IMBHs in galactic nuclei

Potential dynamical and spectral signatures

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Prague Relativistic Astrophysics, Astronomical Institute CAS

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Talk structure

Motivation

Formation channels of IMBHs, IMBHs in galaxies, Galactic center and Nuclear Star Clusters, gravitational waves

Model predictions

Repetitive perturbation of the accretion flow in GRMHD simulations

Candidate sources for electromagnetic and GW detections

"Hot" candidate source under investigation

Occurrence of IMBHs

How can black holes of 10^2-$10^5\,M_{\odot}$ form?

- Stellar black holes upper limit $\lesssim 50\,M_{\odot}$, given by the pair-instability (upper) mass gap (stars of $\sim 130-250\,M_{\odot}$)
- heavier black holes or intermediate-mass black holes (IMBHs) were proposed based typically on indirect arguments
  (a) **heavy IMBHs**: in low-luminosity AGN (NGC 4395, QPE sources); $\sim 10^5\,M_{\odot}$ (constrained by RM, predictions from $M_{\bullet}$-$\sigma_{\star}$)
  (b) **lighter IMBHs** ULXs, globular clusters, Galactic center sources (dynamically not well constrained, often excluded with more precise measurements)

- first precise measurement of the IMBH mass was performed for the LIGO-VIRGO event **GW190521** – merger of two pair-instability mass gap black holes of 85 and 66 $M_{\odot}$, **final black holes mass of 142** $M_{\odot}$

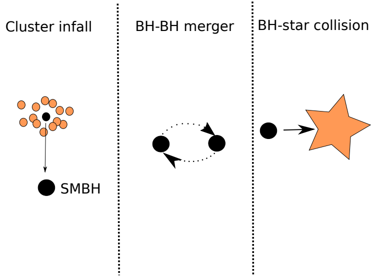
Formation channels

1. **primordial/cosmological origin:** at high z from Pop III stars (Madau & Rees 2001) or the direct gas cloud collapse (Begelman+2006)
2. **consecutive merger of stellar black holes** in globular clusters (e.g. Gültekin+2004, Miller & Hamilton 2002) $\rightarrow$ a **problem with the escape due to recoiling velocity kicks, unless the seed is heavier than** $50\,M_{\odot}$
3. **runaway collisions and mergers of massive stars in dense star clusters**, a collapse into the IMBH (Portegies Zwart & McMillan 2002)

For a review, see Greene, Strader, Ho (2020)

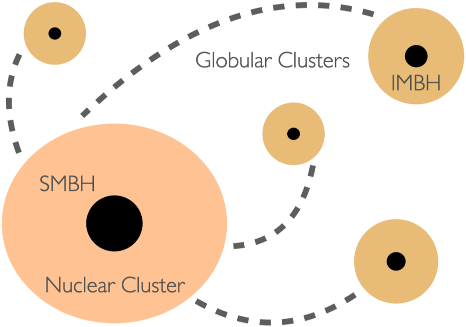
Formation of SMBH-IMBH pairs

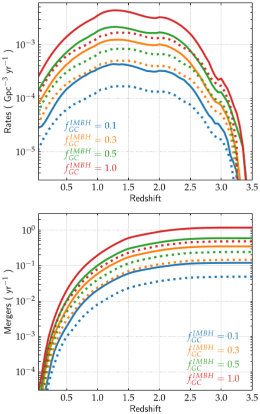
- **infall of massive stellar clusters hosting an IMBH** (Fragione, 2022)
- **stellar black hole - main-sequence star collisions** (Rose+2022); more frequent than BH-BH or BH-NS/WD mergers; $M_{\rm IMBH} \lesssim 10^4\,M_{\odot}$
- **black hole - black hole mergers:** no problem with a recoiling kick velocity in NSCs, most merger products will be retained (Fragione+2022); $M_{\rm IMBH} \sim 10^3 - 10^4\,M_{\odot}$



Formation of SMBH-IMBH pairs: Cluster infall

IMBHs in (globular, dense) stellar clusters - based on the old concept of the cluster core collapse - Spitzer (1969), Vishniac (1978), Portegies Zwart & McMillan (2002), Hansen & Milosavljevic (2003)

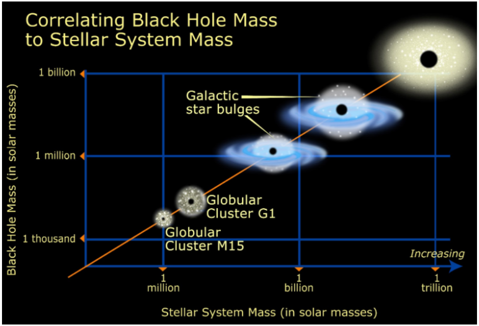




SMBH-IMBH merger rates by Fragione (2022)

IMBH in globular clusters

IMBHs in globular clusters - highly uncertain, except for G1 globular cluster in the halo of M31, other cases are rather hypothetical

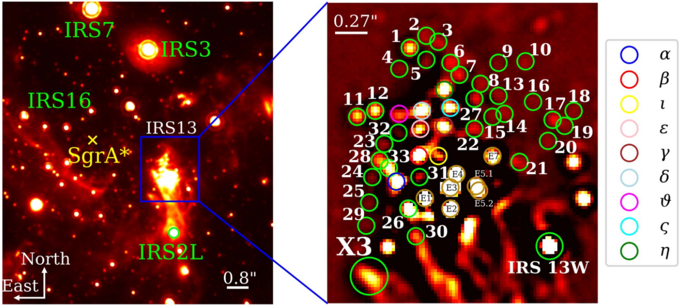


Courtesy of M. Rich (UCLA)

M31 G1 (STIS HST)

IMBH in the Galactic center? Candidate 1 – IRS 13E

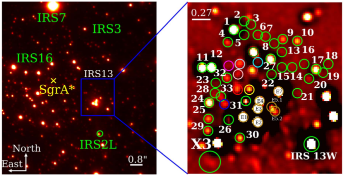
- $\sim 3.5'' = 0.13\,\mathrm{pc}$ from Sgr A*
- based on the theory that young stars are dragged inwards by the IMBH (Hansen & Milosavljevic 2003)
- IMBH of $\sim 10^3 - 10^4\,M_{\odot}$ (Maillard+2004, Schödel+2005)
- X-ray emission due to wind-wind collisions (Zhu+2020)



