MUNI
SCI

A phenomenon of QuasiPeriodic ultrafast Outflows (QPOuts): first detection and dynamical interpretation

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GALCROSS – *Brno Observatory and Planetarium*

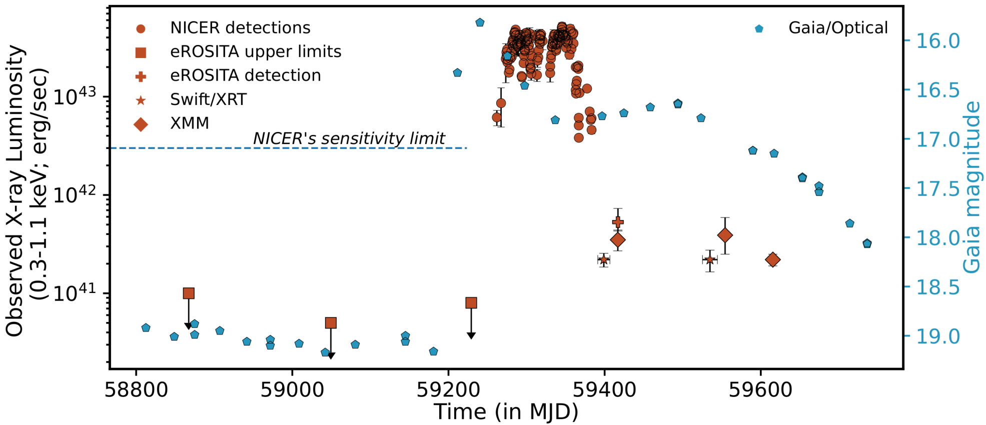
September 20, 2024

ASASSN-20qc: source with QPOuts

- **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

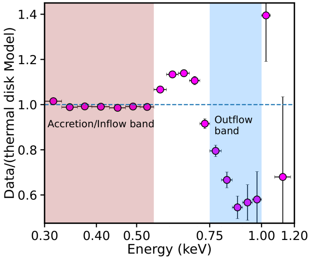
Optical and X-ray light curve

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



Ultrafast Outflow (UFO) detection

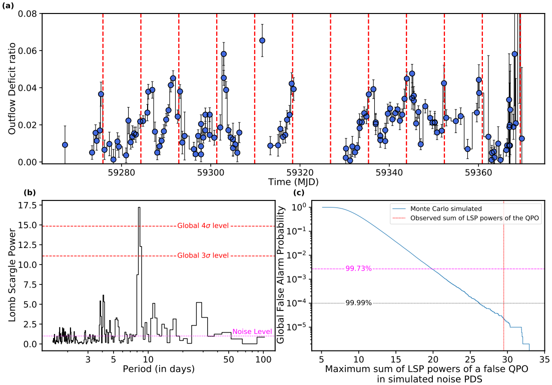
- soft X-ray spectrum is dominated by the thermal disc emission with $kT_{\rm bb} = 0.085\,{\rm keV}$
- ratio of the observed spectrum to the best-fit thermal model leaves a broad absorption feature between 0.75 and 1 keV
- ultrafast outflow $\sim$ 0.33c



- **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

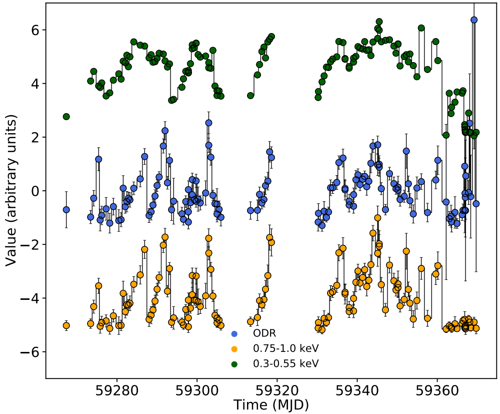
- **ODR exhibits a significant periodicity** of 8.5 days
- lower ODR implies stronger outflow
- 12 recurrent ODR minima detected



- **QuasiPeriodic ultrafast Outflow:** QPOut

Periodic behavior in the ODR

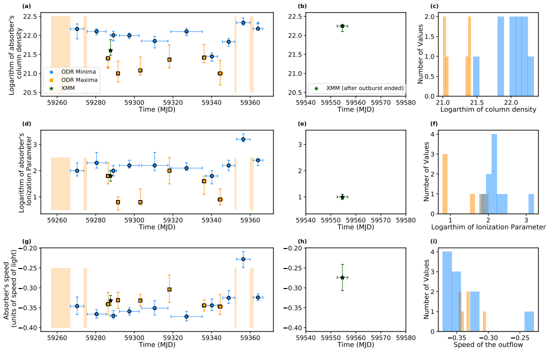
- **ODR exhibits a significant periodicity** of 8.5 days
- driven by the outflow band (red-noise plus periodicity)
- inflow band has a red-noise behaviour with no periodic behaviour



Properties of the recurrent ultrafast absorber

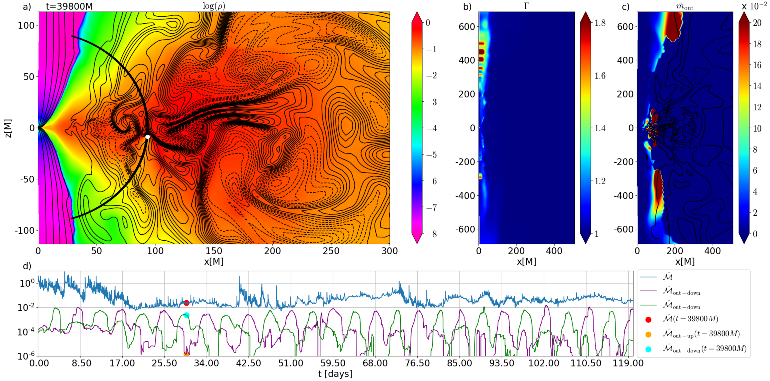
ODR minima (stronger outflow) vs. ODR maxima (weaker outflow)

