Insight-HXMT results on accreting X-ray binaries

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on behalf of the *Insight*-HXMT team
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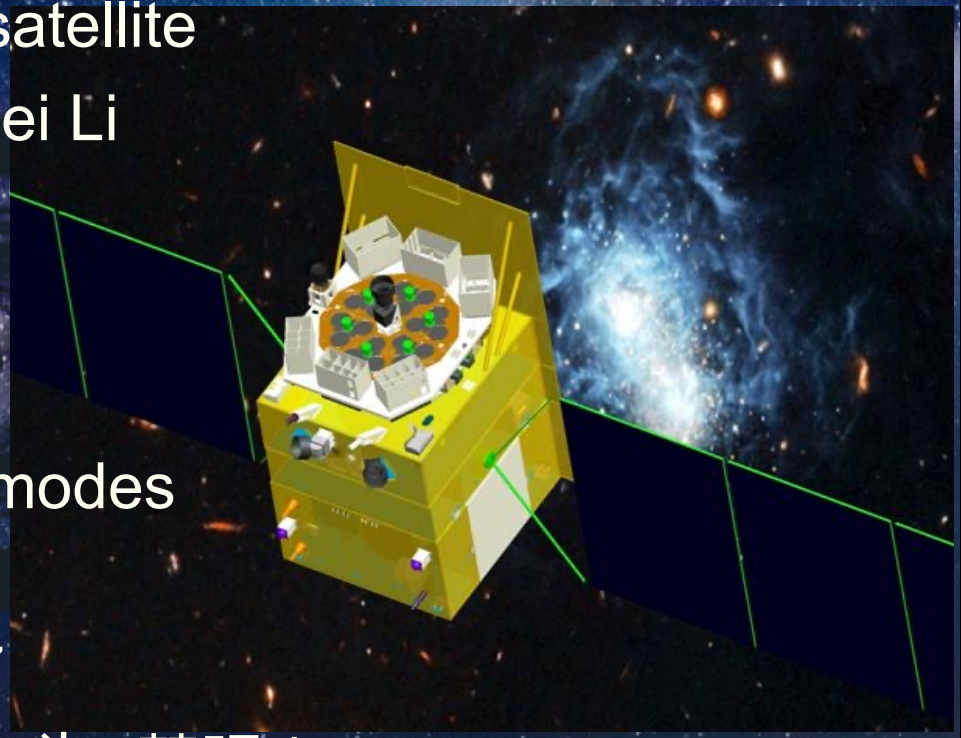
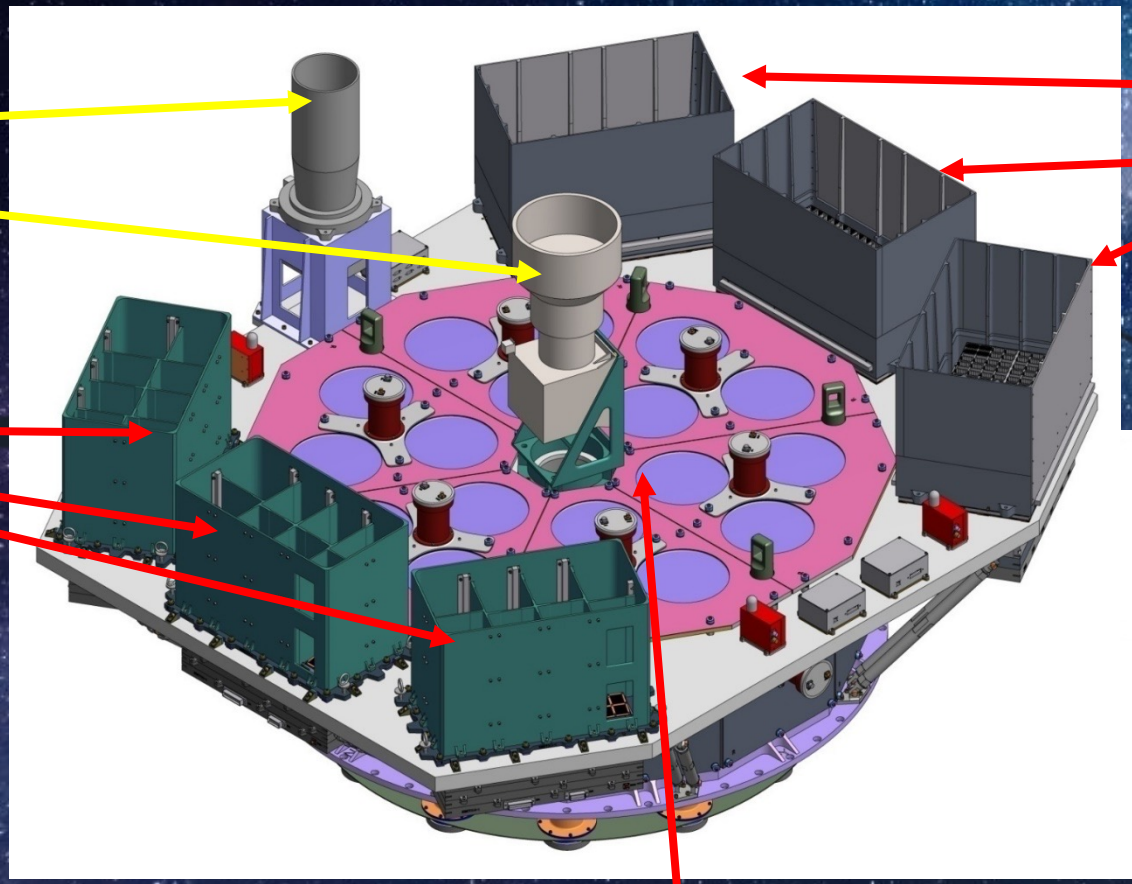
Hard X-ray Modulation Telescope (HXMT) satellite
硬X射线调制望远镜（HXMT）卫星

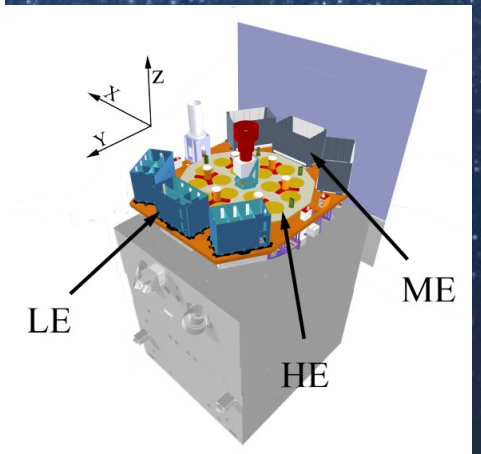
- China's 1st X-ray astronomy satellite
- Proposed in1993 by Prof. Tipei Li
- Selected in 2011
- Total weight ~2500 kg
- Cir. Orbit 550 km, incl. 43°
- Pointed, scanning and GRB modes
- Designed lifetime 4 yrs
- Launched on June 15th, 2017
- Dubbed "*Insight*"（发射后命名为 "慧眼"）



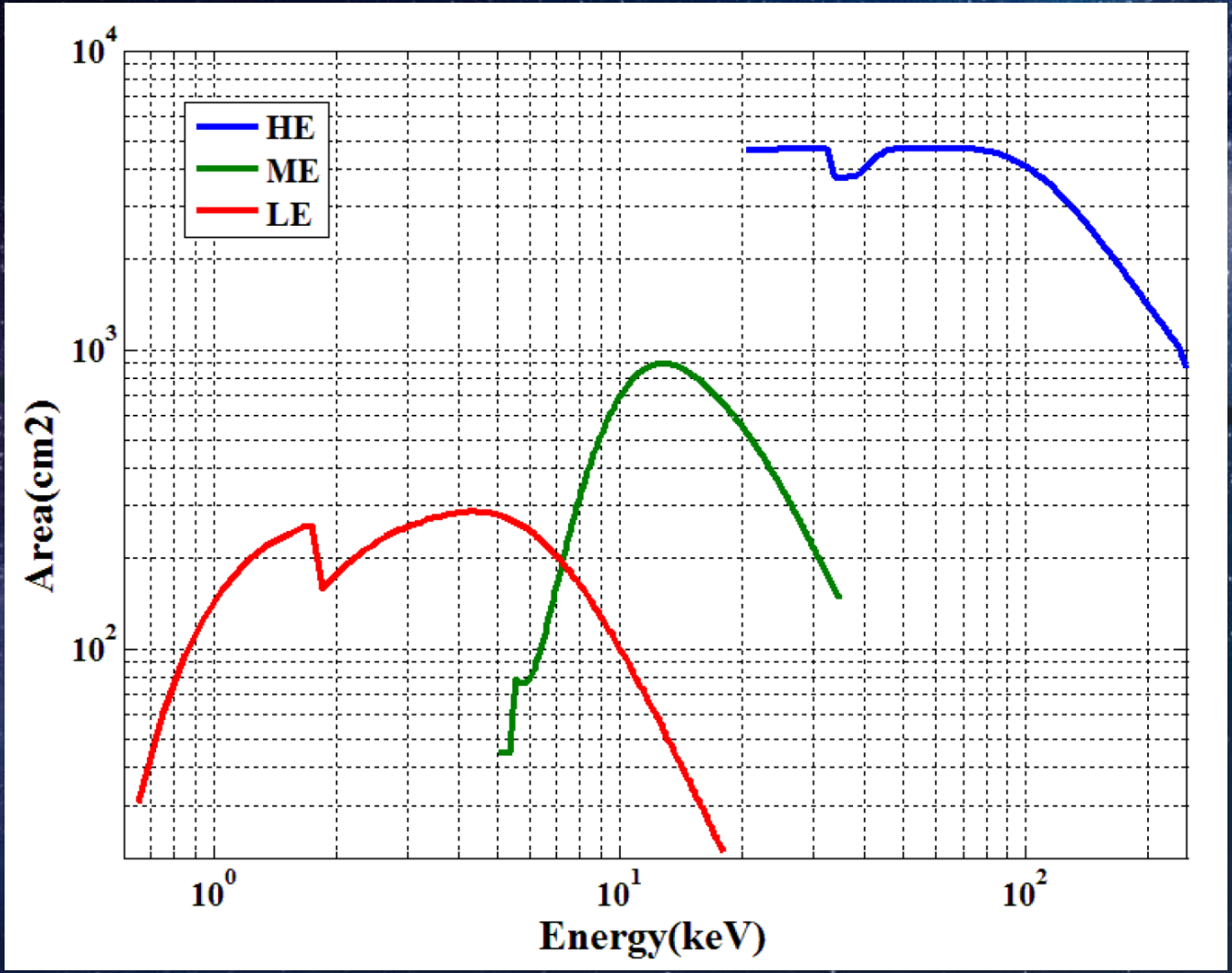
Zhang, S.-N. et al. Overview to the Hard X-ray Modulation Telescope (Insight-HXMT) Satellite. Science China Physics, Mechanics, and Astronomy 63, 249502 (2020)

