SAPIENZA
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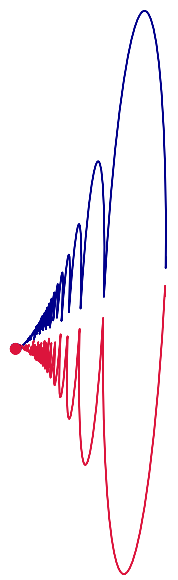
Tor Vergata

Stellar Black Hole Binary Mergers in Open Clusters



Sara Rastello

Collaborators: P. Amaro-Seoane, M. Arca-Sedda, R. Capuzzo Dolcetta, G. Fragione, I.Tosta e Melo

MODEST 18, Santorini, Greece

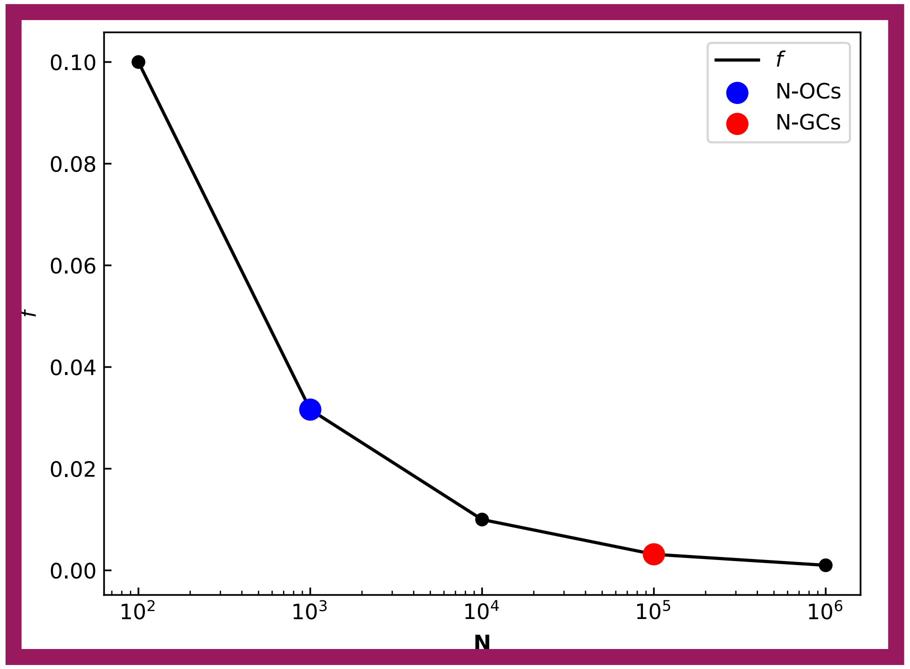
27/06/2018

WHY OPEN CLUSTERS?

- Large fluctuations (amplitude $f = \sqrt{N}/N$) over the mean field can significantly affect the BHB evolution

$N_{GCs} = 10^6$	$>$	$N_{OCs} = 10^3$
$f = 1.0 \cdot 10^{-3}$	$<$	$f = 3.2 \cdot 10^{-2}$

$\longrightarrow$



- Stochastic fluctuations affect the Two-body relaxation timescales (t) *(Spitzer 1987)*

$\longrightarrow$

$$\frac{t_{OC}}{t_{GC}} = \frac{1}{f}\frac{\log(0.11\ N_{OC})}{\log(0.11\ N_{GC})}\left(\frac{R_{OC}}{R_{GC}}\right)^{3/2} \sim 0.02$$

- Short relaxation timescale $\longrightarrow$ short computational times

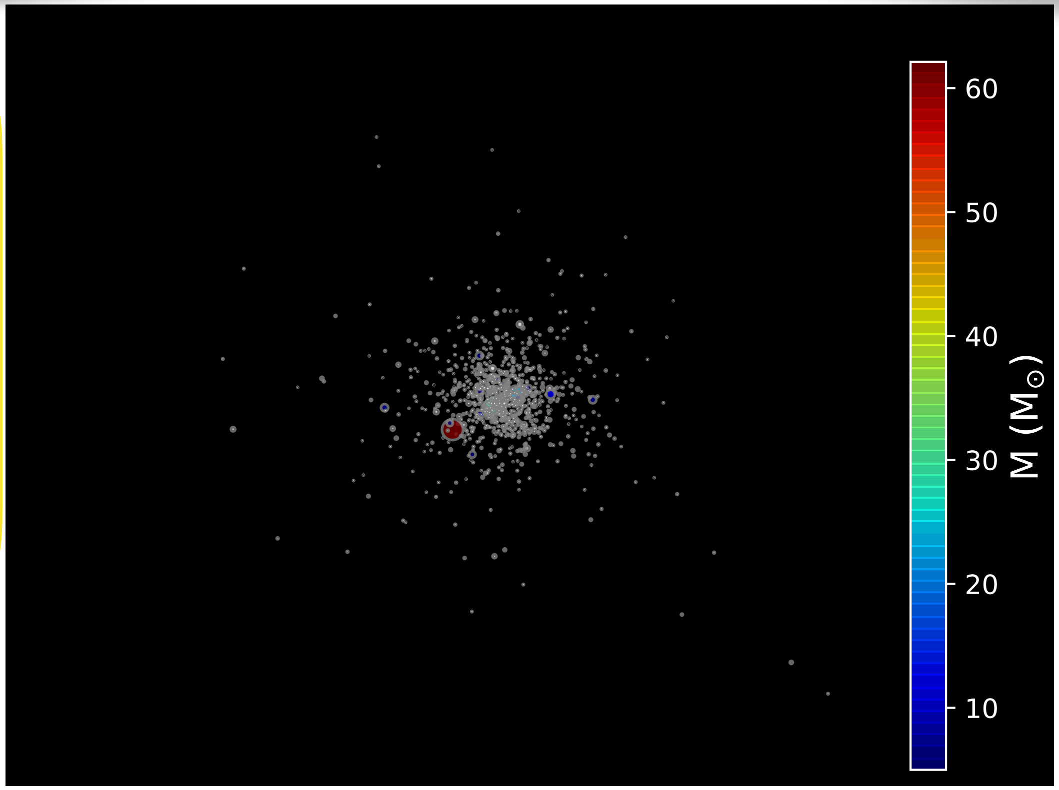
- Low number of stars allows us to fully integrate the system without re-scaling results.

Method and Models

Suite of direct N-Body simulations with **NBODY7** *(Nitadori & Aarseth 2012)*

Cluster		BHB		N-body set
N_{cl}	M_{cl} ($M_\odot$)	a (pc)	e	Model
512	3.2×10^2	0.01	0.0 0.5	A00 A05
1024	7.1×10^2	0.01	0.0 0.5	B00 B05
2048	1.4×10^3	0.01	0.0 0.5	C00 C05
4096	2.7×10^3	0.01	0.0 0.5	D00 D05

All isolated cluster
Plummer density Profile
Virial equilibrium
r_c=1 pc
Kroupa IMF
Z solar
Proxy of the MW OCs



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150 different realisation of each model evolved for ~3 Gyr

All isolated cluster
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Virial equilibrium
r_c=1 pc
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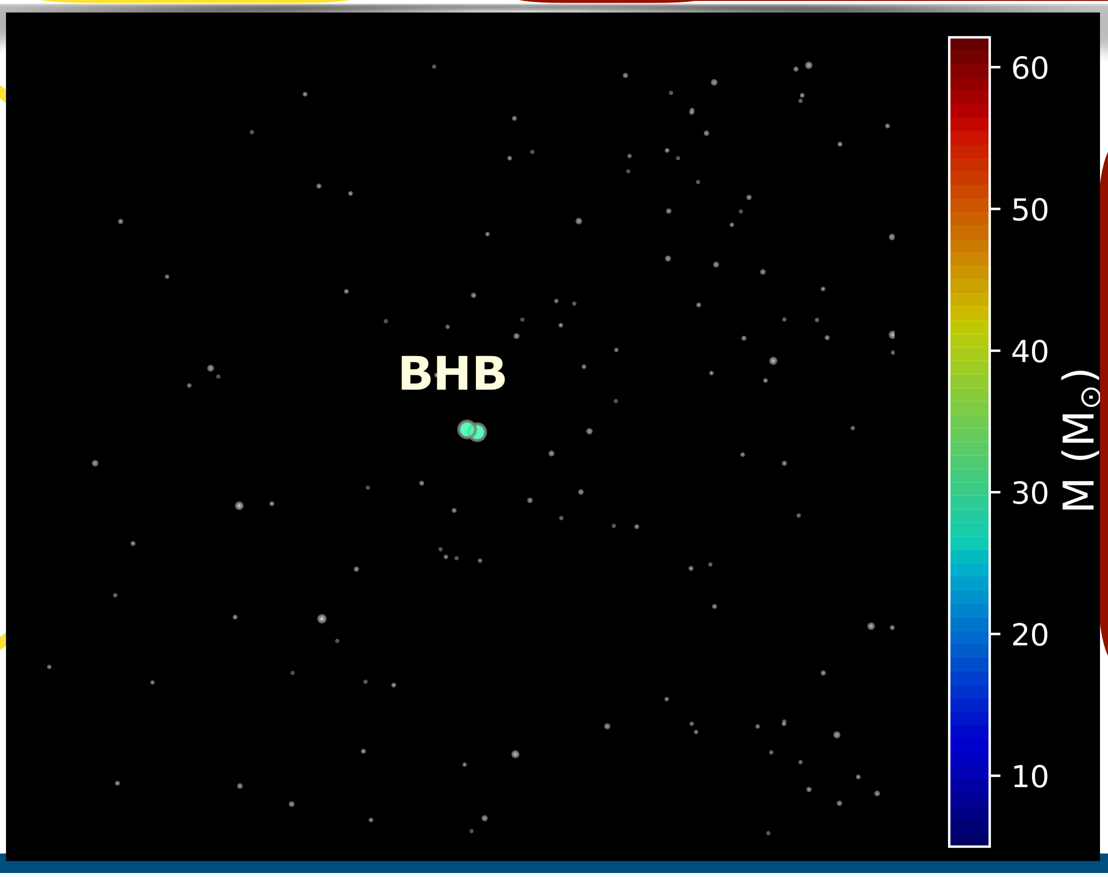
Proxy of the MW OCs



Hard BHB initially at the center of the cluster
BHs 30 & 30 Ms (*,**)
a_i = 0.01 pc
P = 0.012 Myr
e_i = 0.0
e_i = 0.5

*Abbott ate al., 2016a

**Amaro-Seoane & Chen 2016

Results: Dynamics

3 evolutionary channels:

