Massive black hole pairs and binaries in the cosmos

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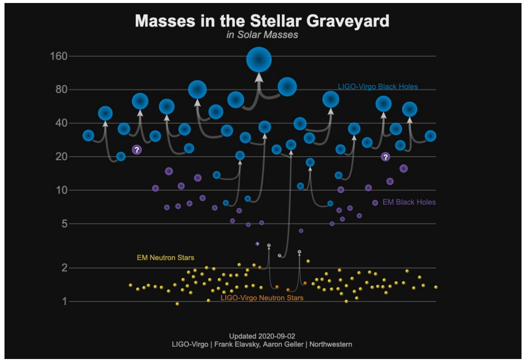
Black Holes in the Universe

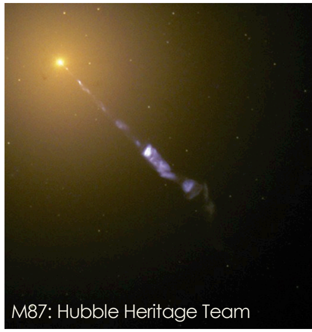
Stellar mass BHs

- Endpoint of the life of massive stars
- Mass from ~2 up to (?) few tens M_{sun}

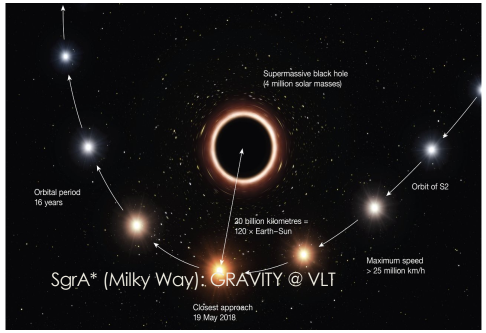


Massive BHs

- Powering AGN and quasars
- Inhabiting the centers of nearby galaxies, including the Milky Way
- Mass > 10^4 M_{sun} up to (?) ~10^{10} M_{sun}

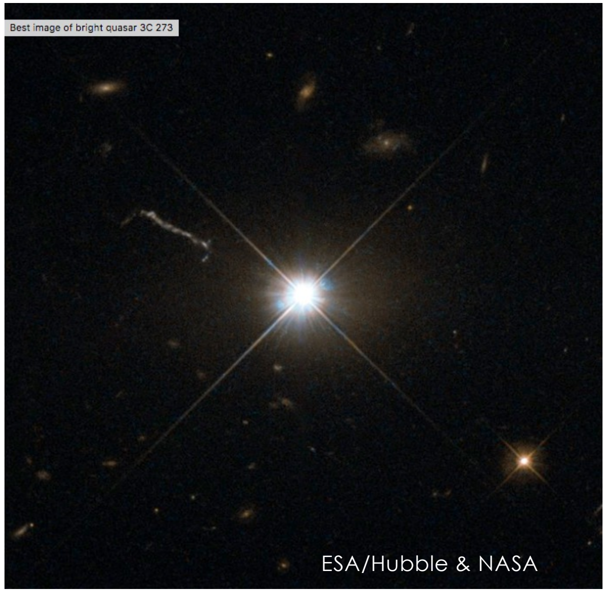

M87: Hubble Heritage Team


M87: Event Horizon Telescope



SgrA* (Milky Way): GRAVITY @ VLT

Active massive black holes



They are as luminous as galaxies: $L \sim 10^{11}-10^{13}\ L_{sun}$

Size of the emitting region is 10^6 times smaller than a galaxy ~ size of solar system

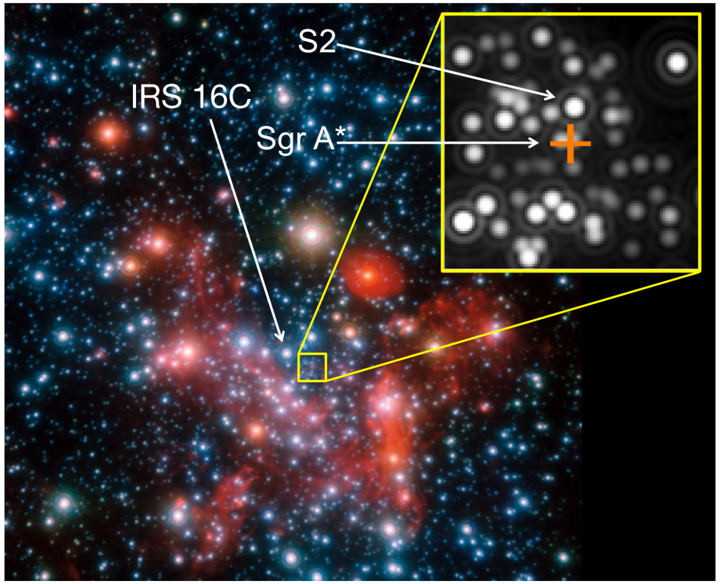
Powered by *accreting* black holes with masses of millions to billions of M_{sun}

Quiescent massive black holes

Many MBHs are quiescent. We have an example in the center of the Milky Way

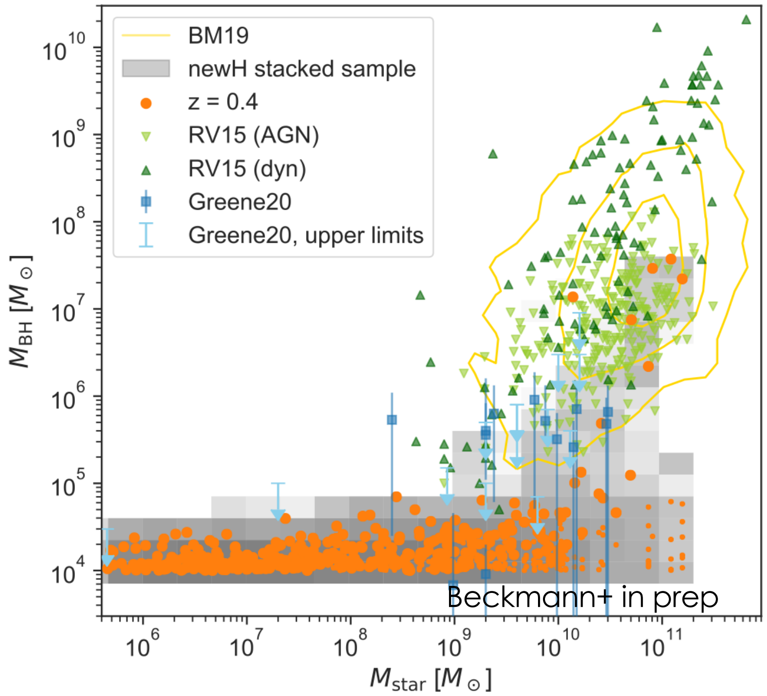
The typical luminosity of Sgr A*, is ~10^{34} erg/s

Not much more than the Sun ($4x10^{33}$ erg/s)



ESO/MPE/S. Gillessen et al.

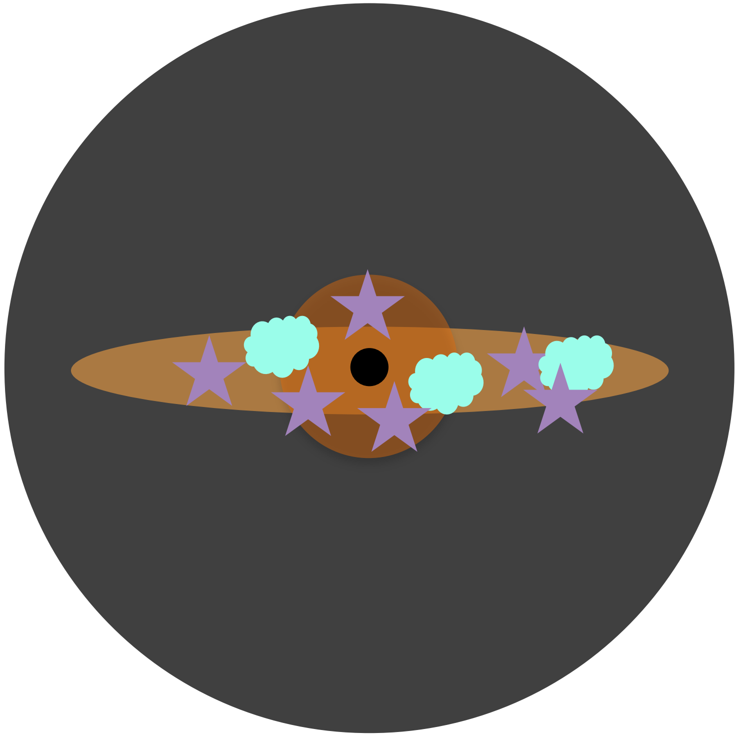
Massive black holes in galaxies



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

Most information is for heavy MBHs in massive galaxies although searches at low masses are being successful (Greene+20 and refs therein)

