

Long-term Evolution of Tidal Disruption Disks

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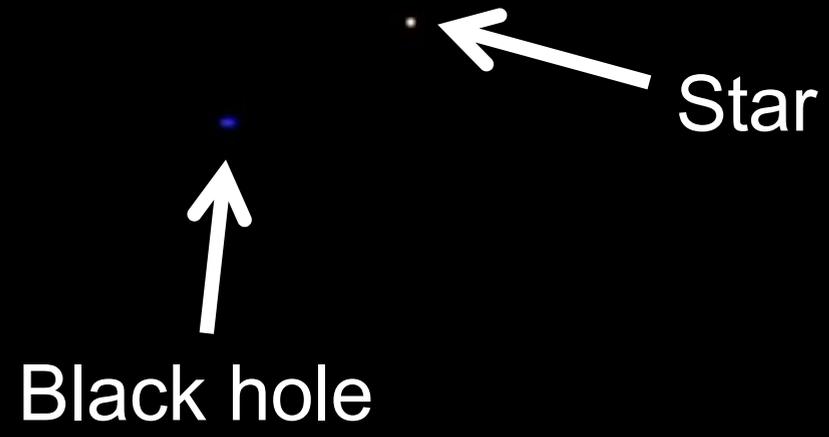
Adjunct Professor of Physics and Astronomy – University of Southern California



CARNEGIE
SCIENCE

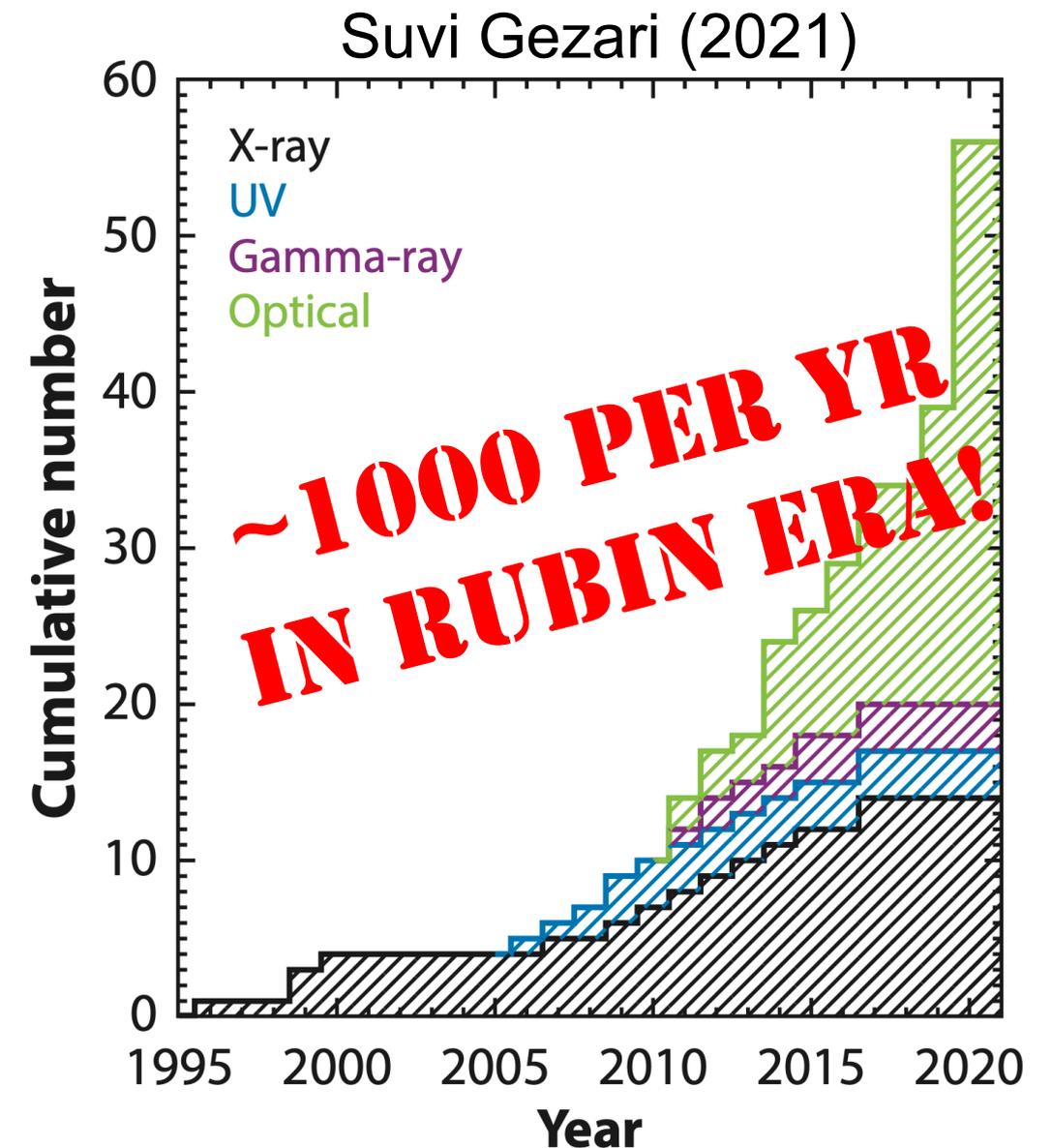


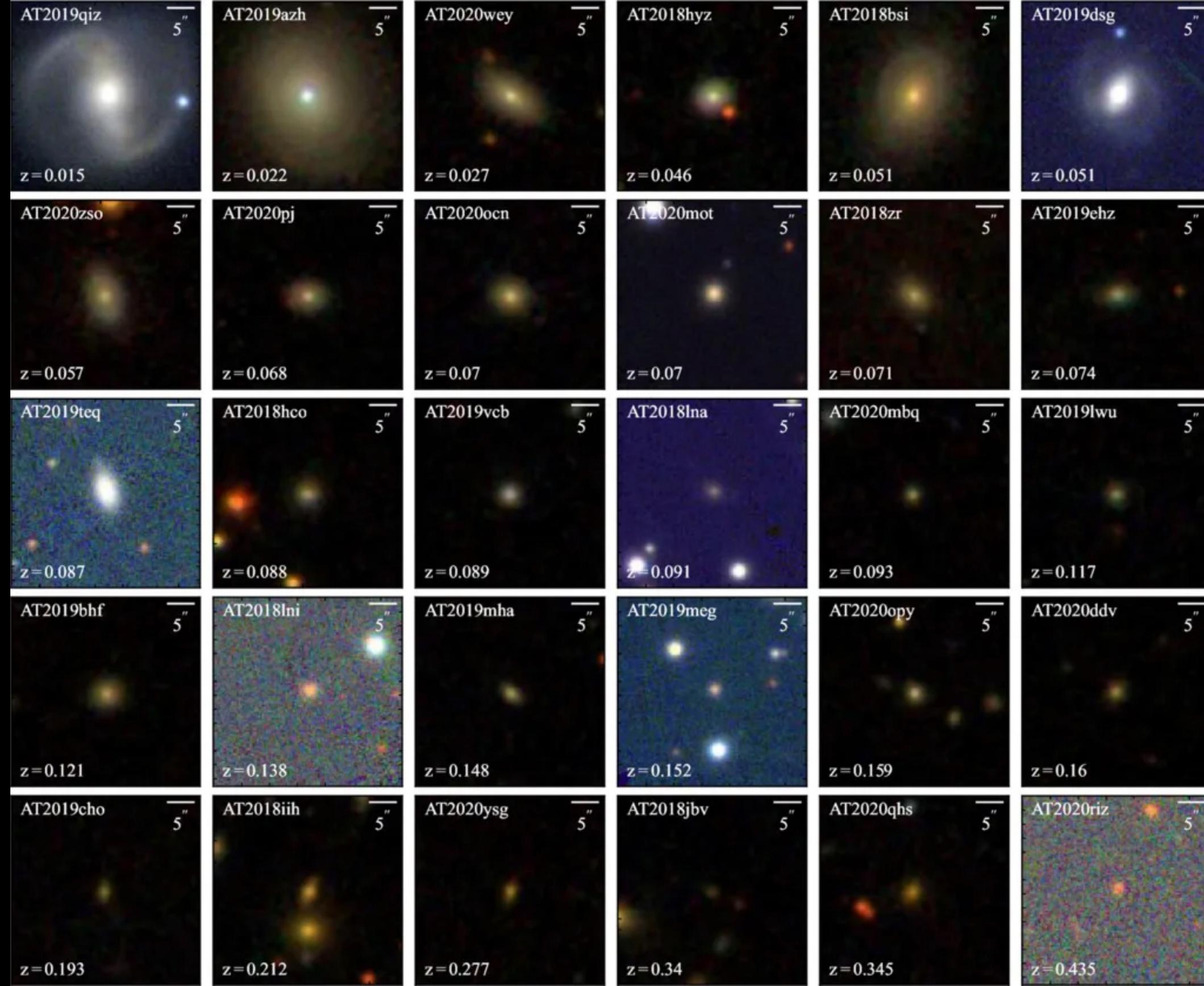
Artwork courtesy of Vadim Sadovski



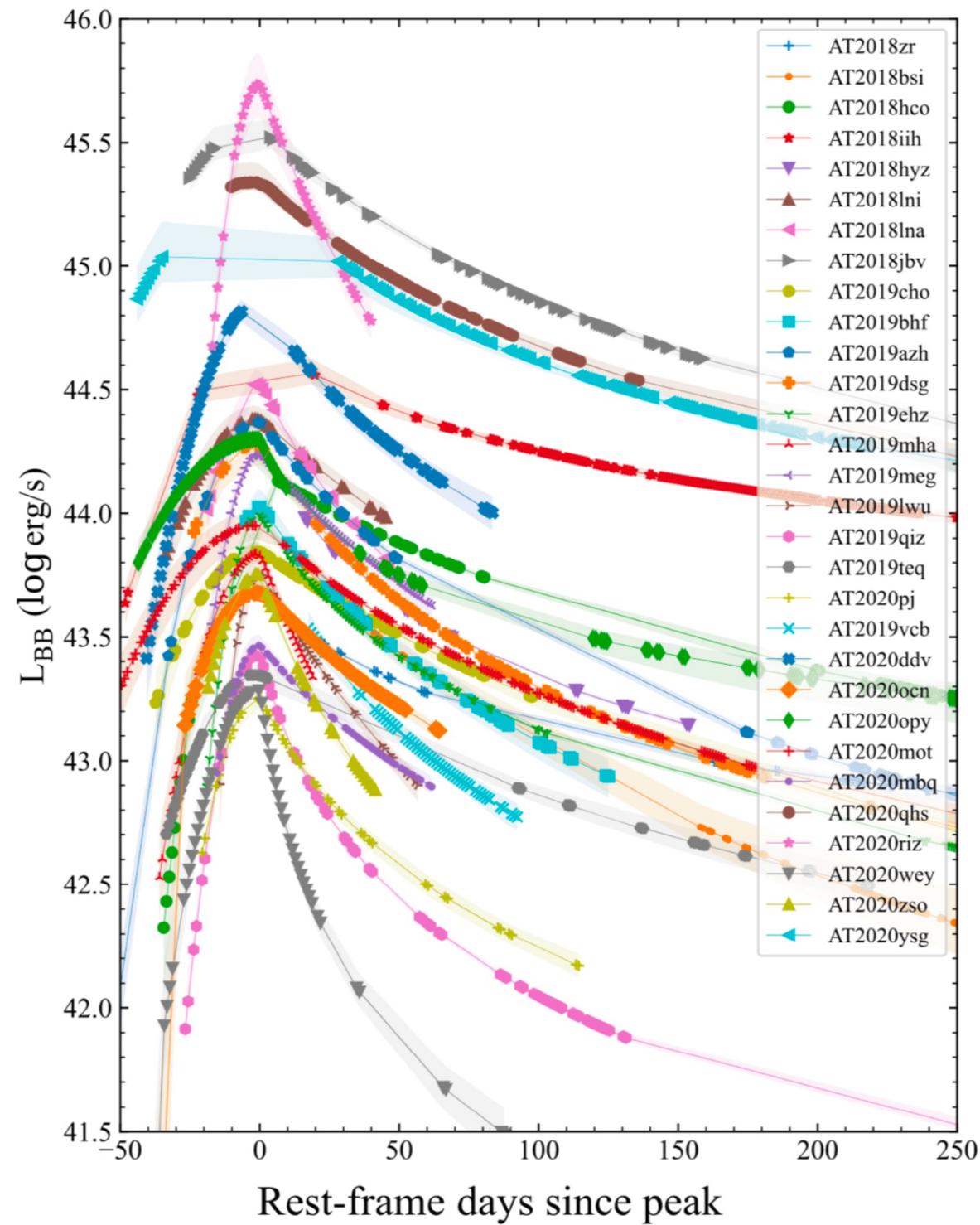
Tidal Disruption Event (TDE)

- When a sun-like star is gobbled up by a black hole (Hills 1975; Rees 1988; Phinney 1989)
- Supermassive black holes are typically $\sim 10^6$ - 10^8 solar masses.
- Black holes switch from being invisible to as bright as 10^9 - $10^{10} L_{\text{sun}}$ for a few months (for reviews, see Alexander et al. 2020; Saxton et al. 2020; Gezari 2021; Mockler et al. 2025)
- 1 per 10,000-100,000 years in a galaxy.

