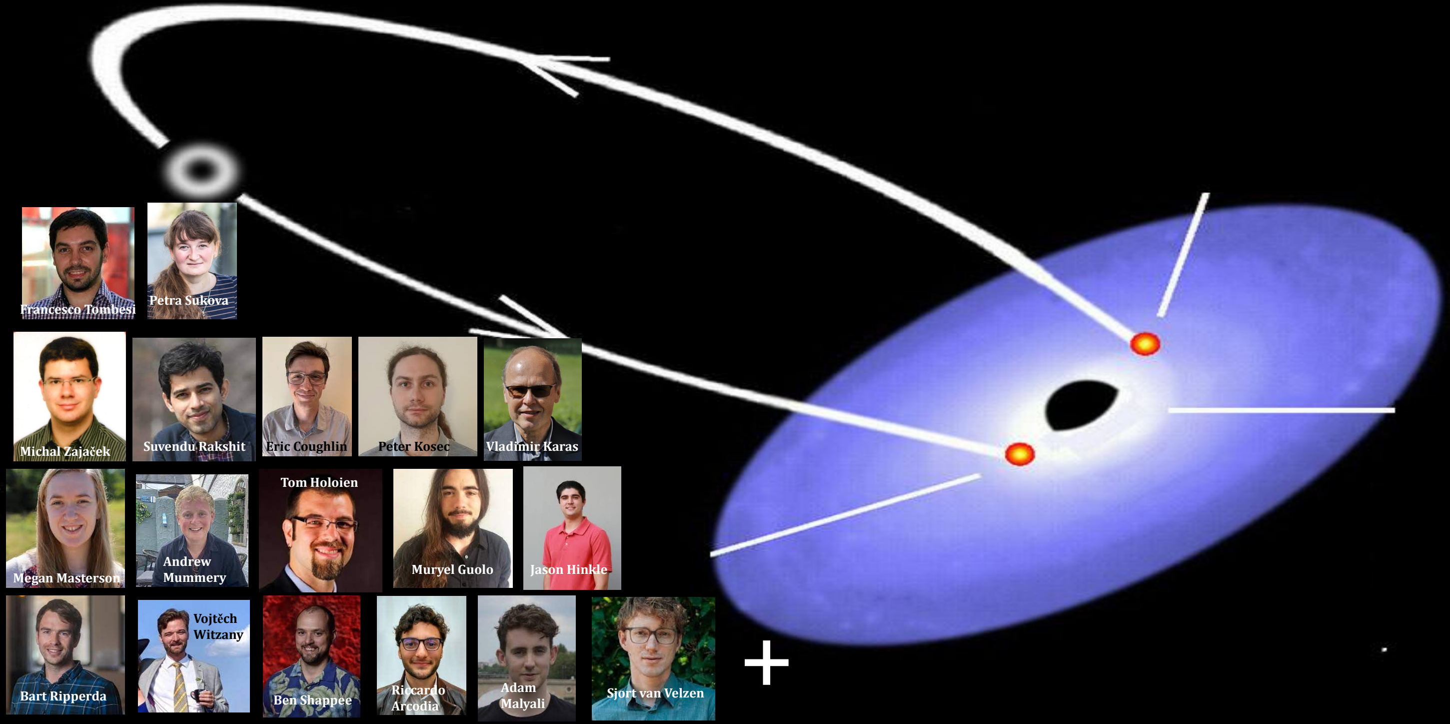
# Recurring Ultrafast Outflows from Repeating Nuclear Transients and a Potential Unification model

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# Three flavors of repeating extragalactic X-ray transients

**Quasi-Periodic *Oscillations***

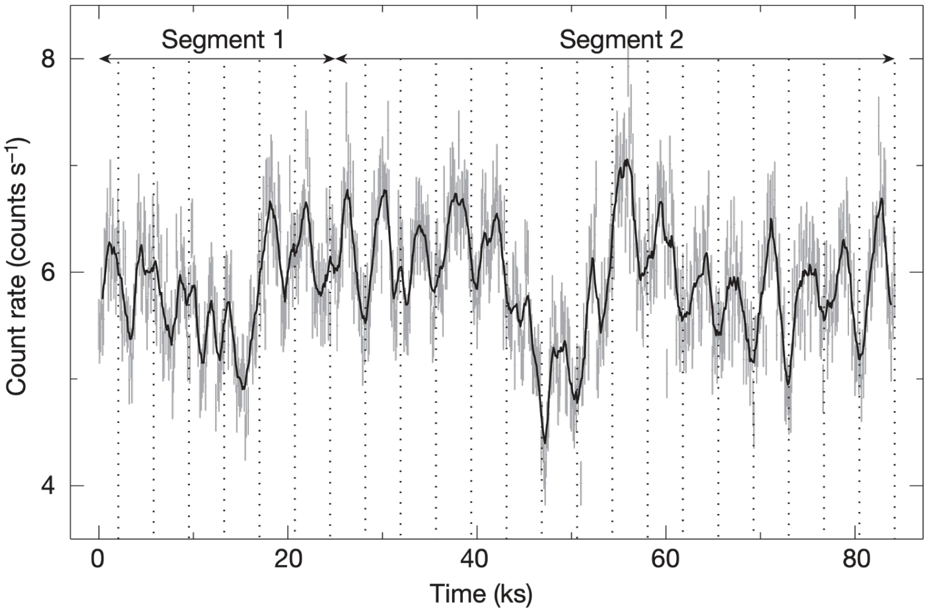
**Quasi-Periodic *Eruptions***

**Quasi-Periodic *Outflows***

# Three flavors of repeating extragalactic X-ray transients

An example system showing an X-ray ***quasi-periodic oscillation*** ~ 1 hour

**Quasi-Periodic *Oscillations***

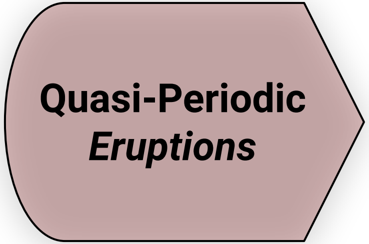


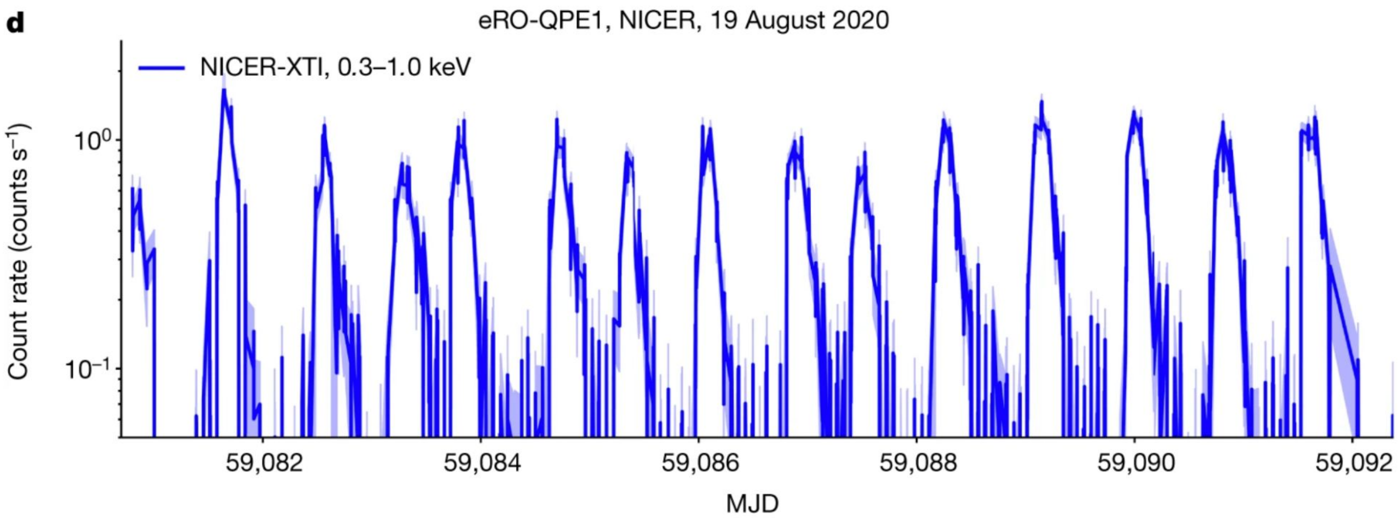

Gierlinski et al. 2008, Nature

Also, see Pasham et al. 2019, *Science* for a 2-minute system

# Three flavors of repeating extragalactic X-ray transients

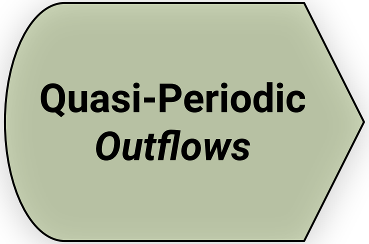
An example system showing X-ray ***Eruptions*** roughly once every 16 hours



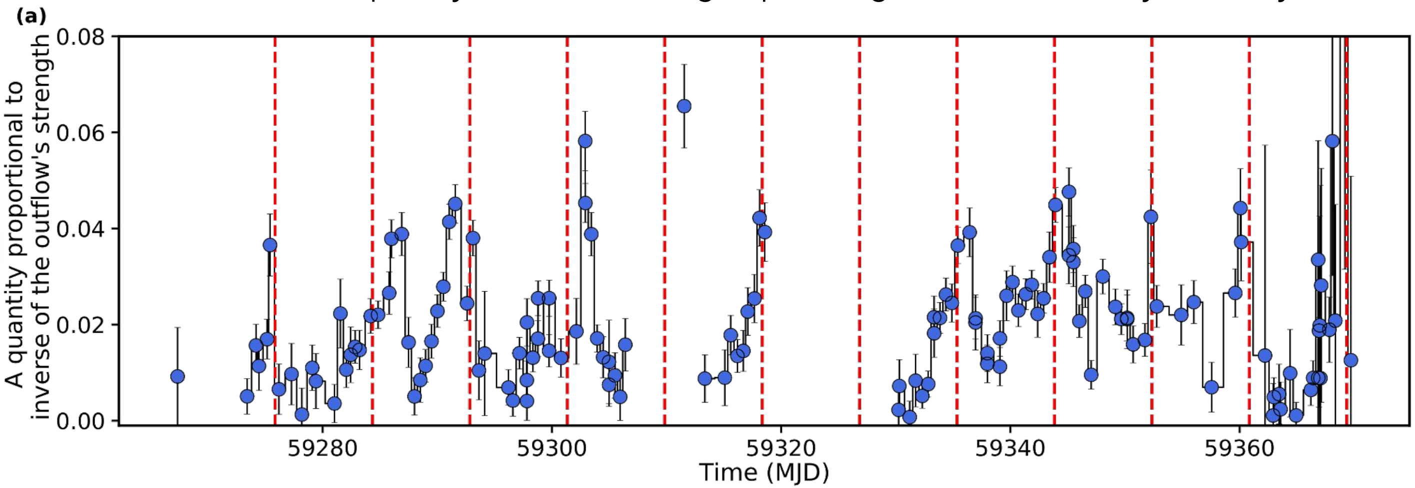




Arcodia+Pasham et al. 2021, *Nature*

# Three flavors of repeating extragalactic X-ray transients



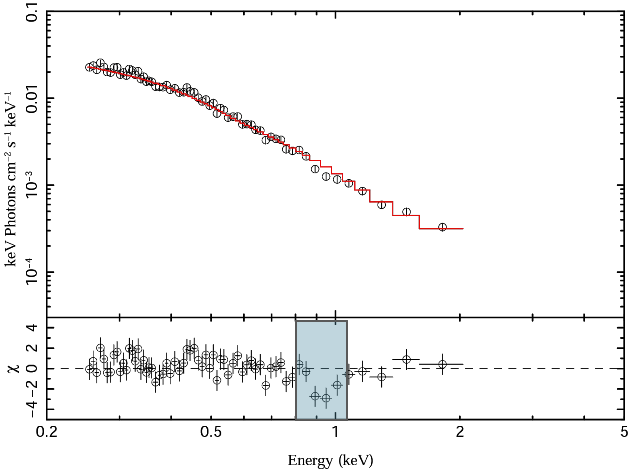

An example system showing repeating ***Outflows*** every 8.5 days




Pasham et al., under review

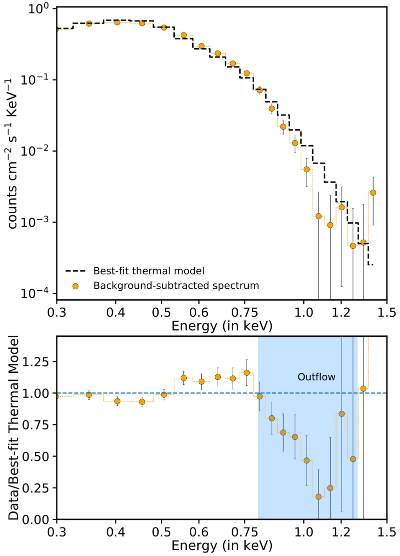
# *Recurring (phase-dependent) spectral deviations that can be interpreted as outflows* maybe present in all <u>*three*</u> classes