Massive black holes in galaxies



100 kpc - 10^{12} solar masses

10 kpc - 10^{11} solar masses

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

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

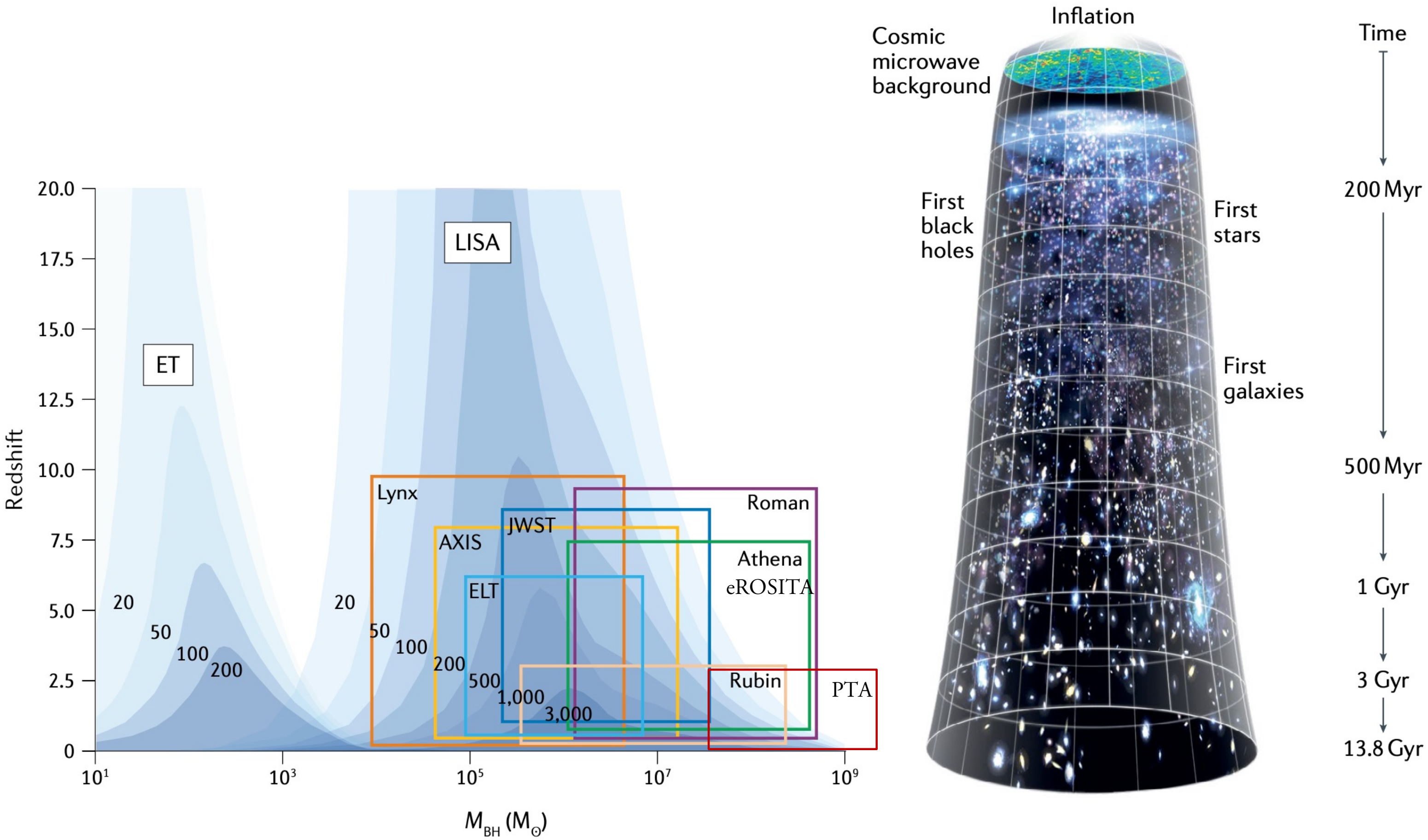
$R_{sch} = 2GM_{BH}/c^2$ MICROPARSEC

$c_s \sim 10\text{-}100$ km/s
$c = 3\times10^5$ km/s

1 parsec=3.26 light years=3×10^{18} cm

$M_{\odot} = M_{sun} = 2\times10^{33}$ g

Finding massive black holes

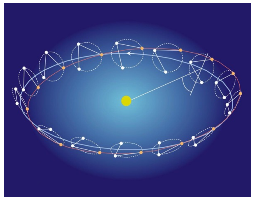


Massive black holes and gravitational waves

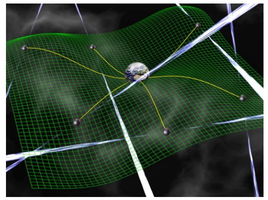
$$f \sim \frac{c}{2\pi R_s} \sim 10^4 \mathrm{Hz} \frac{M_\odot}{M}$$

10 M_{sun} binary
$f<10^3$ Hz
LIGO/Virgo
inspiral/merger

10^6 M_{sun} binary
$f<10^{-2}$ Hz
LISA
inspiral/merger



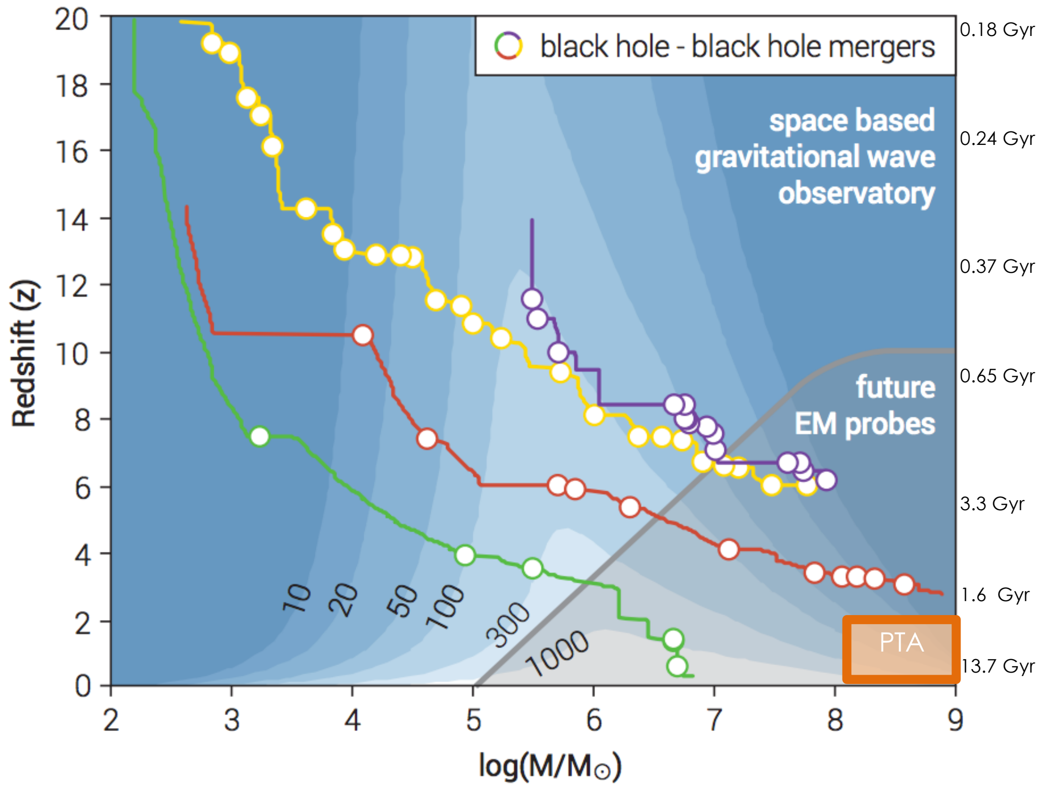
10^9 M_{sun} binary
$f<10^{-6}$ Hz
PTA
inspiral



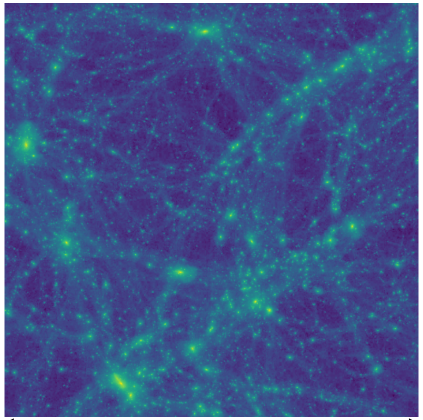
Massive black holes and gravitational waves

MBHs 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 Pulsar Timing Array (PTA) experiments



The journey of two black holes

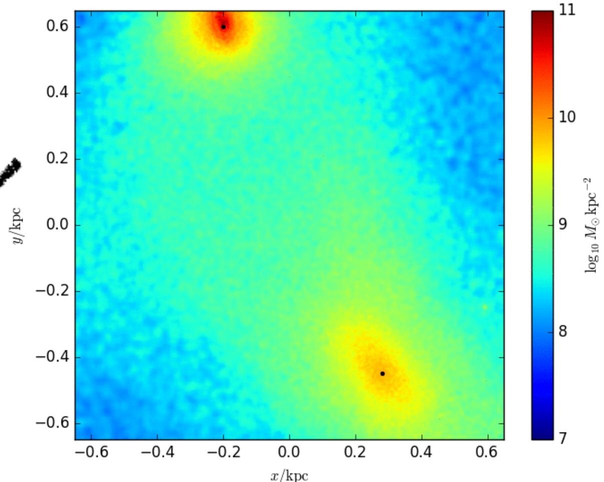


~100 Mpc (cosmology)

