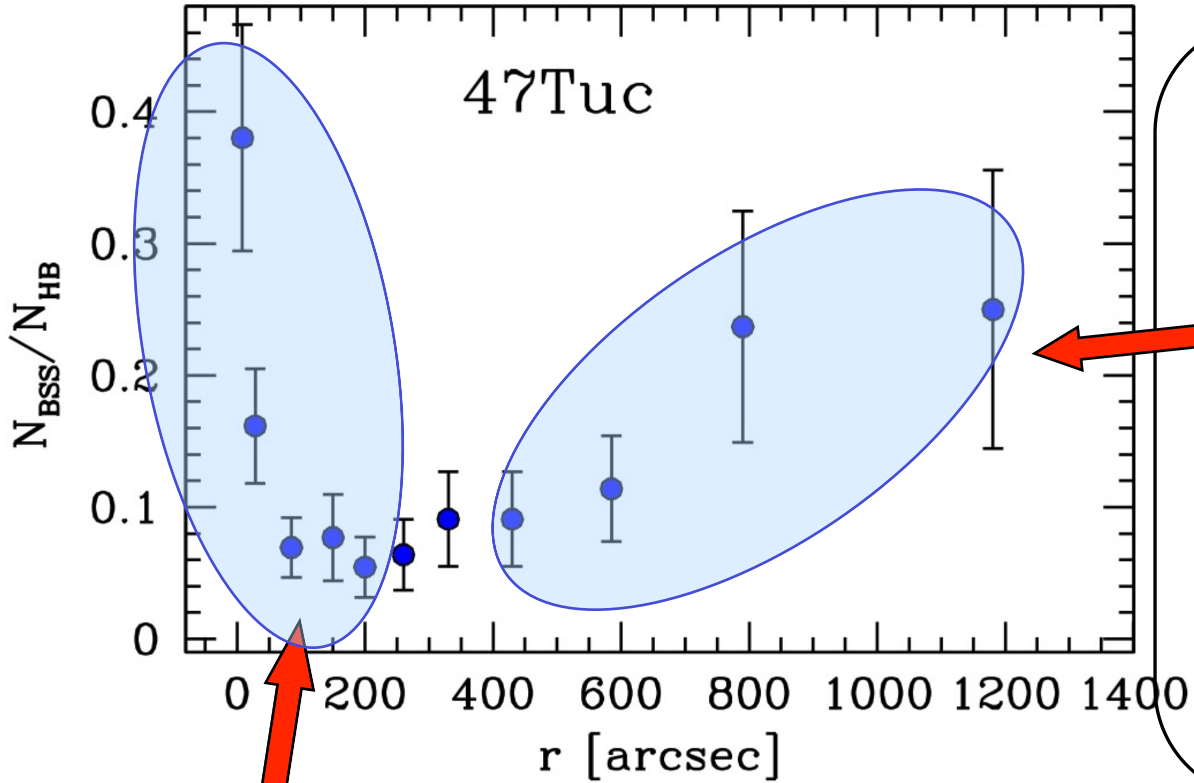


BIMODAL/PEAKED BSS radial distributions



Ferraro et al. (93, 94, 04); Sabbi et al. (04), Lanzoni et al. (07ab); Dalessandro et al. (2008); Beccari et al. (08, 09)

BIMODAL radial distribution



COL-BSS
kicked off
from the cluster
core

or

PB-BSS

?

COL-BSS
or
PB-BSS sunk to the centre
by mass segregation

?

Radius of avoidance

r_{avoid} = radius within which all stars of $M \sim M_{BSS}$ have sunk into the cluster centre in a time comparable to the cluster age because of dynamical friction:

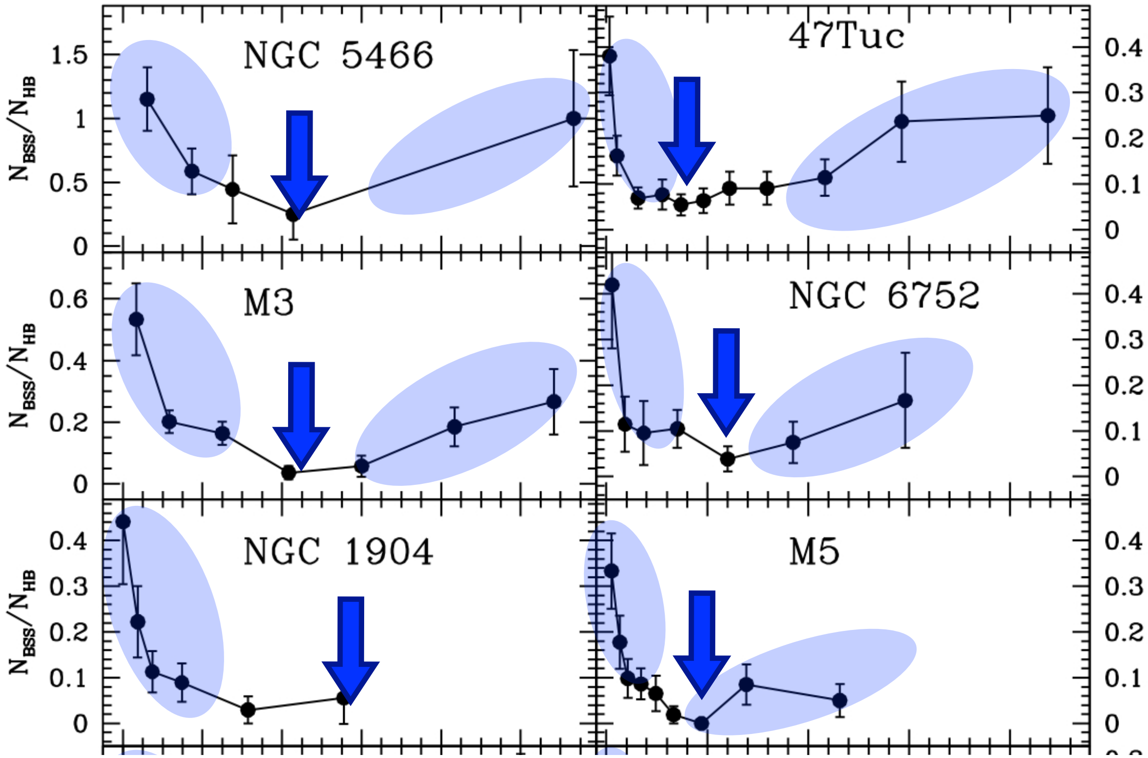
$$t_{df}(r_{avoid}) = \frac{3\,\sigma^3(r)}{4\,\ln\Lambda\, G^2\, (2\pi)^{1/2}\, M_{BSS}\, \rho(r)} = t_{AGE}$$

where:

M_{BSS} = 1.2 Msol

t_{AGE} = 12 Gyr

$\rho(r)$, $\sigma(r)$ from best-fit King model of the observed nb. dens. profile

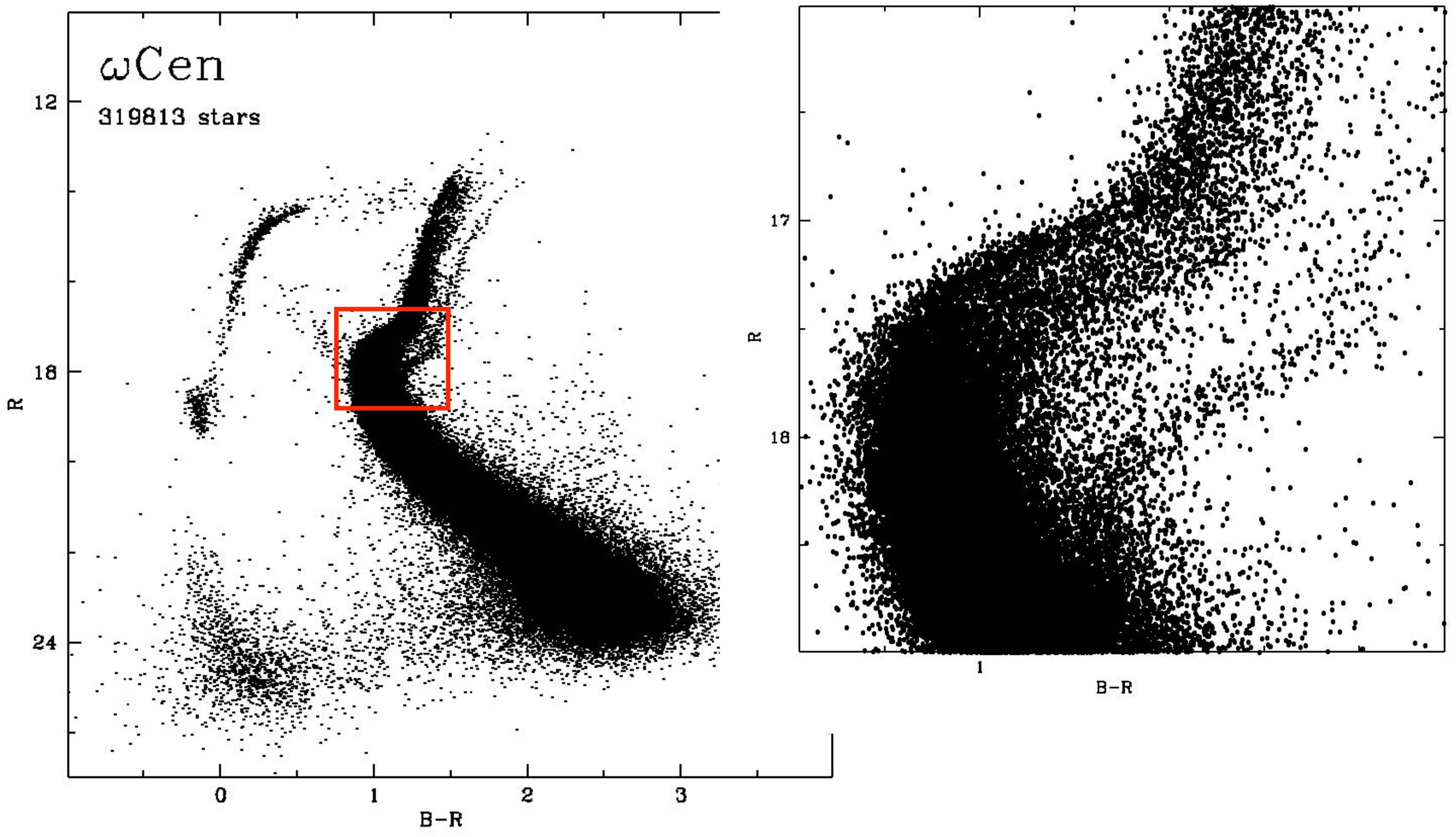


r_{avoid}

position of the observed minimum

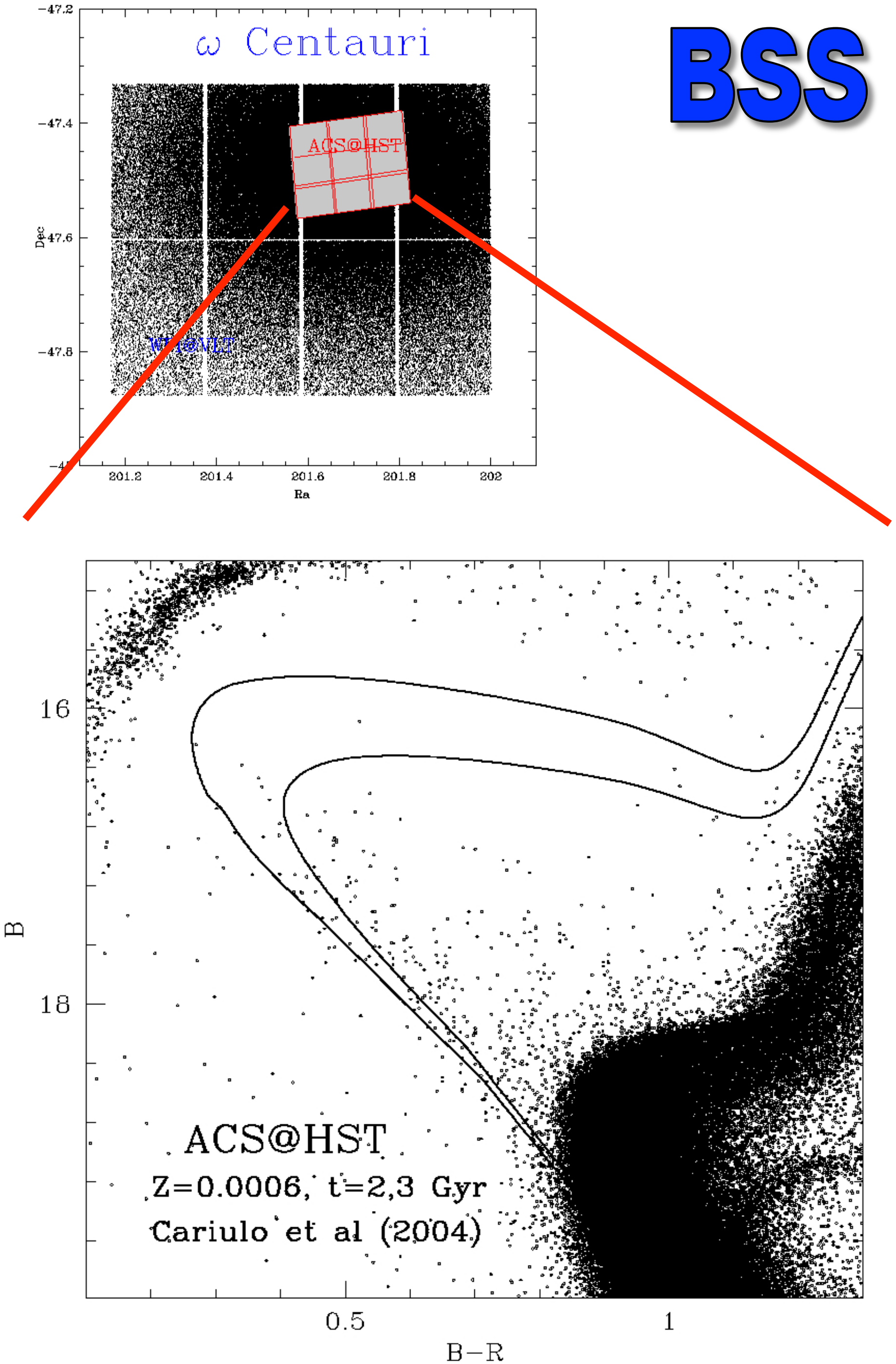
Important signatures of the dynamical evolution of the parent cluster imprinted in the BSS radial distribution?

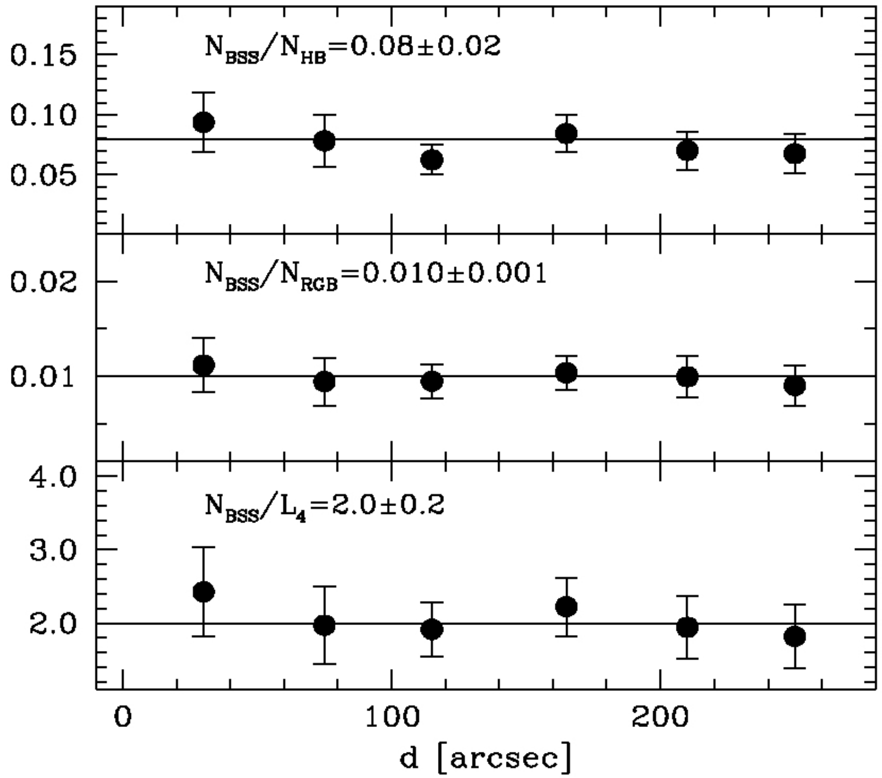
Omega Centauri



Ferraro et al. 2004

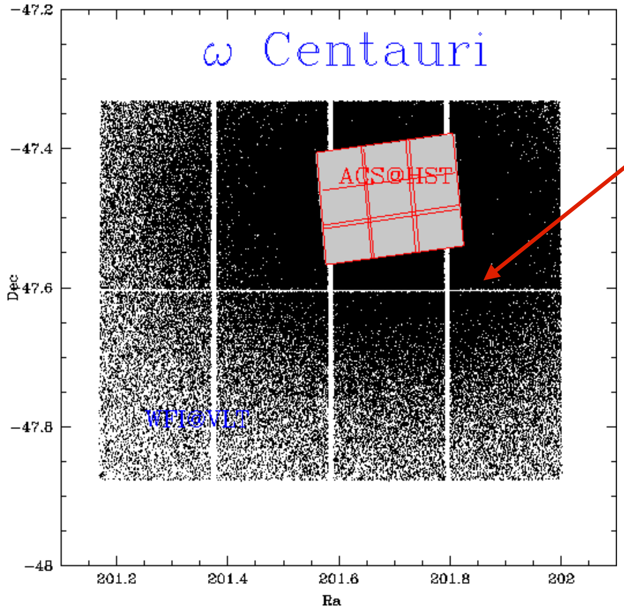
BSS radial distribution





ω Centauri: NO evidence of mass segregation!!!!

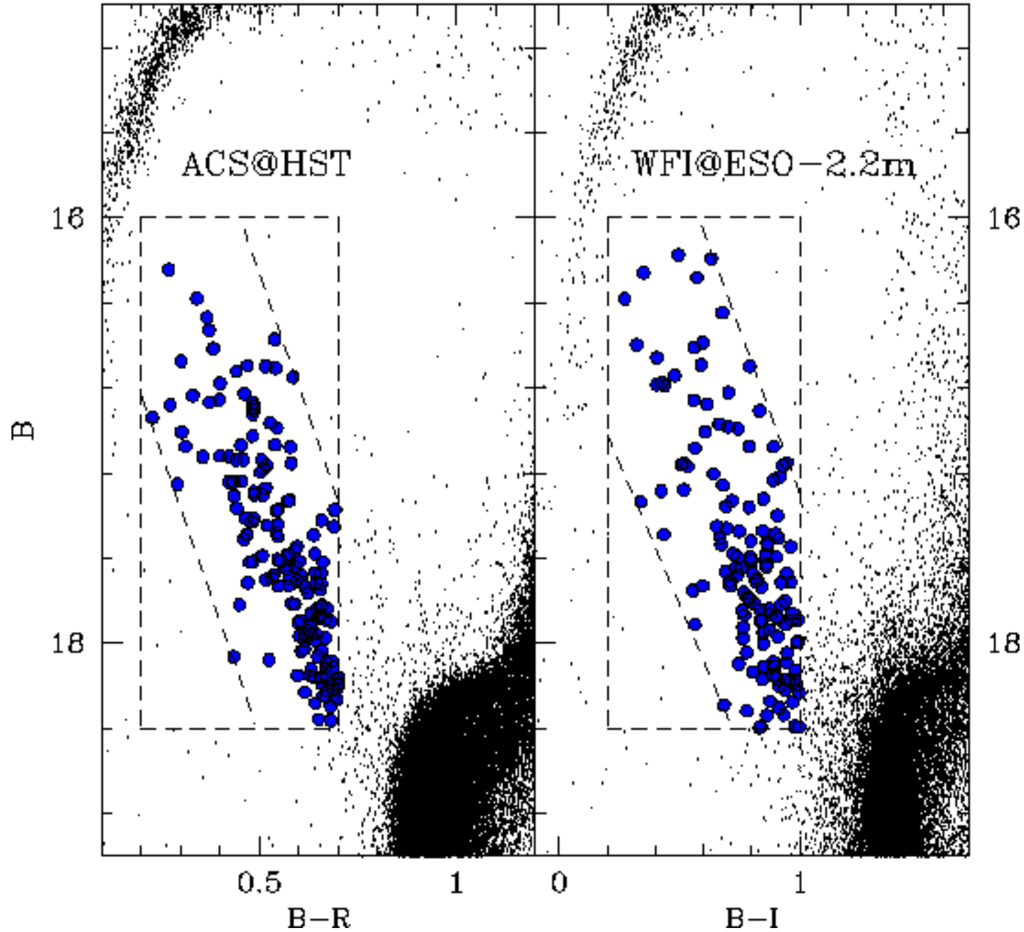
This is the cleanest evidence that the system is not completely relaxed even in the central region.

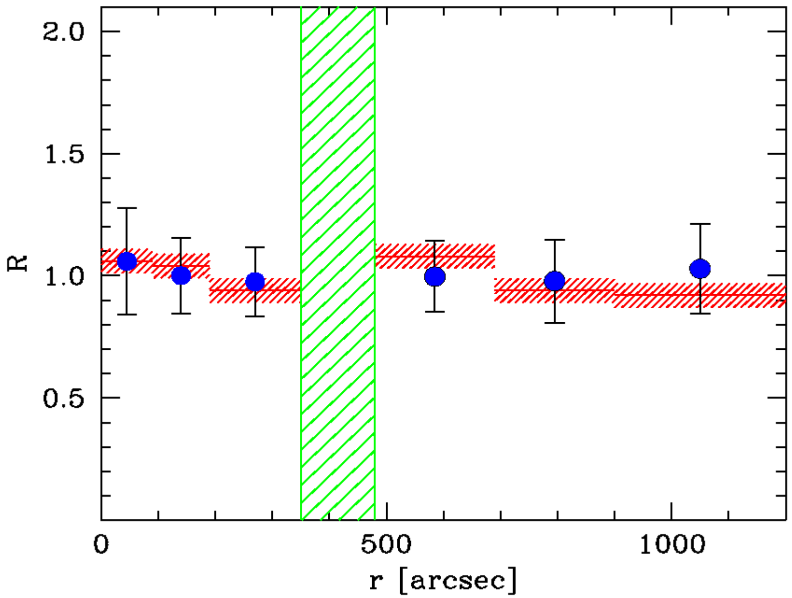


wide-field (

HST

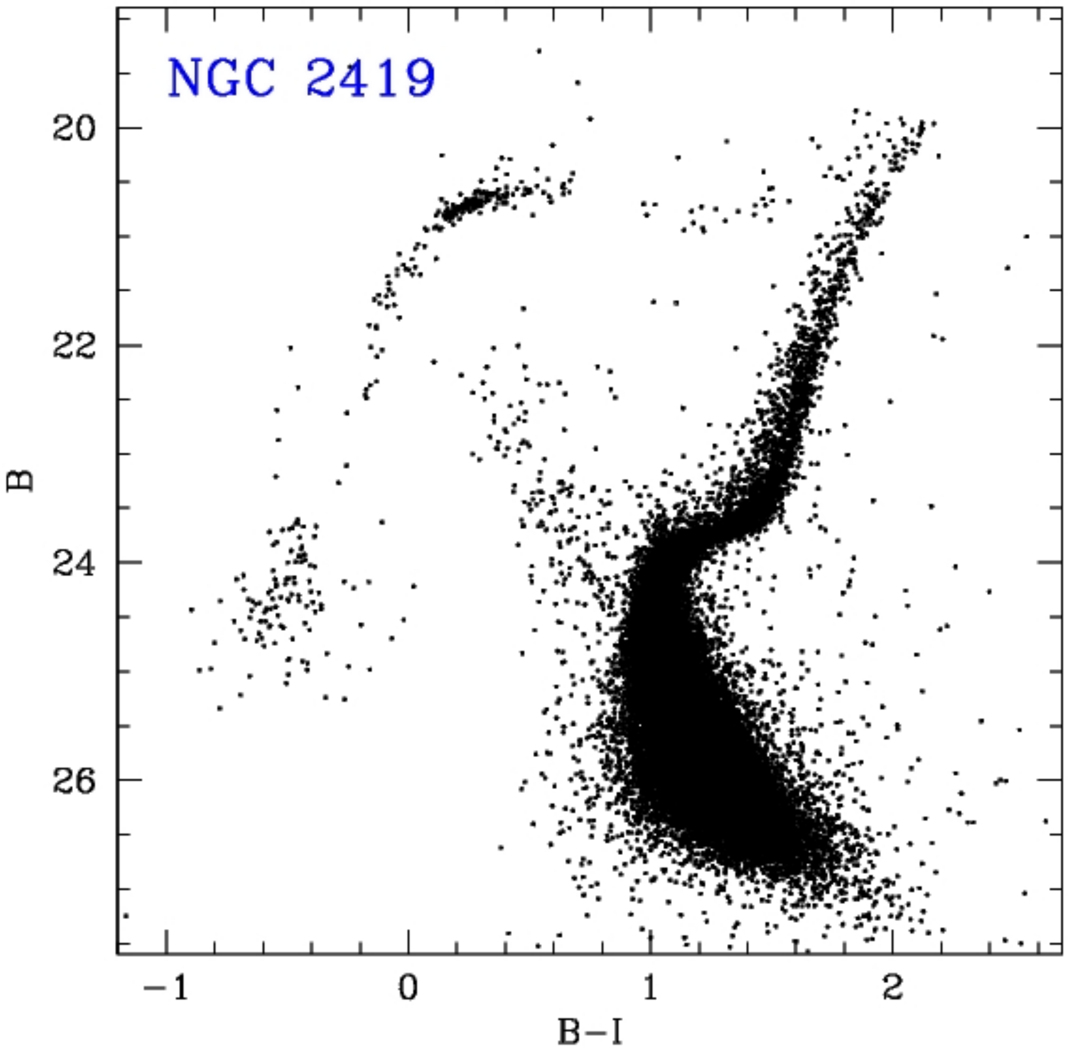
WFI

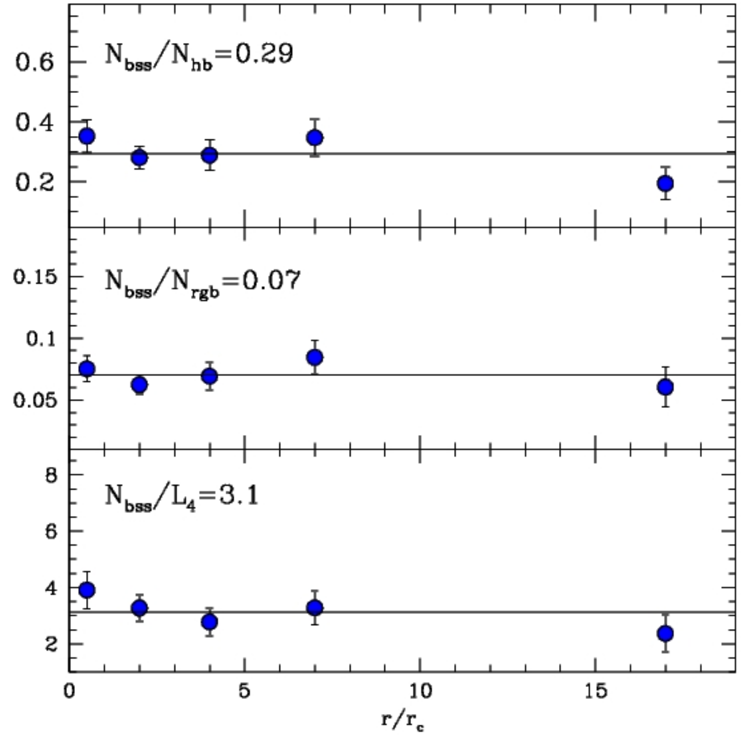




ωCentauri:
totally FLAT
BSS radial distribution!!!

NGC2419: the BSS radial distribution





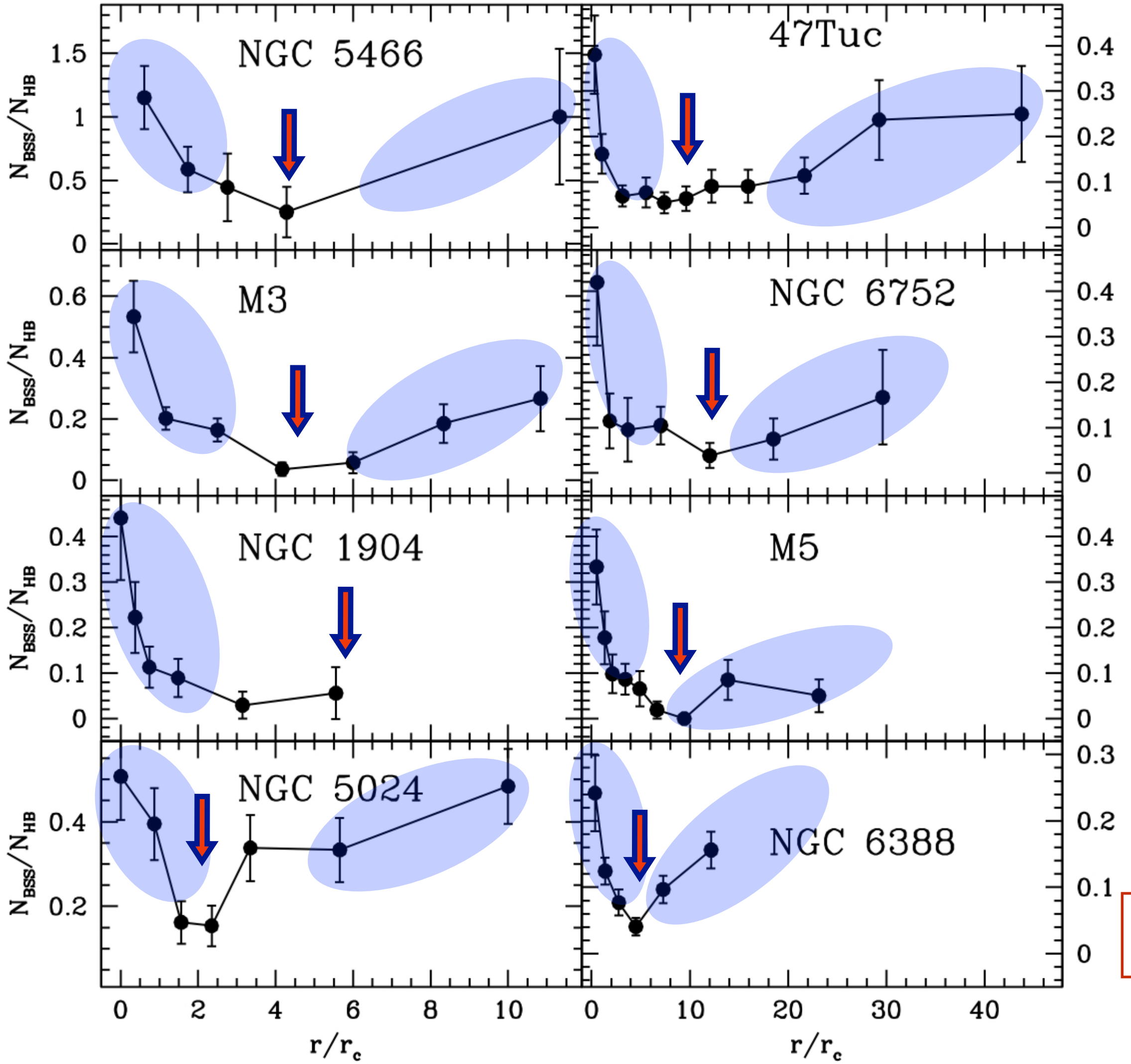
NGC2419: No evidence of mass segregation!!!!

