Massive black hole binaries

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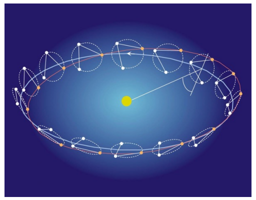
ANR MBH_Waves: IAP+IRAP+APC+Obs Paris

Massive black holes and gravitational waves

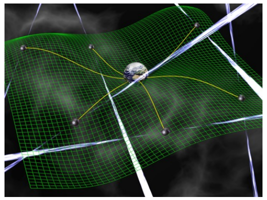
$$f \sim \frac{c}{2\pi R_s} \sim 10^4 \mathrm{Hz} \frac{M_\odot}{M}$$

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+bk

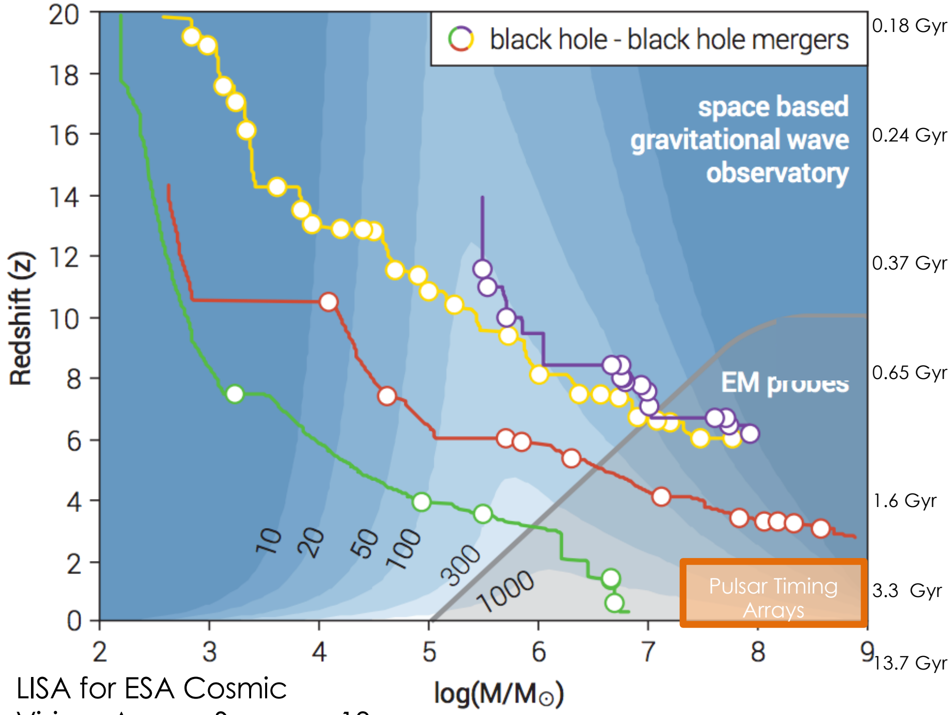


Massive Black Holes, LISA & PTA

Massive black holes grow along with galaxies through accretion and MBH-MBH mergers

Over time they sweep the LISA mass-redshift range

Detection possible in GW + EM

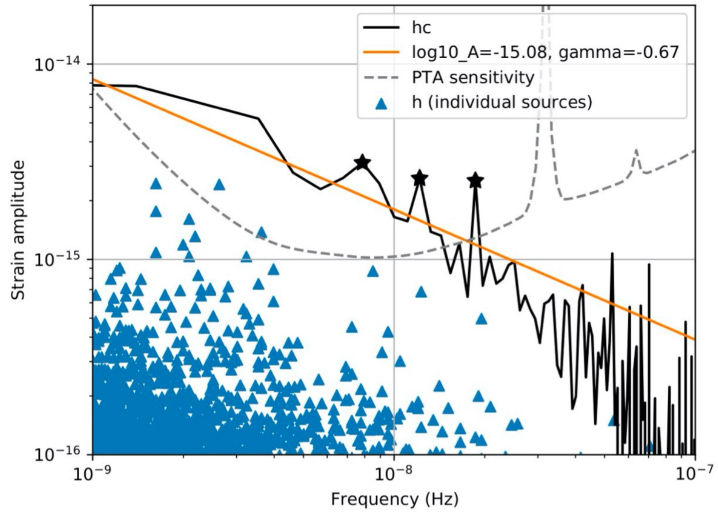


LISA for ESA Cosmic Vision, Amaro Seoane+13

PTA detections in 2023: lots of merging MBHs

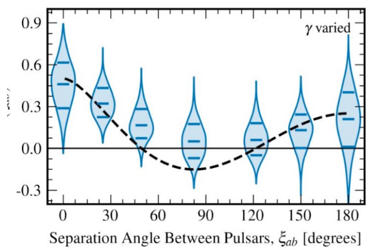
For a large population of SMBHBs in the Universe, we focus on two categories of signals:

- **Gravitational wave background** (GWB)
- **Continuous GWs** (CGWs)



