Evaluating the Merger Rate of Binary Black Holes Using the Milky Way Globular Clusters

Kritos & Cholis, PRD 102, 8, 083016 (2020) (arXiv:2007.02968)

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Ilias Cholis, 10/24/2020

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Very dense stellar environments where multiple dynamical interactions take place. Most stars are in binaries.

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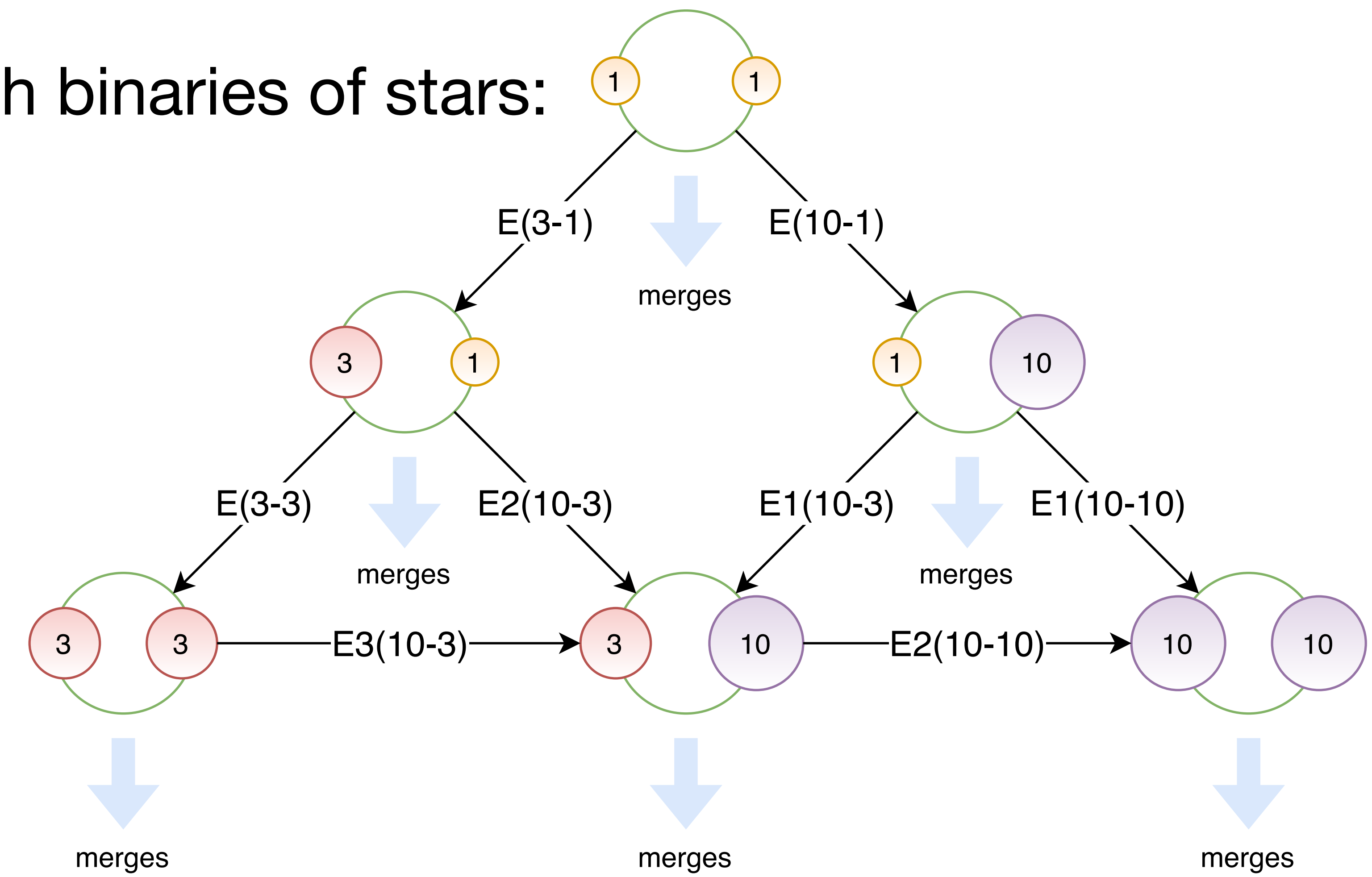

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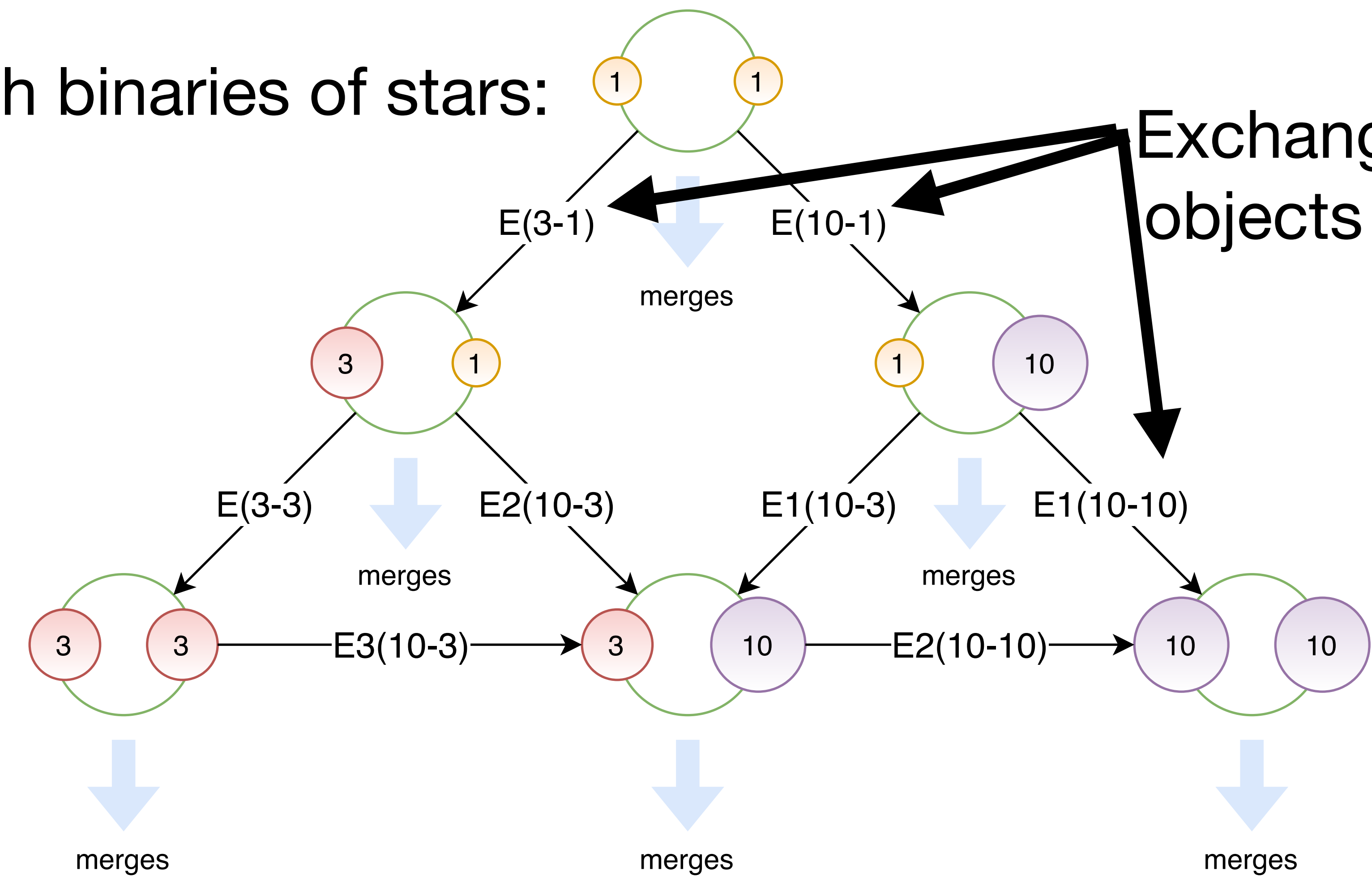

