Formation of massive black hole binaries

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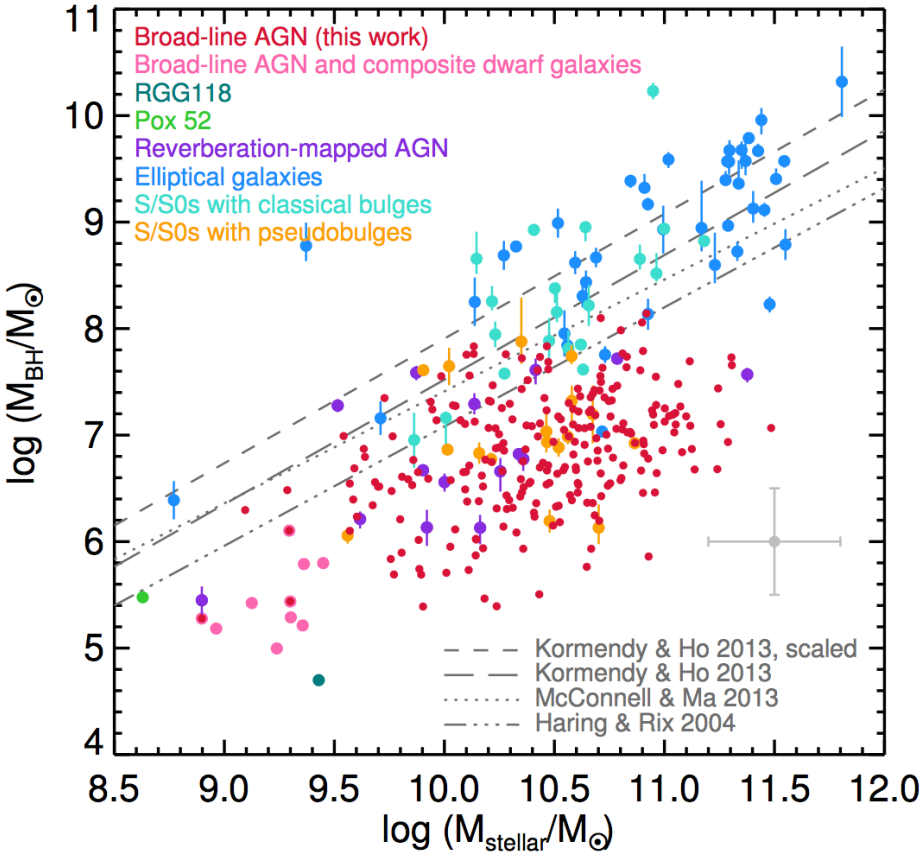
Massive black holes in galaxies



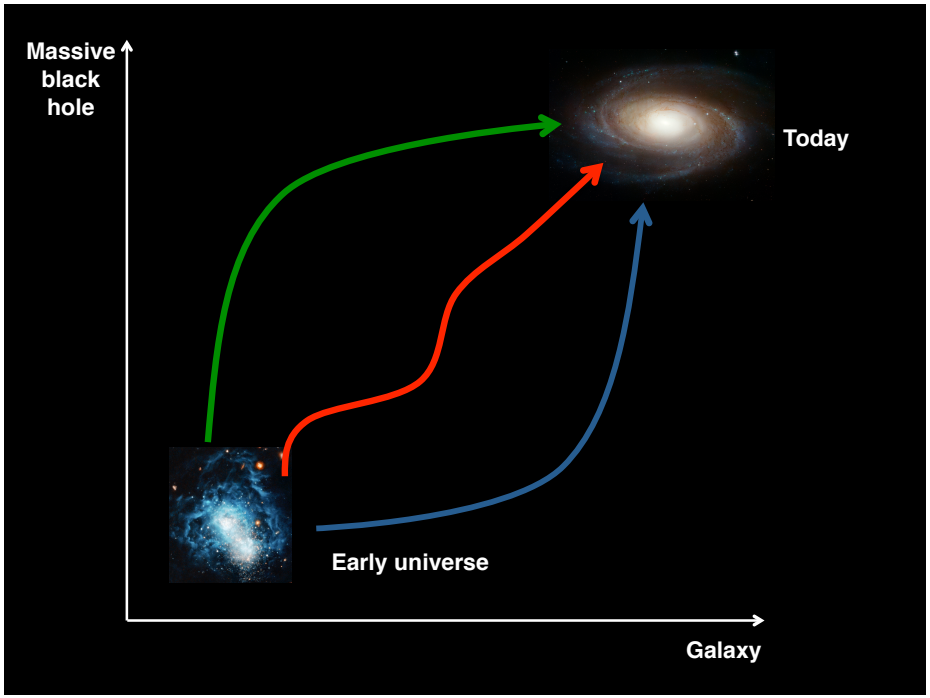
~100 MBHs detected in nearby galaxies to-date

Black hole masses scale with galaxy mass: ~10^{-3}-10^{-4} M_{gal}

Massive black holes in galaxies

- Massive Black Holes (MBHs) are found in the centers of most nearby galaxies

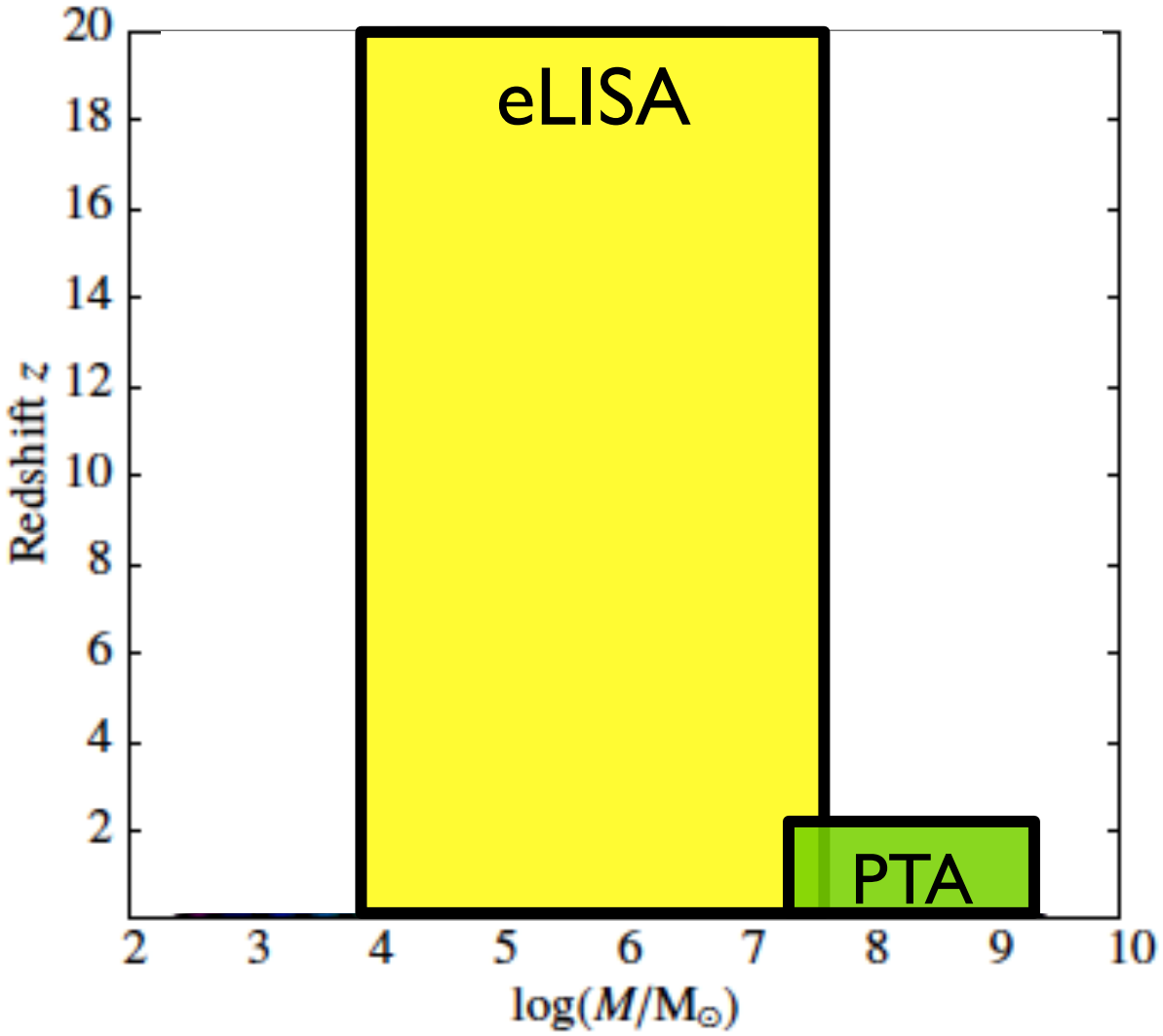
- MBHs should naturally grow along with galaxies through accretion and MBH-MBH mergers and influence the galaxy through feedback



