Will UFOs show us SMRIs?

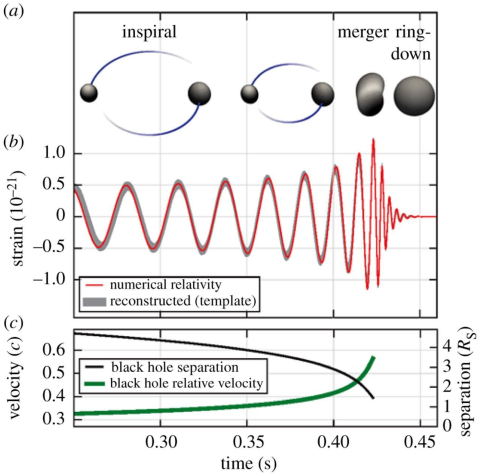
Petra Suková
Astronomical Institute of the CAS
Prague, Czech Republic

Vladimír Karas, Michal Zajaček, Vojtěch Witzany,
Dheeraj Pasham, Francesco Tombesi, Muryel Guolo

Galactic Nuclei in the Cosmological Context
Szczecin
4.6.2024

Current gravitational waves observation

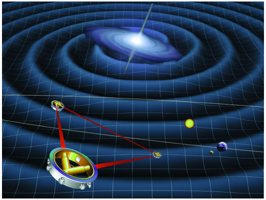
- ground-based detectors LIGO/VIRGO etc. $\sim$ 10 Hz - 10 kHz
- Mergers of stellar-mass black holes/neutron stars
- duration $\lesssim$ second
- one source at the time
- detection: usually match-filtering
- database of GW templates with different parameters



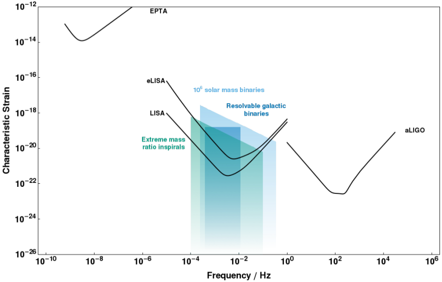
Abbott BP et al. 2016, Phys. Rev. Lett. 116, 061102

Future of gravitational waves observation

- LISA - Laser Interferometer Space Antenna - in 2030s (?)
- three spacecraft, 2.5 million km arms, laser beam



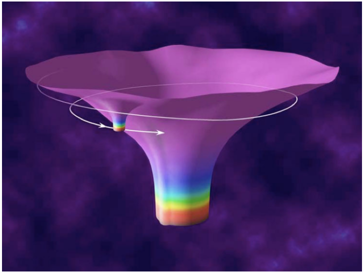
By Christopher Moore, Robert Cole and Christopher Berry

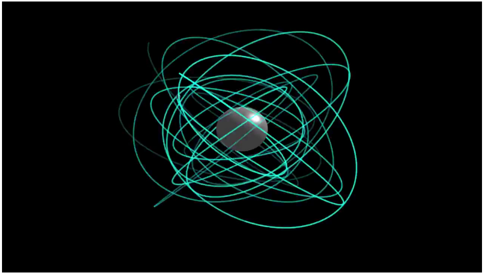


- frequency range → 0.1mHz - 1 Hz (hours to seconds)
- different astrophysical phenomena: e.g. supermassive black hole binaries, small-mass-ratio inspirals (SMRIs) and bursts, binary stars within our galaxy

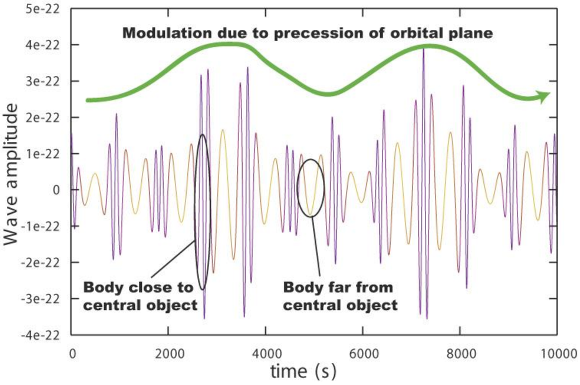
Small mass ratio inspirals (SMRI)

