

Compact Accretion Disks in the Aftermath of Tidal Disruption Events: Parameter Inference from Joint X-ray Spectra and UV/Optical Photometry Fitting

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ABSTRACT

We present a multi-wavelength analysis of 14 tidal disruption events (TDEs)—including an off-nuclear event associated with an ultra-compact dwarf galaxy—selected for having available thermal X-ray spectra during their late-time UV/optical plateau phase. We show that at these stages, the full spectral energy distribution—X-ray spectra and UV/optical photometry—is well described by a compact, yet standard accretion disk, the same disk which powers the X-rays at all times. By fitting up to three epochs per source with a fully relativistic disk model, we show that many system properties can be reliably recovered, including importantly the black hole mass ($M_{\bullet}$). These accretion-based $M_{\bullet}$ values, which in this sample span nearly three orders of magnitude, are consistent with galactic scaling relations but are significantly more precise (68% credible interval $< \pm 0.3$ dex) and physically motivated. Expected accretion scaling relations (e.g., $L_{\text{Bol}}^{\text{disk}}/L_{\text{Edd}} \propto T_p^4 \propto M_{\bullet}^{-1}$), TDE-specific physics correlations ($L_{\text{plat}} \propto M_{\bullet}^{2/3}$ and $R_{\text{out}}/r_g \propto M_{\bullet}^{-2/3}$) and black hole–host galaxy correlations ($M_{\bullet}$ – M_{gal} and $M_{\bullet}$ – σ_*) naturally emerge from the data and, for the first time, are self-consistently extended into the intermediate-mass (IMBH, $M_{\bullet} < 10^5$) regime. We discuss the implications of these results for TDE physics and modeling. We also review and discuss different methods for $M_{\bullet}$ inference in TDEs, and find that approaches based on physical models of the early-time UV/optical emission are not able to recover (at a statistically significant level) black hole–host galaxy scalings.

Keywords: Tidal disruption (1696); X-ray transient sources (1852); Supermassive black holes (1663); Time domain astronomy (2109); High energy astrophysics (739); Accretion (14)

1. INTRODUCTION

Tidal disruption events (TDEs) occur when a star is scattered onto a near-radial orbit around a massive black hole and approaches within the radius at which the tidal forces exerted by the black hole exceeds the star’s own self-gravity. The star is then disrupted, forming a stream of debris whose subsequent evolution ultimately powers a bright flare observed across the electromagnetic spectrum (Rees 1988; Gezari 2021). These rare transients provide clean laboratories for fundamental studies of black hole accretion and turbulence (e.g., Cannizzo et al.

1990; Balbus & Mummery 2018; Mummery 2025a), as well as being unique probes of the demographics of otherwise quiescent black holes in the local Universe (Frank & Rees 1976; Stone & Metzger 2016; Yao et al. 2023; Mummery & van Velzen 2025; Yao et al. 2025).

Importantly, TDEs are particularly sensitive to those black holes at the low-mass end of the black hole mass function, a regime at which TDE observations will prove crucial for understanding black hole growth and seed formation (Kormendy & Ho 2013; Shankar et al. 2016; Greene et al. 2020). If they can be well understood,

TDEs will also inform broader questions in galaxy evolution, such as the black hole occupation fraction in dwarf galaxies (Silk 2017; Bradford et al. 2018; Zou et al. 2025) and the dynamical evolution of dense stellar systems (Miller & Hamilton 2002; Stone & Metzger 2016). This is because TDEs offer a (perhaps the most) promising avenue with which to study accreting intermediate-mass black holes (IMBHs; $10^3\text{--}10^5 M_\odot$), a population still poorly constrained observationally (Greene et al. 2020), with only a handful of strong candidates reported (Farrell et al. 2009; Soria et al. 2017; Lin et al. 2018; Jin et al. 2025). Confirming the masses of TDEs associated with IMBH candidates can shed light on their demographics, formation pathways, and the mass-scale (in)dependence of accretion physics, bridging the gap between stellar-mass and supermassive black holes. This is particularly important for off-nuclear IMBHs, which may otherwise remain undetectable, as gas accretion onto such systems is expected to be negligible in the local Universe (Ricarte et al. 2021).

Realizing this potential of TDEs as probes of black hole demographics depends critically on two requirements: (i) a robust understanding of the physical processes powering their multi-wavelength emission; and (ii) methods capable of *reliably and consistently* recovering key system parameters, especially black hole mass ($M_\bullet$).

While TDEs were first identified as high-energy (X-ray) transients powered by the accretion of the disrupted stellar debris (e.g., Bade et al. 1996; Komossa & Greiner 1999), wide-field optical time-domain surveys have since become the dominant discovery channel. A “canonical”¹ TDE is now typically discovered as a luminous optical flare (van Velzen et al. 2021; Yao et al. 2023), which may or may not coincide with rapid X-ray brightening (e.g., Guolo et al. 2024a). Optical luminosities peak at $L \sim 10^{42}\text{--}10^{44} \text{ erg s}^{-1}$ and decline on month-long timescales (Hammerstein et al. 2023; Yao et al. 2023). On longer timescales (years), a pronounced plateau in their UV/optical light curves (van Velzen et al. 2019a; Mummery & Balbus 2020) dominates, most easily detected in the UV but also observed in the optical (Mummery et al. 2024b). This plateau marks the transition from the poorly understood early-time flare to a long-

lived disk-dominated phase (Cannizzo et al. 1990; Mummery & Balbus 2020; Mummery et al. 2024b).

The physical origin of the early-time UV/optical flare observed from these optically-selected TDE remains uncertain—although it is known that it cannot arise directly from a compact disk—with no current consensus in the community. The two common interpretations are emission from stream–stream shocks (e.g., Ryu et al. 2023) or reprocessing of high-energy radiation by a wind/envelope (e.g., Dai et al. 2018); see Roth et al. (2016) for a review. Parameter inference, particularly of the black hole mass $M_\bullet$ (which can be independently probed with galaxy properties) using analytical prescriptions based on these models (e.g., Ryu et al. 2020a; Mockler et al. 2019), while initially considered successful, relied on individual sources or very small samples of a few sources. Later population level studies showed that these models have not yet been successful in reproducing either (i) established black hole–host galaxy property correlations (e.g., Ramsden et al. 2022; Hammerstein et al. 2023), or (ii) empirical relations between observables (e.g., peak UV/optical luminosity) and black hole mass (Mummery et al. 2024b; Mummery & van Velzen 2025), casting doubt on their accuracy for inferring physical parameters.

By contrast, Mummery et al. (2024b) recently showed that the observed luminosity reached during the late-time “plateau” phase – originating physically from the simultaneous cooling and expansion of the disk – correlates strongly with host galaxy mass (used as a proxy for black hole mass), with the observed correlation emerging naturally from time-dependent accretion disk theory (Mummery & Balbus 2020; Mummery et al. 2024b). Meanwhile, X-ray emission has been firmly established as originating from the innermost regions of newly formed accretion disk (Mummery & Balbus 2020; Wen et al. 2022). Observed as very soft thermal radiation (Saxton et al. 2020; Guolo et al. 2024a), this X-ray emission should, in principle, encode information about the central black hole. Attempts to use this thermal X-ray emission as a mass diagnostic have had some success—both spectrally (e.g., Wen et al. 2020, 2021; Mummery et al. 2023; Jin et al. 2025) and in the time-domain regime (e.g., Mummery & Balbus 2020; Mummery 2021)—but have remained limited by parameter degeneracies, sparse temporal coverage, and the small number of TDEs with high-quality X-ray data.

These findings naturally suggest that the X-ray and UV/optical “plateau” emission arise from the same accretion disk, in agreement with the luminosity function results of Mummery & van Velzen (2025). However, no detailed spectral analysis of the TDE popula-

¹ This classification reflects observational capabilities rather than intrinsic properties: optical discoveries dominate numerically because of survey efficiency not intrinsic higher rate, in fact X-ray emission is physically better understood than the early time optical flare, and their intrinsic rates are consistent in both channels (Yao et al. 2023; Sazonov et al. 2021).

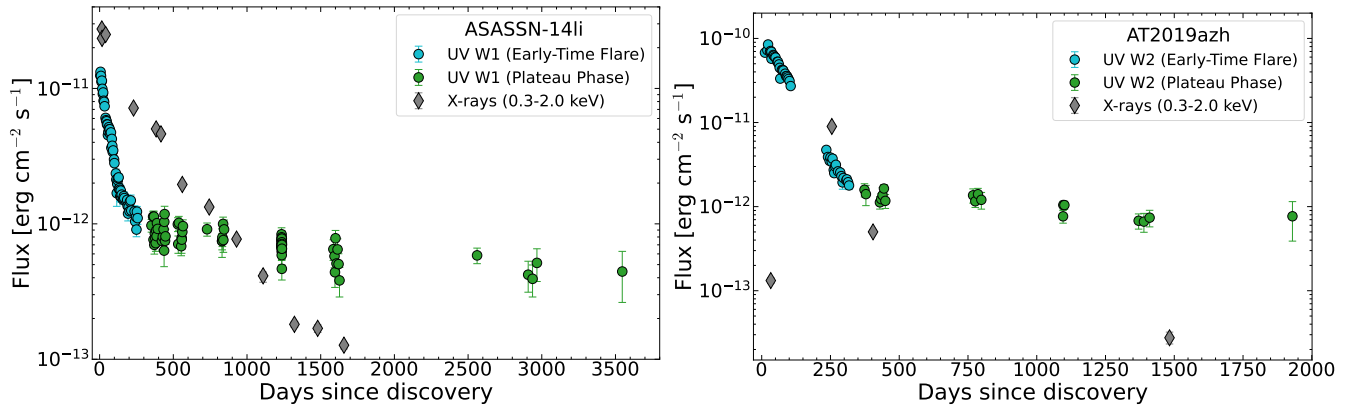


Figure 1. Examples of host-subtracted light curves of well observed TDEs, ASASSN-14li (left) and AT2019azh (right). The two phase UV/optical light curves (early-time flare vs. Plateau) is ubiquitous to TDEs independently of whether X-ray are prompt or delayed. Fluxes shown are not corrected for for any absorption or extinction.

tion has been performed with the aim of testing this key prediction of TDE accretion theory. While some individual sources have been analyzed in this spirit, this has typically been limited to integrated luminosities in the time-domain regime (i.e., optical/X-ray light curve fitting, e.g., Mummery & Balbus 2020; Goodwin et al. 2022, 2024; Nicholl et al. 2024; Chakraborty et al. 2025; Mummery et al. 2024a), which does not utilize the full spectral information available in multi-wavelength multi-epoch data. If the optical–X-ray TDE accretion disk paradigm is correct, it implies that X-ray *spectra* and UV/optical photometry during the “plateau” phase should be simultaneously described by a single disk model.

Until recently, testing this paradigm directly on the population level was not possible: models with the expected characteristics of TDE disks—compact (i.e., small radial extent), thermal, and typically lacking persistent coronal emission—were not available in forms suitable for fitting simultaneous X-ray spectra (e.g. via XSPEC; Arnaud 1996a) and UV/optical photometry. This limitation was overcome by Guolo & Mummery (2025), who implemented such models. Early applications to individual sources (Guolo & Mummery 2025; Wevers et al. 2025; Guolo et al. 2025b) demonstrated their feasibility, paving the way for broader ensemble studies.

The aim of this paper is to show that joint fitting of X-ray spectra and plateau-phase UV/optical photometry with a single disk model is feasible across a diverse sample of TDEs, and that such fits provide compelling evidence for a common disk origin of both (optical–X-ray) emission components. We demonstrate that this approach yields robust inferences of key system parameters—including (for the first time on the population level) black hole masses, spins, and disk sizes. With

these spectral fits we demonstrate that both general accretion disk scaling relations and also those which are specific to TDE disks naturally emerge. Moreover, we show that host–black hole correlations are independently recovered, consistent with other accretion-based relations (e.g., $L_{\text{plat}}-M_{\bullet}$; Mummery et al. 2024b), but at substantially higher precision. This gain in precision arises from the data – multi-wavelength fits simultaneously probe the inner and outer disk, thereby breaking degeneracies and reducing intrinsic scatter.

The structure of this paper is as follows: in §2, we describe our sample and data. Our adopted model and fitting procedures are described §3. In §4 we present our results, which are discussed in broader context in §5. Our conclusions are presented in §6. We adopt a standard Λ CDM cosmology with a Hubble constant $H_0 = 73 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Riess et al. 2022). A Bayesian statistics framework is considered throughout the paper, converging posterior for inferred parameters are reported as median and the uncertainties correspond to the 68% credible intervals, while upper (lower) limits on one side converged posteriors are 90% (10%) credible intervals.

2. SAMPLE AND DATA

Our goal is to analyze the full spectral energy distribution (SED) of TDEs in the late-time “plateau” phase using disk models. It is important, therefore, to define our labeling of the different emission phases carefully. Following, e.g., van Velzen et al. (2019b); Mummery et al. (2024b); Mummery & van Velzen (2025), we divide UV/optical TDE light curves into two phases, which we refer to as the “early-time phase” and the “late-time

Table 1. Sample Information

Source	t_0 (MJD)	z	$E(B - V)_G$	$N_{\text{H,G}}$ (cm^{-2})	$\log_{10}(M_{\text{gal}})$ ($M_{\odot}$)	σ_* (km s^{-1})	Reference
AT2019qiz	58536	0.015	0.09	6.3×10^{20}	10.0 ± 0.2	72 ± 2	(1, 2, 3)
GSN 069	55391	0.018	0.02	2.3×10^{20}	9.8 ± 0.1	63 ± 4	(4, 5, 6)
AT2021ehb	59276	0.018	0.12	9.9×10^{20}	10.2 ± 0.1	93 ± 5	(7, 8)
ASASSN-14li	56983	0.021	0.02	1.9×10^{20}	9.7 ± 0.2	81 ± 2	(9, 10, 11)
AT2019azh	58533	0.022	0.04	4.1×10^{20}	9.9 ± 0.1	68 ± 2	(12, 13)
AT2022dsb	59627	0.023	0.19	1.1×10^{21}	10.6 ± 0.3	84 ± 4	(14, 15, this work)
AT2022lri	59665	0.032	0.015	1.6×10^{20}	9.6 ± 0.1	33 ± 2	(16, 17)
ASASSN-15oi	57248	0.048	0.06	4.8×10^{20}	10.1 ± 0.1	61 ± 7	(18, 19, 20)
AT2018cqh	58283	0.048	0.02	2.4×10^{20}	9.5 ± 0.1	53 ± 10	(21, 22)
AT2019dsg	58582	0.051	0.08	6.6×10^{20}	10.5 ± 0.1	87 ± 4	(23, 24)
3XMM J2150-05	53681	0.055	0.03	2.8×10^{20}	7.3 ± 0.4	...	(25, 26)
AT2023cvb	60016	0.071	0.19	7.5×10^{20}	10.5 ± 0.2	79 ± 5	(27, this work)
AT2019vcb	58803	0.089	0.015	1.5×10^{20}	9.7 ± 0.1	42 ± 8	(28, 29, 30, this work)
AT2020ksf	58951	0.092	0.04	3.6×10^{20}	9.9 ± 0.1	56 ± 2	(31, 32)

NOTE— t_0 corresponds to the first detection of the TDE, in any wavelength. Galaxy extinction color-excess $E(B - V)_G$ values are from [Schlafly & Finkbeiner \(2011\)](#), and Galactic hydrogen-equivalent column density $N_{\text{H,G}}$ from the HI4PI survey ([HI4PI Collaboration et al. 2016](#)). (1, 2, 3) [Siebert et al. \(2019\)](#); [Nicholl et al. \(2020, 2024\)](#); (4, 5, 6) [Saxton et al. \(2011\)](#); [Guolo et al. \(2025b,a\)](#); (7, 8) [Gezari et al. \(2021\)](#); [Yao \(2022\)](#); (9, 10, 11) [Jose et al. \(2014\)](#); [Miller et al. \(2015\)](#); [Holoien et al. \(2016a\)](#); (12, 13) [Hinkle et al. \(2021\)](#); [van Velzen et al. \(2021\)](#); (14, 15) [Fulton et al. \(2022\)](#); [Malyali et al. \(2024\)](#); (16, 17) [Yao \(2022\)](#); [Yao et al. \(2024\)](#); (18, 19, 20) [Brimacombe et al. \(2015\)](#); [Holoien et al. \(2016b\)](#); [Gezari et al. \(2017\)](#); (21, 22) [Saxton et al. \(2011\)](#); [Guolo et al. \(2025b\)](#); (23, 24) [Short et al. \(2019\)](#); [Cannizzaro et al. \(2021\)](#); (25, 26) [Lin et al. \(2018, 2020\)](#); (27) [Yao \(2022\)](#); (28, 29, 30) [Dahiwalé & Fremling \(2020\)](#); [Guolo et al. \(2024a\)](#); [Bykov et al. \(2024\)](#); (31, 32) [Gilfanov et al. \(2020\)](#); [Wevers et al. \(2024\)](#).

plateau phase.” These phases are illustrated in Fig. 1 and are distinguished primarily by the rate of flux decline: rapid in the early phase, and slow or nearly constant in the plateau phase.

To be amenable to the type of spectral modeling we wish to perform, any source in our sample must satisfy two observational requirements: (i) it must be detected with UV/optical emission in the plateau phase, and (ii) have at least one reasonably good (at an absolute minimum 50 background-subtracted counts), thermally dominated X-ray spectrum (a defining feature of TDE disks) *during* the plateau phase. These requirements naturally restrict us to relatively nearby TDEs that have been detected in X-rays, and sources that were not very recently discovered (as the plateau phase becomes observable typically $\gtrsim 1 - 2$ yr post discovery). Using all publicly available data, combined with ongoing late-time follow-up programs with XMM-Newton (0942540 and 094256 PI Guolo; 094080 PI Yao), we identified 14 sources that meet these criteria, which are listed in Table 1. One of our sources, AT2019dsg, does

not technically satisfy our criteria, as it is detected in X-rays only during the (optical) early-time phase and then fades below X-ray detectability (due to its very short ‘viscous’ timescale; [Guolo et al. 2025a](#)). During the plateau phase, only X-ray upper limits are available. Nevertheless, we will show that our modeling and parameter inference remain feasible for this source.

