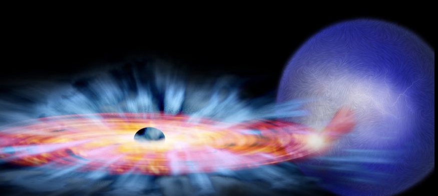
11th Microquasar Workshop
@ Cefalù (Italy)
2025 Sep. 16

High Resolution X-ray Spectroscopy of Black Hole X-ray Binaries

Megumi Shidatsu
(Ehime Univ.)

on behalf of the XRISM collaboration

Collaborators:
Maxime Parra, Chris Done, Maria Diaz Trigo, Ryota Tomaru, Yoshihiro Ueda, Soma Kobayashi, Shogo Kobayashi, Yusuke Sakai, Shinya Yamada, Yuta Okada, Hiromasa Suzuki, Naomi Tsuji, Hideki Uchiyama, Toshihiro Takagi, Marina Yoshimoto, Misaki Mizumoto, and more…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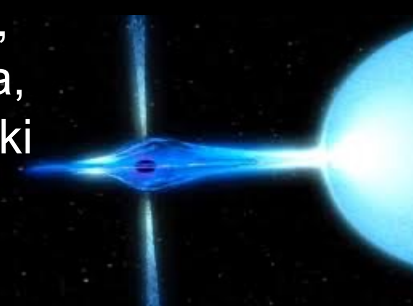
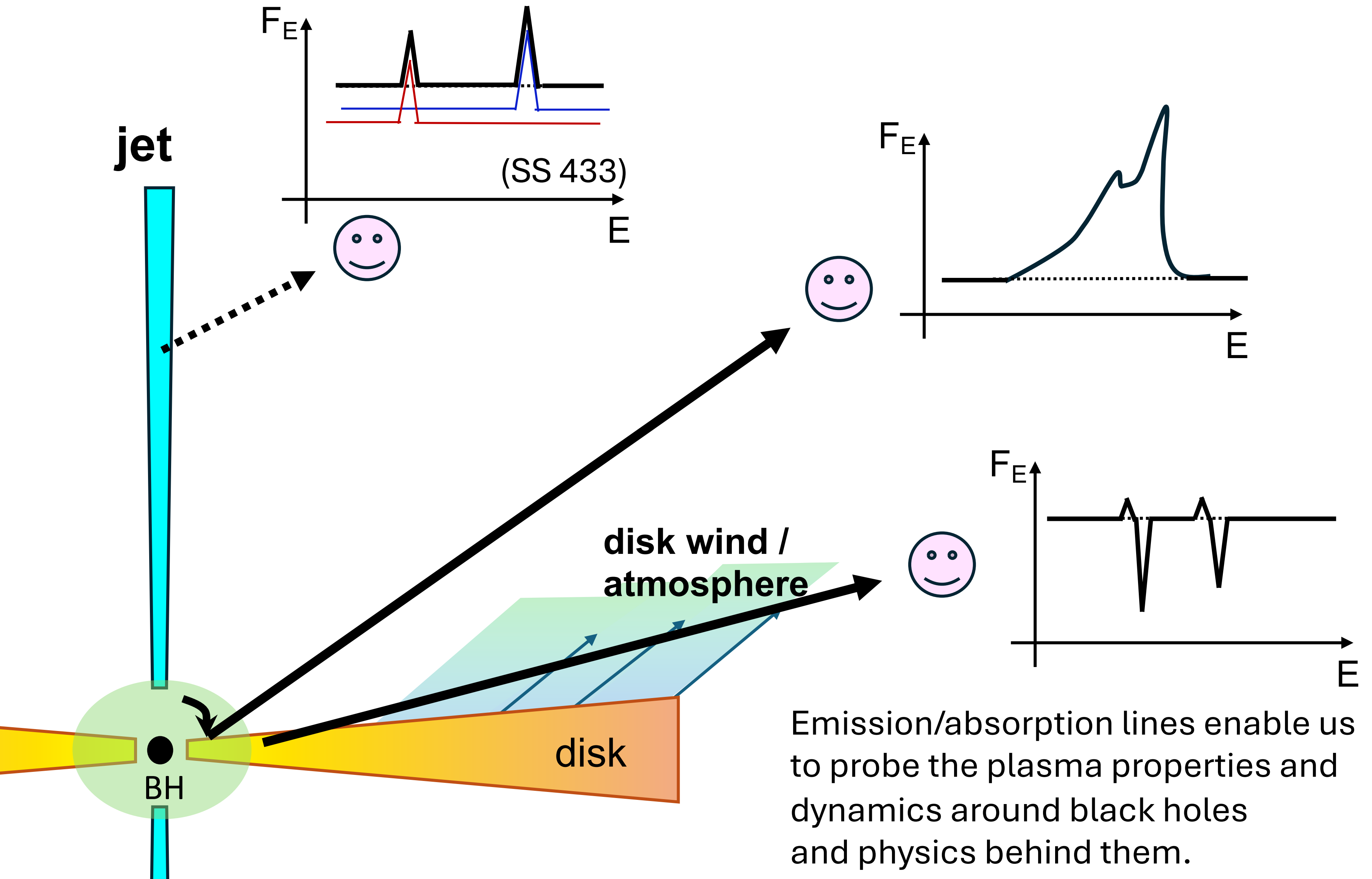
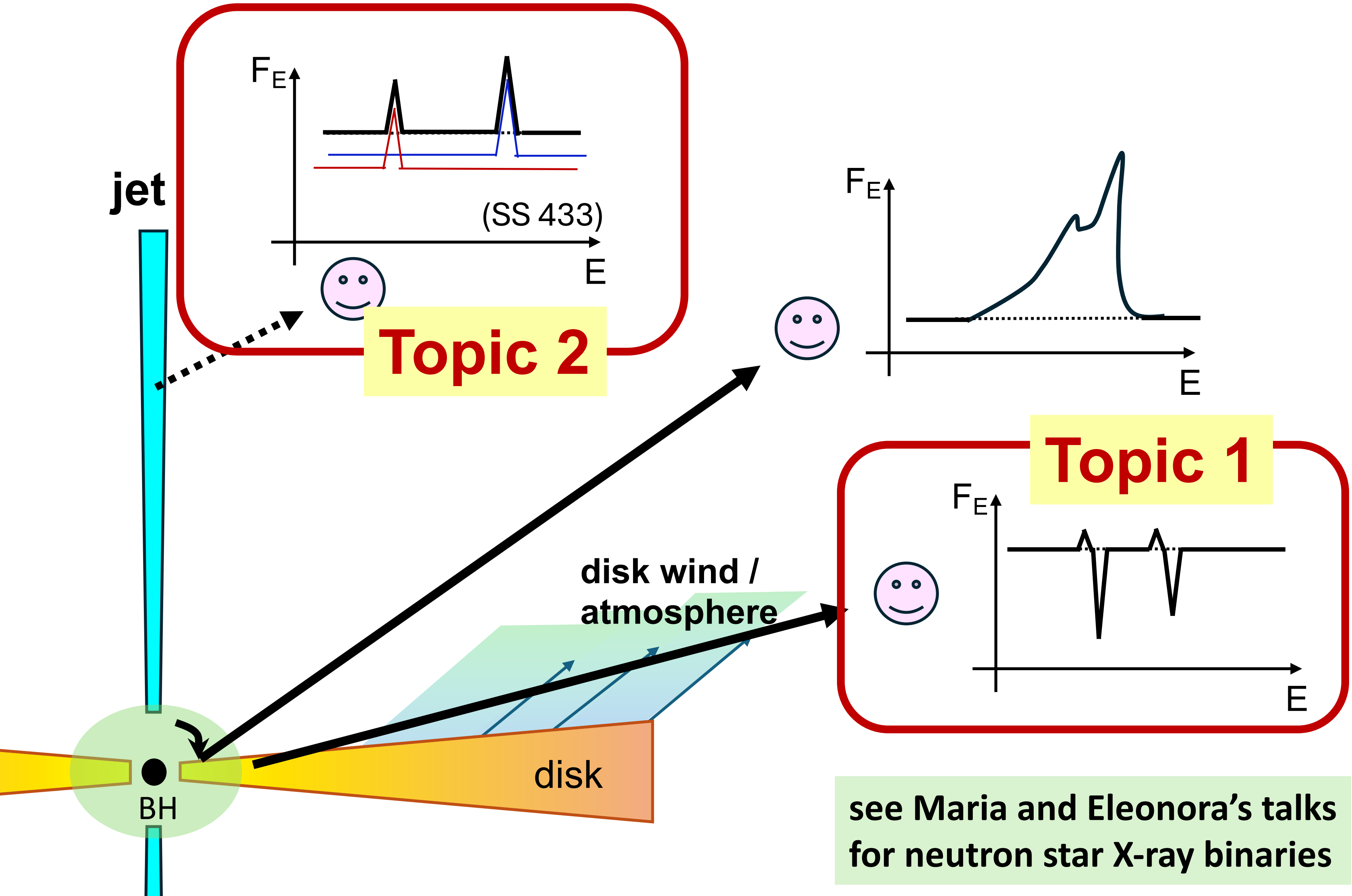


