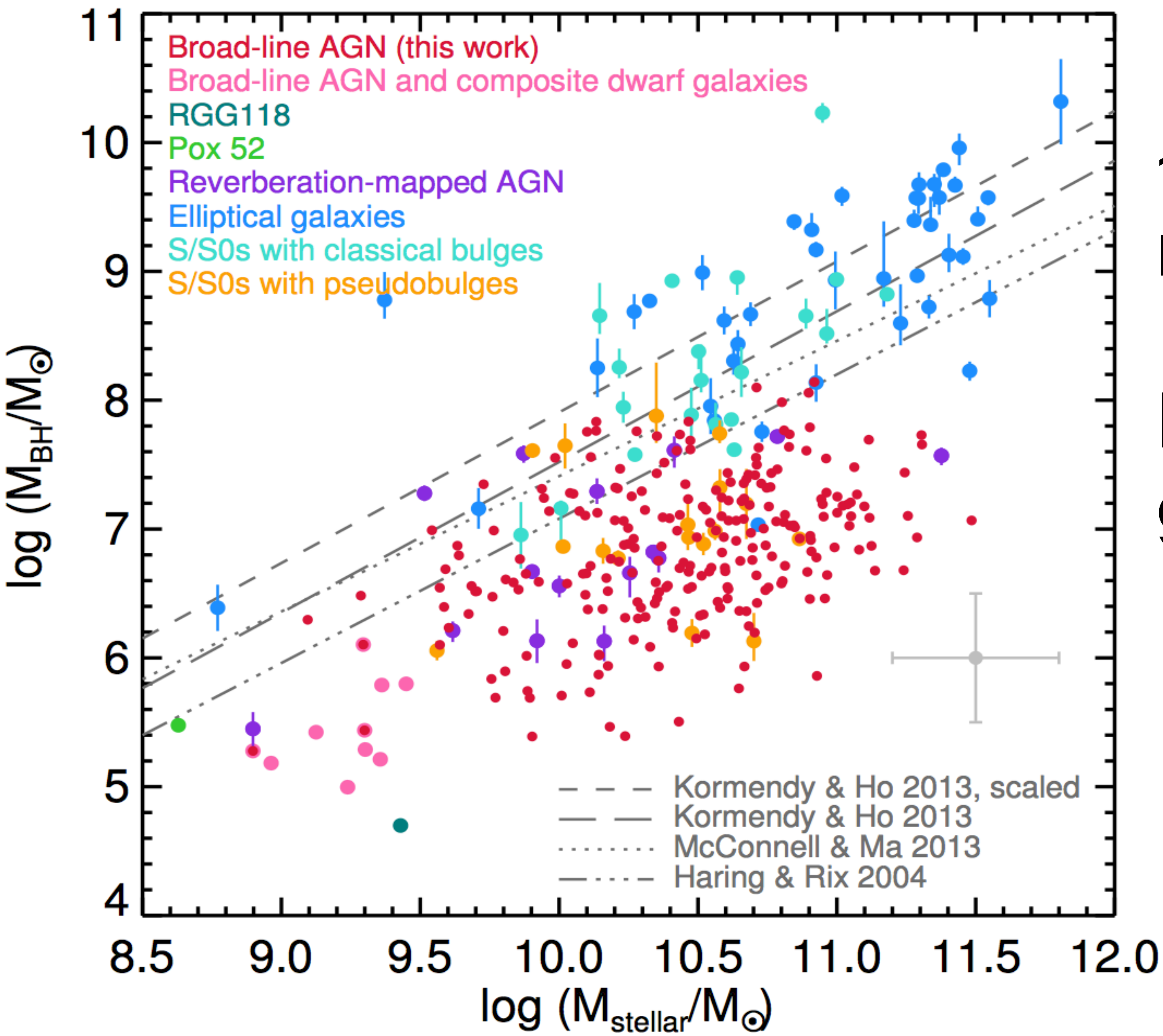
Massive black holes in galaxies



~100 MBHs detected in nearby galaxies to-date

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

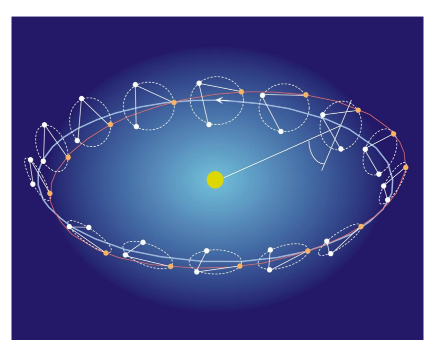
Black hole masses correlate with galaxy properties. Their growth/evolution is connected

Massive black holes and gravitational waves

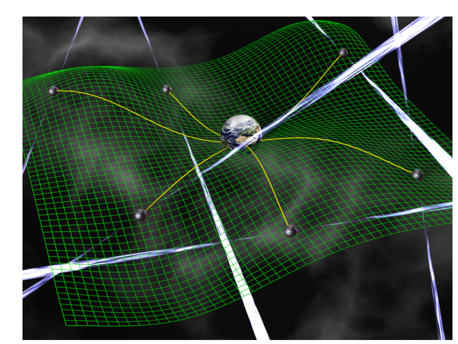
$$f \sim \frac{c}{2\pi R_s} \sim 10^4 \mathrm{Hz} \frac{M_\odot}{M}$$

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

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



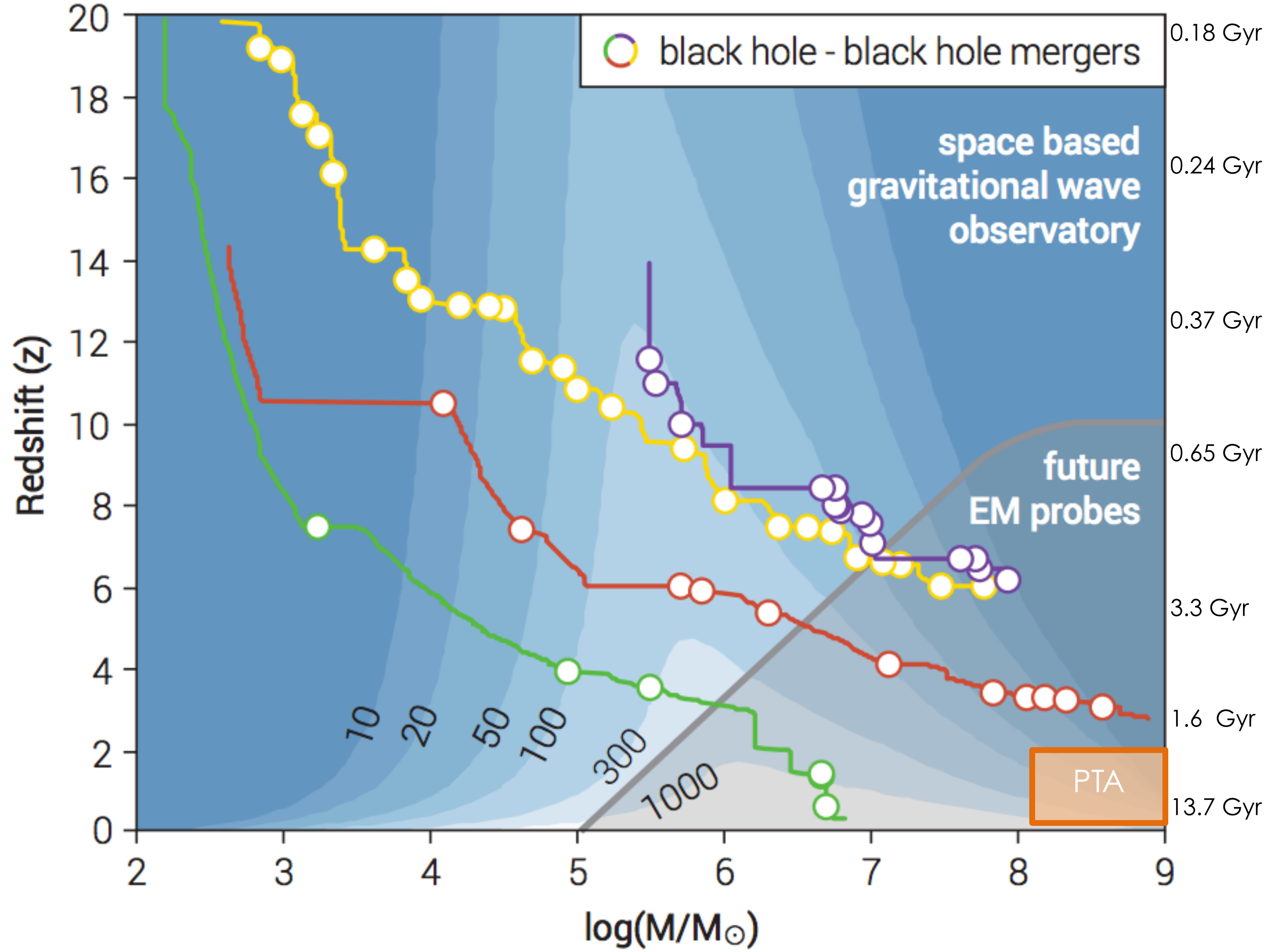
10^9 Msun binary
$f<10^{-6}$ Hz
PTA
inspiral+bk