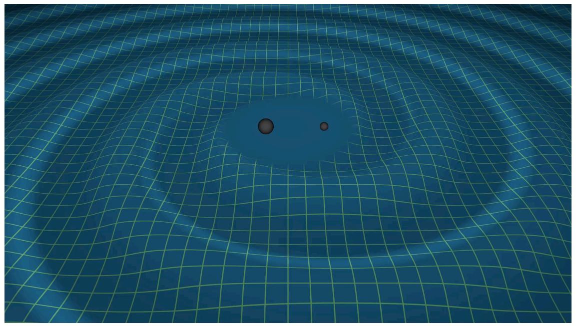
Gravity

~100 kpc -1 kpc (galaxy mergers)

Dynamical
Friction



~1 kpc-1pc (binary formation)



~1 millipc(BH merger)

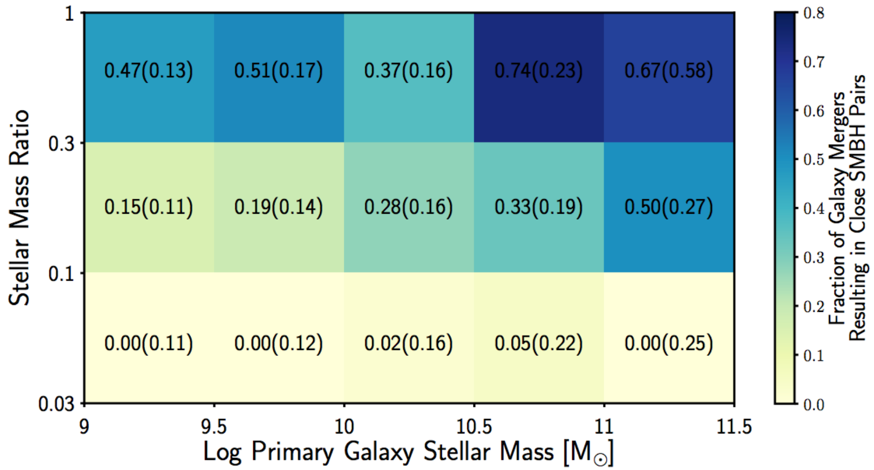
Gas torques?
Stellar scattering?
Last pc problem

Courtesy of Hugo Pfister

The galaxy merger

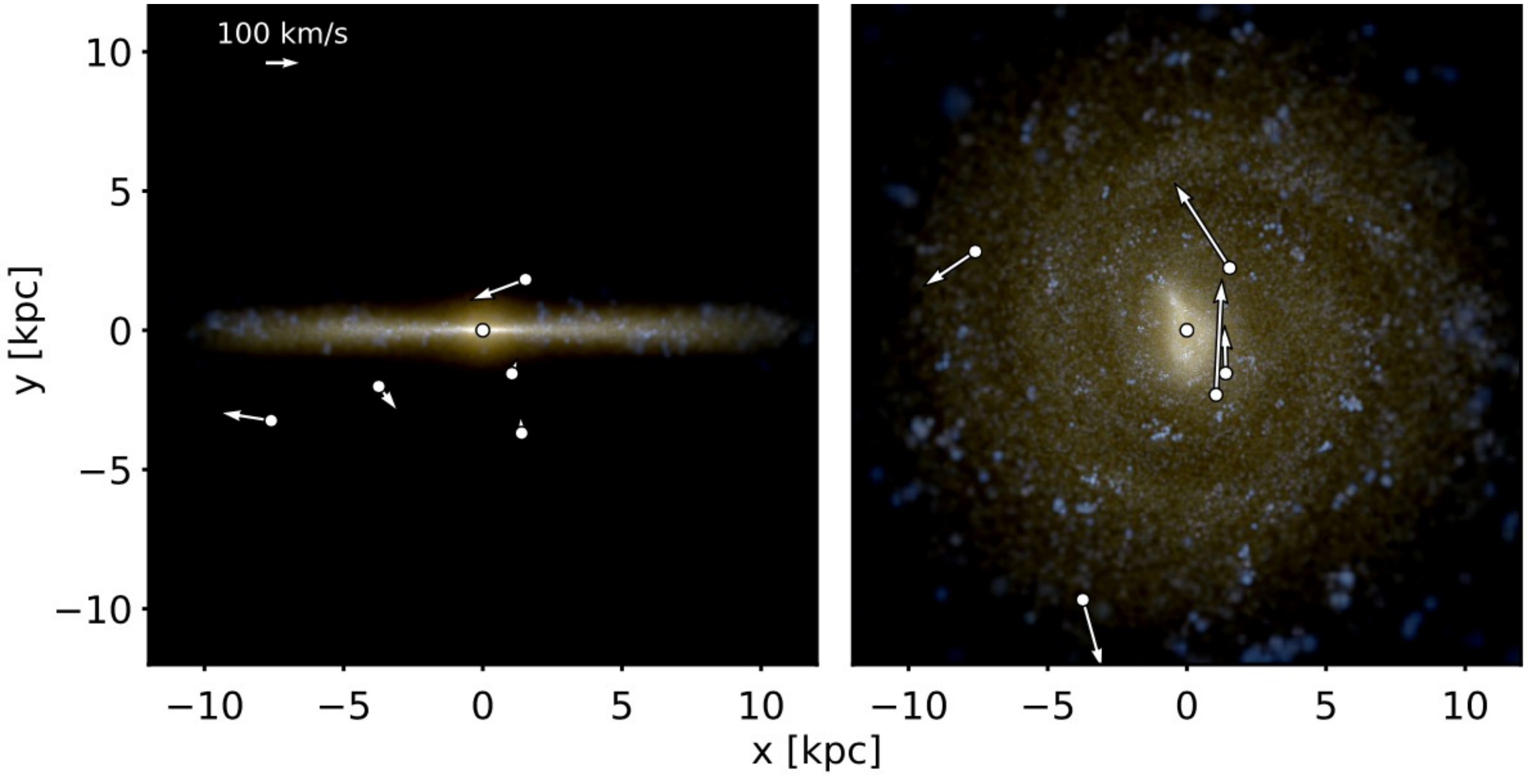
Even if two galaxies each hosting a MBH merge, the formation of a MBH binary and its final coalescence are not guaranteed

When MBHs pair, this occurs on timescales longer than their host halos/galaxies fusion



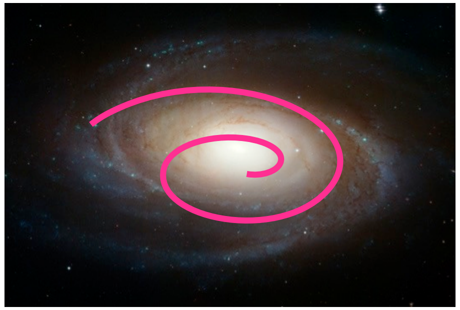
Tremmel+ 2017

Wandering black holes



Tremmel+ 2018
Governato+94; Schneider+02;
Volonteri+03, 05; Bellovary+10

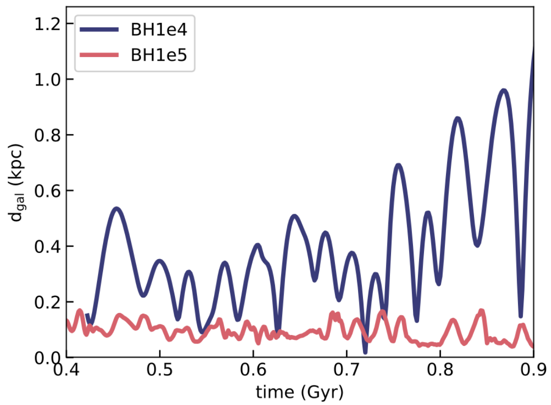
The erratic dynamical life of high-z MBHs



In a smooth potential, e.g., isothermal sphere, dynamical friction causes orbital decay towards the center (Binney & Tremaine) on :

$$t_{\rm df} = 0.67\,{\rm Gyr} \left(\frac{a}{4\,{\rm kpc}}\right)^2 \left(\frac{\sigma}{100\,{\rm km\,s^{-1}}}\right) \left(\frac{M_{\rm BH}}{10^8\,M_\odot}\right)^{-1} \frac{1}{\Lambda}$$

High-z dwarf galaxies have messy, non smooth, time-variable potentials, and no real center:



Pfister+19

Simulating massive black hole mergers in the Universe

We need to sample the large scale structure: *large volume*

We need a statistical sample: *many galaxies*

We need to resolve small physical scales: *high resolution*

We need high-mass MBHs in *massive galaxies* for PTA and low-mass MBHs in *dwarf galaxies* for LISA

