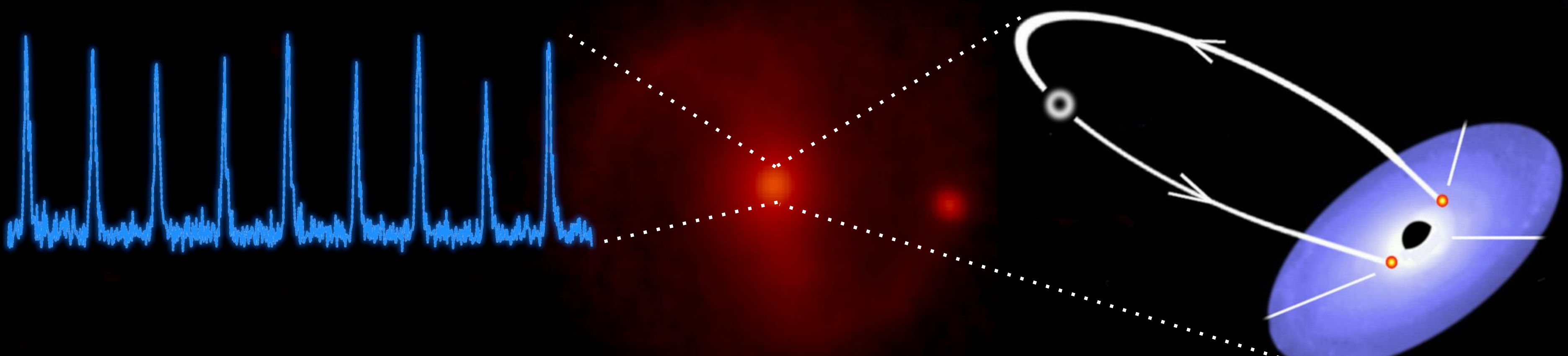
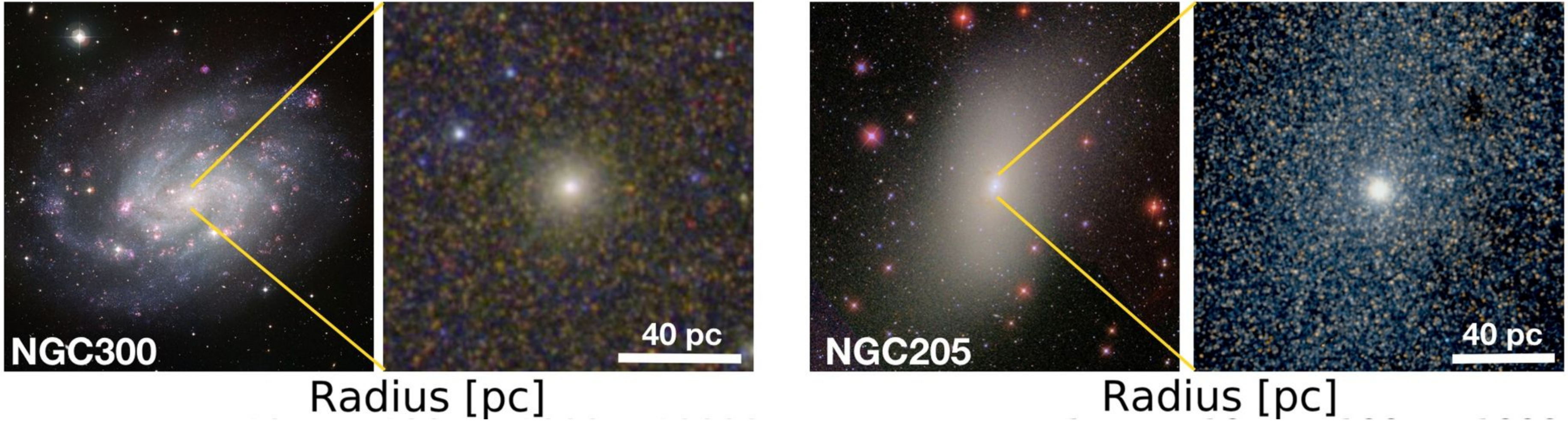
An overview of Repeating Extragalactic Nuclear Transients (RENTs): Potential Objects Orbiting Supermassive Black Holes



Dheeraj R. Pasham (MIT)

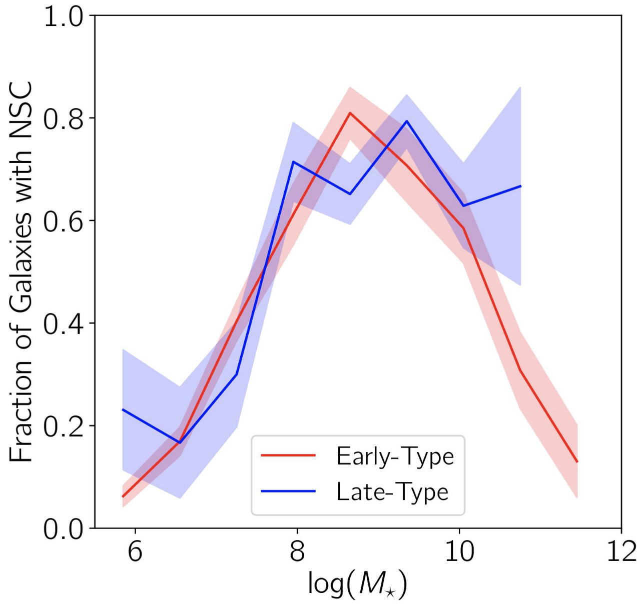
Galaxies contain supermassive black holes and dense nuclear star clusters



Nuclear star clusters can contain old stars (globular clusters) and massive young stars

Neumayer, Seth, Boker 2020, A&A, review

Surveys suggest that a large fraction of galaxies have dense nuclear star clusters

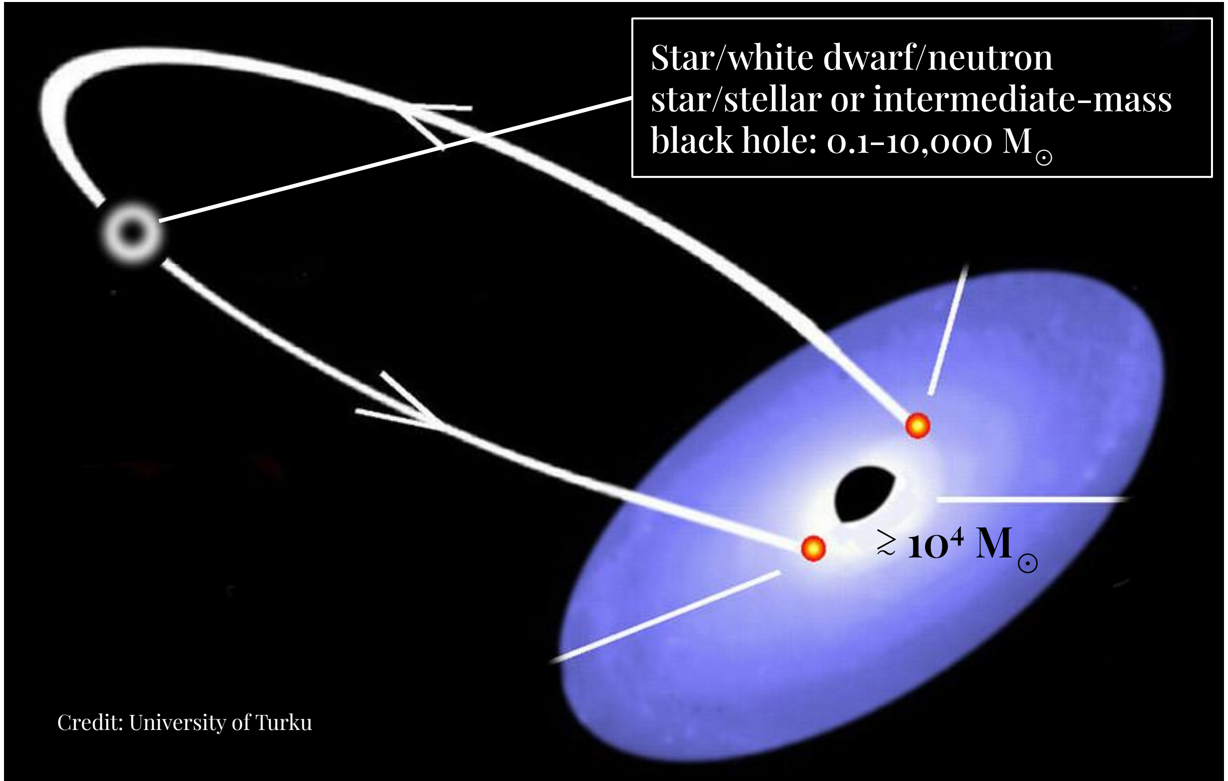


>60% of galaxies in this mass range contain nuclear star clusters

Nuclear Star Clusters are a reservoir of stars and stellar remnants (stellar-mass black holes, neutron stars, white dwarfs and possibly intermediate-mass black holes)

Neumayer, Seth, Boker 2020, A&A, review

Various mechanisms can put these objects into orbit around the central supermassive black hole → Extreme Mass Ratio Binaries

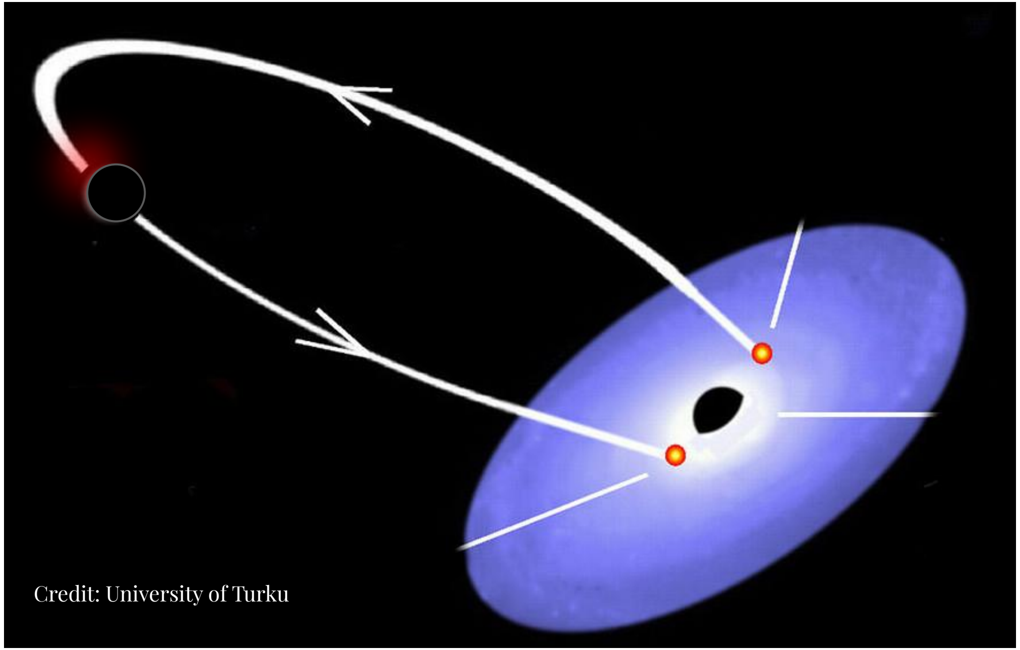


See Hills 1988, Nature, for the classical HIlls Mechanism. Also, e.g., Fragione 2022, ApJ and Rose, Naoz et al. 2022, ApJ for SMBH–IMBH formation mechanisms.

