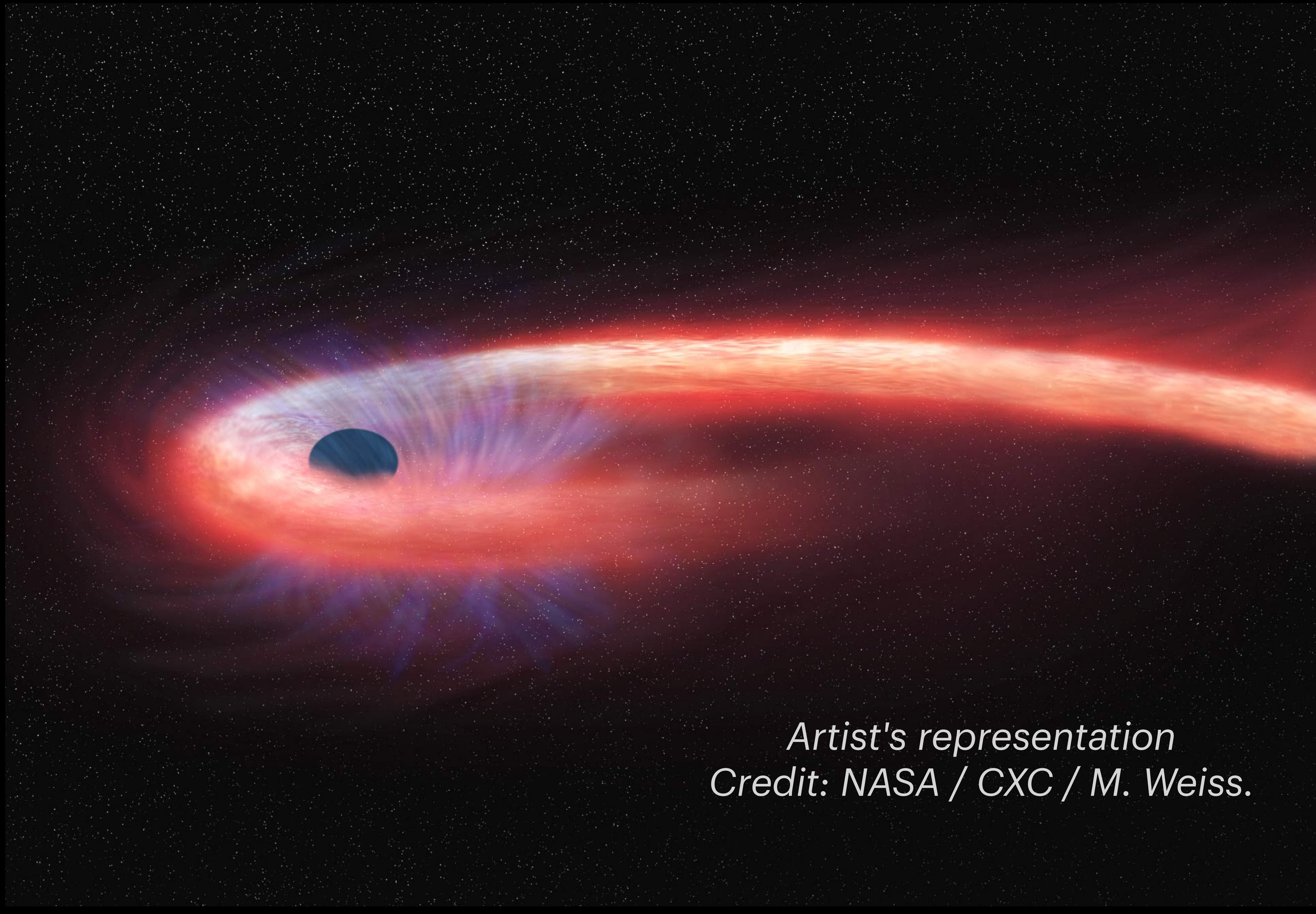
Probing Massive Black Hole Demographics with **Tidal Disruption Events**

Yuhan Yao (UC Berkeley)

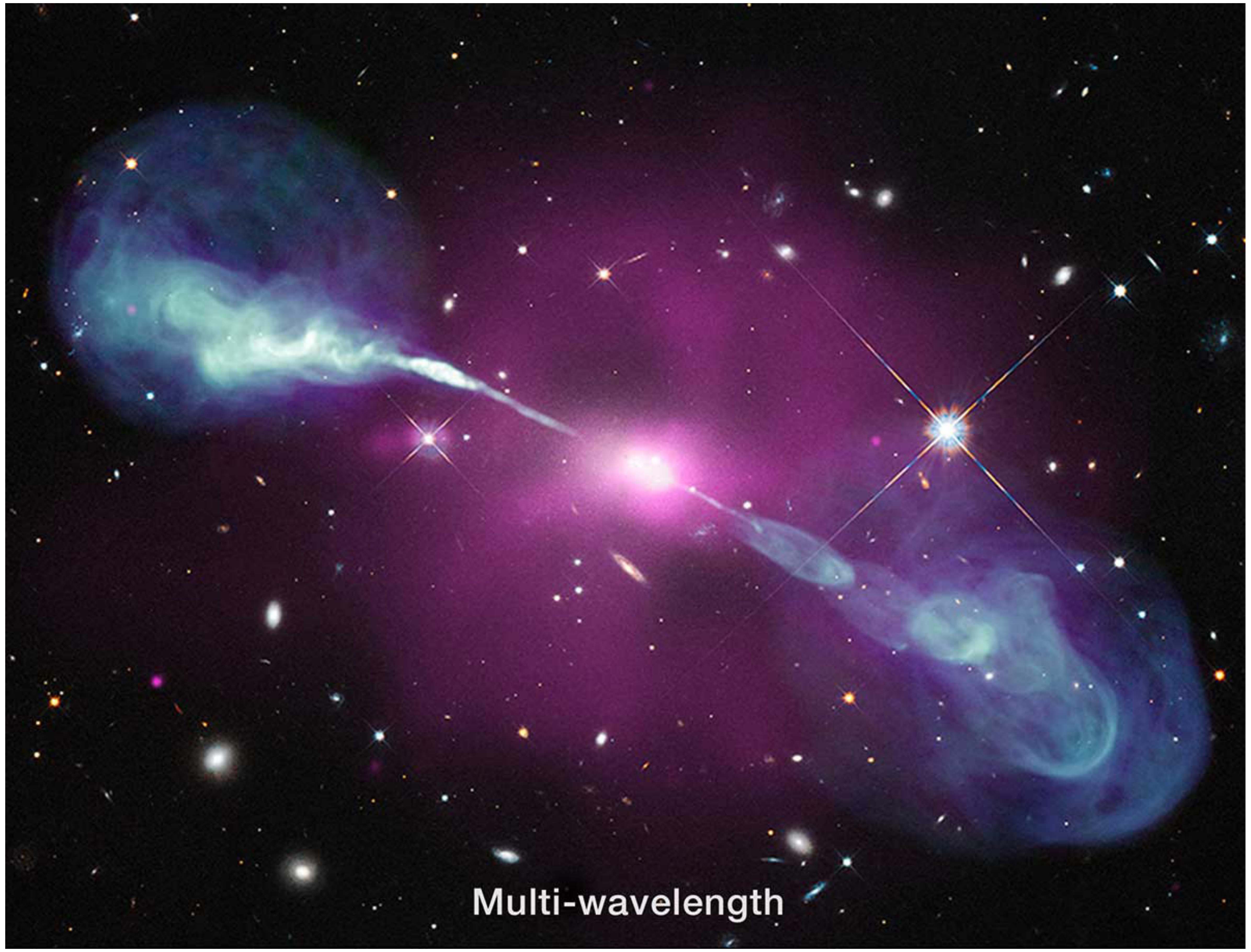


Artist's representation
Credit: NASA / CXC / M. Weiss.

Swift20, 2025 March 27

Massive black holes in our Universe

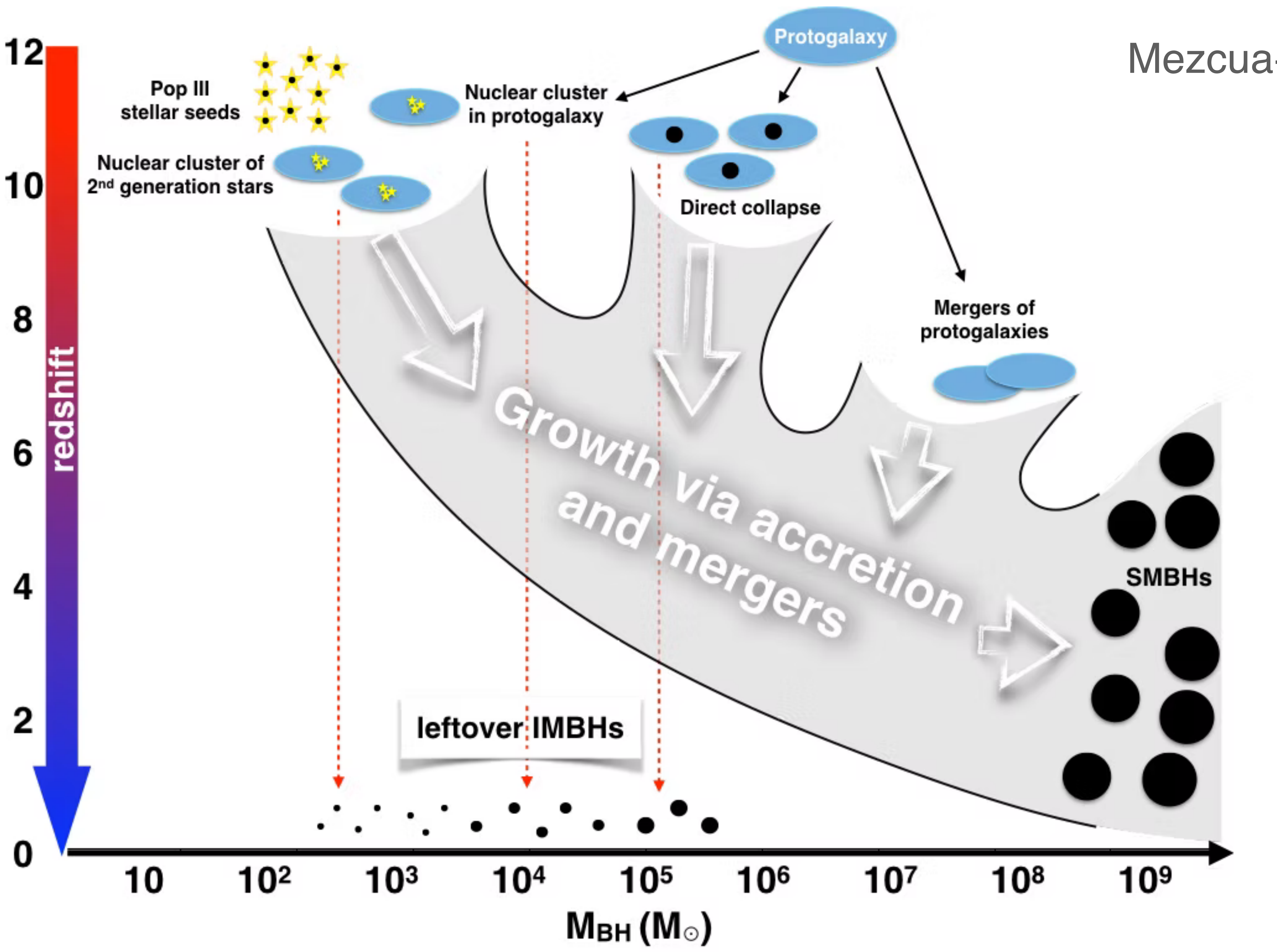
Ubiquitous in big galaxy nuclei



X-ray: NASA/CXC/SAO; visual: NASA/STScI; radio: NSF/NRAO/VLA

ESO/WFI (Optical);
MPIfR/ESO/APEX/A.Weiss et al. (Submillimetre);
NASA/CXC/CfA/R.Kraft et al. (X-ray)

Present-day black hole mass function (BHMF) track MBH Origin



Mezcua+2017

- Three popular scenarios for forming MBH seeds
- Provide the minimum mass for seed mechanism
- Number density can constrain mechanism

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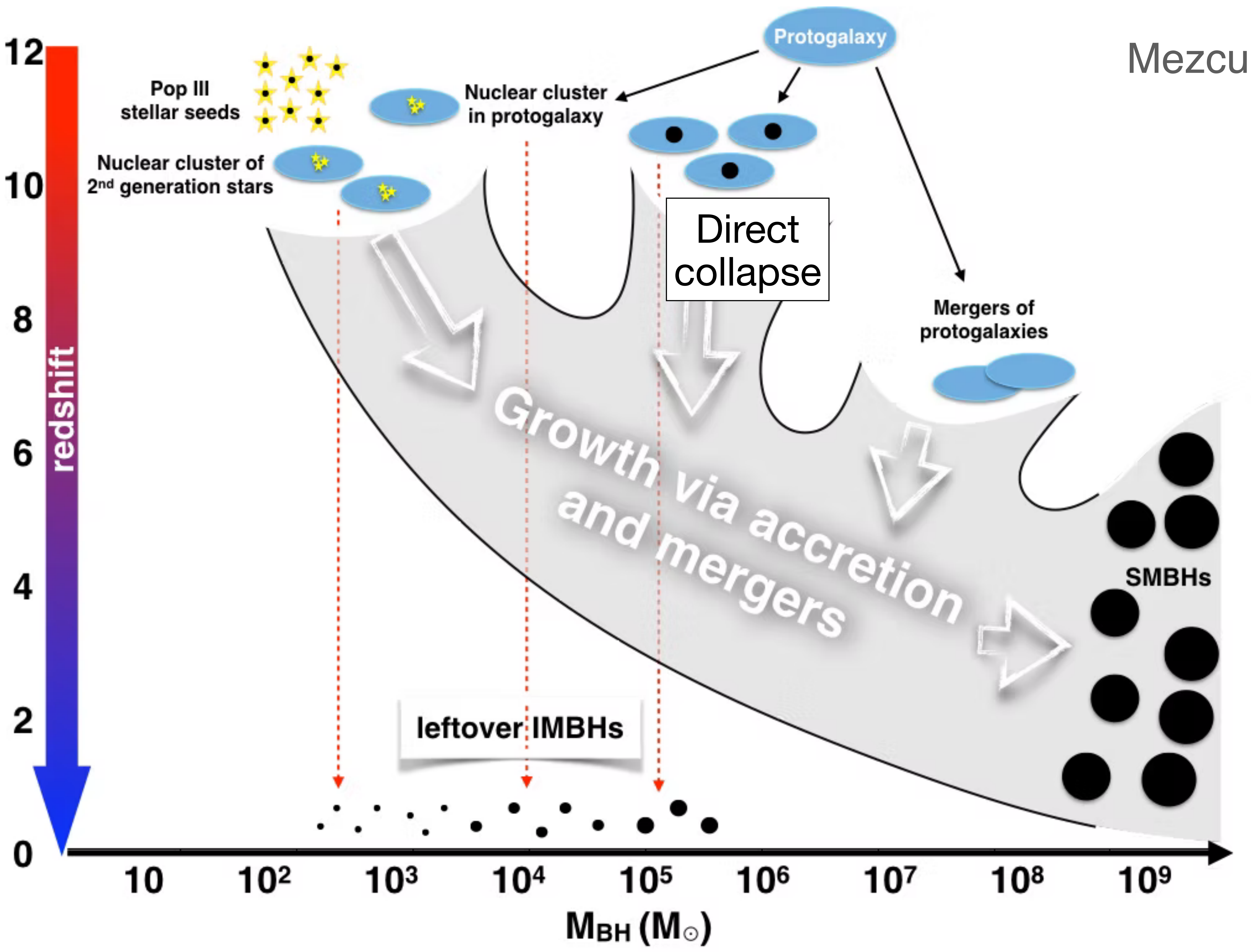

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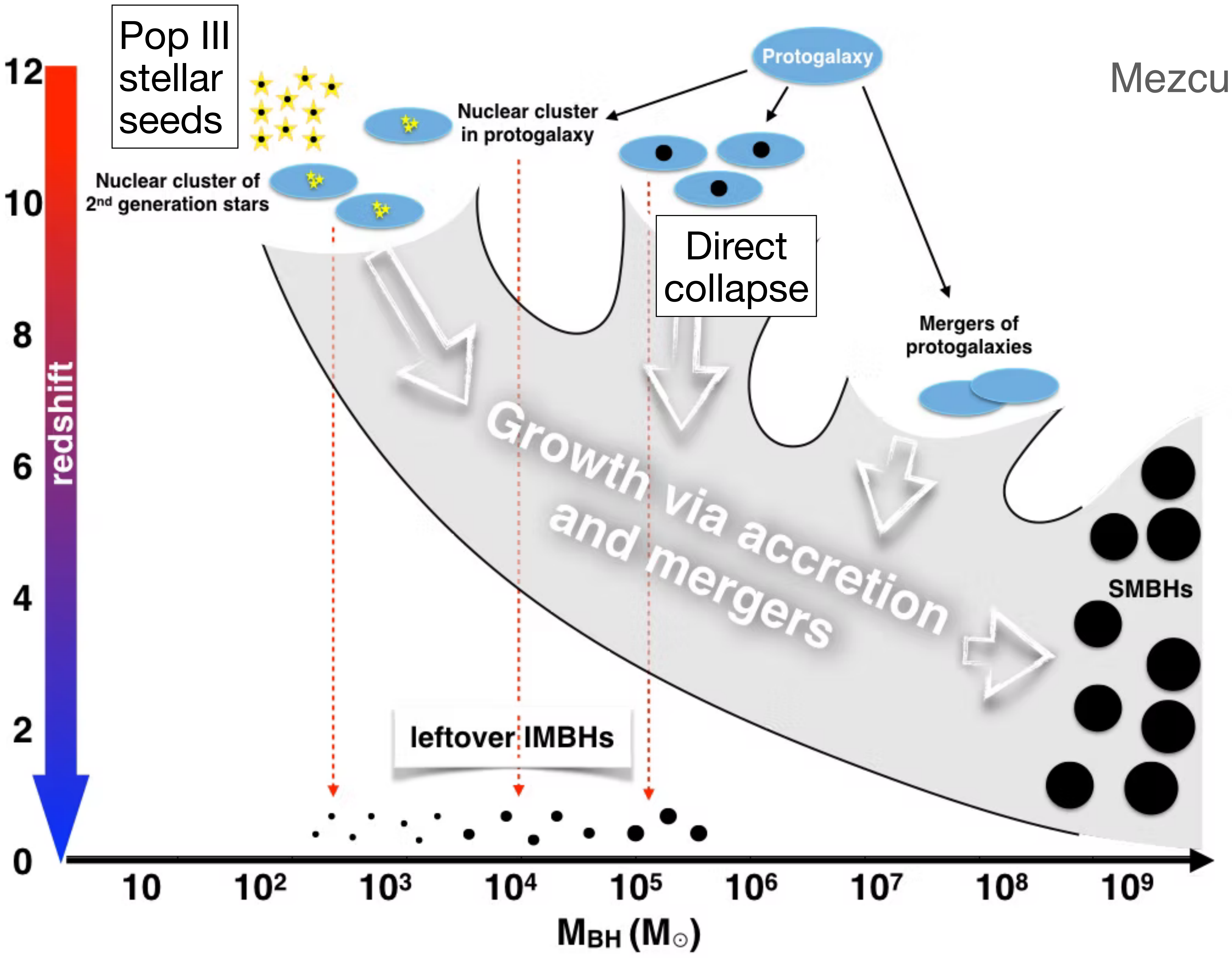

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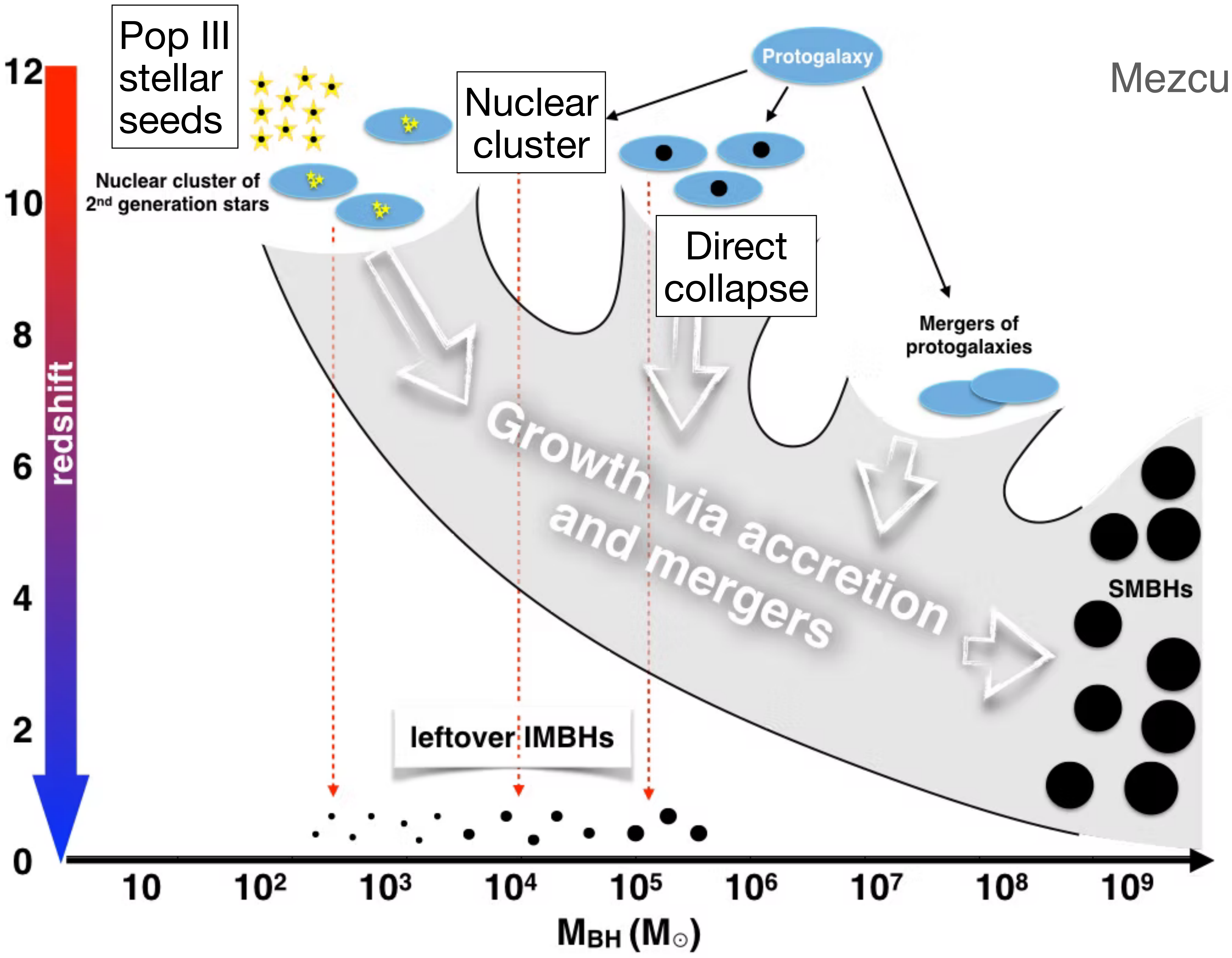

