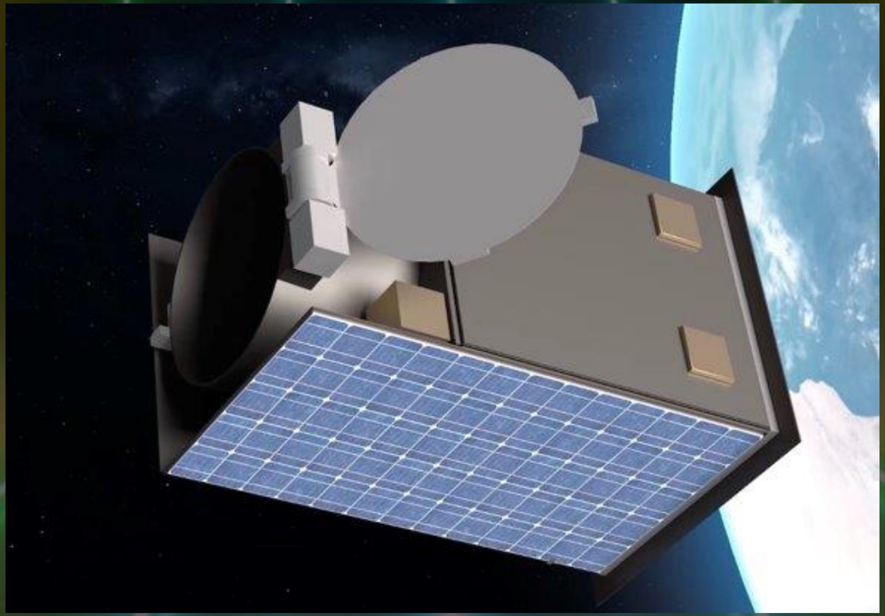
Searching for repeating nuclear transients with QUVIK

Future Czech ambitious UV space telescope



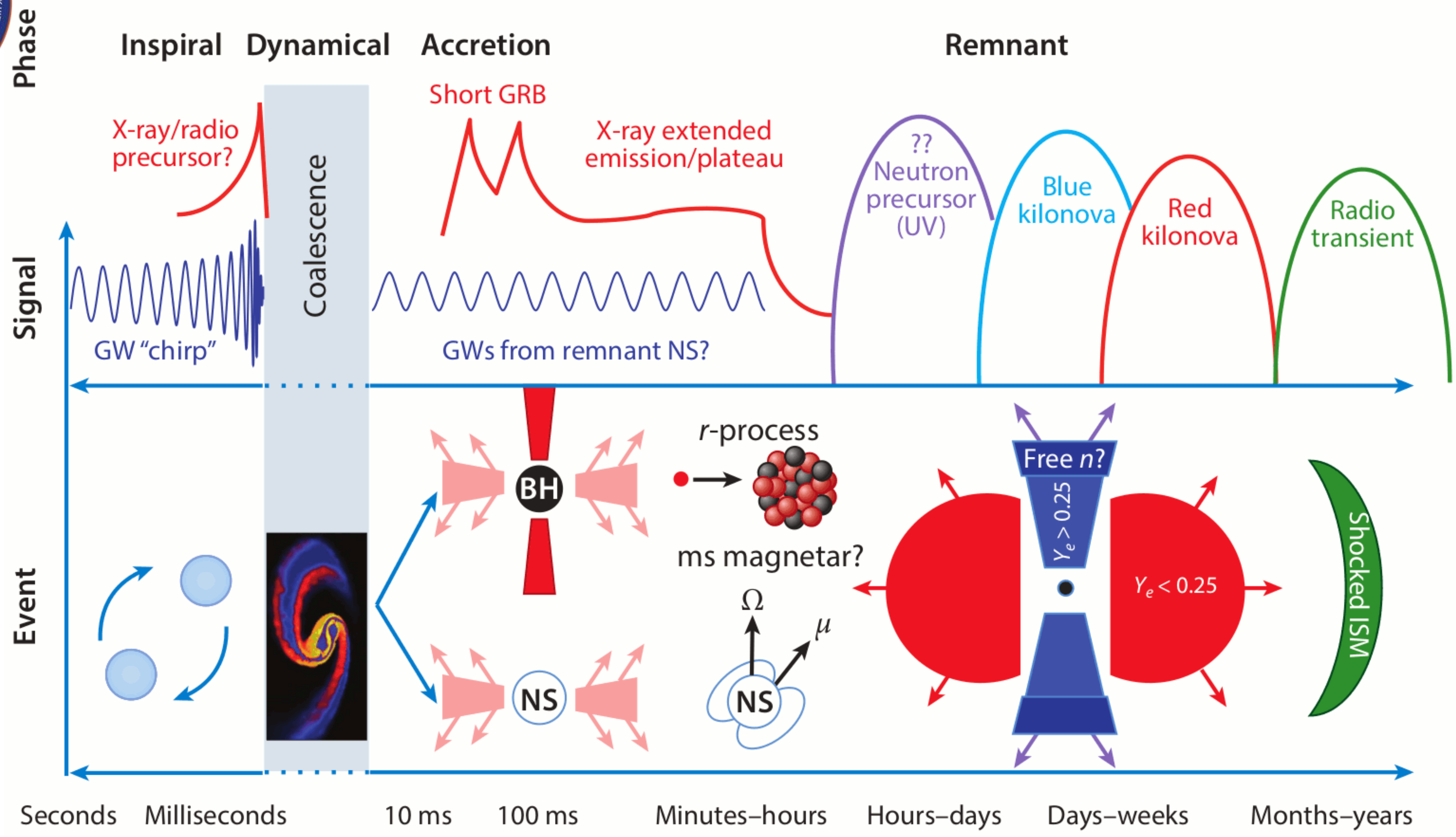
Michal Zajaček (Masaryk University)
on behalf of the *QUVIK* collaboration

November 28, 2025

QUVIK mission objectives

**The mission shall observe the sources of gravitational waves discovered
by LIGO/VIRGO/KAGRA run O5 at the end of this decade.**

The observations will reveal the UV emissions resulting from mergers of neutron stars and black holes, determine their role in the origin of heavy elements, and study physics under exceptionally extreme conditions, providing opportunities for new truly breakthrough discoveries.



Fernandez and Metzger 2016

The **QUVIK** satellite (2 years ago)

Spacecraft is based on the Czech Advanced Platform (CAP)

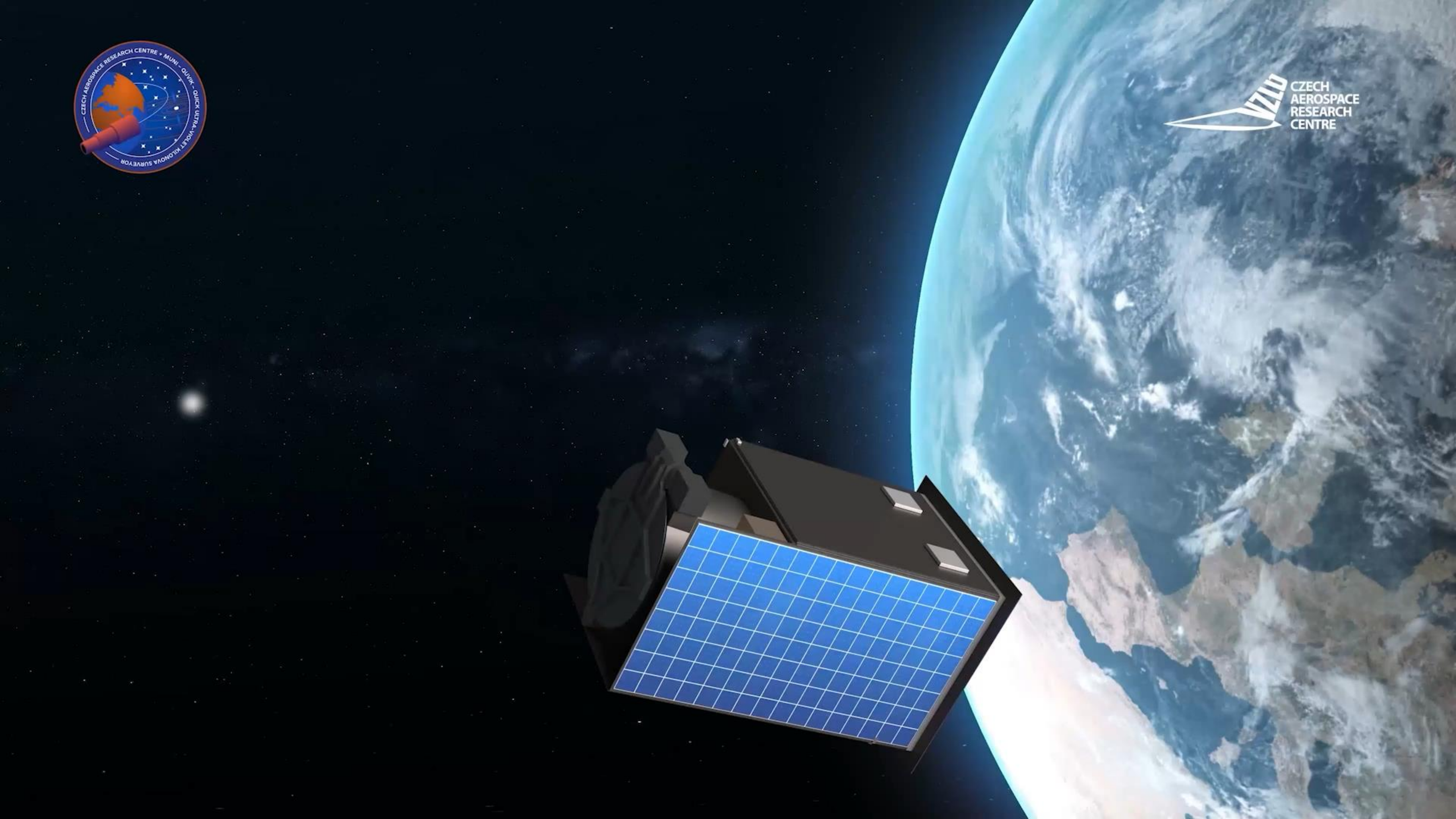
Satellite parameters:
Mass: ~130 kg
Size: 0.7 x 0.7 x 1.1 m
Mission duration: 3 years
Status: B1 phase finished, approved for funding in 2023

Primary payload: 33cm aperture two-band UV space telescope

Fast repointing capability (15 min)
Near-real time communication

Orbit: Low Earth Orbit (LEO)
Sun Synchronous Orbit (SSO) Dawn/dusk orbit orientation

Ready for several launchers (including Vega C and Falcon 9)


CZECH AEROSPACE RESEARCH CENTRE + MUNI - QUVIK - QUICK ULTRA-VIOLET KILONOVA SURVEYOR
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The **QUVIK** satellite

Spacecraft is based on the Czech Advanced Platform (CAP)

Satellite parameters:
Mass: ~200 kg
Size: 0.7 x 0.7 x 1.1 m
Mission duration: 3 years
Status: B1 phase finished, approved for funding in 2023

Past two years QUVIK is undergoing design consolidation, formal B2 expected to start in November

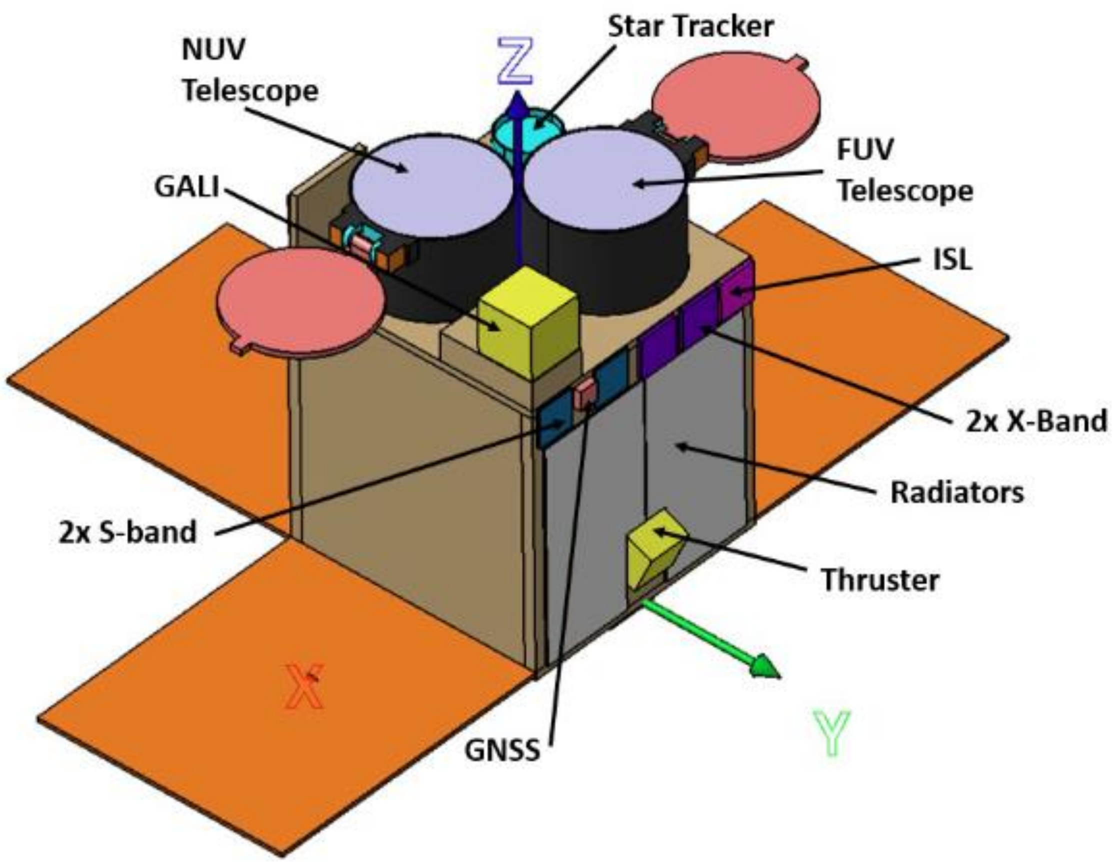
Primary payload: ~25cm aperture NUV (~260–360 nm) telescope with 1 deg^2 FoV
Secondary payload 1: ~25cm aperture FUV (~150–200 nm) telescope with 1 deg^2 FoV contributed by ASI & INAF (led by INAF Brera) in Italy
Secondary payload 2: GALI GRB detector from Technion & ISA in Israel

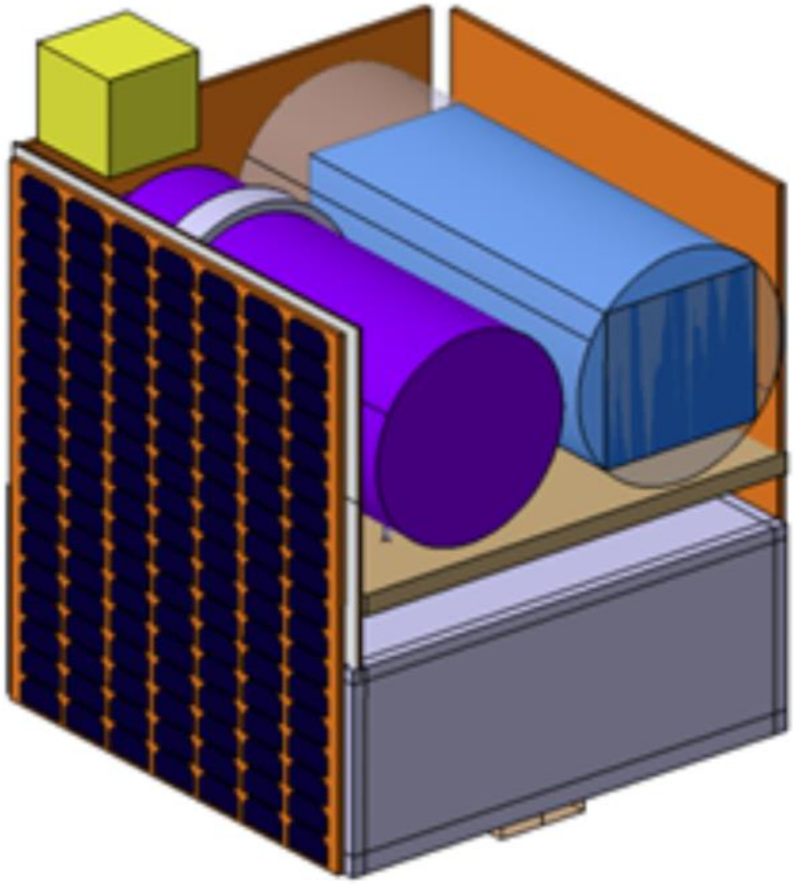
Fast repointing capability (15 min)
Near-real time communication

