KITP - Santa Barbara ; Feb 5, 2009

Blue Straggler Stars in Galactic Globular Clusters: the observational perspective

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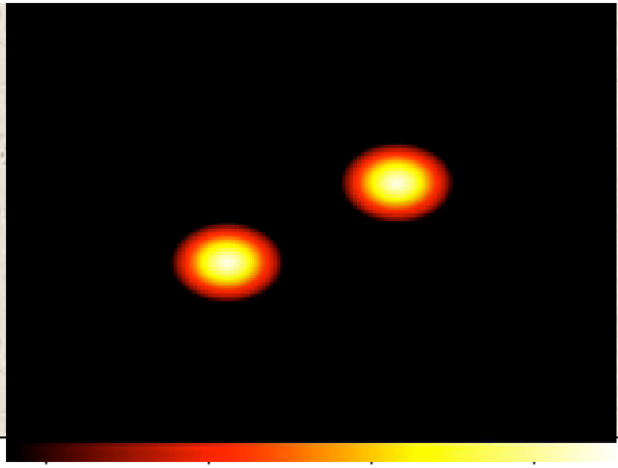
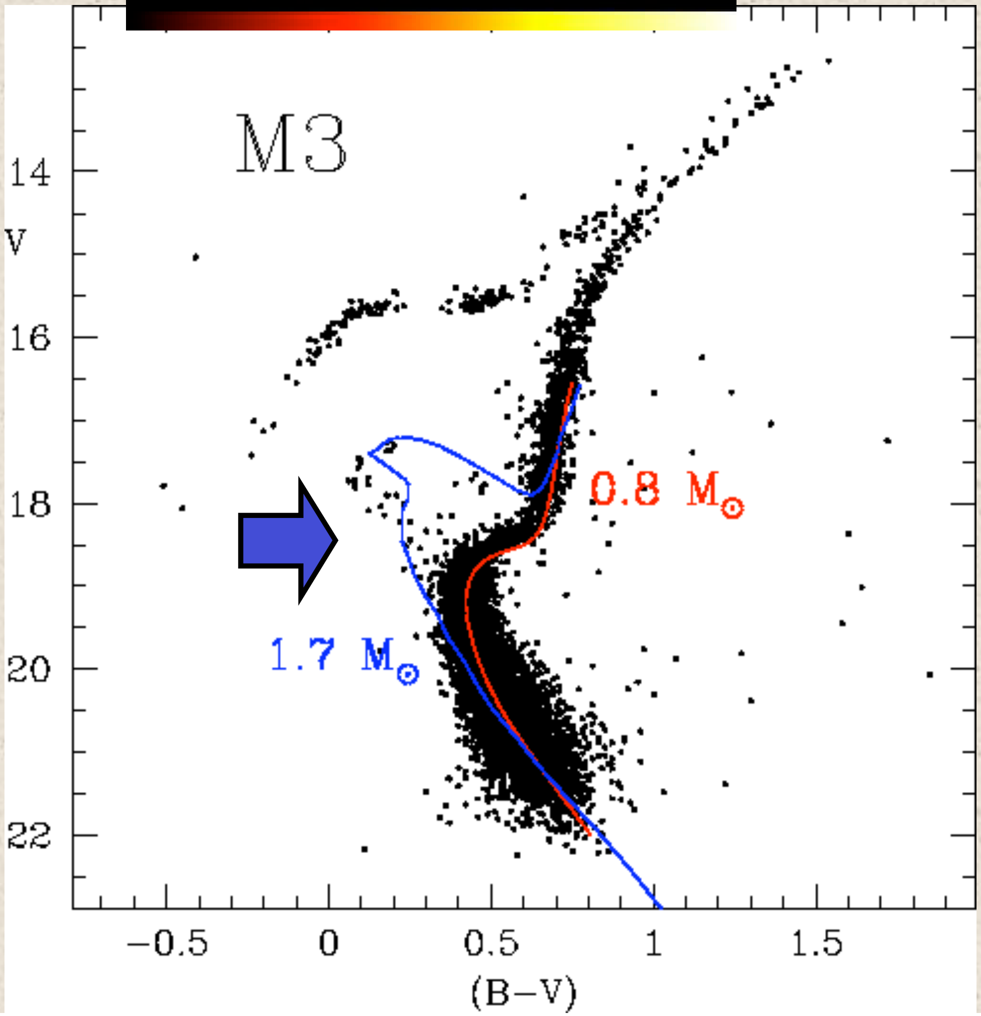




Blue Straggler Stars

BSS have been detected for the first time by Sandage (1953)

according to their position in the CMD, *BSS* should be *more massive* than *normal* stars (see also Shara et al 1997)

merge of 2 low-mass stars ⇨ unevolved, massive star

primordial Binaries

…evolving in isolation In low density GCs

PB-BSS

direct Collisions

..in the central region of high density GCs

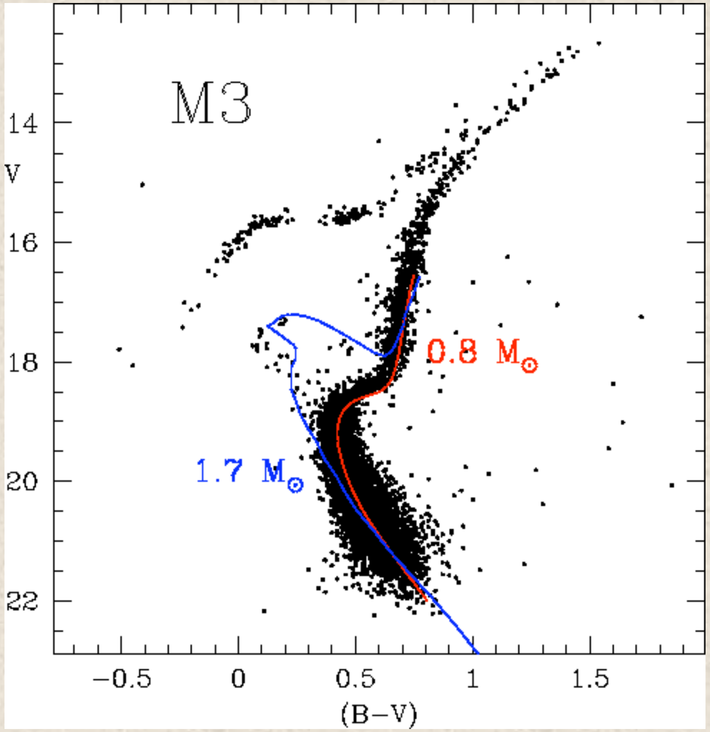
COL-BSS

BSS → **crucial link between stellar evolution & stellar dynamics**

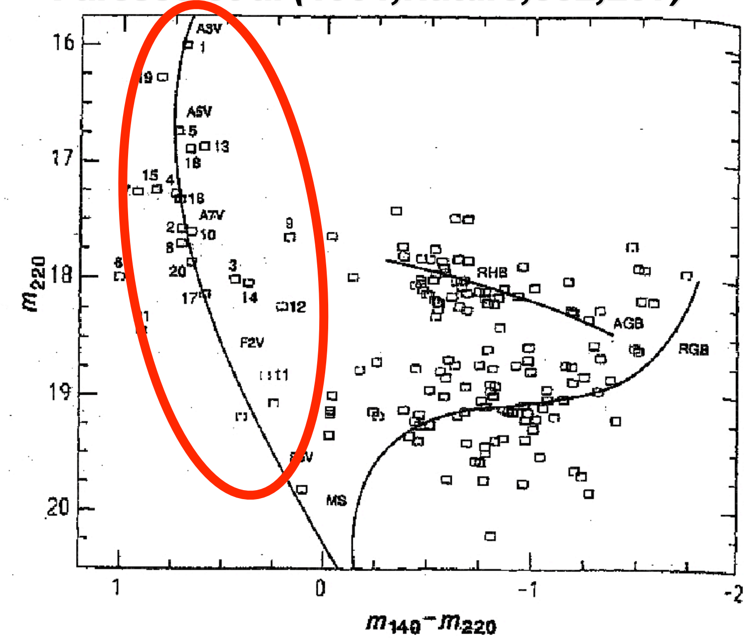
Blue Straggler Stars

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**

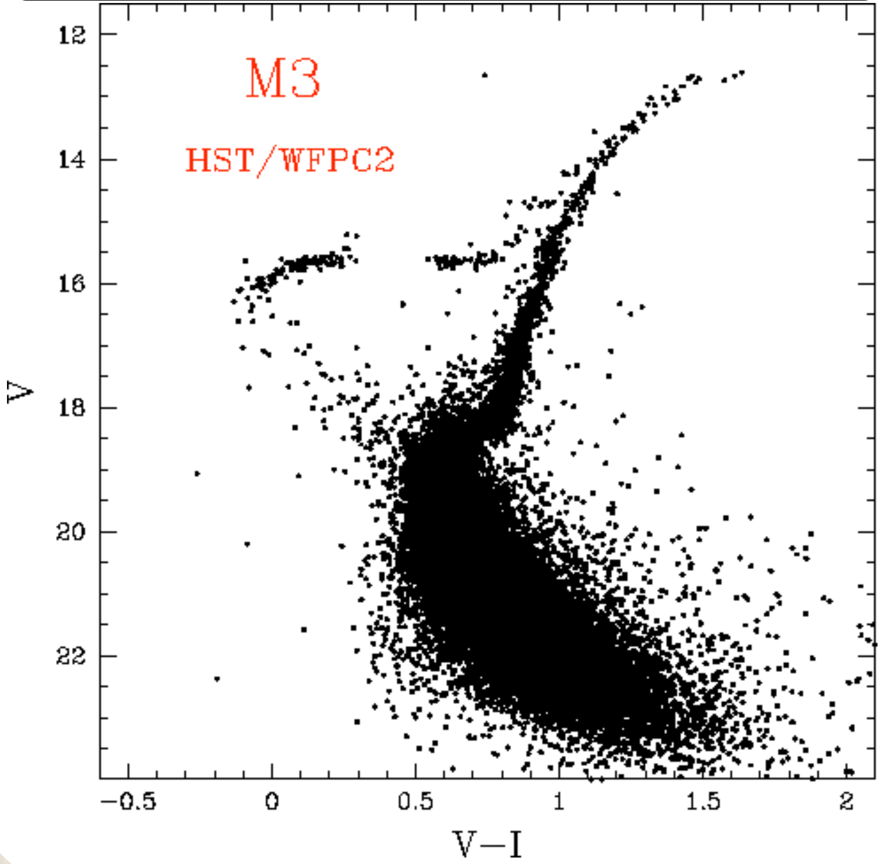
HST

UV sensitivity , high resolution

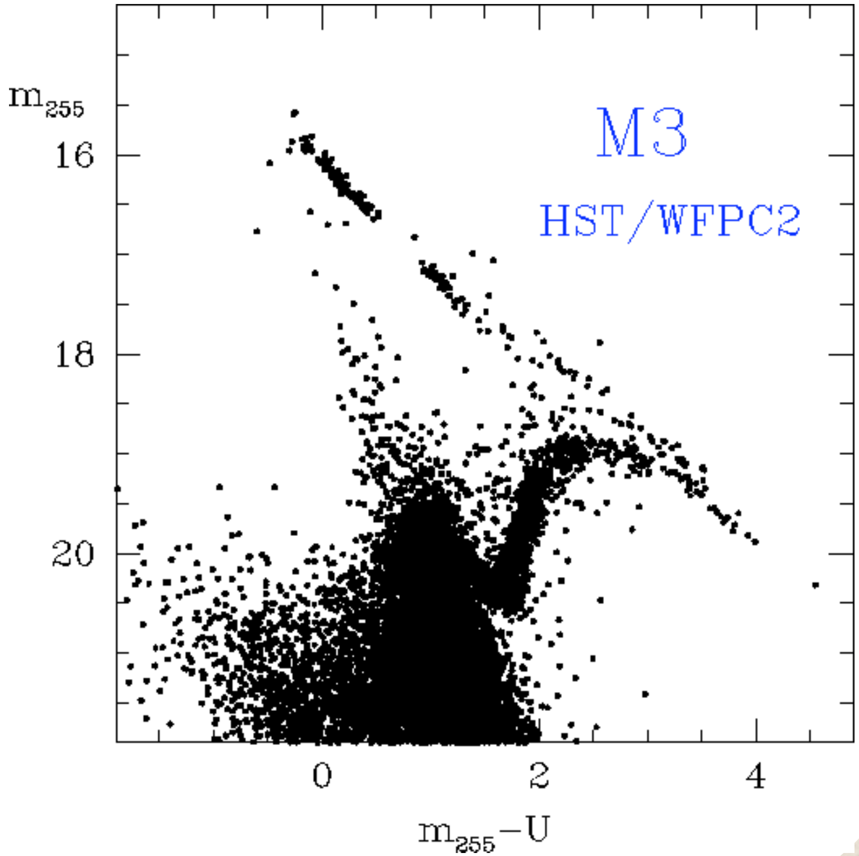
⇩

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

The "classical" plane



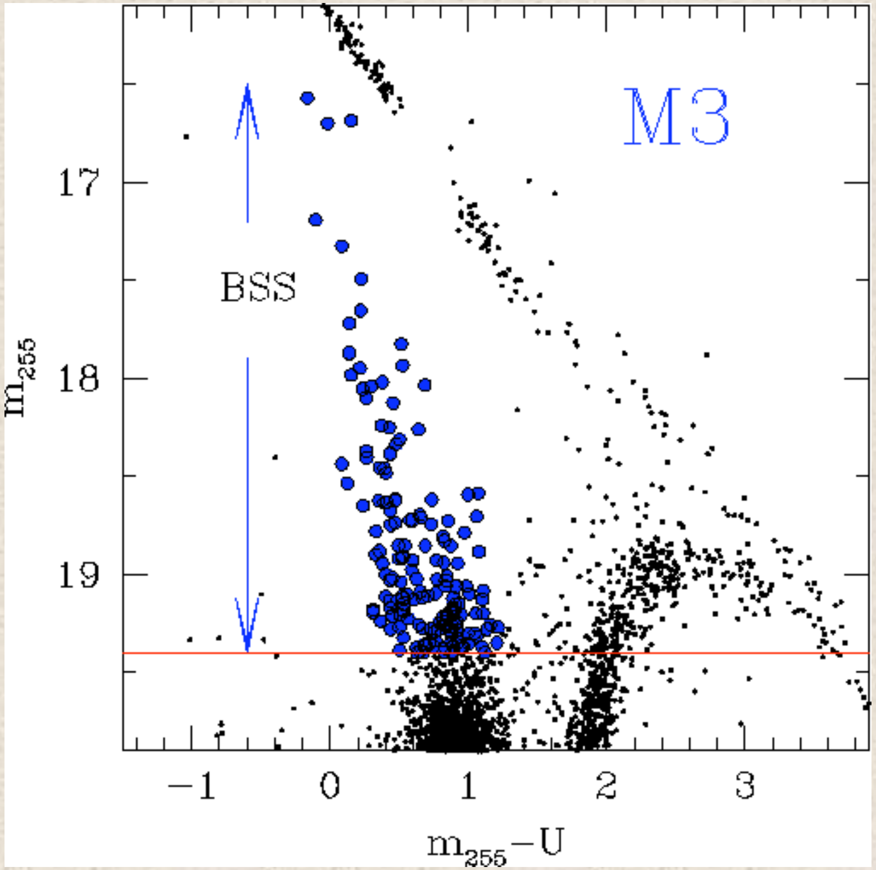
The UV plane



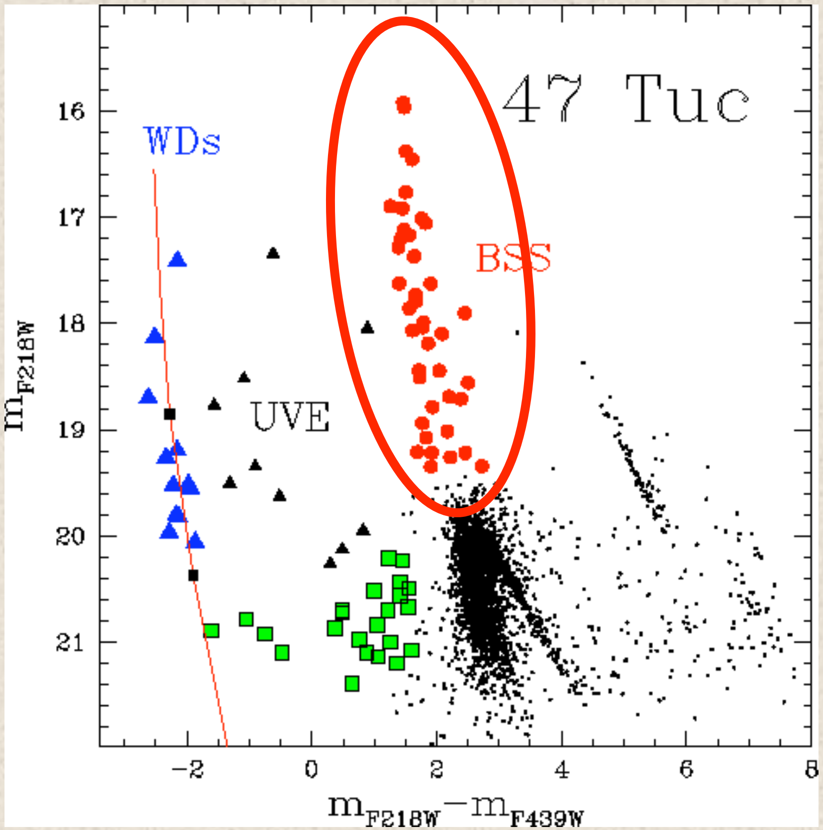
BSS in the UV:

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)



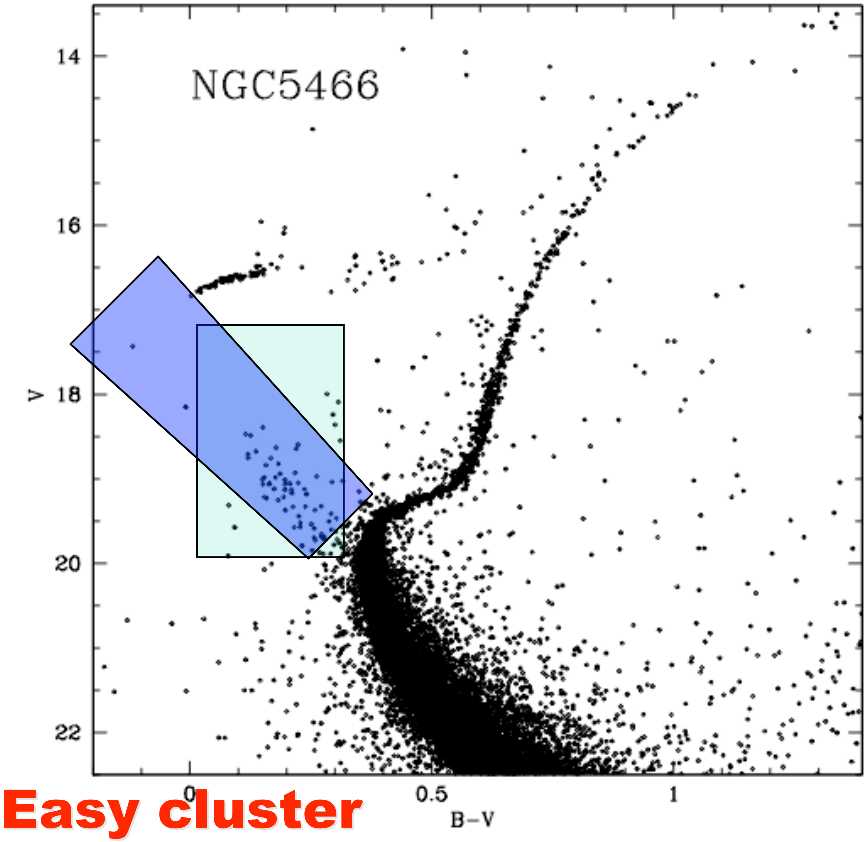
Ferraro et al (2001,ApJ,561,337)

BSS "operative" definition

BSS definition is intrinsically arbitrary since the BSS sequence merge into the upper MS without any discontinuity

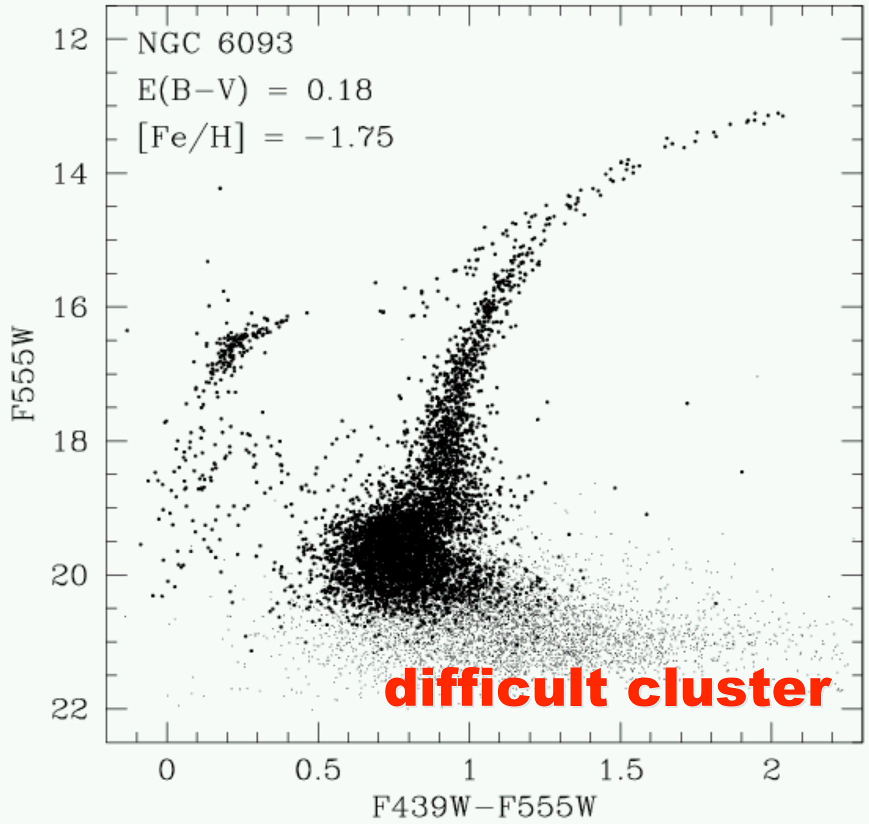
HOMOGENEITY is important !!!

Different authors have different definitions of BSS



Easy cluster

Definition also depends on the quality of the data

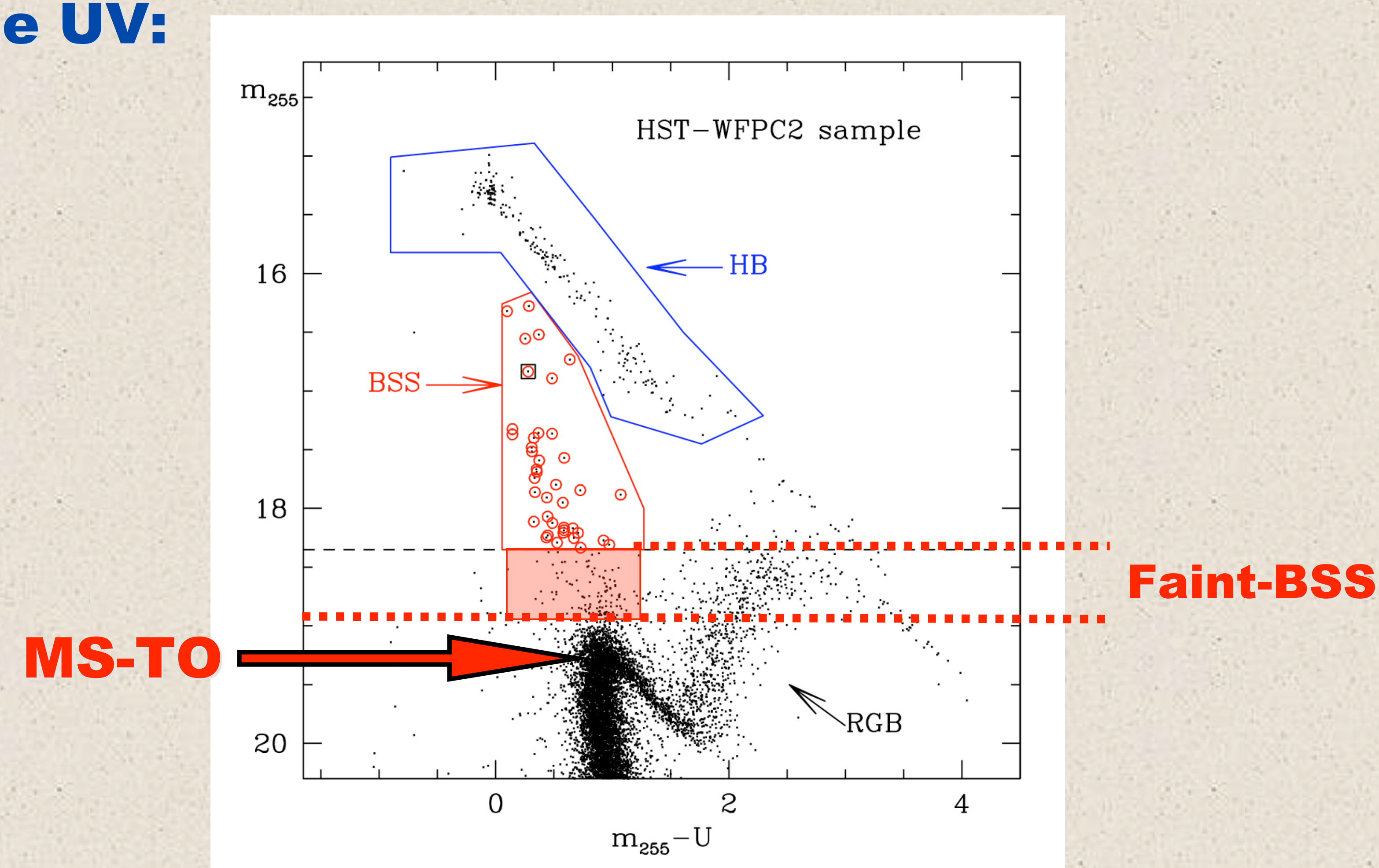


difficult cluster

BSS "operative" definition

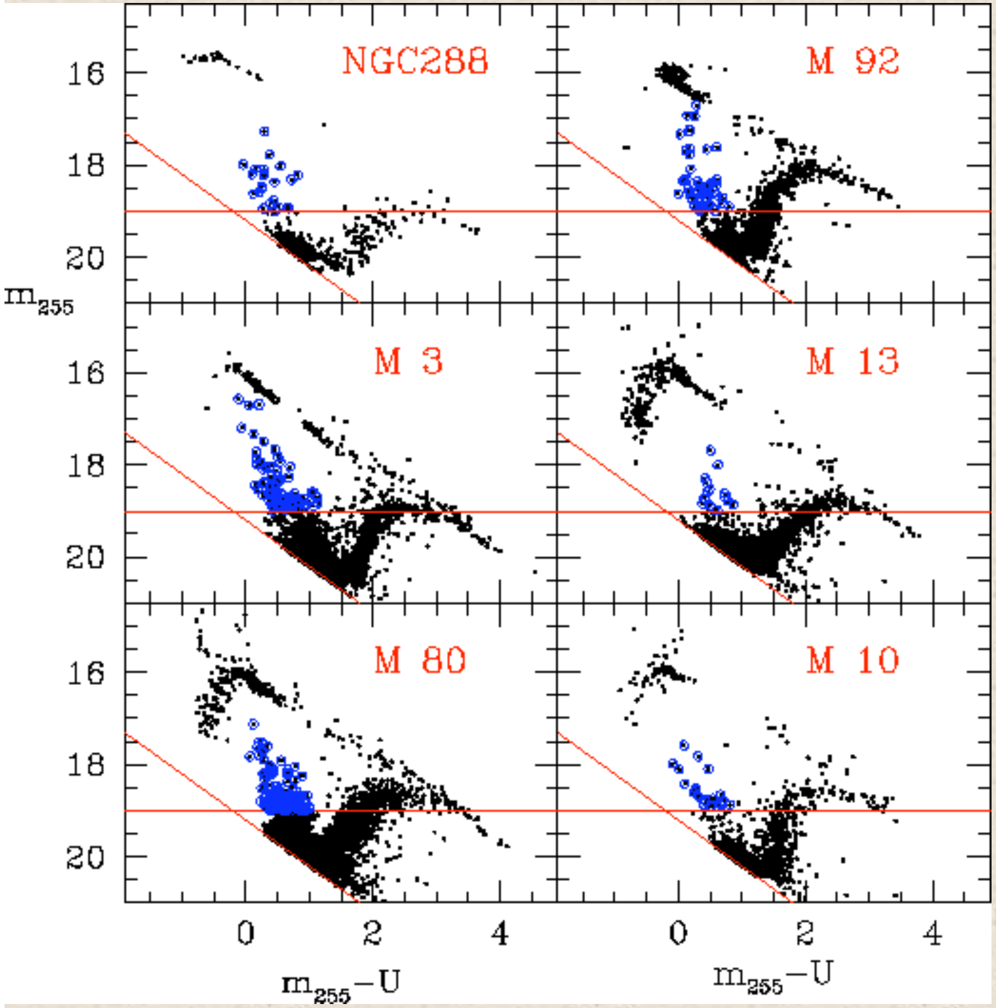
BSS definition is intrinsically arbitrary since the BSS sequence merge into the upper MS without any discontinuity

In the UV:



Direct comparison of BSS populations

HOMOGENEITY +UV is BETTER !!!