- 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 ($\sim 0.35c$)



Perturber-induced outflow model

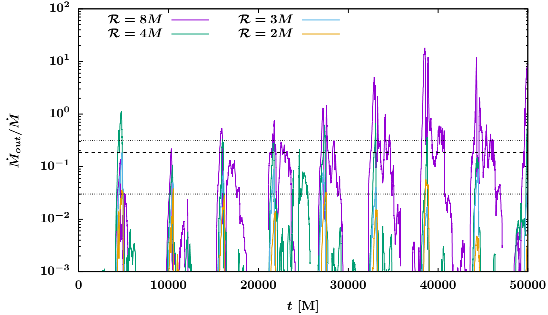
- Based on the original GRMHD simulations by Suková, Zajaček, Witzany, Karas (2021)
- Source-frame period of the perturber (8.05 days), highly inclined



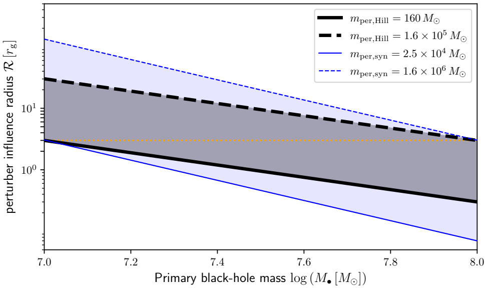
- **RUN ASASSN-20qc:** Click - video

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
- $\mathcal{R} \simeq 3 \rightarrow m_{\rm per} > 100\,M_{\odot}$



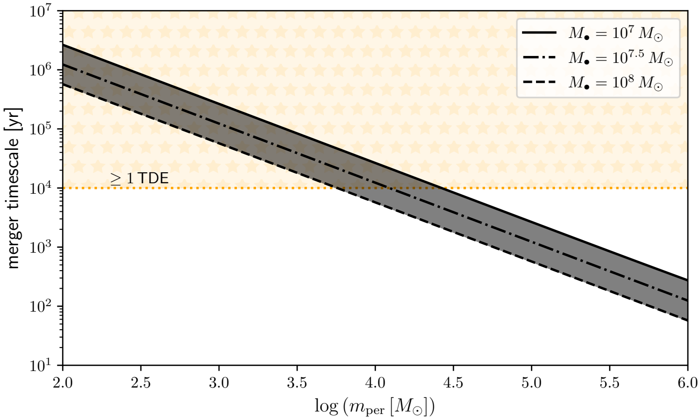
$\dot{m}_{\rm out}/\dot{m}_{\rm in}$ for different $\mathcal{R}$



Tidal and synchronization radii

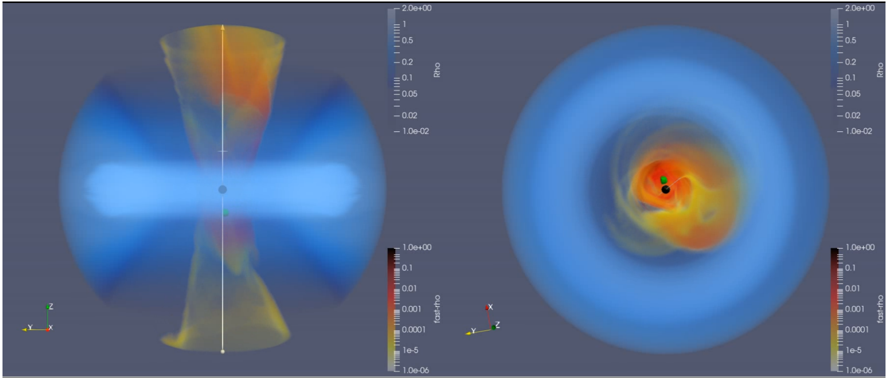
Perturber-induced outflow model

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



Perturber-induced outflow model: Main pros

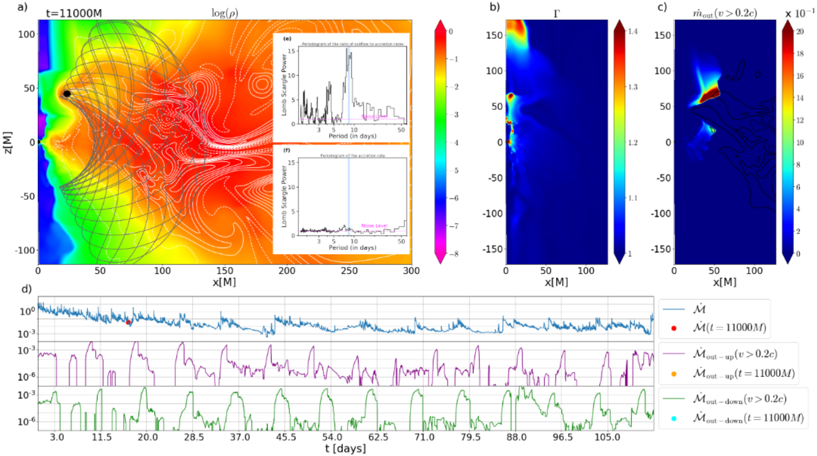
1. it can capture quasiperiodic UFO/absorption



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

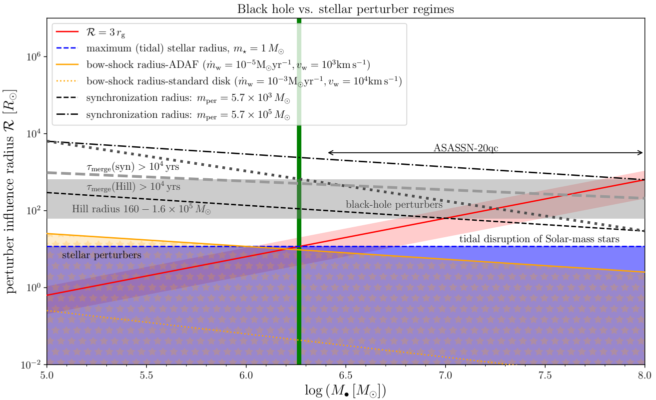
Perturber-induced outflow model: Main pros

