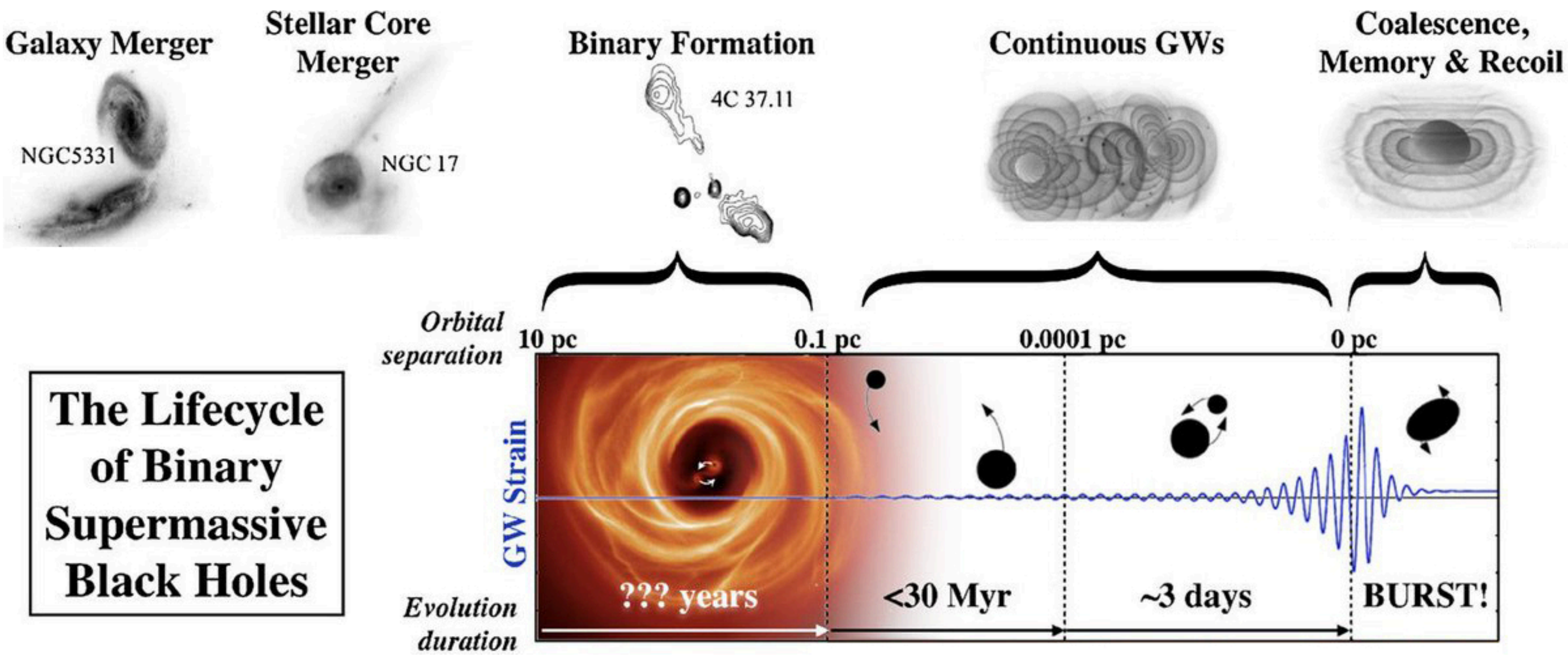
Multimessenger modelling of massive black hole mergers in the Obelisk cosmological simulation

Chi An Dong Páez (Institut d'Astrophysique de Paris)

+ Marta Volonteri, Yohan Dubois, Ricarda Beckmann, Maxime Trebitsch, Alberto Mangiagli, Susanna Vergani, Natalie Webb

A multimessenger view of MBH mergers



Burke-Spolaor et al. 2018

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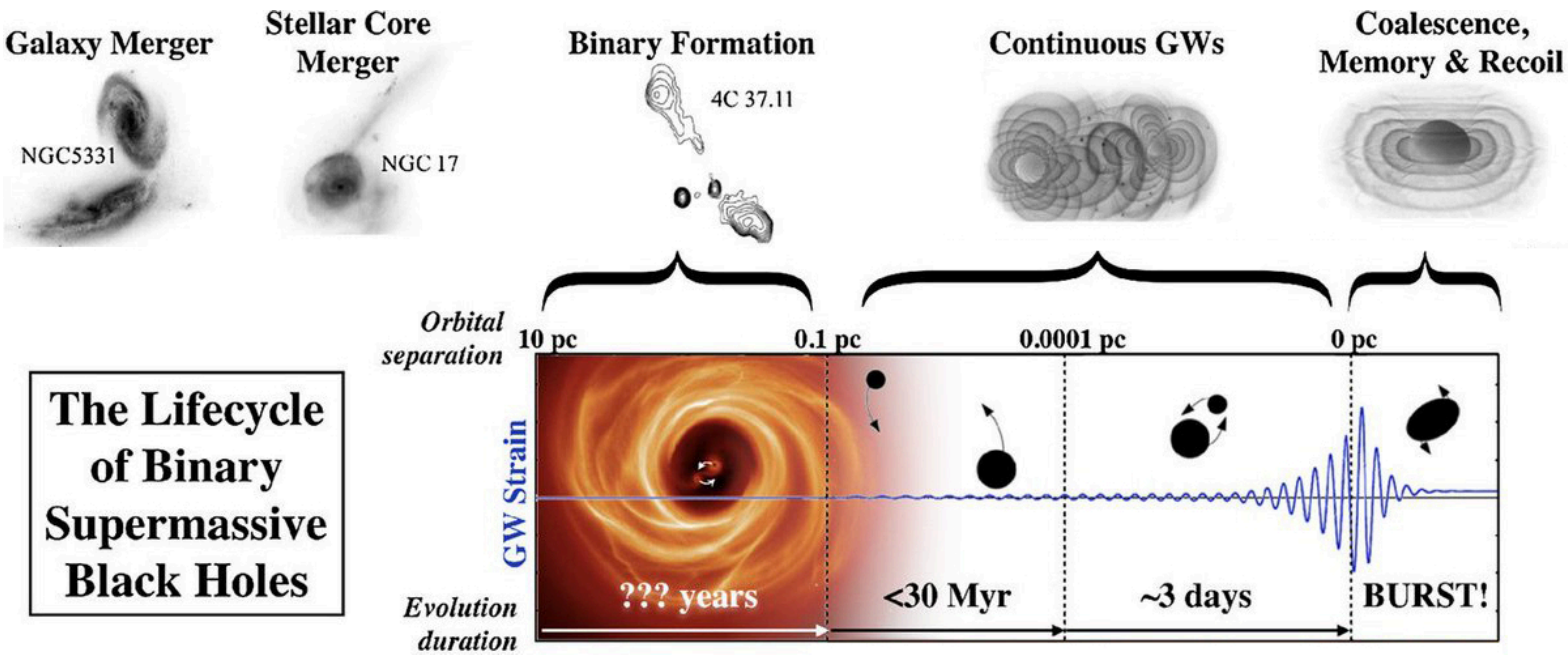

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- Most massive galaxy nuclei host a massive black hole (MBH)

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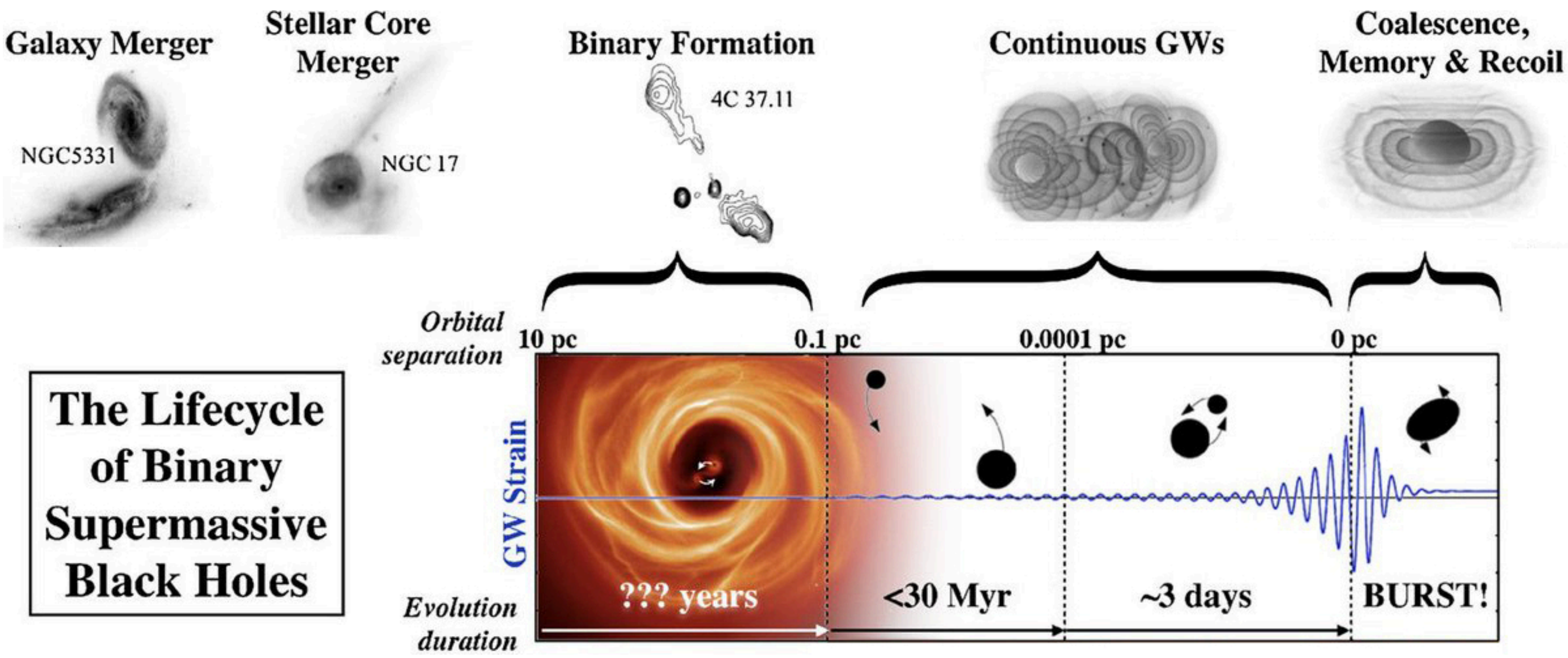

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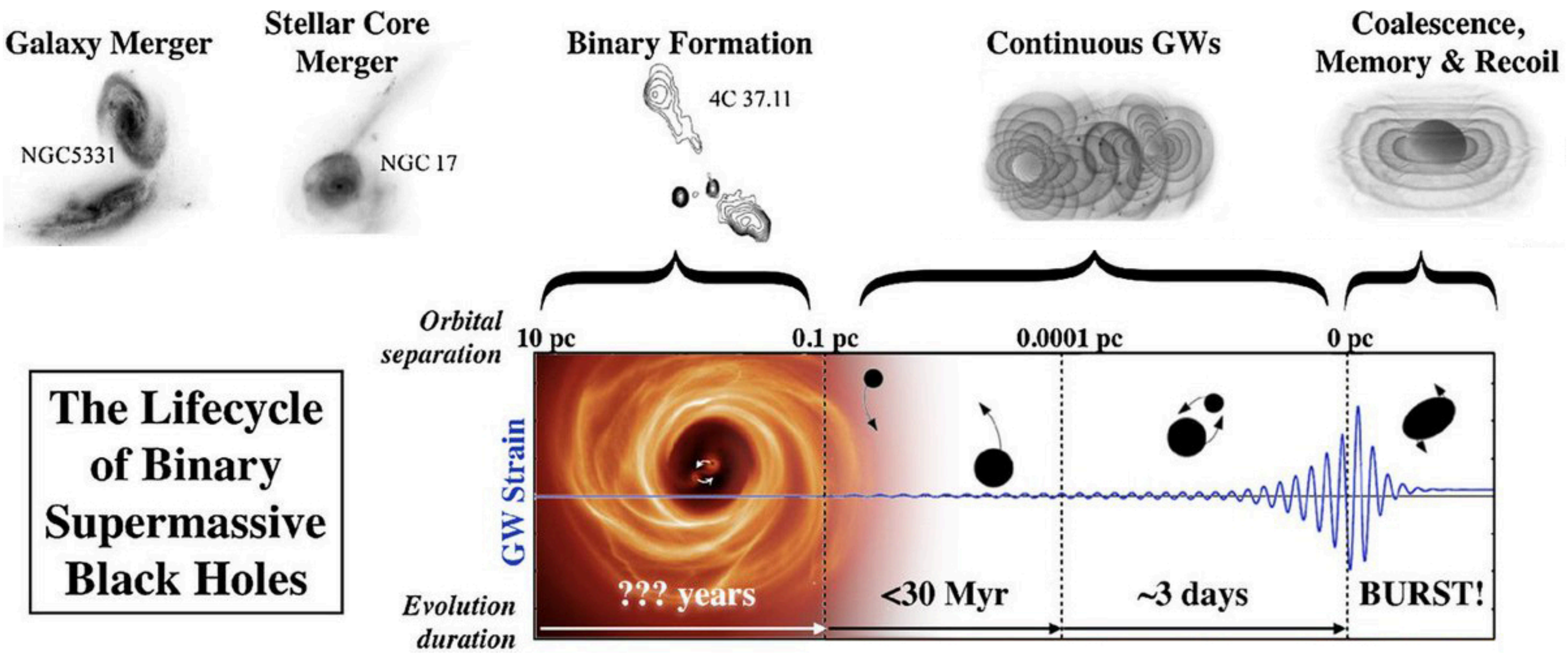

Burke-Spolaor et al. 2018

- Most massive galaxy nuclei host a massive black hole (MBH)
- 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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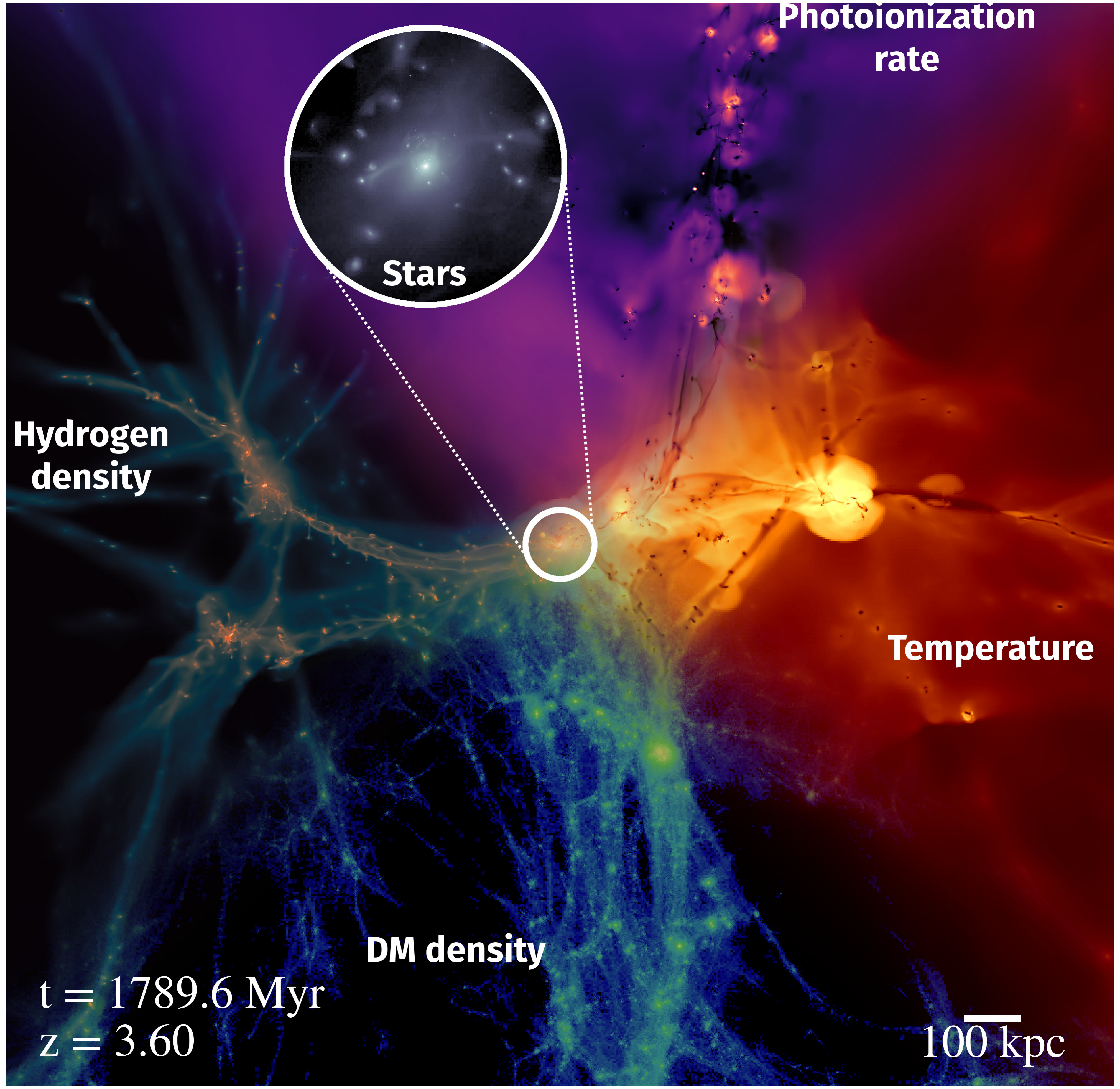
Modelling MBH mergers



Trebitsch et al. 2020

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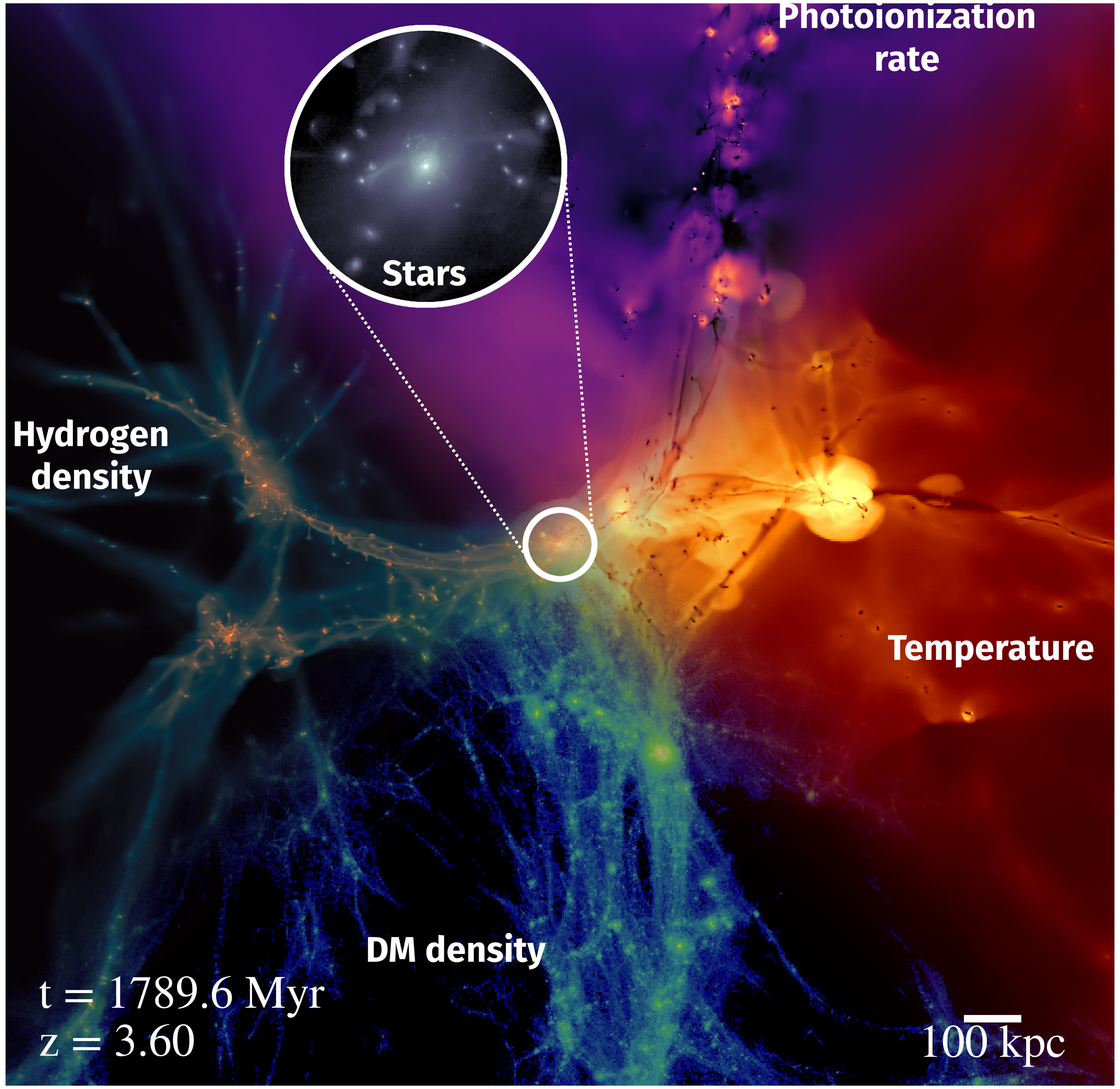
Use BH population in the **Obelisk radiative hydrodynamical cosmological simulation** (Trebitsch et al. 2020)



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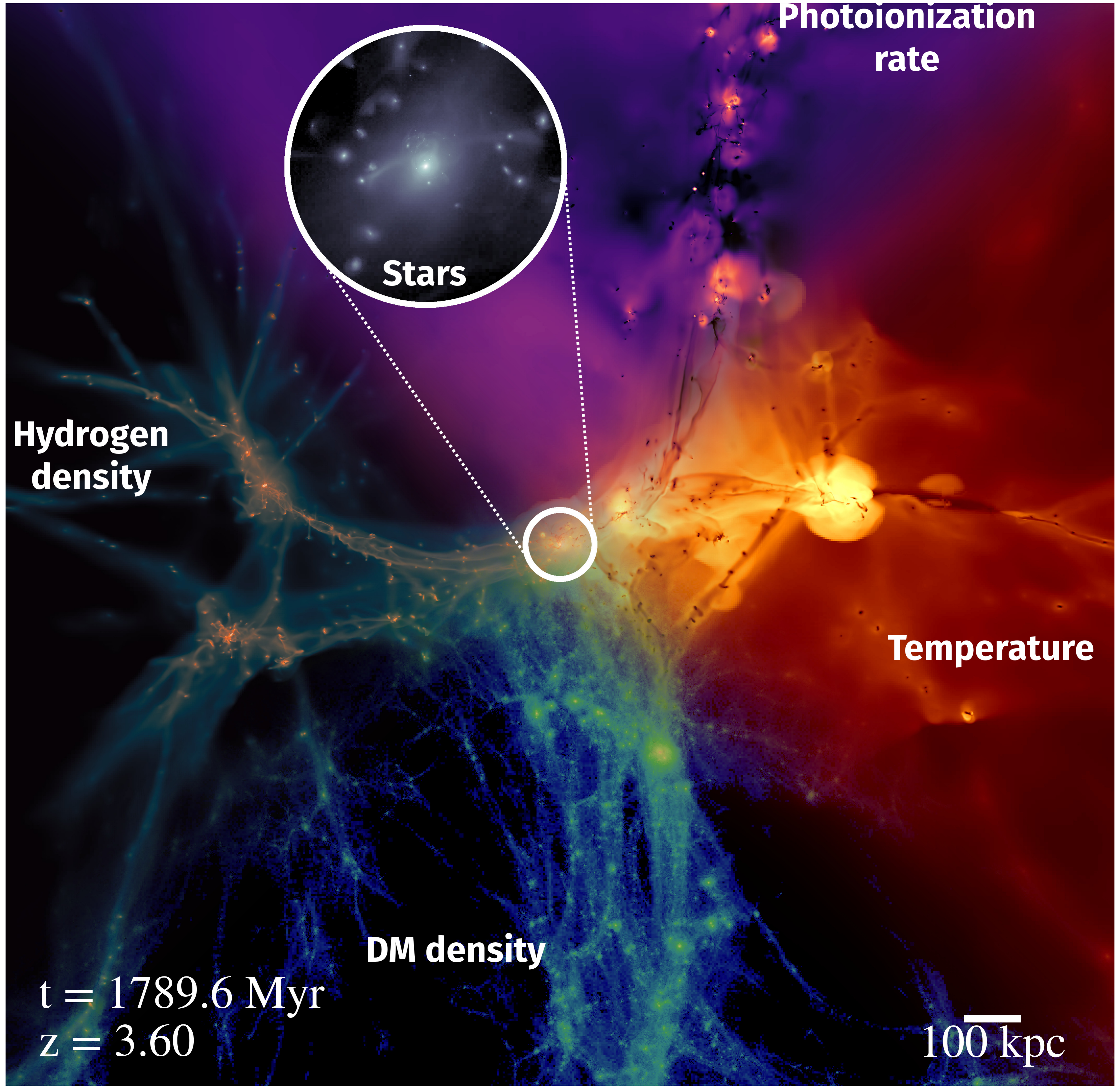

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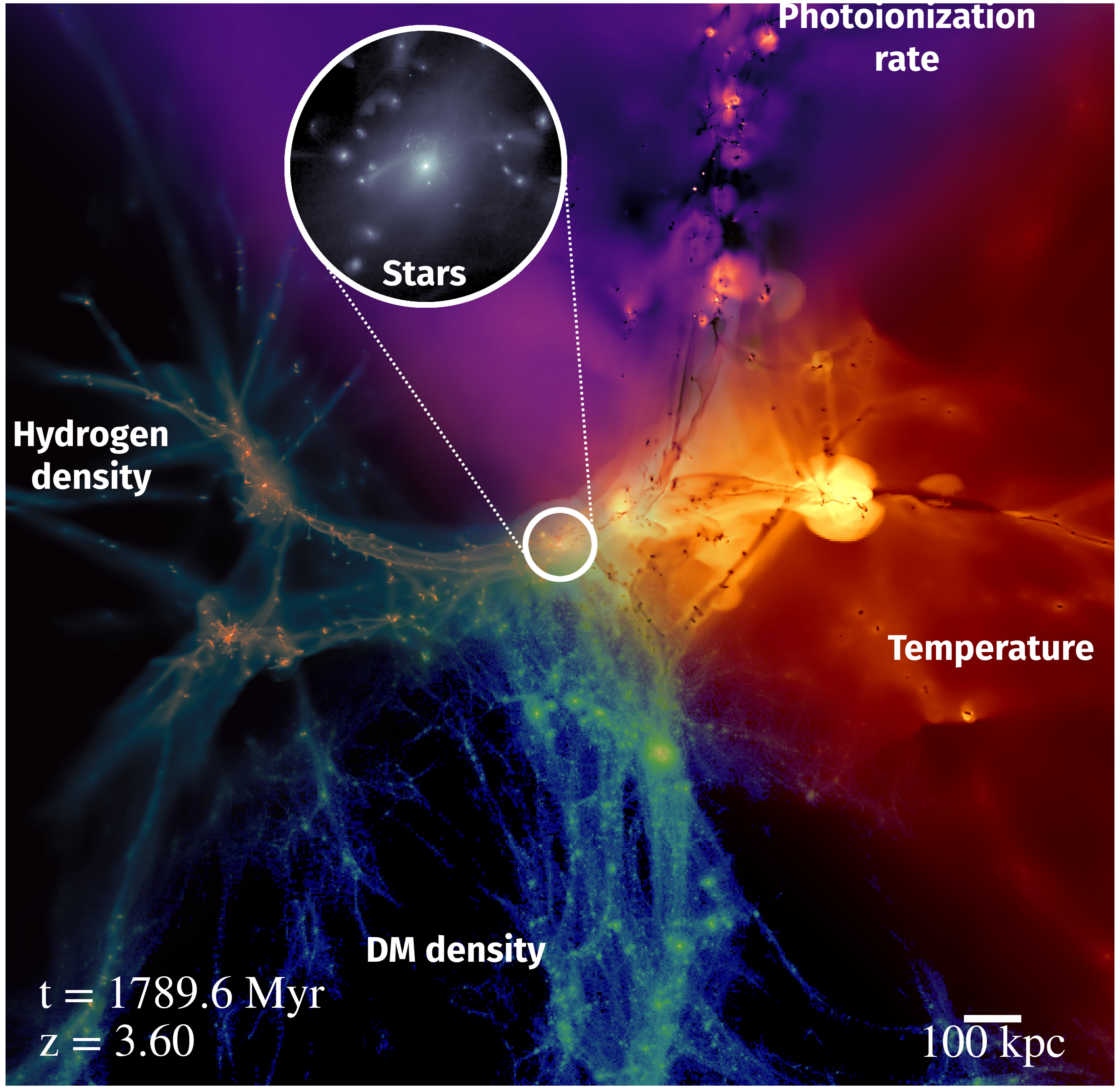

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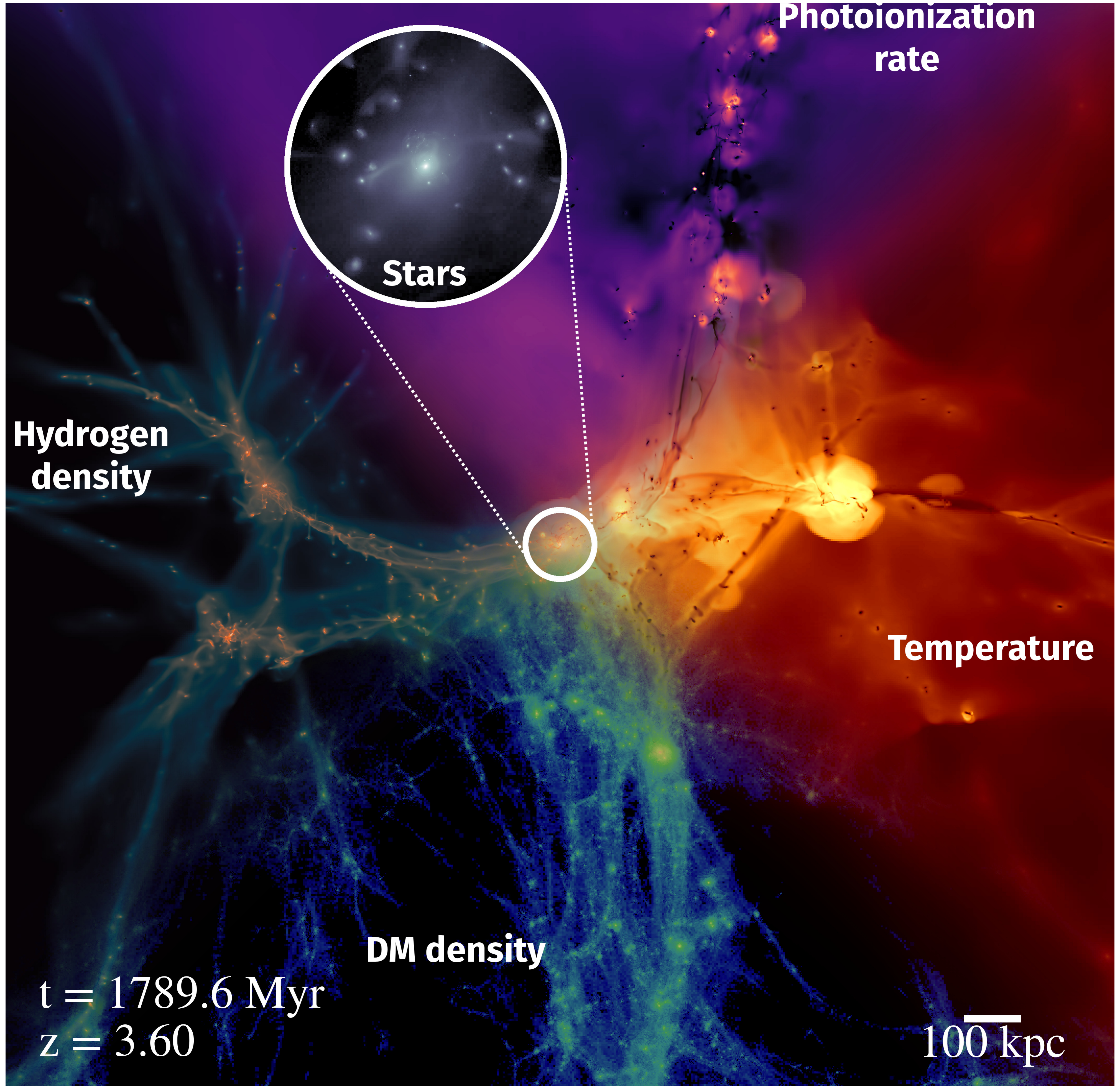