Simulating massive black hole mergers in the Universe

Computational resources are limited: you can have either

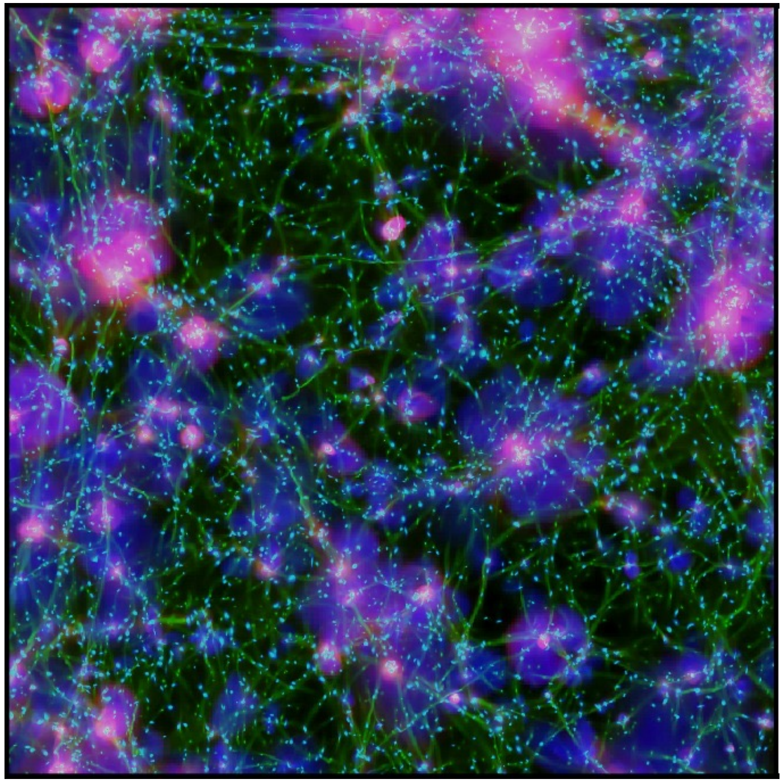
large volume/many objects/low resolution/massive galaxies

or

small volume/few objects/high resolution/dwarf galaxies

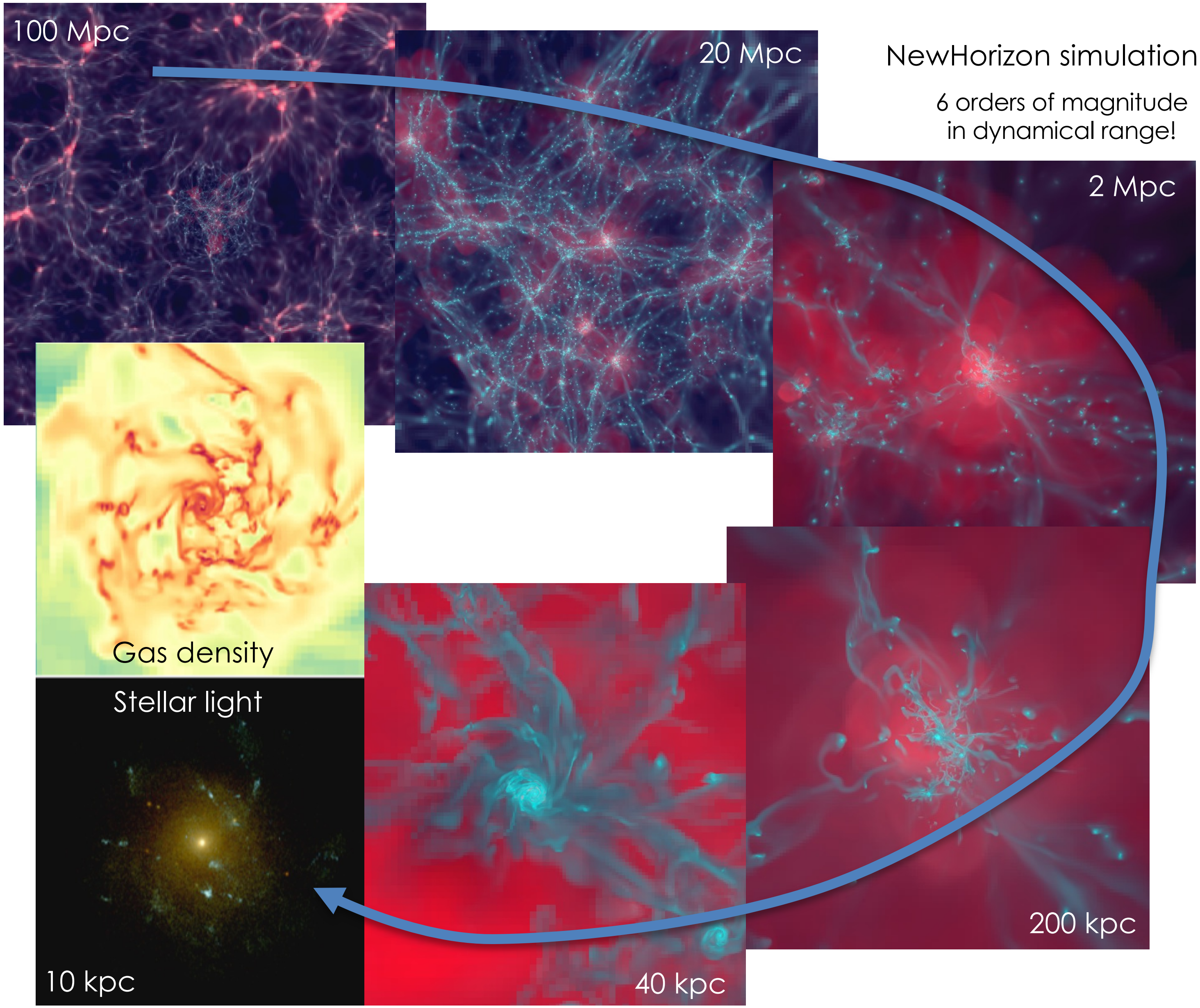
The Horizon-AGN simulation

- Simulation content
  - Run with Ramses (AMR) Teyssier (2002)
  - L_{box}=100 Mpc/h
  - 1024^3 DM particles $M_{DM,res}=8x10^7\ M_{sun}$
  - Finest cell resolution dx=1 kpc
  - Gas cooling & UV background heating
  - Low efficiency star formation
  - Stellar winds + SNII + SNIa
  - O, Fe, C, N, Si, Mg, H
  - AGN feedback radio/quasar *(Dubois+, 2012)*
- Outputs
  - Standard outputs ~200 Myrs
  - MBH outputs ~0.7 Myr
  - Star particles are backed up every 10-20 Myr
  - Lightcones (1°x1°) performed on-the-fly
    - Dark Matter (position, velocity)
    - Gas (position, density, velocity, pressure, chemistry)
    - Stars (position, mass, velocity, age, chemistry)
    - Black holes (position, mass, velocity, accretion rate)
- z=0 using 10 Mhours on 4096 cores
- 150 000 galaxies per snapshot (> 50 particles)
- $7x10^9$ leaf cells (more than Illustris or Eagle)



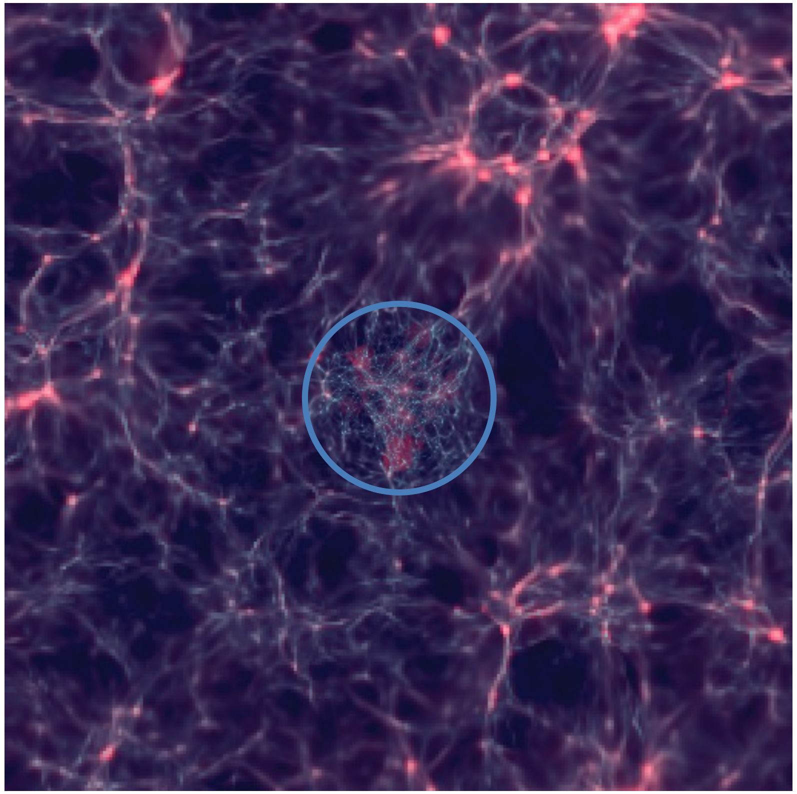
http://horizon-simulation.org/

Dubois+14


NewHorizon simulation
6 orders of magnitude
in dynamical range!
100 Mpc
20 Mpc
2 Mpc
200 kpc
40 kpc
10 kpc
Gas density
Stellar light

NewHorizon

- Simulation content
  - Same IC phases than Horizon-AGN
  - High-res sphere of 10 Mpc radius (average density environment)
  - $M_{DM,hires}=10^6\ M_{sun}$ (vs $10^8\ M_{sun}$ in HAGN)
  - $M_{*,res}=10^4\ M_{sun}$ (vs $10^6\ M_{sun}$ in HAGN)
  - dx=0.04 kpc
  - Turbulent SF criterion *(Padoan & Nordlund, 11, Devriendt et al)*
  - Mechanical SNII feedback *(Kimm et al, 14,15)*
  - AGN accretion and feedback *(Dubois et al, 10)*
  - dynamical friction from gas *(Dubois et al, 12)*
  - BH spin evolution *(Dubois et al, 14)*
  - Gas tracer particles
- Outputs
  - Standard outputs ~15 Myrs
  - MBH outputs ~0.5 Myr
- z=0.25 with ~50 Mhours (French-Korean effort)