- long-duration inspiral and plunge of secondary body (m) into supermassive black hole (SMBH - mass M)
- EMRI: stellar-mass compact object $\rightarrow 10^{-9} < \frac{m}{M} < 10^{-4}$
- IMRI: intermediate-mass black hole $\rightarrow 10^{-4} < \frac{m}{M} < 10^{-2}$
- complicated orbit, duration: $\sim M/m$ orbits $\rightarrow$ weeks to years





Typical waveform of EMRI



- many sources detected simultaneously
- "miss one cycle = miss the template completely!"
  duration: $\sim M/m = 10^2 - 10^9$ orbits! $\rightarrow$ detection challenge
- poor angular resolution

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 SMRI in EM + GW

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

Repeating nuclear phenomena as EM counterpart?

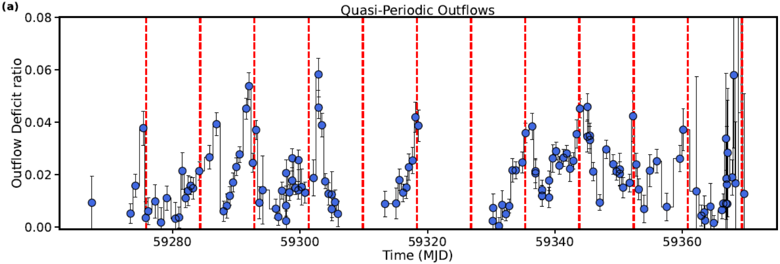
broad class of sources - showing repeating bursts of activity

- QPE - quasiperiodic eruptions
  - four sources (GSN 069, eRO-QPE1, eRO-QPE2, 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)
- quasiperiodic ultra-fast outflows (**Pasham+24, Sci. Adv.**)
  - 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 (**Guolo+24, Nat. Astron.**)
  - 22 day period - between QPE and RNT
  - no UV/optical detection, slightly slower rise, much lower luminosity $\rightarrow$ more similar to QPEs

Ultra-fast outflows (UFOs) from low luminous AGN

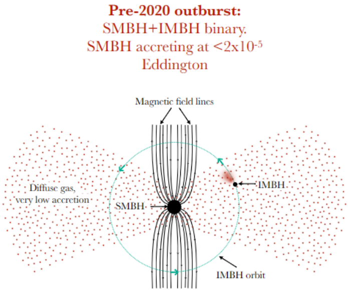
ASASSN: recent observation of nuclear transient ($z = 0.056$)

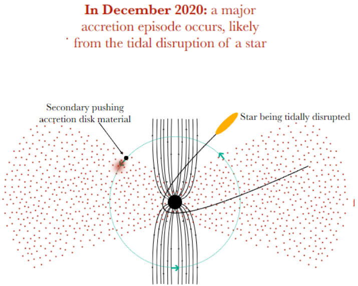
- low-luminosity AGN: $<0.002\%\ \dot{\mathcal{M}}_{\rm Edd}$ prior to the outburst
- $\sim 5\%\dot{\mathcal{M}}_{\rm Edd}$ during outburst ~ 150 days
- UFO with $v \sim 0.35c$ seen in X-rays (0.75-1.0 keV)
- outflow column density variable – period 8.5 days ($> 4\sigma$)
- higher column density together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



in Pasham et al. (2024), Science Advances

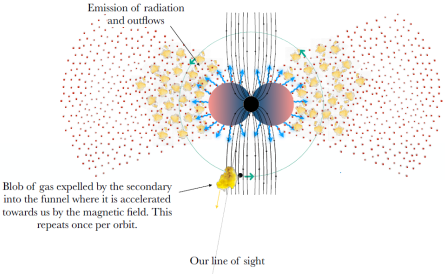
Our model - perturbing body in accretion flow