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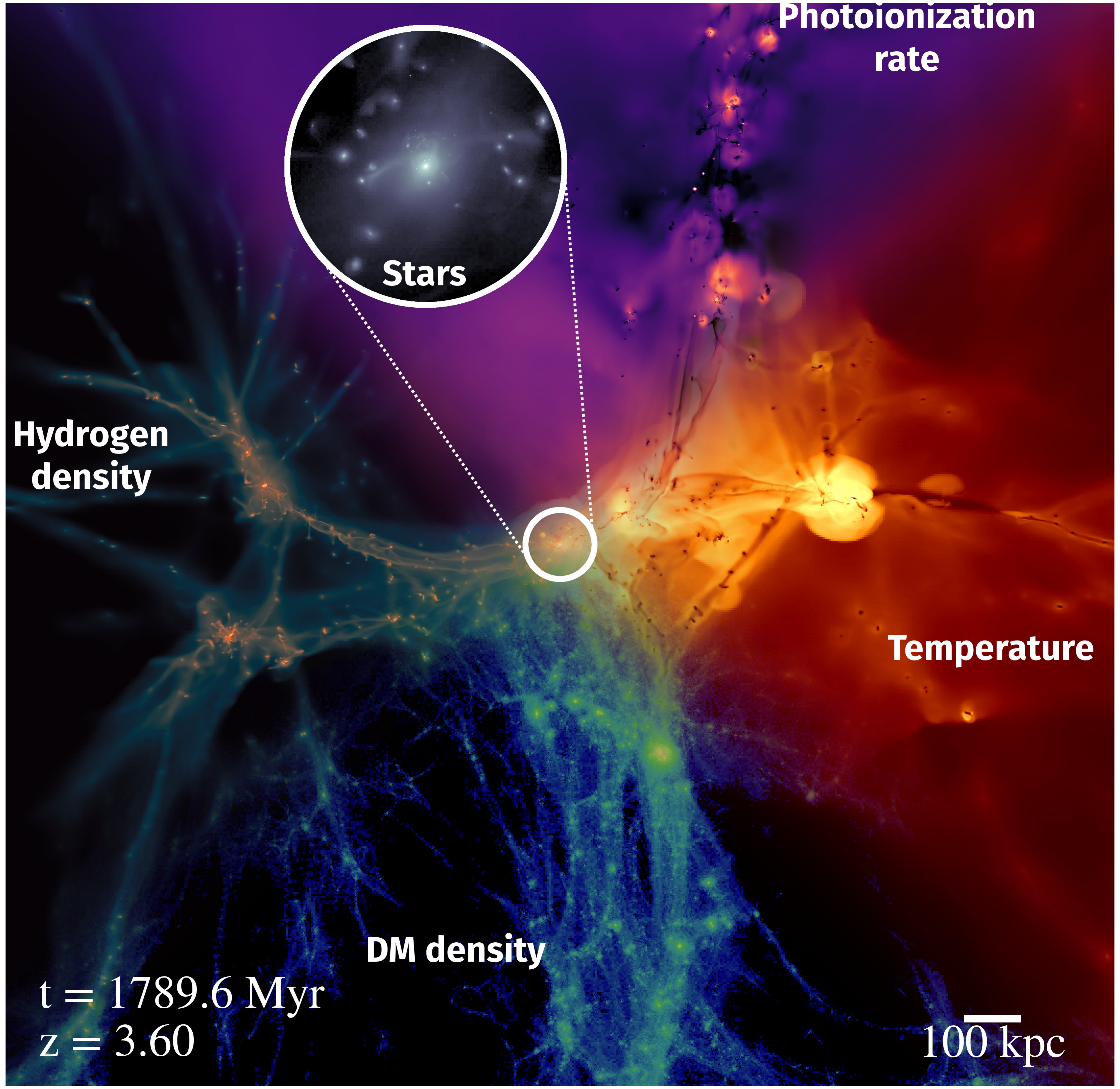
- Usual cooling, star formation, supernovae, metals, etc.
- Detailed BH physics (**seeding, accretion, feedback, spin evolution, dynamics**)
- **High resolution** (35 pc)



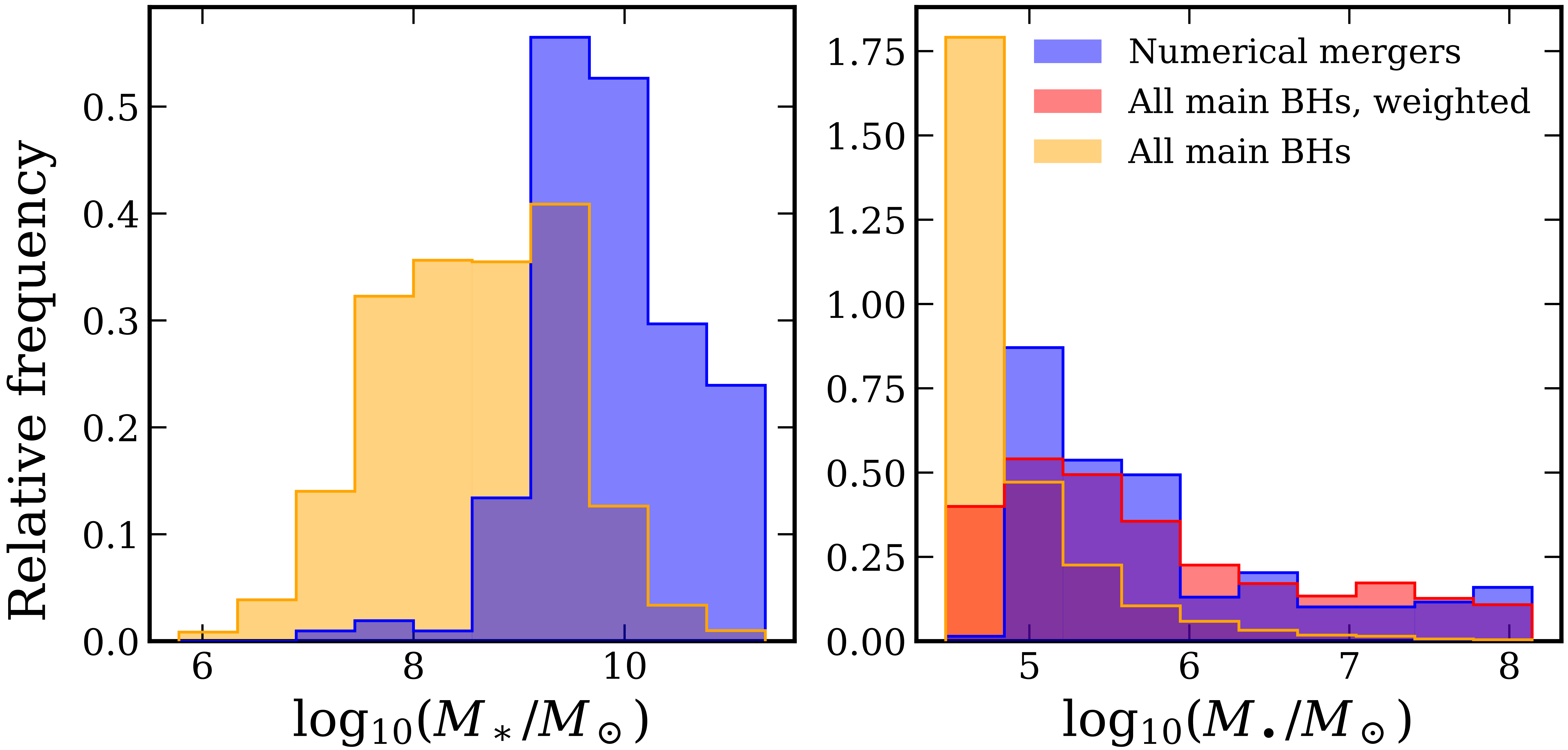
Trebitsch et al. 2020

Question 1:

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

See arXiv:2303.00766

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



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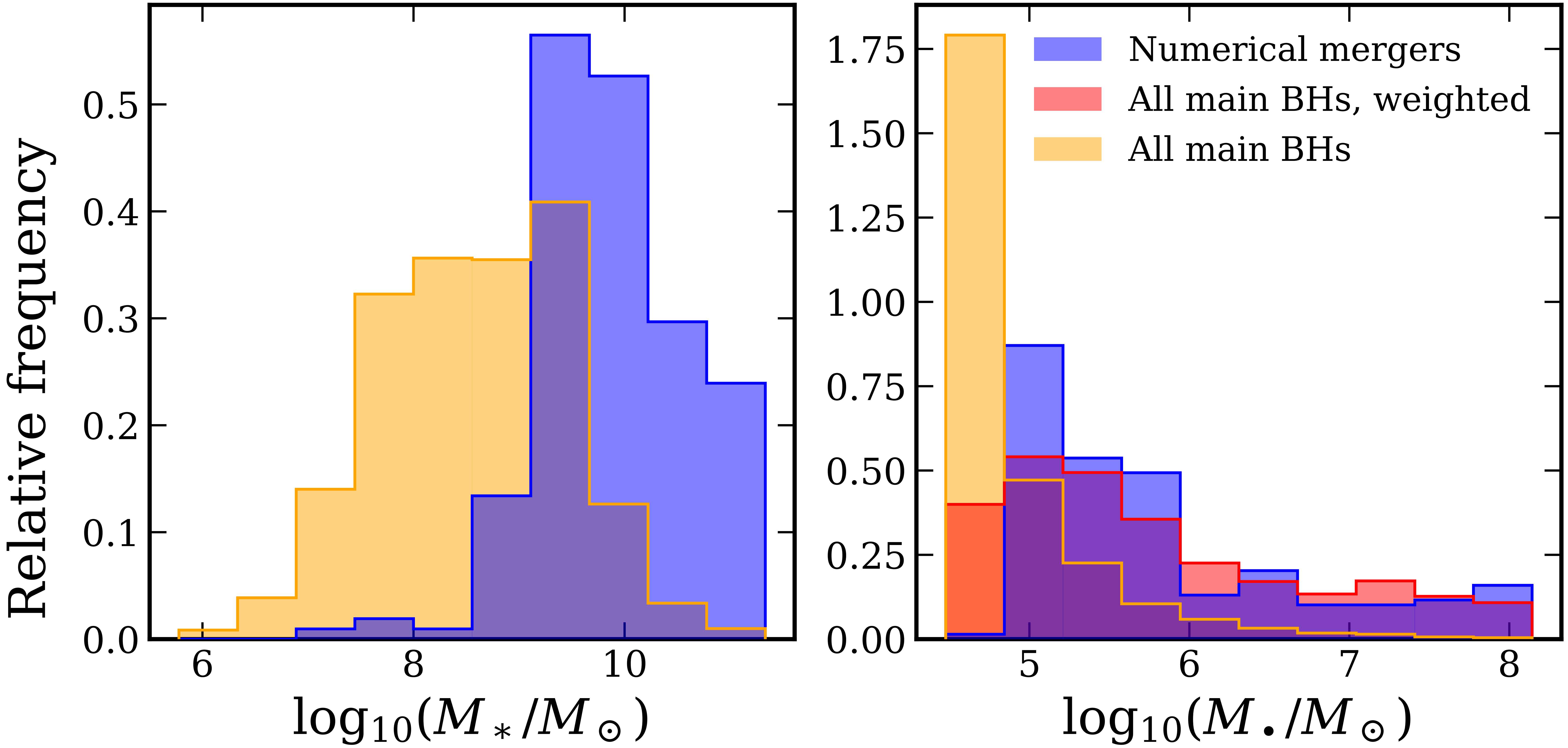

- **MBH merger hosts tend to be more massive than the overall population ($M_* \gtrsim 10^9\,M_\odot$)**

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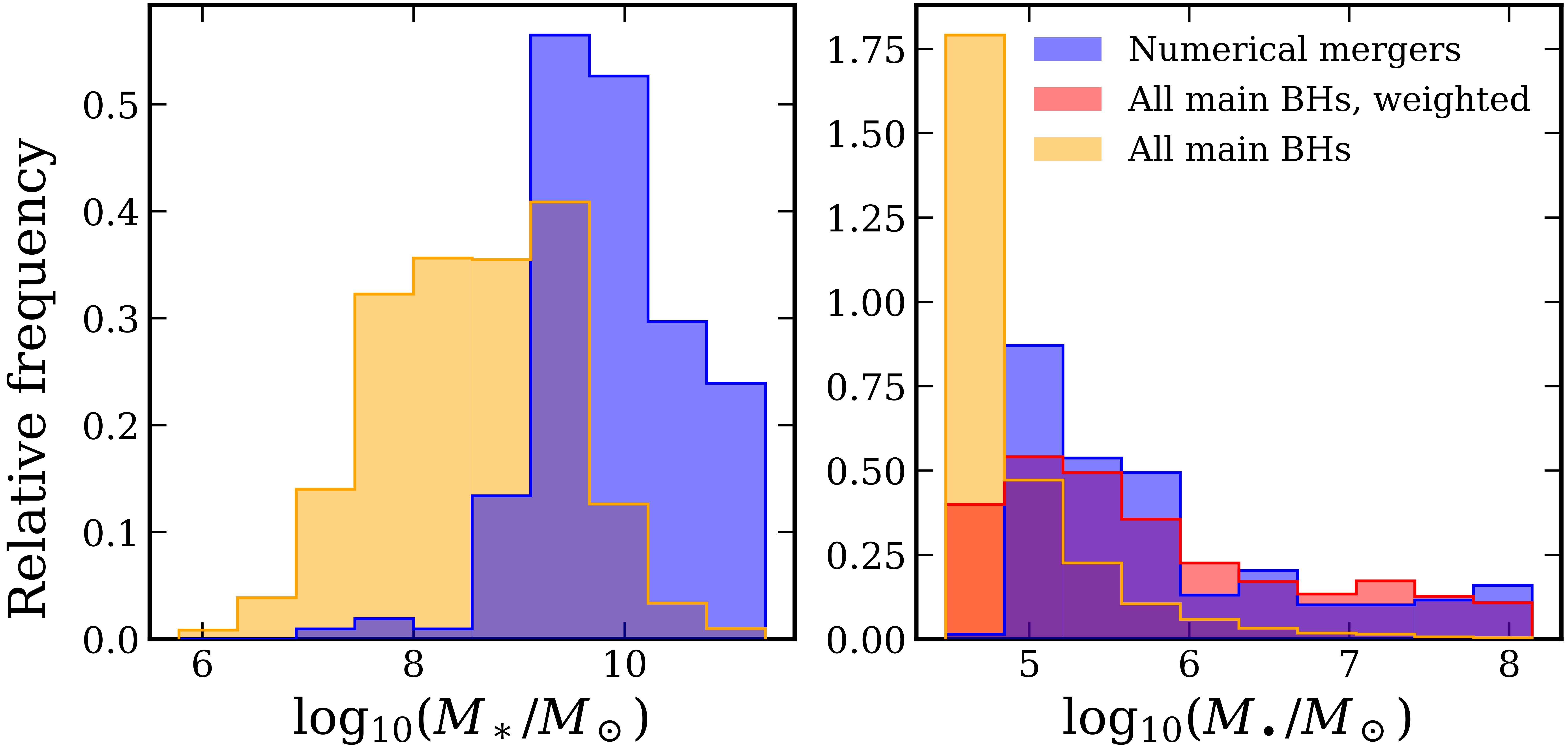

- **MBH merger hosts tend to be more massive than the overall population ($M_* \gtrsim 10^9\, M_\odot$)**
- **Merging MBH are also more massive, since mergers are hosted by massive galaxies**

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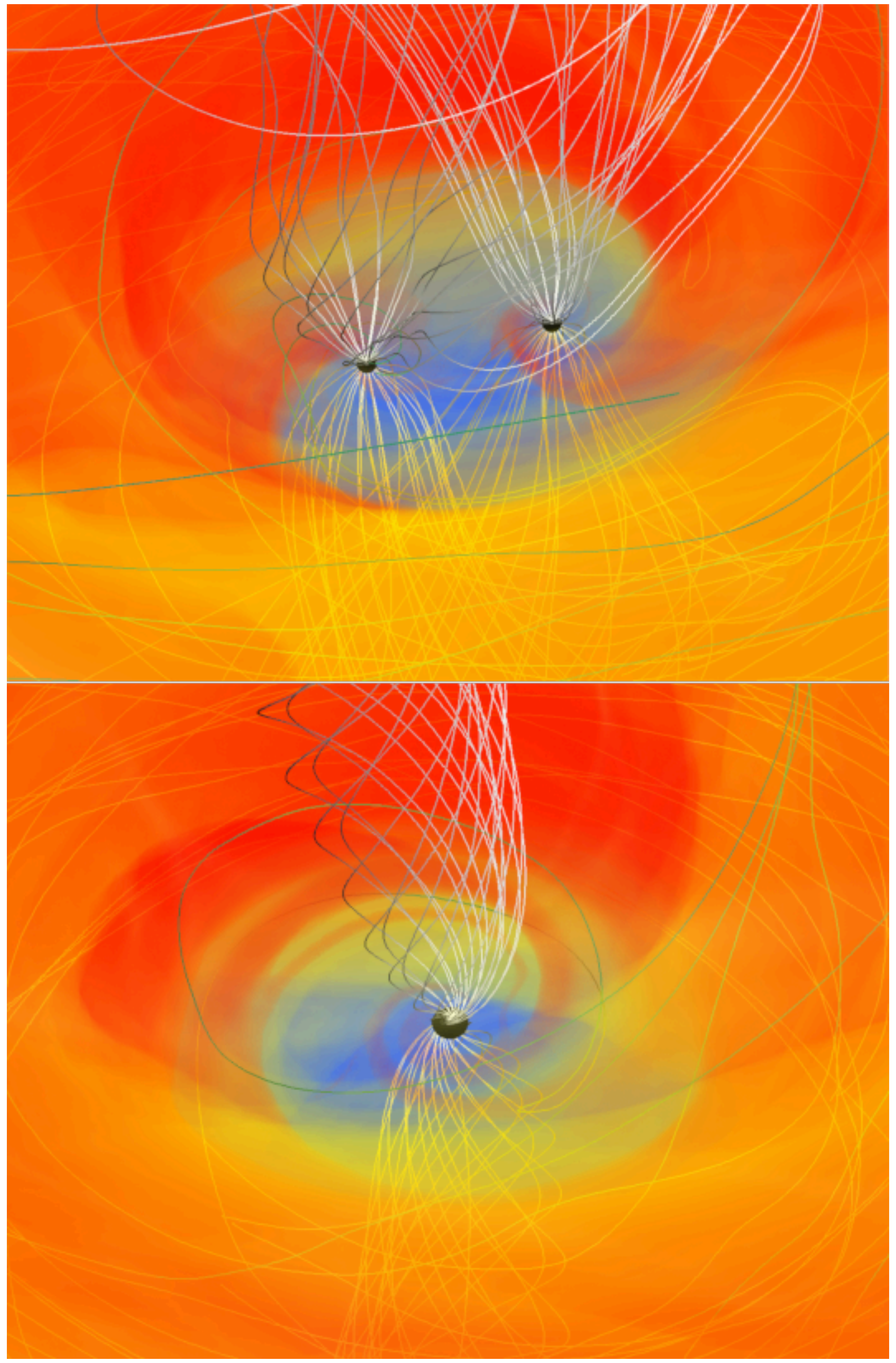
Question 2:

Can MBH mergers be detected?
If so, is the observable population biased?

See arXiv:2303.09569

Modelling the emission from MBH mergers



Gold et al. 2014

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

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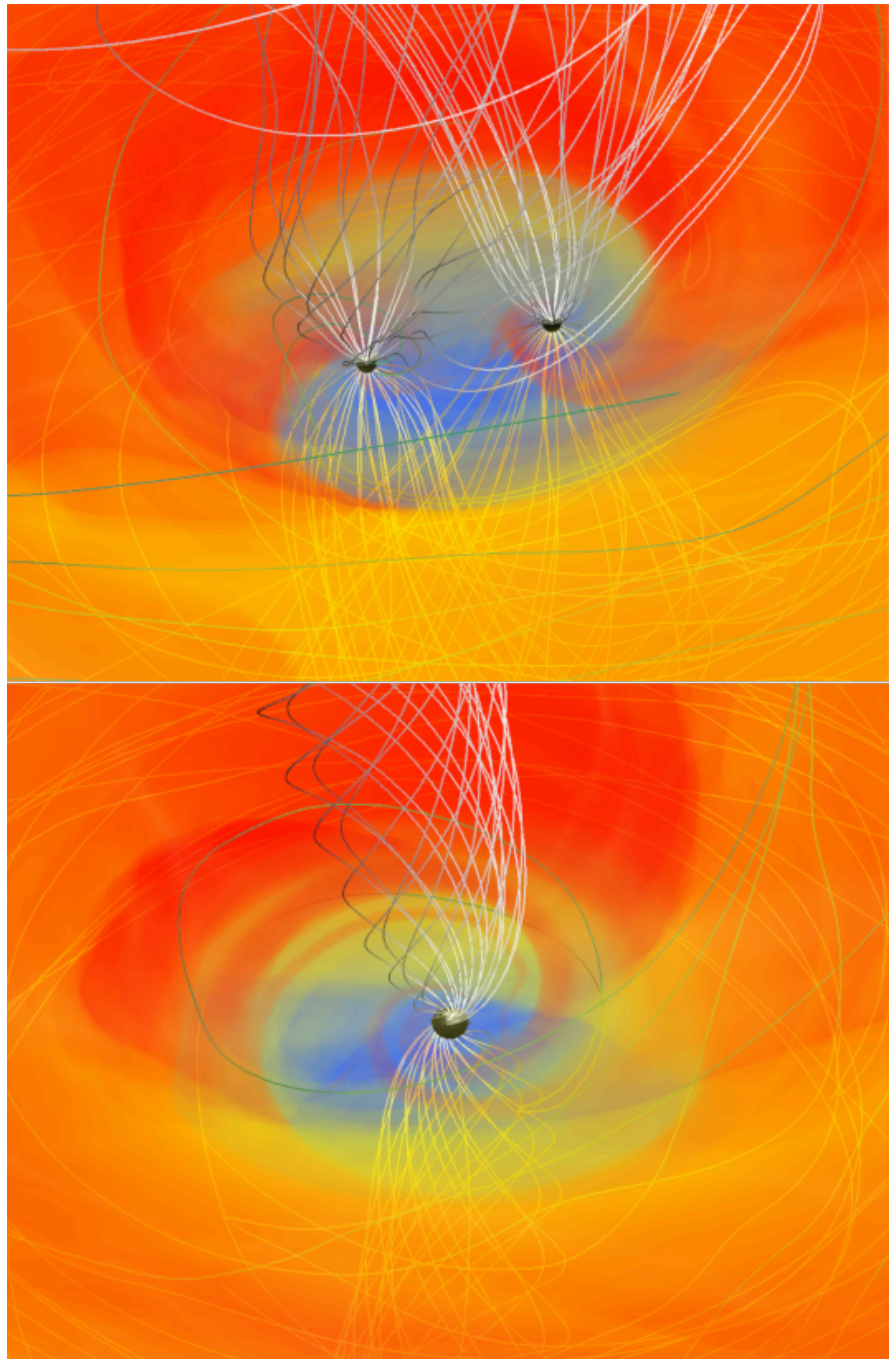
Modelling the emission from MBH mergers

Post-process emission from MBH mergers in the simulation



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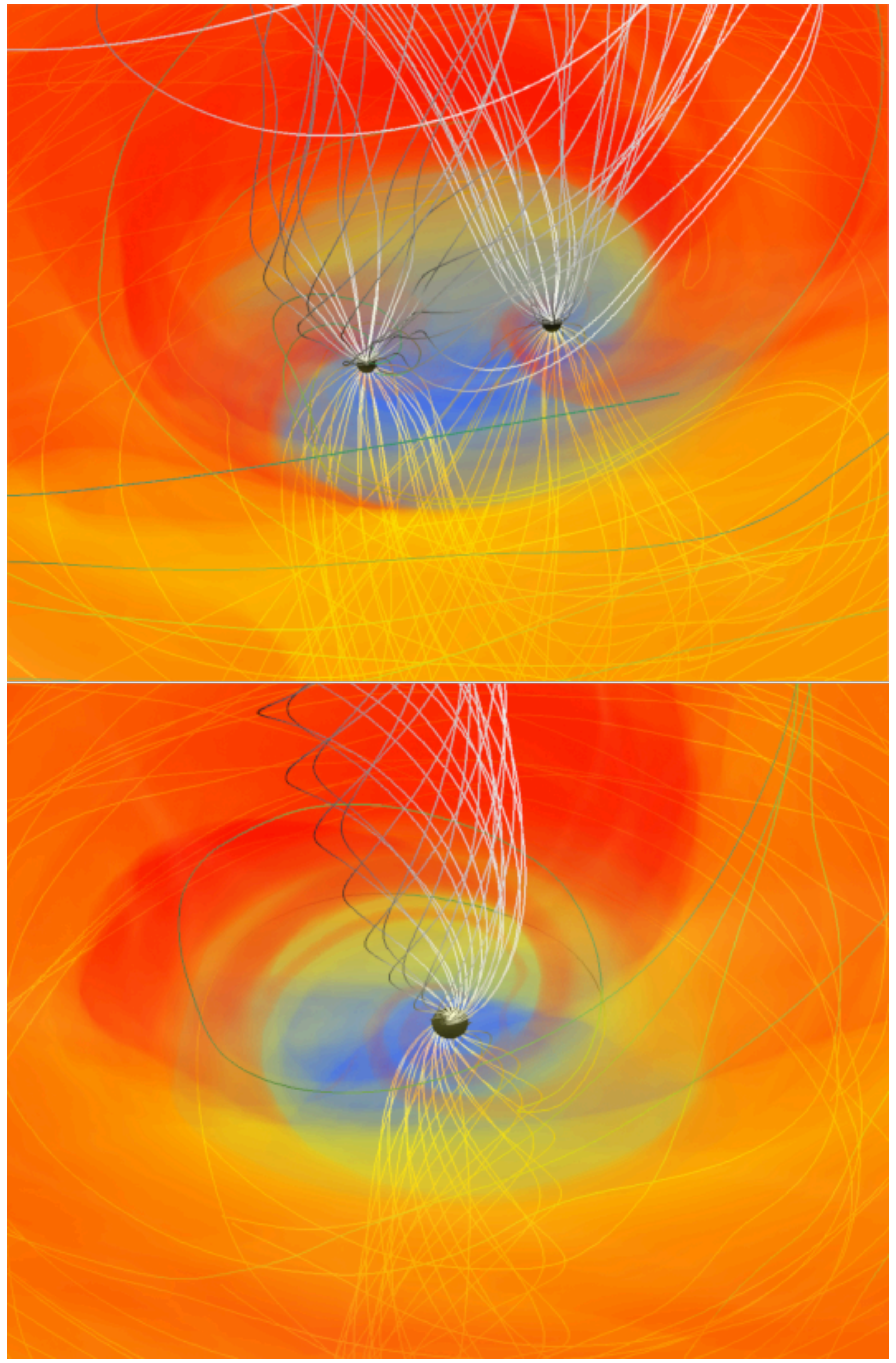

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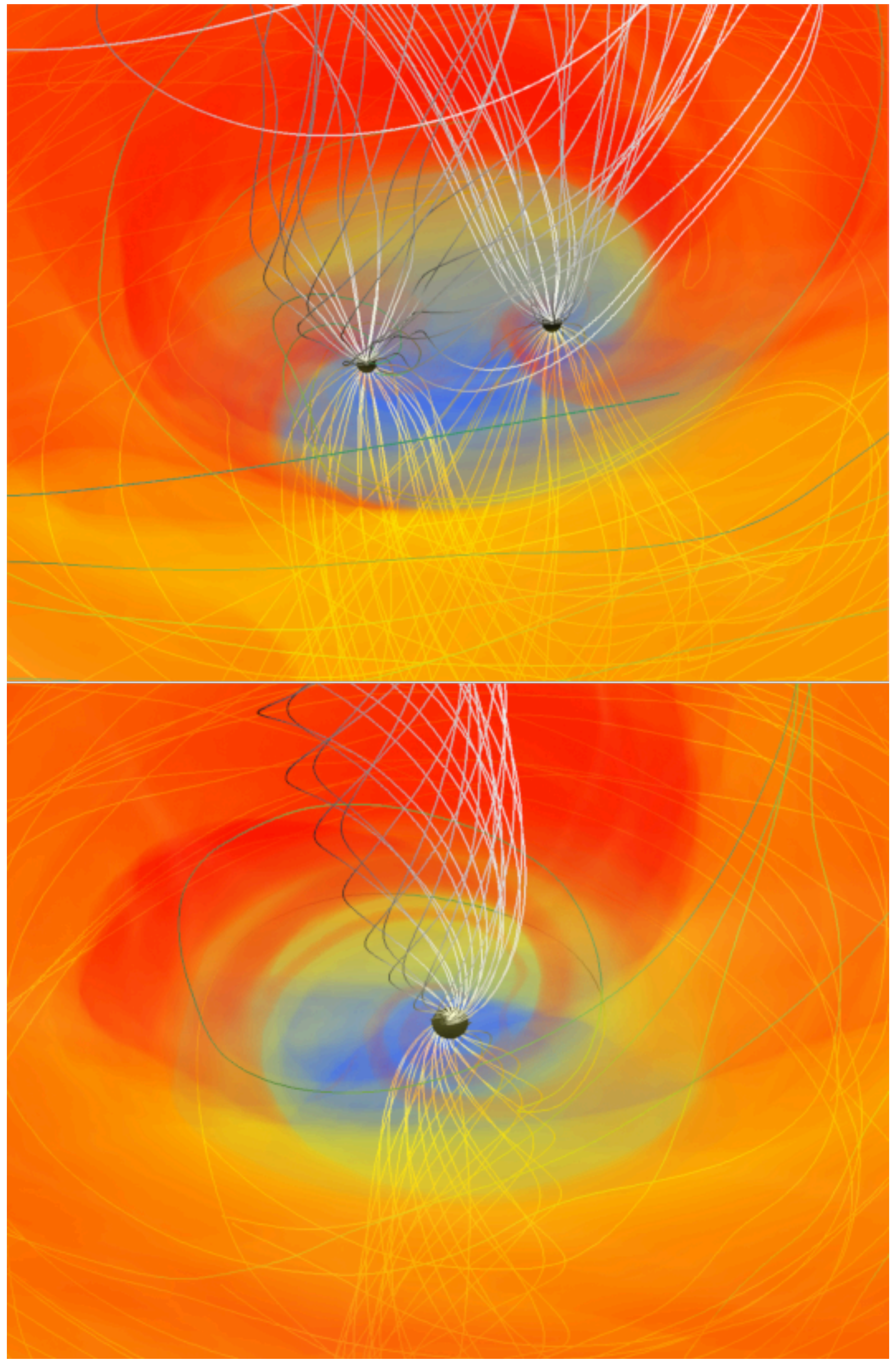

