Multimessenger modelling of massive black hole mergers in the Obelisk cosmological simulation

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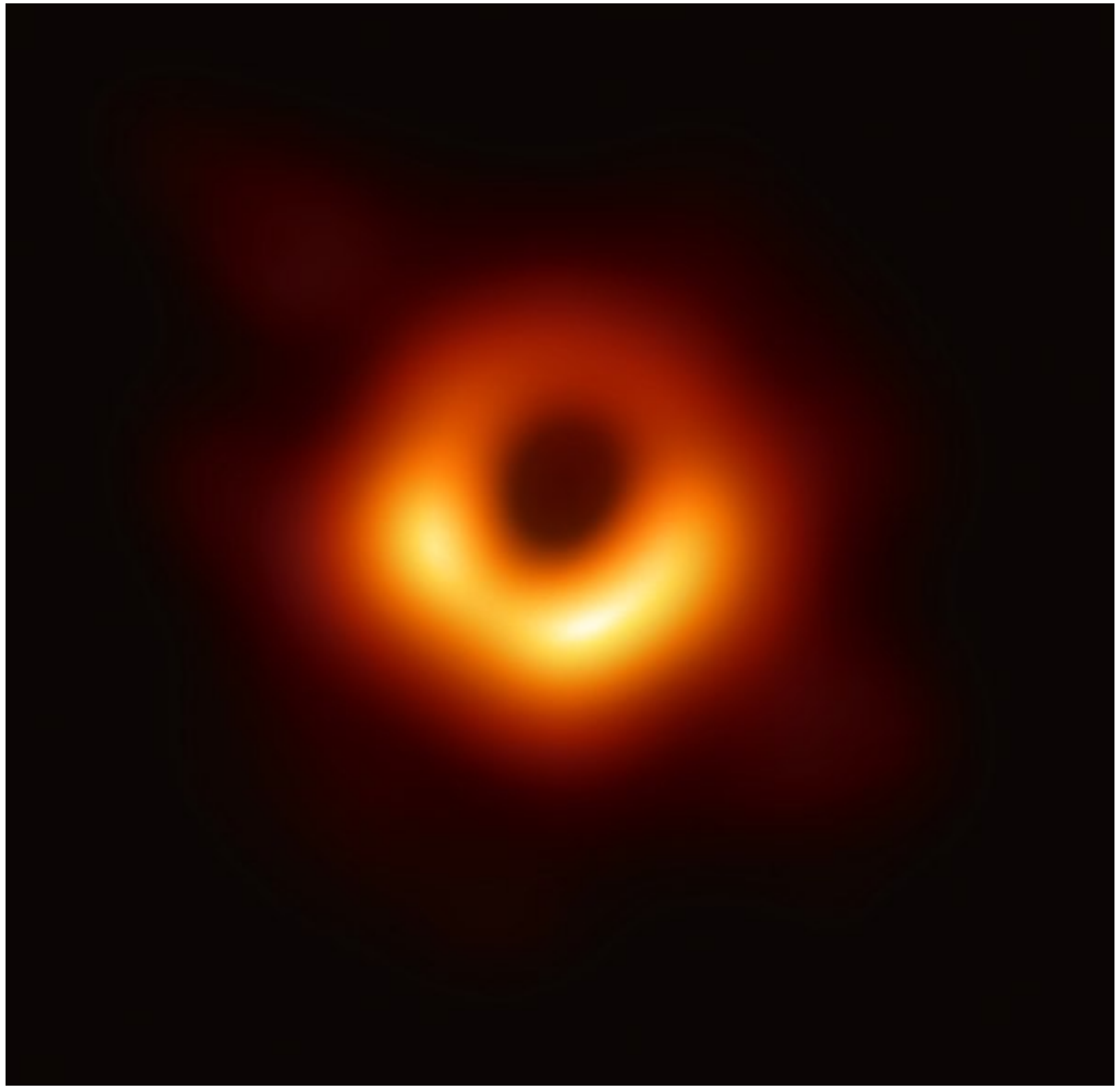
Massive Black Holes

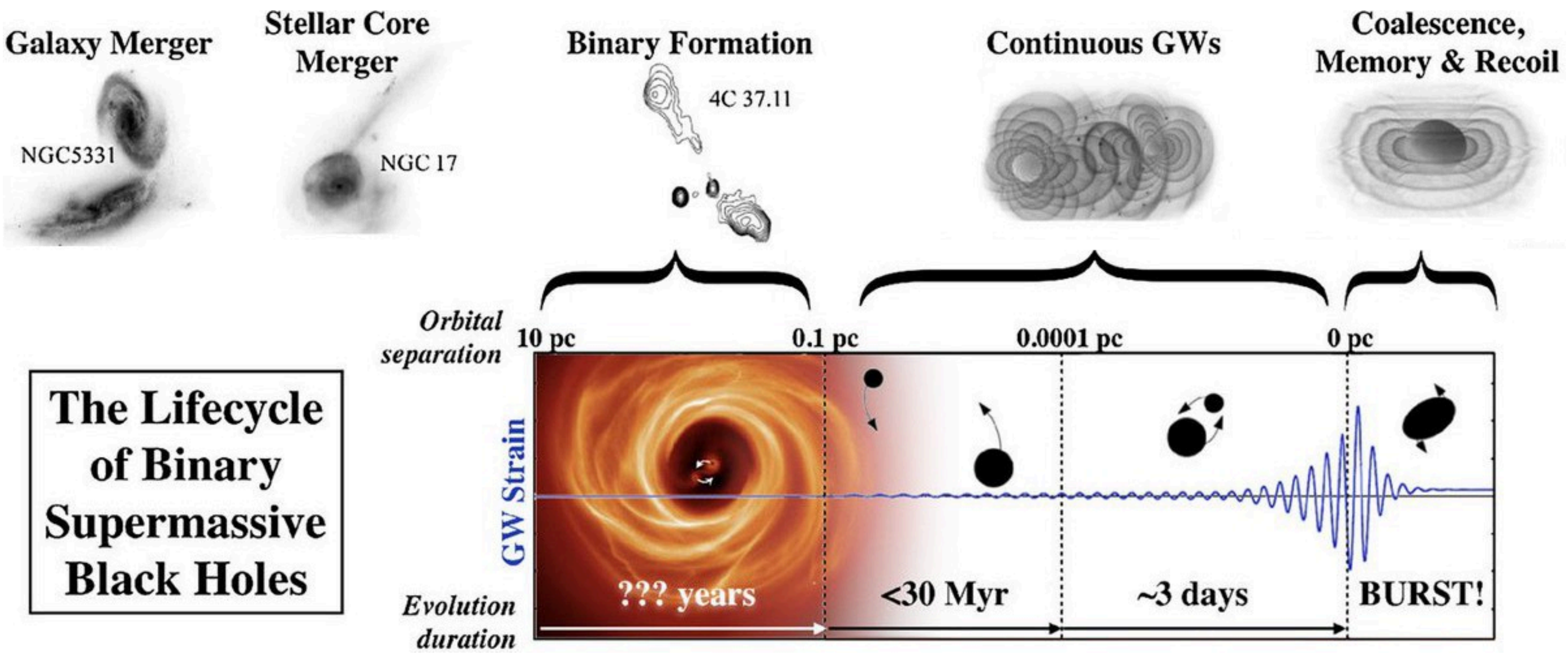
Most massive galaxy nuclei host a **massive black hole** (MBH) $\gtrsim 10^4\, M_{\odot}$. **MBHs play a key role in galaxy formation and evolution**

- MBHs are seeded at high redshift
- MBHs grow through gas accretion and mergers
- MBHs strongly affect the evolution of their host galaxies via AGN feedback



EHT collaboration 2019

A multimessenger view of MBH mergers



Burke-Spolaor et al. 2018

- Galaxy mergers can lead to **massive black hole** (MBH) mergers
- When MBHs merge, they emit **gravitational wave** (GW) and **electromagnetic** (EM) radiation, which can provide complementary information about the merger and the astrophysical population.