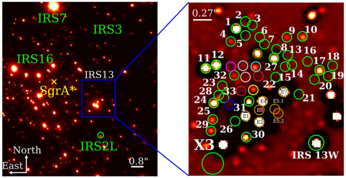
NACO L'-band

IMBH in the Galactic center? Candidate 1 – IRS 13E

- $\sim 3.5'' = 0.13\,\mathrm{pc}$ from Sgr A*
- a compact cluster of early WR stars



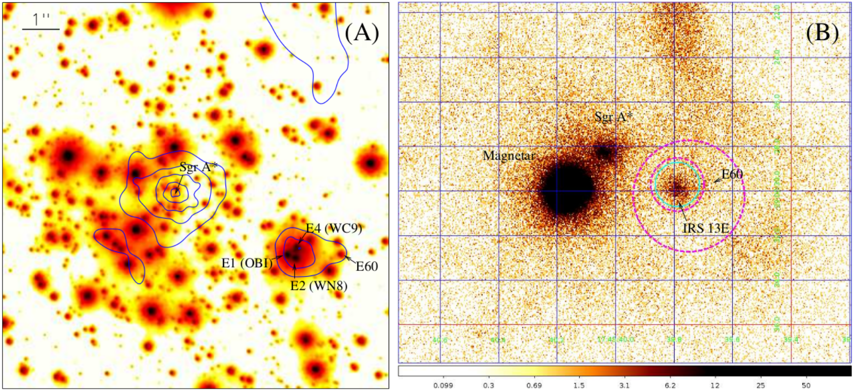
NACO K-band



NACO H-band

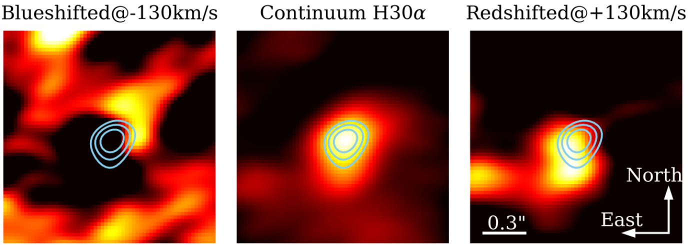
IMBH in the Galactic center? Candidate 1 – IRS 13E

- X-ray emission
- Chandra image 1-9 keV (Wang et al. 2020)



IMBH in the Galactic center? Candidate 1 – IRS 13E

- signs of rotating ionized gas revealed by H30α emission
- rotation around source E3 with the velocity of $\sim 130\,\mathrm{km\,s^{-1}}$ with the angular radius of $0.1'' \sim 825\,\mathrm{AU}$

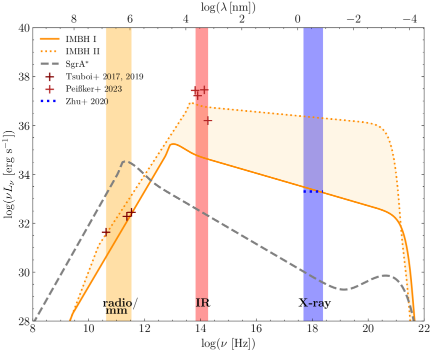


Peissker et al., in prep.; Tsuboi et al. 2019

- $M_{\rm vir} = Rv_{\rm R}^2/G \sim 16\,000\,M_{\odot}$

IMBH in the Galactic center? Candidate 1 – IRS 13E

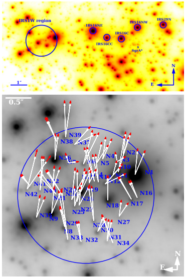
- broad-band SED consistent with the hot flow−ADAF with the relative accretion rate of $2 \times 10^{-6} < \dot{m} < 10^{-4}$ for $M_{\rm IMBH} \sim 30\,000\,M_{\odot}$
- peak in the mid-IR domain close to $28\,\mu m$

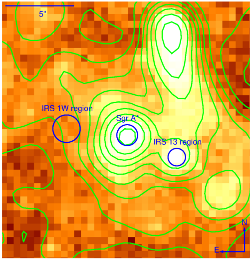


Peissker, Zajaček, Labaj et al., in prep.

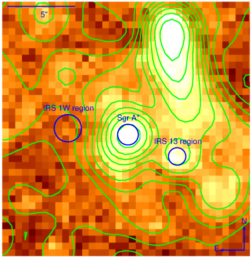
IMBH in the Galactic center? Candidate 2 – IRS 1W

- $\sim 4.6'' = 0.18\,\mathrm{pc}$ NE from Sgr A*
- 29 sources, including the bow shock IRS 1W
- the required binding mass: $\sim 10^3 - 10^5\,M_{\odot}$
- both IRS 1W and IRS 13E associations could be caused by the projection of the disk-like stellar configuration (Hosseini, Eckart, Zajaček+, in prep.)





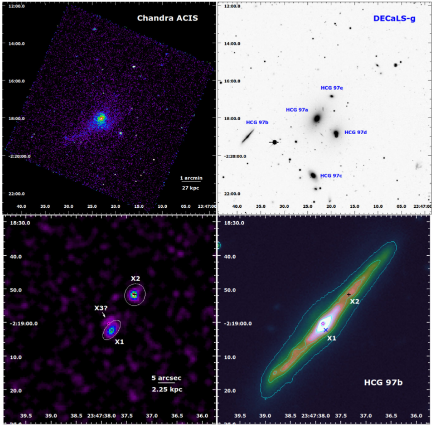
(a) The Chandra image from 0.5 to 8 kev



(b) The Chandra image from 4 to 8 kev

IMBH in galactic disks?