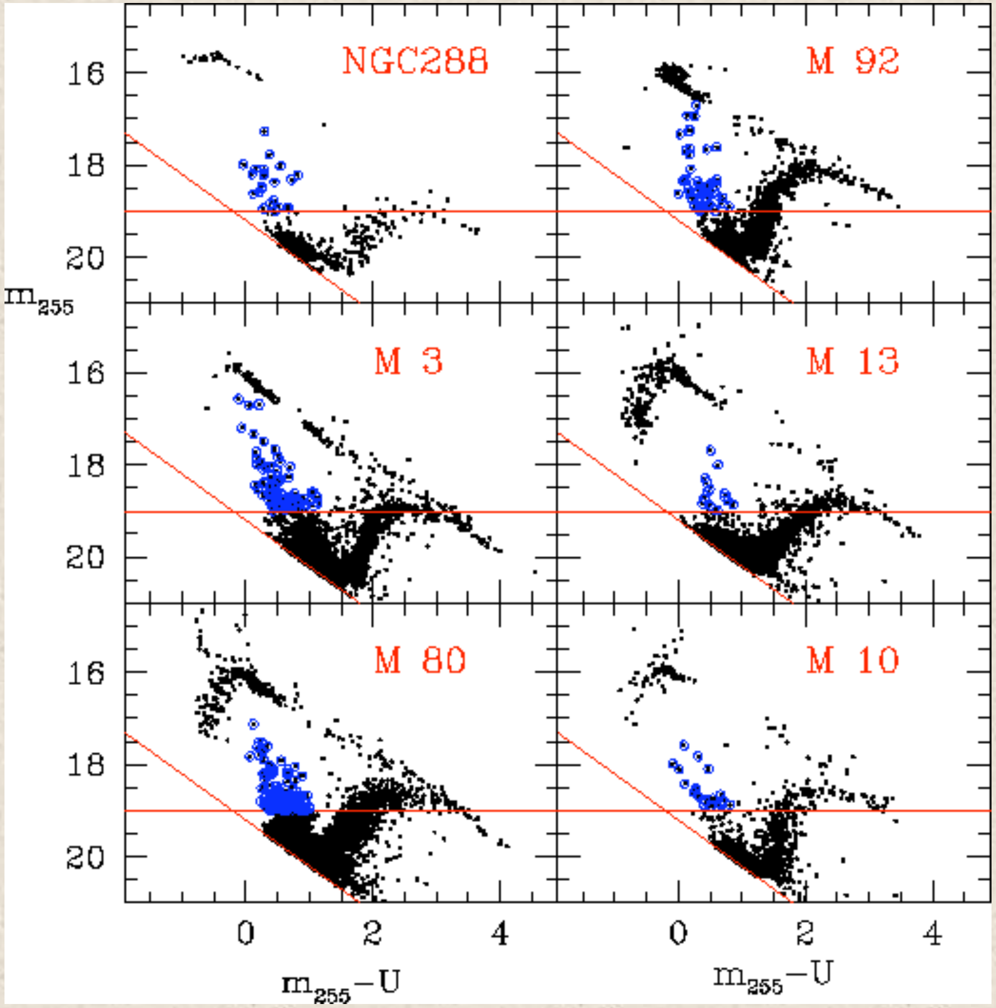


177 orbits in the HST Supplemental Cycle16 have been allocated to observe 45 additional GGCs in the UV

PI: Ferraro
Co-I: Rood,O'Connell, Sigurdsson, Schiavon, Lanzoni, Dalessandro, Mucciarelli, Miocchi, FusiPecci, Origlia, Cacciari, Buzzoni, Valenti,Beccari

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

Direct comparison of BSS populations



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

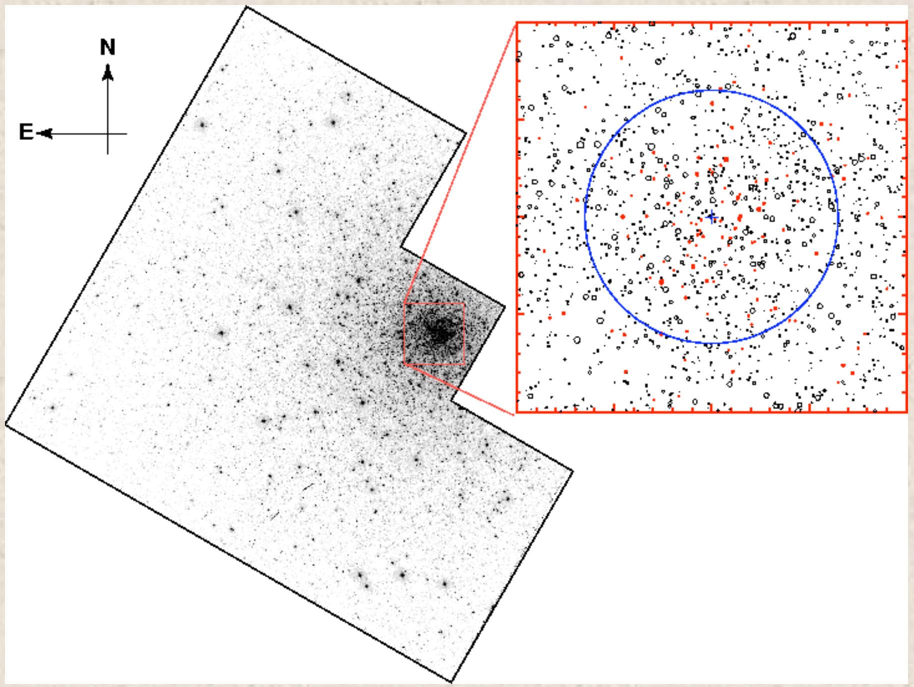
$\mathcal{F}$ = *BSS* specific frequency

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

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

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

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

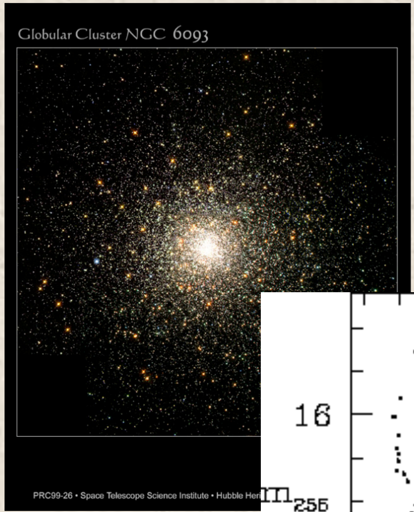


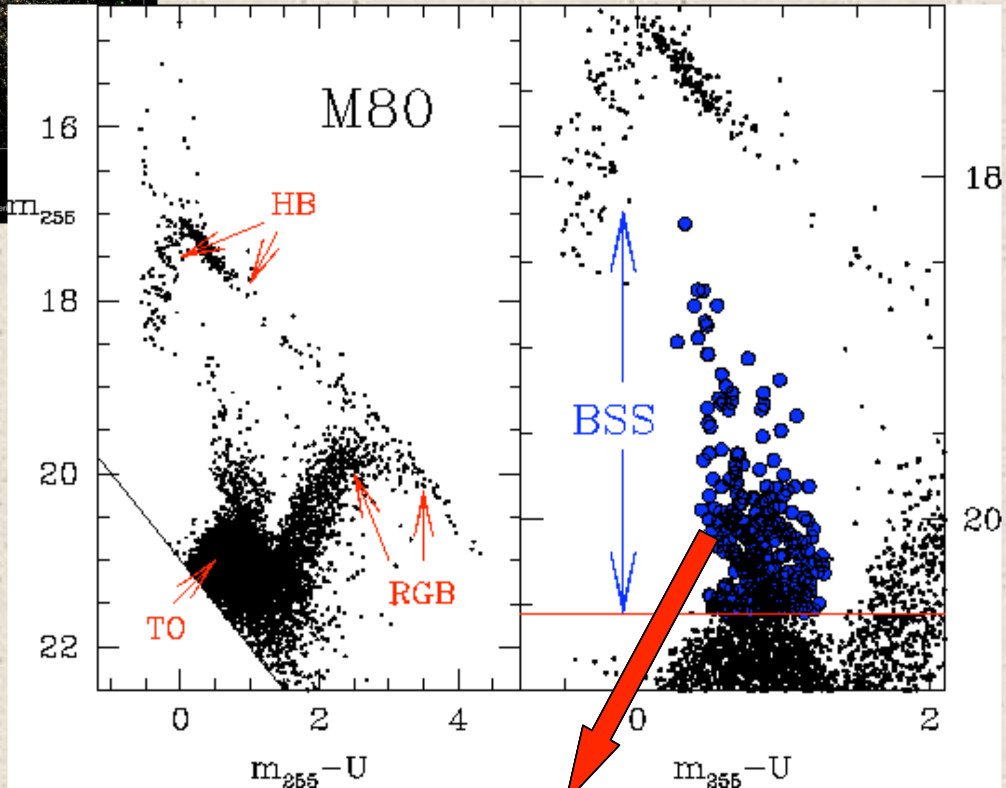
M80 is the densest, not-*PCC* cluster of the Galaxy

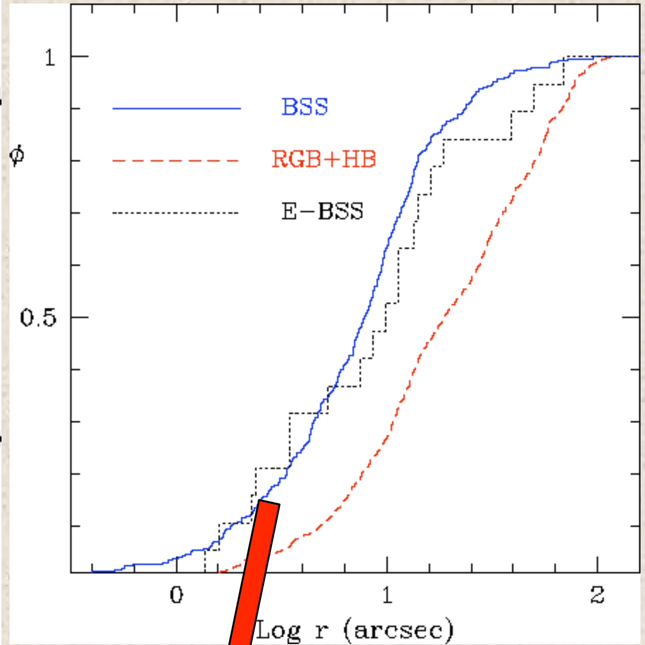
Log ρ_0 = 5.8 M_s/pc^3

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 much more concentrated than M3
(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)

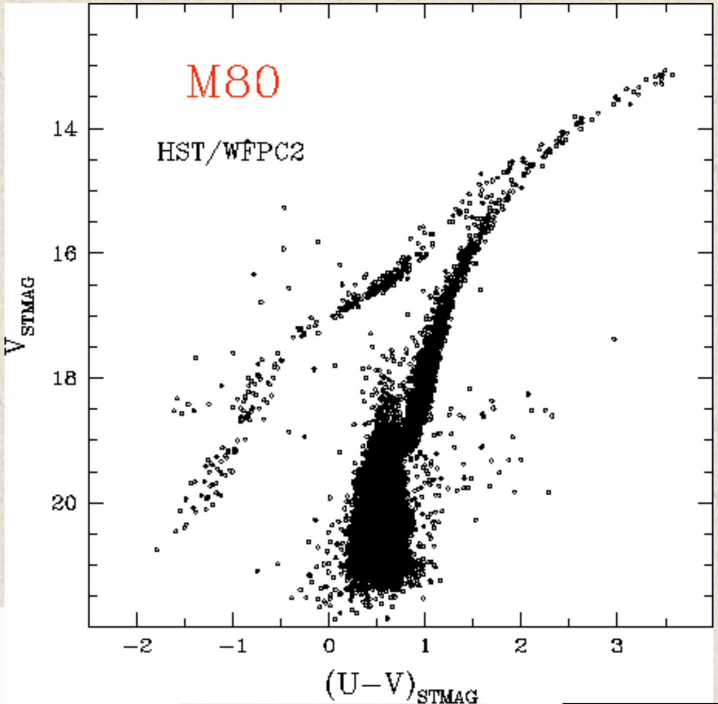
have many fewer *BSS* (N_{BSS} < *100*)

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

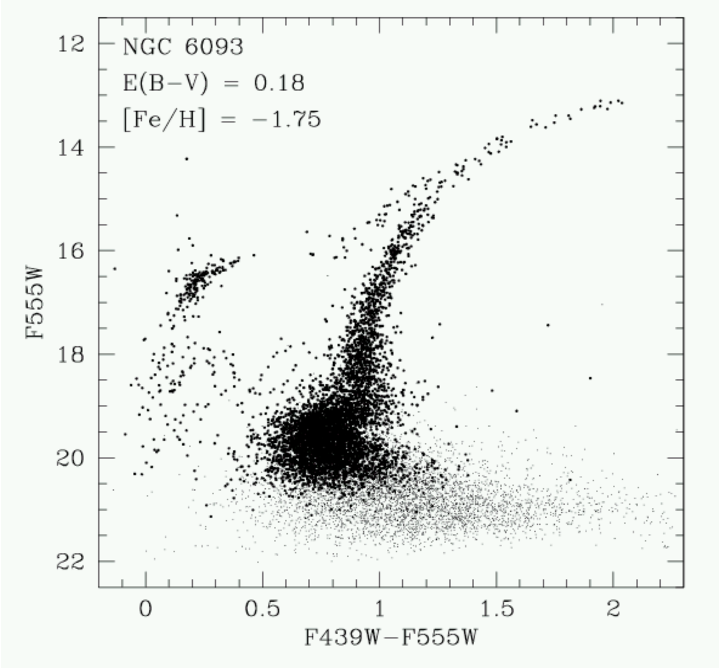
Are collisions delaying the core collapse and generating *COL-BSS*?

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

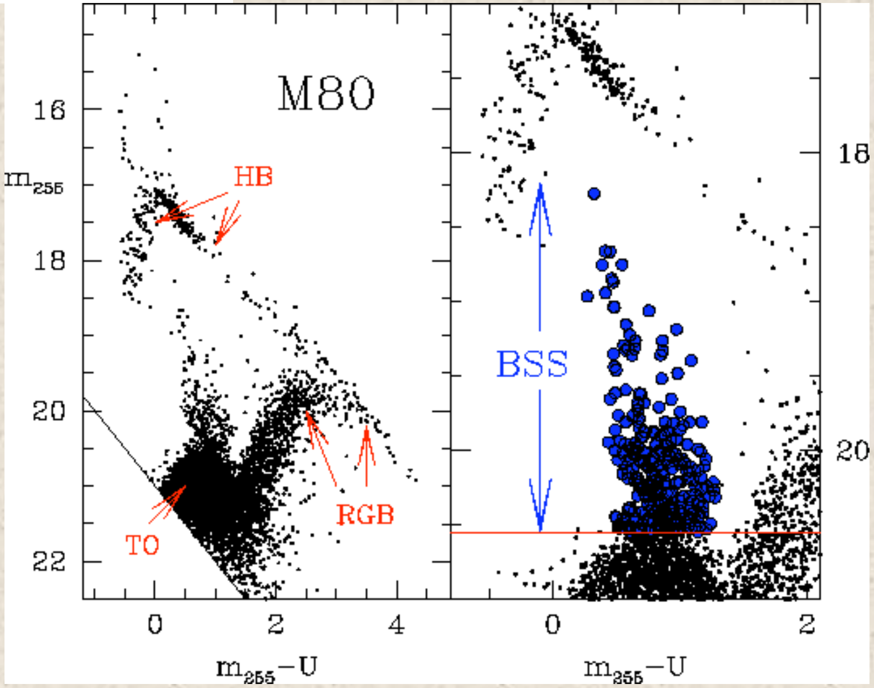


Optical-guided by UV

Pure optical



Pure UV

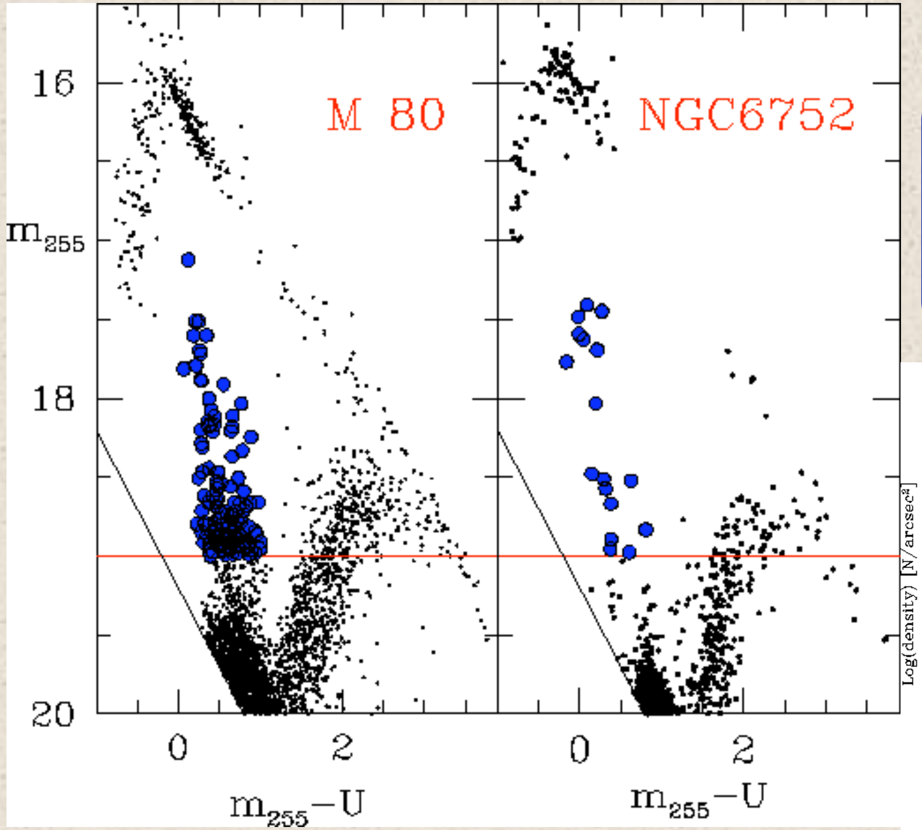


Direct comparison of BSS populations

collapsing

N_{BSS} = *129*

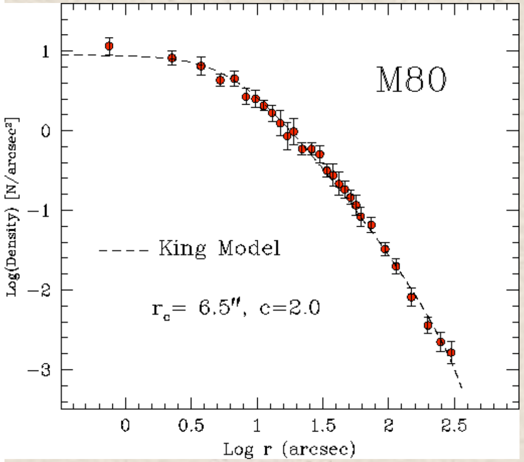
$\mathcal{F}$ = 0.44 – 1.0

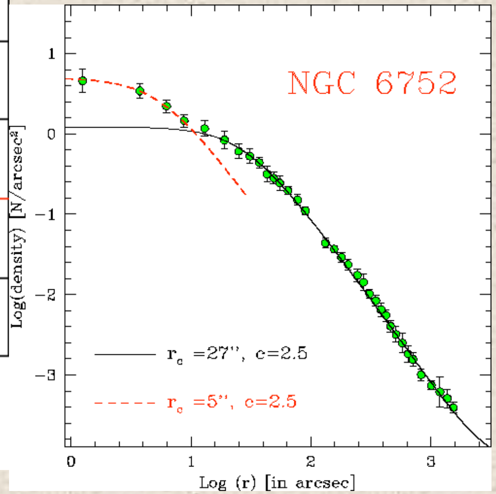


PCC?

N_{BSS} = *17*

$\mathcal{F}$ = 0.16





?

binaries are preventing core collapse ?

are binaries destroyed during the collapse ?

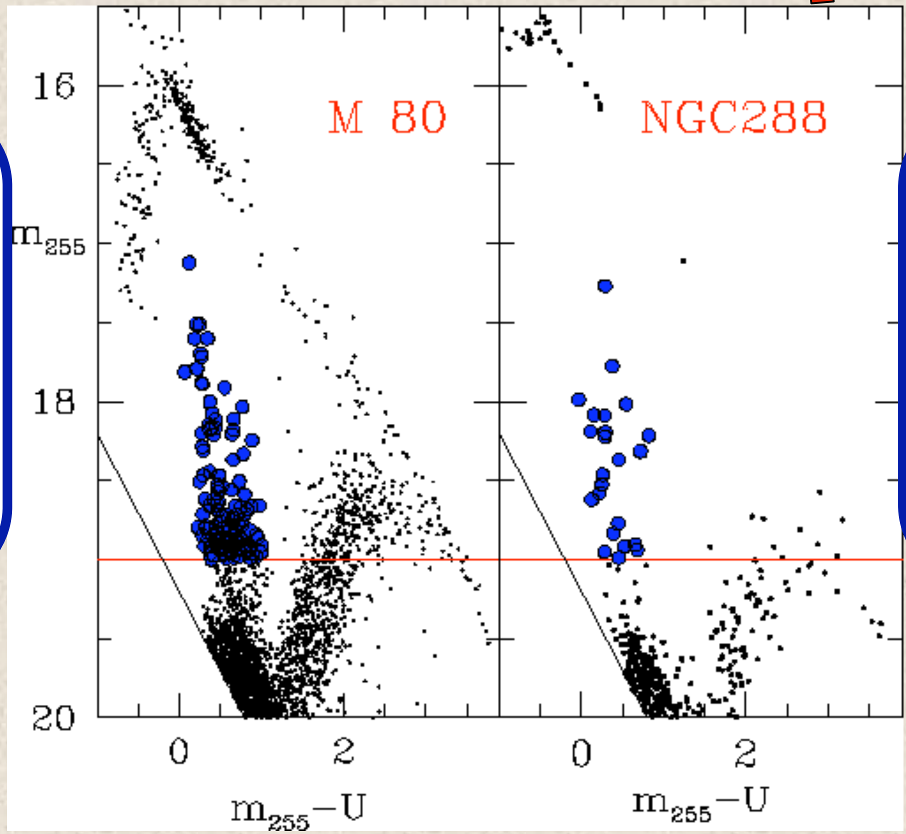
Direct comparison of BSS populations

Log ρ_0 = 5.8 M_s/pc^3

N_{BSS} = *129*

$\mathcal{F}$ = 1.00

if only the PC is considered



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 cluster

Different type of BSS ?

