Outburst of SLX 1746–331 observed by Insight-HXMT and NICER

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On behalf of the co-authors listed in
Peng et al., 2023, ApJ, 955, 96

Institute of High Energy Physics

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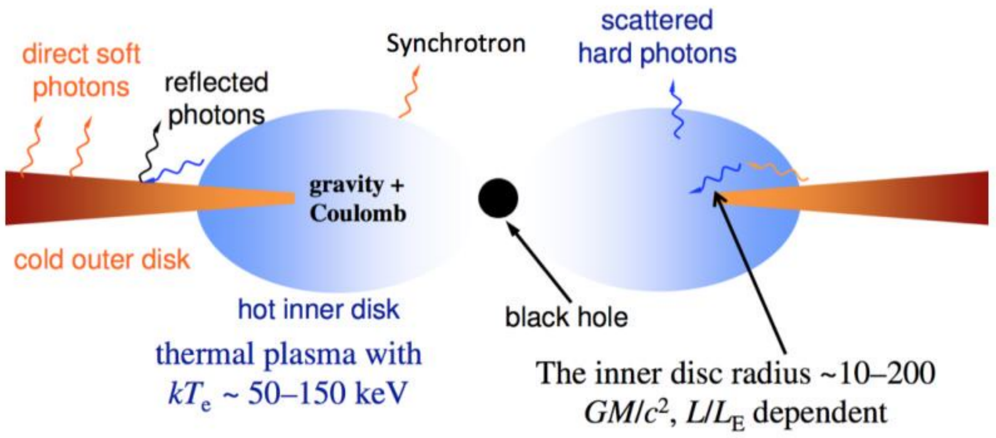
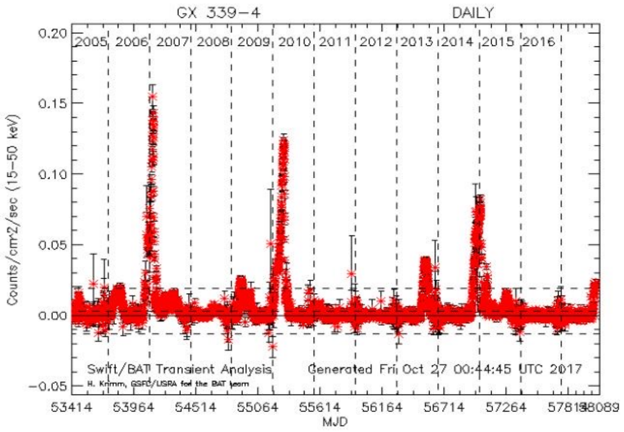
The 32nd Texas Symposium on Relativistic Astrophysics, 2023 December 11-15, Shanghai

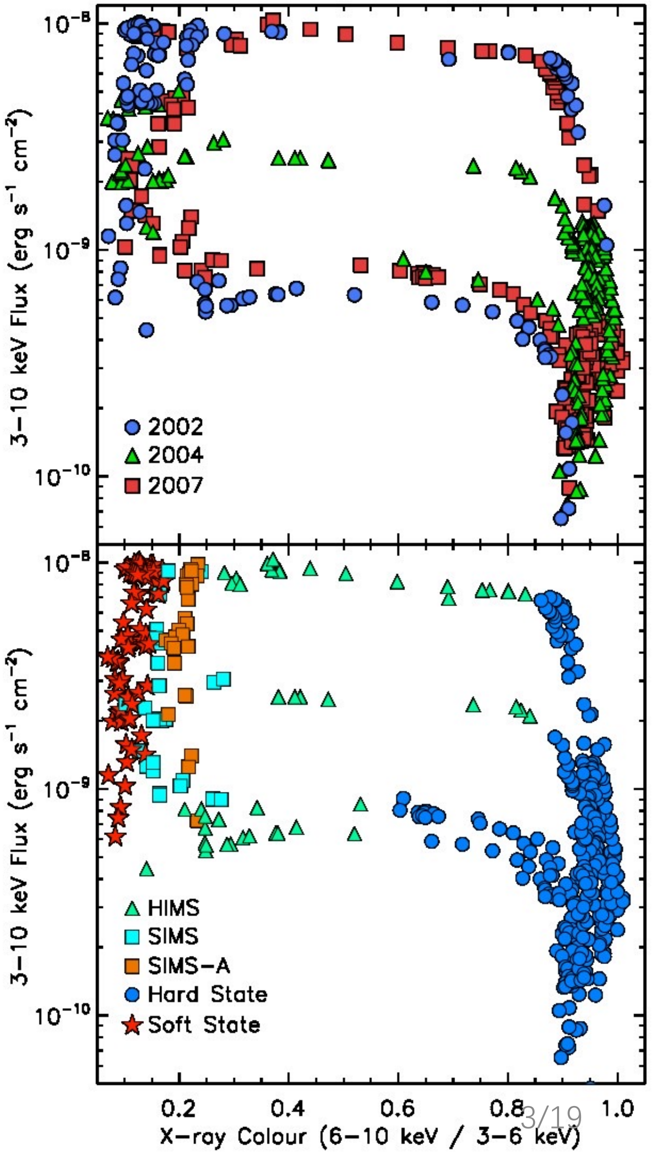
Outline

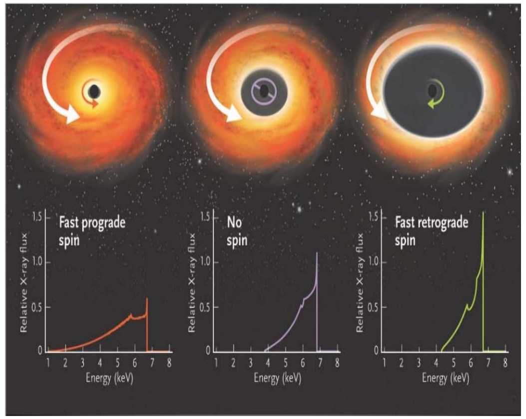
- Introduction
- Observations and results
- Discussions

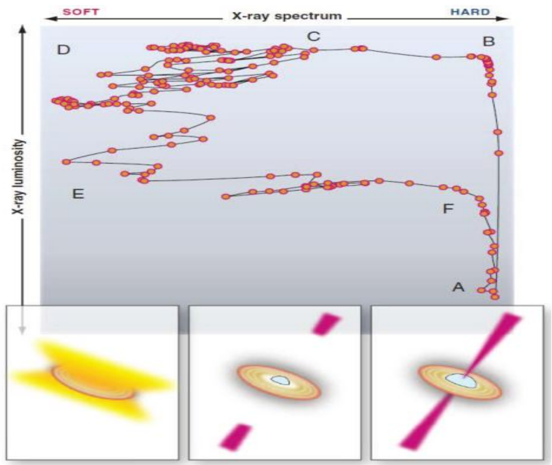
BHXRB accretion and outburst

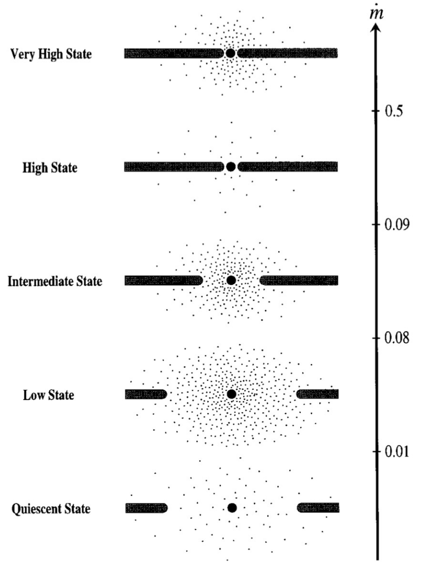




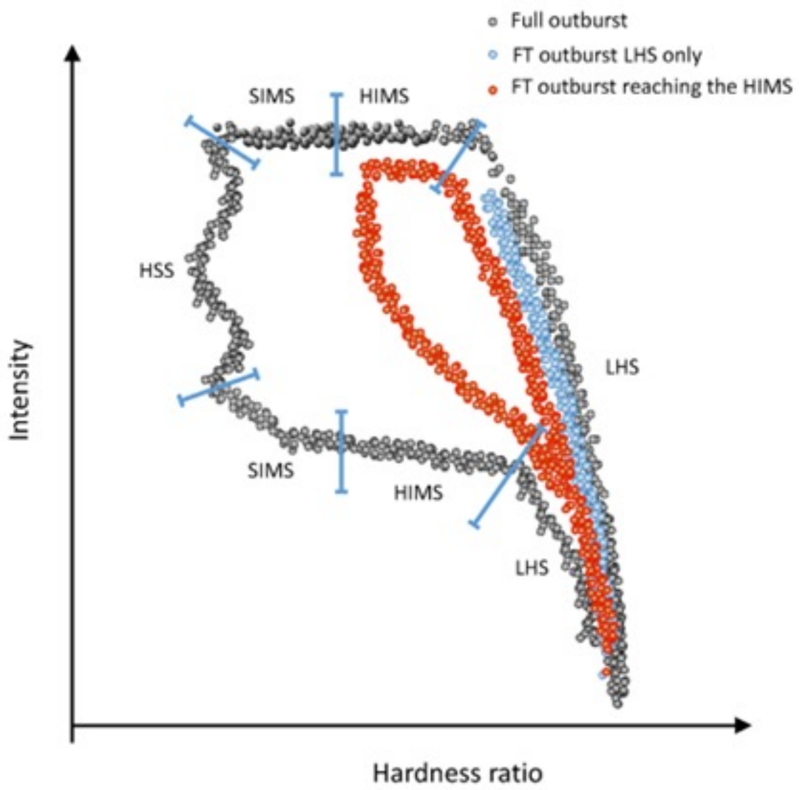








Zoo of BHXRB outbursts



~30% failed outburst

(Alabarta et al. 2021)