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



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

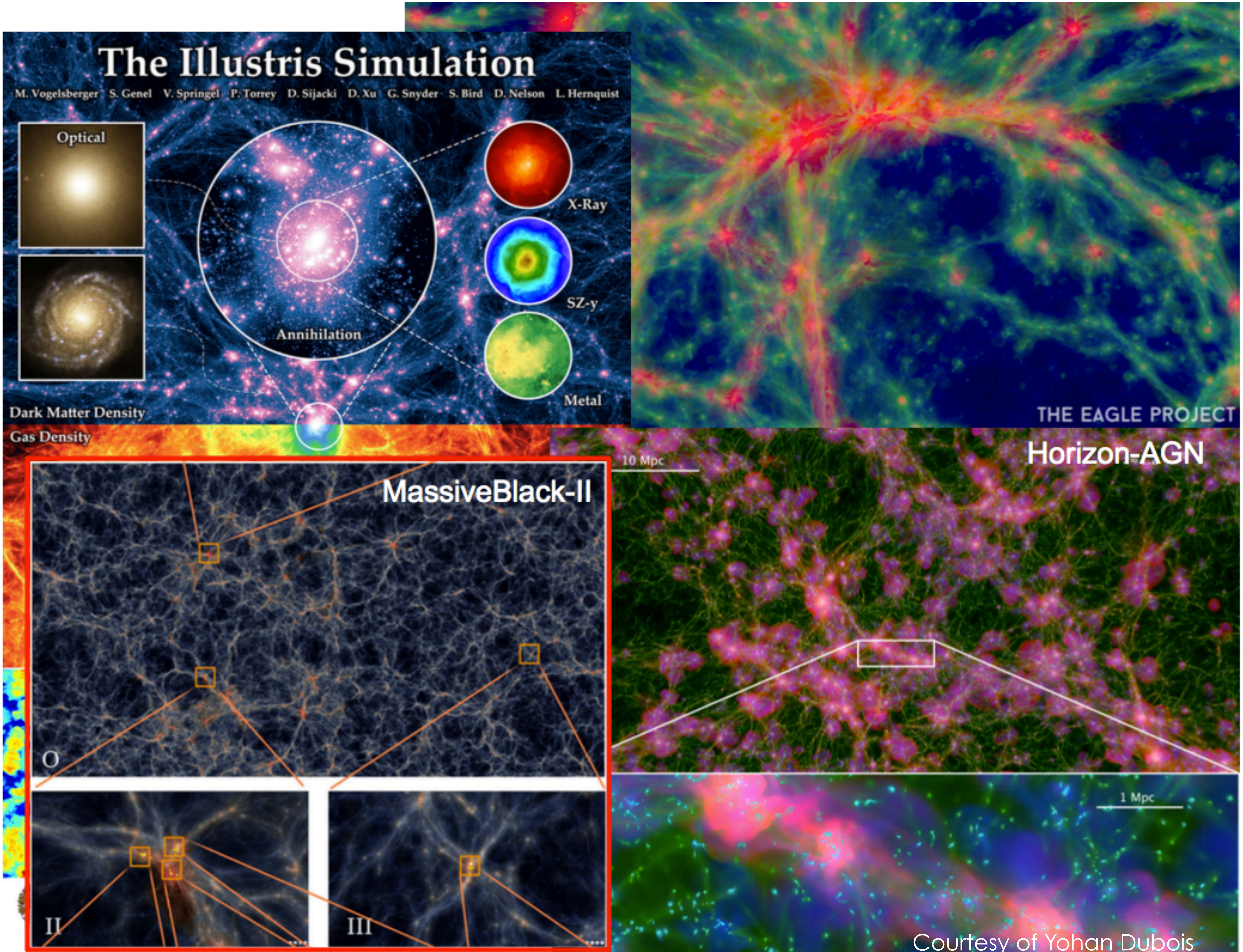
Simulating massive black hole mergers in the Universe

Simulations are like observational surveys: you can have either

large and *shallow* (large volume/many objects/low resolution/massive galaxies)

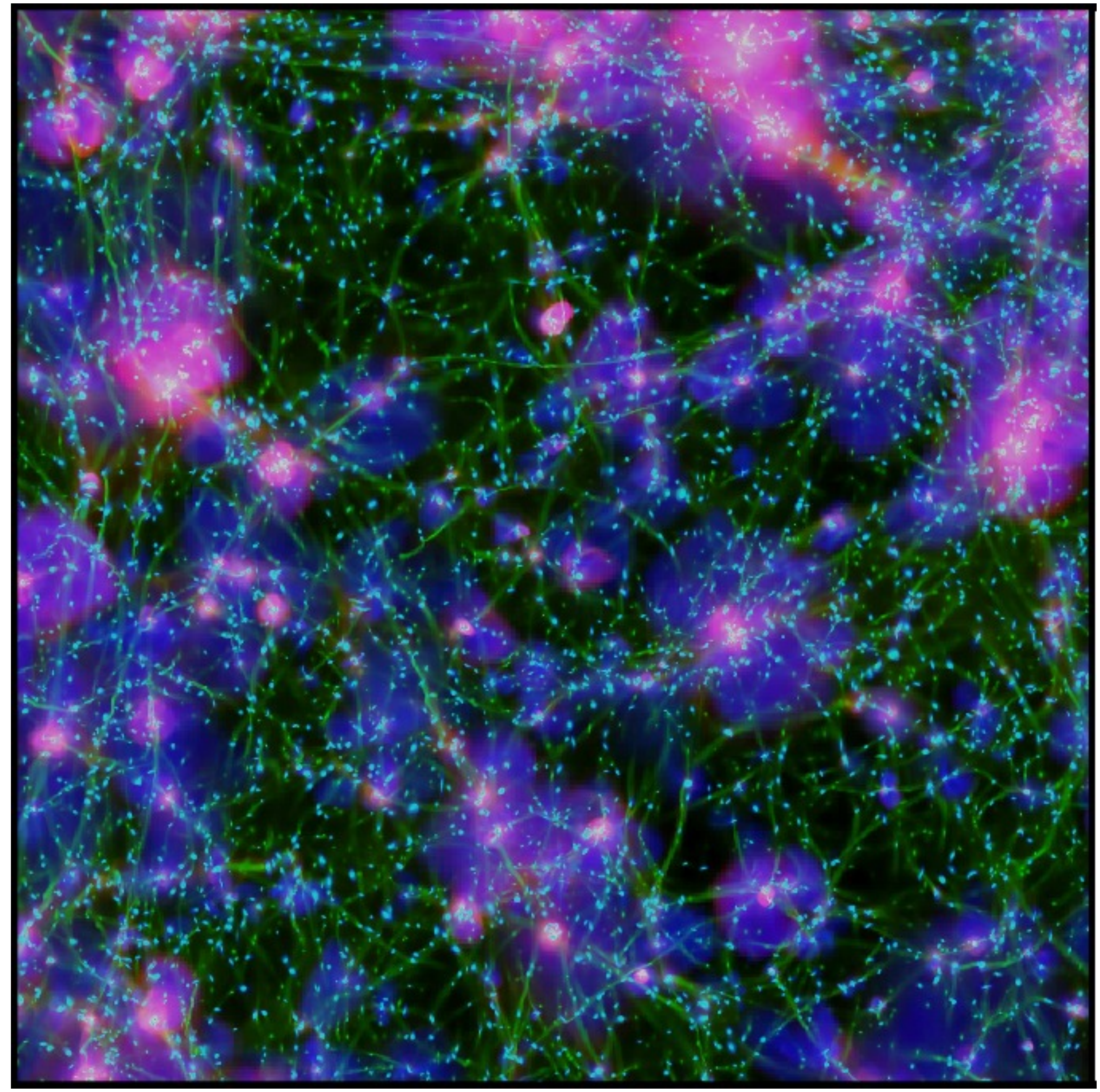
or

small and *deep* (small volume/few objects/high resolution/dwarf galaxies)


The Illustris Simulation
M. Vogelsberger S. Genel V. Springel P. Torrey D. Sijacki D. Xu G. Snyder S. Bird D. Nelson L. Hernquist
Optical
X-Ray
SZ-y
Annihilation
Metal
Dark Matter Density
Gas Density
THE EAGLE PROJECT
Horizon-AGN
10 Mpc
1 Mpc
MassiveBlack-II
O
II
III
Courtesy of Yohan Dubois

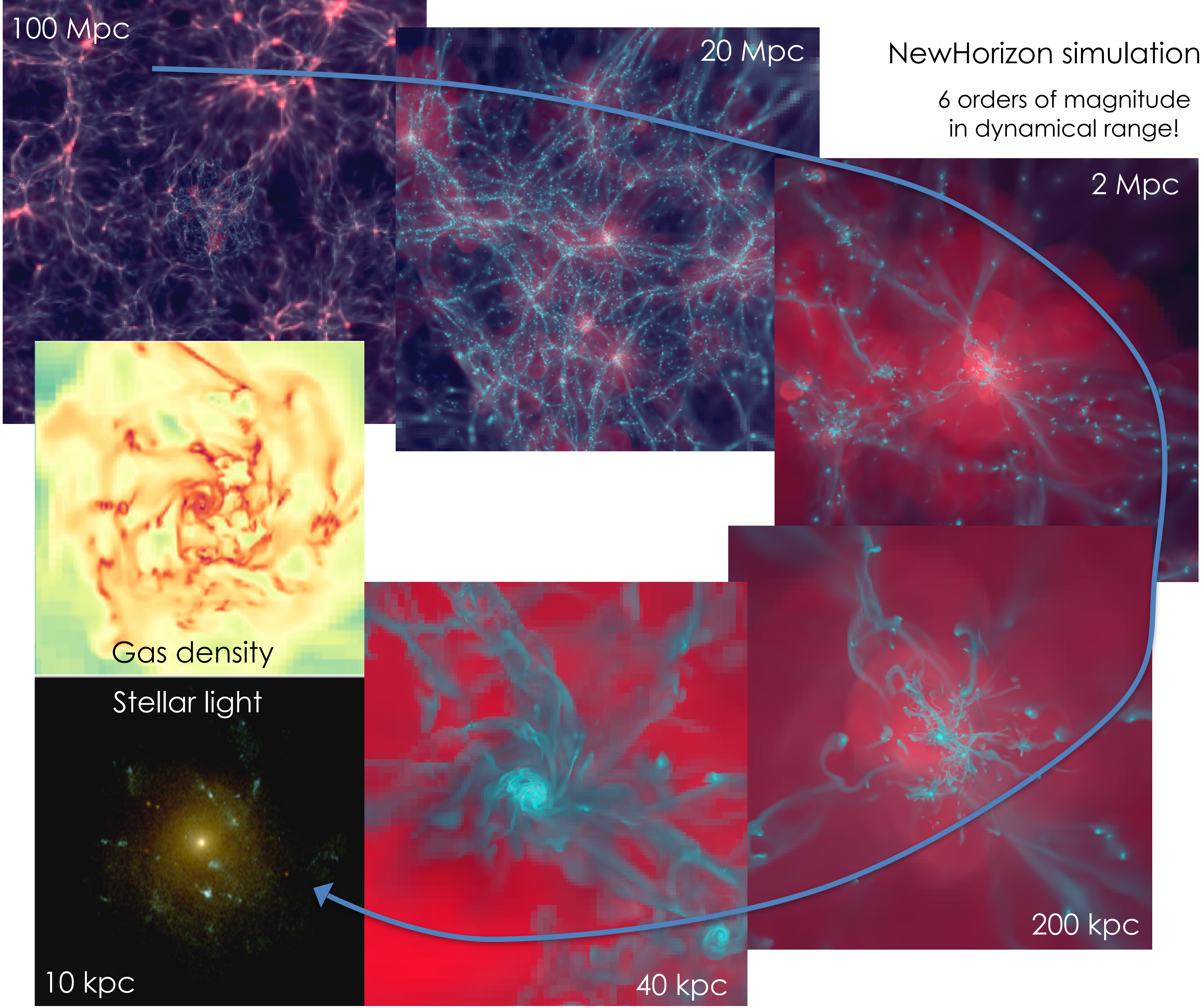
The Horizon-AGN simulation

- Simulation content
  - Run with Ramses (AMR) Teyssier (2002)
  - L_{box}=100 Mpc/h
  - 1024^3 DM particles $M_{DM,res}=8\times10^7\ M_{sun}$
  - 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)
- 7×10^9 leaf cells (more than Illustris or Eagle)



