Massive black holes and gravitational waves

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Cosmic microwave background anisotropies: Has a gravitational wave background been observed?

Alexandre Dolgov and Joseph Silk

Phys. Rev. D **47**, 2619 – Published 15 March 1993

ABSTRACT

We show that in the scale-free chaotic inflationary scenario with the inflaton potential $\frac{\lambda\varphi^4}{4}$, large-scale
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Mon. Not. R. Astron. Soc. **269,** 199–208 (1994)

Low-frequency gravitational waves from supermassive black holes

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Accepted 1994 March 1. Received 1993 October 7

ABSTRACT

Supermassive black holes are investigated as pos
bursts of gravitational waves. The event rate for 'kn
intermediate and high redshifts, inferred from the q
$\sim 0.1\ \mathrm{yr}^{-1}$. A number density of gravitational wave
the number density of galaxies inferred from faint ga
the event rate significantly above one per year. A s
therefore only see several events per year from
additional population of supermassive black holes
waves efficiently. These might reside in the popul
transient population of small dark-matter haloes tha
into larger haloes hosting the galaxies seen today
cosmogony. In the latter case, event rates could be c
due to coalescing supermassive-black-hole binari
process. Event rates could be as high as a few per se
haloes consisted of supermassive black holes in th
produced gravitational waves efficiently. The pro
wave interferometer *LISA*/*SAGITTARIUS* should
events involving supermassive black holes above 10^4

Mon. Not. R. Astron. Soc. **354,** 629–640 (2004) doi:10.1111/j.1365-2966.2004.08227.x

Massive black hole remnants of the first stars – III. Observational signatures from the past

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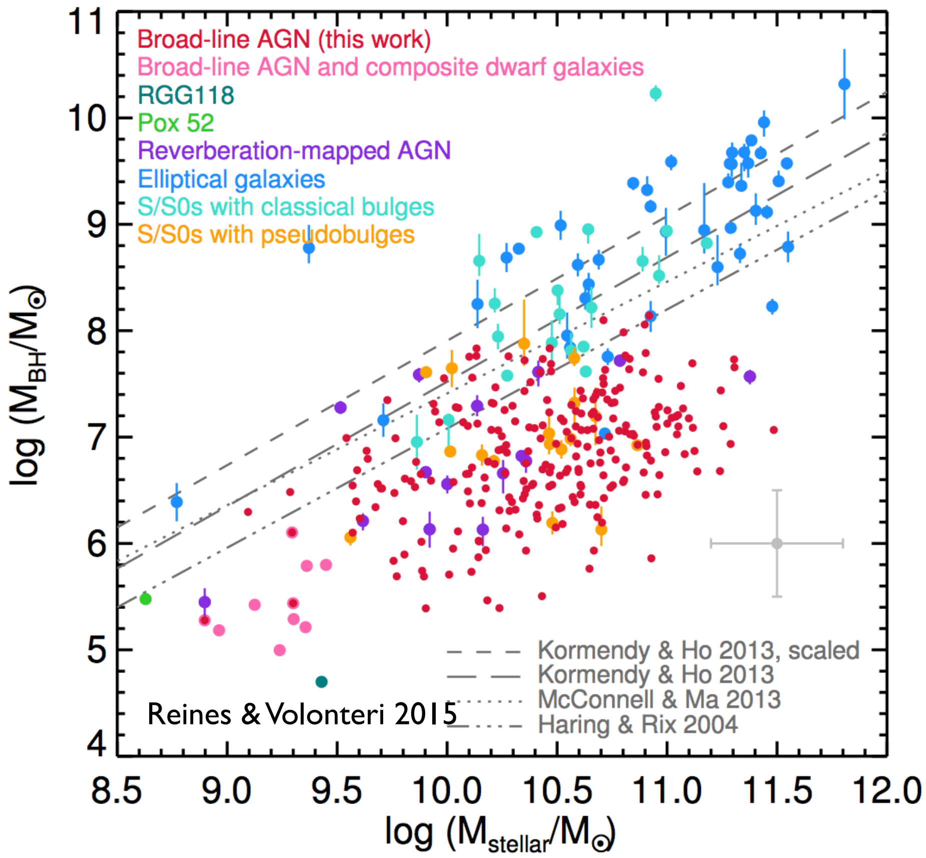
ABSTRACT

The first stars forming in minihaloes at redshifts $z > 20$ may have been very massive and could have left behind massive black hole (MBH) remnants. In previous papers we investigated the hierarchical merging of these 'seed' MBHs and their associated haloes, using a semi-analytical approach consisting of a hierarchical merger tree algorithm and explicit prescriptions for the dynamics of merged substructure inside a larger host halo following a merger. We also estimated accretion luminosities for these MBHs and found them to be consistent with observations of ultraluminous X-ray point sources. Here we compute the strength of gravitational wave events as MBHs merge to form the more massive black holes that we predict reside in galaxy haloes today. If MBHs merge efficiently, we predict that as many as 10^4–10^5 events per year may fall within the sensitivity limits of the proposed *Laser Interferometer Space Antenna* gravitational wave observatory. The collapse of the first massive stars to form MBHs may also be accompanied by gamma-ray bursts (GRBs). If this is the case and if GRBs are observable out to the redshifts of first star formation, we predict that about 10^5–10^6 GRBs per year could be detected. As merging MBH binaries reach their last stable orbits before final coalescence, a fraction of the gravitational wave energy may be released as a pulse of gamma-rays (for instance, through interaction with material enveloping a merging MBH binary). This fraction has to be larger than about 10^{-2} for MBH mergers to account for some beamed GRBs, and greater than 10^{-6} for the gamma-rays to be detectable out to cosmological distances with upcoming GRB detector missions.

