Formation and evolution of supermassive BH binaries

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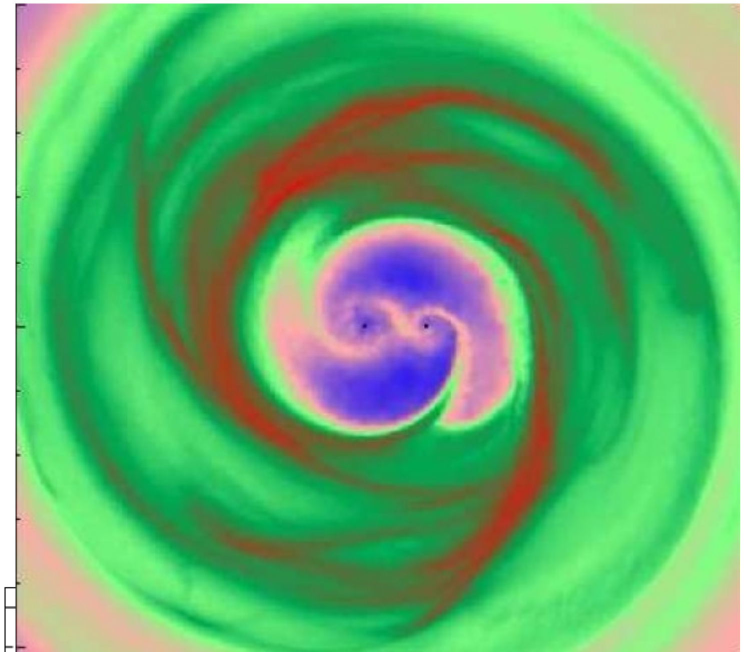
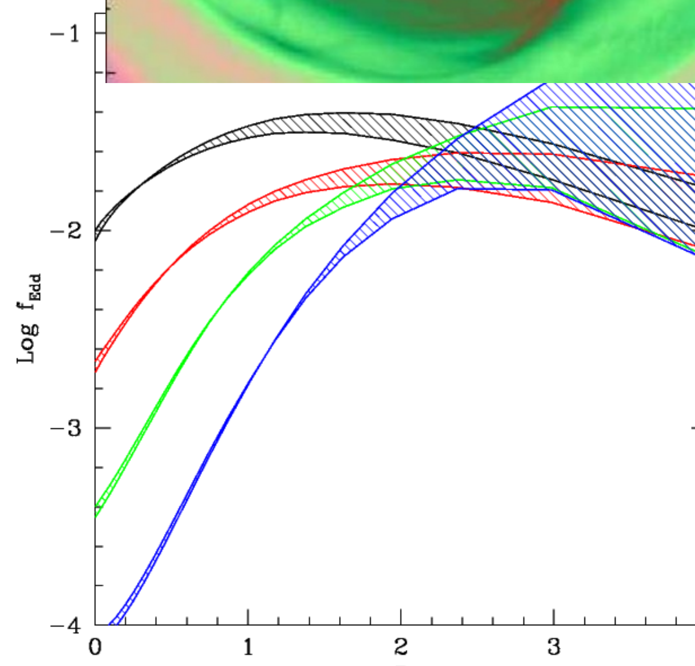
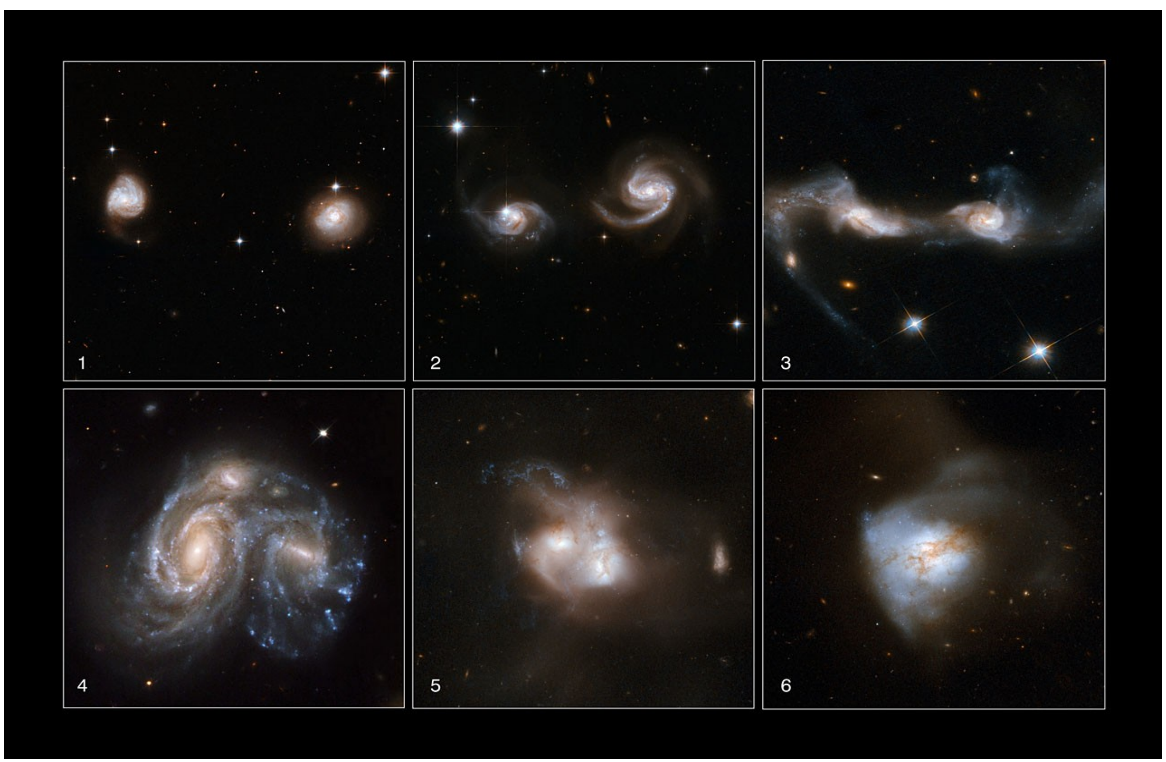
Collaborators:

Andrea Merloni & Carmen Montuori

(and many others)







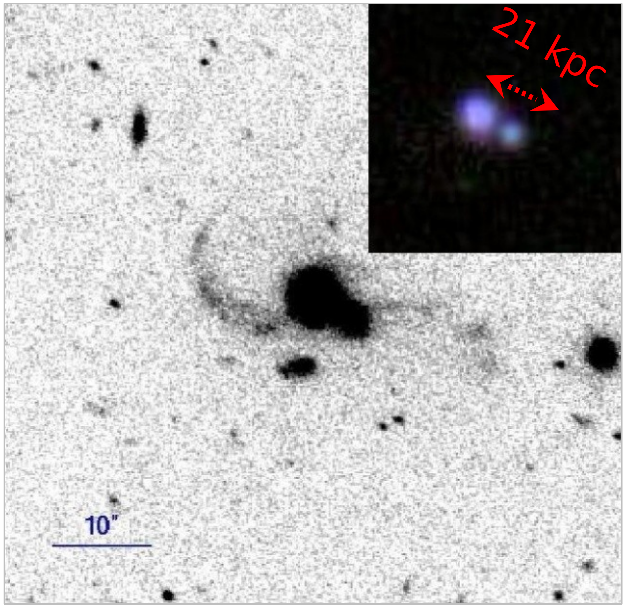
Merger phases

(as in Begelman, Blandford & Rees 1980)

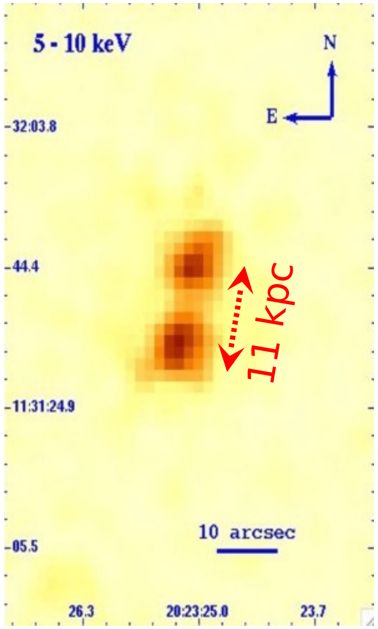
Merger phases

- Dynamical friction (from ~100kpc to ~100 pc) *(tens of pairs AGN known)*

SDSS J0927+2943 A,B
(Decarli et al. 2010)



SDSS J1254+0846
(Green et al. 2010)



IRAS J20210+1121
(Piconcelli et al. 2010)

Merger phases

- Dynamical friction (from ~100kpc to ~100 pc)
- Dynamical friction
  (from ~100 pc down to $\lesssim$ binary formation)

Scales:

i.e., when (where) a binary forms

$$a_{\rm BHB} \sim \frac{G M_{\rm BHB}}{2\sigma^2} \sim 0.2\ M_{\rm BHB,6}\ \sigma_{100}^{-2}\ {\rm pc},$$

… assuming the M-sigma relation (!!!)

$$a_{\rm BHB} \sim 0.5\ M_{\rm BHB,6}^{1/2}\ {\rm pc}.$$

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Note: 0.5 pc ~ 1 mas @ z~0.03 (d~130 Mpc)

Merger phases

- Dynamical friction (from ~100kpc to ~100 pc)
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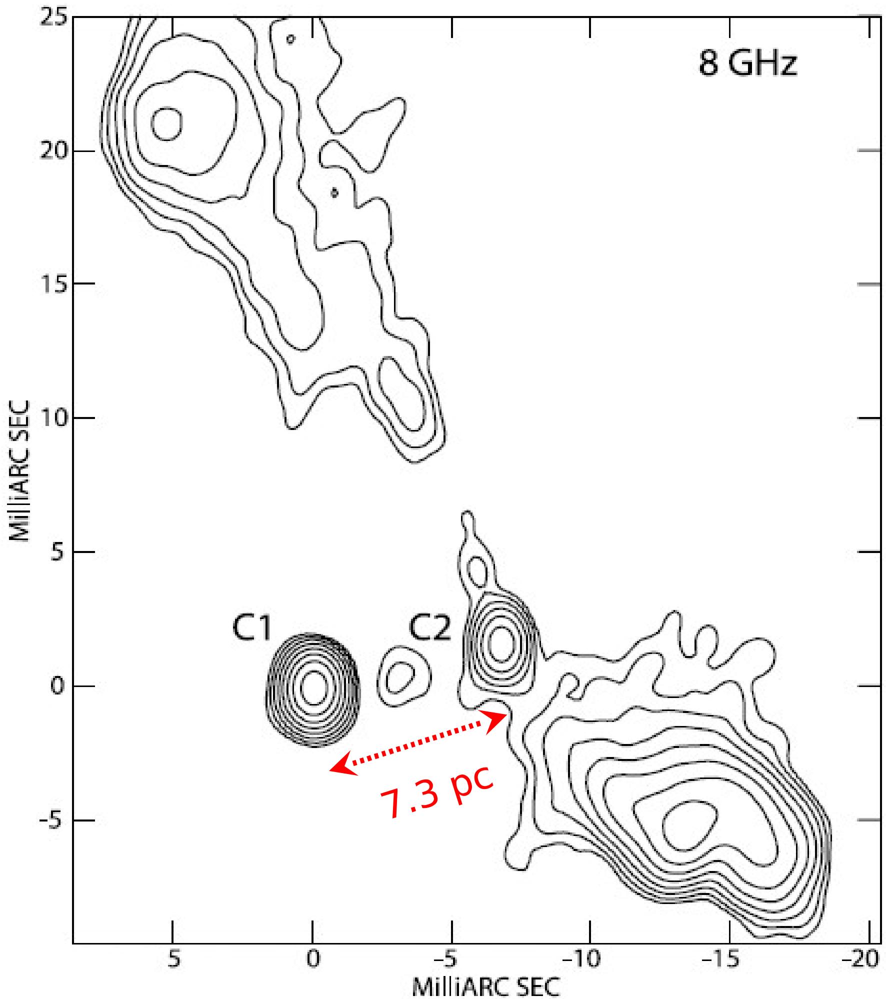

Maness et al. 2004

Rodriguez et al. 2006

Merger phases

- Dynamical friction (from ~kpc to 100 pc)

- Dynamical friction
  (from ~100 pc down to $\lesssim$ binary formation)

- Gravitational wave emission

$$a_{GW} \approx 0.0014\,\mathrm{pc}\,\left(\frac{M M_1 M_2}{10^{18.3}\ \mathrm{M_\odot}^3}\right)^{1/4} F(e)^{1/4}\, t_9^{1/4}$$