http://horizon-simulation.org/

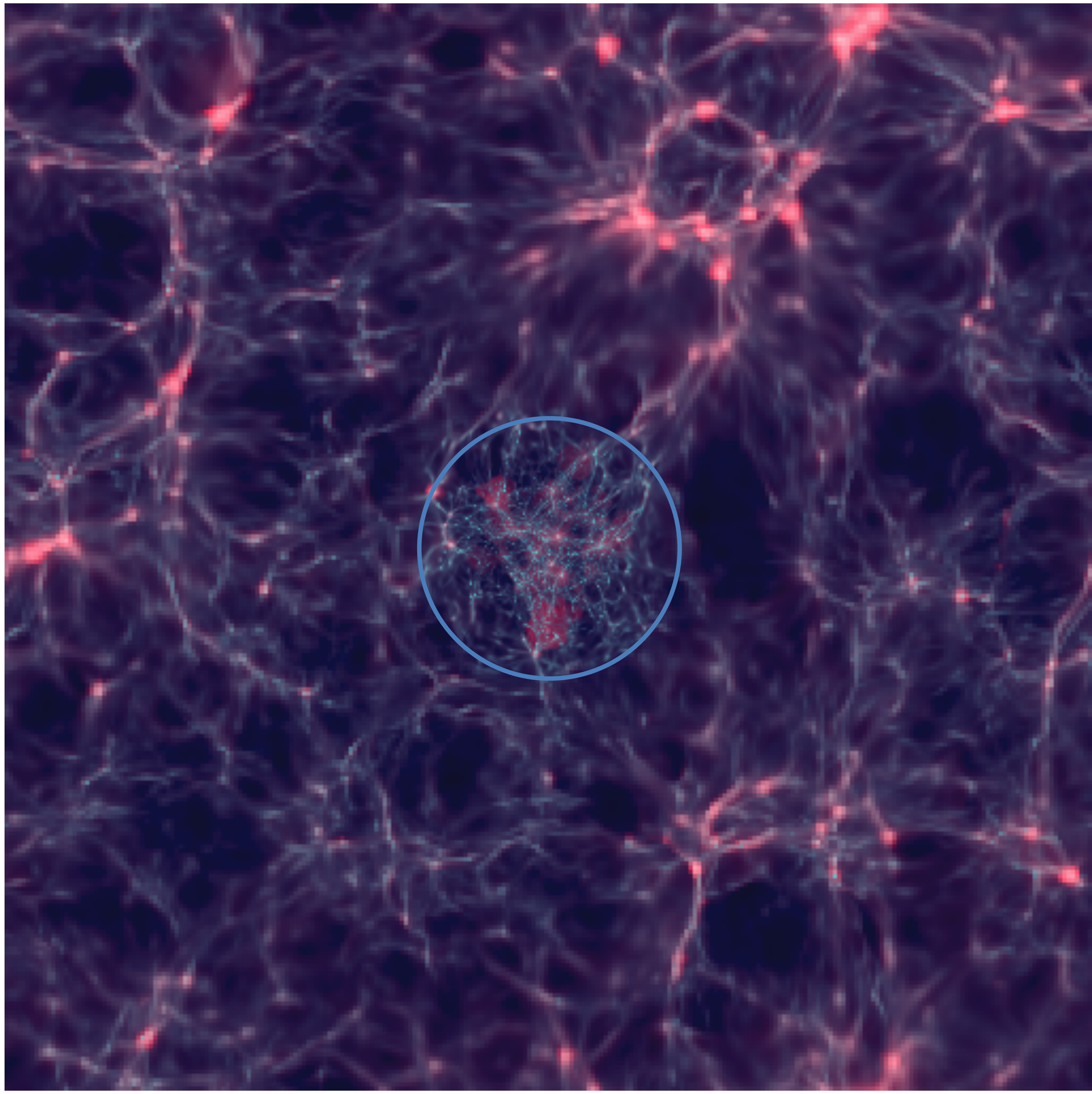
Dubois+14



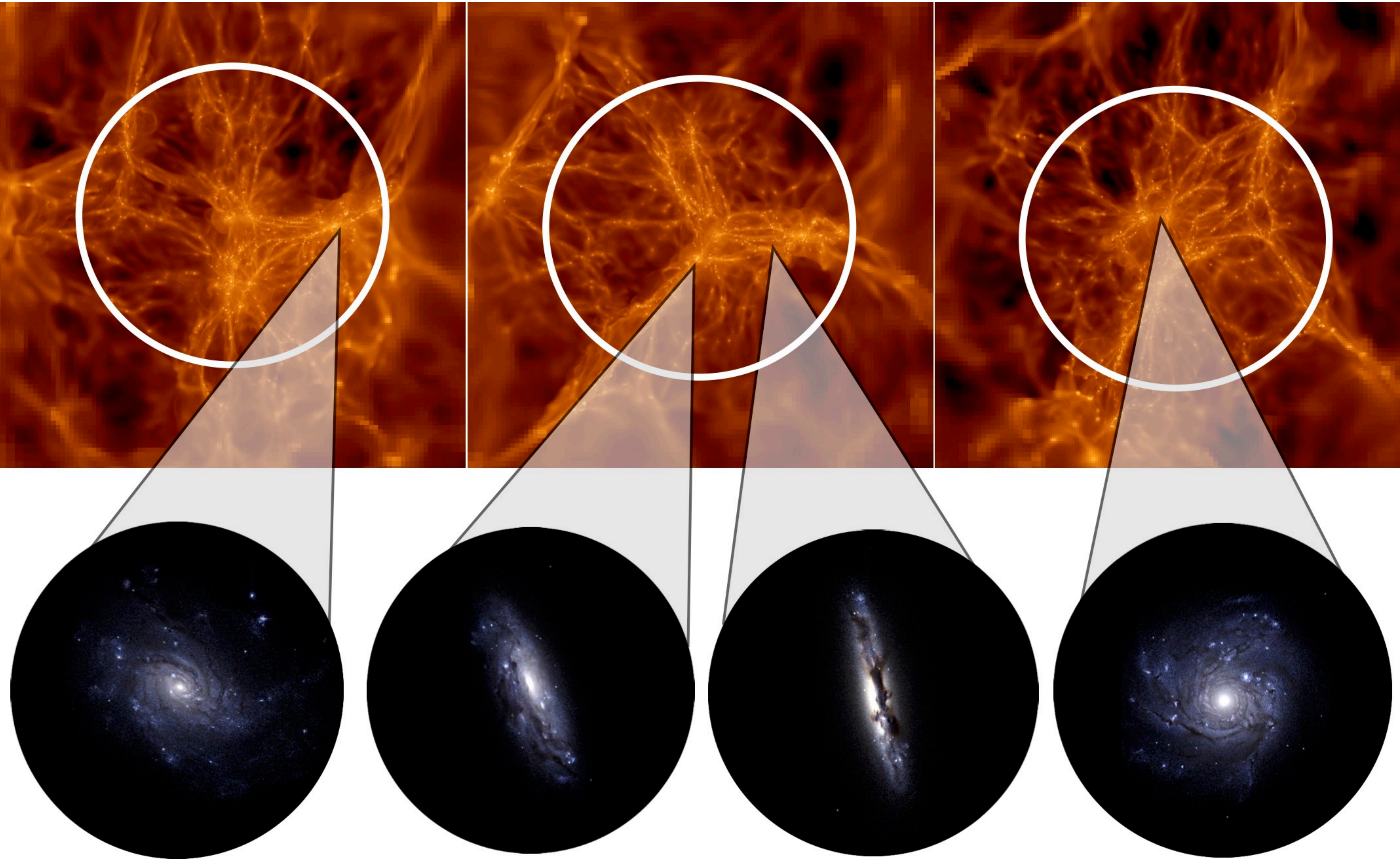
NewHorizon simulation
6 orders of magnitude
in dynamical range!
100 Mpc
20 Mpc
2 Mpc
200 kpc
40 kpc
Gas density
Stellar light
10 kpc

