Blue Stragglers in Globular Clusters: Observations, Statistics, Physics

NASA and the Hubble Heritage Team/A. Cool

Outline

- Physics
  - Blue Straggler Formation Channels
- Statistics
  - N_{BSS} vs ???: the Search for the “Smoking Gun” Correlation
- Observations
  - Radial Trends
  - Double Sequences
  - …
- Summary

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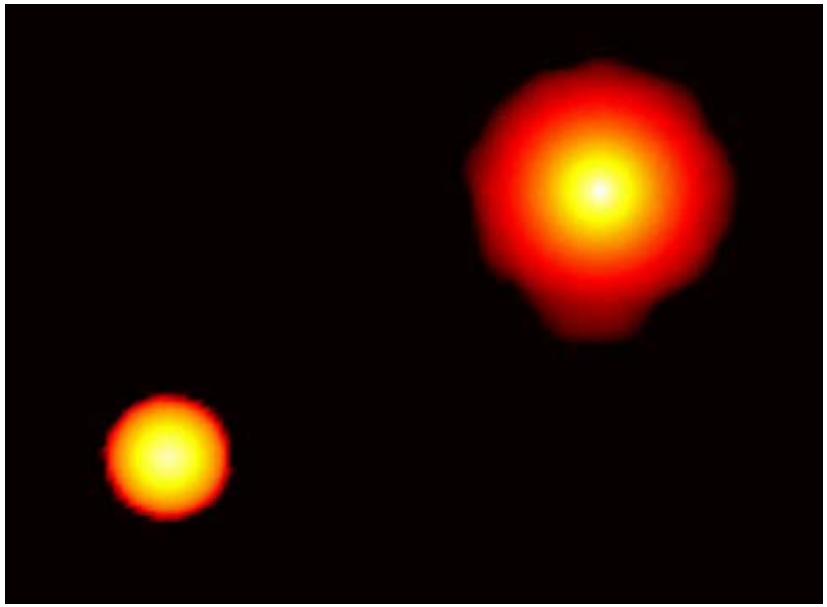
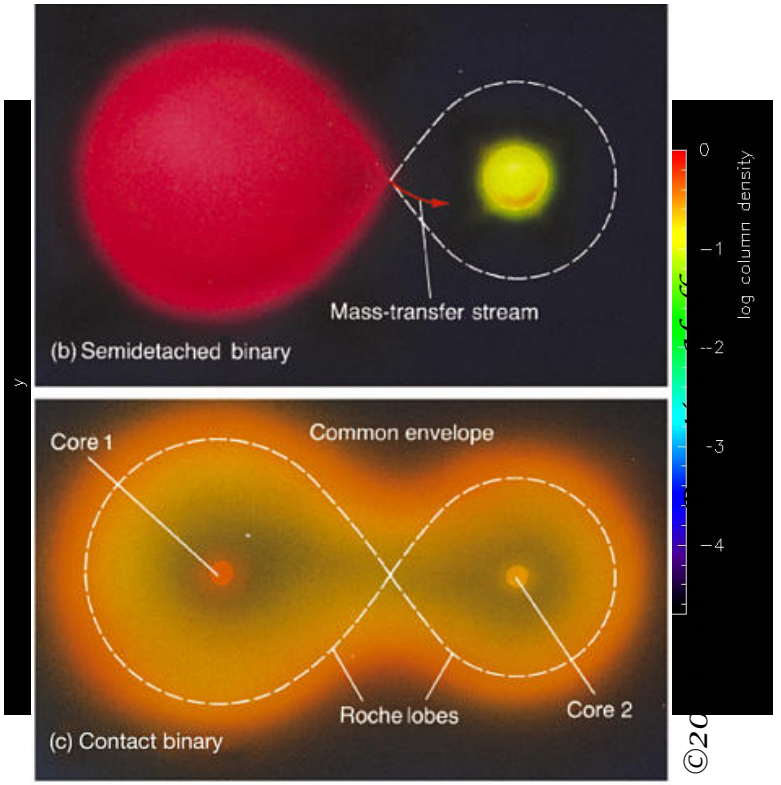
Straw-Man Models for BSS Formation

- Stellar Collisions
  - single-single
- Binary Evolution
  - mass-transfer…



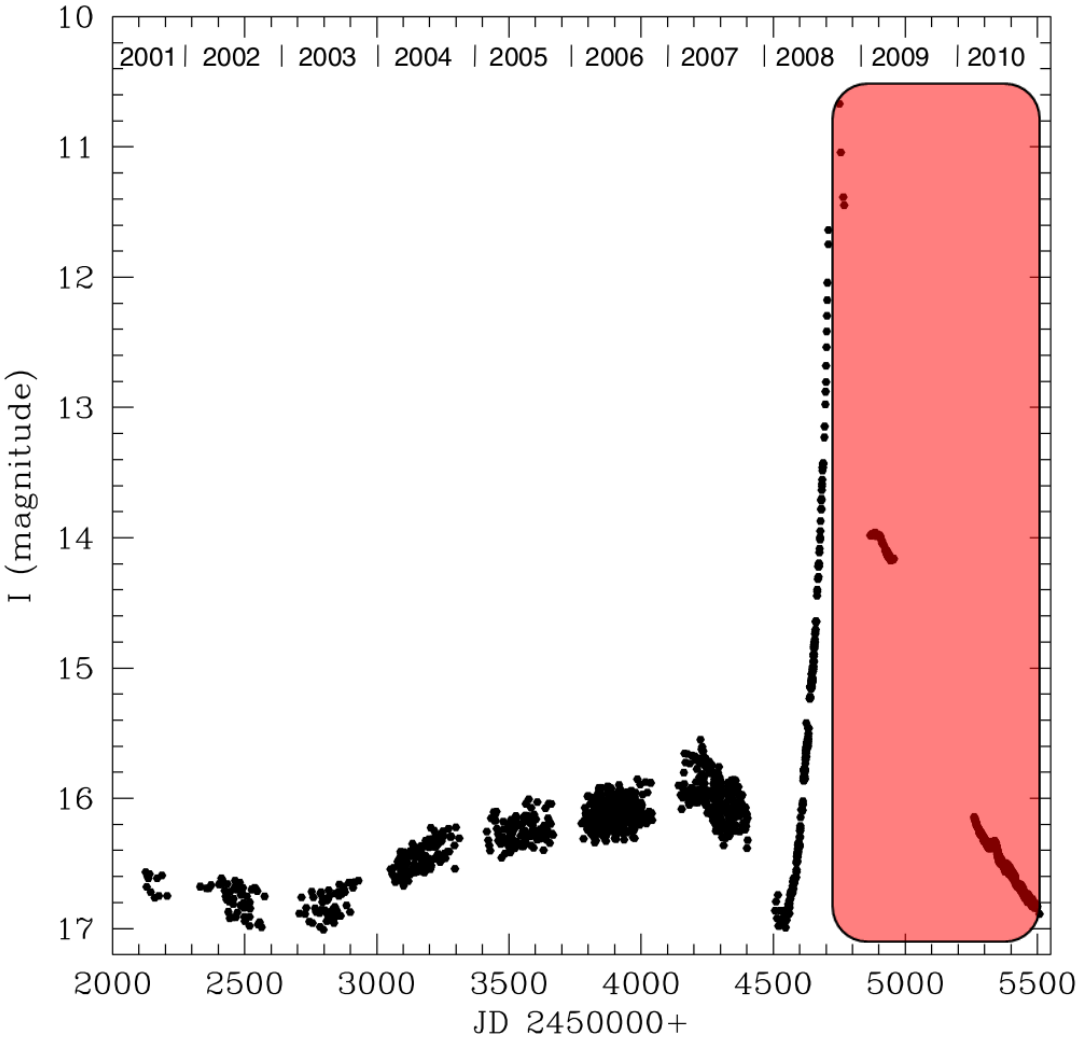
Jamie Lombardi



Jamie Lombardi

Digression I: All Theory is Grey

Binary Coalescence in Practice!



- Astronomers in Japan and China discover Nova Sco 2008
- Spectroscopy (Mason et al. 2010):
  - not a normal classical nova
  - probably a "red nova" (like V838 Mon)
- Tylenda et al. (2011) realize the object is included in OGLE footprint!
  - Amazing outburst light curve
  - Before the outburst, the system was a $P_{orb} \simeq 1.4\ d$ W-UMa contact binary!
  - Dramatic period decrease in the lead-up to outburst → coalescence!
- Still detected post-outburst
  - Incredible chance to witness a binary merger and its aftermath in real time!

