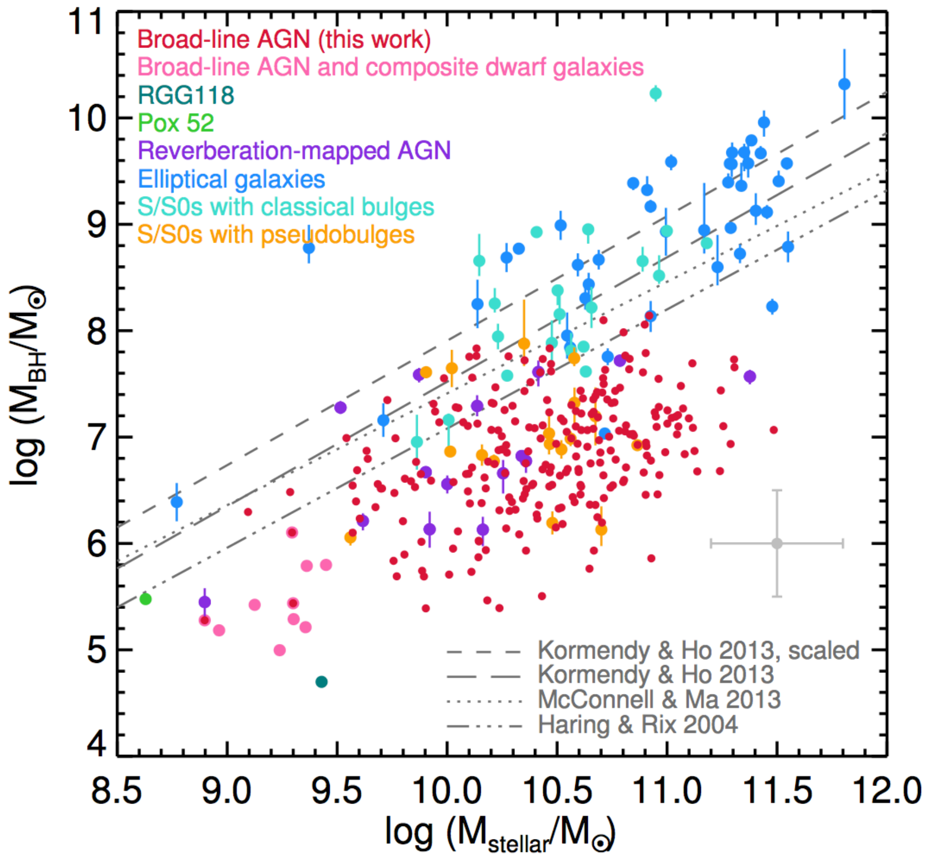
Massive black hole mergers in the Universe

Marta Volonteri
Institut d'Astrophysique de Paris

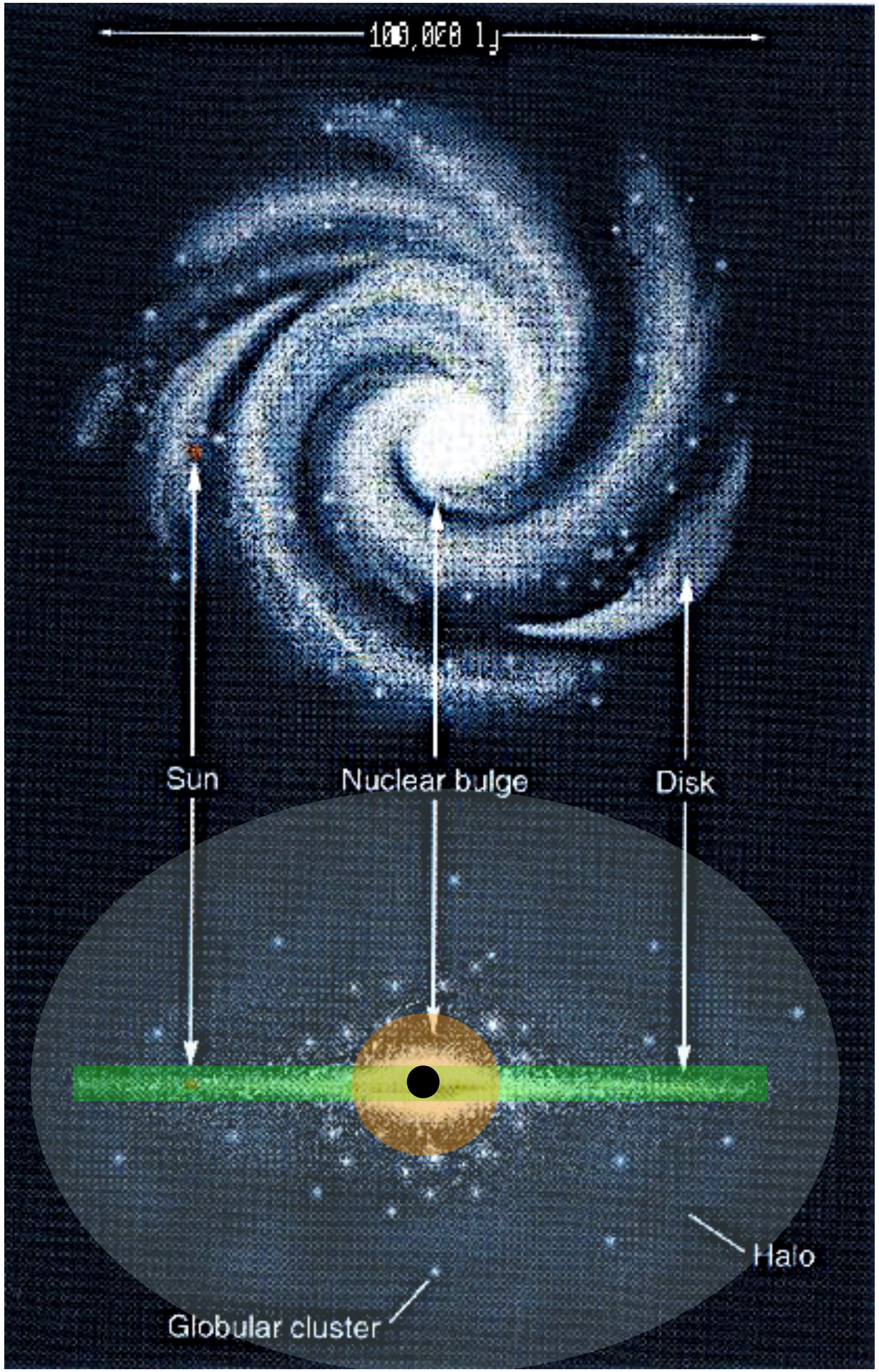
BLACK
erc
European Research Council
Established by the European Commission

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}



Galaxies

mass: 10^9-10^{12} M_{sun}

$R_{halo} \sim GM_{halo}/\sigma^2$ MEGAPARSEC

$R_{bulge} \sim GM_{bulge}/\sigma^2$ KILOPARSEC

1 parsec=3.26 light years=3×10^{18} cm
$\sigma \sim$50-400 km/s for most galaxies

Massive Black Holes

mass: 10^5-10^9 $M_{sun} \sim 10^{-3}$-10^{-4} M_{gal}

$R_{bondi} \sim GM_{BH}/c_s^2$ PARSEC

$R_{inf} \sim GM_{BH}/\sigma^2$ PARSEC

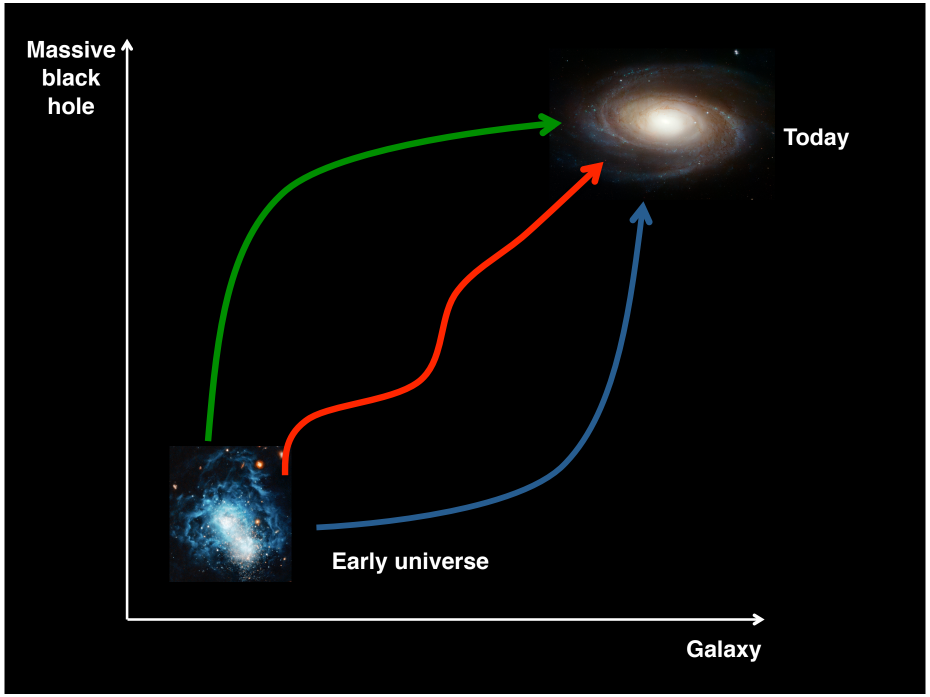
$R_{sch}=2GM_{BH}/c^2$ MICROPARSEC

$c_s \sim$10-100 km/s for most galaxies
$c=3 \times 10^5$ km/s

Massive black holes in galaxies

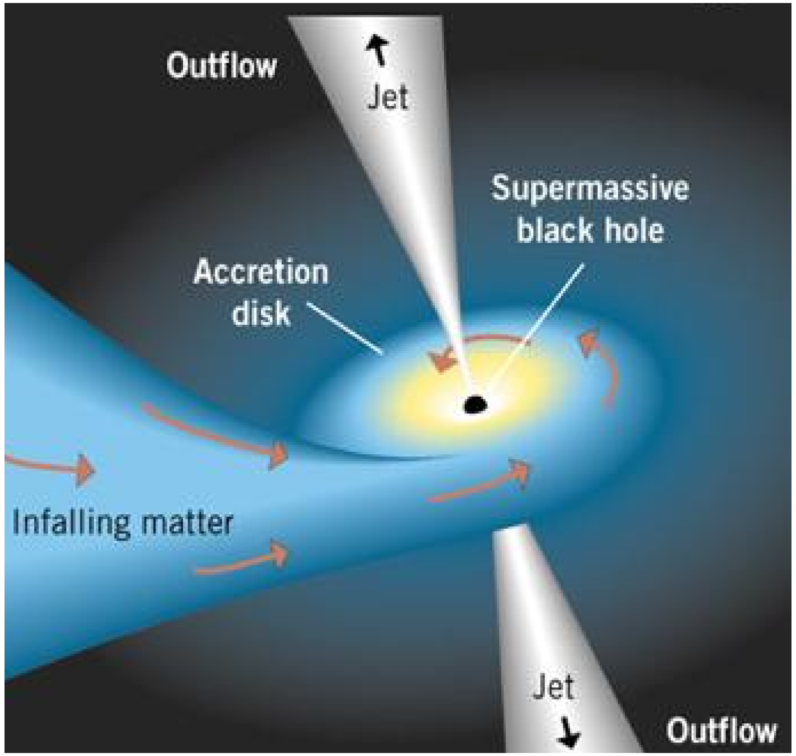
- Massive Black Holes (MBHs) are found in the centers of most nearby galaxies

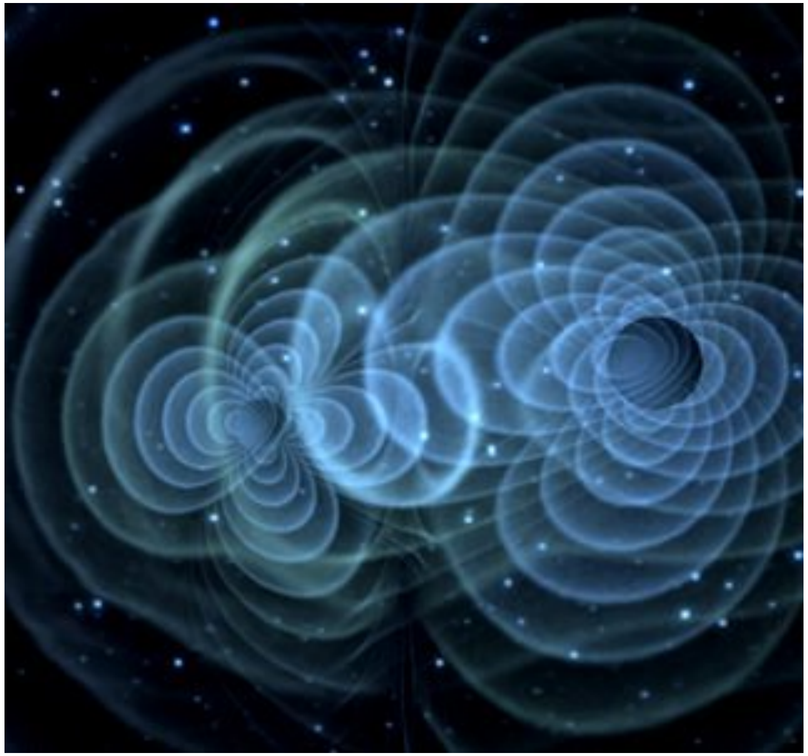
- MBHs should naturally grow along with galaxies through accretion and MBH-MBH mergers and influence the galaxy through feedback



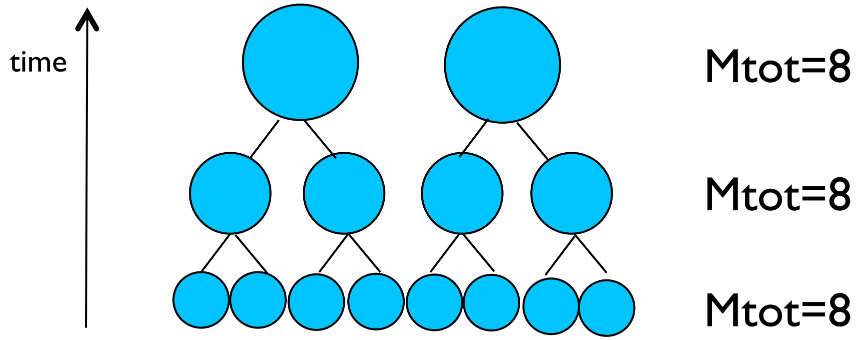
How do MBHs grow ?

Gas accretion vs MBH-MBH mergers

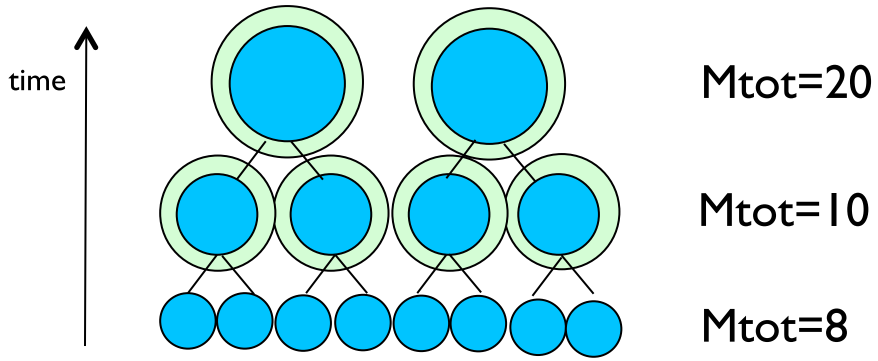




How do MBHs grow ?