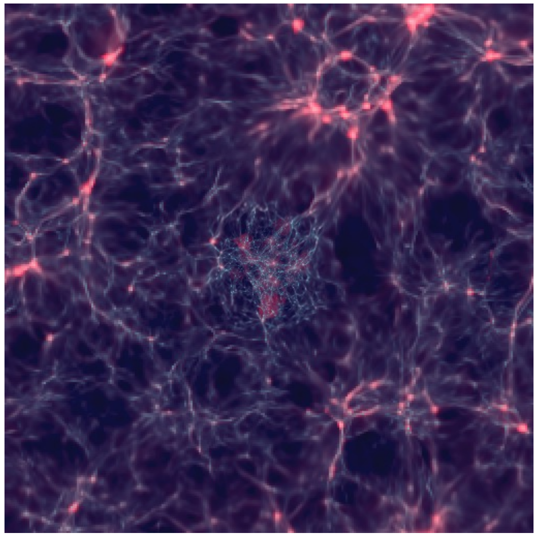


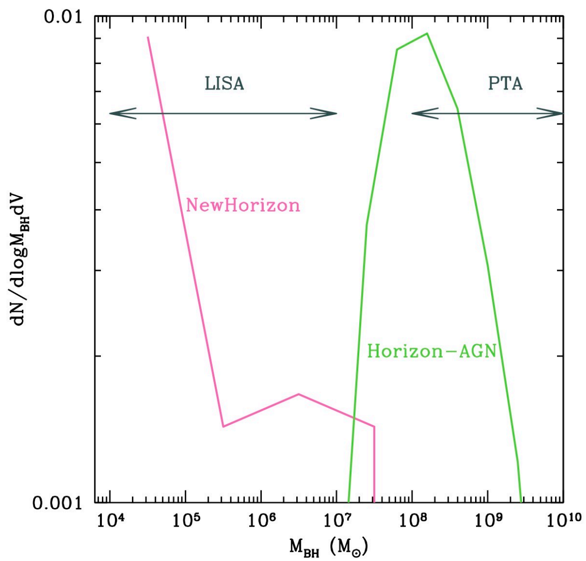
Dubois+20

Simulating massive black hole mergers in the Universe

Horizon-AGN for massive galaxies and high-mass MBHs

NewHorizon for dwarf galaxies and low-mass MBHs

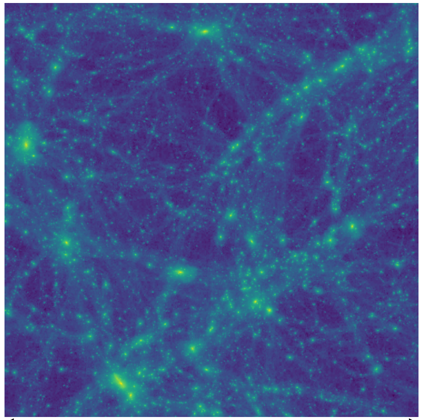




Mass distribution of *merging MBHs* in NewHorizon and Horizon-AGN

Volonteri+20

The journey of two black holes

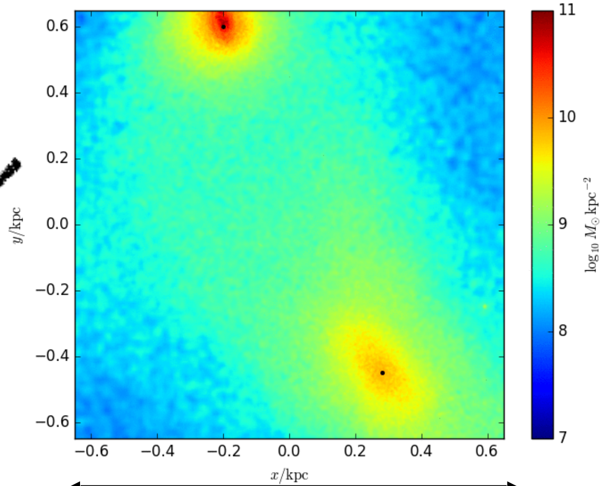


~100 Mpc (cosmology)

Gravity

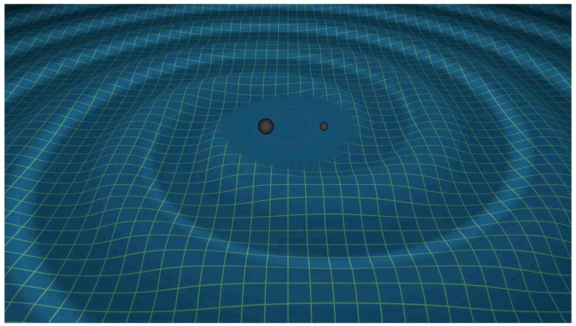
~100 kpc -1 kpc (galaxy mergers)

Dynamical Friction



~1 kpc-1pc (binary formation)

Gas torques?
Stellar scattering?
Last pc problem



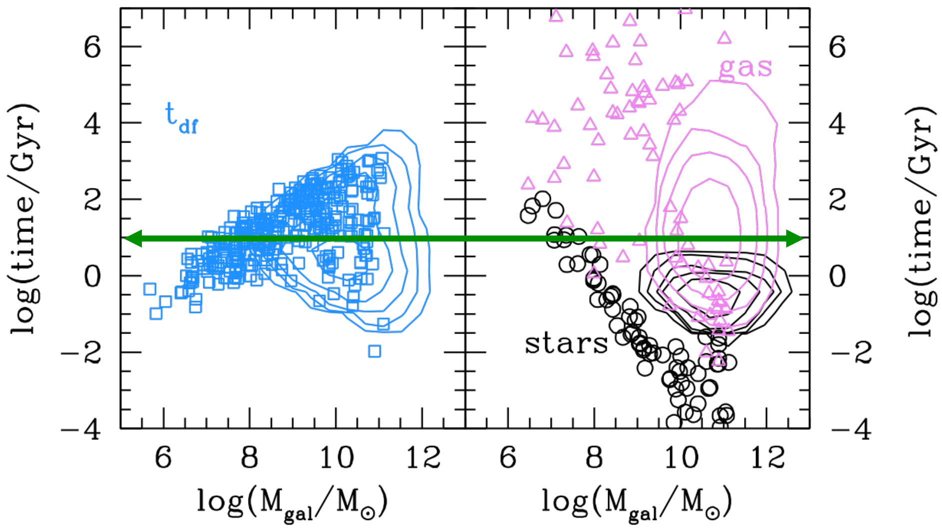
~1 millipc(BH merger)

Courtesy of Hugo Pfister

Simulating massive black hole mergers in the Universe

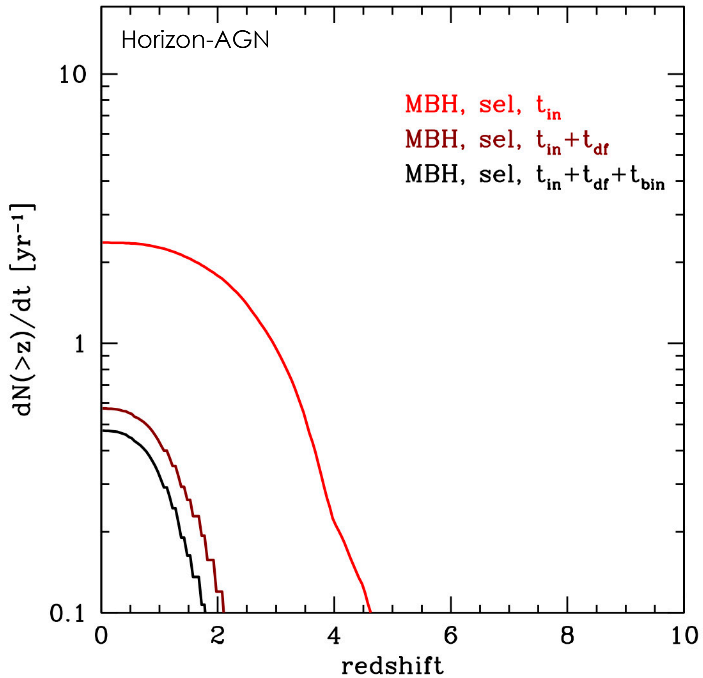
Include in post-processing dynamical delays below resolution:

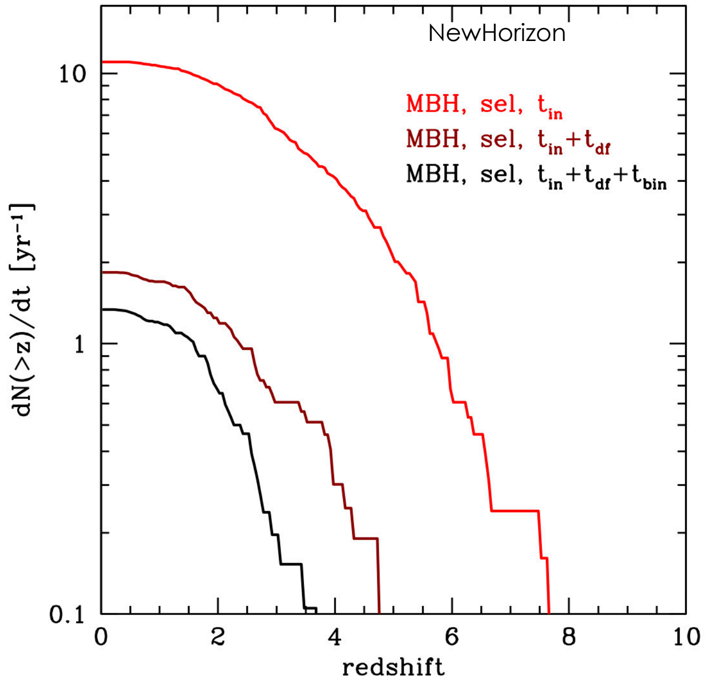
- dynamical friction until the MBHs form a binary
- stellar hardening and disc migration after the MBHs form a binary



