Massive Black Hole Mergers, LISA GW detections, and the nature of dark matter halos in dwarf galaxies

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Black Hole Population(s)

STELLAR MASS BLACK HOLES

micro-quasars powered by ACCRETION

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observed in the Milky Way and in nearby galaxies

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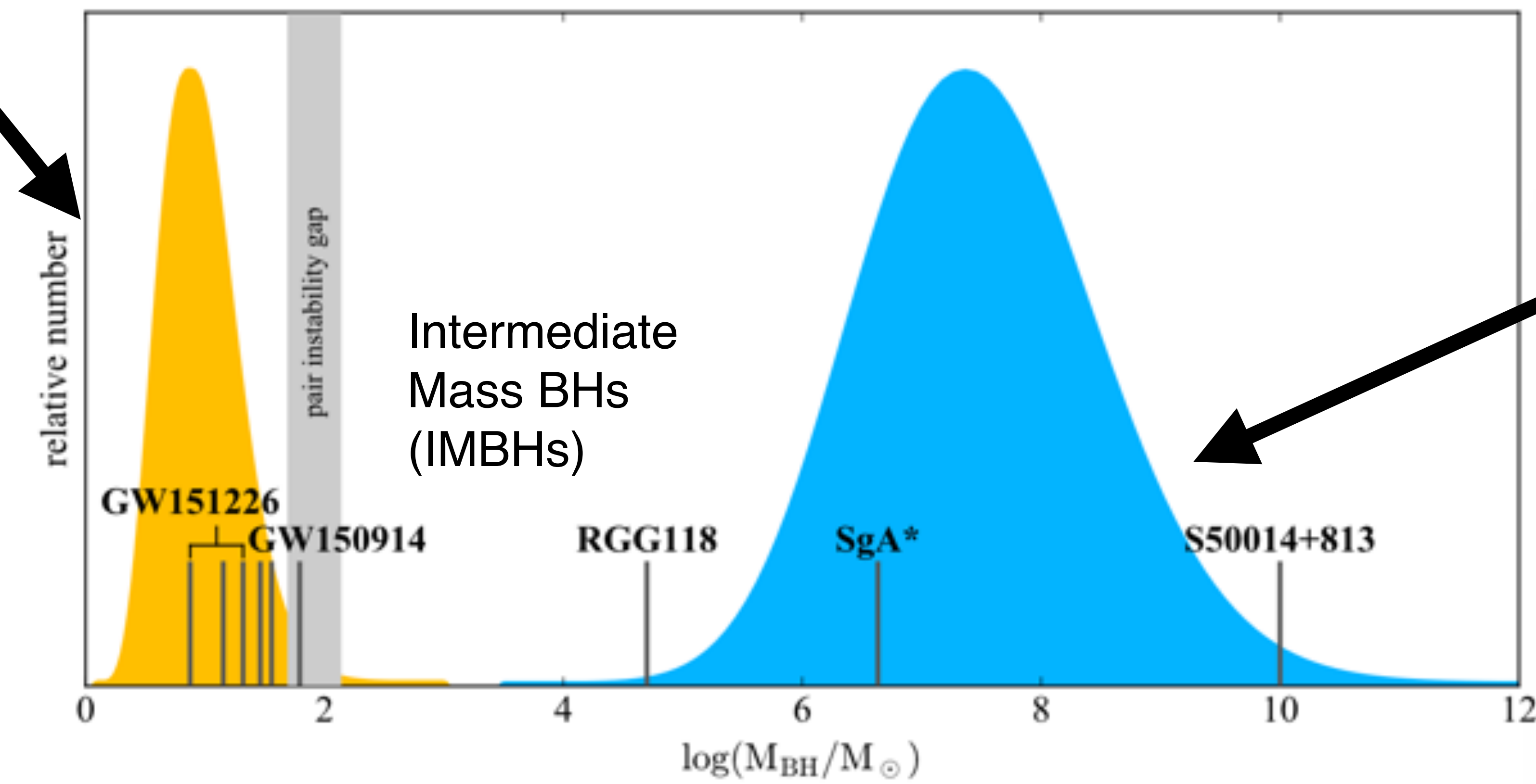
life-cycle of binary stars

-

origin
core collapse of very massive stars

key sources for EMRIs



SUPERMASSIVE BLACK HOLES

AGN

QSOs

part of the life-cycle of galaxies

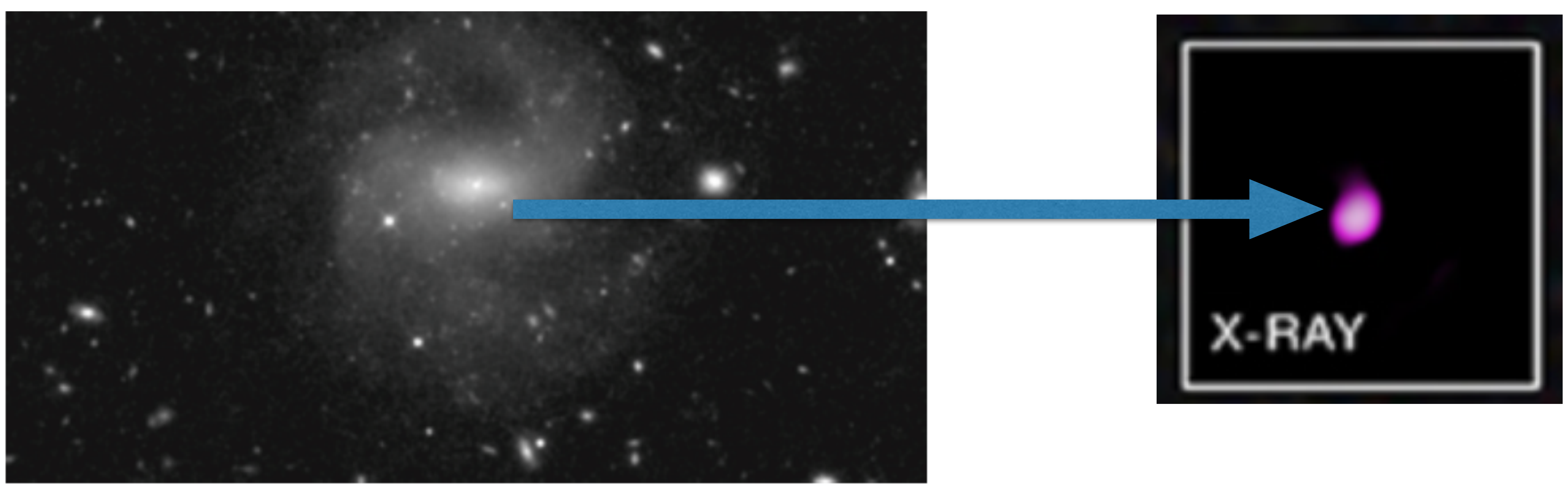
Ubiquitous in the nuclei of galaxies

Observed Radiation Flux (UV/X-ray/optical) from accretion gas disk around BH: gravitational potential energy is (a) converted into thermal energy and then (b) radiated away till gas clouds fall to last stable orbit (= 3 Schwarzschild radii)

A whole new exciting field: intermediate mass BHs in dwarf galaxies

Currently about 200 AGN candidates in low mass/dwarf galaxies at z=0-2.5 (typical stellar masses 10^8-10^9 Mo, but some also as low as 10^7 Mo, see e.g. Mezcua et al. 2018 with CHANDRA Cosmos Legacy Survey).

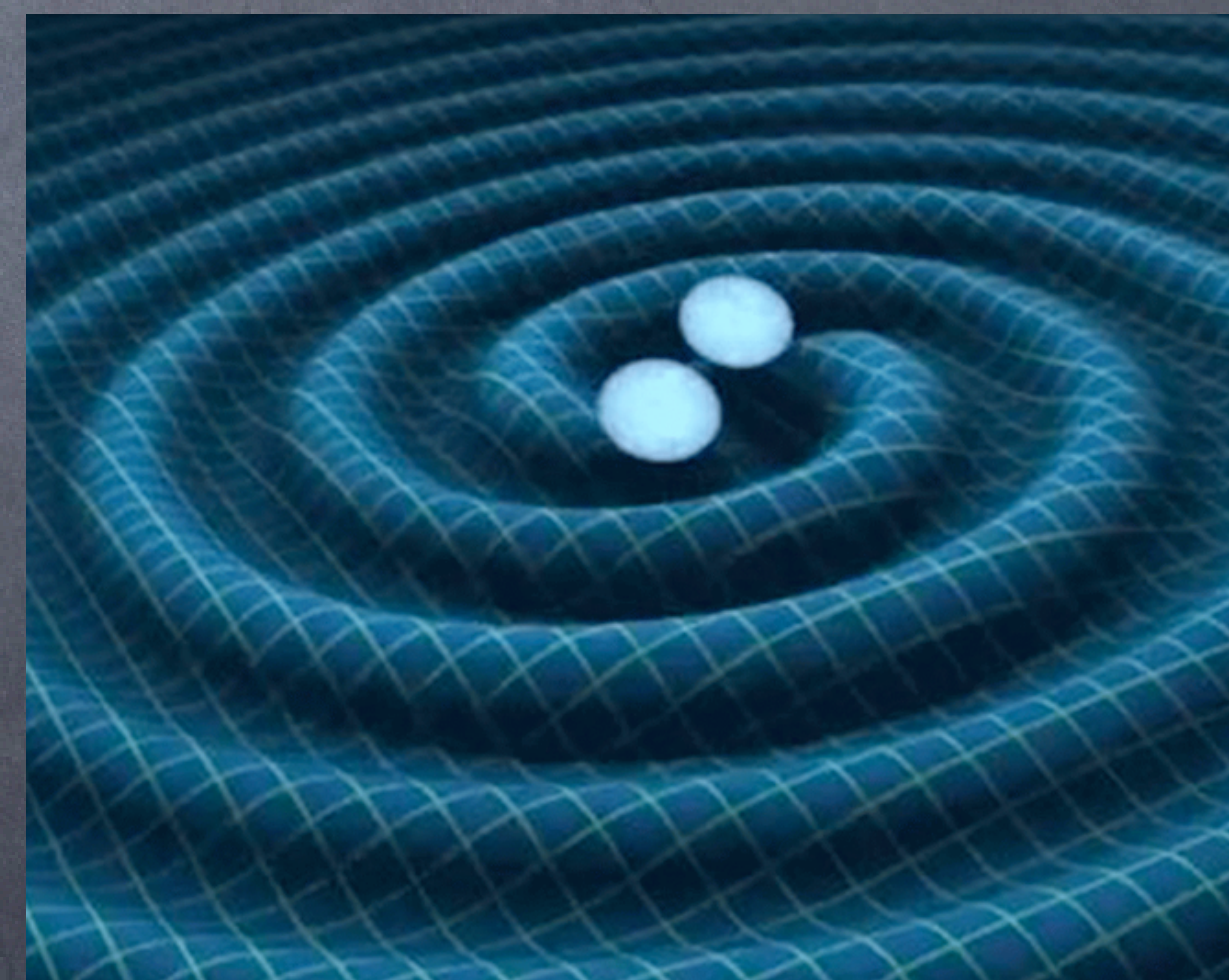
Typically through narrow emission line ratios (optical/X-rays) or specific emission/absorption lines consistent with AGN spectra. Best candidates show X-ray detected compact central source in and yielding more than one spectral feature consistent with AGN spectra, necessary to exclude contamination by on-going star formation (eg Reines et al. 2013 in SDSS, Sartori et al. 2015)



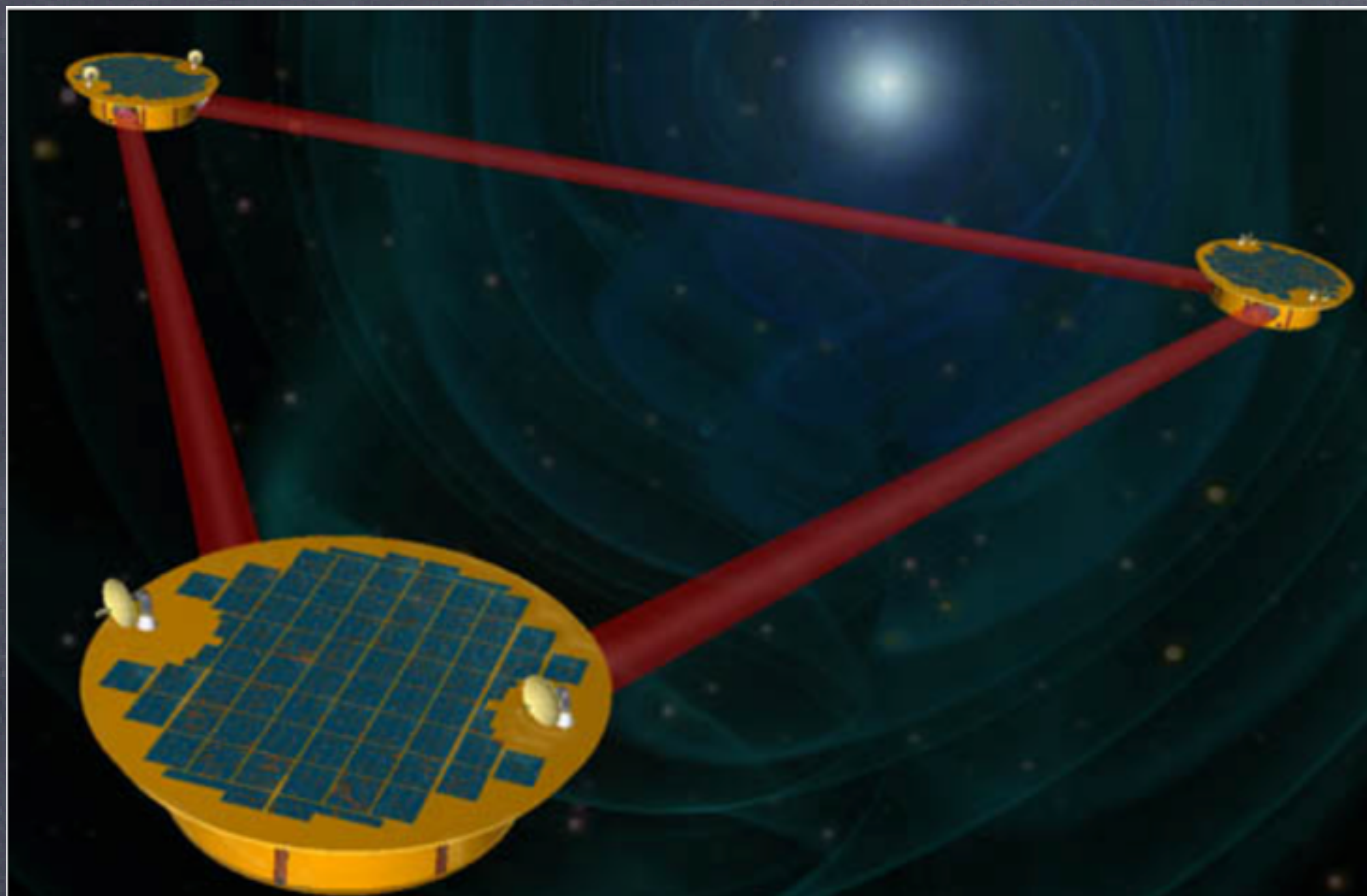
Prototypical system: RGG118 — a nearby dwarf spiral galaxies with stellar mass and disk size similar to the local Magellanic Clouds (M* ~ 4 x 10^8 Mo, Rd ~ 1 kpc).
Compact central source detected in X-rays (Chandra), broad H-alpha emission suggests AGN powered by accretion onto BH with mass ~ 50000 Mo (Baldassare e al. 2016;2017).

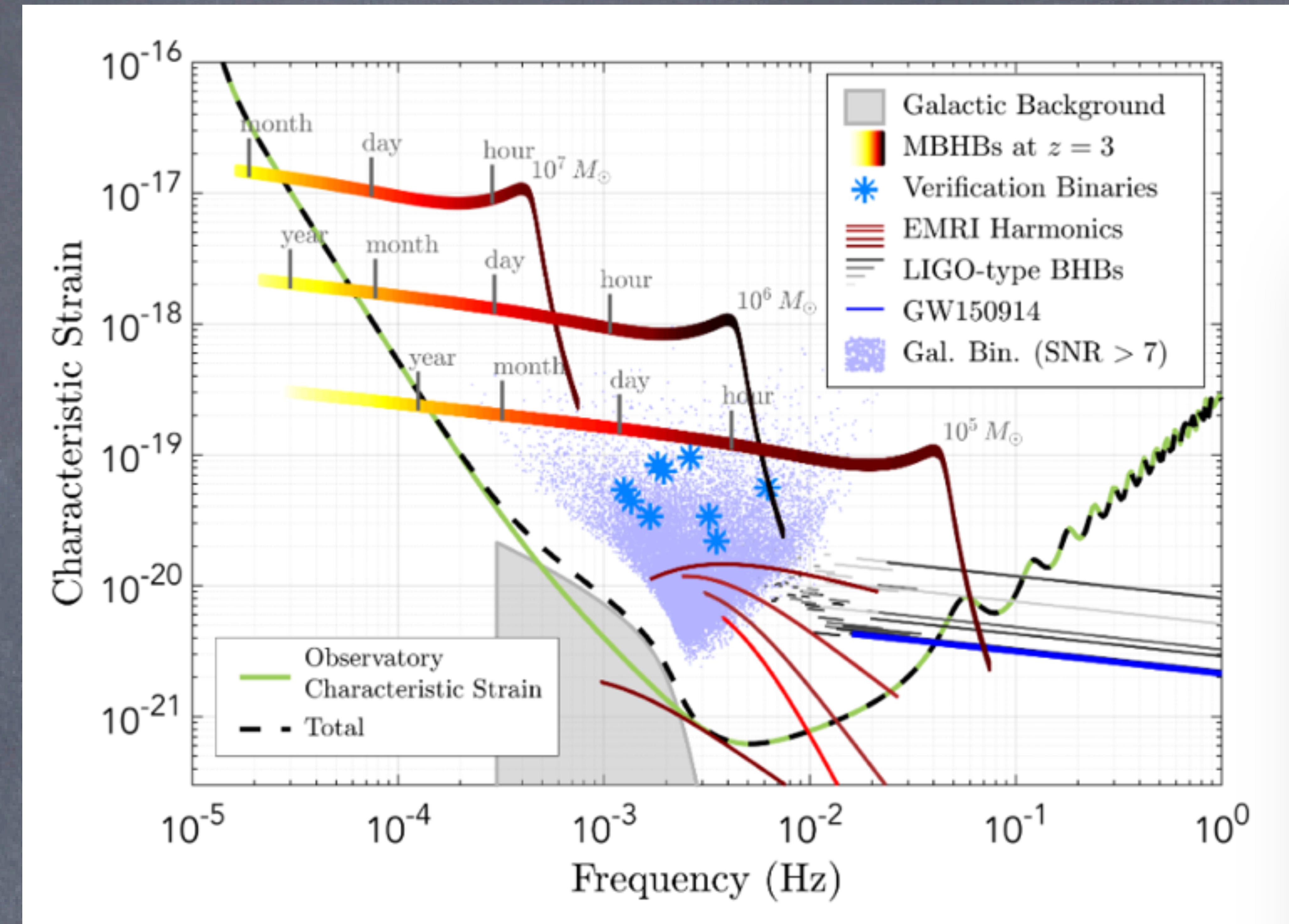
Massive Black Holes in the landscape of the LambdaColdDarkMatter Cosmology

Most galaxies host an MBH at their center. Galaxies form from hierarchical merging in LambdaCDM Universe —-> become a powerful GW source once separation between MBHs < milliparsecs ($t_{gw} < 10^7$ yr for a MBH with 10^6 Mo).