**Quasi-Periodic *Oscillations***



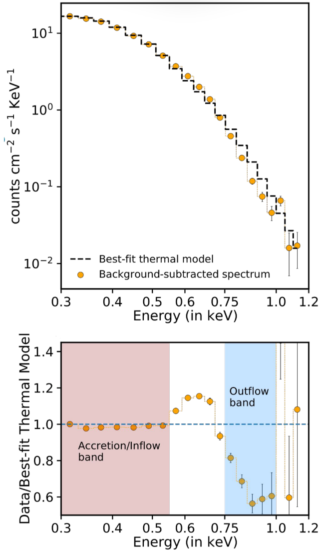

Maitra and Miller 2010, ApJ

**Quasi-Periodic *Eruptions***



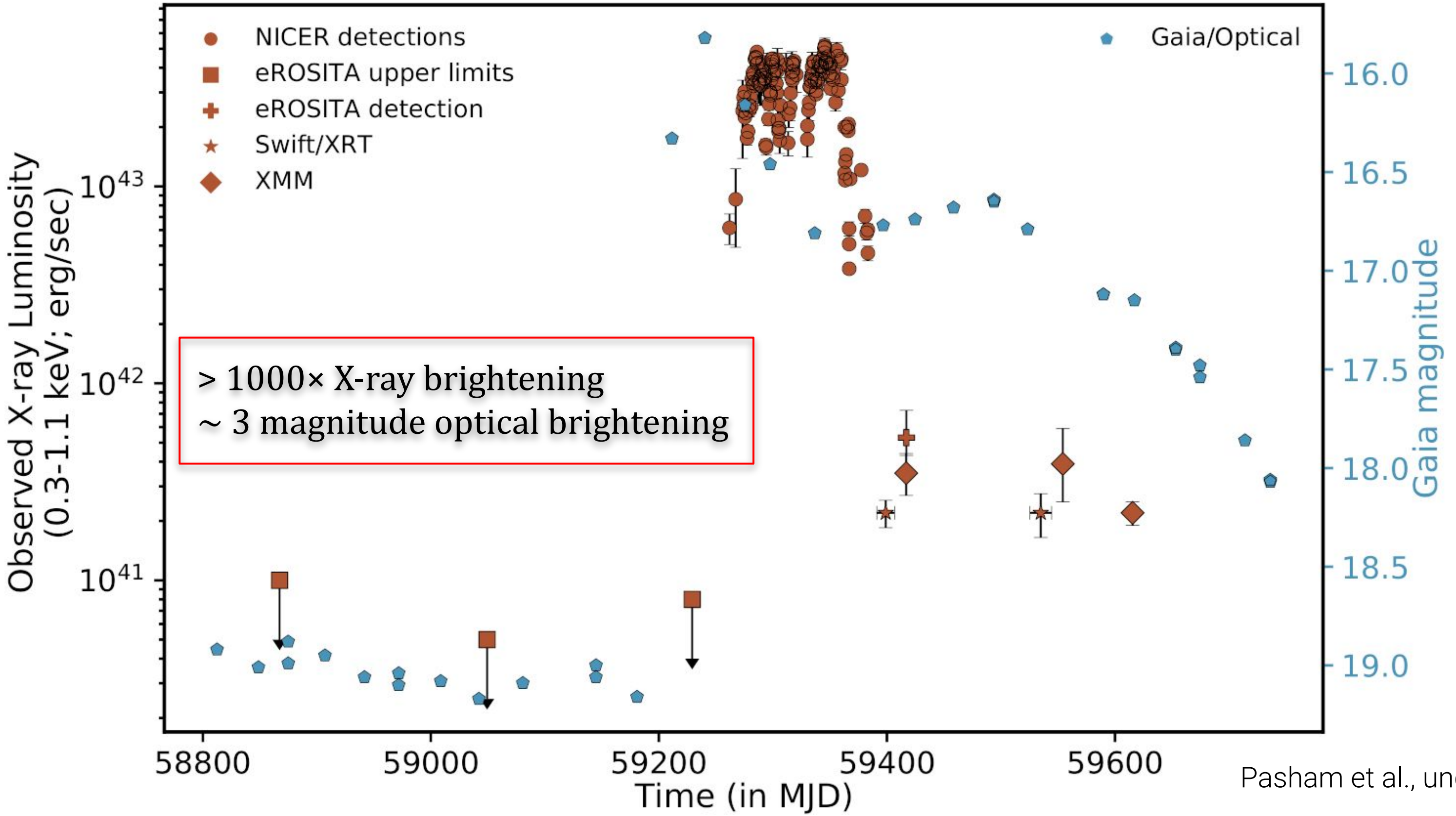

Pasham et al. 2023, in prep.

**Quasi-Periodic *Outflows***




Pasham et al., under review

# A nuclear transient from a nearby galaxy (a few 100 Mpcs)




Pasham et al., under review

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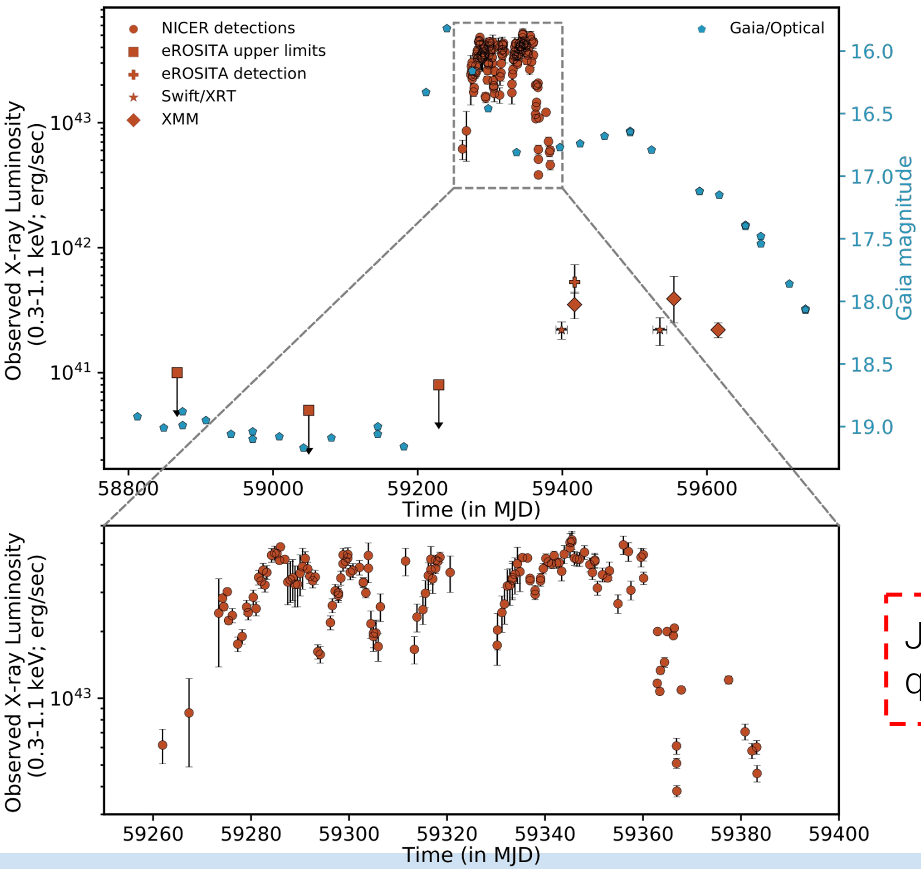
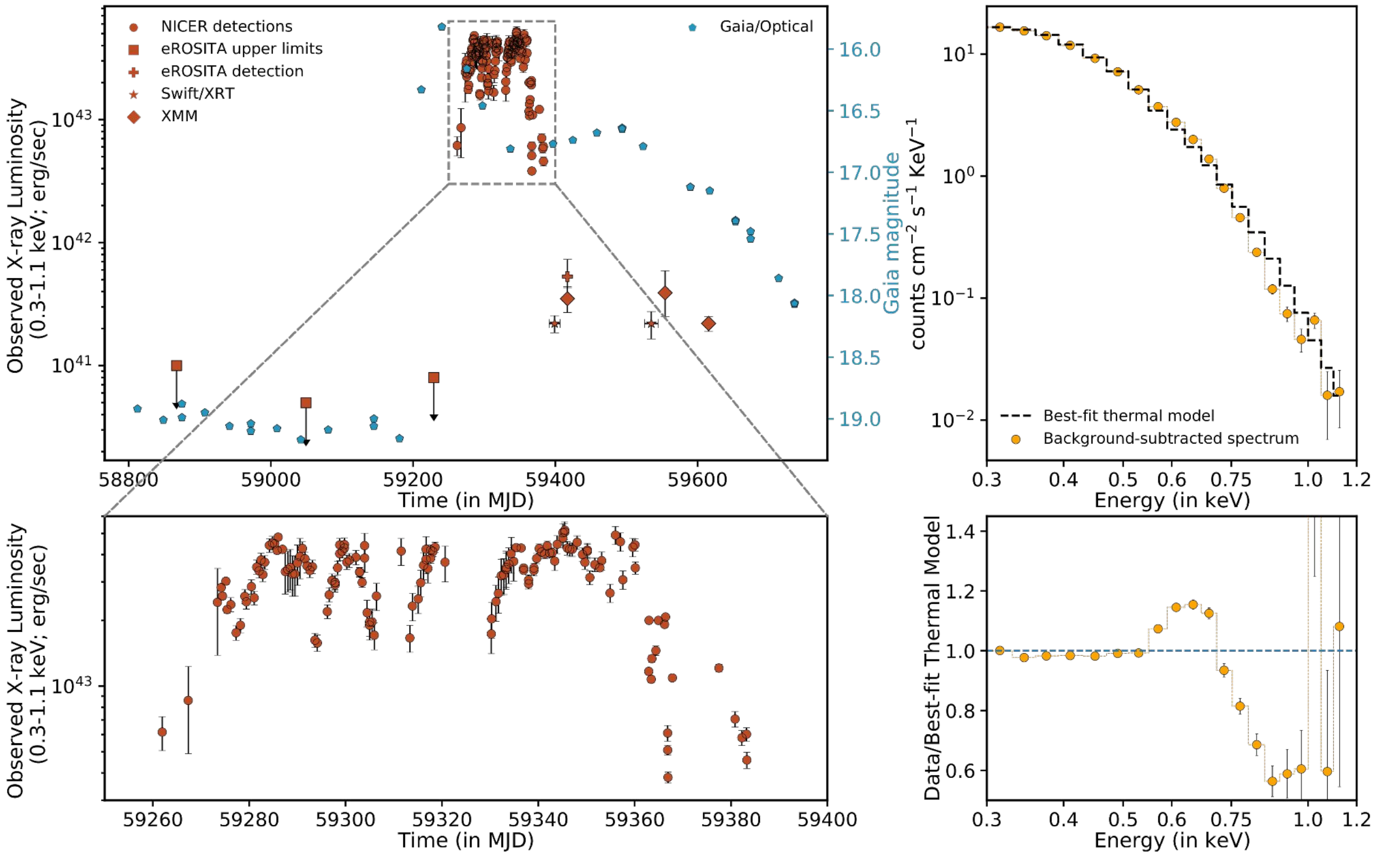
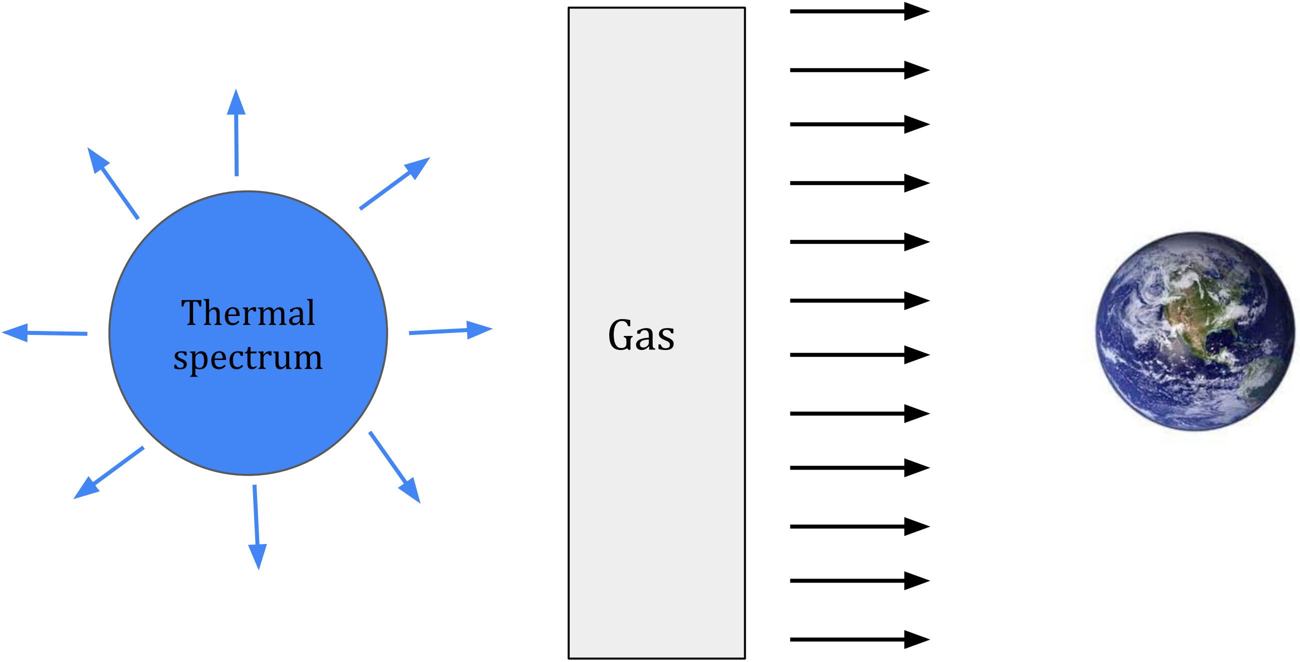