Science payload科学载荷

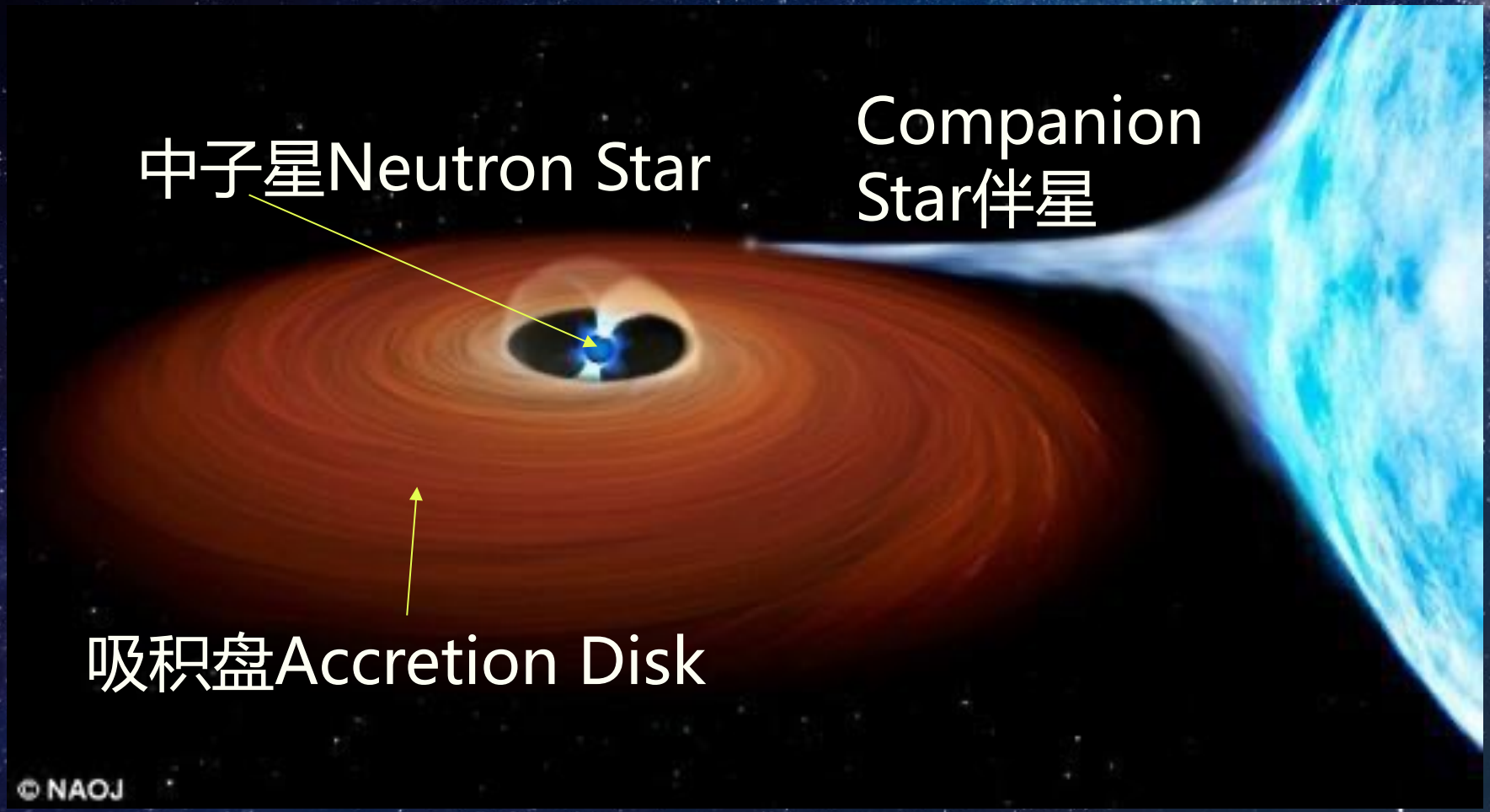




Effective area有效面积



Extremely Complex Interactions in NSXBs
“吸积”中子星和吸积盘复杂的相互作用

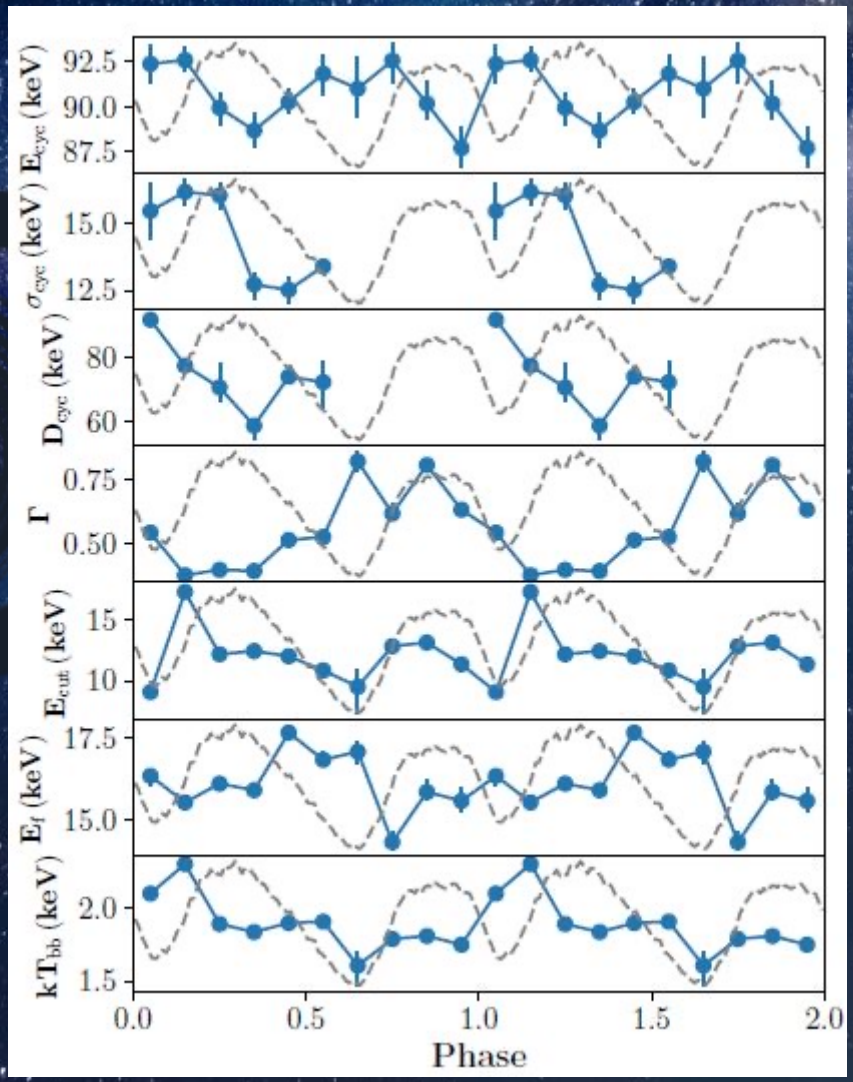


High-E Neutron star cyclotron absorption line
“慧眼”显著探测到高能量中子星回旋吸收线

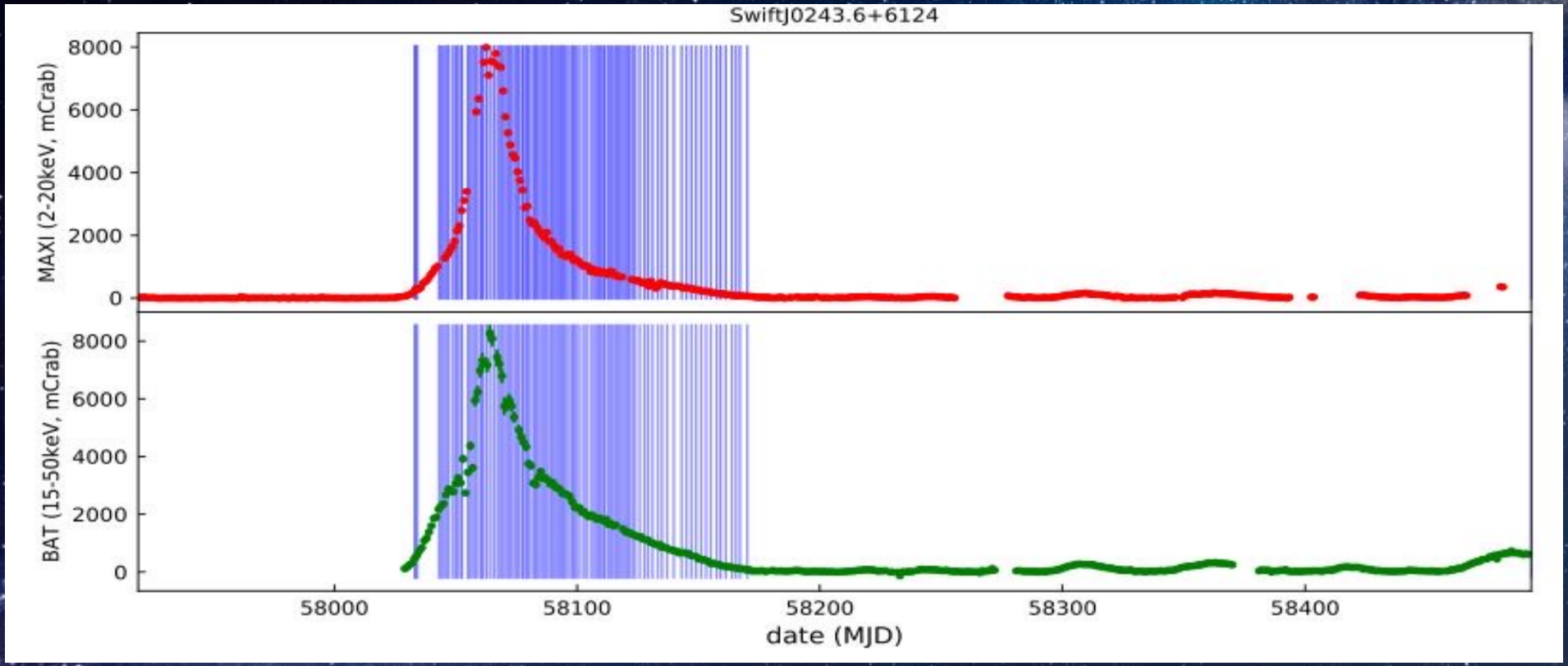
- GRO J1008-57：~90 keV → highest *B* directly measured in the universe ~10^{13}, ~ 4σ with NuSTAR & Suzaku ~79 keV
- 4 HXMT observations ~235 ks ~ 20σ detection

Allow for phase resolved and flux dependent studies

Ge et al. 2020

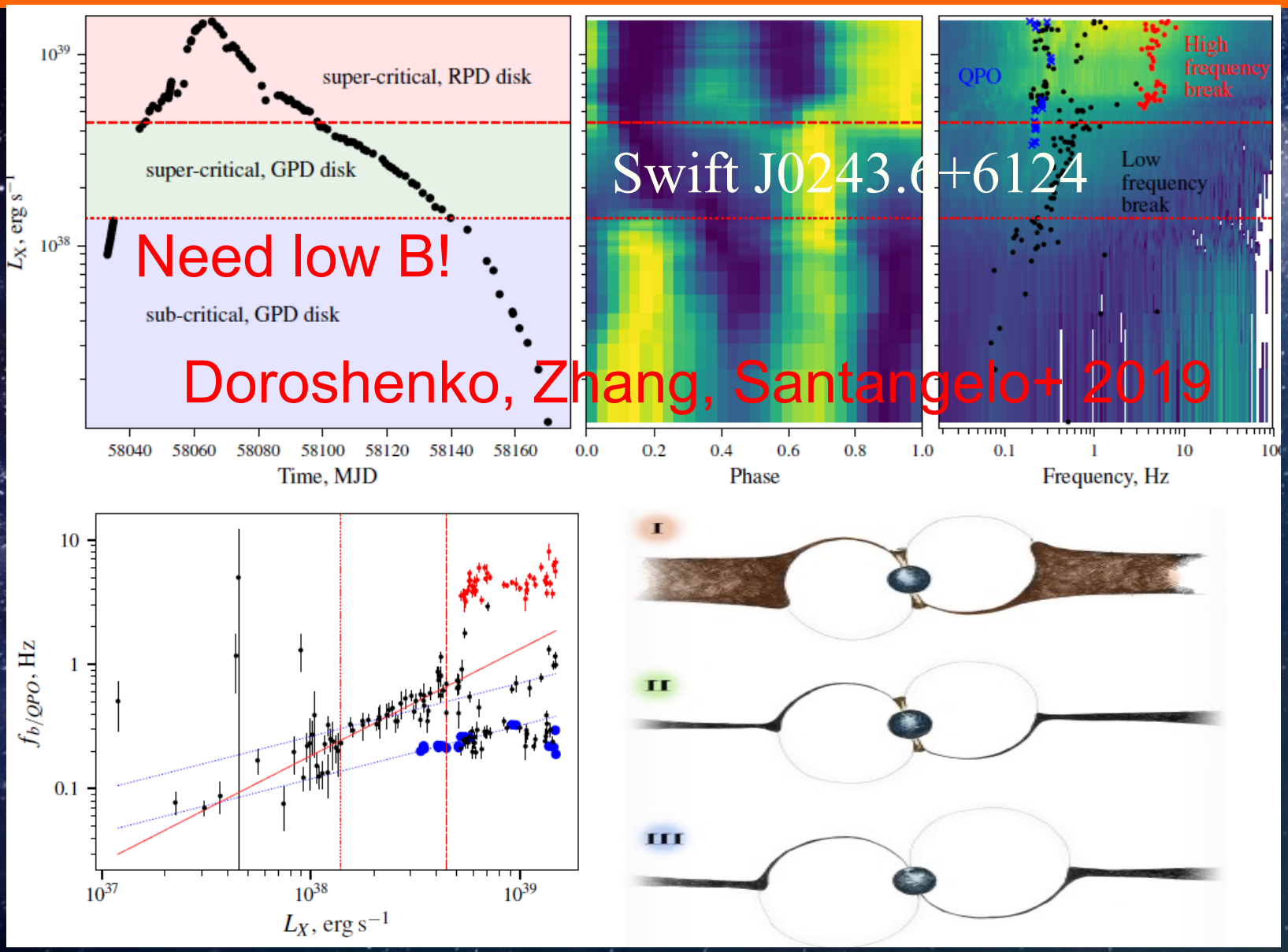


1St Galactic UL NSXB Swift J0243.6+6124

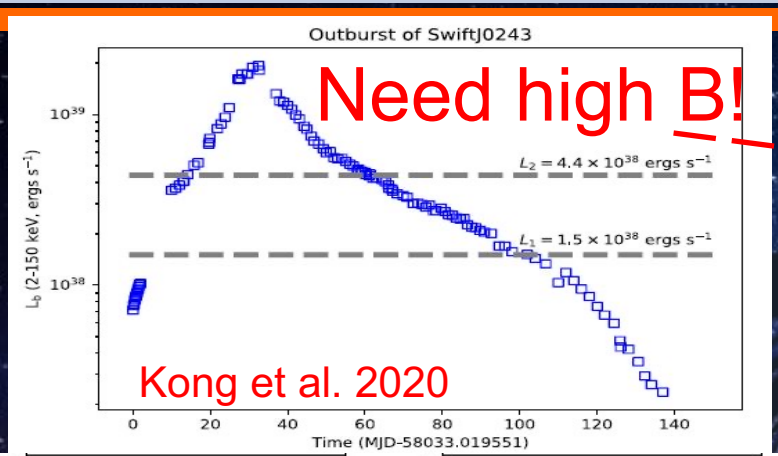


2017 10.3 Swift BAT detected outburst
Insight-HXMT observations：122 pointings；
exposure ~1800 ks

Insight-HXMT discovery of GPD to RPD transition?
“慧眼”发现气压向辐射压转换的吸积盘?

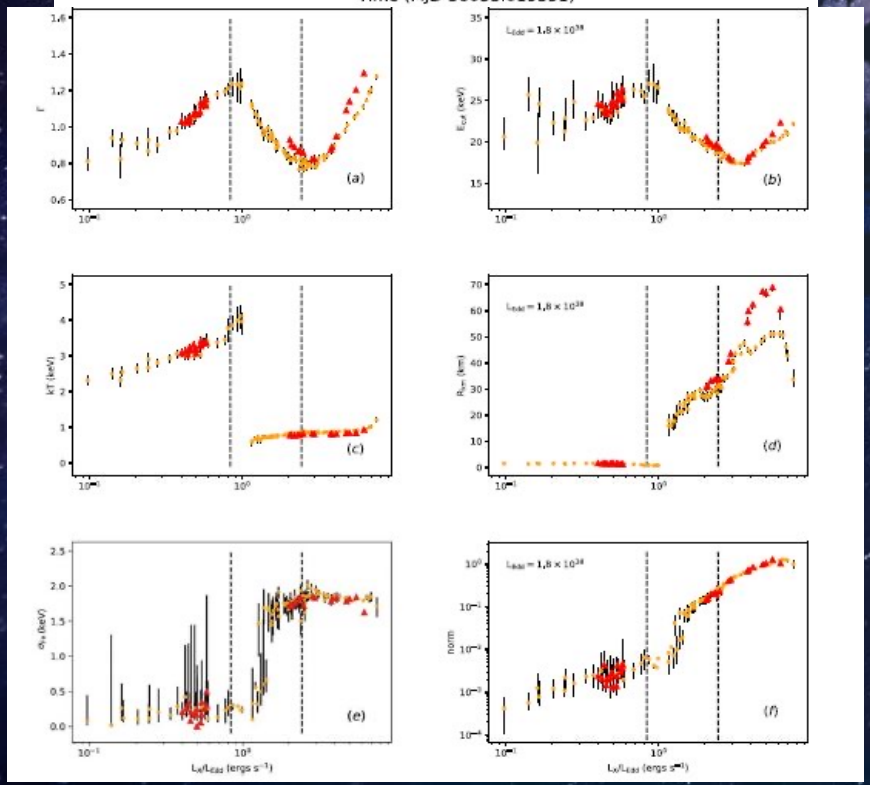


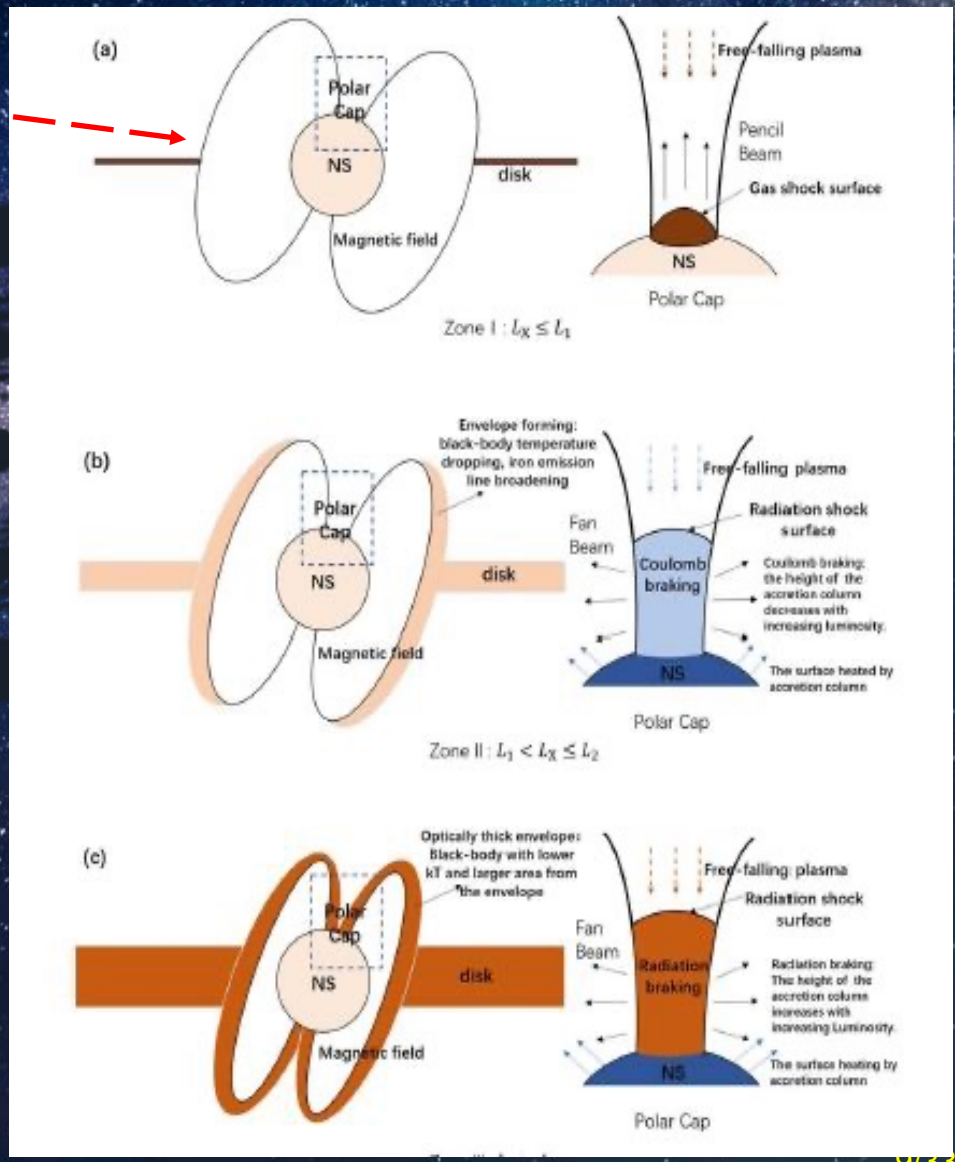
Detailed broad-band spectral evolution



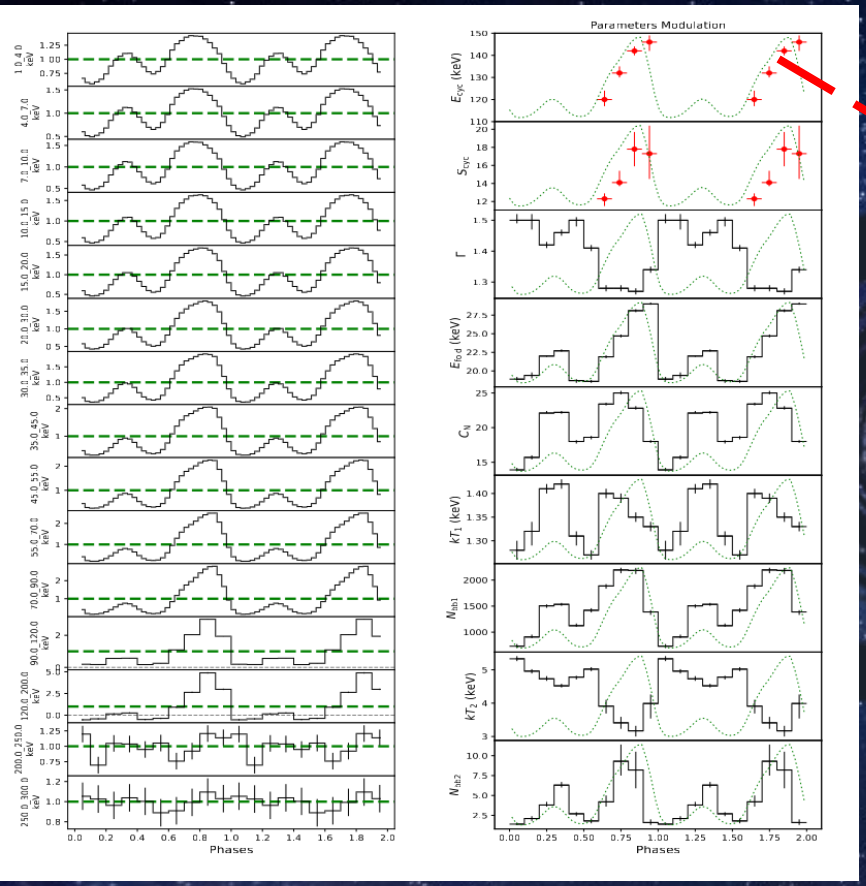
Need high B!