COL-BSS in M80 ? PB-BSS in NGC288

Direct comparison of BSS populations

twin clusters

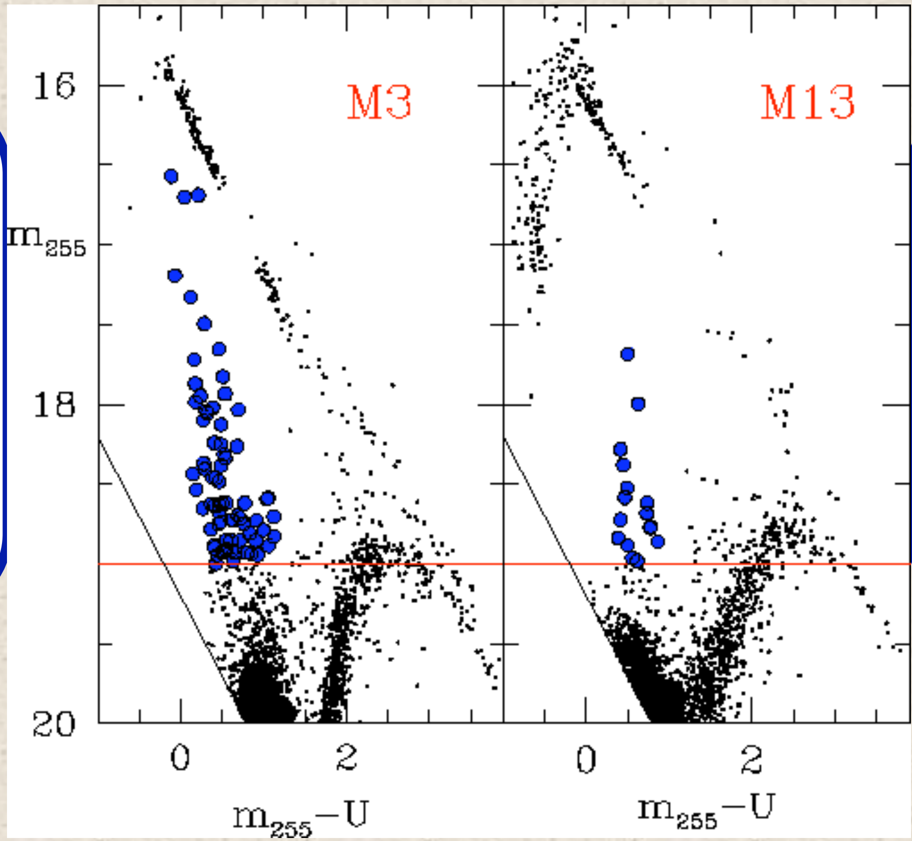
M 3

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 binary content ?

QUESTIONS

Why similar clusters have different central-BSS content?

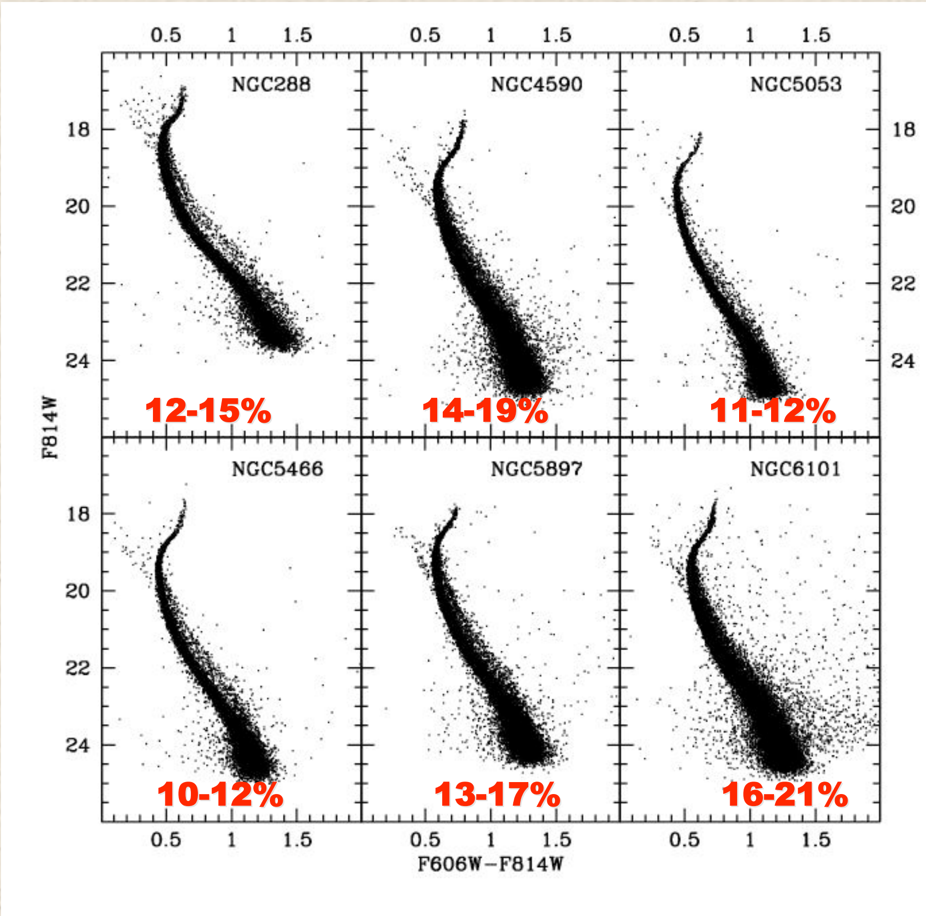
Which is the role of the dynamical evolution in producing/destroying BSS?

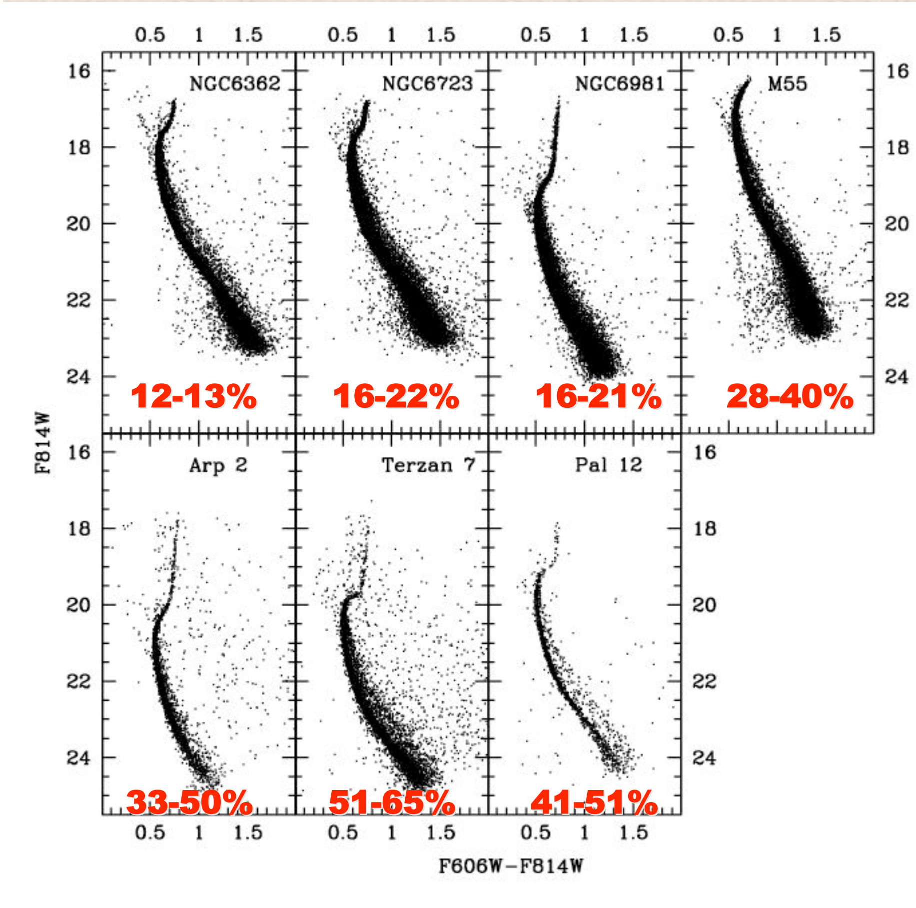
Can anyone please model M80?

Do we have in hand all the “ingredients” we need to reproduce the cluster BSS content?

Which is the binary fraction in GGCs ?

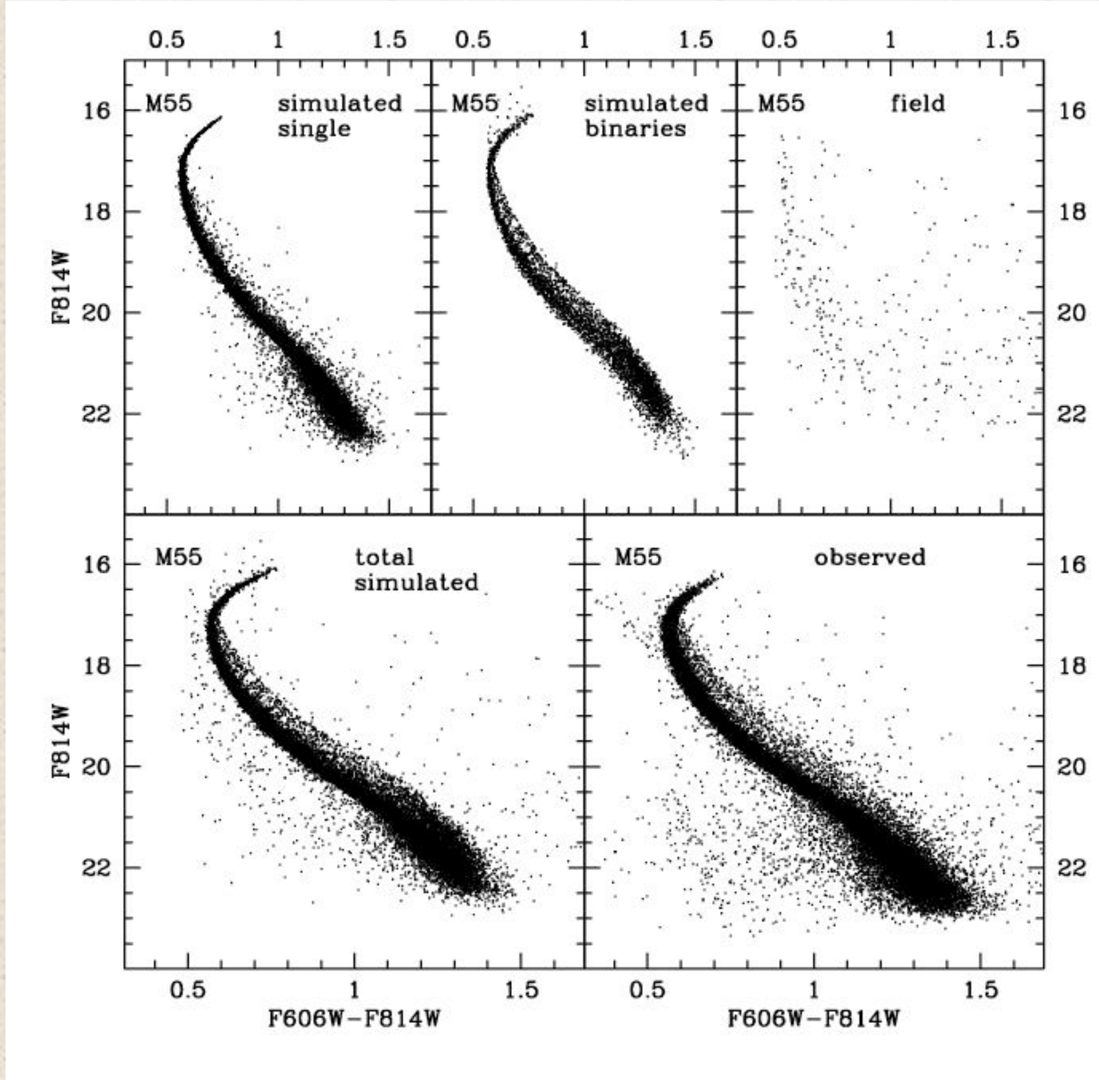
The Binary fraction in 13 low-density clusters from ACS-HST observations





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

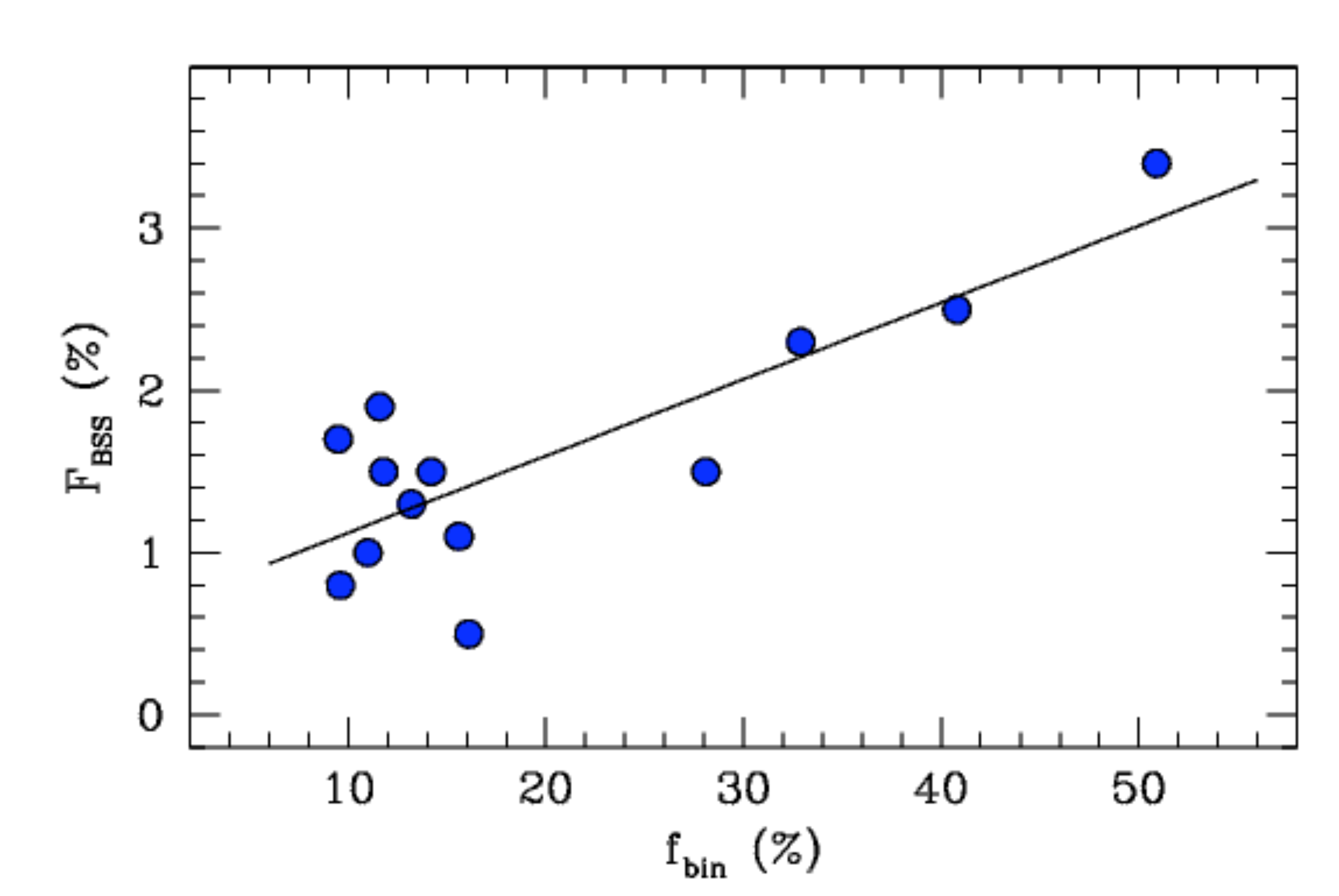
Binaries in GGCs



Global BINARY FRACTION 10-50%

BSS & binary fraction

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



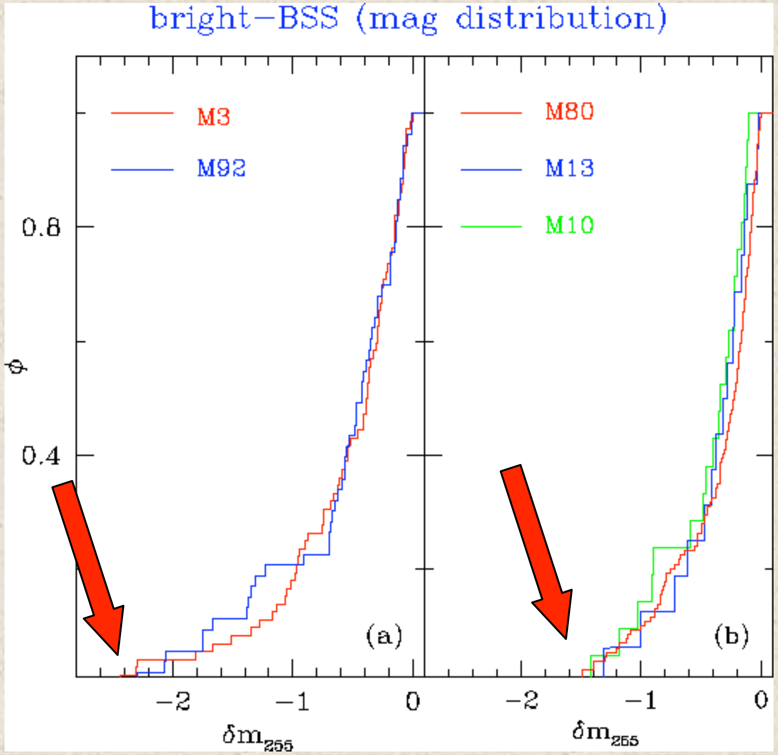
Sollima et al (2008, A&A, 481,701)

Most PB-BSS !!!

BSS LFs in the UV:

M3 & M92

- 2 GGCs without ***HB tails***
- similar ***b-BSS LF*** extending 2.5 mag brighter than m_{255}=19



M3, M13 & M10

- 3 GGCs with ***long HB blue tails***
- similar ***b-BSS LF*** extending <1.5 mag brighter than m_{255}=19

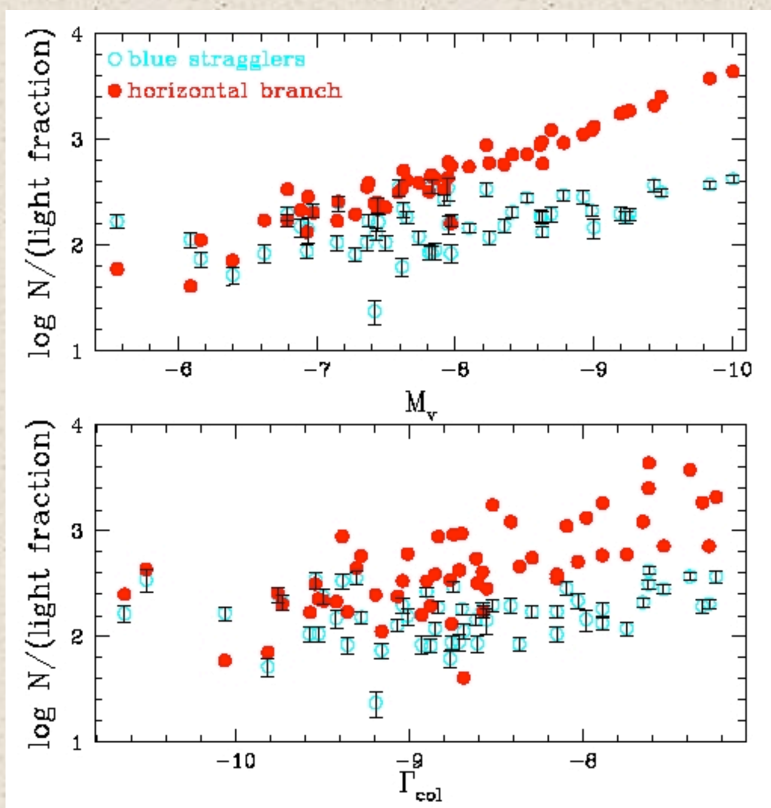
?

are the *BSS* photometric properties and HB morphology linked?

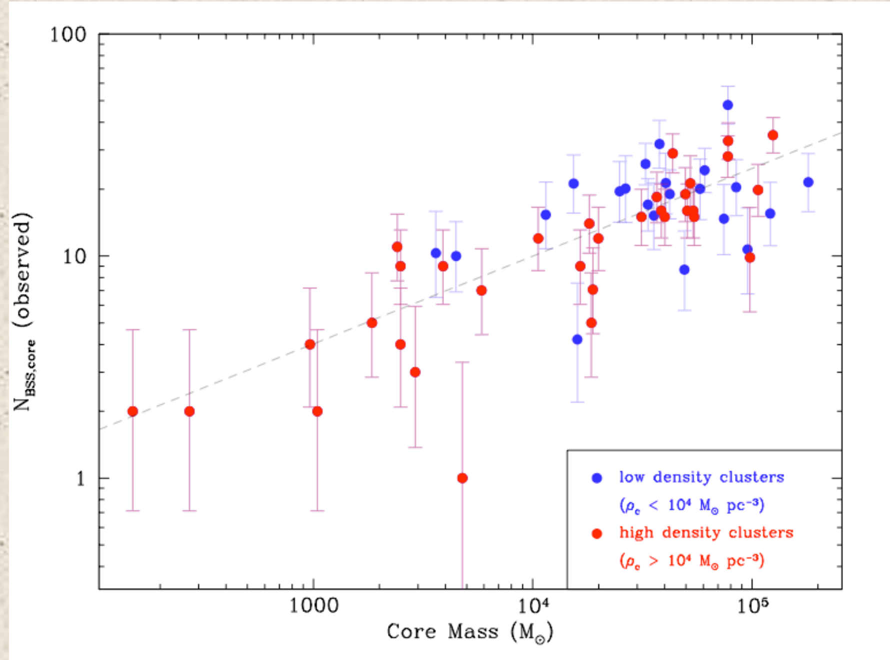
Central-BSS optical catalogs

A Catalog containing 3000 BSS in 56 GGCs from HST optical observations Piotto et al (2004)

See discussion in Davies et al (2004), Leigh et al (2007), Moretti et al (2008) and Knigge et al (2009)



The total number of BSS is independent from the cluster mass and collision rate

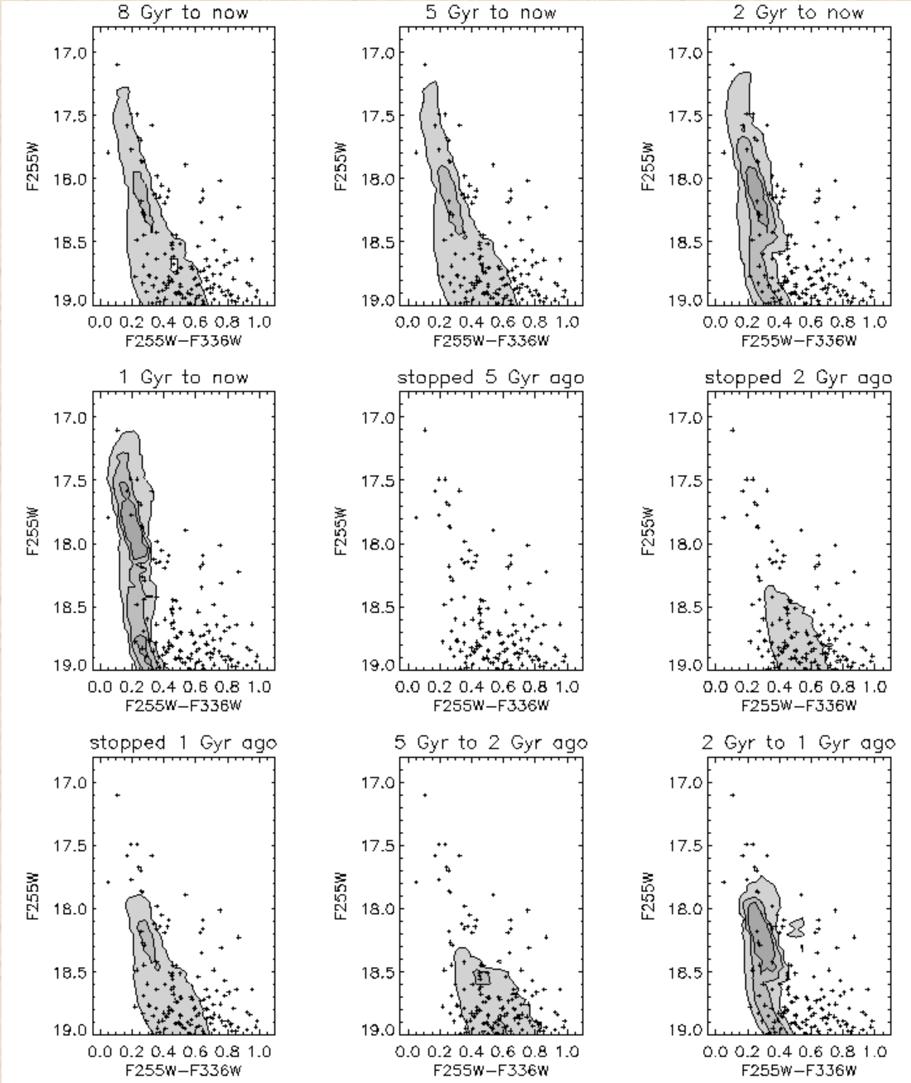


The number of BSS in the core scales with the mass of the cluster core

BSS: comparison with models

M80

- ***b-BSS distribution in the UV-CMD***

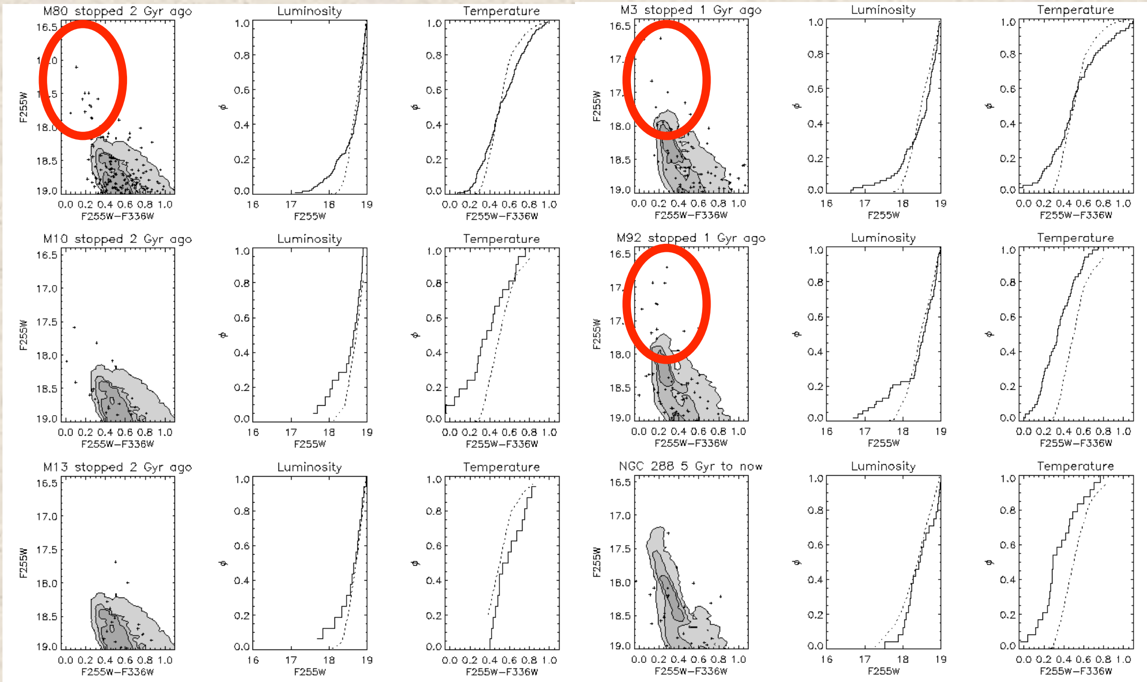


Models by A. Sills:

- **All Collisional BSS: generated by s-b interactions**
- **Binary fraction 20%**
- **BSS formation rate is constant or zero**

***BSS* distribution in the CMD depends on when the BSS are created**

BSS: comparison with models



Models are still too rough to properly reproduce the observations

***BSS* formation has lasted over a relatively long period (even many Gyr …8-2 Gyr)**

The existence of bright BSS could indicate a more recent burst of formation or the results of triple collisions

The BSS radial distribution

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

....Barbara will tell us about this....