Our sample is not selected according to a uniform discovery survey or wavelength, but rather by the availability of long-term, high-quality data. Most sources were discovered by wide-field optical surveys, including the Zwicky Transient Facility (ZTF; [Bellm et al. 2019](#)), the All-Sky Automated Survey for Supernovae (ASASSN; [Shappee et al. 2014](#)), and the Asteroid Terrestrial-impact Last Alert System (ATLAS; [Tonry et al. 2018](#)). Four events—GSN 069, 3XMM J2150–05, AT2018cqh, and AT2020ksf—were instead discovered in the X-rays, either by the XMM-Newton Slew Survey ([Saxton et al. 2008](#)) or by eROSITA ([Predehl et al. 2021](#)), the soft X-ray telescope aboard the Spectrum-Roentgen-Gamma (SRG) mission. Nevertheless, all four have late-time

Table 2. SED Fitting Data Summary

Source	Epoch	Δt	X-ray Data		UV/optical Data	
		(days)	Mission/Instrument	Obs-ID	Telescope/Observatory	Bands
AT2019qiz	E1	750 ± 150	<i>Swift</i> /XRT	00012012043	ZTF, <i>Swift</i> /UVOT	$r, g, W2$
	E2	1750 ± 150	<i>XMM-Newton</i> /PN	0942560101	ZTF, <i>Swift</i> /UVOT	$r, g, W2$
GSN 069	E1	141 ± 1	<i>XMM-Newton</i> /PN	0740960101	...	...
	E2	1160 ± 10	<i>XMM-Newton</i> /PN	0657820101	<i>HST</i> /STIS	G140L + G230L
	E3	3080 ± 10	<i>XMM-Newton</i> /PN	0823680101	<i>HST</i> /STIS	G140L + G230L
AT2021ehb	E1	200 ± 40	<i>Swift</i> /XRT	014217011-8	ZTF, <i>Swift</i> /UVOT	$r, g, W1, M2, W2$
	E2	550 ± 30	<i>XMM-Newton</i> /PN	0902760101	ZTF, <i>Swift</i> /UVOT	$r, g, W1, M2, W2$
ASASSN-14li	E1	8 ± 1	<i>XMM-Newton</i> /PN	0694651201	...	...
	E2	350 ± 20	<i>XMM-Newton</i> /PN	0770980501	<i>Swift</i> /UVOT	$U, W1, M2, W2$
	E3	1200 ± 75	<i>XMM-Newton</i> /PN	0770981001	<i>Swift</i> /UVOT	$W1, M2, W2$
AT2019azh	E1	255 ± 1	<i>XMM-Newton</i> /PN	0823810401	...	...
	E2	410 ± 50	<i>XMM-Newton</i> /PN	0842592601	ZTF, <i>Swift</i> /UVOT	$r, W1, M2, W2$
	E3	1275 ± 75	<i>XMM-Newton</i> /PN	0902761101	ZTF, <i>Swift</i> /UVOT	$r, W1, M2, W2$
AT2022dsb	E1	1540 ± 75	<i>Swift</i> /XRT	00015054021-7	ZTF, <i>Swift</i> /UVOT	$r, g, W1, M2, W2$
AT2022lri	E1	230 ± 1	<i>Swift</i> /XRT	00015378004	...	...
	E2	679 ± 50	<i>XMM-Newton</i> /PN	0932390701	<i>Swift</i> /UVOT	$U, W1, M2, W2$
	E3	990 ± 75	<i>XMM-Newton</i> /PN	0940800101	<i>Swift</i> /UVOT	$r, W1, M2, W2$
ASASSN-15oi	E1	330 ± 50	<i>XMM-Newton</i> /PN	0722160701	<i>Swift</i> /UVOT	$W1, M2, W2$
	E2	1430 ± 60	<i>Swift</i> /XRT	00095141001-11	<i>Swift</i> /UVOT	$W1, M2, W2$
AT2018cqh	E1	2400 ± 100	<i>XMM-Newton</i> /PN	0954191001	<i>Swift</i> /UVOT	$W1, M2, W2$
AT2019dsg	E1	49 ± 1	<i>NICER</i> /XTI	2200680101	...	...
	E2	61 ± 1	<i>NICER</i> /XTI	2200680108	...	...
	E3	530 ± 40	<i>XMM-Newton</i> /PN	0842591901	ZTF, <i>Swift</i> /UVOT	$r, g, W1, M2, W2$
3XMM J1250-05	E1	179 ± 1	<i>XMM-Newton</i> /PN	0404190101	...	...
	E2	3940 ± 630	<i>Chandra</i> /ACIS	17862	CFHT, <i>HST</i> /WFC3	$F775W, r, g,$
AT2023cvb	E1	360 ± 1	<i>XMM-Newton</i> /PN	0942561301	...	...
	E2	820 ± 60	<i>XMM-Newton</i> /PN	0942540801	ZTF, <i>Swift</i> /UVOT	$r, W1, M2, W2$
AT2019vcb	E1	261 ± 1	<i>XMM-Newton</i> /PN	0871190301	...	...
	E2	940 ± 50	<i>XMM-Newton</i> /PN	0882591401	<i>Swift</i> /UVOT	$W2$
AT2020ksf	E2	242 ± 2	<i>NICER</i> /XTI	3639010101-501	...	...
	E2	990.0 ± 70	<i>XMM-Newton</i> /PN	0882591401	<i>Swift</i> /UVOT	$M2, W2$

UV/optical detections during their plateau phase, and three of them (all except GSN 069, for which not meaningful constraints are available) were also detected in the optical during their early-time flare. It is worth noting that 3XMM J2150–05 (Lin et al. 2018) originates from an ultra-compact dwarf galaxy (UCD, $M_{\text{gal}} \sim 10^7 M_{\odot}$) located in the outskirts of a massive ($M_{\text{gal}} \sim 10^{11} M_{\odot}$) lenticular galaxy, and is one of the best (off-nuclear) IMBH candidates known (Lin et al. 2020; Greene et al. 2020; Wen et al. 2021).

On the X-ray side, the majority of the spectra used here were taken with the *European Photon Imaging Camera* (EPIC-pn; Strüder et al. 2001) onboard *XMM-Newton* (Jansen et al. 2001), with complementary observations from the *Neil Gehrels Swift Observatory* X-Ray Telescope (*Swift*/XRT; Burrows et al. 2005), the *Neutron star Interior Composition Explorer* X-ray Timing Instrument (*NICER*/XTI; Gendreau et al. 2016), and the *Chandra X-ray Observatory* Advanced CCD Imaging Spectrometer (*Chandra*/ACIS-S; Garmire et al.

2003). Host-subtracted UV/optical photometry, from which we constructed the spectral energy distributions (SEDs), was in most cases obtained from the manyTDE² database (Mummery et al. 2024b). For a subset of sources, we relied on individual reductions and analyses presented in previous dedicated studies. Details of the data reduction procedures, along with references for each dataset, are provided in Appendix A, but follow standard procedures in the TDE literature. Host-galaxy masses (M_{gal}), and nuclear stellar velocity dispersions ($\sigma_{\star}$) were also collected from the literature (most again from the manyTDE compilation), but also from individual studies. We also present new measurements of $\sigma_{\star}$ for AT2019vcb, AT2022dsb, and AT2023vcb. The corresponding data and measurement procedures are described in Appendix A. With these additions, $\sigma_{\star}$ is now available for all sources in our sample except

² <https://github.com/sjoertvv/manyTDE>

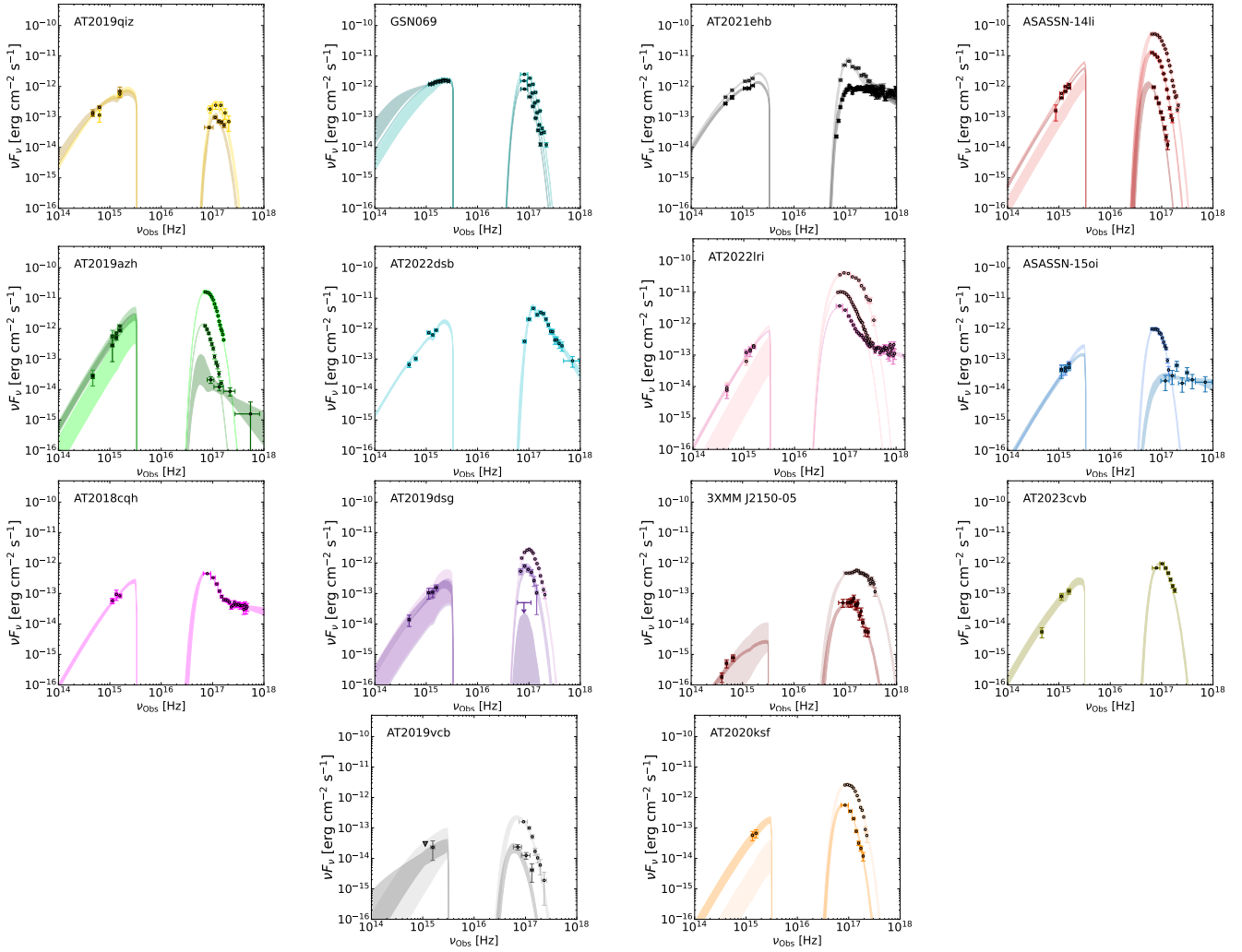


Figure 2. Results of the spectral modeling for our sample. Each panel shows the observed (i.e., uncorrected for absorption or extinction) UV/optical photometry and the unfolded X-ray spectrum. For sources with X-ray-only epochs (see Table 2), the UV/optical flux of the disk component is displayed for illustrative purposes only, as the outer disk parameters are unconstrained. Contours show the 68% credible interval of the model posterior.

3XMM J2150–05. All host galaxy properties are summarized in Table 1.

While light curves serve as our starting dataset—used, for example, to determine the phase of the UV/optical evolution (early vs. plateau)—our final analysis relies on combined spectral energy distributions (SEDs). For each source, we selected between one and three SED epochs, spaced as widely as possible to capture the time evolution of the disk properties. Up to two of these epochs were chosen during the “plateau” phase of the UV/optical light curve, for which contemporaneous X-ray spectral data were available. For each such epoch, we constructed a median UV/optical SED from the light curves using the procedure described

in Appendix A. These median SEDs (without extinction correction) were loaded into the X-ray spectral fitting framework using the `ftflx2xsp` tool in HEASoft v6.33.2 (Heasarc 2014), which generates the appropriate response files.

The corresponding X-ray spectra were, in most cases, either deep single exposures or stacked from multiple shorter observations to achieve high signal-to-noise. For sources where high-quality early-time X-ray spectra were available—taken after or near the X-ray peak, but not during the rise (the reasons for excluding rising data are clarified in Sec. 3)—we included them as an ad-

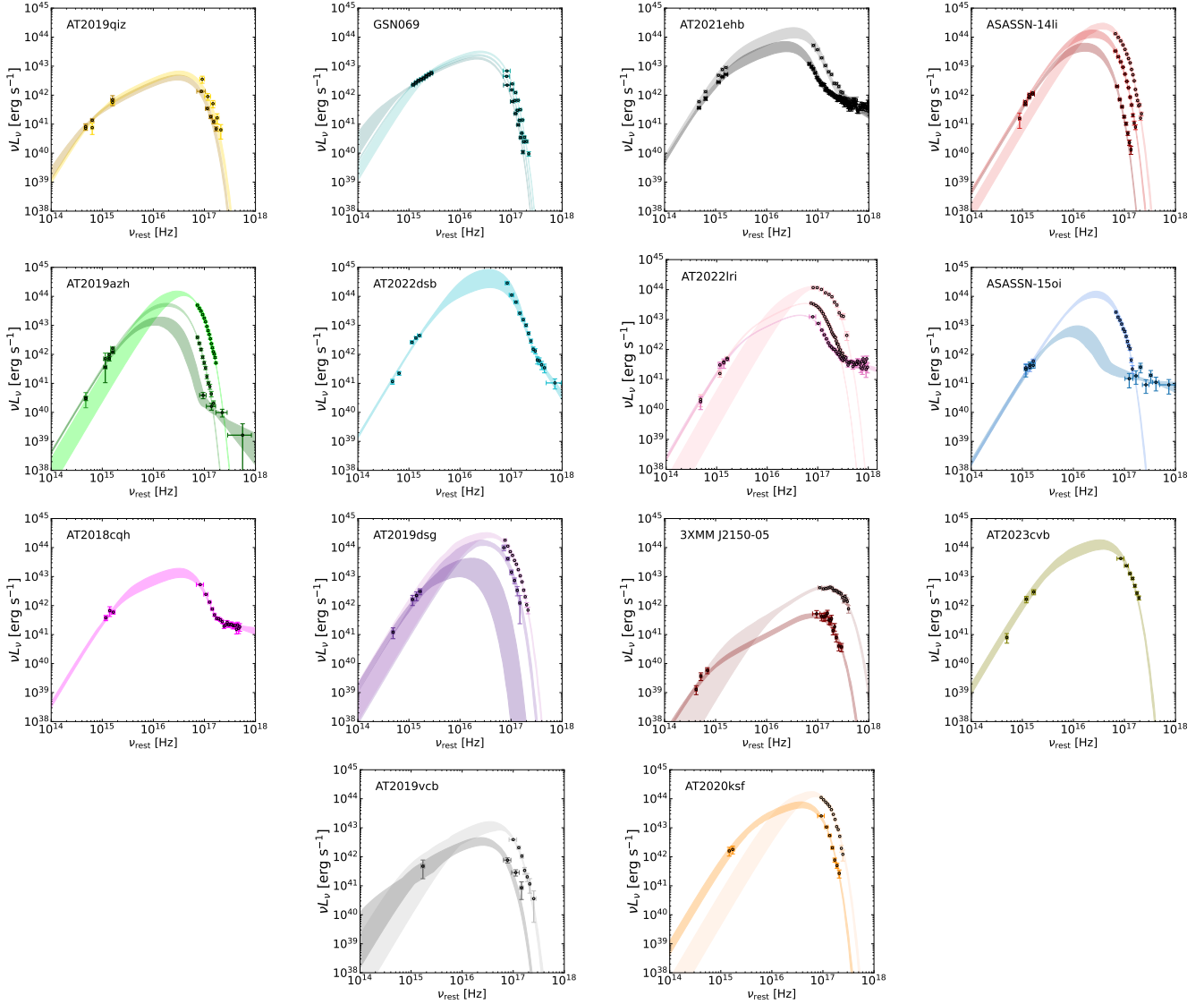


Figure 3. Same as Fig. 2, except that it shows the intrinsic rest-frame luminosity, corrected for both absorption and extinction.

ditional “X-ray only” epoch³. We did not include contemporaneous UV/optical data in these cases, since the early-time optical flare is known not to originate from direct disk emission. Nevertheless, as initially argued on the single source level by [Mummery & Balbus \(2020\)](#), and on a population level by [Mummery & van Velzen \(2025\)](#), the TDE-disk paradigm assumes that the X-ray

emission at peak light is produced by the same accretion disk that powers the late-time UV/optical emission. By including early-epoch X-ray data in our sample we can directly test this key prediction of this framework. Additionally, adding a brighter, and usually high signal-to-noise ratio X-ray spectrum helps to constraints parameters intrinsic to the black hole (e.g., spin). All X-ray spectra were binned using the optimal scheme of [Kaas-stra & Bleeker \(2016\)](#), and 1% systematic uncertainty was added to all data, to account for any differences in the intrinsic flux calibration of distinct X-ray missions.

Even for sources with sufficient data to construct more SED epochs, we restricted our analysis to a maximum of three per source. This choice reflects two considerations: (i) only a small number of epochs are needed

³ For readers concerned about this point, the peak X-ray luminosity function and the UV/optical plateau luminosity function can be reproduced from one another without invoking any additional absorption or reprocessing, as recently shown by [Mummery & van Velzen \(2025\)](#). This demonstrates at least at the population level that the two components arise from the same disk—an idea that goes back to [Mummery & Balbus \(2020\)](#)—and here we will show that this also holds true for individual sources.

to robustly constrain intrinsic black hole and disk properties, with little additional gain in precision (e.g., for $M_\bullet$, as at this point systematics uncertainty and model degeneracy dominated over statistical uncertainty) from including more; and (ii) practical constraints, as our fitting will be performed in a simultaneous fashion (all the epochs and all wavelengths fitted simultaneously), in a Bayesian framework (i.e., full parameter space search), and fully relativistic with (expensive) numerical photon ray-tracing, the computational cost (which is already of order many CPU hours per source with $\leq$ three epochs) scale steeply with the number of epochs. The SED epochs, time ranges and the data used for at both wavelength-band are presented in Table 2.

3. MODEL AND FITTING

As we shall model emission from accreting disks around black holes with a wide range of masses, accretion rates, and temperatures, all of which evolve between the distinct epochs considered here, our approach should include sufficient free parameters and physical detail to explain the data and capture the specifics of TDE disks, while also allowing parameter degeneracies to be broken. At the same time, we should also remain cautious of overfitting, ensuring that no parameters beyond those constrained by the data are introduced.

In the context of TDEs—but also applicable to other thermal X-ray accretion sources—the **kerrSED** model (Guolo & Mummery 2025) is designed to achieve this balance. It is a relativistic, color-corrected, quasi-steady-state disk model with a vanishing-stress inner boundary condition and five free parameters: inner disk radius (R_{in}), peak disk temperature (T_p), outer disk radius (R_{out}), black hole spin ($a_\bullet$), and inclination (i). Implemented in the **python** version of **XSPEC**, it allows multi-wavelength fitting and performs numerical ray tracing on the fly to capture relativistic effects. Relative to the standard soft/thermal spectral models **kerrSED** is a significant improvement: it includes relativistic photon trajectory corrections, treats disk size as a free parameter (essential for TDEs), and applies a temperature-dependent correction for radiative transfer effects.

The reader is referred to Guolo & Mummery (2025) for full details, and for the visual demonstration of the effects of each parameter to the resulting emission; here we briefly summarize the main properties of **kerrSED**. The model essentially fits the following expression to the observed – subscript o – data (after convolving with the instrumental response for the case of the X-ray spectra):

$$F_\nu(\nu_o) = \iint_{\mathcal{S}} g^3 f_c^{-4} B_\nu(\nu_o/g, f_c T_r) d\Theta_o, \quad (1)$$

where $\mathcal{S}(R_{\text{in}}, R_{\text{out}})$ denotes the disk surface, defined by an inner and an outer radius, where the inner boundary is taken to be the innermost stable circular orbit (r_{isco}) of the black hole. The function $g(r, \phi|a_\bullet, i) \equiv \nu_o/\nu_e$ is the photon energy shift factor (capturing the combined impacts of Doppler and gravitational photon energy shifting), and is defined as the ratio between observed and emitted photon energy. For a given black hole spin and observer inclination angle it depends on both the radius and azimuth angle at which the photon was emitted within the disk. We calculate $g(r, \phi|a_\bullet, i)$ numerically using the ray-tracing algorithm described in Mummery et al. (2024a), based on the code YNOGK, itself derived from GEOKERR (Yang & Wang 2013; Dexter & Agol 2009). The factor $f_c(T)$ is the temperature-dependent color-correction (Shimura & Takahara 1995; Hubeny et al. 2001; Davis & Hubeny 2006; Done et al. 2012; Davis & El-Abd 2019), which aims to model non-LTE effects such as metal opacity and electron scattering in the disk atmosphere. The function $B_\nu(\nu, T)$ is simply the Planck function, as the disk emission is quasi-thermal in its rest frame. The radial temperature profile $T_r(r)$ is assumed to follow the standard steady-state-like null-stress boundary condition profile:

$$T_r(r) = \left(\frac{r_{\text{max}}^3}{1 - r_{\text{max}}^{-1/2}} \right)^{1/4} T_p r^{-3/4} \left(1 - r^{-1/2} \right)^{1/4}, \quad (2)$$

with $r_{\text{max}} = 49/36$ (Novikov & Thorne 1973; Shakura & Sunyaev 1973)⁴. Finally, $d\Theta_o$ is the differential solid angle element as seen by the observer, which may be expressed as $d\Theta_o = db_x db_y / D^2$, where b_x and b_y are the photon impact parameters at infinity (Li et al. 2005), and D is the distance to the observer. For this implementation of **kerrSED**, we adopted the f_c prescription from Hubeny et al. (2001).⁵

It is also useful to define quantities that are not free parameters of the model but are derived from them. For example, $M_\bullet$, $a_\bullet$, and R_{in} can be written interchangeably as functions of one another:

⁴ Formally this temperature profile only holds exactly in the asymptotic $t \gtrsim t_{\text{visc}}$ limit, and is unlikely to hold during the rise of a TDEs X-ray light curve which necessarily probes sub-viscous timescales. Beyond t_{visc} this is a good approximation however, see for example Figure 4 of Mummery & Balbus 2020. This is the reason in §2 we did not use X-ray spectra at the rise of the X-ray light curve.

