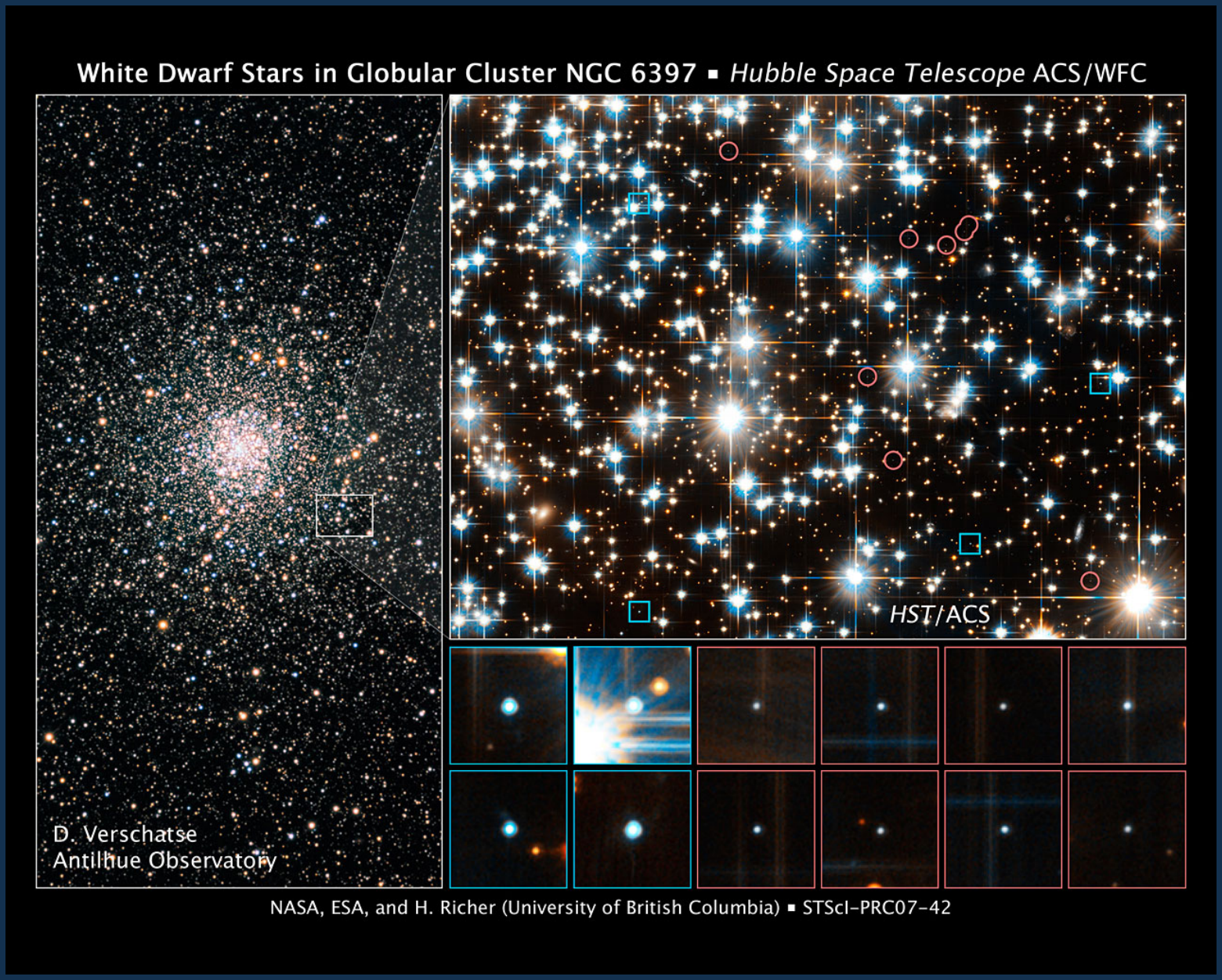
The Role of Stellar Mass Black Holes in Globular Clusters …
or
The Binary Populations of Simulated Star Clusters

Jarrod Hurley (Centre for Astrophysics & Supercomputing)

MODEST-13, Almaty, Aug 18 – 21, Topic: “Globular Clusters”

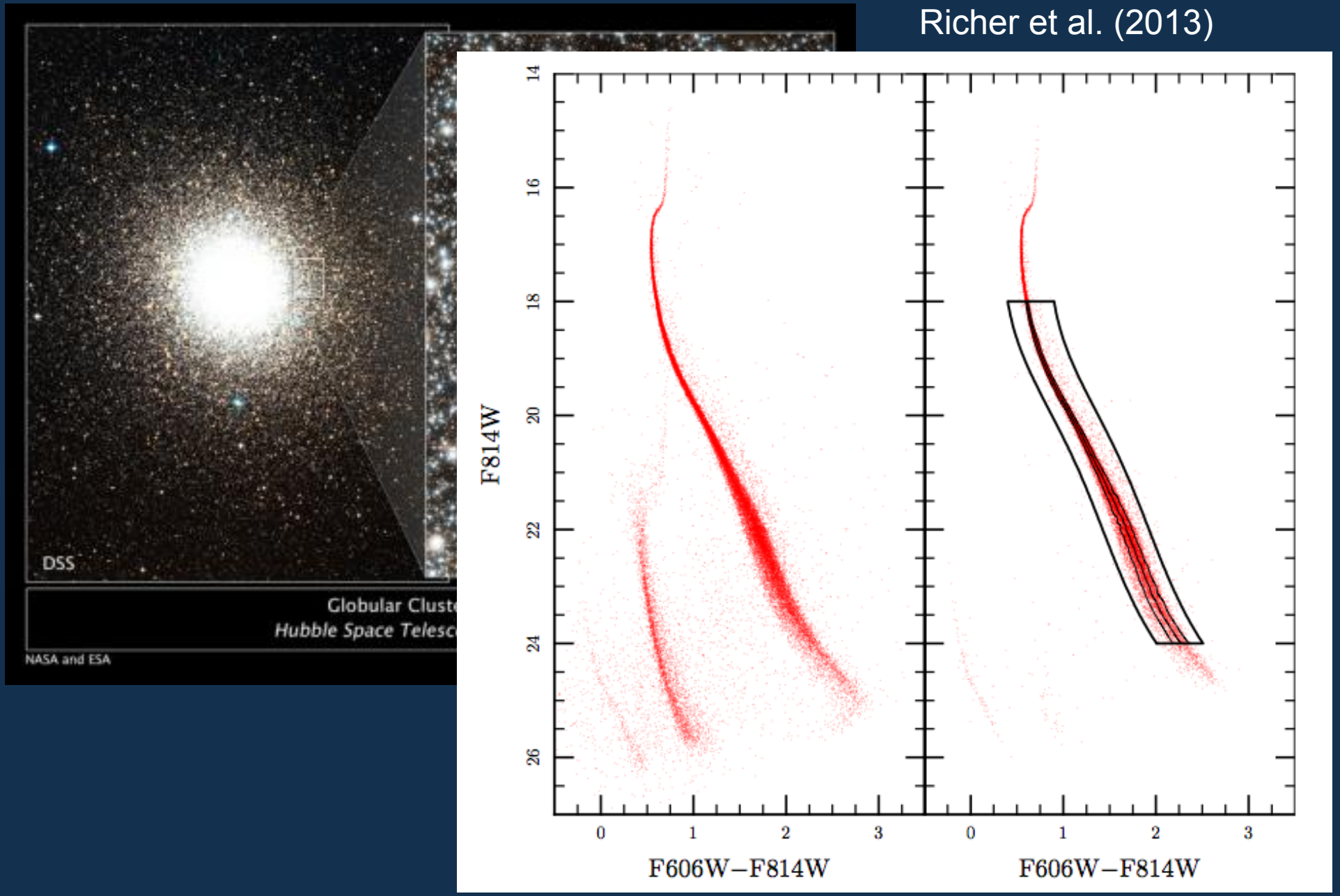
Anna Sippel (Swinburne)

Aaron Geller (Northwestern)


White Dwarf Stars in Globular Cluster NGC 6397 ▪ *Hubble Space Telescope* ACS/WFC
HST/ACS
D. Verschatse
Antilhue Observatory
NASA, ESA, and H. Richer (University of British Columbia) ▪ STScI-PRC07-42

DSS
HST ACS/WFC
Globular Cluster 47 Tuc
Hubble Space Telescope • ACS/WFC
NASA and ESA
STScI-PRC13-25a

Richer et al. (2013)



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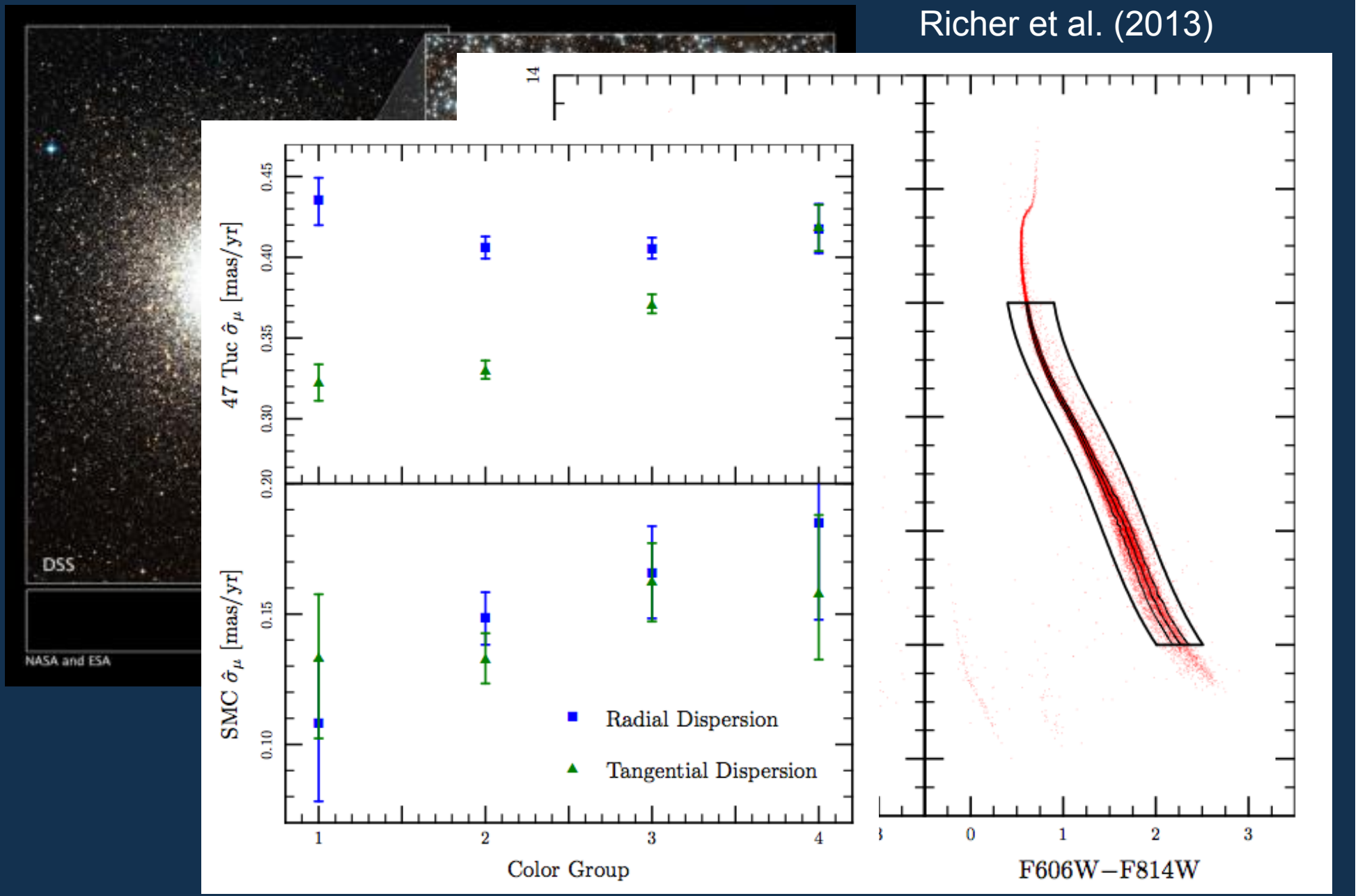
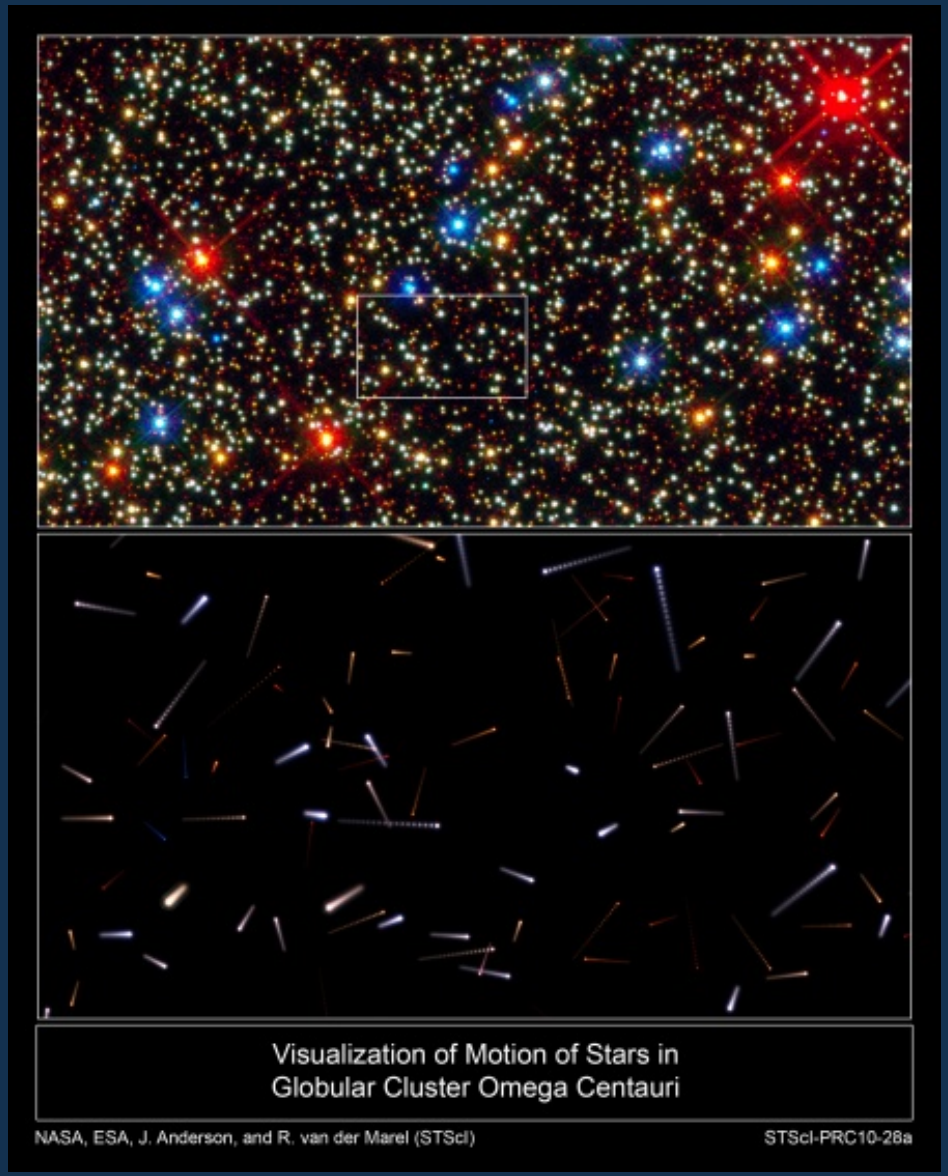
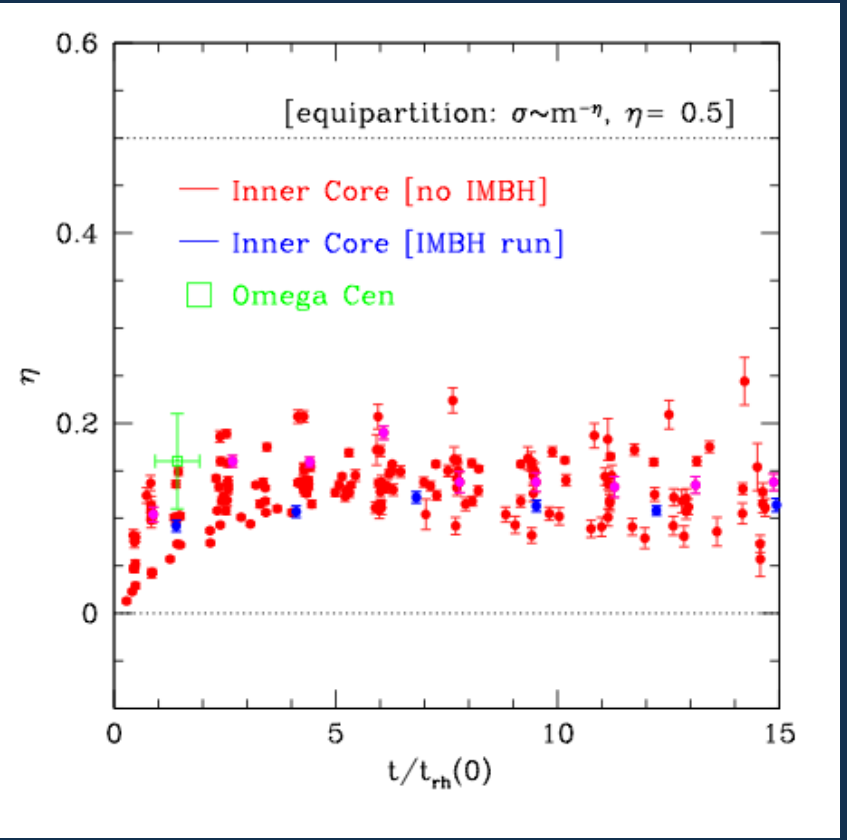


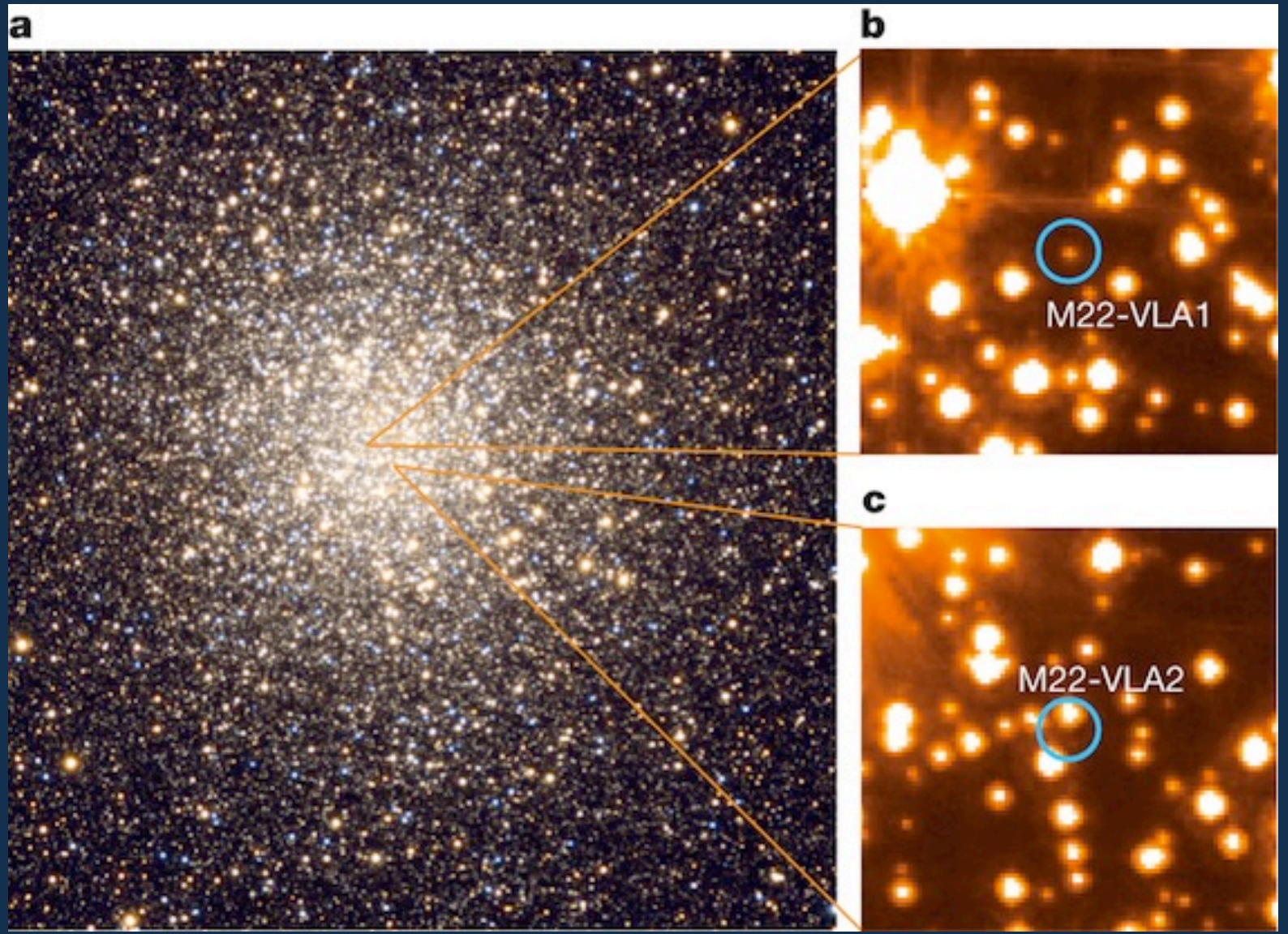


Anderson & van der Marel (2010)

$$\sigma \propto m^{-0.2}.$$

Trenti & van der Marel (2013)