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

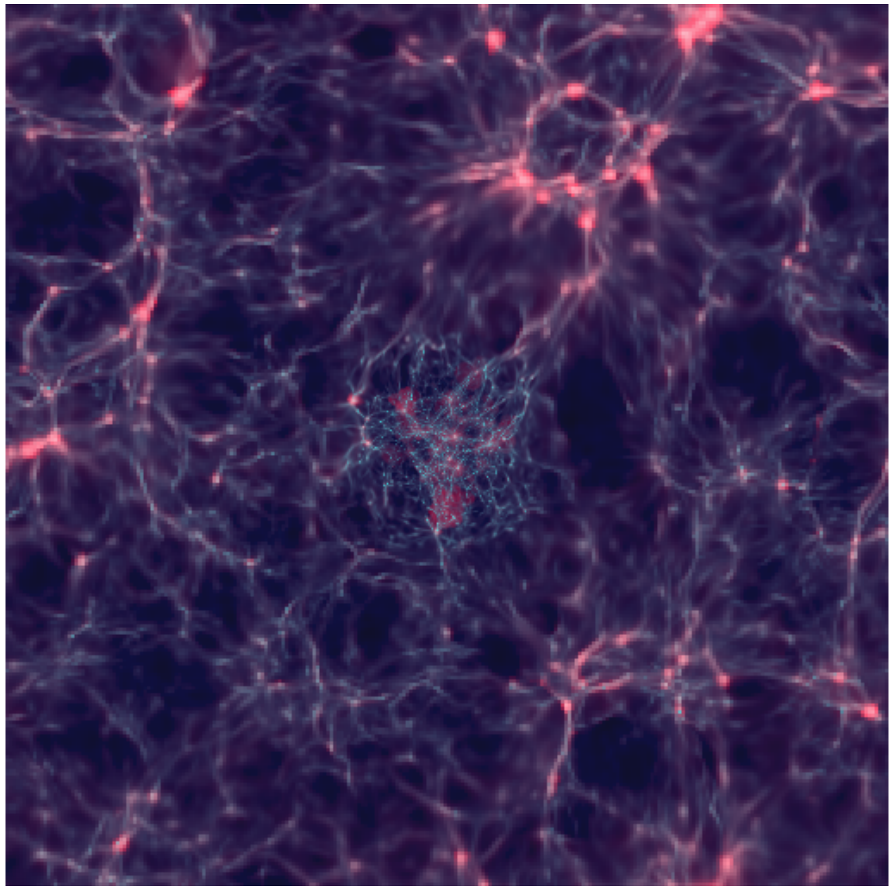


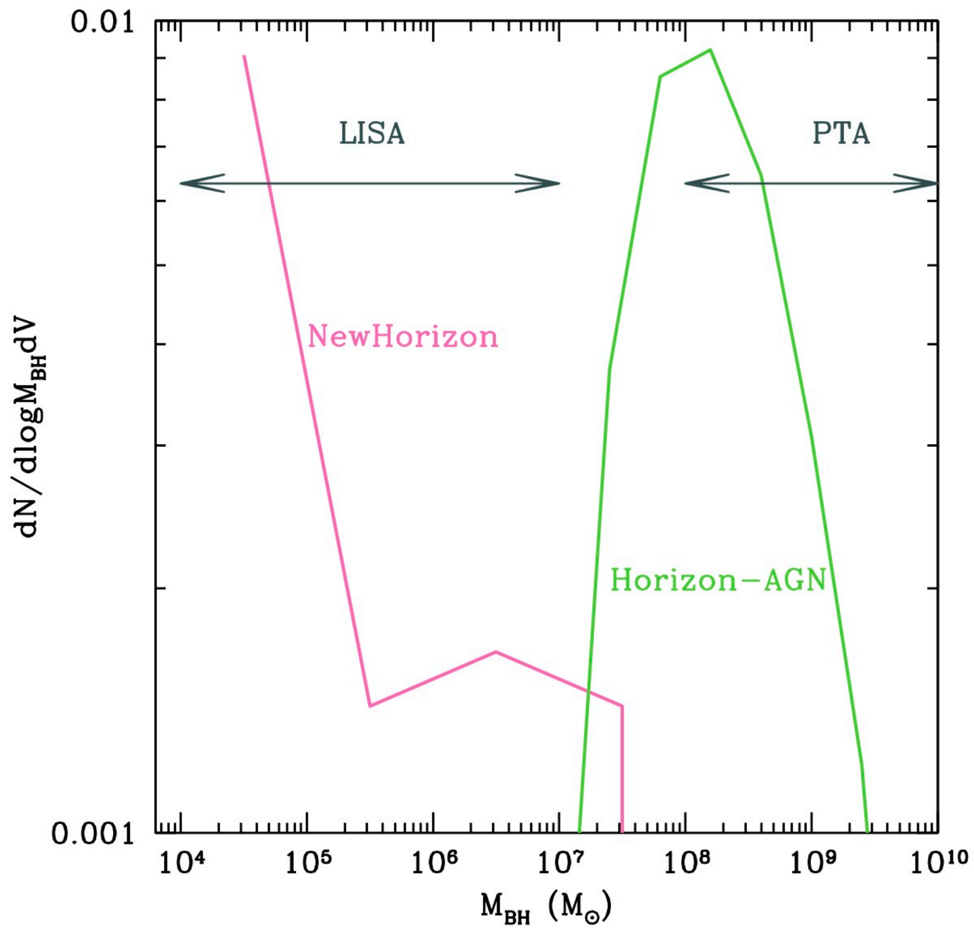
Dubois+20

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

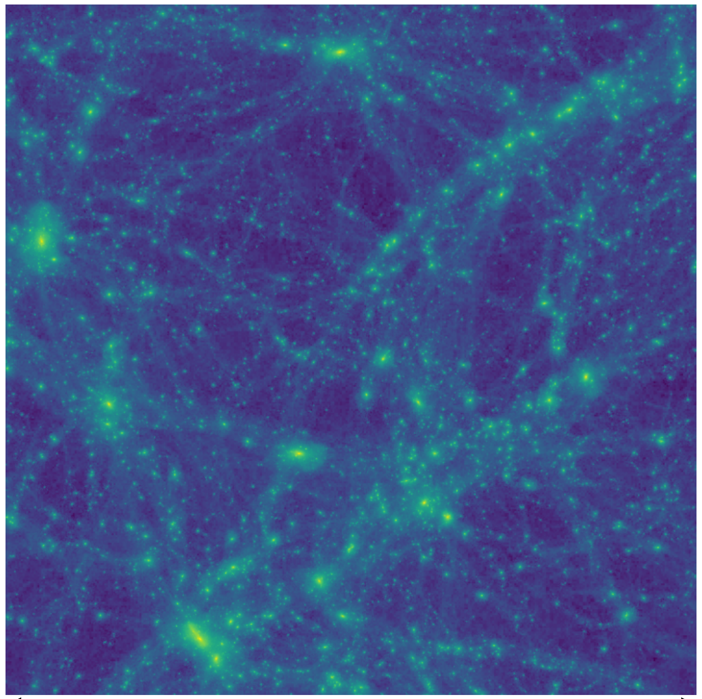




Mass distribution of *merging MBHs* in NewHorizon and Horizon-AGN

Volonteri+20, arXiv:2005.04902

The journey of two black holes

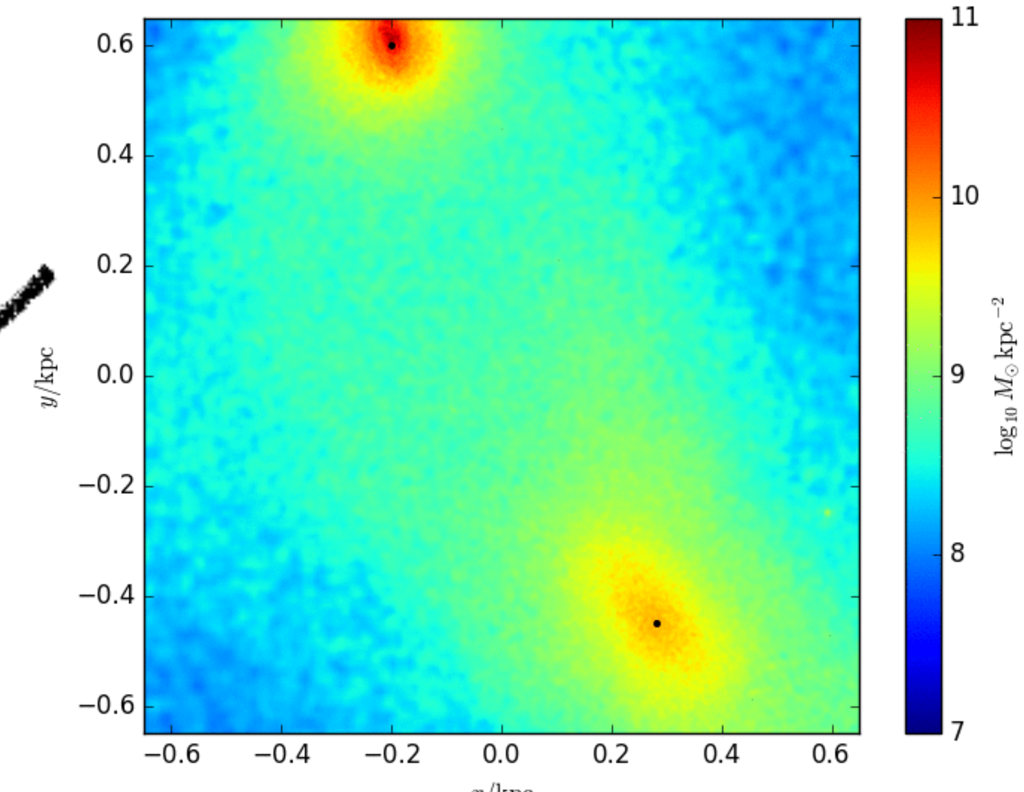


~100 Mpc (cosmology)

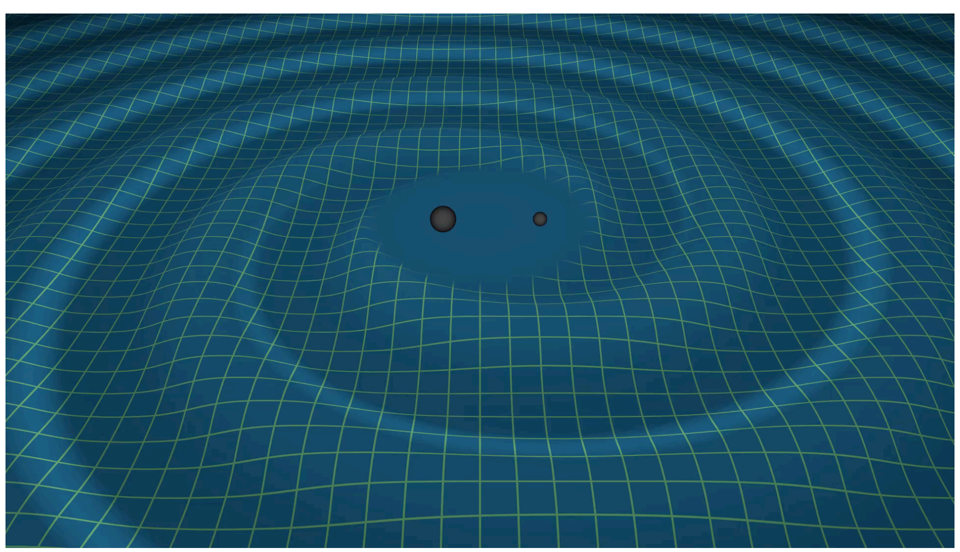
Gravity

~100 kpc -1 kpc (galaxy mergers)

Dynamical Friction



~1 kpc-1pc (binary formation)