Exchanges when compact objects approach binaries

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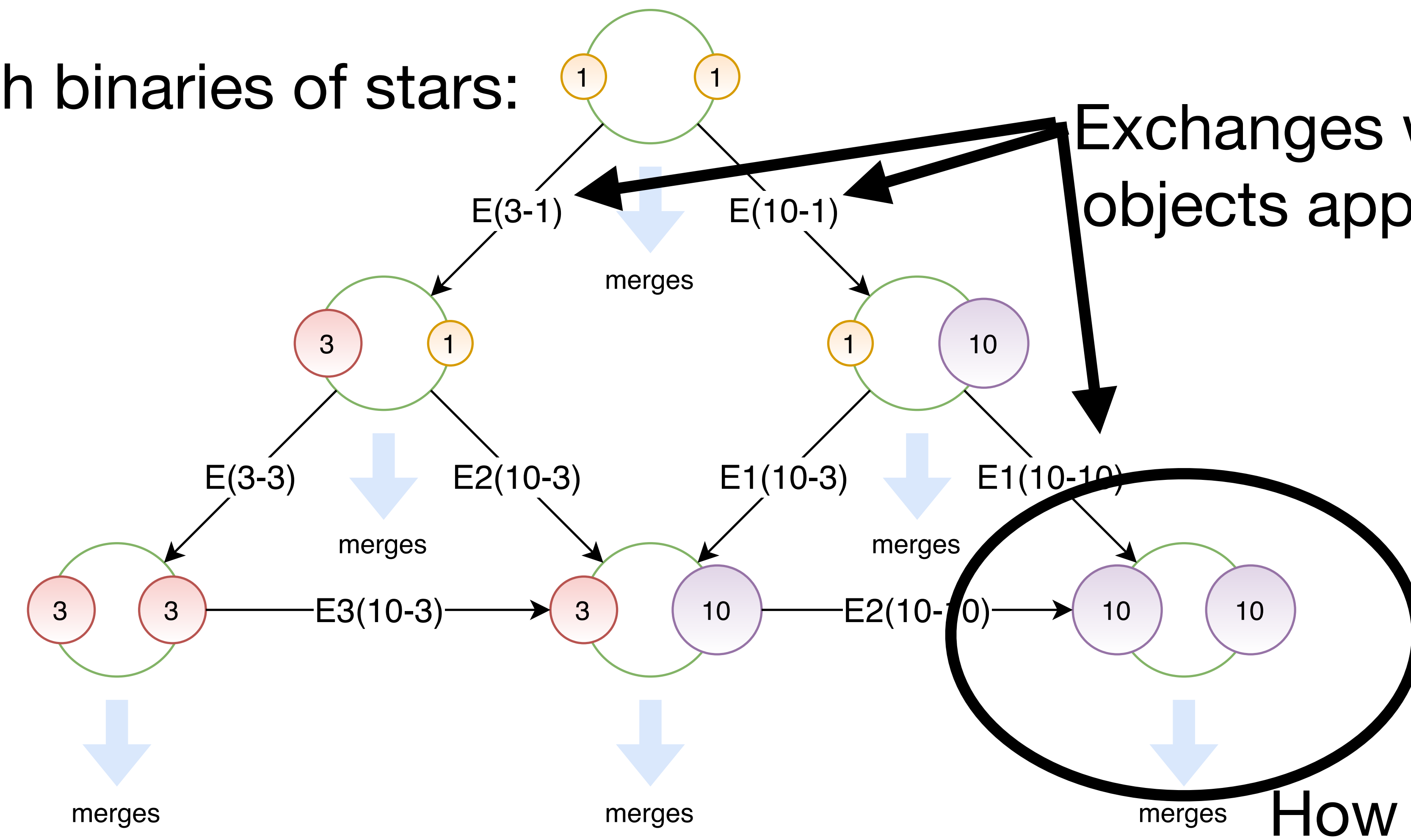


Exchanges when compact objects approach binaries

Focus on the BH-BH binaries. How the binaries evolve while interacting with third-bodies leading to their merger

