A Possible Relativistic Jetted Outburst from a Massive Black Hole Fed by a Tidally Disrupted Star

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While gas accretion onto some massive black holes (MBHs) at the centers of galaxies actively powers luminous emission, the vast majority of MBHs are considered dormant. Occasionally, a star passing too near a MBH is torn apart by gravitational forces, leading to a bright tidal disruption flare (TDF). While

the high-energy transient Sw 1644+57 initially displayed none of the theoretically anticipated (nor previously observed) TDF characteristics, we show that the observations suggest a sudden accretion event onto a central MBH of mass $\sim 10^6 - 10^7$ **solar masses. There is evidence for a mildly relativistic outflow, jet collimation, and a spectrum characterized by synchrotron and inverse Compton processes; this leads to a natural analogy of Sw 1644+57 with a smaller-scale blazar.**

While variability is common to all active galactic nuclei (AGN)—fundamentally tied to the unsteady accretion flow of gas towards the central MBH—the timescale for active MBHs to dramatically change accretion rates (leading the source to, for example, turn "off"), is much longer than a human lifetime. The most variable AGN are a subclass called blazars, with typical masses $M_{\rm BH} \approx 10^8 - 10^9 M_\odot$ ($M_\odot$ is the mass of the Sun), originally found to be radio and optically bright but with luminosities dominated by X rays and gamma rays. Substantial changes in the apparent luminosity over minutes- to hour-long timescales are thought to be predominately caused by Doppler-beamed emitting regions within a jetted outflow moving relativistically [$\Gamma_{\rm j} \approx 10$; (*1*)] toward the observer (*2*). The high-energy emission is thought to be caused by inverse Compton upscattering of the accretion disk photons, photons from within the jet itself, and/or photons from structures external to the accretion disk (*3, 4*).

Inactive MBHs can suddenly "turn on" while being fed by temporary mass accretion established following the tidal disruption of a passing star (*5–9*). If a star of mass M_* and radius R_* passes within the disruption radius $r_d \approx R_*(M_{\rm BH}/M_*)^{1/3} \approx 5M_7^{-2/3} r_s$ (with $M_{\rm BH} = 10^7 M_7 M_\odot$ and $r_s = 2GM_{\rm BH}/c^2$ the Schwarzschild radius of the BH, $M_* = M_\odot$, $R_* = R_\odot$), then a mass of up to $\sim M_*/2$ will accrete onto the MBH with a peak accretion rate on a timescale of weeks (*6*). The accretion rate for typical scenarios with a M_7 BH can be super-Eddington (*10*) for months (*9, 11*). Candidate TDFs have been observed at X-ray, ultraviolet, and optical wavebands (*12*) with inferred rates $\sim 10^{-5}$ yr gal^{-1} (*7*), although the observed light curves and spectra did not always match the simplest theoretical expectations.

Recently, it has been suggested (*13*) that a long-lasting radio event (timescale to peak of $\sim$1 year) could follow a TDF arising from a jetted relativistic outflow as it interacted with (and was slowed down by) the external ambient medium, akin to the afterglow from external shocks following gamma-ray bursts (*14*). The supposition was that the observer viewed the event off-axis from the relativistic jet. Just what would be seen if instead the jet were pointed nearly towards the observer—as in the geometry inferred for blazars—was not considered.

Sw 1644+57 was initially detected as a long-duration gamma-ray burst (GRB 110328A) by the Swift satellite (*15*) at a time t_0 = 2011 March 28 12:57:45 UT. However, given the longevity and flaring of the X-ray afterglow, it was quickly realized that the high-energy emission was unlike that associated with any previous GRB (*16*). Based on the data available in the first two days following the event, it was suggested (*17*) that Sw 1644+57, at a redshift of z =0.3543, could be analogous to a scaled-down version of a blazar impulsively fed by $\sim 1 M_\odot$ of stellar mass.

There are several lines of evidence to suggest an accreting MBH origin. First, the astrometric coincidence of the X-ray, optical, infrared, and radio transient with the light-centroid of the putative host galaxy is strongly indicative of a positional connection to an MBH (*17–19*). Second, the observed X-ray variability timescales are consistent with those of an accreting MBH (see below and SOM). Last, the observed correlation between the X-ray flux and spectral hardness (SOM) is similar to that observed in blazars (*20*). Arguments against alternative interpretations are considered in the SOM.

