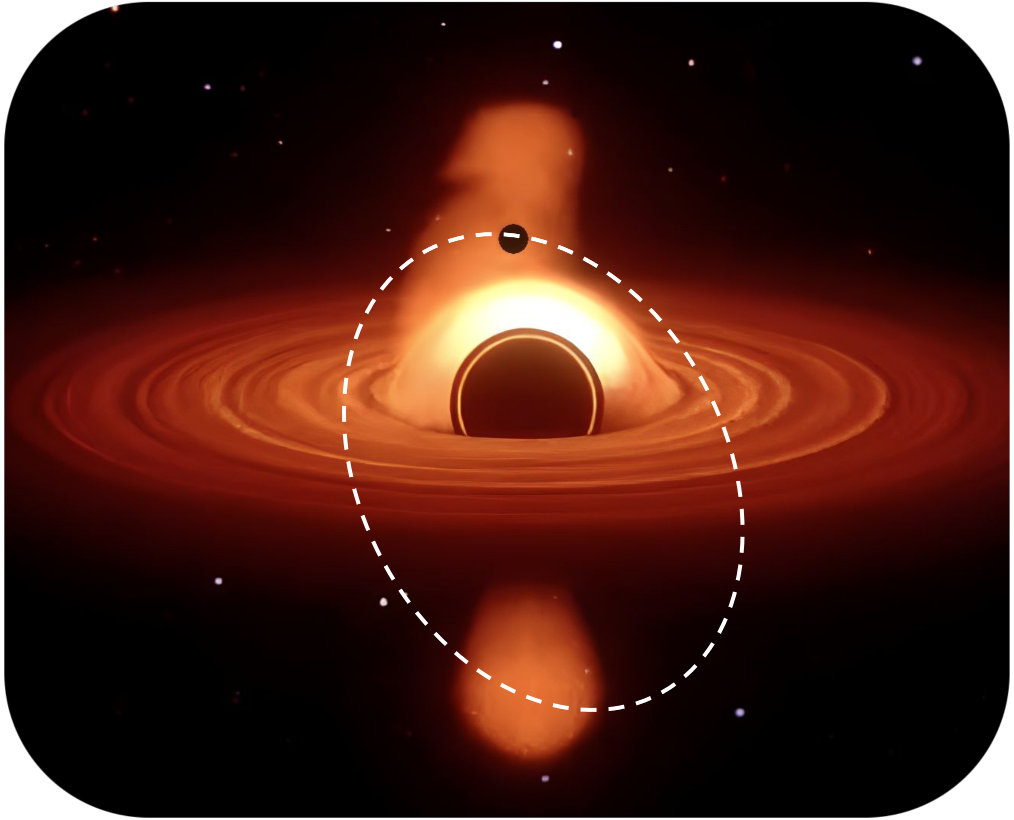
Mysterious Repeating Signals from Centers of nearby Galaxies as *Potential* Extreme Mass Ratio Binaries

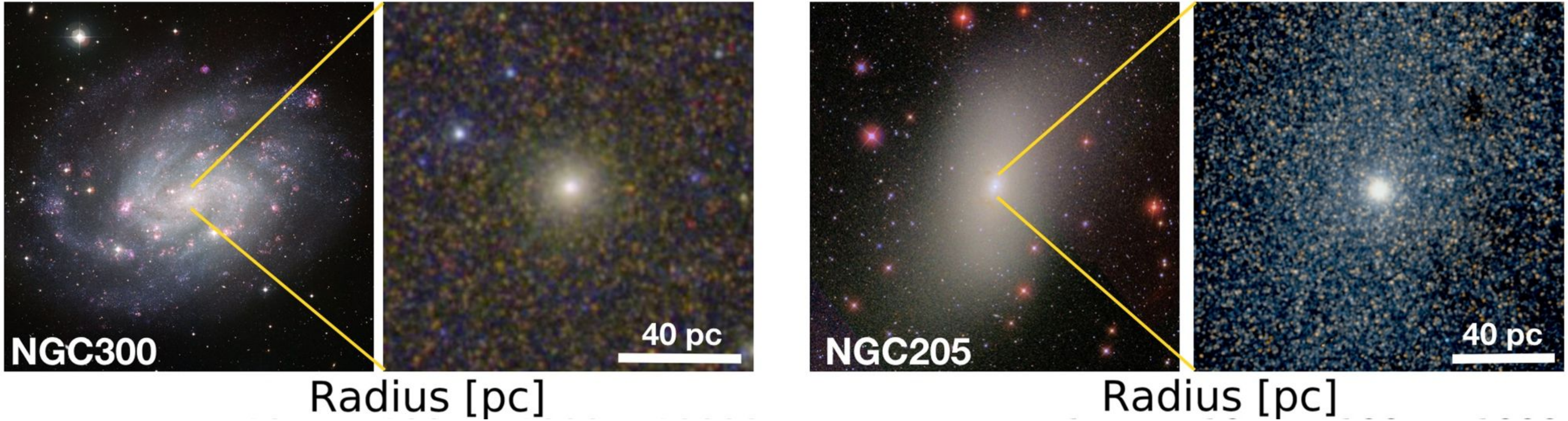
Dheeraj R. Pasham (MIT)

Nicholl, Pasham et al. 2024, *Nature*, arXiv:2409.02181

Matt Nicholl, Petra Sukova, Vladimir Karas, Michal Zajacek, Muryel Guolo, Thomas Wevers, Eric Coughlin, Francesco Tombesi, Vojtech Witzany ……



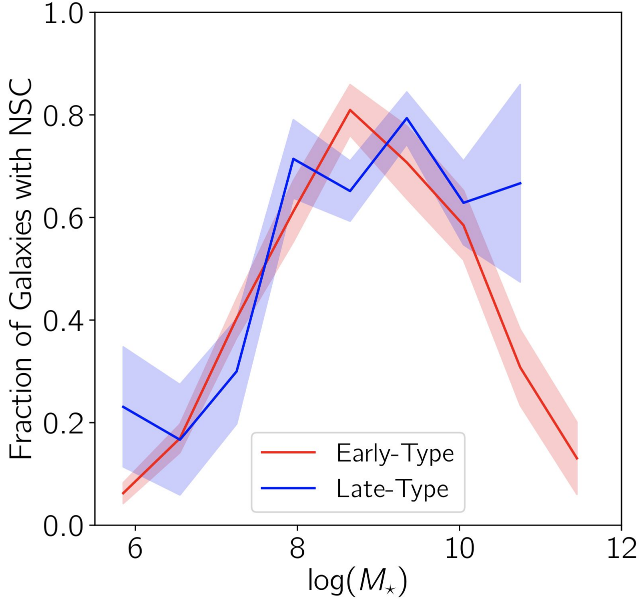
Galaxies contain supermassive black holes and dense nuclear star clusters