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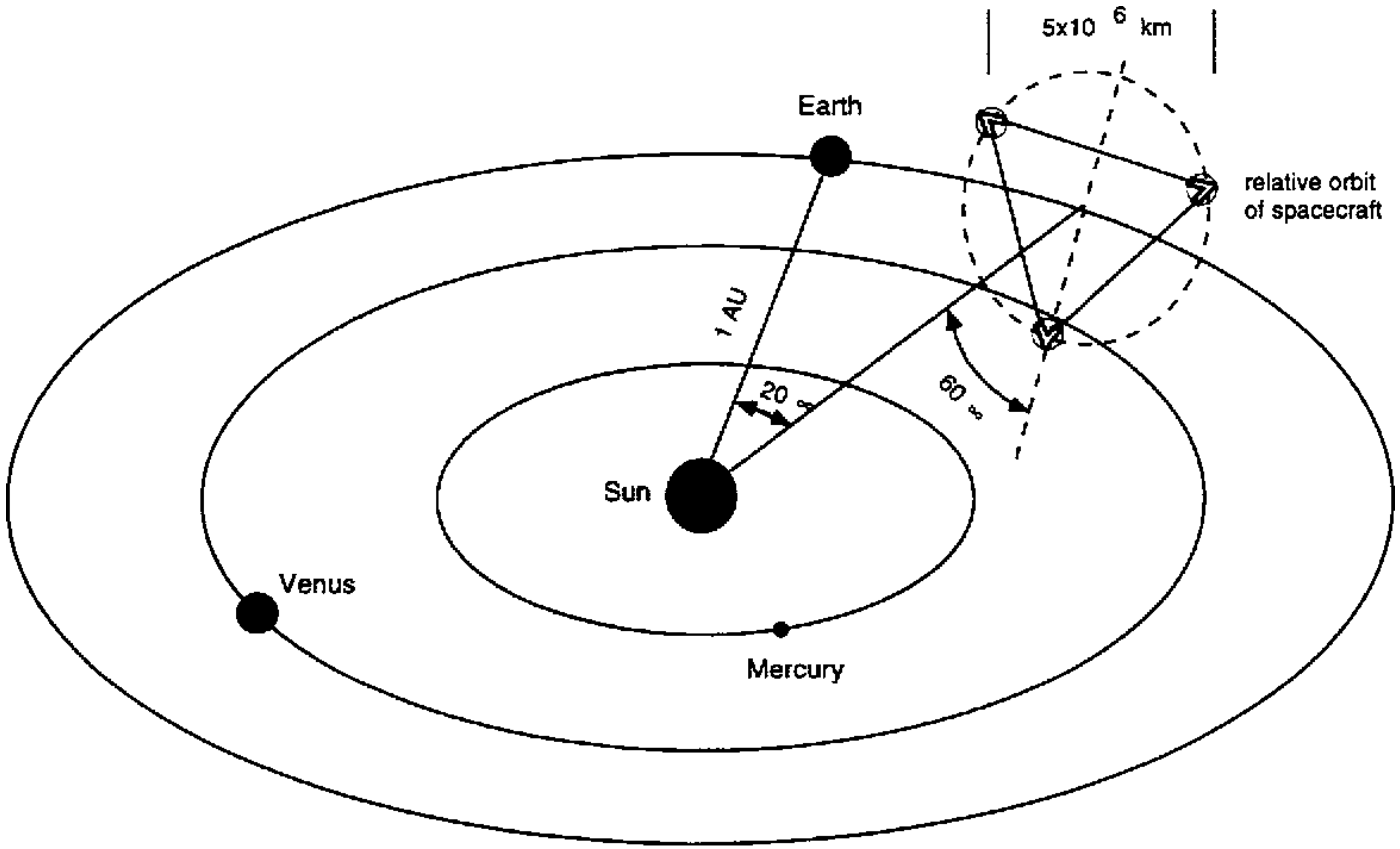
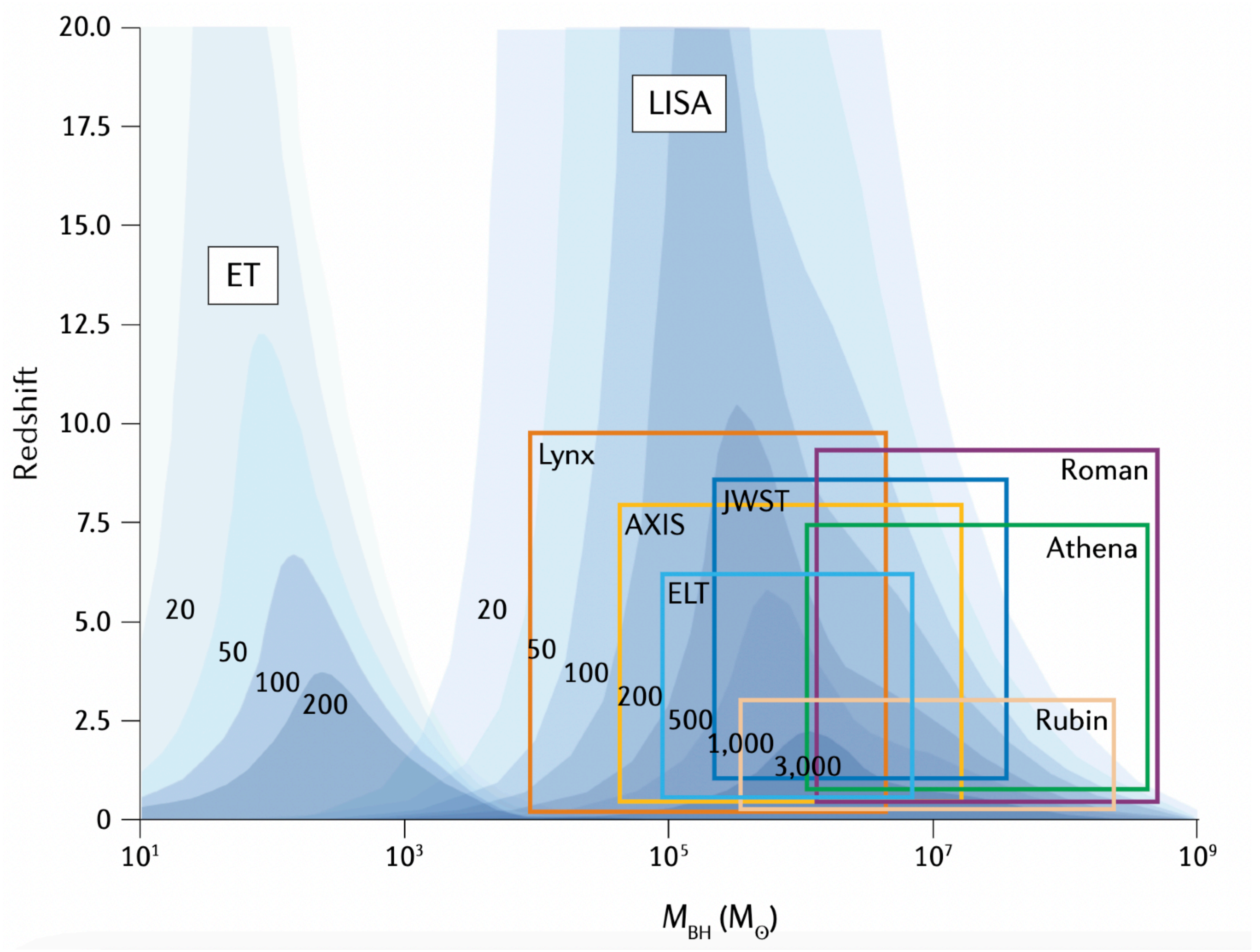
The LISA mission



Folkner et al. 1998



Volonteri et al. 2021

- The future **LISA mission** will be able to detect MBH mergers with mass $10^4 - 10^7\,M_\odot$ with very high SNR up to $z \sim 10$
- **Set to launch in 2037**

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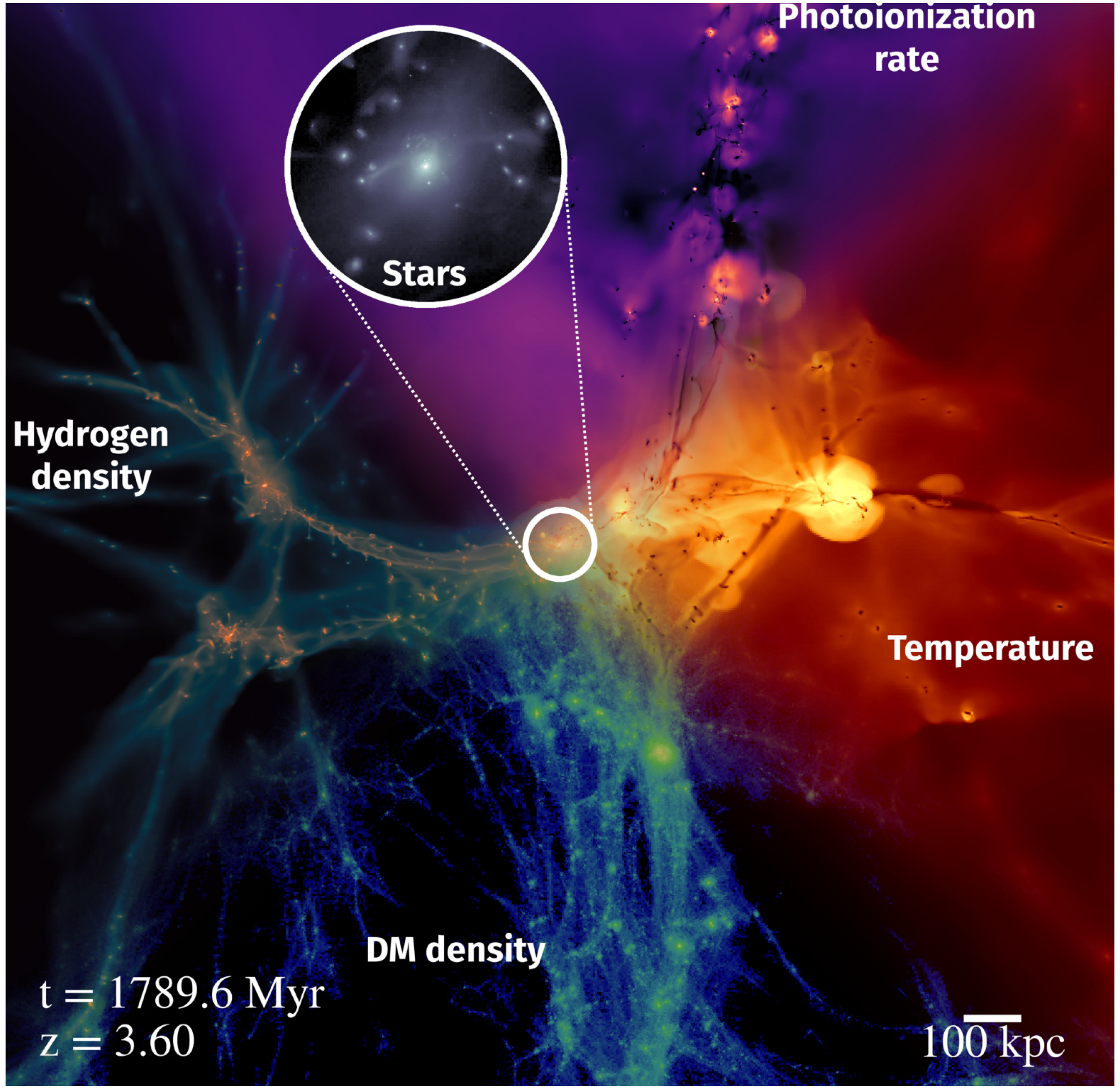
Modelling MBH mergers

Use BH population in the **Obelisk radiative hydrodynamical cosmological simulation** (Trebitsch et al. 2020)

- Formation of protocluster down to $z \sim 3.5$
  $\rightarrow$ **many BH mergers**
- Usual cooling, star formation, supernovae, metals, etc.
- Detailed BH physics (**seeding, accretion, feedback, spin evolution, dynamics**)
- **High resolution** $(35\ \mathrm{pc})$