Dalessandro et al (2008, ApJ,681,311)

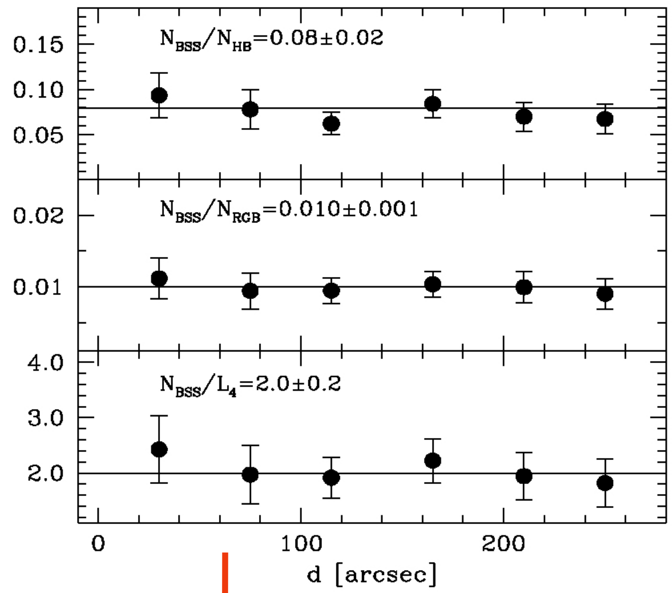
BSS radial distribution

~ 10 GCs with
bimodal/peaked distribution

dynamical friction effect



2 GCs (ωCen, NGC2419)
with FLAT distribution



not mass-segregated yet

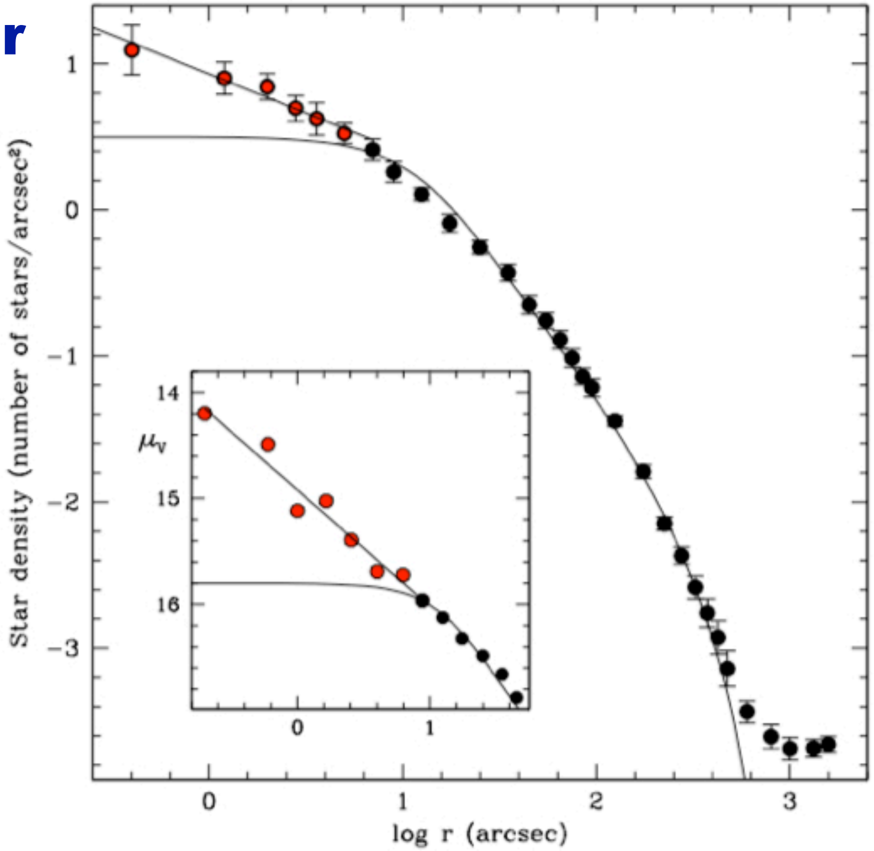
BSS can be used to measure
the dynamical evolution of star clusters

.... Indeed we can do even more....

M30 (NGC 7099)

- GC in the Halo (l=27.18°, b=-46.83°)
  (α=21^{h}40^{m}22.13^s, δ=-23°10'47.4")

- Post-core collapse (PCC) cluster



power-law central cusp:

- scale: r_{cusp} = 5" = 0.2 pc
- slope: α = -0.5

central mass density [$M_\odot$ pc^{-3}]:

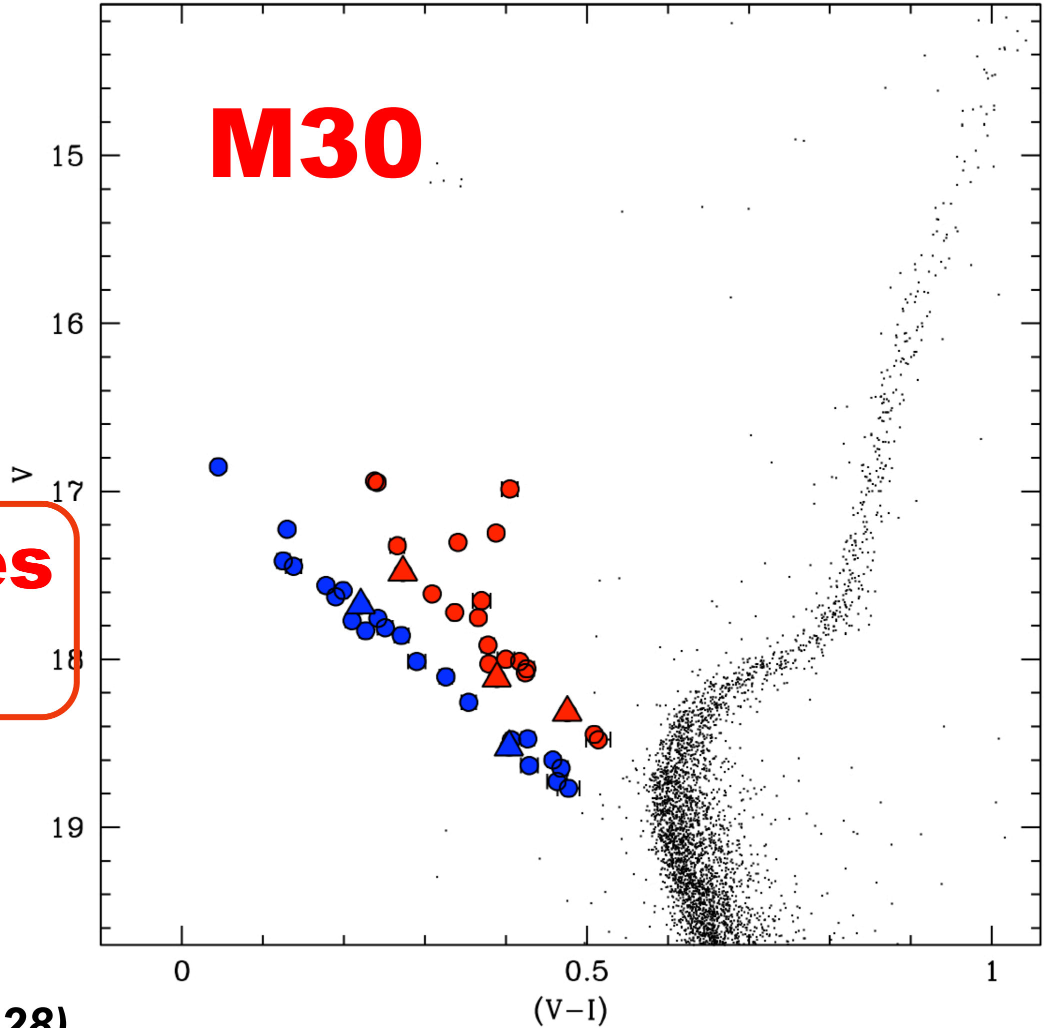
log ρ_0 = 5.48 [M pc^{-3}]

Dataset: HST/WFPC2 + HST/ACS + NTT + MegaCam/CFHT

HST/WPC2 dataset (1999, GO7379, PI: Edmonds)

- 22 images in filter F814W (I)
- 22 images in filter F555W (V)

photometric error
≤ 0.1 mag
both in col and mag
at the BSS level



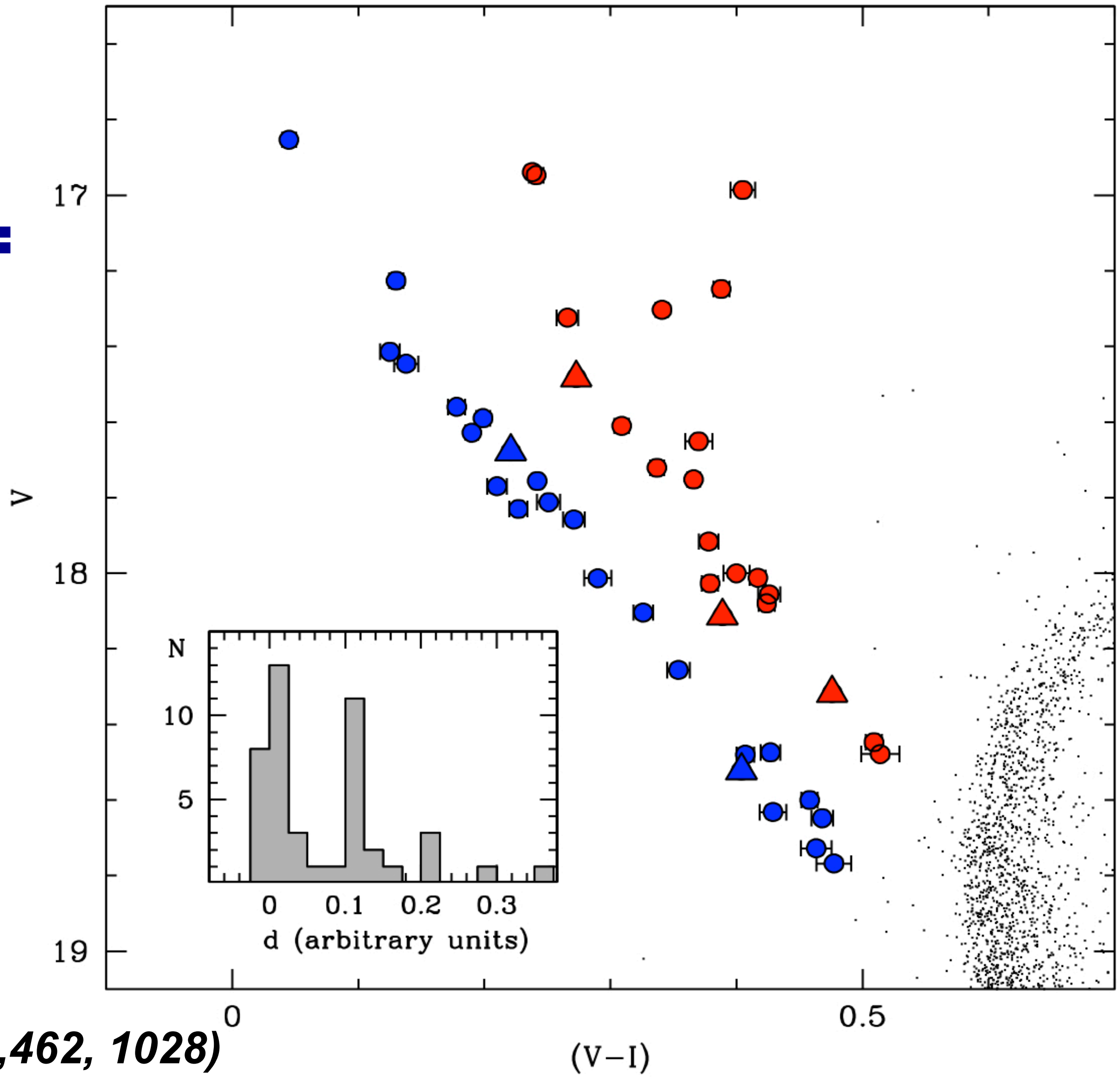
2 distinct sequences of BSS !!

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

2 distinct sequences of BSS

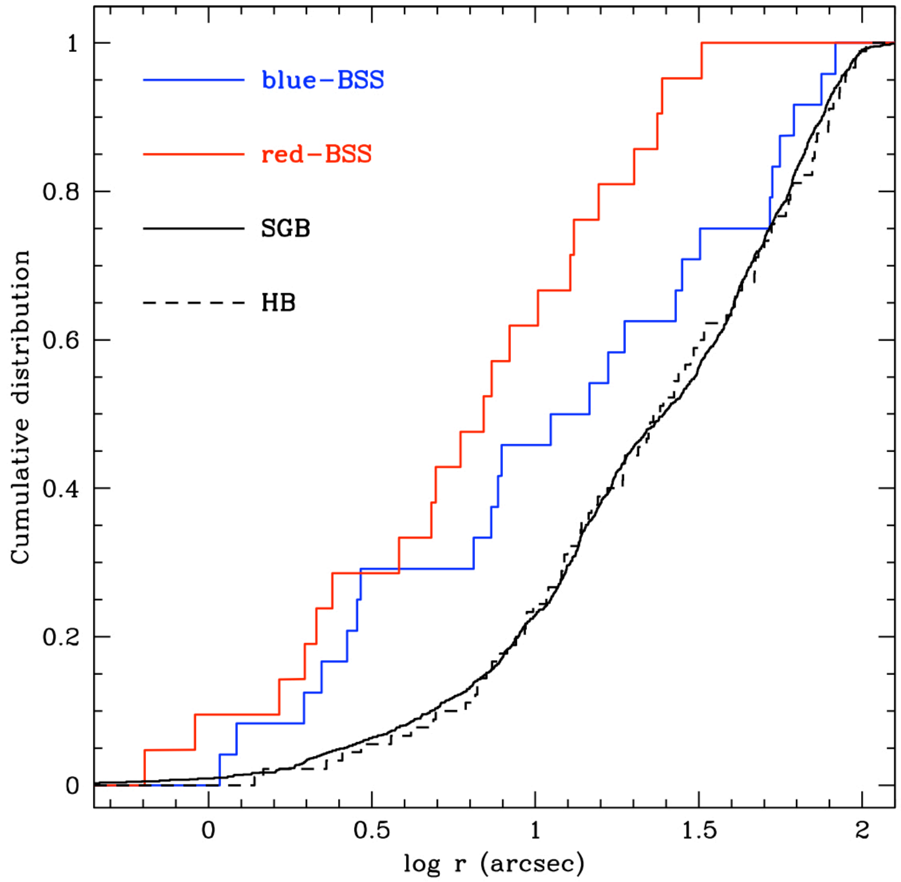
- **similarly populated:**
  24 blue-BSS
  21 red-BSS

- **almost parallel:**
  ΔV ≈ 0.4
  Δ(V-I) ≈ 0.12

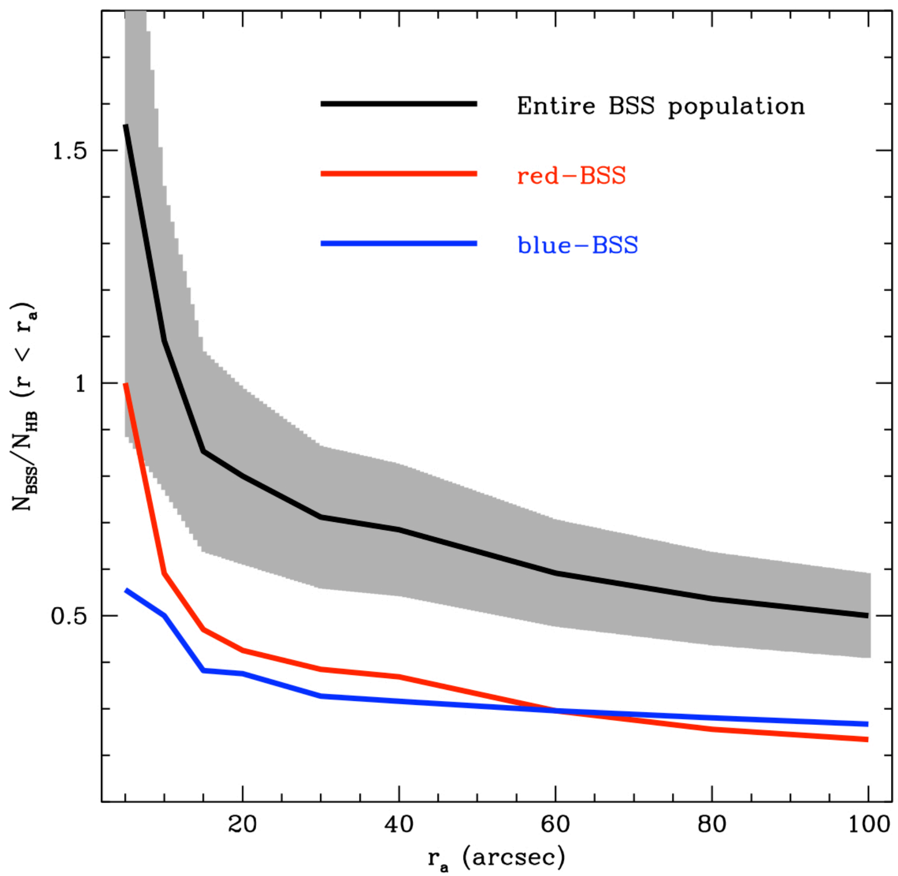


Ferraro et al. 2009(Nature,462, 1028)

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)

- BSS are more numerous than HB within the central cusp

different formation mechanism for red- and blue-BSS?

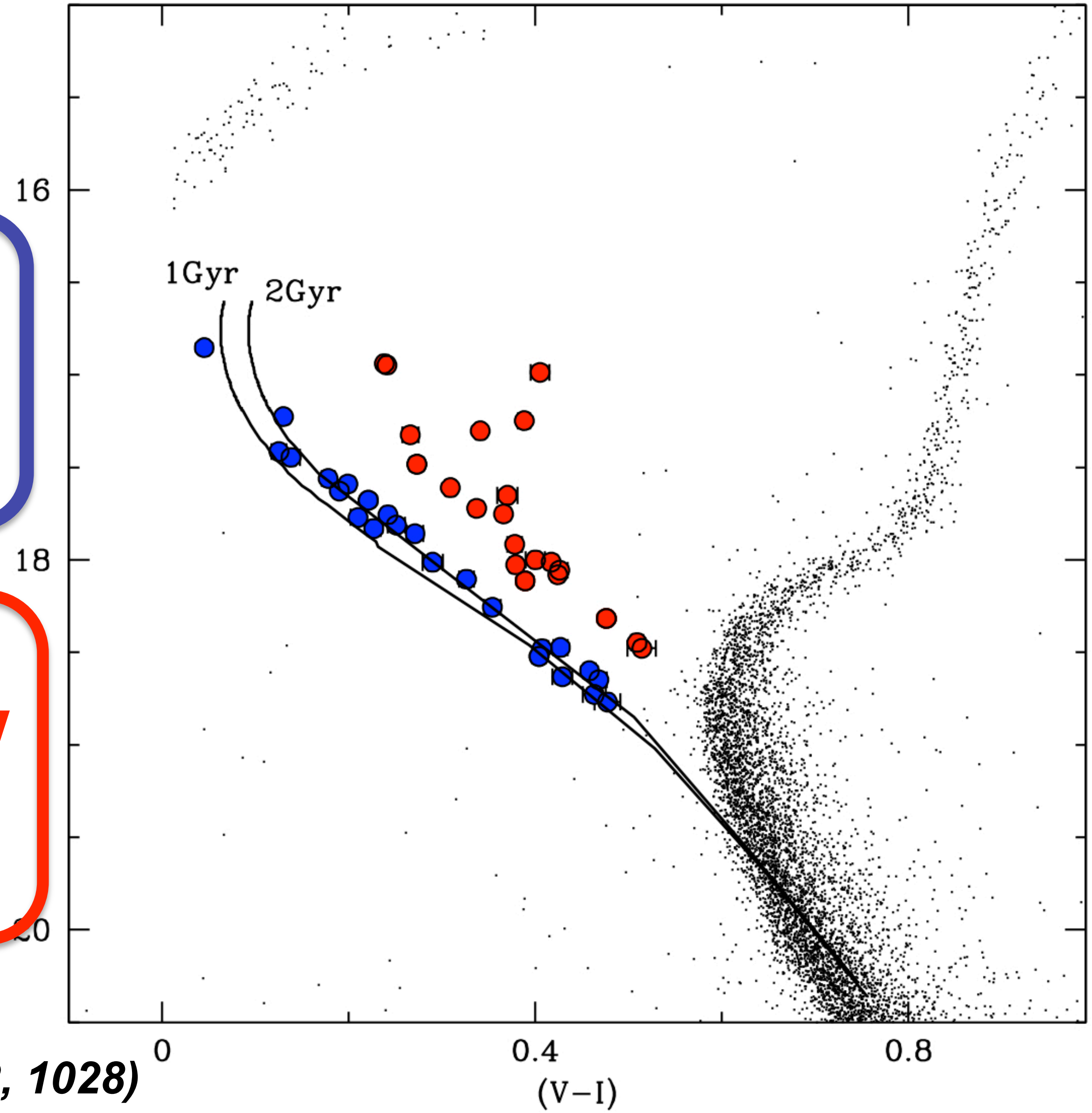
Evolutionary models of COL-BSS

(Sills et al. 2009, 692, 1411):

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

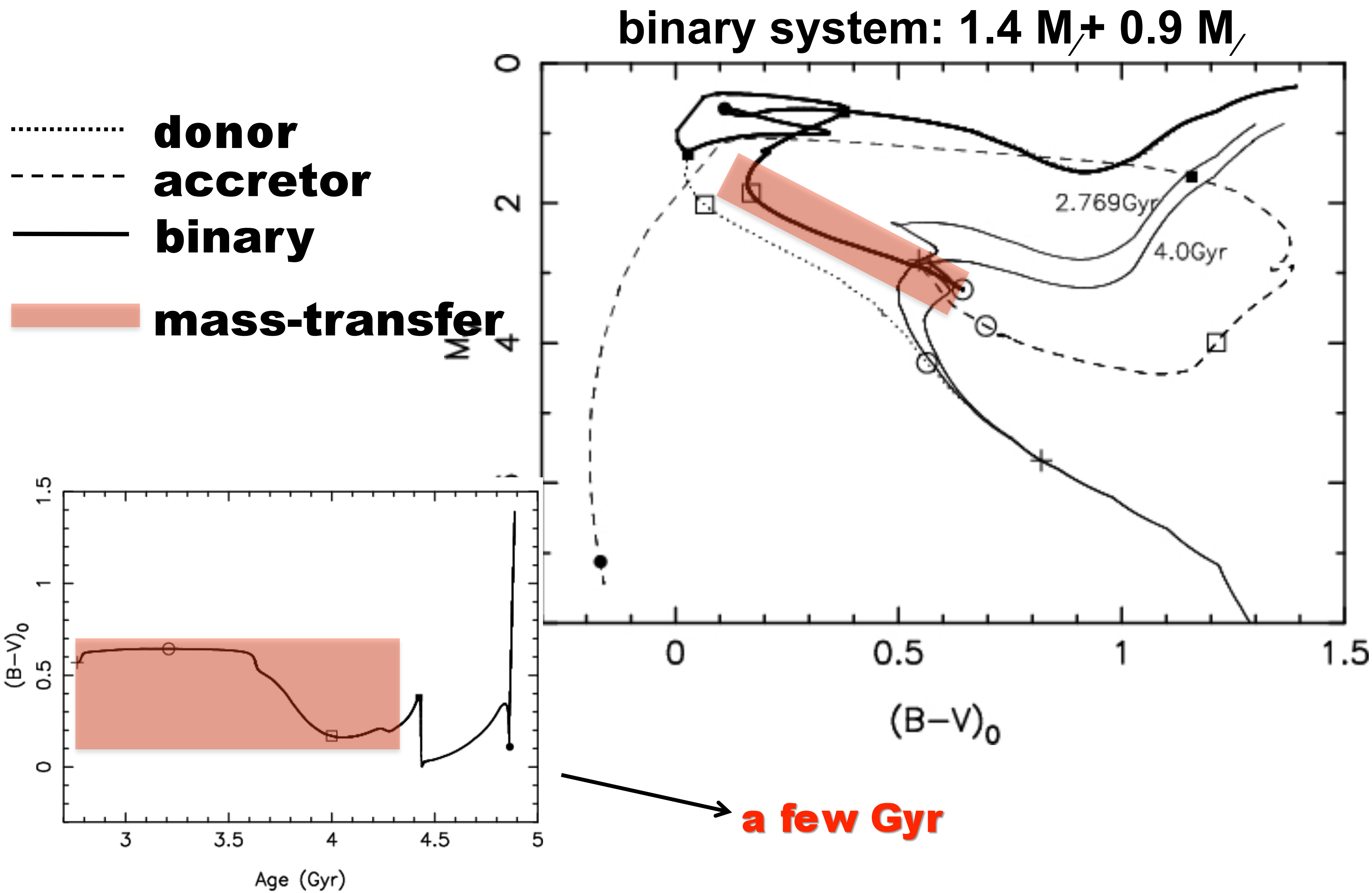
- **blue-BSS sequence well reproduced by collisional isochrones of 1-2 Gyr**

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



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

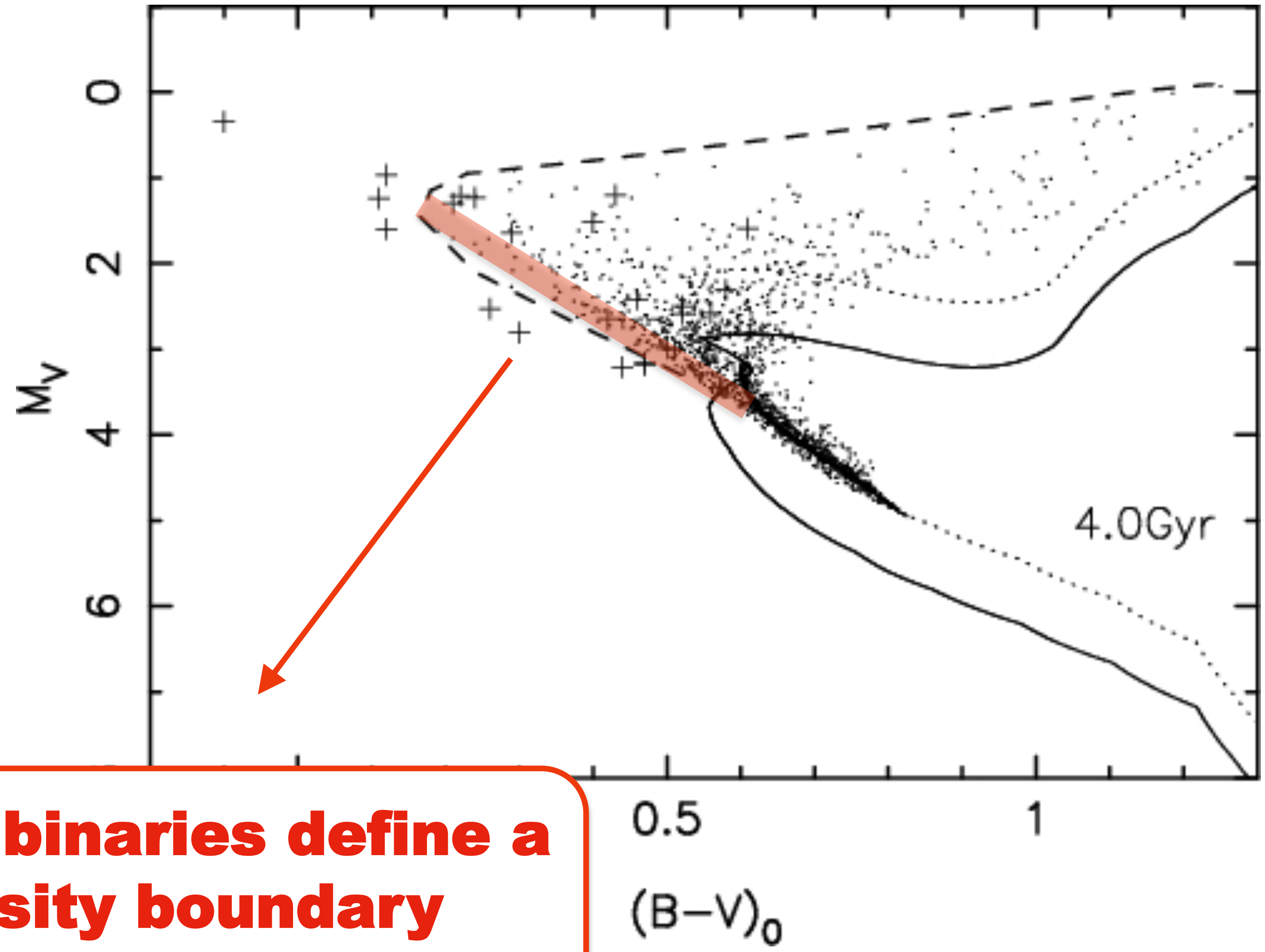
Binary evolution models (Tian et al. 2006, A&A 455, 247):



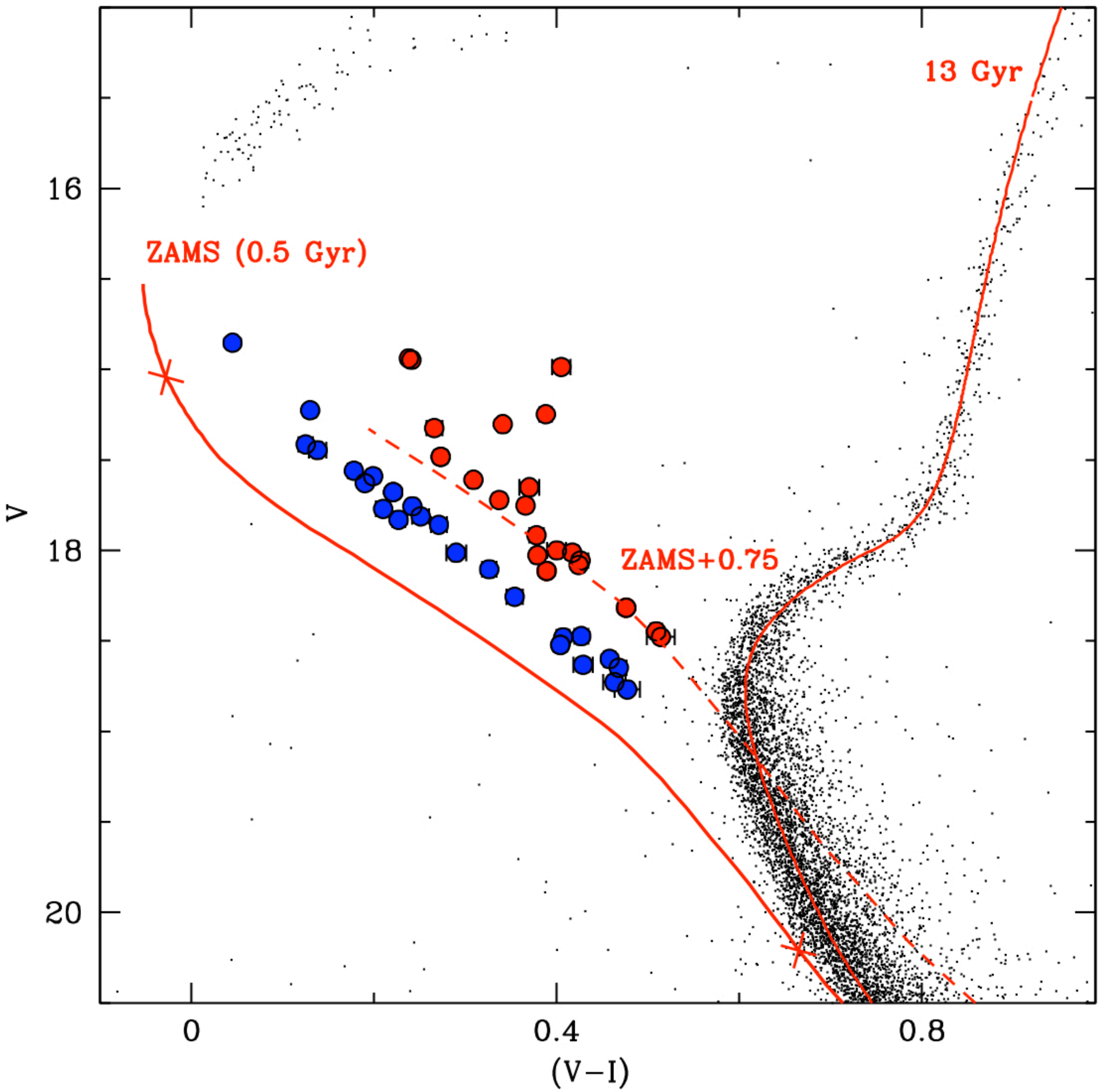
a few Gyr

Binary evolution models (Tian et al. 2006, A&A 455, 247):

