Binary supermassive black holes: theory, observations and constraints

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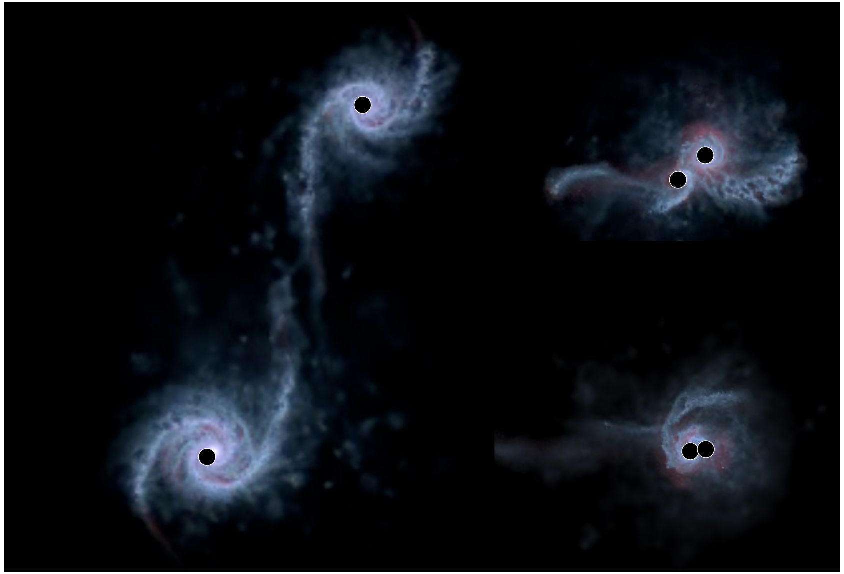
Massive black holes and gravitational waves

When MBHs merge they become a source of gravitational waves

MBH-MBH mergers follow galaxy mergers, providing that the MBHs can find each other at the center of the merger remnant



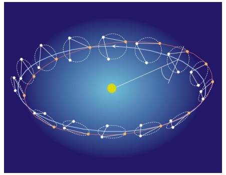
Massive black holes and gravitational waves

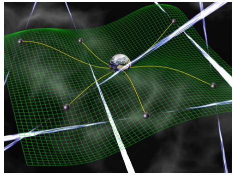
$$f \sim \frac{c}{2\pi R_s} \sim 10^4 \mathrm{Hz} \frac{M_\odot}{M}$$

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

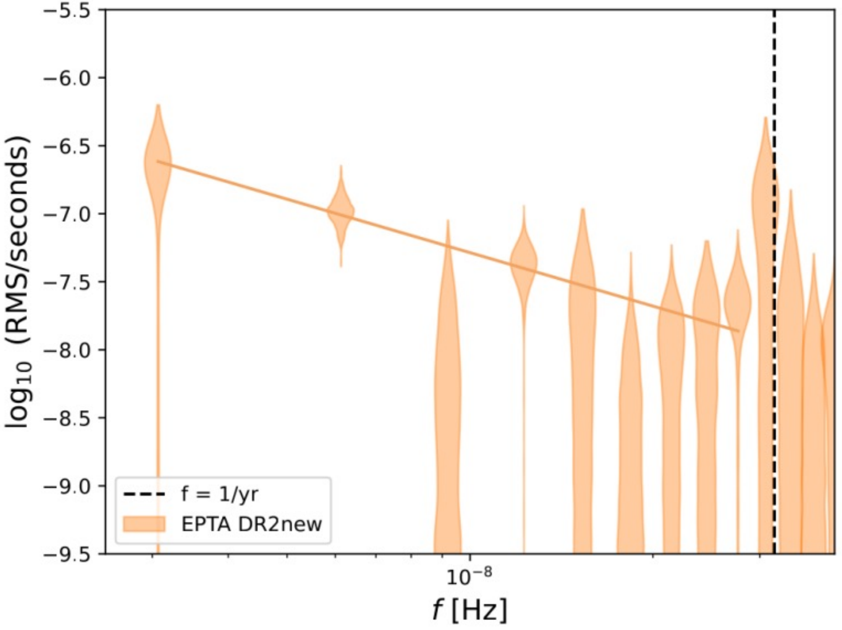
10^6 M_{sun} binary
f<10^{-2} Hz
LISA
inspiral/merger