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

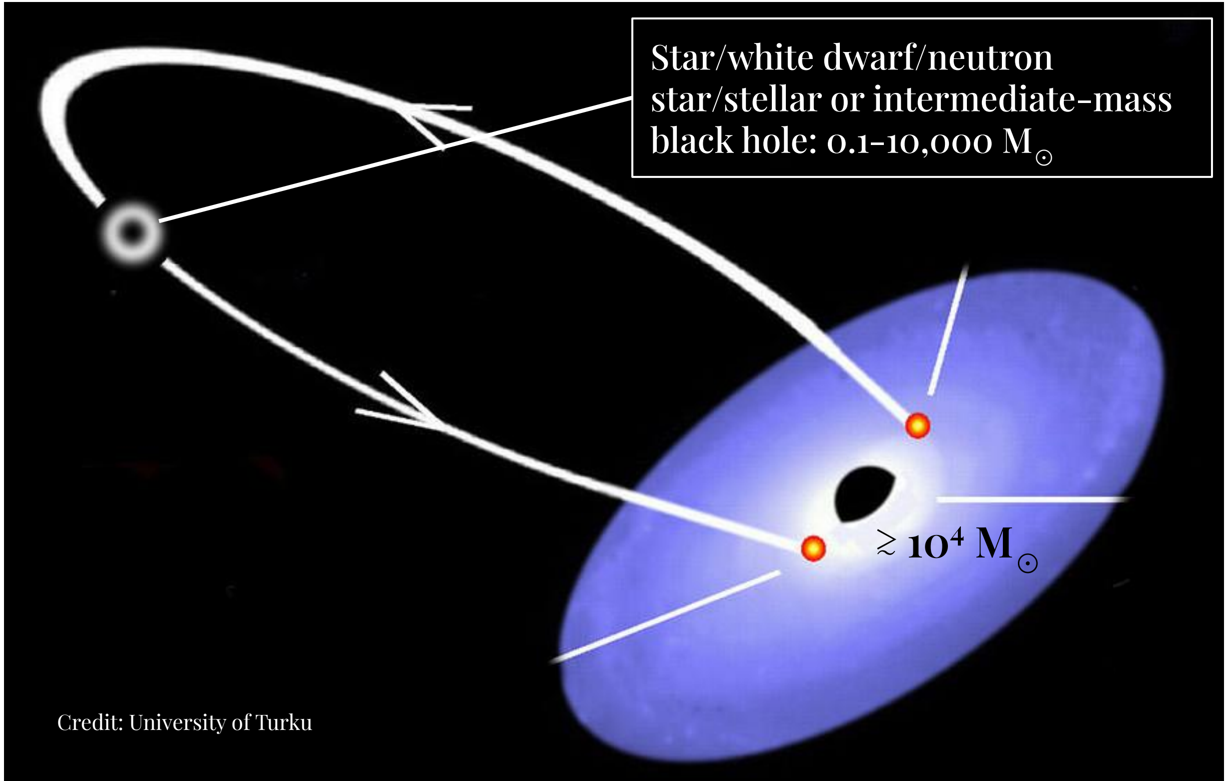


>60% of galaxies in this mass range contain nuclear star clusters

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



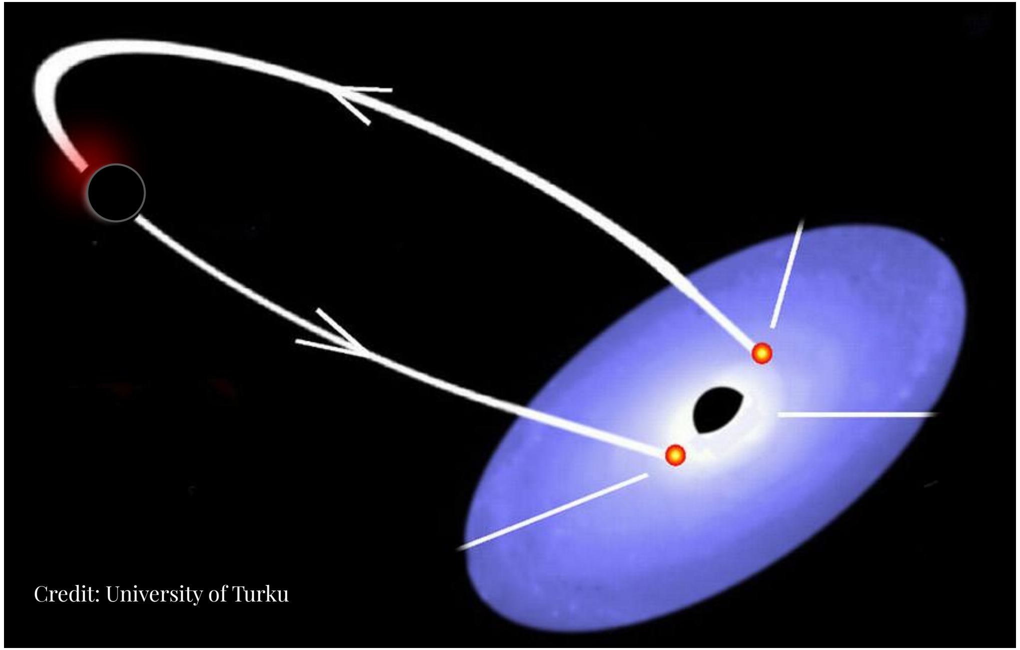
Credit: University of Turku

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:


Credit: University of Turku

- 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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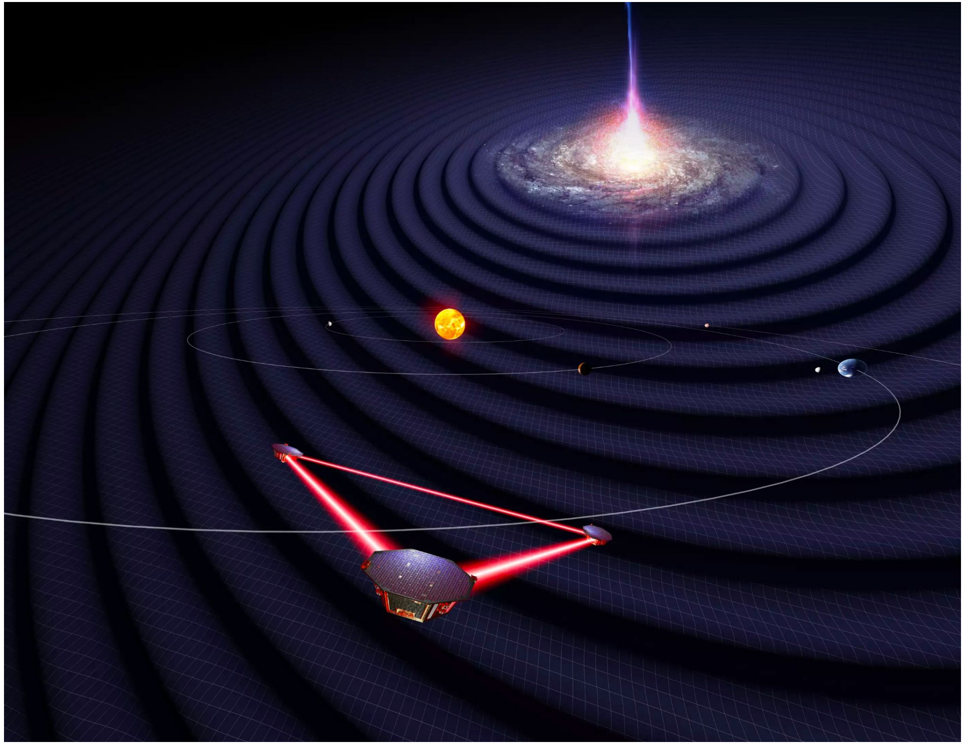

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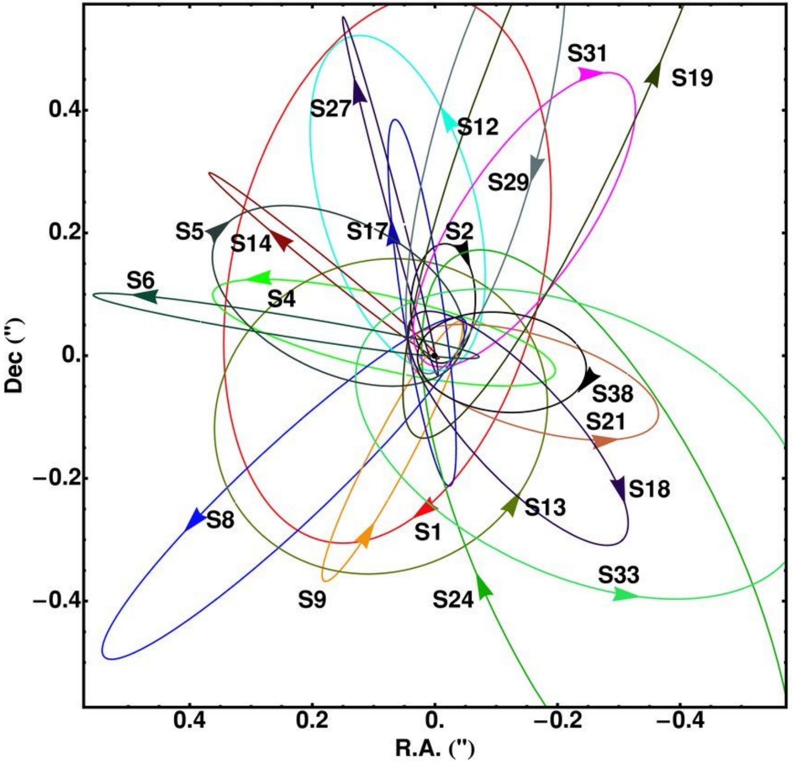
Extreme Mass Ratio Binaries