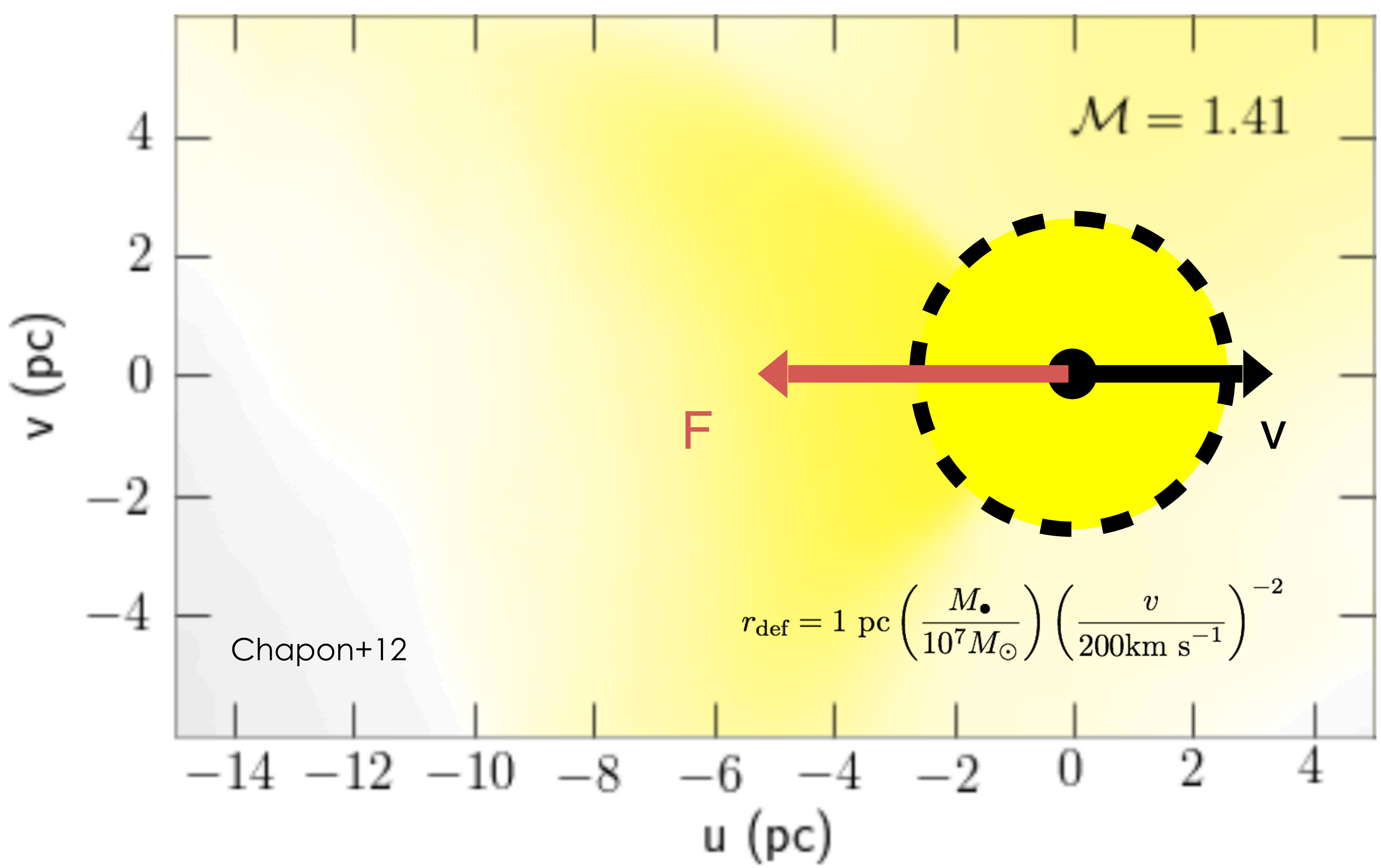


~1 millipc(BH merger)

Gas torques?
Stellar scattering?
Last pc problem

Courtesy of Hugo Pfister

MBH dynamics - friction

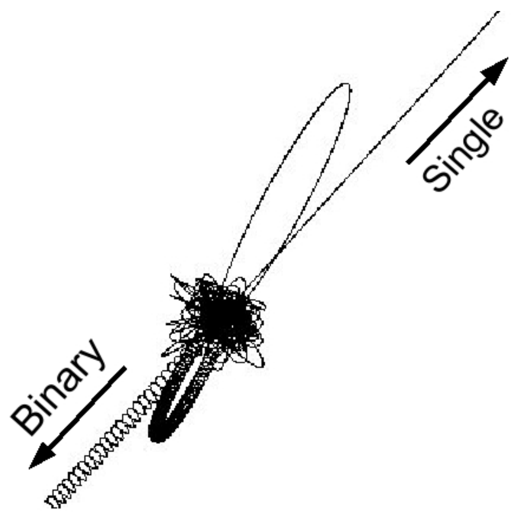


Horizon-AGN and NewHorizon <u>*include*</u> dynamical friction from gas but need to add the DF below resolution

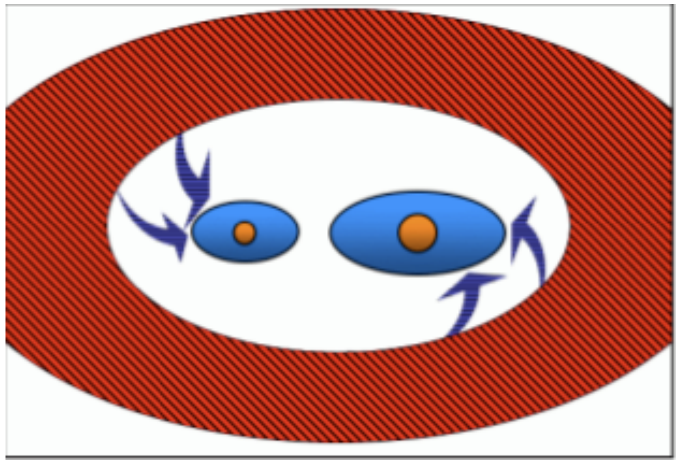
MBH dynamics – binaries

After the MBHs form a bound binary, dynamical friction cannot shrink the binary further: need additional physical processes

In a stellar-dominated environment: 3-body scattering



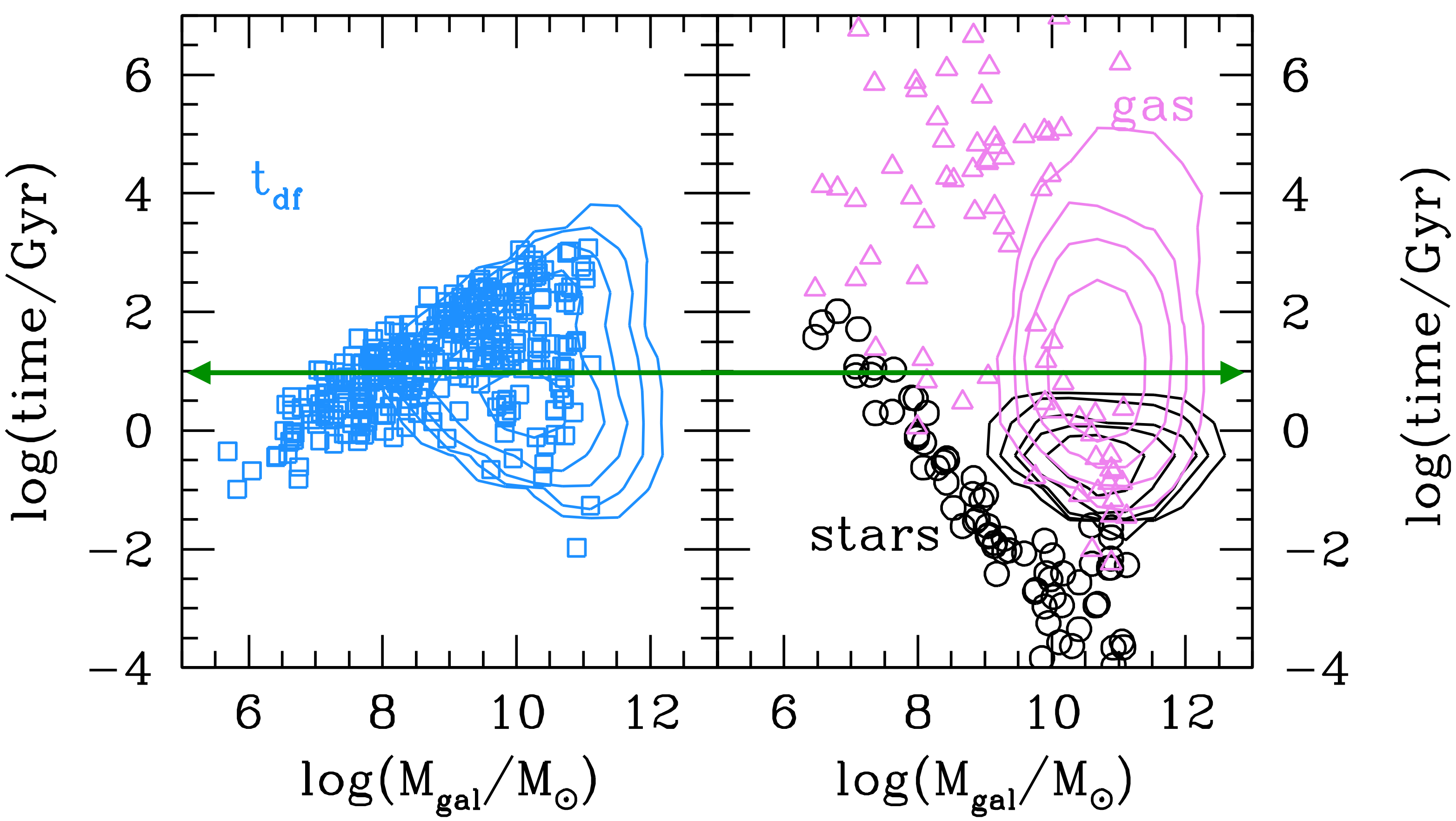
In a gas-dominated regime: migration in a circumbinary disc