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

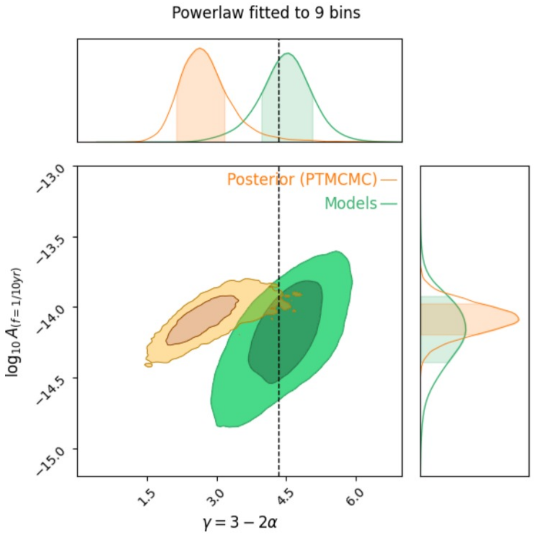




PTA detections in 2023: lots of merging MBHs

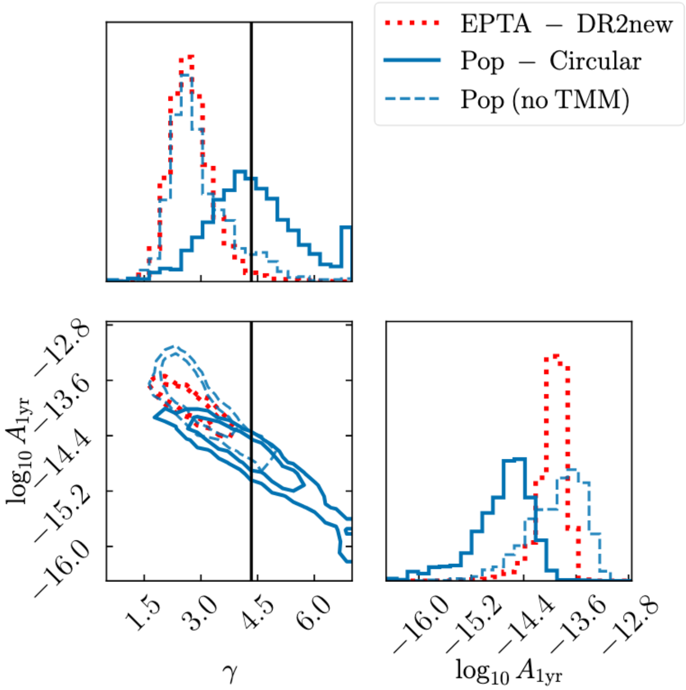


The (current) amplitude of the background is somewhat higher than expected from theoretical models, and the slope shallower



EPTA+InPTA Collaboration 2024
Similar results from NANOGrav, PPTA, CPTA (Agazie+23; Reardon et al. 2023; Xu et al. 2023)

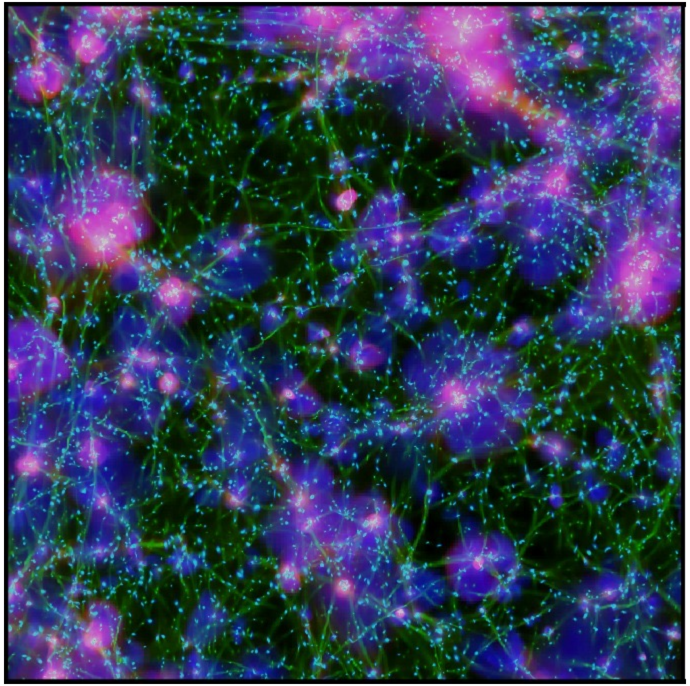
PTA detections in 2023: lots of merging MBHs



The inference on amplitude and slope may be biased because of how pulsar noise is handled (Goncharov+24) or because of spectral leakage (Quelquejay+2025; Crisostomi+25)

The Horizon-AGN simulation

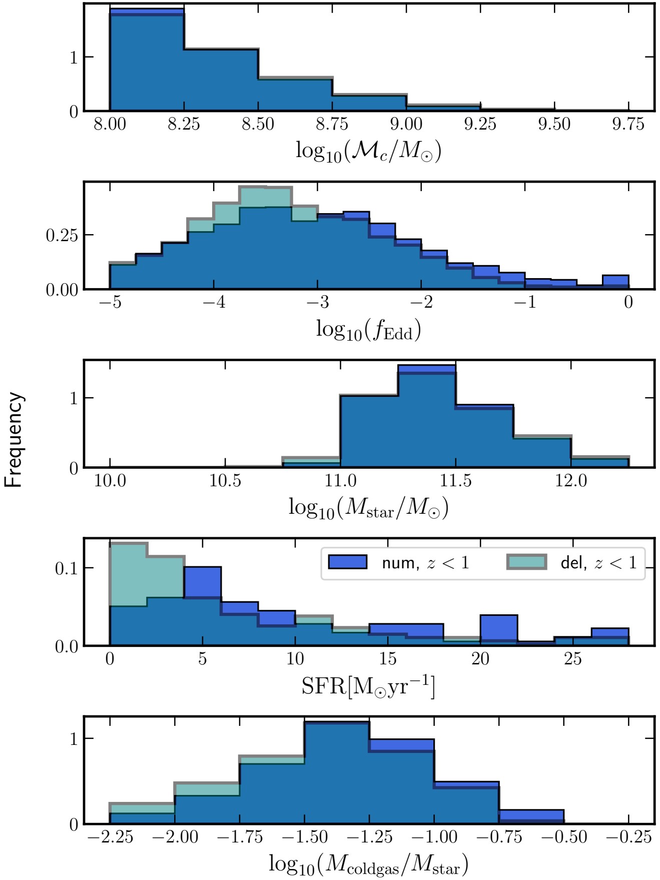
- Simulation content
  - Run with Ramses (AMR) Teyssier (2002)
  - L_{box}=100 Mpc/h
  - 1024^3 DM particles $M_{DM,res}=8x10^7 M_{sun}$
  - Finest cell resolution dx=1 kpc
  - Gas cooling & UV background heating
  - Low efficiency star formation
  - Stellar winds + SNII + SNIa
  - O, Fe, C, N, Si, Mg, 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