Massive black holes in galaxies

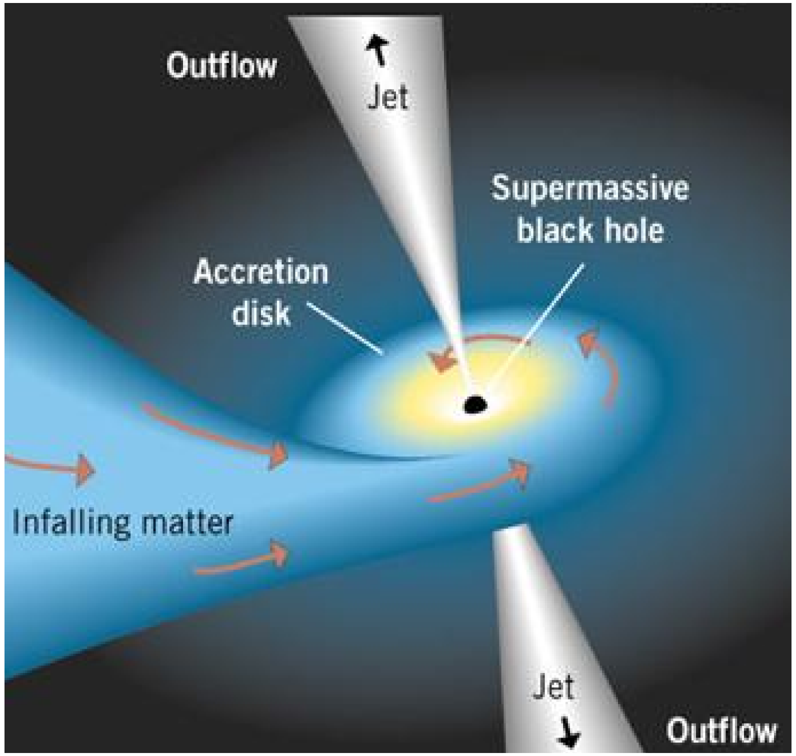


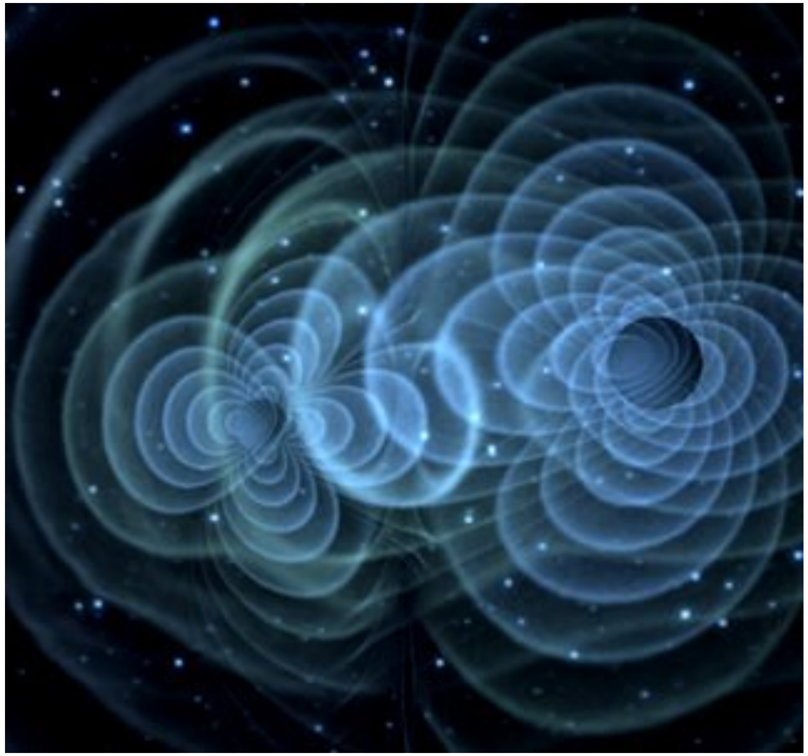
~100 MBHs detected in nearby galaxies to-date

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

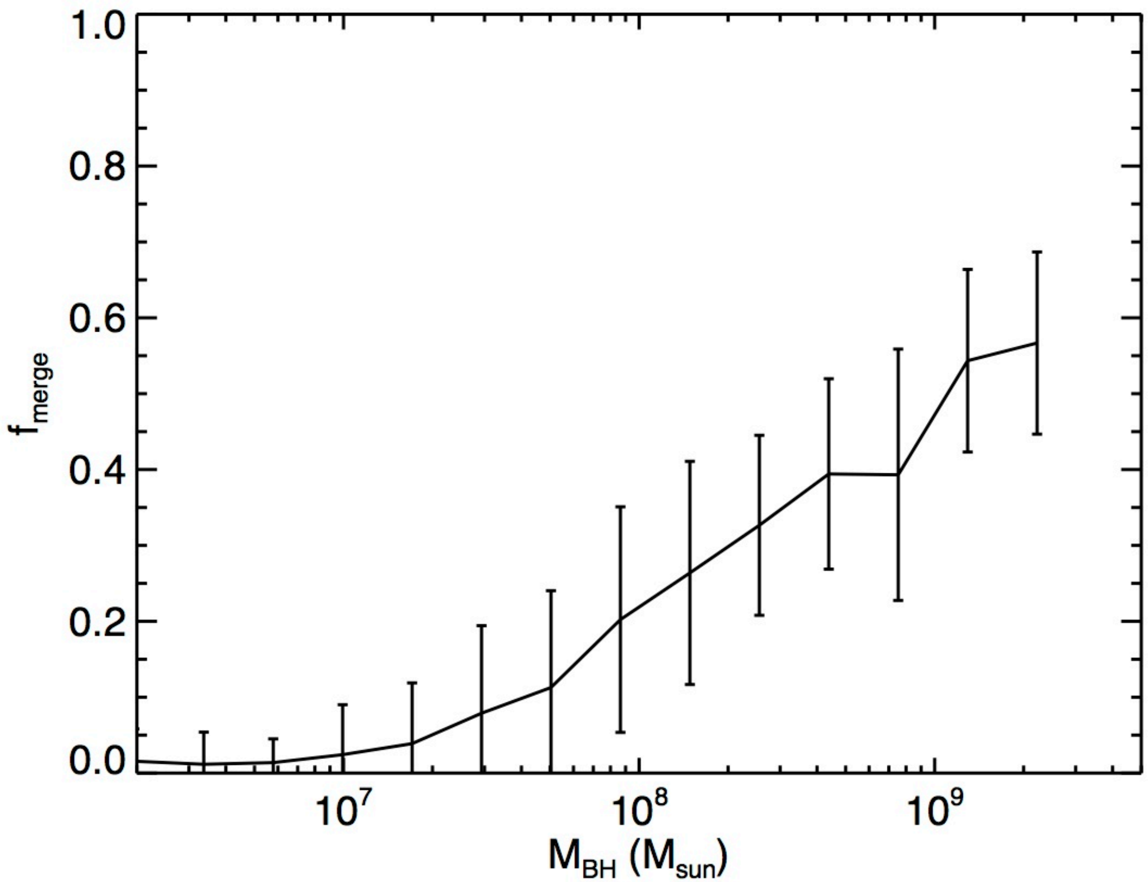
How do massive black holes grow ?

Gas accretion vs MBH-MBH mergers





Are MBH-MBH mergers important?



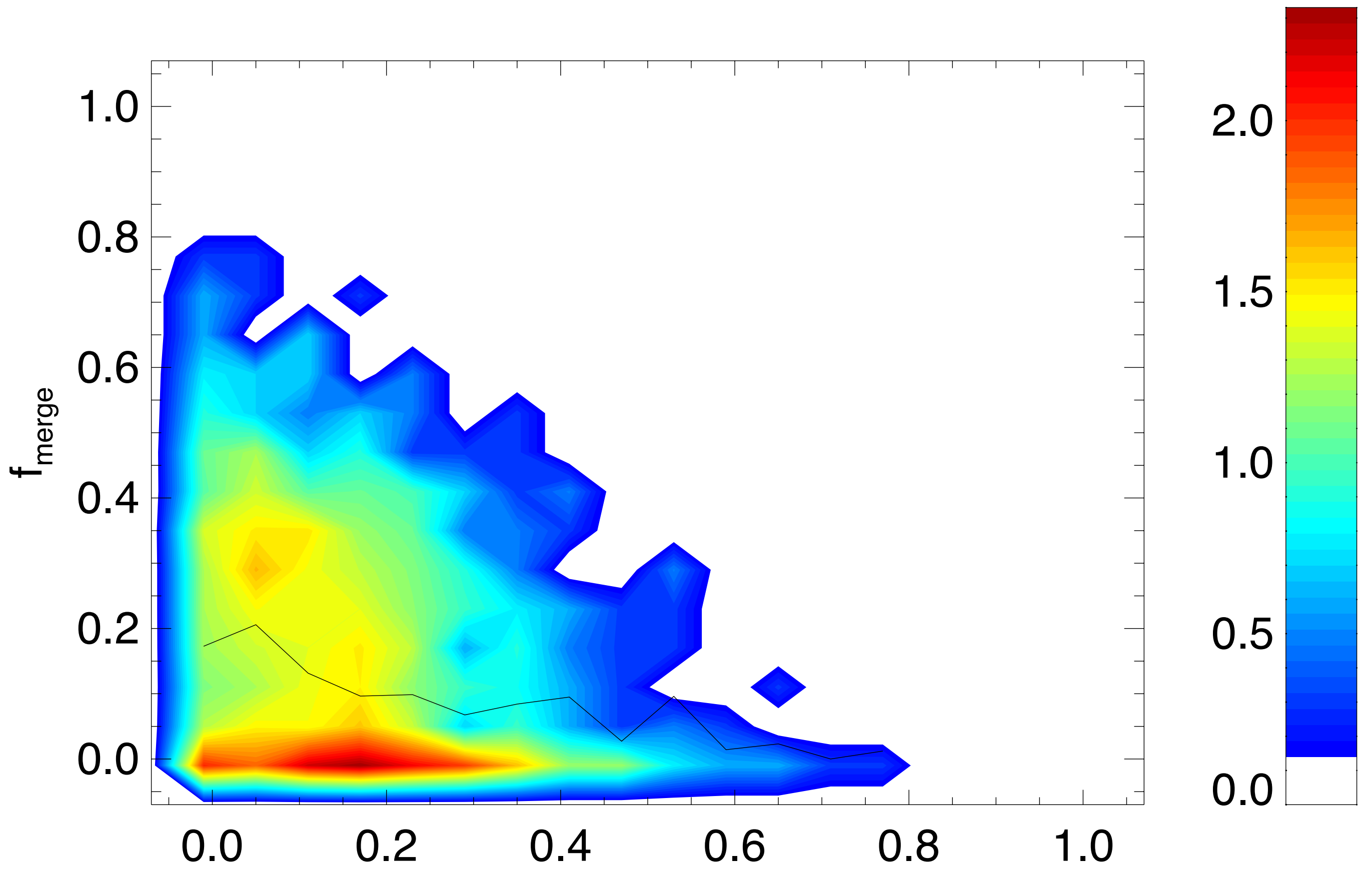
High-mass MBHs!