From binary formation to GW: three body interactions with stars

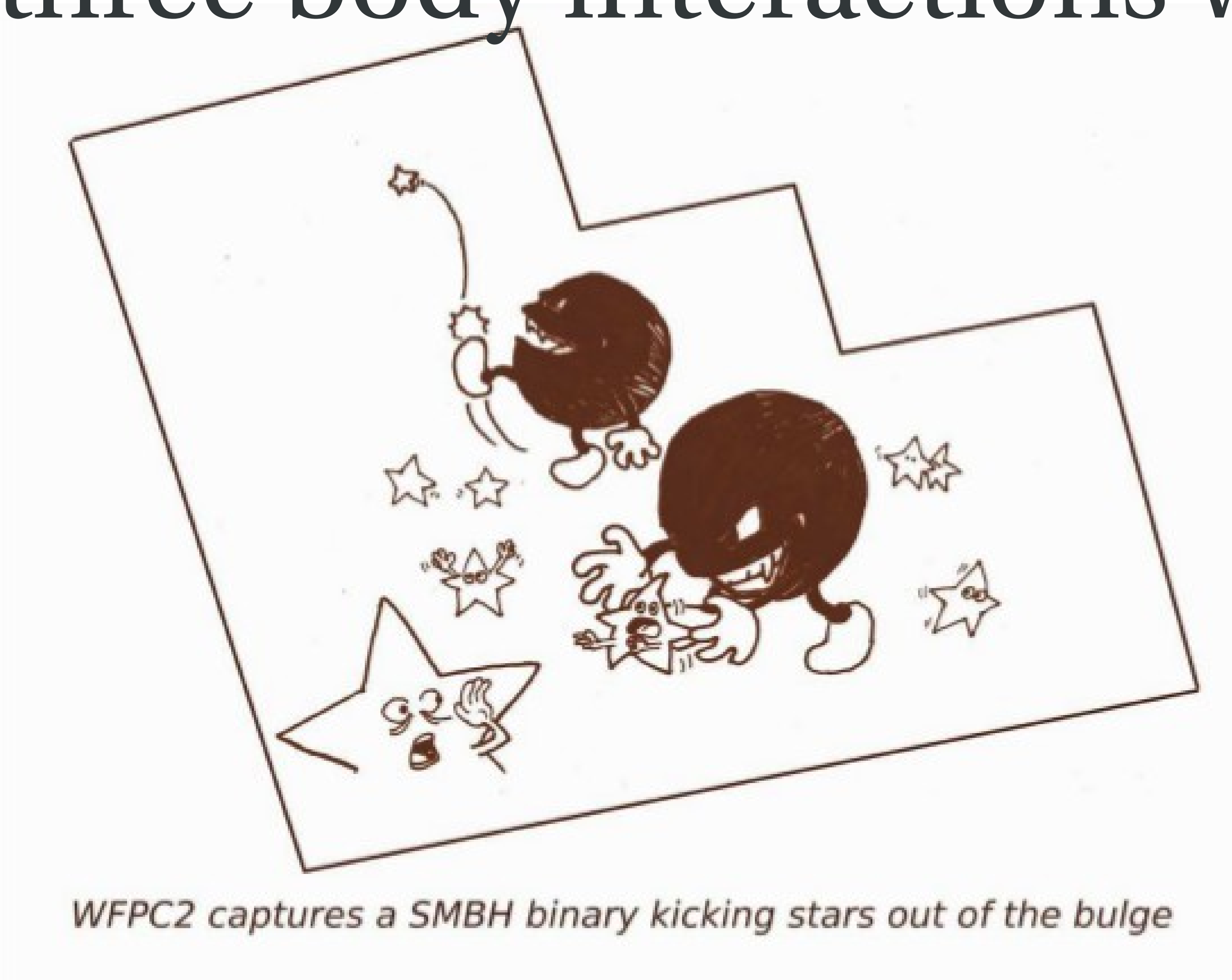

Fig. 7.— Cartoon showing a pair of supermassive black holes kicking stars away as they dance towards coalescence at the centre of a galaxy. Credit: Paolo Bonfini.

(actually taken from Graham arXiv:1501:02937)

Gravitational slingshot

Stars are (on average) ejected with a net energy gain (see, e.g. Merritt 2013) → the binary hardens with time

From binary formation to GW: three body interactions with stars

It has soon been realized that for heavy MBHs there are not enough stars in the immediate proximity of a binary, and that the refilling through 2-body relaxation does not suffice

From binary formation to GW: three body interactions with stars

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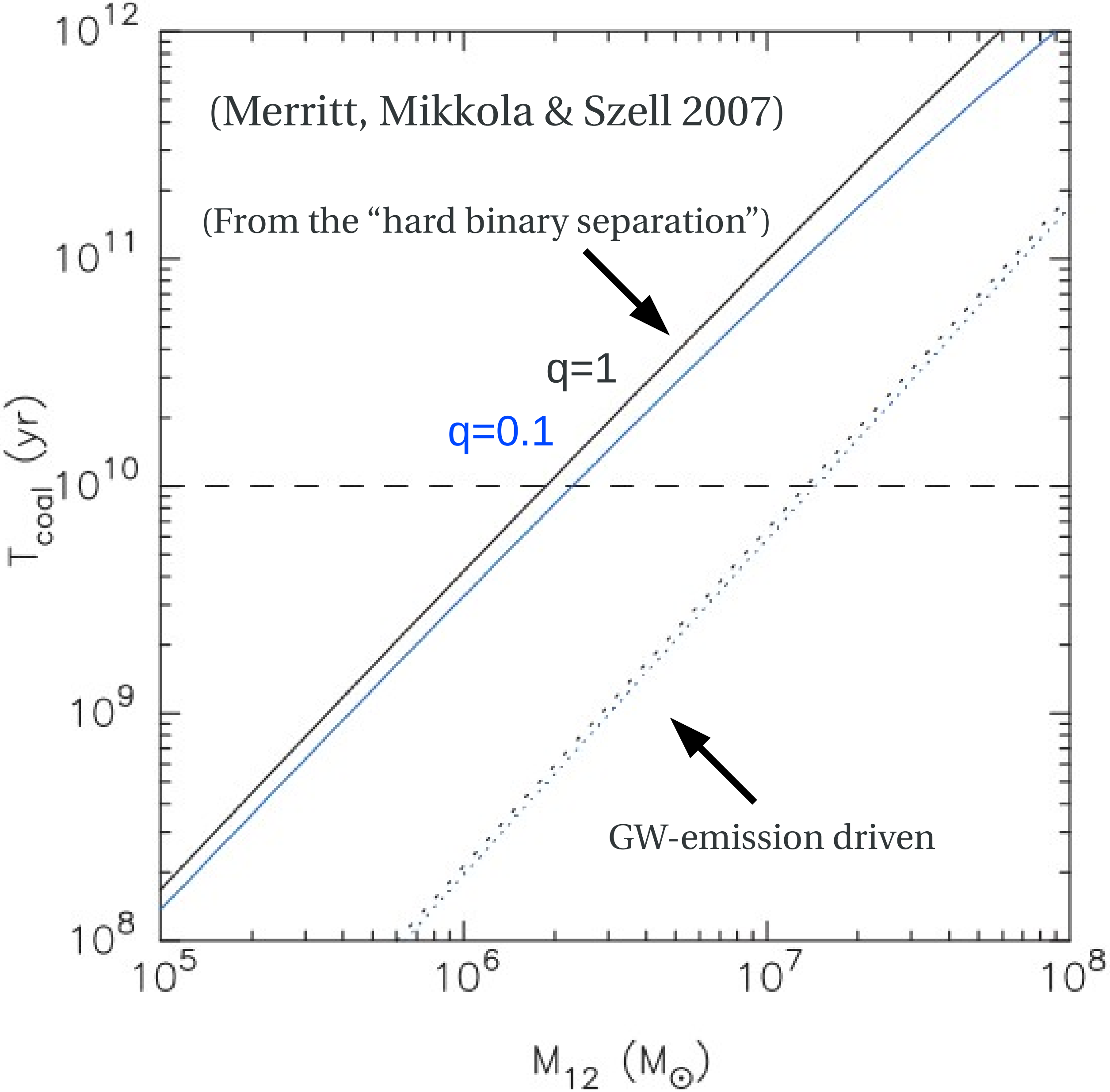


Stellar perspective:
searching for efficient mechanisms to refill the loss cone

Best candidates (to date):

Massive perturbers

(Perets & Alexander 2008)

Non-spherical potentials (leading to centrophilic orbits)
(e.g. Preto+ 2011, Vasiliev+ 2014, Sesana & Khan 2015, Gualandris+2017)

Non-static potentials

(very little done, e.g. Vasiliev+ 2014)

Stellar perspective: timescales
(Sesana & Khan 2015)

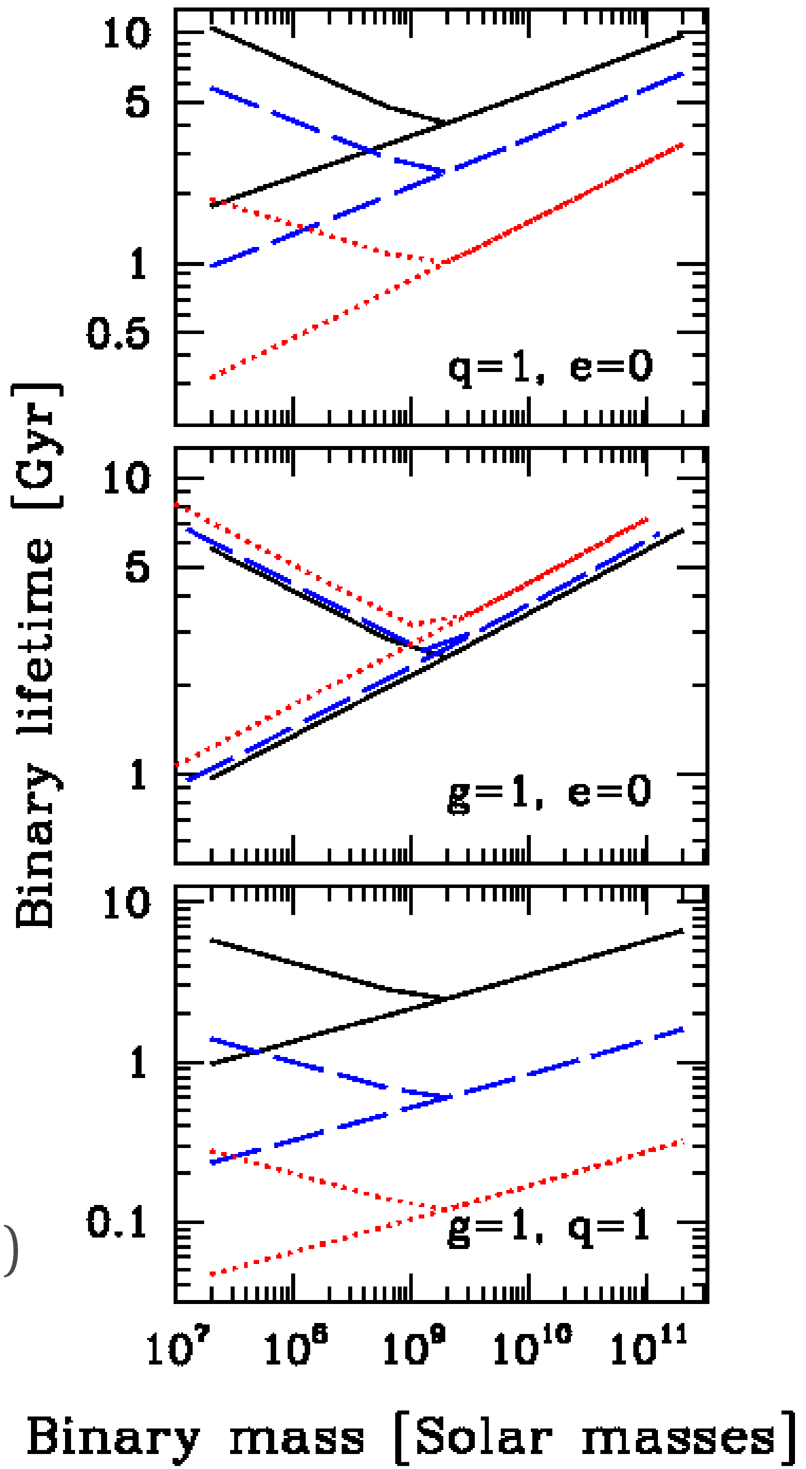
$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{1}{a}\right) = \frac{G\rho_{\rm inf}}{\sigma} H_{3b}$$

$$\rho(r) = \frac{(3-\gamma)M_*}{4\pi}\frac{r_0}{r^{\gamma}(r+r_0)^{4-\gamma}}$$

$$M(< r_{\rm inf}) = 2M_{\rm BHB}$$

With M_* and σ from Kormendy & Ho (2013)

and R_0 from Dabringhausen (2008)



Gas perspective:

Approach 1: full merger simulations, following the binary formation (and possibly a bit of the hardening)
(e.g. Mayer+2007, Hopkins & Quataert 2010, Capelo+2015, Roskar+2015, Chapon+2013,)

Approach 2: idealized initial conditions, to study the gas-binary interaction
(e.g. Escala+05, Escala+06, Dotti+06, Cuadra+08, Roedig+12...)