Accepting the accreting MBH hypothesis, we now examine constraints on the BH mass and the accretion characteristics. The X-ray light curve implies a minimum host-frame variability timescale of $t_{\rm var,min} \approx 78$ sec (SOM; Fig. S1). By requiring (*21*) that $t_{\rm var,min}$ exceeds the light-crossing time of r_s, we derived an upper limit on the MBH mass $M_{\rm BH} \lesssim 8 \times 10^6 M_\odot$. Irrespective of the timing argument, we can place approximate upper limits on the mass of the central BH if we assume the whole mass of the galaxy [few$\times 10^9 M_\odot$; (*16*)] and its light [few$\times 10^9 L_\odot$; (*16*)] arise from the host bulge (i.e., not in the disk) and apply the bulge mass–BH mass and the bulge luminosity–BH mass correlations (*22*). All such analyses suggest $M_{\rm BH} \lesssim 10^7\, M_\odot$, securely under the limit (few$\times 10^8 M_\odot$) required for the tidal disruption of a solar-mass star to occur outside the event horizon of the MBH.

If the emission is isotropic, the average X-ray luminosity of the outburst (SOM), $L_X \approx 10^{47}$ erg s^{-1}, corresponds to the Eddington luminosity of a $\sim 10^9 M_\odot$ BH, incompatible with the upper limit derived from variability. If the source is relativistically beamed (SOM), with beaming factor $f_b = (1 - \cos\theta_{\rm j}) \leq 1$, the beaming-corrected luminosity $f_b L_X \sim 10^{45}$ erg s^{-1} becomes consistent with the Eddington luminosity of a $\sim 10^7 M_\odot$ SMBH if $\theta_{\rm j} = 1/\Gamma_{\rm j} \approx 0.1$, as inferred in blazars (we show below that this value of $\Gamma_{\rm j}$ is also consistent with the inferred rate of Sw 1644+57-like events). We can also infer the presence of relativistic outflow (SOM) by requiring that the true brightness temperature of the radio transient be less than the inverse Compton catastrophe temperature 10^{12} K. Those constraints require a mean $\Gamma_{\rm j} \gtrsim 1.9$ from t_0 to the time of the VLBI observations reported in (*16*). Separately, we can use the observed variability of the radio counterpart to place constraints on the source size, finding $\Gamma_{\rm j} \gtrsim 10$.

If the source had been active in the distant past, we would expect to observe extended radio emission (e.g., jets or other emission knots) in VLBI imaging. Because this was not seen (*16*) and archival searches spanning two decades have yielded no evidence for prior AGN activity from radio to gamma-ray wavebands (SOM), the evidence thus suggests that a $M_{\rm BH} = 10^6 - 10^7 M_\odot$ BH underwent a dramatic turn on to near-Eddington accretion rates, launching an energetic, relativistic outflow in the process. This rapid increase in the accretion rate cannot result from gas entering the sphere of influence (soi) of the MBH, because this would require a timescale $\sim R_{\rm soi}/\sigma \gtrsim 10^4$ yr to appreciably alter the accretion rate near the horizon, where $R_{\rm soi} \sim 1$ pc is the radius of the sphere of influence and $\sigma \sim 100$ km s^{-1} is a typical bulge velocity dispersion. We suggest instead that a TDF provides a natural explanation for Sw 1644+57.

The observed X-ray fluence S_X suggests an energy release of $E_X = 1.6 \times 10^{53} f_b$ erg for the first ~ 50 days. Assuming that the energy released in the XRT band is about 1/3 of the bolometric energy (Fig. 1) and adopting $f_b = 5 \times 10^{-3}$, the total energy release from the jet amounts to 0.3% of the maximum available mass-energy to be accreted if $M_* = M_\odot$. Given a typical accretion efficiency of $\epsilon_{\rm BH} \equiv E_{\rm av}/m_{\rm acc}c^2 = 0.1$, the jet need radiate only about 1/30th of the available energy $E_{\rm av}$; if mass is lost during the circularization phase or to subsequent disk winds, then the required jet efficiency must be higher. The duration of the X-ray light curve and the requisite accretion rate are also broadly compatible with the several-day fallback timescale (SOM).