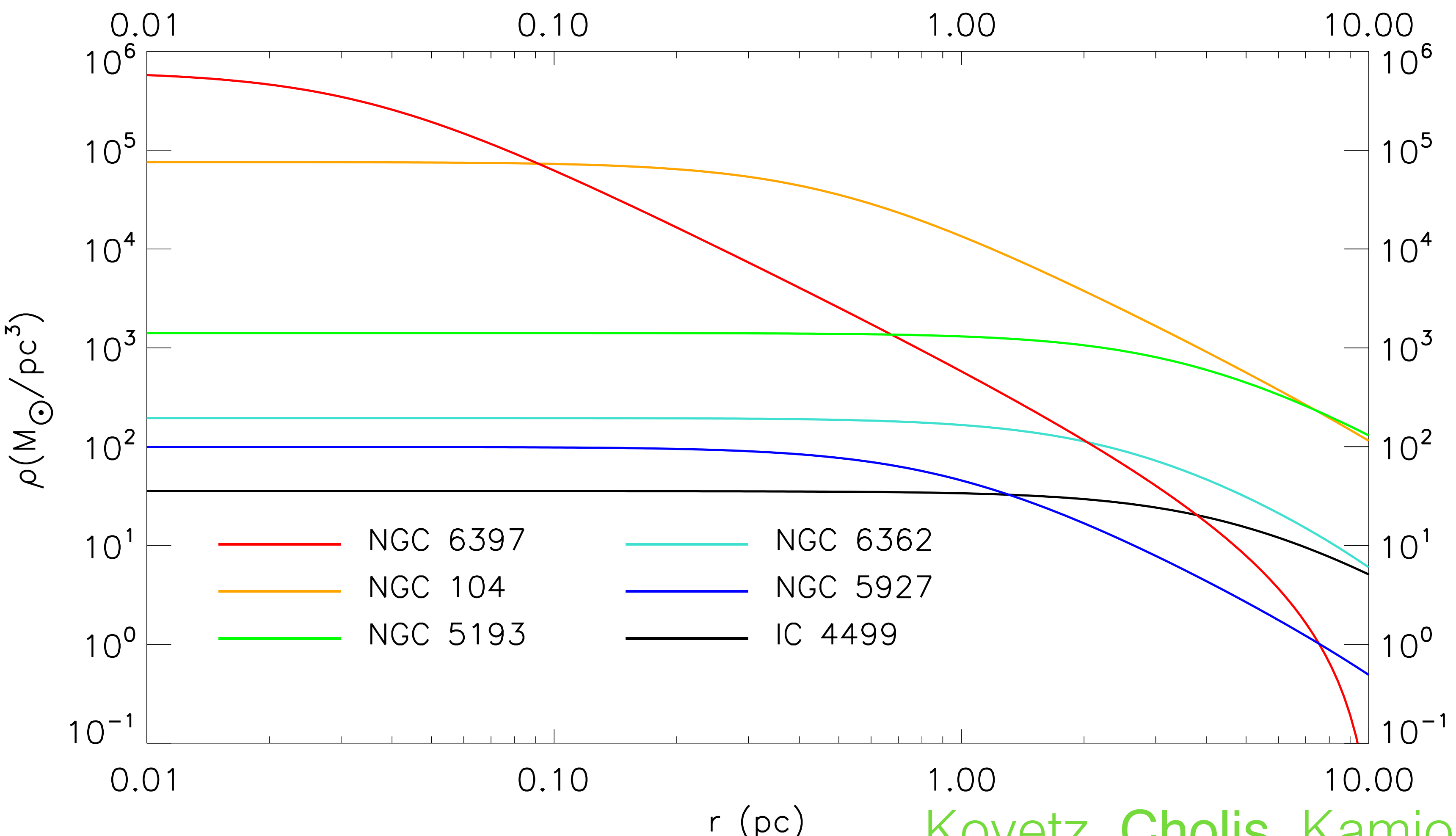
Another channel to produce merging BH-BH binaries comes from direct captures.

The Centers of Globular Clusters

Very dense stellar environments where multiple dynamical interactions take place. Most stars are in binaries.

There are about 150 Globular Clusters in the Milky Way. Significant enough sample for us to evaluate the BH-BH merger rates from globular clusters as a population.

Most of which have well measured properties:



<u>Data from Harris GC catalogue</u>

Kovetz, **Cholis**, Kamionkowski, Silk PRD 2018

Assume for simplicity that all BHs are 10 $M_\odot$

We can estimate the mass fraction of the GC that ends up in BHs,

$$f_{BH} \simeq \frac{1}{3}\frac{1}{M_{GC}} \int_{25M_\odot}^{120M_\odot} d\mathcal{M}\ \mathcal{M}\xi(\mathcal{M}) \approx 0.03$$

mass of stars

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From that we can estimate the maximum number of BHs that were born at any point in a GC,

$$N_{BH}^{\rm max} = f_{BH}\frac{M_{GC}}{10\,M_\odot}$$

and including the natal kicks that are responsible for roughly 90% of the BHs escaping the clusters, the maximum number of retained BHs,

$$N_{BH}^{\rm ret\text{-}max} = f_{\rm ret} \times N_{BH}^{\rm max}$$

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BHs that could end up in binaries Inside the GCs

GC	$\frac{r_c}{1\text{pc}}$	c	$\frac{r_{pl}}{1\text{pc}}$	$log_{10}\left(\frac{\rho_0}{1M_\odot/\text{pc}^3}\right)$	$\frac{M_{GC}}{10^5 M_\odot}$	$N_{BH}^{\text{ret-max}}$
47 Tuc	0.47	2.07	0.73	4.88	38.2	1145
ω Cen	3.60	1.31	5.57	3.15	49.3	1477
M15	0.42	2.29	0.66	5.05	68.7	2060
M22	1.24	1.38	1.92	3.63	7.30	219
NGC 6362	2.50	1.09	3.88	2.29	1.29	38
NGC 5946	0.25	2.50	0.38	4.68	9.44	283
M 30	0.14	2.50	0.22	5.01	3.80	113
Terzan 5	0.32	1.62	0.50	5.14	7.51	225
Pal 2	1.35	1.53	2.09	4.06	36.8	1103
NGC 6139	0.44	1.86	0.69	4.67	11.7	351
NGC 2808	0.70	1.56	1.08	4.66	22.1	661
NGC 5286	0.95	1.41	1.48	4.10	10.6	319
NGC 6316	0.51	1.65	0.80	4.23	4.08	122

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$$a_h = \frac{G\, m_{BH}}{4\,\sigma^2} \simeq 5.58 \times \left(\frac{m_{BH}}{10\, M_\odot}\right) \left(\frac{20\,\mathrm{km/s}}{\sigma_{\mathrm{star}}}\right)^2 \mathrm{AU}$$

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After every encounter the hard BH-BH binaries will typically loose :

$$\frac{\langle \Delta E_b \rangle}{E_b} \simeq 0.12 \times \left(\frac{H}{15} \right) \left(\frac{m_{\mathrm{star}}}{1\, M_\odot} \right) \left(\frac{10\, M_\odot}{m_{BH}} \right)$$

Hardening rate, it takes ~15 encounters for the BH-BH to reach the point where the GW emission will dominate its evolution (see Sesana et al ApJ 2006).

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$$\dot{a} = -\frac{G\, H\, \rho_{\mathrm{star}}}{\sigma_{\mathrm{star}}}\, a^2 - \frac{128}{5}\, \frac{G^3\, m_{BH}^3}{c^5\, a^3}\, F(e)$$

$$\dot{e} = +\frac{G\, H\, K\, \rho_{\mathrm{star}}}{\sigma_{\mathrm{star}}}\, a - \frac{608}{15}\, \frac{G^3\, m_{BH}^3}{c^5\, a^4}\, D(e)$$

