ChatGPT

10-Day Study Plan: TDEs and Accretion Discs in Schwarzschild Spacetime

Day 1: Introduction to Tidal Disruption Events and Accretion Discs

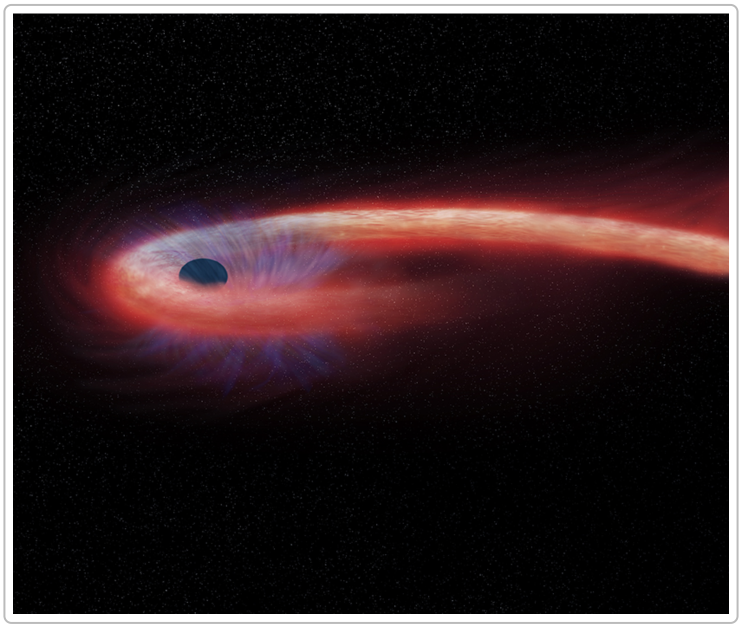

Figure: Artist's impression of a tidal disruption event. A star ventures too close to a black hole, is torn apart by tidal forces, and its debris forms an accretion disc and jets around the black hole.

- **Goals:** Understand what tidal disruption events (TDEs) are and how they involve accretion onto black holes. Grasp the basic scenario: a star is shredded by a supermassive black hole's gravity, gas falls back and forms a transient accretion disc that powers a luminous flare [1]. Recognize the key components: the tidal *radius* (distance at which the star is disrupted) and the concept of an accretion disc forming from the stellar debris.
- **Key Readings:** Read the introductory section of *Stone et al. (2019)* on TDEs [1] [2], which defines TDEs and emphasizes that for large black holes ($\gtrsim 10^7$ solar masses) the disruption occurs so deep in the gravitational well (within ~10 Schwarzschild radii) that general relativity (GR) is required to describe it. Also skim Chapter 1 of *Frank, King & Raine (2002) – Accretion Power in Astrophysics*, which compares accretion power to other energy sources and introduces accretion efficiency [3] [4].
- **Expected Outcomes:** You will be able to **define a TDE** in your own words and outline the sequence of events (stellar approach, tidal disruption, debris stream, disc formation) [1]. You should understand that **accretion of mass onto a compact object releases far more energy per unit mass than nuclear fusion**, especially for black holes – up to ~10% of mc^2 for a non-rotating black hole (vs ~0.7% for H→He fusion) [5] [3]. You'll appreciate qualitatively why **TDEs are important probes of strong gravity**: if the black hole is very massive ($\gtrsim 10^8\ M_\odot$), the star might be

swallowed whole inside the event horizon, cutting off the flare [2]. This introduces the idea that the Schwarzschild radius ($R_S = 2GM/c^2$) and tidal radius together determine whether a disruption is observable or “silent” (direct capture).

