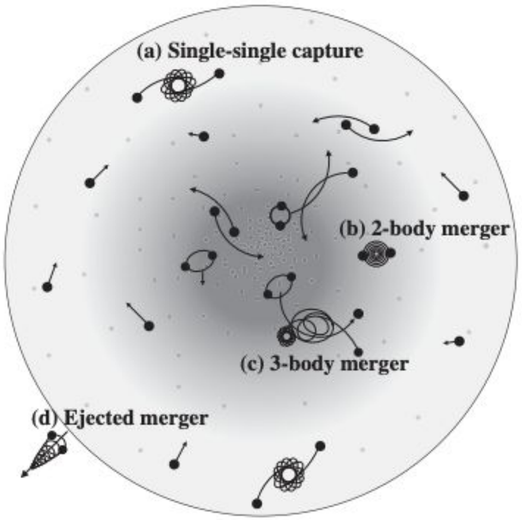
How Initial Size Governs Core Collapse in Globular Clusters

Kremer et al. 2019

Evolution of GCs

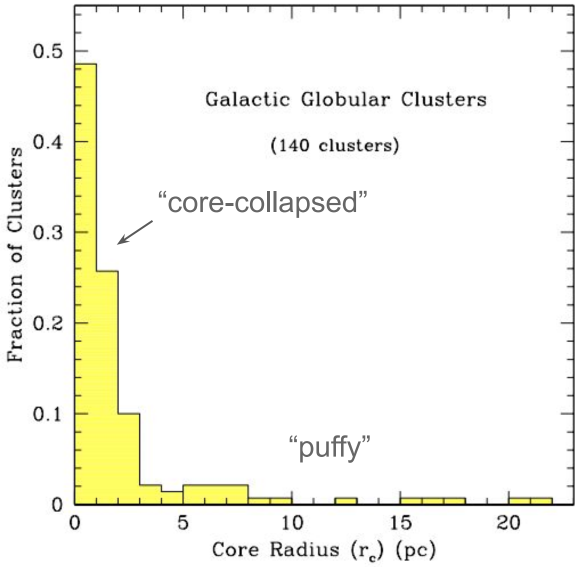


Samsing et al. 2020

High rates of dynamical encounters

Factories of merging BBH systems

Core-collapsed GC

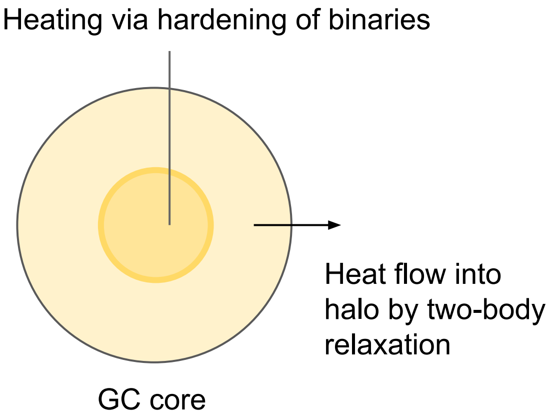


Mackey and Gilmore 2004

cf) Definition of GC 'core radius' from Wilkinson et al. 2003

- mass density-weighted radius (theory)
- half surface brightness of center value (observations)

Core-collapsed GC



Self-gravitating systems with negative heat capacities

- energy transferred from core to halo
- core gets hotter -- runaway contraction (core collapse)

GCs ‘burn’ binaries to support cores against collapse

- binary burning phase - core supported by superelastic dynamical interactions
- outward diffusion of energy is balanced by production of energy via dynamical hardening of binaries

Black Holes in GCs

Initial number of BHs (~10^3) → How many BHs are retained in GCs?

ejection mechanism :

- large natal kicks (immediate after formation)
- dynamical encounters (over several relaxation times)

Several stellar-mass BH candidates identified in GCs

Initial virial radius

Initial cluster size parametrized by virial radius

$$r_v = \frac{GM^2}{2|U|}$$

- Observations indicate size of young massive clusters span narrow range
- Vary initial virial radius : 0.5 - 5pc

Relaxation timescale :

$$t_{\rm rh} = 0.138 \frac{M^{1/2} R_{\rm h}^{3/2}}{\langle m \rangle G^{1/2} \ln \Lambda}$$

- affects evolution of stellar-mass BH in GCs

Simulation

- Cluster Monte Carlo (CMC) code

Remnant formation

Fryer & Kalogera 2001 / Belczynski et al. 2002

Natal kicks

NS : maxwellian w/ $\sigma_{\mathrm{NS}} = 265 \mathrm{km\,s^{-1}}$

BH : sampling from NS kick distribution

Initial cluster parameters :

total particle number, $N = 8 \times 10^5$; King concentration parameter, $w_o = 5$; binary fraction, $f_b = 5\%$; metallicity, Z $= 0.001$; and Galactocentric distance, $d = 8$ kpc.