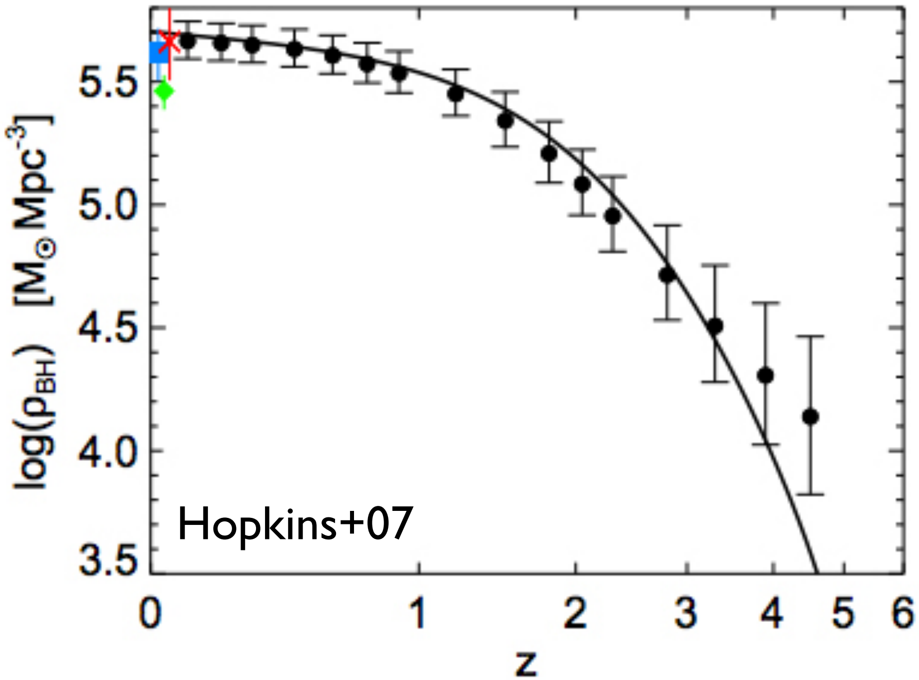
Mergers: total mass density in MBHs is constant in time: just reshuffle the distribution of masses



Accretion: adds external matter => total mass density in MBHs increases with time

Yu & Tremaine 2002

How do MBHs grow ?



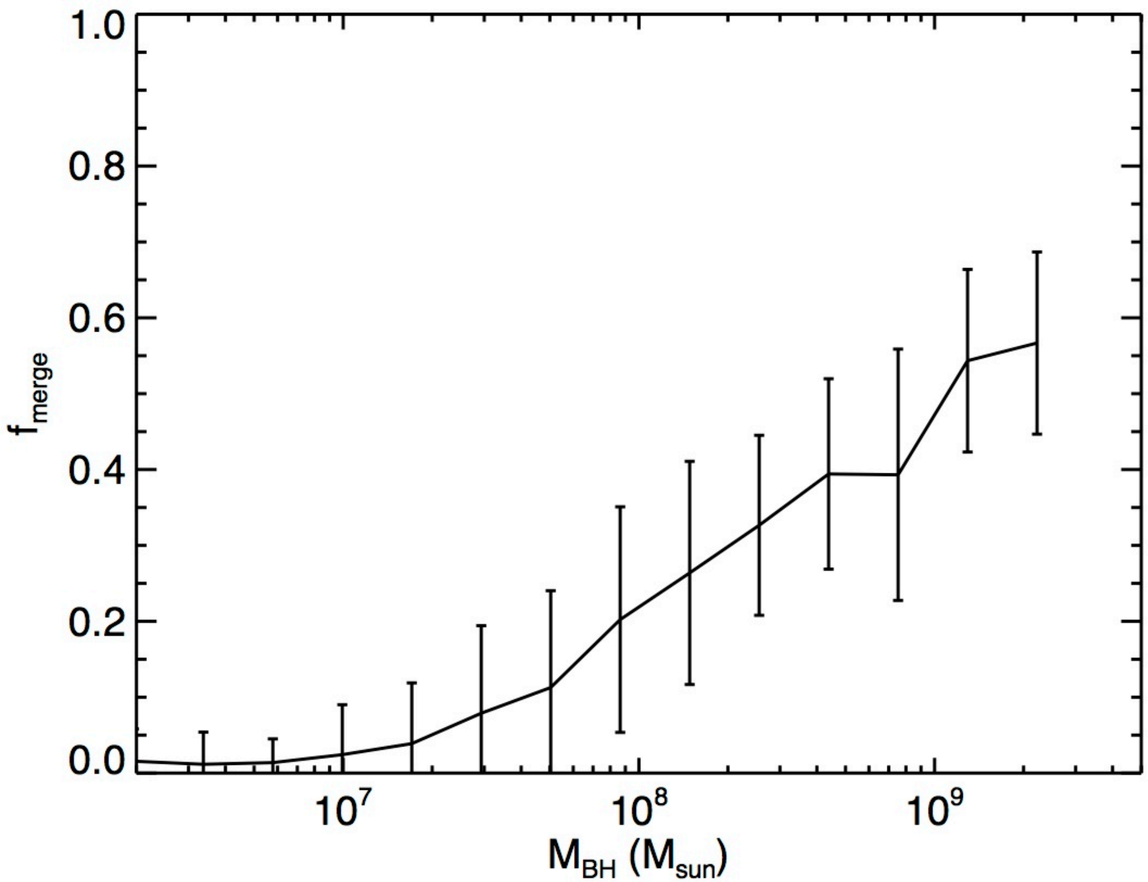
Mergers: total mass density in MBHs is constant in time: just reshuffle the distribution of masses

Accretion: adds external matter => total mass density in MBHs grows with time

Soltan's argument:
BH mass density increases by > one order of magnitude in the last ~10 Gyr: **accretion** leads

Yu & Tremaine 2002

Are MBH-MBH mergers important?



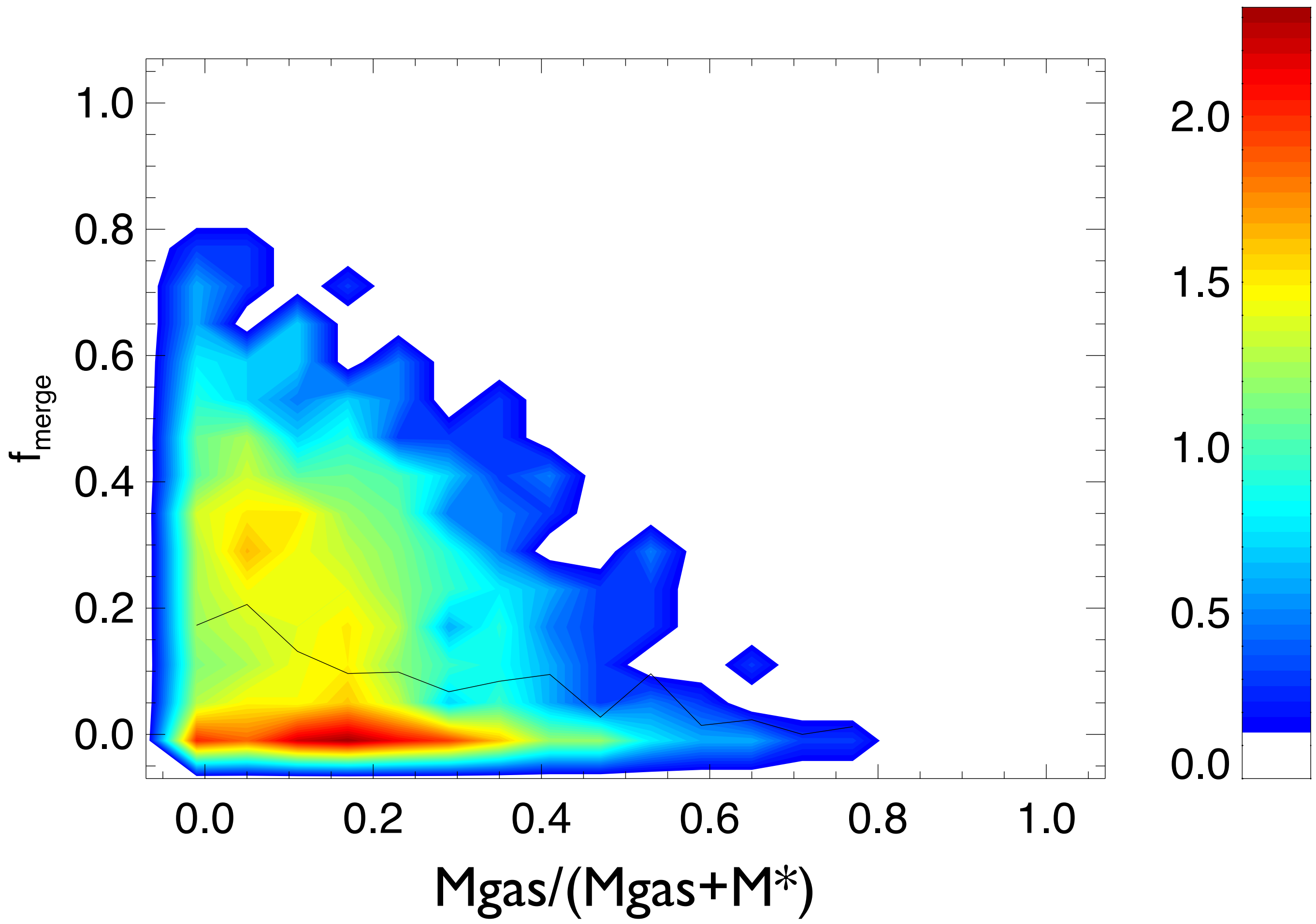
High-mass MBHs!

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 2013

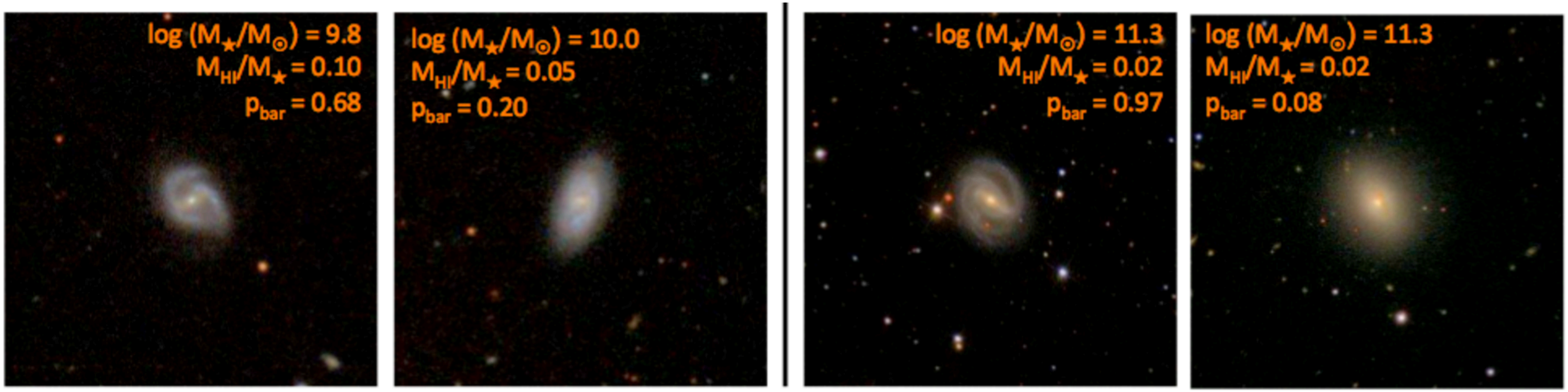
Are MBH-MBH mergers important?



Gas-poor galaxies!

Dubois, Volonteri & Silk 2013

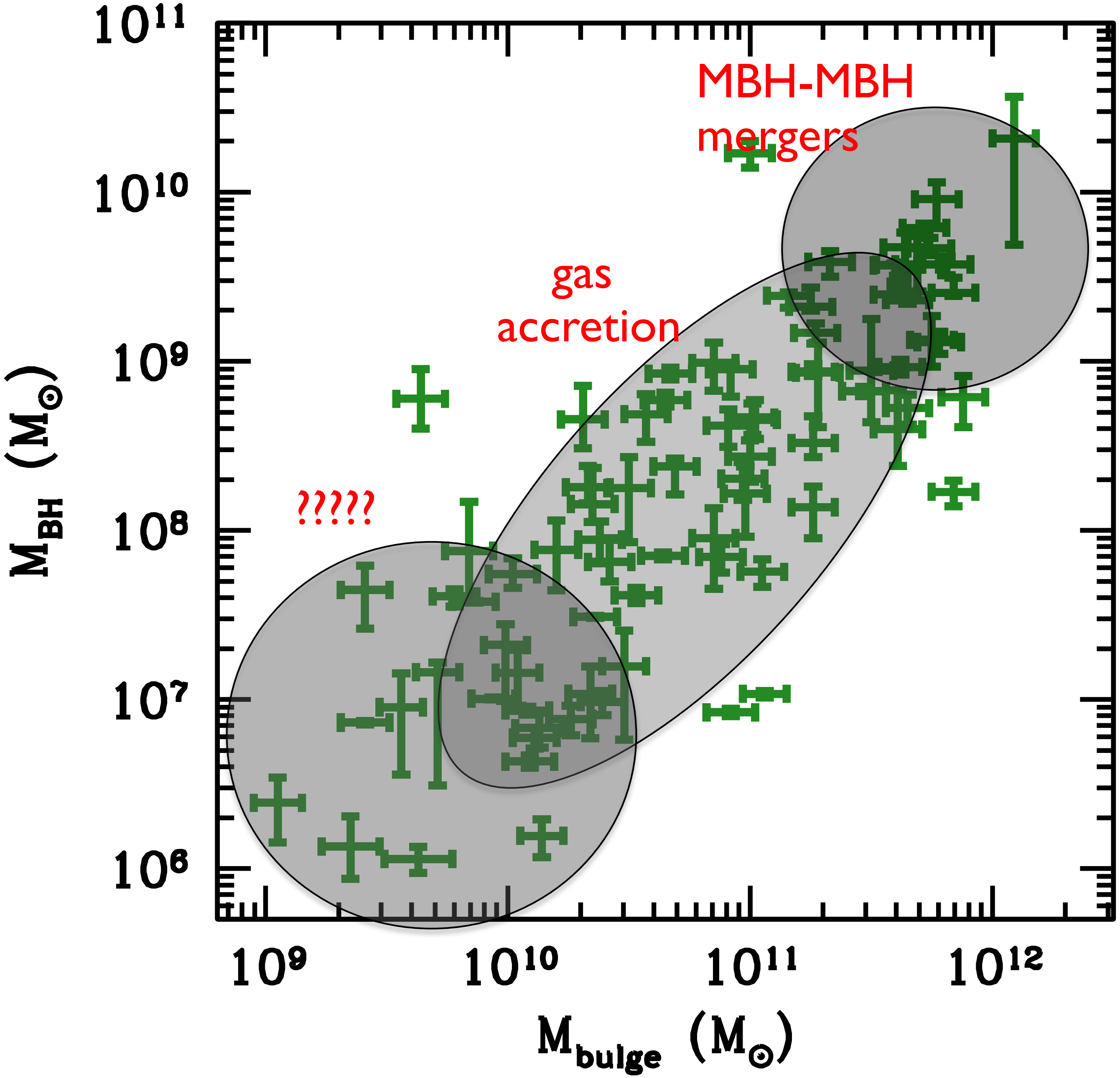
Are MBH-MBH mergers important?



