Observational traces of supermassive black hole companions

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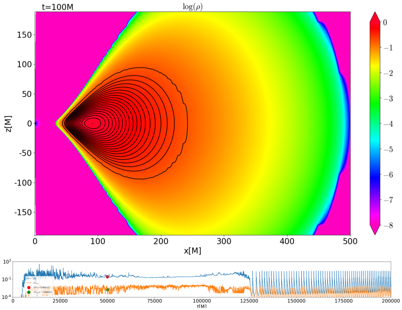
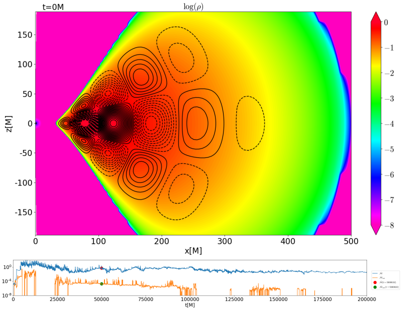
Motivation

- Intermediate/Extreme Mass Ratio Inspirals (IMRI/EMRI)
  - small compact object spiralling into supermassive black hole
  - repeatedly transiting through accretion flow onto SMBH
- $\Rightarrow$ perturbation of discs/Advection Dominated Accretion Flows (ADAF)
- $\Rightarrow$ multiwavelength variability on different time scales $\Rightarrow$ observable consequences in electromagnetic spectrum?
- Can the perturber be revealed by temporal/spectral analysis?
- multimessenger astronomy – localization of possible LISA sources
- possibility to find massive companions like IMBH or secondary SMBH in distant galactic nuclei?
- possibility to detect usual stars or stellar-size compact objects?

- GRMHD simulation of the flow → ideal MHD with `HARMPI` (Gammie et al, 2003; Tchekhovskoy et al., 2016)
  – radiation transfer is not taken into account
- initial conditions: large thick torus up to 500M (Witzany & Jefremov, 2018) + poloidal magnetic field ⇒ MRI
  - one loop → magnetically arrested disc (MAD)
  - more loops → standard and normal evolution (SANE)





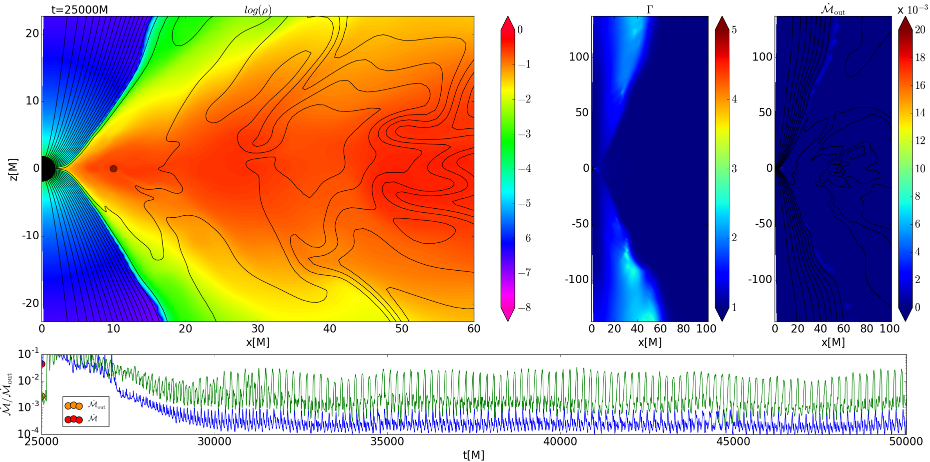
Stellar transit through the flow via GRMHD

- perturber added into evolved torus (quasistationary state) ($t_{\mathrm{init}} \sim 20\,000M - 50\,000M$, $t_{\mathrm{f}} \sim 100\,000 - 200\,000M$)
- stellar structure not considered $\rightarrow$ solid body
- no feedback from the accretion flow on the star trajectory $\rightarrow$ motion along geodesics (Kerr background)
- dynamical effect of the star on the gas
  - consecutive perturbation by moving body:

$$
\begin{aligned}
d &= \sqrt{\left(g^{\mathrm{BL}}_{\alpha\beta}\Delta x^{\alpha}\Delta x^{\beta}\right)} \\
\Delta x^{\alpha} &= x^{\alpha}_{\mathrm{star}} - x^{\alpha}_{\mathrm{gas}} \\
d \leq \mathcal{R} &\Rightarrow v_{\mathrm{gas}} = v_{\mathrm{star}}
\end{aligned}
$$