- Kroupa IMF (0.08-150 M_{sun})

GC models

2D spatial resolutions with snapshots for t=10-12 Gyr

Table 1. Initial and final cluster properties for all models

Model	r_v (pc)	$t_{\rm rh}$ (Myr)	$M_{\rm tot}$ ($10^5\ M_\odot$)	r_c (pc)	r_h (pc)	$N_{\rm BH}$	$N_{\rm BH-LC}$	$N_{\rm BH-MTB}$
1	0.5	49	1.58	0.23	1.38	2	7	2
2	0.6	64	1.94	0.26	1.53	11	7	3
3	0.7	81	2.09	0.75	1.82	16	4	1
4	0.8	99	2.17	0.90	2.22	28	6	1
5	0.9	118	2.21	0.93	2.61	38	9	4
6	1.0	138	2.24	1.72	2.78	50	5	1
7	1.5	255	2.26	2.76	4.26	111	13	0
8	1.75	321	2.31	1.70	4.45	109	4	0
9	2	392	2.42	2.75	5.36	201	16	4
10	3	721	2.33	5.07	6.49	315	14	0
11	5	1552	2.38	9.90	11.7	614	18	8

t = 12Gyr

t = 10-12 Gyr

Time evolution of observational core radii

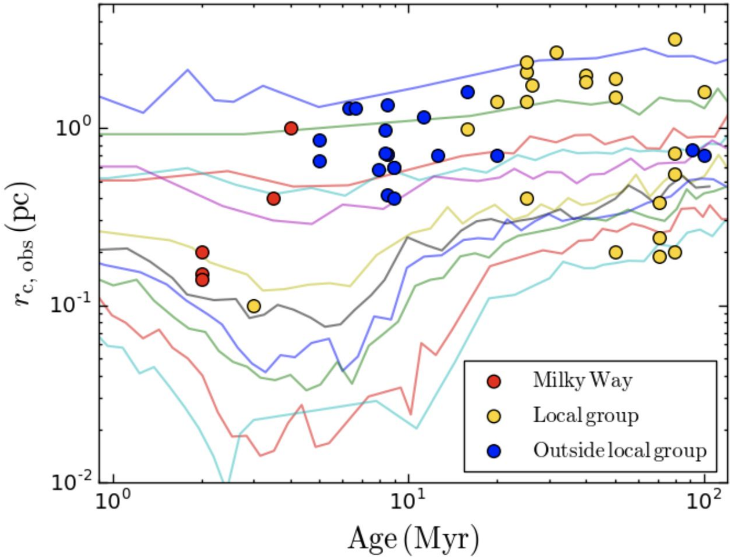


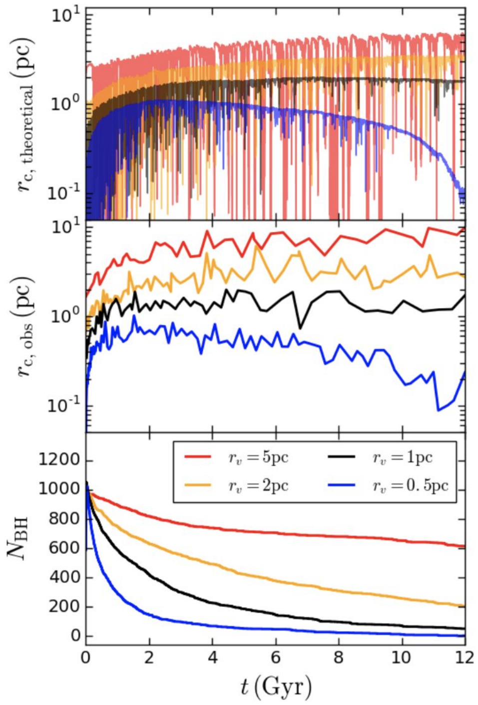
Fig 1 from the paper

Core radius & number of BHs

core radius
(theoretical)