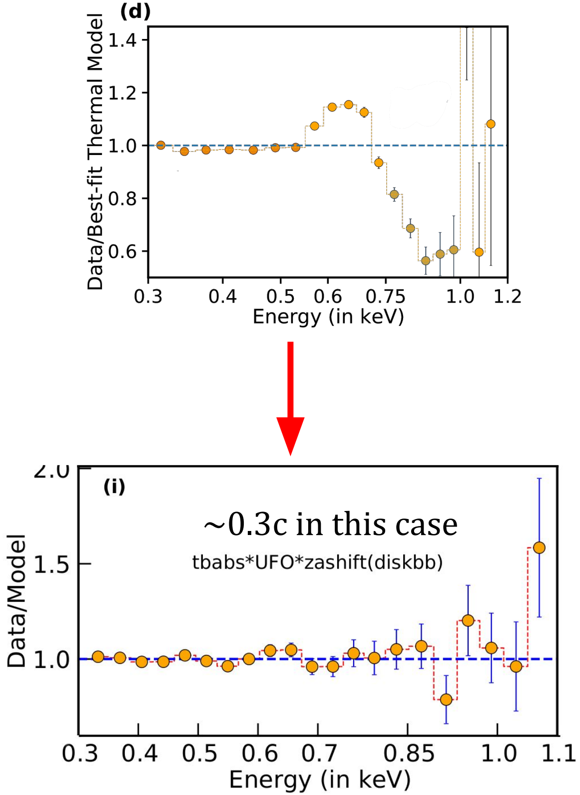

Just stochastic: no clear quasi-periodicity

# An UltraFast Outflow signature in the thermal X-ray spectrum



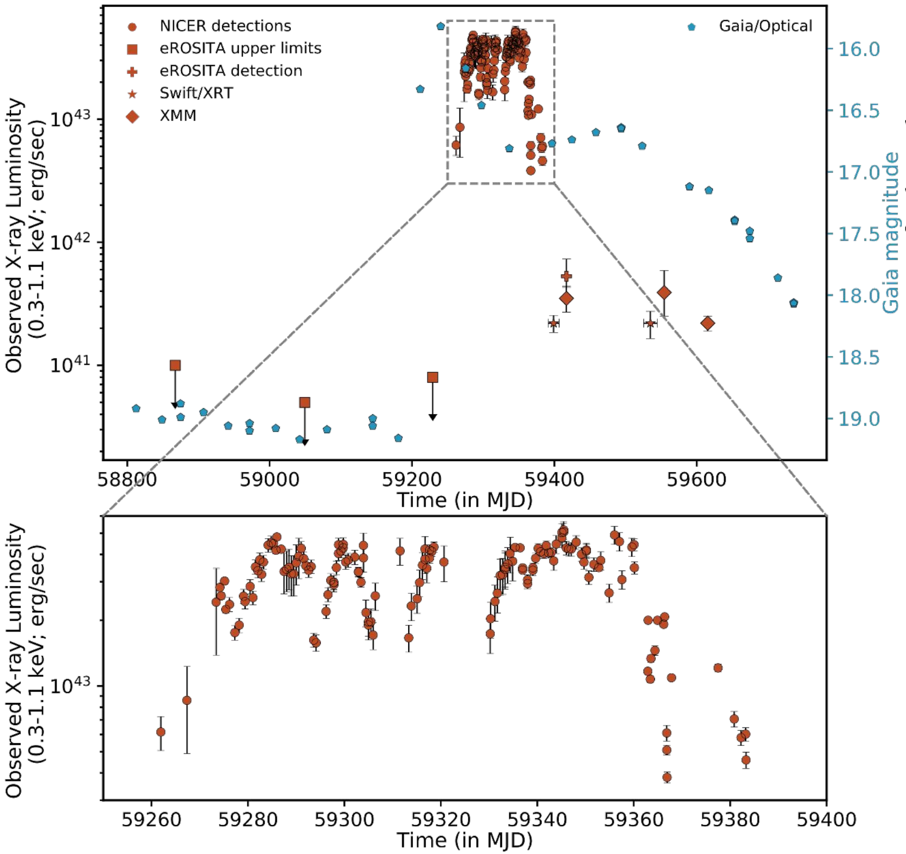
# The residuals can be interpreted as an ultrafast outflow

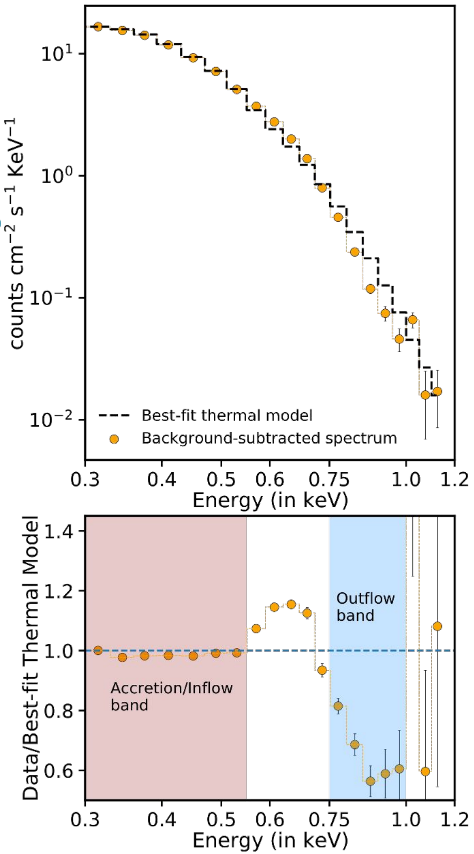



You CANNOT put any line you want for this spectral dip. Continuum (temperature and luminosity) is highly relevant as well.

# An UltraFast Outflow signature in the thermal X-ray spectrum



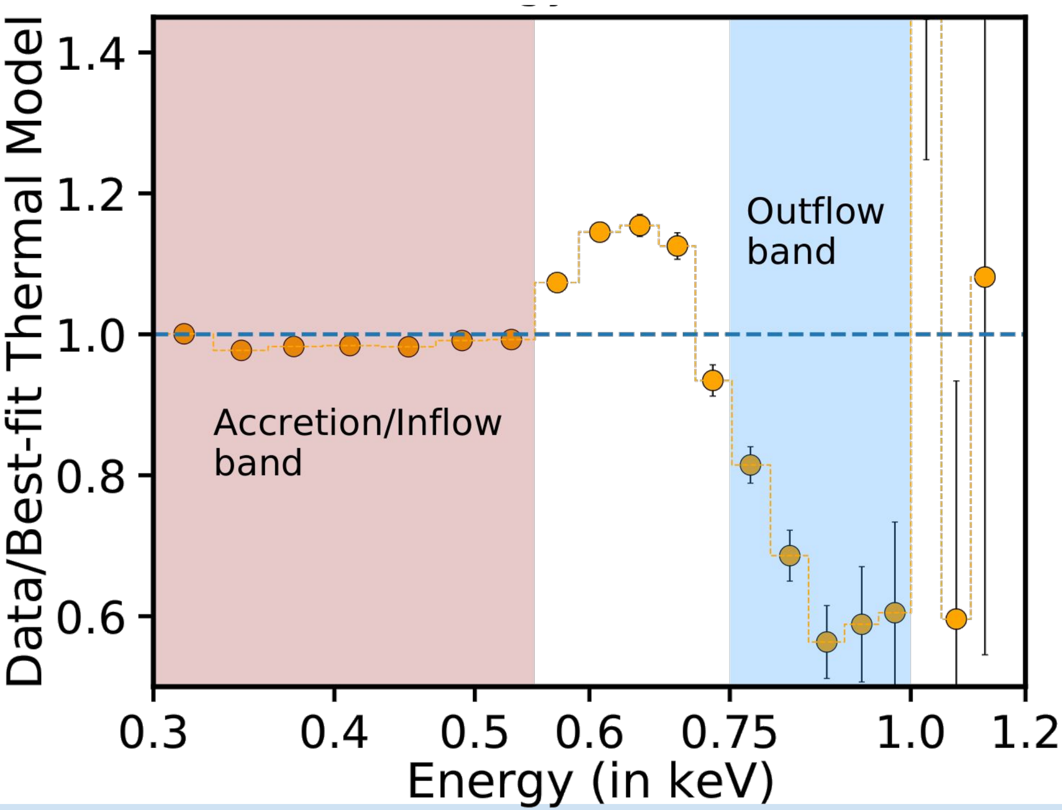



# For the first time, NICER's large effective area allows us to track the strength of this feature with time

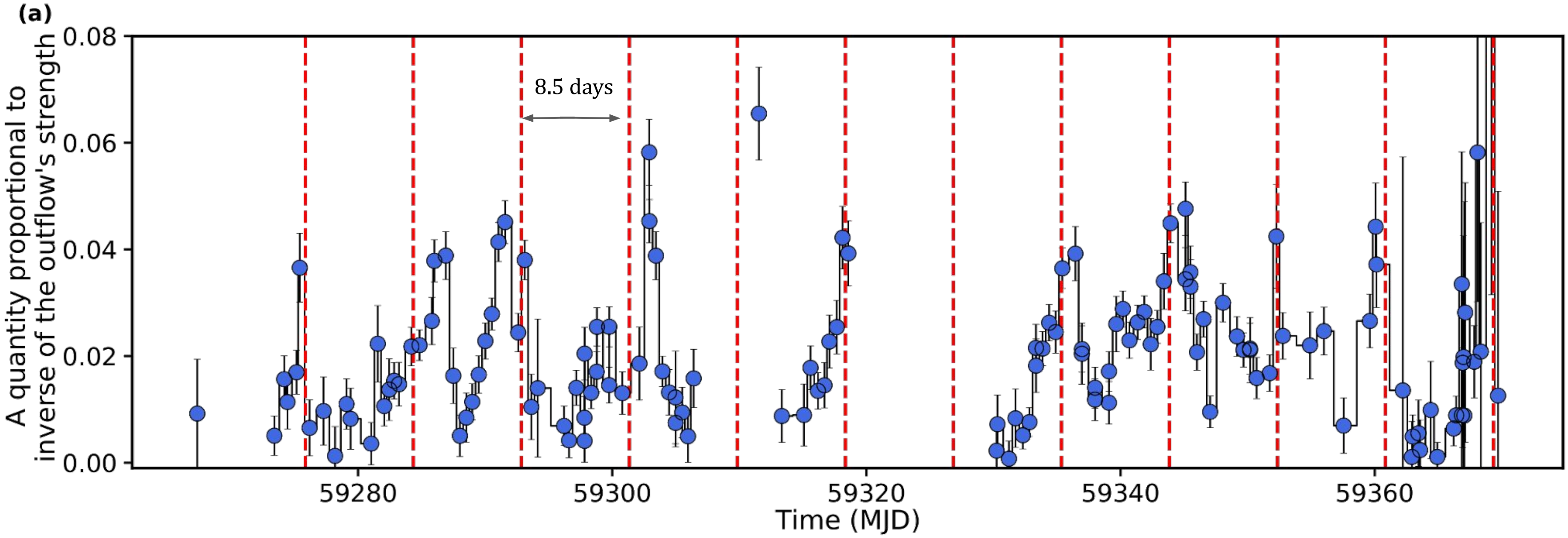
- Astrophysics from the international space station
- Large X-ray collecting area
- 0.3-10 keV bandpass
- Excellent maneuvering capability
- Good energy spectral resolution