Strader et al. (2012)

86 nodes: 16 SandyBridge E5-2660 cores, 1 x K10, 64GB RAM
52 nodes: 12 Xeon X5650 cores, 2 x C2070, 48GB RAM
3 nodes: 12 Xeon X5650 cores, 7 x M2090, 48GB RAM
4 nodes: 32 E78837 cores, 512GB RAM

2.0PB Lustre filesystem, 0.5PB nfs storage, QDR infiniband

N-body Models

Equation of Motion

$$\ddot{r}_i = -G \sum_{j=1}^{N} \frac{m_j (r_i - r_j)}{|r_i - r_j|^3}$$

→ $O(N^3)$

→ GPU/AVX for force integration

[NBODY6: Aarseth 2003; Nitadori & Aarseth 2012]

stellar evolution

binary evolution

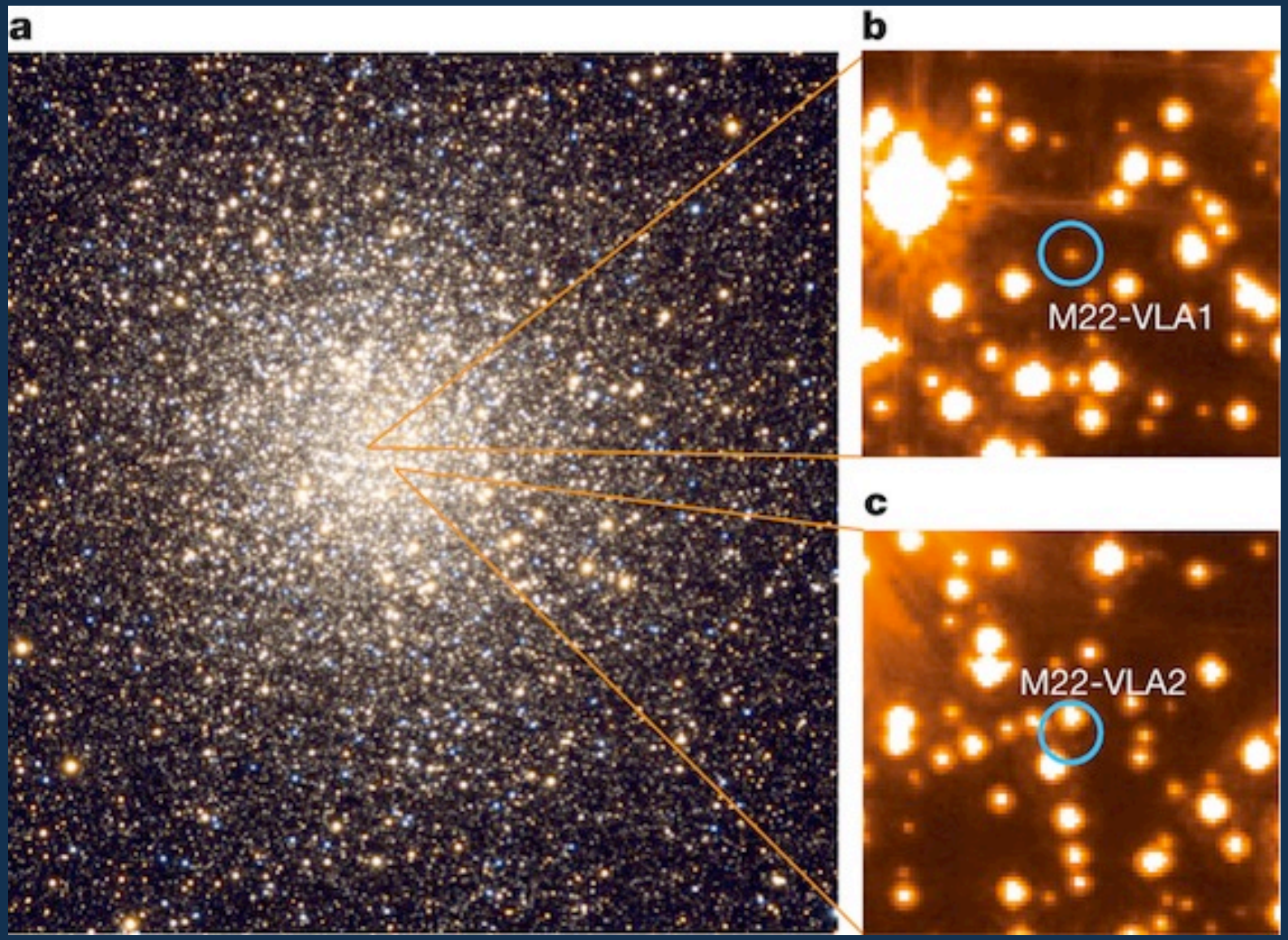
techniques for few-body subsystems

tidal field

[Hurley et al. 2001]

[e.g. Mardling & Aarseth 2001; Mikkola 2006, etc.]

Stellar Mass Black Holes in Globular Clusters



Stellar Mass Black Holes in Globular Clusters

M22 (Strader et al. 2012): two radio sources ➔ accreting stellar-mass BHs (15 $M_\odot$)

➔ 2-40% of BHs in accreting binaries (Ivanova et al. 2010)
➔ ~5-100 BHs in M22

Claim, “all but one predicted to be ejected” … “ejection not as efficient as predicted”
e.g. Kulkarni, Hut & McMillan (1993); Sigurdsson & Hernquist (1993),
Portegies Zwart & McMillan (2000)

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➔“typical cluster will retain between zero and four BHs in the core”
➔ “final number depends on random encounters”
➔ “in systems of intermediate density, some BHs may capture a normal star …”

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(e.g. Aarseth 2012)
➔ BHs form a centralized subsystem on a short timescale: $(r_{BH}/r_c)^2 = m_*/m_{BH}$
➔ BH-BH binaries form, three-body encounters occur
➔ ejections, recoil, mergers
➔ greatly reduced number of BHs well before core collapse
➔ maybe central BH-BH binary remains, maybe no BHs …

M22 not particularly dense (r_c ~ 1.2 pc) and not core-collapsed (t_{rh} ~ 2 Gyr)

Simulations show that significant BH numbers can exist at late times
(e.g. Mackey et al. 2007; Downing 2012; Breen & Heggie 2013)

Stellar Mass Black Holes in Globular Clusters

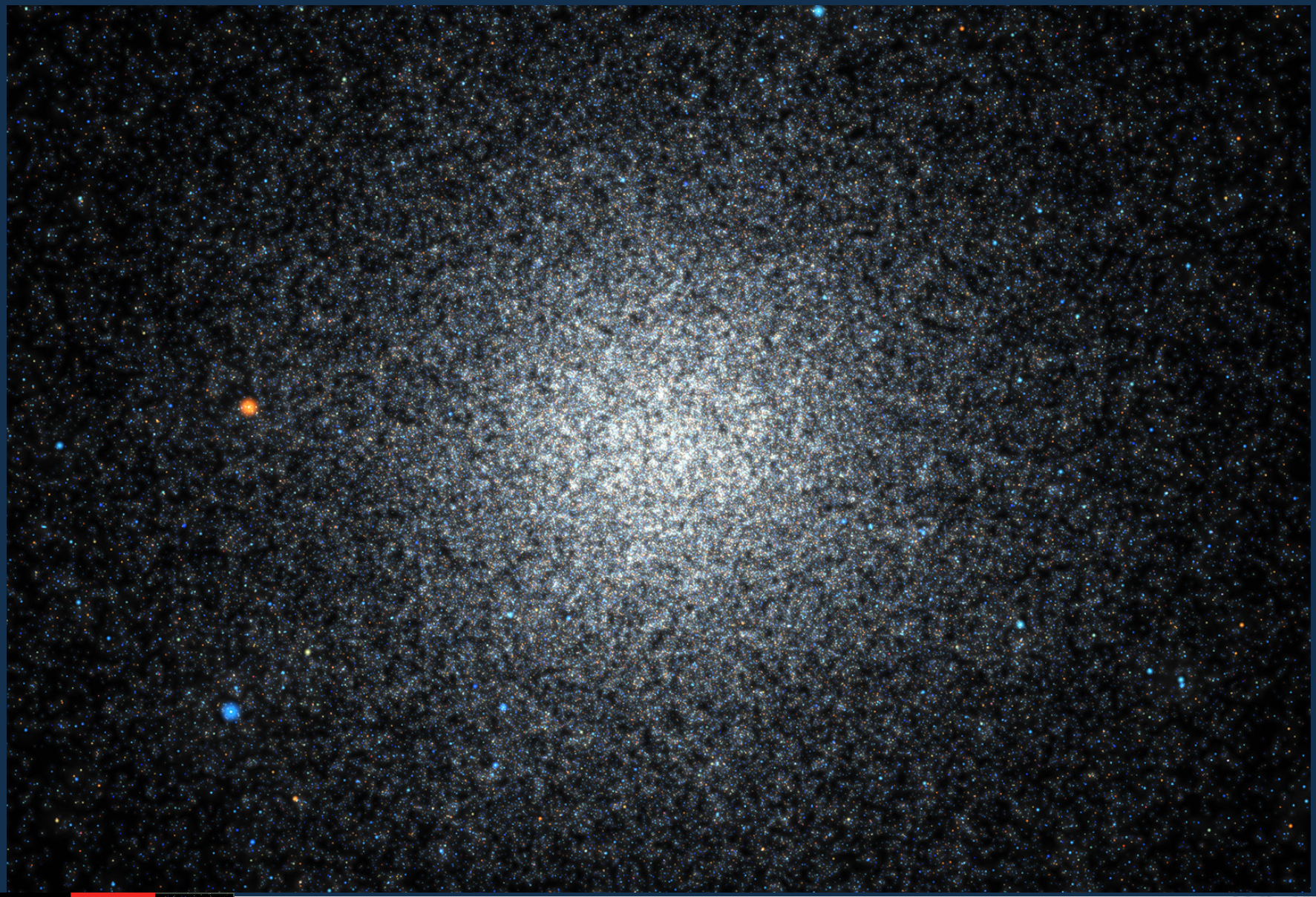
Simulation (Sippel & Hurley 2013)

- ➔ N = 250,000 with 5% binaries
- ➔ M ~ 1.6 x 10^5 $M_\odot$ (0.1 – 50 $M_\odot$)
- ➔ Z = 0.001

- ➔ 3-component galaxy model
- ➔ d_{gc} = 8.5 kpc, r_t ~ 50 pc

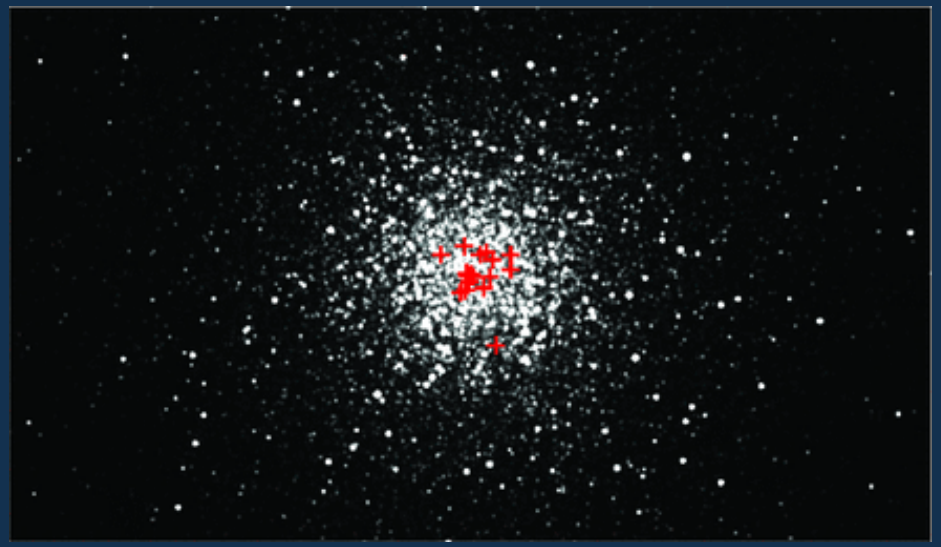
- ➔ 180,000 stars remaining at 12 Gyr

Stellar Mass Black Holes in Globular Clusters



Stellar Mass Black Holes in Globular Clusters

~450 BHs formed ➔ 48 retained after kicks ➔ 16 remain at 12 Gyr



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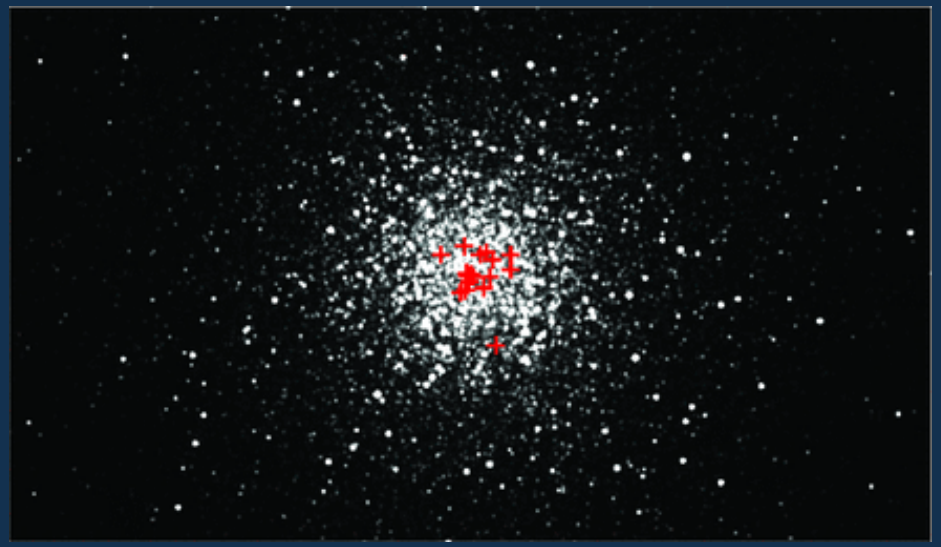

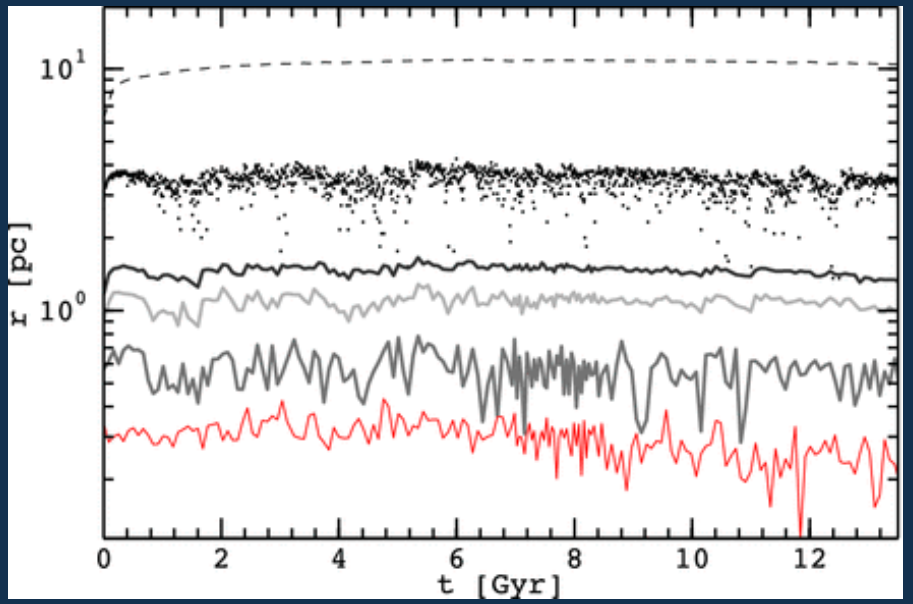

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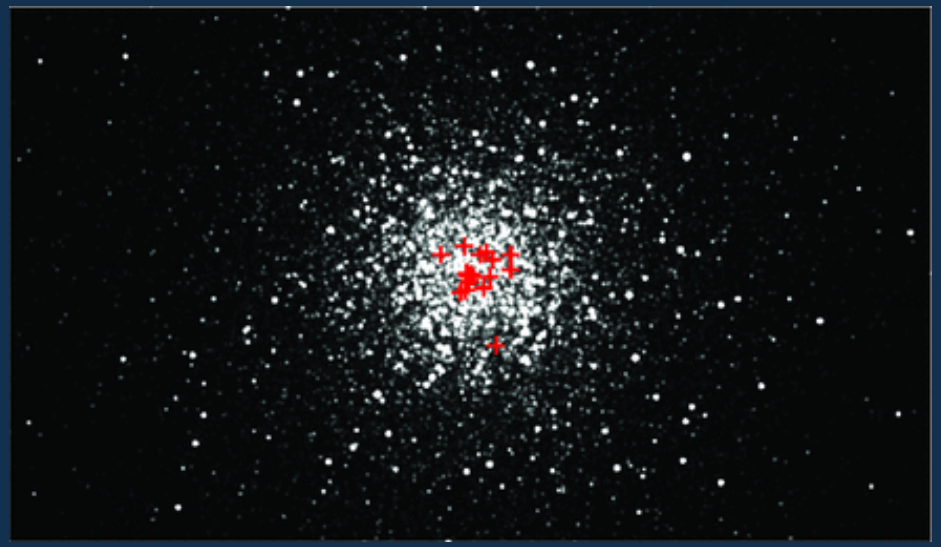

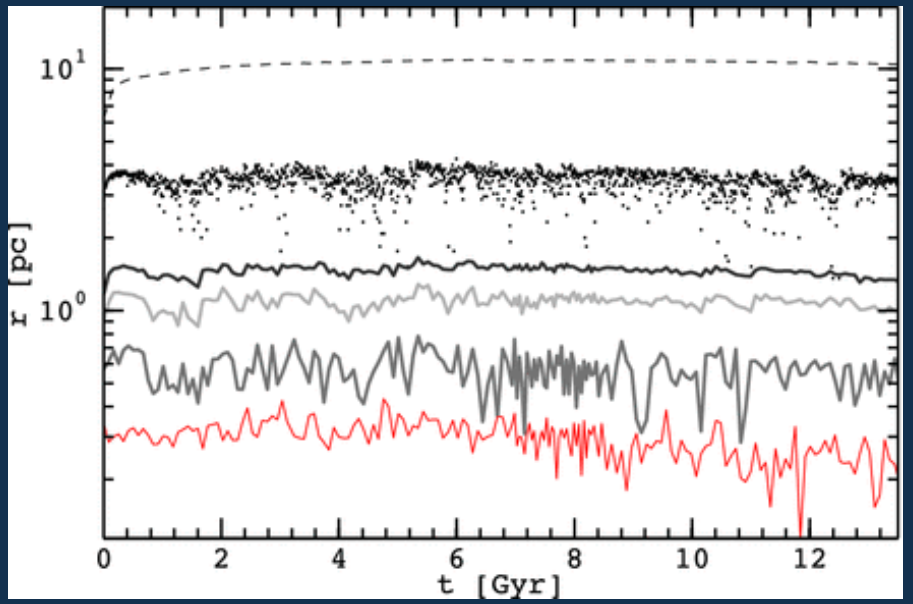

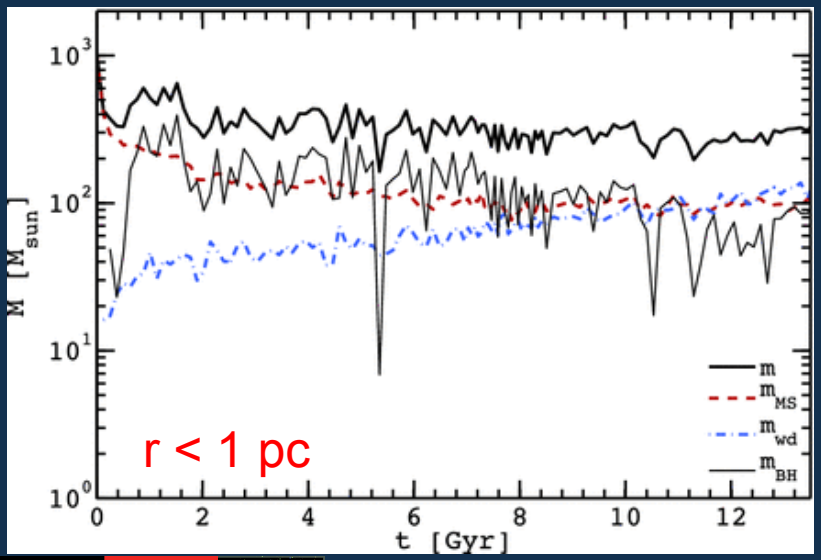

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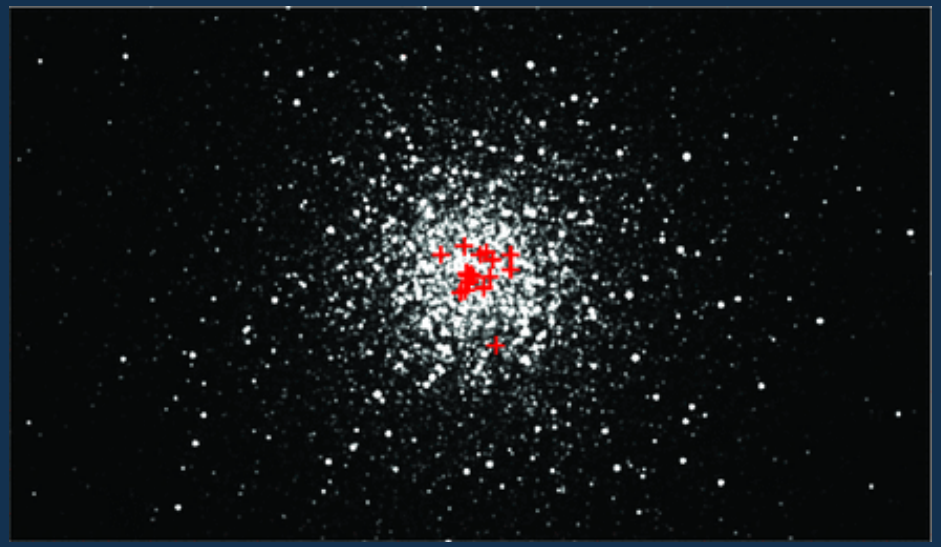