Merging MBHs with 10^3-10^7 Mo at z <~15: the LISA sources





LISA - approved next large (L3) ESA mission (2030-2034)
Laser interferometer in space (2.5 million km arms) to detect low frequency GW sources.
From wave-form strain amplitude $h \sim (\mu/r)(M/R)$
M sum of BH masses, μ reduced mass of binary, r luminosity distance, R binary separation.
Strong-field tests of GR/BH metric and extra physics with EMRIs, Hubble diagram with BH mergers as standard sirens, cosmological GW background, new probe of cosmic structure formation if MBH mergers trace hierarchical galaxy merging (Amaro-Seoane et al. 2013;2017; Danzmann et al. 2017)

Primary LISA sources are MBH mergers. The abundance of such mergers with masses in the LISA frequency band at any redshift will determine the gravitational wave event rate accessible to LISA.

What determines the rate of occurrence of LISA-visible MBH mergers?
(a) The mass distribution of the population of MBHs (at any redshift)
(b) The merger rate for a given MBH population (at any redshift)

(a) depends on the formation mechanism for MBHs, eg
light seeds (100-1000 Mo) from primordial metal-free "Pop III" stars vs. direct collapse massive seeds (M_{seed} >~ 10^4 Mo)

(b) depends on the timescale of galaxy/halo merger rate COMBINED with **the orbital decay timescale (=time to coalescence)** of MBHs in the galaxy merger remnant.

Suppose we want to determine the MBH coalescence timescale t_{mg} in a representative galaxy population.

How do we compute t_{mg}*?*

THE FOUR PHASES:

t_{mg} = galaxy merger timescale (1) + MBH binary formation timescale (2) +binary hardening timescale (3) + the in-spiral timescale dominated by GW radiation (4)

Key point: (2) and (3) non-trivial to determine,tightly linked to the diverse nature of galaxy hosts across cosmic time.

Past semi-analytical work on GW event rates forecasts for LISA has assumed:

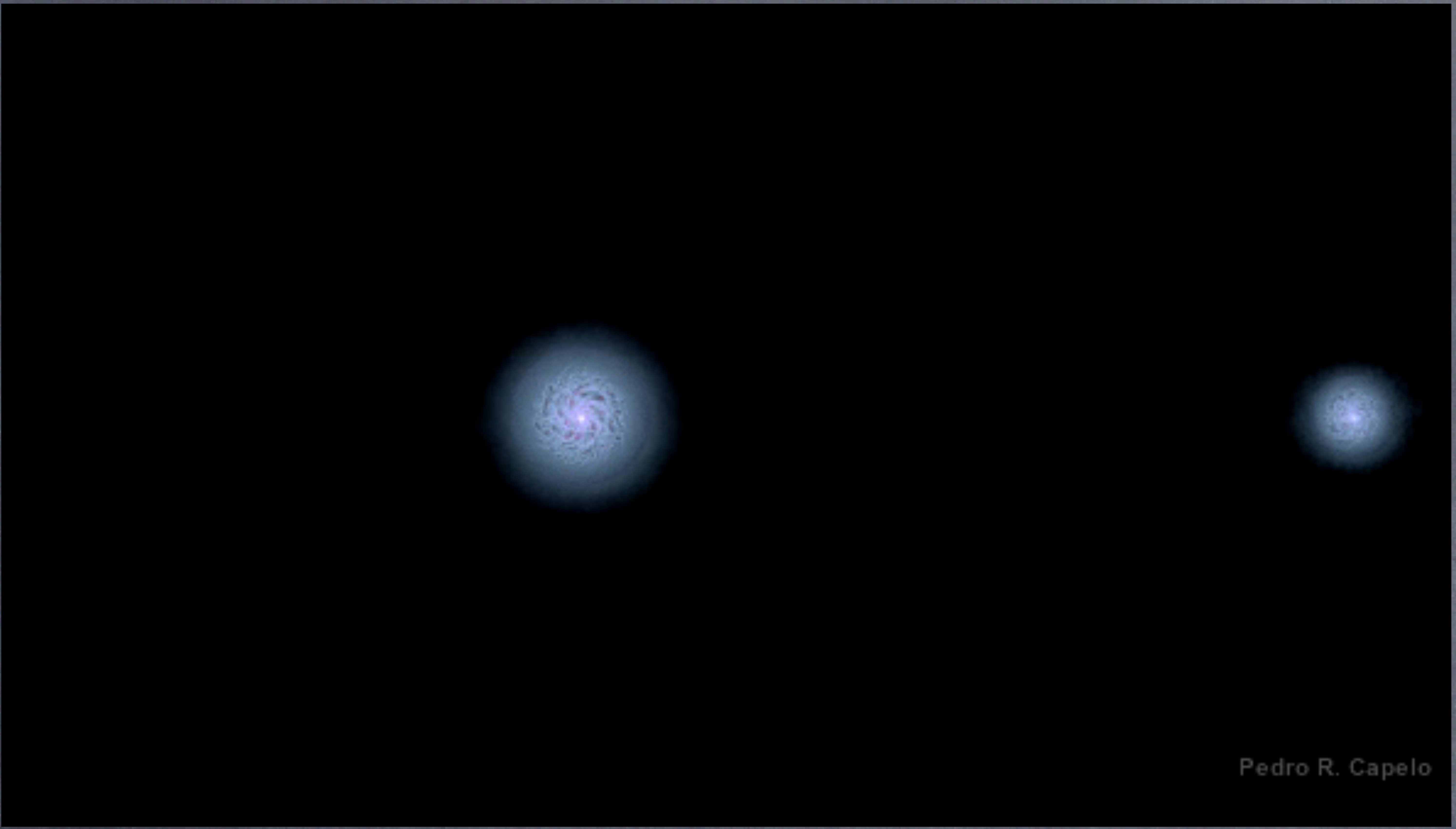
(1) no delay between galaxy mergers and massive MBH mergers (direct mapping - e.g. Sesana et al. 2006;Barausse 2012)

(2) fixed delay in phase 3 (hardening phase) , eg $\sim 10^8$ yr (eg Salcido et al. 2016)

(3) a delay only induced in phase 3 with over-simplified analytical timescale expressions (viscous timescale for gas dominated regime, 3-body hardening timescale for spherical system (see eg Antonini et al. 2015; Klein et al. 2016)

Never considered delay in phase 2 or modeled delay in phase 3 using directly results of numerical simulations of galaxy+MBH mergers

First stage: galaxy merger, with separation of MBHs of order kiloparsecs.



1:4 Galaxy Merger movie (Capelo et al. 2015)

Galaxy merging time

Defined as time when two separate galactic nuclei exist anymore (separation < 100 pc)

$\tau_{mg} \sim 1$ Gyr <~ T_{Hubble}

Note long timescale comes from naturally long dynamical timescale of extended DM halos in Cold Dark Matter model

In CDM model halo/galaxy merging timescale depends on redshift as τ_{mg} of order orbital timescale of halos —-> *at higher z galaxy mergers occur faster*

Torb ~ Rvir/Vcirc ~ $1/H(z) \sim 1/(1+z)^{3/2}$ ($\Omega_0=1$, $\Omega_\Lambda=0$)

Vcirc virial velocity (eg 200 Km/s for Milky Way halo)

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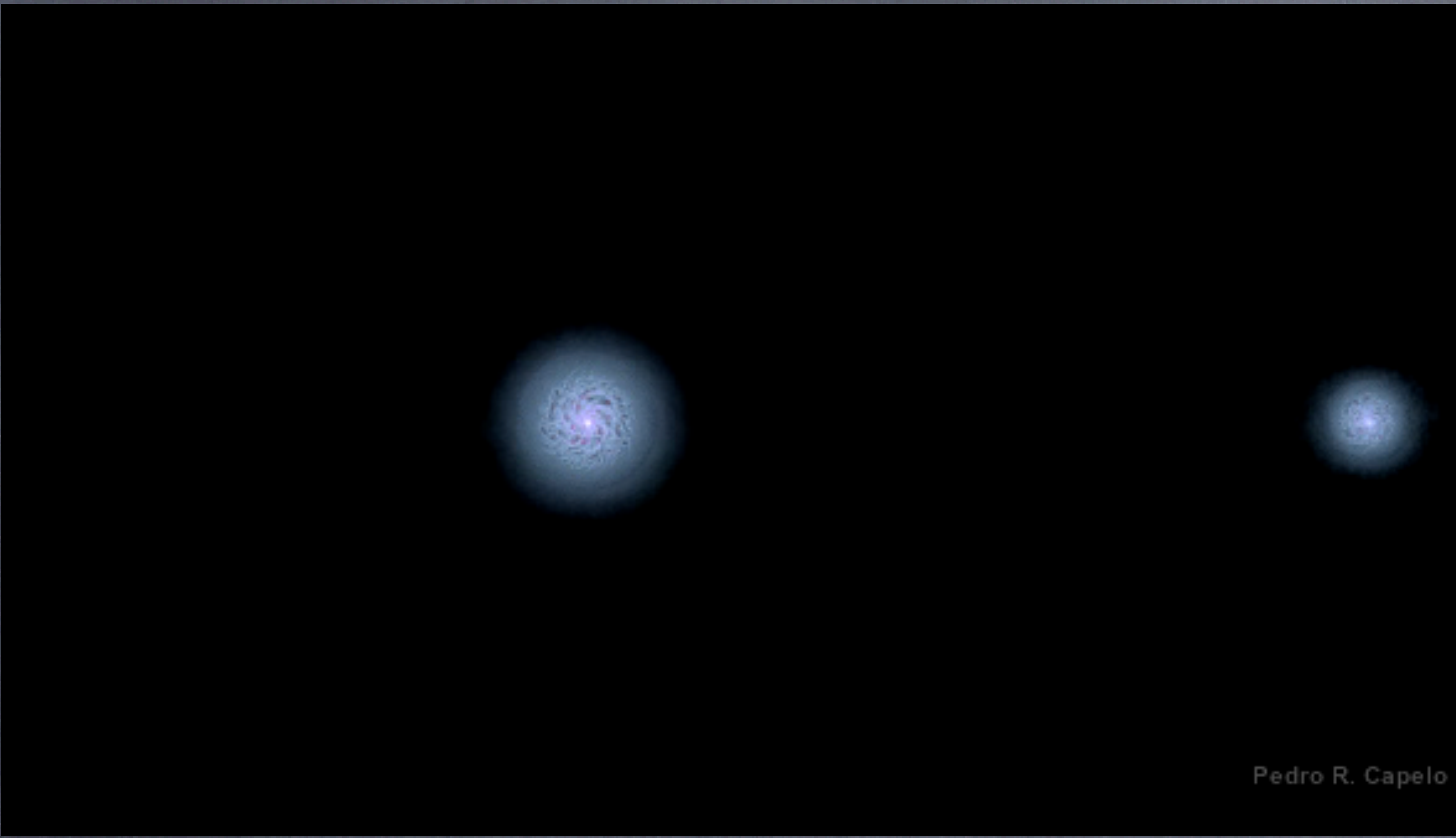

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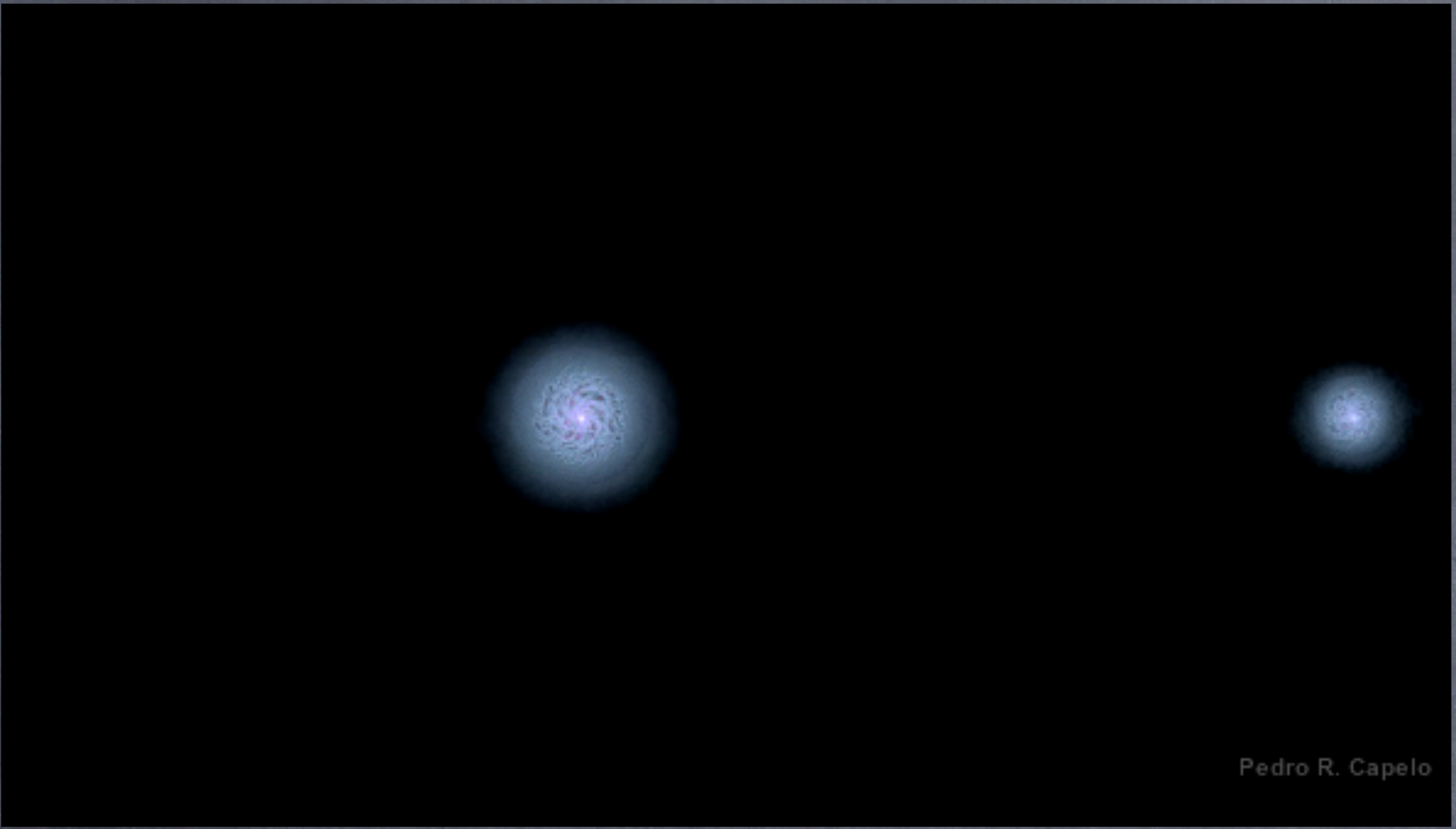

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There are at least **three classes of processes t**hat can shrink the MBH pair from kpc to milliparsecs separation inside galaxy merger remnant (Begelman, Blandford & Rees 1980; Armitage & Natarajan 1999; Colpi & Dotti 2010; Mayer 2013). Different means to extract orbital energy and angular momentum,all have some *dependence on ambient density and background kinematics or thermodynamics*

- *dynamical friction* from the background matter in the galaxy merger remnant (from stars, gas and dark matter surrounding the binary). Acts from **kpc to pc scales**, until binary mass dominates local background gas mass

- if the merger remnant is a cold rotating gas or stellar disk, torques can arise from spiral structure (*disk torques* ***100 pc to pc scales*** *- as in planet migration,eventually gap opening and circumbinary disk formation at* ***~< pc scales***)

- - *3-body encounters* between stars and the binary SMBH. Can dominate orbital shrinking when SMBHs have **separations of <~ pc** (*hard binary*), provided that there is a high density of stars always available for scattering (*full loss cone*)

