# Blue Straggler Star Population in NGC 1261:

## Evidence for a *Triple* BSS sequence and implications for the Dynamical History of NGC 1261

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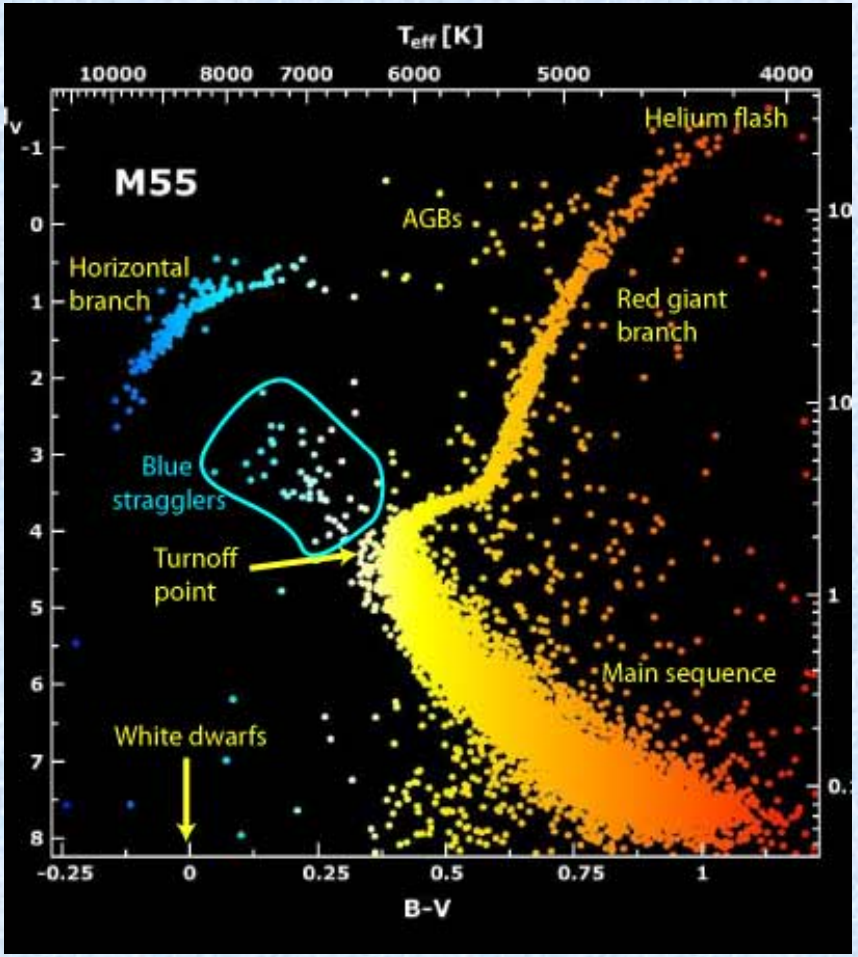
- Complex Stellar Systems research group: Prof. Thomas Puzia
- Milky Way research group: Prof. Eva Grebel (see her talk at 16:00)

Co-Authors: Thomas Puzia, Alison Sills (McMaster)

# Dynamics and BSS are related

- Blue Straggler Stars (BSS) are among the most massive stars in a GC.
- Strong dynamical events playing a major role in BSS formation
- They will respond notoriously to changes in the cluster potential.



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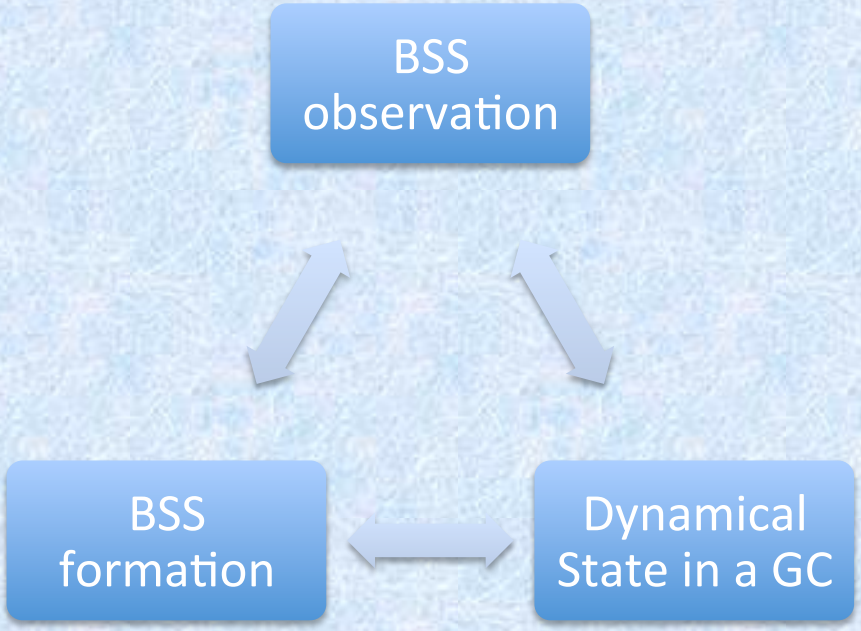
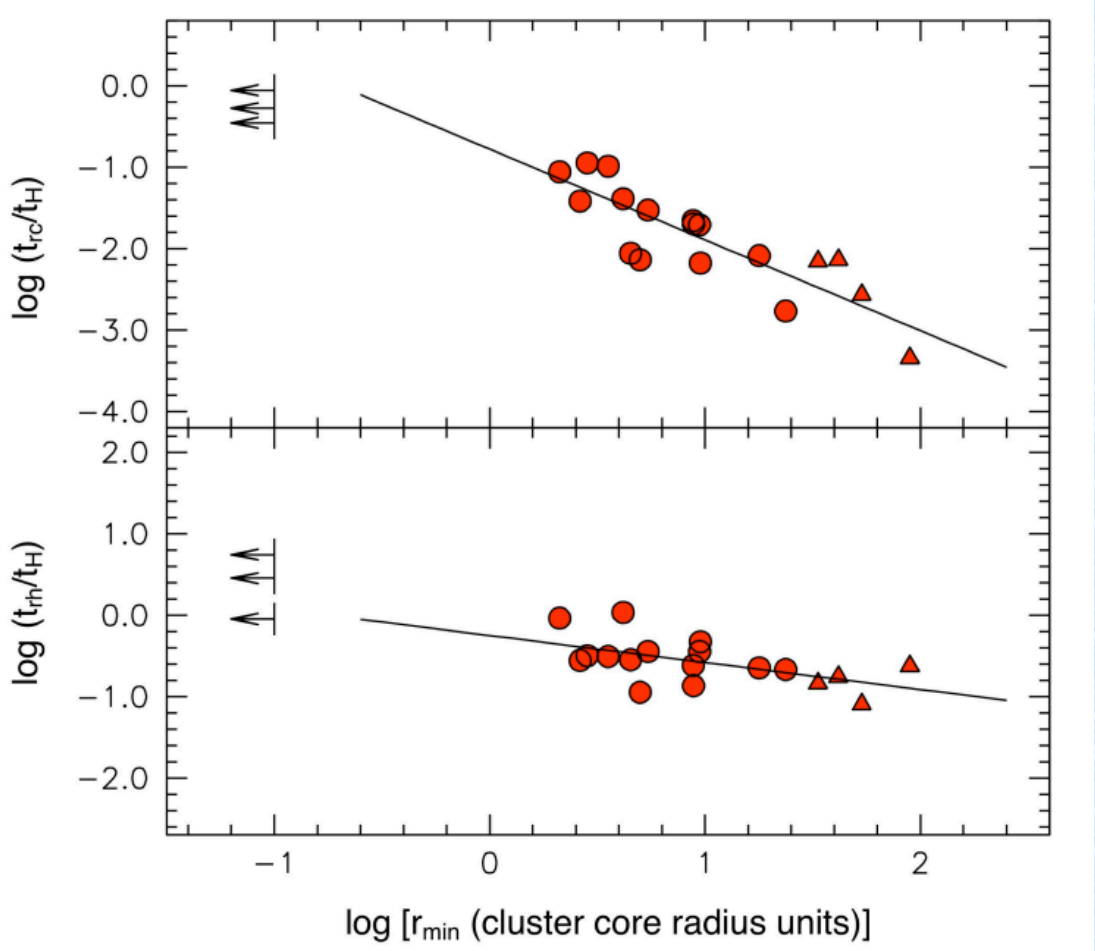


# Dynamics and BSS are related

Ferraro et al. 2012

- The BSS fraction radial profile can be used to derive the cluster's dynamical age (Ferraro et al. 2012)
- The radius at which BSS have sunk inwards will depend on the time it takes the GC to reach energy equipartition.

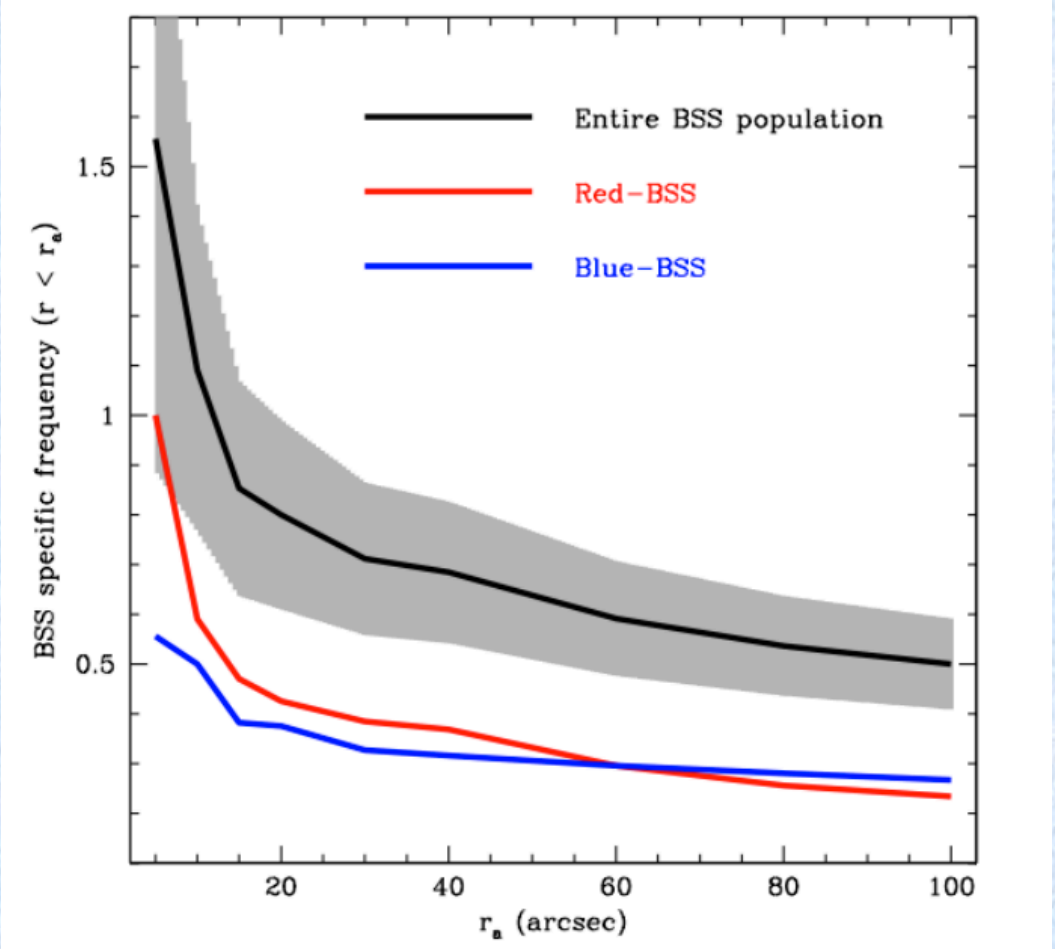


# Fun things happen on the dynamically oldest clusters

- The more evolved clusters will show a strong BSS central segregation

- Two special cases: M 30 (Ferraro et al. 2009) and NGC 362 (Dalessandro et al. 2013).

Ferraro et al. 2009 M 30



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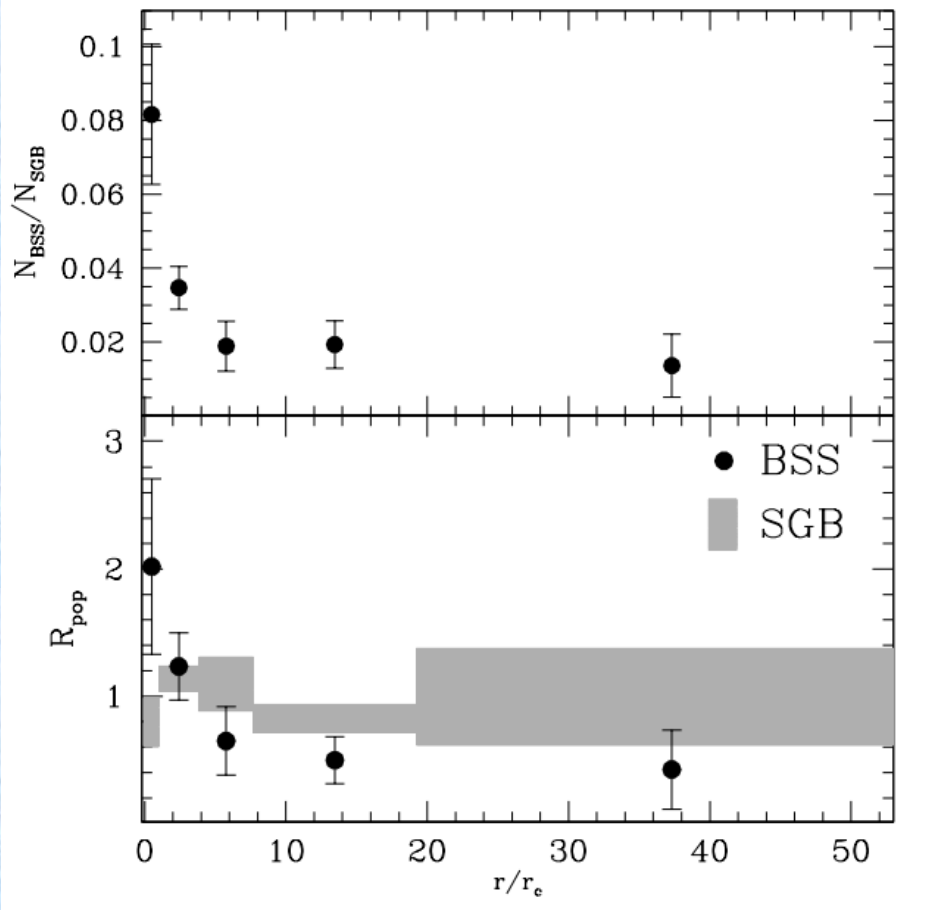
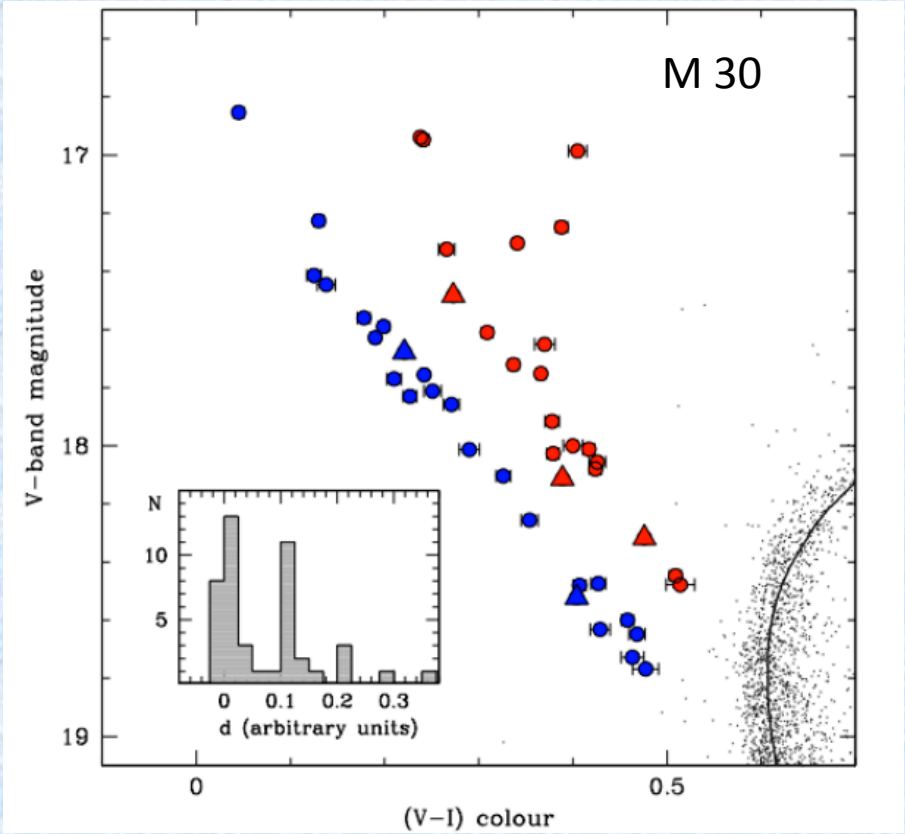
Dalessandro et al. 2013 NGC 362