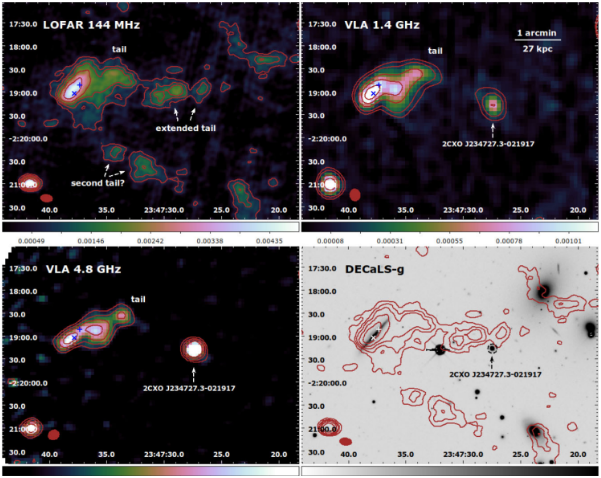
- spiral galaxy HCG 97b hosts 2 ULXs, X1 and X2 ($L_X = 3.78 \times 10^{39}, 1.80 \times 10^{40}\,\mathrm{erg\,s^{-1}}$)



Hu, Zajaček, Werner, et al. (2024)

IMBH in galactic disks?

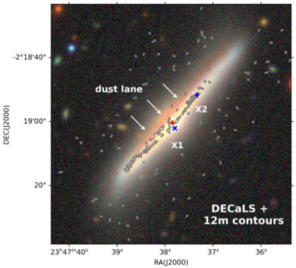
- localized feedback: ram-pressure stripping induced by a ULX?

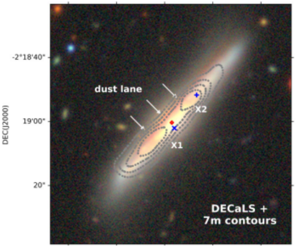


Hu, Zajaček, Werner, et al. (2024)

IMBH in galactic disks?

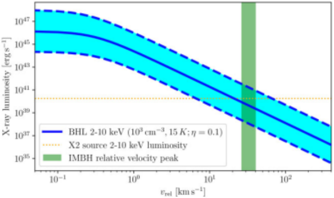
- X2 source is a candidate for an actived IMBH encountering denser molecular gas in the galactic plane





X-ray source	M_{BH} ($M_\odot$) $\lambda_{Edd} = 10^2$	$\lambda_{Edd} = 1$	$\lambda_{Edd} = 10^{-2}$	Fundamental plane
X1	0.4	39.5	1.3×10^5	$\leq(1.9 \pm 1.3) \times 10^7$
X2	3.0	300.4	3.5×10^5	$\leq(5.8 \pm 3.9) \times 10^6$
Accretion mode	Slim disc	Slim/standard disc	ADAF	

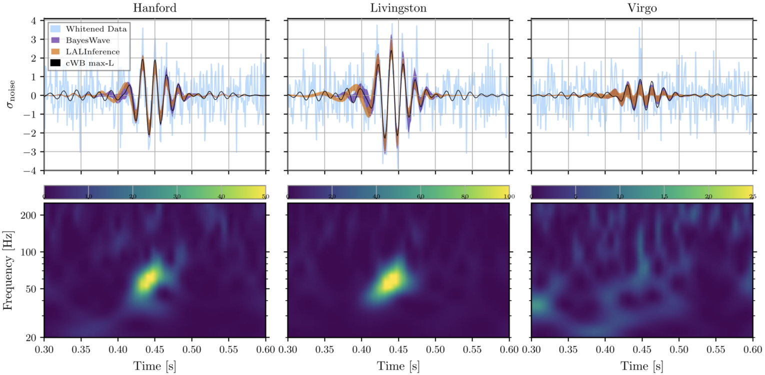
In the last row, we distinguish different accretion modes for the corresponding Eddington ratios.



Hu, Zajaček, Werner, et al. (2024); see also Seepaul, Pacucci, & Narayan (2022)

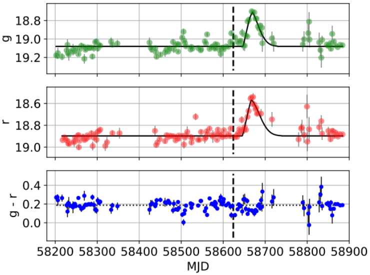
Curious case of GW 190521

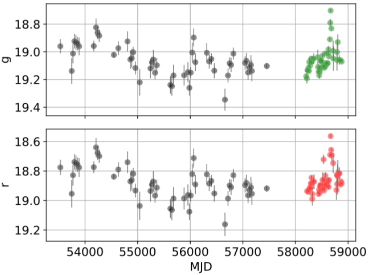
- first confirmed IMBH of 142 $M_{\odot}$ formed by merging two smaller black holes, with one of them in the pair-instability gap as well (85 and 66 $M_{\odot}$, $z \sim 0.82^{+0.28}_{-0.34}$, Abbott+2020, rate $\sim 0.13^{+0.30}_{-0.11}\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$)



Curious case of GW 190521

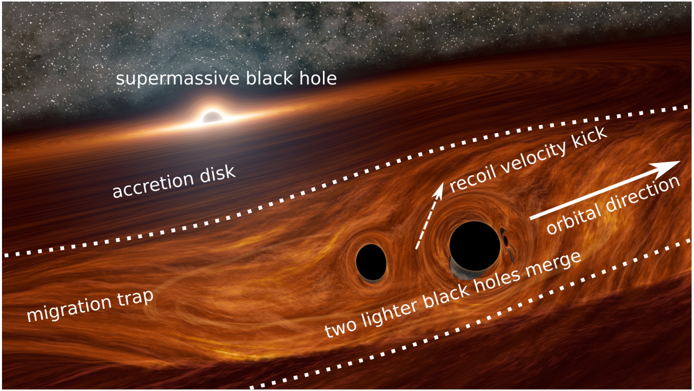
- associated with a potential **delayed electromagnetic signal** detected by the Zwicky Transient Facility (Graham+2020)– putative association with the accretion disc around the SMBH in the galaxy J1249+3449 ($z = 0.438$)