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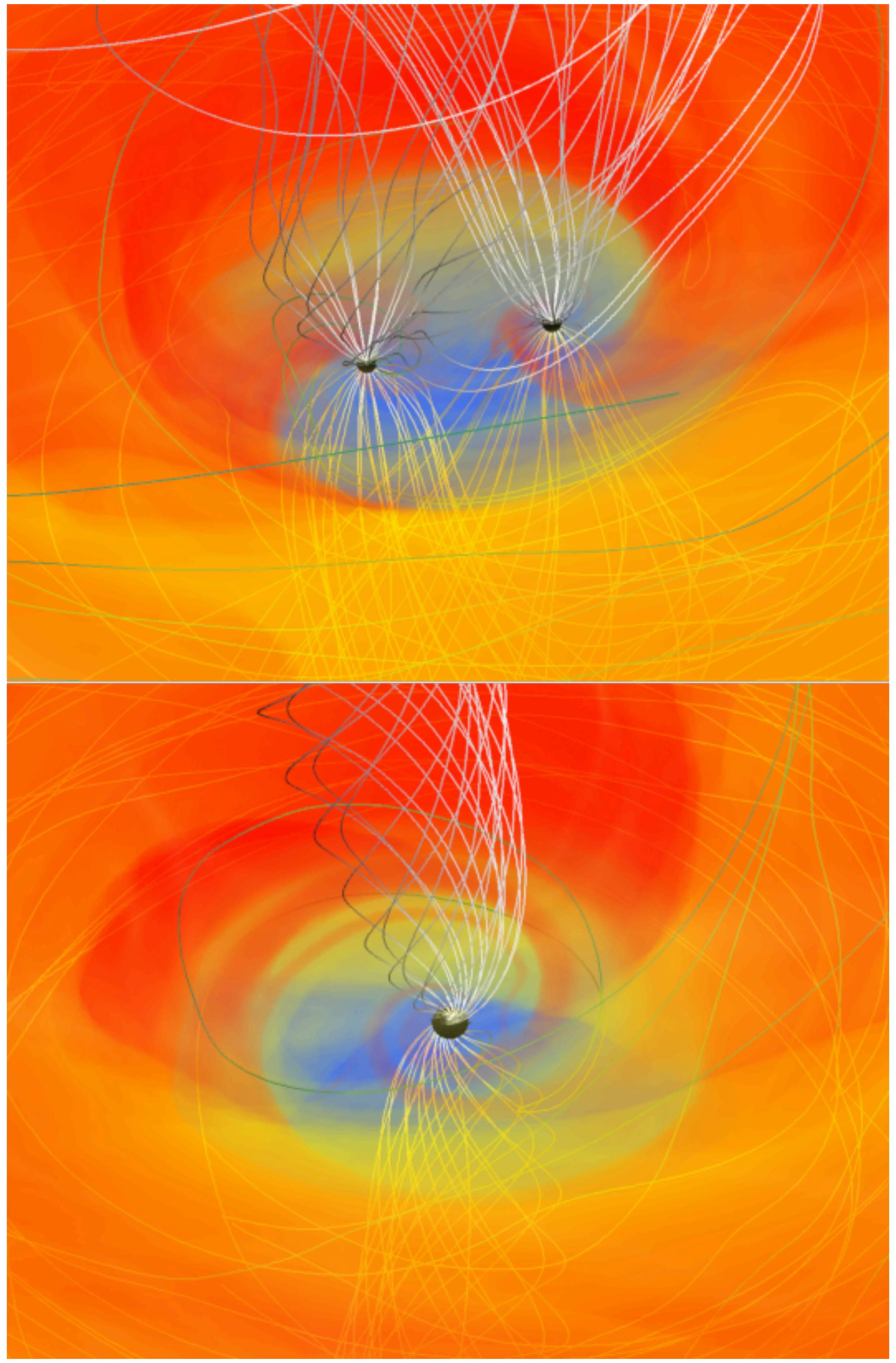

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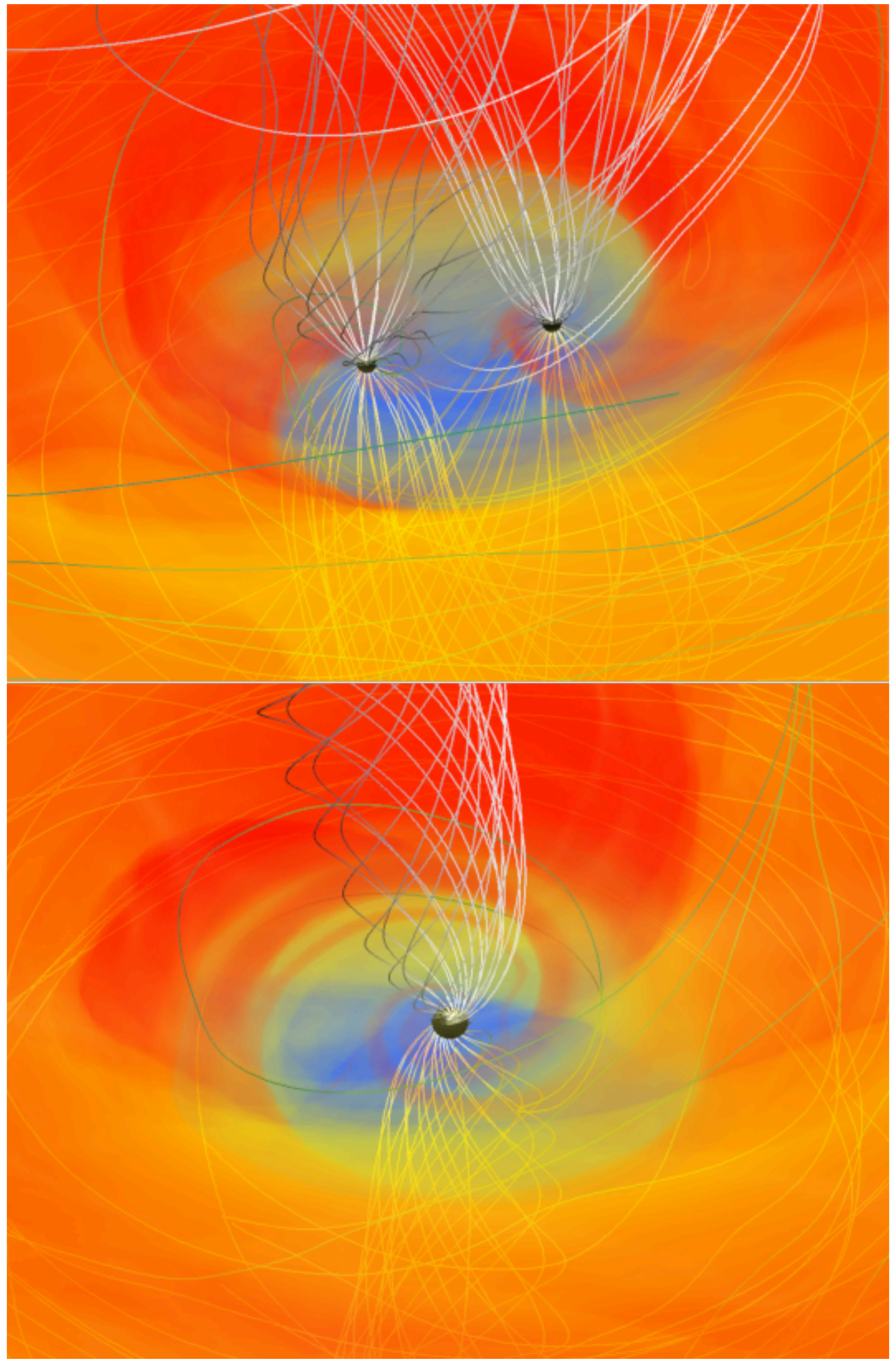

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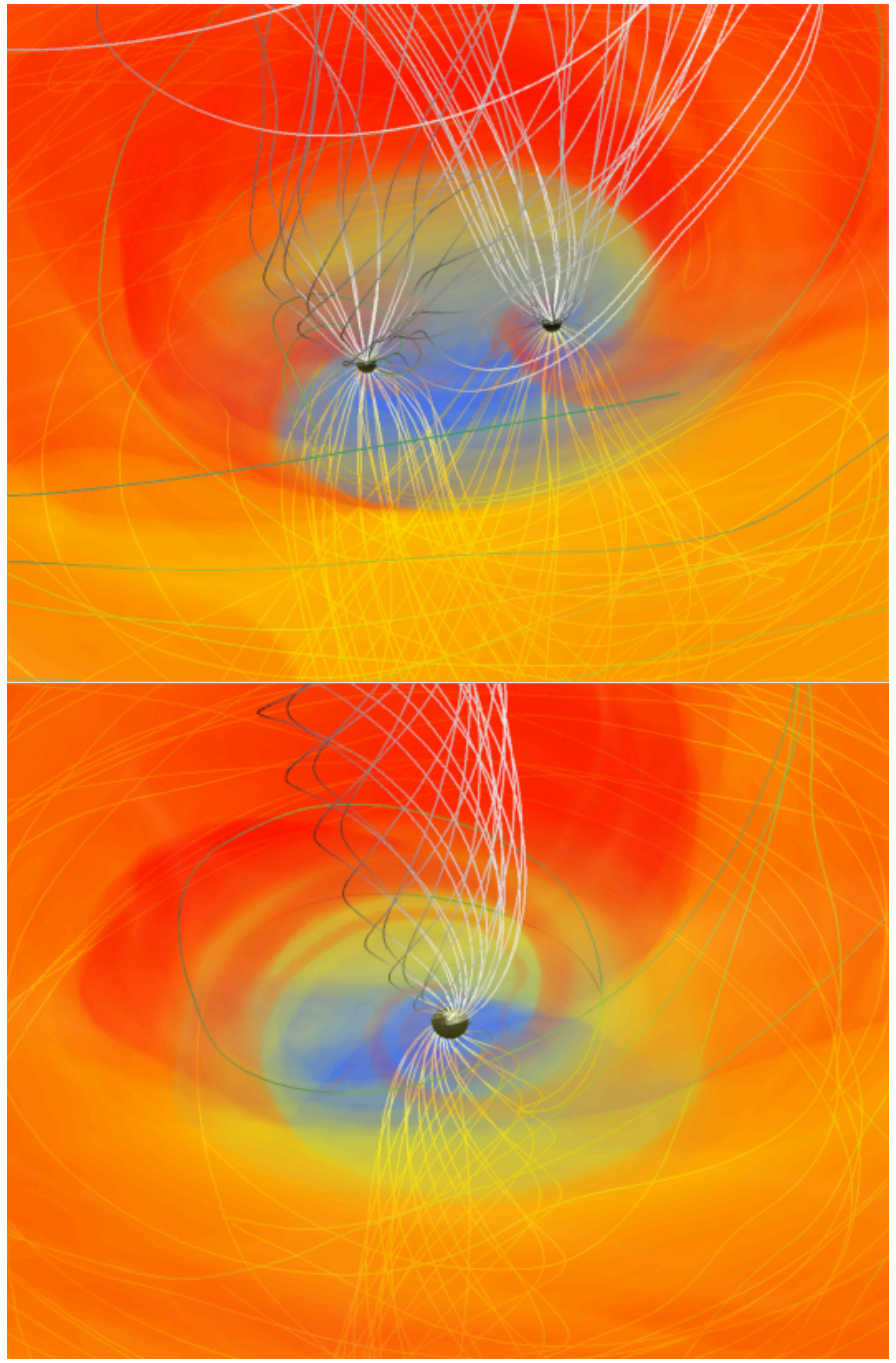

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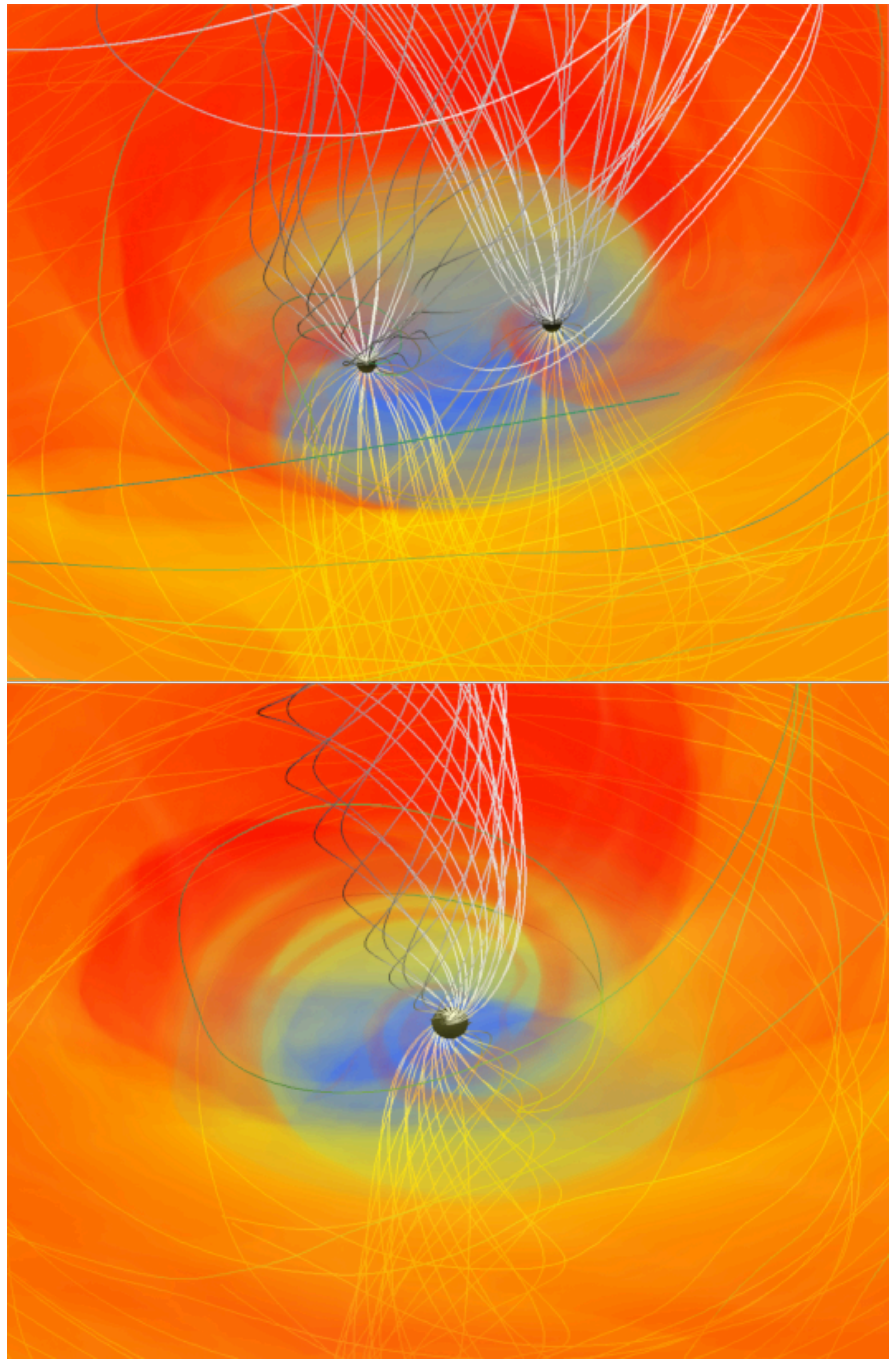
- Model gas, dust obscuration (ISM + torus)
- Model the (contaminant) galactic emission — stellar light, X-ray binaries and SFR radio emission

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



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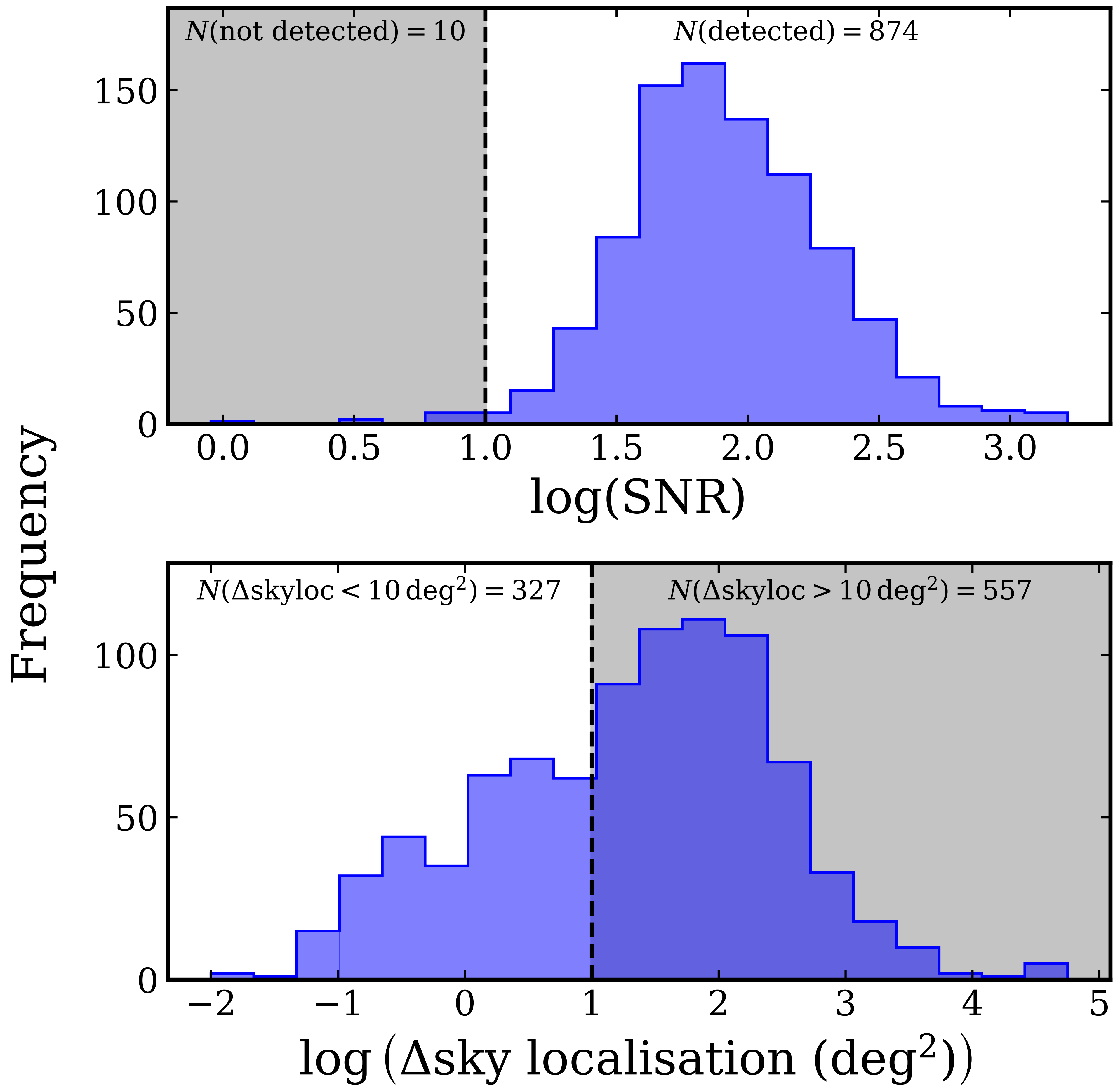
GW observability of MBH mergers



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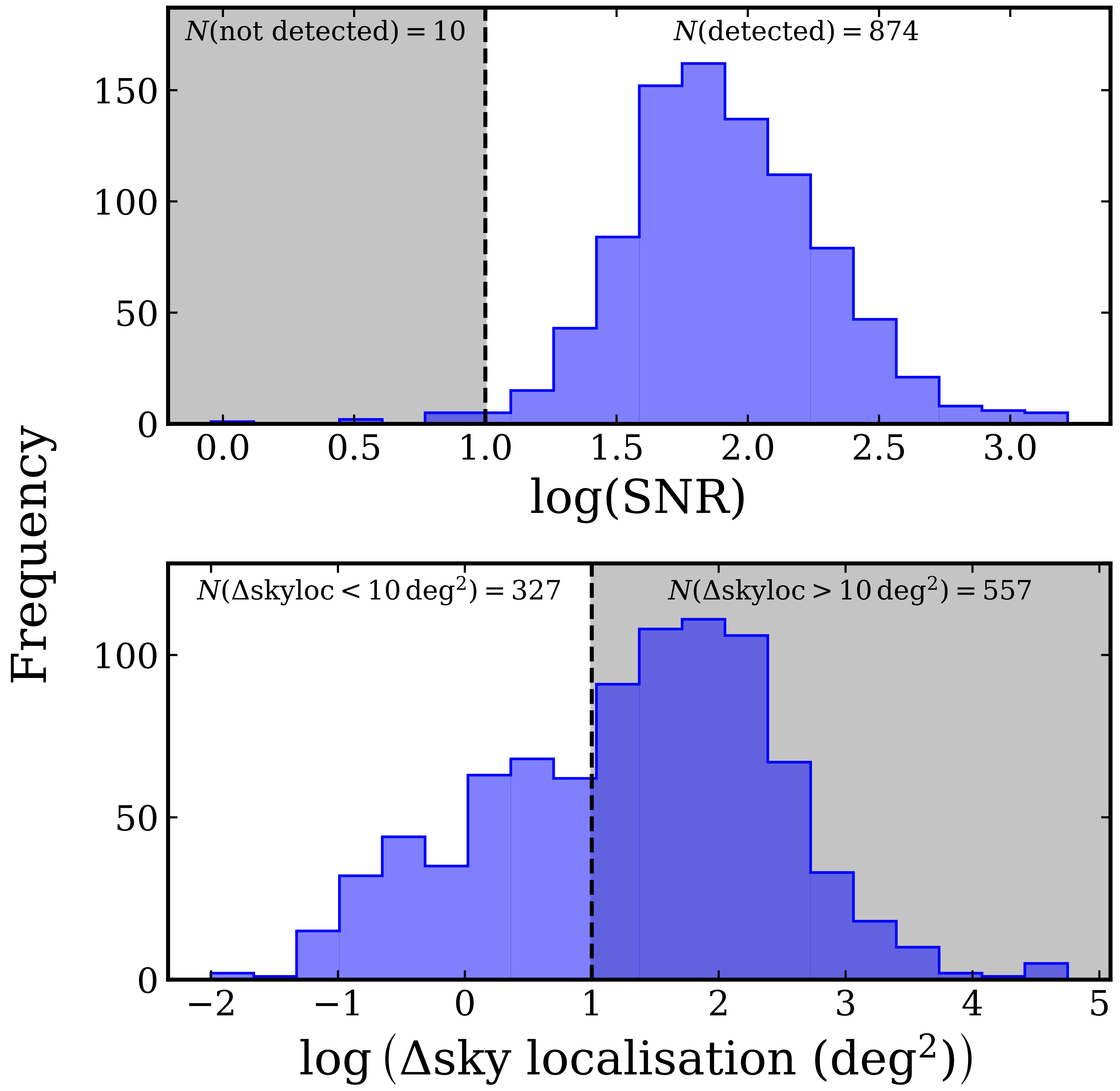
GW observability of MBH mergers

- **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



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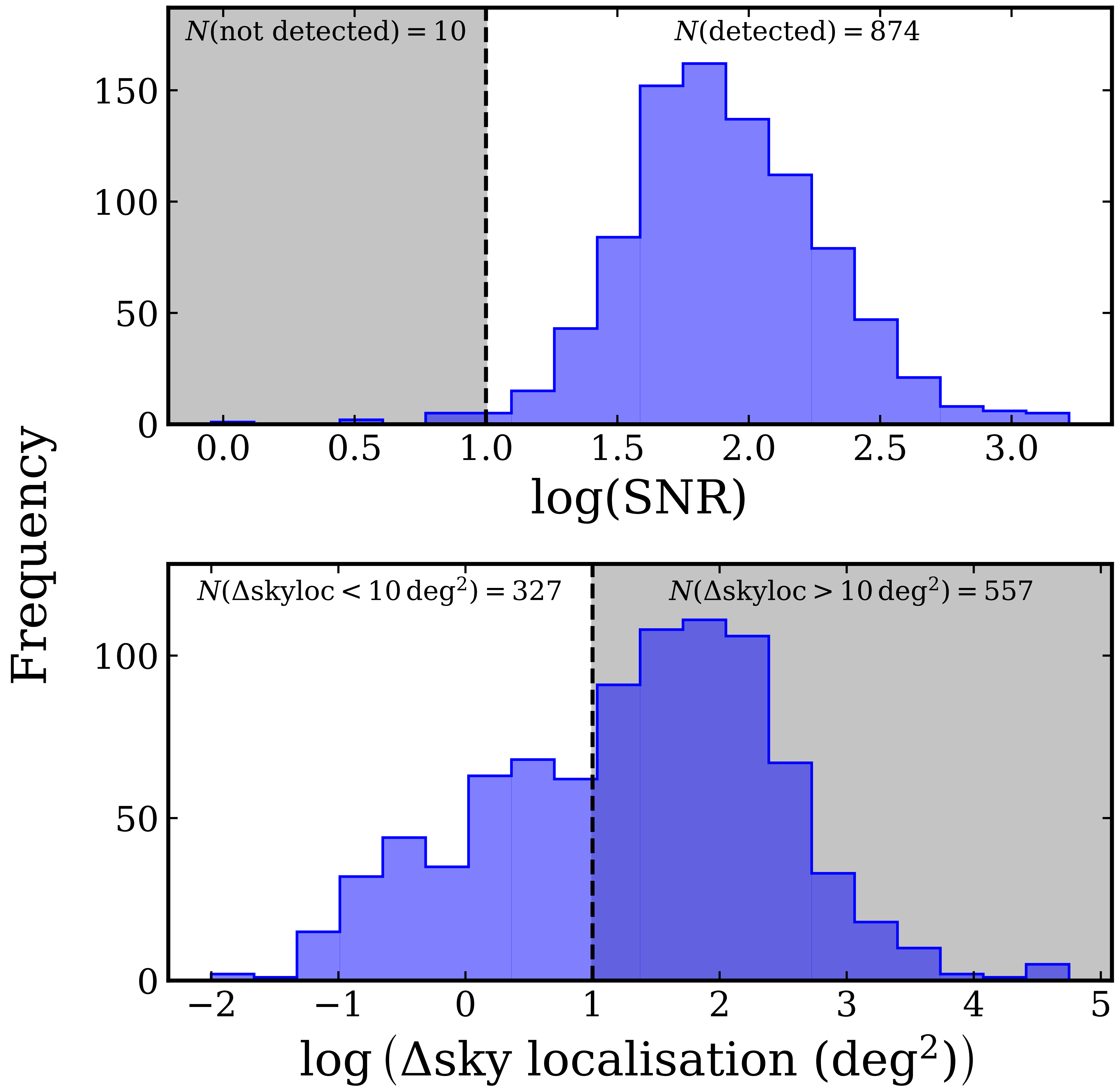

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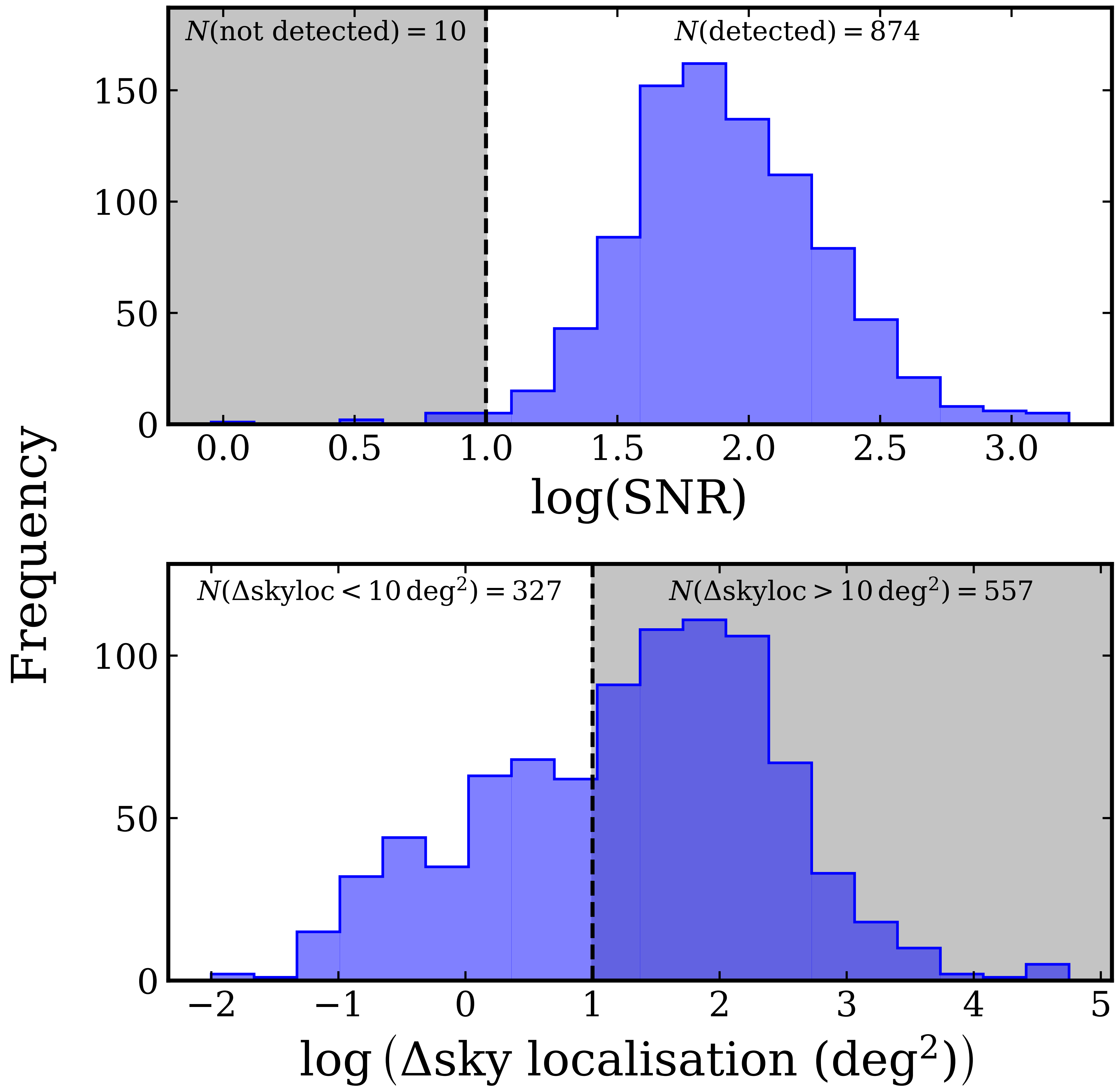
- **Systems are generally not well localised** in the sky — only $37\,\%$ of mergers have a 2σ error smaller than $10\,\mathrm{deg}^2$ → larger than most telescopes' field of view → **telescopes need to tile the sky**