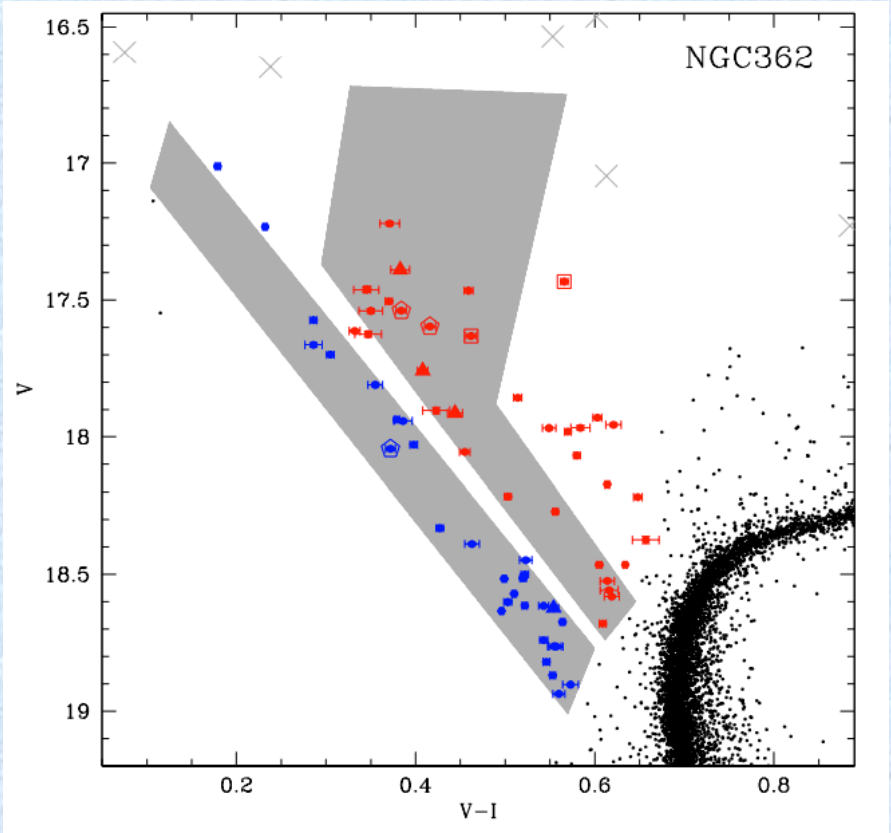


# The occurrence of Double BSS Sequences in the CMD

Ferraro et al. 2009

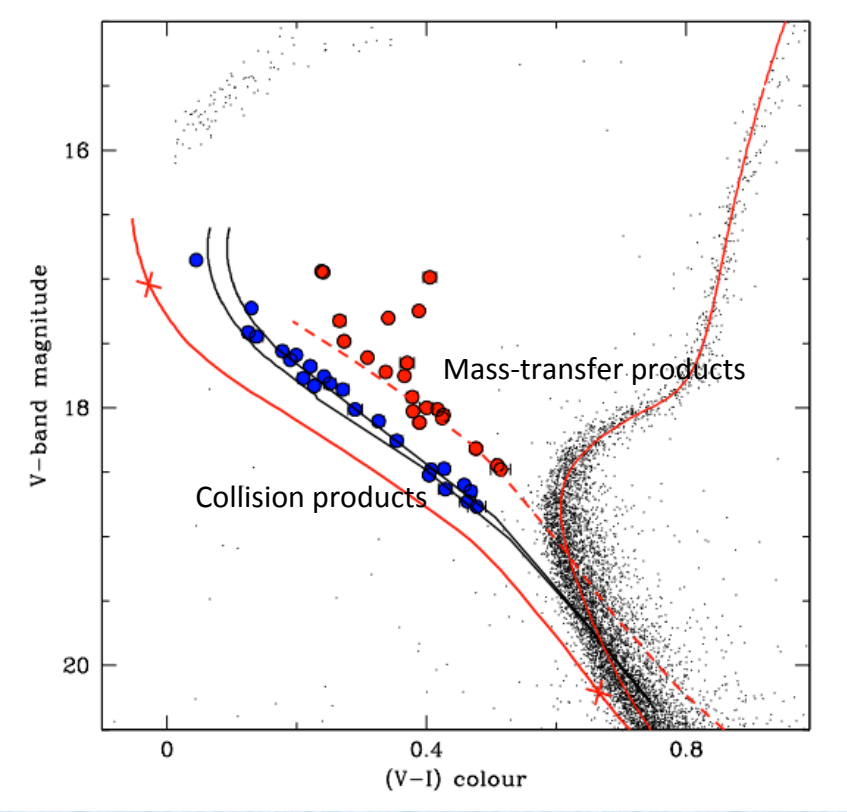



Dalessandro et al. 2013



# Distinct sequences suggest a ***single short*** formation event → ***Core Collapse***

Ferraro et al. 2009

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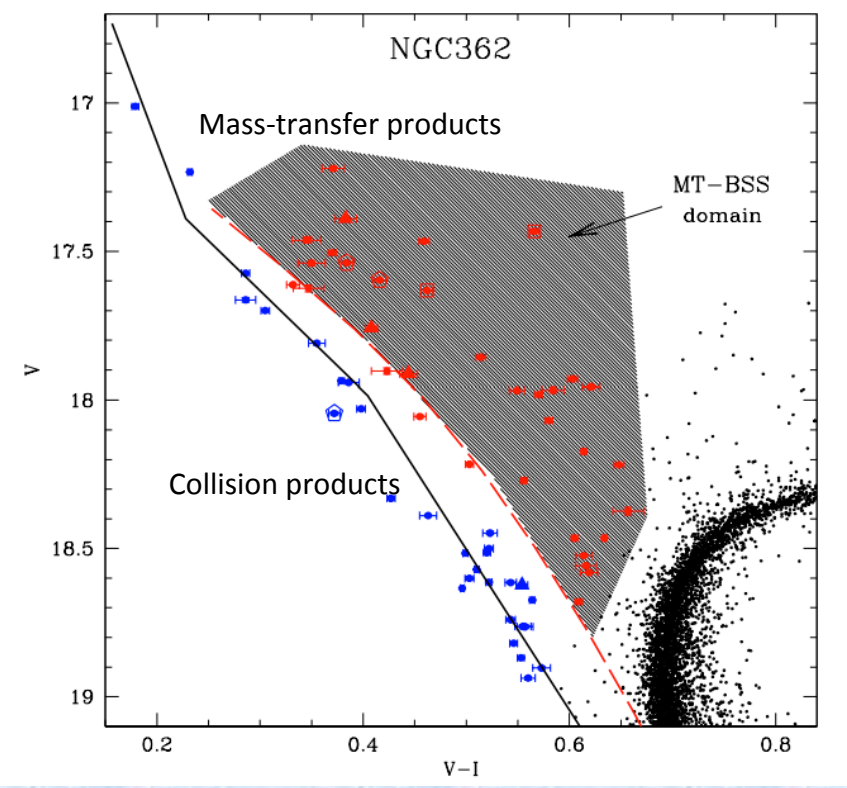
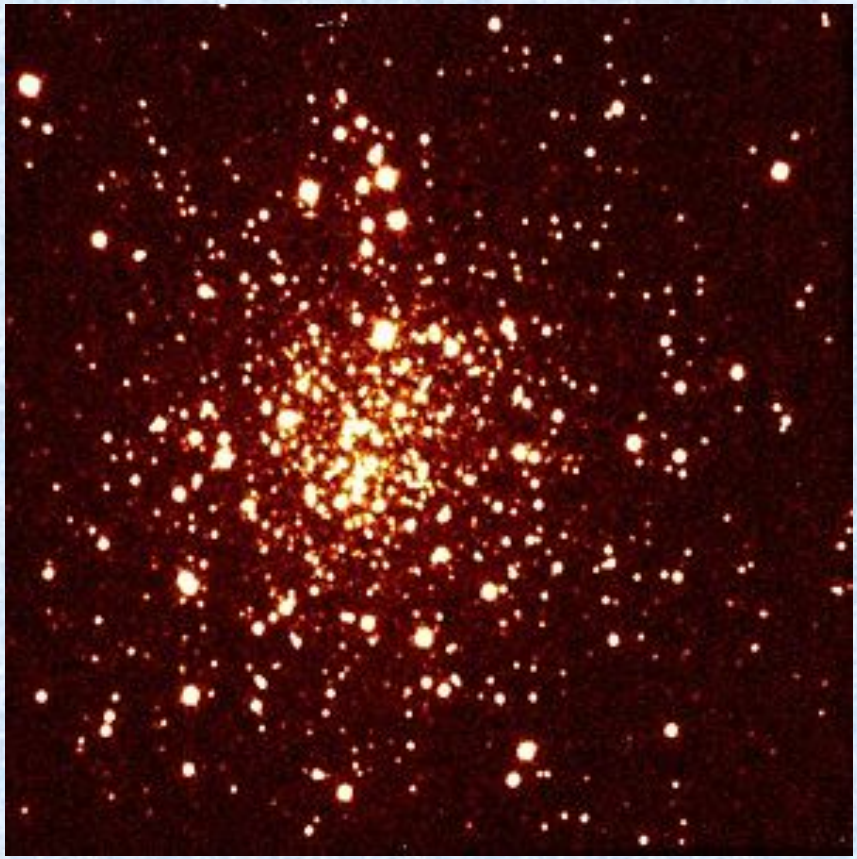



*Tian et al. (2006) simulations predict BSS from case A (MS donor) mass-transfer binaries will populate a region whose fainter boundary is given by the ZAMS+0.75 mag in the V band.

# Looking at NGC 1261

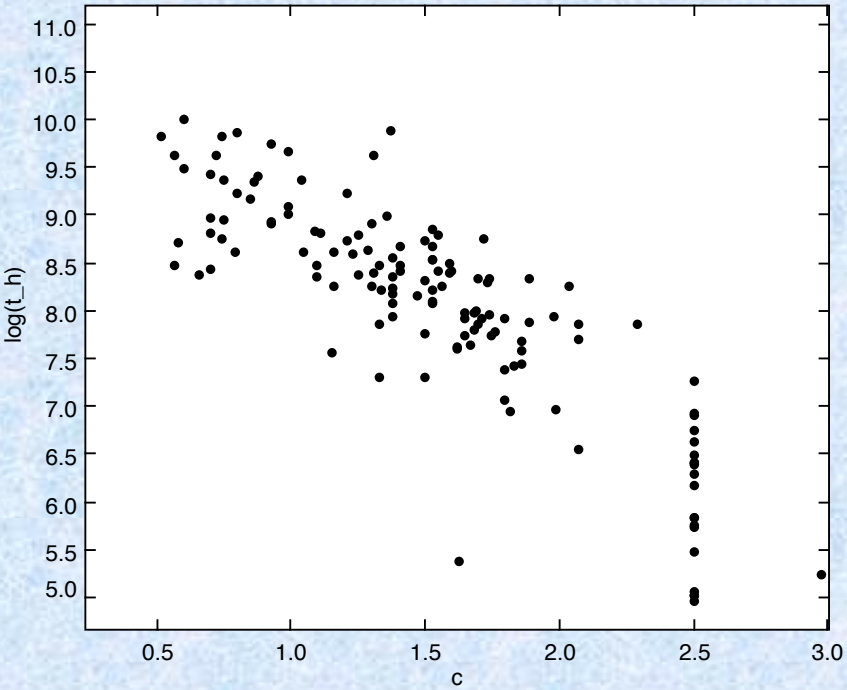
- Mass ≈ $3 \times 10^5$ $M_\odot$ (Boyles et al. 2011 )
- Rgal = 18.1 kpc (Harris catalog)
- [Fe/H] = -1.35 (Dotter et al. 2012)

Credit: ESO



# Looking at NGC 1261

Harris Catalog data

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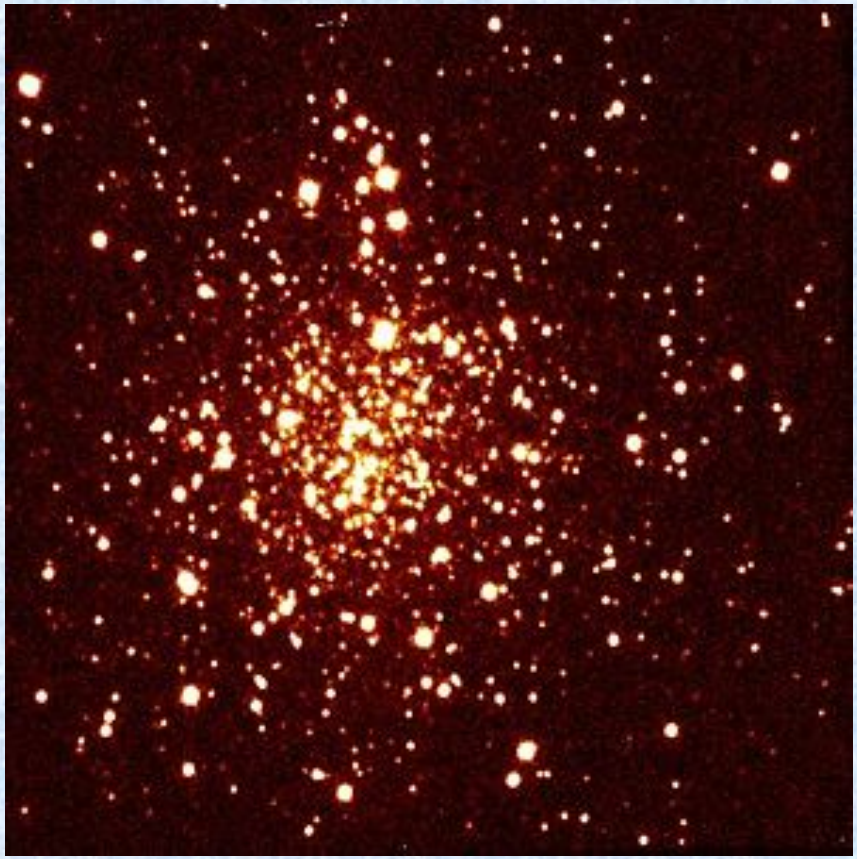

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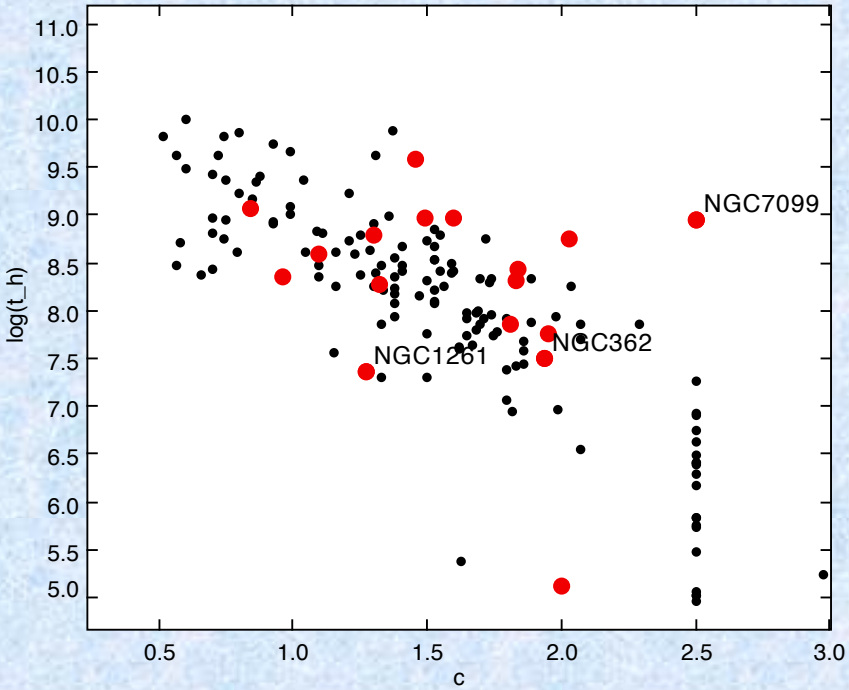
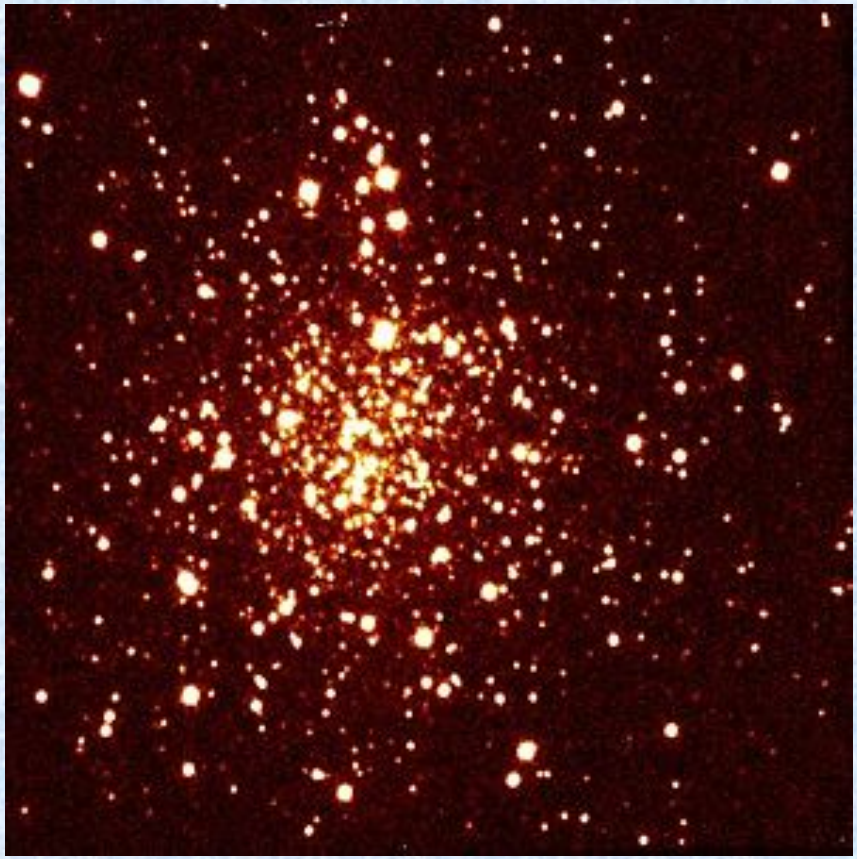