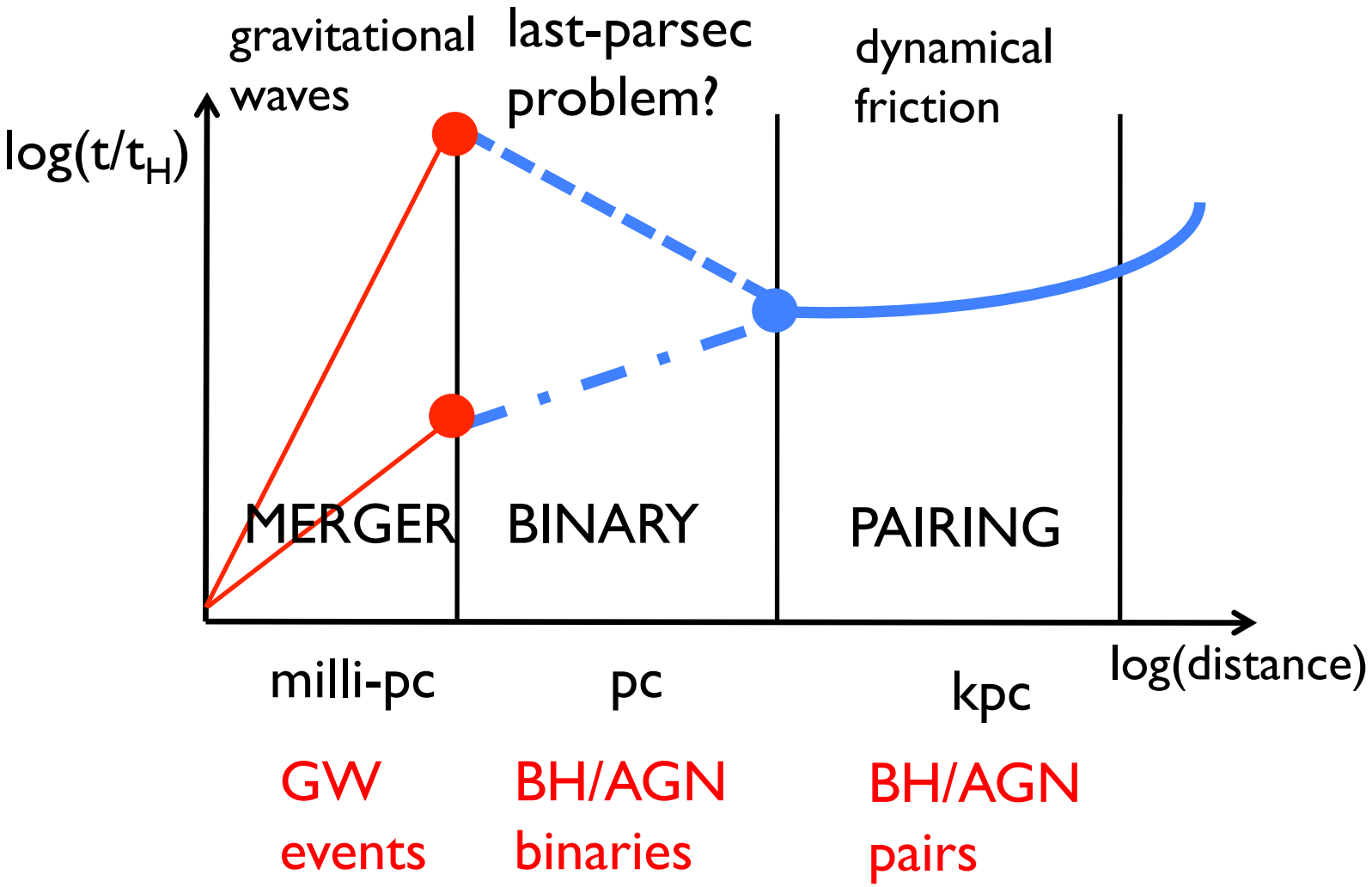
MBHs in galaxy mergers

- High-z and small galaxies: gas is important
- Low-z and large galaxies: star-dominated
- Different MBH-MBH dynamical evolution
- Different gravitational-wave probes (eLISA, PTA)