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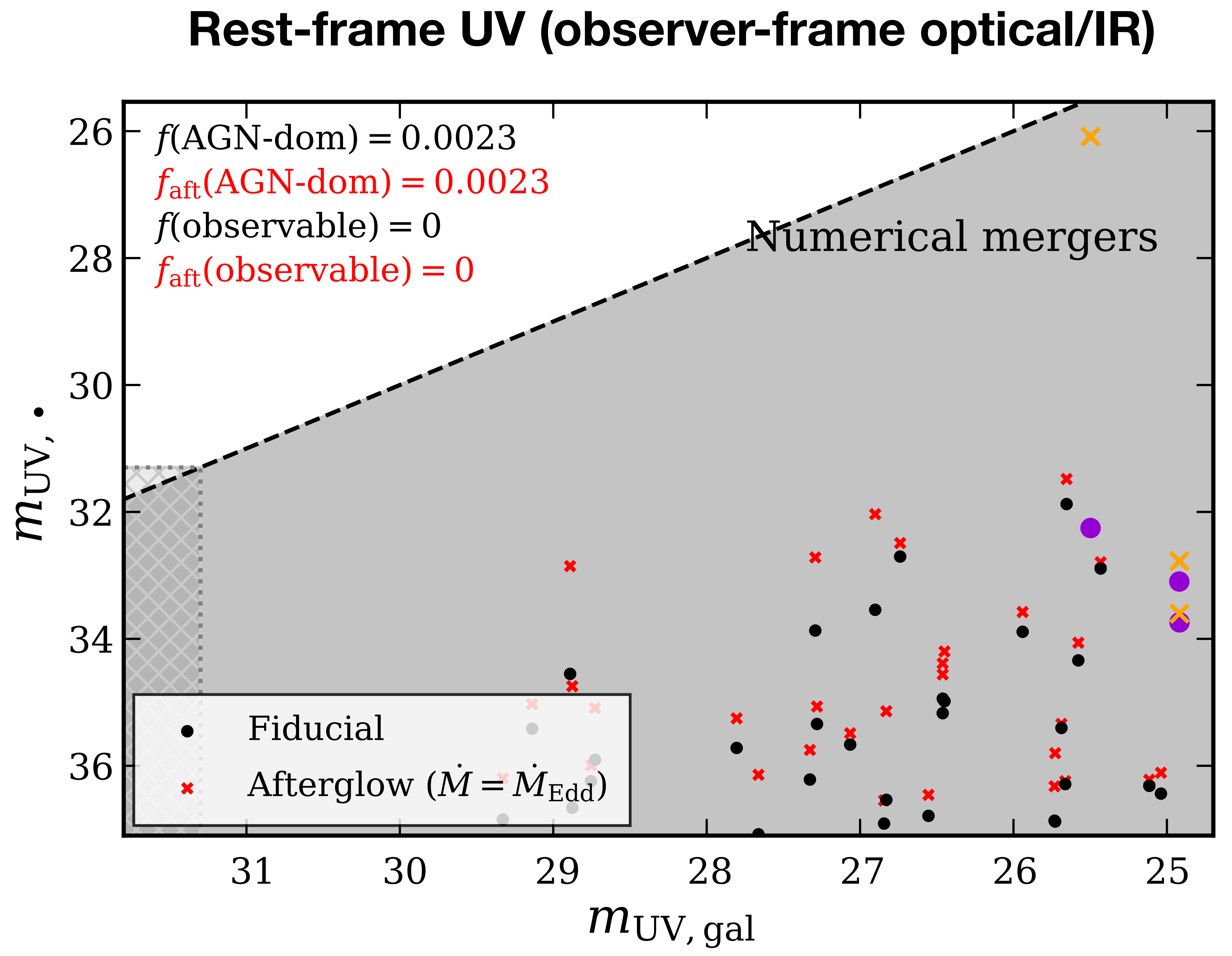
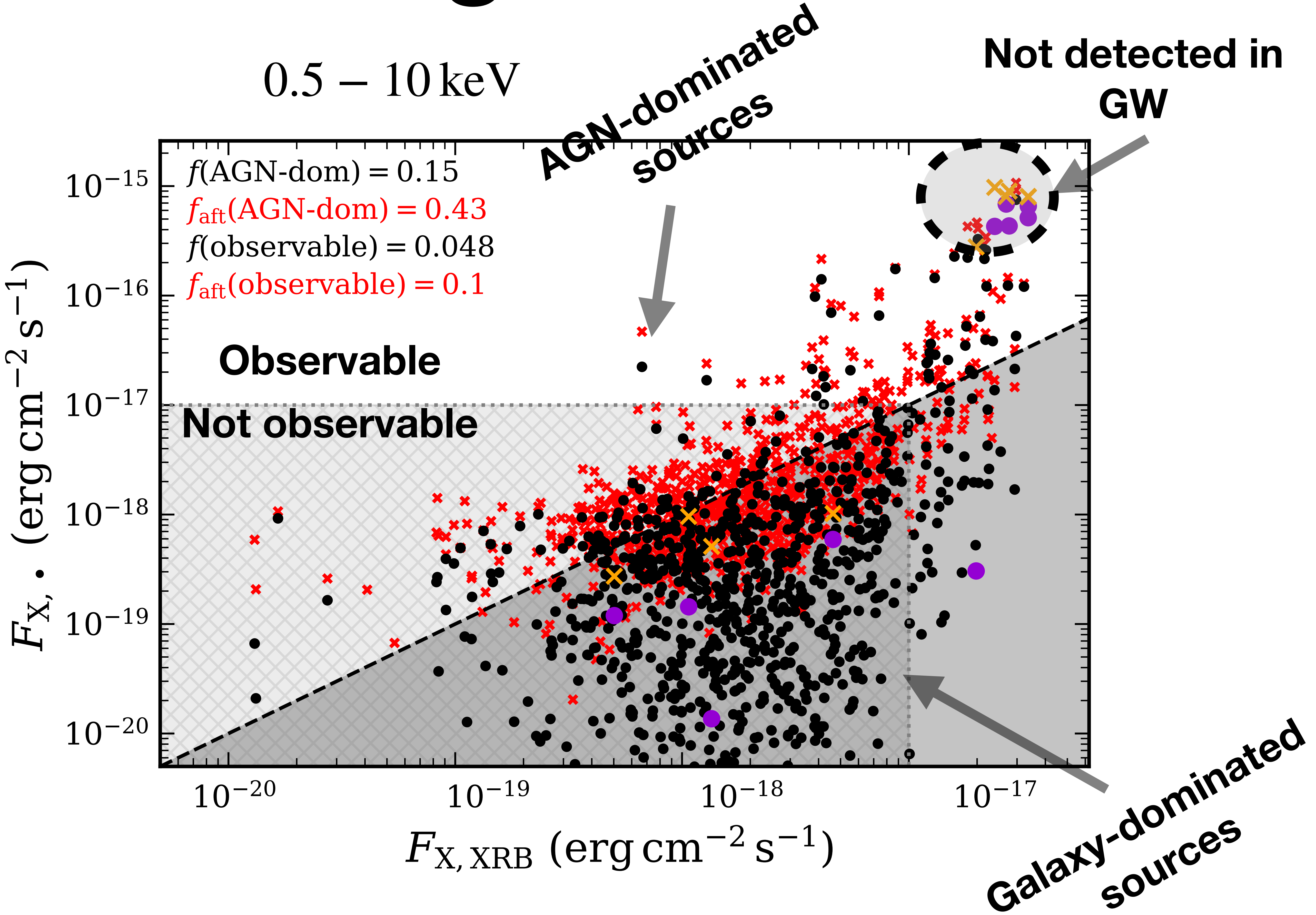
EM observability of MBH merger remnants





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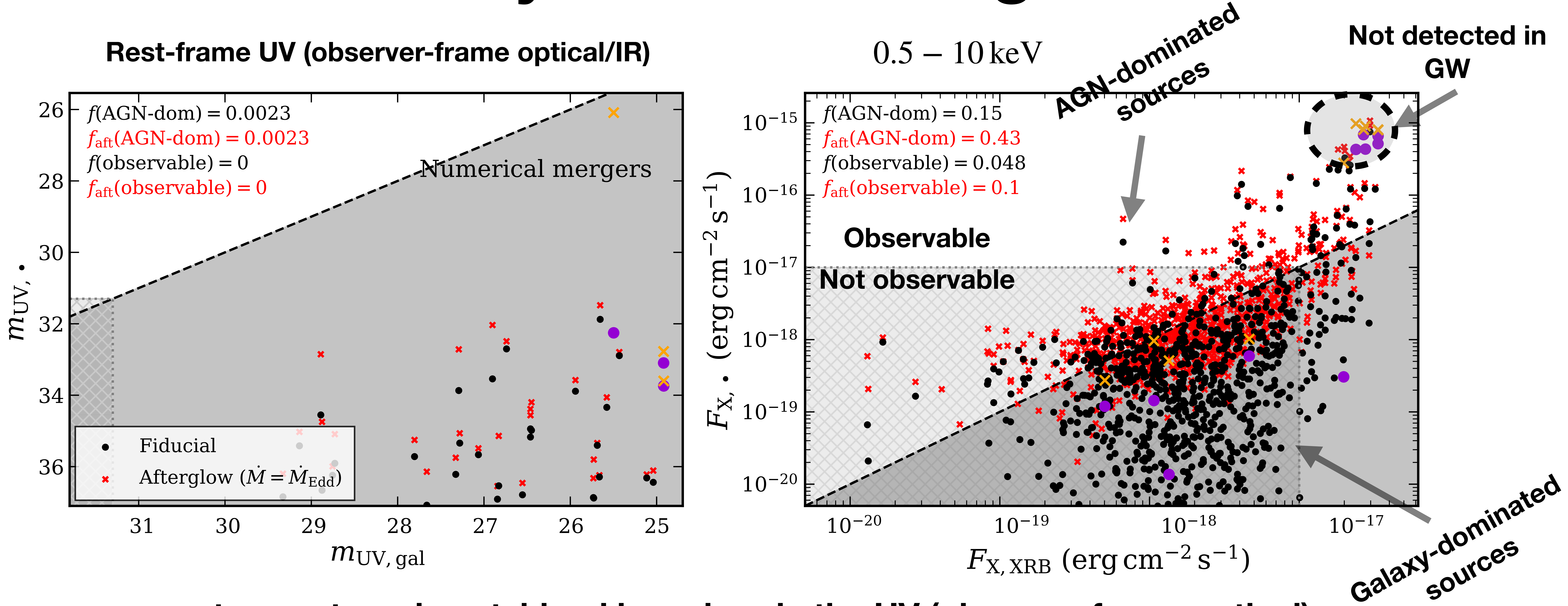
EM observability of MBH merger remnants



- **Merger remnants are strongly outshined by galaxy in the UV (observer-frame optical)**

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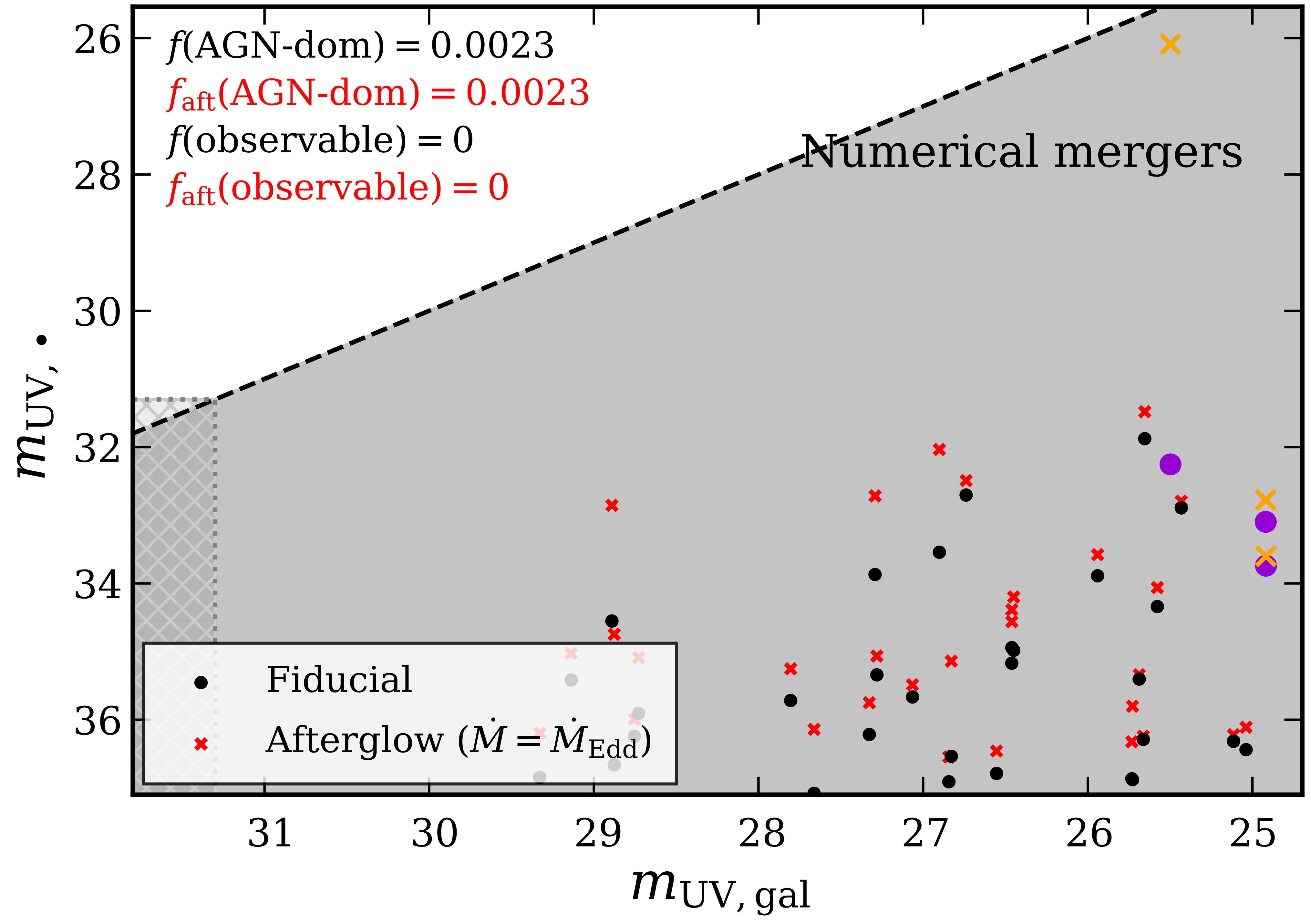
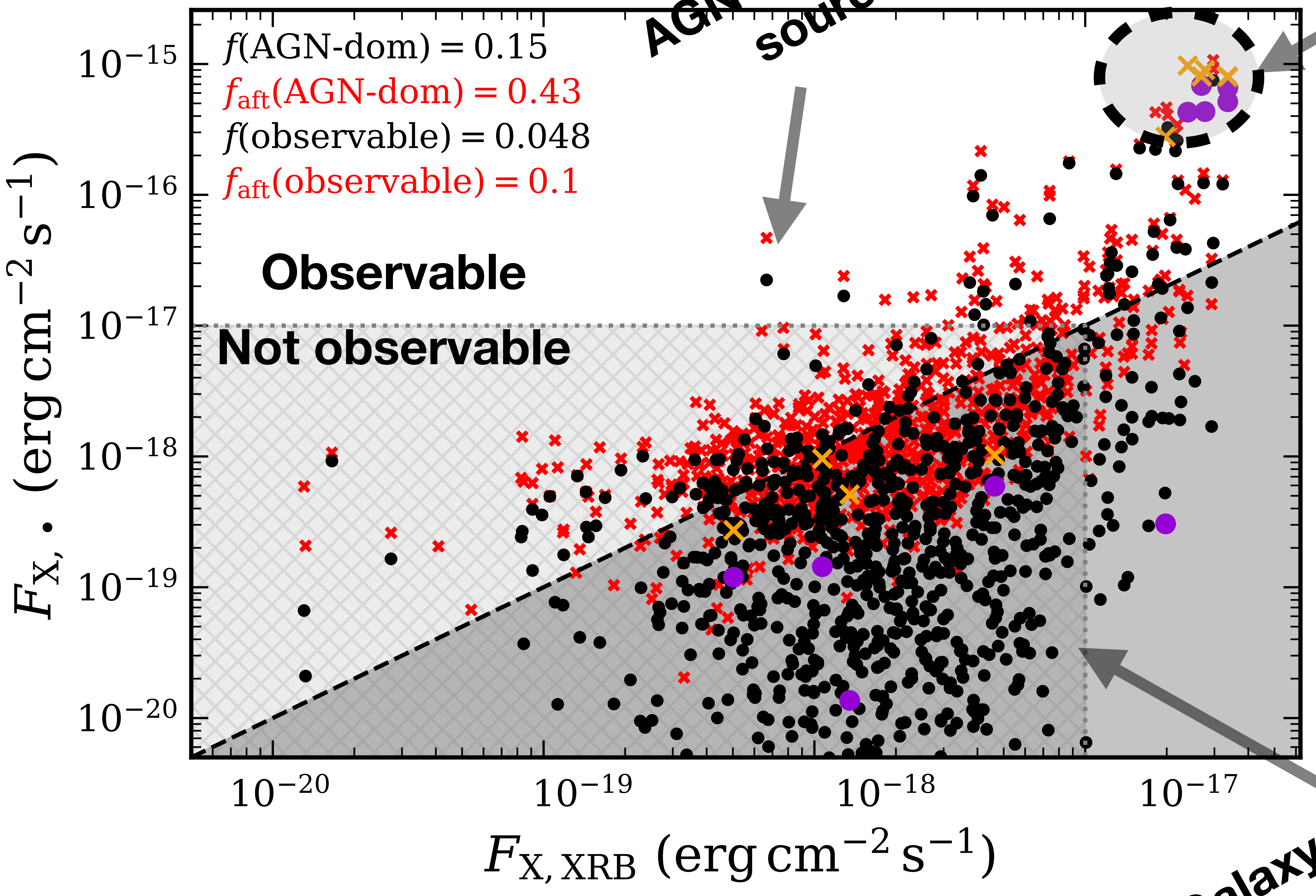
EM observability of MBH merger remnants

Rest-frame UV (observer-frame optical/IR)



$0.5 - 10\,\mathrm{keV}$



- **Merger remnants are strongly outshined by galaxy in the UV (observer-frame optical)**
- **We expect a fraction $5\,\%$ of merger remnants to be observable and brighter than the galaxy in the X-rays**

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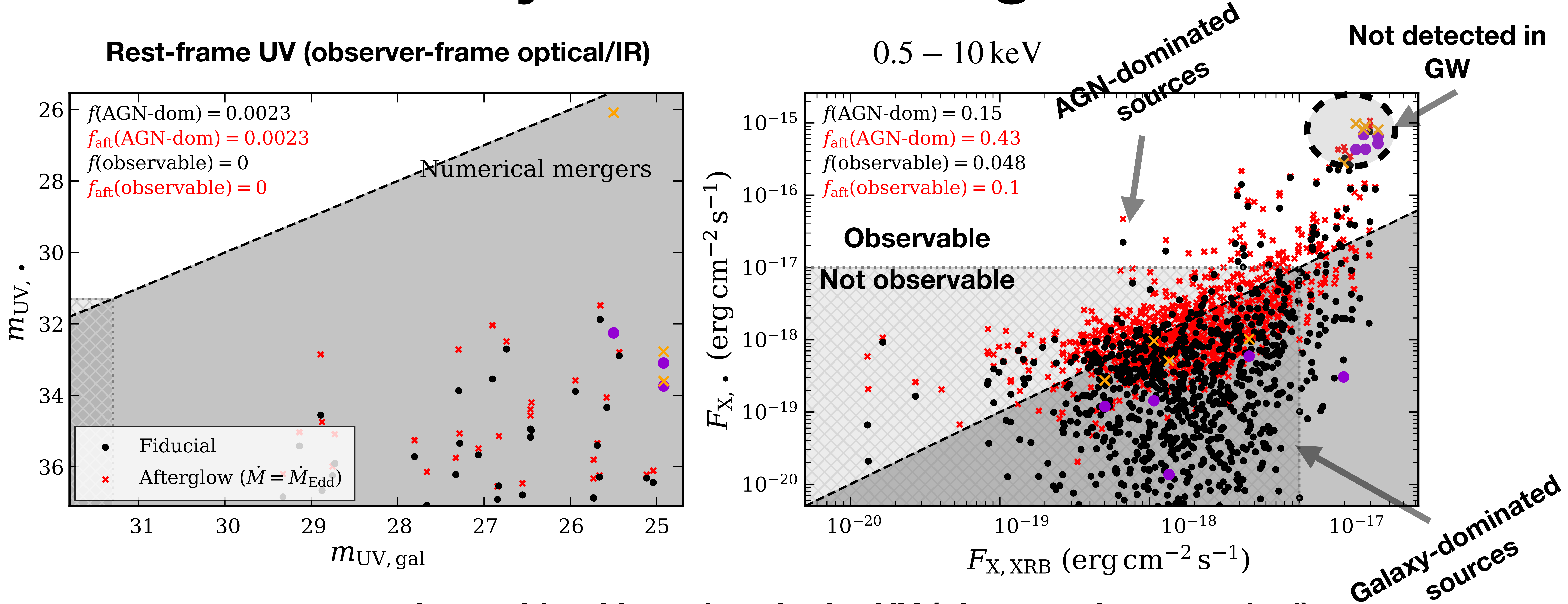

- **Merger remnants are strongly outshined by galaxy in the UV (observer-frame optical)**
- **We expect a fraction $5\,\%$ of merger remnants to be observable and brighter than the galaxy in the X-rays**
- **The fraction is higher ($10\,\%$) in the case of a merger-induced afterglow leading to $f_{\rm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

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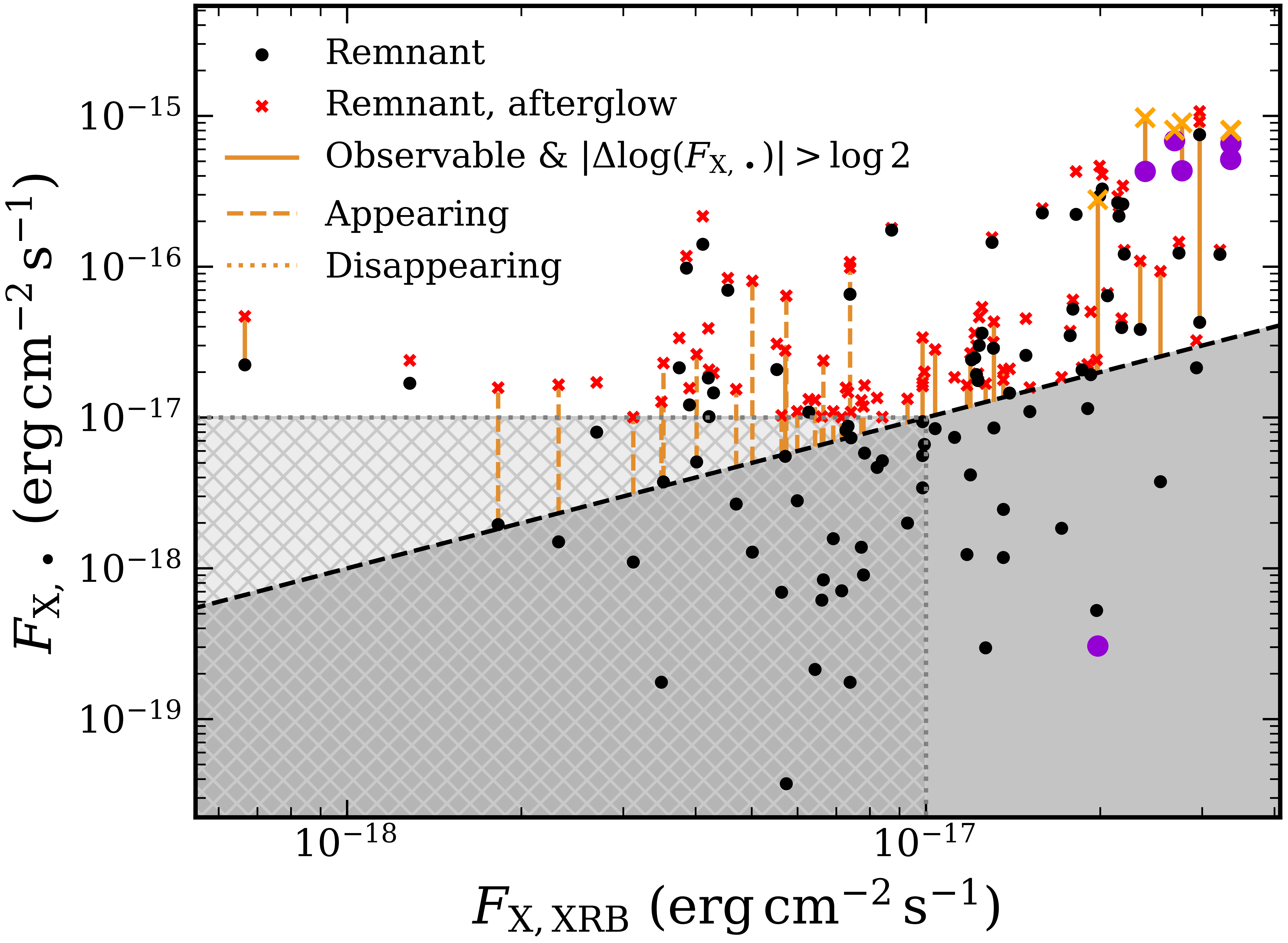
X-ray transients



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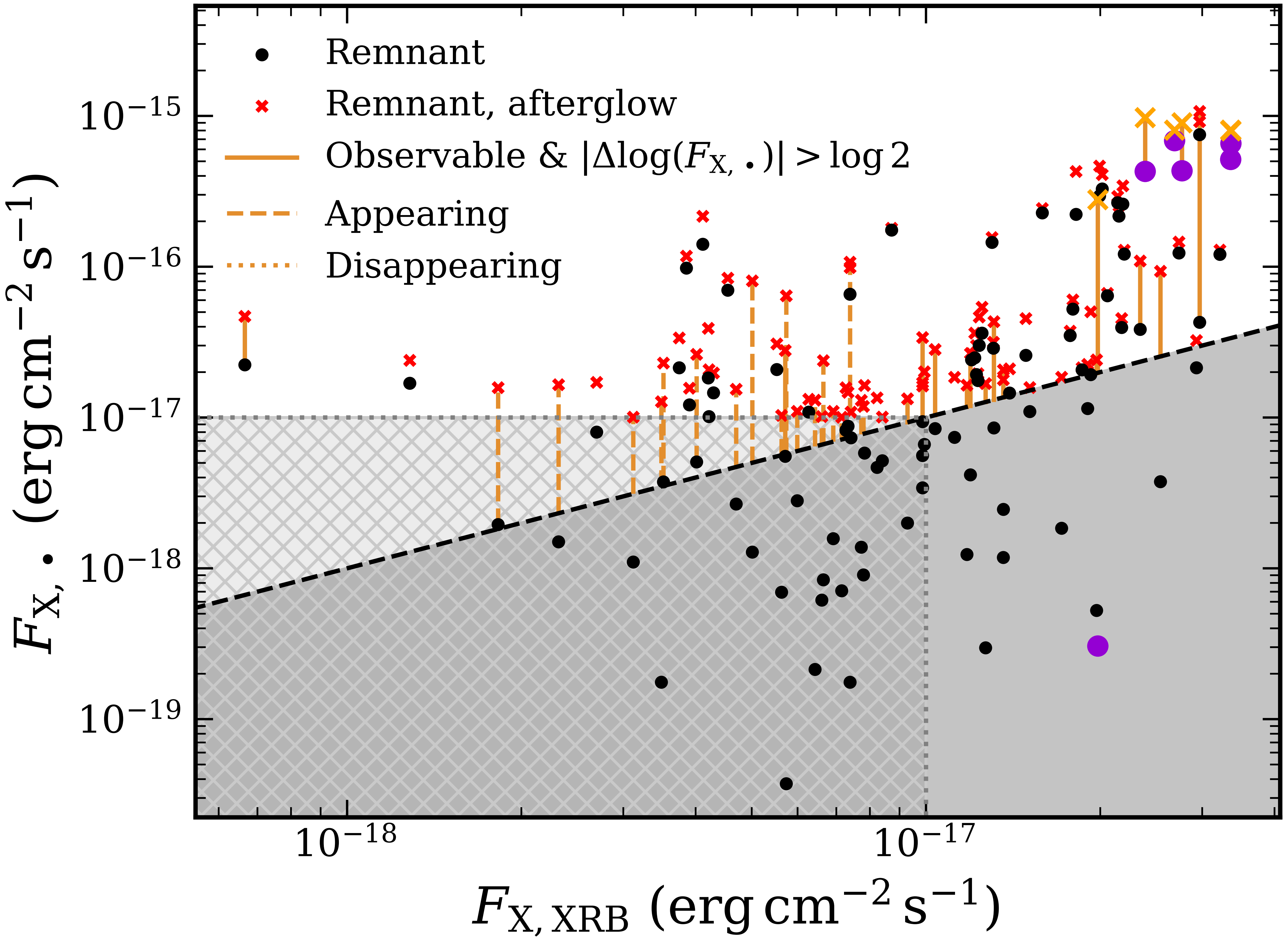
X-ray transients

- **In our model, the accretion rate increases to $f_{\rm Edd} = 1$ due to the merger.**



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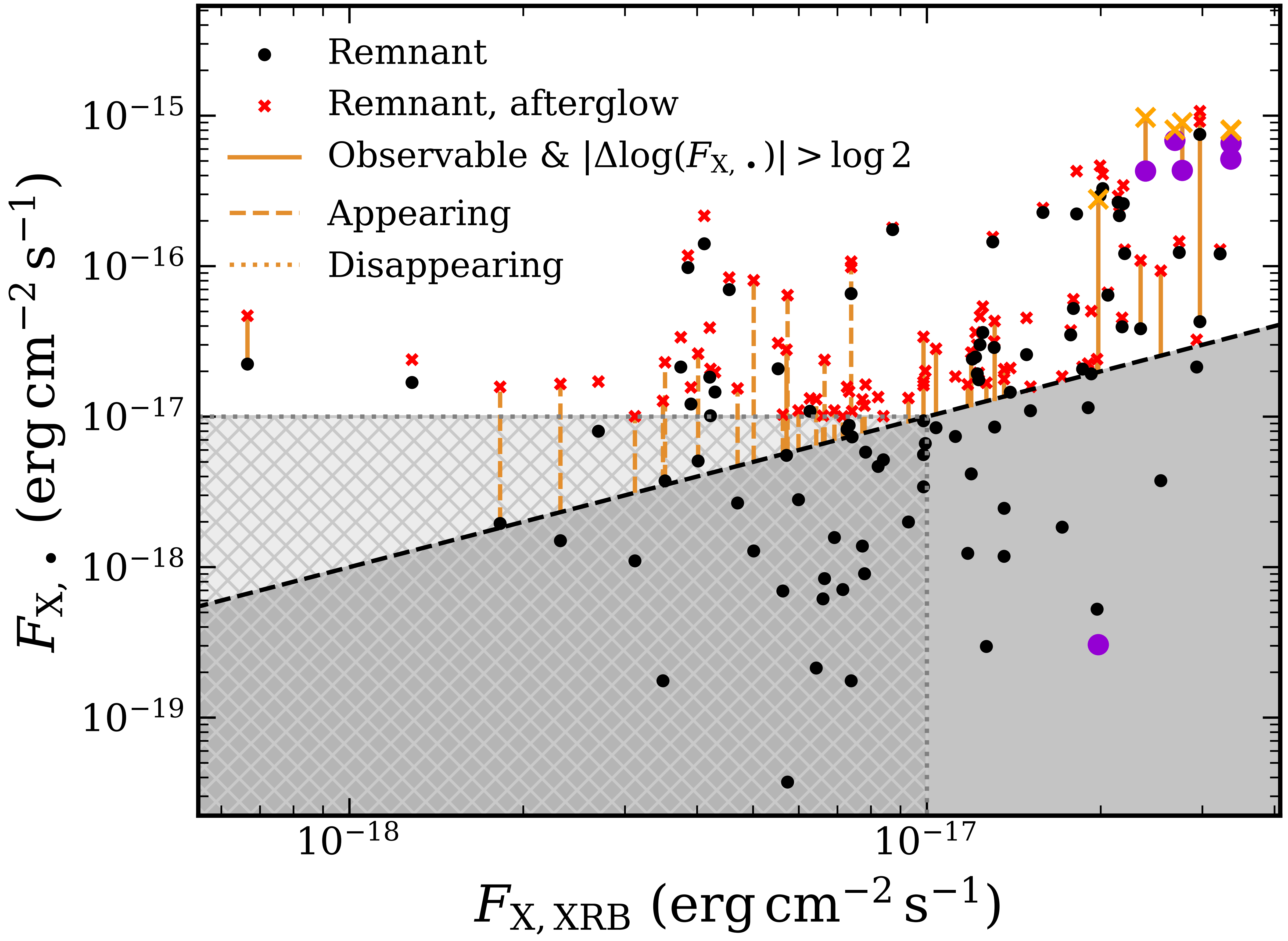