⁵ We tested refitting the same data for some sources using alternative color-correction prescriptions (e.g., Done et al. 2012) and found that the effect on the inferred $M_\bullet$ was < 0.1 dex. For the black hole mass range studied here, the two prescriptions appear very similar, although they are expected to diverge for disks around stellar mass black holes with higher T_p , as in X-ray binaries.

$$R_{\text{in}} = \gamma(a_{\bullet}) \frac{GM_{\bullet}}{c^2} \quad \text{or} \quad M_{\bullet} = \frac{R_{\text{in}} c^2}{\gamma(a_{\bullet}) G}, \quad (3)$$

where $\gamma(a_{\bullet})$ is the standard spin-dependent factor r_{isco}/r_g (e.g., [Misner et al. 1973](#)), with $\gamma(0) = 6$, $\gamma(-1) = 9$, and $\gamma(1) = 1$. Throughout the paper quoted $M_{\bullet}$ values refer to the values derived from this relation as obtained from fitting SED data, unless otherwise stated.

Similarly, the bolometric disk luminosity is given by

$$L_{\text{Bol}}^{\text{disk}} = 4\pi\sigma r_g^2 \int_{R_{\text{in}}}^{R_{\text{out}}} r T_r^4(r) dr. \quad (4)$$

Importantly, $L_{\text{Bol}}^{\text{disk}} \neq 4\pi D^2 \int_0^{\infty} F_{\nu}(\nu) d\nu$, where F_{ν} is the observed flux (Eq. 1) at a given inclination, as a relativistic disk does not emit isotropically (specifically, Doppler shifting breaks the isotropy). Lastly, $L_{\text{Edd}} = 1.26 \times 10^{38} (M_{\bullet}/M_{\odot})$ is the Eddington luminosity.

Before discussing the fitting procedures, it is important to clarify which model parameters are intrinsic to the system and which are dynamical, i.e., expected to evolve between epochs. By construction, R_{in} and $a_{\bullet}$ (and therefore $M_{\bullet}$ as well) are intrinsic properties of the black hole. They cannot vary between epochs: although allowing them to vary may produce formally acceptable statistical fits, such solutions are unphysical and inconsistent with the assumptions of the model⁶. The inclination i is set by the geometry of the disk–observer system. In principle, it could vary over time (e.g., due to disk precession at early times). However, in practice, degeneracies between variable- i solutions and changes in T_p or $a_{\bullet}$ cannot be resolved with current data, such that allowing varying i would result in more free parameters than can be constrained from the data. We therefore assume a constant i across epochs. By contrast, the peak disk temperature T_p and the outer radius R_{out} are dynamical properties of the disk. In a system with finite mass supply, such as a TDE, both must evolve as the disk accretes material ([Cannizzo et al. 1990](#); [Mummery & Balbus 2020](#)).

The spectral energy distribution fitting (X-ray spectra and UV/optical photometry) is performed with the Bayesian X-ray Analysis software (BXA) version 4.0.7

⁶ At extremely low accretion rates ($\ll 10^{-2}$ of the Eddington rate), this assumption may break down, if TDE disks transition through different accretion states in a way analogous to X-ray binary systems. In such regimes, the inner radius of the thin disk may recede (although this is not a settled question in the XRB literature). However, for the accretion rates probed in this work, this transition is not expected to occur, and a fixed R_{in} provides an adequate description of the data, without the need to introduce additional free parameters.

Table 3. Model Parameter Priors.

Model	Parameter	Type ^(a)	Range	Units	Prior
phabs	N_{H}	I	$10^{19} - 10^{22}$	cm^{-2}	Log-uniform
reddenSF	$E(B-V)$	I	$10^{-3} - 1$	...	Log-uniform ^(b)
kerrSED	R_{in}	I	$10^4 - 10^9$	km	Log-uniform
kerrSED	$a_{\bullet}$	I	$-0.998 - 0.998$	...	Uniform
kerrSED	i	I	$0 - 90$	deg	Uniform
kerrSED	T_p	D	$10^5 - 5 \times 10^6$	Kelvin	Log-uniform
kerrSED	R_{out}	D	$10 - 10^5$	r_g	Log-uniform
simPL	f_{sc}	D	$10^{-3} - 0.5$	...	Log-uniform
simPL	Γ	D	$1.5 - 4.0$	...	Uniform

NOTE—(a) Intrinsic (I) parameters are kept constant between epochs, while dynamical (D) parameters are allowed to vary (see §3 for details). (b) The color excess, $E(B-V)$, is either tied to N_{H} assuming a Galactic gas-to-dust ratio, or allowed to vary independently depending on the source (see Table 3).

([Buchner et al. 2014](#)), which connects the nested sampling algorithm **UltraNest** ([Buchner 2019](#)) with the fitting environment **PyXspec** ([Arnaud 1996b](#)), where the E_n epochs are loaded and fitted simultaneously assuming Gaussian statistics. In addition to the disk model, we also account for absorption and reddening by gas and dust along the line of sight, both Galactic and intrinsic to the host, while the source emission is redshifted to the corresponding z . Our fiducial total model (Model 1) in XSPEC notation is **phabs×redden×zashift(phabs×reddenSF×kerrSED)**, where **redden** is the XSPEC native Galactic dust extinction model ([Cardelli et al. 1989](#)), while **reddenSF** implements the [Calzetti et al. \(2000\)](#) law ([Guolo & Mummery 2025](#)). The Galactic extinction color excess, $E(B-V)_G$, the hydrogen-equivalent column density ($N_{\text{H,G}}$), and the source redshift (z from **zashift**) are fixed at their known values, as listed in Table 1.

For some sources, a hard X-ray excess—thought to be produced by Comptonization in a “corona” of hot electrons above the disk (e.g., [Haardt & Maraschi 1991](#))—is observed in addition to the direct disk emission, and in some epochs may even dominate the X-ray spectrum, to model it, we use the convolution model **SimPL** ([Steiner et al. 2009](#)). The corresponding model (Model 2), applied to such epochs, is **phabs×redden×zashift(phabs×reddenSF×(SimPL×kerrSED))**.

Intrinsic and dynamical parameters of **kerrSED** are, as discussed above, fixed or allowed to vary freely between epochs, respectively. The only exception is R_{out} in sources where the first epoch (E_1) is constrained by X-ray data only. In those cases, we impose $R_{\text{out}}(E_1) \leq R_{\text{out}}(E_n)$ for all $n > 1$. This restriction is required physically by angular momentum conservation (fixed

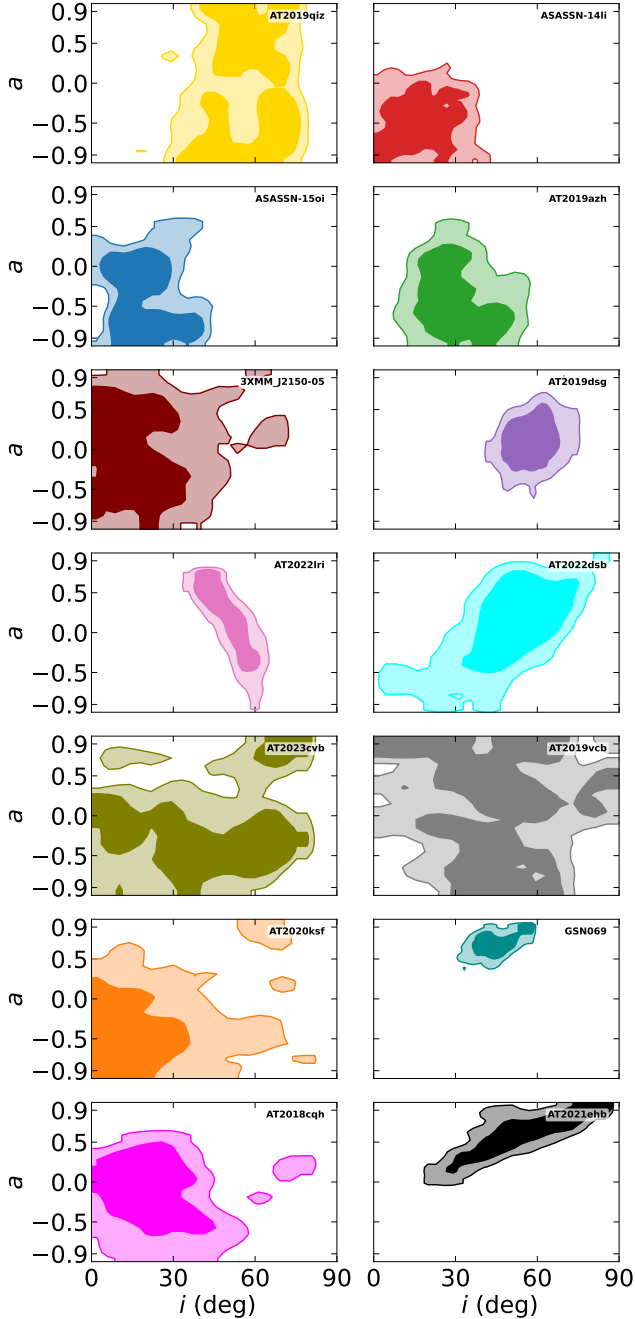


Figure 4. Probability density of the posterior in the spin (a_*)–inclination (i) parameter plane. Contours indicate the 68% and 99% credible intervals. The figure illustrates the varying ability to constrain these parameters from source to source, as well as the advantage of a relativistic model over a classical one: for nearly all sources, a fraction of the prior space can be excluded.

mass disks with conserved angular momentum can only expand), and this restriction also aids in fitting convergence and plotting purposes. No scientific conclusions are drawn from the posteriors of $R_{\text{out}}(E_1)$ in these

sources, since the available data do not constrain this parameter (only UV/optical data constrains R_{out} , see discussion in Guolo & Mummery 2025).

Lastly, for the intrinsic host-galaxy column density and dust attenuation color excess – aiming to use as few free parameters as possible – we first attempt to fit all sources under the assumption of a Milky way-like gas-to-dust ratio. Specifically, we tie N_{H} and $E(B - V)$ using $N_{\text{H}}(\text{cm}^{-2}) = 2.21 \times 10^{21} \times R_V E(B - V)$ (Güver & Özel 2009), where for Calzetti et al. (2000)’s law, $R_V = 4.05$. We then evaluate the fit results using standard Q – Q residual plots (see e.g., Buchner & Boorman 2023). For most sources, this assumption provides a satisfactory description of the data. However, in 2/14 sources the fits fail catastrophically. For those sources, we untie N_{H} and $E(B - V)$, allowing both to vary independently (while remaining fixed across epochs, since they are intrinsic host-galaxy properties), this approach yields successful fits for all sources, with the two sources requiring finite gas/X-ray absorption but negligible extinction. Detailed list of the free parameters, the priors assumed (all either uniform or log-uniform) and ranges adopted, are shown in Table 3.

4. RESULTS

The results of our fitting are shown in Fig. 2, Fig. 3 and Table 4. These results demonstrate that: (i) during the plateau phase, the full SED (X-ray spectra and UV/optical photometry) can be consistently described by a compact but otherwise standard accretion disk; (ii) the parameters of both the black hole and the disk can be constrained with high precision; and (iii) at early times—when the optical light curve is not produced by direct disk emission—the X-ray spectra remain consistent with the same disk. This final point is demonstrated by noting that the early time X-ray spectral fit is feasible even with R_{in} fixed across all epochs and only T_p is allowed to vary.

More specifically, Fig. 2 and Fig. 3 present the resulting SED fits. The first shows the observed fluxes (i.e., without absorption or extinction corrections) together with the unfolded X-ray spectra, while the second shows the intrinsic emission after correcting for both Galactic and intrinsic gas absorption and dust attenuation. In both panels, the contours indicate the 68% credible intervals. For epochs where only X-ray data are fitted (e.g., E1), the model extension to lower energies is shown for illustrative purposes only, as $R_{\text{out}}(E_1)$ cannot be constrained by the data.

Table 4. SED Fitting Parameters

Source	Epoch	Model	$\log_{10}(N_H)$ (cm^{-2})	$E(B - V)^{(a)}$	$\log_{10}(R_{\text{in}})$ (km)	$\log_{10}(T_p)$ (K)	$\log_{10}(R_{\text{out}})$ (r_g)	$\log_{10}(M_{\bullet})$ ($M_{\odot}$)	$\log_{10}(L_{\text{Bol}}^{\text{disk}})$ (erg s^{-1})	$\log_{10}(L_{\text{Bol}}^{\text{disk}}/L_{\text{Edd}})$
AT2019qiz	1	1	$21.36^{+0.05}_{-0.04}$	$< 0.02^{\dagger}$	$6.66^{+0.10}_{-0.10}$	$5.54^{+0.03}_{-0.03}$	$3.08^{+0.18}_{-0.25}$	$5.78^{+0.28}_{-0.26}$	$43.10^{+0.08}_{-0.09}$	$-0.79^{+0.16}_{-0.16}$
	2	1				$5.48^{+0.03}_{-0.03}$	$3.25^{+0.26}_{-0.23}$		$42.92^{+0.10}_{-0.08}$	$-0.93^{+0.16}_{-0.16}$
GSN 069	1	1				$5.47^{+0.03}_{-0.02}$	—		$43.82^{+0.05}_{-0.03}$	$-0.72^{+0.05}_{-0.08}$
	2	1	$20.66^{+0.03}_{-0.03}$	$0.05^{+0.01}_{-0.01}$	$7.16^{+0.06}_{-0.05}$	$5.45^{+0.02}_{-0.02}$	$2.70^{+0.08}_{-0.07}$	$6.45^{+0.13}_{-0.11}$	$43.71^{+0.06}_{-0.06}$	$-0.82^{+0.05}_{-0.08}$
	3	1				$5.42^{+0.02}_{-0.02}$	$3.07^{+0.58}_{-0.24}$		$43.62^{+0.05}_{-0.03}$	$-0.92^{+0.05}_{-0.08}$
AT2021ehb	1	2	$21.02^{+0.12}_{-0.22}$	$0.12^{+0.04}_{-0.05}$	$7.40^{+0.20}_{-0.16}$	$5.52^{+0.04}_{-0.06}$	$2.54^{+0.20}_{-0.20}$	$6.66^{+0.35}_{-0.22}$	$44.49^{+0.17}_{-0.19}$	$-0.30^{+0.18}_{-0.18}$
	2	2				$5.40^{+0.04}_{-0.06}$	$2.49^{+0.24}_{-0.18}$		$44.01^{+0.18}_{-0.22}$	$-0.77^{+0.17}_{-0.22}$
ASASSN-14li	1	1				$5.52^{+0.03}_{-0.03}$	—		$44.49^{+0.18}_{-0.14}$	$-0.05^{+0.07}_{-0.11}$
	2	1	$20.11^{+0.37}_{-0.60}$	$0.01^{+0.01}_{-0.00}$	$7.48^{+0.18}_{-0.12}$	$5.44^{+0.02}_{-0.03}$	$1.90^{+0.10}_{-0.15}$	$6.44^{+0.23}_{-0.15}$	$44.25^{+0.23}_{-0.15}$	$-0.29^{+0.07}_{-0.06}$
	3	1				$5.32^{+0.02}_{-0.03}$	$1.95^{+0.11}_{-0.17}$		$43.77^{+0.24}_{-0.15}$	$-0.76^{+0.08}_{-0.09}$
AT2019azh	1	1				$5.48^{+0.02}_{-0.03}$	—		$44.27^{+0.08}_{-0.10}$	$-0.26^{+0.08}_{-0.11}$
	2	1	< 19.8	< 0.01	$7.48^{+0.08}_{-0.08}$	$5.36^{+0.02}_{-0.03}$	$1.97^{+0.09}_{-0.09}$	$6.52^{+0.15}_{-0.11}$	$43.85^{+0.07}_{-0.05}$	$-0.67^{+0.05}_{-0.06}$
	3	2				$5.23^{+0.04}_{-0.04}$	$1.99^{+0.09}_{-0.09}$		$43.35^{+0.14}_{-0.17}$	$-1.18^{+0.13}_{-0.15}$
AT2022dsb	1	2	$21.45^{+0.06}_{-0.07}$	$< 0.01^{\dagger}$	$7.52^{+0.12}_{-0.13}$	$5.56^{+0.03}_{-0.03}$	$2.16^{+0.15}_{-0.17}$	$6.75^{+0.27}_{-0.22}$	$44.85^{+0.17}_{-0.14}$	$-0.01^{+0.16}_{-0.14}$
AT2022lri	1	1				$5.85^{+0.03}_{-0.02}$	—		$44.29^{+0.09}_{-0.07}$	$0.39^{+0.13}_{-0.07}$
	2	1	< 19.4	< 0.01	$6.69^{+0.07}_{-0.07}$	$5.71^{+0.03}_{-0.02}$	$2.54^{+0.10}_{-0.07}$	$5.79^{+0.07}_{-0.09}$	$43.85^{+0.04}_{-0.03}$	$-0.05^{+0.10}_{-0.06}$
	3	2				$5.62^{+0.03}_{-0.02}$	$2.62^{+0.10}_{-0.08}$		$43.46^{+0.04}_{-0.03}$	$-0.43^{+0.10}_{-0.06}$
ASASSN-15oi	1	1	$19.78^{+0.43}_{-0.39}$	$0.01^{+0.01}_{-0.00}$	$7.40^{+0.13}_{-0.10}$	$5.46^{+0.02}_{-0.02}$	$1.83^{+0.11}_{-0.12}$	$6.38^{+0.19}_{-0.14}$	$44.13^{+0.15}_{-0.08}$	$-0.35^{+0.05}_{-0.05}$
	2	2				$5.15^{+0.11}_{-0.10}$	$1.89^{+0.17}_{-0.15}$		$42.95^{+0.41}_{-0.40}$	$-1.55^{+0.39}_{-0.39}$
AT2018cqh	1	2	$20.20^{+0.24}_{-0.56}$	$0.02^{+0.01}_{-0.01}$	$6.78^{+0.14}_{-0.12}$	$5.56^{+0.02}_{-0.02}$	$2.61^{+0.23}_{-0.18}$	$5.81^{+0.20}_{-0.22}$	$43.38^{+0.15}_{-0.15}$	$-0.53^{+0.04}_{-0.06}$
AT2019dsg	1	1				$5.49^{+0.02}_{-0.02}$	—		$44.78^{+0.11}_{-0.13}$	$-0.06^{+0.09}_{-0.10}$
	2	1	$20.77^{+0.06}_{-0.06}$	$0.07^{+0.01}_{-0.01}$	$7.64^{+0.10}_{-0.09}$	$5.43^{+0.02}_{-0.02}$	—	$6.72^{+0.19}_{-0.15}$	$44.47^{+0.14}_{-0.14}$	$-0.34^{+0.09}_{-0.12}$
	3	1				$5.18^{+0.11}_{-0.10}$	$2.16^{+0.21}_{-0.18}$		$43.60^{+0.36}_{-0.33}$	$-1.21^{+0.36}_{-0.41}$
3XMM J2150-05	1	1	< 20.25	< 0.02	$5.24^{+0.13}_{-0.05}$	$6.18^{+0.03}_{-0.05}$	—	$4.39^{+0.17}_{-0.08}$	$42.84^{+0.05}_{-0.03}$	$0.35^{+0.04}_{-0.05}$
	2	1				$5.94^{+0.03}_{-0.05}$	$3.68^{+0.09}_{-0.10}$		$41.89^{+0.06}_{-0.05}$	$-0.61^{+0.04}_{-0.07}$
AT2023cvb	1	1	$20.27^{+0.26}_{-0.72}$	$0.02^{+0.02}_{-0.02}$	$7.31^{+0.23}_{-0.24}$	$5.55^{+0.08}_{-0.06}$	$2.45^{+0.18}_{-0.23}$	$6.43^{+0.28}_{-0.24}$	$44.42^{+0.21}_{-0.20}$	$-0.08^{+0.06}_{-0.10}$
AT2019vcb	1	1	< 20.33	< 0.02	$6.77^{+0.38}_{-0.25}$	$5.57^{+0.08}_{-0.07}$	—	$5.85^{+0.41}_{-0.25}$	$43.45^{+0.33}_{-0.25}$	$-0.50^{+0.13}_{-0.18}$
	2	1				$5.43^{+0.08}_{-0.07}$	> 2.23		$42.89^{+0.35}_{-0.23}$	$-1.03^{+0.14}_{-0.20}$
AT2020ksf	1	1	$20.07^{+0.45}_{-0.52}$	$0.02^{+0.01}_{-0.01}$	$7.08^{+0.23}_{-0.12}$	$5.70^{+0.03}_{-0.03}$	—	$5.97^{+0.21}_{-0.13}$	$44.33^{+0.16}_{-0.12}$	$0.29^{+0.15}_{-0.10}$
	2	1				$5.59^{+0.03}_{-0.03}$	$2.55^{+0.17}_{-0.19}$		$44.06^{+0.11}_{-0.09}$	$0.04^{+0.05}_{-0.08}$

NOTE—(a) $\dagger$ symbol imply that $E(B-V)$ and N_H were let to vary freely, for the remaining sources they were tied using a Galactic gas-to-dust ratio, see text for details.