MBHs mergers and gravitational waves

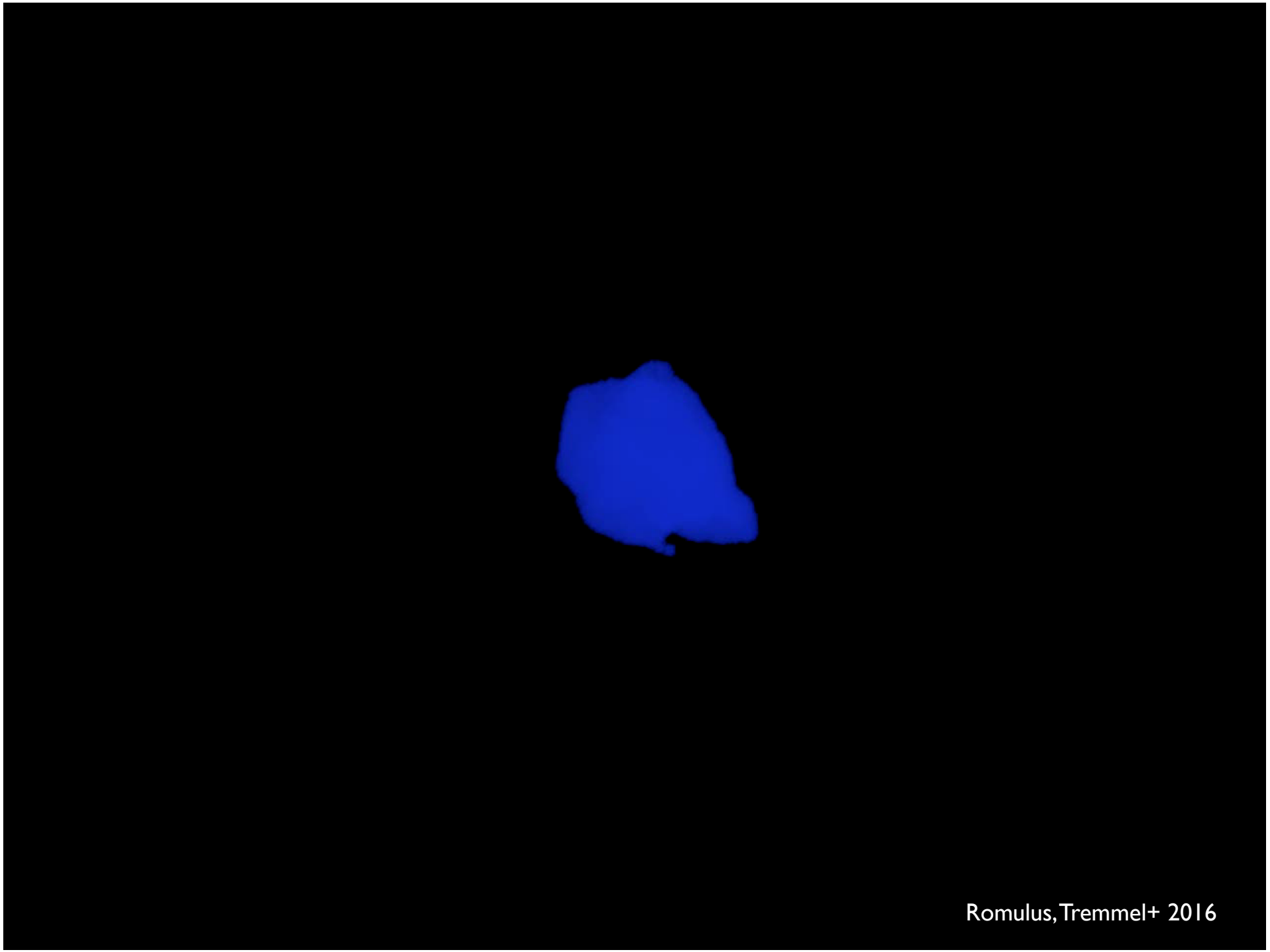


MBHs in galaxy mergers



Courtesy of Monica Colpi

Context: the cosmic merger rate

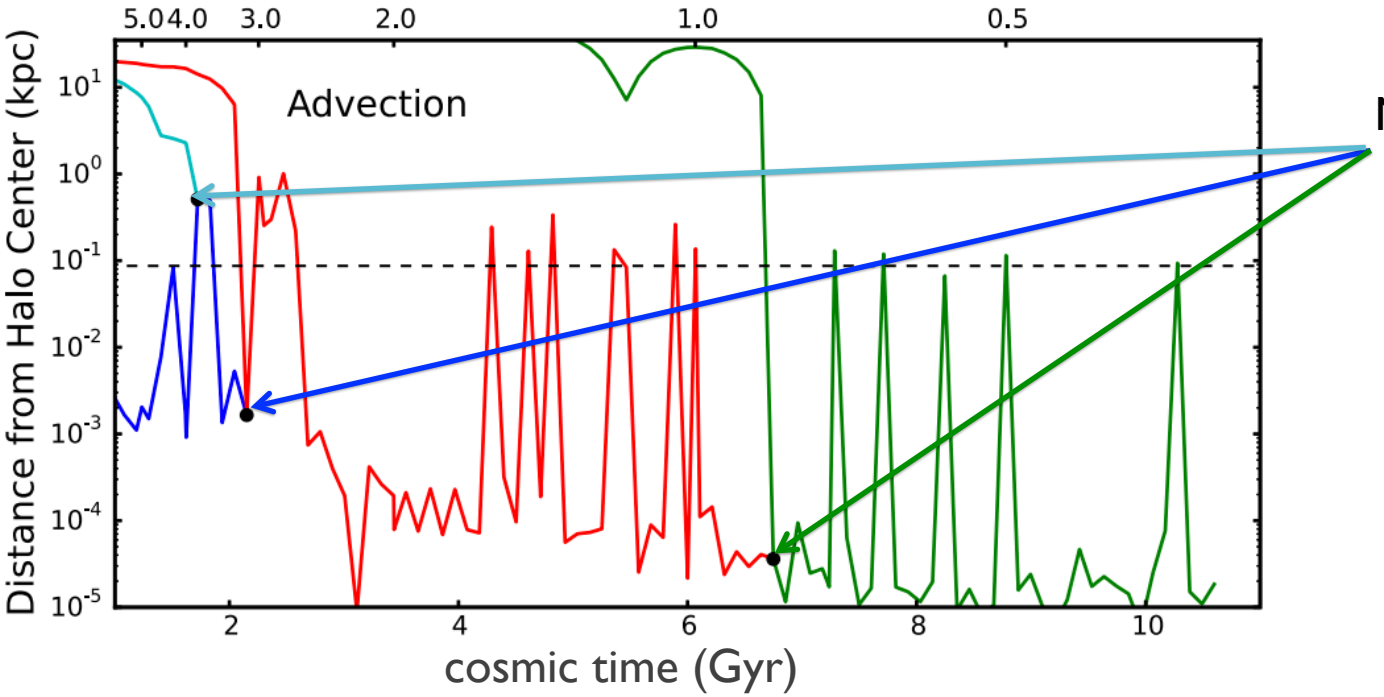

Romulus, Tremmel+ 2016

BH dynamics

How long it takes for BHs to merge in halo/galaxy merger

How often mergers "fail"