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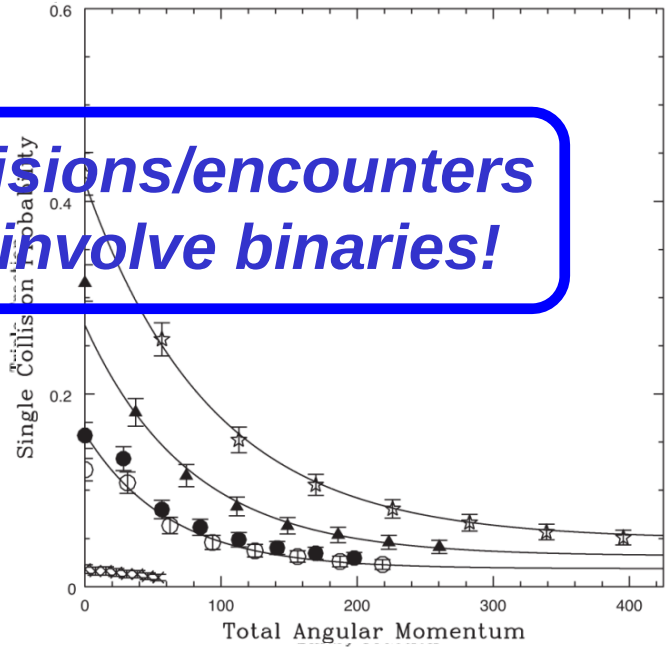
Less Straw, More Model…

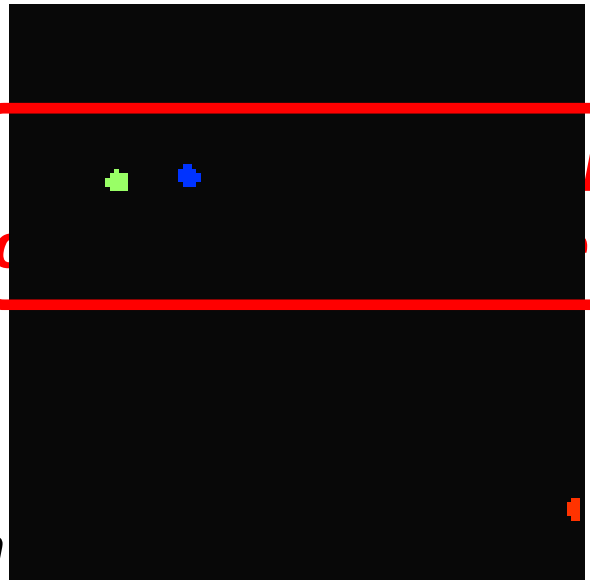
- Collisions
  - What about other encounters?
    - Binary-Single
    - Binary-Binary
    - (Triples? Quads?)
- Binary Evolution
  - What about binaries formed/altered in dynamical encounters?

Collisions/encounters can involve binaries!



Leigh & Sills (2011)

…w man



Steve McMillan

The Utility of Straw-Man Models

- No!
  - If ***dynamical encounters*** dominate BSS production, expect

$$N_{BSS} \propto \Gamma_{coll,1+1}$$

regardless of the multiplicity of the objects involved

→ for example, $\Gamma_{\mathrm{coll},1+2} \propto f_b \left(\frac{a_{bin}}{R_*}\right) \mathrm{P}_{\mathrm{coll},1+2}\, \Gamma_{coll,1+1}$

  - If ***binary evolution*** (mass transfer/coalescence) dominates, expect

$$N_{BSS} \propto N_{bin}$$

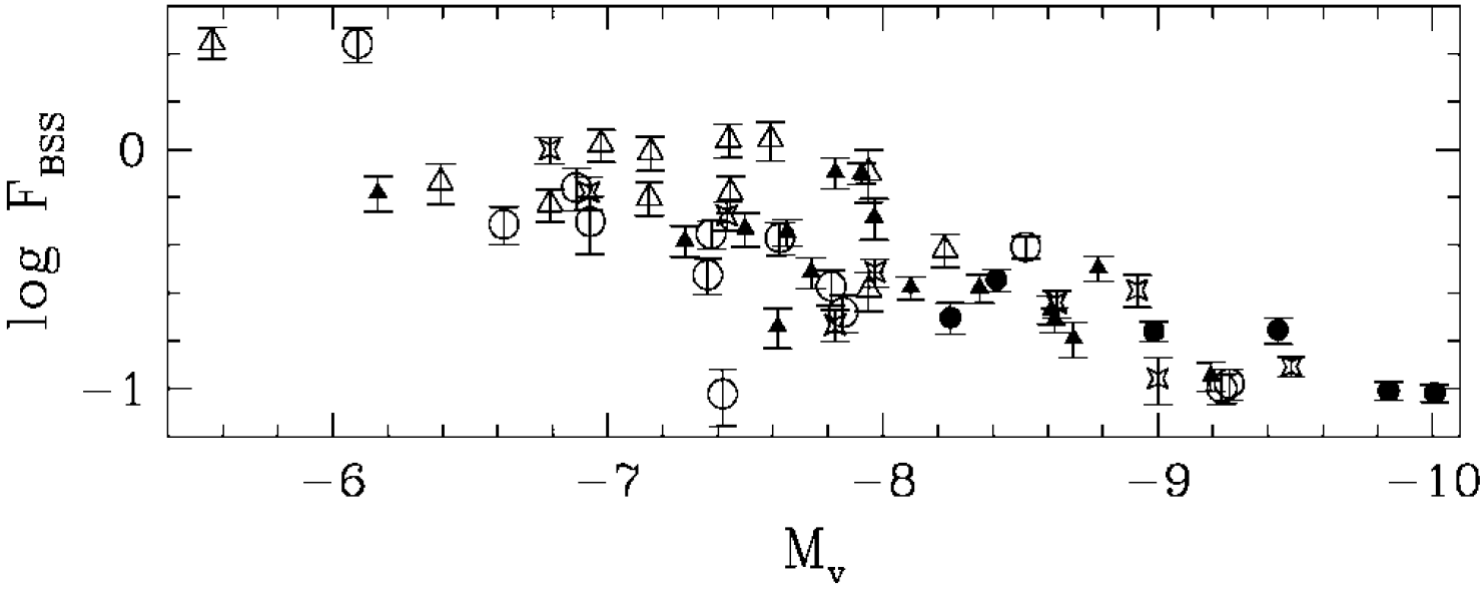
One Last Thing…

- Two different conventions are used in statistical studies of BSSs
  - BSS ***numbers***
    - N_{BSS}, corrected for / normalized to the observed fraction of the relevant area
  - BSS ***frequencies***
    - N_{BSS}/N_{ref}, where N_{ref} is the number of some reference population (e.g. HB stars) in the same field of view
- The difference matters!
  - The scalings shown previously only hold for N_{BSS}!
  - In the ***collision*** scenario, BSS *frequencies* should scale with *specific* encounter rate (Γ/M_{tot})
  - In the ***binary*** scenario, BSS *frequencies* should scale with *binary fraction*

The Search for the Smoking Gun Correlation

- Piotto et al. (2004) presented and analysed the first reasonably complete BSS catalogue, based on the HST/WFPC2 survey of 74 GCs (Piotto et al. 2002)

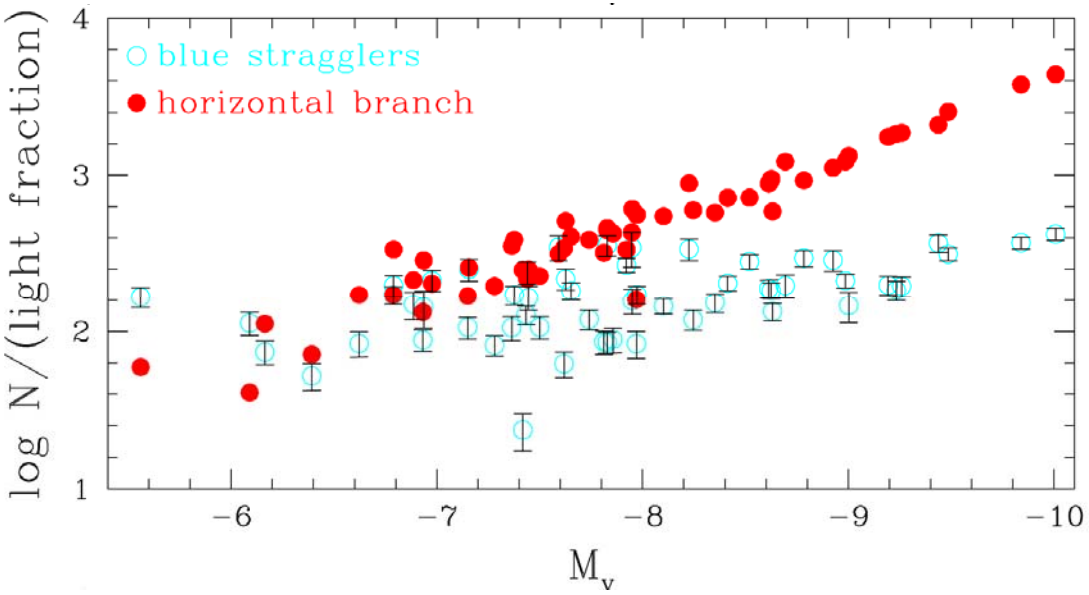
- Surprising results!
  - ***No*** correlation between BSS *frequency* and collision rate!
  - ***Anti***-correlation between BSS *frequency* and cluster luminosity/mass



Piotto et al. (2004)

The Search for the Smoking Gun Correlation

- But remember the issue with *numbers* vs *frequencies*!
  - Is the expected result somehow hidden in the data?
- Here are the same results shown in terms of BSS *numbers*



Davies, Piotto & de Angeli (2004)

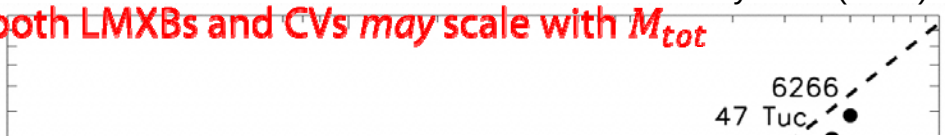
- Still *no* correlation with collision rate
- Maybe a mild (sub-linear) *positive* correlation with cluster mass?