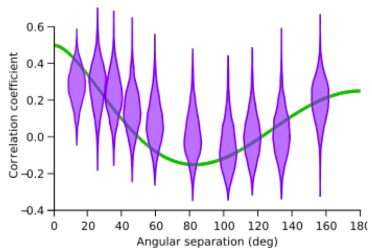
Credit: Mikel Falxa

NANOGrav, 2023
15 years, 70 PSRs
4σ



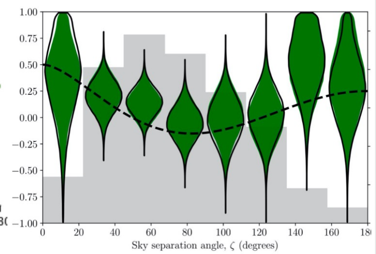
arXiv: 2306.16213

EPTA+InPTA, 2023
10.3 years, 25 PSRs,
3.5σ



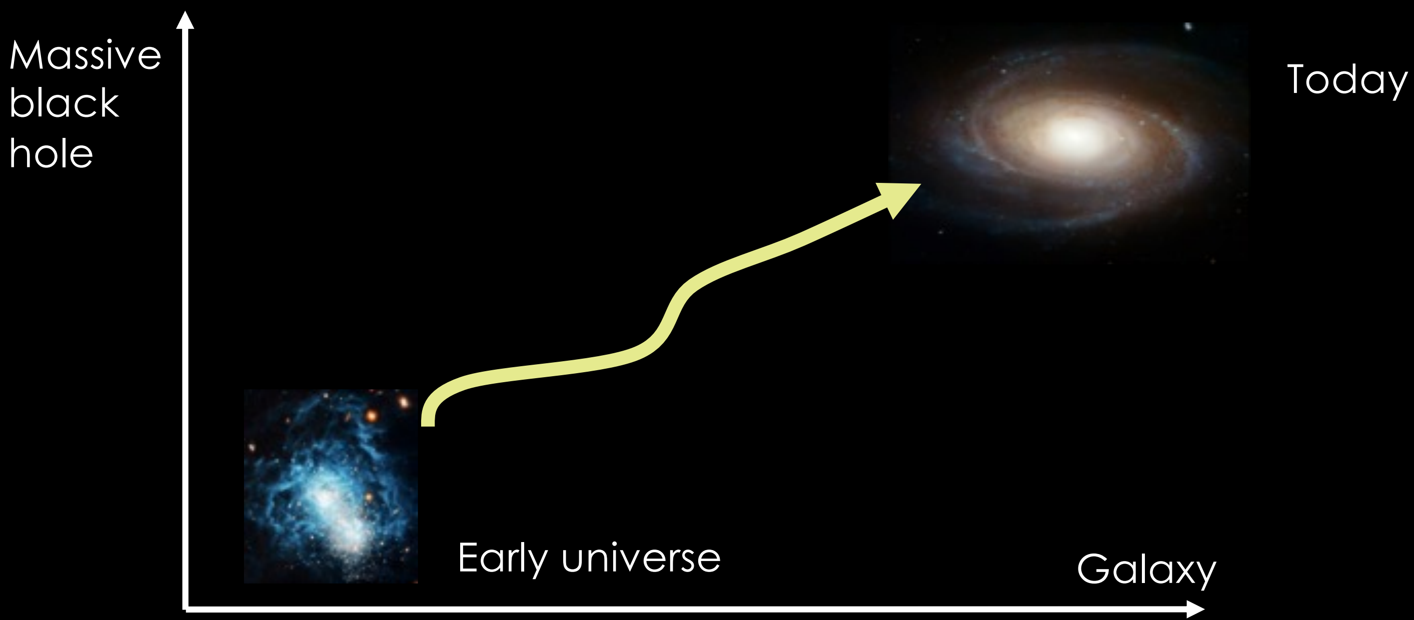
arXiv: 2306.16214

PPTA, 2023
18 years, 32 PSRs
2σ

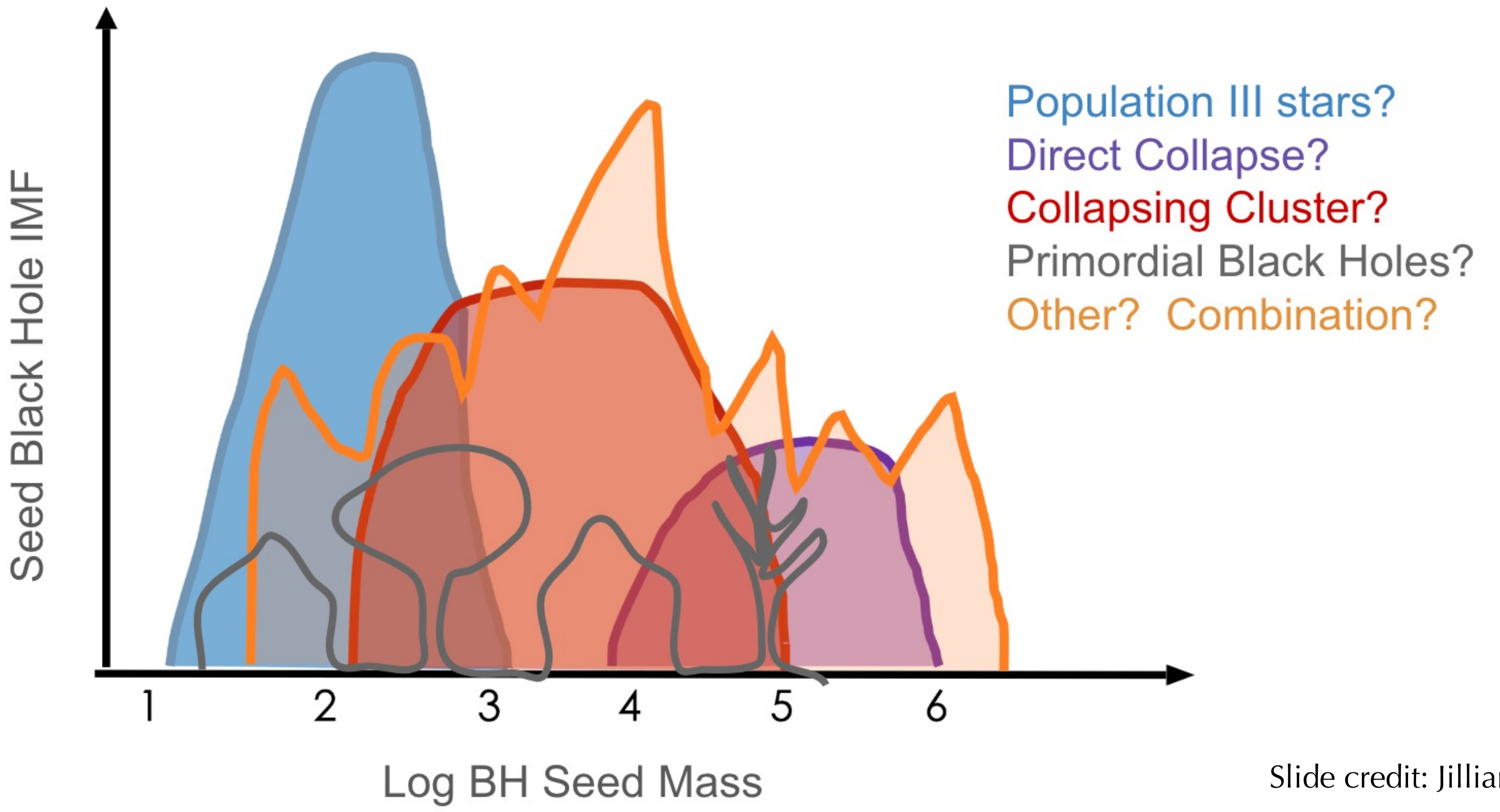


arXiv: 2306.16215

The evolution of massive black holes in galaxies

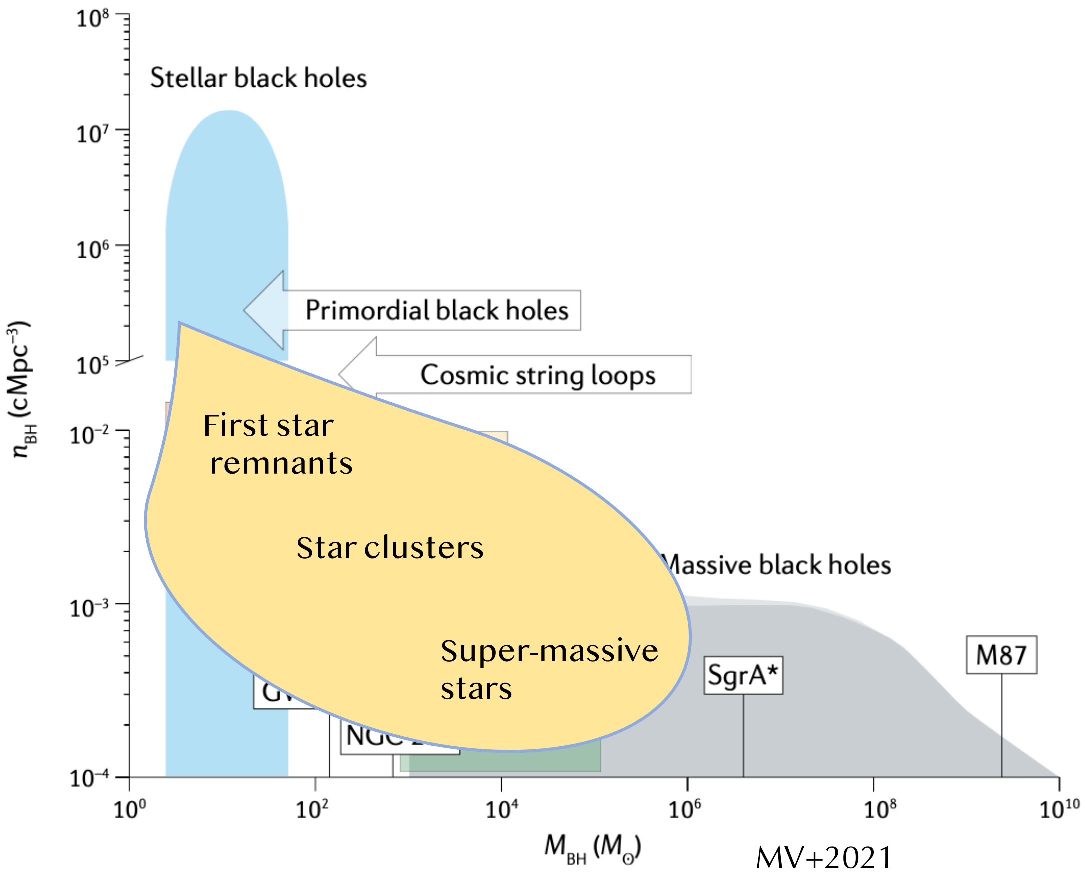


Massive black hole seeds



Slide credit: Jillian Bellovary

Massive black hole seeds



MV+2021

The most recent models suggest that rather than a bimodality between light and heavy seeds instead a continuum exists

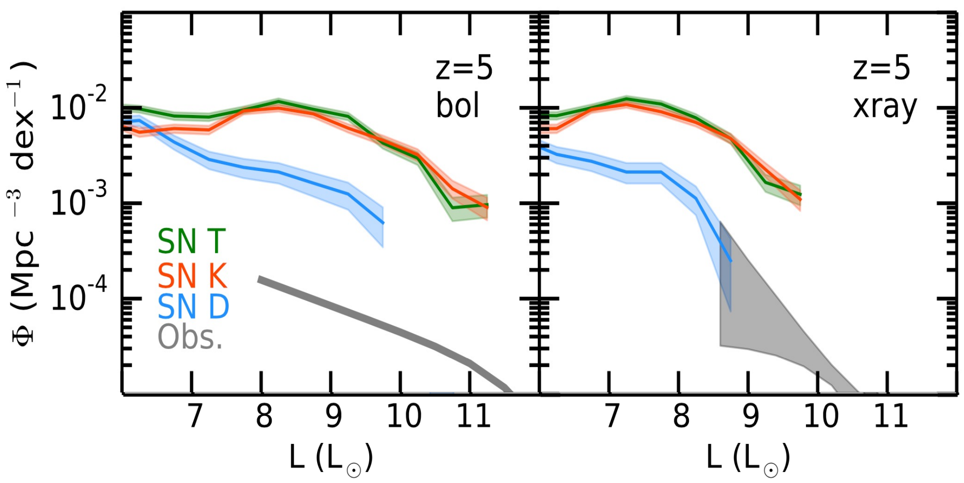
Lighter seeds are more ubiquitous and heavier seeds are less and less abundant