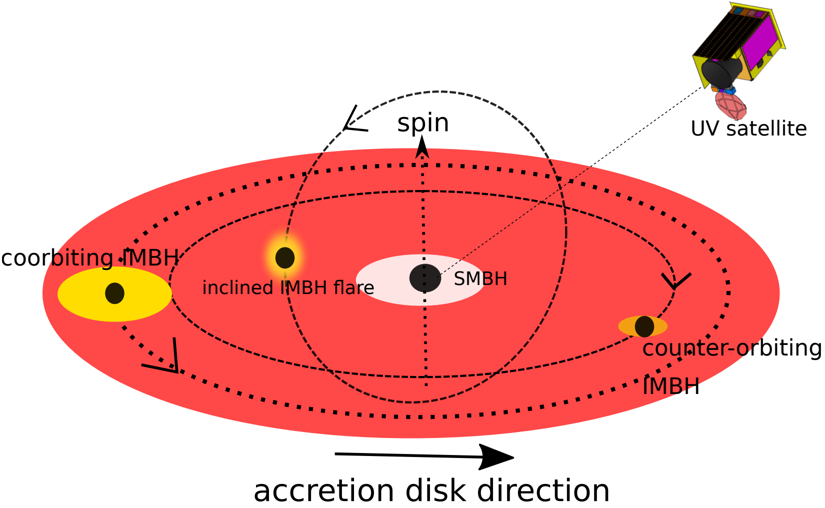
Curious case of GW 190521

- **the optical outburst consistent with the constant temperature shock as the merger product – IMBH – received a recoiling velocity kick and it collided with the surrounding accretion flow**



Courtesy of R. Hurt (IPAC/CALTECH)

Modelling perturber-accretion flow interaction

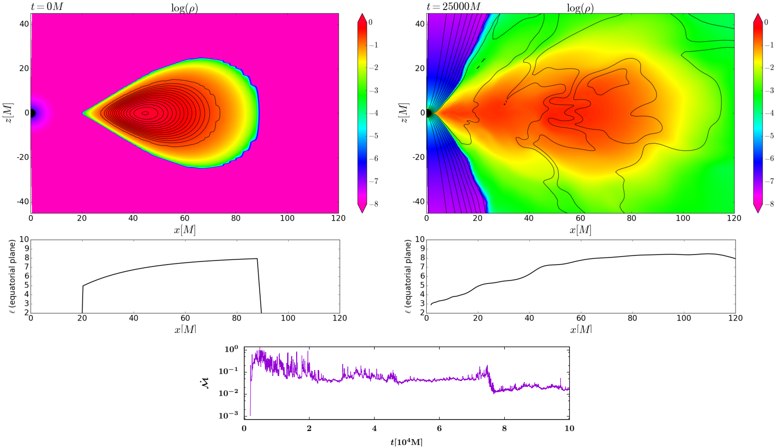


Modelling perturber-accretion flow interaction

- perturbation of the accretion flow by an orbiting object with the influence radius $\mathcal{R}$ - both embedded and highly inclined
- radiatively inefficient accretion flows (geometrically thick, optically thin), radiative cooling not included
- GRMHD simulations of the perturbed flow: modification of the HARM code – HARMPI (Gammie+2003; Tchekhovskoy+2016)
- ideal MHD: no resistivity, magnetic field frozen in gas
- thick, extended torus (90-300 $r_{\rm g}$) as a source of material and magnetic field that follows density equipotentials $\rightarrow$ MRI
- magnetohydrodynamic equations numerically solved on the fixed Kerr background, “inert” perturber drags gas along it inside the cylinder of $\mathcal{R}$

Modelling perturber-accretion flow interaction

Initial conditions - Exemplary case in 2D



Modelling perturber-accretion flow interaction

Run	u_t	u_ϕ	$t_{\rm end}[M]$	$r[M]$	$\mathcal{R}[M]$	$z_{\rm max}[M]$	$i[°]$	Type	$\mathcal{M}_{\rm in}$ $(t > 3 \cdot 10^4\,M)$	$\mathcal{M}_{\rm out}$ $(t > 3 \cdot 10^4\,M)$
A	-0.9557	0.479	$5 \cdot 10^4$	10	1.0	9.9	82.6	I	327.6 (4.1)	355.2 (78.9)
B	-0.9761	3.295	$5 \cdot 10^4$	15 – 25	1.0	17.8	45.3	E	370.1 (97.5)	22.0 (6.1)
C	-0.9871	5.955	$1 \cdot 10^5$	26 – 50	1.0	10.5	12.2	E	2033.1 (1608.2)	39.1 (29.4)
D	-0.9901	0.237	$1 \cdot 10^5$	50	1.0	50.0	88.1	I	5500.9 (3096.2)	90.1 (72.3)
E	-0.9902	3.082	$1 \cdot 10^5$	50	1.0	45.7	65.0	E	4103.2 (3329.4)	54.9 (41.6)
F	-0.9902	3.082	$1 \cdot 10^5$	50	10.0	45.7	65.0	E	1592.4 (510.0)	73.5 (40.9)
G	-0.9557	0.479	$5 \cdot 10^4$	10	0.1	9.9	82.6	I	1631.0 (447.7)	75.5 (39.4)
H	-0.9539	3.352	$5 \cdot 10^4$	10	1.0	3.6	21.4	E	207.8 (64.6)	19.4 (4.2)
I(3D)	-0.9557	0.479	$3 \cdot 10^4$	10	1.0	9.9	82.6	I	1157.1	22.1

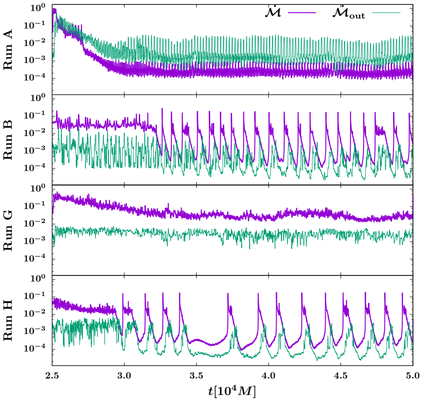
- Different set-ups with inclined and embedded perturbers at different distances and with different radii
- Density $\log \rho$, Lorentz factor Γ, and outflow rate $\dot{m}_{\rm out}$ maps
- Inflow/outflow rate versus time