The Horizon-AGN view of PTA MBH binaries

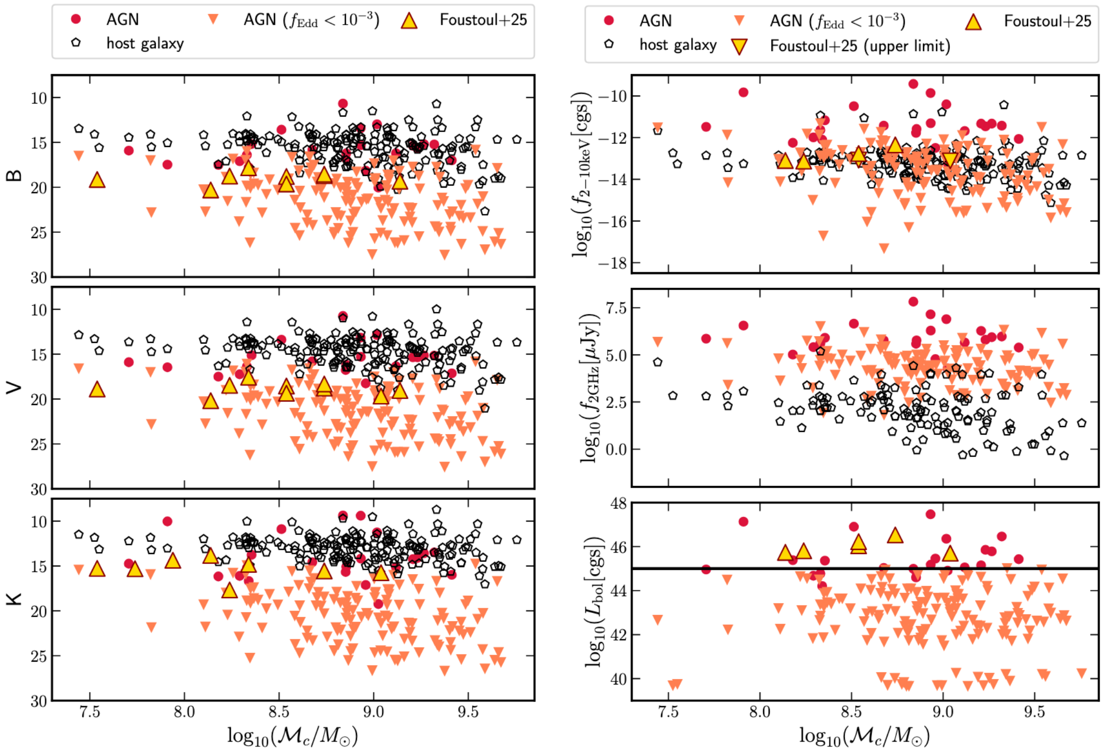


PTA binaries have low Eddington ratios: not quasars!

PTA binaries hosted in massive galaxies with relatively low SFR and gas content, especially when accounting for dynamical delays: any galaxy merger-related SFR burst has had time to decay

Quelquejay+25

The Horizon-AGN view of PTA MBH binaries



PTA binaries have low Eddington ratios: not quasars!

PTA binaries are typically fainter than the host galaxies, except in radio

Quelquejay+25, see also Truant+25

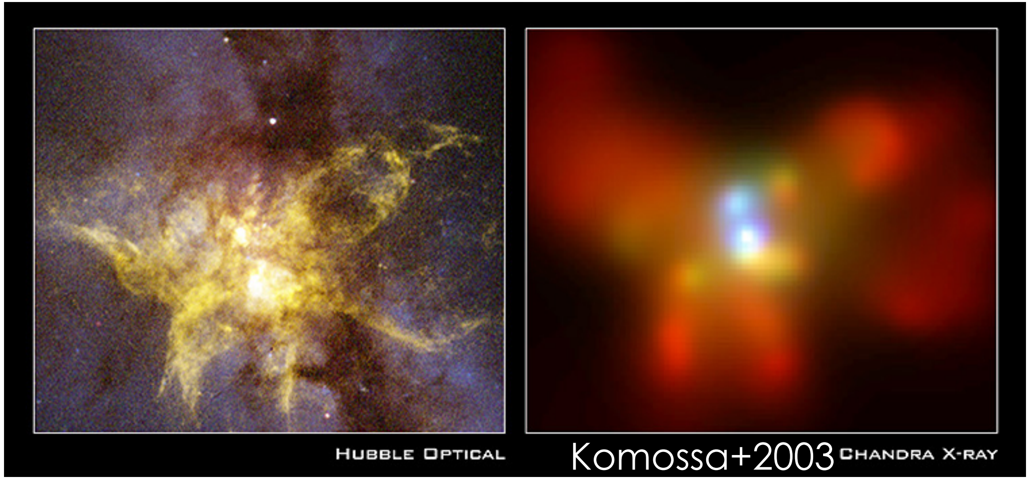
Multimessenger science with MBH mergers

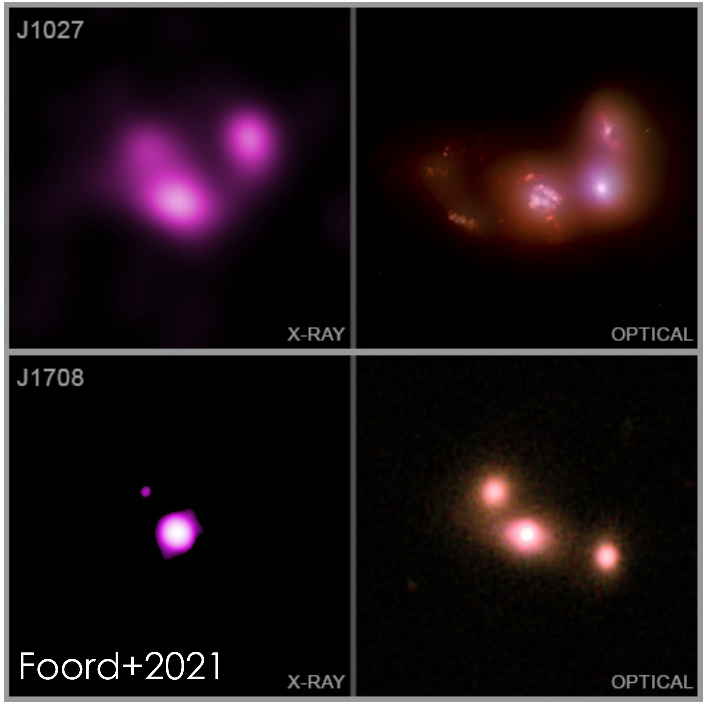
Dual AGN at ~kpc scales: MBHs on their way towards coalescence or stalled dynamical decay?