Volonteri+20

The massive black hole merger rate





The merger rate estimated from a high-resolution simulation is higher than that from a low-resolution simulation because *low-mass galaxies dominate the galaxy merger rate*

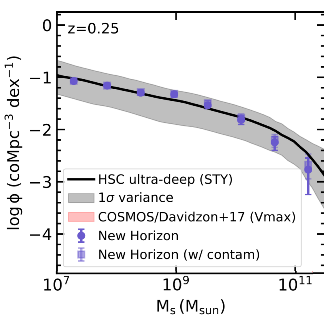
Volonteri+20

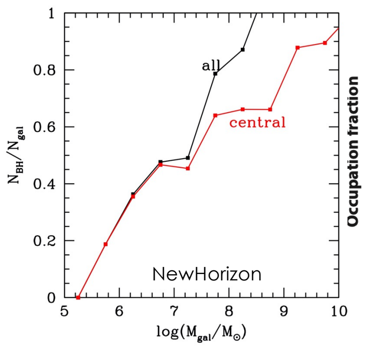
Why more massive black hole mergers in NewHorizon

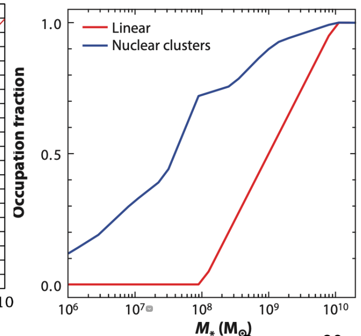
Galaxy mass function: there are more dwarf galaxies than high-mass galaxies

A significant fraction of dwarf galaxies host MBHs: at z ~ 0.5 about 10% of galaxies with mass 10^6 M_{sun} host a MBH, increasing to 100% at 10^9 M_{sun}

Resolving dwarf galaxies is *crucial* for the low-mass MBHs relevant for LISA

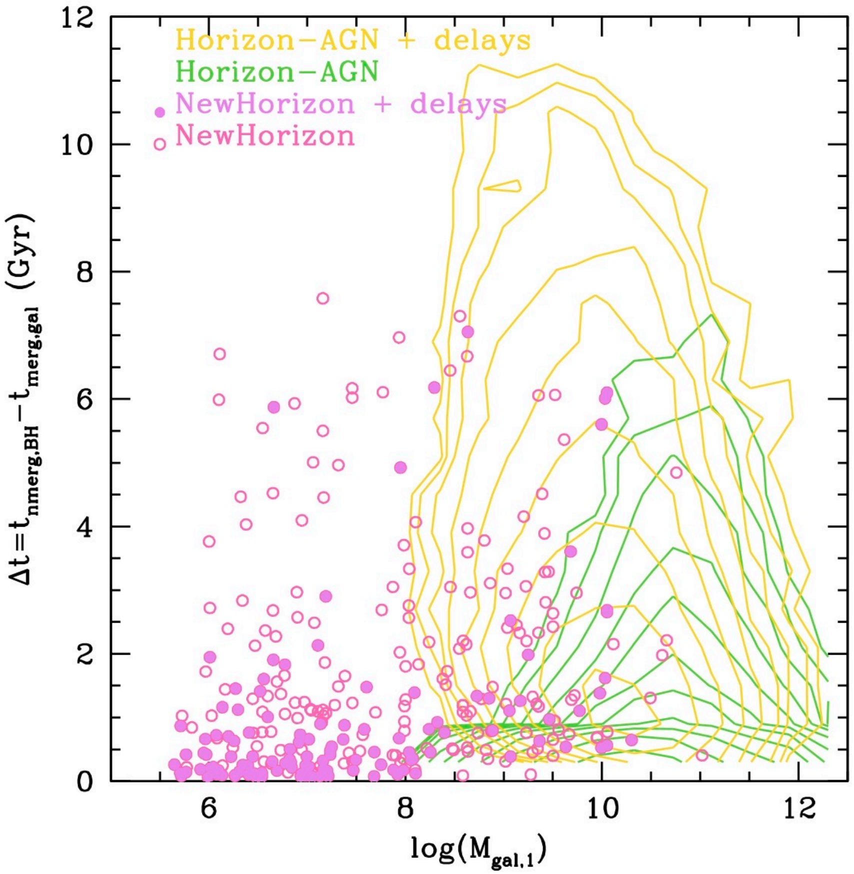






Greene+20

Are merging MBHs found in merging galaxies?

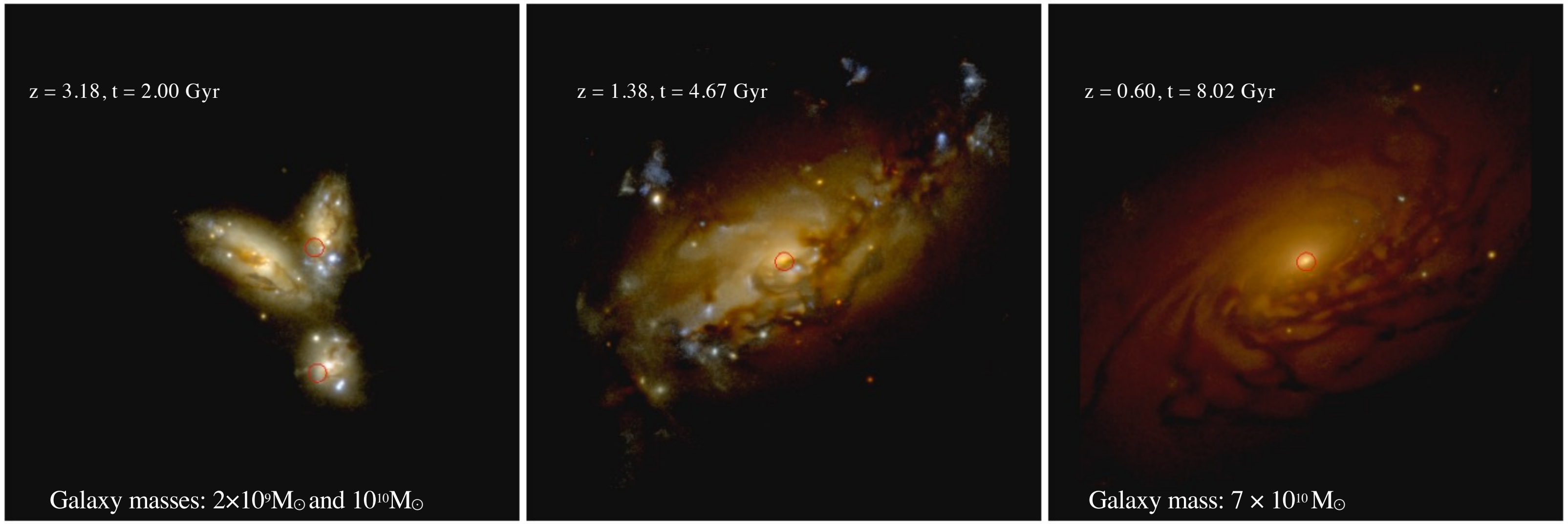


Generally, no.

MBHs often merge long after galaxies do

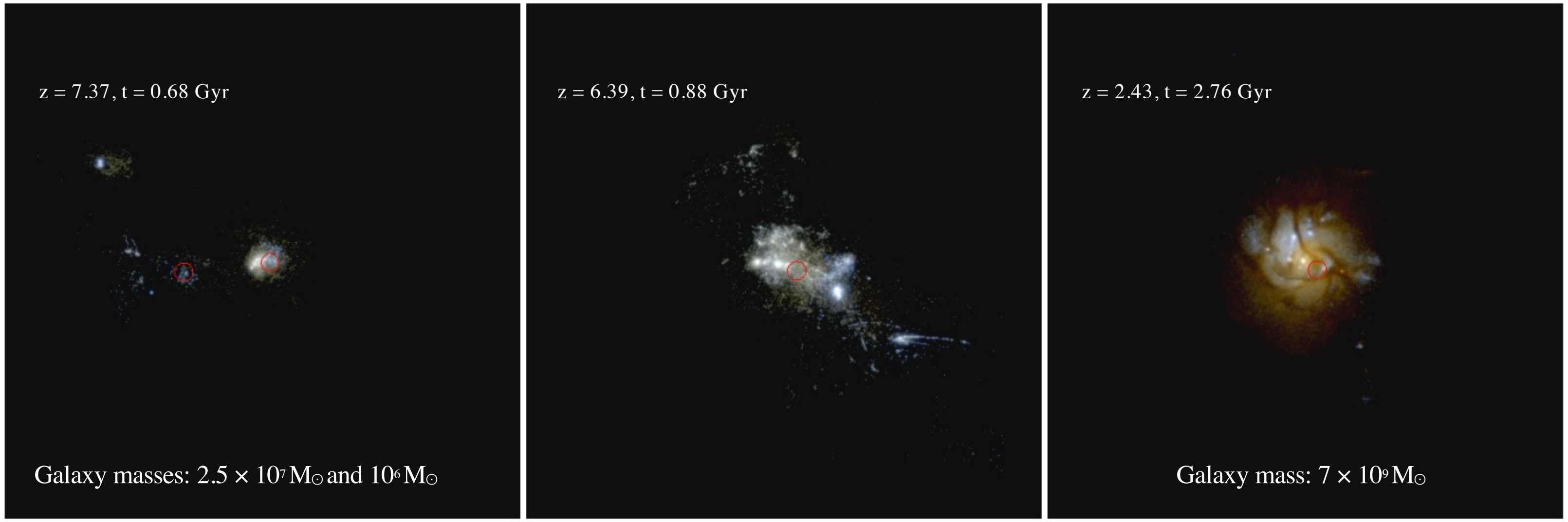
Adapted from Volonteri+20

Are merging MBHs found in merging galaxies?