Model	Harder %	Wider %	Break up %
A00			
A05			
B00			
B05			
C00			
C05			
D00			
D05			

increasing mass

RESULTS: DYNAMICS

3 evolutionary channels:

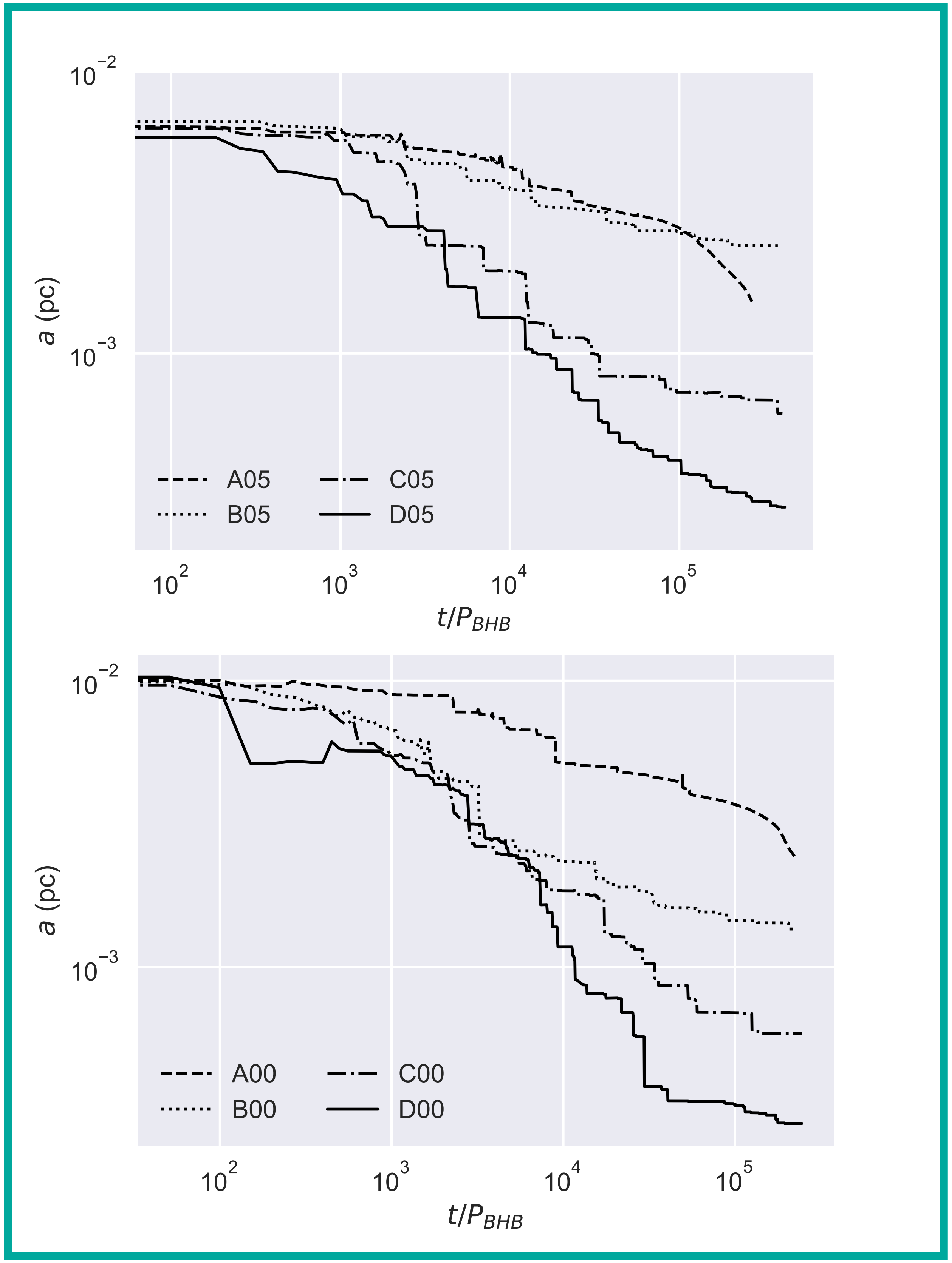
Model	Harder %	Wider %	Break up %
A00	89.1	7.9	2.9
A05	97.1	2.1	0.7
B00	92.5	2.7	4.8
B05	94.0	2.0	4.0
C00	93.6	0	6.4
C05	96.5	0	3.5
D00	94.2	0	5.8
D05	97.1	0	2.8

increasing mass

Harder BHB ~95% of the cases

Shrink the semi major axis up to 2-3 order of magnitude

Initially eccentric BHB → higher % of harder BHBs



Results: Dynamics

3 evolutionary channels:

increasing mass ↓

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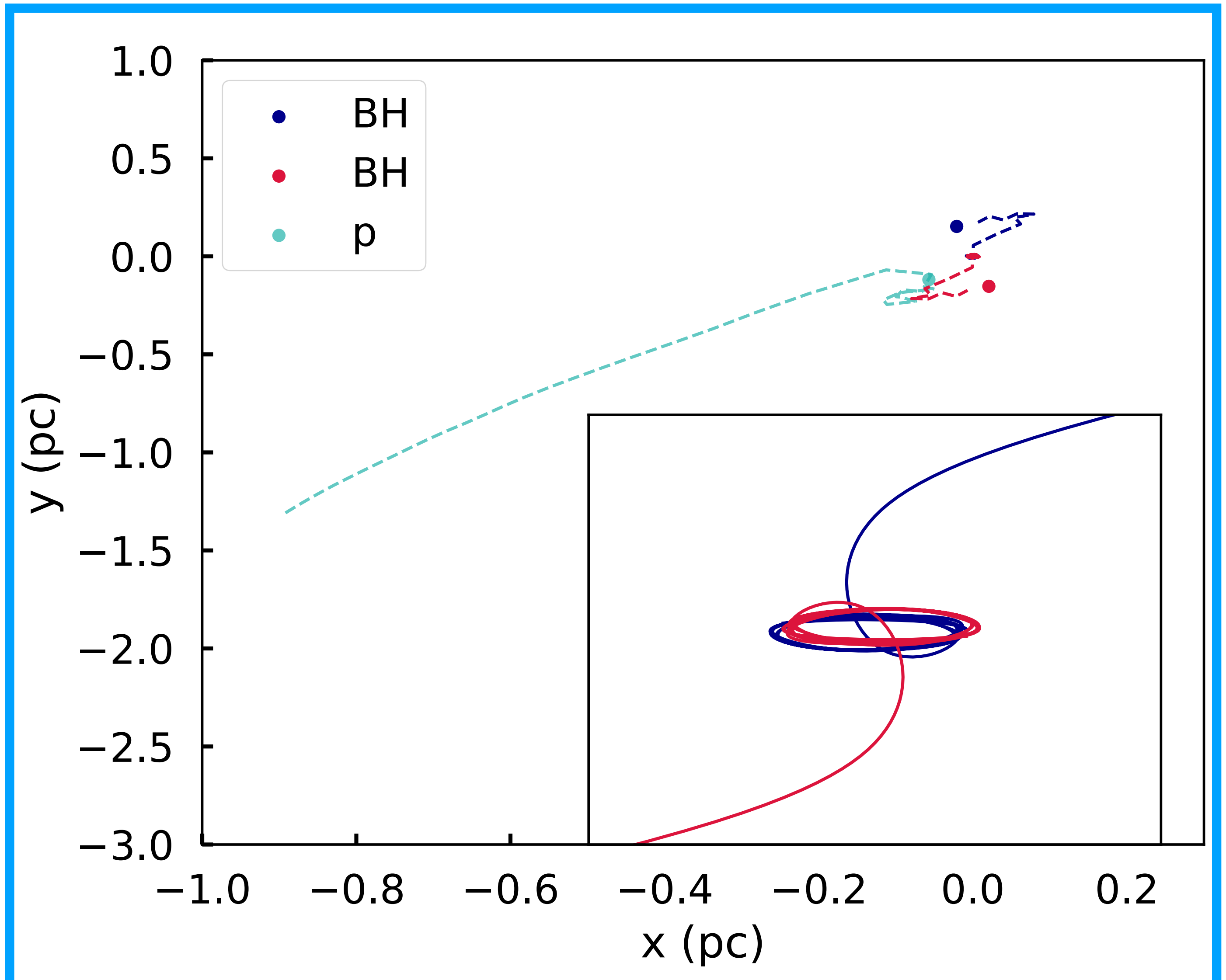
D05	97.1	0	2.8

Wider BHB ~ 1.2 %, few cases

The semi major axis increases

The BHs remain bound each other

Typical of very low mass clusters



A pertuber star (a massive MS star) interacts with the BHB. The binary semi major axis increases.

RESULTS: DYNAMICS

3 evolutionary channels:

increasing mass

Model	Harder %	Wider %	Break up %
A00	89.1	7.9	2.9
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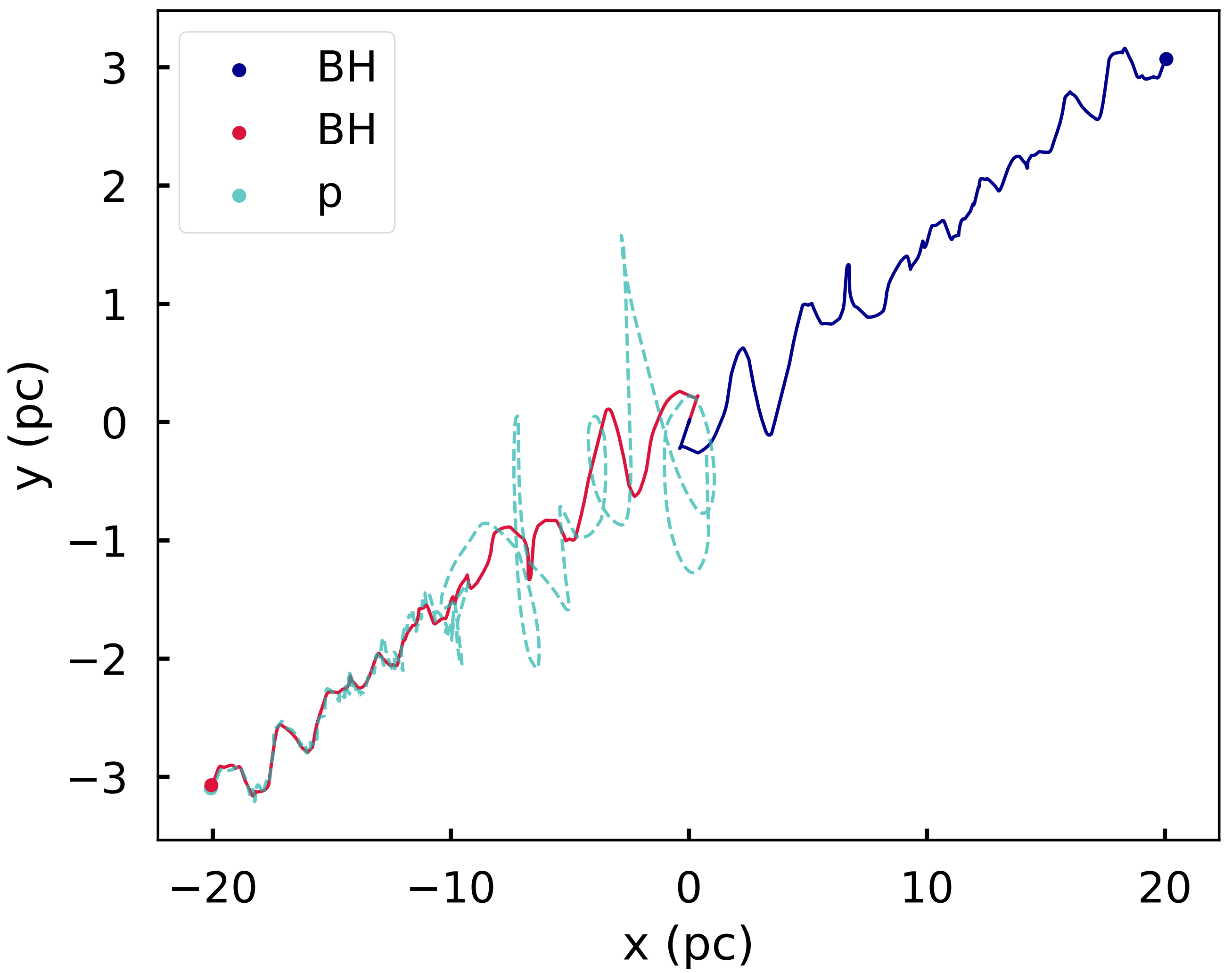