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?

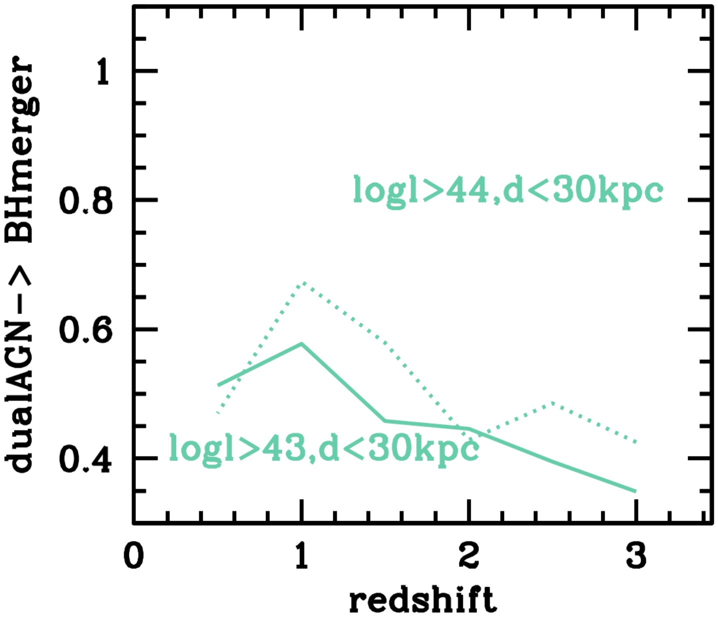
Dual AGN at kpc separations





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

Linking dual AGN and MBH mergers

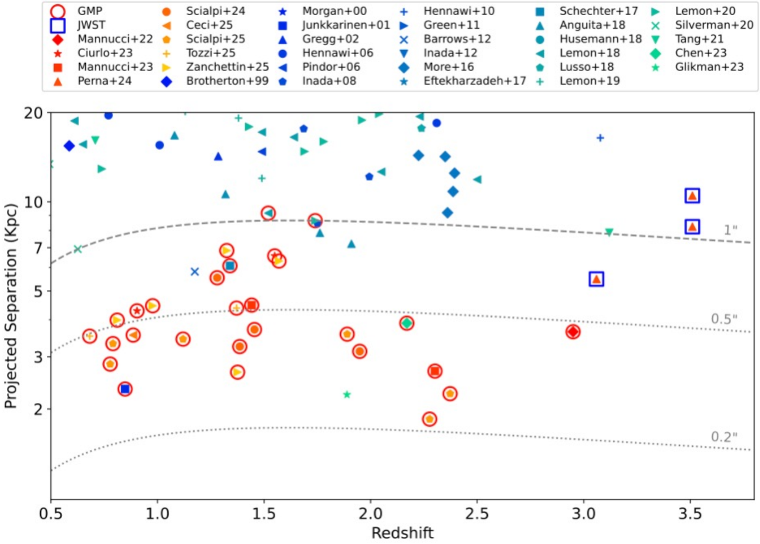


Adapted from Volonteri+21

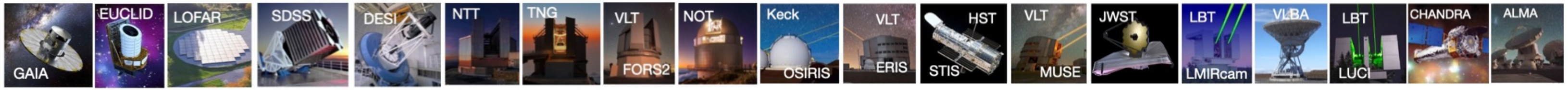
Based on simulations, 30-60% of dual AGN result in a MBH merger

From the dual AGN population one can infer the MBH merger rate

Observing the parent population of merging MBHs

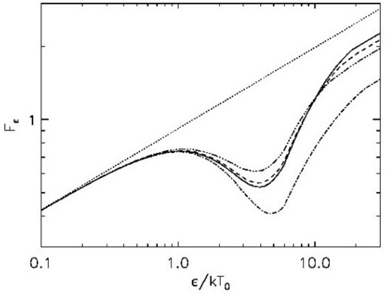


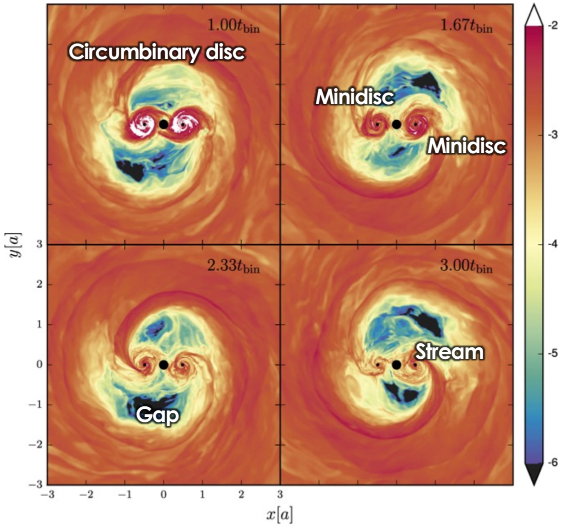
- Using ~20 telescopes/instruments to build a large sample of dual AGN at sub-arcsec separations (common host galaxy) and z>0.5
- well defined selection functions
- Selection with Gaia, Euclid, and LOFAR
- Small but growing set of confirmed dual AGN
- multiple tests to models, applying the same selection functions
- understand BH seeding and basic physical processes
- derive GW event rate from massive BHs



