LISA BLACK HOLE COALESCENCES

ON CLOCK?

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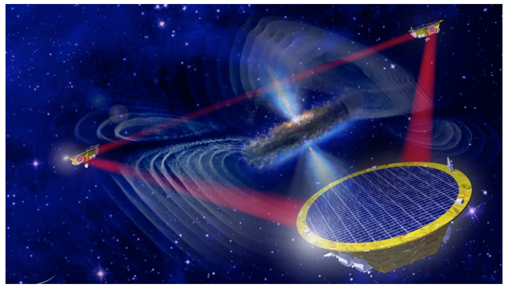

Sackler Conference 2018
Harvard Smithsonian Center for Astrophysics
"Gravitational Wave Astrophysics"
7-9 April 2018

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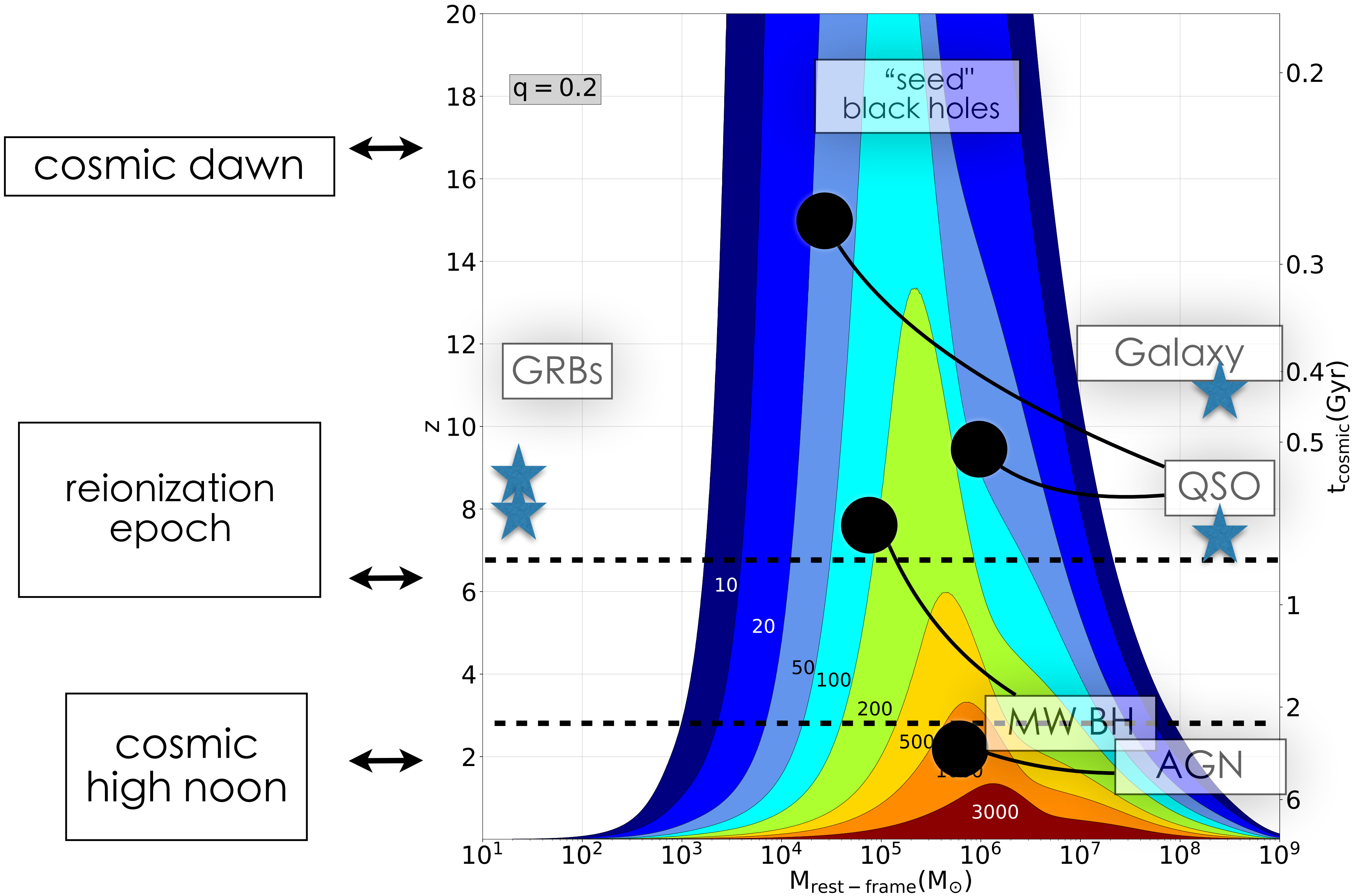
LISA HORIZON



Karsten's talk

- LISA will discover massive black holes across all cosmic epochs
- LISA horizon extends deep into the epoch of formation of the earliest black holes
- LISA traces the black hole cosmic drift to higher masses through accretion & mergers

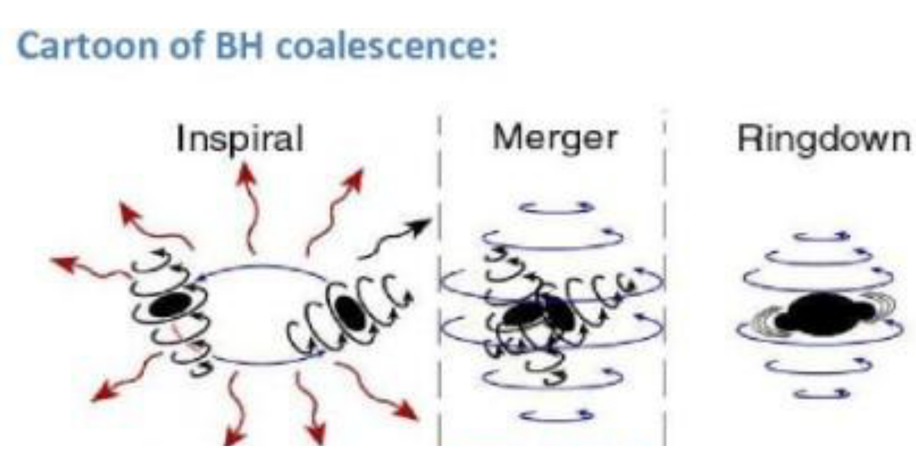
- black holes are minuscule
- coalescing binary black holes are minuscule
- gravity is the weakest interaction in Nature

$$R_{\rm G} = \frac{2GM}{c^2} = 0.1 \left(\frac{M_{\rm BH}}{10^6\, M_\odot}\right) \mu\text{parsec}$$

$$t_{\rm coal} = \frac{5}{256}\frac{c^5}{G^3}\mathcal{G}(e)(1-e^2)^{7/2}\frac{a^4}{\nu\, M_{\rm B}^3}$$

$$\nu = \frac{\mu}{M} = \frac{q}{(1+q)^2}$$

$$M_{\rm B} = M_{\rm BH,1} + M_{\rm BH,2}$$



- the scale of gravitational-wave-driven inspiral is minuscule compared to galactic dimensions

$$t_{\rm coal} = \frac{5}{256}\frac{c^5}{G^3}\mathcal{G}(e)(1-e^2)^{7/2}\frac{a^4}{\nu\, M_{\rm B}^3}$$

$$t_{\rm coal} \sim t_{\rm cosmic}(z)\delta z$$

$$a_{\rm GW} \propto t_{\rm cosmic}^{1/4}\,\nu^{1/4} M_{\rm B}^{3/4}$$

$z = 15$ $t_{\rm cosmic} = 0.27\,{\rm Gyr}$	$M_{\rm B} = 10^5\, M_\odot$	$M_{\rm B} = 10^6\, M_\odot$
$a_{\rm GW}$	$\nu^{1/4} 2.5 \times 10^4\, R_{\rm G}$ $0.25\,{\rm mparsec}$	$\nu^{1/4} 1.4 \times 10^4\, R_{\rm G}$ $1.4\,{\rm mparsec}$
$z = 3$ $t_{\rm cosmic} = 2.16\,{\rm Gyr}$	$M_{\rm B} = 10^5\, M_\odot$	$M_{\rm B} = 10^6\, M_\odot$
$a_{\rm GW}$	$\nu^{1/4} 4 \times 10^4\, R_{\rm G}$ $0.4\,{\rm mparsec}$	$\nu^{1/4} 4.8 \times 10^4\, R_{\rm G}$ $5\,{\rm mparsec}$

- chain of dissipative processes of non-GW origin
  - drive the dynamical formation of a massive black hole binary during a halo-halo galaxy merger - exquisite cosmological problem encompassing more than 10 orders of magnitude in physical scale
  - stars? gas?
  - bottleneck(s)? failures (wandering black holes)?
  - the quest for efficient binary hardening from cosmological scales to galactic, and from galactic to sub-galactic scales is instrumental for the detection of high redshift events and makes predictions on merger rates extremely challenging … *Marta's talk*

- two black holes in a remnant galaxy

$$\mathbf{F}_{\rm DF}^{\rm stars} = -4\pi \ln \Lambda G^2 M_{\rm BH}^2 \rho_* \mathcal{F}\left(\frac{V_{\rm BH,orb}}{\sigma_*}\right) \frac{\mathbf{V}_{\rm BH,orb}}{V_{\rm BH,orb}^3}$$

- Keplerian binary formation in the galaxy remnant

$$a_{\rm binary} \sim \frac{GM_{\rm B}}{\sigma^2} \sim 1 \left(\frac{M_{\rm B}}{10^6\,{\rm M}_\odot}\right) \left(\frac{50\,{\rm km\,s^{-1}}}{\sigma}\right)^2 \,{\rm parsec}$$

- hardening phase

$$a_{\rm binary} \rightarrow a_{\rm GW}$$

- @ $a_{\rm GW} \propto t_{\rm cosmic}^{1/4} \nu^{1/4} M_{\rm B}^{3/4}$ the orbital velocity is 0.01 the speed of light

$$V_{\rm orb} \sim 2000 - 3000\,{\rm km\,s^{-1}}$$

cutting edge questions

- do LISA black holes coalesce “on clock”, as soon as their host halos merge?
- time delay: what is delay distribution and how does it depend on redshift, mass/ratio, gas vs stellar content, orbit, galaxy morphology, …?

ancillary question

- how fast do black holes grow via accretion during a halo-halo merger?

$$\tau_{\rm acc} \sim 470 \frac{\varepsilon_{\rm rad}}{f_{\rm E}(1-\varepsilon_{\rm rad})}\,{\rm Myrs}$$

$$f_{\rm E} = \frac{L}{L_{\rm Eddington}}$$

I. portrait of an isolated gas-rich major (1:4) merger

- Clock: time "zero"

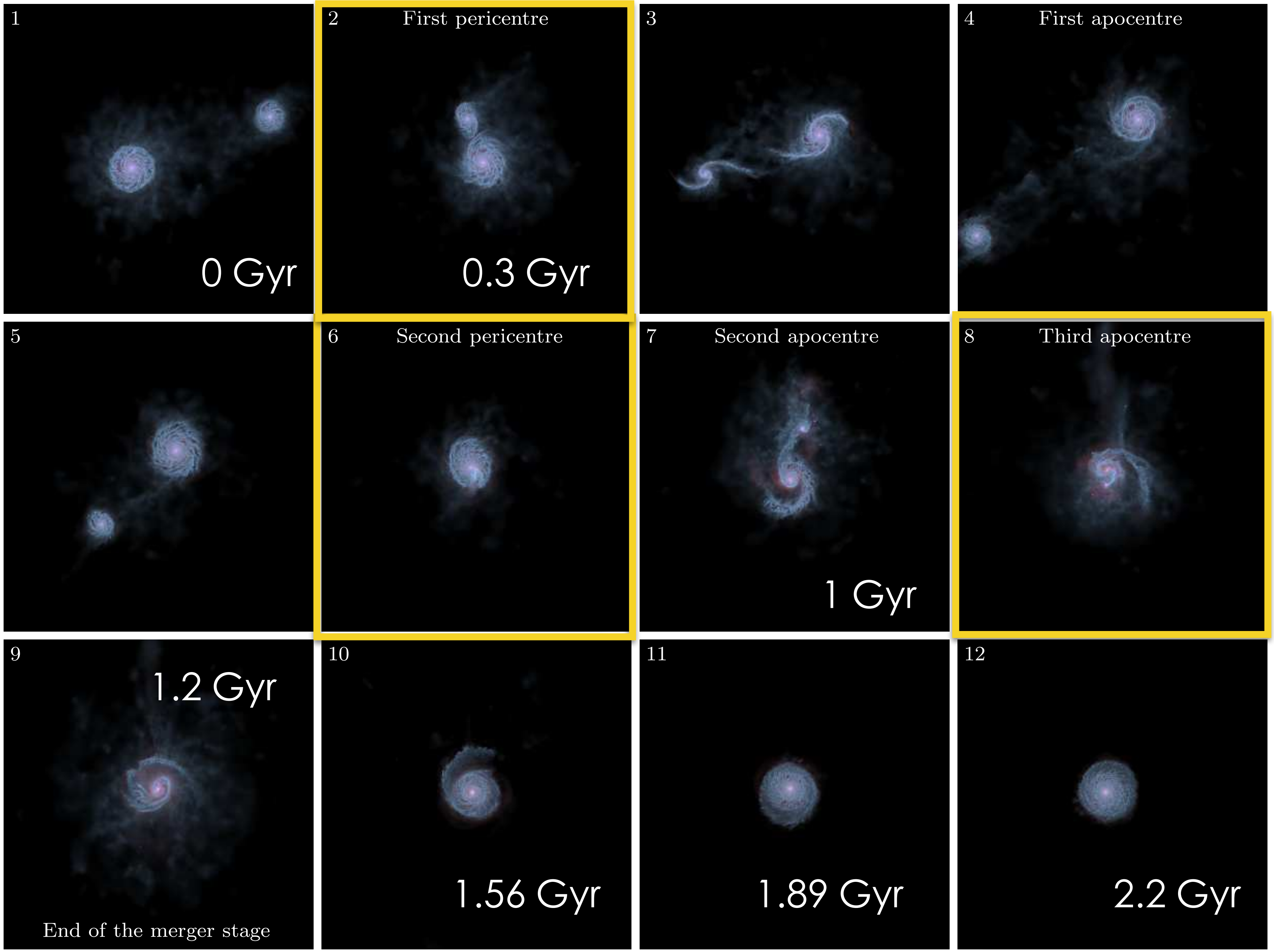
$M_{\rm BH,primary} = 3\times10^6\,M_\odot$
$M_{\rm halo} = 2.2\times10^{11}\,M_\odot;\, M_{\rm bulge} = 2\times10^9\,M_\odot$
$M_{\rm disc,*} = 6\times10^9\,M_\odot;\, M_{\rm disc,gas} = 3\times10^9\,M_\odot$