core radius
(observational)

number of
BHs



~1500 initial BHs, ~500 ejected promptly by natal kicks

Fig 2 from the paper

Core radius & number of BHs

core radius (theoretical)

core radius (observational)

number of BHs

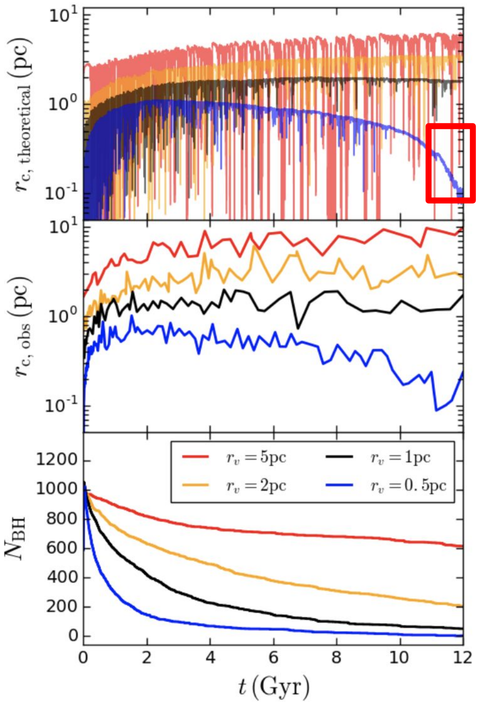


Fig 4 from the paper

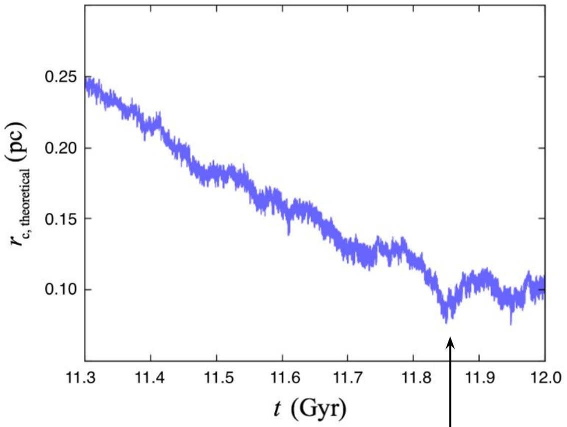


Fig 3 from the paper

~1500 initial BHs, ~500 ejected promptly by natal kicks

Onset of binary-burning

Surface brightness profiles

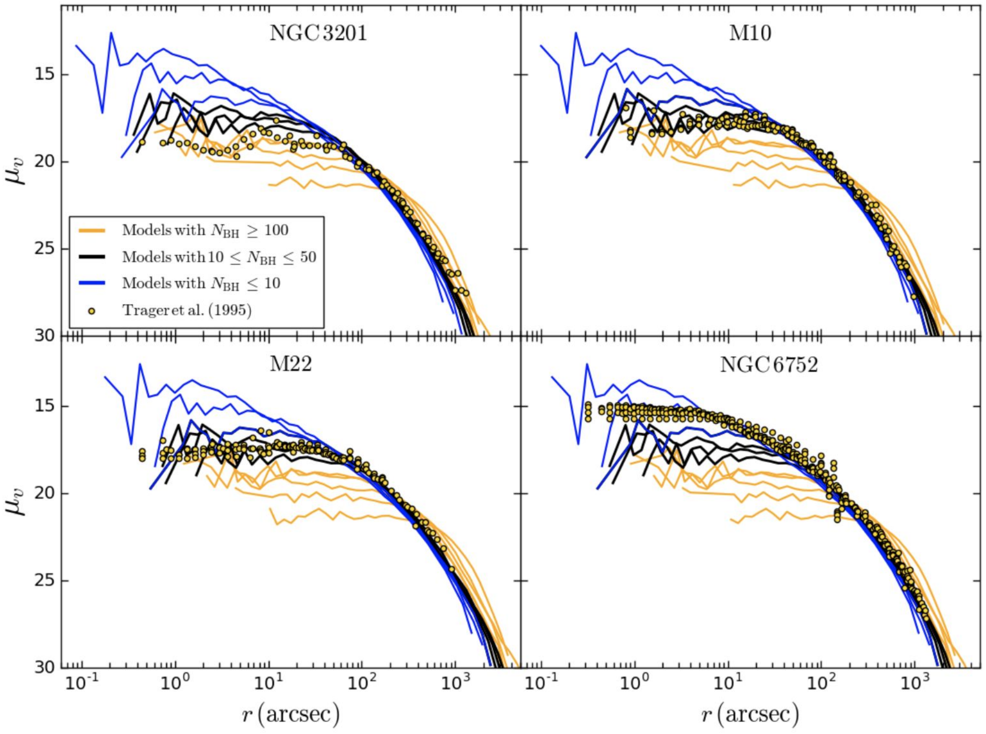


Fig 4 from the paper