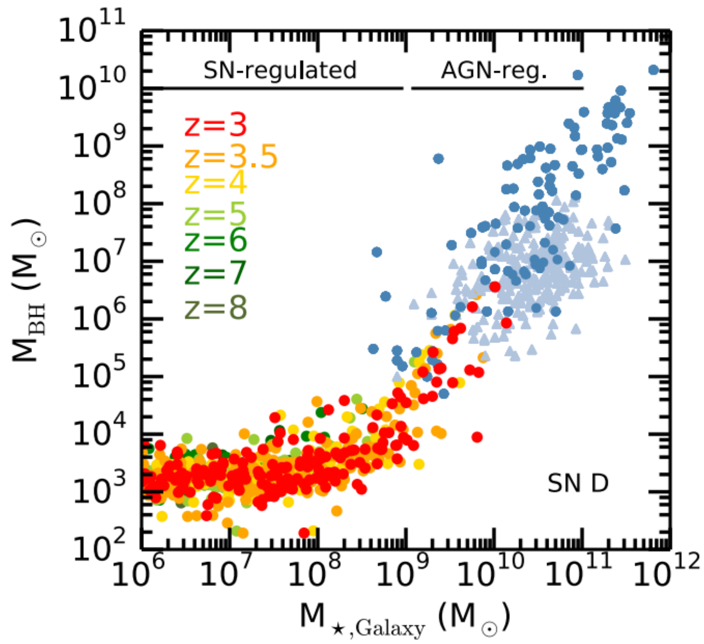
Primordial black holes and cosmic string loops are set at arbitrary number densities

Massive black hole growth

Supernova feedback suppresses BH accretion in low mass galaxies/haloes (Dubois+15; Bower+17; Habouzit+17; Angles-Alcazar+17; Prieto+17; McAlpine+17 etc)

This improved the agreement between theoretical models and pre-JWST observations





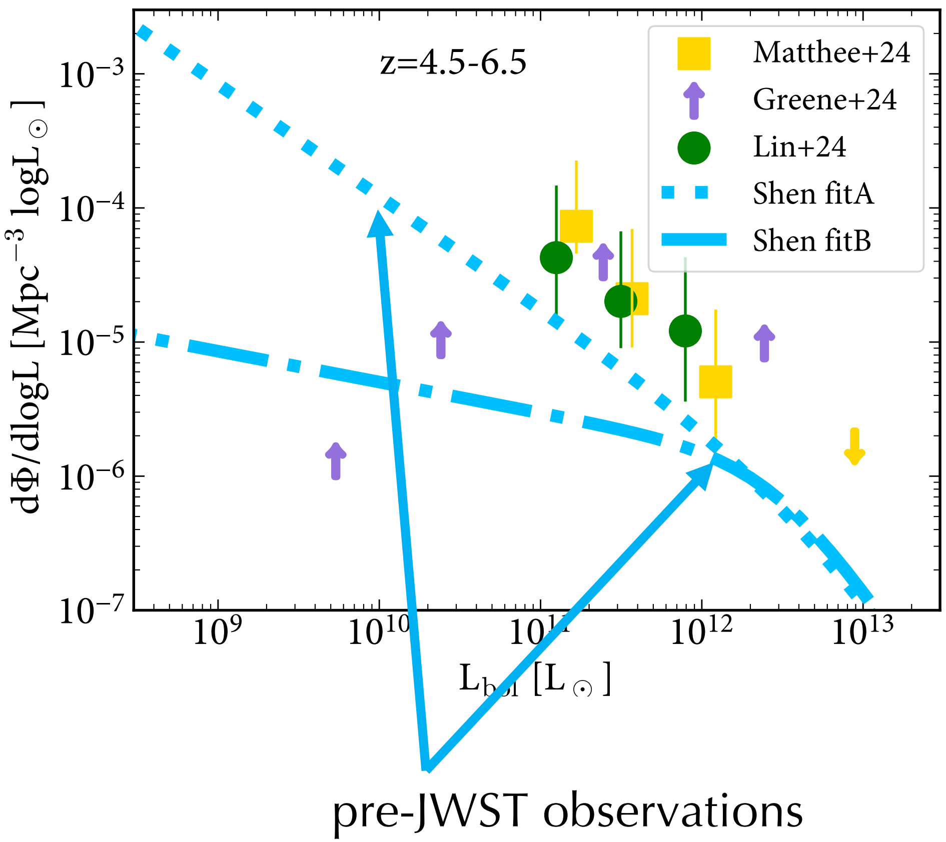
Habouzit+17

Massive black hole growth

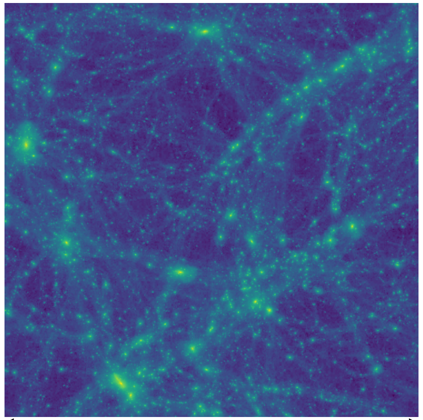
JWST now finds lots of AGN (candidates) in high-redshift low-mass galaxies: should growth be more efficient?

But with weak SN feedback galaxies grow too much… or do they now? (cf. JWST massive galaxies)

Perhaps AGN feedback can replace SN feedback? (Koudmani+22)



The journey of two black holes

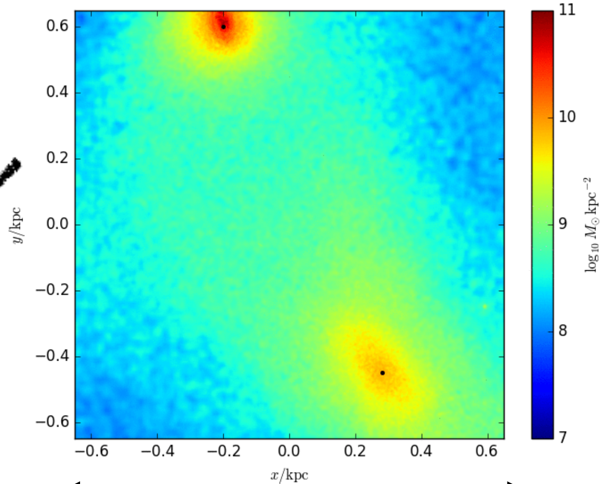


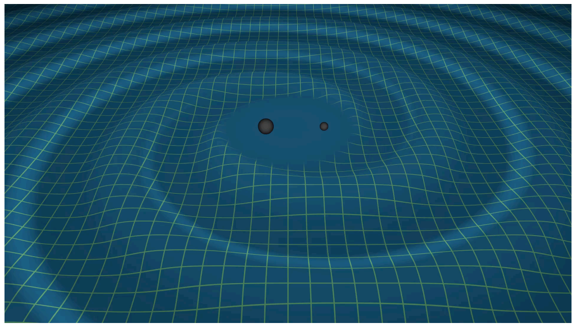
Gravity

~100 kpc -1 kpc (galaxy mergers)

~100 Mpc (cosmology)

