Searching for Small Mass Ratio Inspirals in X-rays

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Small mass ratio inspirals (SMRI)

- Close binary system
  $\rightarrow$ primary = supermassive black hole (SMBH) - mass M
  $\rightarrow$ secondary ($m < 10^{-2}M$) loses angular momentum and energy (GW,HD) and spirals towards final plunge into SMBH
- during SMRI secondary repeatedly transits through accretion flow onto SMBH $\Rightarrow$ perturbation of accretion disc/ADAF
- secondary = BH $\Rightarrow$ possible small accretion disc and jet
- secondary = star $\Rightarrow$ shocks in the atmosphere, Roche lobe overflow, (partial) tidal disruption ($\rightarrow$ no final SMRI)
- secondary = NS $\Rightarrow$ boundary layer, strong magnetic field
- $\Rightarrow$ multiwavelength variability on different time scales $\Rightarrow$ observable consequences in electromagnetic spectrum?

Identification of LISA GW sources by EM?

Questions which we want to answer:

- Can the perturber be revealed by temporal/spectral analysis?
- Can we find massive companions like IMBH or secondary SMBH in (distant) galactic nuclei?
- Is there possibility to detect ordinary stars or stellar-mass compact objects?

if yes

$\Rightarrow$

multimessenger astronomy

$=$ localization of (possible) LISA sources (even prior LISA launch!)

$\Rightarrow$ observation of ongoing EMRI in EM + GW

$\Rightarrow$ possible help to detect GW signal of known SMRI

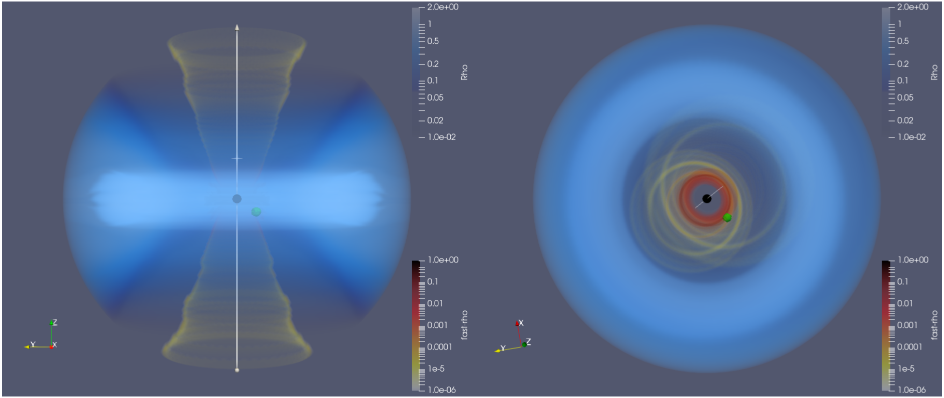
Repeating nuclear phenomena as EM counterpart?

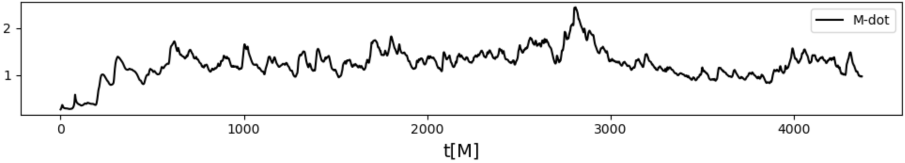
broad class of sources - showing repeating bursts of activity

- QPE - quasiperiodic eruptions
  - five sources (eRO-QPE1, eRO-QPE2, GSN 069, RX J1301)
  - soft X-ray eruptions (amplitude $\sim$ 10-100)
  - time scale: 2 - 20 hours
  - no variability in UV/optical band
- RNT - repeating nuclear transients (or repeating pTDEs)
  - ASASSN-14ko, AT2018fyk, eRASSt J045650.3-203750
  - strong (variable) UV/optical emission, long decay
  - time scale: months - years (110-1200 days)
- UFO - quasiperiodic ultra-fast outflows
  - 1 source, period 8.5 days
  - no periodicity in soft X-rays/UV/optical, quasiperiodic absorption events in harder X-rays $\Rightarrow$ outflow with $\sim 0.3c$
- 1 exceptional case Swift J0230+28
  - 22 day period - between QPE and RNT
  - no UV/optical detection, slightly slower rise, much lower luminosity $\rightarrow$ more similar to QPEs