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



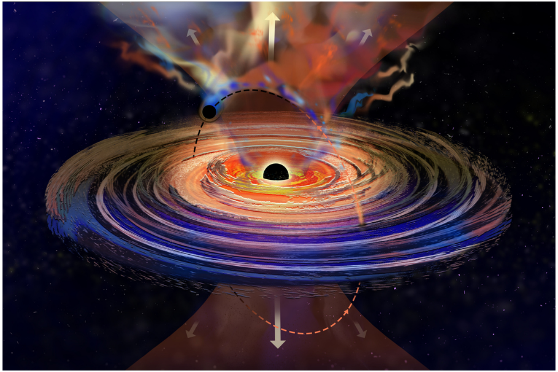
Perturber-induced outflow model: Main pros

3. For SMBHs heavier than $10^{6.27}\,M_\odot$, IMBH is required to yield a sufficiently large influence radius ($R_{\rm inf} \gtrsim 1$ gravitational radius) to launch absorbing clumps of a sufficiently large column density



Summary

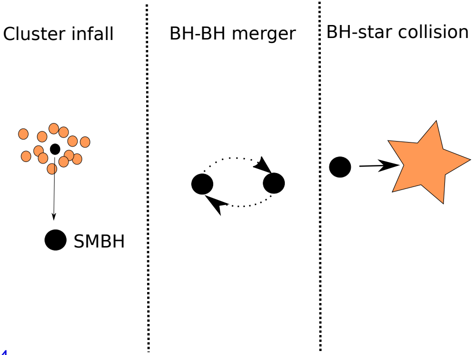
- ASASSN-20qc - a QPOut period of 8.5 days suggests a perturber with the mass in the IMBH mass range (Pasham et al., with the contribution of MZ, *Science Advances*, arXiv: 2402.10140)



Credit: Jose-Luis Olivares, MIT

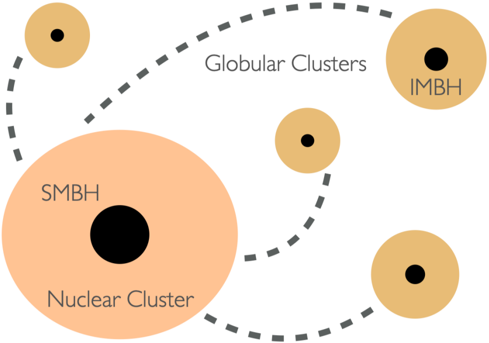
Back-up slides: Formation of SMBH-IMBH pairs

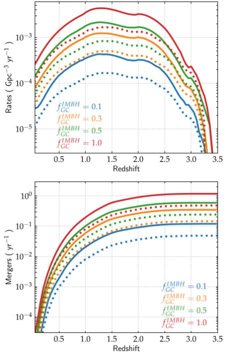
- **infall of massive stellar clusters hosting an IMBH** (Fragione, 2022)
- **stellar black hole - main-sequence star collisions** (Rose+2022); more frequent than BH-BH or BH-NS/WD mergers; $M_{\rm IMBH} \lesssim 10^4\,M_{\odot}$
- **black hole - black hole mergers:** no problem with a recoiling kick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

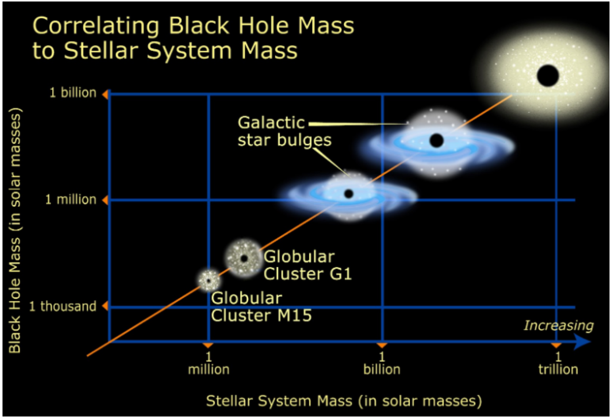




SMBH-IMBH merger rates by Fragione (2022)

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

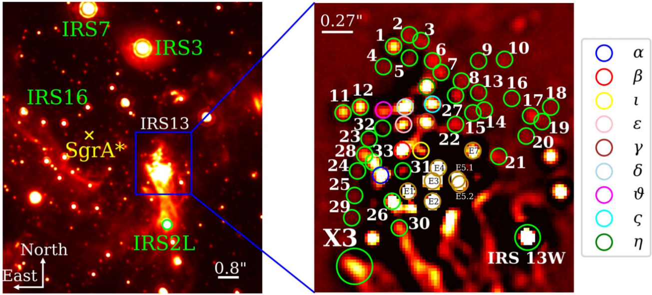


Courtesy of M. Rich (UCLA)

M31 G1 (STIS HST)

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

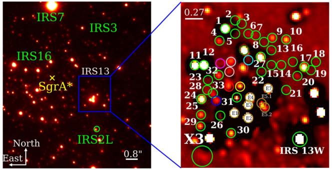
- $\sim 3.5'' = 0.13\,\mathrm{pc}$ from Sgr A*
- based on the theory that young stars are dragged inwards by the IMBH (Hansen & Milosavljevic 2003)
- IMBH of $\sim 10^3 - 10^4\,M_\odot$ (Maillard+2004, Schödel+2005)
- X-ray emission due to wind-wind collisions (Zhu+2020)