Disrupted BHBs ~ 4.8 %

Higher % in models with initial $e_i = 0$

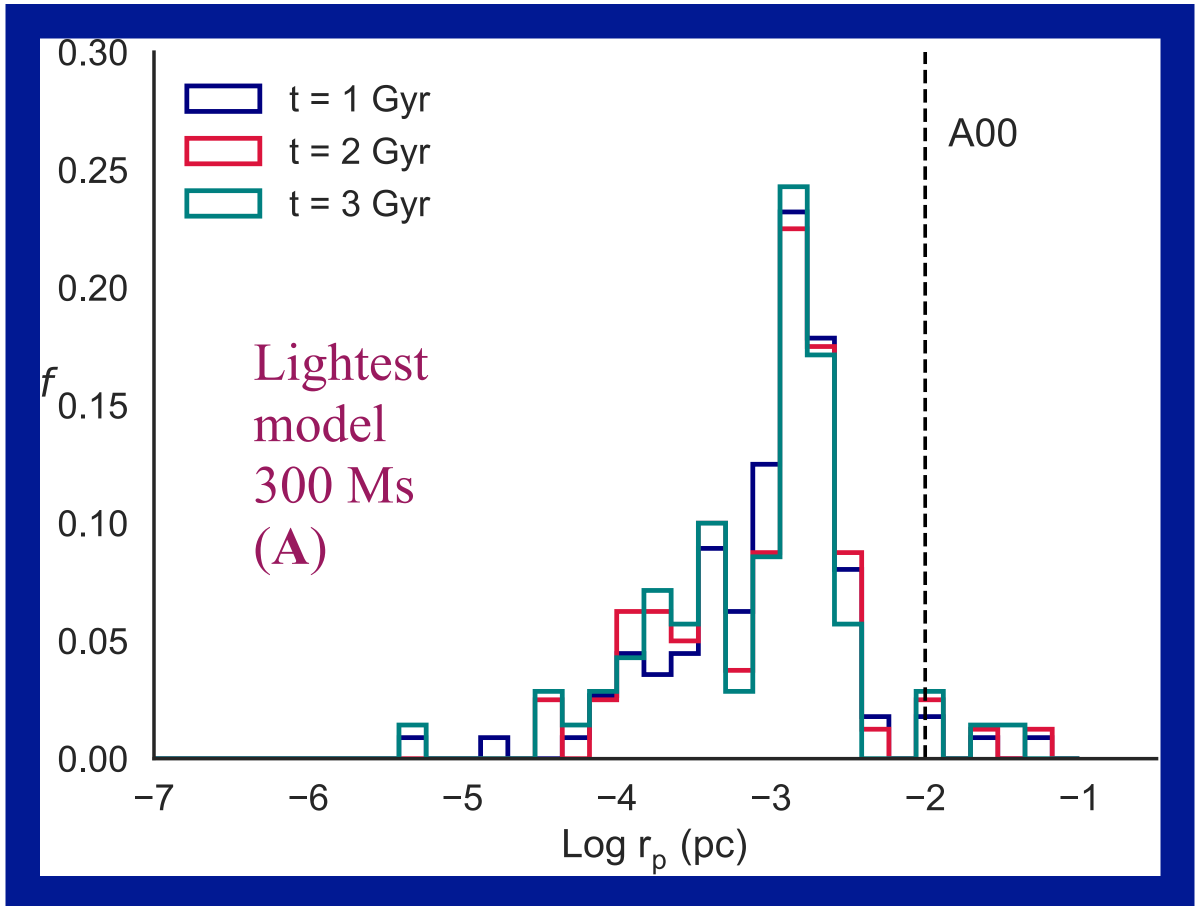
The single BHs tend to form new binary With the pertuber, which survives for a short period

Disruption occurs between ~5 and ~100 Myr

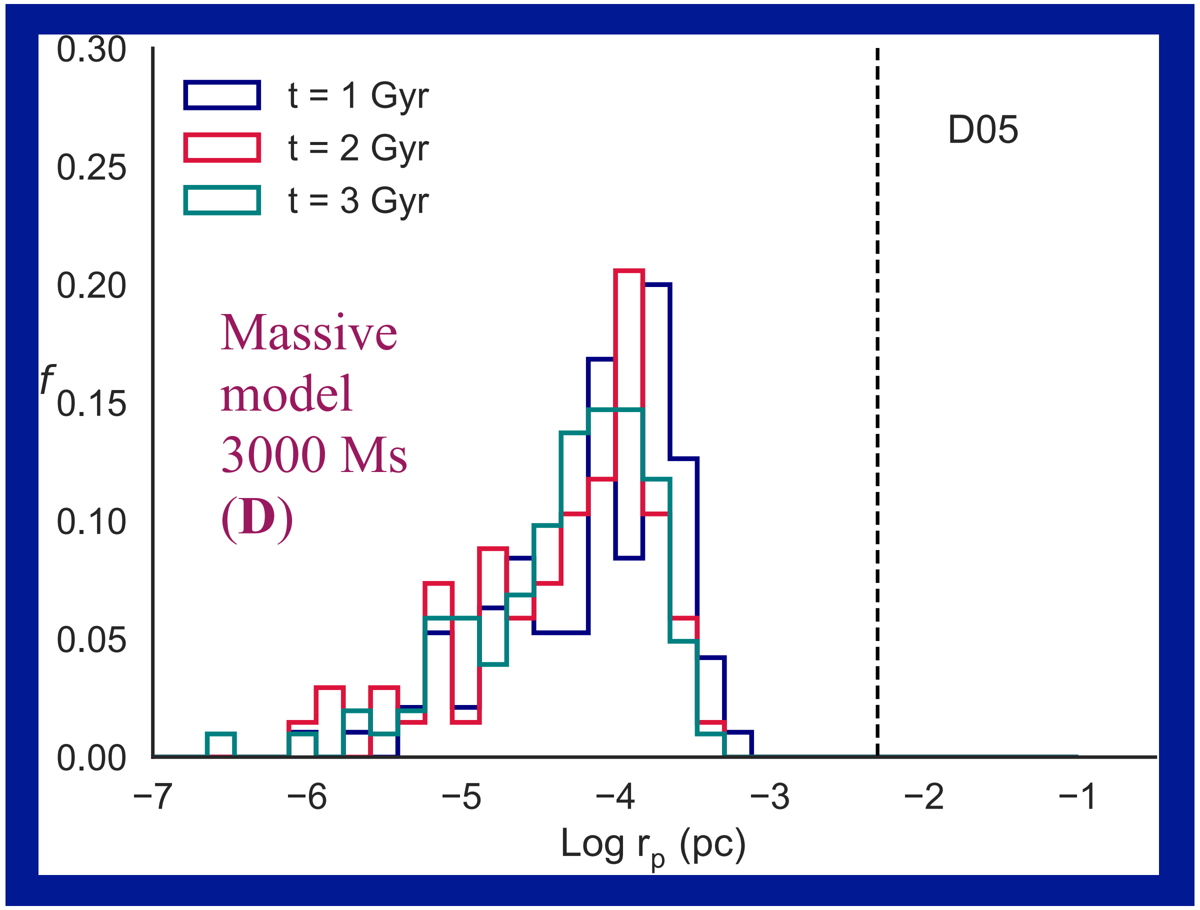
A pertuber star interacts with the BHB that breaks up. In this particular case both the BHs will escape from the OC.

Results: Dynamics

BHB Pericenter (r_p) Distribution



In very low mass clusters (**A**) r_p decreases on average of one order of magnitude after 1 Gyr. Very few cases of shrinking up to 3,4 order of magnitude. Some case of binaries that become wider.



In massive clusters (**D**) r_p decreases on average of two order of magnitude after 1 Gyr. After 3 Gyr there are cases in which r_p shrinks up to 10^{-7} pc. No wider BHBs found.

OUTCOME 1

The gravitational encounters of a massive BHB in a low dense environment, such as an Open Cluster, are efficient enough to significantly shrink the BHB semi major axis and pericenter after few Gyr.

The dominant evolutionary channel is that the BHBs get harder.

Massive OCs are more efficient in favouring the BHB shrinkage but also the initial orbital eccentricity plays a key role.