Orbit: Low Earth Sun Synchronous Orbit (SSO)

Ready for several launchers (including Vega C and Falcon 9)

Payload accommodation is still open





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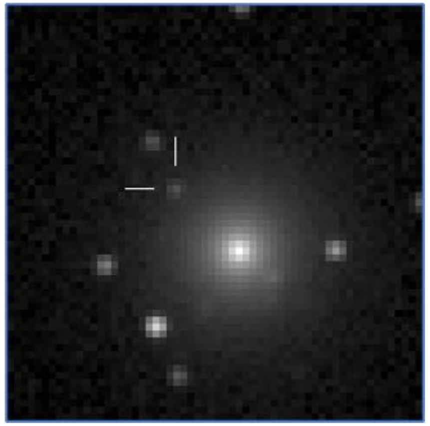
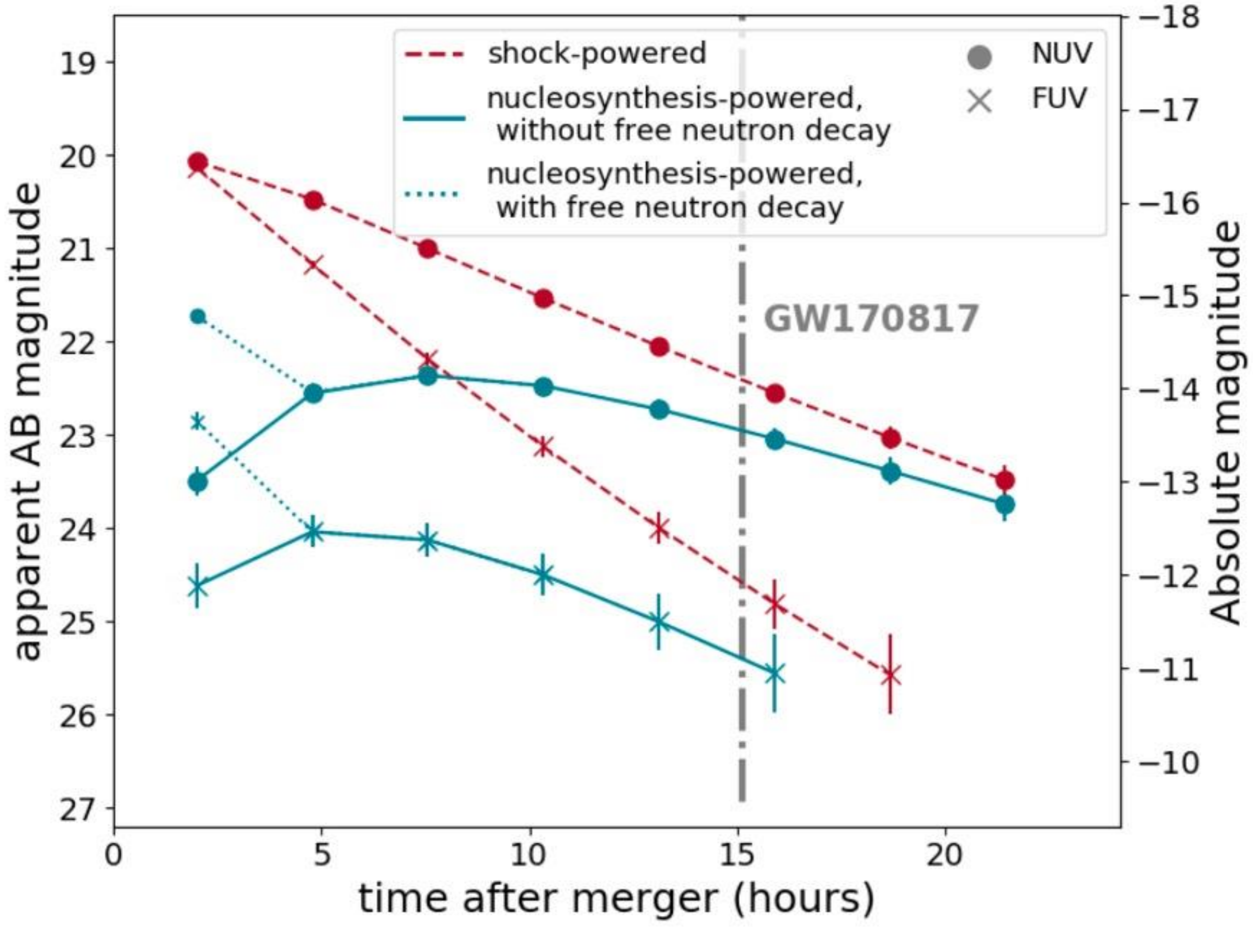
Detection of kilonovae

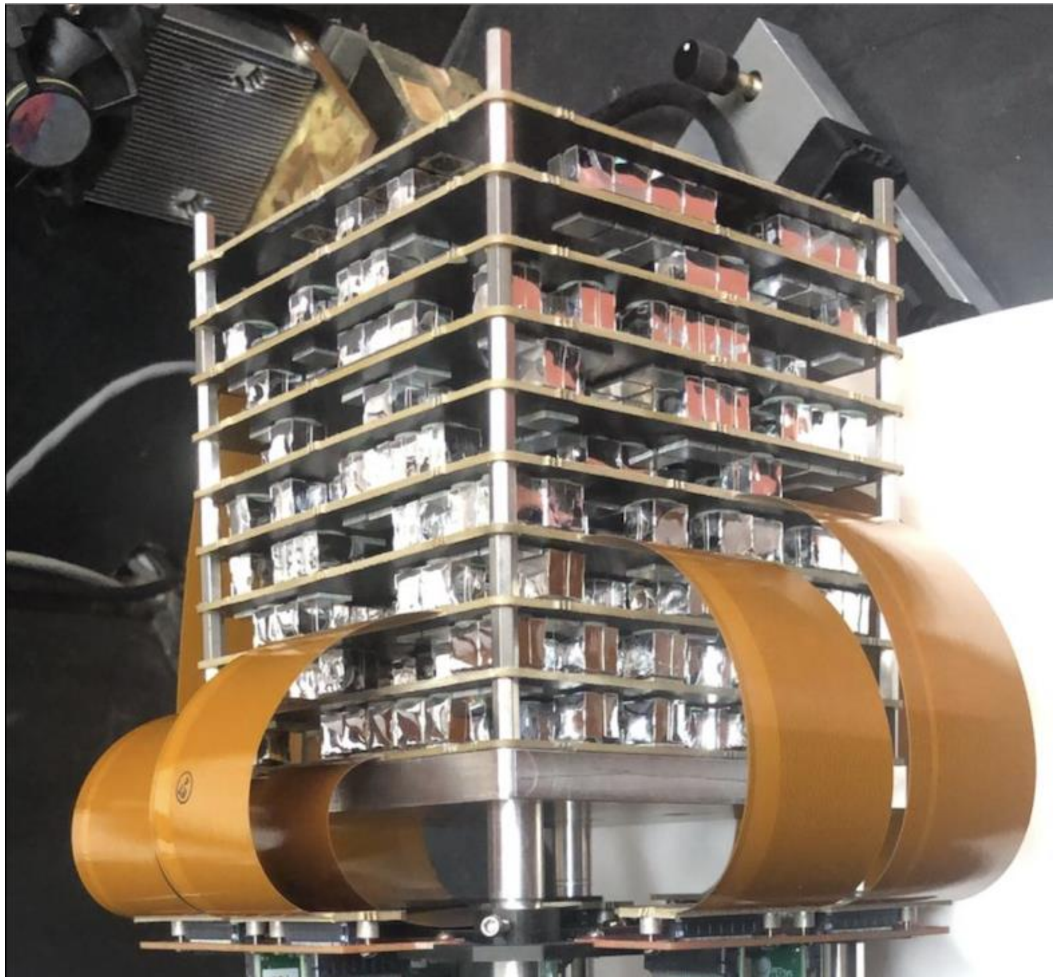




Kulkarni et al. (2022)

- With a limiting magnitude 21.5, we expect to see 5 kilonovae per year, with 22nd mag 9 kilonovae per year
- We designed the instrument to reach the 21.5 magnitude in a single orbit
- To distinguish between kilonova models, observations shall be performed early after the explosion

GALI - an innovative gamma-ray burst detector as a hosted payload



- **New development of Technion Haifa**
- A compact array of many small scintillators - Detecting 3D coded mask
- Localization comes from mutual masking, directionality is statistical, unique photon-count pattern for each burst direction, with high total statistics
- Enabled by SiPM technology
- Scalable detector

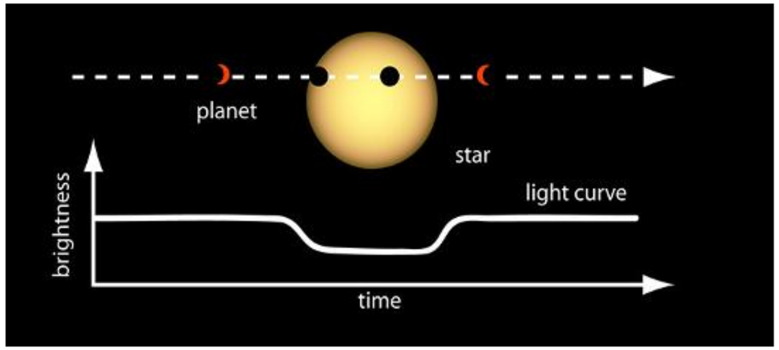
Mission objectives

Primary Mission Objective

Provide UV photometry of transient sources, primarily stellar explosions resulting from mergers of neutron stars or neutron stars and black holes, out to a distance of up to 200 Mpc to distinguish between different explosion scenarios.

Secondary Mission Objectives Serving the Czech and International Astronomy Community

Long and short Gamma-ray bursts, Supernovae, Novae, Physics of stars, Binaries, Intermediate mass mergers, Star Clusters and ISM, Transiting dusty objects, Galactic Nuclei and Tidal Disruption Events, Neutron Stars, Exoplanets



Space Science Reviews (2024) 220:11
https://doi.org/10.1007/s11214-024-01048-3

Science with a Small Two-Band UV-Photometry Mission I: Mission Description and Follow-up Observations of Stellar Transients

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Abstract
This is the first in a collection of three papers introducing the science with an ultra-violet (UV) space telescope on an approximately 130 kg small satellite with a moderately fast re-pointing capability and a real-time alert communication system approved for a Czech national space mission. The mission, called *Quick Ultra-Violet Kilonova surveyor—QUVIK*, will provide key follow-up capabilities to increase the discovery potential of gravitational wave observatories and future wide-field multi-wavelength surveys. The primary objective of the mission is the measurement of the UV brightness evolution of kilonovae, resulting from mergers of neutron stars, to distinguish between different explosion scenarios. The mission, which is designed to be complementary to the *Ultraviolet Transient Astronomy Satellite—ULTRASAT*, will also provide unique follow-up capabilities for other transients both in the near- and far-UV bands. Between the observations of transients, the satellite will target other objects described in this collection of papers, which demonstrates that a small and relatively affordable dedicated UV-space telescope can be transformative for many fields of astrophysics.

Keywords UV space observatory · Kilonovae · Gamma-ray bursts · Supernovae

1 Introduction

The first simultaneous detection of gravitational waves and electromagnetic radiation on 2017 August 17 (Abbott et al. 2017b,a), resulting from a coalescence of neutron stars, marked the onset of multi-messenger astrophysics involving gravitational waves. This exciting observation showed that neutron star mergers are of major importance for enriching the Universe with rare heavy elements such as gold and platinum. The radioactive decay of these heavy elements powers a thermal transient at ultra-violet/visible/infrared wavelengths

Extended author information available on the last page of the article

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Science with a Small Two-Band UV-Photometry Mission II: Observations of Stars and Stellar Systems

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Abstract
We outline the impact of a small two-band UV-photometry satellite mission on the field of stellar physics, magnetospheres of stars, binaries, stellar clusters, interstellar matter, and exoplanets. On specific examples of different types of stars and stellar systems, we discuss particular requirements for such a satellite mission in terms of specific mission parameters such as bandpass, precision, cadence, and mission duration. We show that such a mission may provide crucial data not only for hot stars that emit most of their light in UV, but also for cool stars, where UV traces their activity. This is important, for instance, for exoplanetary studies, because the level of stellar activity influences habitability. While the main asset of the two-band UV mission rests in time-domain astronomy, an example of open clusters proves that such a mission would be important also for the study of stellar populations. Properties of the interstellar dust are best explored when combining optical and IR information with observations in UV.

It is well known that dust absorbs UV radiation efficiently. Consequently, we outline how such a UV mission can be used to detect eclipses of sufficiently hot stars by various dusty objects and study disks, rings, clouds, disintegrating exoplanets or exoasteroids. Furthermore, UV radiation can be used to study the cooling of neutron stars providing information about the extreme states of matter in the interiors of neutron stars and used for mapping heated spots on their surfaces.

Keywords Techniques: photometric · Ultraviolet: stars · Stars: variables: general · Binaries: general · Open clusters and associations: general · Planetary systems

1 Introduction

The new discoveries in astrophysics during the last few decades were frequently connected with the opening of new observational windows into invisible parts of the spectrum. Recently, the advent of observatories working outside the electromagnetic domain founded a

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Science with a Small Two-Band UV-Photometry Mission III: Active Galactic Nuclei and Nuclear Transients

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Abstract
In this review, the third one in the series focused on a small two-band UV-photometry mission, we assess possibilities for a small UV two-band photometry mission in studying accreting supermassive black holes (SMBHs; mass range $\sim 10^6$–$10^{10}\,M_\odot$). We focus on the following observational concepts: (i) dedicated monitoring of selected type-I Active Galactic Nuclei (AGN) in order to measure the time delay between the far-UV, the near-UV, and other wavebands (X-ray and optical), (ii) nuclear transients including (partial) tidal disruption events and repetitive nuclear transients, and (iii) the study of peculiar sources, such as changing-look AGN, hollows and gaps in accretion disks, low-luminosity AGN, and candidates for Intermediate-Mass Black Holes (IMBHs; mass range $\sim 10^2$–$10^5\,M_\odot$) in galactic nuclei. The importance of a small UV mission for the observing program (i) is to provide intense, high-cadence monitoring of selected sources, which will be beneficial for, e.g. reverberation-mapping of accretion disks and subsequently confronting accretion-disk models with observations. For program (ii), a relatively small UV space telescope is versatile enough to start monitoring a transient event within $\lesssim 20$ minutes after receiving the trigger; such a moderately fast repointing capability will be highly beneficial. Peculiar sources within the program (iii) will be of interest to a wider community and will create an environment for competitive observing proposals. For tidal disruption events (TDEs), high-cadence UV monitoring is crucial for distinguishing among different scenarios for the origin of the UV emission. The small two-band UV space telescope will also provide information about the near- and far-UV continuum variability for rare transients, such as repetitive partial TDEs and jetted TDEs. We also discuss the possibilities to study and analyze sources with non-standard accretion flows, such as AGN with gappy disks, low-luminosity active galactic nuclei with intermittent accretion, and SMBH binaries potentially involving intermediate-mass black holes.