High-mass MBHs ←→ High mass galaxies

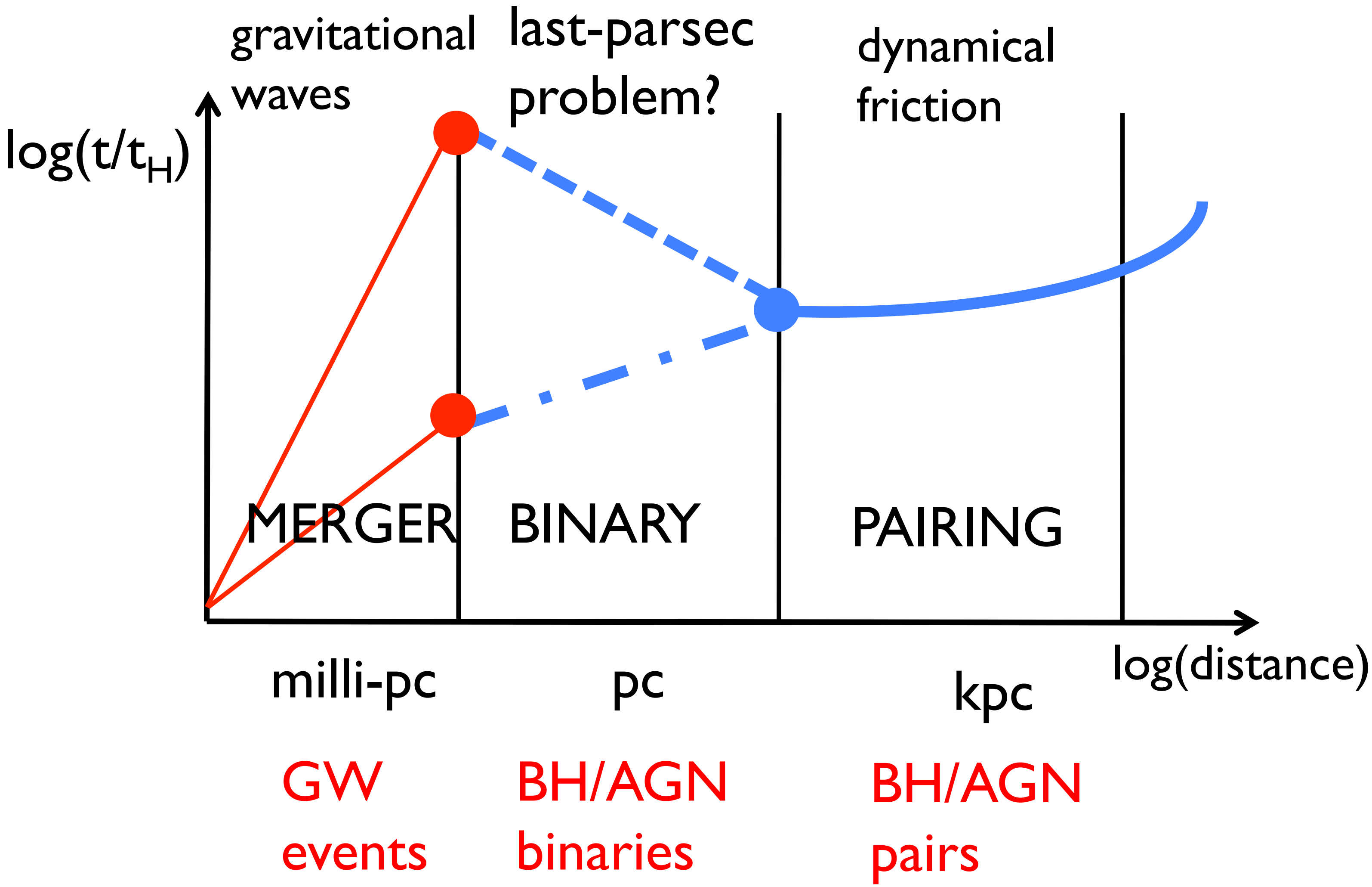
High-mass galaxies ←→ Gas poor galaxies

Credit: Hubble/GalaxyZoo



MBH-MBH mergers
gas accretion
?????
M_{BH} $(M_\odot)$
M_{bulge} $(M_\odot)$
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}
10^{9}
10^{10}
10^{11}
10^{12}

MBHs in galaxy mergers



Courtesy of Monica Colpi

milli-pc → pc → kpc → log(distance)

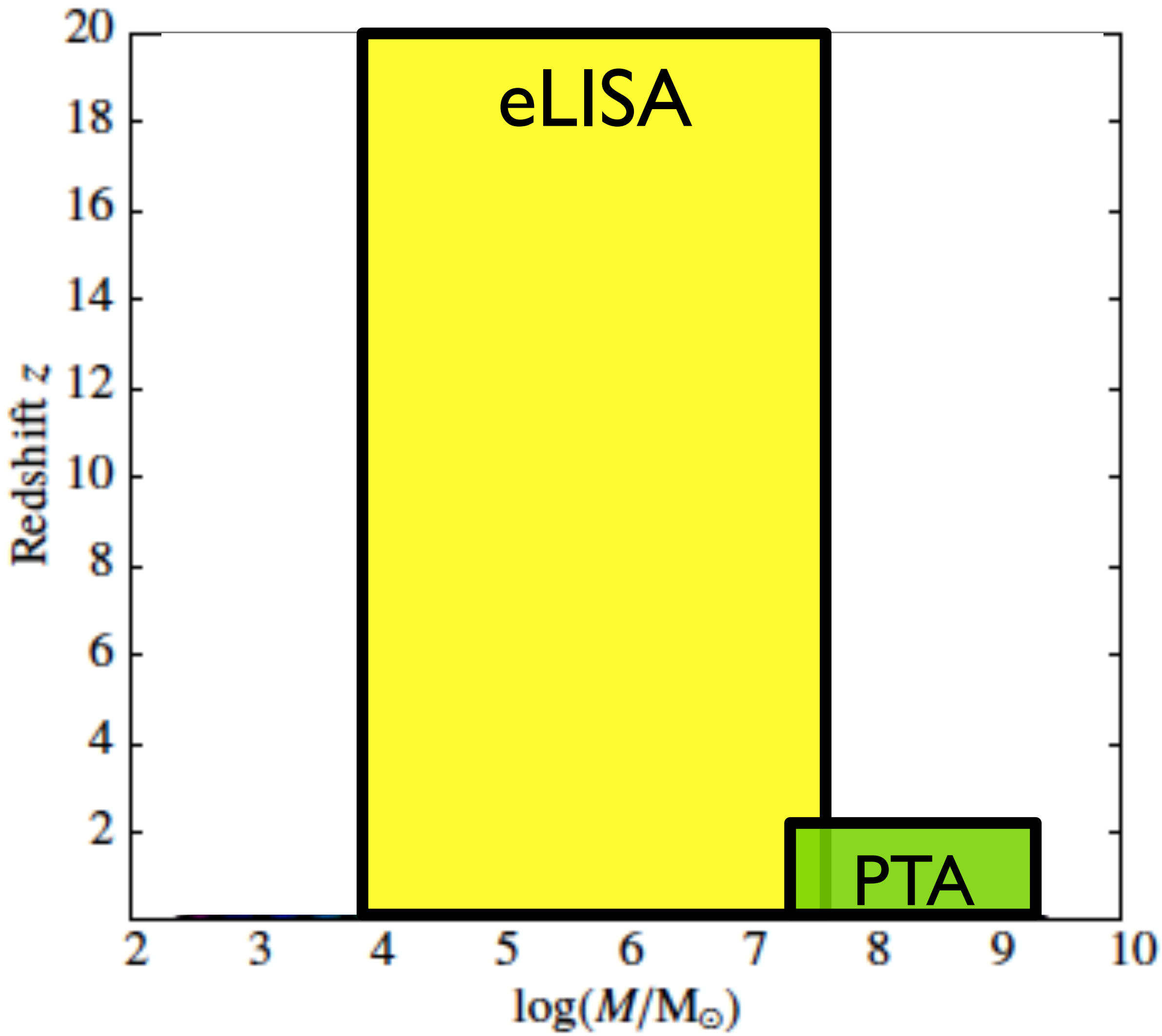
MERGER	BINARY	PAIRING	CONTEXT
Numerical Relativity + analytical techniques	Nuclear discs, circumbinary discs, stellar scattering	Galaxy merger simulations	Cosmological simulations + semi-analytical models

Severely multi-scale problem – at the current time initial and boundary conditions are all idealized and not self-consistent

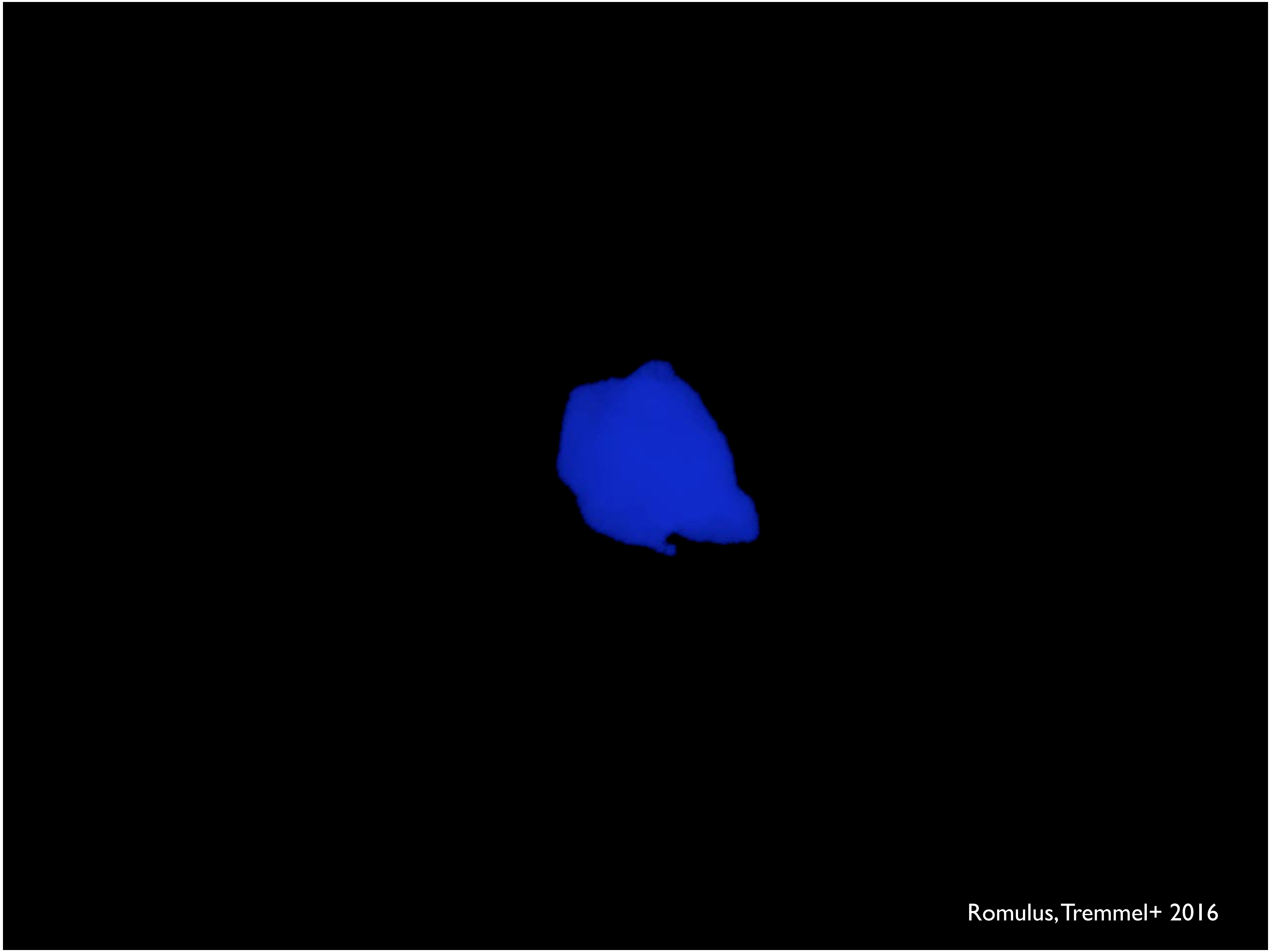
MBHs in galaxy mergers

- 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



Context: the cosmic merger rate


Romulus, Tremmel+ 2016

- BHs sit in the center of galaxies. Galaxies sit in the center of dark matter halos.

- We need the merger rate of BHs with mass between 100 and 10^{10} Msun from today to the Big Bang (or when BHs form in galaxies)

- This means we need to estimate the merger rate of halos with mass from 10^6 Msun when t~100 Myr to 10^{15} Msun when t~14 Gyr

- We need a statistical sample of these halos and the embedded BHs

- Number density of 10^{15} M_{sun} halos ~10 Gpc^{-3} => need to probe a volume of at least 0.1-1 Gpc^3

- We also need to resolve 10^6 Msun halos at redshift ~20 => $m_{res}<10^4\ M_{sun}$

- $N=V\ \rho_{cr}\Omega_m/m_{res} \sim 10^{16}$ particles

- Several (human) years of running time, several millions €

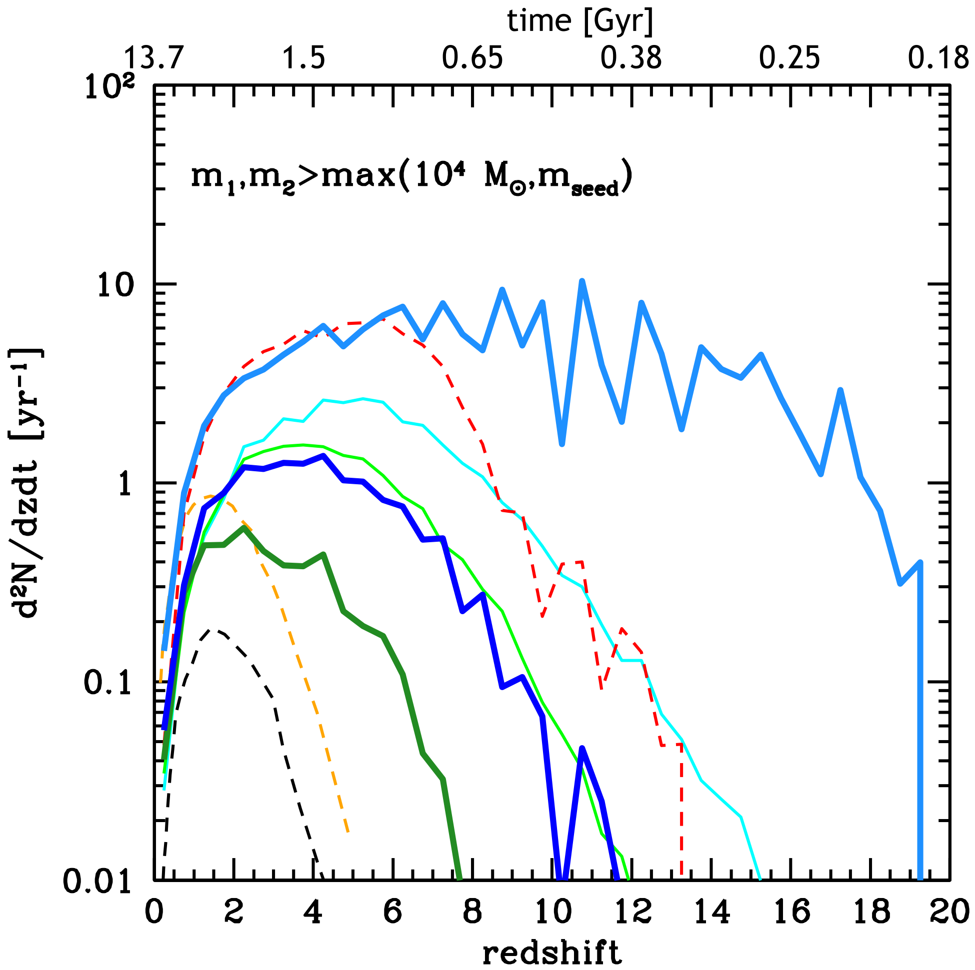
Cosmological simulations vs SAMs

- The advantage of an analytical approach is that in principle it has unlimited spatial and mass resolution

- The disadvantage is that one looses control on non-analytical processes (those that cannot be described by well behaved mathematical functions, e.g., galaxy mergers)

- In cosmological simulations the best possible resolution is ~100 pc, way way way far from when MBHs merge

eLISA pseudo merger rate



SAMs:

Barausse+ (Mh>10⁵-10⁶ Msun)

MV, Sesana+ (Mh>10⁵-10⁶ Msun)

cyan, light blue, blue: large BH seeds

light green, dark green: small BH seeds

SIMs:

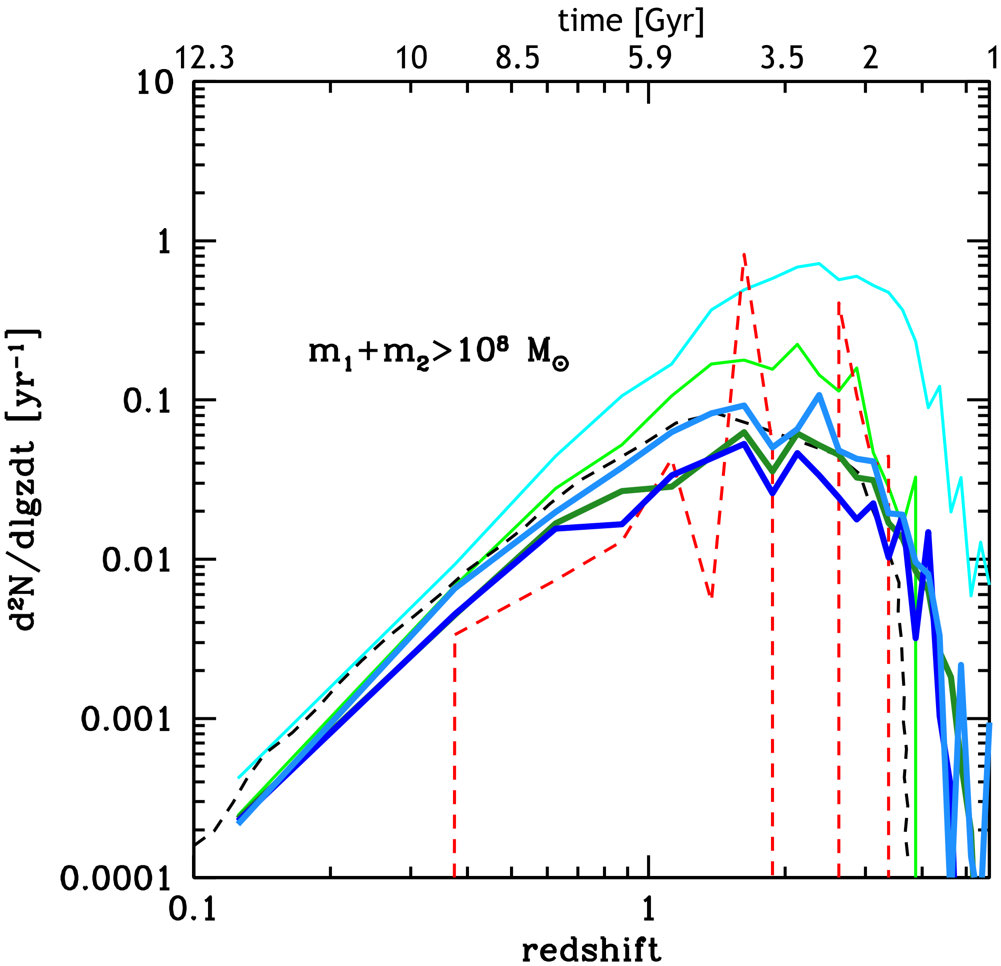
Salcido+ (Eagle, Mh>1.4e10 Msun)

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



SAMs:

Barausse+ (Mh>10⁵-10⁶ Msun)

MV, Sesana+ (Mh>10⁵-10⁶ Msun)

cyan, light blue, blue: large BH seeds

light green, dark green: small BH seeds

SIMs:

Blecha+ (Illustris, Mh>1.4e11 Msun)

Tremmel+ (Romulus, Mh>3.5e8 Msun)

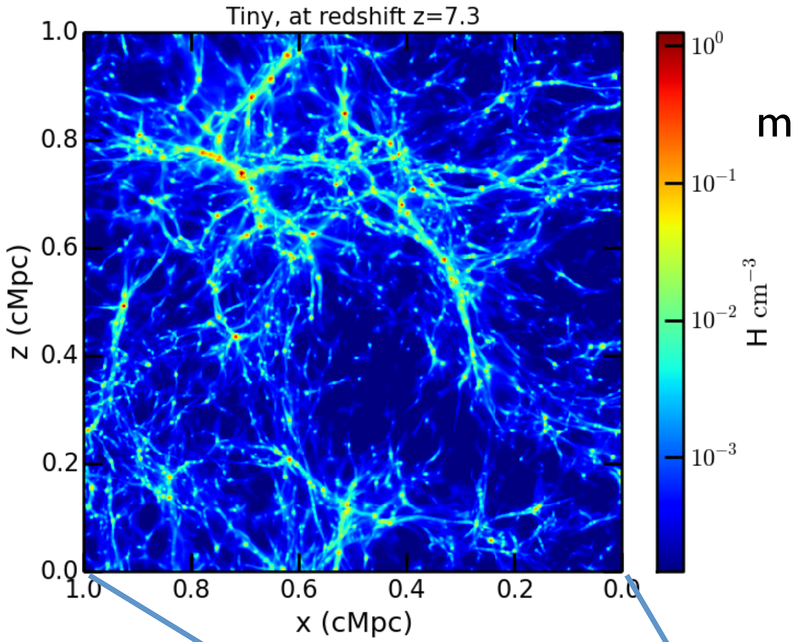
Number of mergers per year: between 0.03 and 0.09

1. Halos and galaxies

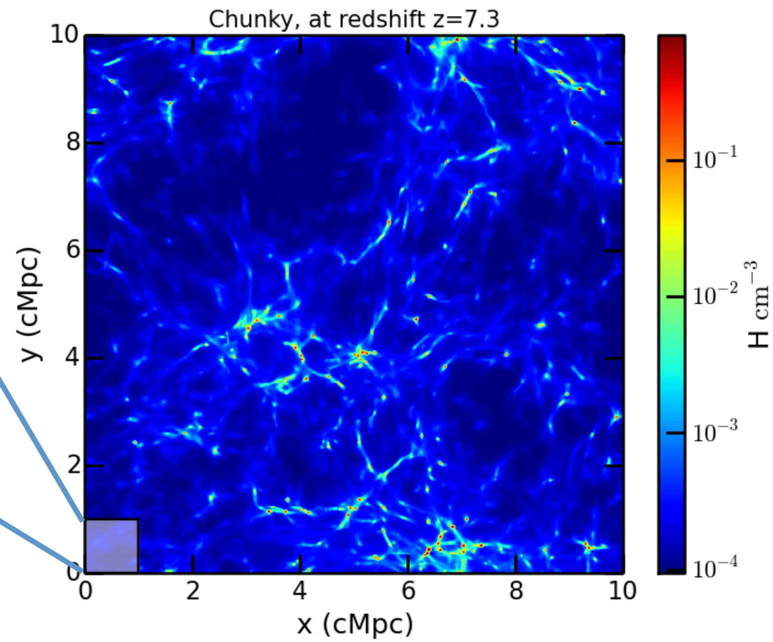
Which galaxies/halos host BHs

How good we are at modelling them

1. Halos and galaxies



$m_{res}=10^3$ Msun



$m_{res}=10^6$ Msun

Habouzit, MV+16

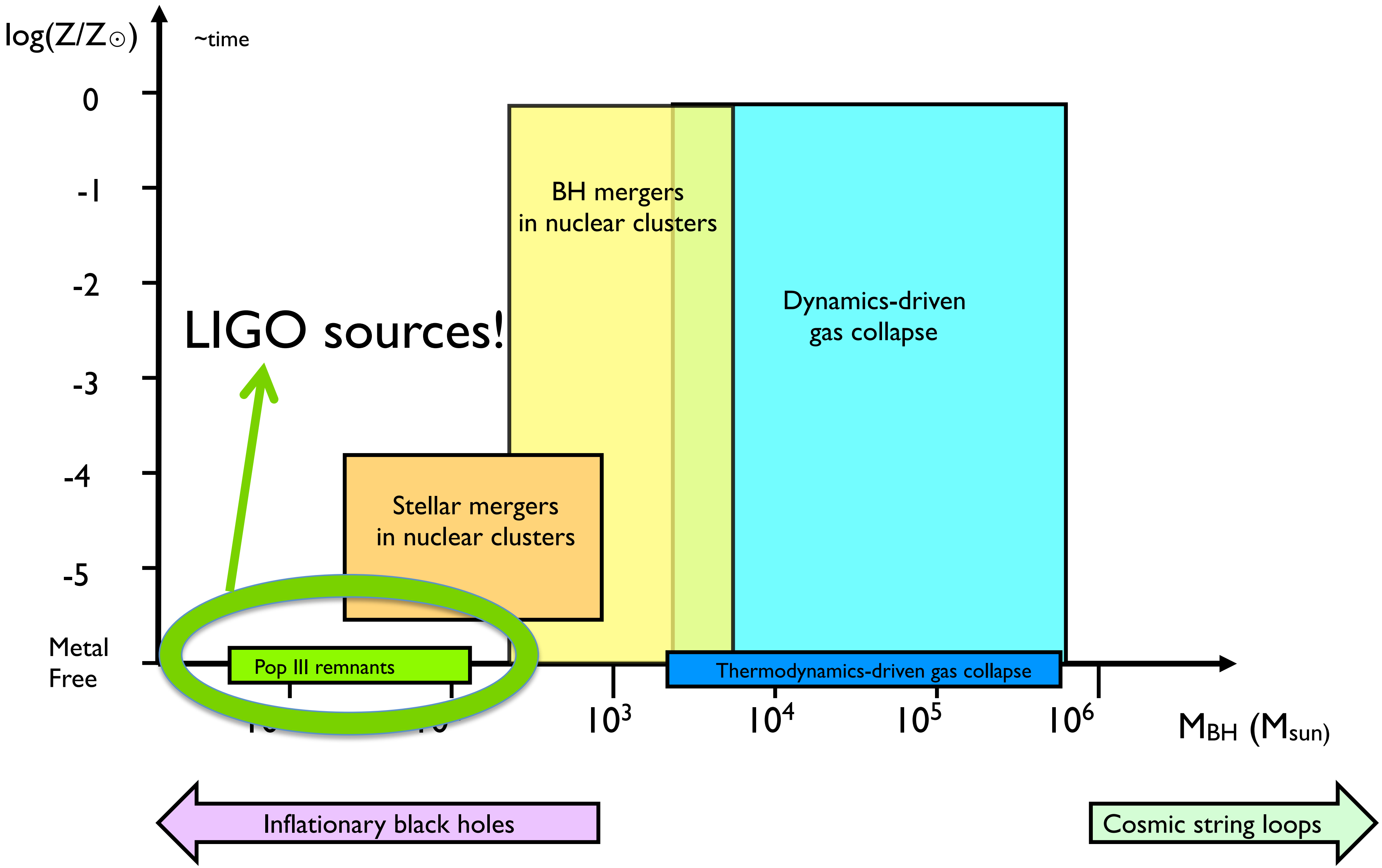
2. BH “seeds”

How massive BHs are at birth

When they form

How many per galaxy

2. BH “seeds”



log(Z/Z⊙)
~time
0
-1
-2
-3
-4
-5
Metal Free
LIGO sources!
BH mergers in nuclear clusters
Dynamics-driven gas collapse
Stellar mergers in nuclear clusters
Pop III remnants
Thermodynamics-driven gas collapse
10^3
10^4
10^5
10^6
M_{BH} (M_{sun})
Inflationary black holes
Cosmic string loops

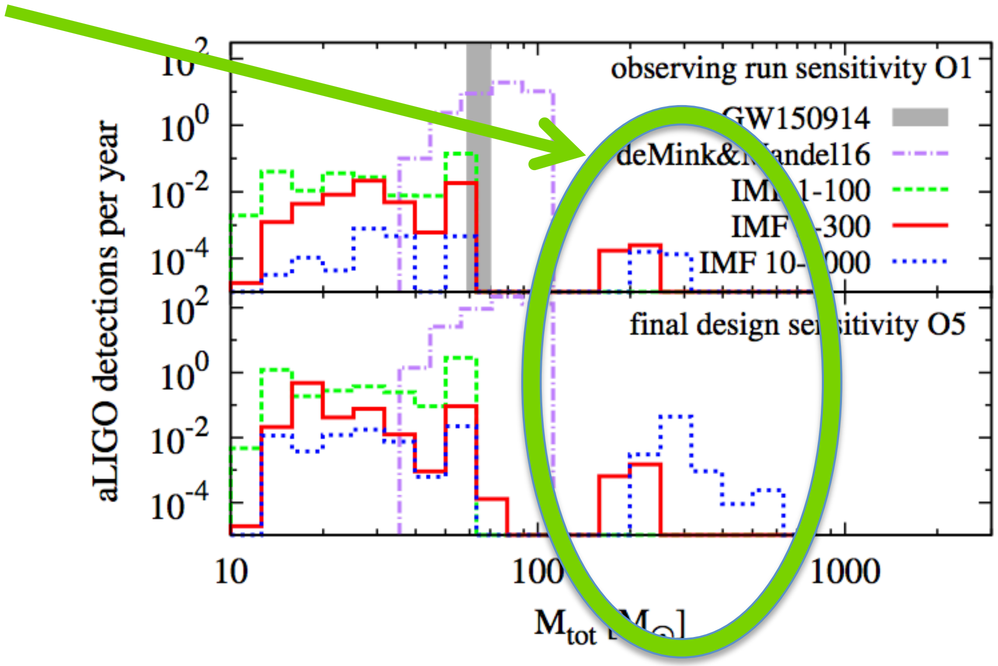
PopIII black holes: LIGO

The most massive remnant BHs for binaries at 0.1Z☉ have a mass of ~ 42 Msun (deMink & Belczynski 15)

“Chemically homogeneous” binary black hole mergers, Mtot ≲ 100 Msun (deMink & Mandel 16)

Binary BHs with Mtot up to ~160Msun may form in globular clusters (Belczynski et al. 2014; Rodriguez et al. 2016)

Mergers with Mtot> 200-300 Msun are of primordial origin, ~0.1-1/yr (Kinugawa+14,16; Hartwig, MV+16; Inayoshi+16; Dvorkin+16)

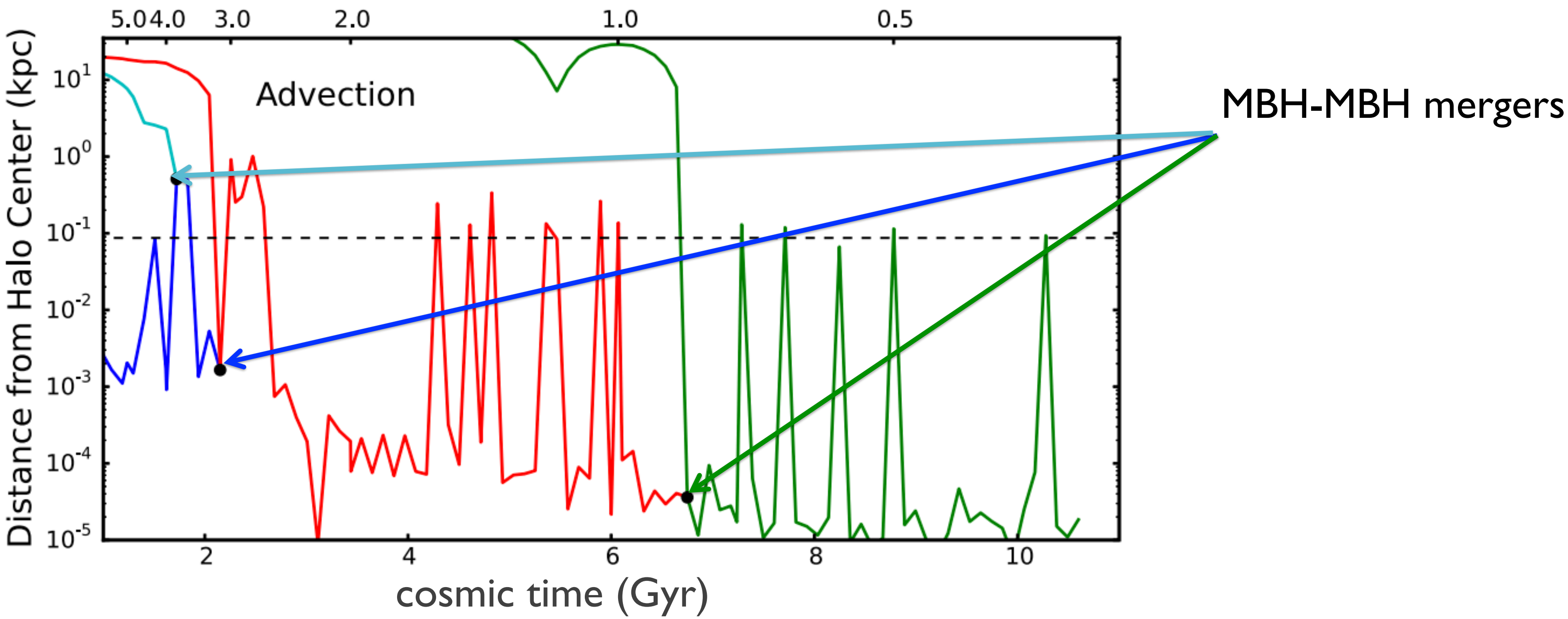


3. BH dynamics

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

How often mergers "fail"