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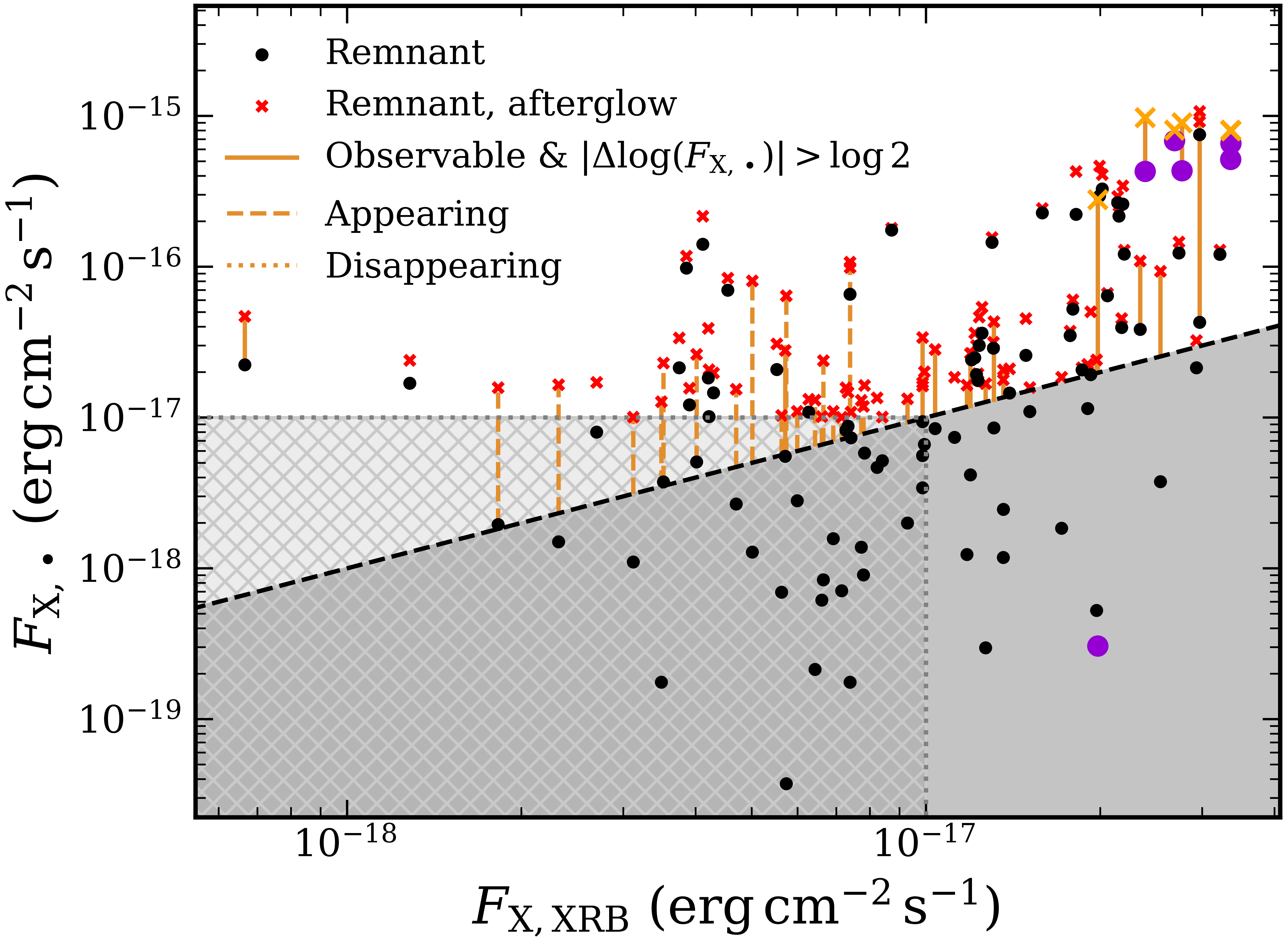

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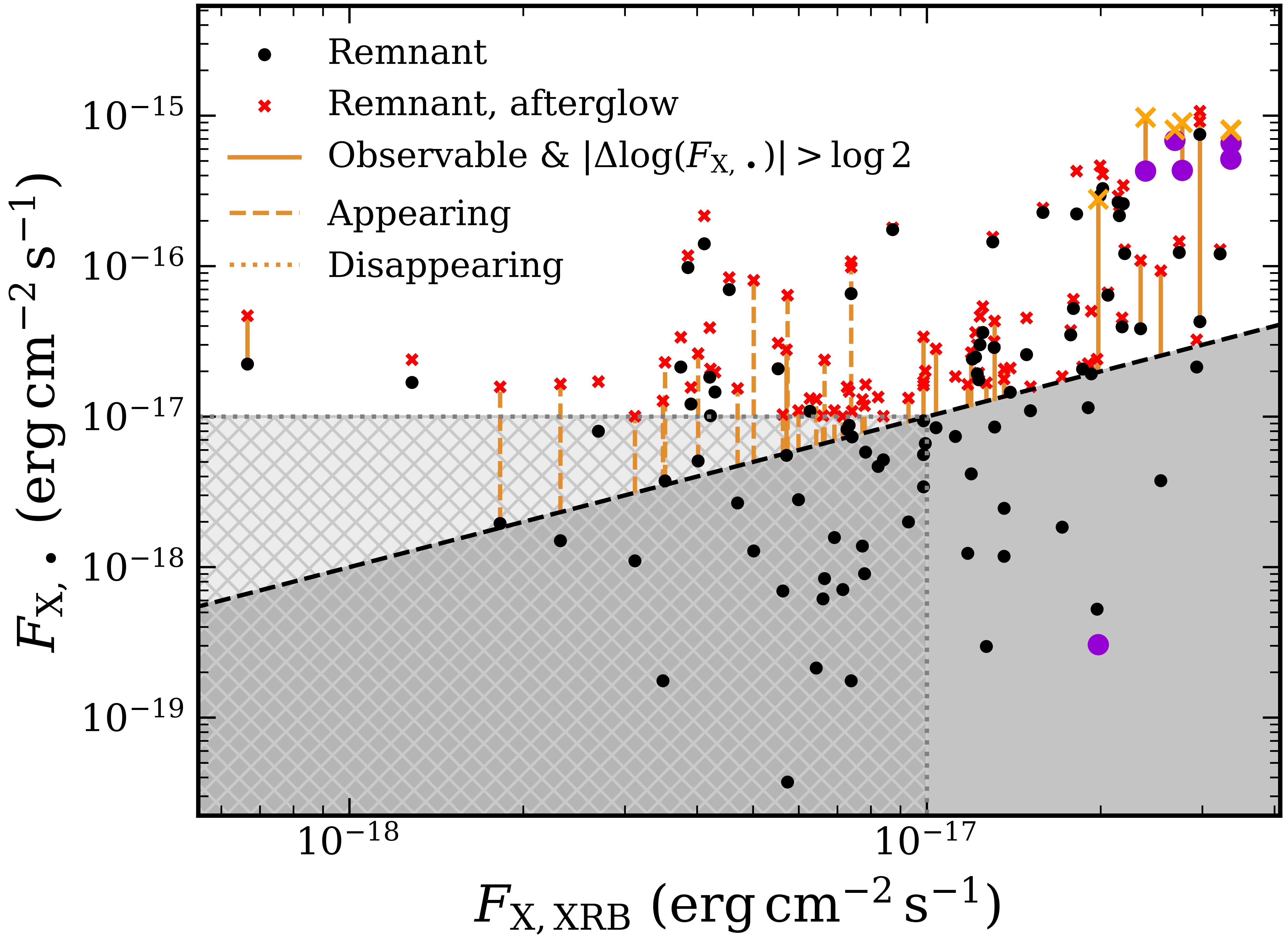

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X-ray transients

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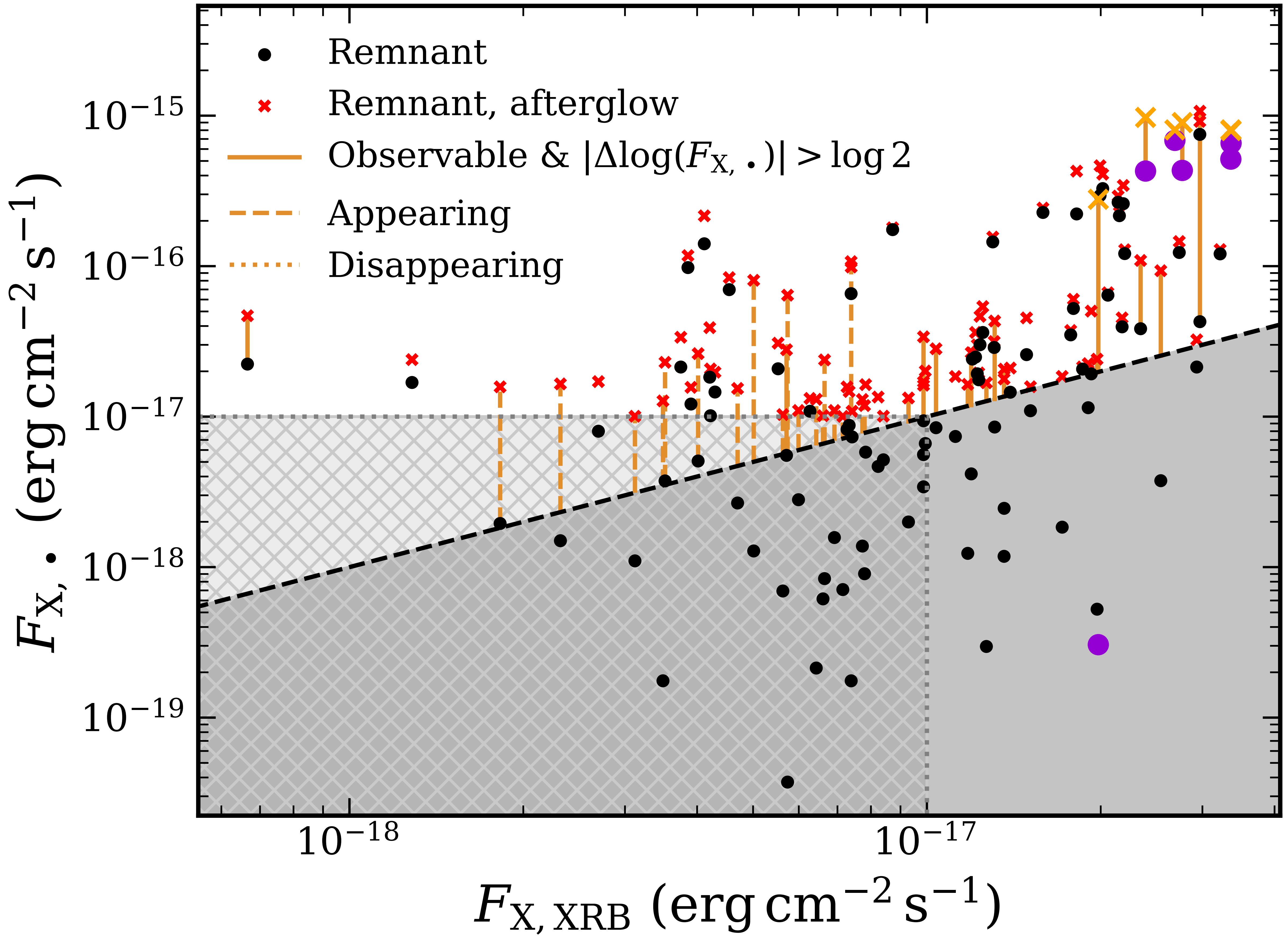
- **In order to detect the transient as an EM counterpart:**
  - **The flux needs to be bright enough to be observed**
  - **The transient change of flux needs to be large enough to be observed**
- $4\,\%$ **of sources have an EM counterpart**



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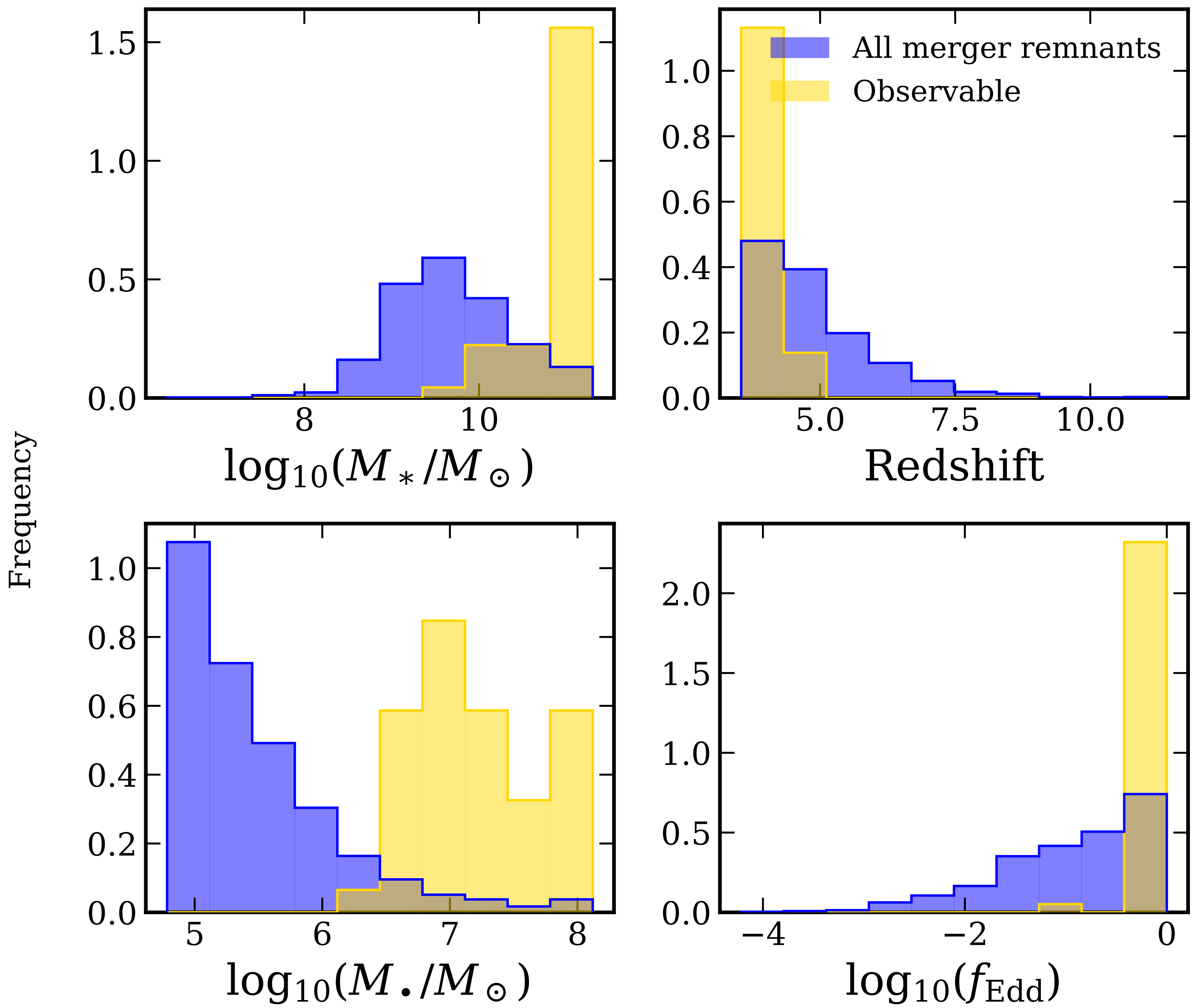
Biases of the X-ray observable MBH mergers



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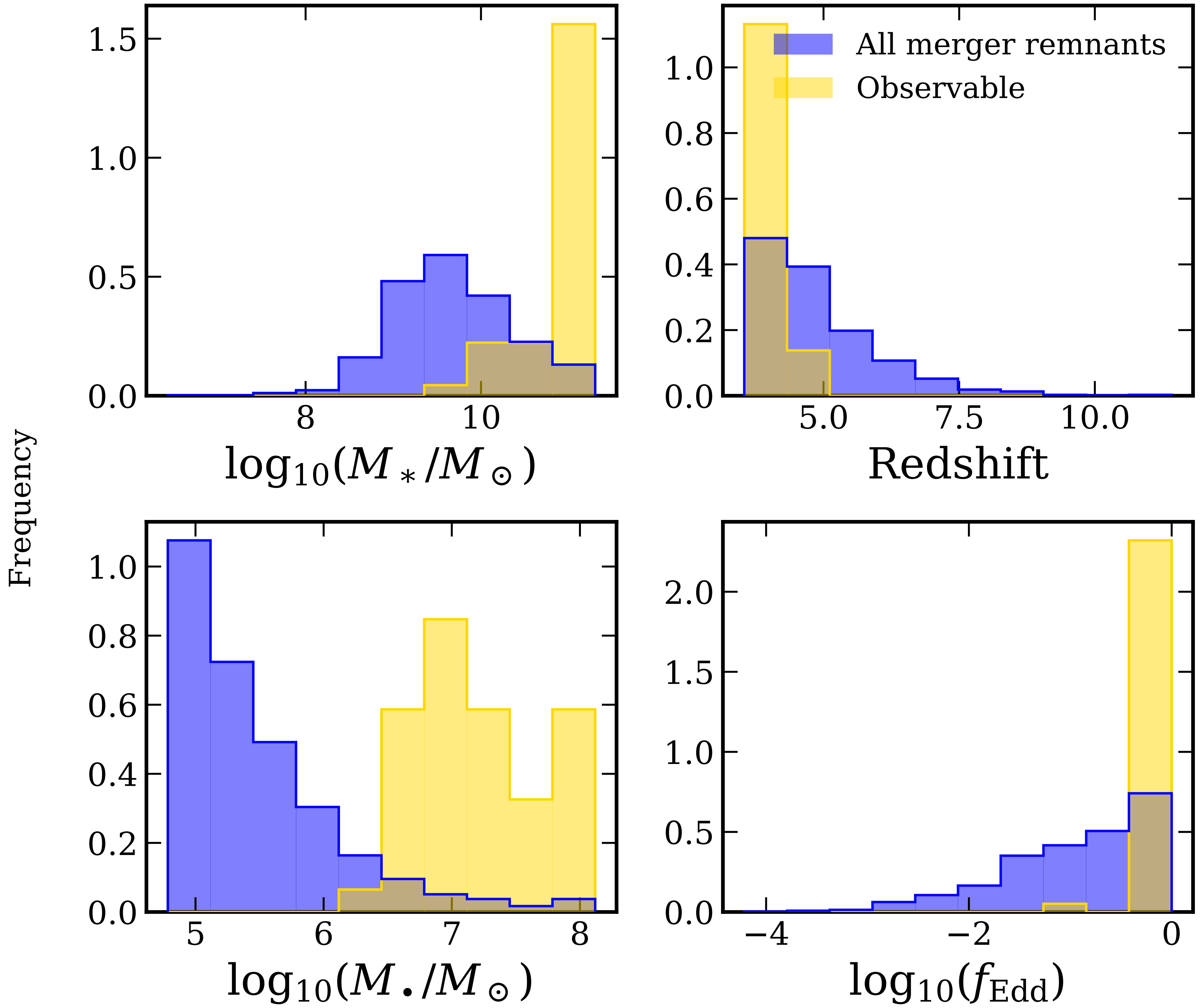

- **Observable mergers have higher BH and galaxy mass and higher accretion rate and occur at lower redshift**

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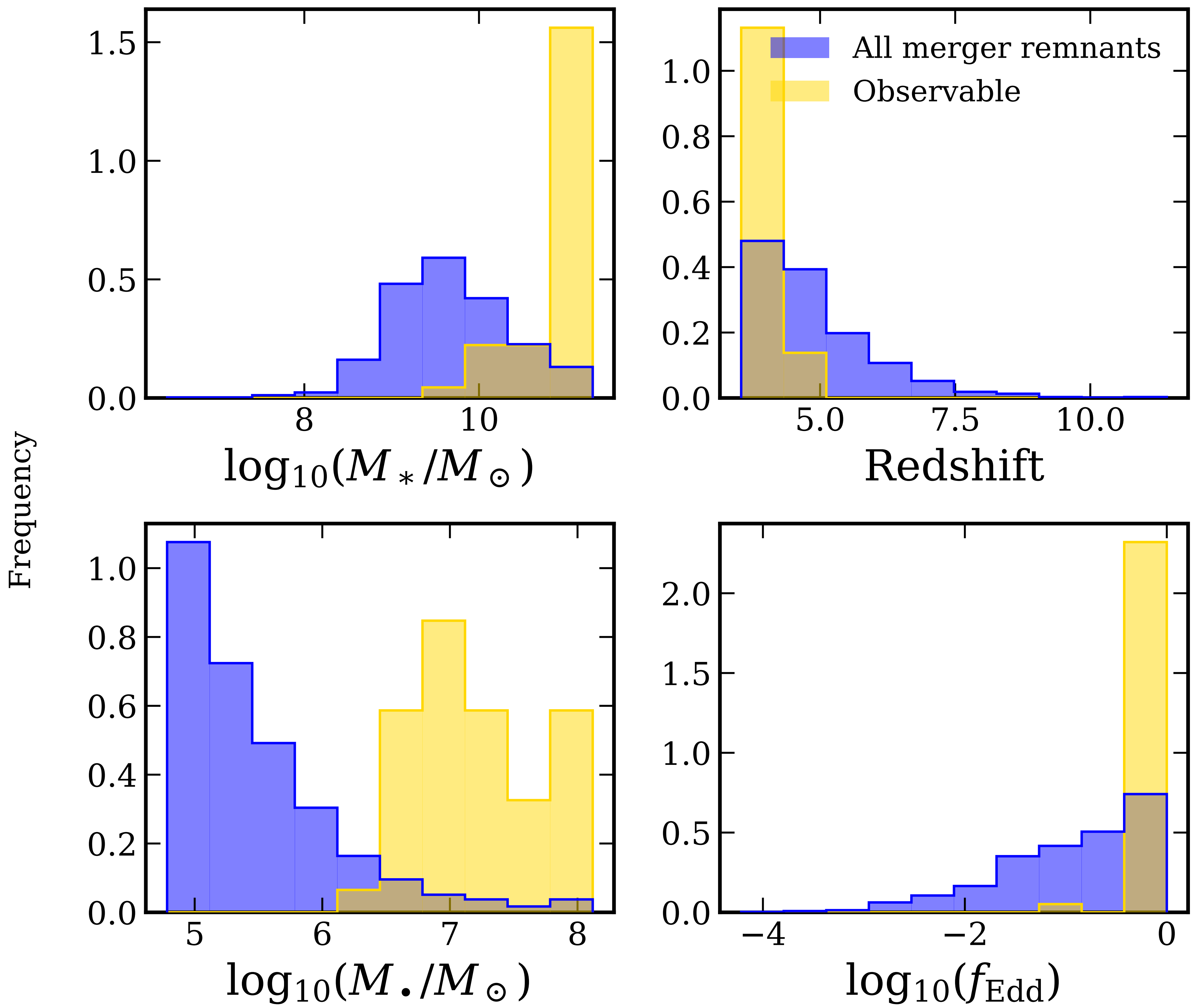

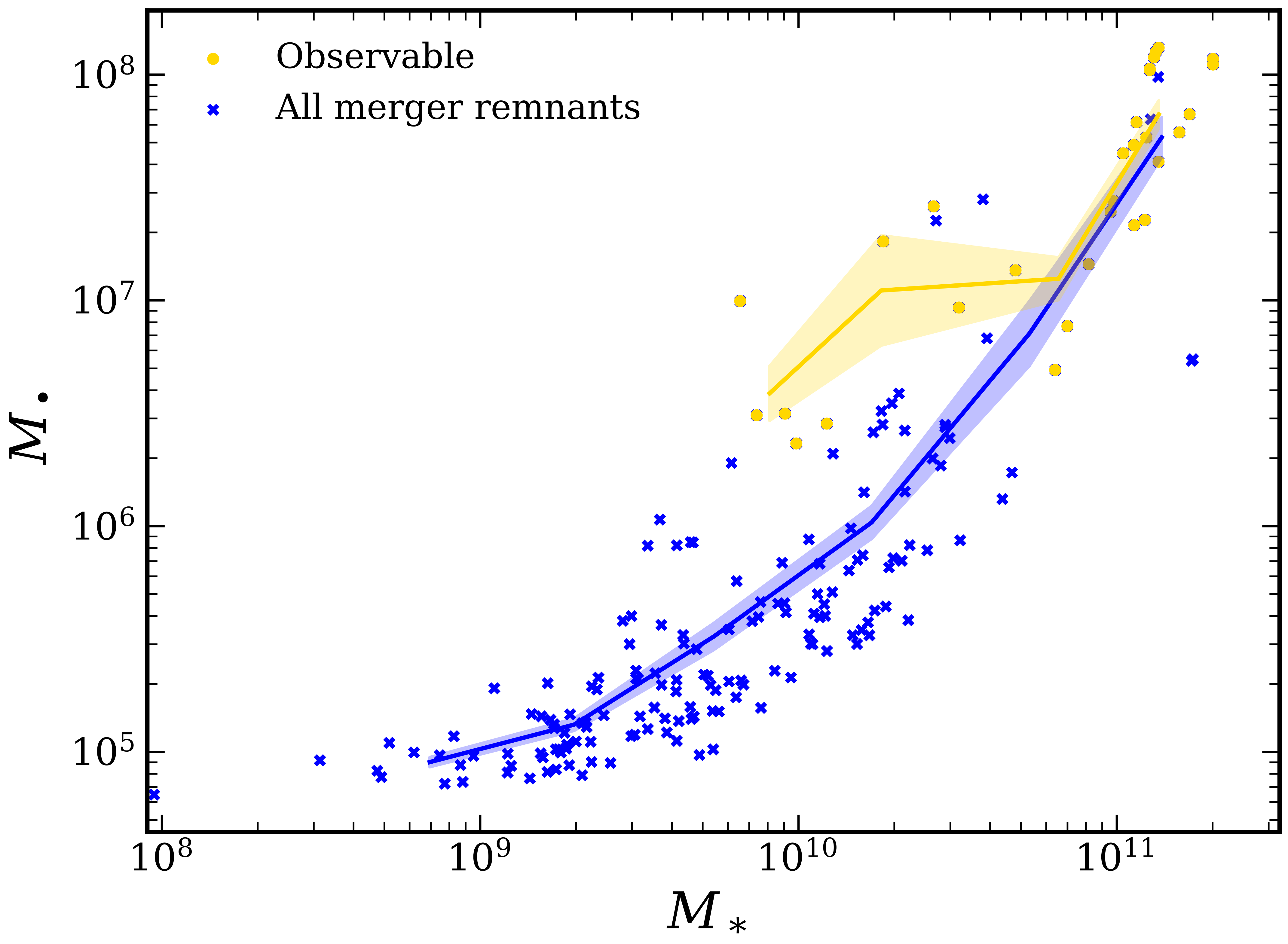

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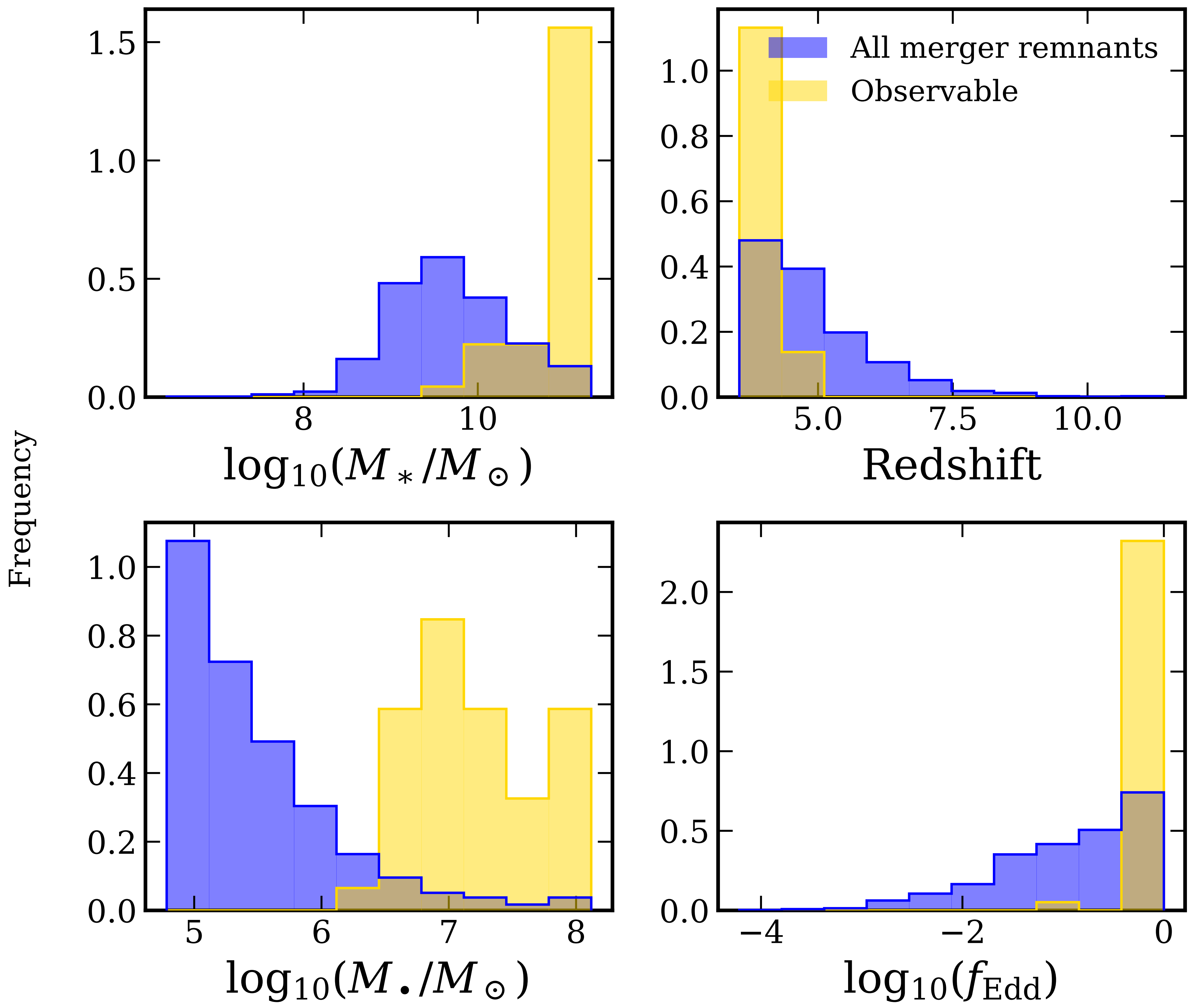