Digression II: Does this stuff ever actually work?

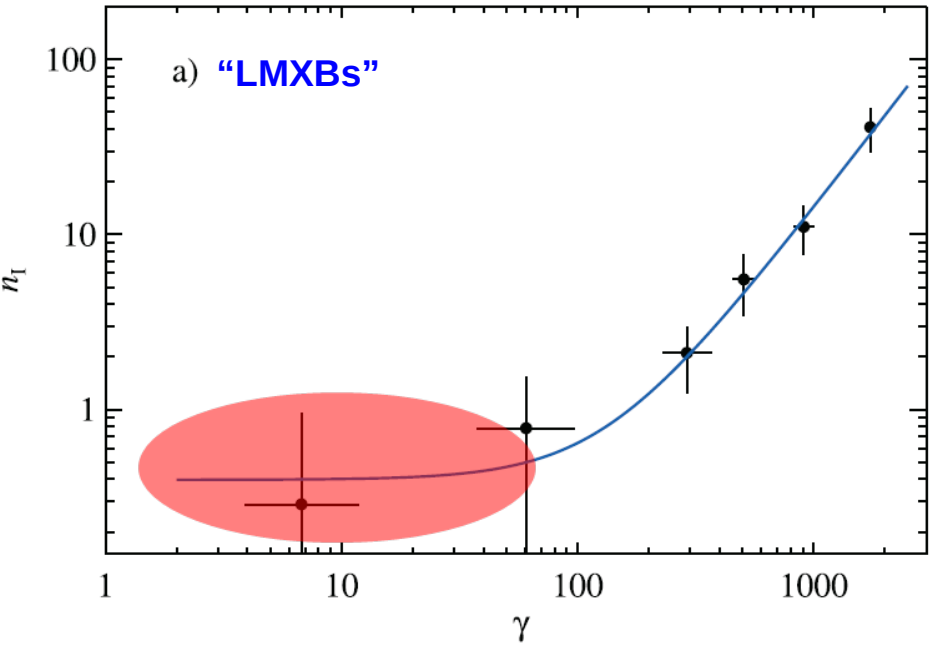
Yes, it does!

- X-ray sources!
  - N_X scales with Γ_{coll}
  - N_{LMXB} scales (mostly) with Γ_{coll}
  - N_{CV} scales (mostly) with Γ_{coll}
  - At low Γ_{coll}, both LMXBs and CVs *may* scale with M_{tot}

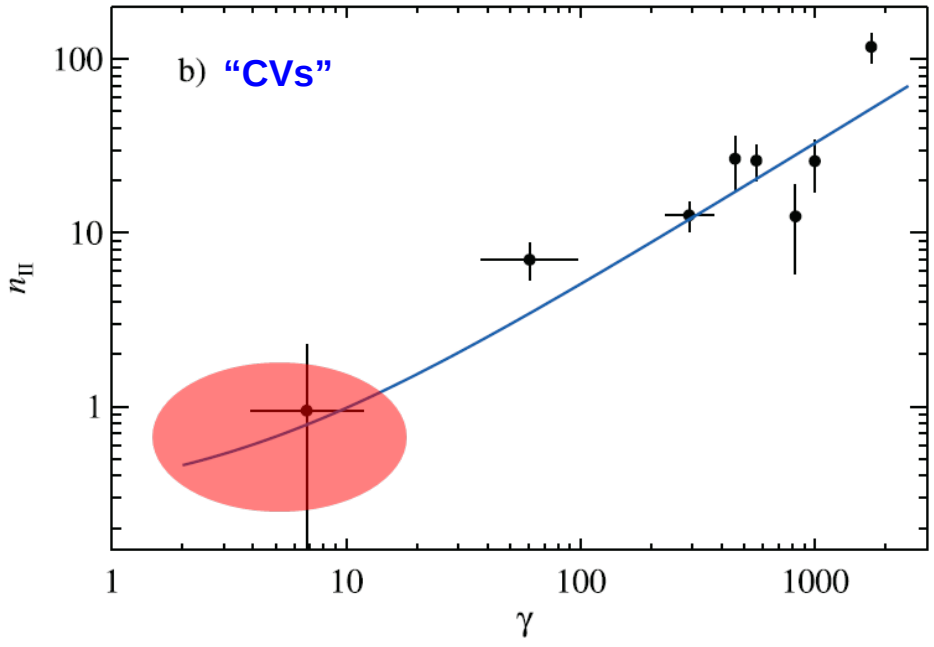
Pooley et al. (2003)



Pooley & Hut (2006)



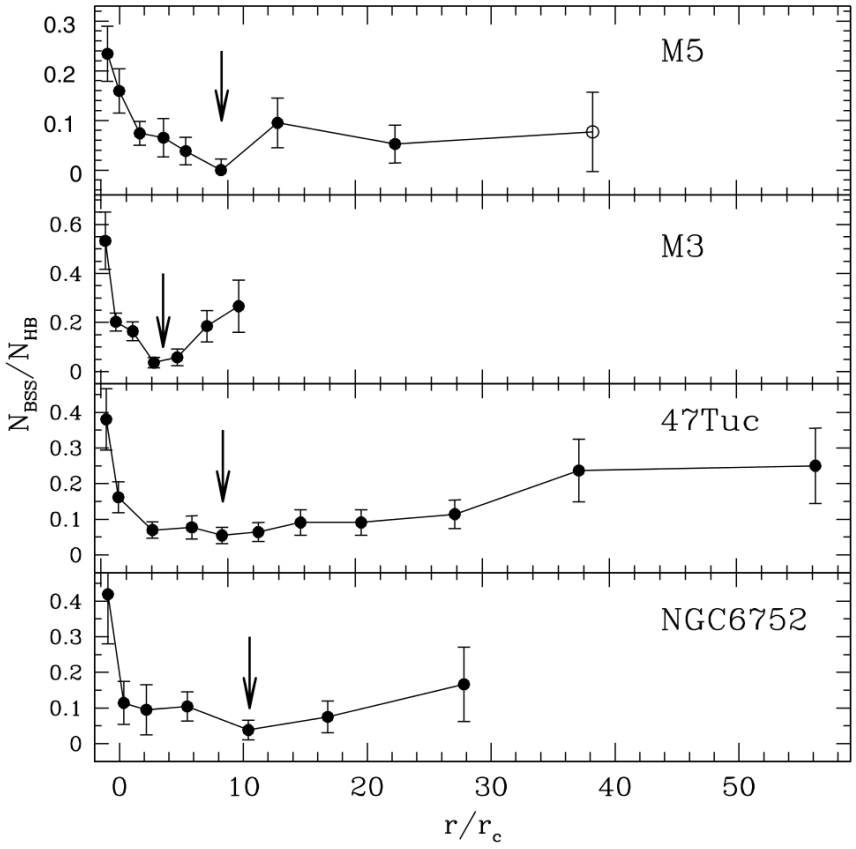
Pooley & Hut (2006)



A Different Approach: Radial Distributions

- Radial distributions of BSS *frequency* are usually bimodal
  (e.g. Ferraro et al. 1997, 2004, 2006a; Sabbi et al. 2004; Warren et al. 2006; Lanzoni et al. 2007ab…)

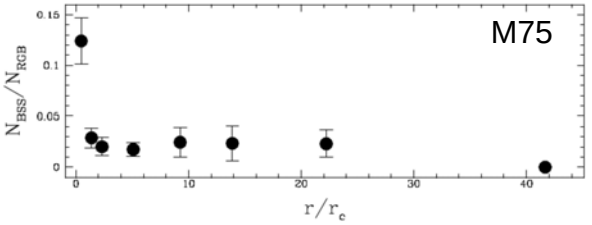
Lanzoni et al. (2007a)