Table 4 lists the inferred values for the free parameters N_H , $E(B - V)$, R_{in} , T_p , and R_{out} , as well as for secondary/derived parameters ($M_{\bullet}$, $L_{\text{Bol}}^{\text{disk}}$, and $L_{\text{Bol}}^{\text{disk}}/L_{\text{Edd}}$), which are all calculated element-by-element in the posterior, as per their definitions in §3. For the three main disk parameters (R_{in} , T_p , and R_{out}), the posteriors for almost all sources and epochs converge to values well within the bounds of our priors; we therefore report the median and 68% credible intervals. This includes the R_{out} values for all epochs with simultaneous X-ray and plateau-phase UV/optical data. The only exception is AT2019vcb (E2), where the single UV W1 detection constrains only a lower limit on R_{out} . Similarly, the posteriors for N_H and $E(B - V)$ show a mixture of convergence and upper limits. The table also indicates which model (1 or 2) was adopted for each epoch, and

whether N_H and $E(B - V)$ were tied or allowed to vary independently.

Importantly, even with a relatively small sample, it is clear that a wide range of parameter values can be recovered. The physical scale of the disk’s inner radii spans from $R_{\text{in}} \sim 1.5 \times 10^5$ km up to $R_{\text{in}} \sim 7 \times 10^6$ km, which translates into inferred black hole masses between $\log(M_{\bullet}/M_{\odot}) \sim 4.4$ and $\log(M_{\bullet}/M_{\odot}) \sim 6.8$. When uncertainties are included, this range expands nearly three orders of magnitude, and notably confirms the interpretation of 3XMM J1250-05 as an IMBH, consistent with previous studies based on X-ray-only data and alternative models (Lin et al. 2018, 2020; Wen et al. 2021). Similarly, we recover a wide range of peak disk temperatures spanning ~ 1 dex, from $\log(T_p/\text{K}) \sim 5.2$ up to $\log(T_p/\text{K}) \sim 6.2$, and relative disk sizes ranging from $\log(R_{\text{out}}/r_g) \sim \text{few} \times 10$ to $\sim \text{few} \times 1000$.

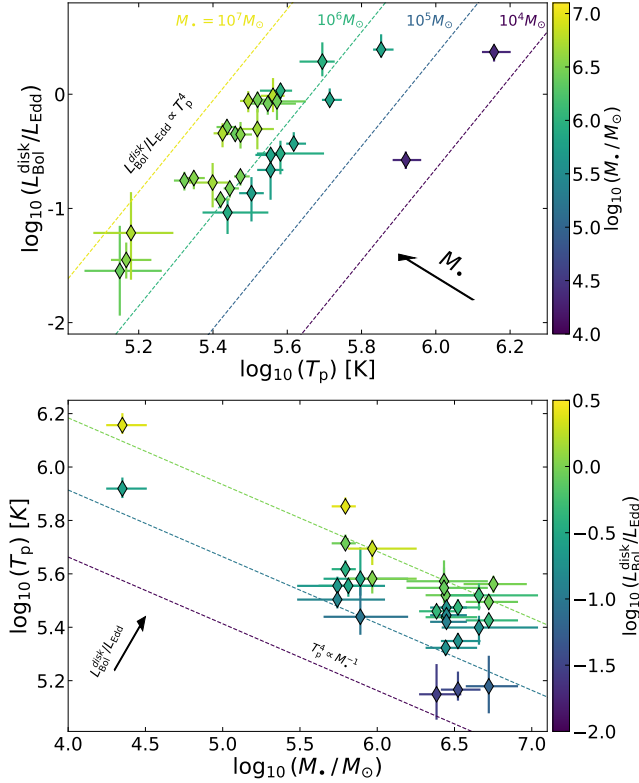


Figure 5. Derived accretion correlations. Top: Eddington ratio ($L_{\text{Bol}}^{\text{disk}}/L_{\text{Edd}}$) versus peak disk temperature (T_p). Lines of constant black hole mass (M_*), spin (a_*), and disk area trace diagonals of the form $L_{\text{Bol}}/L_{\text{Edd}} \propto T_p^4$. Distinct epochs of a given source lie approximately along such lines. Lines perpendicular to these diagonals correspond to different M_* values, as indicated by the color scheme showing the median of the M_* posterior. The lines in the top panel show the correlations for varying $M_*/M_\odot = 10^4, 10^5, 10^6, 10^7$, for $a_* = 0$, and $R_{\text{out}} = 100 r_g$. Bottom: Dependence of T_p on M_* ; at constant Eddington ratio, sources follow $T_p^4 \propto M_*^{-1}$. Lines in the bottom panel show the correlations for varying $L_{\text{Bol}}^{\text{disk}}/L_{\text{Edd}} = 10^{-2}, 10^{-1}, 1$, for $a_* = 0$, and $R_{\text{out}} = 100 r_g$.

For the black hole spin (a_*) and inclination (i), however, these parameters act more as nuisance variables in the sense that varying them across their allowed range produces only mild changes in the model fluxes, unlike the many orders of magnitude variations induced by changing R_{in} , T_p , or R_{out} (see Guolo & Mummery 2025, for a detailed discussion of parameter dependencies on the emitted spectra) throughout the allowed range. Consequently, a_* and i rarely converge to well-defined, Gaussian-like posteriors, and reporting their median values and credible intervals could be uninformative or even misleading. Instead, we present their joint posterior distributions in Fig. 4, with contours marking the 68% and 99% credible intervals. Figure 4 shows that: (i) the ability to constrain a_* and i varies substantially

from source to source, largely depending on data quality; and (ii) employing a relativistic model remains valuable, as in nearly all sources substantial regions of the $a \times i$ parameter space can be excluded with high confidence—a constraint not achievable with a Newtonian-like model. Excluding parts of the a_* – i space directly improves the precision of other parameters, particularly T_p and, most importantly, M_* (Eq. 3).

These spin values, however, should be interpreted with caution, as the inferred values are sensitive to some assumptions. In particular, the results depend on the adoption of a *zero-torque* (or null-stress) inner boundary condition for the disk temperature profile (Eq. 2)⁷ and on the choice of color-correction prescription⁸. In practice, these factors dominate the systematic uncertainties and the budget error in spin measurements (Salvesen & Miller 2021; Mummery et al. 2025).

It is worth noting that we recover a wide range of black hole spins with no clear systematic preferences. In a few sources, maximum or near-maximum spins are clearly excluded. This result contrasts with most previous attempts to recover a_* from TDEs—typically based on slim-disk models fitted to X-ray data only (Wen et al. 2020, 2022, 2021)—which systematically find $a_* \geq 0.8$. The origin of this discrepancy is not yet clear and lies beyond the scope of this work. Nevertheless, the black hole masses we derive are generally consistent with these studies, at least to within an order of magnitude, as for example the extreme cases like ASASSN-14li and 3XMM J1250-05.

We now analyze the results of our parameter inference, their correlations with each other, and their relations to independent host galaxy properties.

4.1. Accretion Correlations

The fact that these sources can be successfully modeled with standard accretion disk physics naturally implies the presence of correlations between key param-

⁷ This assumption, introduced by Shakura & Sunyaev (1973) for simplicity, is commonly used in analytical disk models and in all but one of the fitting implementations currently available (fullkerr; Mummery et al. 2024). However, GRMHD simulations (e.g., Noble et al. 2011; Rule et al. 2025) and detailed modeling of X-ray binary spectra (Mummery et al. 2024; Mummery 2025b) show this assumption to be physically inaccurate. However, current X-ray data quality for TDEs does not allow for testing disk solutions with finite-stress or plunging regions.

⁸ While the use of a color-correction factor, rather than none, is well supported by radiative transfer simulations of disk atmospheres (e.g., Davis & Hubeny 2006), the commonly used analytic prescriptions (e.g., Hubeny et al. 2001; Done et al. 2012) remain simplifications of the real physics.

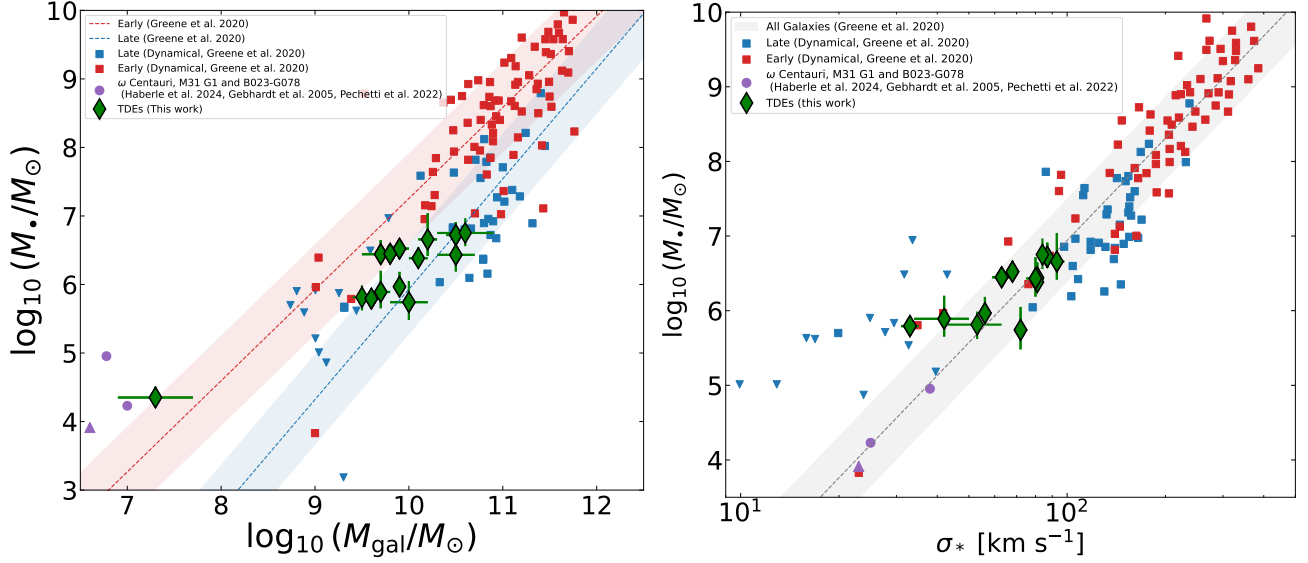


Figure 6. Black hole–host galaxy scaling relations. Left panel: stellar galaxy mass (M_{gal}) versus black hole mass ($M_\bullet$). Right panel: nuclear stellar velocity dispersion (σ_*) versus $M_\bullet$. Blue and red points correspond to late- and early-type galaxies, respectively, with black hole masses measured through stellar or gas dynamical modeling of nearby galaxies; data are taken from Kormendy & Ho (2013) and Greene et al. (2020). Contours represent the best-fit correlations from Greene et al. (2020). Additional purple points indicate massive globular clusters hosting dynamically inferred IMBHs (Gebhardt et al. 2005; Pechetti et al. 2022; Haberle et al. 2024). Our TDE sample, with $M_\bullet$ inferred from full SED fitting, is shown as green points and lies directly on the established correlations. Diamonds and squares are measurements, and upward/downward triangles are upper/lower limits.

ters. Perhaps the most fundamental is

$$L_{\text{Bol}}^{\text{disk}}/L_{\text{Edd}} \propto T_p^4 \propto M_\bullet^{-1}, \quad (5)$$

which expresses the well-known result that, at fixed Eddington ratio, lower-mass black holes host hotter disks, while higher-mass black holes host cooler disks. Equivalently, for a given black hole mass, higher disk temperatures correspond to higher luminosities. Figure 5 demonstrates that these correlations are clearly present in our sample. In the top panels, diagonal tracks of the form $L_{\text{Bol}}^{\text{disk}}/L_{\text{Edd}} \propto T_p^4$ trace the temporal evolution of individual systems (i.e., fixed $M_\bullet$ and $a_\bullet$), while offsets perpendicular to these tracks reflect differences in black hole mass between systems.

Naturally, these correlations are exact only under specific conditions. In particular, Eq. 5 holds in closed form (e.g., Frank et al. 2002) with exact numerical values only for steady-state disks of constant area and same spin. For a sample spanning a range of black hole spins, the relation will not be exact: two black holes with the same $M_\bullet$ and Eddington ratio but different spins (e.g., a rapidly rotating Kerr versus a Schwarzschild black hole) will exhibit slightly different disk temperatures. However, the spin dependence is relatively mild, particularly in our case, where the spin constraints are very limited, and thus its primarily introduces scatter in the three-parameter space of Fig. 5.

Similarly, the relation $L_{\text{Bol}}^{\text{disk}}/L_{\text{Edd}} \propto T_p^4$ holds exactly only for disks with a constant emitting area. In TDE disks, which have a finite mass supply, the emitting area must evolve and only asymptotically approach a steady-state configuration. This evolution in disk size introduces additional scatter in the correlation. Nevertheless, because the bolometric luminosity is dominated by the innermost (hottest) regions of the disk, the effect of variations in the outer disk area is modest, and the expected accretion correlations remain clearly visible, as shown in Fig. 5.

In this context, it is worth noting the recent results of Arcodia et al. (2025), who analyzed the quiescent disk emission of QPE sources (e.g., Miniutti et al. 2019; Nicholl et al. 2024), many of which originate from TDEs. They reported no evidence for a $T_p^4 \propto M_\bullet^{-1}$ correlation. This outcome is not unexpected, given that (i) the relation involves at least three parameters, including $L_{\text{Bol}}^{\text{disk}}/L_{\text{Edd}}$, which was neither estimated nor accounted for, and (ii) black hole masses were not inferred from disk emission but from host scaling relations, with assumed uncertainties of ~ 0.7 dex. Together, these factors, combined with the limited dynamical range of $M_\bullet$ over which nuclear TDEs/QPEs are found, make recovering the correlation essentially impossible. Notably, two of our sources, GSN069 and AT2019qiz, are QPE sources and naturally follow the same trends as

the rest. Extending our analysis to additional QPE sources—particularly those not clearly linked to known TDEs (such as the *SRG*/eROSITA discoveries; Arcodia et al. 2021, 2024)—will be essential to clarify this picture.

4.2. Black Hole vs. Host Galaxy Correlations

A critical reader may note that some of the results presented in the previous section primarily reflect the internal physics of accretion (i.e., Eq. 1) and the models success in describing the data (although we stress again that $T_p^4 \propto M_\bullet^{-1}$ reflects a measurement of the system, not an intrinsic property of the model). The most pessimistic reading of these results would be that they demonstrate internal consistency, rather than directly establishing intrinsic properties of the sources themselves. To address this limitation, it is important to seek independent confirmation that the derived quantities—such as the black hole masses—are not arbitrary, but are instead consistent, at population level, with established empirical relations between black holes and their host galaxies.

In Fig. 6, we present the correlations between black hole mass and host-galaxy properties: the $M_\bullet$ – M_{gal} relation (left panel) and the $M_\bullet$ – $\sigma_\star$ relation (right panel). Blue points (late-type galaxies) and red points (early-type galaxies) are taken from Greene et al. (2020), largely based on the compilation of Kormendy & Ho (2013). In these cases, black hole masses are determined through dynamical modeling of stellar and/or gas kinematics in extremely nearby galaxies. For completeness, we also include a few purple points corresponding to dynamical modeling of massive globular clusters hosting candidate IMBHs (e.g., Haberle et al. 2024). In the left panel, the $M_\bullet$ – M_{gal} relation is shown separately for late- and early-type galaxies, while in the right panel we show the $M_\bullet$ – $\sigma_\star$ relation for the combined sample, as both galaxy types follow essentially the same trend.

Our accretion-based $M_\bullet$ values for the TDE sample lie directly on the established host–black hole correlations (statistical tests will be performed in a later section). In the $M_\bullet$ – M_{gal} plane, the TDE hosts appear to align most closely with the late-type galaxy relation. The only notable outlier is the IMBH in 3XMM J1250–05, which sits above the relations. Such an offset is not unexpected because of astrophysical factors such as the fact the host of 3XMM J1250–05 is a UCD, which are thought to be tidally stripped remnants of larger galaxies that have fallen into the halos of their parent massive systems, naturally producing elevated black hole-to-galaxy mass ratios (e.g., Seth et al. 2014).

The fact that our inferred $M_\bullet$ sit on the expected host–black hole scaling relations indicates that the re-

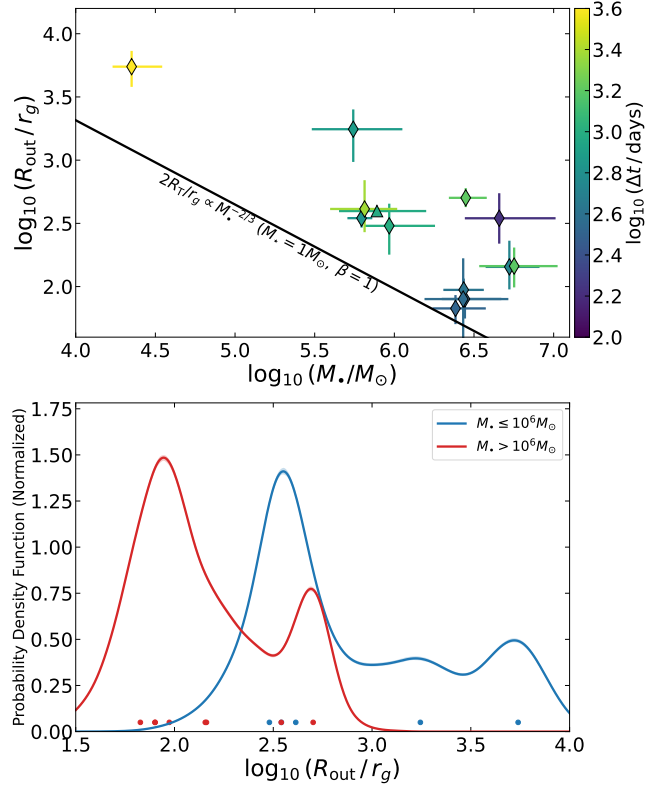


Figure 7. Top panel: correlation between normalized outer disk radius (R_{out}/r_g) and black hole mass ($M_\bullet$). We show one measurement (the first available) for each source. The black line indicates the circularization radius for the disruption of a $1 M_\odot$ star with an impact parameter $\beta = 1$. Diamonds are measurements, triangles are lower limits. Bottom panel: probability distribution of R_{out}/r_g for sources with $M_\bullet$ greater or less than $10^6 M_\odot$, which divides our sample roughly in half. More massive black holes clearly host relatively more compact disks, as expected.

sults presented in §4.1, and those to be discussed in §4.3, are not merely internal consistencies of our assumed model, but instead reflect genuine physical properties of these systems. This strengthens the case that our inferred $M_\bullet$ values are not only precise but also reliable, with uncertainties comparable to, and values consistent with, those obtained from dynamical modeling of extremely nearby galaxies.

4.3. TDE-disk Correlations

While the correlations discussed in §4.1 should be valid, at least approximately, for any accreting black hole system, the disks formed in the aftermath of TDEs are more constrained than the standard steady-state “free- $\dot{M}$ ” solutions. This is because many of the disk properties are constrained (or at least should be if the modeling reflects reality) by the disruption process itself. The characteristic scale of the initial disk is set by the

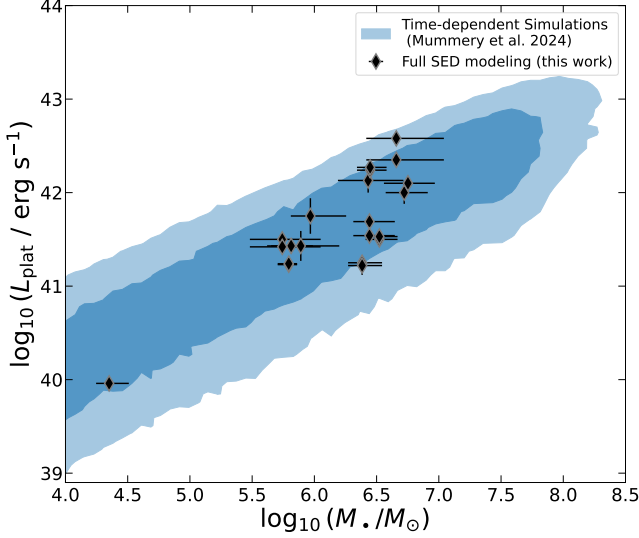


Figure 8. Correlation between the UV luminosity (L_{plat}) during the plateau phase and black hole mass ($M_{\bullet}$). Black points show our sample, computed at $\nu = 10^{15}$ Hz for epochs including UV/optical data. The blue shaded region shows the 68% and 99% credible intervals from the time-dependent simulations of Mummery et al. (2024b), which solve the relativistic disk equations assuming half the stellar debris circularizes, the initial disk radius equals the circularization radius, and luminosities are evaluated 1000 days after disk formation.