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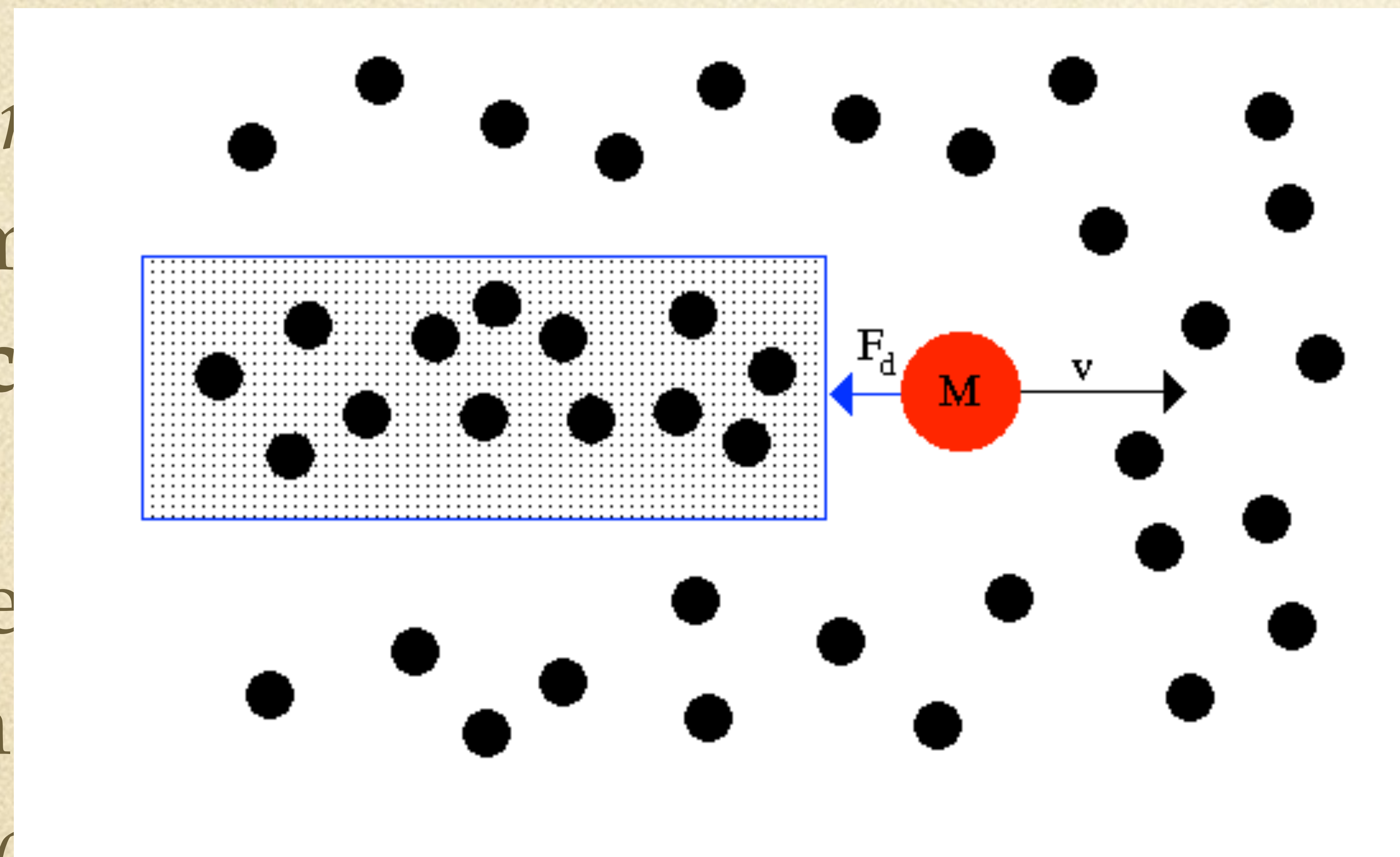

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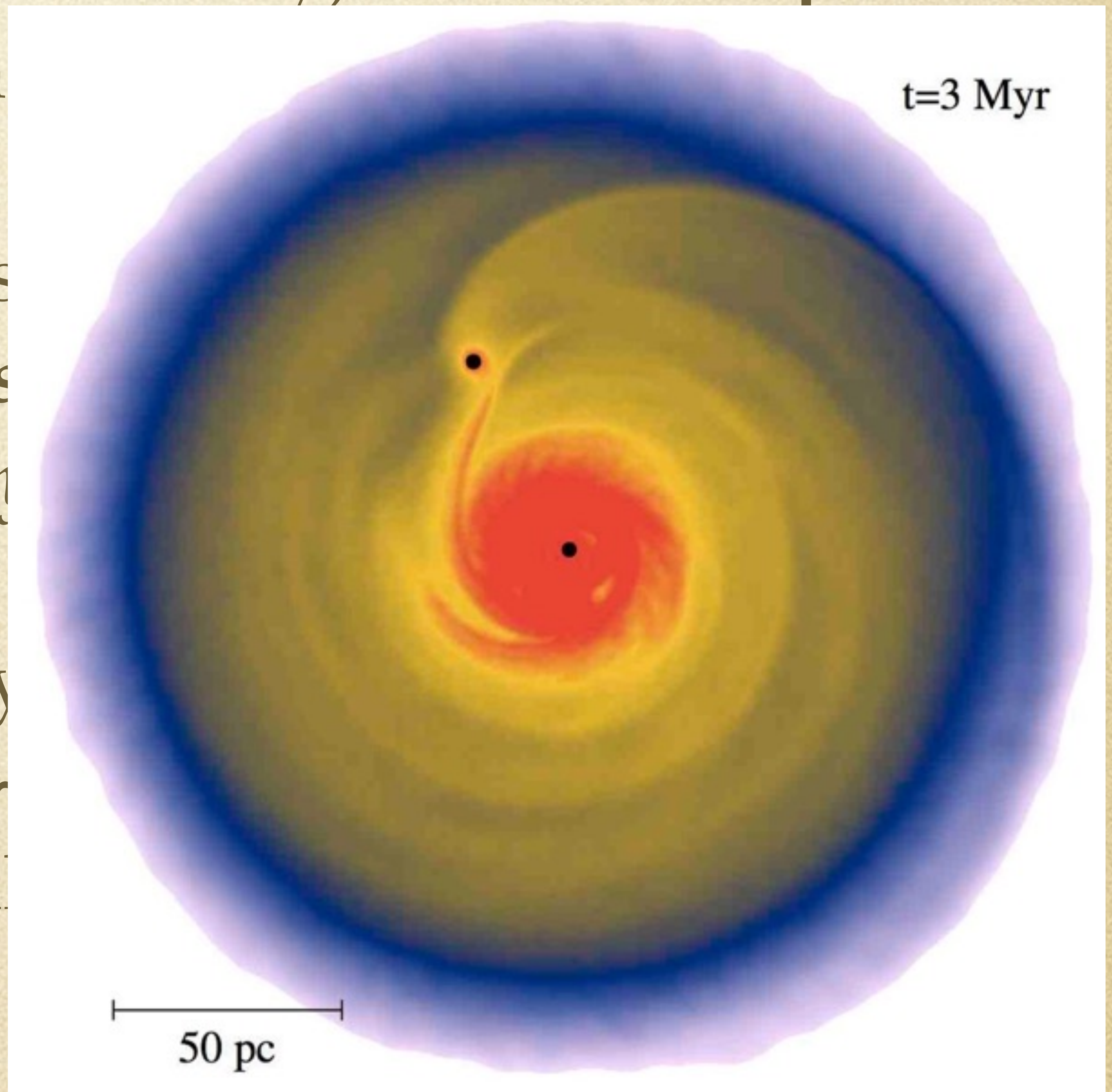

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Should the timescales of binary BH formation and binary hardening depend on the host galaxy structure (dark halo, gas and stellar distribution)?

Yes they should because:

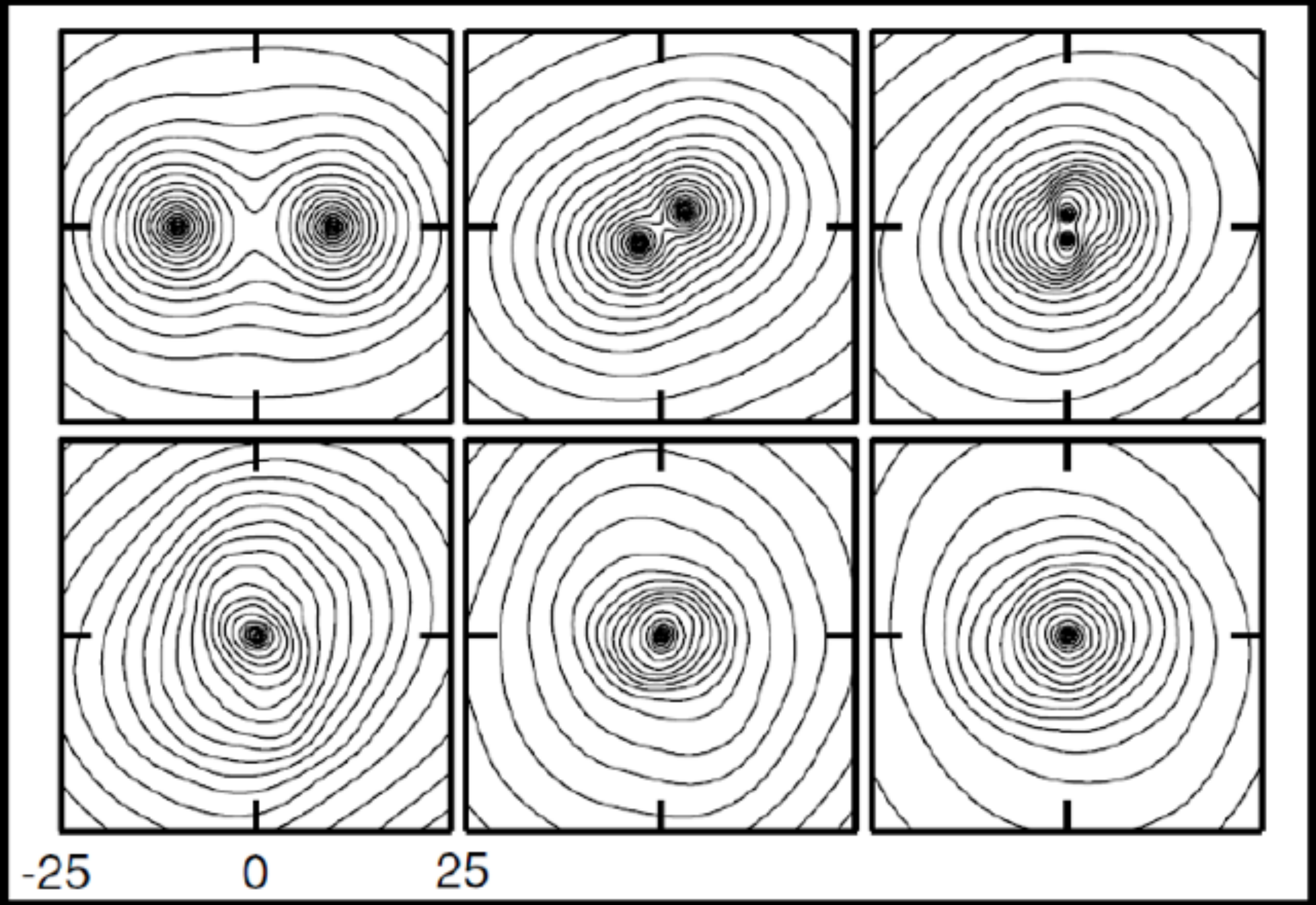
All processes causing orbital decay depend on **background density**, on the **relative velocity** of perturber (MBH) and the background mass distribution, on the **detailed nature of stellar orbits or of the gas flow** (affect nature and strength of torques).

The stellar dominated regime (massive, gas poor galaxies): dynamical friction by stars and DM + pc-scale hardening via 3-body encounters (e.g. Berczik et al. 2006; Khan et al. 2011; Khan et al. 2012; 2013)

Earlier experiments with spherical galaxy models, then mergers of spherical galaxies to produces rotating axisymmetric or non-axisymmetric merger remnant (more realistic as massive elliptical galaxies have triaxial shapes and non-zero rotation)

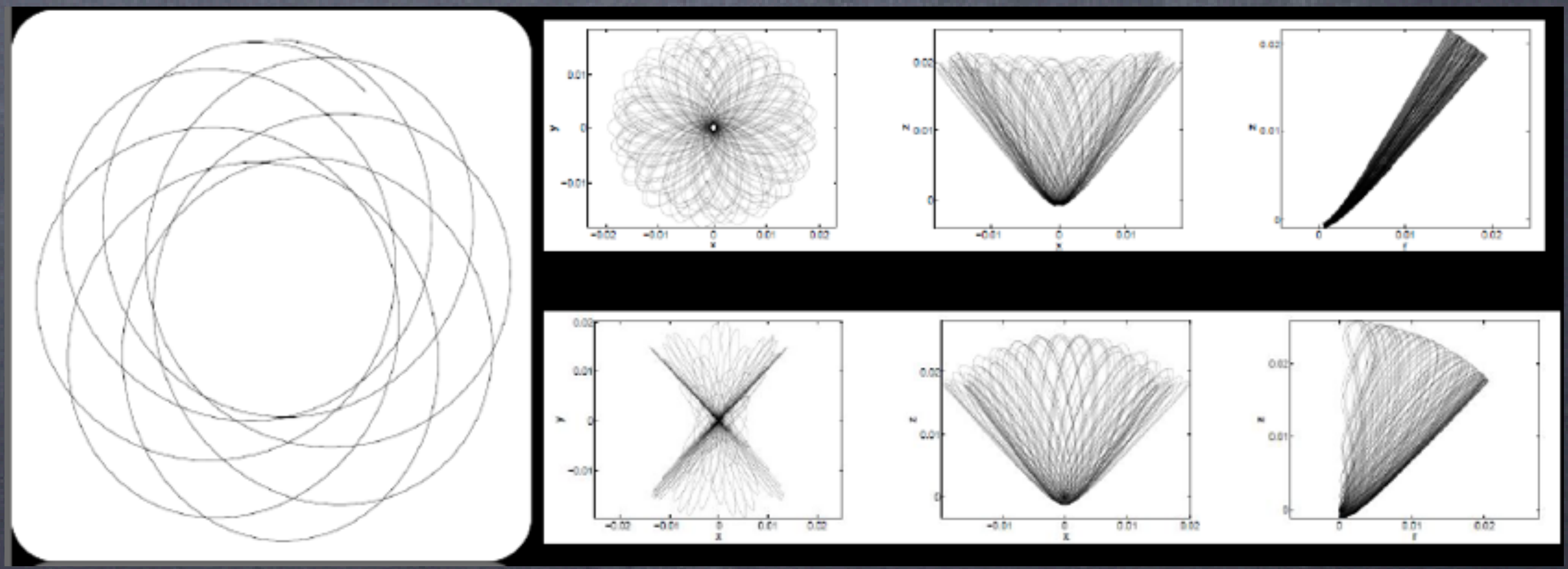
—-> Hardening rates much higher than in spherical systems, no "last parsec problem"

Hi-res collisionless study of loss cone confirms no last parsec problem (Gualandris et al. 2016)
Or else hardening via multiple MBH-MBH interactions even w/empty loss cone (Ryu et al. 2017)



Khan, Just & Merritt 2011, ApJ .

Stellar orbits in spherical vs. triaxial systems



No last parsec problem in realistic massive triaxial galaxies…..but total BH merger timescale (phases 1 to 4) VERY long:

2-4 Gyr, >~ lookback time at z >~3 (Khan et al. 2012;2015)

Low LISA GW detection rates? No detections expected at high z?

Until recently all merger simulations idealized — no connection with cosmological evolution of galaxies in LCDM model.

Step forward: multi-scale ab-initio galaxy + MBH orbital evolution with cosmological ICs AND post-newtonian corrections to follow after GW emission begins (to ~ milliparsec scales, a few R_{sch} of binary)