Day 2: Black Hole Gravity and Schwarzschild Spacetime Fundamentals

- **Goals:** Develop a firm understanding of Schwarzschild spacetime and how it differs from Newtonian gravity in the context of accretion. Key concepts include the **Schwarzschild radius** (event horizon radius), the **innermost stable circular orbit (ISCO)**, and how strong-field gravity influences orbits and tidal forces. We will also calculate the tidal radius and compare it to the Schwarzschild radius for various scenarios.
- **Key Readings:** Review Section 2 of *Stone et al. (2019)* focusing on gravity in TDEs [2], which notes that for black holes above ~10^8 M⊙ the tidal disruption radius r_t is inside the horizon, leading to no luminous TDE (a **GR effect** of direct capture). Read the relevant part of *Accretion Power in Astrophysics* about black hole orbits and efficiency [6] [7], which explains that matter cannot orbit stably inside ~3 R_S for a non-rotating (Schwarzschild) hole. This section gives the binding energy at ISCO (~0.06 c^2 per unit mass for Schwarzschild) and contrasts it with Newtonian expectations and the Kerr case (max ~0.42 c^2 for a rapidly spinning hole) [6] [7]. Also note Equation 1.1–1.2 in Chapter 1 of Frank & Raine [3], highlighting how compactness (M/R) sets accretion efficiency.
- **Expected Outcomes:** You will learn to **calculate the Schwarzschild radius** (e.g. ~3 km for a 1 M⊙ black hole, scaling linearly with mass) [8] and the **tidal disruption radius** $r_t \approx R_*(M_{BH}/M_*)^{1/3}$ for a star of radius R_* [9]. *You should be able to explain why, in Schwarzschild spacetime, there is a minimum stable orbit (the ISCO) and that gas reaching that radius will plunge rapidly into the hole [10] [11]. This means a black hole’s accretion disc has an inner edge at ~3 R_S (for Schwarzschild), and thus the maximum radiative efficiency ~5.7% of rest mass energy [6]. You will understand that in GR, if r_t is smaller than R_S (as happens for very massive SMBHs and compact stars), the star is swallowed without much light (a direct capture) [2]. In summary, by the end of Day 2 you can articulate how Schwarzschild gravity limits where a disc can exist and how much energy can be extracted*, setting the stage for relativistic accretion physics.

Day 3: Accretion Disc Basics – The Shakura–Sunyaev Thin Disc Model

- **Goals:** Build a “hand-waving” yet solid understanding of **thin accretion disc theory** under Newtonian physics as a foundation. Key concepts include the notion of an accretion disc as a rotating, thin, **Keplerian disc** that transports angular momentum outward and mass inward; the role of **viscosity** (turbulent or magnetic) in enabling accretion; and the classic **α-prescription** from Shakura & Sunyaev (1973). We will also consider the thermal and radiative properties of a thin disc (multi-color blackbody emission).
- **Key Readings:** Read Chapter 4.7 in *Accretion Power in Astrophysics* on viscosity and turbulence in discs [12] [13]. This introduces the α-prescription: $\nu = \alpha c_s H$, where α parametrizes the unknown viscosity as some fraction of sound speed times scale height [12]. Note the text’s emphasis that α is just a dimensionless parameter encapsulating our ignorance (typically α ~ 0.1 is inferred in some systems) [13]. Complement this with the original **Shakura & Sunyaev (1973)** paper (at least the introduction and Section 2) to see how they set up steady-state disc equations and find scaling relations (e.g., surface density Σ, disc height H, temperature T as functions of radius). Key results like

the radial dependence of effective temperature $T_{eff} \propto r^{-3/4}$ are derived in that work (and summarized in Frank & Raine Ch.5) [14] [15].

- **Expected Outcomes:** By the end of Day 3, you will be able to **describe the structure of a thin accretion disc**: roughly Keplerian rotation, gradually decreasing surface density outward, and disc height set by hydrostatic equilibrium. You should grasp that **viscous stresses** transport angular momentum outward and allow matter to spiral inwards, releasing gravitational energy as heat. The Shakura–Sunyaev α-prescription will be understood as a practical way to include turbulence: e.g. $\alpha \sim 0.1$ means subsonic turbulence with eddy sizes ~H [12] [13]. You'll also know that a **steady thin disc radiates a multi-color blackbody spectrum**, with temperature peaking in the innermost region (for a SMBH disk, $T \sim 10^5$ K, i.e. UV/soft X-ray) [15]. This gives you a baseline for how a disc behaves in Newtonian physics, setting the stage to incorporate relativistic modifications next.