Keywords Galactic nuclei · Accretion flows · Tidal disruption events · Transients · Photometry · Time series

1 Introduction

The growth of supermassive black holes (hereafter SMBHs) residing in the centres of galaxies is a crucial topic in modern astrophysics (Di Matteo 2019). SMBHs can grow by accre-

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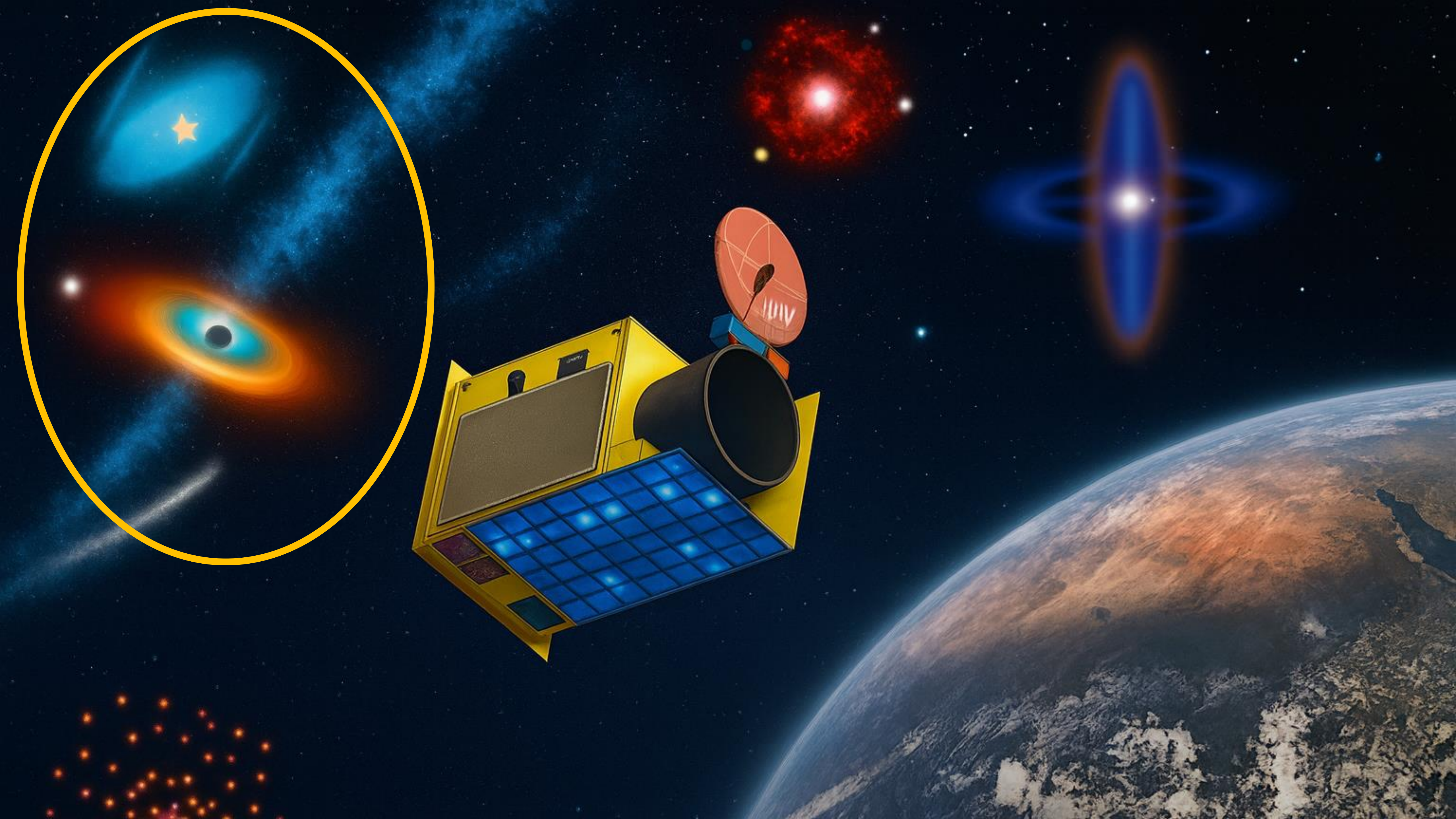
QUVIK papers in Space Science Reviews

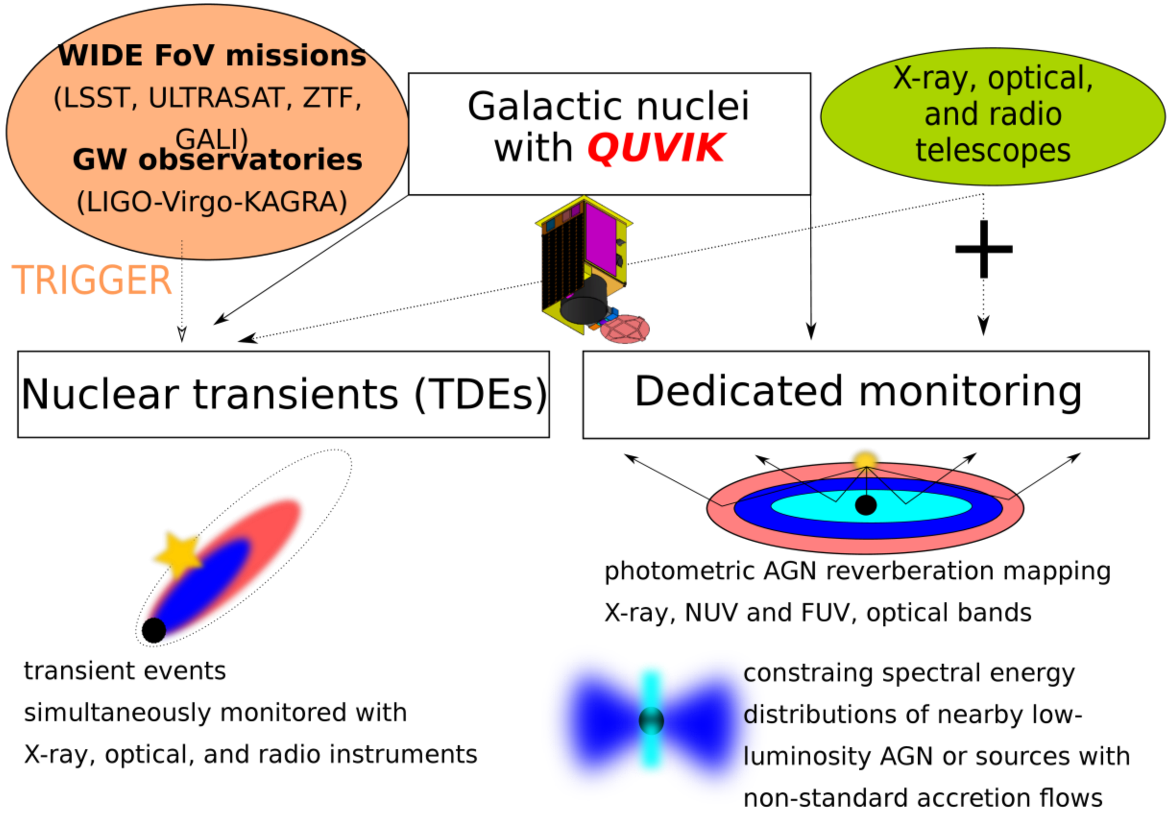
Scientific targets and program elaborated in three review papers published in the Space Science Reviews special issue on QUVIK

- Werner et al. (2024): mission description and stellar transients (2306.15080)
- Krtička et al. (2024): observations of stars and stellar systems (2306.15081)
- Zajaček et al. (2024): active galactic nuclei and nuclear transients (2306.15082)

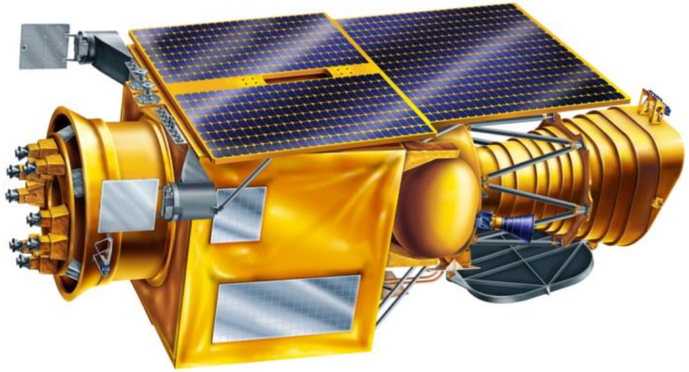


QUVIK galactic nuclei program

- **Monitoring of selected (nearby) AGN**: photometric reverberation mapping
- **Nuclear transients:** tidal disruption events – TDEs, changing-look AGN, repeating nuclear transients (UV quasiperiodic erupters, repeating partial TDEs)



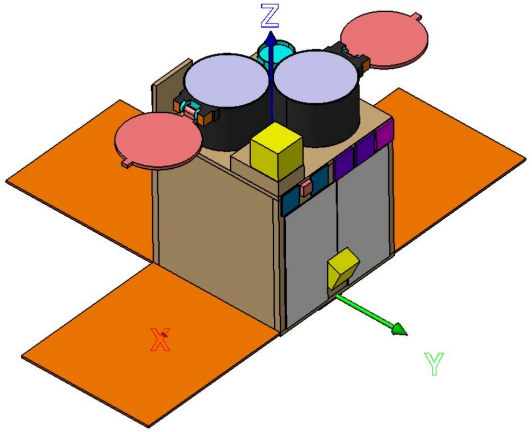
Synergy with other observatories



- QUVIK will fly during the 5th run of the LIGO/VIRGO/KAGRA gravitational detector network, providing key follow-up capabilities and increasing its discovery potential
- QUVIK is complementary to ULTRASAT, providing unique follow-up capabilities in FUV and complementary NUV, multiplying the discovery potential of the mission **QUVIK could also serve as a pathfinder for *UVEX.***
- QUVIK will dedicate part of its observing time to the follow-up of transients discovered by the Vera C. Rubin LSST
- QUVIK will provide open observing time to the international astronomy community as well as an online data archive

QUVIK-ULTRASAT collaboration

QUVIK and *ULTRASAT* provide complementary capabilities that multiply the discovery potential of both missions. *ULTRASAT* will discover the most interesting targets for *QUVIK*, which will then perform unique simultaneous NUV-FUV observations.



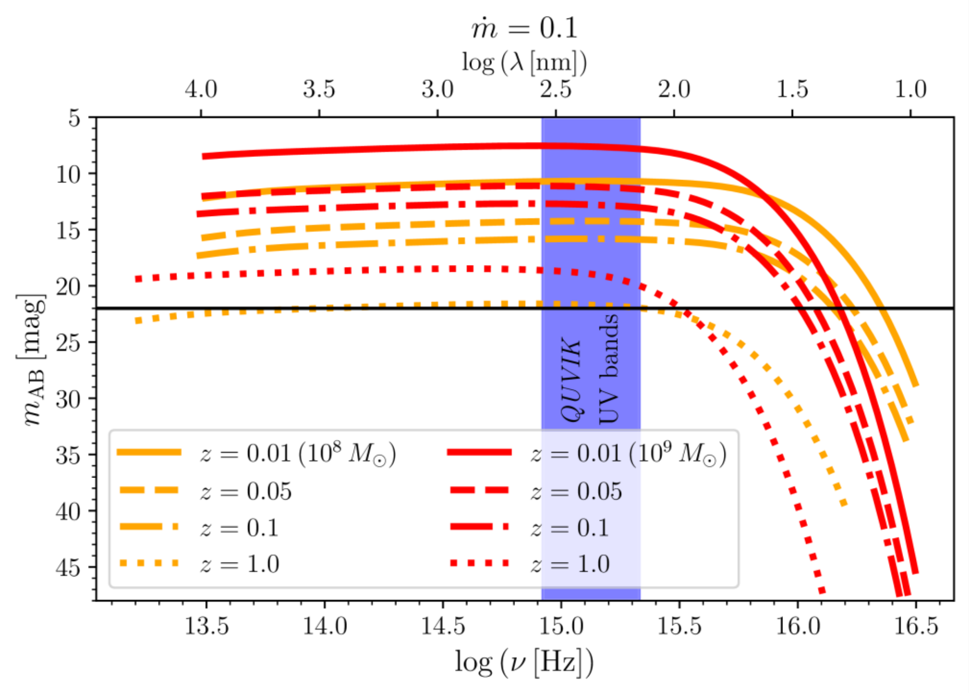
The picture does not reflect the final configuration!

	QUVIK	ULTRASAT
FoV	~1deg^2	204 deg^2
Bandpass	~260—360 nm ~150—200 nm	230—290 nm
Sensitivity	21.5 mag in 3000 s	22.3 mag in 900s
Resolution	<5 arcsec	8.3 arcsec
Observations	pointed	survey
Launch date	2030	2027

QUVIK galactic nuclei program

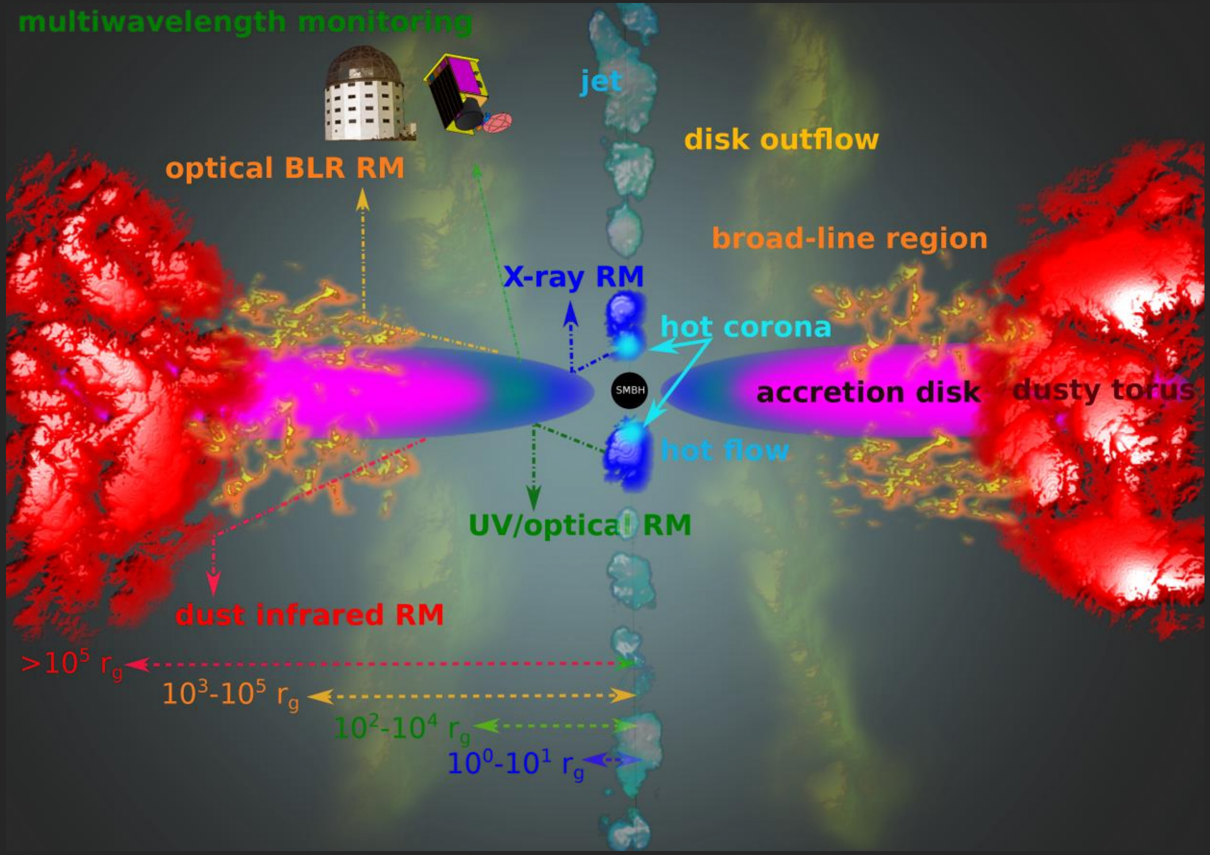
Redshift limit	Limiting u magnitude	Number of SDSS quasars	$t_{\rm int}$ [s], $S/N = 100$
0.5	17.0	151	100.0
0.5	18.0	964	251.2
0.7	17.0	167	100.0
0.7	18.0	1047	251.2