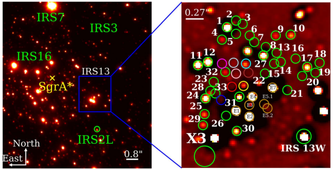
NACO L'-band

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



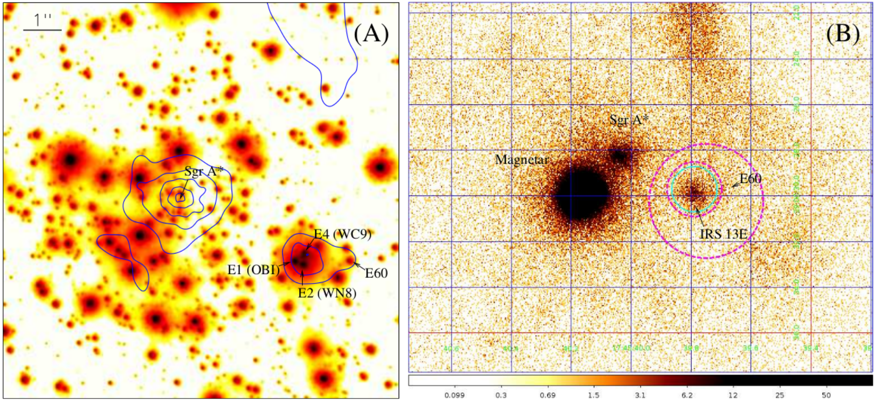
NACO K-band



NACO H-band

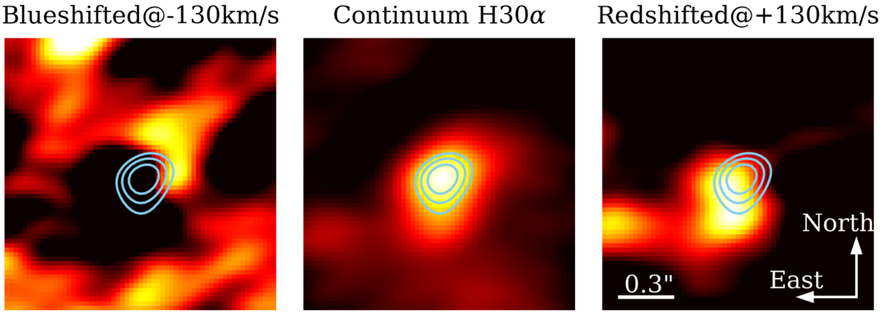
IMBH in the Galactic center? Candidate 1 – IRS 13E

- 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 $0.1'' \sim 825\,\mathrm{AU}$

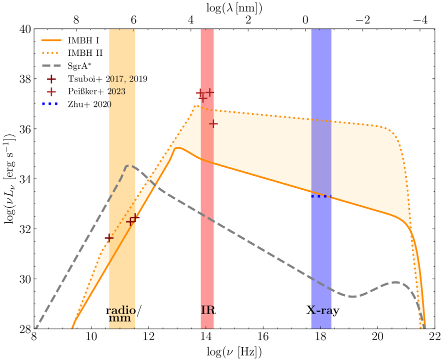


Peissker et al., ApJ, in print; Tsuboi et al. 2019

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

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 μm



Peissker, Zajaček, Labaj et al., ApJ, in print

How likely are SMBH-IMBH pairs in the local Universe?

- Number of pairs:

$$N_{\rm pair} \sim n_{\rm NSC} \nu_{\rm infall} \tau_{\rm merge} V_{\rm com}(< z)\,,$$

- $n_{\rm NSC} \sim 0.037\,{\rm Mpc}^{-3}$ is the number of galaxies hosting a nuclear star cluster
- $\nu_{\rm infall} \sim 1/T_{\rm df}$ where $T_{\rm df} \propto \sigma_{\star}^3/(m_{\rm per}\rho_{\star})$ is the dynamical friction timescale; $T_{\rm df}(10^7\,M_{\odot}) \sim 5 \times 10^5$ years, $T_{\rm df}(10^8\,M_{\odot}) \sim 40 \times 10^6$ years
- $\tau_{\rm merge} \sim 10^4$ years, i.e. selection of SMBH-IMBH pairs that have a long enough merger timescale for a TDE to take place, i.e for $M_{\bullet} = 10^7 - 10^8\,M_{\odot}$, the perturber mass is in the range $m_{\rm per} = 26\,500 - 5700\,M_{\odot}$,
- $V_{\rm com}(< 0.06) \sim 0.068\,{\rm Gpc}^3$, which is a comoving volume within $z = 0.06$

How likely are SMBH-IMBH pairs in the local Universe? Plus with TDE?

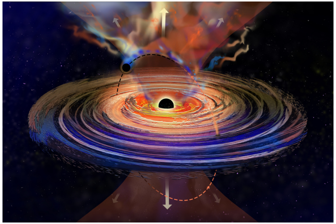
- Number of pairs:

$$N_{\rm pair} \sim n_{\rm NSC}\nu_{\rm infall}\tau_{\rm merge}V_{\rm com}(<z)\,,$$