Day 4: Relativistic Discs and Pseudo-Newtonian Approximations

- **Goals:** Understand how accretion disc theory is modified in strong gravity. Today we connect the thin disc model to **Schwarzschild spacetime**: introducing the Novikov–Thorne relativistic disk solution (the GR generalization of Shakura–Sunyaev) and learning about the use of **pseudo-Newtonian potentials** to mimic GR effects. We'll also discuss what happens at **high accretion rates** – the transition to **thick discs or slim discs** when the luminosity approaches the Eddington limit – since TDEs often have super-Eddington fallback initially.
- **Key Readings:** Read about the **Paczynski–Wiita potential** in a brief article or summary. The Paczynski–Wiita potential (1980) is $\varphi_{PW}(r) = -GM/(r - r_S)$ and is famous for reproducing key Schwarzschild effects in Newtonian form [16]. Notably, it gives the correct ISCO location ($r_{ISCO} = 3\, r_S$) and marginally bound orbit, and yields nearly the same orbital frequencies as full GR [17]. Check the discussion in *Stone et al. (2019)* or *Steinberg & Stone (2024)* where they mention using a pseudo-Newtonian potential for TDE simulations [18] [19]. In parallel, skim *Abramowicz & Fragile (2013, Living Reviews)* sections 2–3 which describe the four disk models: thin (radiatively efficient), **Polish doughnut** (thick, radiation-pressure dominated), **slim disc** (moderately thick, super-Eddington, advection dominated), and **ADAF** (radiatively inefficient hot flow) [20] [21]. Focus on the slim disk: in a super-Eddington regime (like early TDE), the disc puffs up and advects radiation inward, often launching winds.
- **Expected Outcomes:** You will understand that **GR effects alter disk structure near the black hole** – for example, in a Schwarzschild metric the innermost radius is at ISCO (~6 GM/c^2) and the no-torque boundary condition at ISCO means a bit of potential energy is lost into the hole (hence 5.7% efficiency rather than 8% for a hypothetical Newtonian orbit at that radius) [6] [7]. You'll be comfortable with why using a Paczyński–Wiita potential in simulations is useful: it **mimics the Schwarzschild spacetime** by giving an inner stable orbit and capturing the steep potential well [17]. Additionally, you'll appreciate how accretion flows change when **near or above Eddington limit** – the disc becomes **geometrically thick and prone to outflows (winds)** to carry away excess radiation. This sets the stage for understanding TDE discs, which often start in a super-Eddington thick disk phase and then evolve into a thin disk as the fallback rate decreases [22] [23].

Day 5: Stellar Disruption and Debris Fallback Dynamics

- **Goals:** Dive into the **hydrodynamics of tidal disruption** itself. Today you will focus on the process of the star being torn apart and how the bound debris returns to feed the disc. Key concepts: the definition of the **tidal radius** r_t (where tidal force ~ star's self-gravity) and its scaling [9], the energy distribution of the stripped debris (approximately linear in binding energy), and the resulting **fallback rate** of debris onto the black hole. We will derive why the fallback mass rate follows roughly **$\dot{M} \propto t^{-5/3}$** after peak [24].