Monte-Carlo simulation for a population of binaries

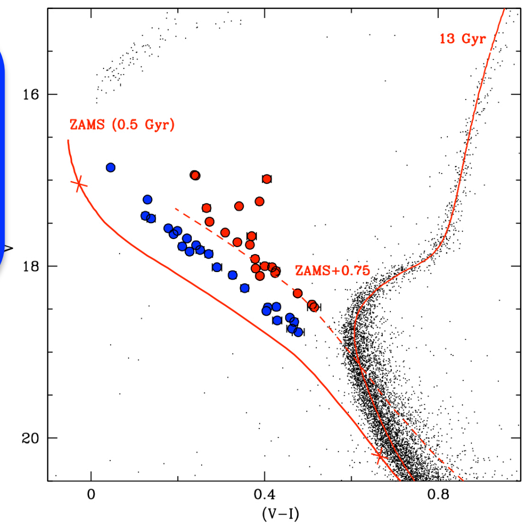


mass-transfer binaries define a low-luminosity boundary ~0.75 mags brighter than ZAMS



13 Gyr
ZAMS (0.5 Gyr)
ZAMS+0.75
16
18
20
V
0
0.4
0.8
(V−I)

- **blue-BSS are COLL-BSS**



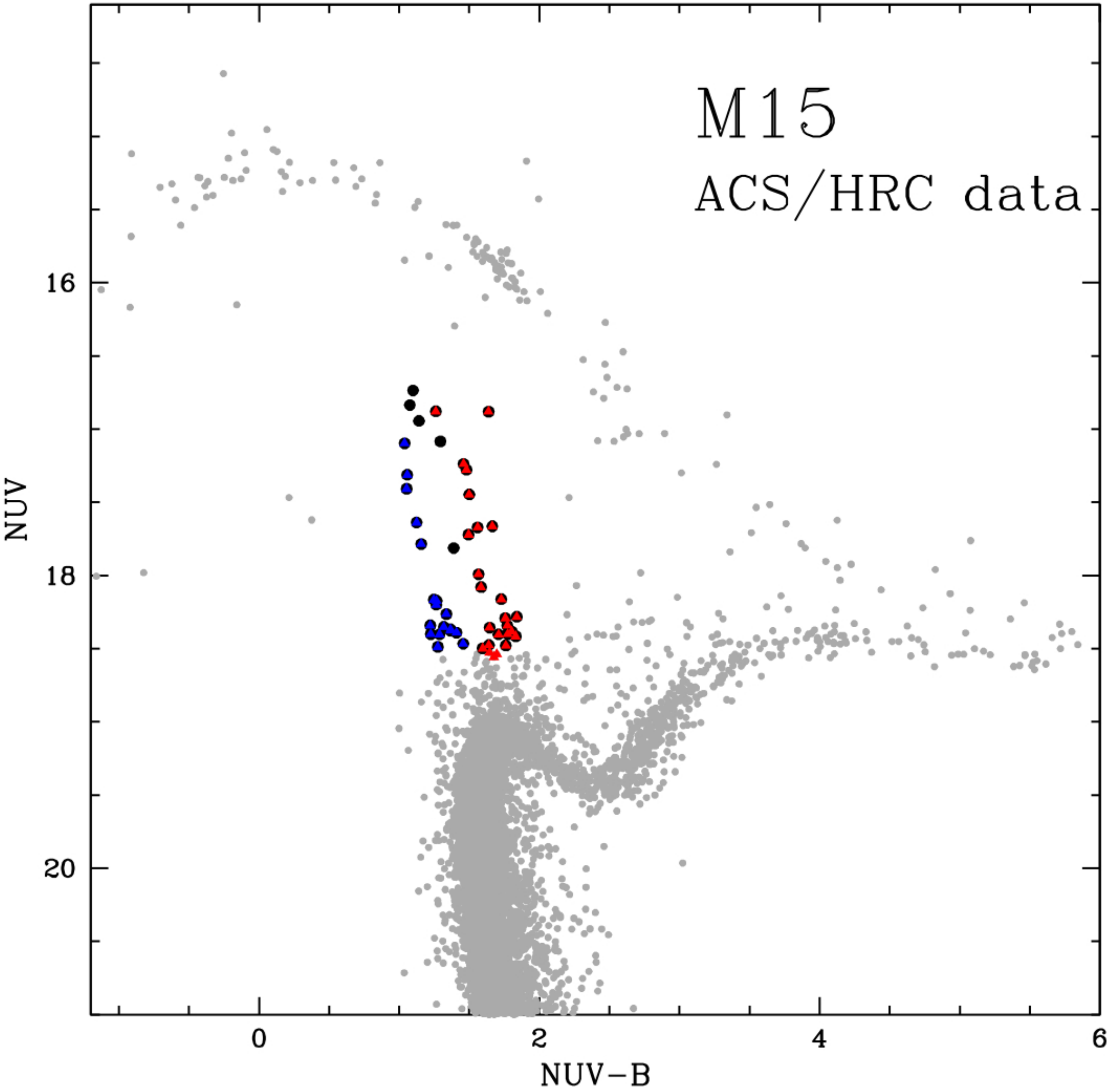
- **red-BSS are MT-BSS**

The fact that we see two distinct sequences suggests that they have been generated by a recent (1-2 Gyr) short-lived event (the CC event?).

In a few Gyrs the evolution of the COLL-BSS will populate the region between the sequences

The double BSS sequence is the signature of the PCC event, that 1-2 Gyr ago increased the stellar interactions and produced (1) the population of COLL-BSS & (2) favoured the formation of MT-BSS

The double BSS sequences in M30 open (for the very first time) the possibility of using the BSS to date the occurrence of the CC event !!!



The double sequence =
Signature of the CC imprinted on the BSS pop

BSS chemical properties

Searching for chemical signatures of the formation mechanism on the surface of BSS

How to distinguish COL-BSS from PB-BSS?

ROTATION: **controversial predictions about COL-BSS**

COL-BSS are FAST rotators
(Benz & Hills 1987)

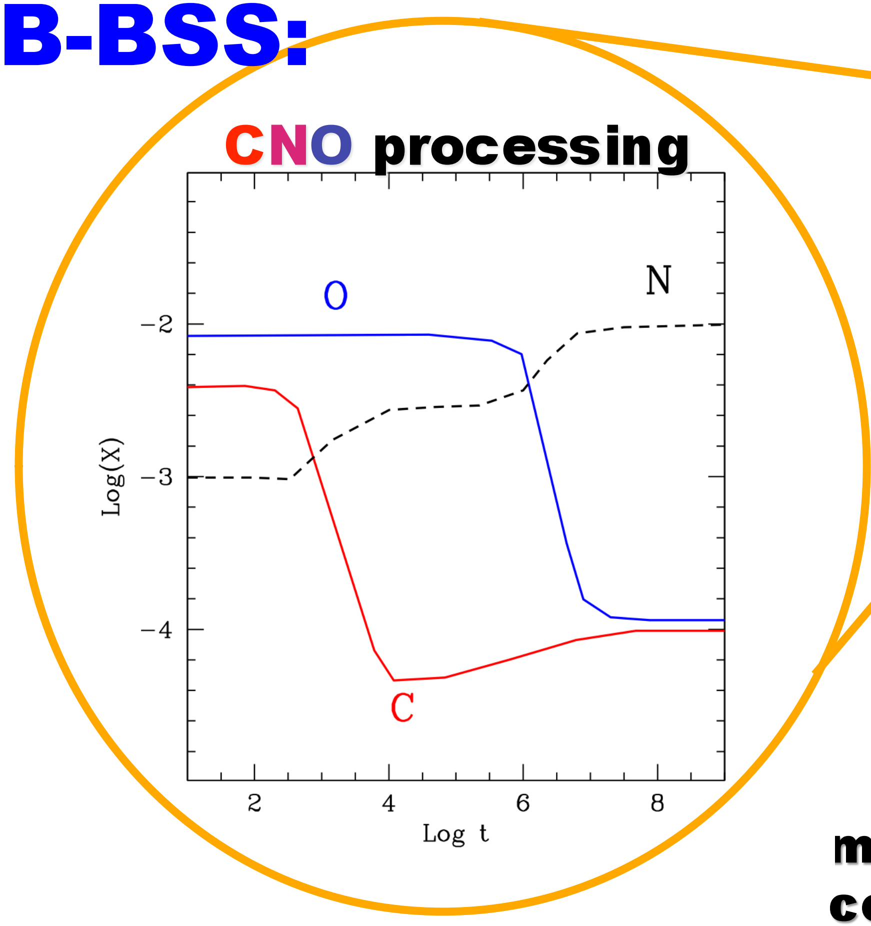
COL-BSS are NOT FAST rotators
(Leonard & Livio 1995)

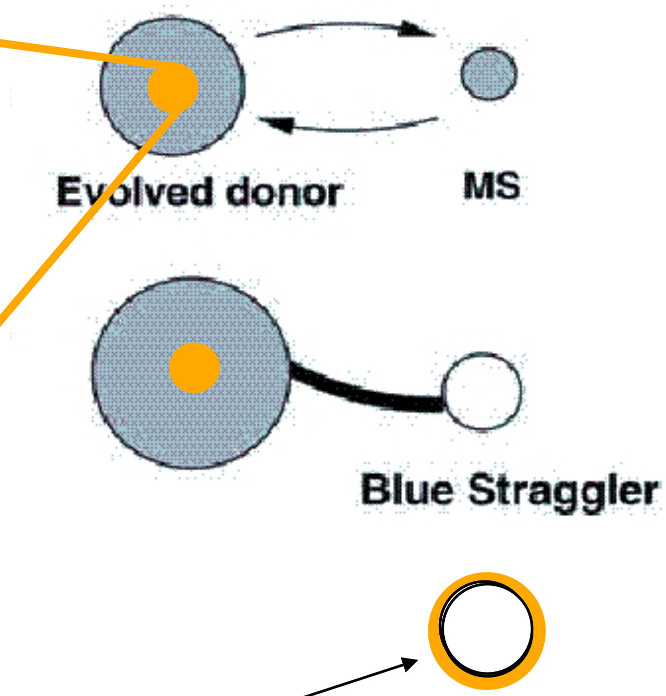
CHEMICAL ABUNDANCES:

COLL-BSS:
negligible mixing between inner cores and outer envelopes
(Lombardi et al. 1995)

PB-BSS:
incomplete CN-burning products expected on the surface of the star
(Sarna & de Greve 1996)

PB-BSS:





material on the BSS surface comes from the core of the donor

C and O DEPLETION expected on the BSS surface

Searching for chemical signatures of the BSS formation process

High-resolution (R=11700) spectroscopy of BSS with UVES and MEDUSA @ESO-VLT

C abundance from CI line at λ=9111.8 A

O abundance from OI line at λ=7774 A

GC	Log ρ	[Fe/H]
47 Tuc	5.1	-0.7
NGC 288	2.1	-1.1
NGC 6397	PCC	-1.8
M4	4.1	-1.2
NGC6752	?	-1.6
Omega Cen	1.3	-1.6

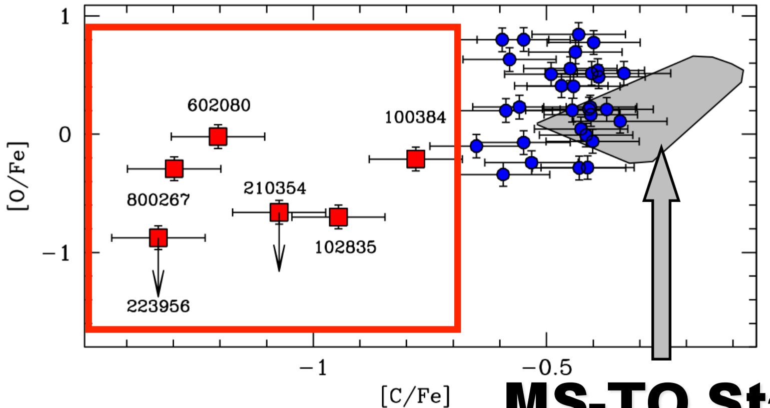
2 successfull runs at the VLT with FLAMES allowed us to collect data for ~ 300 BSS

47 Tuc: First Results

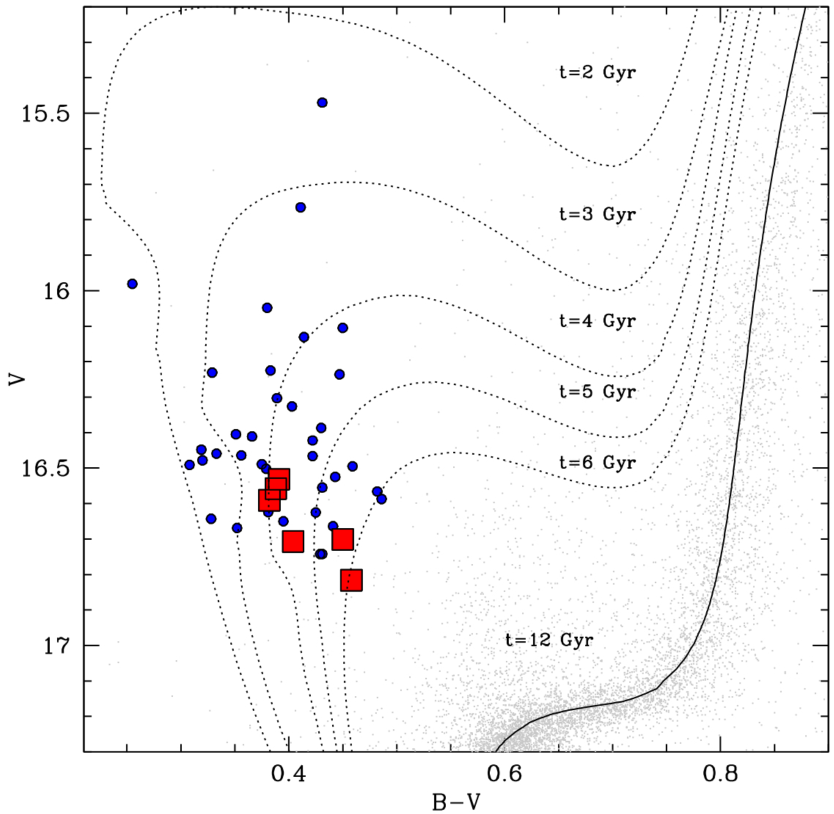
Ferraro et al 2006, ApJ,647,L56

43 BSS selected over the entire cluster extention

A sub-population of CO-depleted BSS



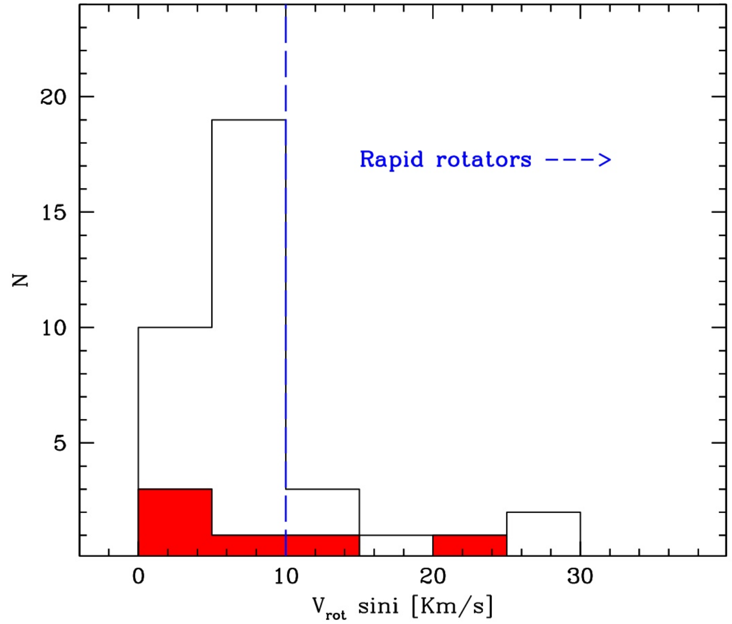
MS-TO Stars
(Carretta et al 2005)

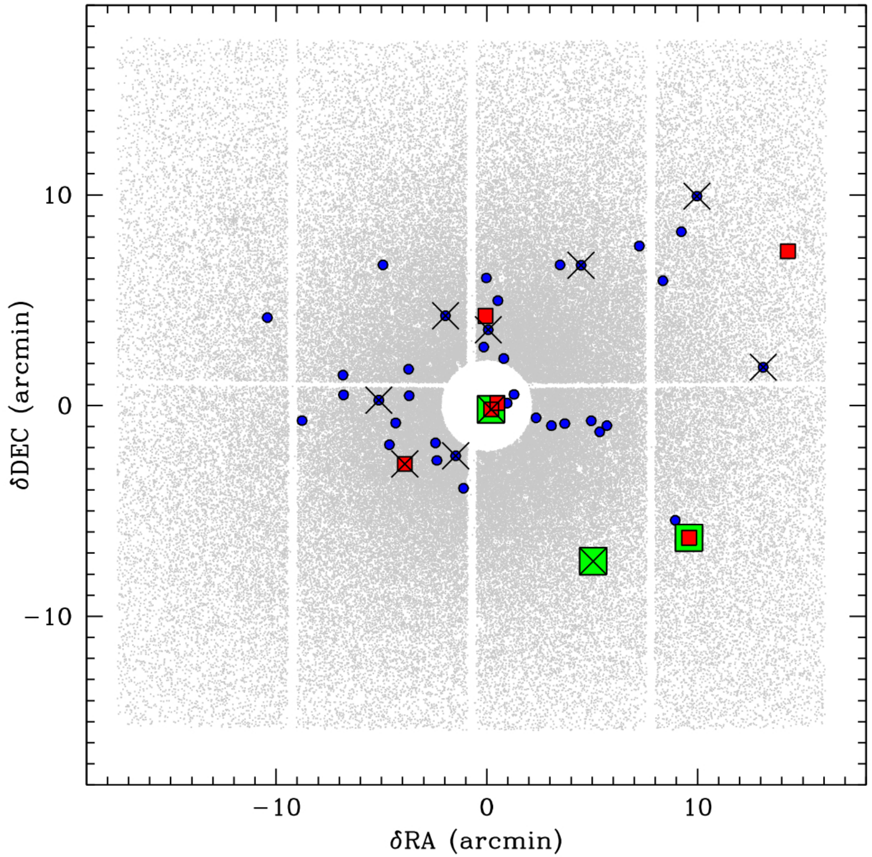


CNO burning products on the BSS surface coming from a deeply peeled parent star as expected in the case of mass-transfer process.

The chemical signature of the PB-BSS formation process?

Most BSS are slow rotators





6 C,O depleted (■)

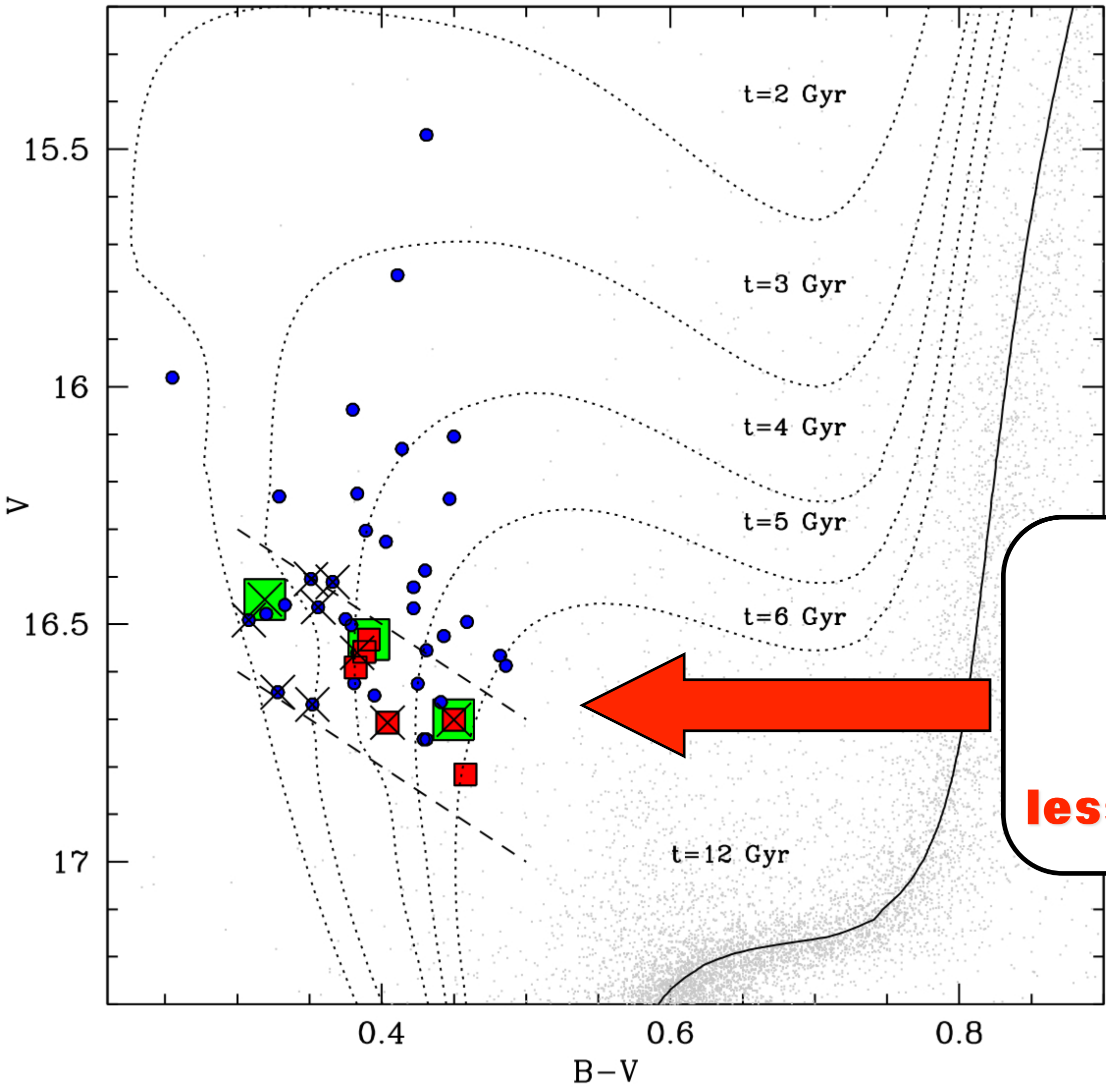
10 "moderate" rotators (X)

3 W Uma systems (■)

(shrinking binary systems which will finally merge into a single star – Vilhu 1982)

No significative radial segregation

47 Tuc: First Results

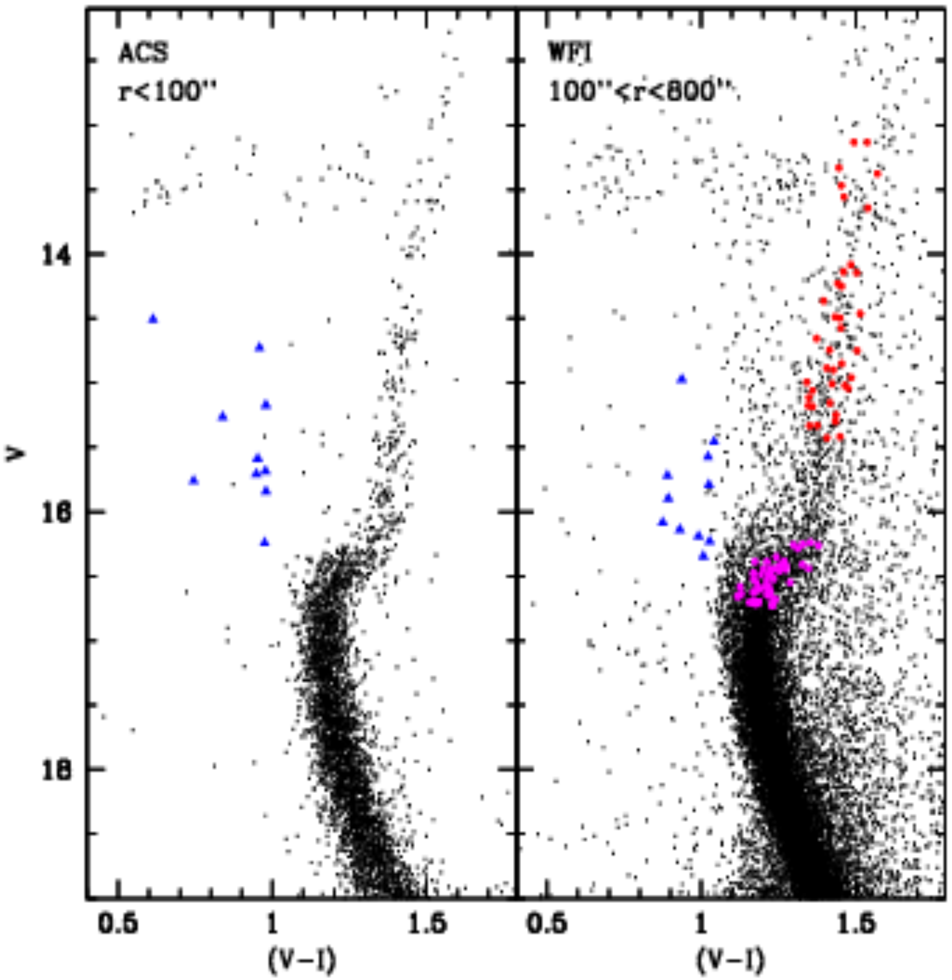


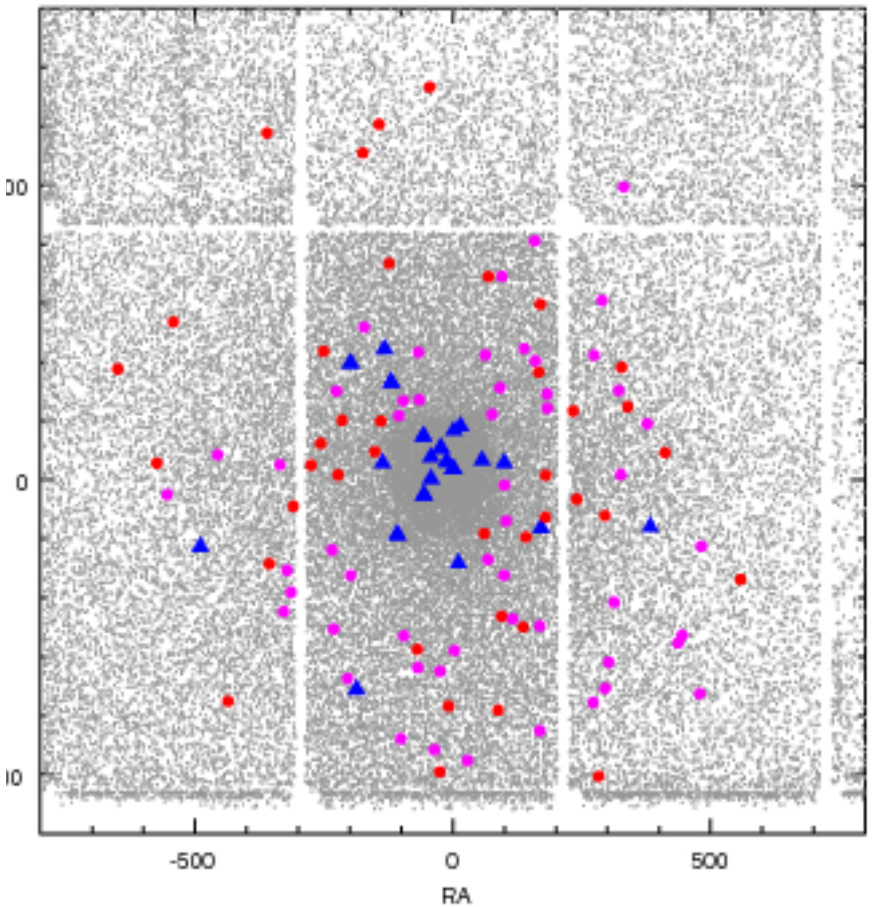
CO depleted BSS
Moderate rotators
W Uma systems
all appear to be
less evolved than normal BSS

Is the CO depletion stage "transient" ?
Can mixing process "clean-up" (mitigate) the chemical anomaly ?