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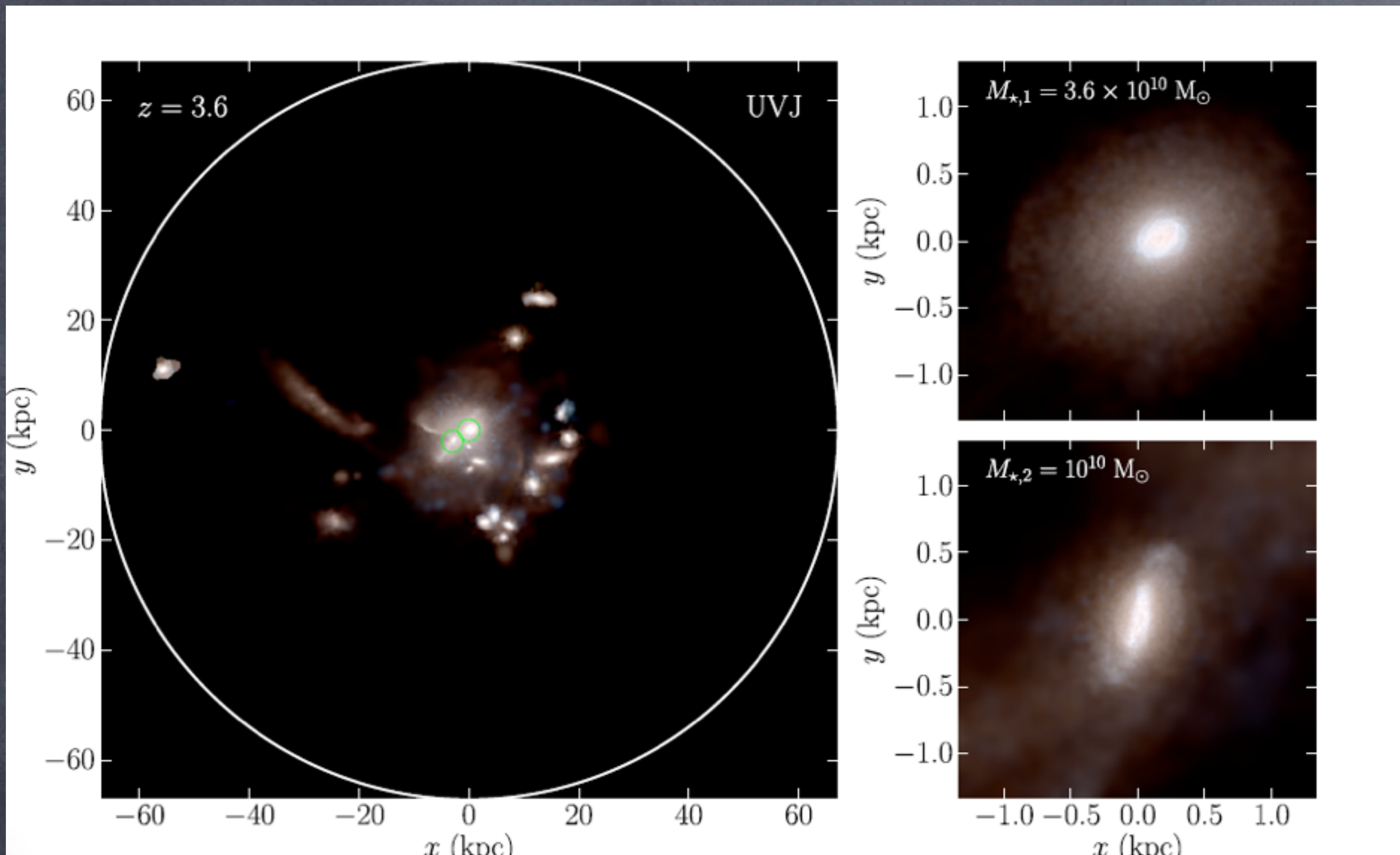
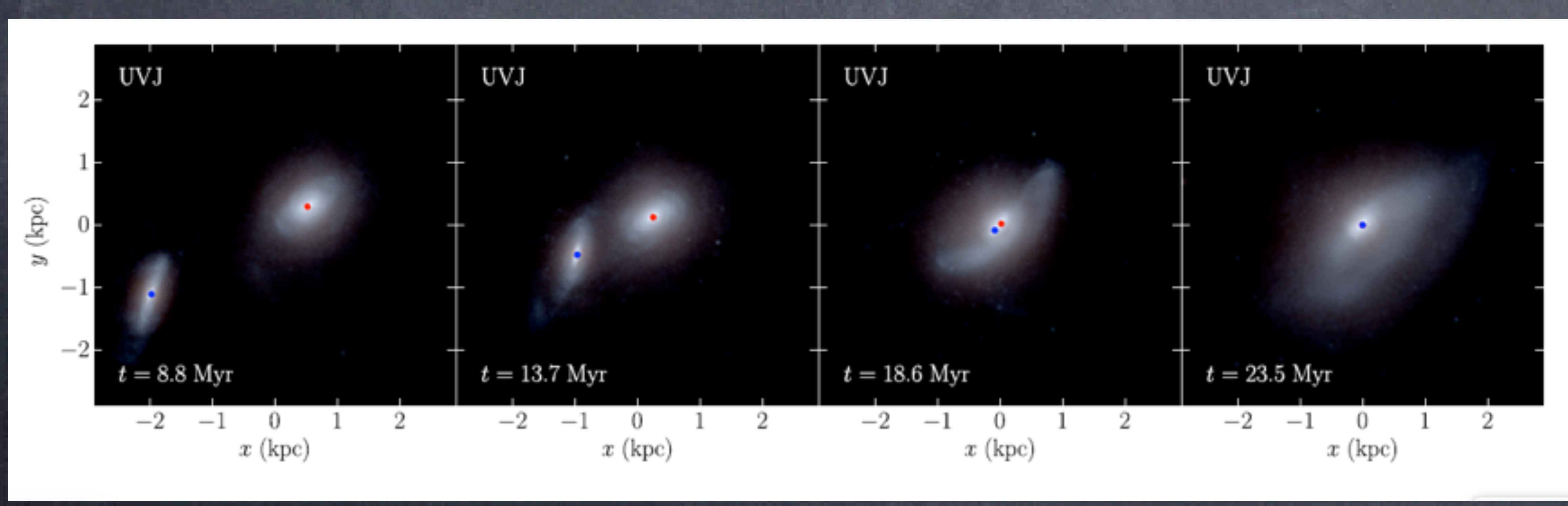
Khan, Fiacconi, Mayer, Berczik & Just et al. 2016
(predecessor was idealized binary galaxy merger in Khan et al. 2013).
SPH code GASOLINE2 (Wadsley et a. 2017) interfaced to direct N-Body calculation of sub-pc stellar dynamics with post-newtonian corrections with **phiGPU code (Berczik et al. 2006)**,

Initial conditions: ARGO Galaxy Group Formation Simulation
(Feldmann & Mayer 2015; Fiacconi, Feldmann & Mayer 2015)





Run on PizDaint Supercomputer at the Swiss National Supercomputing Centre (fastest platform in western world)

At z ~ 3.6, after merger-driven starburst over, we select gas-poor merger, convert residual gas into stars and , increase the resolution to <~ 10^{-3} pc for BH-star interactions in direct N-Body integration of final stage. MBH masses >~ 10^8 Mo

Post-newtonian corrections to PN3.5 to model initial GW-driven in-spiral (Khan, Fiacconi, Mayer et al. 2016).

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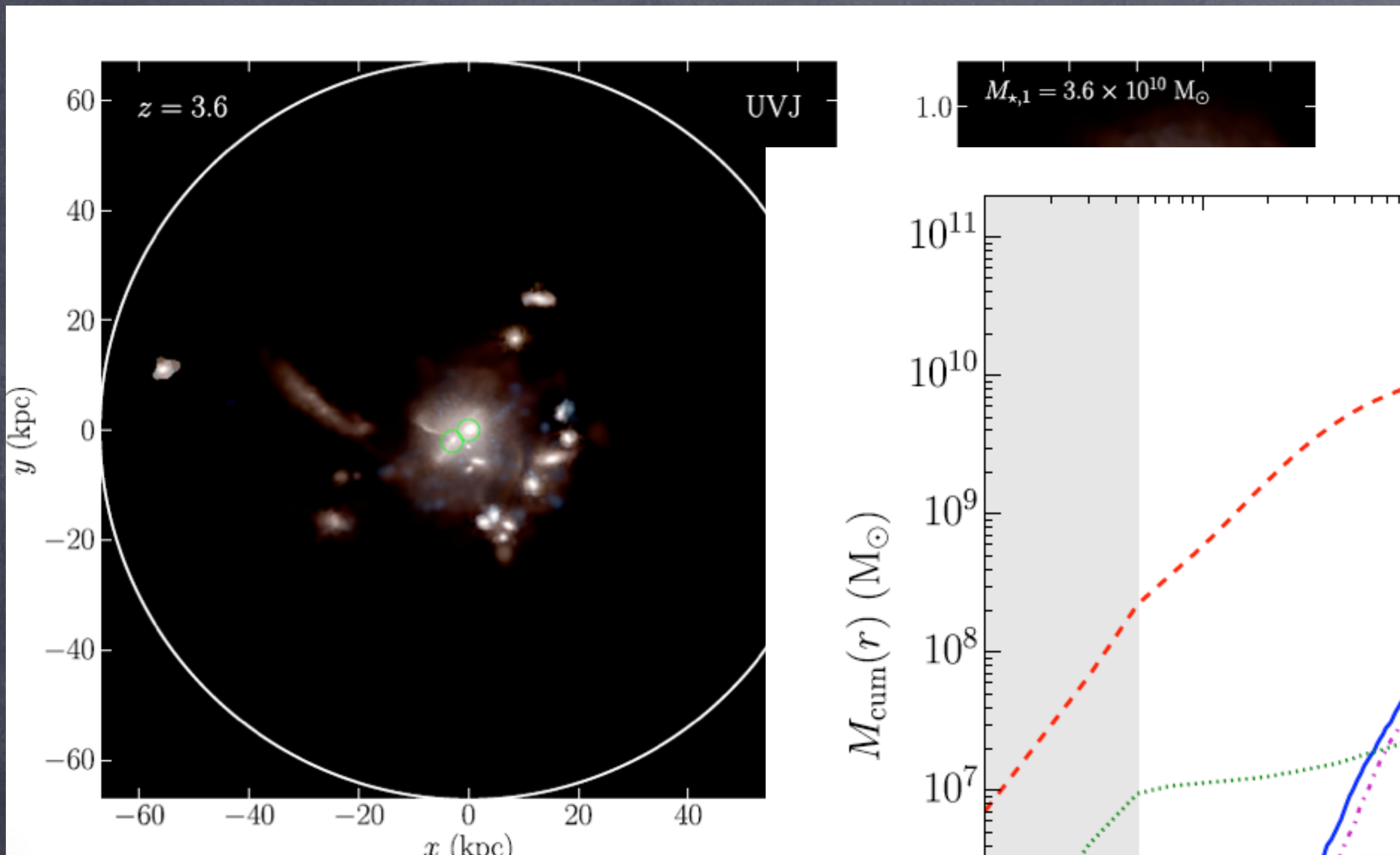

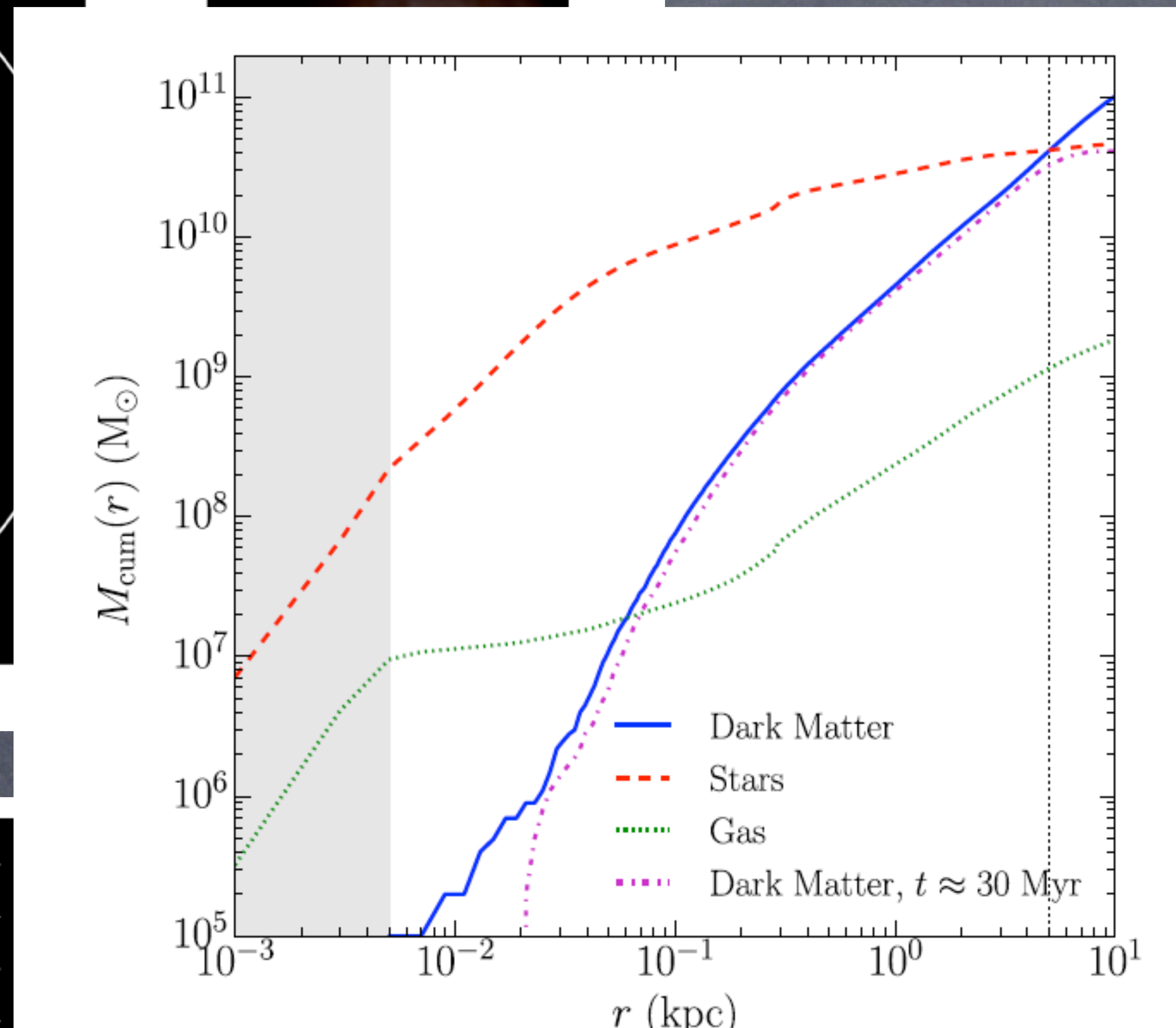

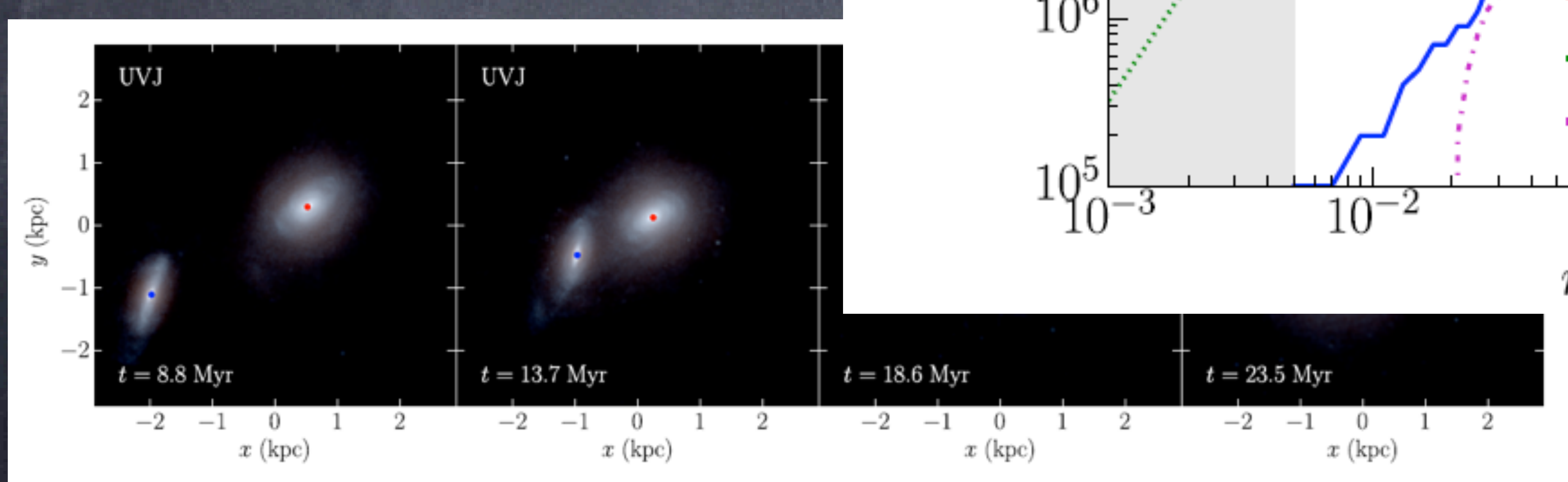

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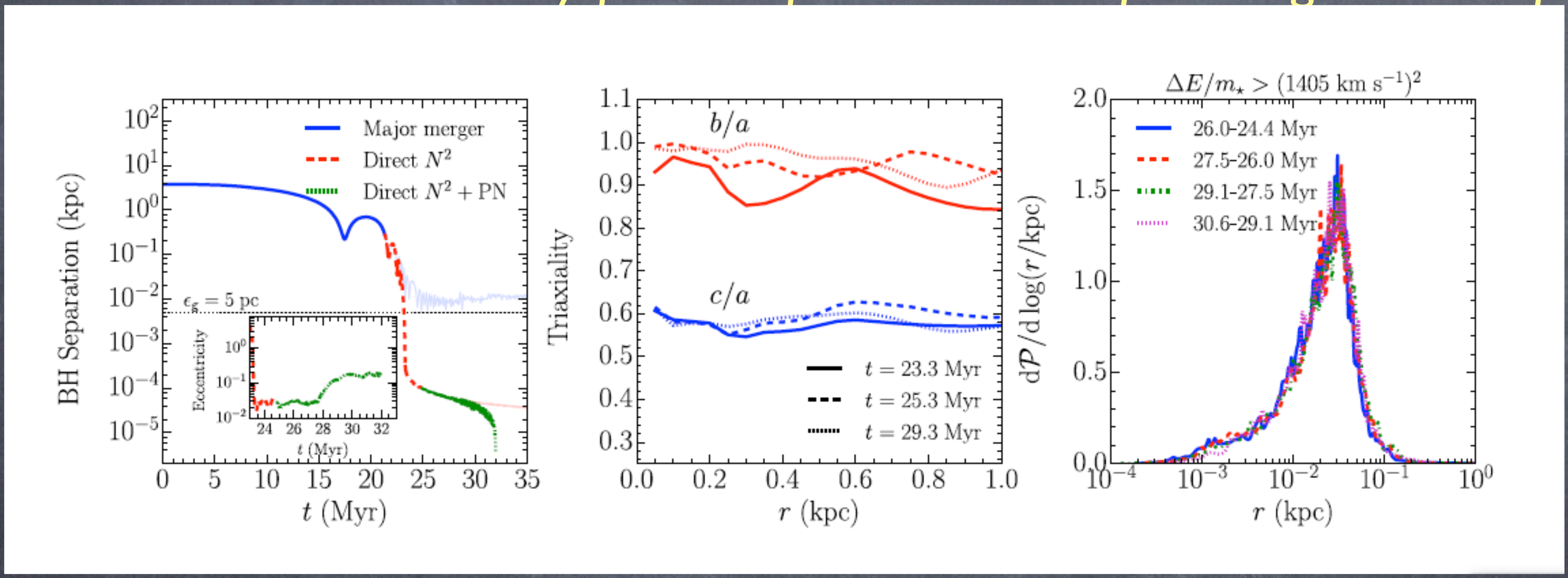
Fast coalescence **in <~ 10 Myr** after the two galaxy cores merge

Sustained encounters with stars because loss cone remains nearly full
(note that star particles here are actually small clusters of a few 100 Mo)

Stars interact with SMBH binary from as far as 10-100 pc owing to centrophilic orbits



Short timescales due to high background density as this is a high-z massive galaxy.
If we rescale density to z=0 galaxies we re-obtain merging timescales of ~ 1 Gyr as in previous work (eg calculation in Mayer 2017, LISA Symposium Procs.)