Closer in: binary MBHs at sub-pc separations

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



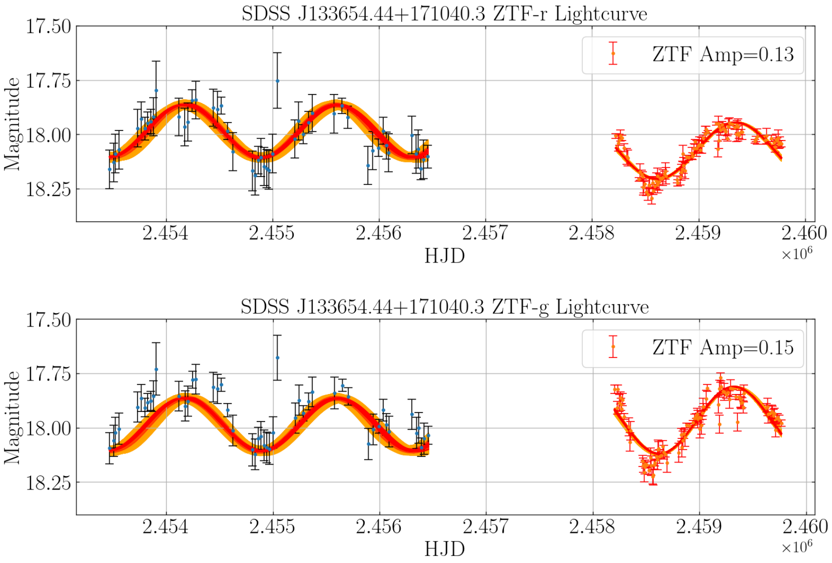


e.g.,Armitage & Natarajan 02; MacFadyen & Milosavljevic 08; Bogdanovic+08; Dotti+08, Cuadra+09; Sesana+12; Roedig+12; Shi+12; Noble+12; D’Orazio+13; D’Ascoli+19

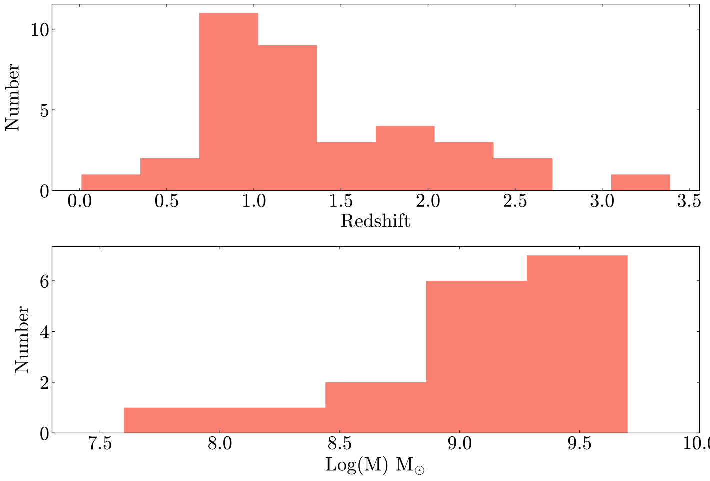
Periodic binaries

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 =>~150 candidates, mostly from Catalina Survey, PTF, PanSTARRS, ZTF

ZTF g and CRTS lightcurve



e.g., Graham+15; Foustoul+24, Agarwal+25



MBH masses and redshift in the PTA range ⇔ connection to PTA sources

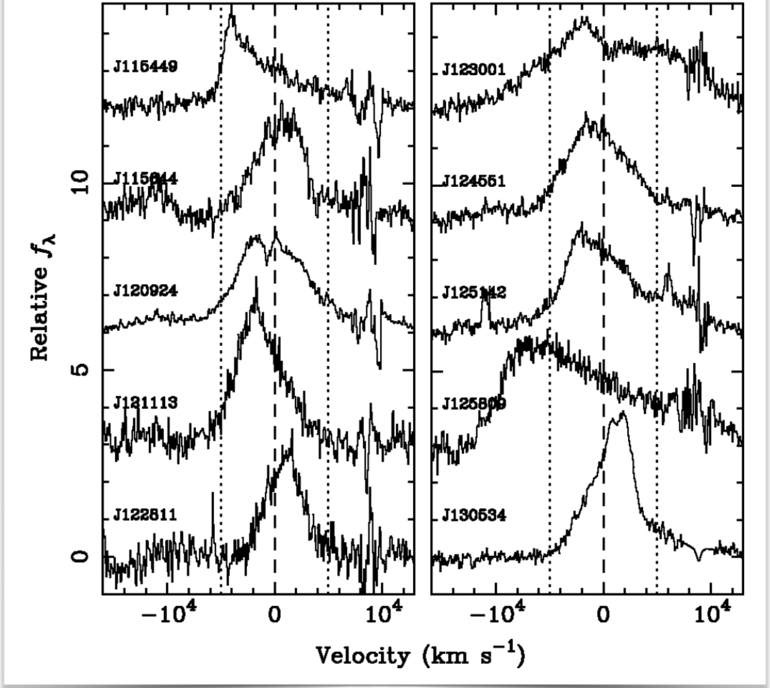
Spectroscopic binaries

- ~16k SDSS QSOs triaged to 88 based on shifted broad Hβ emission line profiles
- Some spectra w/ baseline 20+ years (not for the impatient)
- But, targeted MBHBs have orbital periods 10s to 100s yr (Pflueger+ 18)