BH dynamics



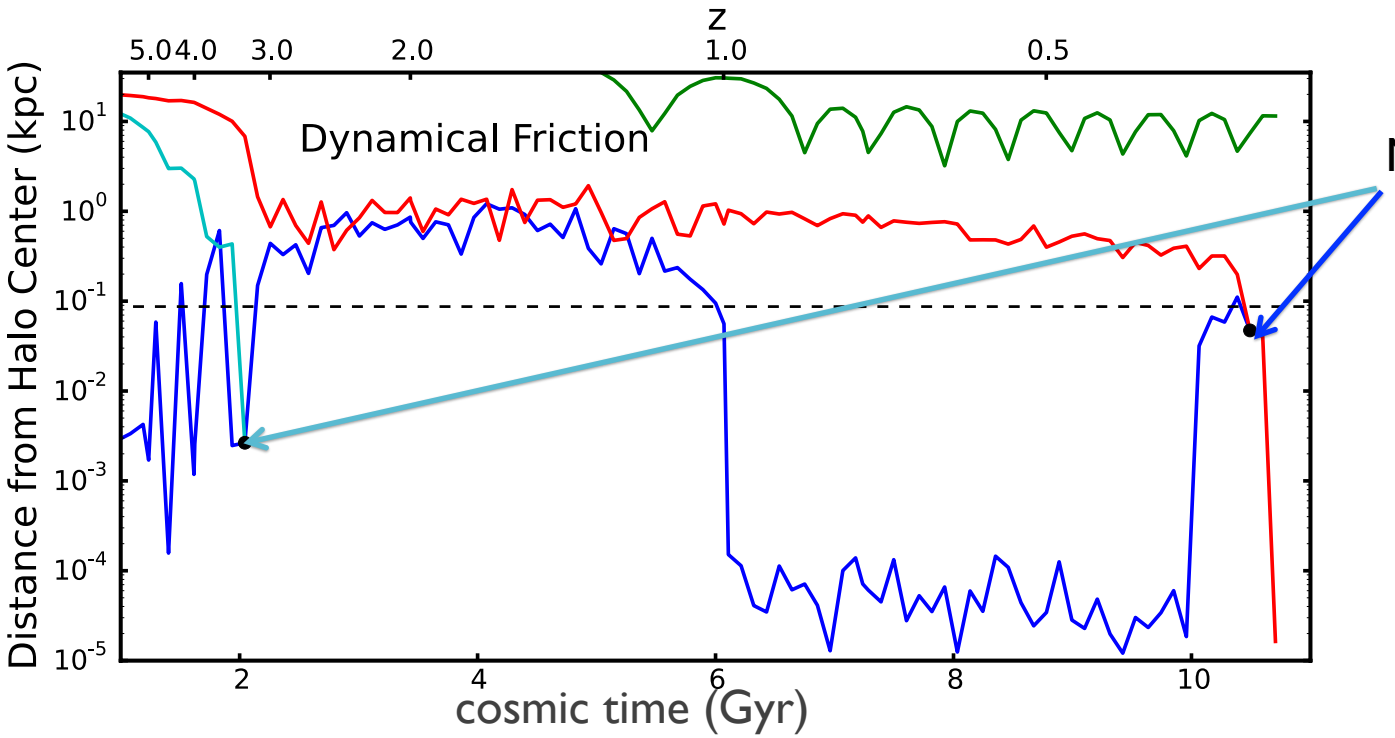
MBH-MBH mergers

Cosmological 'zoomed-in' simulation of dwarf galaxy with mass ~ 10^{10} $M_\odot$ at z = 0.

dark matter particle mass 1.6×10^4 $M_\odot$
gas particle mass 3.3×10^3 $M_\odot$
gravitational softening 87 pc

Tremmel+ 2015

BH dynamics



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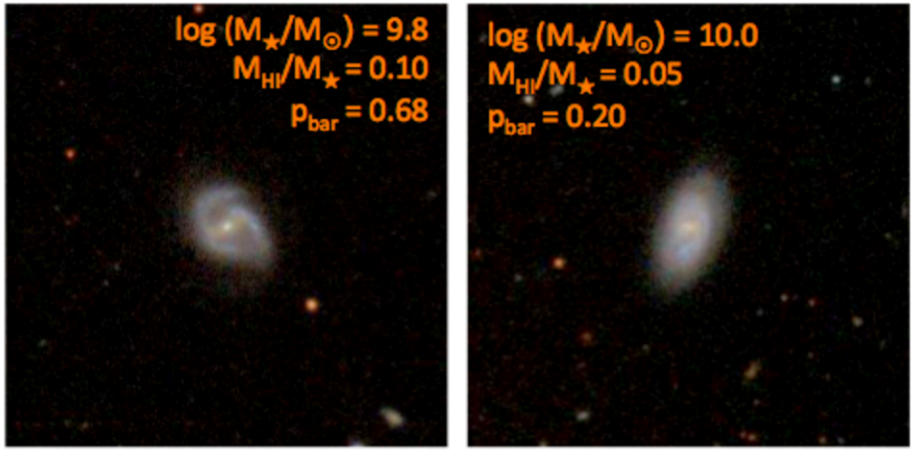
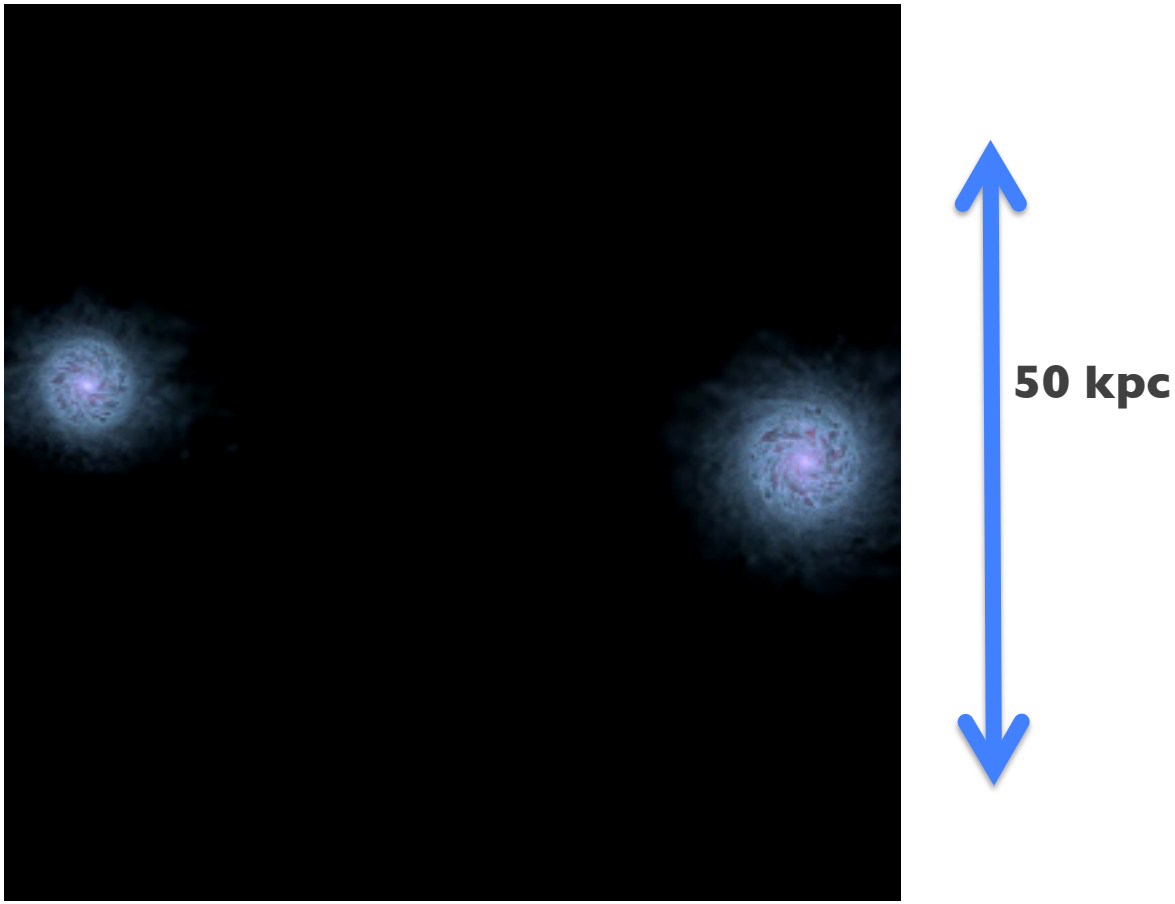
High-z and small galaxies: gas is important