Dynamical Friction





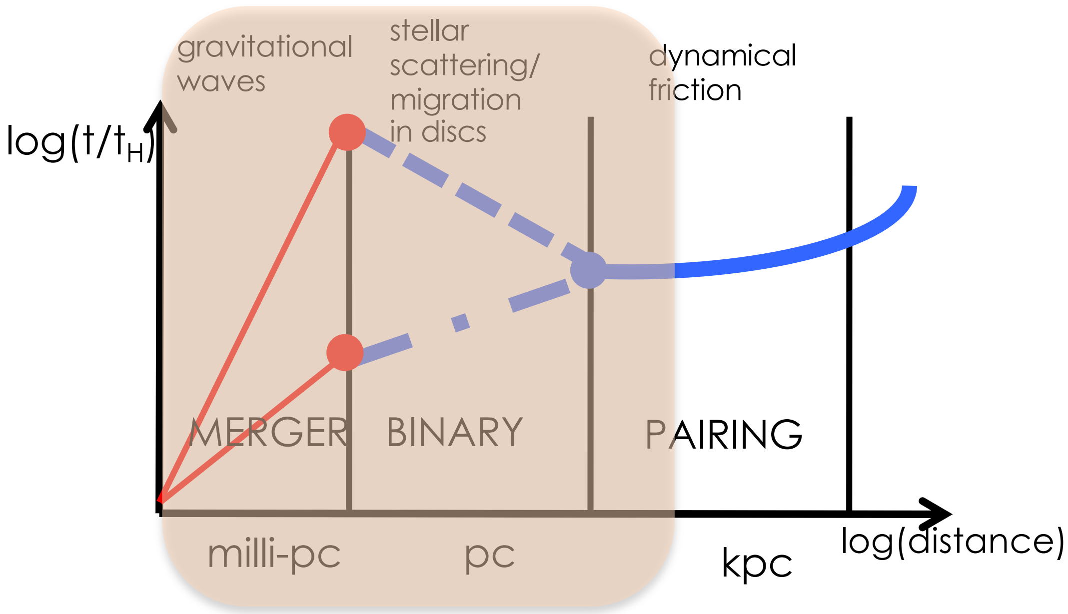
Gas torques?
Stellar scattering?
Last pc problem

~1 millipc(BH merger)

~1 kpc-1pc (binary formation)

Courtesy of Hugo Pfister

Simulating Massive Black Hole dynamics



Most cosmological simulations have a resolution of 0.1-1 kpc

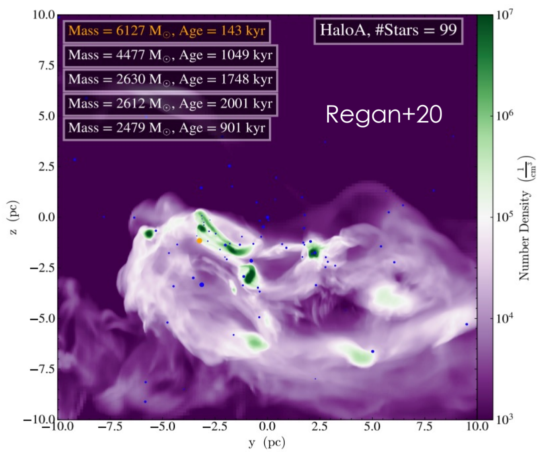
Cannot resolve the late evolution of Massive Black Hole mergers

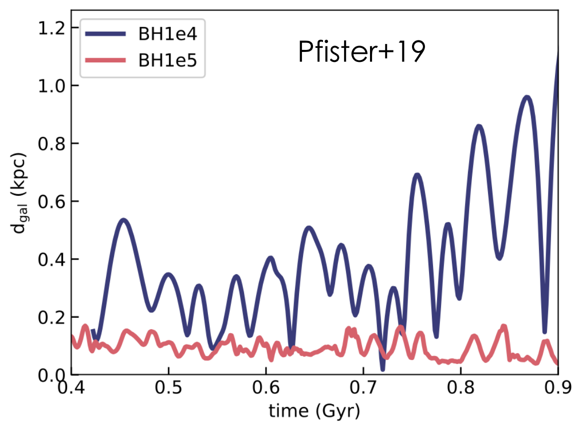
Credit: Monica Colpi

Simulating Massive Black Hole dynamics

Calculate the momentum that should be removed due to unresolved force by gas, stars and dark matter: Massive Black Hole orbits evolve naturally down to the resolution limit (Tremmel+15, Pfister+19; Chen+22)

High-z dwarf galaxies have messy, non smooth, time-variable potentials, and no real center: this affects the ability of "seeds" to bind in binaries and grow in mass by both mergers and accretion





Dynamics & MBH Mergers

KETJU (e.g., Mannerkoski+19,20,21,23;)

The main idea in KETJU is to add small spherical regions centred on the MBHs, where the dynamics are integrated using a high-accuracy integrator

Tracks the interaction with stars to high-level accuracy

- Dynamical friction and hardening of MBHB from interactions with stellar particles are directly captured.
- Post-Newtonian dynamics of MBHBs, such as orbital decay from GW emission and precession of the orbit.

RAMCOAL (Li, Volonteri+24)

A sub-grid model integrated in adaptive mesh refinement code RAMSES:

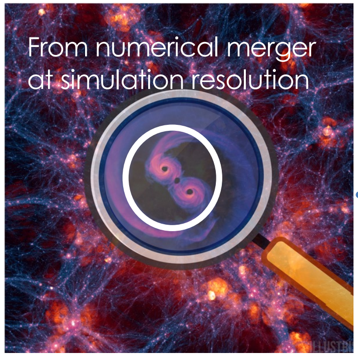
Track the orbit of MBHB to coalescence in galaxy simulation on-the-fly

RAMCOAL

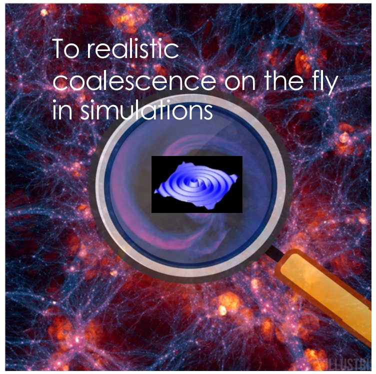
Highly complementary

Slide credit: Kunyang Li

Below the resolution limit: RAMCOAL



- Dynamical friction: Gas, star, DM
- Radiation feedback effect on gas dynamical friction
- Loss-cone scattering
- Viscous drag in circumbinary disk
- Gravitational wave emission
- Accretion & AGN feedback
- Spin evolution and recoils (coming soon!)



RAMCOAL tracks the real-time evolution of Massive Black Hole Binaries within hydrodynamical simulations down to coalescence to avoid uncertainties in post-processing

Sub-grid model of stellar density makes it almost resolution-independent out to 100 pc resolution – Massive Black Holes merge at 10^{-3} pc! Gain of 5 orders of magnitude!