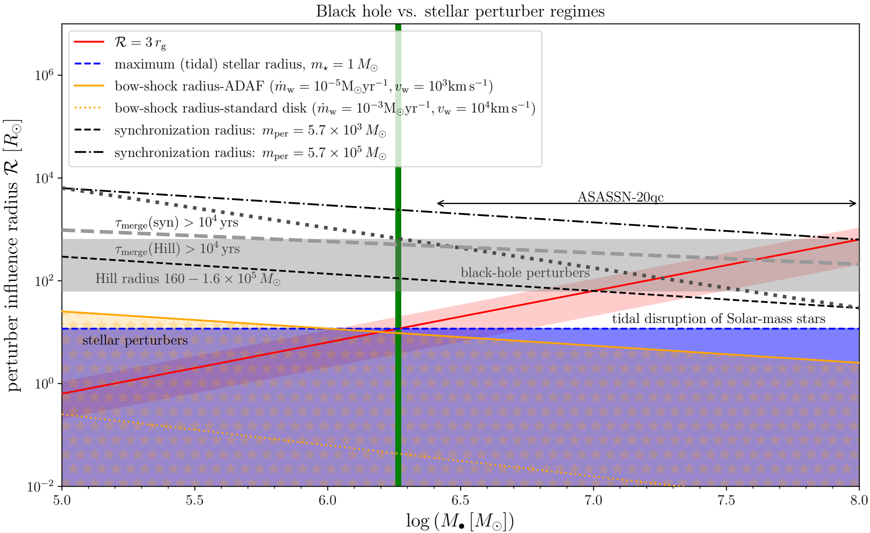
- $N_{\rm pair} \sim 53200 - 700$ SMBH-IMBH pairs considering $M_{\bullet} = 10^7 - 10^8\,M_{\odot}$, with $\mathbf{N}_{\rm pair} \sim$ **9200 pairs** for $M_{\bullet} \sim 10^{7.4}\,M_{\odot}$
- Considering TDE with the rate of $\dot{N}_{\rm TDE} \sim 10^{-4}\,{\rm yr}^{-1}$, we obtain $N_{\rm pair,TDE} = 0.07 - 5.3$ sources per year ($M_{\bullet} = 10^7 - 10^8\,M_{\odot}$) and $\mathbf{N}_{\rm pair,TDE} =$ **0.9 sources per year** for $M_{\bullet} \sim 10^{7.4}\,M_{\odot}$
- the TDE occurrence in a galaxy hosting the SMBH-IMBH pair is 1 in $\sim 5 \times 10^5 - 36 \times 10^6$ galaxies per year
- TDE rate of $\dot{N}_{\rm TDE} \sim 10^{-4}\,{\rm yr}^{-1}$ per galaxy implies the timescale $\tau_{\rm TDE-IMBH} \sim (N_{\rm pair}\dot{N}_{\rm TDE})^{-1} \sim 0.2 - 14.3$ years for the whole range $M_{\bullet} = 10^7 - 10^8\,M_{\odot}$, with $\tau_{\rm TDE-IMBH} \sim 1.1$ years for $M_{\bullet} = 10^{7.4}\,M_{\odot}$

How likely are SMBH-IMBH pairs in the local Universe? Manifesting as QPOuts?

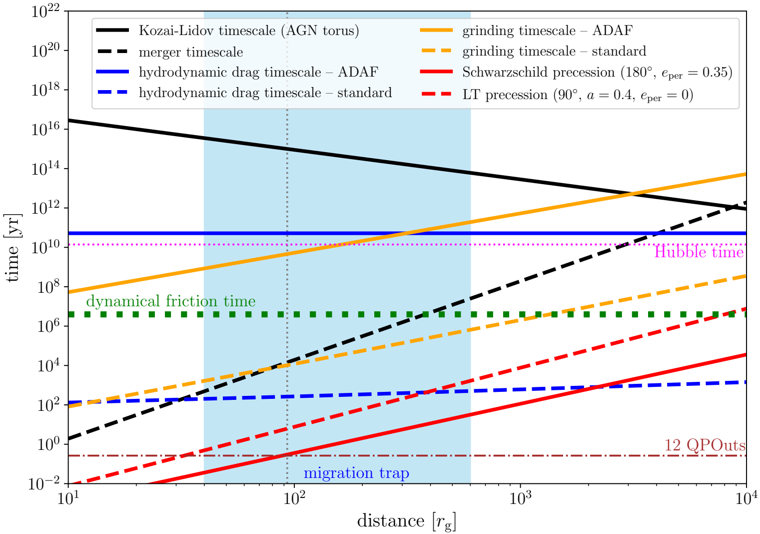
- Number of pairs: $N_{\rm pair} \sim n_{\rm NSC}\nu_{\rm infall}\tau_{\rm merge}V_{\rm com}(< z)$
- Number of IMBH-induced QPOuts: $N_{\rm QPOuts} = f_{\rm I}f_{\rm inc}N_{\rm pair}$
- type I sources ($\lesssim 45°$): $f_I \sim 0.71$
- high enough inclination ($\gtrsim 45°$): $f_{\rm inc} \sim 0.29$
- **$\mathbf{N_{\rm QPOuts} = f_{\rm I}f_{\rm inc}N_{\rm pair} \sim 0.21N_{\rm pair}} \sim$ 11 000–150 sources hosting SMBH-IMBH pairs can be revealed via QPOuts**, i.e. one in 220 up to 17000 galaxies can exhibit QPOuts triggered by an IMBH (massive perturber)



Influence radii of disk perturbers



Dynamical timescales as a function of distance



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** $M_\odot$

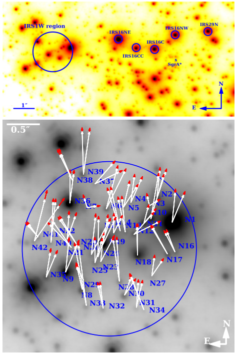
Formation channels

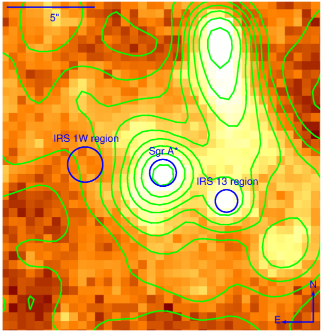
1. **primordial/cosmological origin:** at high z from Pop III stars (Madau & Rees 2001) or the direct gas cloud collapse (Begelman+2006)
2. **consecutive merger of stellar black holes** in globular clusters (e.g. Gültekin+2004, Miller & Hamilton 2002) $\rightarrow$ a **problem with the escape due to 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)

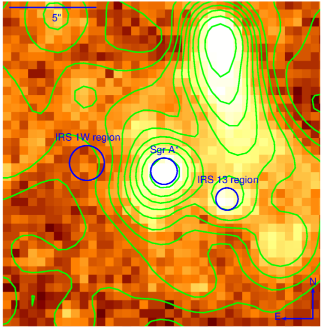
IMBH in the Galactic center? Candidate 2 – IRS 1W

- $\sim 4.6'' = 0.18\,\mathrm{pc}$ 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.)





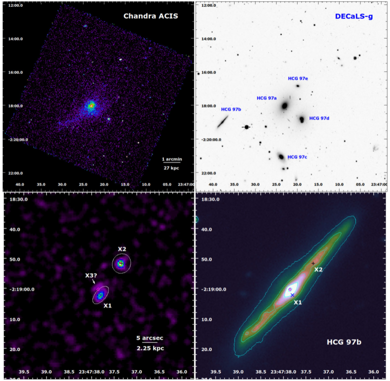
(a) The Chandra image from 0.5 to 8 kev



(b) The Chandra image from 4 to 8 kev

IMBH in galactic disks?