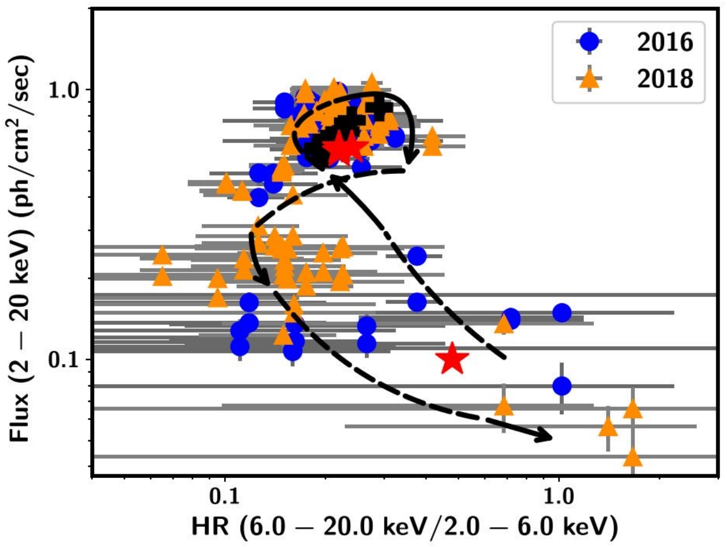
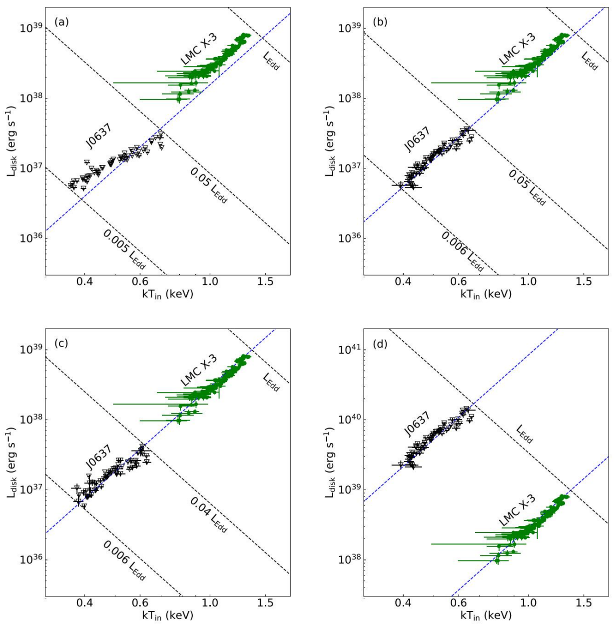


Figure 4. HID obtained with *MAXI* observation of 2016 and 2018 outbursts. The blue circles and orange triangles correspond to *MAXI* data of 2016 and 2018 outbursts respectively.The uncertainties are represented in grey. Hardness ratio is taken as (6.0–20.0 keV/2.0–6.0 keV). The red stars and black filled crosses represent the data obtained using *AstroSat* during the 2016 and 2018 outbursts respectively. The red star at the bottom corresponds to Obs 3 from 2016 outburst. The arrows represent the direction of evolution throughout the outbursts. Note that the HR defined here is different than the one used in Fig. 3 (see the text for details).

Peculiar C-shape outbursts
(4U 1630-472) （without LHS)
(Baby et al. 2020, MNRAS)



MAXI J0637-430
Outburst rising: lack transition from LHS to HSS
HSS:0.01-0.05 L_{Edd}
(Ma et al., 2022, MNRAS)

A peculiar outburst born out of SLX 1746–331

Discover：

Spacelab-2, 2-32keV, two coded mask telescopes Observations of the Galactic Center 1985, July 29-August 6, ended up with 7 hours exposure. Discovery of SLX 1746-331, with a soft energy spectrum, thermal bremsstrahlung temperature 1.5 keV. （Skinner et al., 1990, MNRAS）

Previous Observations：

Outbursts:2003, 2007, 2010, by Integral, RXTE, XRT, MAXI, ASM (Atels)

RXTE data， assumed BH mass 10, distance 5 kpc. The inclination angle takes 60 dg.
This gives via L~T ^4 relation, Rin ~6.7 km, ~ 0.45 Rg (for 10 solar mass BH). （Dunn et al., 2011, MNRAS）

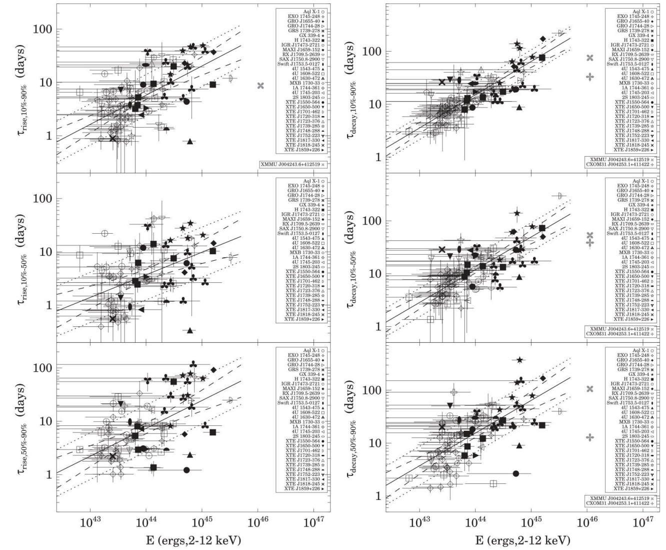
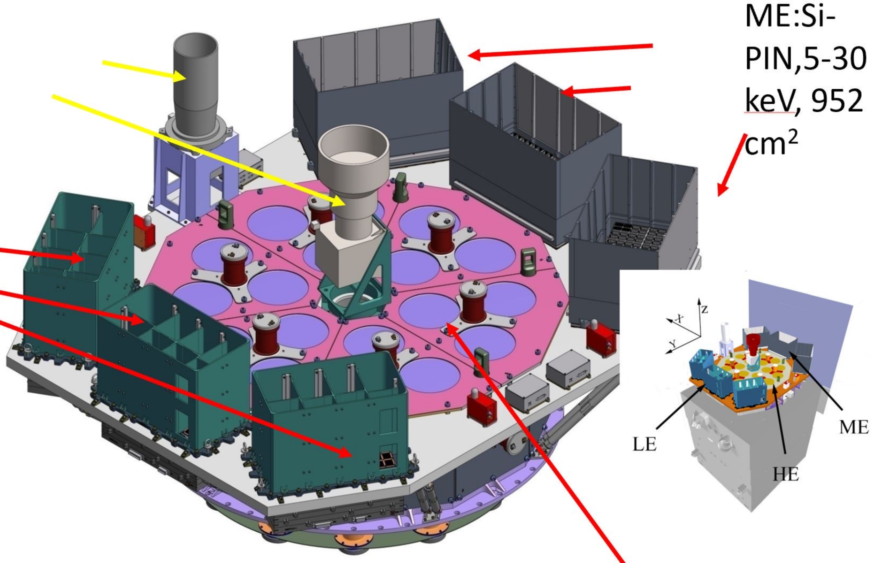


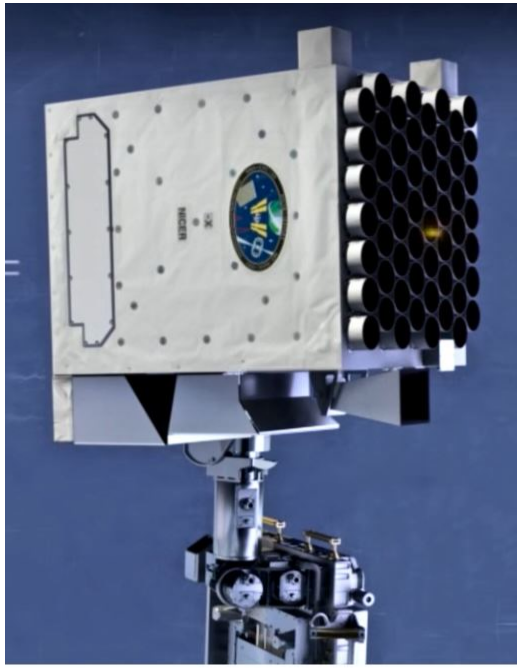
Figure 13. Relation between E-folding rise or timescale and total radiated energy. The filled and unfilled symbols represent BH and NS LMXBTs, respectively. There are positive correlations between E and τ in different rise or decay episodes.The solid line represents the best-fit result with a function $\log \tau = A + B \times \log E$, the dashed lines show the 2σ confidence intervals, and the dotted lines show the range of plus or minus intrinsic scatter.

Take BHXRB samples, the rise and decay time of outbursts follow correlation with the total energy output. With such a correlation and the three outburst of SLX rise/decay time, they estimated a distance of 10.81 ± 3.52 kpc. （Yan et al., 2015 ApJ）

Observations and instruments

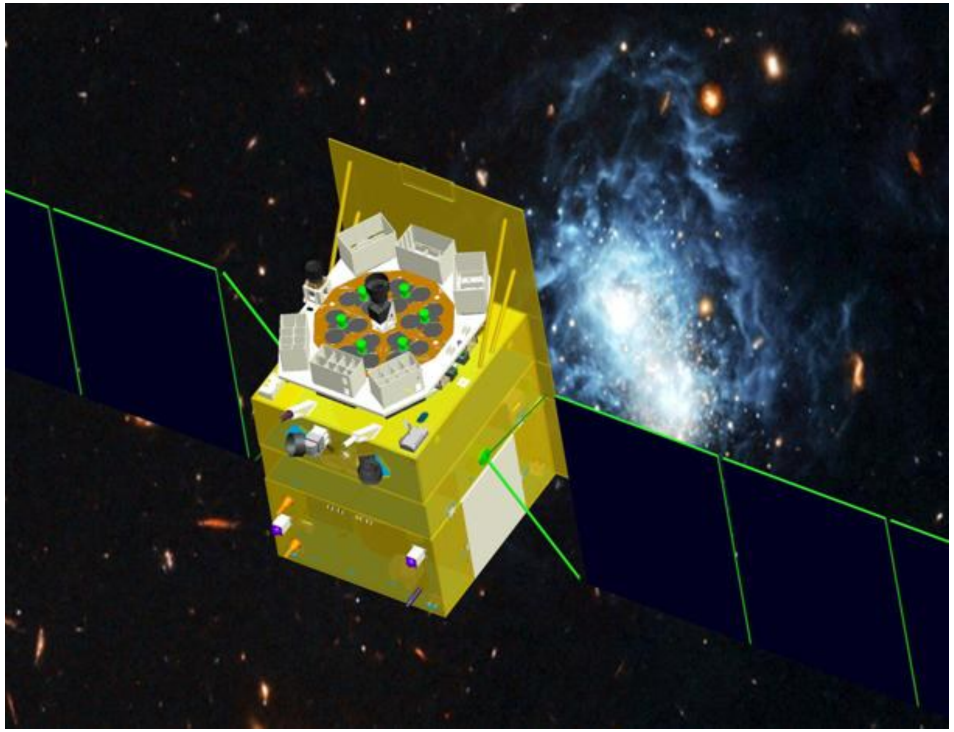
HXMT+NICER: MJD 60011-60125
Thorough observation covering soft X-rays, previous by RXTE only down to above 3 keV
Long-term observations of over 100 days.
HXMT+NICER covers a broad energy band and large detection area, high-quality data.