Absorption / emission lines in black hole X-ray binaries (BHXBs)



Emission/absorption lines enable us to probe the plasma properties and dynamics around black holes and physics behind them.

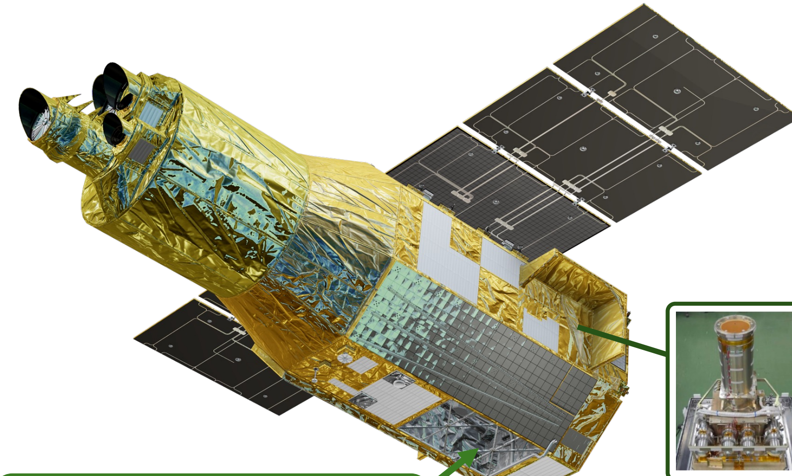
Absorption / emission lines in black hole X-ray binaries (BHXBs)

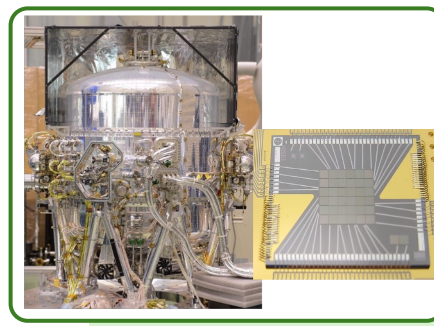


see Maria and Eleonora's talks for neutron star X-ray binaries

XRISM X-Ray Imaging and Spectroscopy Mission

official website (for researchers)
https://xrism.isas.jaxa.jp/research





Xtend (X-ray CCD)
Energy range: 0.4-12 keV
ΔE: ~ 250 eV @ 6 keV
FoV: 38.5' x 38.5'

2023 Sept. 7 Launch success!
2024 Feb. 8 Commissioning completed → PV obs. (by team members) started
2024 late Aug. GO phase started