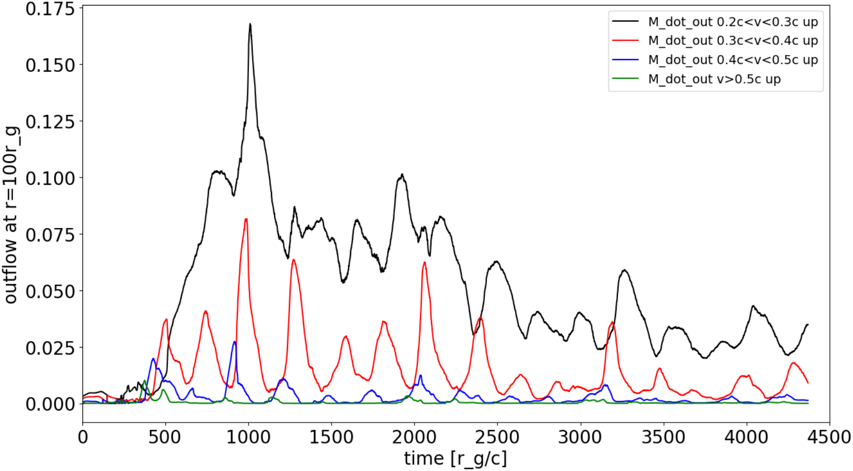
GRMHD 2D/3D simulations with HARM

- Simulations of repeating transits of secondary object through accretion disc on SMBH
- open source code package for GRMHD computations `HARMPI`
- ideal MHD, no radiation transfer $\rightarrow$ advection dominated accretion flows (ADAF)
- initial conditions: large thick torus up to 500M (Witzany & Jefremov, 2018) + poloidal magnetic field $\Rightarrow$ MRI
- perturber added into evolved torus (quasistationary state)
- stellar structure not considered $\rightarrow$ rigid body
- no feedback from the accretion flow on the star trajectory $\rightarrow$ motion along geodesics (Kerr background)
- gas inside the perturber volume (influence radius $\mathcal{R}$) is forced to move with it
- we are looking at the properties of the perturbed gas



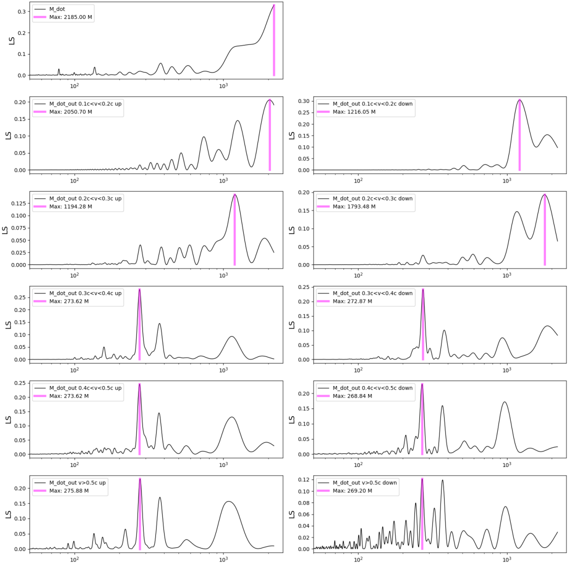


$\gamma_{\rm threshold} = 1.02 \Leftrightarrow v > 0.2c$, orbit: $10 - 14.7M$, $e = 0.19$, $i = 65.5^\circ$,
$P_r = 370M, P_\theta = 273M, P_\phi = 270M$



orbit: $10 - 14.7M$, $e = 0.19$, $i = 65.5^\circ$, $P_r = 370M$, $P_\theta = 273M$, $P_\phi = 270M$

Lomb-Scargle periodograms



$\dot{\mathcal{M}}$

$\dot{\mathcal{M}}_{\rm out}$

$0.1c < v < 0.2c$

$0.2c < v < 0.3c$

$0.3c < v < 0.4c$

$0.4c < v < 0.5c$

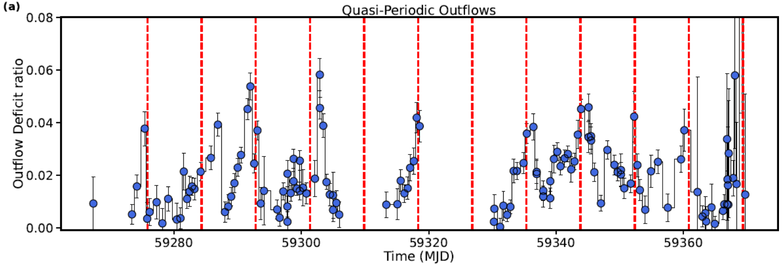
$v > 0.5c$

orbit: $10 - 14.7M$, $e = 0.19$, $i = 65.5^\circ$, $P_r = 370M$, $P_\theta = 273M$, $P_\phi = 270M$

