

Insight-HXMT Research Progress Since 2023*

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Abstract Since the launch in June 2017, Insight-HXMT has been in service smoothly in orbit and particularly productive in 2023 and 2024. Among a total number of 238 papers published so far based on Insight-HXMT data, 63 were published in 2023, and 32 in the early 2024 (till 2024 April), accounting for 40% of the total. These studies cover a variety of scientific subjects including the basic properties of black holes and neutron stars, the outburst of accreting black hole and neutron star X-ray binaries, thermal nuclear burst probes, isolated pulsars, quasi-periodical oscillations, cyclotron resonant scattering features, fast radio bursts and gamma-ray bursts, *etc.* This paper introduces the overall progress with focus on some potential breakthroughs.

Key words Insight-HXMT, Black hole, Neutron star, Outburst

Classified index P17

1 Introduction

The Hard X-ray Modulation Telescope (HXMT) is China's first Chinese X-ray astronomy satellite and was launched in June 2017, dubbed as Insight-HXMT in memory of the Chinese scientist Prof. Zehui He. Insight-HXMT has already demonstrated itself with a large amount of important discoveries even during the early mission phase. Only after two months in orbit, Insight-HXMT joined the global campaign of observing the historical event of the first neutron star merging event GW 170817, and reported the strongest constraint on the flux limit at hard X-rays^[1]. Insight-HXMT observed the outbursts of MAXI J1820+070 roughly nine months in orbit and of the first galactic Ultra Luminous Source (ULX) Swift J0243.6+6124 roughly three months in orbit, and obtained so far the unique data in high cadence monitoring of the outbursts of the two important sources. With these data, breakthroughs have been made on understanding Quasi Periodic Oscillations (QPOs),

disk and jet properties; compared to the QPOs detected by other missions prior to Insight-HXMT, QPOs with the highest energy of about 250 keV was discovered during the long-lasting Low Hard State (LHS) of MAX J 1820+070^[2] and, accordingly, a twisted jet scenario was first proposed. From the measurement of the evolution of the disk reflection feature, it was found that the jet moved outward acceleratively when its size contracts toward the central Black Hole (BH)^[3]. The first observational evidence of radiation pressure dominated disk was obtained from the data of Swift J0243.6+6124^[4]. The most interesting result was obtained from Swift J0243.6+6124 five years after the outburst data were collected with a spin-phase-resolved analysis the highest energy of the Cyclotron Resonant Scattering Feature (CRSF) at 146 keV was detected from Swift J0243.6+6124 during peak phase of the outburst^[5], compared to the previous record of 80 keV from the data of GRO J1008-57 during the early Insight-HXMT mission phase^[6]. As the time goes on, more important discover-

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ies are kept being produced from either the Insight-HXMT data archive or the Insight-HXMT observations on the later activities of some compact objects. This paper has summarized the latest results of the Insight-HXMT research progress conducted since 2023.

2 Instrument and Performance

There are three slat-collimated instruments onboard Insight-HXMT (Figure 1). HE consists of 18 NaI/CsI phoswich modules (main detectors) with a total geometrical area of about 5000 cm^2 in 20–250 keV. The Field of Views (FoVs) for HE (High Energy) are $1.1^\circ \times 5.7^\circ$ (for fifteen modules), $5.7^\circ \times 5.7^\circ$ for two modules, and one blind for measuring the background. ME (Medium Energy) takes 1728 Si-PIN pixels which cover an energy range of 5–30 keV with a total geometrical area of 952 cm^2 . ME has FoVs of $4^\circ \times 1^\circ$, $4^\circ \times 4^\circ$ and blind. LE (Low Energy) adopts the Swept Charge Device (SCD) as its detectors, which is sensitive in 1–15 keV with a total geometrical area of 384 cm^2 . The FoVs of LE are $6^\circ \times 1.6^\circ$, $6^\circ \times 4^\circ$, $60^\circ \times 3^\circ$ and blind. For the details of the three telescopes and the mission, please refer to Liu *et al.*^[7], Cao *et al.*^[8], Chen *et al.*^[9] and Zhang *et al.*^[10].

Insight-HXMT has been operating well since its launch in June 2017. During the last more than six years of operation, the altitude of Insight-HXMT orbit dropped by roughly 15 km, and two re-boosts were carried out in March and May 2023, respectively (Figure 2). All of the 18 HE modules work well and the detector elements dropped by 298 for ME and 7 for LE, accounting for 17% and 8% of the total numbers, respectively.

The Insight-HXMT telescopes were well calibrated on the ground before launch. There are two calibration facilities built specially for the Insight-HXMT^[11–13] (Fi-

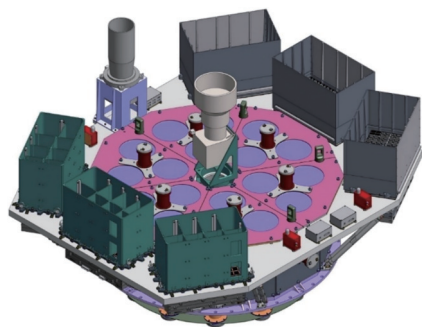


Fig. 1 Insight-HXMT payload configuration

gure 3), one in 15–100 keV built for HE, and one in 0.8–30 keV for ME and LE. For both the mono-energy X-ray beams are produced from the double crystal monochromators, with an intrinsic energy dispersion of roughly 0.1%–1%. The one for HE works in the air under room temperature, while the one for ME/LE is rather complex since supplementary devices like the vacuum chamber and cooling system have to be constructed to satisfy the working conditions of ME/LE.

After launch, Insight-HXMT has been being calibrated in orbit^[14]. The annual calibration consumes about 5% exposure *via* observations of the Crab *etc.* and cross calibration campaigns with other contemporary space X-ray missions for timing and the instrumental response calibrations. Specifically, in 2023 with the dedicated work for subtle correction of the dead time, QPO detection significance can be moderately promoted^[15].

The background models of Insight-HXMT are essential for producing reliable scientific results from the observed celestial sources. However, as a collimated telescope with configuration of different field of views, the background models are completely different from those adopted previously by the collimated telescopes, *e.g.* RXTE. The Insight-HXMT background models are built *via* frequently observing the blank sky, and by taking the advantage of having blind detectors for measuring the instantaneous particle background. The current background models are as precise as 2.1%, 1.6%, and 4.6% for HE, ME and LE, respectively, for a typical exposure^[16]. Meanwhile, background models were also developed for Insight-HXMT by following the traditional way adopted by the previous RXTE mission, used as the backup in case of losing the blind detectors^[17]. The blank sky observations consume roughly 7% of the

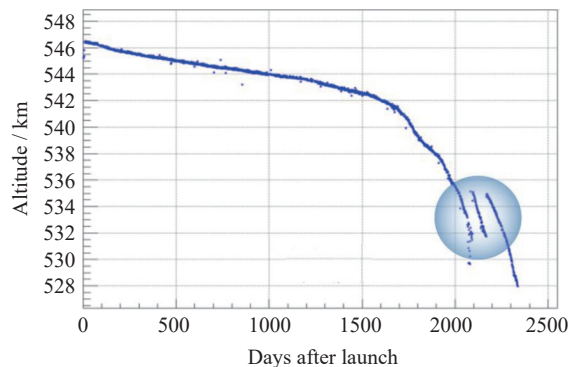


Fig. 2 Maintenances of the orbit

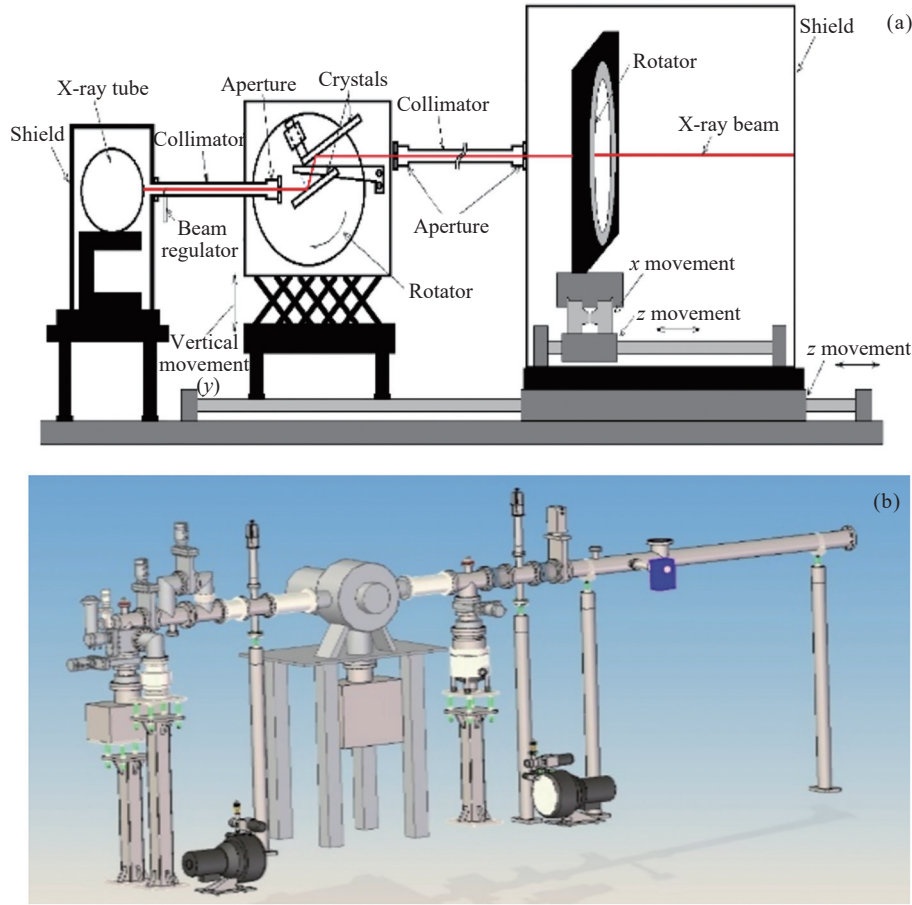


Fig. 3 Ground calibration facilities implemented for HE at hard X-rays (a) and for ME/LE at soft X-rays (b)^[12]

annual total exposure budget.

The scientific observations of Insight-HXMT are organized by the so-called Science Ground Segment (SGS), at the Institute of High Energy Physics (IHEP) of the Chinese Academy of Sciences (CAS)^[13]. Insight-HXMT releases the Announcement of Opportunity (AO) annually to call for the proposals of the scientific observation for each year. It ran into AO 6 in 2023 with a total proposal number of 50. These proposals were submitted by users spreading over the whole world and, accordingly, Insight-HXMT long-term and short-term observational plans are constructed. Insight-HXMT can carry out a triggered Target of Opportunity (ToO) observation within five hours.

Data will be subjected to a proprietary period of one year for regular observations, three months for pre-approved ToOs, and none for *Ad Hoc* ToOs. SGS processes the raw data with the software developed for Insight-HXMT and produces the standard data products

ready for the inputs of Heasoft, a common software maintained by NASA Heasarc for timing and spectral analyses. Please refer to the following links for the Insight-HXMT data archive, web page for proposal submission and Insight-HXMT analysis software: <http://hxmtcn.ihep.ac.cn/>.

3 Scientific Results

The core sciences of Insight-HXMT are: (i) monitoring survey for more weak and short transient sources in a wide energy band (1–250 keV); (ii) high statistics study of bright sources and long-term high cadence monitoring of XRB outbursts; (iii) all sky monitoring for GRBs and pulsars in 0.2–3 MeV. Accordingly, the corresponding observational modes are Galactic plane survey, pointed observation and GRB mode.