PI: Keith Gendreau; Deputy PI: Zaven Arzoumanian

# Tracking the strength of the outflow with time

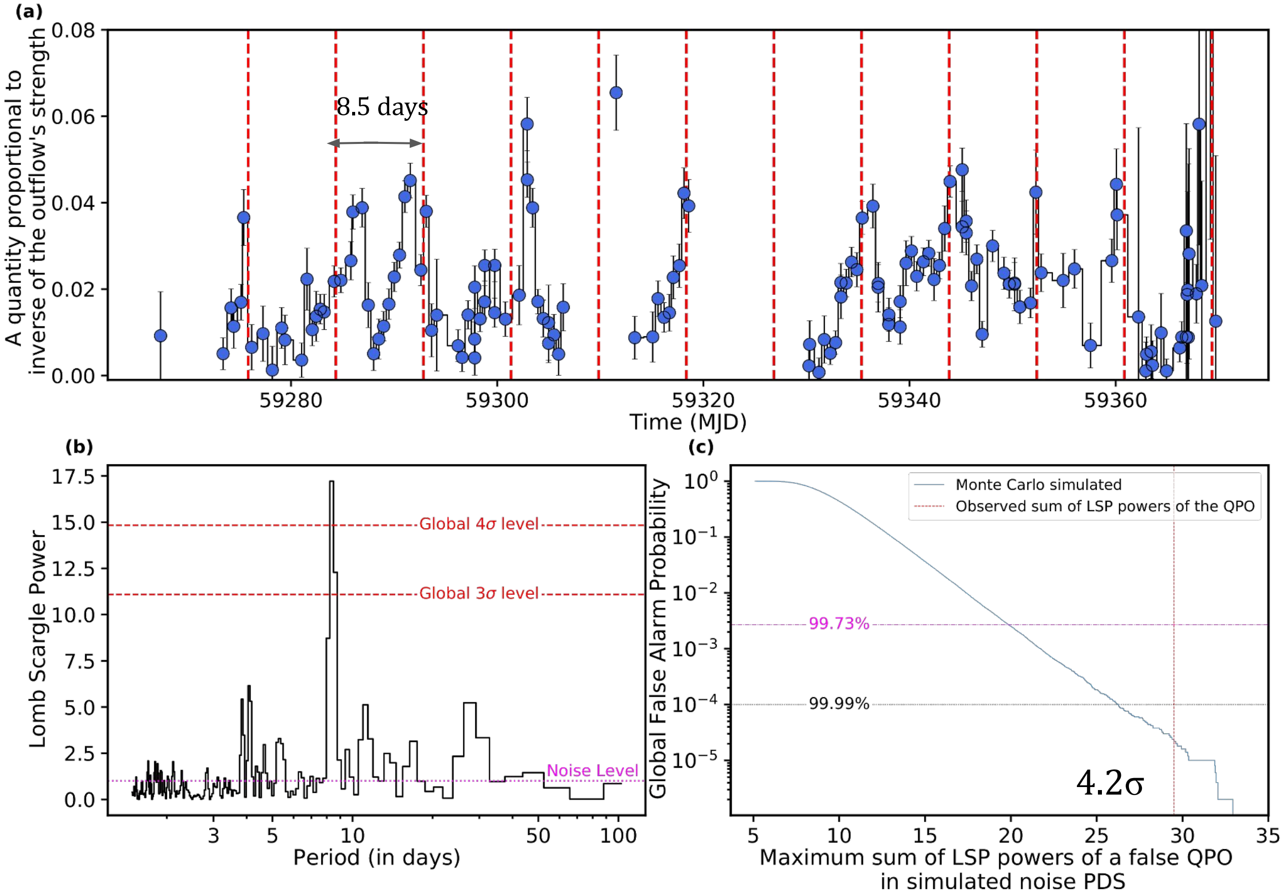


# Tracking the outflow's strength with time

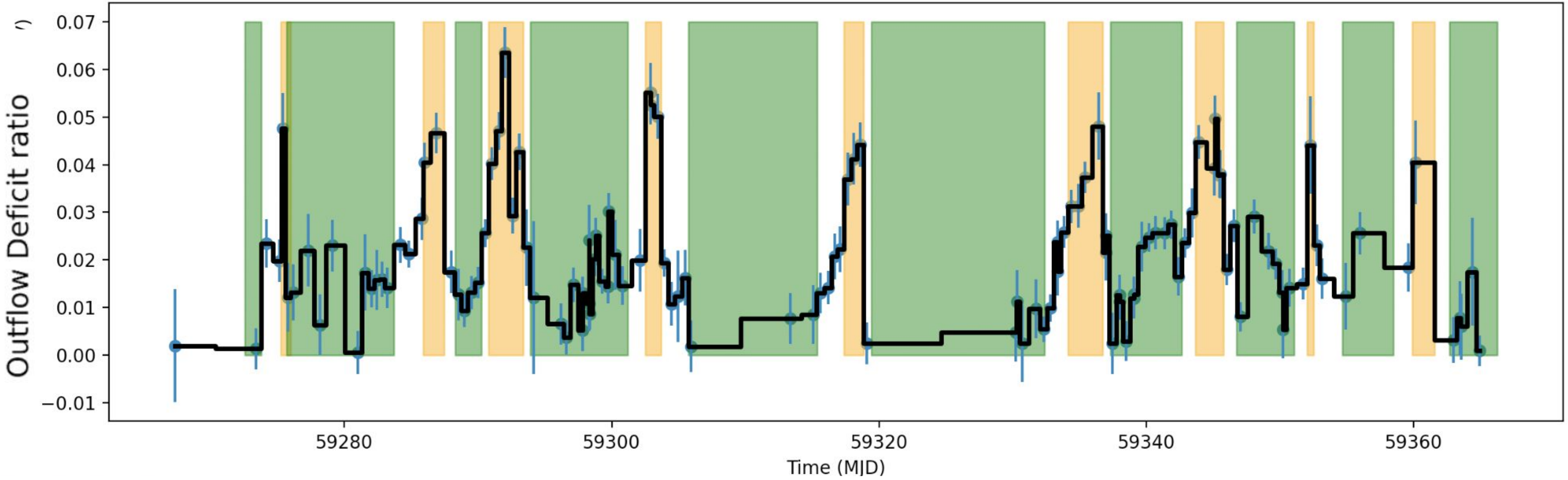



Pasham et al., submitted

# Quasi-Periodic Outflows



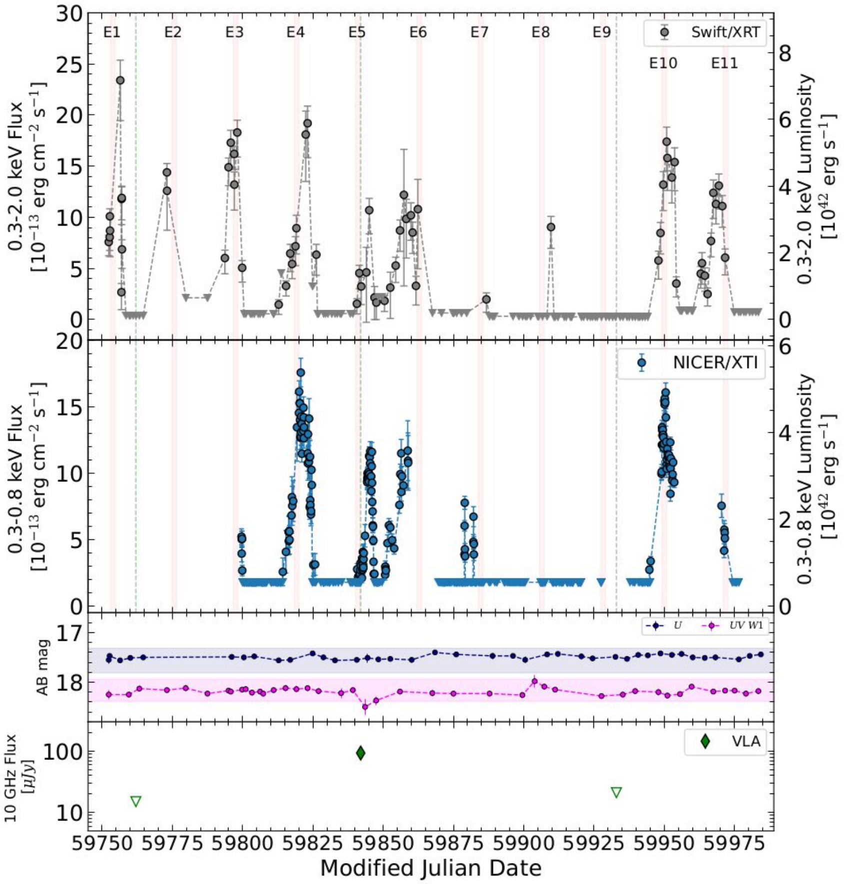
# Phase-resolved spectra strengthens the outflow deficit ratio analysis




| | | | |
|---|---|---|---|
| Strong Outflow | Outflow absorbing column is ~$10^{22}$ $cm^{-2}$<br>$Log_{10}$(Ionization parameter): 2.5 | Weak Outflow | Outflow absorbing column is ~$10^{21}$ $cm^{-2}$<br>$Log_{10}$(Ionization parameter): 1.2 |

Ionization parameter = Incident luminosity/(density of gas x interaction area)

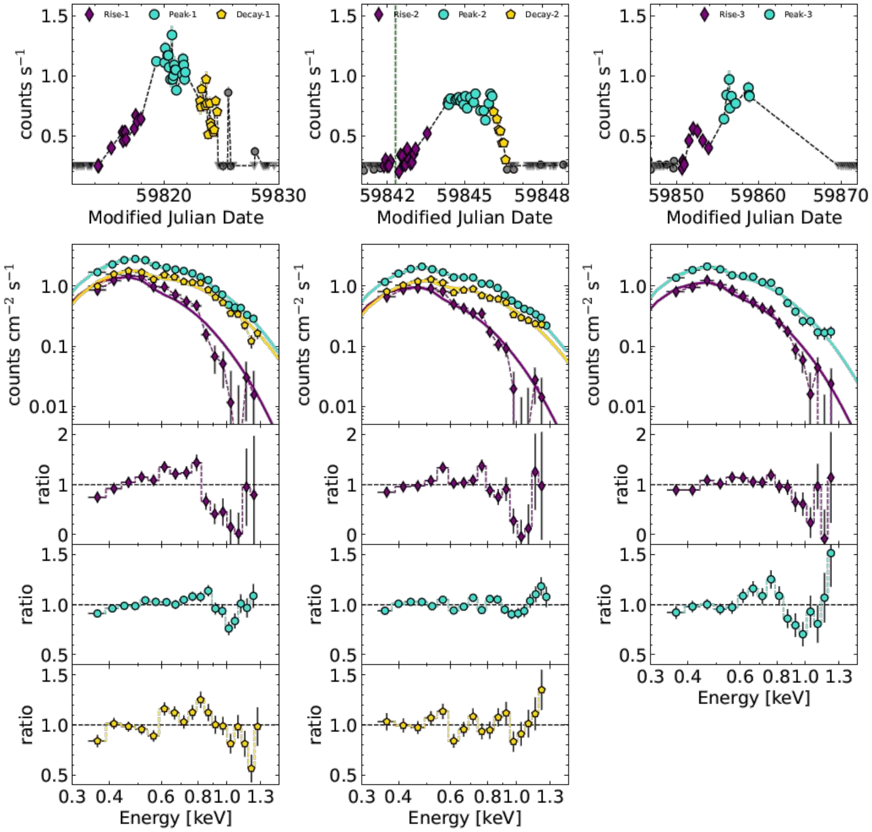
# A source showing Quasi-Periodic Eruptions




Graduate Student at Johns Hopkins

Guolo, Pasham et al., under review
Pasham et al., in prep.