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Environment-dependent terms

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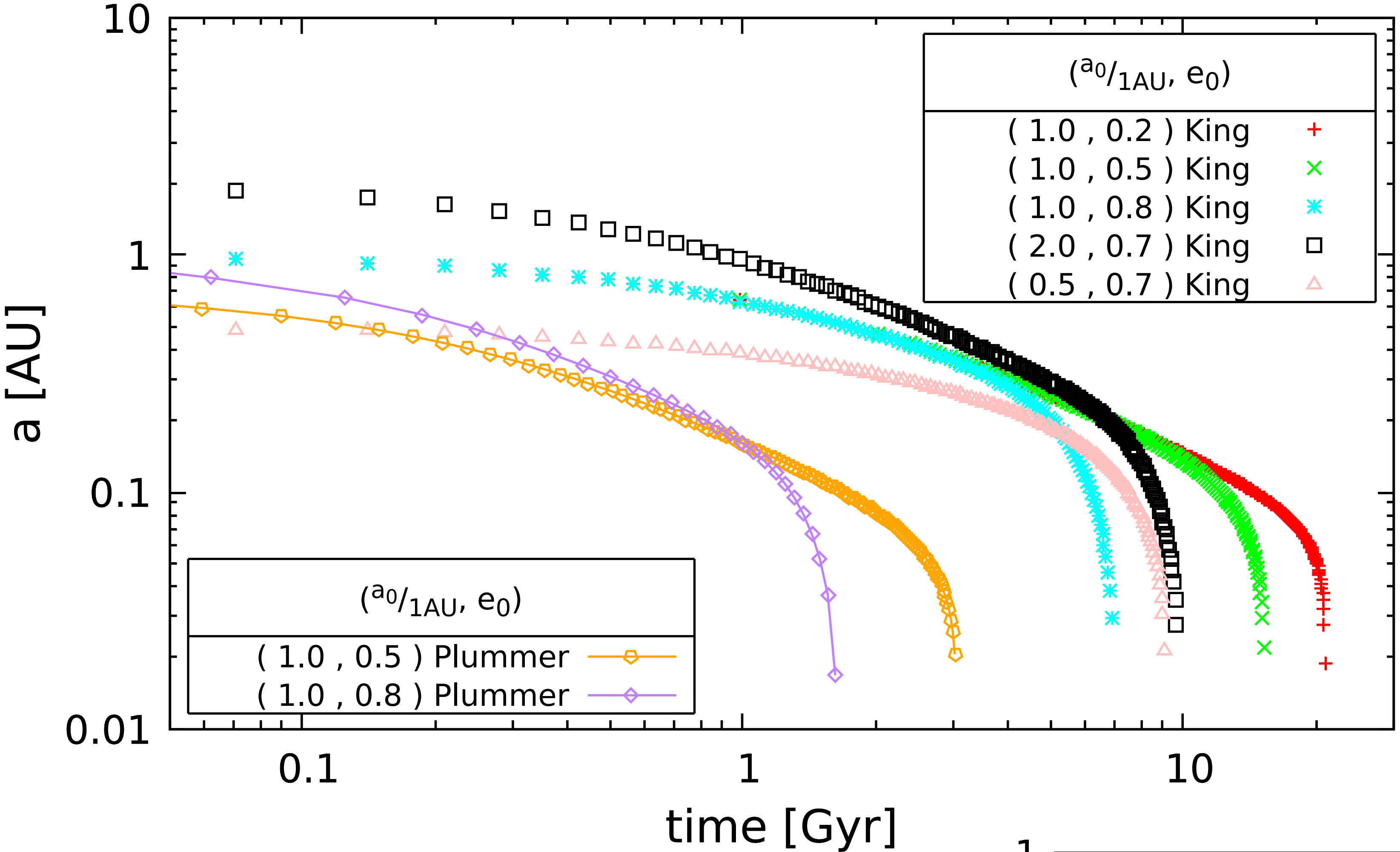
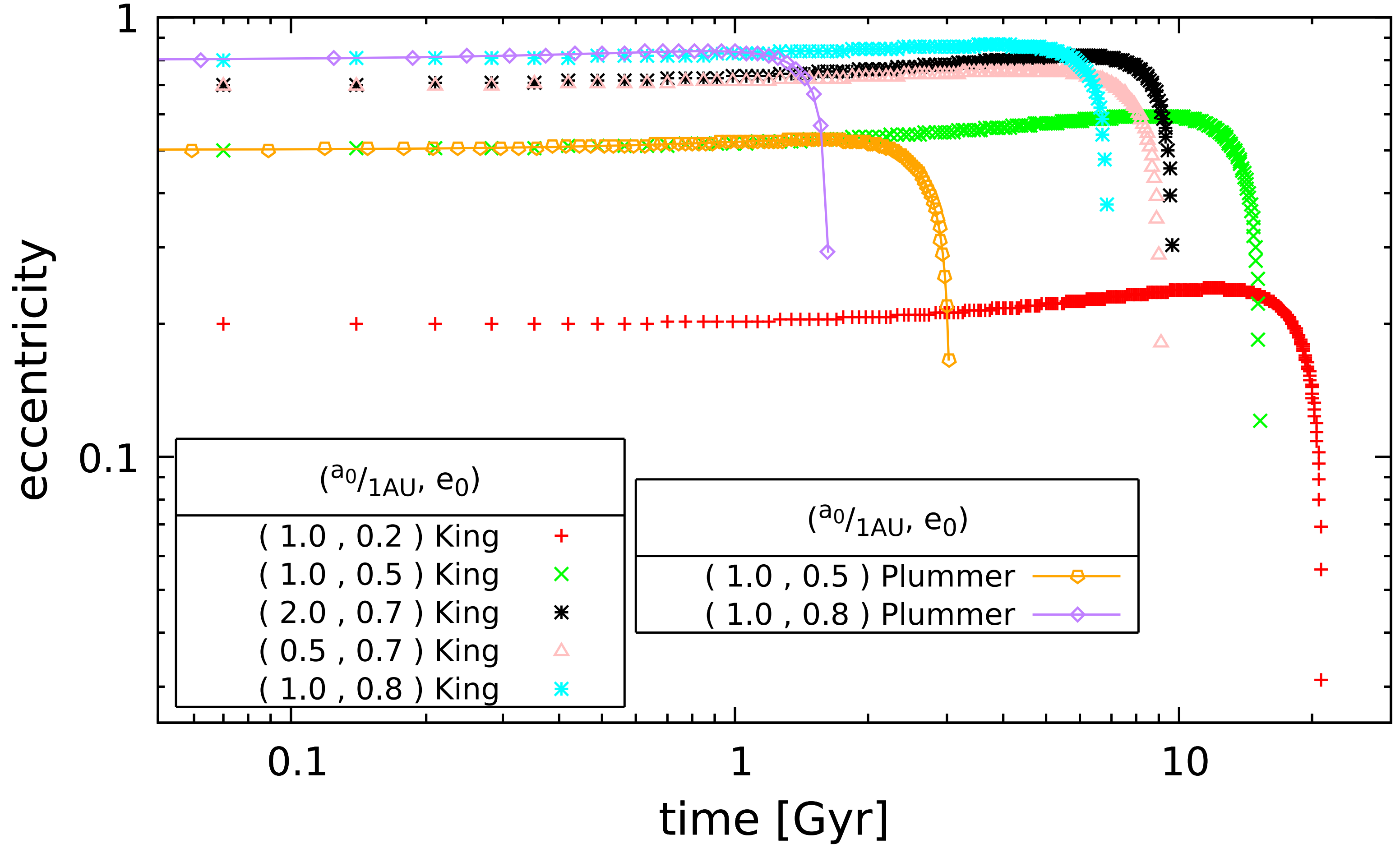
Example: Environment of 47 Tuc (NGC 104)

The evolution of a 10 + 10 solar masses BH-BH binary, for different initial assumptions on its semi-major axis and eccentricity