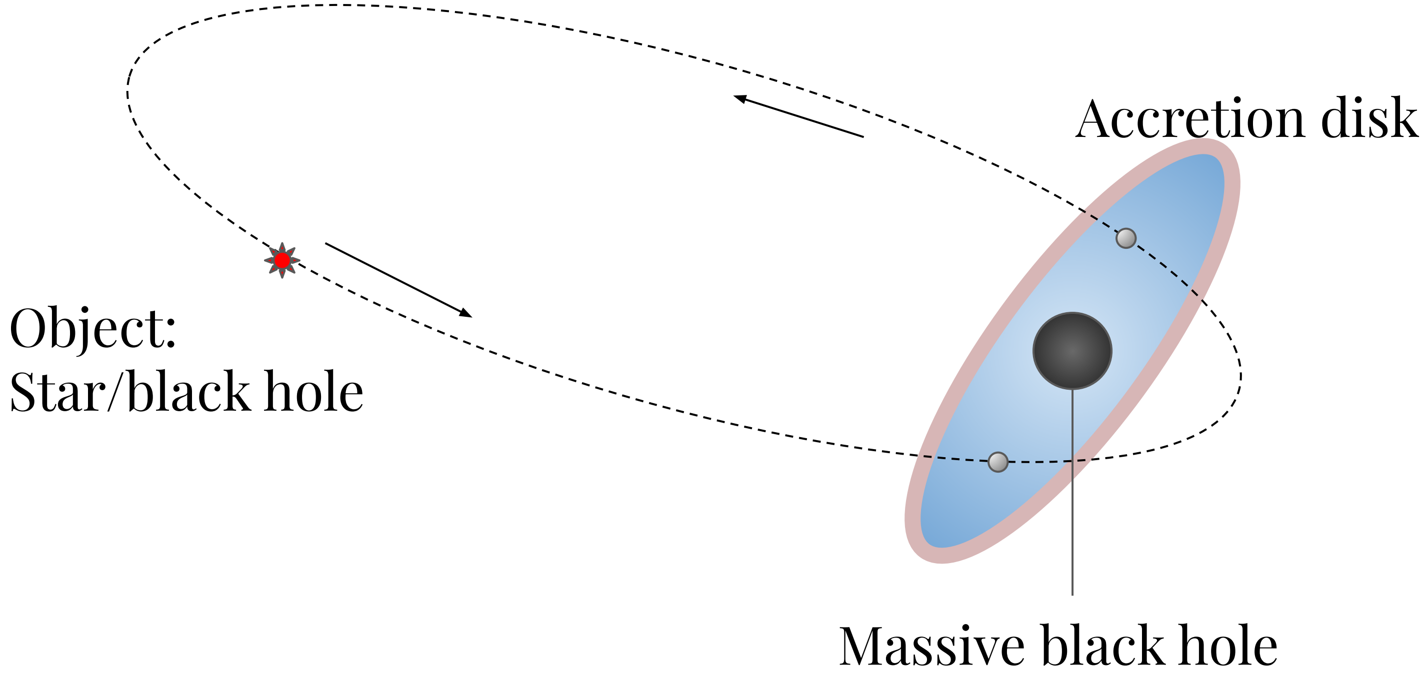
If the companion is a star:



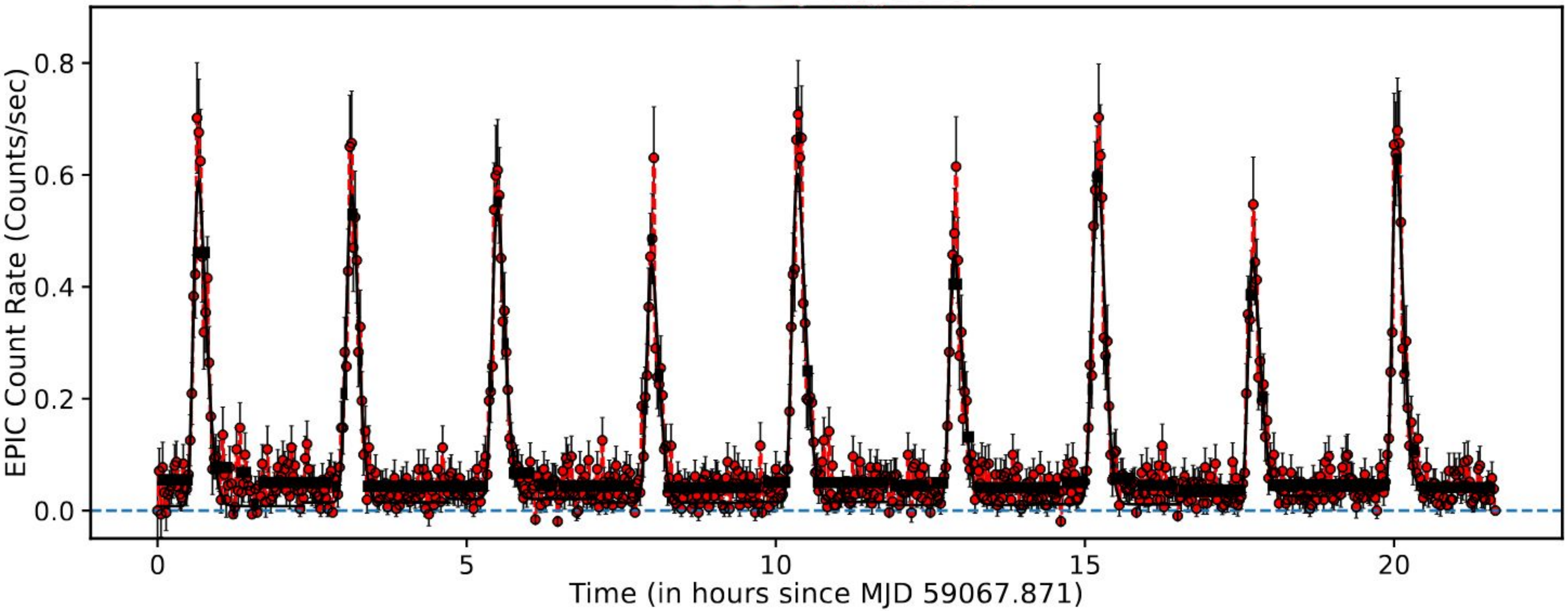
Unprecedented way of tracing test particle orbits around supermassive black hole in external galaxies (many more orbits than possible from S0 stars near Sgr A*)

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?



Quasi-Periodic Eruptions: Mysterious (almost) regular bursts of X-rays



Also see Miniutti et al. 2019, 2023; Arcodia et al. 2021, 2024 A&A; Pasham et al. 2024a …

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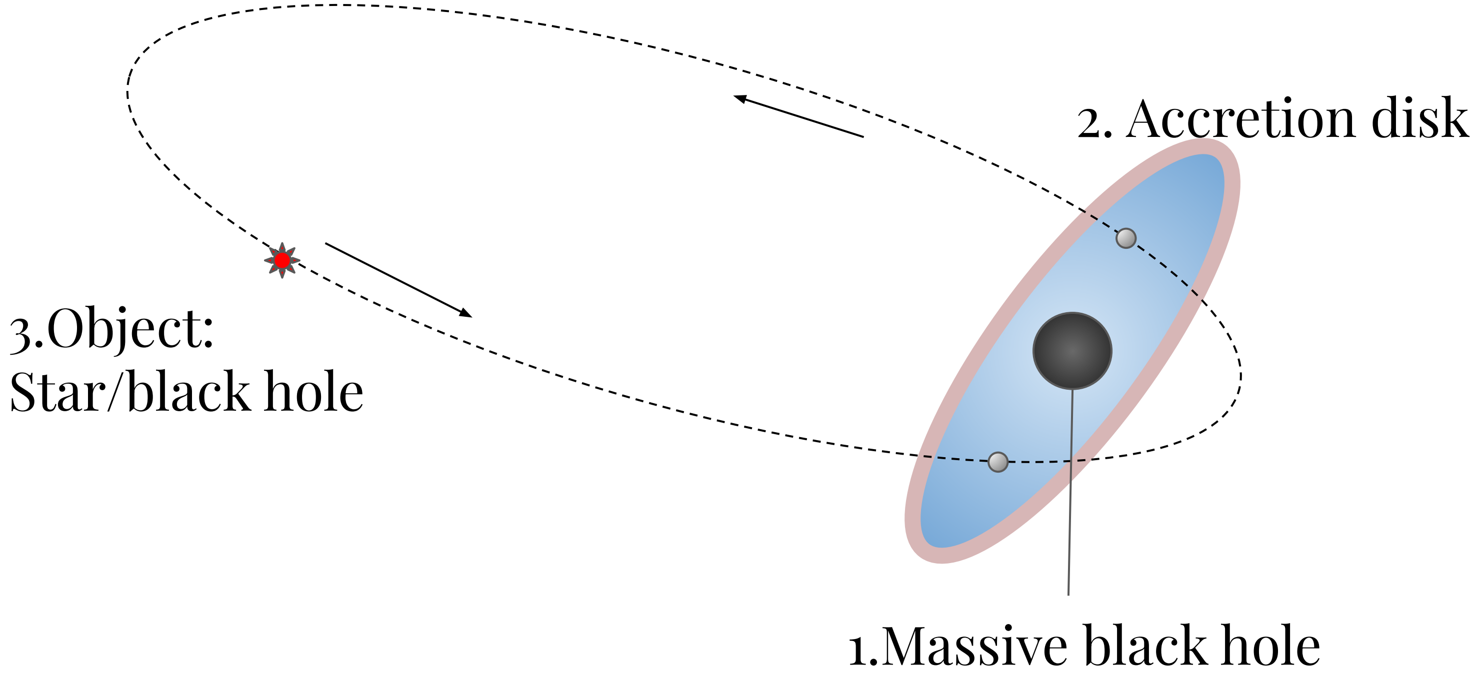