Fraction of mass gained through MBH-MBH mergers

$f_{merge}=\Delta M_{merge}/M_{BH}$
ΔMmerge is the sum of the masses of all merged MBHs and does not account for gas accretion on these MBHs

Dubois, Volonteri & Silk 2014

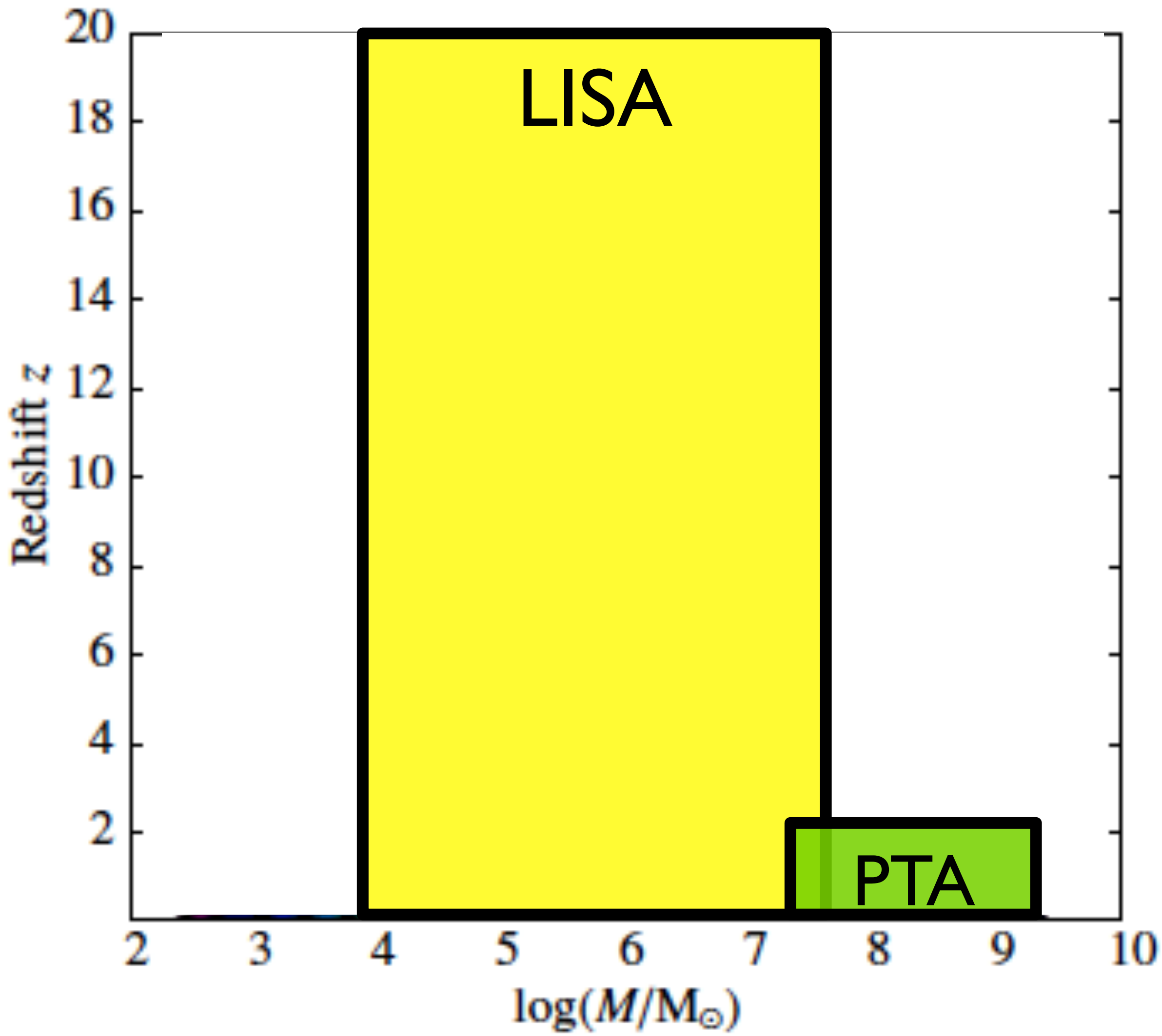
Are MBH-MBH mergers important?



Gas-poor galaxies!