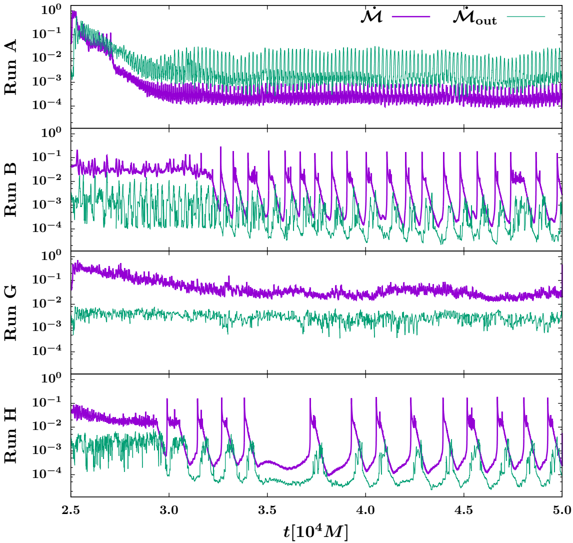
  - radius $\mathcal{R}$ corresponds to stagnation/synchronization radius
- 2D runs: ϕ coordinate of the star is "forgotten" $\Delta x^{\phi} = 0$

Run A – gas evolution: density, Lorentz factor, outflow



$\mathcal{R} = 1M$, $r = 10M$, MAD disc, $\beta = p_g/p_m = 100$

Accretion (purple) + outflowing (green) rate



Inclined
$r \sim 10\,M$, $\mathcal{R} = 1\,M$

Embedded
$r : 10 - 25\,M$,
$\mathcal{R} = 1\,M$

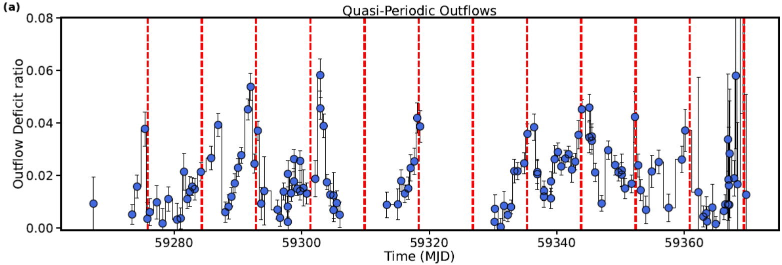
Inclined
same as Run A
$\mathcal{R} = 0.1\,M$

Embedded
$r \sim 10\,M$, $\mathcal{R} = 1\,M$

results ⇒ `Suková et al., 2021, ApJ, 917, 43`

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

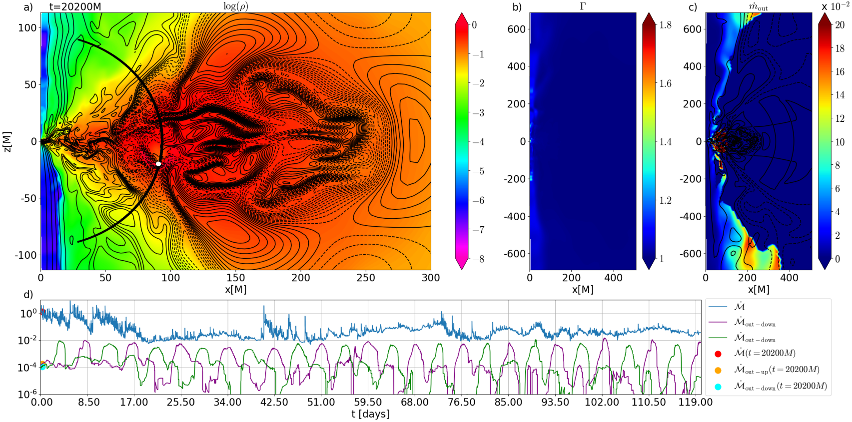
- low-luminosity AGN: $<0.002\%\ \dot{\mathcal{M}}_{\rm Edd}$ prior to the outburst
- $\sim 5\%\dot{\mathcal{M}}_{\rm Edd}$ during outburst ~ 150 days
- ultrafast outflow with $v \sim 0.35c$ seen in X-rays (0.75-1.0 keV)
- outflow column density variable – period 8.5 days ($> 4\sigma$)
- higher column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



in cooperation with D. Pasham and F. Tombesi

Our model - perturbing body in accretion flow

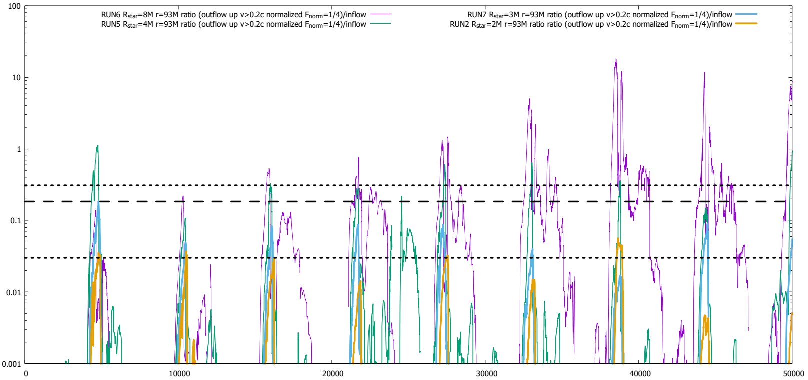
- outburst - tidal disruption of star OR
  - episodic accretion
- enhanced supply of matter reveals presence of perturbing body
- perturber expells blobs of matter into funnel
- blobs accelerated by the magnetic field in the funnel (velocity depends on magnetic field and spin)
- $\sim 5\% \dot{\mathcal{M}}_{\rm Edd}$ during outburst $\rightarrow$ ADAF in the inner part?
- outflow observed as absorption event $\rightarrow$ only outflow going towards us seen (i.e. one flare per orbit)
- mass estimate used in simulations:
  $M = 10^{7.4} M_{\odot} \Rightarrow$ circular orbit $r_* \sim 93$M
  $M = 10^{7.95} M_{\odot} \Rightarrow$ circular orbit $r_* \sim 40$M
- current mass estimate: $M = 10^{7.2 \pm 0.8} M_{\odot}$