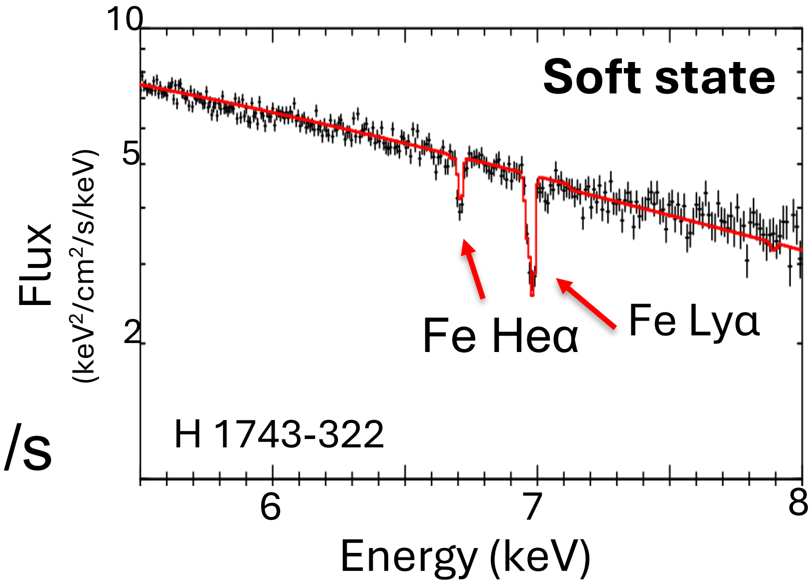
Resolve (X-ray microcalorimeter)
Energy range: 0.4 (1.7) -12 keV
ΔE ≦ 5 eV @ 6 keV
FoV: 2'.9 x 2'.9 (6 x 6 pixel)
Effective area: >=210 cm^2 @ 6 keV

10 x improvement in energy resolution and line detection sensitivity!!
-> best instrument to study line profiles

Disk winds in BHXBs

Observed as highly ionized, blueshifted absorption lines

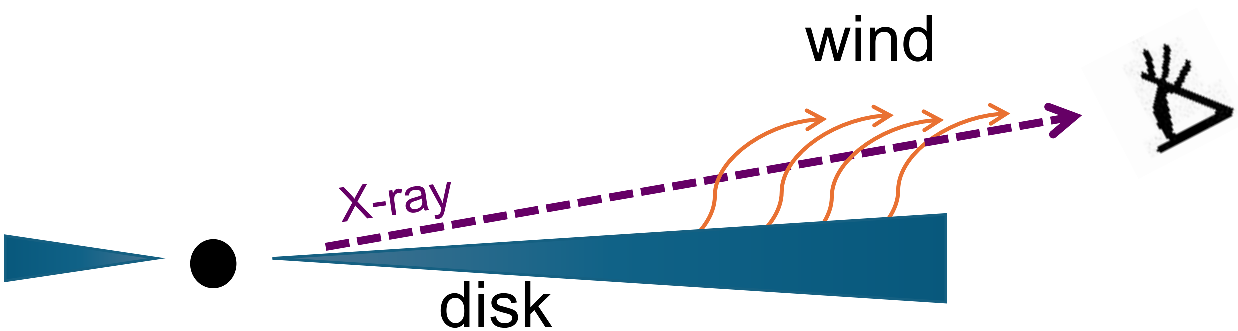
(e.g., Ueda+ 1998, Miller+ 2006 & 2008, Diaz Trigo+ 2014, Hori+ 2019 etc.)



- line-of-sight velocity: $10^2 \sim 10^3$ km/s

- seen only in high inclination sources (>~60 deg)

  → likely to have a small solid angle



Disk winds in BHXBs

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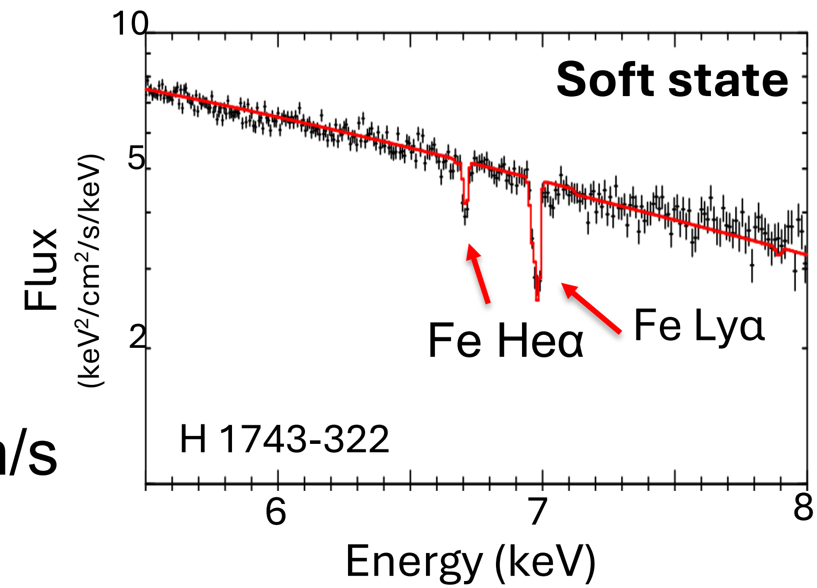
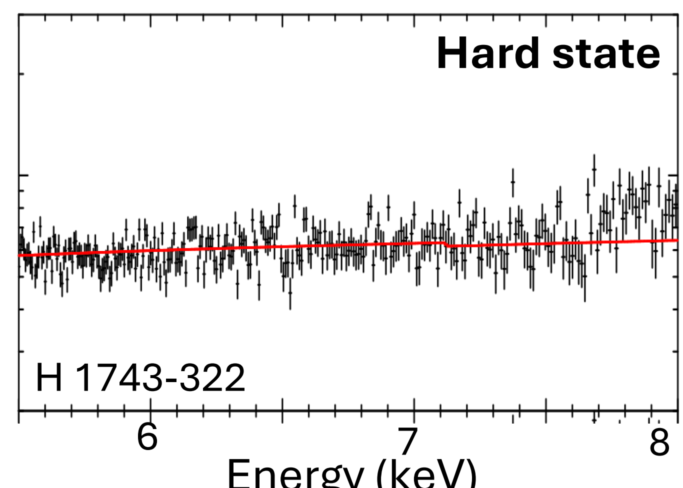