Trebitsch et al. 2020

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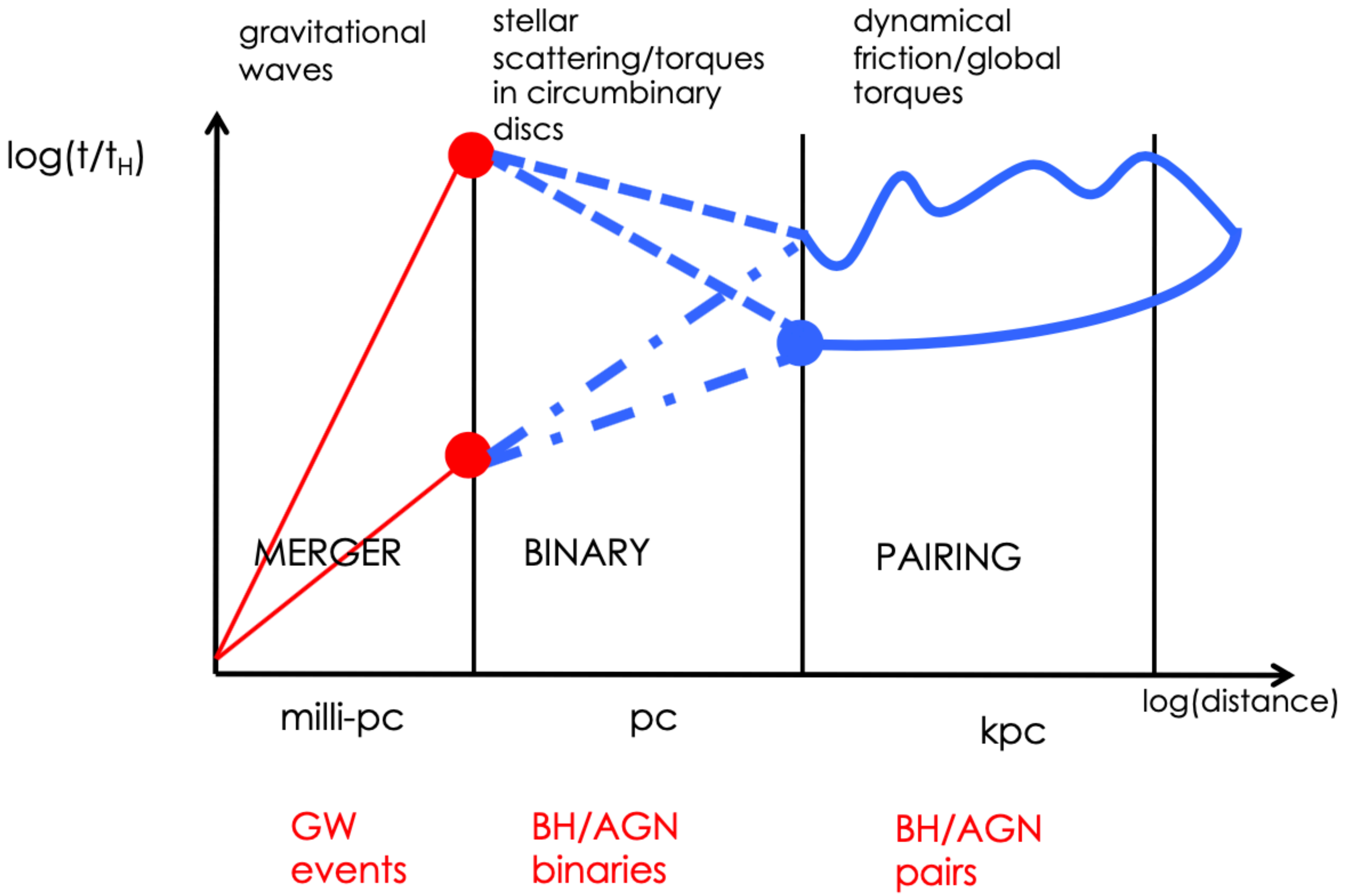
Merger dynamical delays

In our simulation BH merge numerically at distance $140\,\mathrm{pc} \rightarrow$ **need to take into account the sub-grid delay until the actual merger** (in post-processing)

- **Dynamical friction phase**: interaction with **stars**
- **Binary hardening phase**: evolution by **stellar hardening or viscous torques from circumbinary disc**
- If both phases finish before the end of the simulation $\rightarrow$ **delayed merger**

Note: the final mass ratio $q = M_2/M_1$ is not well defined for delayed mergers — **we consider both numerical and delayed mergers to bracket our uncertainty**



Monica Colpi

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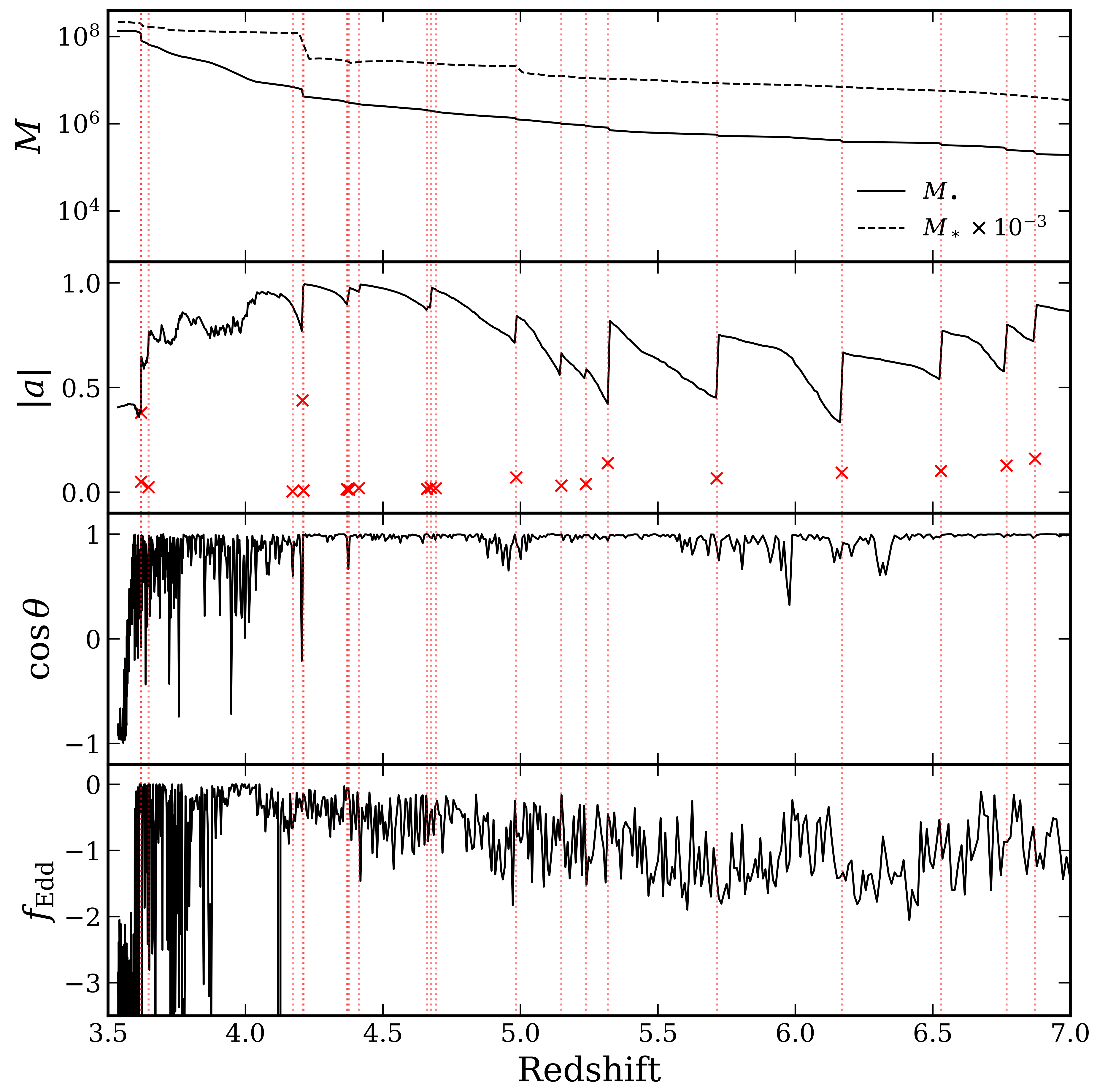
The life of a MBH in Obelisk

The cosmic evolution of a MBH is closely influenced by the properties of its host galaxy

- Low-mass galaxies ($M_* \lesssim 10^9\, M_\odot$): galaxy has chaotic dynamics, no well-defined centre → **chaotic MBH accretion, slow mass and spin growth**
- For $M_* \gtrsim 10^9\, M_\odot$: galaxy settles in disk/proto-disk → **coherent, efficient MBH accretion, fast mass and spin growth**.
- For $M_* \gtrsim 10^{11}\, M_\odot$: availability of gas decreases → **inefficient accretion, slow mass growth, mergers drive spin**.

Mergers tend to decrease the MBH spin



$$f_{\rm Edd} = \dot{M}_\bullet / \dot{M}_{\rm Edd}$$

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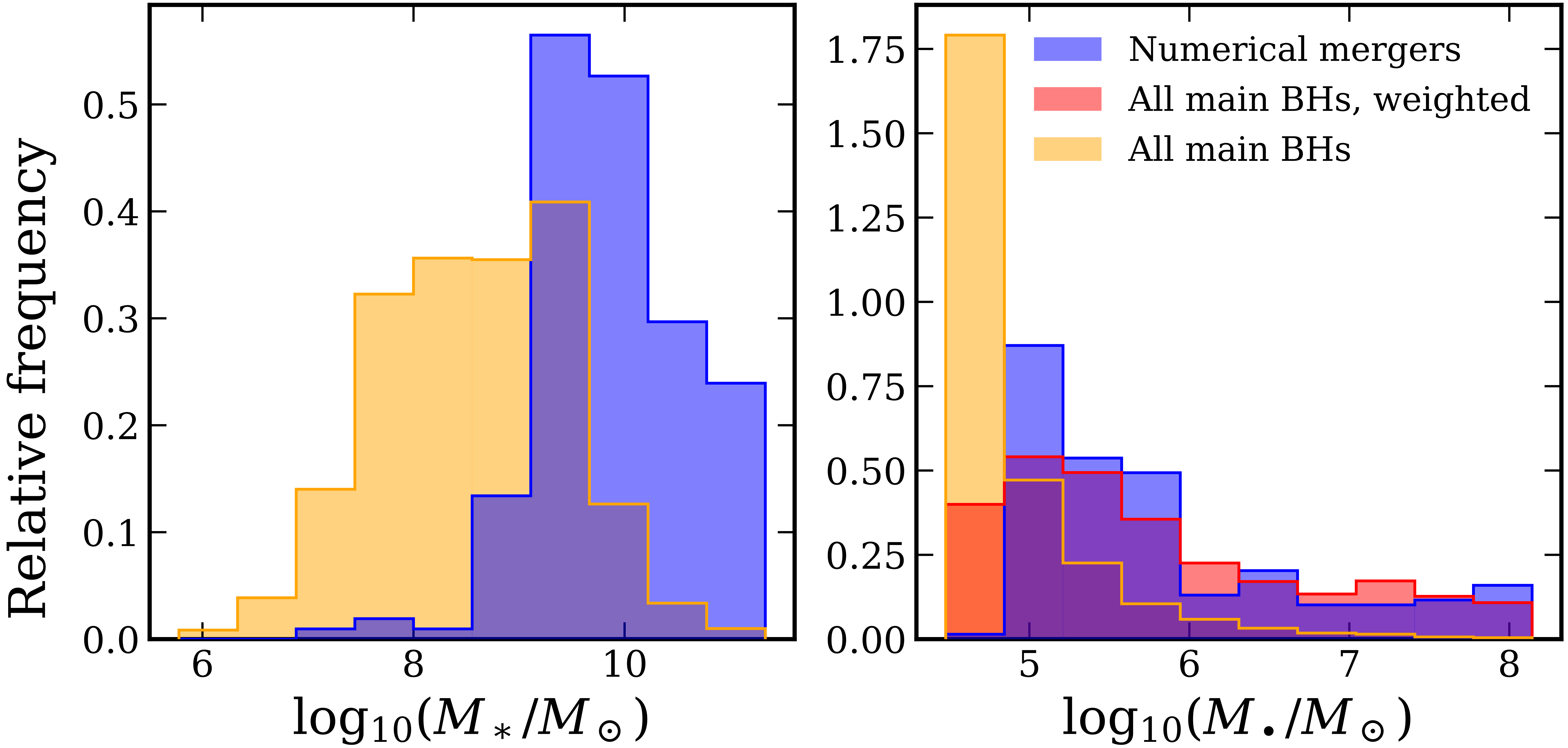
Question 1:

How does the merging MBH population compare to the global MBH population?