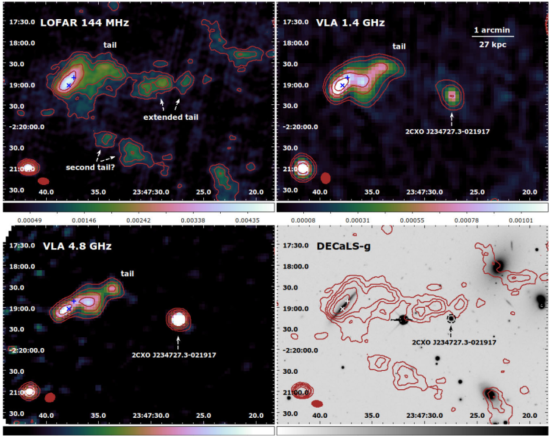
- spiral galaxy HCG 97b hosts 2 ULXs, X1 and X2 ($L_X = 3.78 \times 10^{39}$, $1.80 \times 10^{40}\,\mathrm{erg\,s^{-1}}$)



Hu, Zajaček, Werner, et al. (2024)

IMBH in galactic disks?

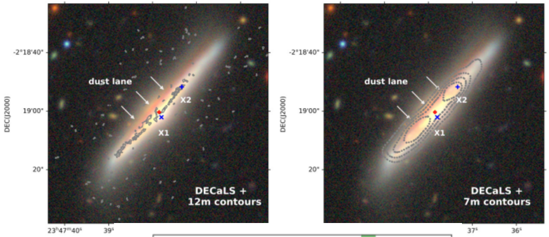
- localized feedback: ram-pressure stripping induced by a ULX?

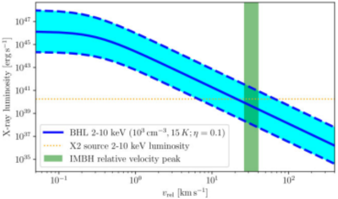


Hu, Zajaček, Werner, et al. (2024)

IMBH in galactic disks?

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





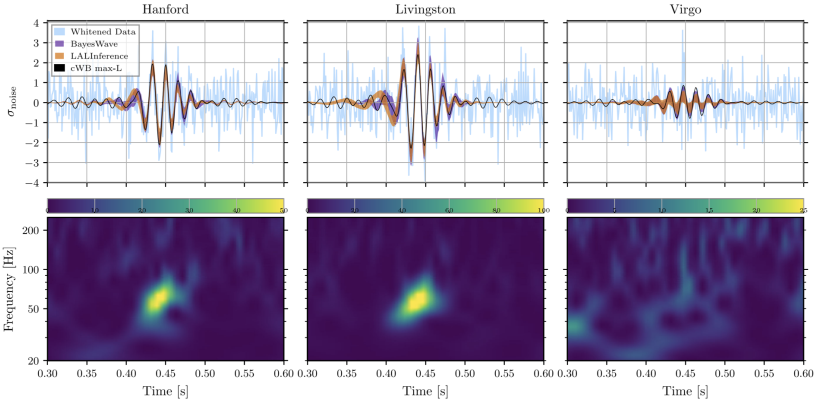
X-ray source	$M_{\rm BH}$ ($M_\odot$) $\lambda_{\rm Edd} = 10^2$	$\lambda_{\rm Edd} = 1$	$\lambda_{\rm Edd} = 10^{-2}$	Fundamental plane
X1	0.4	39.5	1.3×10^5	$\leq (1.9 \pm 1.3) \times 10^7$
X2	3.0	300.4	3.5×10^5	$\leq (5.8 \pm 3.9) \times 10^6$
Accretion mode	Slim disc	Slim/standard disc	ADAF	

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)

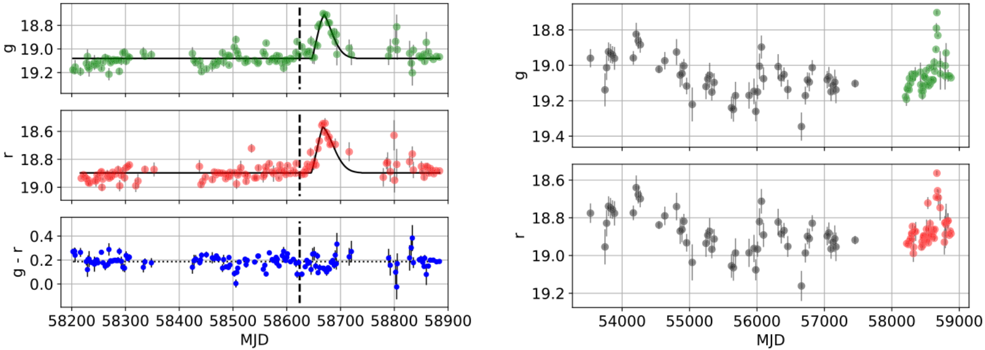
Curious case of GW 190521

- 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 $\sim 0.13^{+0.30}_{-0.11}\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$)



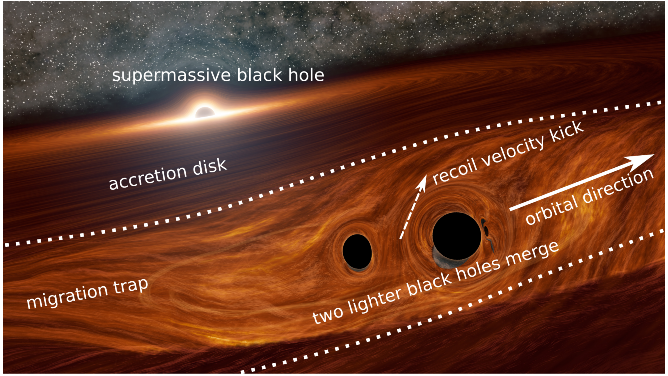
Curious case of GW 190521

- 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 ($z = 0.438$)