Mezcua+2017

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- Provide the minimum mass for seed mechanism
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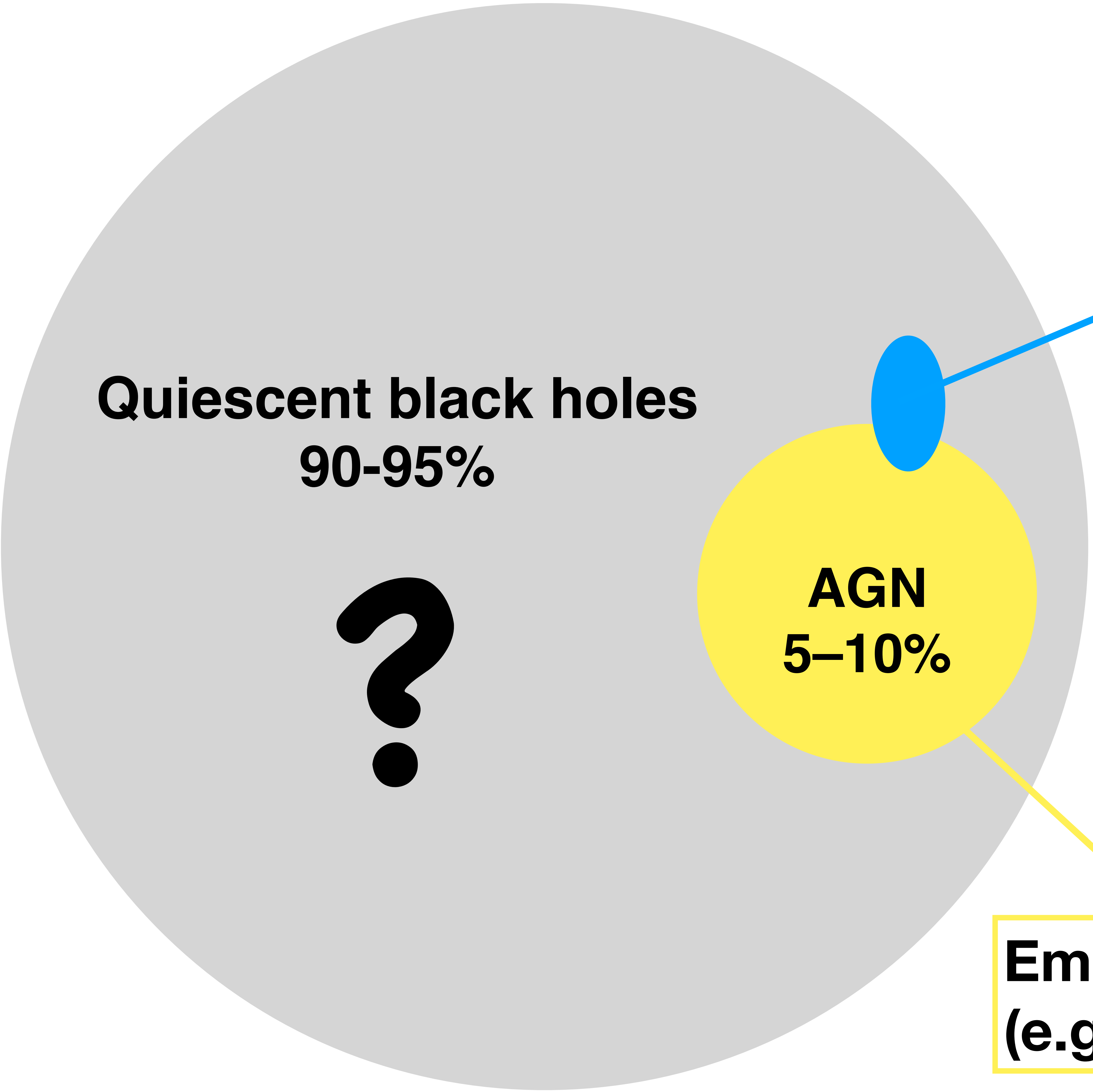
How to probe MBHs with light?



Spatially resolved dynamics (~100 galaxies)

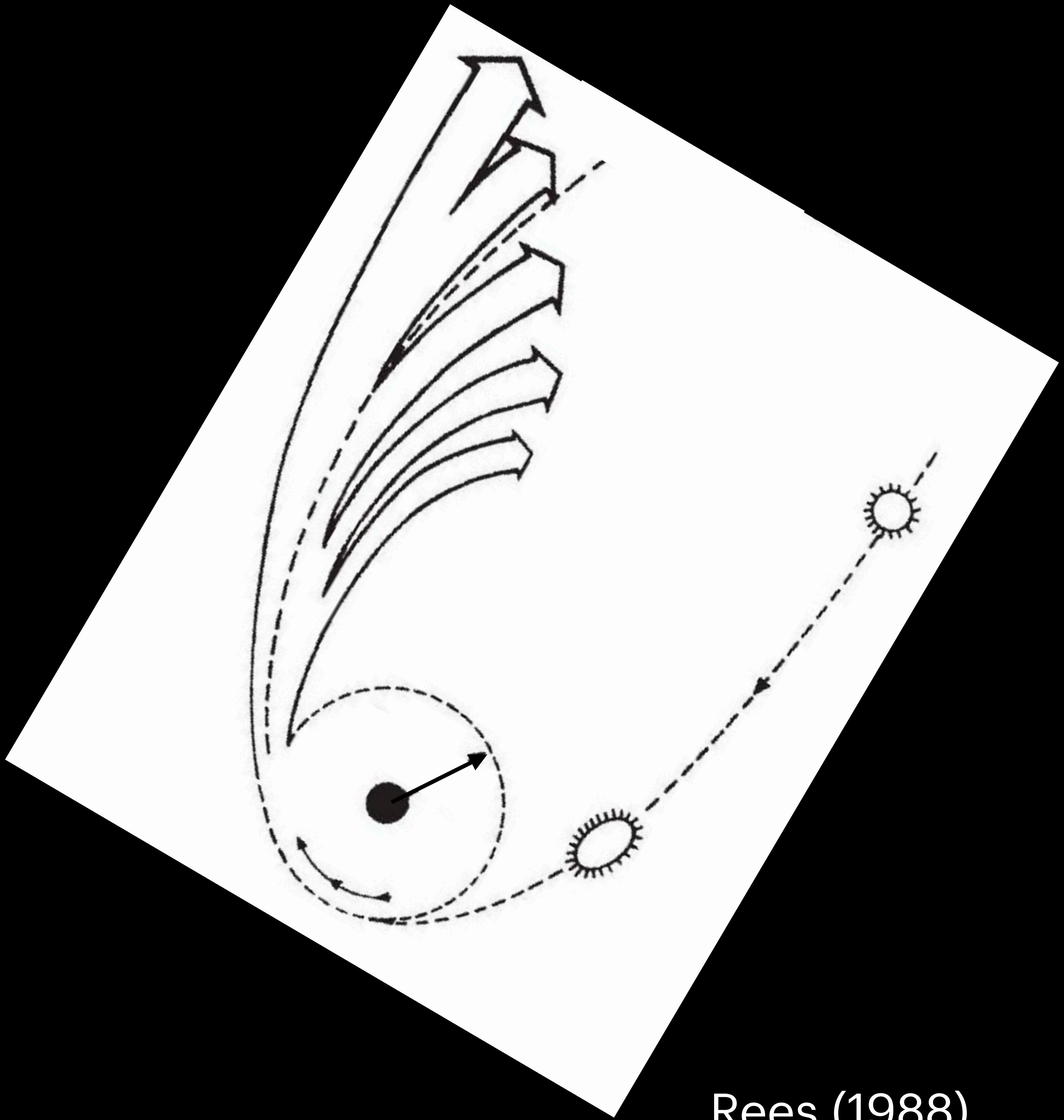
$$r_{\rm infl} \equiv \frac{GM_{\rm BH}}{\sigma^2}$$

Empirical relations
(e.g., width of broad emission lines and AGN luminosity)

Tidal disruption event (TDE)

Animation/DESY

Tidal disruption event (TDE)

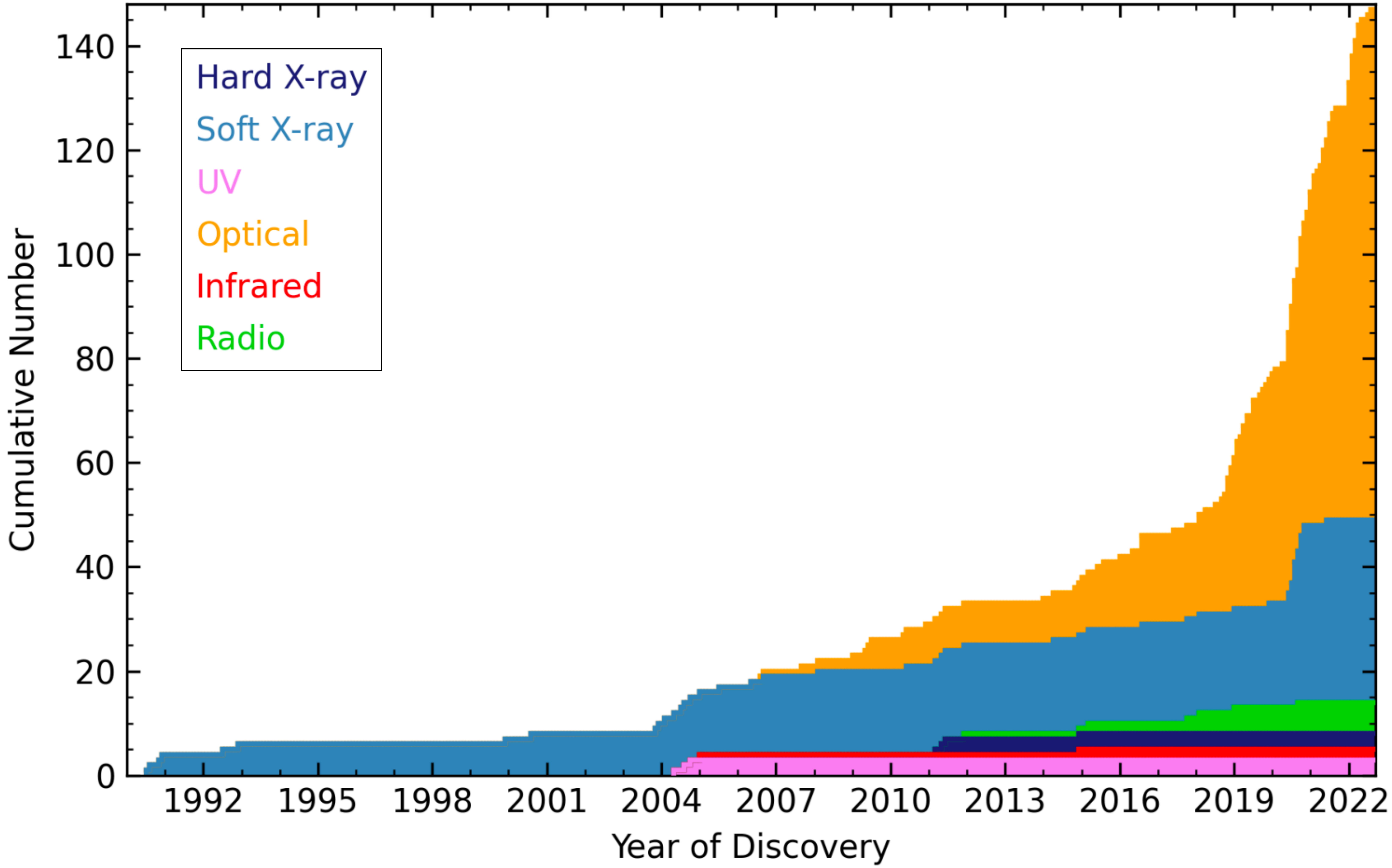


Rees (1988)

$$r_T \sim 7 \times 10^{12} (M_{BH}/10^6\, M_\odot)^{1/3}\ \mathrm{cm}$$

$$r_T > r_S \quad \rightarrow M_{BH} < 10^8\, M_\odot$$

A surge in TDE discoveries



Bade+1996; Komossa+1999; Grupe+1999; Saxton+2020; Sazonov+2021; Gezari+2006, 2012; Chornock+2014; van Velzen+2011, 2021, Arcavi+2014; Holoien+2014; Hung+2017; Hammerstein+2023, Yao+2023, Masterson+2024, …

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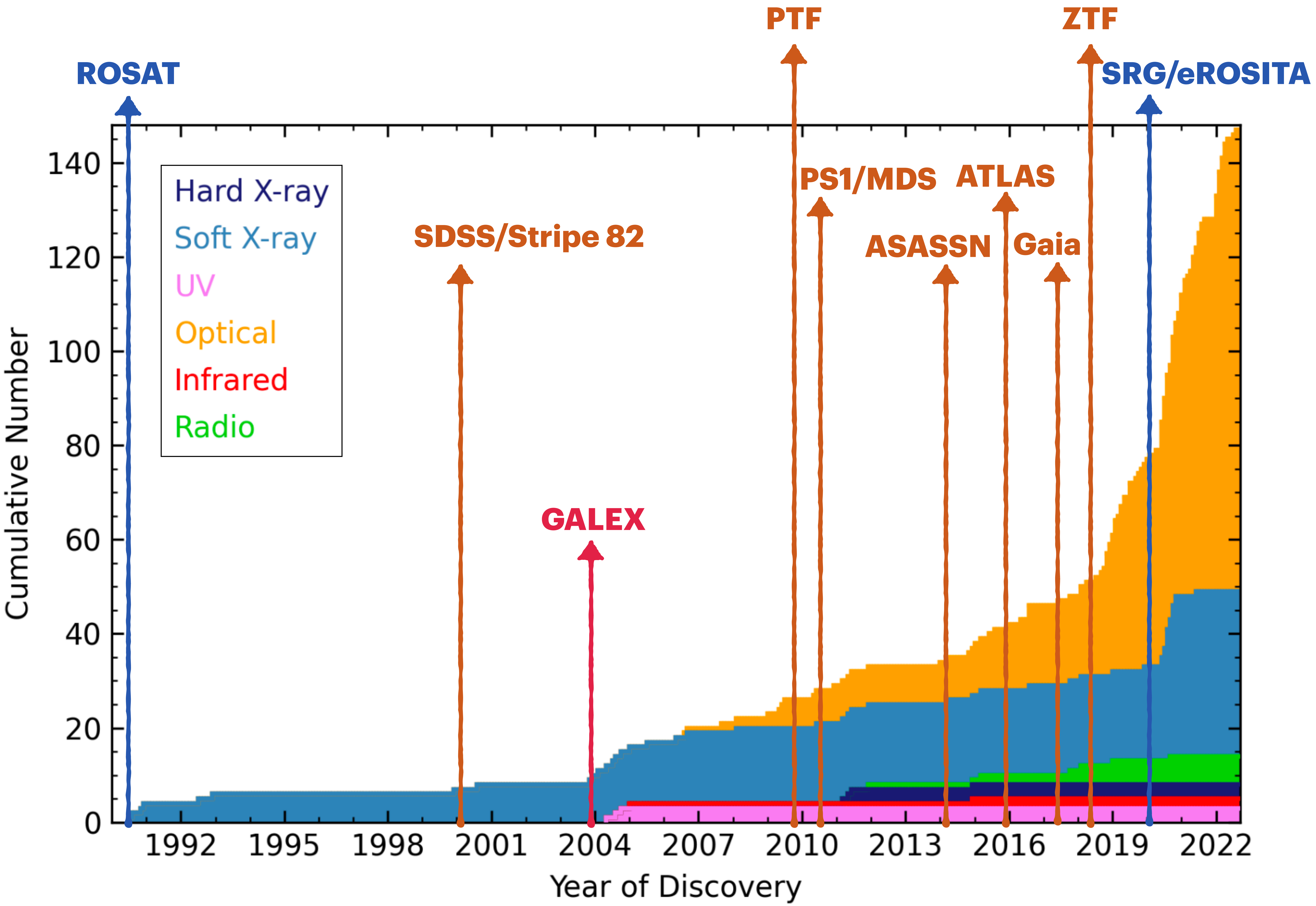

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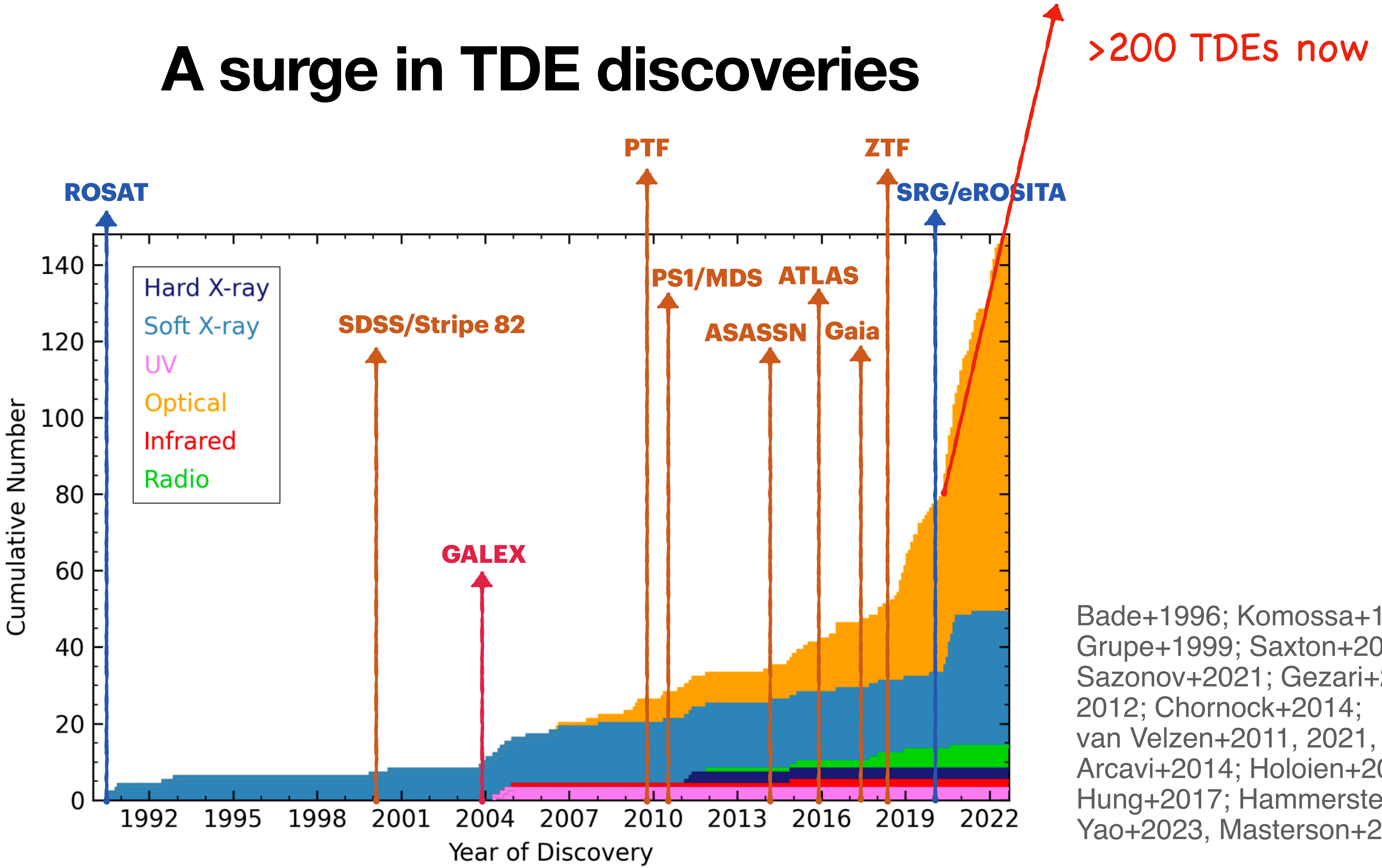