Stellar densities consistent w/galaxies at z ~ 2-3 (eg Szomoru et al. 2012; Papovich et al. 2015)

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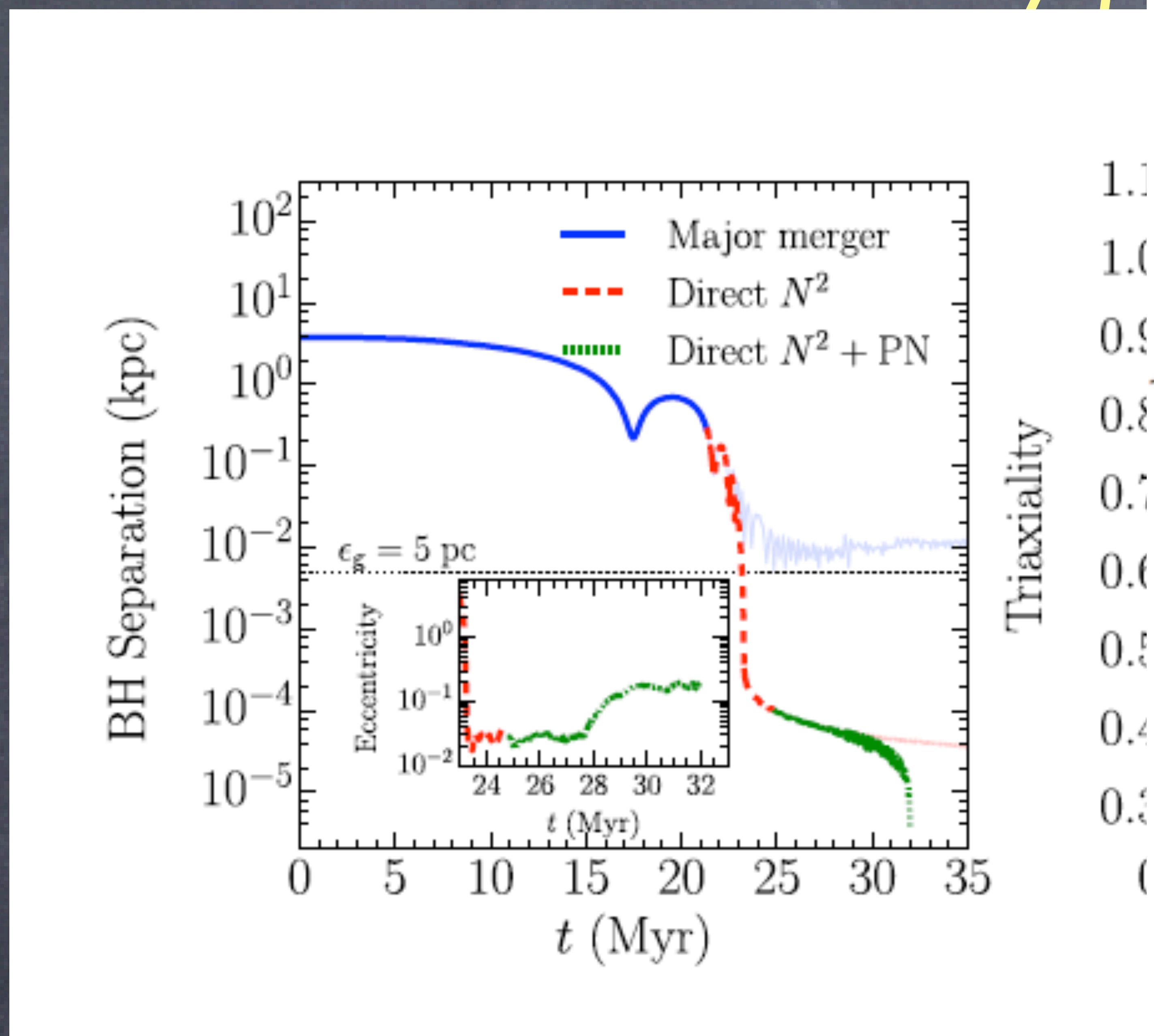

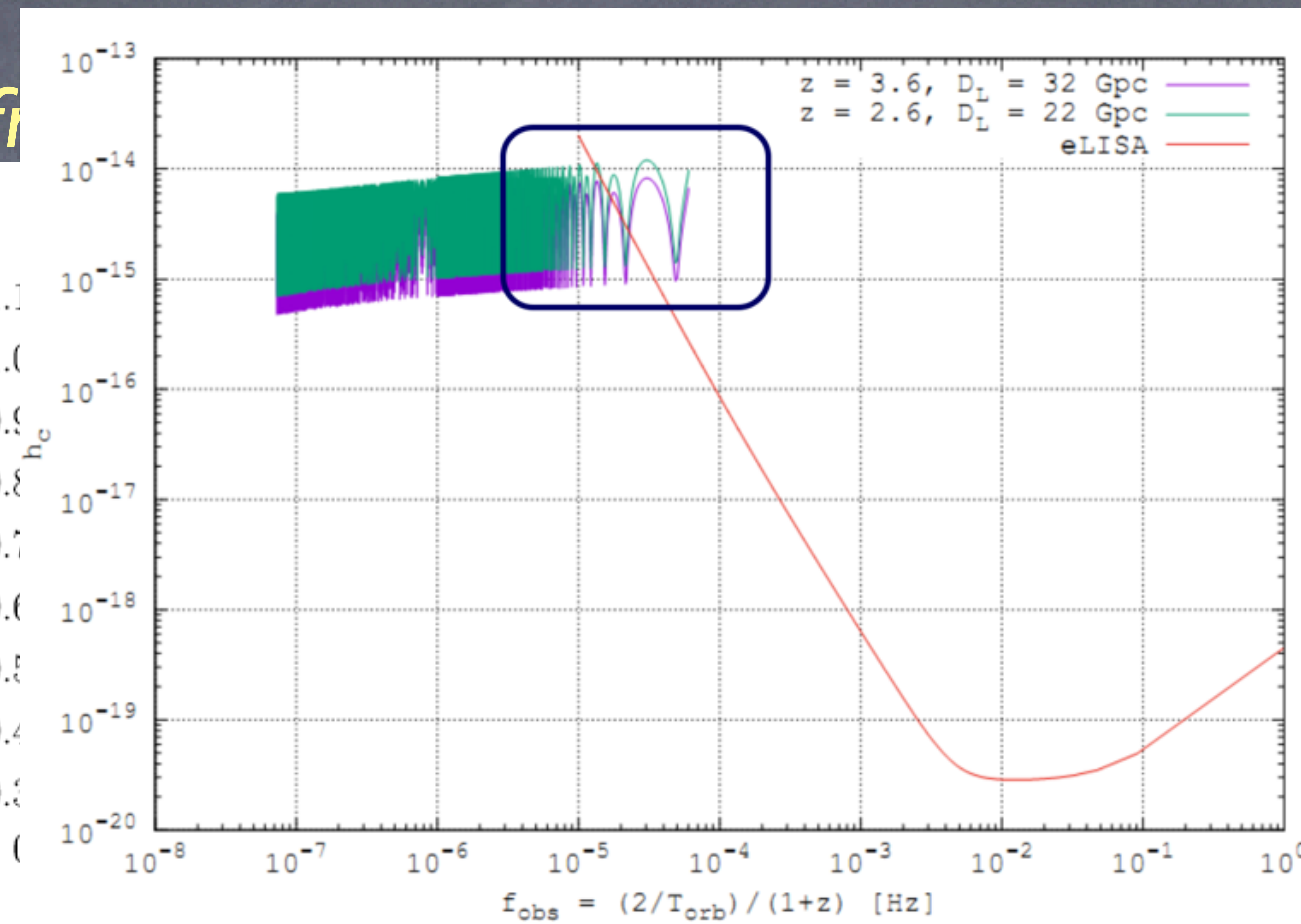

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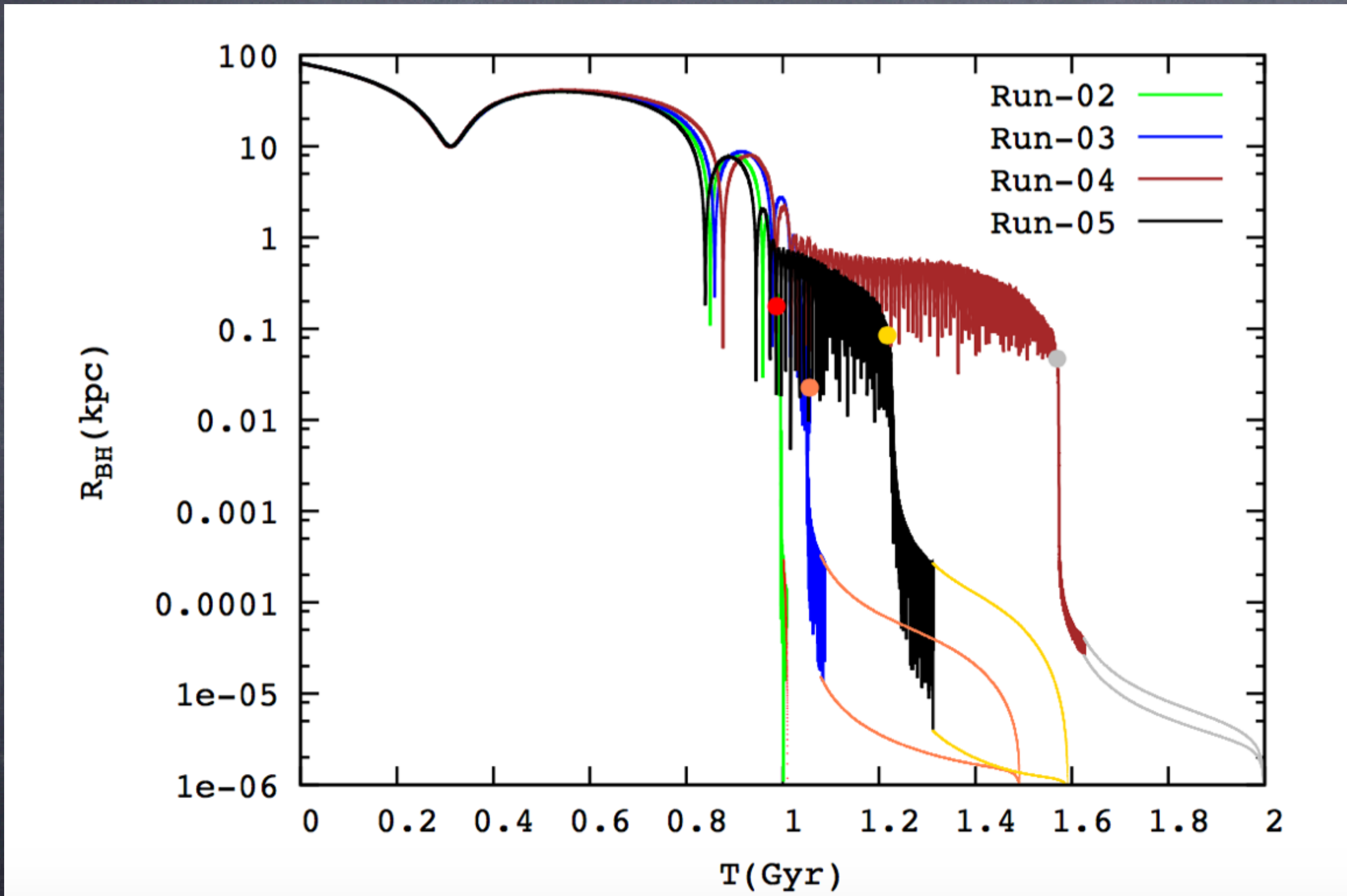
10^6-10^7 Mo black hole mergers in MW-sized disk galaxies (in prep.)

MBH decay curves in 5 unequal mass disk galaxy mergers (1:2 mass ratio in all, ICs from Capelo et al. 2015)



Wide range of BH coalescence timescales (10 Myr to 2 Gyr) but **hardening timescales <u>a few hundred Myr</u> —>10 times longer than in** Khan et al. (2016).

Main reason: 10 times lower nuclear density than in the massive early type galaxy of Khan et al. (2016)

Note these are unequal mass mergers hence the galaxy/halo merger timescale is > 1 Gyr (still dominates total MBH merger time)

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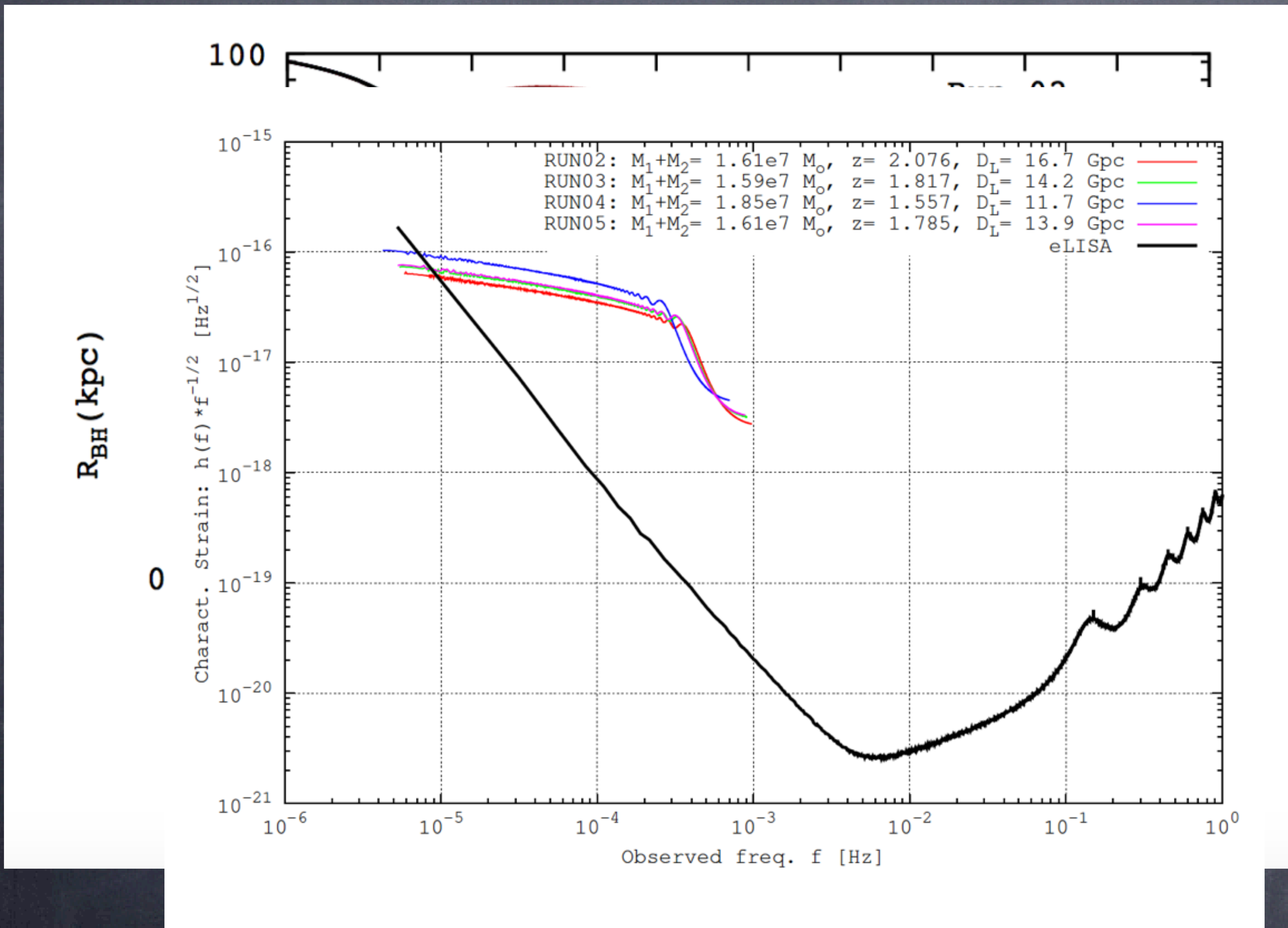

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The gas-dominated regime

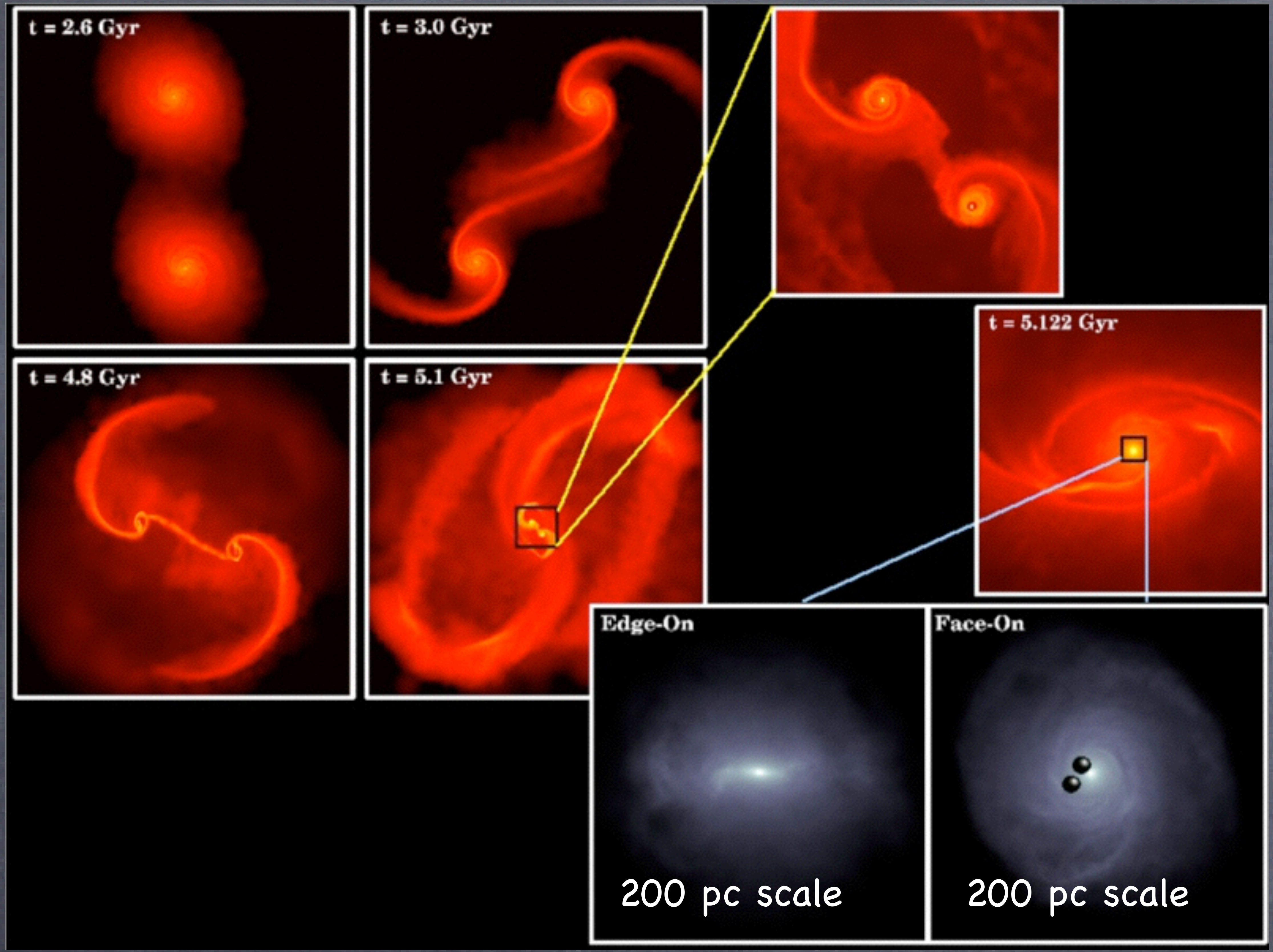
MBH binary formation and hardening in galaxies gas-dominated at kpc scales and below (f_{gas} >~ 50%)?
—-> many nuclei of local merger remnants (eg Medling et al. 2015) as well as in star forming (clumpy) galaxies at z ~ 2-3.