The broadband Spectral Energy Distribution (SED) of Sw 1644+57 (Fig. 1) displays two peaks, at far infrared and at X-ray/gamma-ray wavebands. Thermal emission from the disk or accretion-powered outflows (*8, 9*) does not naturally account for either component. Instead, the overall spectral shape is reminiscent of blazars, for which the peaks at low and high energies are typically modeled as synchrotron and Inverse Compton (IC) emission, respectively. The X-ray emission shows both a bright/flaring and a dim/slower-varying ("quiescent") state. Under the TDF hypothesis, what could account for the observed spectrum and temporal behavior?

- **Single Component Synchrotron with Dust Extinction:** In low-luminosity BL Lac objects, the νF_ν synchrotron spectral peak may occur at energies as high as hard X-rays. Thus, one possibility is that the entire emission from radio to X-rays is part of a single non-thermal synchrotron spectrum originating from shocked relativistic electrons. In this scenario, the suppressed optical emission and red IR colors of the transient could result from dust extinction with $A_V > 10$ mag. Thus, although a single extinguished synchrotron spectrum cannot be ruled out, the large required extinction may disfavor this interpretation (Fig. S3). Furthermore, although a synchrotron origin is still likely for at least the radio emission, there is evidence that the radio and X-ray emitting regions may not be coincident (SOM).

- **Two-Component Blazar Emission:** The FIR and hard X-ray peaks may, instead, represent distinct spectral components, corresponding to synchrotron and IC emission, respectively, as in blazars (SOM, Fig. S3). The νF_ν luminosity of the low-energy peak is $\sim 1 - 2$ orders of magnitude weaker than the high energy peak (Fig. 1). This extreme ratio, and the relatively low frequency of the synchrotron peak, are both compatible with Eddington-accreting blazar emission (*4*).

- **Forward Shock Emission from Jet-ISM Interaction:** Although the above models generally assume that the low- and high-energy spectral components are directly related, evidence suggests that they may originate from distinct radii, at least during the X-ray flaring state. While the rapid variability of the X-ray emission strongly indicates an "internal" origin (*23*), the radio-IR emission varies more smoothly and could instead result at larger radii from the interaction of the jet with the surrounding interstellar medium (SOM). If no AGN activity occurred prior to the recent onset of emission, the jet must burrow its way through the gas in the nuclear region (*24*). Because of its fast motion, the newly-formed jet drives a shock into the external gas (forward shock), while simultaneously a reverse shock slows it down. Particles accelerated at these shocks may power synchrotron afterglow emission beginning simultaneously when the jet forms, yet lasting long after the internal emission has faded. This model, the geometry of which is depicted in Fig. 2, appears to best accommodate the data, and predicts for the long-term evolution of the radio and IR transient (SOM).

No rising UV-optical transient nor slowly evolving thermal X-ray component has been seen to date from Sw 1644+57, in contrast with the nominal expectations of TDFs. However, if Sw 1644+57 was obscured by dust, then UV-optical suppression of the transient would be expected. And if we understand the thermal X-ray emission as being outshone by the jetted emission in the first weeks, the thermal component may emerge on a timescale of months. For this to occur, the jet emission must be quenched due, e.g., to a transition of the accretion flow to a soft/thermal state once the accretion rate becomes sub-Eddington, in analogy to the behavior of stellar-mass X-ray binaries. Even in this case, whether and when thermal emission will be observable hinges on the degree of dust extinction and its brightness relative to the host bulge.

If the TDF hypothesis is correct, Sw 1644+57 will fade over the coming year and will not repeat. If our interpretation about the relativistic flow and spectral origin is correct, then we would expect the transient emission to be polarized at a (low) level similar to that seen in gamma-ray burst afterglows [as opposed to blazars (*25*)]. Moreover we expect to see evidence for superluminal motion of the radio source as seen in VLBI monitoring over the next few months; the source itself may become resolved on timescales of a few months if it remains bright enough to detect at radio wavebands.

Adopting a beaming fraction $f_b \lesssim 10^{-2}$ consistent with that inferred from Sw 1644+57 (SOM), we conclude that for every on-axis event, there will be $1/f_b \gtrsim 10^2$ events pointed away from our line of sight. Because Swift has detected only one such event in ~ 6 years of monitoring, the total inferred limit on the rate of TDFs accompanied by relativistic ejecta is $\gtrsim 10$ yr^{-1} out to a similar distance. Although the majority of such events will not produce prompt high-energy emission, bright radio emission is predicted once the ejecta decelerates to non-relativistic speeds on a timescale ~ 1 year (*13*). The predicted peak flux is sufficiently high ($\sim 0.1-1$ mJy at several GHz frequencies and redshifts similar to Sw 1644+57) that $\sim 10-100$ may be detected per year by upcoming radio transient surveys.