Hard X-ray Modulation Telescope (HXMT) satellite

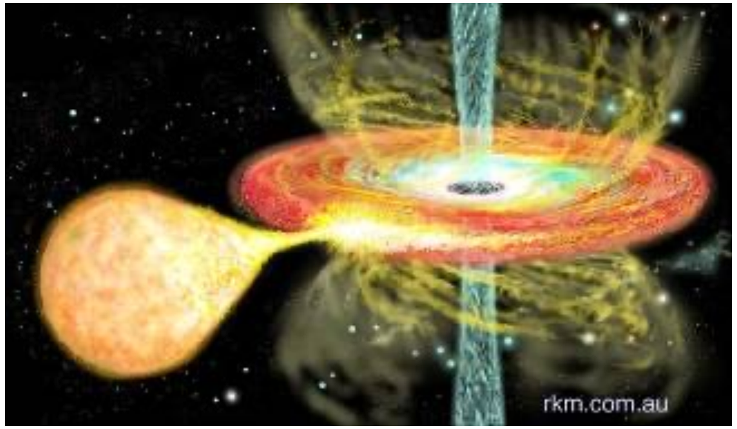
- China's 1st X-ray astronomy satellite
- Selected in 2011
- Total weight ~2500 kg
- Cir. Orbit 550 km, incl. 43°
- Pointed, scanning and GRB modes
- Designed lifetime 4 yrs
- Launched on June 15th, 2017
- Dubbed "*Insight*"

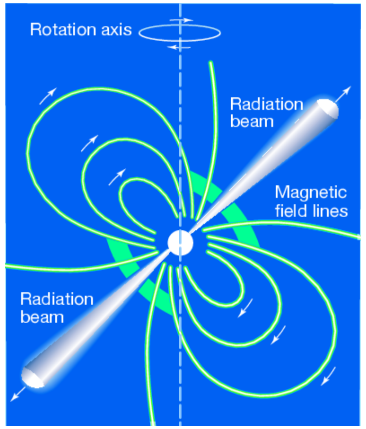


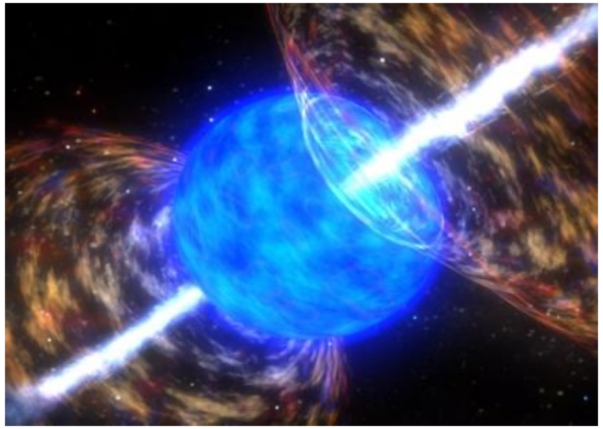
Zhang, S.-N. et al. Overview to the Hard X-ray Modulation Telescope (Insight-HXMT) Satellite. Science China Physics, Mechanics, and Astronomy 63, 249502 (2020)

Core sciences of Insight-HXMT

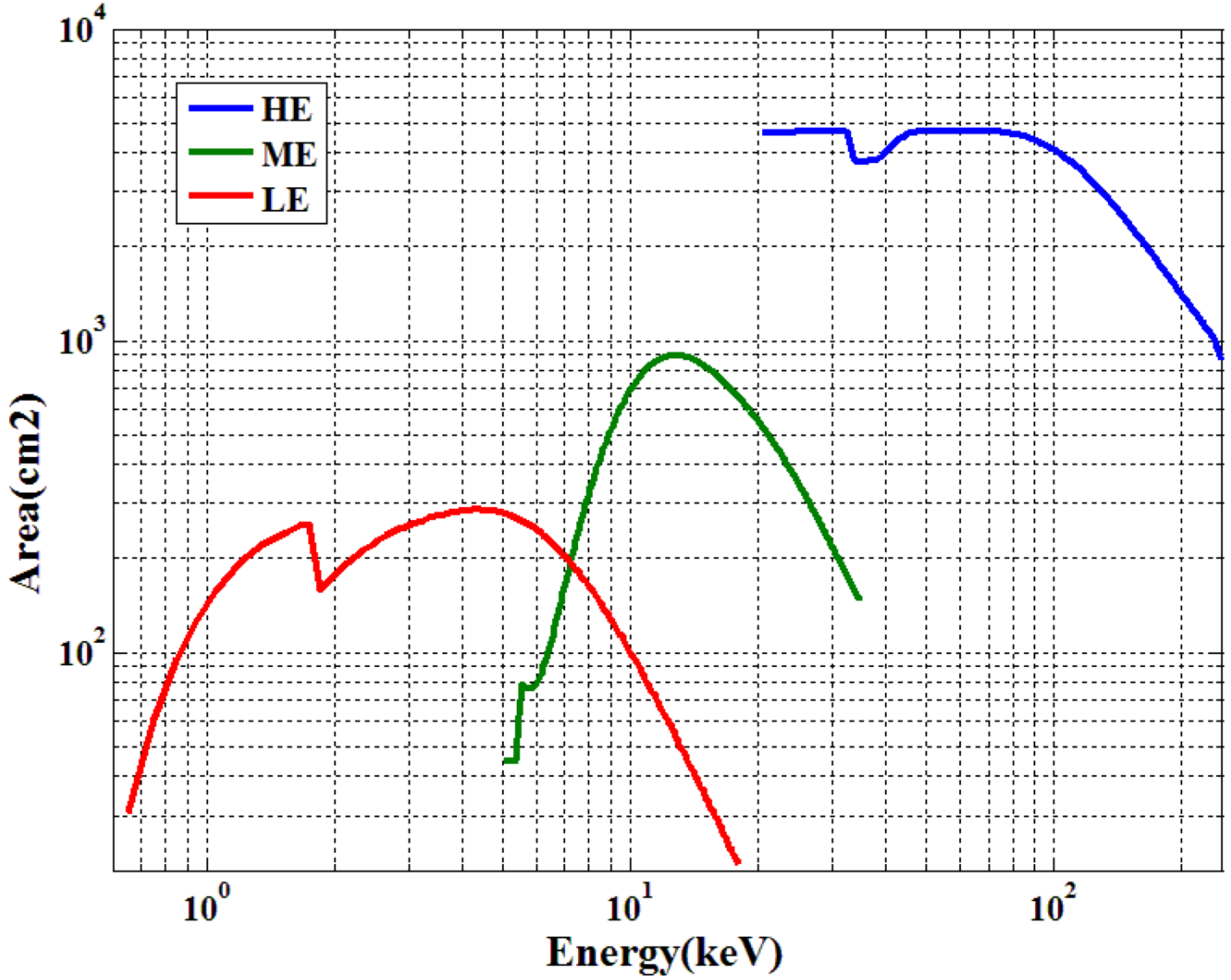
- Galactic plane scan and monitor survey for more weak & short transient sources in very wide energy band (1-250 keV)
- Pointed observations: High statistics study of bright sources and long-term high cadence monitoring of XRB outbursts
- All sky monitor for GRBs & pulsars (0.2 – 3 MeV)



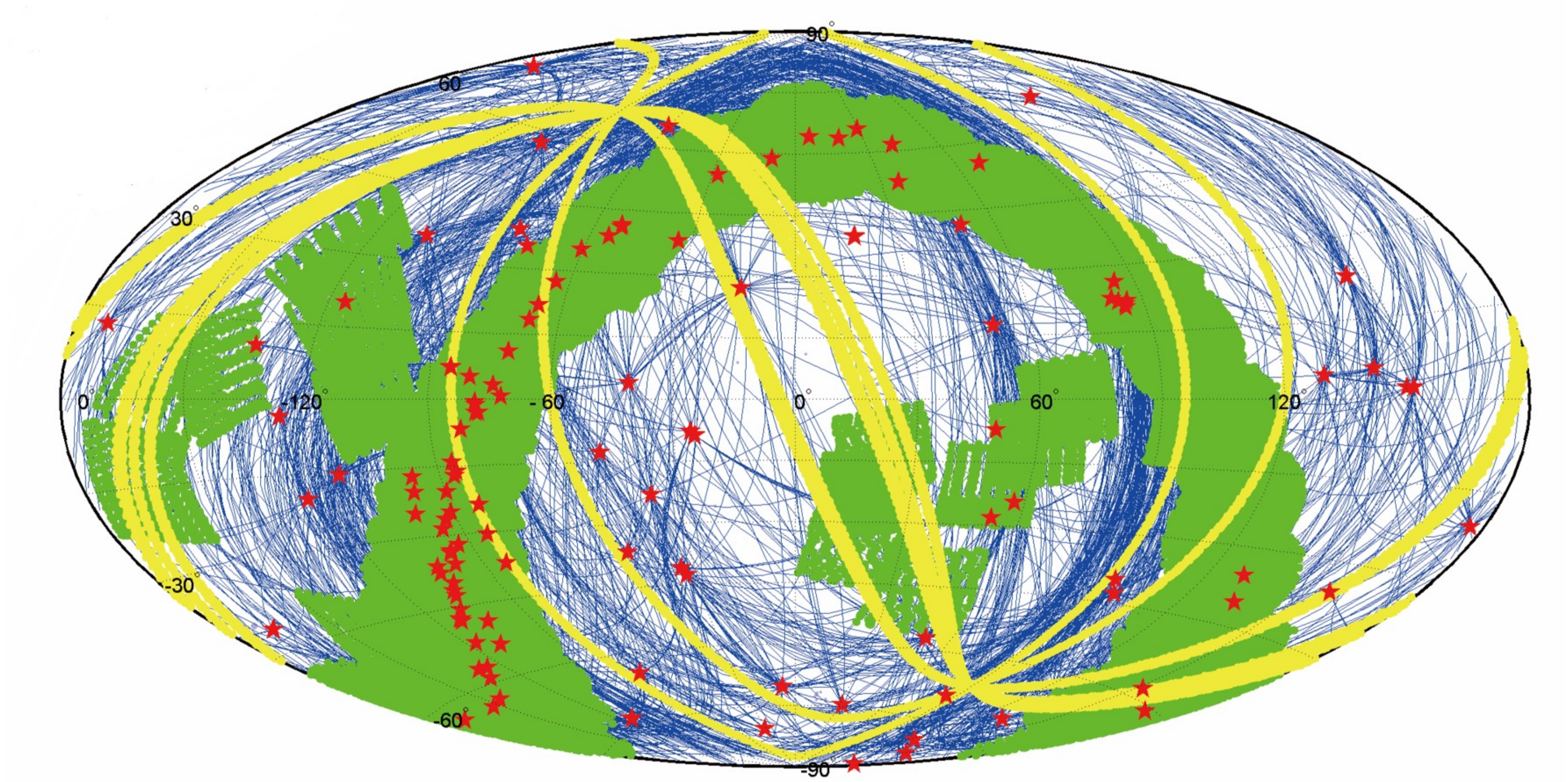




Effective area



Insight-HXMT exposure map



Insight-HXMT observation till June 30 2023:
19 BH XRB, 20.1Ms；57 NS XRB, 33.2 MS；account for 51% of total exposure.