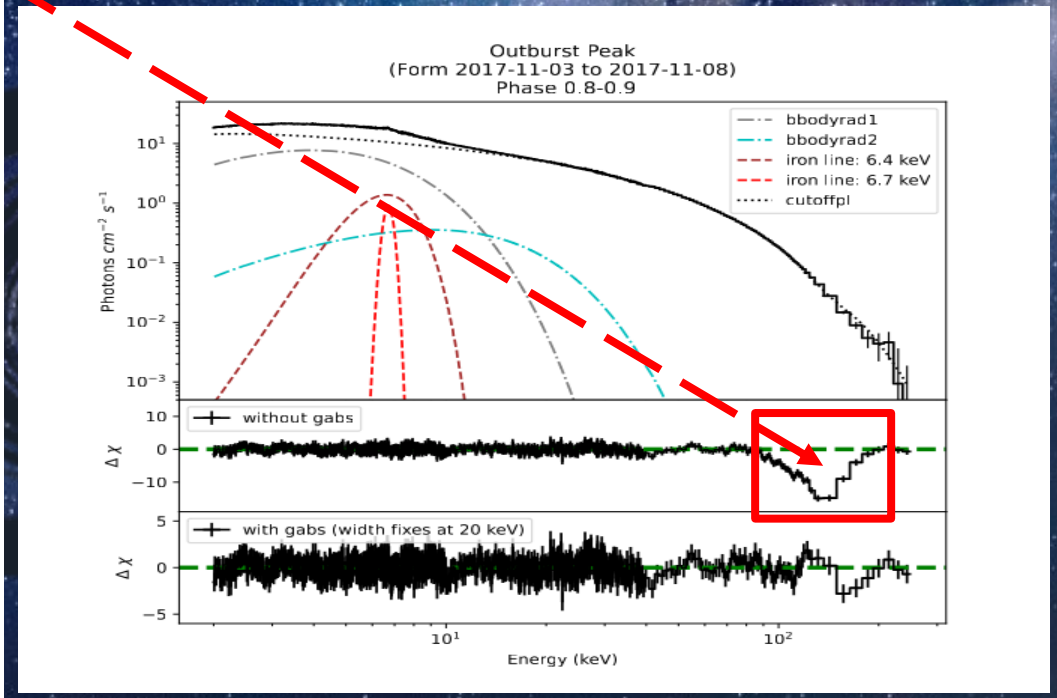
Kong et al. 2020





Highest-E Neutron star cyclotron absorption line
“慧眼”显著探测到最高能量中子星回旋吸收线





1st Galactic ultraluminous X-ray pulsar Swift 0243: 146 keV→1.6x10^{13} G
>> ~10^12 G dipole B-field: evidence for multipole B-field? (Kong+2022)

1A0535+262： 1st complete evolution of CRSF

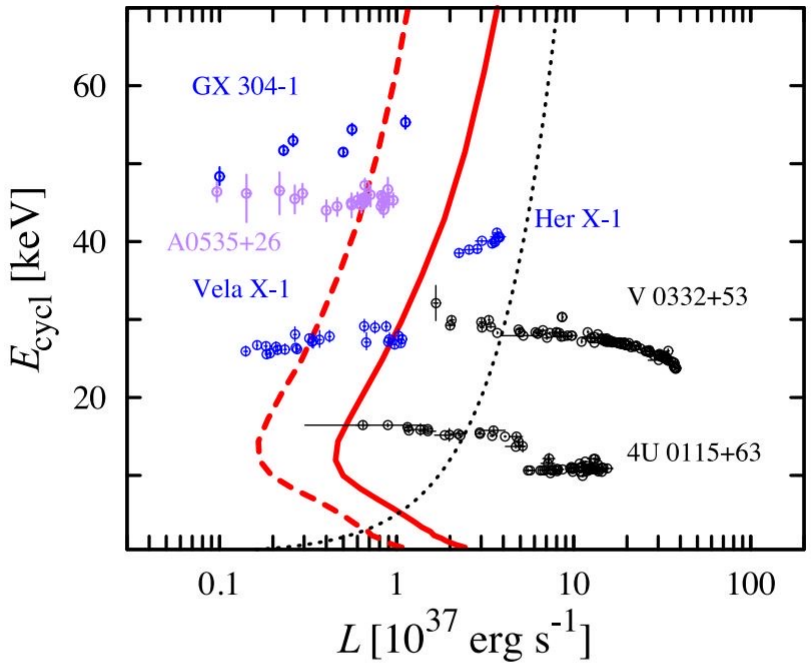
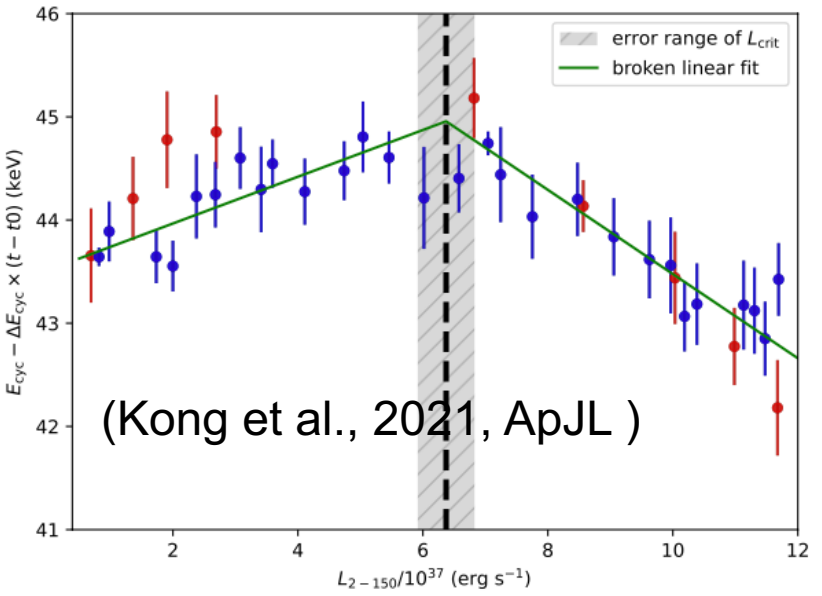
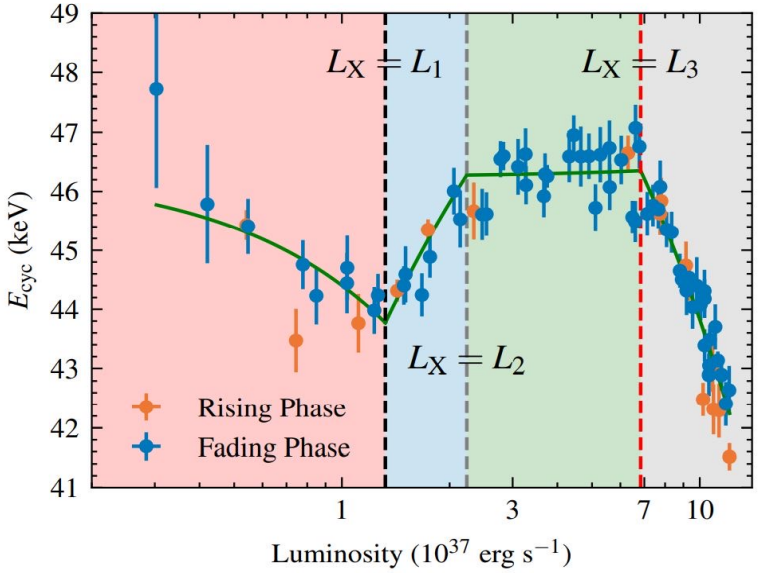


Figure 7. Red solid and dashed curves correspond to the disc-accretion case with different parameters. The dashed curves is for $l_0/l = 0.5$ and mixed polarization (the flux in X- and O-modes are equal), while the solid curve is for $l_0/l = 1.0$ and pure X-mode polarization. In both cases $T_e = 1$ keV, $\Lambda = 0.5$ and $\zeta = 1.5$. The real critical luminosity value lies likely between

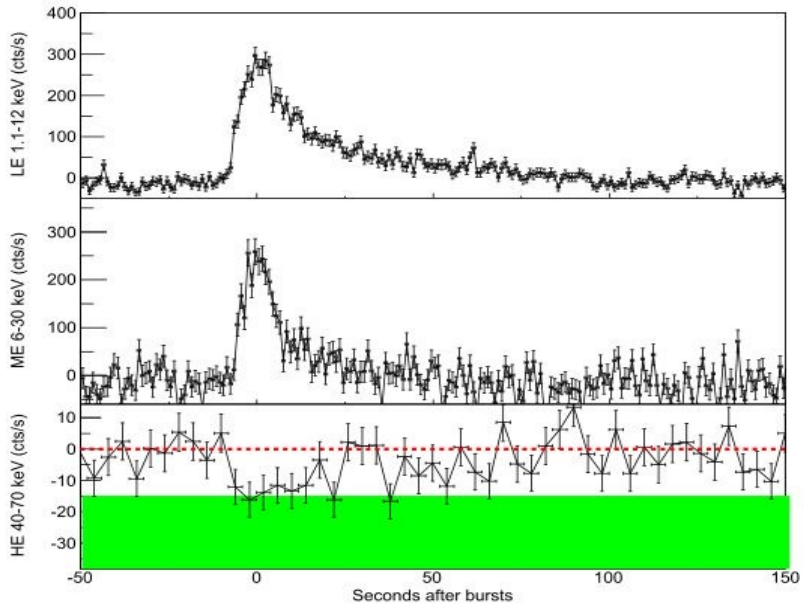
Pulse-pulse analysis: 3 charac. lumi. regions (Shui+ 2023, submitted)



(Kong et al., 2021, ApJL)



Corona cooled by *single* Type-I X-ray burst
“慧眼”发现中子星高温冕被单个X射线暴冷却



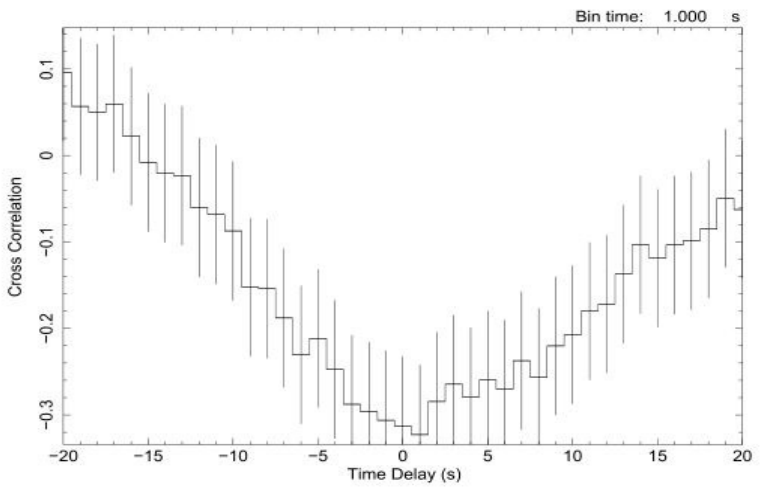
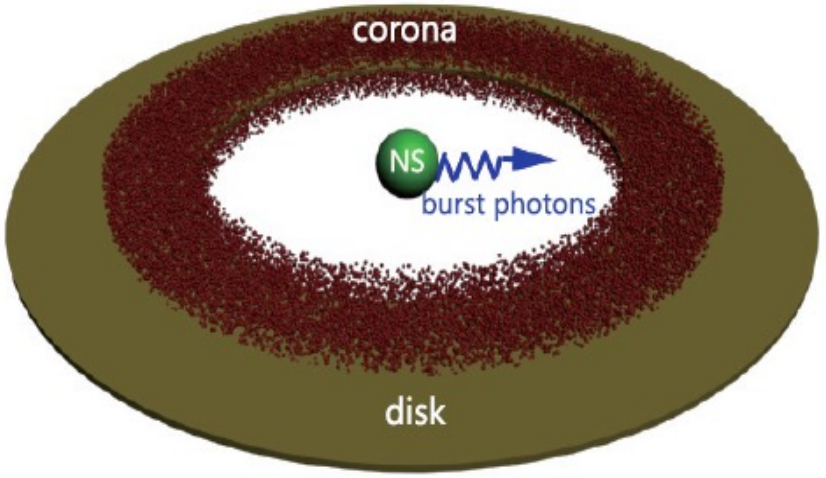


Figure 2. Left panel shows the LE, ME, and HE light curves of the burst in 1.1–12 keV, 5–30 keV, and 40–70 keV, respectively. The time bin for LE and ME is 1 s and HE is 4 s, the green zone in the bottom panel indicates the background level for HE detectors. The right panel shows the cross-correlation between the left panel's LE and HE re-extracted light curves with a time bin of 1 s.