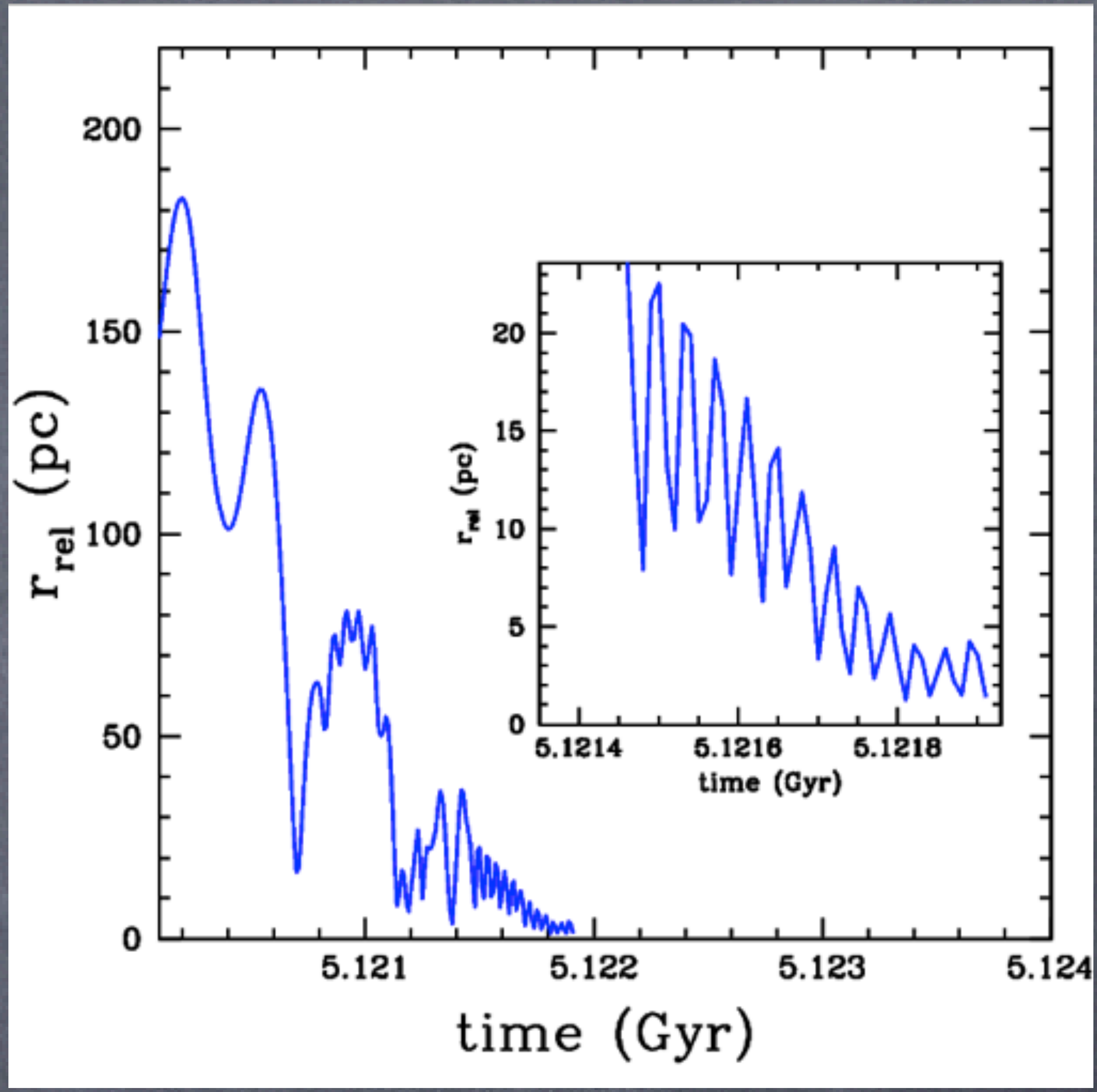
(Note: LISA will be mostly sensitive to SMBHs with mass below <~ 10^7 Mo — at any z, and especially at
z > 1, these should be hosted in star forming, **gas-rich** galaxies).

(SMOOTH) GAS-RICH MAJOR MERGERS: ACCELERATED PHASE II

SMBH binary formation to pc separations just few Myr after galaxies merge.

Binary SMBH forms in gaseous circumnuclear disk (CND)





Mayer et al. 2007, Science

In CND forming after merger, dynamical friction by gas x10 stronger than by stars and dark matter

() Simulations adding star formation confirm result even when a substantial fraction of the CND mass is converted into stars (Dotti et al. 2007) --> key point is high density in CND gives strong drag

() Gas thermodynamics plays crucial role in drag (here idealized, with effective equation of state)

BUT PHASE II-III BECOME STOCHASTIC IN MASSIVE CNDs DUE TO CLUMPY GASEOUS MEDIUM

CLUMPINESS ARISES NATURALLY IN GAS-DOMINATED SELF-GRAVITATING DISKS THAT COOLS RAPIDLY ($T_{COOL} < T_{ORB}$).

GIANT MOLECULAR GAS CLOUDS >~ 10^6 MO IN GALACTIC NUCLEI.

PARAMETER SPACE STUDY (COOLING RATE, BLACK HOLE MASSES, ORBITAL ECCENTRICITY, FEEDBACK) PROCESSES).

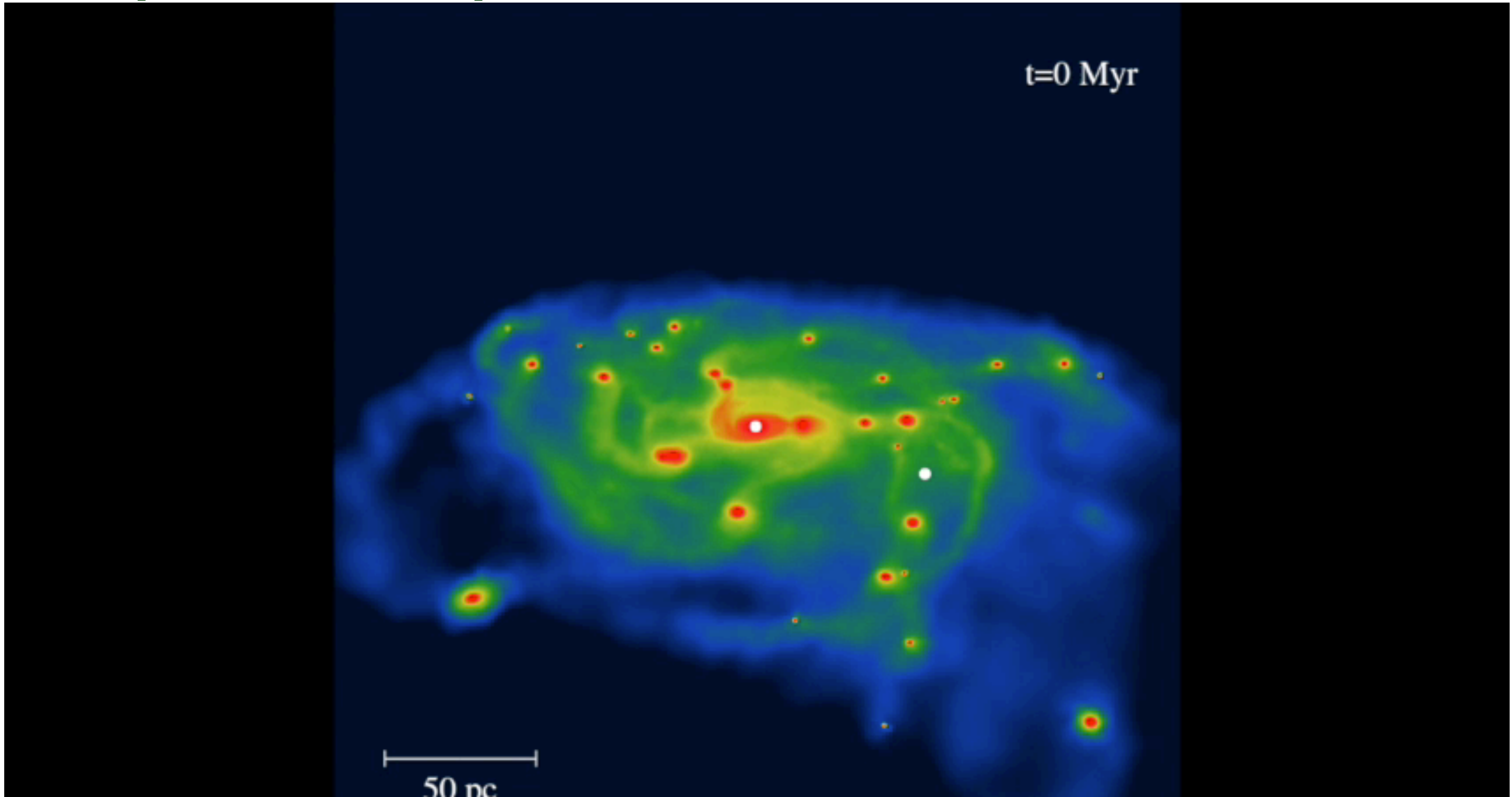
Fiacconi, Mayer et al. (2013)
(also del Valle et al. 2015)

Use simple radiative cooling prescription: cooling time proportional to local orbital time (Gammie 2001)

Impose adiabatic evolution above high density threshold

$$\Lambda_{\rm cool} = -\frac{u}{t_{\rm cool}}$$

$$n_{\rm th} = 5 \times 10^5 \ \rm H\,cm^{-3}$$



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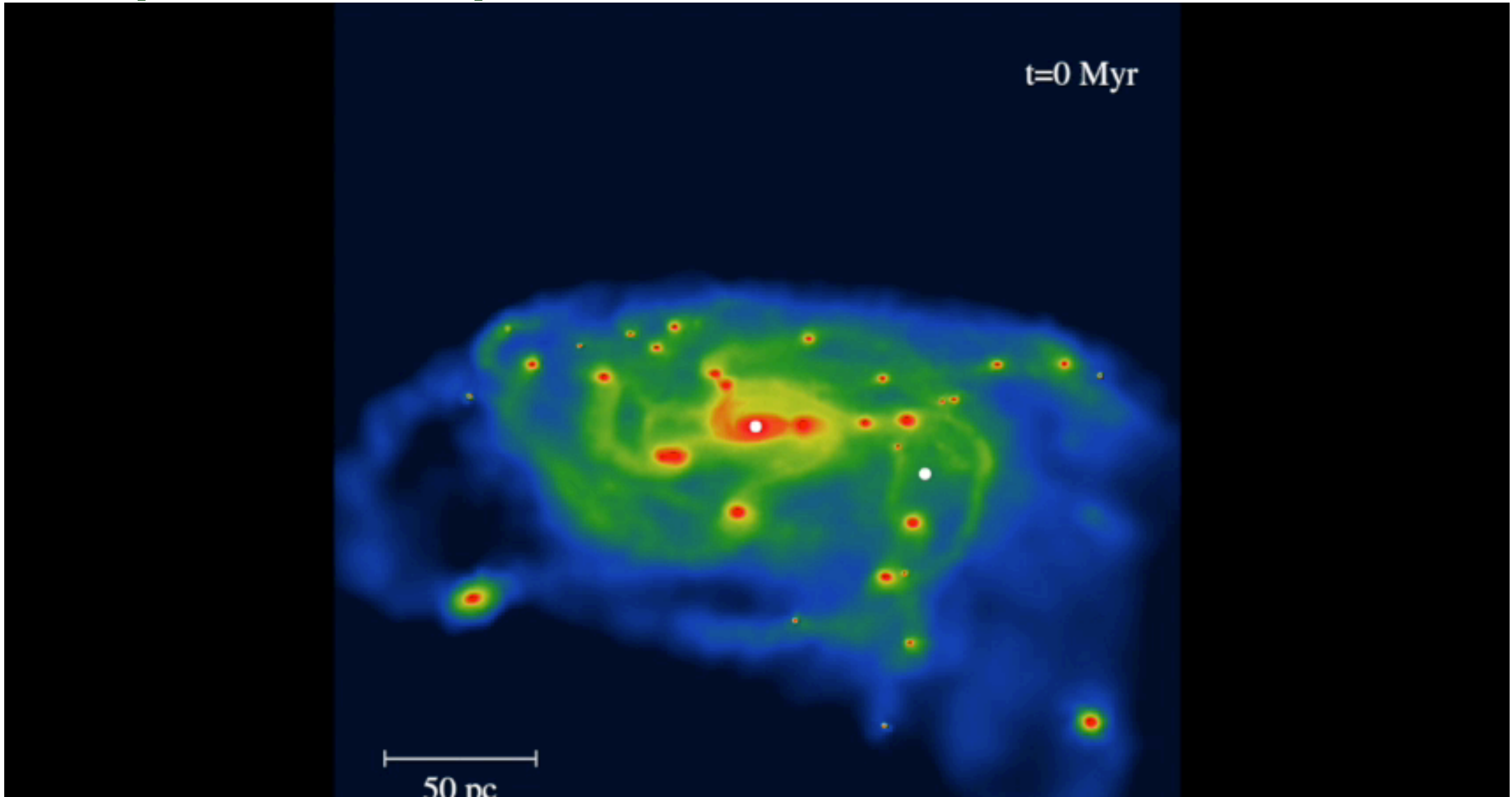
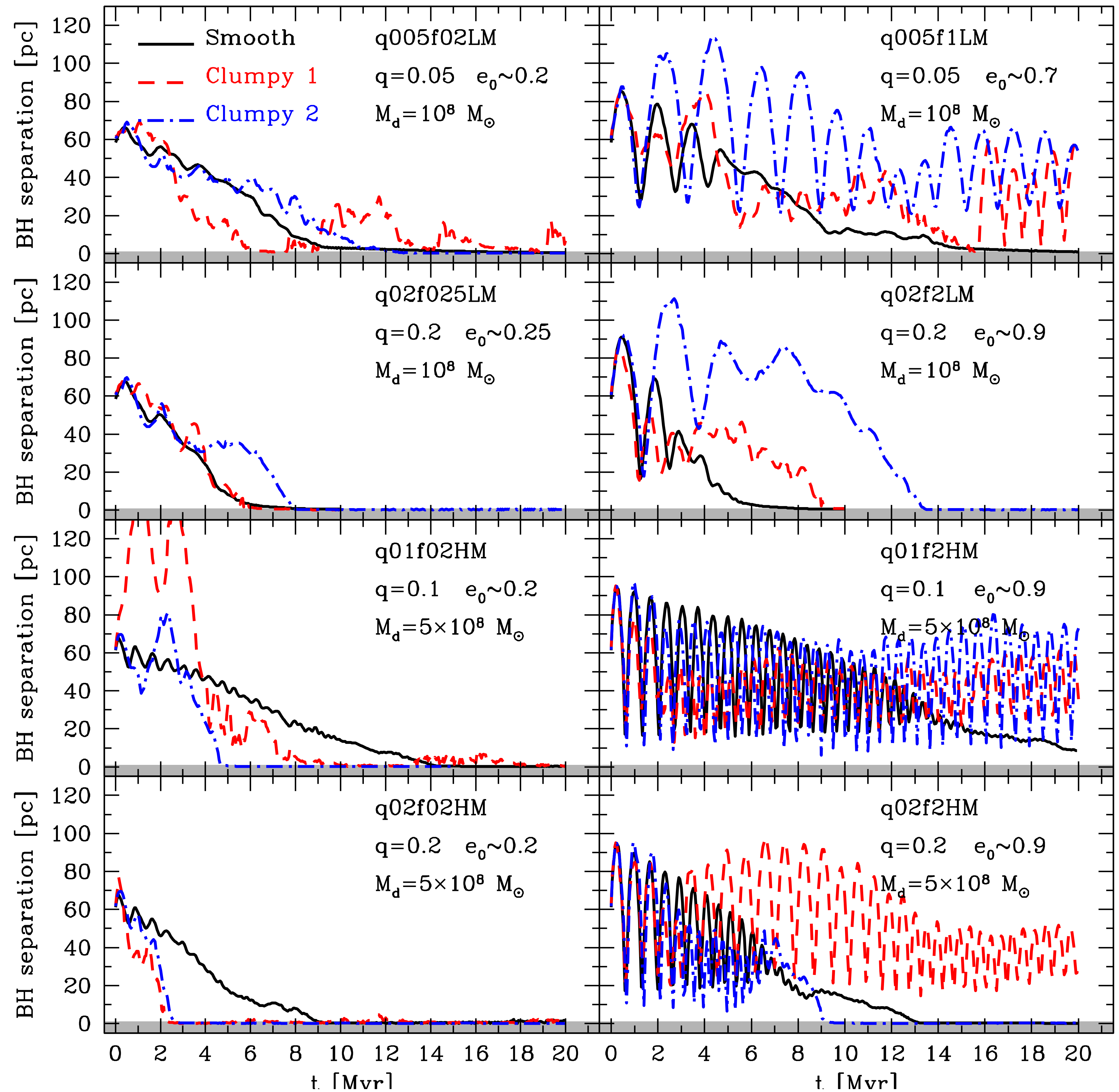