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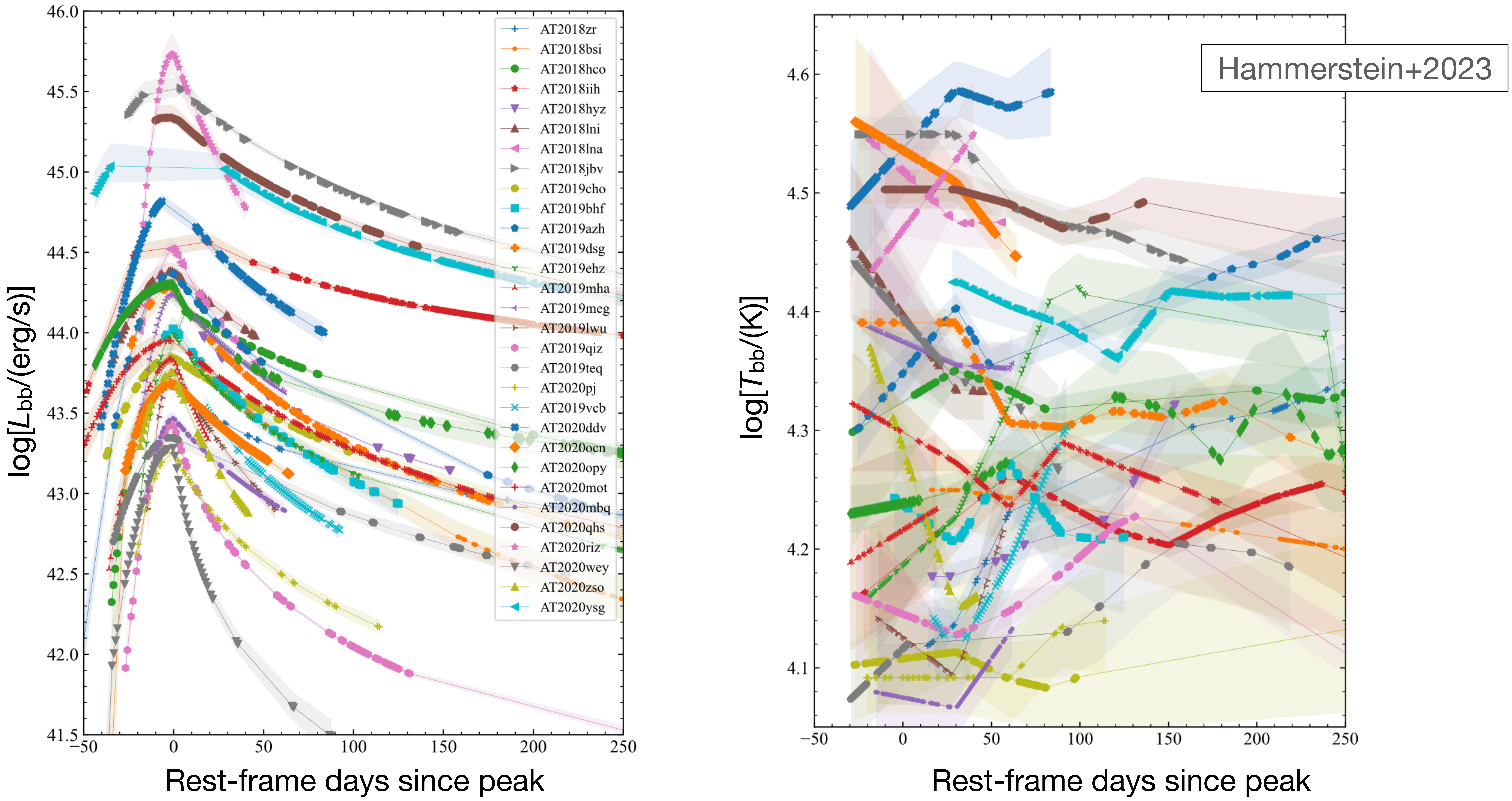
TDE UV/optical properties: hot ~all the time



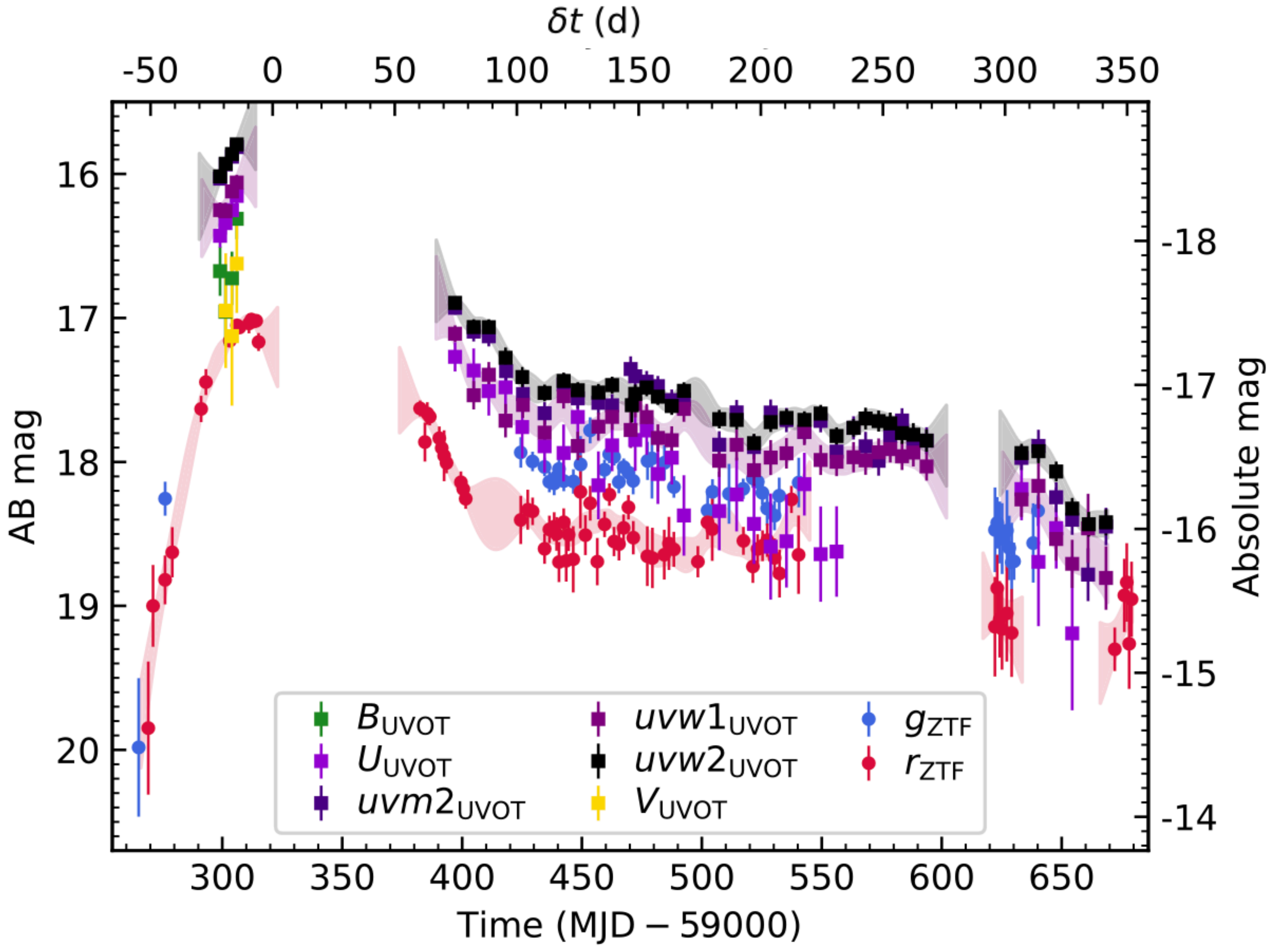
TDE Search Part I:
MBHs in Galaxy Centers

TDE Search Part II:
Off-nuclear (Wandering) MBHs

TDE Search Part I:
MBHs in Galaxy Centers

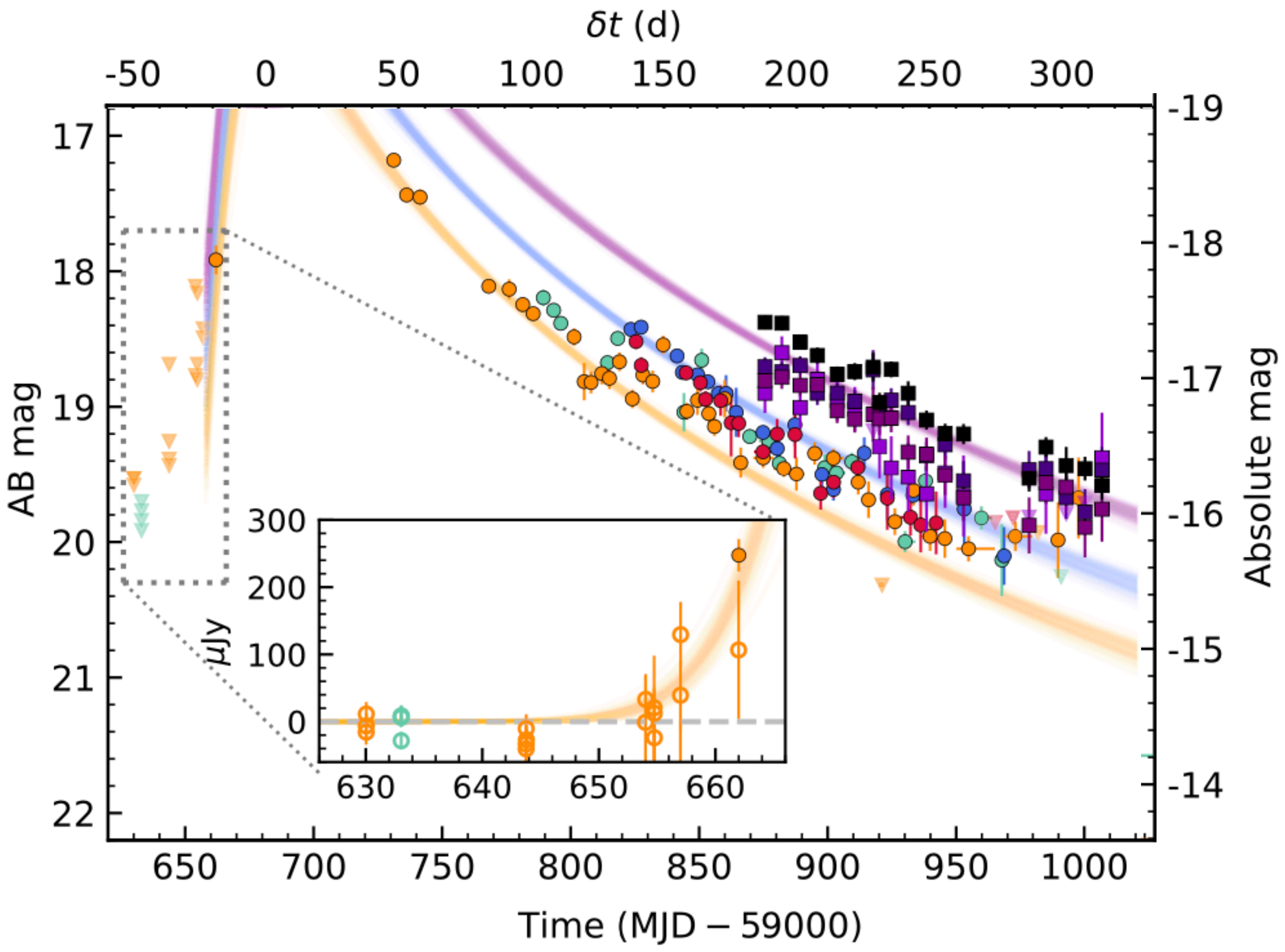
TDE identification: Zwicky Transient Facility (ZTF) + *Swift*

AT2021ehb (z=0.018; $M_{BH} \approx 10^7\,M_\odot$)



Yao+2022

AT2022lri (z=0.033; $M_{BH} \approx 10^5\,M_\odot$)



Yao+2024

How to use TDEs to measure the BHMF?

Observed TDE rate vs. M_{BH} = BHMF X TDE possibility vs. M_{BH} X Event horizon suppression factor vs. M_{BH}

How to use TDEs to measure the BHMF?

= × TDE possibility vs. M_{BH} ×

↑

Rate of stars being scattered into the loss cone with

$$J < J_{LC} \equiv \sqrt{GM_{BH}R_T}$$

How to use TDEs to measure the BHMF?

= × TDE possibility vs. M_{BH} ×

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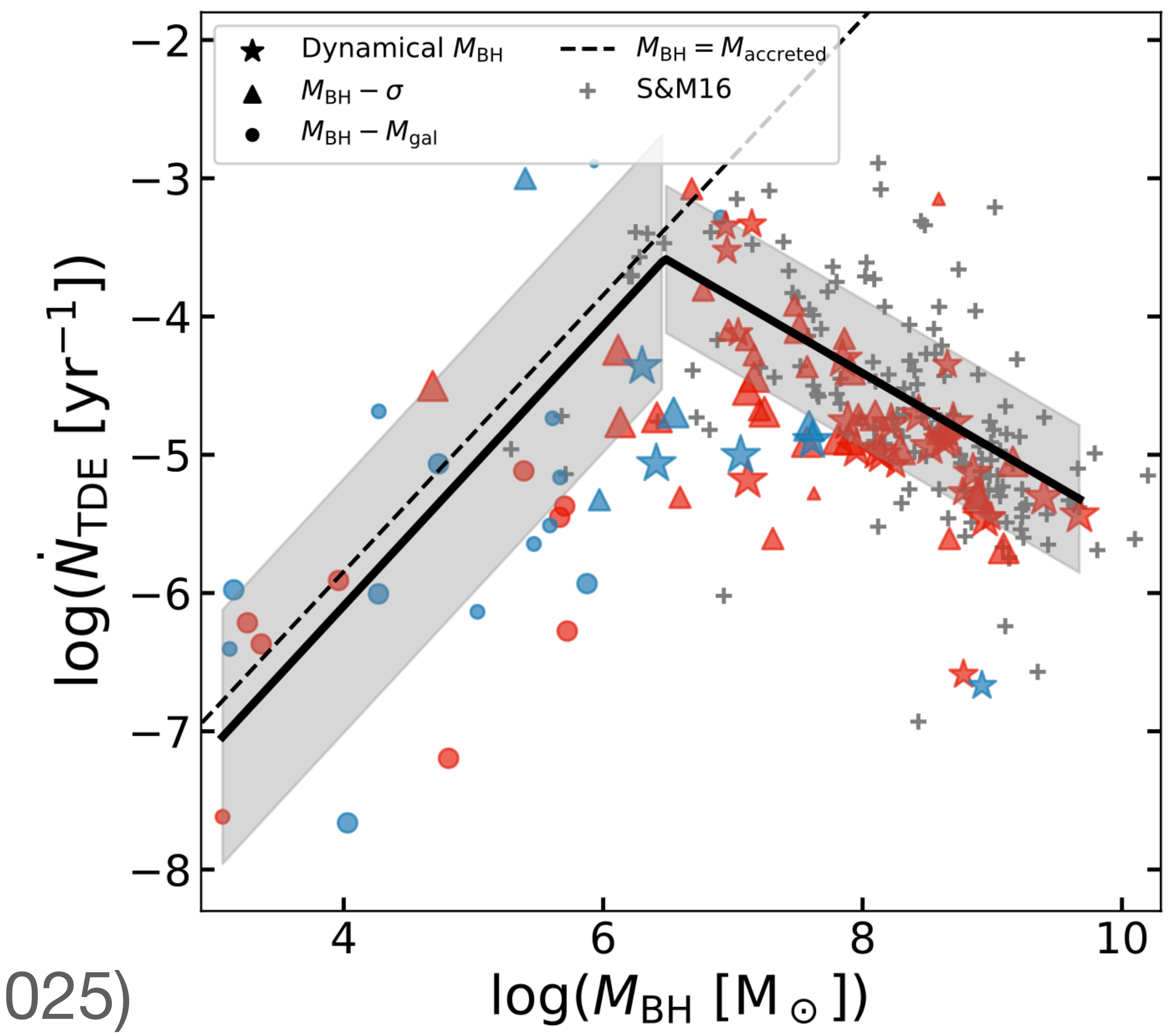
Rate of stars being scattered into the loss cone with $J < J_{\rm LC} \equiv \sqrt{GM_{\rm BH}R_{\rm T}}$



Hannah et al. (2025)

also see Lightman & Shapiro (1977), Cohn & Kulsrud (1978), Magorrian & Tremaine (1999), Merritt (2013), Stone & Metzger (2016)

How to use TDEs to measure the BHMF?

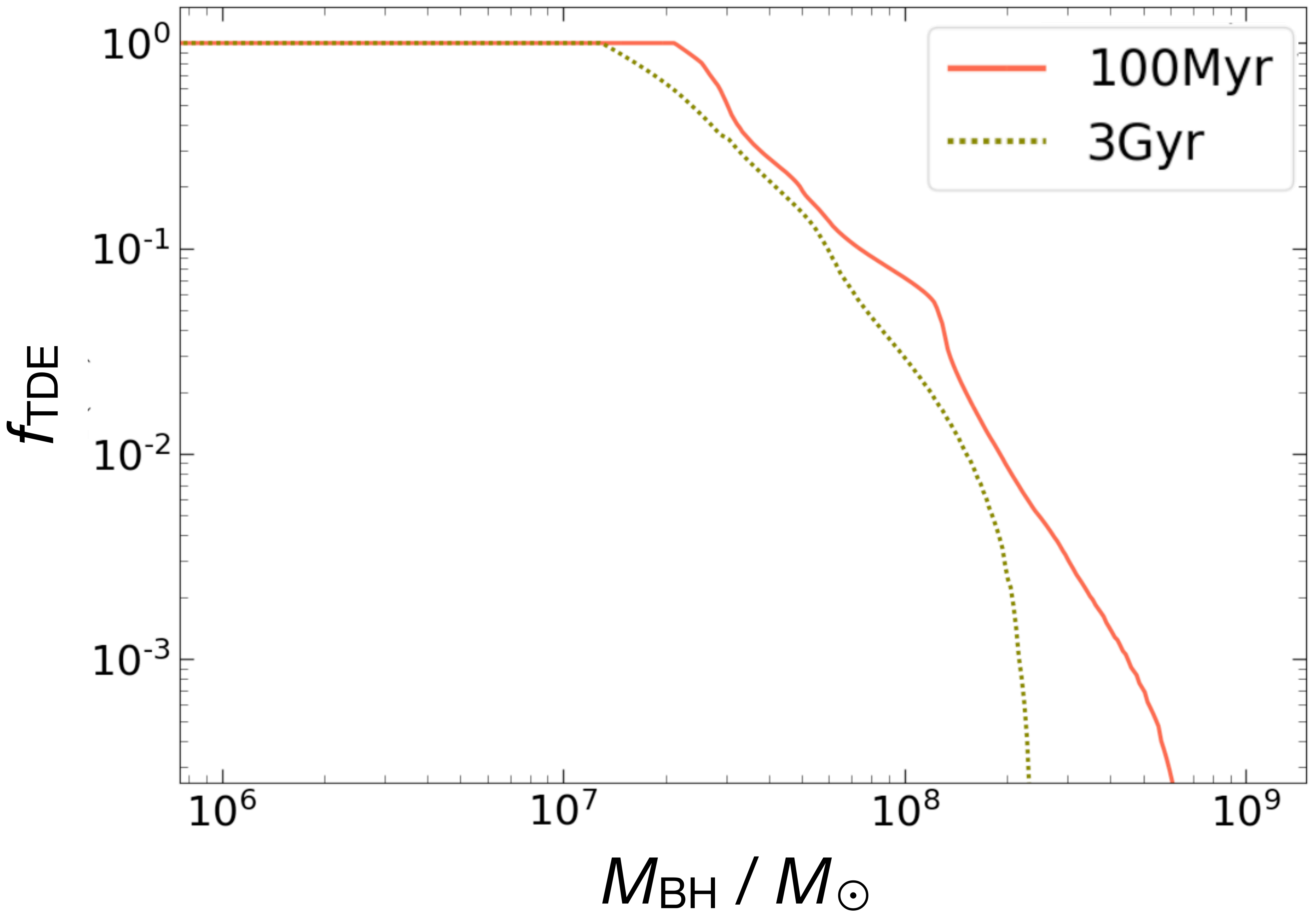
= X X Event horizon suppression factor vs. M_{BH}

Fraction of stars creating TDE (instead of being swallowed whole)

How to use TDEs to measure the BHMF?

= X X

Event horizon suppression factor vs. M_{BH}



Fraction of stars creating TDE (instead of being swallowed whole)

Huang & Lu (2024)

Depends on BH spin and stellar population age, but close to unity when $M_{BH} < 10^7\ M_\odot$

Observed TDE rate vs. M_{BH}

The $1/V_{max}$ method:

Schmidt 1968

In a flux-limited survey, each detected object is assigned a maximum volume V_{max} within which it could have been observed, given the survey's sensitivity and selection criteria.

The total space density is: $\mathscr{R} = \Sigma_i 1/V_{\mathrm{max},i}$

Observed TDE rate vs. M_{BH}

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- Get unique **nuclear** transients, require n_g>10, n_r>10, t_{dur}>30 days
- Remove known quasars and hosts with strong WISE variability
- Require mean g-r<0.2 mag, post-peak d(g-r)/dt < 0.02 mag/d; rise & fade timescale between 2 and 300 days

Yao+2023
ApJL 955 L6

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The $1/V_{max}$ method:

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- **ZTF-I** (Oct 2018 — Sep 2020): $m_{g,peak} < 18.75$ mag, 16 out of 27 candidates are TDEs
- **ZTF-II** (Oct 2020 — Sep 2021): $m_{g,peak} < 19.1$ mag, 17 out of 28 candidates are TDEs
- In total: **33 TDEs (a complete flux-limited sample)**

Yao+2023
ApJL 955 L6

Observed TDE rate vs. M_{BH}

The 1/V_{max} method:

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The total space density is: $\mathscr{R} = \Sigma_i 1/V_{max,i}$

Simulate light curves into survey scheduler, compute recovery fraction.