Previously multiple bursts were added to see the cooling, but with Insight-HXMT it's seen in a single burst for the 1st time. 以前需要几十个暴叠加，慧眼单暴就显著看到（4U1636-536, Chen+2018, ApJL)

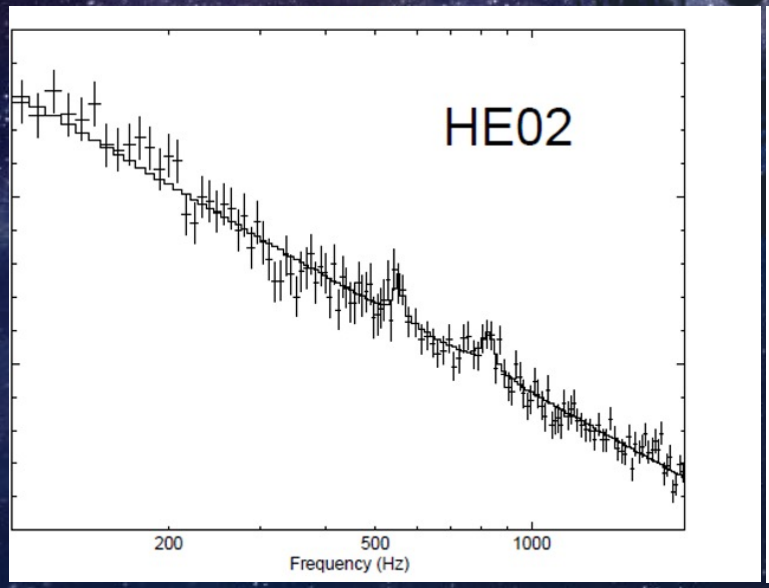


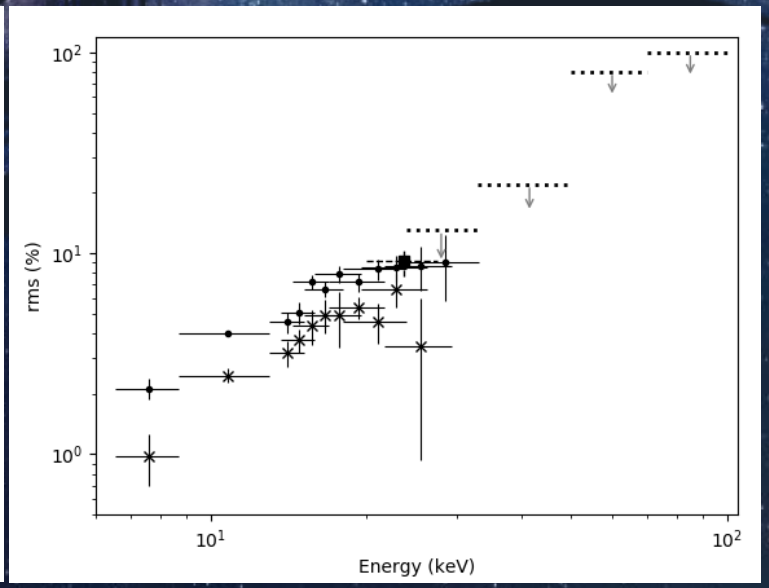
kHz QPOs>20 keV from Sco X-1 with Insight-HXMT
“慧眼”发现最亮X射线源的高能千赫兹准周期振荡

Discovery of Submillisecond Quasi-periodic Oscillations in the X-Ray Flux of Scorpius X-1

M. van der Klis[1], J. H. Swank[2], W. Zhang[2], K. Jahoda[2], E. H. Morgan[3], W. H. G. Lewin[3], B. Vaughan[4], and J. van Paradijs[5]

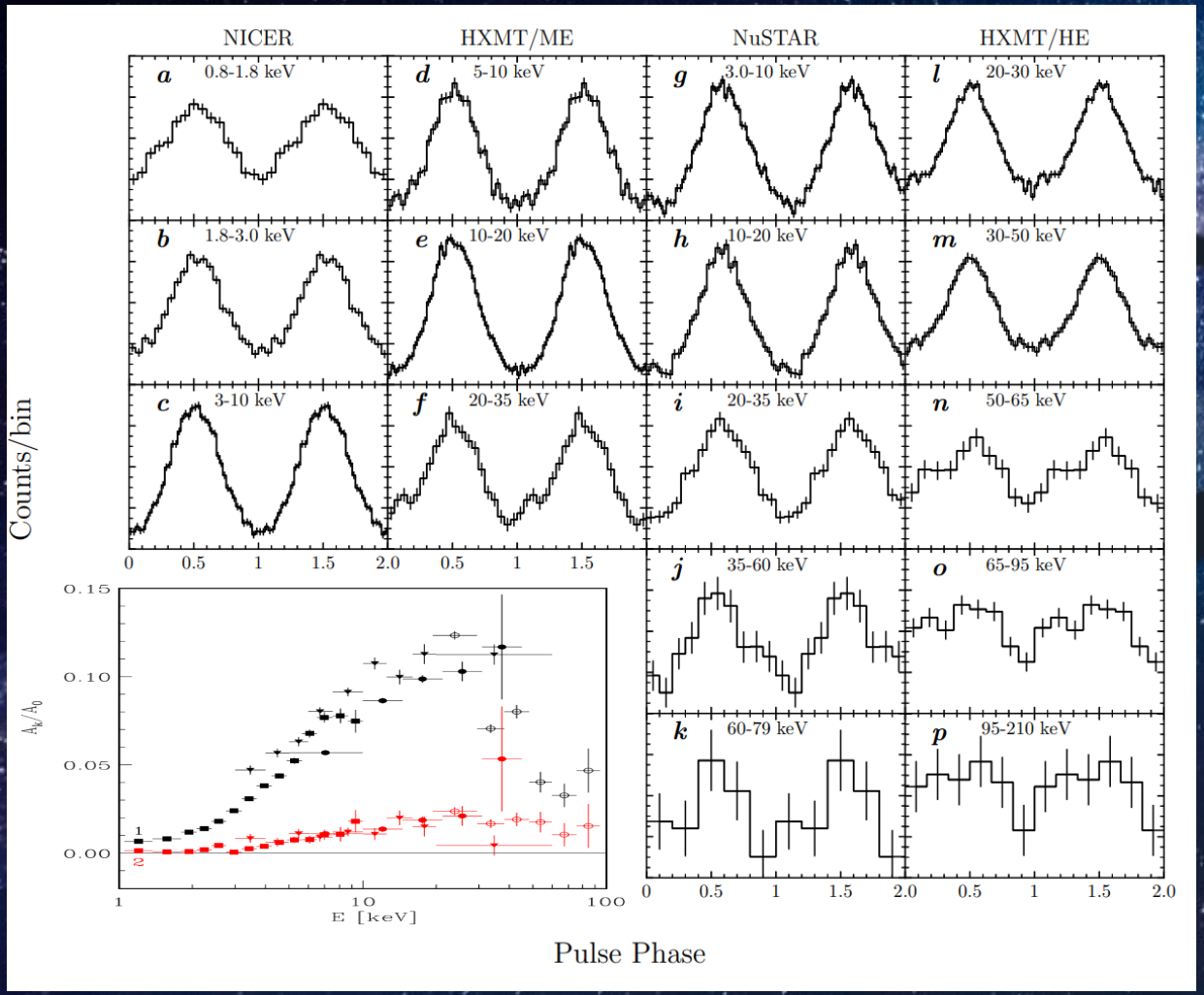
The Astrophysical Journal Letters, Volume 469, Number 1





Insight-HXMT on Sco X-1 (Jia+ 2020, JHEAP, arXiv:1910.08382)

Highest-E pulsation from ms pulsar MAXI J1816-195



Li+2023, ApJ

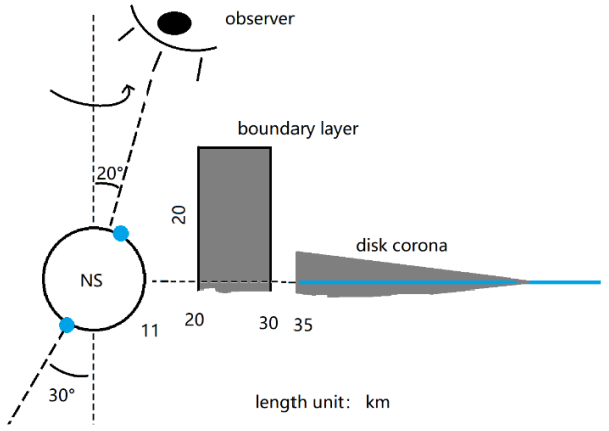


Figure 4. The geometric model of MAXI J1816-195 obtained by MC simulations. The physical dimension of NS, boundary layer and accretion disk are marked in the figure in length unit of km.

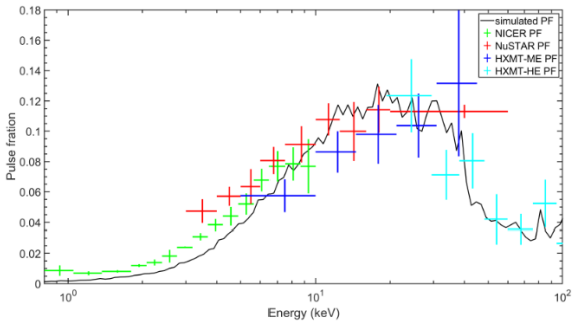
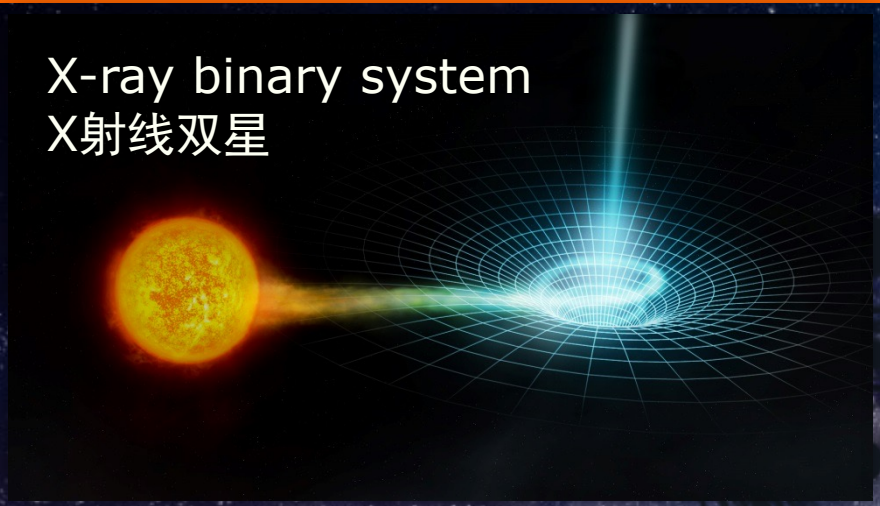


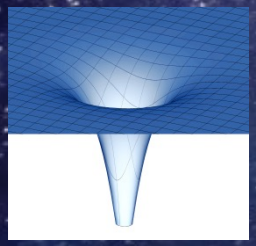
Figure 6. The PF of MAXI J1816-195 as a function of energy. The observed PF data of NICER, NuSTAR and Insight-HCMT corresponds to the crosses, and the PF of simulation result is shown by the black solid line.

You+, in prep.:

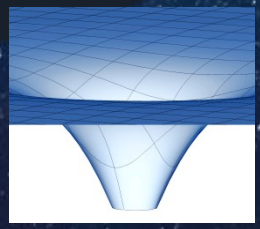
Extreme Gravity Near Black Holes
黑洞附近存在宇宙最强引力



X-ray study covers wide mass range in uniform setting



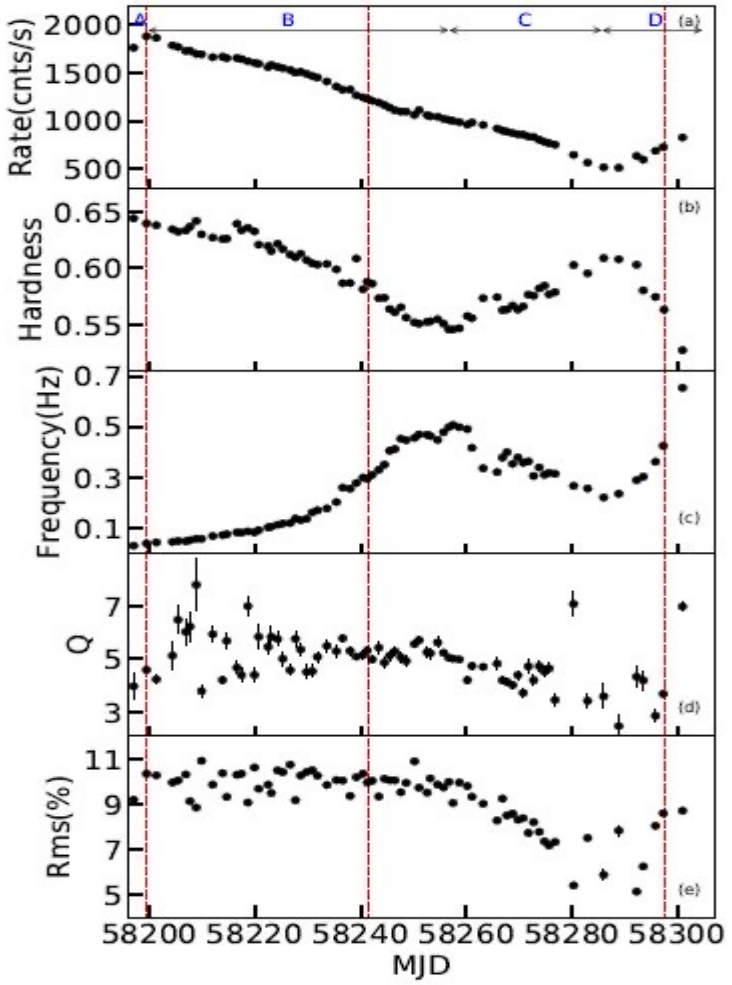
Stellar mass black hole
(or neutron star)
Strongly curved spacetime.
(10^{16} times Solar)

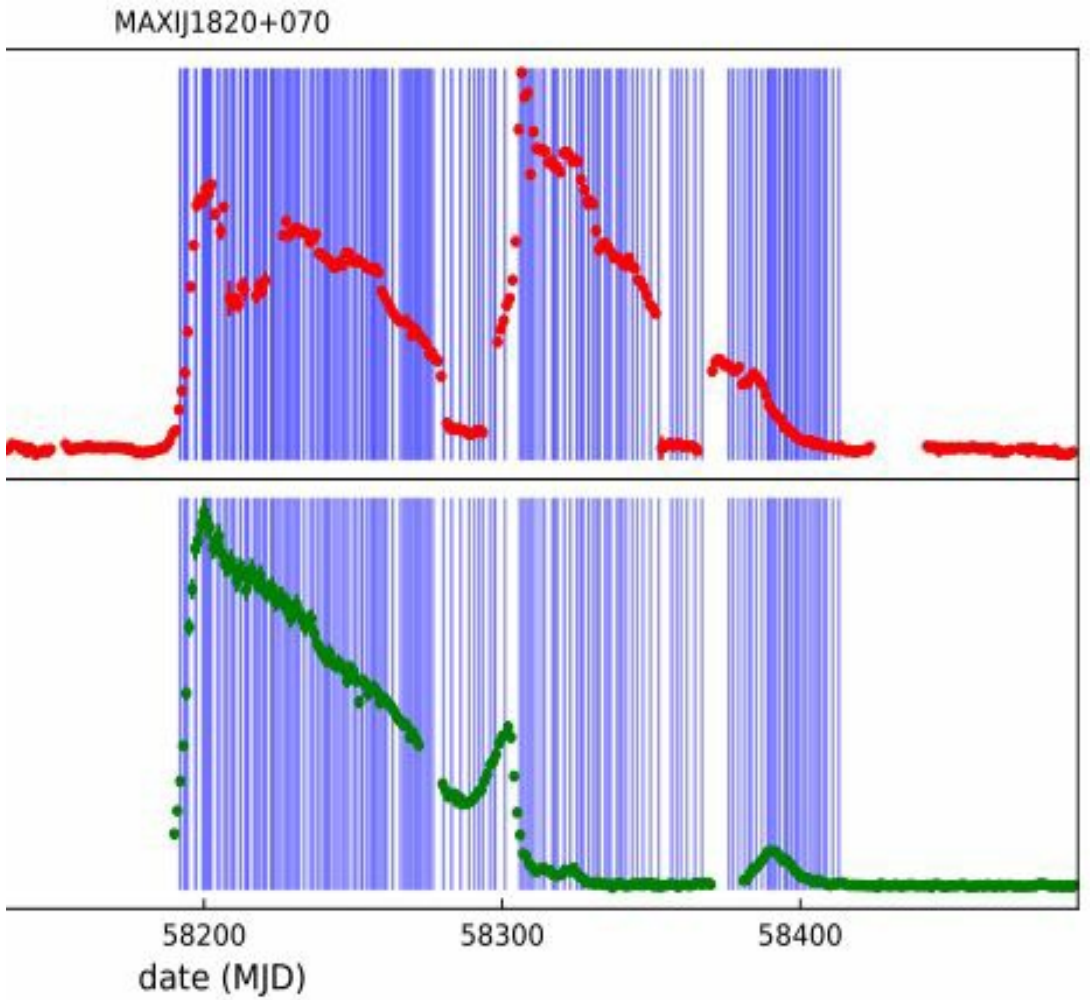


Supermassive black hole
Weakly curved spacetime
(~Solar)

Tests of GR predictions in the strong field regime of Gravity.
Complementary to gravitational wave experiments.