Dubois, Volonteri & Silk 2014

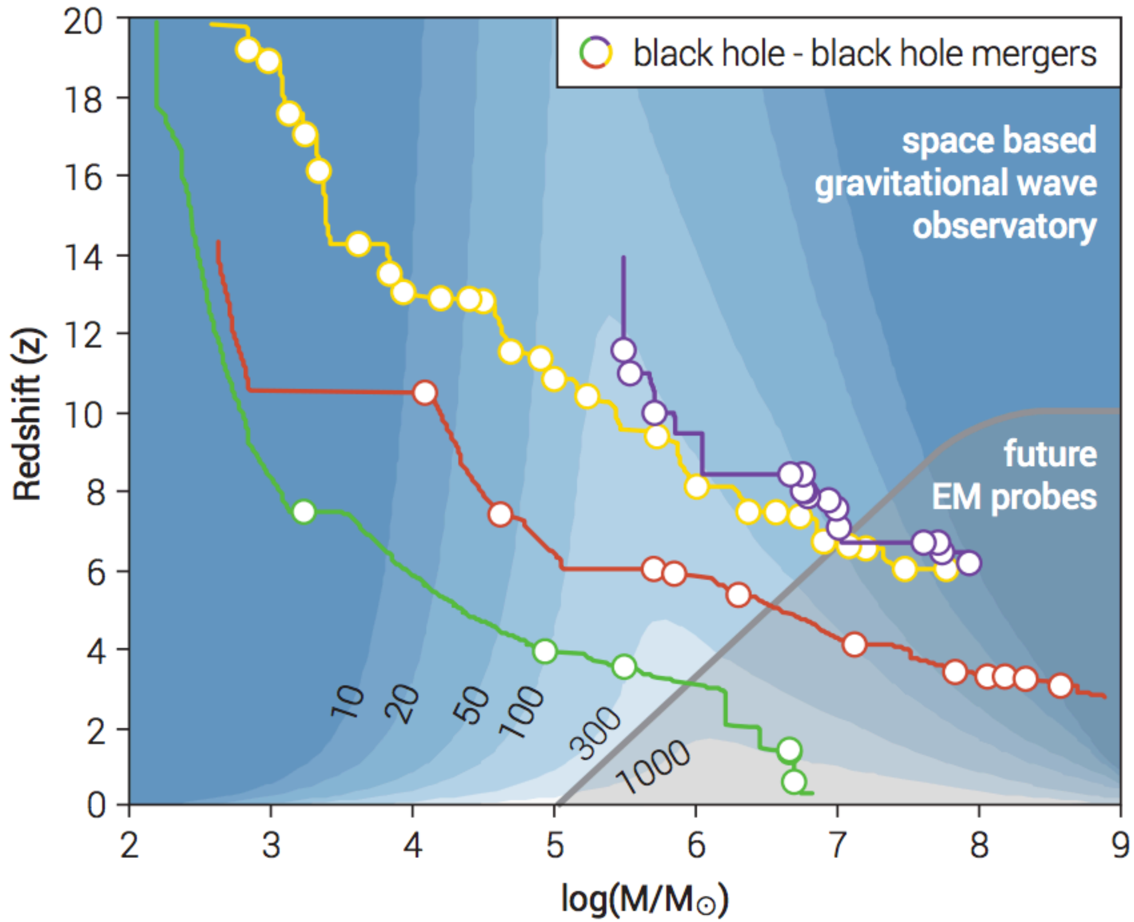
MBHs mergers and gravitational waves



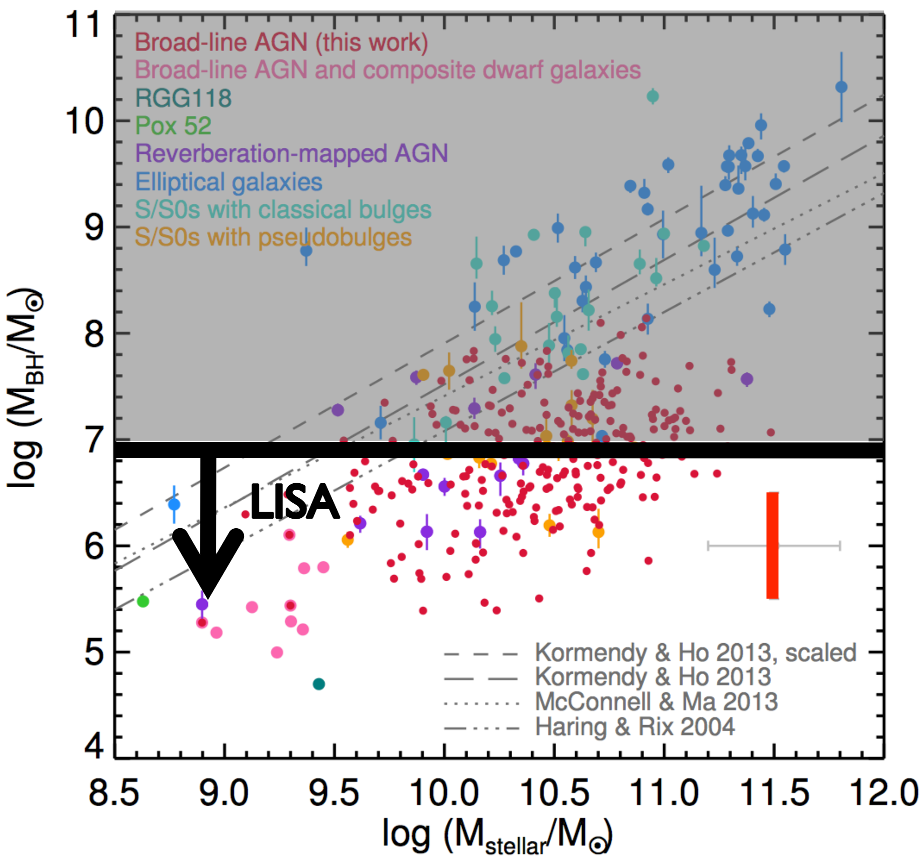
Massive black holes in galaxies

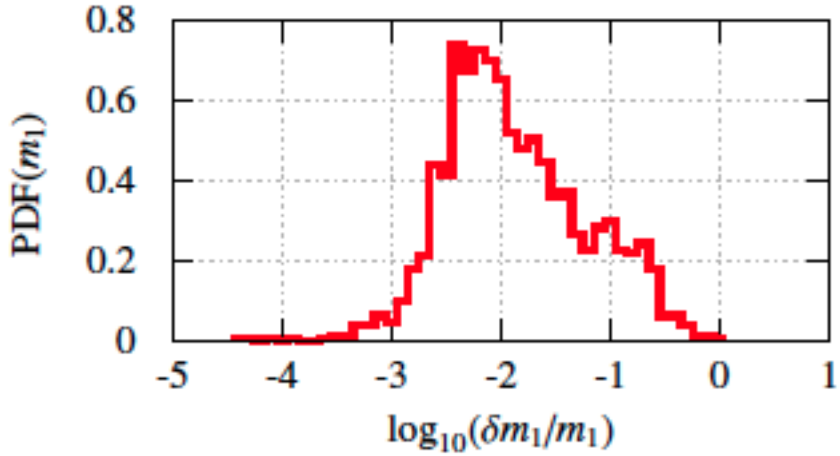
MBHs should grow along with galaxies through accretion and MBH-MBH mergers

Over time they sweep the LISA band, and if sufficiently massive, they become emitters for PTA experiments



What can GWs do for MBHs?





What can GWs do for MBHs?

What can we infer about the black hole population from the full set of events observed by LISA?

Use observed distribution of source parame models. Which model provides the better ex data?

With a two-year observation we have more probability that the parent model of an obse be safely identified at >95% confidence level

LISAPE taskforce, Arun et al. 2008
Sesana, Gair, Berti, MV 2011

MBH mergers and GWs

How many galaxies host MBHs

➔ when, where, how they form

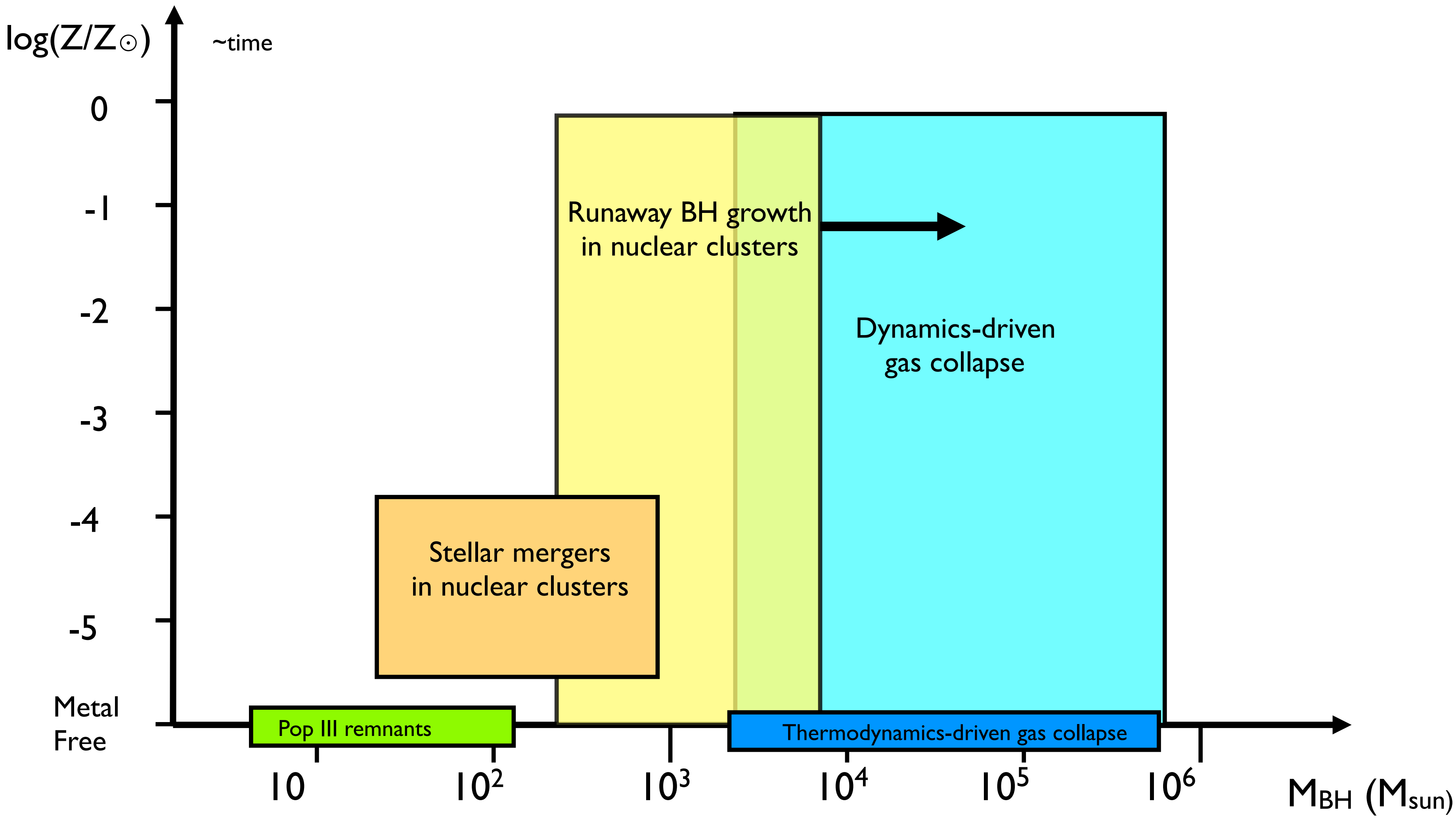
How long it takes for MBHs to merge in halo/galaxy merger