Kunyang Li; Li+24, arXiv:2410.07856

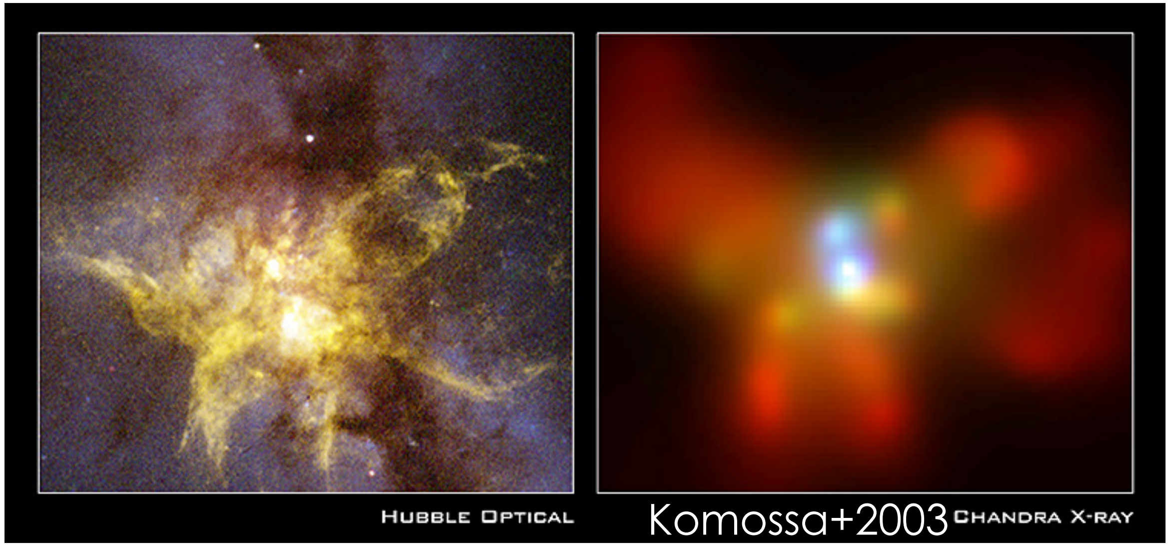
Multimessenger science with MBH mergers

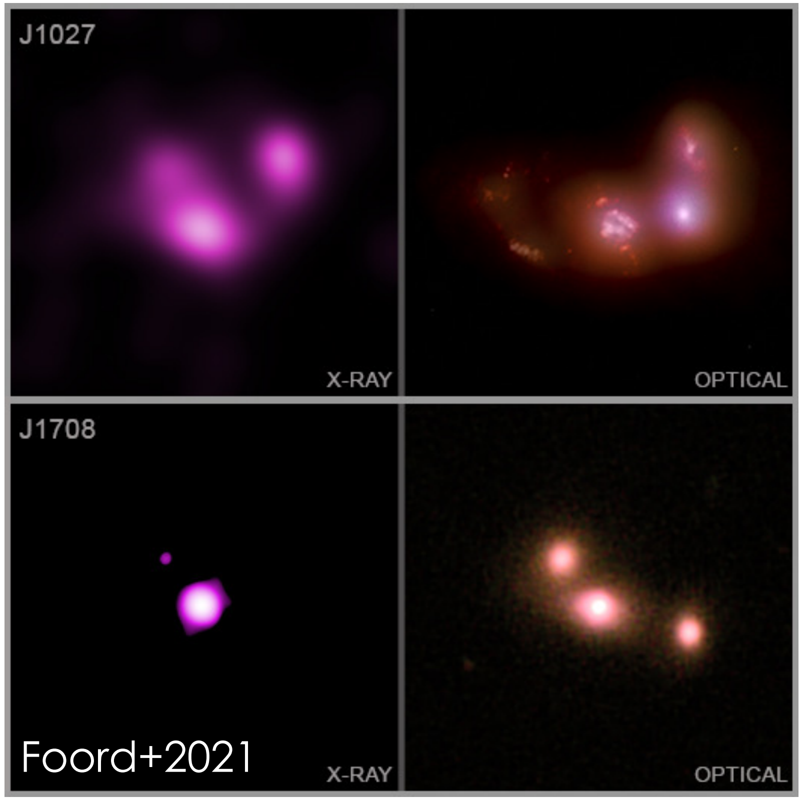
Dual AGN at ~kpc scales: MBHs on their way towards coalescence or stalled dynamical decay?

Binary AGN at ~subpc scales: how many do we expect to detect with current/upcoming surveys?

Merging MBHs: what are the probabilities of finding EM counterparts and/or associated transients?

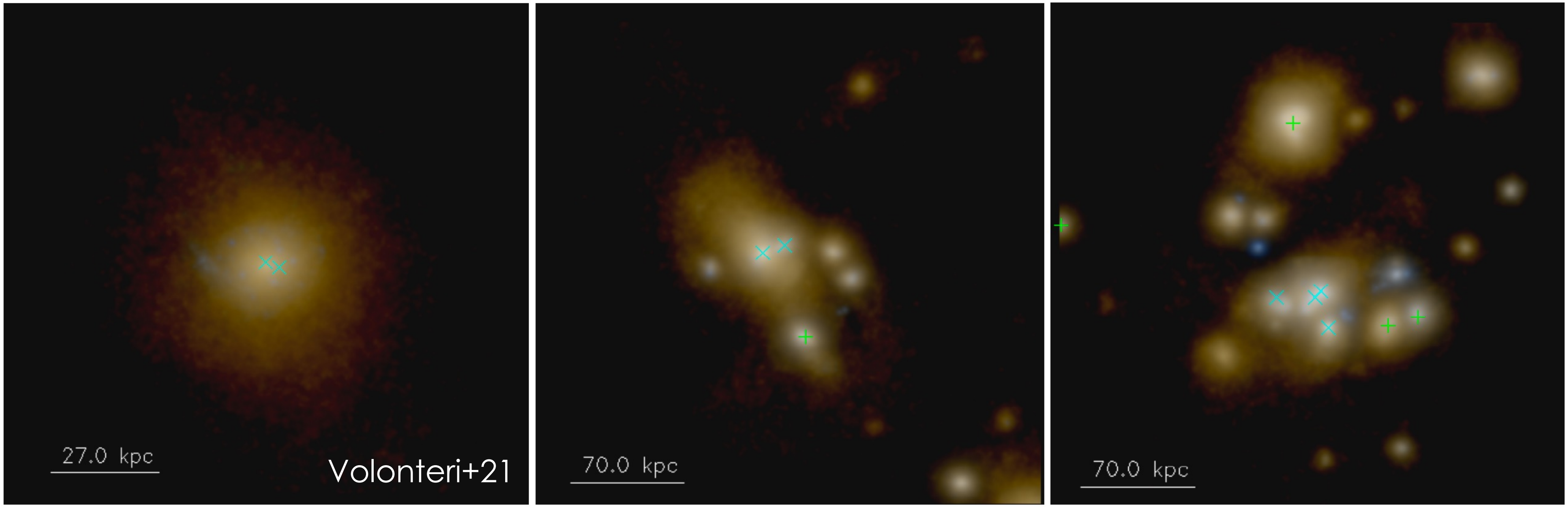
Dual AGN at kpc separations





During their journey during galaxy mergers MBHs sometimes accrete at the same time: dual/multiple AGN