See arXiv:2303.00766

The population of merging MBHs at $z \sim 3.5$



- **MBH merger hosts tend to be more massive than the overall population ($M_* \gtrsim 10^9\,M_\odot$)**
- **Merging MBH are also more massive, since mergers are hosted by massive galaxies**

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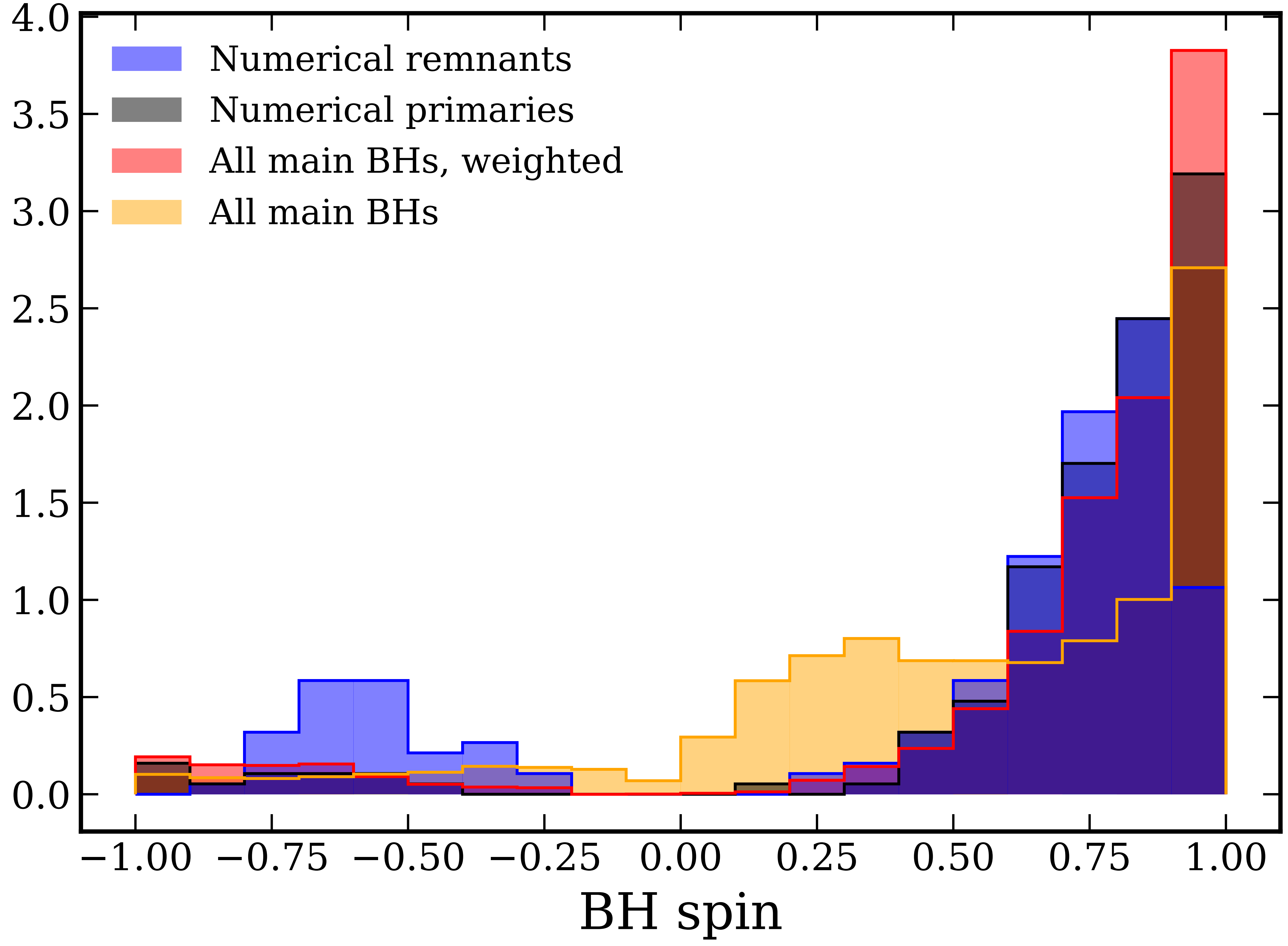
The effect of mergers on MBH spin



- **Merging MBHs hosts tend to have higher spins than the global MBH population**
- **Mergers tend to decrease the spin**

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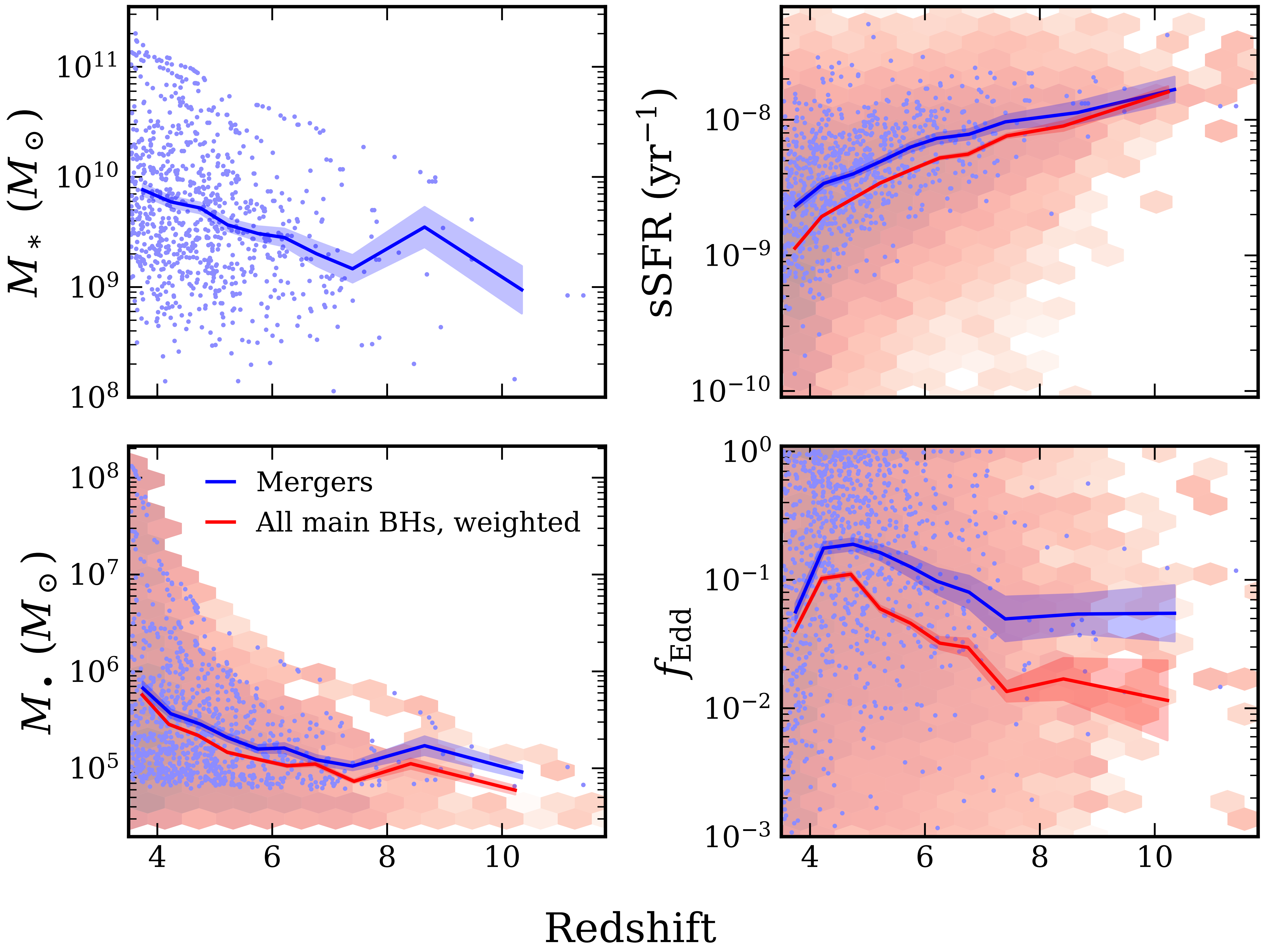
Redshift evolution of merger properties

- **The average MBH and galaxy mass of MBH mergers increase with time**
- The preceding galaxy merger compresses the ISM gas → boosts sSFR and MBH accretion rate → **typically sSFR and MBH accretion rate are higher for merging MBHs**
- **These biases have to be taken into account when making inferences about the global population**



$$\mathrm{sSFR} = \mathrm{SFR}/M_*$$

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Question 2:

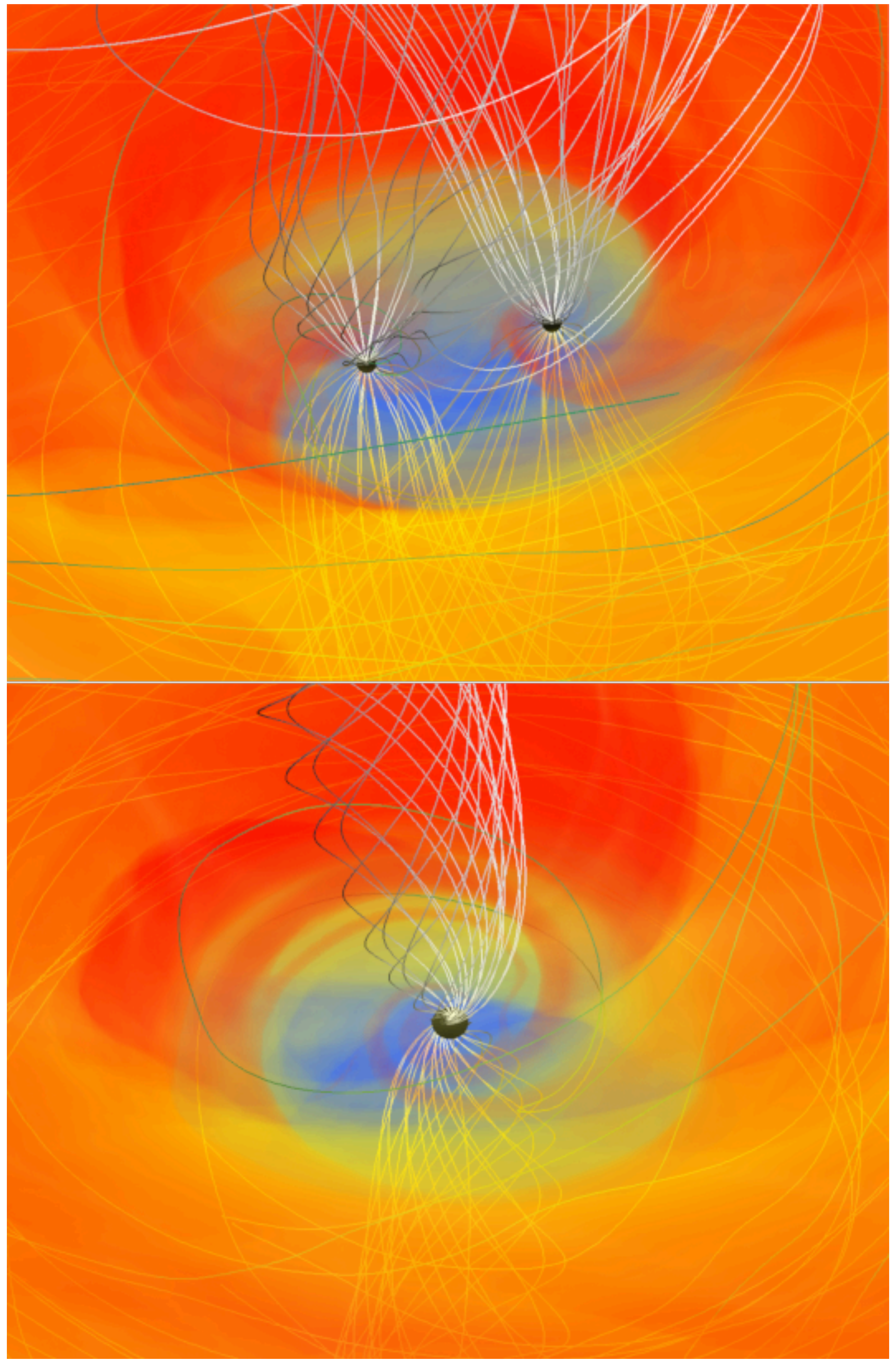
Can MBH mergers be detected?