↓

NOT MEASURING MULTIPLE ORBITAL CYCLES

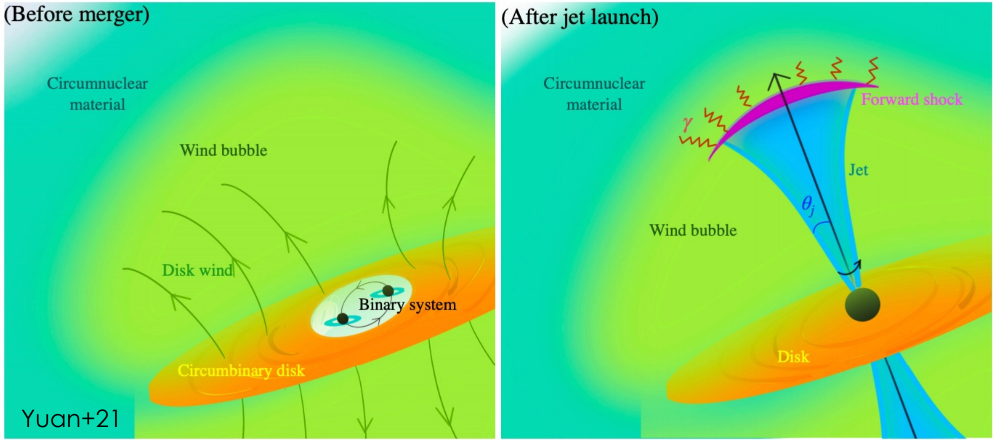
broad Hβ emission line profiles
(Eracleous+ 12, Runnoe+ 15, 17)

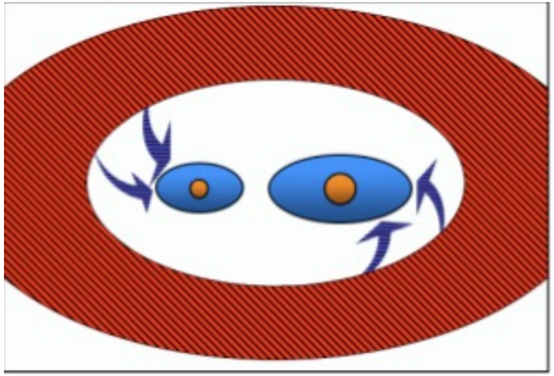


Slide credit: T. Bogdanovic

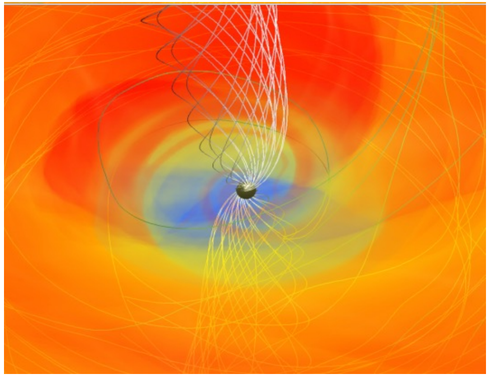
After the fact: modelling the emission from MBH mergers

- Burst at merger as gas plows in from gap
- Perturbed discs
- Effect of recoils
- Dual/single jets





Credit: T. Bogdanovic



Gold et al. 2014

e.g., Armitage & Natarajan 02; Milosavljević & Phinney 05; Schnittman & Krolik 08; Palenzuela+10, Gold+14, Yuan+21 etc etc