3. BH dynamics

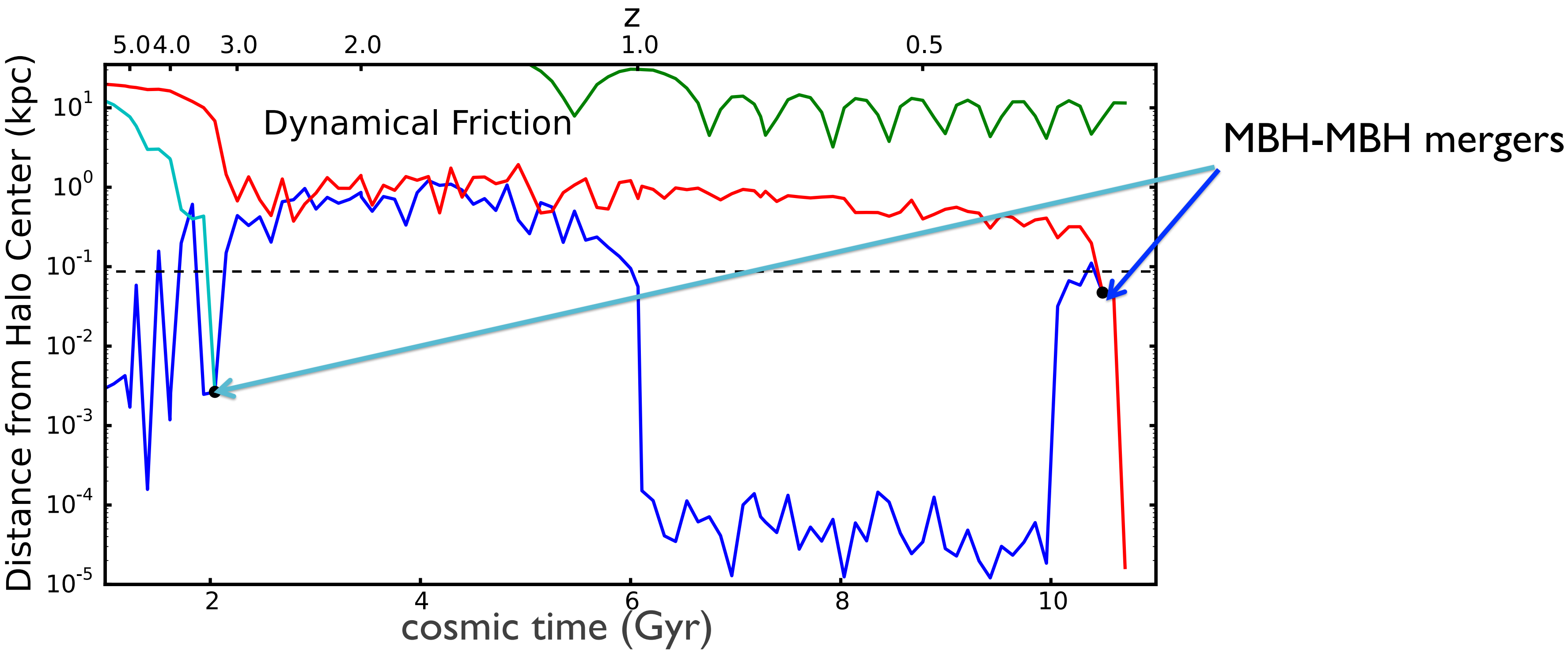


Cosmological 'zoomed-in' simulation of dwarf galaxy with mass ~ 10^{10} $M_{\odot}$ at z = 0.

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

3. BH dynamics



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

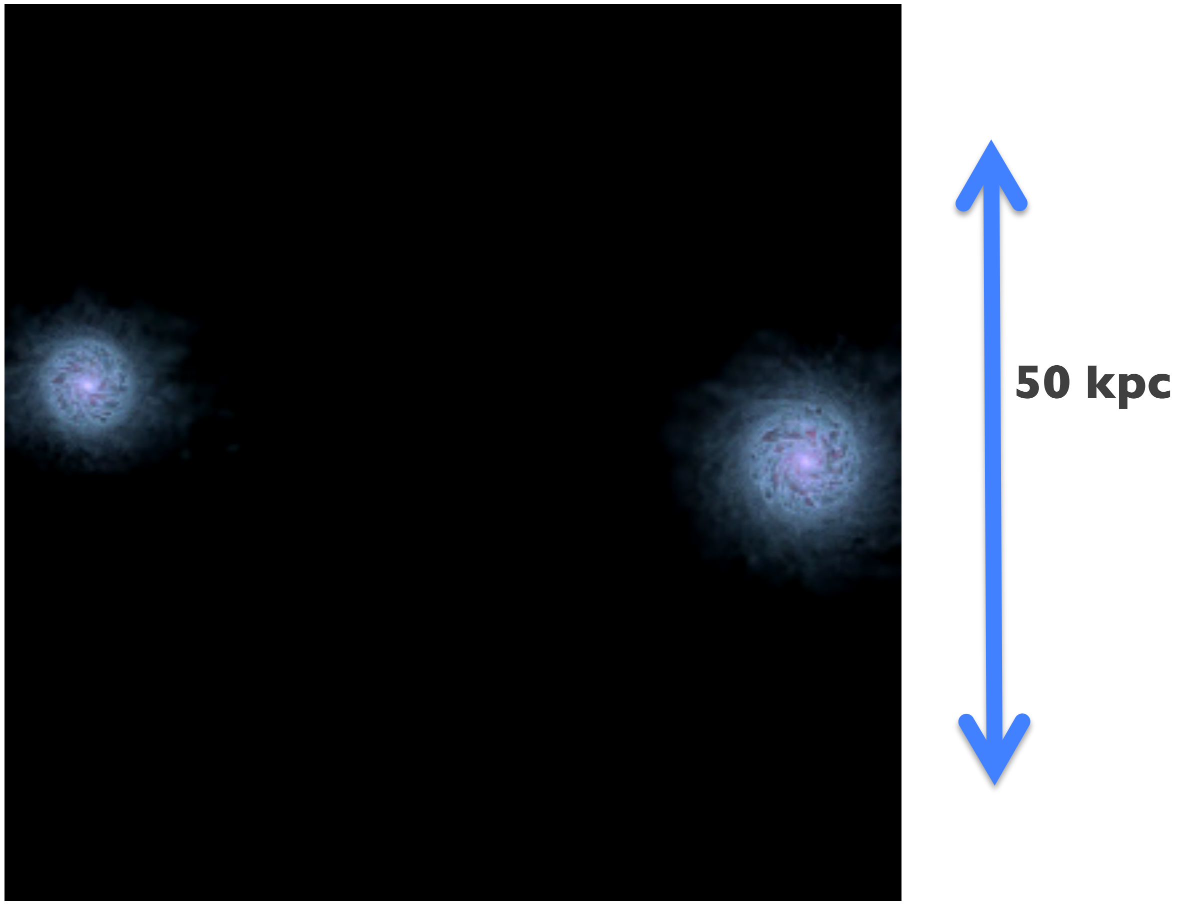
Tremmel+ 2015

3. BH dynamics

- High-z and small galaxies: gas is important
- Low-z and large galaxies: star-dominated

High-z and small galaxies: gas is important

Galaxy scales:100 kpc-10 pc



Galaxy scales: 100 kpc-10 pc

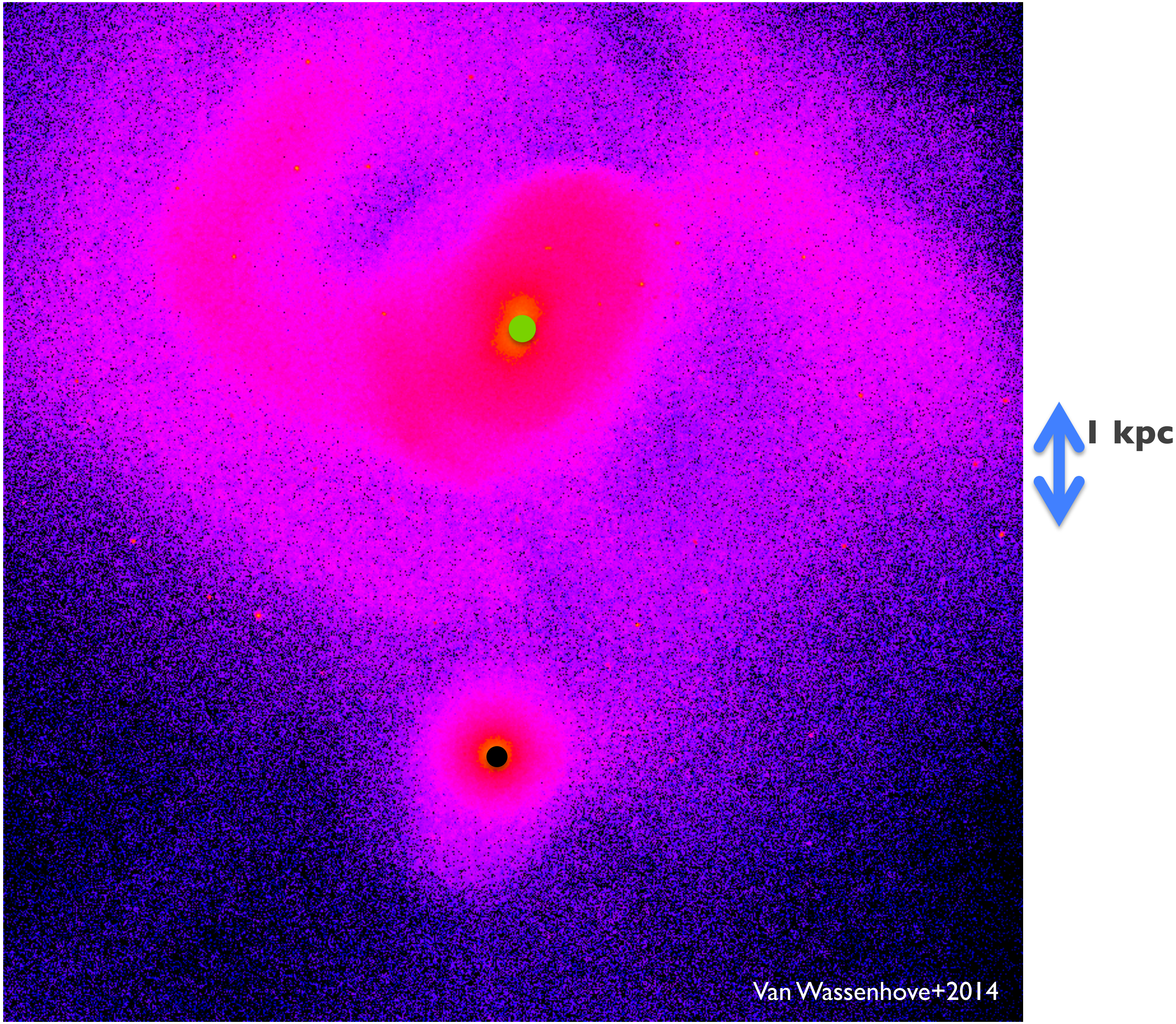
- A large bound nucleus speeds up MBH pairing

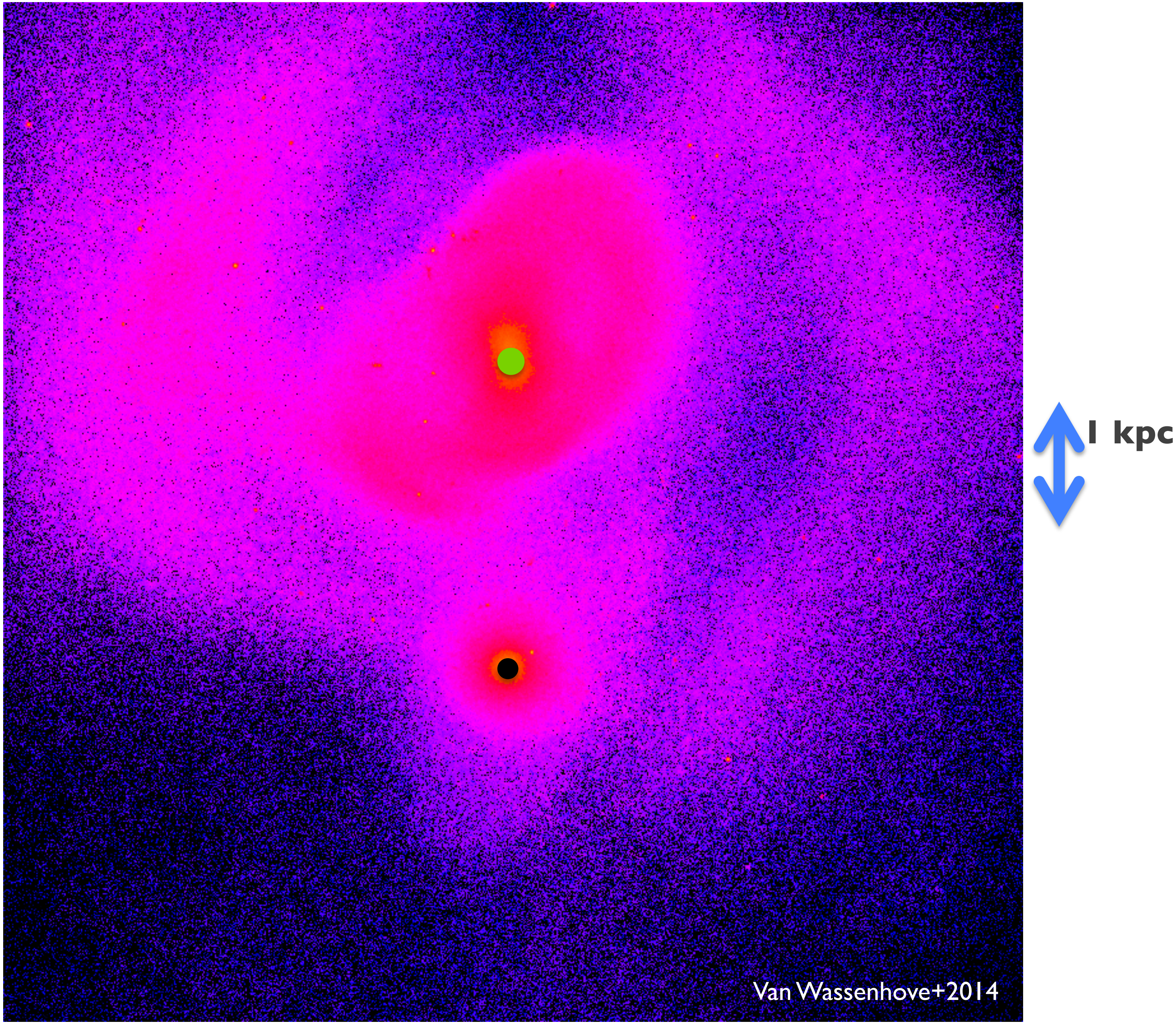
- Galaxy merger simulations with idealized initial conditions, resolution ~1-10 pc