The emerging jet from the tidal disruption event appears to be powerful enough to accelerate cosmic rays up to $\sim 10^{20}$ eV, i.e., the highest observed energies (*26*). The observed rate of jets associated with the tidal disruption of a star, $\dot{R} \sim 10^{-11}\mathrm{Mpc}^{-3}\mathrm{yr}^{-1}$, and the energy released per event of $3 \times E_X \sim 5 \times 10^{53}$ erg, however, imply an energy injection rate of $\dot{E}_{\rm TDF} \sim 5 \times 10^{42}$ erg $\mathrm{Mpc}^{-3}\mathrm{yr}^{-1}$. Despite the large uncertainty, this rate is substantially smaller than the injection rate $\dot{E}_{\rm inj} \sim 10^{44}$ erg $\mathrm{Mpc}^{-3}\mathrm{yr}^{-1}$ required to explain the observed flux of cosmic rays of energy $> 10^{19}$ eV (*27*). This conclusion is, however, subject to uncertainties associated with the radiative efficiency of the jet.

There is much evidence that AGN jets are accelerated by magnetohydrodynamic, rather than hydrodynamic, forces (*28*). A key unsolved question is whether the large-scale magnetic field necessary to power the jet is advected in with the flow (*29*), or whether it is generated locally in the disk by instabilities or dynamo action. If the jet is launched from a radius $R_{\rm in}$, the magnetic field strength at its base (B) is related to the jet luminosity by $L_{\rm j} \sim \pi R_{\rm in}^2 c \times (B^2/4\pi)$. If we assume $L_{\rm j} \sim 10^{45}$ ergs s^{-1}, similar to the Eddington limit for a $\sim 10^7 M_\odot$ MBH (as appears necessary to explain the bright non-thermal emission), the required field strength is $B \sim 10^5$ G for $R_{\rm in} \sim 1.5 r_s$. This field is much higher than the average field strengths of typical main sequence stars ($< 10^3$ G). The stellar field is further diluted because of flux freezing by a factor $\sim (R_*/R_{\rm in})^2$ as matter falls into the BH, where $R_\star \sim R_\odot$ is the stellar radius prior to disruption. Hence, the large-scale field responsible for launching the jet associated with Sw 1644+57 must have been generated in situ. Placing similar constraints has not previously been possible in the context of normal AGN or X-ray binary disks, because of the much larger ratio between the outer and inner disk radii in these systems.

References and Notes

1. The inferred typical Lorentz factor of blazar jets $\Gamma_{\rm j} = (1 - \beta^2)^{-1/2} \approx 10$, with velocity $v = \beta c$ of the jetted outflow (c is the speed of light in vacuum).

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10. The Eddington accretion rate is a theoretical upper limit to spherical mass accretion whereby mass inflow due to gravitation attraction to a central source is balanced by radiation pressure from that source. Super-Eddington luminosities are possible when mass accretion is not homogeneous, spherical, and/or the main source of emission near the radiation source is not in the form of photons (e.g., neutrinos). For a $10^7 M_\odot$ ($= M_7$) black hole, the Eddington luminosity is $L_{\rm edd} = 1.3 \times 10^{45}$ erg s^{-1}.

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19. Within the uncertainties from Hubble imaging [$\sim$300 pc; (*16*)], the central stellar and gas density could be high enough to allow other progenitors, such as supernovae.

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moving fast within the jet [e.g., D. Giannios, D. A. Uzdensky, M. C. Begelman, *MNRAS* **395**, L29 (2009)].

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24. This situation is not encountered in normal (long-lived) blazars because a large $\gtrsim$ kpc scale cavity has been carved by the preceding outflow.

25. Here the departure from the blazar analogy is worth noting in that the physics of the radio emission is likely to be different in this case: we have suggested that the emission is originating from the shocked surrounding material (forward shock), not the shocked jet as in normal blazars, which could contain large scale fields. Even so, only 10% of flat-spectrum radio quasars and BL Lac objects have polarization larger than our VLBI limits [e.g., M. F. Aller, H. D. Aller, P. A. Hughes, *ApJ* **586**, 33 (2003).]