Additional references: Syer et al. 1991; Pan & Yang 2021, PRD; Sigurdsson & Rees, 1997, MNRAS, etc

Extreme Mass Ratio Binaries

If the companion is a compact object:



- Detectable with LISA and Taiji (Electromagnetic + Gravitational waves)
- Dark energy/Hubble tension
- Probe gravity in strong regime
- Galaxy/supermassive black hole evolution studies

Extreme Mass Ratio Binaries

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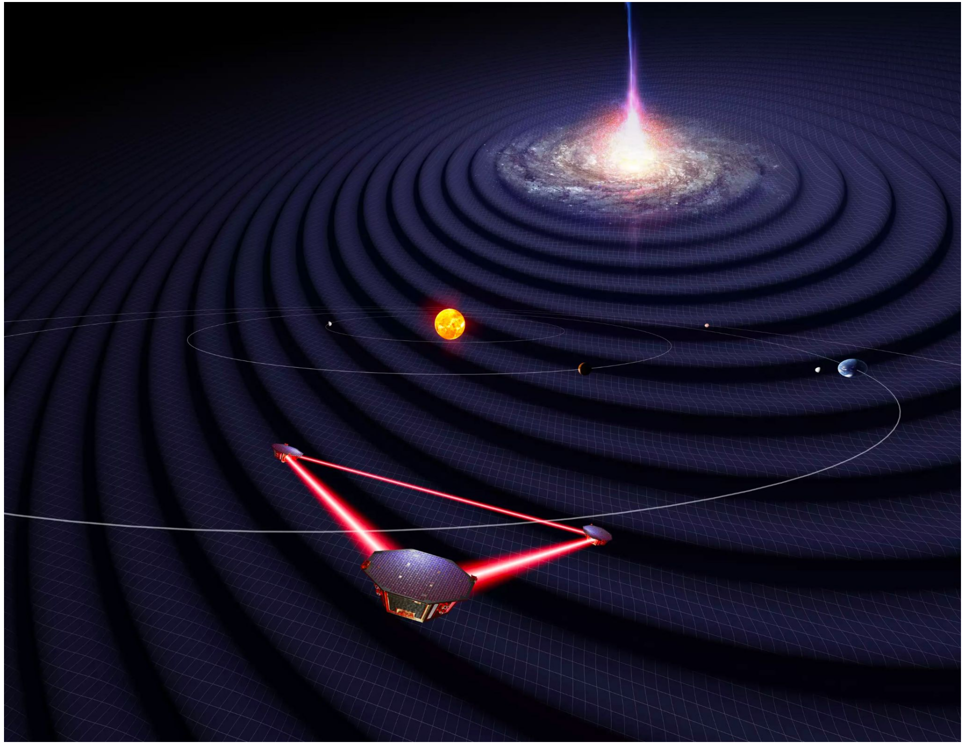

- Detectable with LISA and Taiji (Electromagnetic + Gravitational waves)
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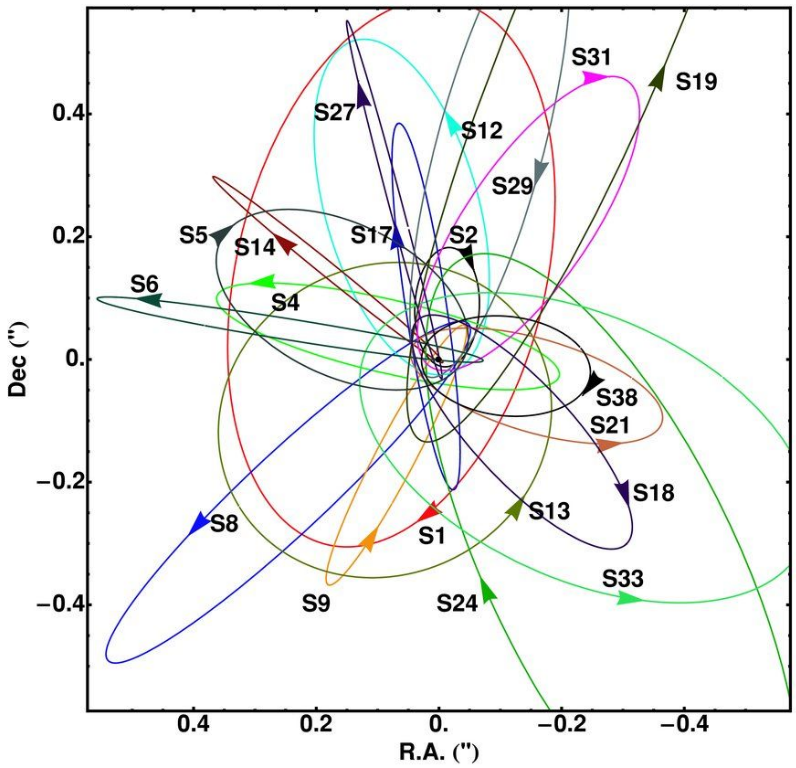
Extreme Mass Ratio Binaries

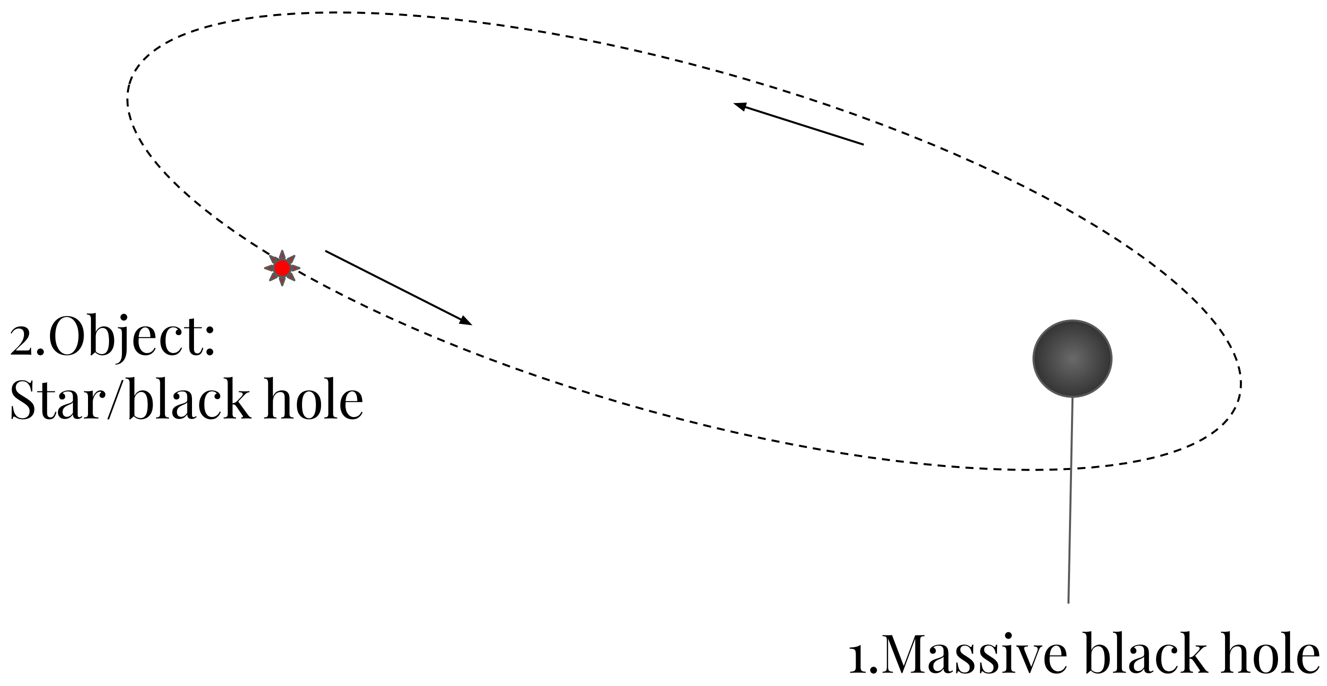
If the companion is a star:



Unprecedented way of tracing test particle orbits around supermassive black hole in external galaxies (many more orbits than possible from S0 stars near Sgr A*)

Credit: Andrea Ghez, Sylvana Yelda, Leo Meyer, Jessica Lu, Seth Hornstein, Tuan Do, Shoko Sakai, Aurelien Hees and Angelle Tanner

Can we identify such binaries with the current technology?