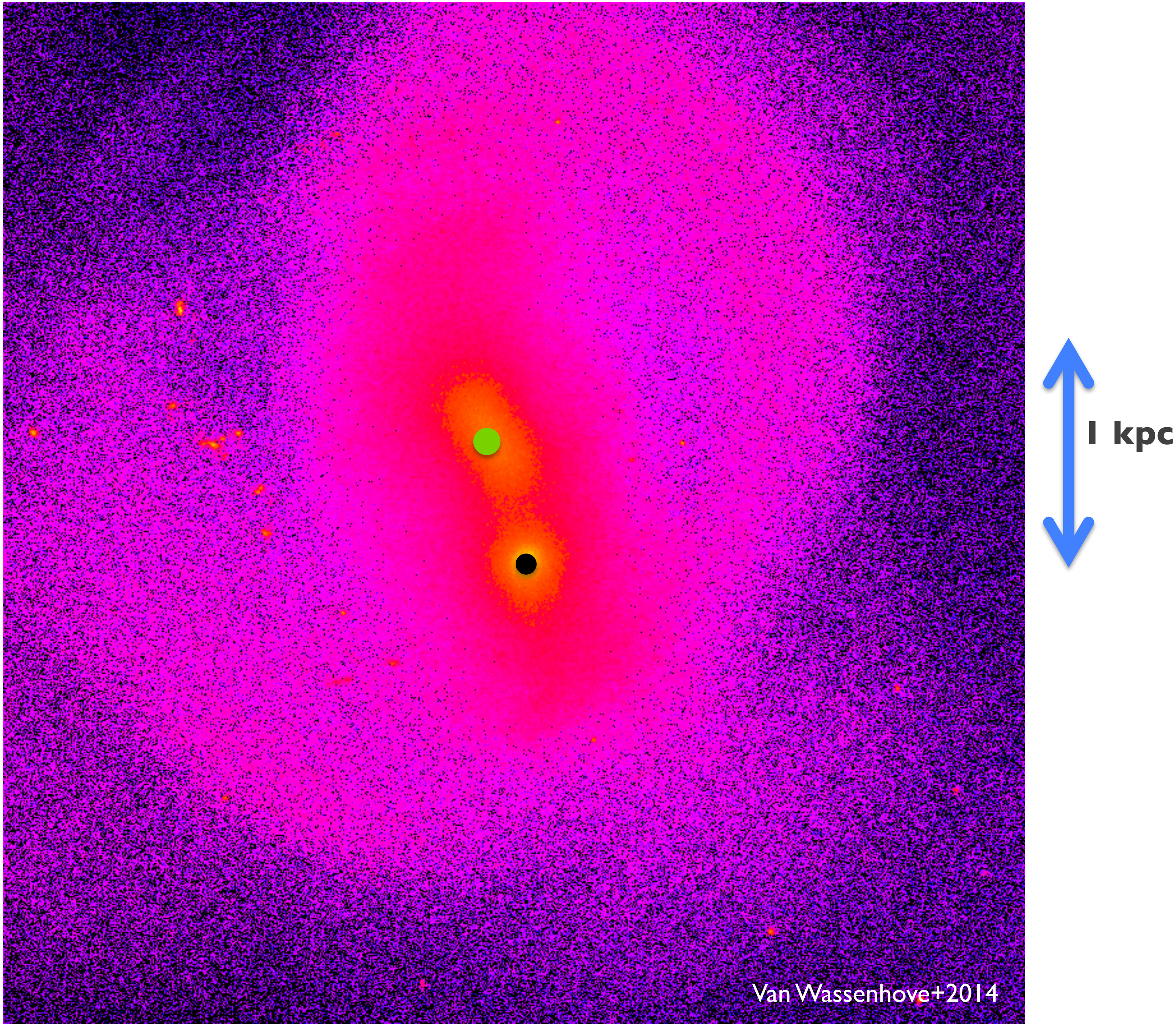
- When the mass ratio of the merging galaxies is >0.1 the two MBHs "find each other", in about ***1-5 Gyr***

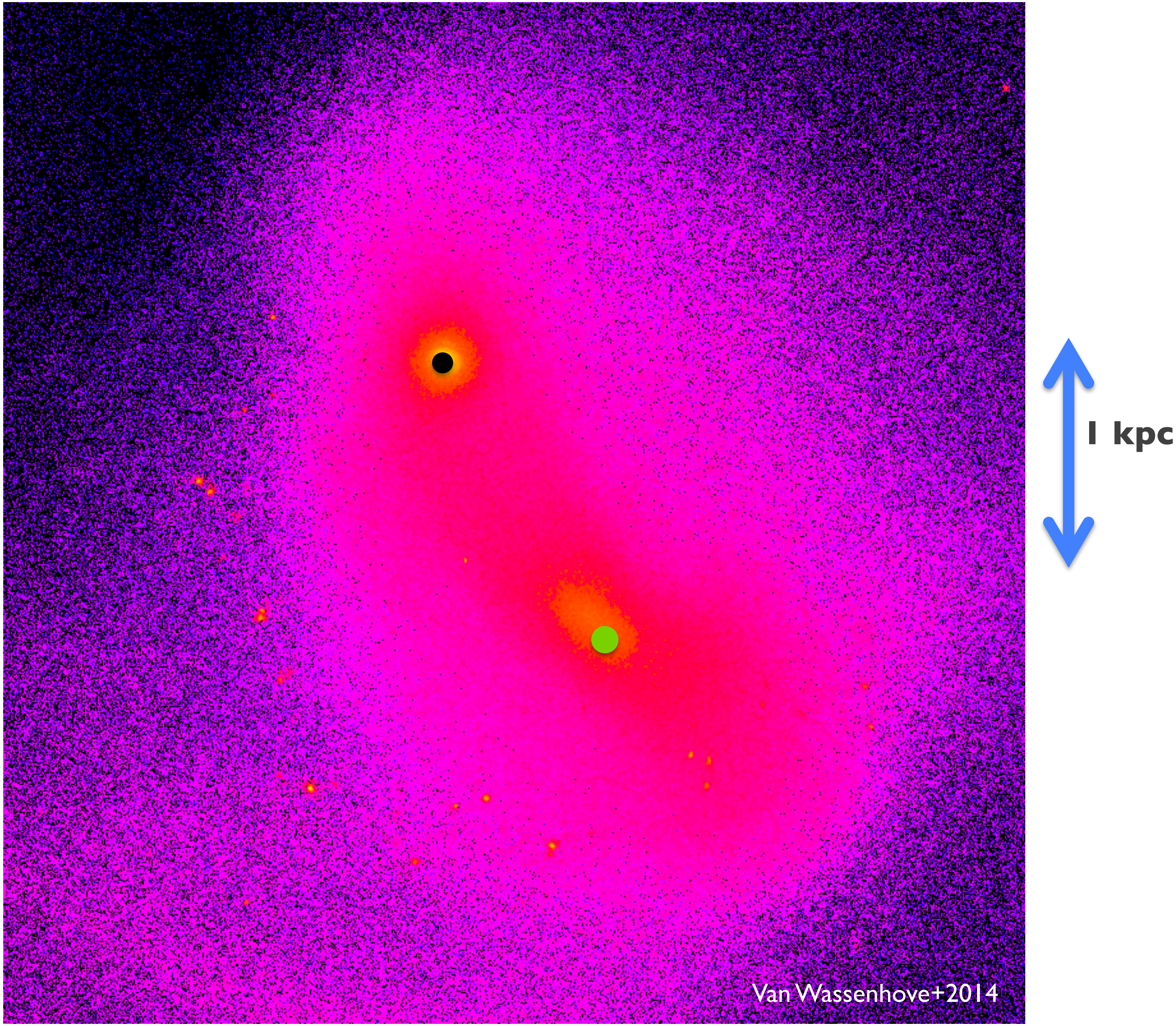
- When the separation of the MBHs reach the minimum resolution of the simulation cannot follow dynamics anymore

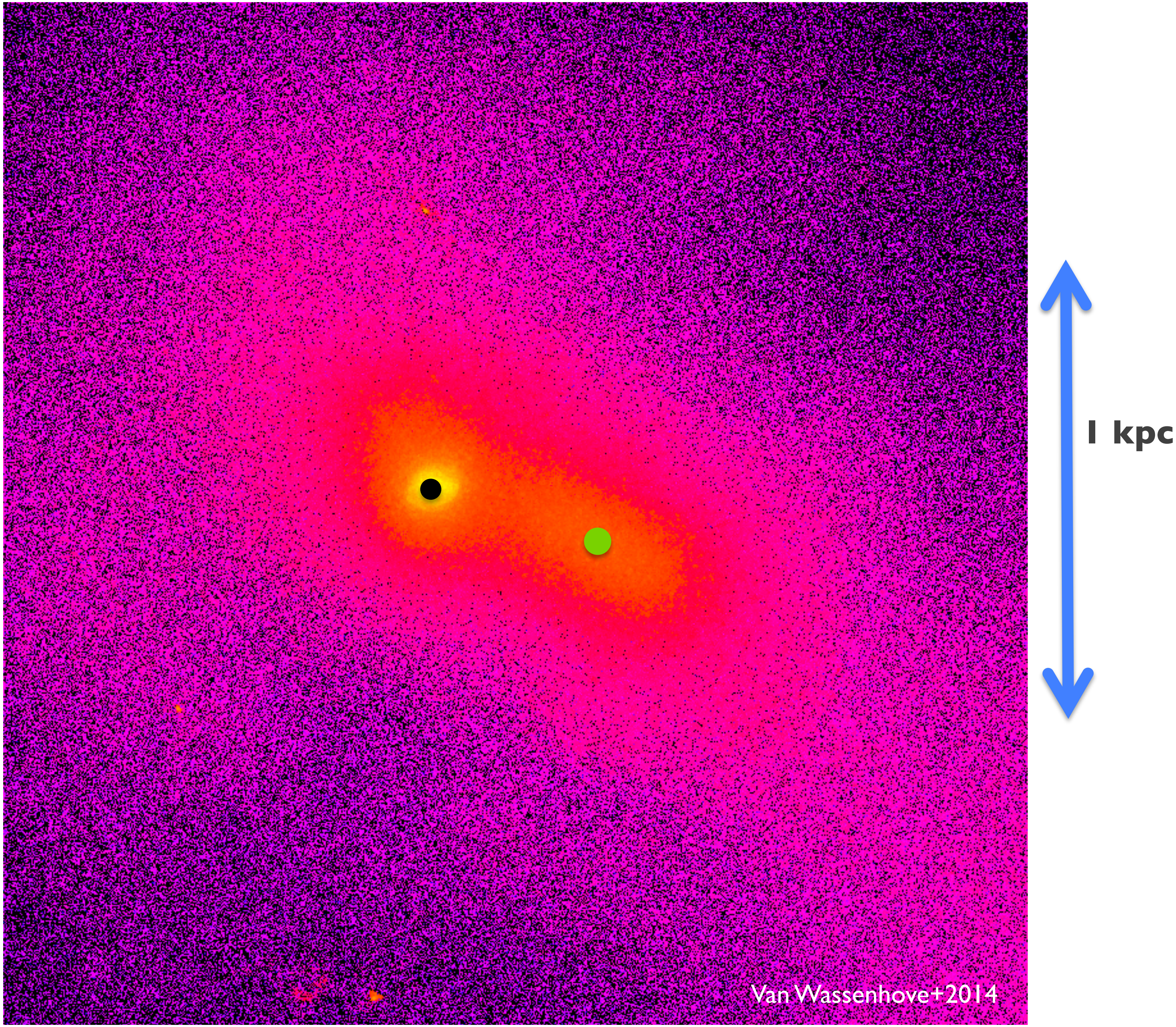
(e.g., Yu 2002, Callegari+2009, 2011; Van Wassenhove+2012; Van Wassenhove+14, Capelo+15, Roskar+15)