Stochastic MBH orbital decay in CNDs

Stochastic Orbital Decay due to *gravitational scattering of BHs by clumps/spiral density waves* ——> delayed MBH binary formation



Fiacconi et al. (2013)

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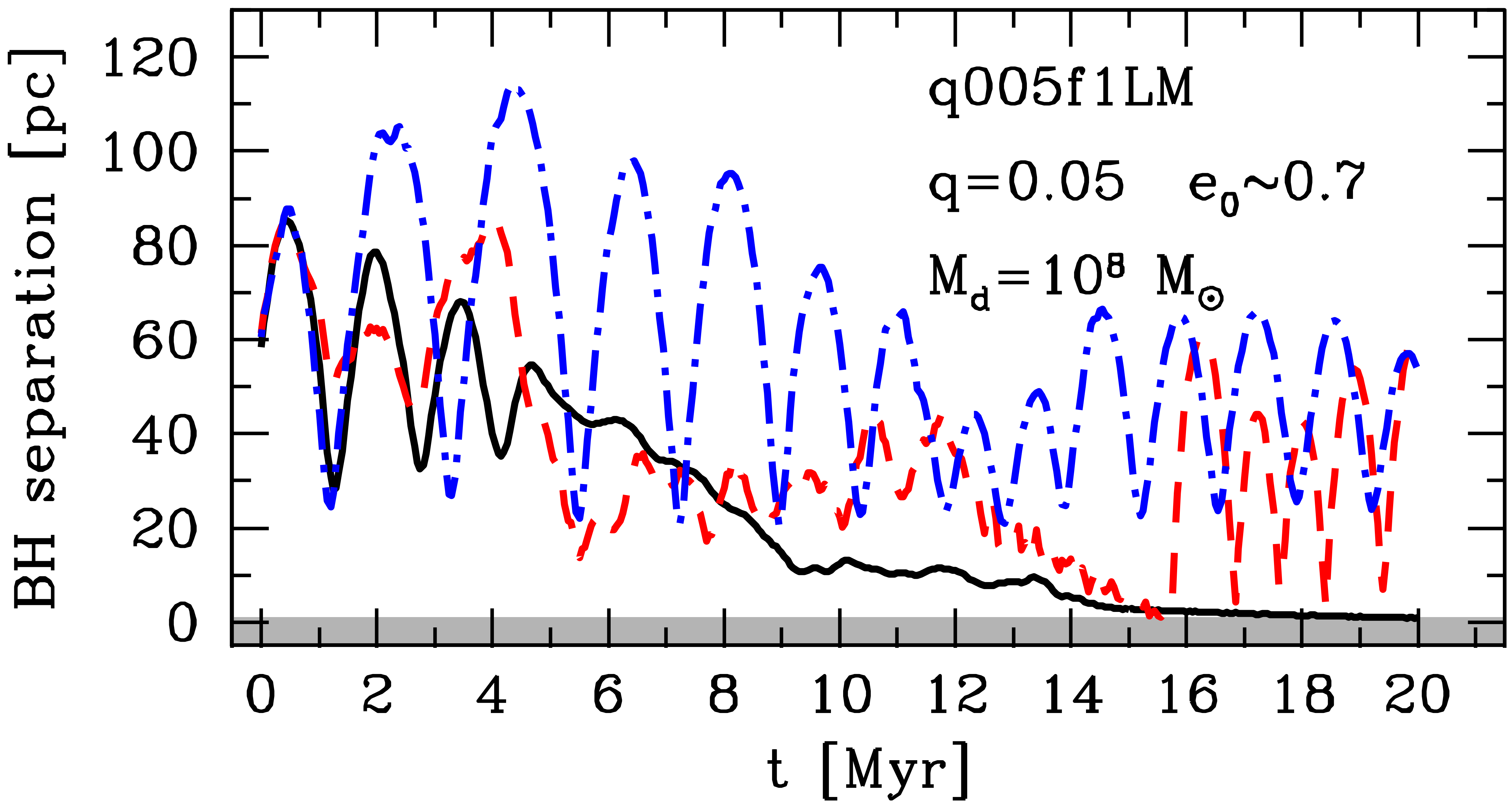


BH-Clump Scattering: Disk Ejection

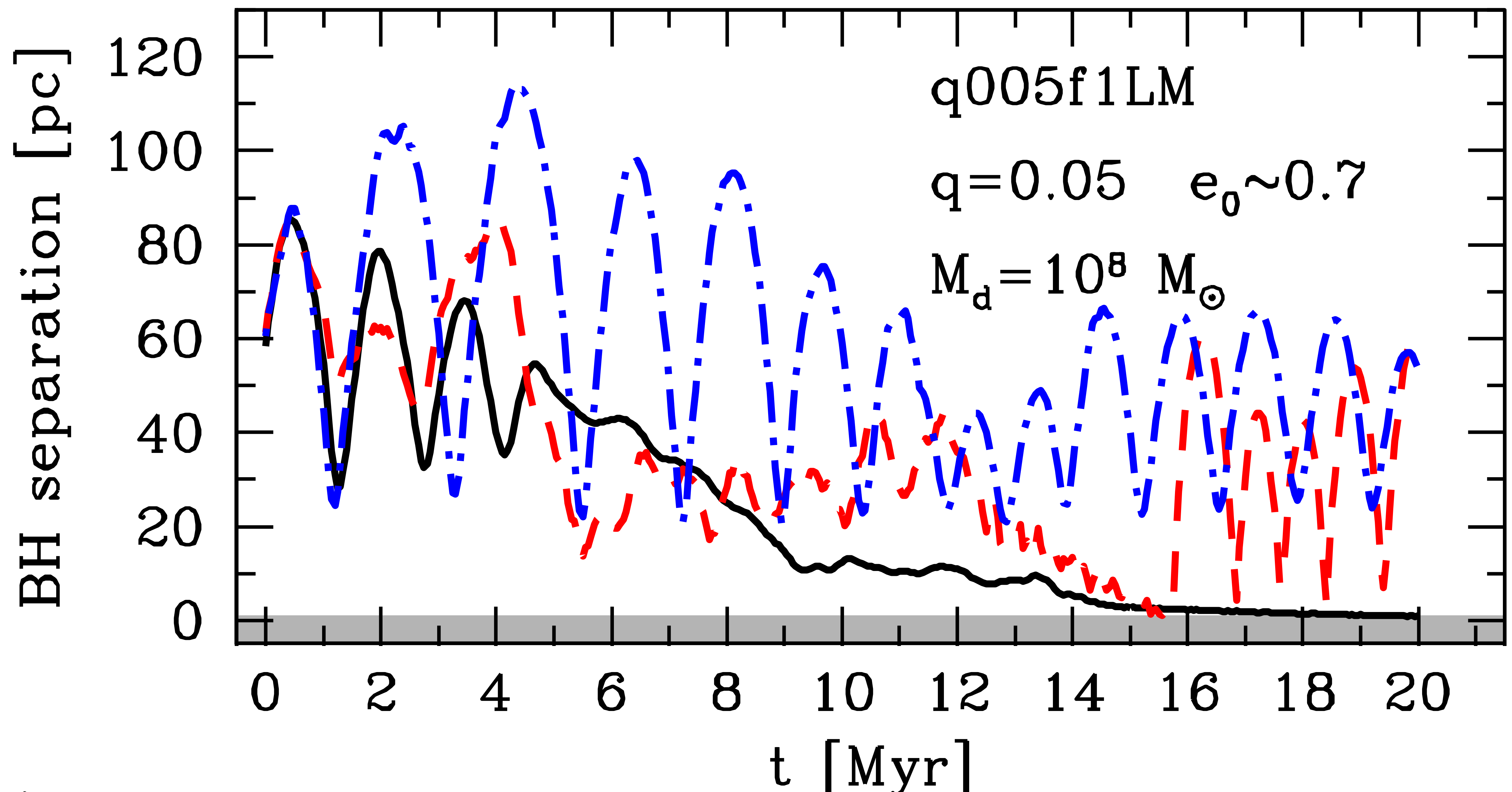
BH-Spiral Arms Scattering

BH-Clump Capture and Destruction

Fiacconi et al. (2013)

Stochastic MBH orbital decay in CNDs

Stochastic Orbital Decay due to *gravitational scattering of BHs by clumps/spiral density waves* ——> delayed MBH binary formation



BH-Clump Scattering: Disk Ejection

BH-Spiral Arms Scattering

BH-Clump Capture and Destruction

decay time to resolution scale ~ 0.1 pc separation (HARD BINARY)

$$1 \lesssim \tau_{\rm decay}/{\rm Myr} \lesssim 50$$

BH-Clump Binary | Clump Scattering | BH Ejection

$$\xi = \frac{M_\bullet}{M_{\rm cl}} \lesssim 1$$

For significant effect on SMBH orbit

Fiacconi et al. (2013)

The dark matter dominated regime

Merging MBHs in the 10^4-10^5 Mo range are the ideal target for LISA given its sensitivity curve in frequency space.
These should be hosted in low-mass/dwarf galaxies.
Only recently X-ray detections of sources compatible with such low mass MBHs (IMBHs) have been collected in dwarf galaxies (eg Reines et a 2013; Baldassare et al. 2015)

—-> New regime for BH orbital dynamics since dwarf galaxies are dark matter dominated as opposed to stellar or gas dominated (Tamfal, Capelo, Mayer, in prep.)

Dwarf galaxy mergers with MBHs: numerical simulations (Tamfal et al. in prep.)

Major mergers between dwarf spiral/irregular galaxies, w/varying resolution.
Galaxy models; Exponential Stellar Disk embedded in DM halo plus central MBH (highly stable N-body models with GALACTICS code by Widrow & Dubinski).
Pilot study: mergers of analogs of RGG118 (halo mass set from M^*-M_{halo} relation)
Generalized dark matter density profile (eg Kravtsov et al. 1998; Zhao 2002)

$$\rho = \frac{\rho_s}{(r/r_s)^\gamma [1 + (r/r_s)^\alpha]^{(\beta-\gamma)/\alpha}}$$

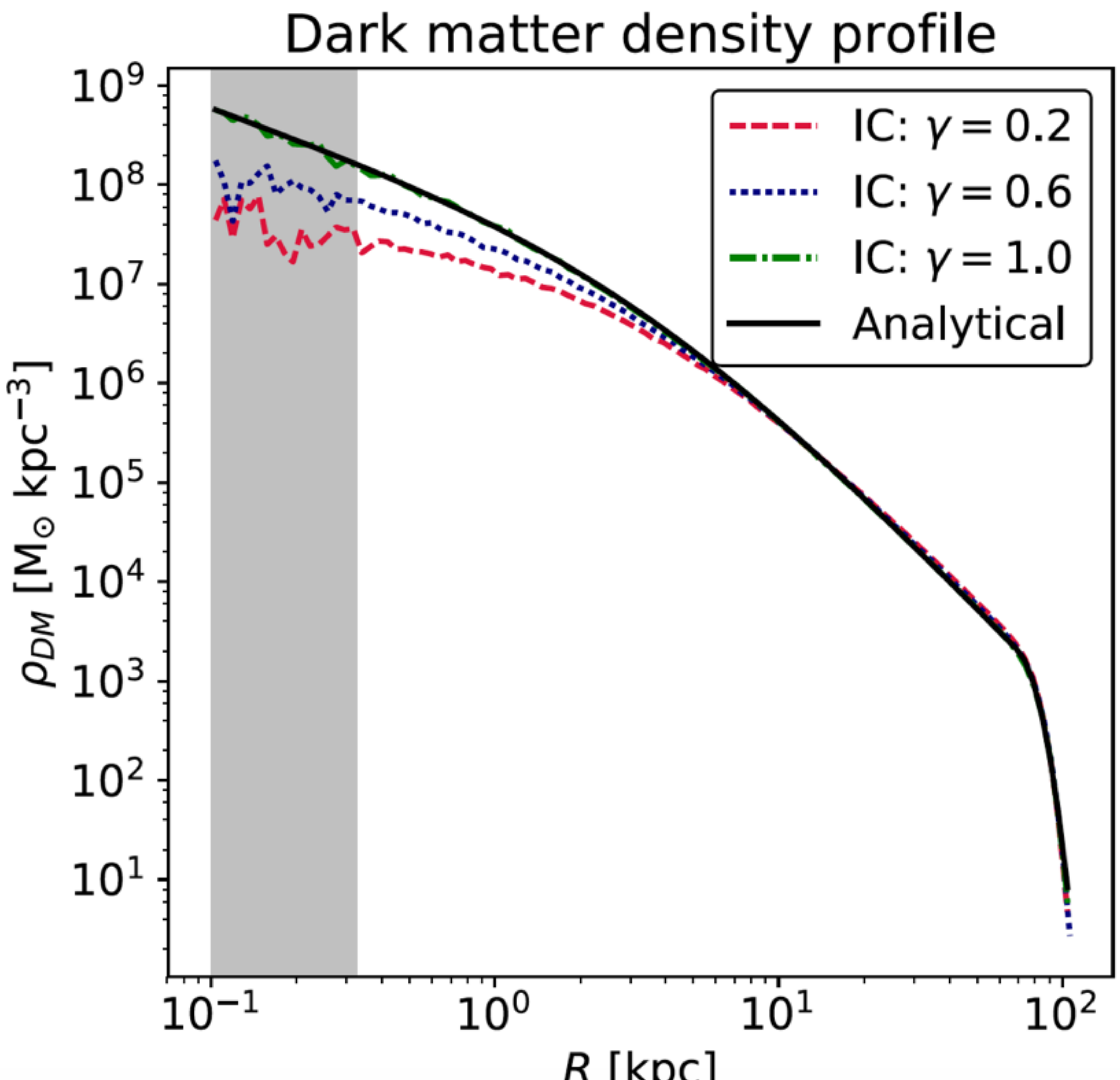
NFW corresponds to **γ = 1 (α=1, β=3).**
But cosmological dwarf galaxy formation simulations show that SN feedback-driven winds can lead to flattening of DM density profile (“dark matter heating”):

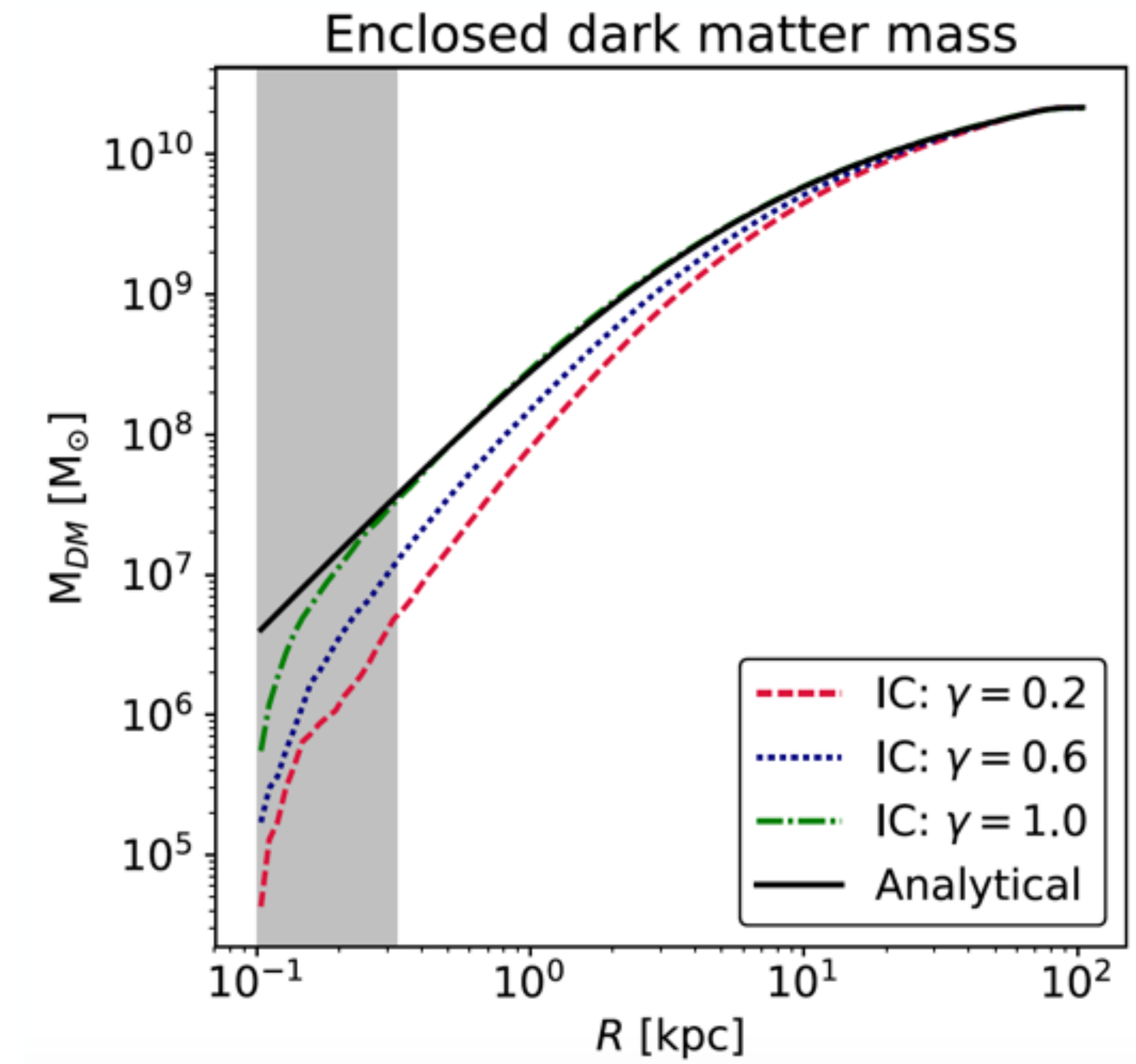
→ $\gamma = 0.2 \text{ and } \gamma = 0.6$