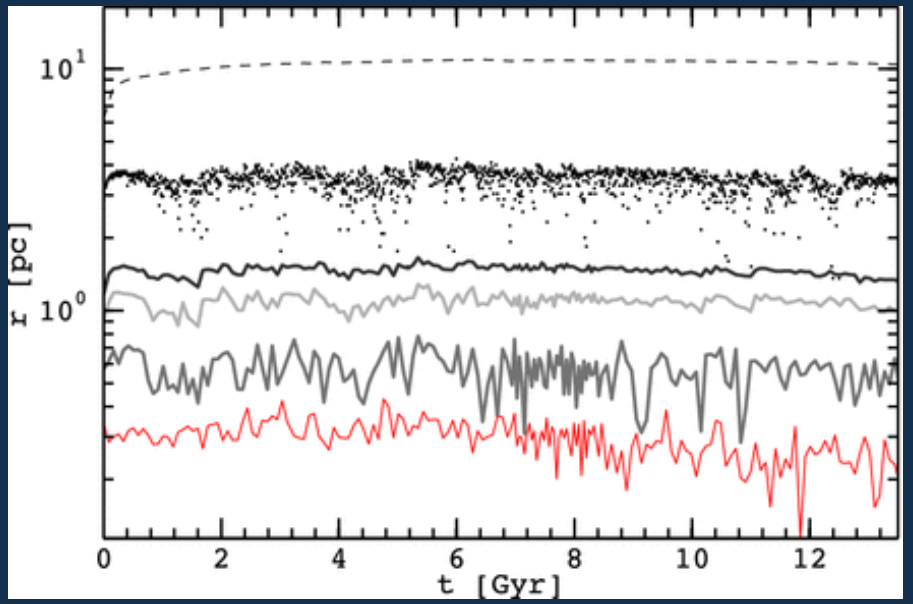

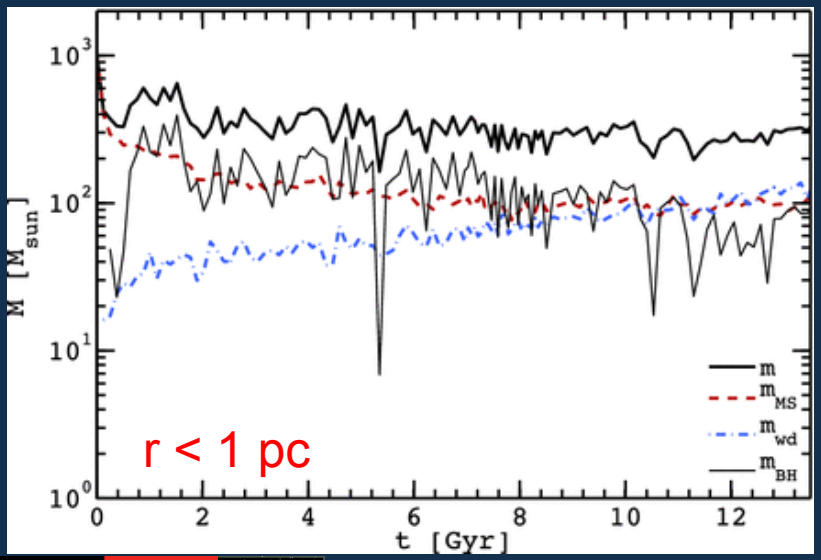

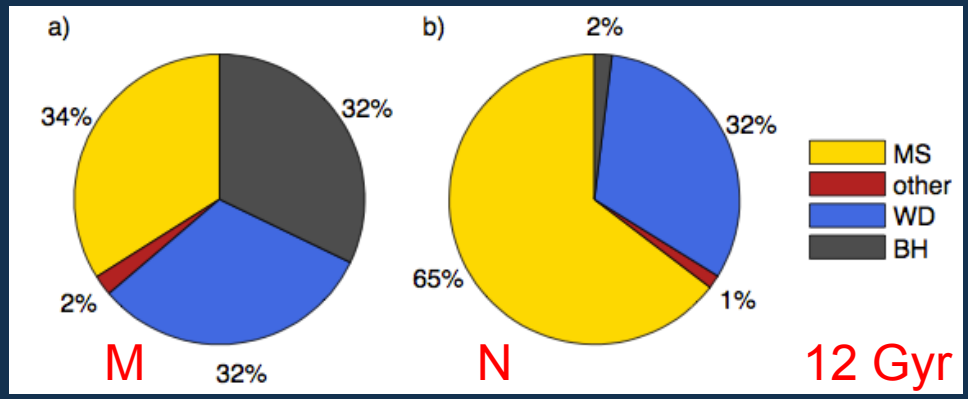

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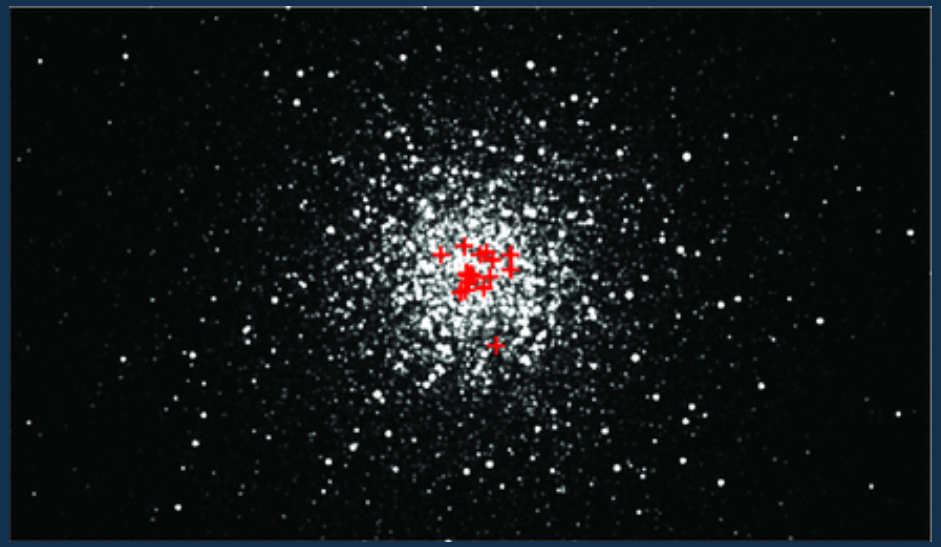

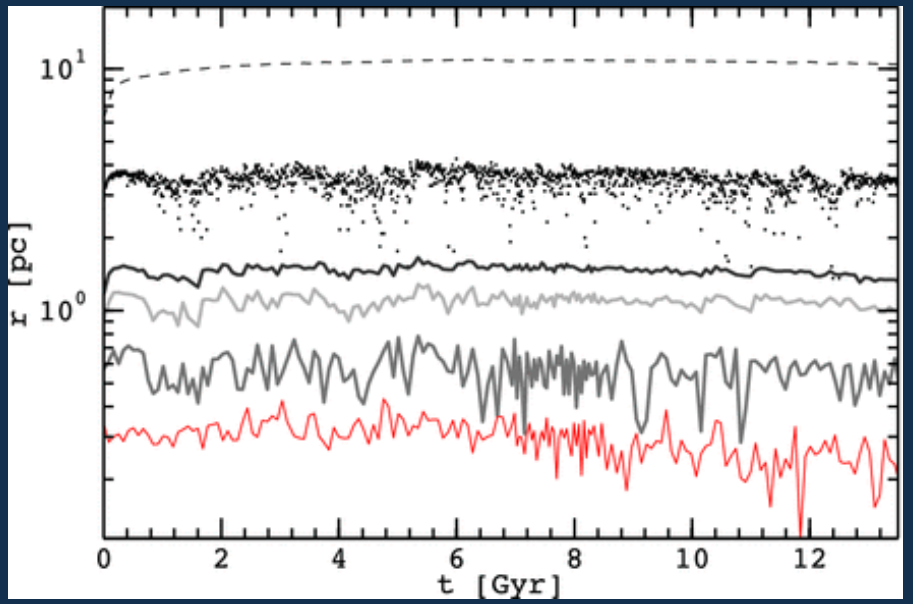

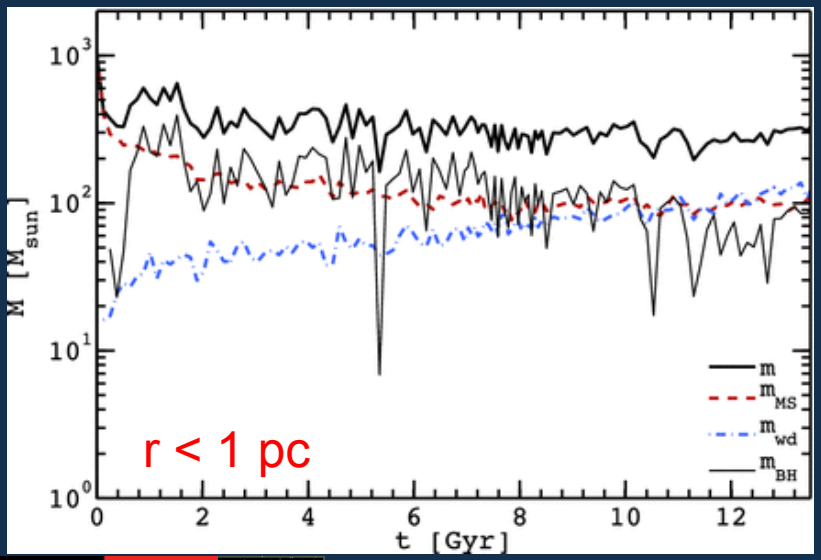

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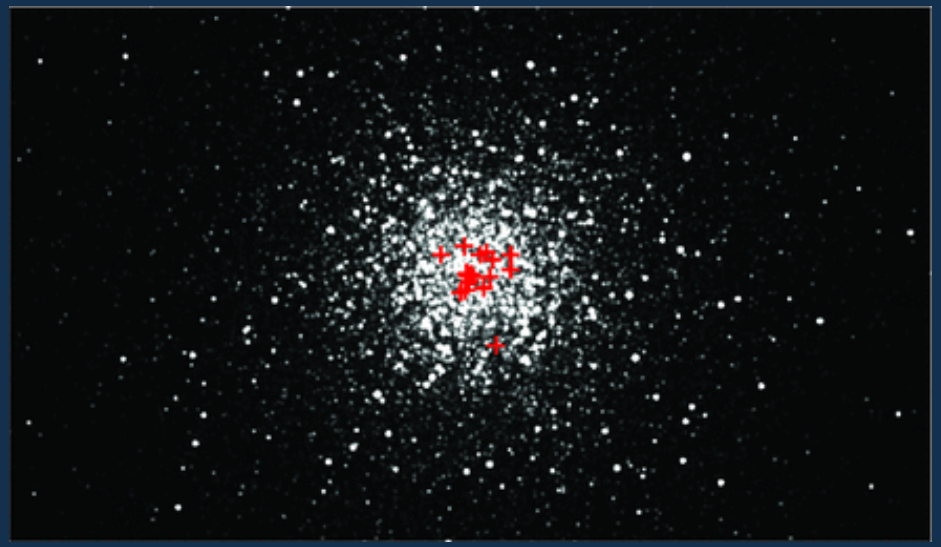

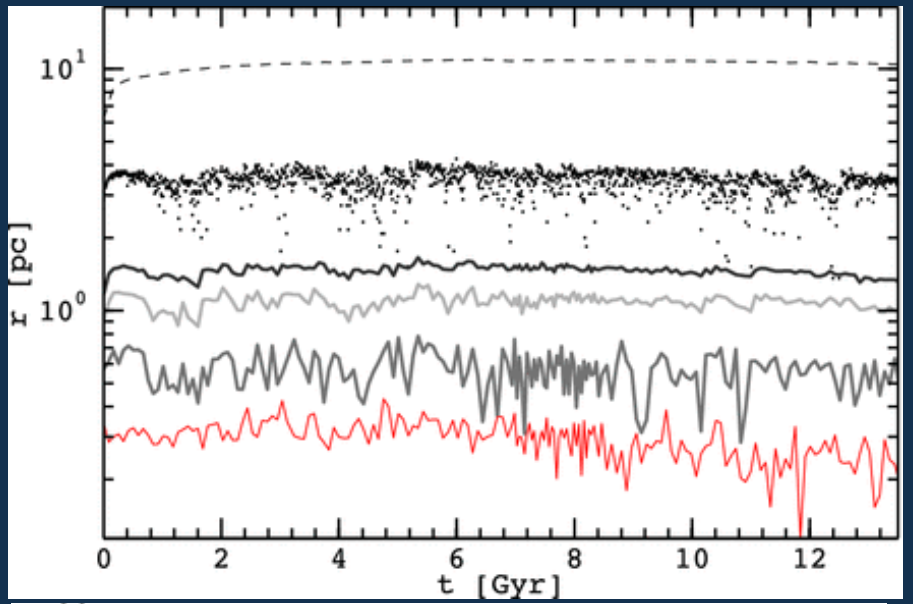

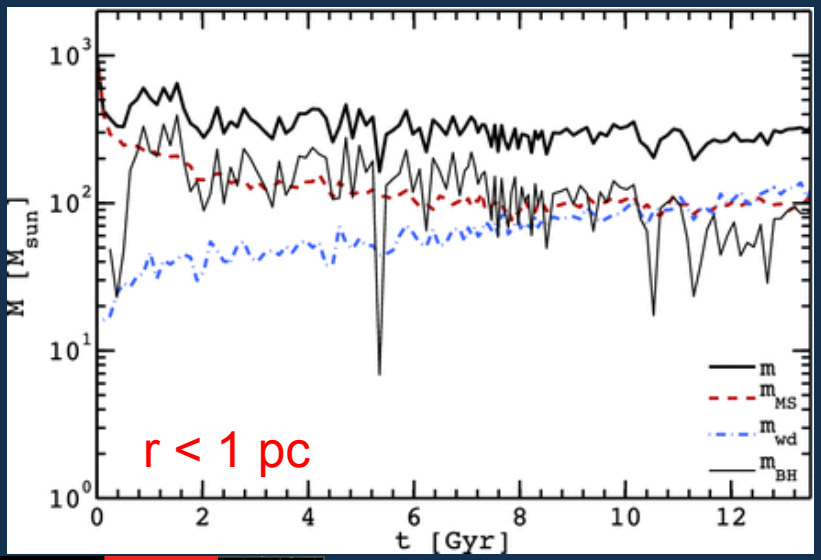

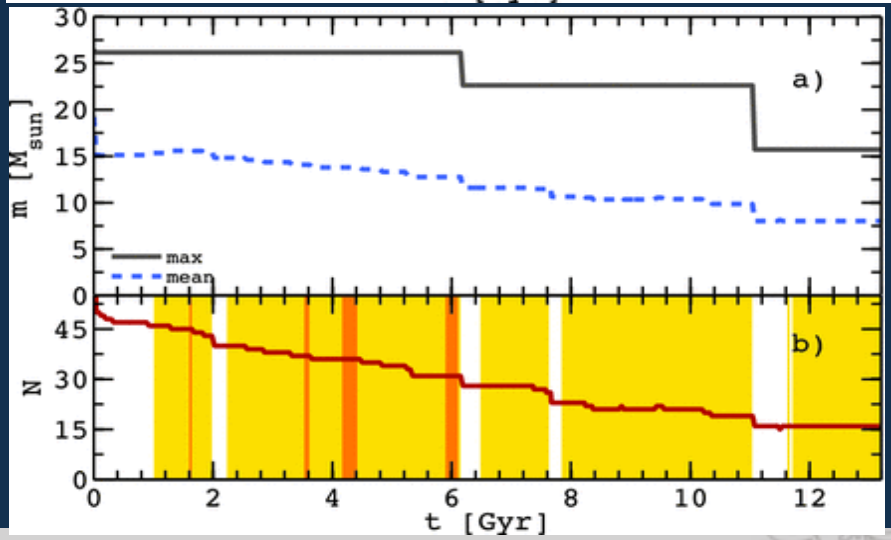

Stellar Mass Black Holes in Globular Clusters

Simulation (Hurley & Shara 2012): N = 200,000 at d_{gc} = 3.9 pc

➔ core-collapse at 10.5 Gyr, N ~ 30,000

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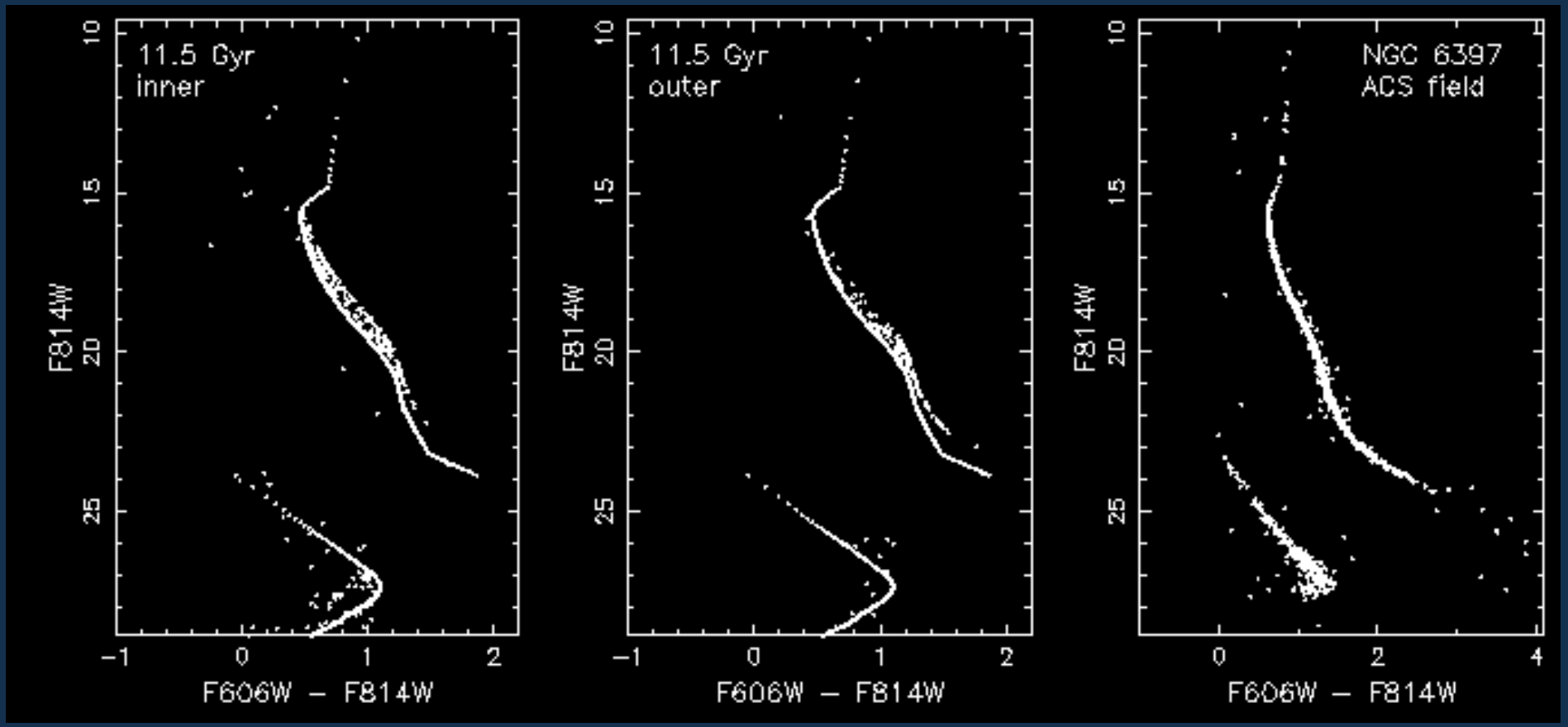

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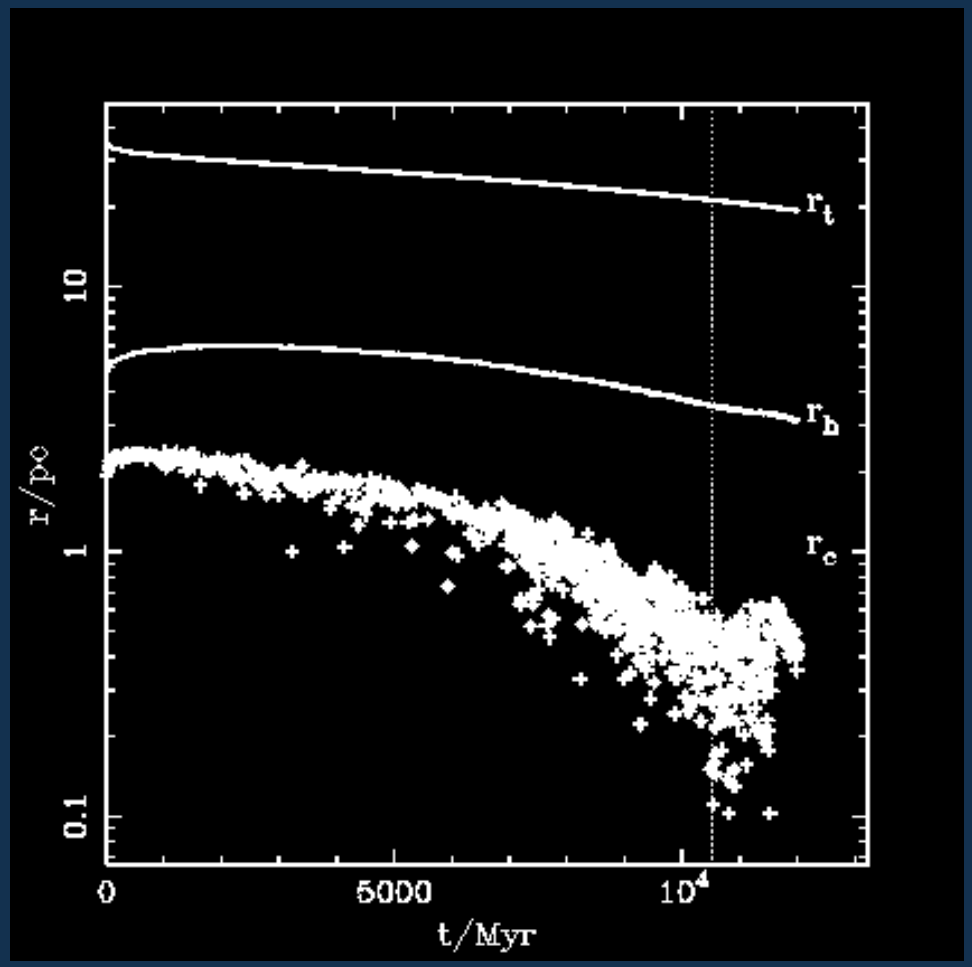