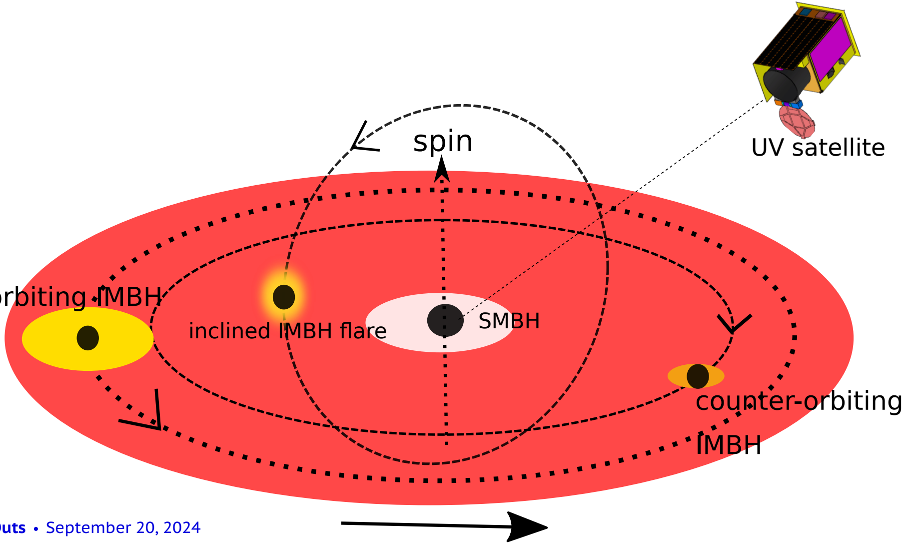
Curious case of GW 190521

- 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

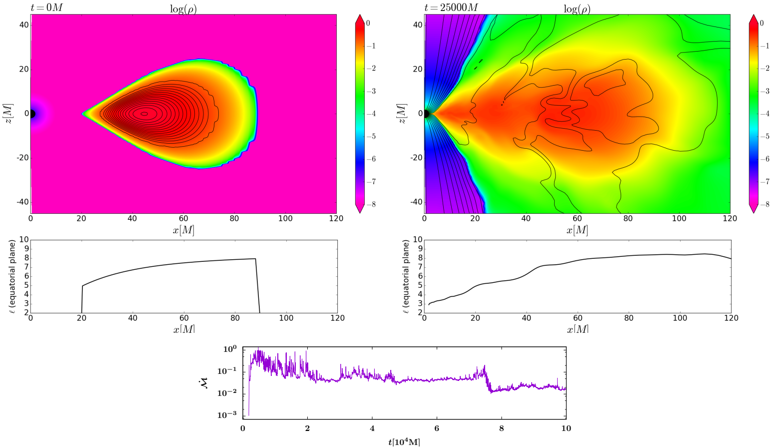


Modelling perturber-accretion flow interaction

- 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	$t_{\rm end}[M]$	$r[M]$	$\mathcal{R}[M]$	$z_{\rm max}[M]$	$i[^\circ]$	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

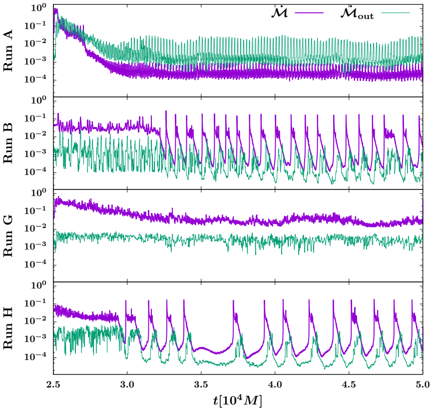
- Different set-ups with inclined and embedded perturbers at different distances and with different radii
- Density $\log \rho$, Lorentz factor Γ, and outflow rate $\dot{m}_{\rm out}$ maps
- Inflow/outflow rate versus time

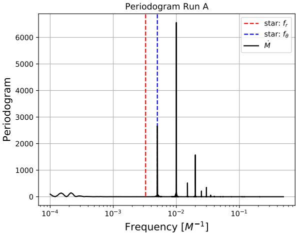
RUN A: Click - video

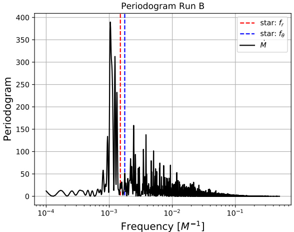
Results published in **Suková, Zajaček, Witzany, Karas 2021**

Modelling perturber-accretion flow interaction

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

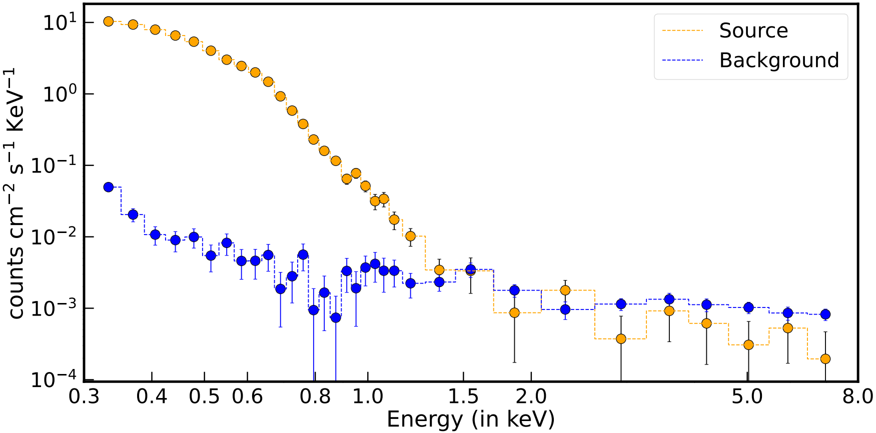






Soft X-ray spectrum

- 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)