- accretion disk UV emission (type I) observable up to the redshift of ~1
- depends on the SMBH mass and relative accretion rate (0.1-1.0)



Dedicated monitoring of AGN

- Lack of spatial resolution ⟷ temporal resolution
- Different wavelengths probe different length-scales of an accretion disk and its immediate surroundings



Dedicated monitoring of AGN

- Driving ionizing radiation (X-ray corona – but not present in all AGN)
- Reprocessed emission in far-UV, near-UV, optical, and infrared

$$\Delta F_{\rm r}(t) = \int_0^{\tau_{\rm max}} \psi(\tau)\Delta F_{\rm i}(t-\tau){\rm d}\tau\,,$$

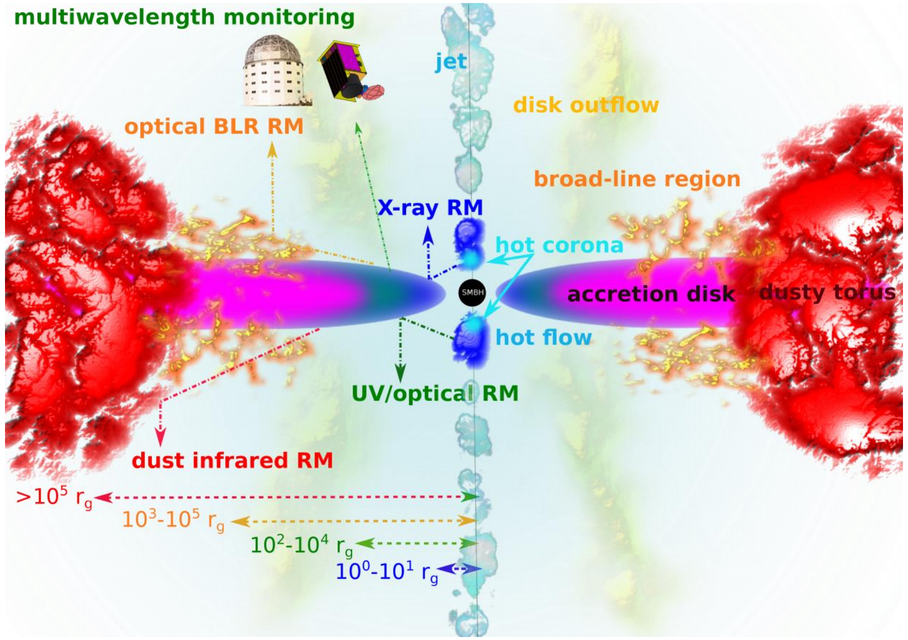
where $\tau = r/c$ is the mean time-delay due to light-travel time,
$\psi(\tau)$ is the transfer function of the accretion disk (delay and blurring)

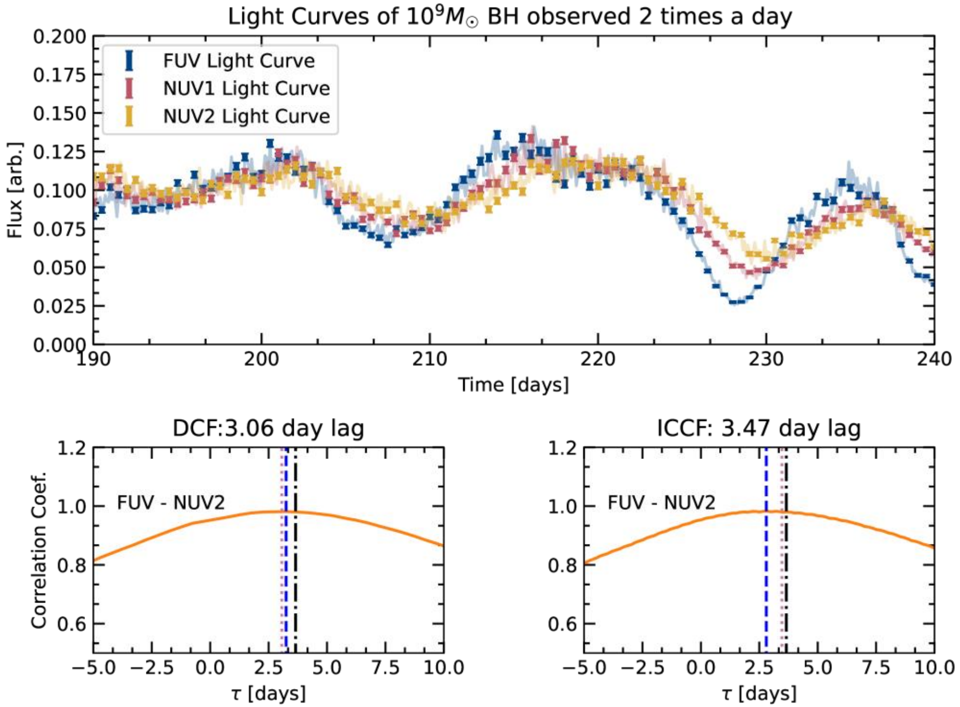
Required cadence of a fraction of a day to a few days

Reverberation mapping		Light-crossing time [days]		
Wavelength domain	Spatial length scale [r_g]	10^7 M$_\odot$	10^8 M$_\odot$	10^9 M$_\odot$
X-ray	1–10	5.7×10^{-4}–5.7×10^{-3}	5.7×10^{-3}–5.7×10^{-2}	5.7×10^{-2}–0.57
UV/optical (*QUVIK*)	10^2–10^4	5.7×10^{-2}–5.7	0.57–57	5.7–570
optical BLR	10^3–10^5	0.57–57	5.7–570	57–5700
optical/infrared dusty torus	$>10^5$	>57	>570	>5700

Dedicated monitoring of AGN

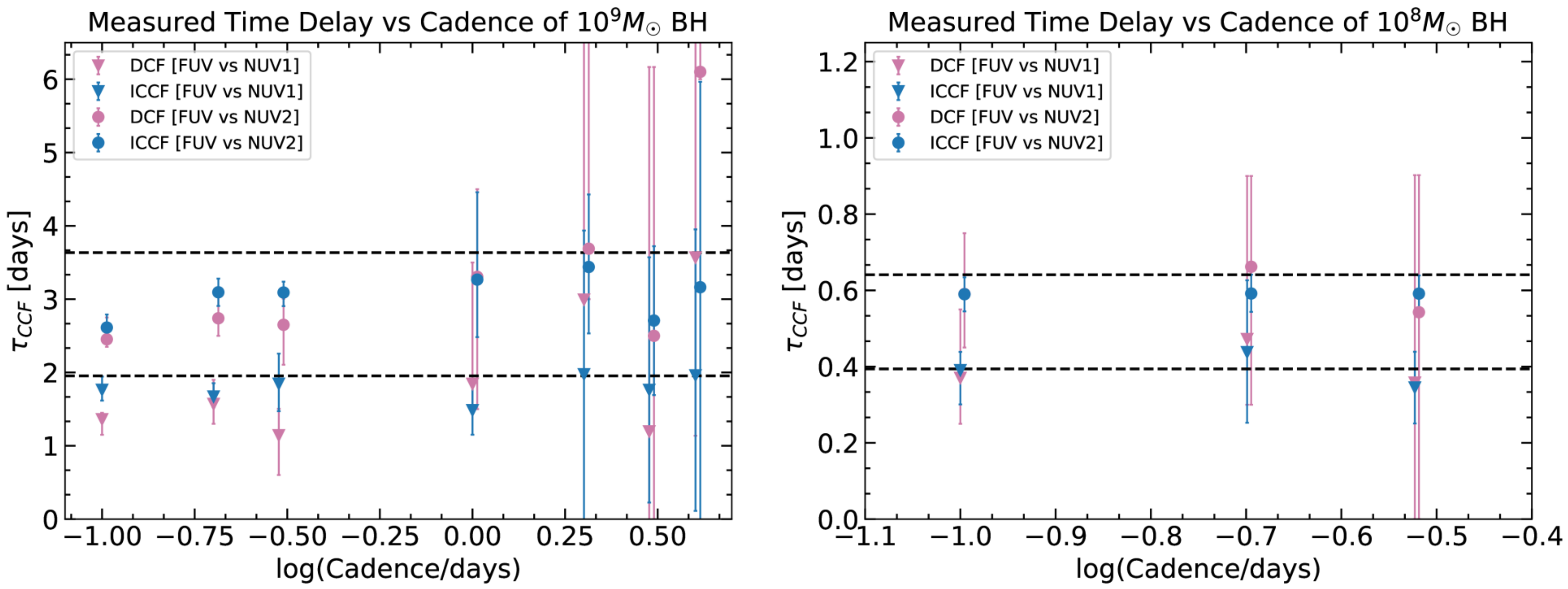
- mock UV light curves of different cadences for 10^8 and 10^9 Solar-mass black holes
- **FUV** (175 nm), **NUV1** (260 nm), and **NUV2** (325 nm) light curves
- driving X-ray signal modelled using broken power-law power spectral density (Timmer-Koenig algorithm) + transfer function of the standard accretion disk





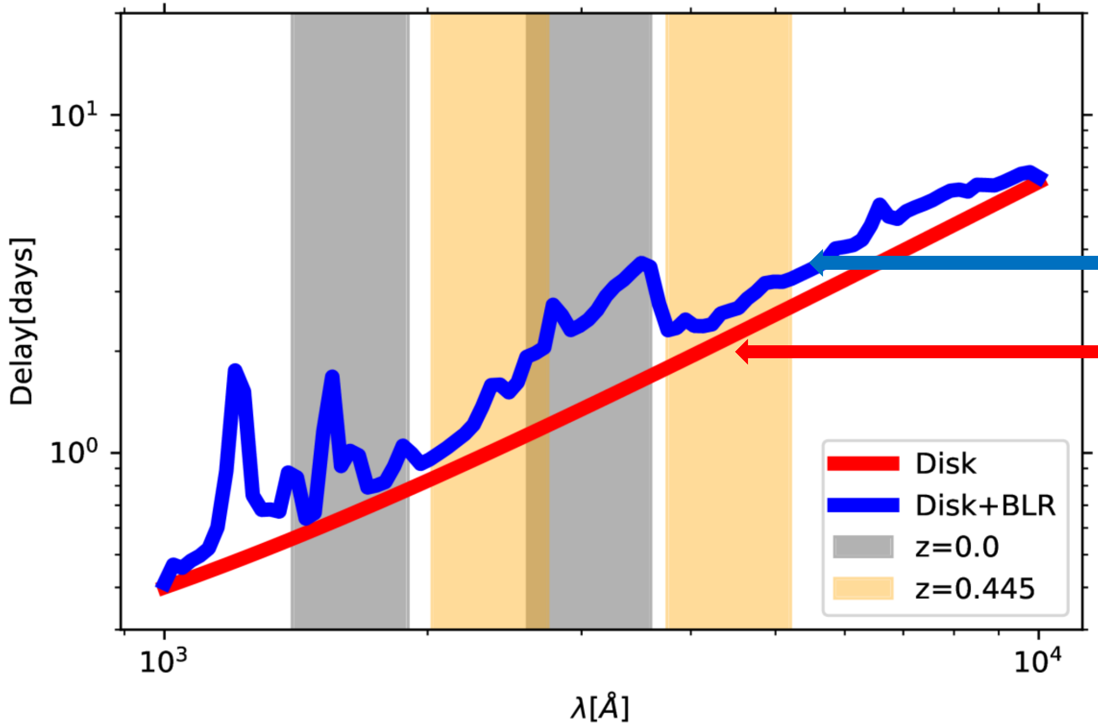
Dedicated monitoring of AGN

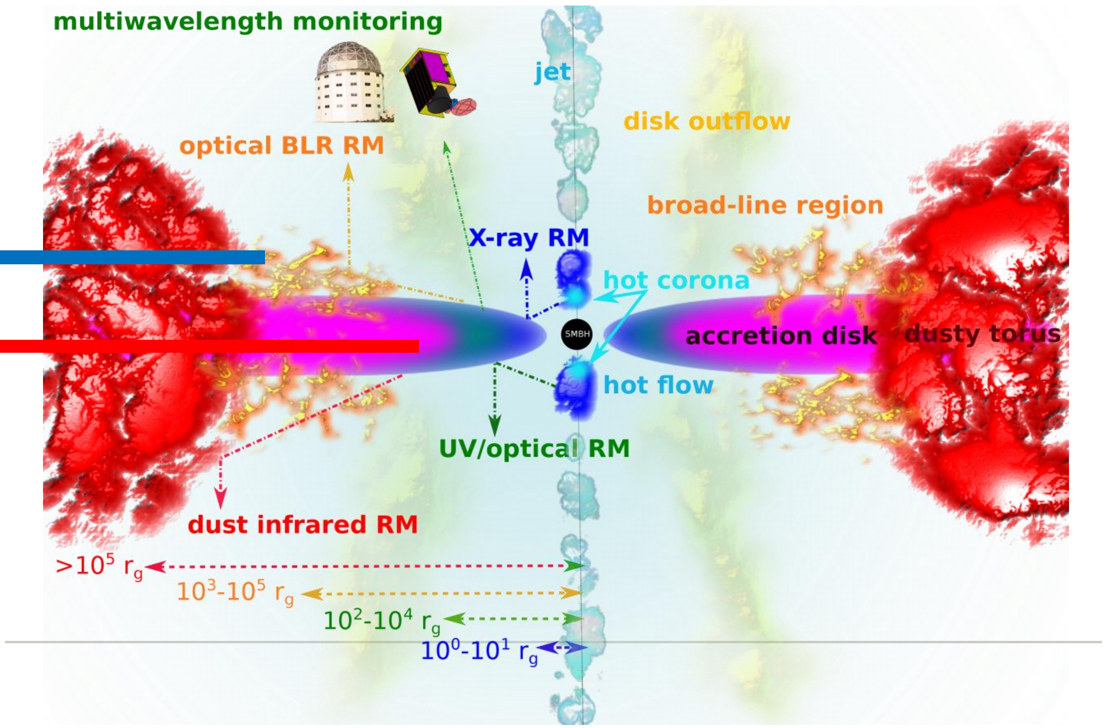
- AGN with supermassive black holes of ~10^8 Solar masses require a cadence of < 0.3 days to detect difference between FUV-NUV1 and FUV-NUV2 time delays
- AGN with supermassive black holes of ~10^9 Solar masses require a cadence of < 1 day to detect difference between FUV-NUV1 and FUV-NUV2 time delays