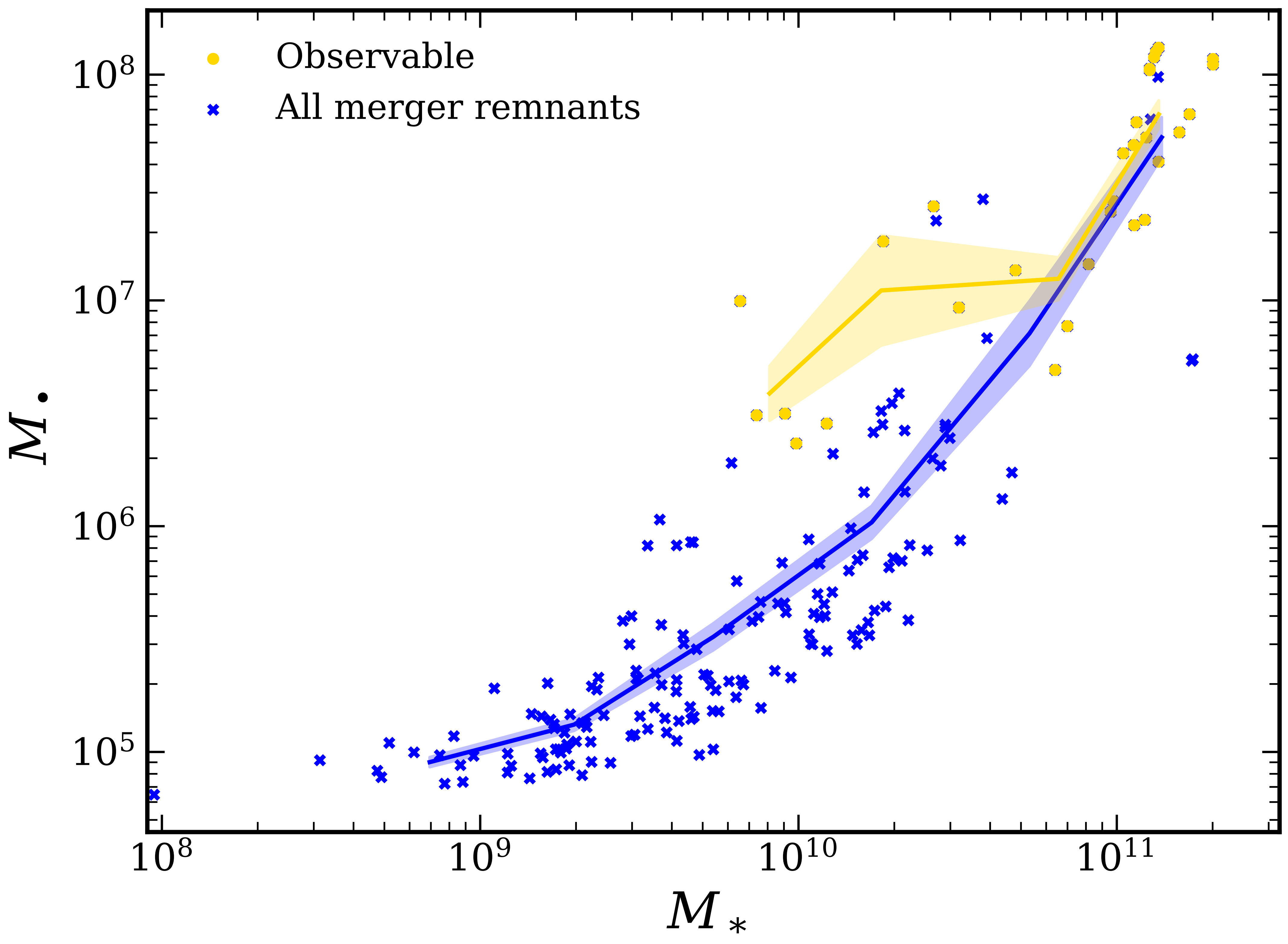

- **Observable mergers have higher BH and galaxy mass and higher accretion rate and occur at lower redshift**
- **Observable merger remnants are overmassive at fixed galaxy mass**

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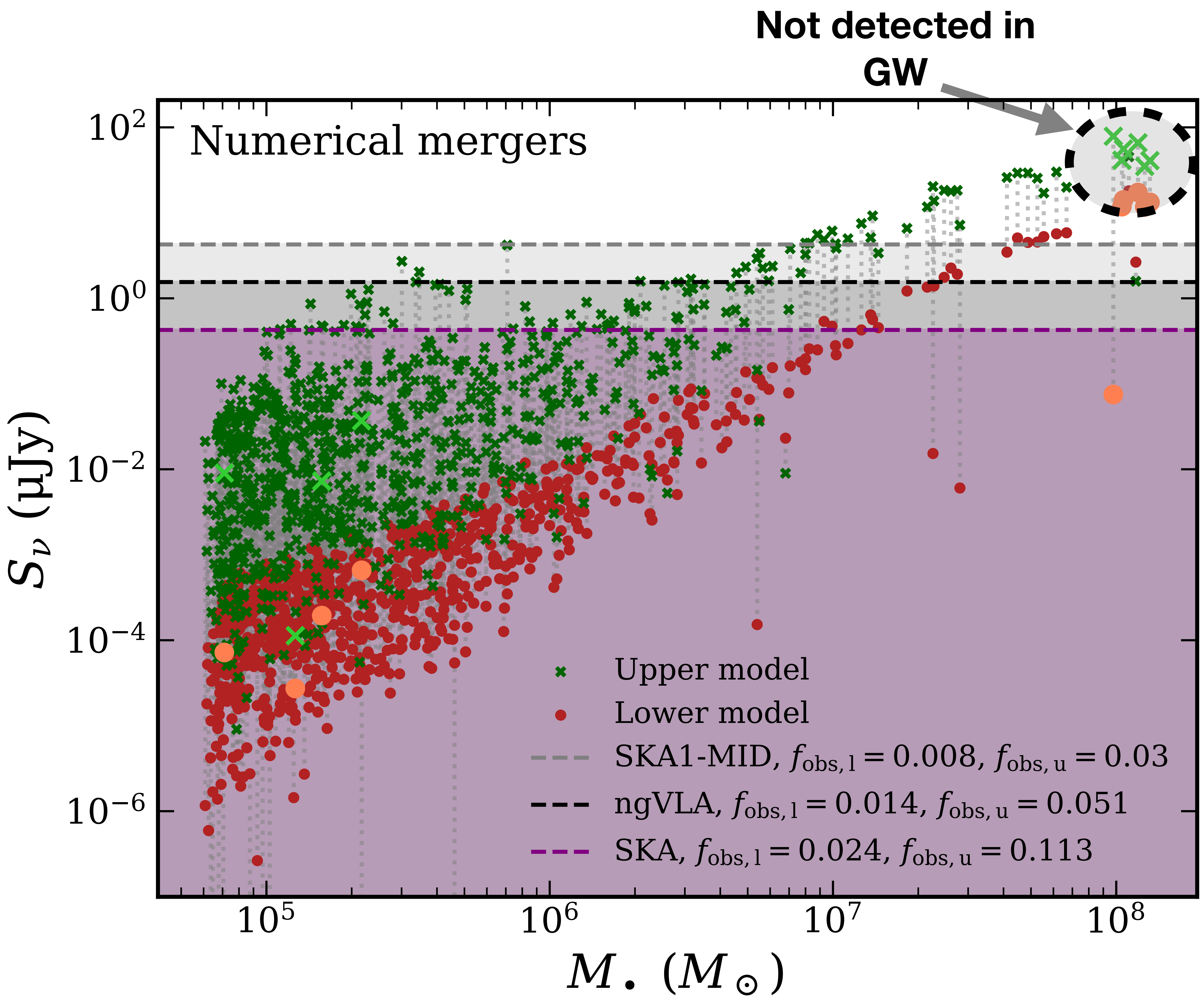
Radio observability of MBH mergers



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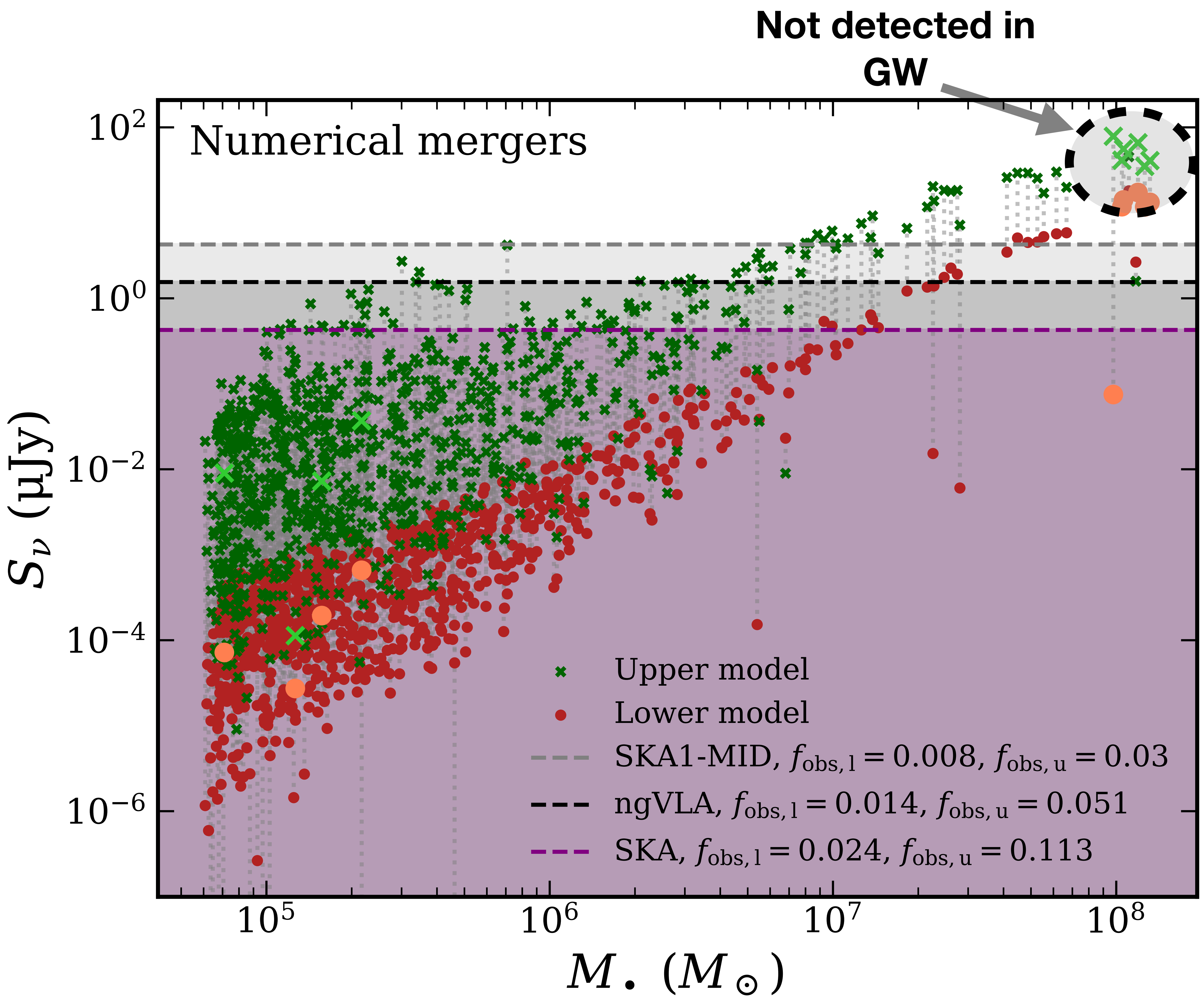
- **About $1 - 10\,\%$ of merger remnants can be detected in the radio** by future instruments, dependent on the model and instrument assumed.



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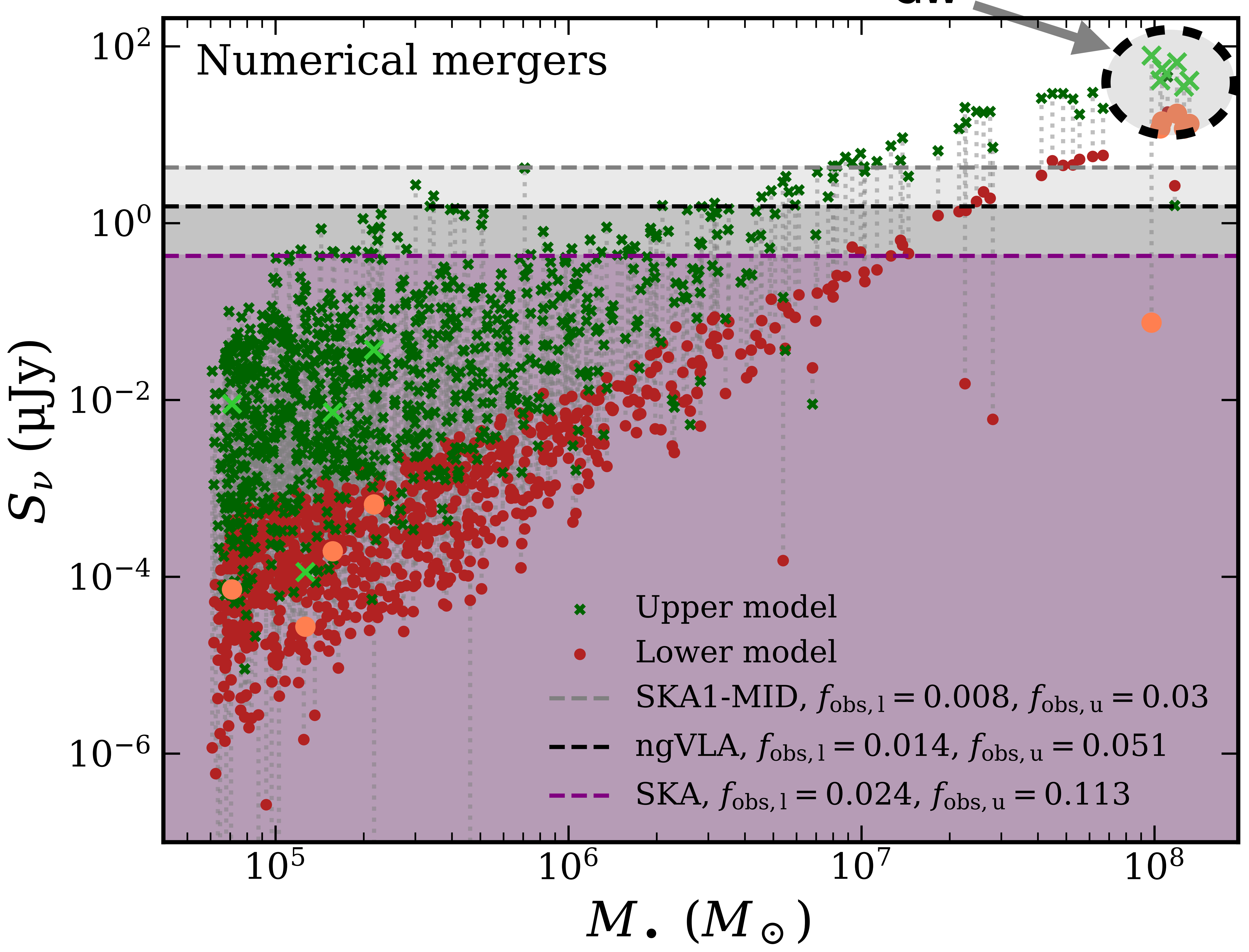
- For the pessimistic model (core luminosity modelled with empirical relation), only BHs with $M_\bullet > 10^7\,M_\odot$ can be observed

Not detected in GW



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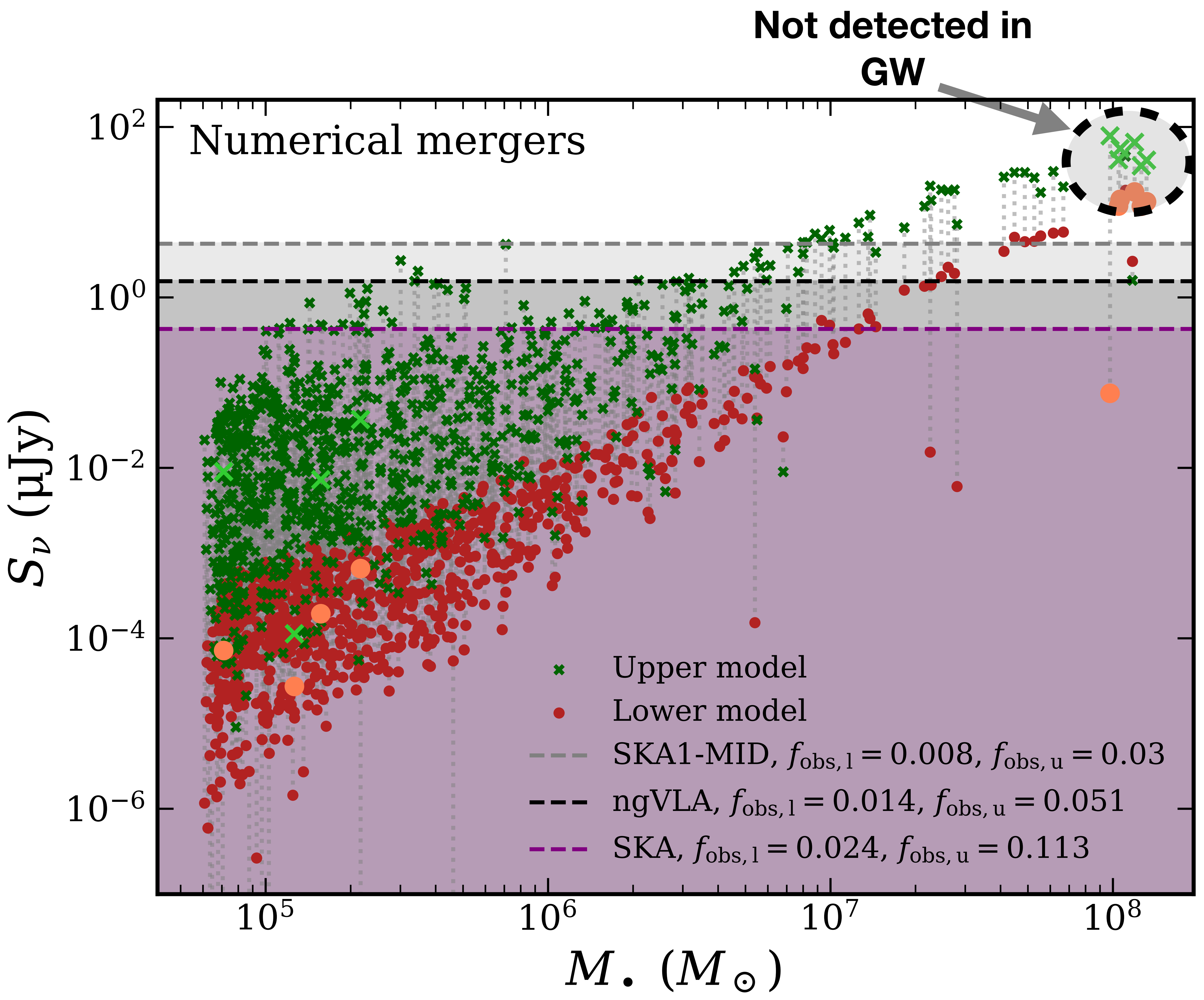
- For the pessimistic model (core luminosity modelled with empirical relation), only BHs with $M_\bullet > 10^7\,M_\odot$ can be observed
- In the following, **we use the pessimistic model and SKA sensitivity**



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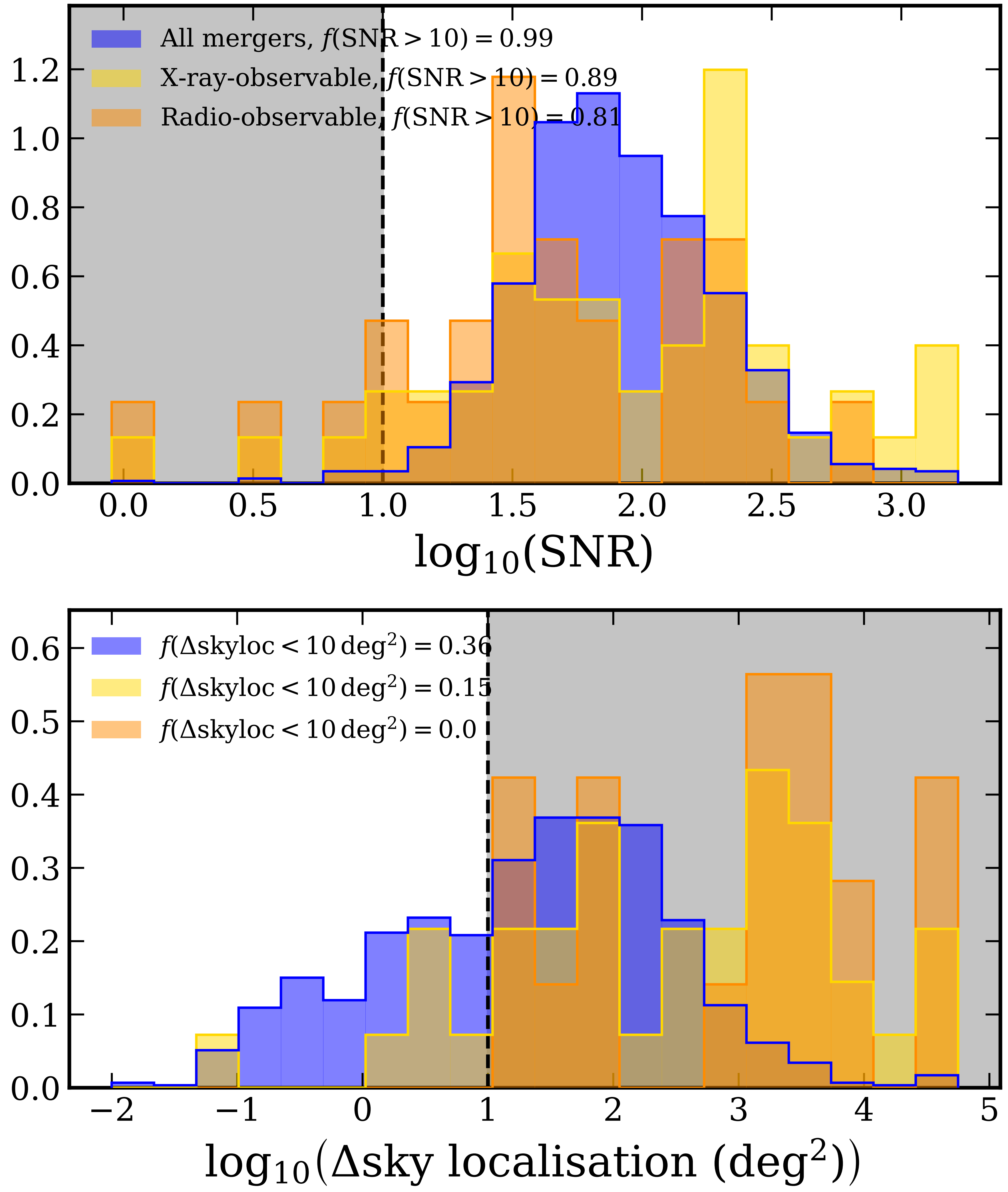
Multimessenger GW+EM observability



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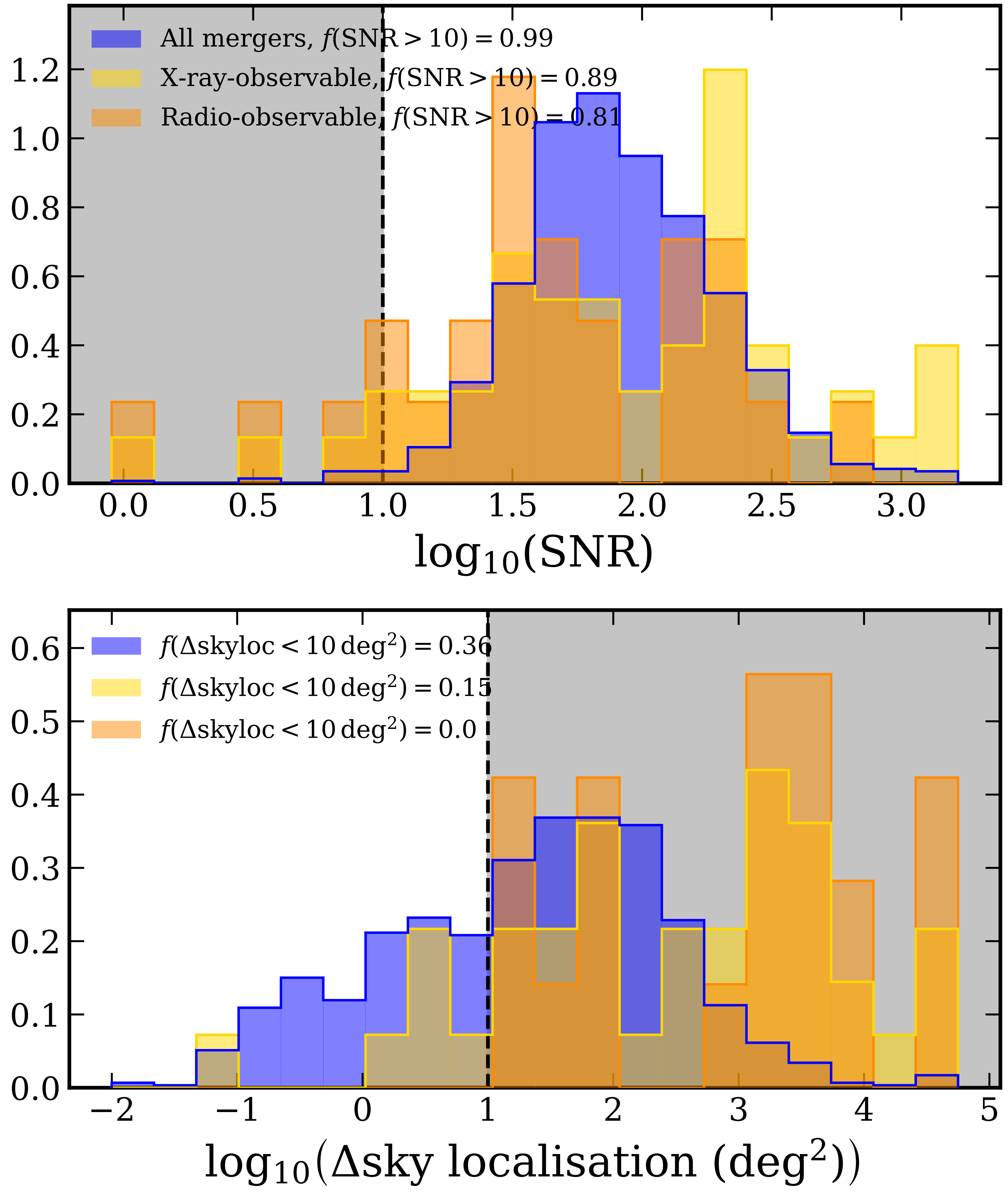
Multimessenger GW+EM observability

- **Most X-ray- and radio-observable mergers are also detectable with LISA in the GWs**



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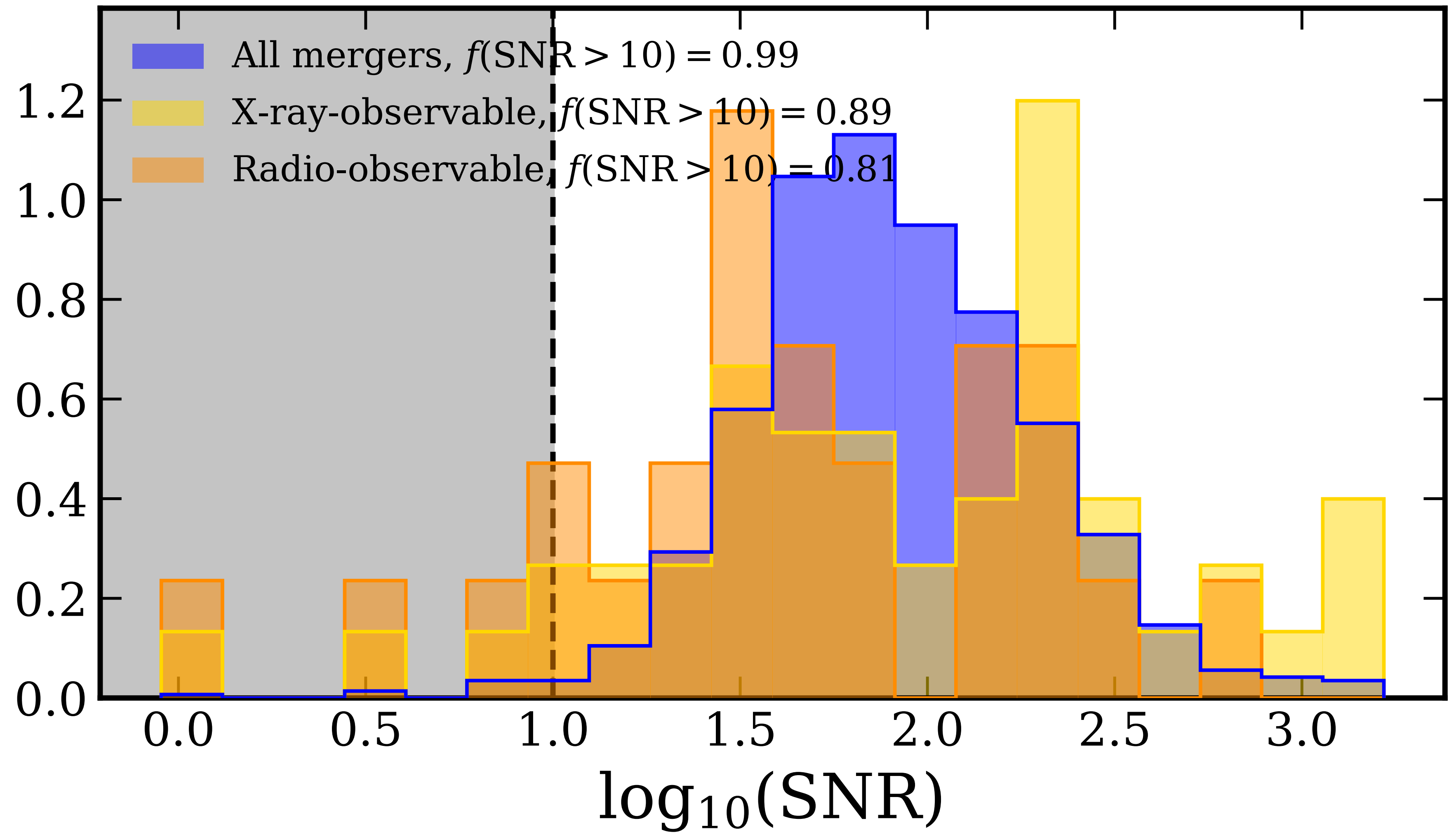
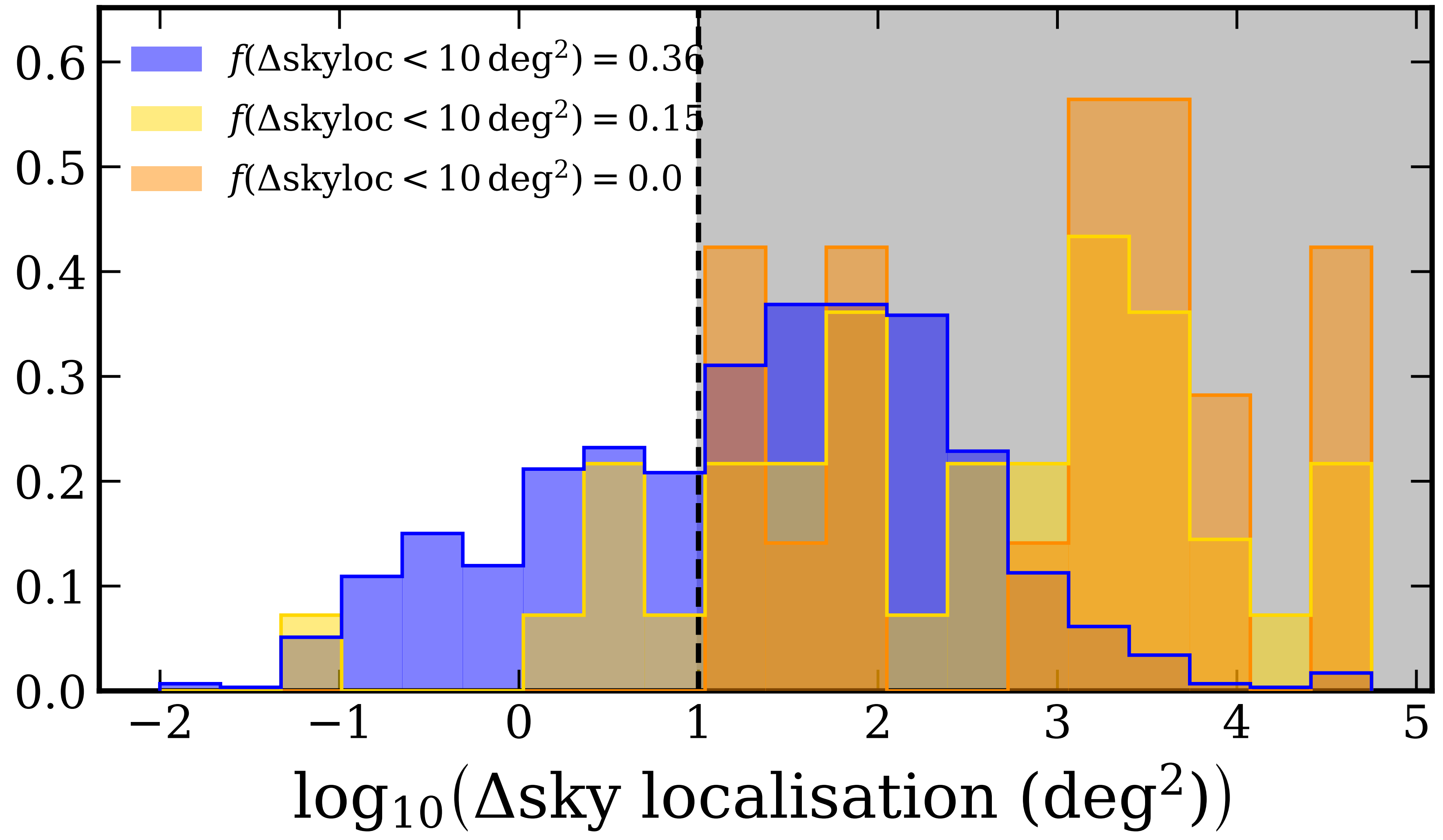
Multimessenger GW+EM observability