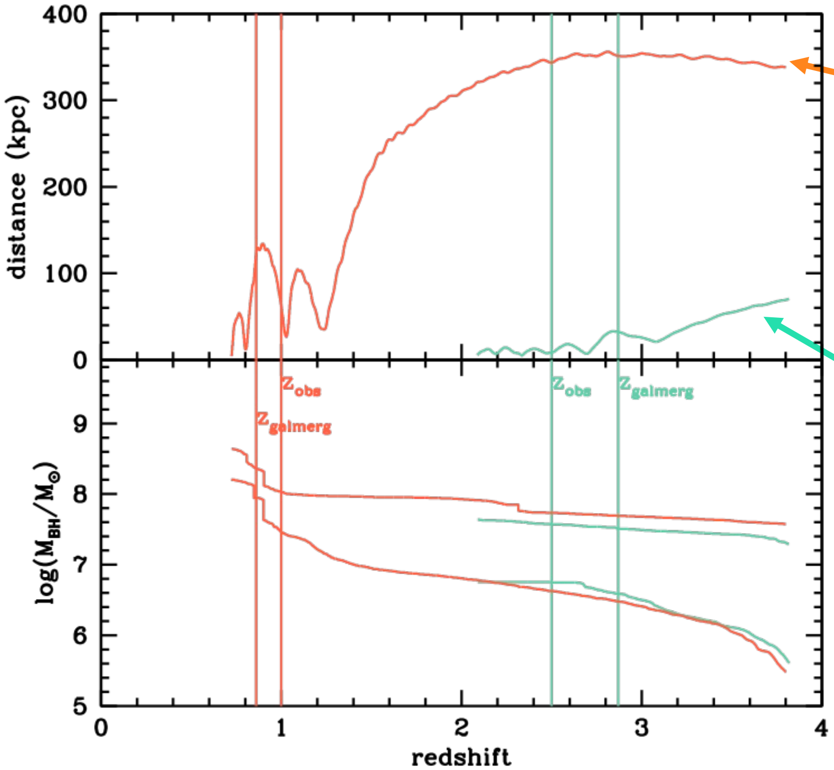
Dual AGN in Horizon-AGN



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 to galaxy and MBH mergers

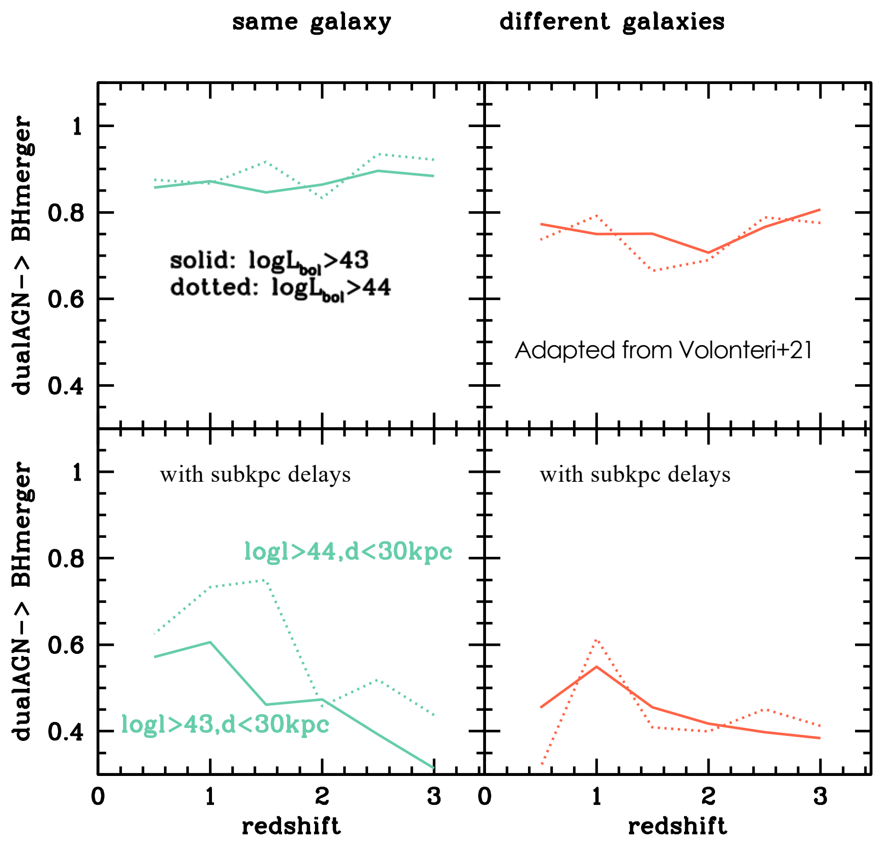


Dual AGN can be observed in *separate* galaxies *before* the galaxies merge => $z_{galmerg} < z_{obs}$

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

Volonteri+21

Linking dual AGN and MBH mergers

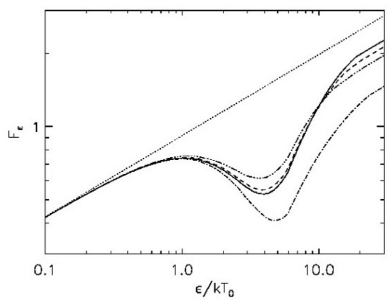


If MBHs decay rapidly from ~4 kpc to coalescence, dual AGN hosted in different galaxies lead to a MBH merger by z = 0 in 70-80% of cases, and >80% for dual AGN hosted in one galaxy

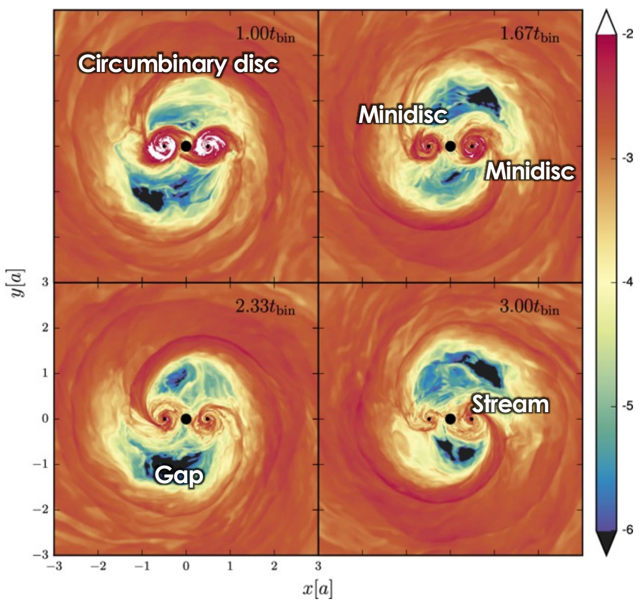
Adding dynamical delays levels the difference between duals in two galaxies or one, and overall decreases the probability to 30-60%

Closer in: binary MBHs at sub-pc separations

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

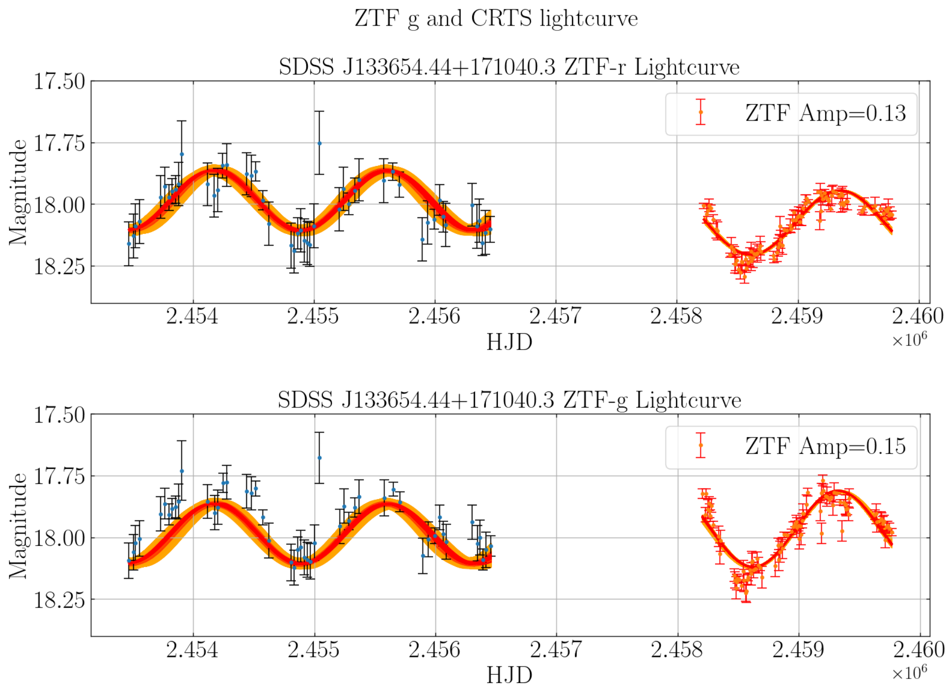


e.g.,Armitage & Natarajan 02; MacFadyen & Milosavljevic 08; Bogdanovic+08; Dotti+08, Cuadra+09; Sesana+12; Roedig+12; Shi+12; Noble+12; D'Orazio+13; D'Ascoli+19

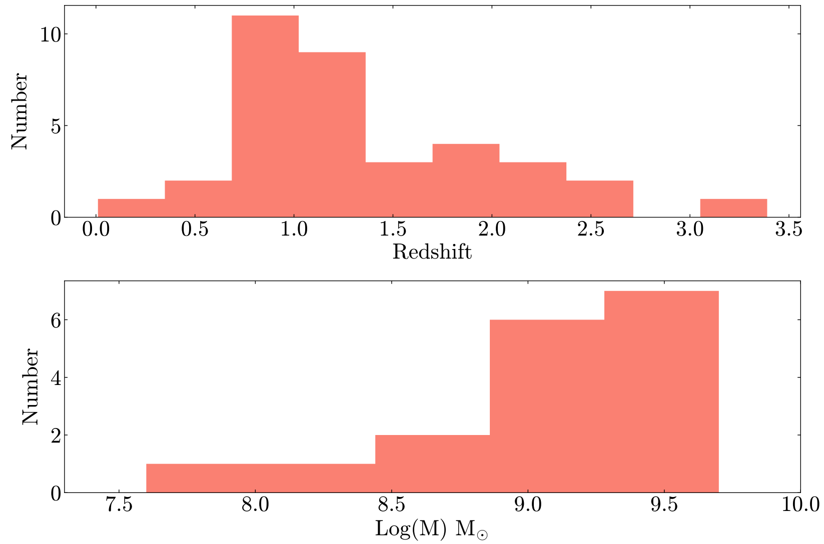


Closer in: binary MBHs at sub-pc separations

Search for periodic binaries in two time-domain surveys performed a few years apart => long time baseline to search for periodicities of ~yr-tens of yr