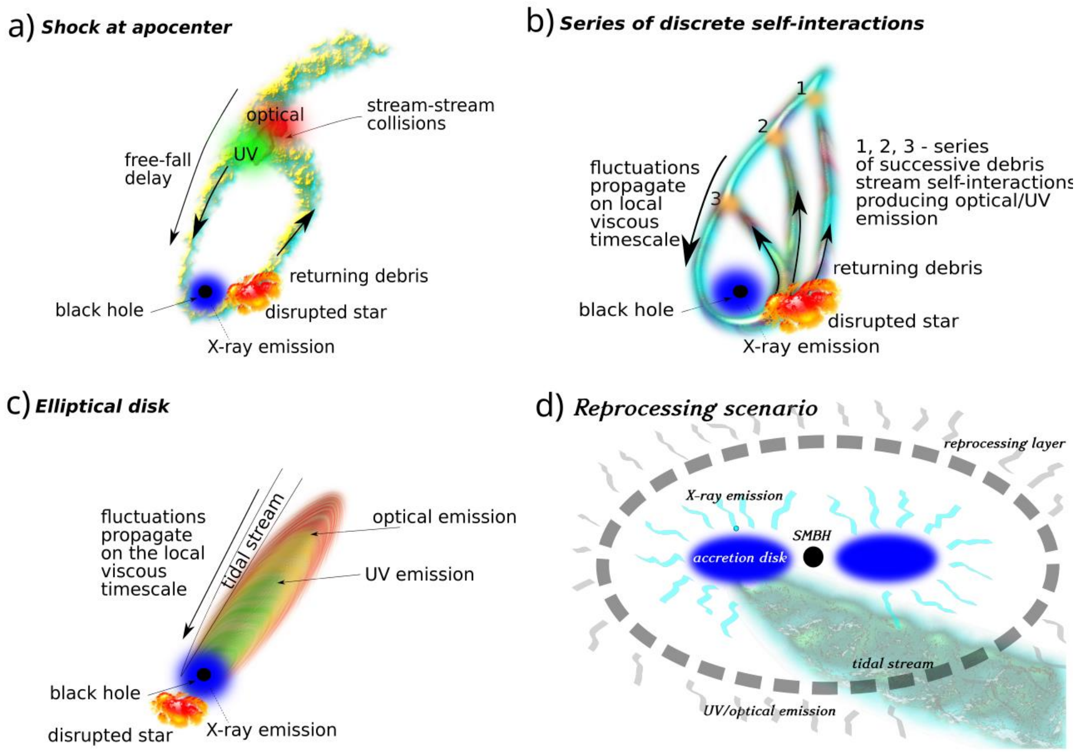
Dedicated monitoring of AGN

- Potential effect of **extended media** (ultrafast outflows, broad-line region) on the measured time delays: prolongation with respect to the standard accretion disk reprocessing $\tau(\lambda) \propto \lambda^{4/3}$
- Redshift-dependent
- Pure **accretion disk** reprocessing + **disk-BLR** reprocessing





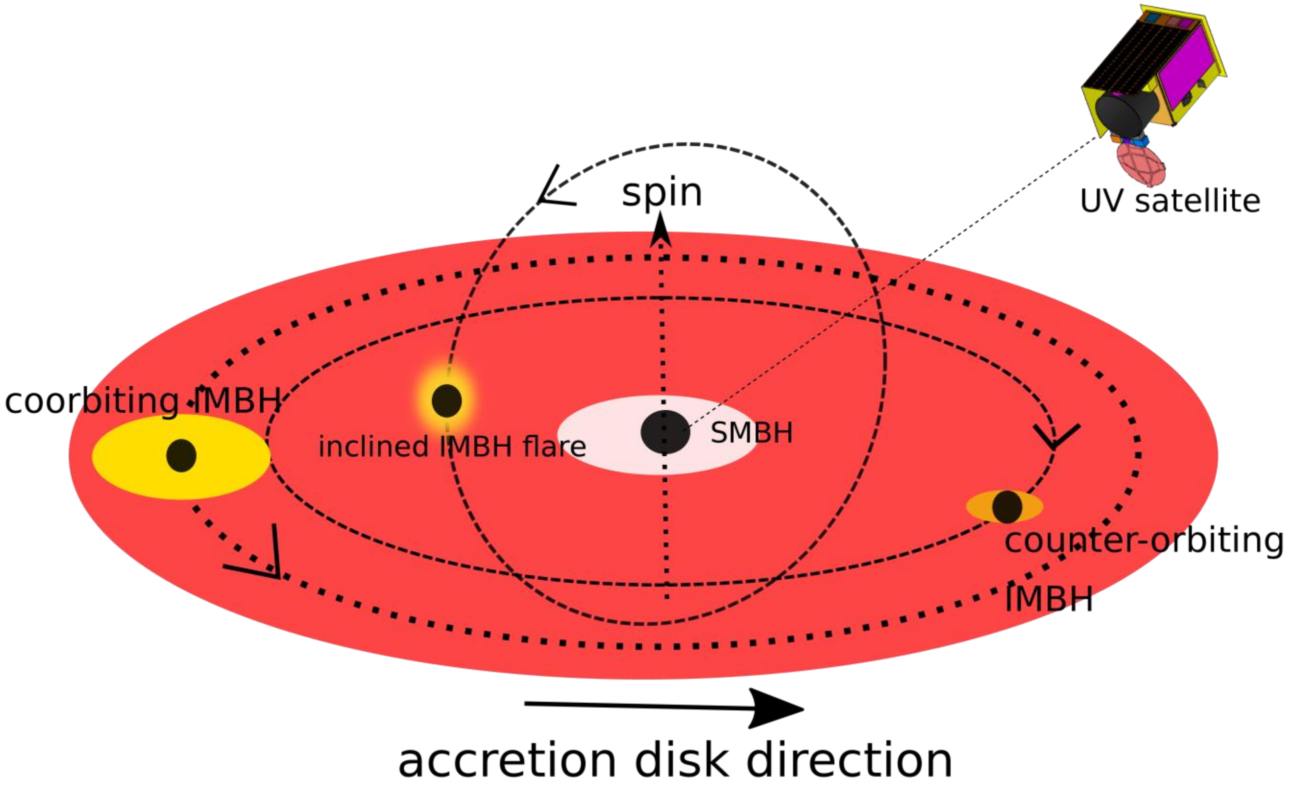
Nuclear transients



- Tidal disruption events with the peak luminosities of ~10^{44}-10^{45} erg/s in the optical/UV domain
- Typically power-law decay and late-time UV/optical plateau – related to the decay in the fall-back rate

$$\dot{M}_{\rm fallback} \propto t^{-5/3}$$

- QUVIK can help determine the colour evolution (TDEs vs. SNe distinction)
- **Unclear origin of UV/optical emission: shock-or accretion-powered?**



Repeating Nuclear transients

- Potential relation to **supermassive black hole binary** and **triple systems** with a large range of mass ratios: extreme-mass/intermediate-mass/nearly-equal SMBH binaries
- An orbiting **intermediate-mass black hole** (>10^3 Solar masses) can produce significant emission, exceeding the luminosity of a primary AGN accretion disk

Repeating Nuclear Transients

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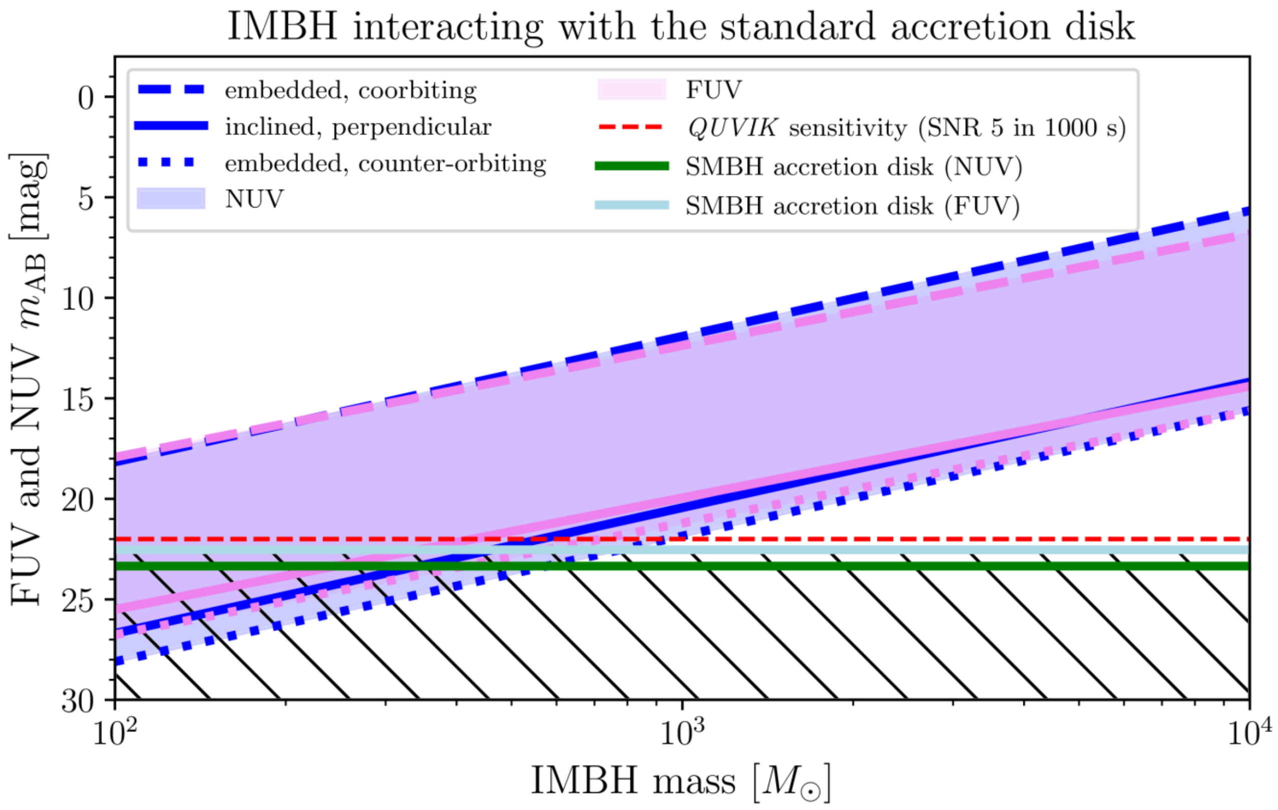
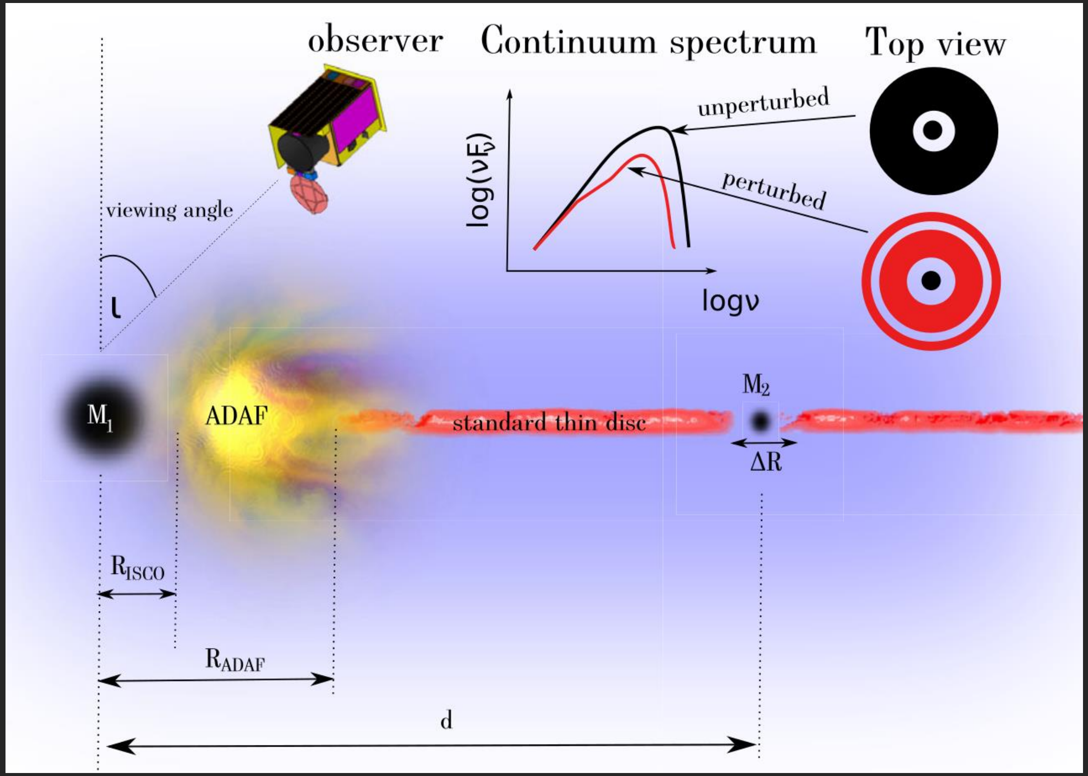


AGN at *z=0.1* with the relative accretion rate of 0.01.

Repeating Nuclear Transients

- QUVIK will obtain FUV and NUV flux densities to constrain the SED
- Potential signatures of "hollows" and "gaps" due to companions (Štolc et al. 2023)



Instrument	Filter	Central Wavelength (Å)
Small UV mission	FUV	1500
	NUV	3000
LSST	u	3671
	g	4827
	r	6223
	i	7546
	z	8691
	y	9712
Swift	uvw2	1928
	uvm2	2246
	uvw1	2600
	u	3465
	b	4392
	v	5468
WISE	w1	33,680
	w2	46,180

Repeating Nuclear Transients

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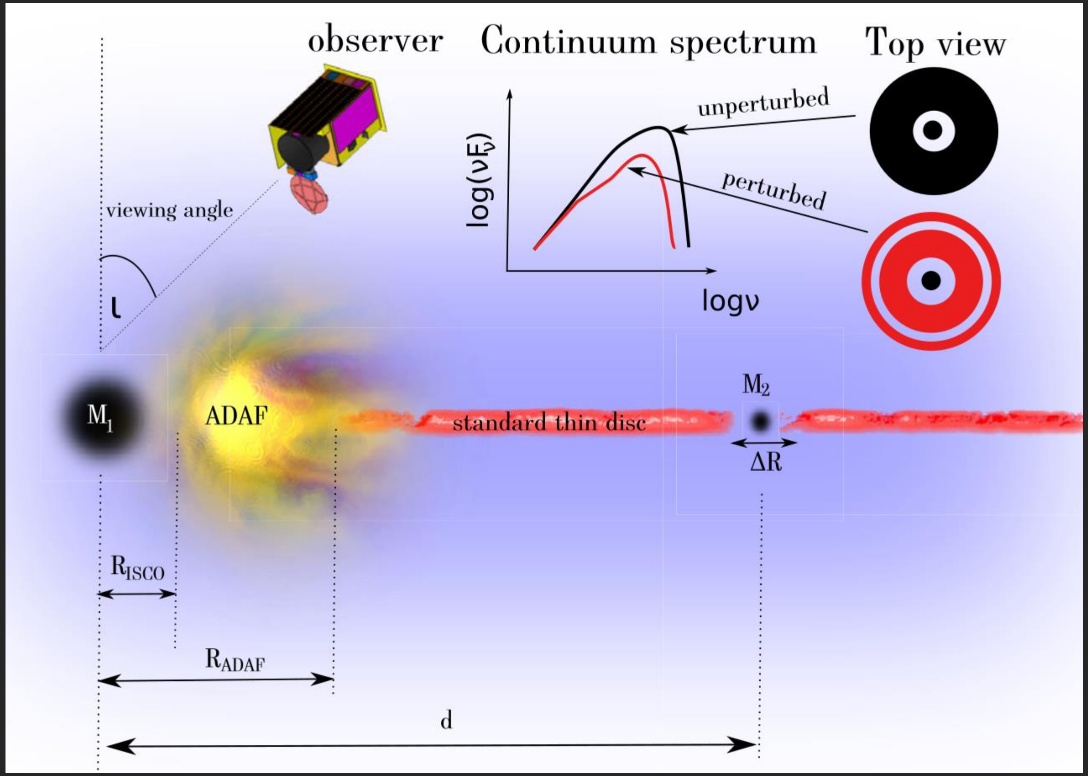