- **Key Readings:** Read Section 3 of *Stone et al. (2019)* which reviews the classical theory of stellar disruption. It defines r_t = R_ *(M_BH/M_)*^(1/3) and explains that once the star enters within r_t, it is stretched and ultimately disrupted [25] [26]. Focus on the derivation of debris energy spread: the most bound debris has specific energy ~ –GM/r_t and the least bound ~ +GM/r_t, leading to a range of orbital periods. A key result (originally from Rees 1988 and Phinney 1989) is that the **mass fallback rate** rises to a peak and then declines ~t^(-5/3). Figure 1 of *Evans & Kochanek (1989)* (as shown in Dai et al. 2021) plots this – note how for a 10^6 M☉ BH the fallback can initially exceed the Eddington accretion rate by orders of magnitude [27]. Also read the classic work of *Carter & Luminet (1983)* (or summaries thereof) on how the star is **spaghettified** and even compressed during pericenter passage.
- **Expected Outcomes:** You will be able to **calculate the tidal radius** for a given star–BH system (and thus determine which stars can be disrupted outside the horizon for a given BH mass) [28]. You'll understand that roughly **half of the star's mass becomes unbound** (ejected) and the other half remains bound, returning to the black hole on a spread of orbits [29] [30]. Crucially, you will internalize why the **fallback rate peaks then decays as t^(-5/3)** [24]: the most bound debris returns first, then progressively less bound material returns later, leading to a power-law decay in accretion rate. By the end of Day 5, you should be comfortable narrating the TDE sequence: stellar approach, disruption at r_t, formation of an elongated debris stream, and the beginning of fallback towards forming an accretion flow.

Day 6: Circularization of Debris and Disc Formation in TDEs

- **Goals:** Examine how the infalling stellar debris transitions into a **circular accretion disc**. The focus is on the mechanisms and timescale of **circularization** – i.e. how the highly eccentric orbits of the tidal debris are converted into a roughly circular, bound disc. We will explore the role of **relativistic apsidal precession** and **stream self-intersection shocks**. Key questions: Why might disc formation be **delayed** in TDEs? Where and how do the debris streams collide to dissipate energy?
- **Key Readings:** Read the discussion of stream circularization in *Stone et al. (2019)* [31]. They point out a general relativistic effect: strong **apsidal precession** (perihelion shift of the orbit) in Schwarzschild (and especially Kerr) spacetime means the returning debris stream does *not* trace the original path and can collide with itself or other streams. In a Schwarzschild geometry, per-orbit precession can be tens of degrees for orbits near the black hole [28], which is essential for **stream self-intersection**. Next, study *Steinberg & Stone (2024)*, a simulation paper that examines shocks in TDEs. Focus on their findings around the time of **peak light**: early on, when the first debris returns, there is a "nozzle shock" near pericenter (as the stream gets squeezed vertically) but it does not circularize the flow completely [32] [33]. Later, as more debris comes back, the stream hits the already-formed partial disc – these **stream–disc collision shocks** efficiently convert orbital energy into heat and circularize the material [34] [35]. The paper notes that **relativistic precession** is crucial: it sets the self-intersection radius where the stream collides with the earlier debris (farther from the BH than the pericenter), affecting the timescale of disc formation [19].
- **Expected Outcomes:** You will understand that **disc formation in TDEs is not instantaneous** – the debris initially follows elongated trajectories. In Newtonian gravity with no precession, the stream might just re-accrete gradually at pericenter. But in **Schwarzschild spacetime, the orbits precess**, so the returning stream misses the black hole and collides with itself at some intersection point [31].

This leads to **shock heating and dissipation** of kinetic energy, gradually forming a bound circular disk. You should be able to explain what a **"nozzle shock"** is (a shock at pericenter due to vertical compression of the stream [33]) and why it alone might not fully circularize the flow. By the end of today, you can describe how the combination of relativistic orbital dynamics and hydrodynamic shocks leads to a disk – and why this process can **delay the brightening of the TDE** (the disk – and thus efficient accretion – might form only after some orbits, affecting the early light curve) [31] . In short, you'll grasp **how Schwarzschild spacetime influences the birth of the accretion disc** in a TDE.