Outburst: dominated thermal emission and BH mass estimation

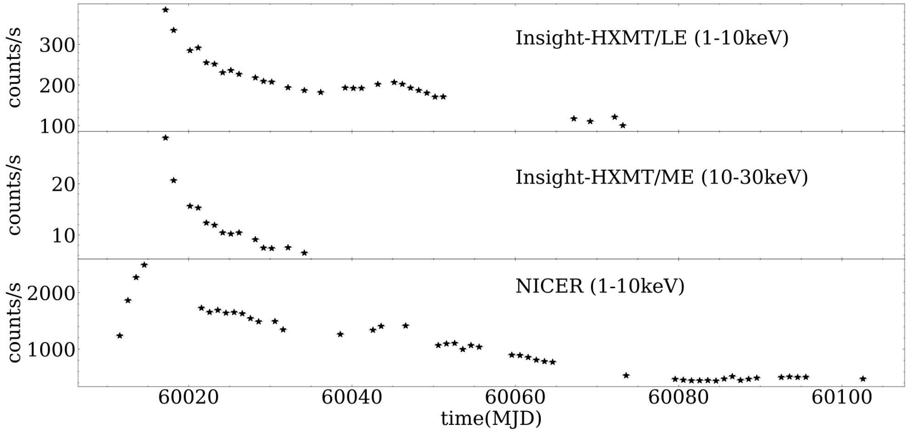
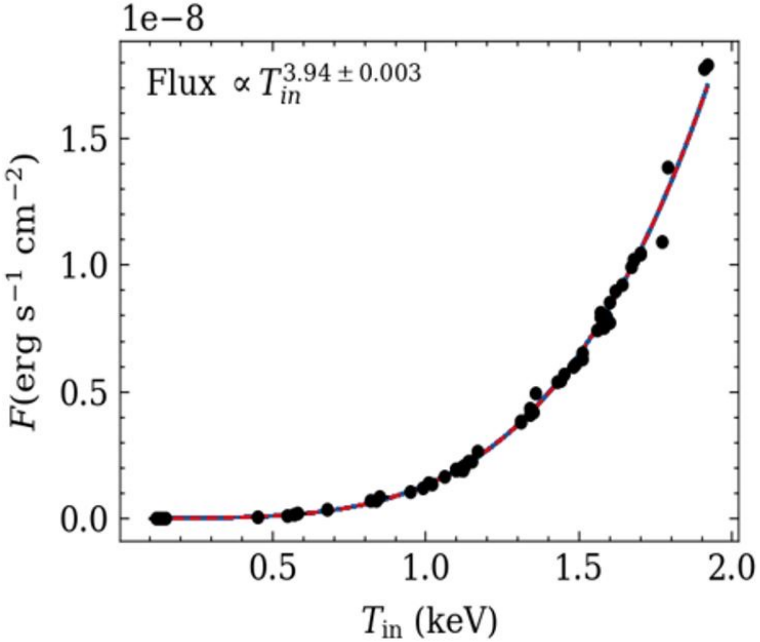
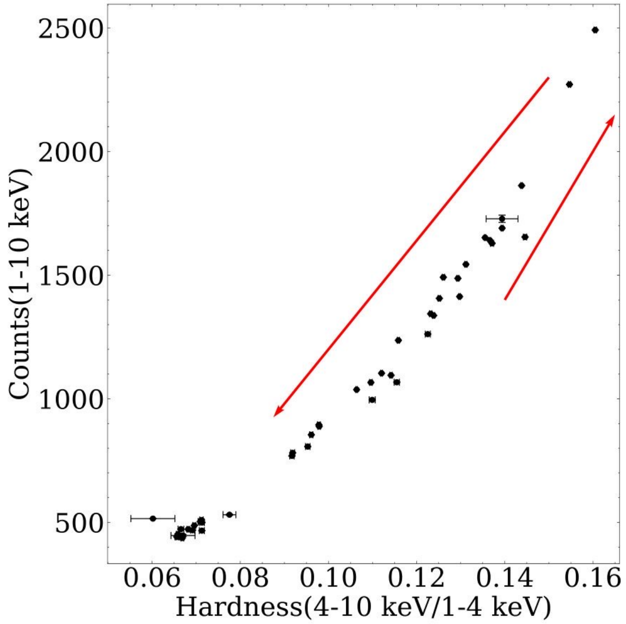


Figure 1. Light curve of SLX 1764–331 during the 2023 outburst. Top panel: the light curve of *Insight*-HXMT LE 1–10 keV Middle panel: the light curve of *Insight*-HXMT ME 10–30 keV Bottom panel: the light curve for *NICER* 1–10 keV.



L coverage: 3 magnitudes
BH mass lower limit:



$$L_{\rm disk} \approx 4\pi R_{\rm in}^2 \sigma T_{\rm in}^4$$

Luminosity range:
$0.001 L_{Edd} \lesssim L_{disk} \lesssim 0.3 L_{Edd}$

($L_{Edd} = 1.26\times10^{38} M/M_{\odot}$)

$L_{disk} \approx 2\pi F d^2/\cos\theta$

d=10.81±3.52kpc

$L_{disk} = 1.24\pm0.81\times10^{38}$ /cosθ erg s^{-1}

Suppose:
θ=24°， $L_{disk} = 0.3 L_{Edd}$ M =3.58 $M_{\odot}$
θ=48° ， $L_{disk} = 0.3 L_{Edd}$ M =4.9 $M_{\odot}$

BH mass estimation: from a sample of BH outbursts

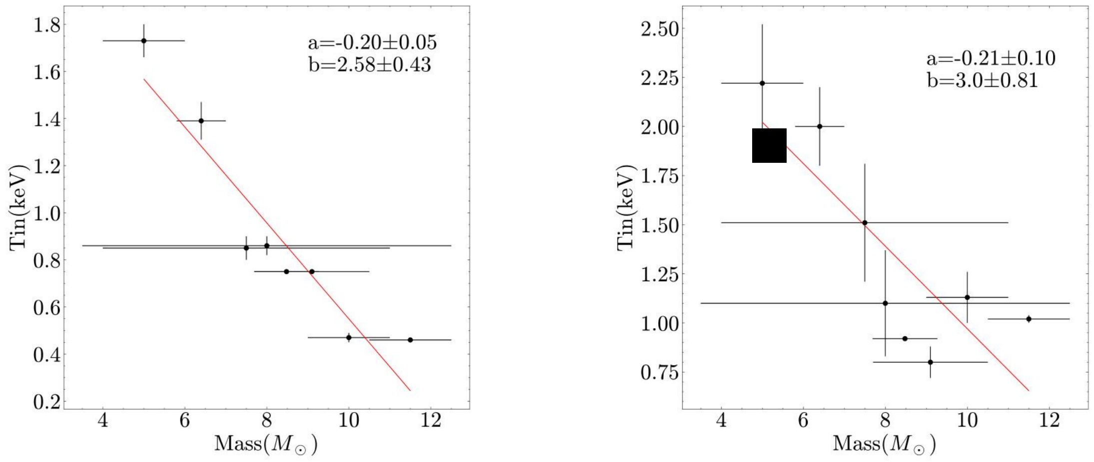


Figure 5. The relationship between the mass of a black hole and the maximum temperature of the inner disk in the soft stat Left panel: The observed maximum temperature of the inner disk in the soft state. For different maximum temperatures o disks with different outbursts of BHXRBs, we took the mean value. Right panel: Estimated temperature of the inner disk at luminosity of 0.3 $L_{\rm Edd}$

Sources	**Mass** $M_\odot$	**Spin** **a**	$T^a_{\rm in}$ **keV**	$T^b_{\rm in}$ **keV**	**References**
MAXI J1348–630	$9.1^{+1.6}_{-1.2}$	$0.78^{+0.04}_{-0.04}$	$0.75^{+0.01}_{-0.01}$	$0.80^{+0.08}_{-0.06}$	1,2,3
MAXI J1803–298	3.5-12.5	$0.991^{+0.001}_{-0.001}$	$0.86^{+0.04}_{-0.04}$	$1.10^{+0.27}_{-0.27}$	4,5
GRS 1758–258	≈ 10	$0.97^{+0.02}_{-0.05}$	$0.47^{+0.02}_{-0.02}$	$1.13^{+0.13}_{-0.13}$	6,7,8
MAXI J1727–203	≥ 11.5	$0.986^{+0.012}_{-0.159}$	$0.46^{+0.001}_{-0.001}$	$1.02^{+0.02}_{-0.02}$	9,10
4U 1957+11	5^{+1}_{-1}	$0.95^{+0.02}_{-0.04}$	$1.73^{+0.07}_{-0.07}$	$2.22^{+0.3}_{-0.3}$	10,11,12
V4641 Sgr	$6.4^{+0.6}_{-0.6}$	$0.86^{+0.02}_{-0.02}$	$1.39^{+0.03}_{-0.13}$	$2.0^{+0.3}_{-0.3}$	10,13
H 1743–322	$11.21^{+1.65}_{-1.96}$	$0.98^{+0.01}_{-0.02}$	$0.70^{+0.10}_{-0.14}$	$1.06^{+0.16}_{-0.17}$	10,14,15,16
MAXI J1820+070	$8.48^{+0.79}_{-0.79}$	$0.988^{+0.006}_{-0.028}$	$0.75^{+0.01}_{-0.01}$	$0.92^{+0.01}_{-0.01}$	17,18
GX 339–4	4–11	$0.95^{+0.02}_{-0.08}$	$0.85^{+0.03}_{-0.12}$	$1.5^{+0.3}_{-0.3}$	19,20