70x70 kpc box

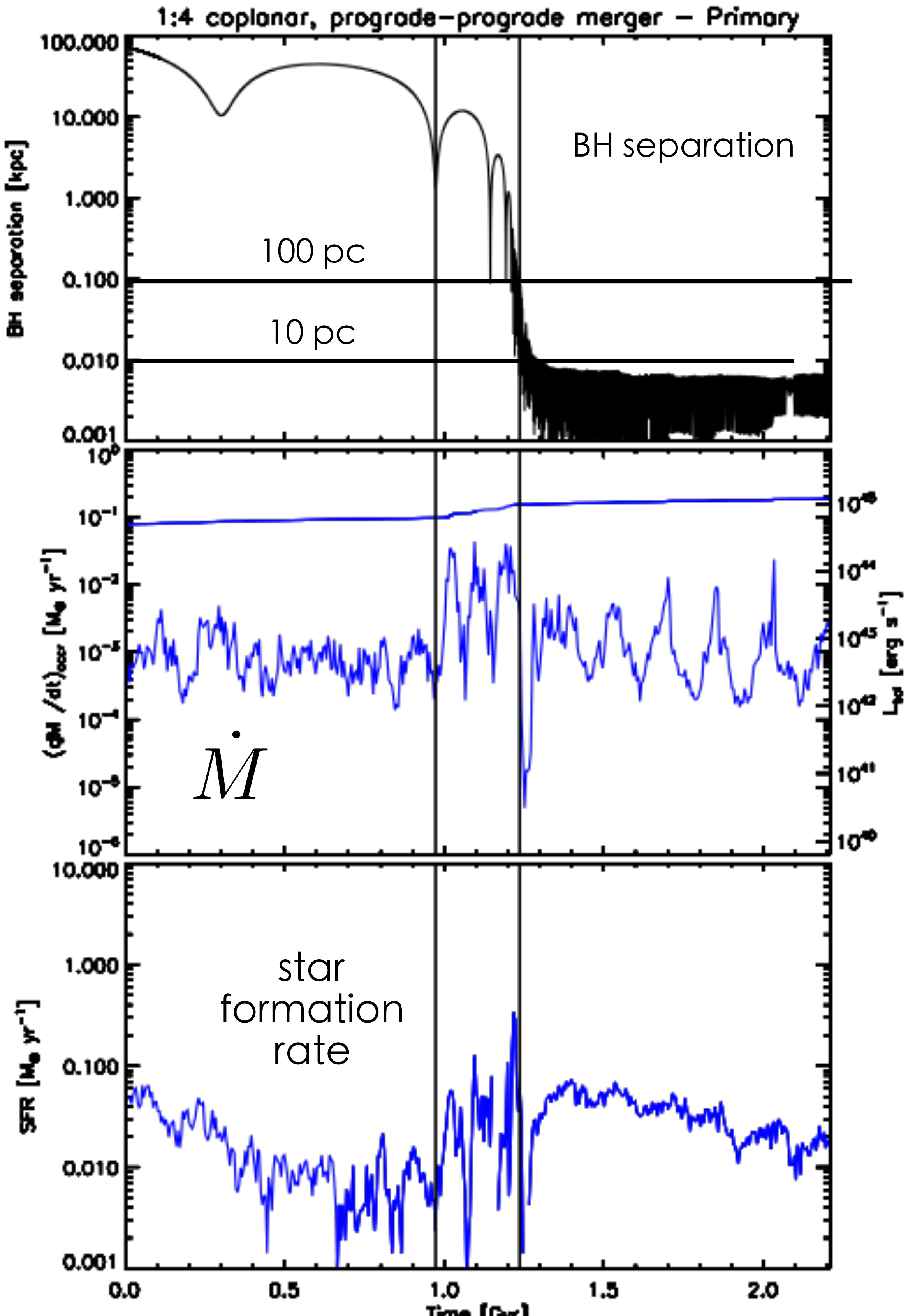
1:4 merger between two disc galaxies

gas fraction 30%

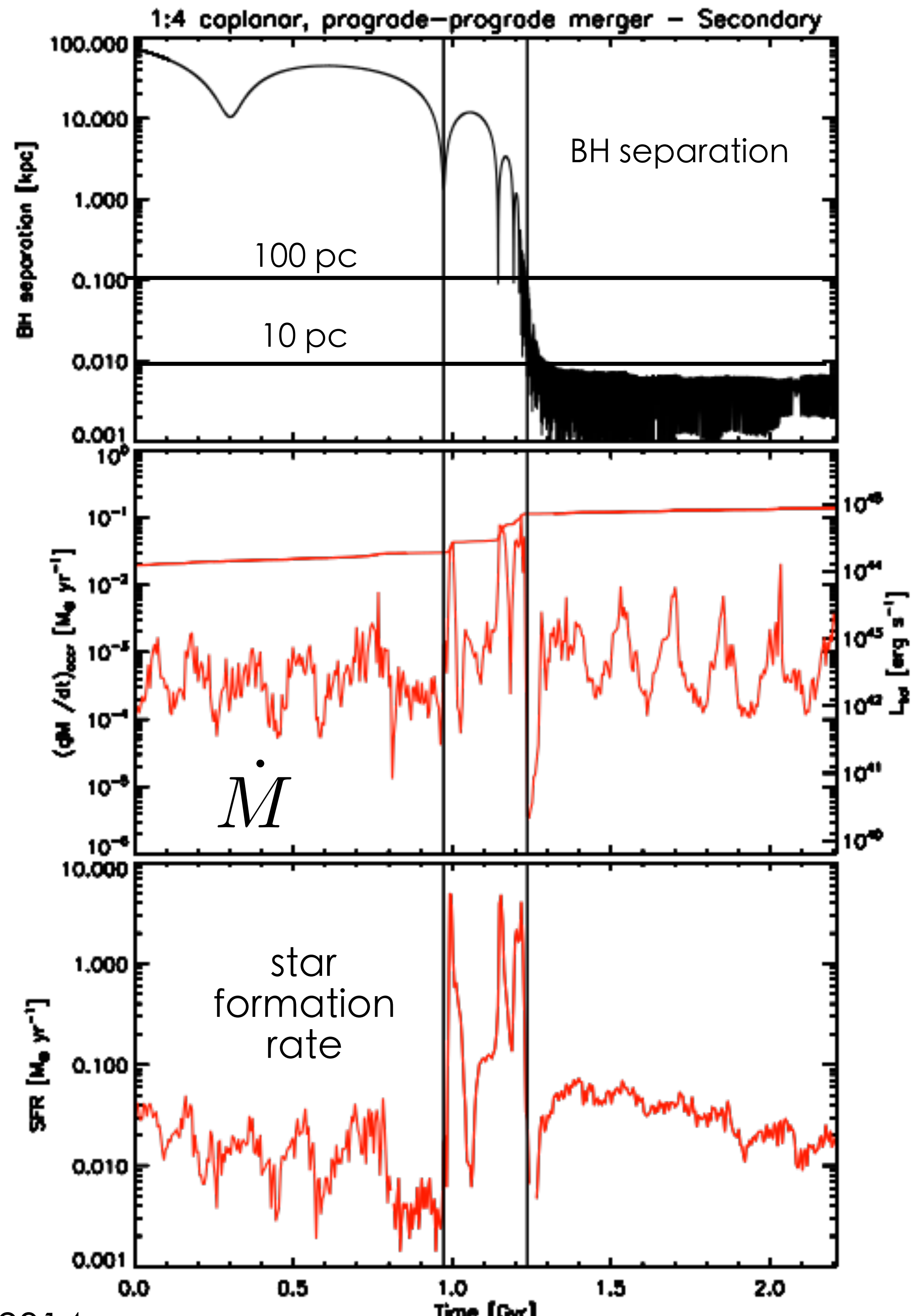
Capelo+2014



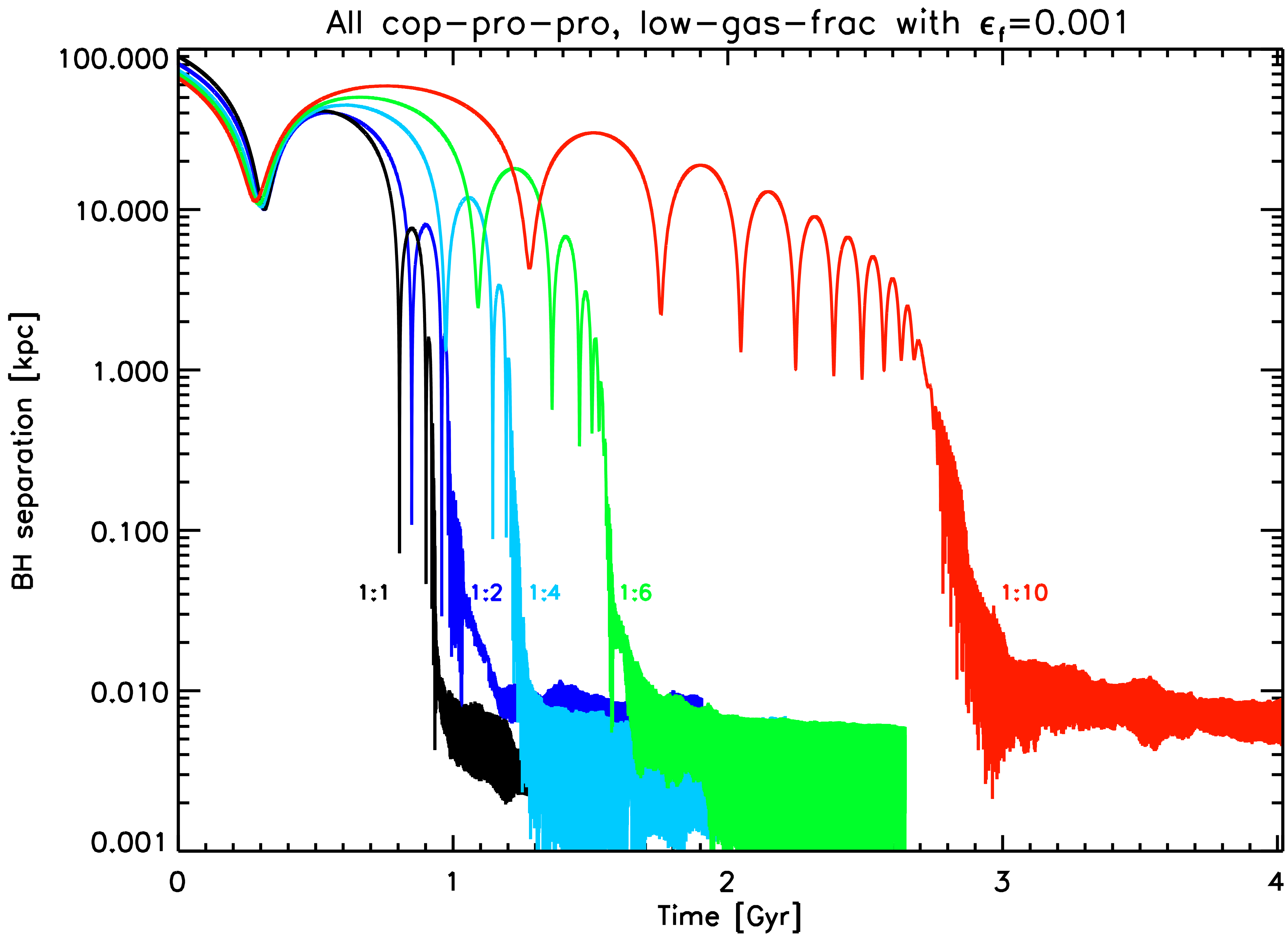
primary black hole



secondary black hole



Capelo+2014



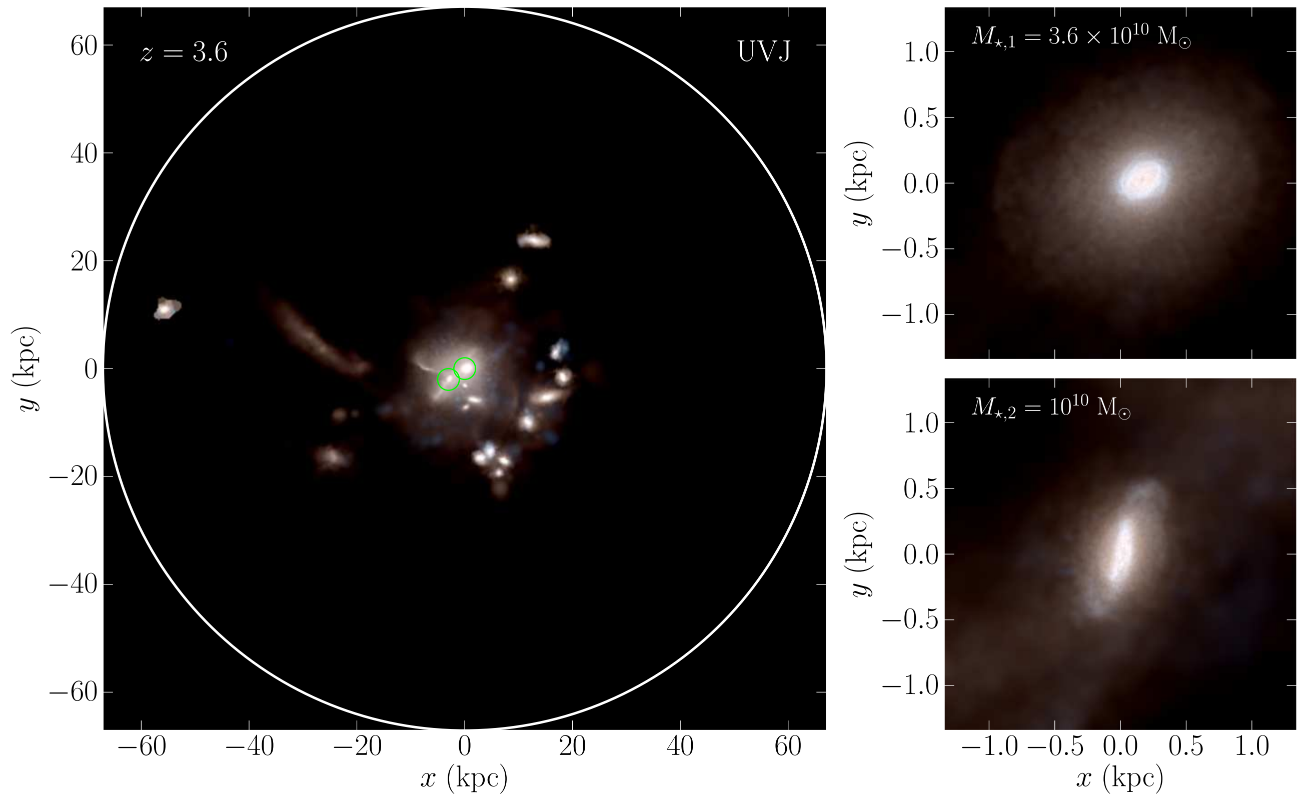
All cop–pro–pro, low–gas–frac with ϵ_f=0.001
100.000
10.000
1.000
0.100
0.010
0.001
BH separation [kpc]
0
1
2
3
4
Time [Gyr]
1:1
1:2
1:4
1:6
1:10

Take home message

- importance of tracking the tidal interaction between the two galaxies since the early stages - key feature of many simulations
- wandering black holes - lower mass ratio mergers ($q<0.1$)
- black hole mass contrast tends to decrease (increase) in minor (major) mergers - preferential range of mass ratios
- narrowing of q - LISA events - select te most favorable channels

Callegari+2009,2011;Kazantzidis+2012; Capelo+2017a,b;Bellovary+2010; Van Vassenhove+2014; Colpi 2014; Tremmel+2015,2017

II. portrait of a cosmological merger



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

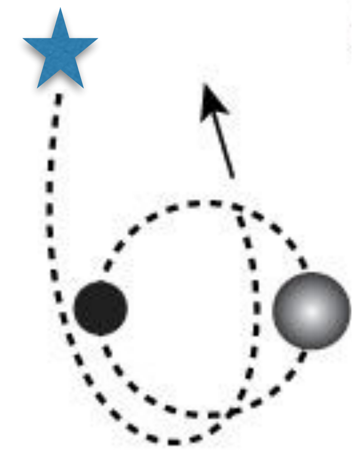
$$m_2^{\mathrm{BH}} = 3 \times 10^7\,\mathrm{M}_\odot$$