MBHs growth through gas accretion

MBHs growth through gas accretion

Baby black hole, credits: ButterflyLove1.Etsy.com

MBHs growth through gas accretion

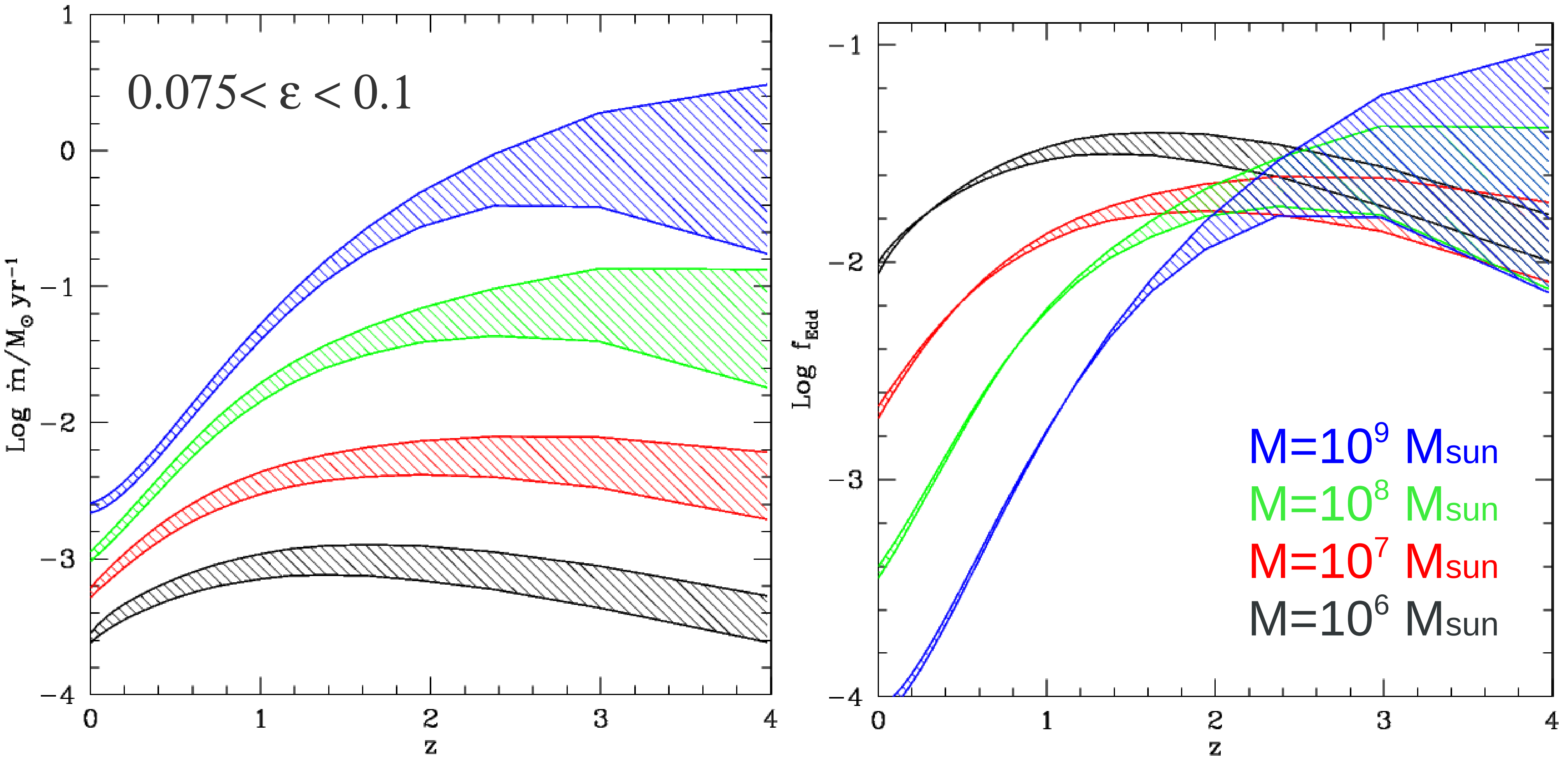


Figure 1. Average Eddington ratios (left panel) and mass accretion rates (right panel) of MBHs as function of z. Black, red, green and blue colors refer to MBH masses of 10^6, 10^7, 10^8, and 10^9 $M_\odot$, respectively. The shaded areas show the range of values comprised between the two limiting cases considered for the radiative efficiency (see discussion in the text) corresponding to $\epsilon = 0.075$ and $\epsilon = 0.1$.

(Dotti, Merloni & Montuori 2015, revisited from Merloni & Heinz 2008)

Gas perspective:

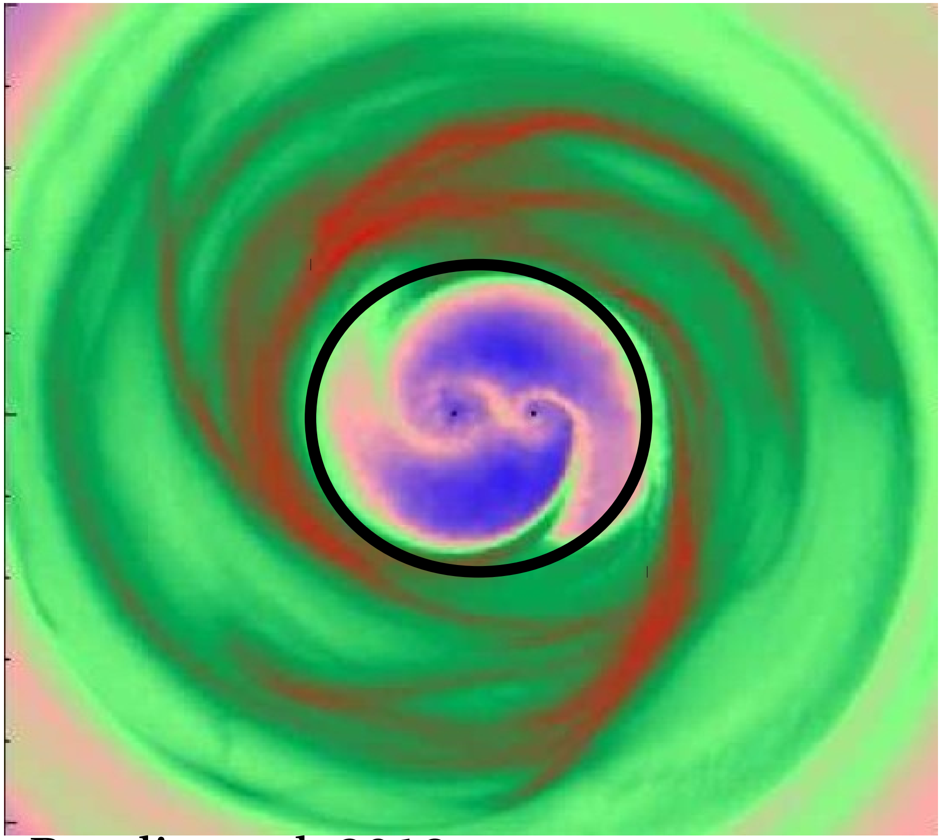
Approach 1: full merger simulations, following the binary formation (and possibly a bit of the hardening)

Approach 2: idealized initial conditions, to study the gas-binary interaction

Timescales: idealized gas-binary interaction, with a prescription for a mass and time dependent gas inflow from the AGN luminosity function

(BBR1980, Dotti Merloni Montuori 2015)

The model in a nutshell



Roedig et al. 2012

$$\left.\begin{aligned} \mathrm{dL_{BHB}} &= -\mathrm{dL_{gas}} = -\dot{m}\,\mathrm{d}t\,\sqrt{G\,M\,r_{\mathrm{gap}}} \\ \mathrm{L_{BHB}} &= \mu\,\sqrt{G\,M\,a} \end{aligned}\right\}$$

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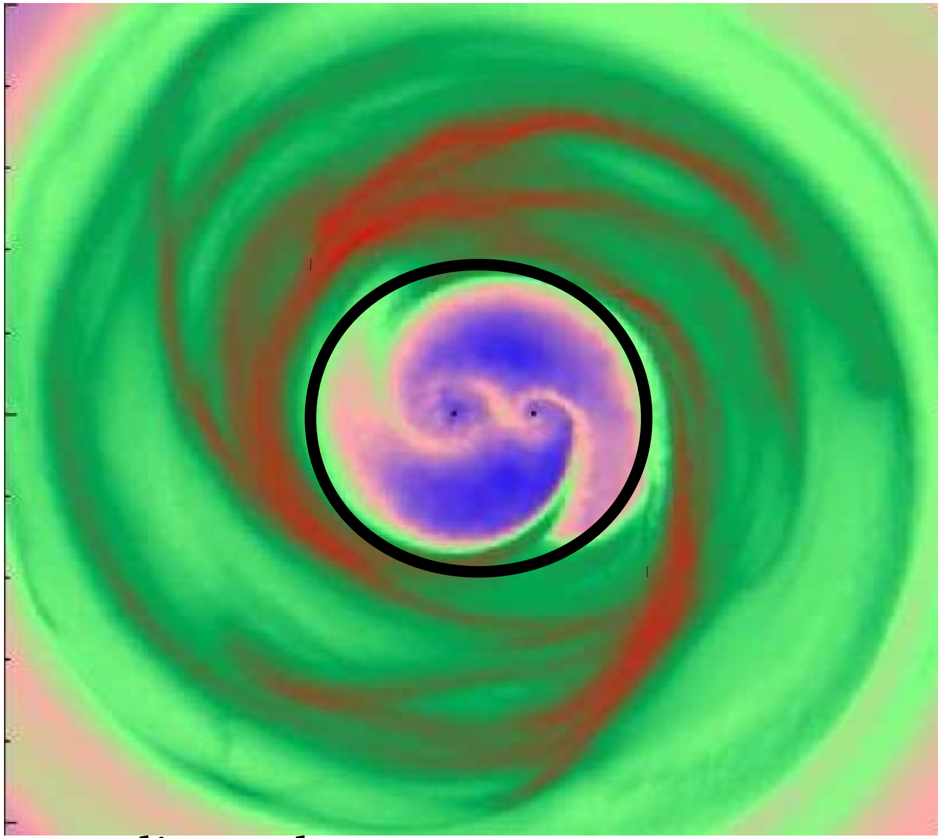

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$$\frac{\mu}{2\sqrt{2}}\,\frac{\mathrm{d}a}{a} \approx -\dot{m}\,\mathrm{d}t$$

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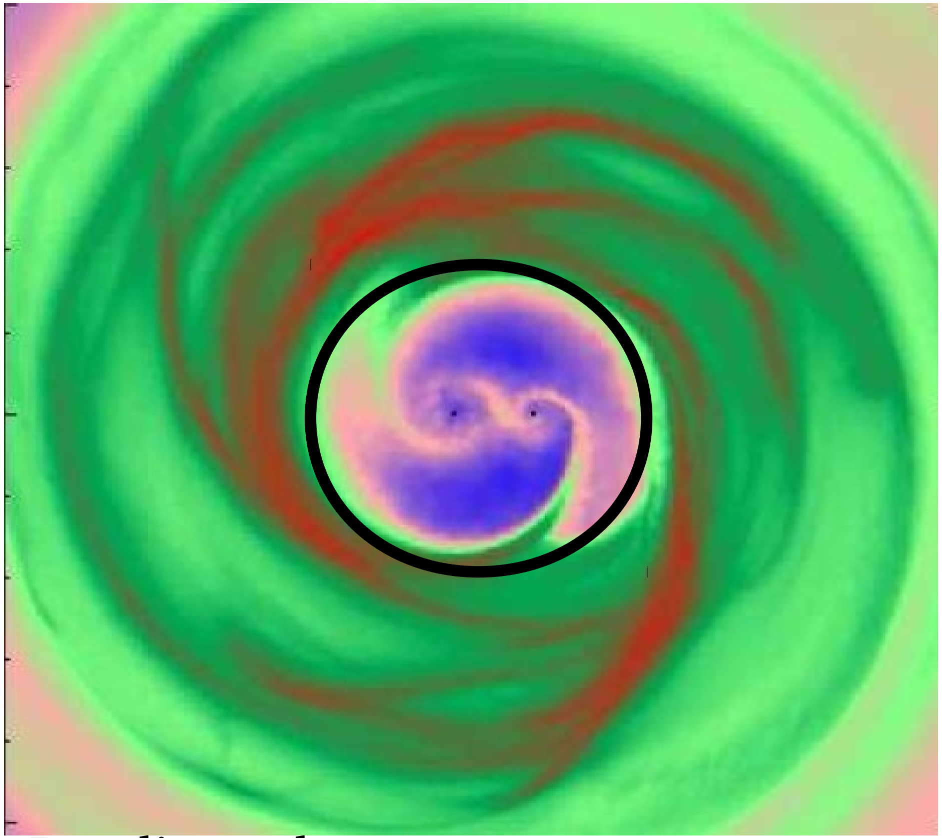

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$$\frac{\mu}{2\sqrt{2}}\,\frac{\mathrm{d}a}{a} \approx -\dot{m}\,\mathrm{d}t$$