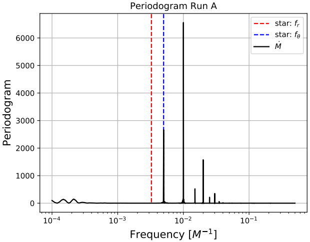
RUN A: Click - video

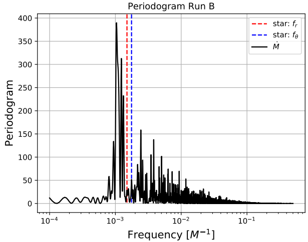
Results published in **Suková, Zajaček, Witzany, Karas 2021**

Modelling perturber-accretion flow interaction

- inflow/outflow temporal behavior depends on the perturber's inclination, eccentricity, and the influence radius





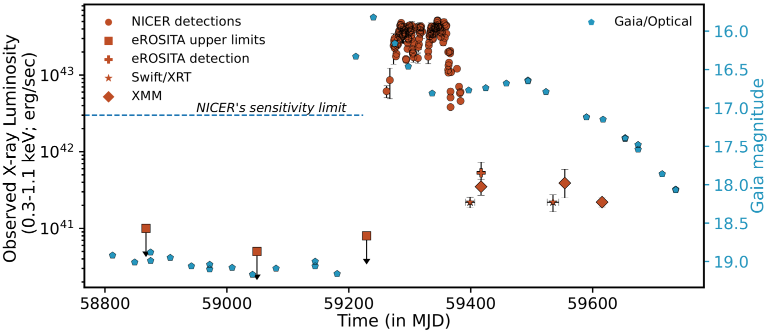


New candidate source

- **optical flare ASASSN-20qc/Gaia21alu/AT2020adgm**
- galaxy at redshift $z = 0.056$ (250 Mpc)
- discovered on Dec. 20, 2020 (ASAS-SN)
- spectroscopy and broad-band photometry: $M_{\bullet} = 3^{+5}_{-2} \times 10^7\,M_{\odot}$
- eROSITA upper limits January and July 2020: $L_X \lesssim 6 \times 10^{40}\,\mathrm{erg\,s^{-1}} \rightarrow \eta \lesssim 2 \times 10^{-5}$, **low-luminosity AGN**
- 52 days after the first ASASSN detection, **Swift** detected X-ray emission
- high-cadence **NICER** observations started on February 13, 2021
- **XMM-Newton** took the first spectrum on March 14, 2021

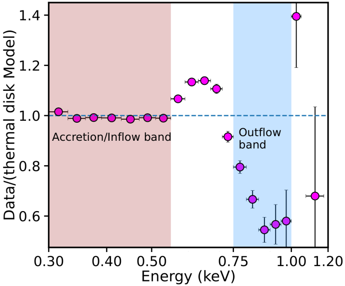
Optical and X-ray light curve

- X-ray and optical light curve; X-ray outburst follows the optical one



Ultrafast Outflow (UFO) detection

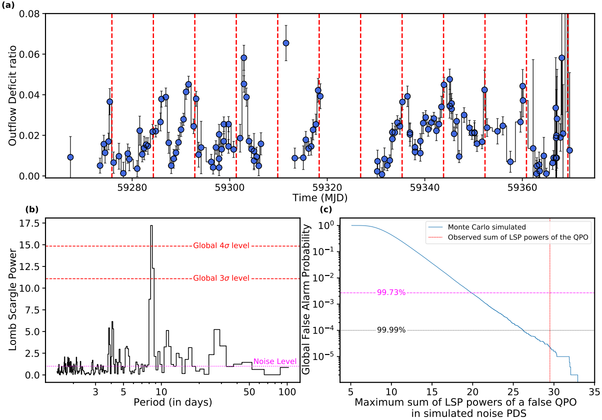
- soft X-ray spectrum is dominated by the thermal disc emission with $kT_{\rm bb} = 0.085\,{\rm keV}$
- ratio of the observed spectrum to the best-fit thermal model leaves a broad absorption feature between 0.75 and 1 keV
- ultrafast outflow $\sim$ 0.33c



- **ODR**= ratio of the flux in the outflow ($0.75 - 1$ keV) to the inflow band ($0.30 - 0.55$ keV)

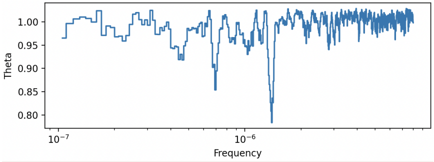
Periodic behavior in the ODR

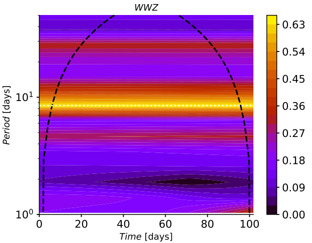
- **ODR exhibits a significant periodicity** of 8.5 days
- lower ODR implies stronger outflow
- 12 recurrent ODR minima detected



Periodic behavior in the ODR

- **ODR exhibits a significant periodicity** of 8.5 days
- periodicity can also be recovered using the phase dispersion minimization (PDM) and the weighted wavelet Z-transform (WWZ)

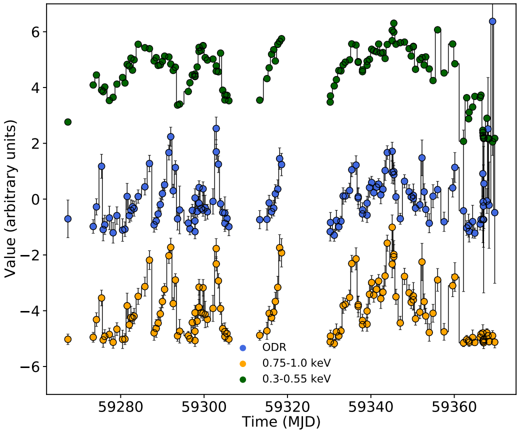




Left: PDM; *Right:* WWZ

Periodic behavior in the ODR

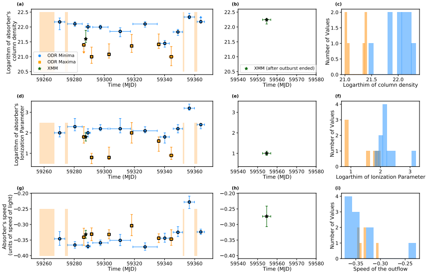
- **ODR exhibits a significant periodicity** of 8.5 days
- driven by the outflow band (red-noise plus periodicity)
- inflow band has a red-noise behaviour with no periodic behaviour