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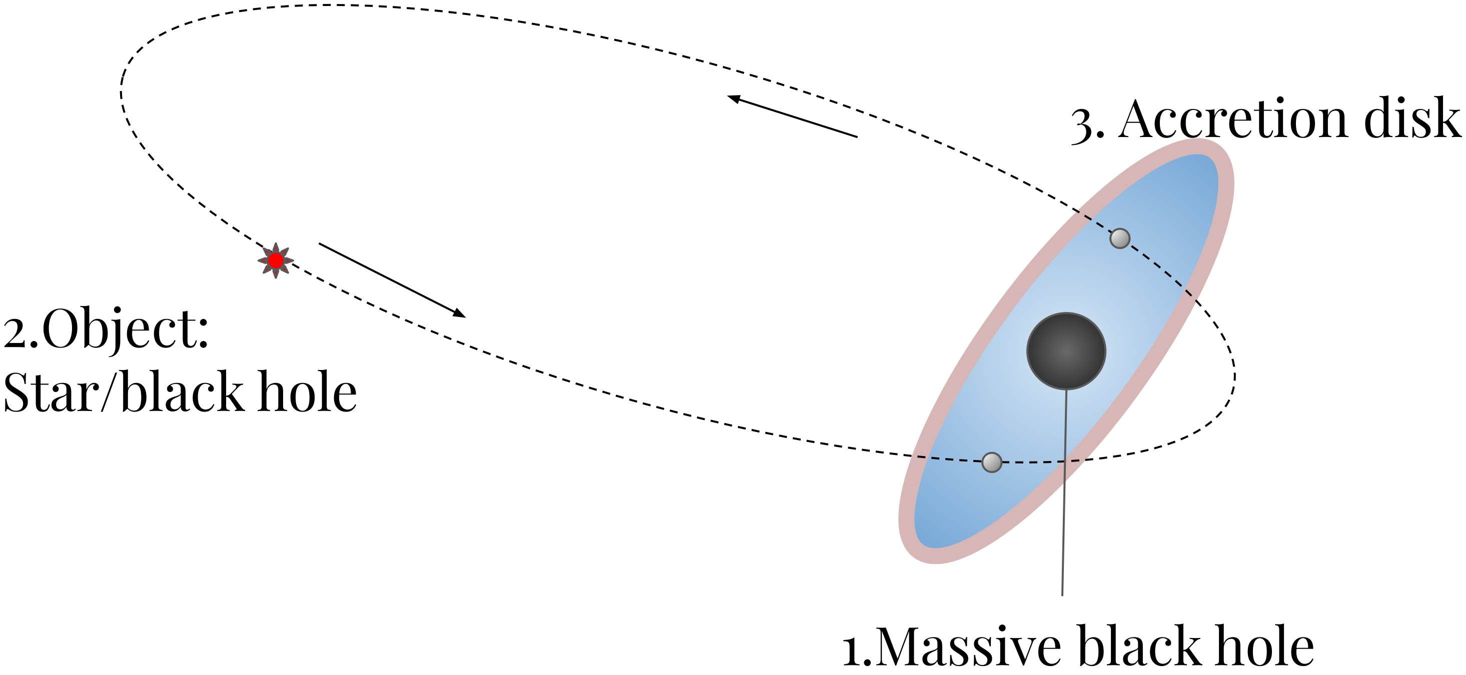

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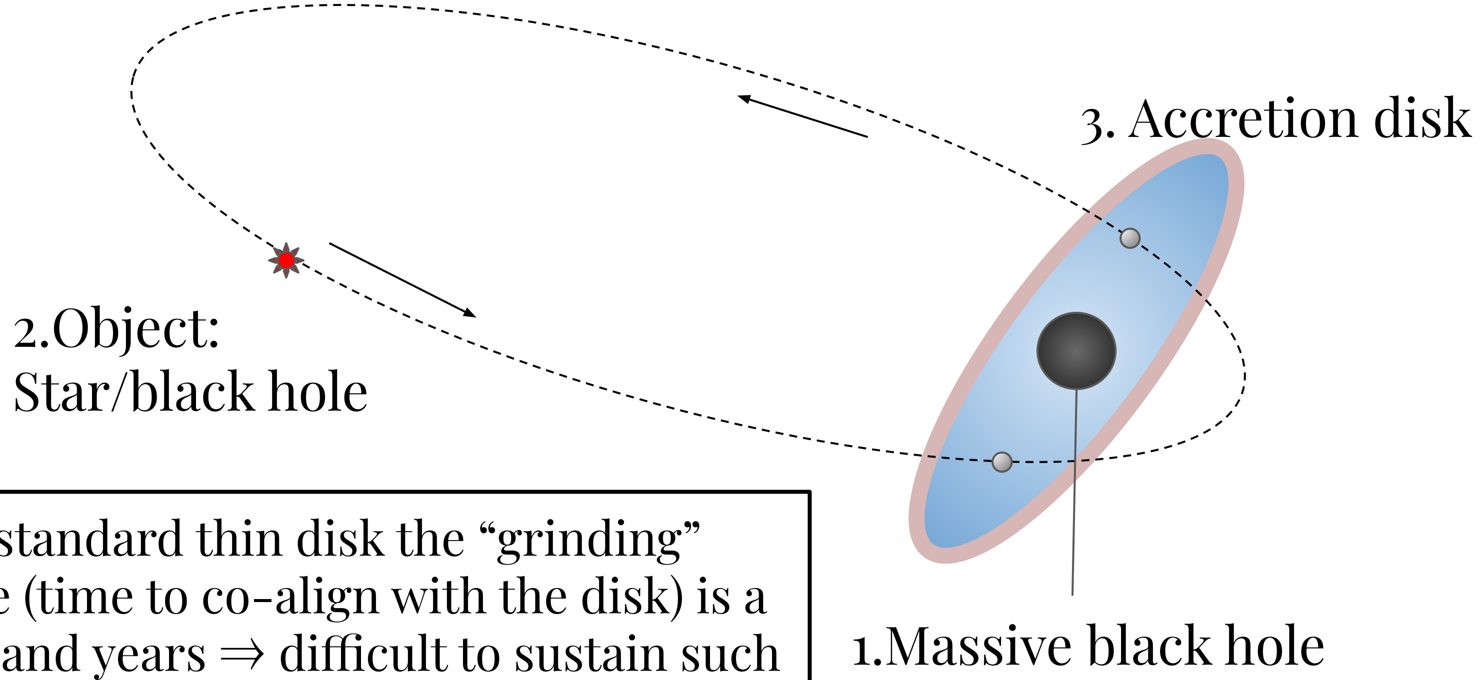
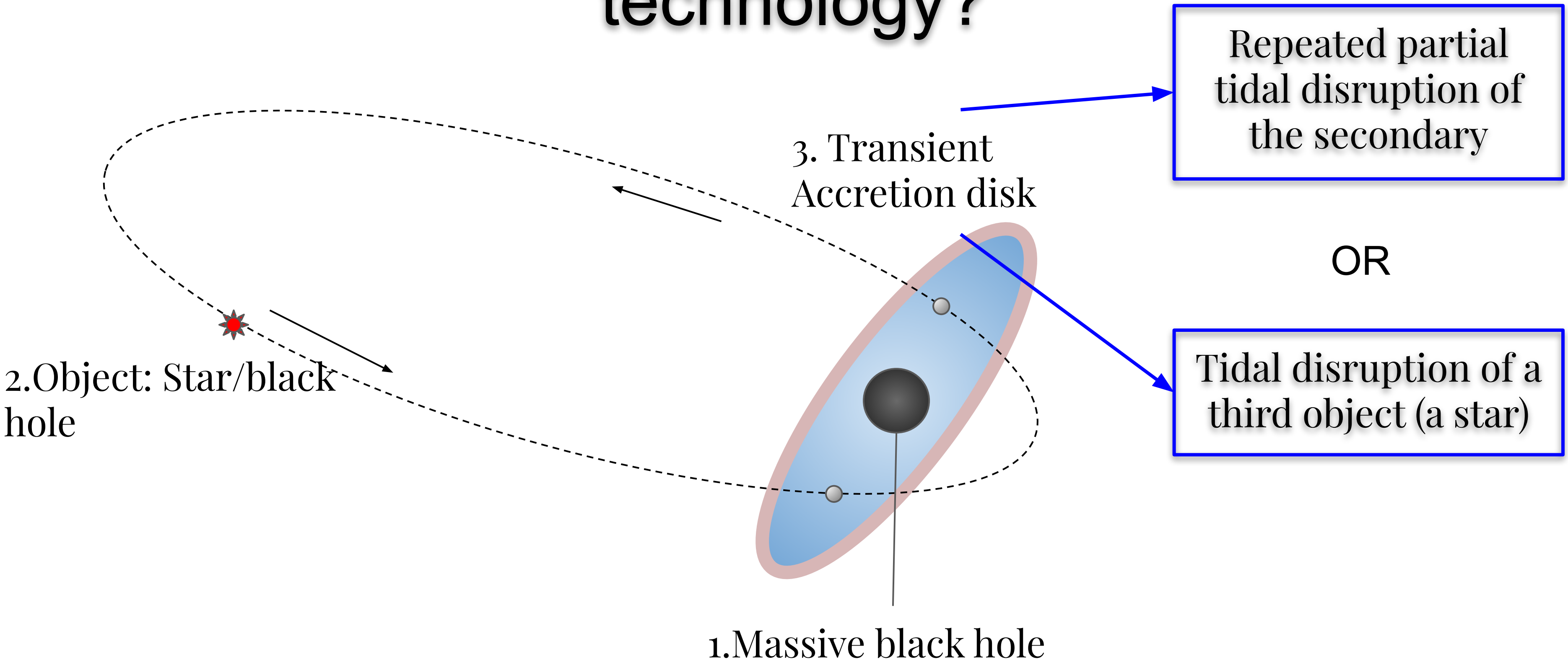


For a standard thin disk the "grinding" timescale (time to co-align with the disk) is a few thousand years ⇒ difficult to sustain such misaligned binaries with high-accretion AGN

Can we identify such binaries with the current technology?