METHODOLOGY :

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

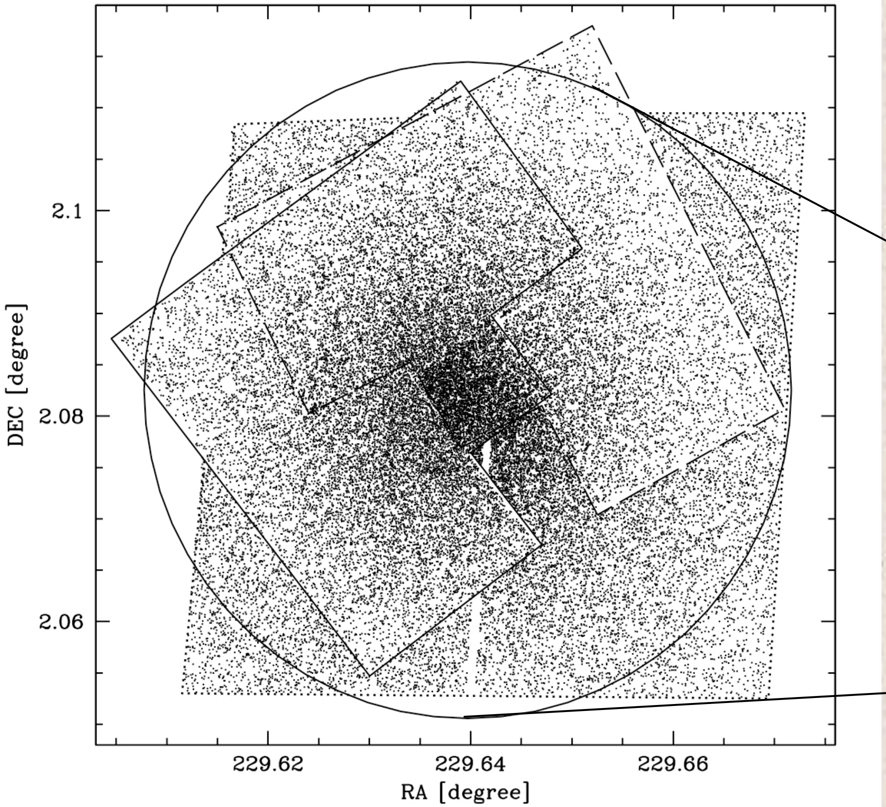
+

Wide-Field observations: cluster outskirts

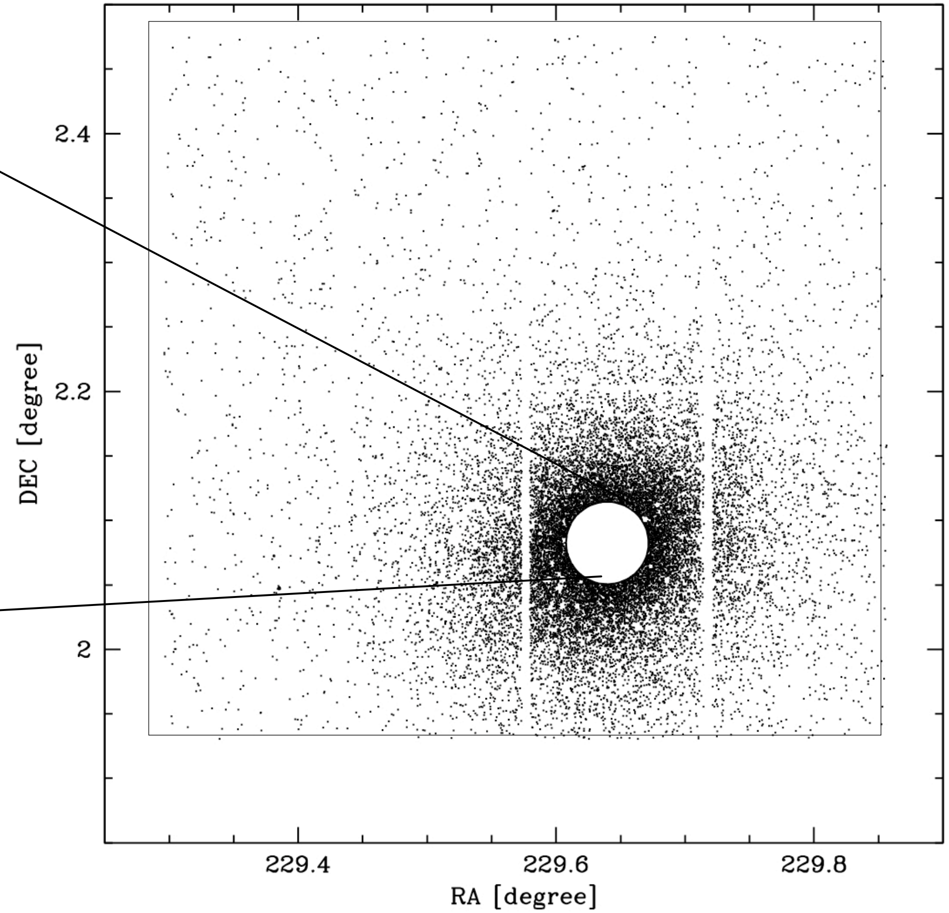
- ✓ **ground-based (optical bands)**
- ✓ **GALEX satellite (UV)**

M5 (NGC5904)

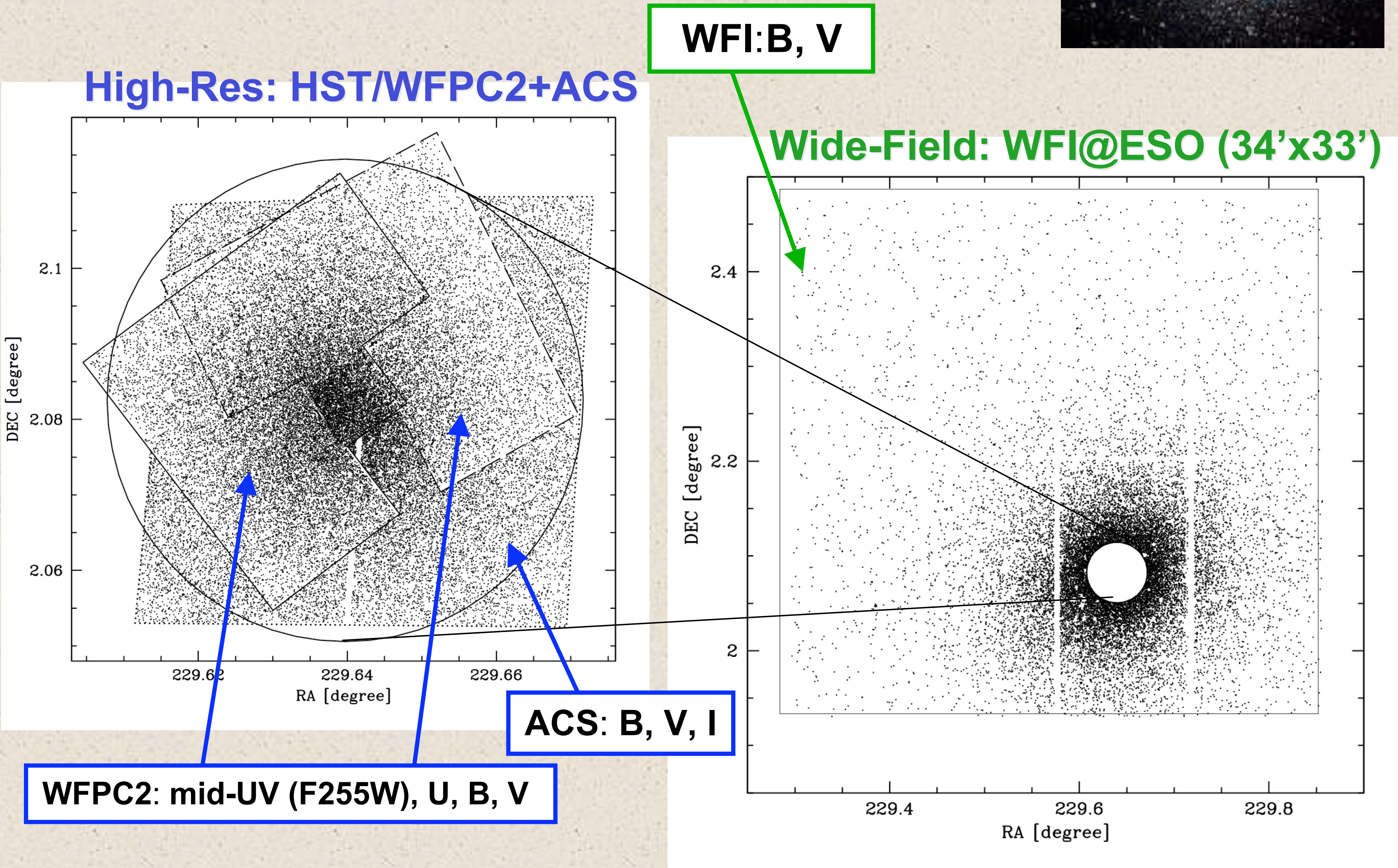
High-Res: HST/WFPC2+ACS



Wide-Field: WFI@ESO (34’x33’)



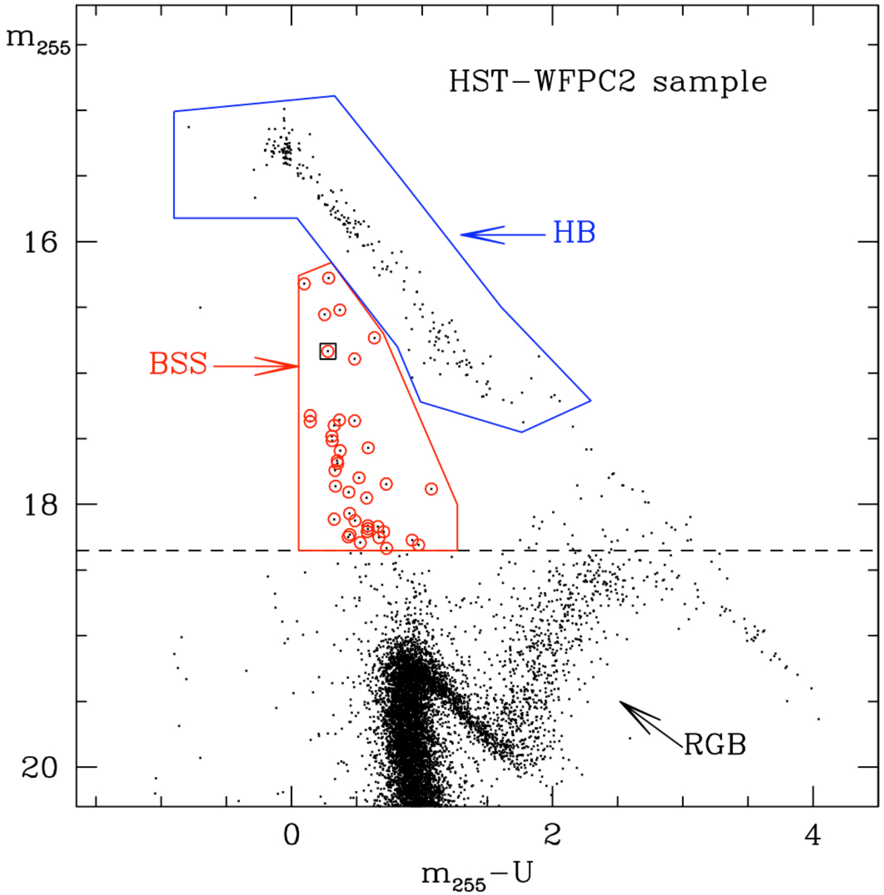
M5 (NGC5904)


WFI:B, V
High-Res: HST/WFPC2+ACS
Wide-Field: WFI@ESO (34'x33')
2.1
2.08
2.06
DEC [degree]
229.62
229.64
229.66
RA [degree]
2.4
2.2
2
DEC [degree]
229.4
229.6
229.8
RA [degree]
ACS: B, V, I
WFPC2: mid-UV (F255W), U, B, V

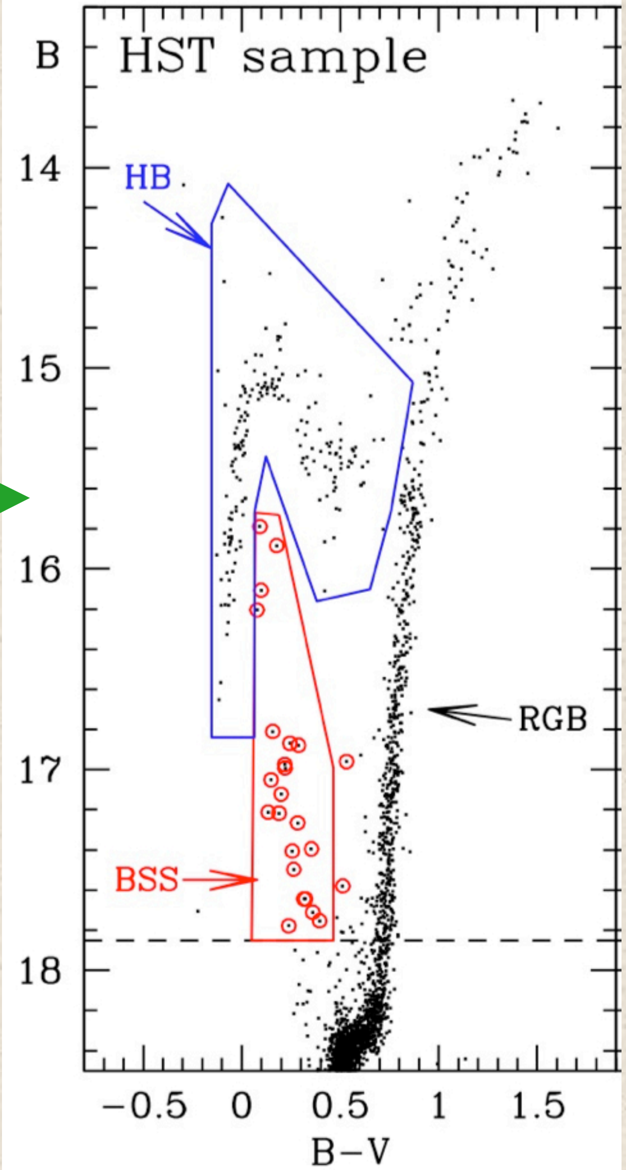
BSS selection

M5 (NGC5904)

in the UV-plane

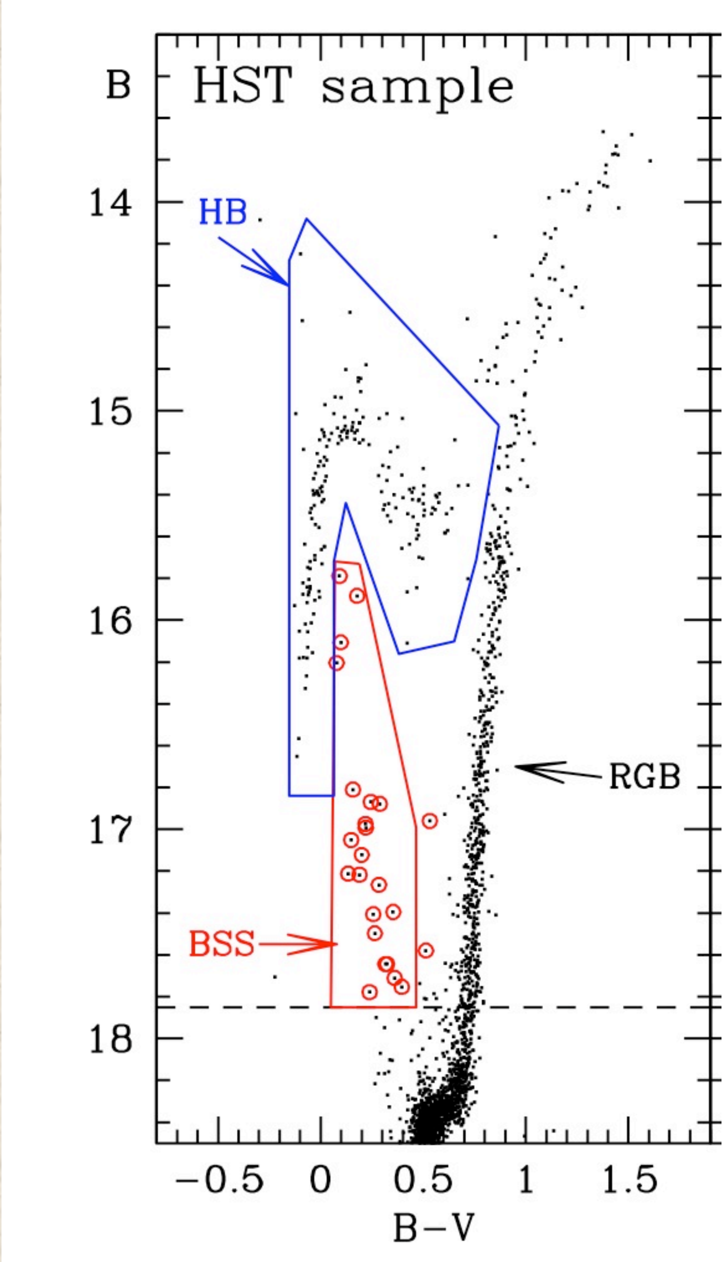


optical plane (HST)



M5 (NGC5904)

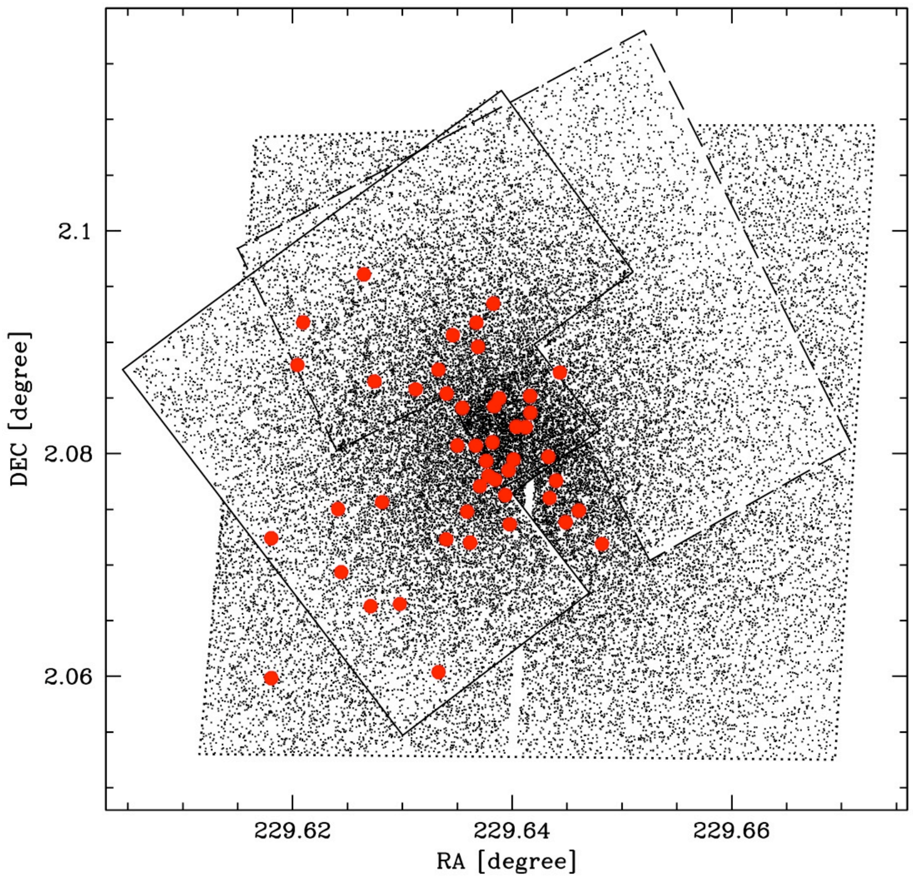
from HST



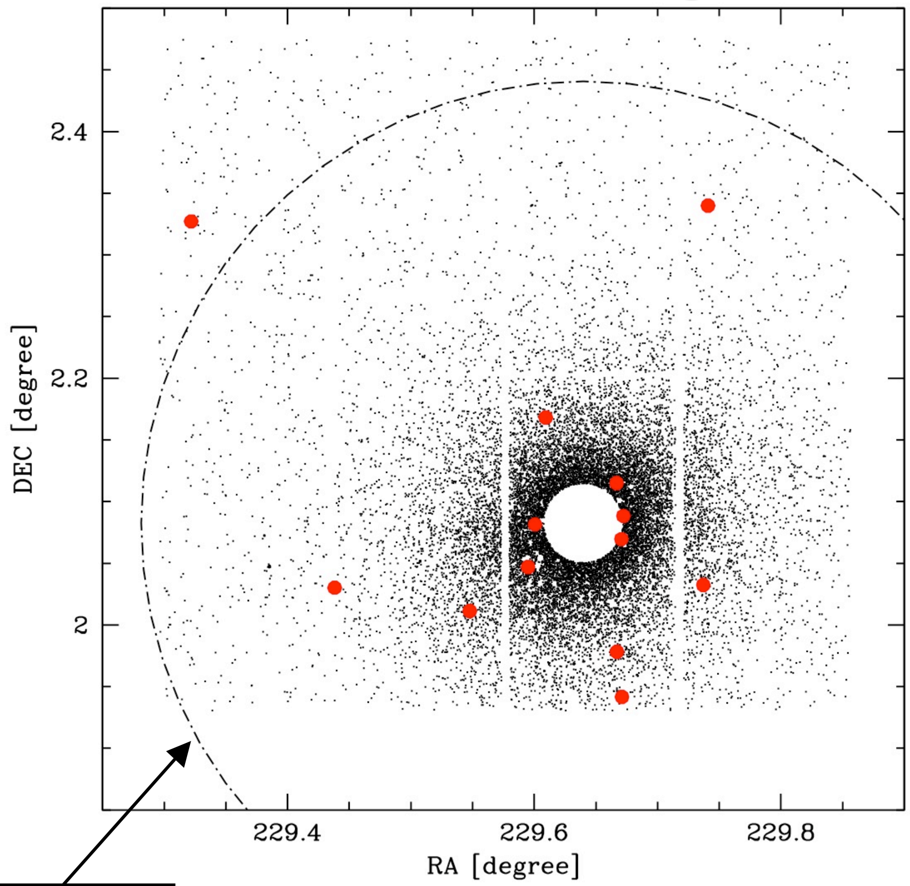
M5 (NGC5904)