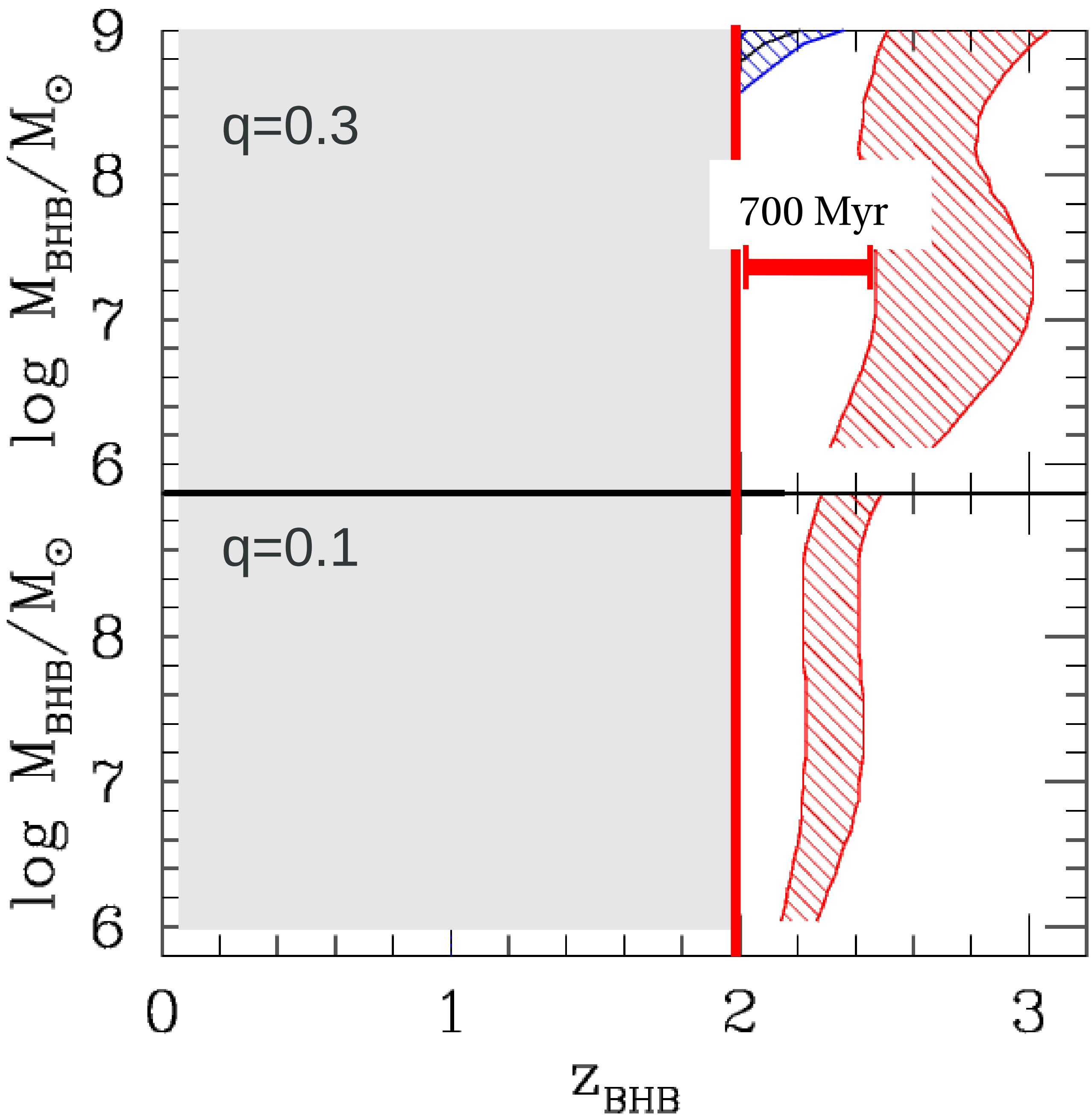
$$\Delta t_{\mathrm{BHB}} \sim \ln\left(\frac{a_i}{a_c}\right)\frac{\mu\,\epsilon\,c^2}{2\sqrt{2}\,L_{\mathrm{Edd}}} \sim 10^7\,\frac{q}{(1+q)^2}\,\ln\left(\frac{a_i}{a_c}\right)\,\mathrm{yr}$$

Conservative assumptions:

- Mergers do not boost accretion
- Gas accretion always radiatively efficient and no outflows from the binary separation down to few gravitational radii

Timescales

Dotti et al. (2015)



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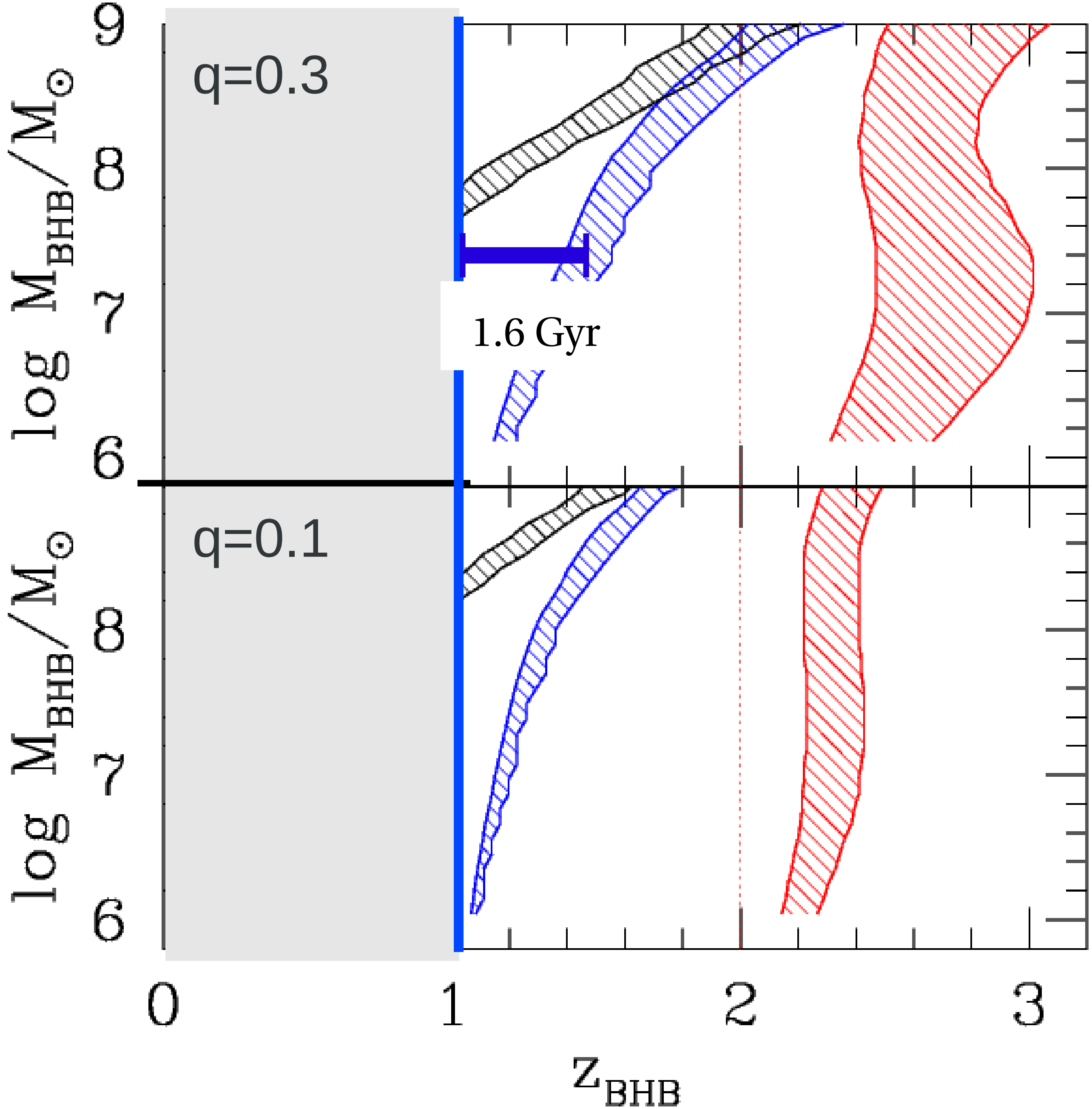

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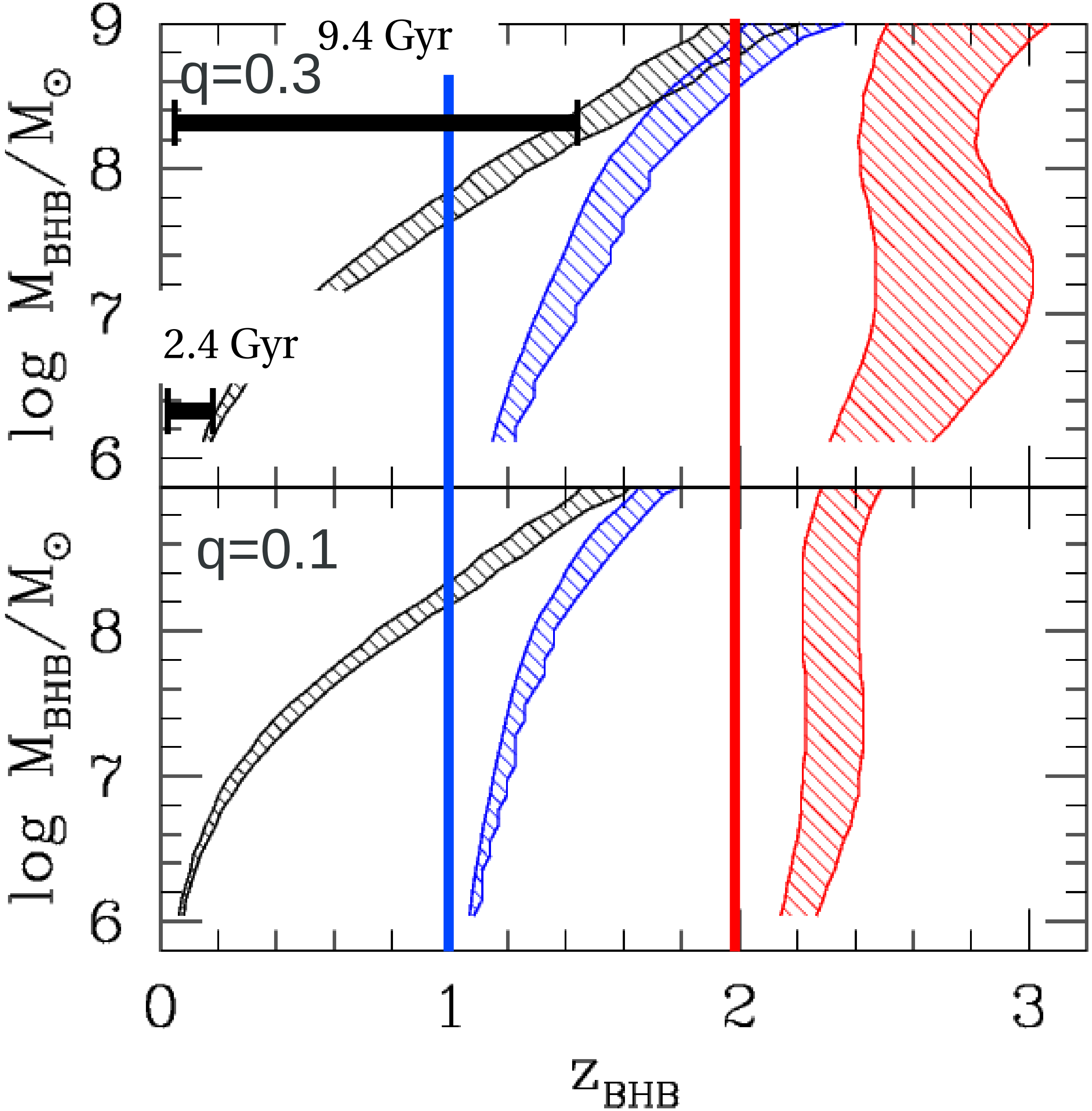