Exception 1: Unimodal

M79 (Lanzoni et al. 2007c)

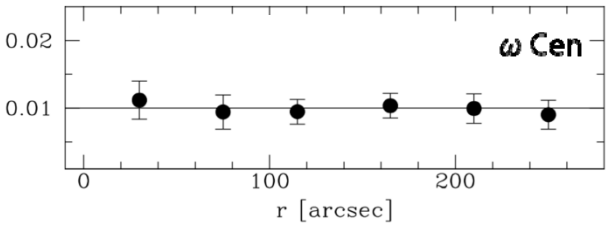
M75 (Contreras Ramos et al. 2012)



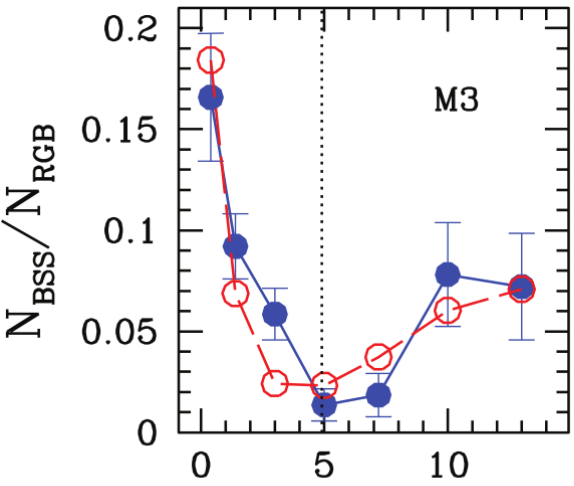
Exception 2: Flat

ω Cen (Ferraro et al. 2006b)

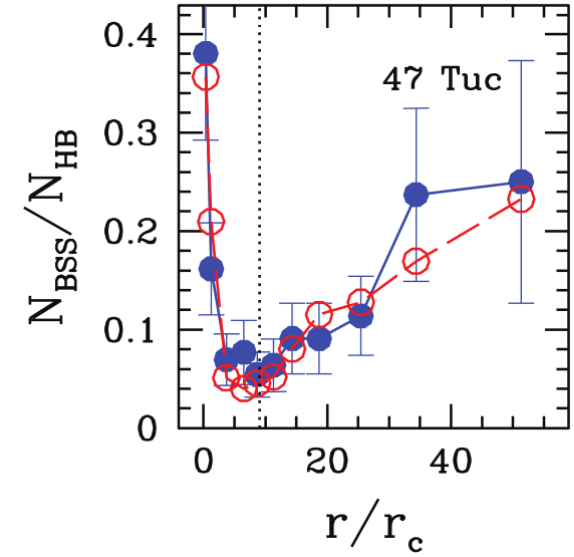
NGC 2419 (Dalessandro et al. 2008)

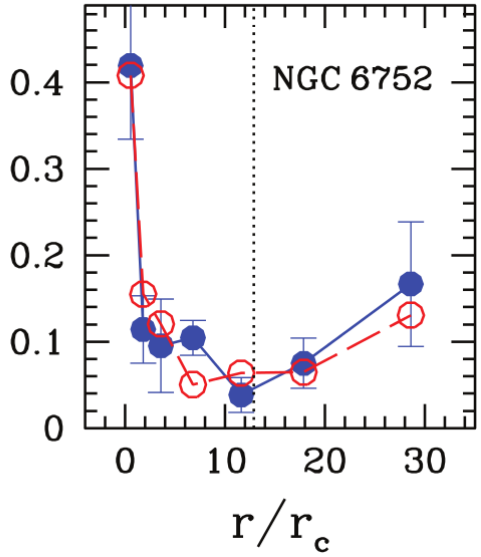


Modelling Radial BSS Distributions



NGC	$f_{BIN,\ all\ r}$	f_{COLL} $<r_c$	f_{BIN} $>r_{min}$
104	46%	100%	95%
5272	41%	100%	91%
6752	41%	98%	97%





Mapelli et al. (2004, 2006)

- Assumptions
  - Static GC background
  - COLL-BSS form inside core
  - BIN-BSS form outside core
  - BIN-BSS uniformly distributed

- Results (for bimodal GCs)

Both channels contribute

$R < R_c$: 100% COLL-BSS

$R > R_{min}$: 100% BIN-BSS

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Radial Distributions: Issues, Questions, Caveats

- *Why* is the BSS distribution bimodal?
  - BIN-BSS progenitors experience dynamical friction
  - Those born inside $R(t_{DF} = t_{GC})$ have sunk to the core
  - Those born outside $R(t_{DF} = t_{GC})$ have not yet moved

  → "zone of avoidance"

  $$R_{min} \sim R(t_{DF} = t_{GC})$$

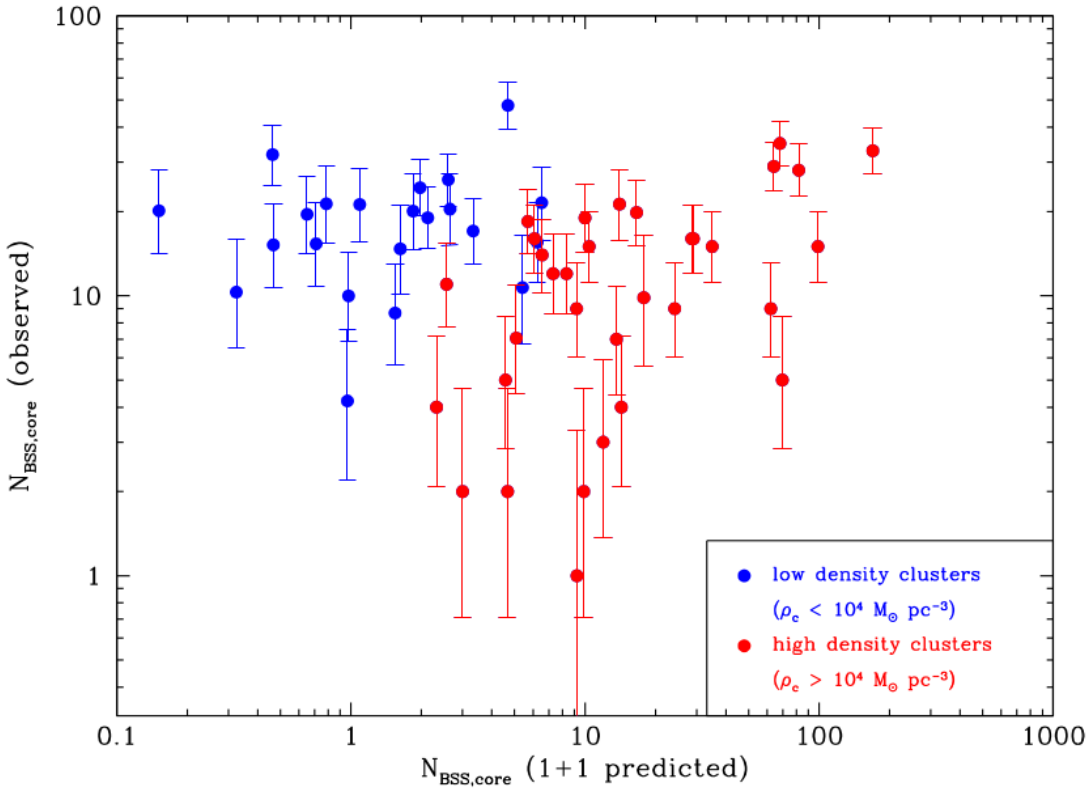
  → ***Pure BIN-BSS populations should still be bimodal!***

- So why the need for COLL-BSS at all?
  - Not enough BIN-BSS are born inside R_{min} by assumption
  - ***Centrally-peaked BIN-BSS birth distribution may also match data (Mapelli et al. 2004)***

- Very different scenario from Davies et al. (2004)!
  - Both favour a combination of BIN-BSS & COLL-BSS
  - Davies et al. (2004): different channels dominate in different GCs
  - Mapelli et al. (2006): different channels dominate in different locations within a given GC

The Search for the Smoking Gun Correlation II: An Obvious Idea

Knigge, Leigh & Sills (2009)



- Does the lack of global correlations arise because *both* channels contribute?
- Well, if collisions dominate anywhere, it's in GC cores!