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30. The uncertain relative contributions of the host galaxy and the optical/infrared (IR) transient result in very large uncertainties for the J and z photometric data points. In this model, the radio and IR emission are produced by synchrotron radiation from an extended source, while the X-ray emission is dominated by the Compton scattering of external photons from

the accretion disk (for illustrative purposes, we assume a $10^6 M_\odot$ MBH). As in the orange model, the X-ray emission is dominated by external Compton scattering, while the peak at high energies results from synchrotron self-Compton emission. An additional synchrotron component from a mildly relativistic blast-wave afterglow at larger radius is invoked to explain the bright radio and millimeter fluxes.

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32. Although we have modeled the "quiescent" SED, a similar external Compton model can be made to fit the "flaring" X-ray state provided that the jet luminosity is accordingly increased.

33. H. Krawczynski, *et al.*, *ApJ* **601**, 151 (2004). For the models, $\Gamma_j = 10$ and the magnetic field strength $B = 10$ (0.001) Gauss for the sync+ec+afterglow (sync+ec+self-compton) model. In the sync+ec+aft model, we find a disk luminosity of $L_{\rm disk} = 0.4 L_{\rm edd}$, with $L_{\rm edd} = 1.3 \times 10^{44}$ erg s^{-1}, corresponding to a black hole with 10^6 $M_\odot$. In the sync+ec+self-compton model, we find a disk luminosity of $L_{\rm disk} = 0.04 L_{\rm edd}$, with $L_{\rm edd} = 1.3 \times 10^{45}$ erg s^{-1}, corresponding to a black hole with 10^7 $M_\odot$.

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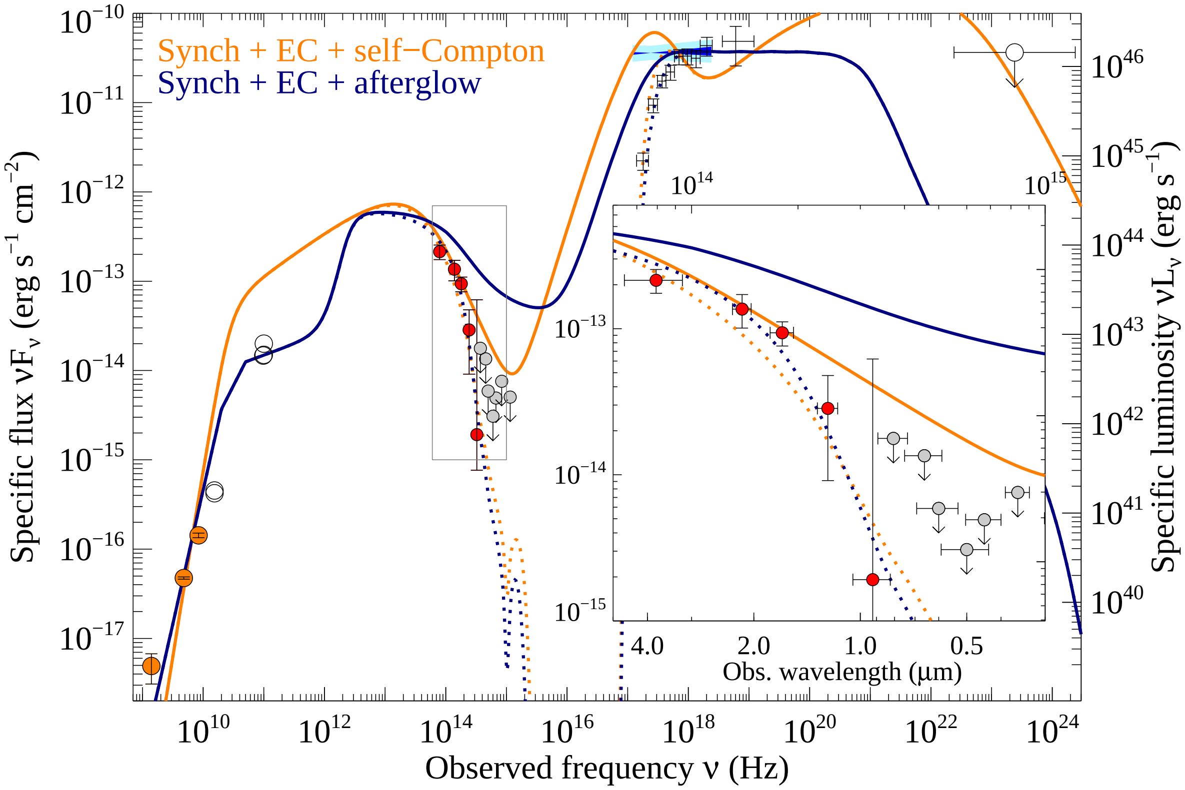