Timescales

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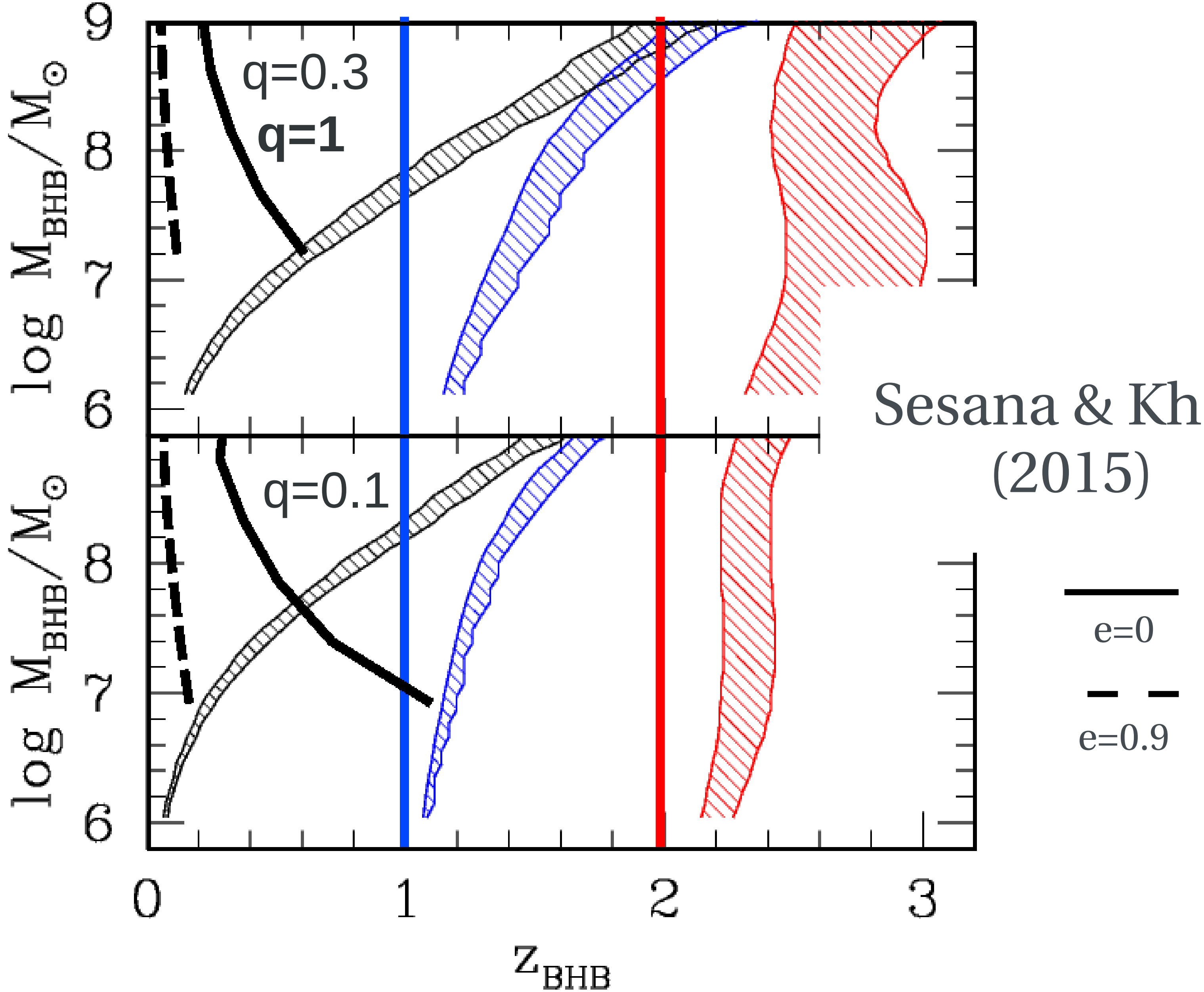
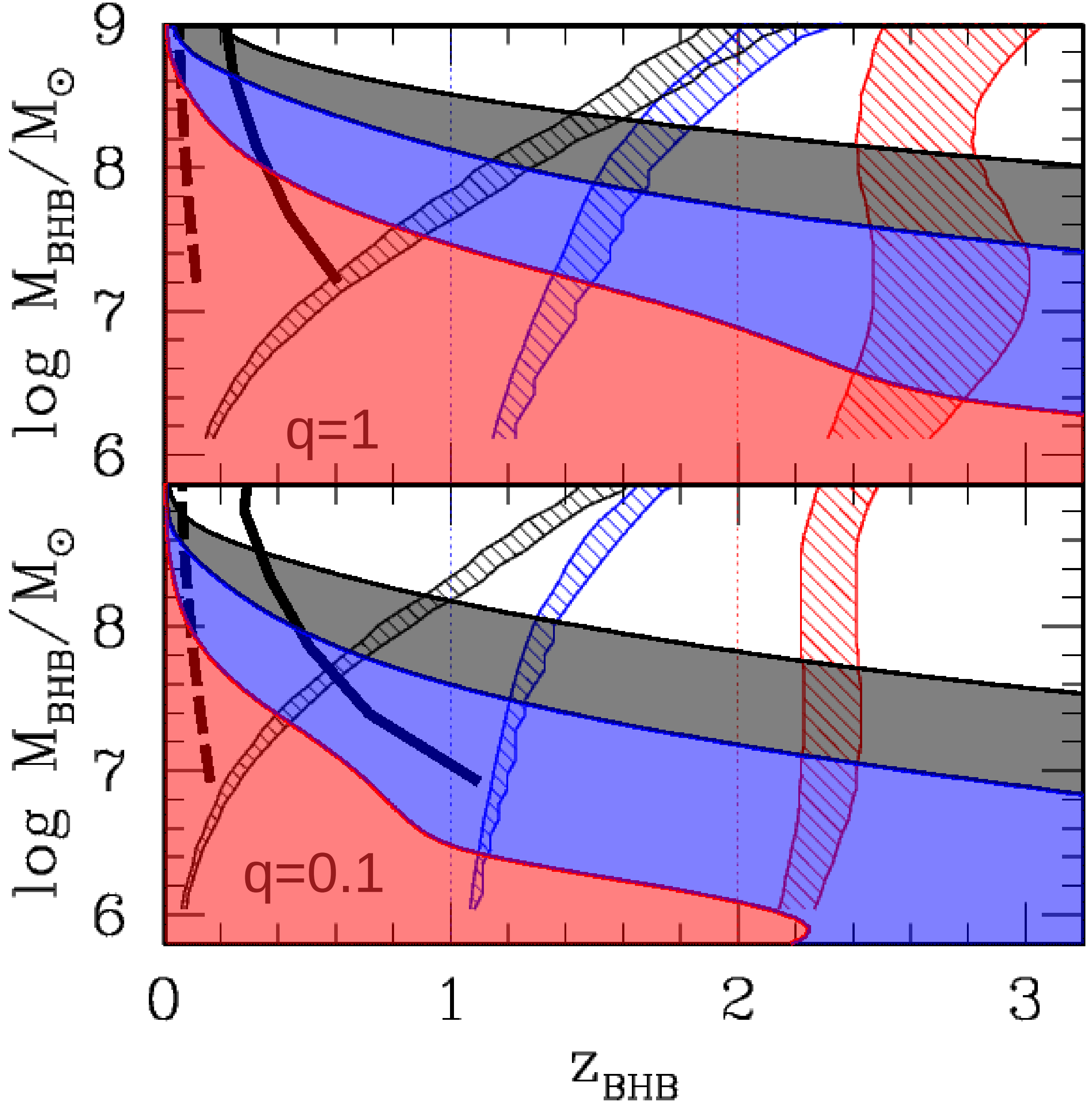


Sesana & Khan (2015)

Timescales

Dotti et al. (2015)- Sesana & Khan (2015)



LISA: a=0

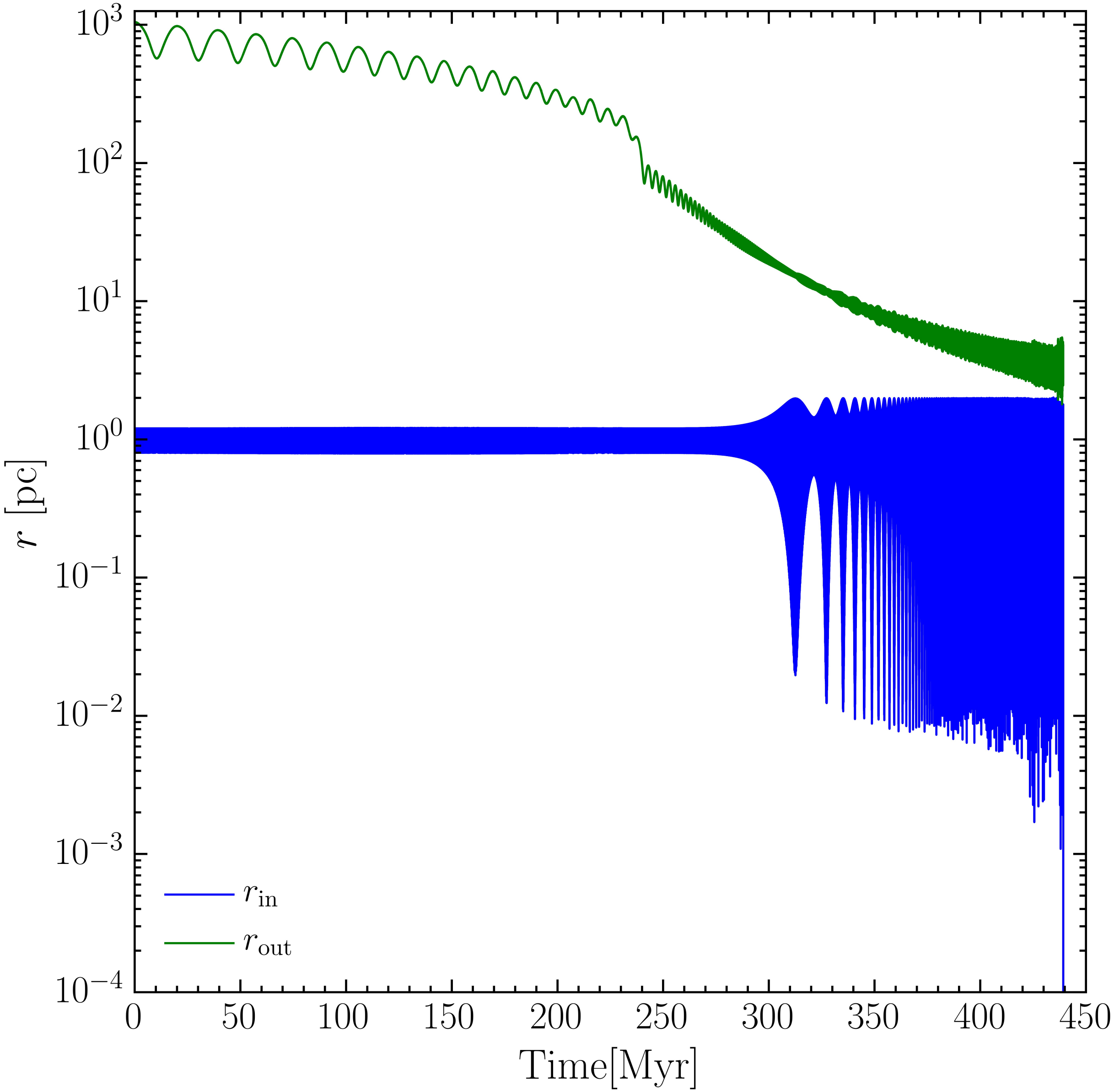
SNR=10

SNR=100

SNR=1000

What if...

Bonetti et al. (2016)-Bonetti et al. in prep.



$m_1 = 10^8\ \mathrm{M}_\odot$

$m_2 = 3 \times 10^7\ \mathrm{M}_\odot$

$m_3 = 5 \times 10^7\ \mathrm{M}_\odot$

$a_{\mathrm{in}} = 1$ pc

$e_{\mathrm{in}} = 0.2$

$a_{\mathrm{out}} \simeq 1$ kpc

$e_{\mathrm{out}} = 0.3$

Conclusions

High z BHBs of any mass coalesce on very short timescales

Low mass BHBs coalesce within z=0 even if binding at low z ($z \gtrsim 0.5$ for $M \lesssim 10^7$ Msun – $z \gtrsim 0.2$ for $M \lesssim 10^6$ Msun) due to interaction with gas

Very massive BHBs can still merge… often hosted in massive triaxial ellipticals, where non-collisional loss cone refilling may play a role

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Very massive BHBs can still merge... often hosted in massive triaxial ellipticals, where non-collisional loss cone refilling may play a role

The fate of (many) BHBs is linked to the MBH fueling/galaxy relaxation mechanisms!

$$\frac{\partial \psi(m,t)}{\partial t} + \frac{\partial}{\partial m}\left(\psi(m,t)\langle \dot{M}(m,t)\rangle\right) = 0$$

$$\langle \dot{M}(M,z)\rangle = \int \dot{M} F(\dot{m},m,z)\,\mathrm{d}\dot{m}$$

$$\phi(\ell,t) = \int F(\ell-\zeta,m,t)\psi(m,t)\,\mathrm{d}m$$

$$\ell = Log\, L_{\rm bol} \text{ and } \zeta = Log\,(\epsilon c^2)$$

$$\frac{\langle\epsilon\rangle}{1-\langle\epsilon\rangle} \approx 0.075\left[\xi_0(1-\xi_i-\xi_{\rm CT}+\xi_{\rm lost})\right]^{-1}$$