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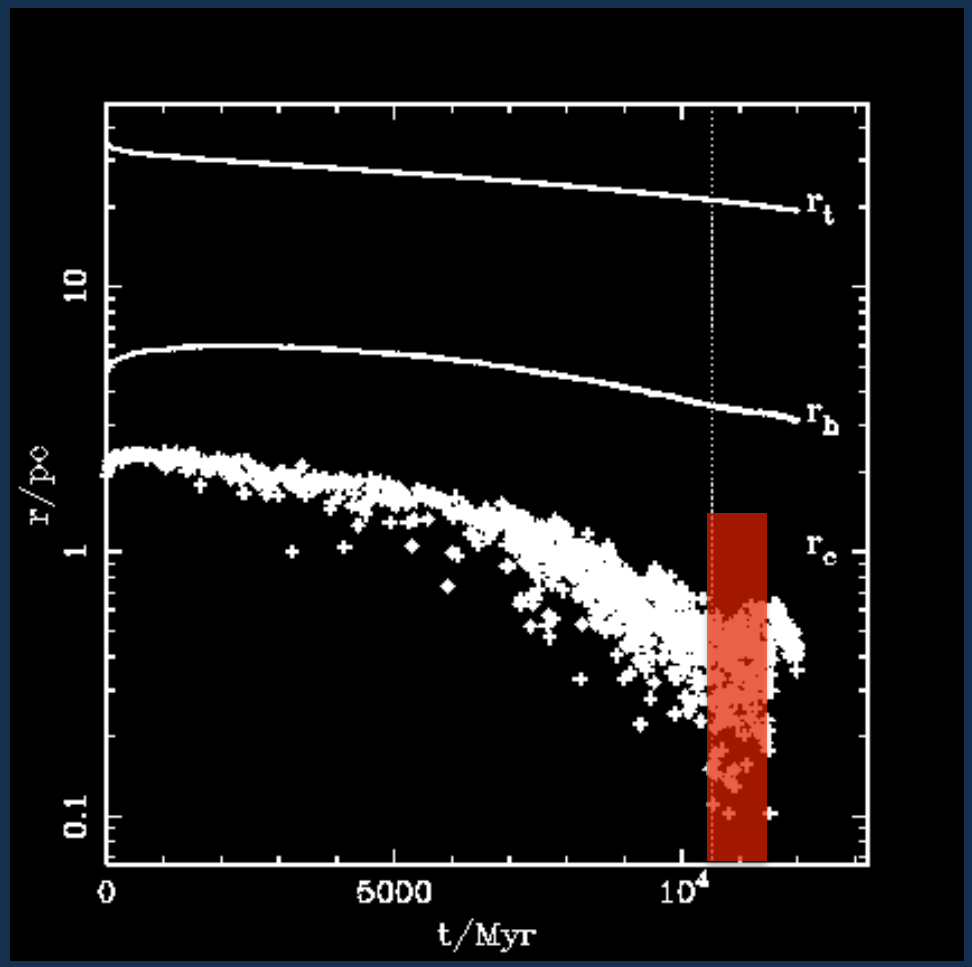

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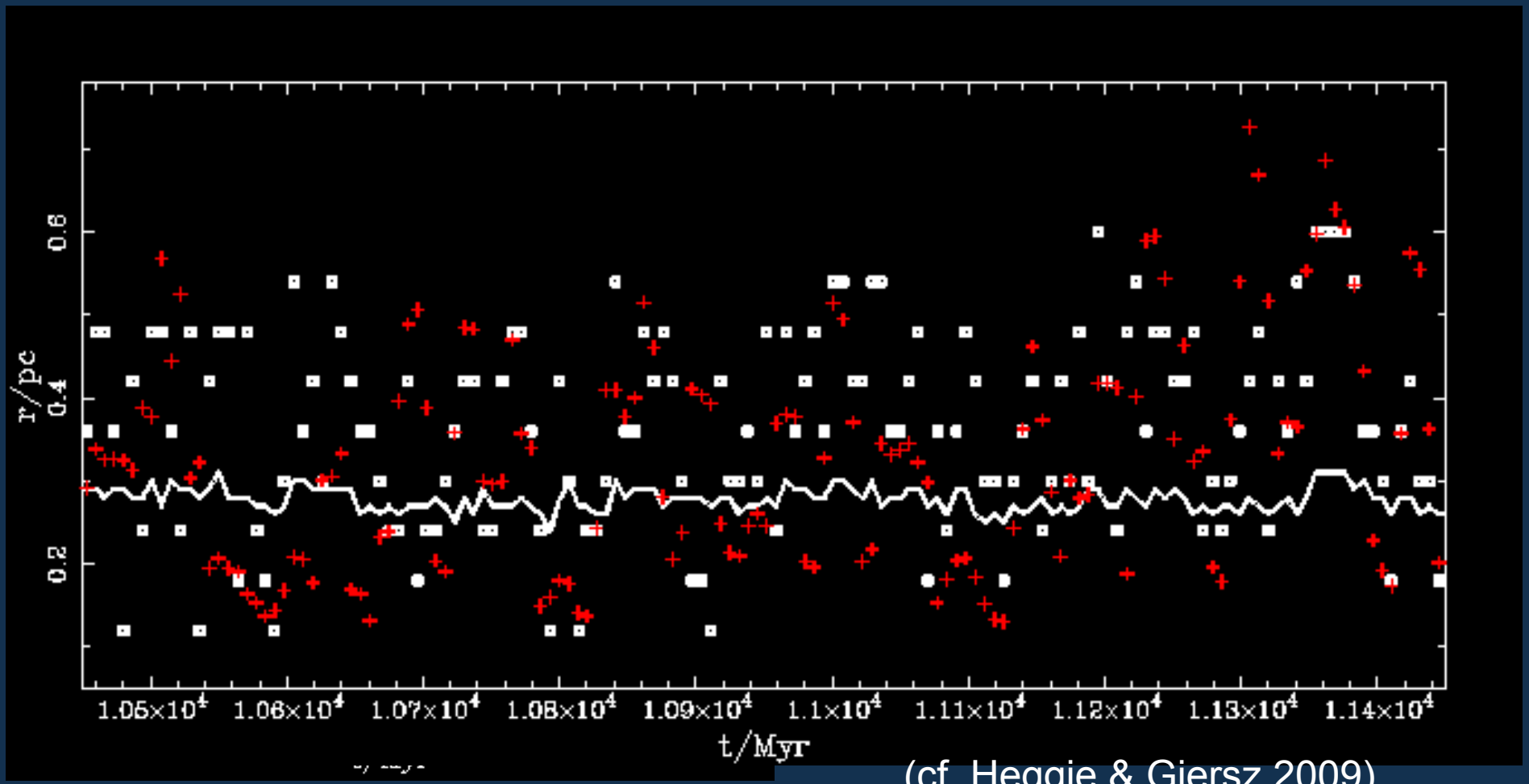

(cf. Heggie & Giersz 2009)

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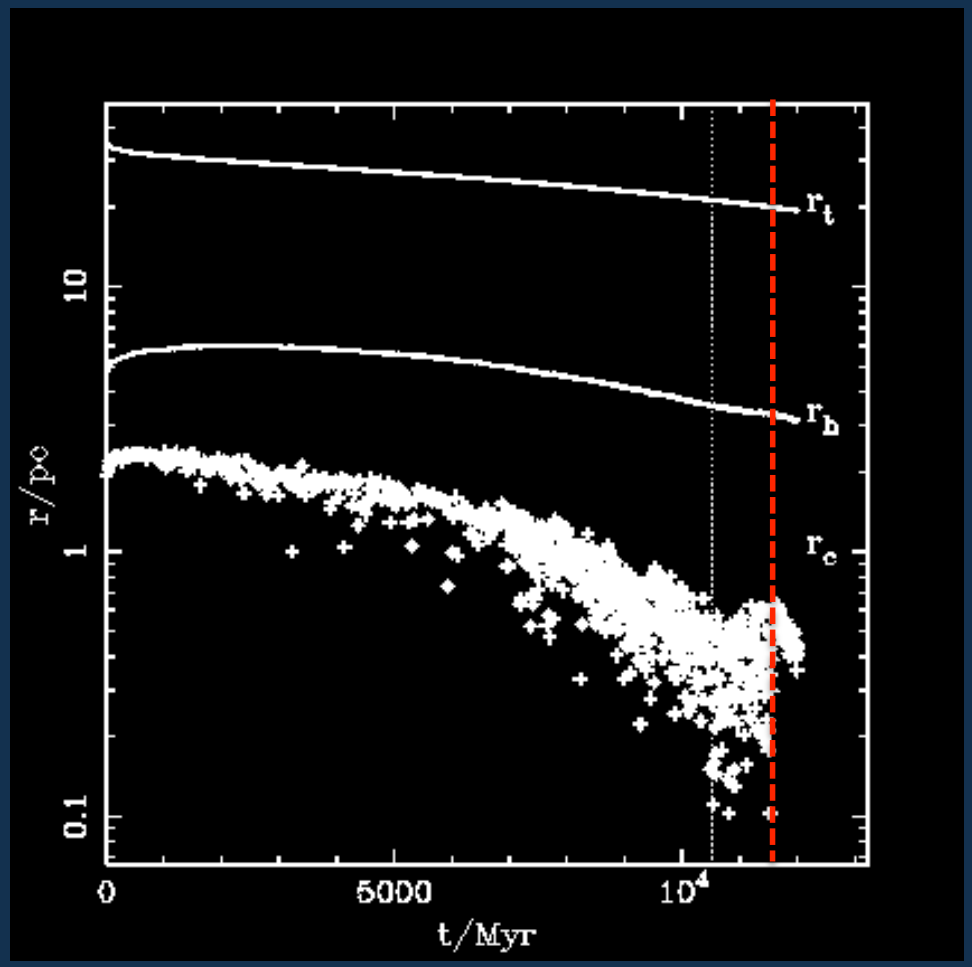

BH-BH binary (13 d) at 11.5 Gyr

4-body interaction

Recoils out of core & cluster

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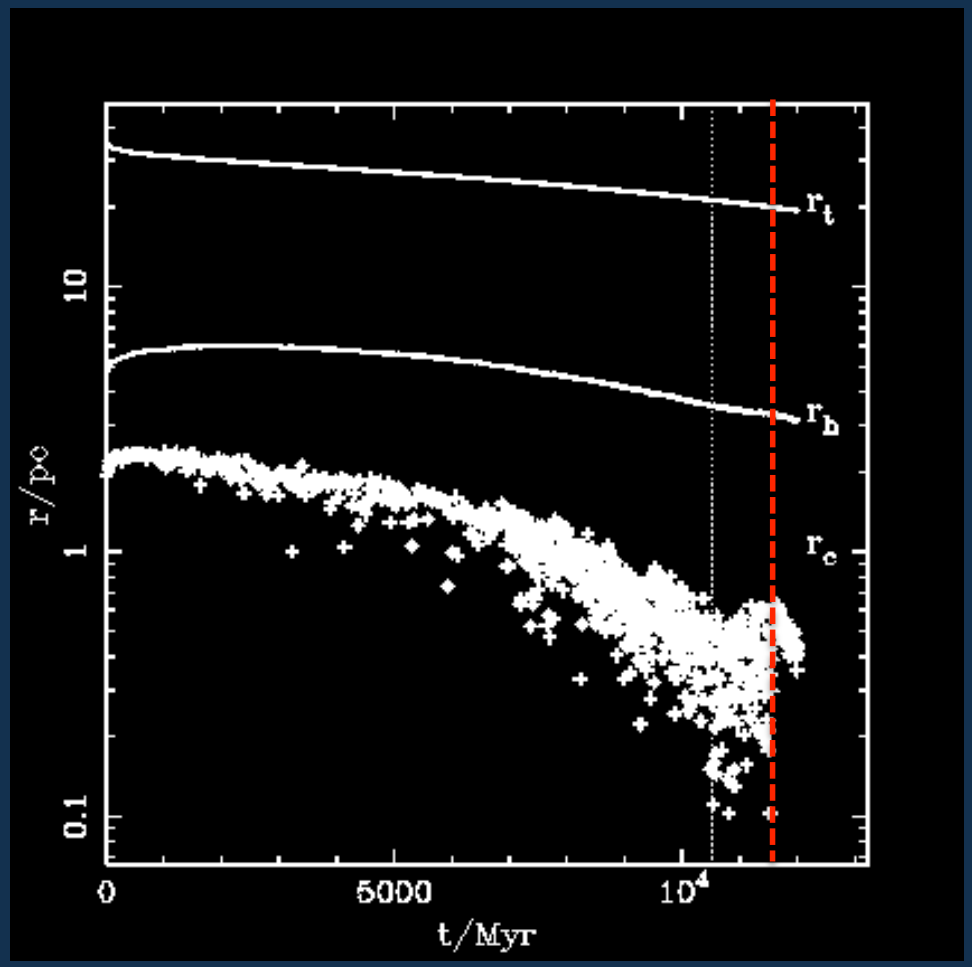

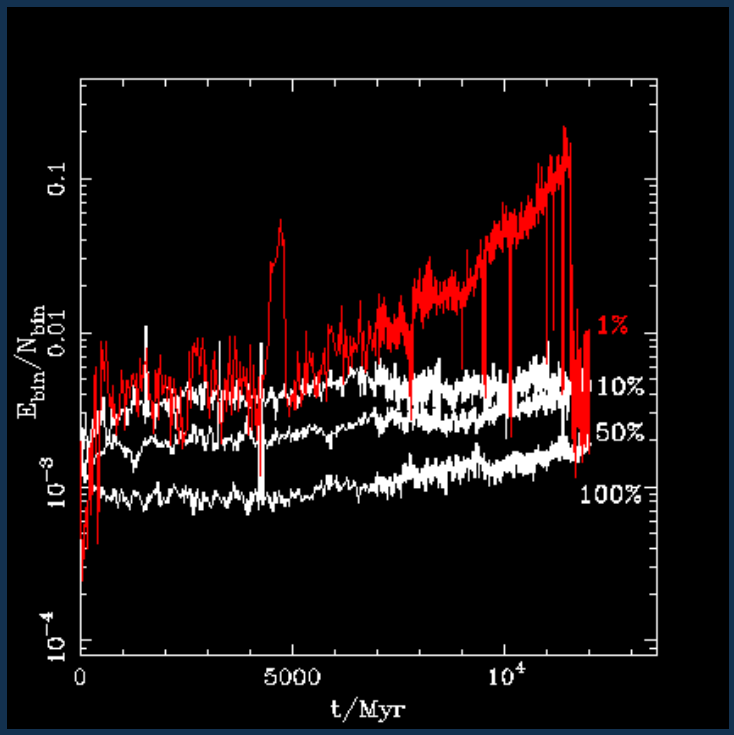

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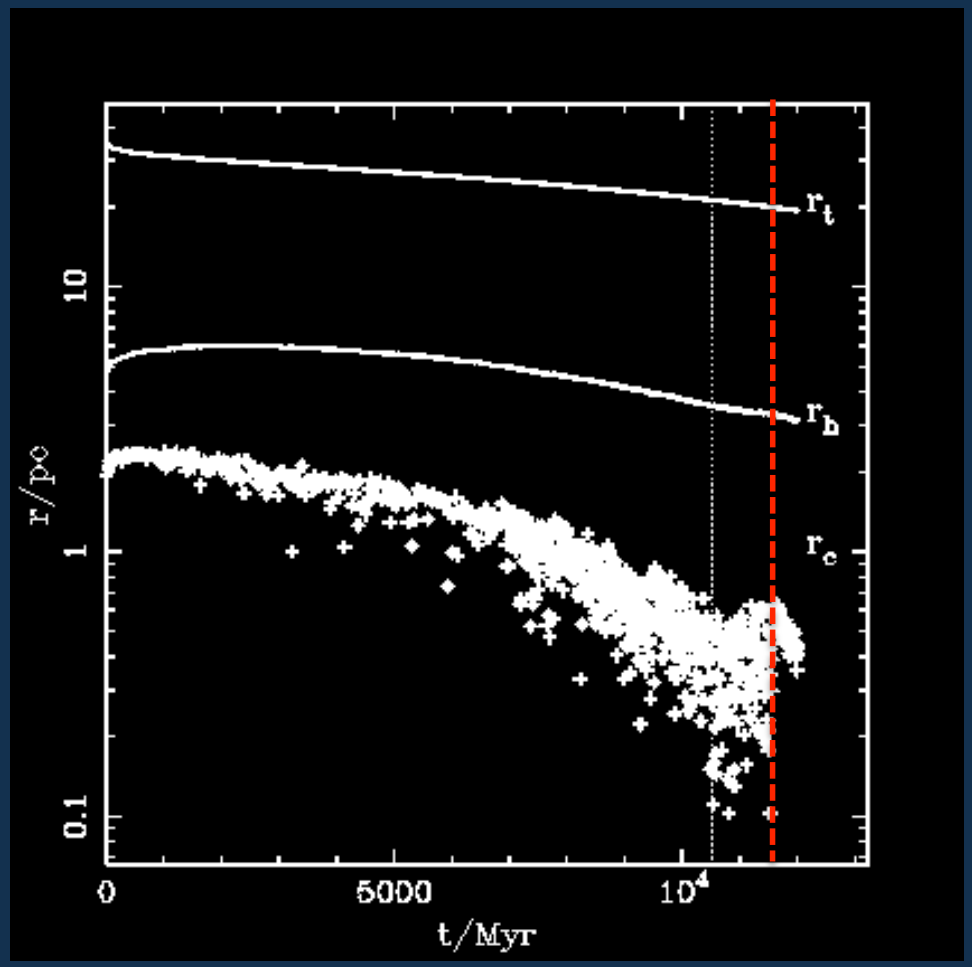