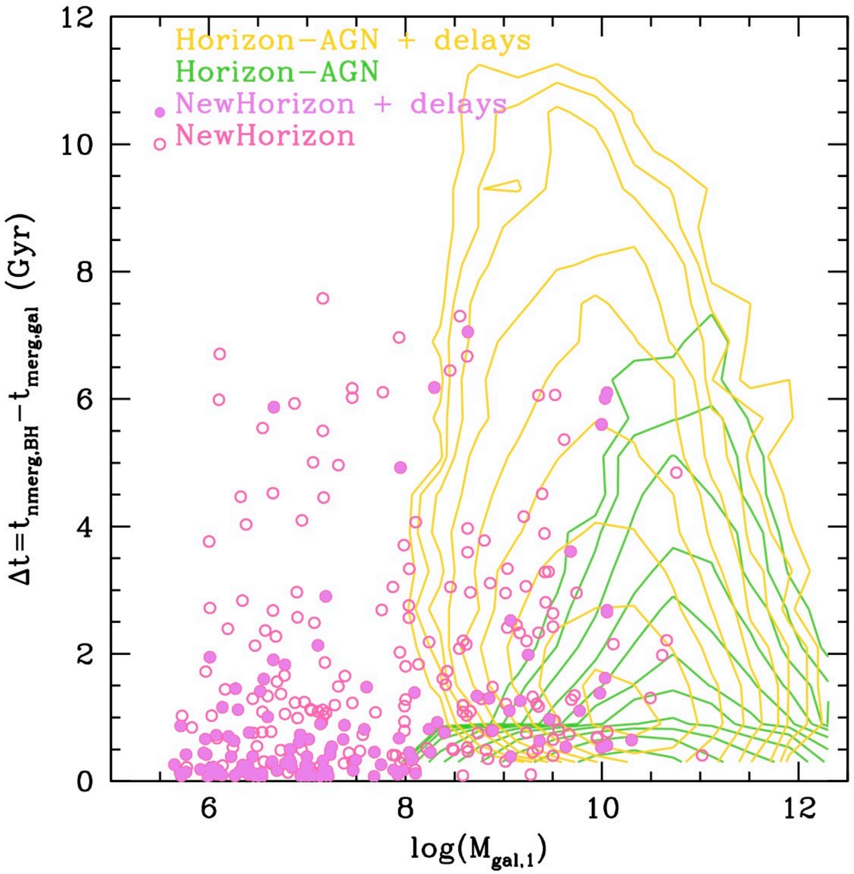


Foustoul+24



MBH masses and redshift in the PTA range ⇔ connection to PTA sources, both contributing to the background and resolved sources

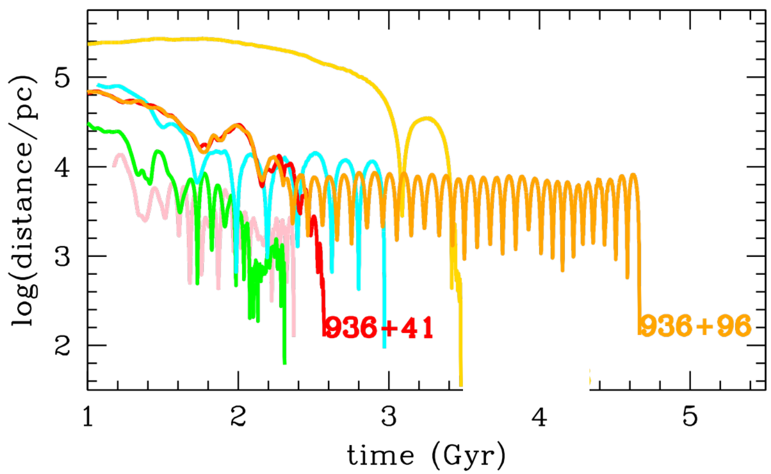
Are merging MBHs found in merging galaxies?

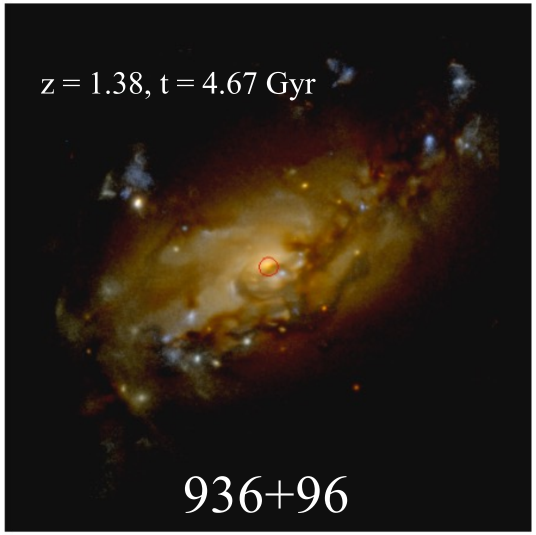


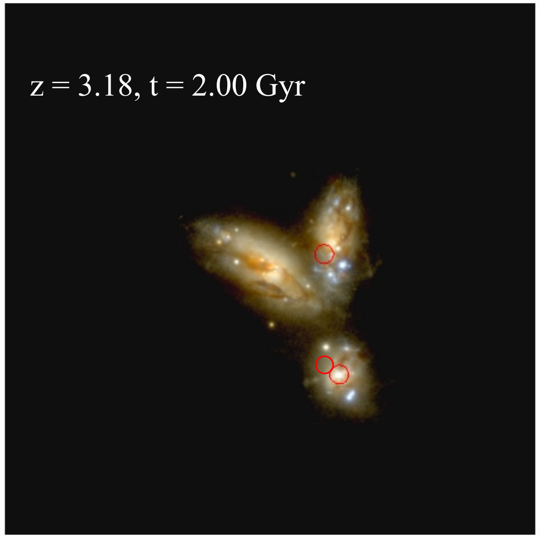
Generally, no.

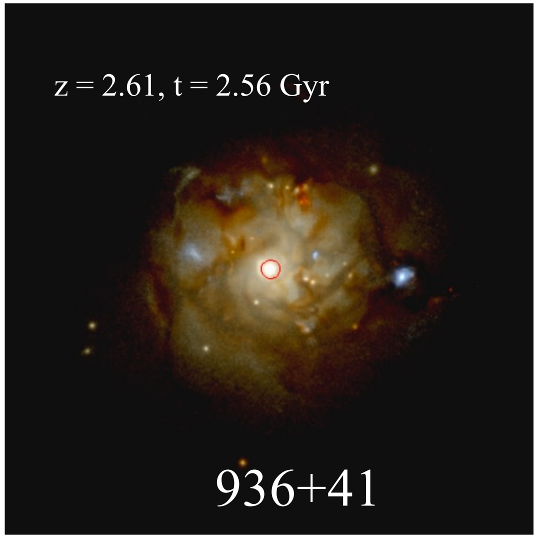
MBHs often merge long after galaxies do

Adapted from Volonteri+20









The MBH binary

NewHorizon simulation

The galaxy merger

The MBH binary

Volonteri+20

After the fact: modelling the emission from MBH mergers

Post-process emission from MBH mergers

- Model GW parameter estimation by LISA
- Model AGN SED (IR to X-rays)
- Model post-merger rebrightening due to cavity refilling
- Model gas, dust obscuration (ISM + torus)
- Model radio jets, merger flares (theoretical BZ models, fundamental plane)
- Model the (contaminant) galactic emission — stellar light, X-ray binaries and SFR radio emission

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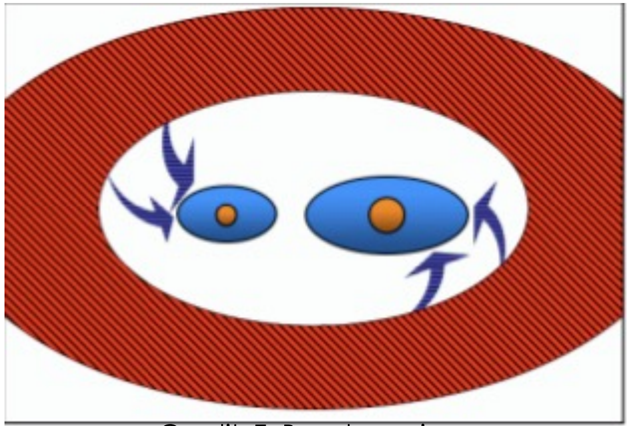
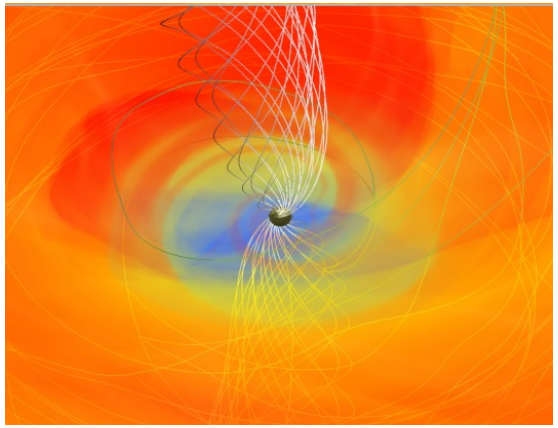