Yao+2023
ApJL 955 L6

Observed TDE rate vs. M_{BH} = TDE possibility vs. M_{BH} X BHMF X Event horizon suppression factor vs. M_{BH}

Yao+2023
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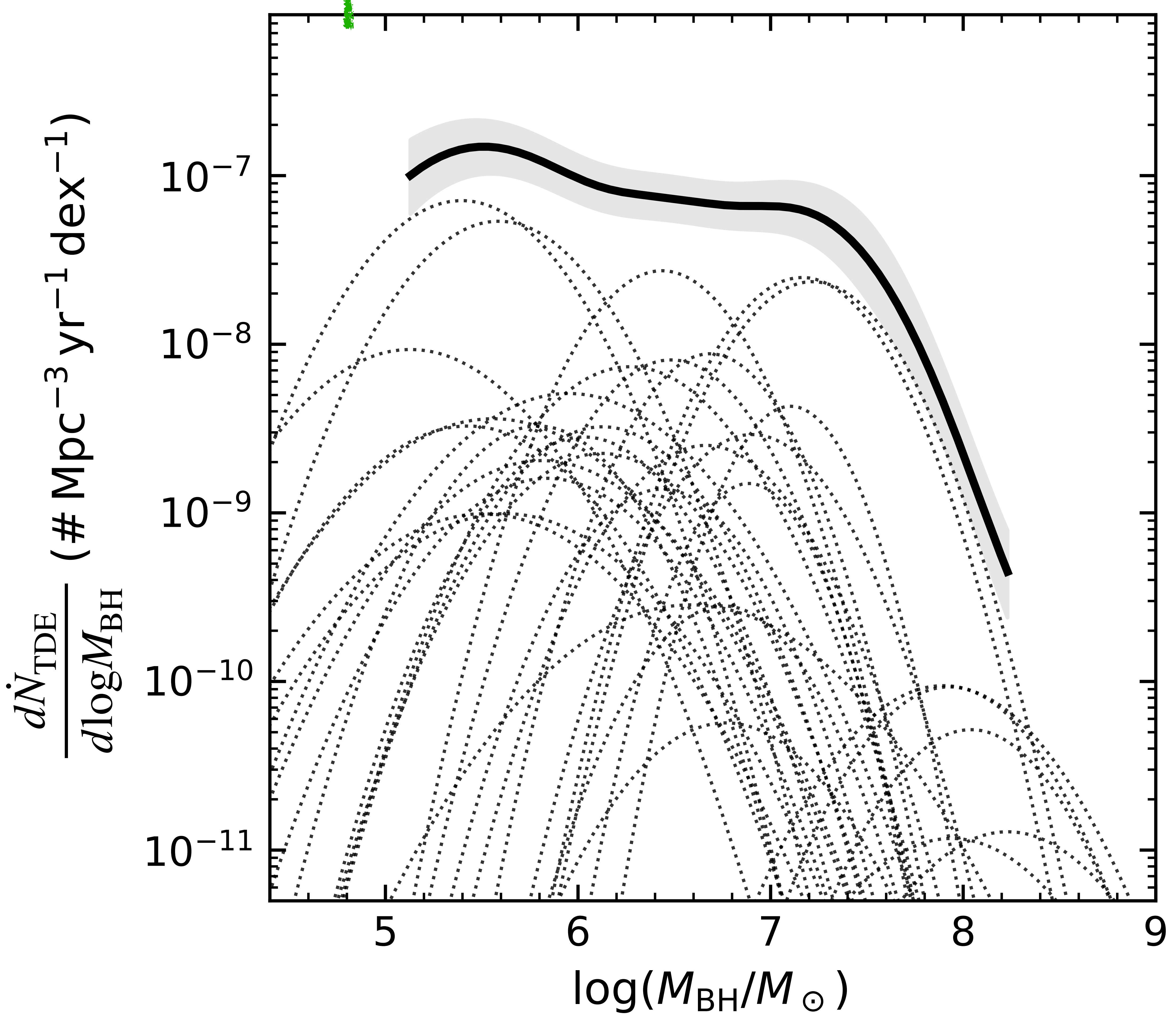
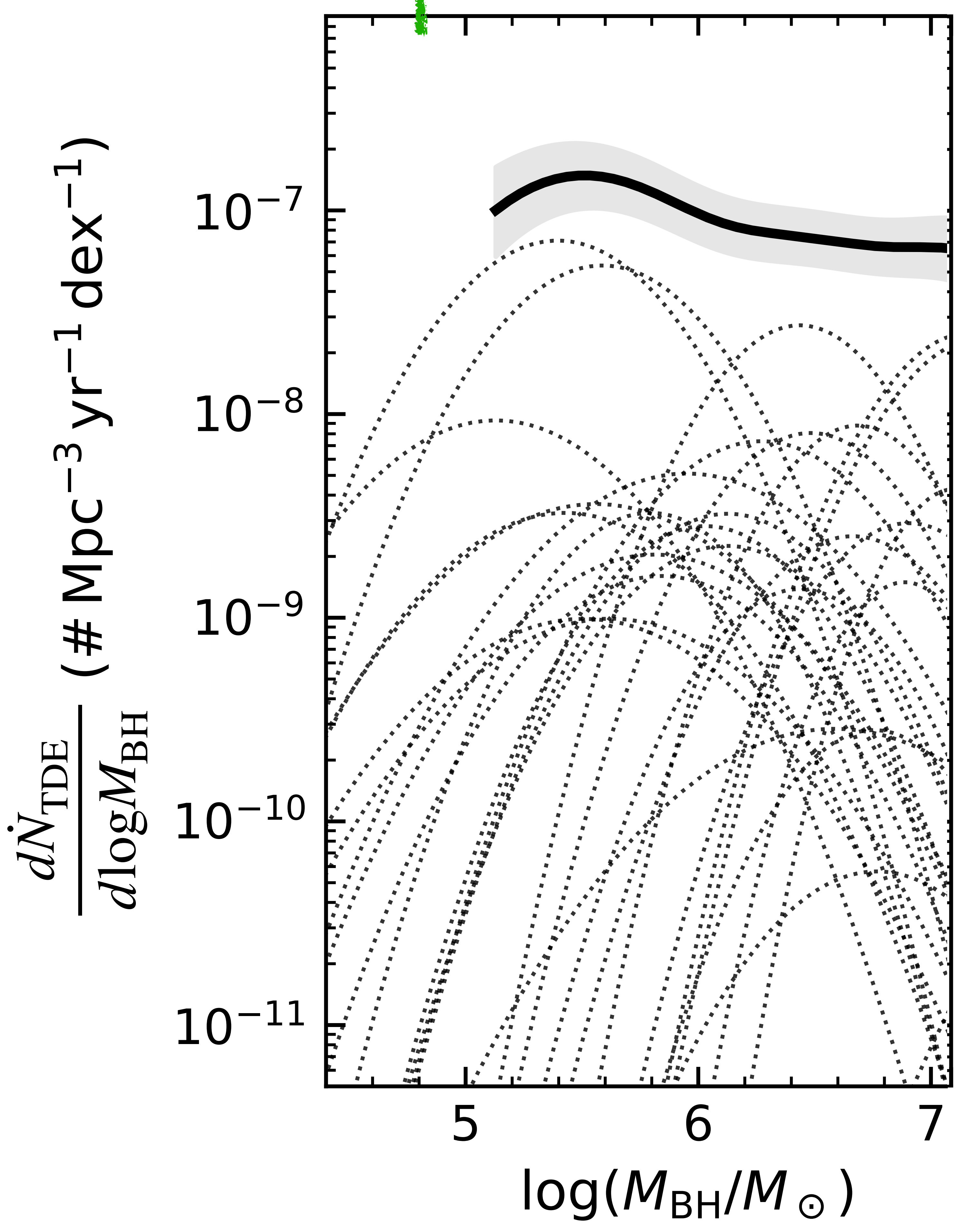


Yao+2023
ApJL 955 L6

Observed TDE rate vs. M_{BH} = TDE possibility vs. M_{BH} X BHMF X ≈1

Provided by **Hannah et al. (2025)**



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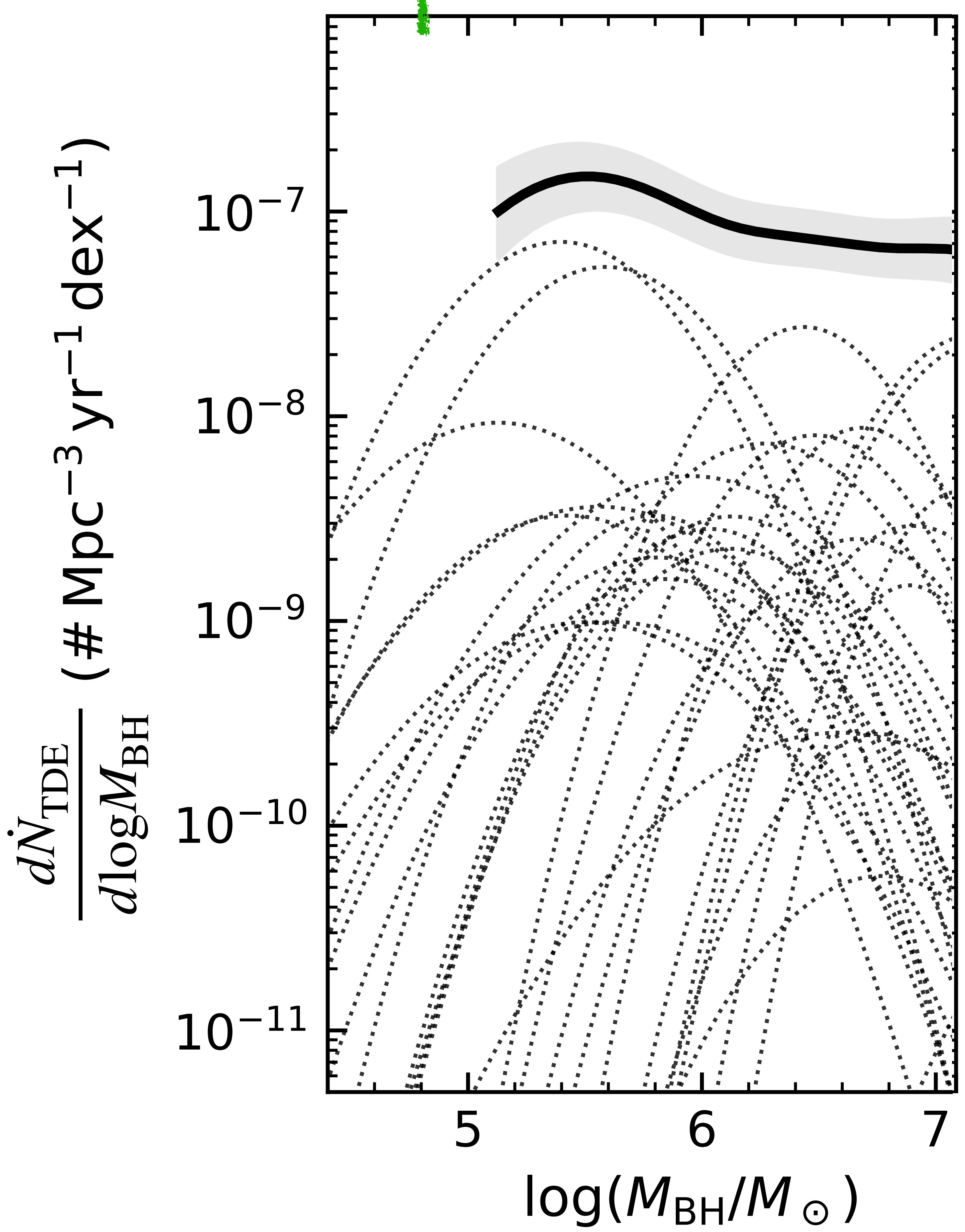

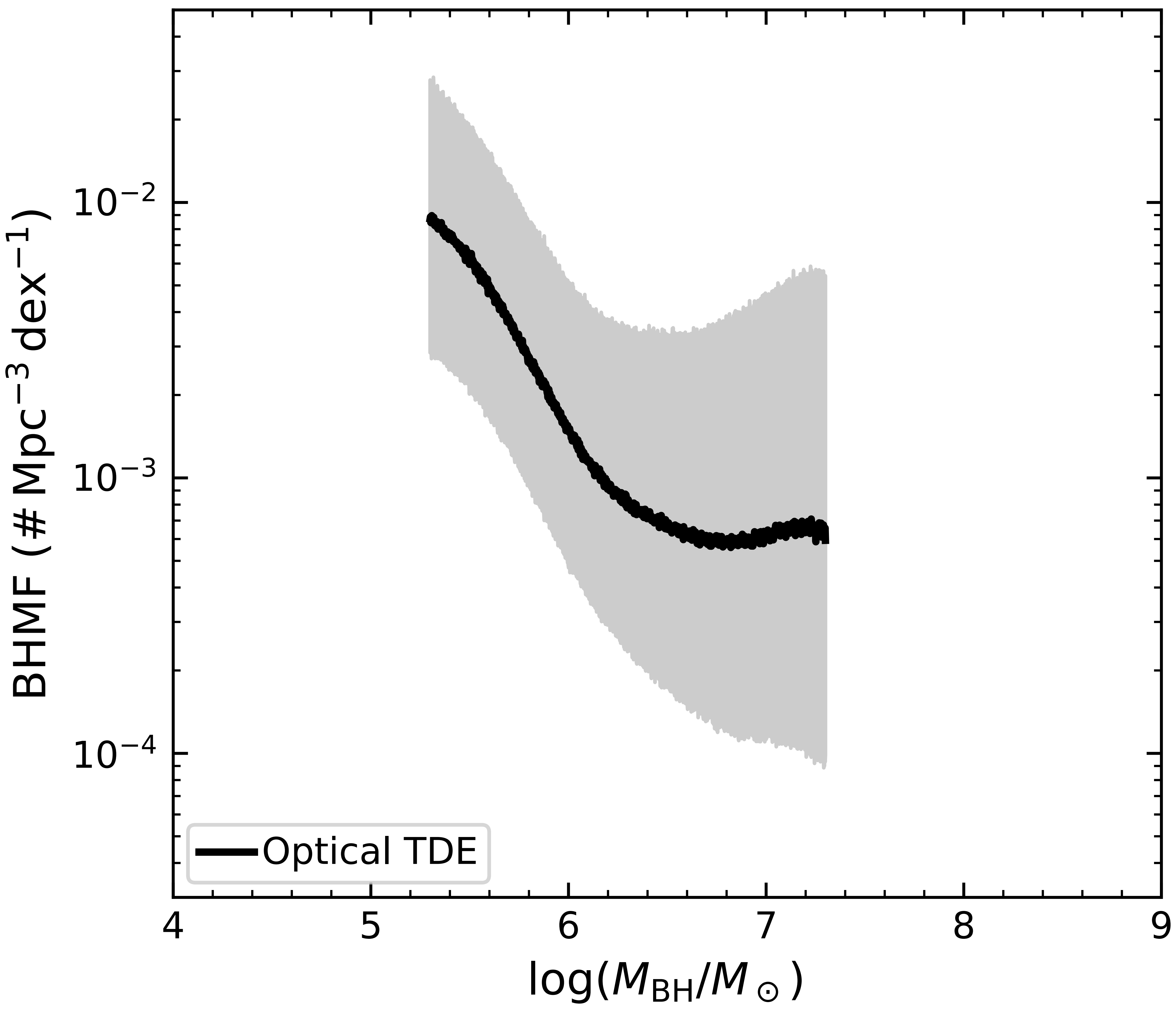

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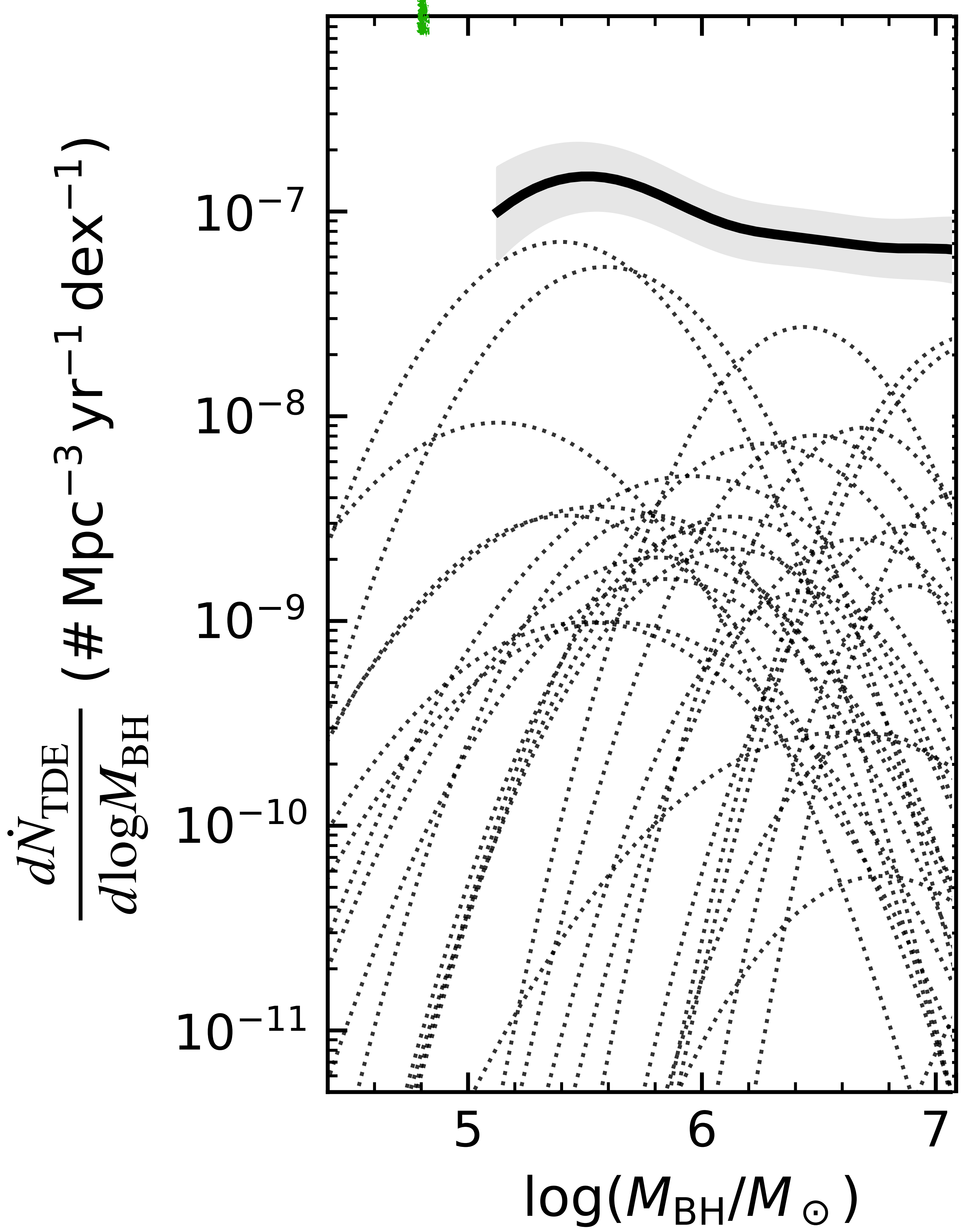