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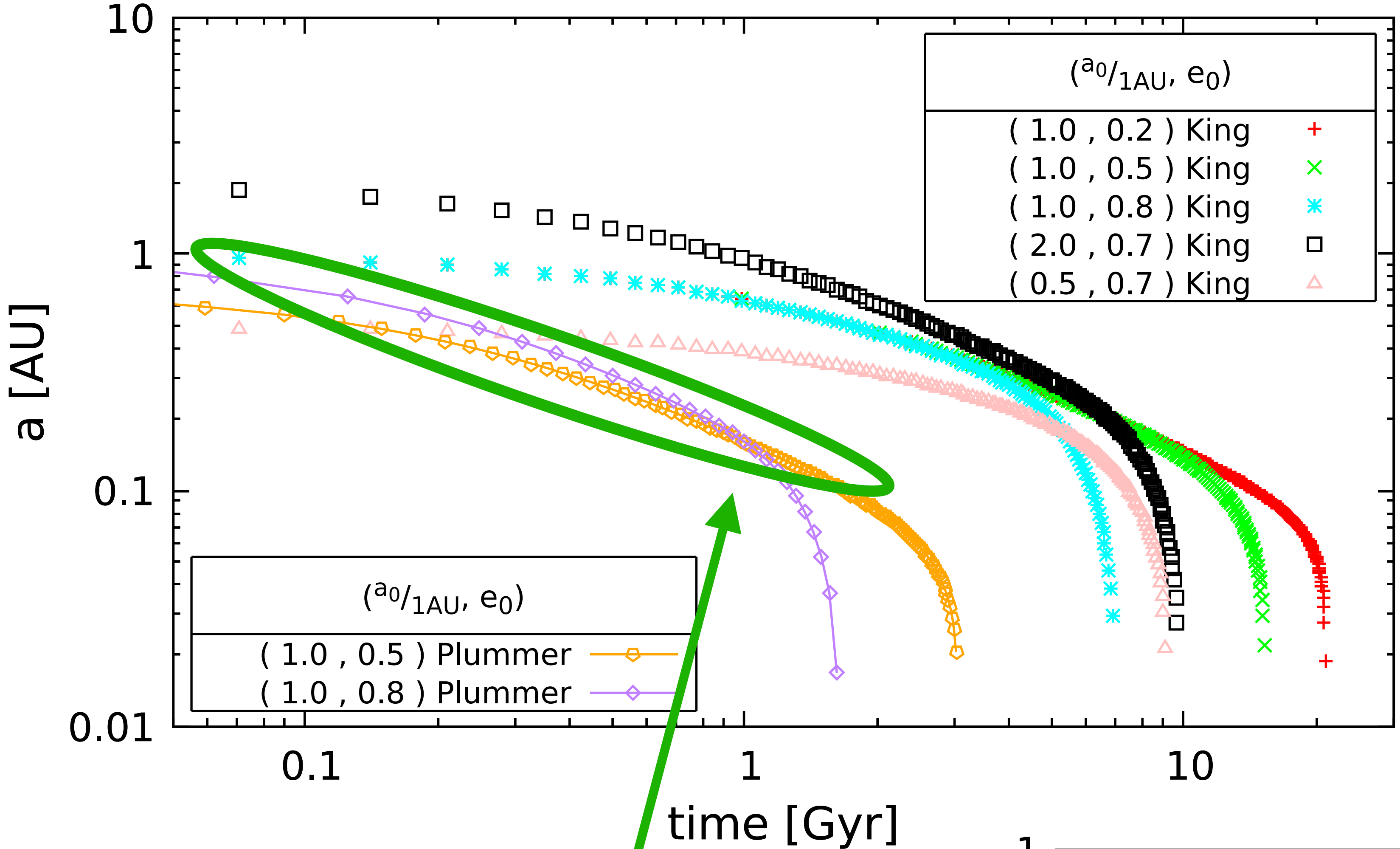
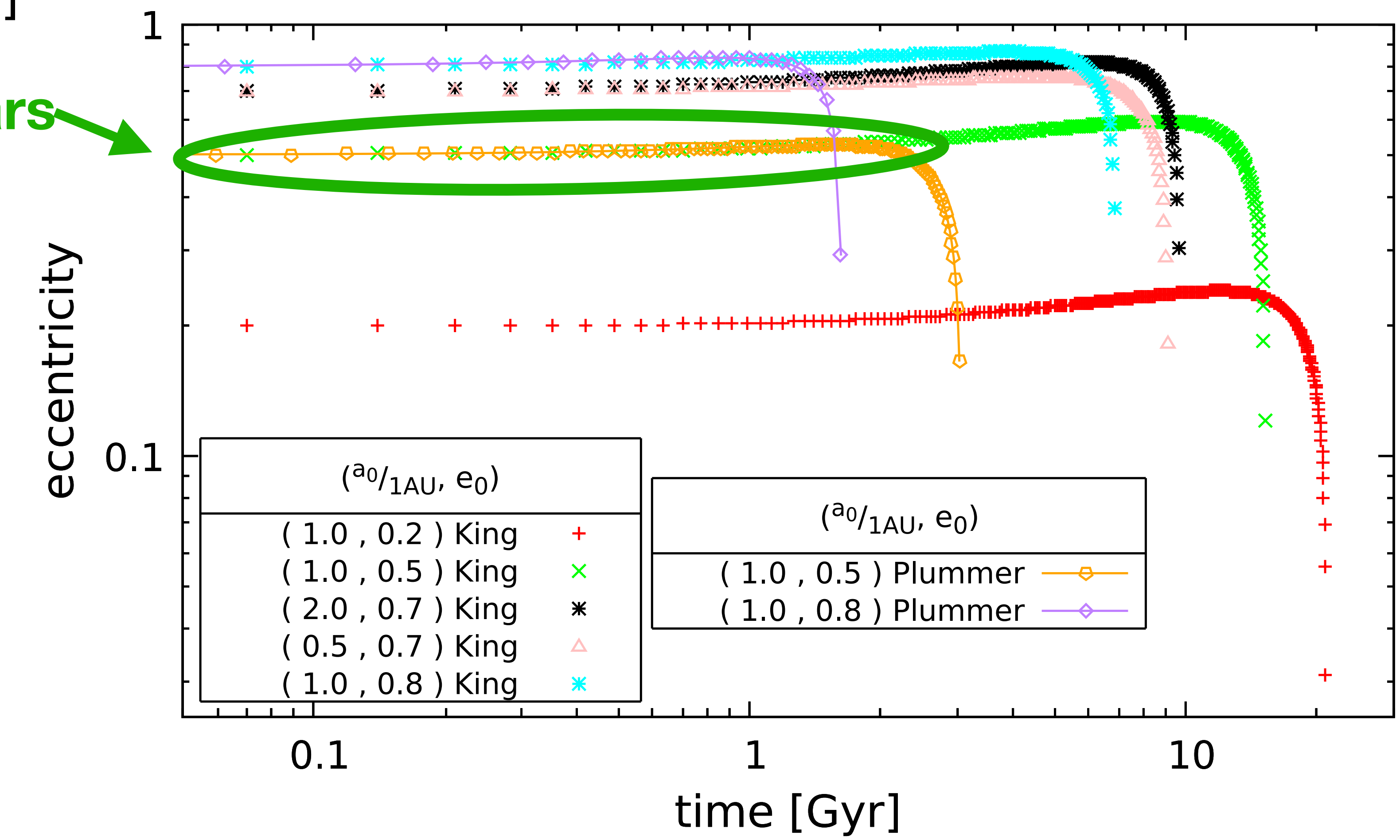