$$\alpha = \chi^2_{\mathrm{SBP}} + \chi^2_{\sigma_v}$$

Pick lowest-alpha model snapshots for NGC 3201, M10, M22, NGC 6752

BH-poor models represents “core-collapsed” GCs

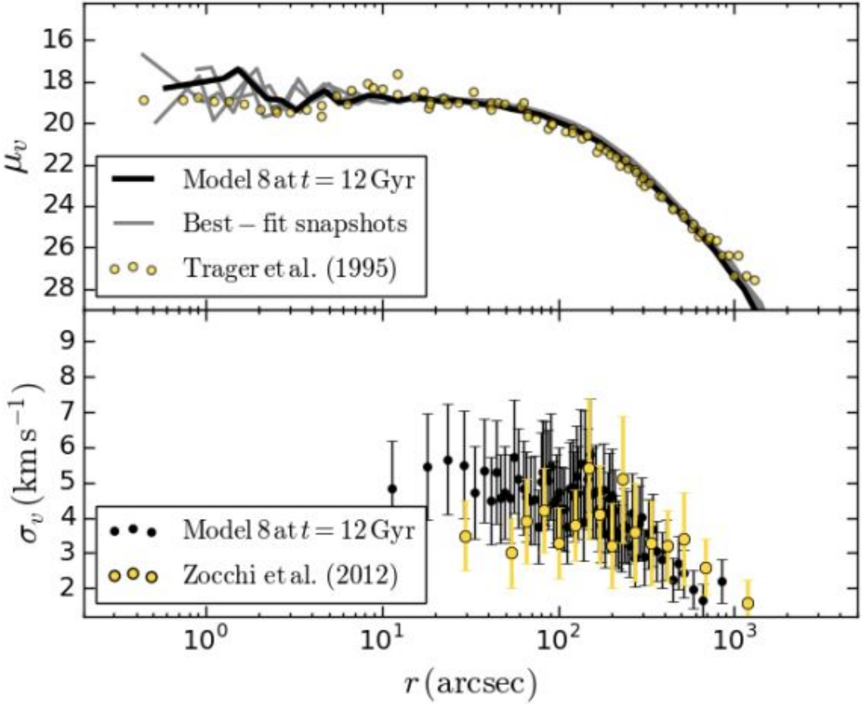
BH-rich models produce “puffy” clusters

NGC 3201

Observational Status:

- Giesers+2019: 3 BH-LC binaries
  Possible discrepancy in binary eccentricities? (Kremer 2018a)
  They predict fewer binaries?

	NGC 3201
$r_{v,0}$ (pc)	1.75-2
$N_{\rm BH}$	121 ± 10
$N_{\rm BH-LC}$	2.5 ± 0.5
$N_{\rm BH-MTB}$	1