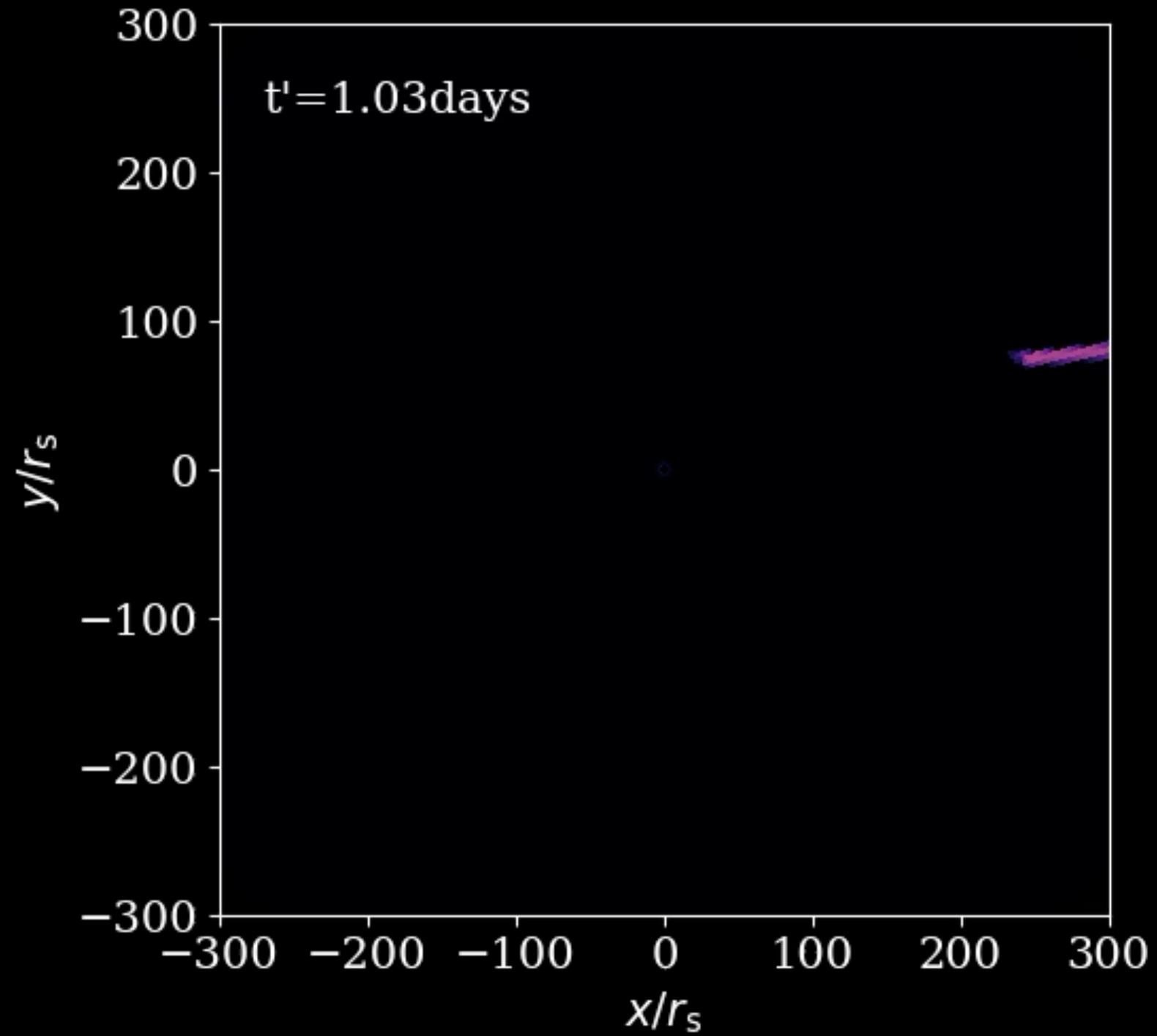




Optical TDE flares



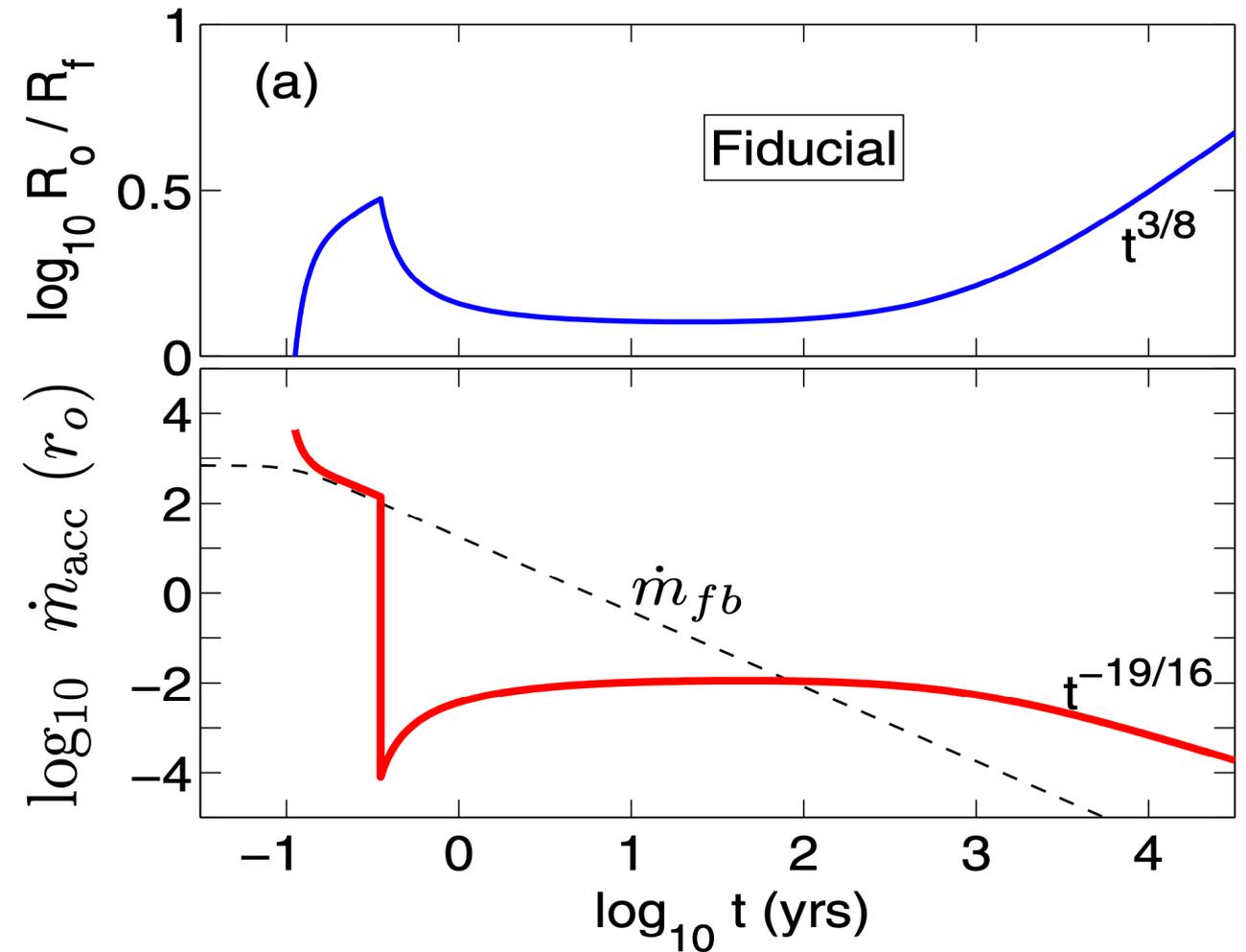
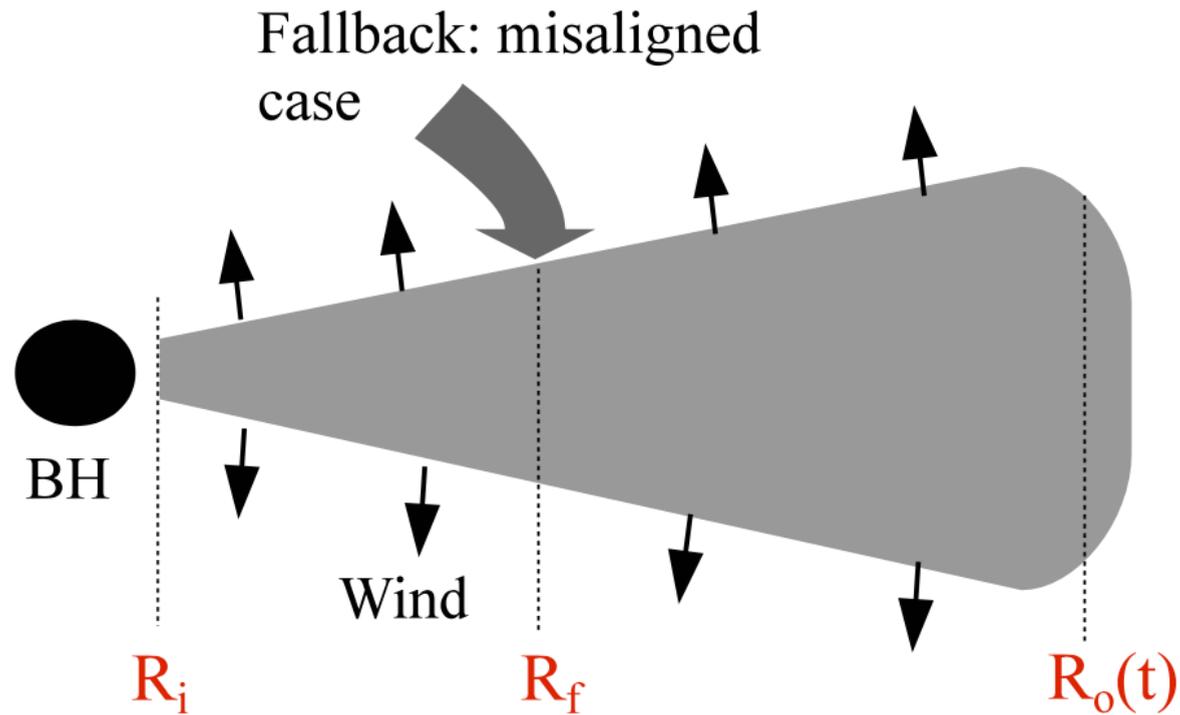
- SN-like luminosities for ~months with ~10,000 K inferred temperature.
- Timescale “weighs” the BH mass (e.g., Mockler et al. 2019)
- But what should we expect to see ~years later?



Simulation courtesy of Xiaoshan Huang

One-zone TDE Disk Evolution

Shen & Matzner (2014)



Abrupt accretion rate drop at ~ 100 s of days!

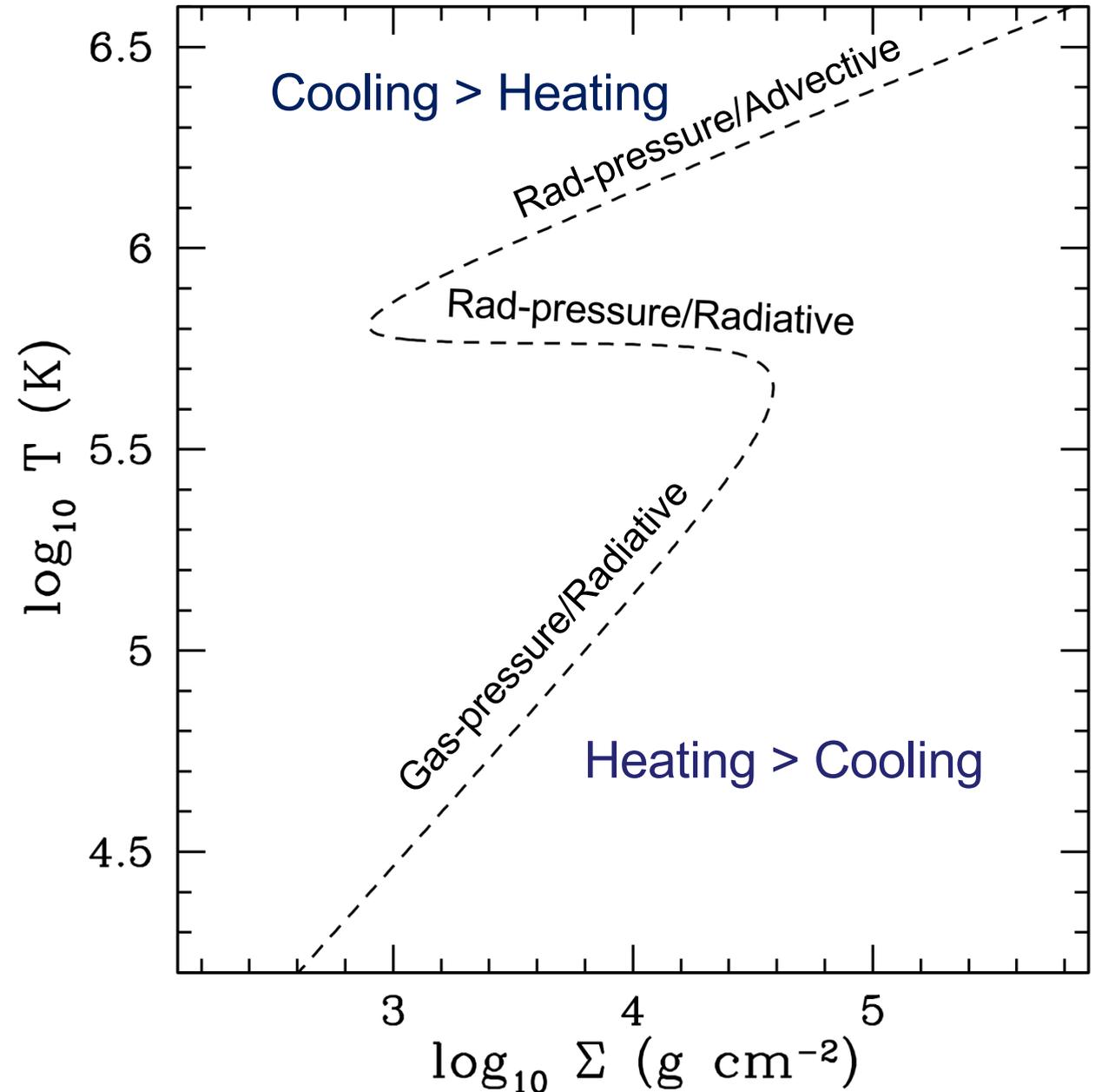
Accretion Disks 101

(Shakura & Sunyaev 1973, 1976; Pringle 1973; Lightman & Eardley 1974. Piran 1978)

- Assume energy balance

$$Q^+ = Q_{\text{rad}}^- + Q_{\text{adv}}^{-1}$$

- Step from high to low accretion rate and solve for $\Sigma - T$.
- Equilibrium solutions have S-curve.
- Radiation pressure/radiative solutions are thermally unstable!



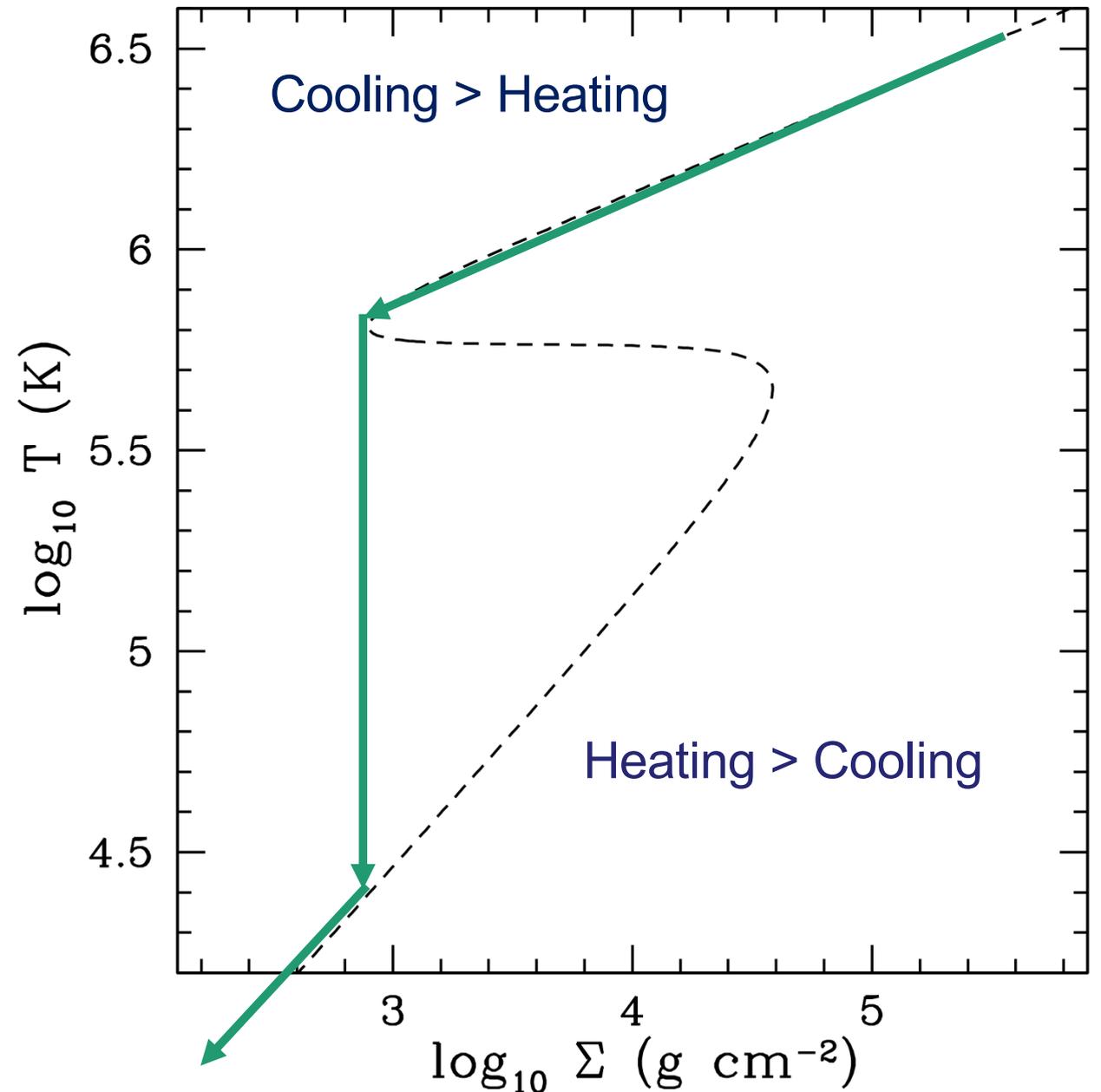
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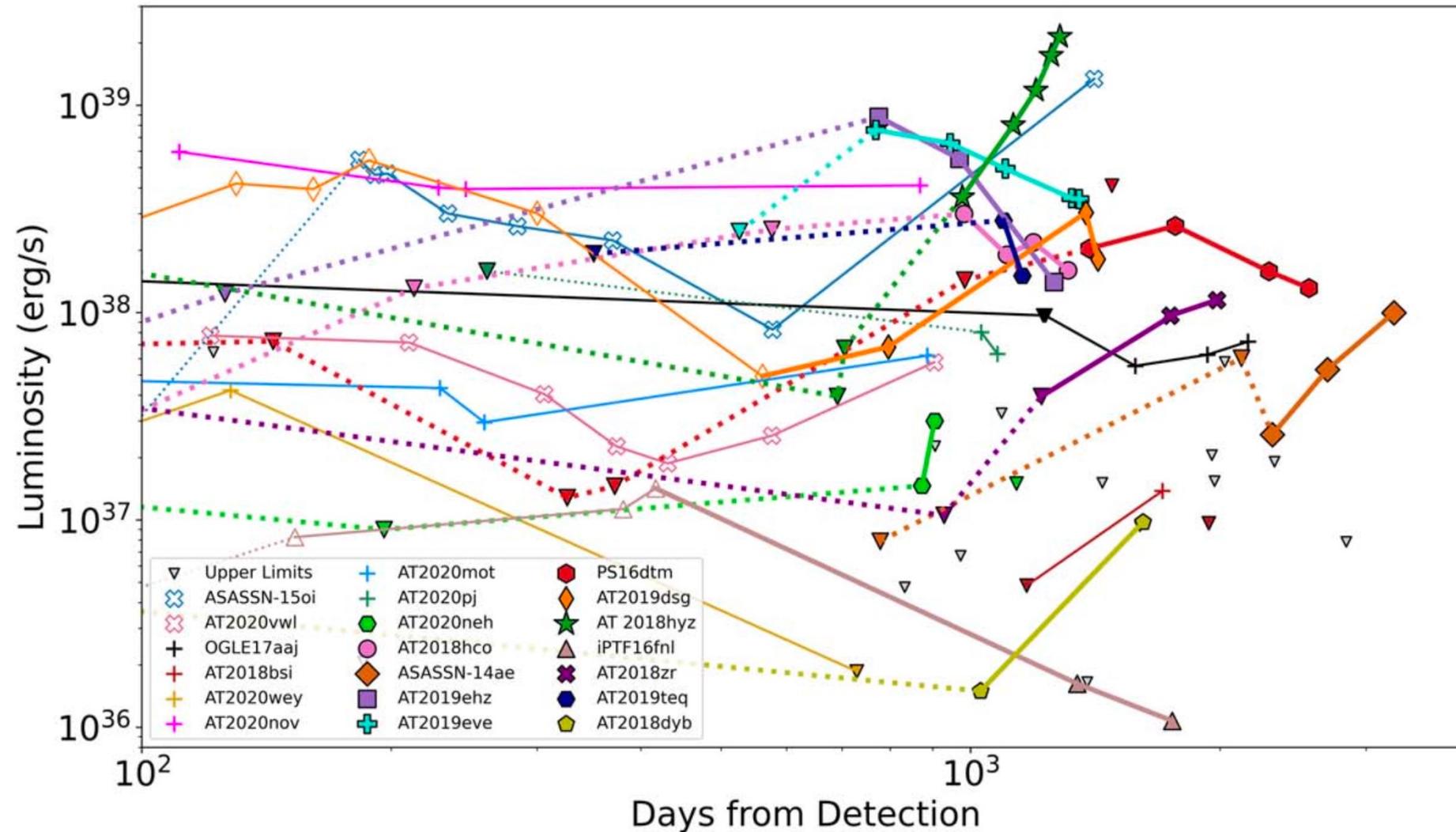
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- Step from high to low accretion rate and solve for $\Sigma - T$.
- Equilibrium solutions have S-curve.
- Radiation pressure/radiative solutions are thermally unstable!
- Potentially explains shutoff of J1644+57 jet at ~ 500 days (Shen & Matzner 2014), but also make disks very dim at late times.
- So we shouldn't see anything at late times...right?