BSS radial distribution

High-Res WFPC2+ACS HST



Wide-Field WFI@ESO



$r_t = 21.'5$

Cumulative radial distributions

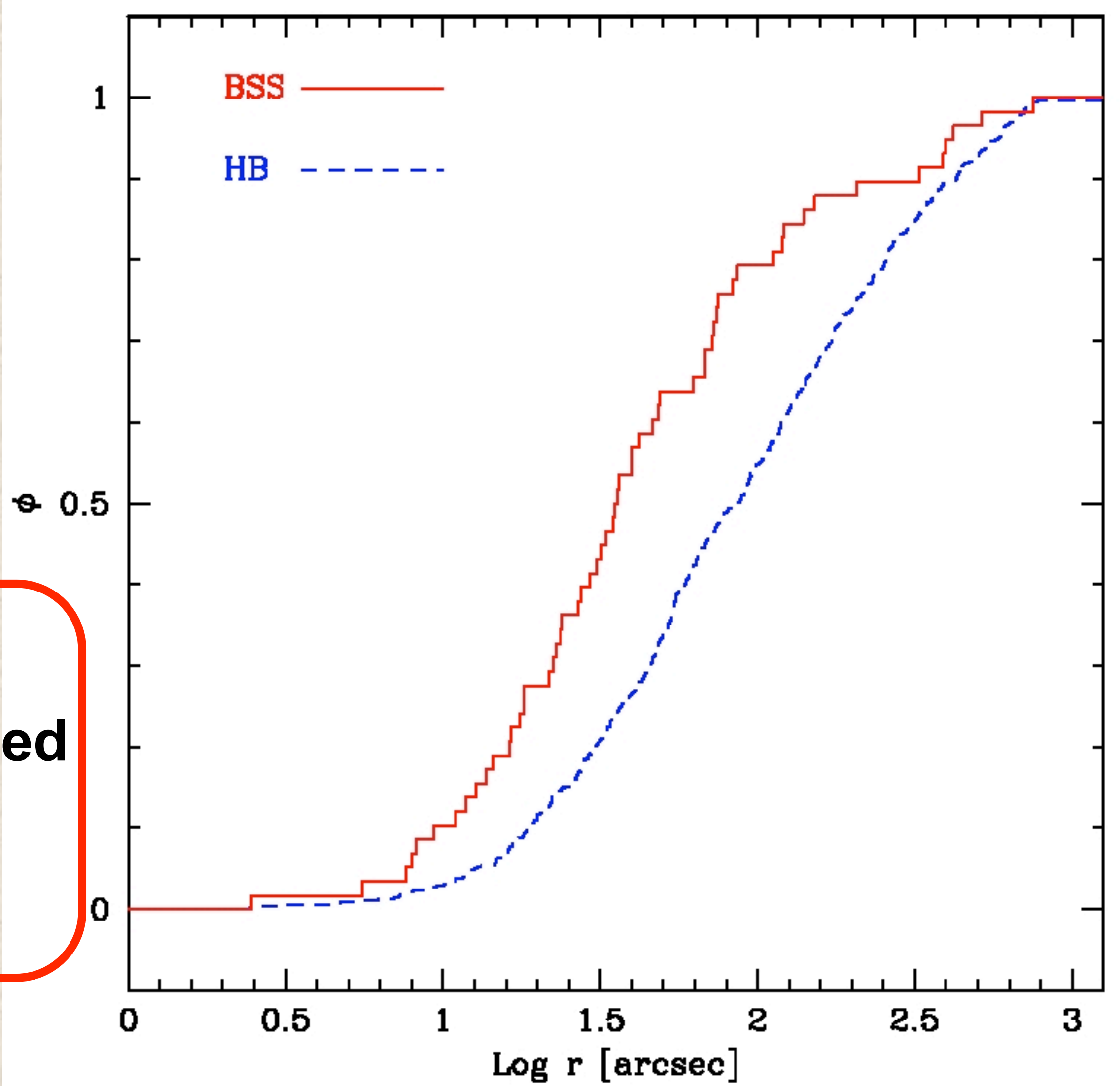
M5 (NGC5904)

KS-test:

10^{-4} probability that BSS and HB stars are exctracted from the same population

⬇

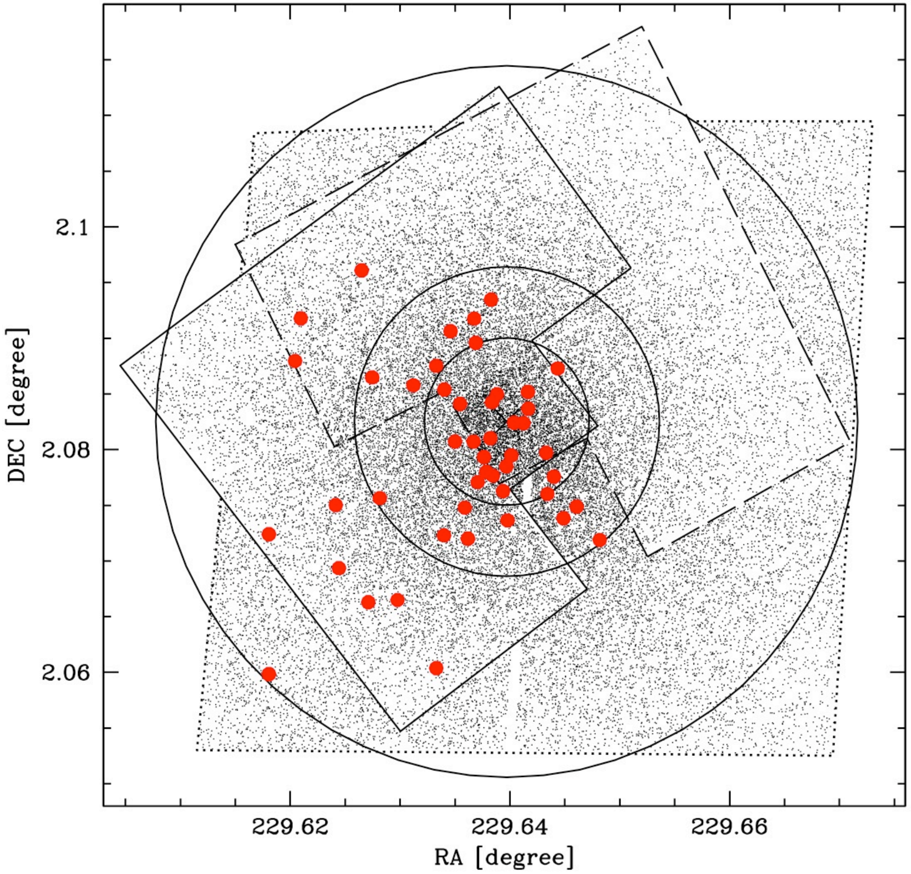
BSS are more centrally concentrated than HB at more than 4σ level



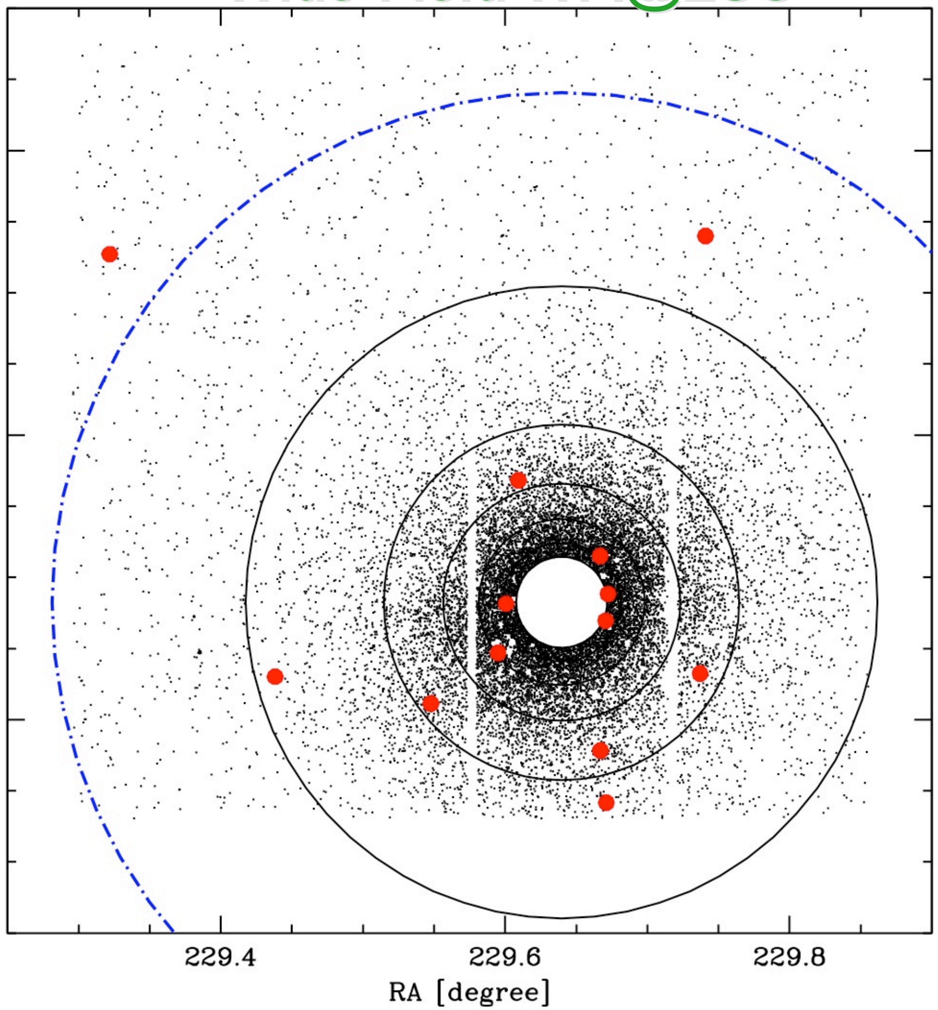
M5 (NGC5904)

BSS radial distribution

High-Res WFPC2+ACS HST

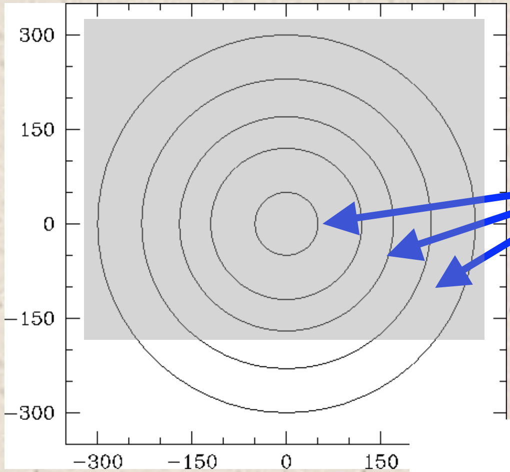


Wide-Field WFI@ESO



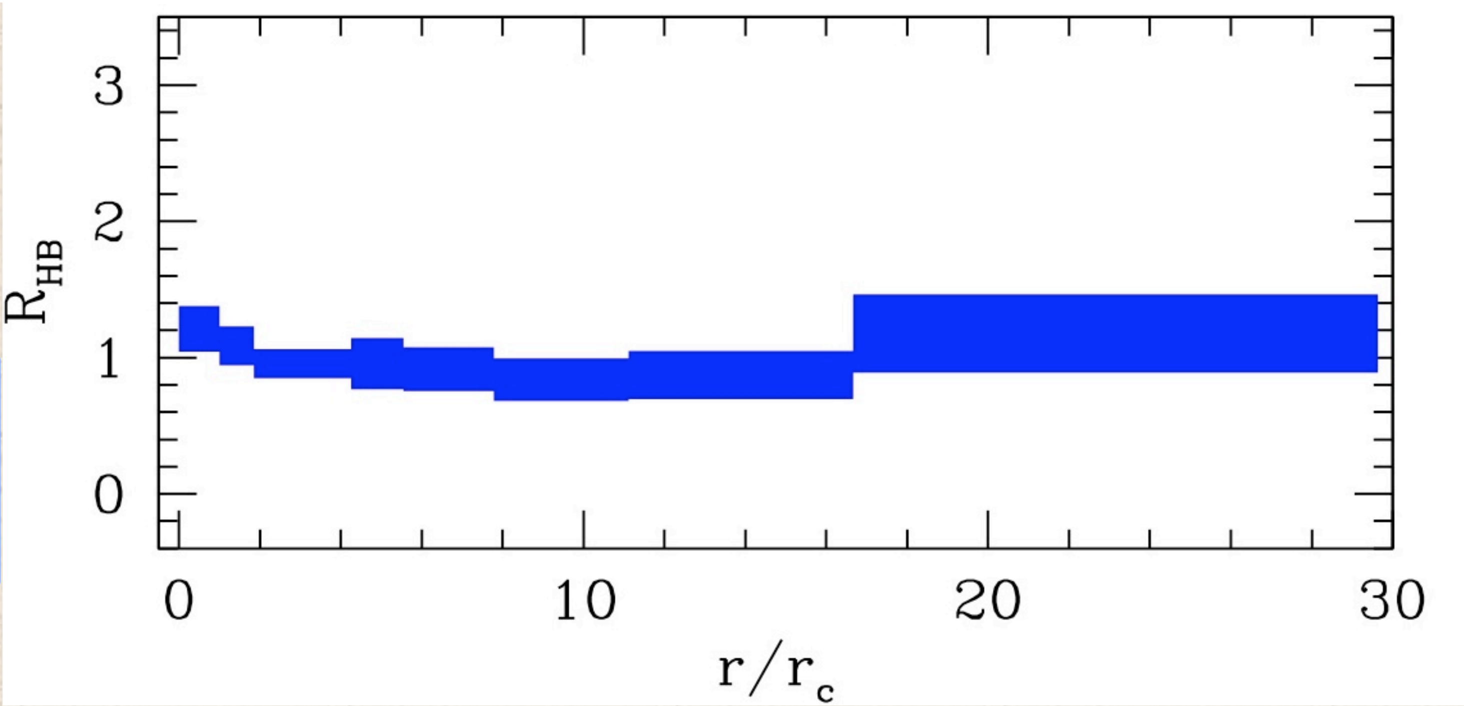
Double normalized ratio

M5 (NGC5904)



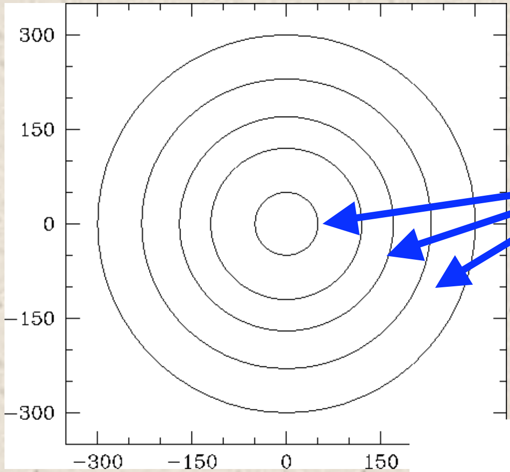
$$R_{HB} = \frac{N_{HB}/N^{TOT}}{L_S/L_{TOT}}$$

HB stars NOT segregated in the center

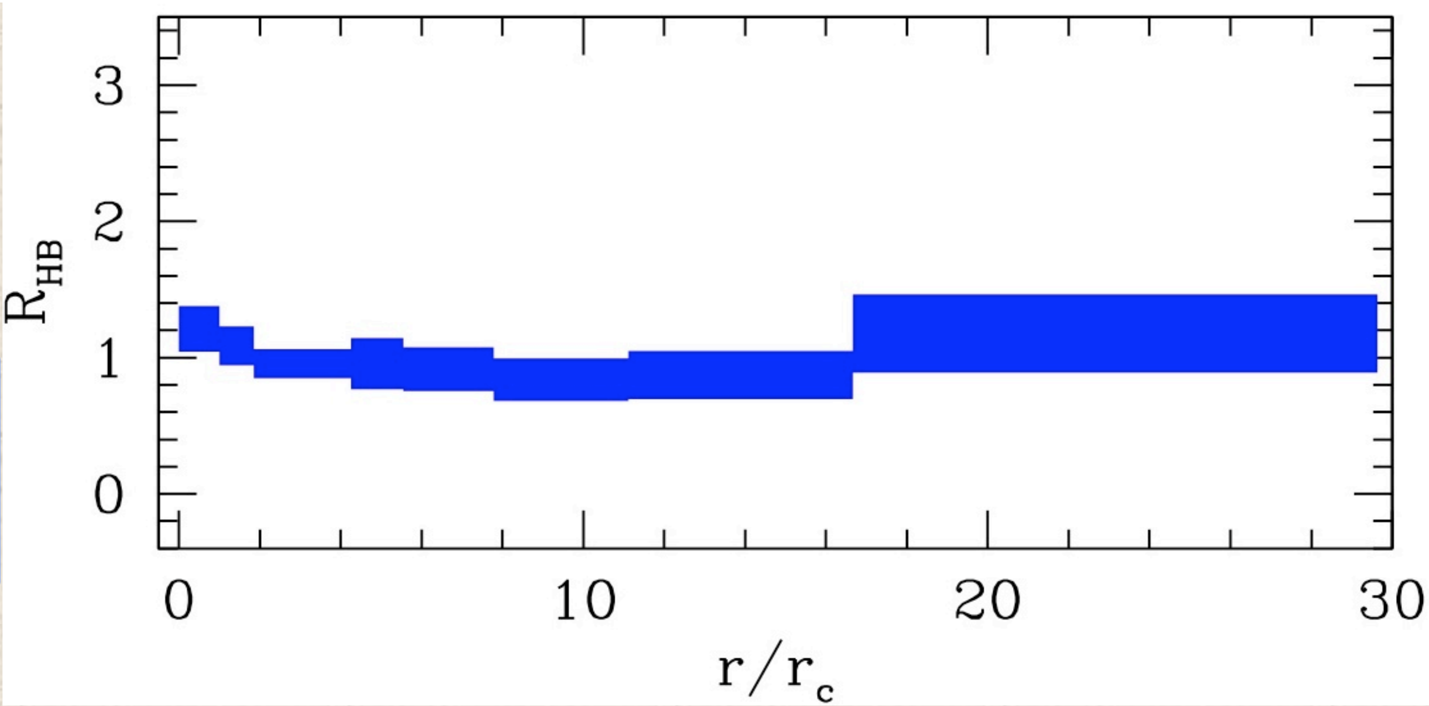


Double normalized ratio

M5 (NGC5904)



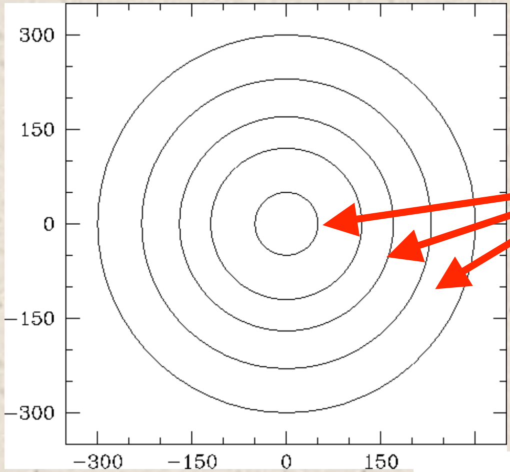
$$R_{HB} = \frac{N_{HB}/N^{TOT}}{L_S/L_{TOT}}$$



HB stars NOT segregated in the center

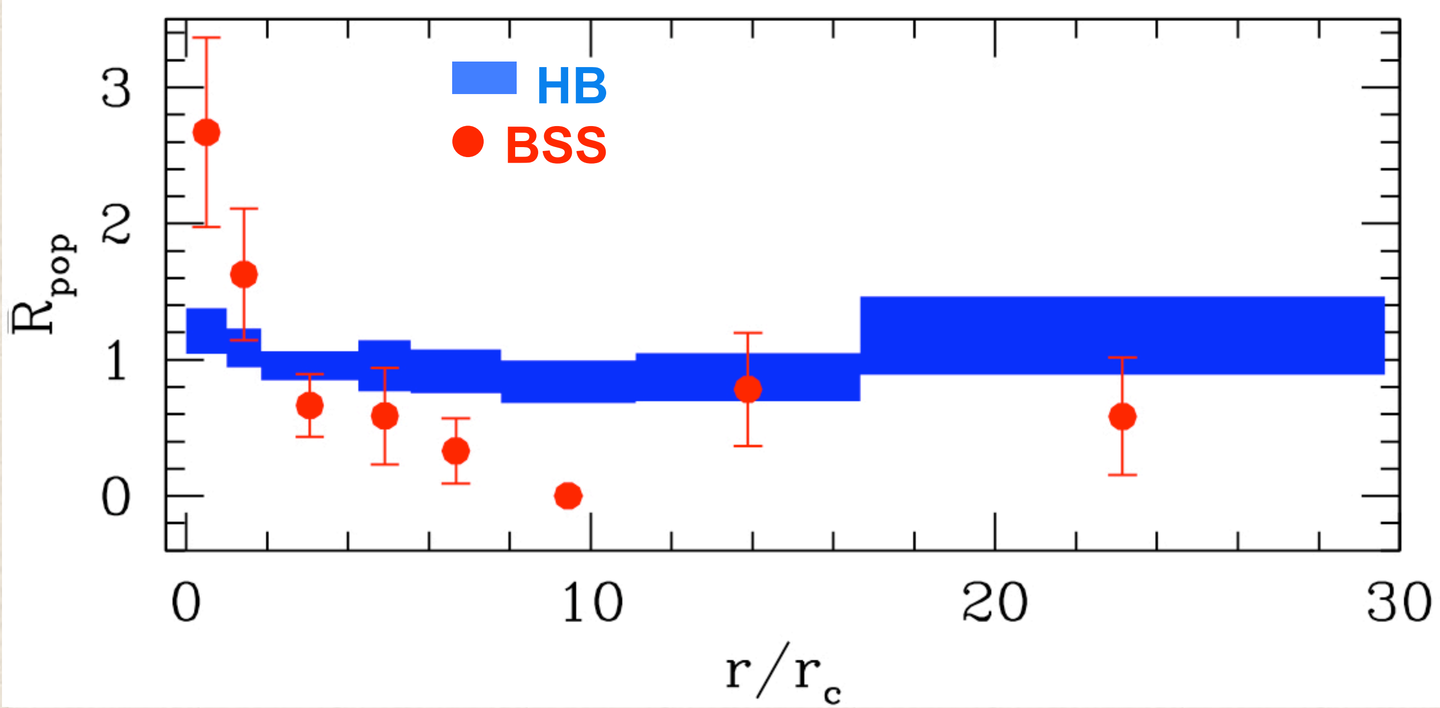
M5 (NGC5904)