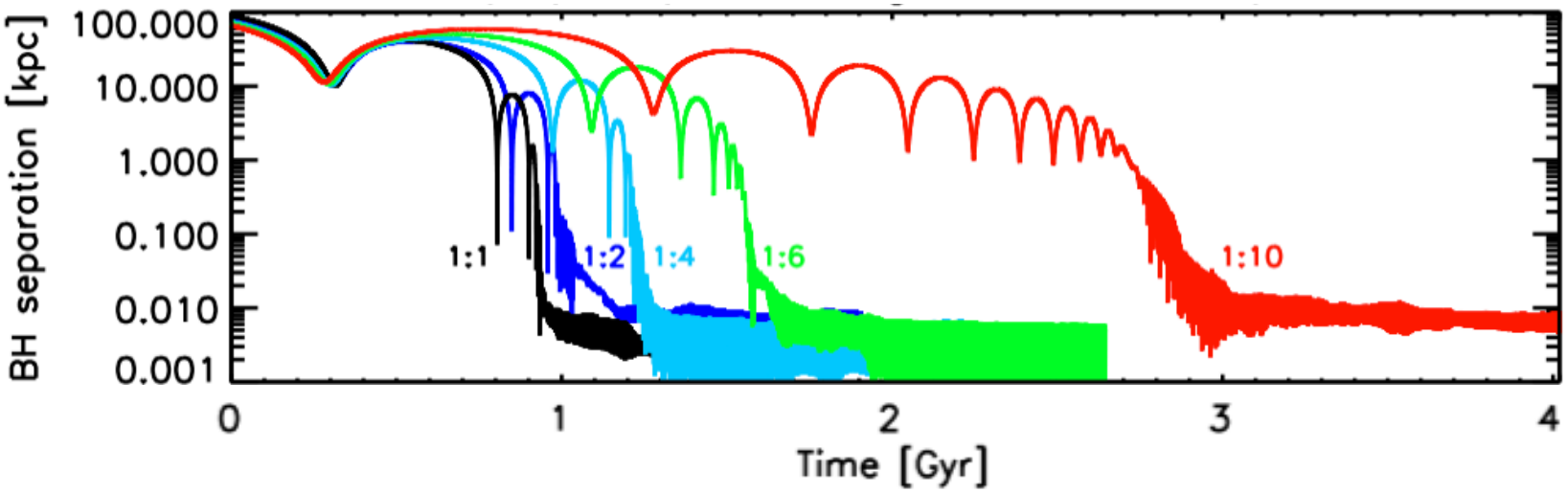
Galaxy scales: 100 kpc → 1 pc



Galaxy scales: 100 kpc→1 pc

- Galaxy merger simulations with idealized initial conditions, resolution ~1-10 pc

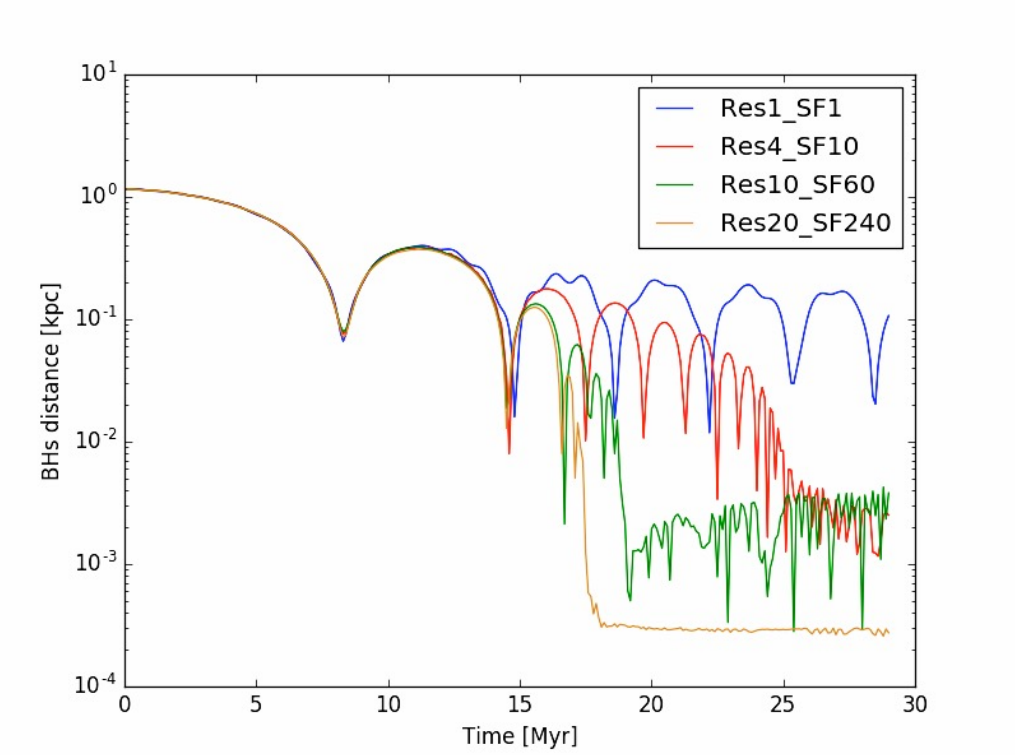
- When the mass ratio of the merging galaxies is >0.1 the two MBHs "find each other", in ***a few Gyr***



(e.g., Yu 2002, Callegari+2009, 2011; Van Wassenhove+2012; Van Wassenhove+14, Capelo+15, Roskar+15)

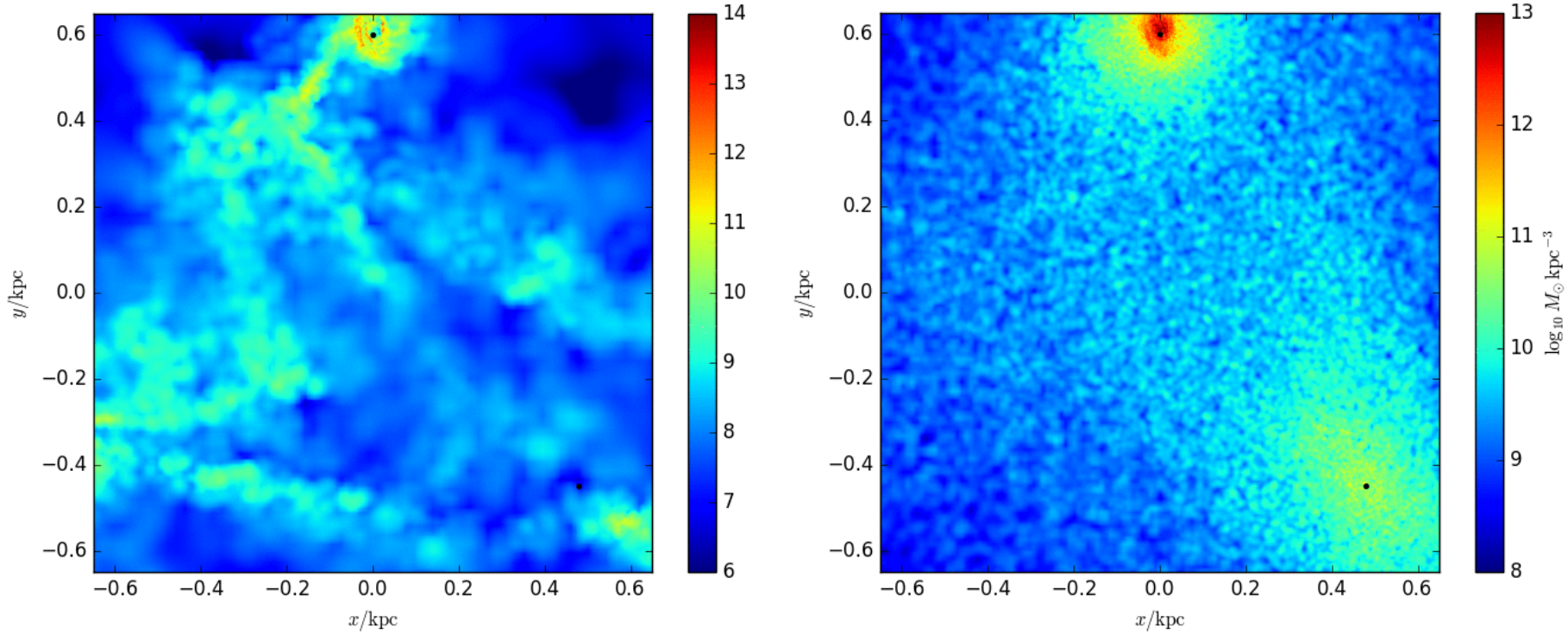
Galaxy scales: 100 kpc→1 pc

- When the separation of the MBHs reach the minimum resolution of the simulation cannot follow dynamics anymore → controlled re-simulations