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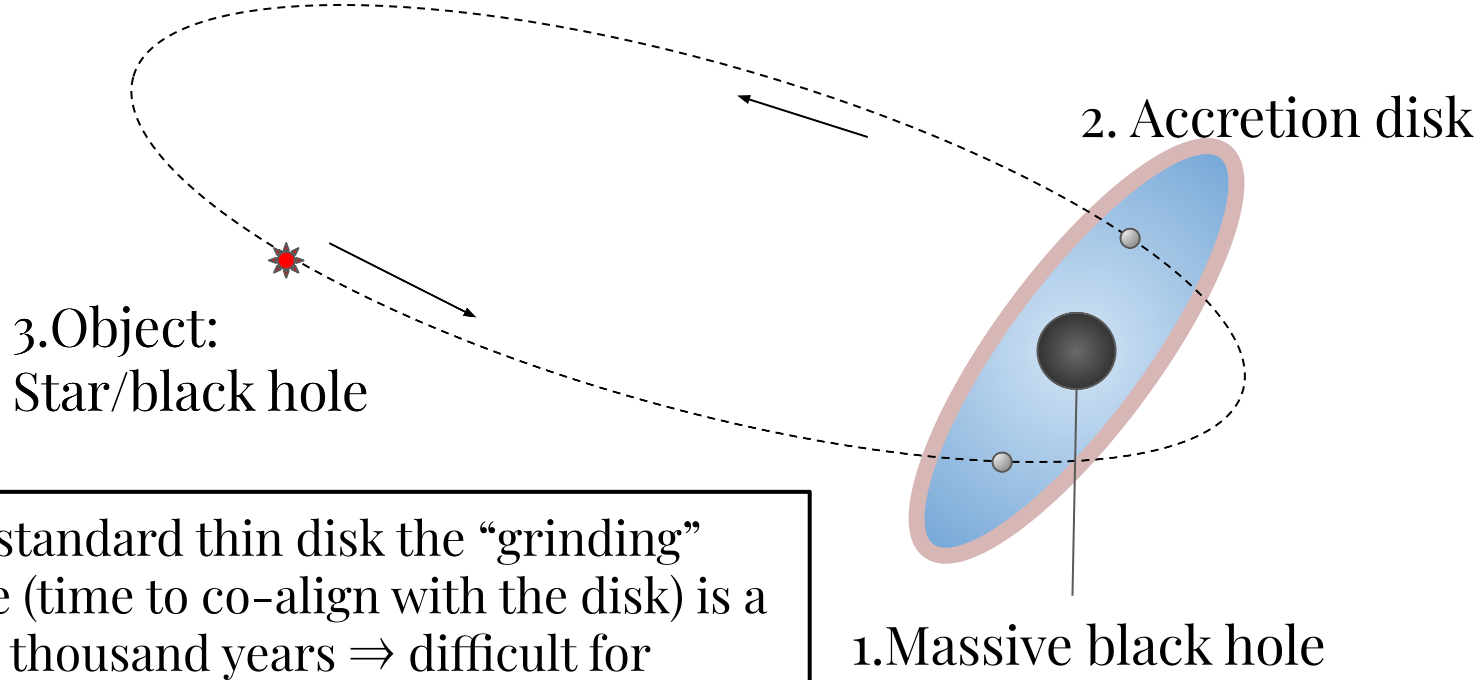

For a standard thin disk the “grinding” timescale (time to co-align with the disk) is a few thousand years $\Rightarrow$ difficult for high-accretion AGN

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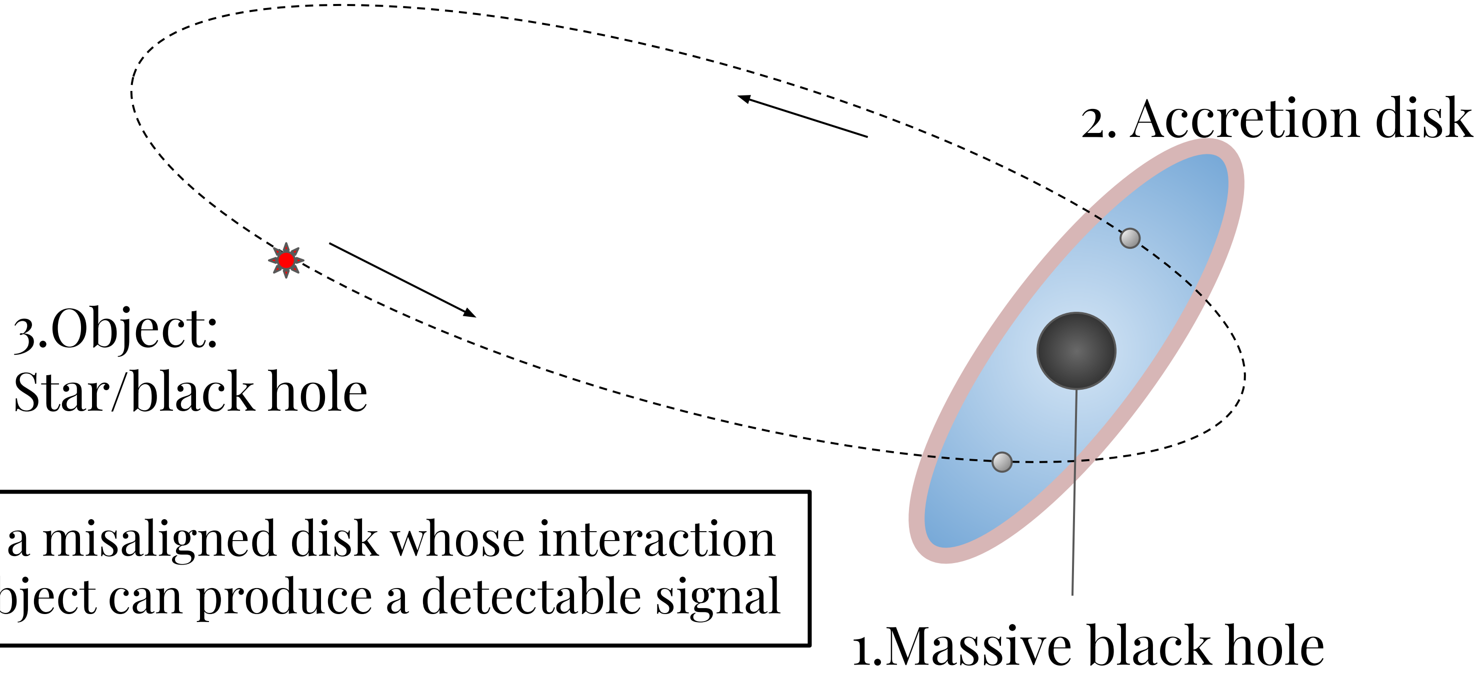
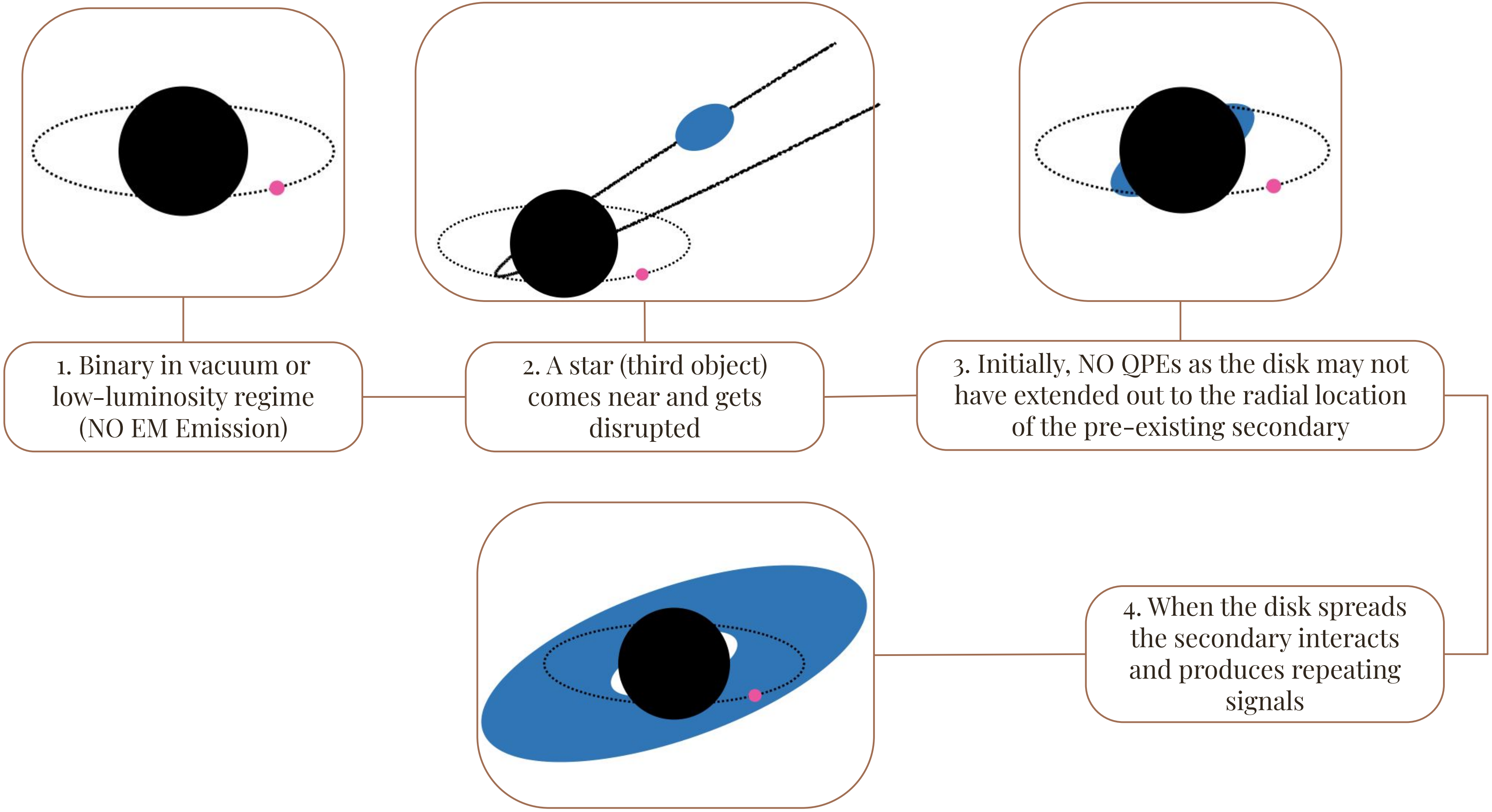