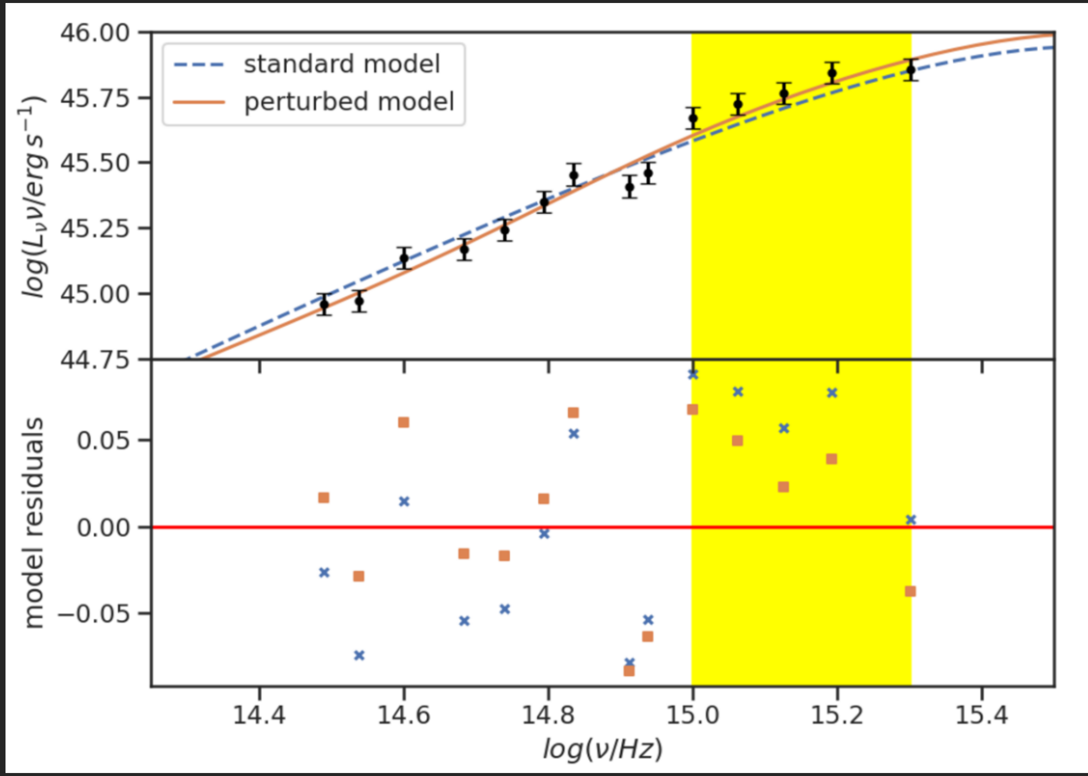

Repeating Nuclear Transients

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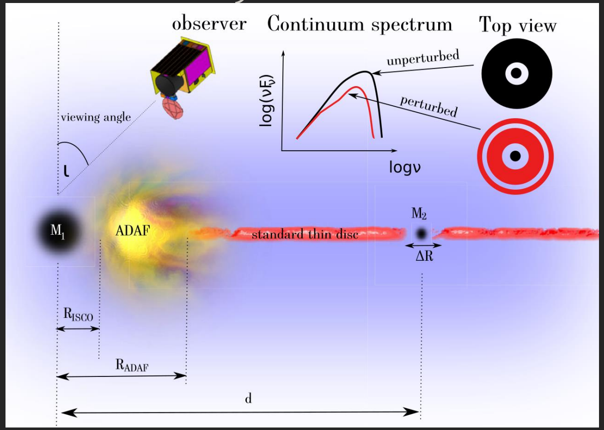
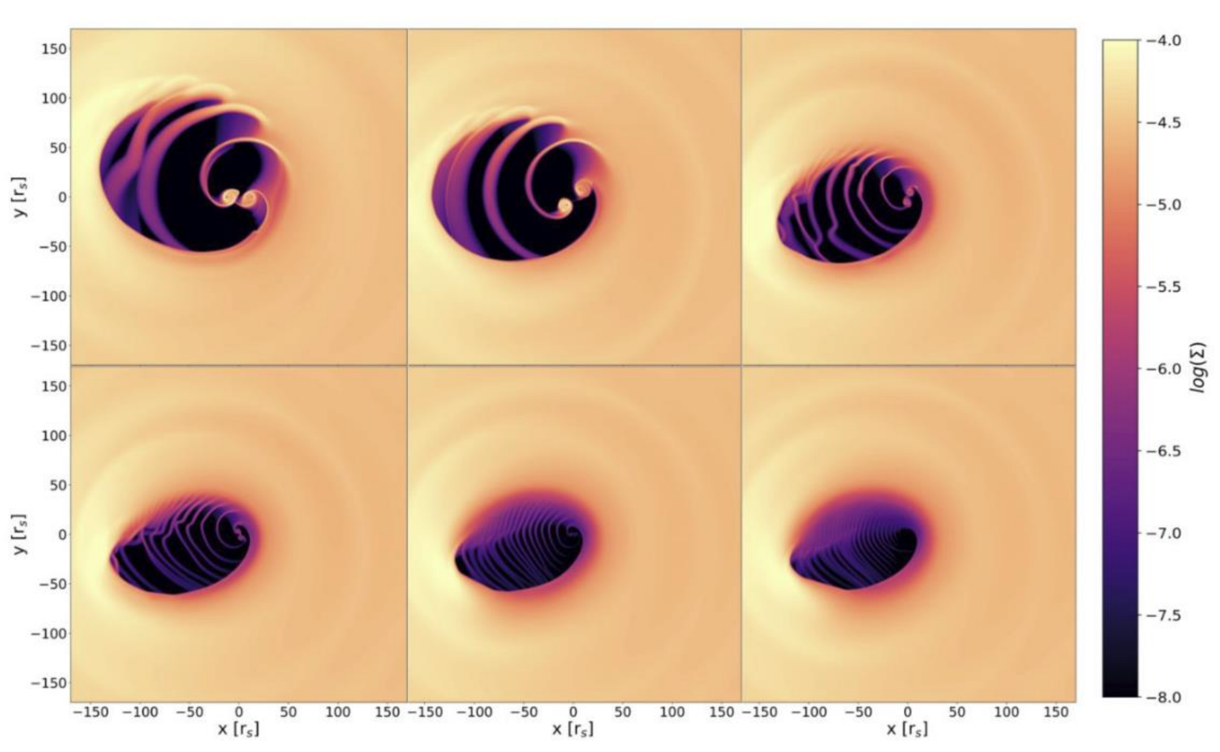
- Potential signatures of "hollows" and "gaps" due to companions (Štolc et al. 2023)

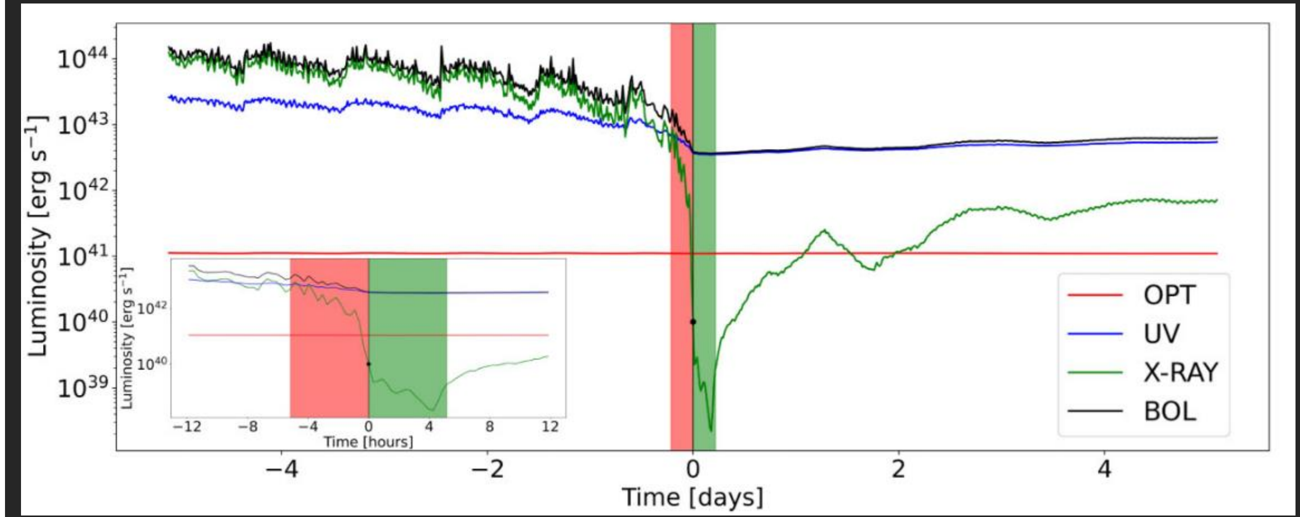
assumed values			fit values							
$\dot{m}$	$R_{\rm gap\,in}$ ($r_{\rm g}$)	$R_{\rm gap\,out}$ ($r_{\rm g}$)	$\dot{m}$	$R_{\rm gap\,in}$ ($r_{\rm g}$)	$R_{\rm gap\,out}$ ($r_{\rm g}$)	χ^2_ν	*AIC*	*BIC*	Δ *AIC*	Δ *BIC*
∼ 10% uncertainty										
0.1	255	345	0.11 ± 0.01	193 ± 76	291 ± 108	1.7	11.1	13.4	–	–
0.1	255	255	0.091 ± 0.004	–	–	2	11.9	12.7	0.8	−0.7
0.1	340	460	0.10 ± 0.01	263 ± 100	397 ± 155	1.4	8.4	10.7	–	–
0.1	340	340	0.089 ± 0.004	–	–	1.8	10.5	11.3	2.1	0.6
0.1	425	575	0.10 ± 0.01	331 ± 153	453 ± 223	1.1	4.1	6.4	–	–
0.1	425	425	0.093 ± 0.003	–	–	1.2	4.5	5.3	0.4	−1.1
∼ 2% uncertainty										
0.1	255	345	0.098 ± 0.001	251 ± 28	324 ± 36	1.1	3.5	5.8	–	–
0.1	255	255	0.090 ± 0.001	–	–	5.6	28.4	29.2	24.9	23.4
0.1	340	460	0.098 ± 0.001	338 ± 45	444 ± 62	1.5	9.3	11.6	–	–
0.1	340	340	0.091 ± 0.002	–	–	6.4	30.8	31.6	21.5	20
0.1	425	575	0.099 ± 0.001	501 ± 51	684 ± 79	1.2	5.5	7.8	–	–
0.1	425	425	0.094 ± 0.002	–	–	6.2	30.1	30.9	24.6	23.1



Repeating Nuclear Transients

- Supermassive black hole binaries can be revealed by the combined X-ray and UV monitoring of a candidate source
- After the merger, X-ray emission disappears while the UV emission is relatively stable