➔dynamics of MBHs in mergers

How MBHs grow in mass over time

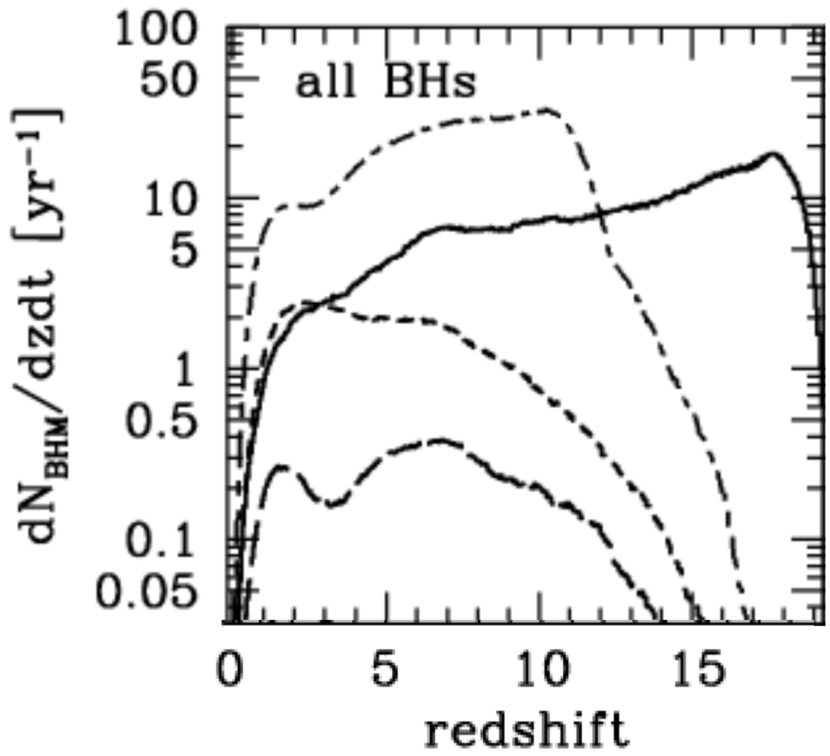
➔accretion vs MBH-MBH mergers

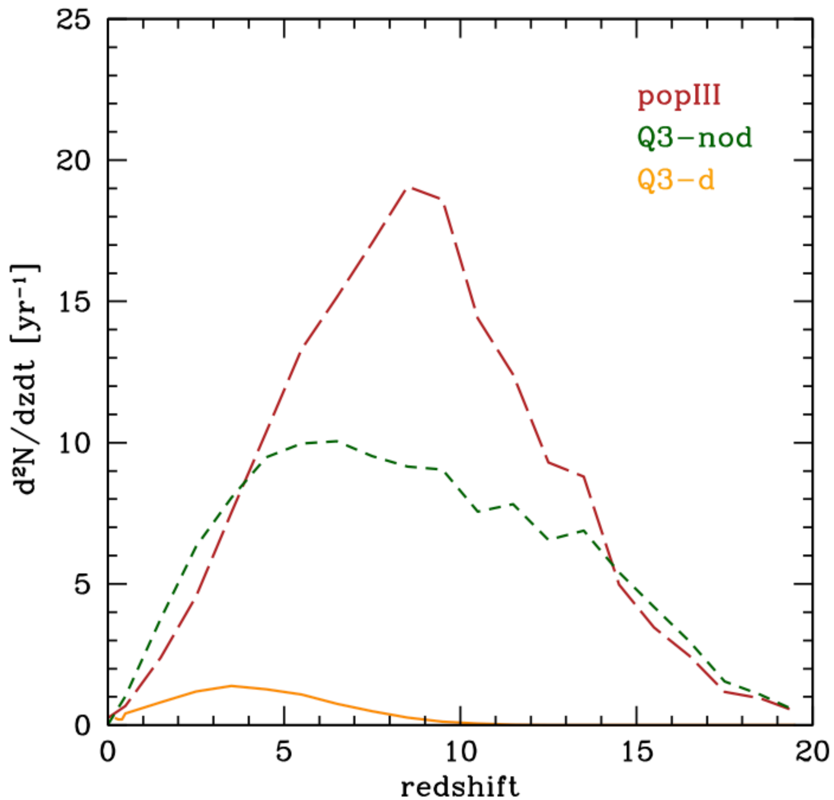
MBH formation



Common ⟶ Rare

MBH formation





Sesana+07

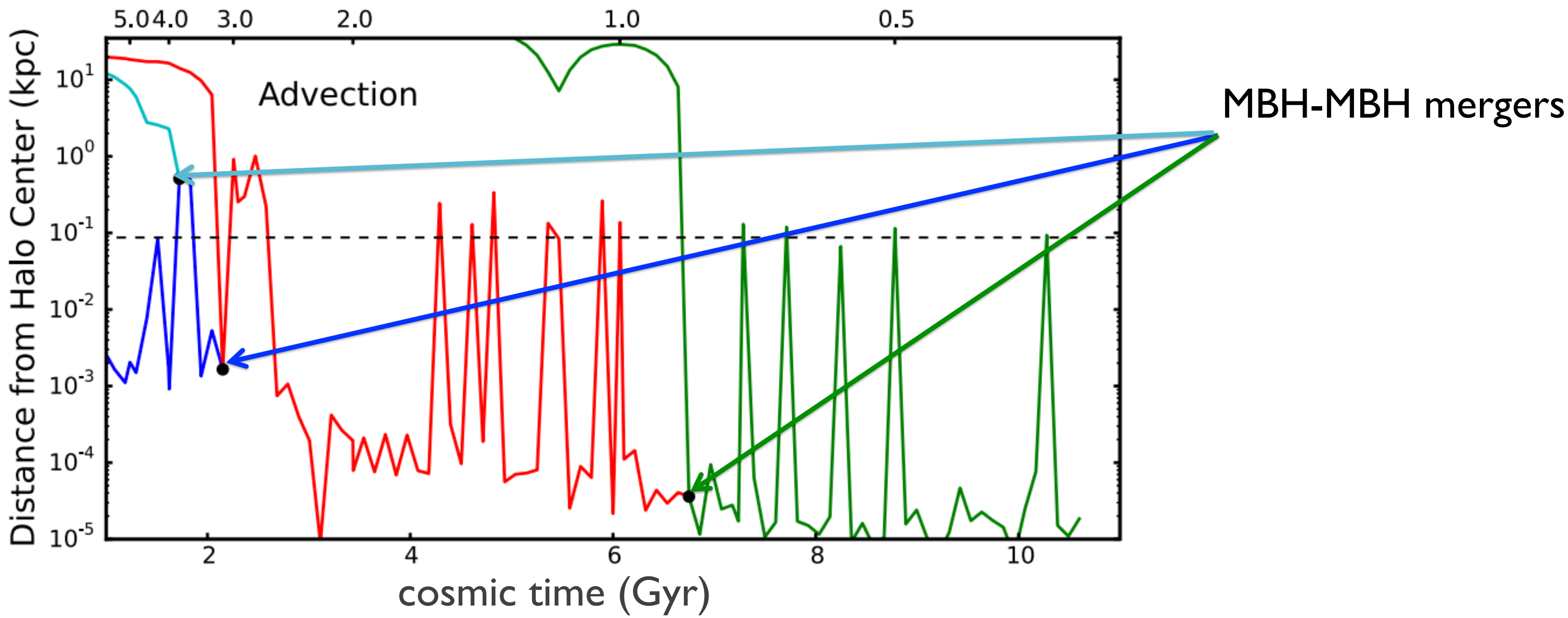
Klein+16

MBH dynamics

How long it takes for MBHs to merge in halo/galaxy mergers

How often mergers “fail”