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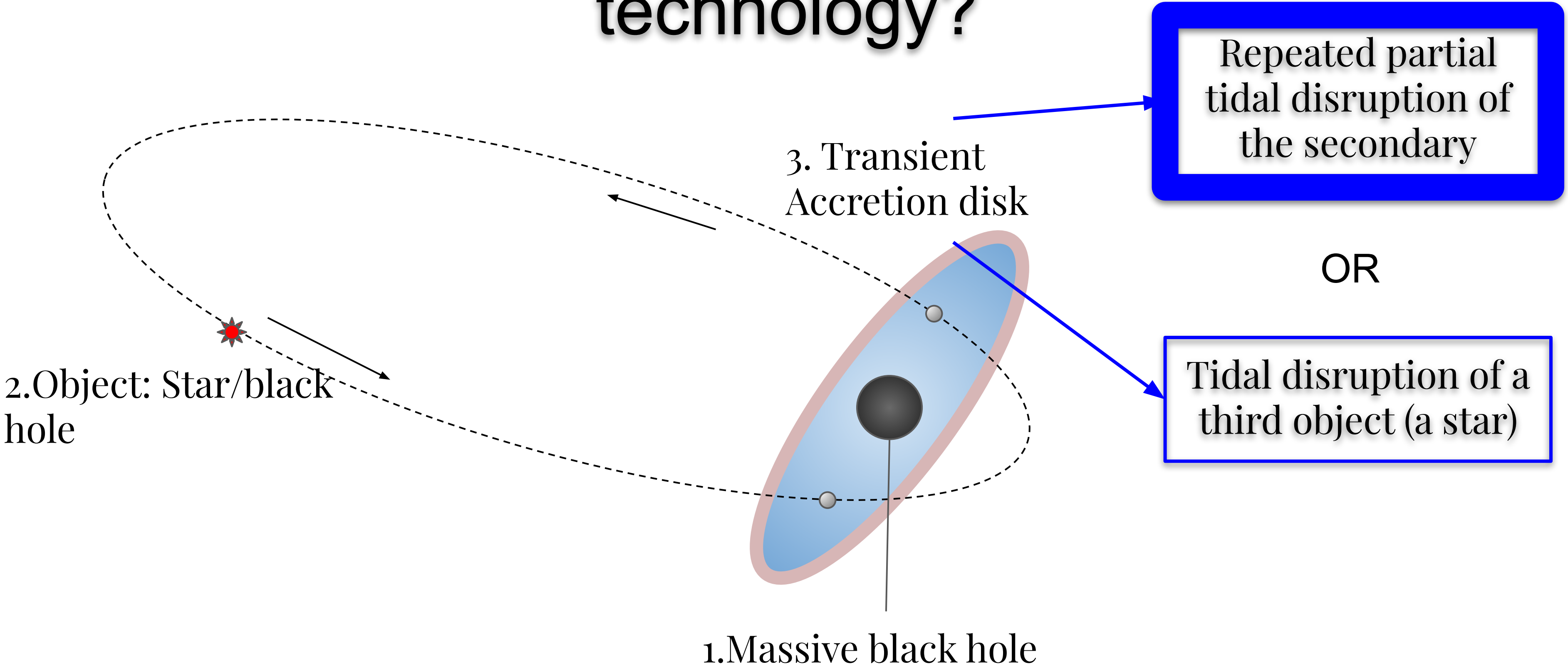
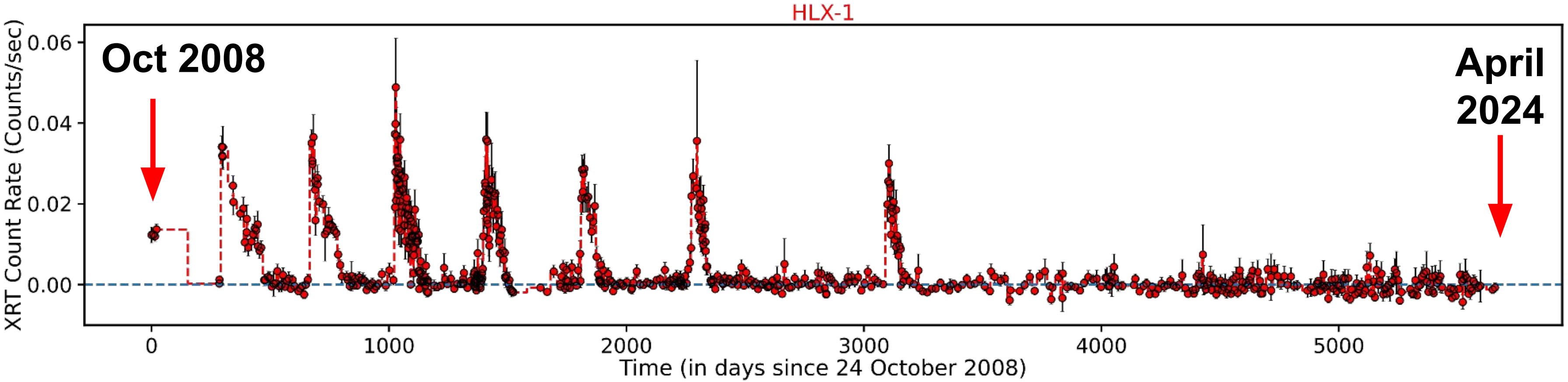


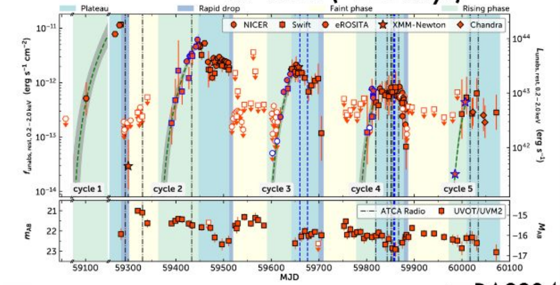
Swift has a Long Legacy of tracking HLX-1: candidate repeating partial TDE by an intermediate-mass black hole (monitoring since 2008)



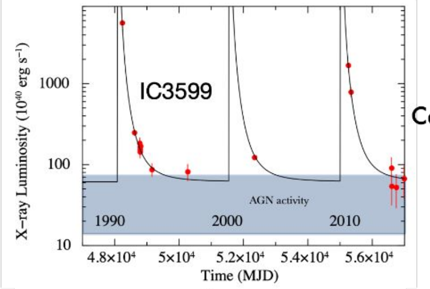
Lin et al. 2020, MNRAS; Servillat et al. 2015, ApJ; Farrell et al. 2008, Nature; Lasota et al. 2011, ApJ and many, many more

Modern optical surveys like ZTF and ASASSN have revived this field by enabling the discovery of repeating TDEs

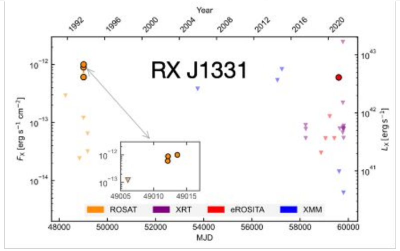
Liu+2023 (~220 days)

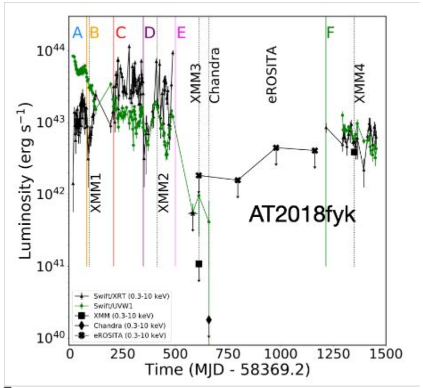


eRASS0456

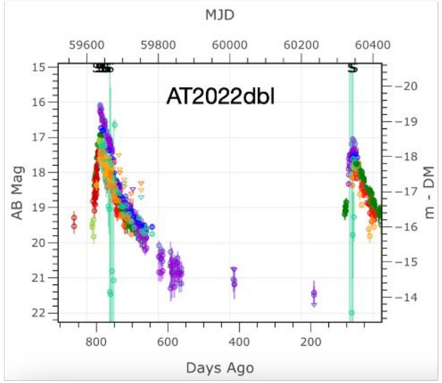


Campana+2015 (~9.5 yr)

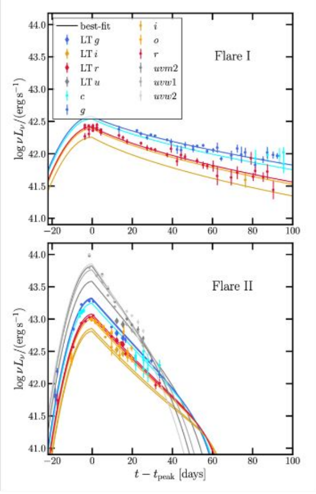




Wevers+2023 (~600 days)

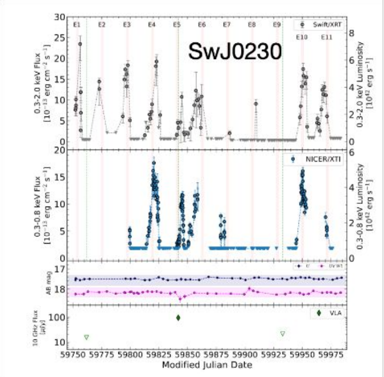


Yao+2024 (~700 days)

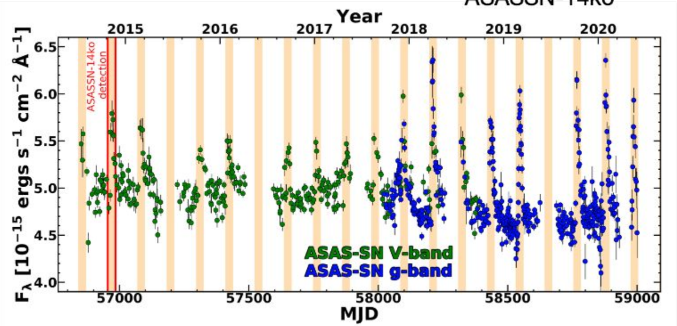


Somalwar+2023 (~900 days)

Guolo+2023, Evans+2023 (~22 days)

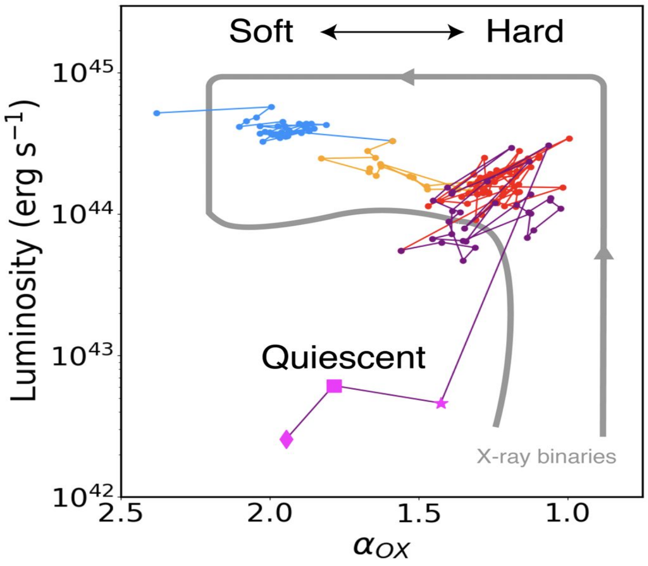


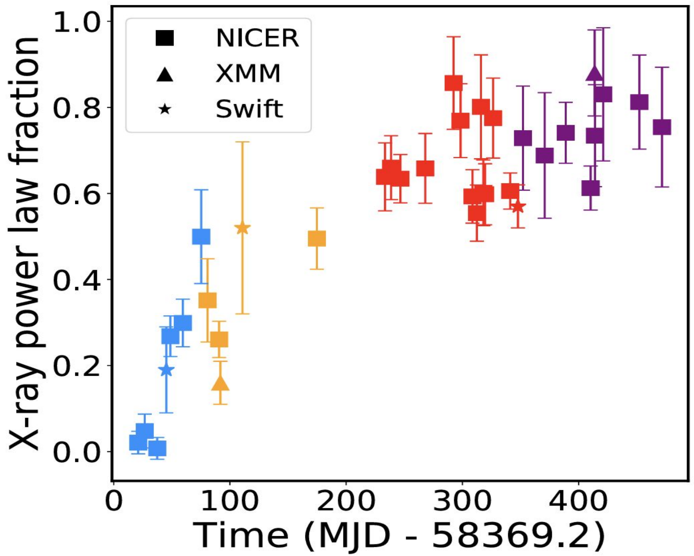
Payne+2021,2023 (~110 days)