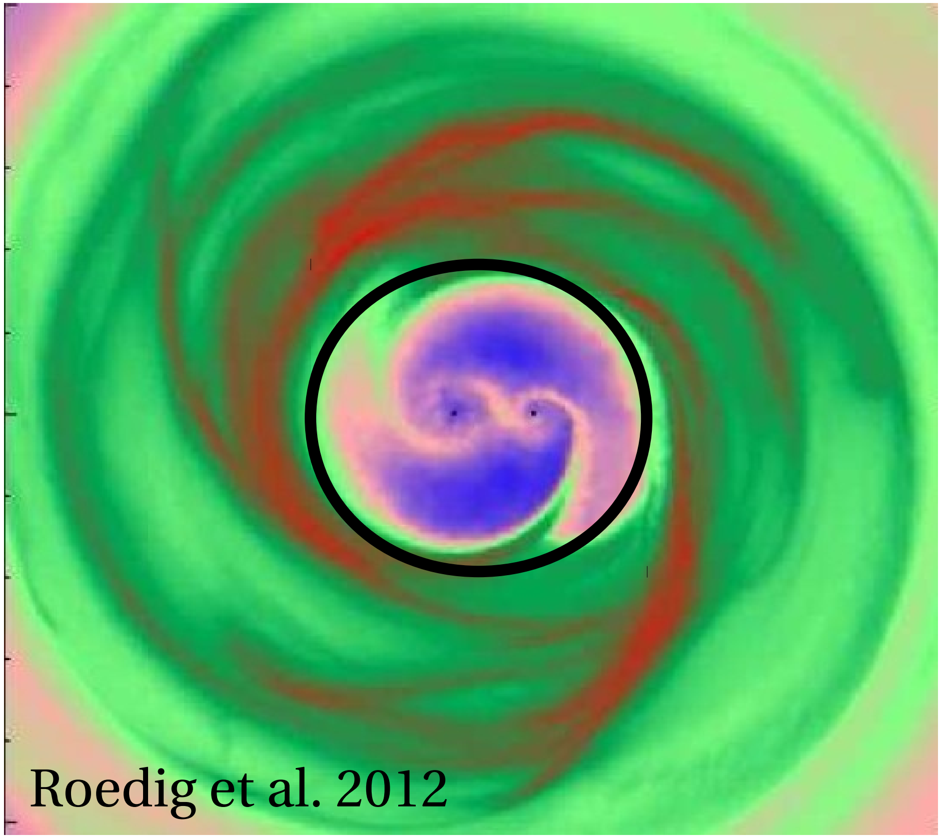
$\rho_{\rm BH,z=0}/4.2\times10^5 M_\odot {\rm Mpc}^{-3}$

(Marconi et al. 2004)

0.35
(Buchner et al. 2015)

0 – 0.3
(Lousto et al. 2014)

The model in a nutshell 2:



A fraction of the gas could manage to cross the gap edge (the system is not exactly axisymmetric, see e.g. D'Orazio et al. 2013).

It also would exert a (different) torque (e.g. Roedig 2012).

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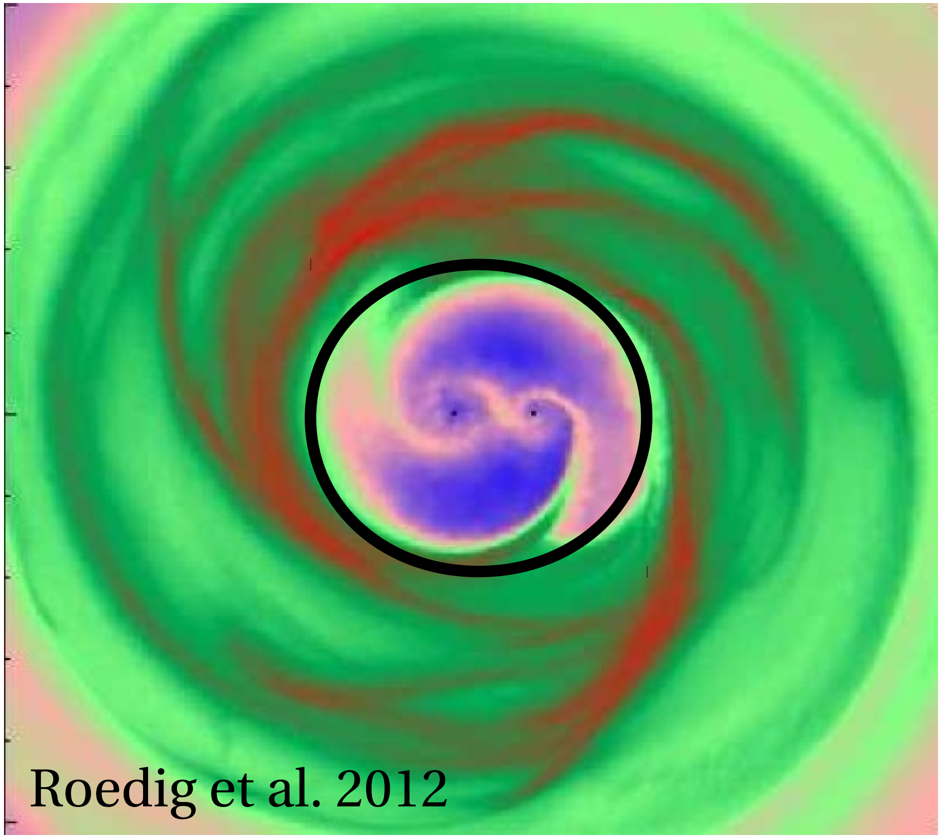

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What if only a fraction ***f*** of the gas interacts dynamically with the binary?

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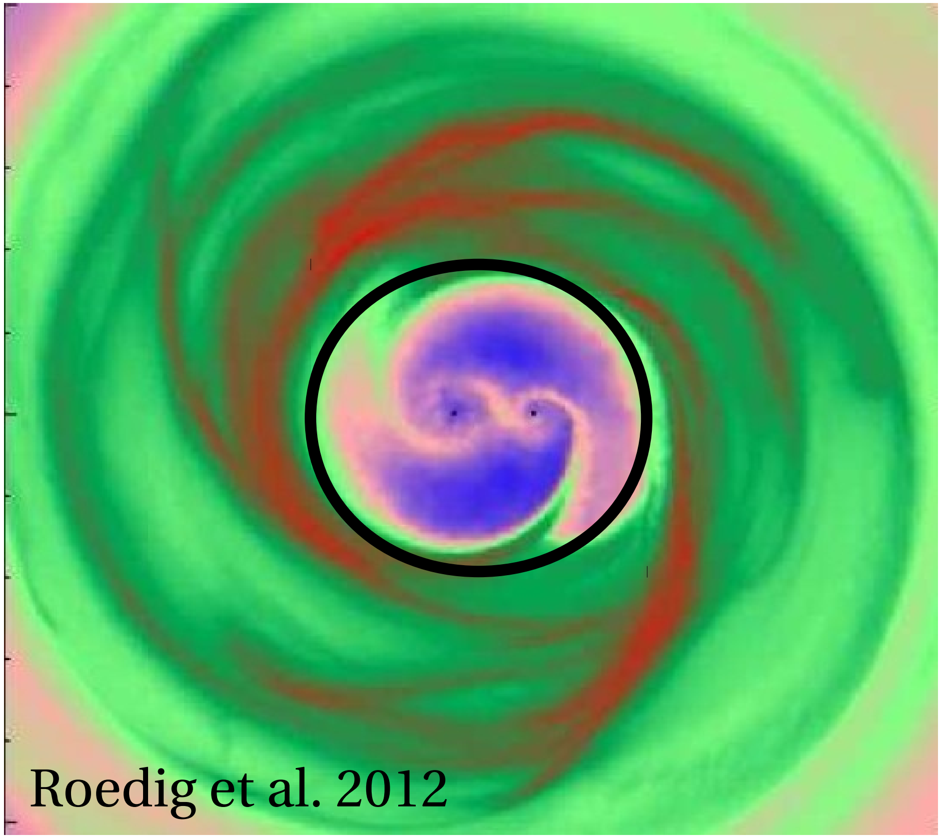

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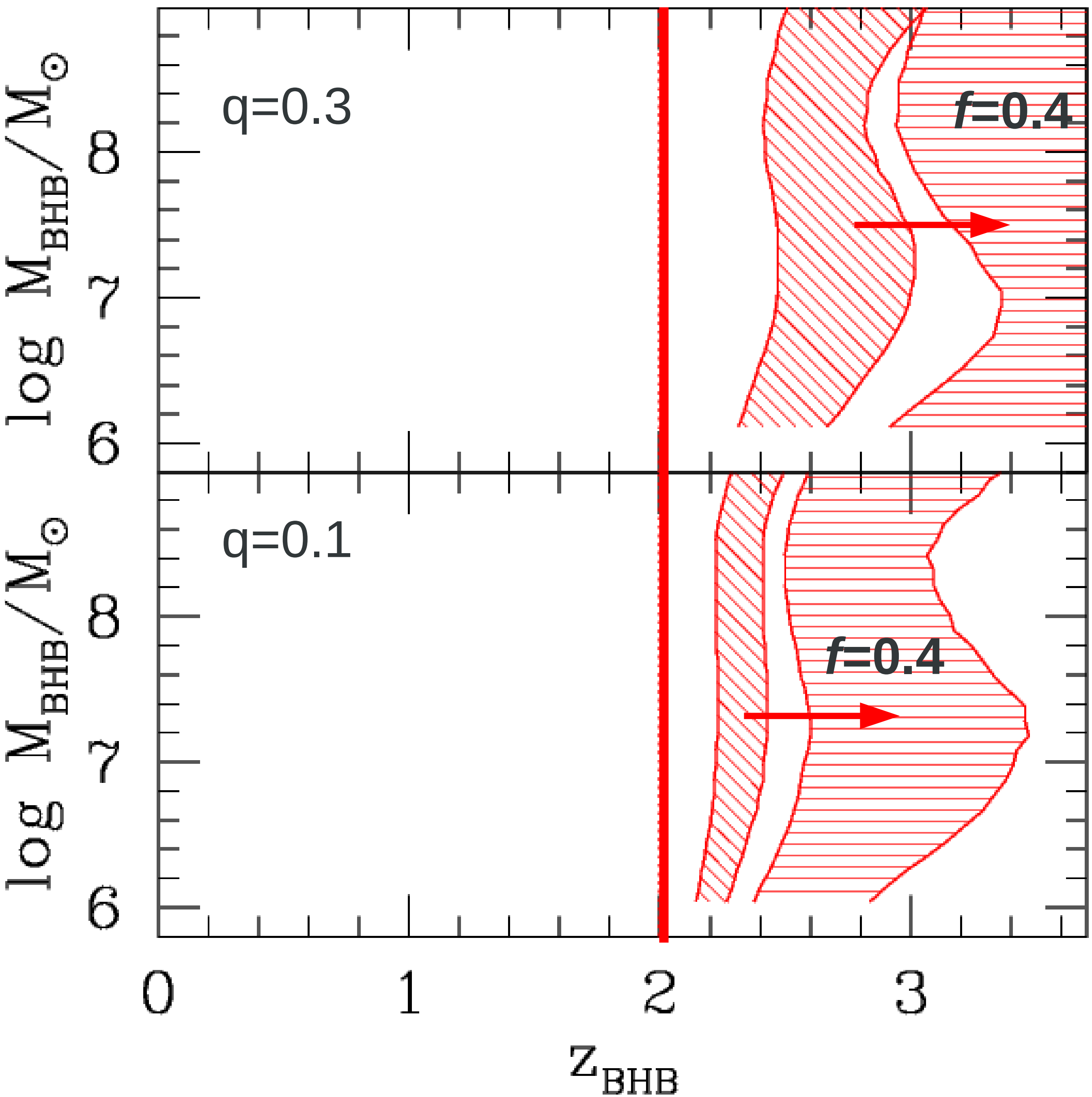
Test: f=0.4