Merging BHBs

Outcome 1 → ***Can OCs be candidates for hosting BHBs mergers?***

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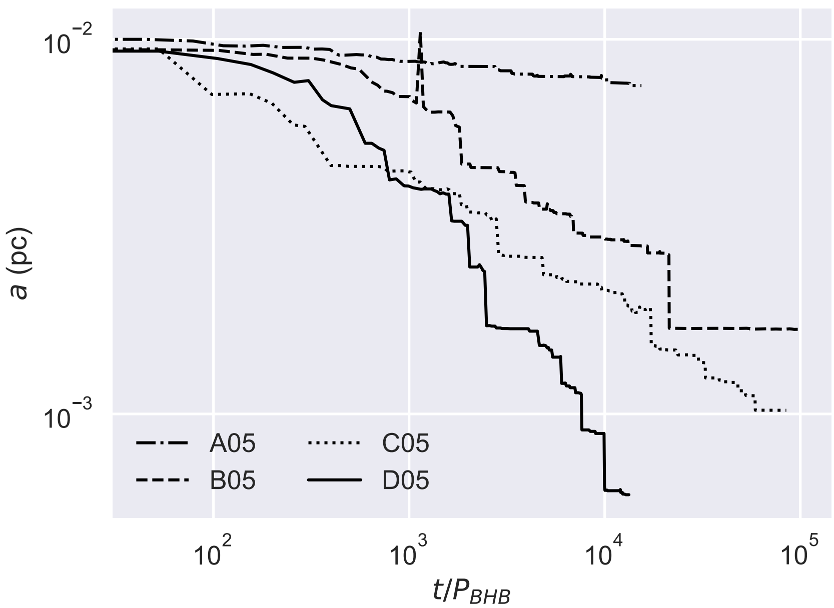
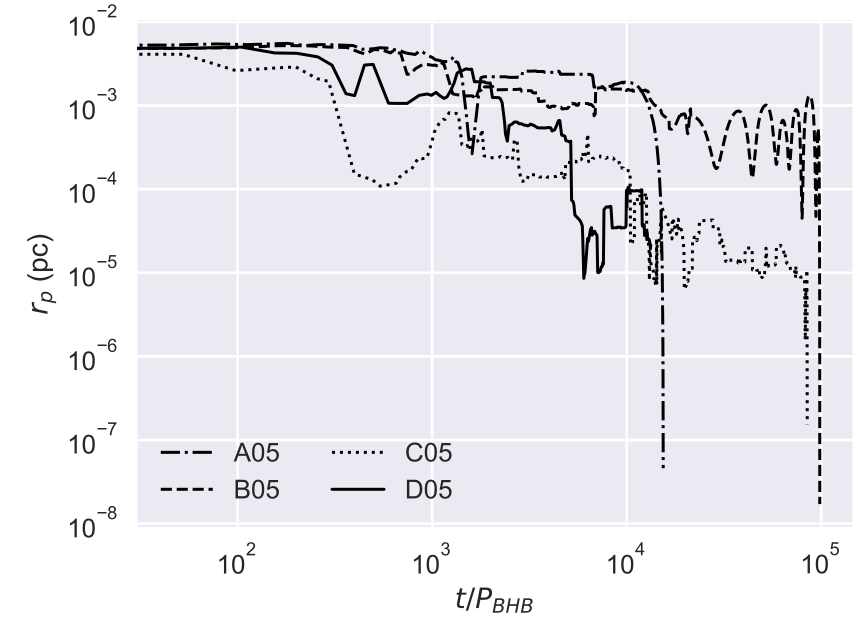
Yes!



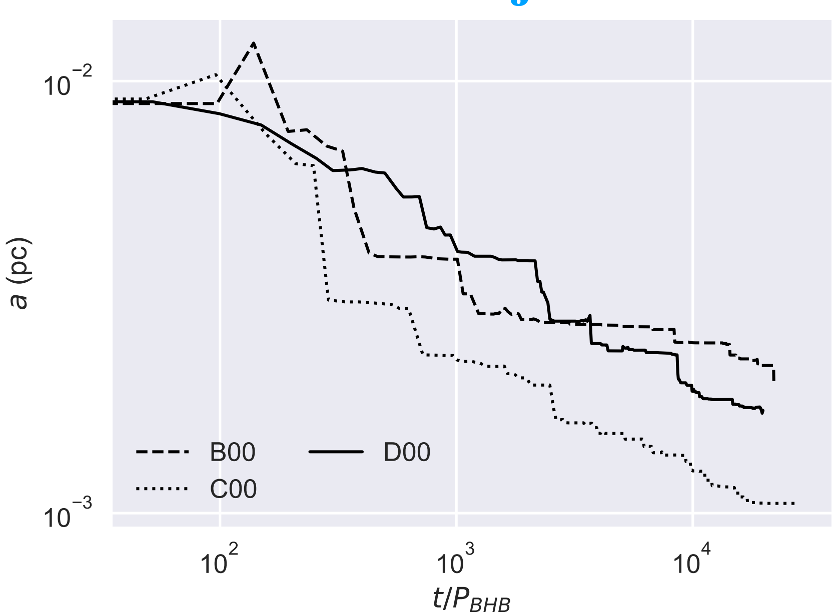
Semi maj. Axis

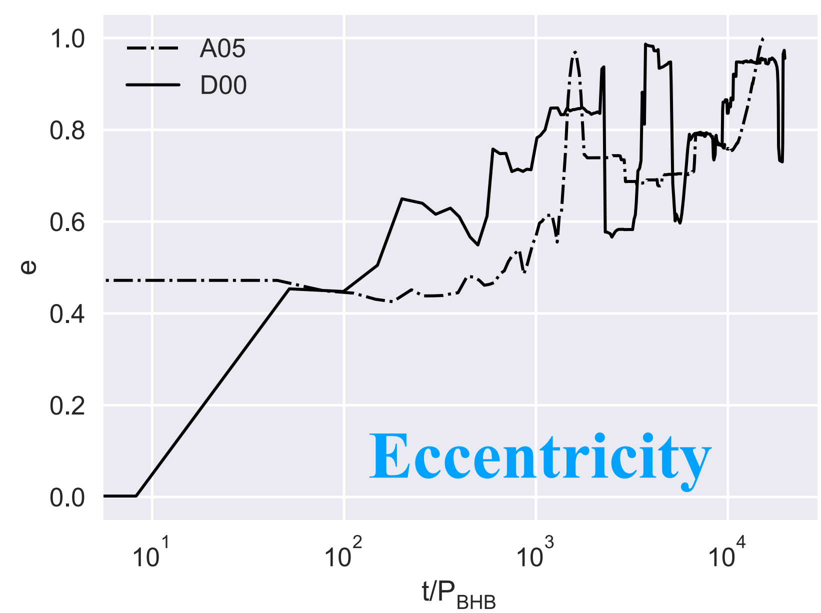
increasing mass

Model	% Mergers
A00	0.0
A05	0.7
B00	0.7
B05	0.7
C00	2.1
C05	4.3
D00	7.1
D05	5.7

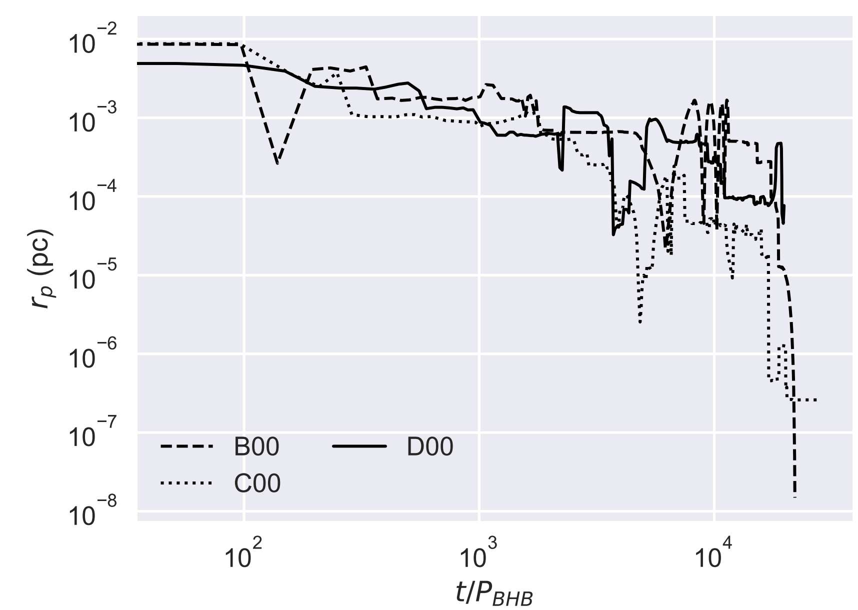


Pericenter



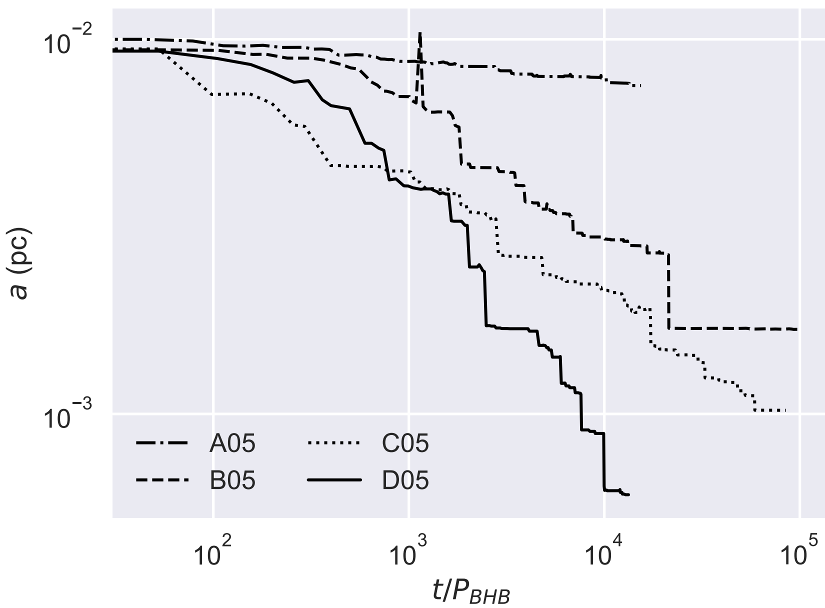


Eccentricity



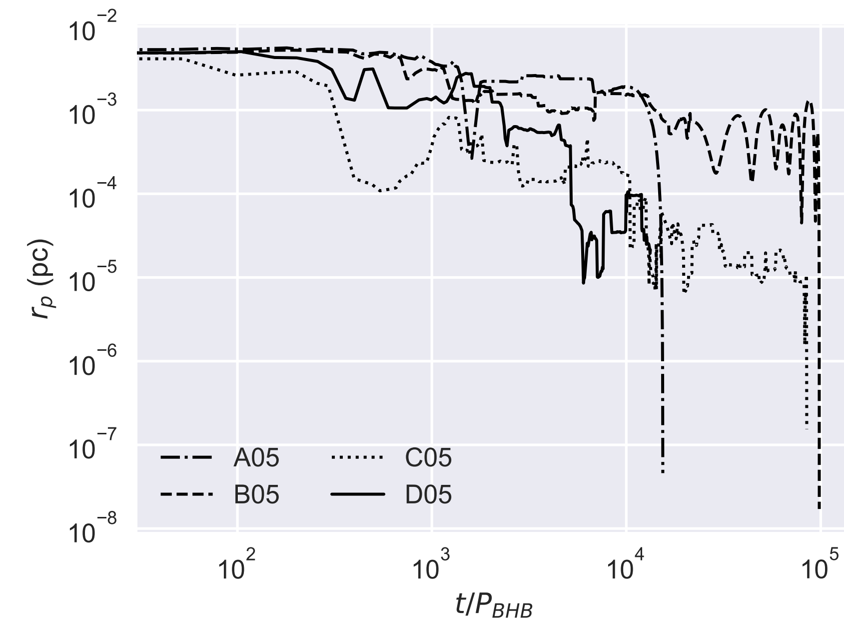
MERGING BHBS

More massive OCs → higher % of mergers.
All mergers occur inside the clusters.
Coalescence time ranges between 5 Myr and 1.5 Gyr (NBODY7)