So far a total number of 238 papers have been published based on Insight-HXMT data, including 63 in

2023, and 32 in the early 2024. These studies cover a variety of scientific subjects, such as the basic properties of black holes and neutron stars, the outburst of accreting black hole and neutron star X-ray binaries, thermal nuclear burst probes, isolated pulsars, quasi periodical oscillations, cyclotron resonant scattering features, fast radio bursts and gamma-ray bursts, solar flares, terrestrial gamma-ray flashes, *etc.*, as well as the instrumental performance.

3.1 Outburst of Black Hole X-ray Binaries

A Black Hole X-ray Binary (BHXR) consists of a BH as the compact object and a stellar star as the companion. The accretion matter overflows through the Roche lobe and forms an accretion disk around the BH. The instability of the accumulated matter can lead to ionization of the outer part of the disk and thus causes an outburst: the matter moves inward *via* transforming the angular momentum outward through viscosity that heats the gas to radiate away part of the gravitational power in X-rays in the vicinity of the BH. An outburst behaves a variety of observational features in both the temporal and spectral domains. Usually, the outburst will start with a LHS, and evolves through a Hard Intermediate State (HIMS), a Soft Intermediate State (SIMS), a High Soft State (HSS) and finally returns to a LHS again but at a luminosity level lower than the initial LHS, forming the so-called hysteresis in a typical q shape in the Hardness-Intensity Diagram (HID). Low Frequency Quasi Periodic Oscillations (LFQPOs) usually show up in the LHS and HIMS (type-C QPO) and SIMS (type-B and type-A QPO).

Since the X-rays are released at the inner most region of the accretion disk where the strong gravitational field takes effect, the outbursts of BHXR are regarded as one of the ideal labs to test the General Relativity (GR). Testing the fundamental theories of GR under the extremes of gravity is the key objective of the future mission eXTP (enhanced X-ray Timing and Polarimetry Mission) beyond Insight-HXMT. As we know, BHXR outburst evolution is generally believed as the changing balance between thermal emission from the disk and the non-thermal emission from either the hot corona or moderately relativistic jet. Obviously, to better understand such labs, one has to perform sufficient high cadence observations of the outbursts and investigate in much more

details at least the basic properties of each of the key elements (disk, corona, jet, and magnetic field *etc.*) and the roles they play in governing the outburst evolution.

MAXI J1820+070 underwent a huge outburst in 2018. In the late decay phase of this outburst, You *et al.*^[18] found the most direct evidence for the existence of the so-called magnetic arrested disk (MAD), a phenomena theoretically predicted long time ago. The joint Insight-HXMT, radio and optical observations show the unprecedented long-term time lags of the latter with respect to the X-rays. This reveals for the first time the observational evidence of magnetic transportation within the accretion flow, and the whole process of forming a MAD as well (Figure 4).

The spectral and temporal properties of the black hole X-ray transient binary MAXI J1820+070 during the 2018 outburst are studied systematically with

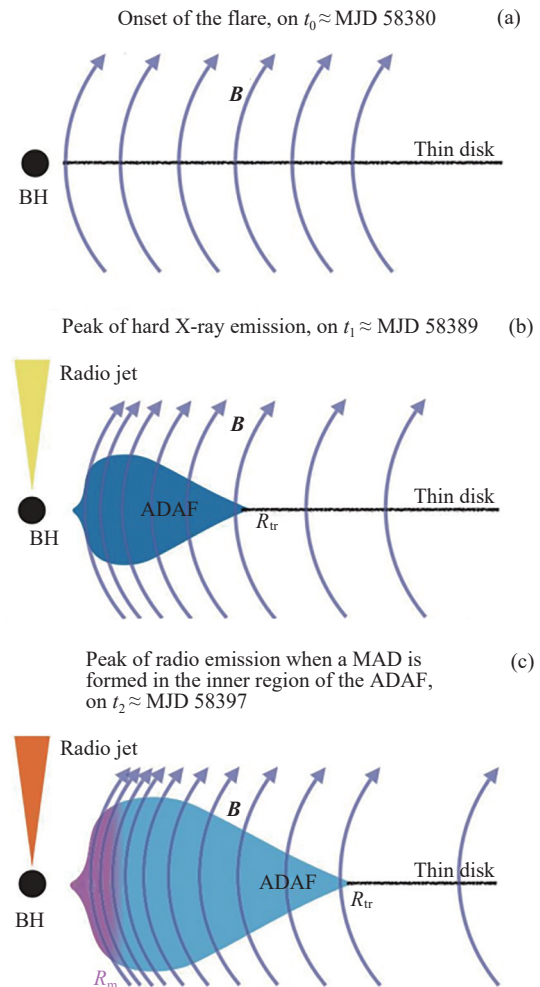


Fig. 4 MAD discovered during the decay phase of MAXI J1820+030^[18]

Insight-HXMT observations. The outburst of MAXI J1820+070 can be divided into three intervals. For the two intervals of the outburst, we find that low-energy (below 140 keV) photons lag high-energy (140–170 keV) ones, while in the decay of the outburst, high-energy photons lag low-energy photons, both with a time-scale of the order of days. Based on these results, the canonical hysteresis effect of the q shape in the HID can be reformed into a roughly linear shape by considering the lag corrections between different energy bands (Figure 5). Timing analysis shows that the high-frequency break of hard X-rays, derived from the power-density spectrum of the first interval of the outburst, is in general higher and more variable than that of soft X-rays. The spectral fitting shows that the coverage fraction of the hard X-rays drops sharply at the beginning of the outburst to about 0.5, and then increases slightly. The coverage fraction drops to roughly zero once the source steps into the soft state and increases gradually to unity when the source returns to the low-hard state. These provide a possible overall scenario for the outburst evolution of MAXI J1820+070 revealed by Insight-HXMT^[19].

Further investigations on the 2018 outburst of MAXI J1820+070 bring us more interesting results. By introducing a scenario that the inner part of the disk provides variability of the soft seed photons, which feed into the outer part of the hot corona and results in the soft comptonization, and the inner part of the hot corona provides the hard Comptonization with the local seed photons, the energy spectrum, power spectrum and the time lag spectrum are jointly fitted^[20]. As shown in Figure 6, the joint fit cannot reproduce the data at energies above 50 keV, suggesting the necessity of introducing an addi-

tional component, *e.g.*, a jet to account for the emission at the high energy part. A complicated corona structure is also indicated in Wang *et al.*^[21] in their study of the correlation between noise RMS and flux: they found that along with the decay during the initial LHS, apart from a slab one, a vertical corona emerged and continuously expanded.

The black hole candidate system SLX 1746-331 was back to business in 2023, after a long silence of roughly 13 years. An outburst was observed thoroughly by Insight-HXMT and NICER. The outburst is characterized by spectral dominance of the soft state, where the joint Insight-HXMT and NICER spectral analysis shows the temperature dependence of the disk flux follows about T^4 and thus suggests that the inner disk reached the Inner Most Stable Orbit (ISCO) during almost the entire outburst^[22,23] (Figure 7). No low hard state and intermediate states may mean the disk evaporation is very low during the entire outburst. The 2023 outburst of SLX 1746-331 differs from those of normal black hole transient X-ray binaries in their evolution patterns in HID: instead of a low-hard state toward a soft state, SLX 1746-331 stayed around the ISCO during the whole outburst. Although such an outburst phenomenon is relatively rare, we notice that so far a similar case was also observed in the outburst of another black hole X-ray binary system MAXI J0637-430^[24]. Peng *et al.*^[22] compared SLX 1746-331 with MAXI J0637-430, and suggested that such peculiar outburst could be related to the special configuration of the binary system. Unlike MAXI J0637-430, which had a peak luminosity of about $0.08 L_{\text{Edd}}$ and a soft-to-hard transition at about $0.007 L_{\text{Edd}}$, SLX 1746-331 remains in the soft state, with no state transition observed even at a luminosity < 500 times

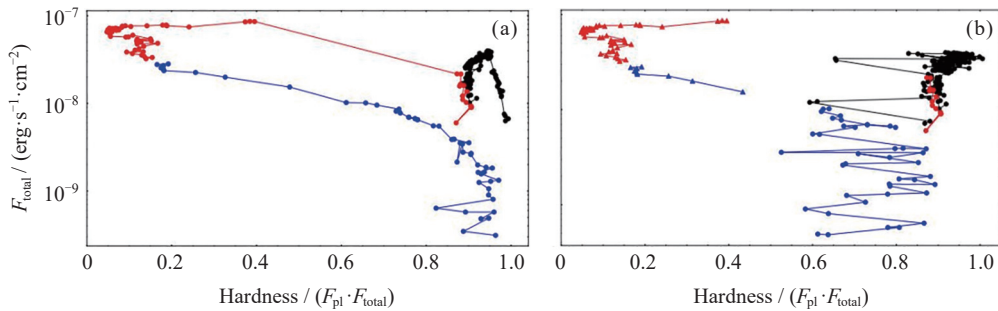


Fig. 5 HID modification by accounting for the lag corrections between different energy bands for the outburst of MAXI J1820+070^[19]

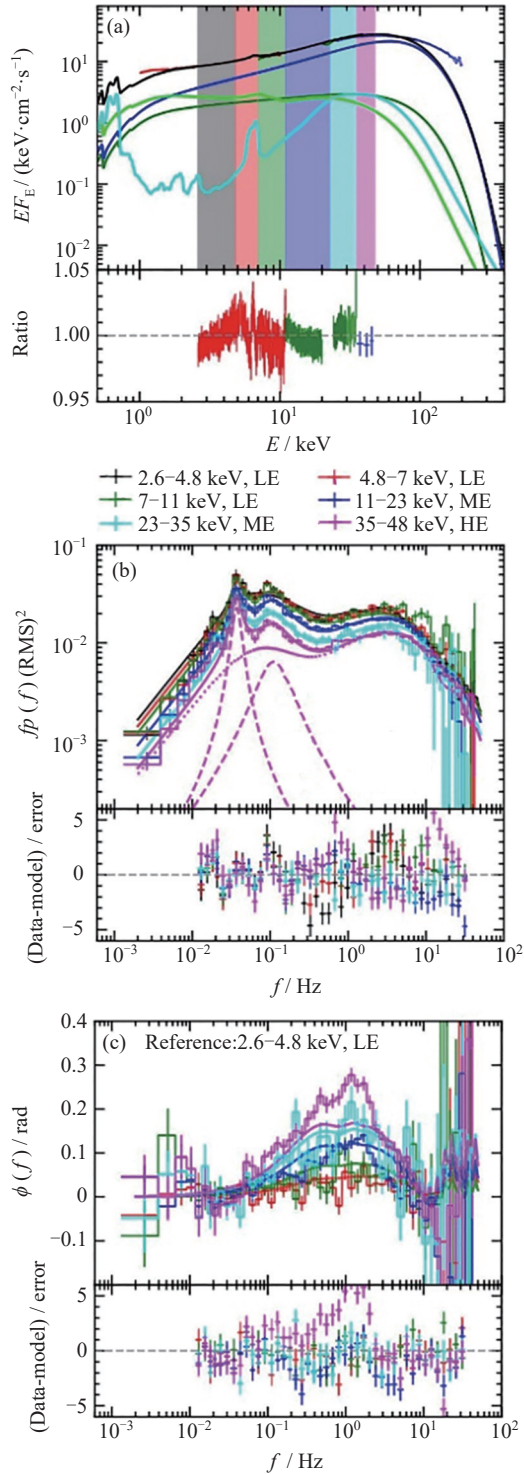


Fig. 6 Joint fits to the spectra in energy, frequency and time lag domains for the outburst of MAXI J1820+070^[20]

lower than the peak luminosity of the outburst.