Simulating massive black hole mergers in the Universe

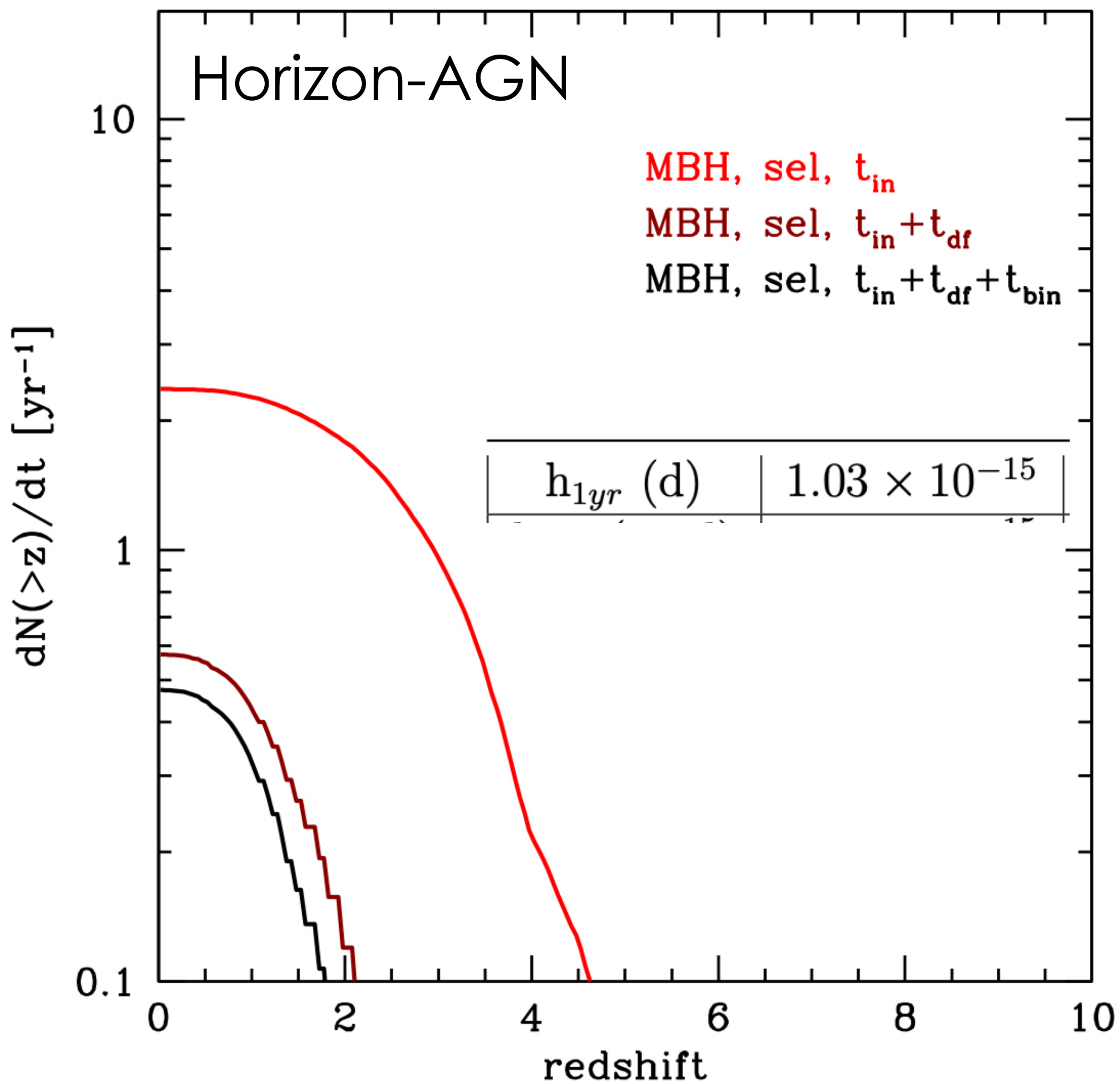
Include in post-processing dynamical delays below resolution:

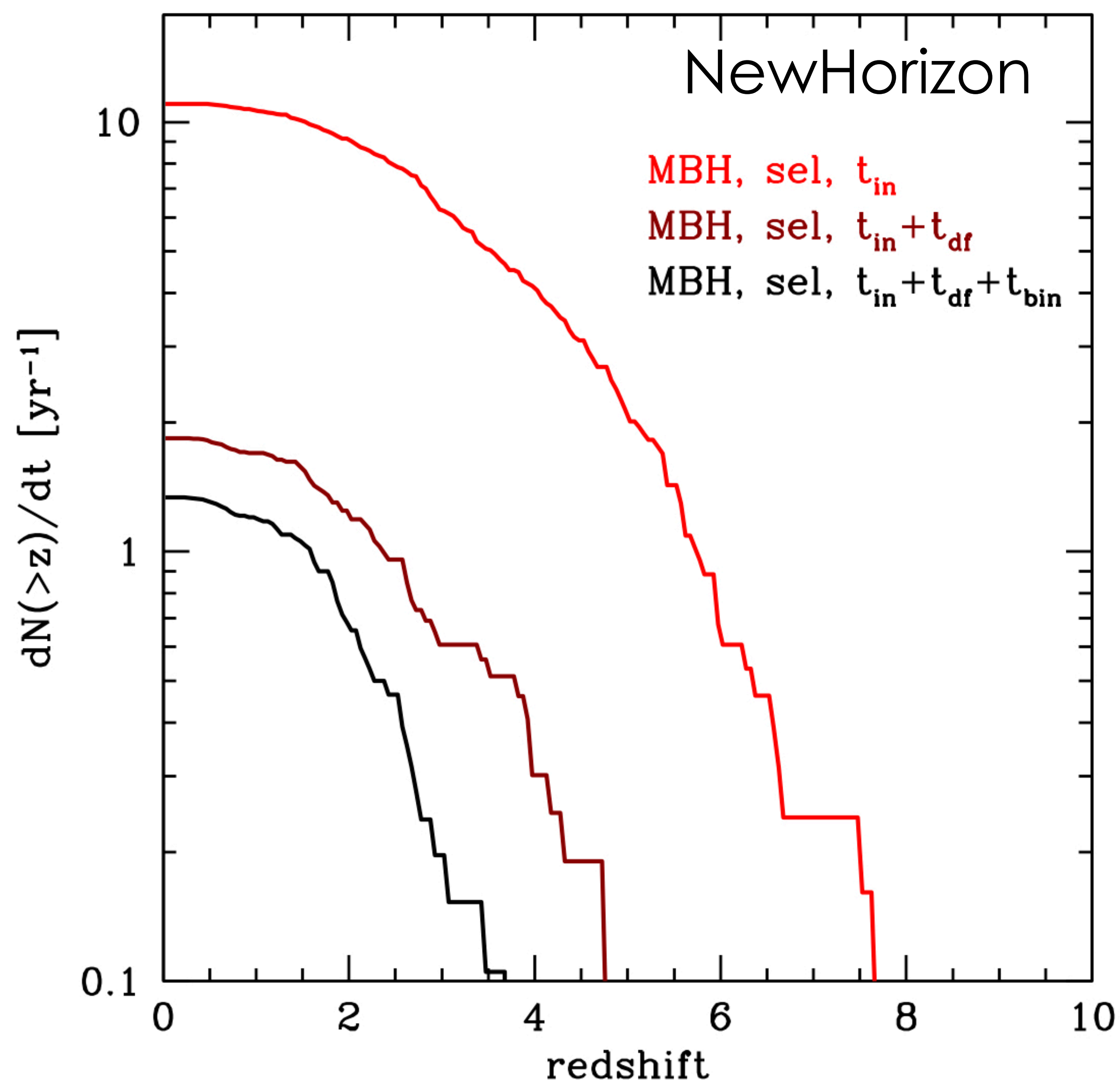
- dynamical friction until the MBHs form a binary
- stellar hardening and disc migration after the MBHs form a binary



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*

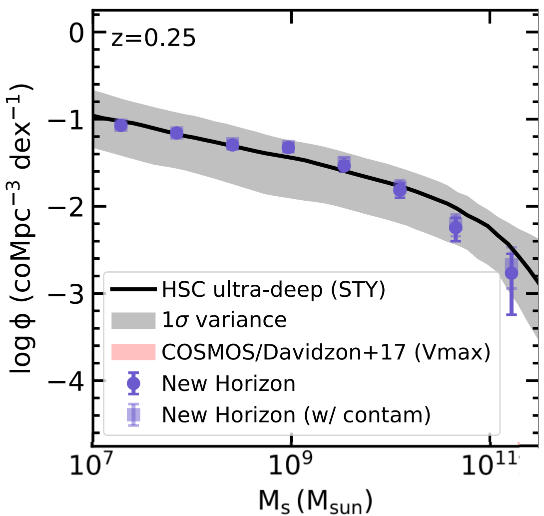
Volonteri+20

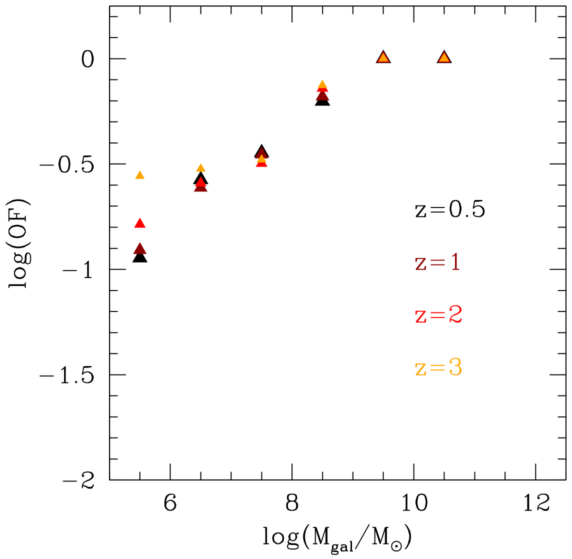
Why more massive black hole mergers in NewHorizon