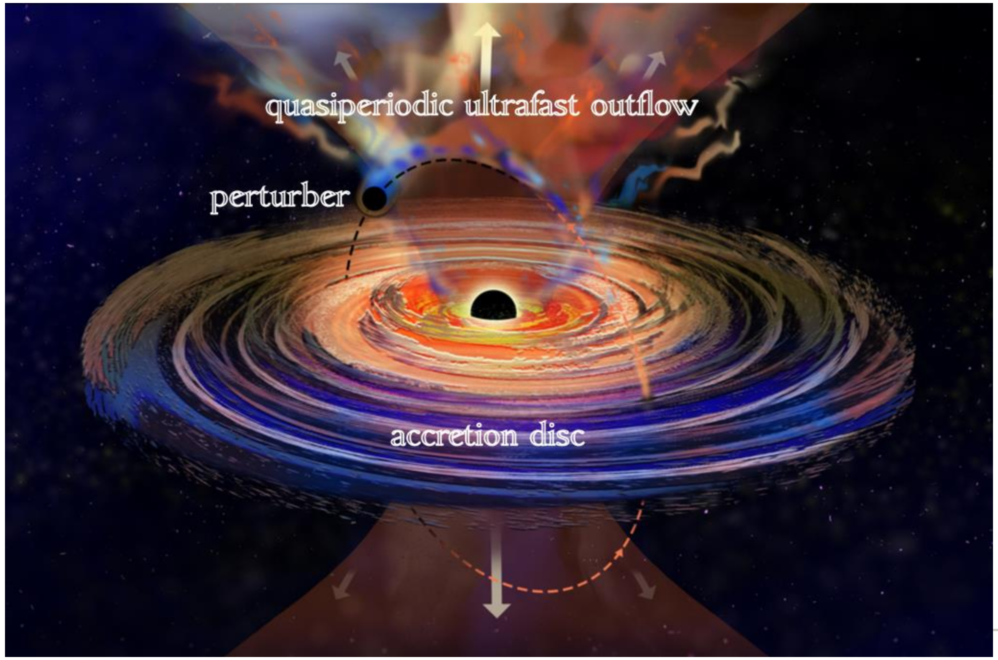


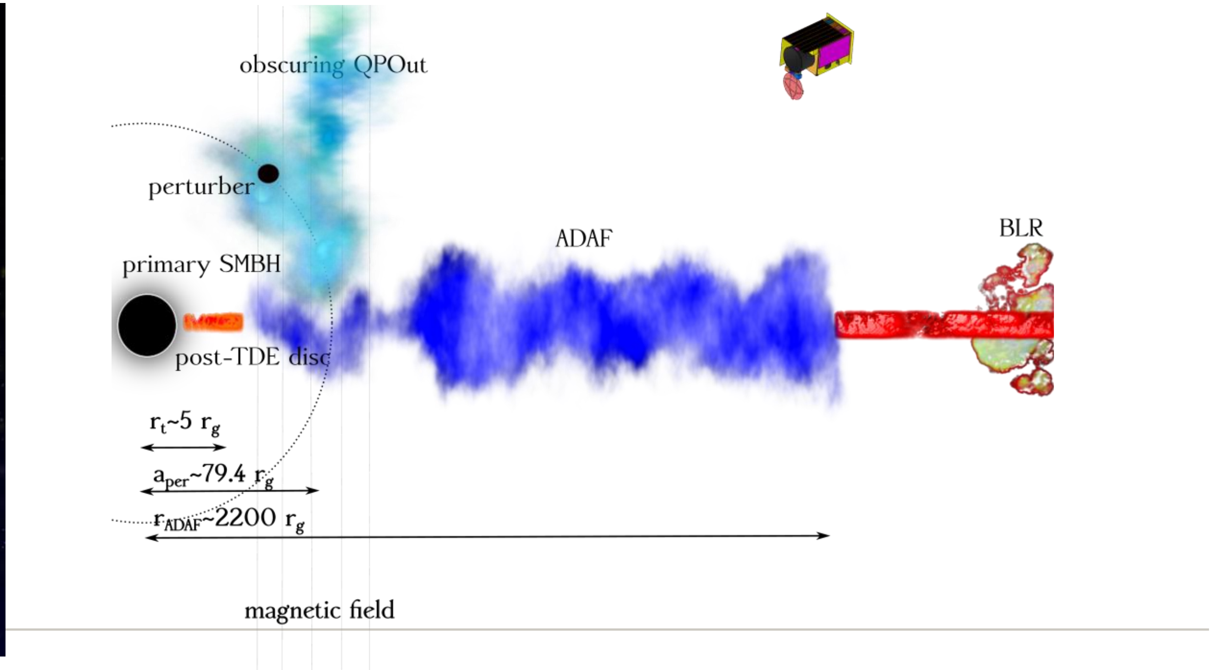


Krauth et al. 2023

Repeating Nuclear Transients

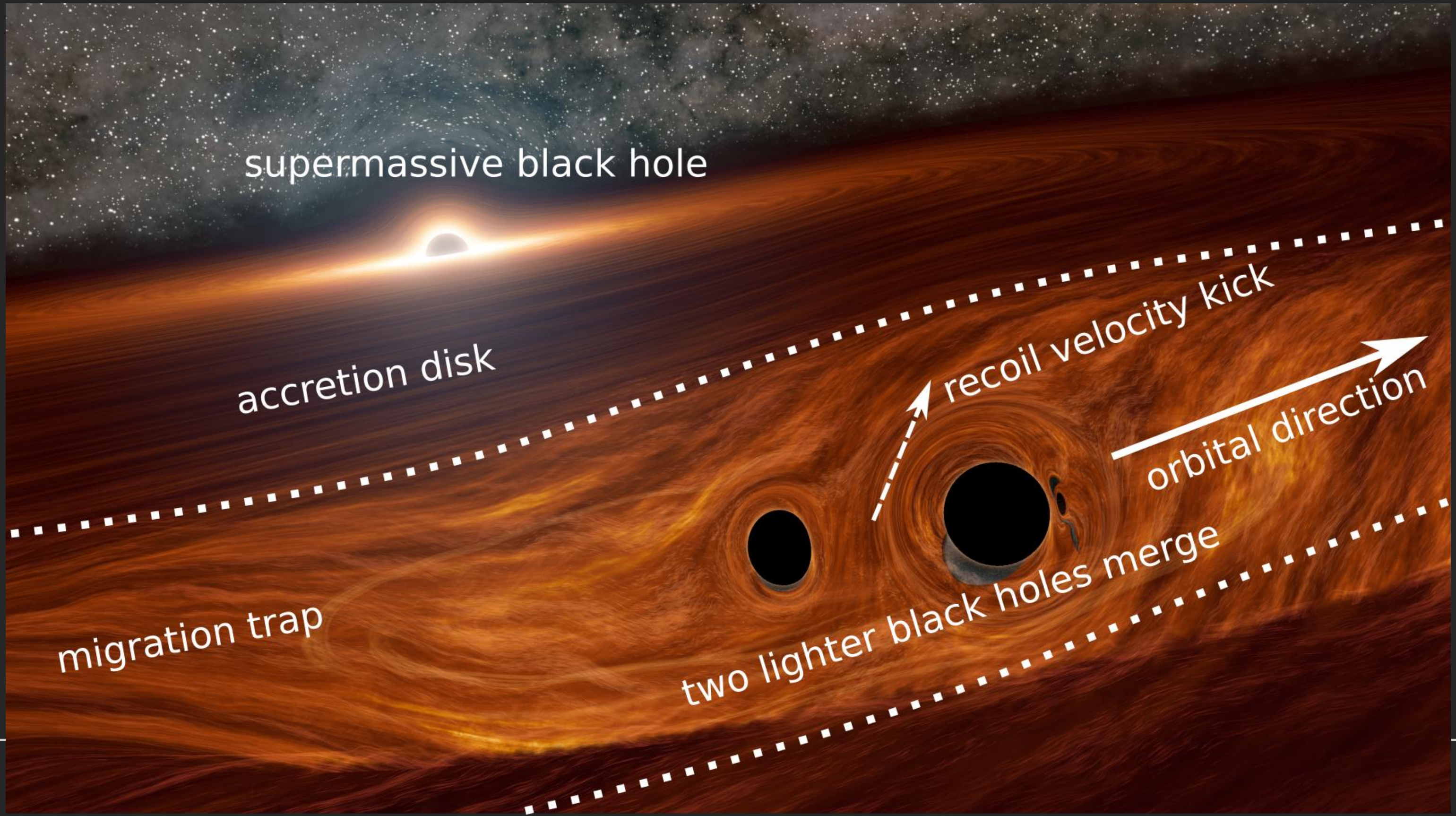
- Inclined SMBH-binary systems may be revealed by quasiperiodic eruptions and outflows
- **Quasiperiodic erupters** (QPEs; Miniutti+2019) in soft X-ray domain may be the manifestation of such systems (detailed interpretation is still unclear!)
- At larger distances (~100 r_g) the continuum related to accretion is not significantly affected but the launched outflow causes the absorption in soft X-ray, potentially also UV (**Quasiperiodic Ultrafast Outflow – QPOut**; ASASSN-20qc, Pasham et al. 2024)



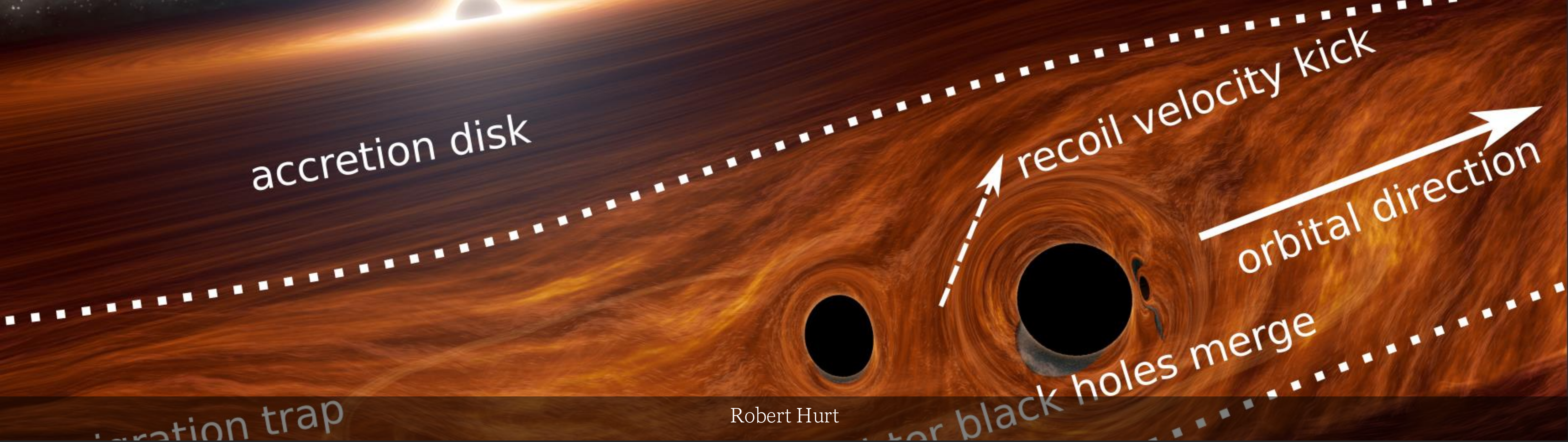


Repeating Nuclear Transients

- stellar black holes can accumulate within the AGN accretion disks within "migration traps"
- Bellovary et al. 2016 estimate the trap radius of ~40-600 gravitational radii
- **stellar black hole binaries, hierarchical formation of intermediate-mass black holes with inclined orbits due to recoil velocity kick**



Robert Hurt
IPAC/Caltech



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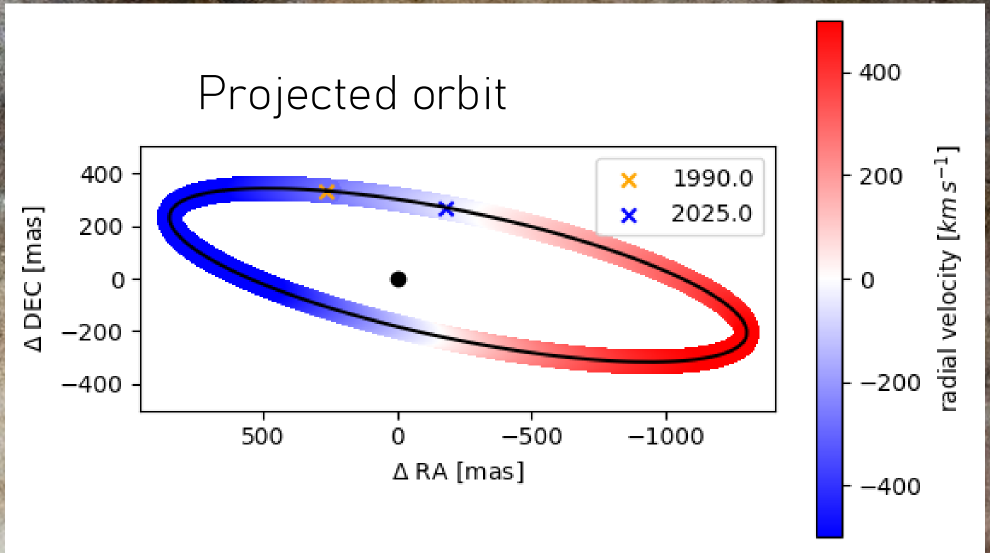
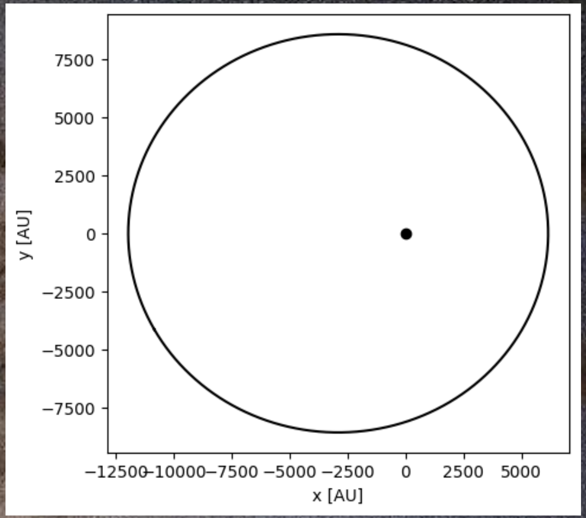
Repeating Nuclear Transients

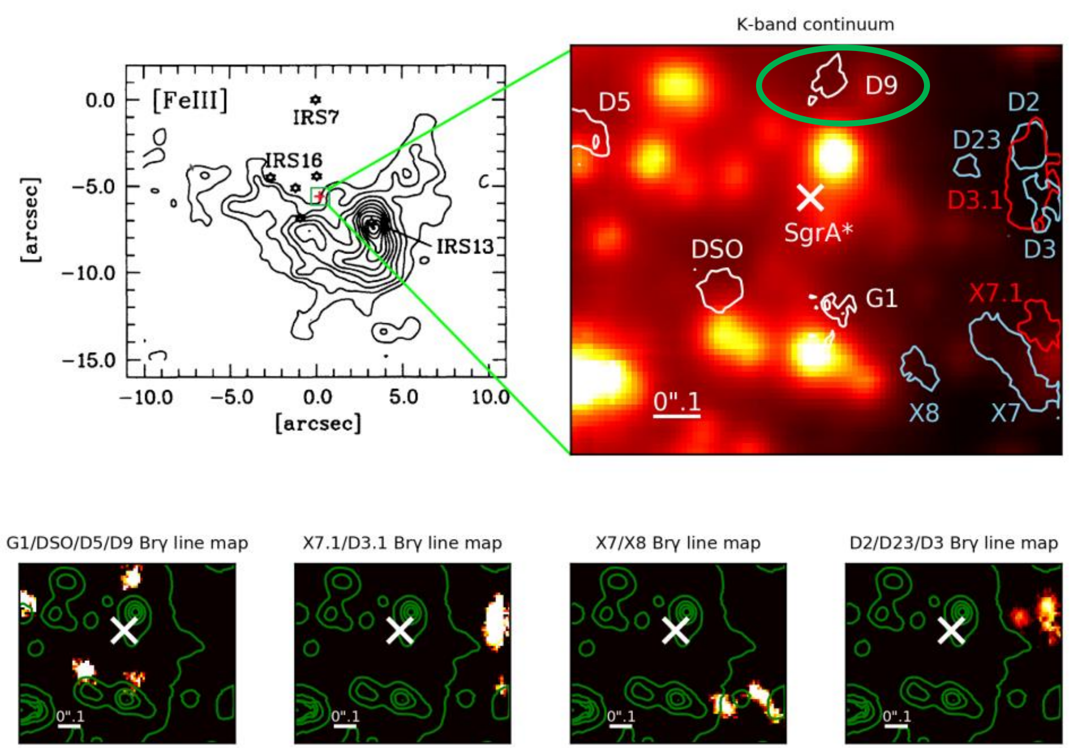
- At the moment we do not observe a large-mass triple system in galactic nuclei, but such a bound system of young stars was identified in the Galactic center…