→ Try correlating

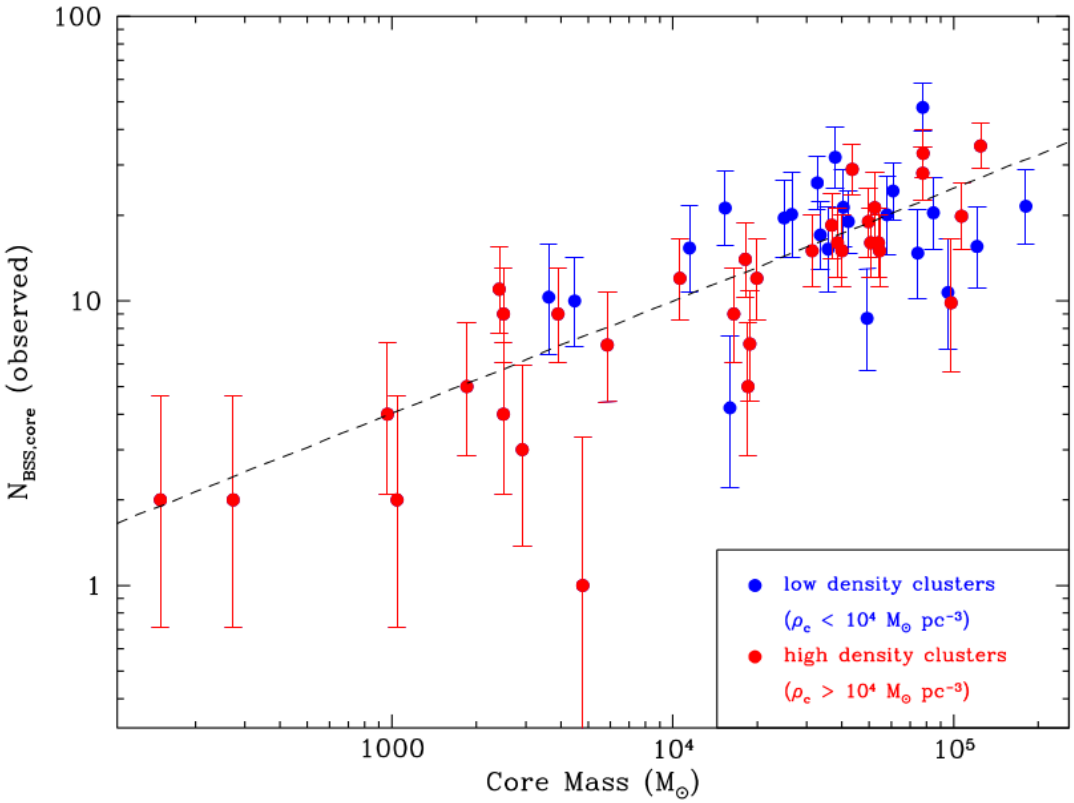
$N_{BSS,core}$ vs Γ_{coll}

(Leigh, Sills & Knigge 2007; Knigge, Leigh & Sills 2009)

- !&%$£!!!!

The Search for the Smoking Gun Correlation II: A Last-Ditch Attempt

Knigge, Leigh & Sills (2009)



- May as well also try binaries

$N_{BSS,core}$ vs $N_{bin,core}$

- Since $f_{bin,core}$ was unavailable for most GCs in 2009, try

$N_{BSS,core}$ vs M_{core}

- What the !&*£$!!!!????
- *Does the binary channel dominate even in GC cores?*

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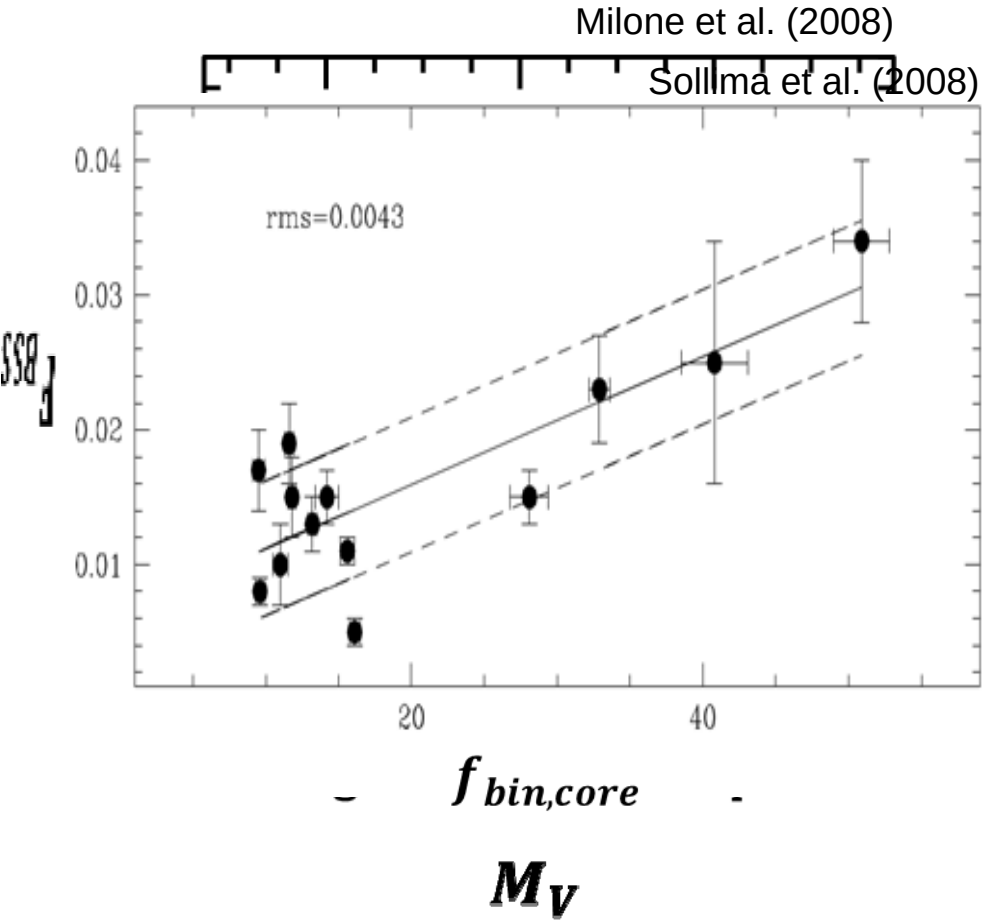
The $N_{BSS,core}$ vs M_{core} correlation



- The correlation is strongly sub-linear

$$N_{BSS,core} \propto M_{core}^{0.4}$$

- Simplest interpretation (prediction!)

$$f_{bin,core} \propto M_{core}^{-0.6}$$

then

$$N_{BSS,core} \propto N_{bin,core} \propto f_{bin,core} M_{core} \propto M_{core}^{0.4}$$

- Any evidence for all this (in 2009)?
  - Hints! (Sollima et al. 2007/8; Milone et al. 2008)

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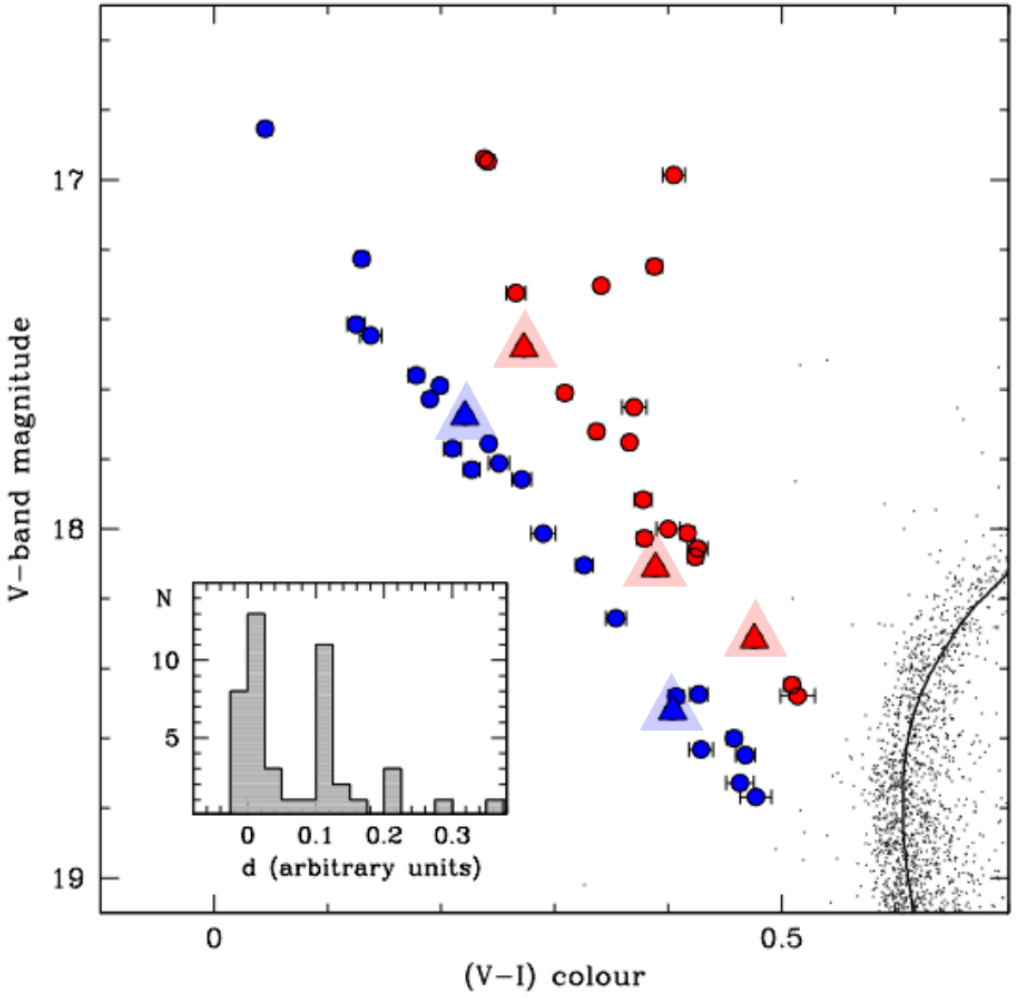
So, it's all binaries then?