Late-time Radio Activity

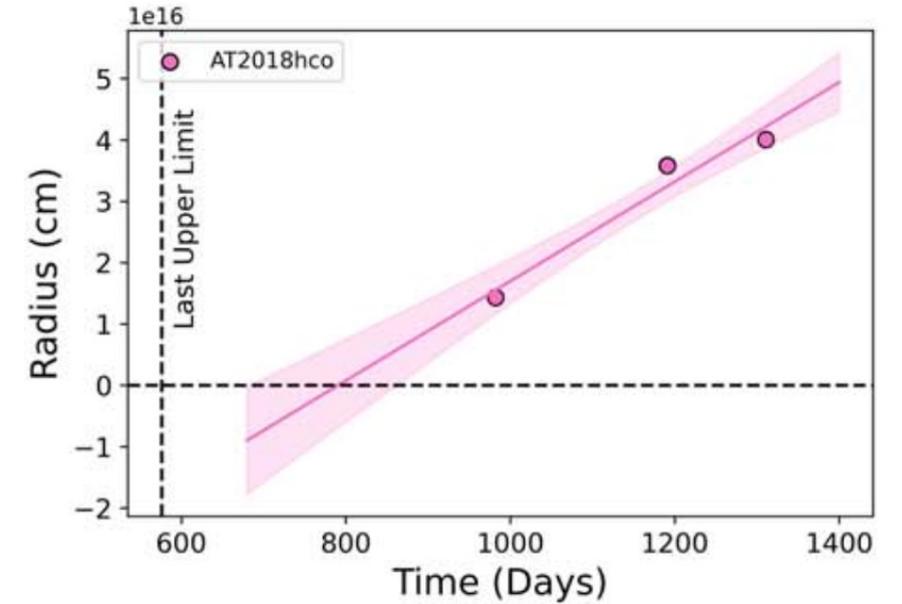
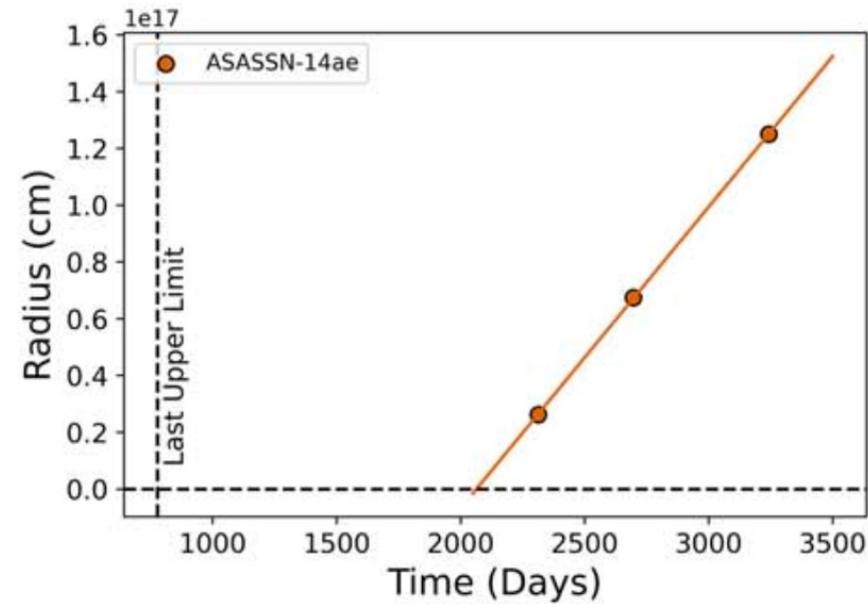
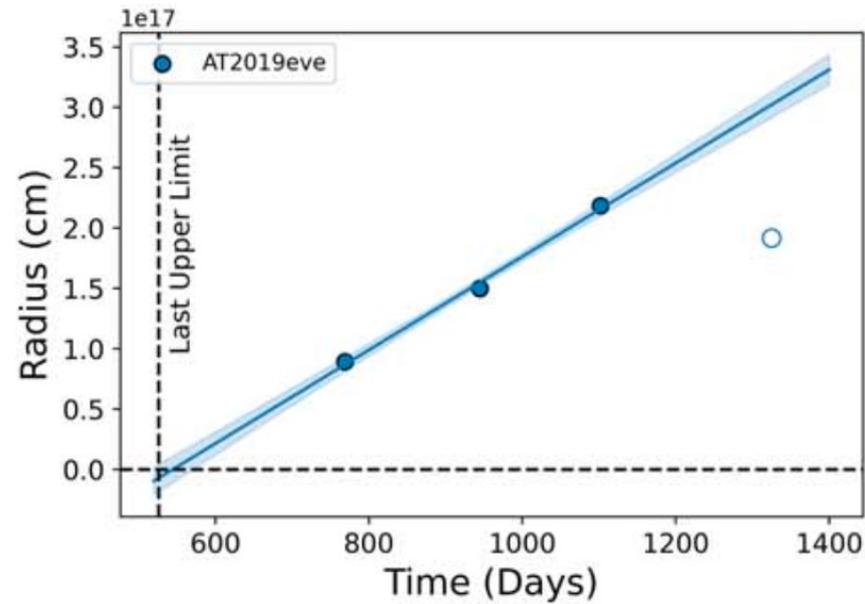
(e.g., Horesh et al. 2021; Cendes, Berger, Alexander, et al. 2024; Goodwin et al. 2025)



Distinct from jet emission seen for some TDEs (e.g., Zauderer, Berger, Soderberg, et al. 2011; Andreoni, Coughlin, Perley, et al. 2022)

Late-time Radio Activity

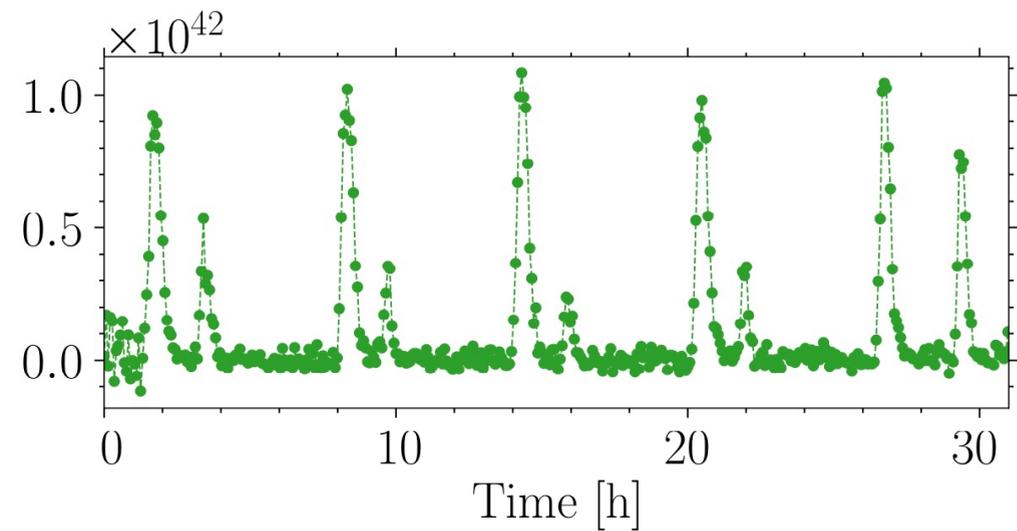
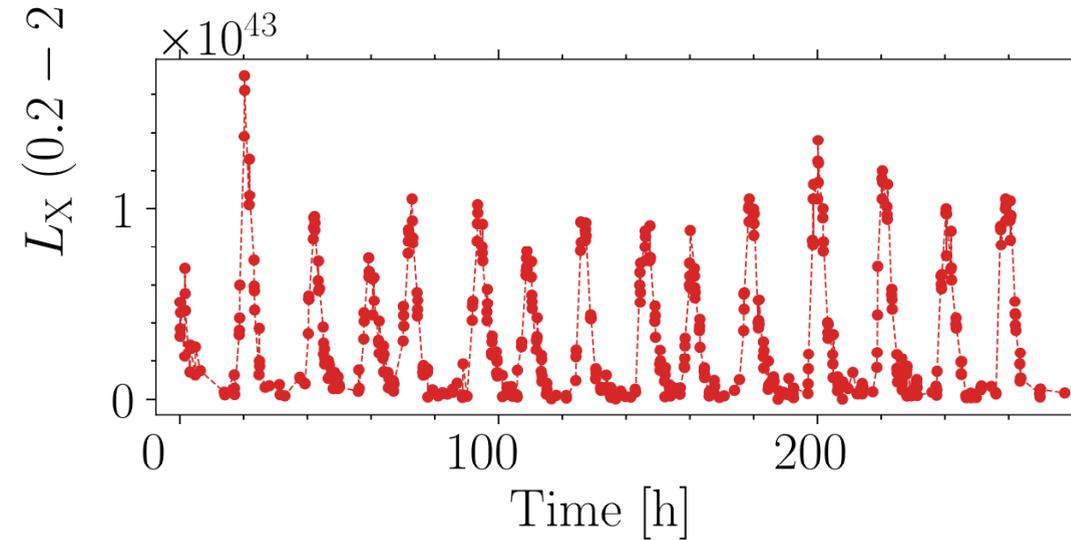
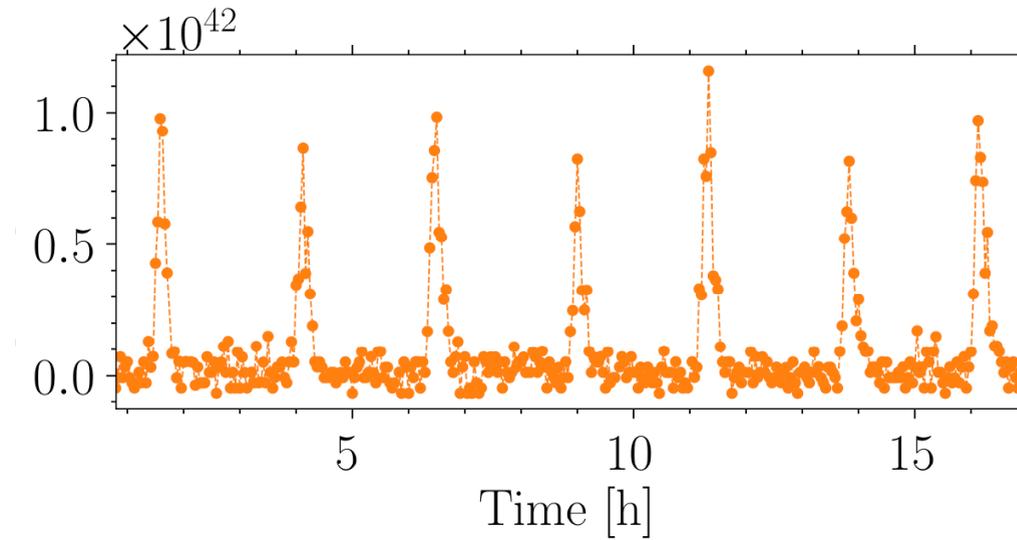
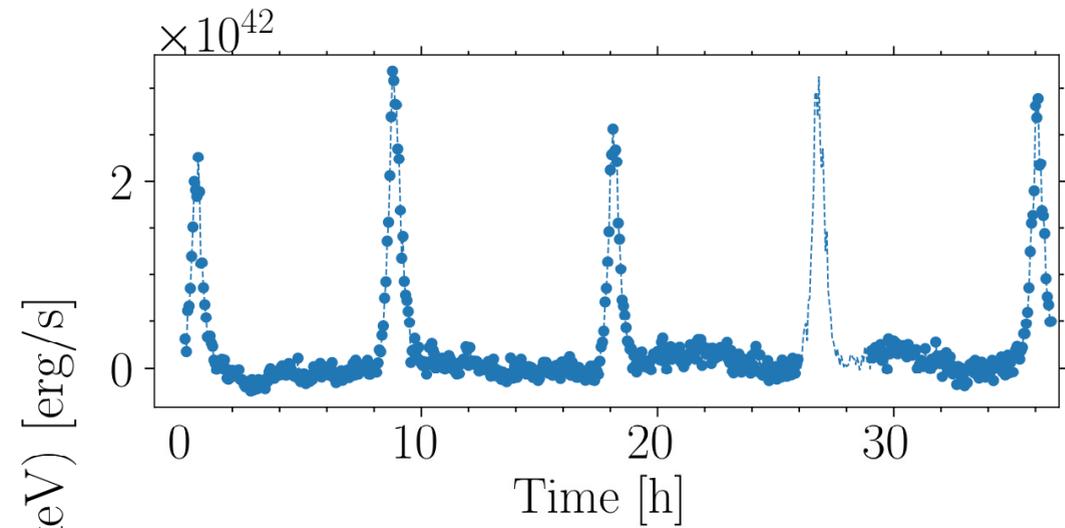
(e.g., Horish et al. 2021; Cendes, Berger, Alexander, et al. 2024; Goodwin et al. 2025)



Tracing expanding radio emission back in time does NOT intercept $t=0$!

Quasi-Periodic Eruptions (QPEs)

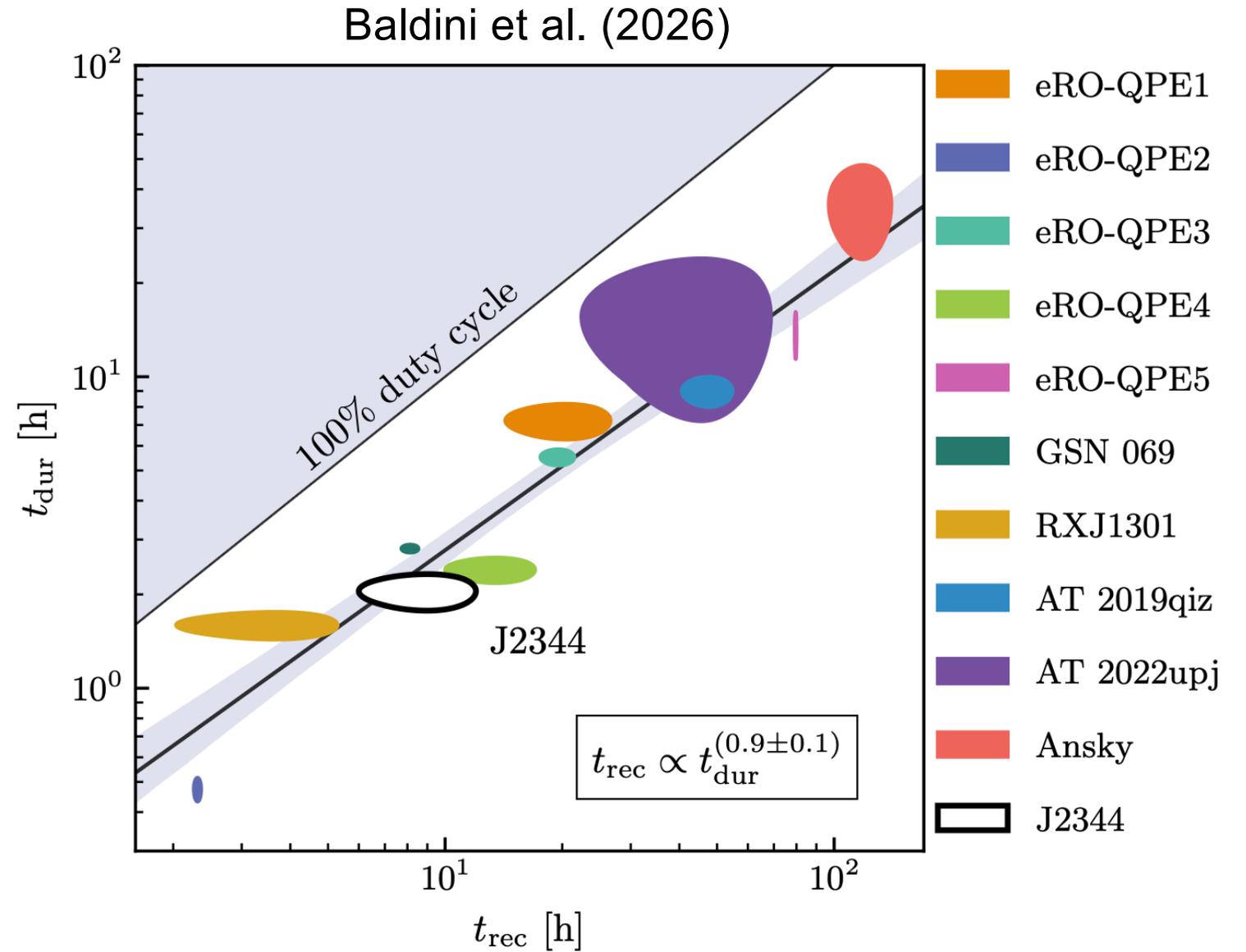
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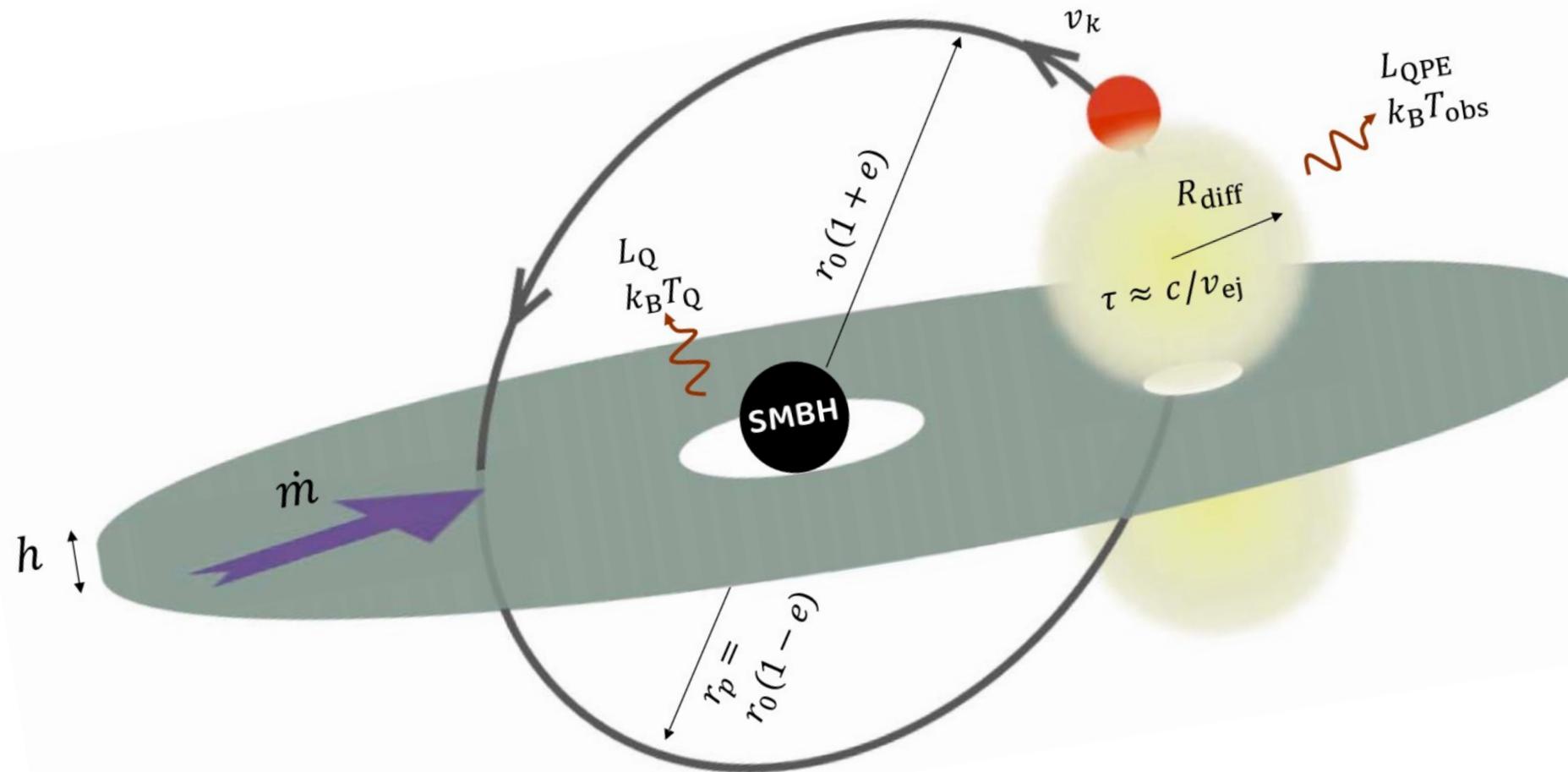
- Recurrence time of hrs-wks, durations of hr-day
- Same types of galaxies and BH masses as TDEs (Wevers et al. 2022)
- Sometimes follow \sim yrs after TDEs (Nicholl et al. 2024)
- Popular model is star-disk collisions due to an EMRI