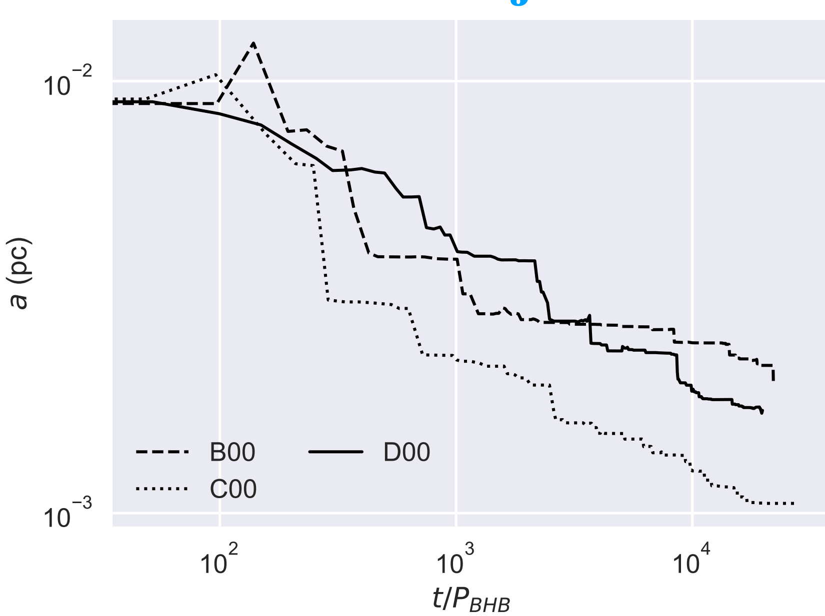
increasing mass

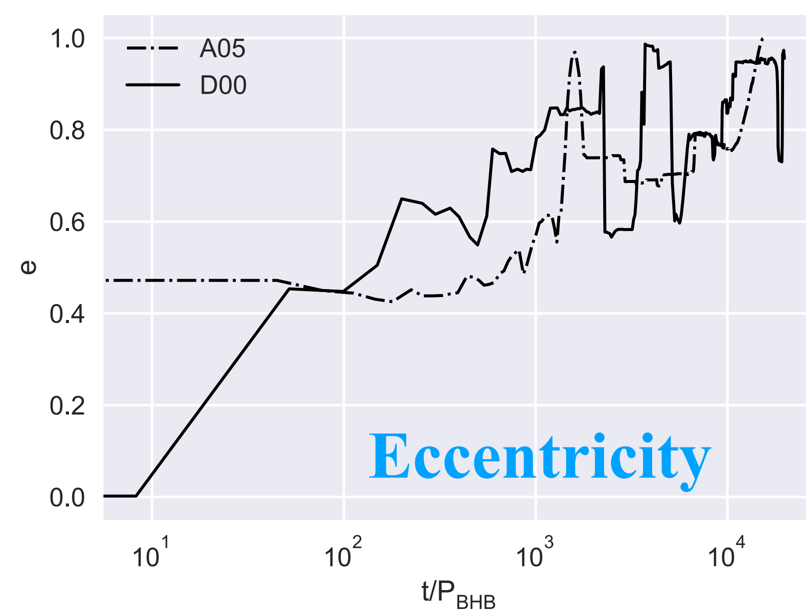
Model	% Mergers
A00	0.0
A05	0.7
B00	0.7
B05	0.7
C00	2.1
C05	4.3
D00	7.1
D05	5.7