Paust et al. 2010 HST/ACS data

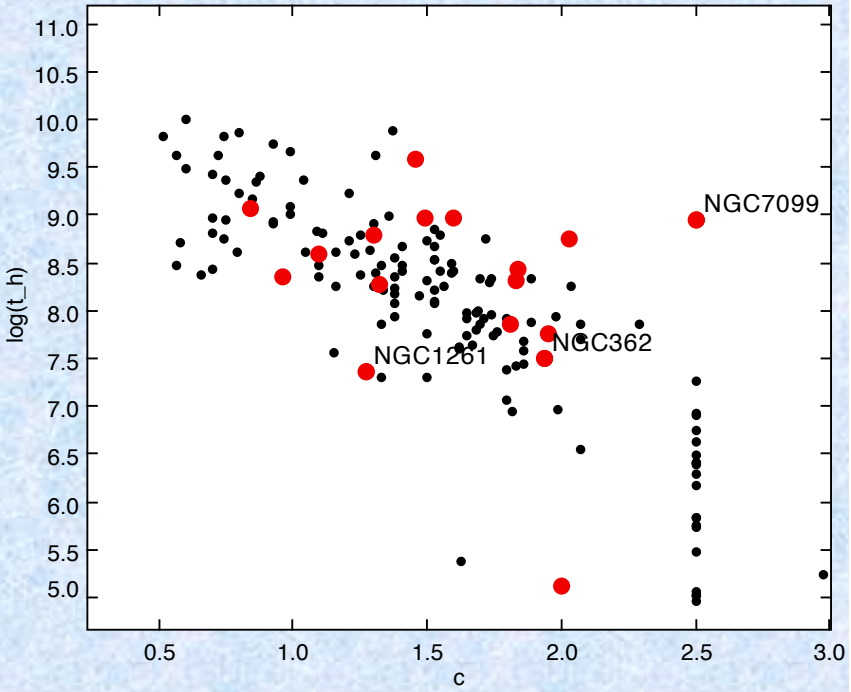
Credit: ESO



# Looking at NGC 1261

Leigh et al. 2011

Harris Catalog data




Paust et al. 2010 HST/ACS data

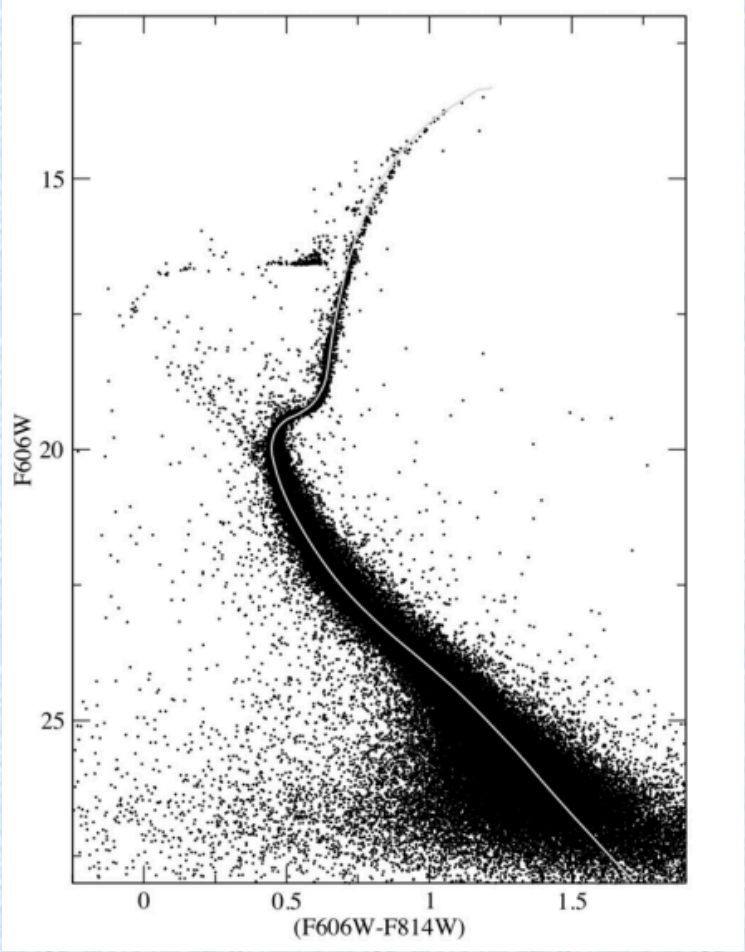
| Cluster ID | Alternate ID | Core Radius (in arcmin) | $N_{BS}$ | | | |
|---|---|---|---|---|---|---|
| | | | $< r_c$ | $< 2r_c$ | $< 3r_c$ | $< 4r_c$ |
| 104 | 47 Tuc | 0.36 | 62 | 100 | 120 | 128 |
| 1261 | | 0.35 | 56 | 79 | 95 | 104 |
| 1851 | | 0.09 | 34 | 58 | 74 | 90 |
| 2298 | | 0.31 | 27 | 32 | 37 | 38 |
| 3201 | | 1.30 | 40 | – | – | – |
| 4147 | | 0.09 | 16 | 26 | 30 | 34 |
| 4590 | M 68 | 0.58 | 29 | 59 | – | – |
| 5024 | M 53 | 0.35 | 57 | 103 | 133 | 149 |
| 5139 | Ω Cen | 2.37 | 49 | 87 | – | – |
| 5272 | M 3 | 0.37 | 74 | 111 | 127 | 135 |
| 5286 | | 0.28 | 82 | 120 | 138 | 144 |
| 5466 | | 1.43 | 30 | – | – | – |
| 5904 | M 5 | 0.44 | 37 | 57 | 64 | 68 |
| 5927 | | 0.42 | 28 | 71 | 93 | 122 |
| 5986 | | 0.47 | 57 | 88 | – | – |
| 6093 | M 80 | 0.15 | 79 | 114 | 133 | 135 |
| 6101 | | 0.97 | 26 | – | – | – |
| 6121 | M 4 | 1.16 | 11 | 18 | – | – |
| 6171 | M 107 | 0.56 | 19 | 43 | 54 | – |
| 6205 | M 13 | 0.62 | 41 | 58 | – | – |
| 6218 | M 12 | 0.79 | 28 | 50 | – | – |
| 6254 | M 10 | 0.77 | 36 | 52 | – | – |
| 6304 | | 0.21 | 19 | 36 | 51 | 67 |
| 6341 | M 92 | 0.26 | 41 | 73 | 84 | 91 |
| 6362 | | 1.13 | 35 | – | – | – |
| 6535 | | 0.36 | 7 | 11 | 12 | 12 |
| 6584 | | 0.26 | 36 | 54 | 63 | – |
| 6637 | M 69 | 0.33 | 50 | 85 | 96 | 106 |
| 6652 | | 0.10 | 16 | 19 | 24 | 27 |
| 6723 | | 0.83 | 39 | – | – | – |
| 6779 | M 56 | 0.44 | 21 | 41 | 48 | 49 |
| 6838 | M 71 | 0.63 | 17 | 45 | – | – |
| 6934 | | 0.22 | 35 | 54 | 57 | 60 |
| 6981 | M 72 | 0.46 | 31 | 49 | 56 | – |
| 7089 | M 2 | 0.32 | 83 | 129 | 143 | 150 |

# Collecting Data for NGC 1261

- HST/ACS Globular Clusters Survey. High quality optical photometry in F606W (~V) and F814W (~I) bands for 65 GCs.
  (Sarajedini et al. 2007)

- Complementary F336W (~U) band HST/ WFC3 photometry from Hubble Legacy Archive. PI: Piotto, Proposal ID: 13297. PSF photometry performed with DoPHOT
  (Alonso-Garcia et al. 2012)

Paust et al. 2010 NGC 1261



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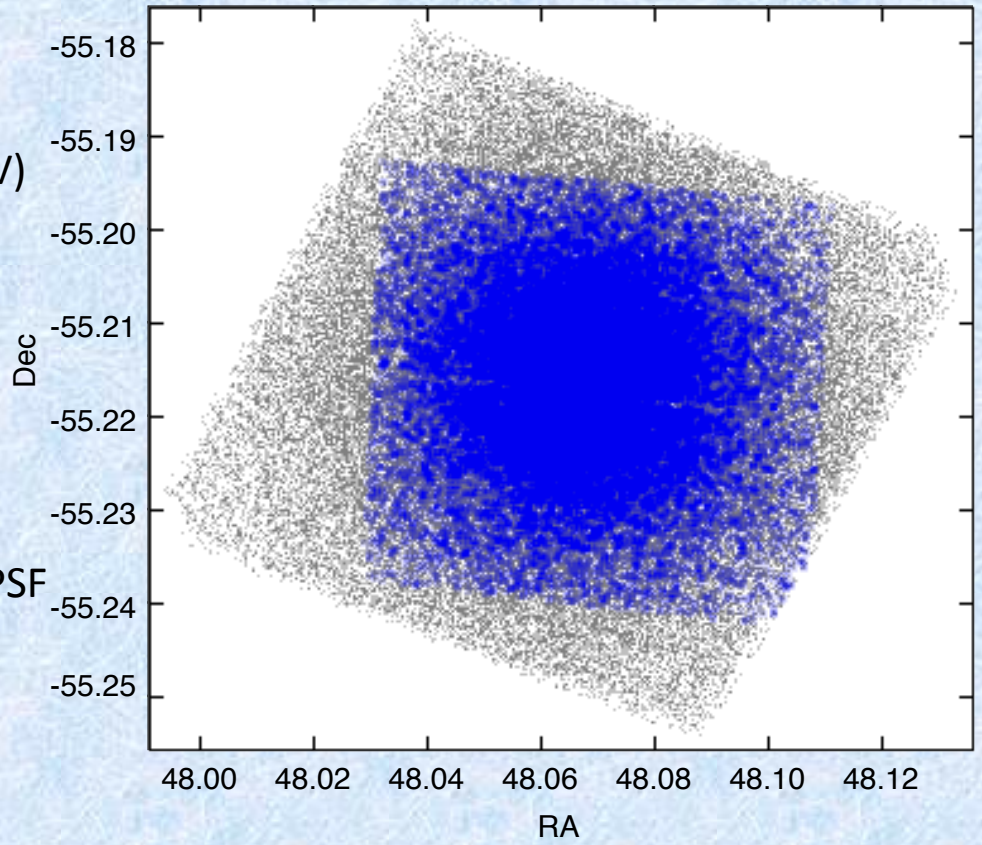
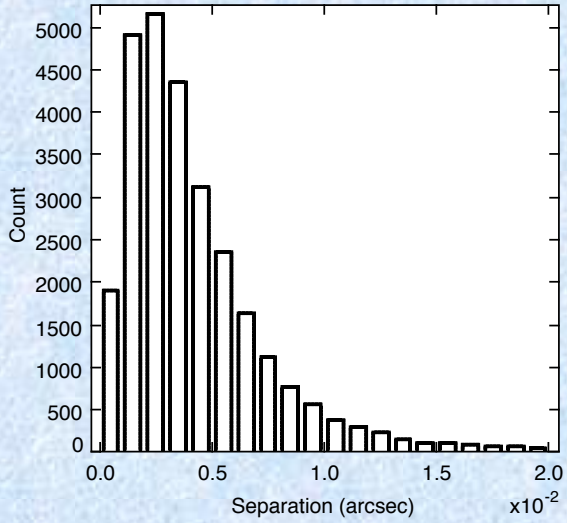
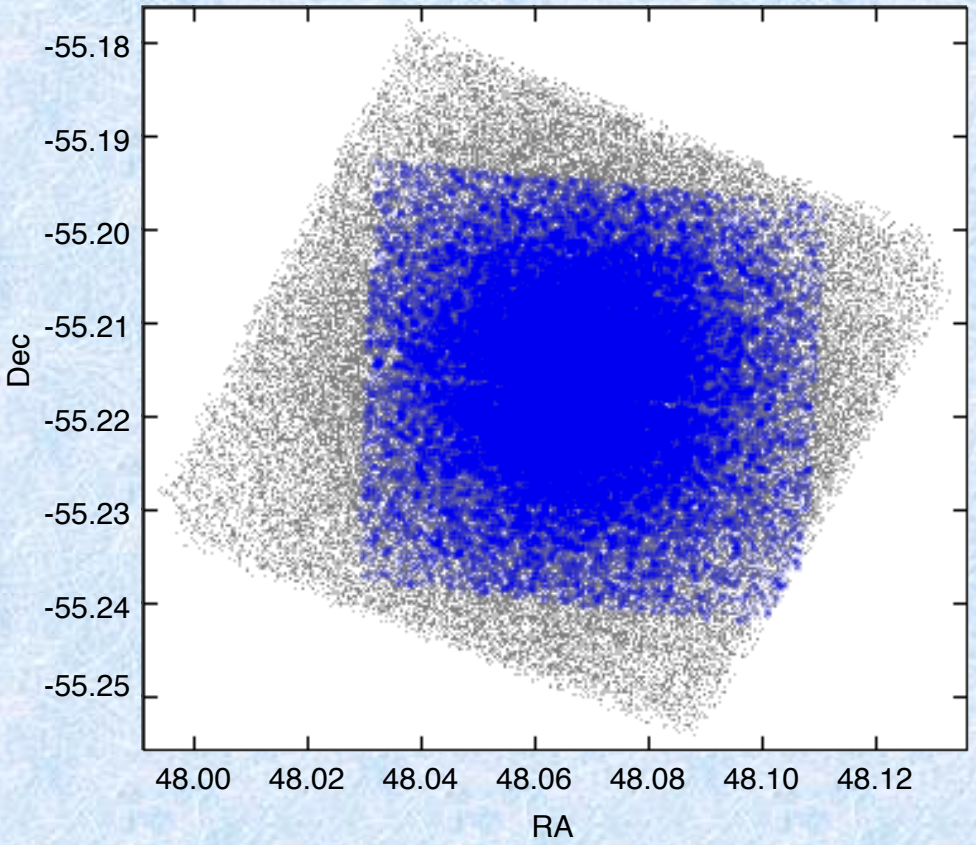


# Final Photometric Catalog

- We correct astrometry. Median accuracy 0.002” between U and optical catalogs.
- We keep sources with separations less than 0.02”, i.e. about 0.5 pixels of ACS camera.