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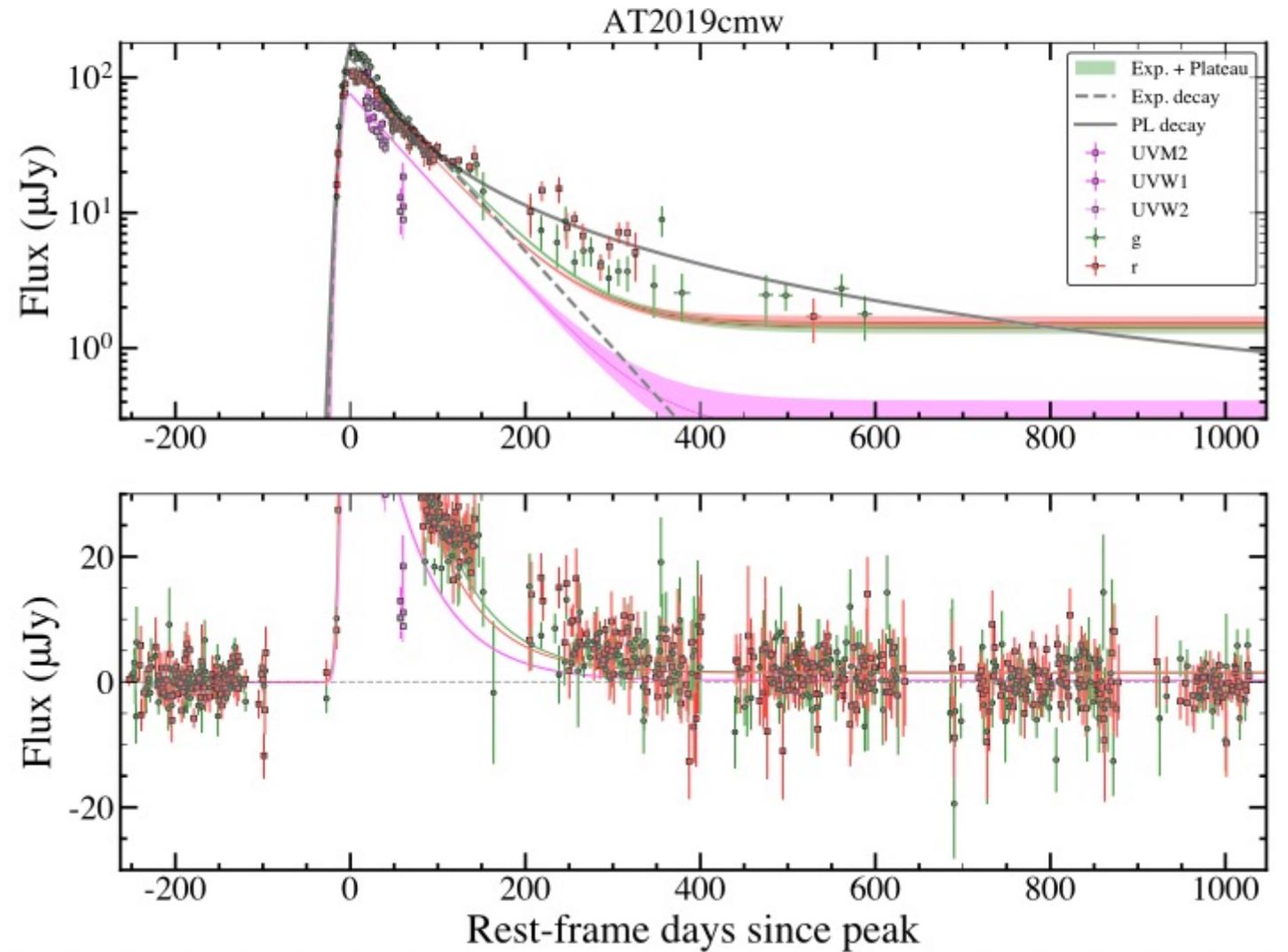
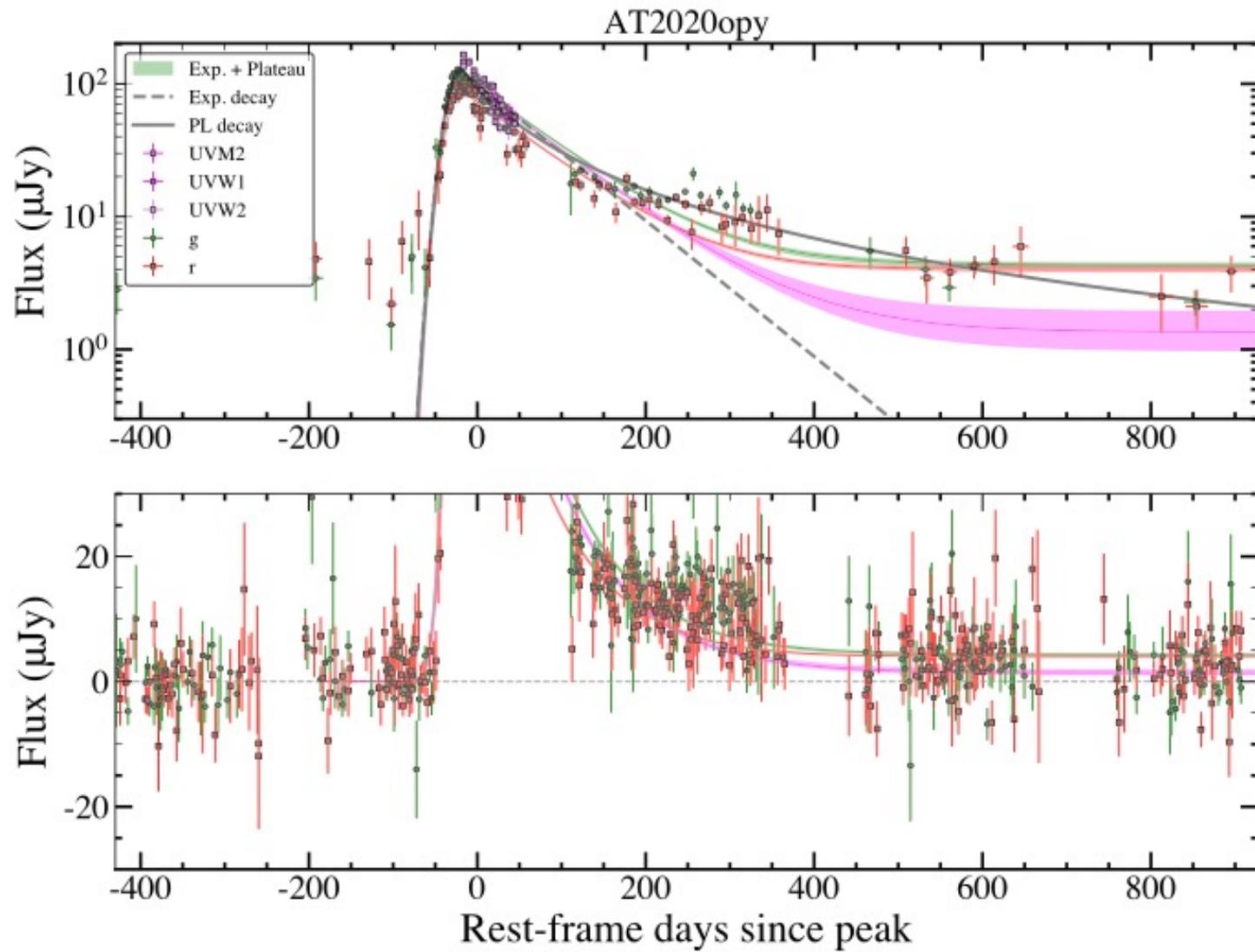
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(Linial & Metzger 2023, also see Suková et al. 2021; Xian et al. 2021; Franchini et al. 2023; Yao et al. 2025; Huang et al. 2025; Suzuguchi & Matsumoto 2026)

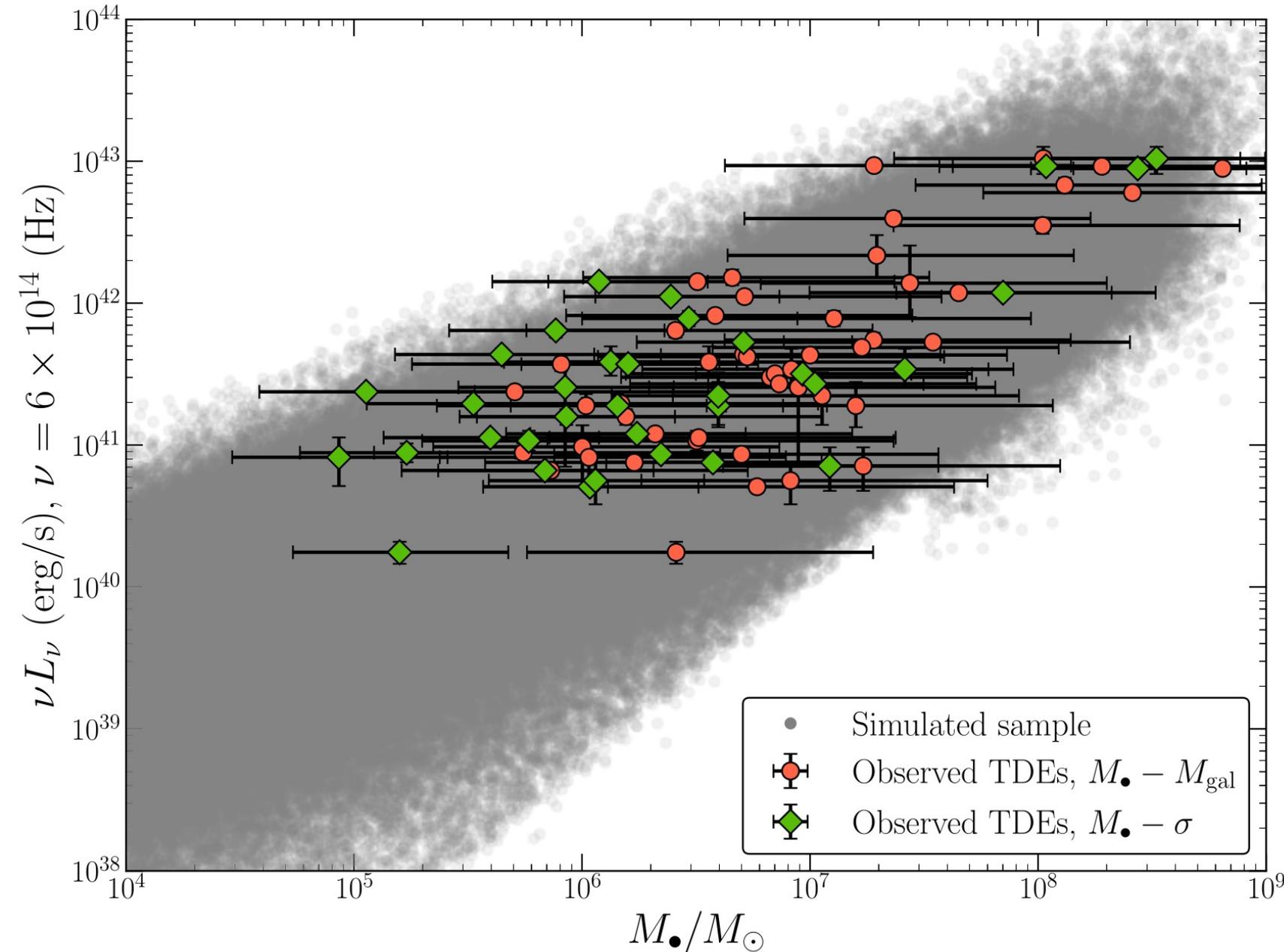
Late-time “plateaus”

(Mummery, van Velzen et al. 2024; also see Gezari et al. 2015; van Velzen, Stone, Metzger, et al. 2019)



Late-time “plateaus”

Mummery, van Velzen et al. (2024)



Plateau luminosity
scales with BH mass

$$L \propto M_{\text{BH}}^{2/3}$$

How do we reconcile this?

1. Fit observations with a parameterized viscous stress (e.g., Mummery & Balbus 2020, Mummery & van Velzen et al. 2025; Mummery et al. 2025)
2. Inhibit instability by using magnetically-dominated disk prescription (e.g., Alush & Stone 2025; Alush, Stone & van Velzen 2025; Winter-Granic & Quataert 2025)

$$\nu = \alpha c_s^2 / \Omega \quad P = P_m = \Omega R \rho \sqrt{\frac{k_B T}{\mu m_p}}$$

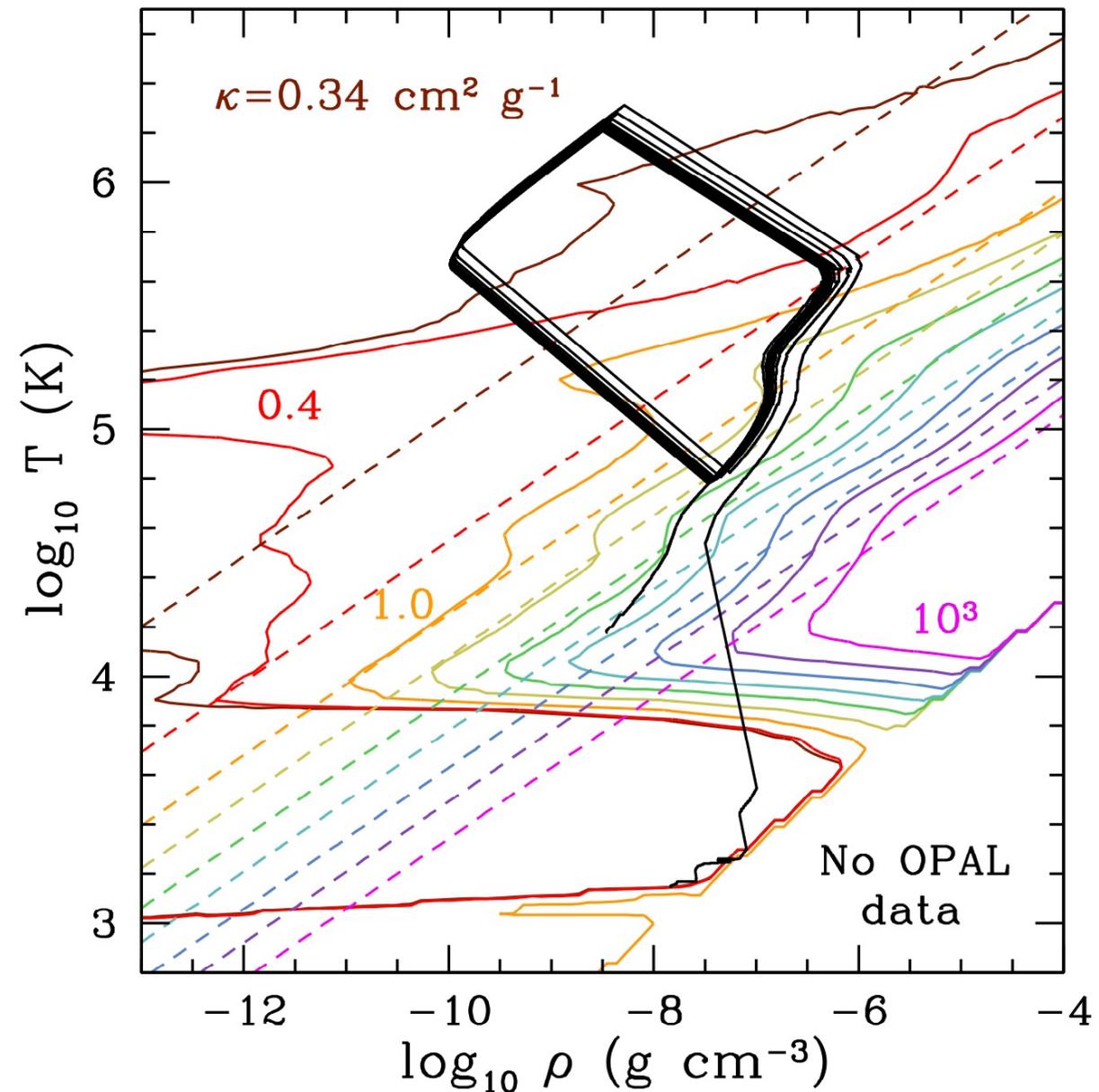
or with additional heating (Piro & Mockler 2025)

3. Lean into the simple disk models and explore their implications!

Updates to one-zone model

(Piro & Mockler 2025; also see Wenbin Lu's chapter in the Handbook of X-ray and Gamma-Ray Astrophysics, 2022)

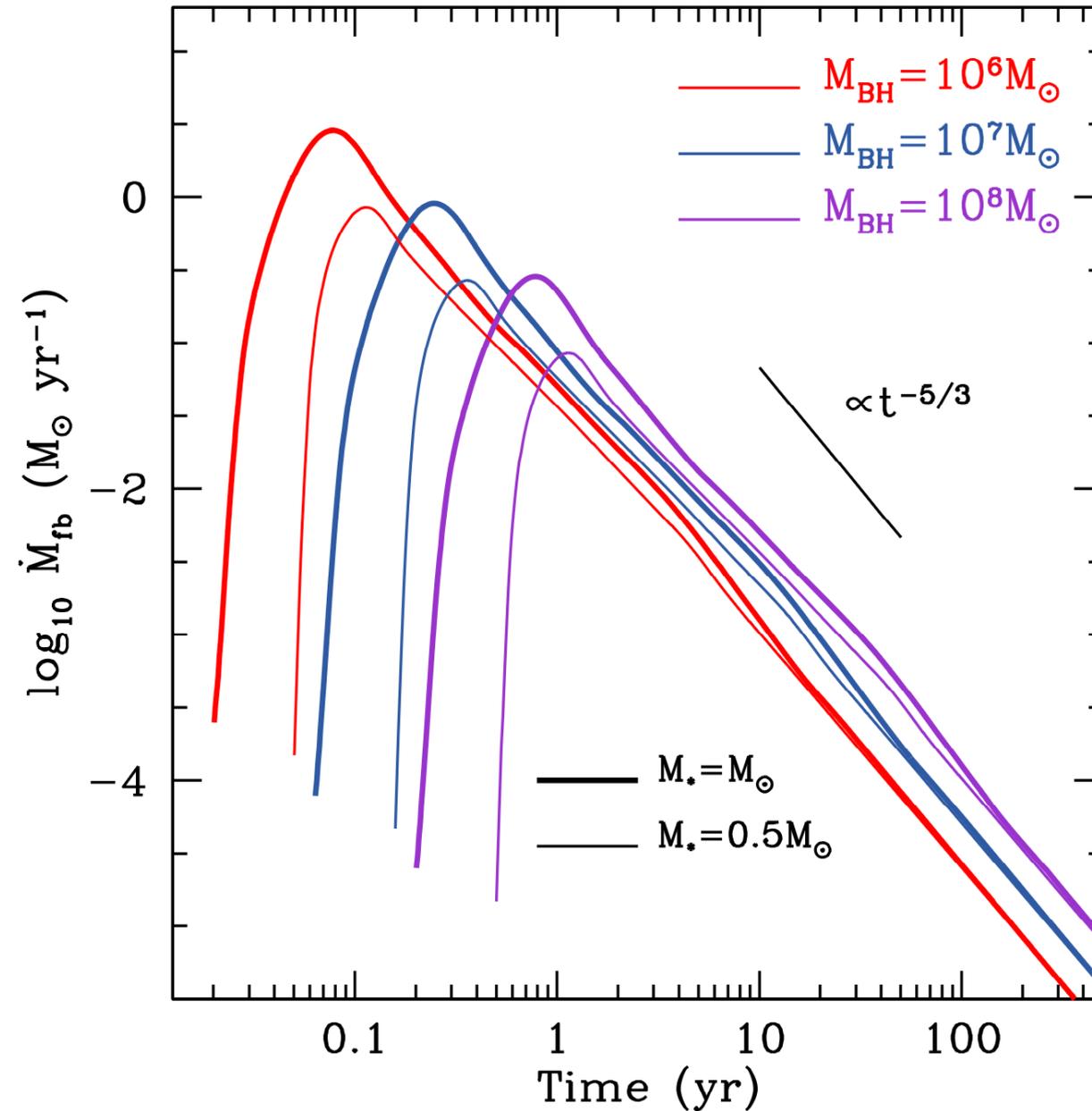
- More detailed opacities
- Explore a variety of alpha's (Shen & Matzner focused on alpha=0.01)