- 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 $\rightarrow$ enhanced accretion rate up to $5 \cdot 10^{-2} \dot{\mathcal{M}}_{\rm Edd}$

Our model - perturbing body in accretion flow

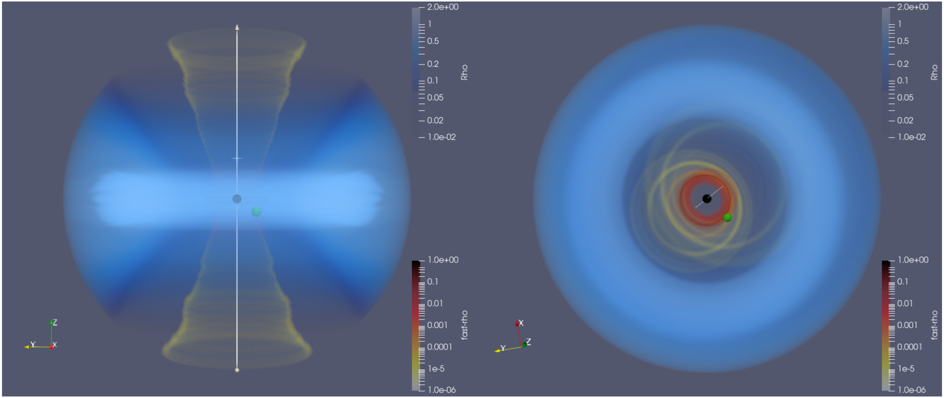


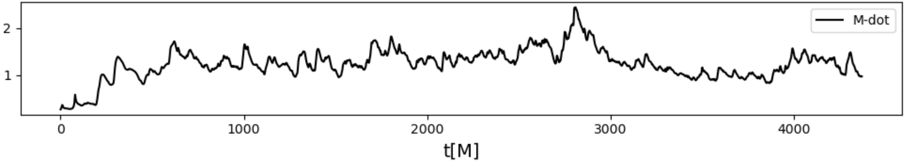
After December 2020: SMBH accretes/radiates at a level high enough to illuminate the surrounding environment

- $\sim 5\%\dot{\mathcal{M}}_{\rm Edd} \Rightarrow$ very small optically thick disc in the innermost region + ADAF from previous low luminosity state around?
- enhanced accretion → brighter → better spectral resolution
- outflow observed as absorption of the radiation from center → only outflow going towards us seen (i.e. one event per orbit) → reveals presence of perturbing body

GRMHD 2D/3D simulations with HARM

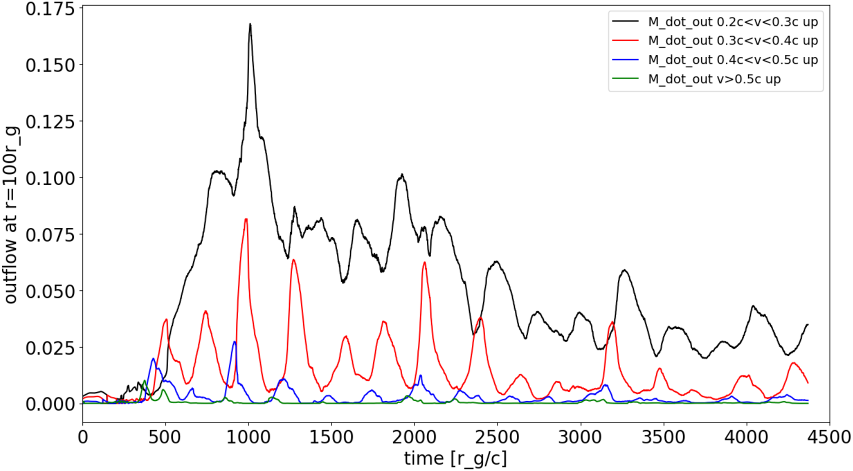
- Simulations of repeating transits of secondary object through accretion disc on SMBH
- open source code package for GRMHD computations `HARMPI`
- ideal MHD, no radiation transfer $\rightarrow$ advection dominated accretion flows (ADAF)
- initial conditions: large thick torus up to 500M (Witzany & Jefremov, 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