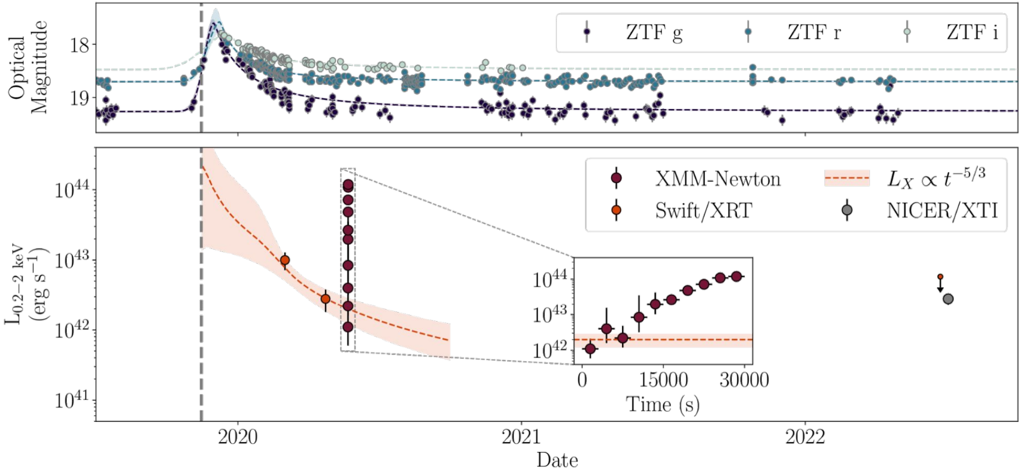
You need a misaligned disk whose interaction with an object can produce a detectable signal

How can we identify objects orbiting supermassive black holes?

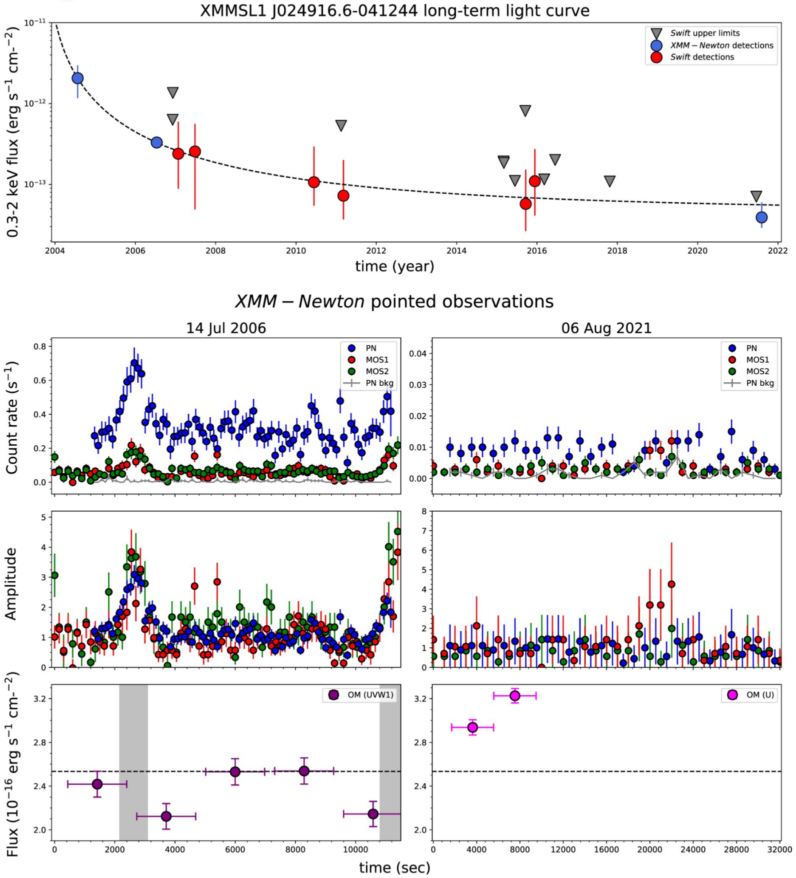


Optical TDE AT2019vcb and XMMSLJ0249 showed *"hints"* of X-ray eruptions

Half a eruption in X-rays from AT2019vcb



Quintin et al. 2023, A&A



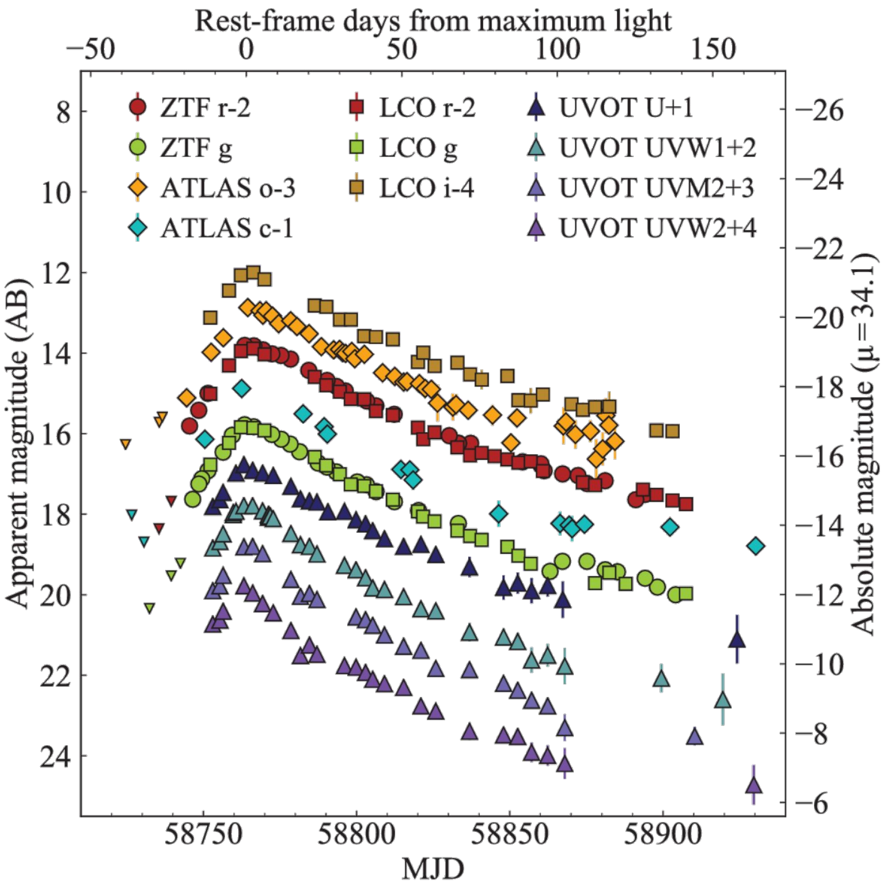
Chakraborty et al. 2021, ApJL

Unambiguous QPEs following a Tidal Disruption event (TDE) have never been seen before .....