Day 7: Powering TDE Emission – Shock Energy vs. Accretion Energy

- **Goals:** Understand the physical origin of the luminosity in tidal disruption events. This involves comparing the two leading models for TDE emission: **stream-shock powered** emission versus **accretion (disk) powered** emission (with reprocessing). We will examine how the light curve and spectrum can inform us about which mechanism dominates. This day also covers the role of **outflows/winds** from the disc, which can reprocess high-energy photons to optical light.
- **Key Readings:** Re-read the results from *Steinberg & Stone (2024)* focusing on the origin of the luminosity. They find that at **early times** (soon after disruption), shocks near pericenter inject some energy (and even produce a faint X-ray source), but a lot of the debris remains eccentric – **circularization is inefficient initially** [36] . **Near peak light, however, stream–disk shocks become very effective**, circularizing most of the returning debris and powering strong outflows [35] . The simulation reproduces the observed peak optical/UV luminosities when shock-powered [37] . Read their conclusion that **peak emission is shock-powered** in their model, while accretion power (energy from matter actually plunging into the BH) is still subdominant at peak – though it grows as the disk becomes fully formed [37] [38] . Also review the debate context they give: some models assume the luminosity comes from an inner accretion disk and is then **reprocessed** by a radiatively driven wind or an optically thick envelope into optical light [39] . To connect theory with data, read Section 3.4 of *Gezari (2021, Annual Review)* on TDE light curves and line formation. Notice the discussion of optical/UV photospheres and that **reprocessing** by outflows could explain why many TDEs are optical/UV bright but X-ray faint initially [40] .
- **Expected Outcomes:** You will be able to summarize **two paradigms for TDE emission**: (1) the **"shock-powered" scenario**, where the kinetic energy of infalling streams is converted to heat at self-intersection shocks and radiated (this tends to produce thermal optical/UV emission from large radii), and (2) the **"accretion-powered" scenario**, where the energy comes from matter falling onto the BH (released in the inner disk as X-rays) and is then reprocessed by an outflow or envelope into UV/optical light [39] . You should cite evidence for shock power: e.g., simulations that match optical luminosities when including stream–disk collisions [35] . You should also understand the role of **winds**: a super-Eddington disk will drive an optically thick wind that can absorb and re-emit high-energy photons, affecting the observed spectrum [23] [40] . By the end of Day 7, you can answer: "What makes a TDE shine brightly?" with a nuanced explanation that **both shocks and accretion are important**, possibly at different phases – early on shocks dominate, while once a disk is fully formed, standard accretion luminosity (some of it in X-rays) can take over [37] . You'll also be aware that this is an ongoing research question being actively tested with simulations and observations.