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

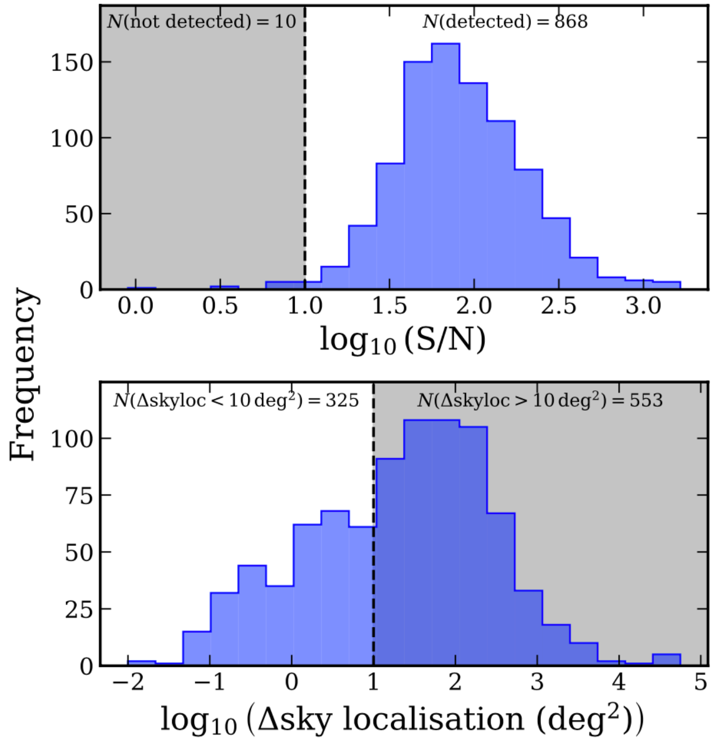
Chi An Dong Páez+23

GW observability of high-z MBH mergers with LISA

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

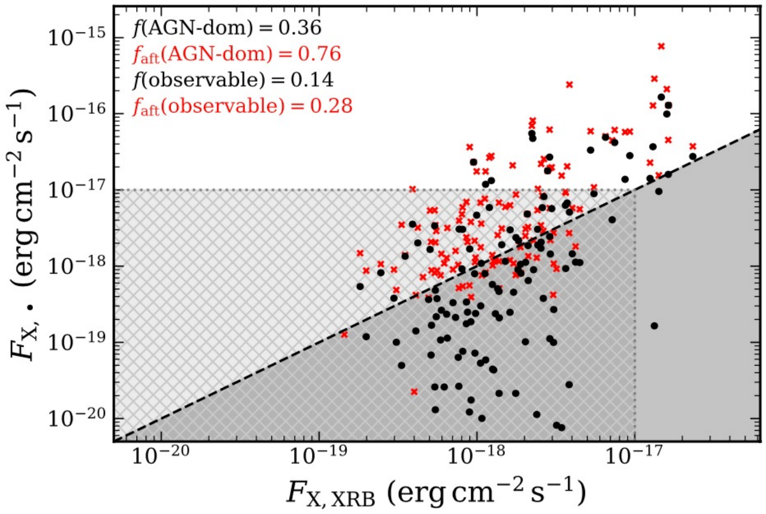


Chi An Dong Páez+23

EM observability of z>3.5 MBH mergers

15-30% of MBH mergers are sufficiently bright – and brighter than the host galaxy – in X-rays

In optical the AGN emission is typically outshined by the host galaxy



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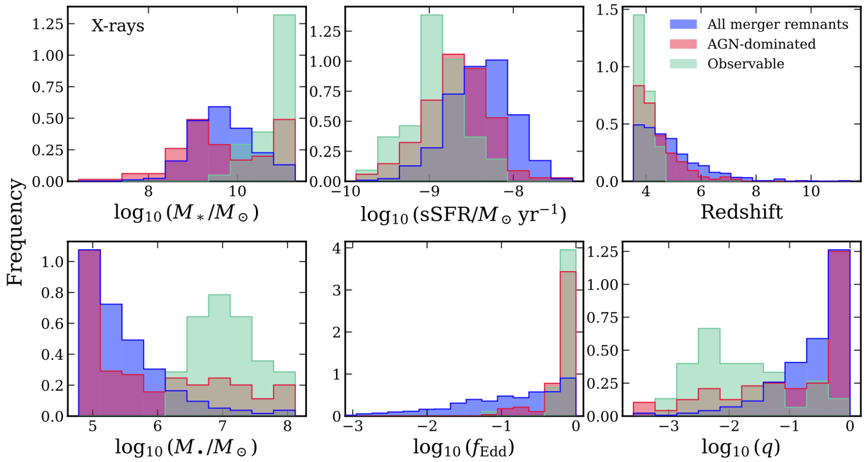
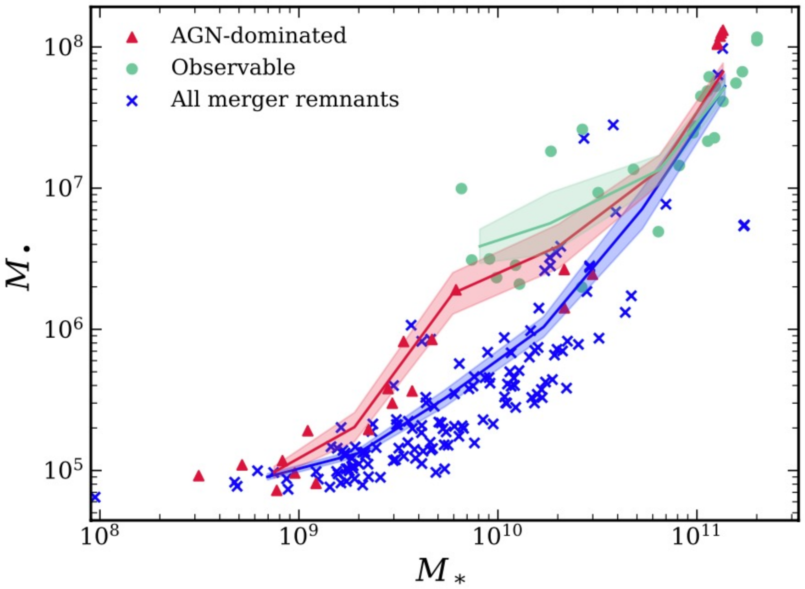
Biases of EM observable MBH mergers



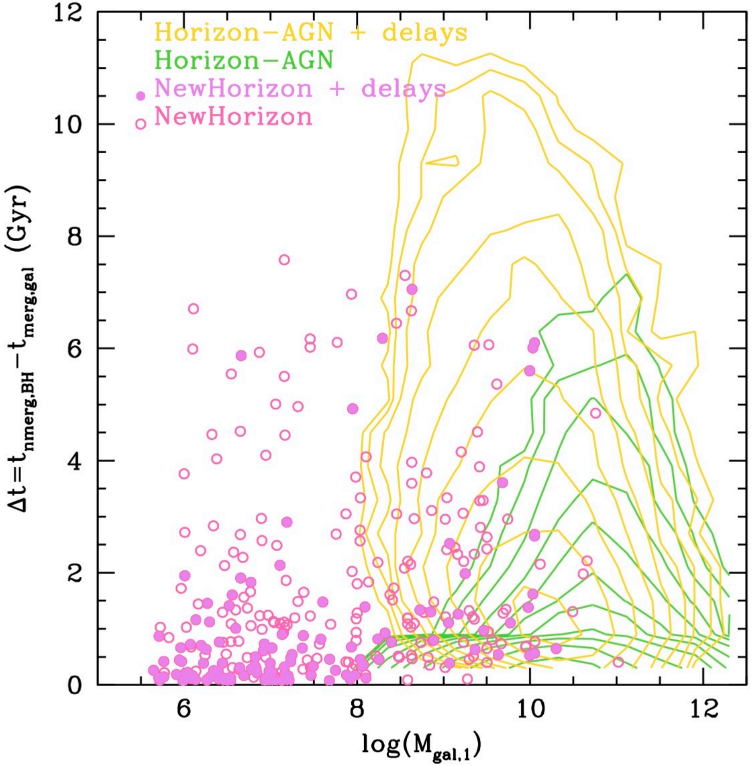


Observable MBH mergers are not unbiased tracers of the full merging population

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

Chi An Dong Páez+23

Are merging MBHs found in merging galaxies?