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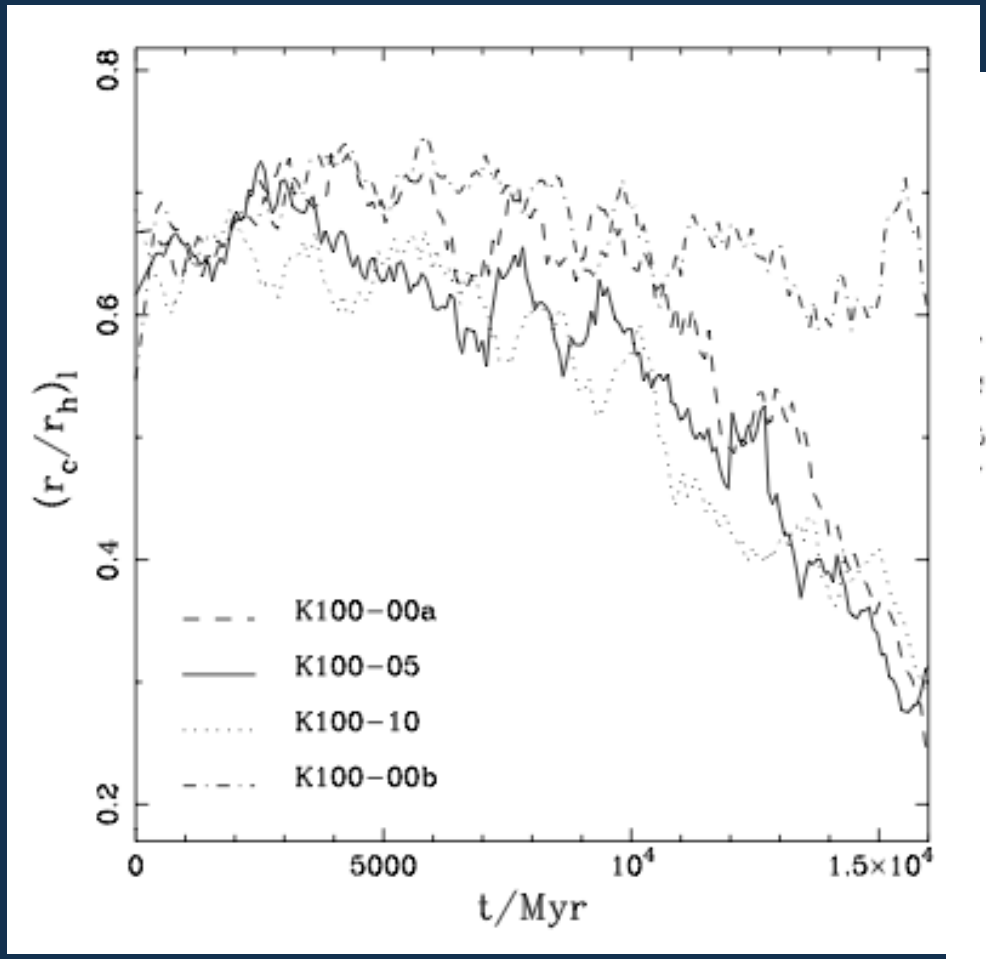
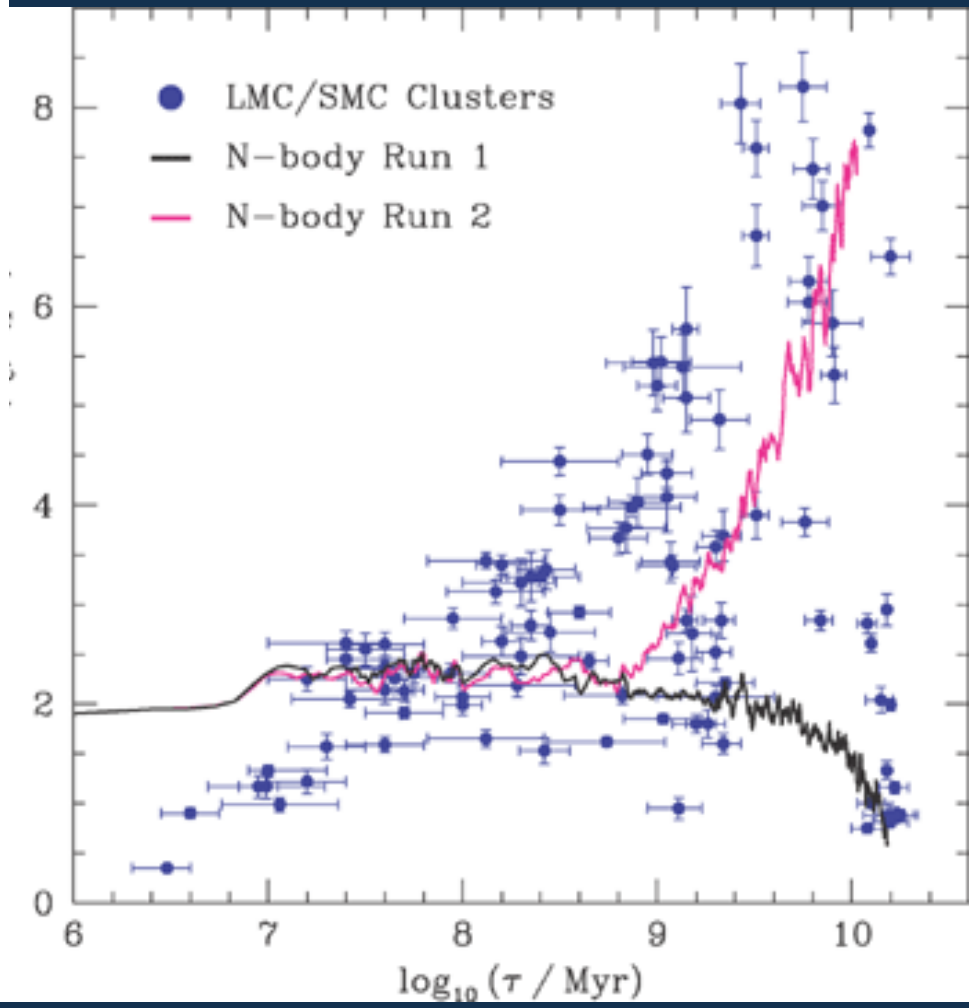
No BHs at 12 Gyr

R_c/R_h ratio evolution



Hurley (2007)

Mackey et al. (2007)
-> many BH-BH binaries



Binaries in NGC1818

de Grijs et al. (2013)

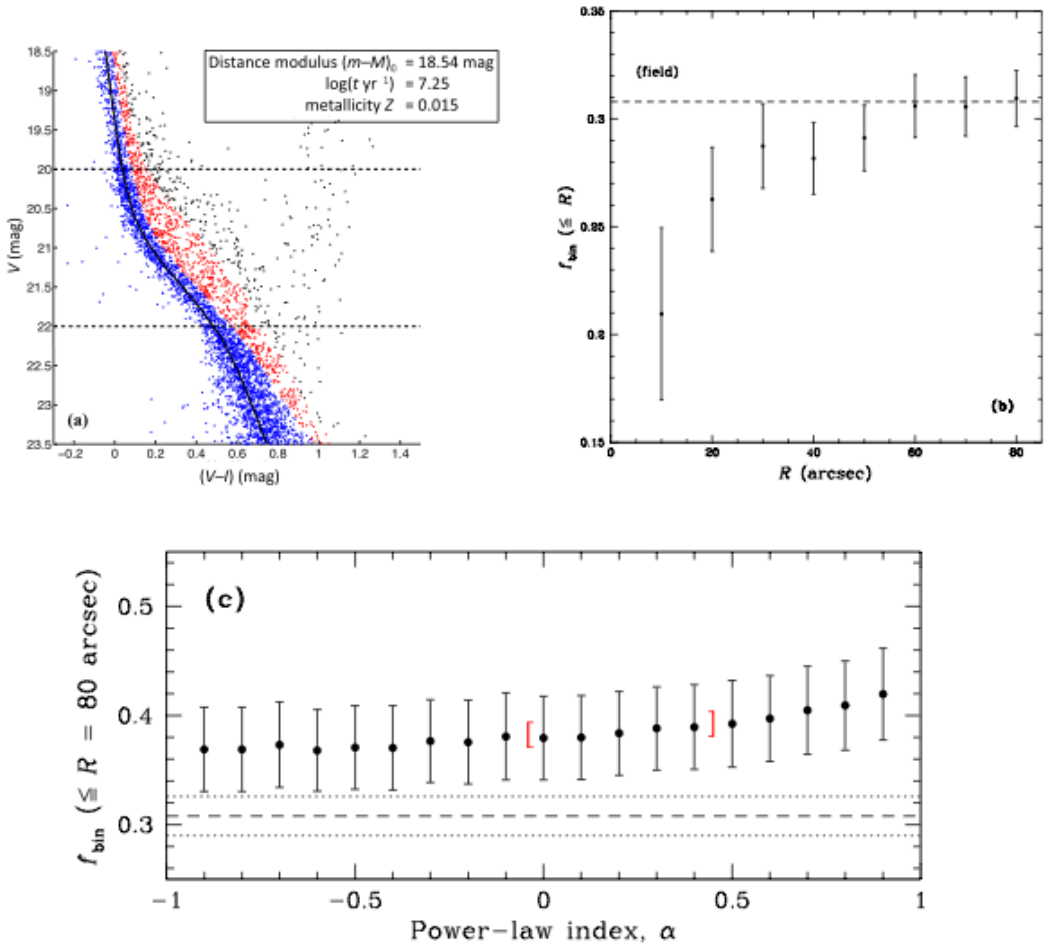


Figure 3. (a) NGC 1818 CMD, including the best-fitting isochrone (parameters indicated), where we have indicated the regions used for our poor man's approach. Blue: single-star area, red: "binaries," black: discarded stars outside our selection regions. (b) Cumulative binary fraction in NGC 1818 as a function of radius from the cluster center, based on our isochrone-fitting approach. (c) Total binary fraction as a function of power-law index, α, adopted for the full cluster region within $R = 80''$ and for binary systems characterized by $q \gtrsim 0.55$. The dashed and dotted lines indicate the (lower limit to the) binary fraction and the 1σ error bars, respectively, obtained from our isochrone-fitting approach. The (red) square brackets indicate the range in α adopted.

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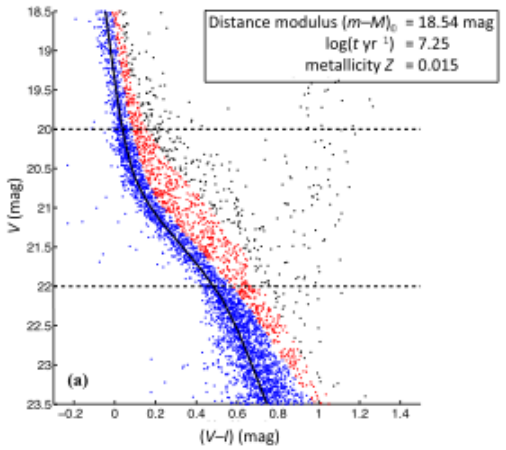
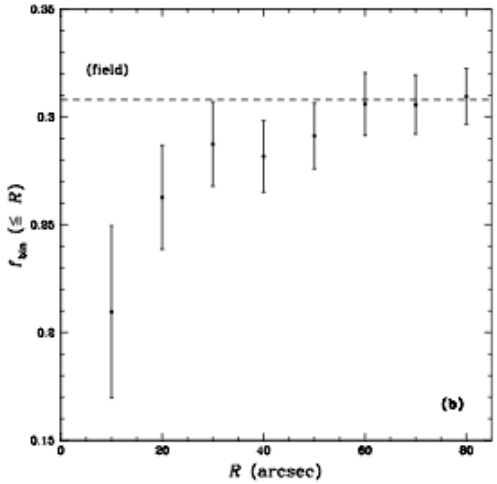
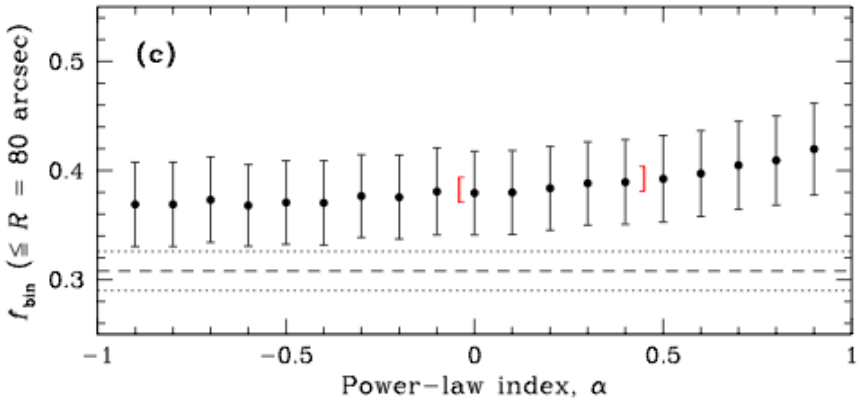






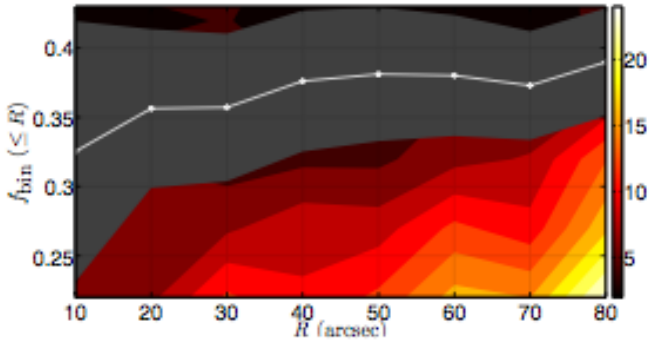
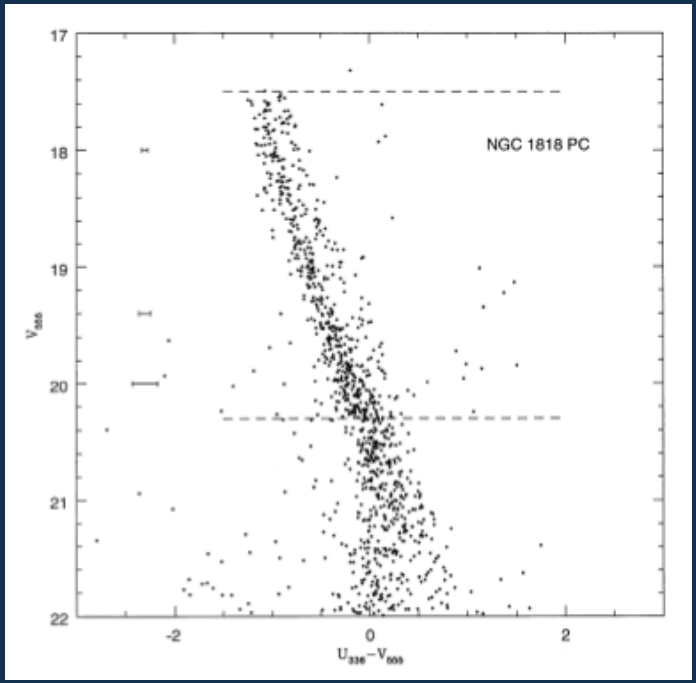
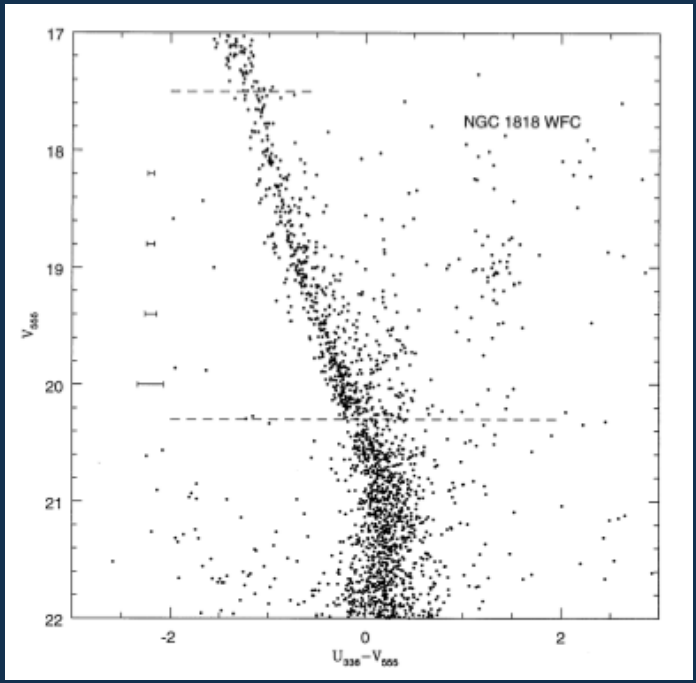


Figure 3. (a) NGC 1818 CMD, including the best-fitting isochrone (parameters indicated), where we have indicated the regions used for our poor man's approach. Blue: single-star area, red: "binaries," black: discarded stars outside our selection regions. (b) Cumulative binary fraction in NGC 1818 as a function of radius from the cluster center, based on our isochrone-fitting approach. (c) Total binary fraction as a function of power-law index, α, adopted for the full cluster region within $R = 80''$ and for binary systems characterized by $q \gtrsim 0.55$. The dashed and dotted lines indicate the (lower limit to the) binary fraction and the 1σ error bars, respectively, obtained from our isochrone-fitting approach. The (red) square brackets indicate the range in α adopted.

Binaries in NGC1818

Elson et al. (1998)





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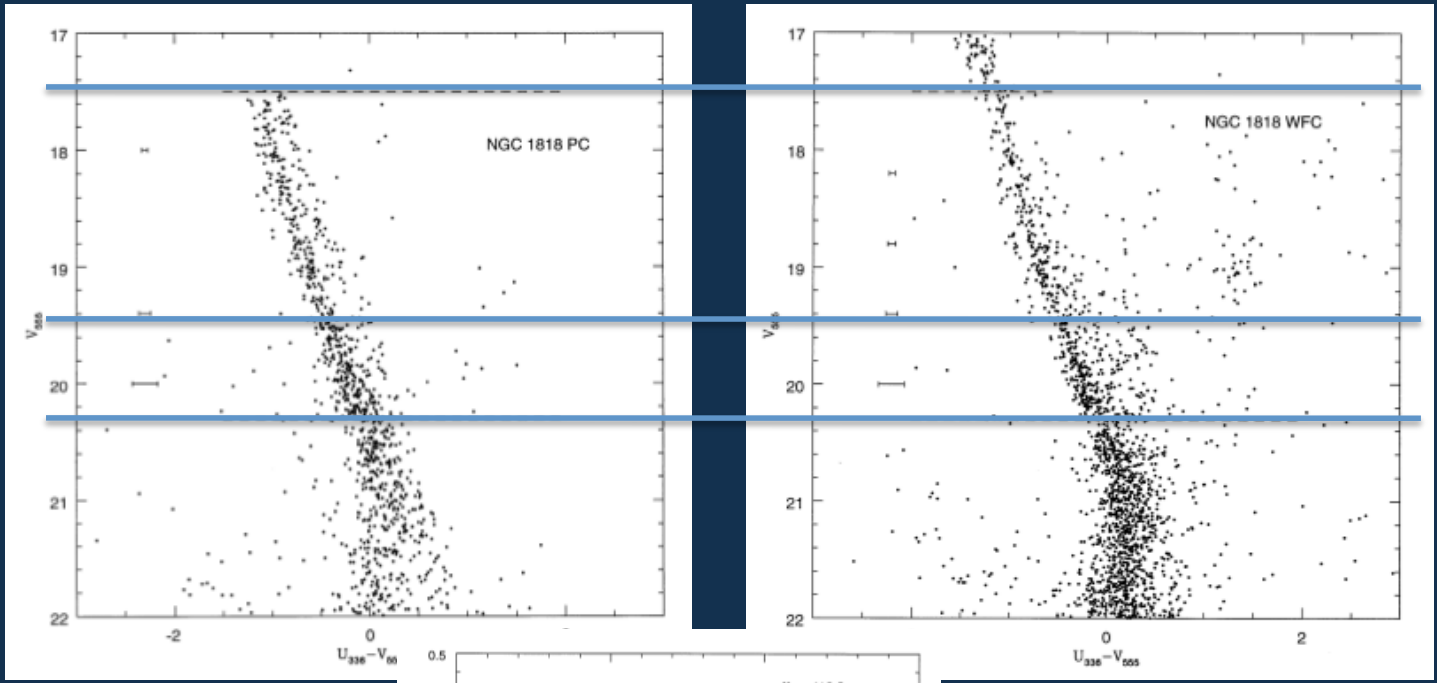

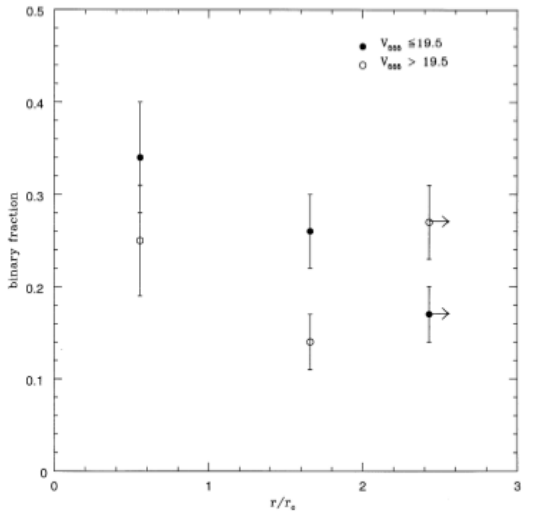

Binaries in NGC1818

NBODY4 simulation (Elson et al. 1998):

- ➔ N = 15,000
- ➔ M ~ 8.5 x 10^3 $M_\odot$
- ➔ 2,500 binaries (q > 0.5, no soft)
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NGC1818

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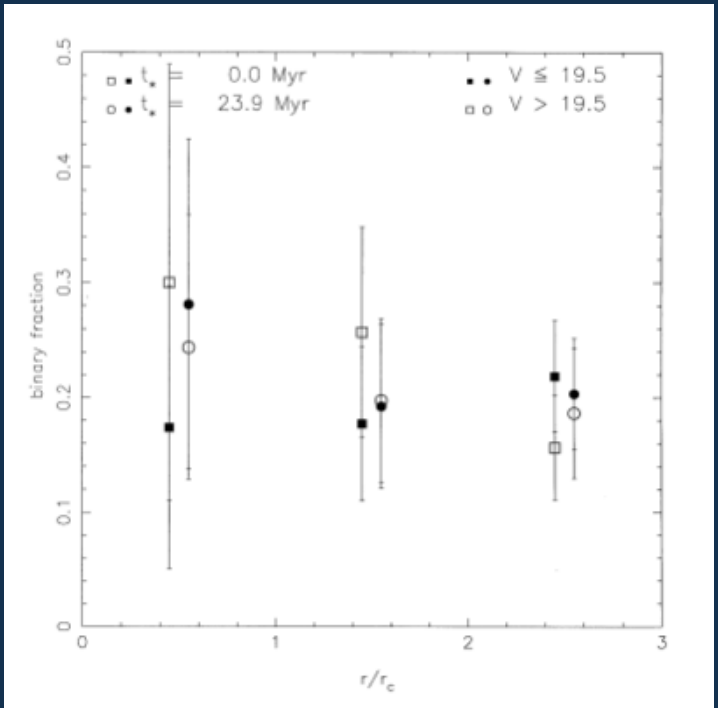