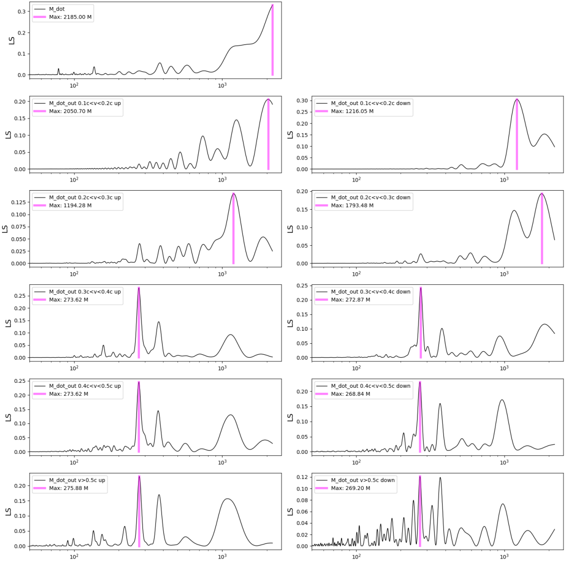
$\gamma_{\text{threshold}} = 1.02 \Leftrightarrow v > 0.2c$, orbit: $10 - 14.7M$, $e = 0.19$, $i = 65.5^\circ$,
$P_r = 370M$, $P_\theta = 273M$, $P_\phi = 270M$