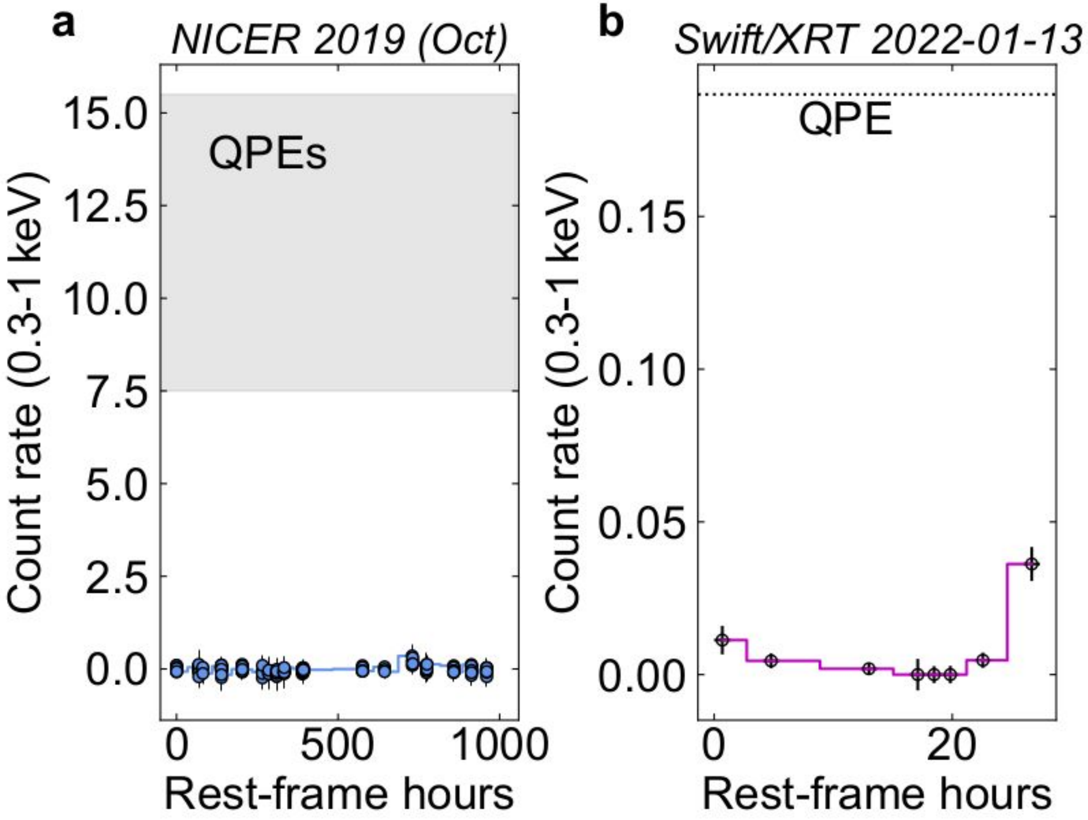
Unambiguous QPEs following a Tidal Disruption event (TDE) have never been seen before .....