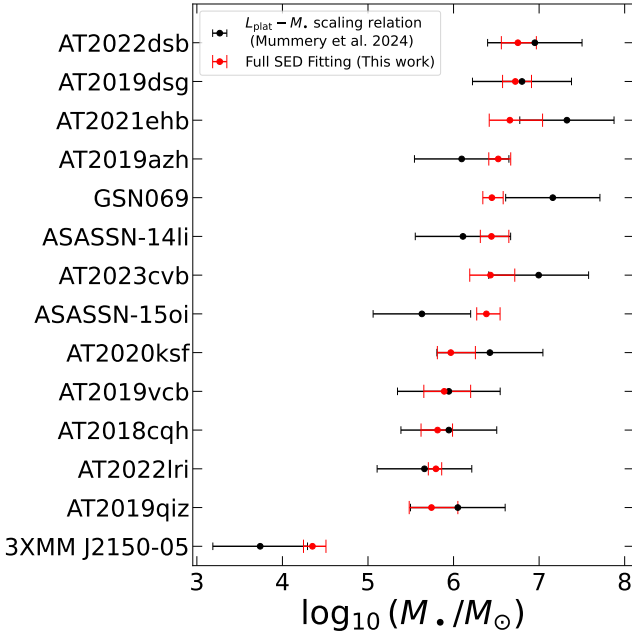


Figure 9. Comparison between the black hole masses obtained here from full SED fitting (red) and those derived from the plateau luminosity scaling relations (black, Mummery et al. 2024b). The measurements are consistent within $\leq 1.5\sigma$ for all sources.

disruption process itself—i.e., it forms and is fed close to the black hole where the star is disrupted—rather than at large radii, as in the case of ISM-fed active galactic nuclei (AGN) or Roche-lobe overflow in X-ray binaries (XRBs). In addition, TDE disks are supplied with only a finite mass reservoir (at most $\sim$ one half of the disrupted stellar mass, and in practice only the fraction that successfully circularizes), in contrast to AGN and XRB disks, where the mass contained in the disk at any given time is only a tiny fraction of the supply available from the ISM or the companion star.

The first obvious constraint imposed by the finite mass supply is that a TDE-fed disk will have a finite—albeit long in human terms (see Figure 1)—lifetime. Equally important, the peak disk temperature will necessarily decrease over time. This occurs because, in an accretion disk, the local temperature depends on the product of the local surface density, $\Sigma(r)$, and the local stress (Balbus & Papaloizou 1999; Mummery & Balbus 2020). Since the long-term evolution of $\Sigma(r)$ is fundamentally limited by the finite mass supply and hence should inevitably decrease, the peak disk temperature must decrease as well⁹. This behavior has been confirmed observationally in TDEs, as expected (e.g., Guolo et al. 2024a; Yao et al. 2024), and is evident in the T_p values reported in Table 4.

A more novel result arises from the fact that the origin of these disks should also impose a characteristic scale on their size. Not only are they expected to be compact, but, in a simplified picture of the disk formation process, they should form at approximately the so-called circularization radius,

$$R_{\text{circ}} \approx \frac{2R_T}{\beta} \approx \frac{92}{\beta} \left(\frac{M_*}{M_{\odot}} \right)^{7/15} \left(\frac{M_{\bullet}}{10^6 M_{\odot}} \right)^{-2/3} r_g, \quad (6)$$

where $R_T \simeq R_* (M_{\bullet}/M_*)^{1/3}$ is the tidal radius, M_* and R_* are the stellar mass and radius, β is the impact parameter (the ratio of the pericentre of the incoming stars orbit to the tidal radius), and we have assumed a main-sequence mass-radius relation in going to the final expression on the right.

This implies that, even when accounting for a distribution of disrupted stellar masses and impact parameters, the general expectation is that lower-mass black holes should host relatively larger disks (in units of r_g)

⁹ The stress cannot drop more quickly than $1/\Sigma$ if the disk evolution is to be stable (Lightman & Eardley 1974) – as it clearly is in TDE sources which display smooth evolution over years-to-decades.

than higher-mass ones, following a relation of the form $R_{\text{out}}/r_g \propto M_{\bullet}^{-2/3}$.

In Fig. 7, we show that our inferred R_{out} values - here shown just the first epoch with measured values - are consistent with this expectation. The top panel presents R_{out}/r_g as a function of $M_{\bullet}$, while the lower panel shows the probability distributions of the measured R_{out}/r_g for systems with $M_{\bullet}$ above and below $10^6 M_{\odot}$ (effectively dividing our sample in half). It is clear that our inferred disk sizes retain information about the black hole mass and broadly follow the simple expectation that lower-mass black holes have relatively larger disks.

In the top panel, we also compare our inferred R_{out} to $2R_T/r_g$ for $M_* = 1 M_{\odot}$ and $\beta = 1$. Our values are systematically larger than the circularization radius, as expected: R_{circ} sets only the initial disk size. The disk must expand as it evolves in order to conserve angular momentum, initially rapidly and later more slowly (e.g., $dR_{\text{out}}/dt \propto t^{2n-3}$, where $n \approx 1.2$, Cannizzo et al. (1990)). Thus, by the epochs at which we measure R_{out} (see Tables 2 and 4), the disk should already be substantially larger than its formation scale. Nevertheless, the overall expected behavior is clearly visible in the data. Importantly, this scaling is not imposed by our modeling, but emerges naturally from the SED fits, demonstrating again that the inferred disk sizes trace genuine physical properties of these systems.

Another important scaling relation, arising from the compact initial configuration of TDE disks, their finite mass supply, and the constraints of mass and angular momentum conservation, is that the late-time luminosity in the disk-dominated phase of the UV/optical light curve (i.e. the plateau phase) should scale with black hole mass. This relation has been analyzed in detail by Mummery et al. (2024b), who confirmed its validity through analytic arguments, numerical simulations, and observational tests. Although the relation exhibits a relatively large intrinsic scatter (~ 0.5 dex), reflecting additional free parameters beyond $M_{\bullet}$, Mummery et al. (2024b) showed that it can be approximated as $L_{\text{plat}} \propto M_{\bullet}^{2/3}$, where L_{plat} is the plateau νL_{ν} luminosity measured over a narrow wavelength range. A key result of their work was the simulation of a large ensemble ($N = 10^6$) of relativistic, time-dependent disk models (Balbus 2017; Mummery & Balbus 2020; Mummery 2023), assuming initial radii equal to the circularization radius and sampling the remaining parameters from probability distributions. From these simulations, the authors extracted L_{plat} at a characteristic time ($t \simeq 1000$ days after disk formation) and constructed the $L_{\text{plat}}-M_{\bullet}$ relation, enabling black hole mass inference in TDEs with a (theoretical) scatter of ~ 0.5 dex.

The scaling relationship of Mummery et al. (2024b) relied on assumed distributions for stellar properties, the scale of the turbulence in the disk, the orientation of the observer, and the properties of the black holes. It is therefore firmly rooted in *assumed* TDE physics, which in principle could be inaccurate (if TDEs do not behave as assumed). Here we need make no assumptions about any distributions, beyond broad priors, as we are constraining the physical parameters of the system from the data. Our results therefore act as a direct test of the assumptions in Mummery et al. (2024b), and the validity of their reported black hole mass scaling relationship.

In Fig. 8, we overplot the measured L_{plat} and inferred $M_{\bullet}$ for our sample on top of the simulated population from Mummery et al. (2024b), demonstrating excellent agreement. Consistently, Fig. 9 shows that our inferred black hole masses also agree with those obtained via the $L_{\text{plat}}-M_{\bullet}$ scaling relation: the vast majority are consistent within 1σ , and all lie within $\leq 1.5\sigma$. This agreement provides further confidence in the robustness of both the model developed here and the plateau scaling relationship.

Naturally, the black hole masses we infer from direct SED fitting are significantly more precise. This is because the $L_{\text{plat}}-M_{\bullet}$ relation relies on assumed probability distributions for all other parameters of the theory (describing both the black hole and the disrupted star), which introduces substantial scatter. By contrast, our method directly marginalizes over the disk and black hole parameters that can be constrained by the data themselves. In the approach presented here the parameter inference is rooted in a time-independent accretion framework, where the key parameters are recovered from their direct imprints on the observed emission, without explicitly assuming any dynamical evolution or initial conditions. These complementary approaches can ultimately be combined to form an even more powerful framework for black hole and TDE parameter inference, by fitting multi-wavelength data with a time-dependent model, particularly when abundant high-quality data are available (e.g., Mummery et al. 2024a; Guolo et al. 2025a).

5. DISCUSSION

5.1. Black Hole Mass Inference in TDEs

Having demonstrated that full SED fitting provides precise (uncertainty $\lesssim \pm 0.3$ dex; Table 4) and reliable method —successfully reproducing established black hole–galaxy scaling relations (§4.2) and yielding internally consistent inferred parameters (§4.1, 4.3)—for $M_{\bullet}$ inference in TDEs, we now compare this approach with

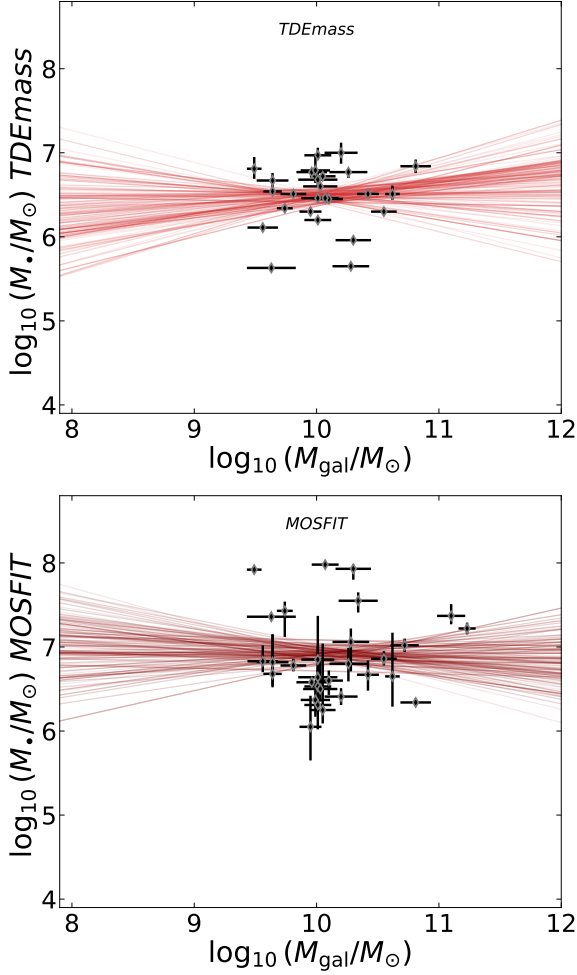


Figure 10. Black hole mass as inferred from either TDEmass (Top) or MOSFIT (bottom) versus galaxy mass for the first 30 ZTF-discovered TDEs (Hammerstein et al. 2023). Lines are random draws from a MCMC sample of power-law fitting correlations. Both cases are consistent with non-correlations.

the various alternative methods previously adopted in the literature.

5.1.1. Host Scaling Relations

The most common and straightforward way to estimate a black hole mass is to make use of a host–scaling relation, where a host galaxy property (e.g., total stellar mass, bulge mass, or nuclear velocity dispersion) is inserted into the respective empirical correlation. This approach provides a simple and relatively “model-independent” estimate, and is often the most practical option when only limited information is available for a quick, first-order characterization. At the same time, it is important to keep in mind its limitations.

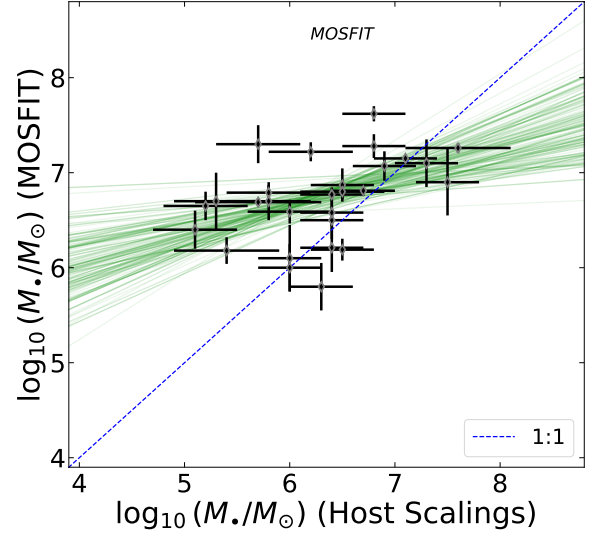


Figure 11. Black hole mass as inferred from MOSFIT versus black hole mass inferred from galaxy scaling relation (mostly σ_* using Kormendy & Ho 2013) for a sample of TDEs analyzed in Alexander et al. (2025). Lines are random draws from a sample of MCMC power-law fitting correlations. Significance for non-zero correlation is 2.6σ . Blue shows the expected 1:1 correlation, inferred $\beta = 0.30 \pm 0.12$ is 4.6σ from the expected value.

First, this method does not directly infer $M_\bullet$ for an individual source, but instead assumes that population-level correlations apply to the specific host–black hole system. Second, the intrinsic systematic scatter (without accounting for statistical uncertainties) in these relations can be very large. For instance, the $M_\bullet$ – σ_* relation can yield 1σ scatter as low as ~ 0.3 dex in the high-mass regime $\sigma_* \gg 100 \text{ km s}^{-1}$ (Kormendy & Ho 2013), but most TDE hosts fall in the range $50 < \sigma_*/\text{km s}^{-1} < 100$ (Hammerstein et al. 2021; Yao et al. 2023), where the scatter increases to $\gtrsim 0.5$ dex (Greene et al. 2020). The scatter becomes even larger for correlations such as $M_\bullet$ – M_{gal} in the relevant mass regime (see Greene et al. 2020, and Fig. 6).

The statistical limitations become particularly relevant when host-based estimates are used to derive secondary quantities, such as Eddington ratios, on an individual-source level, where $M_\bullet$ enters linearly. In practice, two approaches are often taken in the literature. (i) One may adopt the central value as the representative $M_\bullet$ and proceed as though it were the true mass. While convenient, this choice can be statistically misleading. For example, for a Gaussian-like distribution with $\log_{10}(M_\bullet/M_\odot) = 6.0 \pm 0.5$ (1σ), one can ask what is the probability that the true value lies within a small interval $\pm\delta$ around the central value, $P(\log_{10} M_\bullet = 6.0 \pm \delta)$. This probability is only $\sim 16\%$

Table 5. Summary Review of $M_\bullet$ Inference Methods and Their Ability to Reproduce Black-Hole vs. Host-Galaxy Correlations

Method		Correlation	N	β	ϵ	$P(\beta > 0)$	Data References
Accretion Disk Emission	Plateau Scaling Relation	$M_\bullet - M_{\text{gal}}$	49	$1.24^{+0.12}_{-0.12}$	$0.28^{+0.07}_{-0.08}$	$\geq 0.9999995 (\geq 5\sigma)$	Mummery et al. (2024b)
		$M_\bullet - \sigma_\star$	34	$2.57^{+0.31}_{-0.31}$	$0.29^{+0.09}_{-0.11}$	$\geq 0.9999995 (\geq 5\sigma)$	
		$M_\bullet - M_{\text{bulge}}$	40	$1.23^{+0.13}_{-0.13}$	$0.26^{+0.09}_{-0.11}$	$\geq 0.9999995 (\geq 5\sigma)$	Ramsden et al. (2025)
	Full SED Fitting	$M_\bullet - M_{\text{gal}}$	14	$0.73^{+0.06}_{-0.06}$	$0.17^{+0.05}_{-0.04}$	$\geq 0.9999995 (\geq 5\sigma)$	This Work
		$M_\bullet - M_{\text{gal}}(a)$	13	$0.75^{+0.15}_{-0.16}$	$0.18^{+0.06}_{-0.05}$	$0.99996 (4.1\sigma)$	
		$M_\bullet - \sigma_\star$	13	$1.99^{+0.29}_{-0.27}$	$0.11^{+0.07}_{-0.06}$	$0.999996 (4.6\sigma)$	
Optical Flare Scaling or Modeling	TDEMass	$M_\bullet - M_{\text{gal}}$	26	$0.11^{+0.16}_{-0.15}$	$0.36^{+0.04}_{-0.03}$	$0.75 (1.15\sigma)$	Hammerstein et al. (2023)
		$M_\bullet - M_{\text{gal}}$	30	$0.01^{+0.16}_{-0.16}$	$0.50^{+0.06}_{-0.05}$	$0.51 (0.7\sigma)$	Hammerstein et al. (2023)
	MOSFIT	$M_\bullet - M_{\text{bulge}}$	29	$0.23^{+0.10}_{-0.10}$	$0.15^{+0.06}_{-0.07}$	$0.988 (2.5\sigma)$	Ramsden et al. (2022)
		$M_\bullet - M_\bullet(\text{host})$	29	$0.30^{+0.12}_{-0.12}$	$0.34^{+0.08}_{-0.06}$	$0.991 (2.6\sigma)$	Alexander et al. (2025)
		$L_{\text{peak}} - M_{\text{gal}}$	49	$0.83^{+0.11}_{-0.11}$	$0.46^{+0.04}_{-0.03}$	$\geq 0.9999995 (\geq 5\sigma)$	Mummery et al. (2024b)
		$L_{\text{peak}} - \sigma_\star$	33	$1.67^{+0.28}_{-0.28}$	$0.47^{+0.05}_{-0.04}$	$\geq 0.9999995 (\geq 5\sigma)$	

NOTE— N is the number of sources used in the fitting. (a) 3XMM J2105-05 was excluded on this fitting.

for $\delta = 0.1$, and $\sim 8\%$ for $\delta = 0.05$; and, of course, $P \rightarrow 0$ as $\delta \rightarrow 0$. This simply reflects that it is highly unlikely that $M_\bullet = 10^6 M_\odot$ is the exact true value for an individual source. Therefore, adopting only the central value without propagating the substantial uncertainties into any derived quantities that depend on the mass is not a statistically sound approach. (ii) Alternatively, one may propagate the uncertainties into quantities such as the Eddington ratio. In this case, however, the challenge becomes physical interpretability: at the 1σ level, a system radiating at 50% is statistically indistinguishable from one at 5% of its Eddington luminosity. This ambiguity has important implications for how we interpret the physics and multi-wavelength emission of black hole systems.

A more profound consideration is that reliance on host-galaxy scaling relations alone risks overlooking one of the key promises of the TDE field: the ability to use the emission itself to *independently* constrain the demographics of quiescent black holes. In effect, this approach assumes that the large-scale properties of the host galaxy provide more reliable information about the black hole than the radiation generated in its immediate vicinity during or after the disruption—an assumption that is hardly physically justifiable.

These limitations are even more important for TDEs associated with dwarf galaxies ($M_{\text{gal}} \ll 10^9 M_\odot$), such as 3XMM J2150-05 and the recently discovered EP240222a (Jin et al. 2025). In this low-mass regime, host-black hole scaling relations remain essentially unconstrained, and extrapolating them down to the inferred stellar masses ($M_{\text{gal}} \sim 10^7 M_\odot$) is unjustifiable.