$$\dot{m}_{\rm out}(t,r,\theta,\phi) = \rho(t,r,\theta,\phi)u^r(t,r,\theta,\phi) \quad \text{for } \gamma > \gamma_{\rm diag}$$

$$\dot{\mathcal{M}}_{\rm out}(t) = \int \dot{m}_{\rm out}(t, r_{\rm diag}, \theta, \phi)\sqrt{-g}\,\mathrm{d}\theta\mathrm{d}\phi$$

Outflow/inflow ratio for ASASSN source



purple: $\mathcal{R} = 8M$, green: $\mathcal{R} = 4M$, blue: $\mathcal{R} = 3M$,
orange: $\mathcal{R} = 2M$
observation during peaks: average 0.184 (black dashed), min 0.03 (black dotted), max 0.31 (black dotted)

Relation between $\mathcal{R}$ and perturber mass and nature

- observations: $\dot{\mathcal{M}}_{\rm out}/\dot{\mathcal{M}} \sim 0.2$ during peaks
- simulations $\Rightarrow$ perturber size $\sim 3M$: star or compact object?
- $\mathcal{R}$ - not physical radius – stagnation/synchronization radius
- star – $\mathcal{R}$ = wind kinetic and gas ram pressure equilibrium
  S2-like star: $\mathcal{R} \sim 10^{-2}M$ (ADAF), $\mathcal{R} \sim 10^{-6}M$ (thin disc)
- black hole – synchronization radius – two estimates:
  - Hill's radius – lower estimate on $m_{\rm per}$

$$m_{\rm per}^{\rm Hill} = 5052 \left(\frac{P_{\rm orb}}{8.05\,{\rm d}}\right)^{-2} \left(\frac{\mathcal{R}}{3}\right)^{3} \left(\frac{M_\bullet}{10^{7.5}\,M_\odot}\right)^{3} M_\odot$$

  - full momentum transfer – upper limit on $m_{\rm per}$

$$m_{\rm per}^{\rm syn} \sim 2 \times 10^5 \left(\frac{\mathcal{R}}{3}\right) \left(\frac{M_\bullet}{10^{7.5}\,M_\odot}\right)^{5/3} \left(\frac{P_{\rm orb}}{8.05\,{\rm d}}\right)^{-2/3} \left(\frac{10}{I}\right) M_\odot$$

$\Rightarrow$ **Indication of IMBH!**

(further work on details of interaction needed)

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 – sometimes connected with orbital period
- broad discussion of observational consequences in the paper `Suková et al., 2021, ApJ, 917, 43`
- candidate system discovered with ASASSN – ultrafast quasiperiodic outflows from AGN
- outflow strength $\rightarrow \mathcal{R} \sim 1M \Rightarrow$ IMBH ($\geq 100 M_\odot$, best agreement $\sim 10^4 M_\odot$)

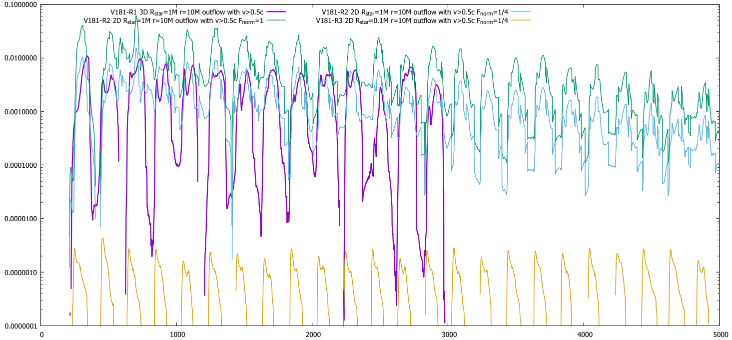
Thank you for your attention!

Outflow strength – 2D versus 3D, $r_* = 10M$

2D – axisymmetric

3D – only small part of flow in ϕ direction affected

$\Rightarrow$ 2D outflow scaled by $\frac{2\mathcal{R}}{(2*\pi*r)} F_n$



purple: 3D, green: $F_n = 1$, blue: $F_n = 1/4$; $\mathcal{R} = 1M \Rightarrow F_n = 1/4$

orange – 2D run $F_n = 1/4$; $\mathcal{R} = 0.1M$