# A source showing Quasi-Periodic Eruptions + Quasi-Periodic Outflows

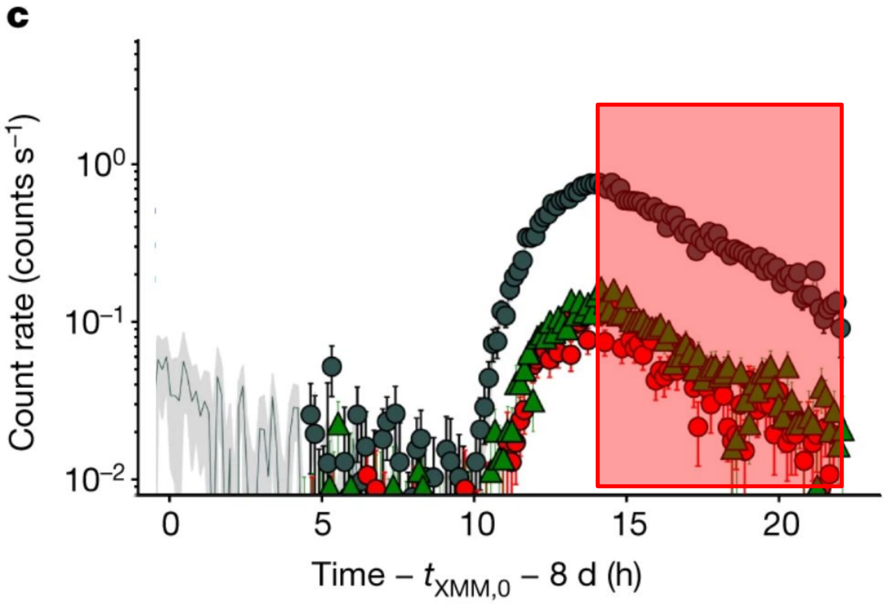



Outflows are present during the rise of each eruption

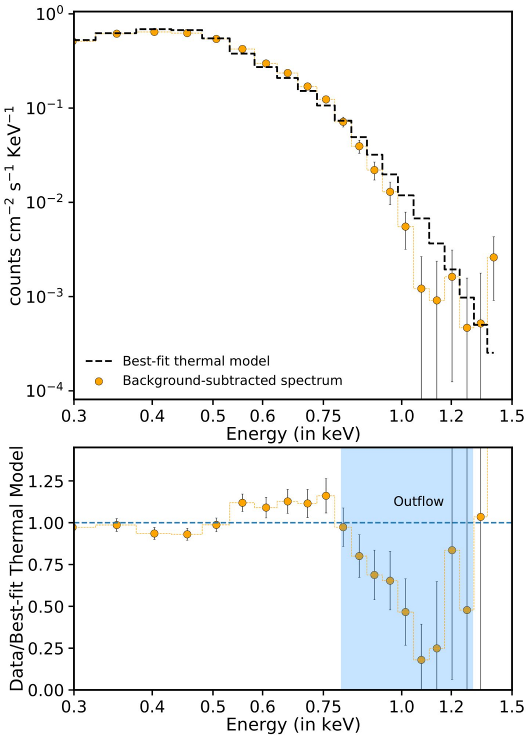
+

Transient radio emission

# I went back into the archives to look for outflows in other published QPE sources




Pasham et al., in prep.



# Current Models for Quasi-Periodic Eruptions:

## 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

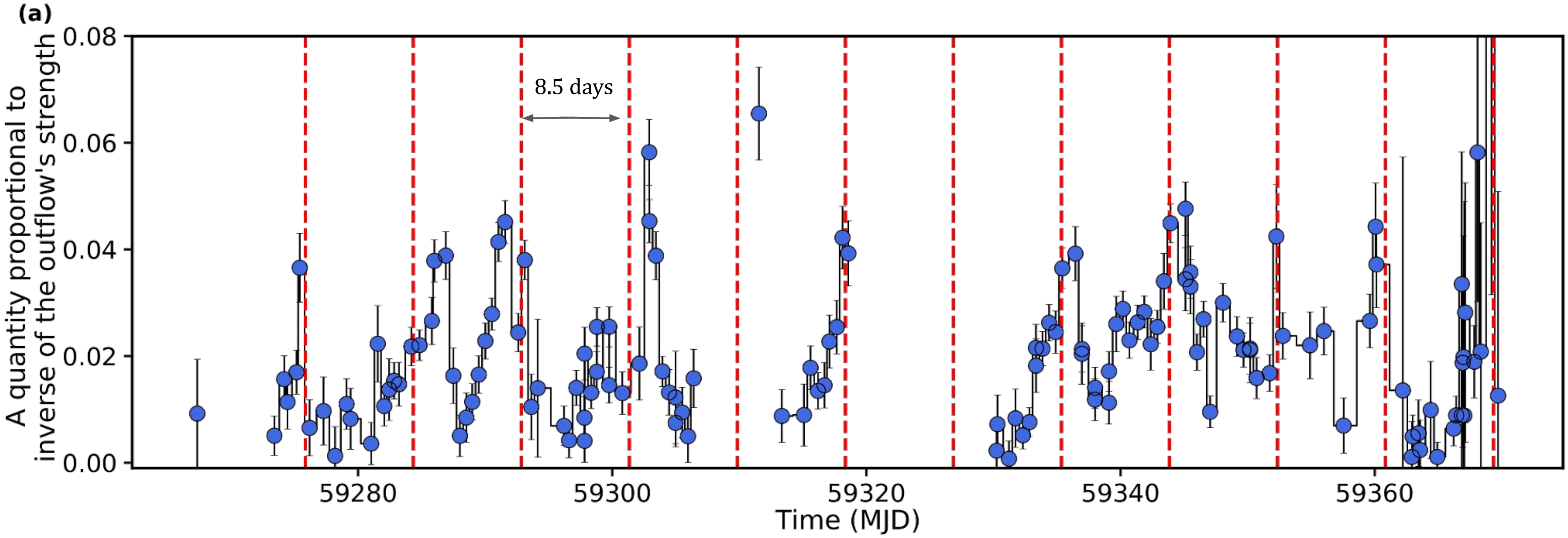
# Quasi-periodicity is consistent with all of these models

- **Accretion disk instability based models:** the radius at which the instability occurs can vary and thus the recurrence periods.
- **Orbiting objects based models:** combination of General relativistic effects (Lense-Thirring precession of the secondary's orbit and the inner accretion disk + nodal precession of the secondary's orbit + ellipticity) and the geometric orientation of the system.

Pasham et al. 2023, ApJL, under review

Any viable model MUST be able to explain repeating ultrafast outflows from these systems

# A potential SMBH + IMBH binary:
## Based on an in-depth theoretical analysis




Pasham et al., submitted

# We consider several classes of models

| Model/class of models | Strengths | Weaknesses | Notes |
|---|---|---|---|
| Inner disc precession | Thought to be commonly seen in stellar-mass black hole binaries (*119*) | The observed changes from high column, high ionization parameter to low column, low ionization along with constant outflow speed are inconsistent with precession with all known types of outflows (*110–114*) | Disfavoured (see main text for more details) |
| Clumpy wind | - | The wind geometry would need to be fine tuned to have uniformly separated clumps. The probability of formation of such clumps by chance is less than 1 in 50,000 | Disfavoured (see “A single clumpy outflow is disfavoured” in Methods) |
| Slow absorber | Slow absorbers can, in principle, produce similar spectral signatures | - The *XMM-Newton*/RGS and EPIC/pn spectrum rule out a slow absorber that can produce such a broad feature<br>- A typical slow/warm absorber is distant from the SMBH and cannot produce a rapid (∼ week timescale) quasi-periodic variability seen here | Disfavoured (see “The broad residuals cannot be explained with slow absorbers” in Methods) |
| X-ray reflection by a corona | Seen in several highly accreting AGN with an X-ray corona (*120*) | Lack of a Compotonizing corona/powerlaw component in the X-ray spectrum | Disfavoured (see “Relativistic reflection is disfavoured” in Methods) |
| X-ray reflection by a disc | Argued to operate at least in one changing-look AGN (*96*) | - Lack of a geometrically thick surface for reflection, would require a fine-tuned disc geometry<br>- Unphysically large amounts of reflected emission than the primary thermal emission | Disfavoured (see “Relativistic reflection is disfavoured” in Methods for more discussion) |
| Magnetically arrested accretion disc | Preliminary work by (*117*) suggests that outflows can be produced through repeated magnetic reconnection events | - Based on state-of-the-art high-resolution simulations it is unclear if such outflows would be quasi-periodic in nature<br>- Such regular outflows are not seen in lower-resolution simulations | Plausible, but with important caveats (see Figure 8 of (*117*)) |
| Quasi-periodic eruptions (QPEs) | Seen in a small sample of AGN | - QPEs manifest as large amplitude flux bursts as opposed to changes in ODR.<br>- Variable outflows have not been reported in known QPE sources.<br>- ASASSN-20qc’s X-ray spectrum is distinct compared to known QPE sources (*93, 94, 115*) | Disfavoured (see “A spectral model with two thermal components akin to quasi-periodic eruptions is ruled out” in Methods) |
| Repeating partial stellar tidal disruption | - Argued to operate in at least 3 systems (*53, 121, 122*) | - The expected orbital period would be orders of magnitude longer than what is seen here (*123*)<br>- No evidence for a similar variability in the optical light curve<br>- A stellar core’s influence radius would be too small to produce the observed outflow | Disfavoured |
| Radiation pressure driven outflows | Observed in a sample of accreting stellar-mass black holes (*124*) | - The persistence of the outflow over a factor of >200 change in X-ray flux suggests negligible radiation driving | Disfavoured |
| An orbiting object repeatedly perturbing the SMBH accretion disc | - Naturally explains QPOuts<br>- Supported by 2D and 3D GRMHD simulations<br>- Consistent with theoretical rates of formation of SMBH–IMBH binaries (*125*) | | Favoured (see “Perturber-induced outflow scenario” in Methods) |

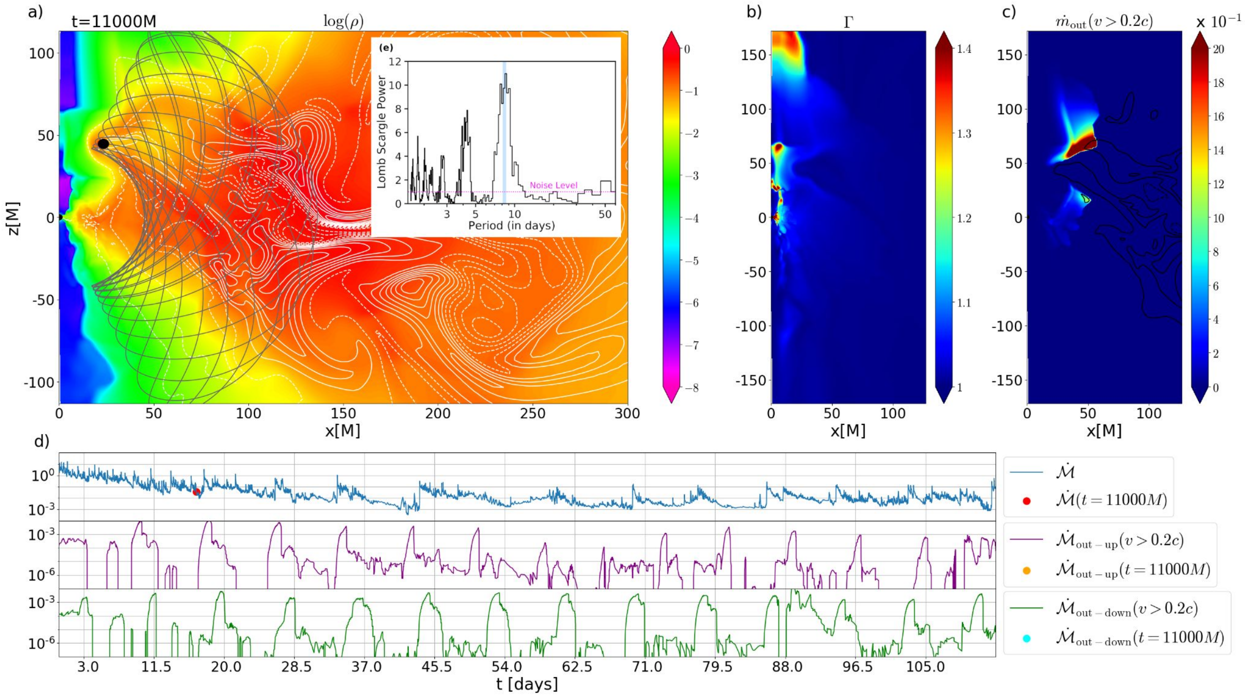
Happy to discuss more in Q&A

# An orbiting peturber-induced outflow model

# Simulations suggests object–AGN disk interactions can drive regular outflows

Matter pushed towards the magnetic poles to launch ultrafast outflows

Observational consequence: a quasi-periodically varying outflow (provided favorable orientation: +-20 degrees around the axis)