But what about…



- The double BSS sequence in M30 (Ferraro et al. 2009)
  - Interpreted as:
    - Blue sequence: collisions
    - Red sequence: binaries
  - Why the clean separation?
    - COLL-BSS formed in a short burst during recent core collapse
    - All share the same evolutionary stage
  - Both seqs present in most GCs?
    - Just happen to be distinct in M30…
  - However, BSS sample includes
    - 3 W UMa contact binaries
    - 2 other variables/binaries
    - One of each on COLL-BSS sequence

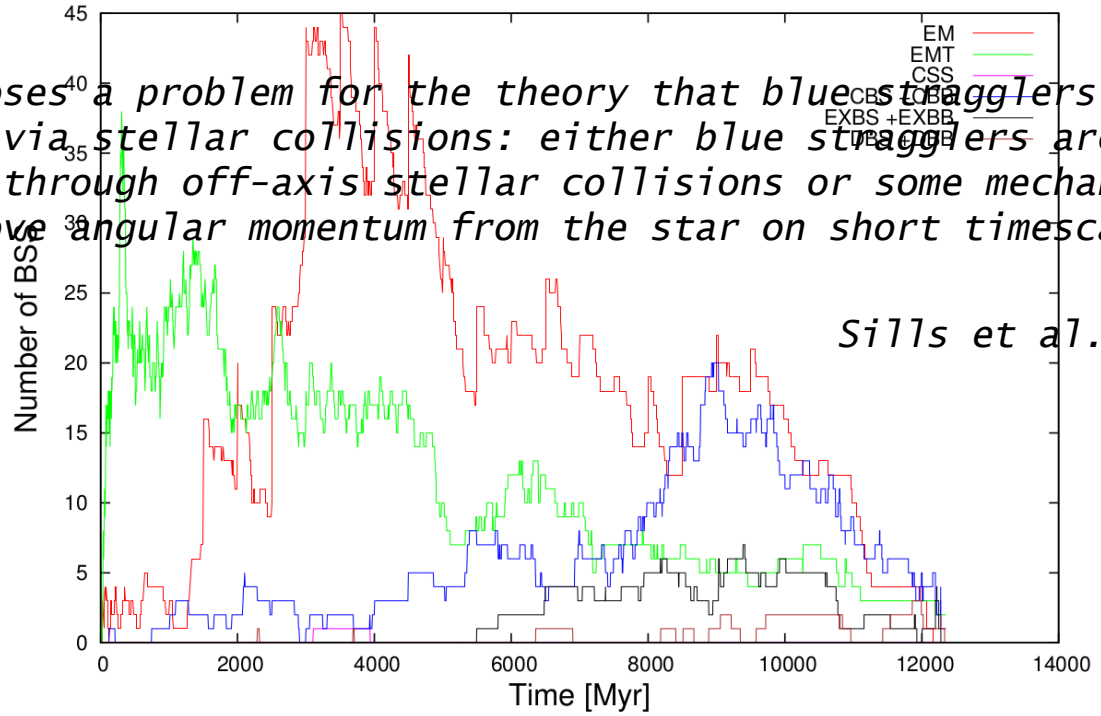
So, it's all binaries then?

But what about…

- Theoretical expectations
  - Physical collisions **must** occur at something like the predicted rate
  - Simulations suggest both channels can contribute (Hypki & Giersz 2012)
  - (But remember: "collision → BSS" is just an ***assumption)***

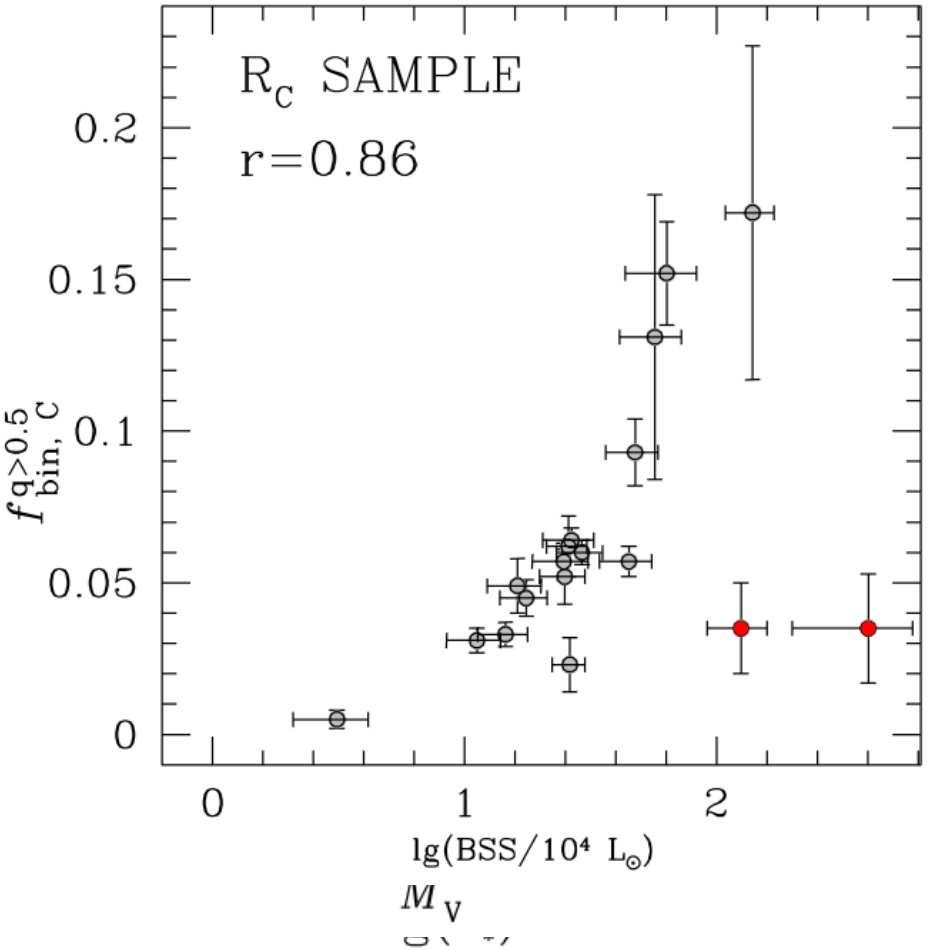
"This poses a problem for the theory that blue stragglers are created via stellar collisions: either blue stragglers are not created through off-axis stellar collisions or some mechanism(s) can remove angular momentum from the star on short timescales."

Sills et al. (2001)



The Search for the Smoking Gun Correlation III: Once more, with feeling XXXXXX binary fractions