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Q	D	R_V (pc)	N_{sims}	P_{obs} (%)
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0.5	1.6	11	2	34.5
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0.3	2.6	9	2	87.2
0.3	2.0	10	2	73.3
0.3	1.6	11	2	90.6
0.1	3.0	10	10	9.82
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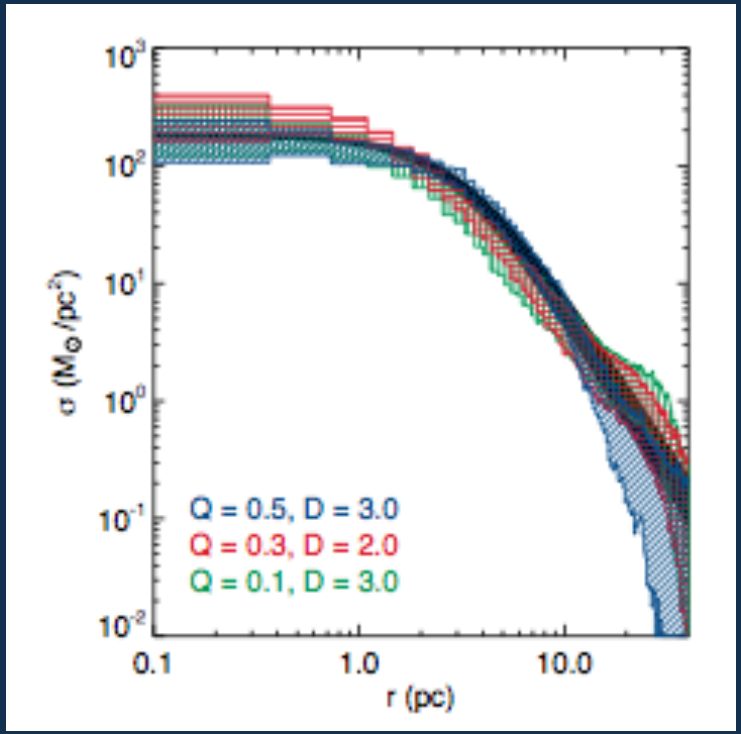

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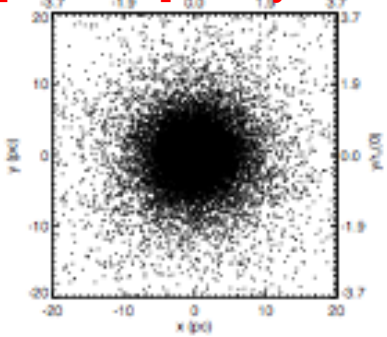
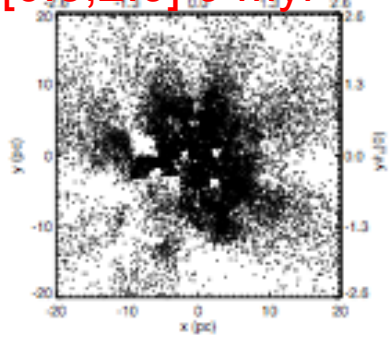
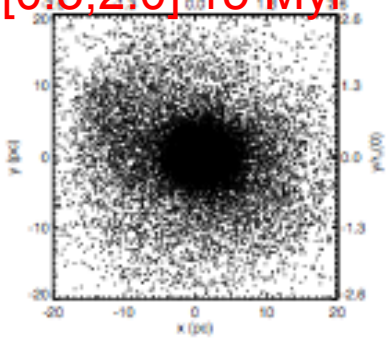
[0.5,3.0] 0 Myr



[0.3,2.0] 0 Myr



[0.3,2.0] 15 Myr



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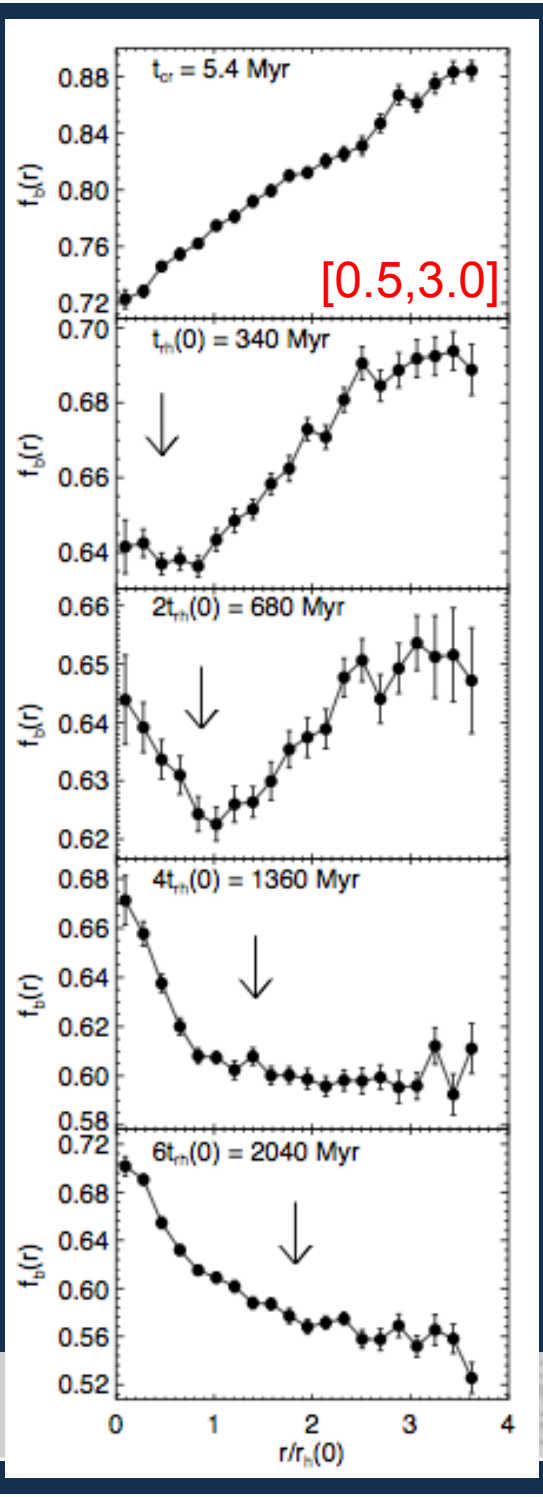

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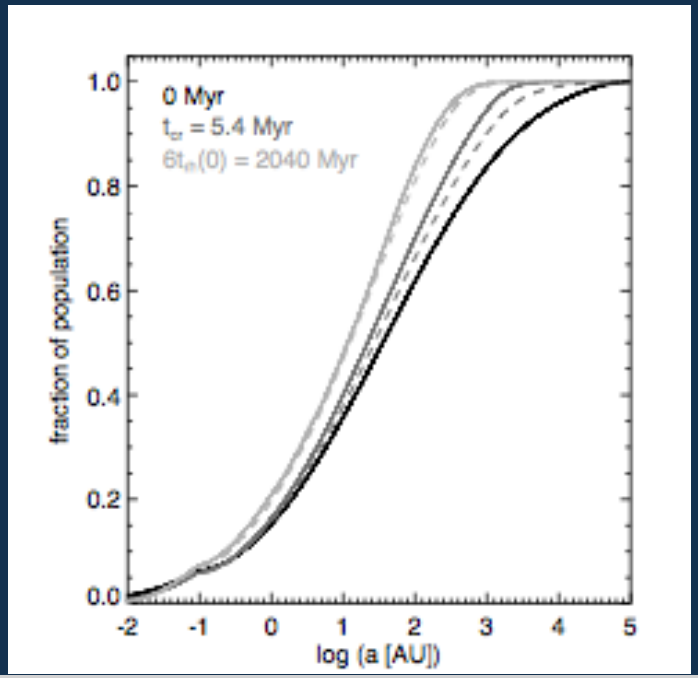

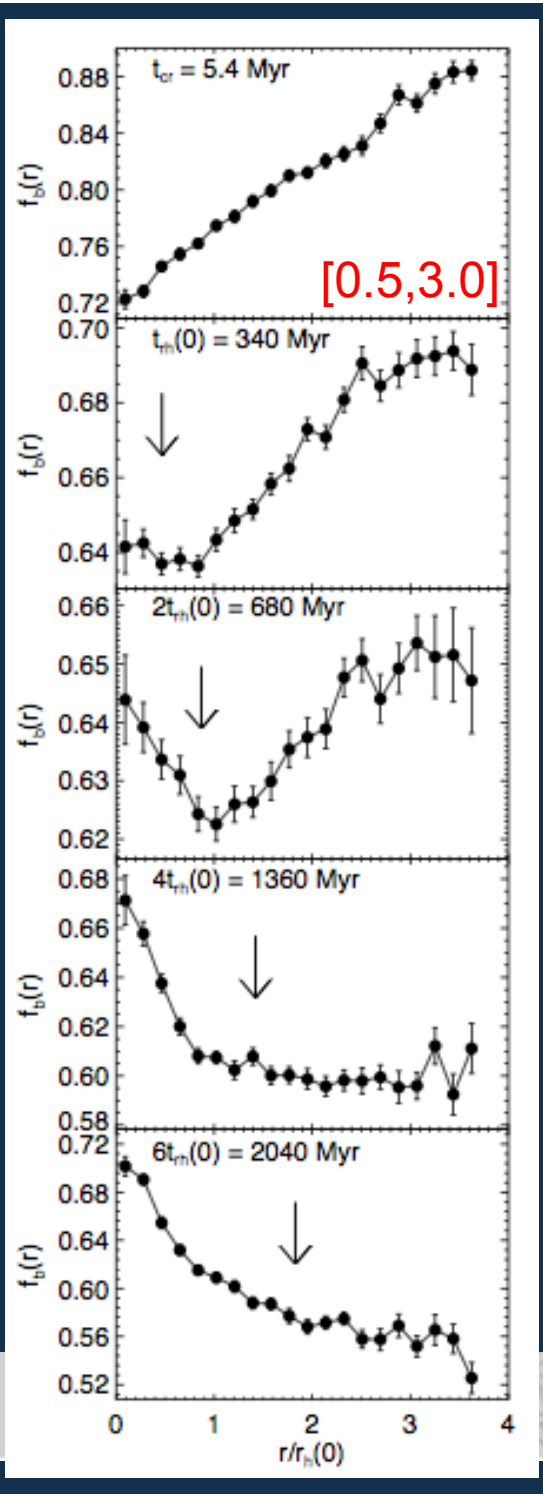

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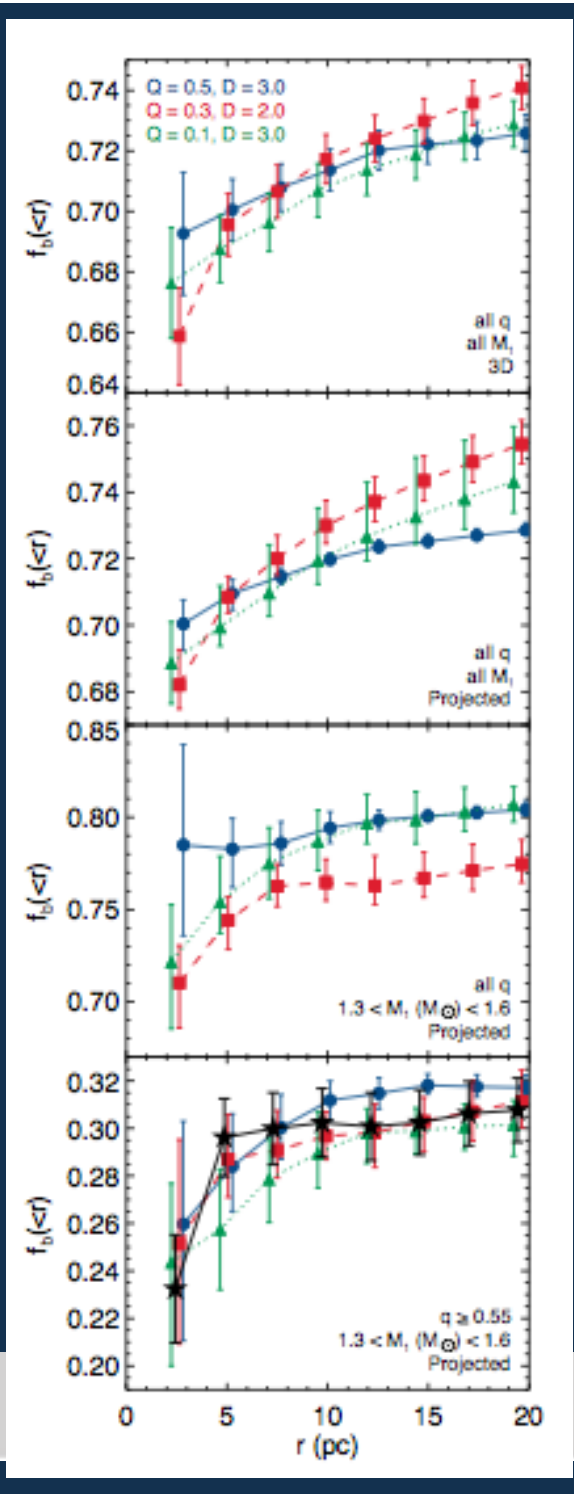