Swift (X-ray + UV) enabled the discovery of accretion state transitions in an SMBH for the first time

Corona formation in real time

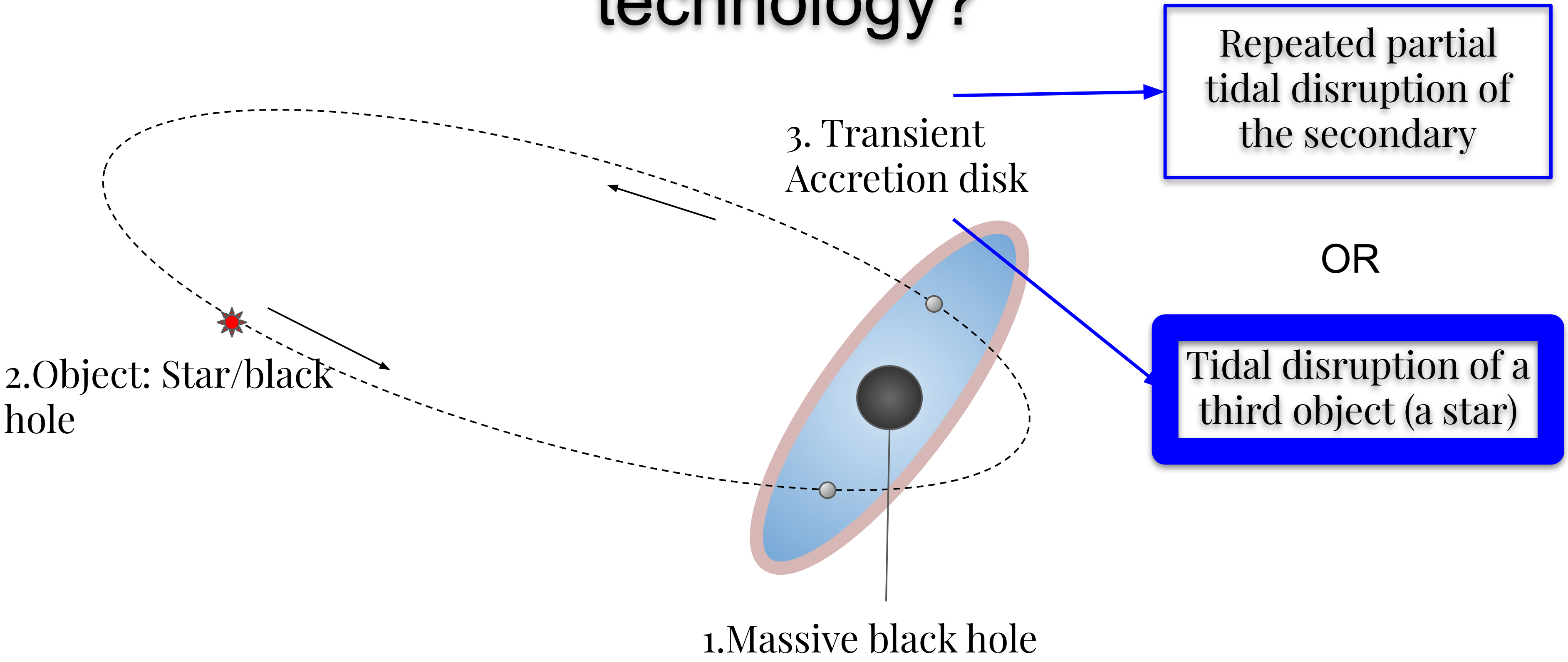




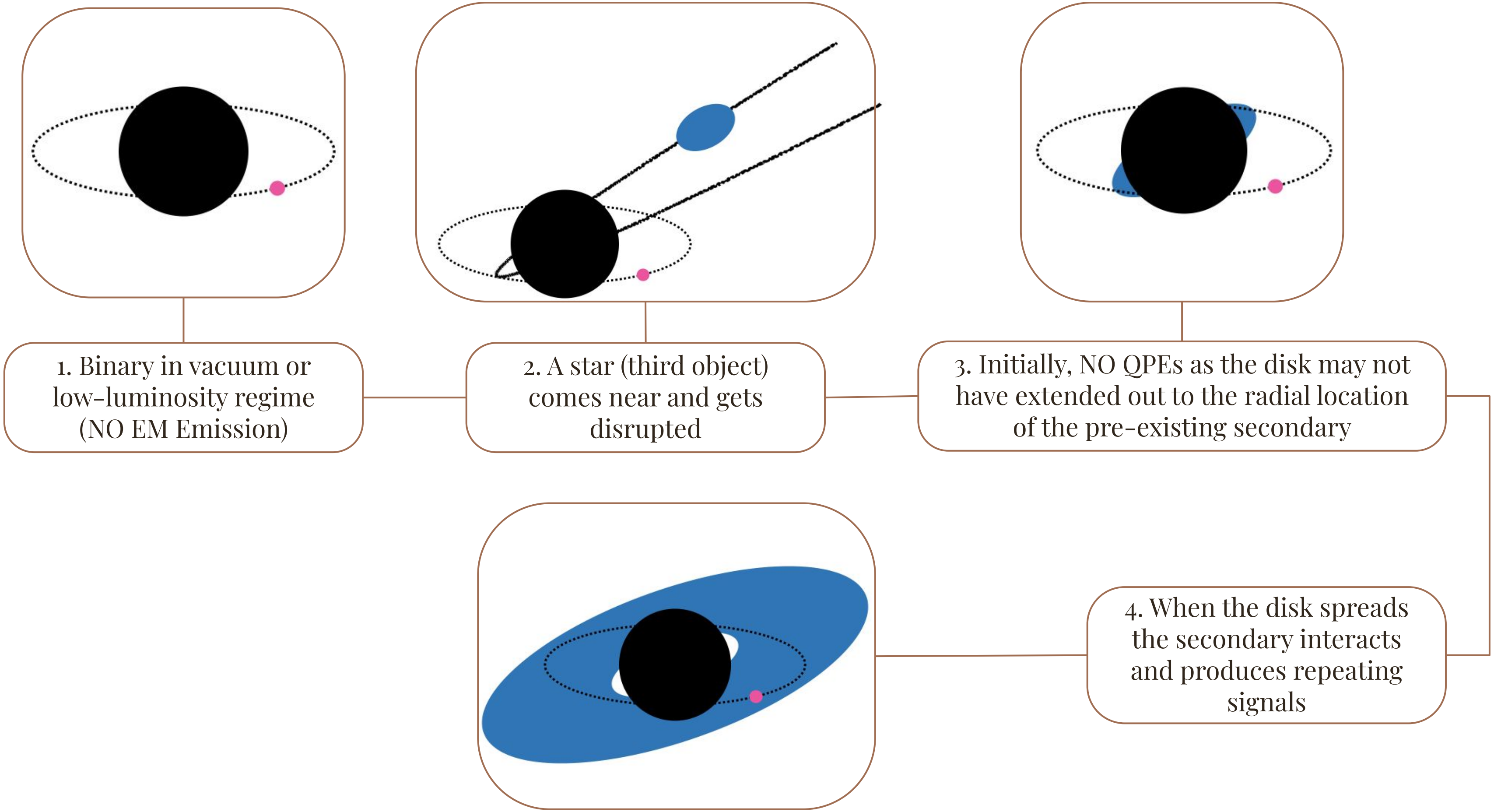
Wevers, Pasham et al. 2018, ApJ

Similar "repeated" accretion state transitions seen in eRASSt J045650.3 203750: Liu et al. 2018, A&A

Can we identify such binaries with the current technology?



How can we identify objects orbiting supermassive black holes?



Some fraction of TDEs should manifest as repeating nuclear transients if they have a pre-existing/orbiting object

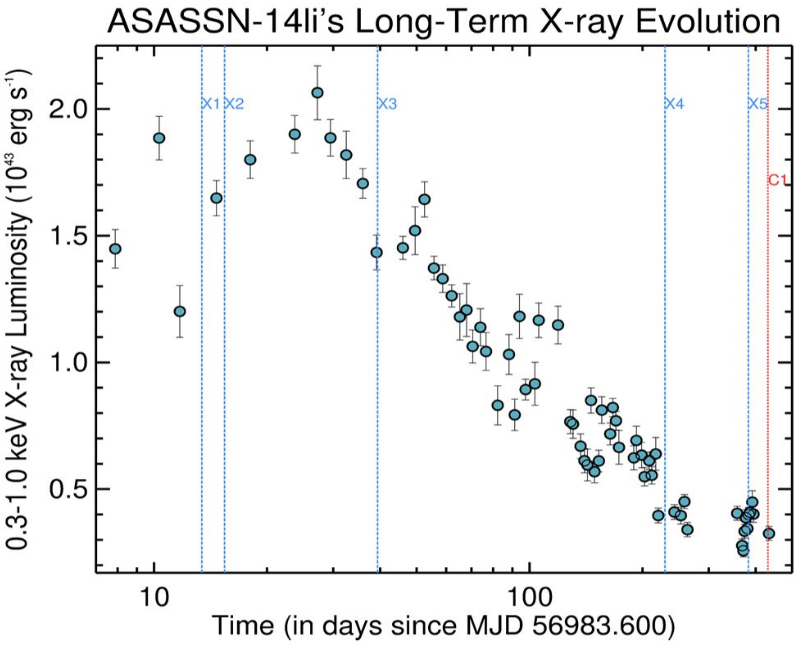
Three flavors of repeating extragalactic X-ray transients discovered in the last few years following TDEs