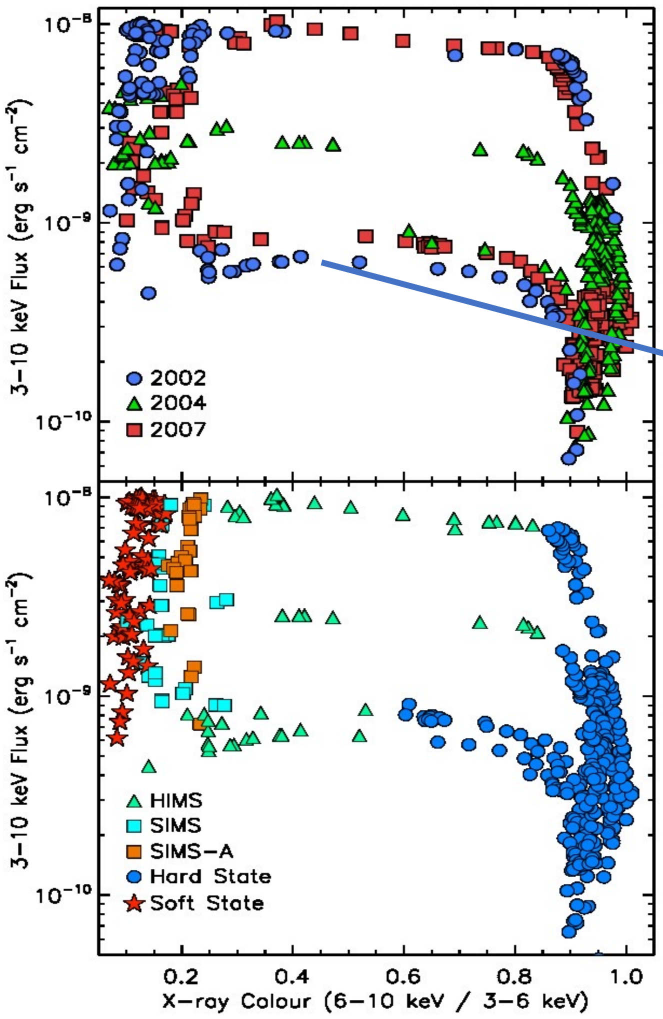
NOTE:

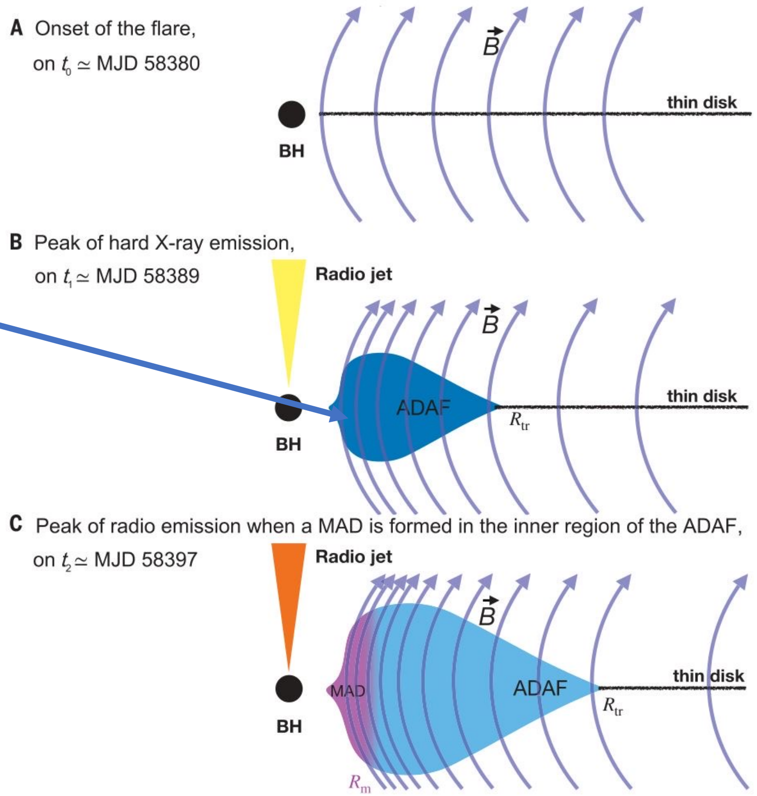
[a] The maximum temperature of the inner disk in the soft state. The average value is taken for those with multiple outbursts.

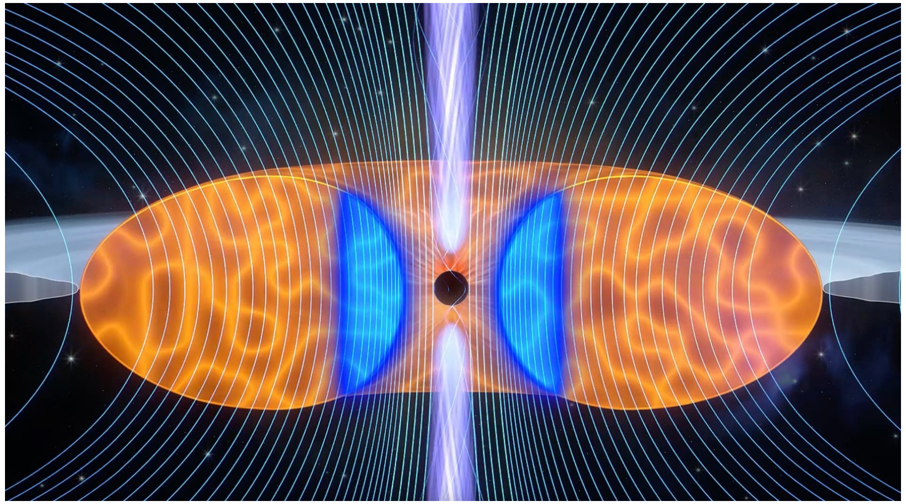
[b] Estimated inner disk temperatures for 0.3 $L_{\rm Edd}$

BH mass: 5.2 ± 4.5$M_\odot$

Role of disk magnetic field in outburst evolution of BH XRB

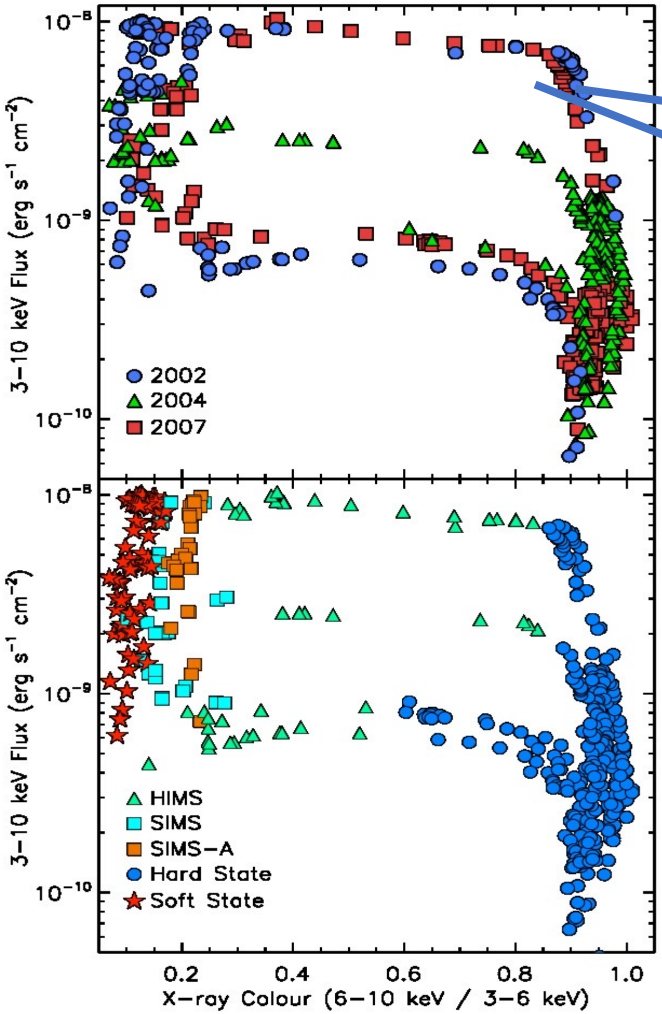






(Bei You*, Xinwu Cao* , Zhen Yan* et al. Science, 2023)