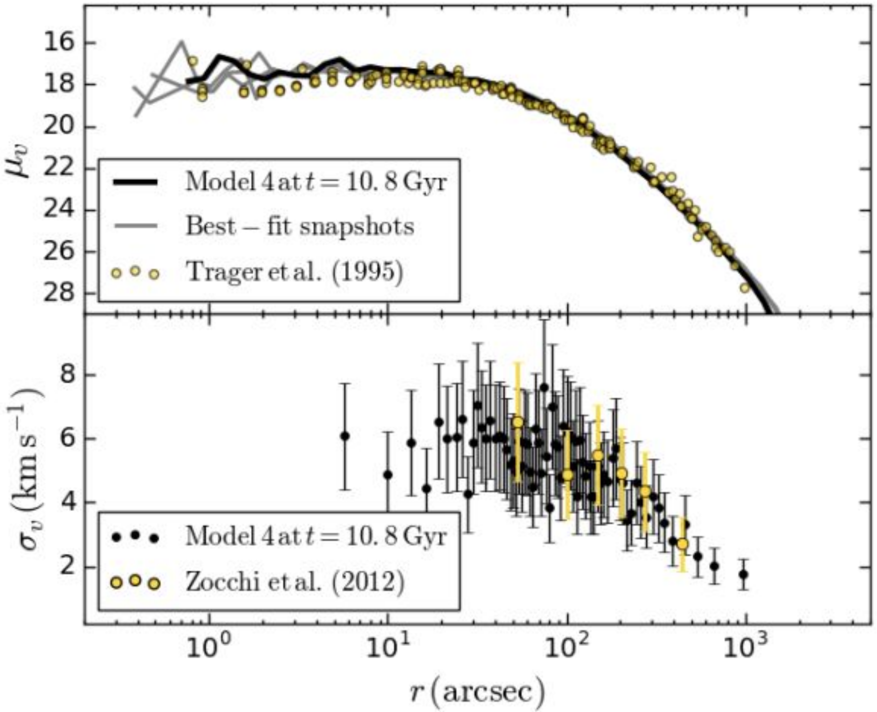


Velocity dispersion calculated using radial bins of 25 stars, only giants included, after Zocchi et al 2012

M10 = NGC 6254

Shishkovsky+2018 - there is one radio selected BH binary candidate

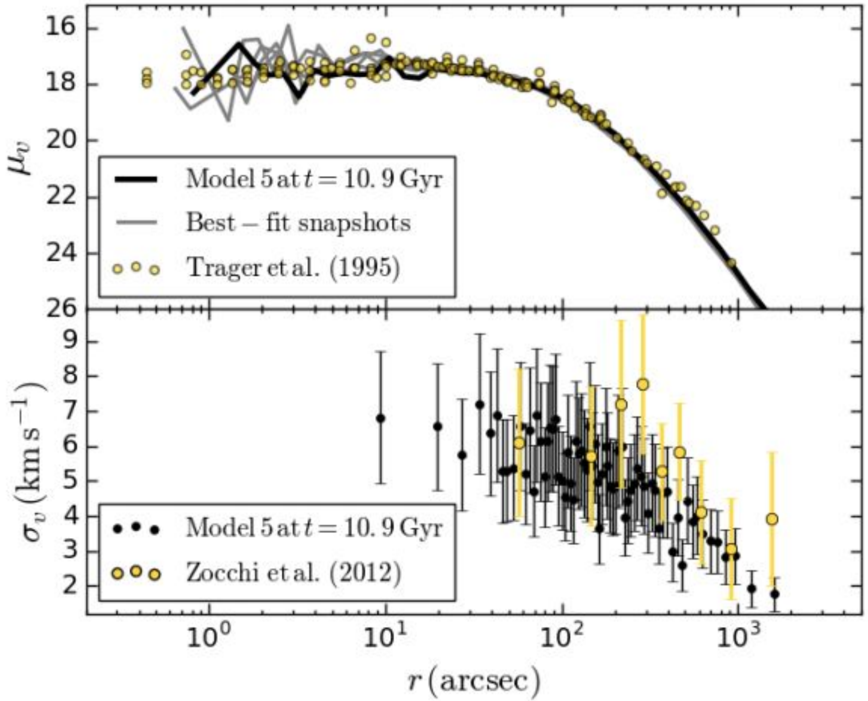
	M10
$r_{v,0}$ (pc)	0.7-0.9
$N_{\rm BH}$	39 ± 9
$N_{\rm BH-LC}$	2.6 ± 1.1
$N_{\rm BH-MTB}$	1.5 ± 0.95