Double normalized ratio

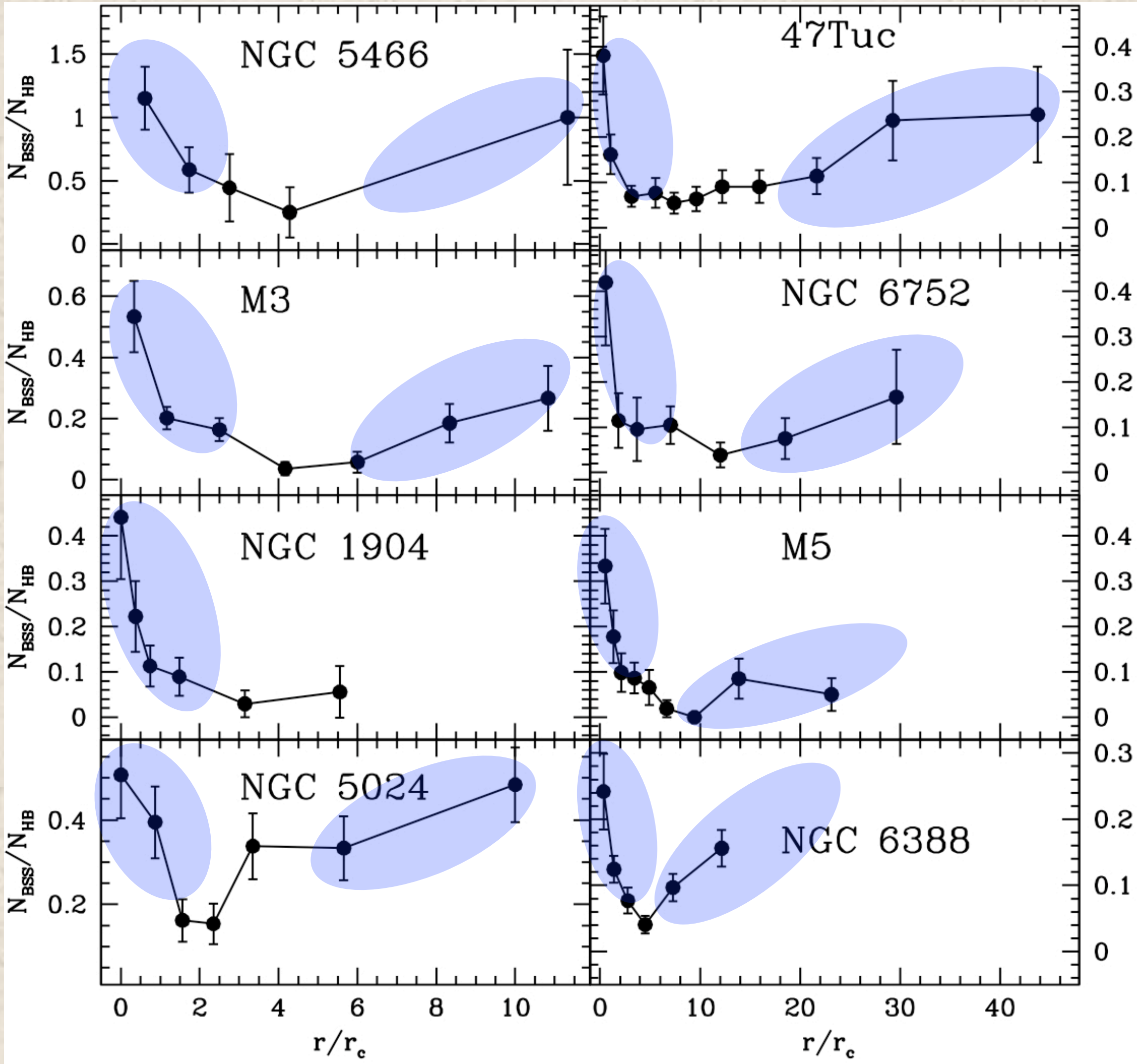


$$R_{BSS} = \frac{N_{BSS}/N^{TOT}}{L_S/L_{TOT}}$$

BSS are highly segregated in the center

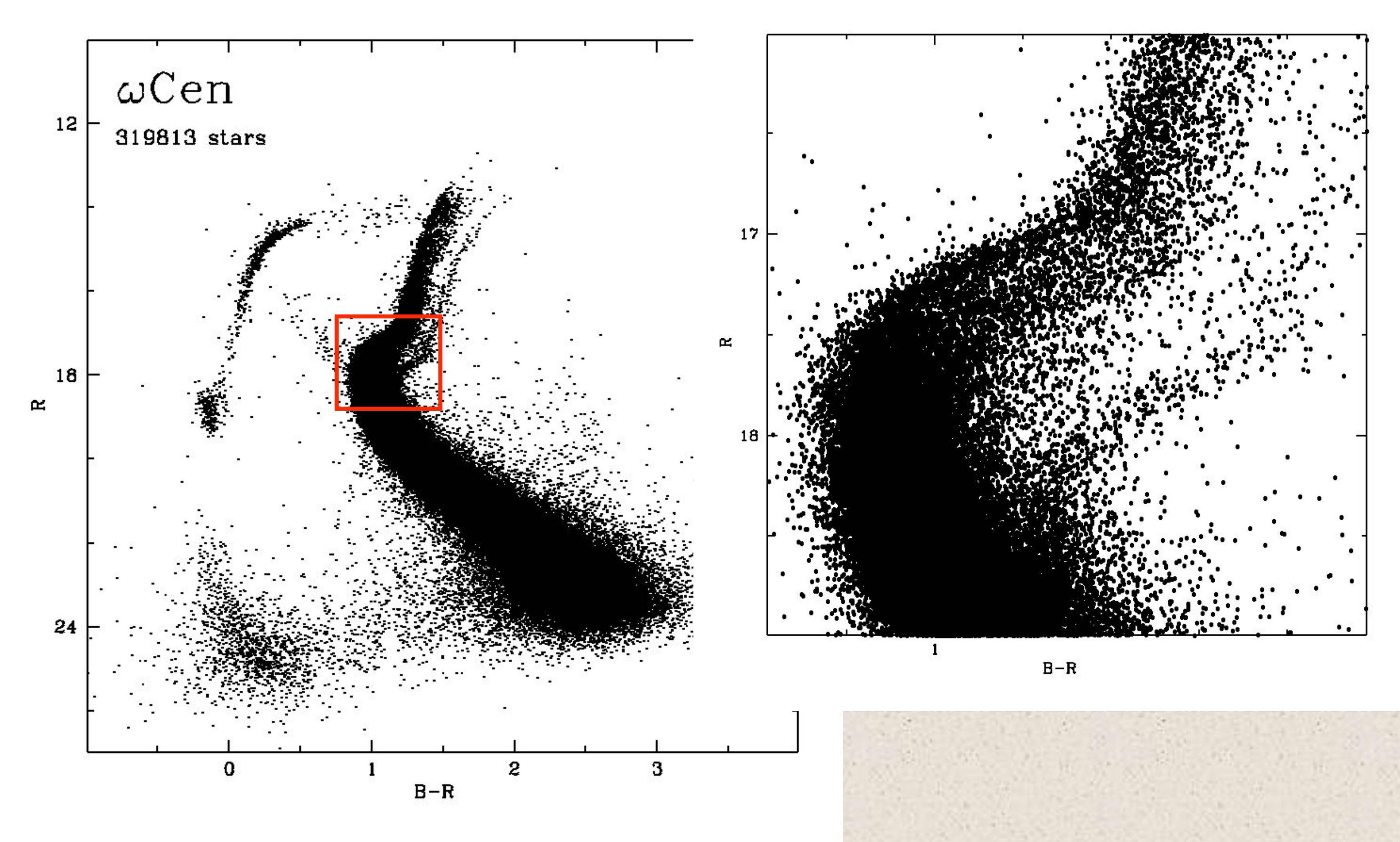


BIMODAL/PEAKED BSS radial distributions



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

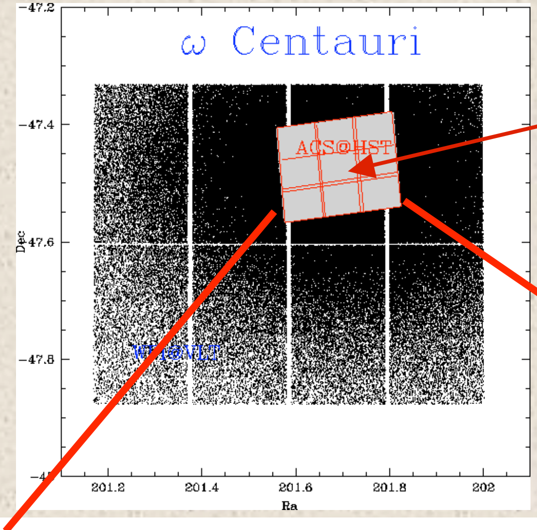
Omega Centauri

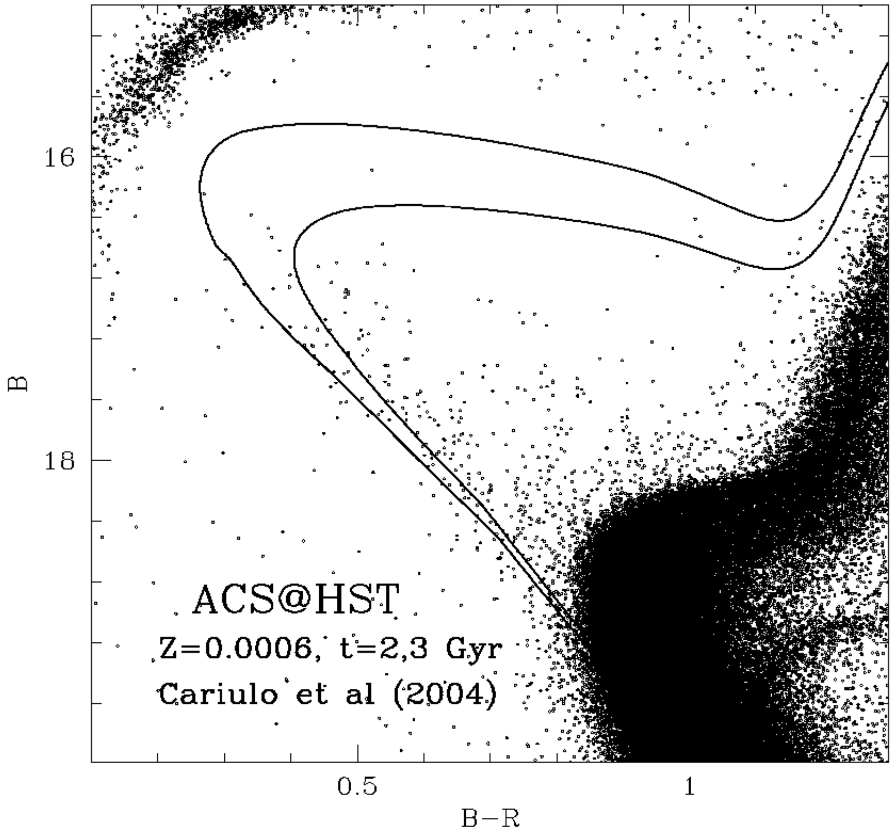


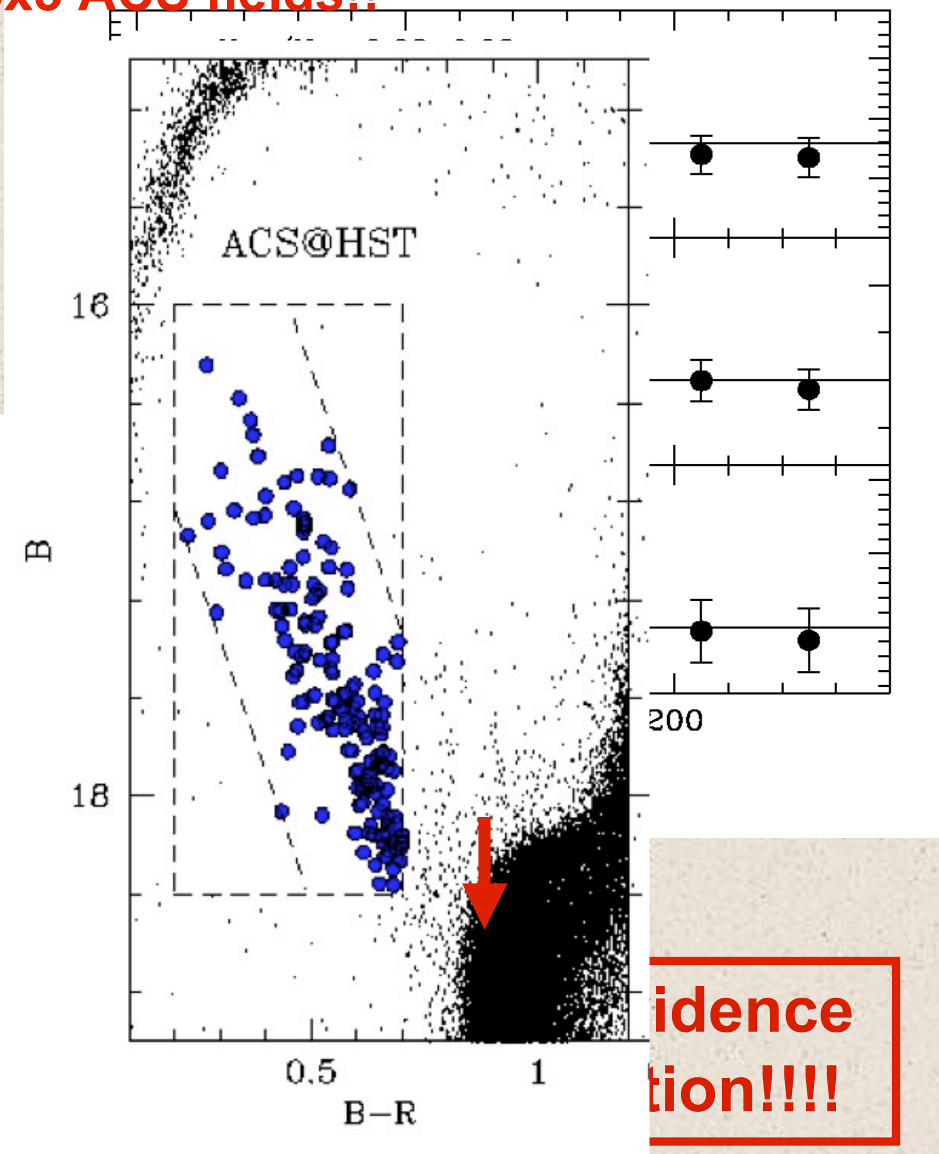
Ferraro et al. 2004

inner BSS radial distribution

mosaic of 3x3 ACS fields!!



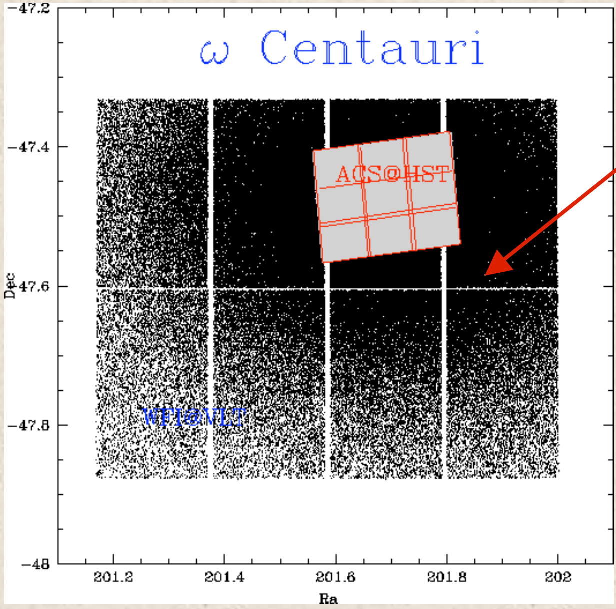




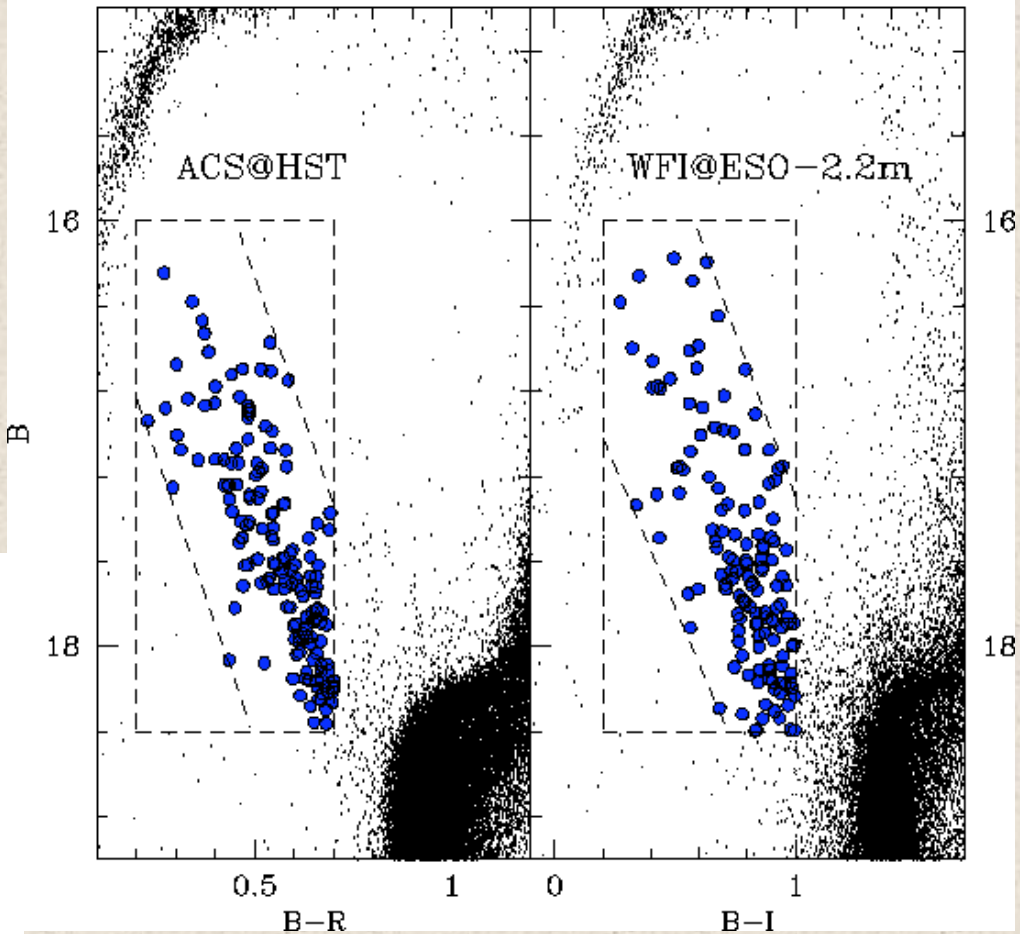
idence

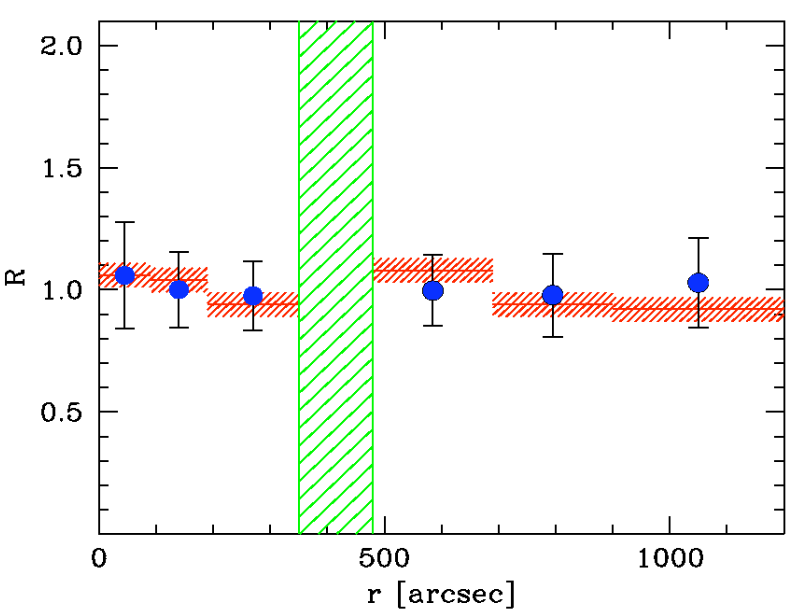
tion!!!!

wide-field (



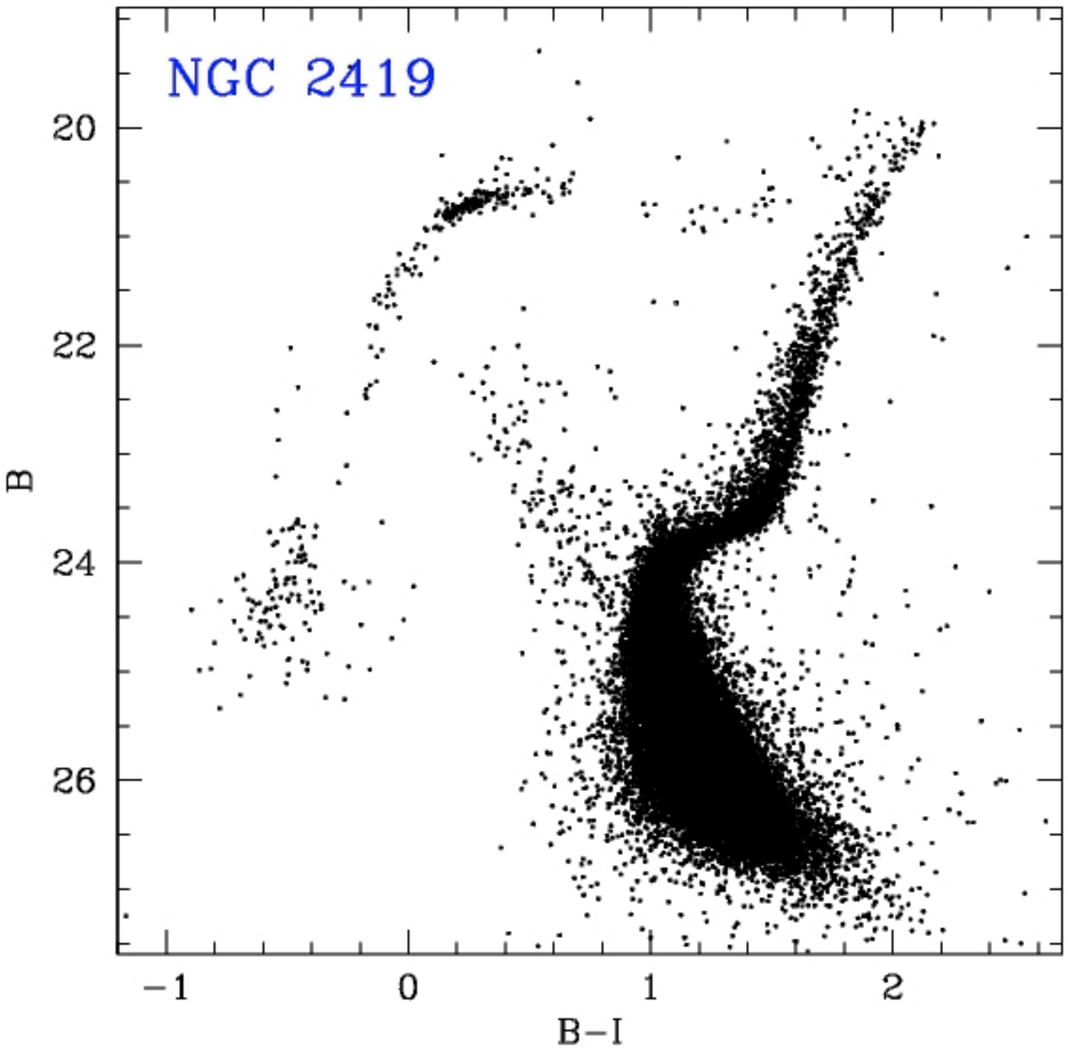
HST WFI

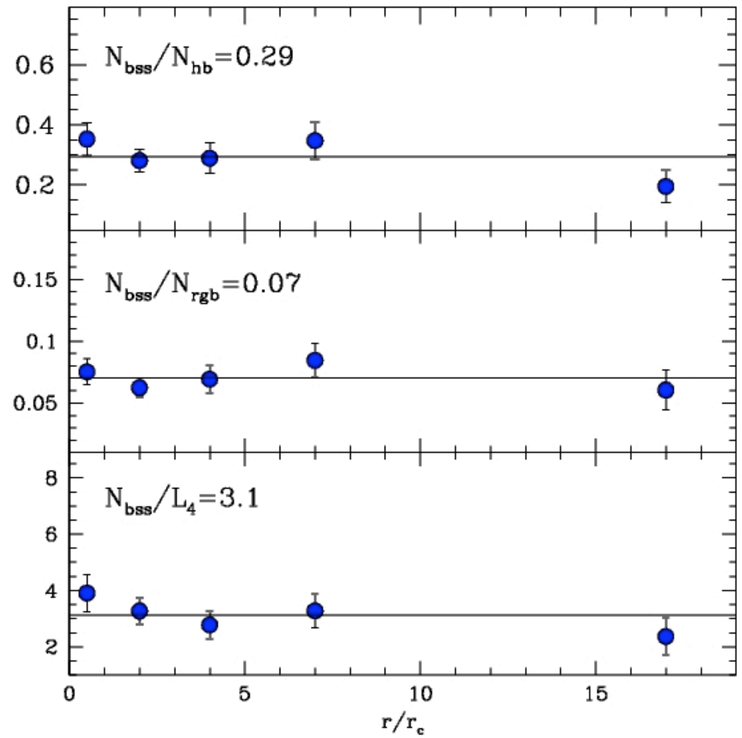




ωCentauri:
totally FLAT
BSS radial distribution!!!

NGC 2419



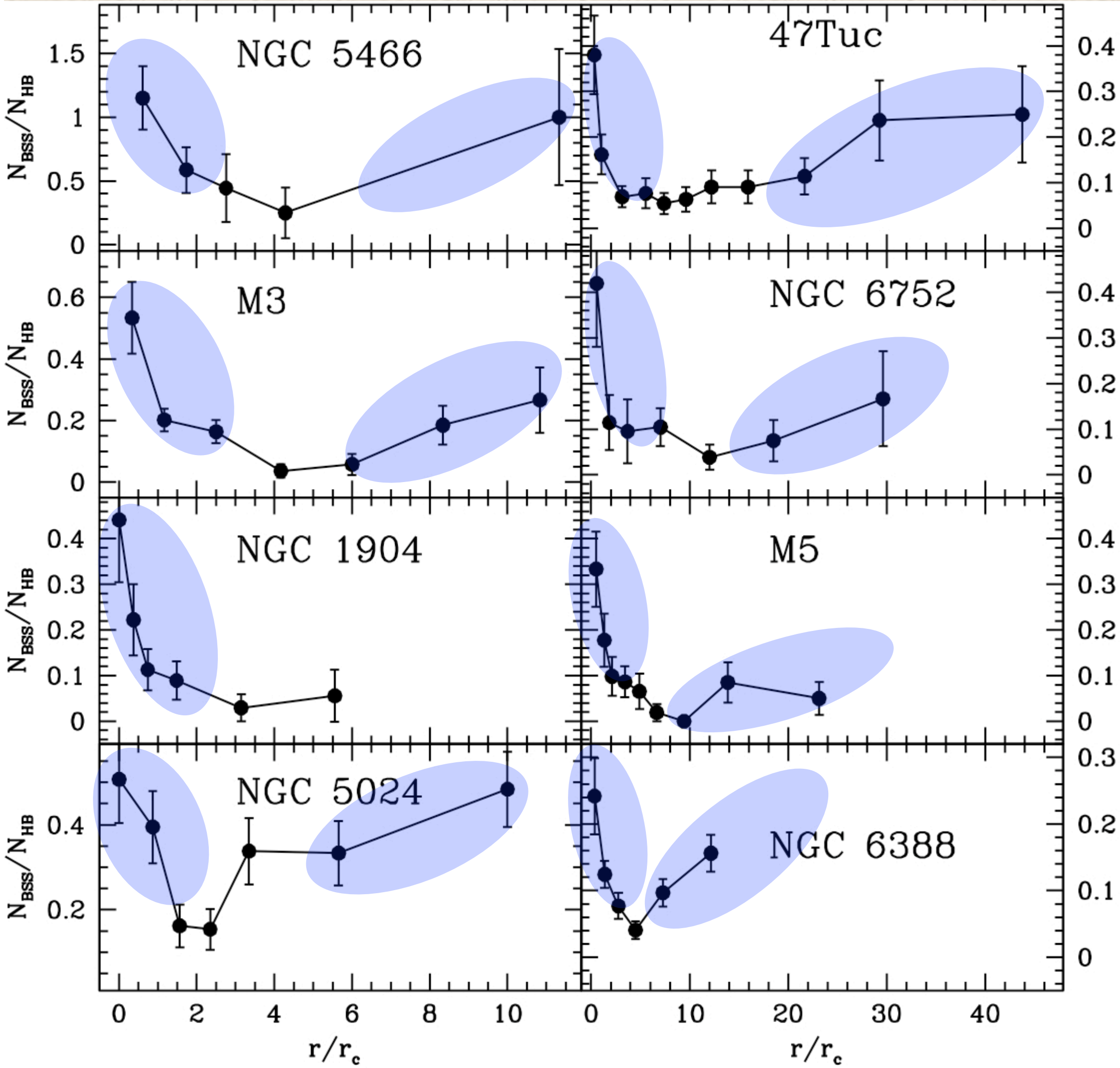


NGC2419: NO evidence of mass segregation!!!!

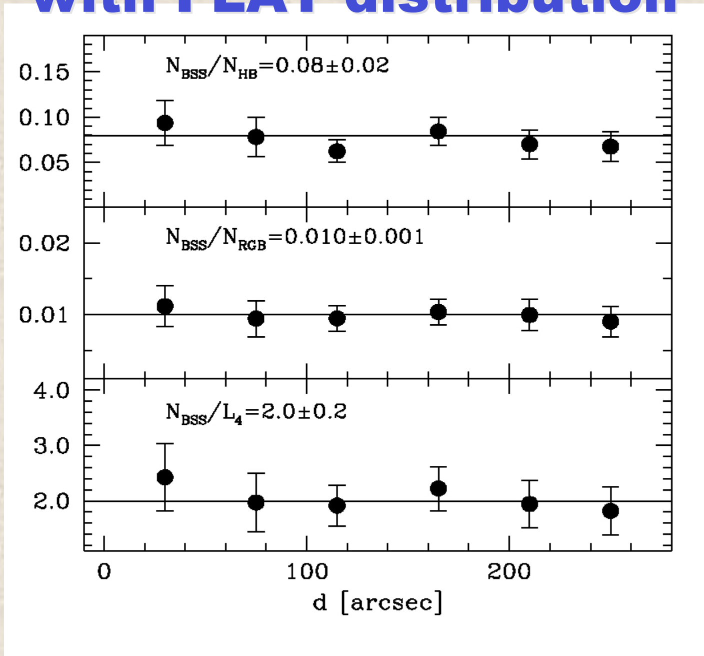
Dalessandro et al. (2008, ApJ 681,311)

BSS radial distributions

~ 10 GCs with bimodal/peaked distribution



2 GCs (ωCen, NGC2419) with FLAT distribution



Which is the origin of the bimodal distribution?