In such cases, methods that infer $M_\bullet$ directly from the TDE emission are an indispensable approach. A similar situation arises for (candidate) TDEs that are off-nuclear with respect to their hosts and lack an obvious or detected stellar counterpart. Examples include the off-nuclear TDE AT2024tvd (Yao et al. 2025), the off-nuclear TDE candidates NGC 6099 HLX-1 (Chang et al. 2025) and eRASS J1421-29 (Grotova et al. 2025), for which host-based correlations are simply not applicable. As the number of such sources is expected to grow substantially with upcoming wide-field time-domain surveys and missions, such as the Vera C. Rubin Observatory’s Legacy Survey of Space and Time (LSST, Ivezić et al. 2019) and Einstein Probe (Yuan et al. 2018), one should attempt to move beyond these scalings. In particular, if aiming to use TDEs to independently populate, extend and refine these correlations.

5.1.2. Early-time Optical Flare Scaling and Modeling

The discovery of optically selected TDEs with prominent optical flares, enabled by modern wide-field time-domain surveys, has motivated extensive theoretical efforts to understand and model the physical origin of this emission component. These studies have generally converged on two main competing scenarios. In a simplified picture, the optical emission may arise either from (i) stream shocks at apocenter (e.g., Ryu et al. 2020b, 2023), or (ii) reprocessing of high-energy fallback-driven radiation (e.g., Dai et al. 2018; Mockler et al. 2019).

From the perspective of parameter inference, these scenarios have been translated into widely used publicly available modeling and parameter inference packages. TDEmass (Ryu et al. 2020a) uses the peak ‘blackbody’

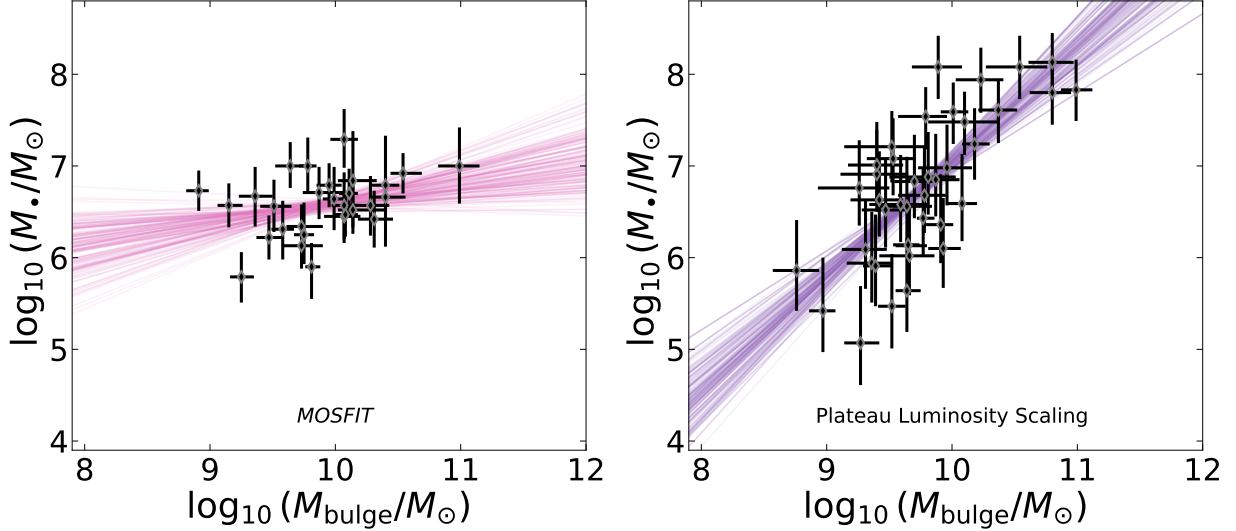


Figure 12. Black hole mass ($M_{\bullet}$)—estimated either with MOSFIT by Nicholl et al. (2022) (left) or from the plateau scaling relation (Mummery et al. 2024b) (right)—versus host galaxy bulge mass (M_{bulge}), as measured and presented in Ramsden et al. (2022, 2025). Statistical significance for non-zero correlation are 2.5σ (MOSFIT) and $\geq 5\sigma$ (plateau scaling).

luminosity and UV/optical color temperature to infer the black hole and disrupted stellar masses based on analytic expressions calibrated on global simulations of the disruption process. In contrast, MOSFIT (Mockler et al. 2019) assumes that the luminosity directly follows the fallback accretion rate, such that $L(t) = \eta c^2 \dot{M}_{\text{fb}}(t)$, where the efficiency parameter η converts the fallback rate into observable luminosity (which is then passed through reprocessing functions to produce optical emission). Both original studies applied these approaches to individual observed TDEs, and consistency with black hole–host galaxy scaling relations was suggested. However, these applications involved relatively small samples, and a formal statistical quantification was not presented.

With the rapid increase in TDE discovery rate (Hammerstein et al. 2023; Yao et al. 2023), particularly through the ZTF, population-level applications of these methods have become feasible. In what follows, we review these results and apply statistical methods to assess whether current implementations can recover black hole–host scaling relations at statistically significant levels.

In this and the next sections, following Greene et al. (2020) and Mummery et al. (2024b), we shall fit power-law profiles of the general form

$$\log_{10}(Y) = \alpha + \beta \log_{10}(X), \quad (7)$$

where

$$Y \equiv \frac{M_{\bullet}}{M_{\odot}}, \quad (8)$$

and X denotes a normalized scaling variable. To account for intrinsic scatter in the host–scaling relations, we in-

corporate an additional scatter term ϵ into the black hole mass uncertainties:

$$(\delta \log_{10} Y)^2 \rightarrow (\delta \log_{10} Y)^2 + \epsilon^2, \quad (9)$$

where $\delta \log_{10} Y \equiv \delta \log_{10}(M_{\bullet}/M_{\odot})$ is the measurement uncertainty on the logarithm (base 10) of each black hole mass. We then use `emcee` (Foreman-Mackey et al. 2013) to maximize the likelihood

$$\mathcal{L} = -\frac{1}{2} \sum_i \frac{(\log_{10}(Y_i) - \alpha - \beta \log_{10}(X_i))^2}{(\delta \log_{10}(Y_i))^2 + \epsilon^2} + \ln \left[2\pi \left((\delta \log_{10}(Y_i))^2 + \epsilon^2 \right) \right], \quad (10)$$

where the summation runs over all pairs (X_i, Y_i) of normalized scaling variables and black hole masses.

We begin with the analysis of Hammerstein et al. (2023), who applied both `TDEmass` and `MOSFIT` to infer $M_{\bullet}$ for the first 30 TDEs discovered by ZTF. In the top two panels of Fig. 10, we plot the reported values of $M_{\bullet}$ and M_{gal} . In this case $X = M_{\text{gal}}/(3 \times 10^{10} M_{\odot})$. Random draws from the posterior distributions of our MCMC fits are shown as colored lines, while the best-fit values and statistical properties are listed in Table 5. Consistent with the conclusions of Hammerstein et al. (2023), $M_{\bullet}$ inferred from both `TDEmass` and `MOSFIT` show no clear correlation with M_{gal} , as the fitted slopes β are consistent with zero. Quantitatively, the probabilities $P(\beta > 0)$ are 0.75 and 0.51 for `TDEmass` and `MOSFIT`, respectively, corresponding to statistical significances of 1.15σ and 0.7σ . Full posterior distributions are provided in Appendix B.

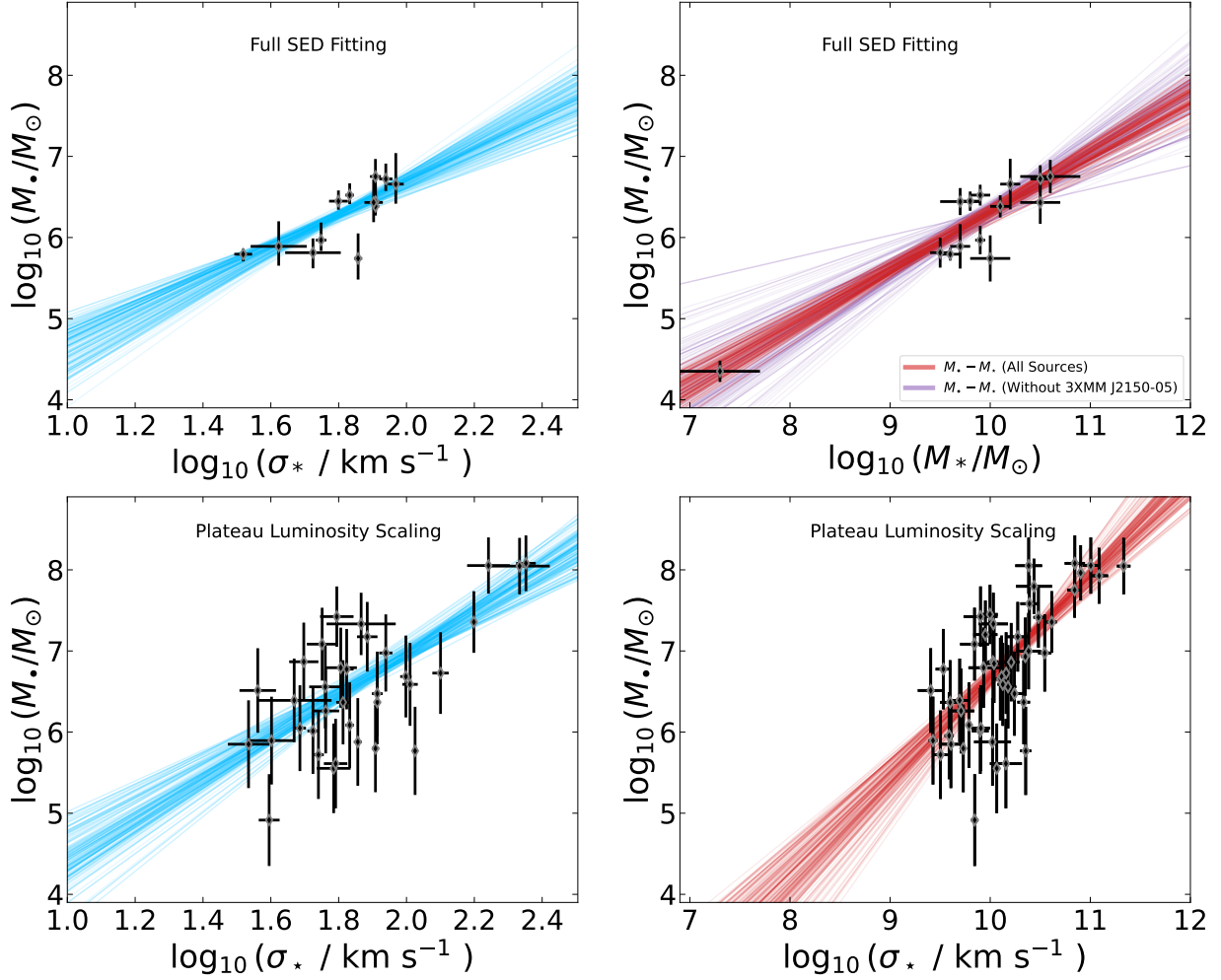


Figure 13. Black hole mass inferred from accretion methods, either Full SED fitting (top, this work), or the plateau scaling relation (bottom, Mummery et al. 2024b), versus galaxy mass (right panels) or nuclear velocity dispersion (left panels). Lines show random draws from MCMC power-law correlation fits. All panels have statistically significant correlation, from 4.1σ to $\geq 5\sigma$, see Table 5.

A recent work by Alexander et al. (2025) presented further population-level inferences of $M_{\bullet}$ from the early-time UV/optical flare. In this case, the authors compared $M_{\bullet}$ inferred from MOSFIT with $M_{\bullet,\text{host}}$ derived from galaxy scaling relations, primarily via σ_{*} (Kormendy & Ho 2013). Here we perform a statistical assessment of their results.

In the bottom panel of Fig. 10, we plot their reported $M_{\bullet}$ and $M_{\bullet,\text{host}}$, and perform the same MCMC fitting, adopting $X = M_{\bullet,\text{host}}/10^6 M_{\odot}$. As summarized in Table 5, the best-fit slope is $\beta = 0.30 \pm 0.12$, which correspond to 2.6σ statistical significance for a non-zero correlation. Because this is a $M_{\bullet} - M_{\bullet}$ comparison however, a real correlation should yield a β statistically consistent with $\beta \approx 1$ with some scatter $\epsilon \gtrsim 0.3$ (the scatter of Kormendy & Ho 2013). Instead, we find that β is $\sim 4.5\sigma$ away from the expected value.

The fact that $\beta \ll 1$ indicates that at the low-mass end MOSFIT systematically overestimates $M_{\bullet}$ relative to $M_{\bullet,\text{host}}$ expected from the host scaling relations, as also visible in Fig. 10, where *all* sources with $\log_{10}(M_{\bullet,\text{host}}/M_{\odot}) \lesssim 6$ have instead $\log_{10}(M_{\bullet}/M_{\odot}) \gtrsim 6$ as per MOSFIT. While at the high mass end, it will underestimate as compared to expected values from the host scaling relations.

We also apply the same analysis to the comparison between $M_{\bullet}$ values inferred from MOSFIT in Nicholl et al. (2022) and M_{bulge} reported by Ramsden et al. (2022). The results, summarized in Table 5 and show in the left panel of Fig. 12, yield a 2.5σ significance for a non-zero correlation.

Taken together, these findings suggest that packages aimed at inferring $M_{\bullet}$ from physical models of the early-time UV/optical emission in TDEs have not yet been able to recover host scaling relations at statistically sig-

nificant levels. This highlights the need for caution when interpreting black hole masses inferred from such methods.

Given these findings, one may ask whether *any* property of the early optical flare correlates with host-galaxy quantities such as M_{gal} or σ_* . Recent work by [Mummery et al. \(2024b\)](#) found that the peak luminosity of the flare—either the observed $L_{g,\text{peak}}$ or the so-called ‘blackbody’ peak luminosity $L_{\text{BB,peak}}$ —does correlate with both M_{gal} and σ_* , finding approximately linear relations of the form $L_{\text{peak}} \propto M_{\bullet,\text{host}}^{0.95 \pm 0.25}$, with empirical scatter $\epsilon \sim 0.5$ dex. We have repeated the same statistical fits for both the $L_{\text{peak}}-M_{\text{gal}}$ and $L_{\text{peak}}-\sigma_*$ relations, adding more recent sources from [Mummery & van Velzen \(2025\)](#), as shown in Table 5 and Appendix B, and confirm that both correlations are recovered at high significance ($\gtrsim 5\sigma$), with $\beta = 0.83 \pm 0.11$ and $\beta = 1.67 \pm 0.28$, respectively, both with $\epsilon \approx 0.5$ dex. This is a somewhat surprising but potentially important result: a purely empirical quantity (L_{peak}) appears to show much stronger correlations with host-galaxy properties than $M_{\bullet}$ values inferred from physical models for the optical flare.

As discussed by [Mummery et al. \(2024b\)](#) and [Mummery & van Velzen \(2025\)](#), the recovered empirical relation $L_{\text{peak}} \propto M_{\bullet,\text{host}}^{0.95 \pm 0.25}$ may help explain why neither TDEmass nor MOSFIT currently reproduce the observed black hole–host scaling relations. The TDEmass model ([Ryu et al. 2020a](#); [Krolik et al. 2025](#)) assumes $L_{\text{peak}} \propto M_{\bullet}^{-1/6} \Xi(M_{\bullet})^{5/2}$, where $\Xi(M_{\bullet})$ is a decreasing function of $M_{\bullet}$, resulting in an approximately $L_{\text{peak}} \propto M_{\bullet}^{-3/8}$ scaling. This prediction is in clear tension ($> 5\sigma$) with the data ([Mummery & van Velzen 2025](#)). Similarly, MOSFIT assumes a fallback-scaled luminosity of the form $L(t) = \eta c^2 \dot{M}_{\text{fb}}(t)$, such that $L_{\text{peak}} \propto \eta \dot{M}_{\text{fb,peak}} \propto \eta M_{\bullet}^{-1/2}$. This scaling can only be reconciled with the data if the ‘efficiency’ scales with black hole mass as $\eta \propto M_{\bullet}^{3/2}$.

Perhaps unsurprisingly, [Nicholl et al. \(2022\)](#), by fitting a sample of TDEs with MOSFIT, recovered a scaling of $\eta \propto M_{\bullet}^{0.97 \pm 0.36}$. This result raises several considerations. Substituting $\eta \propto M_{\bullet}^{0.97 \pm 0.36}$ back into the MOSFIT luminosity prescription gives $L_{\text{peak}} \propto \eta(M_{\bullet}) M_{\bullet}^{-1/2} \propto M_{\bullet}^{0.47 \pm 0.36}$, which is broadly consistent, within uncertainties, with the empirical relation $L_{\text{peak}} \propto M_{\bullet,\text{host}}^{0.95 \pm 0.25}$. However, this result is inconsistent with MOSFIT’s built-in assumption that the luminosity directly tracks the fallback rate, $L \propto \dot{M}_{\text{fb}}$, given that $\dot{M}_{\text{fb,peak}} \propto M_{\bullet}^{-1/2}$.

This, of course, implies that the model assumptions for each individual source are not consistent with the results at the population level, and that the outcomes of applying the model are themselves inconsistent with

its underlying assumptions. Instead, this appears to be a likelihood maximization-driven outcome of treating η as a free parameter within a prescription, $L_{\text{peak}} \propto \eta M_{\bullet}^{-1/2}$, that cannot describe the observed $L_{\text{peak}} \propto M_{\bullet}$ trend. Such an interpretation is supported by the fact that, to our knowledge, no physical mechanism predicts or explains a positive correlation between radiative efficiency and black hole mass. Without fine-tuning η , MOSFIT makes a physical assumption that is in strong ($> 5\sigma$) tension with the data.

Together, these findings indicate that the common assumption that the luminosity of the early-time UV/optical component directly tracks the fallback rate does not hold ([Mummery et al. 2024b](#)).

Finally, it is worth emphasizing that the observed correlation $L_{\text{peak}} \propto M_{\bullet}$ is, at present, mostly empirical, and the physical mechanism responsible for driving it remains uncertain (though see discussion in [Mummery et al. 2024b](#); [Metzger 2022](#)). Nevertheless, reproducing this relation within a physically motivated framework should be an important goal for future modeling efforts of the early-time optical emission in TDEs.

5.1.3. Accretion Based Measurements

Here we consider methods for inferring $M_{\bullet}$ from standard accretion emission, with a focus on their ability to recover black hole–host galaxy scaling relations. In §4.3, we compared our approach with the plateau luminosity relation of [Mummery et al. \(2024b\)](#), highlighting both their similarities and differences, as well as the degree of consistency between the results. The late-time SED fitting method can provide smaller uncertainties on $M_{\bullet}$ but requires high-quality multi-wavelength coverage, which naturally limits its use to well-observed, nearby TDEs. The plateau relation, although less precise, depends only on a single luminosity measurement and is therefore applicable to a broader set of sources.

The accuracy of SED fitting comes from its ability to probe both the inner (e.g., peak temperature) and outer disk properties. At the same time, this method becomes more challenging to apply to very massive black holes ($M_{\bullet} \gg 10^7 M_{\odot}$), whose cooler disks are unlikely to produce detectable thermal X-ray emission (§4.1). Such systems may instead show only hard X-ray emission from a corona ([Mummery & Balbus 2021](#)), or possibly no X-ray signal at all. While hard X-ray spectra could in principle be incorporated into fits, the absence of a measurable T_p limits the achievable precision. Consequently, the tight uncertainties obtained for thermally dominated systems are unlikely to extend to higher-mass, non-thermal cases.

Following §5.1.2, we statistically assessed whether these accretion-based methods can reproduce known black hole–host scaling relations. Using both the plateau scaling and full SED fitting, we repeated the MCMC analysis for the $M_\bullet$ – M_{gal} and $M_\bullet$ – σ_* relations, where $X = M_{\text{gal}}/3 \times 10^{10} M_\odot$ and $X = \sigma_*/160 \text{ km s}^{-1}$. Results are presented in Table 5 and Fig. 5.1.2, with posteriors in Appendix B. For the SED fitting method, we recover a $P(\beta > 0) \geq 5\sigma$ correlation for $M_\bullet$ – M_{gal} with the full sample, which decreases to $\sim 4.1\sigma$ when excluding 3XMM J2150-05. For $M_\bullet$ – σ_* , despite the small sample size, we still obtain $P(\beta > 0) \sim 4.6\sigma$. With the plateau relation, both $M_\bullet$ – M_{gal} and $M_\bullet$ – σ_* are recovered at $\geq 5\sigma$, in agreement with Mummery et al. (2024b). Thus, both methods reproduce the expected trends, with their main differences lying in data requirements, measurement uncertainties, and the scatter in the resulting correlations (see ϵ in Table 5).