Results: 2



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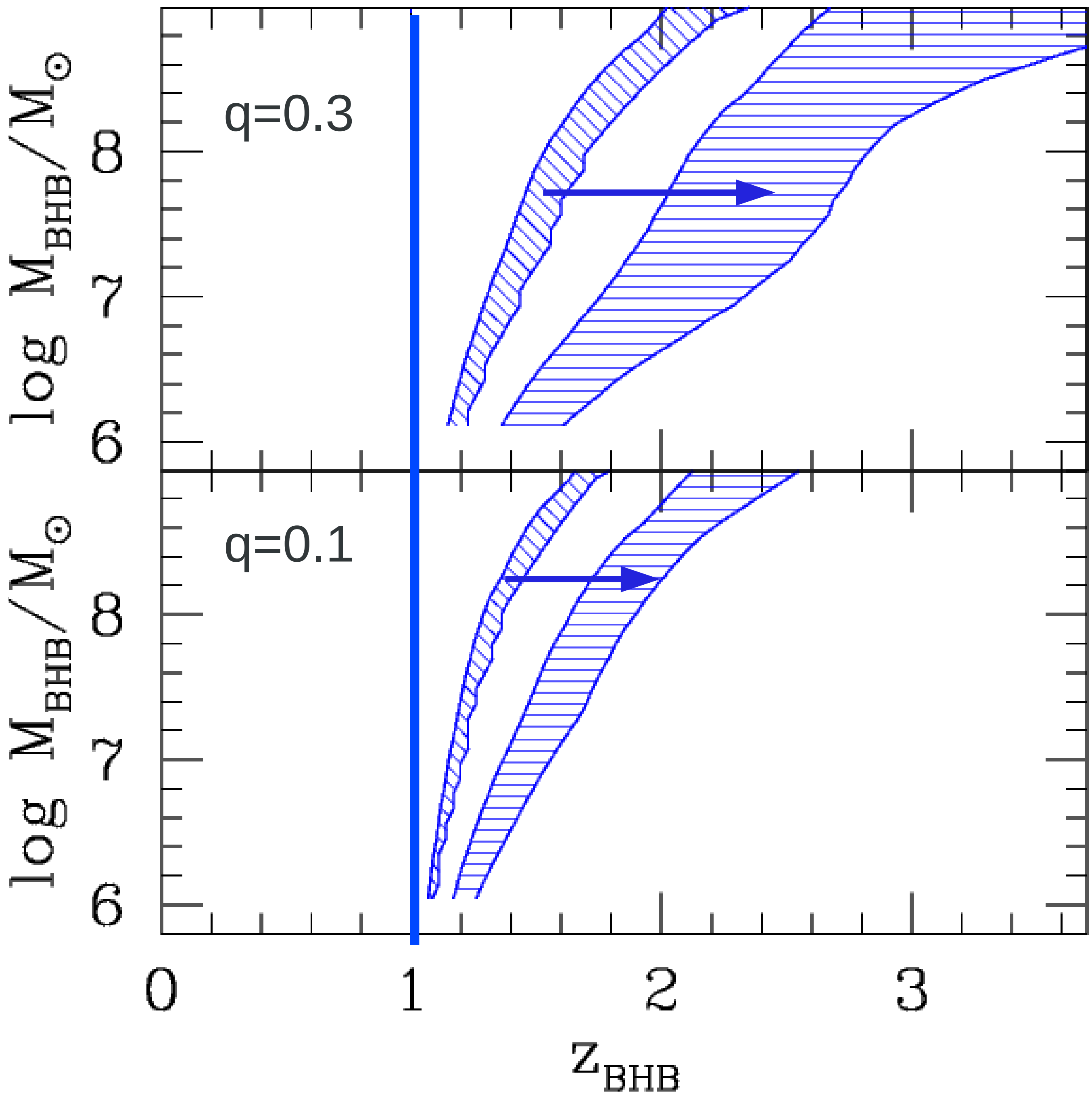

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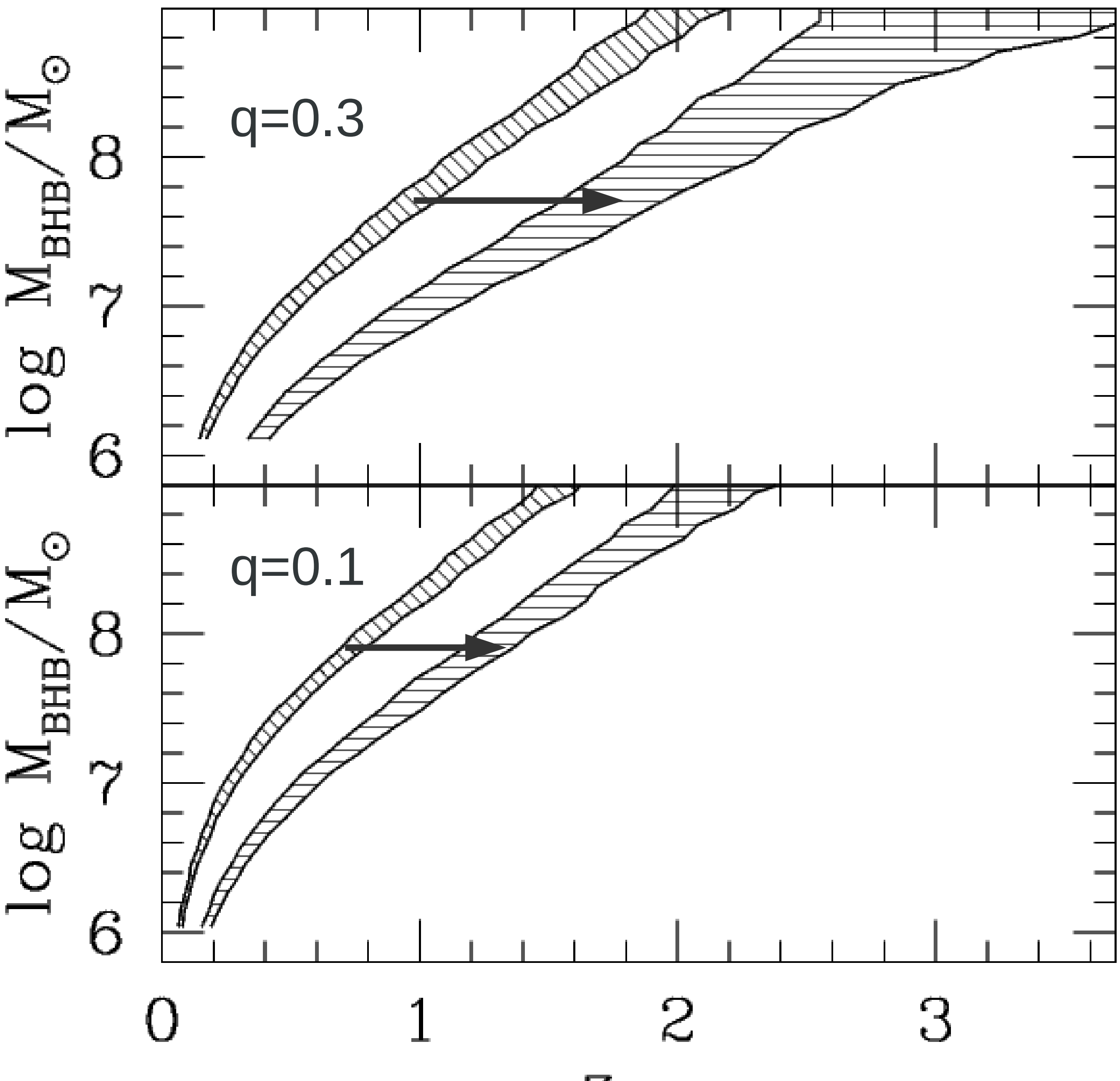

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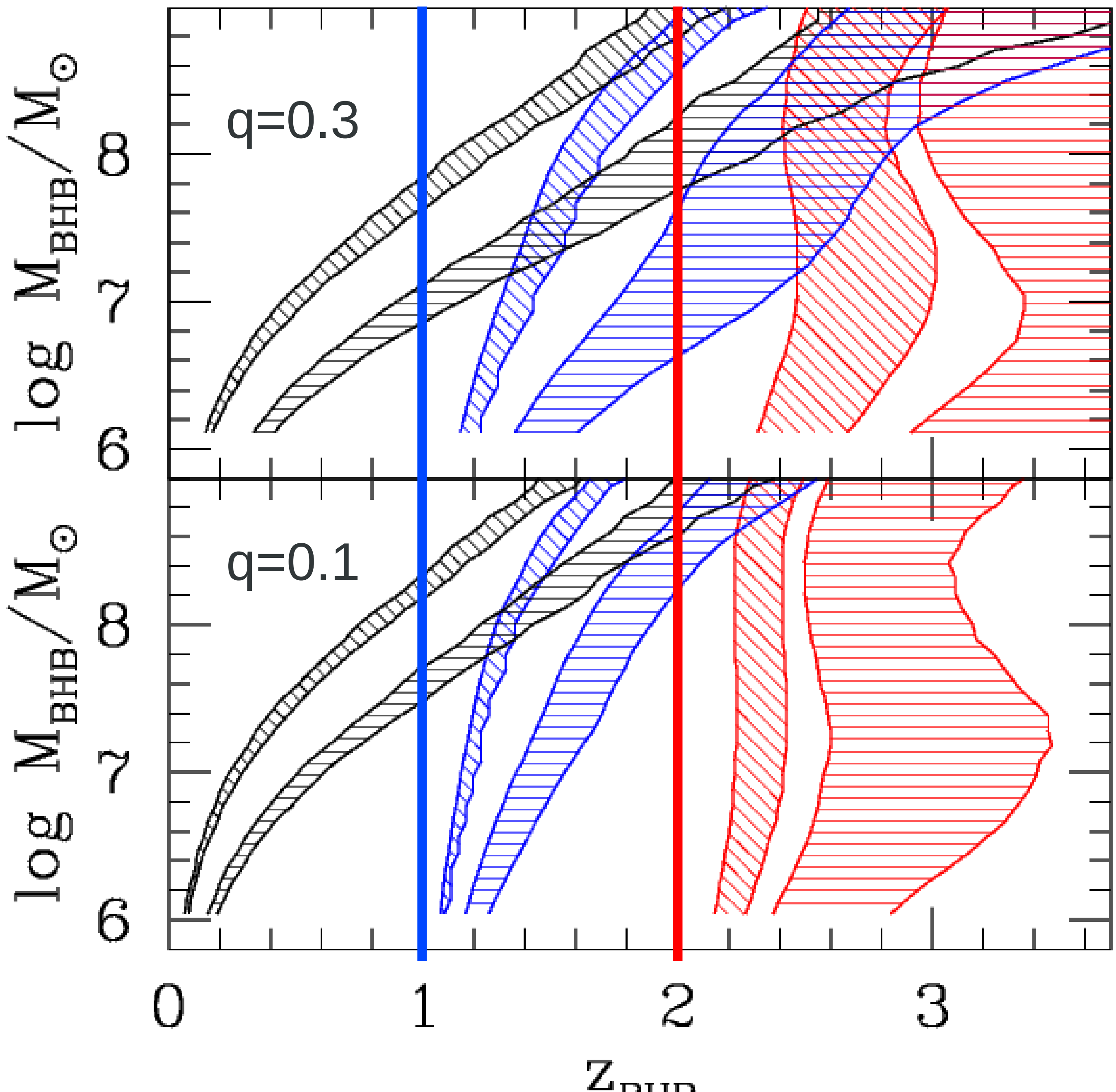
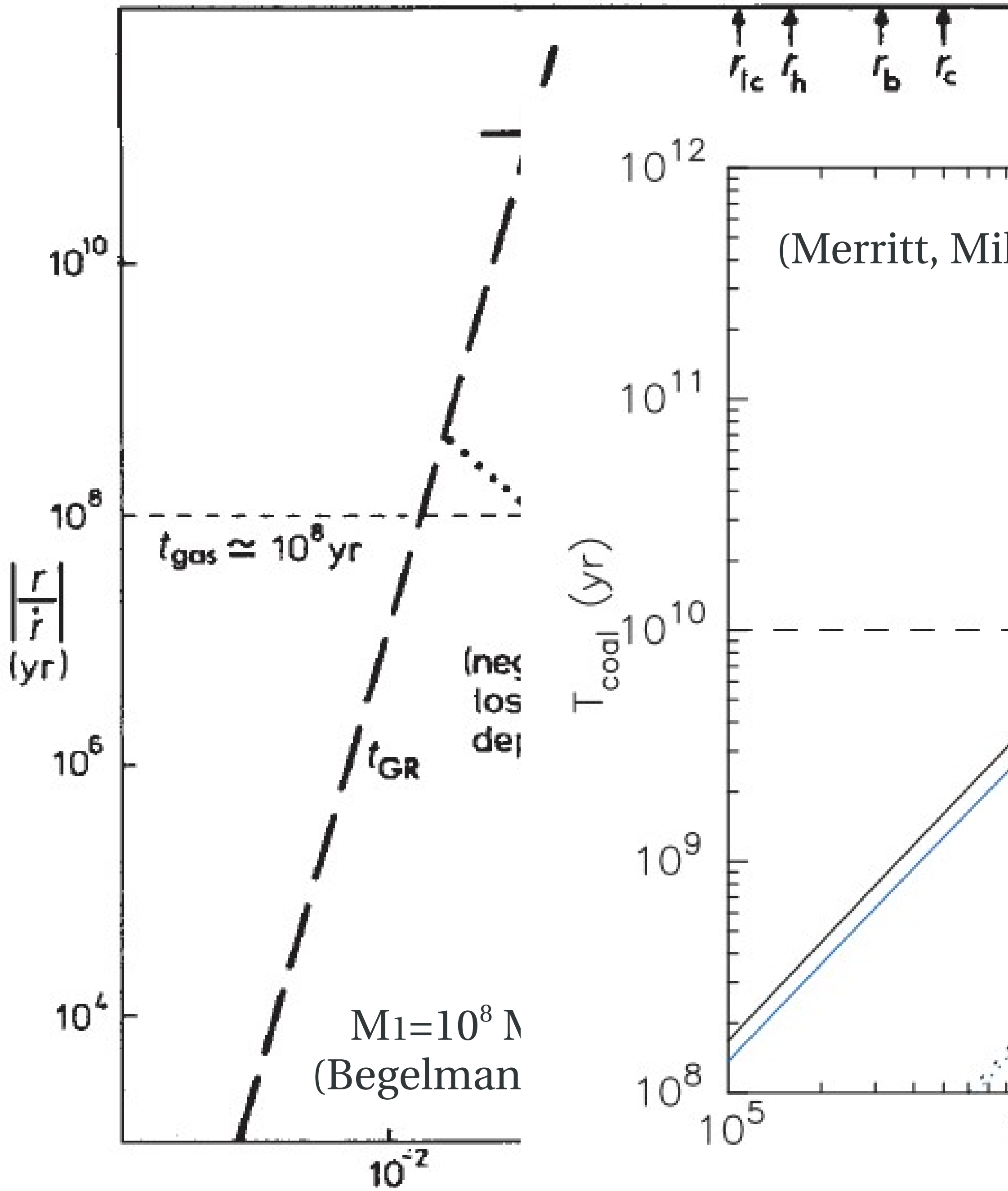
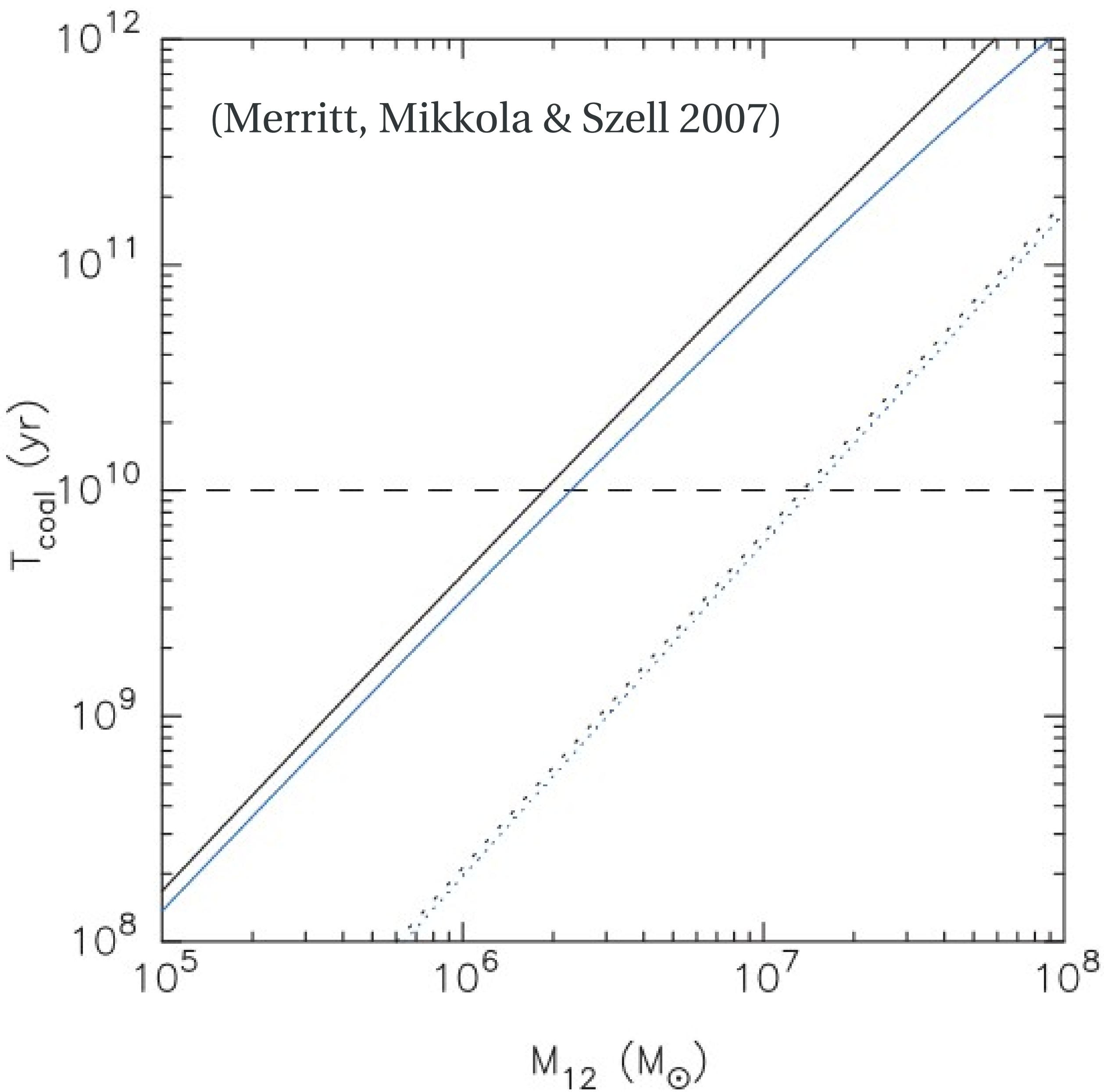