Ultra-fast outflows (UFOs) from low luminous AGN

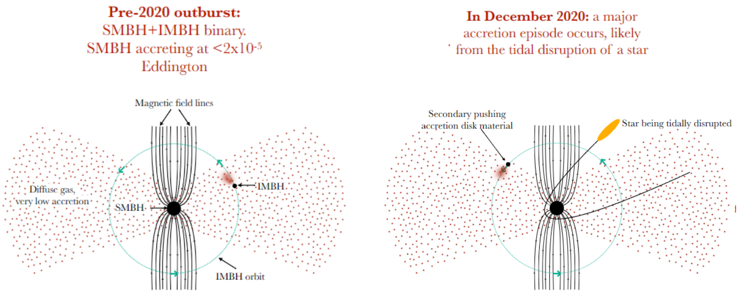
ASASSN: recent observation of nuclear transient ($z = 0.056$)

- low-luminosity AGN: $<0.002\% \ \dot{\mathcal{M}}_{\rm Edd}$ prior to the outburst
- $\sim 5\%\dot{\mathcal{M}}_{\rm Edd}$ during outburst ~ 150 days
- UFO with $v \sim 0.35c$ seen in X-rays (0.75-1.0 keV)
- outflow column density variable – period 8.5 days ($> 4\sigma$)
- higher column density together with higher ionization
- velocity constant



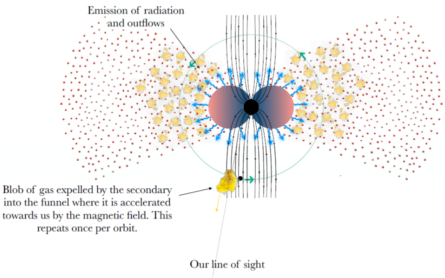
in Pasham et al. (2023, to appear in Science Advances)

Our model - perturbing body in accretion flow



- pre-outburst: perturber in diluted accretion flow (ADAF)
- perturber expells blobs of matter into funnel
- blobs accelerated along boundary of torus and funnel (velocity depends on magnetic field, spin, perturber speed)
- outburst - tidal disruption of star / episodic accretion → enhanced accretion rate up to $5 \cdot 10^{-2} \dot{\mathcal{M}}_{\rm Edd}$

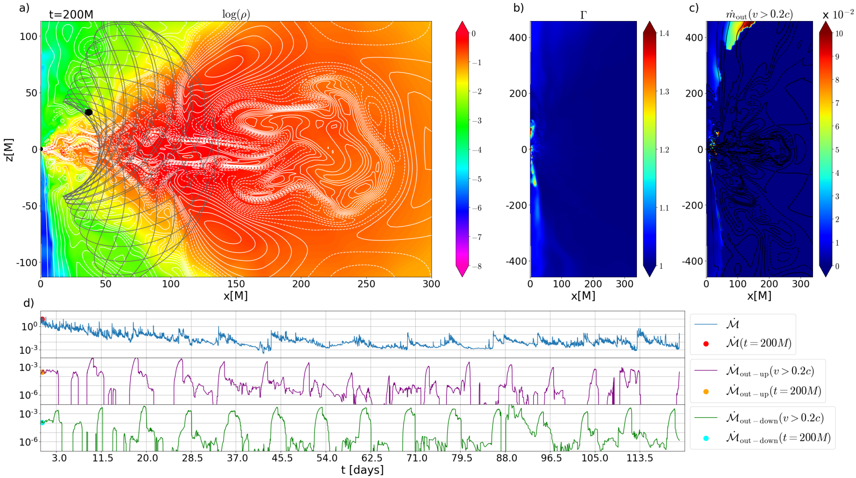
Our model - perturbing body in accretion flow



After December 2020: SMBH accretes/radiates at a level high enough to illuminate the surrounding environment

- $\sim 5\% \dot{\mathcal{M}}_{\rm Edd} \Rightarrow$ very small optically thick disc in the innermost region + ADAF from previous low luminosity state around?
- enhanced accretion $\rightarrow$ brighter $\rightarrow$ better spectral resolution
- outflow observed as absorption of the radiation from center $\rightarrow$ only outflow going towards us seen (i.e. one event per orbit) $\rightarrow$ reveals presence of perturbing body
- mass estimate used in simulations:
  $M = 10^{7.4} M_{\odot} \Rightarrow r_* \sim 93$M; $M = 10^{7.95} M_{\odot} \Rightarrow r_* \sim 40$M

Simulation for ASSASN source



observed outflow/inflow ratio at peaks $\sim 0.2 \Rightarrow$ in simulations best agreement for $\mathcal{R} \sim 3M \Rightarrow$ IMBH $(10^3 - 10^4 M_\odot) \Rightarrow$ future IMRI!