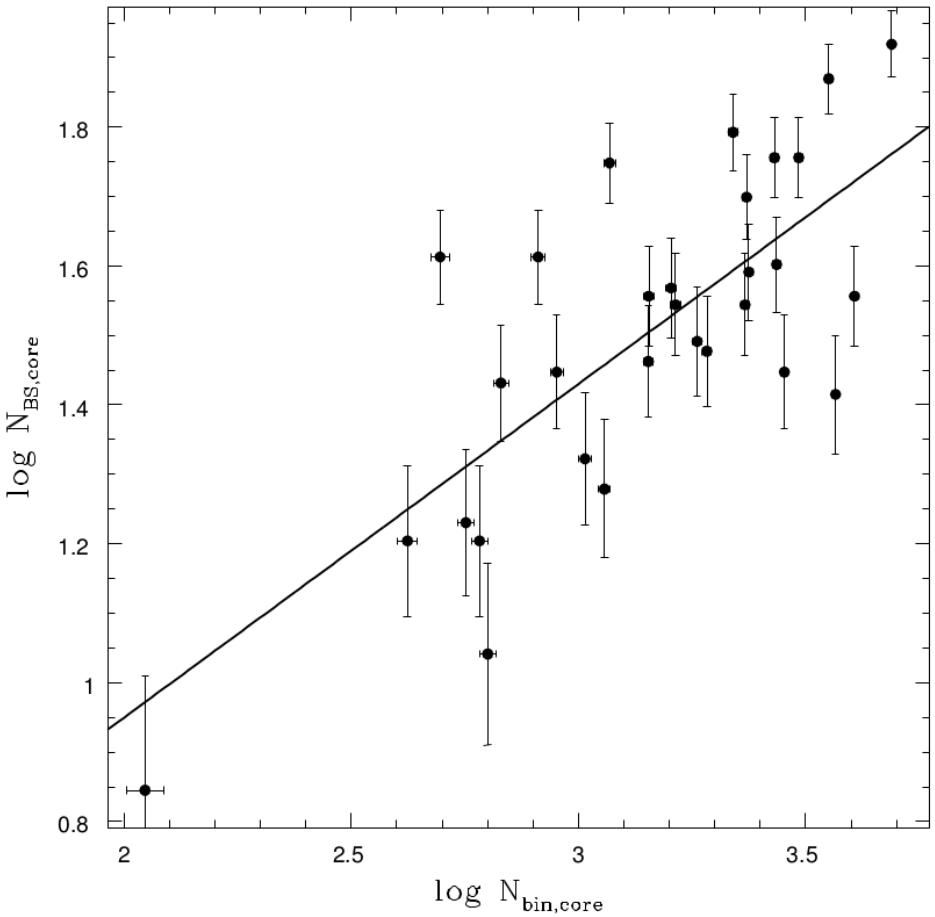
Milone et al. (2012)



- A New Resource:
  - The ACS Survey of Galactic GCs (Sarajedini et al. 2007)
  - Photometric binary fractions for 56 GCs (Milone et al. 2012)
- Core binary fractions
  - Correlate weakly with Γ_{coll}
  - Correlate more strongly with M_V , so ***anti-correlate strongly with*** M_{tot}
  - ***Correlate strongly with*** F_{BSS}
- ***Promising for binary scenario?***

The Search for the Smoking Gun Correlation III: Once more, with binary fractions

Leigh, Knigge, Sills, Perets, Sarajedini & Glebbeek (2012)



- **Collisions:**
  - $N_{BSS,core}$ vs $\Gamma_{coll,1+1}$ ✗
  - $N_{BSS,core}$ vs $\Gamma_{coll,1+2}$ ✗
  - $N_{BSS,core}$ vs $\Gamma_{coll,2+2}$ ✗

  → *collisional trends are weak*

- **Binary Evolution:**
  - $N_{BSS,core}$ vs M_{core} ✓
  - $f_{bin,core}$ vs M_{core} ✓
  - $N_{BSS,core}$ vs $N_{bin,core}$ ✗

- What the &*%$! is going on?

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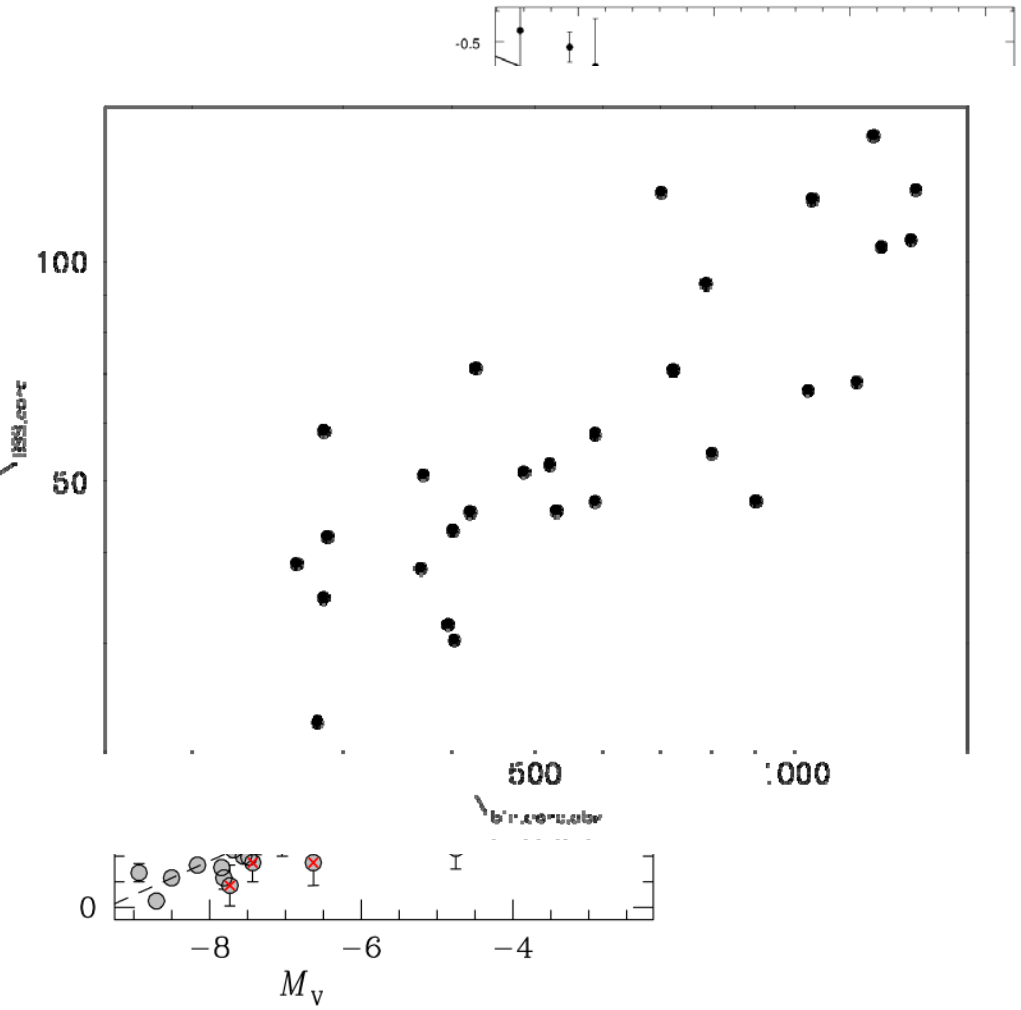
The Search for the Smoking Gun Correlation III: A Thought Experiment…

Leigh et al. (2012)



- Suppose BSS are exclusively formed from (primordial) binaries:

  $$N_{BSS,core} \propto N_{bin,core}$$

  with just some modest intrinsic scatter

- We know that the observed $f_{bin,core}$ anti-correlates pretty well with M_{core} and M_{tot}

- What if the true correlation is even stronger?
  → Then scatter in $f_{bin,core}$ vs M_{core} is mostly observational (σ_{obs}), not intrinsic (σ_{int})

- But if $\sigma_{obs} > \sigma_{int}$, M_{core} is a better tracer of the true $f_{bin,core}$ than the measured fractions!

- And $N_{BSS,core}$ would track M_{core} more closely than the estimated $N_{bin,core}$… as observed!

- So the binary scenario *might* work…

…if binary fractions are extremely closely coupled to core/total cluster masses (Leigh et al. 2012)

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Summary

- Collisions, binary mass transfer and mergers must all happen in GCs!
  - Mass transfer *definitely* produces BSS
  - Mergers can be survived (V1309 Sco) and *probably* produce BSS
  - Collisions *may* produce BSS (if enough AM can be lost)

- There is no clean correlation between N_{BSS} and Γ_{n+m}, even in GC cores
- There is a strong, sub-linear correlation with M_{core} / M_{tot}
- There is a strong correlation with f_{bin}

→ ***A binary origin for BSS, even in GC cores?***

(since no correlation with Γ_{coll} , have these binaries not even been *affected* by encounters?)

- But we do not get the best (and linear) correlation with $N_{bin} = f_{bin} M_{tot}$!
  - Is M_{tot} actually a better trace of f_{bin} than observationally measured binary fractions?