M22 = NGC 6656

Strader+2012 → 2 accreting stellar mass BHs
They predict ~5-100 total

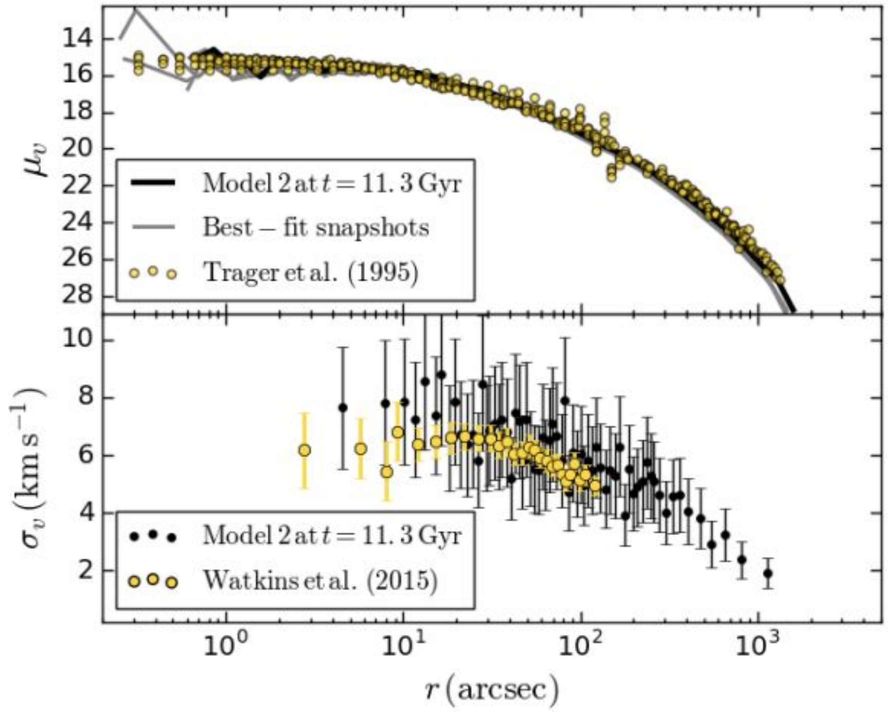
	M22
$r_{v,0}$ (pc)	0.8-0.9
N_{BH}	40 ± 9
$N_{\mathrm{BH-LC}}$	2.7 ± 1.1
$N_{\mathrm{BH-MTB}}$	1.5 ± 1



NGC 6752

Core collapsed cluster

	NGC 6752
$r_{v,0}$ (pc)	0.5-0.7
N_{BH}	16 ± 7
$N_{\mathrm{BH-LC}}$	2.7 ± 1
$N_{\mathrm{BH-MTB}}$	2.0 ± 0.97



Black Hole Binary Formation

- 29 accreting black hole - luminous companion binaries in all simulations (t = 10-12 Gyr)

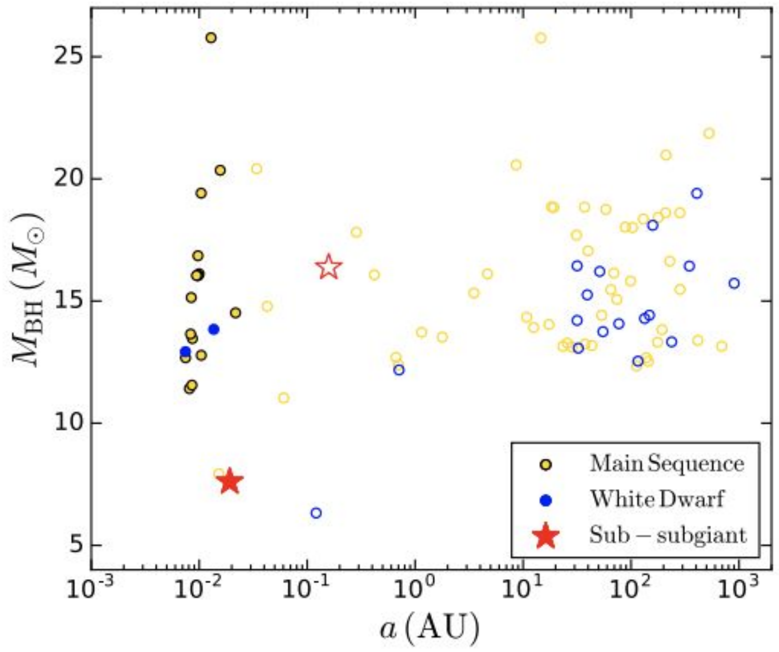
  26 MS, 2 WD, 1 sub-subgiant donor

- 68 detached BH-LC binaries in all simulations (t = 10-12 Gyr)