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}

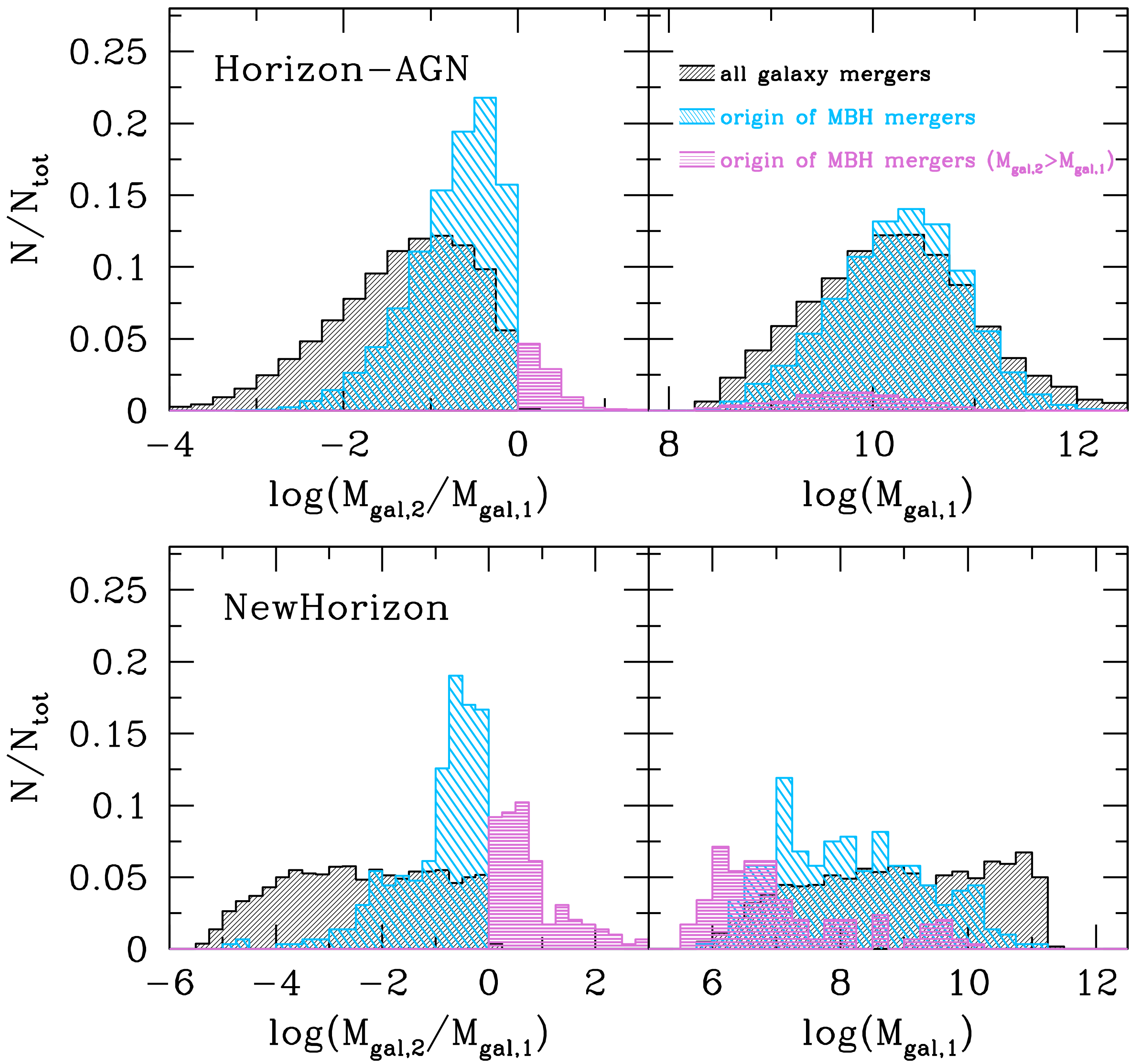
Resolving dwarf galaxies is *crucial* for the low-mass MBHs relevant for LISA





Volonteri+20

Which galaxy mergers lead to MBH mergers?



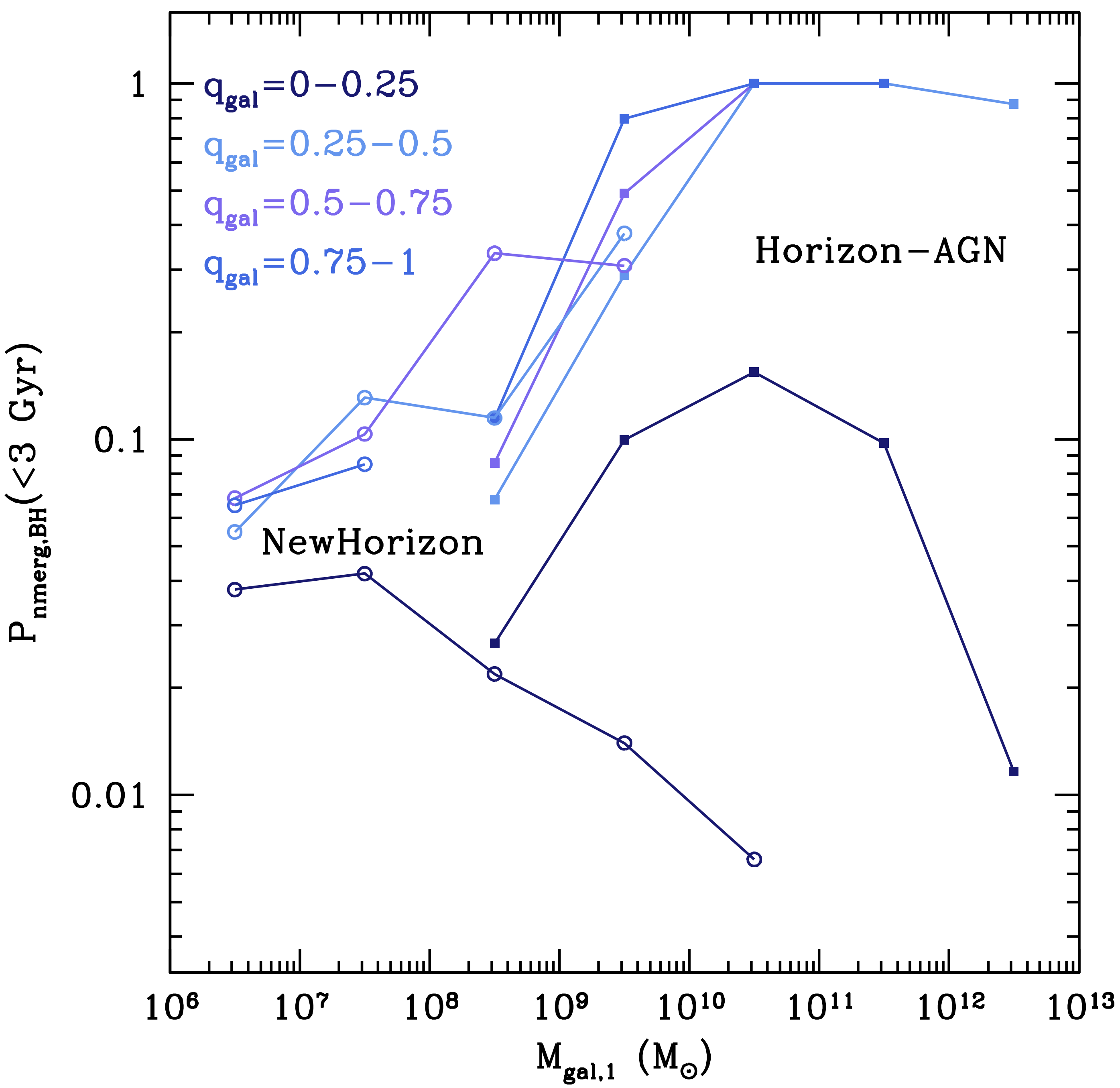
Mass ratio >~0.1

But there are minor mergers! Importance of cosmological simulations vs isolated mergers

The most massive galaxies merge “too late”

Volonteri+20

Which galaxy mergers lead to MBH mergers?