MBH dynamics – galaxy scale

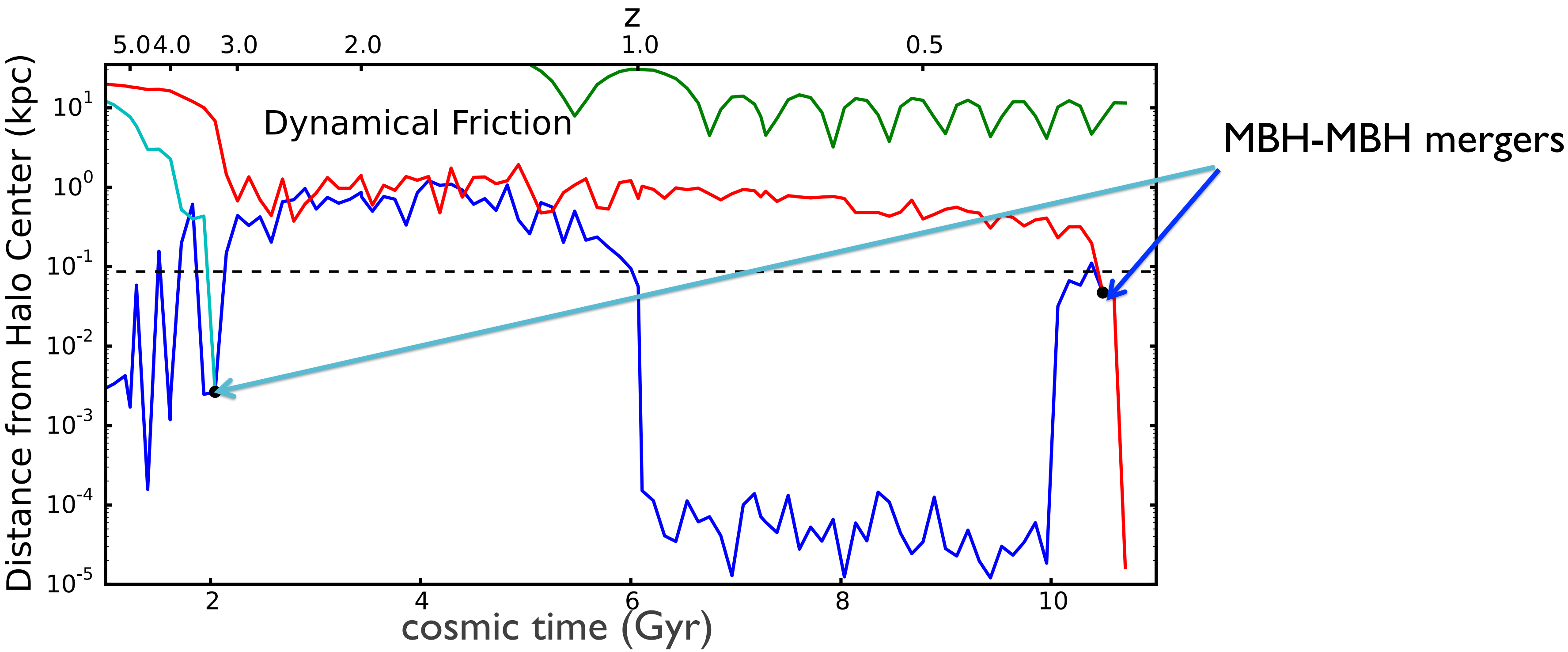


Cosmological ‘zoomed-in’ simulation of dwarf galaxy with mass ~ $10^{10}\,M_\odot$ at z = 0.

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

Tremmel+ 2015

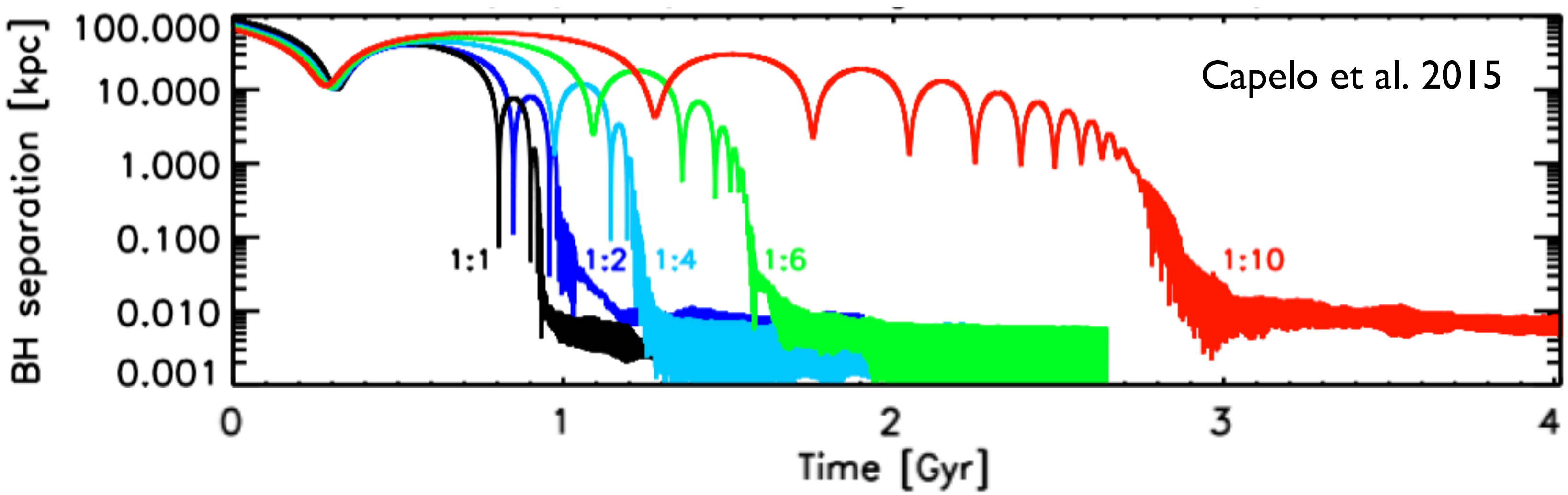
MBH dynamics – galaxy scale



It can take up to a few Gyr for two MBHs to reach ~10-100 pc separation from beginning of halo merger