M4

20 BSS + 100 SGB+RGB (reference stars)

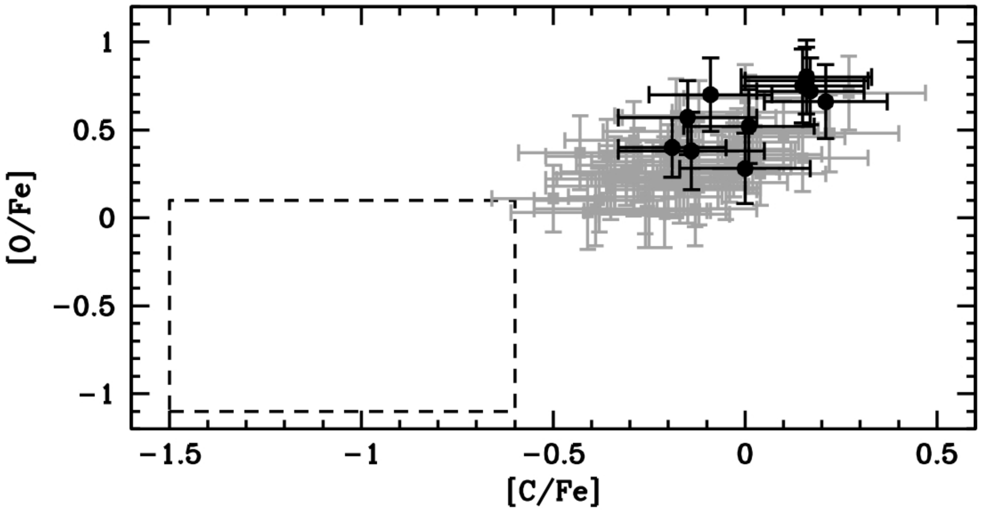




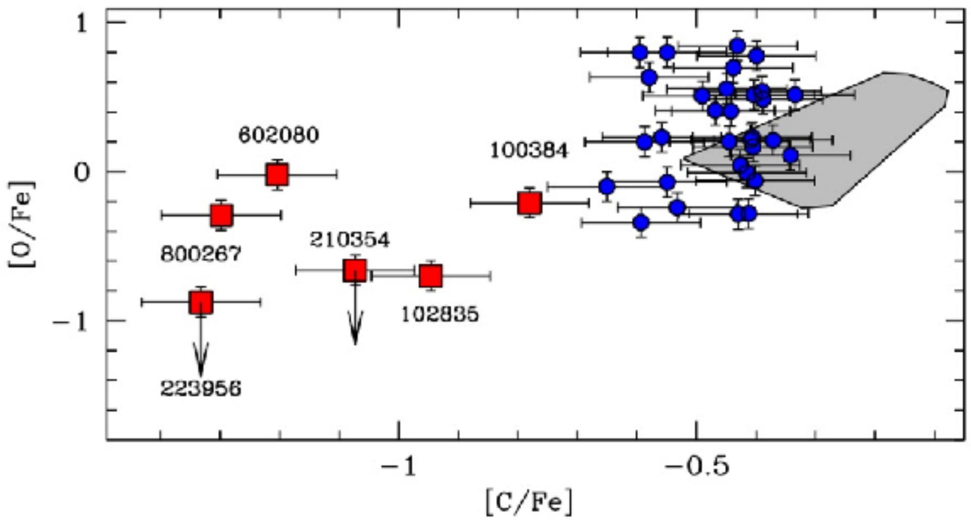
Lovisi et al 2010(ApJ,719,L121)

The case of M4

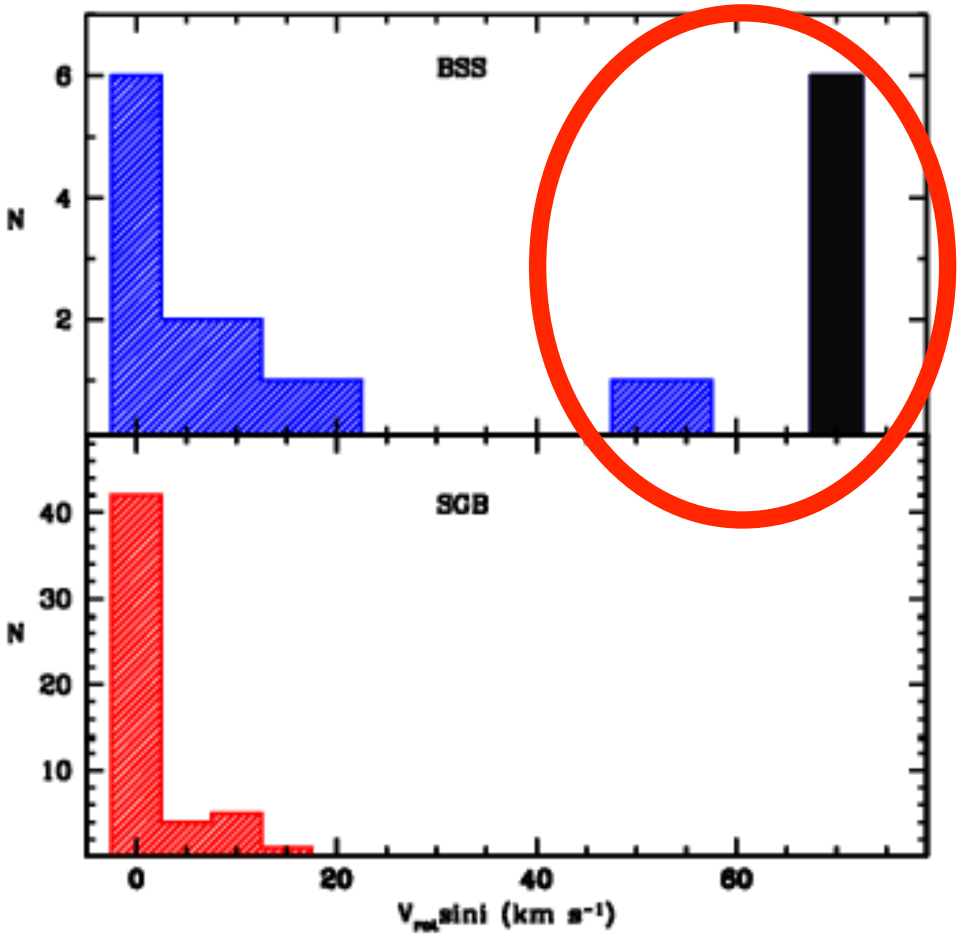
M4



47 Tuc



The case of M4: fast rotating BSS



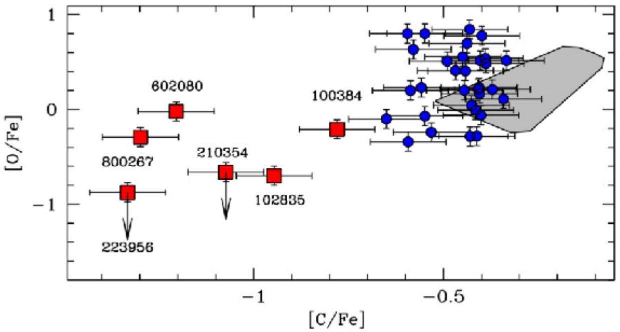
40% of BSS are fast rotators

The largest sample ever found in a Globular Cluster

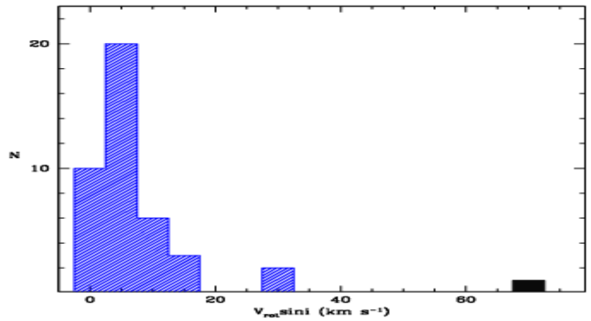
Comparing GCs

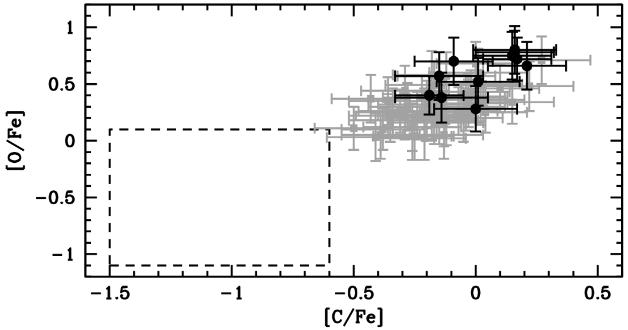
Depletion

Rotational velocities

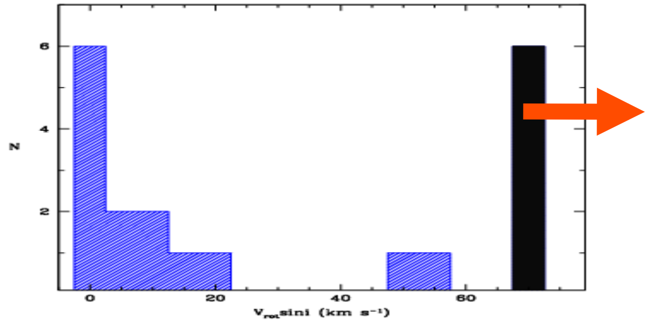


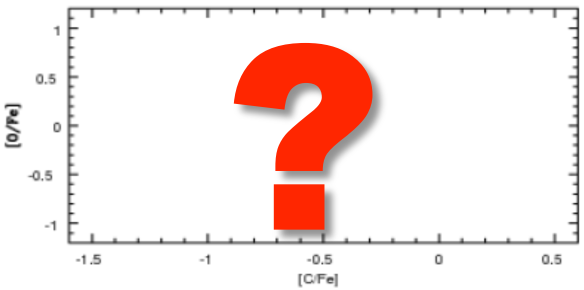
47 Tuc



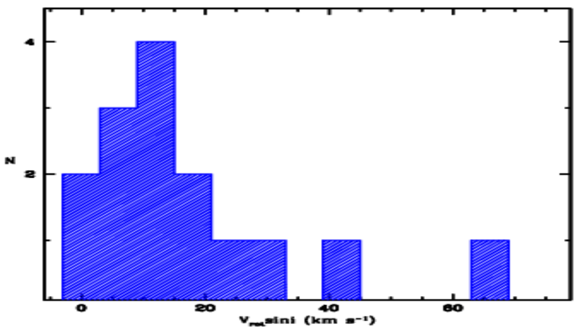


M4

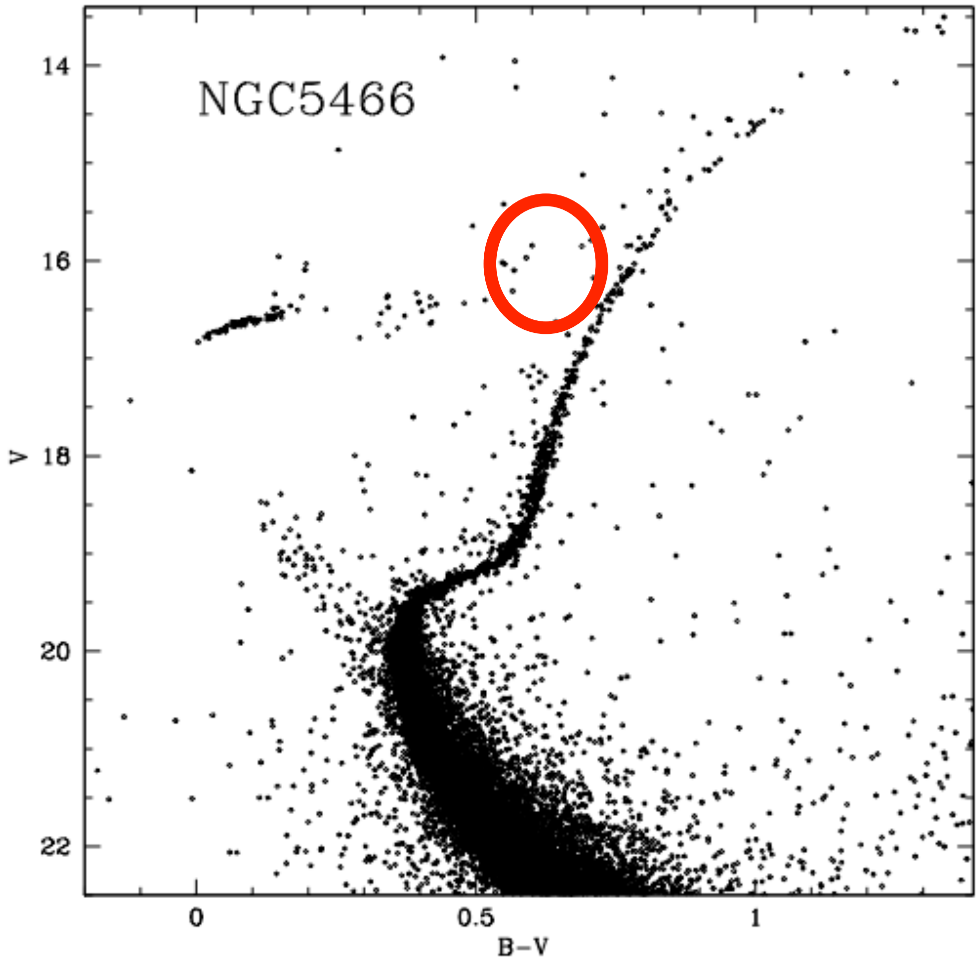




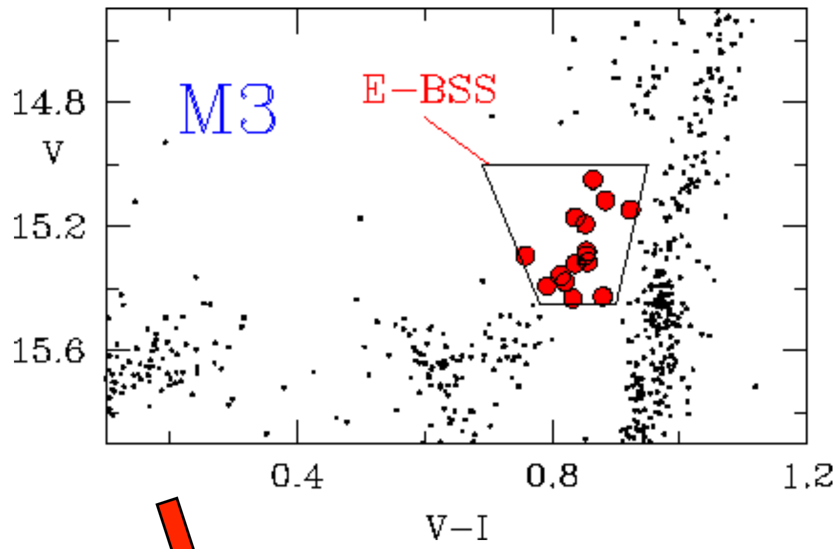
NGC6397

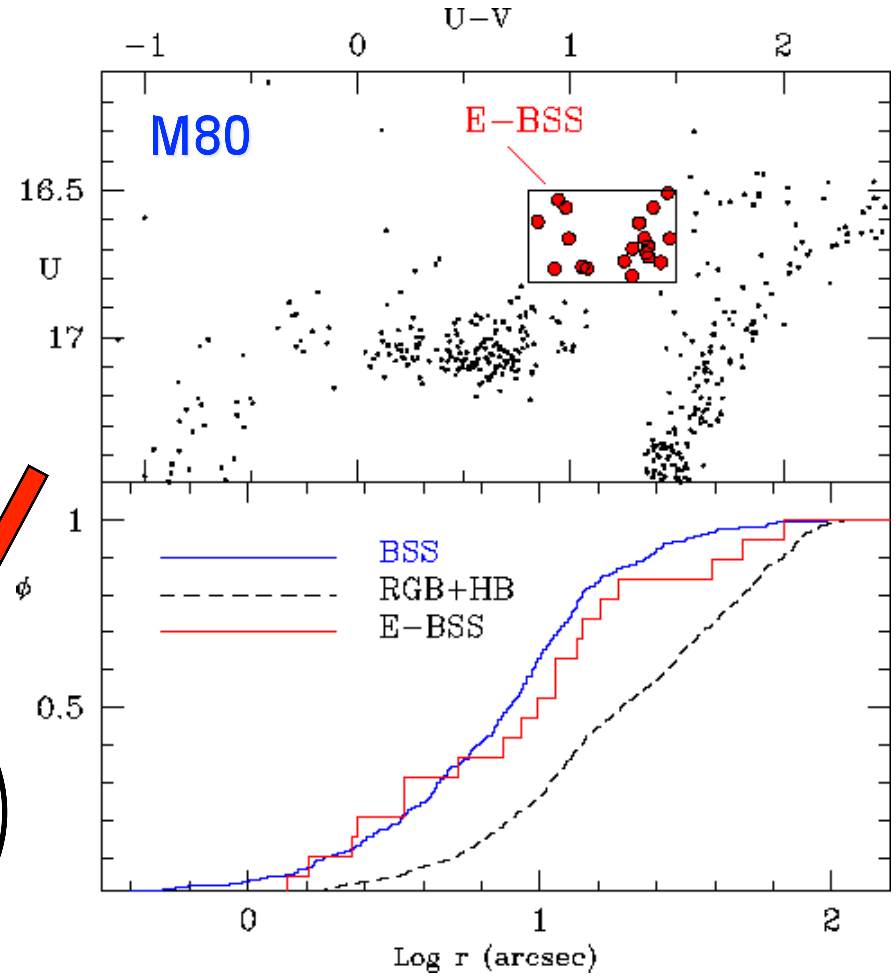


Evolved-BSS: where in the CMD?



Searching for Evolved BSS





19 *E-BSS* candidates

M 3

entire cluster

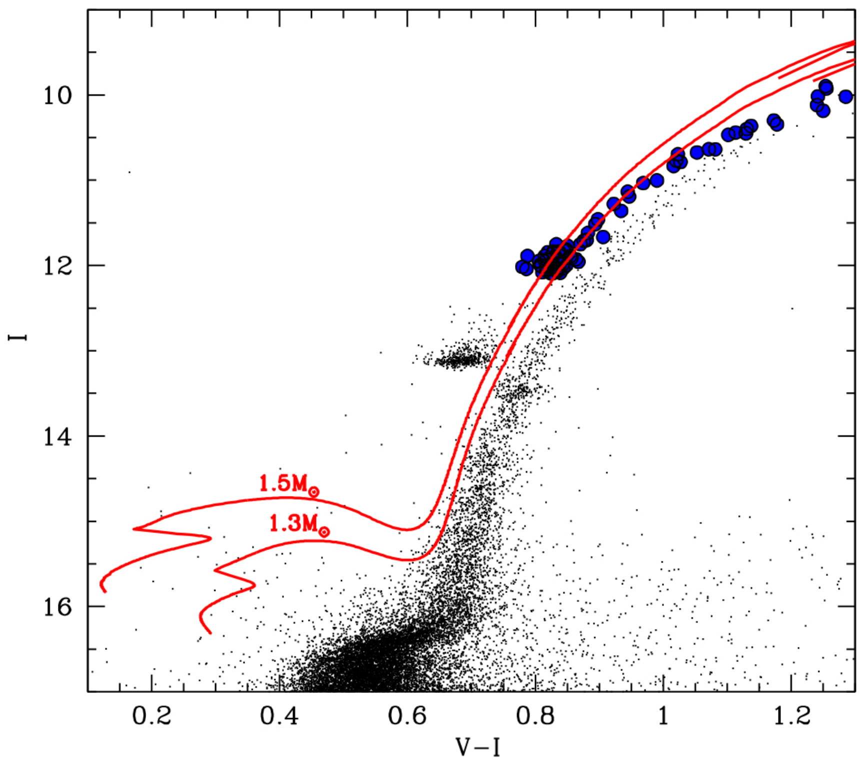
$\mathcal{F} = N_{b\text{-}BSS} / N_{EBSS} =$ ***122 / 19 = 6.4***

M 80

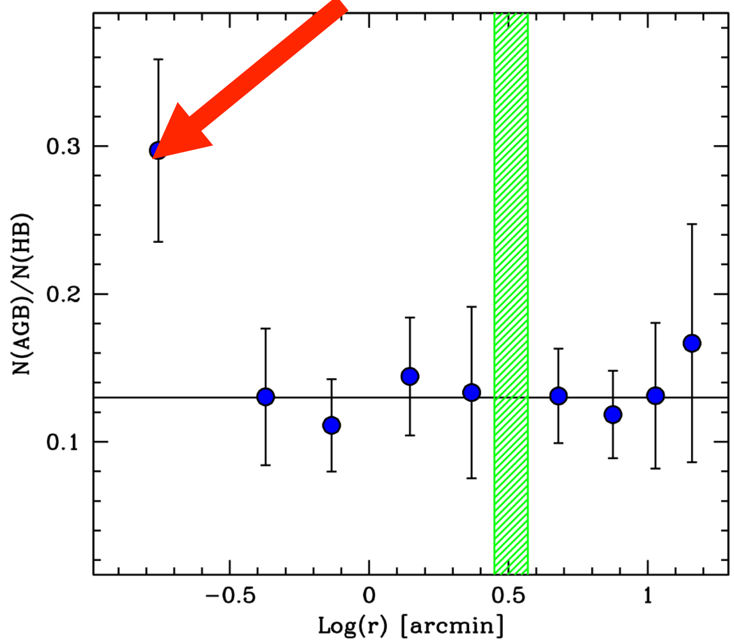
central region

$\mathcal{F} = N_{b\text{-}BSS} / N_{EBSS} =$ ***129 / 19 = 6.5***

Evolved BSS in the AGB of 47 Tuc?



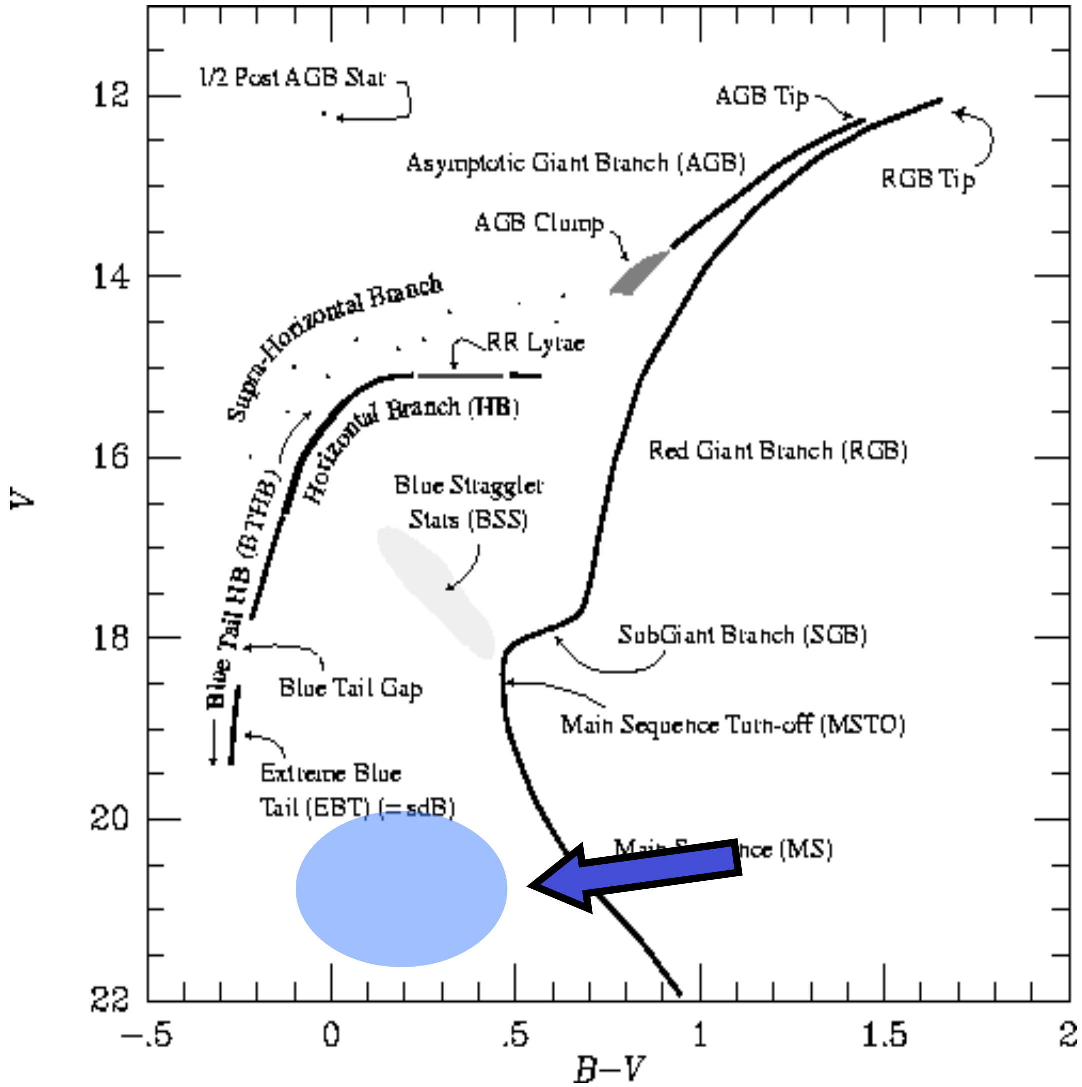
Contamination by non genuine low-mass AGB ???



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

Pay attention to the E-BSS contamination of the "canonical" evolutionary sequences !!!

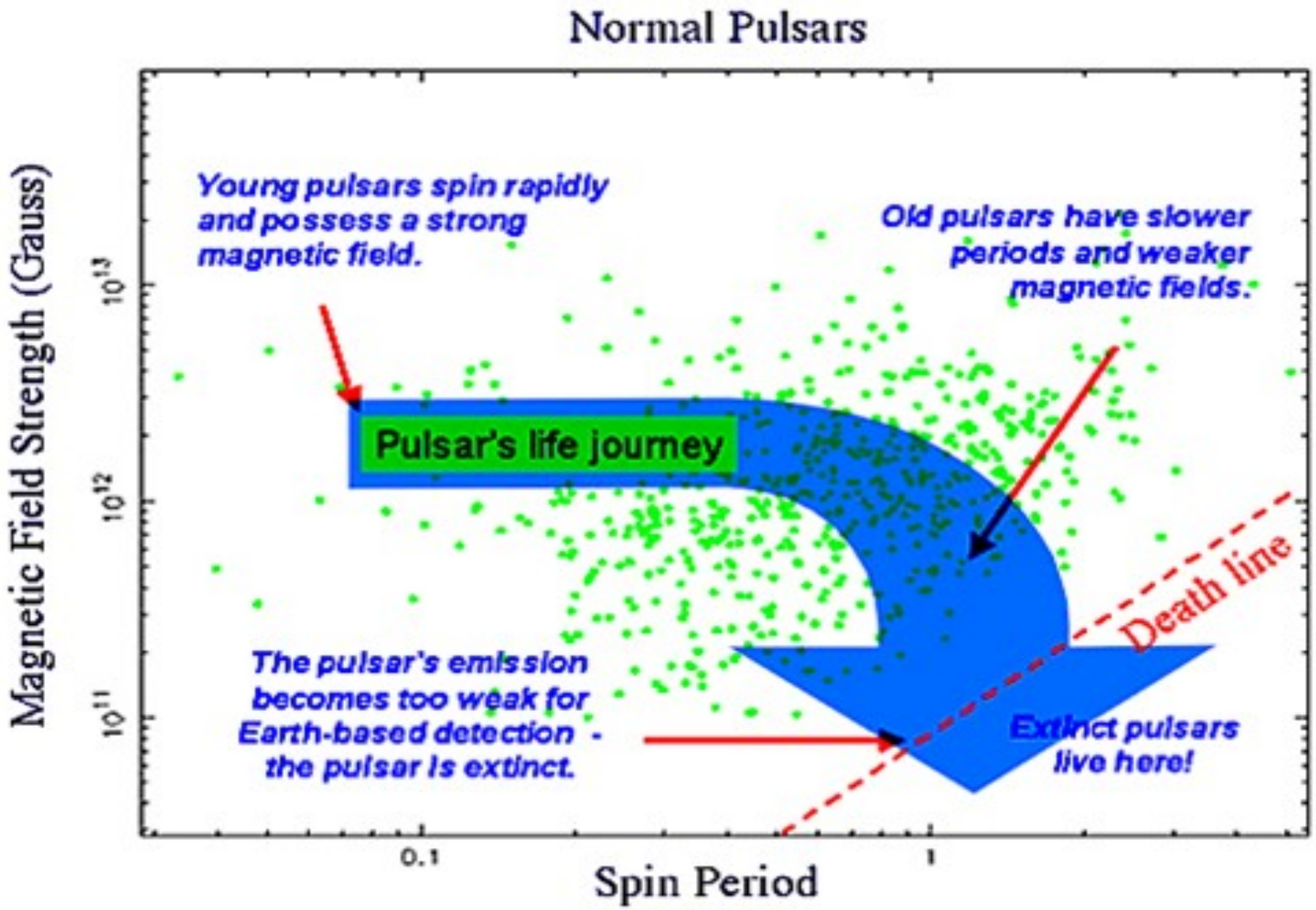
Exotic stellar populations: the MSP companions



Millisecond pulsars (MSP)

MSP (recycled-pulsars):

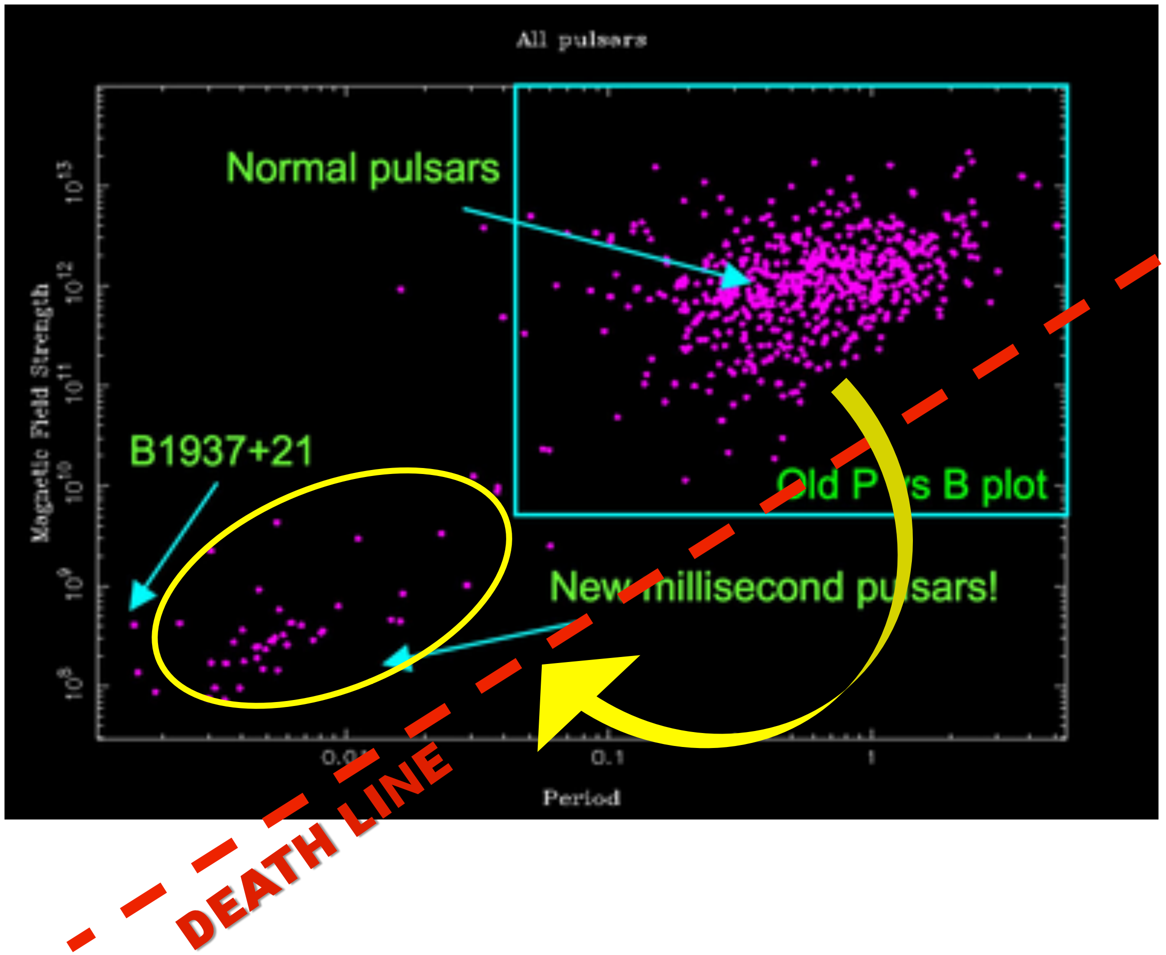
pulsars with $dP/dt < 10^{-17}$ (OLD) $P \sim 10^{-3}$ sec (RE-ACCELERATED)



Millisecond pulsars (MSP)

MSP (recycled-pulsars):

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



Millisecond pulsars (MSP)

BSS(rejuvenated)

MSP (resuscitated!!)

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

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

fast rotating pulsar (MSP) + an exhausted star

which has lost most of its envelope

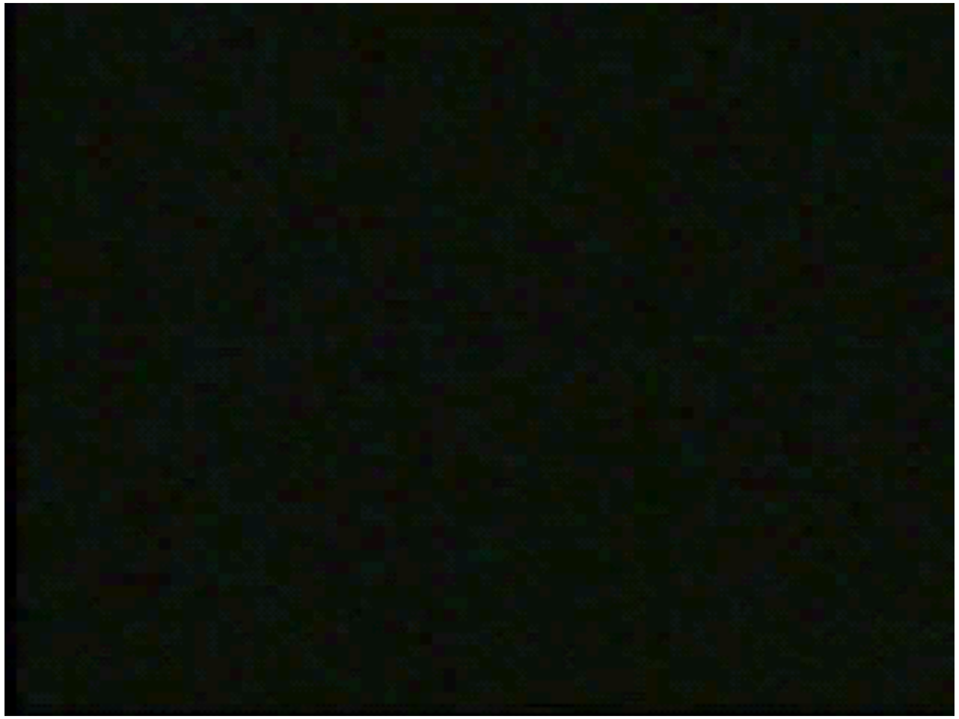
=

the core of a peeled star

=

He-WD

THE RECYCLING SCENARIO AND THE FORMATION OF A "BLACK WIDOW"



MSP

More than 250 MSP are known in the Galaxy

- **Galactic disc 100 times more massive than the GGC System**
- **More than 50% of the entire MSP population found in GGCs**

Note that 34 MSP (corresponding to 25% of the TOTAL GC-MSP population) are harboured in just one cluster: TERZAN 5 !!!