The galaxy merger Before adding delays After adding delays

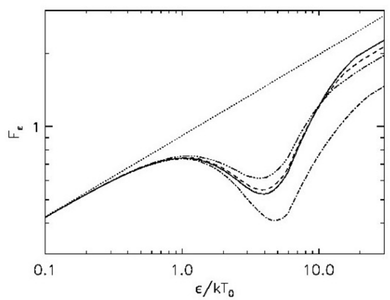
Are merging MBHs found in merging galaxies?



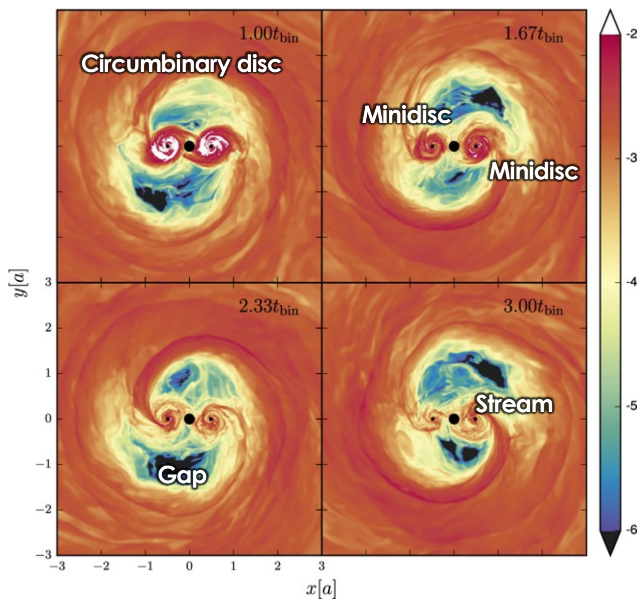
The galaxy merger | Before adding delays | After adding delays

How can we find binary MBHs?

- Possible periodicities in the light curve
- Double peaked emission line profiles (Doppler shift caused by binary motion)
- Gaps in the spectrum ("notch")
- Shocks when streams hit the edges of mini-discs



e.g.,Armitage & Natarajan 02; MacFadyen & Milosavljevic 08; Bogdanovic+08; Dotti+08, Cuadra+09; Sesana+12; Roedig+12; Shi+12; Noble+12; D'Orazio+13; D'Ascoli+19



How can we find binary MBHs?

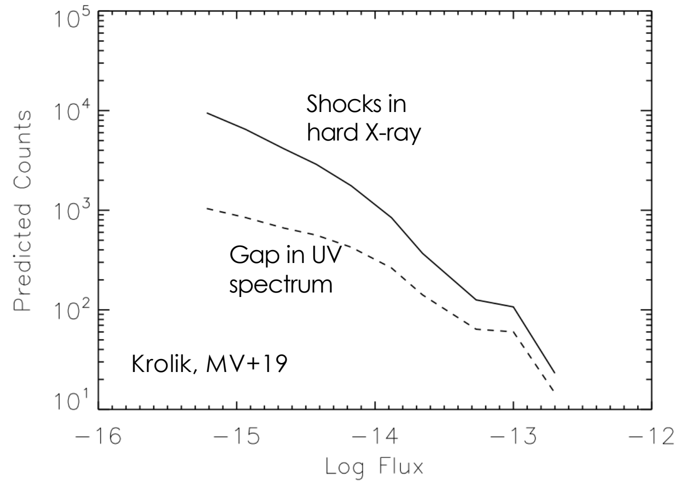
Hydrodynamical cosmological simulations ~(100 Mpc)^3 box: masses, mass ratios, accretion rates of MBH binaries + postprocessing of MBH binary emission

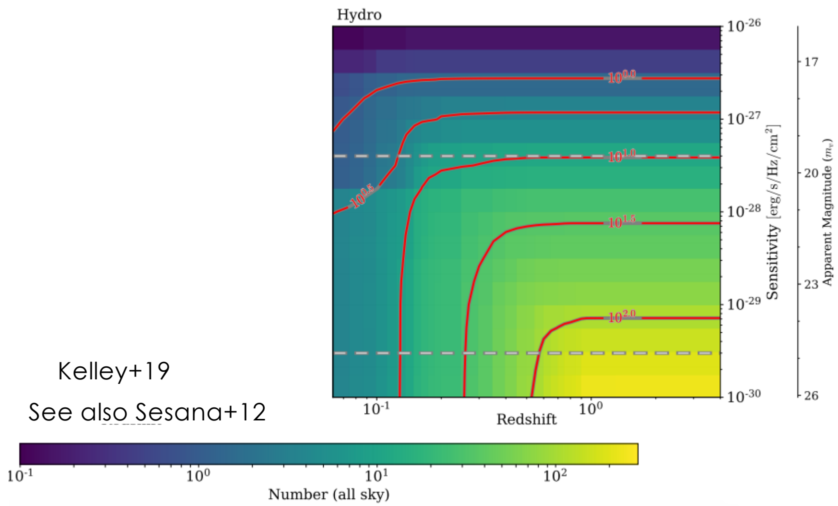
- Gaps in the spectrum
- Shocks when streams hit the edges of mini-discs

- Possible periodicities in the light curve

eROSITA can detect the hard X-ray sources (unusual spectra/periodicities)

SDSS V will take thousands of spectra of AGN: possible detection of "notch" sources