- **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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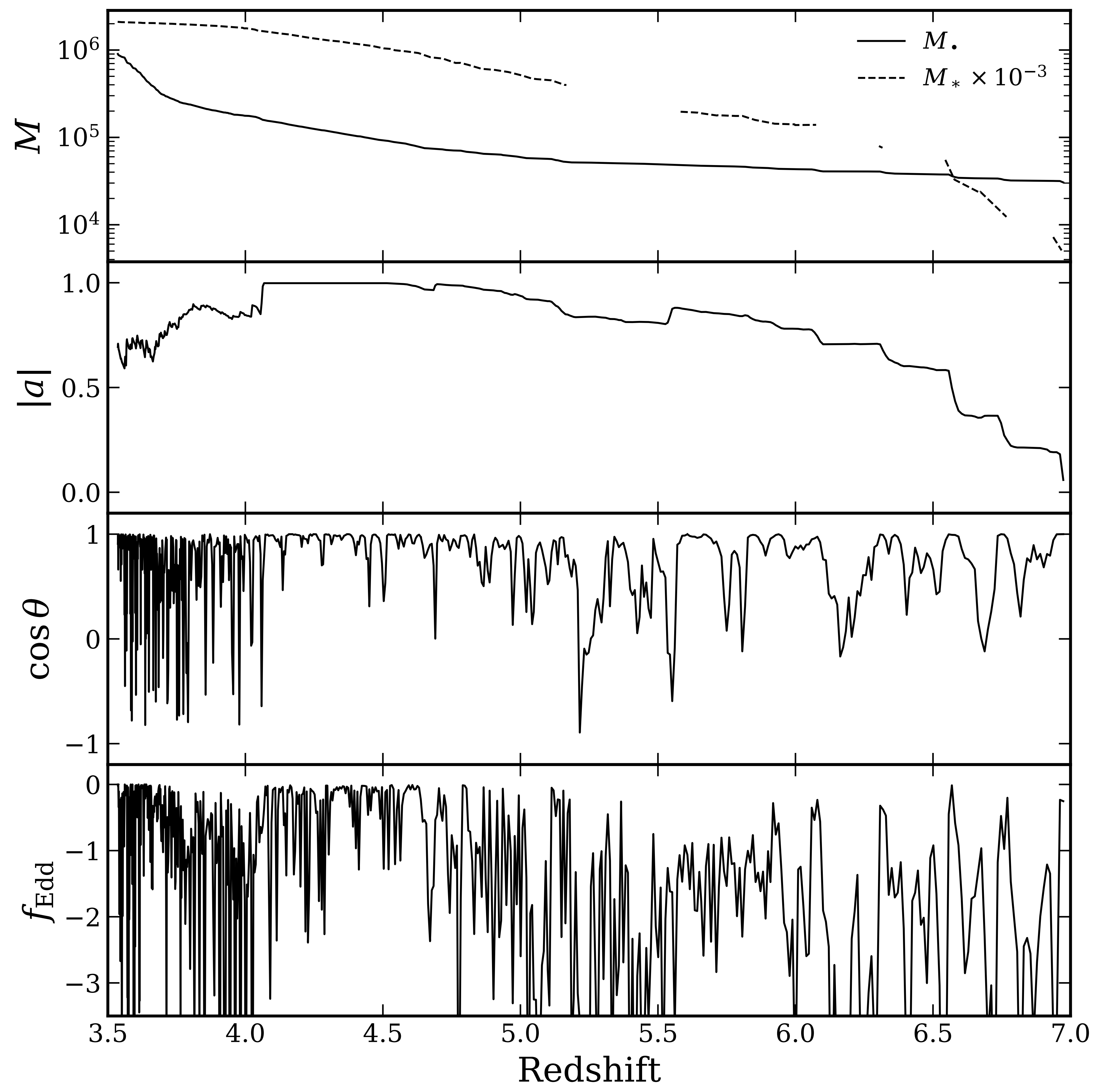
Summary

- We study the MBH merger population from a cosmological simulation and study its GW and EM emission and detectability.
- MBH mergers tend to be more massive and reside in more massive galaxies than the global population.
- Most of our MBH mergers can be detected with GWs by LISA, but the sky localisation error is generally suboptimal.
- 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 and radio. A fraction of transients is observable in the X-rays.
- The observable merger sample is biased toward high MBH and galaxy masses, accretion rates, and low redshifts.

The life of a MBH in Obelisk



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

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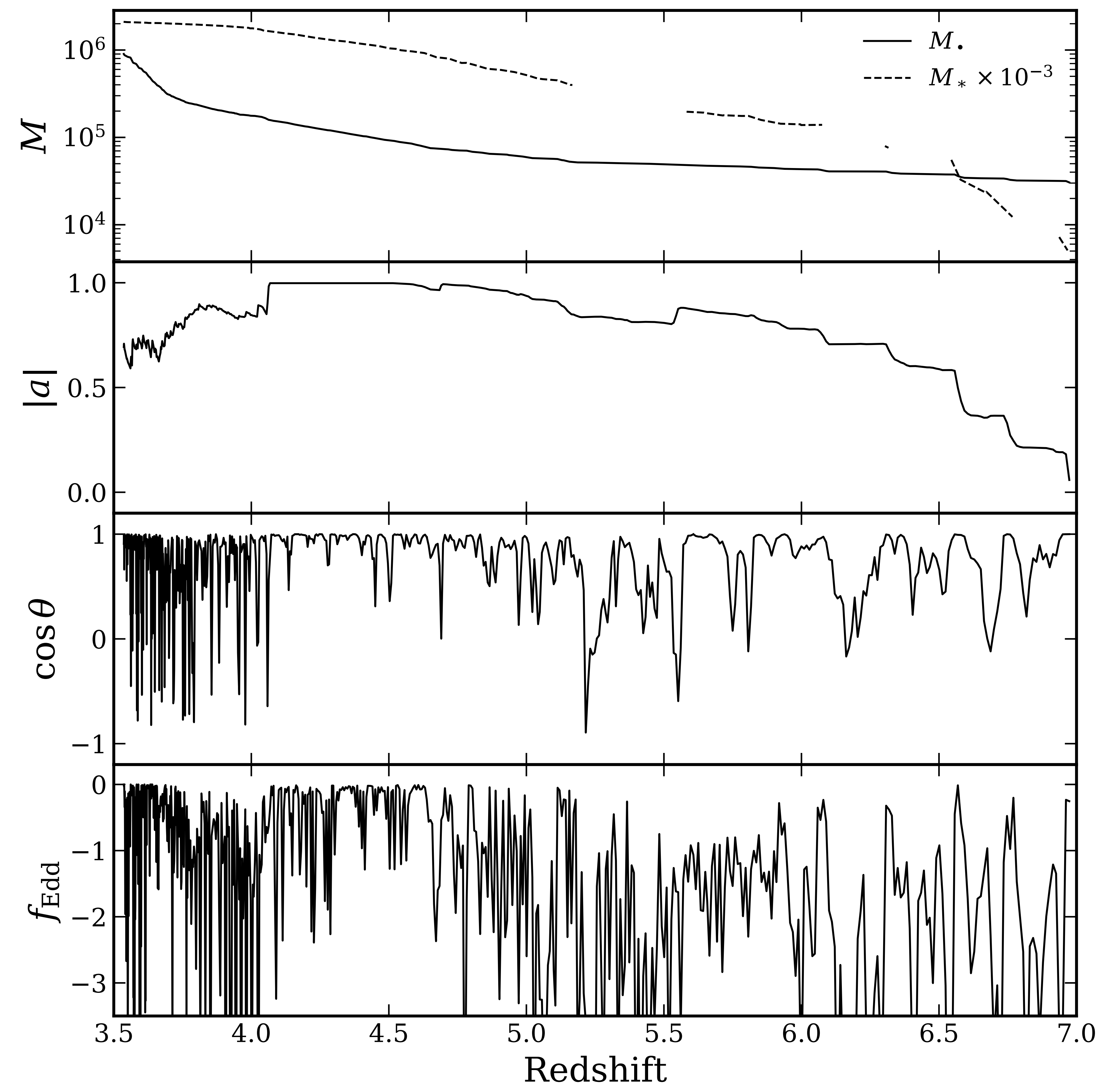
The life of a MBH in Obelisk

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



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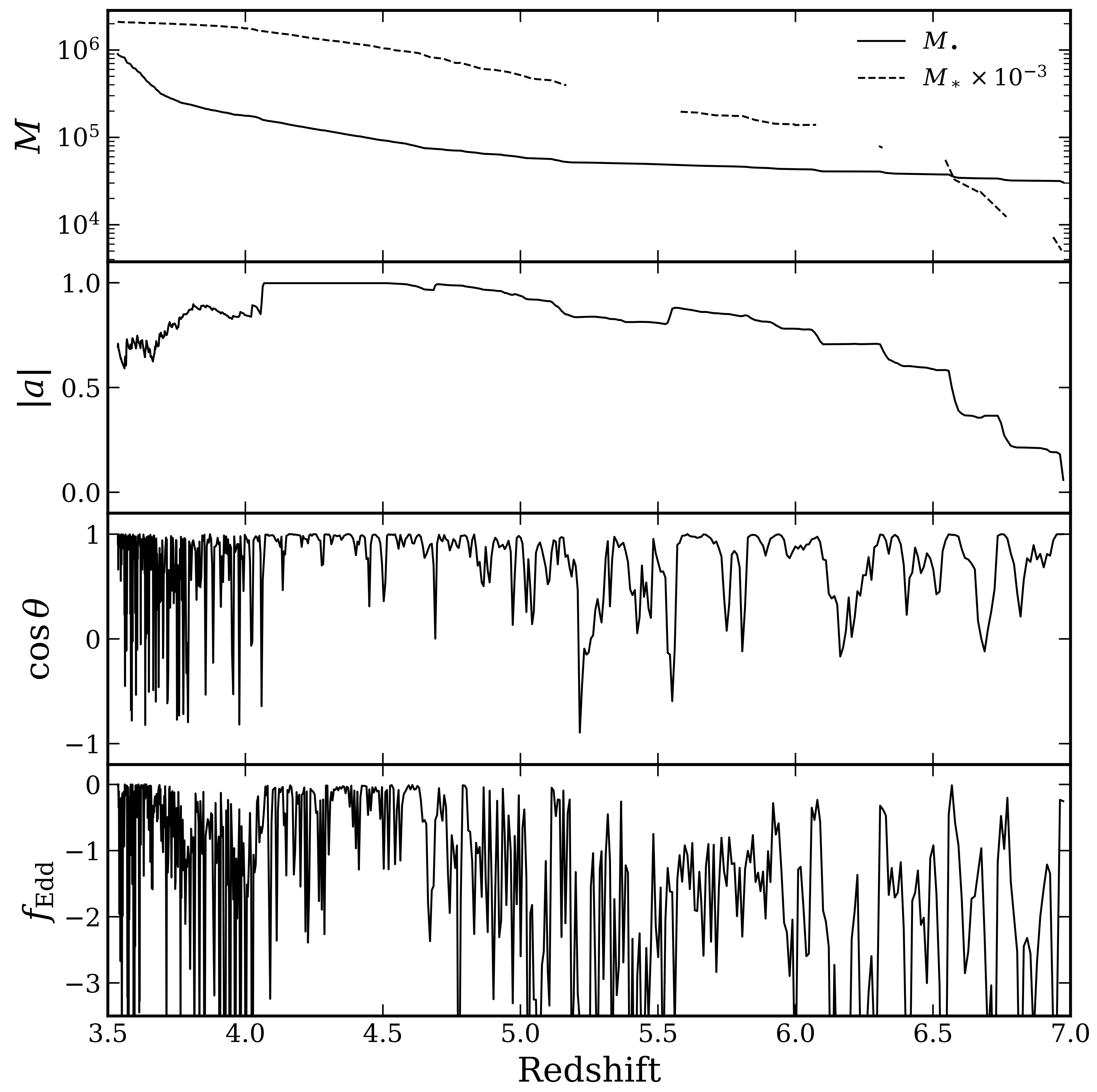
- Low-mass galaxies ($M_* \lesssim 10^9\, M_\odot$): galaxy has chaotic dynamics, no well-defined centre → **chaotic MBH accretion, slow mass and spin growth**



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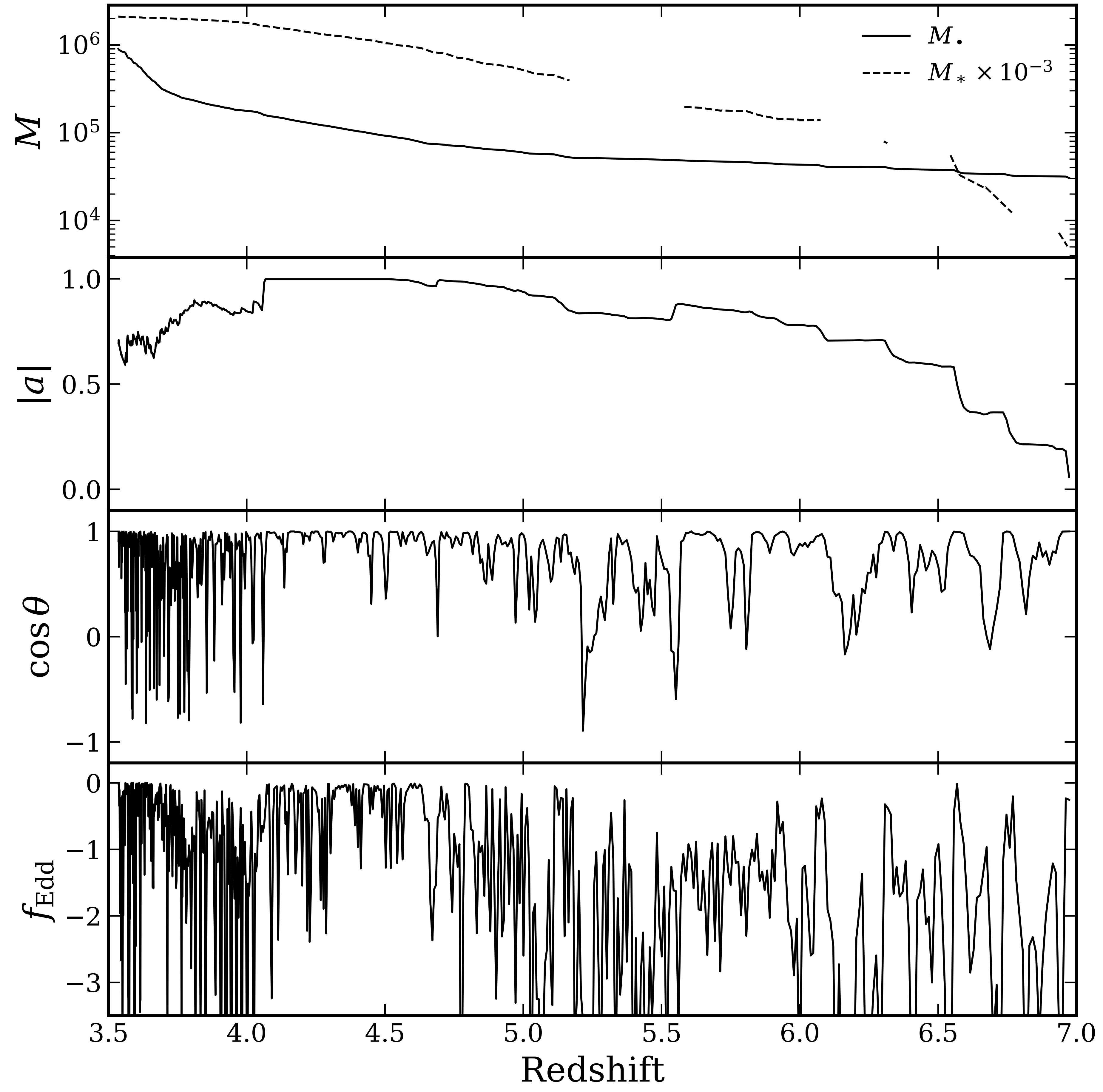

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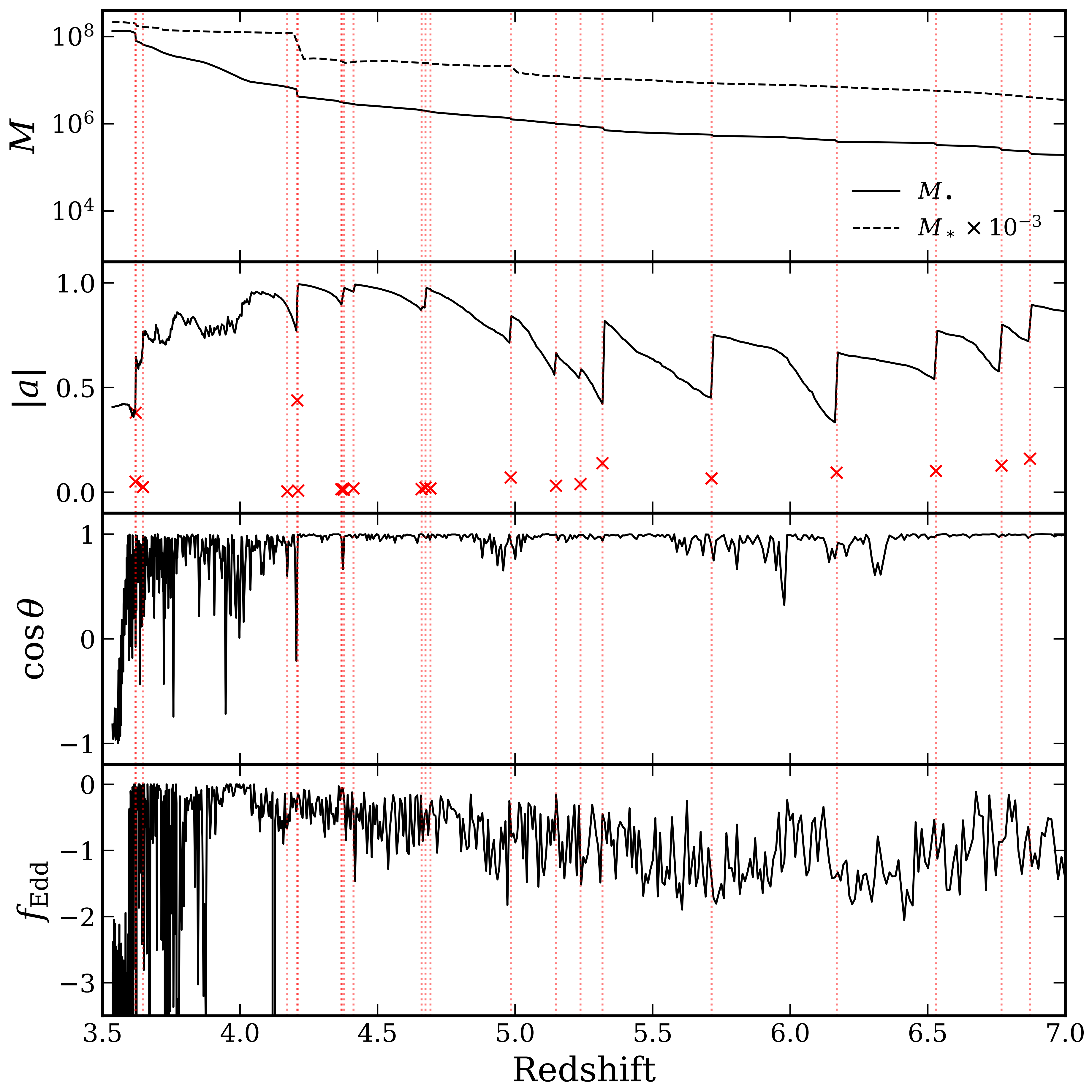

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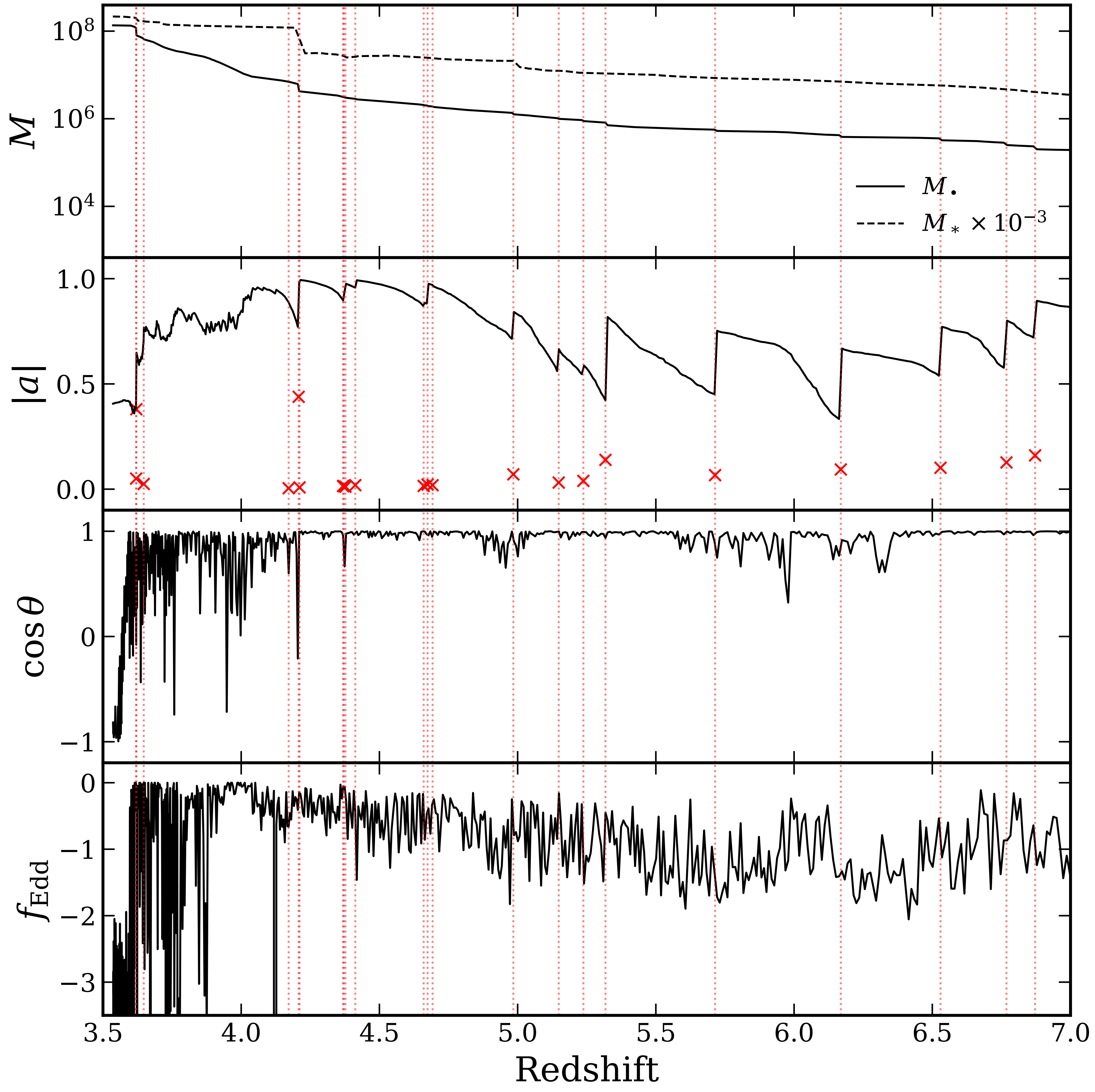

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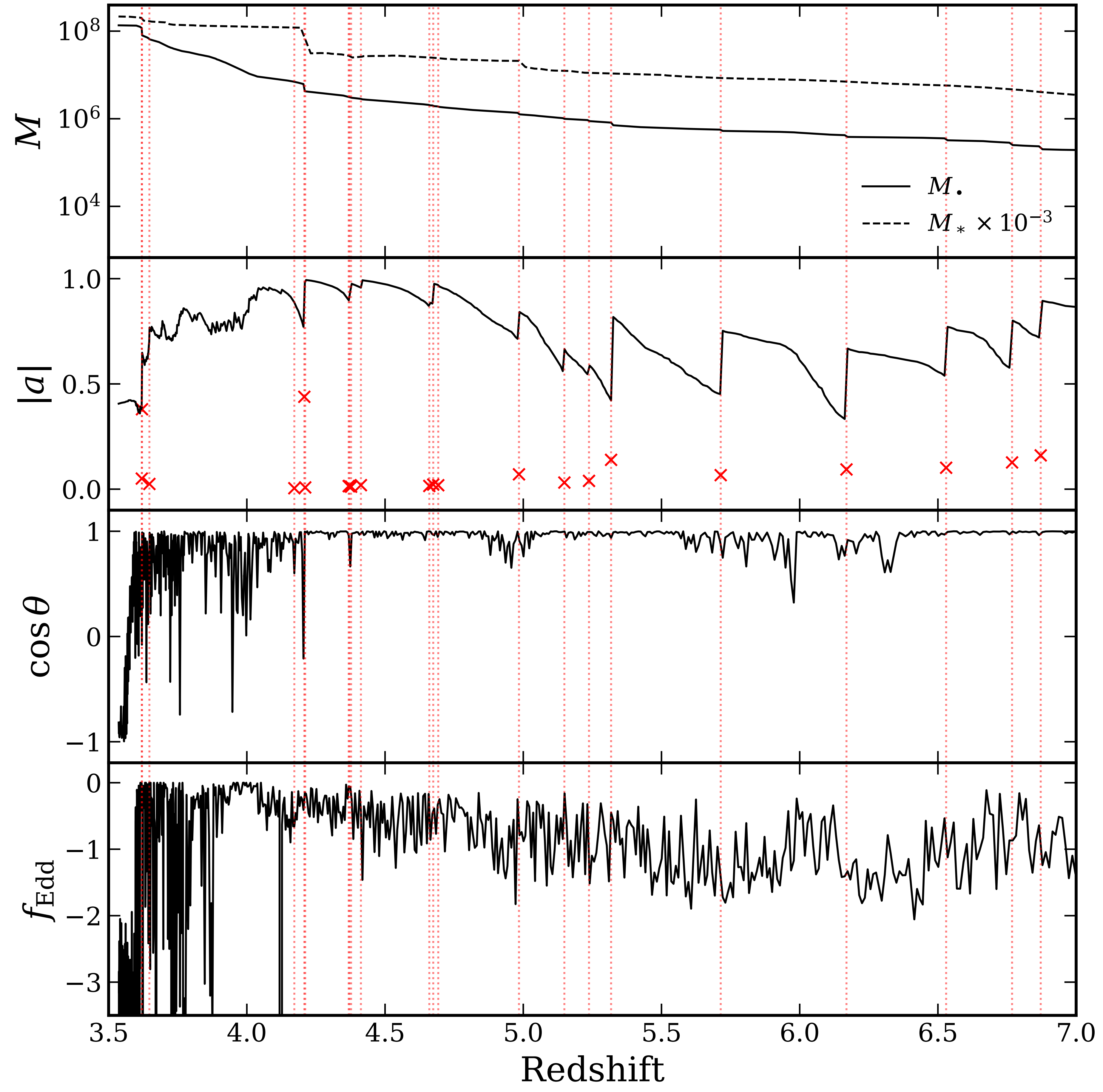
Mergers tend to decrease the MBH spin



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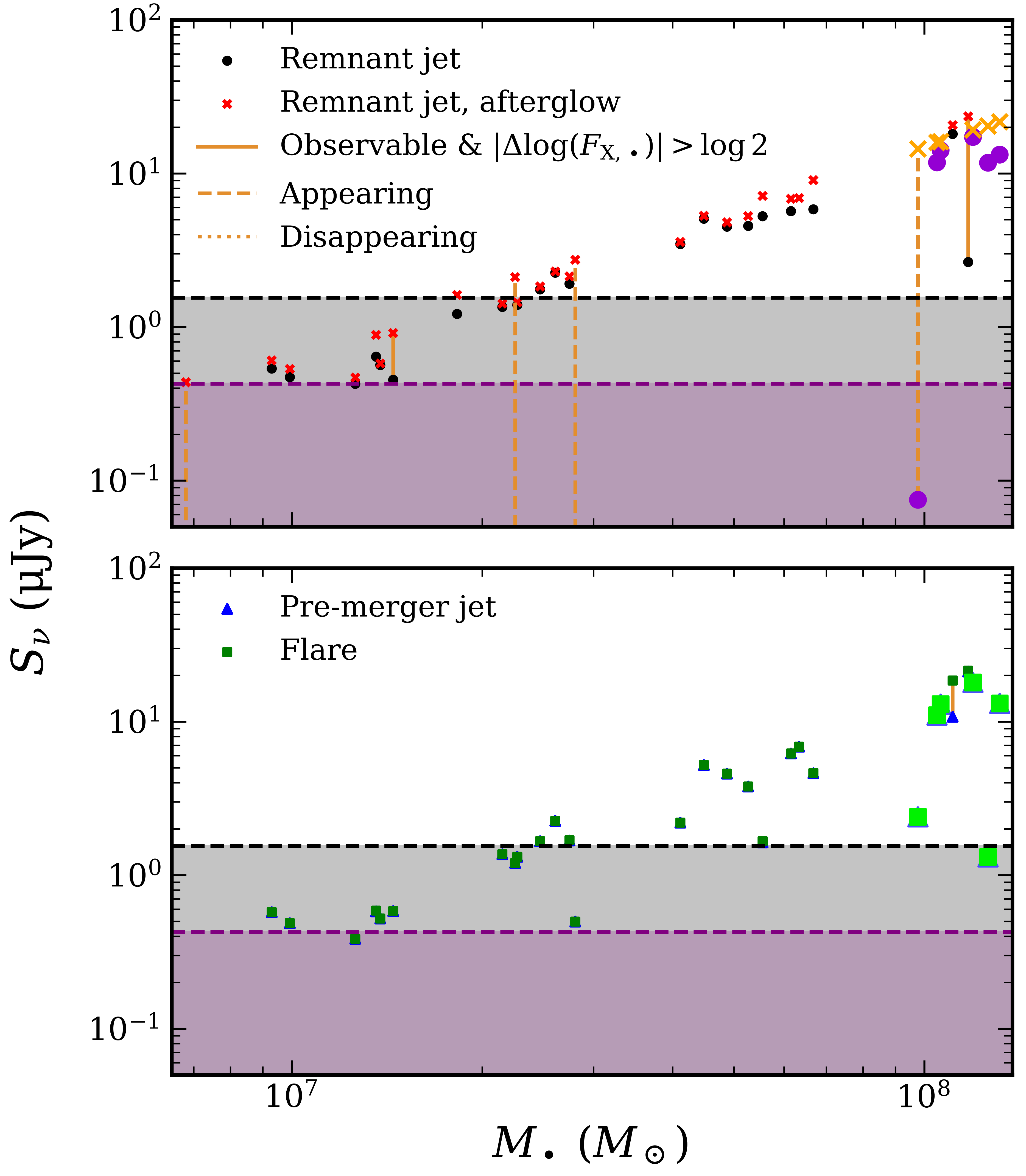
Radio transients