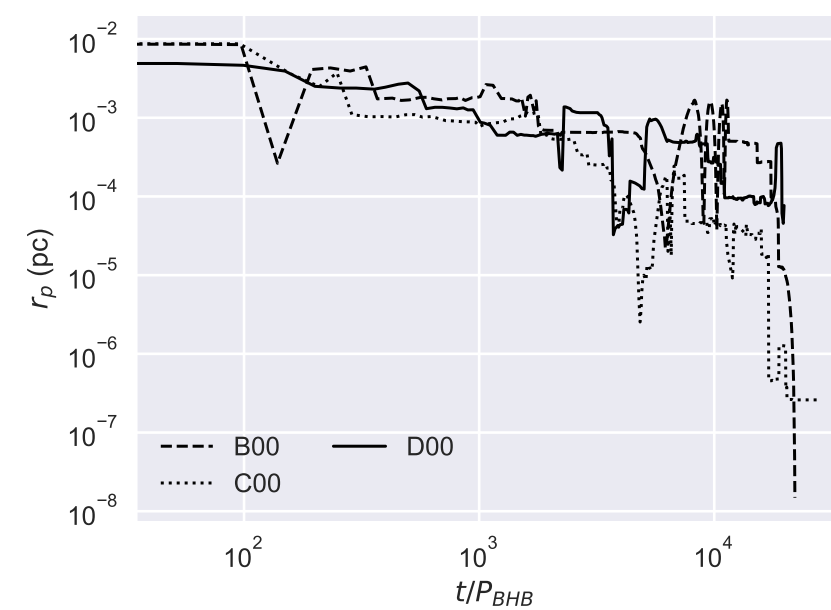


Semi maj. Axis

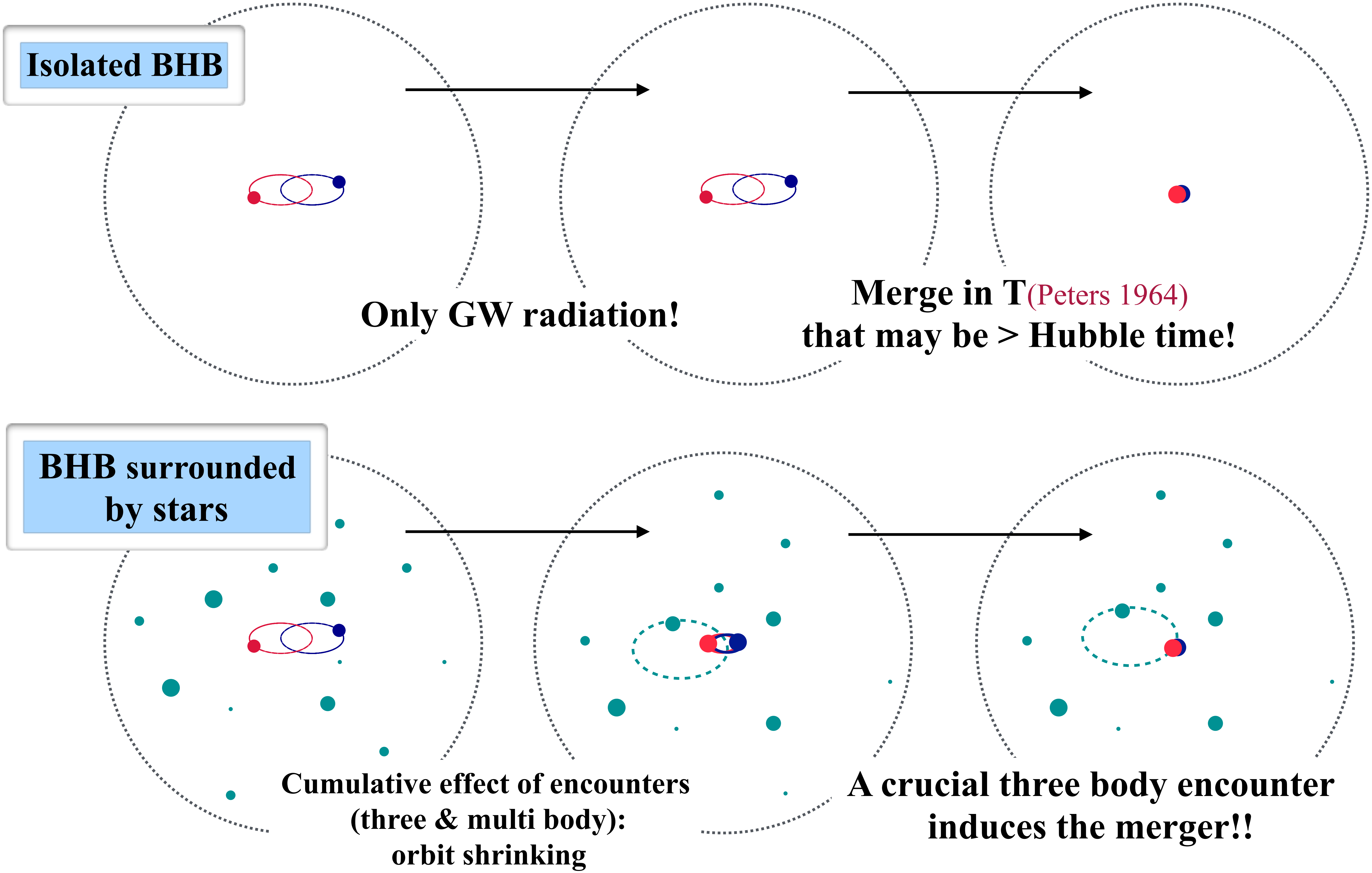
Pericenter







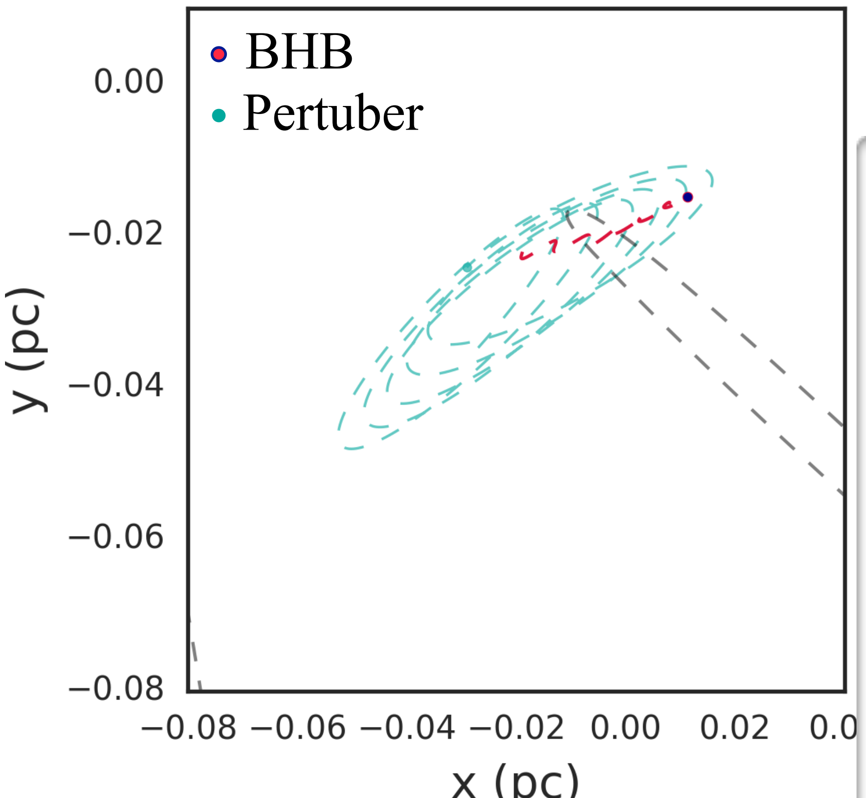
MERGING BHBS

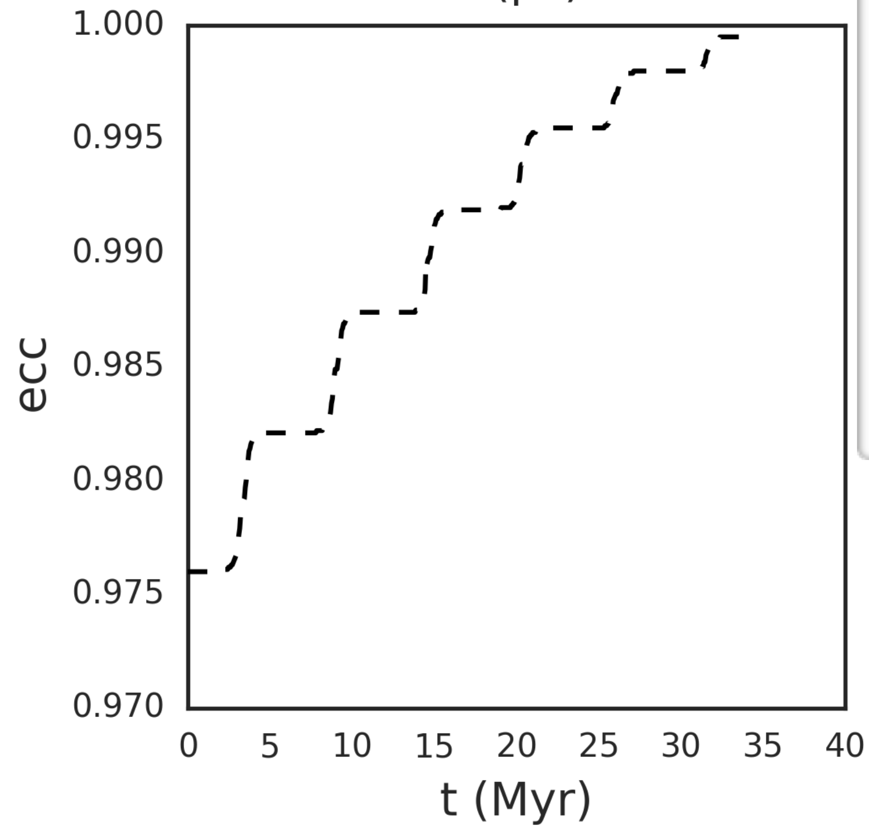


A DETAILED MERGER EXAMPLE

A detailed merger example studied with ARGDF*

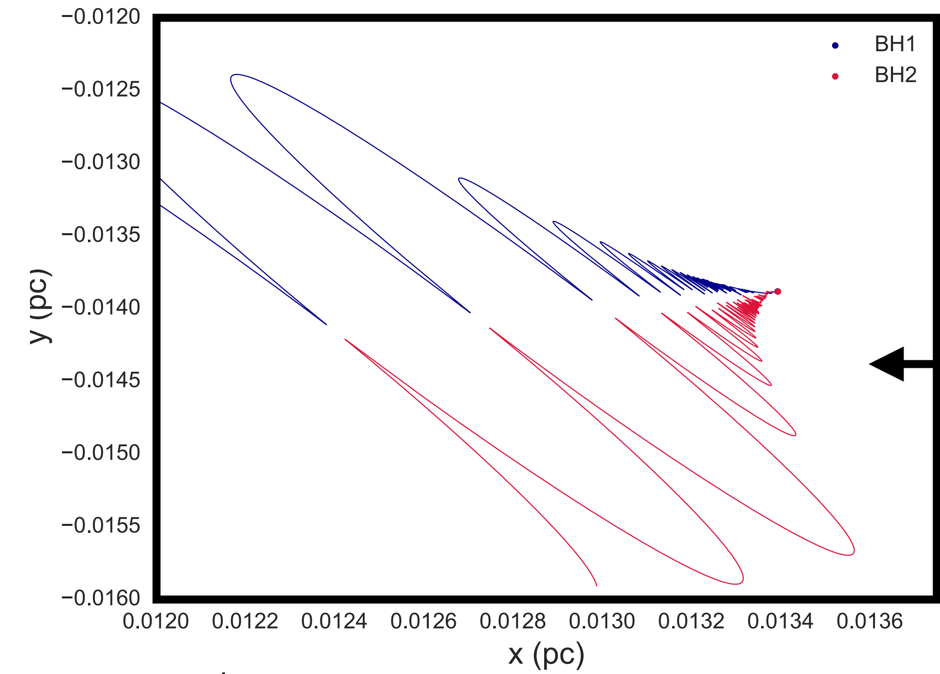
*(*Arca Sedda & Capuzzo-Dolcetta 2017, Mikkola 1999)*

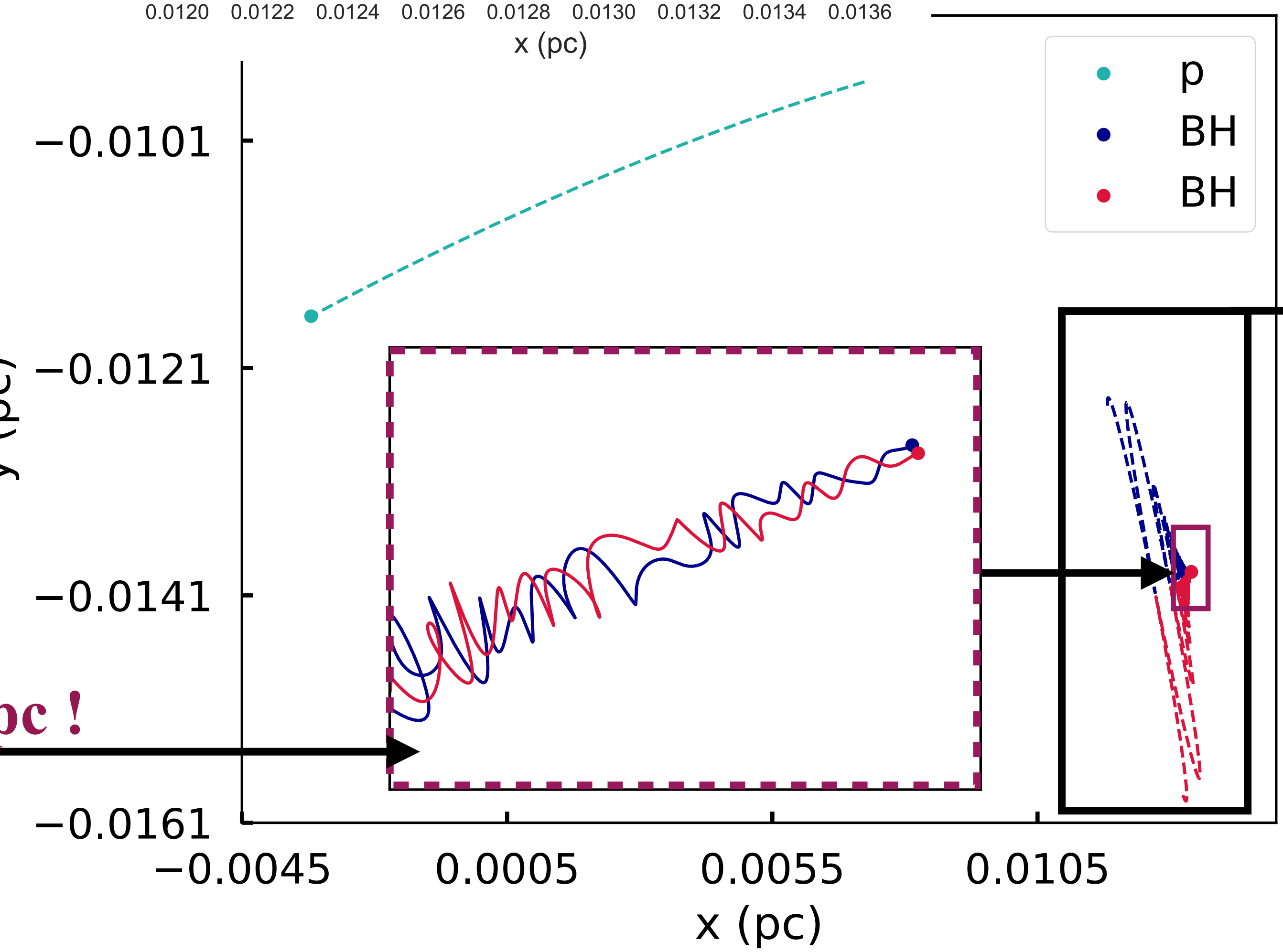




The BHB shrinks interacting with a third star (pertuber): **THREE BODY ENCOUNTER**

Each orbit of the perturber around the BHB make it increases the eccentricity up to value close to 1.