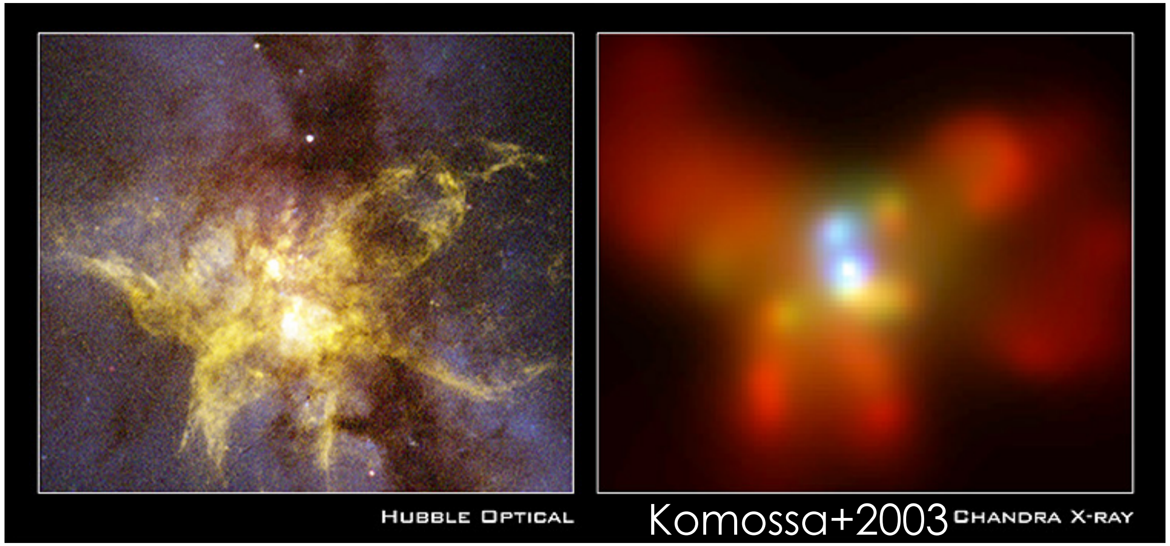


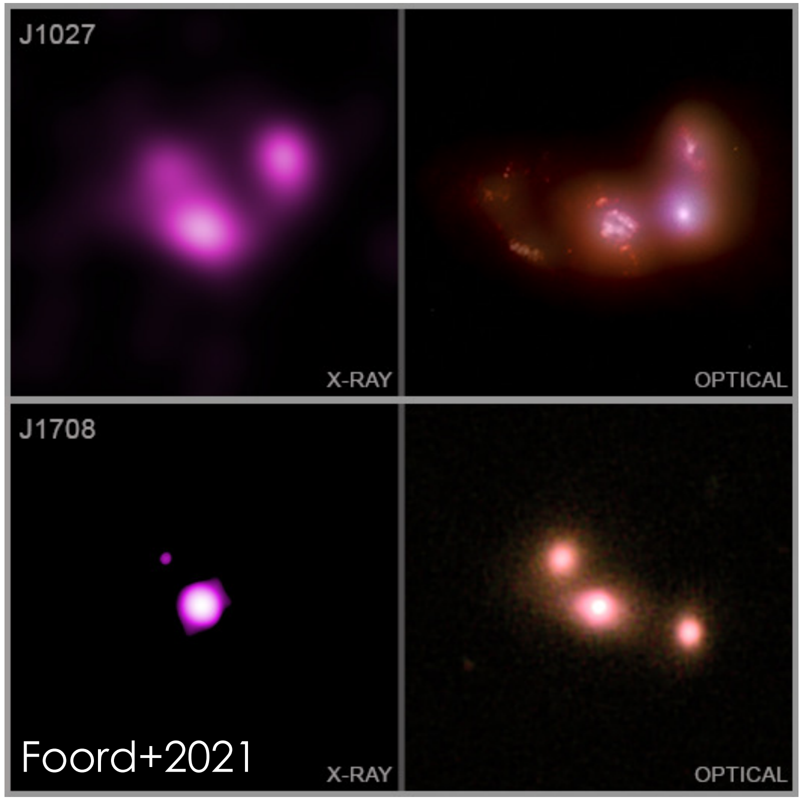


Kelley+19

See also Sesana+12

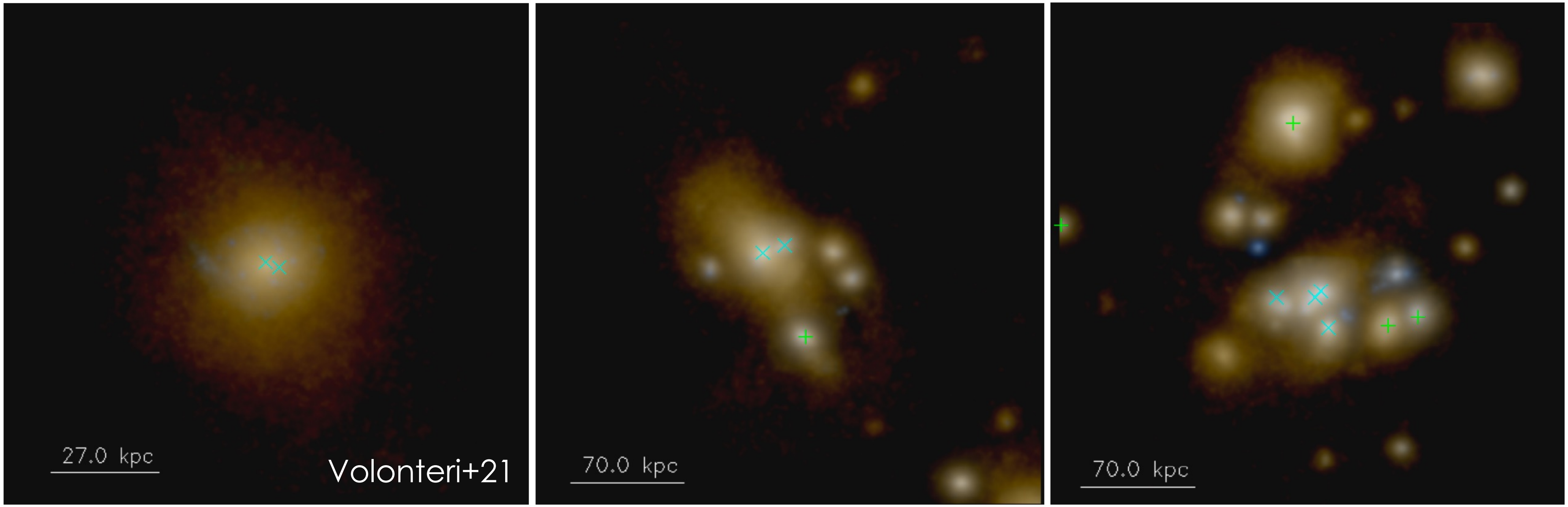
A step back: dual AGN





During their journey the MBHs sometimes accrete at the same time: dual AGN

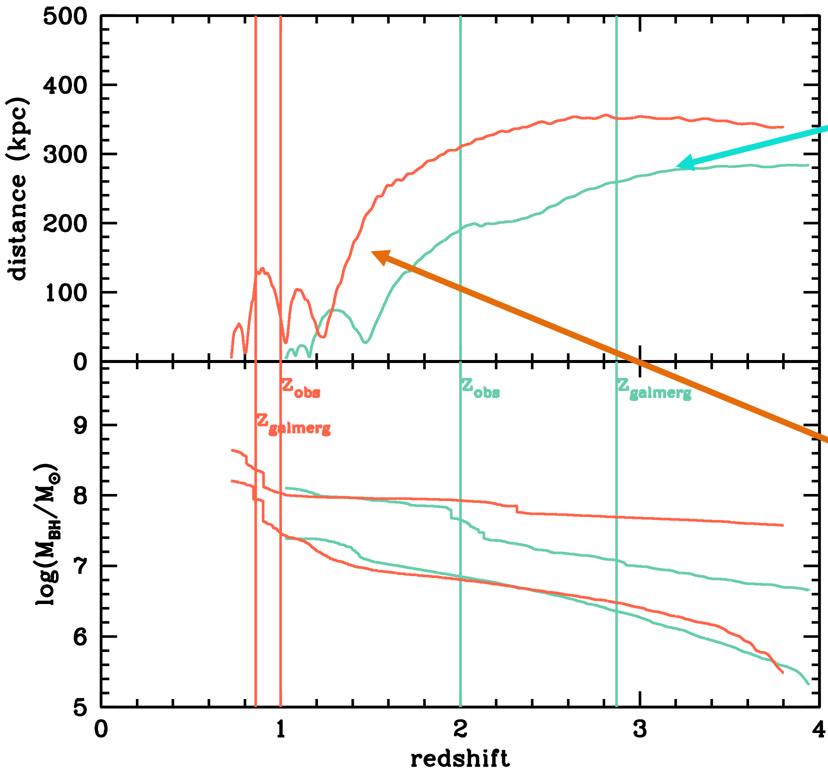
A step back: dual AGN in Horizon-AGN



During their journey the MBHs sometimes accrete at the same time: dual AGN (also in simulations)

Van Wassenhove et al. 2012; Blecha et al. 2013; Steinborn et al. 2016; Volonteri et al. 2016; Capelo et al. 2017; Rosas-Guevara et al. 2019; Bhowmick et al. 2020a; Li et al. 2021; Ricarte et al. 2021

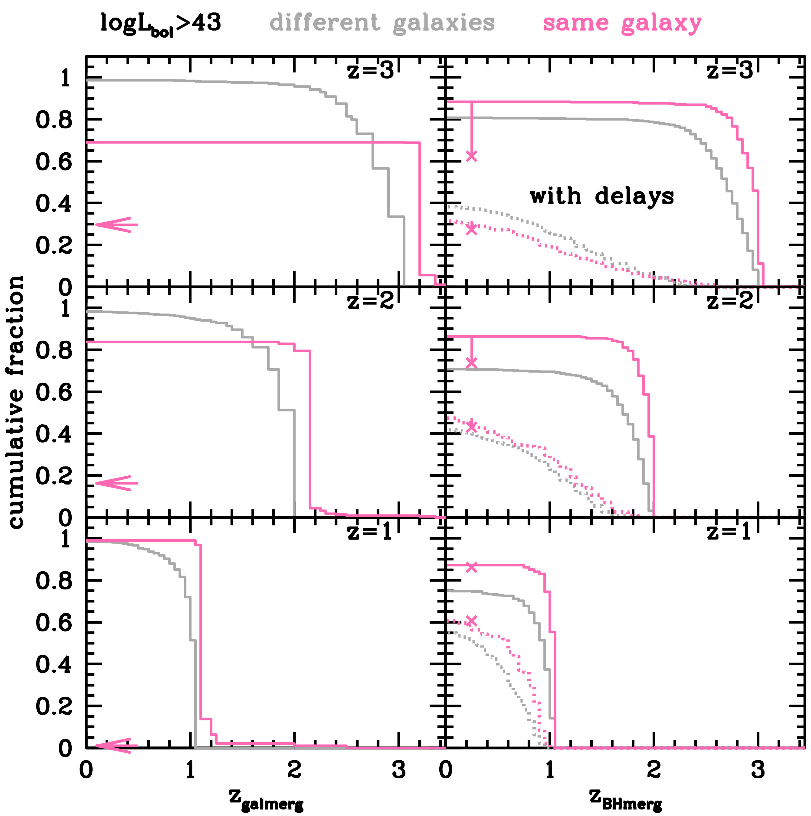
Linking dual AGN and MBH mergers in Horizon-AGN



Dual AGN can be observed in *separate* galaxies *before* the galaxies merge => $z_{galmerg} > z_{obs}$

Dual AGN can be observed in *the same* galaxy *after* the galaxies merge => $z_{galmerg} < z_{obs}$

Linking dual AGN and MBH mergers in Horizon-AGN



Dual AGN hosted in different galaxies lead to a MBH merger by z = 0 in 70-80% of cases and higher probability for duals hosted in one galaxy

With postprocessed delays this decreases to 30-60%

Dual AGN can be used to infer the MBH merger rate after corrections

Summary

The changing environments affect the dynamics of massive black holes and as a consequence their growth by accretion and mergers

Lively high-z galaxies challenge our classic mental picture

Tracking MBH evolution in low-mass galaxies is crucial for gravitational wave studies with LISA and for tidal disruption event searches

To study MBH growth and mergers in the cosmological context we need to trace a statistical population of galaxies, from dwarfs to massive

Dual AGN and searches for MBH binaries in the electromagnetic spectrum can help us understand the population of merging MBHs that LISA/PTA can see