third-body interactions with stars



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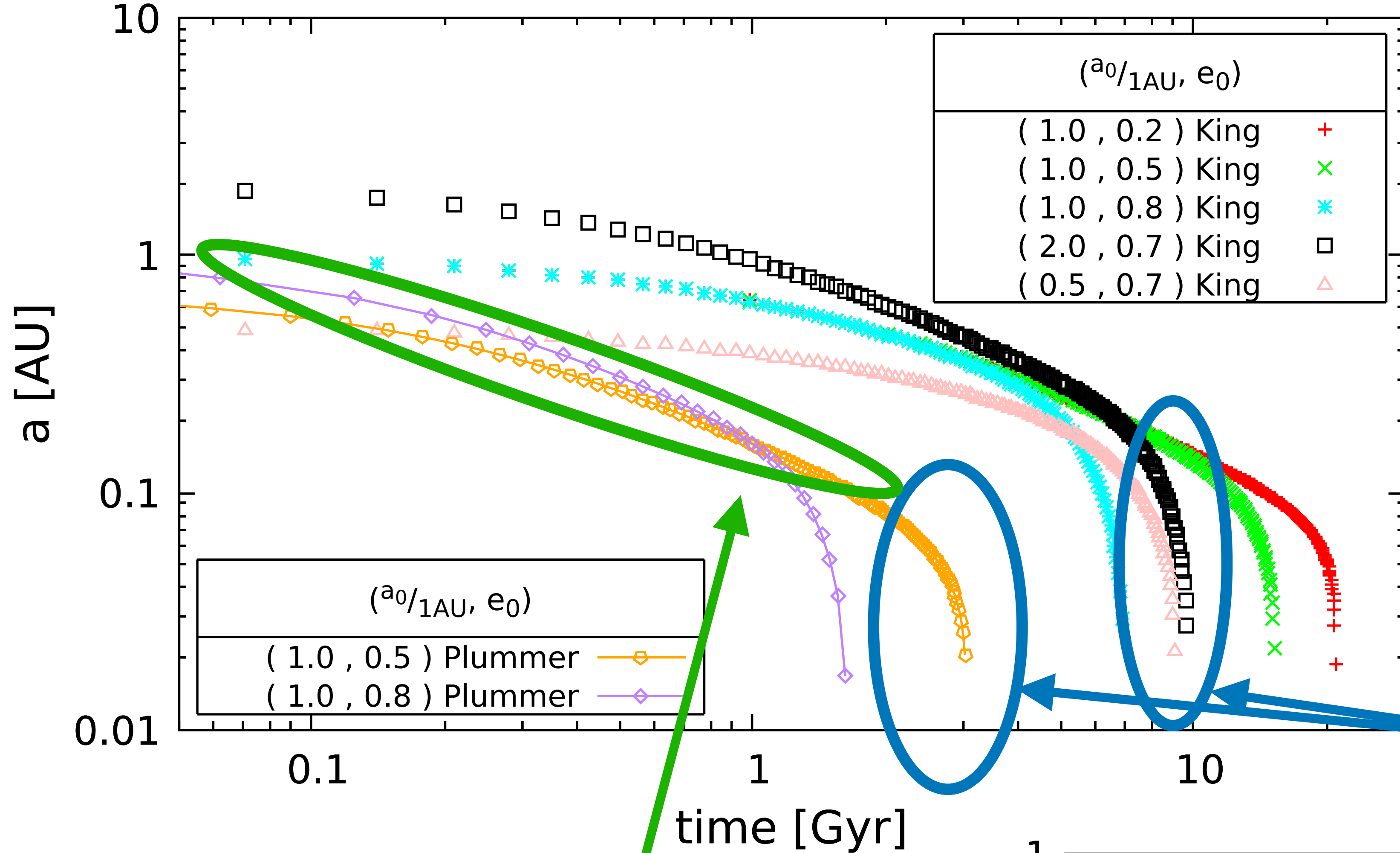