Swift J1727.8-1613 is a black hole X-ray binary newly discovered in 2023. The joint Insight-HXMT, NICER and NuSTAR observations during LHS reveal

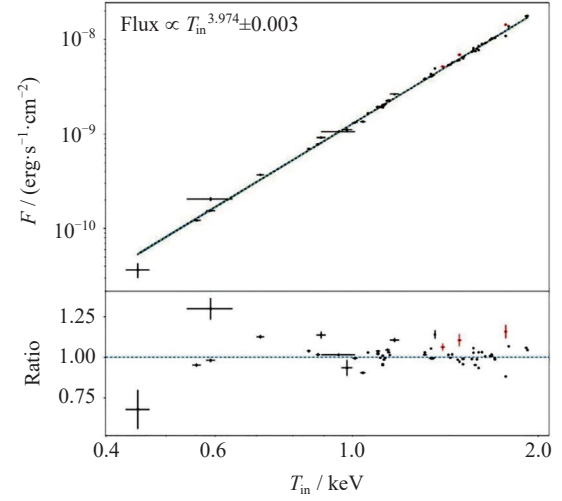


Fig. 7 A standard accretion disk exists during the whole outburst of SLX 1746-331^[23]

an additional hard component apart from the normally observed hard component with reflection in the spectrum, indicating a distinguished outburst of Swift J1727.8-1613. A hybrid jet/corona configuration is adopted to account for the spectral fitting with different model trials^[25] (Figure 8).

The latest results from Insight-HXMT observations of the outbursts from MAXI J1348-630 in 2019, GRS 1915+105 in 2017–2021, MAXI J1535-571 in 2017, 4 U 1543-47 in 2021 also bring us interesting findings. Analysis of the joint NuSTAR and Insight-HXMT observations of the reflare 4 months later than the major outburst of MAXI J1348-630 in 2019 shows the disk-corona behavior at low Eddington luminosity: it seems that there exists a critical luminosity to govern the balance between heating up the corona and forming a disk which needs efficient transfer of the angular momentum outward *via* viscosity^[26]. Yu *et al.* performed a spectral-timing study of the inner flow geometry in MAXI J1535-571 during an outburst observed with Insight-HXMT and NICER in 2017^[27]. The reverberation mapping shows that the soft lag evolves to about zero at a specific frequency, which might denote the connection point between the inner disk and the corona. Thus, the evolution of such frequency can serve as a new viewer on if the inner disk is truncated during the outburst. The outburst of 4 U 1543-47 in 2021 serves as a nice example for investigation of the accretion disk at luminosity around Eddington level. The analyses carried out by

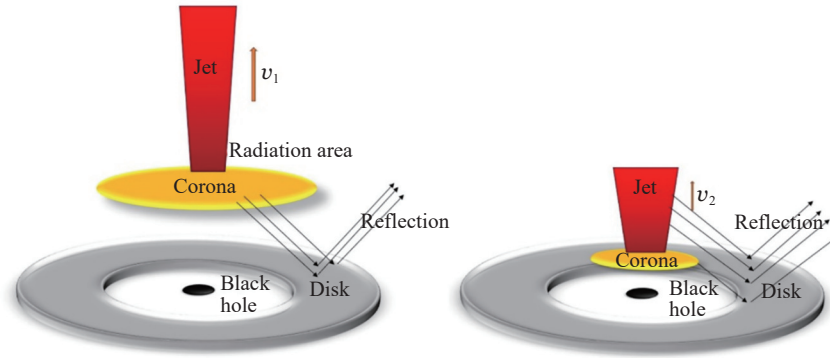


Fig. 8 A hybrid jet/corona scenario introduced to the outburst evolution of Swift J1727.8-1613^[25]

Zhao *et al.*^[28] based on the joint Insight-HXMT and NuSTAR observations result in a self-irradiation inner disk, highly consistent with the theoretical prediction of having a slim disk under a high accretion rate. The same outburst was also studied by Jin *et al.*^[29] but with focus on the decay phase based on only the Insight-HXMT high cadence observations. It turns out that the source can experience a state transition to LHS at luminosity around Eddington limit and the aforementioned self-disk-illumination feature disappeared after the state transition, thus proves the possibility for existence of a LHS at an accretion rate of as high as around Eddington limit. The exploration of the timing and spectral properties of GRS 1915+105 based on X-ray observations of NICER and Insight-HXMT during the long outburst from 2017 to 2021 revealed new class of variability in the rising stage of the outburst that differs from the previously reported patterns of light curves, which helps to understand the class transition mechanism in GRS 1915+105^[30].

3.2 Black Hole Mass and Spin

As a peculiar theoretical singularity BH can be probed with only two observables of mass and spin. The interests in the measurements of BH spin and mass are not only about understanding BH, but also relevant to the evolution of the stars in their processes of collapsing into BHs and probably as well the formation and evolution of the X-ray binary systems. The Gravitational Wave (GW) experiments measure the BH masses *via* observing the GW from the compact merger events, and put forward a new puzzle regarding to the BH mass distribution (Figure 9): it seems that there exists a mass gap

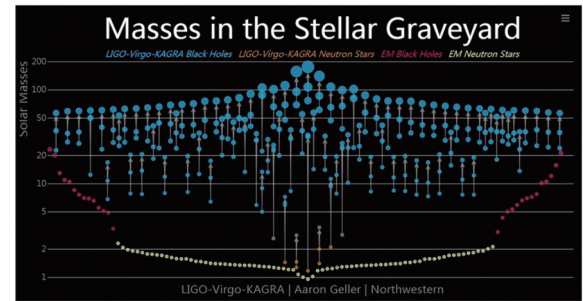


Fig. 9 Mass gap puzzle^{*}

of 2.5–5 solar mass where only two GW-detected BHs and one XRB system GRO J0422+32 are currently in, which is not consistent with the theoretical expectations of either having a lot or none^[31]. To solve this problem, Gao *et al.*^[32] proposed a scenario that, with specific system configuration, a neutron star hosted in a Pulsating Ultra-Luminous X-ray (PULX) source can grow up in mass *via* accreting the material from the companion in a super-Eddington manner and finally turns into BH with relatively small mass. Such a theory is supported by the Insight-HXMT discovery of the highest CRSF line at 146 keV^[5] which in turn proves that the PULX should really have an accretion rate beyond Eddington limit. Here we find that one more BH candidate may fall into this mass gap: the outburst from SLX 1746-331 was observed by Insight-HXMT to keep in disk-dominated state covering a luminosity range roughly 500 times lower than the maximum, wider than the canonical 0.001–0.3 Eddington ratio and thus results in a reasonable assumption for the peak flux of the outburst around 0.3% Eddington ratio. From fitting the reflection component with the joint Insight-HXMT and NuSTAR obser-

^{*} <https://ligo.northwestern.edu/media/mass-plot/index.html>

vations, the BH spin is first measured as 0.85 ± 0.03 and an inclination angle can be constrained as $53^\circ \pm 0.5^\circ$. With a distance of 10.81 ± 3.52 kpc measured by Yan *et al.* with an outburst sample^[33], the BH mass is estimated as $5.5 \pm 3.6 M_\odot$ for SLX 1746-331^[22] which, albeit with relatively large error bar inherited from the larger uncertainty in distance, is consistent with $5.2 \pm 4.5 M_\odot$ obtained from the empirical correlation between the disk peak temperature and BH mass established from a sample BH outburst^[22] (Figure 10). We notice that SLX

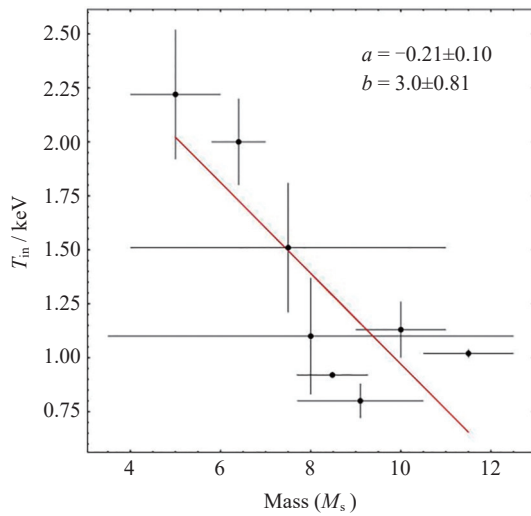


Fig. 10 BH mass estimated from an empirical correlation between disk temperature and BH mass from a BH outburst sample^[22]

1746-331 shares similar characters with MAXI J0637-430 in aspects that their outbursts are short of the clear spectral states prior to HSS and dominated by disk emissions at rather low accretion rates^[24]. Interestingly, the BH mass was measured as $5.1 \pm 1.6 M_\odot$ for MAXI J0637-430, and thus makes MAXI J0637-430 another candidate with a small BH mass falling into the BH mass gap. The peculiar outburst behaviors of SLX 1746-331 and MAXI J0637-430 require the systems having rather small accretion disks, which is in line with the small BH mass held by these systems and as well so far the shortest orbital period of 2.2. hours reported in MAXI J0637-430^[34]. We speculate that both sources may constitute low mass BHs in the BH ZOO (Figure 11).

Since 2023 more BH spins have been measured by Insight-HXMT with the canonical methods of disentangling disk reflection component in energy spectrum or fitting the continuum dominated by the standard disk emission, under assumption that the inner disk stays around the ISCO. MAXI J1348-630 was discovered by the MAXI/GSC instrument during the outburst in 2019, and the follow-up observations from Insight-HXMT covered the spectral states from LHS to HSS. Song *et al.*^[35] analyzed the Insight-HXMT data with the reflection models and found that a moderate spin of $0.82^{+0.04}_{-0.03}$ can be derived in all the spectral states covered by Insight-HXMT observations. Wu *et al.*^[36] instead took the