Outflow launched by the secondary



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

Lomb-Scargle periodograms



$\dot{\mathcal{M}}$

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

$0.1c < v < 0.2c$

$0.2c < v < 0.3c$

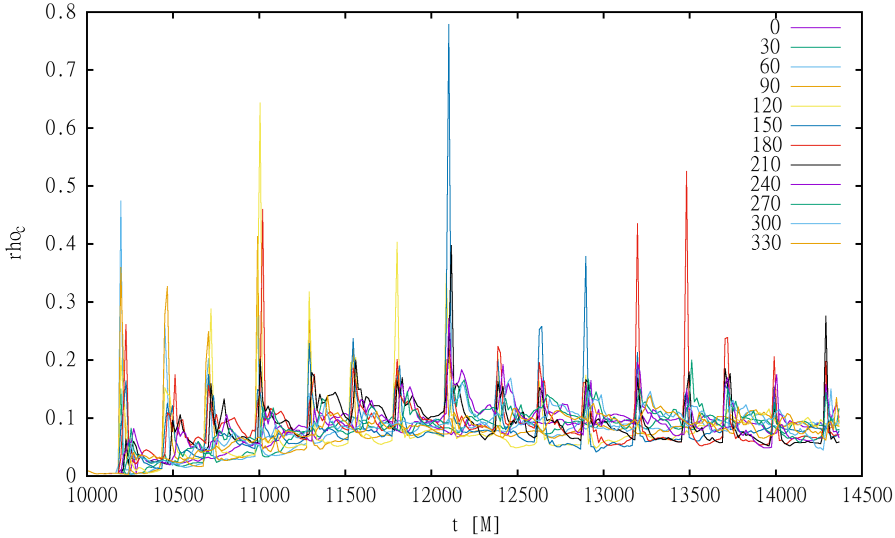
$0.3c < v < 0.4c$

$0.4c < v < 0.5c$

$v > 0.5c$

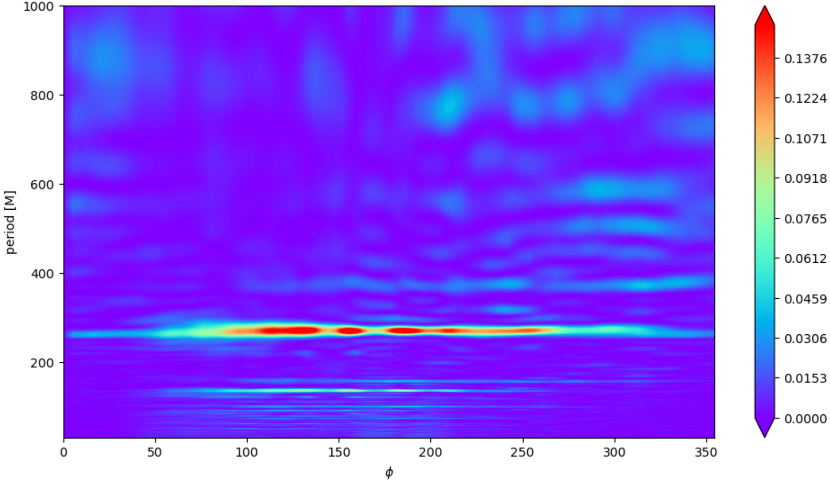
orbit: $10 - 14.7M$, $e = 0.19$, $i = 65.5^\circ$, $P_r = 370M$, $P_\theta = 273M$, $P_\phi = 270M$

Outflow column density variations ($\theta = 30^\circ$, changing ϕ)



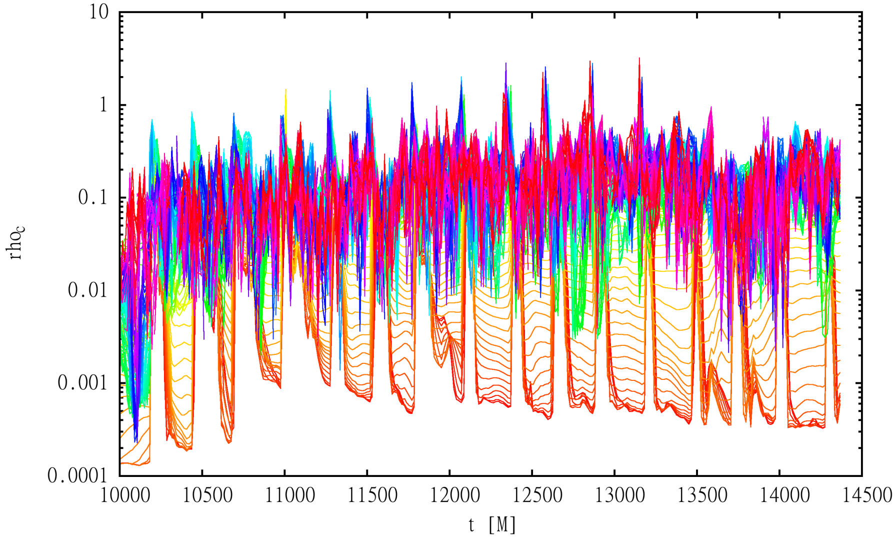
orbit: $10 - 14.7M$, $e = 0.19$, $i = 65.5^\circ$, $P_r = 370M$, $P_\theta = 273M$, $P_\phi = 270M$

Outflow column density variations ($\theta = 30^\circ$, changing ϕ)

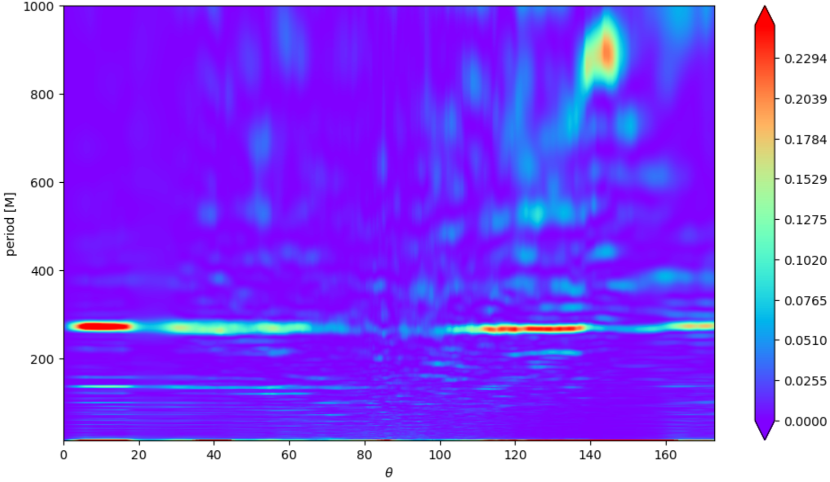


orbit: $10 - 14.7M$, $e = 0.19$, $i = 65.5^\circ$, $P_r = 370M$, $P_\theta = 273M$, $P_\phi = 270M$