Day 8: Observational Signatures and Phenomenology of TDEs

- **Goals:** Connect the theoretical models to actual observations of tidal disruption events. Today you will survey the diverse **observational characteristics**: light curves, spectra, and event rates. We will categorize TDEs by their spectral lines (H-rich, He-rich classes) and discuss what these imply about the disrupted star or emission region. We'll also cover extreme cases like **jetted TDEs** (which produce relativistic jets and bright non-thermal emission).
- **Key Readings:** Read Section 3.3 of *Gezari (2021)*, which classifies TDEs into spectral types. Note the definitions: **TDE-H** (show hydrogen Balmer emission lines), **TDE-He** (only helium lines like He II 4686Å), and hybrids [41] [42]. The presence or absence of H lines can indicate either a helium-rich stellar core was disrupted or that radiative transfer conditions favor certain lines. Gezari discusses how some TDEs show Bowen fluorescence lines (e.g. N III) signaling high-energy photons reprocessing [41]. Next, read *Gezari (2021)* Section 4 about **multiwavelength light curves** – e.g., some TDEs are "X-ray soft" (thermal emission from the inner disk) while others are "optical/UV bright" with little X-ray (perhaps due to an obscuring wind). Pay attention to the interpretation that viewing angle and outflow geometry can unify these: in the **unified model of Dai et al. (2018)**, all TDEs form a thick disk + wind, and an observer seeing the system face-on can see X-rays, whereas an edge-on observer sees an optically thick wind and mainly optical light [40]. Also, examine notable cases like **ASASSN-14li**, a TDE that showed both optical and X-rays and even a soft X-ray QPO (more on this tomorrow), and **Swift J1644+57**, a TDE with a powerful relativistic jet discovered via its hard X-ray and radio emission [43] [44]. Swift J1644 is an example of a **jetted TDE**, likely a rare case where the newly formed disk launched a relativistic jet (perhaps pointing toward us) [45].
- **Expected Outcomes:** By the end of Day 8, you will be familiar with the **spectral classification of TDEs** and what it implies. For example, you can explain that a **"helium-only" TDE** (TDE-He) might indicate the disrupted star was a helium-rich stellar core or that hydrogen lines were obscured or ionized away [41]. You'll know that **most TDEs have a thermal blue continuum** (T ~ 20,000–50,000 K) and broad emission lines of H, He II, etc., while a minority launch **relativistic jets** visible in X-ray and radio (the "jetted TDEs" like Swift J1644) [45]. You should also be able to describe a typical TDE light curve: a months-long rise and decay, roughly following the fallback t^(-5/3) law after peak, but sometimes with bumps or plateaus possibly from delayed disk formation or secondary shocks. Importantly, you will appreciate how **viewing angle effects** and the presence of outflows can make the same underlying event appear X-ray bright or X-ray faint (optical bright) to different observers [40]. Overall, you will have a "big picture" view of TDE phenomenology and how it ties back to the physical models.

Day 9: Disk Oscillations, QPOs, and Relativistic Precession Effects

- **Goals:** Explore the **dynamical instabilities and oscillations** in accretion disks, especially as probes of strong gravity. We focus on **diskoseismology** – the study of normal mode oscillations in the disc – and on **quasi-periodic oscillations (QPOs)** observed in TDEs and black hole binaries. We will learn how certain oscillation modes are allowed in relativistic disks (but not Newtonian disks) due to the presence of an ISCO, and how Lense–Thirring (frame-dragging) precession can induce global disk precession and QPO signals.
- **Key Readings:** Start with *Nowak & Wagoner (1991)*, **Diskoseismology I: Trapped Adiabatic Oscillations** [46] [47]. This seminal paper analyzes small perturbations of a thin disk around a black hole. They explain that **general relativistic effects allow certain modes to be trapped** in the inner region of the disk [48]. In particular, the GR prediction that the **radial epicyclic frequency drops to**

zero at the ISCO creates a natural reflective boundary, trapping oscillations (sometimes called g-modes and p-modes) between the inner edge and some outer turning point. Note their use of a modified Newtonian potential (like Paczyński–Wiita) to emulate this effect [47] . Then, review how this might appear observationally: *Stone et al. (2019)* highlights that a **misaligned disk around a spinning BH** will undergo **Lense–Thirring precession**, causing the entire inner disk (and any jet) to precess and potentially modulate the emission [31] . Finally, read the discovery by *Pasham et al. (2019)*: they reported a **131-second X-ray QPO in ASASSN-14li** (a TDE) [49] . This is a stable oscillation with frequency ~7.7 mHz, analogous to QPOs in X-ray binaries but on a much longer timescale, consistent with the larger BH mass. Pasham's work (Science 2019) suggests it could be related to a disk p-mode or a Lense–Thirring precession of the disk.