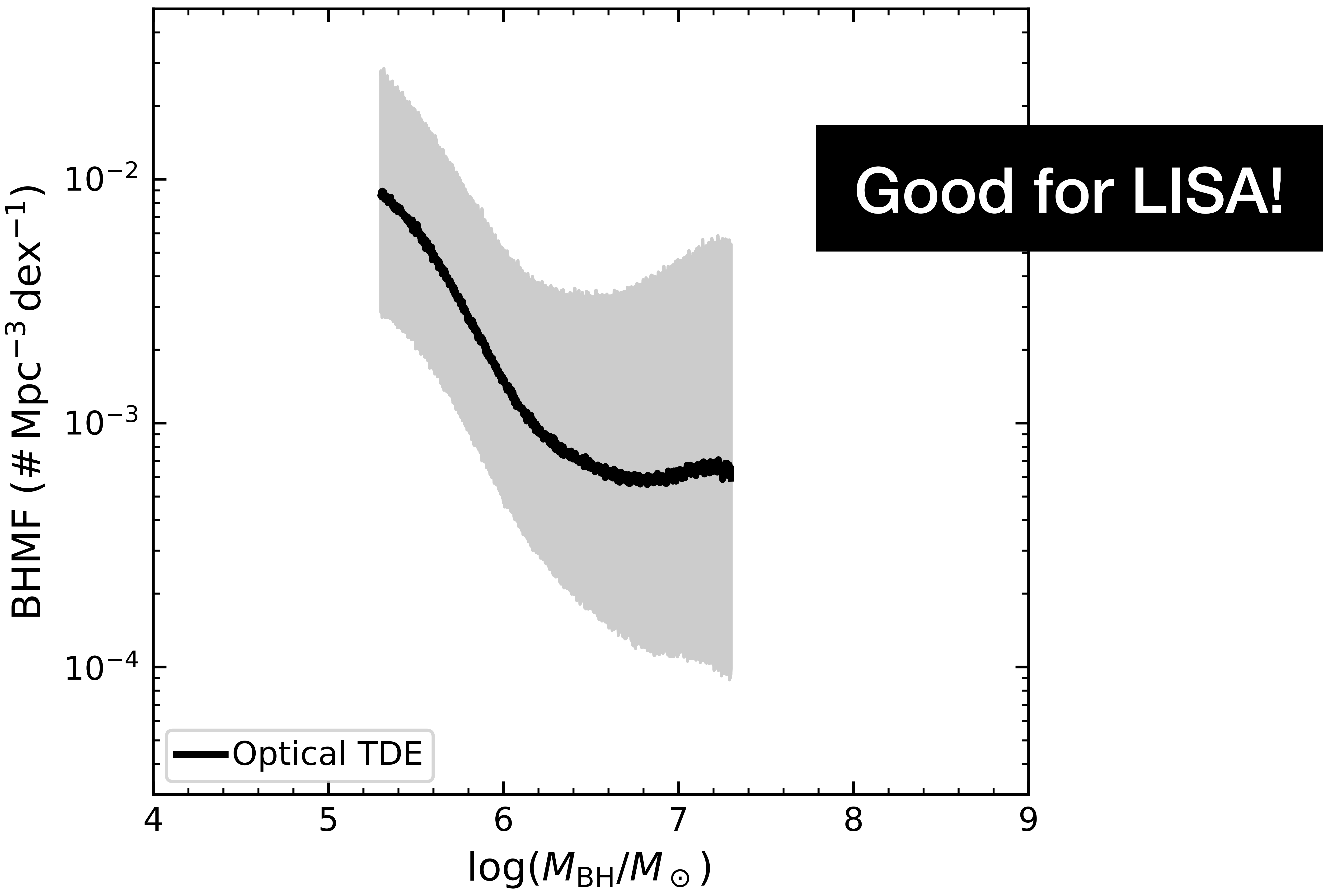

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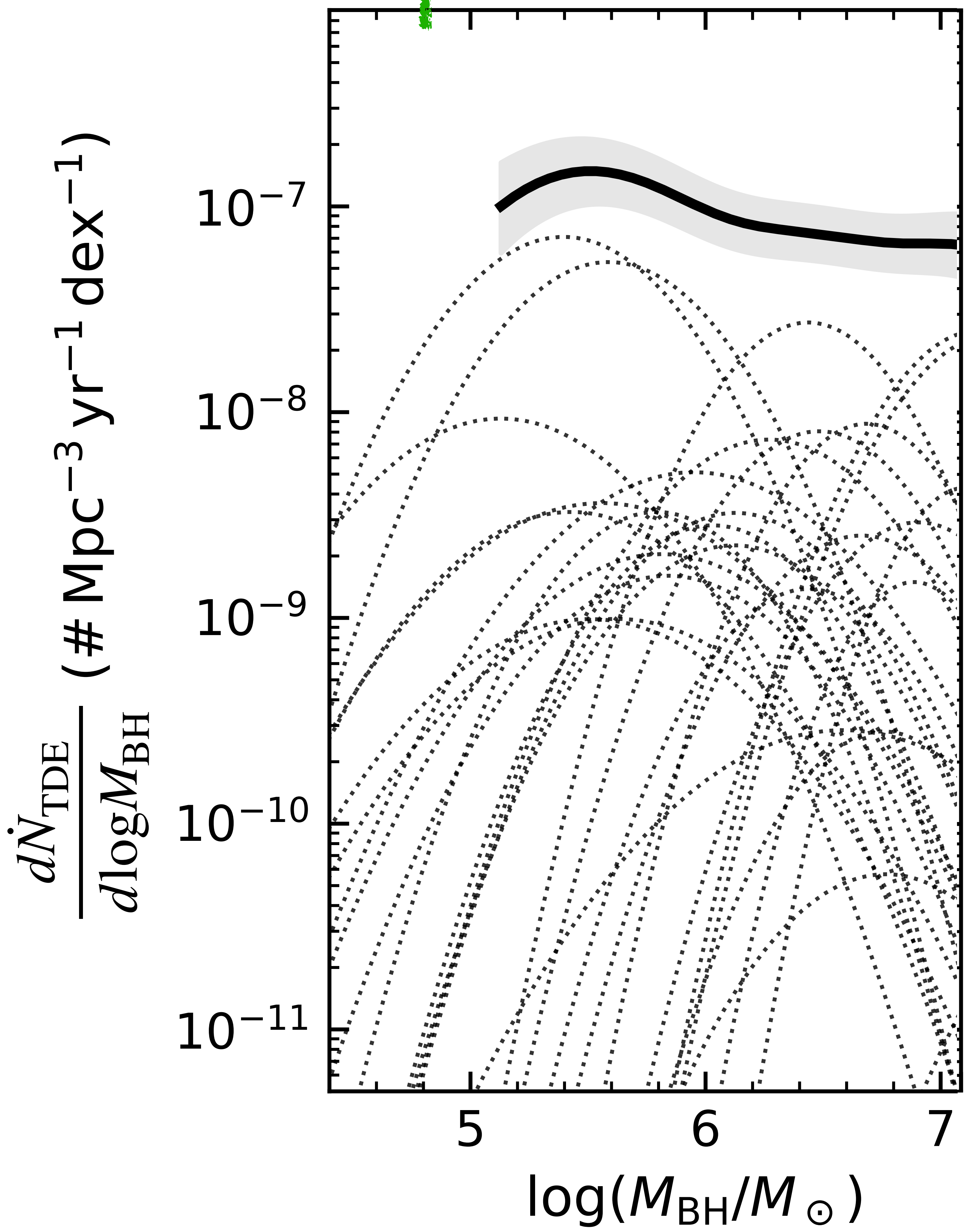
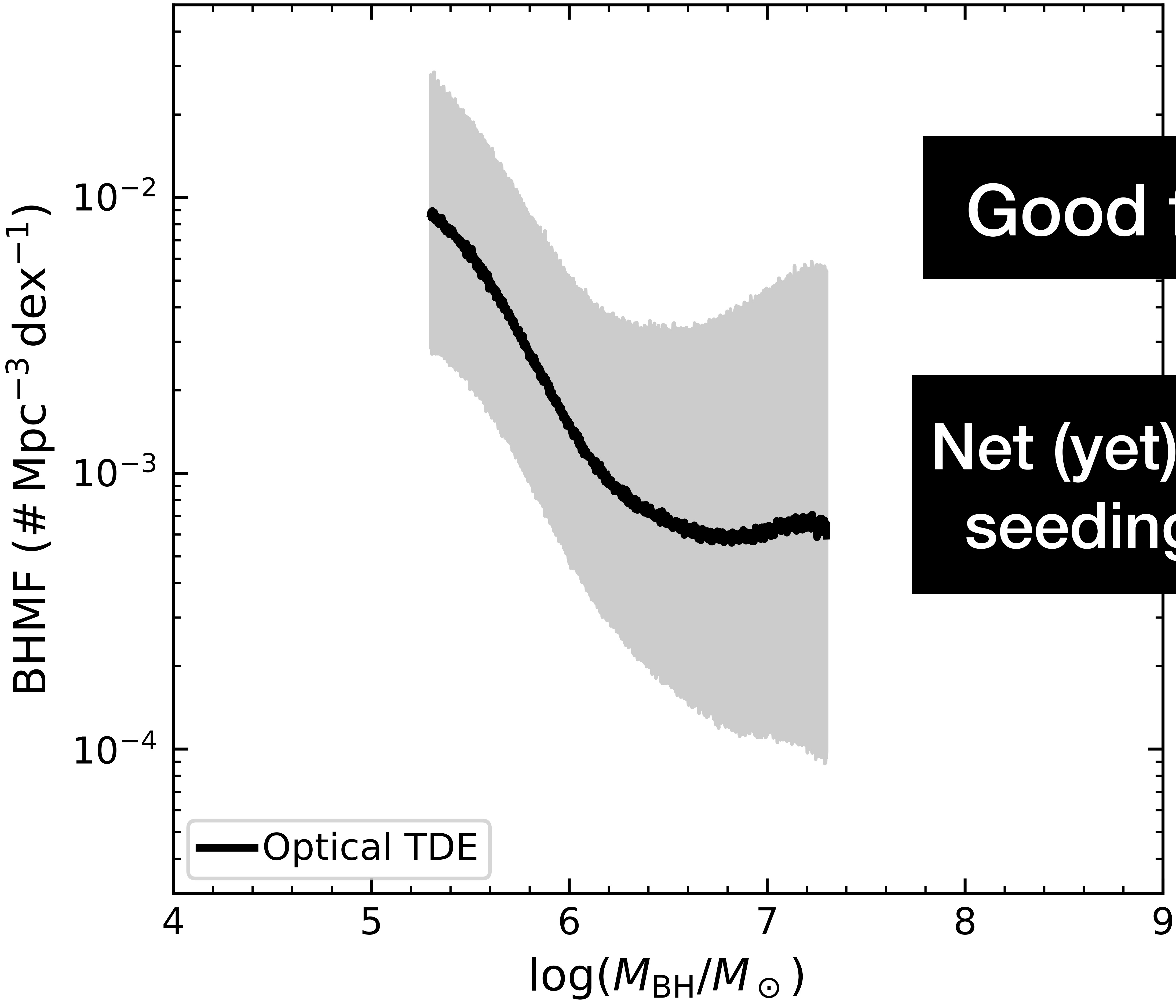
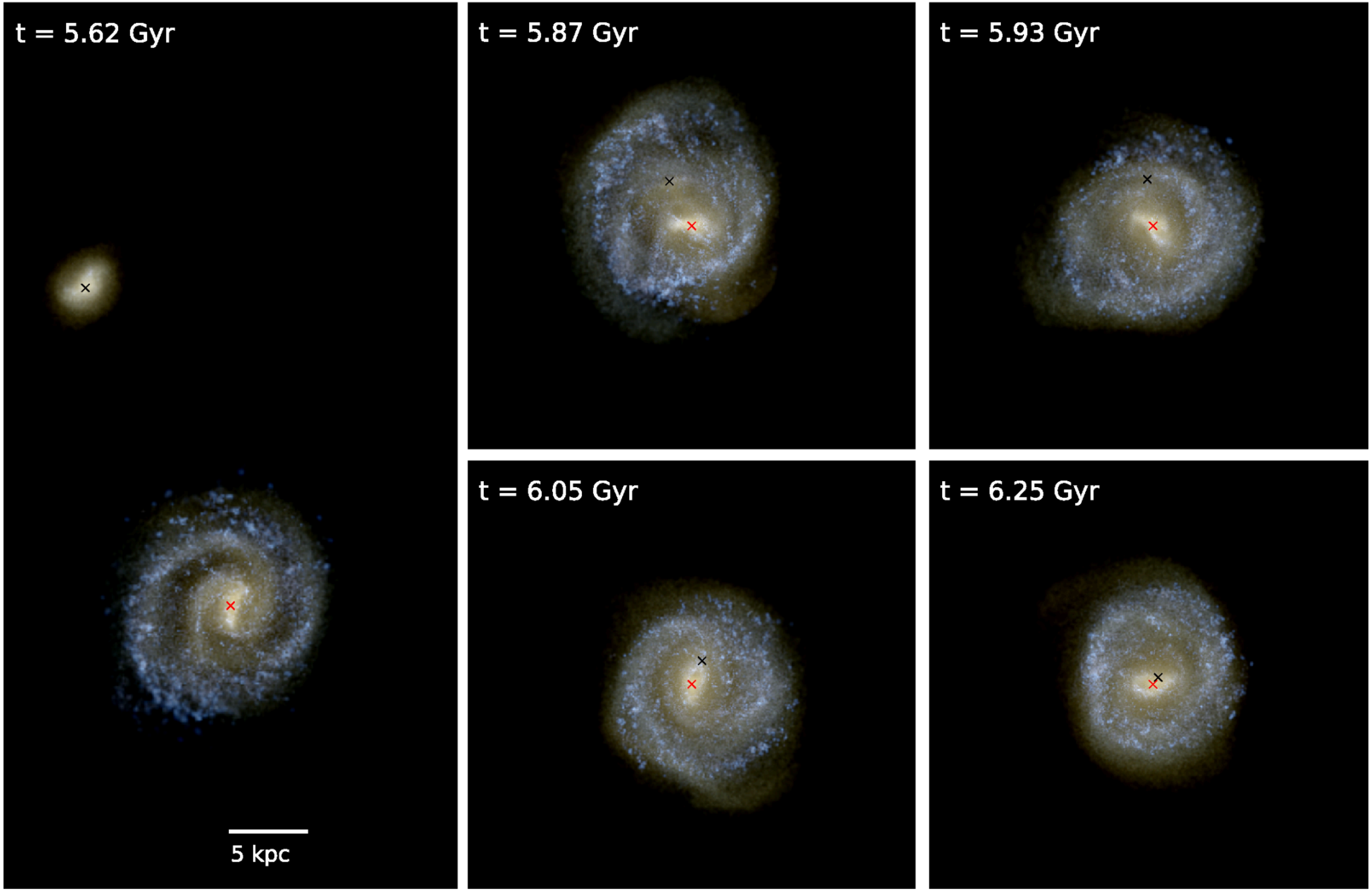




Good for LISA!

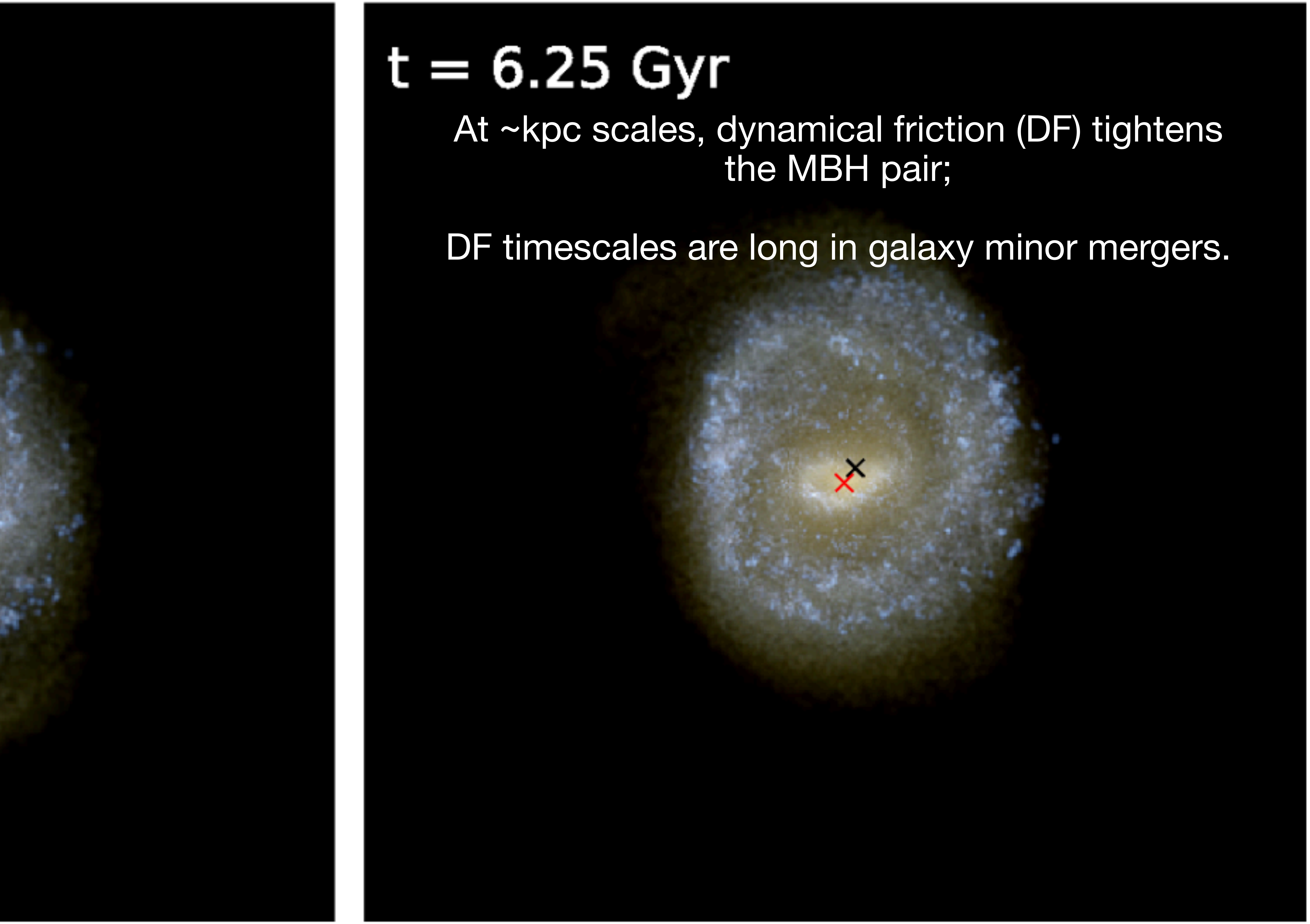
Net (yet) sensitive to BH seeding mechanisms.

TDE Search Part II:
Off-nuclear (Wandering) MBHs



Cosmological simulation

Tremmel+2018

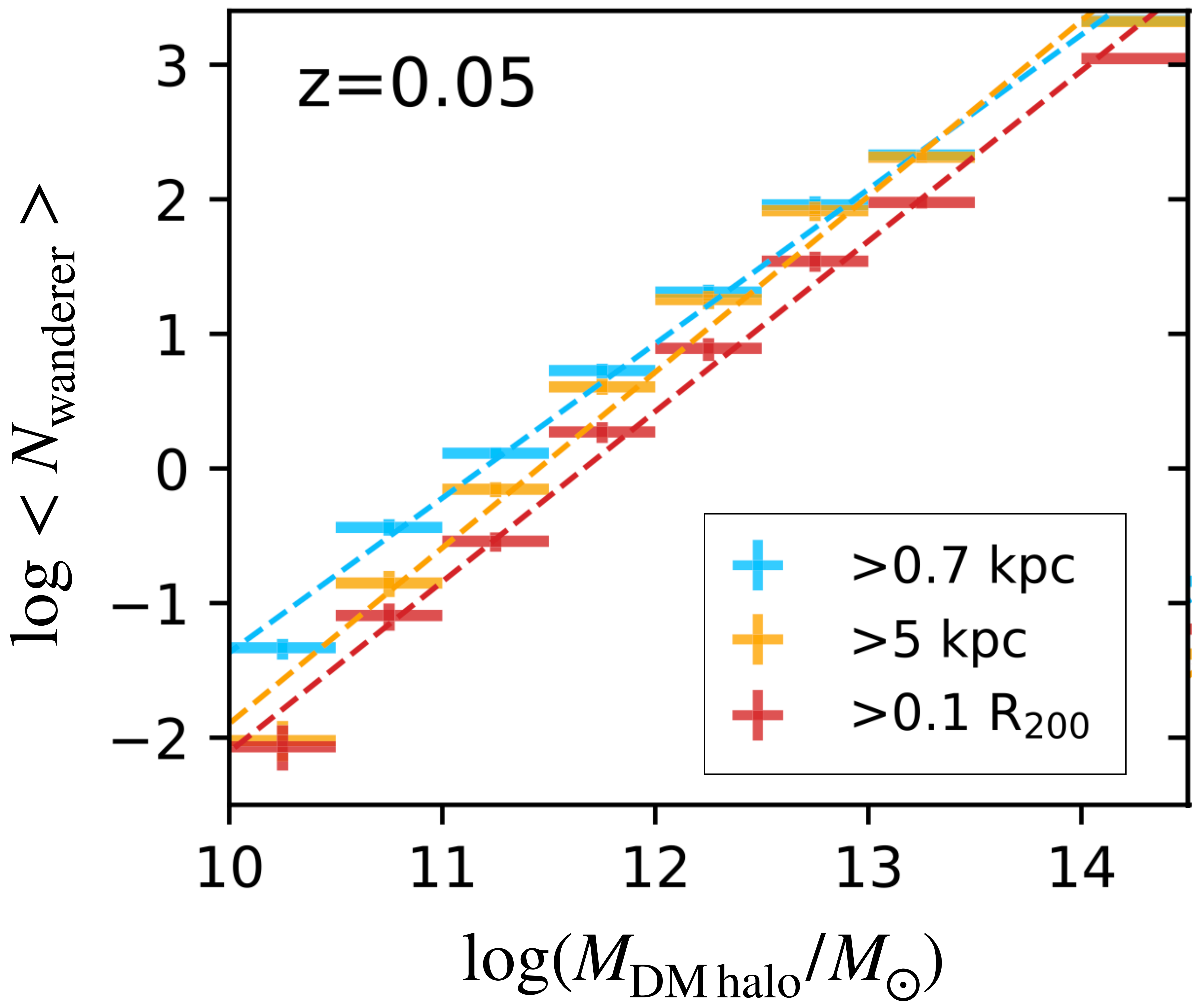


Cosmological simulation

Tremmel+2018

Offset MBHs in cosmological simulations

Scales linearly with halo mass



Ricarte+2021a

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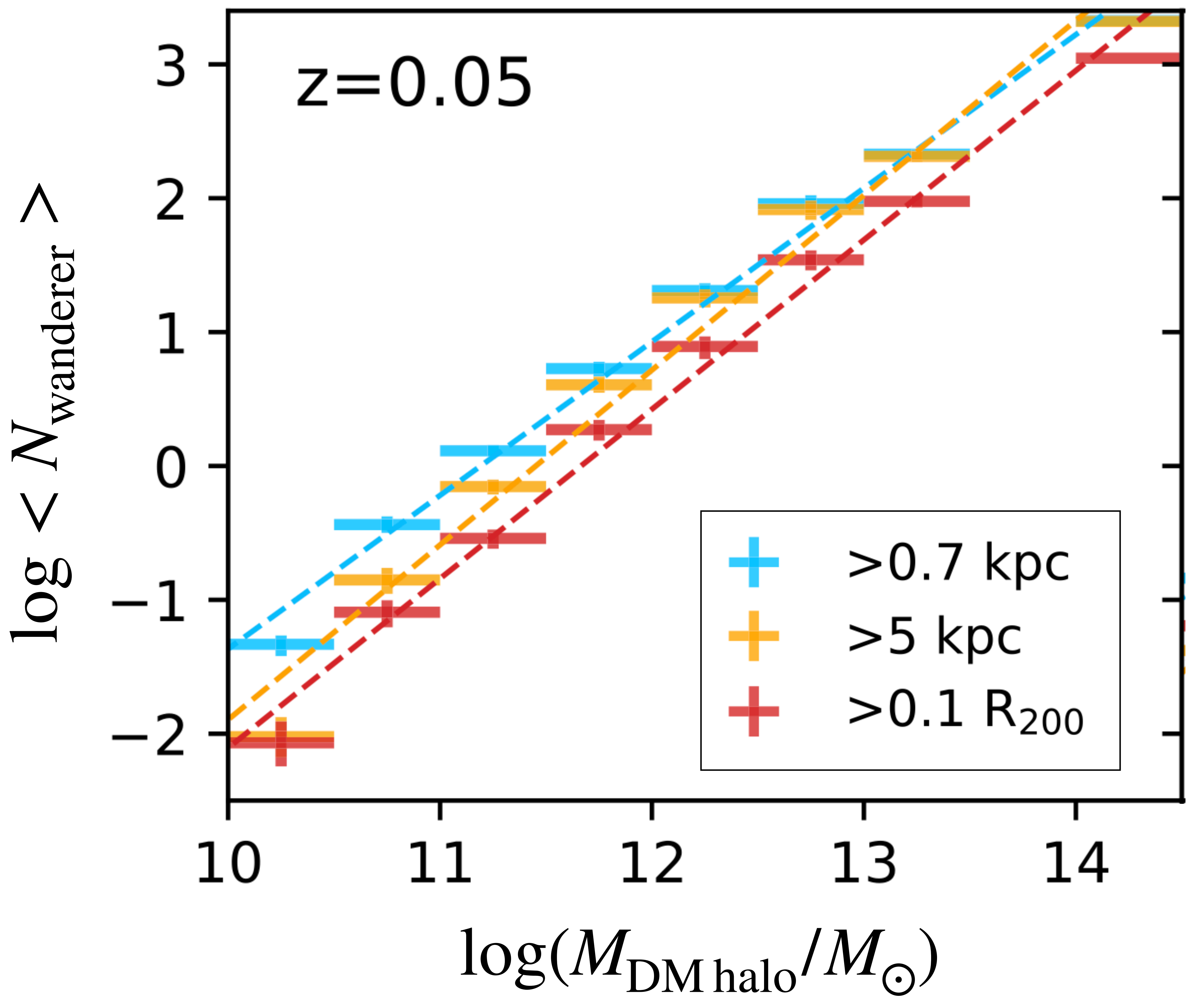
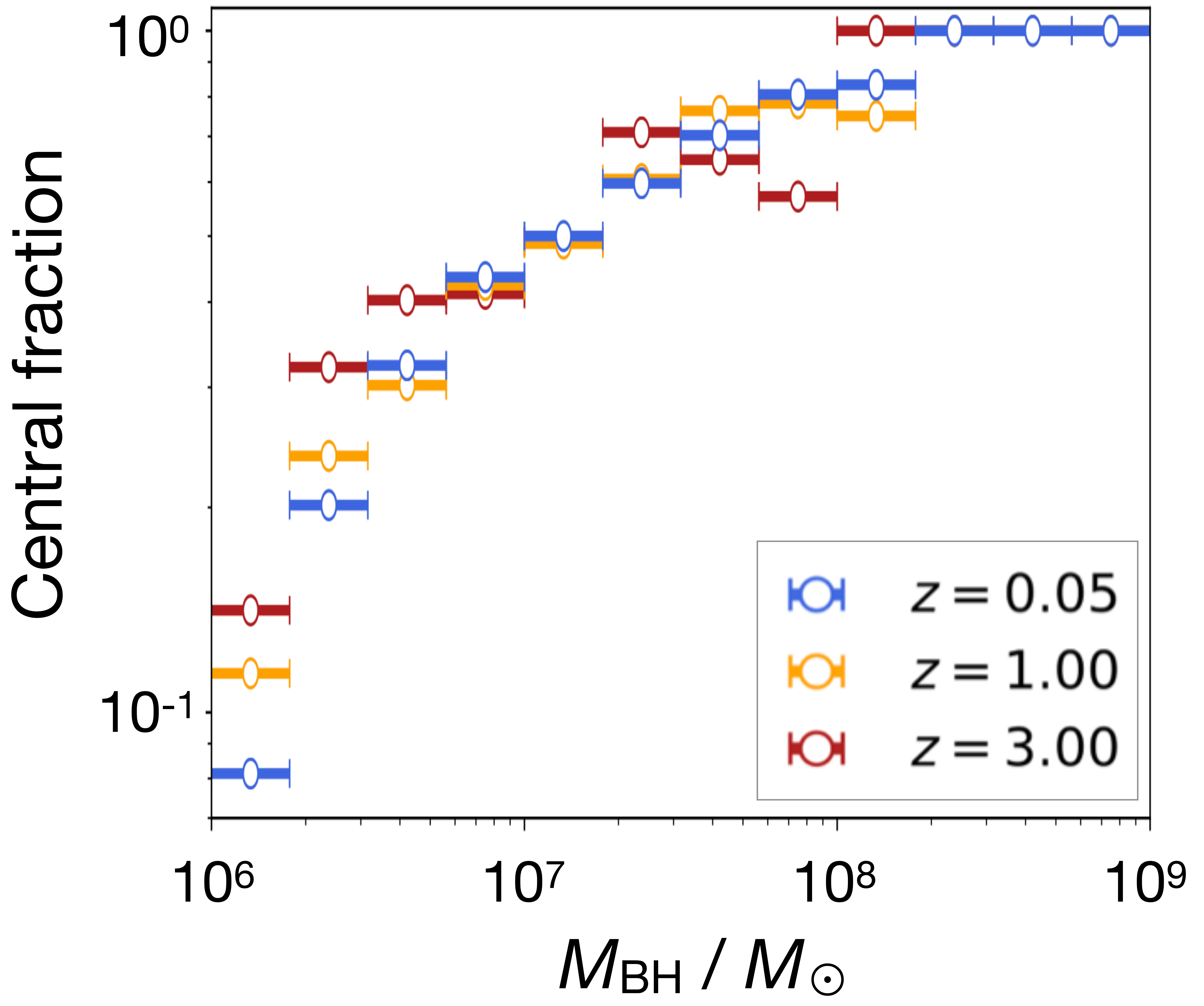