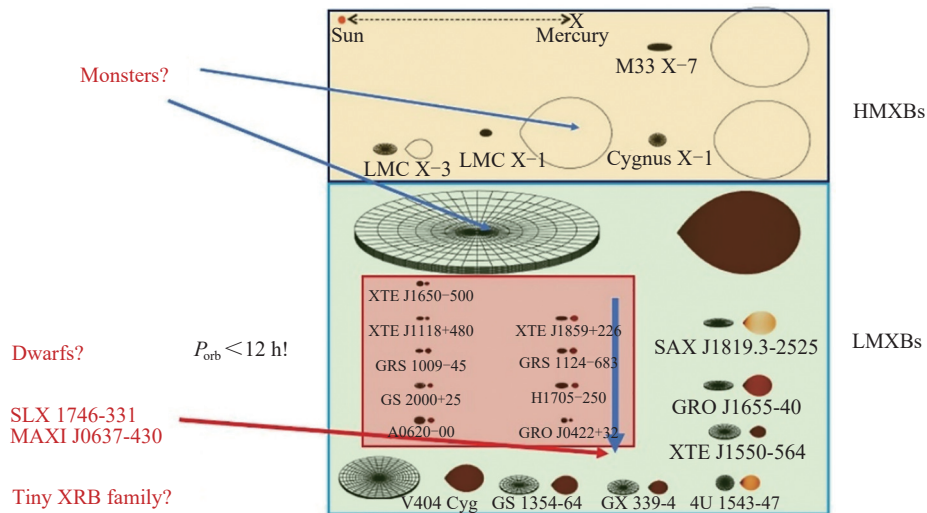


Fig. 11 The BH zoo*

* private communication with Li Xiangdong

continuum-fitting method to estimate the BH spin with the Insight-HXMT HSS data, and reported a BH spin of $0.42^{+0.13}_{-0.50}$, significantly lower than that derived by the disk-reflection method. Interestingly, BH spin was reported as $0.78^{+0.04}_{-0.04}$ with NuSTAR data^[37] and 0.80 ± 0.02 with NICER data^[38], by adopting the methods of reflection and continuum fitting, respectively. Although the source of the discrepancies for measurements of the BH spin with different methods remains unclear, it is probably due to the different ways the spin estimation is made: based on the GR effect on the broadened iron line or purely the ISCO radius. Obviously, the latter is highly dependent on the precisions of the input parameters of BH mass, system distance and disk inclination angle, which may cause the differences in BH spin estimation with NICER or Insight-HXMT observations. 4U 1543-47 is another example that previous spin measurements are largely inconsistent with each other. 4U 1543-47 underwent a huge outburst in 2021, reaching a peak intensity of about 9 Crab. By taking the Insight-HXMT observations with the source luminosity staying within about $0.28\text{--}0.31 L_{\text{Edd}}$, and the state-of-art parameters of BH mass, distance and inclination angle, Chen *et al.*^[39] reported a BH spin of 0.46 ± 0.12 . Since most part of the outburst exceeded the thin-disk luminosity limit, Yorgancıoglu *et al.*^[40] picked up the Insight-HXMT and NICER observations dominated by the disk thermal emission with a low/stable disk inner radius, which end up with a dataset covering luminosity up to about $1 L_{\text{Edd}}$. They instead tried for the first time a slim disk model to account for the continuum disk emission and derived an overall BH spin of $0.65^{+0.14}_{-0.24}$, roughly consistent with that reported by Chen *et al.*^[39].

3.3 Quasi Periodic Oscillation

QPOs remain a puzzle since its discovery in the last century, although the previous RXTE telescope has accumulated great amount detections for QPOs of different types. The LFQPOs, subdivided into type-C, type-B and type-A, mainly reside in the initial different spectral states of the BH outbursts on their ways entering into the HSS. The current popular models on the LFQPOs are either the pure geometry effect, caused by the relativistic Lense-Thirring (LT) precession of the inner disk, corona or jet due to the frame dragging effect for a BH system where the BH spin is not aligned with the disk^[41],

or the intrinsic properties of the accretion flow. The latter concerns the instability of the accretion rate and includes trapped corrugation modes^[42], the accretion-ejection instability model^[43], and the two-component advection flow model^[44], *etc.* However, none of them can fully account for all the properties discovered so far for the LFQPOs. Obviously, a breakthrough requires further observational clues in at least the following aspects: (i) QPO phase-resolved spectrum; (ii) the QPO properties beyond the energy limit of RXTE around 30 keV; (iii) QPO phase-resolved polarization, and probably as well others that cannot be foreseen at the moment.

Recovering the QPO waveform is a tough task and thus carrying out QPO phase-resolved spectral analysis is extremely difficult, due to that QPO in definition is a phenomenon of a rather broad peak component showing up in the power spectrum, which means that it covers a series of frequencies. The early effort of recovering the QPO waveform and the QPO phase-resolved analysis was performed by Ingram & van der Klis^[45] using the statistical phase difference of QPO between the fundamental and harmonic components. This Fourier method, as will be discussed later, depends on the existence of an obvious harmonic component and handle the QPO phases in a statistically averaged way. An empirically chosen peak and trough of QPO in a specific light curve during the hard state of the bright outburst from MAXI J1820+030 revealed the spectral difference between the peak and trough phases^[46]. The wavelet technique was also tried on the LHS of the MAXI J1820+030 outburst, and found that the QPOs have an averaged lifetime of around 5 oscillation cycles^[47] (Figure 12).

As a non-traditional temporal analysis technique, Hilbert–Huang Transform (HHT)^[48] is a powerful tool for analyzing phenomena with nonstationary periodicity and has been successfully applied in astronomical research. HHT enables us to not only trace the variation in frequency in the QPO but also to process phase-resolved analyses even though the periodicity is unstable. HHT consists of two main components: mode decomposition and Hilbert Spectral Analysis (HSA). The mode decomposition aims to decompose a time series into several Intrinsic Mode Functions (IMFs), while the HSA allows obtaining both the frequency and phase functions of the desired IMFs, such as the QPO compo-

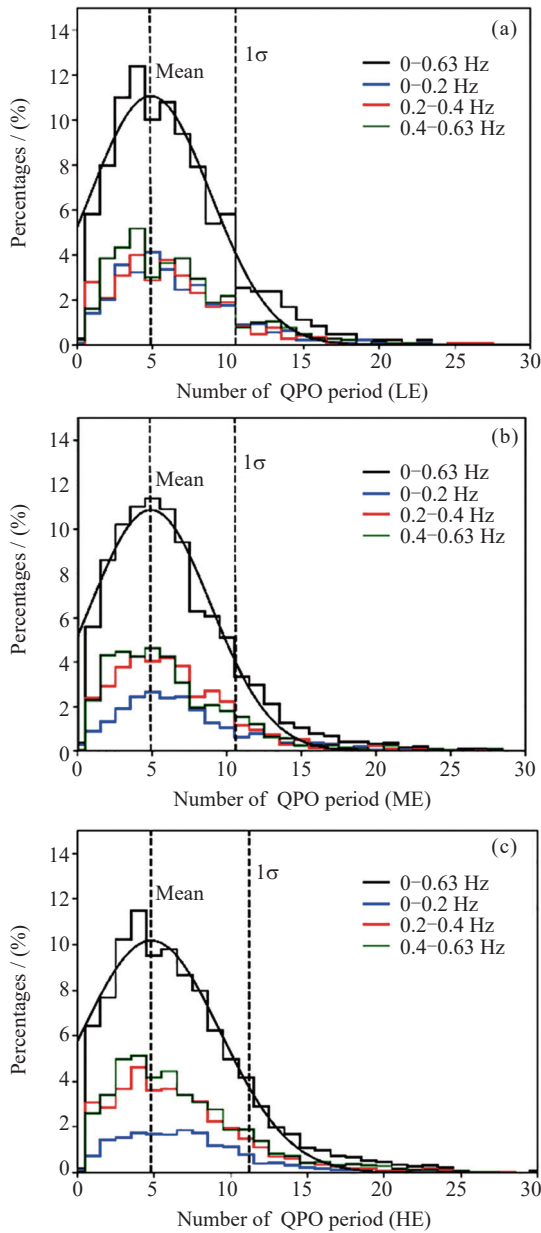


Fig. 12 QPO lifetime distribution over all the March to June 2018 Insight-HXMT observations in units of cycles^[47]

ment. Shui *et al.*^[49] replaced the original Empirical Mode Decomposition (EMD) proposed by Huang *et al.*^[48], which directly operates in the temporal space and adaptively decomposes the input signal into several IMFs, with a novel Variational Mode Decomposition (VMD) that surpasses traditional decomposition approaches such as EMD^[50]. By employing the HHT method, Shui *et al.*^[49] extracted the intrinsic QPO variability, and obtained the corresponding instantaneous amplitude, phase, and frequency functions for each data point. With well-

defined phases, the QPO waveforms and phase-resolved spectra are constructed. By comparing the phase-folded waveform with that obtained from the Fourier method adopted in Ingram & van der Klis^[45], they found that phase folded on the phase of the QPO fundamental frequency leads to a slight reduction in the contribution of the harmonic component (Figure 13). This suggests that the phase difference between QPO harmonics exhibits time variability. Phase resolved spectral analysis reveals strong concurrent modulations of the spectral index and flux across the bright hard state (Figure 14). The modulation of the spectral index could potentially be explained by both the corona and jet precession models, with the latter requiring efficient acceleration within the jet. Furthermore, significant modulations in the reflection fraction are detected exclusively during the later stages of the bright hard state. These findings provide support for the geometric origin of LFQPOs and offer valuable insights into the evolution of the accretion geometry during the outburst in MAXI J1820+070.

QPO signals at energies above 30 keV are one of the major discoveries from BHXRB outbursts observed by Insight-HXMT. For MAXI J1820+070 the large detection area of CsI onboard Insight-HXMT allows for the QPO detection up to energies around 250 keV with a traditional FFT analysis tool^[2]. As demonstrated in Shui *et al.*^[51], with an HHT technique QPO waveform can be reconstructed at even high energies. An example to demonstrate such power is the recovery of the QPO waveform for MAXI J1535-571 with HHT at energies above 170 keV (Figure 15), significantly higher than 100 keV reported for the same Insight-HXMT data but with a traditional Fourier method^[52]. Although QPO in polarimetry view goes beyond the scope of this paper since it is probed by IXPE but not Insight-HXMT, recent IXPE/NICER investigation on the phase-resolved QPO polarization from the outburst of Swift J1727.8-1613, with HHT technique developed by Shui *et al.*^[49], revealed polarization degree lower than the predication of LT precession model^[53].

The other QPO research progresses from Insight-HXMT since 2023 are listed as follows. A thorough timing analysis was carried out by Yu *et al.*^[54] based on the Insight-HXMT observations of the outburst from Swift J1727.8-1613. Apart from the canonical type-C QPOs

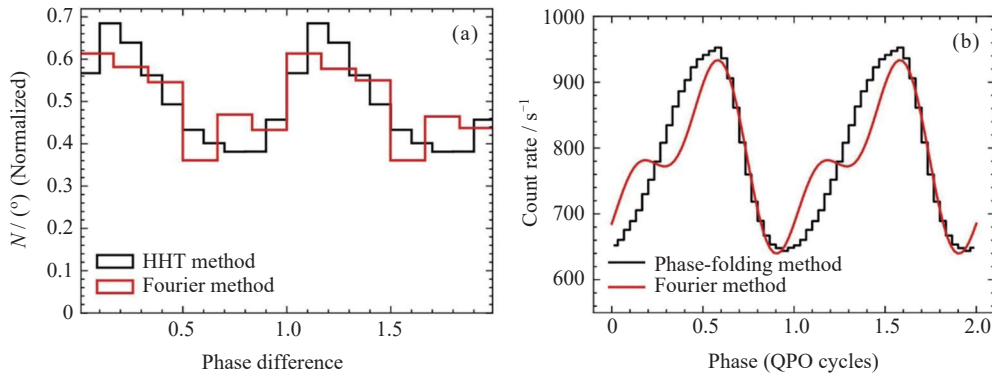


Fig. 13 (a) Histogram of measured values of the phase difference between harmonics obtained using the HHT (black) and Fourier (red) methods. To show a clear peak, we repeat the data from 0 to π . (b) Reconstructed QPO waveform derived from the HHT phase-folding (black) and Fourier (red) methods^[49]

they found the peaked noise oscillation which correlates with the LFQPO in a manner of Psaltis-Belloni-van der Klis (PBK) relationship^[55]. This finding helps to diagnostic the QPO origin in the context of investigating the instability in a rather broad frequency range. They also took the HHT technique to investigate the QPO time lags in the outburst of MAXI J1820+070 and got results consistent with Ma *et al.* who estimated the QPO time lag by subtracting off the underlined noise contribution in the cross spectrum^[2,56]. Ma *et al.* supplemented their previous QPO report based purely on the Insight-HXMT observations of the MAXI J1820+070 outburst by enclosing as well the contemporary NICER observations at soft X-rays, and found that a twisted jet scenario still holds^[57]. Timing analysis of the new black hole candidate MAXI J1803-298 with Insight-HXMT and NICER revealed type-C and type-B QPOs^[58]. While the RMS and time lag behaviors of type-C QPO can be understood in LT precession model, those for type-B are rather peculiar which may be explained with a dual-corona model. The fast transitions of X-ray variability in the black hole transient GX 339-4 was compared with MAXI J1820+070 and MAXI J1348-630 by Yang *et al.*^[59]. They found transitions between band-limited noise-dominated PDS and type-B QPOs, accompanied with rapid appearance or disappearance. A detailed comparison between the fast transitions in GX 339-4 with those seen in MAXI J1820+070 and MAXI J1348-630 was conducted. They argued that there may exist possible change of the geometry of the inner accretion flow and/or jet during the transitions. QPOs in GX 339-

4 during the 2021 outburst observed with Insight-HXMT were also studied by Jin *et al.*^[60]. They reported the first findings of the type-C QPOs and their RMS/time-lag properties during state transitions from LHS to HIMS. The bicoherence can be used to measure the phase coupling at different Fourier frequencies. With this technique, Ding *et al.*^[61] presented the timing analysis of the nonlinear variability in two BHXRBS MAXI J1820+070 and MAXI J1535-571. They found the different patterns, *e.g.*, “cross” and “hypotenuse”, for LFQPOs in different outburst states can be shared to some extent with the type-C and type-B QPOs. Thus, they suggested that different types of QPOs may originate from similar underlying mechanisms and the nonlinear variability may be a promising approach to disentangle different QPO models which assume different interactions between the broadband noise and QPO components.