Thanks to Petra Suková, Michal Zajaček, Vojtech Witzany, Vladimir Karas

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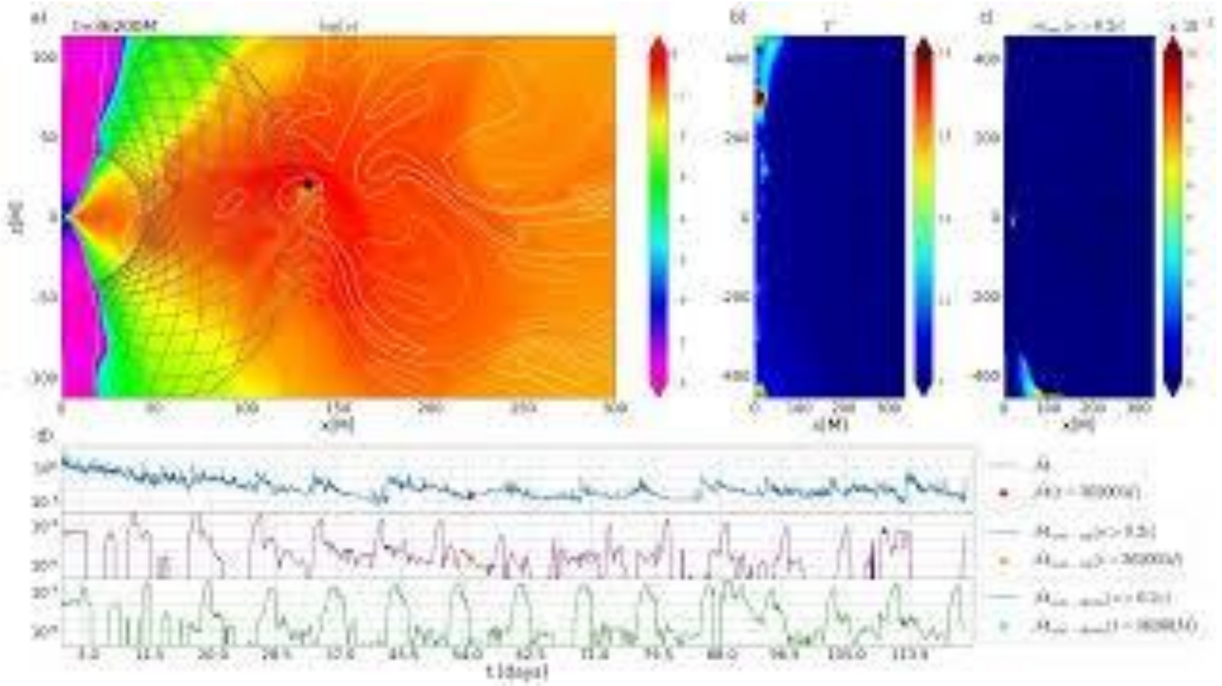
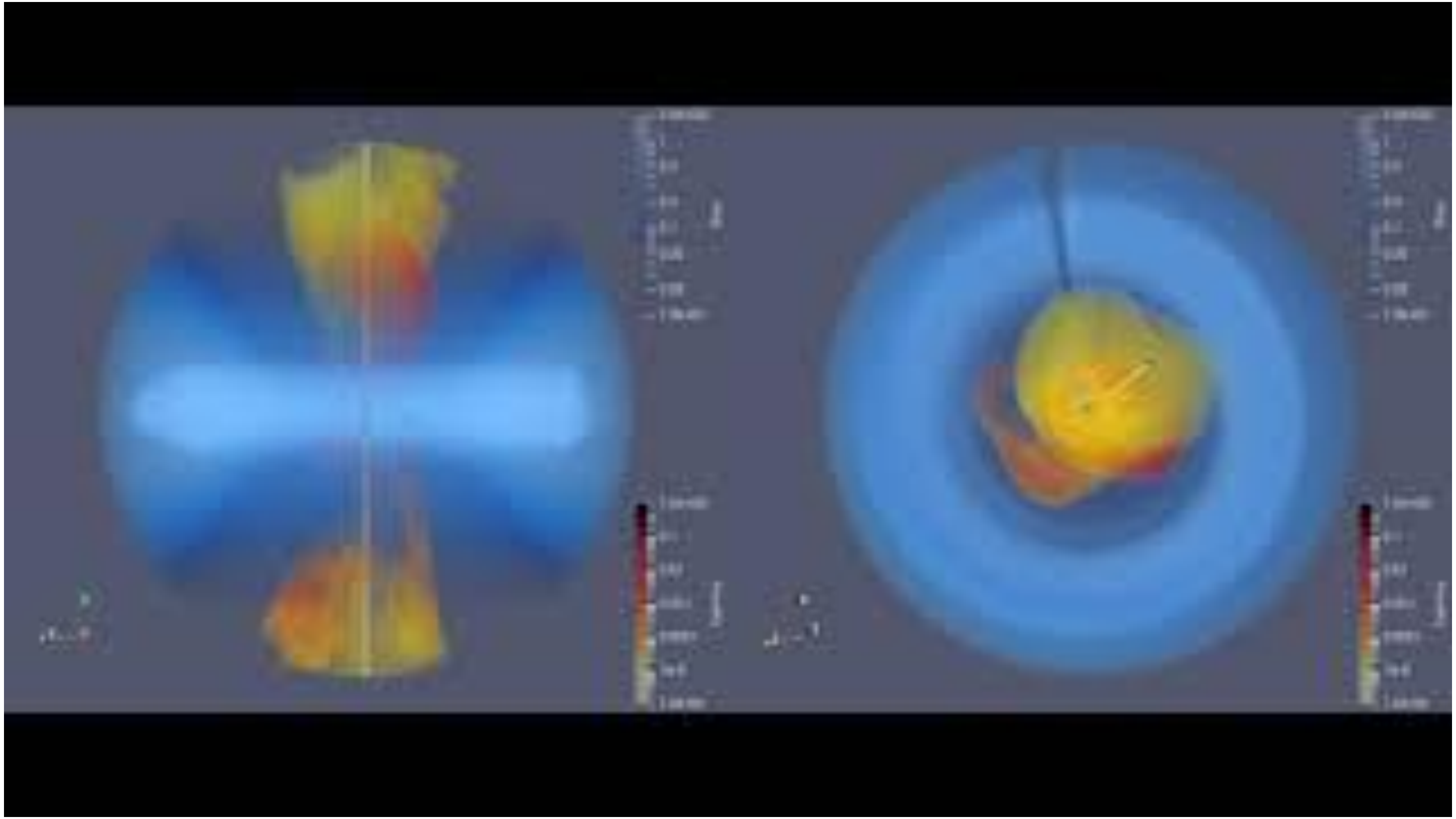


Thanks to Petra Suková, Michal Zajaček, Vojtech Witzany, Vladimir Karas

# Simulations suggests object–AGN disk interactions can drive regular magnetically-driven outflows

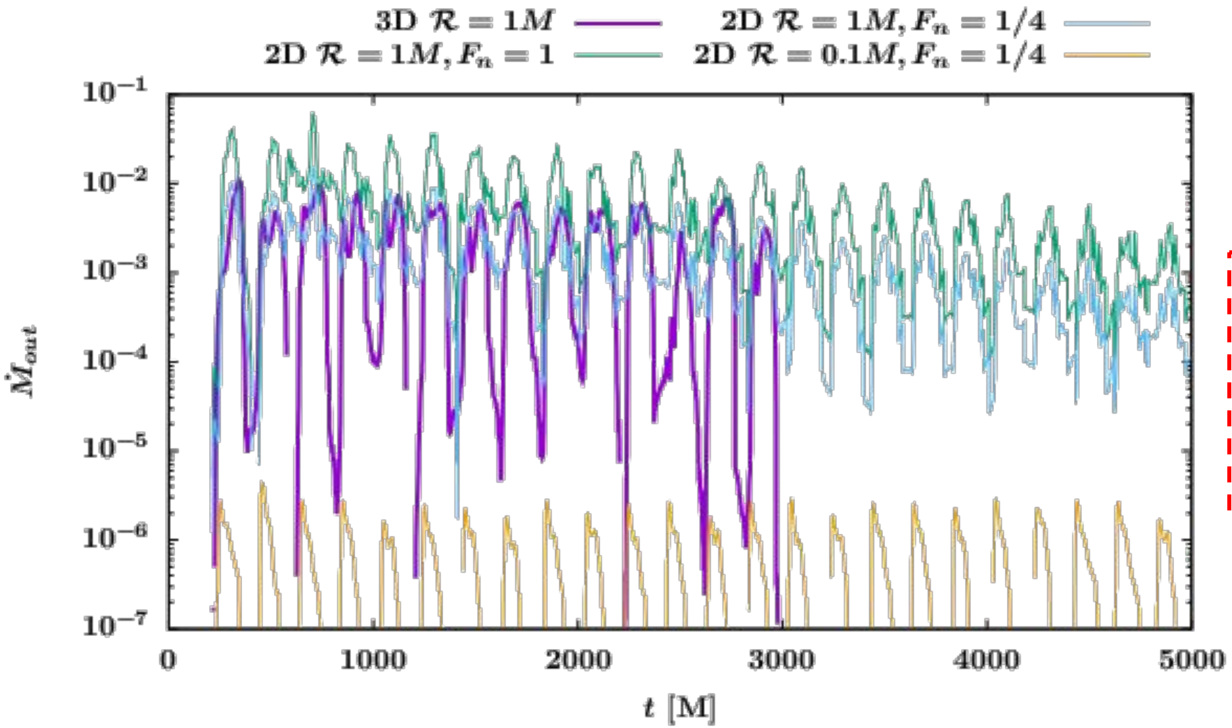


Working on fine tuning the color scheme

# Nature of the perturber/secondary

The strength of the outflow depends on the influence radius of the perturber

Outflow rate (arbitrary units)

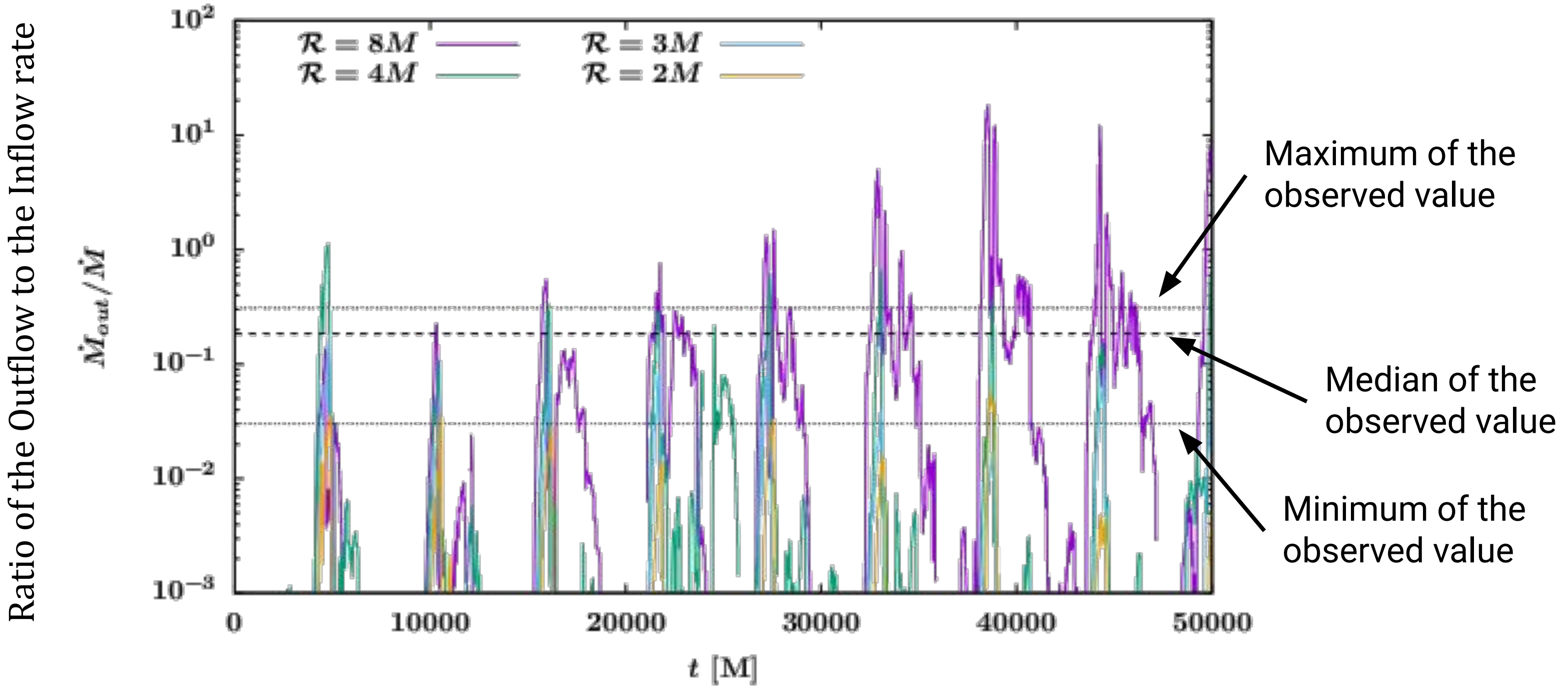



In one case, this implies the secondary is an intermediate-mass black hole ($10^{2\text{-}4}\,M_\odot$) orbiting a $10^7\,M_\odot$, i.e., an SMBH−IMBH binary