Khan, Mayer, Fiacconi 2016

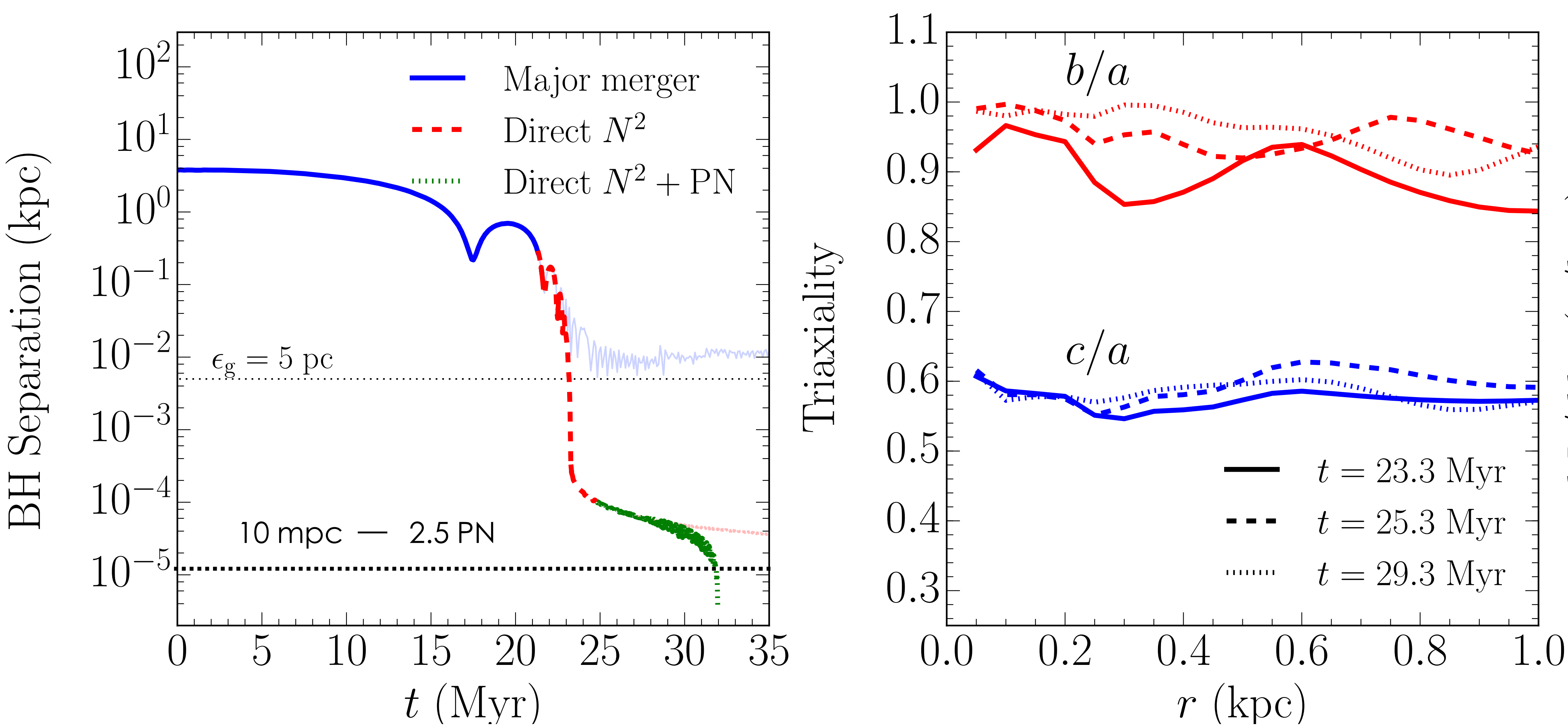
- first ab initio simulation of a galaxy group @ z=3.5 from Argo cosmological simulation
- identification of the two main spirals undergoing a major merger (1:3.6 mass ratio) on a nearly parabolic orbit with co-rotating stellar discs inclined by 67 degrees
- gas fractions of about 10%
- splitting procedure to attain a force resolution of 5 pc - Direct N-Body code
  (mass resolution 6000 gas,10,000 stars, 100,000 dark matter)

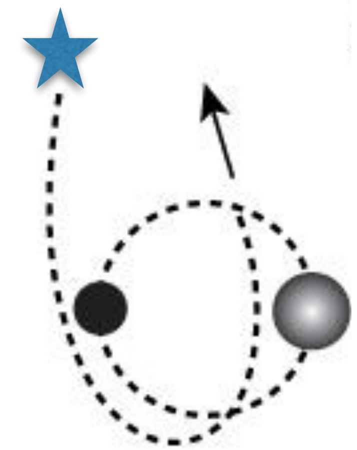
$$M_{2,*} \sim 10^{10}\,M_\odot$$
$$M_{1,*} \sim 3.6 \times 10^{10}\,M_\odot$$
$$M_{\mathrm{halo}} \sim 10^{13}\,M_\odot \quad @ \quad z = 0$$

- gas inflows in the inner 500 pc from cosmological streams are conducive to an intense burst of star formation around the secondary black hole
- the black holes are surrounded by a stellar cusp which enhances their "effective mass" - the orbital decay is governed by dynamical friction of the stellar cusps



- the binary hardens by the slingshot mechanisms with individual stars impugning on the binary form low-angular momentum orbits in a triaxial potential. The binary mergers 10 Myrs after the merger of the stellar cusps

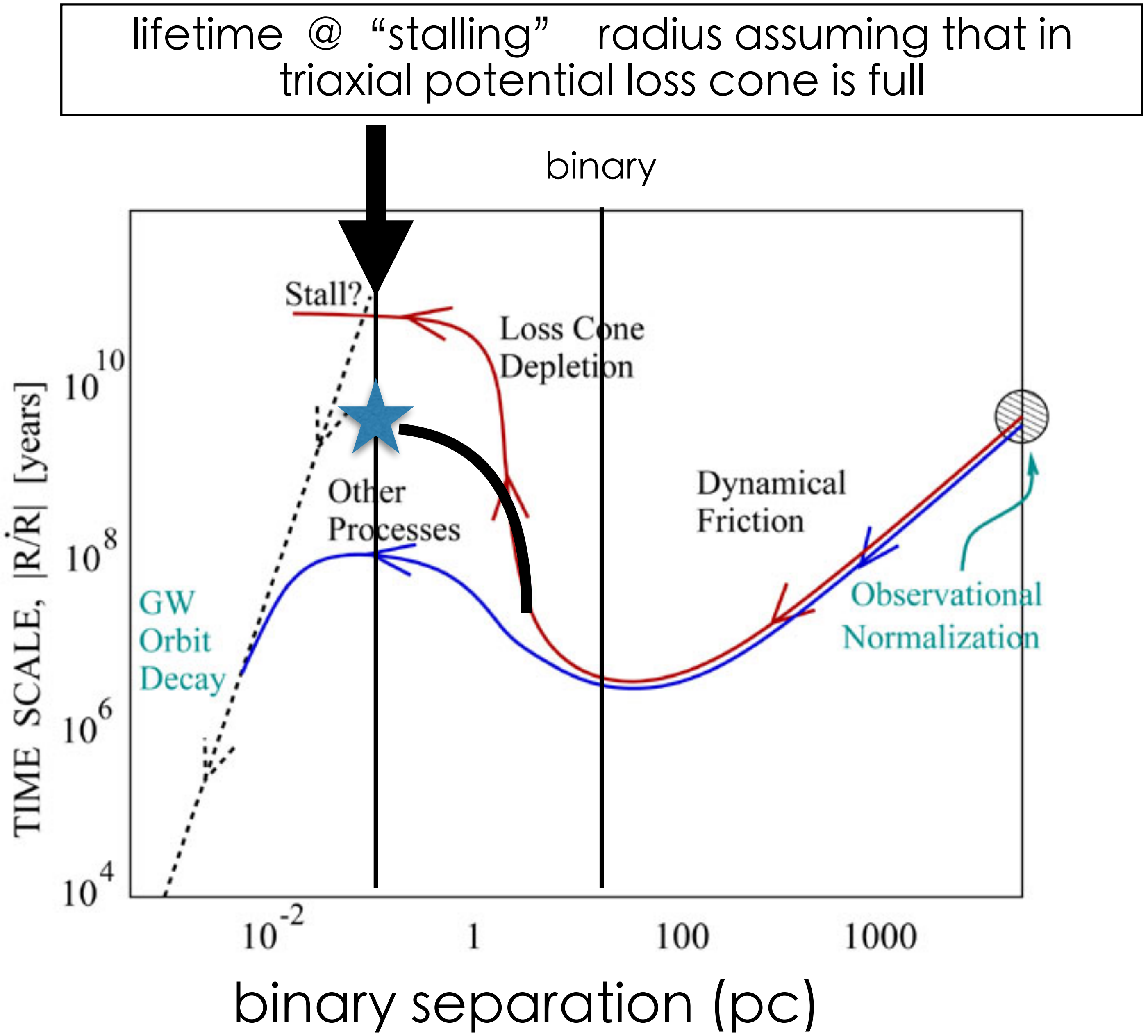




Take home message

- nuclear inflows of gas and episodes of star formation in the vicinity of the black holes are instrumental in creating the conditions for rapid pairing as they enhance the effective mass of the black hole and thus the dynamical friction drag
- provide the reservoir of stars for the slingshot mechanism to become effective in the triaxial potential of the new galaxy
- stars are "key players" for the merger to stay on clock with the "help" of gas: having a higher degree of dissipation/ability to loose angular momentum gaseous stream lead to formation of stellar cusps
- just a single simulation with "massive" black holes

III. hardening in stellar backgrounds



$$t_{\rm hardening} \propto a^{-1}$$

$$t_{\rm coal} \propto a^4$$

$$t_{\rm hardening}(\rho_*, \sigma_*; a) = t_{\rm coal}(a)$$

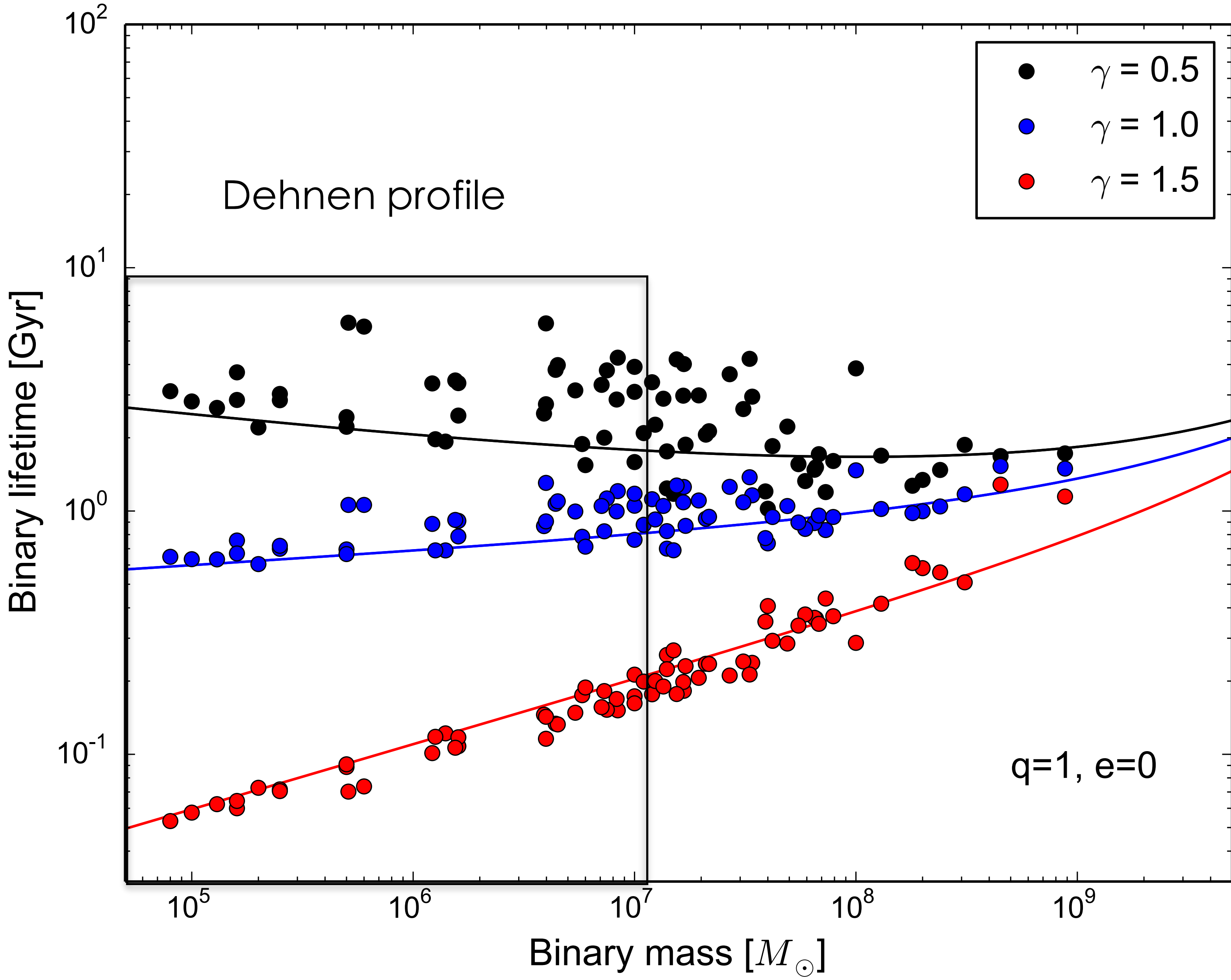
$$R_{\rm inf} \approx \frac{G_{\rm BHB}}{\sigma_*^2}$$

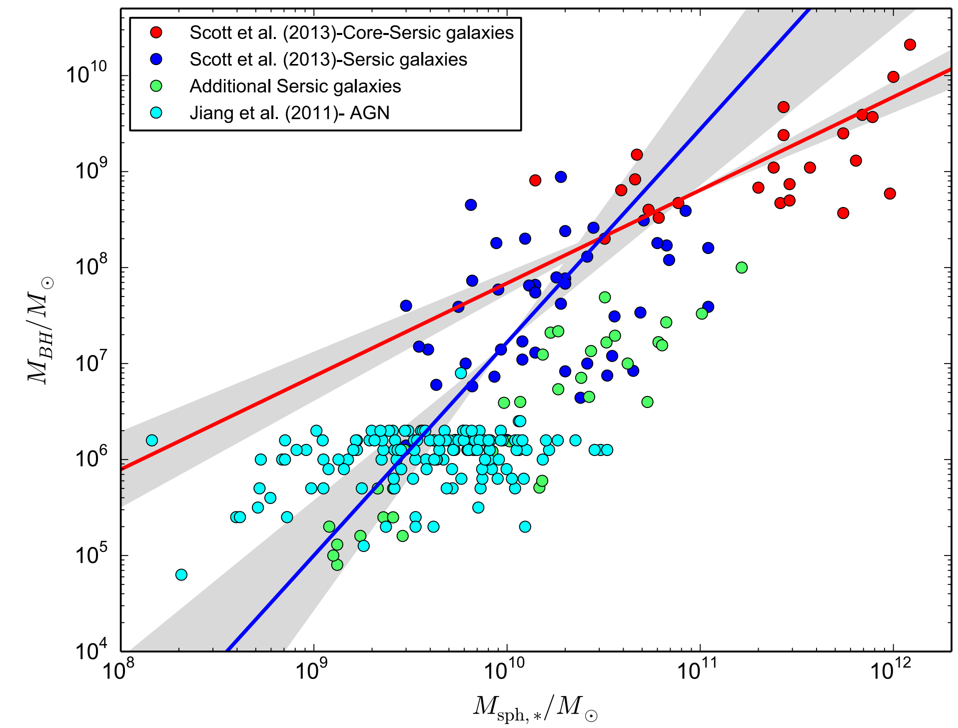
$$a_{*/\rm gw} = \left[\frac{64 G^2 \sigma_{\rm inf} q M^3_{\rm BH,T} F(e)}{5 c^5 (1+q)^2 H \rho_{\rm inf}}\right]^{1/5}$$

$$t(a_{*/\rm gw}) = \frac{\sigma_{\rm inf}}{G H \rho_{\rm inf} a_{*/\rm gw}}$$

Begelman, Blandford & Rees 1980
Milosavljevi´c & Merritt 2005
Vasiliev+2014a,b,2015
Sesana & Khan 2015