Soft X-ray spectrum

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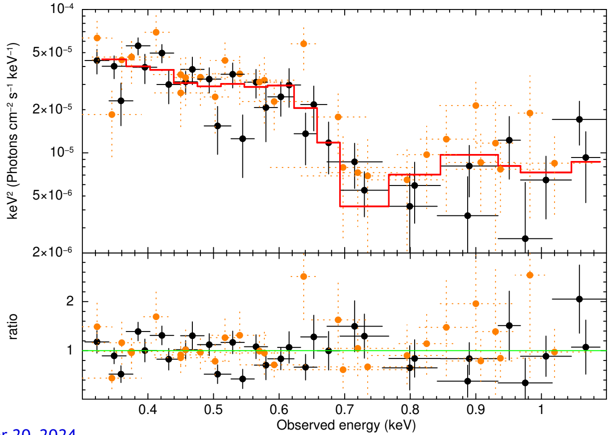
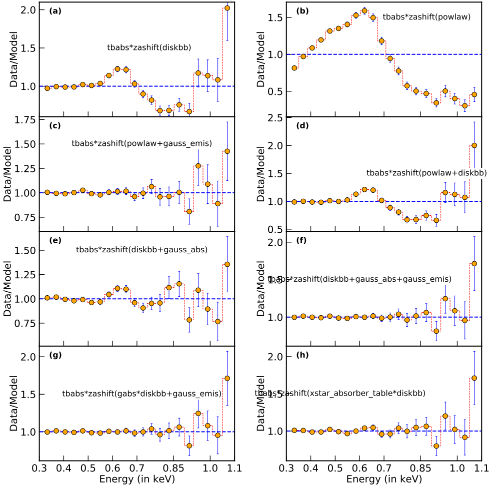
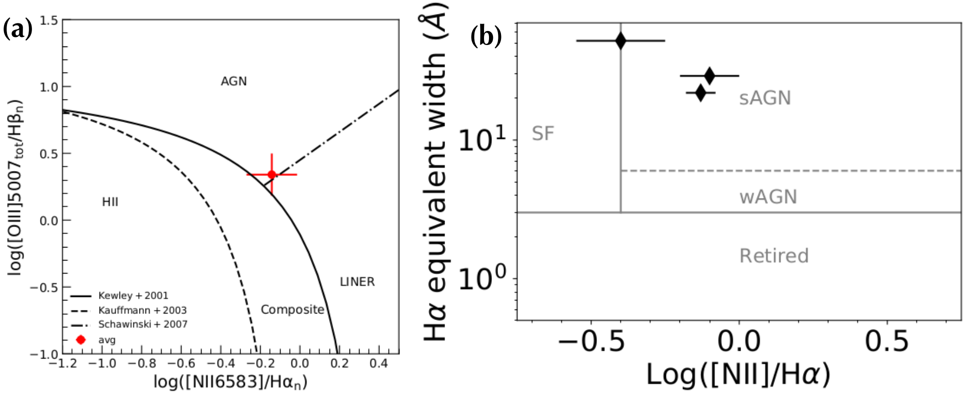


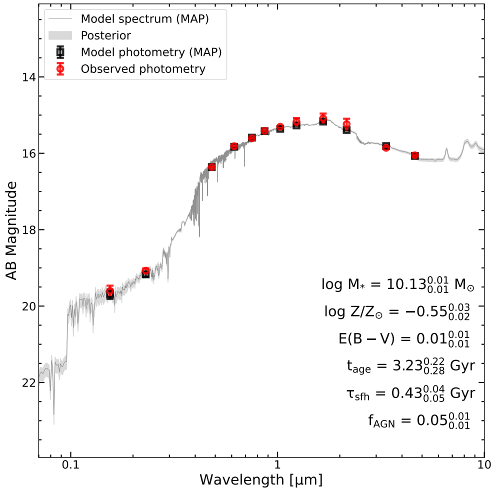
X-ray fitting



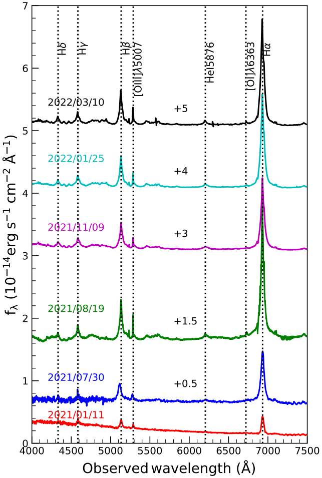
BPT and WHAN diagrams



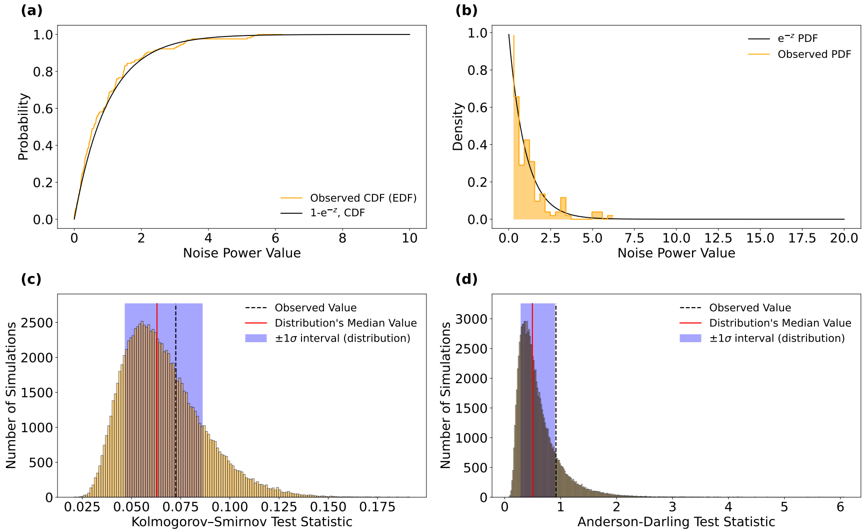
Broad-band photometry



Optical spectra



White noise test



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