... Until now

AT2019qiz: A "run of the mill" tidal disruption event

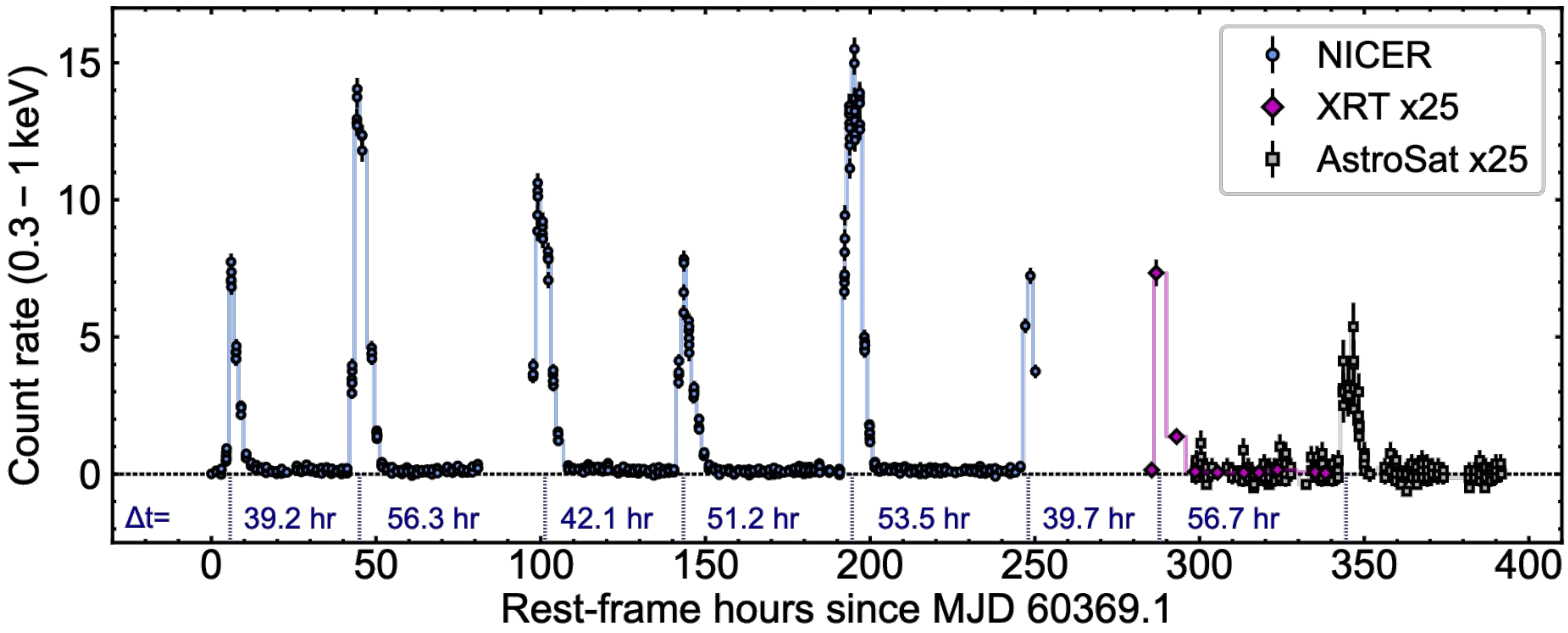


NICER X-ray observations near the optical peak showed no X-rays or eruptions



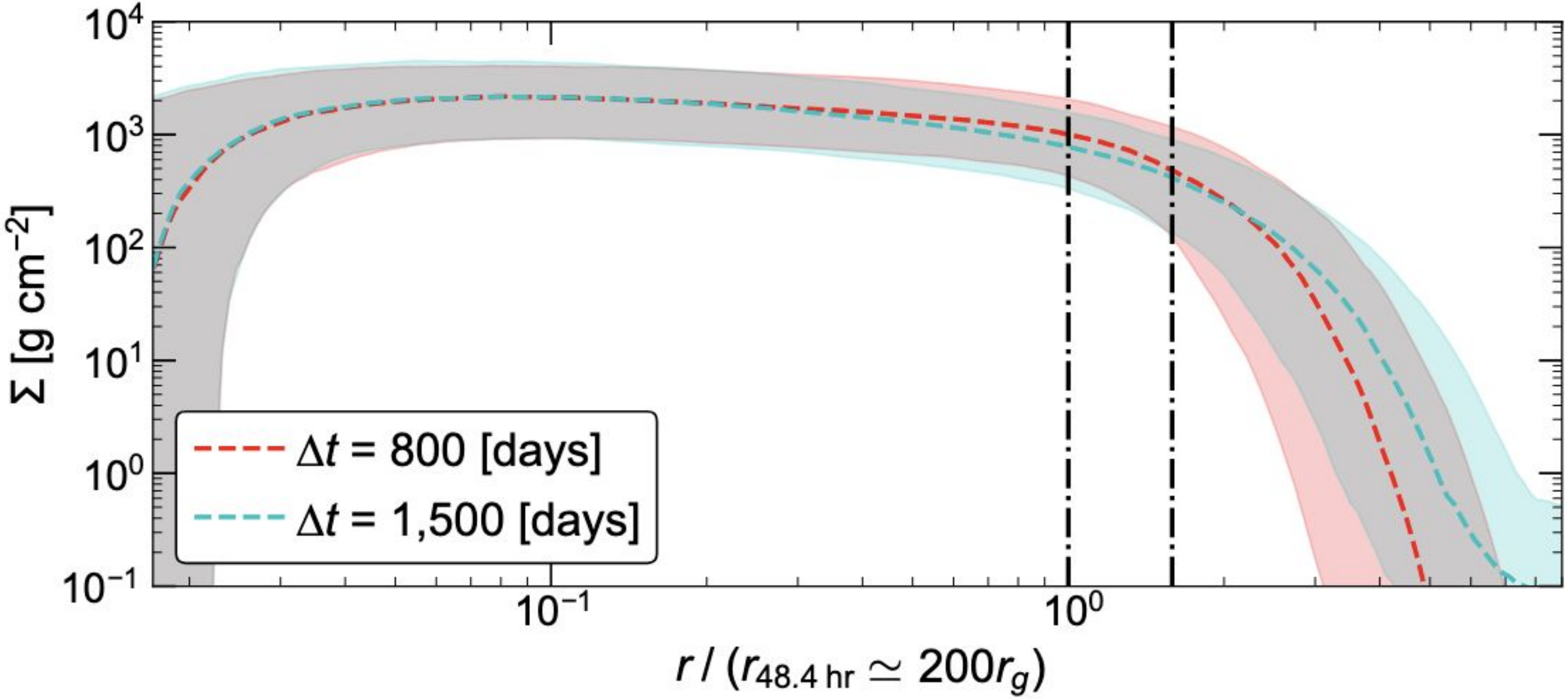
Nicholl, Pasham, Mummery, Guolo et al., 2024, Nature: arXiv:2409.02181

But 4+ years later …. QPEs separated by about 2 days

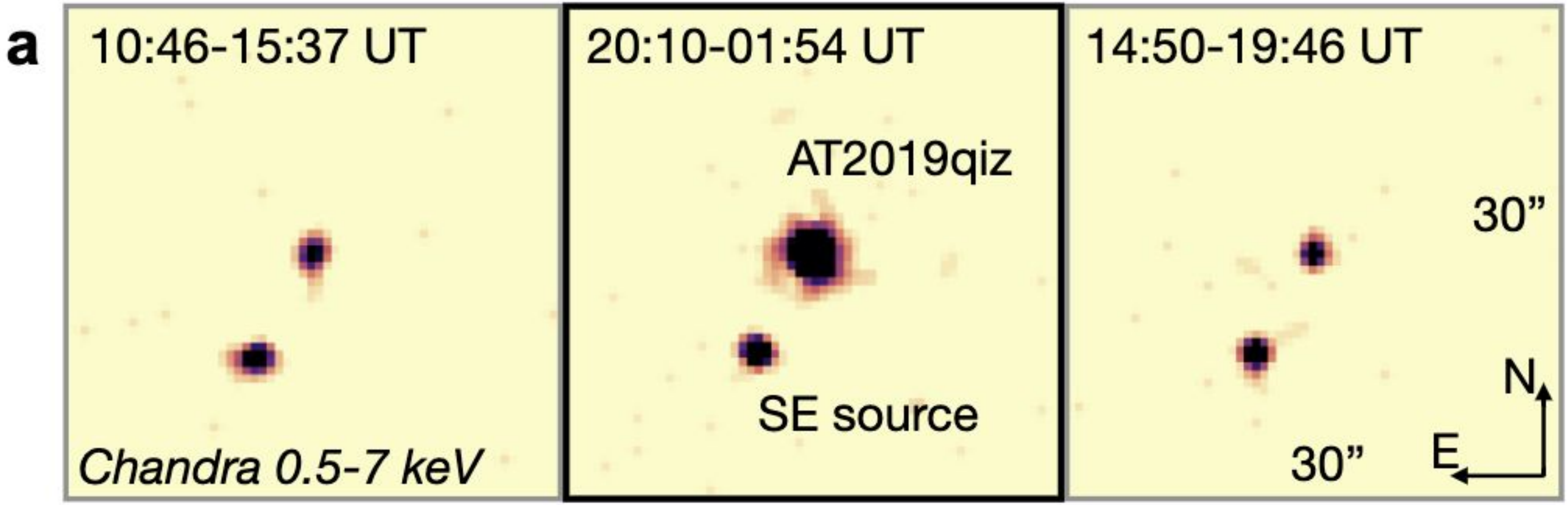


Nicholl, Pasham et al. 2024

Simple modeling using UV suggests that the disk intersects with the orbit of the object.



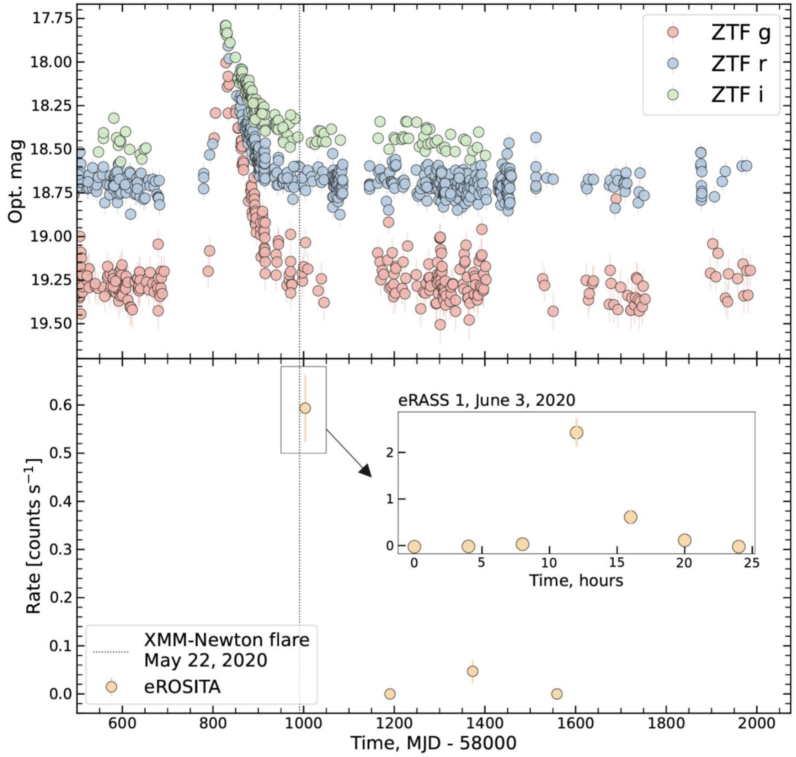
Chandra's had a crucial role in this discovery



A 50 ks exposure was broken into 3 epochs separated by a few hours.