Role of disk magnetic field in outburst evolution of BH XRB



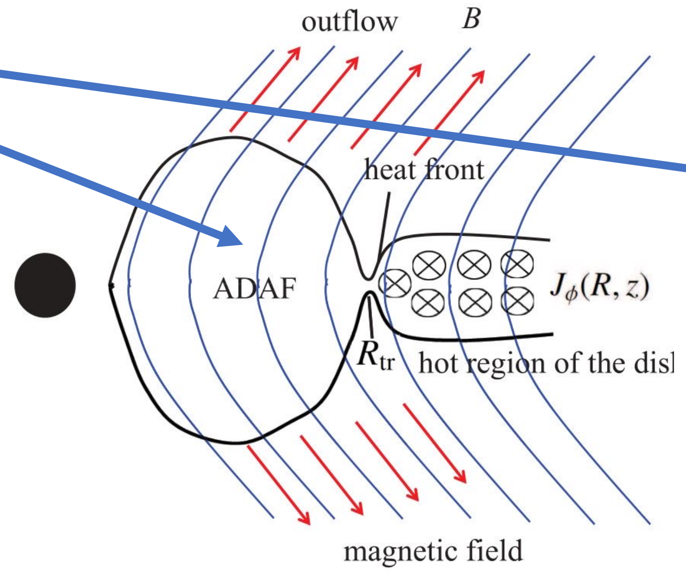
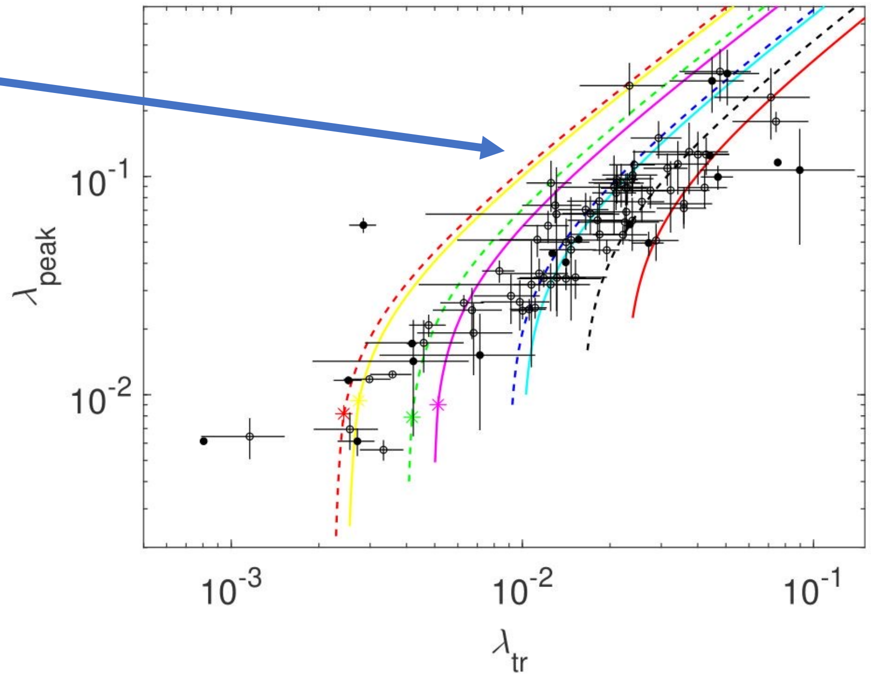
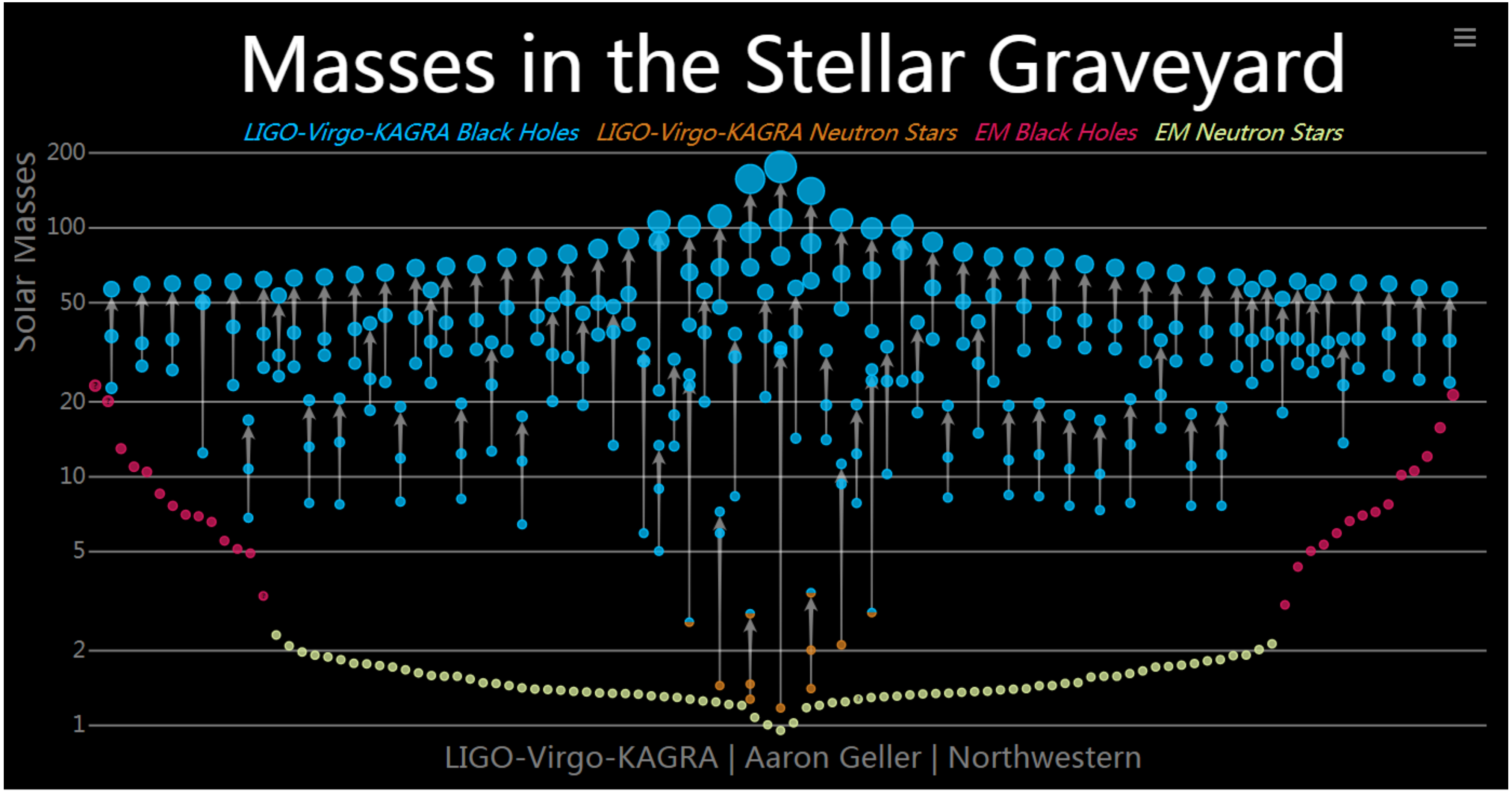


Fig. 1. Illustration of the model. The large-scale magnetic f formed through an inverse cascade process of dynamo generated scale field in the outer thin disk. Such a large-scale poloidal produced by the azimuthal currents in the disk.



(Cao et al., 2018, A&A)

The mass gap of 2.5-5.0 solar mass for BH



90 GW events

85 DBH

2 DNS

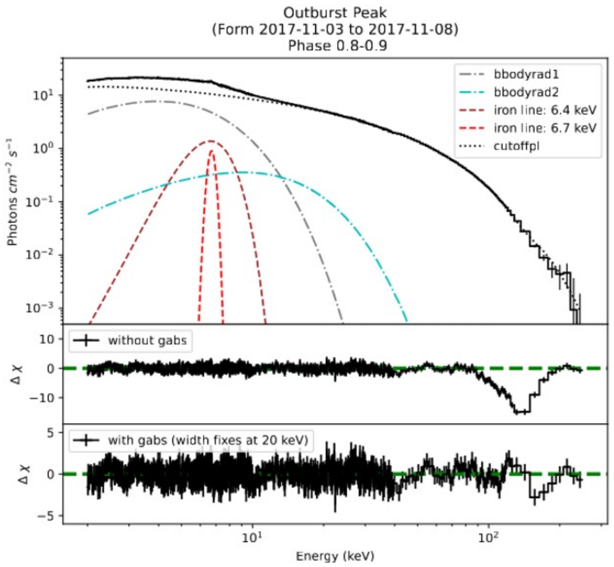
3 BH-NS

2 mass-gap

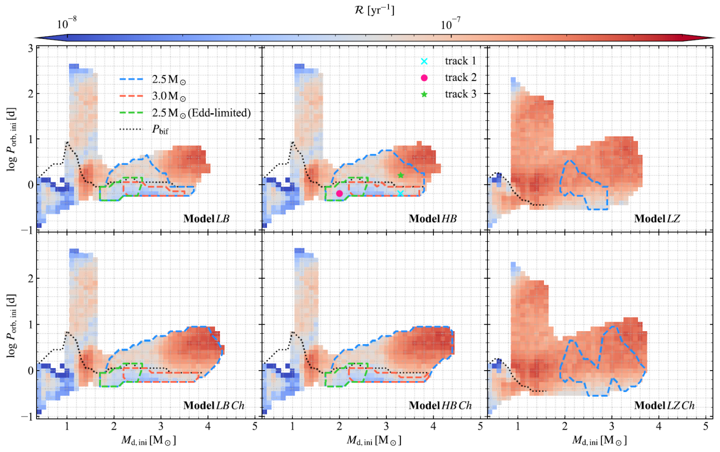
1 EM counterparts (GW 170817)

From ULX to tiny BH

- Swift J0243.6+6124: 146 keV CRSF, ULX has super Eddington accretion.
- New channel to form tiny BH from accretion of ULX.
- Two more samples with BH mass may fall in 2.5-5 solar mass gap.



(Kong et al. 2022, ApJL)



(Gao et al. 2022, MNRAS)