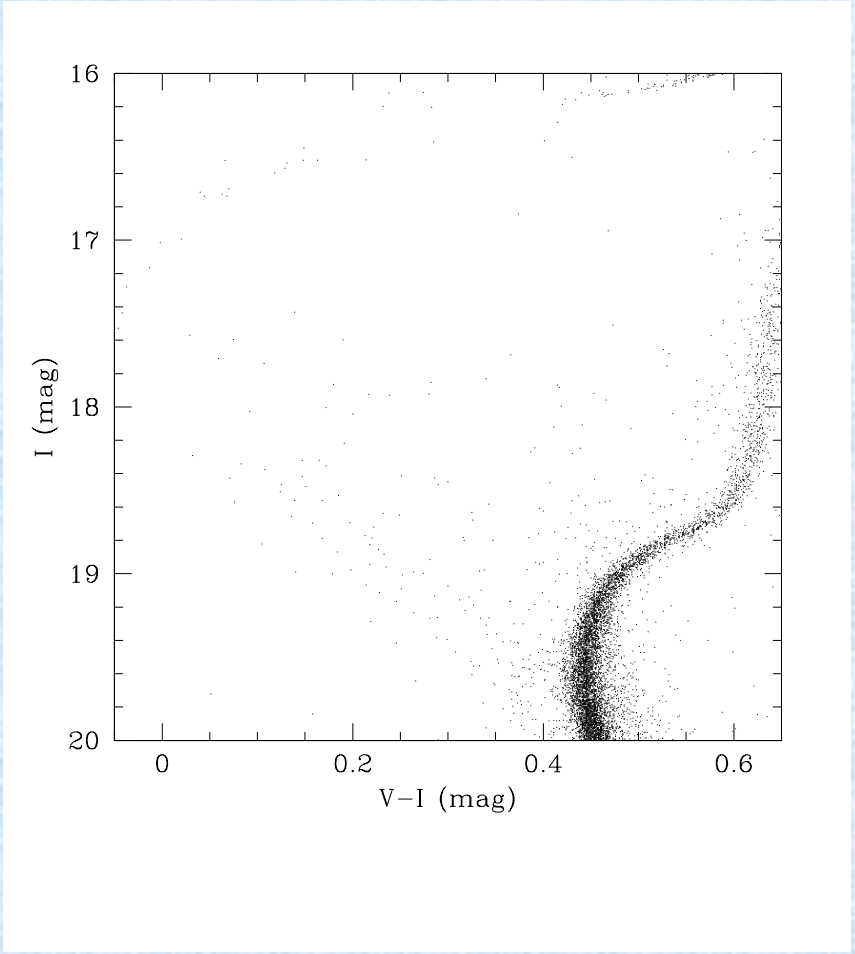



**Final Catalog with about 27k sources in U,V and I**

# Selecting BSS candidates

- We select BSS candidates photometrically based on their **location in the (V-I) vs I color-magnitude diagram**. We use the region defined by Leigh et al. (2011).



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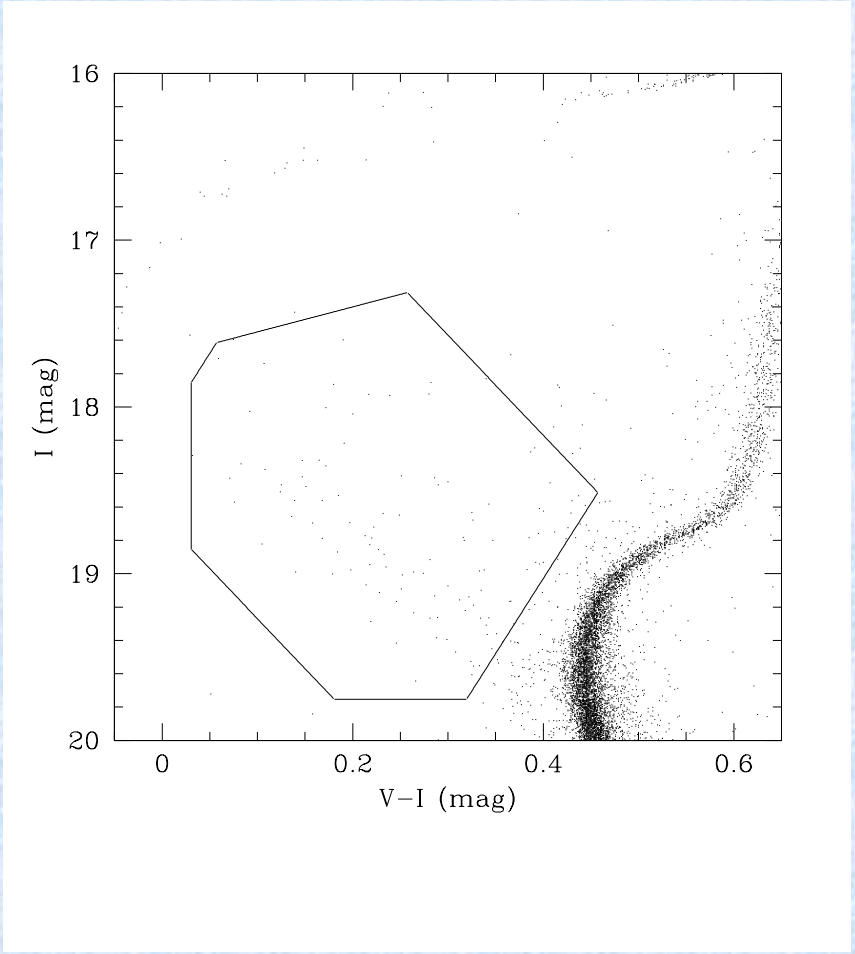

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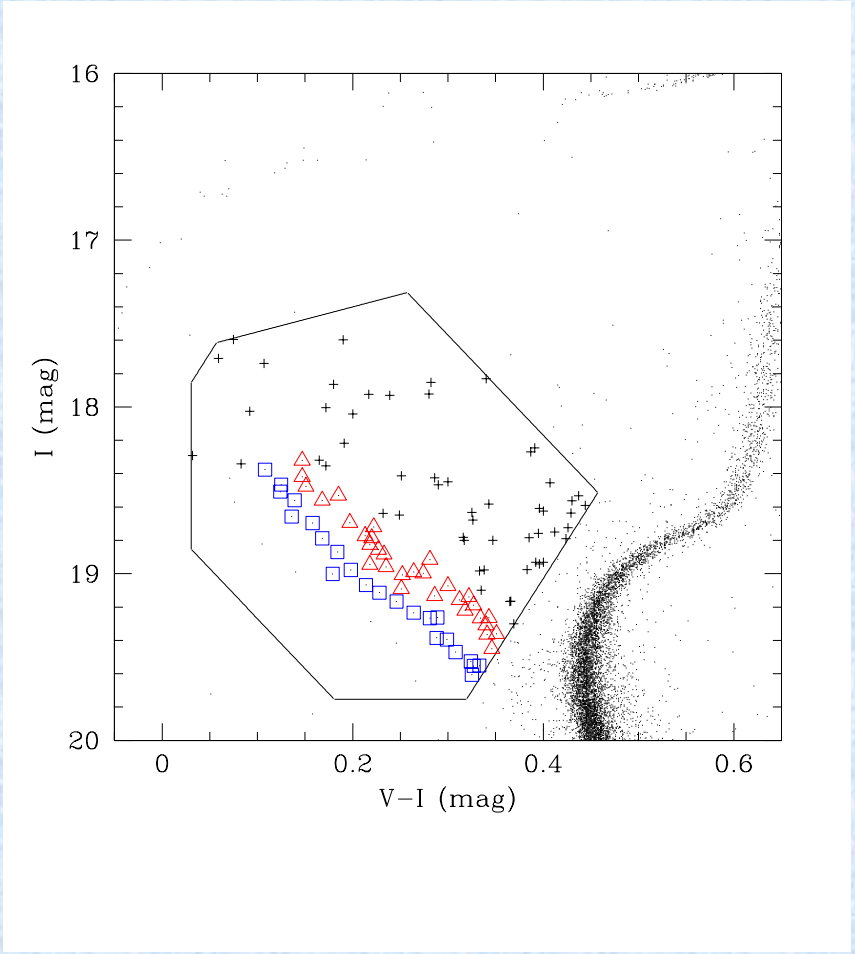

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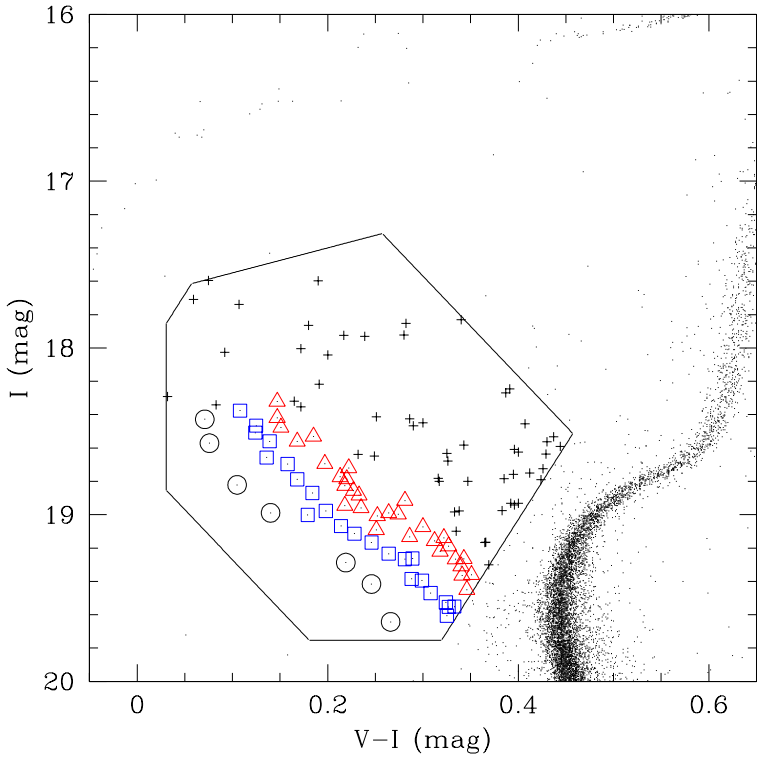
- We detect 7 BSS candidates all roughly located similarly bluer than the B-BSS and extending in the same magnitude range.
- Preliminary evidence for a third component. We identify them as extremelyB-BSS (eB-BSS).



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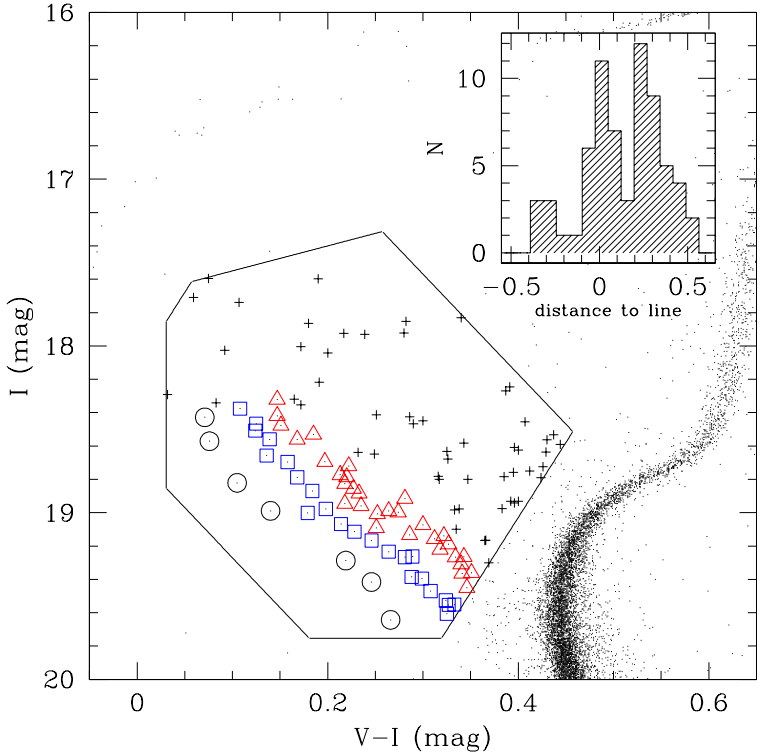
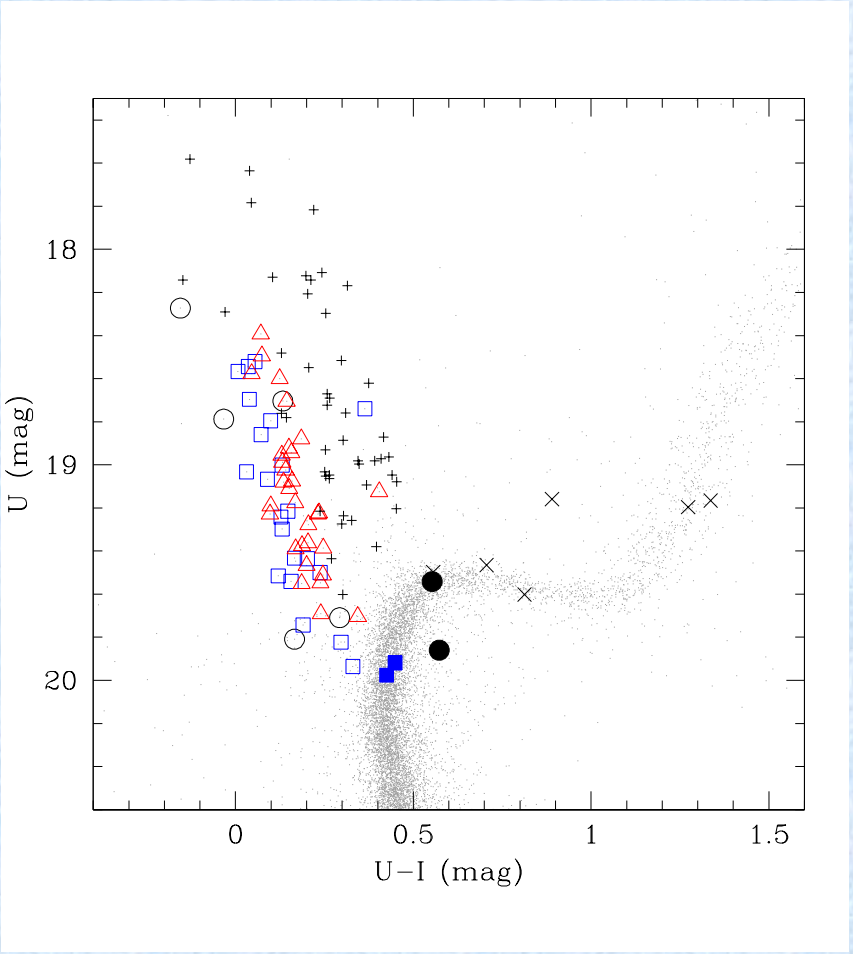
- The BSS distribution in the region of the sequence is clearly ***bimodal*** at least.



# Looking for contaminants.

- The U band photometry allows for detection of potential cooler star blending or EHB+MS blend.
- Two B-BSSs and two eB-BSSs cannot be distinguished from *normal* stars.
- These stars are removed from statistical and population tests.