BHXB MAXI J1820+070



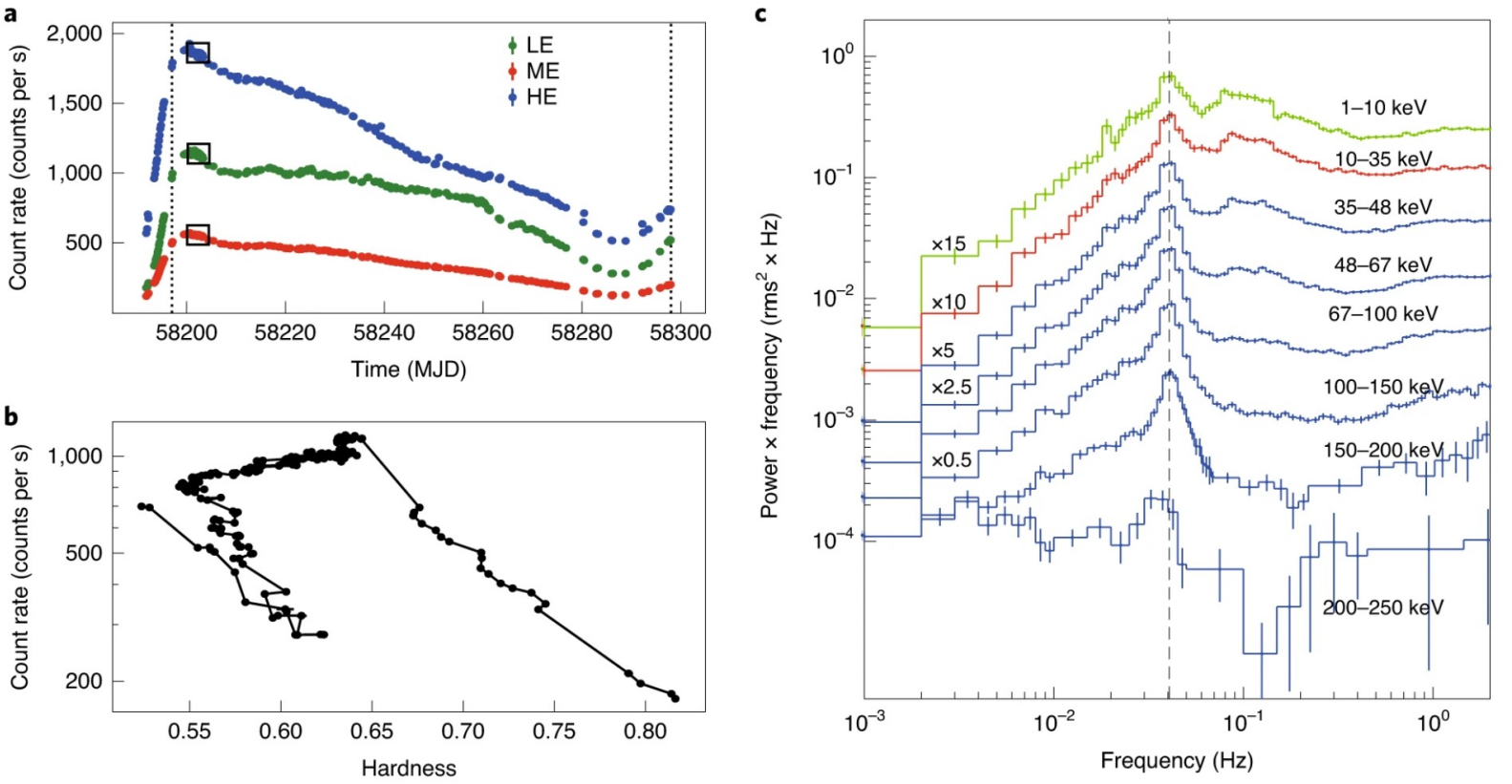


2018 3.11 outburst detected by MAXI Insight-HXNT: 146 pointings, exposure 2560 ks

QPOs of BH binaries: < 30 keV → >200 keV
“慧眼”发现黑洞周围最高能量的准周期振荡

Fig. 1: Light curves, hardness–intensity diagram and power density spectra of MAXI J1820+070 in the X-ray hard state.

From: Discovery of oscillations above 200 keV in a black hole X-ray binary with Insight-HXMT

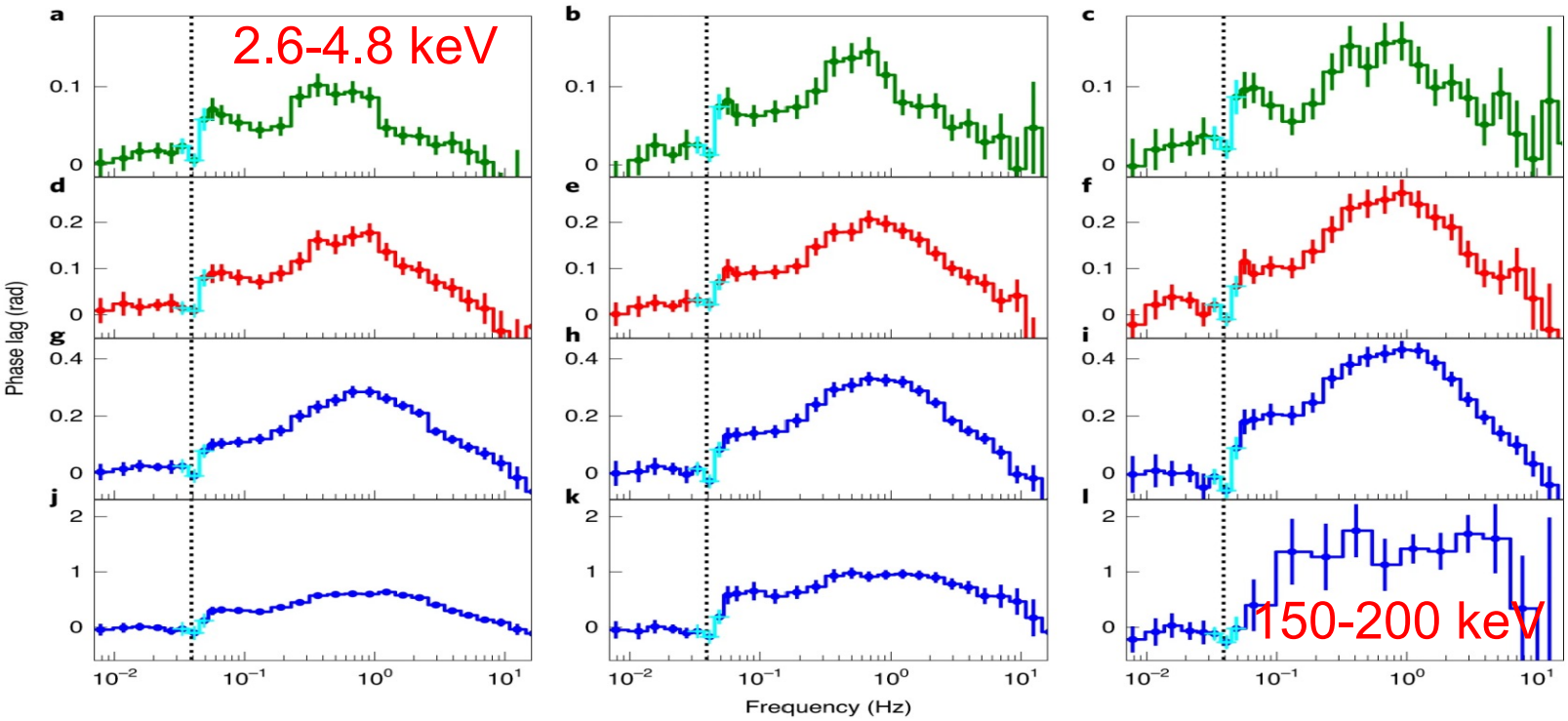


Ma, Tao, SNZ+ 2021, Nature Astronomy

Dip in the lag-freq. spectra at QPO

Fig. 2: Frequency-dependent phase-lag spectra for MAXI J1820+070 in different energy bands. All lags are relative to 1-2.6 keV; negative lag: behind

From: Discovery of oscillations above 200 keV in a black hole X-ray binary with Insight-HXMT



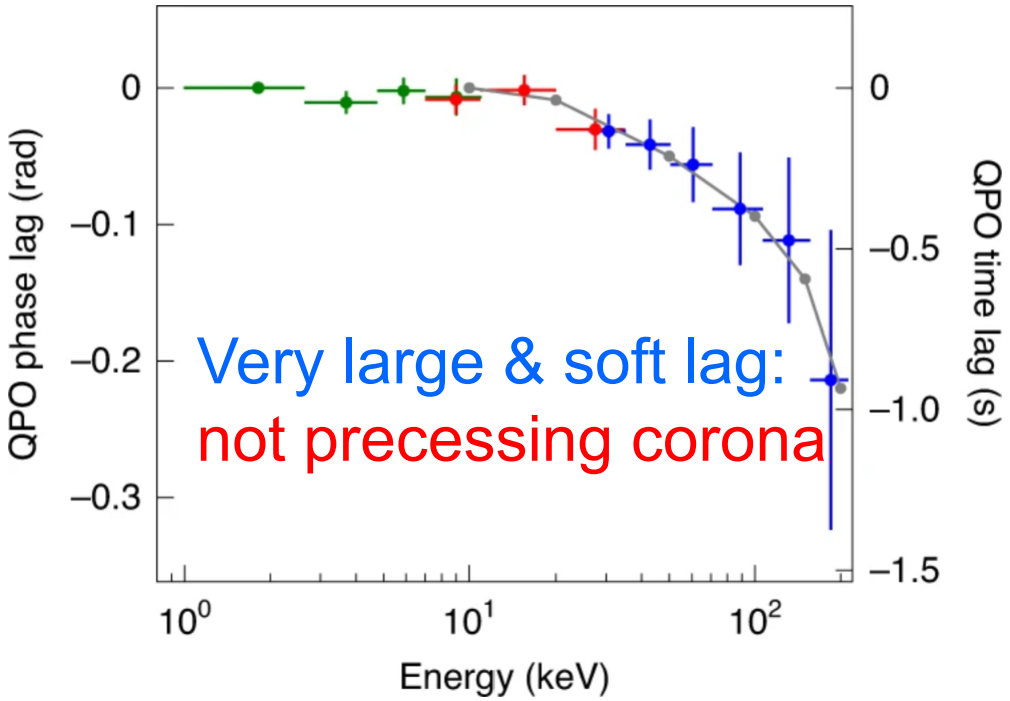
All spectra are relative to the 1–2.6 keV band for a typical observation taken on MJD 58199.5–58200.9 (ObsID P0114661003). **a**–**c**, Spectra for 2.6–4.8 keV (**a**), 4.8–7 keV (**b**) and 7–11 keV (**c**) from LE. **d**–**f**, Spectra for 7–11 keV (**d**), 11–23 keV (**e**) and 23–35 keV (**f**) from ME. **g**–**l**, Spectra for 25–35 keV (**g**), 35–48 keV (**h**), 48–67 keV (**i**), 67–100 keV (**j**), 100–150 keV (**k**) and 150–200 keV (**l**) from HE. To compare the results from different telescopes, we used some overlapping energy bands: **c** for LE and **d** for ME, and **f** for ME and **g** for HE. The frequency-dependent phase-lag spectra confirm consistency between different telescopes. The vertical dashed lines indicate the LFQPO frequency. In all cases, we observe a narrow dip-like feature (cyan points) at the LFQPO frequency. Error bars correspond to 1σ confidence intervals.

Ma, Tao, SNZ+ 2021, Nature Astronomy

Lag contradicts Comptonization delay in corona: Geometrical effect outside inner disk

Fig. 3: The evolution of the LFQPO phase lag as a function of photon energy for ObsID P0114661003.

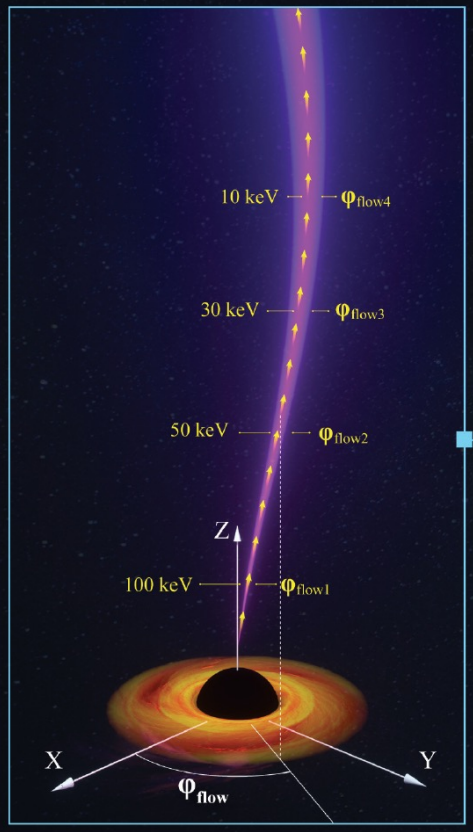
From: Discovery of oscillations above 200 keV in a black hole X-ray binary with Insight-HXMT

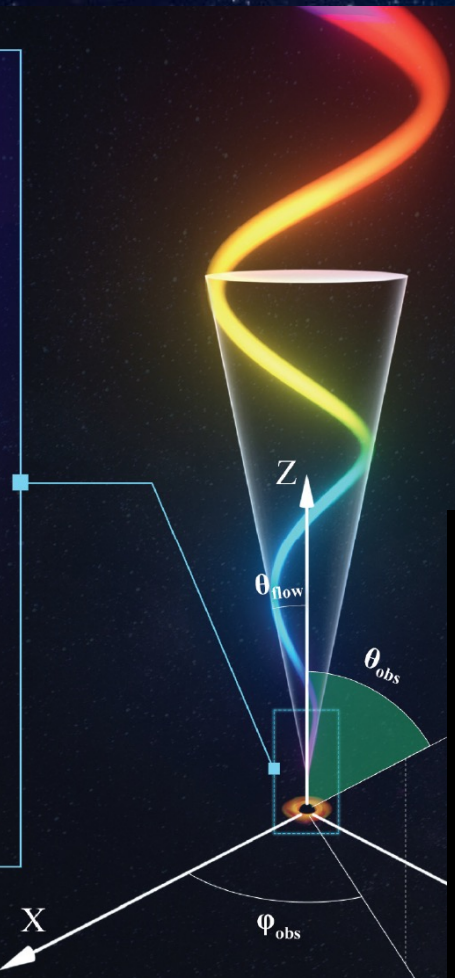


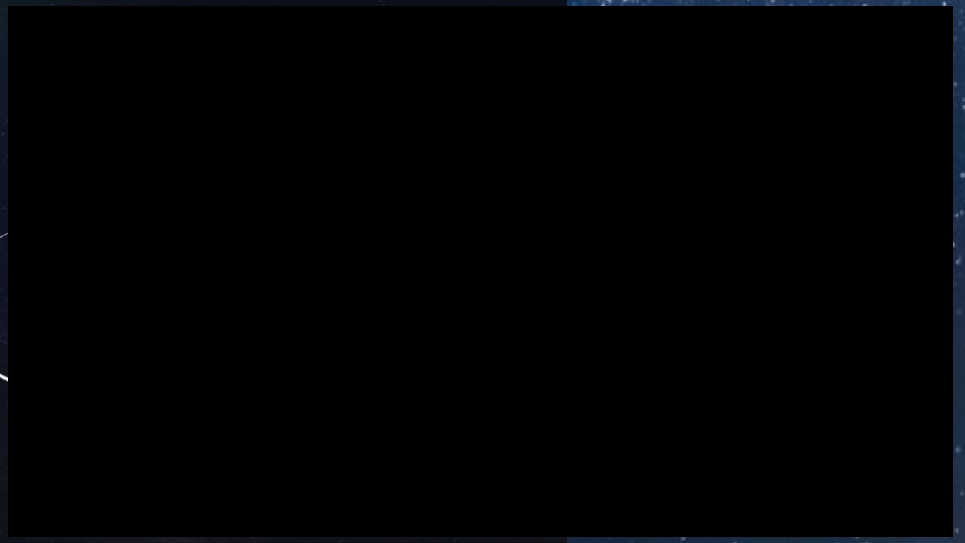
In the jet precession model, as the jet is curved, different parts of the jet have different $\varphi_{\rm flow}$ values (see Fig. 4), which causes the phase lags between different energies (green, LE; red, ME; blue, HE). The curvature of the jet ($\Delta\varphi_{\rm flow}$) is tuned to match the observed phase lags (see the grey line). Error bars correspond to 1σ confidence intervals.