MAXI J0637-430 BH mass： $5.1 \pm 1.6\ M_\odot$

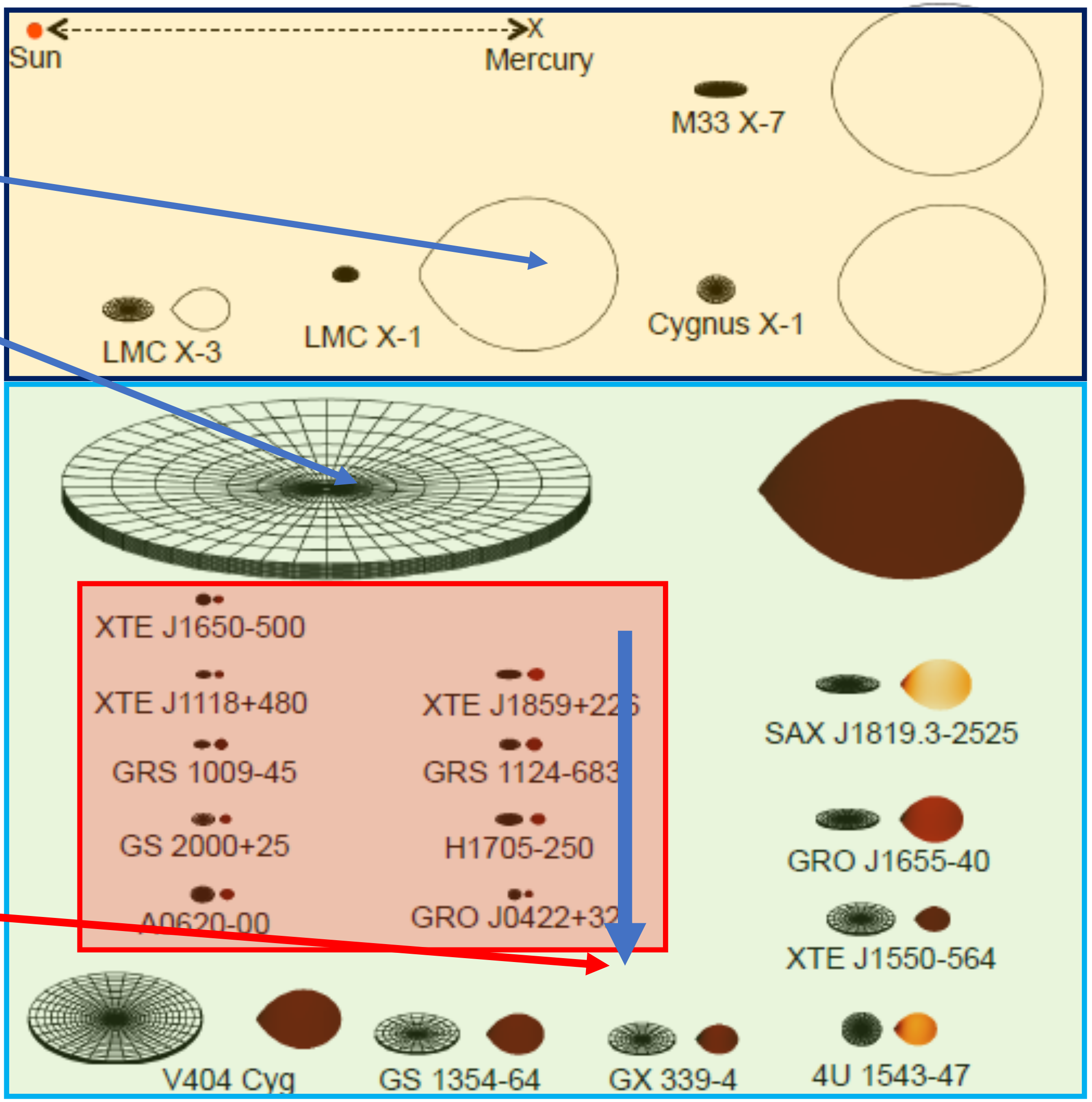
（Soria, et al., 2022, MNRAS）

SLX 1746–331 BH mass: $5.2 \pm 4.5\ M_\odot$

(Peng, et al., 2023, ApJ)

The BH XRB Zoo: monster vs. dwarf ?

Monsters?



HMXBs

LMXBs

Dwarfs?

$P_{orb} < 12$ h !

SLX 1746–331
MAXI J0637-430

Tiny XRB family?

Comparison with MAXI J0637-430

- The hard state was absent or too quick to be detected, and the outburst was dominated from the very beginning by thermal emission.
- Observed the soft-to-hard transition luminosity at the end of the outburst.

(Ma et al., 2022, MNRAS)

Parameters of the MAXI J0637-430:
It is the currently known Milky Way BH candidate located farthest from the Galactic Centre.
BH~(5.1 ± 1.6)M ☉, spin~0.25,
Donor star mass ~ (0.25 ± 0.07)M ☉,
Peak Eddington ratio ~0.17 ± 0.11
Binary period P_{orb} ~$2.2^{+0.8}_{-0.6}$ hr. This is the shortest period measured or estimated so far for any Galactic BH X-ray binary.

(Soria et al., 2022, MNRAS)

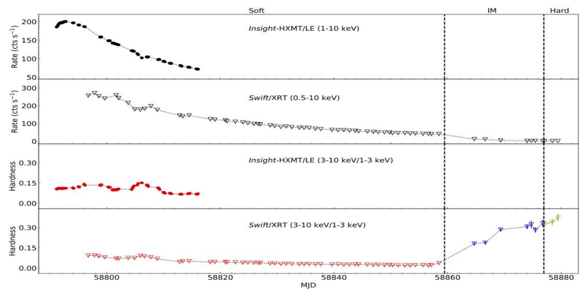


Figure 1. From top to bottom: *Insight-HXMT*/LE light curve; *Swift*/XRT light curve; *Insight-HXMT*/LE hardness ratio (3–10 keV over 1–3 keV count rate ratio); *Swift*/XRT hardness ratio (also 3–10 keV over 1–3 keV). The filled circles represent *Insight-HXMT* measurements, and open triangles are for *Swift*/XRT. In the *Swift*/XRT hardness ratio plot, the soft state (Soft), intermediate state (IM), and hard state (Hard) are displayed with red, blue, and yellow symbols, respectively. Note that the error bars are so small as to not be clearly indicated in the figure.

MAXI J0637-430

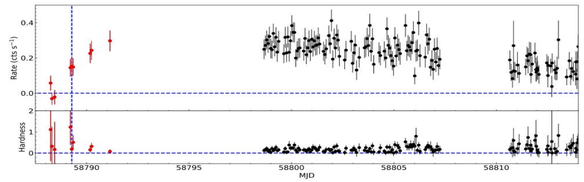
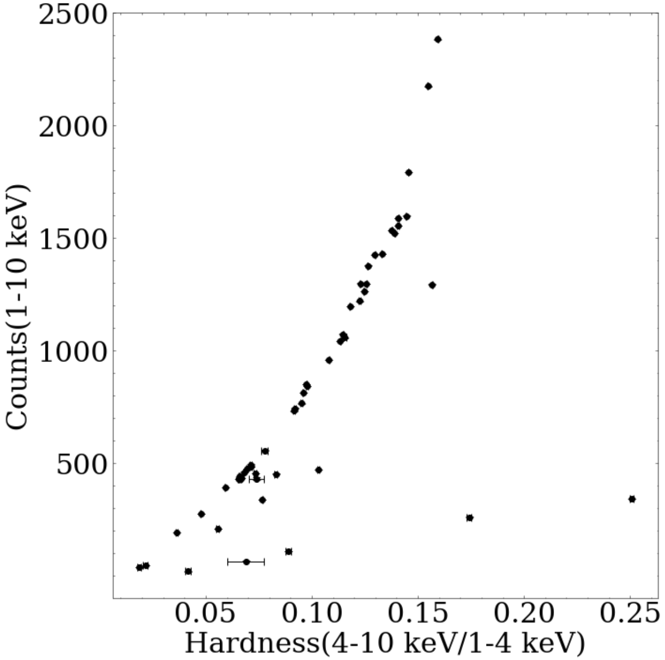


Figure 2. Top panel: *MAXI* light curve in the 2–20 keV band, binned to one data point per orbit. The dashed vertical line represents the time of discovery, and the data points plotted in red correspond to a time interval of ±6 h before/after the discovery. Bottom panel: corresponding hardness ratios (4–20 keV over 2–4 keV count rate ratio).



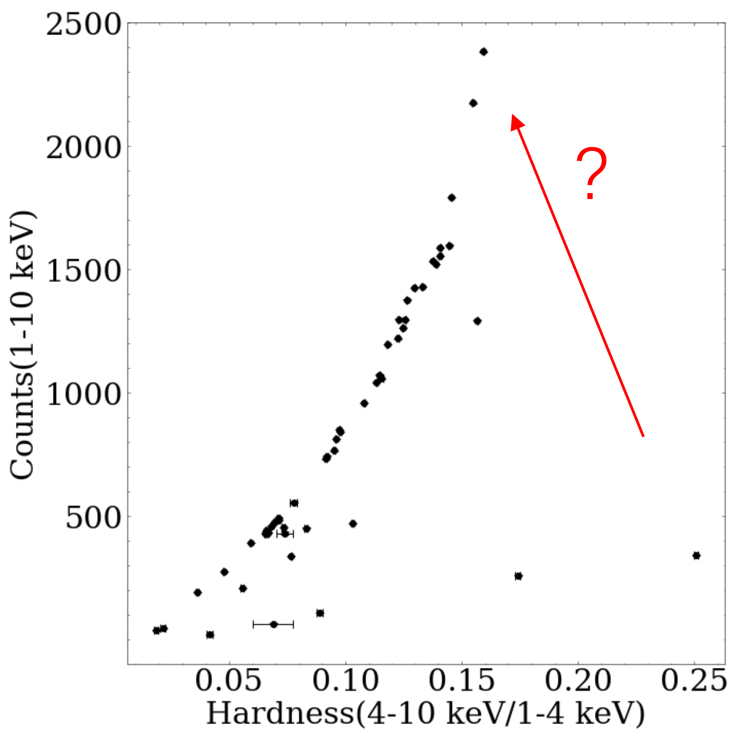
SLX 1746–331

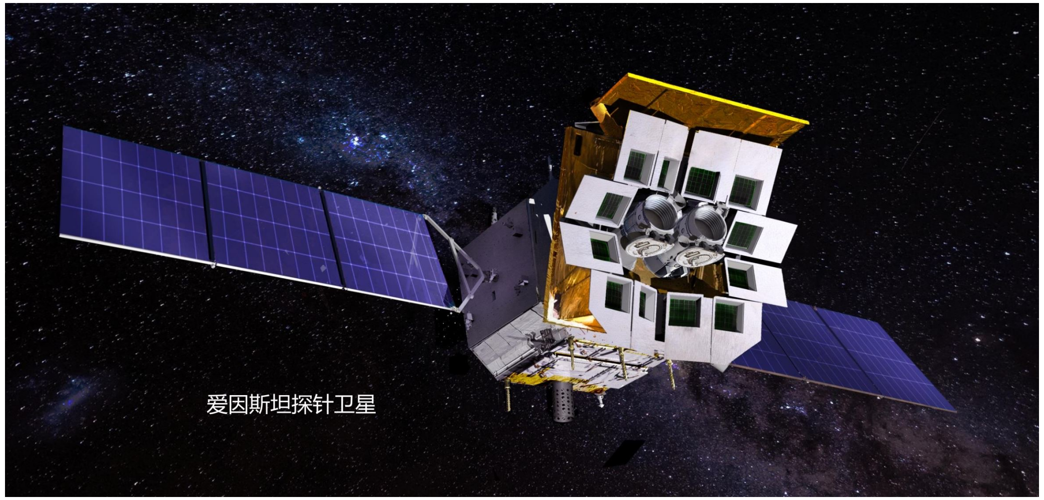
System parameters and future observations by EP/WXT/FXT

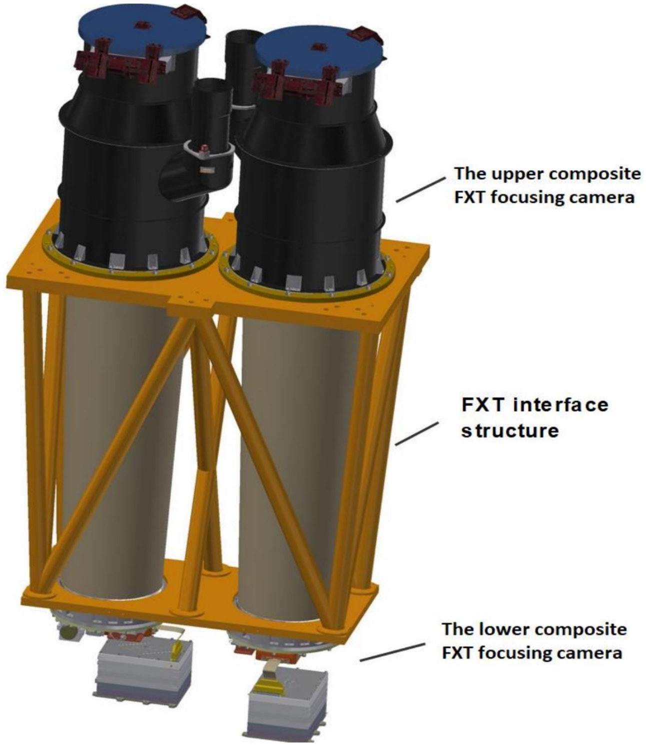
SLX1746-331: orbit period? Inclination angle? Mass function? Distance?
More precise estimation of the lower limit of BH mass.