Binary orbiting supermassive black hole in the Galactic center

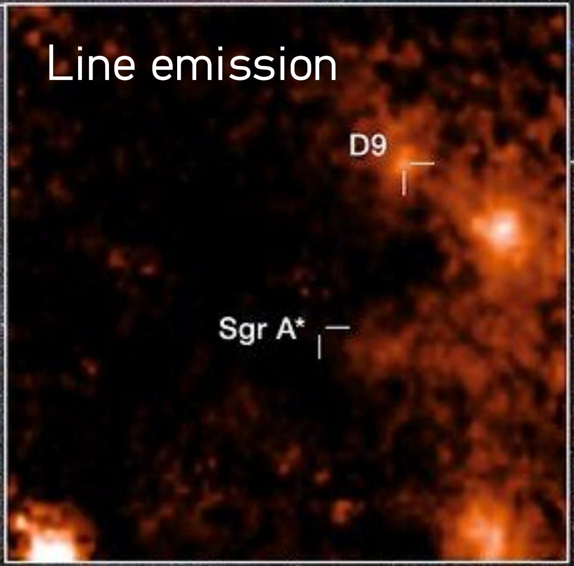




K-band continuum

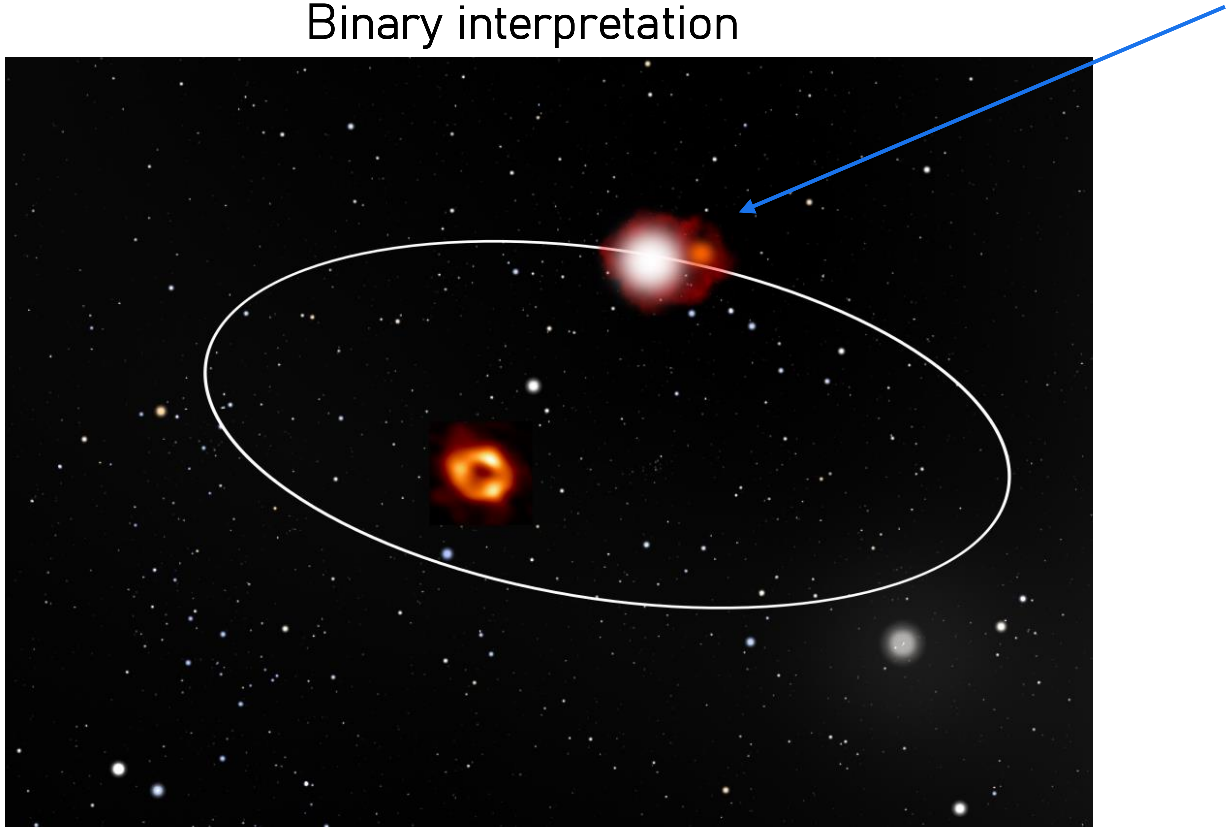


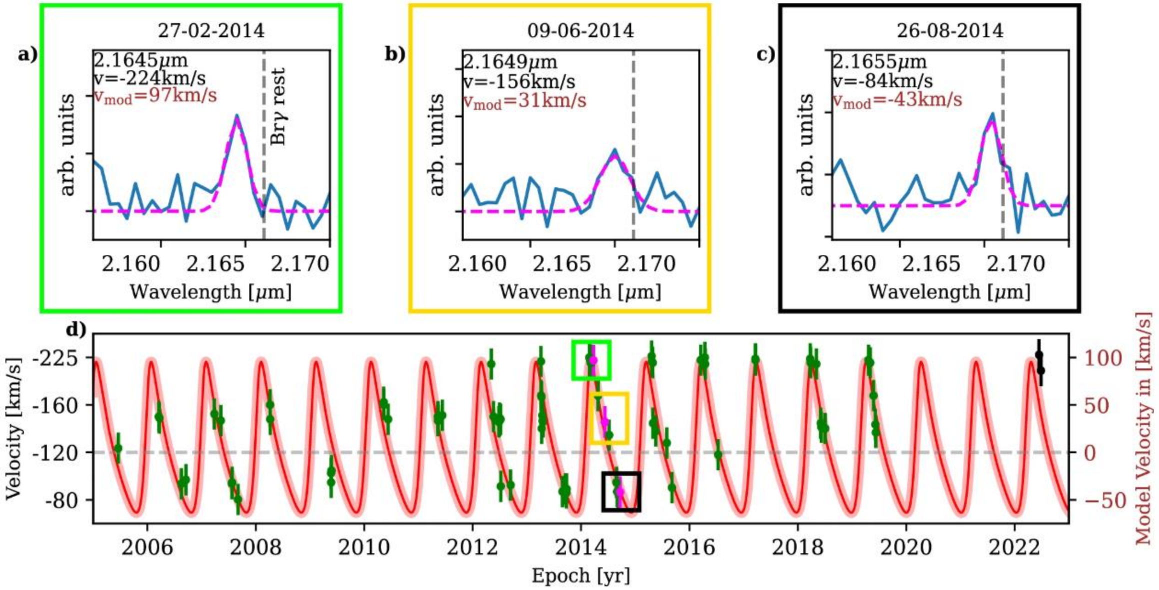
D9 system

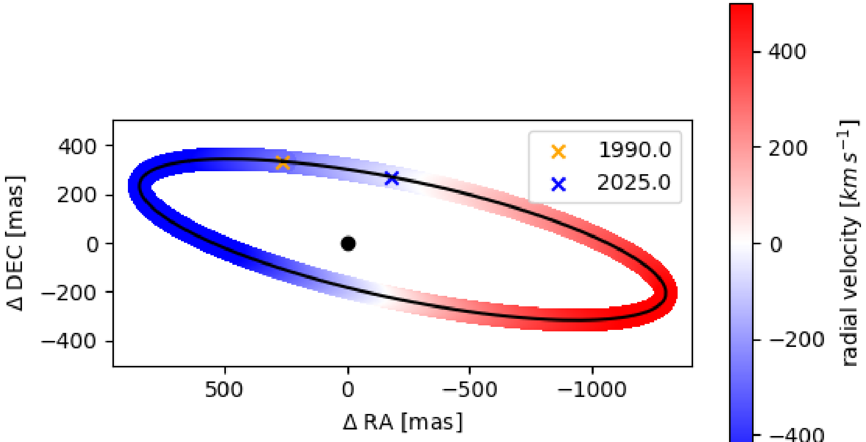


Periodic variations of Br-gamma line (2005-2023) on the time scale of ~ one year

Binary interpretation







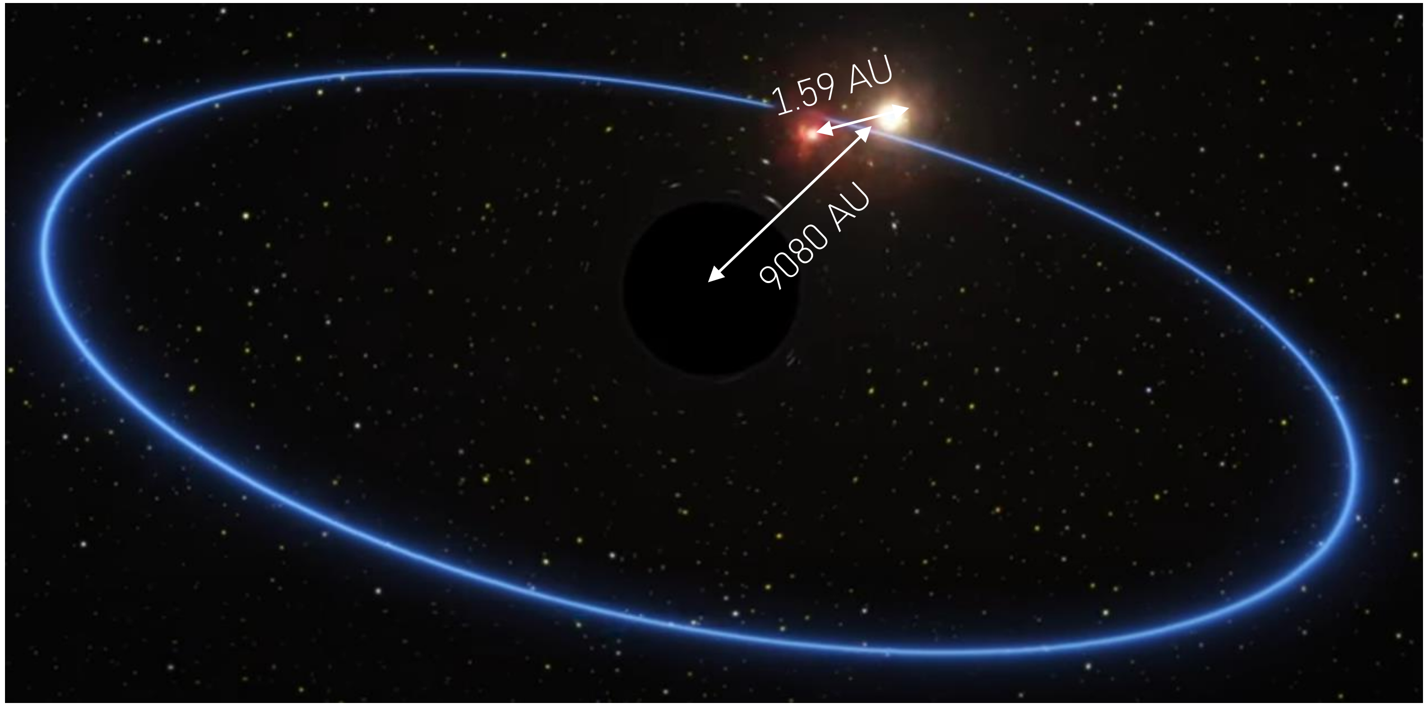
Peissker, Zajaček, Labadie, Bordier+2024

D9 binary parameters

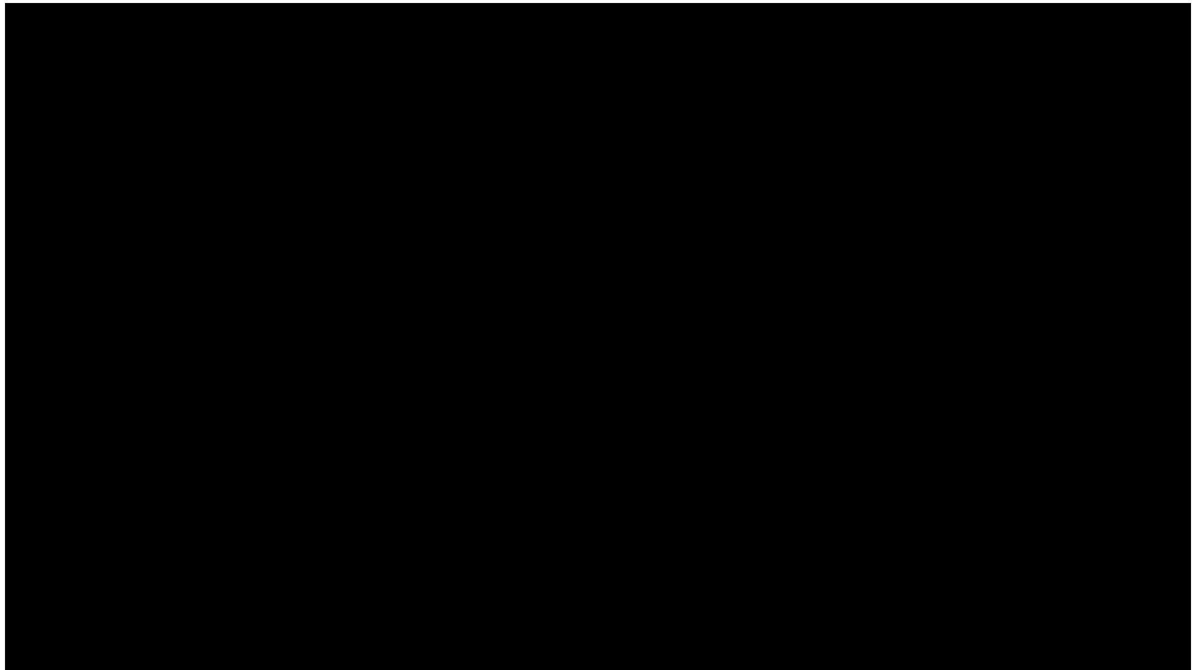
Best-fit orbital parameters

Secondary Keplerian Parameter	
P_{D9b} [year]	1.02 ± 0.01
e_{D9b}	0.45 ± 0.01
ω_{D9b} [deg]	311.75 ± 1.65
a_{D9b} [au]	1.59 ± 0.01
i_{D9b} [deg]	90.00
$m \sin(i_{D9b})$ [$M_\odot$]	0.73
RV_{off} [km s^{-1}]	−29.19 ± 3.00
χ^2_ν	0.31
rms [km s^{-1}]	16.38
Keplerian parameter for D9 orbiting Sgr A*	
e_{D9a}	0.32 ± 0.01
i_{D9a} [deg]	102.55 ± 2.29
a_{D9a} [mpc]	44.00 ± 2.42
ω_{D9a} [deg]	127.19 ± 7.50
Ω_{D9a} [deg]	257.25 ± 1.61
P_{D9a} [yr]	432.62 ± 0.01
Radiative transfer model	
$i_{intrinsic}$ [deg]	75.0 ± 19.0
R [$R_\odot$]	2.00 ±l 0.13
$\log(L/L_\odot)$	1.86 ± 0.14
$\log(T_{D9a}[K])$	4.07 ± 0.05
M_{D9a} [$M_\odot$]	2.80 ± 0.50
M_{Disk} [10^{-6} $M_\odot$]	1.61 ± 0.02

Peissker, Zajaček et al., Nat. Comm., 2024



ESO/M. Kornmesser

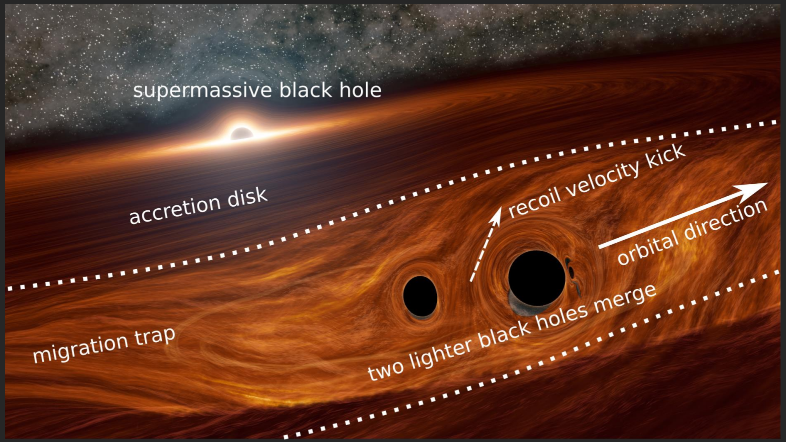


Credit:
Pavel Karas

Brno Observatory and Planetarium

Conclusions

- Small UV satellite (**QUVIK**) can be used to provide high-cadence light curves in the UV domain (~ 1 day and less)
- Time delay between FUV and NUV bands (reverberation mapping); transfer function of the accretion disc can bear traces of the embedded companion
- Signatures of SMBH-IMBH binaries (embedded) in the spectral energy distribution: hollows and gaps
- Inclined systems: quasiperiodic erupters (like QPEs) and outflows (QPOuts)
- SMBH binaries have a distinct X-ray/UV pattern during the merger: the X-ray emission disappears while the UV emission stays stable
- More details: Zajaček et al. (2024, 2025), Štolc et al. (2023)



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QUVIK summary

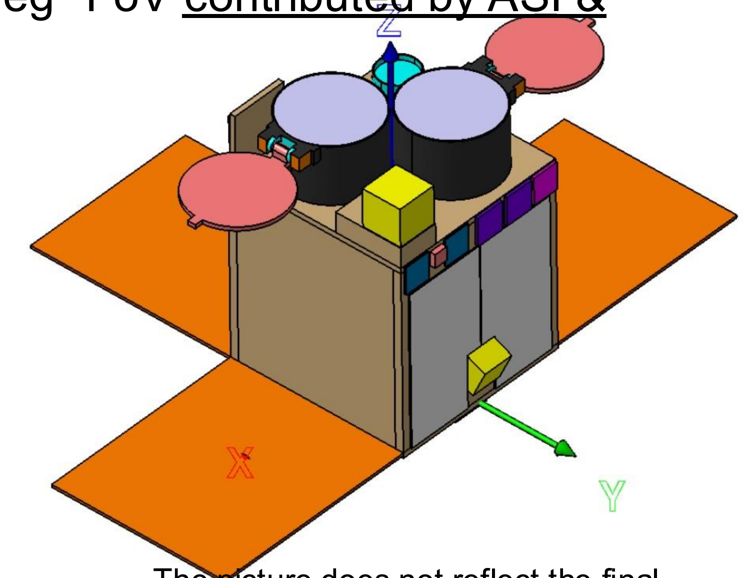
Mass: ~200 kg
Size: 0.7 x 0.7 x 1.1 m
Mission duration: 3 years
Status: B1 phase finished, approved for funding in 2023,

Primary payload: ~25cm aperture NUV (~260–360 nm) telescope with 1 deg^2 FoV
Photometric sensitivity in NUV: 21.5 mag (5 sigma in 3000 s) in an early type galaxy at 1.5 effective radii
Resolution: <5 arcsec
Detector: Developed by the Dunlap Institute, University of Toronto, based on CMOS (GSENSE4040) by GPIXEL

Secondary payload 1: ~25cm aperture FUV (~150–200 nm) telescope with 1 deg^2 FoV contributed by ASI & INAF (led by INAF Brera) in Italy
Secondary payload 2: GALI GRB detector from Technion & ISA in Israel

Observation start latency: <15 min
Near-real time inter-satellite communication for triggers
Data downlink: X-band (1600 images per day)

Orbit: Low Earth Sun Synchronous Orbit (SSO)
Launch: 2030



The picture does not reflect the final configuration!