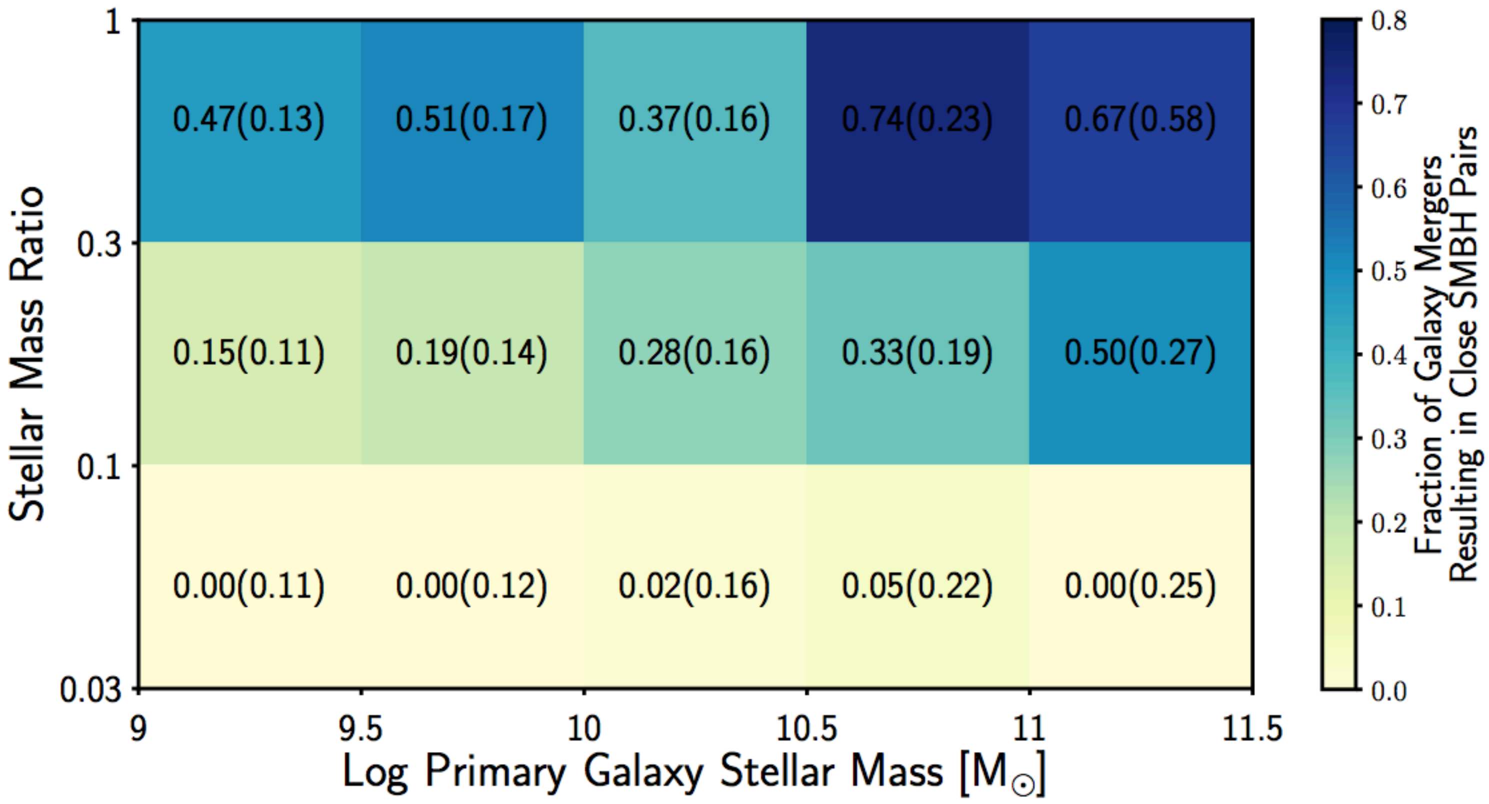
MBH dynamics – galaxy scale

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



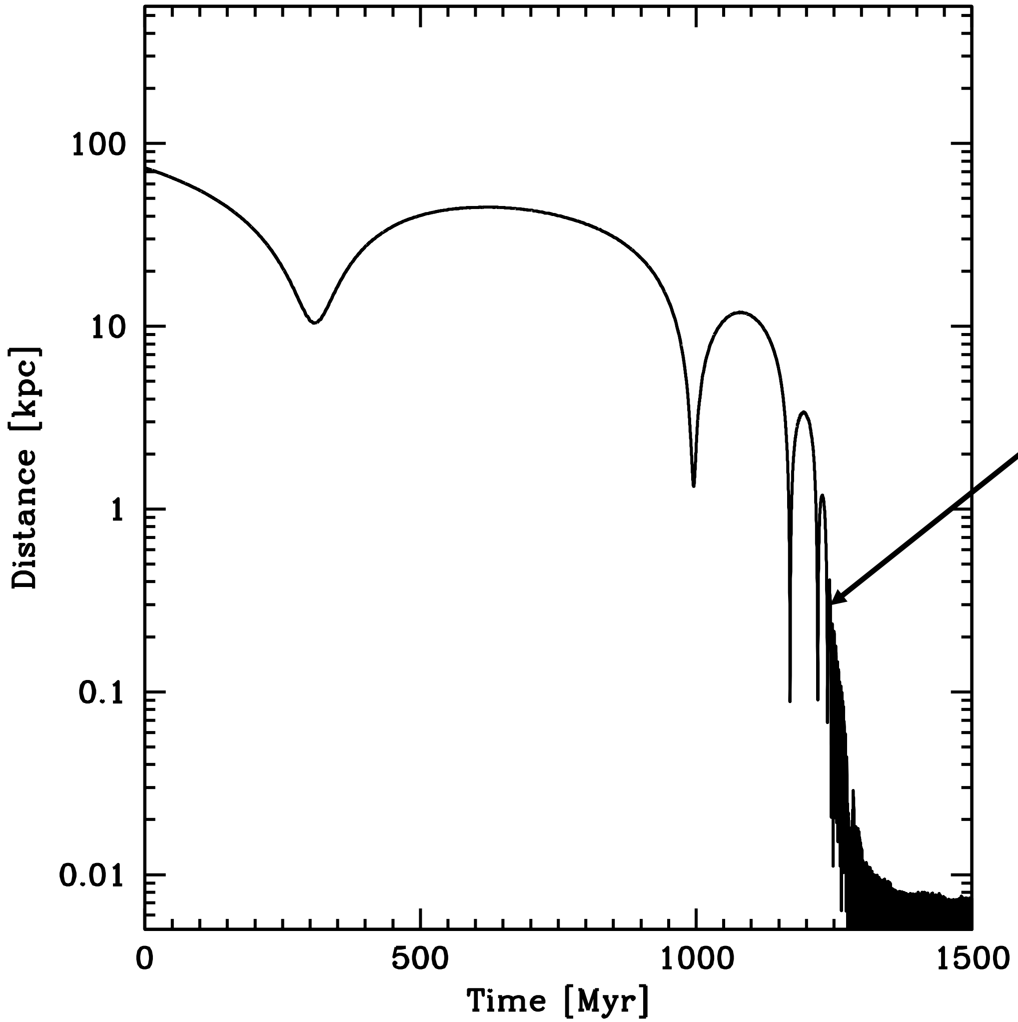
(e.g., Yu 2002, Callegari+2009, 2011; Van Wassenhove+2012,2014, Capelo+15, Roskar+15)