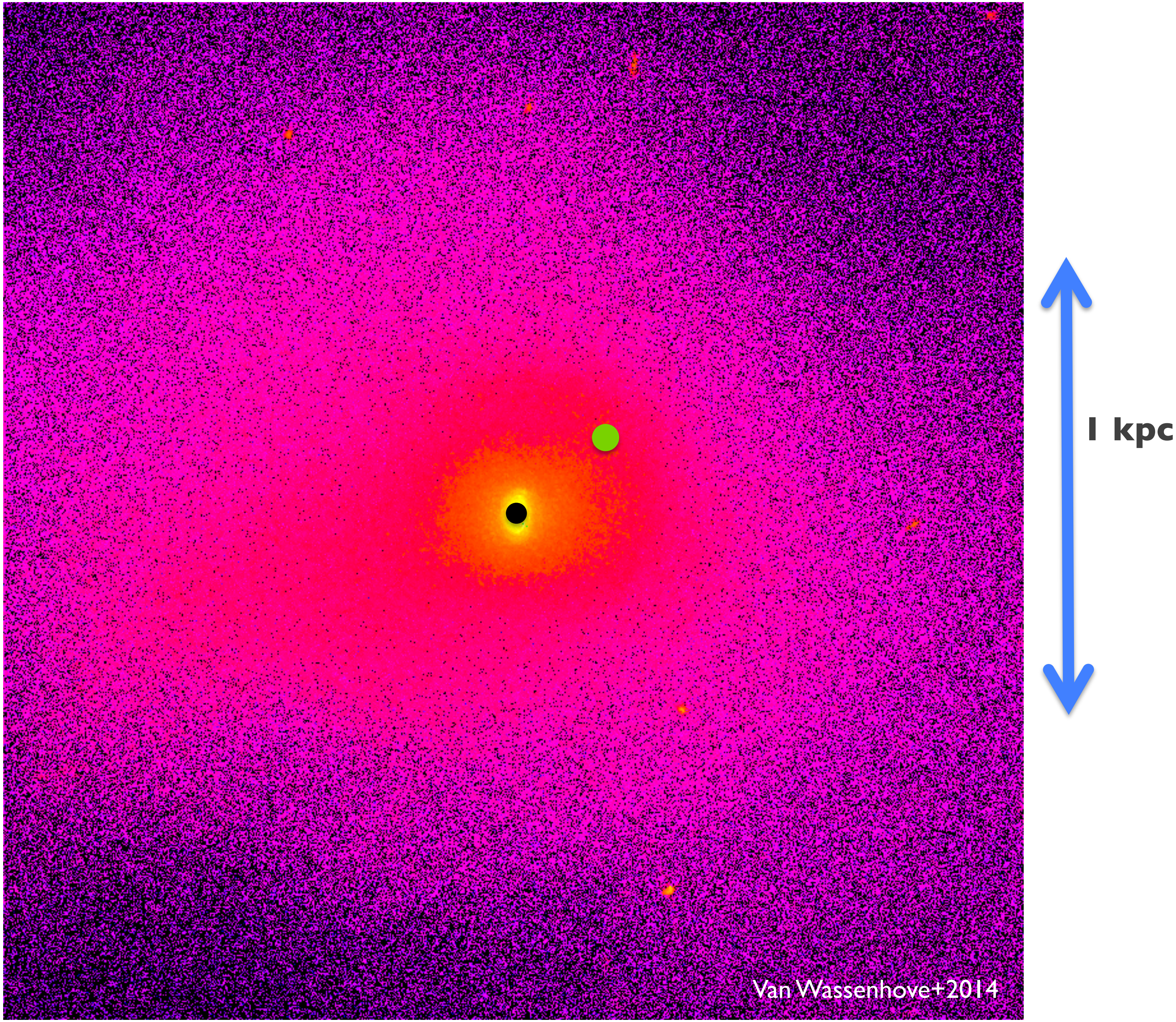

1 kpc
Van Wassenhove+2014

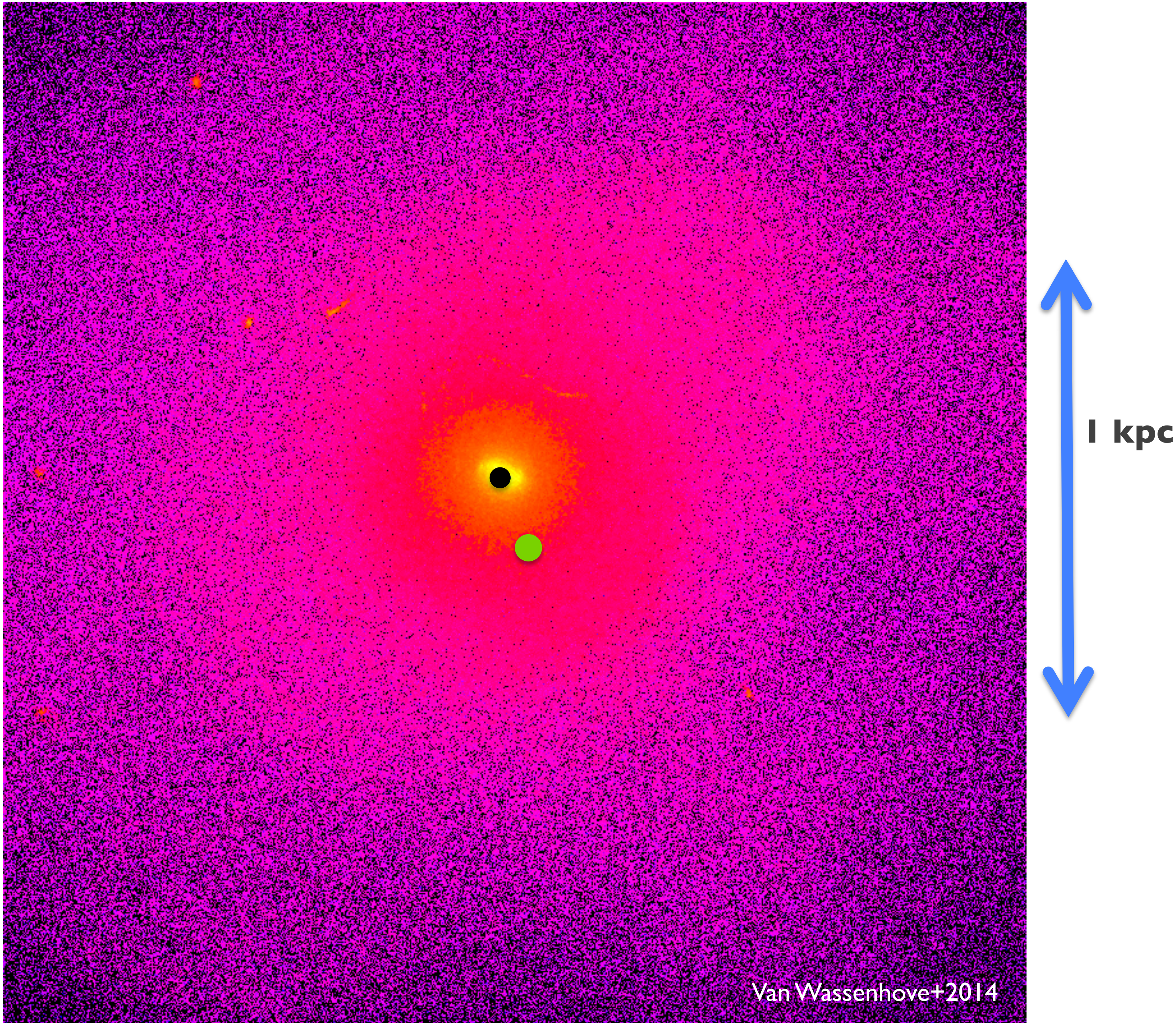

1 kpc
Van Wassenhove+2014

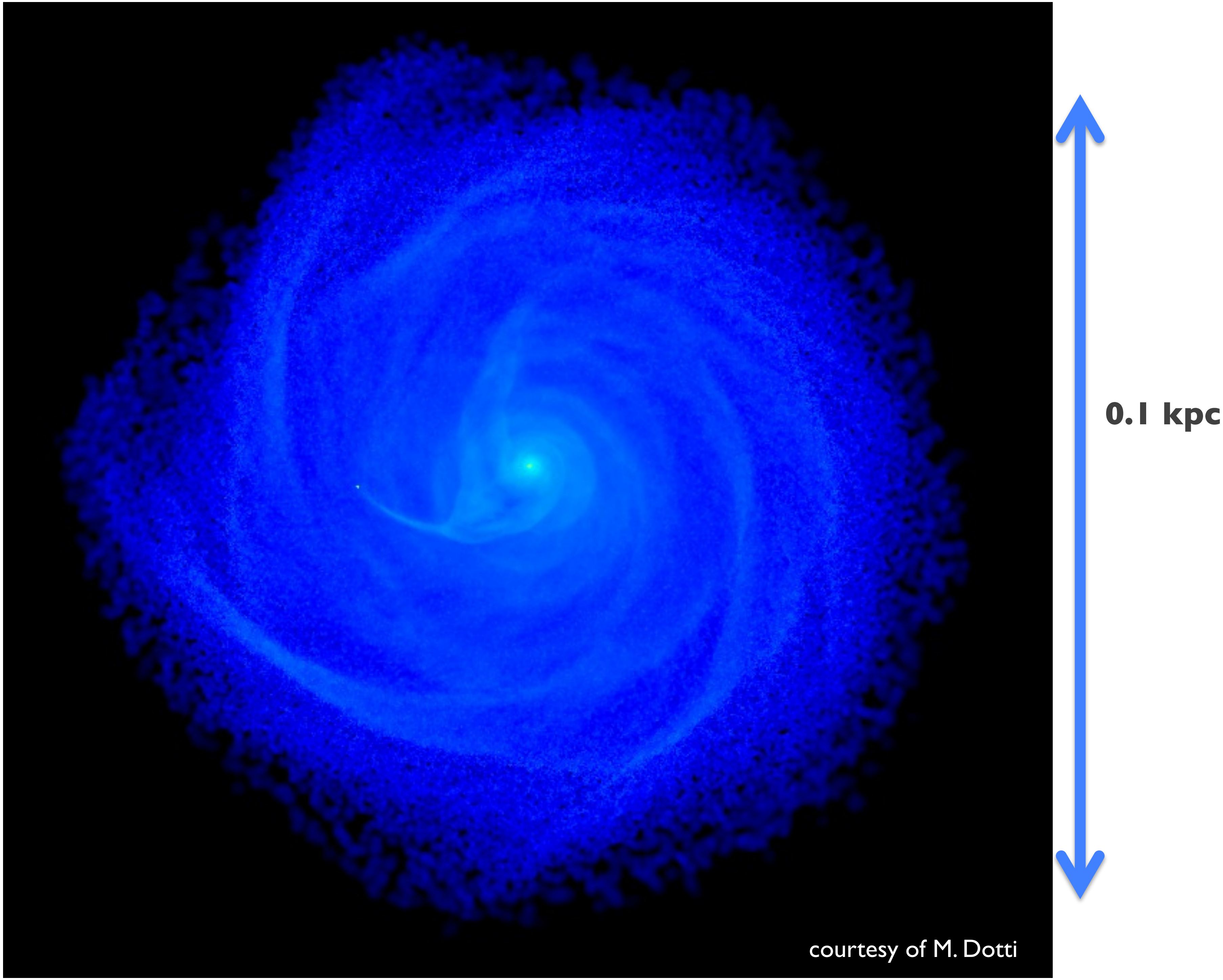

1 kpc
Van Wassenhove+2014


1 kpc
Van Wassenhove+2014


1 kpc
Van Wassenhove+2014


1 kpc
Van Wassenhove+2014


Van Wassenhove+2014
1 kpc


0.1 kpc
courtesy of M. Dotti

Circumnuclear disc simulations:
1 kpc-0.1 pc

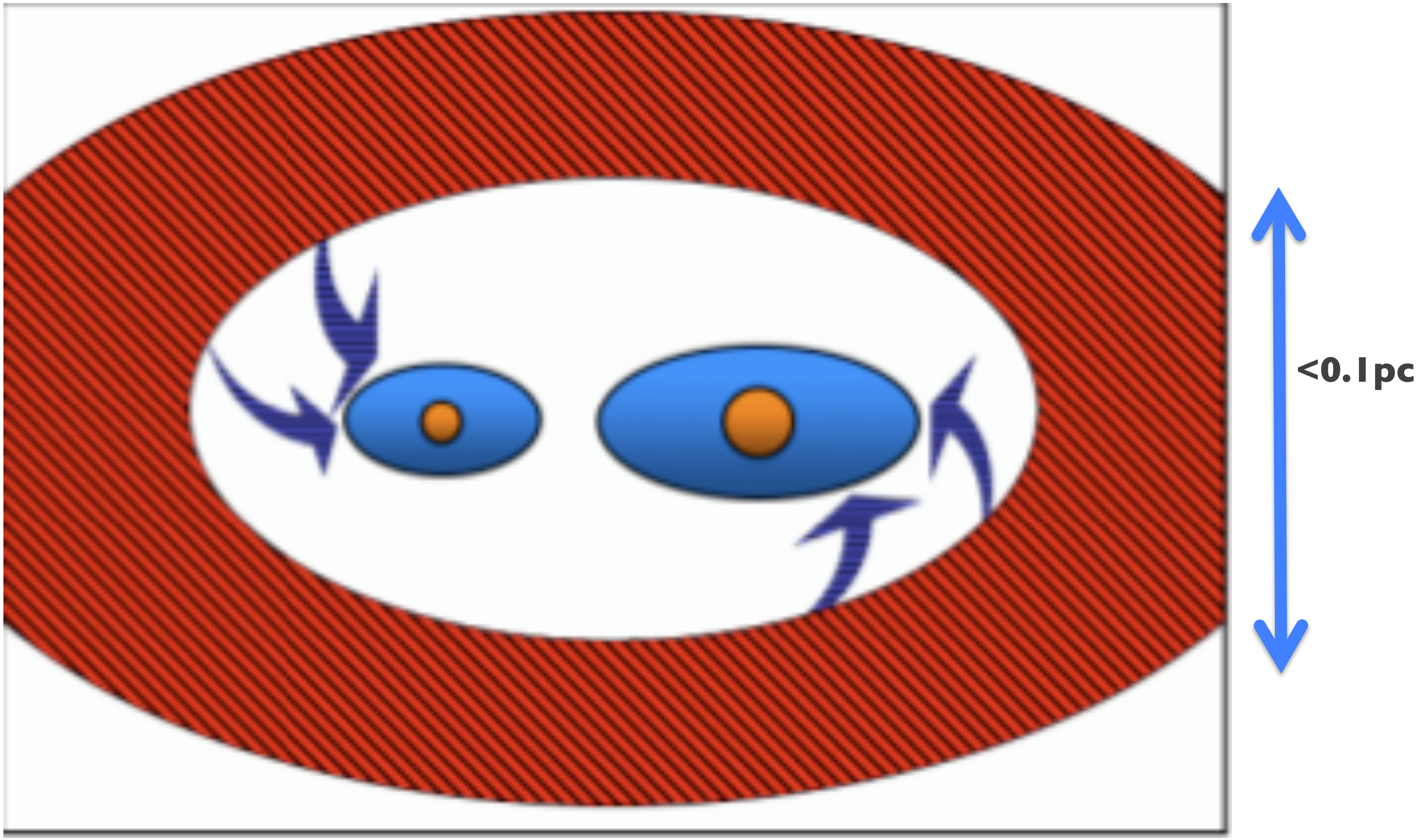
- Idealized initial conditions

- Sensitively depend on thermodynamic properties of the gas disk (i.e., hot, cold, lumpy, star formation, SN feedback)

- AGN feedback not included

- Within ***1-100 Myr*** MBHs reach resolution limit

e.g., Fiacconi+13, del Valle+15, Lupi+15, Amaro-Seoane+13



Bogdanovic+08

Circumbinary discs:
0.1-0.001pc

- 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

- Migration to the GW-dominated regime should occur rapidly, ***~1-10 Myr***

e.g., Armitage & Natarajan 2005; MacFayden & Milosavljevic 2008, Roedig+2012; Shi+12; Noble+12; D'Orazio et al. 2013; Farris et al. 2014; Shi & Krolik 2015…

Low-z and large galaxies: star-dominated

Galaxy merger simulations: 100 pc-0.01 pc

- Idealized initial conditions, start well within the galaxy merger phase (100 pc vs 100 kpc)

- Direct N-body, collisionless particles only

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

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

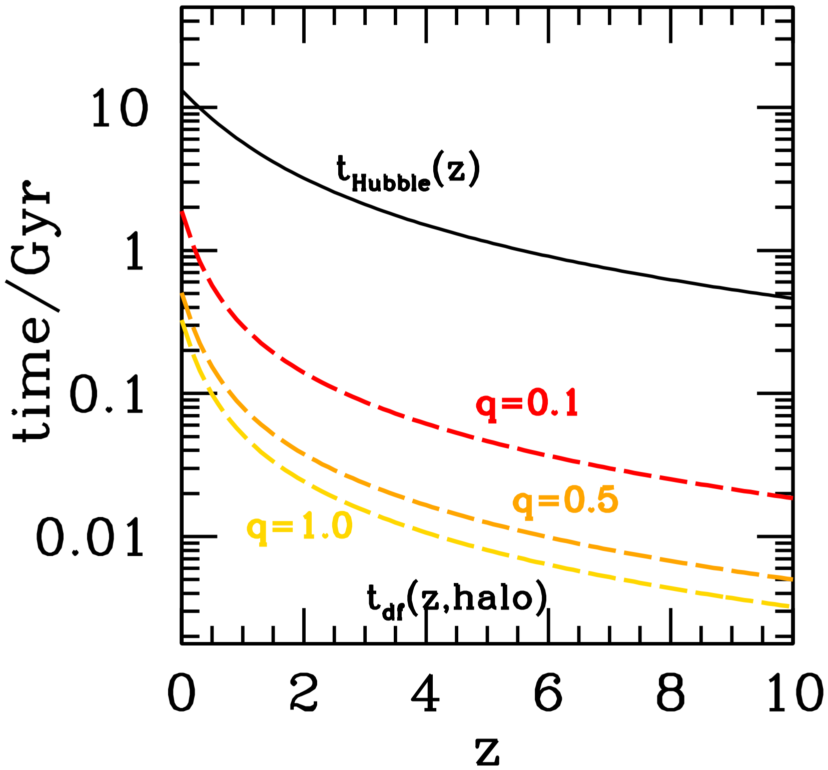
e.g., Gualandris & Merritt 2012, Vasiliev+14, Khan+12, Holley-Bockelmann and Khan 2015; Vasiliev et al. 2015; Sesana and Khan 2015

How long does this all take?

brief review: MV, Bogdanovic, Dotti, Colpi 2015

How long does this all take?

- First, halos merge.



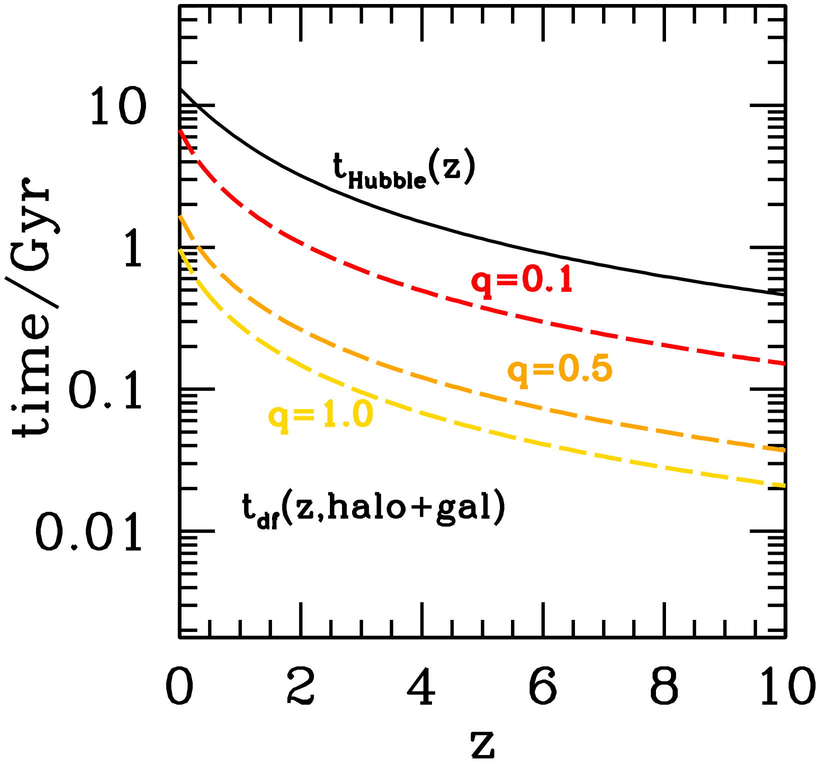
~ Gyr at low-z

0≤q≤1 : mass ratio

DF timescale from Boylan-Kolchin+08

How long does this all take?

- Then, galaxies.