If so, is the observable population biased?

Modelling the emission from MBH mergers

Post-process emission from MBH mergers in the simulation

- Model GW parameter estimation by LISA
- Model AGN SED (IR to X-rays)
- Model radio jets (theoretical BZ models — total emission, fundamental plane — core emission)
- Model merger-induced transients: (i) afterglow producing $f_{\rm Edd} = 1$ due to e.g. disc cavity refilling or (ii) radio flares.
- Model gas, dust obscuration (ISM + torus)
- Model the (contaminant) galactic emission — stellar light, X-ray binaries and SFR radio emission



Gold et al. 2014

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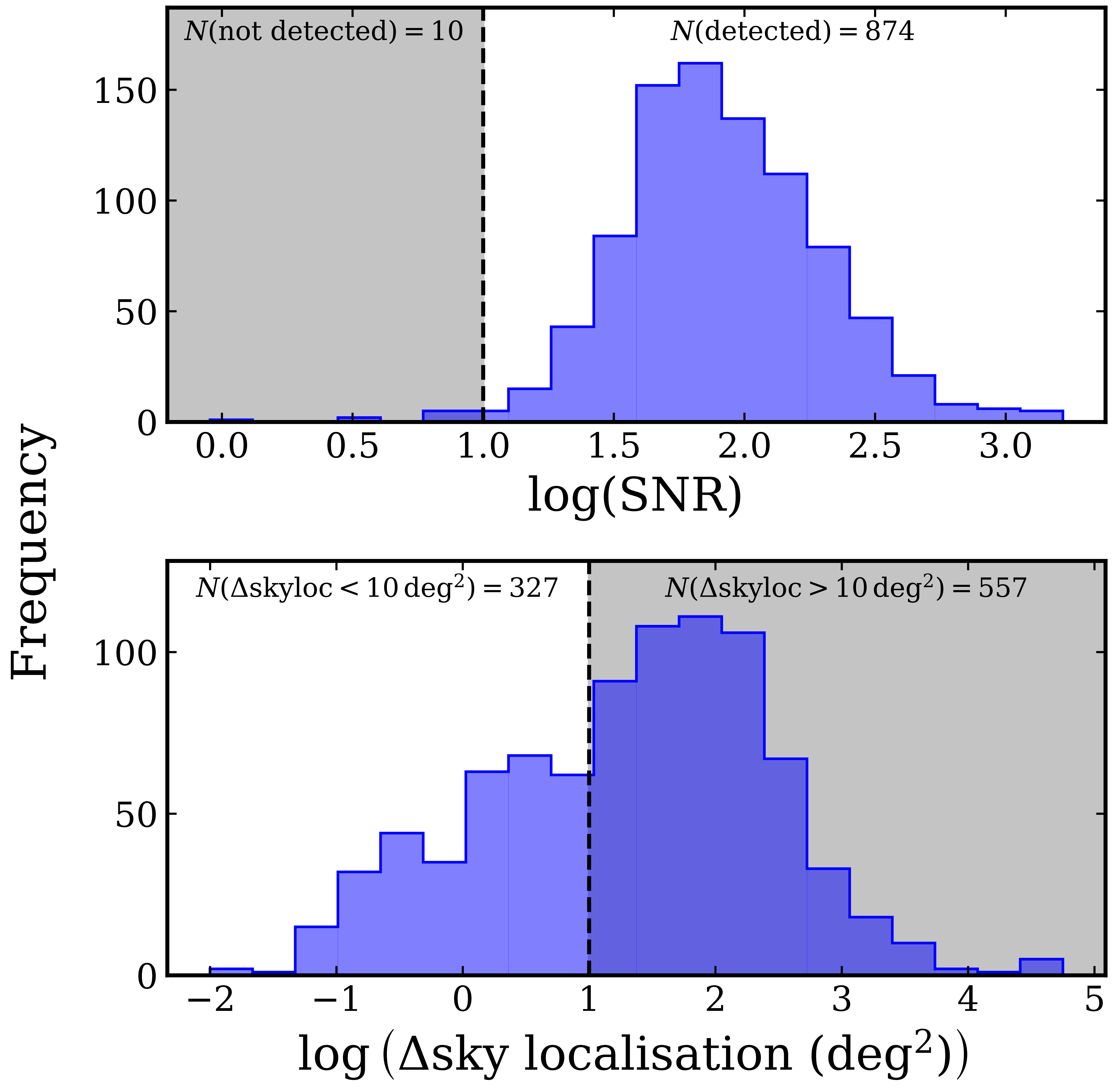
GW observability of MBH mergers

- **Around** $99\,\%$ **of mergers** can be detected with LISA, generally with **very high SNR**. High-mass mergers with very unequal mass ratio are not detected

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

- **Systems are generally very poorly localised** in the sky — only $37\,\%$ of mergers have a 2σ error smaller than $10\,\mathrm{deg}^2$ → larger than most telescopes' field of view → **low probability of guiding an EM counterpart**



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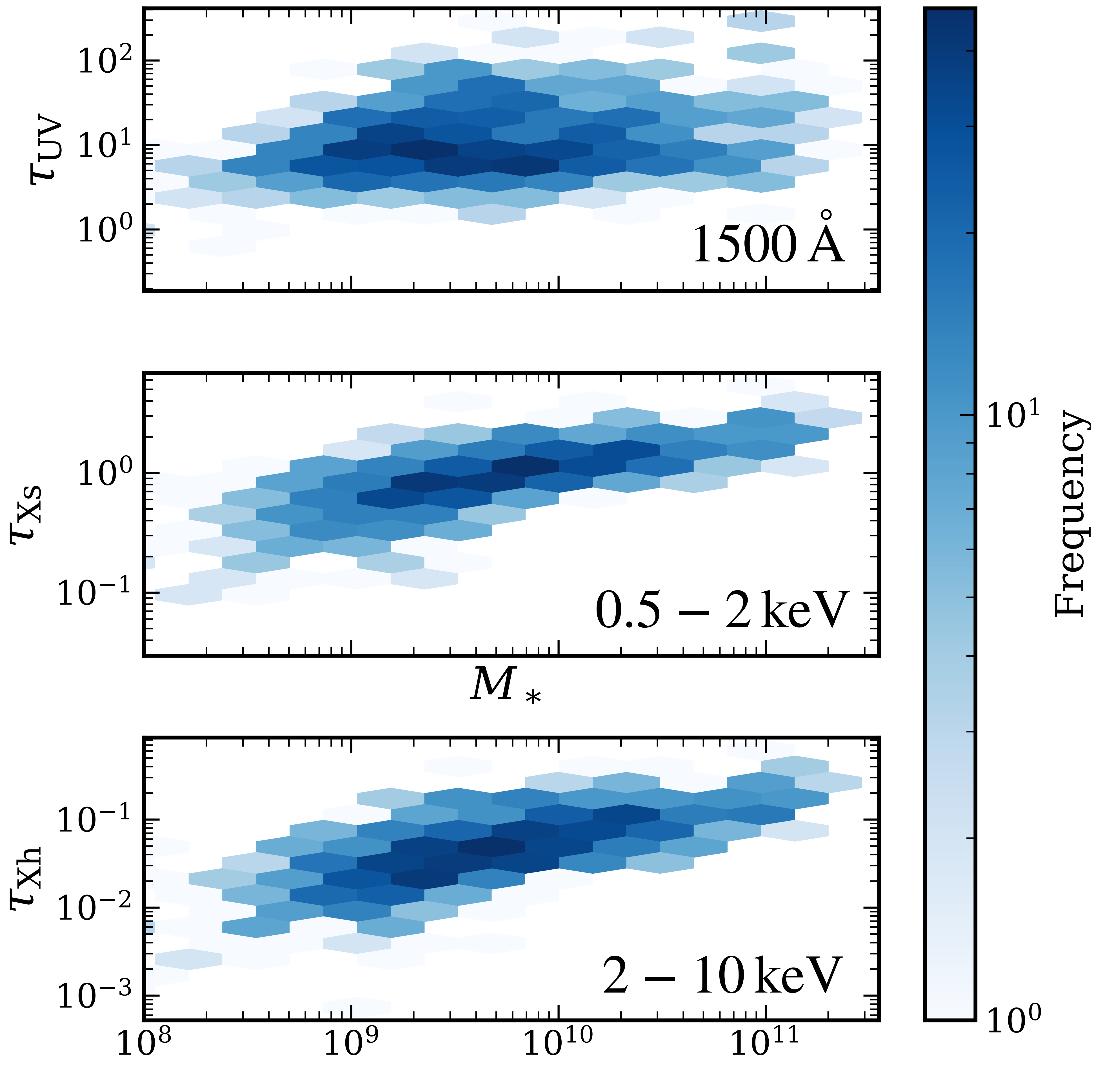
Obscuration in UV/X-rays

- Obscuration due to gas (X-rays) and dust (UV) is computed from the simulation (ISM contribution) and using a semi-analytical model (torus contribution)