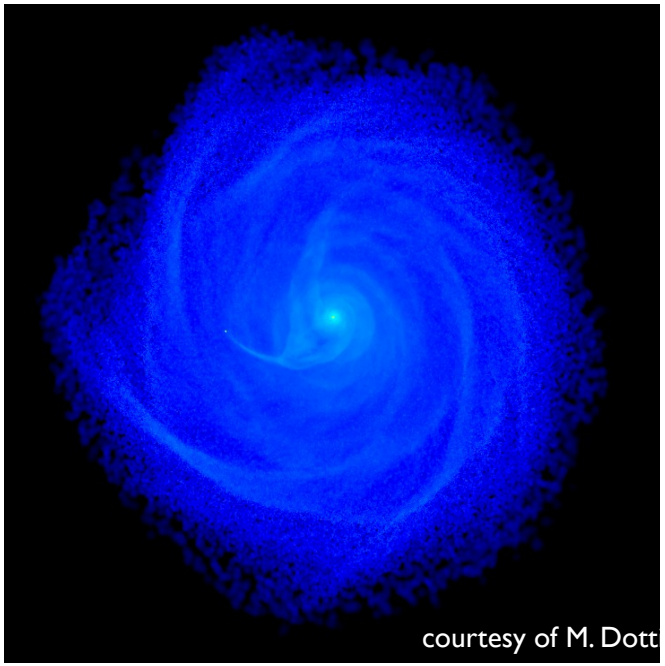
Res1=10 pc resolution
Res4=2.5 pc resolution
Res10=1 pc resolution
Res20=0.5 pc resolution

(e.g., Mayer+2007; Khan+12; Pfister+inprep)


0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
y/kpc
−0.6
−0.4
−0.2
0.0
0.2
0.4
0.6
x/kpc
14
13
12
11
10
9
8
7
6
log10 M⊙ kpc−3

Circumnuclear/binary disc: 0.1kpc→0.01 pc

- When the separation of the MBHs reach the minimum resolution of the simulation cannot follow dynamics anymore → idealized circumnuclear/binary disc simulations

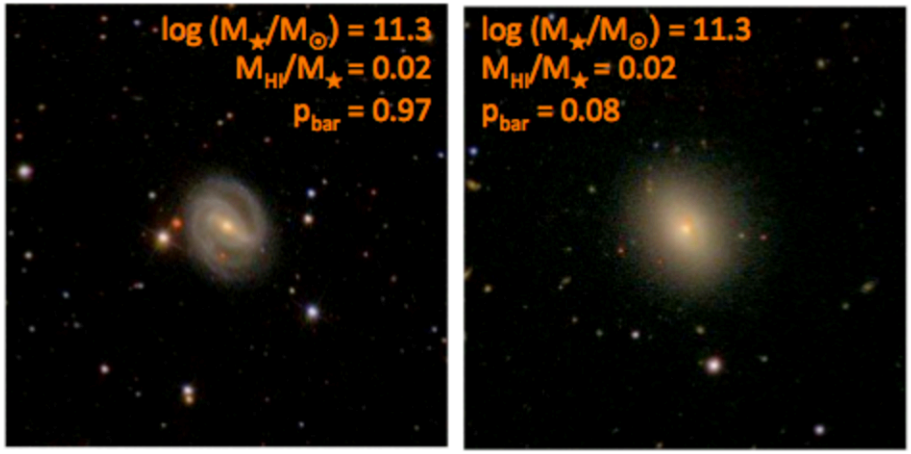


0.1 kpc

- Within ***1-100 Myr*** MBHs reach resolution limit
- Migration to the GW-dominated regime should occur rapidly, ***~1-10 Myr***

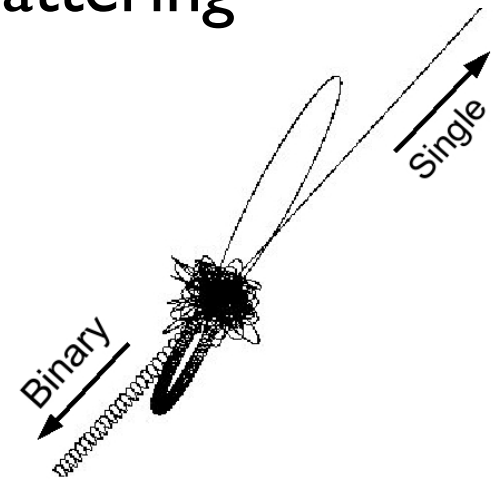
e.g., Armitage & Natarajan 2005; MacFayden & Milosavljevic 2008; Dotti+09; Roedig+2012; Shi+12; Noble+12; D'Orazio et al. 2013; Fiacconi+13, Amaro-Seoane+13; Farris et al. 2014; del Valle+15, Lupi+15; Shi & Krolik 2015…

Low-z and large galaxies: star-dominated



Collisionless evolution

- Initially dynamical friction
- When separation <~pc scale, 3-body scattering dominate



- The evolution of binaries continues at ~constant rate leading to merger in less than ***~1 Gyr***

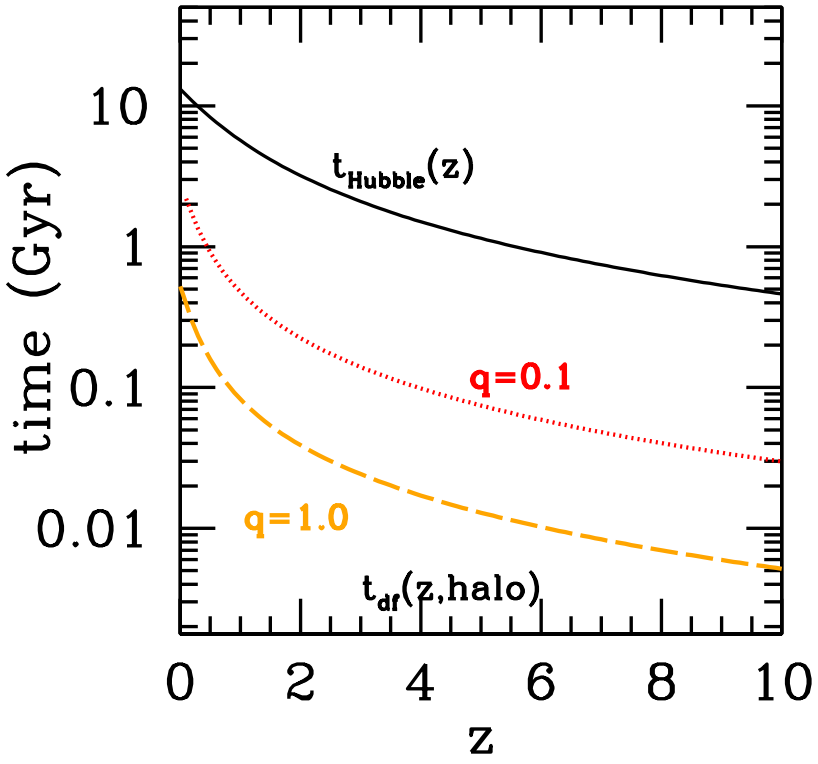
e.g., Gualandris & Merritt 2012, Vasiliev+14, Khan+12, Holley-Bockelmann and Khan 2015; Vasiliev et al. 2015; Sesana and Khan 2015

How long does this all take?

brief review: MV, Bogdanovic, Dotti, Colpi 2015

How long does this all take?