From binary formation to GW: ...s with stars





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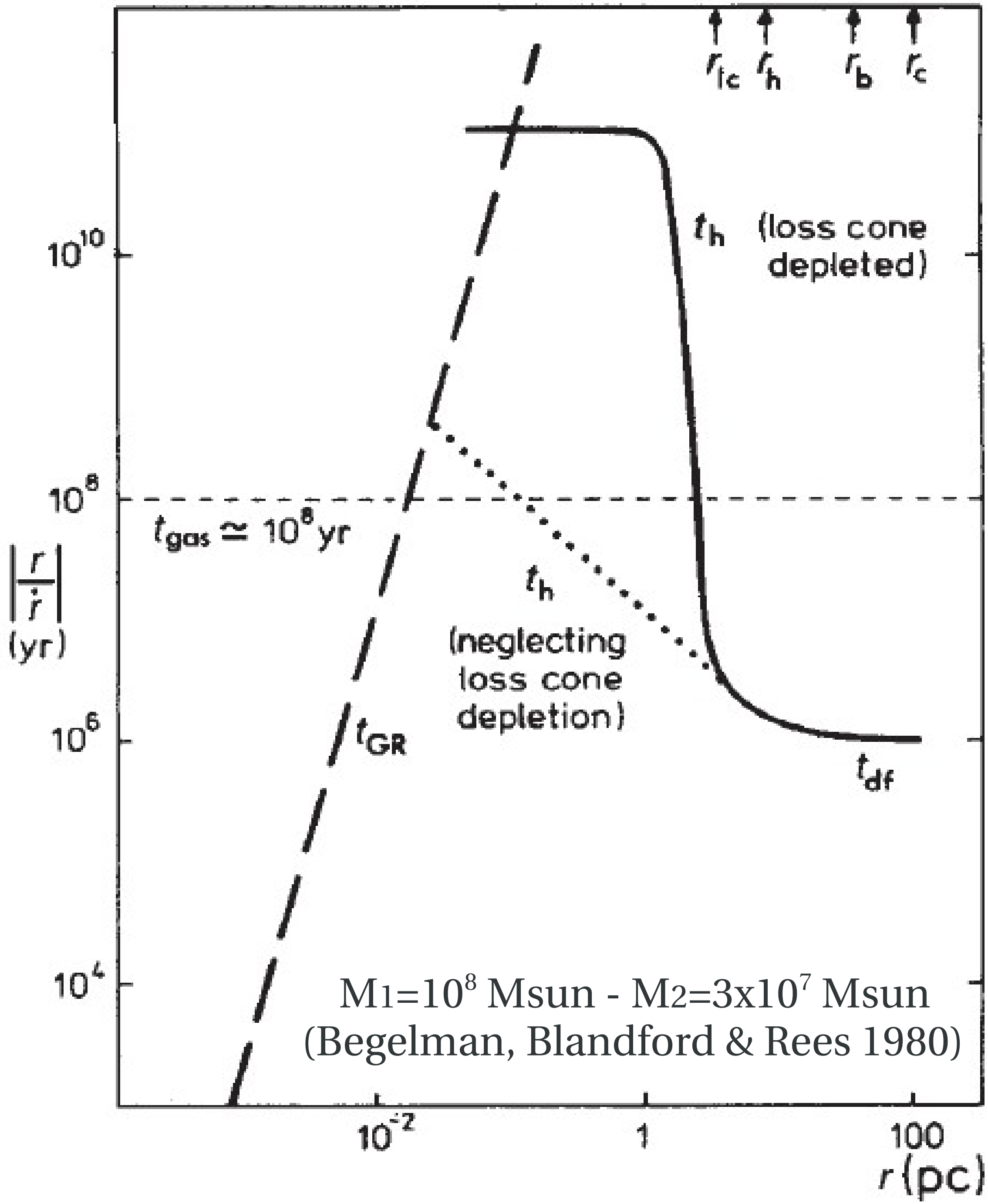
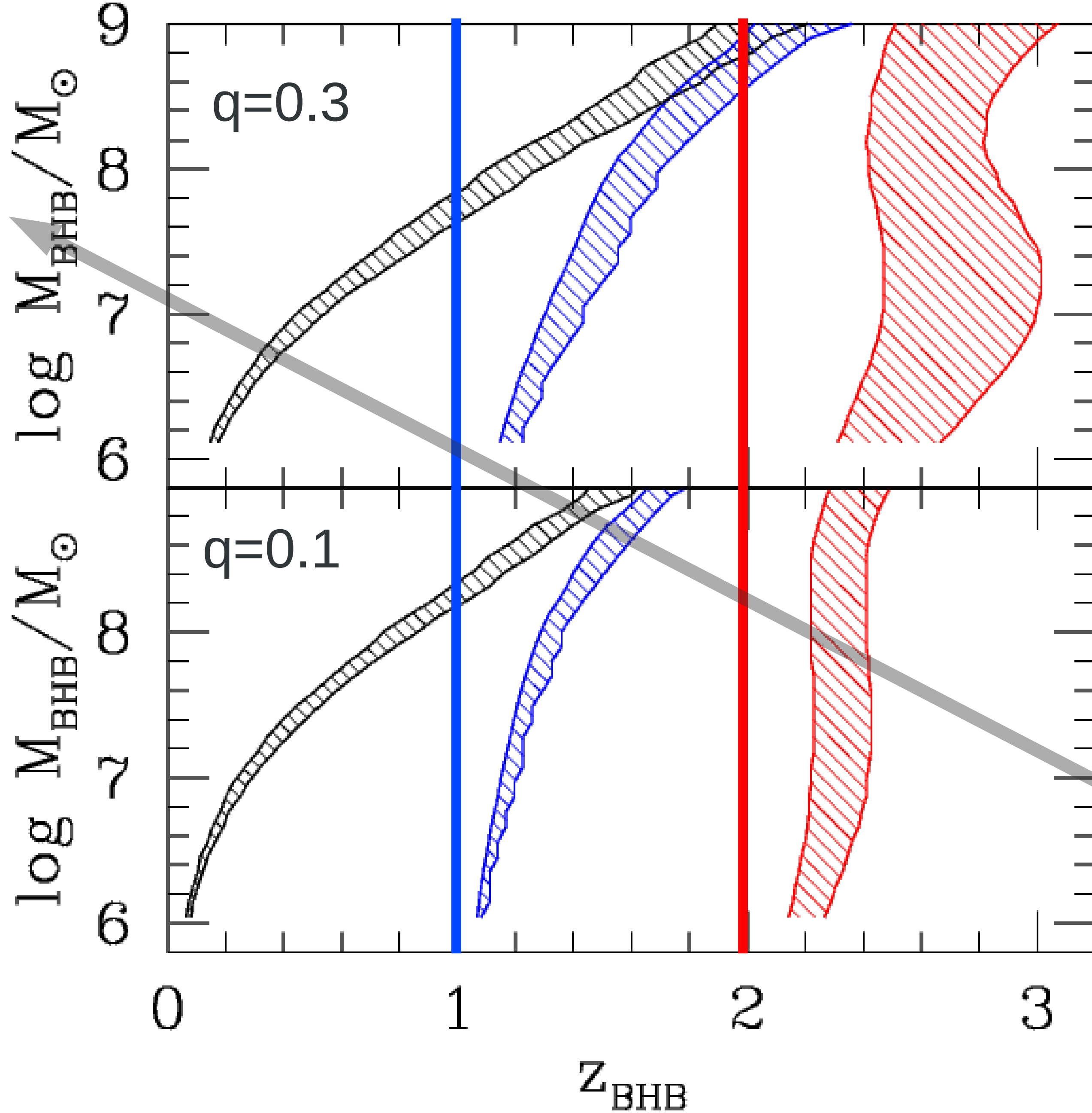
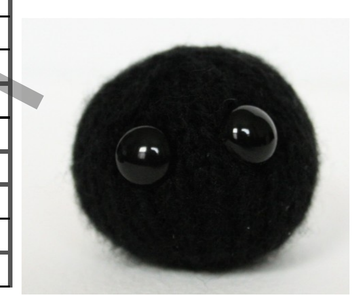


$M_1 = 10^8$ Msun - $M_2 = 3 \times 10^7$ Msun
(Begelman, Blandford & Rees 1980)

Results: 1





Stellar perspective:
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Massive perturbers
(Perets & Alexander 2008)

Non-spherical potentials (leading to centrophilic orbits)
(e.g. Khan+ 2011, Preto+ 2011, Gualandris+ 2011, Vasiliev+ 2014…)

Non-static potentials (very little investigated)
(e.g. Vasiliev+ 2014)

Often quite detailed though very idealized studies