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:

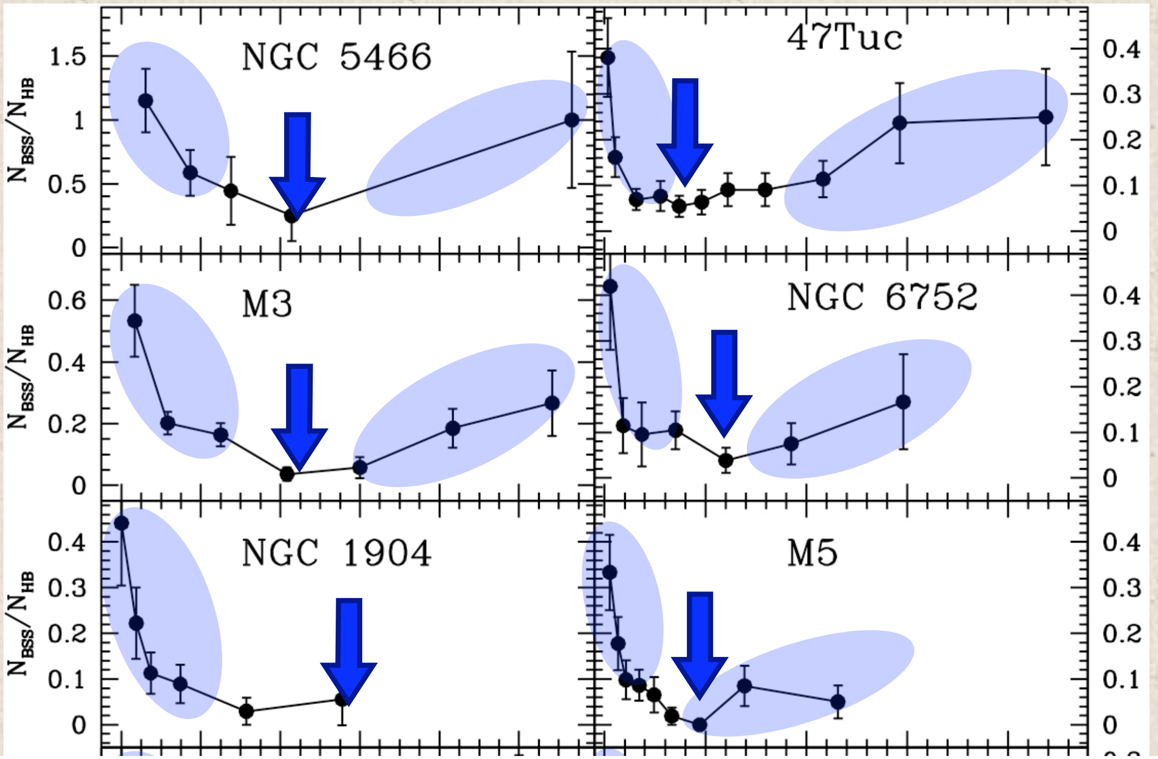
$$t_{df}(r_{avoid}) = \frac{3\,\sigma^3(r)}{4\ \ln\Lambda\ G^2\,(2\pi)^{1/2}\,M_{BSS}\,\rho(r)} = t_{AGE}$$

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



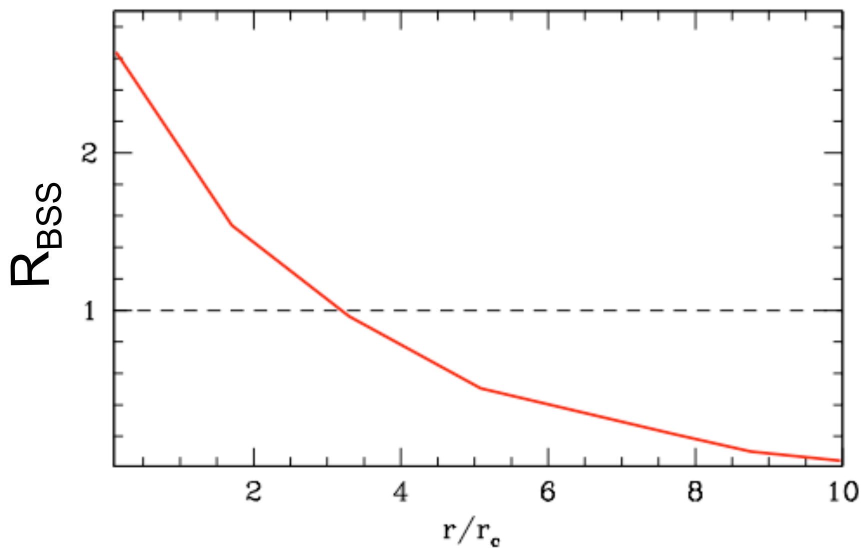
r_{avoid}

↕

position of the observed minimum

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

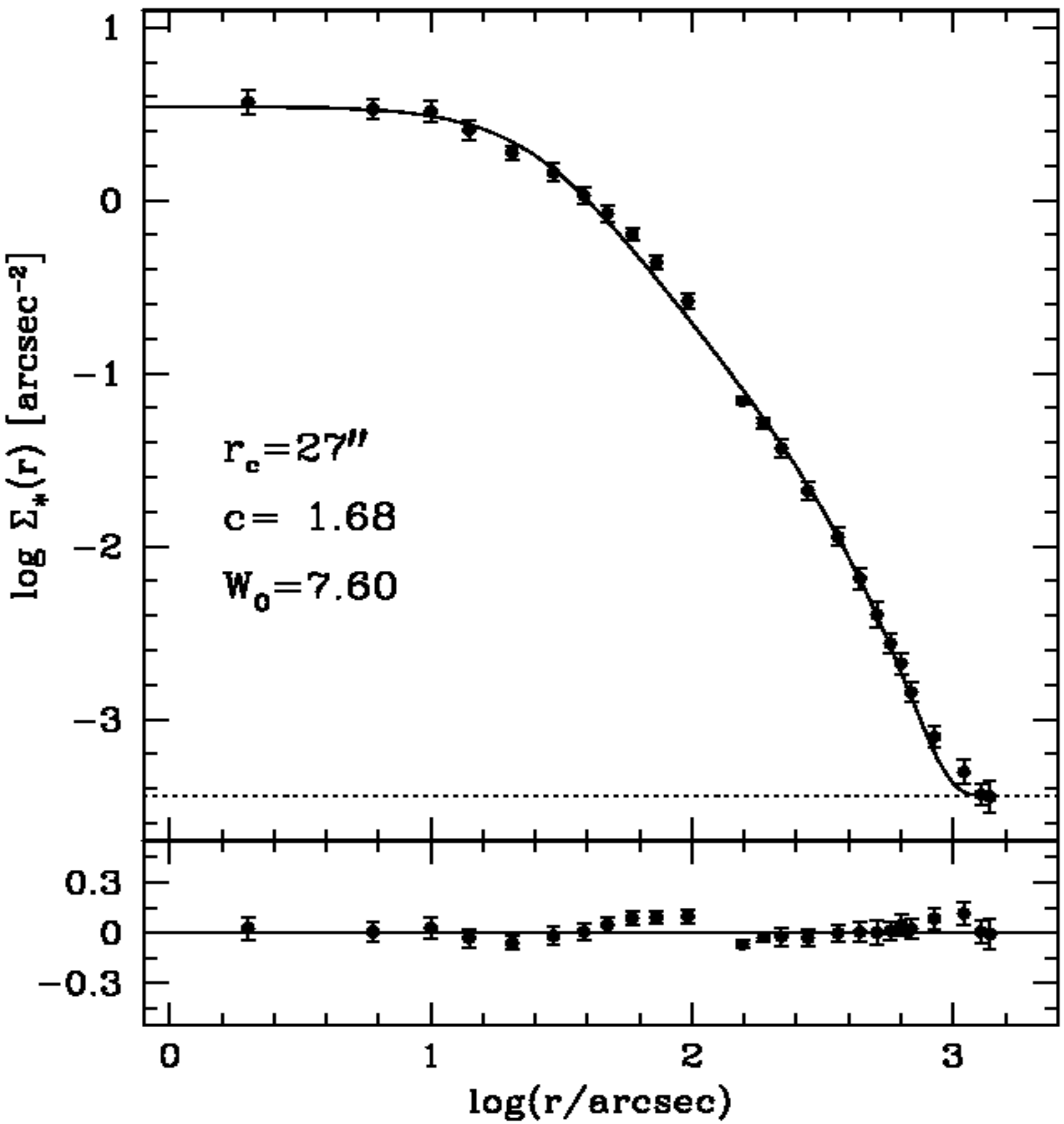
Can we define a sort of "dynamical clock"?

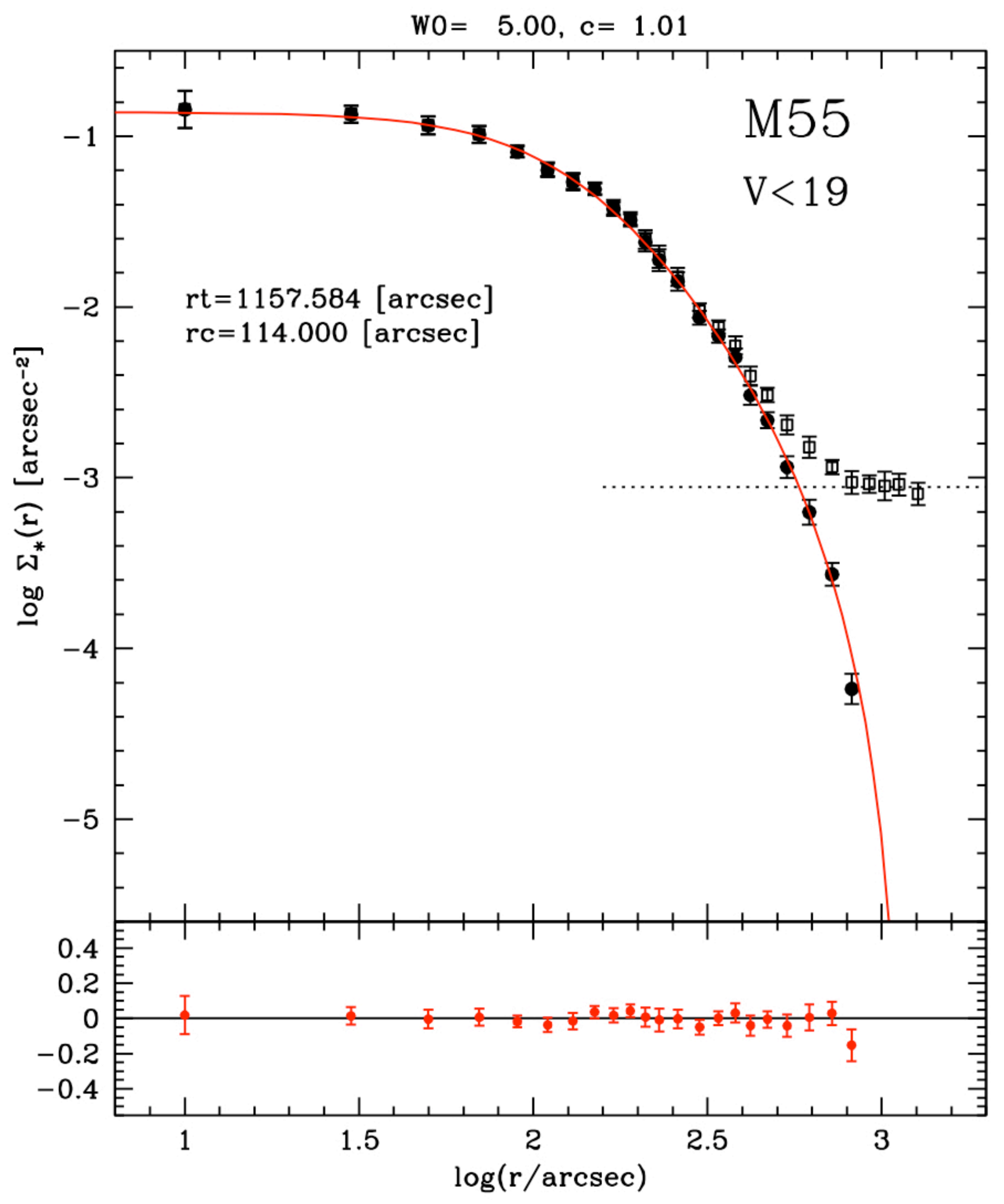


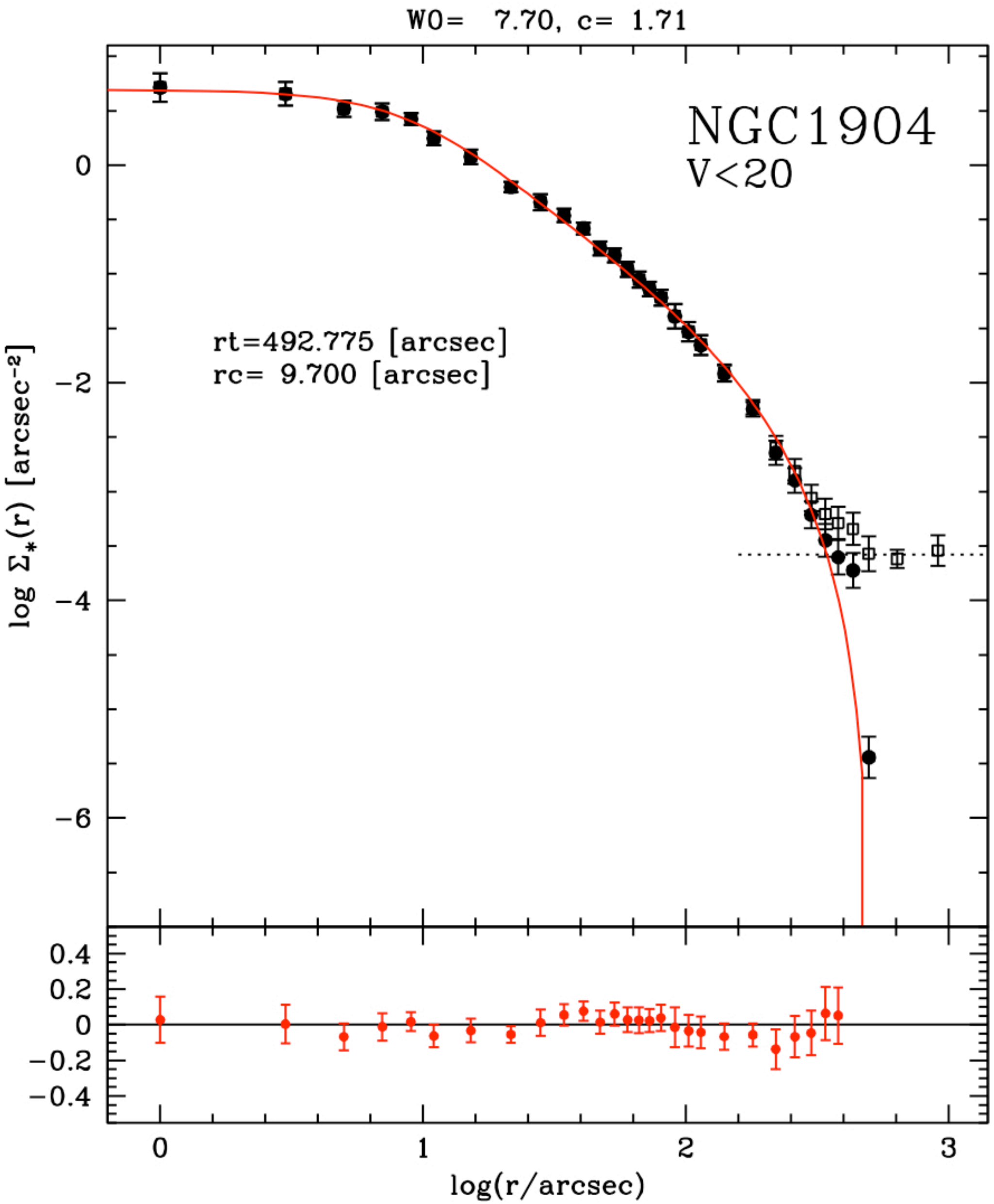
Important side-products:

High-accuracy star density profiles over the entire cluster extention

M5 (NGC5904)




W0= 5.00, c= 1.01
M55
V<19
rt=1157.584 [arcsec]
rc=114.000 [arcsec]
log Σ*(r) [arcsec⁻²]
log(r/arcsec)
-1
-2
-3
-4
-5
0.4
0.2
0
-0.2
-0.4
1
1.5
2
2.5
3


W0= 7.70, c= 1.71
NGC1904
V<20
rt=492.775 [arcsec]
rc= 9.700 [arcsec]
log Σ*(r) [arcsec⁻²]
log(r/arcsec)
0
−2
−4
−6
0.4
0.2
0
−0.2
−0.4
0
1
2
3

BSS chemical properties

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

How can we distinguish COL-BSS & PB-BSS?

Theoretical Predictions

Models give controversial predictions on the resulting properties of COL-BSS:

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

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

- **Negligible mixing between inner cores and outer envelopes of colliding stars is expected** (Lombardi et al. 1995)
- **Binary mass transfer is likely to create a fast rotating BSS and to lead an abundance pattern indicative of mixing with regions of incomplete CN-burning** (Sarna and de Greve 1996)

Looking for abundance signatures of the formation process with the VLT

Searching for chemical signatures of the BSS formation process

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

Ferraro, Lanzoni, Gratton, Piotto,Mucciarelli, Fusi Pecci, Beccari, Lucatello, Rood, Sills...

C abundance from CI line at λ=9111.8 A
O abundance from OI line at λ=7774 A

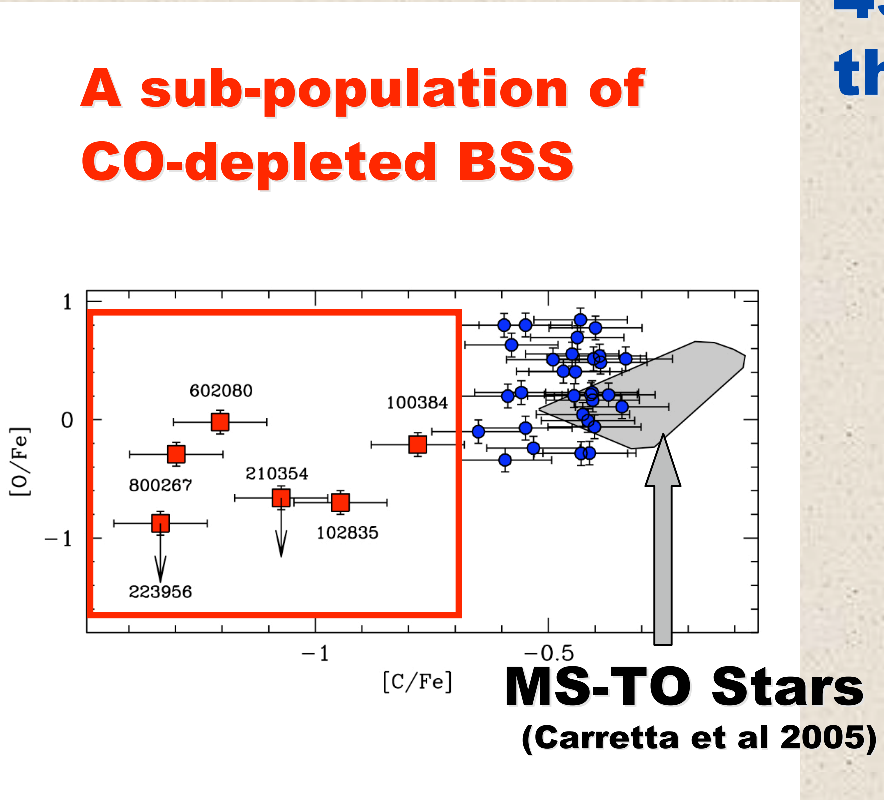
GC	Log ρ	[Fe/H]
47 Tuc	5.1	-0.7
NGC 288	2.1	-1.1
NGC 6397	PCC	-1.8
M4	4.1	-1.2
NGC6752	?	-1.6
Omega Cen	1.3	-1.6

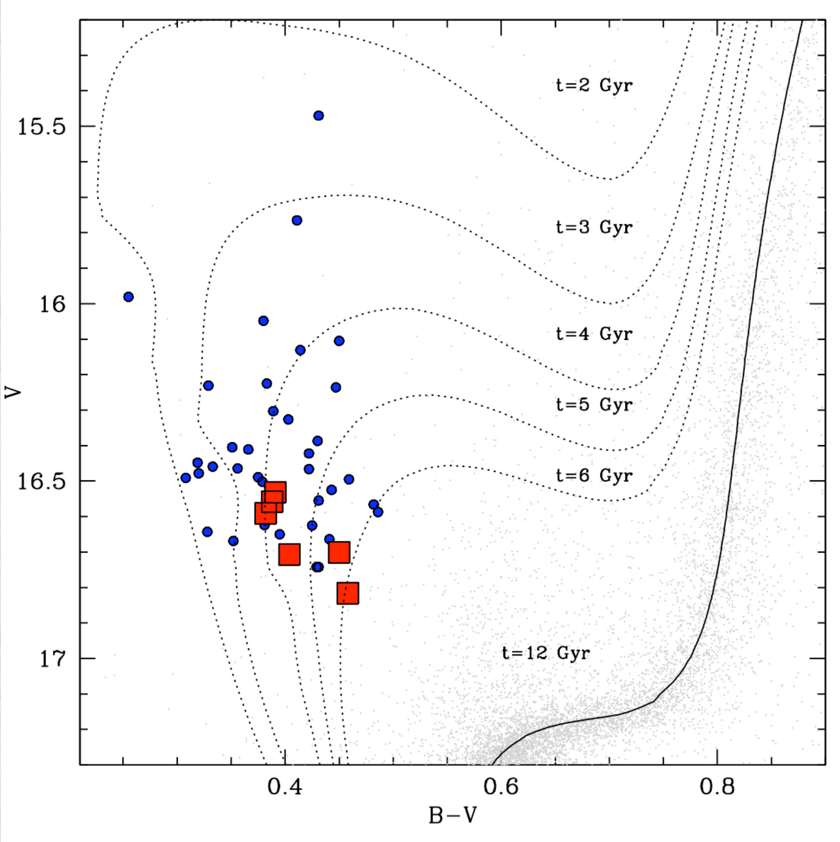
2 successfull runs at the VLT with FLAMES allowed us to collect data for ~ 300 BSS

47 Tuc: First Results

Ferraro et al 2006, ApJ,647,L56

43 BSS selected over the entire cluster extention

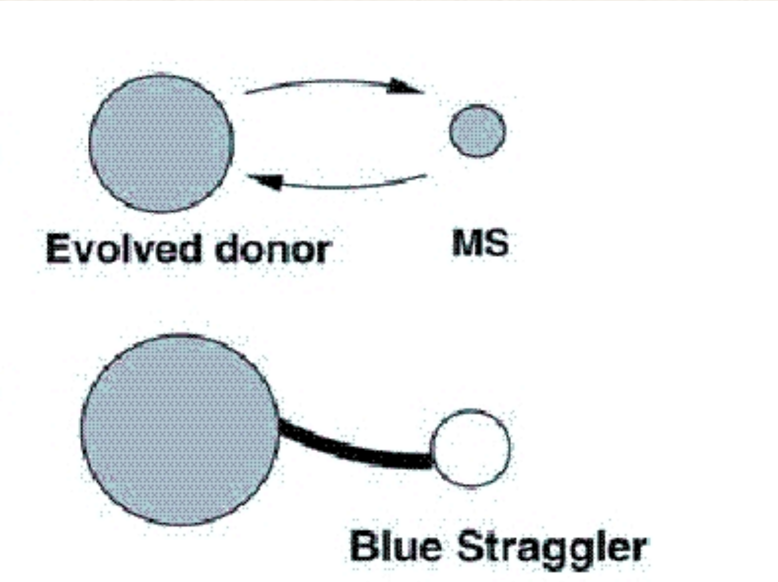




CNO burning products on the BSS surface coming from a deeply peeled parent star as expected in the case of mass-transfer process.

The chemical signature of the PB-BSS formation process?