Ma, Tao, SNZ+ 2021, Nature Astronomy

New model of BH QPOs: L-T precession Jet
基于“慧眼”观测结果建立的黑洞喷流进动模型





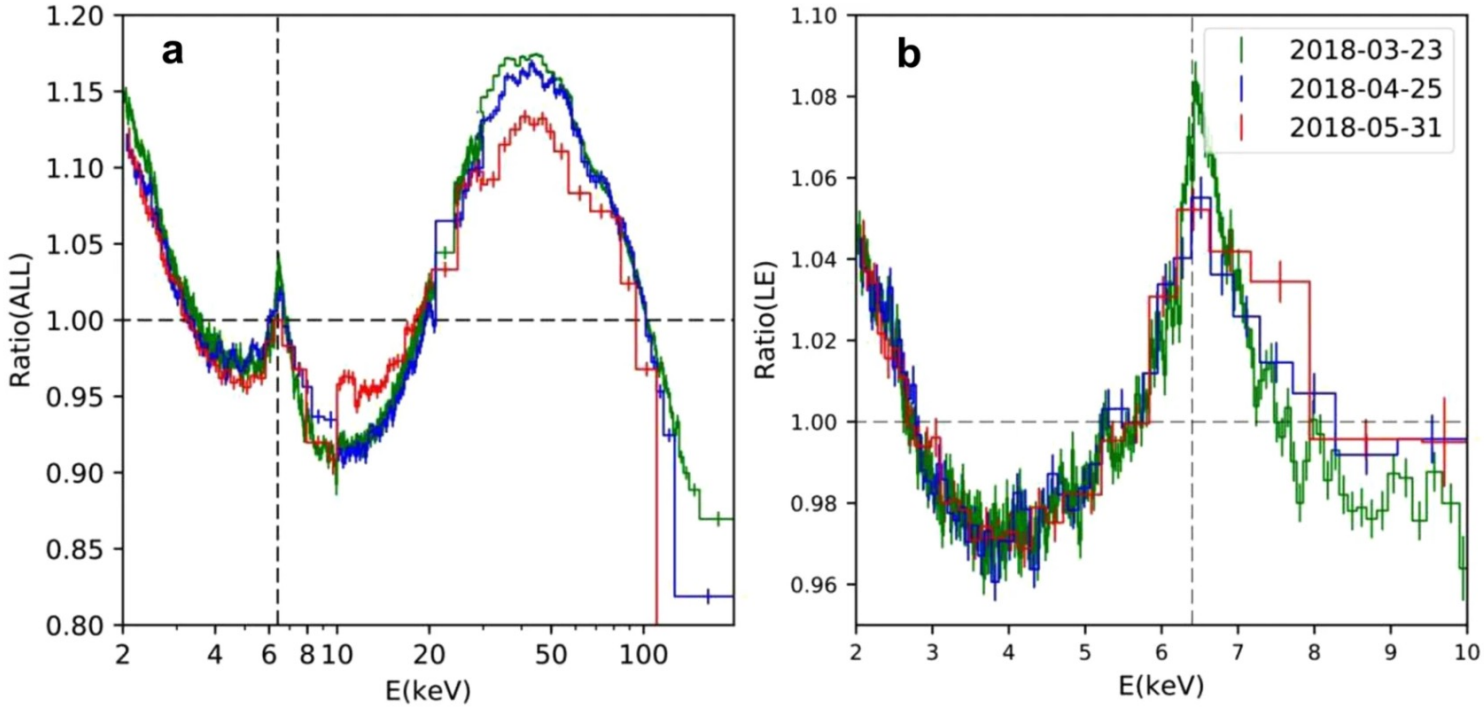


Ma et al. 2020, Nature Astronomy

Broad band energy spectra with Insight-HXMT
慧眼的宽能段能谱

Fig. 2: Ratio of the spectrum to the best-fitting cutoff power law.

From: Insight-HXMT observations of jet-like corona in a black hole X-ray binary MAXI J1820+070



a Ratio of the spectrum of three epochs to the best-fitting cutoff power law (cutoffpl in XSPEC) in 2–200 keV. Time runs from top to bottom, corresponding to the early, middle and late echo of this decay, i.e., 2018-03-23 (MJD = 58201, ObsID = P0114661003), 2018-4-25 (MJD = 58233, ObsID = P0114661028), 2018-05-31 (MJD = 58269, ObsID = P0114661060). **b** Ratio of the spectrum of the same epochs to the best-fitting power law in 3–10 keV. The vertical dashed line indicates the rest energy (6.4 keV) of the iron line. Fluorescence lines due to the photoelectric effect of electrons in the K-shell of silver are detected by the Si-PIN detectors of ME, which dominates the spectrum over 21–24 keV. Therefore, the spectrum over 21–24 keV is ignored.

You+2021, Nature Communications

Decreasing reflection contradicts contracting corona
慧眼观测到的反射减少与不久前发现的收缩高温冕矛盾

Fig. 3: Time-evolutions of the free parameters in the best-fitting of the spectral model (1).

From: Insight-HXMT observations of jet-like corona in a black hole X-ray binary MAXI J1820+070

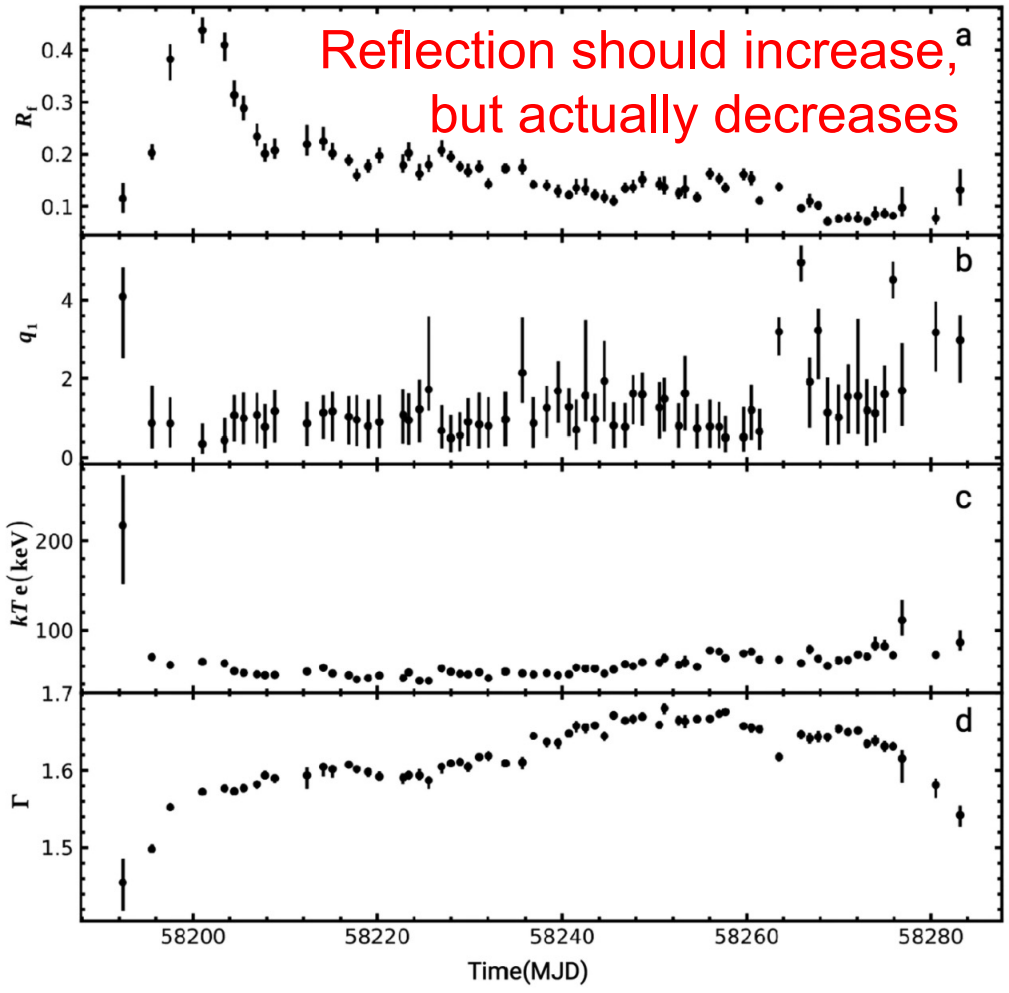
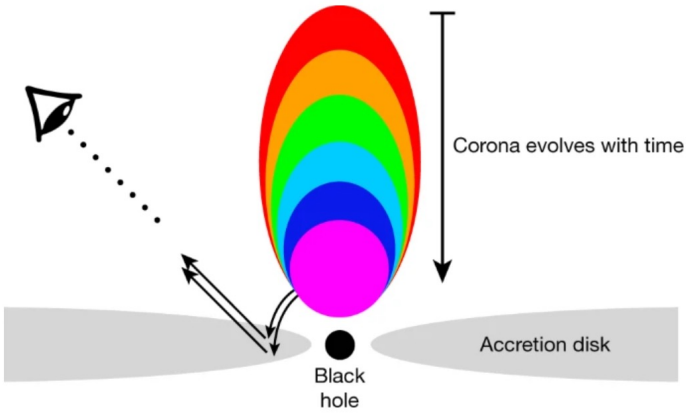


Fig. 4: Schematic of the proposed geometry.



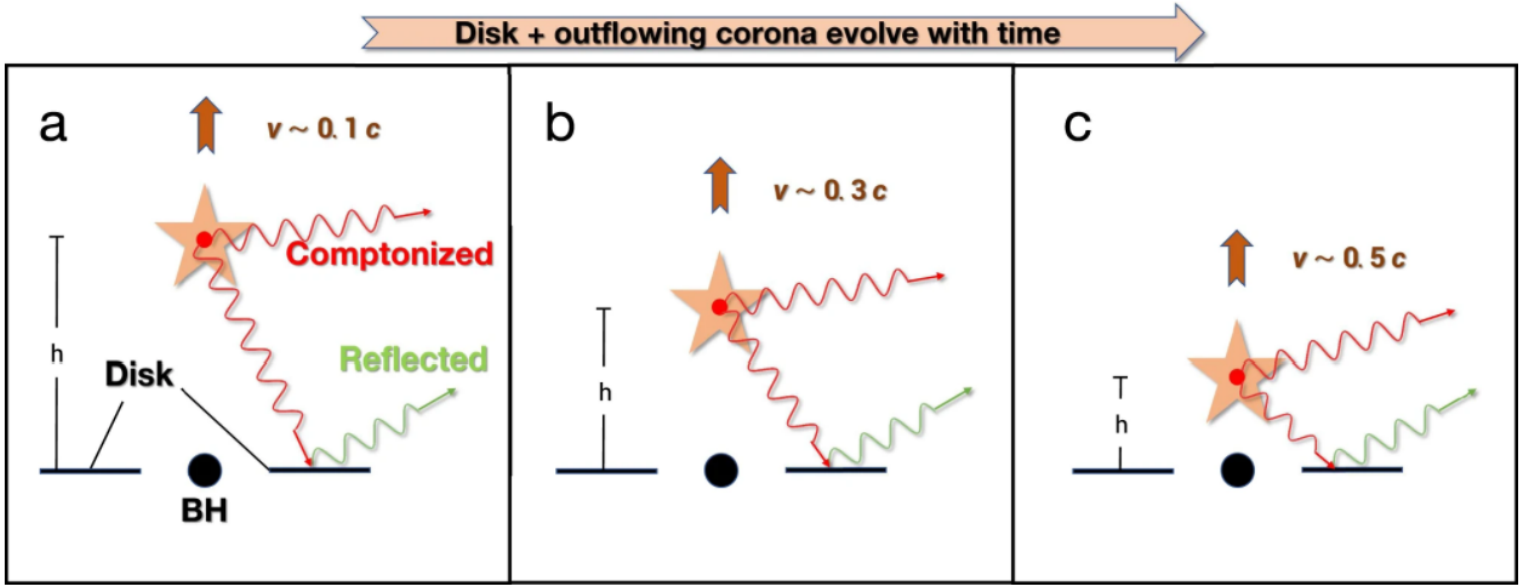
Shown is a schematic of the proposed geometry, evolving from a vertically extended corona at early times to a more compact corona at late times. The corona has a static core at small radii that is responsible for most of the flux irradiating the disk, and the constant shape of the broad Fe line is due to this static core. As the corona decreases in vertical extent, the coronal variability timescale shortens, causing the shift in the thermal reverberation lag to higher frequencies. The decrease in vertical extent of the corona is also responsible for the decrease in the equivalent width of the narrow component of the Fe line at 6.4 keV.

Kara+2020, Nature

The contracting corona is an X-ray jet!
慧眼发现收缩的高温冕实际上是X射线喷流！

Fig. 5: Schematic of the proposed jet-like corona in the decay phase.

From: Insight-HXMT observations of jet-like corona in a black hole X-ray binary MAXI J1820+070



'BH' stands for Black Hole, and the symbol `star' represents the coronal region where the X-ray radiation comes from. The corona at height h can be understood as a standing shock where the material flowing through. The Comptonized hard photons (red arrow) from the corona illuminates the accretion disk, resulting in the observed reflection component (green arrow). Panel **a**, **b** and **c**, represents the peak, middle and end of the decay phase, respectively. As the corona contracts towards the black hole (e.g., from panel **a** to **b**) with decreasing height, the fitted reflection fraction decreases, which suggests that the bulk motion of the outflowing coronal material (sketched as an upward arrow) gets faster in the deeper gravitational potential well, with the increase of the outflowing velocity *v* in units of light speed c. Note that the values of *v* are not taken from the spectral fits, but for the sake of depicting faster outflowing corona.

You+2021, Nature Communications

Disk-Jet co-precession with broad band QPO

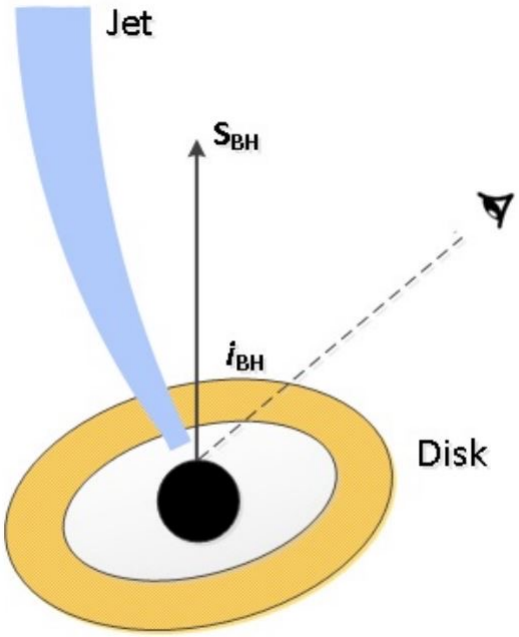
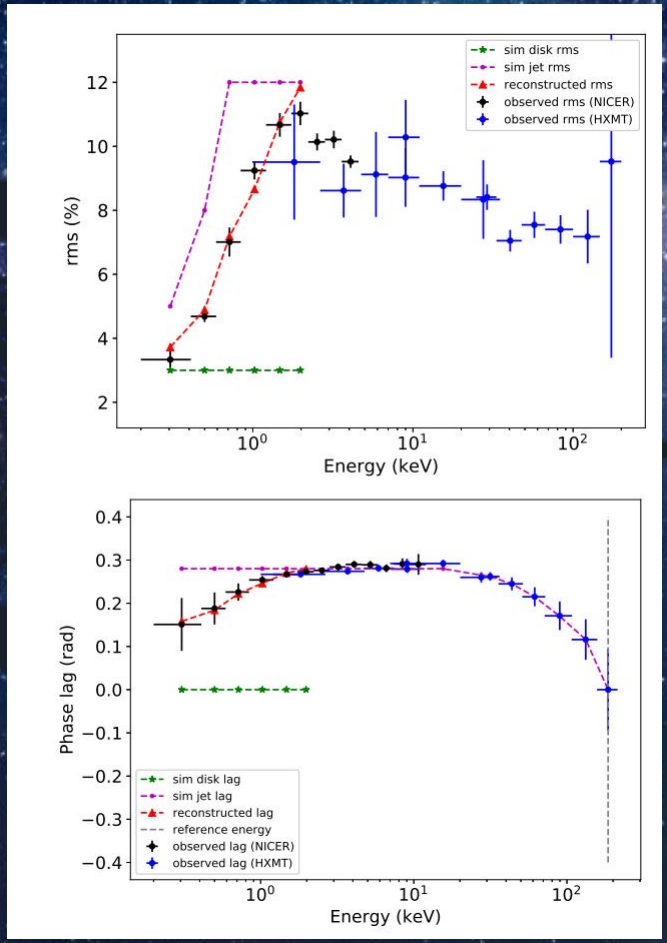
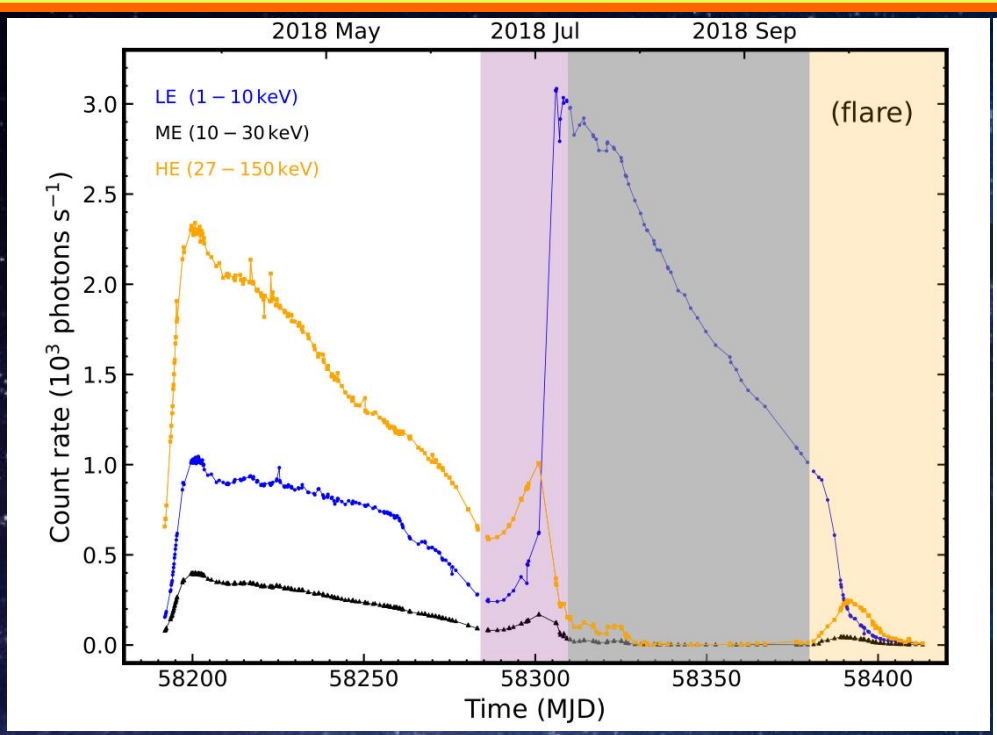