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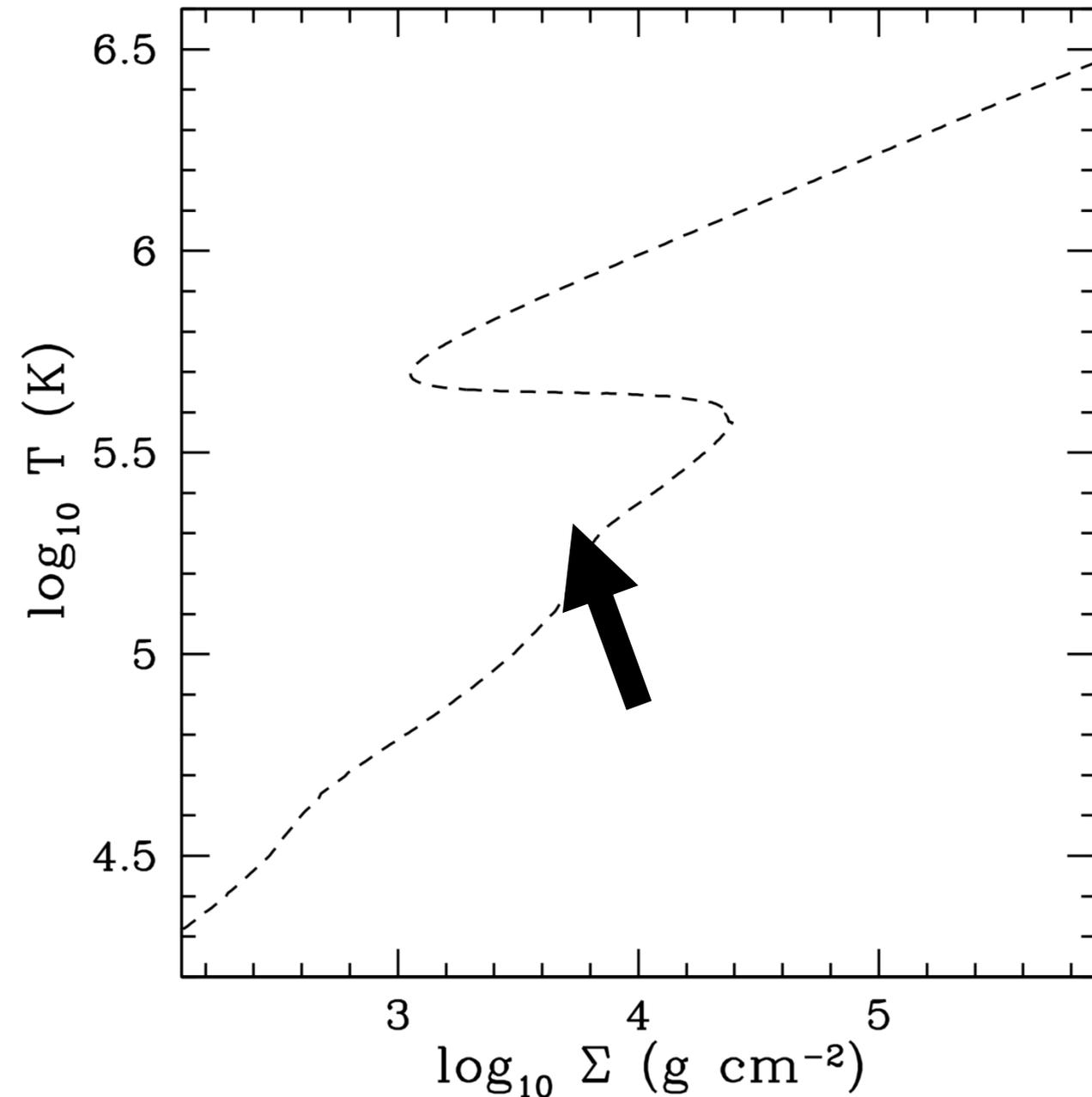
- More detailed opacities
- Explore a variety of alpha's (Shen & Matzner focused on alpha=0.01)
- Numerical fallback rates from (Guillochon & Ramirez-Ruiz 2013)



Updated $\Sigma - T$ Plane

Piro & Mockler (2025)

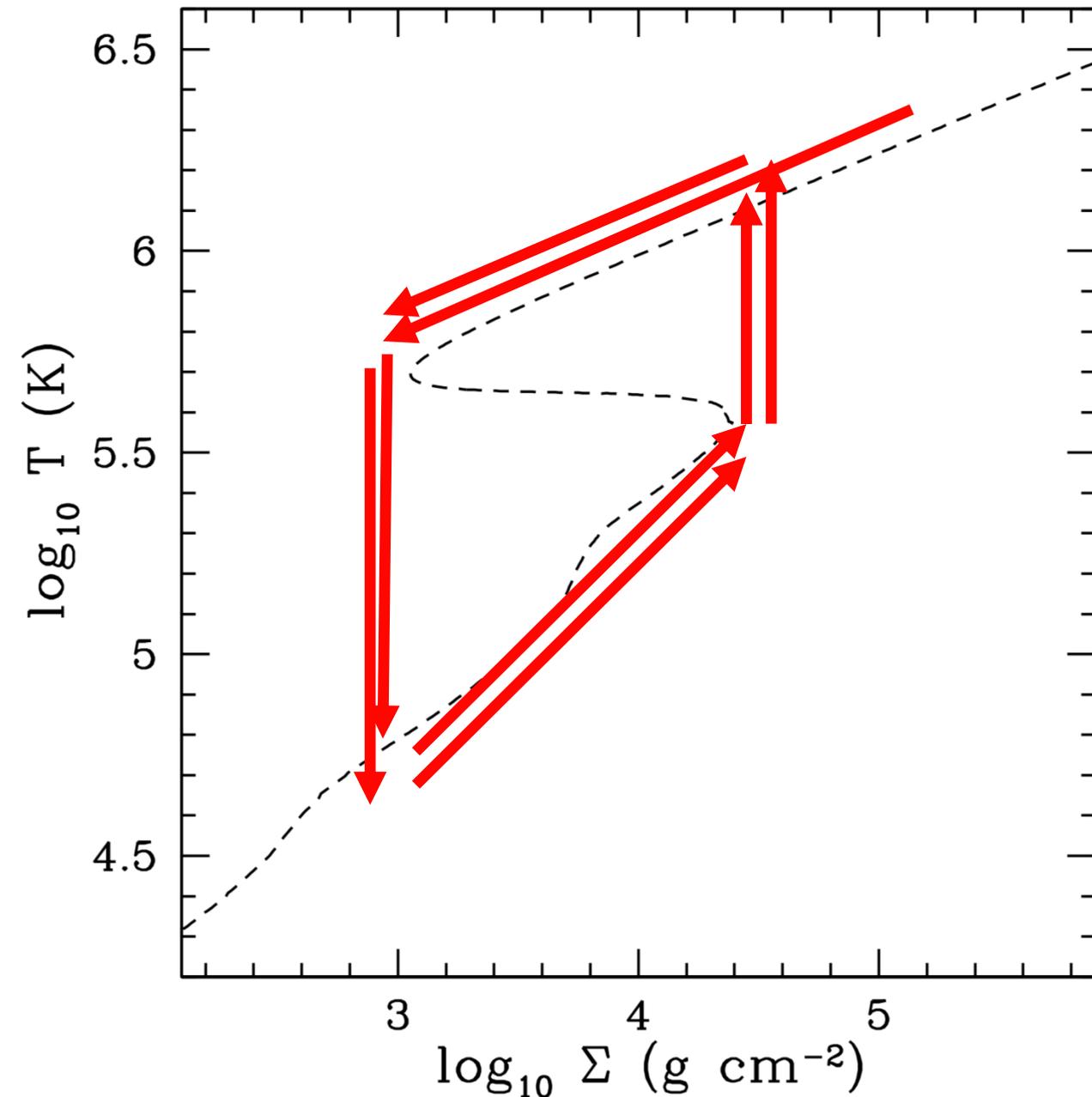
- Larger opacity shifts up the lower branch.
- $\alpha=0.1$ (rather than 0.01) speeds up the disk evolution



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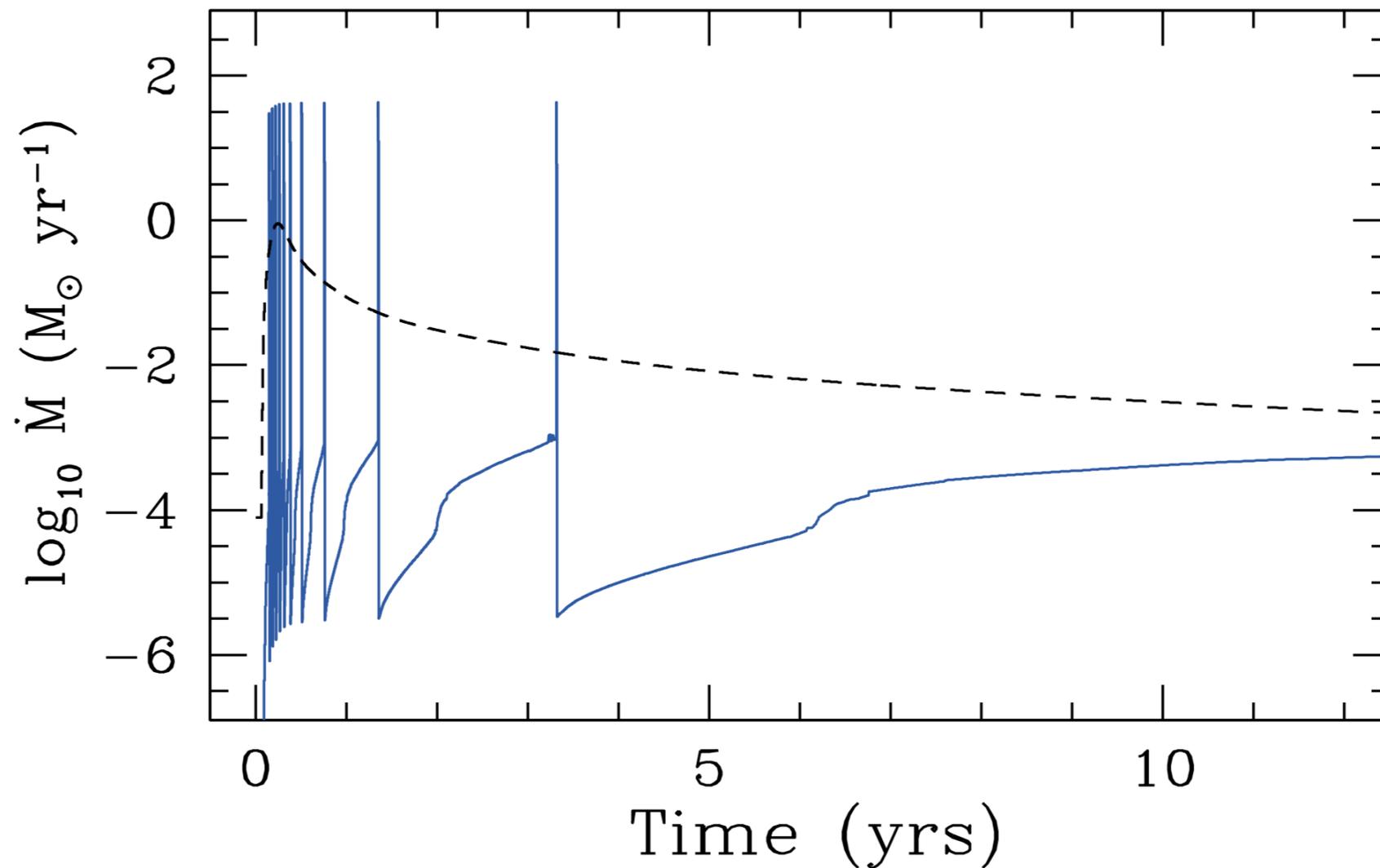
Piro & Mockler (2025)

- Larger opacity shifts up the lower branch.
- $\alpha=0.1$ (rather than 0.01) speeds up the disk evolution
- Generally find the disk experiences global-limit-cycle behavior.



Flaring TDE Disks

Piro & Mockler (2025)

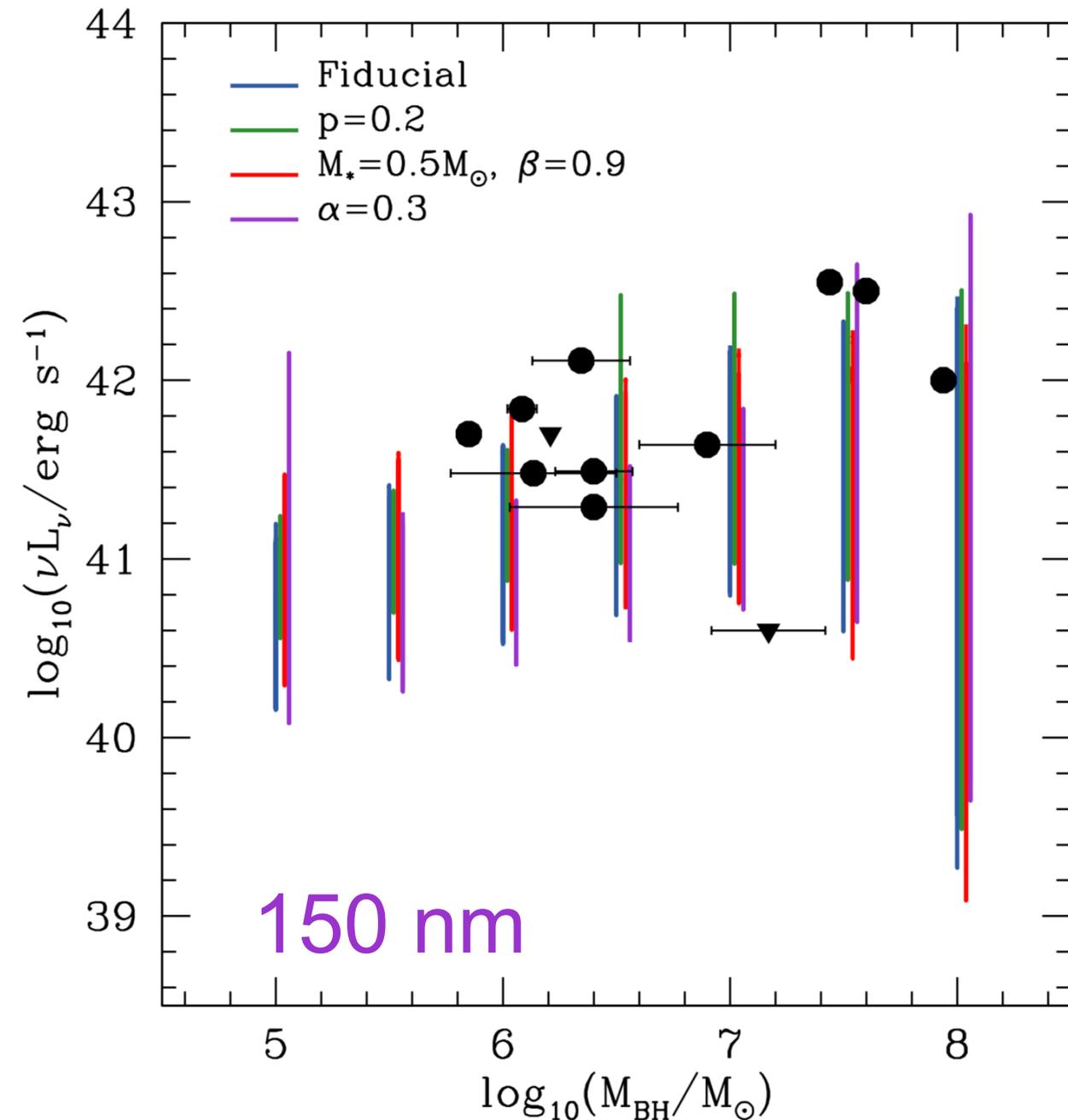


- ~ 1 -2 day high states with months to years in the low state
- Low state is now brighter than previous models due to opacity and fallback feeding
- Super-Eddington high state ejects $\sim 10^{-2} M_{\text{sun}}$ with a speed of $\sim 0.1c$

Late-time UV Plateau?