- Obscuration is very high in the UV. It is smaller in the X-rays, especially at higher frequencies



$$\tau = -\ln(F_{abs}/F)$$

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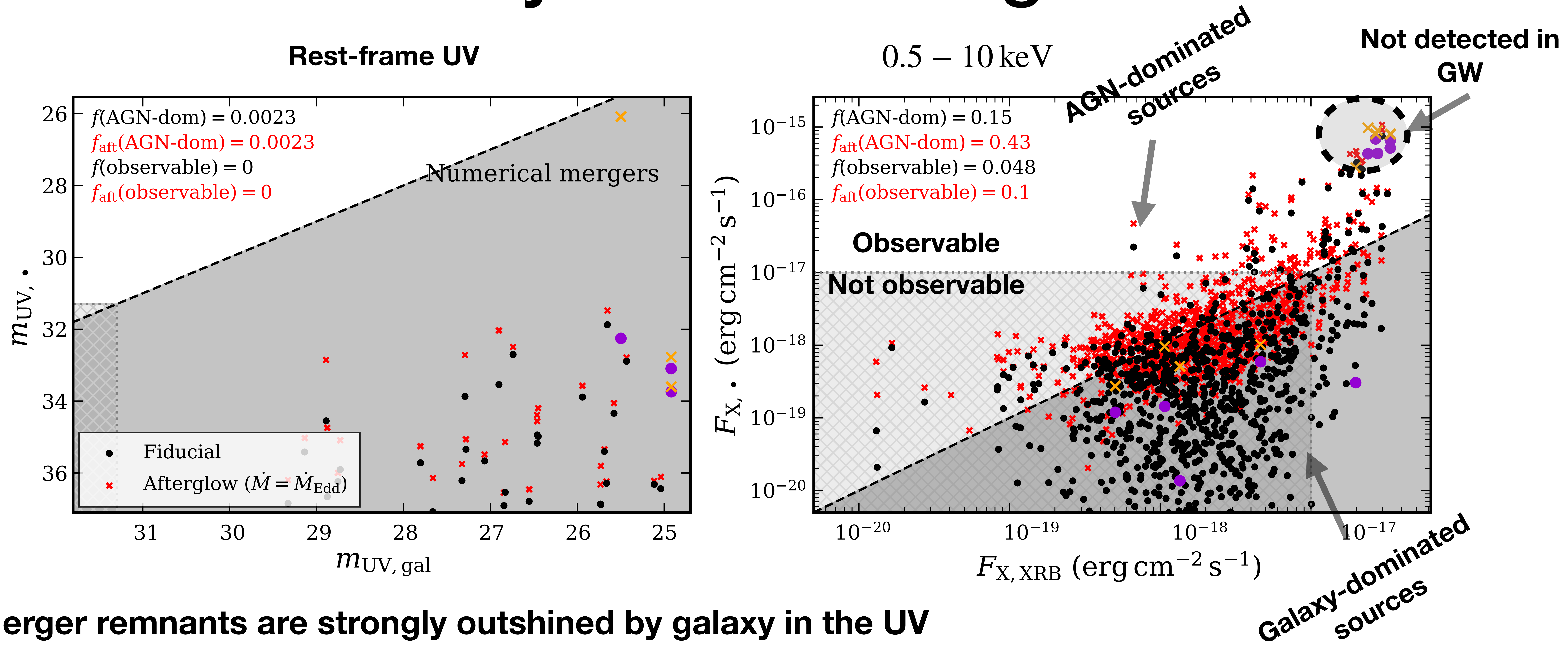
EM observability of MBH merger remnants



- **Merger remnants are strongly outshined by galaxy in the UV**
- **We expect a fraction $5\,\%$ of merger remnants to be observable and brighter than the galaxy in the X-rays**
- **The fraction is higher ($10\,\%$) in the case of a merger-induced afterglow leading to $f_{\text{Edd}} = 1$**

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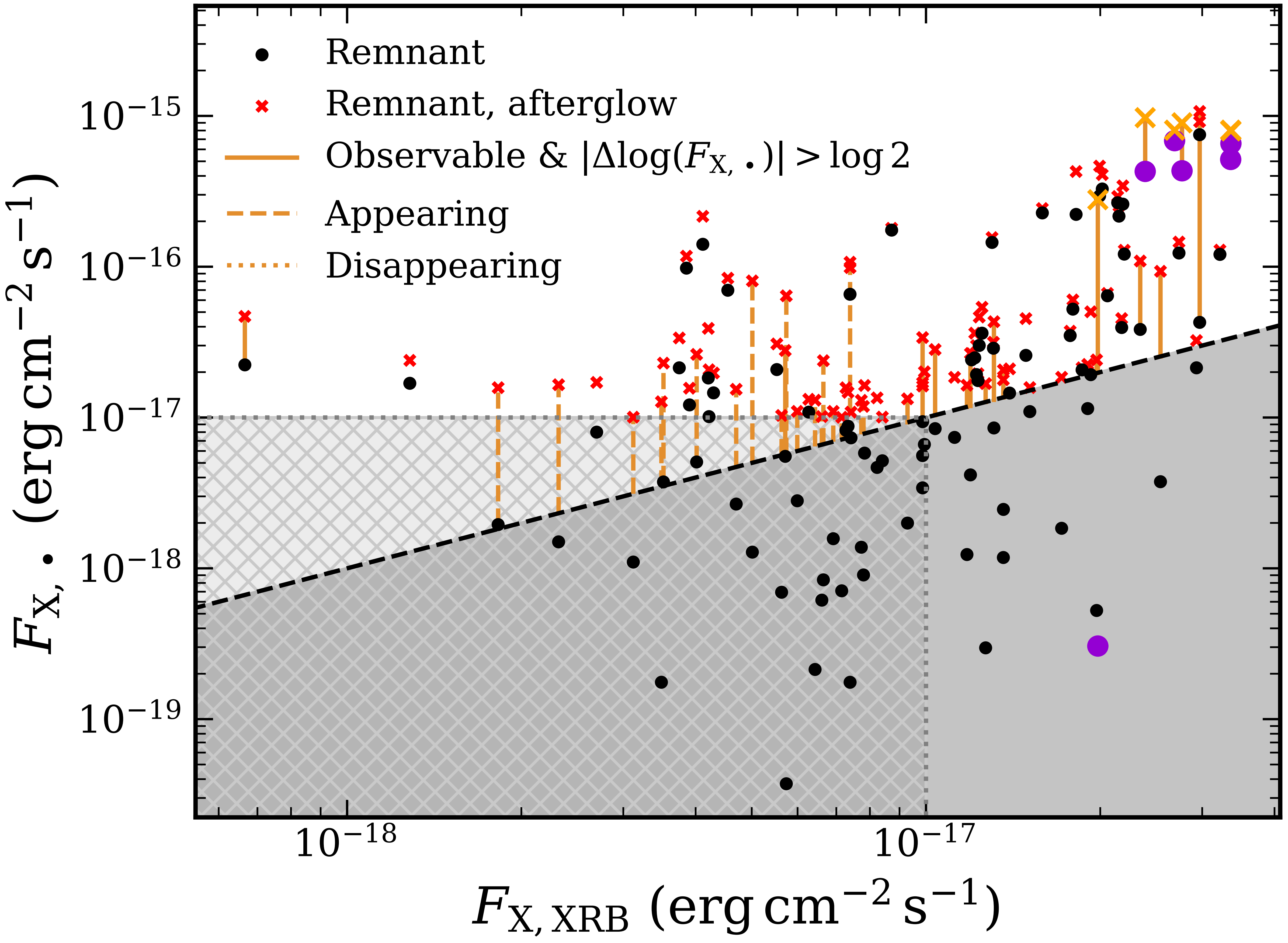
X-ray transients

- **In our model, the accretion rate increases to $f_{\rm Edd} = 1$ due to the merger.**
- **In order to detect the transient as an EM counterpart:**
  - **The flux needs to be bright enough to be observed**
  - **The transient change of flux needs to be large enough to be observed**
- $4\,\%$ **of sources have an EM counterpart**