$$(M_{\rm BHB}, M_*, R_{\rm eff})$$





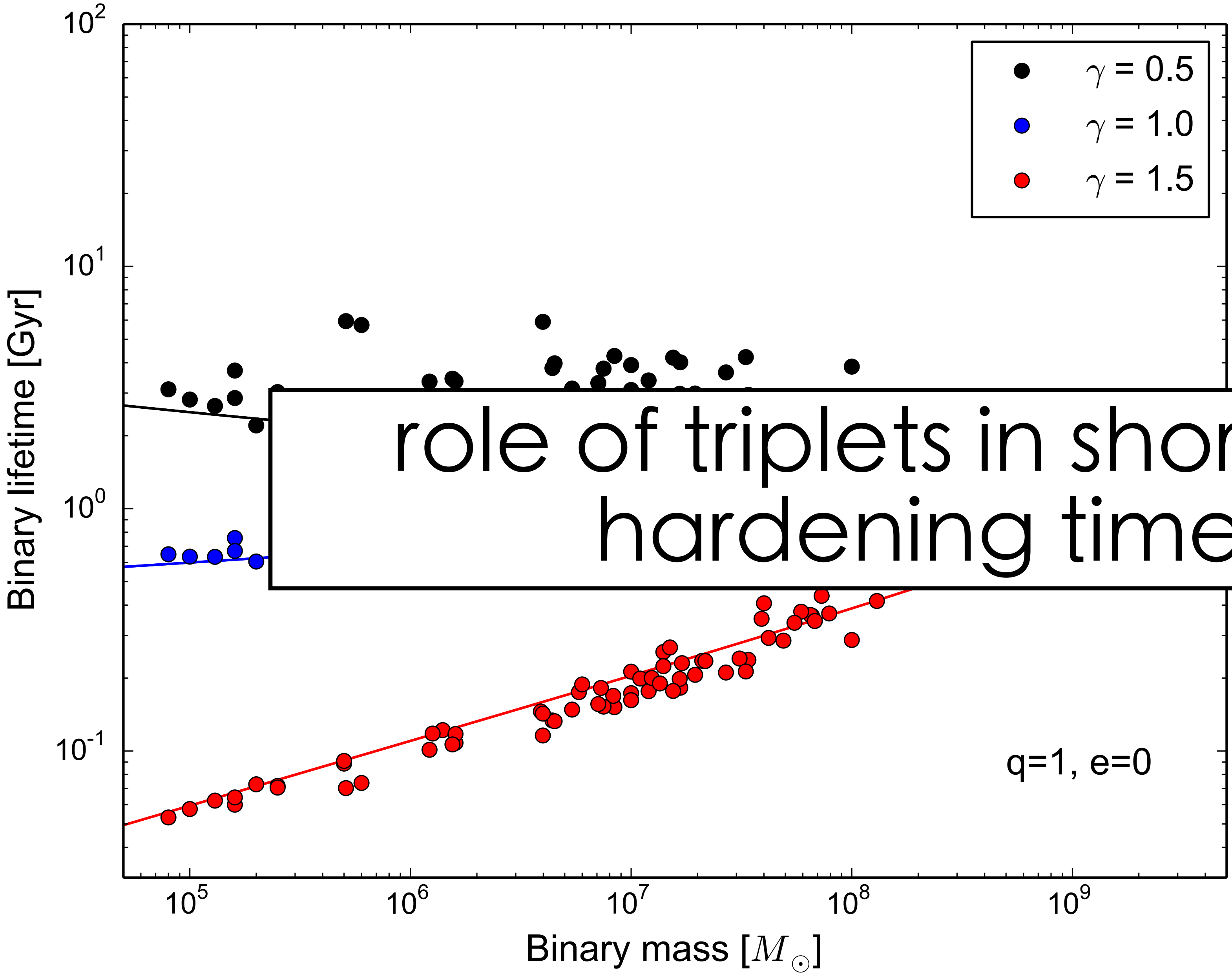
$$\rho(r) = \frac{(3-\gamma)M_*}{4\pi}\frac{r_0}{r^\gamma (r+r_0)^{(4-\gamma)}}$$

$$\sigma^2(r) = GM_* r^\gamma (r+r_0)^{4-\gamma}\int_r^\infty \frac{r'^{1-2\gamma}dr'}{(r'+r0)^{7-2\gamma}}$$

$$R_{\rm eff} \sim 0.75 r_0 (2^{1/(3-\gamma)}-1)^{-1}$$

$$R_{\rm eff}/{\rm pc} \; = \; 2.95({\rm M}_*/{\rm M}_\odot)^{0.596}$$

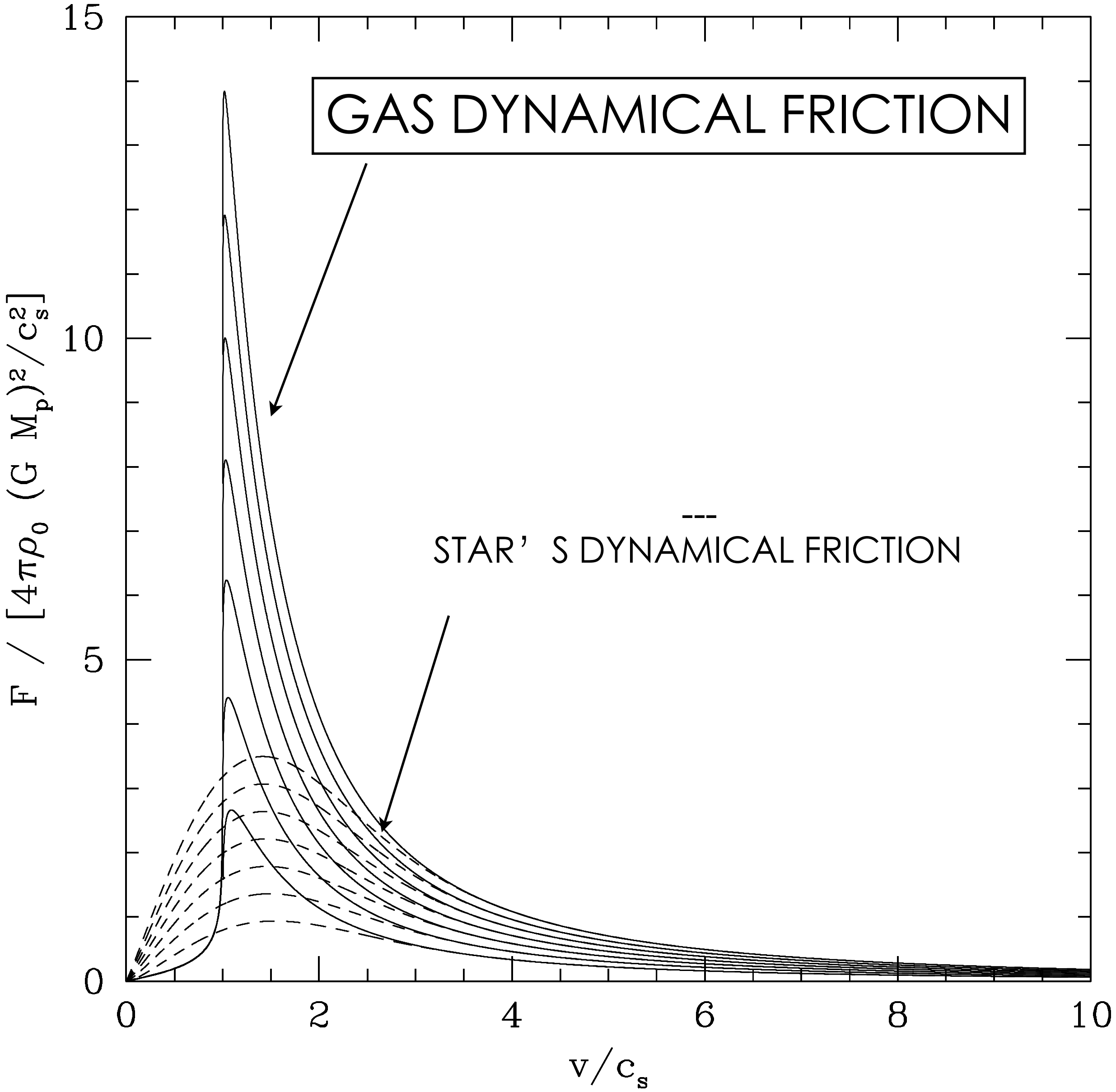
Biava+2018 in preparation



role of triplets in shortening the hardening timescale

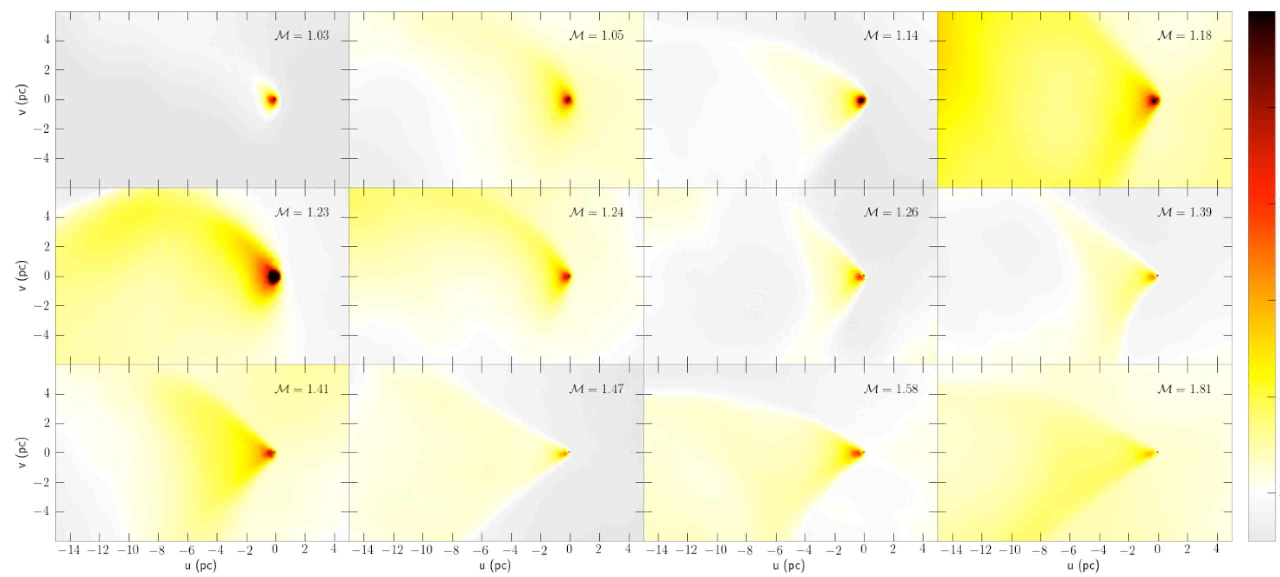
Bonetti+ 2017,2018
Hoffman & Loeb 2012,
Kulkarni & Loeb 2007,
Blaes+2002
Mikkola+1990

IV. 100 - 1 pc scale - binary formation in gaseous backgrounds



$$\mathbf{F}_{\rm DF}^{\rm gas} = -4\pi \ln\Lambda G^2 \, M_{\rm BH}^2 \rho_{\rm gas} \mathcal{F}\left(\frac{V}{c_{\rm sound}}\right)\frac{\mathbf{V}}{V^3}$$