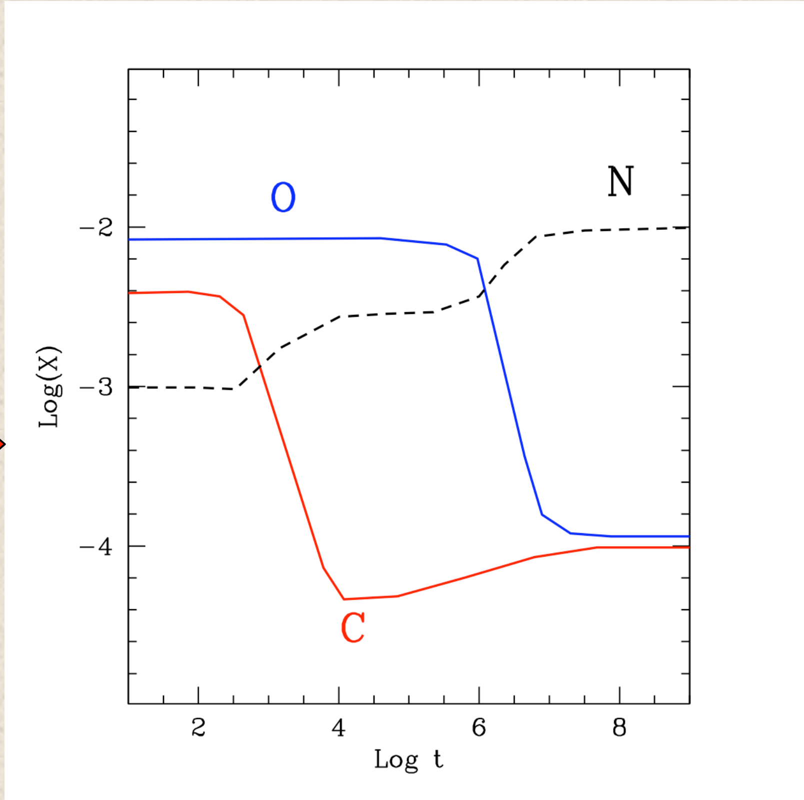
Forming a BSS through mass transfer



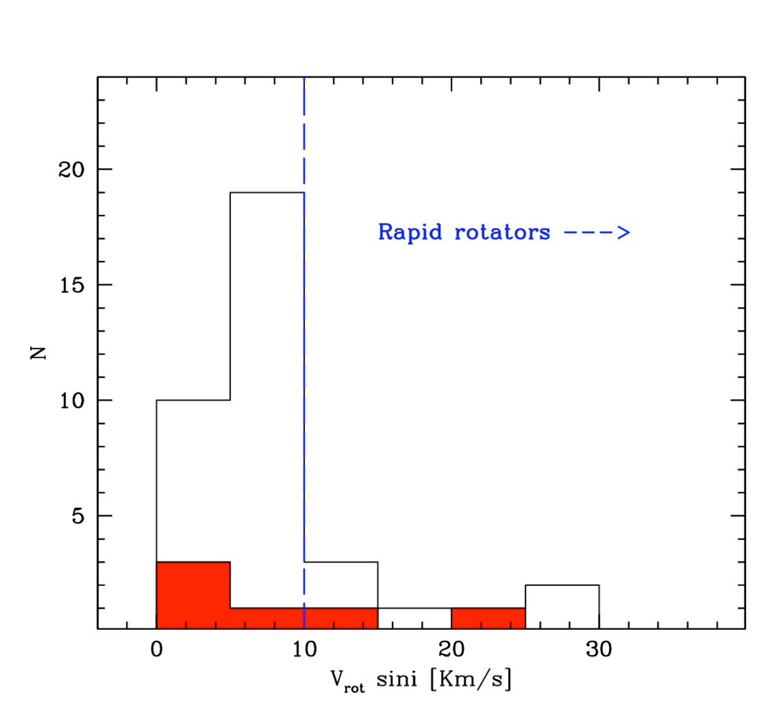
McCrea (1964)

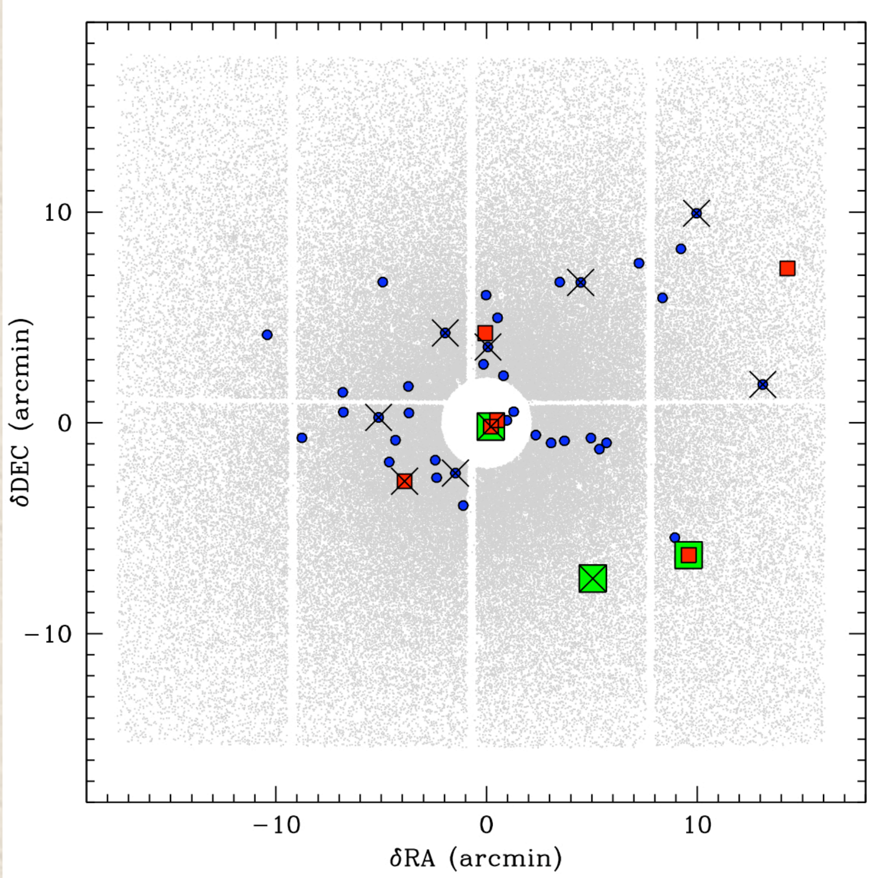
In the scenario in which a BSS is generated by mass transfer we can expect to see the "inner" material of the donor star on the BSS surface

CNO processing



Most BSS are slow rotators





6 C,O depleted (■)

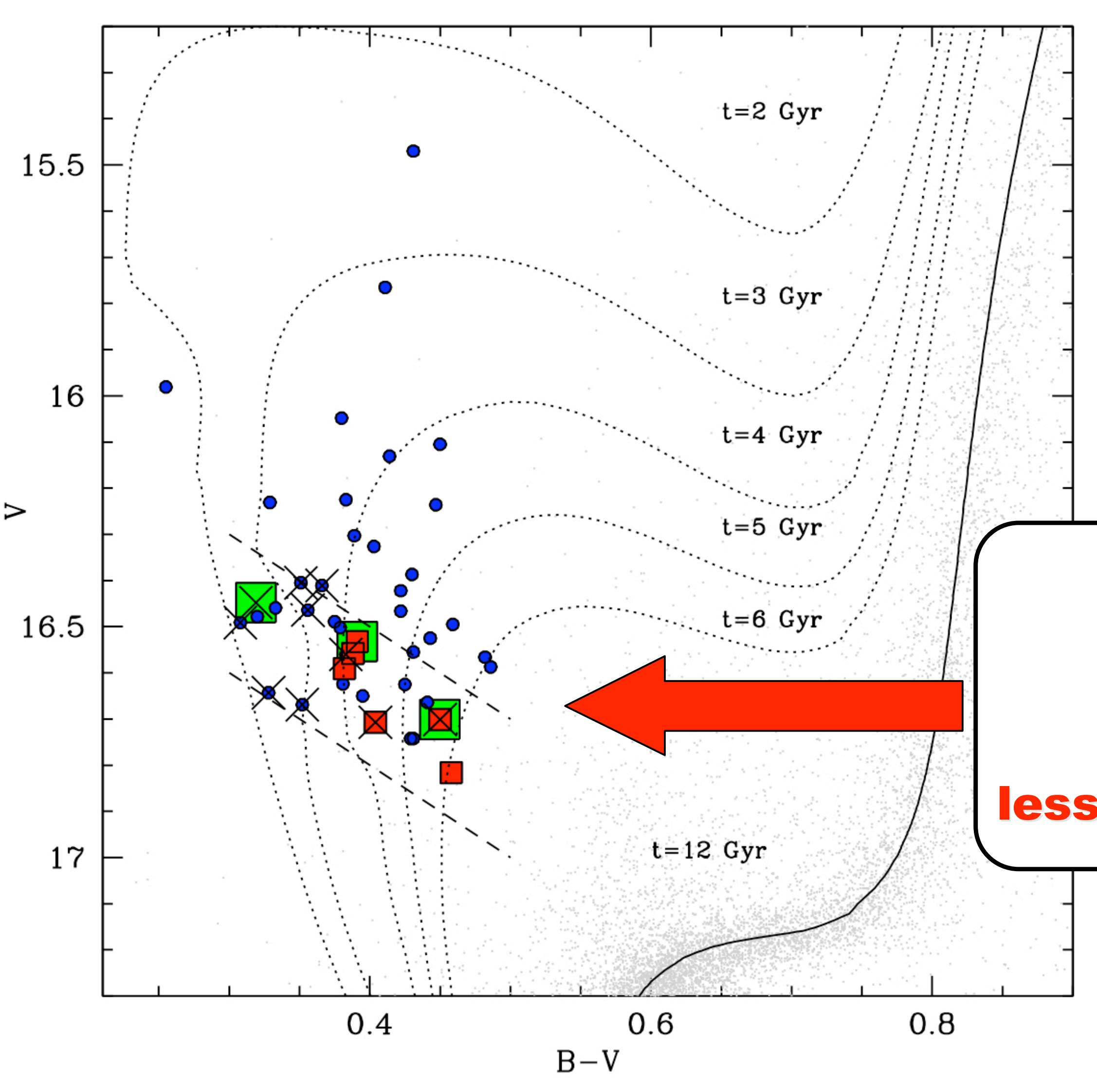
10 "moderate" rotators (X)

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

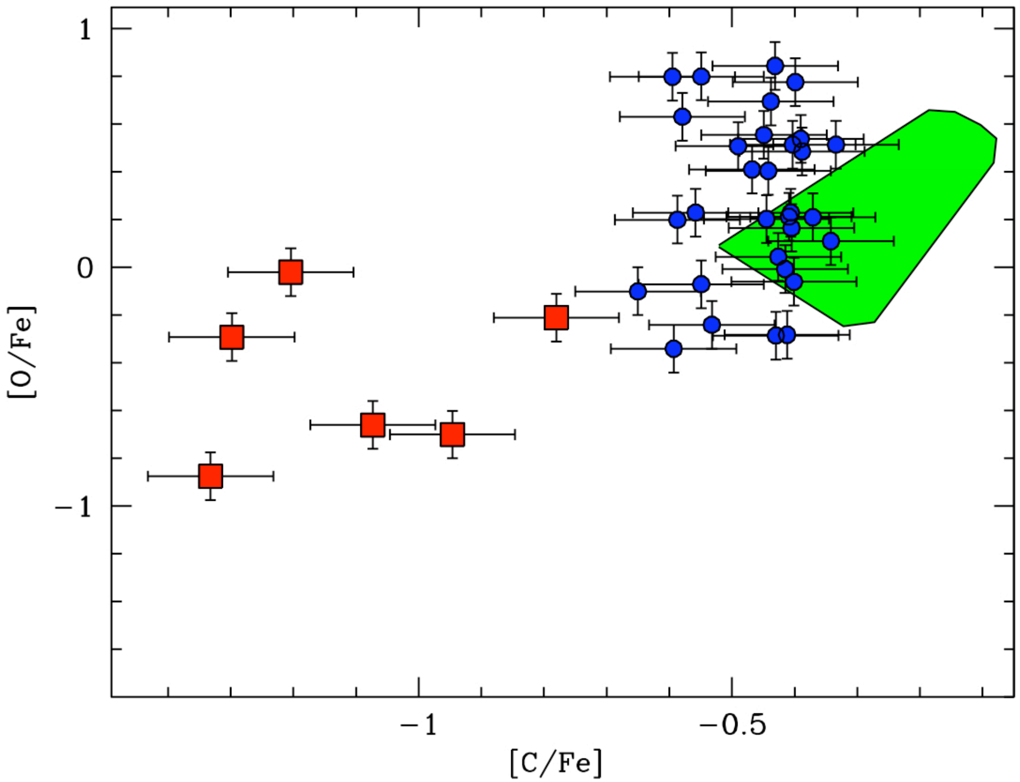


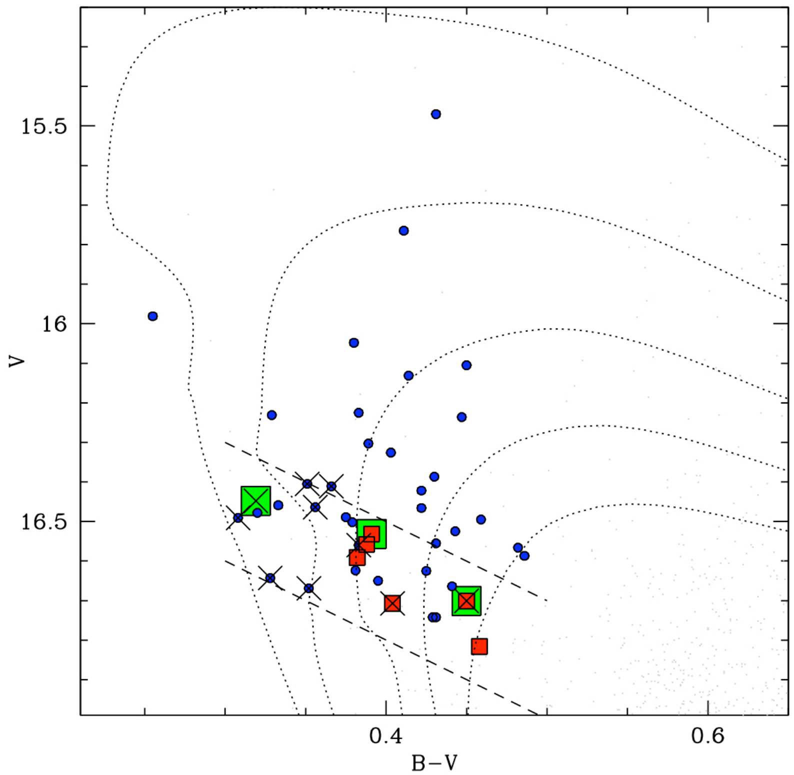
CO depleted BSS
Moderate rotators
W Uma systems
all appear to be
less evolved than normal BSS

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

Stage 1- trasferred material is un-processed. BSS appear as normal stars

Stage 2- trasferred material comes from CNO processed region C first and then O appear depleted





Stage 3- after the merge the BSS would appear as a non-variable CO depleted star

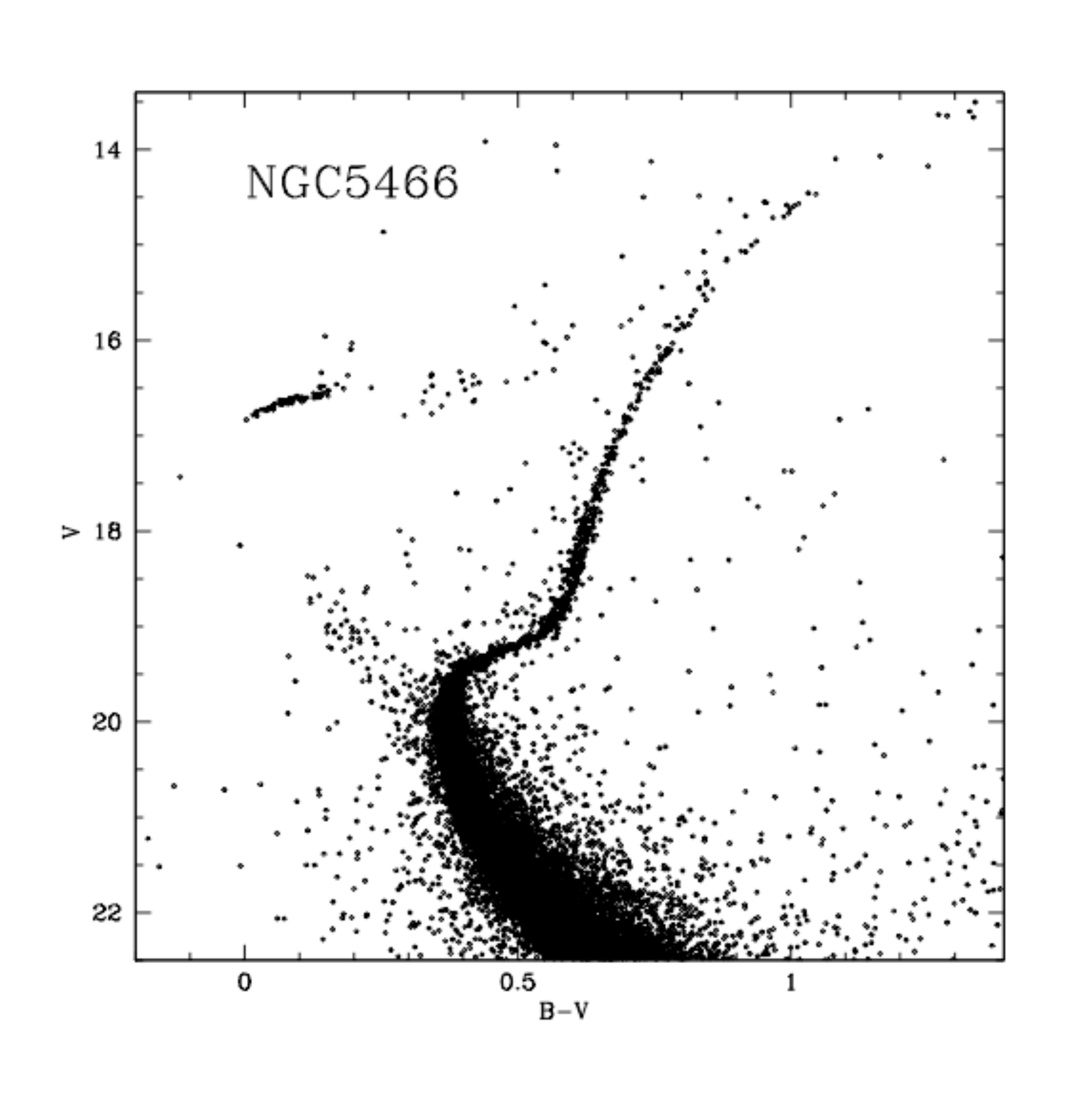
Stage 4- rotation decreases and internal mixing reduces the surface CO anomaly

QUESTIONS:

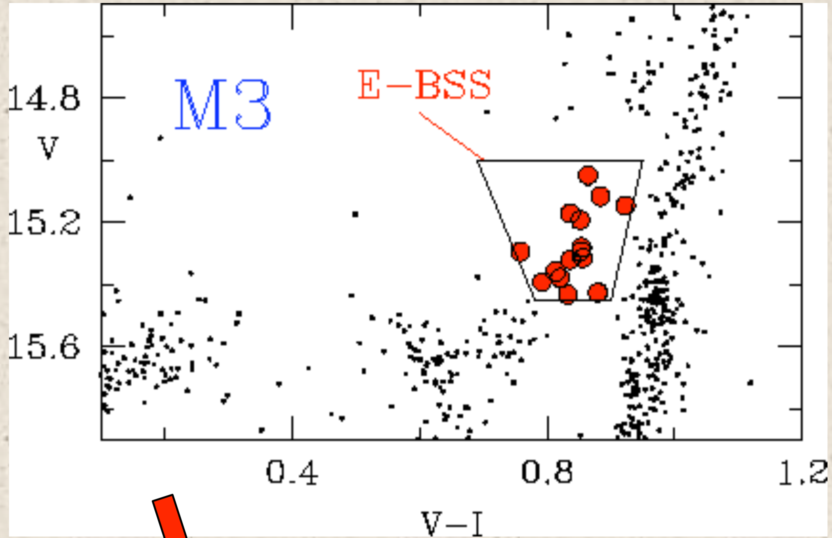
Why only a few BSS show CO depletion?
Is this a transitory effect? Mixing?

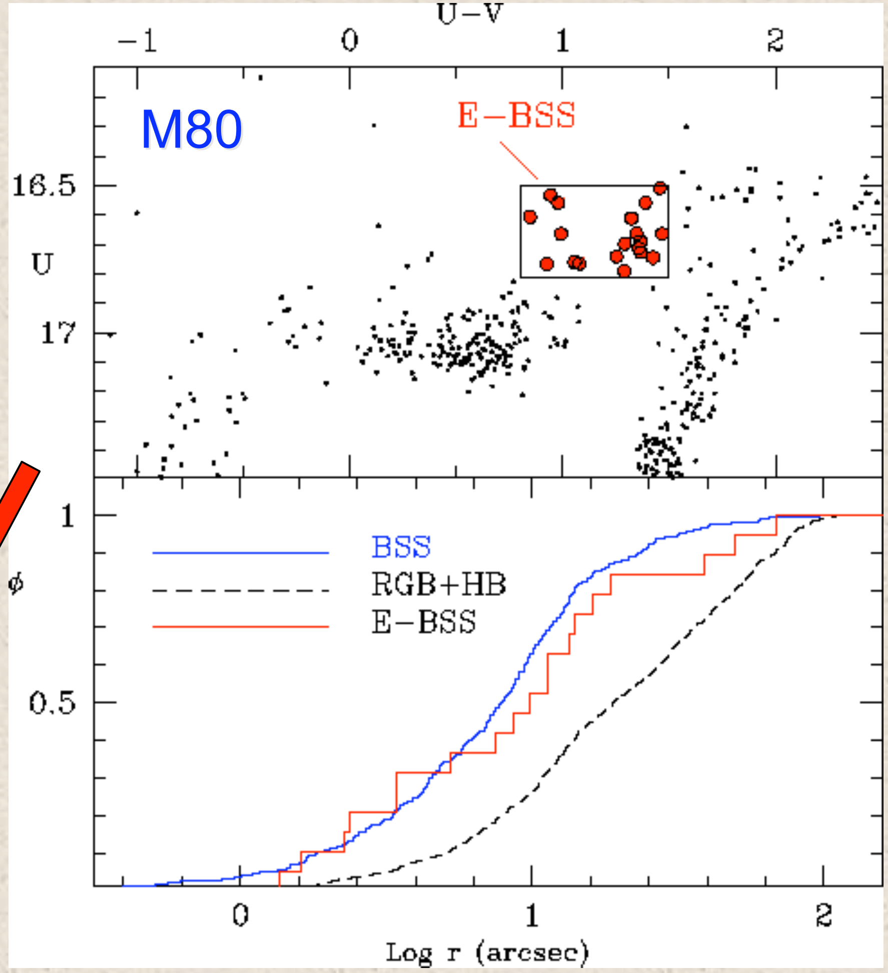
Apparently BSS are slow rotators!
Braking mechanism?

Evolved-BSS: where in the CMD?



Searching for Evolved BSS



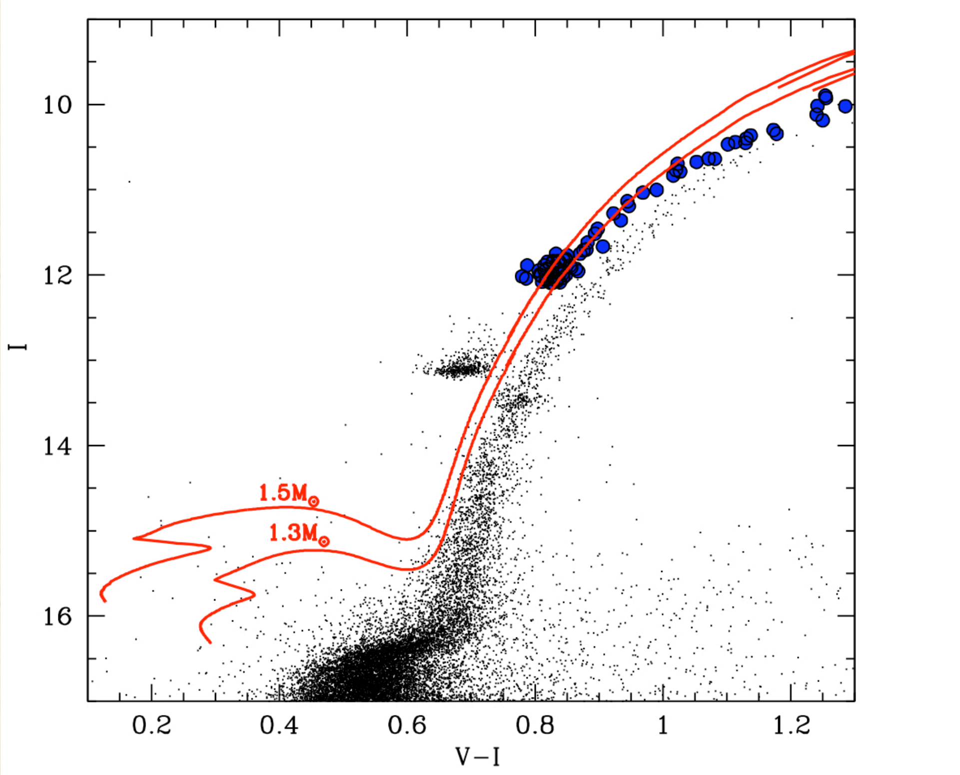


19 *E-BSS* candidates

M 3
entire cluster
$\mathcal{F} = N_{b-BSS} / N_{EBSS} =$ *122 / 19 = 6.4*

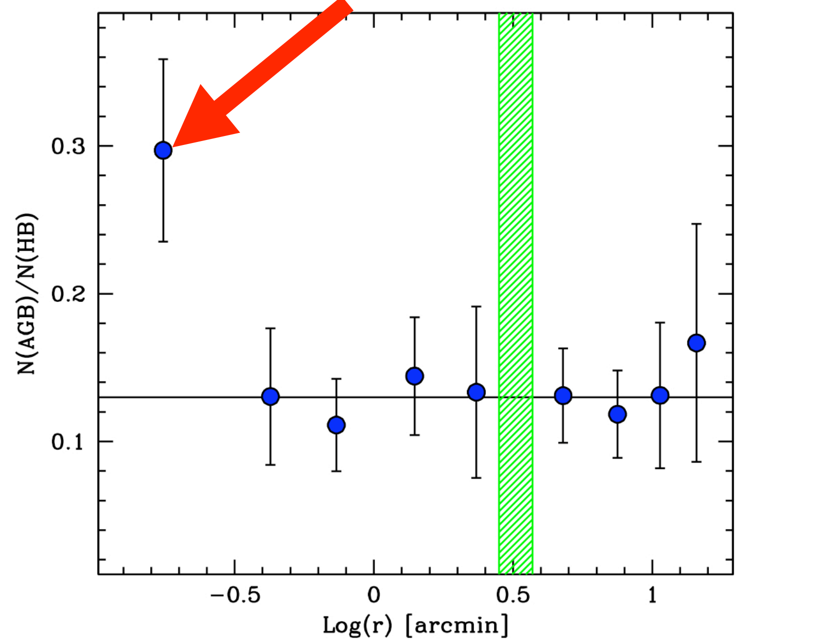
M 80
central region
$\mathcal{F} = N_{b-BSS} / N_{EBSS} =$ *129 / 19 = 6.5*

Evolved BSS in the AGB of 47 Tuc?



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

Contamination by non genuine low-mass AGB ???



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

OPEN ISSUES:

OBSERVATIONS:

1. BSS radial distribution in more clusters
2. More binary fraction determinations (expecially in high-density clusters... hard!!)
3. More chemical abundance and rotation velocity measurements
4. More info on the properties of E-BSS

THEORY:

1. More accurate modelling of collisional and not collisional BSS (hard!!)
2. Accurate Modelling of a few cases: M80? M3-M13?

Our group + Steinn + Mapelli is working to model the BSS radial distribution.... Any additional help is very welcome...


The End