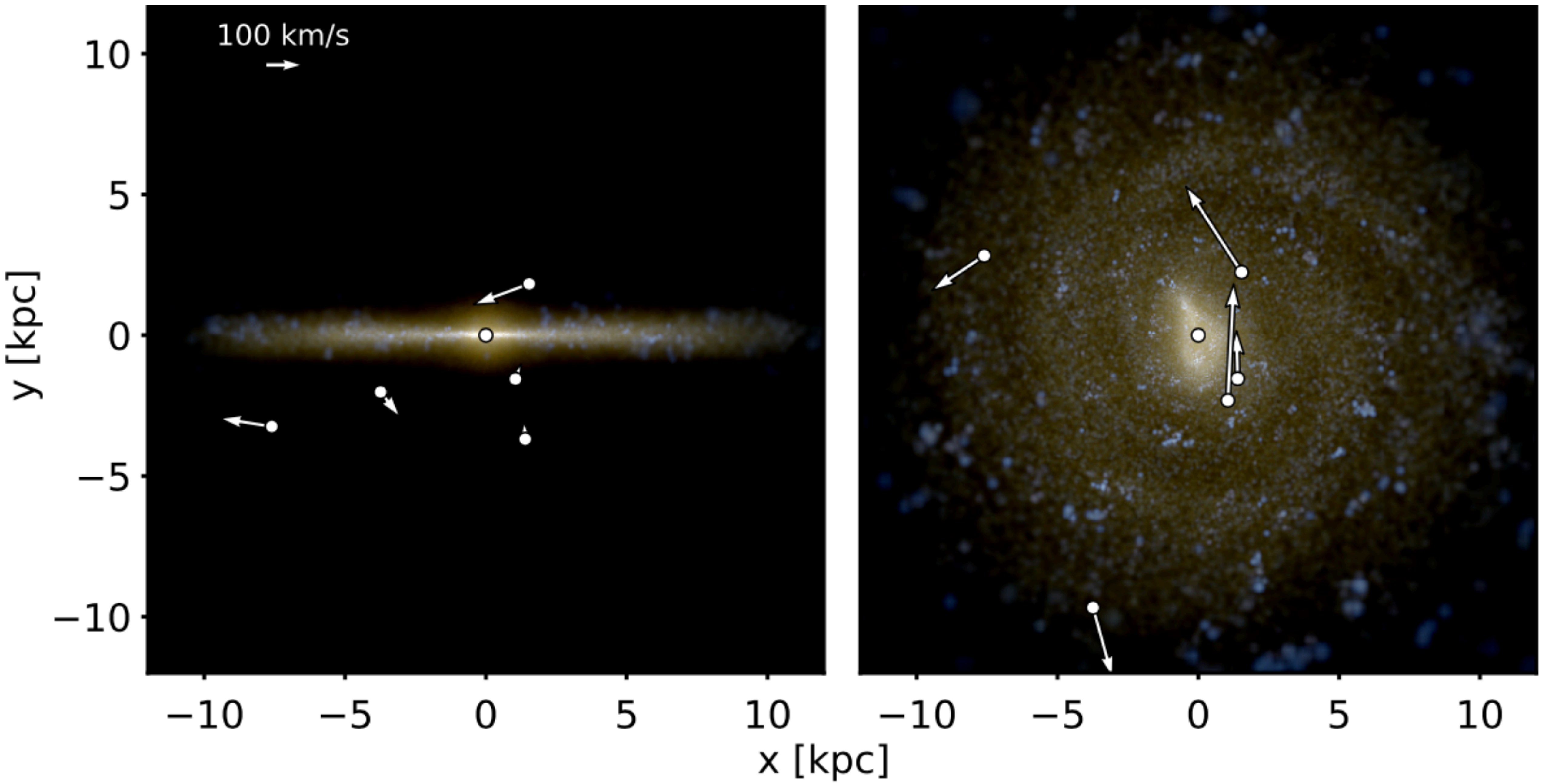


Only between 5-15% of galaxy mergers lead to a MBH merger

- one or both galaxies do *not* host MBHs
- ineffective dynamics

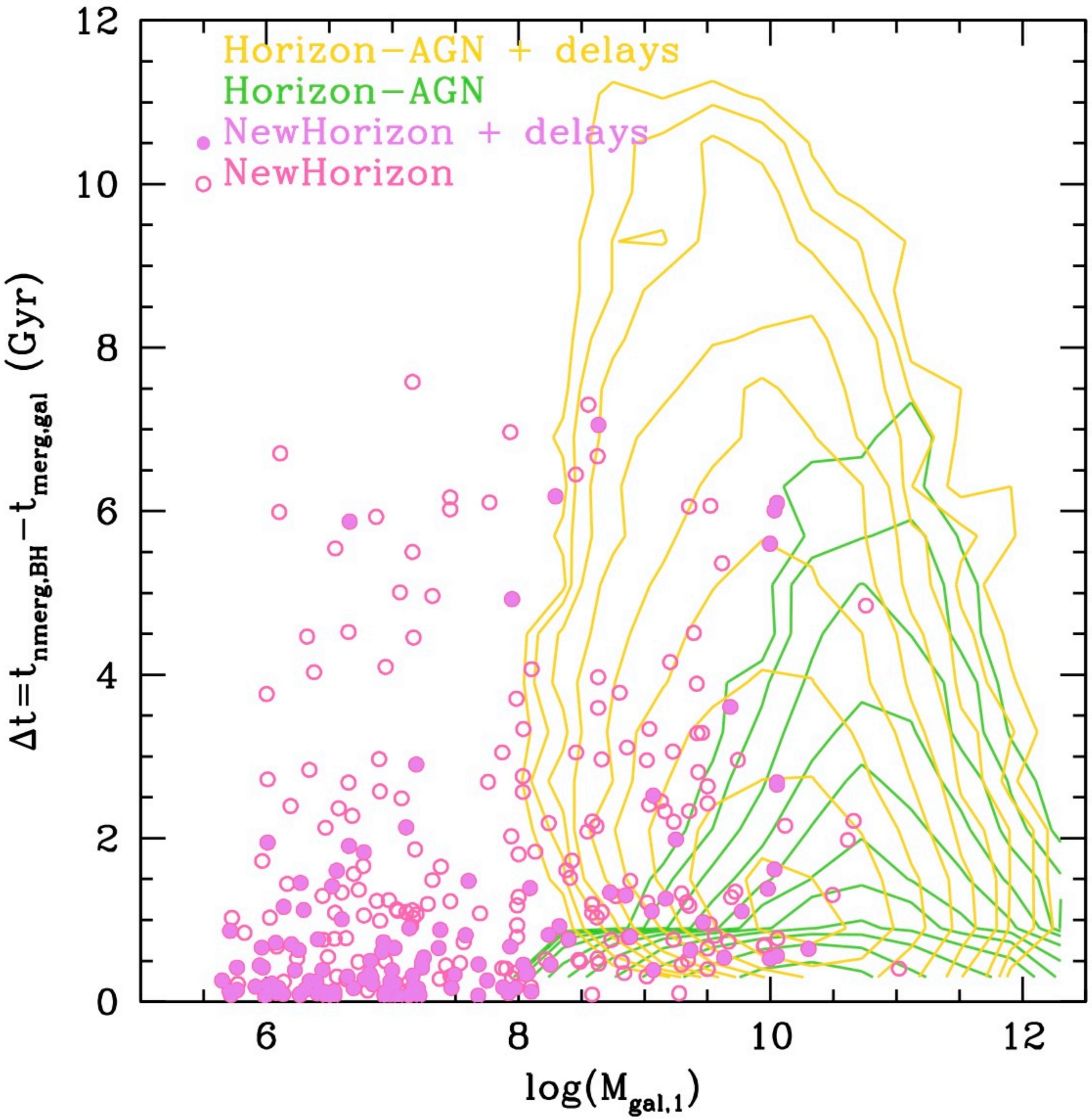
Volonteri+20

Wandering black holes



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

Are merging MBHs found in merging galaxies?

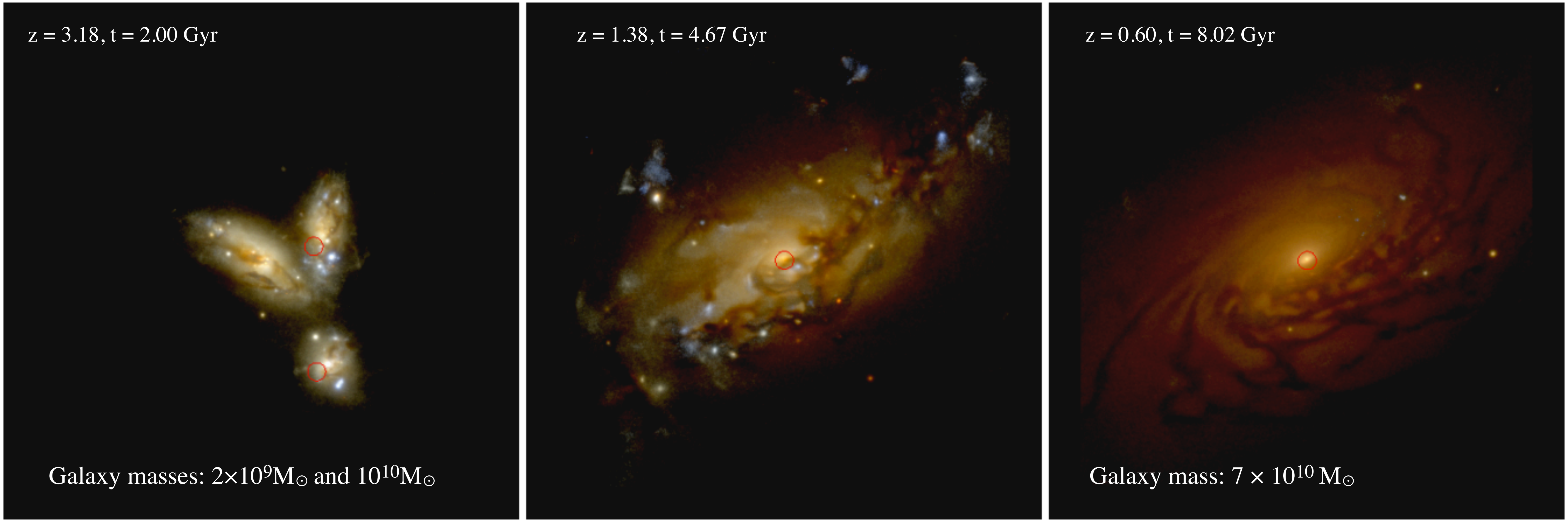


Generally, no.

MBHs often merge long after galaxies do

Adapted from Volonteri+20

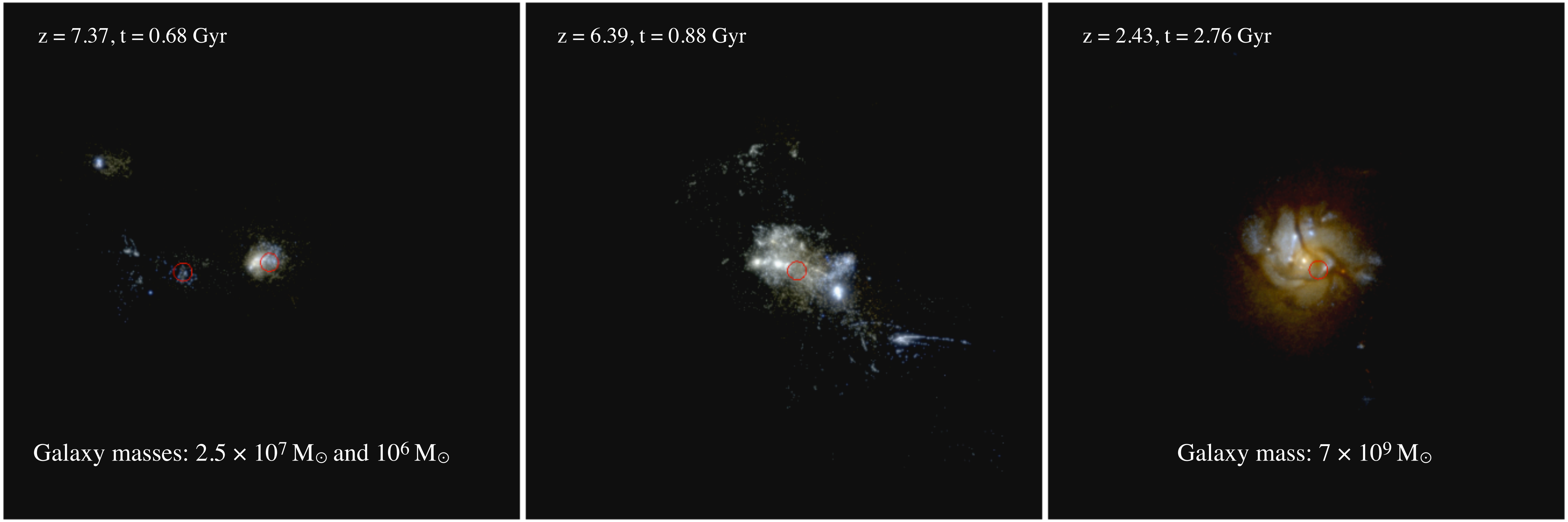
Are merging MBHs found in merging galaxies?



The galaxy merger | Before adding delays | After adding delays

Volonteri+20

Are merging MBHs found in merging galaxies?



The galaxy merger | Before adding delays | After adding delays

Volonteri+20

Summary

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

Tracking MBH mergers in low-mass galaxies is crucial to probing the MBH merger rate for LISA and investigate the properties of the host galaxies.

Time delays between the galaxy and the MBH merger shift the peak of the MBH merger rate to $z \sim 1 - 2$

MBHs typically merge after galaxies do: the galaxy morphology at the time of the MBH merger is no longer determined by the galaxy merger that brought in the two MBHs