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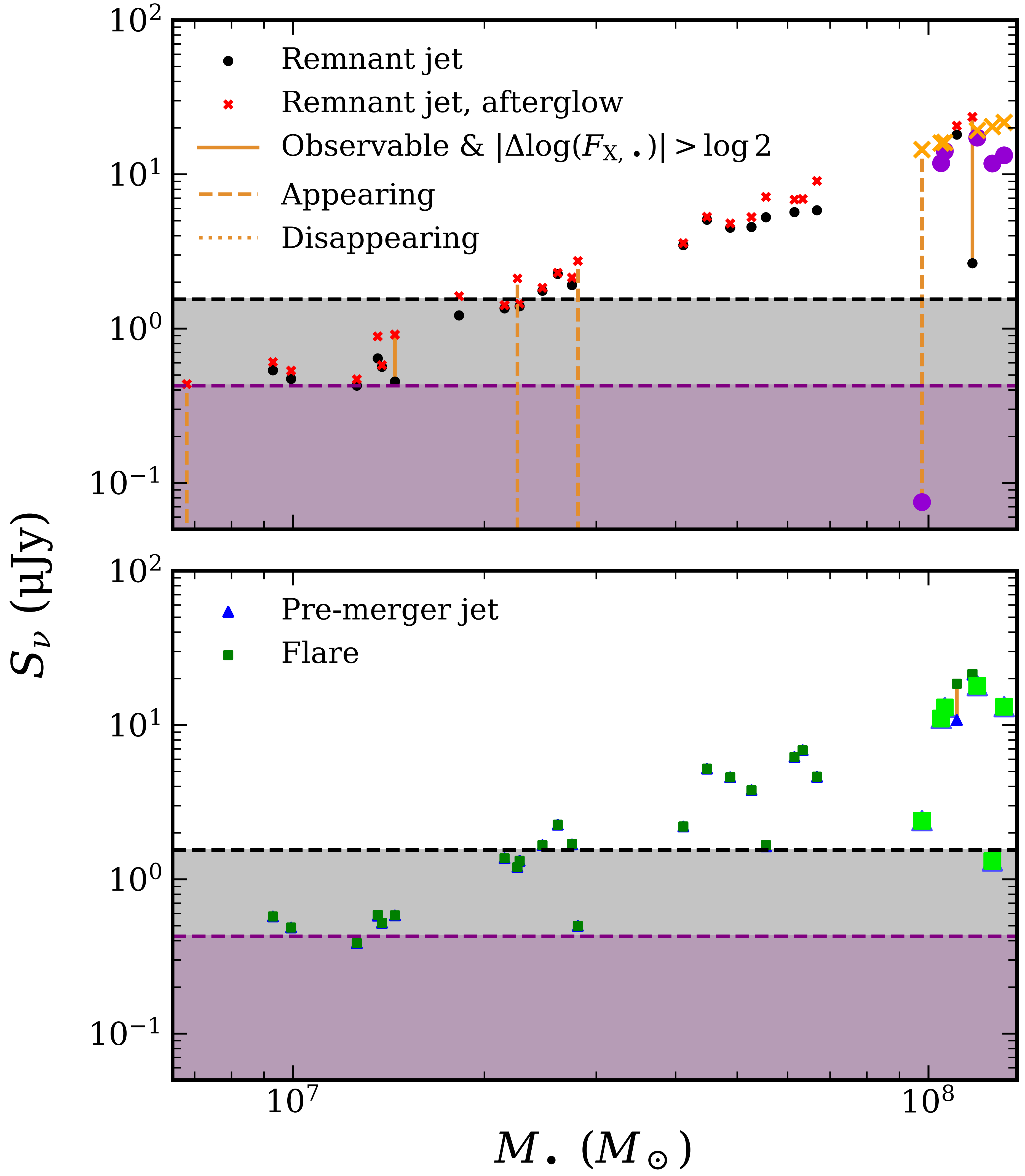
Radio transients

- **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).**



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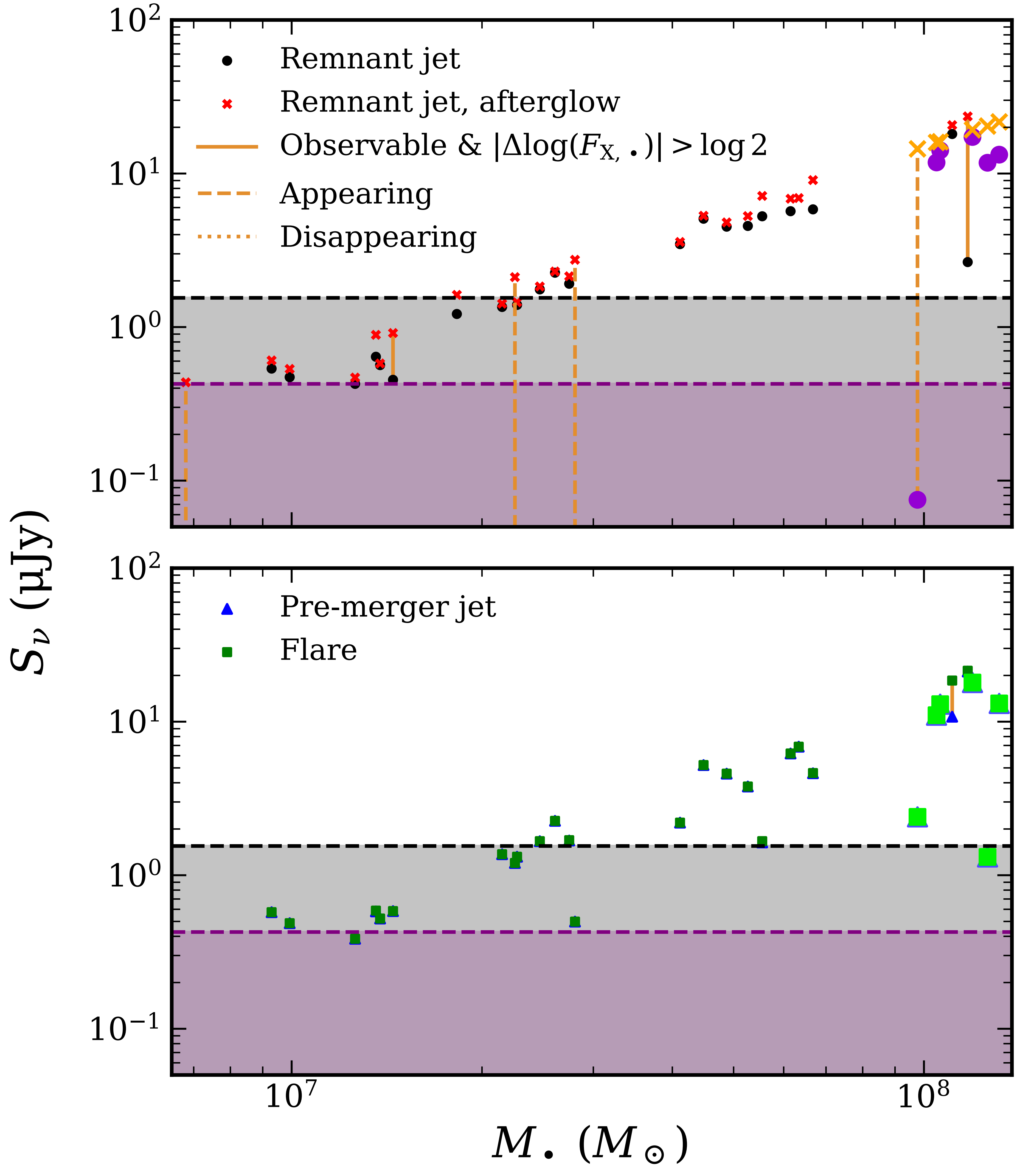

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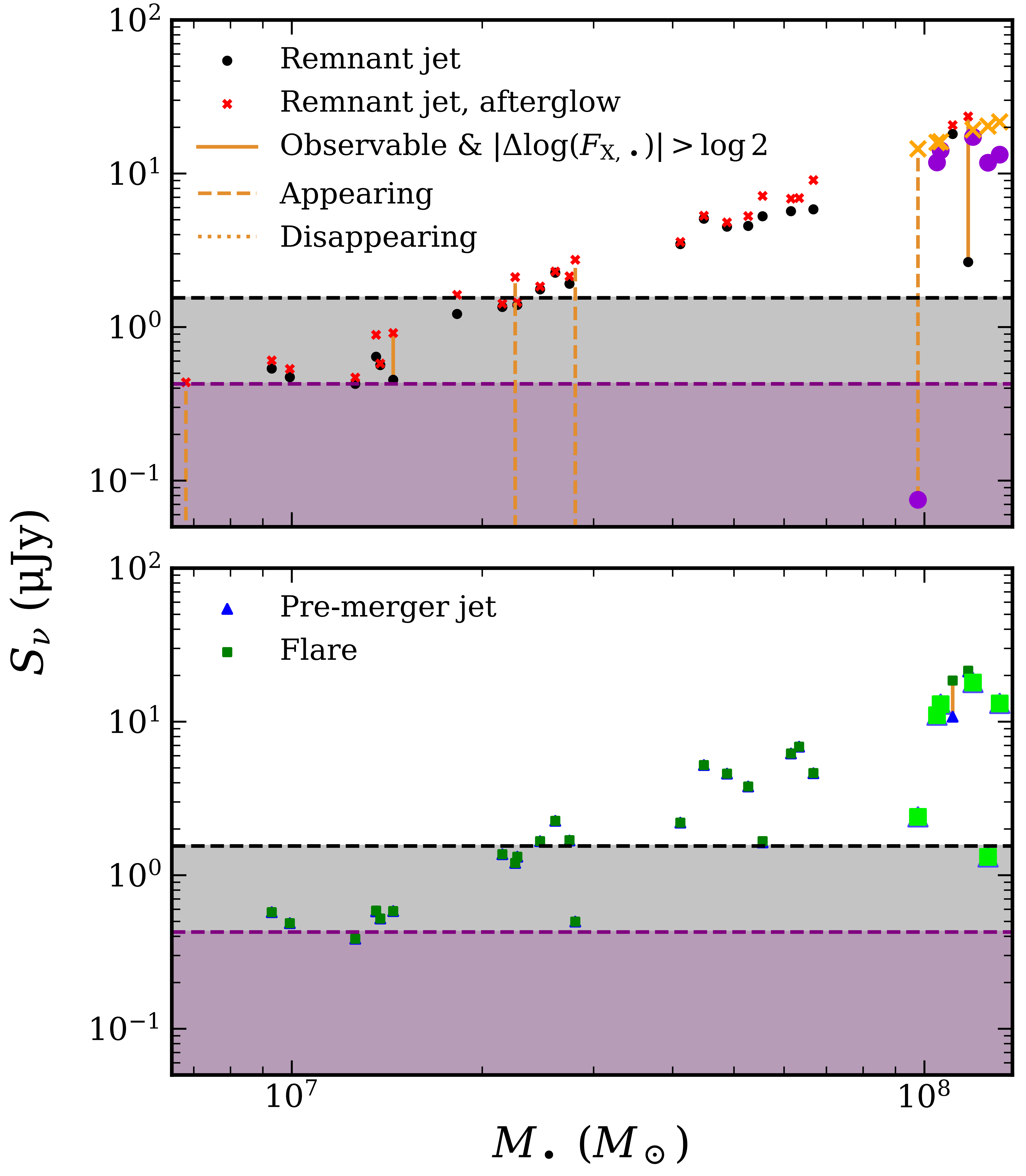
  - **Few sources are bright enough to be observable**



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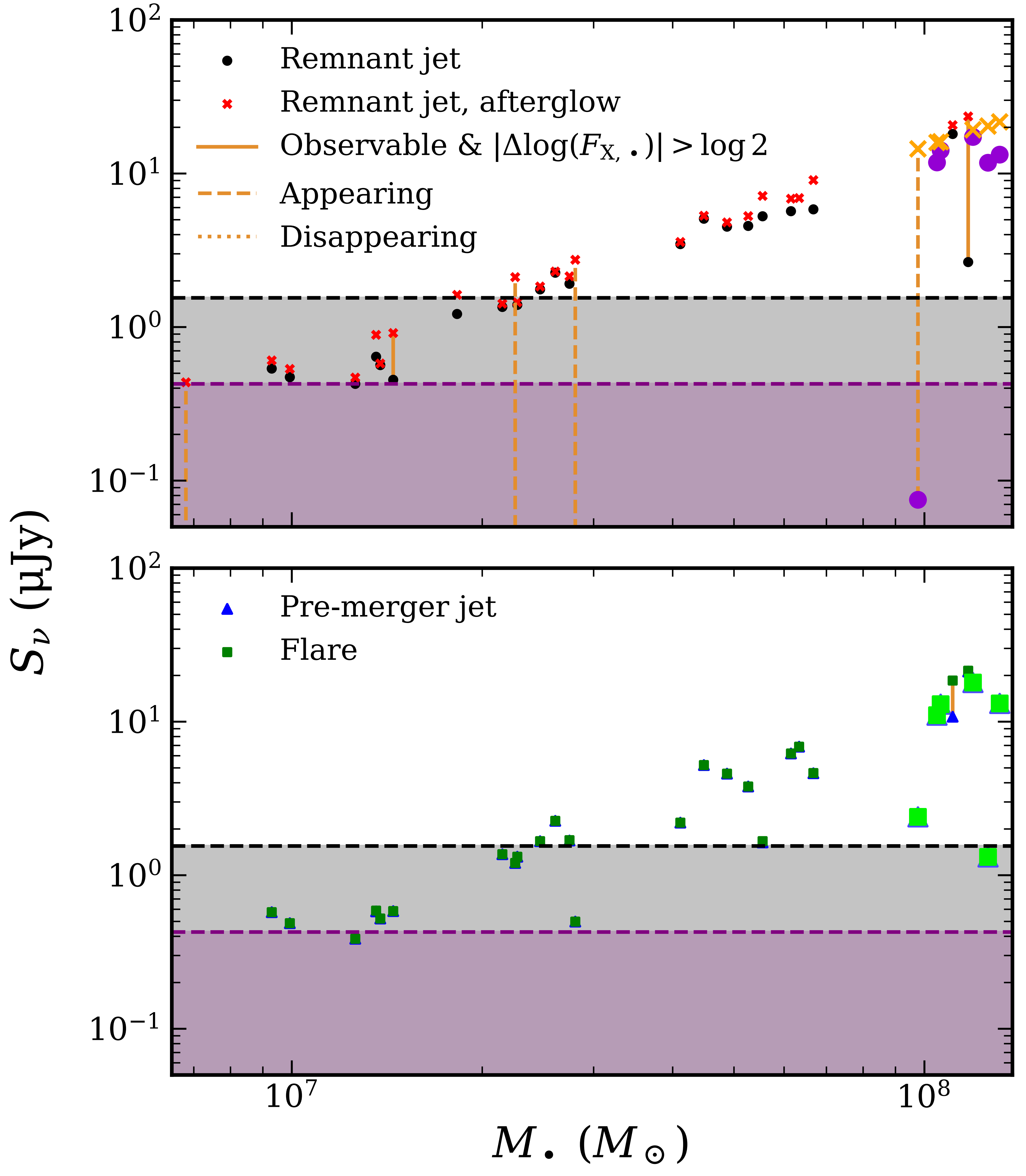
- **Very few sources have EM counterparts:**

  - **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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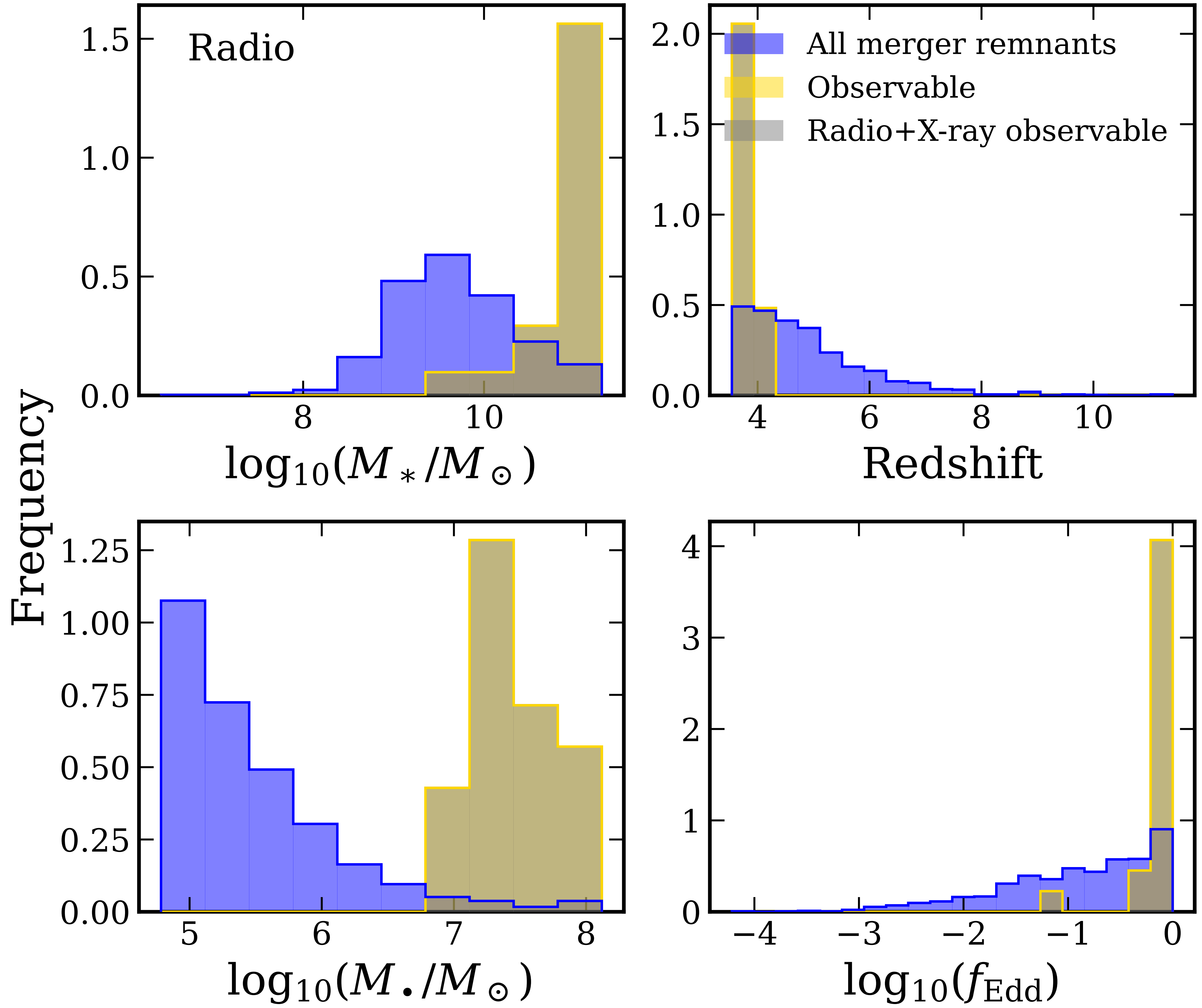
Biases of the radio-observable MBH mergers



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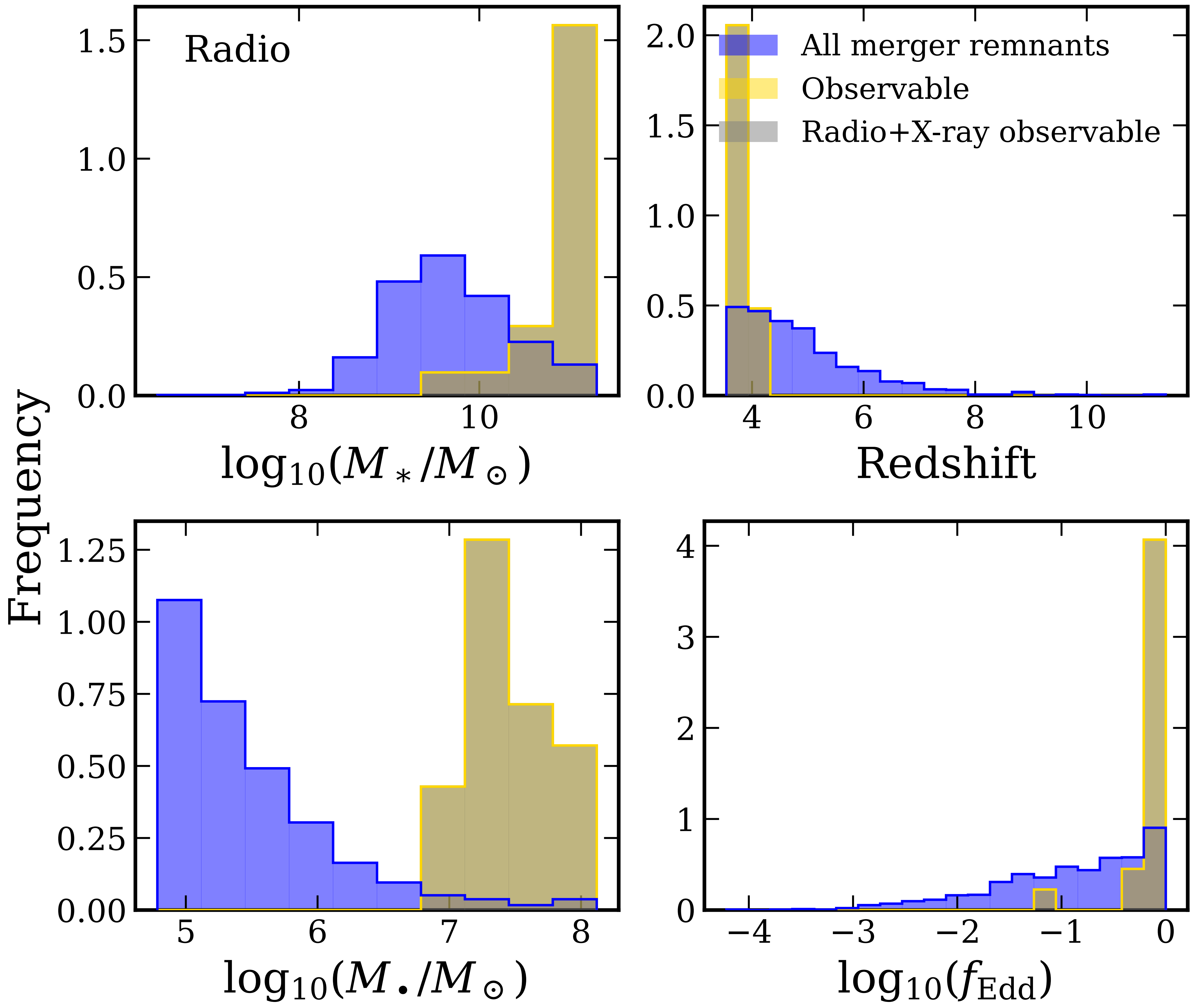
Biases of the radio-observable MBH mergers

- As in the X-rays, **radio-observable mergers have higher BH, galaxy mass and accretion rate and occur at lower redshift**



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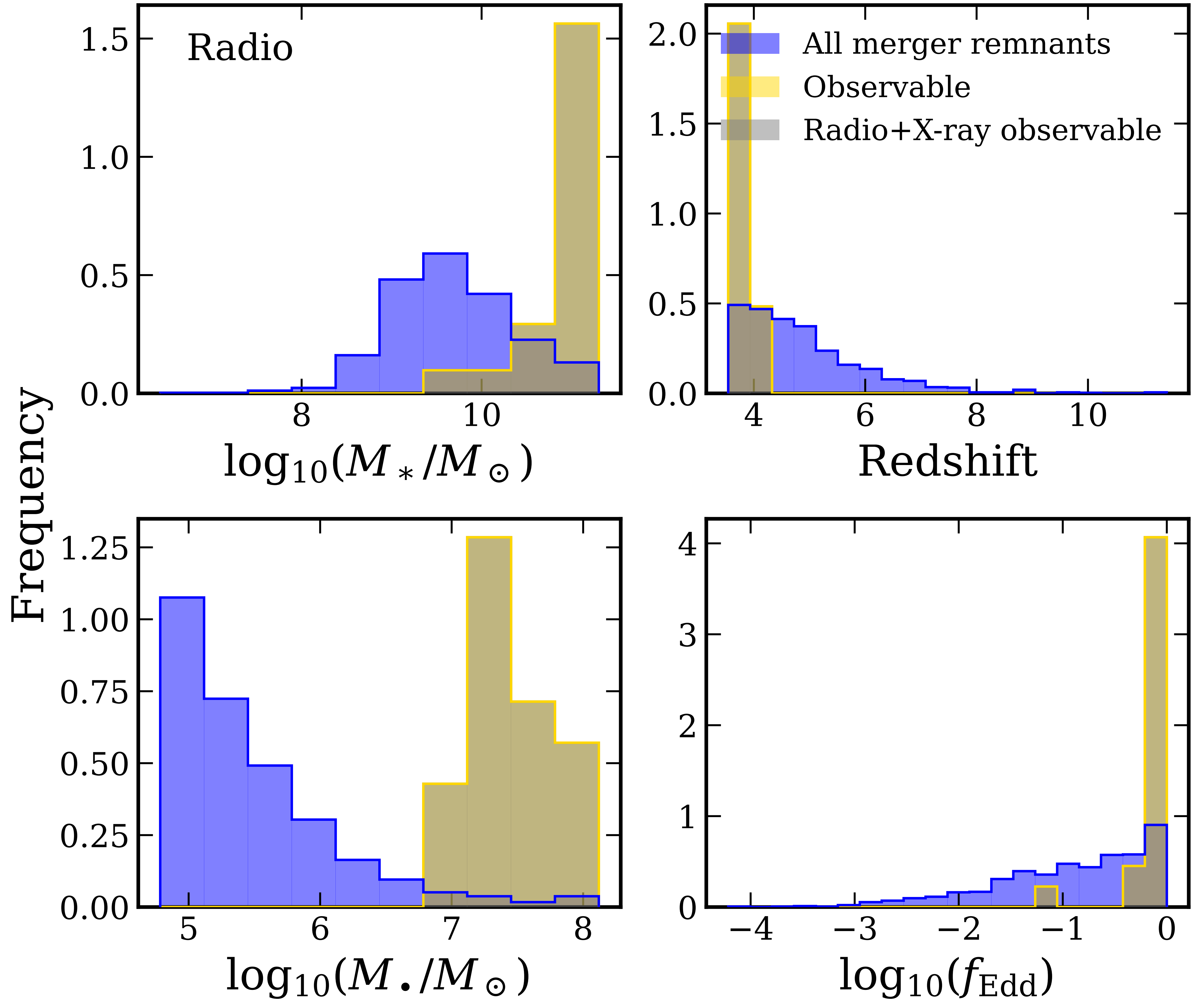

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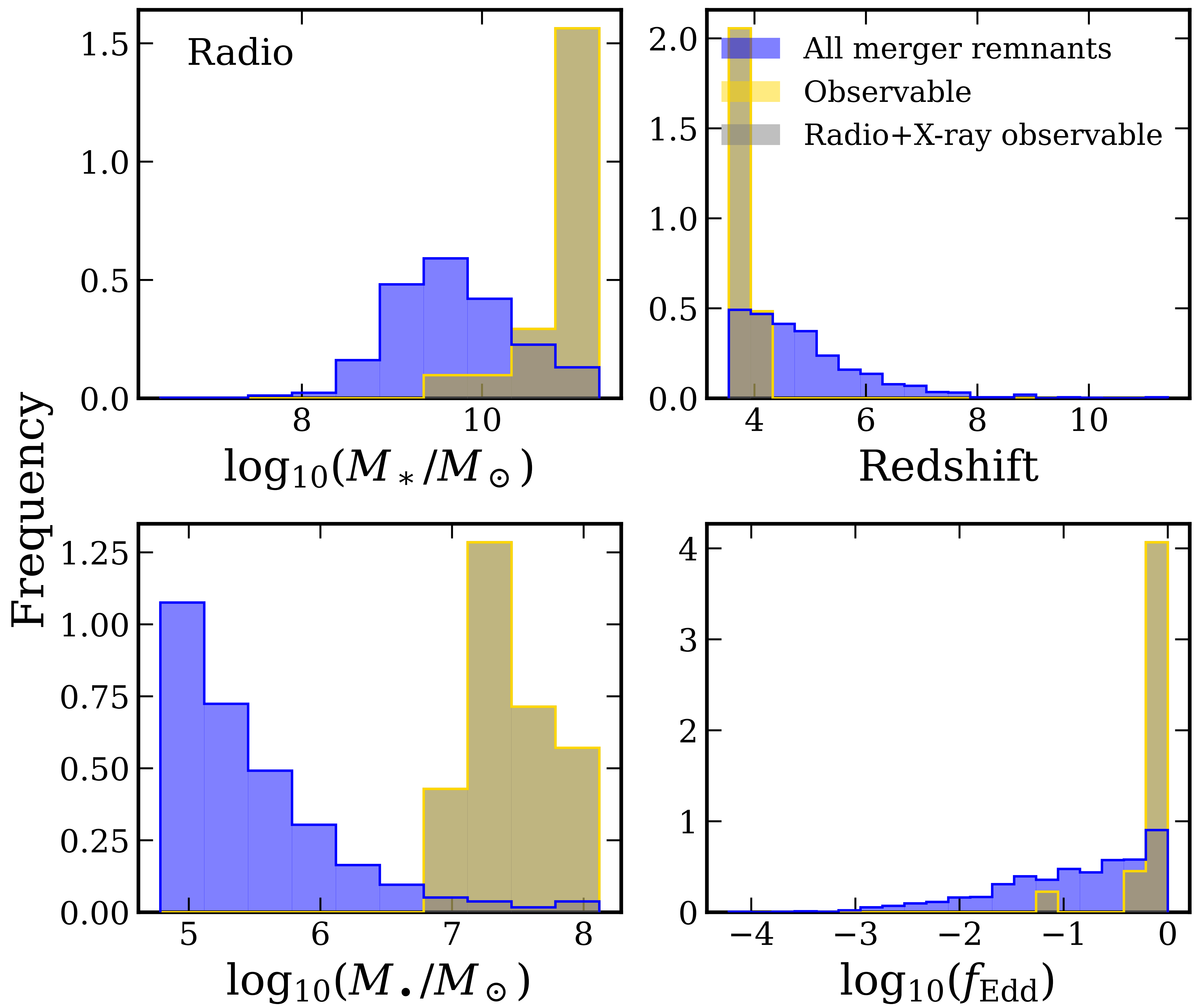
- **Most of radio-observable mergers are also X-ray observable.**
- **Observable merger remnants are overmassive at fixed galaxy mass**



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