- **Expected Outcomes:** You will be able to explain that **disk oscillations can serve as tests of strong gravity**: in Schwarzschild spacetime, the existence of an ISCO means certain global oscillation modes (axisymmetric "breathing" modes or non-axisymmetric warp modes) can persist in the innermost disk. You should know that *Nowak & Wagoner* found **trapped g-mode oscillations** with frequencies related to the radial epicyclic frequency – a purely relativistic phenomenon (such modes wouldn't be trapped if the disk extended smoothly to r=0) [47] . Furthermore, you can discuss the idea of **Lense–Thirring precession**: a tilted disk around a Kerr black hole precesses like a top, which could produce a **QPO in flux or spectral lines** as the disk (or jet) orientation changes periodically [50] . You will also be aware of the observational evidence: e.g., the detected QPO in ASASSN-14li's X-rays (131 s period) hints at the presence of a stable inner disk oscillation [51] . By the end of Day 9, you can articulate why these oscillations are important: they potentially allow us to **measure black hole properties** (mass, spin) from TDEs and verify GR effects (like frame dragging and the existence of ISCO) in the time domain.

Day 10: Synthesis, Key Papers, and Future Directions

- **Goals:** Consolidate everything learned and put it in a broader context. Today, you will revisit key papers and ensure you see the "forest for the trees." We will identify how TDEs and accretion discs around black holes tie together the concepts of general relativity, hydrodynamics, and radiation we've studied. We'll also look at current and future research directions: What are the open questions? How will new observations (e.g. from the Vera Rubin Observatory **LSST**) and new simulations advance the field?
- **Key Readings:** It's time to tackle a comprehensive review: **Suvi Gezari (2021, Annual Review of Astronomy & Astrophysics)** from start to finish, if possible. This review covers both the theoretical underpinnings and observational status of TDEs in a coherent way. As you read, identify how the review links the presence of optical emission to reprocessing by winds, the causes behind different spectral line profiles, and the demographics of TDE host galaxies. Additionally, skim the conclusion of *Stone et al. (2019)* and *Bonnerot & Stone (2021, Space Sci. Rev.)* (if available) which outline open issues: e.g. the efficiency of circularization, the origin of optical vs X-ray dichotomy, the role of magnetic fields (MHD effects) in disk formation, etc. Note any mention of upcoming facilities – for instance, LSST is expected to discover thousands of TDE candidates in the next few years [52] , which will provide statistical power to test these models.
- **Expected Outcomes:** By the end of Day 10, you will have a **deep and rigorous understanding** of how TDEs serve as a bridge between stellar dynamics and accretion physics in strong gravity. You should be able to summarize **each stage of a TDE** – from star disruption to disc formation to emission and decay – citing the relevant physics and papers (e.g., Shakura & Sunyaev for disk viscosity, Rees for fallback theory, Stone et al. for GR effects, Steinberg & Stone for hydrodynamic

simulation, Nowak & Wagoner for disk modes). You will also be conversant with the **classic literature**: for example, you can mention Shakura & Sunyaev (1973) as the foundation of accretion disk theory [12], Paczyński & Wiita (1980) for the pseudo-potential that reproduces Schwarzschild orbits [17], and Rees (1988) for the TDE flare concept. Finally, you will be aware of the **frontiers**: ongoing debates (shock vs reprocessing power), the need for multi-dimensional simulations (including MHD and radiation) to fully capture TDE physics, and the observational campaigns (e.g. **LSST**, new X-ray monitors) that will soon vastly increase the TDE sample [52]. With this 10-day intensive study, you will have achieved both a "hand-waving" intuitive picture *and* a rigorous, citation-backed understanding of how tidal disruption events and accretion discs illustrate the marvels of Schwarzschild (and Kerr) spacetime in action.

Sources: The study plan above drew from *Frank, King & Raine (2002) – Accretion Power in Astrophysics* [6] [7] [12], the TDE theory review by *Stone et al. (2019) in GRG* [2] [31], the recent Nature article by *Steinberg & Stone (2024)* [35] [37], the classic *Nowak & Wagoner (1991)* work on diskoseismology, the *Paczynski & Wiita (1980)* potential [17], and the observational review by *Gezari (2021)* [41] [45], among other key papers as cited in-line. Each day's content includes precise references to these works for further reading and verification of facts.

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