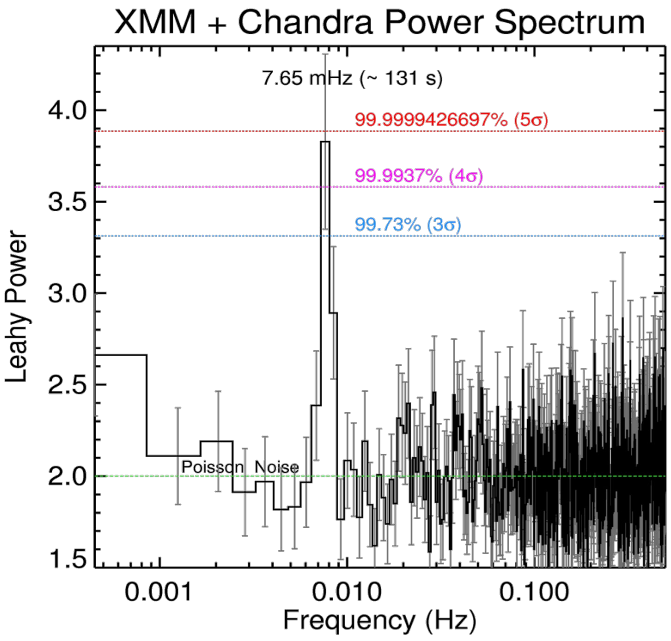
Quasi-Periodic ***Oscillations***

Quasi-Periodic ***Eruptions***

Quasi-Periodic ***Outflows***

1. Quasi-periodic oscillation from ASASSN-14li for 500+ days after the initial tidal disruption





Pasham et al., *Science*, 2019

Also, see Masterson et al. 2025, *Nature*, and Lin et al. 2013, *ApJ* for a 3.8 hour system, and Gierlinski et al. 2008, *Nature*

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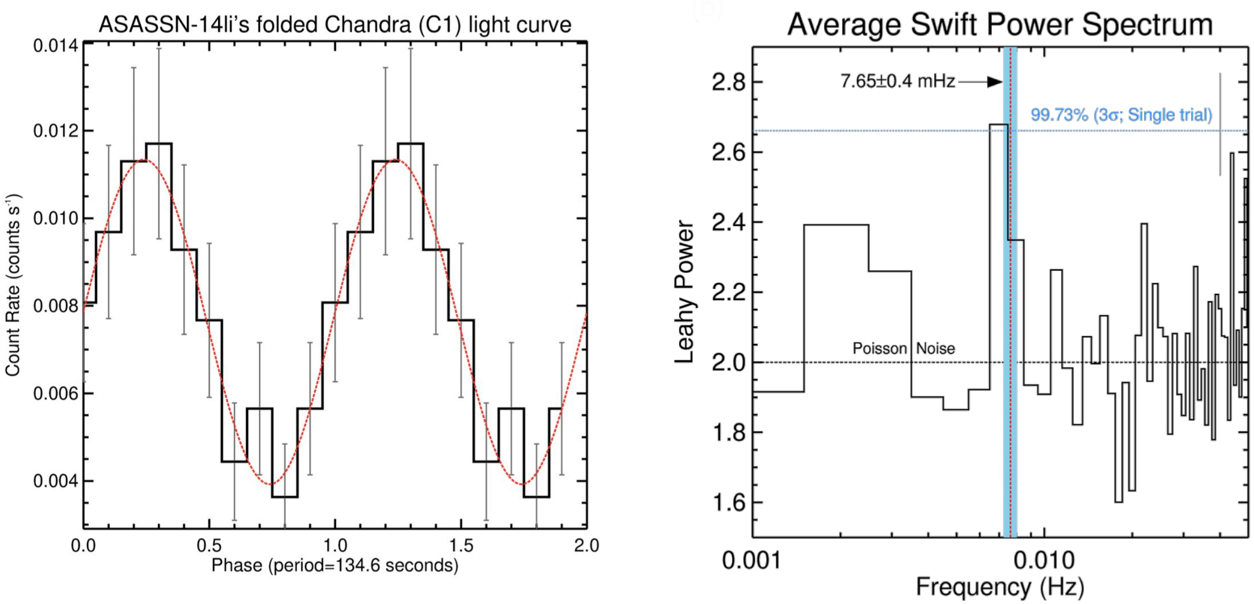


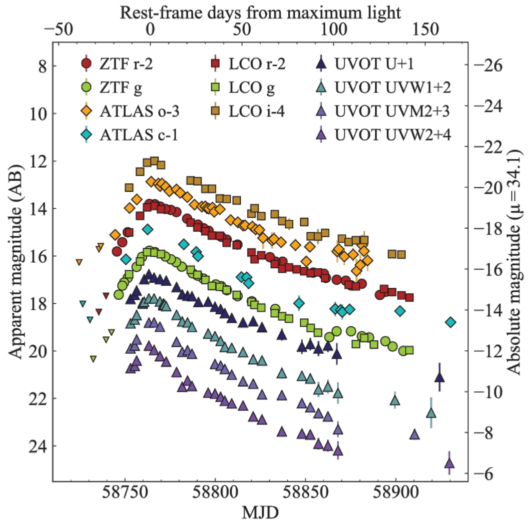
Swift/XRT provided an independent support for the QPO

Pasham et al., *Science*, 2019

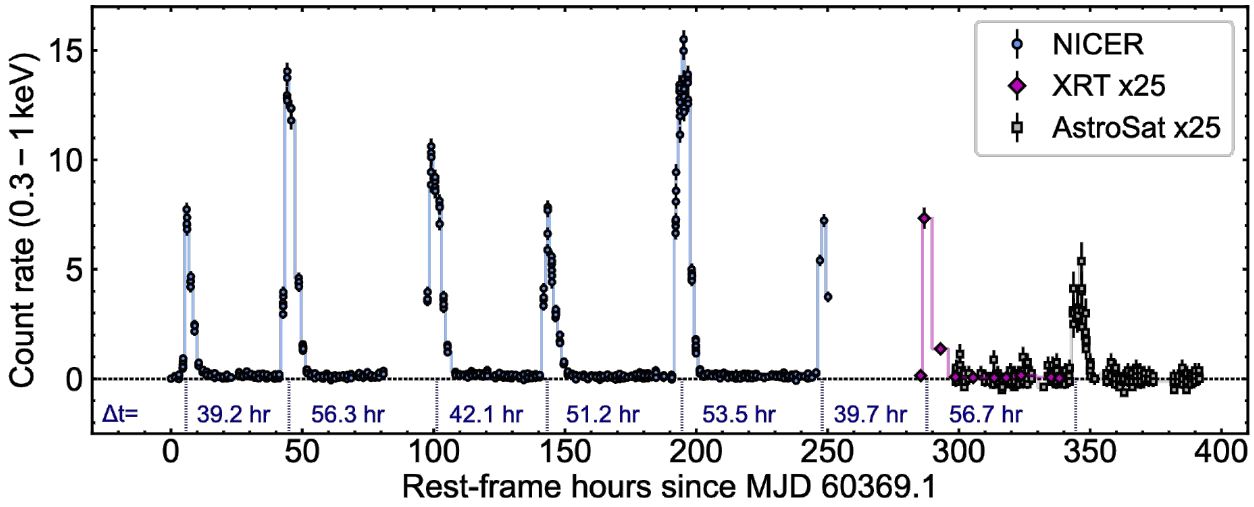
Also, see Masterson et al. 2025, *Nature*, and Lin et al. 2013, *ApJ* for a 3.8 hour system, and Gierlinski et al. 2008, *Nature*

2. Quasi-periodic eruptions 4+ years after a tidal disruption event

An example system showing X-ray *quasi-periodic eruptions* roughly once every 48 hours