We extended this analysis to the $M_\bullet$ – M_{bulge} relation, using Ramsden et al. (2025) results with $M_\bullet$ derived from the plateau scaling. As shown in Table 5 and the right panel of Fig. 12, we find a $\geq 5\sigma$ significance for a non-zero correlation, a much stronger result than earlier work by the same authors (Ramsden et al. 2022), who obtained only $\sim 2.5\sigma$ significance using MOSFIT-derived $M_\bullet$.

Taken together, these findings suggest that, while early-time optical methods have not yet recovered black hole–host scaling relations, the accretion-based approaches are able to do so. This indicates that mass estimates derived from early optical emission should be treated with caution, while also underscoring the advantages of models grounded in accretion physics (§5.1.2). The accretion-based framework, whether time-dependent or not, provides a physically transparent means of modeling TDE emission, capable of reproducing multi-wavelength data and simultaneously recovering known scaling relations. This highlights the potential of TDEs as an independent probe of black hole demographics.

This perspective is consistent with broader efforts to use TDEs for demographic studies. Notably, attempts to recover the black hole mass function using TDEs, have so far relied on $M_\bullet$ inferred from either host scaling relations (Yao et al. 2023) or the plateau scaling relation (Mummery & van Velzen 2025), but never from early-time optical modeling.

Ultimately, the choice between these different accretion-based methods to be used depends on the quality and type of data available for each source, and goals of the analysis. Still, they are expected to give consistent results: although the assumptions differ in the

details, all are rooted in the same underlying physics. As demonstrated here, this framework is capable of recovering expected scaling relations while providing self-consistent parameter estimates.

5.2. Implications for TDE physics and modeling

The fitting results and parameter correlations presented in §4 have several important implications for the physics and modeling of TDEs. First, the ability of a simple thin-disk model to reproduce both the X-ray spectra and the UV/optical photometry during the plateau phase strongly supports a common origin in direct disk emission for these components. Moreover, the fact that the same disk model (with fixed R_{in} and $a_\bullet$) can also describe the X-ray spectra at earlier epochs—when the optical emission was still dominated by a non-disk component—simply by allowing the peak disk temperature to increase, demonstrates that the accretion disk consistently powers the X-rays at all times.

In those systems where the X-rays can be modeled by varying only T_p while the early-time optical flare is still ongoing (see Fig. 1 and Appendix A), the implication is clear: the X-rays are neither absorbed nor reprocessed into optical emission by a spherical outflow surrounding the disk (as is often assumed). If reprocessing were dominant and spherically symmetric, the direct disk emission could not remain visible with unchanged intrinsic disk parameters. These findings are consistent with independent results by Mummery & van Velzen (2025) based on the luminosity functions of TDEs.

Another important result, already noted in Guolo et al. (2024a) using $M_\bullet$ inferred from host scaling relations and confirmed here with accretion-based $M_\bullet$ estimates, is that there is no preference in black hole mass for whether X-rays appear promptly or are delayed relative to the UV/optical flare. For instance, ASASSN-14li and AT2019azh have nearly identical black hole masses (within small uncertainties), yet in ASASSN-14li the X-rays peaked immediately, while in AT2019azh the X-rays peaked only several months later, after the early-time optical component had nearly disappeared. This rules out models in which delayed X-ray emission is primarily driven by differences in $M_\bullet$.

A commonly proposed alternative to spherical reprocessing is a geometric explanation – the obscuring/reprocessing material is not spherically distributed, but instead contained within some fixed (or time varying) solid angle to the equatorial plane. Within this framework in high-inclination systems X-rays and other high-energy photons could be reprocessed to lower energies, suppressing the early X-ray signal while powering the optical flare (e.g. Dai et al. 2018). Guolo et al.

(2024a) suggested this as a possible explanation for why fitting rising X-ray spectra with a standard disk model sometimes yields unphysical results (e.g., unrealistically small inner radii) at the early-time/rise of the X-ray light curve. While appealing, inclination constraints derived in this work (§4) also fail to support an orientation-driven scenario: both low- and high-inclination systems show prompt and delayed X-ray emission. For example, ASASSN-14li (prompt) and AT2020ksf (delayed) are both inferred to be nearly face-on, while AT2019dsg (prompt) and AT2011ehb (delayed) are likely higher-inclination. Furthermore, the previous discussion regarding the inability of reprocessing proportional to the fallback rate—an assumption also adopted by Dai et al. (2018)—to reproduce the observed correlation between L_{peak} and $M_{\bullet}$ continues to hold in any model (even if orientation-dependent) in which the luminosity tracks the fallback rate, and therefore also disfavors this class of models.

Nevertheless, a key conclusion from Guolo et al. (2024a) remains valid: X-ray-selected and optically selected TDEs are drawn from the same underlying black hole population, a result independently - via luminosity function analysis - further supported by more recent studies Mummery & van Velzen (2025). The results presented here provide additional confirmation of this picture, as our sample includes both X-ray- and optically selected sources, all of which can be consistently modeled within the same physical framework, with no evident dependence on $M_{\bullet}$.

An alternative explanation which is consistent with these recent findings is that delays in X-ray rise times simply represent the diversity in viscous timescales present in a population of TDEs (an argument that goes back to Mummery 2021, but which we make more precise here). The viscous timescale of an accretion flow is equal to

$$t_{\text{visc}} \propto \frac{\sqrt{GM_{\bullet} r_0^3}}{W_{\phi}^r}, \quad (11)$$

where W_{ϕ}^r is the turbulent stress-tensor (Balbus & Papaloizou 1999). If one takes an Shakura & Sunyaev (1973) α -prescription for the turbulent stress, then $W_{\phi}^r = GM_{\bullet}(h/r)^2\alpha$, where (h/r) is the aspect ratio of the flow. The viscous timescale of a TDE disk should therefore show no dependence on black hole properties, a potentially surprising result which originates from the scaling of the tidal radius with black hole mass $R_T \approx R_{\star}(M_{\bullet}/M_{\star})^{1/3}$, leading to a viscous timescale of

$$\begin{aligned} t_{\text{visc,TDE}} &\approx \alpha^{-1}(h/r)^{-2} \sqrt{R_T^3/GM_{\bullet}} \\ &\approx \alpha^{-1}(h/r)^{-2} \sqrt{R_{\star}^3/GM_{\star}}. \end{aligned} \quad (12)$$

An accretion flow that forms at $\sim R_T$ and then propagates inwards rises in the X-ray's to peak after a time $\delta t \sim t_{\text{visc}}$ ¹⁰. The viscous timescales in TDE disks are known to span (at least) ~ 2 orders of magnitude (Guolo et al. 2025a), likely reflecting variance in both the stellar density ($t_{\text{visc}} \sim \rho_{\star}^{-1/2}$) and the nuisance parameters $\alpha(h/r)^2$. The independence of whether a TDE shows a delayed/prompt X-ray rise on black hole mass is entirely consistent with simple viscous disk theory, and warrants further study.

Another important implication of our results concerns the inference of bolometric luminosities and, by extension, accretion rates (or Eddington ratios). The normalized accretion rate is typically expressed as the ratio between the bolometric luminosity and the Eddington luminosity, with the bolometric luminosity defined as the total emission integrated over all wavelengths. The key challenge is how to estimate this quantity when observations cover only a limited portion of the electromagnetic spectrum.

Several approaches have been employed in the literature. A common method is to fit the UV/optical SED with a single-temperature blackbody and adopt its integrated luminosity (L_{BB}) as the bolometric luminosity. For example, this procedure is implemented by MOSFIT. However, this procedure cannot account for the observed X-ray emission (which routinely reaches $L_X \sim 10^{43}$ erg/s).

Another approach is to fit a model to the X-ray spectrum and calculate the luminosity in a finite energy range,

$$L_X = 4\pi D^2 \int_{0.3 \text{ keV}}^{10 \text{ keV}} F_E dE, \quad (13)$$

where F_E is the best-fitting spectral model, and then define $L_{\text{Bol}} = L_X + L_{\text{BB}}$. This too is problematic, since there is no physical justification for truncating the emission at 0.3 keV.

The only appropriate way to truly estimate the bolometric luminosity is to use a physically motivated model that can describe the SED self-consistently across the full range of relevant wavelengths—not only where data are available, but also in the unobserved regions, i.e., in the energy range between the Lyman limit and the soft X-ray regime (~ 0.2 – 0.3 keV). This is precisely the approach we have taken in this work. The implications are significant: any model that estimates the bolometric luminosity but does not self-consistently describe the

¹⁰ This δt , is the time between ‘circularization’ of the debris and the X-ray peak, and should not be confused with Δt used previously, which is the time between discovery and an observation.

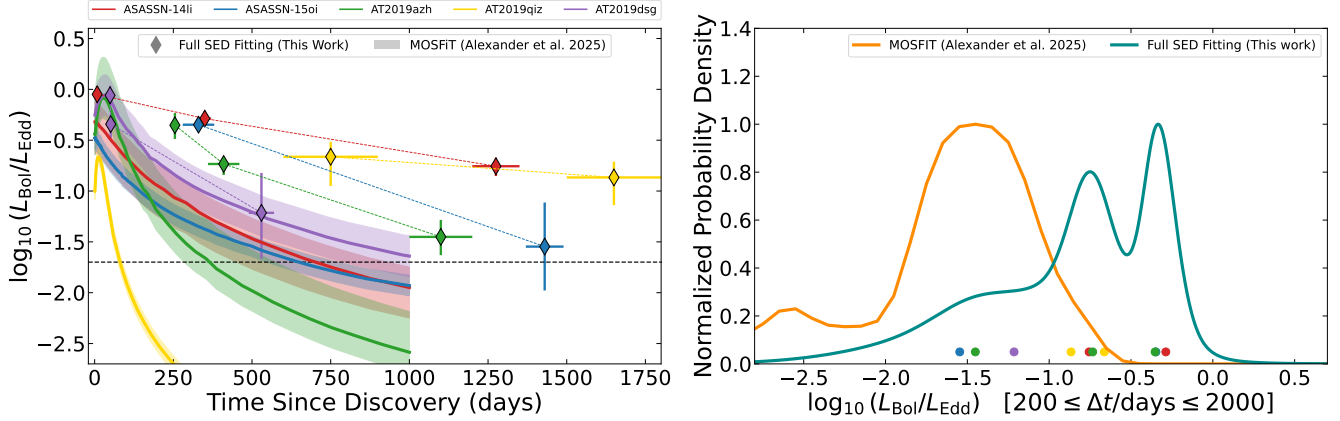


Figure 14. Comparison of late-time between $L_{\text{Bol}}/L_{\text{Edd}}$ from full SED fitting and the ‘accretion rate’ predicted from MOSFIT for the 5 sources commonly analyze here and in Alexander et al. (2025). Left panel show $L_{\text{Bol}}/L_{\text{Edd}}$ as a function of time and right panel show the probability density distribution from $200 \leq \delta t/\text{days} \leq 2000$. MOSFIT systematically underestimates this value, all 5 sources have $\leq 3\%$ Eddington at $\delta t = 1000$ days, while the data (i.e. the full SED) implies that only AT2019dsg has. Such underestimation grows with time.

emission across multiple wavelengths at the same time will always underestimate L_{bol} , and by implication produce incorrect inferences about the properties of the system. The reason for this is relatively (observationally) simple, a typical observed TDE SED is rising toward the Lyman limit in the UV, and only begins to decline after emerging in the X-ray, meaning the peak of the emission must lie in the unobserved extreme ultraviolet (see SEDs in Fig. 2 and Fig. 3).

This has practical, and very important, implications. One of the most important open questions in the study of accretion is whether accretion is a truly scale-invariant process and, for example, the question of whether supermassive black hole disks undergo state transitions at Eddington ratios $\dot{m} \sim 0.02$ (like X-ray binary disks do e.g., Fender et al. 2004) remains unsolved. TDEs represent the ideal systems to ask this question, owing to their short evolutionary timescales. One can of course only look for correlations between accretion state and Eddington ratio by both (i) modeling the accretion flow itself, and (ii) accurately measuring the accretion rate in the system.

In what follows we compare bolometric luminosities and (Eddington normalized) accretion rates found in this work, with those recently inferred by (Alexander et al. 2025) using MOSFIT. In Fig. 14 we compare the

“accretion rates”¹¹ inferred by Alexander et al. (2025) from fitting the early time optical flare in TDEs, with that inferred here by fitting the emission which do result from the accretion flows in these TDEs (the late time UV/optical and X-ray emission).

As can be clearly seen in Figure 14, the values inferred by Alexander et al. (2025) are not compatible with the data analyzed here (at a minimum because these do not account for the X-ray or the UV/plateau emission, which are both produced by accretion). Beyond $\Delta t \sim 250$ days, every value inferred by MOSFIT is inconsistent with the values inferred here (which were derived from fitting the entire SED) by at least one order of magnitude (except the rapidly evolving AT2019dsg). A particularly striking example is that of AT2019qiz, which is inferred (by MOSFIT) to have a peak Eddington accretion rate which is lower than the full-SED fitting value at 1750 days. AT2019qiz is particularly well constrained at these late times (see Figs. 2, 3, and also Nicholl et al. 2024).

This point is important because, in Alexander et al. (2025), the authors correlate radio properties with the MOSFIT-derived values, finding no evidence for the $\dot{m} \sim$

¹¹ MOSFIT does not have any accretion physics (or a disk) as part of its modeling so this terminology – which is regularly used – is confusing. MOSFIT aims to track mass back to pericentre, the “fallback” rate. This material, of course, has angular momentum, so it cannot simply propagate to the event horizon, so $\dot{M}_{\text{acc}}$ never equals $\dot{M}_{\text{fb}}$. To account for this effect, MOSFIT adds a “viscous delay” parameter; this parameter is, however, found to be consistent with zero in most sources (Alexander et al. 2025), and therefore shorter than the light-crossing time for the inferred black hole masses, which is not a physical result.

0.02 transition. However, these “accretion rate” estimates differ substantially from those obtained through full SED modeling: every source in that study has an Eddington ratio below 3% at 1000 days, whereas only one source in our sample of 14 (AT2019dsg) does. The lack of correlation is therefore not physically meaningful and instead reflects an attempt to infer an accretion rate from emission that is not disk-emitted, using a model that does not include accretion physics, and which infer black hole masses inconsistent with host scaling relations. Consequently, the analysis of [Alexander et al. \(2025\)](#) provides evidence neither for nor against the assumption of scale invariance in black hole accretion, which remains an open question.

Another interesting point to note from Figure 14 is that the bolometric luminosities of the disk systems in TDEs decays much more slowly than their X-ray luminosity (see Figure 3), a result of the exponential dependence of the X-ray luminosity on disk temperature ([Mummery & Balbus 2020; Mummery et al. 2023](#)). Thus, the “bolometric correction” from X-ray to bolometric luminosity grows exponentially with time, which combined with the $\geq$ decade long lasting disk, naturally resolves the ‘missing energy problem’ (as shown in e.g., [Mummery 2021; Mummery & van Velzen 2025; Guolo & Mummery 2025; Guolo et al. 2025a](#)).

Finally, it is interesting to comment on the fact that our full SED fitting, where $E(B - V)$ is allowed to vary, results in a non-zero host galaxy extinction for many sources (Table 4), whereas most studies of TDEs simply assume this to be zero. Although the derived $E(B - V)$ values are low, because dust extinction effects increase strongly at shorter (UV) wavelengths, this may still have relevant implications for, e.g., measurements of the early-time optical flare luminosities and color temperatures, and thus warrants further investigation.

6. CONCLUSIONS

We present a multi-wavelength analysis of 14 TDEs with available X-ray spectra during the UV/optical plateau phase of their evolution, using full spectral energy distribution fitting as a methods for black hole and disk parameter inference, alongside a comparative review of the methods used to estimate black hole masses in TDEs. Our main conclusions are as follows:

- During the late-time “plateau phase” of TDE evolution the entire SED from optical to X-ray wavelengths can be described by an evolving accretion flow, with no need for any additional spectral components.

- The very same disk models, simply with a larger peak disk temperature, reproduce the X-ray emission observed from TDEs at all times. This means that the disks observed at late times in the UV/optical are the same accretion systems which produce X-rays at all observational epochs.
- Full SED fitting provides a robust and accurate (uncertainty $< \pm 0.3$ dex) way of measuring black hole masses in TDEs. These masses independently recovers known galactic scaling relationships at high significance $> 4\sigma$, despite the small sample size. Showing our method is not only precise, but also reliable. In the case of the $M_{\bullet} - \sigma_{\star}$ correlation, our method recovers the correlation with a scatter of only $\epsilon \sim \pm 0.1$ dex.
- Detailed modeling of late-time TDE disks recovers the expected accretion-disk scaling relations, $L_{\text{bol}}^{\text{disk}}/L_{\text{Edd}} \propto T_p^4 \propto M_{\bullet}^{-1}$. Characteristic TDE correlations are also recovered, including the UV plateau scaling $L_{\text{plat}} \propto M_{\bullet}^{2/3}$ and, for the first time, the compact-disk size scaling $R_{\text{out}}/r_g \propto M_{\bullet}^{-2/3}$. This second result confirms the TDE interpretation of all sources in our sample.
- Both the general accretion correlations and those specific to TDE disks are, for the first time, self-consistently extended—through a homogeneous sample analysis—into the intermediate-mass black hole regime, using the off-nuclear TDE 3XMM J2150–05.
- We have reviewed different techniques for inferring black hole masses in TDEs, finding that approaches based on models of the early-time UV/optical emission are not able to recover (at a statistically significant level) black hole–host galaxy scalings, and assume luminosity scalings in strong ($> 5\sigma$) tension with observations, implying that parameter inference with these techniques is unreliable.
- We have demonstrated that the accretion rates ($L_{\text{Bol}}/L_{\text{Edd}}$) in TDEs cannot be estimated from the the fall-back based modeling of the emission produced by the early-time optical flare. Given that this approach is based on: inferred $M_{\bullet}$ that can not reproduce host-scaling relations, and L_{Bol} that can not explain the data (UV/optical plateau and X-ray at any time) which combined leads to errors at the order of magnitude level within the first year of the event, these errors then grow rapidly with time.

The results presented in this paper highlight the value of detailed modeling of accreting TDE disks, particularly at late times. This powerful observational approach will be especially important as we enter the era of LSST, with its anticipated capability to discover large numbers of TDEs, and as future missions at complementary wavelengths—such as UVEX (Kulkarni et al. 2021), CASTOR (Cote et al. 2012) and AXIS (Reynolds et al. 2023)—enabling combined multi-wavelength studies.

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APPENDIX

A. DATA REDUCTION AND BASIC ANALYSIS

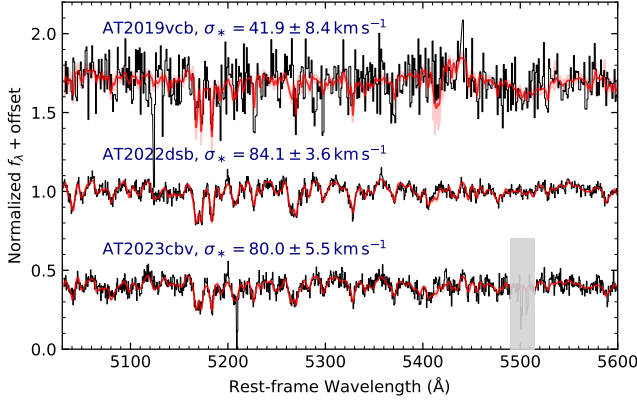
A.1. *New σ_* Measurements*

Figure 15. ESI spectra of the host galaxies of three TDEs (black) and the best-fit models (red).

The host galaxies of AT2019vcv, AT2022dsb, and AT2023cbv were observed by the Echelle Spectrograph and Imager (ESI; Sheinis et al. 2002) on the Keck II telescope (see Table 6 for a log). The slit width for all observations is $0.75''$, corresponding to $\sigma_{\text{inst}} = 23.7 \text{ km s}^{-1}$. We follow the same procedures as outlined in Yao et al. (2023) to reduce the data and measure σ_* by fitting the rest-frame 5030–5600 Å spectrum with the penalized pixel-fitting (pPXF) software (Cappellari & Emsellem 2004; Cappellari 2017). The data and best-fit models are shown in Figure 15.