While the QPOs are relatively rare in outburst of the accretion NSXRB systems, unlike those showing up in BHXRBS which suffer from degeneracy in models of geometric and accretion instability, it is generally the consensus that QPOs in accretion pulsar NSXRBs can inherit the information of the accretion instability in the inner region of the accretion disk. Progresses made in this aspect come from Li *et al.* in their studies on the outbursts from two accreting pulsar systems RX J0440.9+4431 and MAXI J1816-195^[62,63]. A strong 2.5 Hz periodic oscillation was detected from the newly discovered accretion millisecond pulsar MAXI J1816-195, which is likely attributed to an unstable corona^[62]. The timing analysis on the Be/X-ray binary pulsar RX

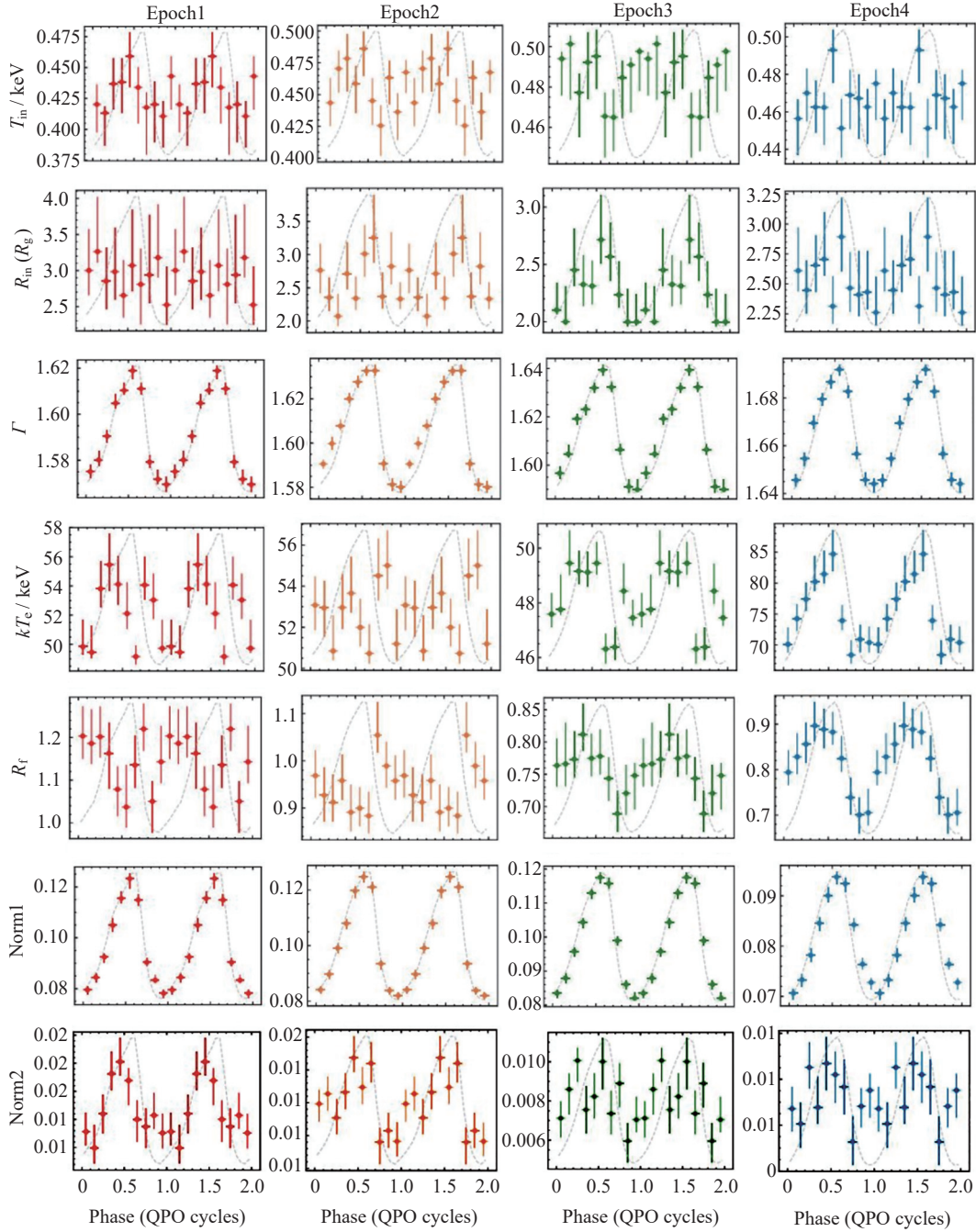


Fig. 14 Phase dependence of the seven free spectral parameters, including the temperature of the inner radius of the disk (T_{in}), inner radius (R_{in}), spectral index (Γ), electron temperature (kT_e), reflection fraction (R_f), and the normalization of relxillCp (Norm1) and xillverCp (Norm2), across the four epochs^[49]

J0440.9+4431 using observations from NICER and Insight-HXMT during the 2022–2023 outburst resulted in discover of QPOs at 0.2–0.5 Hz, characterized with the accompanied short flares. Again, they argued that the origin of QPOs is related to the instabilities within the

accretion flow^[63].

3.4 Outburst of Neutron Star X-ray Binaries

The X-ray outbursts caused by matter accreted to the NSs can be classified into two categories: high mass and low mass XRBs. In high mass XRBs the accretion

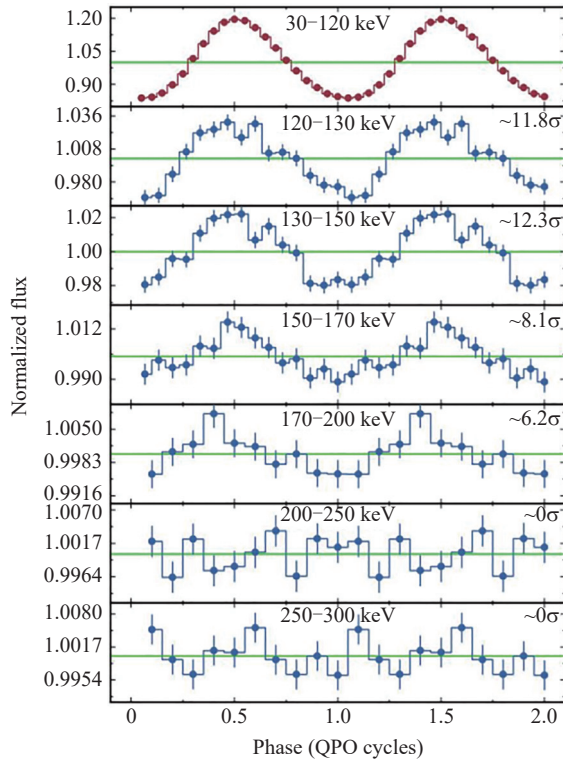


Fig. 15 HHT phase-folded QPO waveforms of MAXI J1535-571 from Insight-HXMT/HE light curves^[51]

matters are channeled by their strong magnetic field lines onto the magnetic poles of NSs, forming the so-called Accretion-Powered Pulsars (APP). In low mass XRBs, typically observed as Atoll and Z sources, the accretion matters are accreted on the entire surfaces of NSs, behaving persistent emission for Z sources, and outbursts resembling BHXRB but with only the Island (hard) and banana (soft) states for Atoll sources. Because of such similarity, the type-I burst of the thermal nuclear burning on the surface of a NS provides a nice probe into the accretion environment surrounding the NS during the outbursts, and the research progresses will be introduced in the following section of “burst probe”. Thus, here we mainly focus on the outbursts observed by Insight-HXMT in APP systems.

One major interest regarding to the outbursts from APP systems is the region around the co-rotation radius, where the angular velocity of accretion matter controlled by the magnetic field of the NS becomes comparable to that of Keplerian velocity maintained by the gravitational force of the NS. The angular velocity of the former depends on the NS spin and hence is indepen-

dent of the magnetic radius which can be compressed by the accretion matter. At radius beyond the co-rotation one, the accretion will in principle be stopped *via* the propeller effect, and otherwise an outburst usually shows up *via* releasing the gravitational power at the magnetic poles, along with the inner part of a truncated disk located always around the co-rotation radius. Therefore, the instability inherited around this particular region will leave footprint in its temporal behaviors for emissions observed around the magnetic poles. For example, the early Insight-HXMT reported a transition from gas to radiation dominated disk emissions from the first Galactic ULX Swift J0243.6+6124^[4], mainly based on the detection of two breaks in the power spectrum. The QPO features, as introduced in the last section, detected by Insight-HXMT in the outbursts from the accreting millisecond pulsar MAXI J1816-195 and Be APP system RXJ0440.9+4431 strengthen again that the intrinsic temporal features as observed around the magnetic poles are highly relevant to the instability for the accretion flow residing outside of the NS magnetosphere^[62,63].

The other major interest regarding to the outbursts from APP systems is the region around the magnetic poles, where the gravitational power is released and radiates away mainly in X-rays. The general consensus on the physical process in this region is that, the accretion matter channeled to the top of the NS surface can form a shock due to either the local radiation pressure at high luminosity or the gas pressure at low accretion rate. In the former case, the accretion matter heated by the shock will sink toward the NS surface and forms an accretion column, where the emission is released mainly from the lateral side of the column in a so-called fan-mode. The hot materials will be cooled *via* inverse Compton scatterings off the seed photons from either outside of the column or the internal synchrotron emissions on their way settling on the NS surface. In case of low accretion rate, a pencil mode is foreseen, where the shocked materials will heat directly the NS magnetic poles and radiate away along the magnetic field lines. However, a great amount of the details is still in debate. For example, in which region of the column do the hard X-rays come from? Is the height of column comparable to its base where a hot spot is expected to exist? How does the emission region evolve from fan to pencil

mode? What will happen in case of the co-existence of both dipole and multipole magnetic fields? Are the emissions from PULX systems beamed or intrinsic? To answer these questions, one needs thorough observational information in both the energy and time domains. To this end one of the key parameters is the critical luminosities under which the transitions between different modes occur. Previous results obtained by Kong *et al.*^[64] with Insight-HXMT observations of the outburst from the PULX Swift J0243.6+6124 present the first complete sample to describe how the spectral parameters evolve within a wide scope of luminosity. The critical luminosity responsible for the mode transition to fan-mode turns out consistent with a strong magnetic field discovered by the detected CRSF with a centroid energy as high as 146 keV^[5].