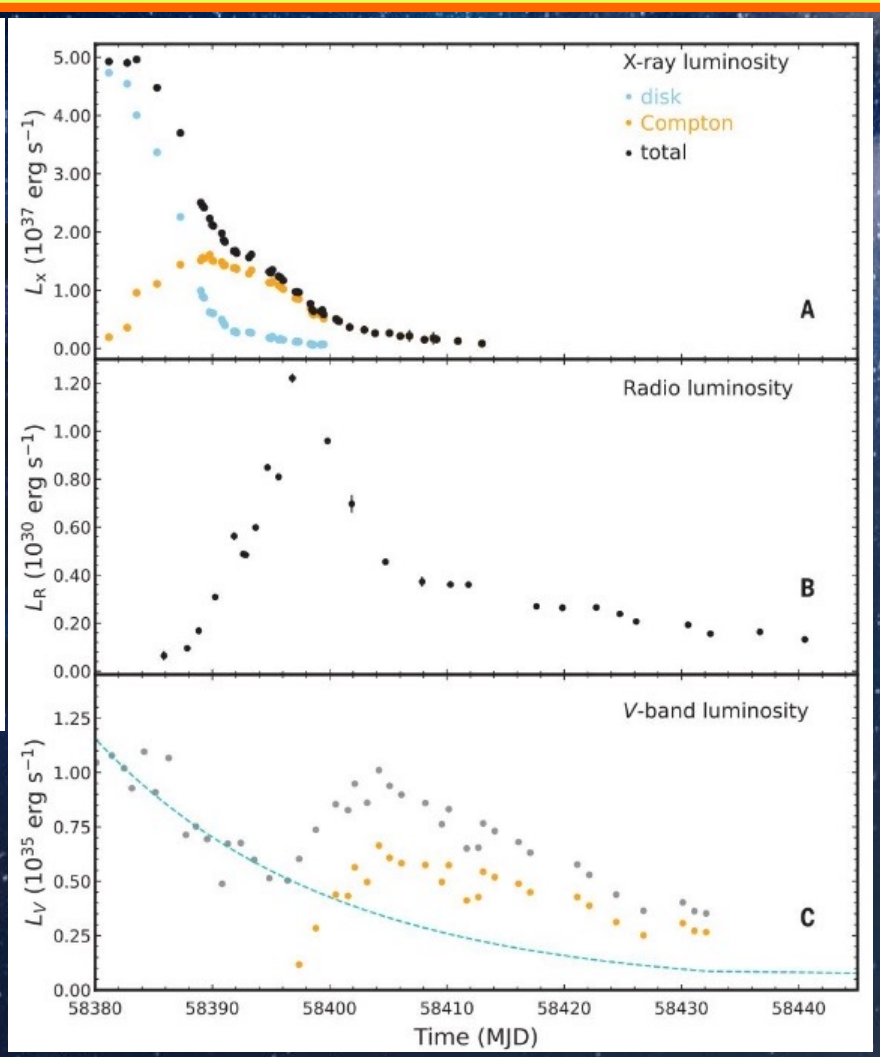
Figure 8. The model shows the jet and inner disk ring precess together.



Jet and inner disk precess together in MAXI 1820+070 (Ma et al. 2023, ApJ)

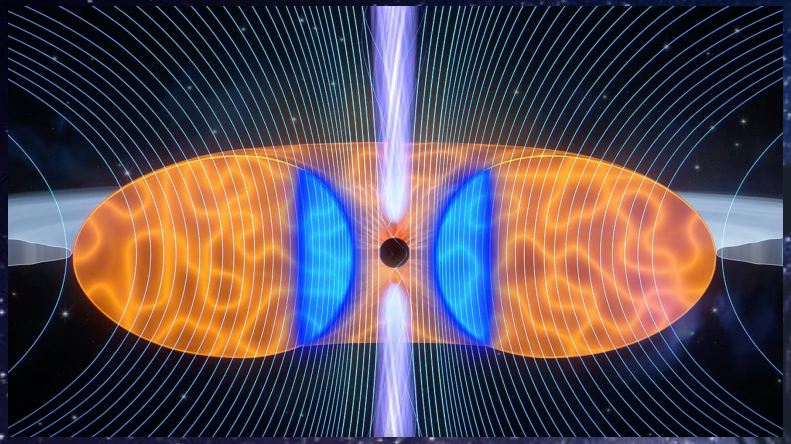
Evidence of MAD in MAXI J1820+070



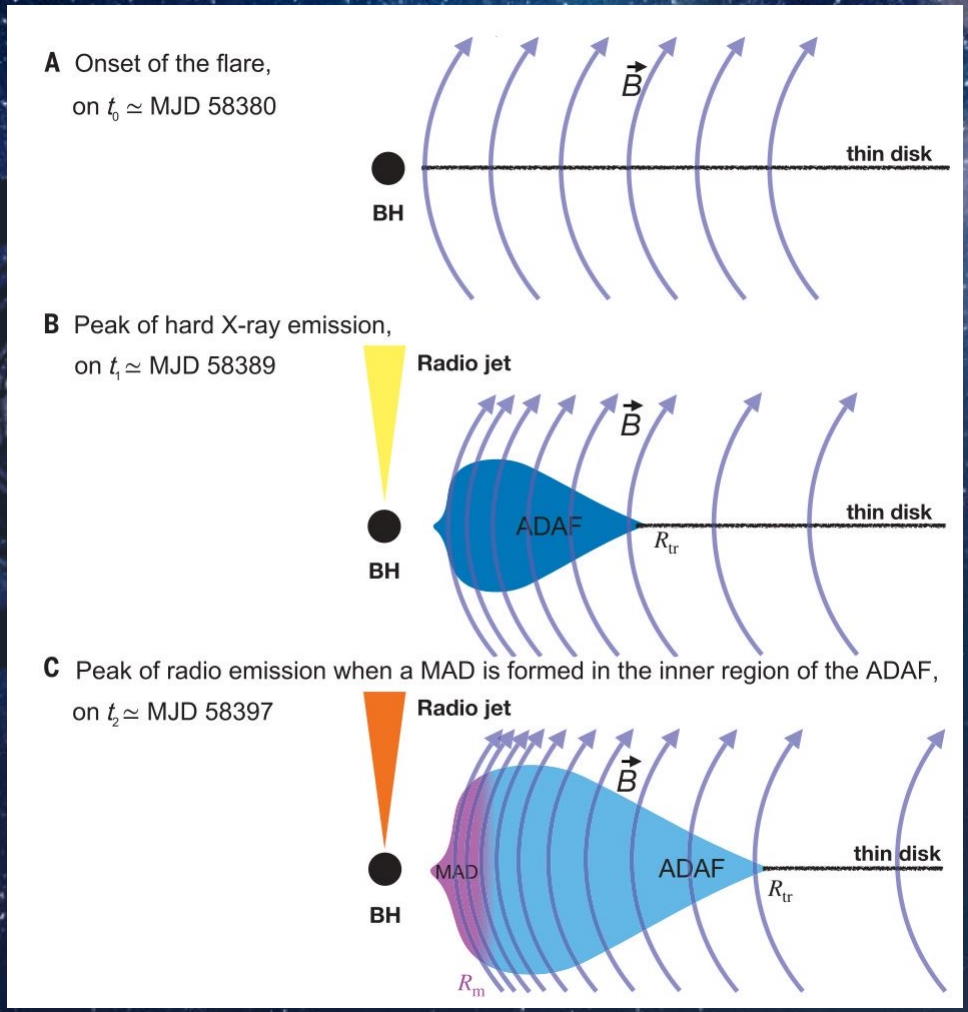


Bei You*, Xinwu Cao* , Zhen Yan* et al. Science,2023

Evidence of MAD in MAXI J1820+070



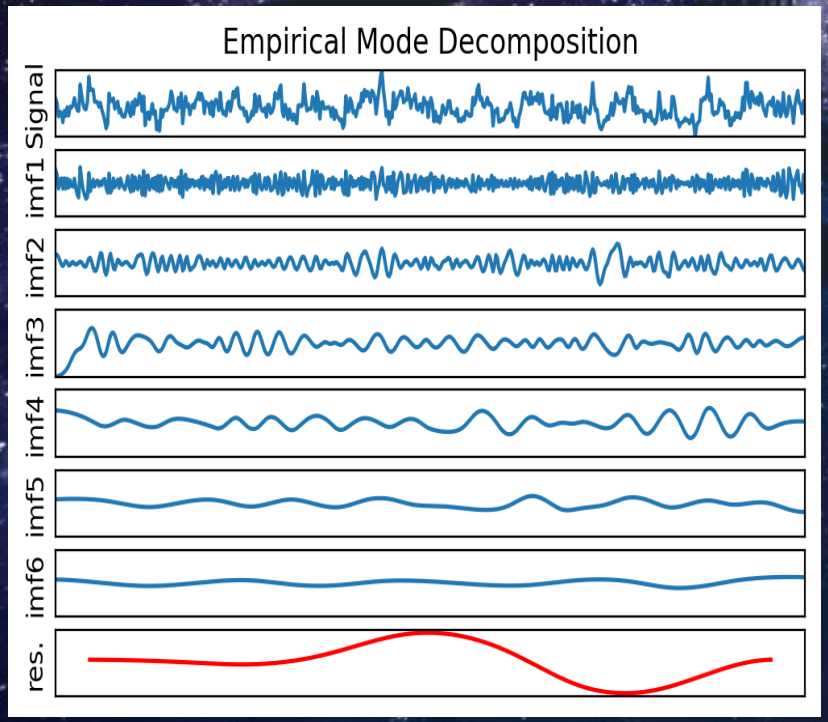
Bei You*, Xinwu Cao* , Zhen Yan* et al. Science,2023

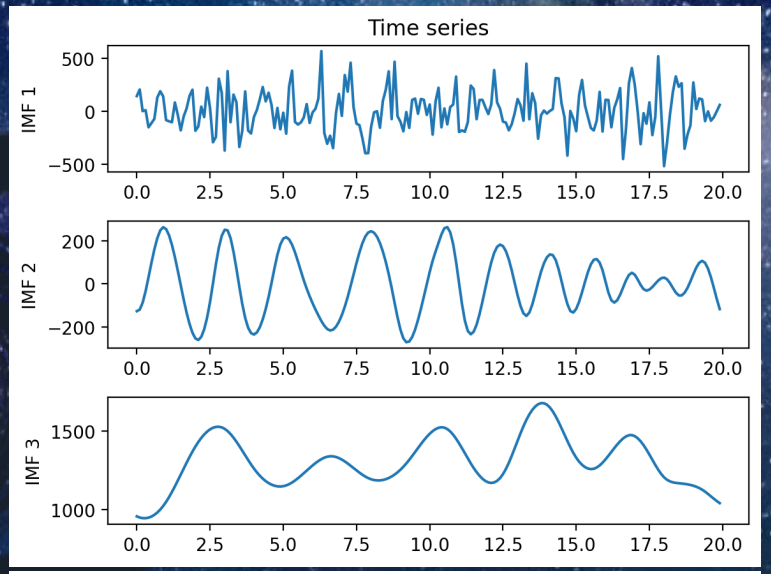


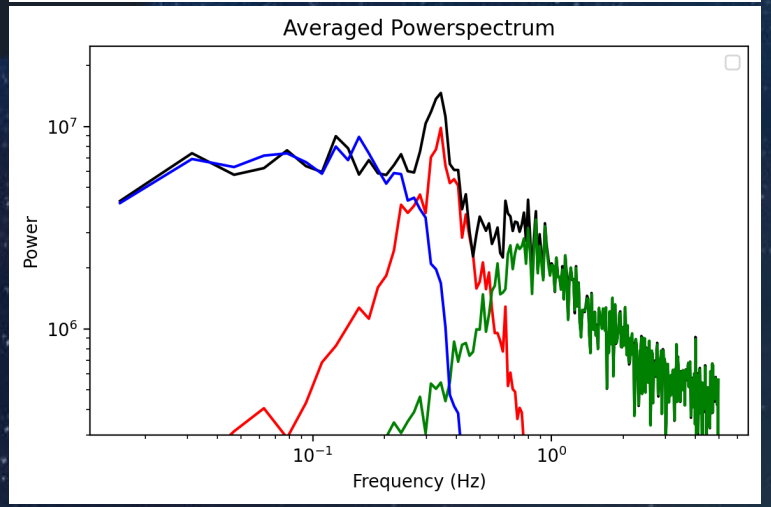
Hilbert-Huang Transformation (HHT)

Hilbert-Huang Transform (HHT) = Empirical Mode Decomposition (EMD) + Hilbert Transform (HT)