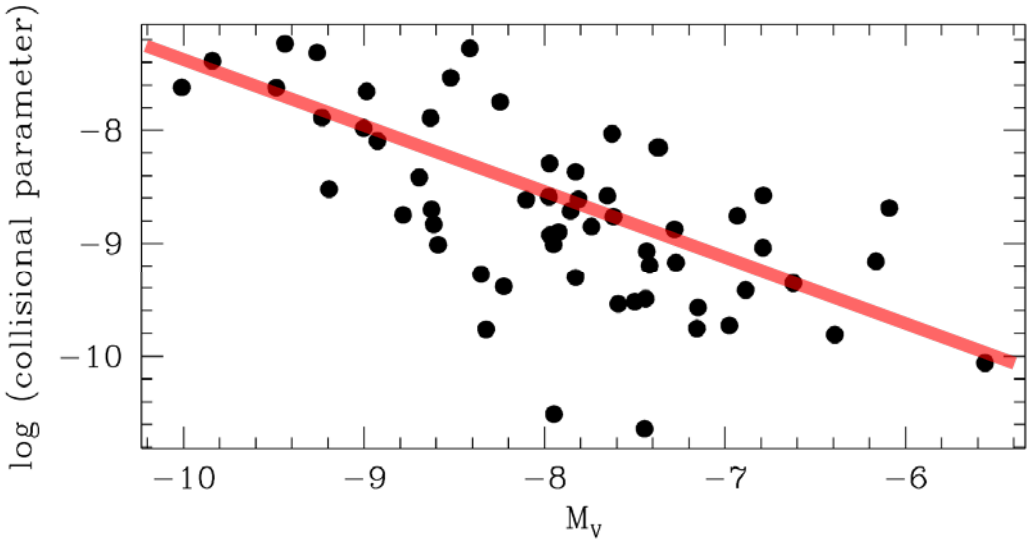
- What about other evidence for COLL-BSS channel?
  - Radial distributions? Double sequences?

There is no smoking gun yet!

Now with free bonus slides…

But let's remember that…

- Other factors may mask/alter the naïve straw man scalings
- N/M_{tot} and Γ are *always* correlated themselves
  - Encounter rates always scale with the available number of objects



$$\Gamma \propto M_{tot}^{1.5}$$

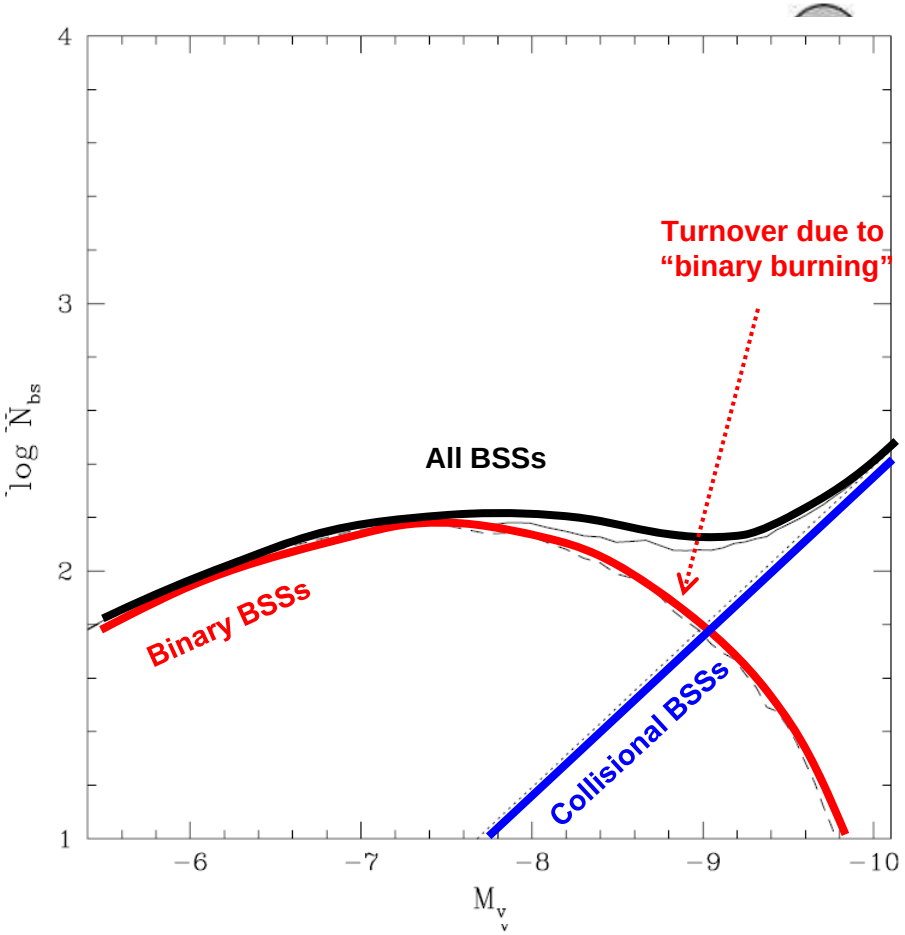
$$log\Gamma = -0.6\, M_V$$

Davies, Piotto & de Angeli (2004)

- Even if all BSS form via binary evolution, expect a scaling with encounter rate if the requisite binaries are dynamically formed/altered

A Possible Interpretation?

Davies et al. (2004)



- In high-mass / high-collision-rate GCs, massive stars exchange into binaries early
  - By today, most suitable proto-BSS binaries have been "used up"
- In low-mass / low-collision-rate GCs, collisions just don't produce enough BSS
- So scaling with M_V is mild or absent because

→ Binaries dominate in low-mass / low-collision-rate GCs

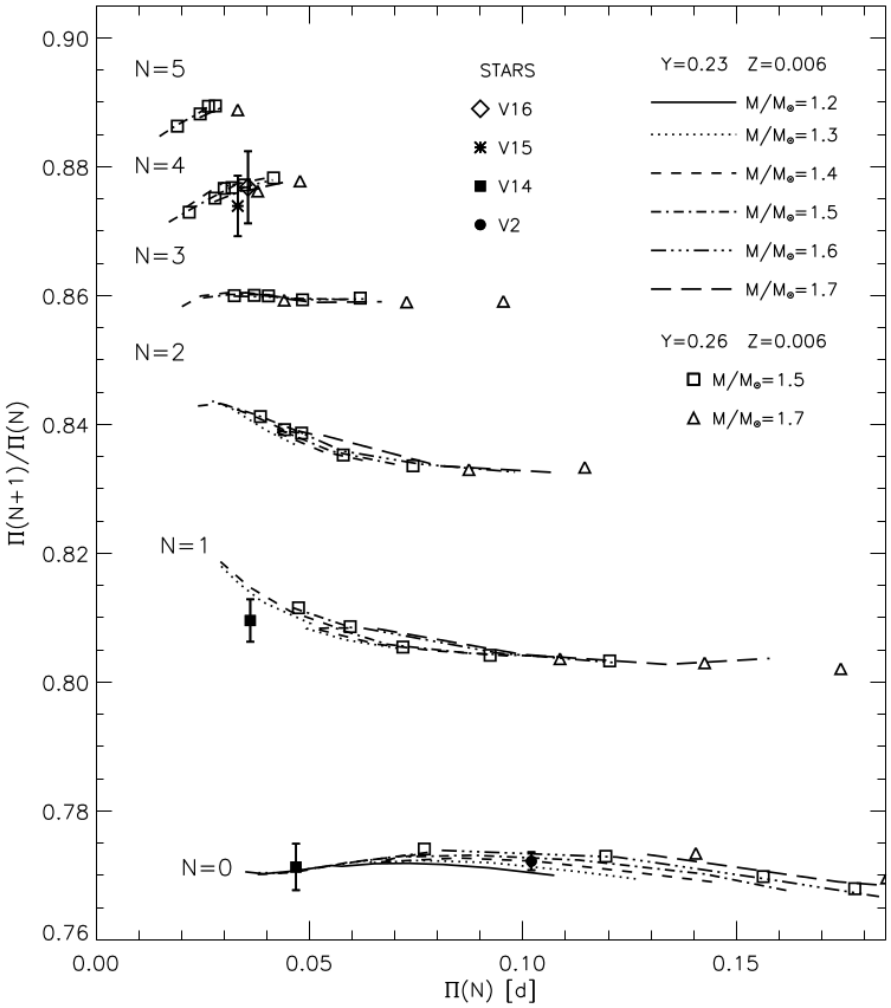
→ Collisions dominate in high-mass / high-collision-rate GCs

Predictions & Problems

- Should still see a linear scaling with Γ_{coll} at the high-Γ_{coll} end
  - Not really observed
- In this picture, even binary BSSs require dynamical encounters, so actually still expect a linear scaling with Γ_{coll} (via Γ_{1+2})
  - Not observed
- "Binary burning" scenario is speculative
  - Ignores late supply of binaries from halo to core
  - Ignores changing environment as cluster evolves
  - Specific implementation assumes persistent availability of stars with $M > M_{TO}$
  - Should high-collision-rate GCs should have lower core binary fractions?
    - Not observed (see later)

What else can we still do?

Gilliland et al. (1998)



- **Spectroscopy**
  - Abundances
    - Are MT-BSS CO-depleted?
  - Rotation
    - Is the $v \sin i$ distribution bimodal?
  - Kinematics
    - Do COLL-BSS get a measurable kick?
- **Binarity**
  - Radial velocity variations?
  - Photometric variability
    - Eclipses, W UMa, …
  - Direct detection of companions
    - UV, X-ray…
- **Pulsations**
  - Some BSS are SX Phe pulsators
    - Mode analysis can yield masses!