The latest results from Insight-HXMT about this ULX come from the investigation of the pulsed iron line^[65]. The phase-resolved spectral results show, for the first time, the pulsed characteristics of the broad iron line in a PULX Swift J0243.6+6124. The variation in the width and intensity of this iron line has a phase offset of about 0.25 from the pulse phase. They suggest that the

uneven irradiation of the thick inner disk by the accretion column produces the modulated variation of the broad iron line. In addition, the non-pulsed narrow line is suggested to come from the outer disk region (Figure 16)^[65]. 1 A 0535+262 is another example with the high cadence observations of Insight-HXMT during a huge outburst in 2020. The latest results about this outburst come from the investigation of the beam pattern by Hu *et al.*^[66] and a deep search in gamma-ray with Fermi gamma-ray observatory by Hou *et al.*^[67]. With a decomposition technique, the pulse profile of 1 A 0535+262 during a giant outburst observed by Insight-HXMT in 2020 can be described with a geometry consisting of a distorted dipole magnetic field^[66]. 1 A 0535+262 has been monitored by Fermi for over 13 years and the deep search in gamma-rays resulted in no significant detection during its previous outbursts^[67]. This is not of surprise since the neutron star in this system has a spin much slower than that held in the accretion millisecond pulsar and the gamma-rays beyond 511 keV, if any, would be absorbed locally in a compact emission region of the accretion column.

Other studies carried out since 2023 are listed in

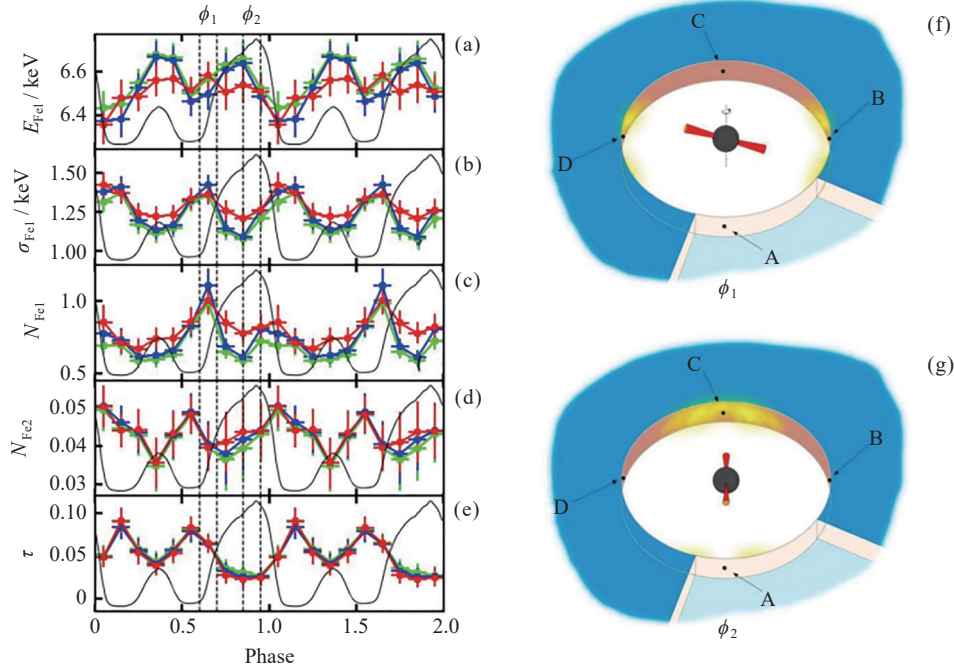


Fig. 16 Geometric sketch of the broad iron line emission region on the accretion disk of two specific phase intervals from the observer's perspective. The accretion disk is divided equally into regions A, B, C, and D toroidally, with the region A being on the side closest to the line of sight of the observer^[65]

what follows. The Centaurus X-3 orbital ephemerides was improved using Insight-HXMT, RXTE, Swift/BAT and NuSTAR observations^[68]. A hard tail was detected from Sco X-1 with Insight-HXMT observations^[69], which requires a non-thermal component in addition to a normal corona. 4 U 1700-37 is an eclipsing high-mass X-ray binary holding a compact object of 2.44 ± 0.27 solar mass. Although a NS or BH nature of this compact object is not clear, the studies carried out by Xiao *et al.*^[70] based on Insight-HXMT observations found short flares with stable spectral hardness, which resembles to the superfast giant X-ray transients (SgXBs) observed with flares produced by the clumpy stellar wind of the companion. Furthermore, hints for detection of CRSFs also point to the NS nature of this compact object^[70]. Broadband X-ray timing and spectral characteristics of the accretion-powered millisecond X-ray pulsar MAXI J1816-195 were analyzed by Li *et al.* with a report of the stable X-ray pulsations above about 95 keV detected in a combination of Insight-HXMT HE observations^[71]. As an atoll source, 4 U 1730-22 underwent two outbursts in 2021 and 2022 after 49 years of silence. The joint Insight-HXMT and NICER observations showed a transition to LHS during the decay phase which, if a propeller effect is at work, can be used to estimate the magnetic field of the NS as $(1.8-2.2) \times 10^8$ G^[72].

3.5 Cyclotron Resonant Scattering Features

Strong magnetic field can quantize the movement of the hot electrons confined in the emission region around the magnetic poles into the Landau levels, and hence CRSFs can show up in the observed energy spectrum at the specific energies needed for the electron to stay at different quantum status. The centroid energy of CRSF E_{cyc} is correlated to the magnetic field in form of $E_{\text{cyc}} \approx 11.6 \times B_{12}$ keV, where B_{12} is the magnetic field strength in units of 10^{12} G, providing the only manner to estimate directly the magnetic fields of NSs. A NS's magnetic field is highly relevant to many issues regarding to understanding the accretion process of an NS XRB system which is governed jointly by accretion rate and the NS's magnetic field. For example, the discovery of the highest CRSF centroid energy of 146 keV has already proved that the PULX should have the super-Eddington luminosity intrinsically instead of beamed^[5]. Since the CRSFs are generally thought to be produced at the site where the hard X-rays are produced, evolution of the CRSF E_{cyc}

against luminosity serves as a probe to investigate how the emission region could evolve between different emission modes, and discriminate the different models at work. For example, the E_{cyc} -luminosity correlation will change from positive to negative once the luminosity increases across the critical one. Thus, measurement of such a critical luminosity may discriminate the popular models at work currently^[73]. However, as shown in Mushtukov *et al.*^[73], the sporadic observational results for E_{cyc} -luminosity correlation are far from sufficient for fulfilling this task. A possible breakthrough may come from Insight-HXMT observation of the outburst from 1 A0535+262, where a clear change in E_{cyc} -luminosity correlation at a critical luminosity seems to be consistent with model prediction of Becker *et al.*^[74]. Recently, by taking a pulse-to-pulse method, Shui *et al.*^[75] obtained more detailed results which refined the fine structures of the E_{cyc} -luminosity correlation from 1 A0535+262. As shown in Figure 17, three critical luminosities (denoted as L_1 , L_2 and L_3) are found in the E_{cyc} -luminosity diagram, which subdivides the entire E_{cyc} -luminosity evolution into four regions: the correlation

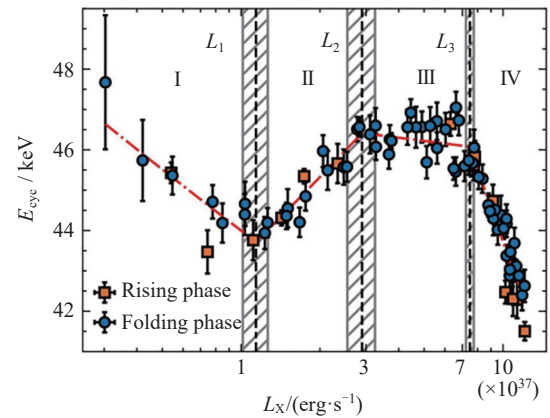


Fig. 17 Luminosity dependence of cyclotron line centroid energy with the linear energy drift of $E_{\text{cyc}} = 0.047 \text{ keV} \cdot \text{d}^{-1}$ taken into account. The red dashed line represents the best fitting result with the broken power-law model which has three break luminosities (L_1 , L_2 , and L_3). These three vertical dashed lines and shaded areas are the best fitting break luminosities and corresponding uncertainties, respectively. These transitional luminosities suggest the division of the $E_{\text{cyc}}-L_X$ relation into four zones (Regions I, II, III, and IV) with different types of the $E_{\text{cyc}}-L_X$ correlation^[75]

changes from negative to positive at L1 (from Regions I to II), remains flat after L2 (Region III) and finally turns into negative across L3 (Region IV). Apart from the positive and negative correlations as predicted by the current models at high luminosities, the new components of Region III located between L2 and L3, and Region I at below L1 definitely put new/strong constraints on the current popular models. Specifically, the flat Region III may suggest a smooth transition between modes dominated by radiation and Coulomb pressures in deceleration process of the infalling material after the shock. Moreover, if Region I below L1 could be responsible to the gas shock dominated mode, where a pencil beam is expected, the continuous evolution of E_{cyc} can put for the first time a very strong constraint on the evolution manner of the emission site. For example, Figure 17 requires that, if the CRSF in Region I is produced from the accretion mound on the surface of the NS, the column in fan-mode in Region IV should have a size comparable to the mound since all the regions (I–IV) share the similar variation range of E_{cyc} .

Other CRSF research progresses since 2023 are summarized in what follows. From two observations of the NSXRB system Cen X-3 performed by Insight-

HXMT during 2017 and 2018, Yang *et al.* reported for the first time both fundamental and harmonic lines, located at 27 KeV and 48 keV in the energy spectrum, respectively^[76]. However, during the Insight-HXMT observations of this source in 2022, only the fundamental line of 29 keV was detected with a weak correlation against the luminosity^[77]. These may denote some episodes that the source has experienced different evolutionary behaviors. For the Be XRB system XTE J1946 + 274, Ashwin Devaraj *et al.* analyzed the AstroSat and Insight-HXMT observations during the rising and peak phases of the 2018 outburst, respectively. They confirmed for the first time the previously debated reports on the existence of CRSF around 40–50 keV (Figure 18), and clarified its dependences on the luminosity and pulse phase^[78]. These discoveries contribute the complementary patches which help to build a complete scenario for understanding the E_{cyc} -luminosity correlation.