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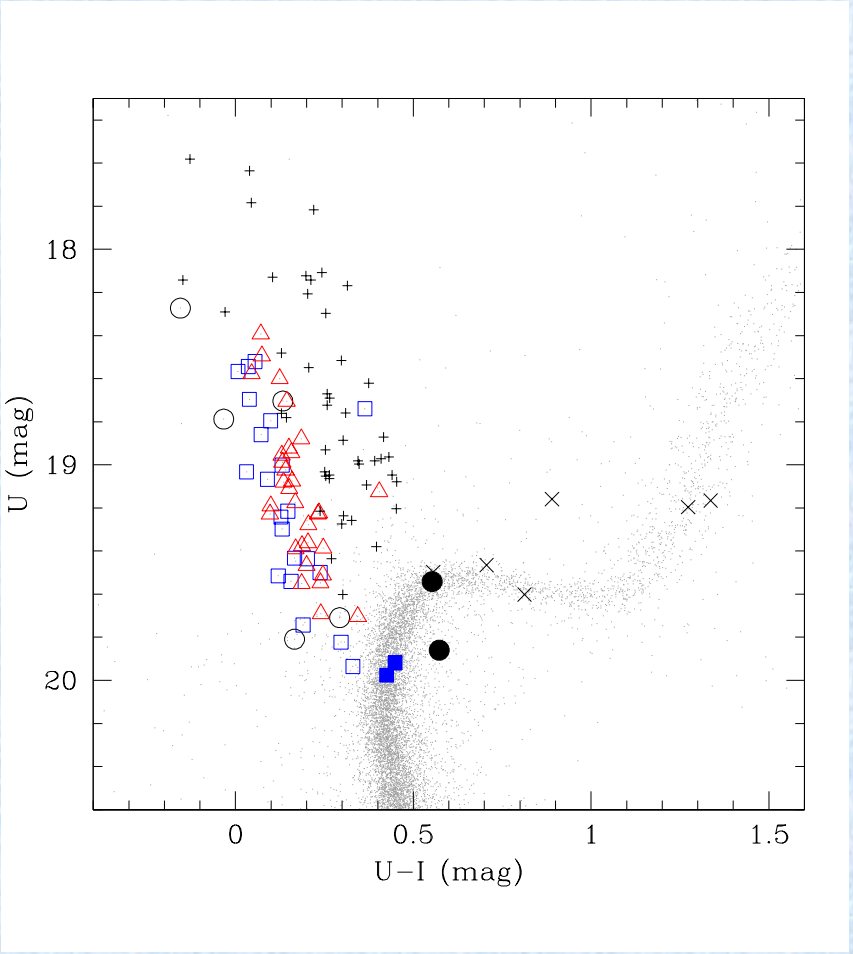
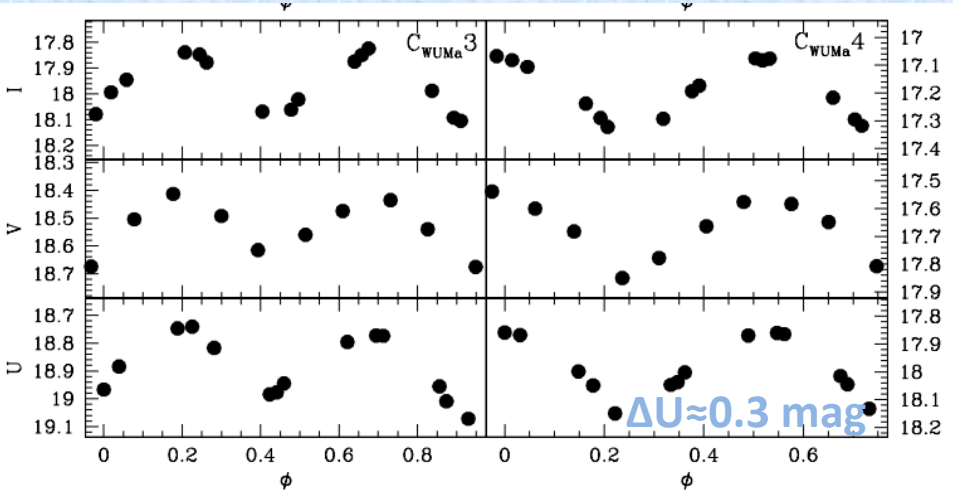
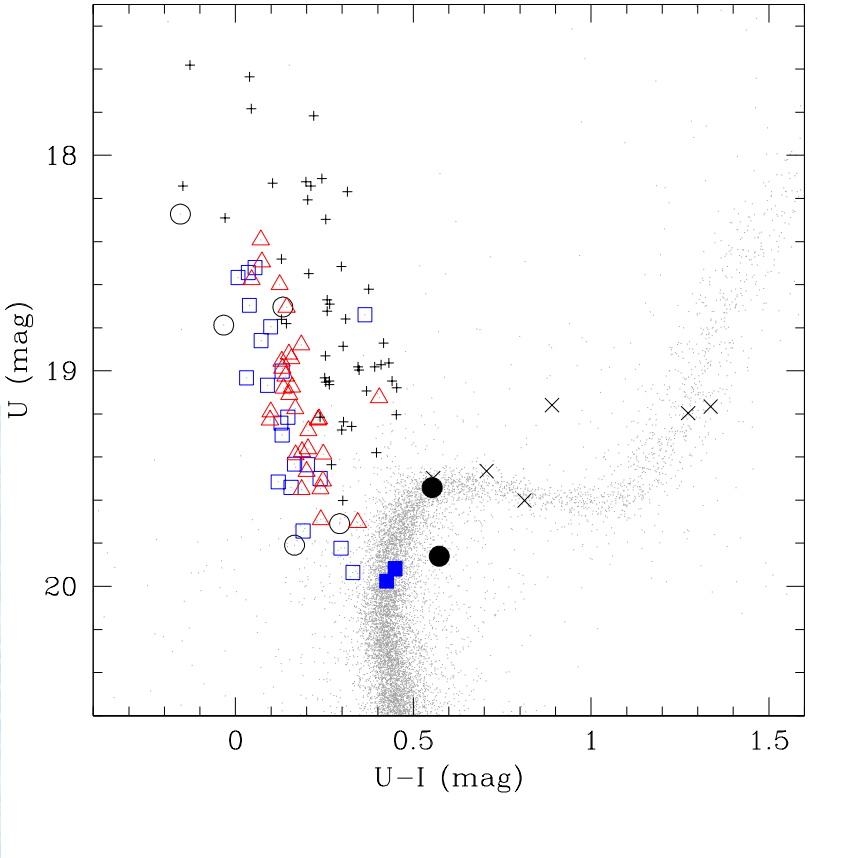
- Variability can be an explanation. U and I images are taken 7 years apart. SX Phe stars and W Uma stars are common among BSSs. Have been found in M 30 and NGC 362. (Ferraro et al. 2009; Dalessandro et al. 2013)



# Looking for contaminants.

W Uma BSS in NGC 362, Dalessandro et al. 2013

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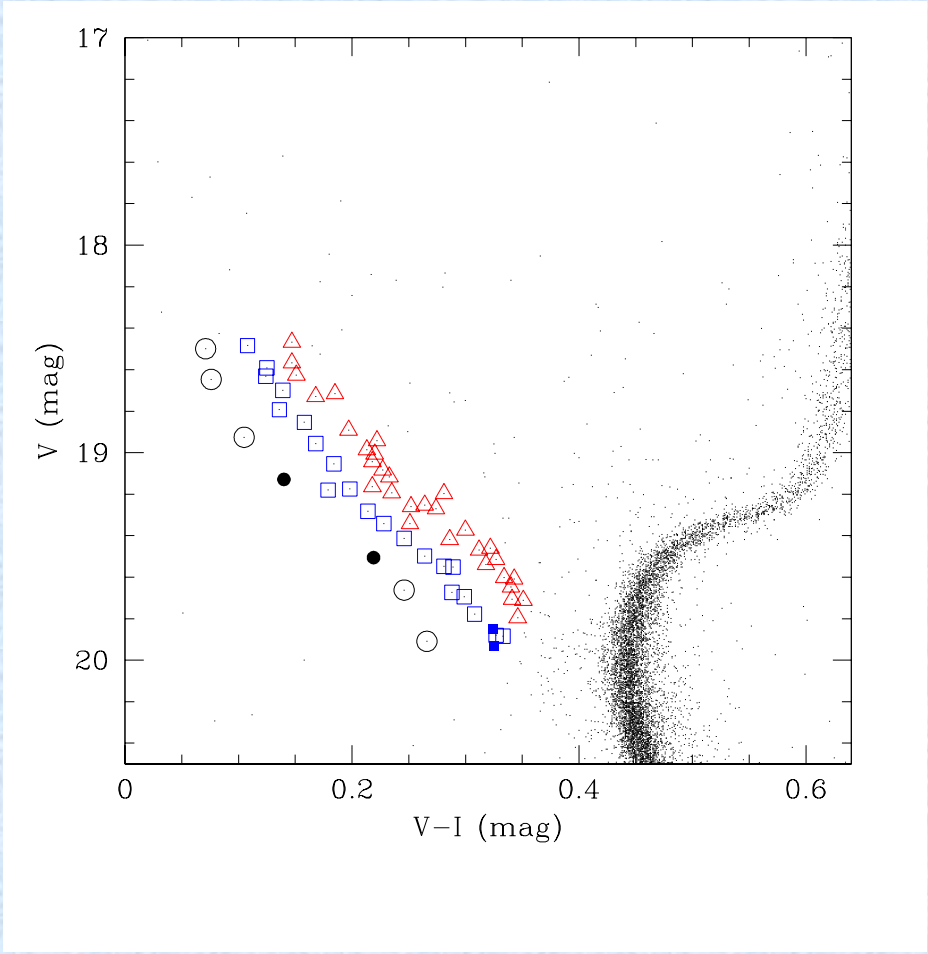
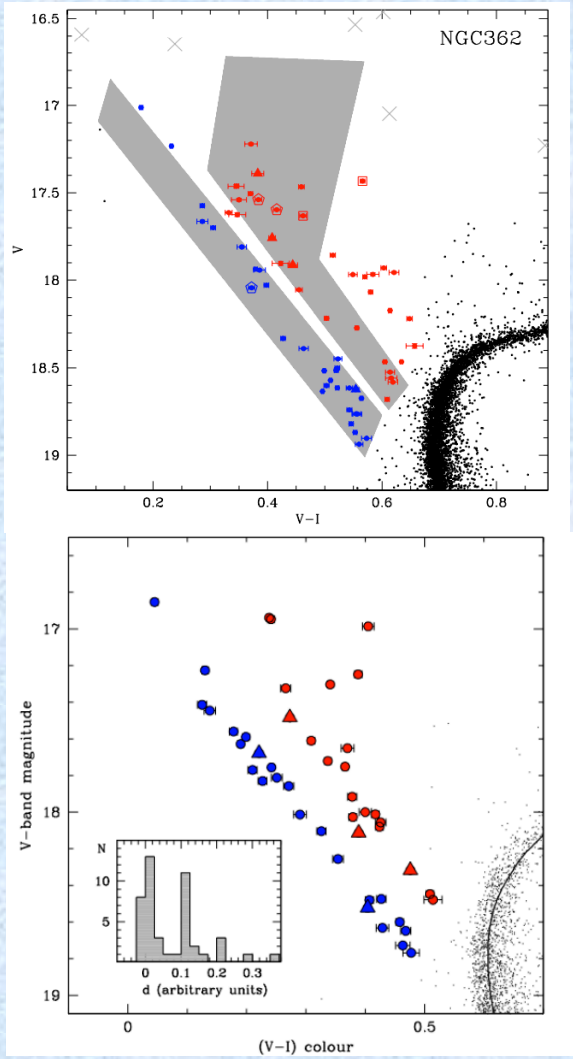
# NGC 1261 has BSS sequences.




NGC 362.
Dalessandro et al. 2013

M 30
Ferraro et al. 2009

# Comparison with Collision Models.

- We use **collision models from Sills et al. (2009)**.
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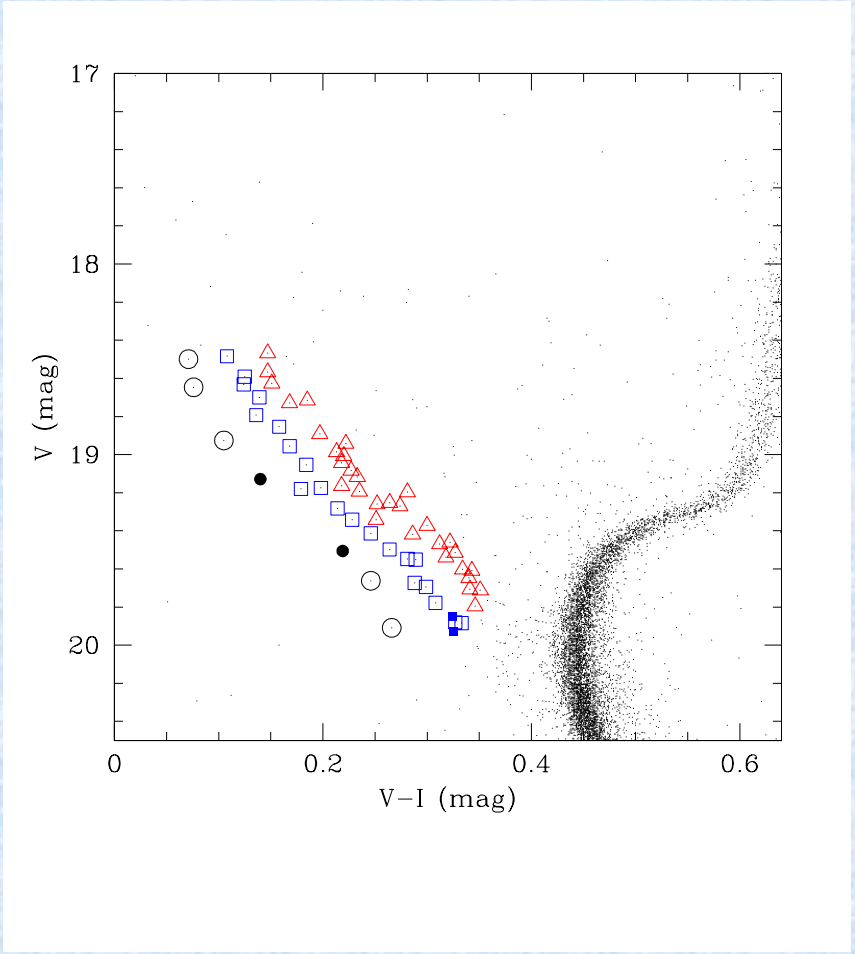
- The models represents collisions of pairs of stars with masses between 0.4 and 0.8 solar masses which then reach equilibrium.
- We adjust for distance modulus and reddening as found in Dotter et al. (2012)



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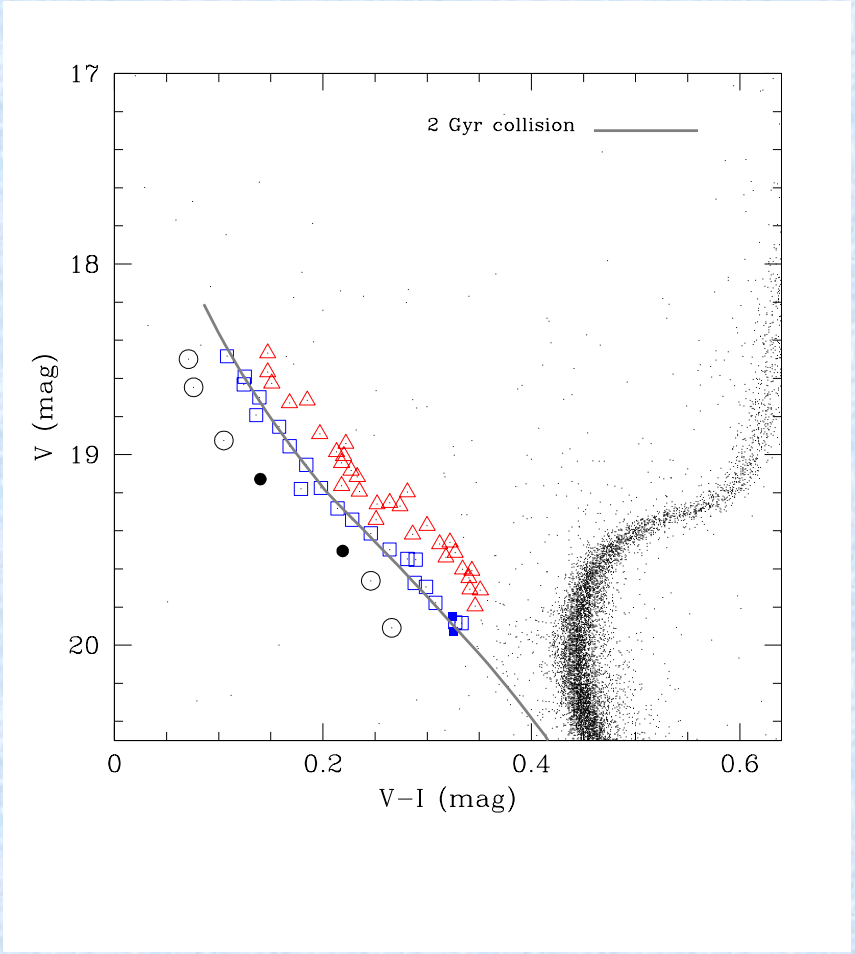

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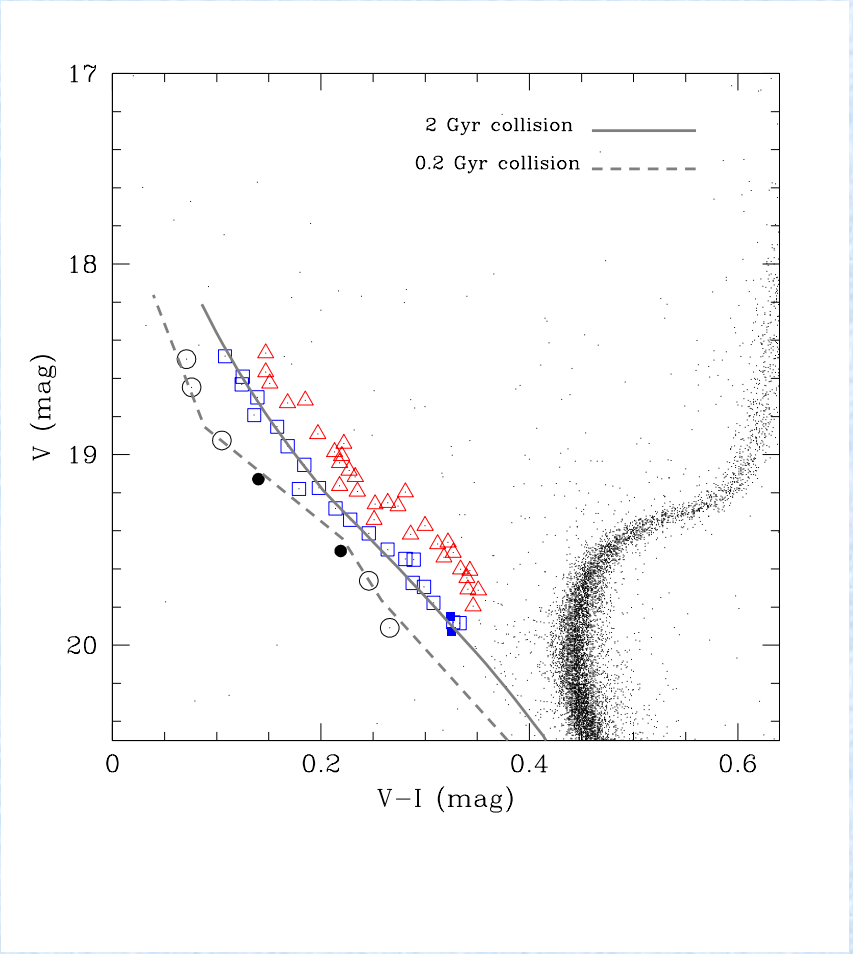
**eB-BSS group consistent with a 200 Myr old collision model**