⇓

GGCs efficient "furnaces"

✓ **Field: primordial binaries only**

✓ **GCs: primordial & collisionally-induced binaries**

Companions to MSP in binary in GCs

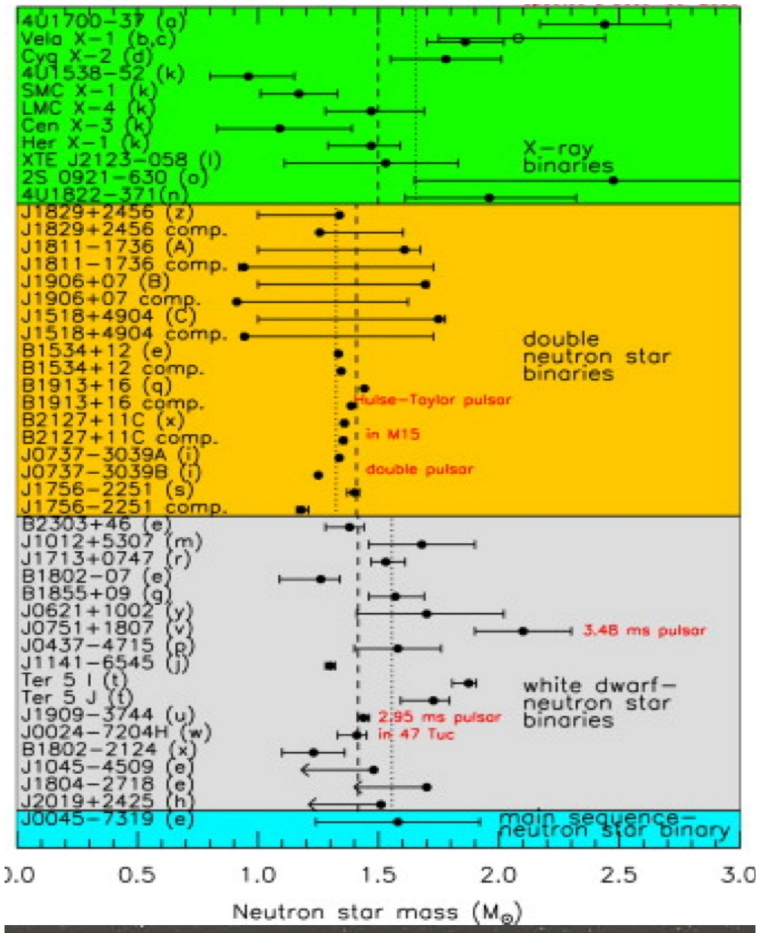
Optical identification → companion mass → pulsar mass

Light curve → orbital inclination

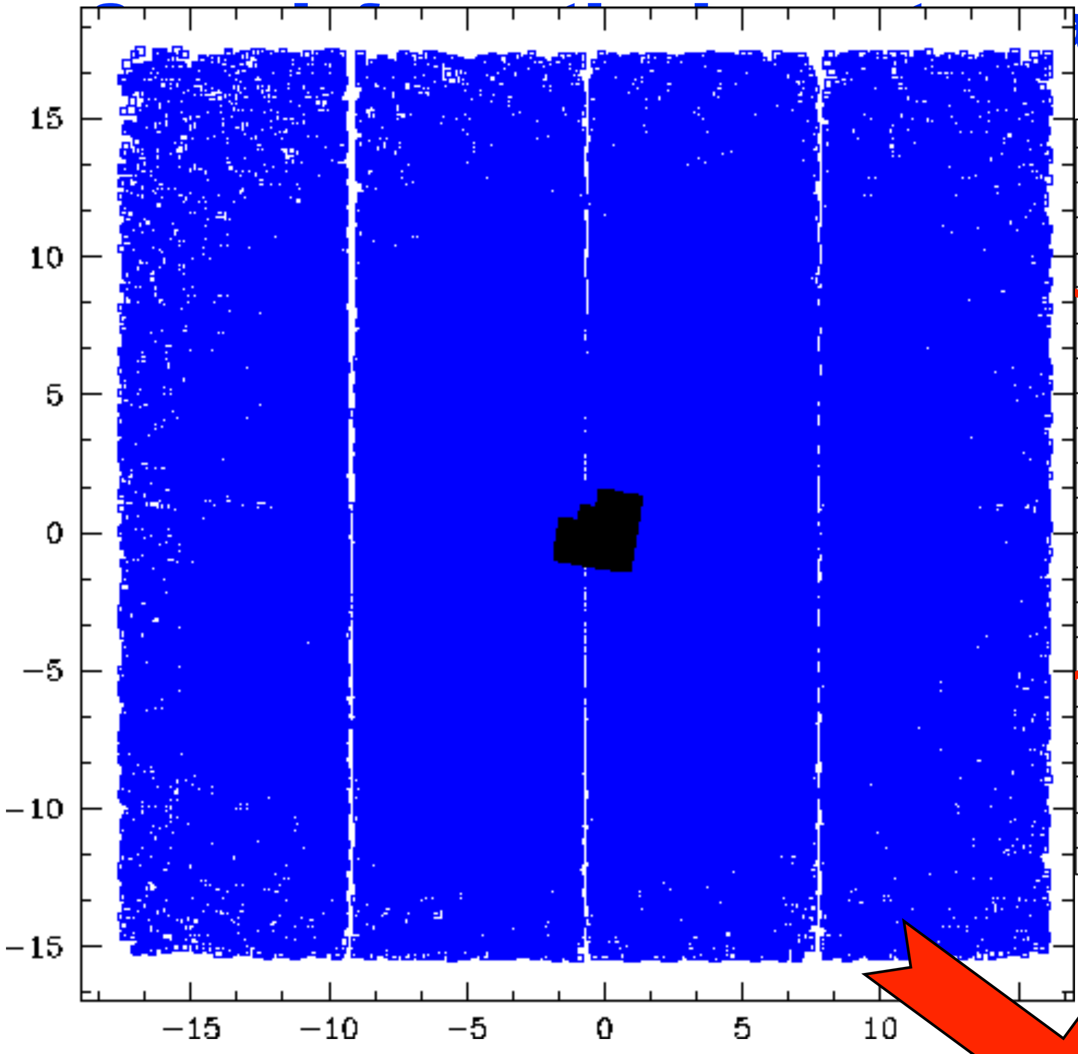
Spectroscopic follow-up → velocity curve → pulsar mass

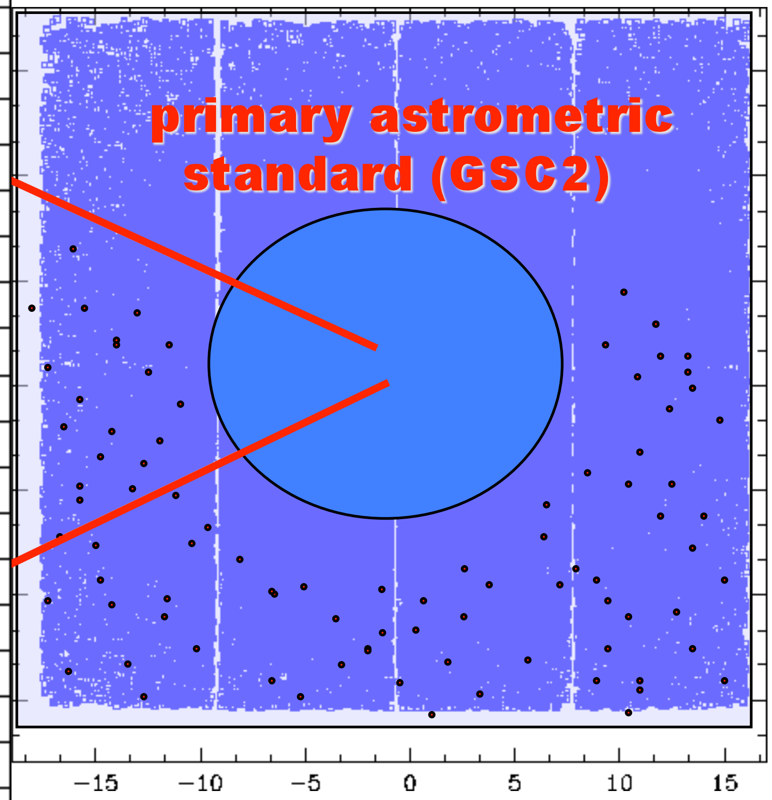
Maximum pulsar mass

Equation of state of the degenerate matter



art: a methodological



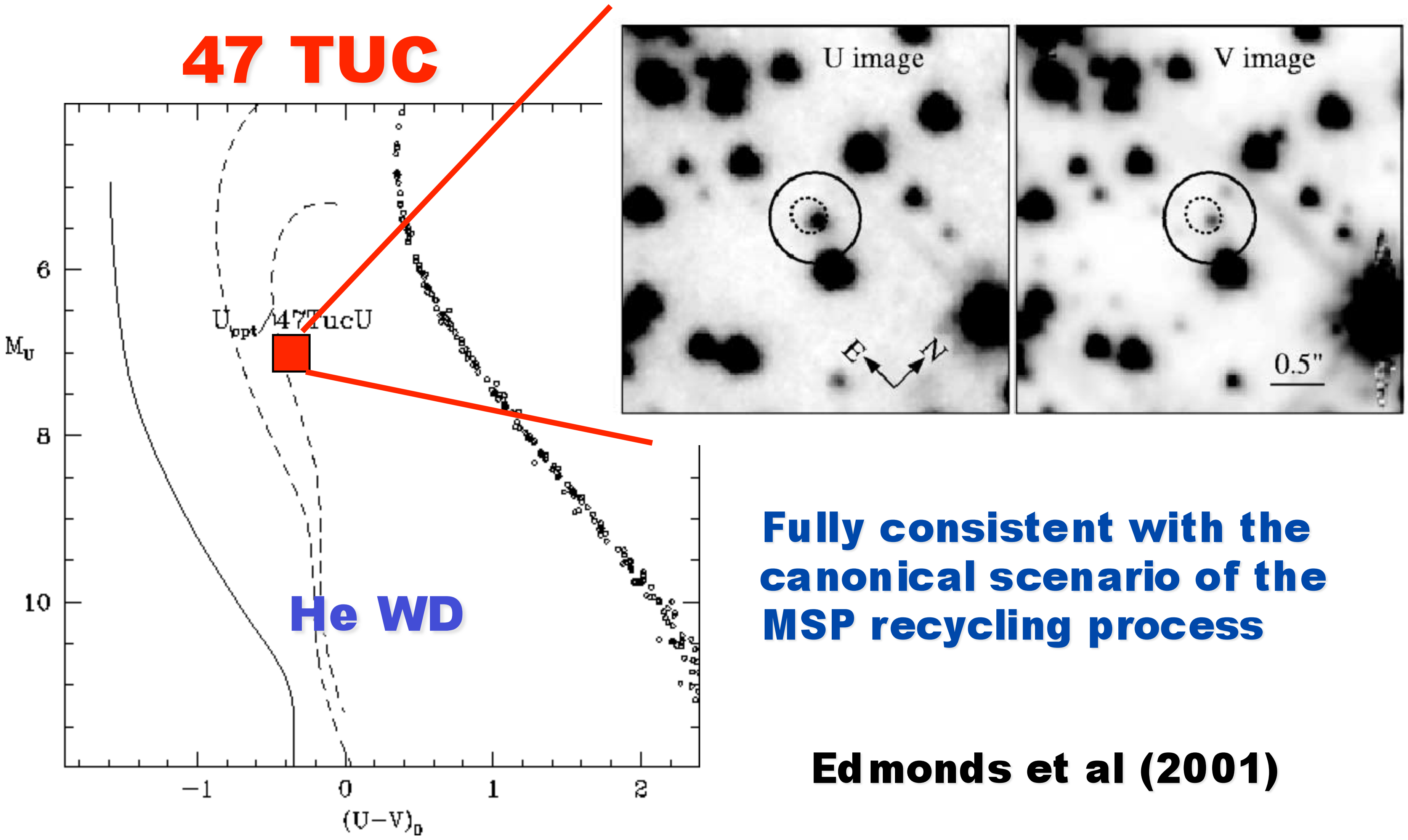


Wide-Field images
WFI@ESO-2.2m
(FoV 30'x30')

The Main problem: getting accurate absolute astrometry

Fully astrometized catalog (σ<0.2")

Optical companion to MSP in GGCs



Fully consistent with the canonical scenario of the MSP recycling process

Edmonds et al (2001)

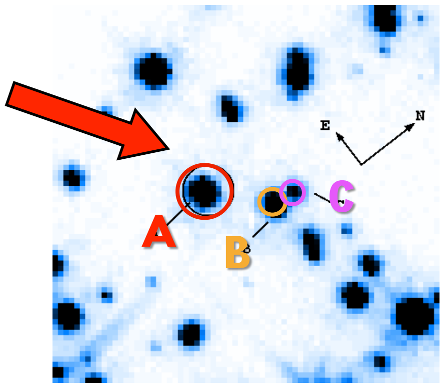
NGC 6397: the first surprise

PSR J1740-5340 **in NGC6397** ***(D'Amico+01):***

- member of a binary system with P_{orb} = 1.35 d
- eclipse of the radio signal for about 40% of the orbit

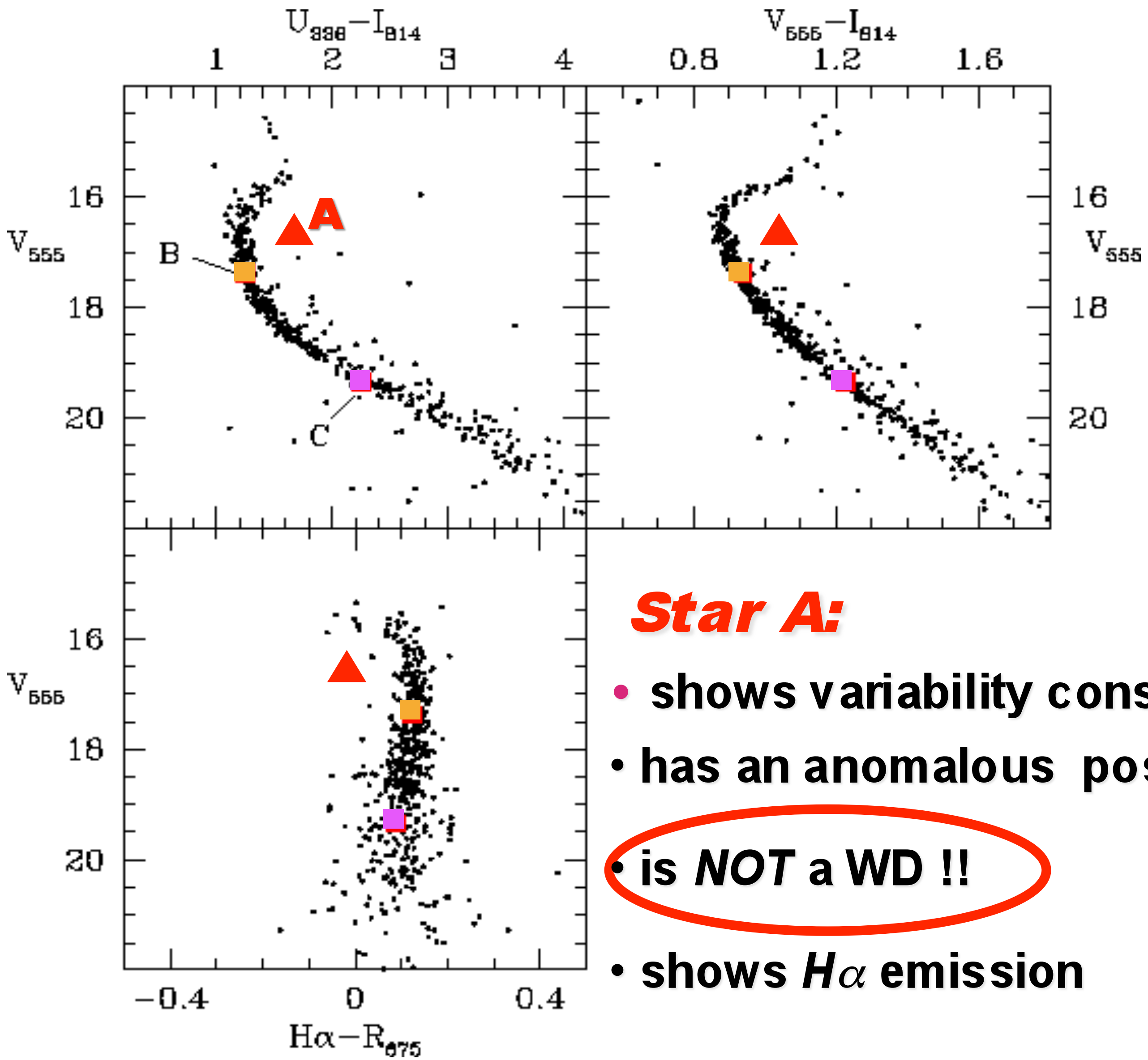
NS orbiting within a large envelope of matter released by the companion

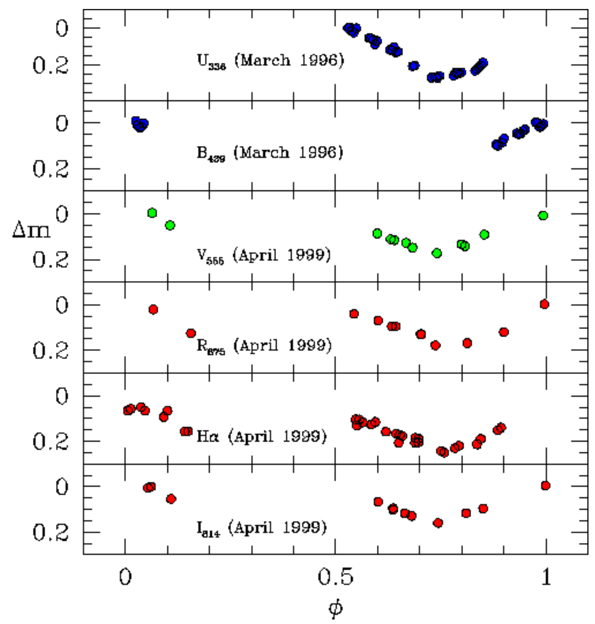
WFPC2/HST + WFI images



***Star A*:**
a bright variable star nearly coincident with the MSP nominal position
(Ferraro et al. 2001)

NGC 6397





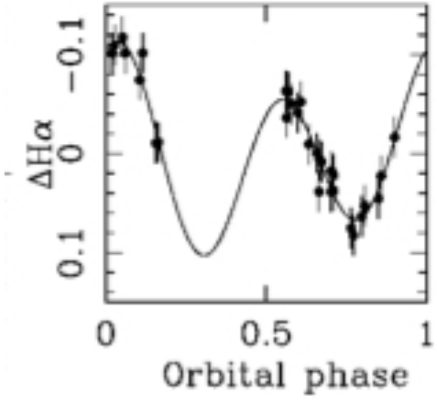
Star A:

- shows variability consistent with the MSP P_{orb}
- has an anomalous position in the CMD
- is ***NOT*** a WD !!
- shows $H\alpha$ emission

NGC 6397

- optical light curve shape:

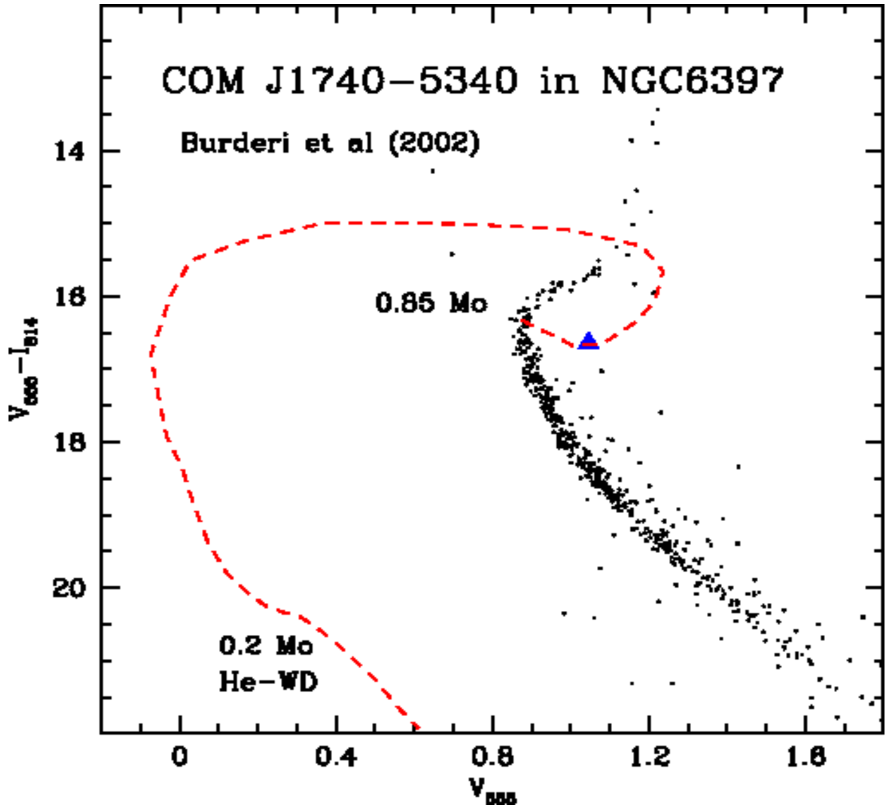
Star A is tidally distorted and losing mass from its Roche lobe



- anomalies in the radio signals + Hα emission:

presence of *ionized matter* along the light of sight

Star A consistent with a slightly evolved TO star orbiting the NS and loosing mass.
The evolution will generate a He-WD.
(Burderi et al. 2002)



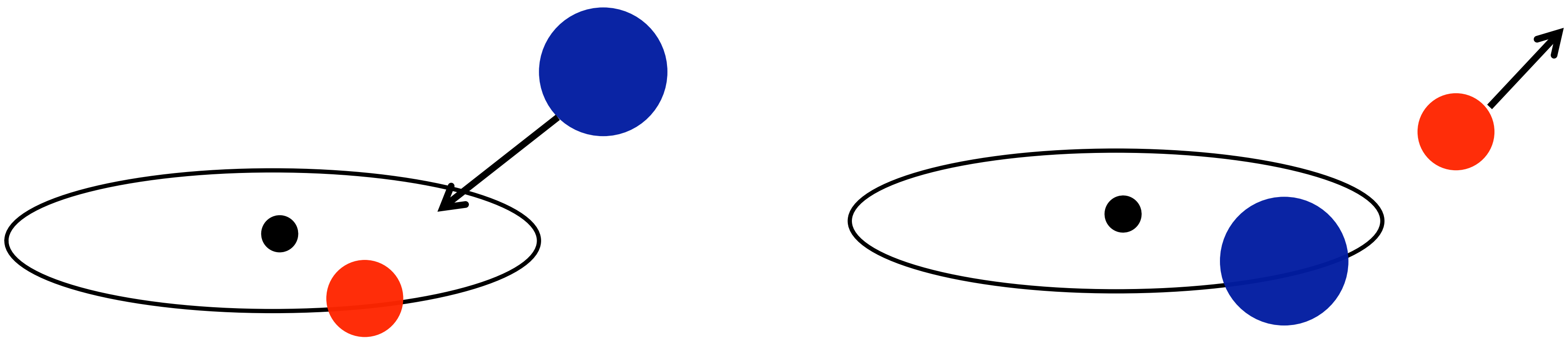
NGC 6397

Is Star A the star that spun up the MSP ?

(if so, we are observing a JUST-BORN MSP!!!)

or

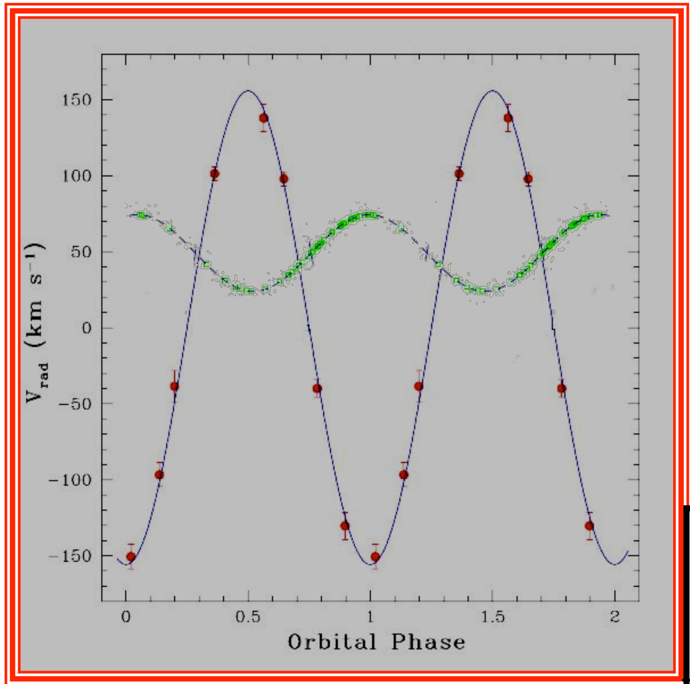
Is this peculiar system the end-product of an exchange interaction between the original binary & an isolated MS star ?



High-resolution spectroscopy with UVES/VLT

(*Star A:* bright object => ideal for spectroscopic follow-up)

(Ferraro et al. 2002; Sabbi et al. 2003)



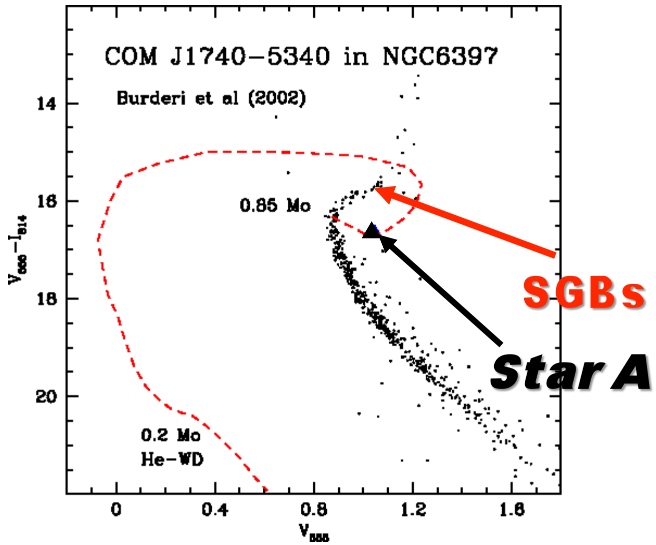
Vsin i = 49.6 ± 0.9

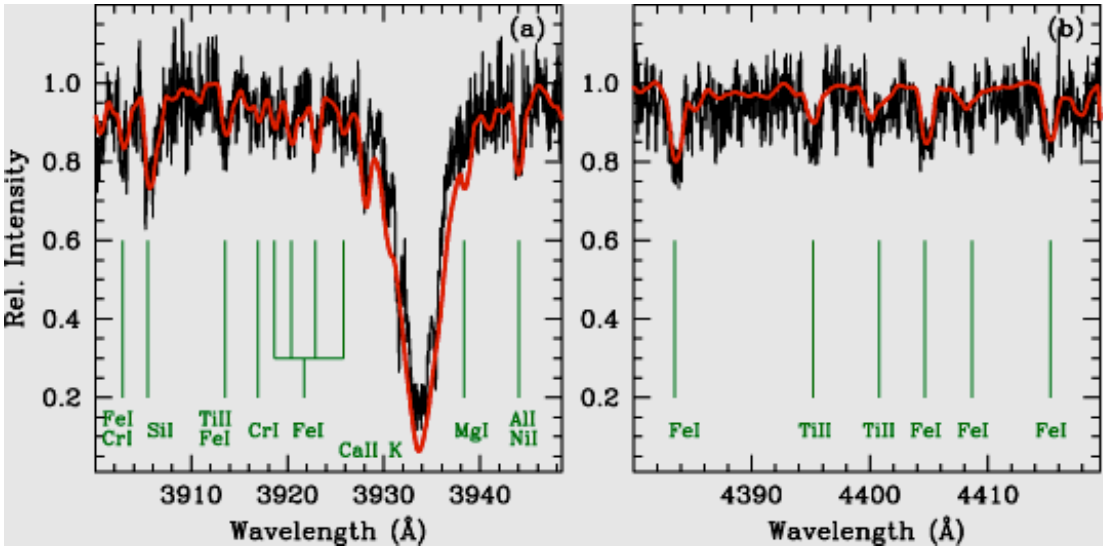
Mass ratio q=5.85±0.13

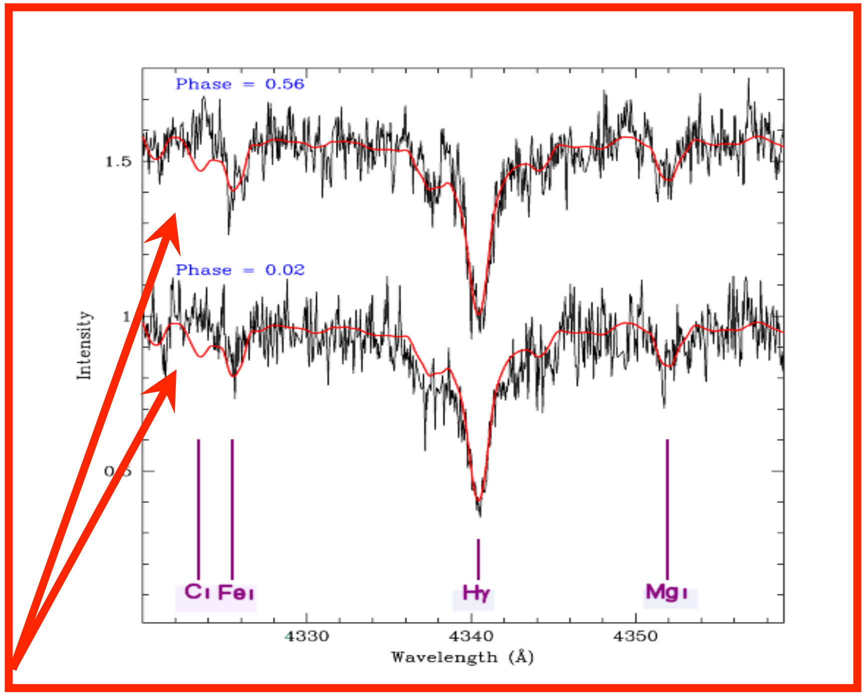
V_{rad} amplitude of Star A: 155.8±3.6 km/s

Mass of MSP	1.30 : 1.90 $M_{\odot}$
Mass of Star A	0.22 : 0.32 $M_{\odot}$
Inclination angle	56 : 47 deg
Orbital separation	6.1 : 7.0 $R_{\odot}$
Roche lobe radius	1.5 : 1.7 $R_{\odot}$

High-resolution spectroscopy with UVES/VLT







STAR A:

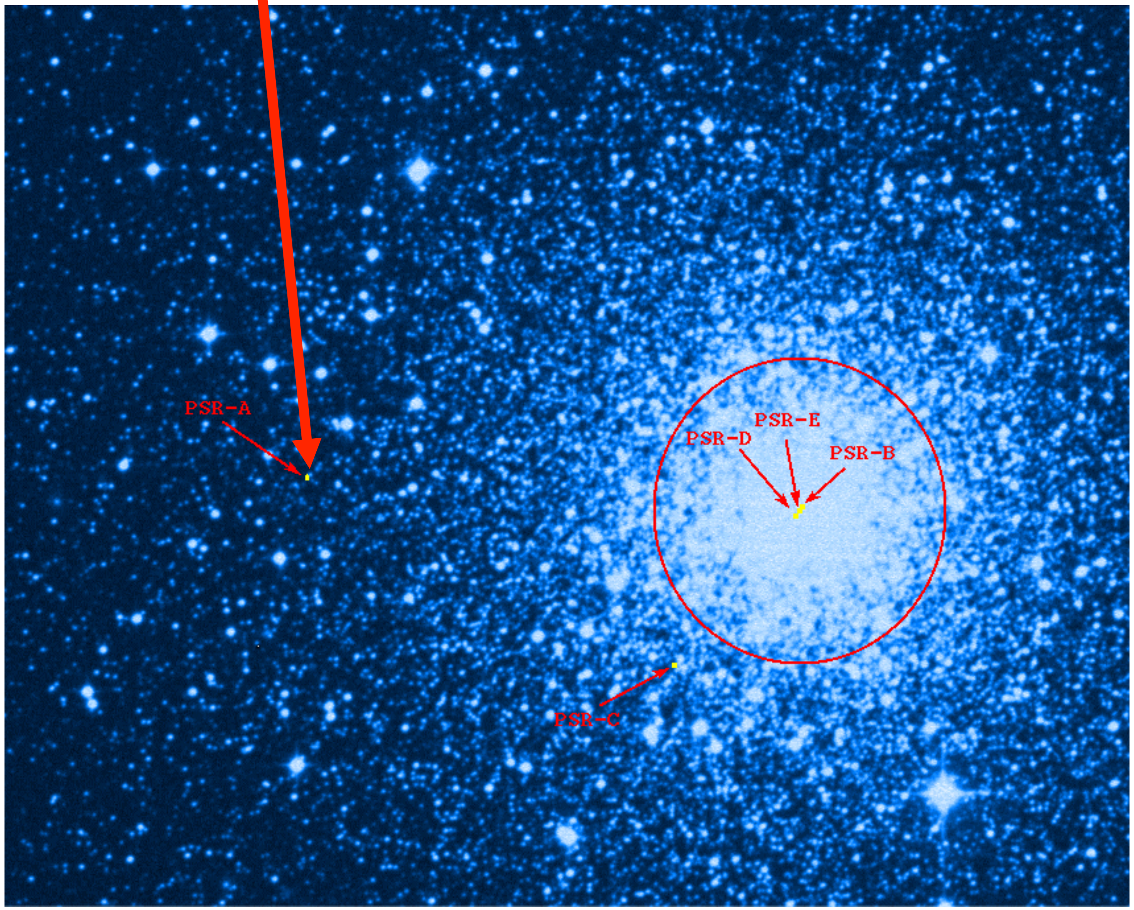
- **same overall chemical composition of SGB stars**

- **no C in its atmosphere => material processed by CNO-burning => deeply peeled star**

The bright companion to the MSP in NGC6397

NGC 6752: the most off-centred MSP

- 5 MSPs in total
- 3 (isolated) in the centre
- anomalously large acceleration for 2 of the central three
- ***PSR-A***: **the most off-centre ever observed in a cluster !!**



Ejected from the core?