# Nature of the perturber/secondary

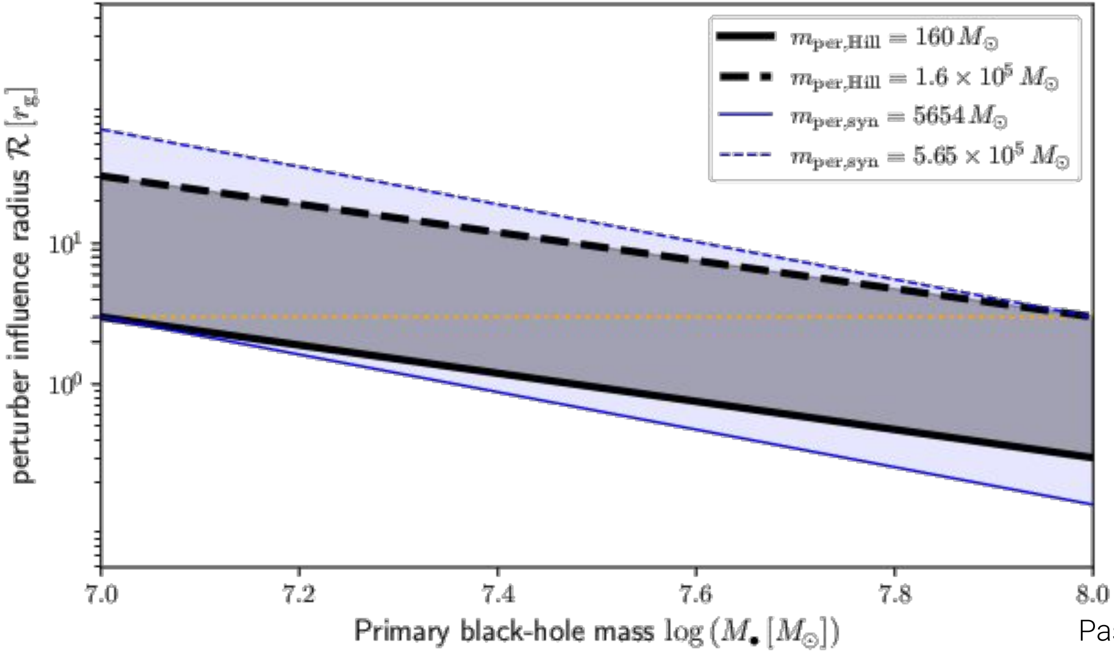
## The strength of the outflow depends on the influence radius of the perturber

Comparing observations with simulations suggests an influence radius of ~ 1 gravitational radius



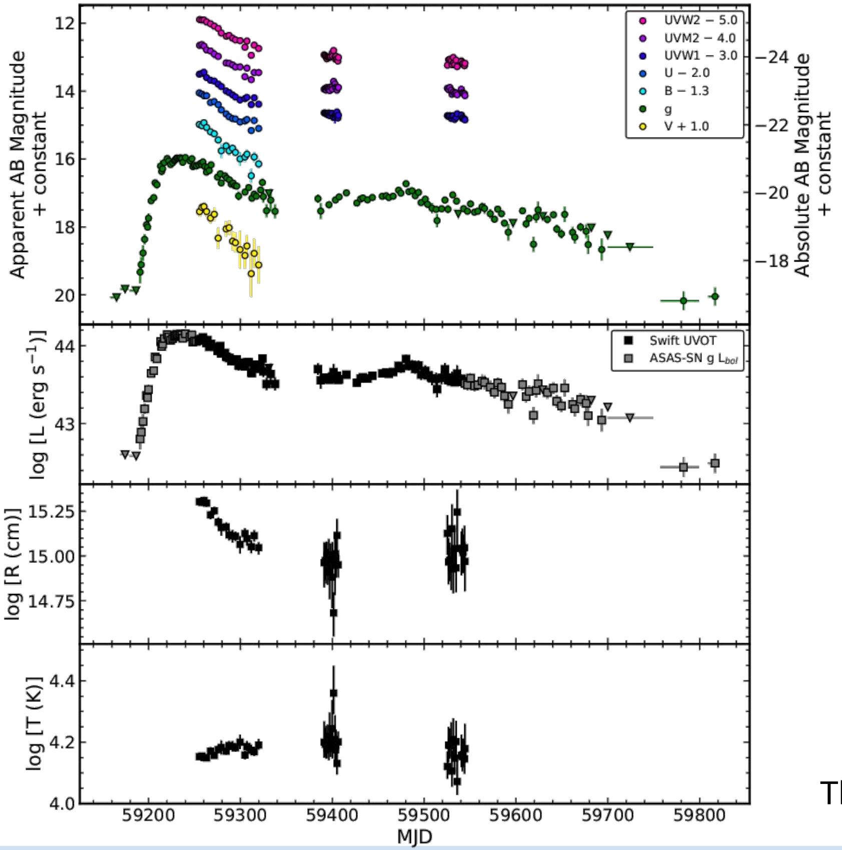
# Nature of the perturber/secondary

What objects can have an influence radius of ~ $R_g$?
Intermediate-mass Black holes (100-100,000 $M_\odot$)




Pasham et al., submitted

# Overall outburst is consistent with a tidal disruption event

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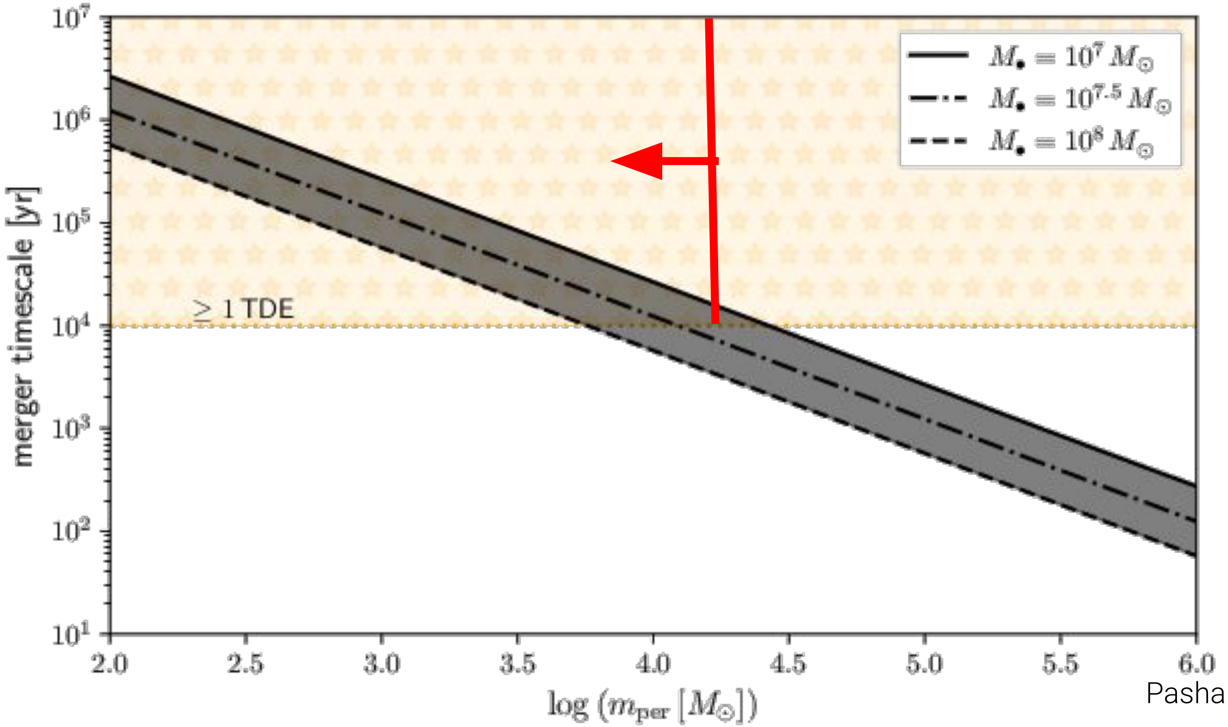
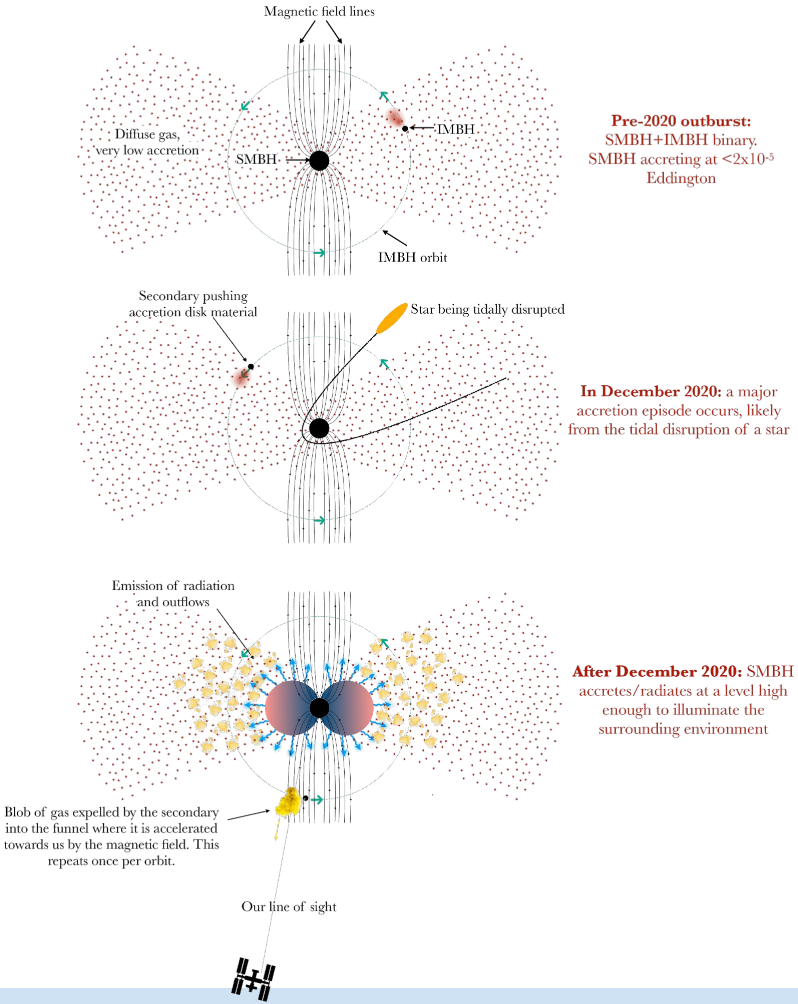
- A soft thermal spectrum
- Optical–X-ray time delay