Ostriker 1999

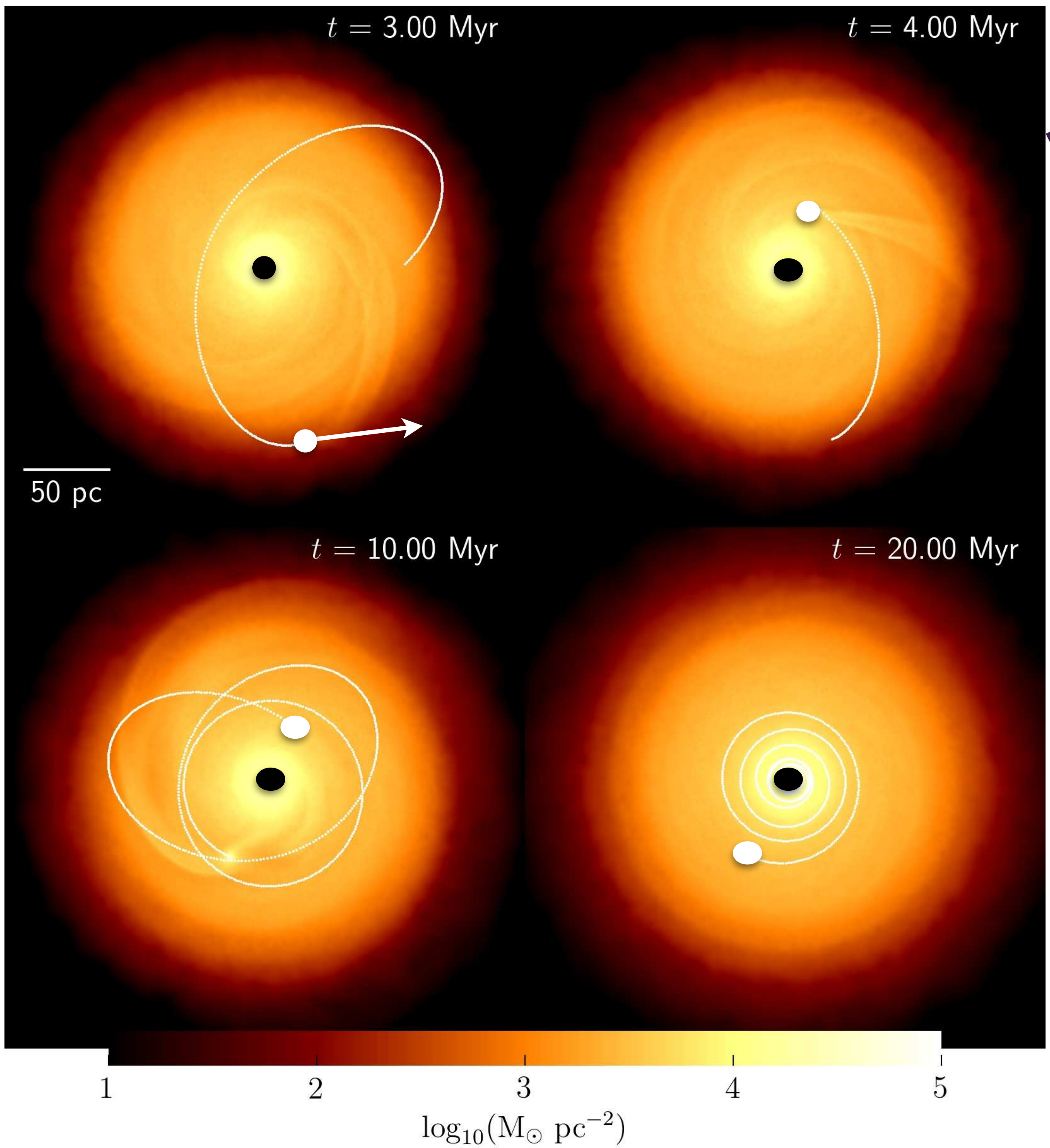


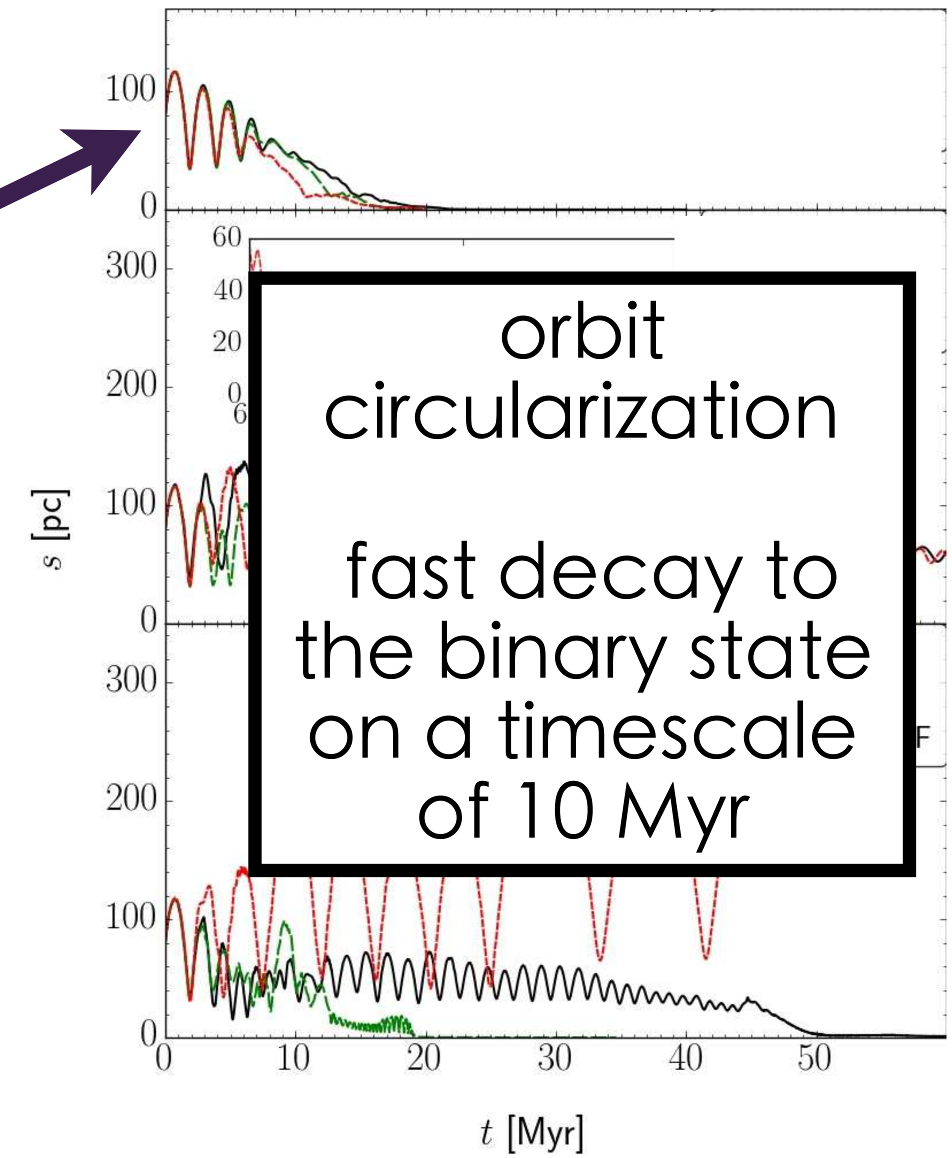
Chapon+2011

IV. black hole dynamics in massive circum-nuclear gas discs on ~(100 - 1)pc

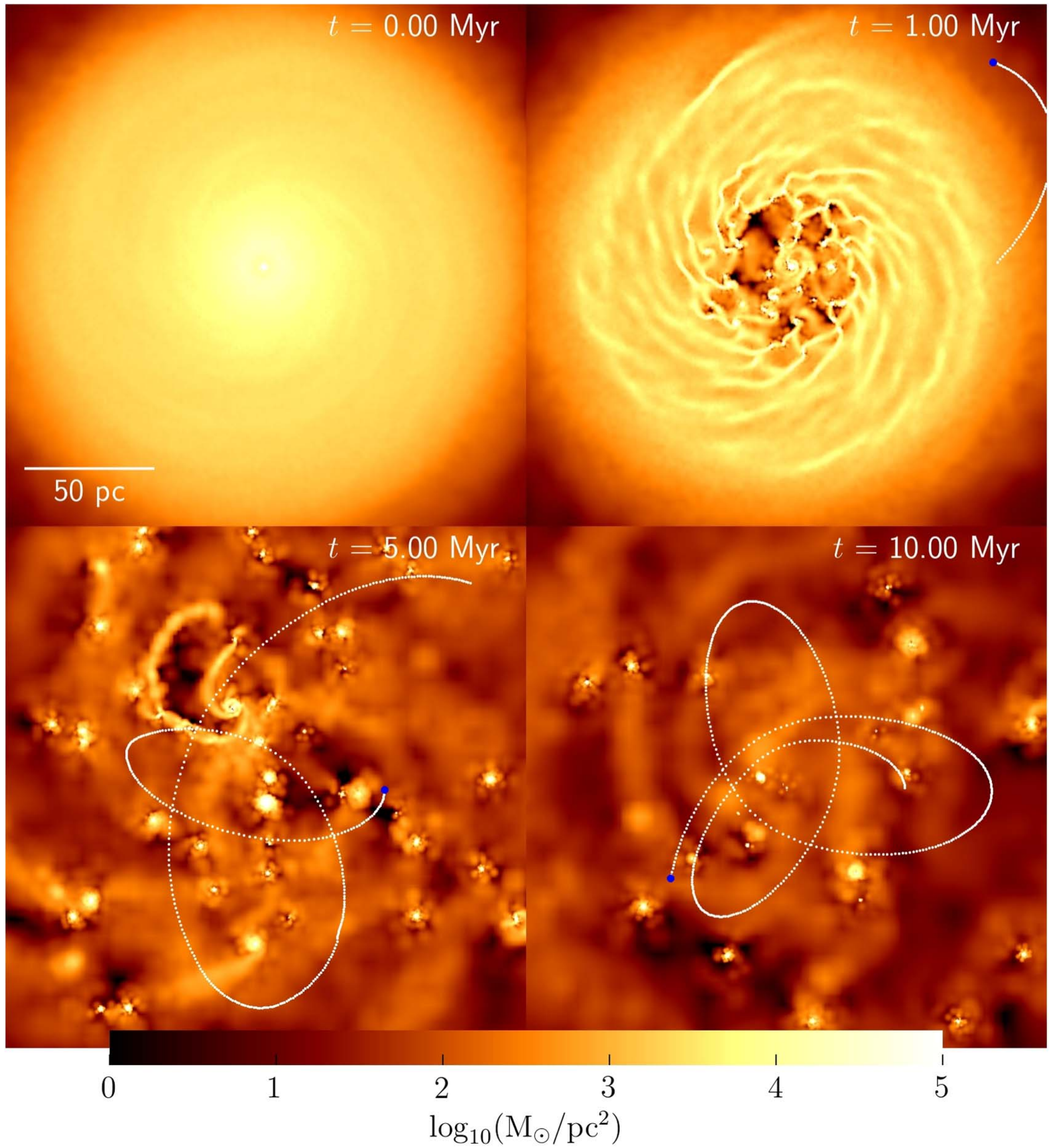
$M_{\rm disc} = 10^8\, M_\odot$

$M_{\rm BH,1} = 10^7\, M_\odot$ $M_{\rm BH,2} = 5 \times 10^5\, M_\odot$



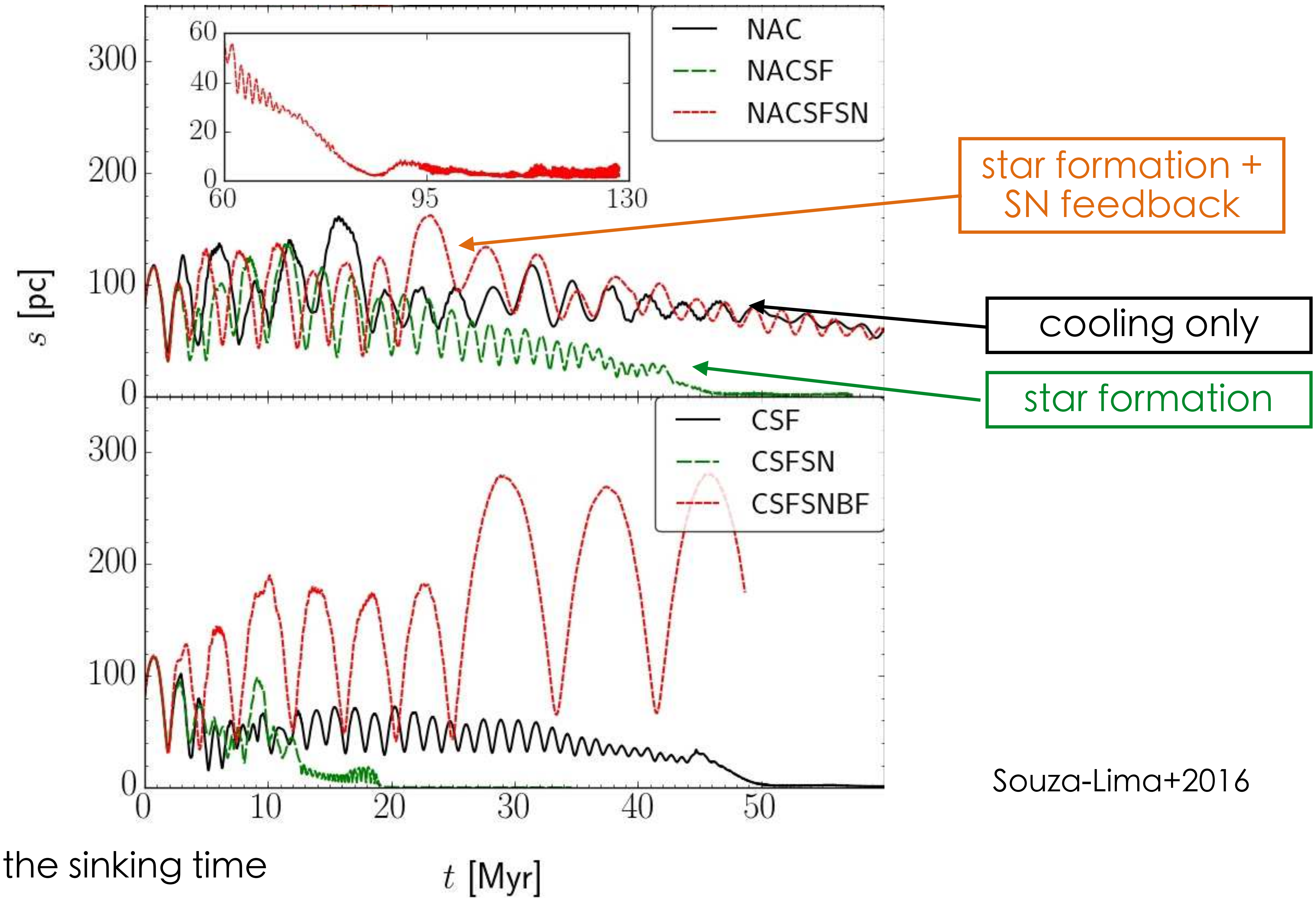


Souza Lima+2016
Dotti+2007-2010
Fiacconi+2013
Lupi+2015
del Valle+2015,
Roskar+2015,
Tamburello+ 2016



- fragmentation from inside out occurs on a timescale smaller than the orbital decay time
- dense gaseous clumps form, interact, merge to form fewer and larger clump, and migrate to the centre
- clumps can have masses comparable or larger than the black hole masses
- high density contrast leading to a completely different dynamics

Souza Lima+2016, del Valle+2015, Fiacconi+2013

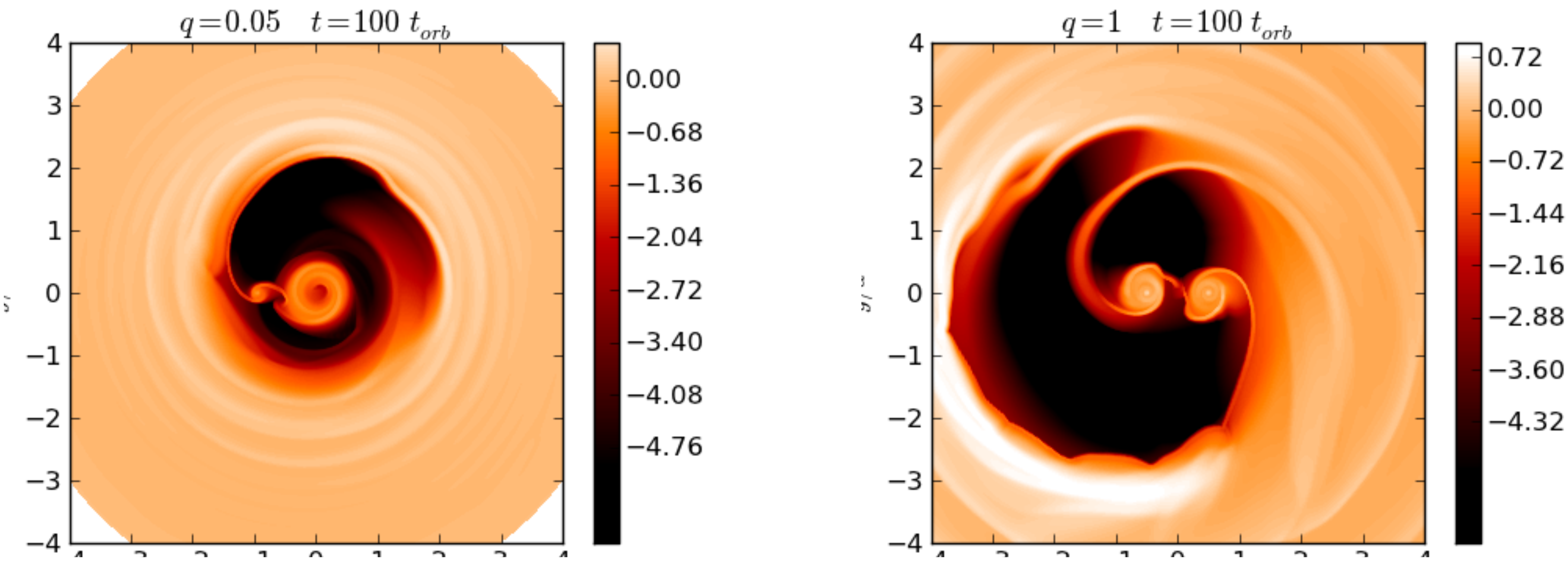


Souza-Lima+2016

- increase in the sinking time
- no-circularization in this multi-phase medium
- scattering off the disc plane - postponed merger
- rare cases in which the secondary black hole is drag inside a clump rapidly to the centre
- spread in the delay times (stochastic dynamics): 2–100 Myrs

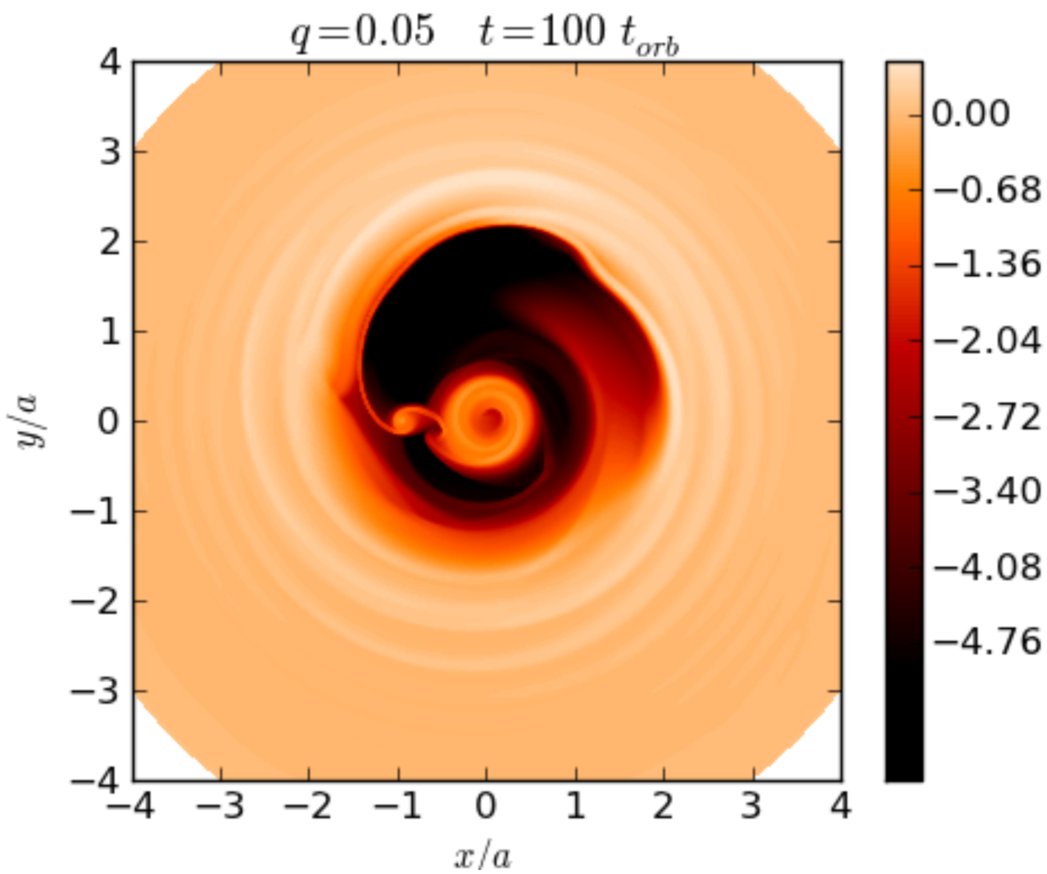
V. type II migration in a circum-binary disc