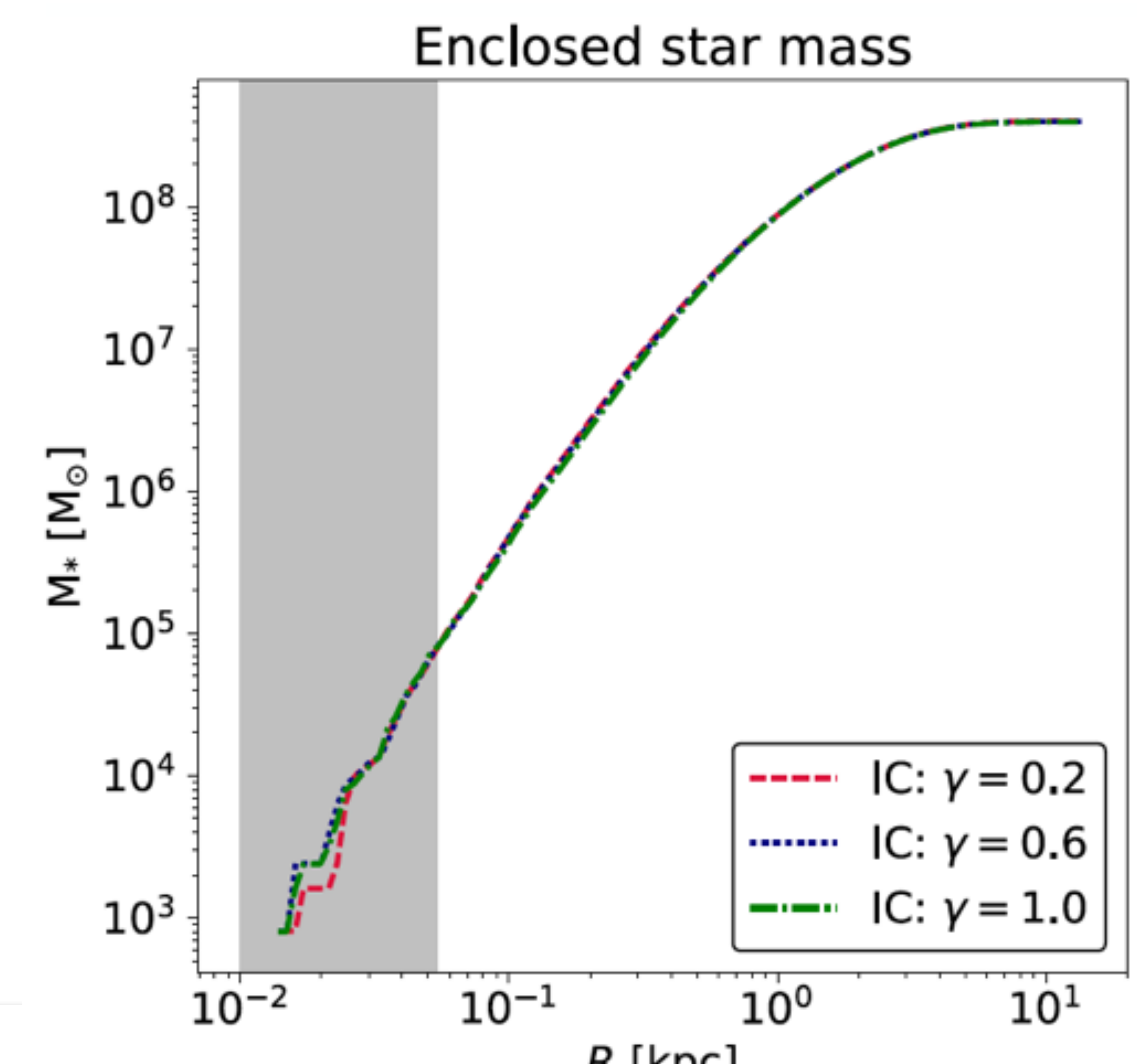
(e.g. see *Governato, Brook, Mayer et al., 2010; Shen et al. 2014; Hopkins et al. 2015; Read et al. 2016*)

Dark matter “cores” /shallow inner profiles also in alternative dark matter models such as Self-Interacting Dark Matter (SIDM - Rocha et al. 2013;di Cintio et al. 2017) and Fuzzy Dark Matter (FDM - eg Hui et al. 2016)

Properties of initial galaxy models







MBH pairs in dwarf galaxy mergers

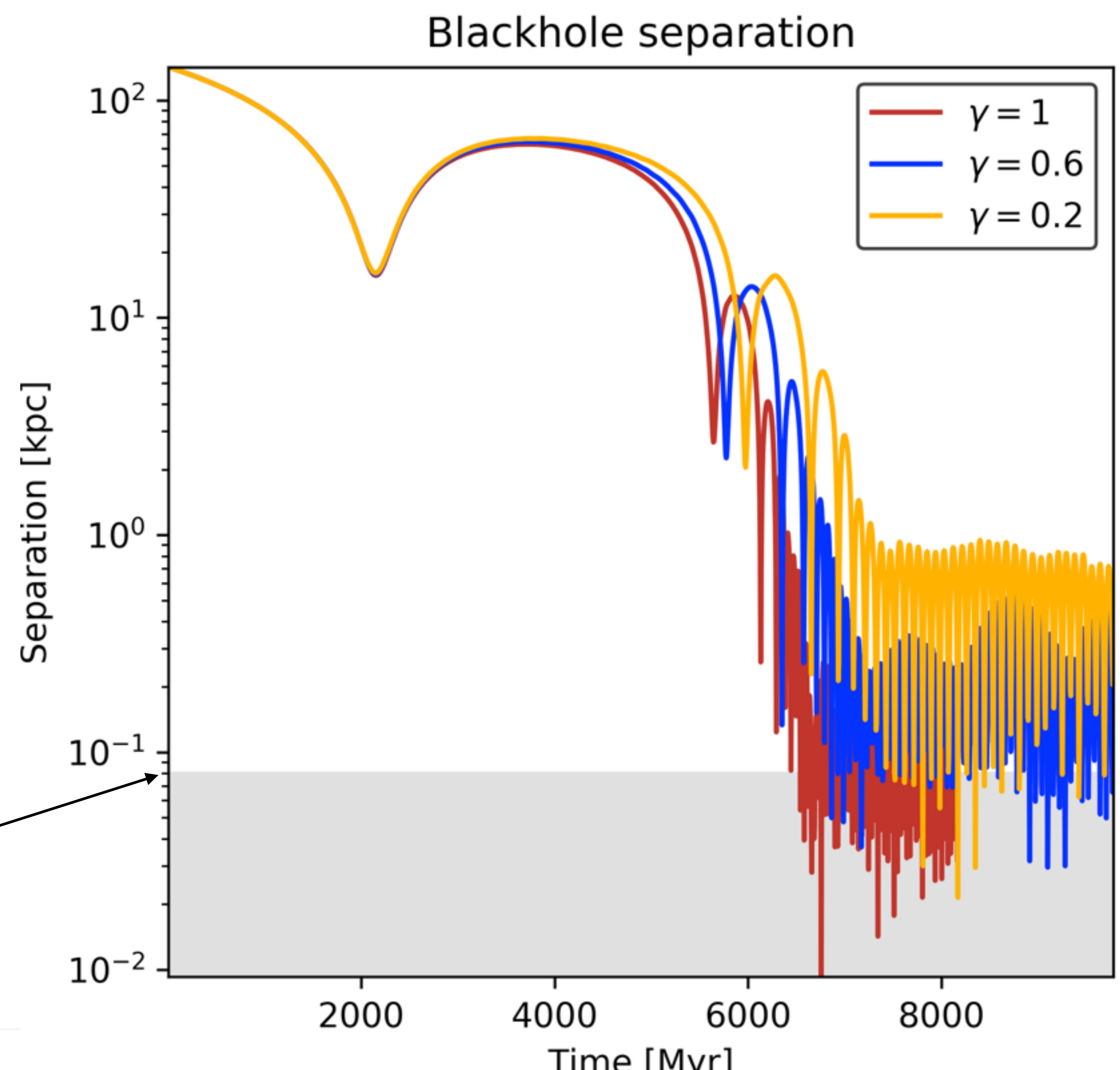
BH binary Formation/Suppression depends on dark matter density distribution

(Tamfal, Capelo, Kazantzidis & Mayer 2018)

Evolution of BH pair separation in dwarf galaxy mergers

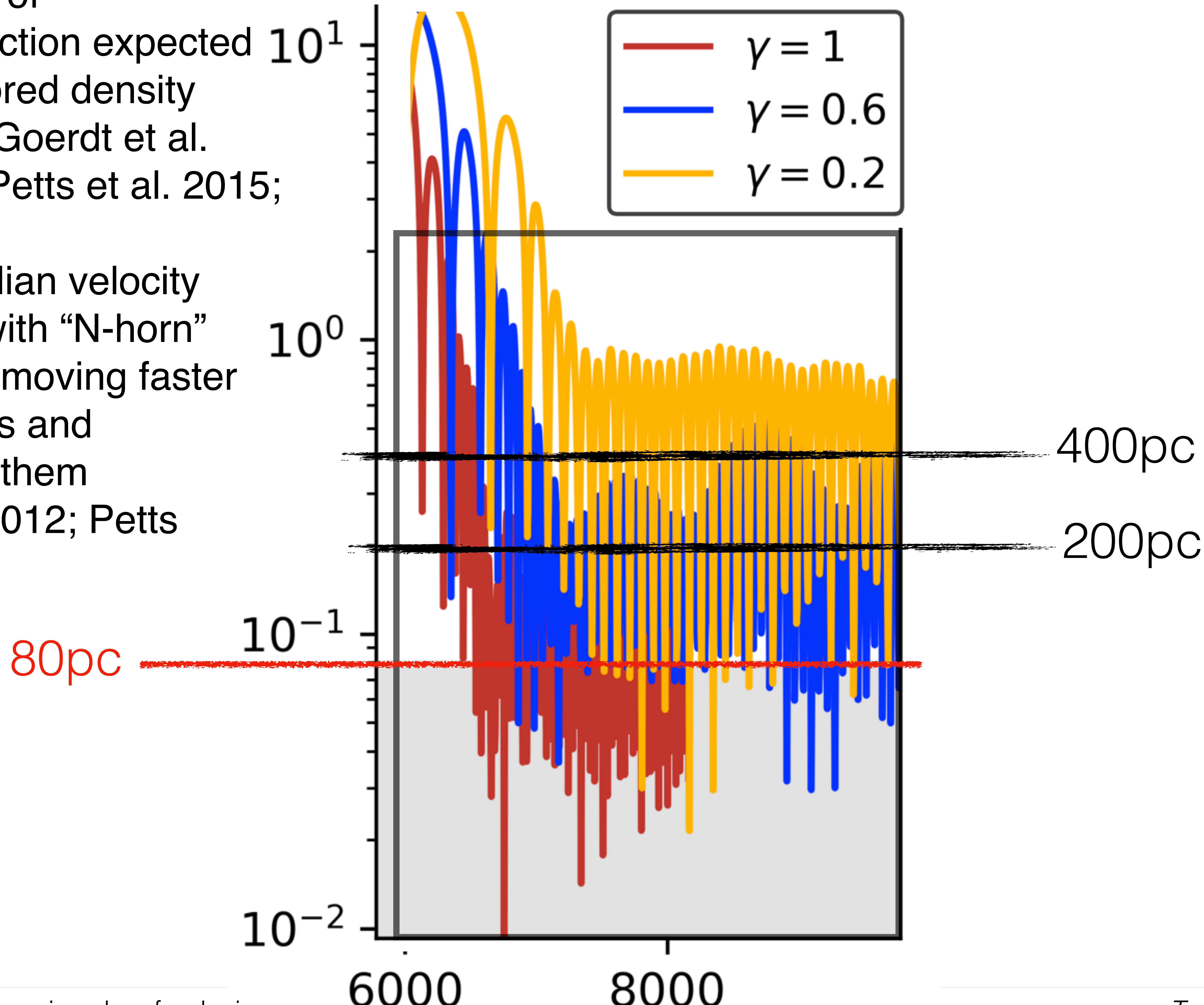
Galaxy models have stellar exponential disk embedded in DM halo with varying slope

resolution limit



Suppression of dynamical friction expected in shallow/cored density distribution (Goerdt et al. 2007,2010; Petts et al. 2015; 2017).

Non-maxwellian velocity distribution with “N-horn” dm particles moving faster than the BHs and accelerating them (Cole et al. 2012; Petts et al. 2016).



Suppressio
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2017).
Non-maxwe
distribution
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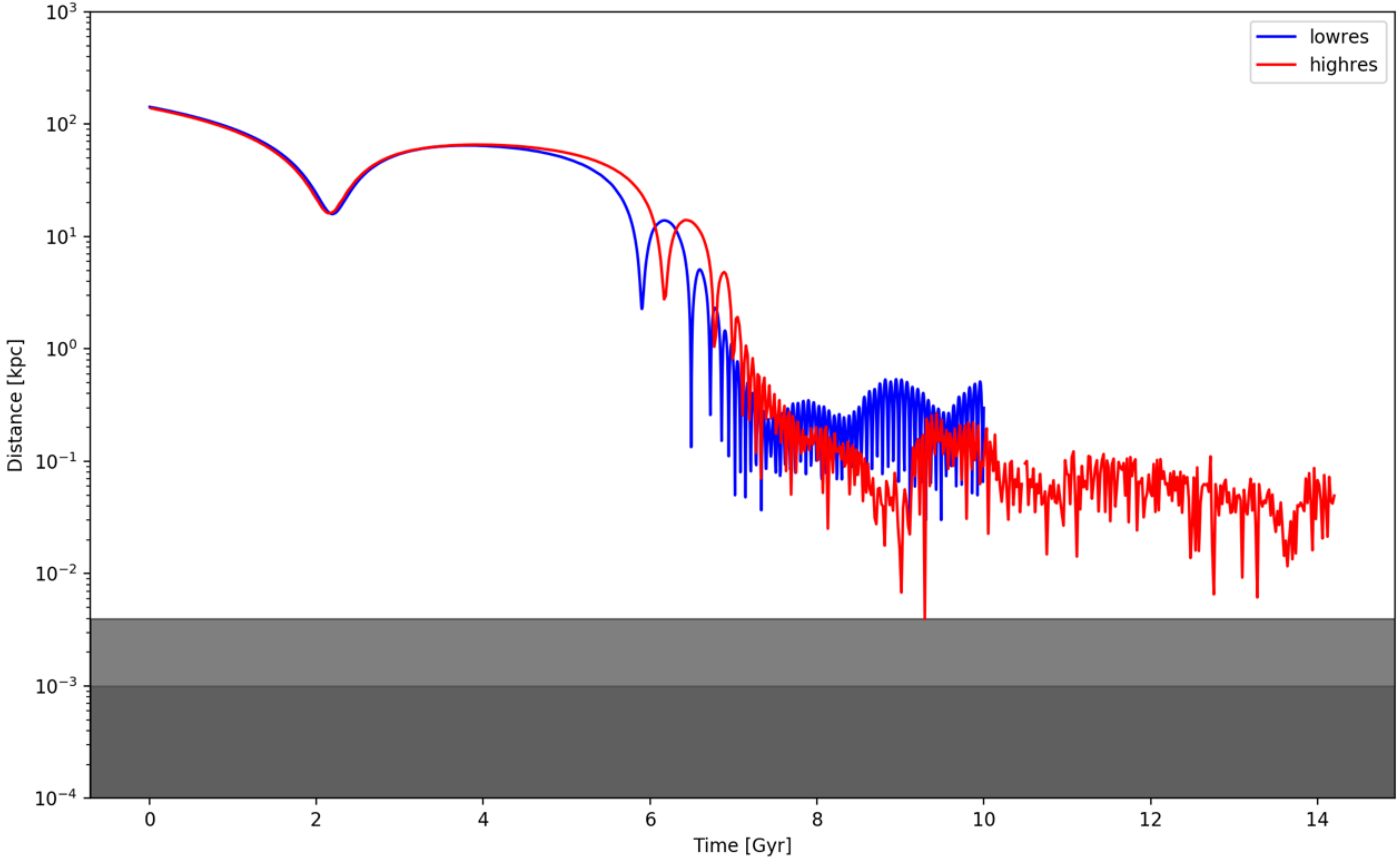

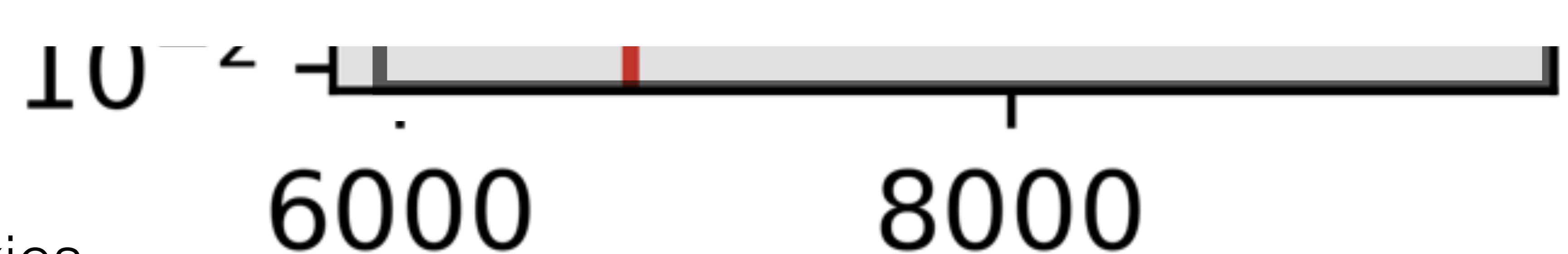

Conclusions

() The Process of MBH binary formation and hardening is tightly connected with the properties of the host galaxy at all scales

Must be studied in the full galaxy formation context and it is highly dependent on redshift. Multi-scale pproach necessary to enable the future LISA data stream as probe of galaxy assembly — and viceversa to predict robust event rates —as well as to inform observations of MBH binaries in EM domain

() **gas-rich and gas-poor mergers:** two different modes of SMBH mergers

() in DM dominated galaxies (dwarfs) third mode + potential stalling

In gas-rich mergers a variety of processes can delay or speed-up the orbital decay of SMBHs (decay time to sub-pc separations from 10 Myr to > 1 Gyr) ISM clumpiness crucial at all scales, regime of **stochastic decay**, to be modeled statistically (likely most relevant to upper mass end, >~ 10^6 Mo MBH, of LISA sources)

() Hardening of SMBHs in stellar dominated nuclei of high-z mergers of massive galaxies very fast **(<~ 10^7 yr)** due to high environmental density at low redshift timescales of >~ Gyr because nuclear density lower