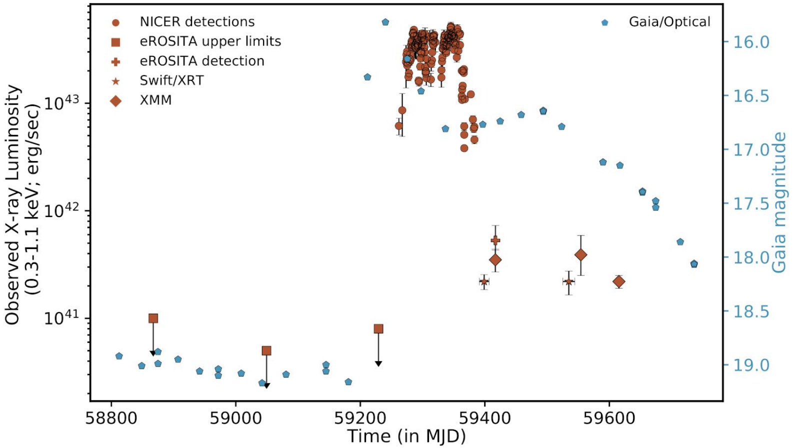
4+ years after the TDE



Nicholl, Pasham et al. 2024, *Nature*

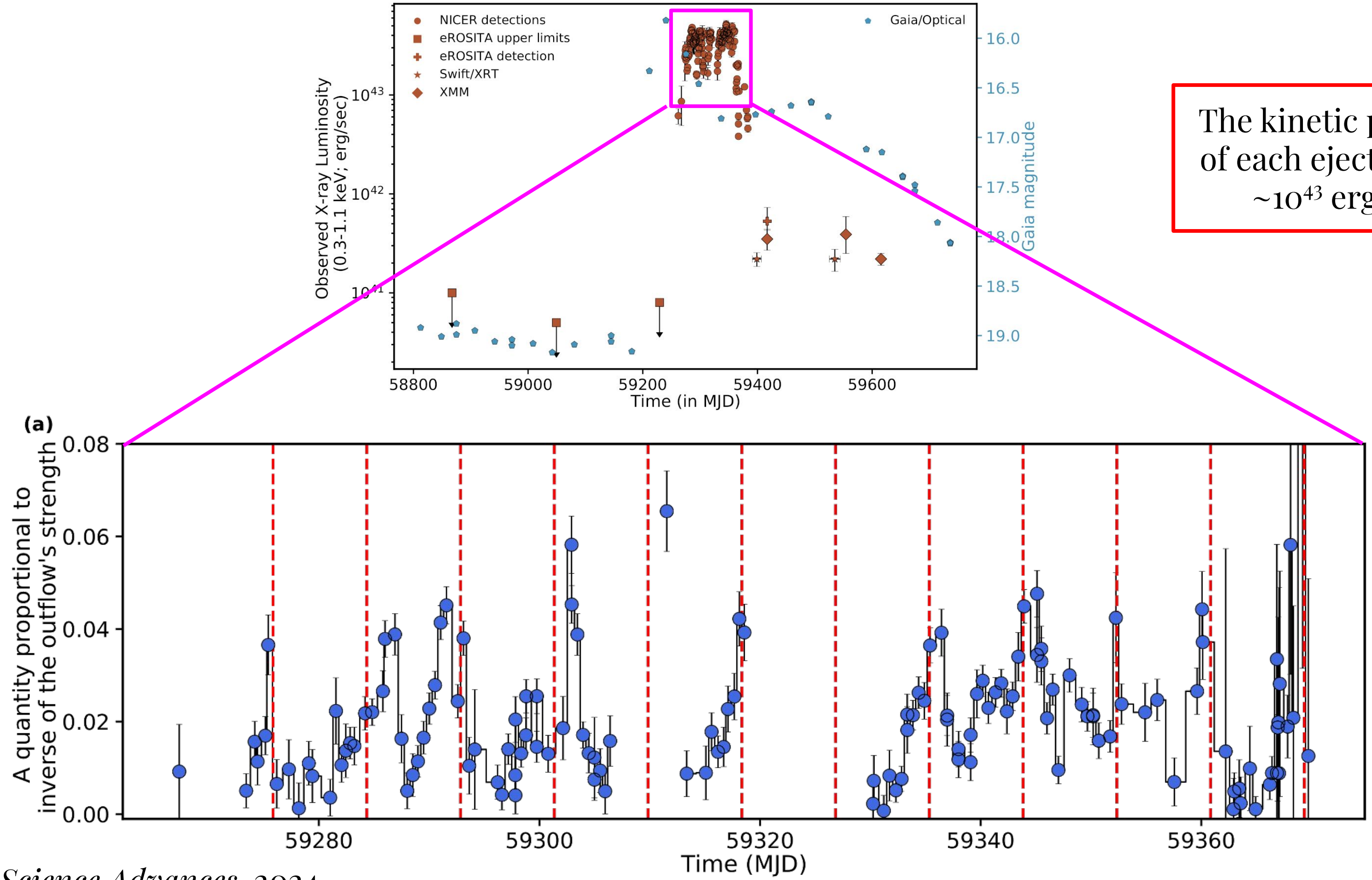
Also see, Bykov et al. 2024, arXiv:2409.16908v1; Miniutti et al. 2019, Nature; A&A 2021; Giustini et al. 2019, A&A; Arcodia et al. 2021, *Nature,*; and many more

3. Quasi-periodic outflows a few months after a tidal disruption event



Pasham et al., *Science Advances*, 2024

3. Quasi-periodic outflows a few months after a tidal disruption event



The kinetic power of each ejection is ~10^{43} erg/s

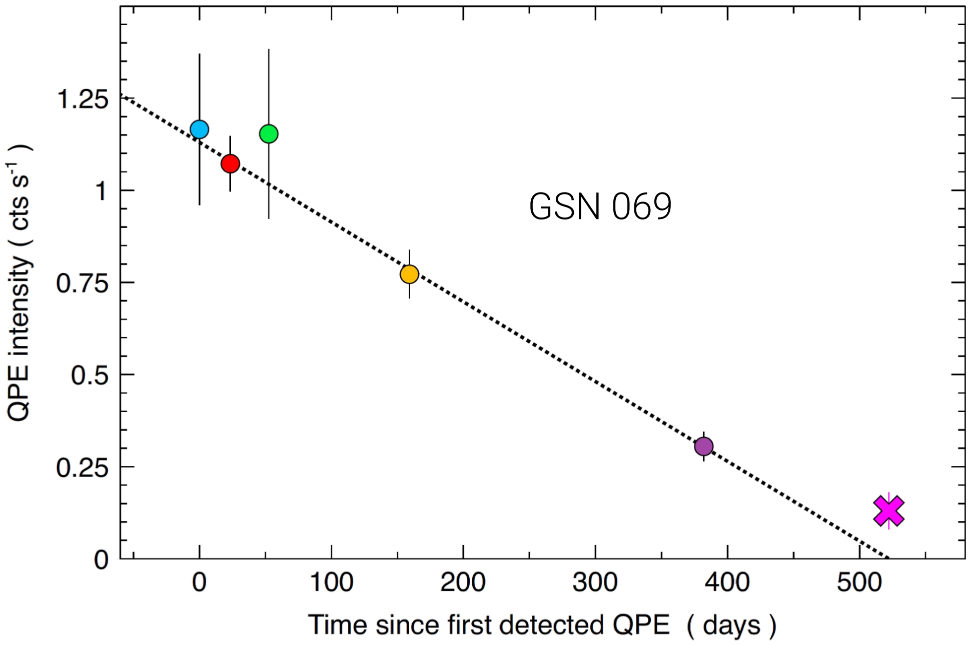
Pasham et al., *Science Advances*, 2024

Some fraction of TDEs show these repeated soft X-ray signals (QPOs/QPEs/QPOuts) some time after the initial disruption

If these repeating signals are from repeated interactions of an object with the TDE disk, shouldn’t you expect the strength of these signals to go down with time as the TDE disk fizzles out?

Long-term evolution of QPEs

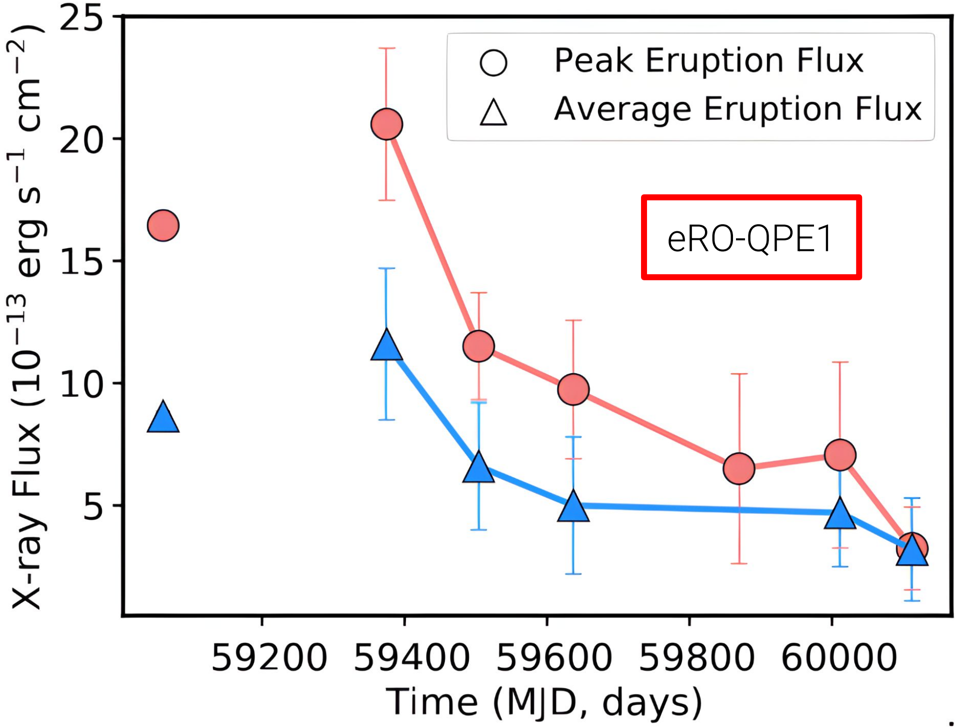
Strength of eruptions



Miniutti et al. 2023, A&A, 674, L1

Long-Term evolution suggests limited lifespan (~ a few years)

Strength of eruptions



Pasham et al. 2024, ApJL

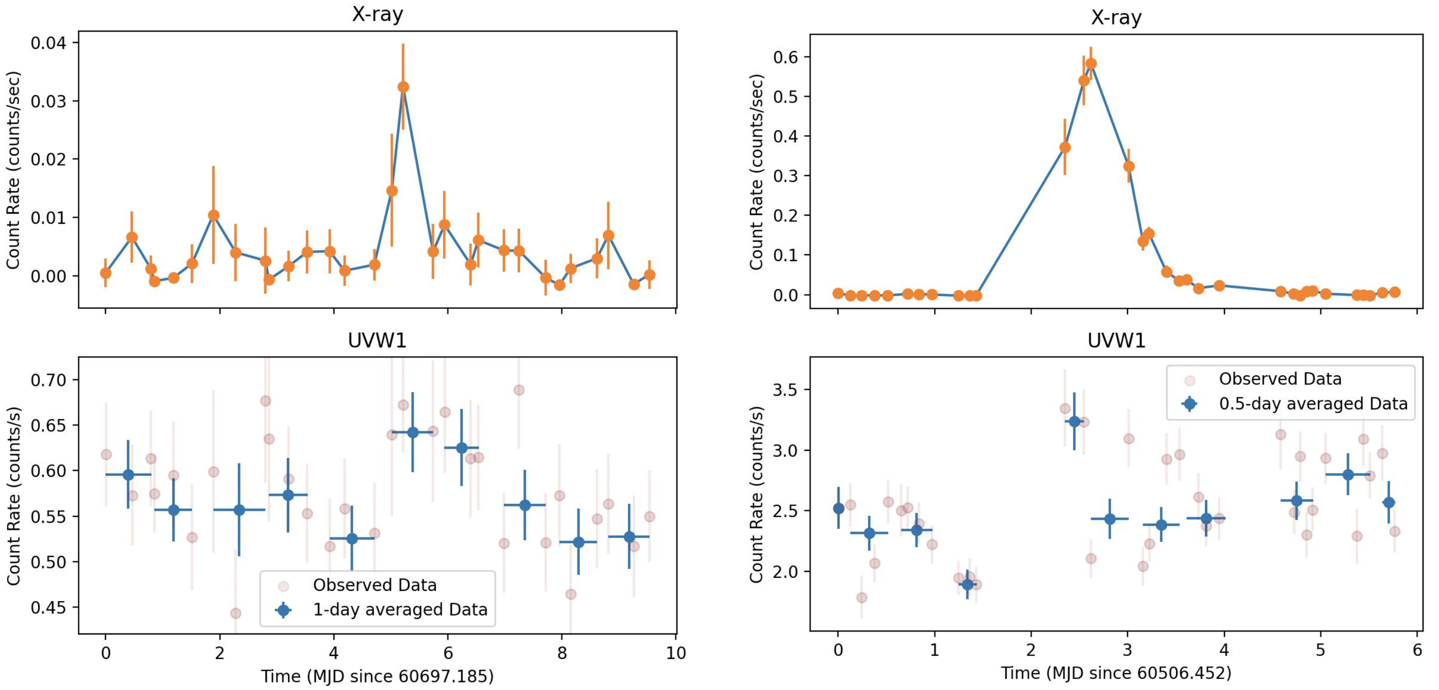
Swift performed repeated high-cadence observations over years

What about counterparts at non X-ray wavelengths?