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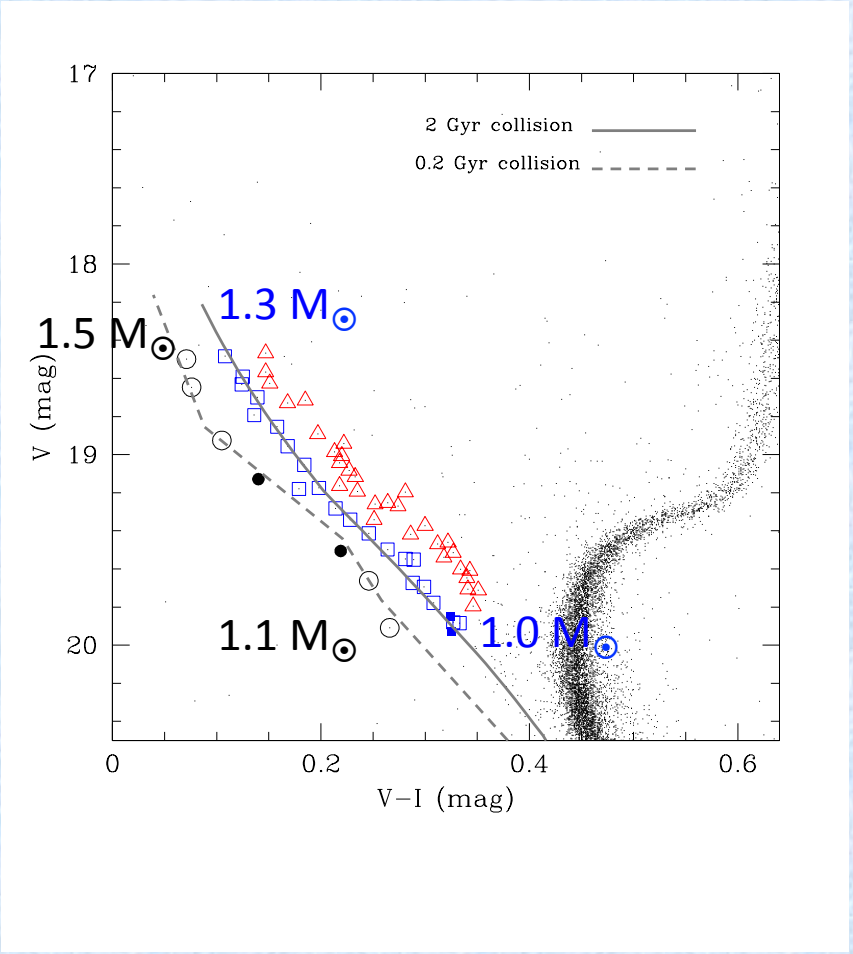
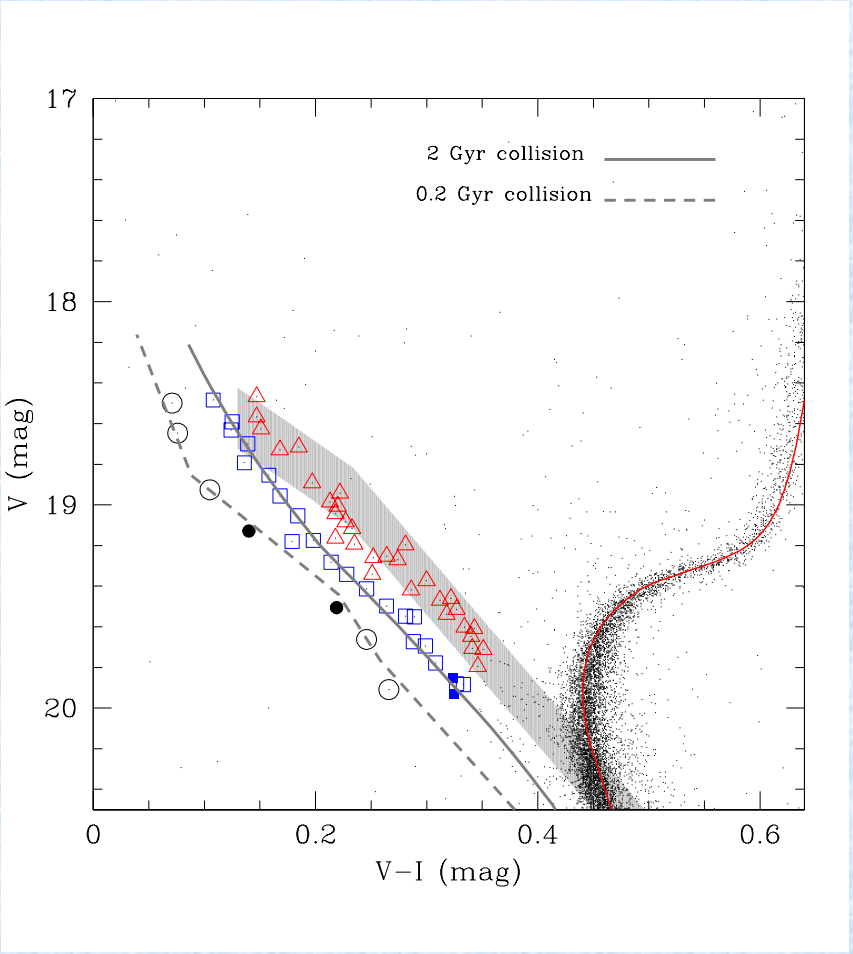


# What can we learn about the R-BSS sequence?

- We use 0.25 Gyr old isochrones (~ZAMS) from Dartmouth data base (Dotter et al. 2008).
- We find that the **R-BSSs populate a region bracketed by ZAMS+0.45 and ZAMS+0.75 mag limits**.
- The ZAMS+0.75 mag boundary does not well represent the location of the R-BSS sequence in NGC 1261.

**(q = M1/M2 = 1) Case A mass trasnfer BSS is not consistent with the location of the R-BSS sequence.**



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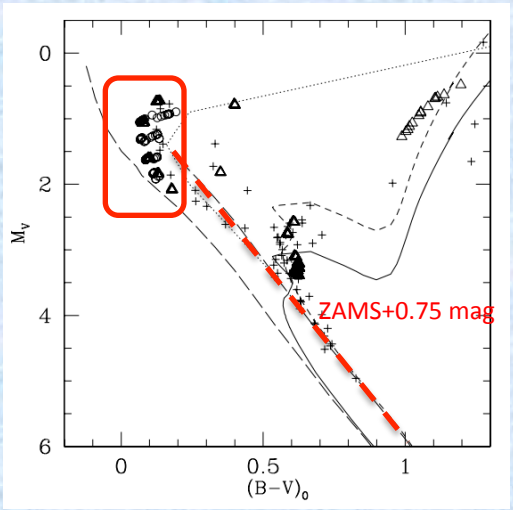
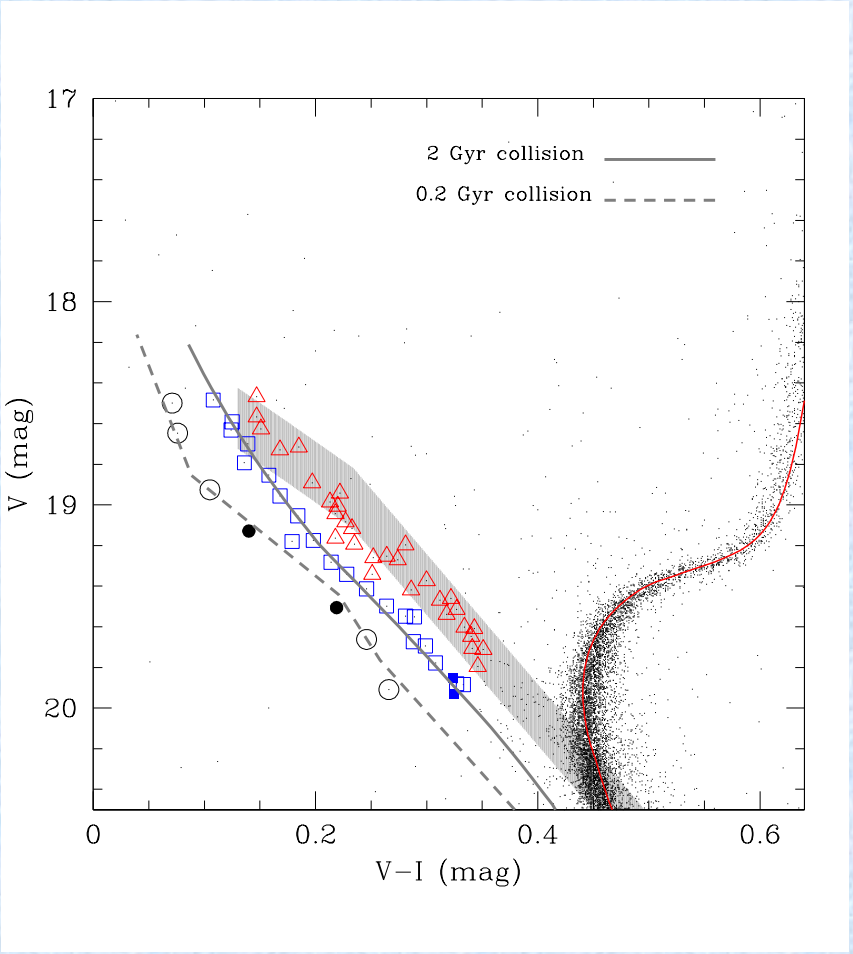
- The R-BSSs in NGC 1261 are binaries with q<1 ??
- Case B (RGB donor) mass transfer BSS are actually expected to be bluer.




Lu et al. 2010



# Results so far…

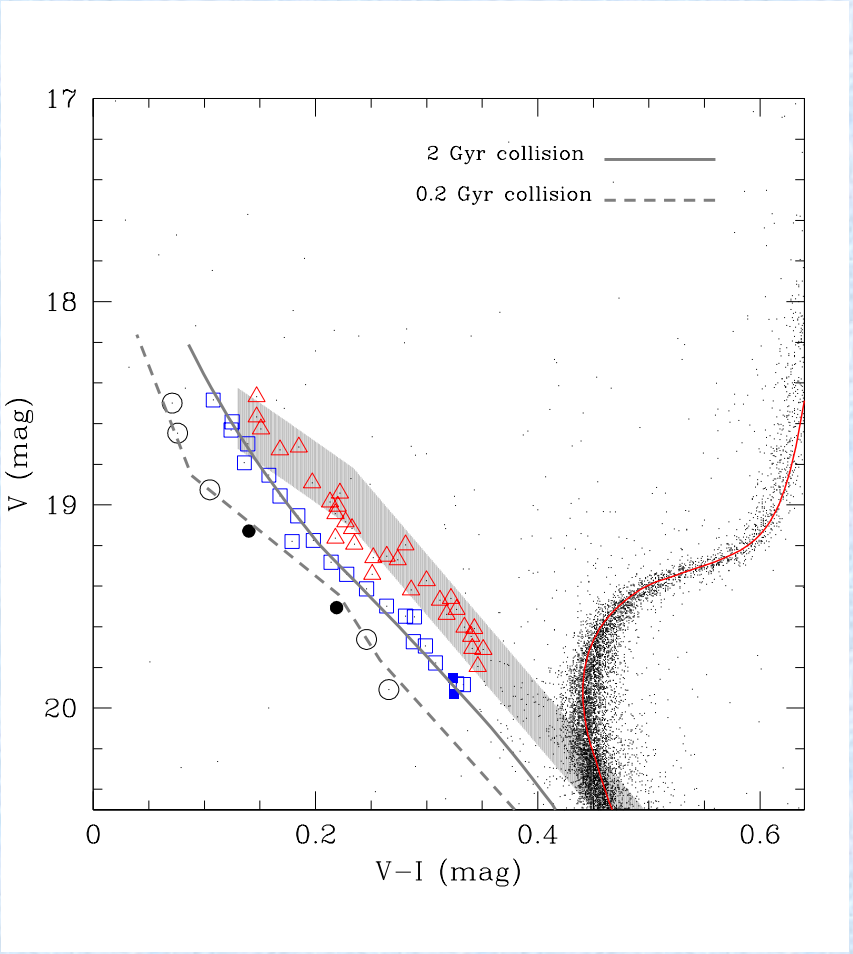
- We have a pretty good chance of having detected a new double BSS sequence in NGC 1261.
- The B-BSS and R-BSS sequence are similar in shape and extension to what has been found in M 30 and NGC 362.
- We have evidence of a third BSS population, presumable much younger.

**B-BSS sequence consistent with a 2 Gyr old collision model**

**eB-BSS group consistent with a 200 Myr old collision model**

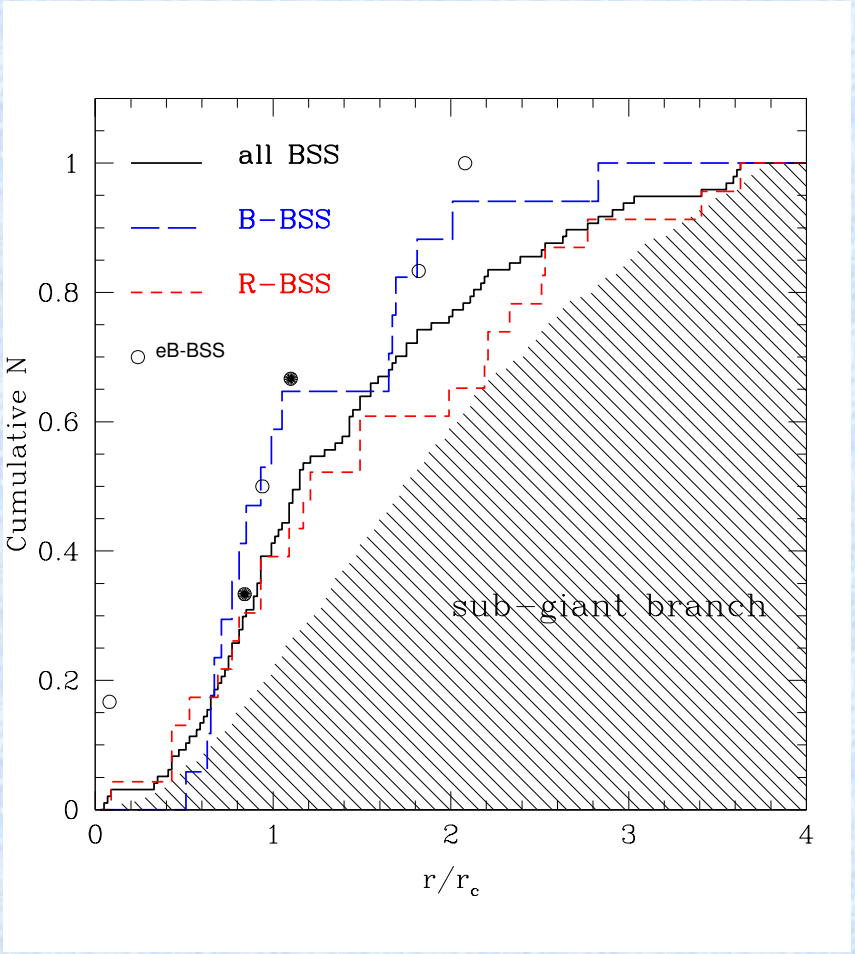
**(q = M1/M2 = 1) Case A mass trasnfer BSSs are brighter (redder) than the location of the R-BSS sequence.**

-R-BSSs are binaries with q<1??
-case B mass- tranfer??



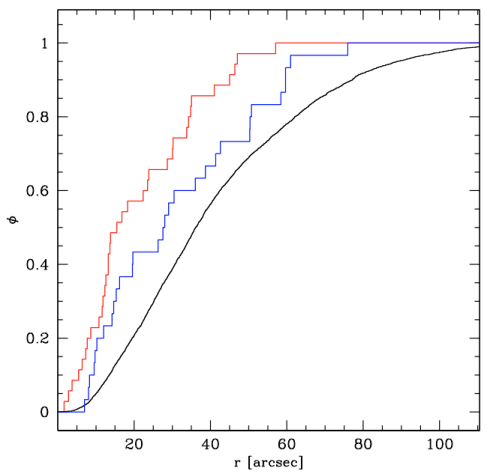
# The segregation of BSSs -> Dynamics

- We construct cumulative radial profiles. The center of gravity of NGC 1261 given by ACS data analysis of Goldsbury et al. (2010).
- We find the full BSS sample more concentrated than SGB stars. This is expected.
- We find the B-BSS population **more centrally concentrated** than the R-BSS population. (K-S test ***p-value=0.33-0.14***)
  - Collision BSS formation more concentrated?
  - BSS binary profile evolved radially outwards?
- M30 and NGC362 show the opposite.
  - What can this tell us about BSS formation in them?
- Are collision products expected to be distributed along the cluster similarly?. This could suggest they are simply following the density profile.