- line-of-sight velocity: $10^2 \sim 10^3$ km/s
- seen only in high inclination sources (>~60 deg)

  → likely to have a small solid angle

- predominantly seen in the soft state (Ponti+ 2012, Parra+ 2024)

  → connection to disk & jet?



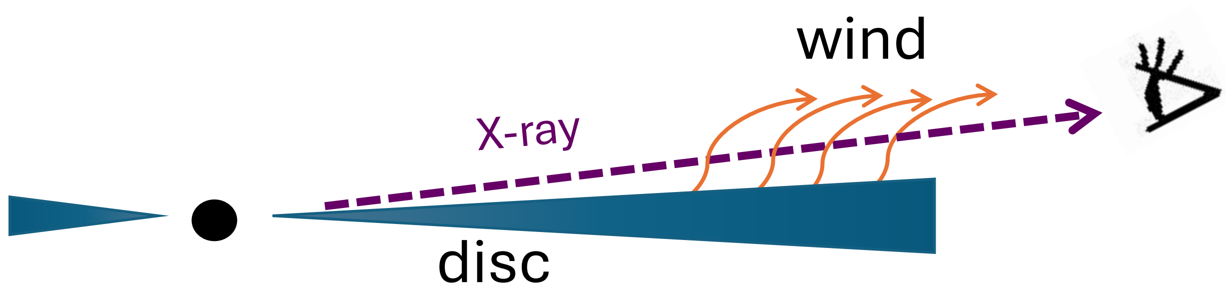
Shidatsu & Done (2019)