Sample for BHXRB that only experiences HSS?
Sample of 2.5-5 solar mass gap for BH?
EP WXT/FXT observation of the state transition from LHS?
EP will be launched in early 2024.

- WXT (Wied fov X-ray Telescope)
  - FOV: 3600 sq.deg.(1.1sr)
  - 0.5-5 keV
- FXT(Follow-up X-ray Telescope)
  - FOV: 30’
  - 0.3 – 10 keV







Thanks

Backup slides

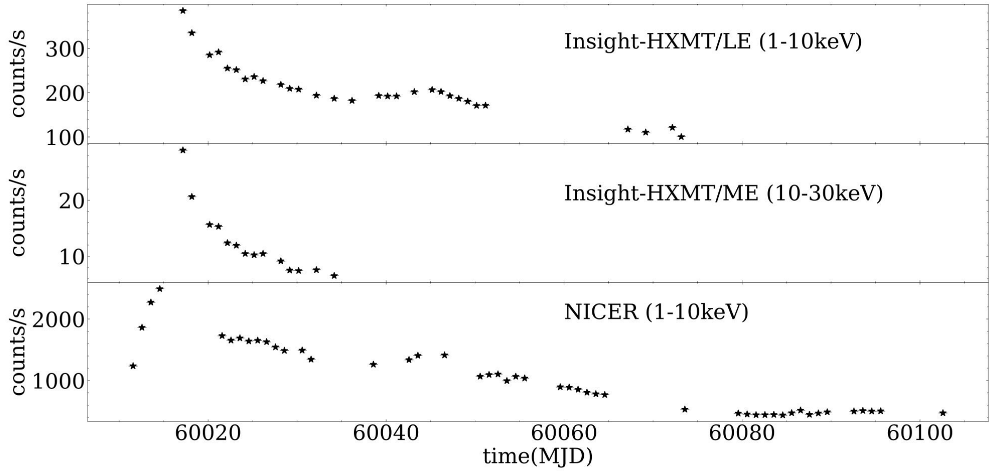
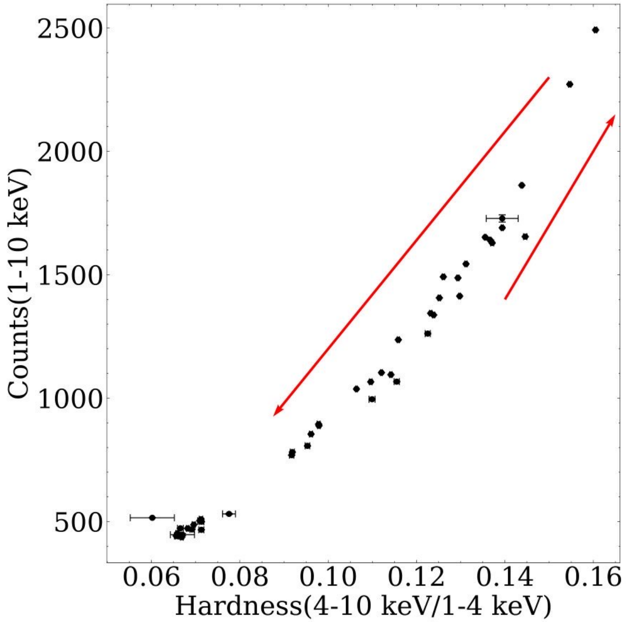


Figure 1. Light curve of SLX 1764–331 during the 2023 outburst. Top panel: the light curve of *Insight*-HXMT LE 1–10 keV Middle panel: the light curve of *Insight*-HXMT ME 10–30 keV Bottom panel: the light curve for *NICER* 1–10 keV.



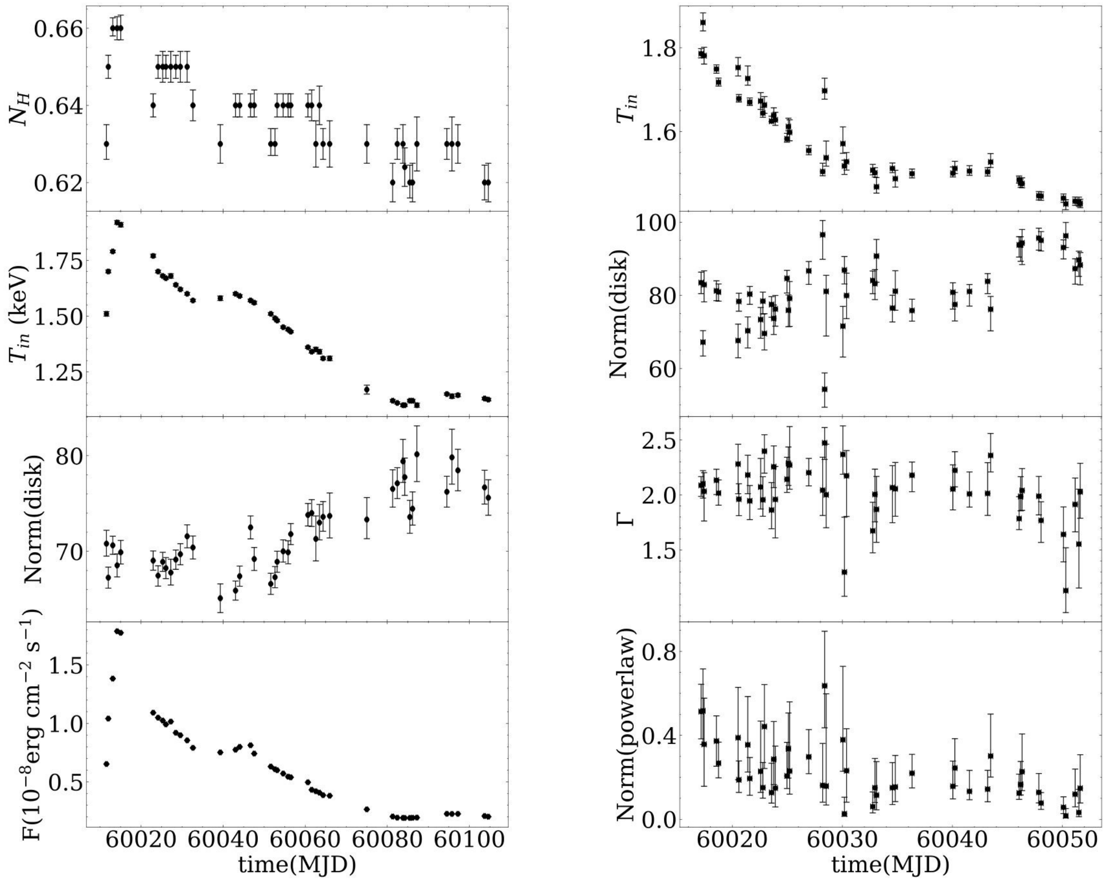


Figure 3. Left panel: Evolution of the spectral parameters by the fitting of *NICER* with M1. $N_{\rm H}$ is the interstellar absorption, $T_{\rm in}$ is the inner disk temperature, Norm(disk) is the normalization of the disk, and F is the flux of the unabsorbed disk from 1 to 100 keV. Right panel: Evolution of the spectral parameters by the fitting of *Insigth*-HXMT with M2. $T_{\rm in}$ is the inner disk temperature, Norm(disk) is the normalisation of the disk, Γ is the photon index, and Norm(powerlaw) is the normalisation of the powerlaw component.

Spectral analysis:

M1: TBABS*DISKBB (NICER data)

M2: TBABS*(DISKBB+POWERLAW) (HXMT+NICER data)

M3: TBABS(THCOMP*KERRBB) (HXMT+NICER data)

	$M = 3.4M_\odot$	$M = 5.7M_\odot$
D=7.29 kpc	$\theta = 70°$, a=$0.80^{+0.01}_{-0.01}$	$\theta = 84°$, a=$0.86^{+0.02}_{-0.04}$
D=10.81 kpc	$\theta = 16°$, a=$0.93^{+0.02}_{-0.03}$	$\theta = 55°$, a=$0.99^{+0.001}_{-0.04}$
D = 14.33 kpc	$\theta = 0°$, $a = 0.99^{+0.001}_{-0.01}$	$\theta = 18°$, $a = 0.99^{+0.01}_{-0.01}$

R_{in} is the physical inner radius, defined as $R_{in} = \xi f_{col}^2 \left(\frac{N D_{10}^2}{cos(i)} \right)^{1/2}$, where N is the dis

hardening factor), ξ is the geometric correction factor described in Kubota et al. (1998),

Therefore, in LHS and IMS, color factor changes and hence Rin deviates from the real values. For example, even if the inner disk keeps at around ISCO, because of the color factor, Rin is observed not at ISCO, which causes the relation between F and T^4 does not hold any more.

In HSS observations show rough stable color factor.
Ledd within 0.001-0.3 Ledd is observed from XRBs, that the inner disk keeps at ISCO. At higher L, slim disk results in deviation form L-T4 relation. Also disk is not standard one (geometrically thin optically thick). Rin is not solidly measured at ISCO.
At lower L, color factor increases and this disk may be truncated, so L-T4 changes as well.
Note that it disk can be observed to truncate within 0.001-0.3 Ledd.

For SLX, a smaller distance could lead to smaller Rin and, if at ISCO, would corresponds to smaller BH mass.

As we know, with Rin to measure the BH spin, one needs BH mass, distance and inclination angle. Therefore, with different possible combinations of these parameters, the BH spin can be constrained with model KERBB, as a moderate spinning BH.