Outflow column density variations ($\phi = 120^\circ$, changing θ)

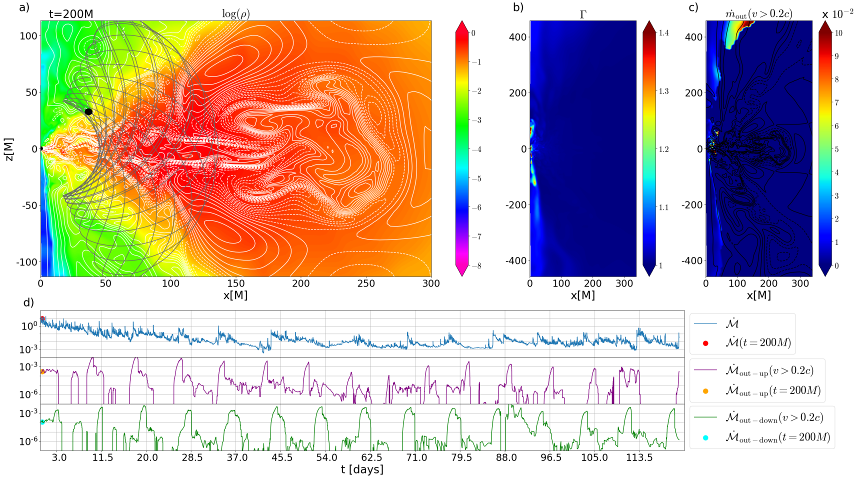


orbit: $10 - 14.7M$, $e = 0.19$, $i = 65.5^\circ$, $P_r = 370M$, $P_\theta = 273M$, $P_\phi = 270M$



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

Simulation for ASSASN-20qc ($M = 10^{7.4} M_\odot \Rightarrow r_* \sim 93M$)



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!

Case of Swift J0230+28 - extraordinary QPE?

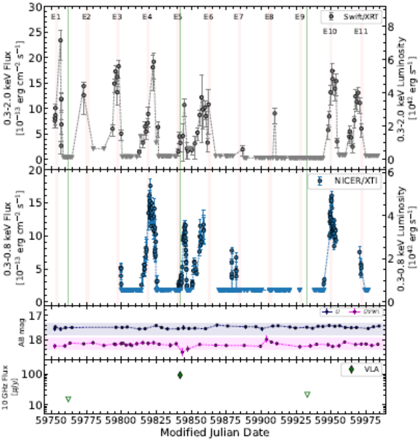


Figure 1: **Light curves of Swift J0230+28. Top**: *Swift*/XRT 0.3-2.0 keV flux and luminosity evolution. Stacked 3σ upper limits between the eruptions are 2×10^{-14} erg s^{-1} cm^{-2}. **Middle**: *NICER* 0.3-0.8 keV flux and luminosity evolution. In both X-rays panels, circles are detections, reverse triangles are 3σ upper limits of non-detections, and shaded pink regions indicate the $21.8^{+1.2}_{-0.6}$ 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