Ricarte+2021a

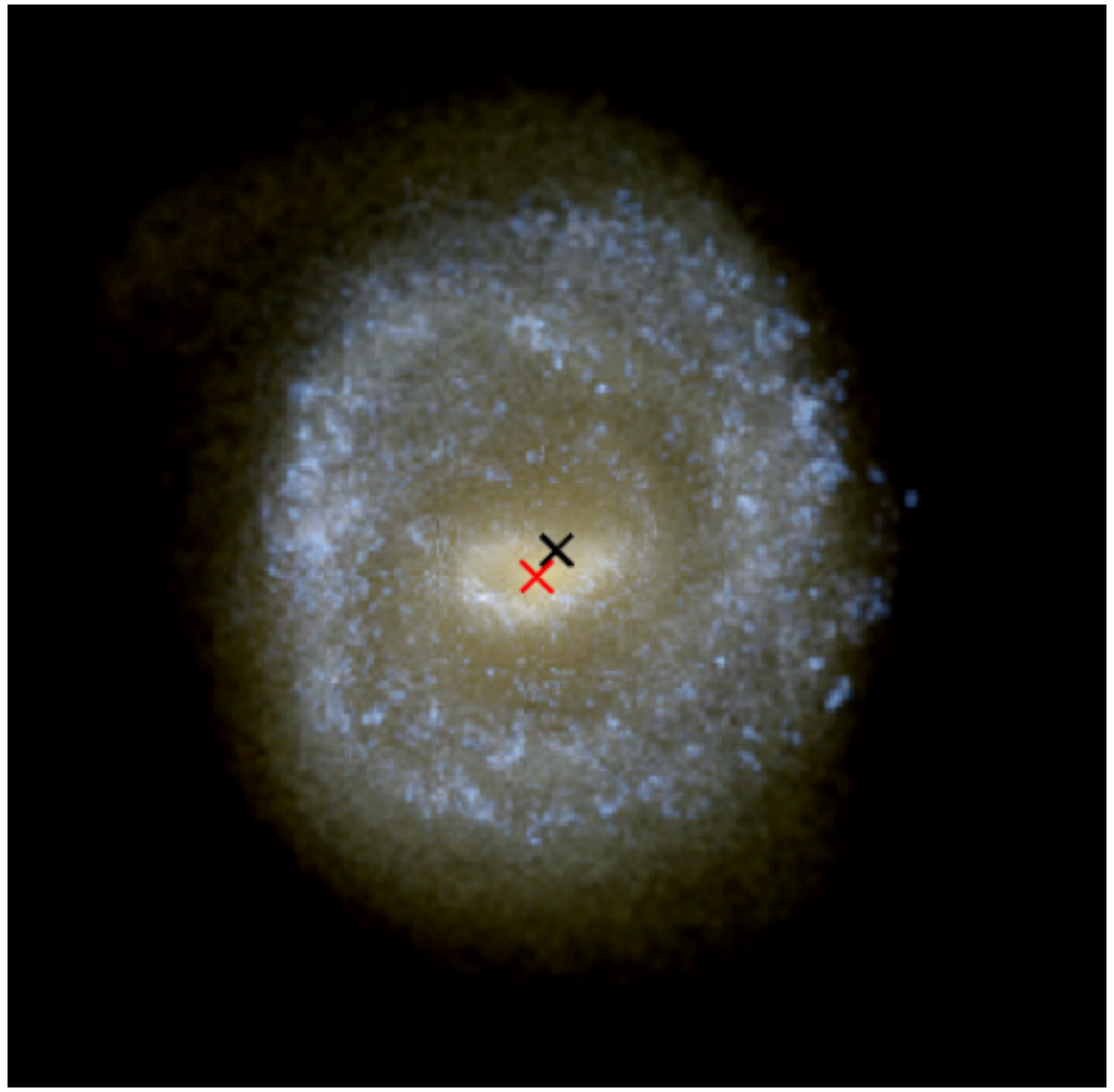
Dominate in low-mass MBHs



Ricarte+2021b

Origin of offset MBHs

Channel 1: From mergers with a DF timescale longer than the age of the Universe



Tremmel+2018, Ricarte+2021a,b

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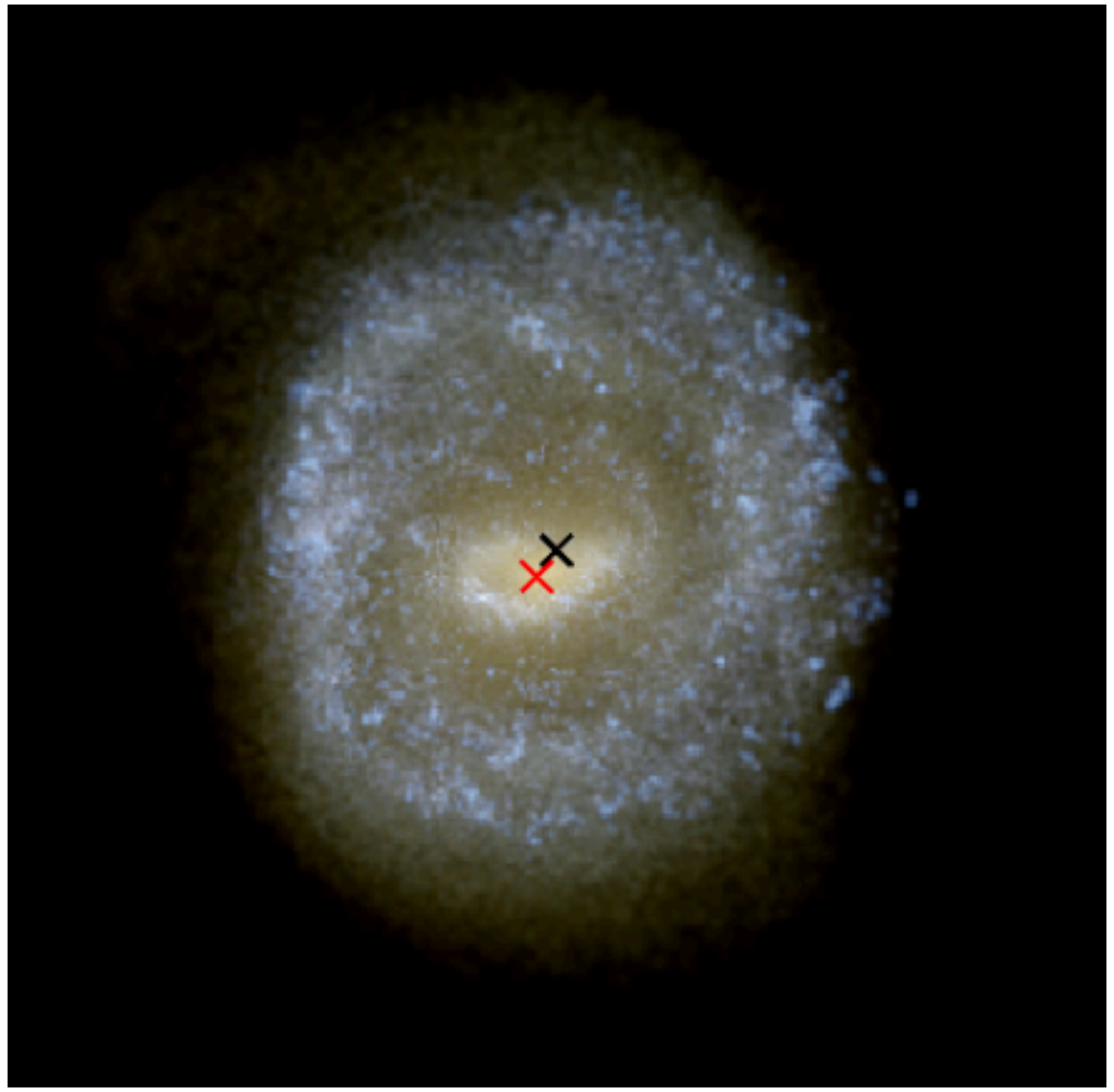
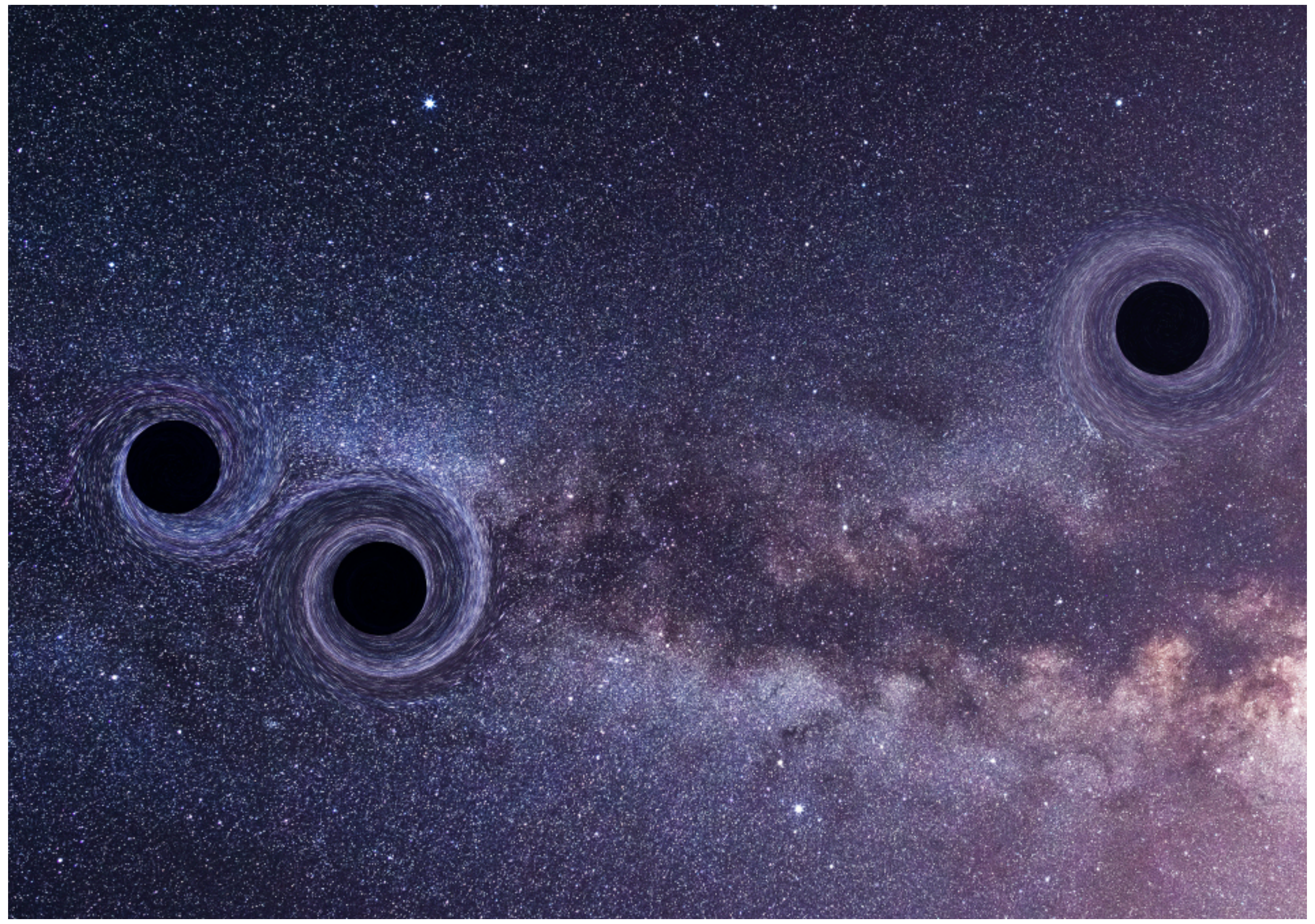


Tremmel+2018, Ricarte+2021a,b

Channel 2: From 3-body interaction "slingshot kick"



Hoffman & Loeb 2007, Bonetti+2018, Ryu+2018

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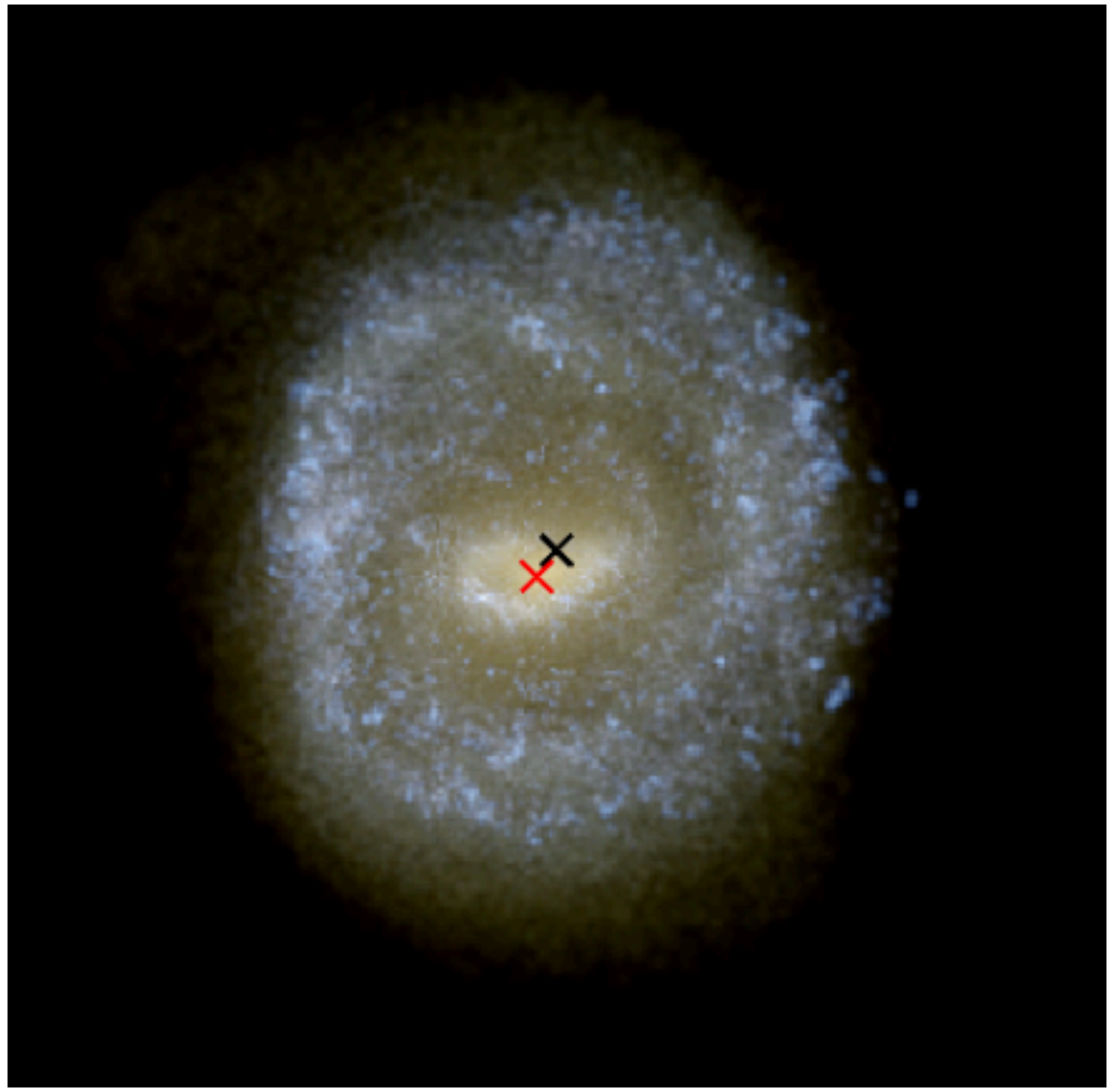

Tremmel+2018, Ricarte+2021a,b

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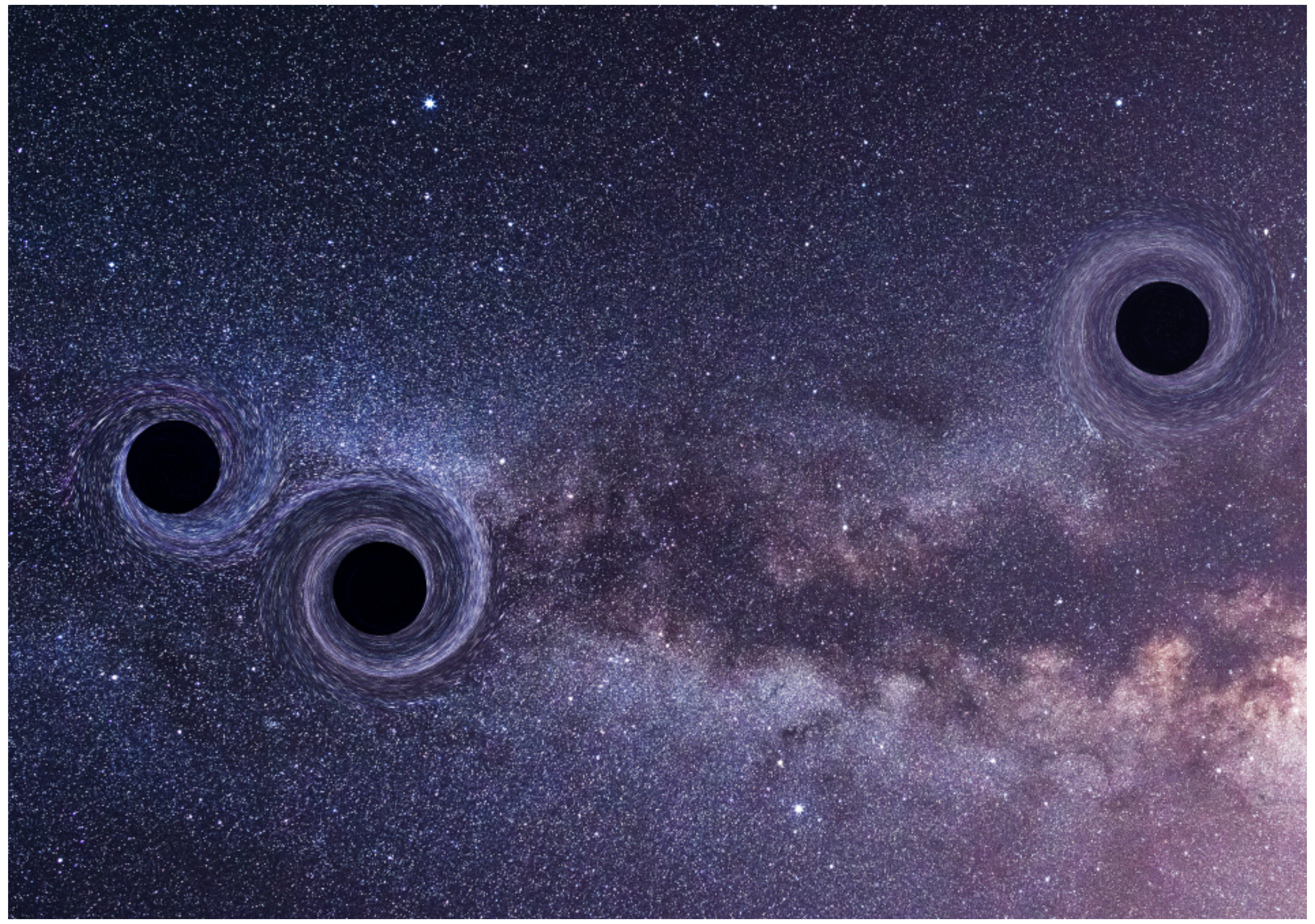
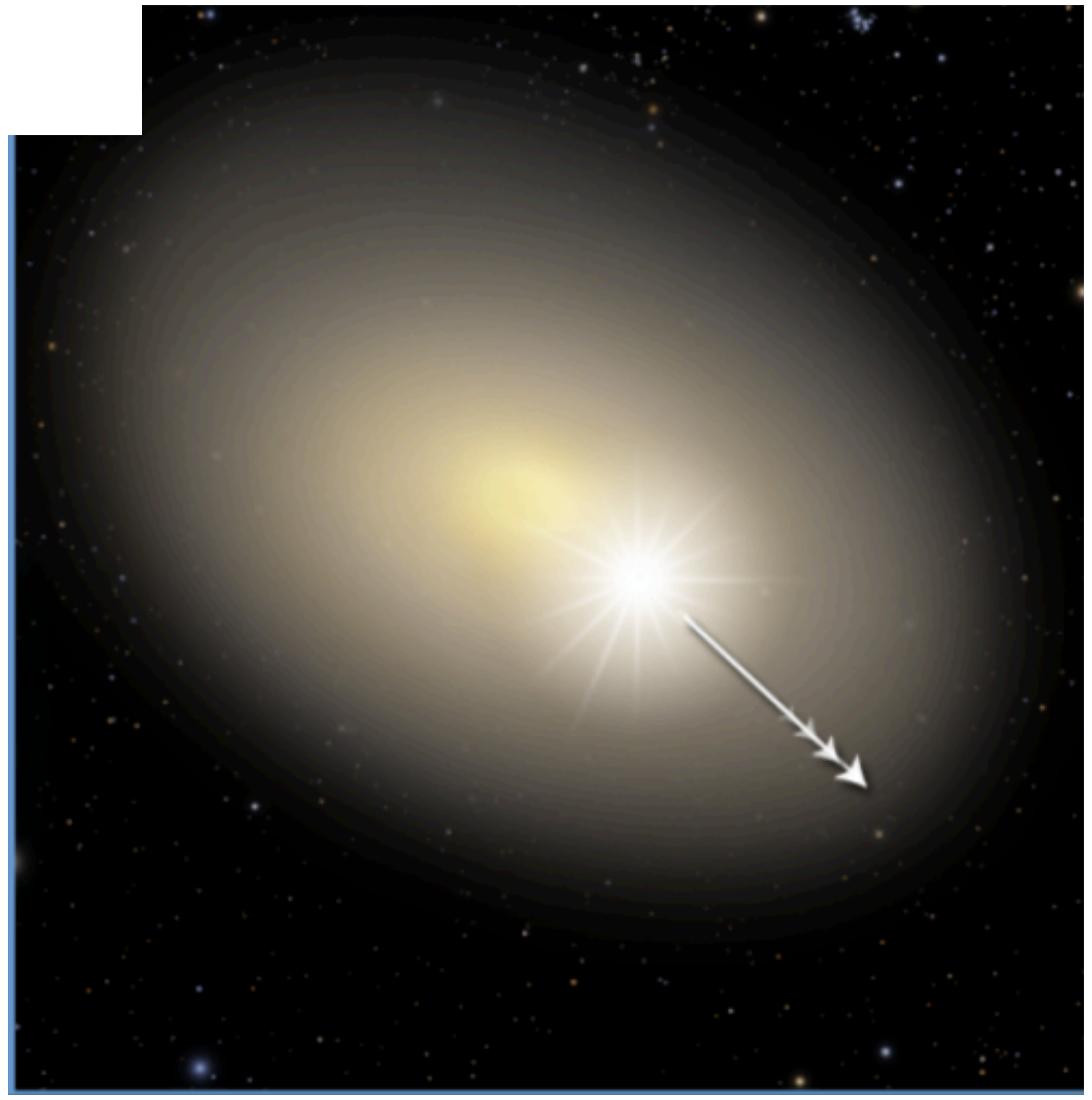