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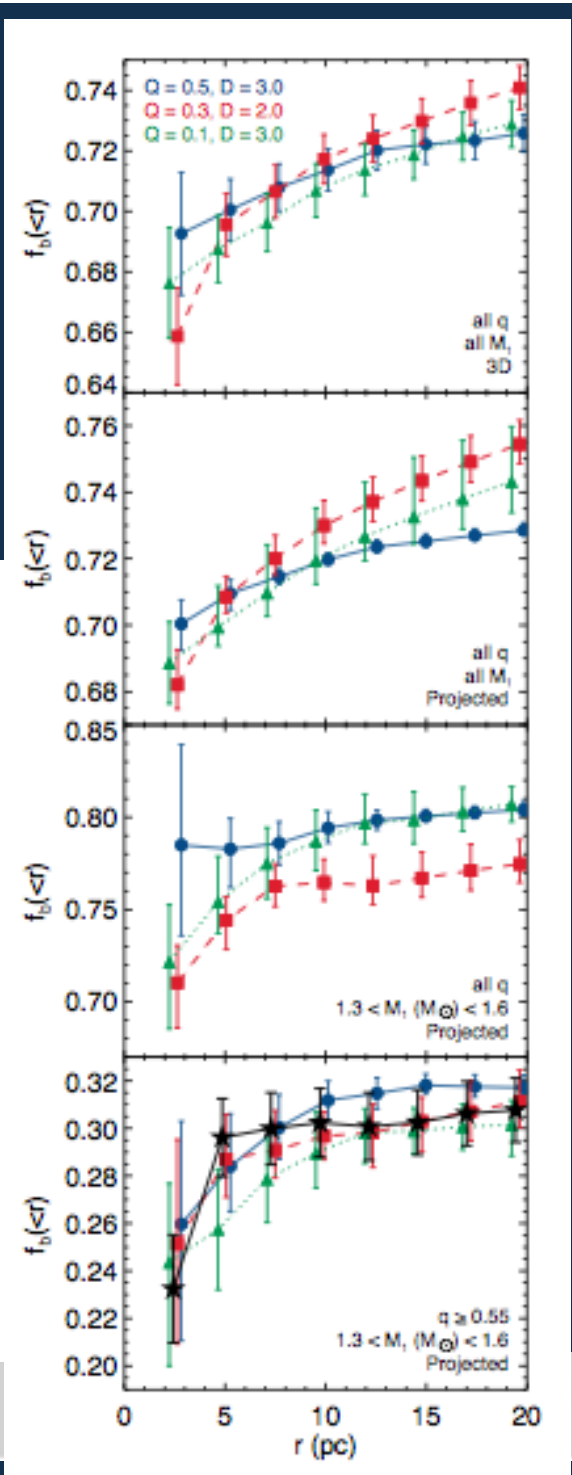
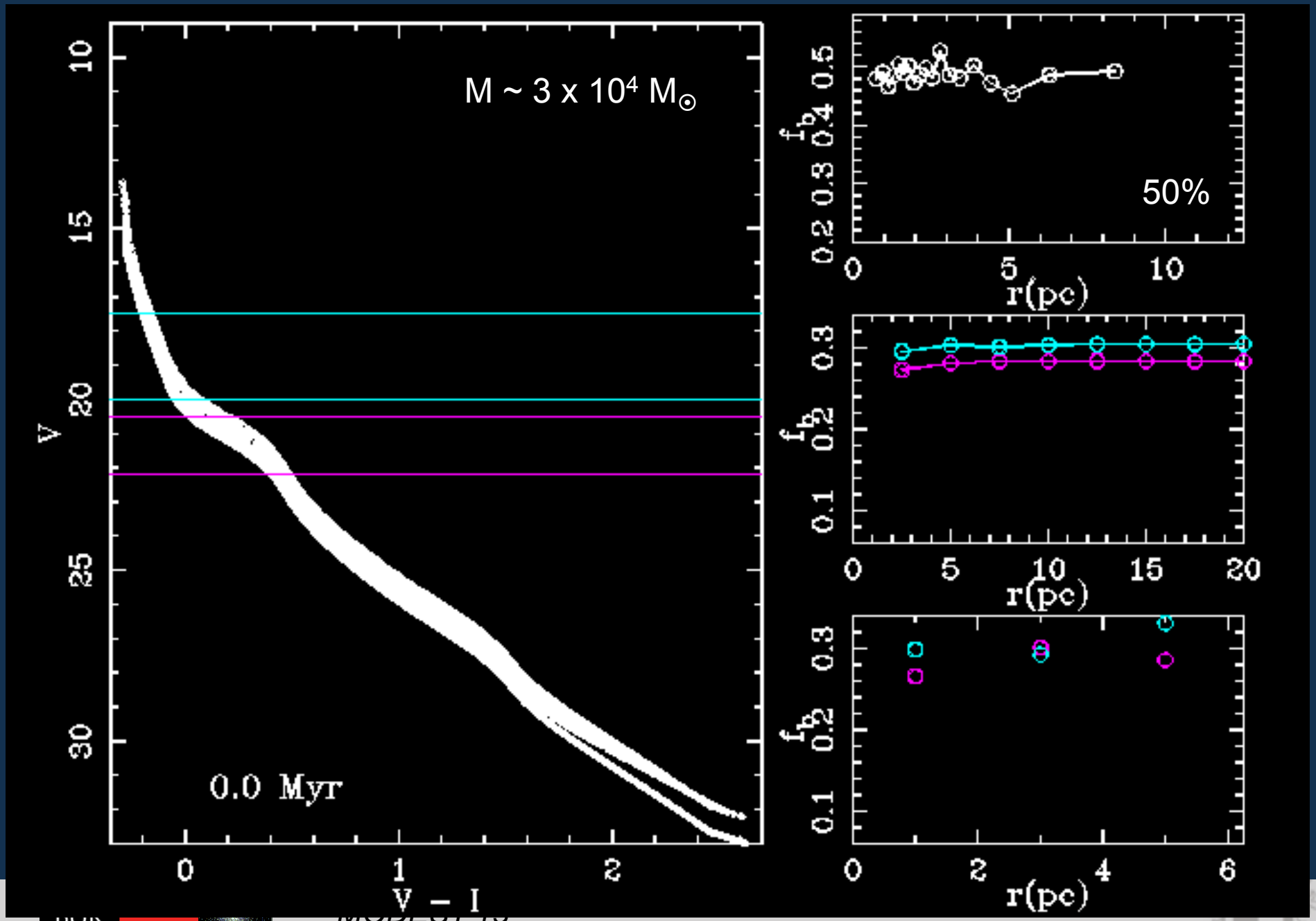
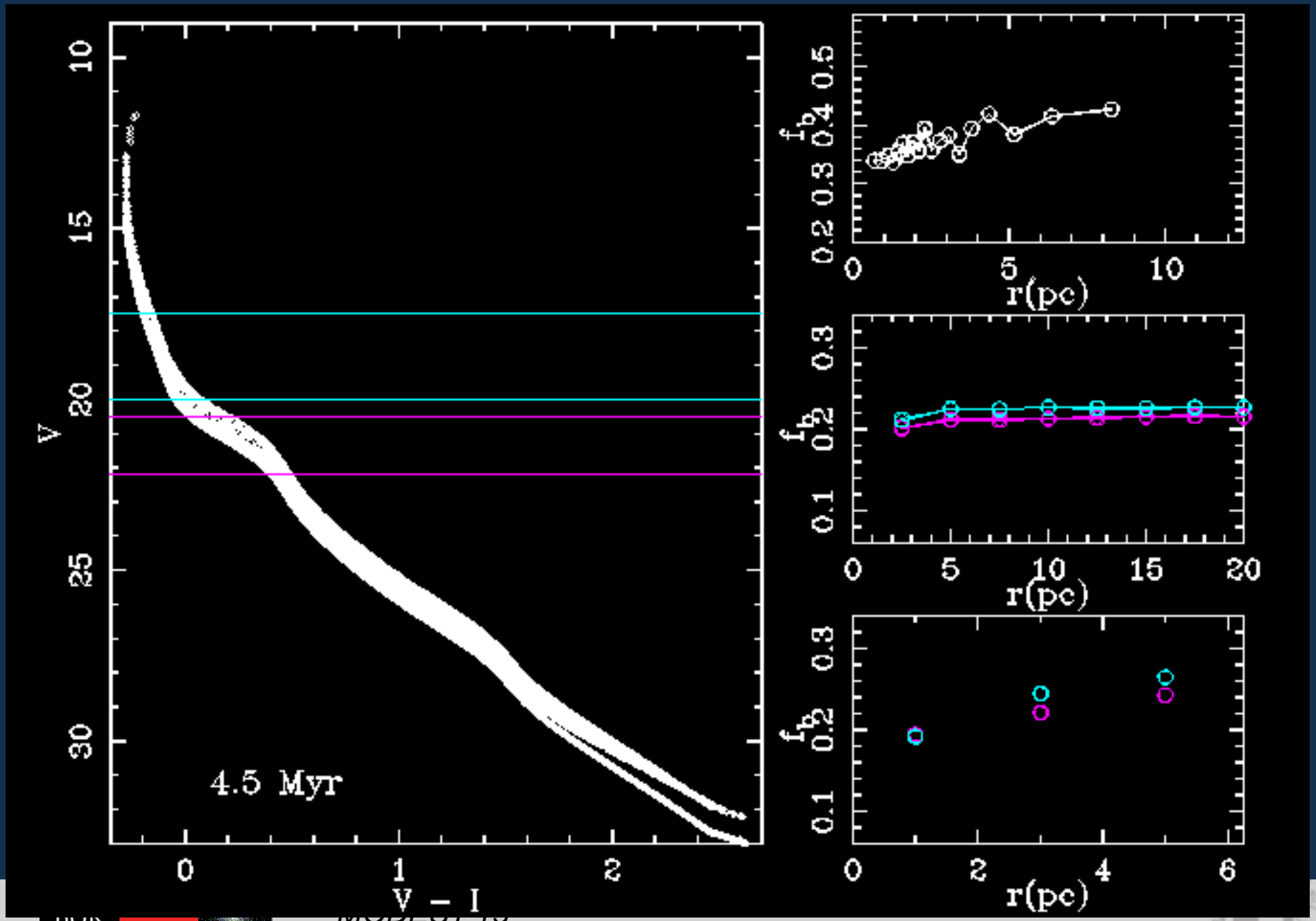
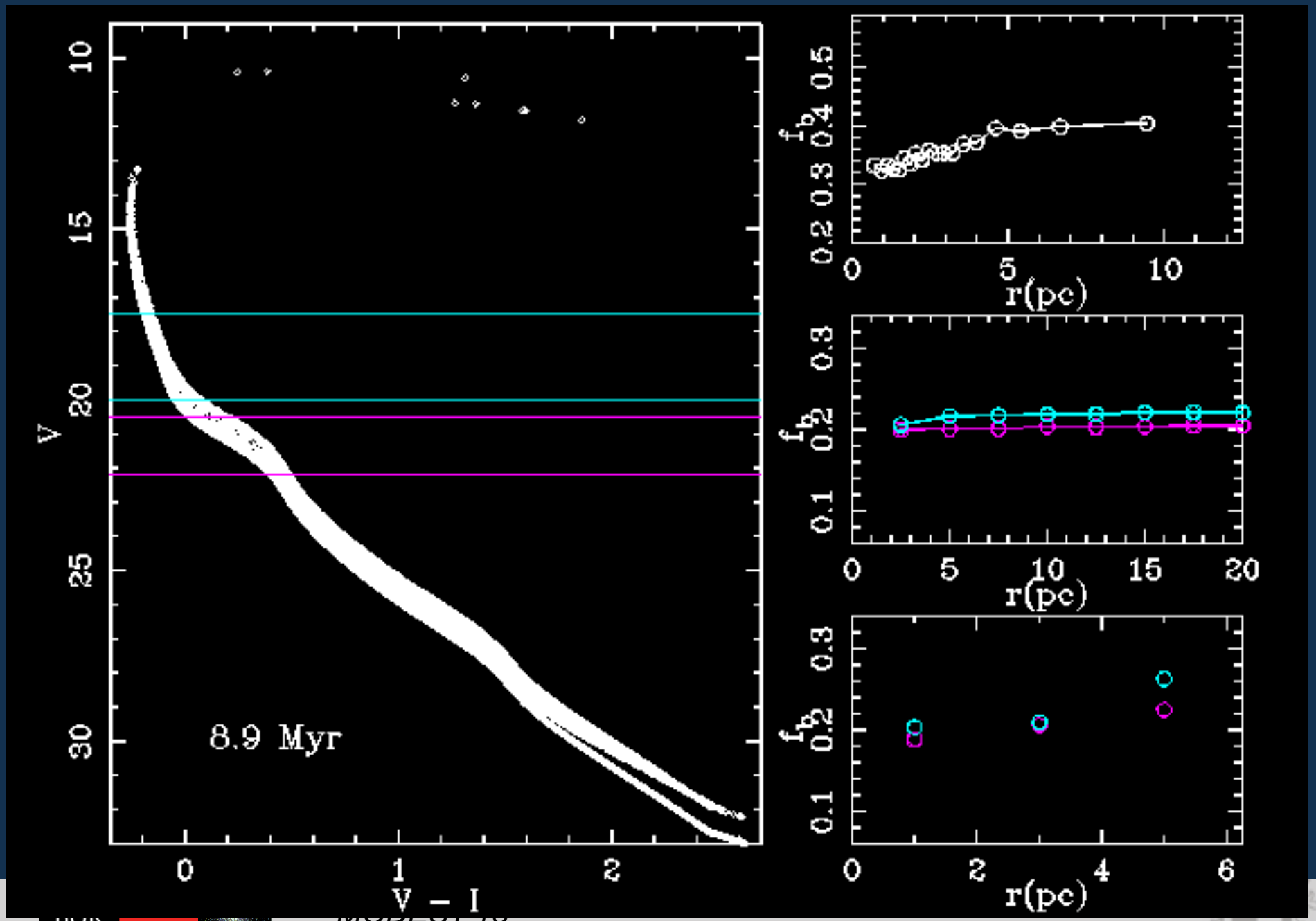
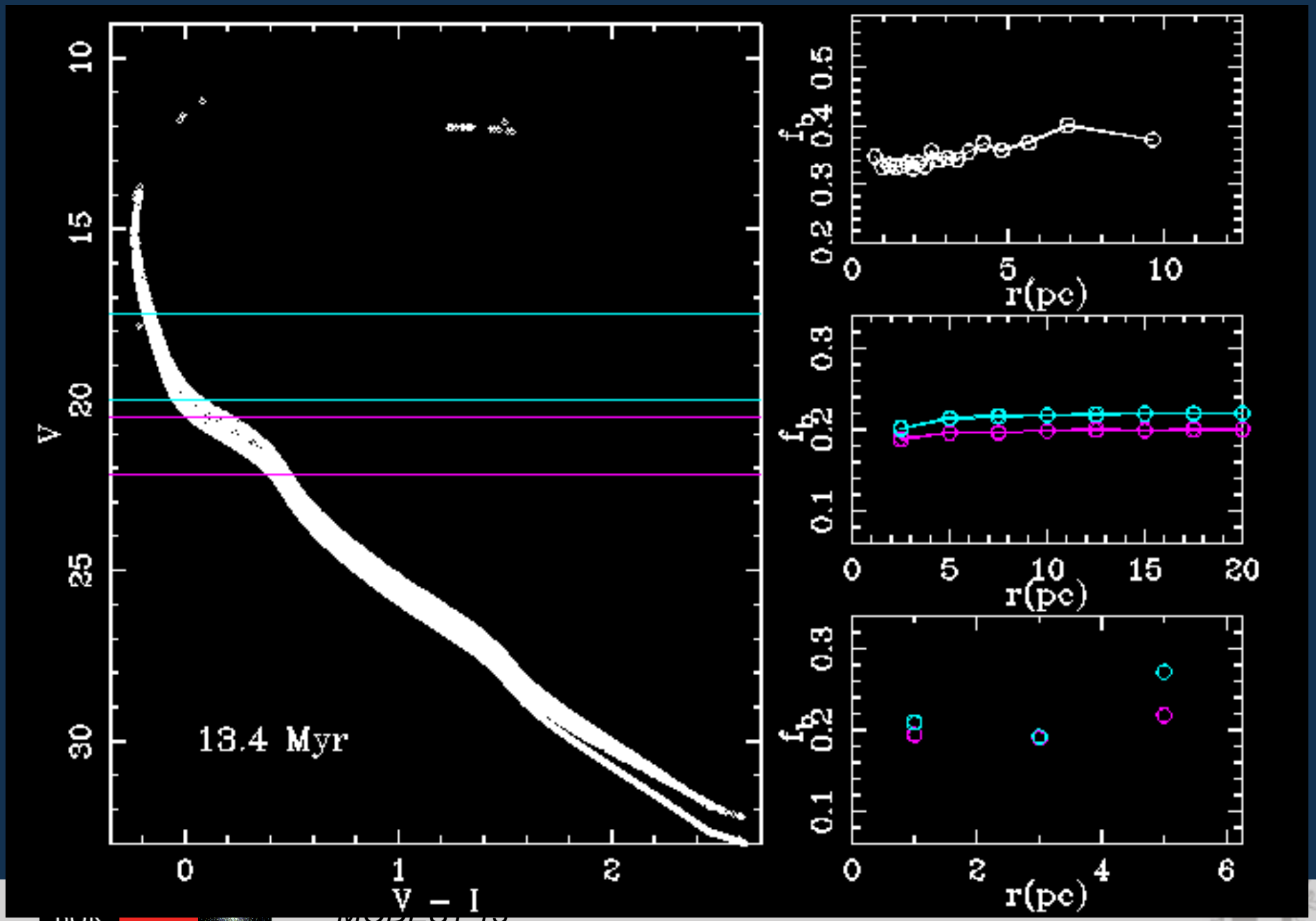
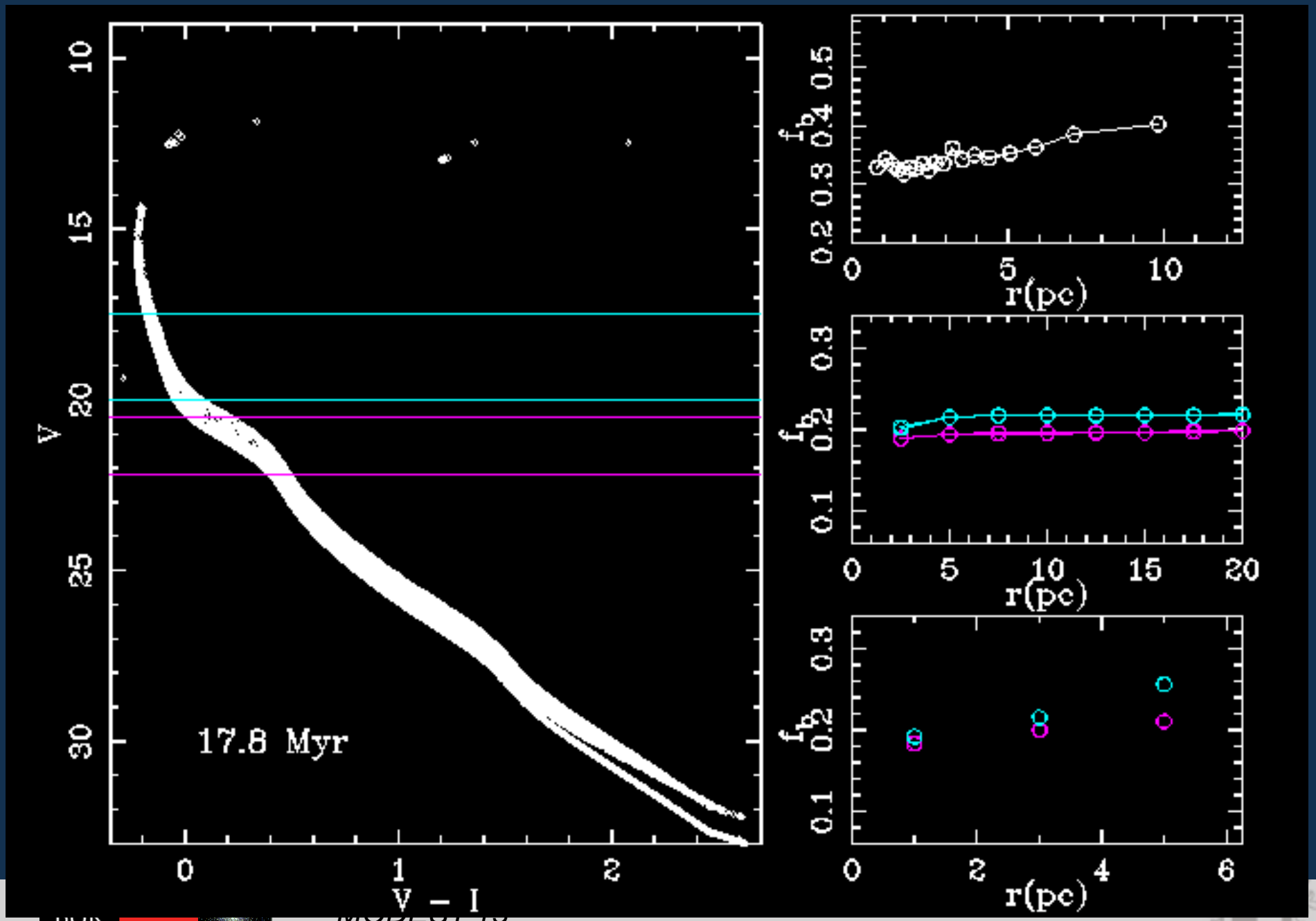


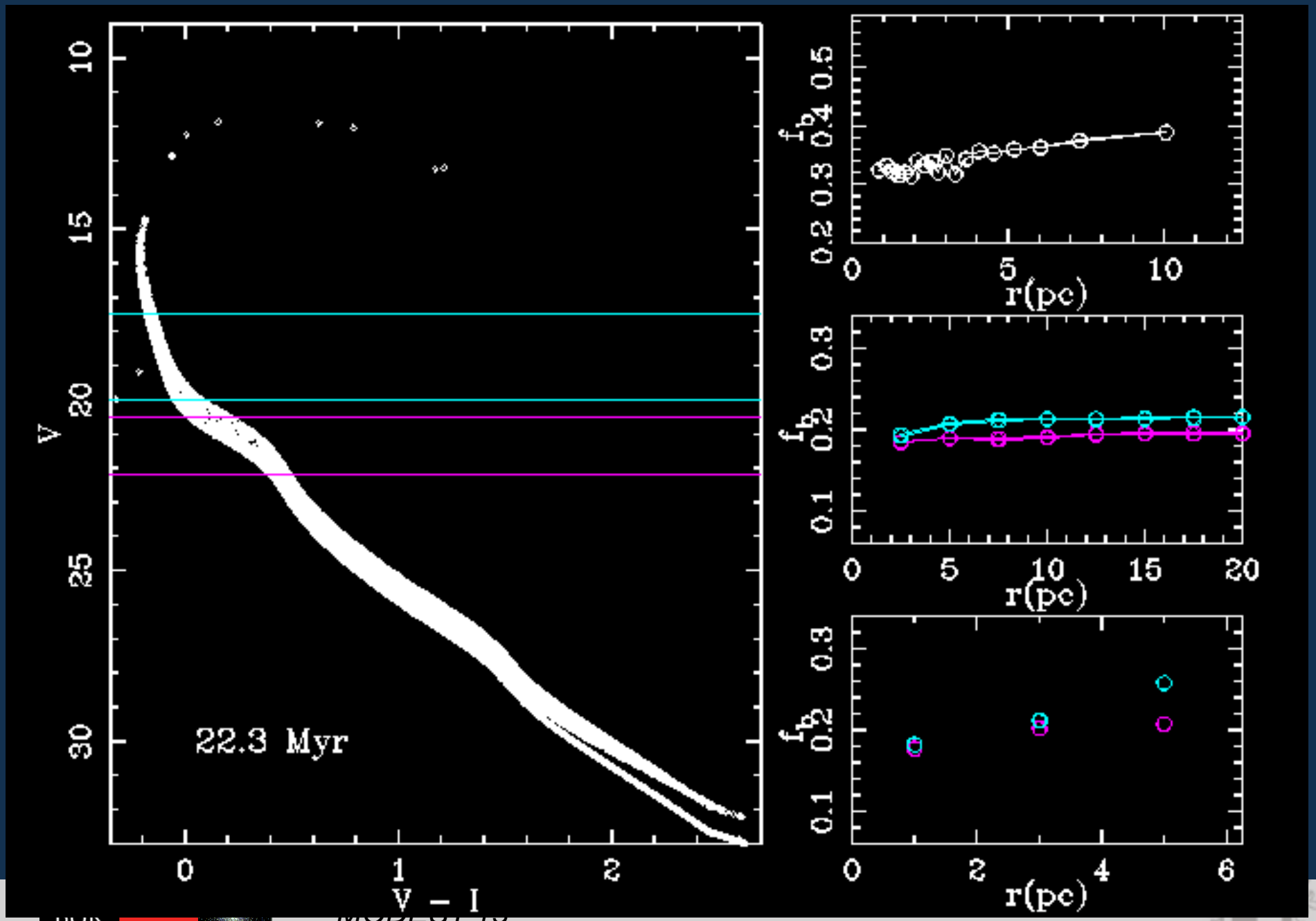

M ~ 3 x 10⁴ M⊙
0.0 Myr
V
V − I
50%
r(pc)
f_b

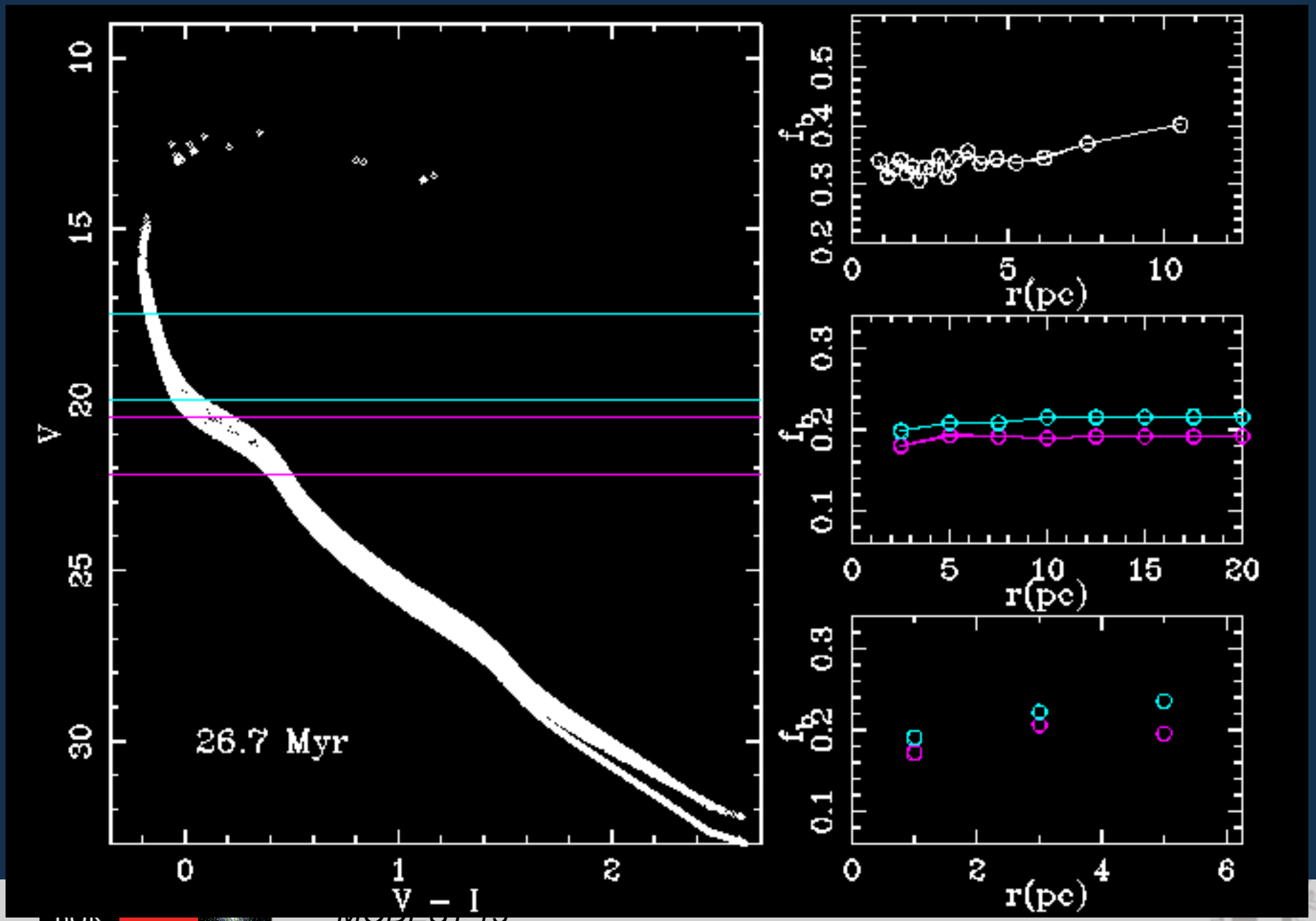

V
V − I
4.5 Myr
f_b
r(pc)
f_b
r(pc)
f_b
r(pc)