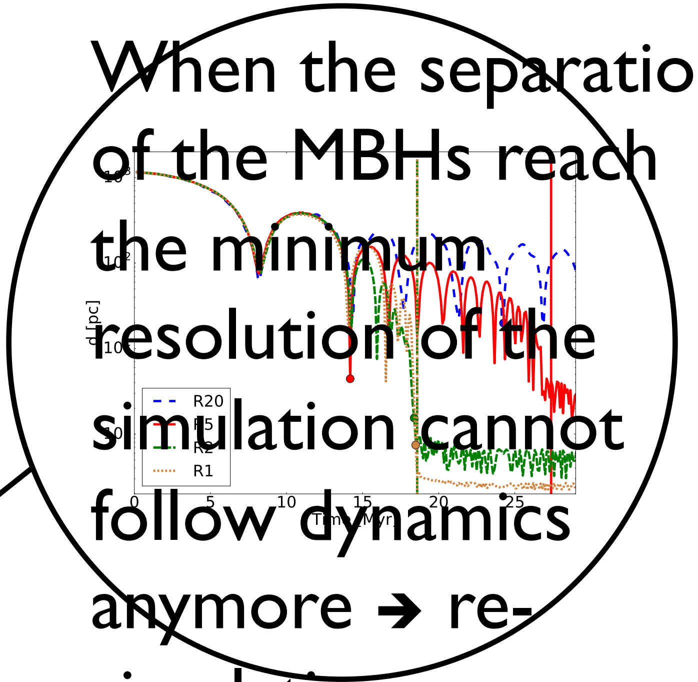
MBH dynamics – galaxy scale



Tremmel+ 2017

MBH dynamics – nuclear scale

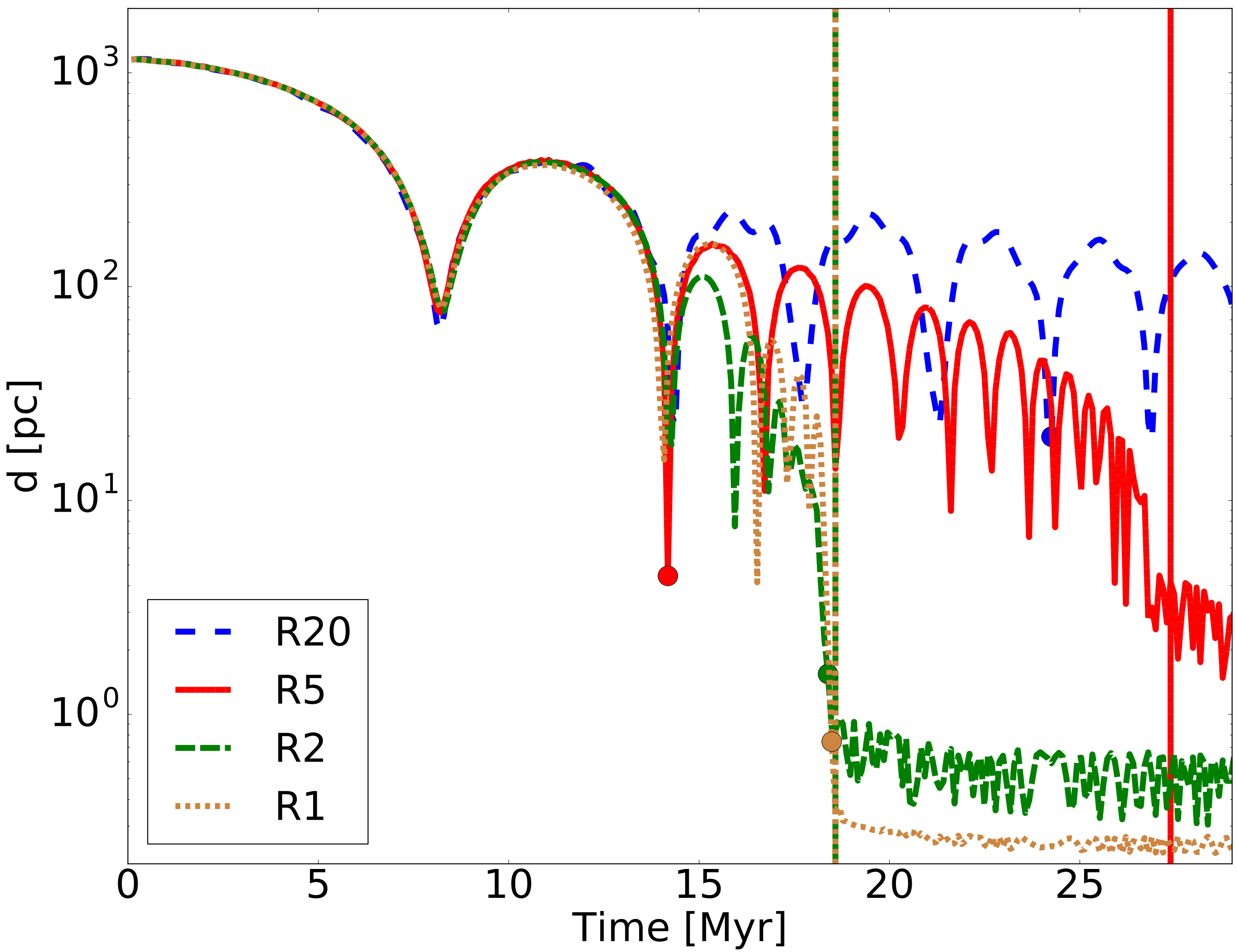




When the separation of the MBHs reach the minimum resolution of the simulation cannot follow dynamics anymore ➔ re-simulations

(e.g., Mayer+2007; Khan+12; Pfister+17)

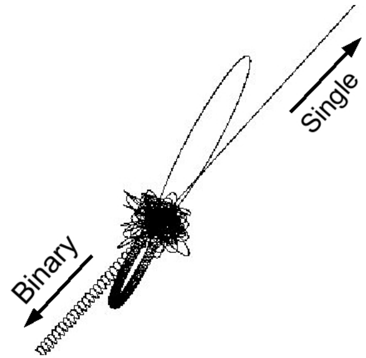
For numerical simulations to capture the formation of the binary, dynamical friction must be well resolved, meaning that the *spatial resolution must be comparable to the influence radius*!



R20=20 pc resolution
R5=5pc resolution
R2=2 pc resolution
R1=1 pc resolution

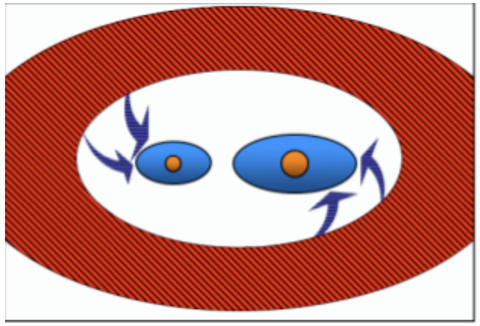
(Pfister+17)

Final step: 1→0.01 pc



In a stellar-dominated environment: 3-body scattering, bringing the MBH to GW regime in ***~1 Gyr*** **.** The "last parsec problem", i.e. running out of low-angular momentum stars (Begelman, Blandford & Rees 1980) is less of a "problem" once triaxiality and rotation are taken into account (Berczik et al. 06; Gualandris+2012,17; Holley-Bockelmann and Khan 2015; Vasiliev et al. 2015; Sesana and Khan 2015 for recent results)

Final step: 1→0.01 pc

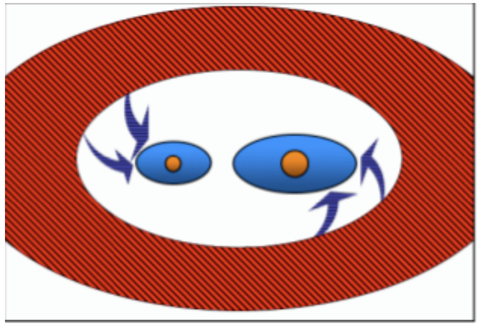


A binary clears a cavity in its surroundings due to the binary's tidal torques. The cavity does not prevent gas inflows and eventual accretion.

(e.g., Armitage & Natarajan 2005; MacFayden & Milosavljevic 2008; Dotti+09; Haiman+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…)

AGN feedback?

Final step: 1→0.01 pc

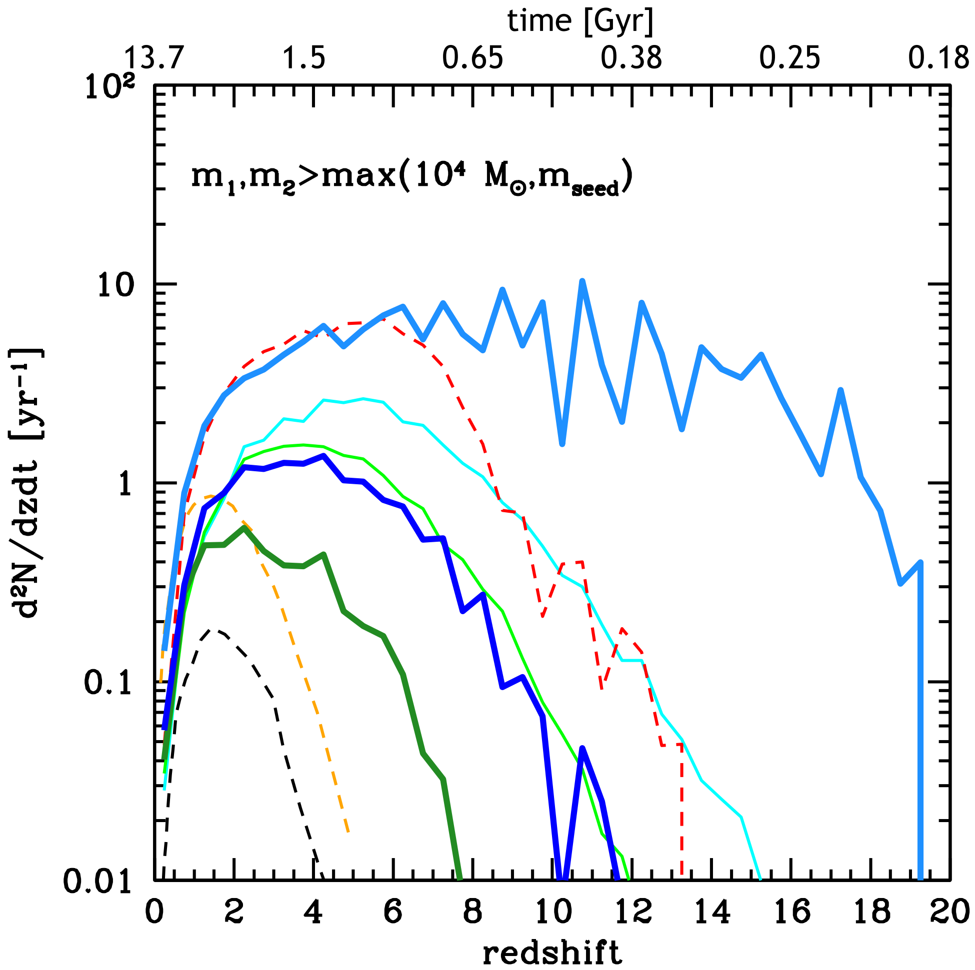


AGN feedback?

del Valle+

All together now!

LISA 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

Summary

MBHs in merging galaxies have along journey: beginning to end, it takes between 1 and 10 Gyr with large uncertainties

Full "merger rate" predictions still have large uncertainties – be careful when you pick a merger rate!

Turning this around, GWs are a unique way of probing MBH evolution

- Best and cleanest way to find the first MBHs!
- Will know about MBH dynamics!