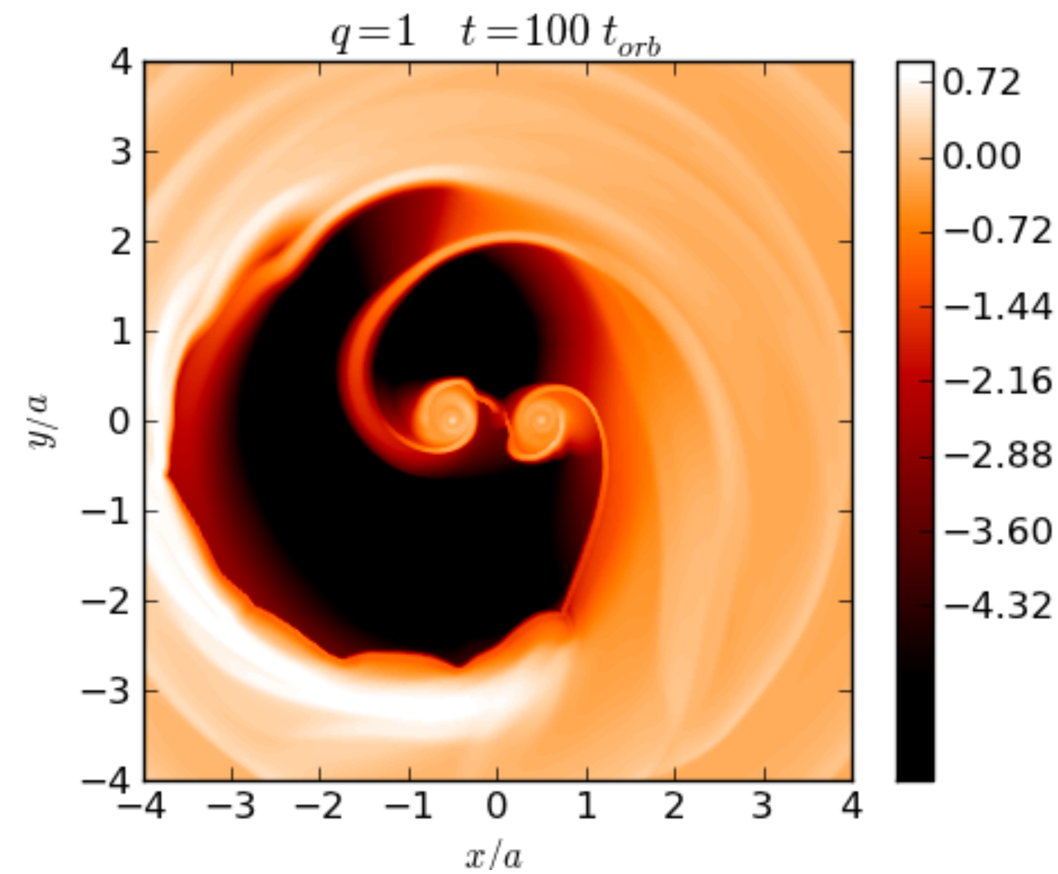
Courtesy by Zoltan Haiman +2017



- black holes deposit orbital angular momentum exciting both leading and trailing spiral waves opening a gap of size twice the size of the binary separation

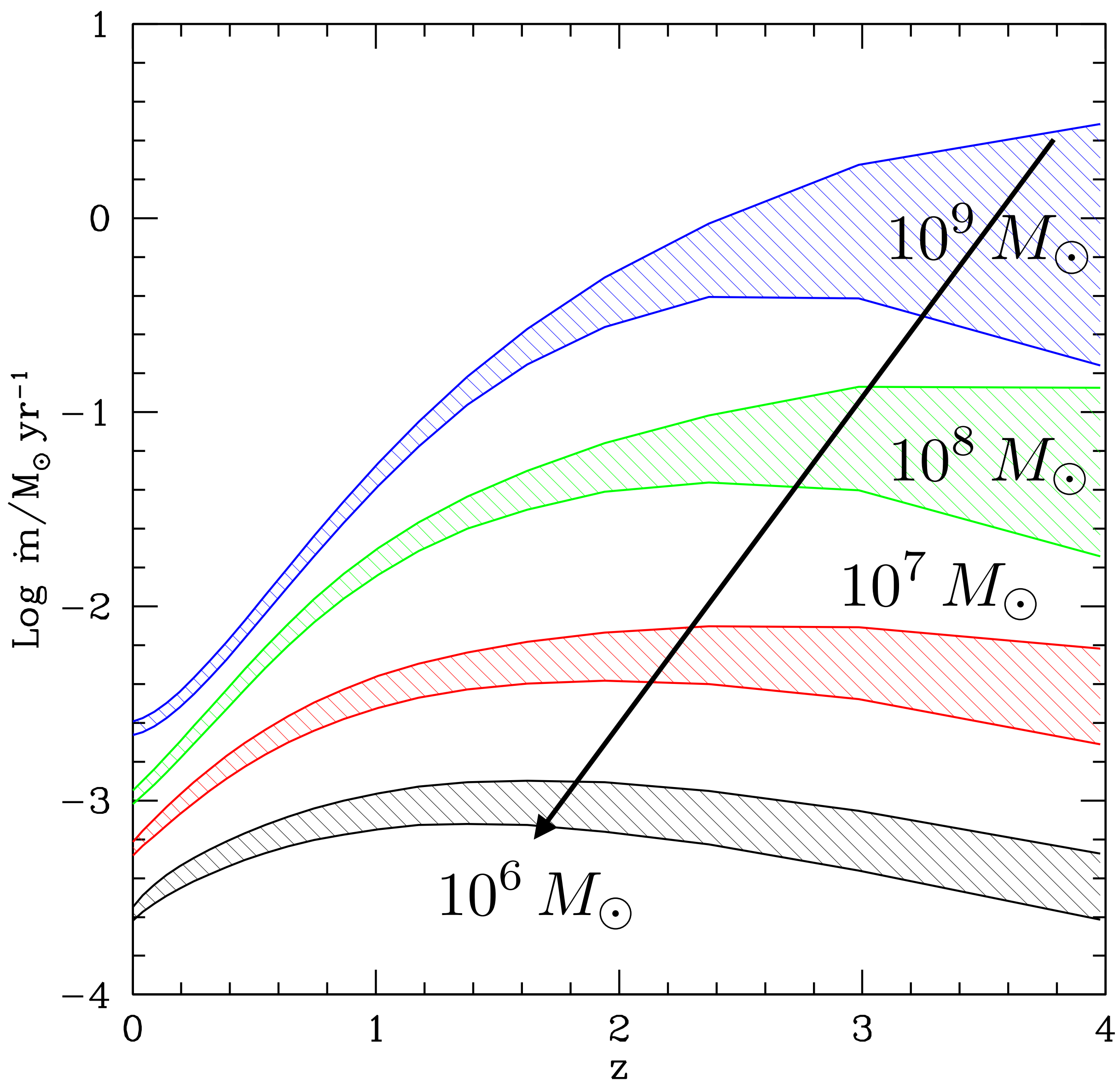
Kocsis+ 2007,2012; MacFadyen+2008; Roedig et al. 2011,12,14; D' Orazio et al. 2013; Farris et al. 2015; Dunhill et al. 2015; Tang et al. 2017; Maureira-Fredes 2018; Dotti+2015





- turbulence and viscosity in the circum-binary disc maintain the contact between the disc and the black hole
- the two black holes "migrate" inwards
- the gap "follows" the binary
- mini discs and not empty cavity

- assuming that black hole binaries in the LISA range are fueled as isolated black holes are, the accretion rates are such that there is sufficient fuel for LISA black holes forming at z>2-3 to coalesce during the peak of the star formation rate



$$\frac{dL_{\rm BHB}}{dt} \sim -\dot{M} l_{\rm Kep}(r_{\rm gap})$$

$$r_{\rm gap} \sim 2a$$

Dotti, Merloni, Montuori 2015

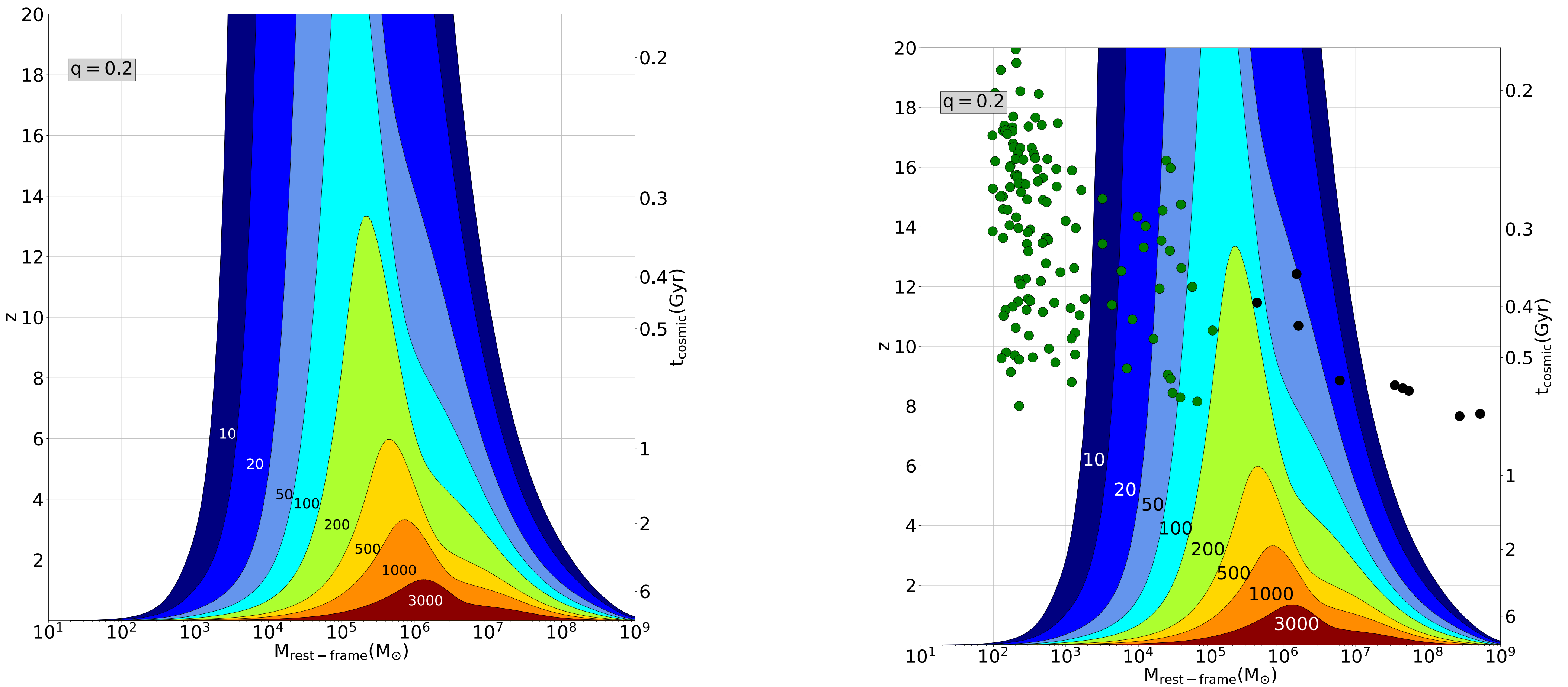
T

Take home message

- in massive nuclear discs, gas fragmentation leads to a broadening of times for binary formation
- star formation and SN-feedback are critical in determining the properties of the black hole nearest environment
- migration in a circum-binary disc surrounding the binary likely drive the binary down to the GW driven inspiral ($z<3$)

- two regimes?
- presence of a massive stellar cusp leads to swift coalescence (z-dependent? wait until $z \sim 4$-5?)
- presence of large inflows of gas - long-lived phase of "accretion" (50 Myrs) to promote migration
- setting the "clock" is both a cosmological and local problem

- it is still difficult to quantify the level of broadening of the time delay distribution in the formation of LISA coalescing binary black holes: 10 Myrs - 4 Gyrs to asses the differential merger rate
- LISA signal dominated
- observability of black holes not sensitivity limited