Properties of the recurrent ultrafast absorber

ODR minima (stronger outflow) vs. ODR maxima (weaker outflow)

- larger column density ($\log N \sim 22$) in ODR minima, while a smaller column density ($\log N \sim 21$) in ODR maxima
- **larger ionization parameter** in ODR minima
- **LOS velocity is constant** between the minima and the maxima (~ 0.35c)



Possible interpretations

1. inner disk precession **x** changes in continuum flux

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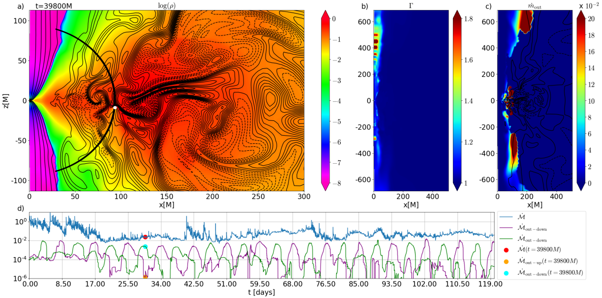
6. Repeating partial TDE **x** continuum variability, longer period
7. Radiation-pressure driven outflows **x** low accretion
8. **Orbiting perturber: perturber-induced ultrafast QPOuts**

Perturber-induced outflow model

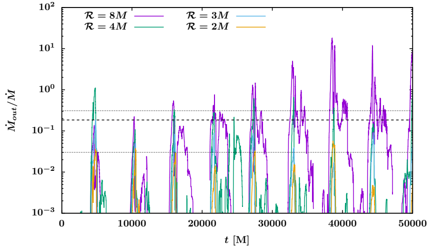
- Based on the original GRMHD simulations by Suková, Zajaček, Witzany, Karas (2021)
- Source-frame period of the perturber (8.05 days), highly inclined



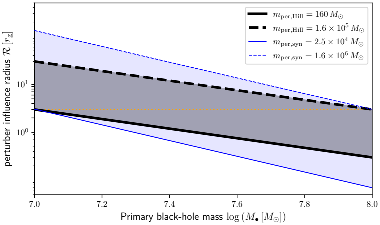
- **RUN ASASSN-20qc:** Click - video

Perturber-induced outflow model

- based on the ratio $\dot{m}_{\rm out}/\dot{m}_{\rm in}$ we constrain the perturber's influence radius to $\mathcal{R} \simeq 3$ gravitational radii
- $\mathcal{R} \simeq 3 \rightarrow m_{\rm per} > 100\,M_{\odot}$



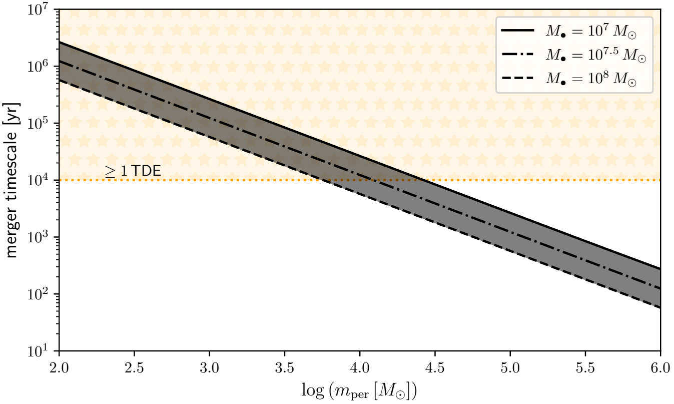
$\dot{m}_{\rm out}/\dot{m}_{\rm in}$ for different $\mathcal{R}$



Tidal and synchronization radii

Perturber-induced outflow model

- Optical outburst+ delayed X-ray flare likely caused by the TDE (stream-stream collisions and flow circulalization)
- $\gtrsim 1 TDE$, SMBH-IMBH merger timescale $\gtrsim 10^4$ years $\rightarrow$ $m_{\rm per} \lesssim 10^4\,M_{\odot}$

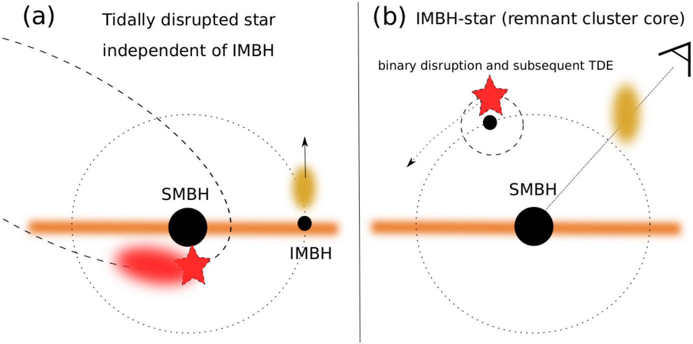


Perturber-induced outflow model

Basic picture:

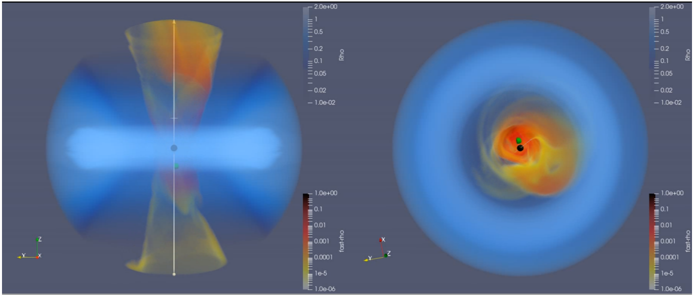
(a) inclined IMBH orbiting SMBH+ **unrelated TDE**