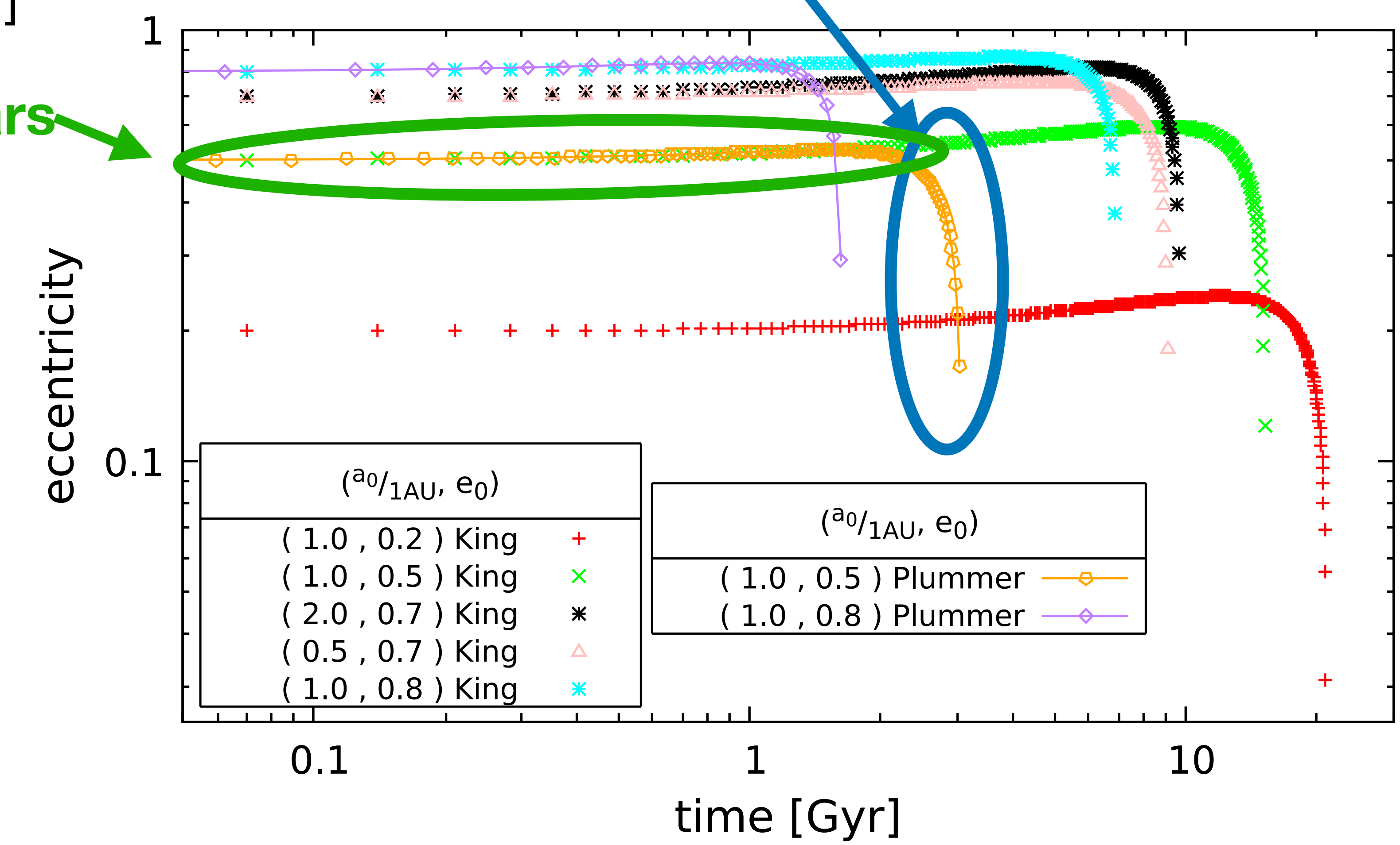

BH-BH binaries with high initial eccentricities will merge faster and within the age of the GC. Instead the initial semi-major axis assumptions are of little significance.