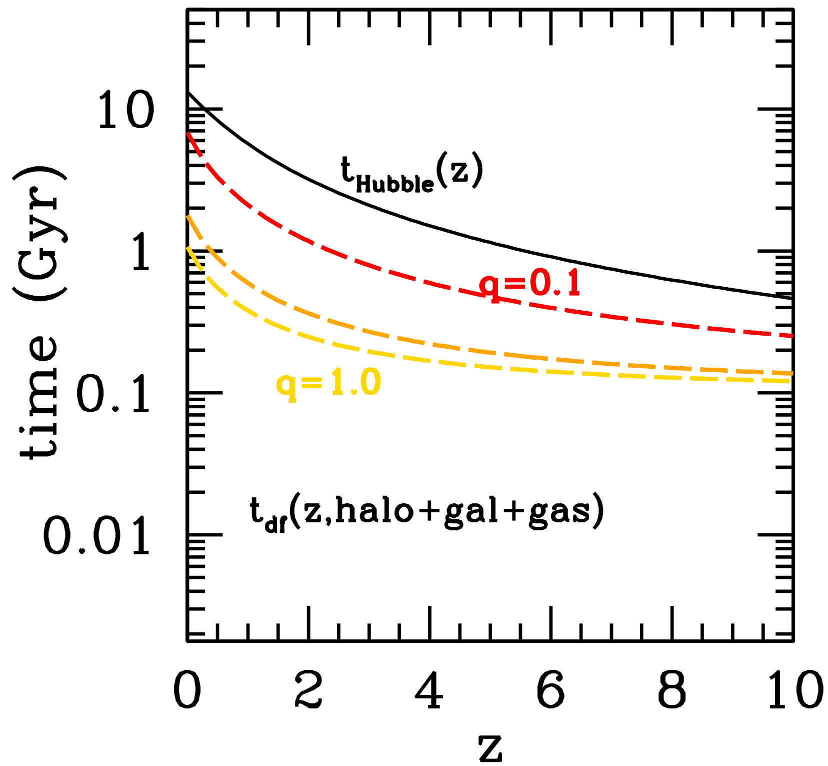
> Gyr at low-z

DF timescales from
Boylan-Kolchin+08
+
McWilliams+14

0≤q≤1 : mass ratio

Gas dominated mergers

- Finally, black holes.



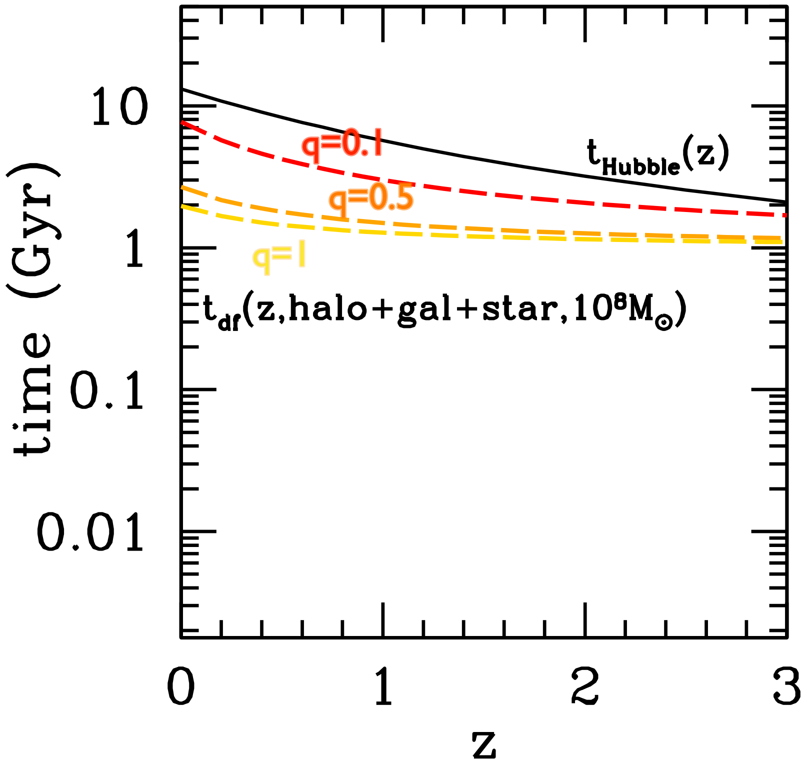
in TOTAL
> Gyr at low-z

0≤q≤1 : mass ratio

DF timescales from
Boylan-Kolchin+08
+
McWilliams+14
+ 100 Myr (nuclear/binary disc evolution)

Star-dominated mergers

- Halos, galaxies, black holes



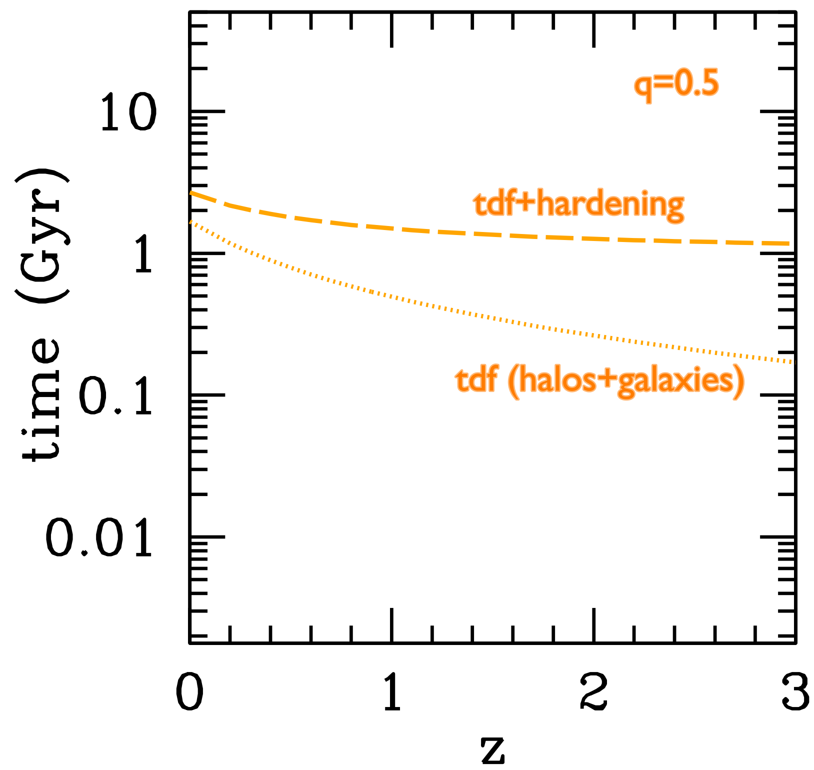
in TOTAL
> Gyr at all z

0≤q≤1 : mass ratio

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

Star-dominated mergers

- Halos, galaxies, black holes



in TOTAL

> Gyr at all z

How long does this all take?

- For both gas and star-dominated mergers

An e=0, 10^8 M_{sun} binary with:

- q=1 will coalesce by z=0 if halo merger started by z~0.1-0.2 => **~1.5 Gyr**

- q=0.1 will coalesce by z=0 if halo merger started by z~0.4-0.5 => **~5 Gyr**

Bottlenecks

Gas-dominated:

- at z>2-ish the circumnuclear/binary disc phase is the longest – should look for BINARY AGN

- at z<2-ish dynamical friction is long, should look for DUAL AGN (but see Dotti et al. 2015)

Star-dominated:

- dynamical friction and scattering phases are ~ equally long, should look for DUAL AGN and BINARY AGN (if enough gas to shine!)

Where are the dual AGN?

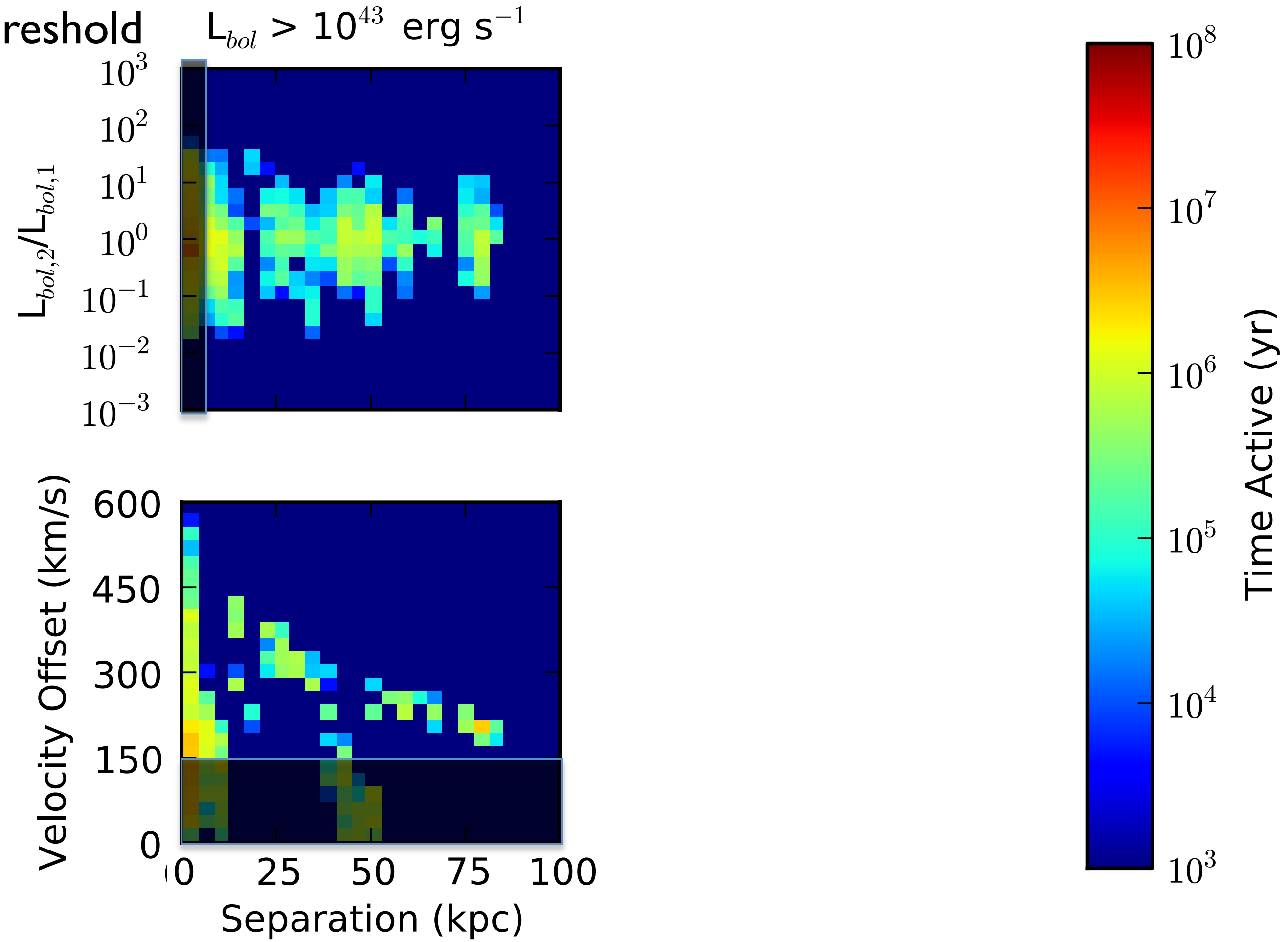
- Spectroscopy
  If a MBH is moving and accreting, the emission lines will be blue- or red- shifted with respect to the host galaxy rest frame (Comerford et al. 2009)

- Imaging
  Search for AGN pairs that are not lenses

Offset/dual AGN fraction from a few % (Mortlock+99; Foreman+09) up to 30% (Koss et al. 2012, Comerford & Greene 2014)

Luminosity threshold

1:2 Spiral-Spiral Merger



Van Wassenhove, MV+12

Dual fraction– 1:2 Coplanar Spiral-Spiral

	Dual Timescale	Dual Fraction
No cutoff	12 Myr	19.2%
d > 1 kpc	10 Myr	16.5%
d > 10 kpc	0.06 Myr	0.1%
v > 150 km/s	3 Myr	4.8%

Imaging: HST (16.5%), SDSS (0.1%)

Spectroscopy (4.8%)

- Observational limitations reduce detectable dual emission
- Secondary has higher Eddington ratio (cf. Comerford+15), but (early on) lower luminosity

Van Wassenhove, MV+12; Capelo, MV+15

Where are the binary AGN?

- Optical surveys:
  Offset broad lines + periodicities

- Radio:
  Imaging – one serendipitous binary (Rodriguez+2006), none in systematic searches (Burke-Spolaor+2011,2014)

At most a few %

See Bogdanovic 2015 for a review

Where are the binary AGN?

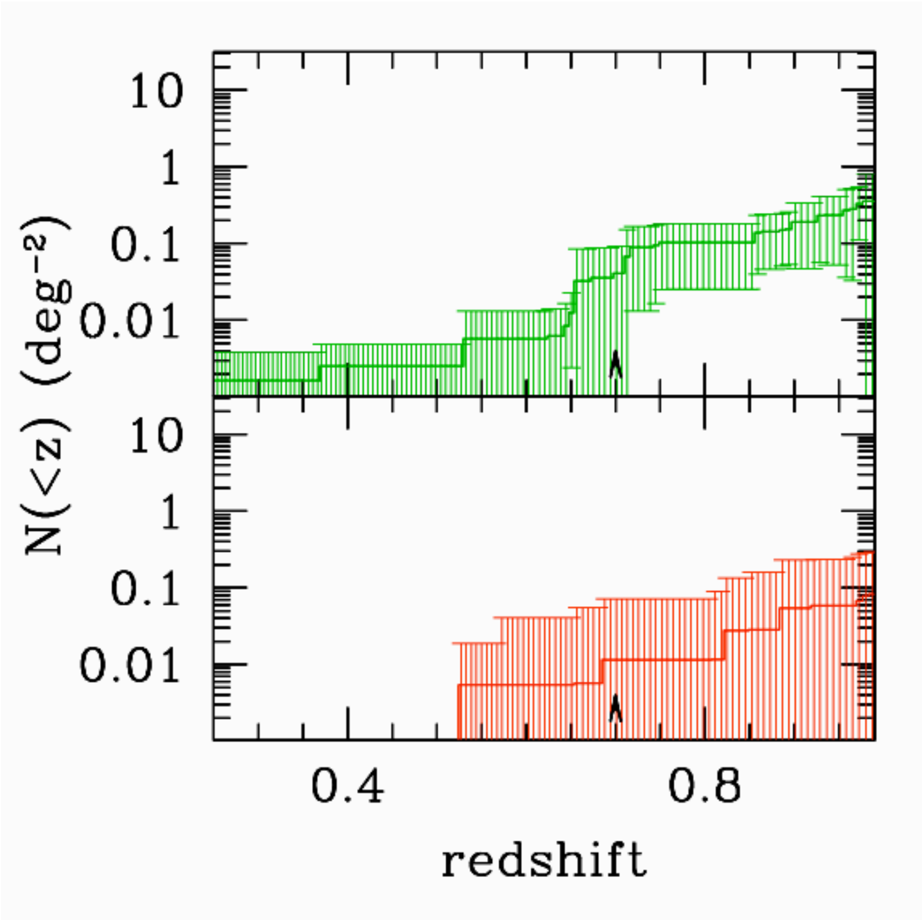
- MBH merger rate from hierarchical evolving MBH population
- select only MBHs with v_{orb}>2000 km/s

- assign luminosity
  - all MBHs are active at some level (Merloni 2009)
  - quasars are triggered by galaxy mergers

- select only QSOs detectable in the SDSS (M_i>-22)

- assign lifetime $t_{\rm life} = 6{\rm Myr} \left(\frac{M_{\rm bin}}{10^7\,{\rm M}_\odot}\right)^{3/4} \left(\frac{4\,q}{1+q^2}\right)^{3/8} \left(\frac{10^\lambda}{0.1}\right)^{-5/8}$ (Haiman et al. 2009)

MV, Miller & Dotti 2009



All MBHs are active at some level

Merger-driven quasar activity

MBH binaries are expected to occur at

- higher redshift
- lower masses

than sampled by the SDSS quasar catalog

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!

Summary

- Because of lifetimes/observability requirement the fraction of detectable duals and binaries is expected to be low

- Although a variety of signatures have been predicted by theoretical studies, in practice, only a few approaches have been used to systematically search for binaries in observational campaigns