(b) **IMBH-star binary that disrupts** (Hills-like mechanism): causal connection between the TDE and the IMBH perturbation of the outflow; the IMBH could increase the likelihood of the TDE



Perturber-induced outflow model: Main pros

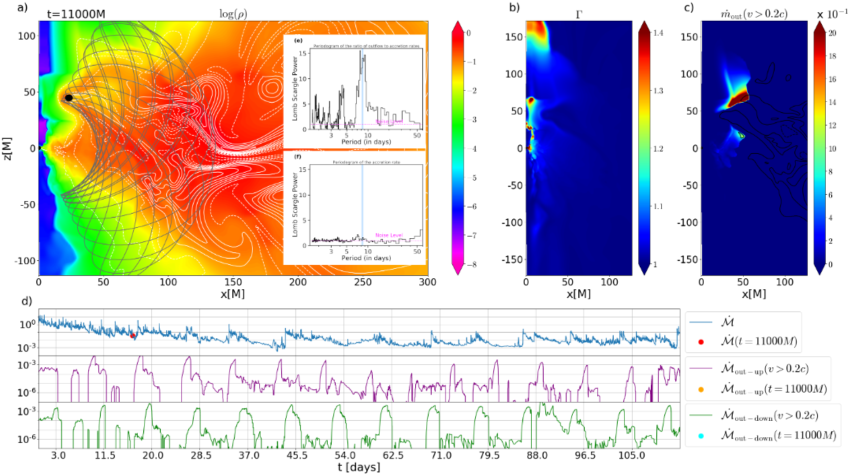
1. it can capture quasiperiodic UFO/absorption



- **3D RUN ASASSN-20qc:** Click - video

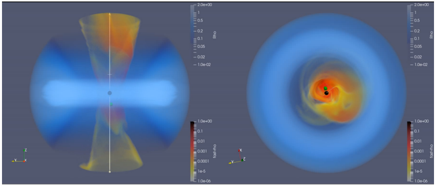
Perturber-induced outflow model: Main pros

2. For the distance of 100 r_g, there is no significant variability in the inflow rate – exemplary elliptical 2D run



Summary

- IMBHs still a mystery
- very few confirmed cases (mostly at the lowest and highest IMBH mass values)
- we may see their indirect signatures
- **quasiperiodic ultrafast outflows (QPOuts)** - a new type of transients with a significant perturbation of the outflow rate
- **ASASSN-20qc** - a period of 8.5 days suggests a perturber with the mass in the IMBH mass range (***Science Advances*, submitted**)



Postdoc Advertisement!
Till the end of January

Postdoctoral Fellow in Astrophysics

Submission Information

Publish Date: Friday, November 24, 2023
Archive Date: Friday, January 26, 2024
To event remaining 17 days

Job Summary

Job Category: Post-doctoral Positions and Fellowships
Institution Classification/Type: Large Academic
Institution/Company: Masaryk University
Department Name: Department of Theoretical Physics and Astrophysics, Faculty of Science
City: Brno
State/Province: Moravia
Country: Czech Republic

Announcement

Job Announcement Text:

The Galactic Nuclei and High-Energy Astrophysics research groups in the Department of Theoretical Physics and Astrophysics at Masaryk University in Brno, Czech Republic, invite applications for a postdoctoral fellowship. The current research of the group includes studies of active galactic nuclei (AGN), AGN feedback, Galactic centre, black hole-star interaction, star-formation/stellar evolution in galactic nuclei, intra-cluster medium and its physics and chemical enrichment, as well as the use of nano- and small-satellites for monitoring the energetic transient sky. The group leads the science team of QUVIK, an approved Czech national UV space telescope mission and is involved in a number of nano-satellite projects (see hea.physics.muni.cz for more information). The successful applicants will collaborate closely with the research groups of Michal Zajaček and Norbert Werner, are expected to carry out an independent research program and collaborate with the growing young, international team of researchers at Masaryk University. Candidates with experience in both computational and observational astronomy are encouraged to apply.

Informal inquiries about the position can be sent to Michal Zajaček or Norbert Werner, email: zajacek@physics.muni.cz and werner@physics.muni.cz. Applicants should provide a curriculum vitae, a brief statement of research interests, a list of publications, and the contact information of at least two reference letter writers through the e-application system https://www.muni.cz/en/about-us/careers/vacancies/76925 by January 31, 2024.

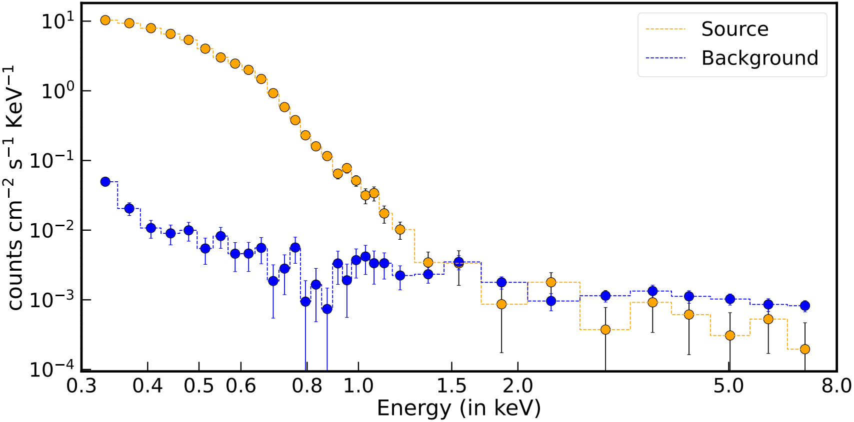
Related URLs: Research group website
Application Deadline: Wednesday, January 31, 2024
Selection Deadline: Thursday, February 15, 2024
Current Status of Position: Accepting Applicants

Apply to Job

Attention To: Dr. Michal Zajaček and Prof. Norbert Werner
URL: E-Application

Soft X-ray spectrum

- soft X-ray spectrum is dominated by the thermal disc emission with $kT_{\rm bb} = 0.085\,{\rm keV}$ (X-ray analysis by D. Pasham)