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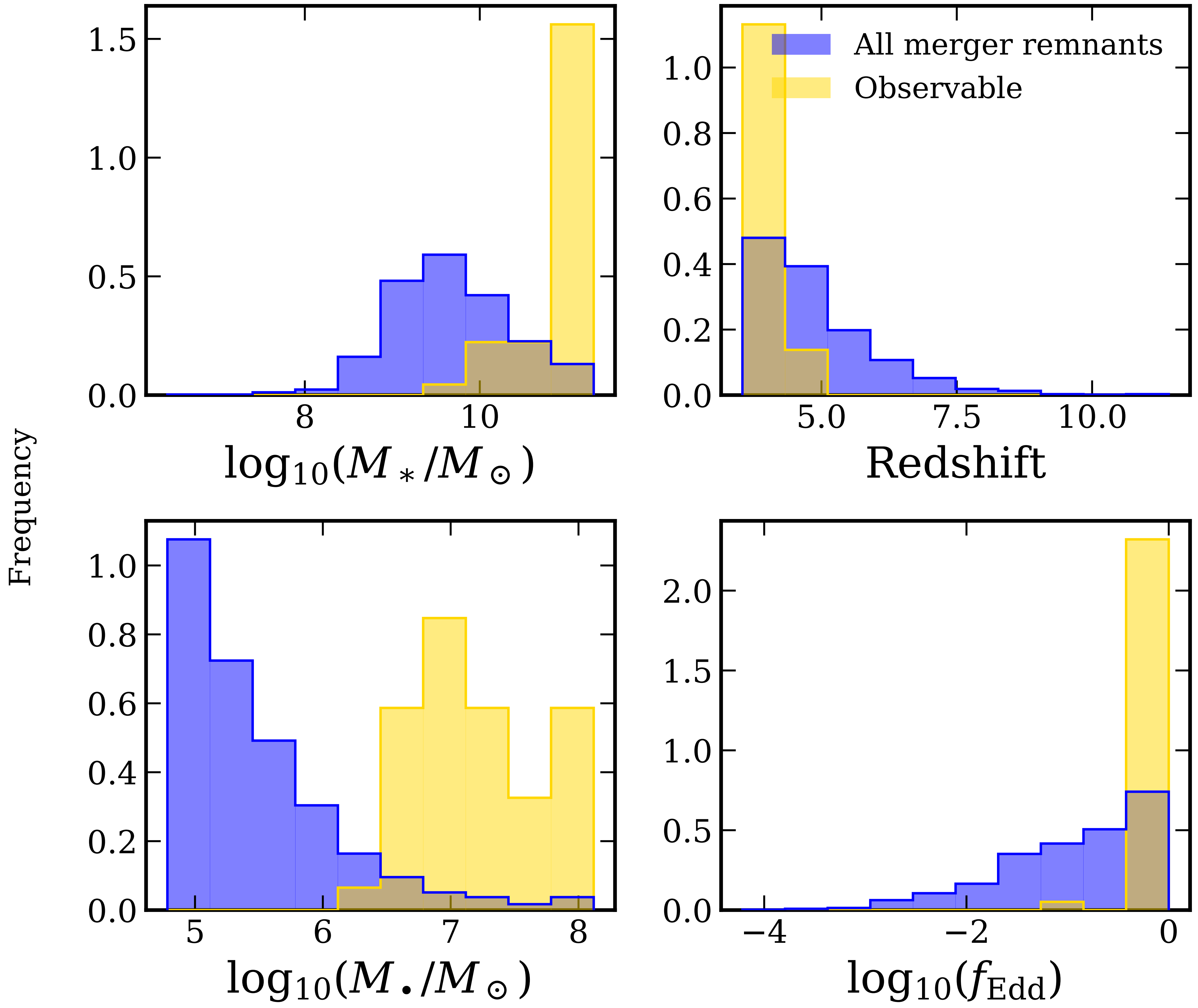
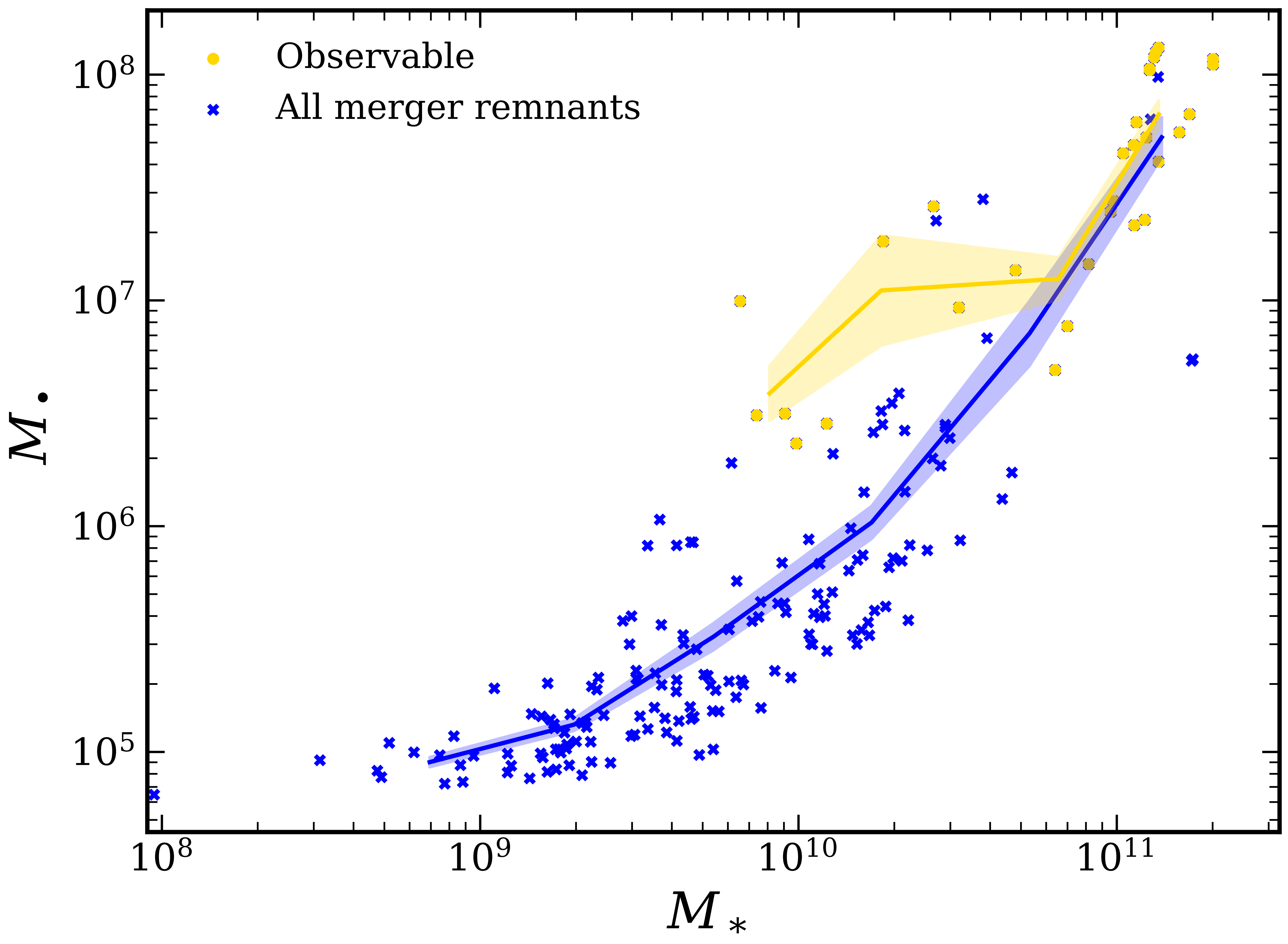
Biases of the X-ray observable MBH mergers





- **Observable mergers have higher BH and galaxy mass and higher accretion rate and occur at lower redshift**
- **Observable merger remnants are overmassive at fixed galaxy mass**

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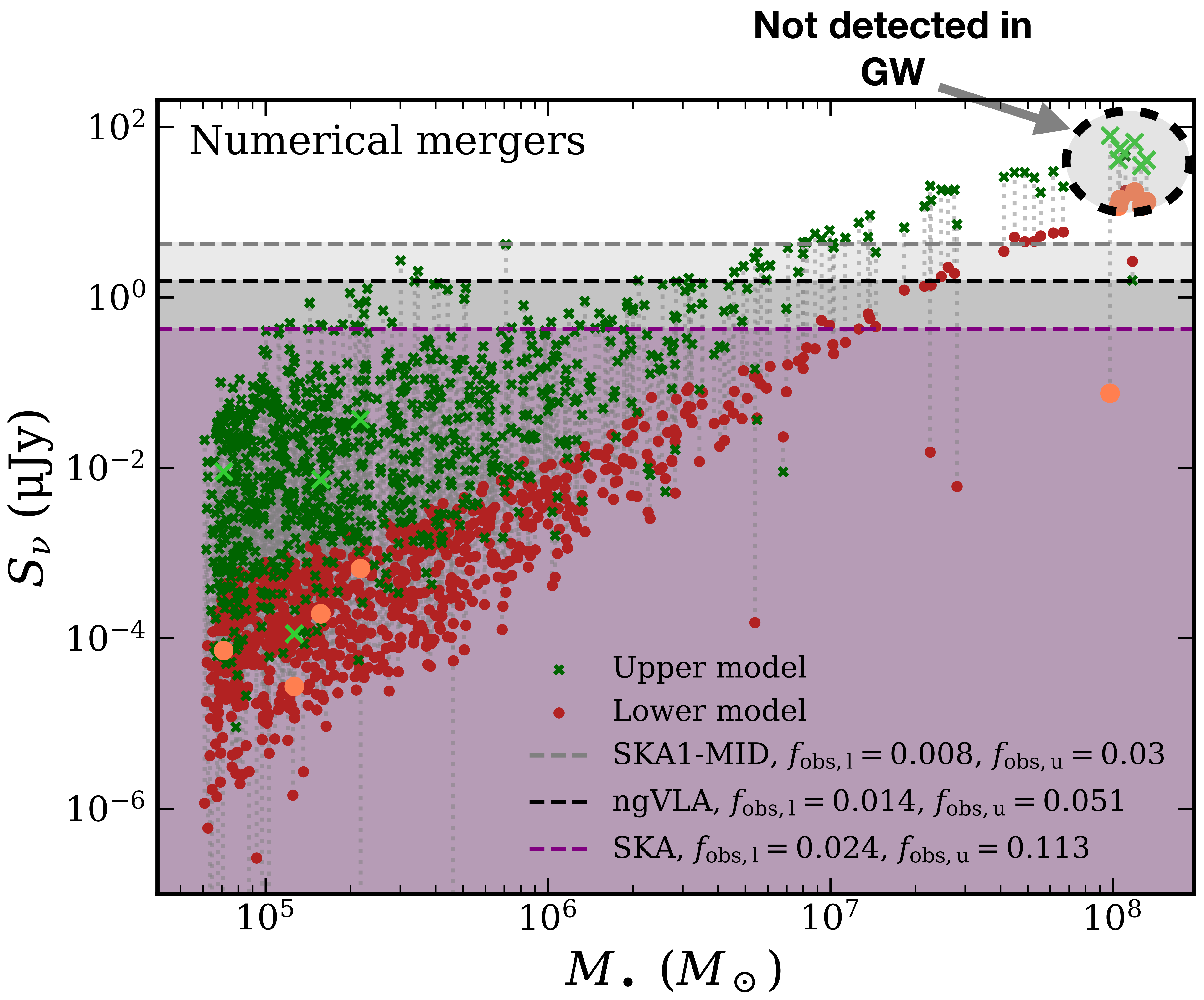
Radio observability of MBH mergers

- **About $1 - 10\,\%$ of merger remnants can be detected in the radio** by future instruments, dependent on the model and instrument assumed.

- For the pessimistic model (core luminosity modelled with empirical relation), only BHs with $M_\bullet > 10^7\,M_\odot$ can be observed

- In the following, **we use the pessimistic model and SKA**



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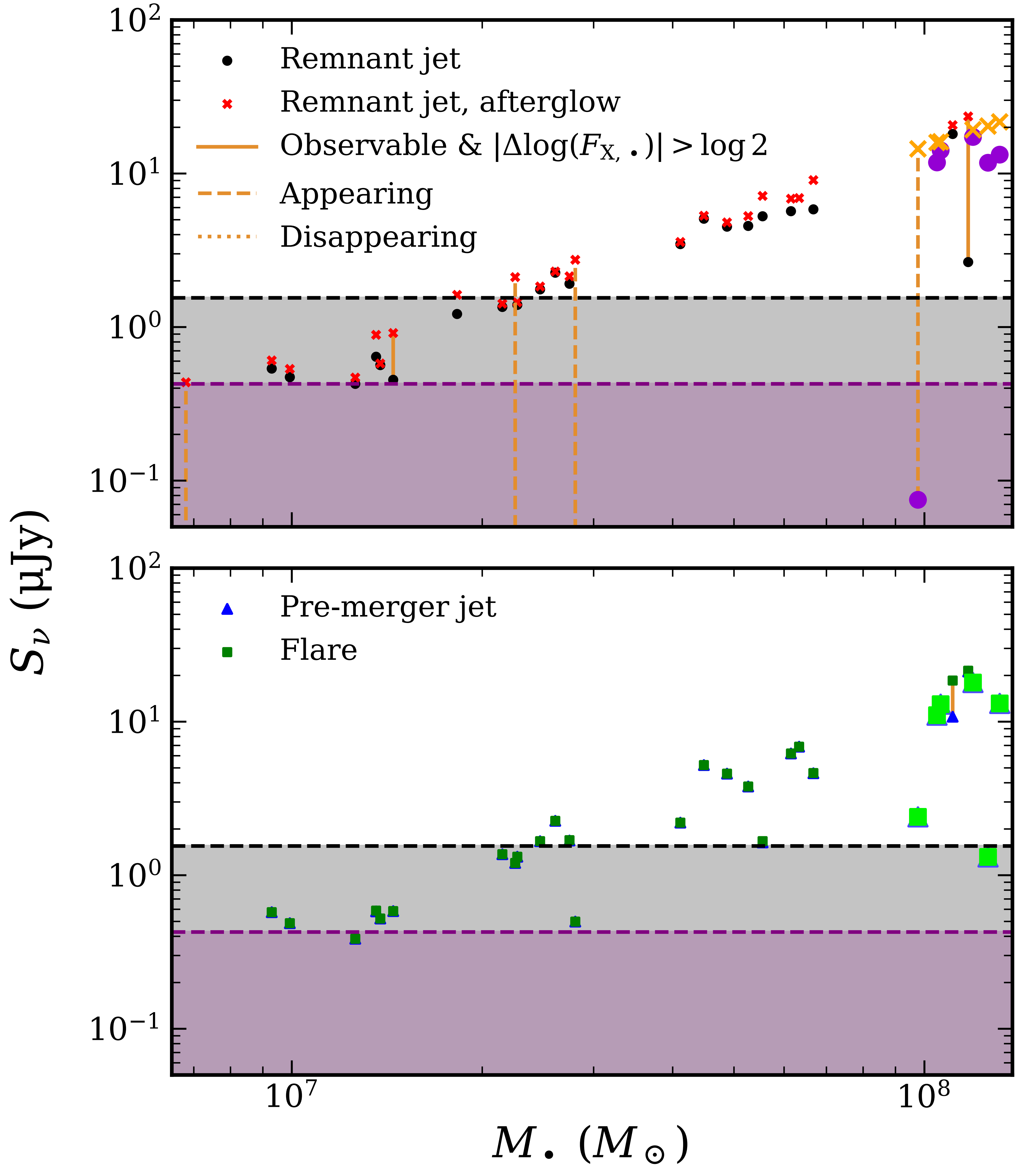
Radio transients