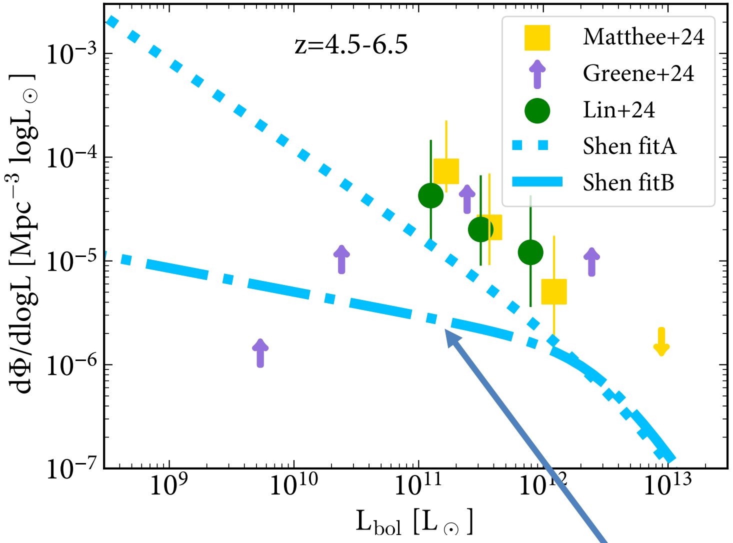


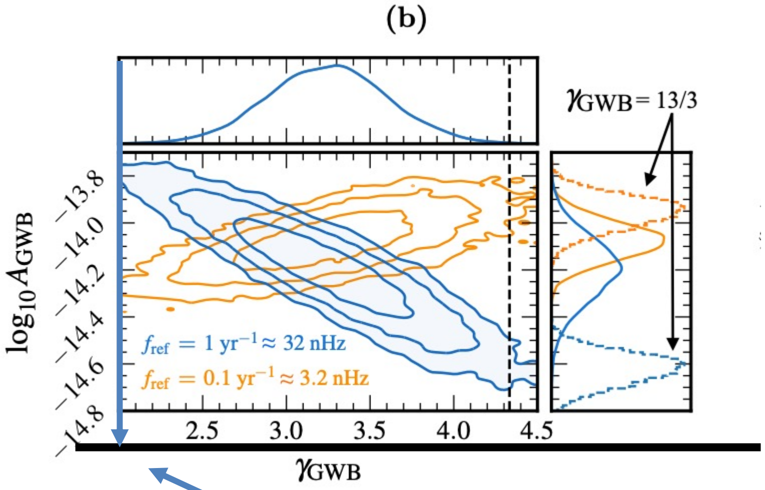
Generally, no.

MBHs often merge long after galaxies do

Adapted from Volonteri+20

Bonus topic: JWST and PTA





"old" luminosity functions

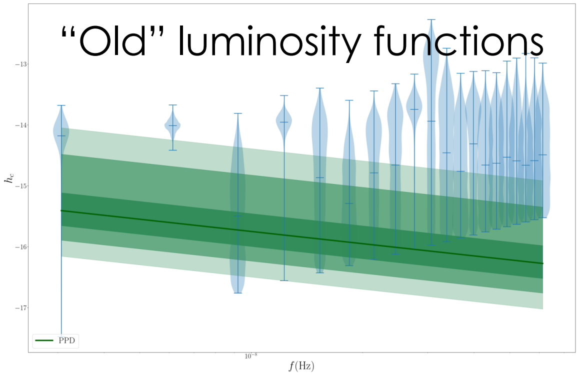
"old" upper limit -15

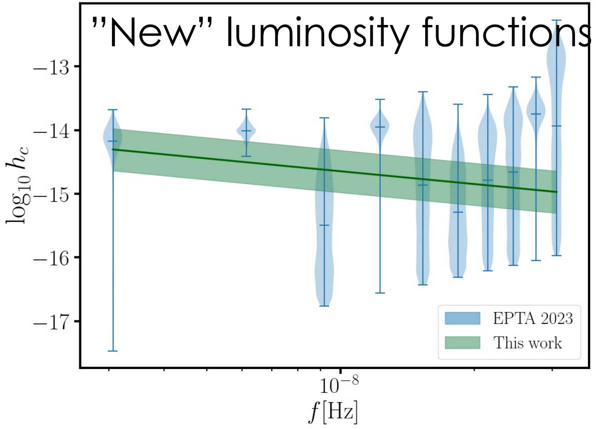
What if we include the "new" high-z Massive Black Hole populations in modeling PTA and LISA?

Bayesian approach that determines the "best" Massive Black Hole evolution based on fitting the luminosity function and PTA

Toubiana+24, arxiv: 2410.17916

Bonus topic: JWST and PTA





Within our bayesian model, there isn't much room for allowing a much lower luminosity function at high z and producing a high background for PTA

Toubiana+24, arxiv: 2410.17916

see also Ellis+24 for JWST/PTA connection and Steinle+23; Barausse+23; Izquierdo-Villalba+24; for PTA/LISA connection

Summary

Merging massive black holes can be detected by PTAs and LISA, in different mass and redshift windows

PTAs have announced their first detection of GWs at nanoHz frequencies, but the properties of the signal are still in flux

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

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