A.2. *Sources of Data*

X-ray data from *XMM-Newton*/EPIC-pn, *NICER*/XTI, *Swift*/XRT, and *Chandra*/ACIS were used in this work. The *XMM-Newton* data were reduced following the procedures described in Guolo et al. (2024a). The *Swift*/XRT data were processed using the *Swift*/UK automated online tool¹² (Evans et al. 2009). The *NICER*/XTI data were reduced as in Guolo et al. (2024b), except for the background modeling: instead of using 3C50 (Remillard et al. 2021), we employed the SCORPION model by setting `bkgmodeltype=scorpeon` `bkgformat=file` in `nicerl3-spec`. The *Chandra* data utilized in this work comprises only the ACIS-S ob-

servation (Obs-ID 17862) of 3XMM J2150-05. We performed all the data reduction using CIAO 4.17 and CALDB 4.12.0, starting with reprocessing the data using the `chandra_repro` tool. We then extracted the spectral files, including the ARFs and RMFs, using the `specextract` tool in CIAO, with a circular source region of radius $2.5''$ and an annular background region with inner and outer radii equal to $4''$ and $9''$.

For AT2019qiz, AT2021ehb, ASASSN-14li, AT2019azh, AT2022dsb, AT2022lri, ASASSN-15oi, AT2018cqh, and AT2023vcv, host-subtracted UV/optical photometry was obtained from the ManyTDE library, whose reduction procedures are described in Mummery et al. (2024b). From this library, we use both *Swift*/UVOT and ZTF light curves.

For AT2019vcv and AT2020ksf, individual ManyTDE observations do not yield significant ($\geq 3\sigma$) detections of the plateau phase. For these sources, we instead stacked the *Swift*/UVOT images over the time intervals listed in Table A, and adopted the stacked fluxes for epochs detected at $\geq 3\sigma$ above the host level. For display purposes only, we also include the ATLAS (Tonry et al. 2022) light curve of AT2020ksf, the only instrument that captured its optical peak; the reduction of these data is described in Wevers et al. (2024).

For GSN 069, we use the two epochs of binned, host-subtracted UV *HST*/STIS spectroscopy, processed as detailed in Guolo et al. (2025b) and Guolo et al. (2025a).

For 3XMM J2150-05, we use both pre-transient (host) and post-transient photometry as reported in Lin et al. (2018, 2020). Host subtraction for this source follows the methods described in Mummery & Guolo et al., in prep.

A.3. *Median SED computation*

We compute the mean UV/optical SED in bins during the plateau phase as shown Table 2. Within each bin, the mean of N measurements of the flux F_i is computed using inverse-variance weighting:

$$\bar{F} = \frac{\sum_i^N F_i \sigma_{F_i}^{-2}}{\sum_i^N \sigma_{F_i}^{-2}} \quad (\text{A1})$$

with σ_F the measurement uncertainty of the flux. The variance of this mean flux is given by

$$\sigma_{\bar{F}}^2 = \frac{1}{\sum_i \sigma_{F_i}^{-2}} \quad (\text{A2})$$

If the flux measurement contain a source of systematic uncertainty, this will be apparent from the sample vari-

¹² https://www.swift.ac.uk/user_objects

Table 6. Log of medium-resolution optical spectroscopy with Keck-II ESI.

IAU Name	Start Date MJD	Exp. (s)	r_{extract} (pixel) ^a	S/N	σ_*
AT2019vcb	2021-12-28.53	1200	—	4.6	$41.86^{+8.70}_{-8.09}$
AT2022dsb	2023-04-15.59	900	6.5	20.0	$84.07^{+3.82}_{-3.45}$
AT2023cvb	2022-11-27.6	1500	6.5	18.1	$79.98^{+5.92}_{-5.01}$

^aThe radius used for extracting the spectrum. r_{extract} can be converted to angular scale using a conversion factor of $0.154''$ per pixel. For AT2019vcb, due to the low S/N of the observation, we extracted the spectrum from the full trace.

ance, $\sigma_{\text{sample}}^2 = (N-1)^{-1} \sum_i^N (F_i - \bar{F})^2$. Systematic uncertainty dominates when the square root of the sample variance is larger than the typical measurement uncertainty. For bins with $N > 5$ data points, we therefore also compute the uncertainty on the mean flux under the assumption that true uncertainty of each observation follows from the sample variance:

$$\sigma_{\bar{F}, \text{sample}}^2 = \frac{\sigma_{\text{sample}}^2}{N} . \quad (\text{A3})$$

If the statistical uncertainty (Eq. A2) is smaller than the sample-variance based estimate (Eq. A3), we use the latter in our likelihood function.

B. STATISTICAL SUPPLEMENTS

Here we present additional statistical information. Fig. 17 shows the posterior distributions corresponding to the MCMC fits presented in Figs 10 and 11, while Fig 18 shows the posterior distributions for the fits in Fig 5.1.2. Fig 20 presents the posterior distributions of the correlations (or lack thereof) between the inferred black hole mass, $M_{\bullet}$ —estimated either with MOSFIT or from the plateau scaling relation (Mummery et al. 2024b)—and the host galaxy bulge mass, M_{bulge} , as measured and presented in Ramsden et al. (2022, 2025). Finally, Fig 19 shows, in the top panels, the posterior distributions and, in the bottom panels, the correlations between the peak luminosity of the early-time optical flare (L_{peak}) and host galaxy properties: total stellar mass (M_{gal} , right) and nuclear velocity dispersion (σ_* , left).

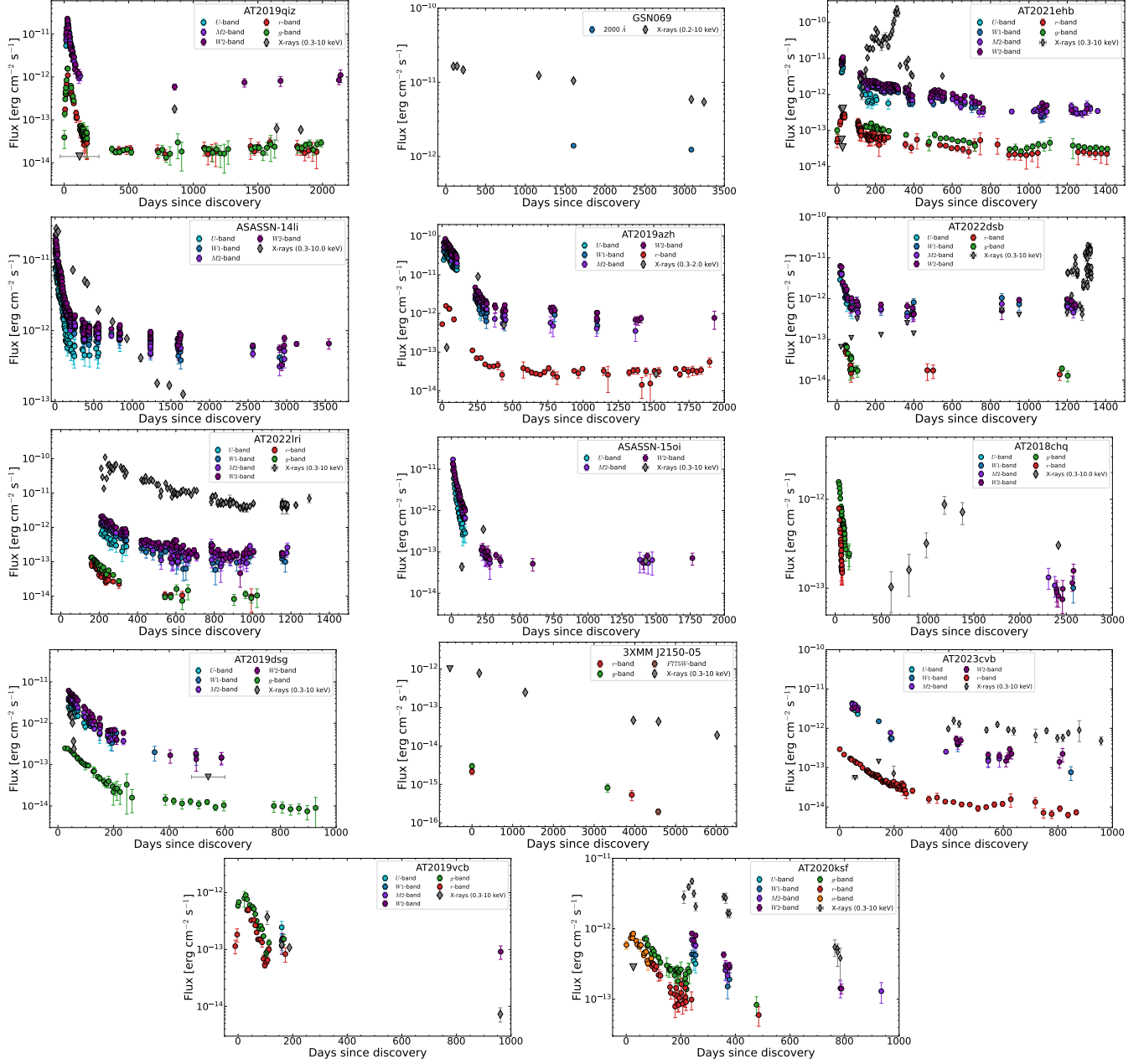


Figure 16. Host subtracted multi-wavelength light curves for all sources, shown as observed with no correction for extinction Galactic or intrinsic. X-ray light curves show absorbed fluxes.

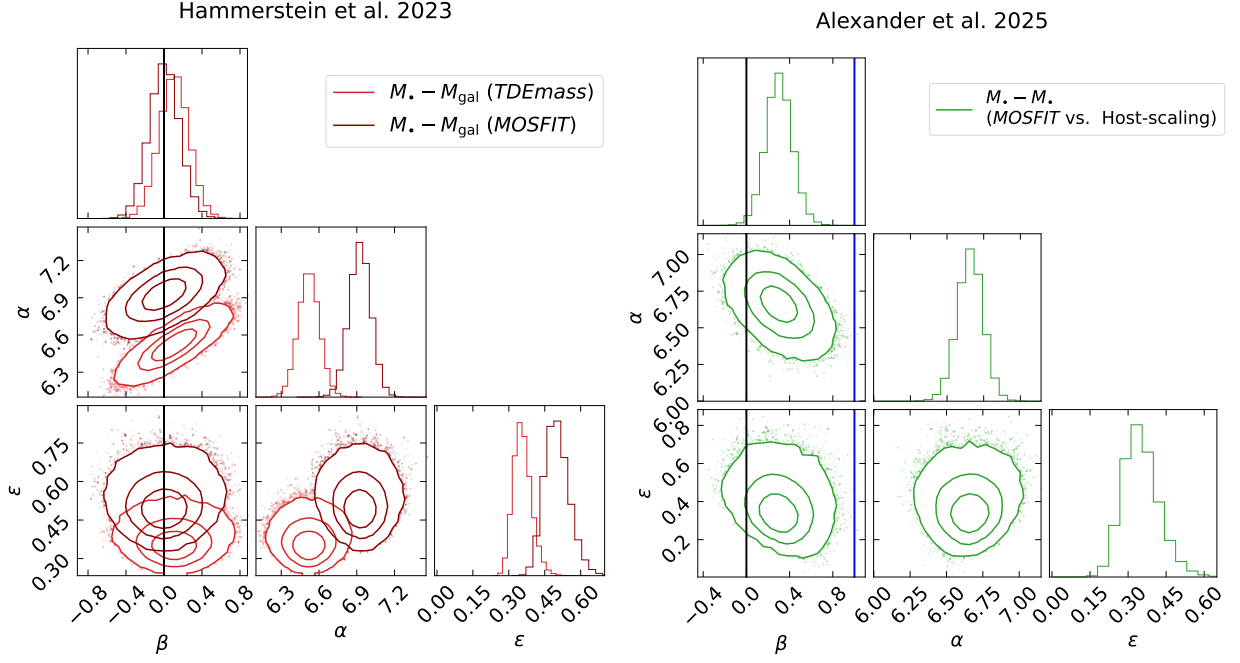


Figure 17. Posterior distributions corresponding to the MCMC fits presented in Figs 10 and 11. In both panel black line shows the demarcation for non-correlation, i.e., $\beta = 0$. In the right panel the blue line shows the expected 1:1 ($M_{\bullet} - M_{\bullet}$) correlation, i.e. $\beta = 1$.

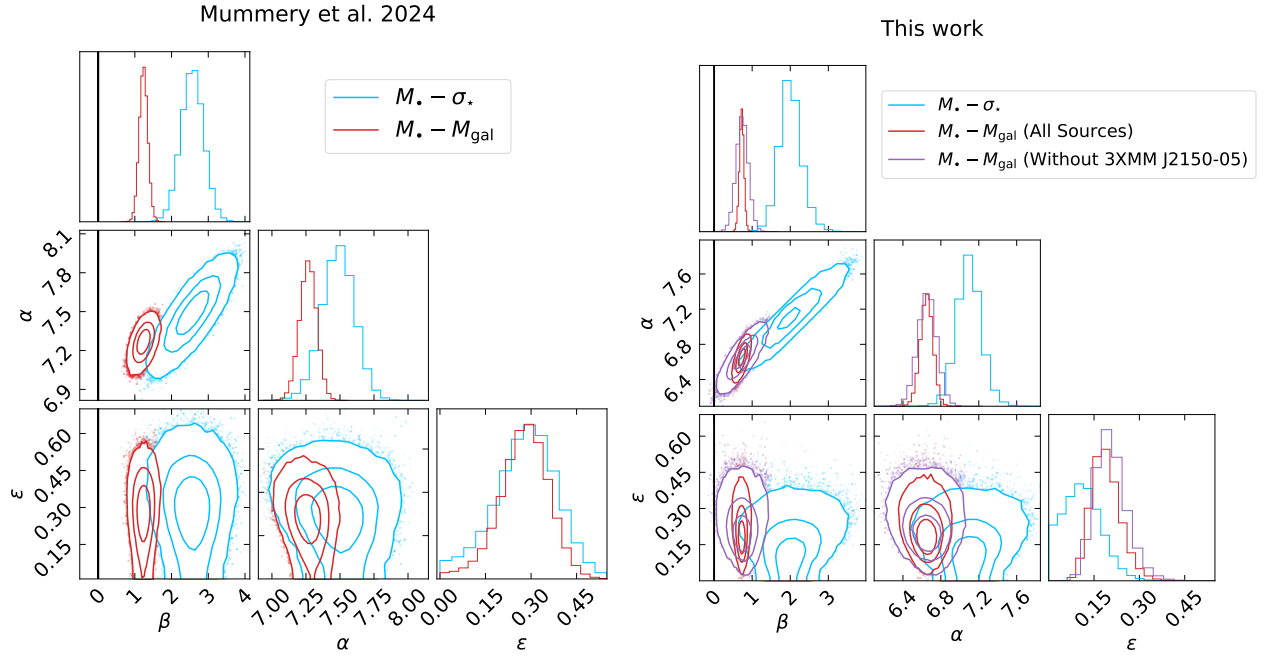


Figure 18. Posterior distributions corresponding to the MCMC fits presented in Fig 5.1.2.

Mummery et al. 2024

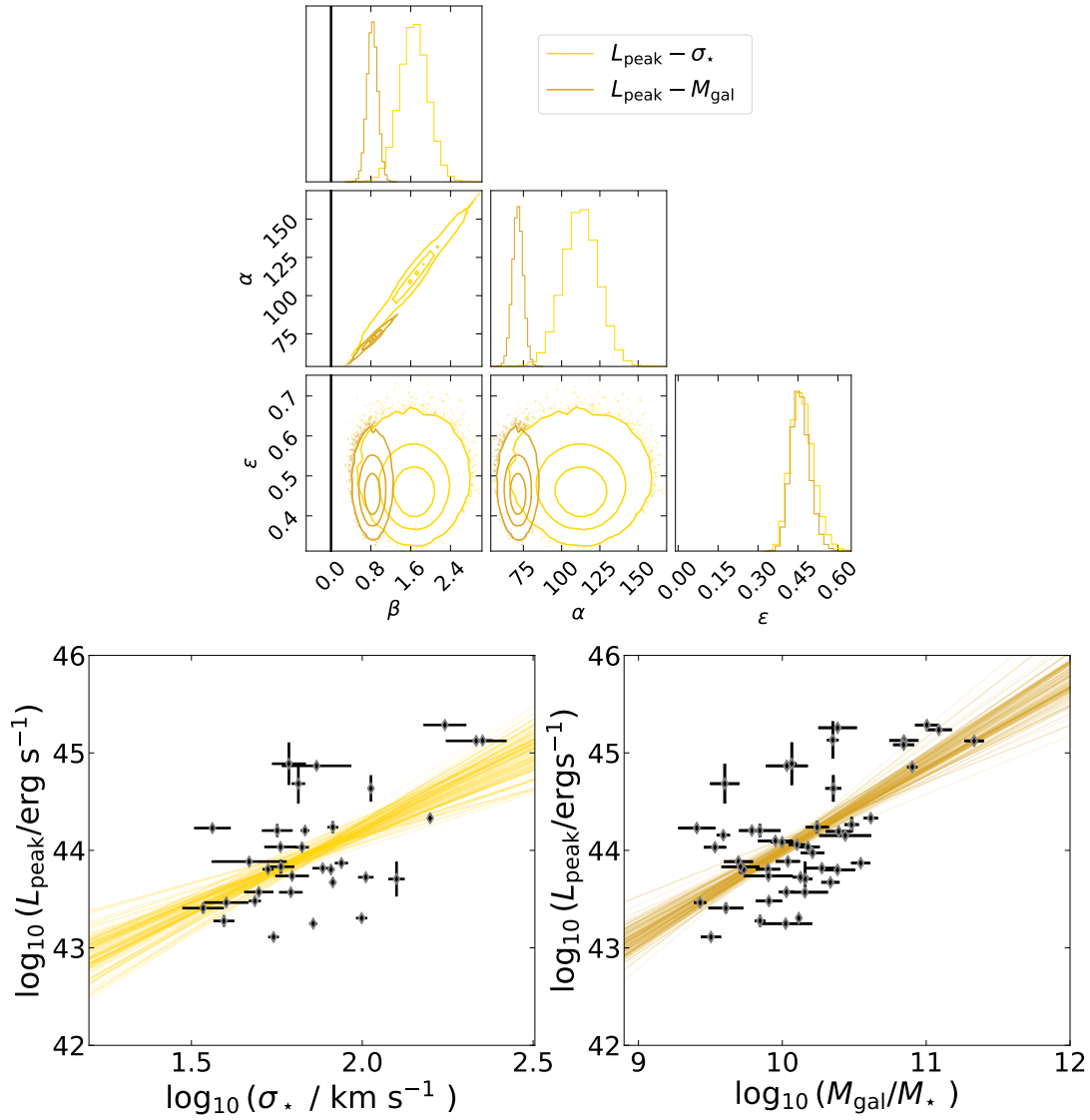


Figure 19. Top panel shows the posterior distributions and, in the bottom panels, the correlations between the peak luminosity of the early-time optical flare (L_{peak}) and host galaxy properties: total stellar mass (M_{gal} , right) and nuclear velocity dispersion (σ_* , left).

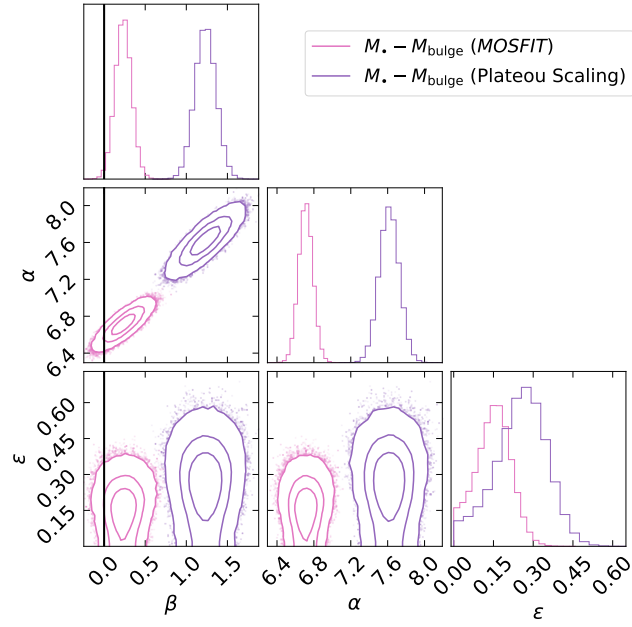


Figure 20. Posteriors of correlations (or lack thereof) between black hole mass ($M_{\bullet}$) —estimated either with MOSFIT (left) or from the plateau scaling relation (Mummery et al. 2024b) — and host galaxy bulge mass (M_{bulge}), as measured and presented in Ramsden et al. (2022, 2025).