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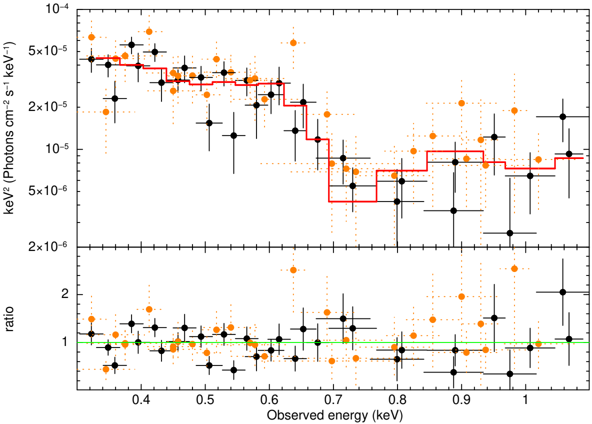
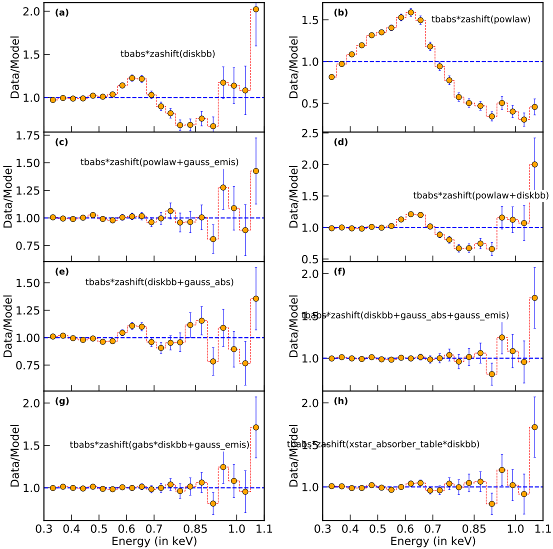
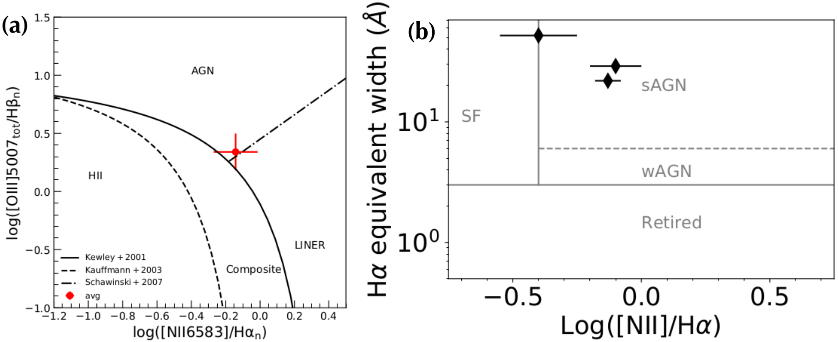


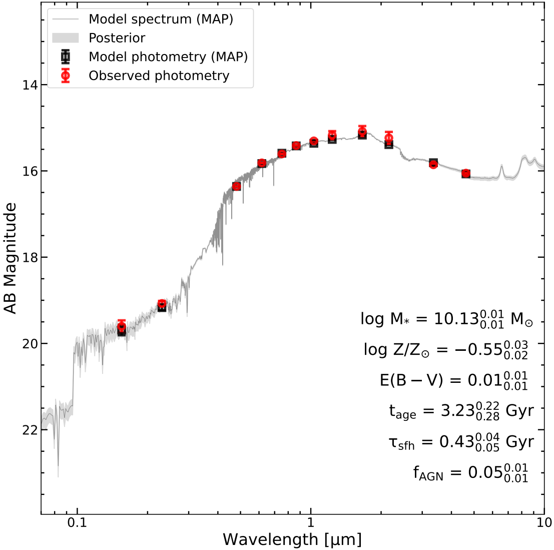
X-ray fitting



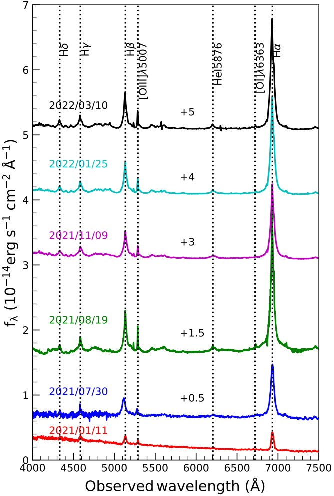
BPT and WHAN diagrams



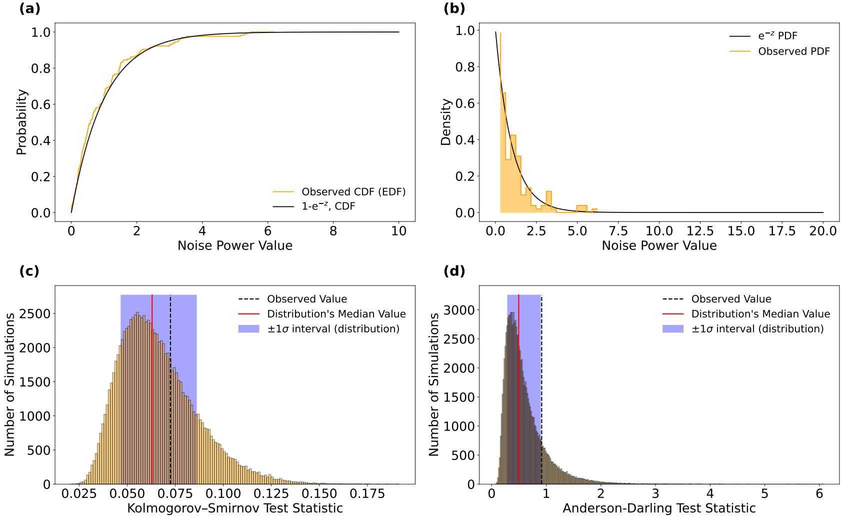
Broad-band photometry



Optical spectra



White noise test



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