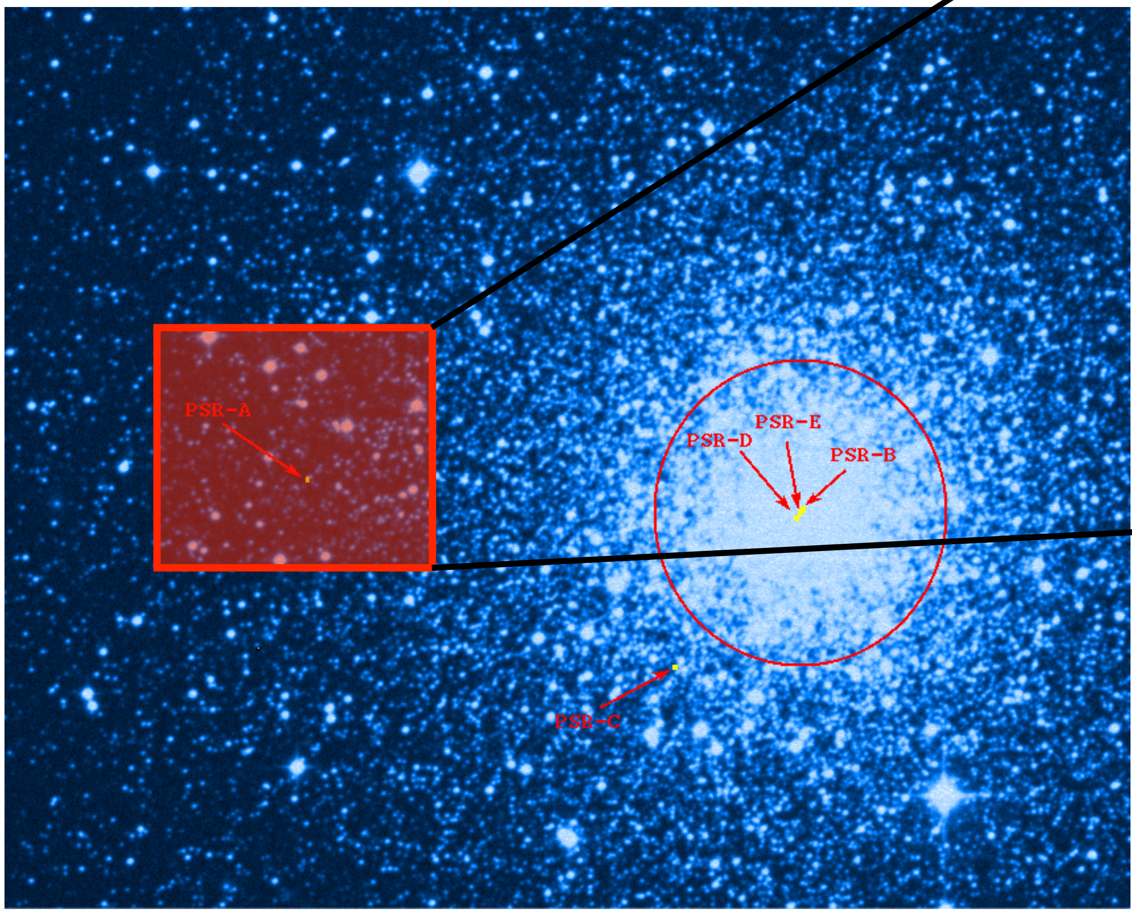
1000-2000 Ms of under-luminous matter within 0.08 pc from the centre!!

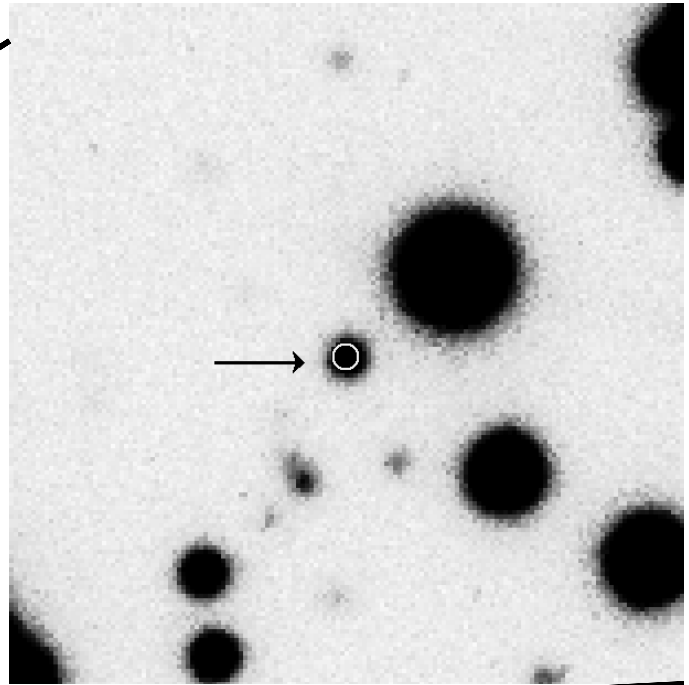
binary/single BH?

(Colpi et al. 2002, 2003)

NGC 6752

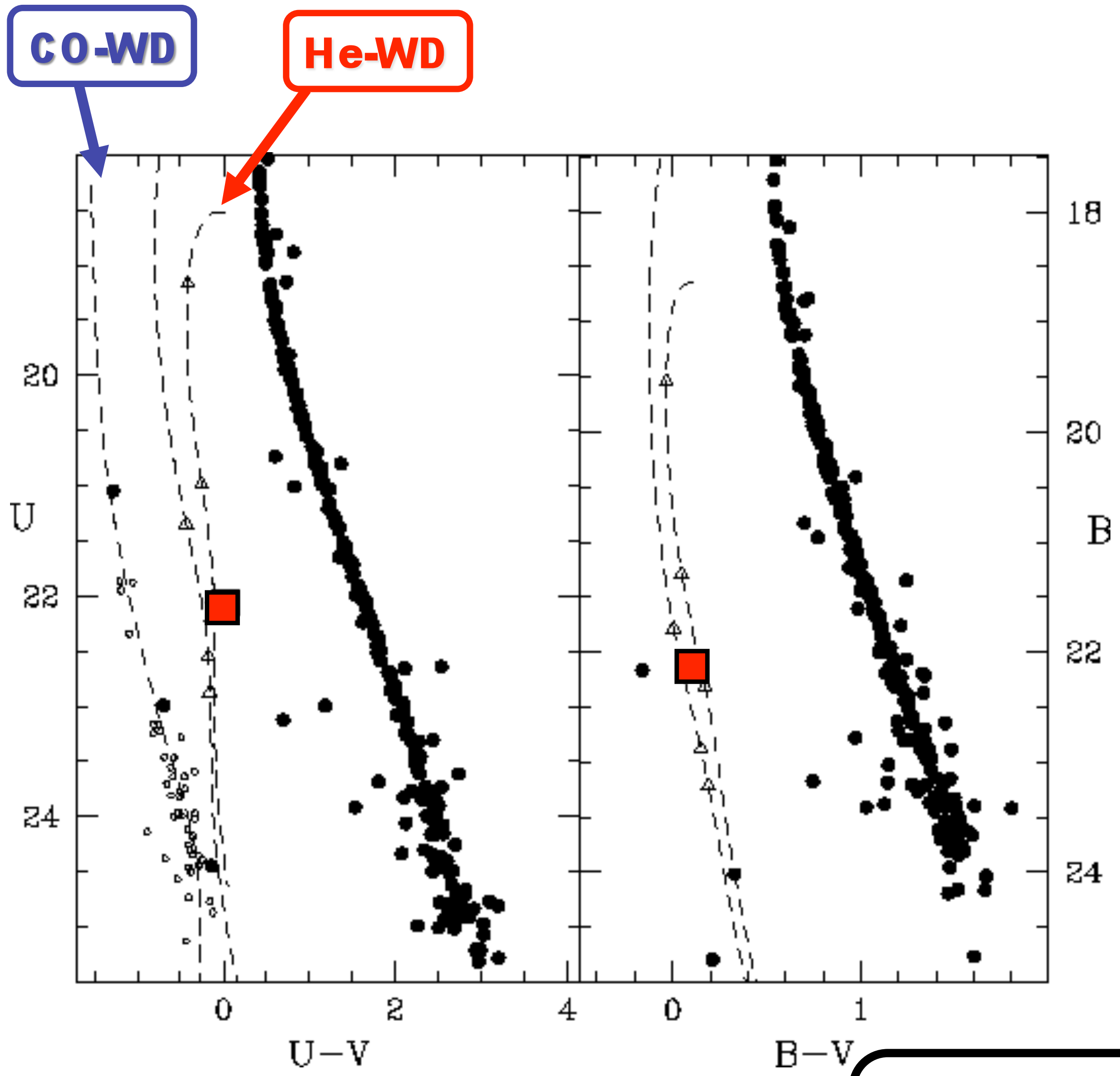
VLT-FORS1 multi-λ (U,B,V) high-resolution imaging





(Ferraro et al. 2003; Bassa et al. 2003)

NGC 6752



He-WD

M = 0.17-0.19 Ms

t_{cool} = 1.2-2.8 Gyr

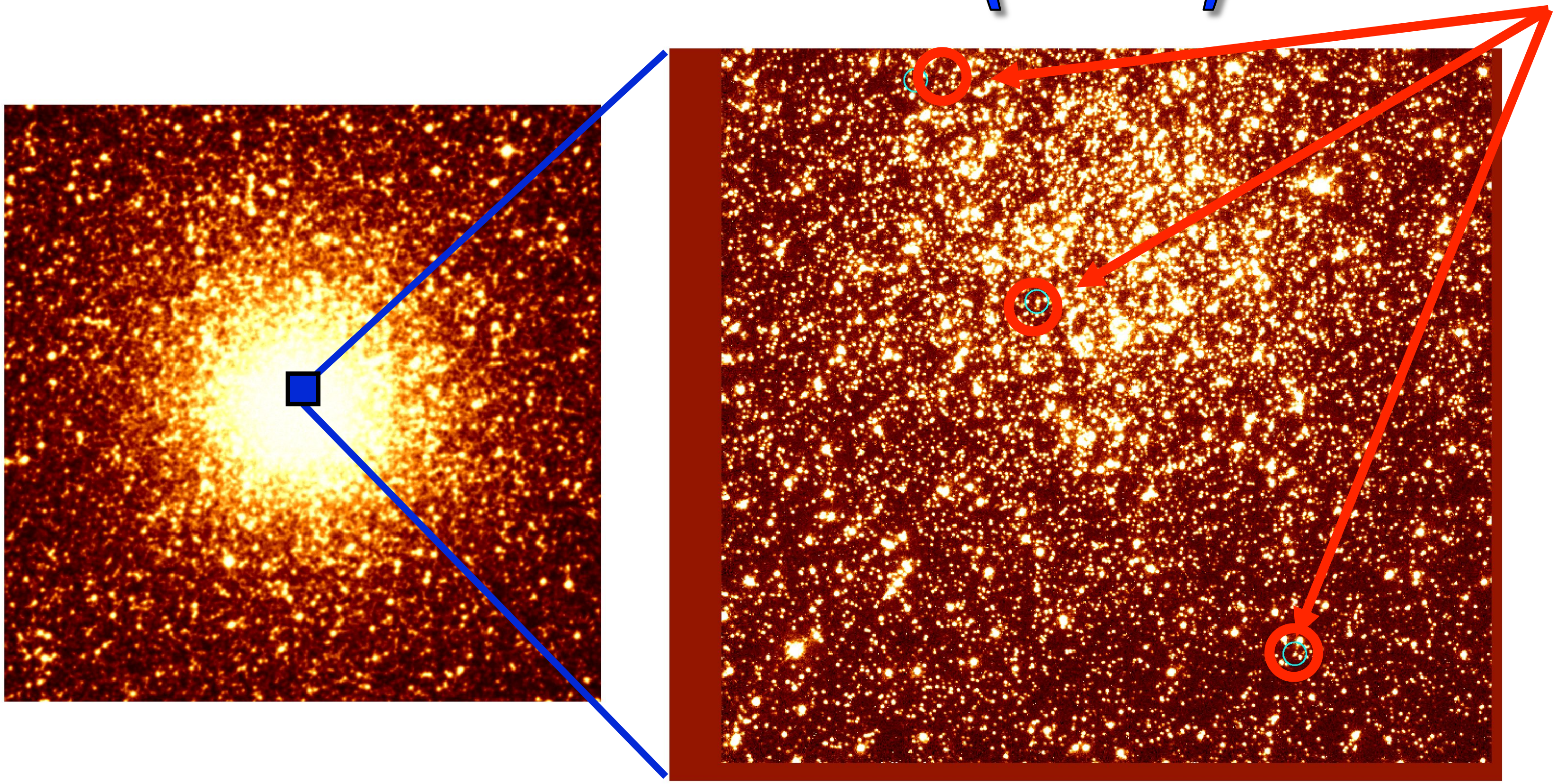
t_{df} (r_{MSP}) < 1 Gyr

(time needed to drive the system back into the core)

the ejection acted on an already formed MSP

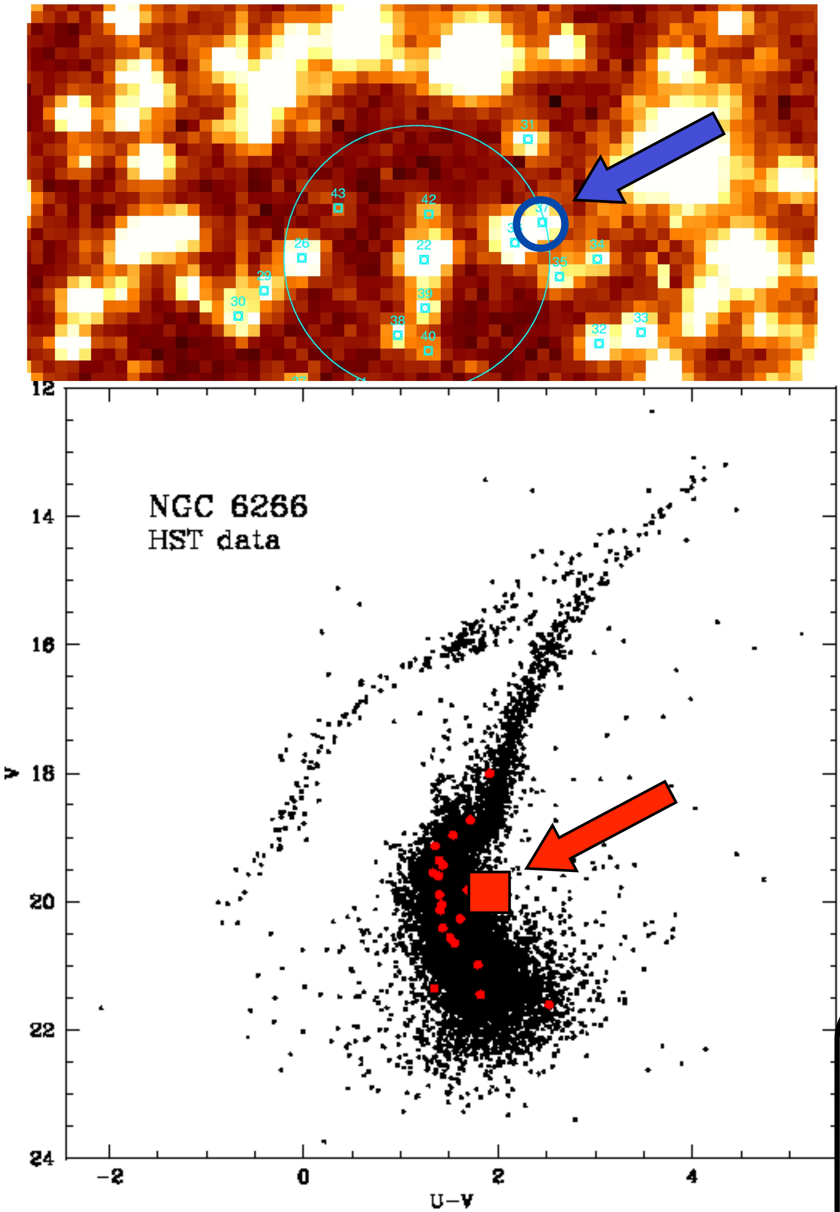
(Ferraro et al. 2003; Bassa et al. 2003)

MSPs in NGC6266 (M62)



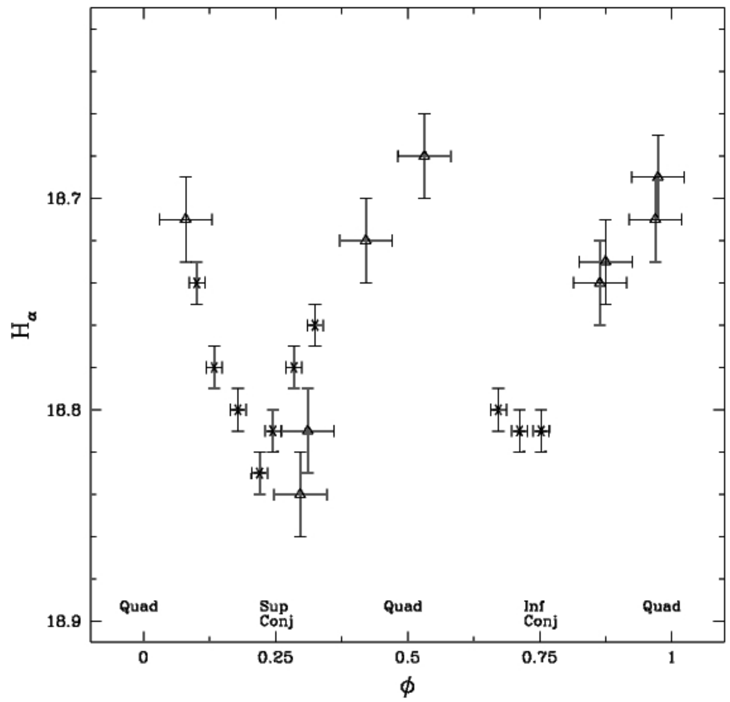
All the MSPs discovered so far in NGC6266 are in binary systems

PSRJ1701-3006B in NGC6266 (M62)



Cocozza et al (2008)

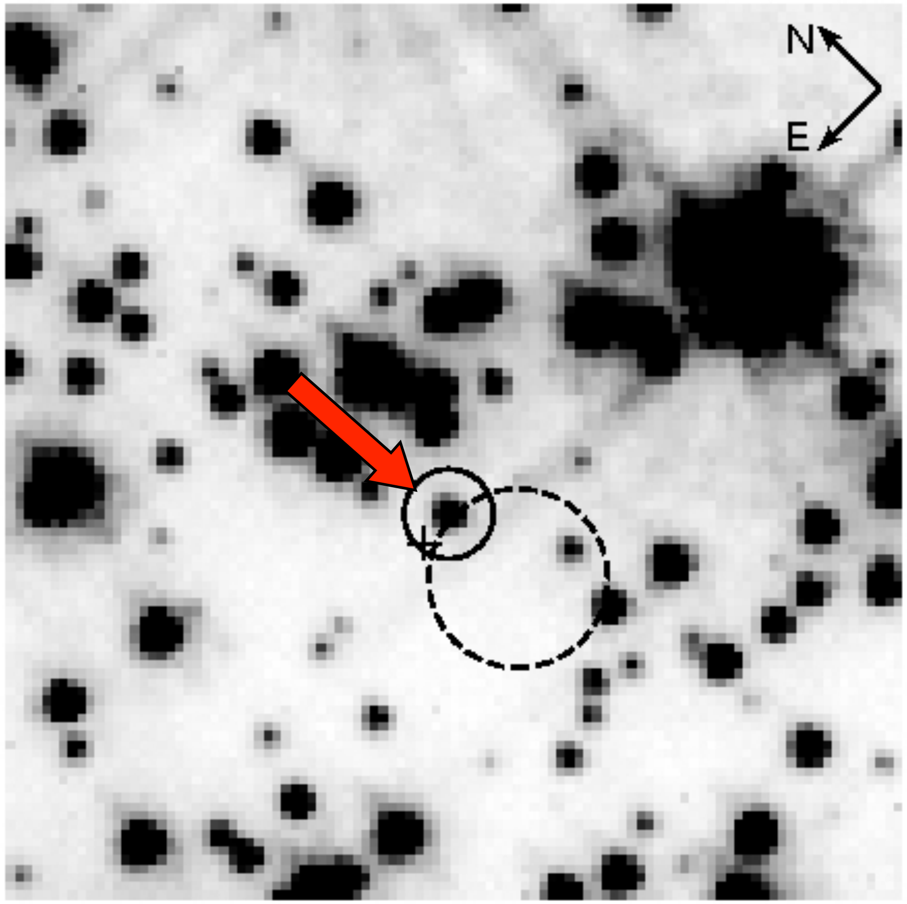
We have identified a bright variable star with anomalous red color and optical variability which nicely correlates to the orbital period of the pulsar.



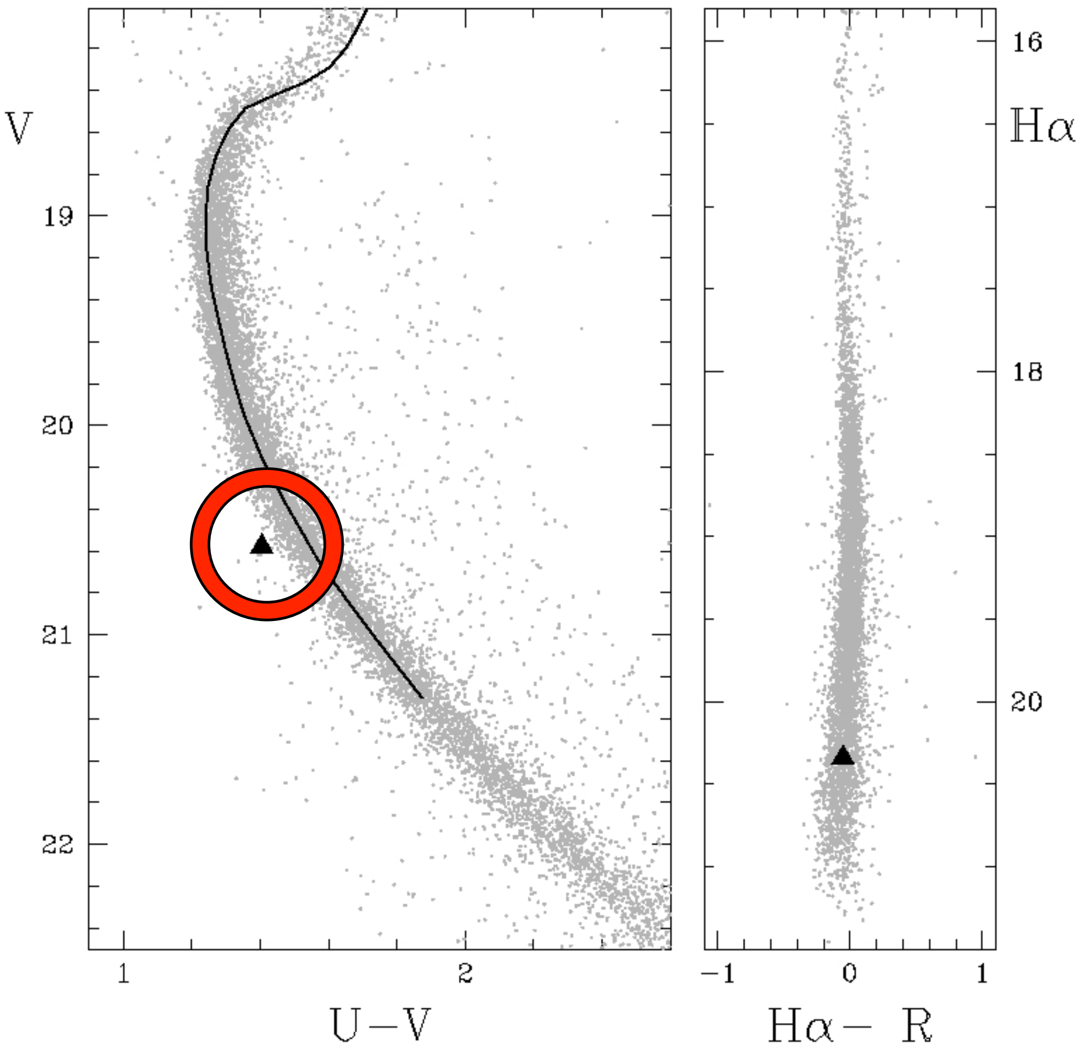
The position in the CMD and the shape of the light curve suggest that this object is quite similar to COM-J1740-5340 discovered in NGC6397.

The MSP- H in M28

- **An object similar to that detected in NGC6397 and M62 has been identified in M28.**
- **The star is located at *0.17” from the radio source* (+) and ~0.4” from the X-ray source (dashed circle)**

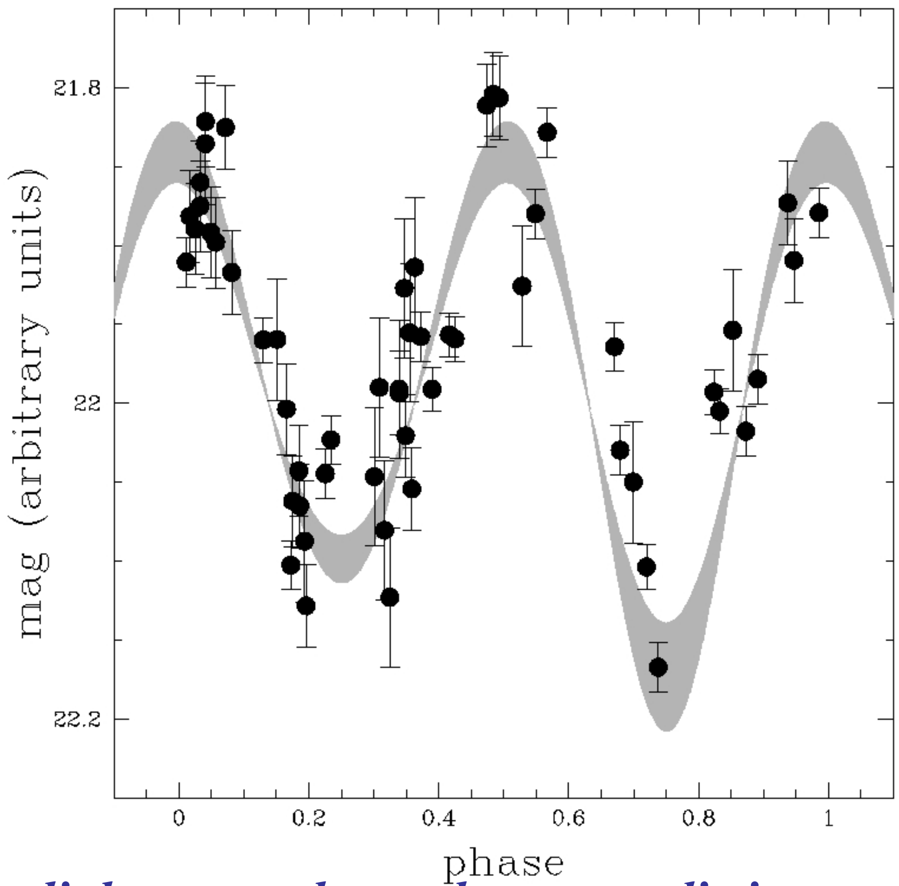


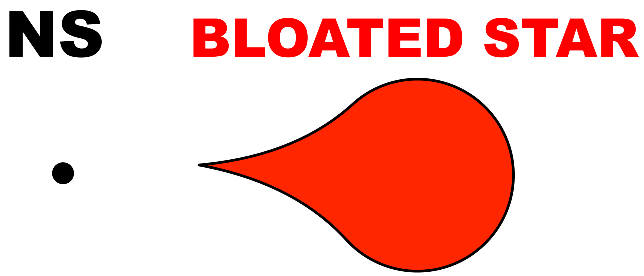
The MSP- H in M28



Another NON-DEGENERATE companion

The optical modulation of the identified star nicely agrees with the orbital period of the MSP, thus fully confirming that ***the variability is associated with the pulsar binary motion***



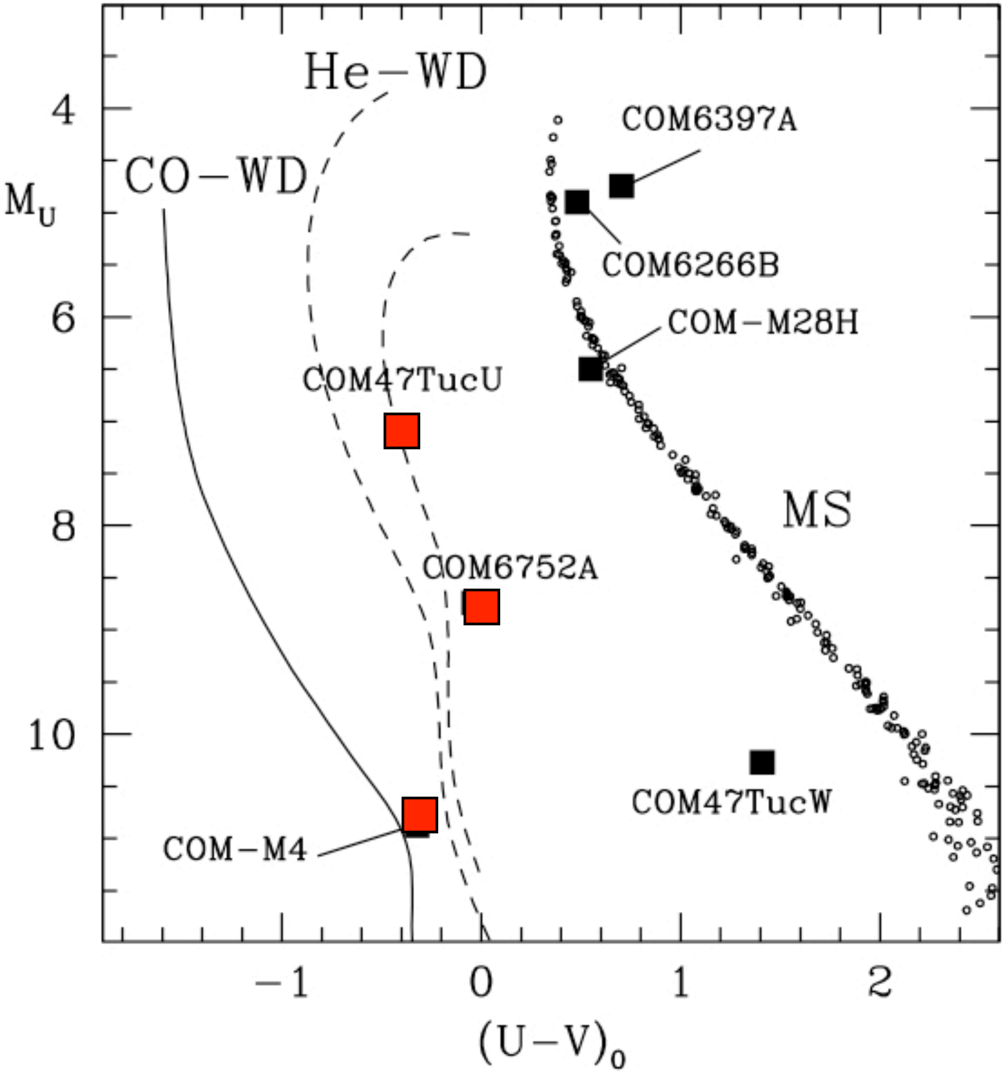


The light curve shape shows two distinct and asymmetric minima

Such a shape is a clear signature of ellipsoid variations induced by the NS tidal field on a highly perturbed bloated star