- **Consider two models for the transient: afterglow ($f_{\rm Edd} = 1$ due to the merger) and a flare (increase in Poynting flux as found in simulations).**

- **Very few sources have EM counterparts:**

  - **Few sources are bright enough to be observable**

  - **Transient flux change is small since: (i) for massive BHs accretion rates are already high before the transient and (ii) mergers tend to be minor**



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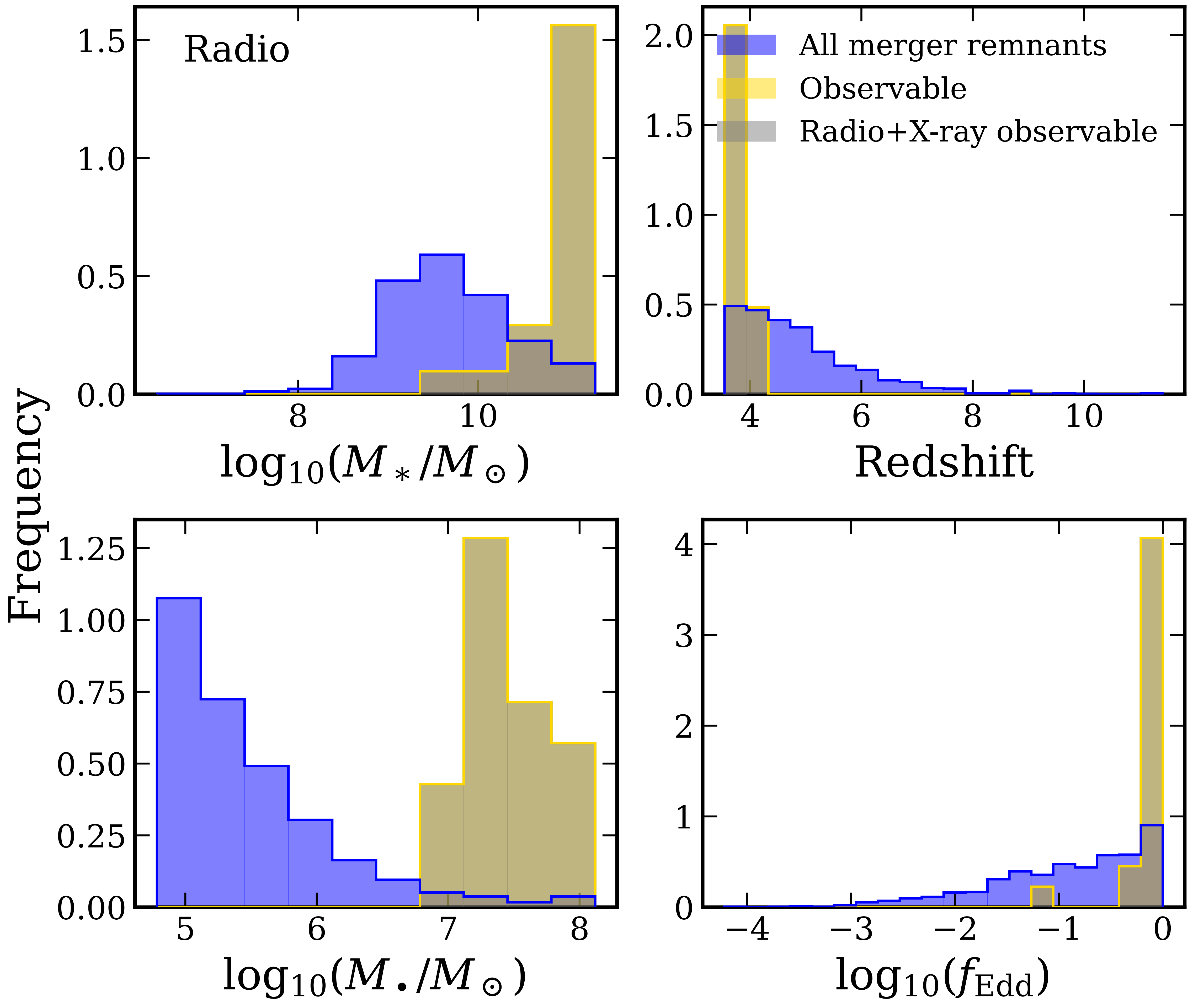
Biases of the radio-observable MBH mergers

- As in the X-rays, **radio-observable mergers have higher BH, galaxy mass and accretion rate and occur at lower redshift**
- **Most of radio-observable mergers are also X-ray observable.**
- **Observable merger remnants are overmassive at fixed galaxy mass**



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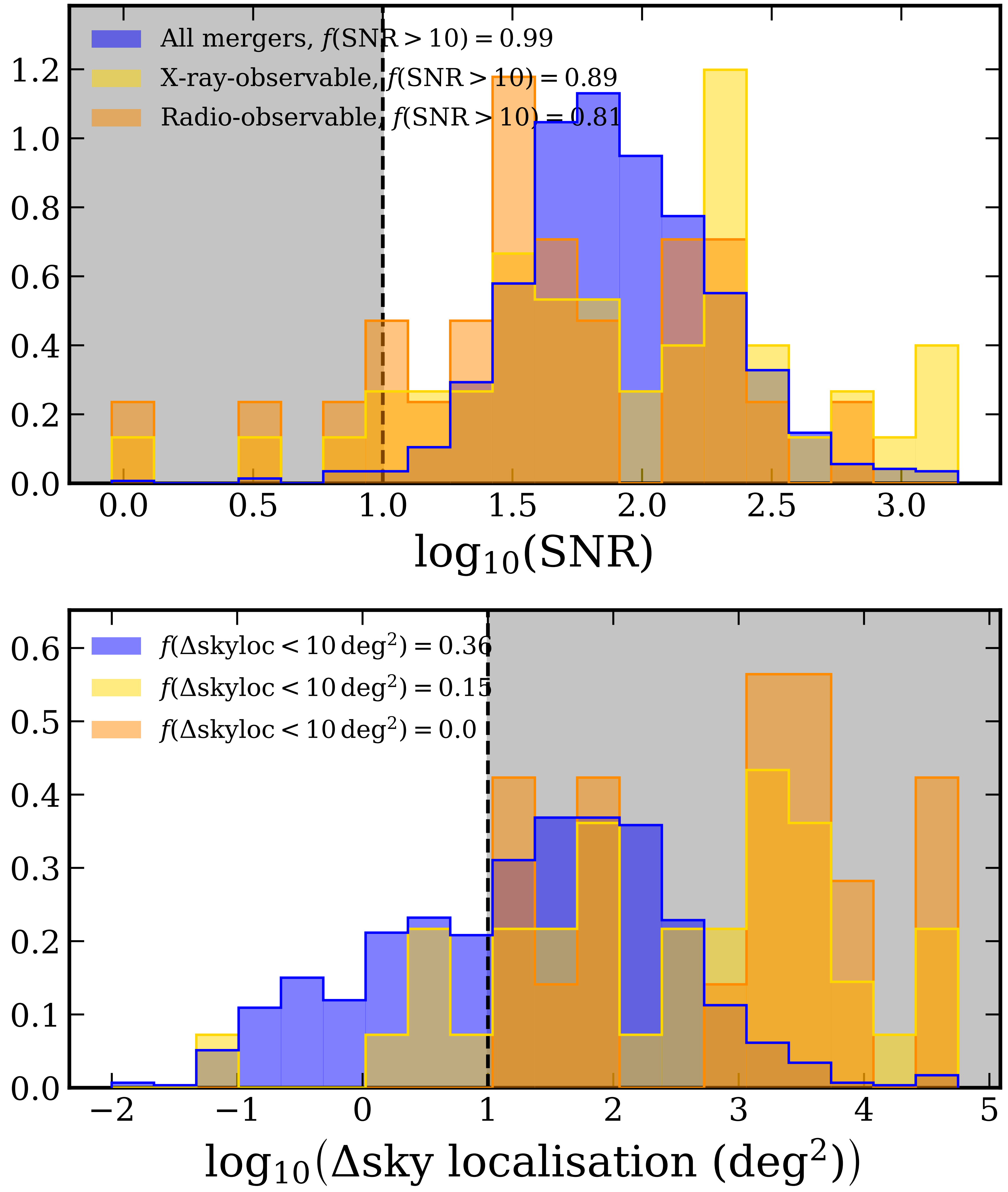
Multimessenger GW+EM observability

- **Most X-ray- and radio-observable mergers are also detectable with LISA in the GWs**
- **The sky localisation of EM-observable mergers is poorer than for the global merger population.** This is because EM-observable mergers tend to have high masses and unequal mass ratios**.**



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Summary

- The GW and EM emission provide different and complementary information about the properties of the MBH merger
- MBH mergers tend to be more massive, have higher spin and reside in more massive galaxies than the global population. They can also have higher accretion rate and reside in more highly star-forming galaxies.
- Most of our MBH mergers can be detected in the GW by LISA
- We don’t expect MBH merger remnants to be observable in the UV, although a fraction of them could be observed in the X-rays. A fraction of transients is observable in the X-rays.
- A fraction of mergers can be observed in the radio
- The observable merger sample is biased toward high MBH and galaxy masses, accretion rates, and low redshifts. EM-observable mergers are generally poorly localised from GWs

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