- ONLY LISA will tell us the true story

Valiante+2016,17,18

- Triplet to solve for the bottleneck

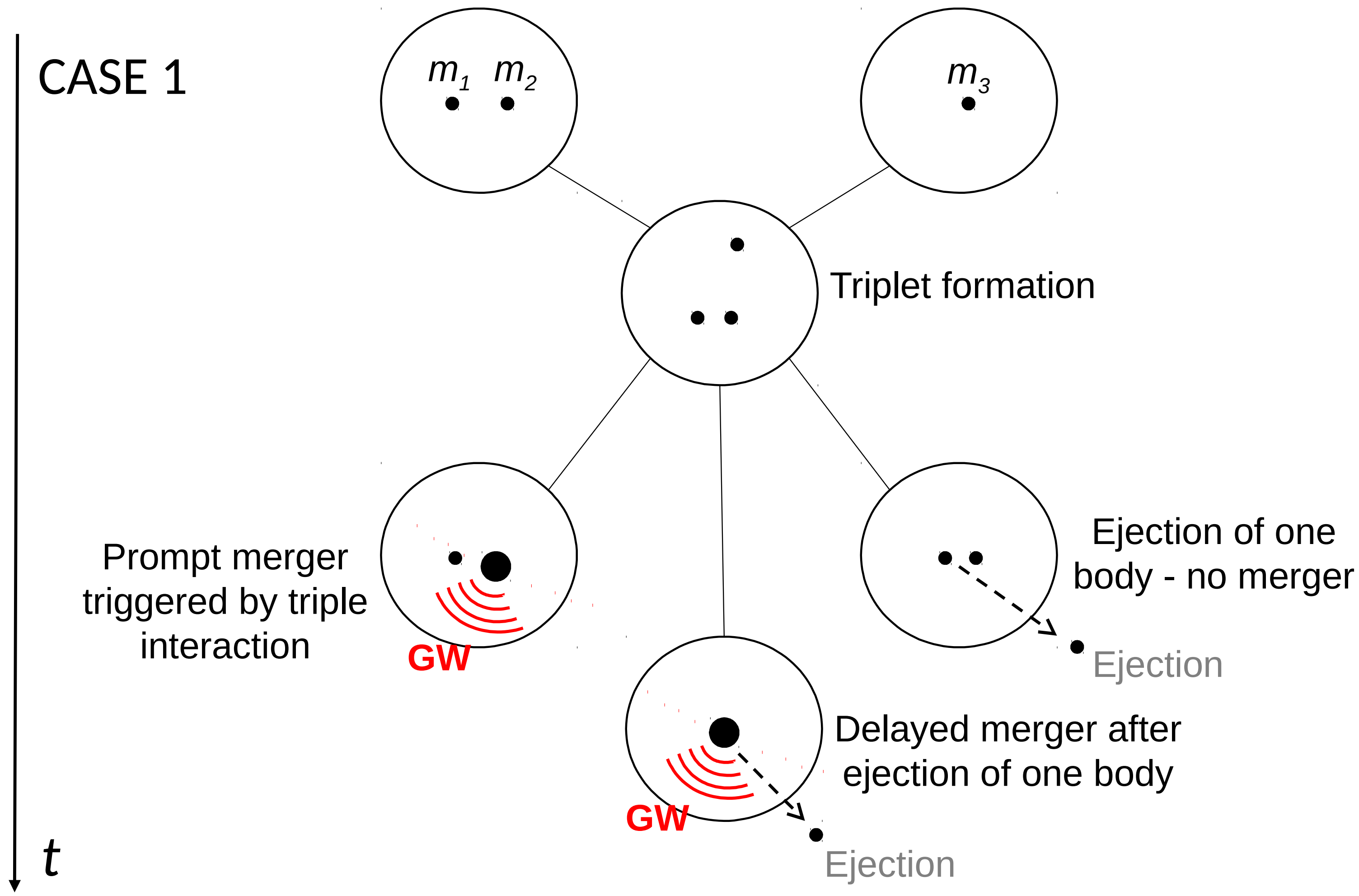
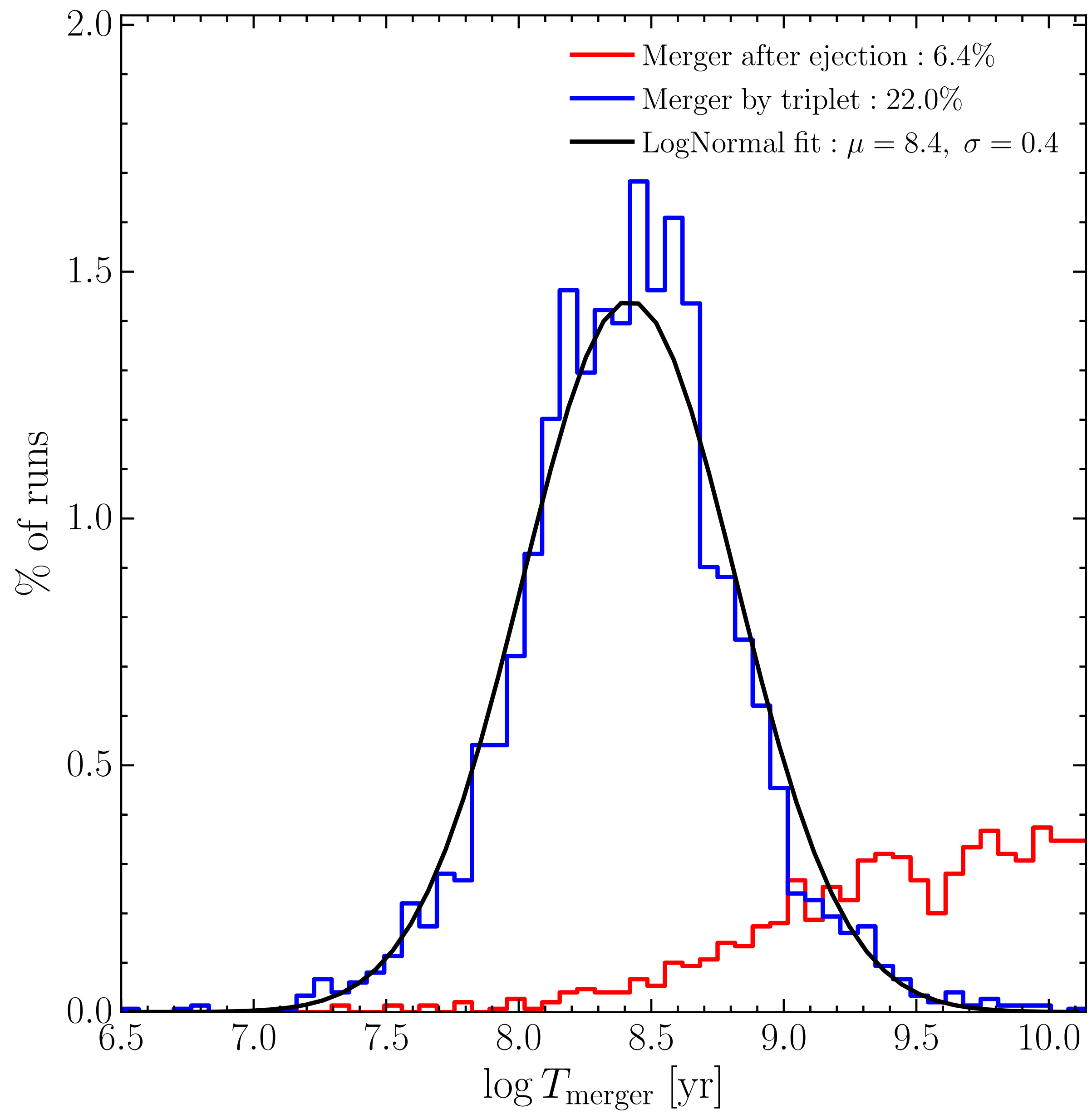
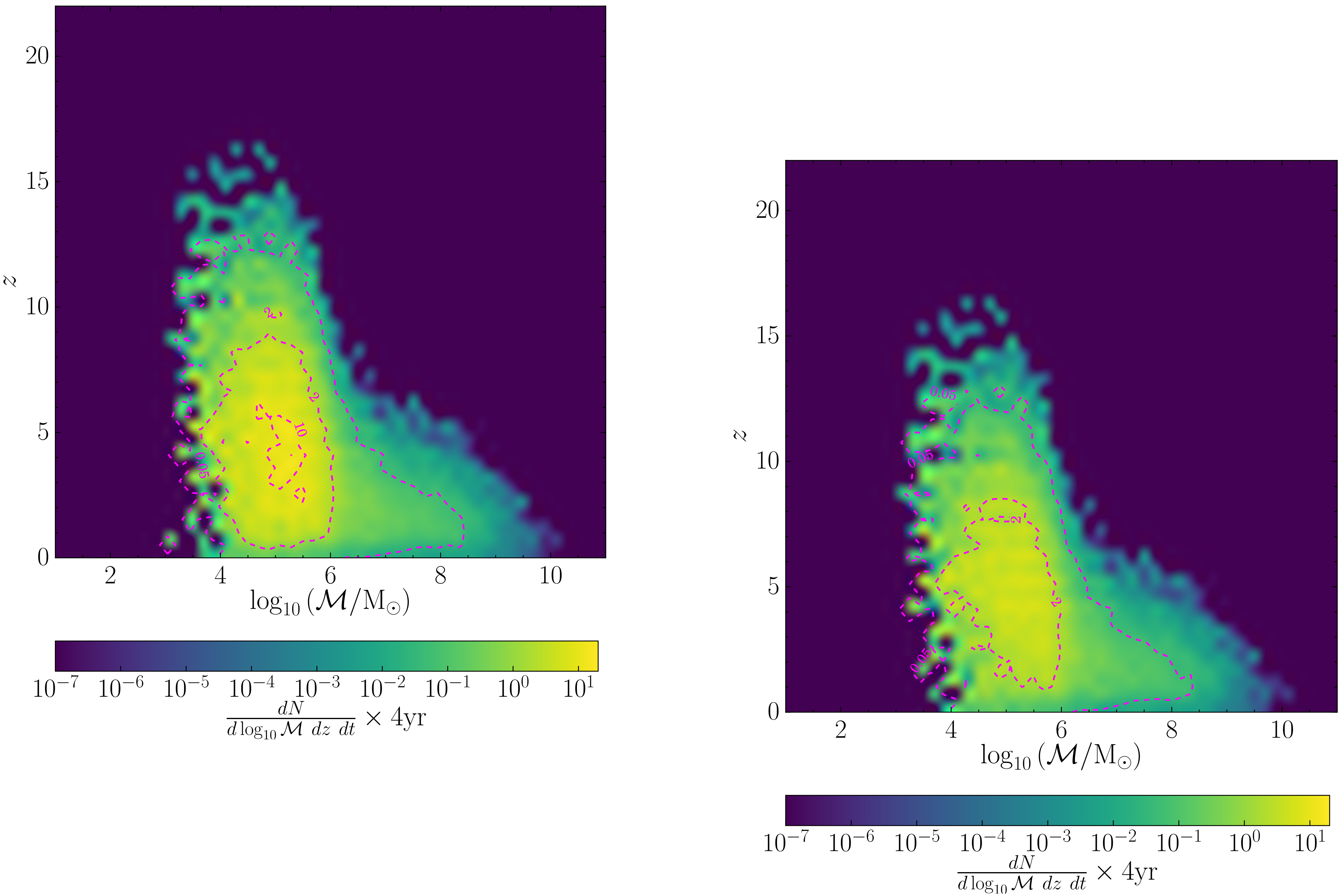


Figure 1. Cartoon representation of how triple MBH interactions are treated in the semianalytic model described in Section 2.

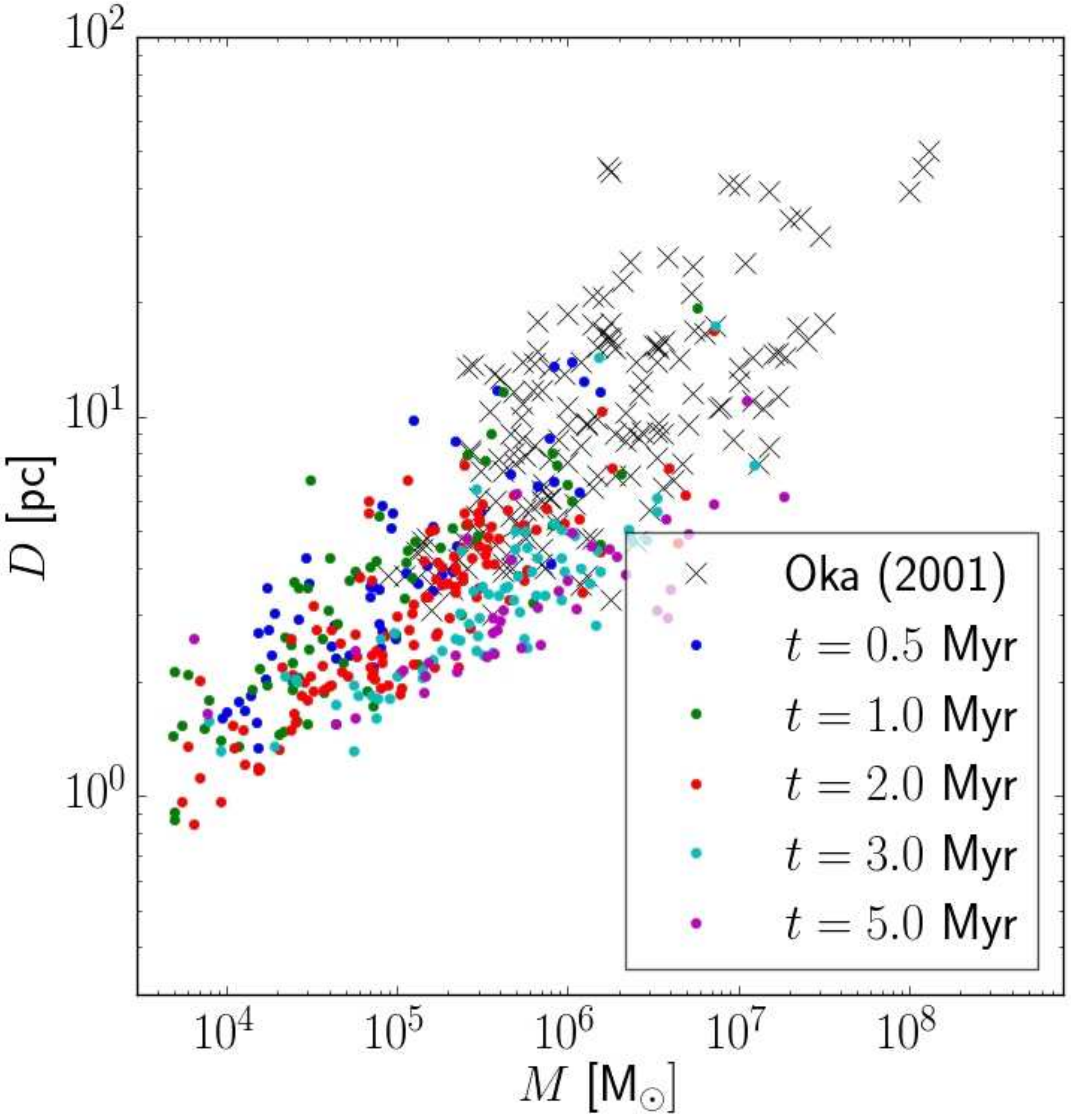
Bonetti + 2018 a,b,c,



Merger after ejection : 6.4%
Merger by triplet : 22.0%
LogNormal fit : $\mu = 8.4,\ \sigma = 0.4$
% of runs
$\log T_{\rm merger}$ [yr]
0.0
0.5
1.0
1.5
2.0
6.5
7.0
7.5
8.0
8.5
9.0
9.5
10.0



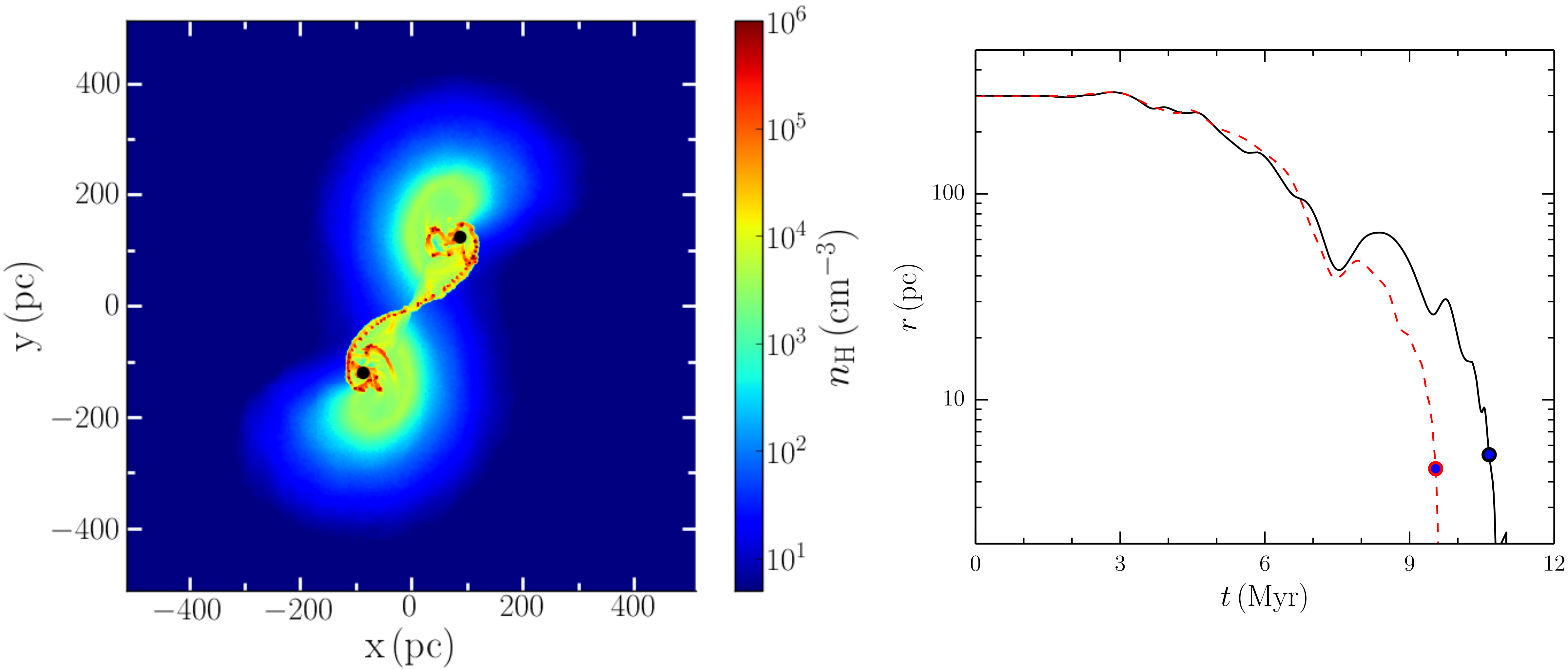
z
20
15
10
5
0
2
4
6
8
10
$\log_{10}(\mathcal{M}/\mathrm{M}_\odot)$
0.05
2
10
10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1}
$\frac{dN}{d\log_{10}\mathcal{M}\ dz\ dt} \times 4\mathrm{yr}$
z
20
15
10
5
0
2
4
6
8
10
$\log_{10}(\mathcal{M}/\mathrm{M}_\odot)$
0.05
2
10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1}
$\frac{dN}{d\log_{10}\mathcal{M}\ dz\ dt} \times 4\mathrm{yr}$