Optical companion to MSP in GGCs

7 objects in 6 GGCs



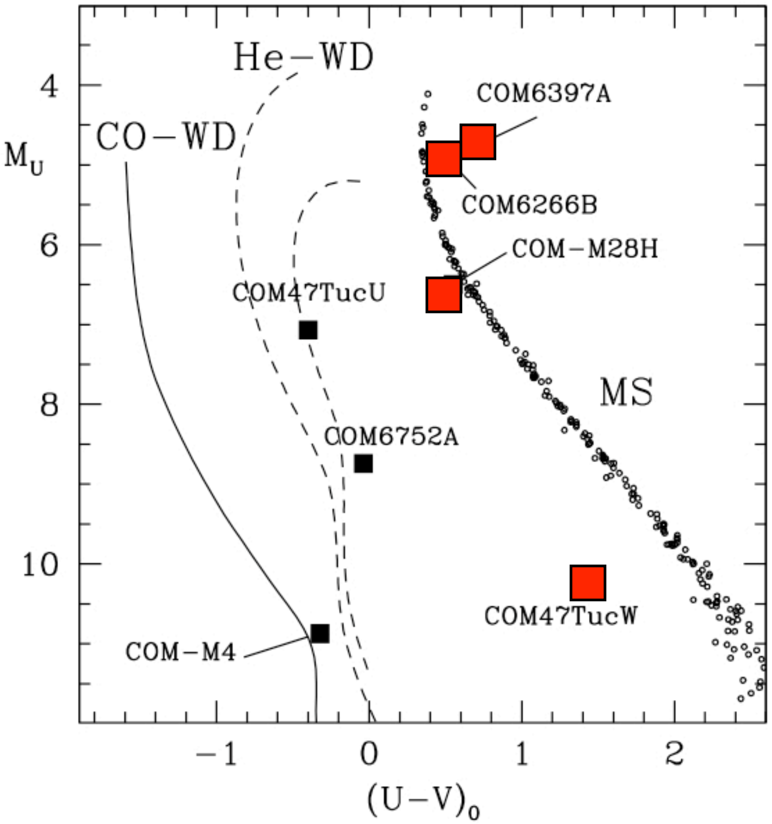
3 HeWDs

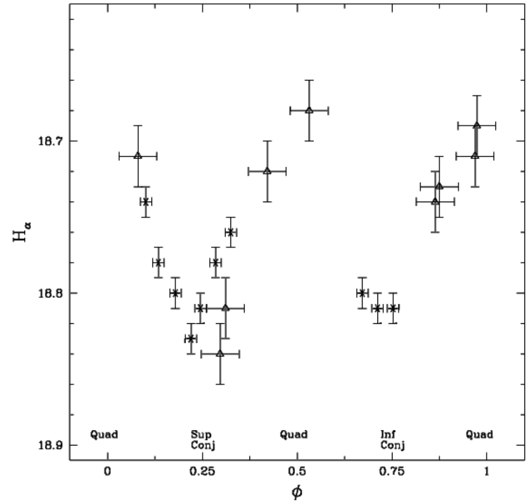
CONFIRMATION OF THE RECYCLING SCENARIO

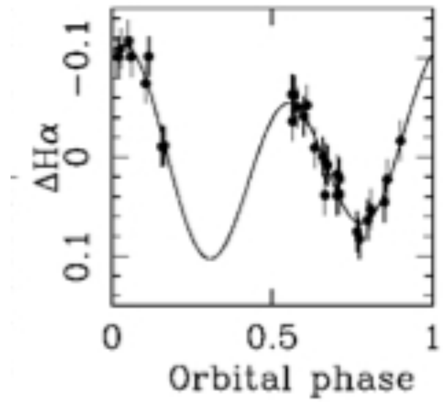
Low mass He-WD orbiting a MSP is the preferred "final stage system" of the pulsar recycling process

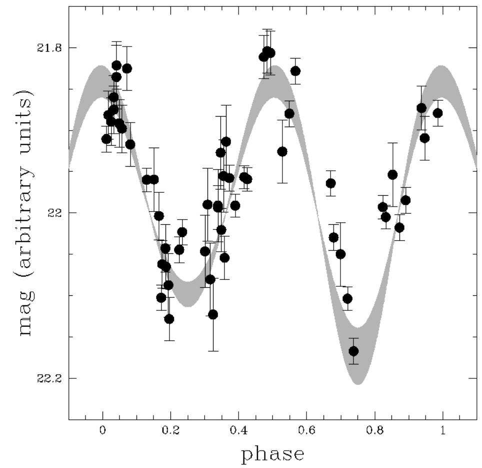
Optical companion to MSP in GGCs

7 objects in 6 GGCs





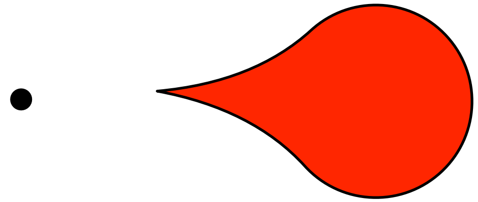




4 non-degenerate companions

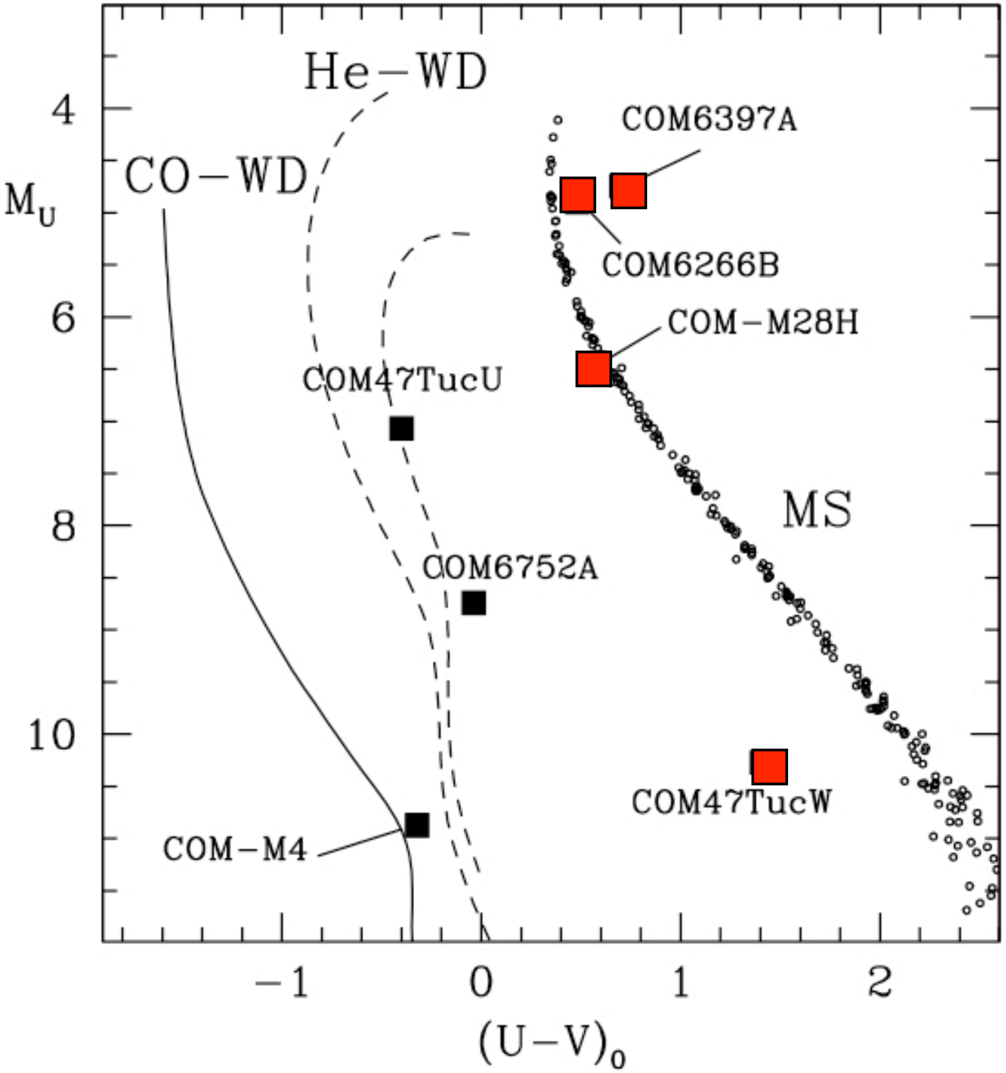
3 deformed MS (pre-HeWD stage?)
+1 low-mass MS

NS **BLOATED STAR**



Optical companion to MSP in GGCs

7 objects in 6 GGCs

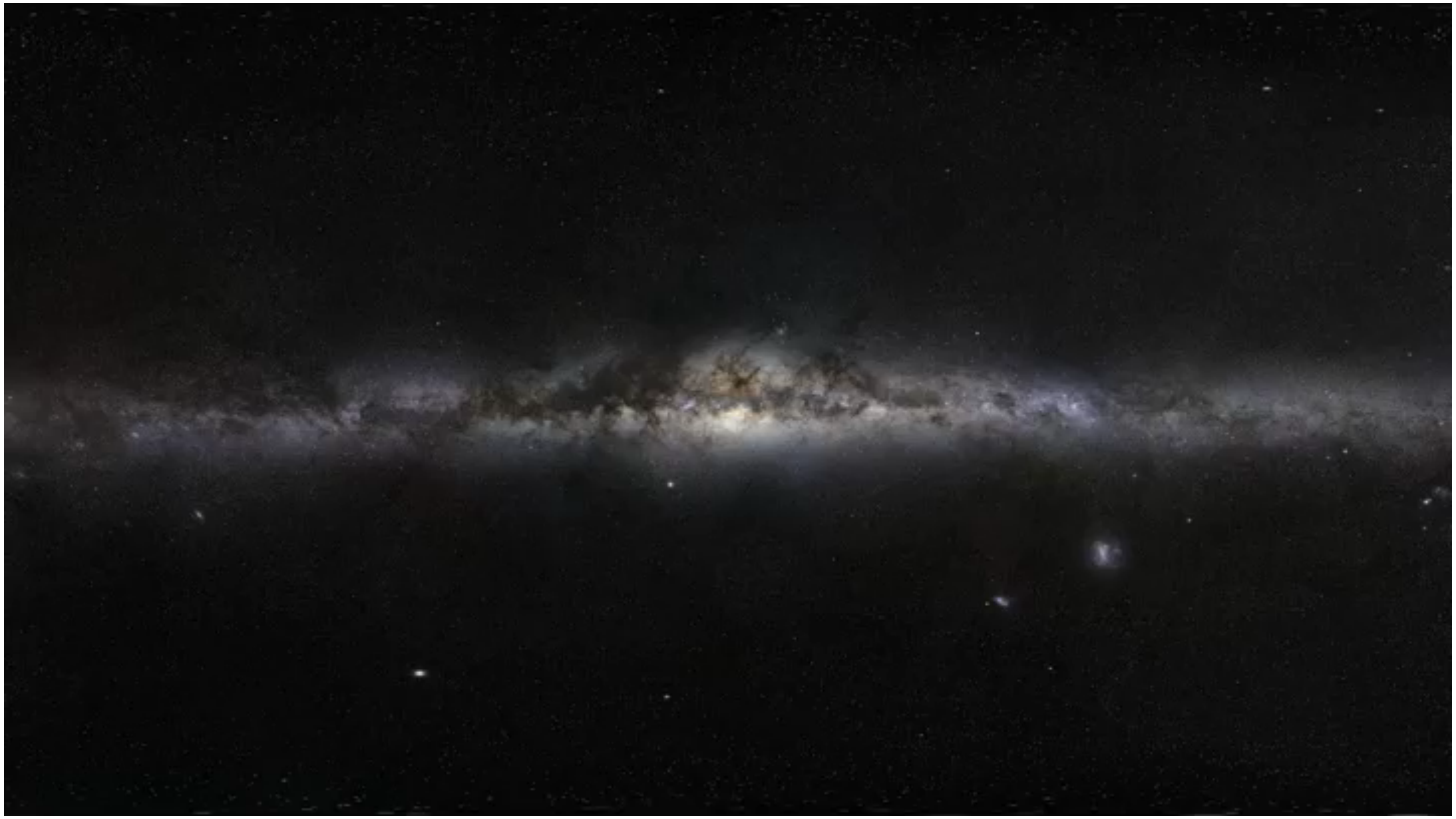


4 non-degenerate companions

3 deformed MS (pre-HeWD stage?)
+1 low-mass MS

EXCHANGE INTERACTIONS?
the high-density enviroment favours exchange interactions

THE TRUE NATURE OF TERZAN 5
THE LARGEST GALACTIC "FURNACE"
OF MSPs

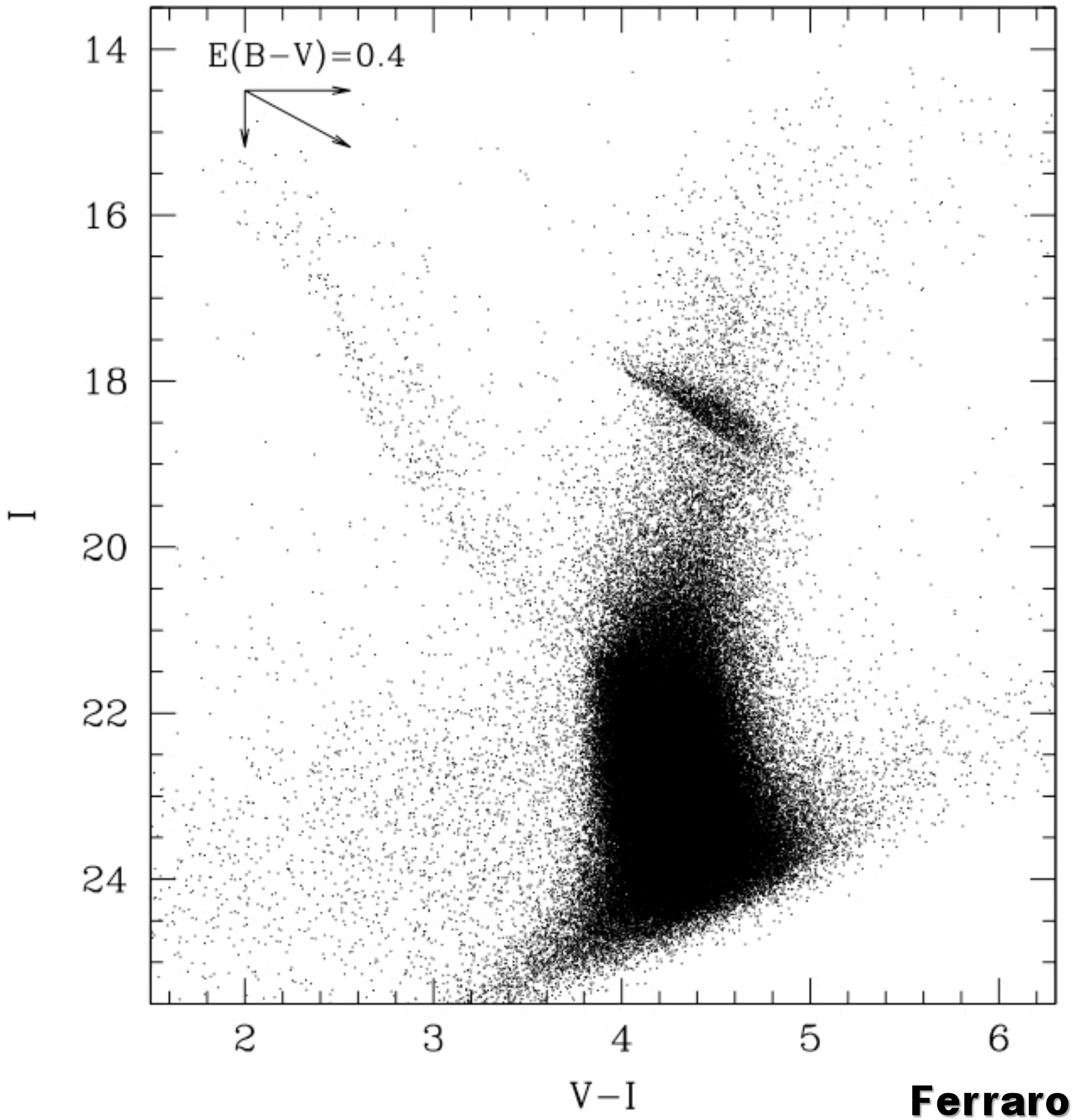


E(B-V)=2.3; d = 6Kpc; d_{GC}=2.1 kpc (Valenti et al 2007) i.e. in the outskirts of the inner Bulge

Suspected to have the largest collision rate of the entire GC system (Verbunt & Hut 1987, Lanzoni et al 2010)

33 MSPs have been discovered by Ransom et al (2005) in TERZAN 5 : this is the largest population of MSP ever detected in a GC

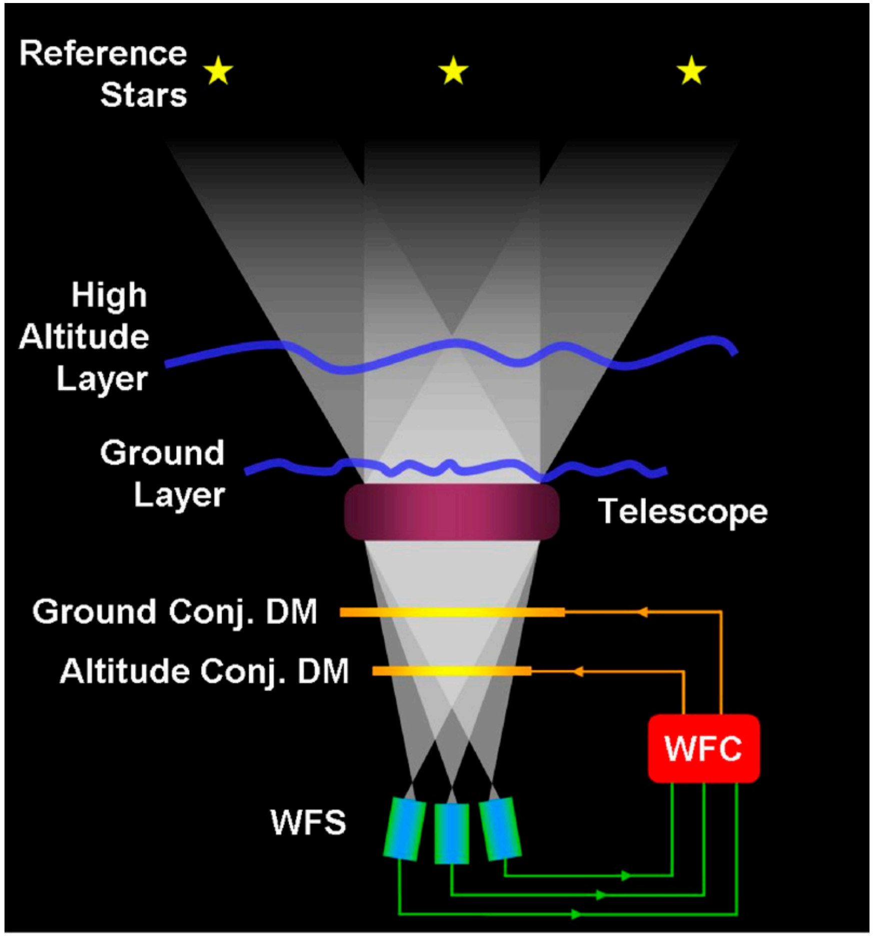
The deepest optical CMD of Terzan5 from ACS@HST



Main Problem:
Differential reddening

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

MAD = Multi-conjugate Adaptive Optics Demonstrator



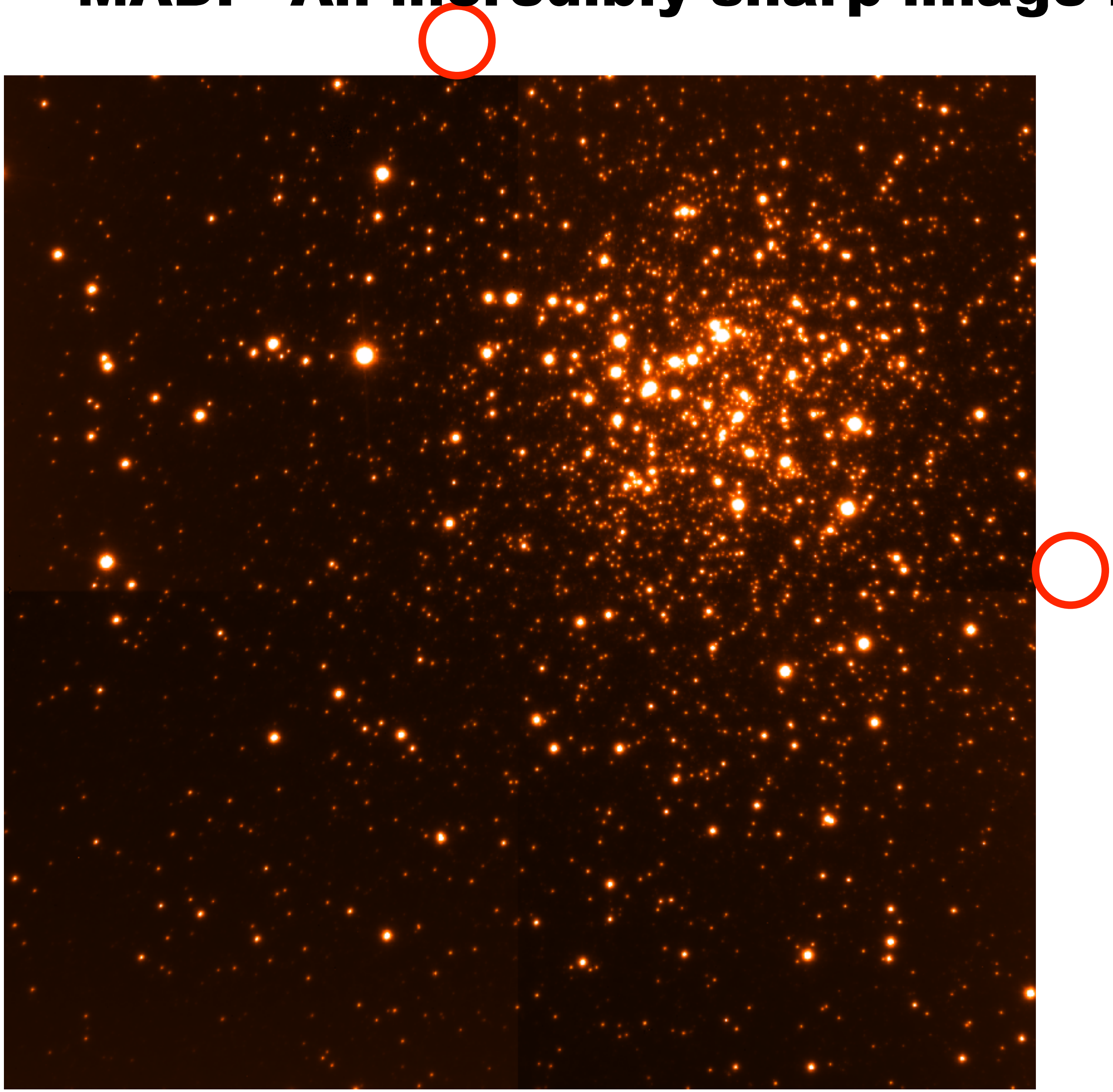
The MCAO Concept

ESO Press Photo 19c/07 (30 March 2007)

MAD operates in the near-IR
By using up to three Reference stars MAD is able to perform good and uniform AO correction over a large FoV (1` x 1`)
MAD was temporally installed on VLT in summer 2008

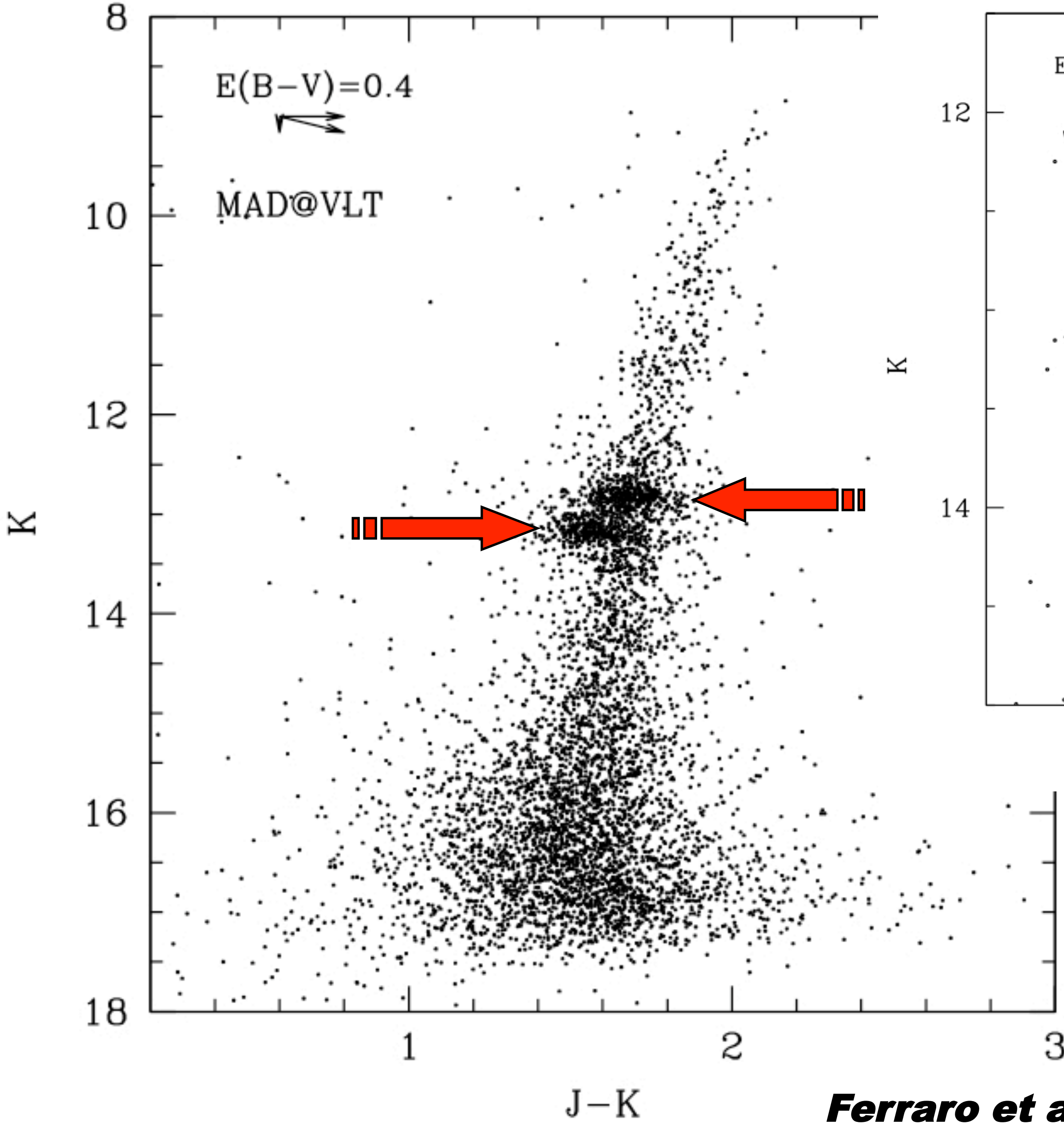
9 hours of observations were granted to our proposal:
Hunting for optical companions to binary MSP in Terzan 5
Observations were executed in August 2008.

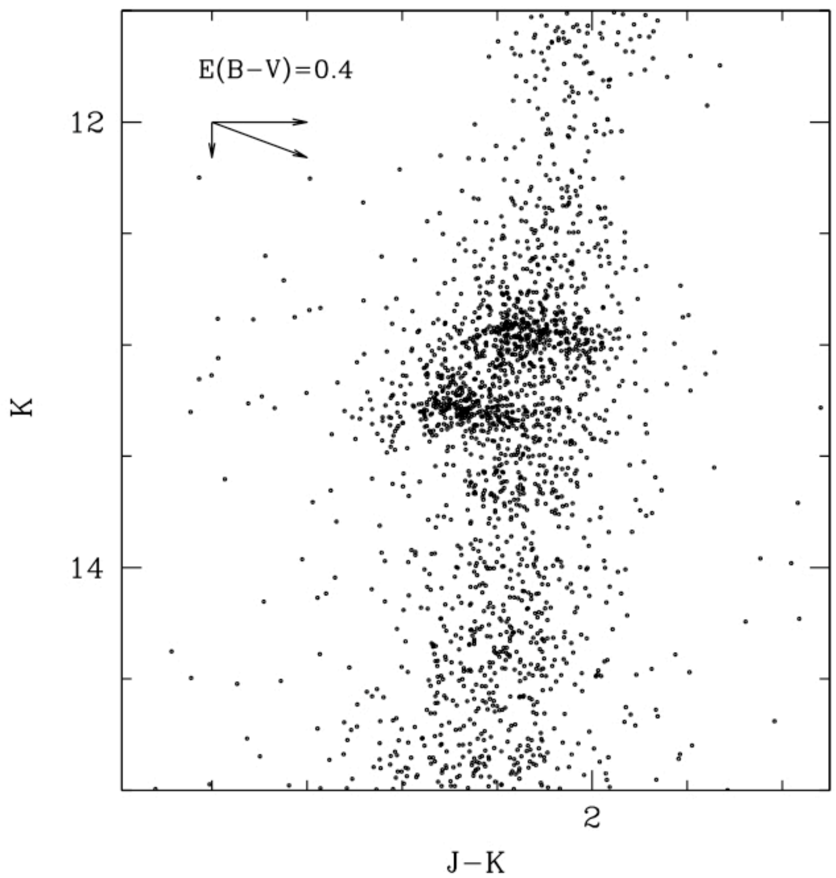
MAD: An incredibly sharp image in the K band !!



FWHM=100mas
By using
only 2 AOGS !!!!

THE MAD CMD OF TERZAN 5





TWO Horizontal Branches !!!

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

WHICH IS THE ORIGIN OF THE TWO HBs?

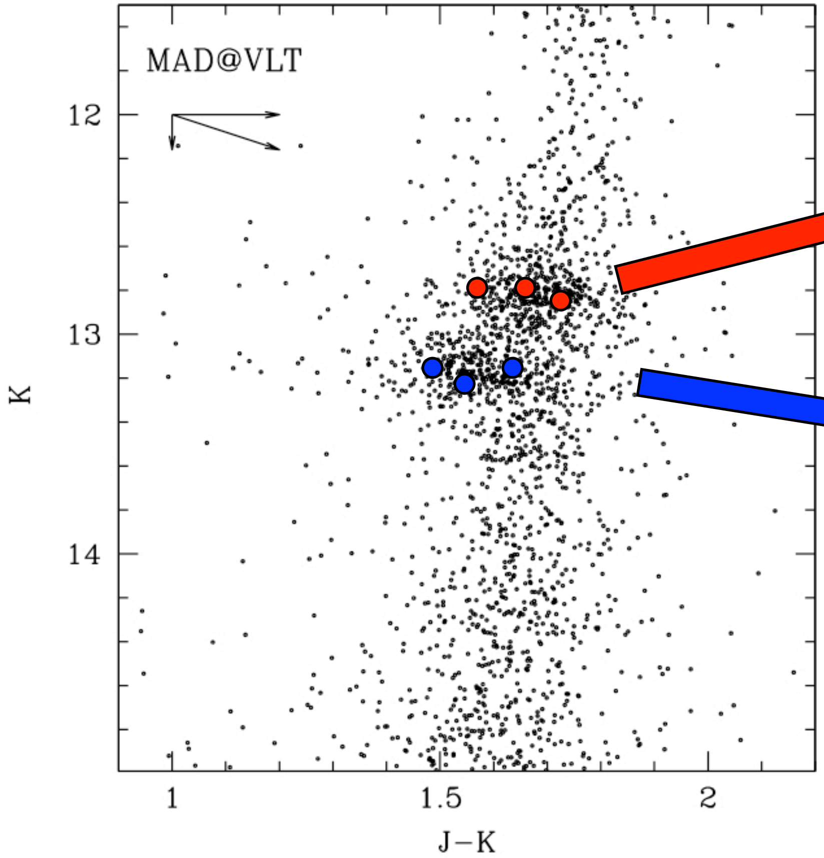
AGE & METALLICITY ..