- First, halos and galaxies merge.



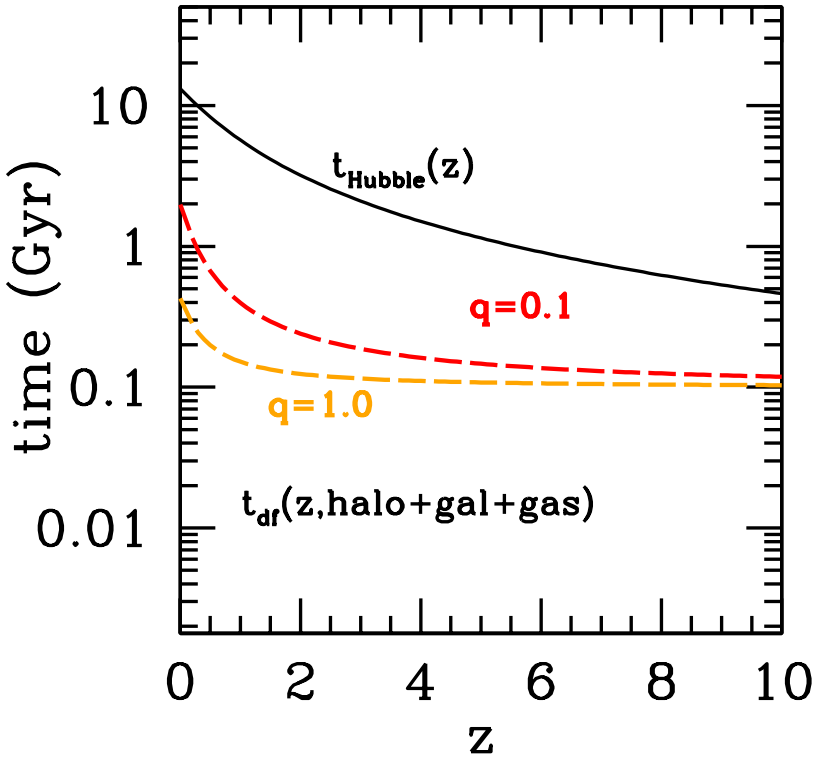
~ Gyr at low-z

$0 \leq q \leq 1$: mass ratio

DF timescale from Boylan-Kolchin+08

Gas dominated mergers

- Then, black holes.



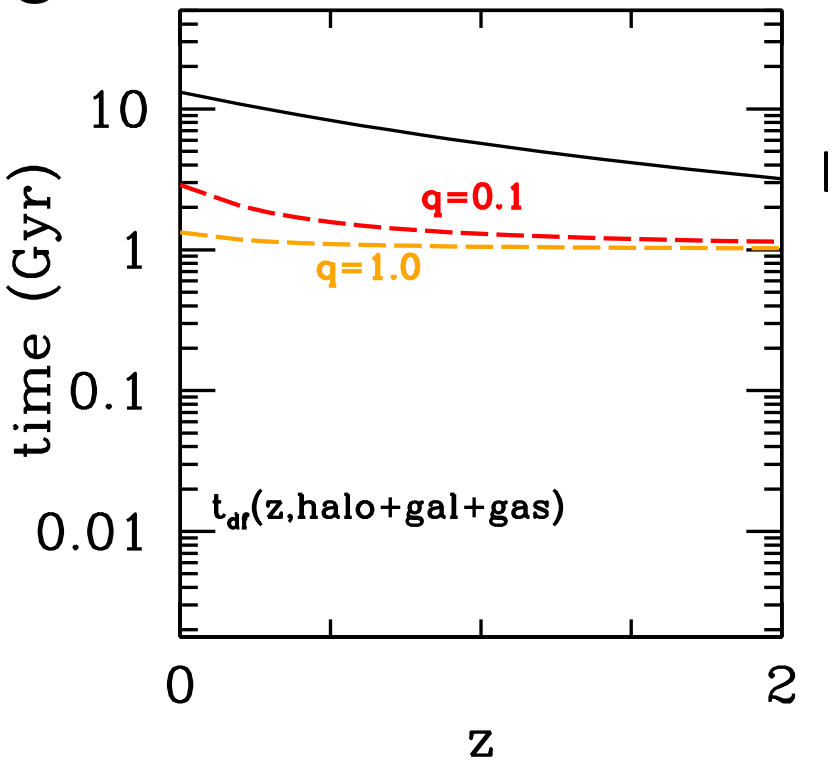
in TOTAL
> Gyr at low-z

0≤q≤1 : mass ratio

DF timescales from
Boylan-Kolchin+08
+ 100 Myr (nuclear/binary disc evolution)