Fig. 1: Multiwavelength spectral energy distribution of Sw 1644+57 at t_0 + 2.9 day. Our radio-through-UV measurements are represented by filled circles, with data from the published circulars (*16*) represented by open circles (*30*). X-ray and soft gamma-ray points from the Swift XRT and BAT (uncorrected for host-galaxy absorption) are shown as black crosses, and the Fermi/LAT gamma-ray upper-limit (*31*) is shown at the far right. The 90% uncertainty region of a power-law fit to the XRT data (with N_H absorption removed) is represented by the blue bow-tie. (inset) The same data zoomed in on the optical-NIR window. Overplotted are two different multi-component models for the SED (*32*) (Fig. 2). The orange curve shows a model with synchrotron, synchrotron self-Compton, and external Compton contributions. The purple curve shows a model in which the IR emission originates from a compact source of synchrotron emission ($\sim 4 \times 10^{14}$ cm). Both models require moderate extinction ($A_V \sim 3-5$ mag). Additional synchrotron models are shown

in Fig. S3. The model SEDs here and in Fig. S3 were generated using the computer code from (*33*).

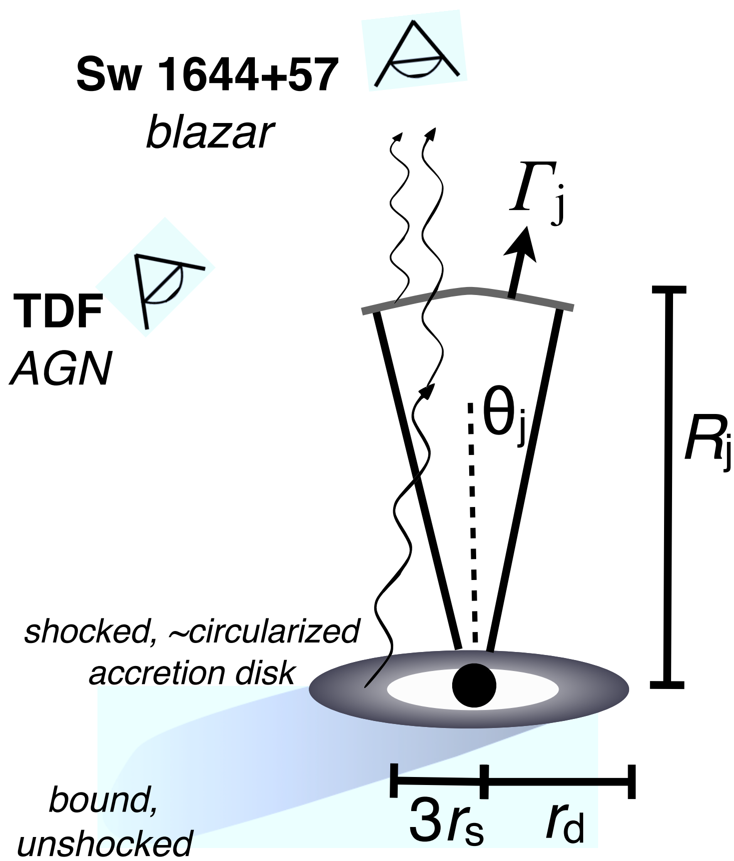

Fig 2. Schematic representation of the geometry and emission regions for Sw 1644+57. A star is disrupted at distance $r_{\rm d}$ from a black hole of mass $M_{\rm BH}$ with Schwarzschild radius $r_{\rm s}$. Half of the mass of the star escapes on unbound orbits while the other half remains bound. Shocked, circularized fallback mass sets up a temporary accretion disk with inner radius $3r_{\rm s}$ (for a non-spinning BH). A two-sided jet is powered starting at the time of accretion and plows through the interstellar region surrounding the BH at a Lorentz factor $\Gamma_{\rm j}$. At some later time, the jet has reached a distance $R_{\rm j}$ where the forward shock radiates the observed radio and infrared light. Emission from the accretion disk is Compton upscattered giving rise to the observed X-rays. Different viewing angles (whether the observer is inside $\theta_{\rm j} \approx 1/\Gamma_{\rm j}$ or not) determines what sort of phenomena is observed. An analogy with blazars and AGN for more massive BHs is given.