Thanks Jason Hinkle and Ben Shappee

# The expected rate of TDEs and GW inspiral time can further constrain the perturber's mass to < 10,000 $M_\odot$



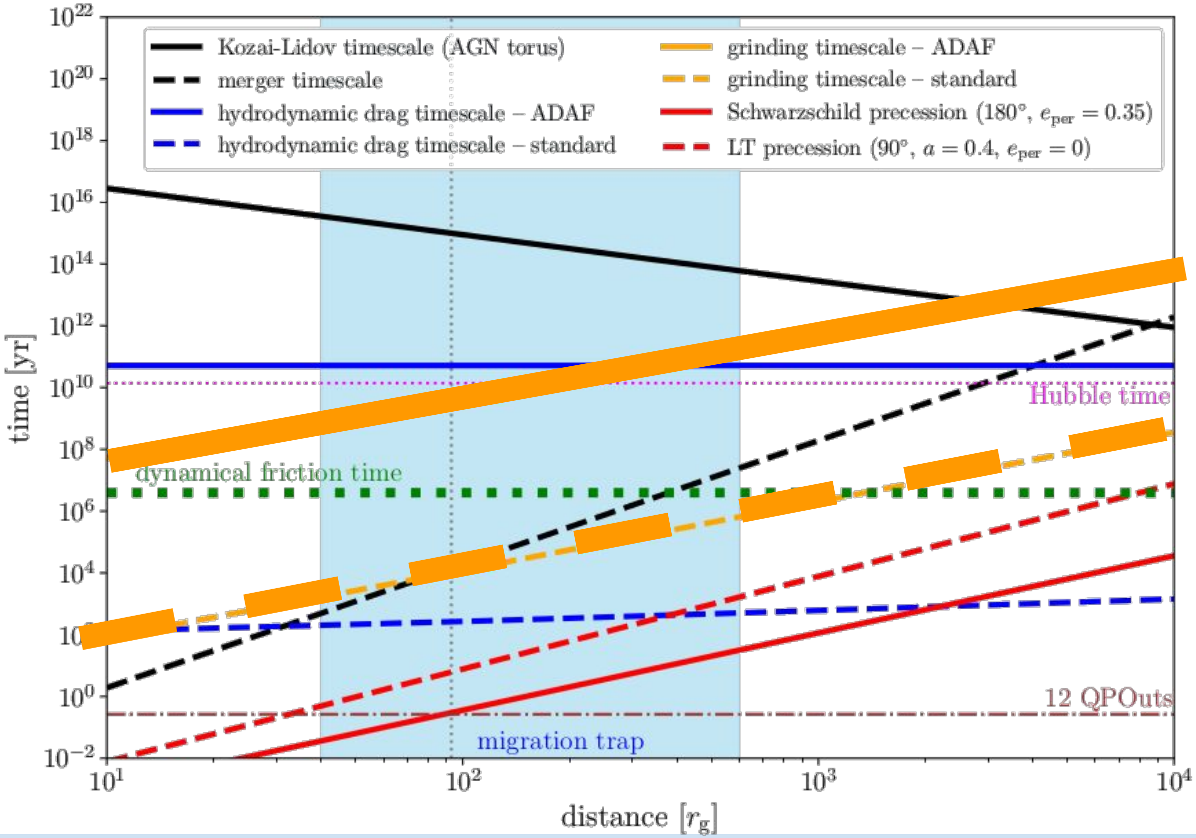

Pasham et al., submitted




# A potential model: A case for a pre-existing 10 million solar SMBH−IMBH binary (orbital separation about 100 Rg)

**Pre-existing EMRI/IMRI + TDE = QPOuts**

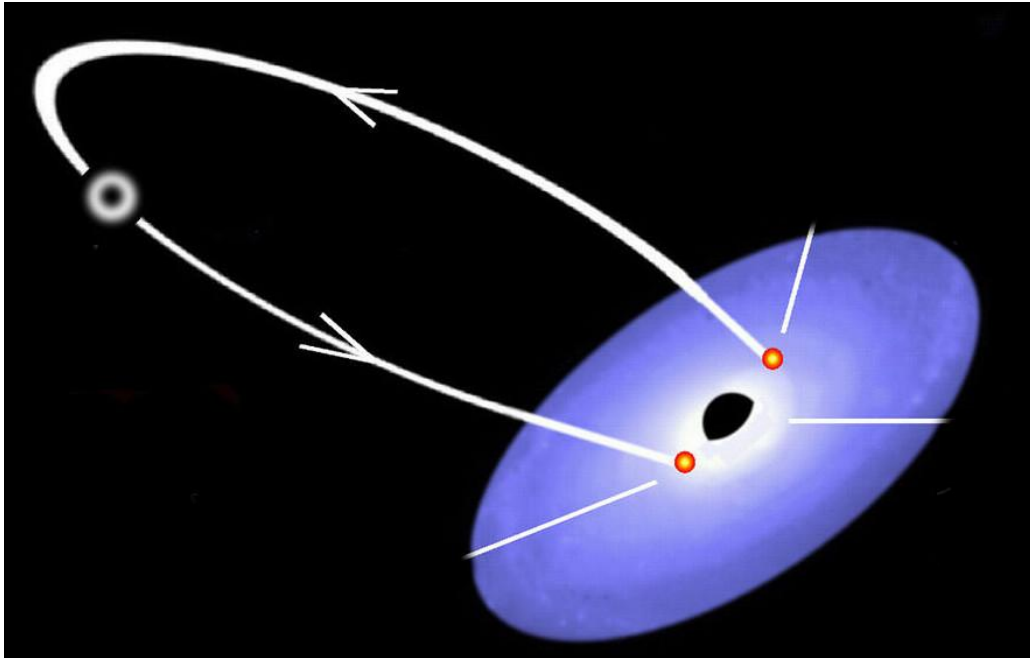
# Dynamical timescales vs IMBH ($10^4$ $M_\odot$) radial distance




Grinding timescale is long for ADAF/low-luminosity AGN

This source was a low-luminosity AGN ($<10^{-5}$ $L_{Eddington}$) prior to the outburst

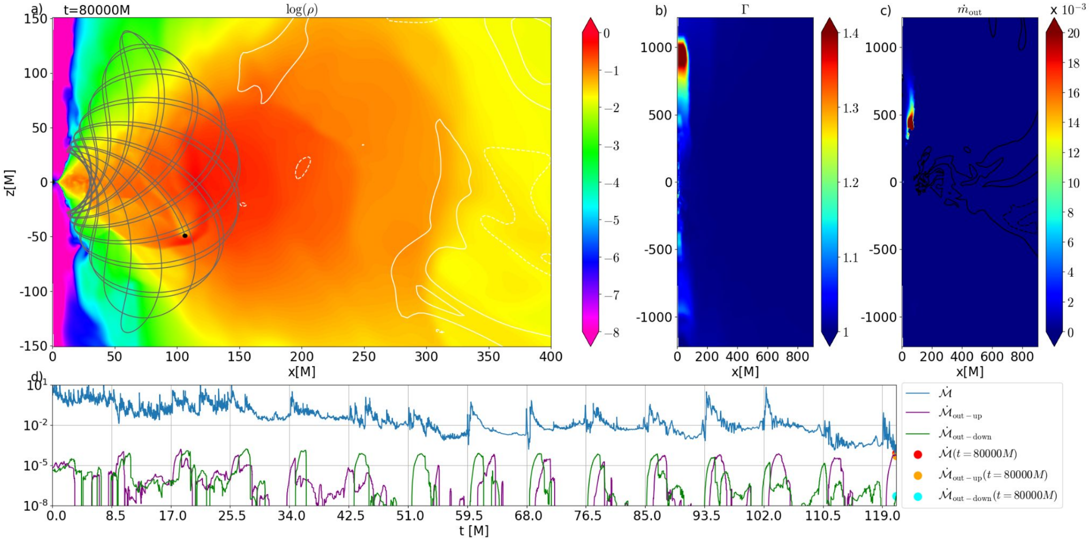
# A potential unification model: An Object Embedded in an AGN disk illuminated by a tidal disruption event

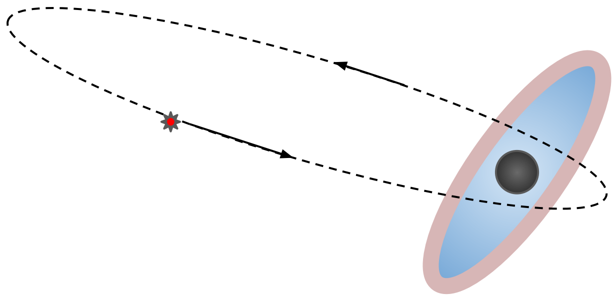


Based on work by Suková,  Zajaček, Witzany, Karas et al. 2021, ApJ, 917, 43

# The strengths of the unequal mass binary model/framework

- Minimal parameters:
    - Eccentricity
    - Geometric orientation with respect to us

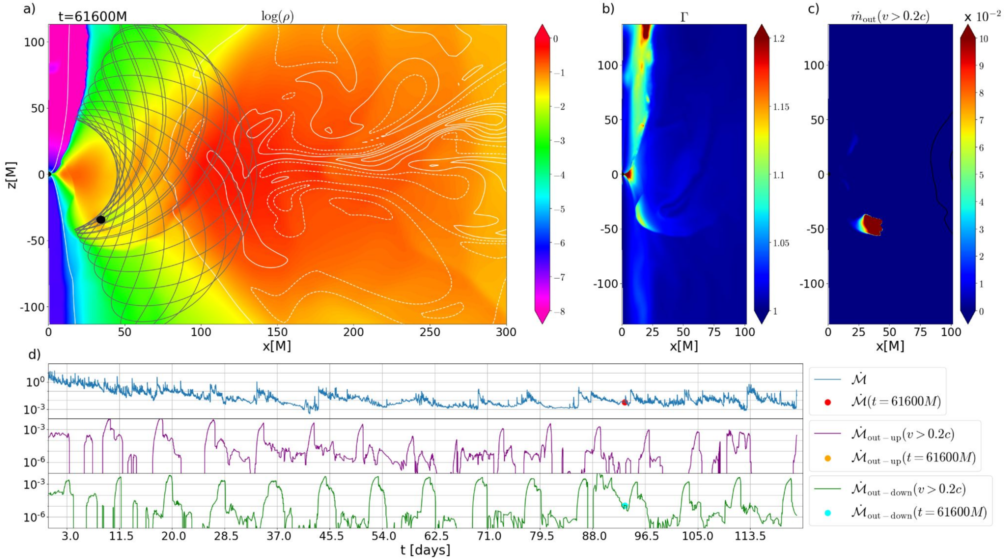


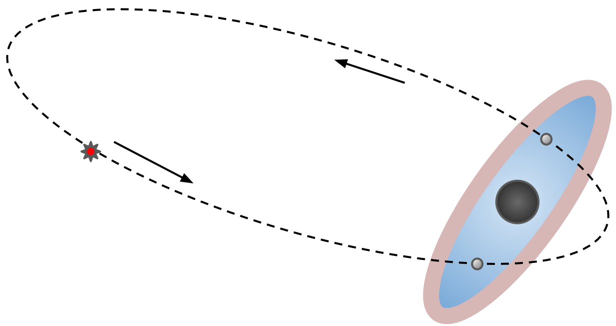



High eccentricity → secondary gets close to the primary's event horizon → modulates X-ray flux and outflows

# The strengths of the unequal mass binary model/framework

- Minimal parameters:
    - Eccentricity
    - Geometric orientation with respect to us



**Low** eccentricity → secondary **does not** get close to the primary's event horizon → weakly modulates X-ray flux (no QPEs, only QPOuts)

# The strengths of the unequal mass binary model/framework

- Minimal parameters:
    - Eccentricity
    - Geometric orientation with respect to us
- Can explain:
    - Outflows and their timing
    - The range of observed periods
    - The quasi-periodicities (eccentricity)
    - Why only some have QPOuts vs QPEs+QPOuts
    - Stochastic nature of the individual eruptions
- Strength of the outflows is determined by mass ratio

# The caveats of the unequal mass binary model/framework

- Rates of such binaries is unknown (but consistent with theoretical estimates)
- Need to explore the role of magnetic field structure and the spin on outflows
- Our simulations ignore drag/back-reaction of the accretion flow on the perturber (optically thin accretion flows)
  - Justified based on the M-σ masses and observed quiescent luminosities (low-luminosity AGN)

# Summary

- Repeating extragalactic nuclear transients <u>could be</u> from objects embedded in *low-luminosity* AGN disks
- Future work includes identifying more systems and investigating their multi-messenger potential