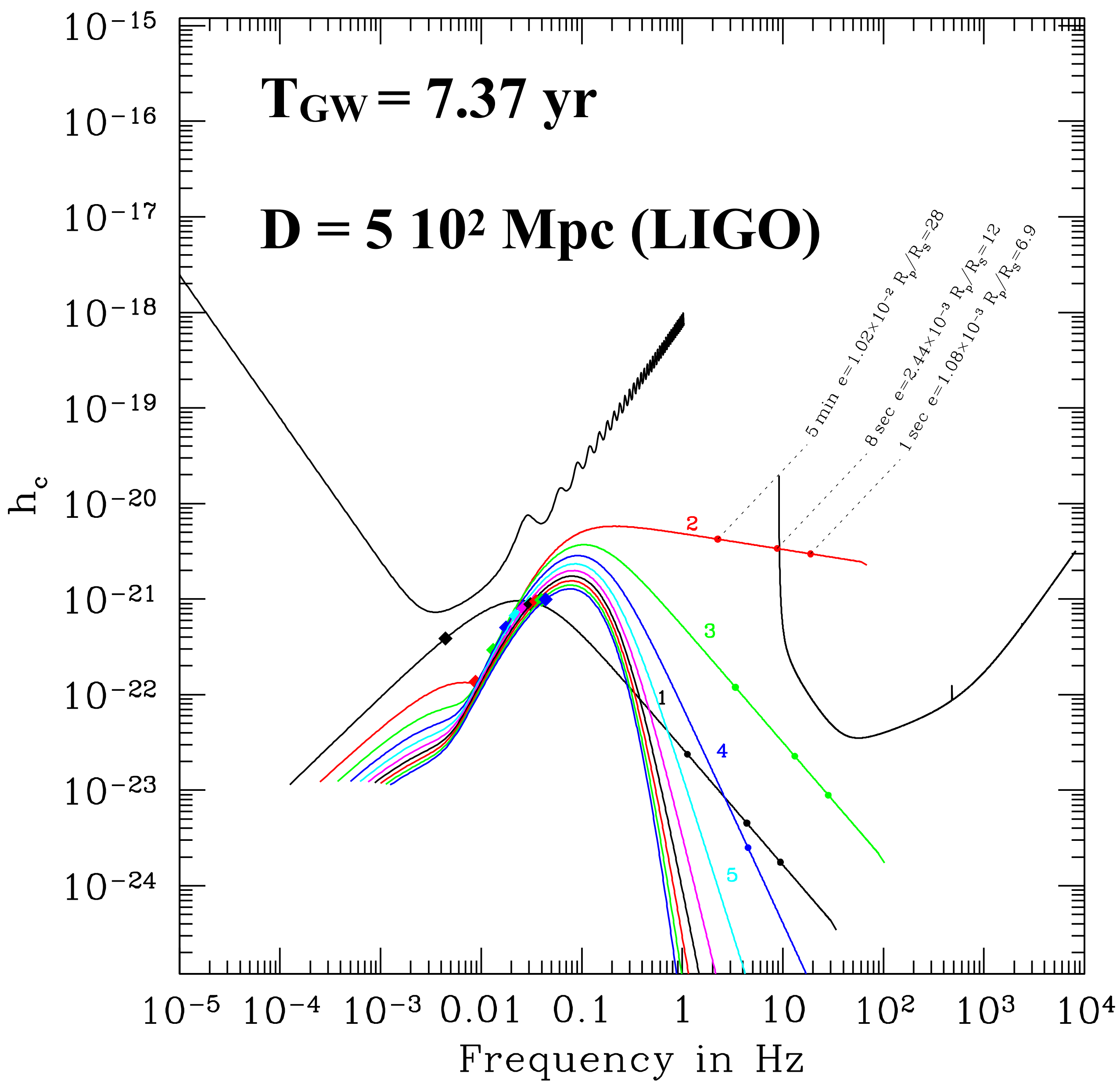


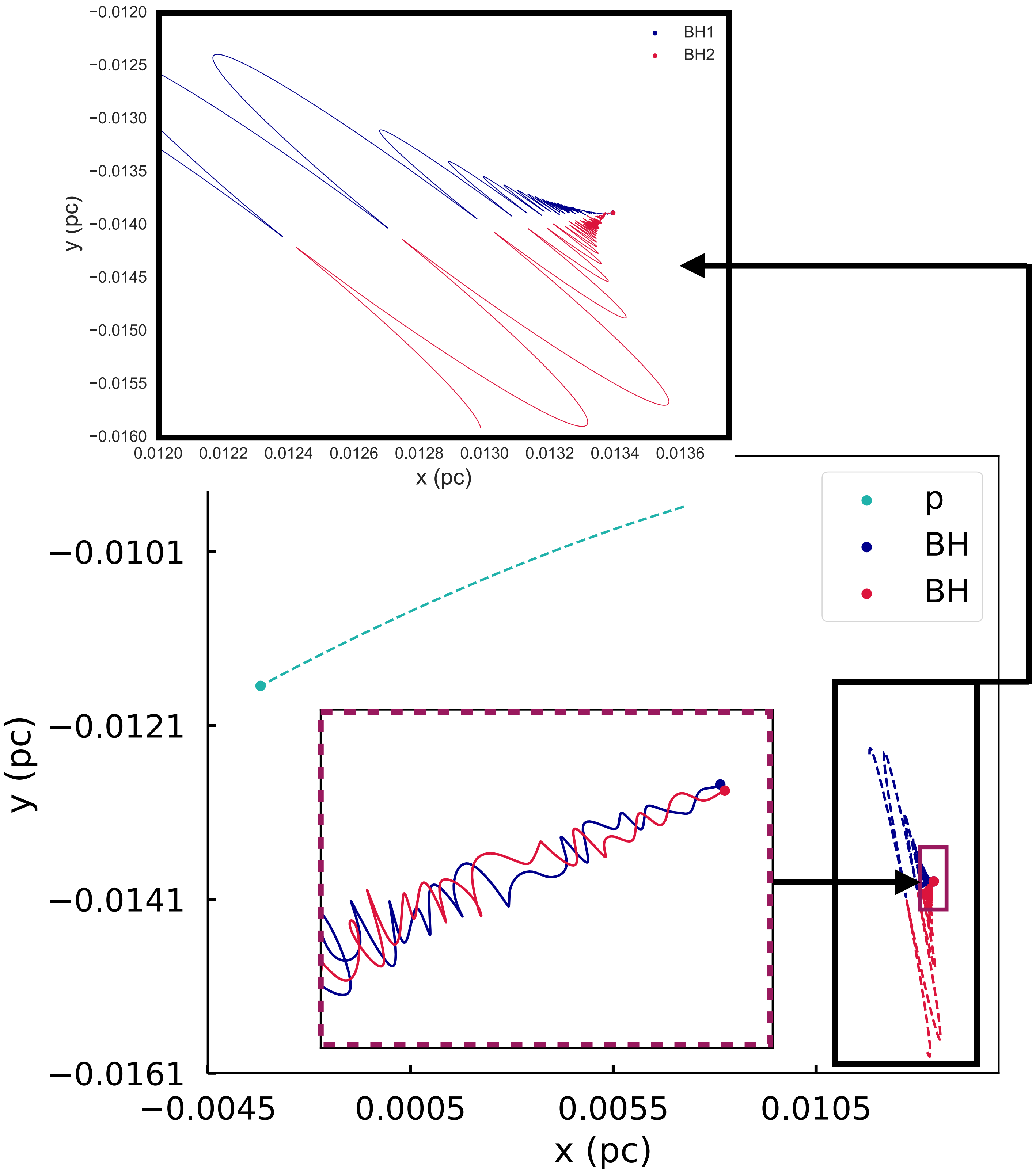


Scales here 10^{-7} pc !

A DETAILED MERGER EXAMPLE

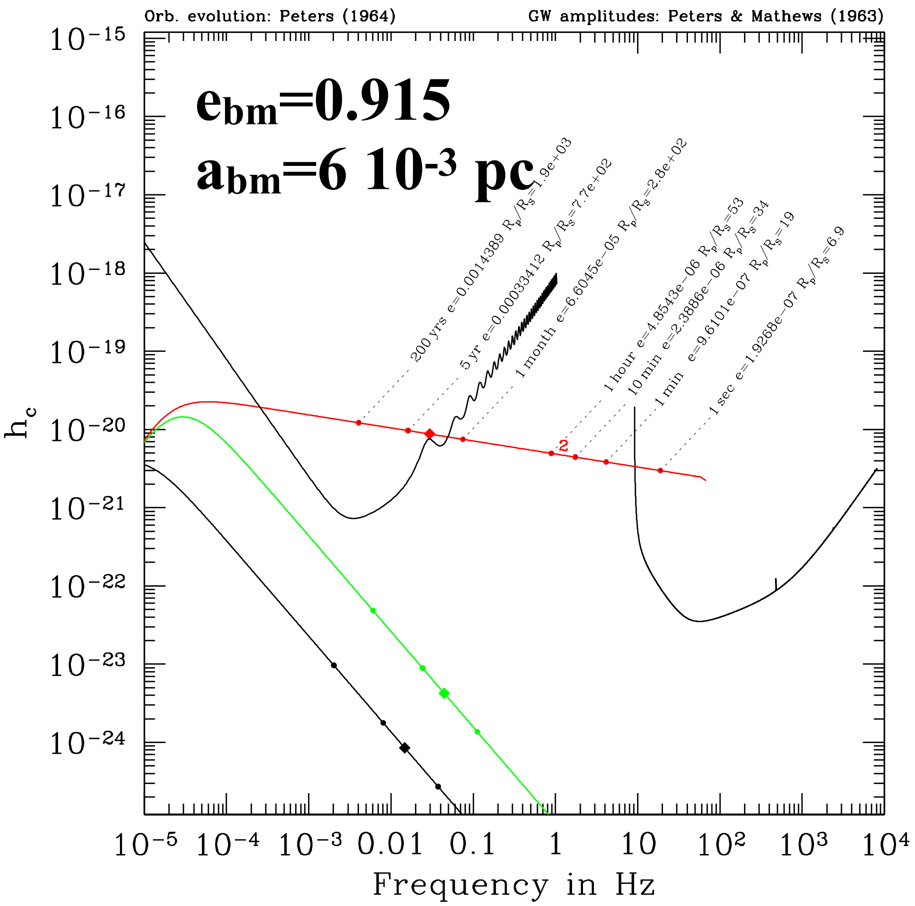
A detailed merger example studied with ARGDF* *(*Arca Sedda & Capuzzo-Dolcetta 2017, Mikkola 1999)*