Hoffman & Loeb 2007, Bonetti+2018, Ryu+2018

Channel 3: From gravitational wave kick

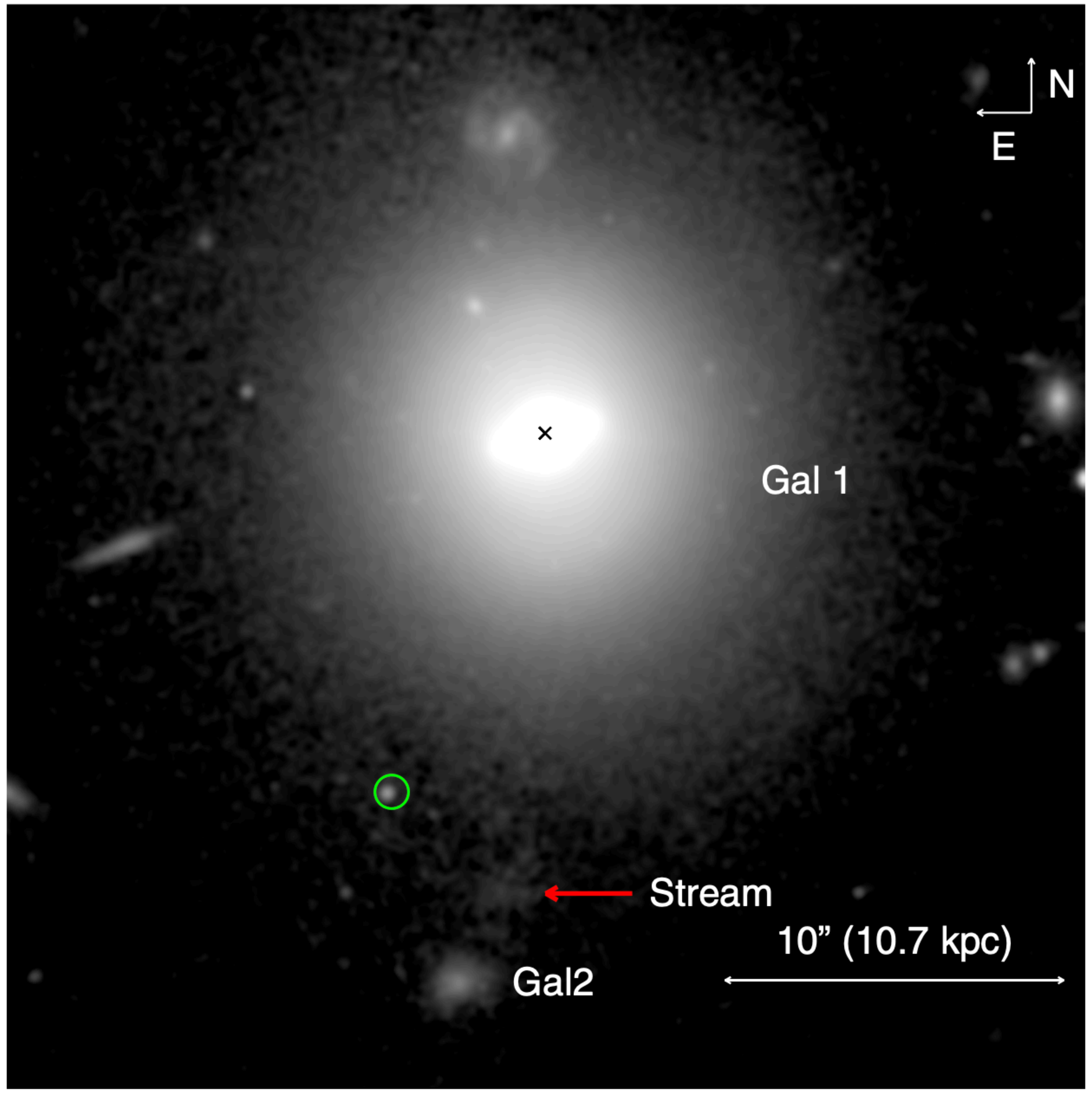


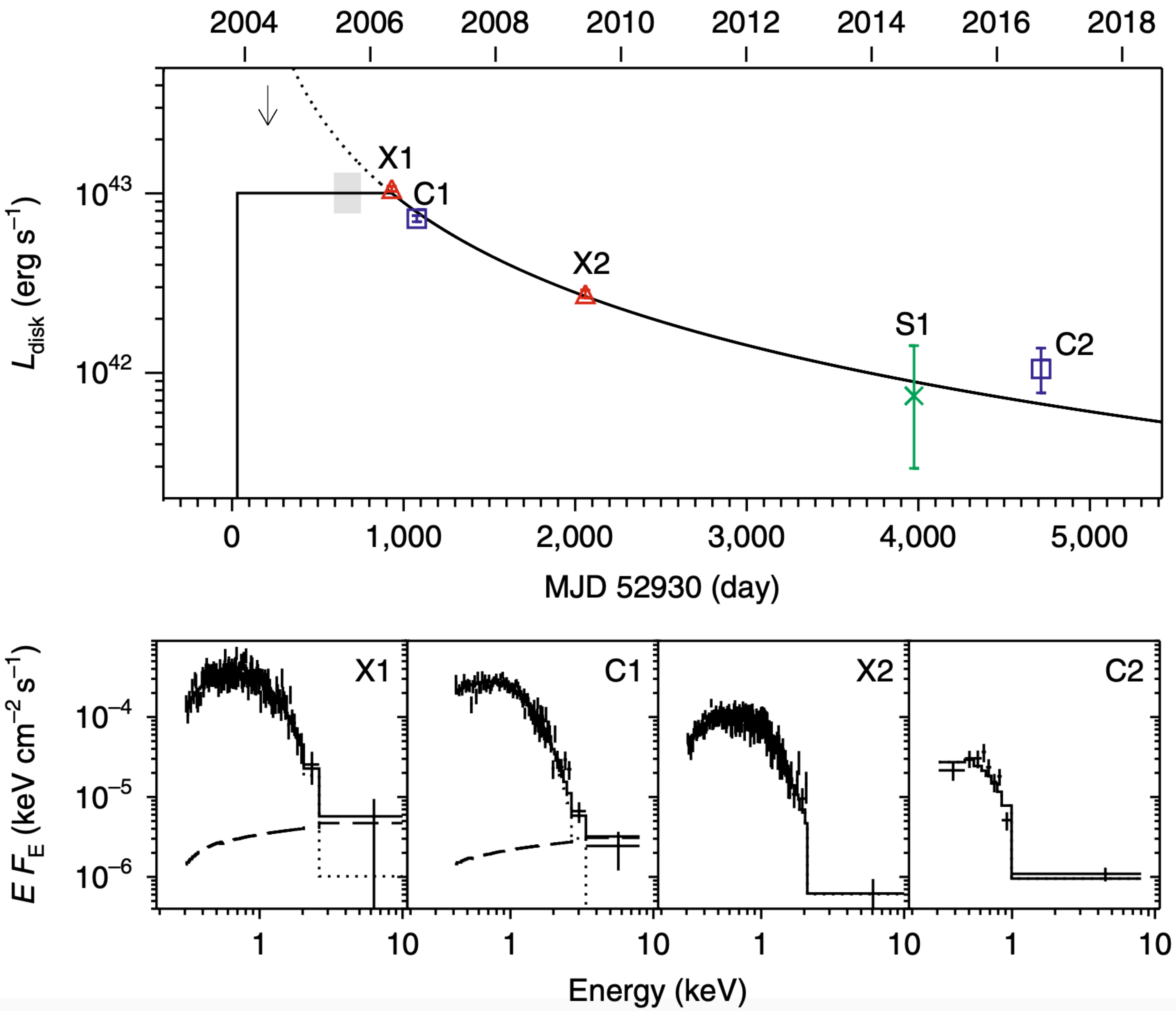
Volonteri & Madau 2008, Stone & Loeb 2011, Blecha+2016

1st offset TDE: XMM Archival Search

Lin+2018, 2020

3XMM J2150; 12.5 kpc offset

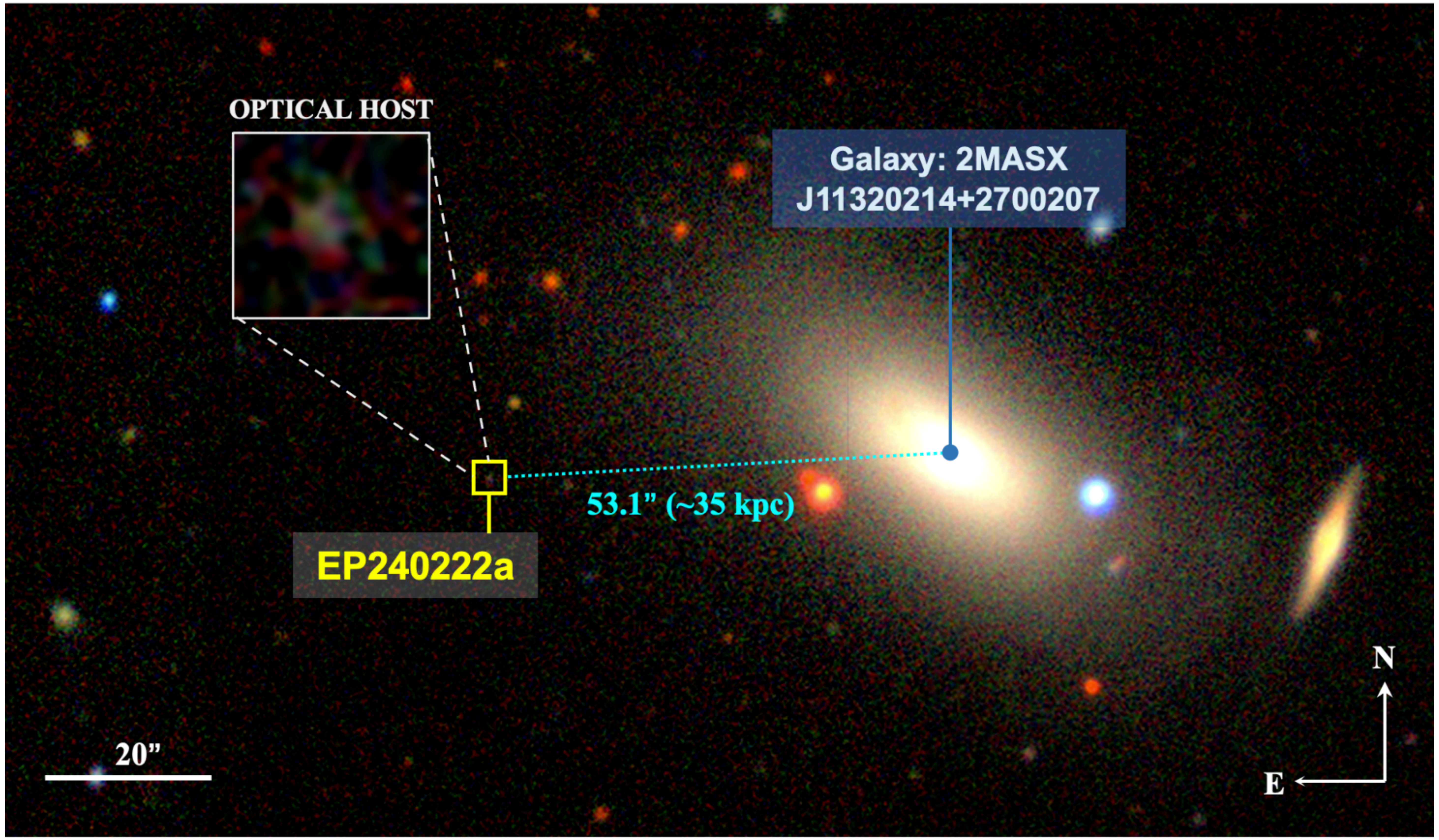


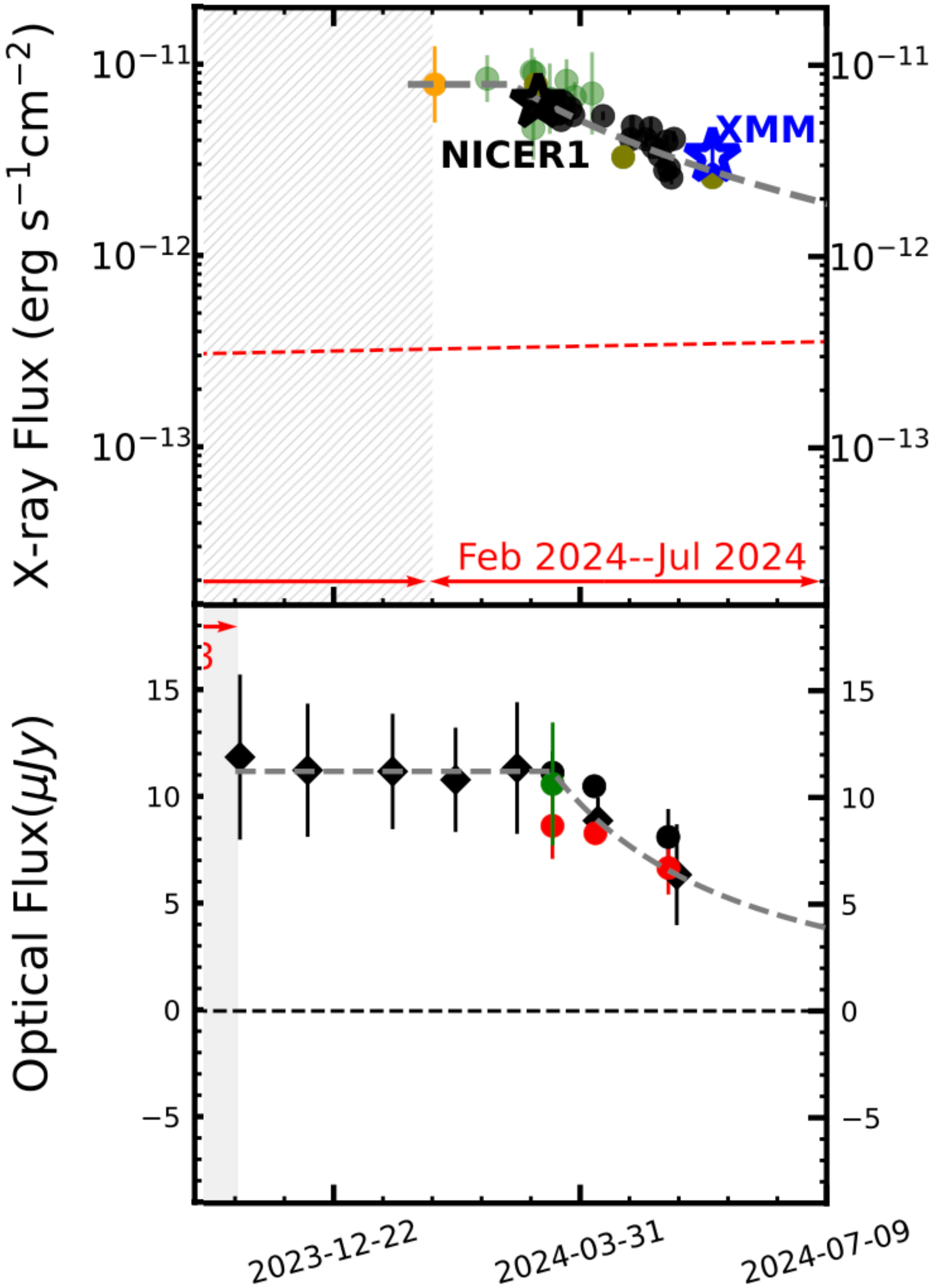


2nd offset TDE: Einstein Probe Discovery

Jin+2025

EP240222a; 34.7 kpc offset



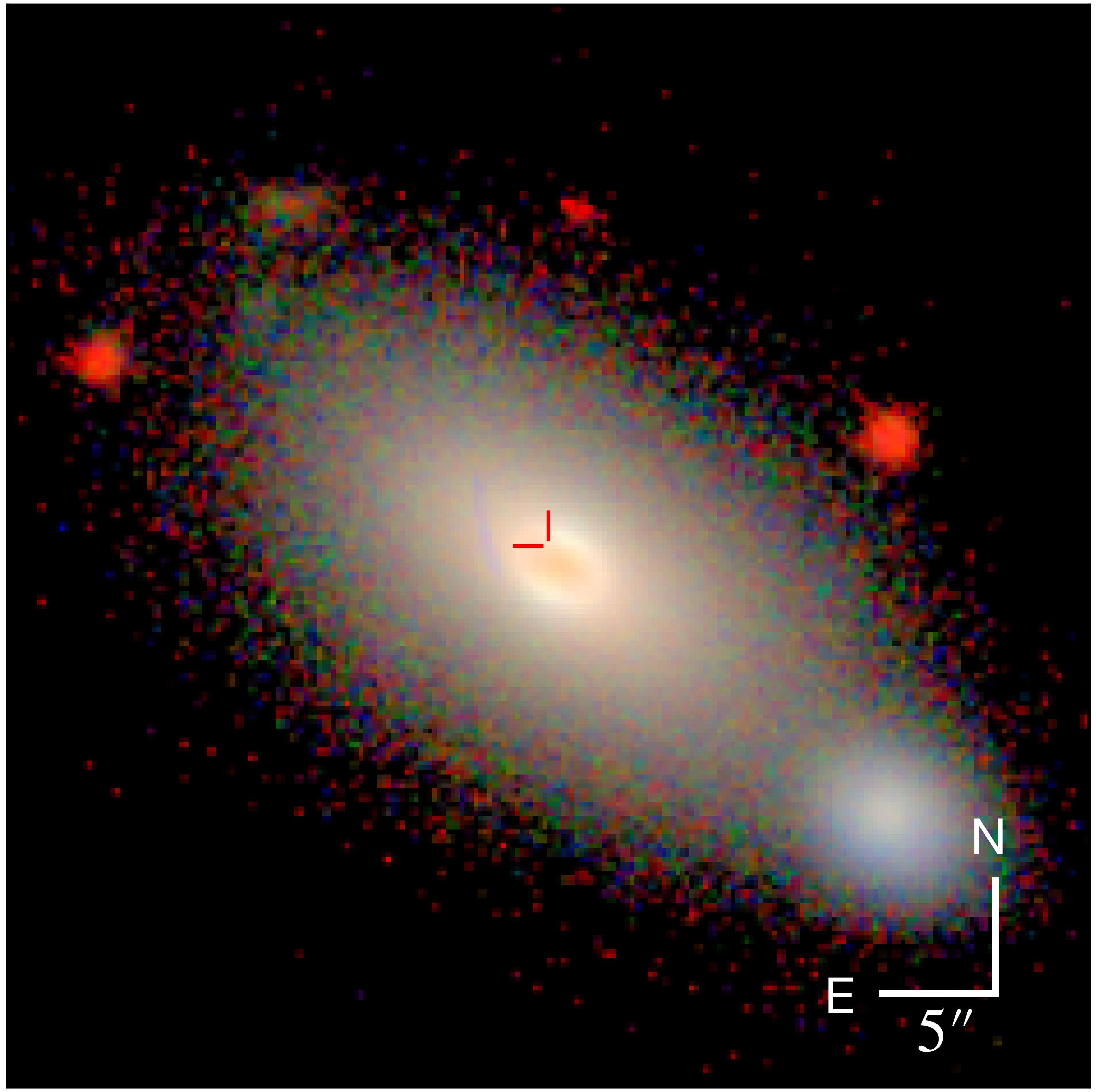


Yao+2025, submitted
arxiv: 2502.17661

3rd offset TDE: ZTF Discovery

AT2024tvd

ZTF location of AT2024tvd within its host galaxy (legacy survey image)