Credit: T. Bogdanovic



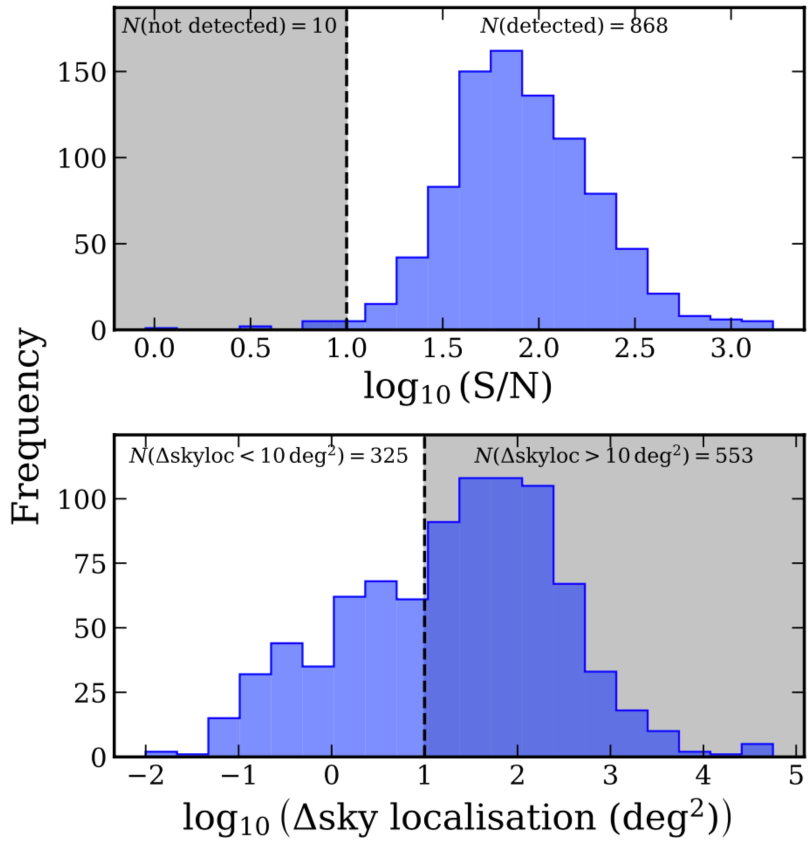
Gold et al. 2014

GW observability of numerical MBH mergers

Around 99%of mergers can be detected with LISA
High-mass mergers with low mass ratio are not detected

Parameters (redshift, masses, spins) are recovered generally with high precision

Systems are generally very poorly localized in the sk
— only 37%of mergers have a 2σ error smaller than 10 deg^2



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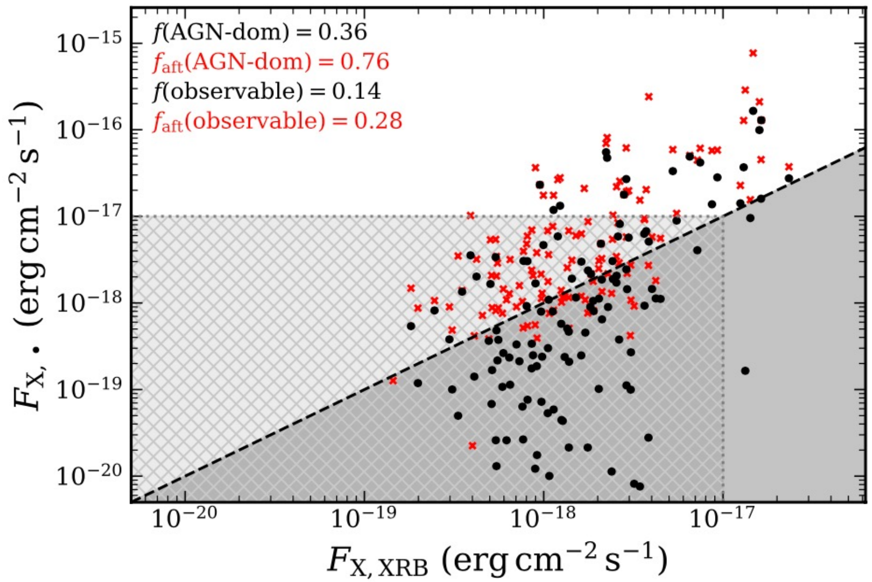
EM observability of z>3.5 MBH mergers

A higher fraction is brighter than the galaxy in X-rays



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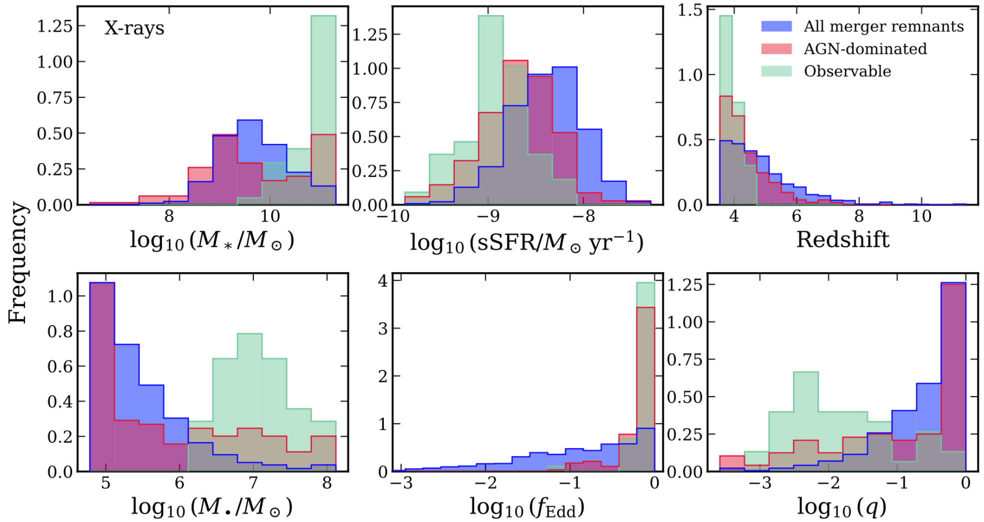
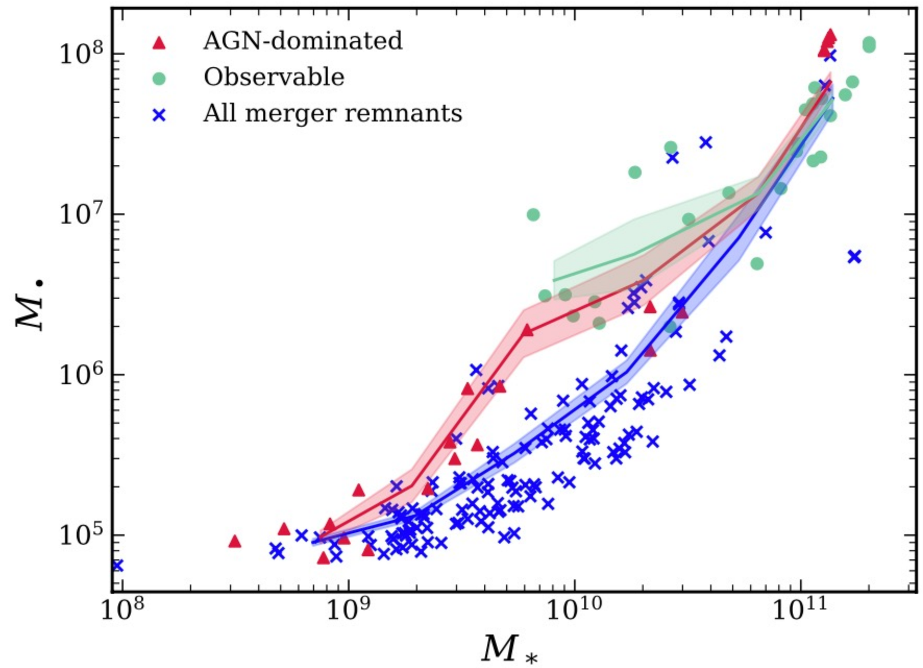
Biases of EM observable MBH mergers





Observable MBH mergers are not unbiased tracers of the full merging population

E.g., Observable merging MBHs are overmassive at fixed galaxy mass

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Summary

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

Cosmological simulations can help understand the MBH binaries that contribute to GWs at nanoHx frequencies in PTAs

MBHs merge at sub milli-pc separations: a challenge to cosmological simulations => KETJU & RAMCOAL

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