The simplest solution..

The most NATURAL (& EXCITING) possibility is that the TERZAN 5 harbours two distinct populations

The two HBs would be the signature of a complex star formation history

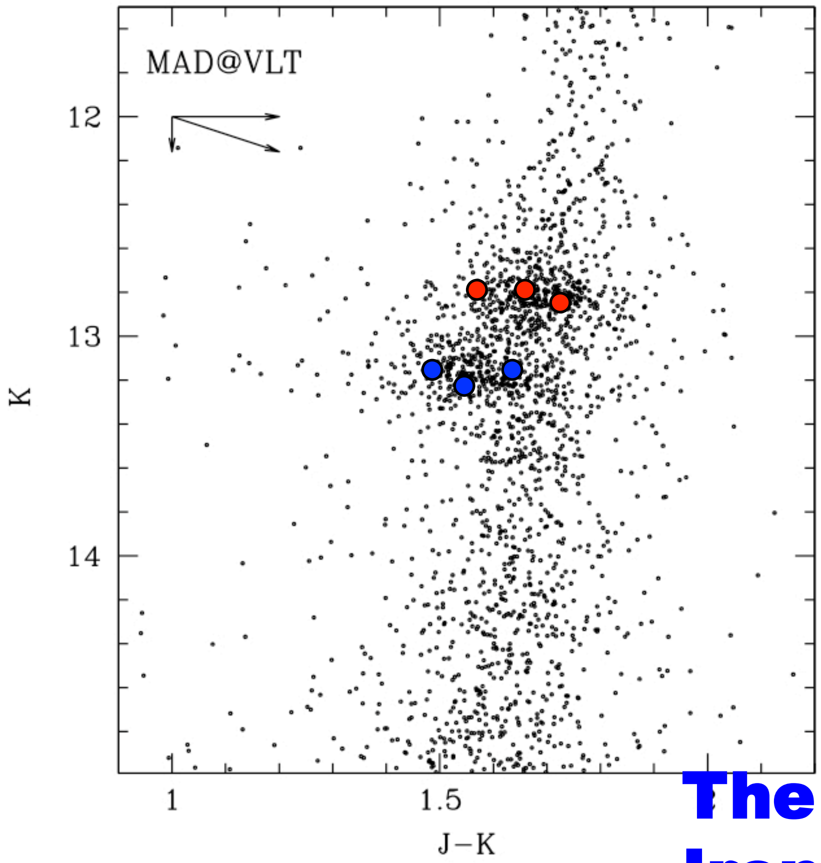
On July 2009 we observed 6 HB stars (3 in the BHB and 3 in the FHB) with NIRSPEC at Keck II

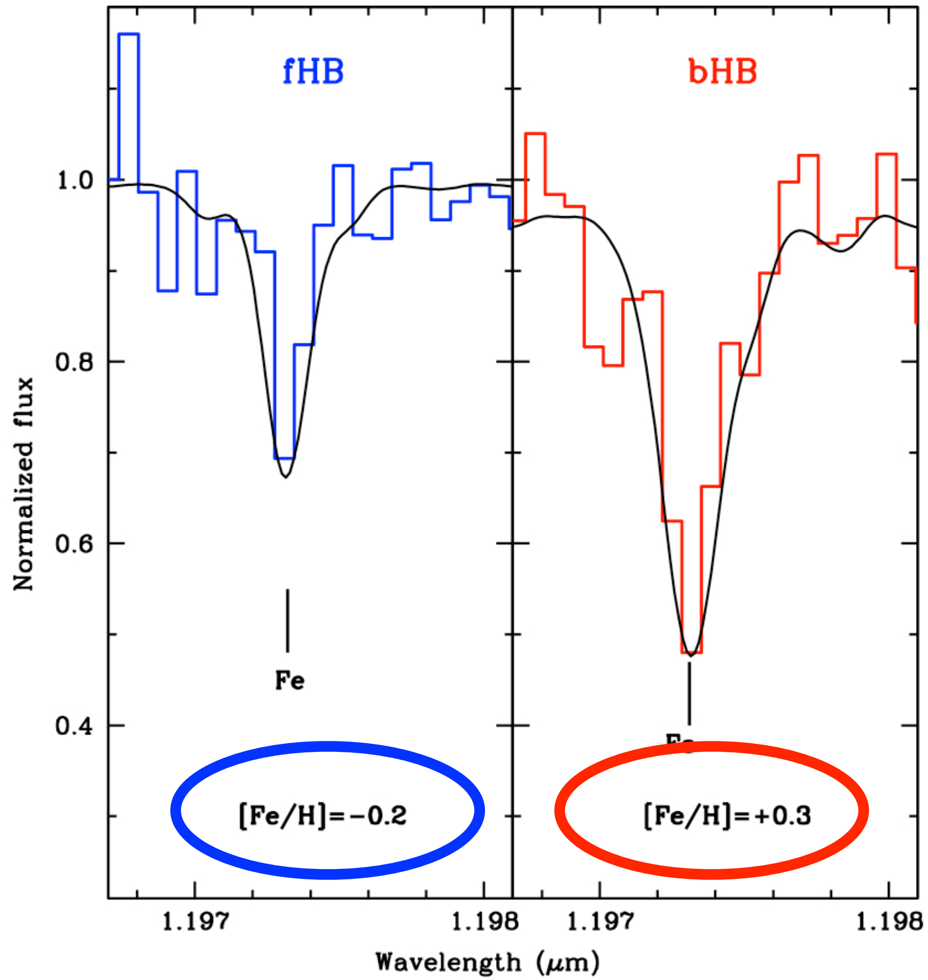


V_{rad} = -85 Km/s (σ=10 Km/s)

V_{rad} = -85 Km/s (σ=9 Km/s)

The two populations belong to the same stellar system

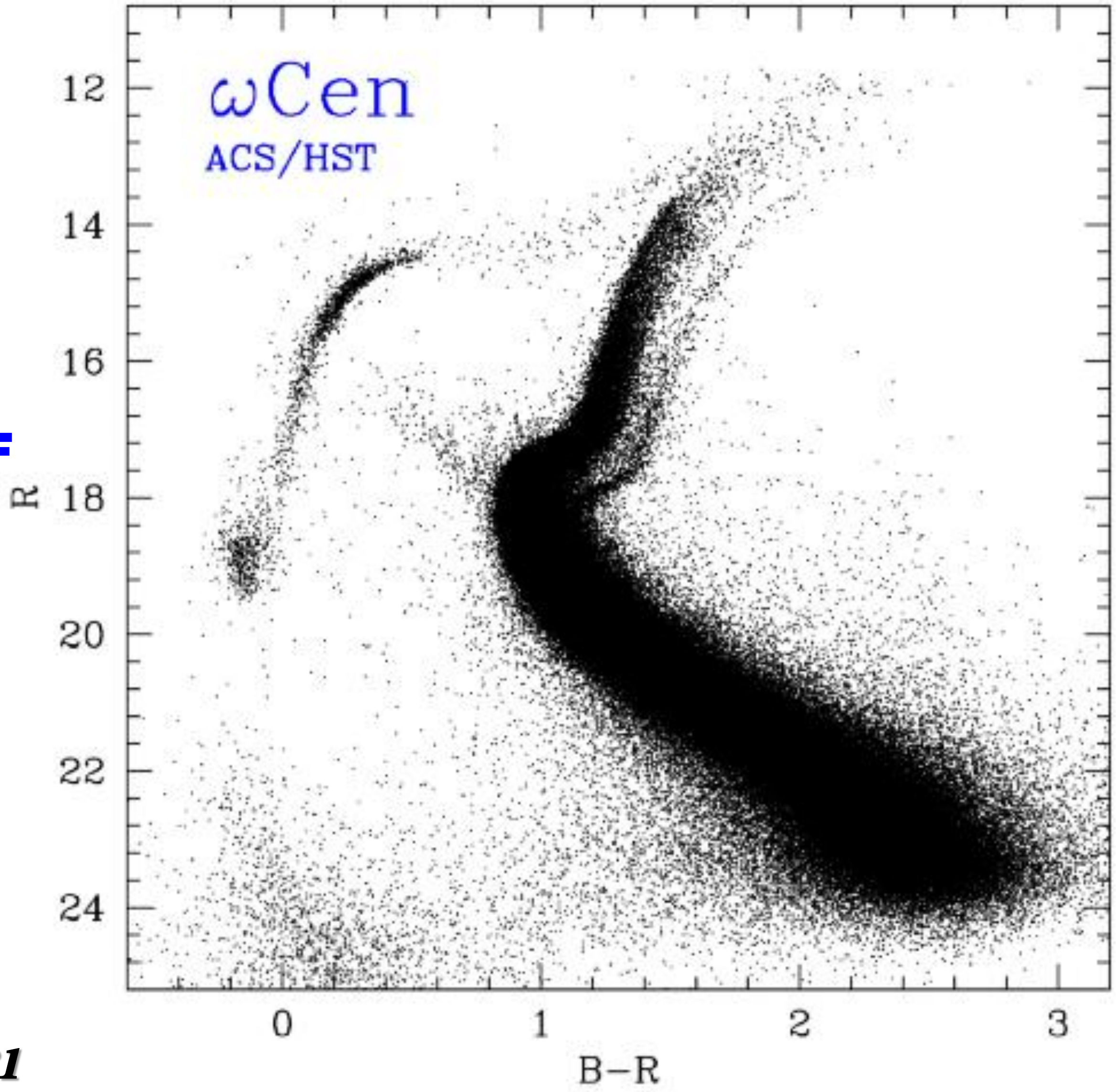




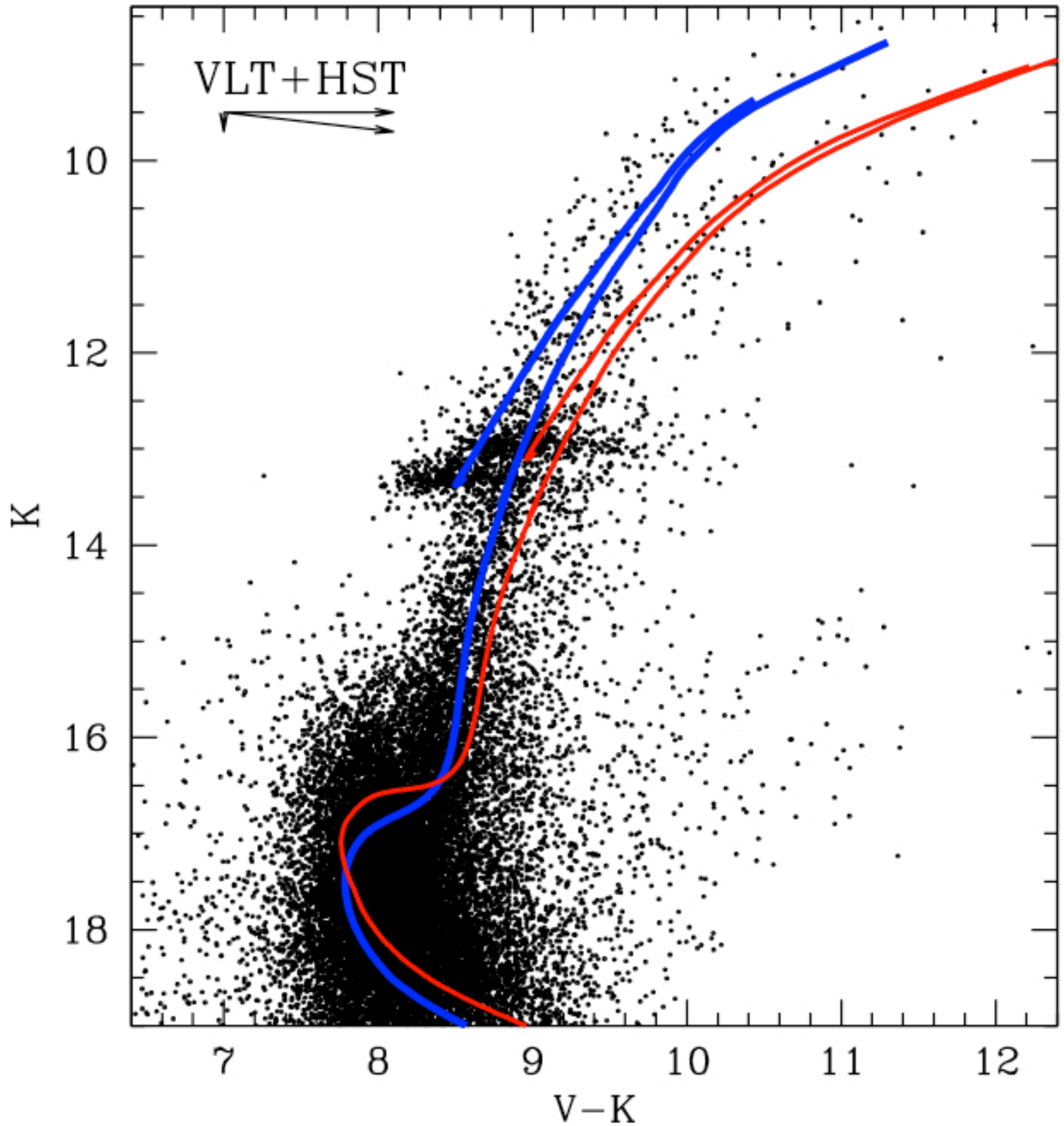
The two populations have different Iron abundance !!!

THIS IS A QUITE EXCEPTIONAL RESULT SINCE NO GENUINE GCS HAS BEEN FOUND TO HARBOUR STARS WITH DIFFERENT IRON ABUNDANCE

THE ONLY KNOWN EXAMPLE IS OMEGA CENTAURI WHICH IS CONSIDERD TO BE THE REMNANT OF A LARGER STRUCTURE



Ferraro et al., 2004 ApJ, 603, L81



Z=0.01 t=12 Gyr

Z=0.03 t=6 Gyr

By adopting the measured abundances, the two HB clumps can be reproduced by assuming that the two populations have different ages.

TERZAN 5 experienced at least two main episods of star formation → IT IS NOT A GENUINE GC

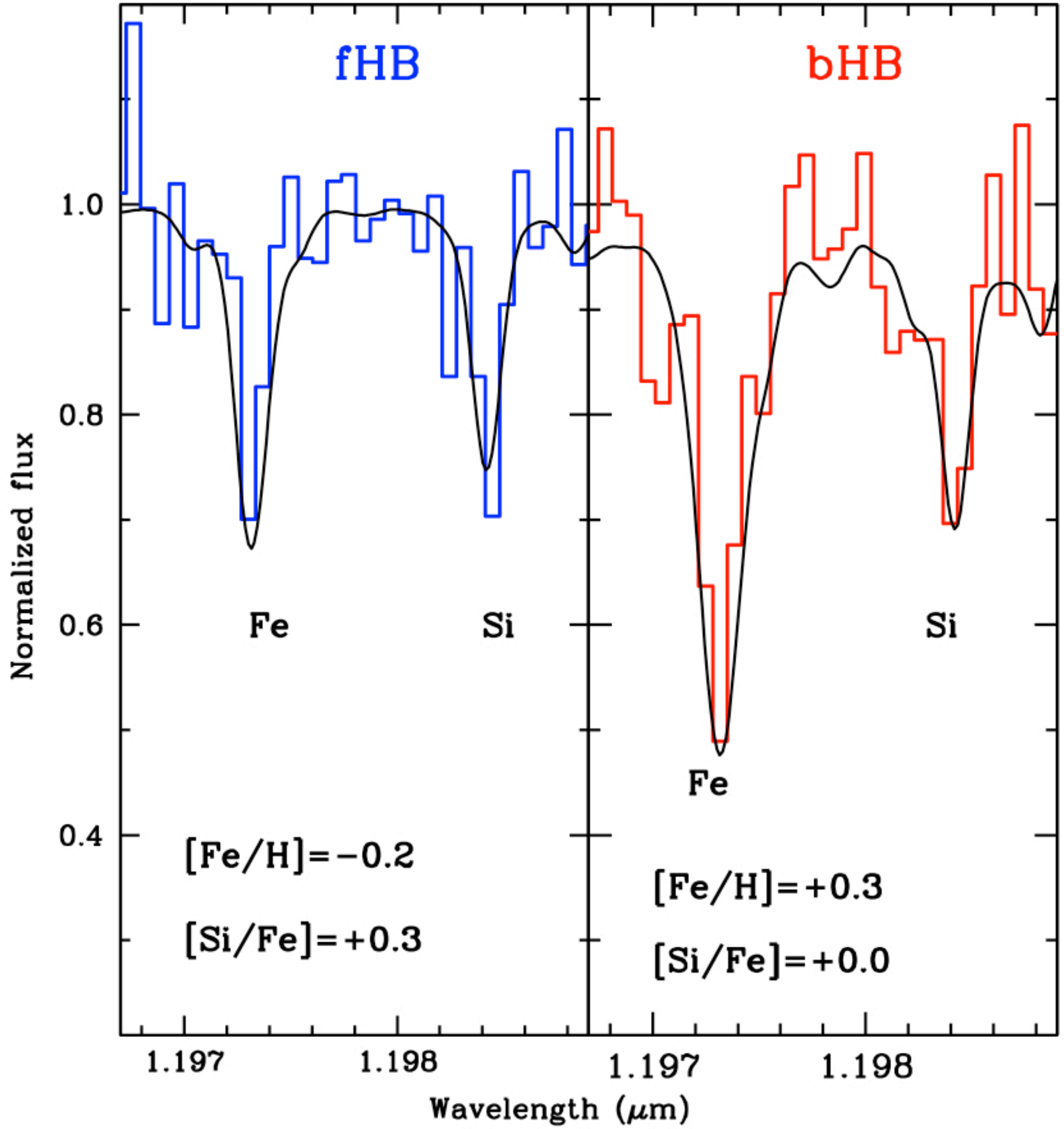
The observational facts demonstrate that Terzan 5 has experienced a quite complex formation history:

1.IT IS A STELLAR SYSTEM SELF-ENRICHED IN IRON.
Hence it should have been much more massive in the past than what observed now (in order to retain the SN ejecta). We estimate that the current mass of Terzan 5 is a few 10^6 Mo.
It could be the relic of a large stellar system (like Omega Cen or M54).

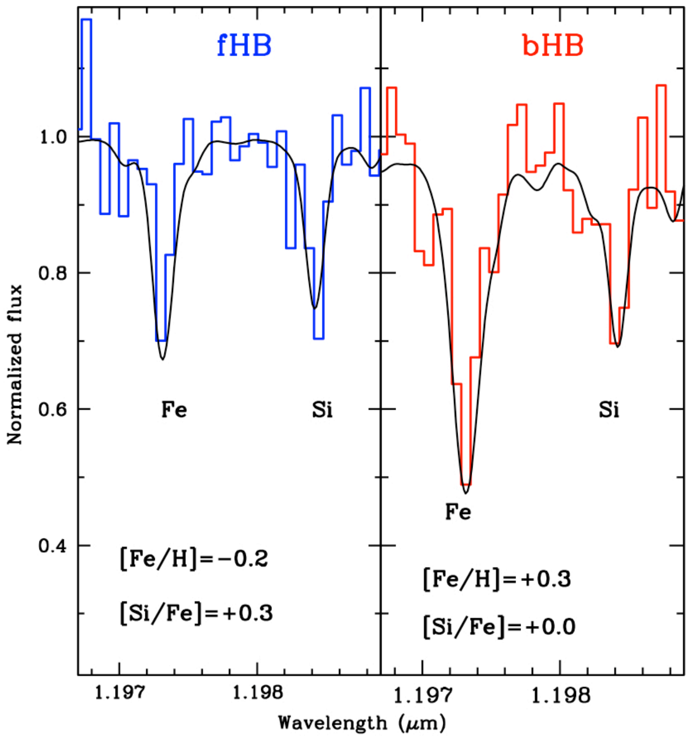
2. However it is unlikely that Terzan 5 is a system "accreted" From outside the Galaxy, since the chemical composition of the two Populations are similar to that measured in Bulge stars, Thus suggesting a Terzan5-Bulge "common" evolution
(Terzan 5 a building block of the bulge?)

[α /Fe]=+0.3 at [Fe/H]=-0.2

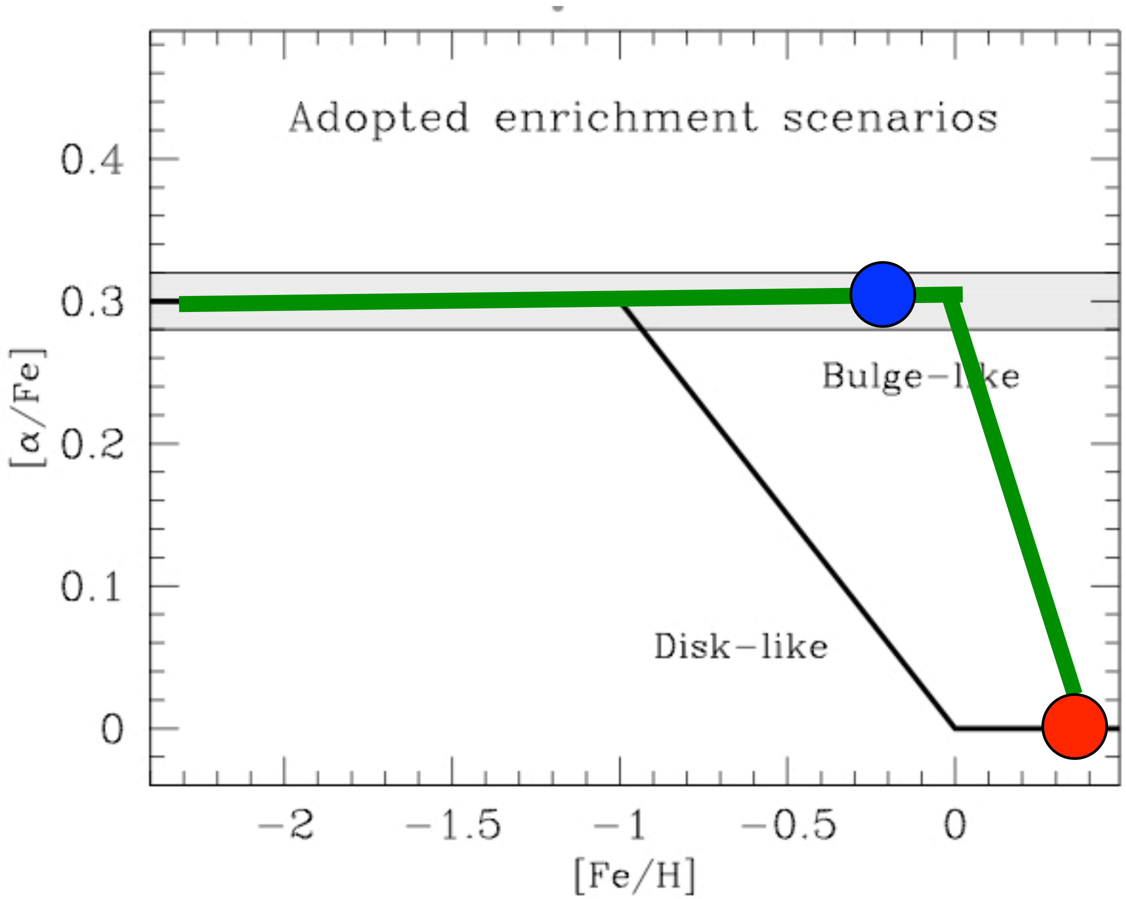
[α /Fe]=0.0 at [Fe/H]=+0.3

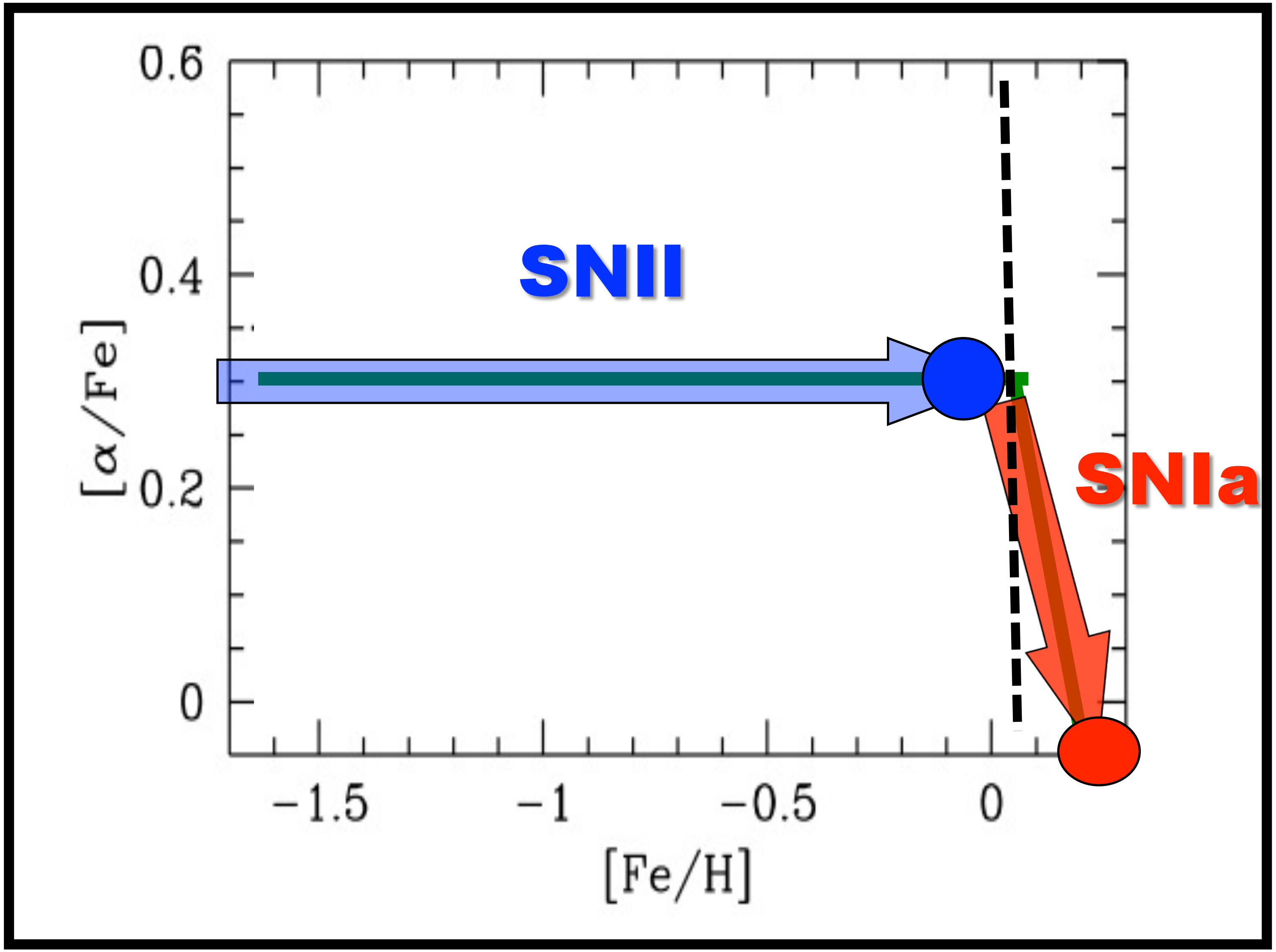


Iron and alpha –elements abundance are similar to those measured in the Bulge suggesting a quite similar star formation and chemical enrichment processes



BULGE-LIKE





Chemical evolution models (Ballero et al 2007) suggest that this trend can be reproduced by a high SFR and a flat IMF .. i.e. with a large number of SNII !!!

The assumption of a similar scenario for TERZAN5 would naturally explain the large number of MSP

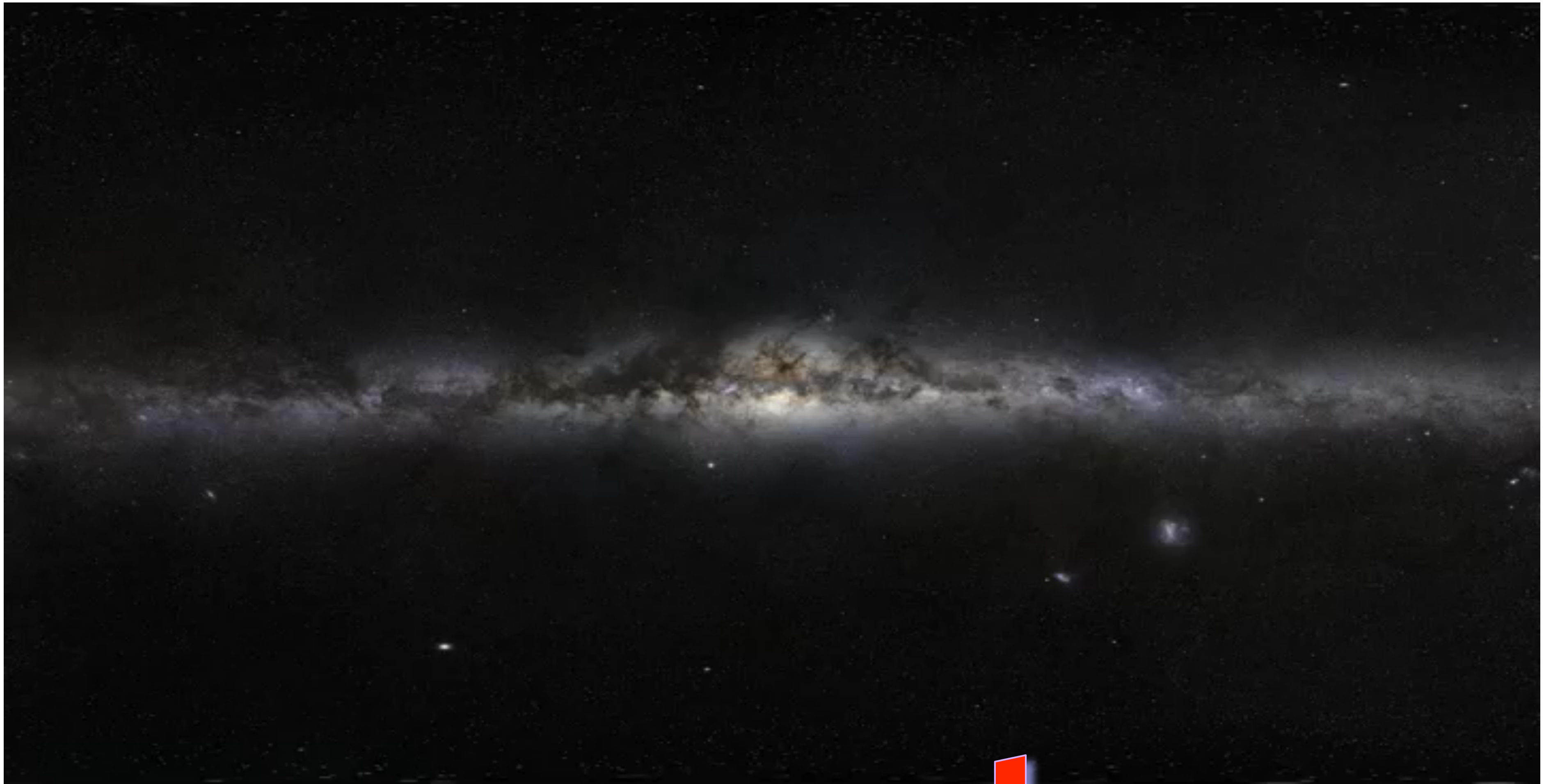
Many SNII → Many NS (most of them retained by the Massive Proto-Terzan 5 system)

+ high collision rate ($\Gamma \approx \rho_0^{1.5} \times r_c^{0.5}$)

New values : $\rho_0 \approx 2 \times 10^6$ Mo/pc^3 $r_c \approx 0.26$ pc
Lanzoni et al (2010, ApJ, 717, 653)

Terzan 5 has the largest collision rate of any stellar aggragate in the Galaxy

→ many recycled NS → MSP



The End