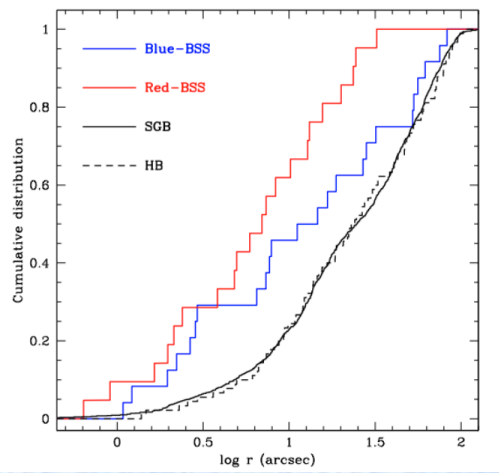


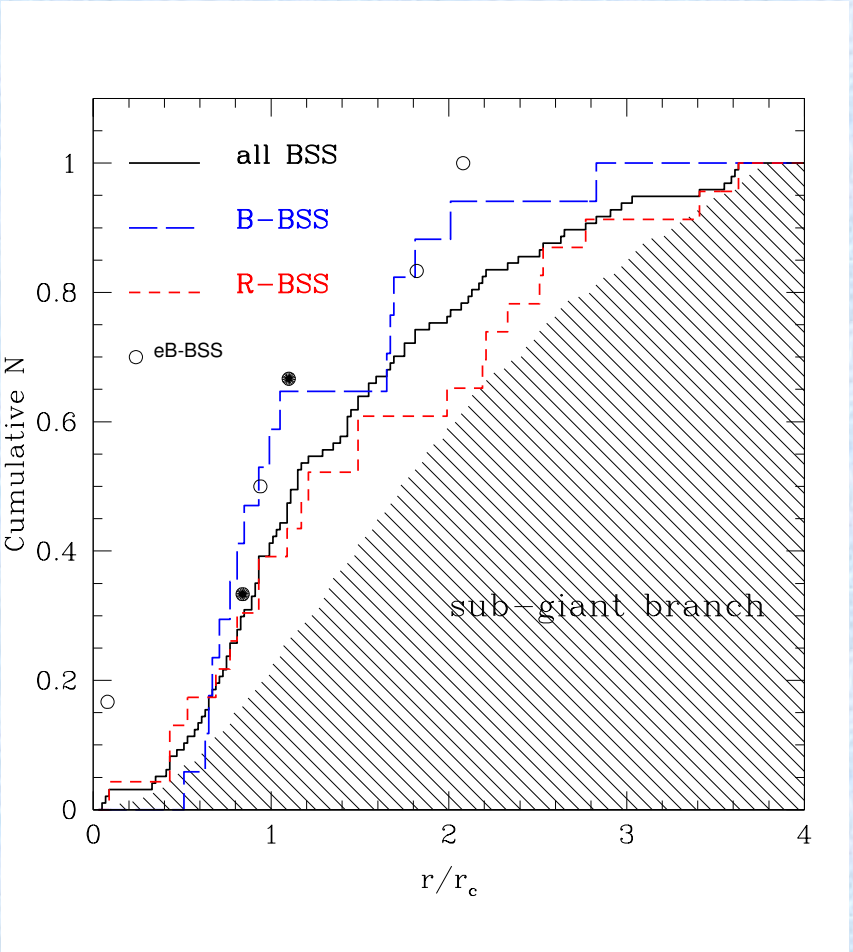
# The segregation of BSSs -> Dynamics

NGC 362.
Dalessandro et al. 2013

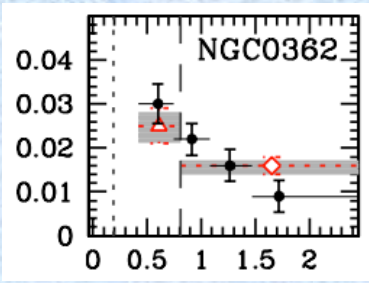



M 30
Ferraro et al. 2009

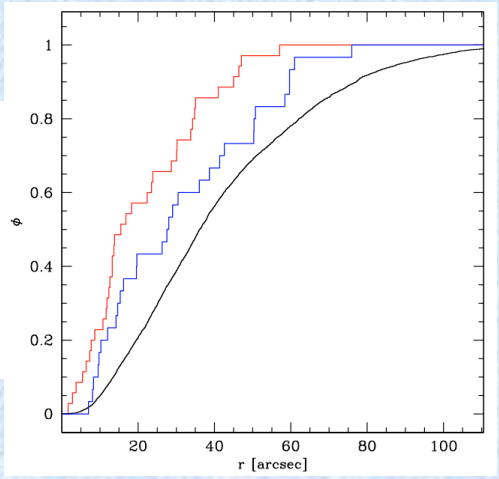


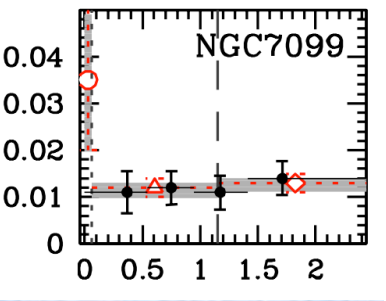



# The segregation of BSSs -> Dynamics

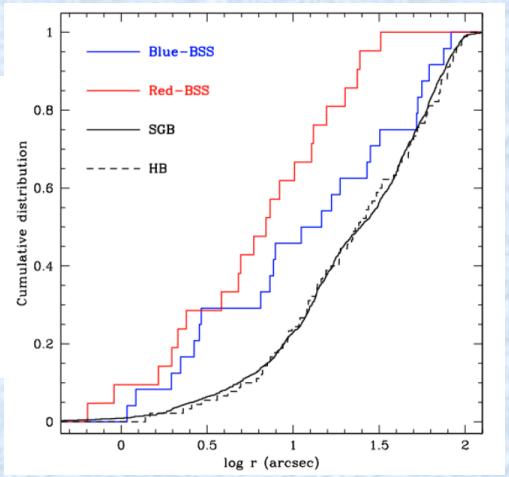


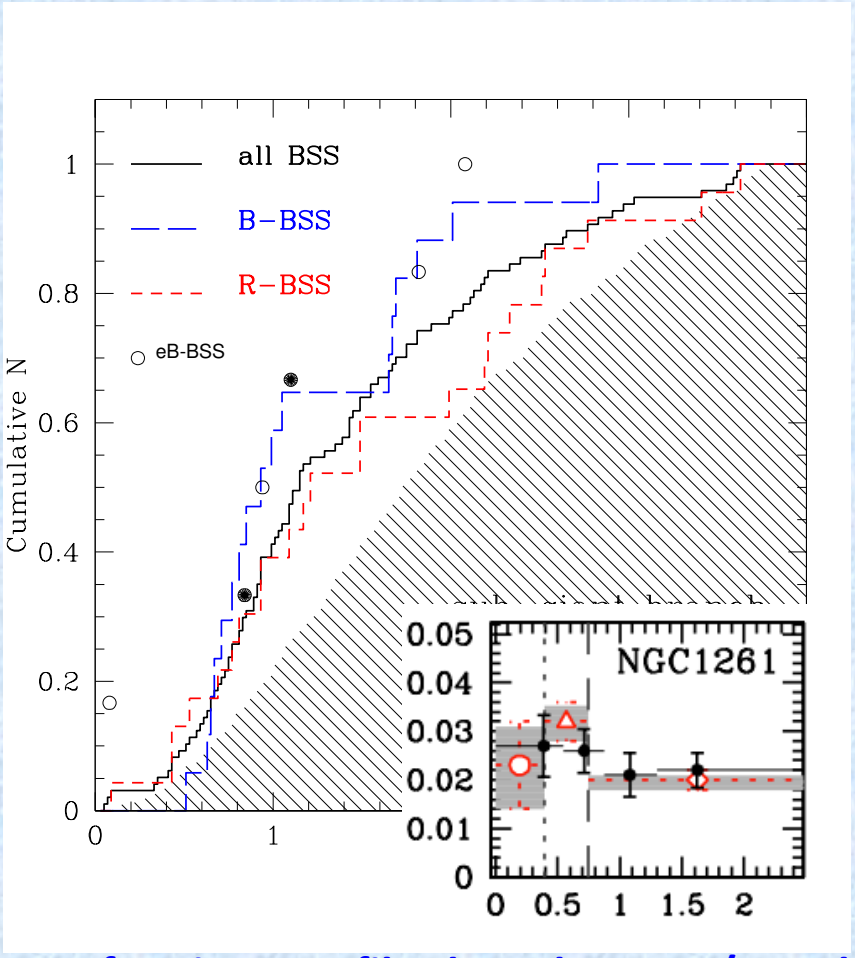

NGC 362.
Dalessandro et al. 2013




M 30
Ferraro et al. 2009

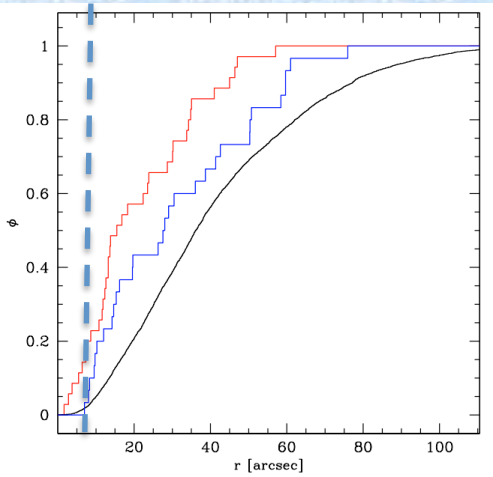



**Milone et al. (2012): Binary fractions profiles based on HST/ACS data**

# The segregation of BSSs -> Dynamics

NGC 362.
Dalessandro et al. 2013




M 30
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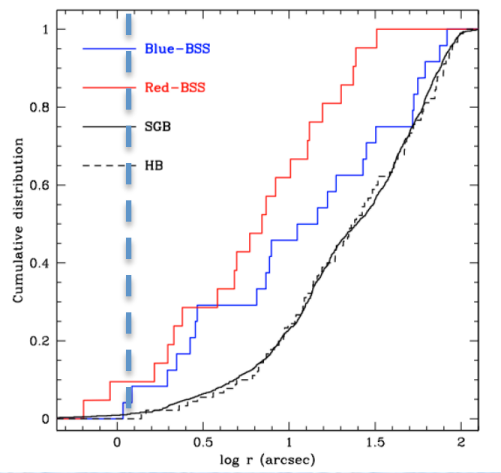
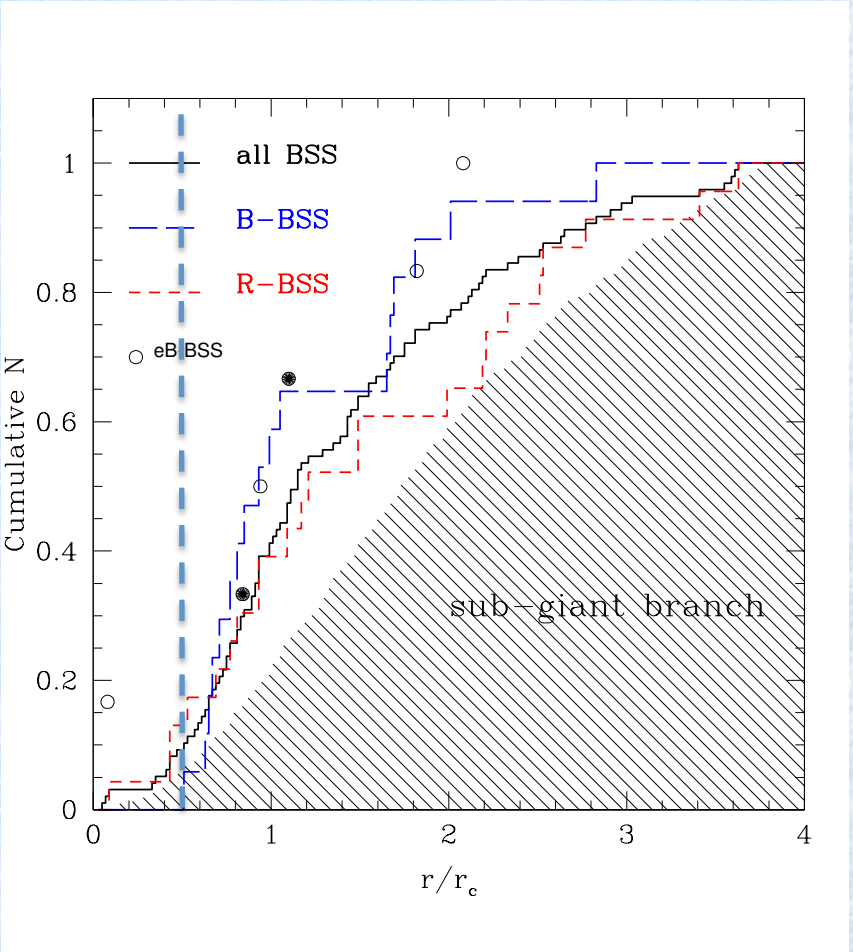
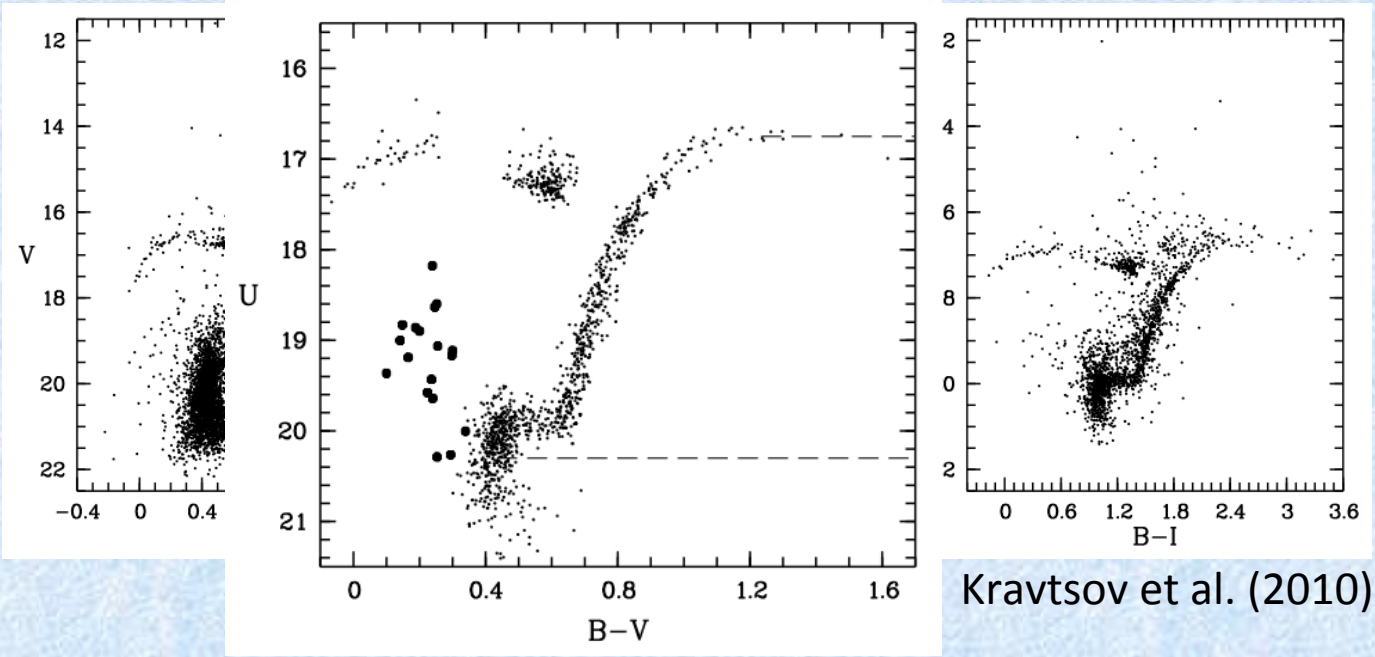


# Introducing a wide-field catalog

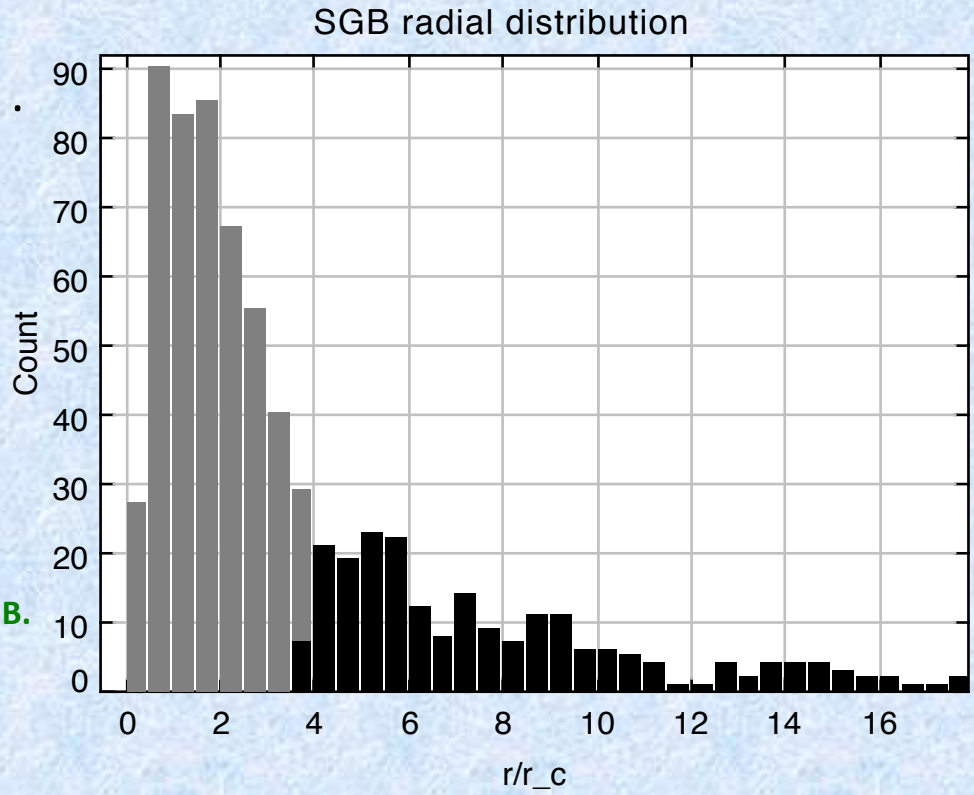
- We use the wide-field photometric catalog produced by Kravtsov et al. (2010).
- 1.3m Warsaw Telescope UBVI photometry in a 14'x14' field of view centered in NGC 1261.
- Kravtsov et al. (2010) select **BSS candidates based on their location on all CMDs**.