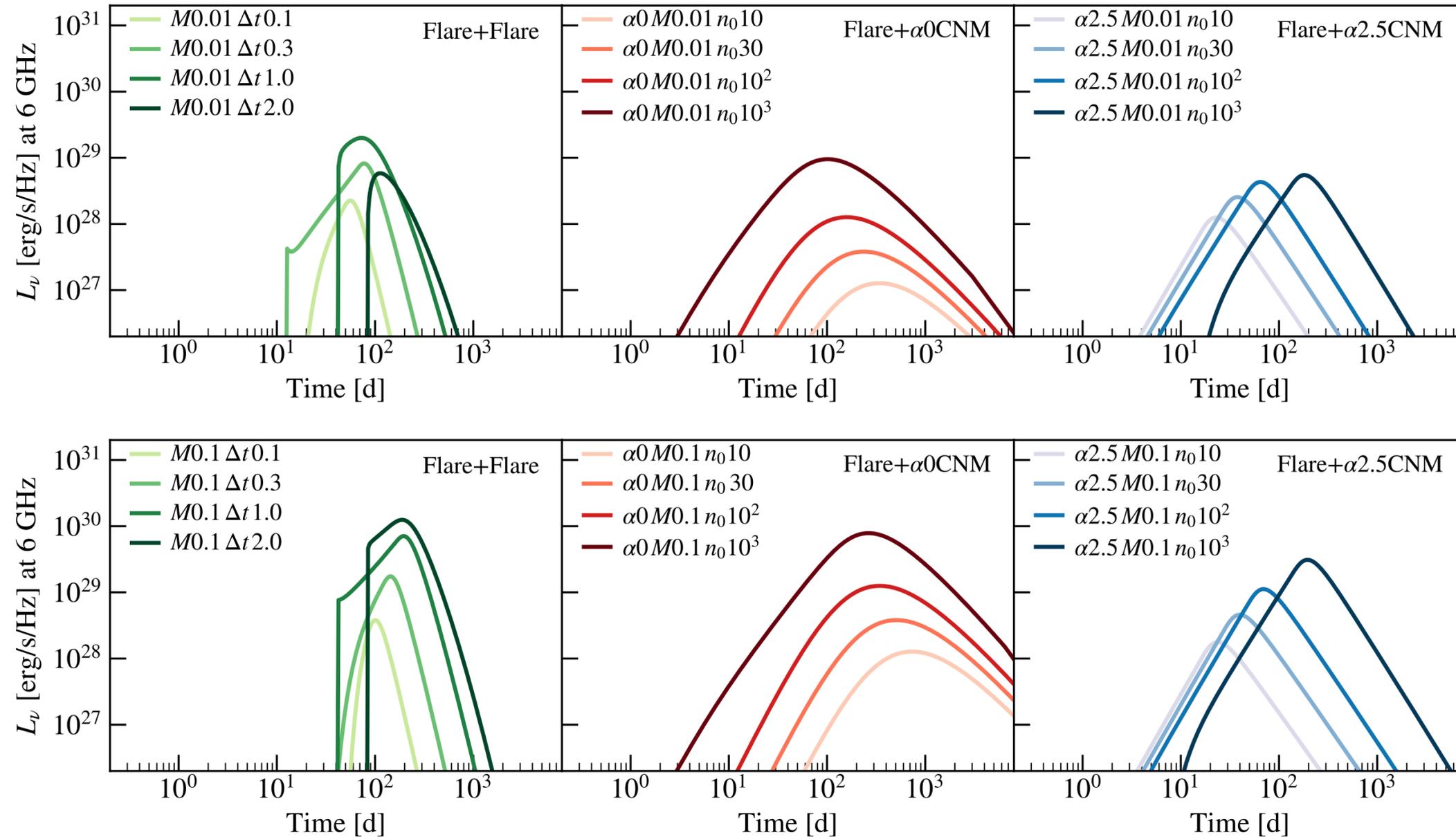
(Piro & Mockler, in prep; data from van Velzen et al. 2019)

- Disks would typically be observed in low state but could have a range of luminosities.
- Multi-epoch UV data may reveal this variability
- What about the ~ 1 -2 days outbursts?



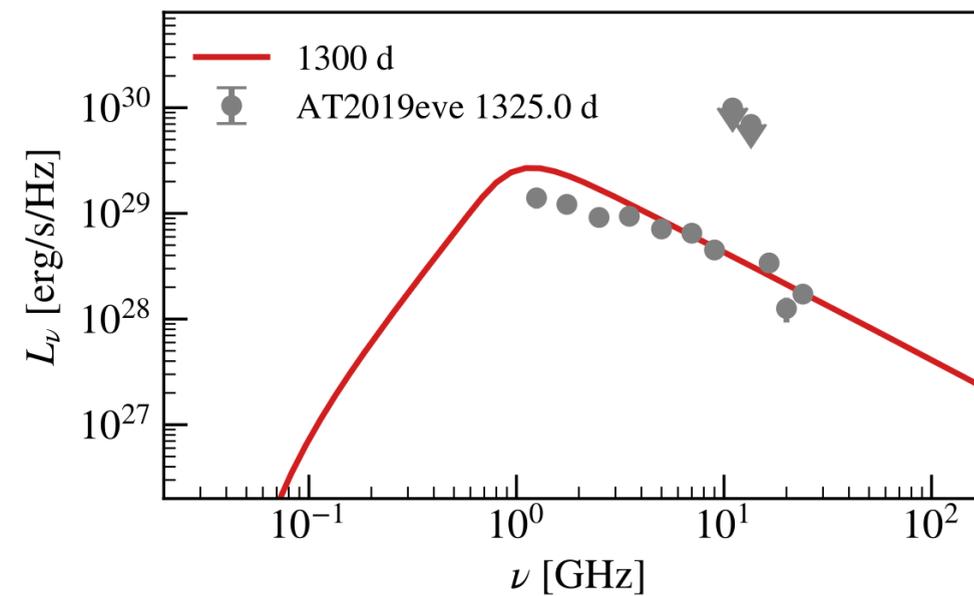
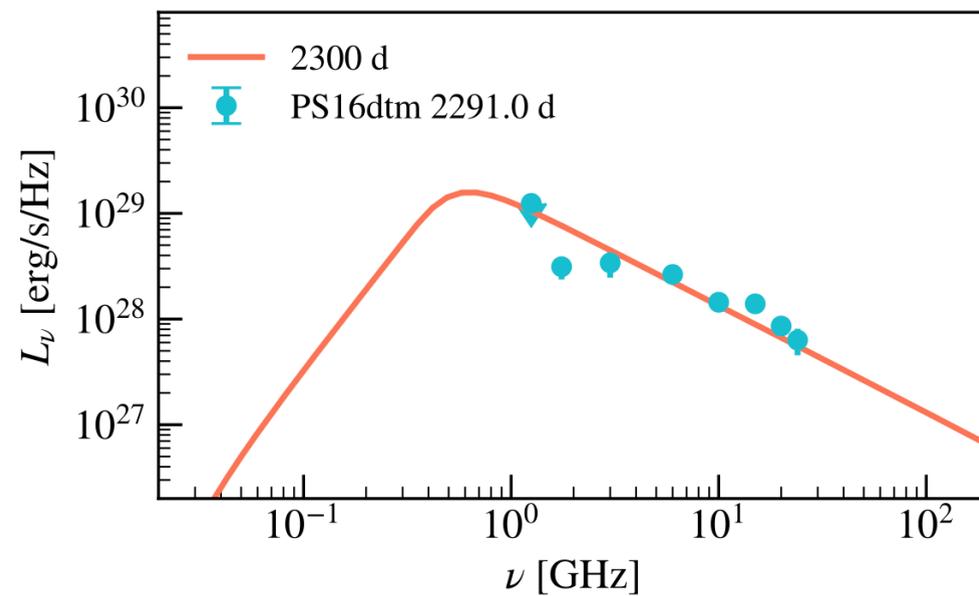
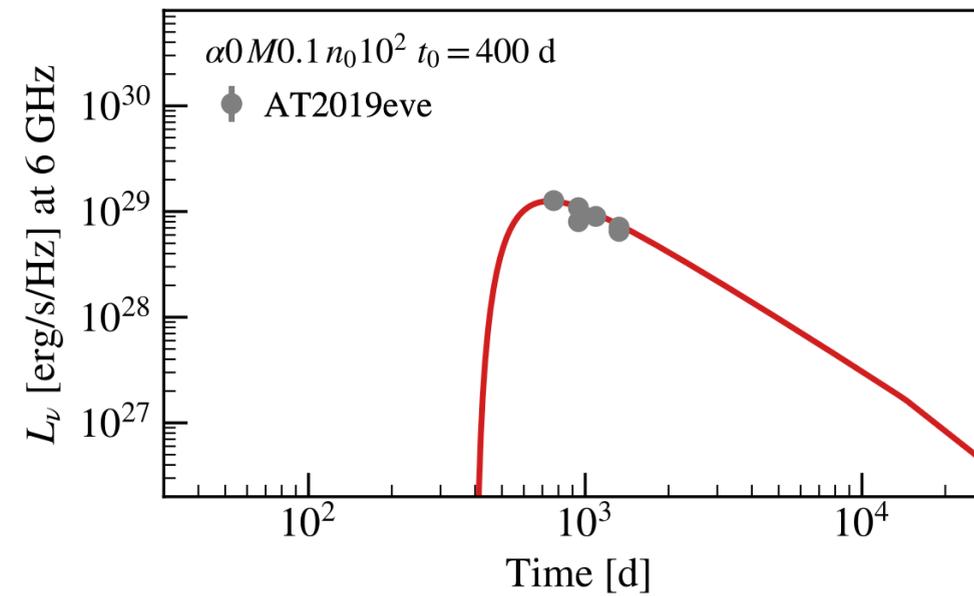
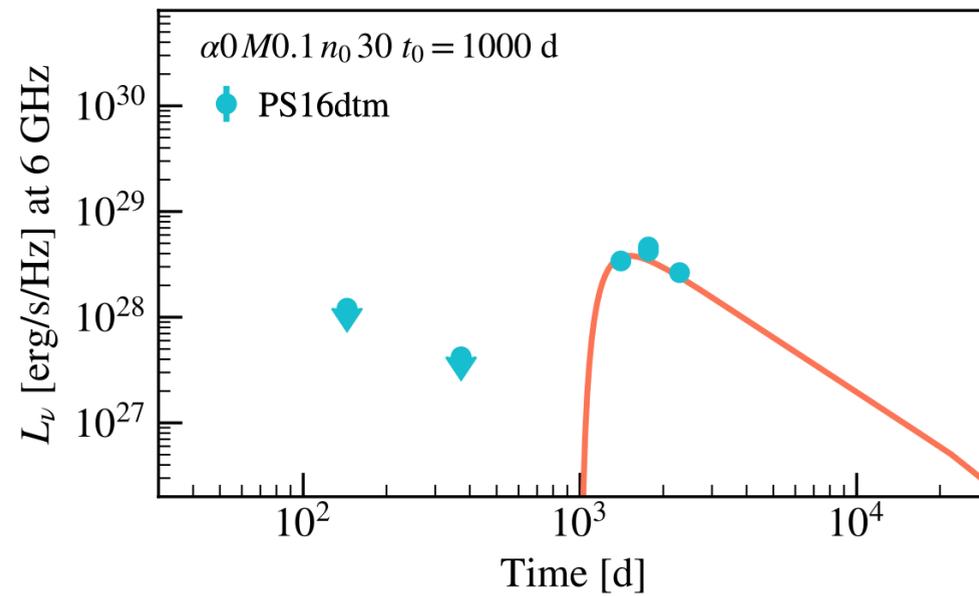
Radio Flares from Outbursts?

(Wu, Tsuna, Mockler, Piro 2025; also see Sato, Bhattacharya, Carpio, Capili & Murase 2025)



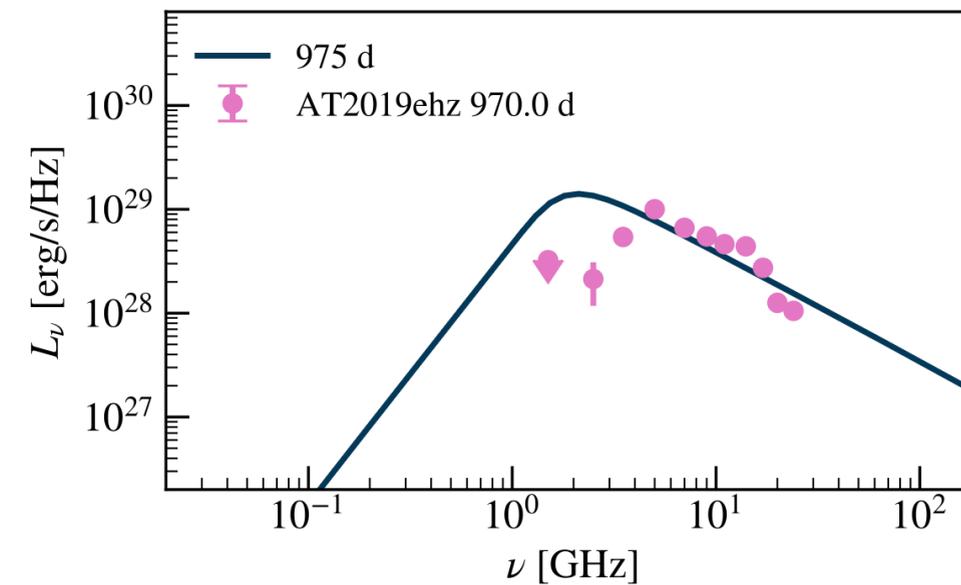
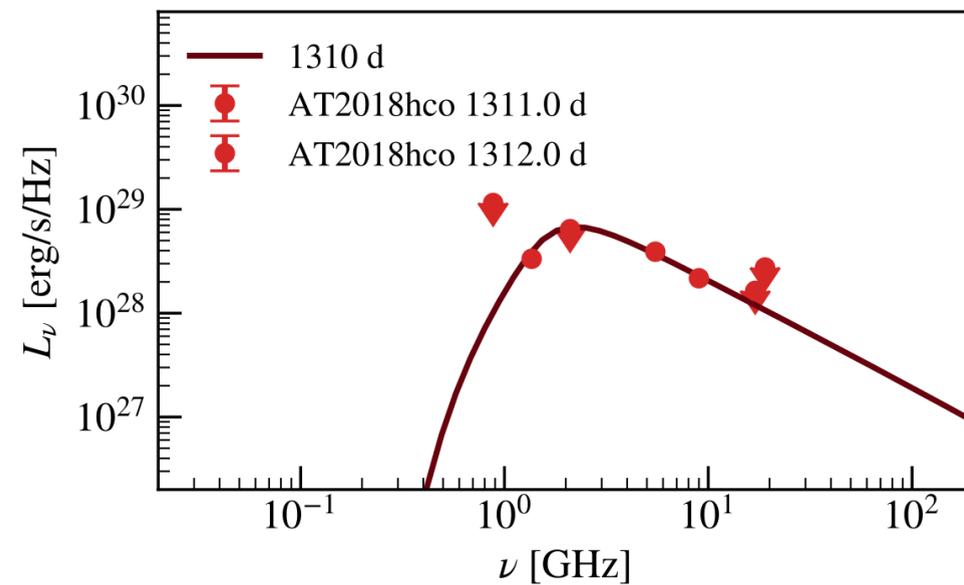
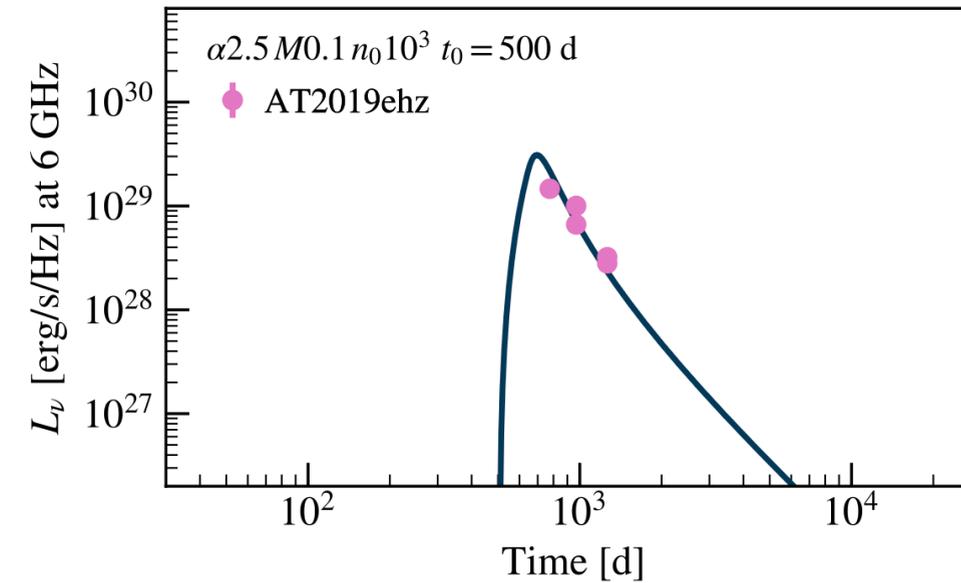
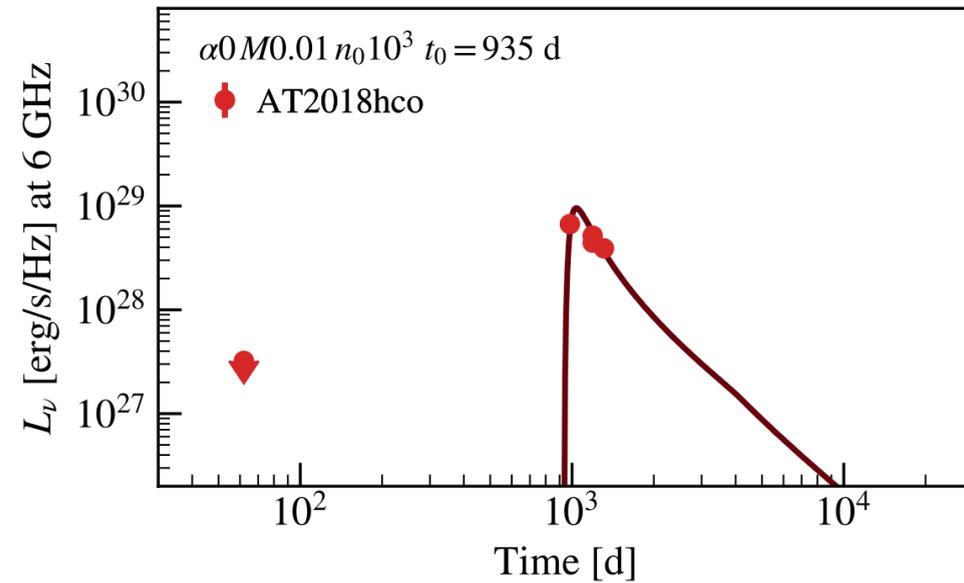
Flares naturally match LCs and spectra

Wu, Tsuna, Mockler, Piro (2025)