- numerical effect

Souza Lima+2016, del Valle+2015, Fiacconi+2013

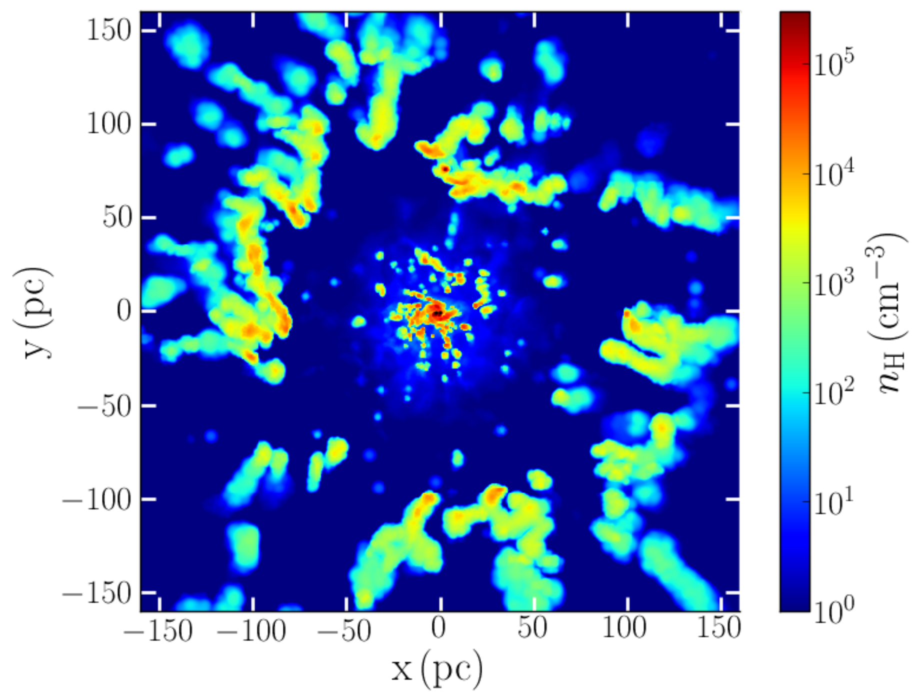
V. black hole dynamics in "colliding massive" gas discs on ~(100 - 0.5)pc

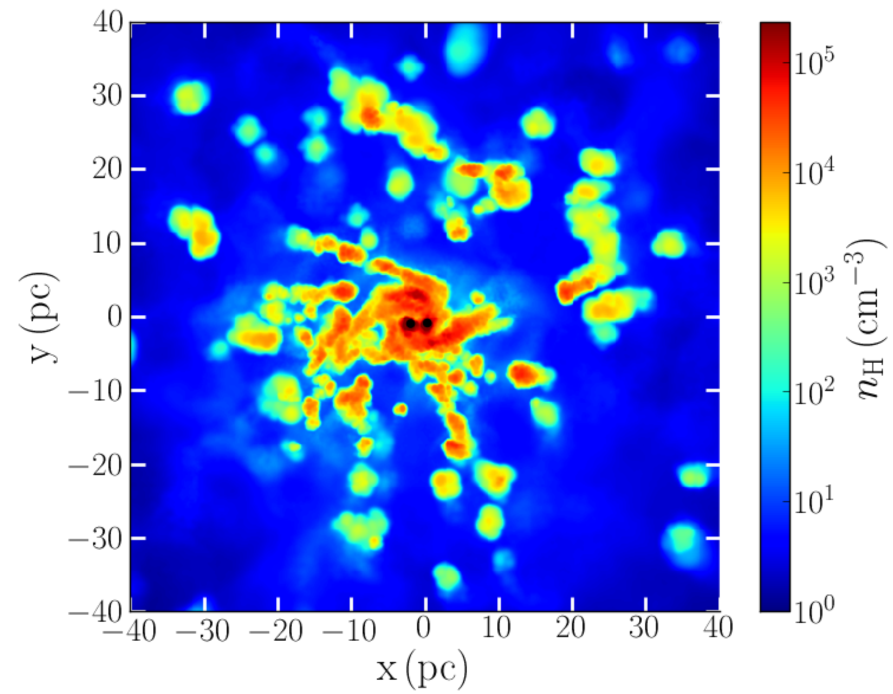


- collision of two massive discs (100 million suns) embedded in an Hernquist stellar bulge (twice more massive), each housing a black hole of 10 million sun

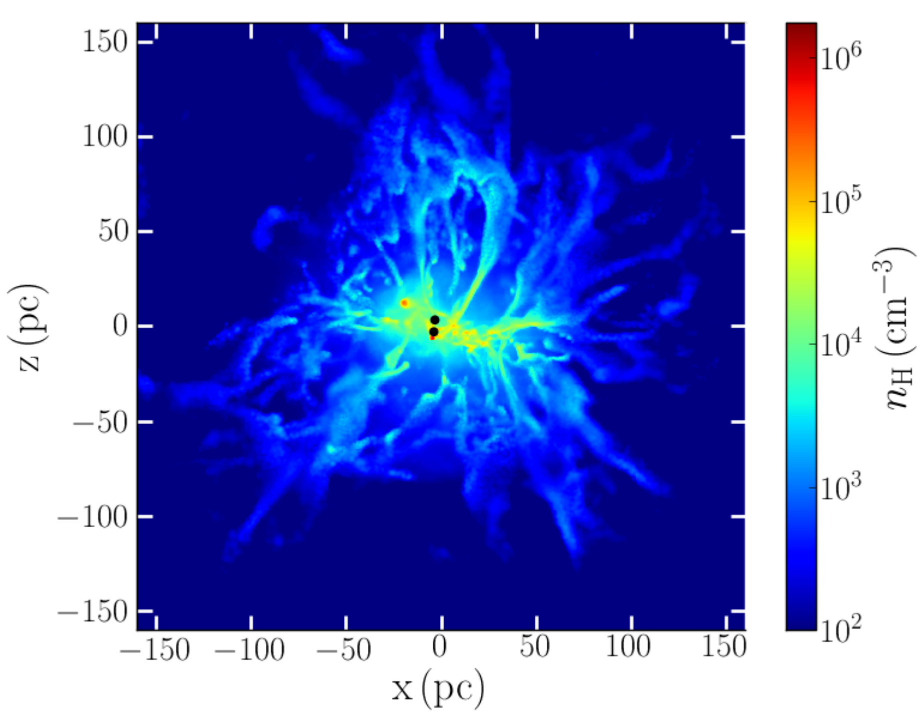
Lupi+2015

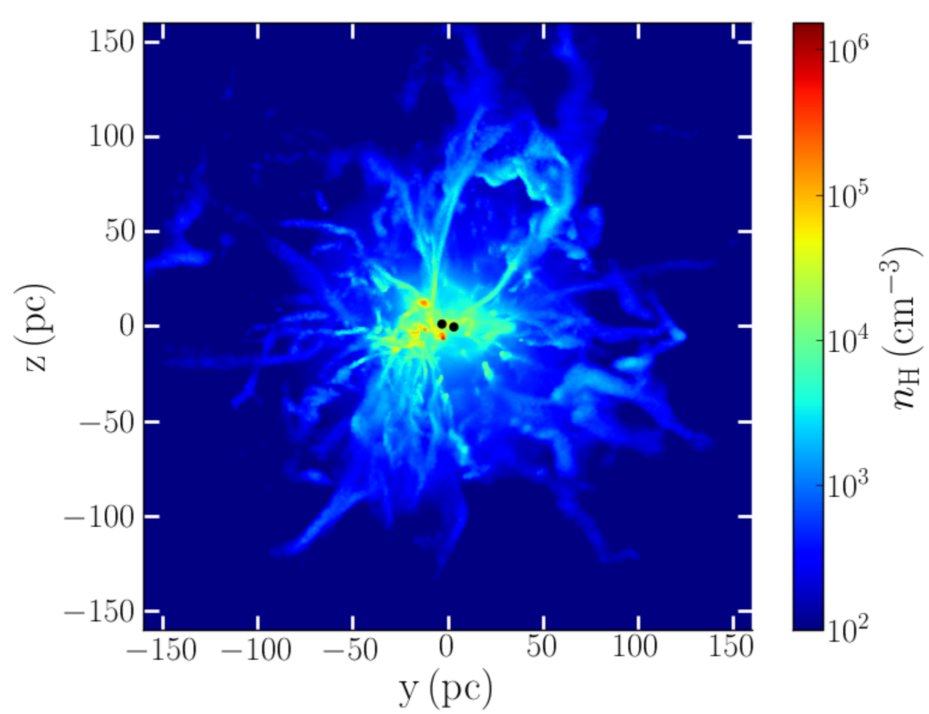
- thermal-feed-back: gas cools immediately after SN blow-ff
- no large scale disc but a residual coronating disc around the black holes



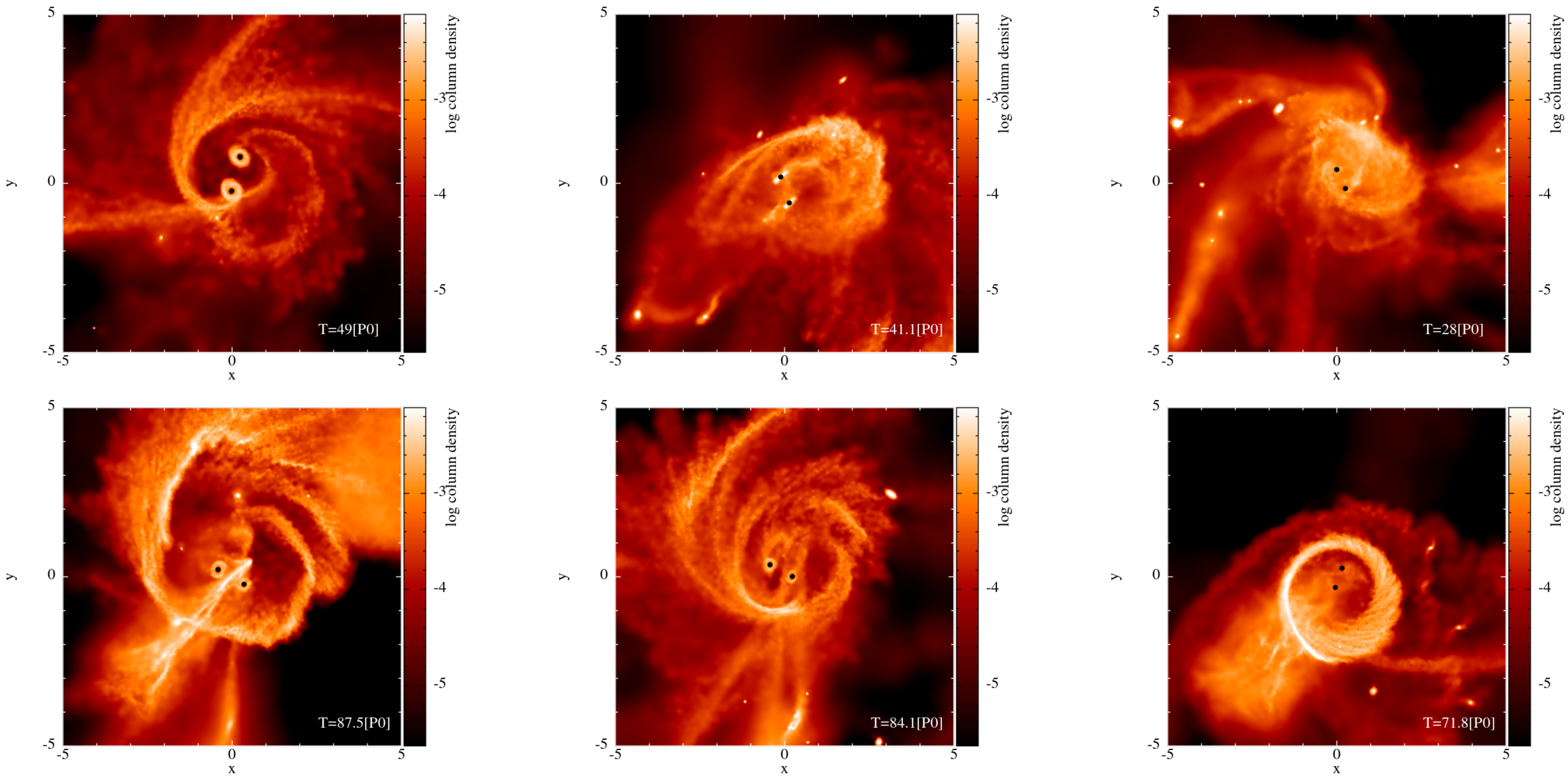


- blast-wave-feed-back: SN energy is decoupled from gas-cooling - a momentum driven blast wave
- black holes inhabit a triaxial less dense region with denser core

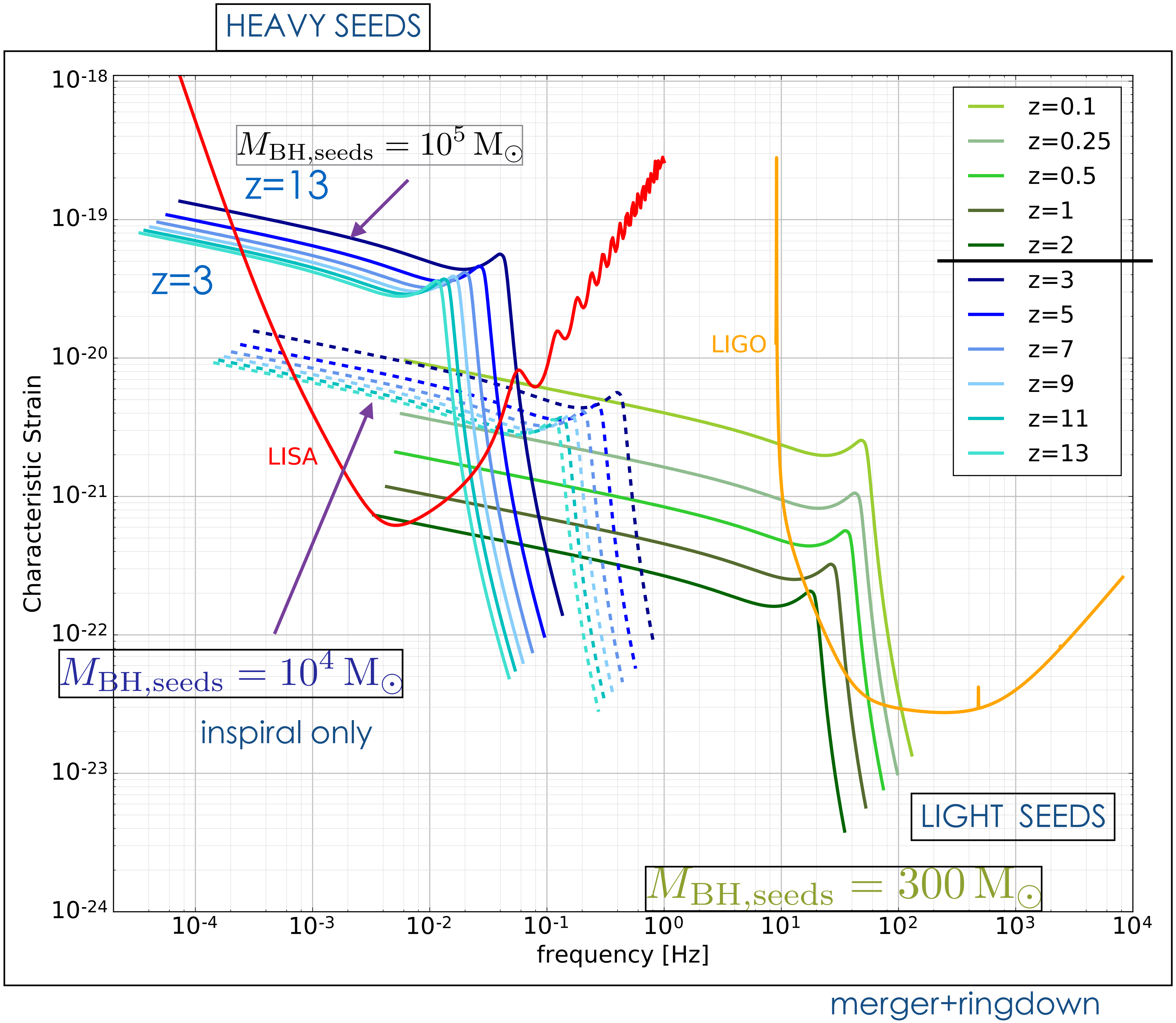




V. hardening during interaction of falling clouds



Maureira-Fredes + 2018


HEAVY SEEDS
$M_{\rm BH,seeds} = 10^5\,{\rm M_\odot}$
z=13
z=3
LISA
LIGO
$M_{\rm BH,seeds} = 10^4\,{\rm M_\odot}$
inspiral only
LIGHT SEEDS
$M_{\rm BH,seeds} = 300\,{\rm M_\odot}$
merger+ringdown
z=0.1
z=0.25
z=0.5
z=1
z=2
z=3
z=5
z=7
z=9
z=11
z=13
Characteristic Strain
frequency [Hz]
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}