  50 MS, 17 WD, 1 sub-subgiant companion

Binaries formed through the exchange encounter channel

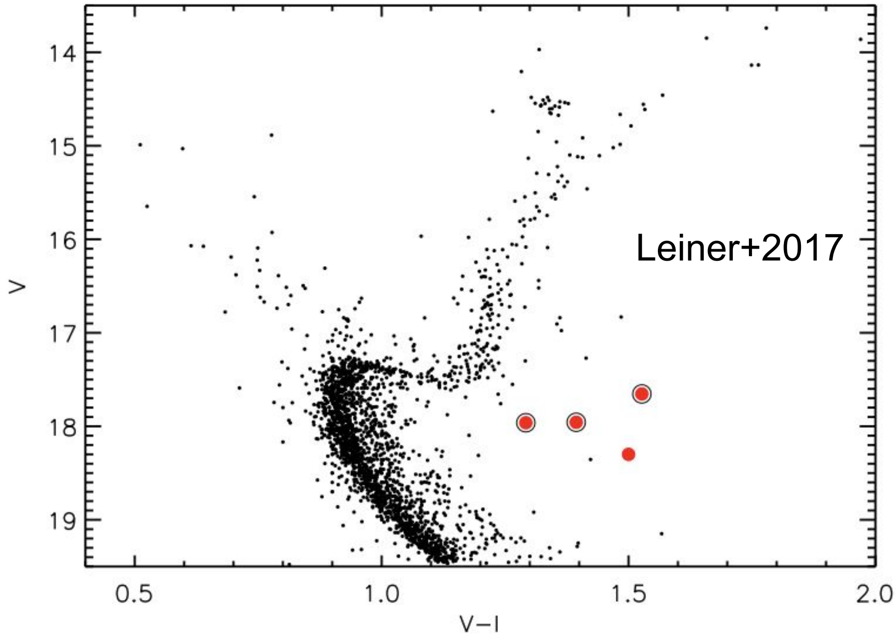
Filled marker = mass transfer



Brief digression on sub-subgiants

From Geller+2017

- Unique location on CMD
- Many X-ray sources (10^{30-31} erg s^{-1})
- Hα emission (chromospheric activity)
- Photometric/radial velocity variables
- Many radial velocity binaries
- Lower specific frequency in lower mass clusters



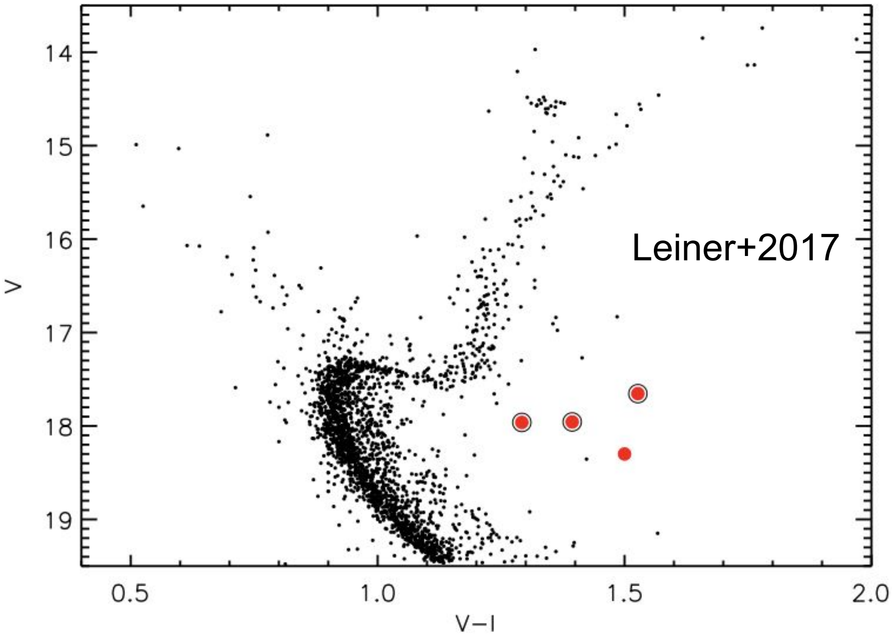
Brief digression on sub-subgiants

From Geller+2017

“SG Mag” - reduced convective efficiency (which can alter stellar temperature and radius) due to increased magnetic activity

Close binary spins up a subgiant star → increased magnetic activity

“MS Coll” - main-sequence-main-sequence collision. Collision product will become brighter, then contract and release grav. pot. energy



Conclusions

- Can reproduce a range of GC types
  → models can predict the BH populations of MW GCs

- “the specific way that BHs are removed may matter less in shaping the present-day structure of the host GC than the number of BHs retained at present”

- Extreme example: Palomar 5? Gieles+2021

Caveats

Includes:

- The initial *N* is fixed
- Neglect eccentric galactic orbits
  → dissolution timescales may be long enough that this is fine
- GC formation is uncertain