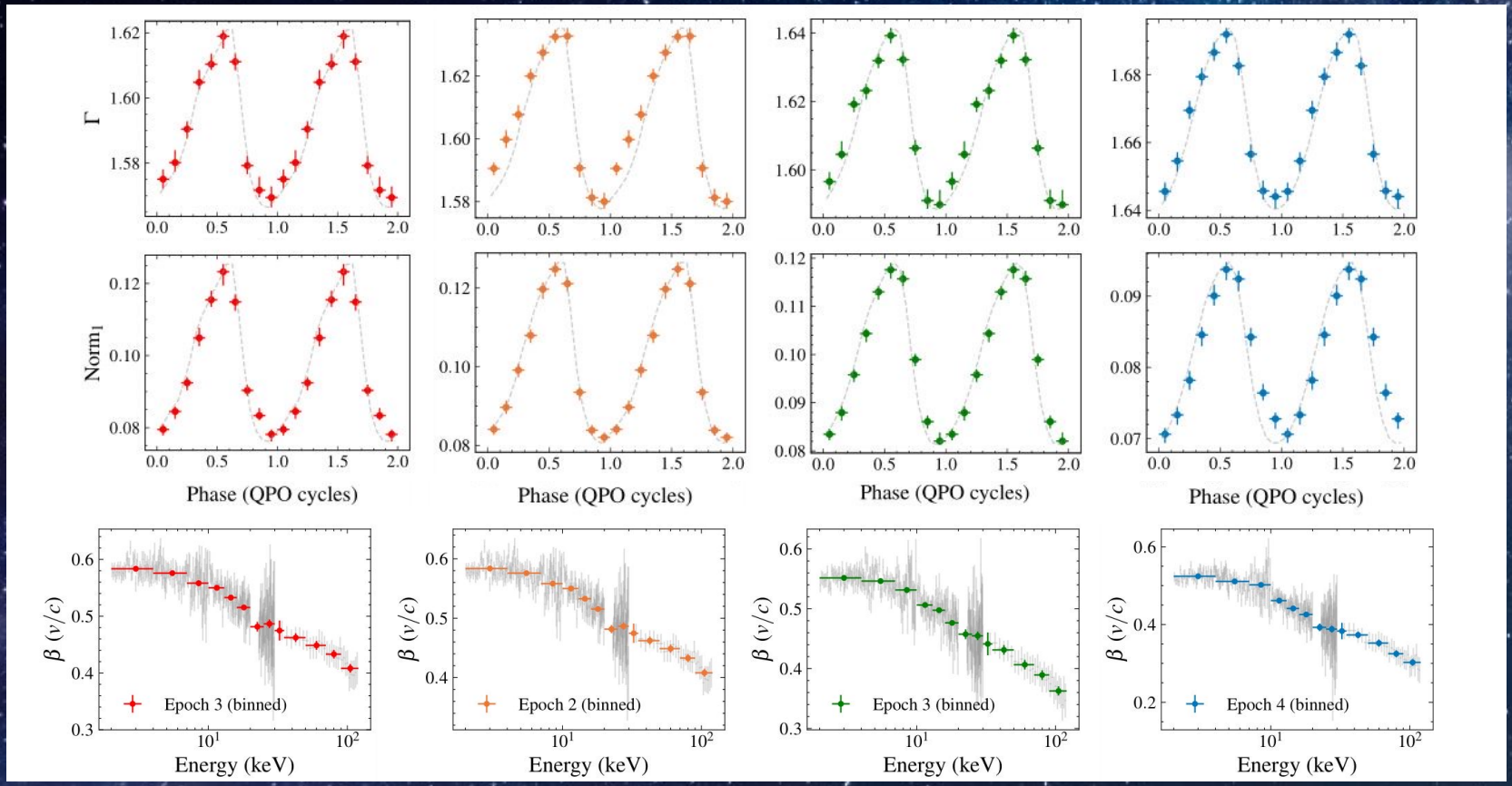
EMD ≈ narrow band filter: decompose adaptively a signal into several Intrinsic Mode Functions (IMFs)





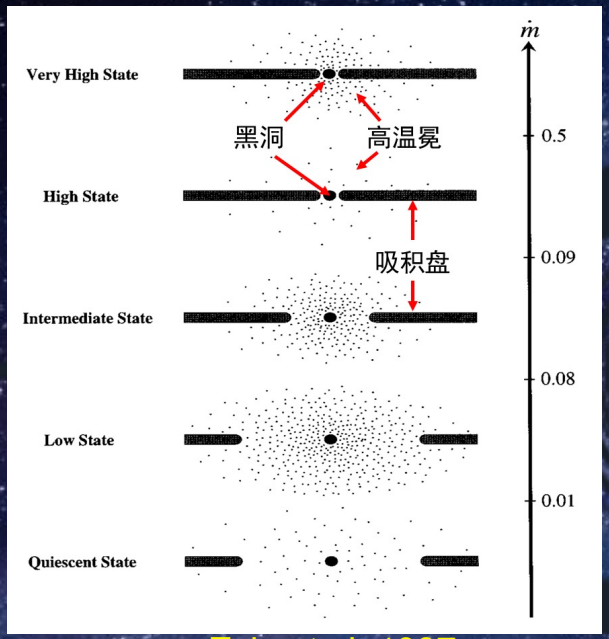


HHT QPO phase-resolved spectral analysis



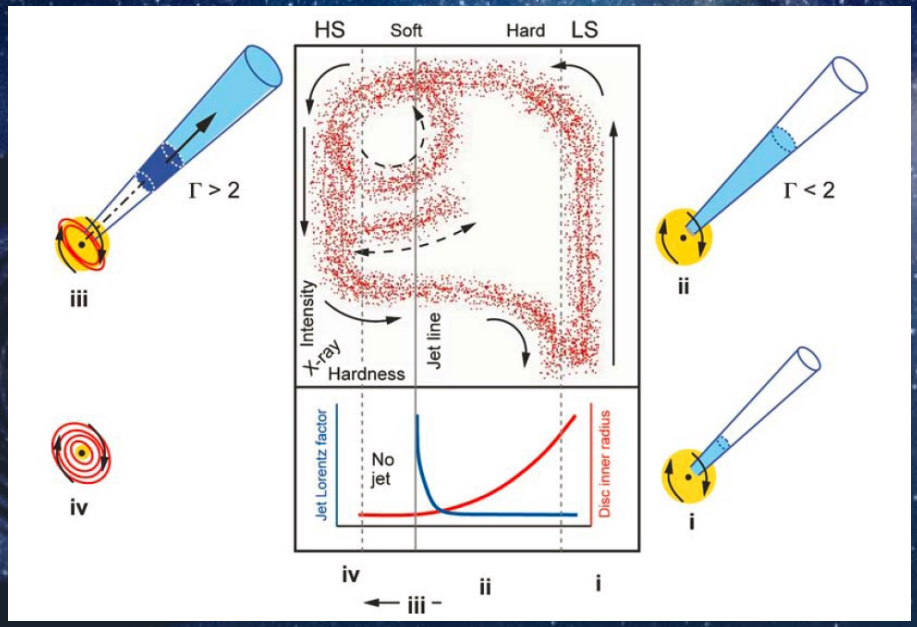
The modulation of the spectral index could be explained by either the coronal or jet precession model; the latter requires efficient acceleration within the jet. (Shui et al., 2023, ApJ)

The standard “q”diagram of BHXBs
黑洞X射线双星的“q”型图（统一模型）



Esin et al. 1997

软态　硬态



Fender et al. 2004

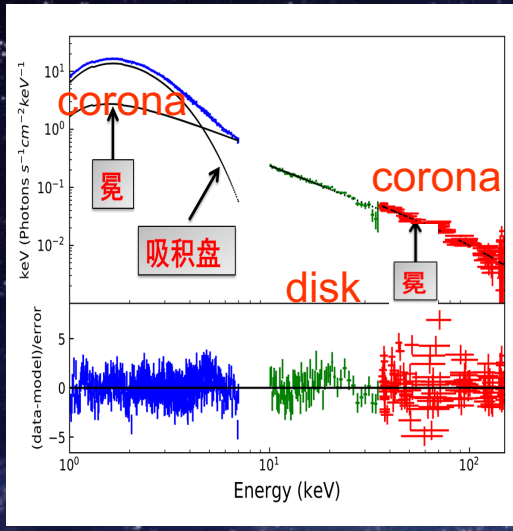
Most studies assume that the accretion disk/corona are uniquely determined by accretion rate; however, how disk and corona evolve with accretion rate is not clear.

大部分理论、观测研究通常假设，吸积盘/冕的性质仅由吸积率**唯一**决定。

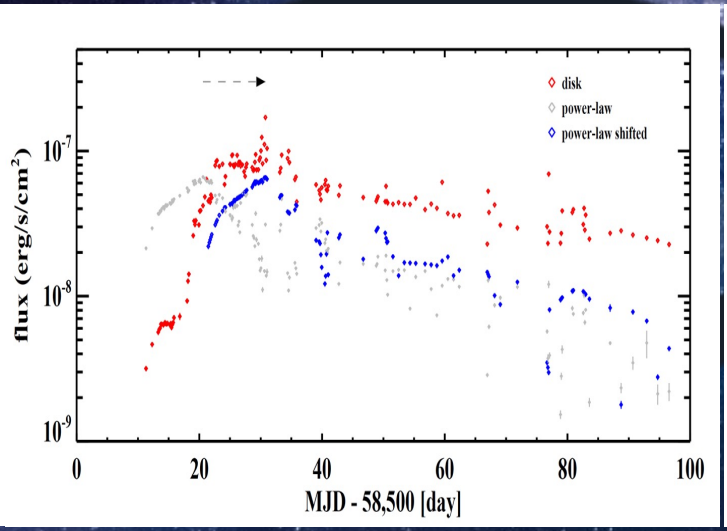
针对随着吸积率的变化，两个成分之间有何联系，理论上已有广泛探讨，但一直缺乏观测研究！

Observation result of Insight-HXMT
慧眼卫星对MAXI J1348-630的观测结果

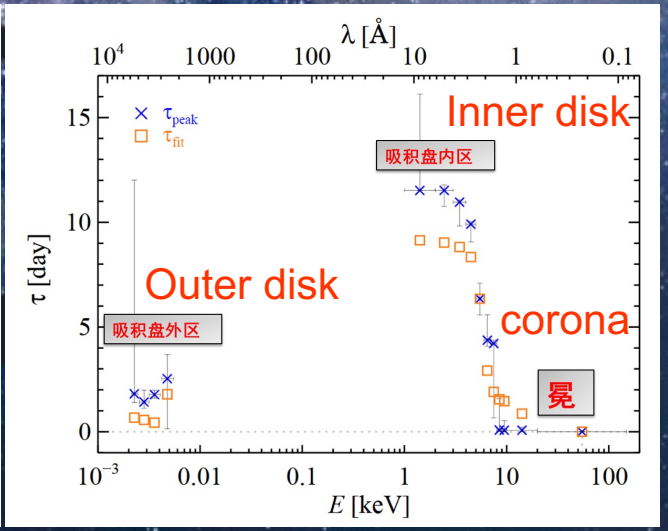
MAXI J1348-630能谱
Broad-band spectrum



MAXI J1348-630
不同能谱成分流量随时间的演化
Evolution of different components



MAXI J1348-630
不同成分相对冕成分的时间延迟
Delay wrt corona component

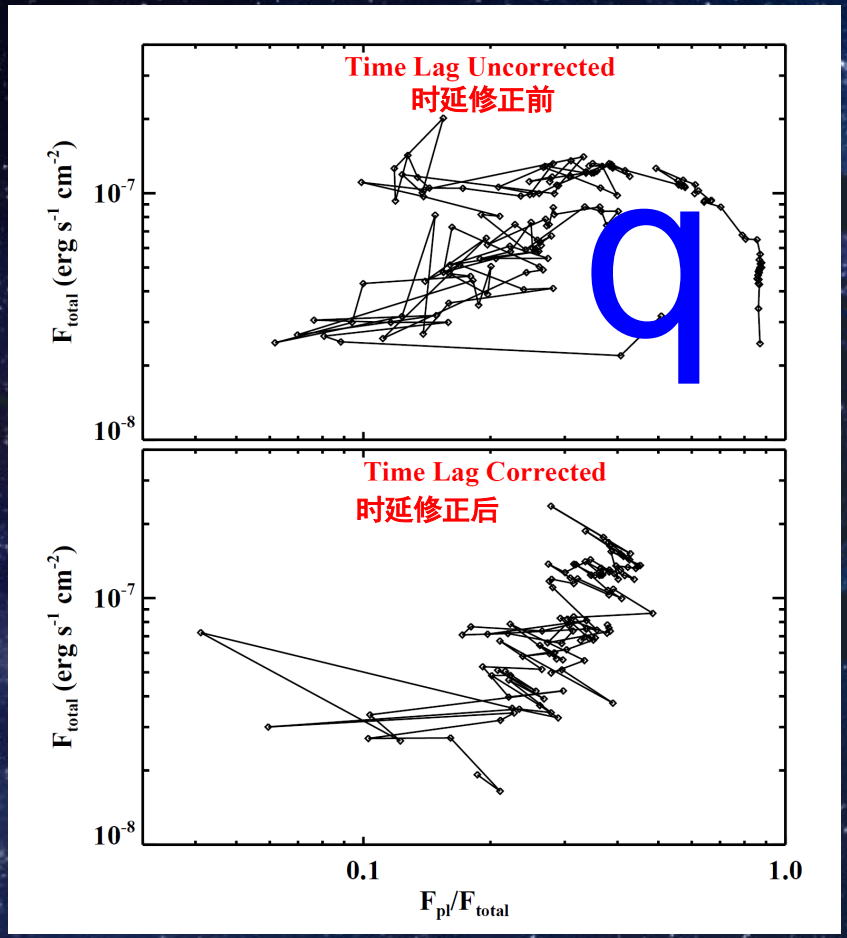


MAXI J1348-630在2019年的爆发过程中，冕的辐射（灰色数据点）**领先** 吸积盘内区辐射（红色数据点）的演化~ 8-12天。

Corona emission lead inner-disk emission by ~8-12 days in 2019 outburst

翁山杉、蔡振义、张双南等，Weng et al, 2021，ApJL

Hardness-intensity diagram of MAXI J1348
MAXI J1348-630的能谱硬度和流量关系图



总流量

总流量

MAXI J348-630的原始观测数据呈现典型的“q”型图。
Typical “q” diagram with original data

考虑吸积盘内区辐射相对冕演化滞后约 10天，“q”型图可被修正为线性相关关系。
“q” shape becomes linear relation after correcting for 10 day delay. But why?

翁山杉、蔡振义、张双南等，Weng et al, 2021，ApJL

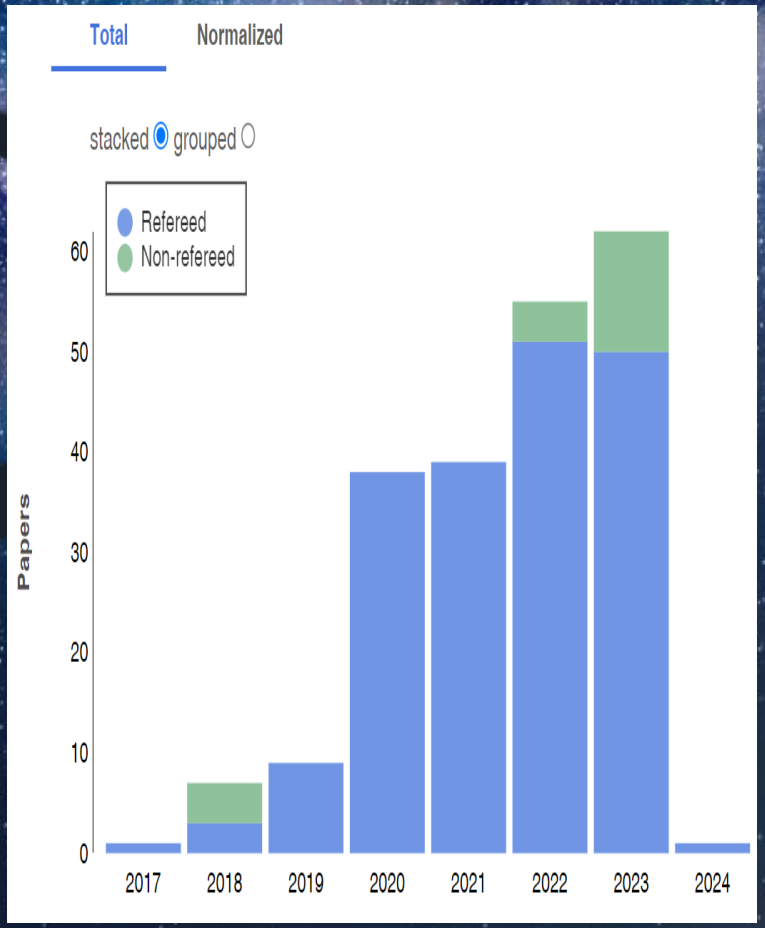
Panorama of BHXB in Outburst
慧眼“看到了”吸积黑洞爆发全景

翁山杉、蔡振义、张双南等，Weng et al, 2021，ApJL

Summary总结

- ✓ *Insight*-HXMT is China's 1st X-ray astronomy satellite.
  - ✓ 1-15, 5-30, 20-250 keV (pointed) and **0.2-3 MeV (all-sky monitor)**
- ✓ An open small-observatory
  - ✓ Core program: all scientists working in China (most data now public)
  - ✓ Guest program: world-wide
    - ✓ AO-6 started in Sept. 2023 (more guest time than core program).
  - ✓ Satellite just had orbit maintenance.
  - ✓ Coordinated multi-λ observations: space & ground

ads: HXMT publications



hxmt.cn for all information and data download. Thanks!