Superior angular resolution established AT2019qiz as the source

eROSITA's archival data of TDE AT2019vcb recently strengthened its QPE nature



Bykov, M. Gilfanov, R. Sunyaev, P. Medvedev, 2024, arXiv:2409.16908v1

By no means is the EMRI model the ONLY solution

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

Current Models for Repeating X-ray signals:

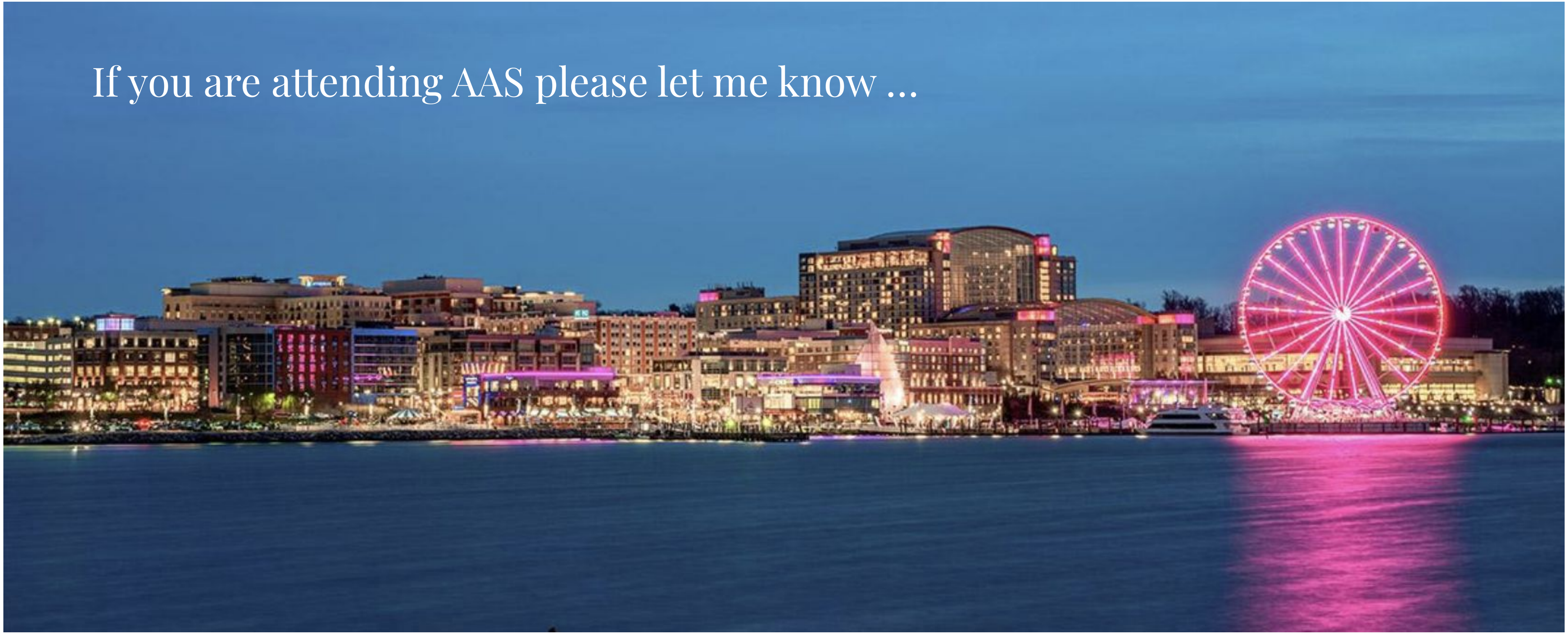
Inner disk instabilities

- 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)

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

A special session on “**repeating nuclear transients**” at the AAS in Washington D.C. from 11-15 Jan 2025



Future outlook: How can we find more?

Two strategies:

1. Blind search (all-sky X-ray surveys)
2. Systematic follow-up of TDEs (Depends on lifetime of these signals)

Future outlook I: Blind search for quasi-periodic eruptions

Assuming a 0.1 keV blackbody spectrum and that they reach a 0.3-10.0 keV luminosity > 5×10^{41} erg s^{-1}

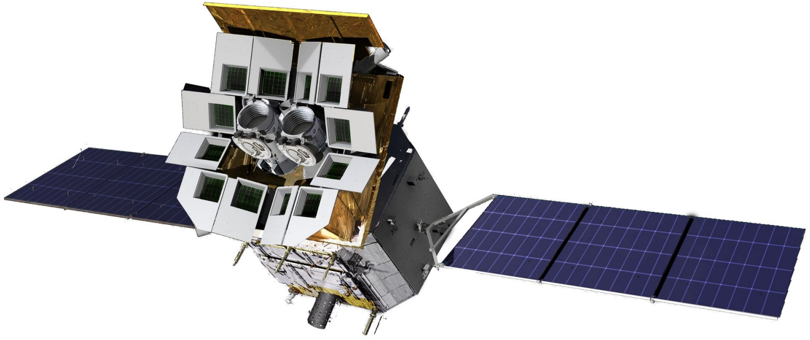
Redshift (Luminosity distance)	**Flux threshold (0.3-10 keV)**	**Number of QPEs (per year)**
0.02 (90 Mpcs)	10^{-12} erg $s^{-1}cm^{-2}$	2_{-2}^{+14}
0.05 (200 Mpcs)	2×10^{-13} erg $s^{-1}cm^{-2}$	25_{-18}^{+192}
0.1 (464 Mpcs)	4×10^{-14} erg $s^{-1}cm^{-2}$	180_{-130}^{+1410}

This is assuming you can reach a certain sensitivity level within a few tens of minutes (longer for long period systems)

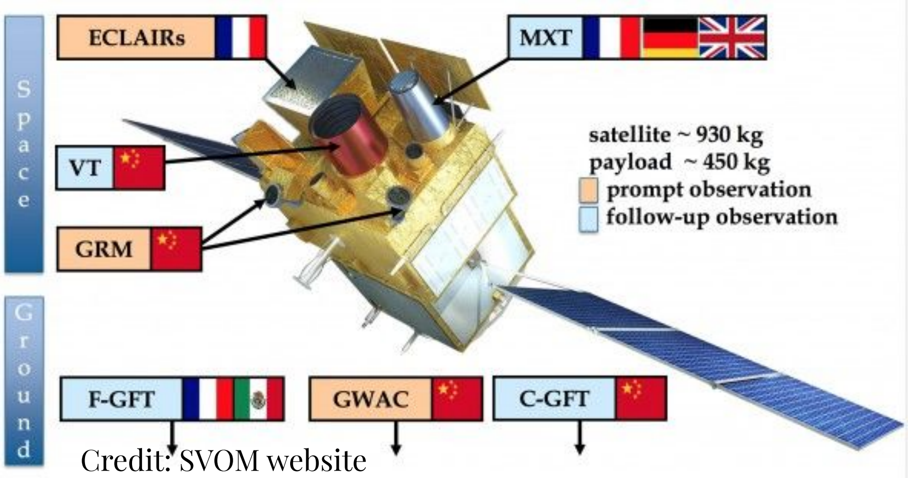
Assuming the luminosity function of Arcodia et al. 2024, A&A

Future outlook I: Blind search for quasi-periodic eruptions

Einstein Probe (Led by Chinese Academy of Sciences with MPE collaboration)



The Microchannel X-ray Telescope on SVOM (Recently launched French–Chinese Mission)

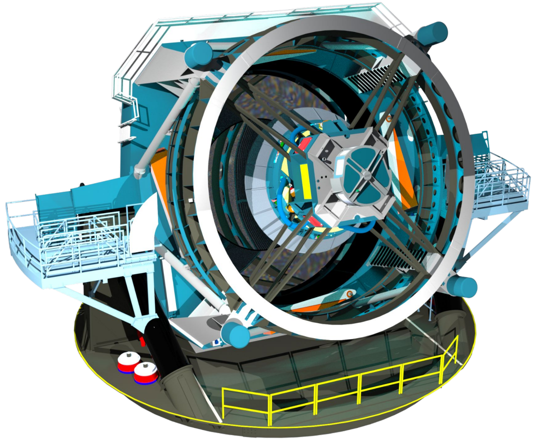


Credit: SVOM website

The sensitivity of both of these missions in the soft X-rays (at best 10^{-12} erg s^{-1} cm^{-2}) may not be adequate to find many QPEs in blind searches.
Would be even more challenging to identify the short–period ones!

Future outlook II: Targeted Follow-Up of Rubin Tidal Disruption Events

LSST/Rubin (2025): thousands of TDEs expected to be identified



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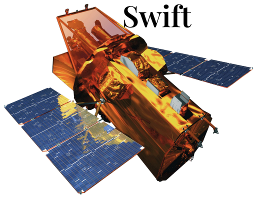
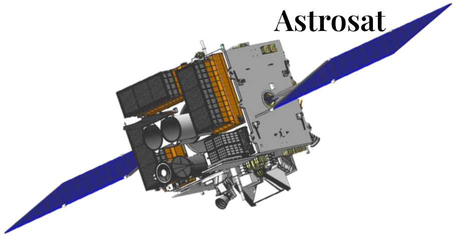
Current slew of X-ray telescopes





With current X-ray facilities (XMM-Newton/Chandra/NICER/AstroSAT/Swift) we can get down to a few x 10^{-14} erg $s^{-1}cm^{-2}$

In principle, Rubin + X-ray Follow-up could detect several dozens (or even hundreds) of repeating systems in the coming years depending on the <u>lifespan</u> of these systems

With the advent of Rubin, the next couple of years is the perfect time to understand and build a census of these systems

Summary

- Tidal Disruption Events can produce the “spark” to notice repeating transients
- If orbiting objects ↠ Multi-messenger astronomy in the coming decade