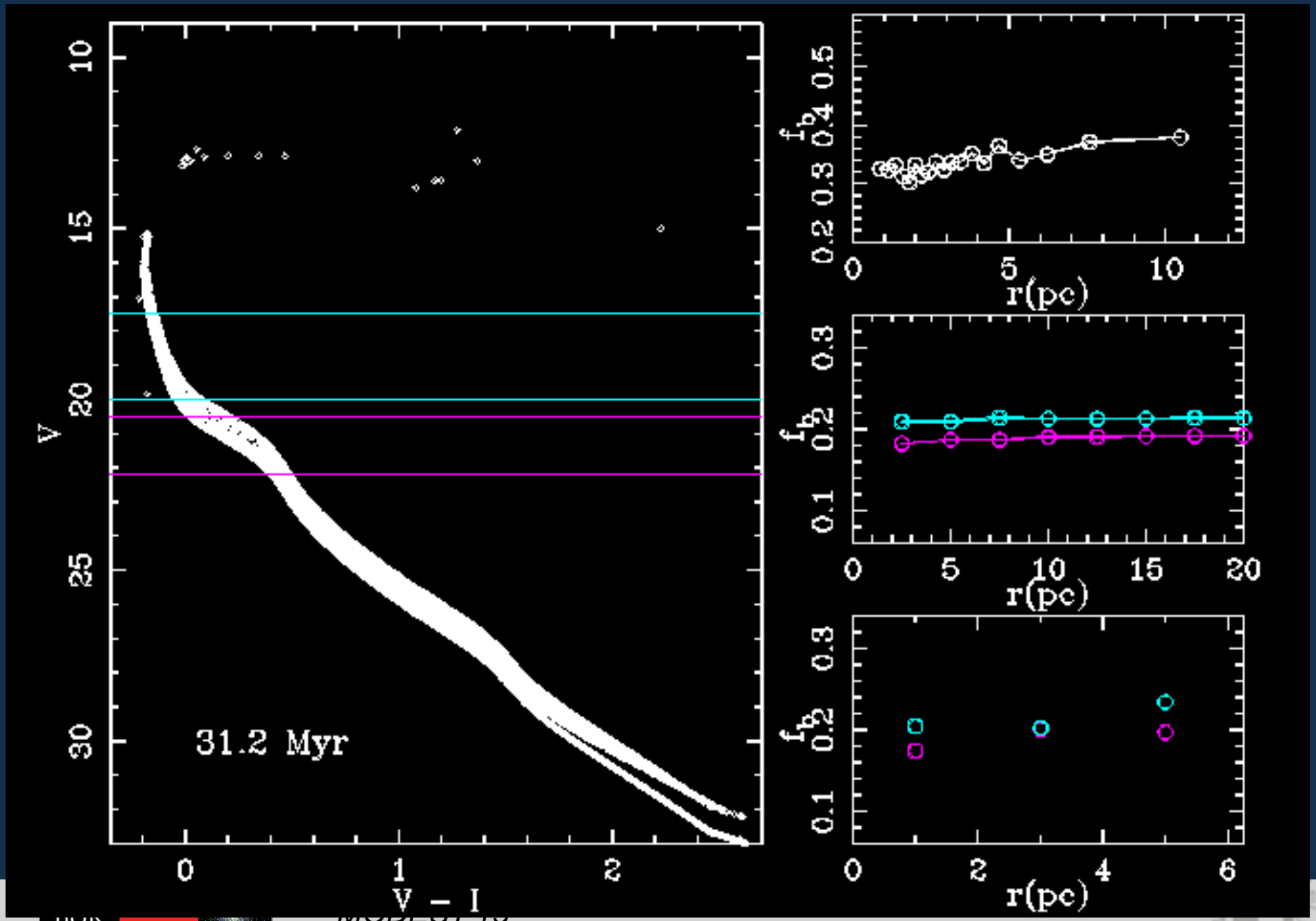

V
V − I
8.9 Myr
f_b
r(pc)
f_b
r(pc)
f_b
r(pc)

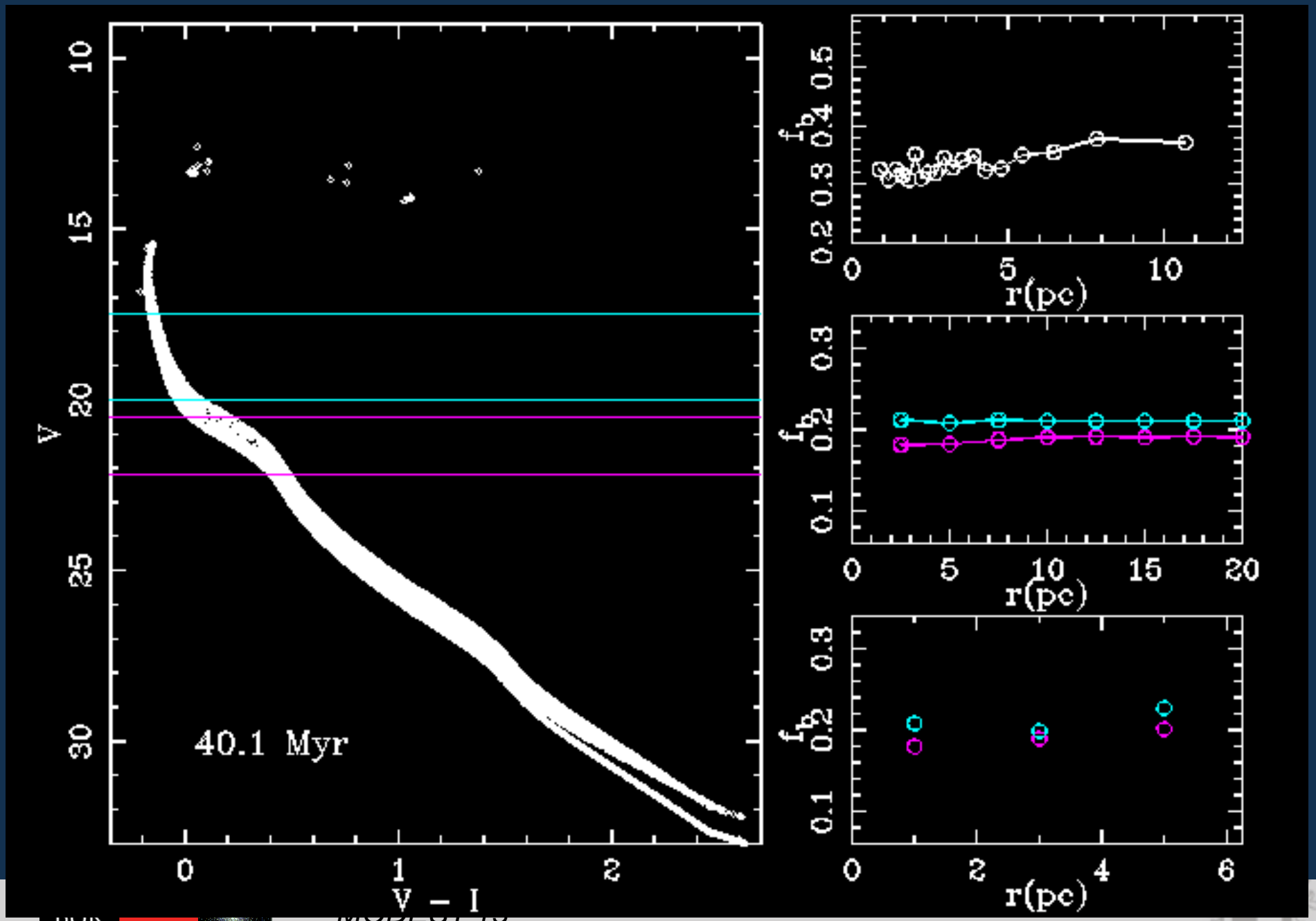

V
V − I
13.4 Myr
r(pc)
r(pc)
r(pc)

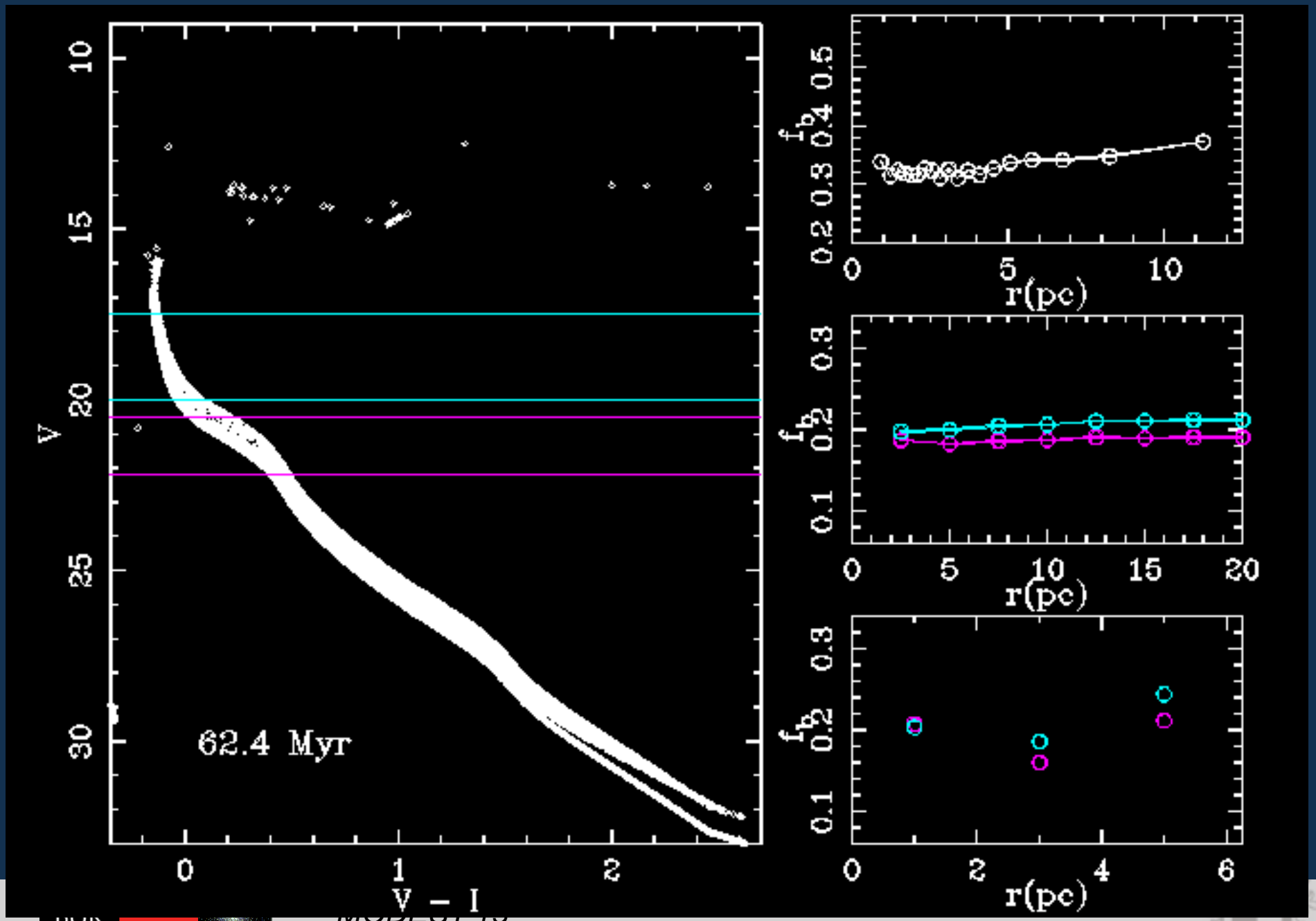

V
V − I
17.8 Myr
f_b
r(pc)
f_b
r(pc)
f_b
r(pc)

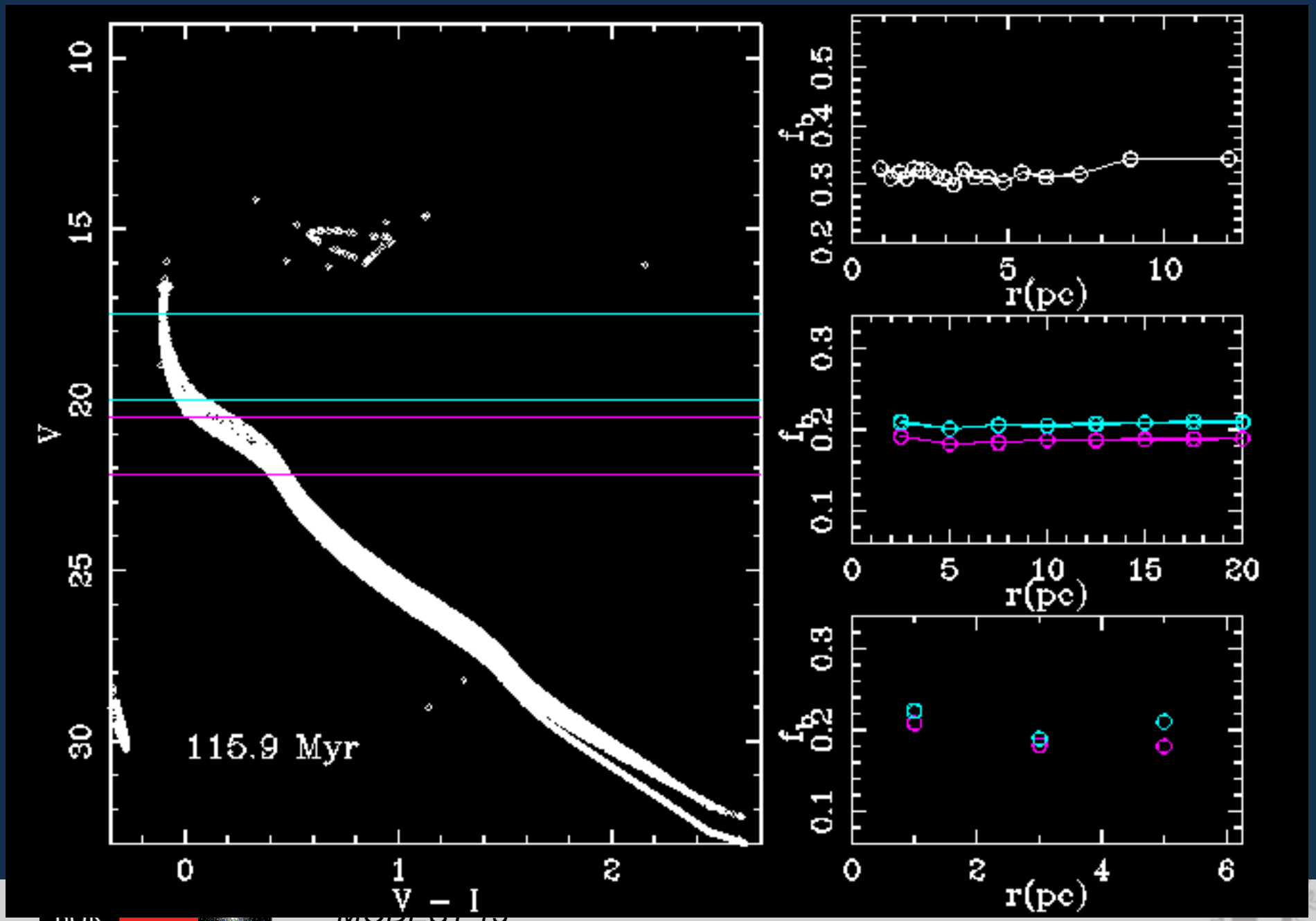

V
V − I
22.3 Myr
f_b
r(pc)

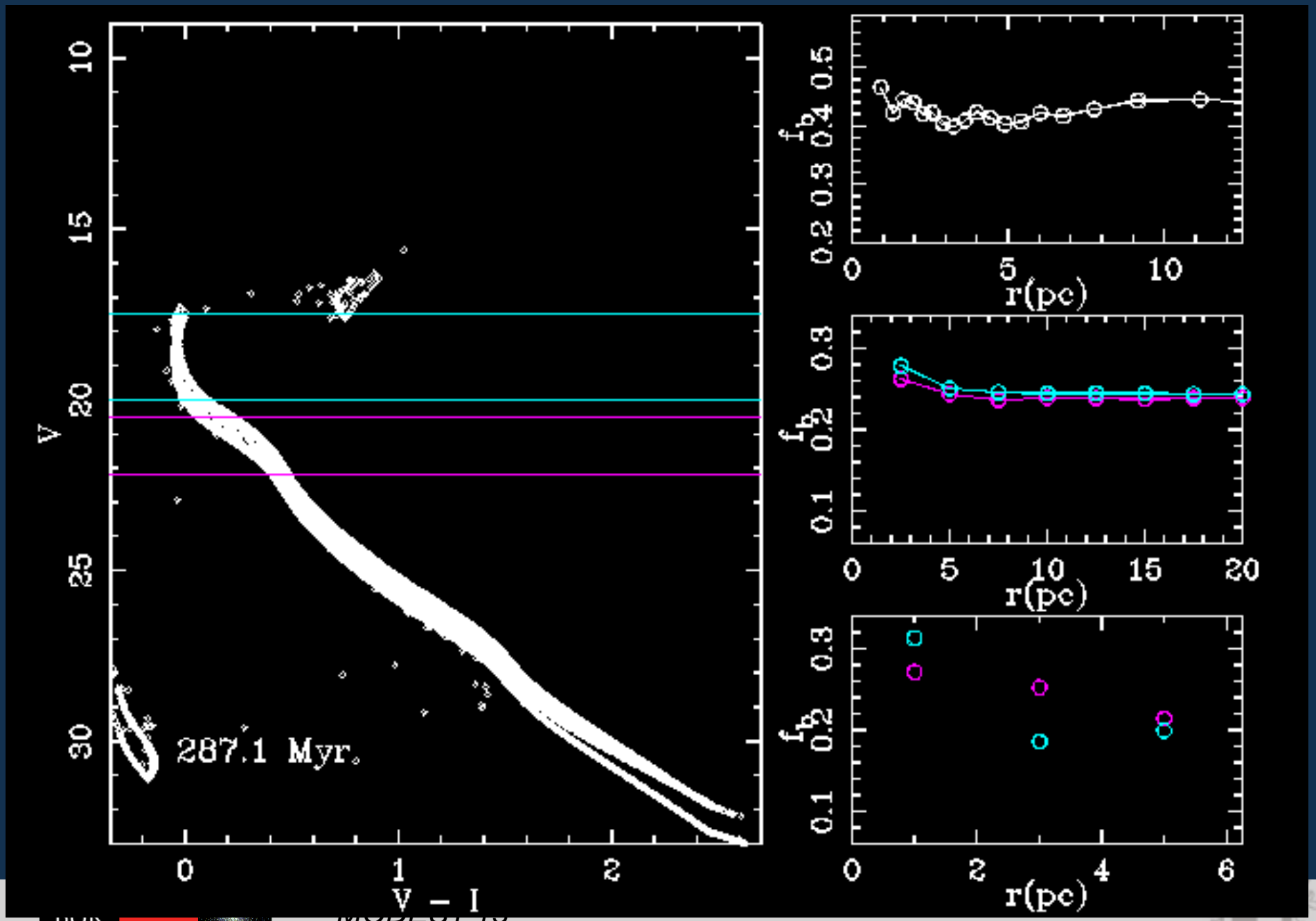

V
V − I
26.7 Myr
f_b
r(pc)
f_b
r(pc)
f_b
r(pc)

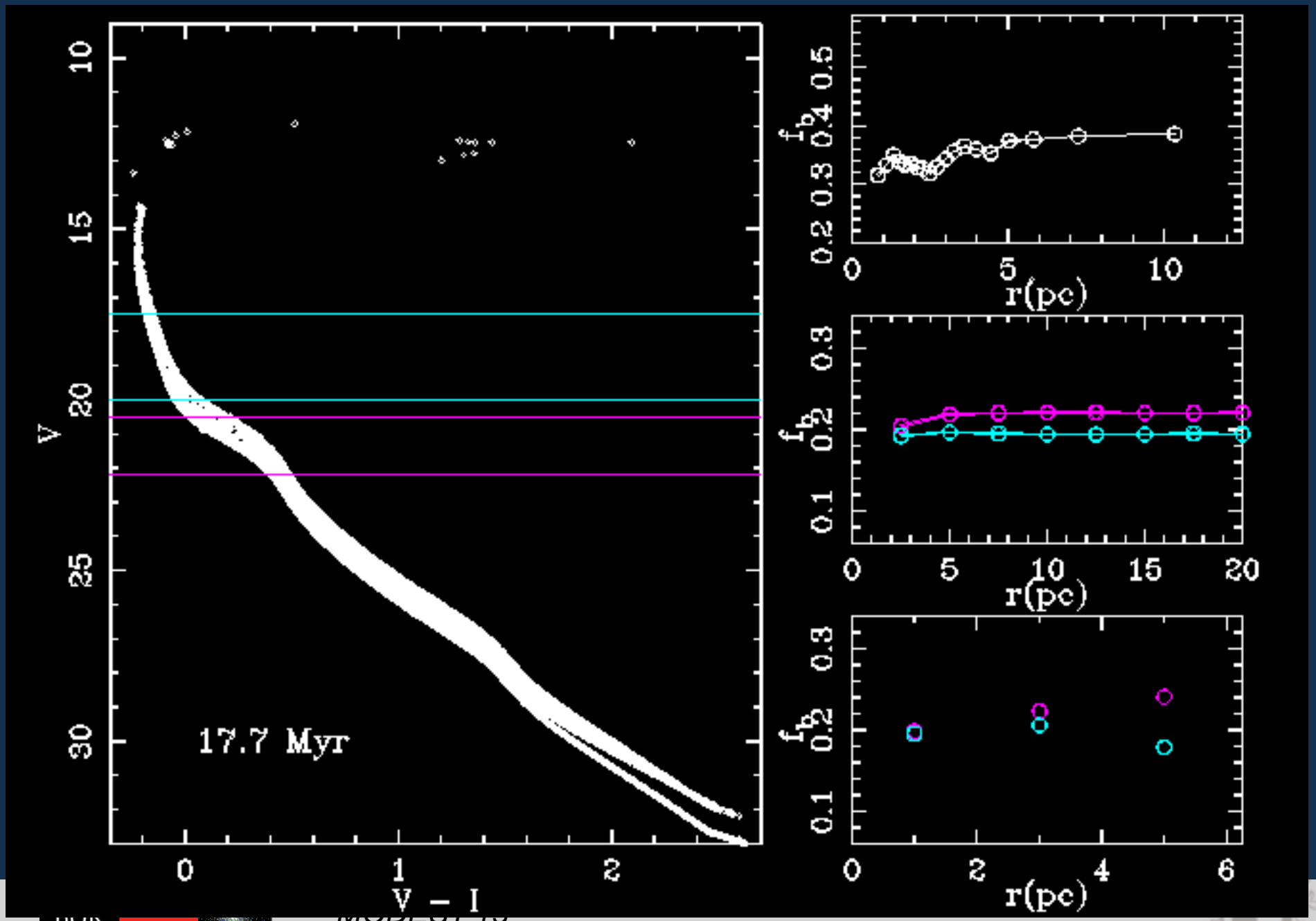

V
V − I
31.2 Myr
f_b
r(pc)


V
V − I
40.1 Myr
f_b
r(pc)


V
V − I
62.4 Myr
f_b
r(pc)
f_b
r(pc)
f_b
r(pc)


V
V − I
115.9 Myr
f_b
r(pc)
f_b
r(pc)
f_b
r(pc)


V
V − I
287.1 Myr.
f_b
r(pc)


V
V − I
17.7 Myr
f_b
r(pc)
f_b
r(pc)
f_b
r(pc)