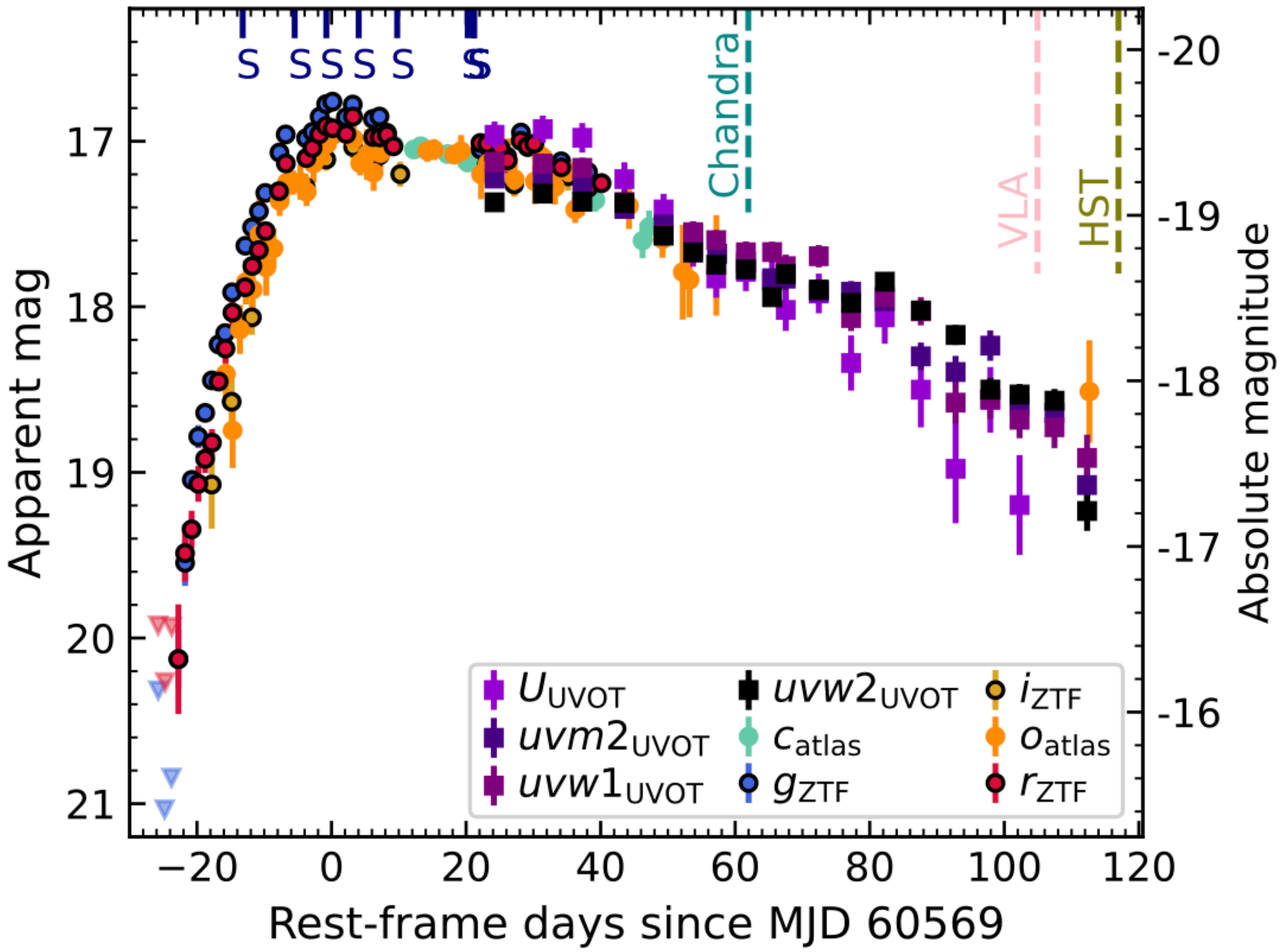


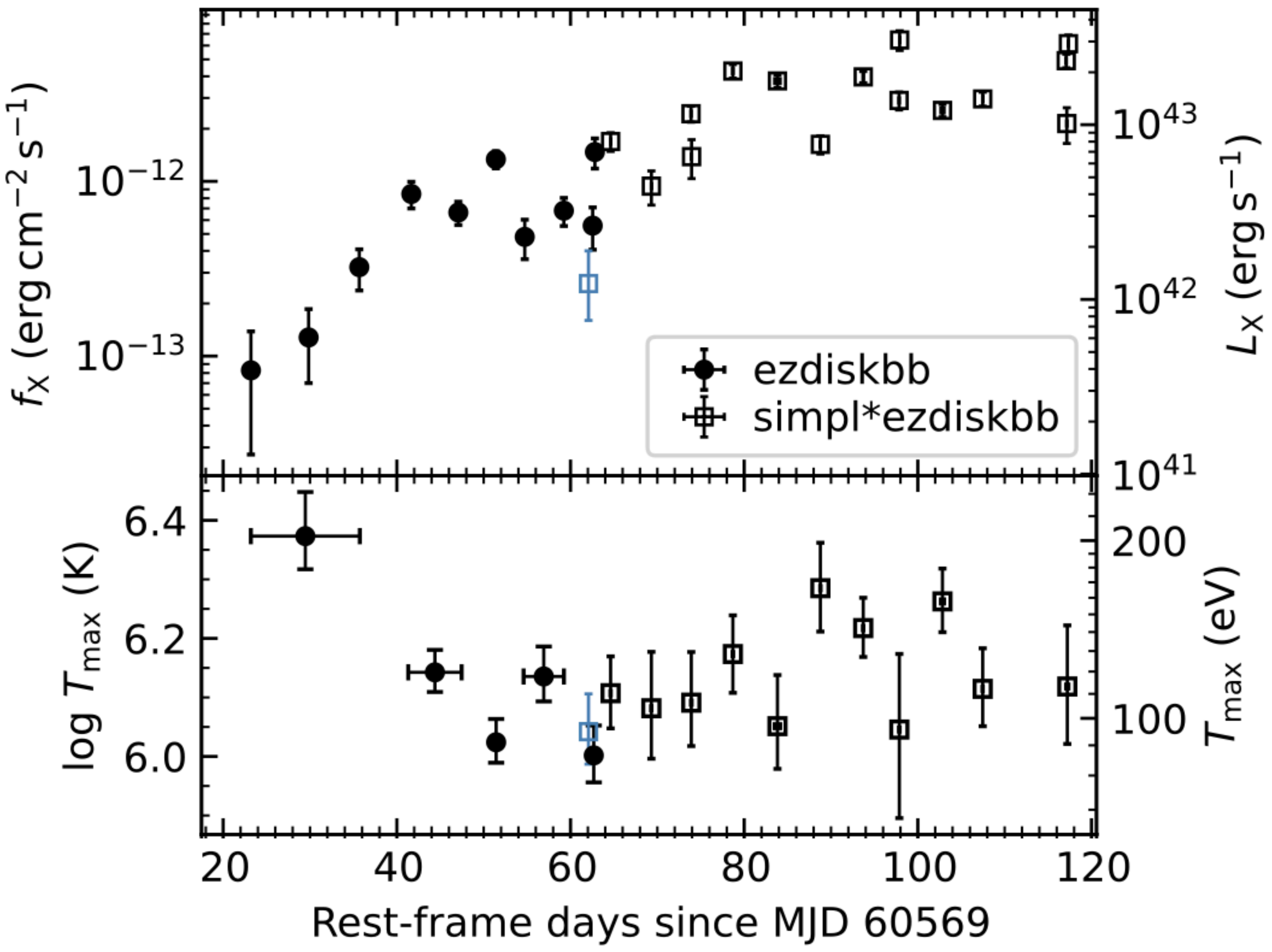
Yao+2025, submitted
arxiv: 2502.17661

3rd offset TDE: ZTF Discovery

AT2024tvd

$$10^5\,M_\odot < M_{\rm BH,offset} < 10^7\,M_\odot$$





3rd offset TDE: ZTF Discovery

AT2024tvd

Yao+2025, submitted
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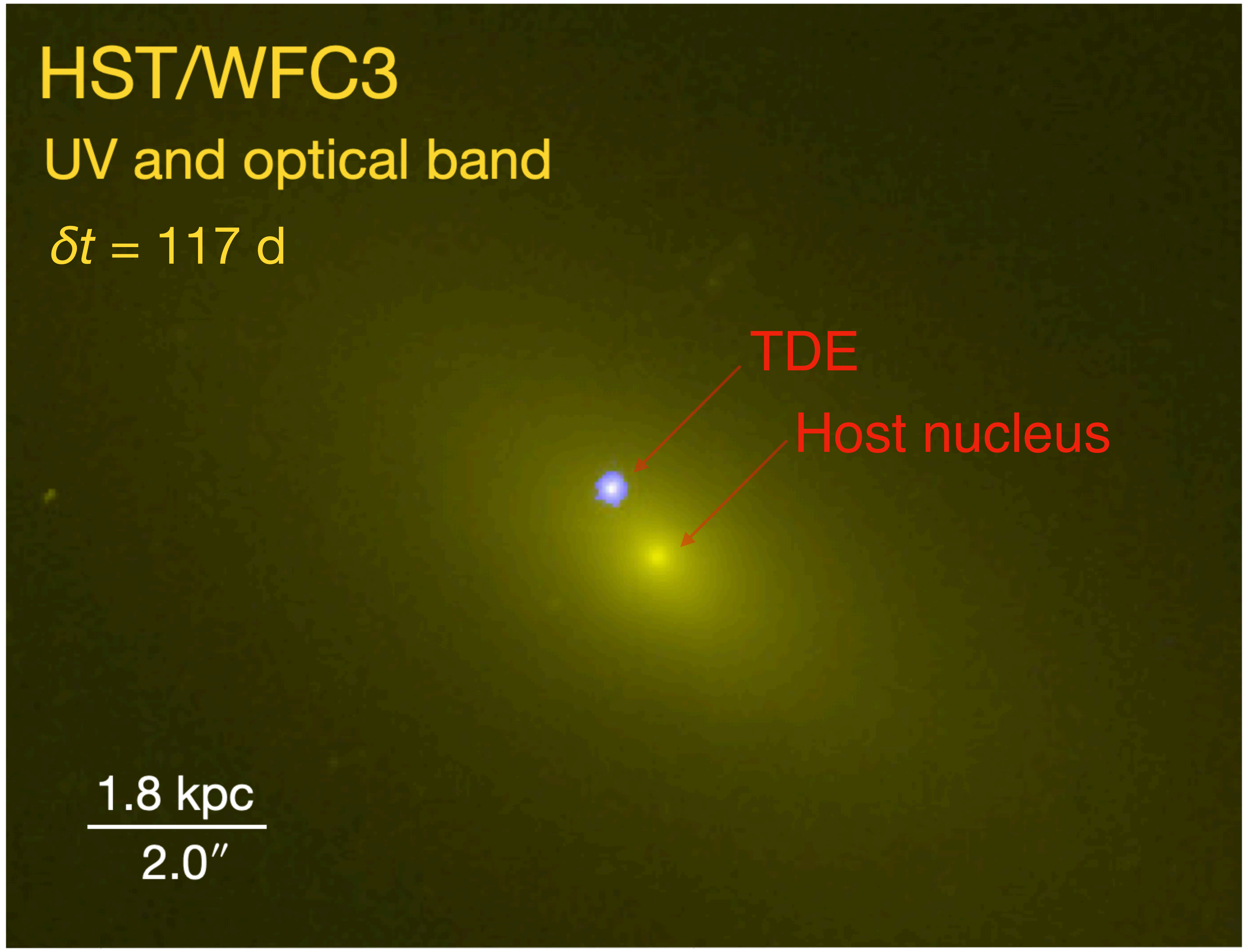
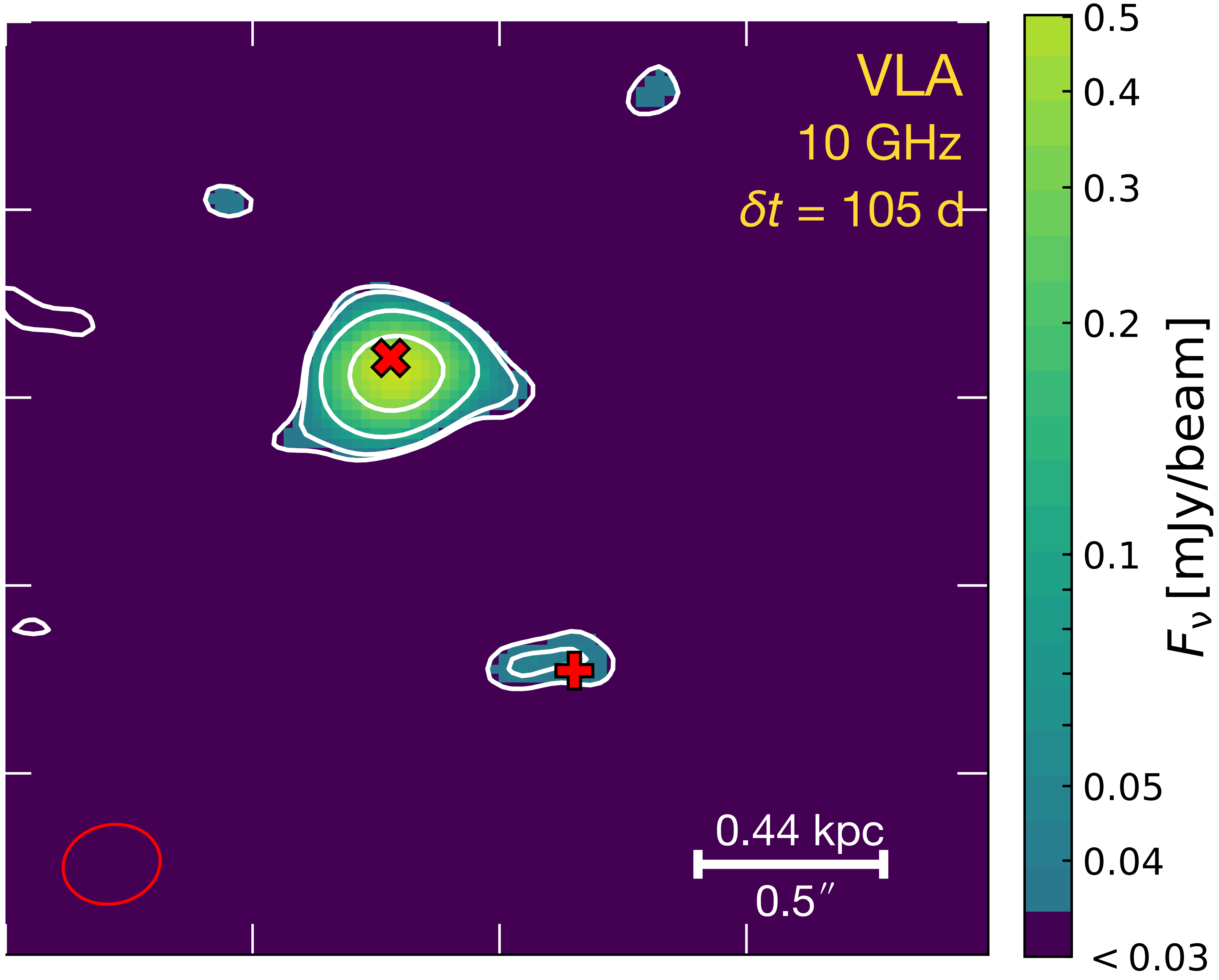
$10^5\,M_\odot < M_{\rm BH,offset} < 10^7\,M_\odot$



Separation Δx=0.8 kpc (0.9")

$M_{\rm BH,central} \sim 10^{8.4}\,M_\odot$



See also radio paper by Sfaradi+2025, in prep

Yao+2025, submitted
arxiv: 2502.17661

Summary of off-nuclear TDEs

Name	z	offset (kpc)	Parent galaxy stellar mass ($M_\odot$)	Satellite dwarf stellar mass ($M_\odot$)	Central M_{BH} ($M_\odot$)	TDE M_{BH} ($M_\odot$)	Origin channel
3XMM J2150	0.055	12.5	$10^{10.93\pm0.07}$	$10^{7.3\pm0.4}$	$10^{8.16\pm0.83}$	$\sim10^{4.9}$	1
EP240222a	0.033	34.7	$10^{10.89\pm0.07}$	$10^{7.0\pm0.3}$	$10^{8.09\pm0.83}$	$\sim10^{4.9}$	1
AT2024tvd	0.045	0.81	$10^{10.93\pm0.02}$	N/A	$10^{8.42\pm0.36}$	$\sim10^{6}$	1 or 2

Yao+2025, submitted
arxiv: 2502.17661

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All in massive galaxies with $\sim10^{10.9}$ $M_\odot$ — cut-off mass of local galaxy mass function.

Consistent with expectation: massive galaxies have rich merger history, host more wandering MBHs.

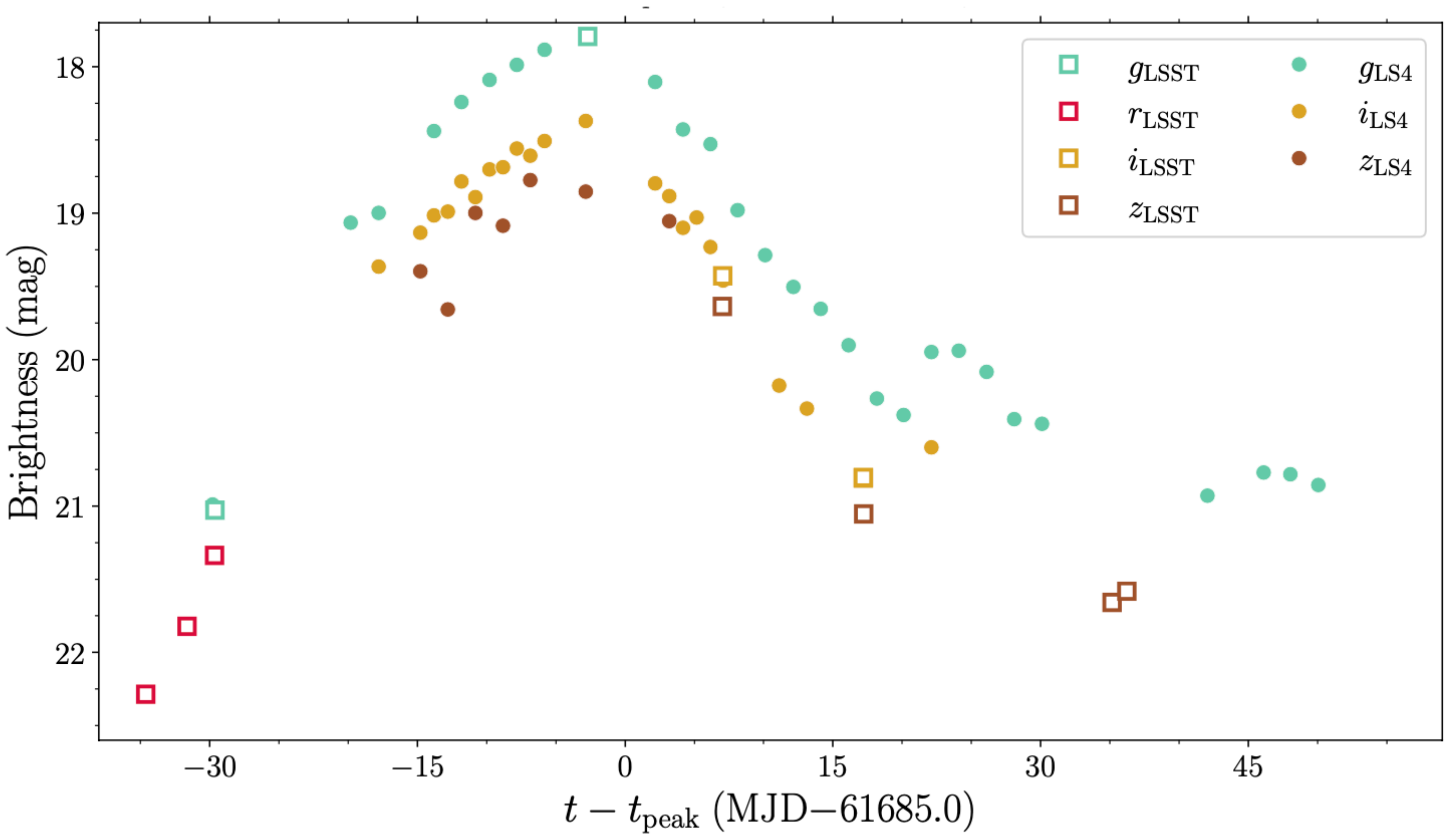
New (optical) surveys to explore TDEs

La Silla Schmidt Southern Survey (LS4)

Miller+2025

arxiv: 2503.14579

- Observable sky dec<20 deg
- Filters: *g*, *i*, *z*
- FoV: 20 deg²
- Limit AB mag ~ 21
- Fills Rubin light curve with high-cadence data



Rubin/LSST

- Filters: *u*, *g*, *r*, *i*, *z*, *y*
- FoV: 9.6 deg²
- Limit AB mag ~ 24.5
- Astrometric precision of ~10 mas

TDEs as MBH Probes

- Little (M_{BH} ~ few x 10^5 $M_\odot$) MBHs are more abundant then bigger ones.
- Three known offset TDEs, all have massive parent galaxies, two from IMBHs.
- LSST and LS4 will uncover the population of nuclear & offset TDEs, illuminate how MBHs formed and grew.
- Contamination rate is high at off-center locations (mostly from interaction powered supernovae), UV (*Swift+UVEX*) is needed to better select TDEs.

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