3.6 Type-I Burst Probe

The spectral state transitions are almost the unique processes for understanding the basic elements of the BHXR systems: disk, corona and jet, *etc.* Particularly, the nature of the corona still remains a puzzle since in definition it is a radiation-inefficient hot flow which is in

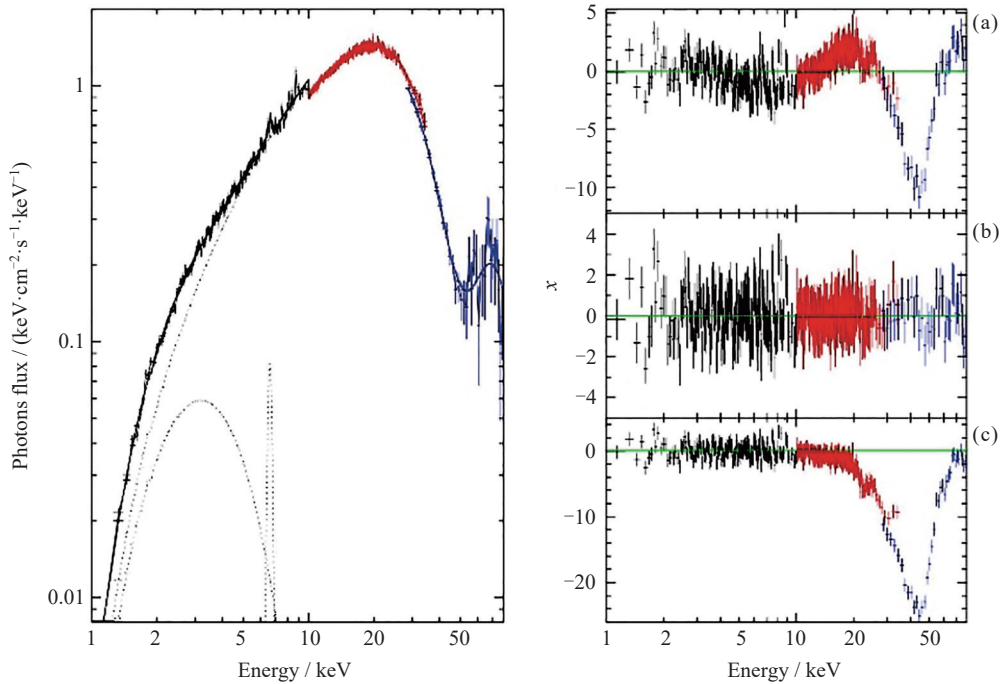


Fig. 18 Unfolded spectrum of the HXMT 2018 observation with the best fit of NPEX model is shown on the left panel. The right panel shows the residues^[78]

principle hard to be observed directly unless with seed photons lighting it up. However, the intrinsic properties of the corona cannot be readily recovered from an outburst since the state transitions and the recovery of the corona in the initial and delayed LHSs are governed by the viscous time scales of the disk accretion which may not be intrinsic to the corona itself. Type-I burst is the explosive thermal nuclear burning on the surface of NS and can serve as a probe to corona due to its well known properties of location, luminosity, spectrum and duration. It provides an intense shower of the soft X-rays which can be reminiscent to the effect of the accretion rate changes of the disk and hence the possible influences on the evolution of the corona and probably as well the jet. In fact, such a burst probe was adopted to investigate the accretion environment and a series of burst-induced effects were discovered: during type-I burst, the accretion rate can be enhanced^[79]; the corona can be cooled and recovered with a few tens of seconds^[80]; jet can be produced by the type-I burst^[81].

Prior to the launch of Insight-HXMT, the persistent emission from the corona was observed to have shortage during type-I burst *via* stacking tens of burst samples due to the relative small detection area of the previous hard X-ray missions, *e.g.*, RTXE (see the series of reports from Chen *et al.*^[82] and Ji *et al.*^[83], *etc.*). Obviously, Insight-HXMT demonstrated its power and advantage to this end, initially *via* detecting a burst-induced corona cooling event from a single normal type-I burst in the early Insight-HXMT phase^[84]. Recently more studies were carried out on the burst influences on the corona and jet by observing the spectrum of the persistent emission at hard X-rays, as are introduced in what follows.

Wang *et al.* found that the newly discovered millisecond pulsar MAXI J1816-195 shows a rare likely clocked-burst behavior outburst observed by Insight-HXMT in 2022^[85]. Chen *et al.* investigated the energy spectrum of the hard X-ray deficit during these bursts, and reported that the energy spectrum for Deficit Fraction (DF) of the hard X-rays becomes more or less saturated at higher energies^[86] (Figure 19). DF was obtained in other systems observed by Insight-HXMT: in 4 U 1608-52 the hard X-ray shortage remains around 50% of the persistent emission at energies above 50 keV^[87] (Fig-

ure 20), while in 4 U 1636-536 it shows a positive correlation between DF and energy^[88] (Figure 21). We speculate that these results may be relevant to how a hybrid corona/jet population contributes the persistent emission at hard X-rays, where the jet is relatively harder to be cooled down by the burst shower than the corona. The outburst of MAXI J1816-195 presents the accretion-produced pulsation originated around the magnetic pole of the NS harbored in this system and, during the clocked-burst events, Ji *et al.* found that the strength and profile

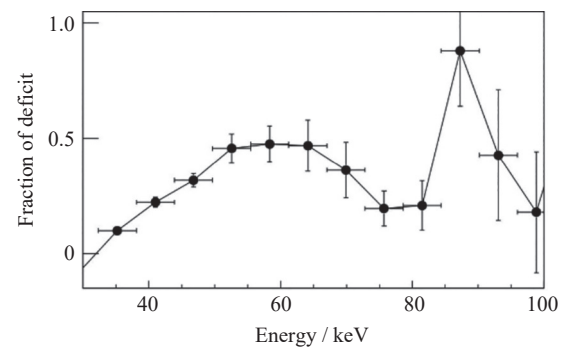


Fig. 19 Deficit fraction versus energy during the bursts detected by HE in MAXI J1816-195^[86]

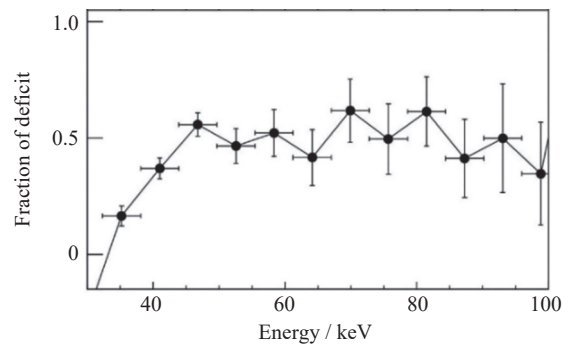


Fig. 20 Deficit fraction versus energy during the bursts detected by HE in 4 U 1608-52^[87]

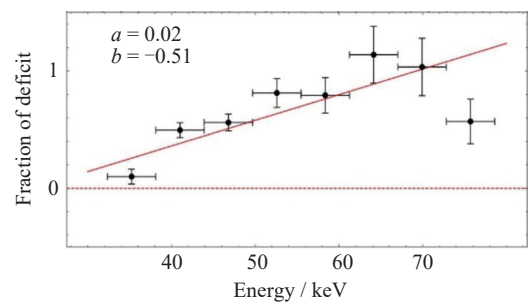


Fig. 21 Deficit fraction versus energy during the bursts detected by HE in 4 U 1636-536^[88]

of the pulsations remained unchanged, which means that the accretion matters channeled onto the magnetic poles are not influenced by the explosive burning on the NS surface^[89]. They therefore suggested that the interaction with burst photons can be used as a direct diagnostic to distinguish contributions from the hot plasma near polar caps and the corona around the accretion disk, which are highly degenerate in their spectral shapes. Yan *et al.* conducted an analysis of 45 bursts observed from 4 U 1636-53 and they observed an inverse correlation between the maximum increase of the persistent component during the non-PRE bursts and the persistent emission prior to the bursts^[90]. By analyzing the profiles of the Photospheric Radius Expansion (PRE) events during the outbursts of 4 U 1730-22, Lu *et al.* proposed the pure helium as the fuel and updated the source distance^[91].

3.7 Galactic Plane Scanning Survey

Galactic plane survey is one of the core sciences of Insight-HXMT. Roughly 20%–30% of the Insight-exposure was spent on the Galactic plane survey in order to investigate the variability of the X-ray sources. A Galactic region enclosed with $0^\circ < l < 360^\circ$, $-10^\circ < b < 10^\circ$ is subdivided into small patches on which the survey is carried in a scanning mode. The schematic diagram of the scanning method of a small sky area is shown in Figure 22. The source information can be extracted from the scanned data with either fitting the triangle response of the telescope as adopted in Wang *et al.*^[92], or a modified direct demodulation method which can handle the variable source *via* setting in the detector response matrix with an additional column dedicated to the target

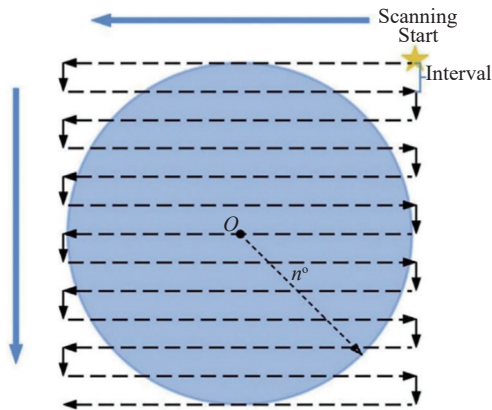


Fig. 22 Schematic diagram of the scanning method of a small sky area^[92]

source^[93]. The preliminary results from the Insight-HXMT Galactic plane survey were reported by Sai *et al.*^[94], and Wang *et al.*^[92] presented the long-term monitoring results of Insight-HXMT in the first 4 years of its Galactic plane scanning survey (GPSS). It is shown that, the 4-year limit sensitivities at main energy bands can reach $8.2 \times 10^{-12} \text{ erg} \cdot \text{s}^{-1} \cdot \text{cm}^{-2}$ (2–6 keV), $4.21 \times 10^{-11} \text{ erg} \cdot \text{s}^{-1} \cdot \text{cm}^{-2}$ (7–40 keV), and $2.78 \times 10^{-11} \text{ erg} \cdot \text{s}^{-1} \cdot \text{cm}^{-2}$ (25–100 keV). More than 1300 sources have been monitored in a wide band (1–100 keV), of which 223 sources have a signal-to-noise ratio greater than 5. By combining the GPSS data of Insight-HXMT and MAXI, long-term light curves established are used to study the flux variabilities at different energy bands for 223 bright sources. The first Insight-HXMT catalogue of X-ray sources of different types was released and the detailed investigations with parameters, *e.g.*, the hardness ratio and variability *etc.*, show distinguished differences between different source types, in line with the specific intrinsic properties known for each of the individual source types^[95].

3.8 Isolated Pulsars

Isolated pulsars are mainly used for in-orbit timing calibrations and Insight-HXMT spent over 4 M_s on Crab observations. The long-term evolution of Crab as monitored by Insight-HXMT demonstrated a correlation in the form of $L_x \propto L_{sd}^\alpha$ between the pulsed flux L_x and the spin down flux L_{sd} , where α is constant across the Insight-HXMT energy band. The hard X-ray flux evolution shows that the performance of HE, such as effective area, keeps stable^[96]. As an exploration of the non-thermal emission, a sample of MeV pulsars observed by different high energy telescopes including Insight-HXMT were studied with findings of a harder spectrum and a higher radiation efficiency in 0.3–10 keV energy bands compared to the Fermi pulsars. Such a difference may be attributed to either the different viewing angle of the spin axis or the different inclination angles of the magnetic axis^[97]. Isolated pulsars can also be observational targets for navigation; a review and an updated research were given by Wang *et al.*^[98,99].