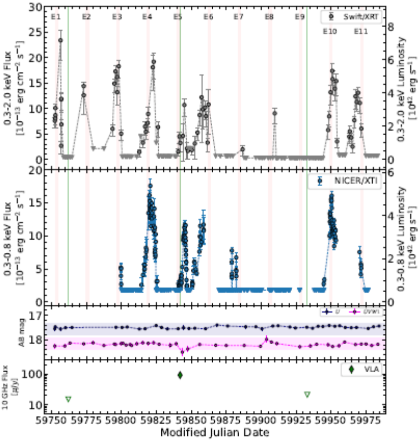


Figure 1: **Light curves of Swift J0230+28. Top**: *Swift*/XRT 0.3-2.0 keV flux and luminosity evolution. Stacked 3σ upper limits between the eruptions are 2×10^{-14} erg s^{-1} cm^{-2}. **Middle**: *NICER* 0.3-0.8 keV flux and luminosity evolution. In both X-rays panels, circles are detections, reverse triangles are 3σ upper limits of non-detections, and shaded pink regions indicate the $21.8^{+1.2}_{-0.5}$ days peak period found in the LSP analysis (see "Time-resolved X-ray analyses" in Methods). **Bottom**: UV/optical and Radio light curves. *Swift*/UVOT UV $W1$ and U bands are respectively dark blue and magenta points. The shaded region represents the $\pm 2\sigma$ dispersion of the magnitude before the start of the X-ray eruptions (Dec 2021 to Jan 2022). Radio VLA observations are shown in green diamond (detection) and inverse triangles (non-detection upper limits), green dashed lines marks the epochs of the radio observations for reference. Error bars

- large X-ray flares
- non-detection prior and in between flares
- no UV/optical activity
- period 22 days
  - 25x longer than QPEs
- $\log(M_{\rm BH}/M_{\odot}) = 6.6 \pm 0.4$ (same as Sgr A*)
- $\sim 30\%$ longer rises
- fainter than RNTs $\rightarrow$ mass accreted per eruption $\sim 10^{-4} - 10^{-5} M_{\odot}$
- more similar to QPEs
- Guolo et al. (2024, Nat. Astron.)

Comparison of Swift J0230+28 and other QPEs

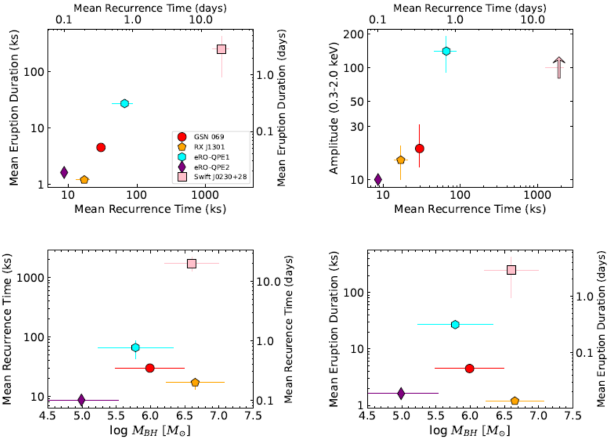


Figure 3: **Phase space diagrams for QPEs and Swift J0230+28. Upper Left:** mean QPE duration vs. mean recurrence time. **Upper Right:** Amplitude (0.3-2.0 keV band) vs. mean recurrence time. **Bottom Left:** Mean recurrence time vs. black hole mass ($M_{\rm BH}$) derived from host-galaxy stellar velocity dispersion. **Bottom Right:** Mean Eruption Duration vs. black hole mass ($M_{\rm BH}$). The top panels show some tentative correlations, such correlations are extended by at least an order of magnitude if Swift J0230+28 is considered a QPE source. There is no correlation between the timing properties and the $M_{\rm BH}$. This figure is based on (*46*). The values are shown in Extended Data Table 5, uncertainties in the timing properties and amplitudes