Kravtsov et al. (2010)

# Merging inner and outer catalog

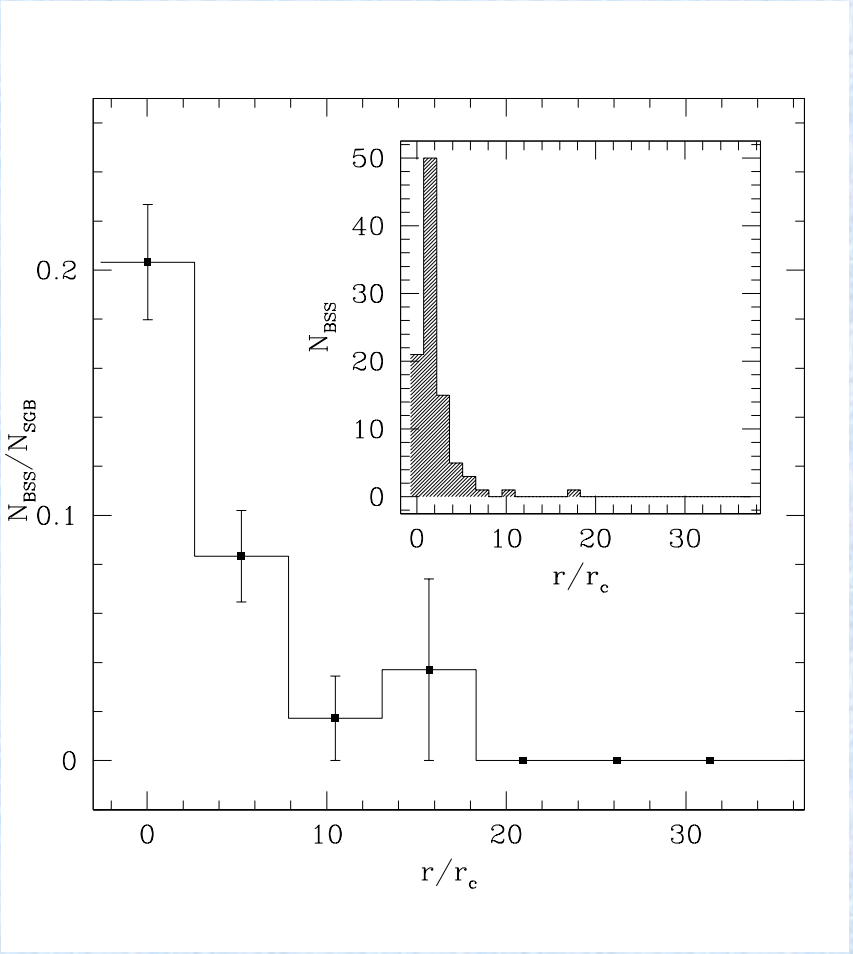
- We combine both catalogs at 3.8 $r_c$ .
- The combined SGB radial profile shows fair completeness.
- We use the reference SGB population to calculate the **BSS fraction radial profile, i.e. $N_{BSS}/N_{SGB}$.**



# BSS Fraction Radial Profile

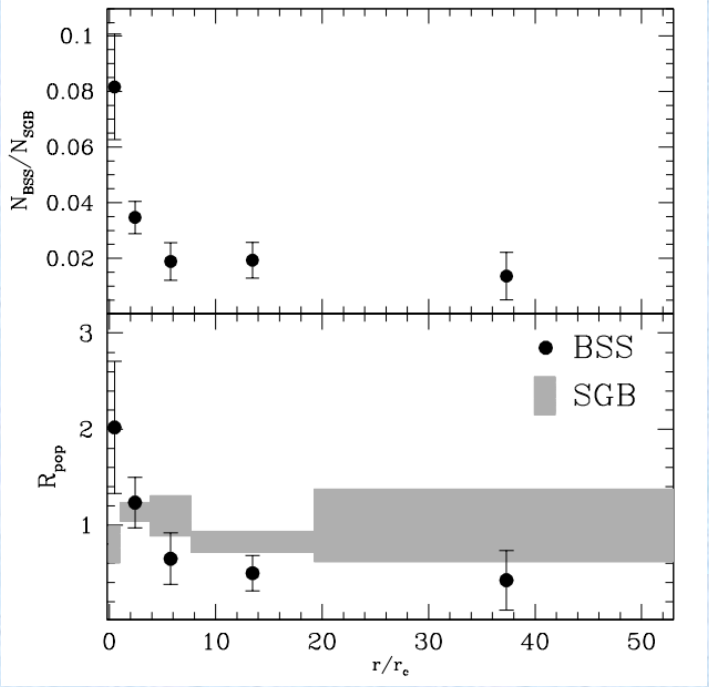
- We find a central peak in $N_{BSS}/N_{SGB}$ without clear signs of a subsequent secondary peak.
- BSS appear to have all (or most) experienced mass segregation.
- NGC 1261 would classify as a dynamically old GC (Ferraro et al. 2012).

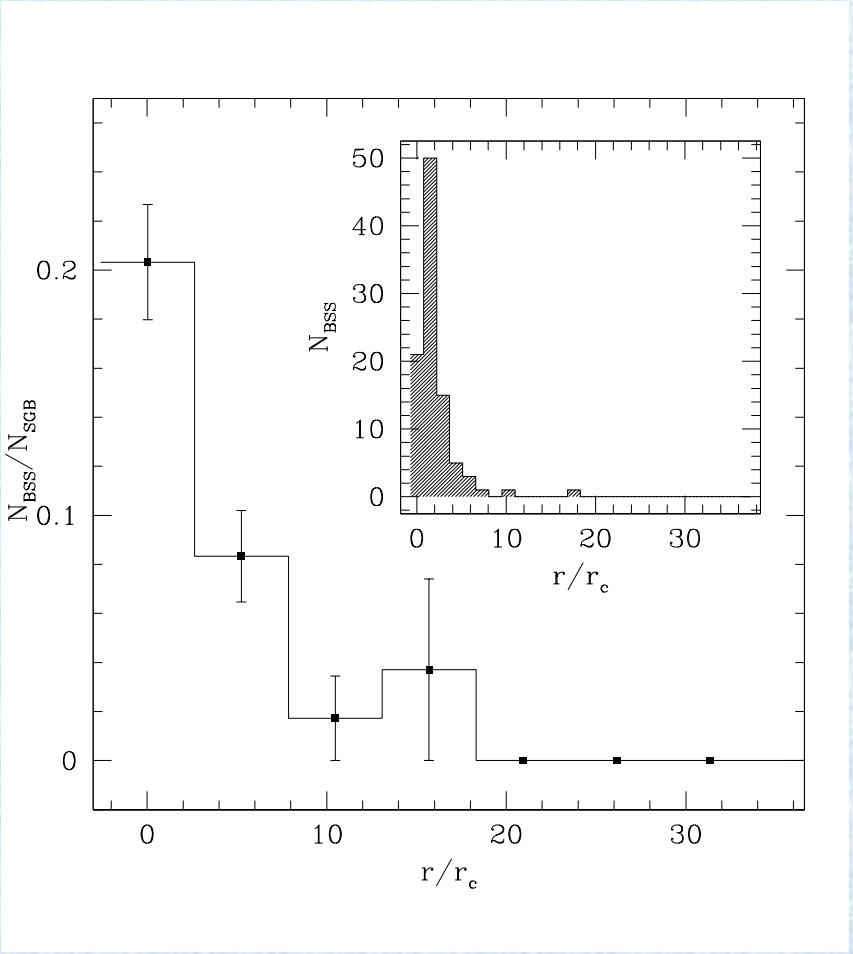
**The BSS population points to NGC 1261 being dynamically old.**



# BSS Fraction Radial Profile

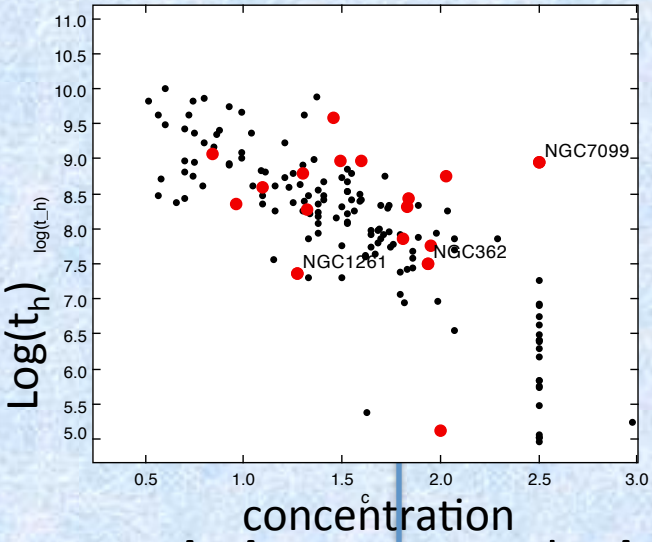
Dalessandro et al. 2013 NGC 362

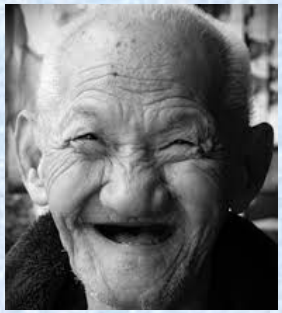



**The BSS population points to NGC 1261 being dynamically old.**

# NGC 1261: Dynamically Young or Old?



- The **core appears extended**. Concentration c ≈ 1.2
- The central stellar density is low. ρ=2.22 $L_{\odot}/pc^3$ (Paust et al. 2010)
- The binary fraction profile lacks central segregation.(Milone et al. 2012)

- The **half-mass relaxation time is short: log($t_h$)** ≈ 8
- The occurrence of a double BSS sequence. (Core-collapse)
- The BSS affected by segregation

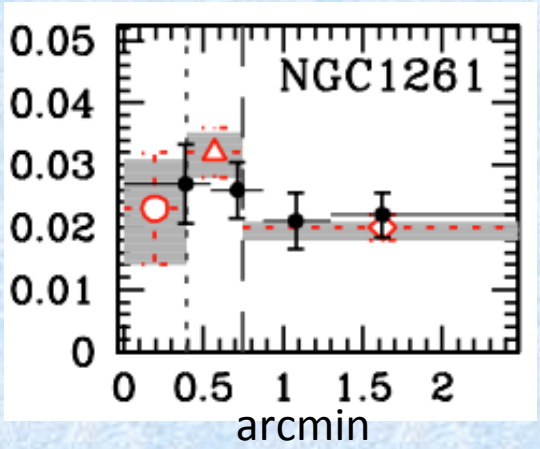
**The BSS population points to NGC 1261 being dynamically old.**

# NGC 1261: Dynamically Young or Old?

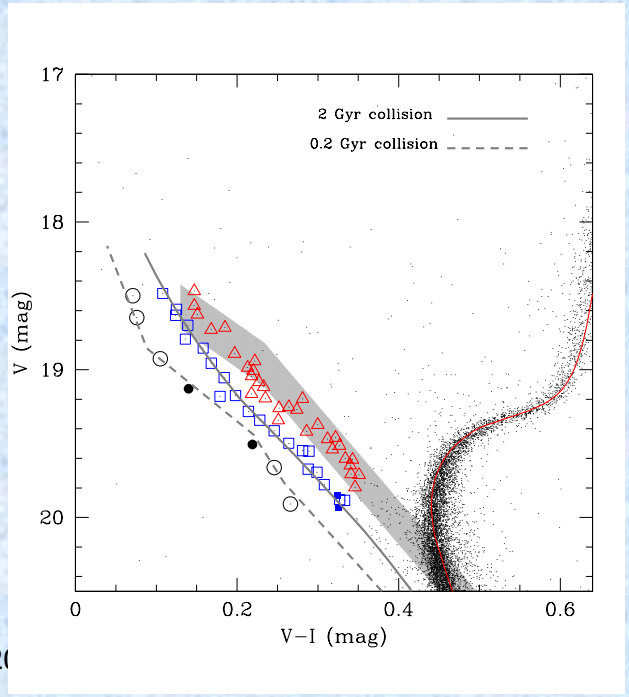
Maybe is both

# NGC 1261: Dynamically Young or Old?

- Monte Carlo dynamical models (Heggie & Giersz 2008) and N-body models (Hurley & Shara 2012): **GCs can go through core-collapse** and then **stay or pass through a long-lived post-core-collapse bounce state**.
- M 4 went through core collapse at 8 Gyr and then roughly stayed in a non-collapsed (but centrally more concentrated) state for another ~2-3 Gyr due to **binary burning** in the core. (Heggie & Giersz 2008)




Milone et al. 2012



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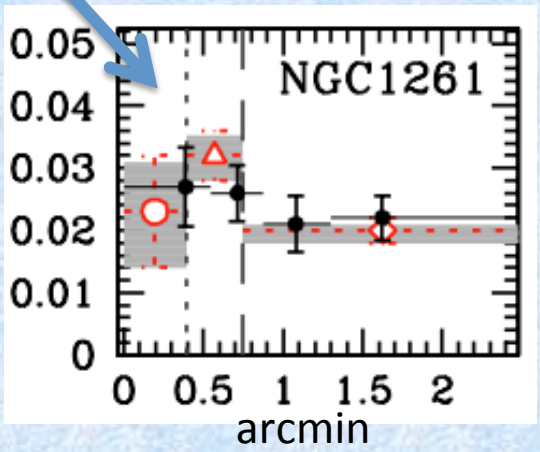
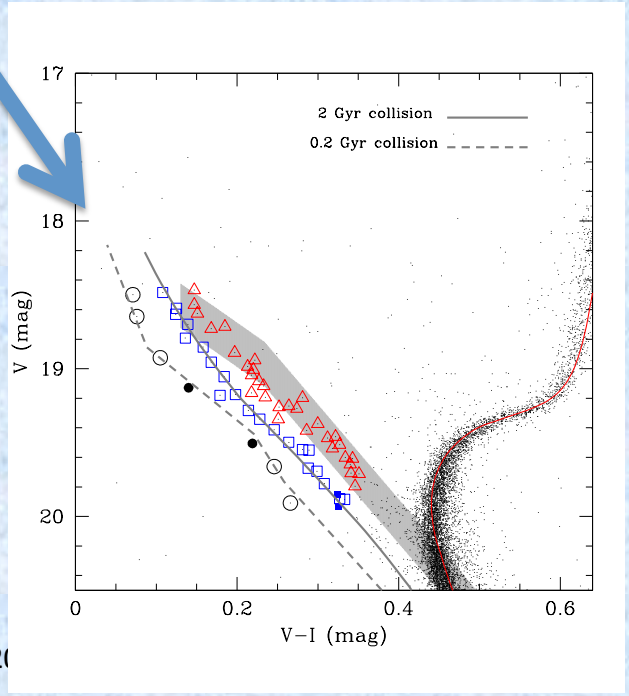



Milone et al. 2012



# Conclusions

1. The inner BSS population of **NGC 1261 has a double sequence** in the CMD, much similar to what's found in M30 and NGC 362.

2. We find photometric **evidence for a third bluer BSS population**.

3. Collision models are able to reproduce the **B-BSSs as a 2 Gyr old** population and the **eB-BSSs as a 200 Myr old** population.

4. The dynamical state of NGC 1261 is unclear, one possible scenario:
   - NGC 1261 could have **gone through core-collapse or some similar phase about 2 Gyr ago**, and since then it has been bouncing around through **core oscillations**, occasionally creating more BSSs during short time-scale processes -one in particular 0.2 Gyr ago-, and also likely burning some of its core binaries up.
   - NGC 1261 is currently in a post core-collapsed state which, according to different simulations, **may look as an unevolved GC**.