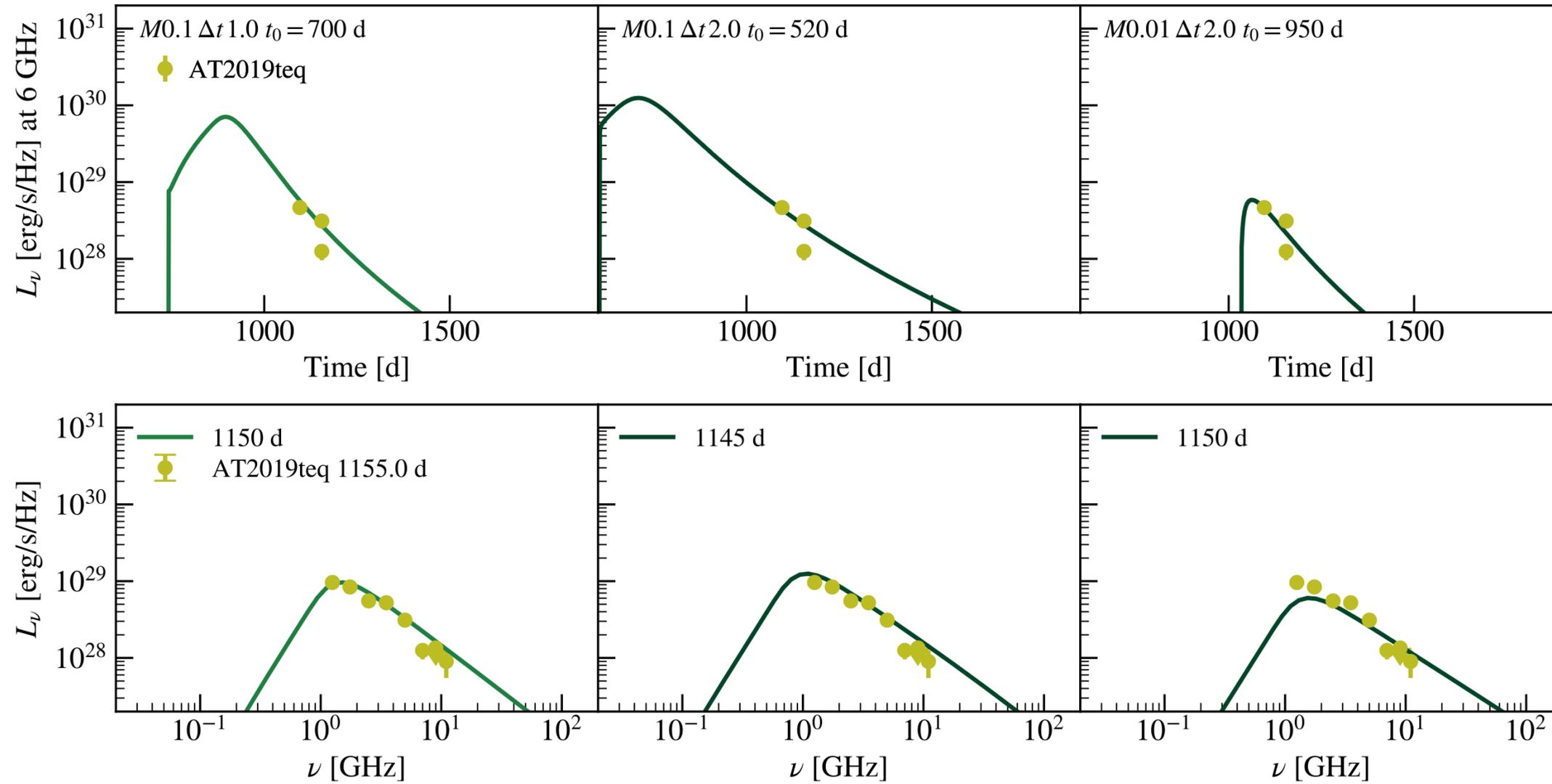
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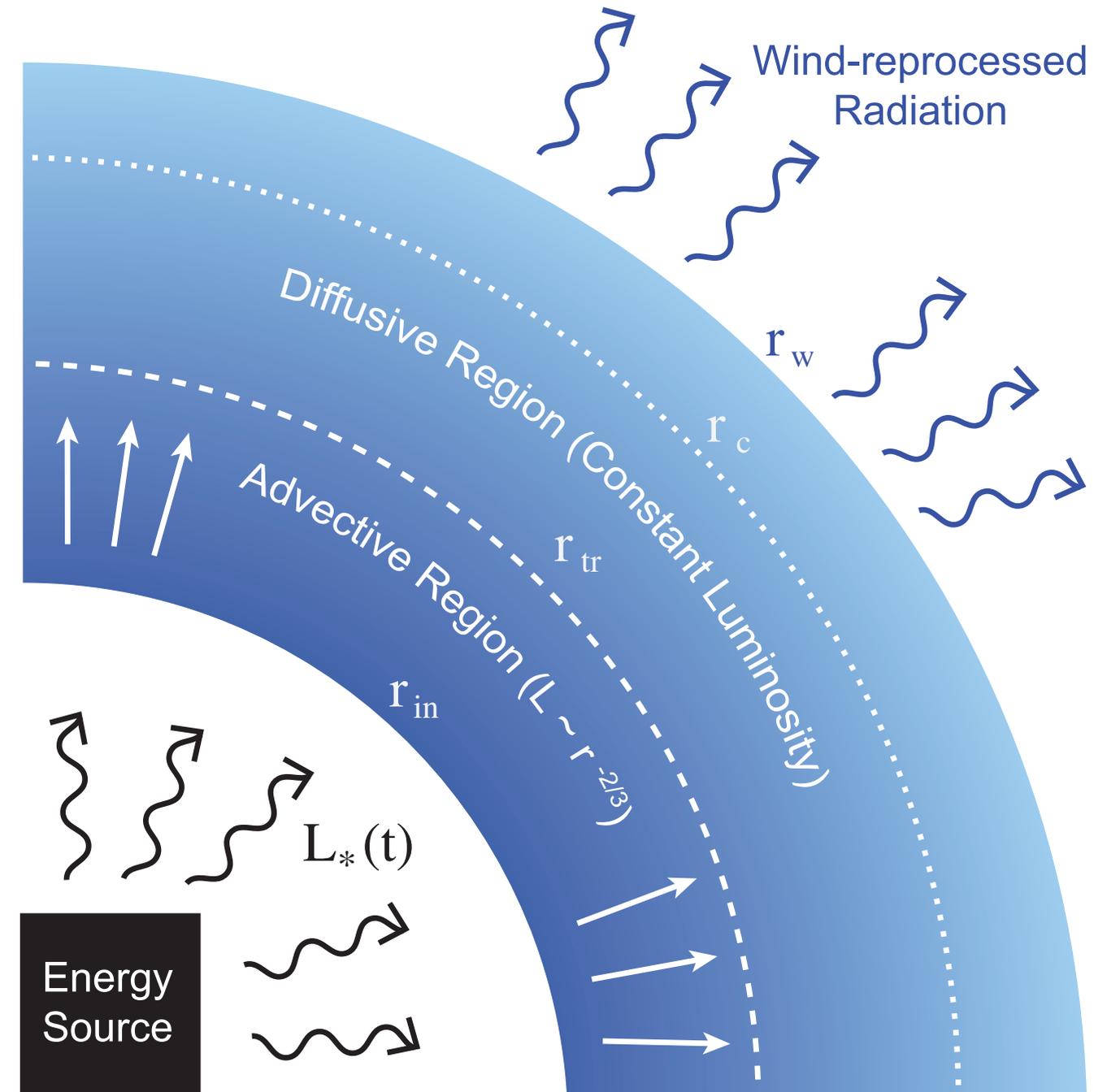
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UV/optical flares from Outbursts?

(Tsunaga, Villar, Piro, Wu, in prep; using Piro & Lu 2020, also see Uno & Maeda 2020)

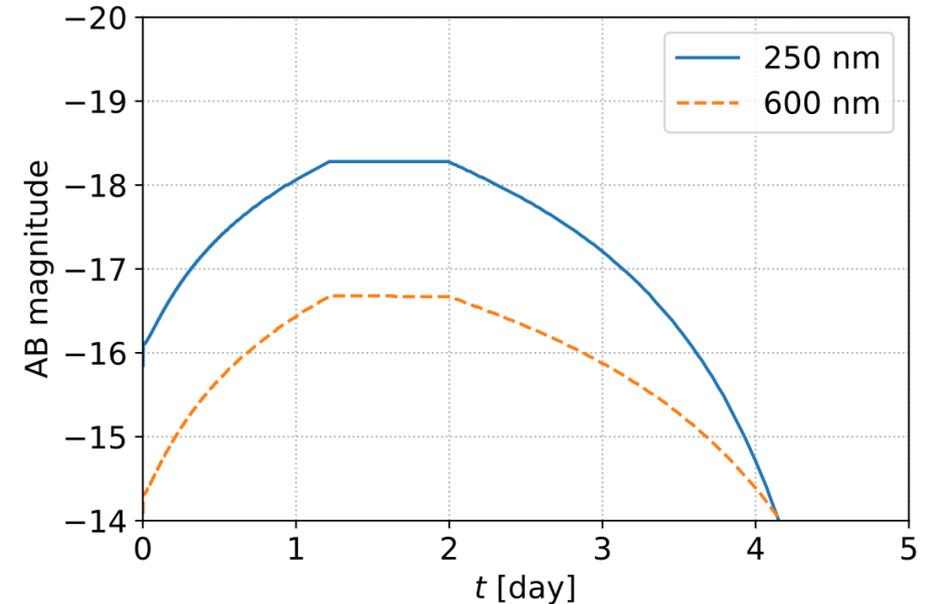
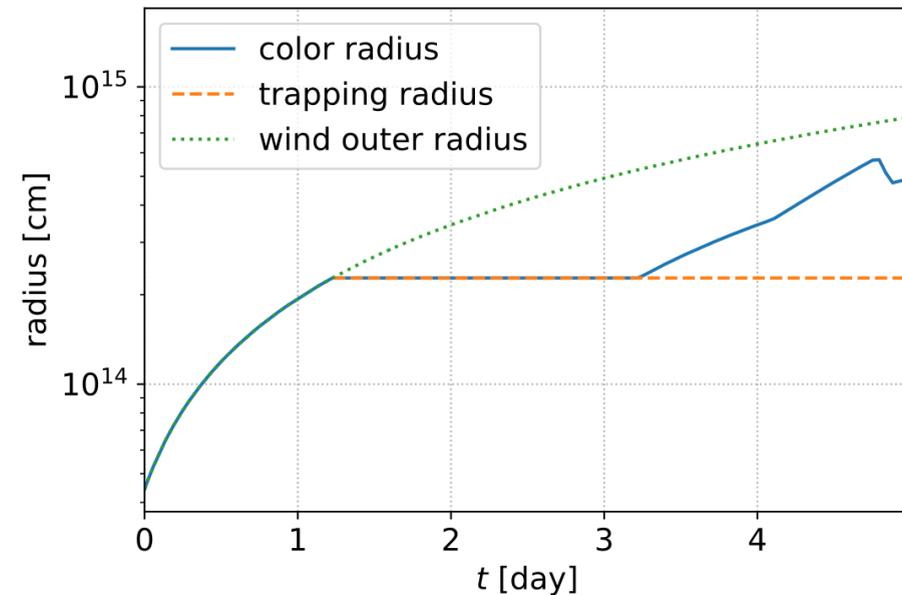
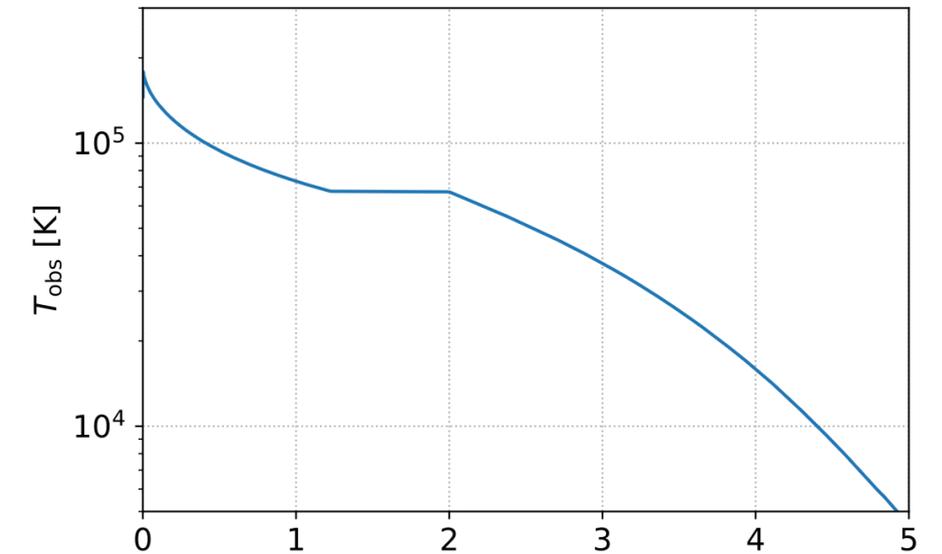
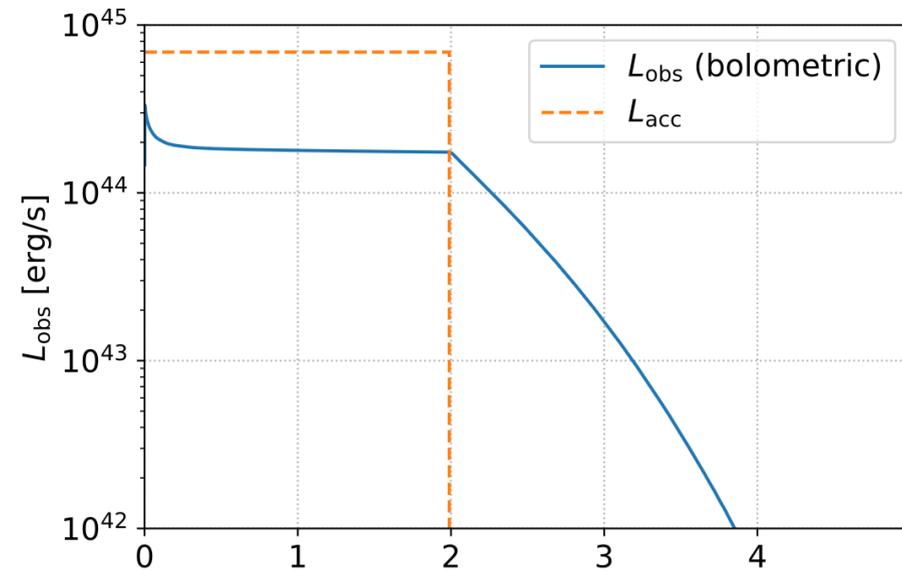
- Super-Eddington disk emission reprocessed by disk outflows.



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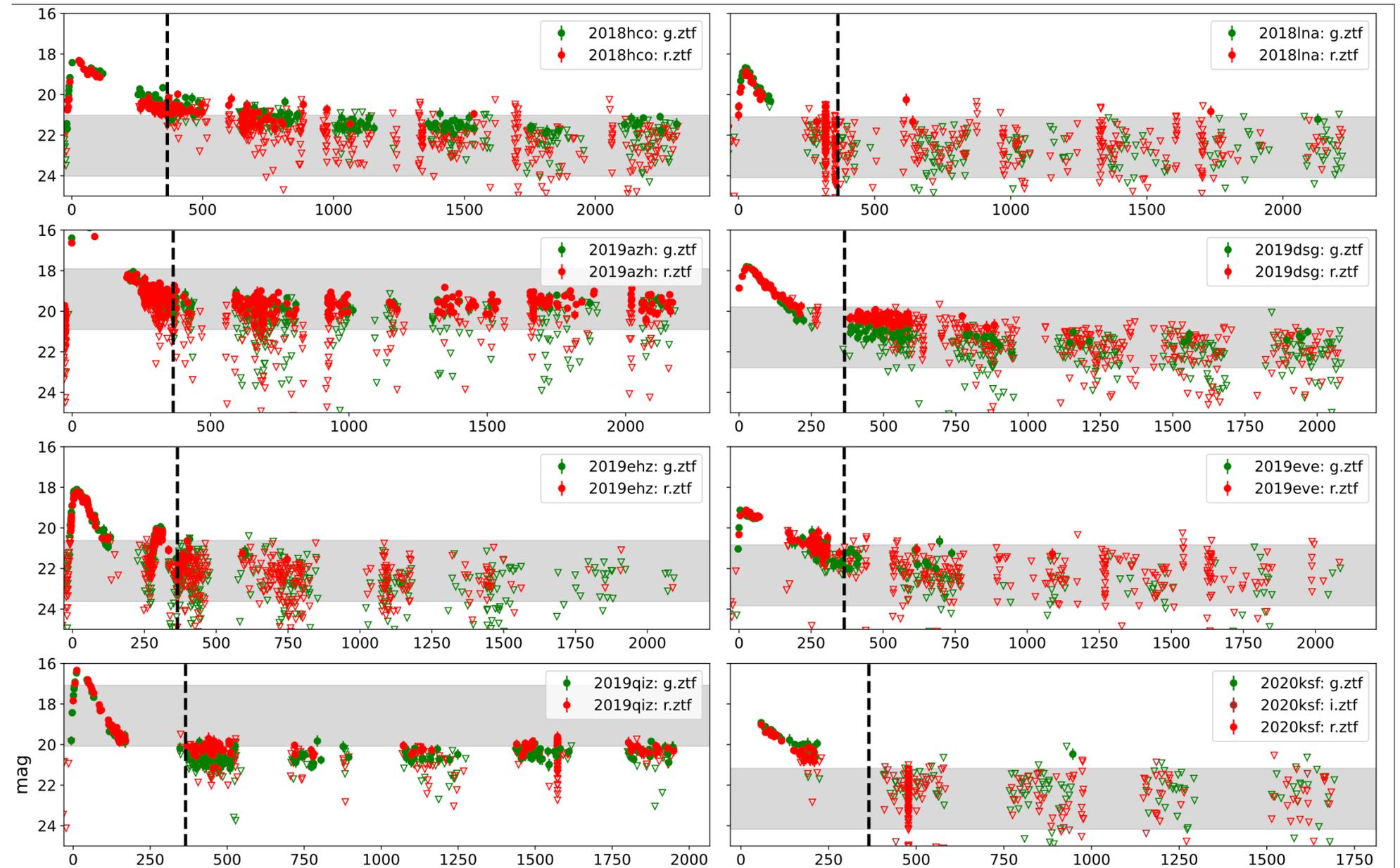
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- Bright ~1-2 day UV/optical transient.
- Is this already ruled out?