Possible physical models for Swift J0230+28
I. accretion flow instabilities

- ionization instability
  - no variability at $\sim$ 2500nm
- radiation-pressure instability
  - typically longer period (can be fine-tuned)
  - operates at high luminosity $\lambda_{\mathrm{Edd}} = 0.6$
  - ! non-detection between flares: $\lambda_{\mathrm{Edd}} = L_{\mathrm{bol}}/L_{\mathrm{Edd}} < 0.002$

  $\Rightarrow$ no standard thin disc exists
- Lense-Thirring precession and the warping of an accretion disc misaligned with the black-hole spin
  - order or two shorter period,
  - different shape of flares
  - non-existing thin disc

$\Rightarrow$ disfavored

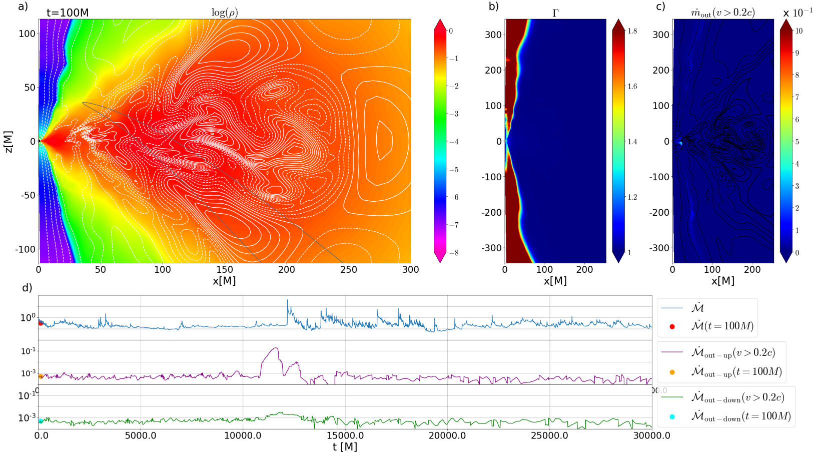
Possible physical models for Swift J0230+28
II. orbiting secondary body (SMRI)

$P = 22(44)$ days $\Rightarrow \sim 1(2)10^5 M \Rightarrow$ semi-major axis $\sim 620(985)M$

- partial TDE of white dwarf - prefered for other shorter QPEs
  - tidal radius r_t inside horizon, partial tidal radius $\sim 2r_t$
  - only $\lesssim 10^{-4} M_\odot$/flare - pericenter fine-tuned $\sim 2r_t \Rightarrow$ e $\rightarrow 1$
  - "eruption holidays" - some flares are weak/short/missing
- partial TDE of a main sequence star
  - $R_* \sim 0.4R_\odot, M_* \sim 0.4M_\odot \rightarrow r_t \sim 10M$
  - fine-tuned pericenter, "eruption holidays"
- compressed reformed clumps from a past TDE - shorter flares
- stellar-mass transfer via Roche lobe overflow
  - evolved star with $R_* \gtrsim 33R_\odot$ and slightly eccentric orbit
- two interacting stellar EMRIs
  - two stars $m_1 < m_2$ at very close co-planar circular orbits
  - enhanced matter overflow from m_2, when close together

Possible physical models for Swift J0230+28
our scenario: perturber-induced accretion events

- excentric orbit - pericenter distance $20M - 150M$
- $\mathcal{R} \sim 1 - 10M \Rightarrow$ increased accretion rate for $\sim$ days



Conclusions

- GRMHD simulations of repetitive star transits through ADAF:
  - ingoing/outgoing density waves in the accretion flow
  - outgoing relativistic blobs along the torus/funnel boundary
  - influence on the matter distribution
  - changes of the accretion rate (drops and peaks)
  - quasiperiodic features in accretion and/or outflowing rate – may be connected with orbital period
- broad discussion in **Suková+21, ApJ, 917, 43**
- candidate system discovered with ASASSN – quasiperiodic UFOs from LLAGN $\rightarrow$ studied in **Pasham+24, Sci. Adv.** - outflow strength $\rightarrow \mathcal{R} \sim 3M \Rightarrow$ IMBH ($10^3 - 10^4 M_\odot$)
- possible model for ultra-long QPE Swift J0230+28 (details on different models in **Guolo+24, Nat. Astron.**)
- show possible observable EM traces of SMRI

Thank you for your attention!