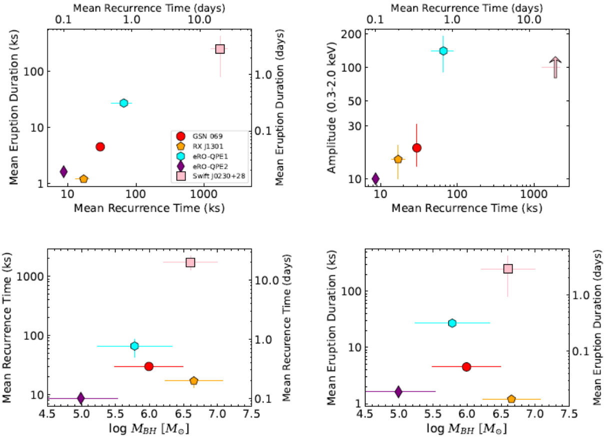
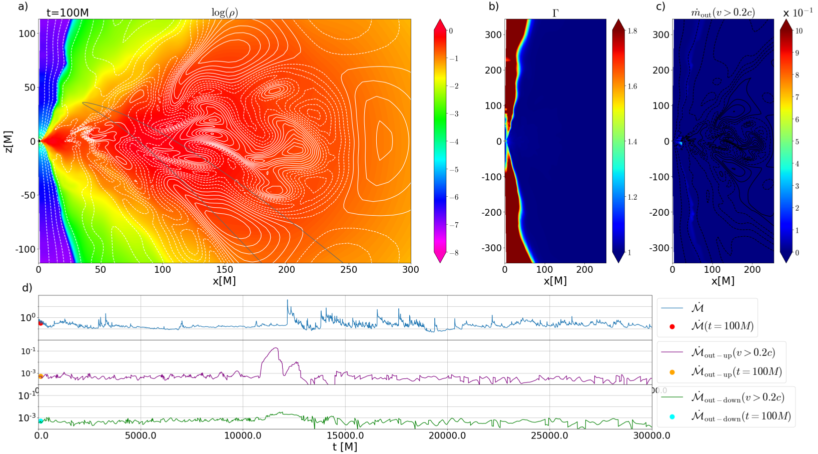


Figure 3: **Phase space diagrams for QPEs and Swift J0230+28. Upper Left:** mean QPE duration vs. mean recurrence time. **Upper Right:** Amplitude (0.3-2.0 keV band) vs. mean recurrence time. **Bottom Left:** Mean recurrence time vs. black hole mass ($M_{\rm BH}$) derived from host-galaxy stellar velocity 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

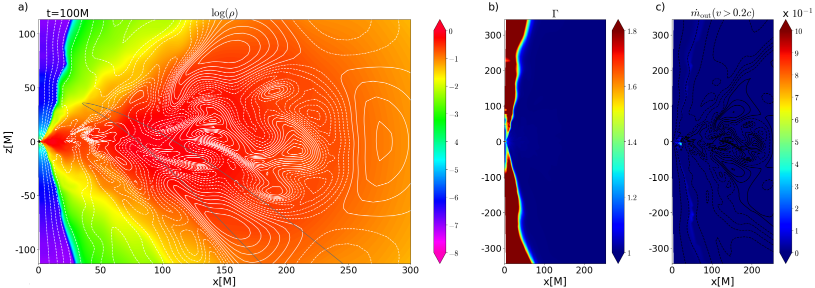
Possible physical models for Swift J0230+28
our scenario: perturber-induced accretion events

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



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



- ✓ increased accretion rate, UFOs, generic orbit parameters
- ✗ shorter flares ($\sim$ 1 day), big secondary ($\mathcal{R}$)

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!

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

- ionization instability
  ✗ no variability at ~ 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 star: $R_* \sim 0.4 R_\odot$, $M_* \sim 0.4 M_\odot \rightarrow r_t \sim 10M$
  ✗ fine-tuned pericenter, "eruption holidays"
- compressed reformed clumps from a past TDE: ✗ shorter flares
- stellar EMRI with Roche lobe overflow (Krolik & Linial, 2022)
  ✓ evolved star with $R_* \gtrsim 33 R_\odot$ and slightly eccentric orbit
- two interacting stellar EMRIs (Metzger et al., 2022)
  - two stars $m_1 < m_2$ at very close co-planar circular orbits
  ✓ enhanced matter overflow from m_2, ✗ fine-tuned