What about counterparts at non X-ray wavelengths?

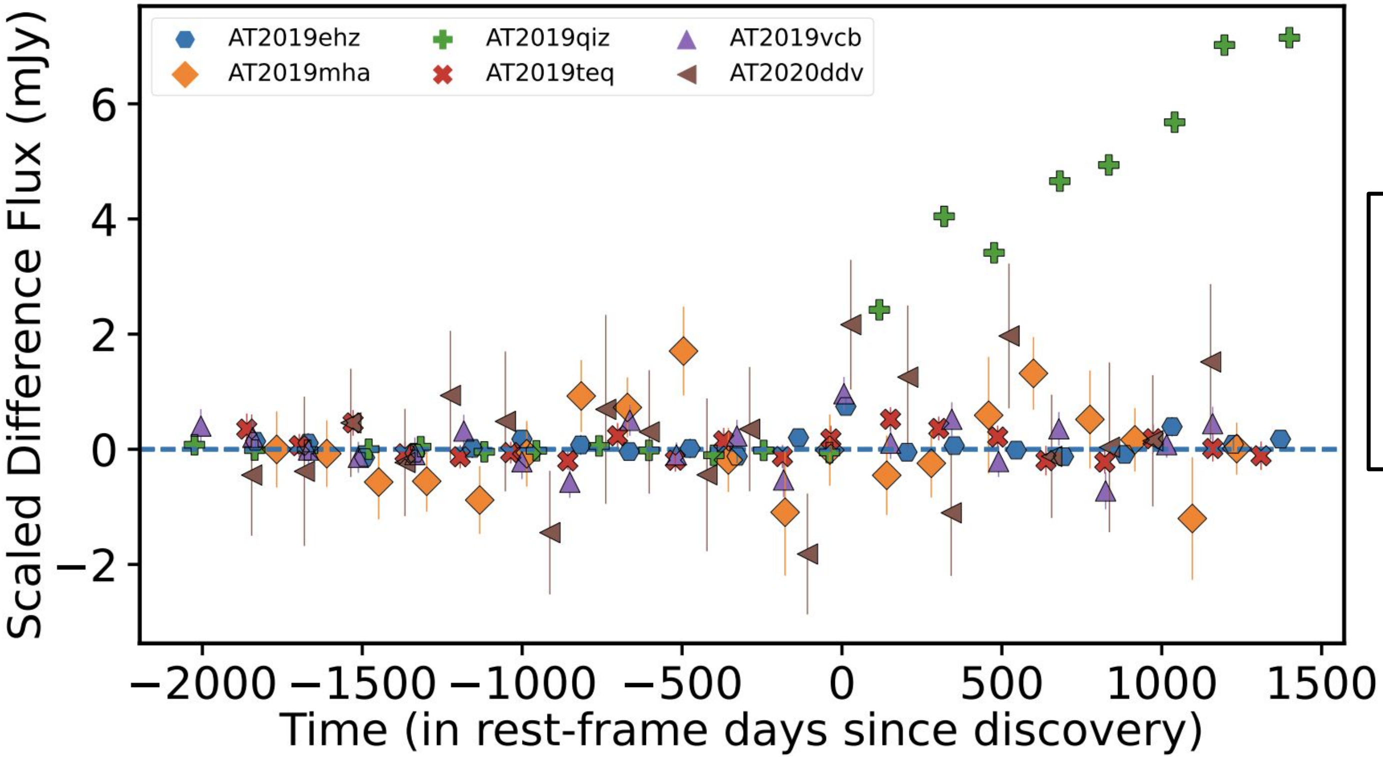
Limited (at present) … but

Preliminary results from high-cadence Swift XRT+UVOT observations of a few QPE sources



Maybe at the cusp of UV detectability? Perhaps ULTRASAT could find more through a systematic search (independent of X-rays)

Rising InfraRed Echoes to identify *bright* quasi-periodic eruptions

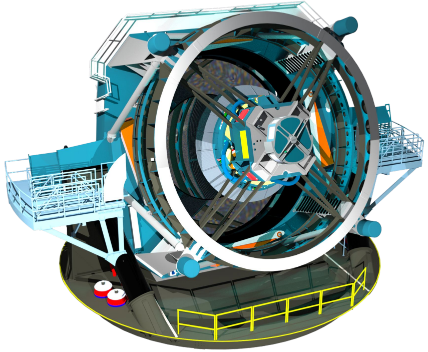


QPEs can continuously heat up the dust and produce a rising IR echo

Pasham, Coughlin et al. ApJ Letters (under review)

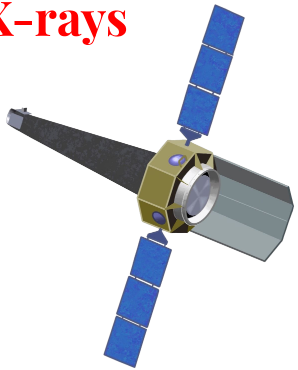
Rubin – Roman – (X-ray observatory) synergy can result in a burgeoning industry of repeating extragalactic transients

Optical



Infrared

X-rays



1000s of TDEs

tens of QPE candidates

A manageable number for X-ray telescopes

By no means is the binary model the ONLY solution

Accretion disk instabilities may explain it but some known types are disfavored

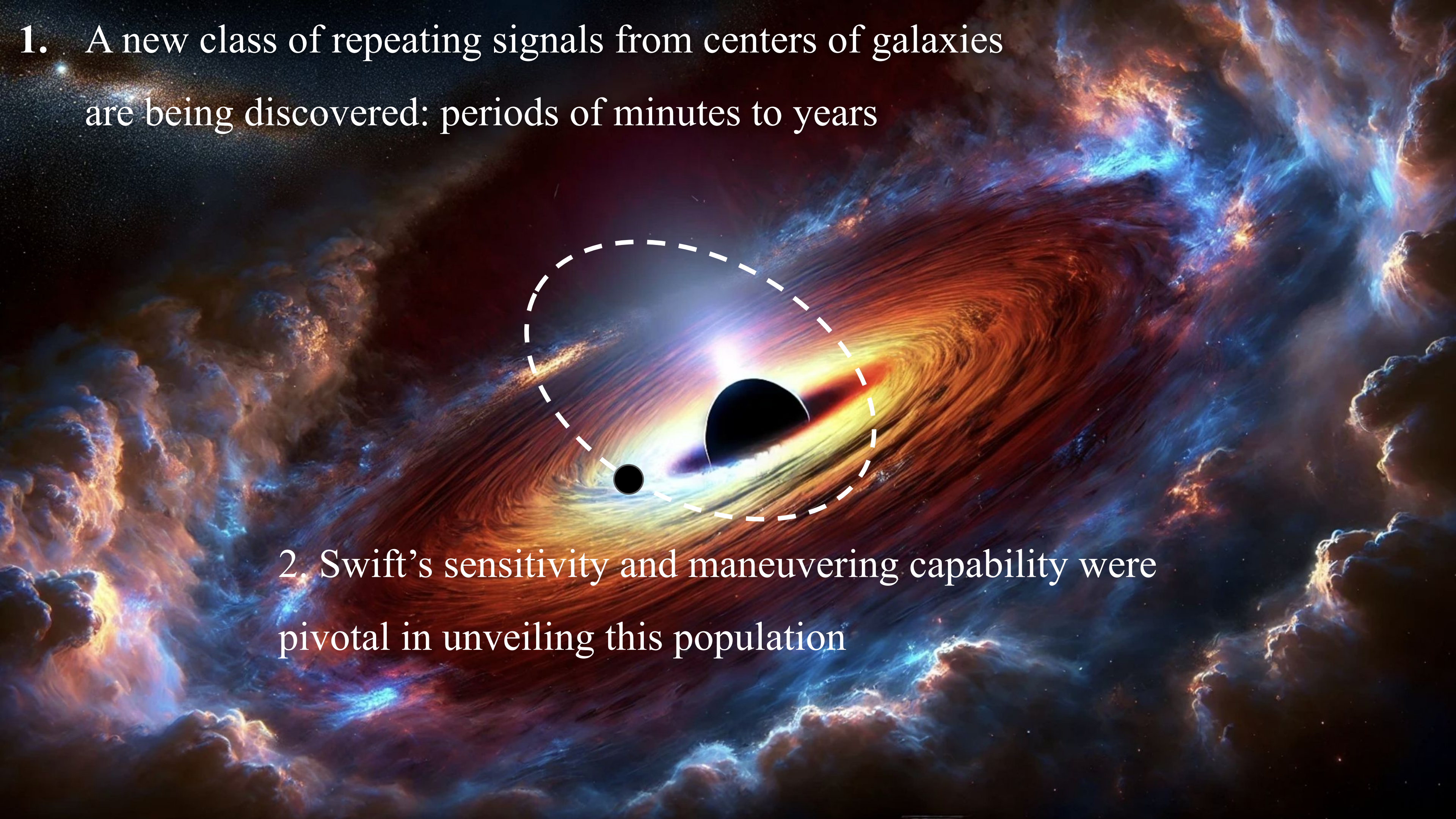
Current Models for Repeating X-ray signals:

Inner disk instabilities

- Radiation pressure instability (e.g., Śniegowska et al. 2023, AA, 672,19)
- Inner disk instability (Pan et al. 2022, ApJ, 928,18)
- Oscillating inner shock instability (Sukova et al. 2017, MNRAS, 472, 4)
- Disk tearing instability (e.g., Raj and Nixon 2021, ApJ, 909, 82)
- Precession of super-Eddington flows (Middleton et al. 2025, MNRAS)

Orbiting objects

- SMBH disk + object interactions: Xian et al. 2021, ApJ, 921, 32; Krolik & Linial 2022, ApJ, 941, 24; Linial & Metzger 2023, arxiv: 2302.16231; Lu & Quataert arXiv:2210.08023 + many more
- Intermediate-mass black hole + white dwarf: repeated partial tidal disruption events: e.g., King 2022, MNRAS, 515, 4344
- Multiple extreme mass ratio inspirals: e.g., Metzger, Stone, Gilbaum 2022, ApJ, 924, 35
- SMBH binary self-lensing: e.g., Ingram et al. 2021, MNRAS, 503, 1703


1. A new class of repeating signals from centers of galaxies are being discovered: periods of minutes to years
2. Swift’s sensitivity and maneuvering capability were pivotal in unveiling this population