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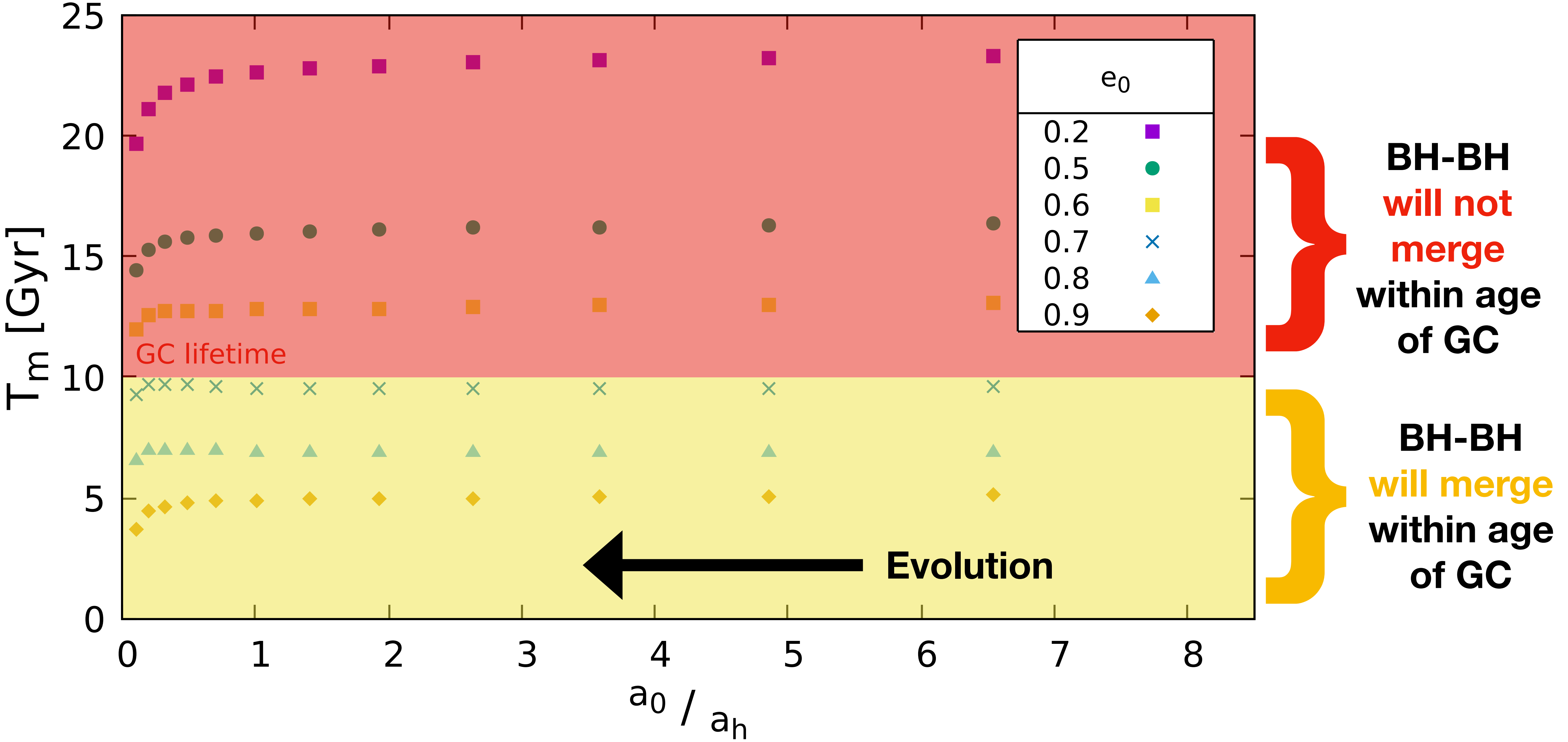
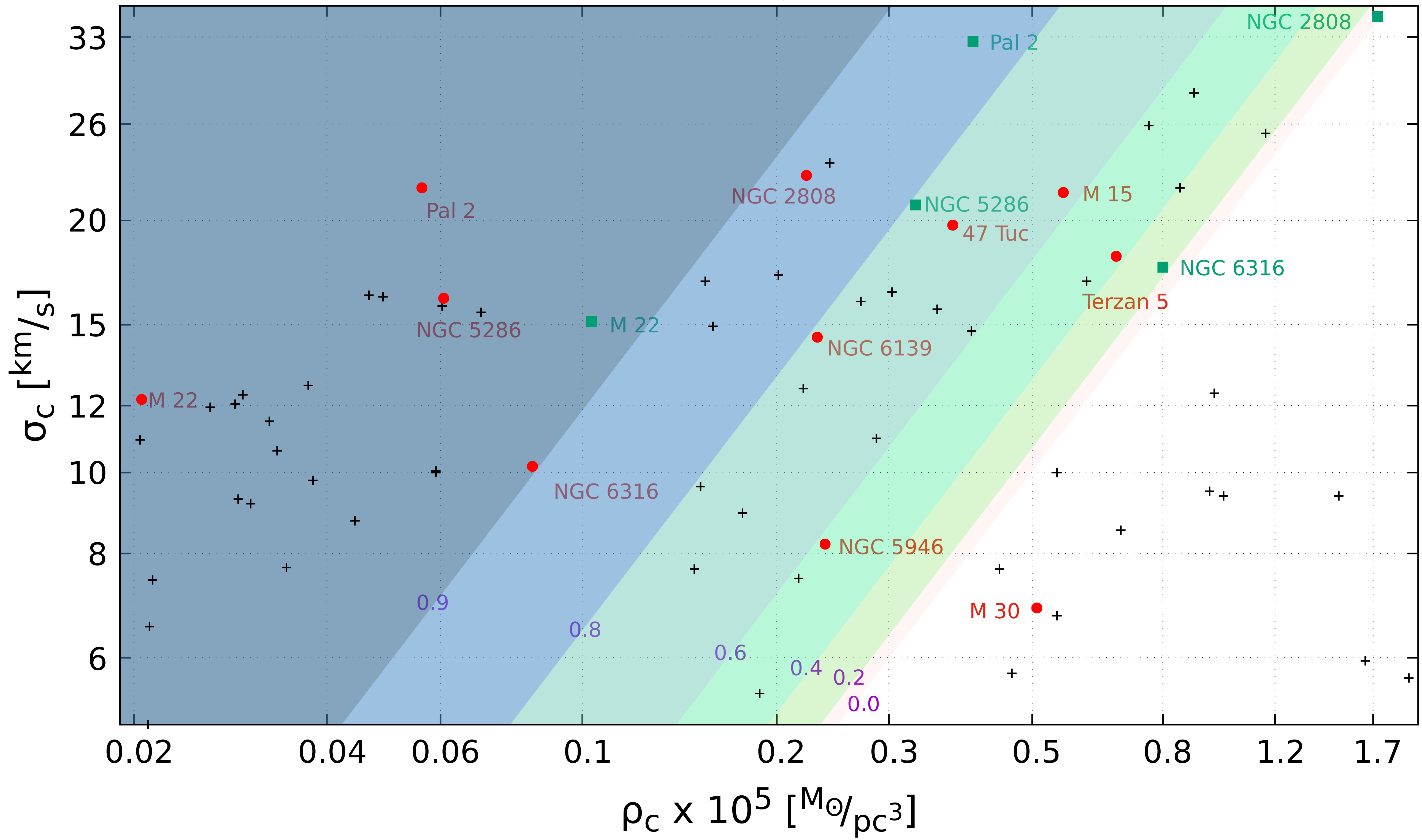
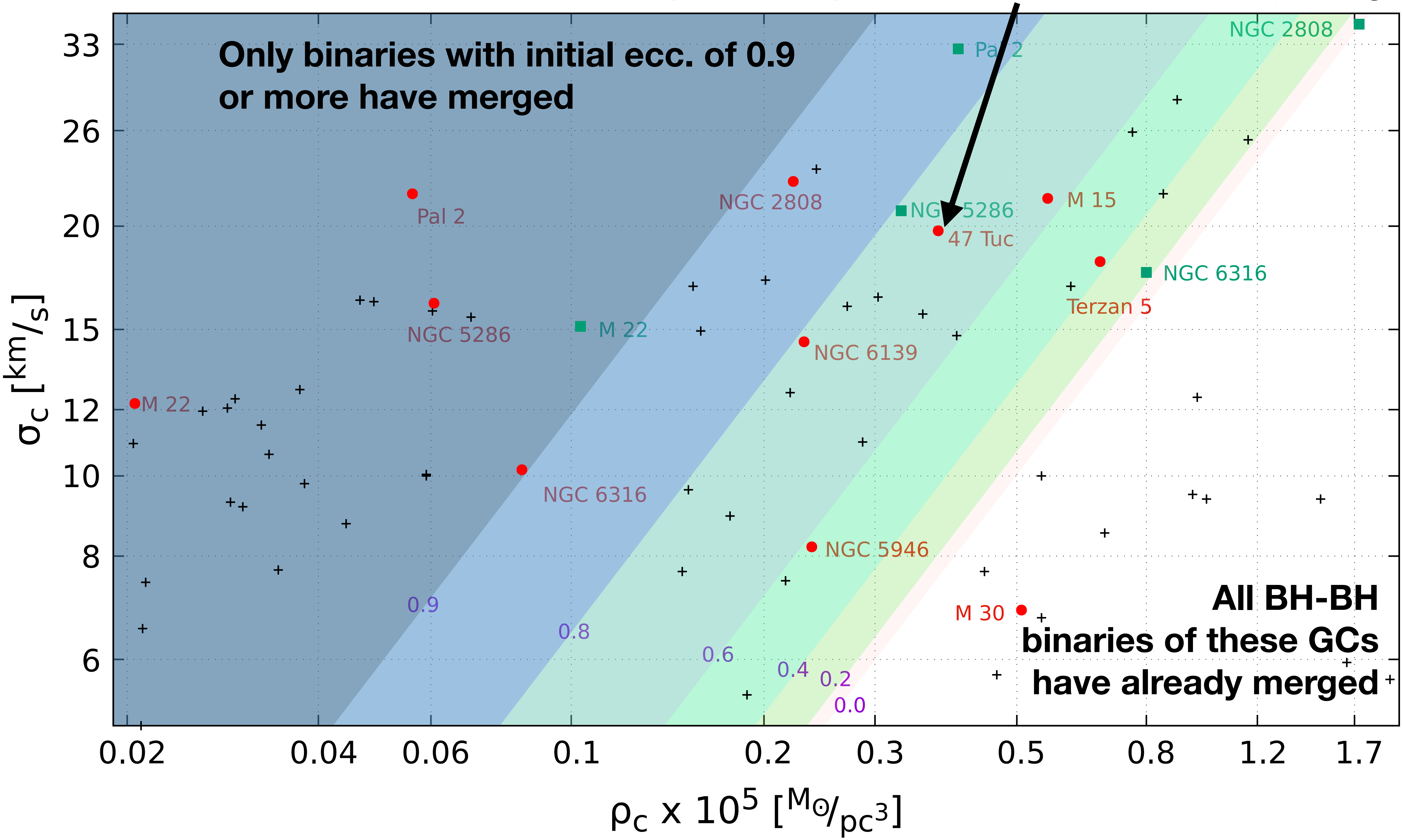


Connecting to the observed properties of Milky Way Globular Clusters



Connecting to the observed properties of Milky Way Globular Clusters

About half of the BH-BH binaries (ecc. > 0.7) inside 47 Tuc have already merged



Concluding

- Once averaging over the Milky Way sample third-body soft interactions give an averaged rate of $2 - 4 \times 10^{-10} \mathrm{yr}^{-1}$ per cluster.

- Accounting for direct capture events adds $0.3 - 5 \times 10^{-11} \mathrm{yr}^{-1}$ per cluster.

- The BBH mergers inside globular clusters can be responsible for ~100 mergers per year up to redshift of z=1.

- We have made a connection between the observed properties of clusters and the expected BH-BH merger events.

- Further observations of cluster properties on their total mass, density and velocity profiles and a better modeling of their cosmological distribution will allow us to more accurately evaluate those environments' contribution to the coalescence events observable from GW detectors.