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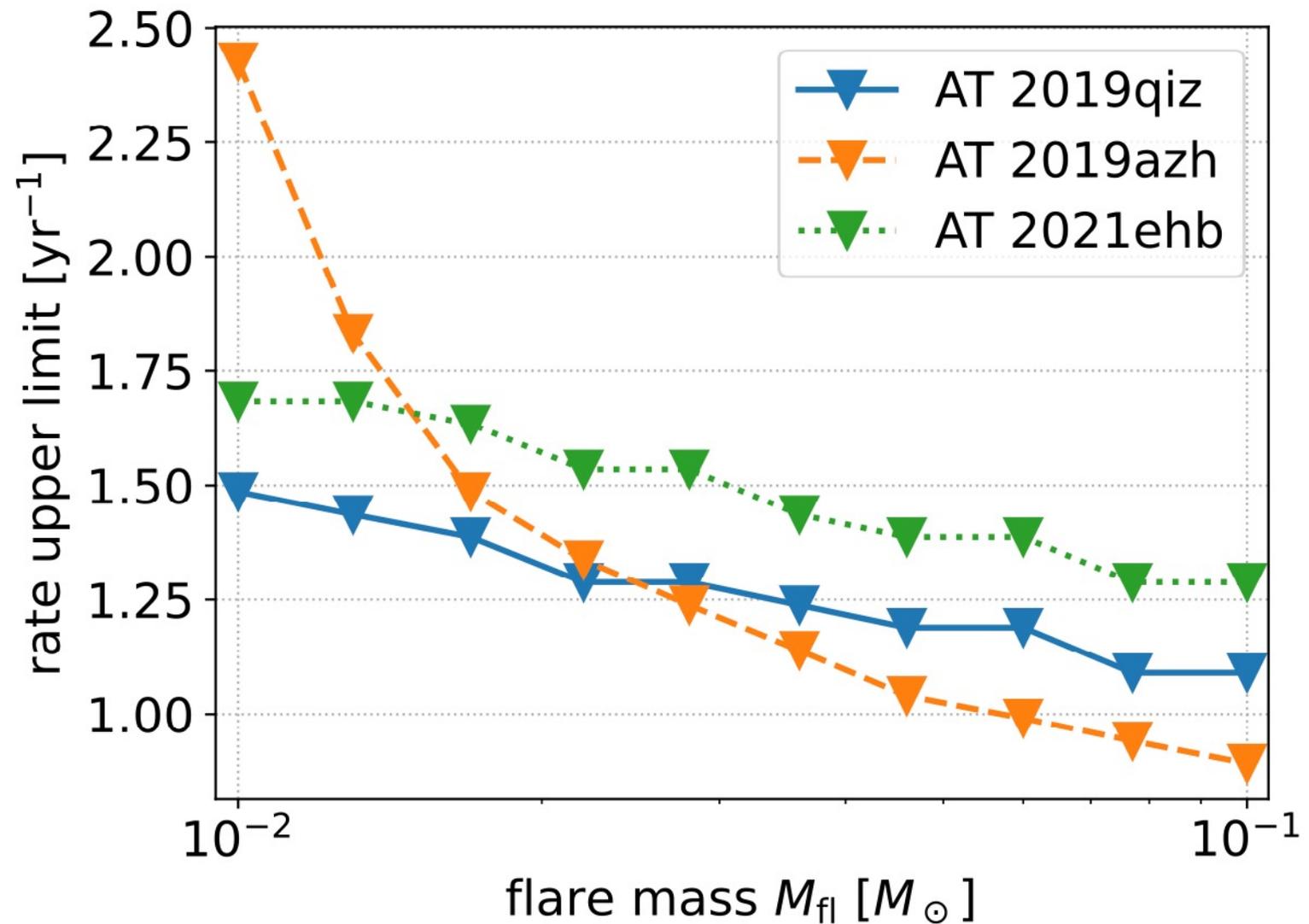
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- Is this already ruled out?
- Searched 28 nearest TDEs



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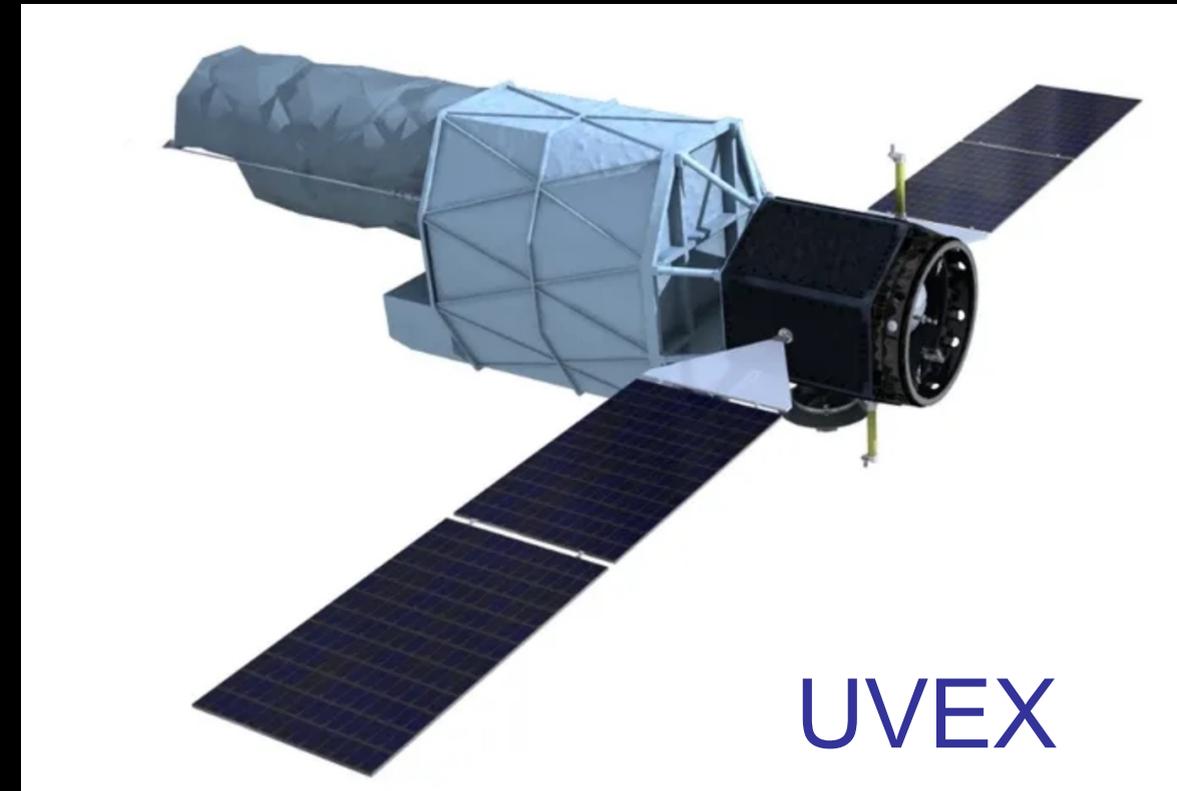
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- Bright ~ 1 -2 day UV/optical transient.
- Is this already ruled out?
- Searched 28 nearest TDEs
- Upper limit of 1-2 flares per yr per TDE



Future UV Missions

ULTRASAT

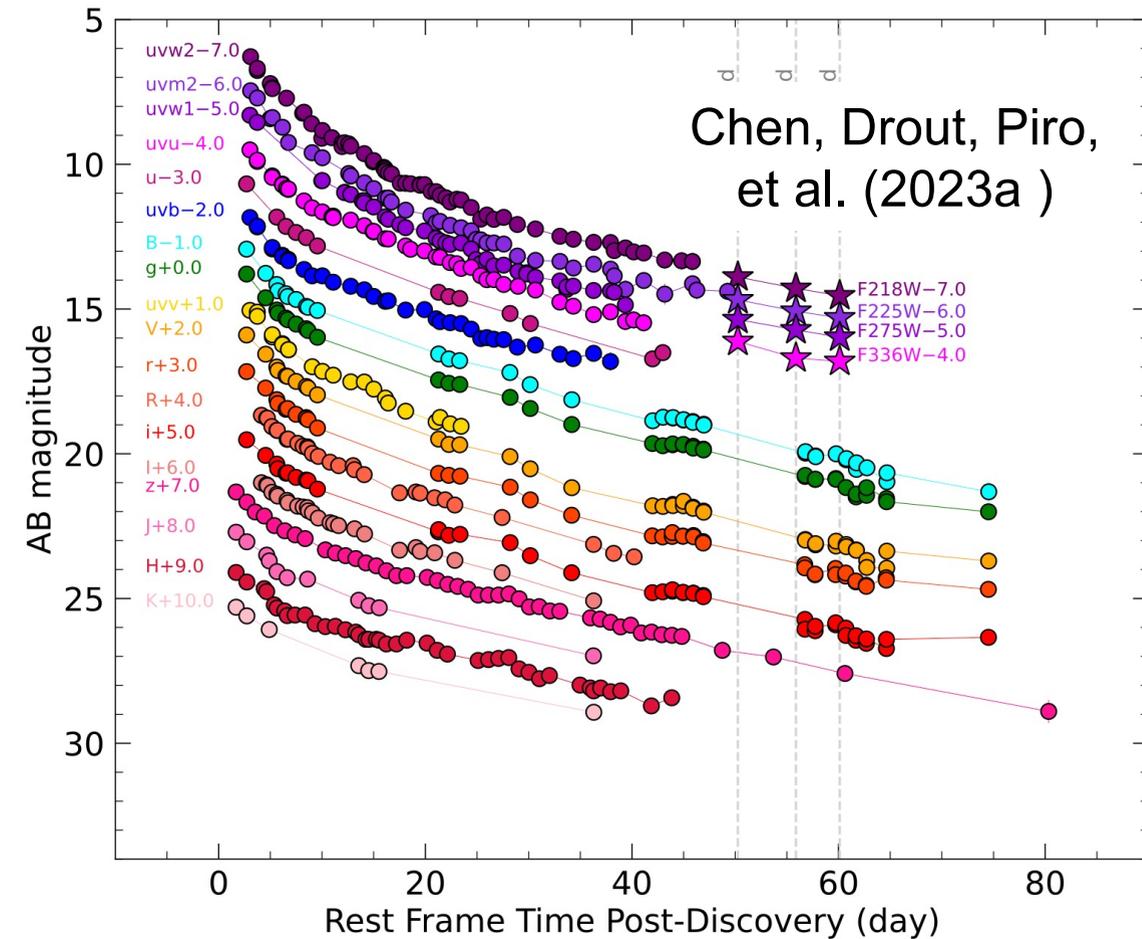
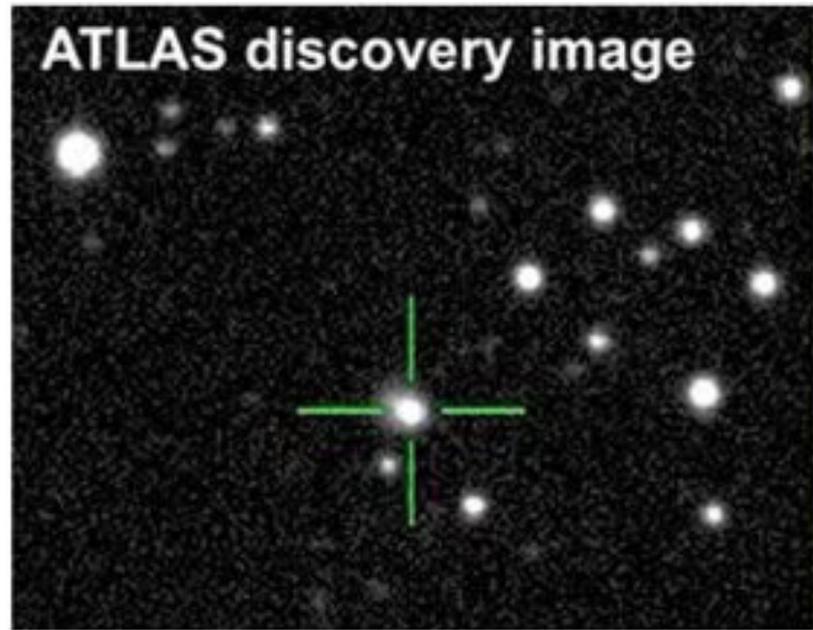


UVEX

UV will be crucial for constraining flaring AND disentangling TDE disk from galaxy emission.

AT2018cow or “The Cow”

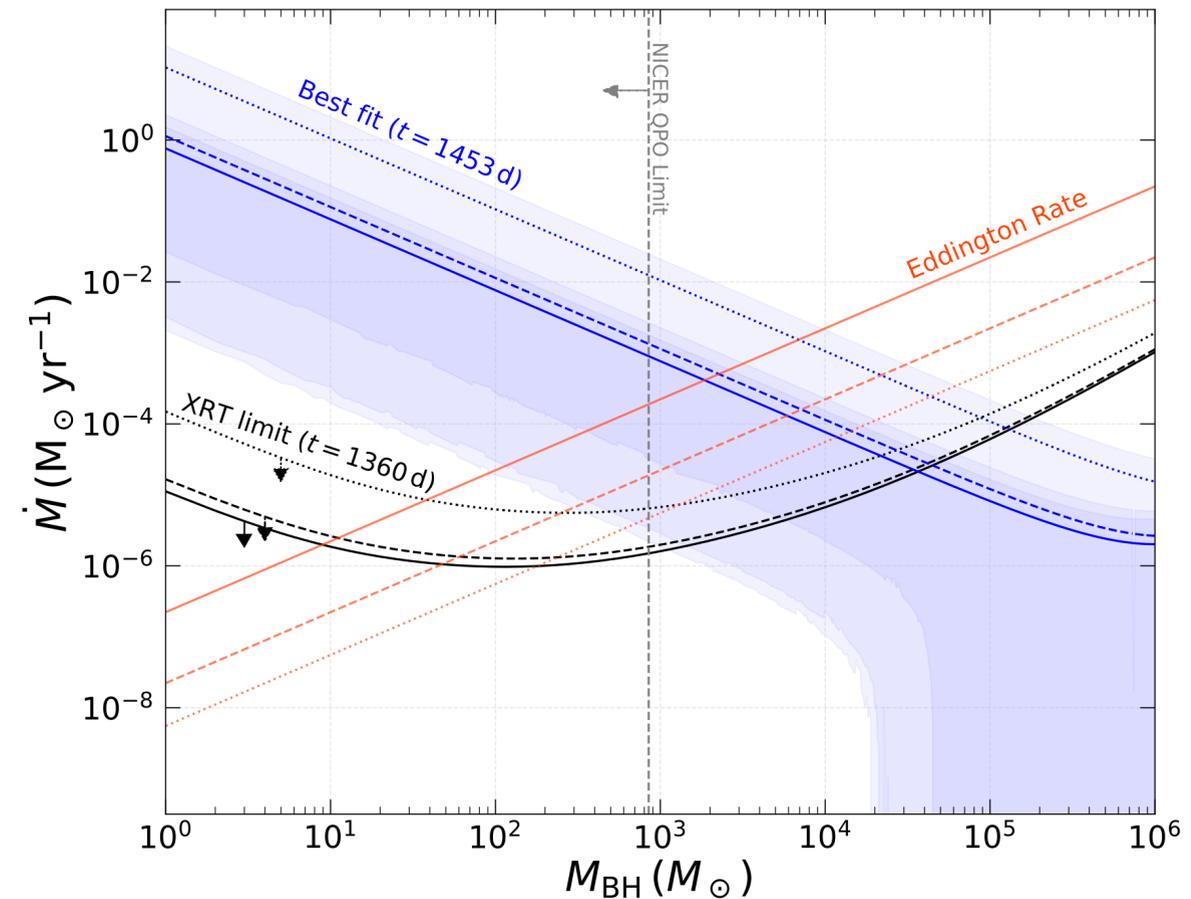
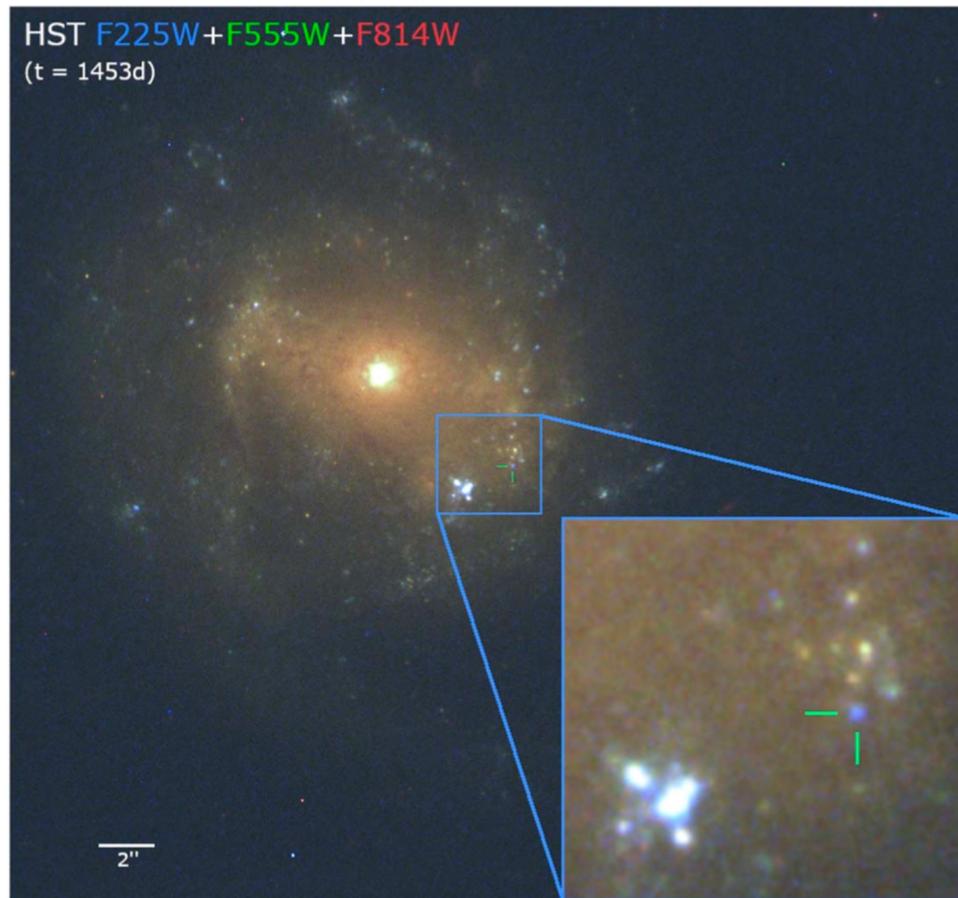
(Smartt et al. 2018; Prentice et al. 2018; Rivera Sandoval et al. 2018; Kuin et al. 2019; Ho et al. 2019; Margutti et al. 2019; Perley et al. 2019; Huang et al. 2019; Bietenholz et al. 2020; Xiang et al. 2021; Pasham et al. 2021)



- FBOT (or LFBOT?) that became as bright as $100L_{\text{sun}}$ in < 2 days
- Observed at essentially all wavelengths
- Could this be a very bright and fast tidal disruption?

The Cow 4 years later

(Chen, Drout, Piro, et al. 2023b, also see Sun et al. 2022; Ikenhaag et al. 2023; Migliori et al. 2024)



- HST reveals a bright UV source evolving over 3 epochs ~ 700 -1500 days
- Consistent with a disk around 10^3 - 10^4 solar mass BH (although see Winter-Granic & Quataert 2025 who argue inner disk is still super-Eddington and BH mass is lower)
- Good news for theorists: there is more work to do on remnant disks!

Conclusions

- TDEs are one of the fastest growing areas of transient study and are poised to become even more exciting in the near future.
- Multiple observational probes show TDEs are active on years to decade timescales (radio, optical/UV plateau, QPEs).
- Standard disk models show thermal instabilities, with \sim day long flares that repeat every \sim few yrs and continue for \sim decade.
- Instabilities may help explain radio flares, but optical/UV non-detections constrain the flares to $<1-2$ per yr per TDE.
- With new UV missions coming soon, now is the ideal time to test these models and explore the late time evolution of TDEs!