3.9 Fast Radio Bursts

A Fast Radio Burst (FRB) was first reported in 2007^[100] with characteristics of bright millisecond radio pulses, random arrival direction and time, some repeating and even periodic, but remained a puzzle with counterpart or

radiation at any other wavelengths not known until 28 April 2020, when an identification the counterpart of the FRB 200428 with a magnetar SGR J1935+2145 was reported by Insight-HXMT^[101]. A series of studies were carried out since 2023 based on the Insight-HXMT observation on this unique FRB-SGR association event and the bursts from SGR J1935+2145 monitored by Insight-HXMT and GECAM *etc.*

Refined information was reconstructed by Ge *et al.* from Insight-HXMT observations of the flares from FRB200428, with improved temporal and spectral analyses. Accordingly, the measurements for the properties of the accompanied X-ray bursts were updated^[102]. In Cai *et al.*^[103], 75 X-ray bursts produced by magnetar SGR J1935+2145 during an active period in 2020 were published. The cumulative distributions of the parameters of this burst sample can be interpreted by a self-organizing criticality theory, supporting a possible magnetic reconnection scenario in magnetars^[104]. With the same sample, the phase distribution of the bursts is found to correlate with the type of the burst spectrum^[105]. To account for the light curves and spectra measured by Insight-HXMT in association with the FRB 200428, Xie *et al.* proposed a model that the FRB-associated X-ray bursts originate from QED magnetic reconnections^[106]. As shown in Figure 23, individual magnetic islands will be created in the magnetosphere due to magnetic reconnections, where the QED will take effects on the particle acceleration and cooling. With such a scenario, adjust-

ments of the QED parameters can recover the light curves and energy spectra observed by Insight-HXMT (Figure 24). About five months later, radio pulses from SGR 1935+2154 were detected by FAST, with profiles anti-aligned with the X-rays. The observed differences in phase distributions of the radio and X-rays suggest fixed emission region for radio but random for X-rays^[107].

SGR J1935+2145 was active in 2020–2022, and hundreds of bursts were detected by Insight-HXMT, GECAM Fermi/GBM. With this burst sample, Xiao *et al.* carried out a series of studies. They found that the Minimum Variation Timescale (MVT) of the X-ray bursts associated with FRB 200428 is significantly longer than that of most bursts and implies its special radiation mechanism^[108]. No obvious QPO exists for the sample but for some individual bursts a feature of 40 Hz is hinted to resemble the X-ray burst associated with FRB 200428^[109]. About 61 percent bursts from SGR J1935+2145 have spectral lags that are linearly dependent on the photon energy^[110]. The differential and cumulative distributions for the parameters of MVT and spectral lag follow a power law shape. The distributions of fluctuations in both parameters follow the Tsallis q -Gaussian distributions^[111], and the q values are consistent for different scale intervals, thus indicating a scale-invariant nature for both parameters^[112].

3.10 Gamma-Ray Bursts

Gamma-Ray Bursts (GRBs) are among the core sciences of Insight-HXMT and there are normal mode and

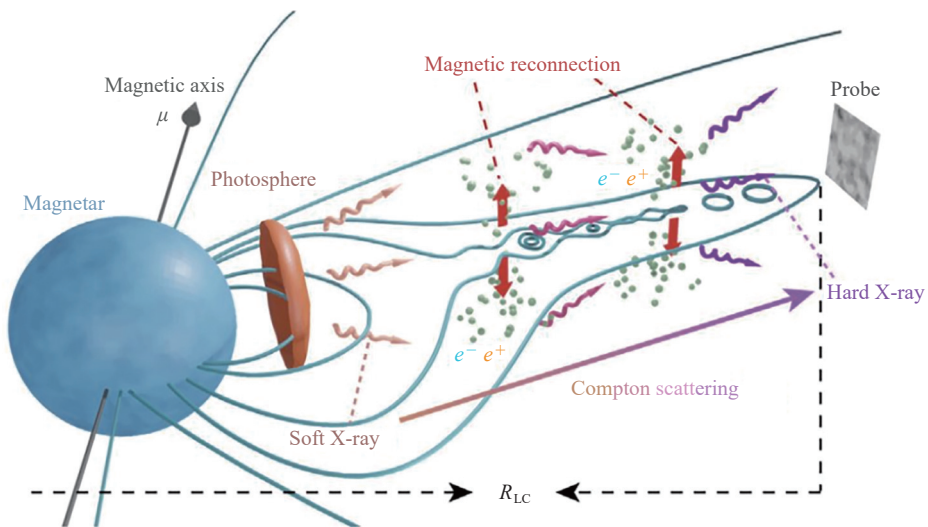


Fig. 23 Schematic of the proposed origin model for the FRB 200428-associated X-ray burst^[106]

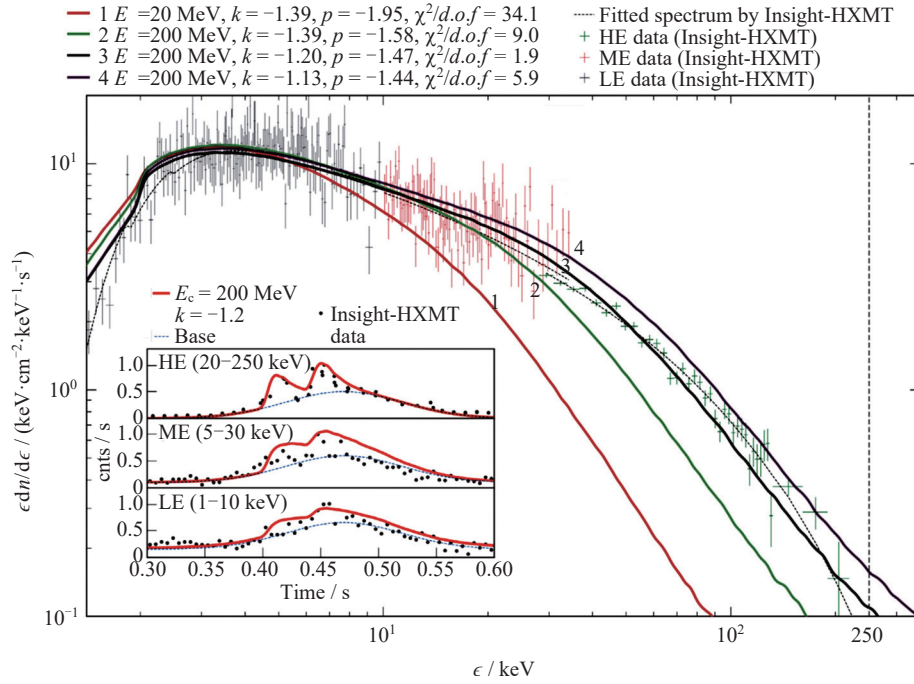


Fig. 24 Insight-HXMT X-ray light curves and energy spectrum fitted by the model configured in a QED scenario^[106]

GRB mode for GRB observations. For the latter, the high electric voltage of PMTs will be lowered so that the band passes for both NaI and CsI detectors can be promoted to higher energies and the corresponding FoVs can be enlarged to more than half of the whole sky unblocked by the earth. Particularly, CsI detectors can cover energies from 200 keV up to several MeV with a rather large detection area. The first Insight-HXMT GRB catalogue was released^[113]. The capability of Insight-HXMT GRB detection is about 80 events per year. The brightest GRB 221009 A was detected and the joint GECAM and Insight-HXMT observations present almost unique data covering the main peak phases by the unsaturated detections of GECAM and the precursor/afterglow jointly by Insight-HXMT.

The unconventional precursor of GRB 221009 A detected by Insight-HXMT may provide a peculiar case study for GRB precursor phenomena. A two-stage collapsar scenario is proposed by Song *et al.*^[114] as the most likely origin for GRB 221009 A: the jet for the precursor is produced during the initial core-collapse phase, and should be weak enough not to disrupt the star when it breaks out of the envelope (relevant to the gap after the precursor), so that the fallback accretion process could continue to form the main GRB phase (Figure 25).

Zheng *et al.* analyzed the energy spectrum of the early afterglow observed by Insight-HXMT, GECAM and Fermi/GBM. They found that the spectrum of the early afterglow in 0.02–20 MeV can be well described by a cutoff power law with an extra power law that dominates the low- and high-energy bands, respectively. The spectral index changed at time around the jet break^[115]. The optical afterglow of GRB 221009 A was investigated by Kann *et al.* together with the contemporary Insight-HXMT and Swift-XRT data. The results they derived suggest that the observed afterglow is produced by synchrotron radiation at the forward external shock during the deceleration of a top-hat relativistic jet by a uniform medium, with a tension between the observed temporal and spectral evolution^[116].

Together with the Insight-HXMT GRB catalogue, the GRB catalogues built so far from different detectors make it feasible for comprehensively investigating the GRB properties by studying their fine structures. Camisasca *et al.* took the catalogues produced from Insight-HXMT and Swift/BAT, and used the peak detection algorithm *mepsa* to identify the shortest pulse within a GRB light curve. They confirmed that short GRBs have significantly shorter MVTs than long GRBs, which is important because it provides a new clue con-

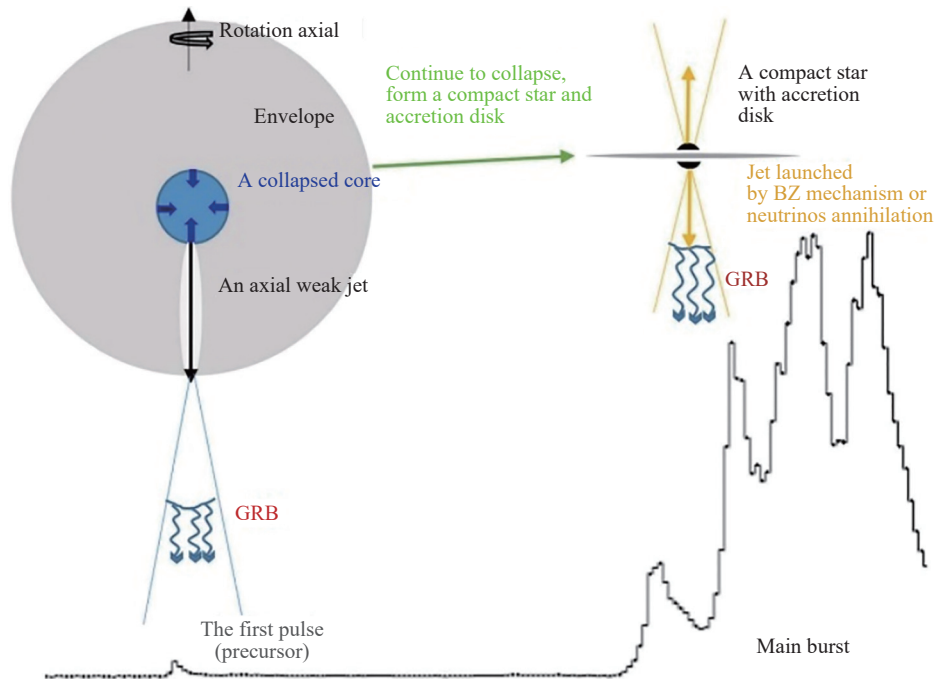


Fig. 25 A scenario for the “two-stage” model of precursors for GRB221009 A^[114]

cerning the progenitor’s nature^[117]. With two more catalogues from CGRO/BATSE and BeppoSAX/GRBM, Guidorzi *et al.* analyzed the stochastic process by extracting and modelling for the first time the distribution of the number of peaks within a GRB profile, and grouped the long duration GRBs into two classes: peak poor and peak rich, which account for 80% and 20% of the total GRB sample, respectively. They associated the class of peak-rich GRBs with the presence of sub-second variability and suggested two different regimes for the inner engines to release energy^[118].

4 Summary and Outlook

The rich scientific results of Insight-HXMT since 2023, as highlighted in this paper, show the scientific capability and power of Insight-HXMT. Among these results, one notices that the potential breakthroughs were accomplished with either the multi-wavelength campaigns or the development of new analysis techniques. Actually, these may serve as the main interests in future to better use Insight-HXMT, which is open to the international community for observations and data archives. The mission currently is still operating quite well and will be available to the world-wide community for years to come. Please visit hxmt.org for further information

about Insight-HXMT and downloading data.

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