Star-dominated mergers

- Halos, galaxies, black holes

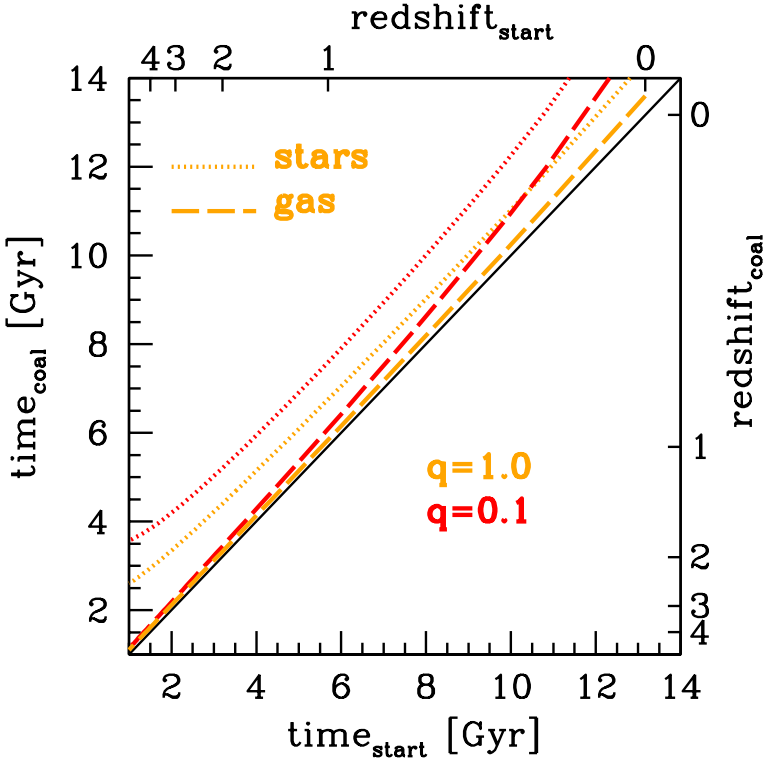


in TOTAL
> Gyr at all z

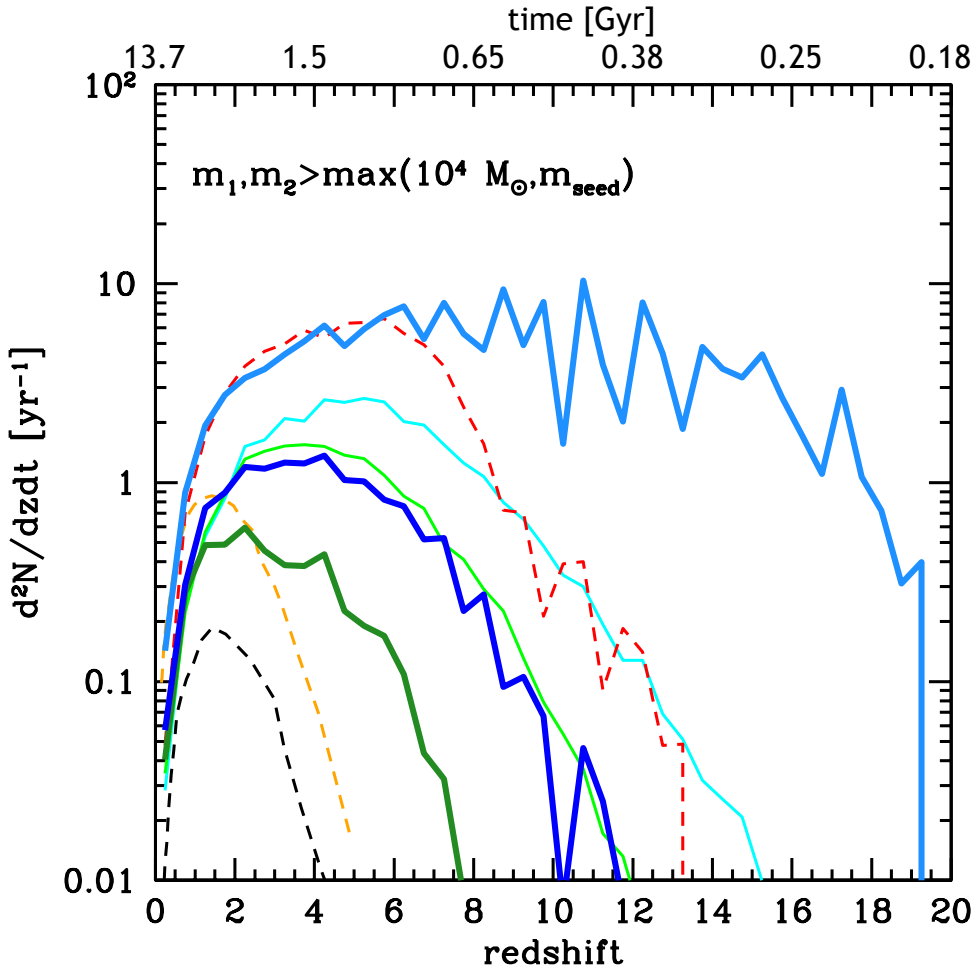
0≤q≤1 : mass ratio

Timescales from
Boylan-Kolchin+08
+
McWilliams+14
+
Sesana & Khan 15

Star-dominated mergers



eLISA pseudo merger rate



SAMs:

Barausse+ (Mh>10^5-10^6 Msun)

MV, Sesana+ (Mh>10^5-10^6 Msun)

cyan, light blue, blue: large BH seeds

light green, dark green: small BH seeds

SIMs:

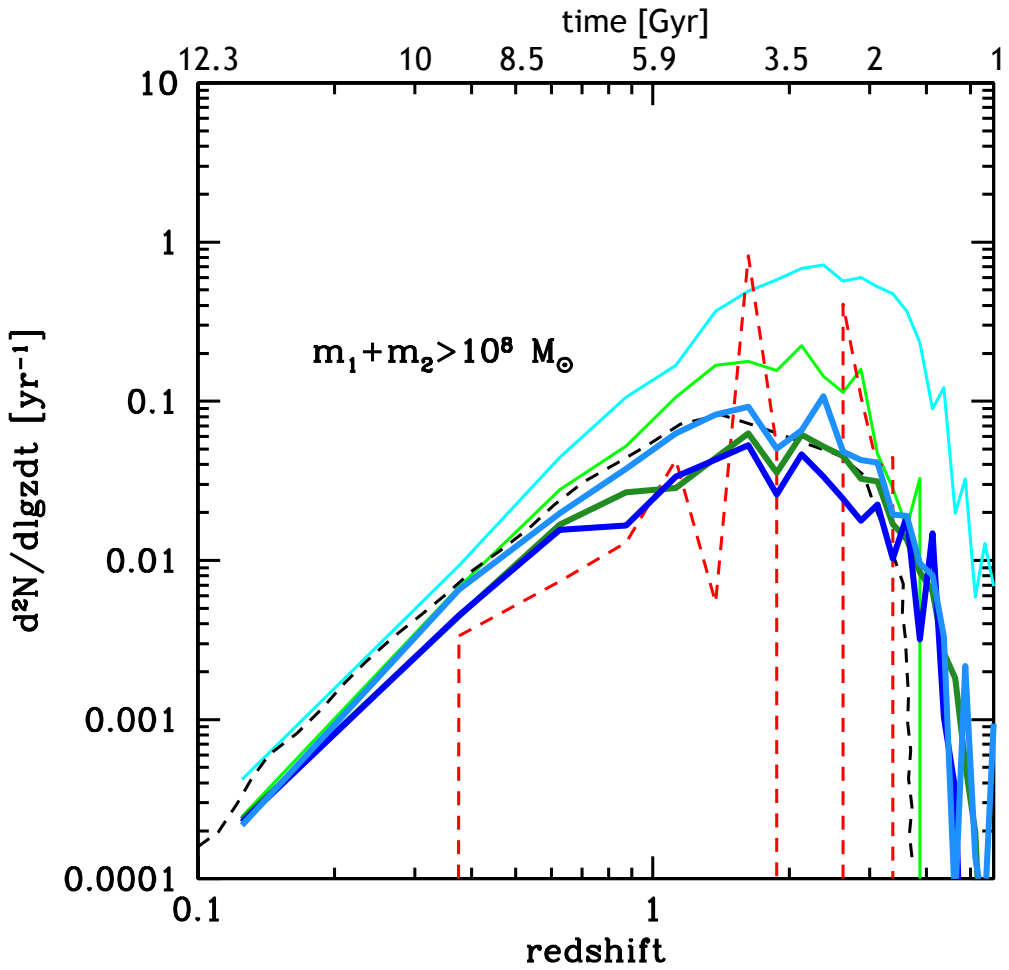
Salcido+ (Eagle, Mh>1.4e10 Msun)

Blecha+ (Illustris, Mh>1.4e11 Msun)

Tremmel+ (Romulus, Mh>3.5e8 Msun)

Number of mergers per year: between 1 and 80

PTA pseudo merger rate



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SIMs:
Blecha+ (Illustris, Mh>1.4e11 Msun)
Tremmel+ (Romulus, Mh>3.5e8 Msun)

Number of mergers per year: between 0.03 and 0.09

Summary

- MBHs in merging galaxies have along journey
- Beginning to end, it takes between 1 and 10 Gyr
- Caveat: multi-scale problem, most studies are highly idealized and not connected self-consistently to the previous "level"
- Full "merger rate" predictions still have large uncertainties – be careful when you pick a merger rate!