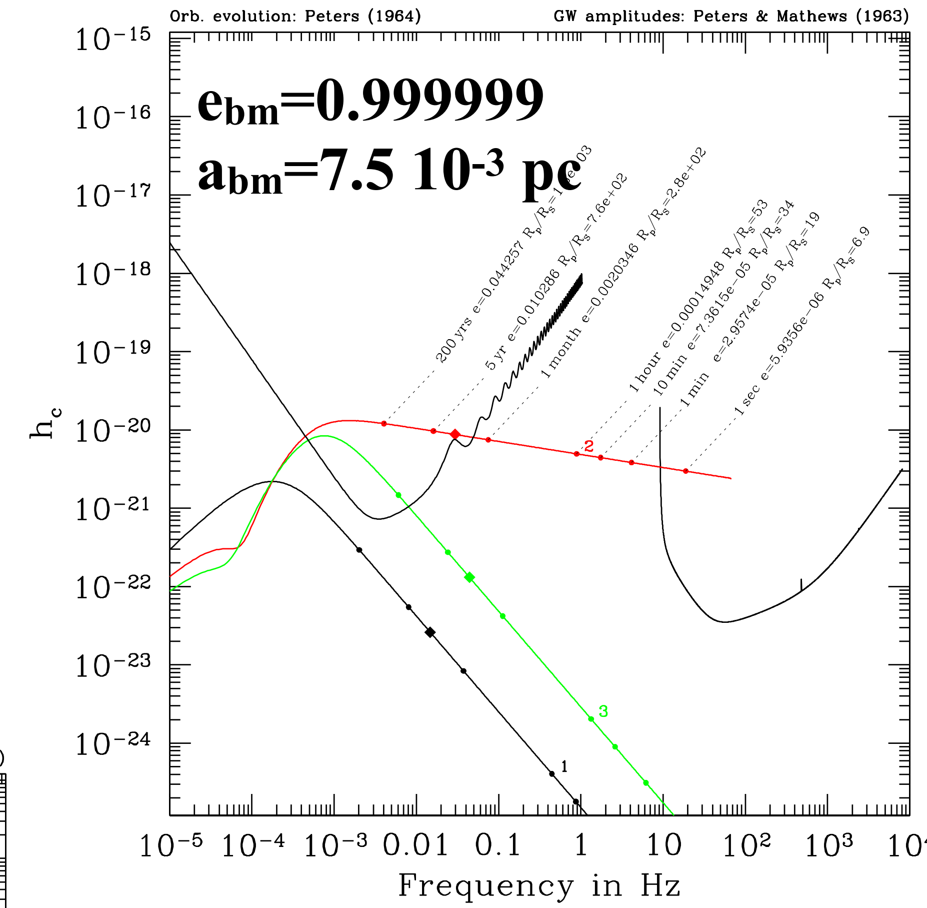


High eccentricity makes this coalescence event audible only by LIGO, because LISA is "deaf " *(Chen, Amaro Seoane 2017)*

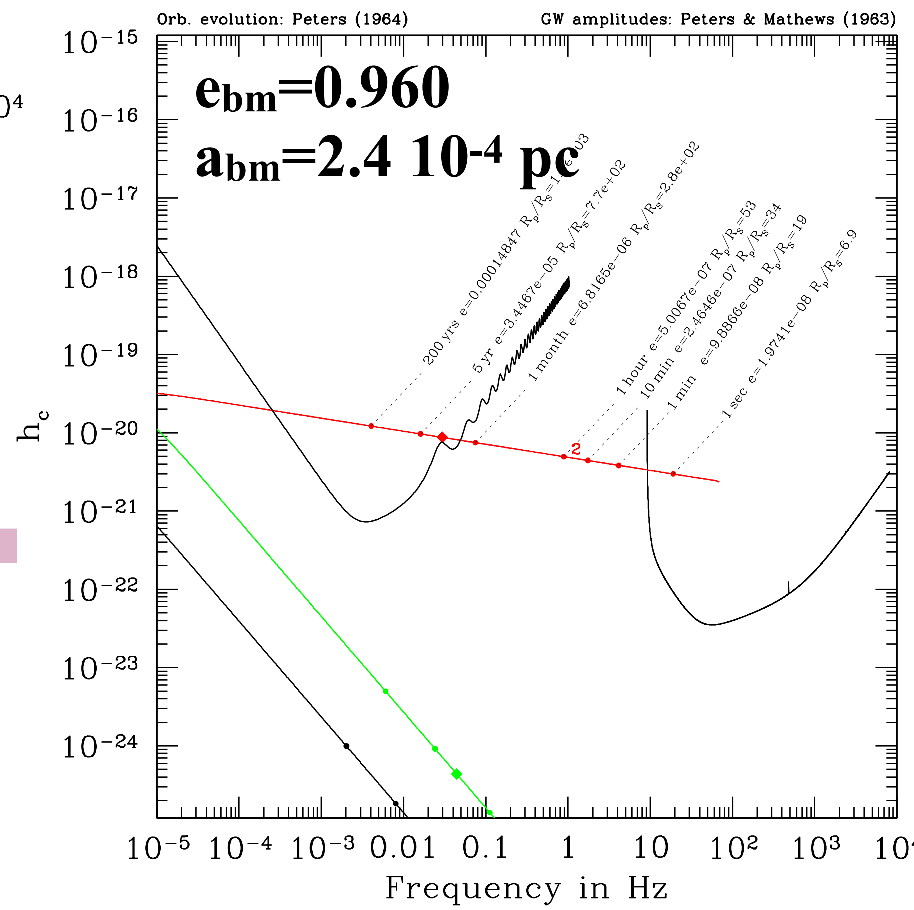
GWS: LISA VS LIGO



Some examples of coalescing BHBs….



Audible both by LISA and LIGO!!



Eccentricity & Semi-Major Axis → **Fundamental ingredients!**

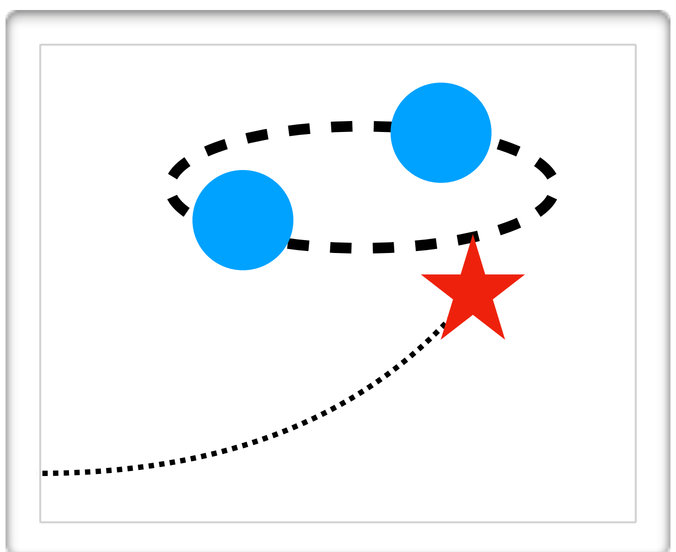
Tidal Disruption Events

Supplementary models

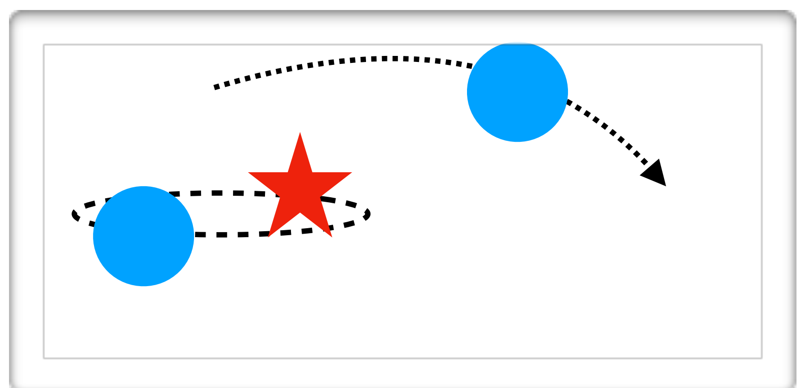
Model	M_1 $M_\odot$	M_2 $M_\odot$	q	Z $Z_\odot$	SE	P_{TDE} %
M1	30	30	1	10^{-4}	BSEB	2.8
M2	30	30	1	10^{-4}	BSE	6.9
M3	13	7	0.54	1	BSE	14.0
M4	30	7	0.23	1	BSE	28.5
M5	30	30	1	10^{-4}	BSE	0.0

$\sim 3\ 10^3\ M_\odot$

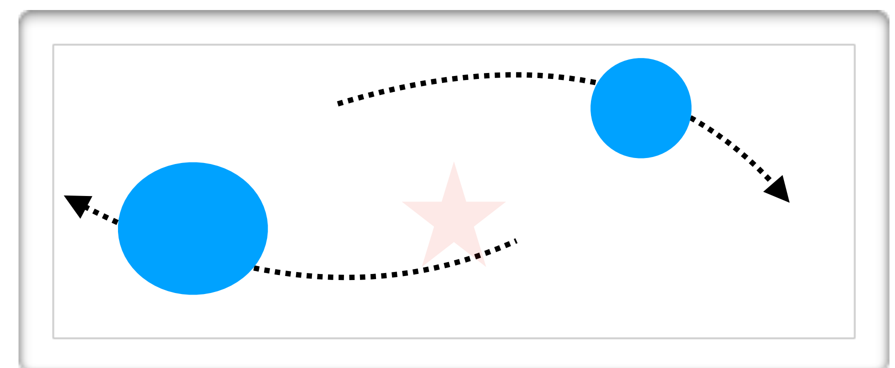
Process involve Main sequence stars (**MS**), stars in the core He burning phase (**HB**) or in the early asymptotic giant branch (**AGB**) phase.



BHB disruption mediated by a third star



BH-star pair formation



TDE,
BH with +10% mass

$$\boldsymbol{\Gamma_{TDE} = 0.3\text{-}3.08\ 10^{-6}\ yr^{-1}}$$

per MW-like galaxies in the Universe

CONCLUSIONS

- **The gravitational encounters between a massive BHB and the stellar population of an Open Cluster-like system are efficient to make the BHB orbit significantly harder**
- **The percentage of BHBs that merge in OCs is of the order of ~ 3 %**
- **All the mergers occur inside the cluster as driven by three body encounters**
- **The coalescence time is in the range ~few Myr ~ 1.5 Gyr**
- **These merger events are audible both by LIGO and LISA.**
- **Assuming the number of OCs in the MW (10^5, Piskunov 2008 & Portegies Zwart et al. 2010) and the fraction of Milky Way-like galaxies inside z = 1 (10^8, Tal 2017) we get the (optimistic) merger rate of: $R \sim 2.1$ yr^{-1} Gpc^{-3}**
- **A serendipity output of our simulations is the TDE rate which is of the order of $\Gamma_{TDE} = 0.3\text{-}3.08\ 10^{-6}$ yr^{-1} per MW-like galaxies in the Universe.**

Rastello et al., 2018 ***(to be submitted)***

THANK YOU!!