Possible launching mechanisms

(1) Radiation pressure driving

(2) Thermal driving

(3) Magnetic driving



Possible launching mechanisms

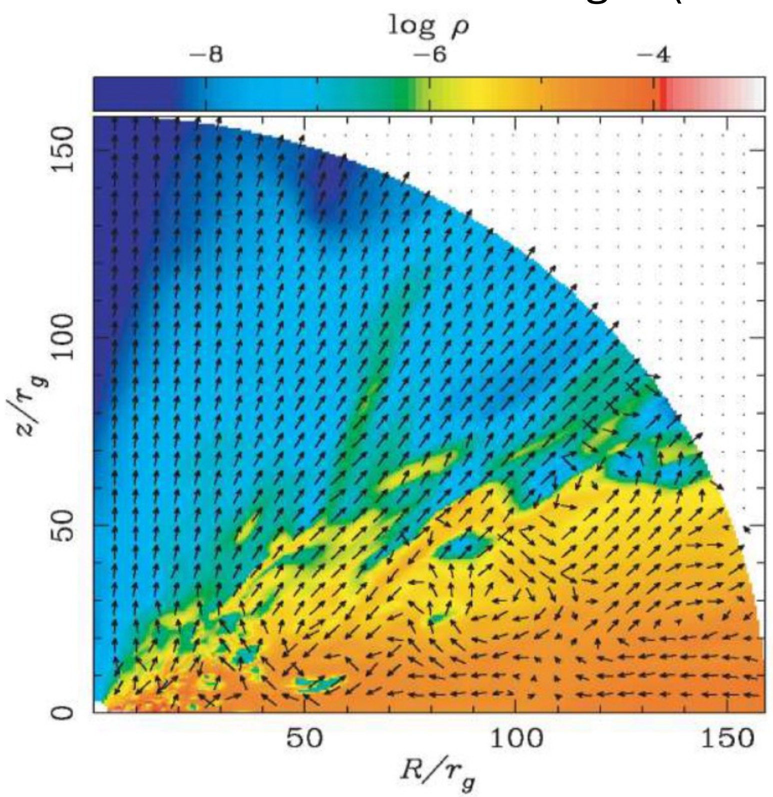
(1) Radiation pressure driving

- launch when radiation force > local gravity
- continuum driving (electron scattering),
  instead of UV line driving (e.g., Proga+ 2000, Nomura+ 2016)

- work when $L > L_{Edd}$

  but the Galactic BHXBs rarely reach L_{Edd} …

Ohsuga+ (2005)



Possible launching mechanisms

(2) Thermal driving

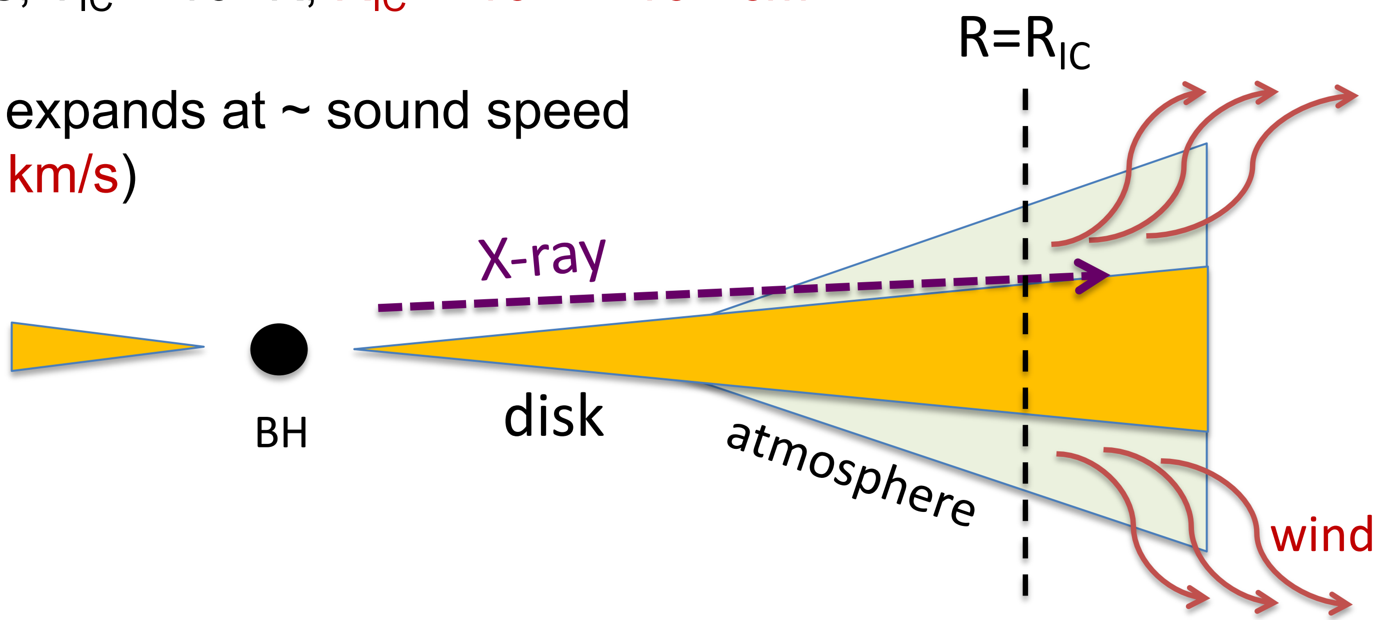
- heating of gas on the disk surface by irradiation

$$T_{\rm IC} = \frac{\int_0^\infty h\nu L_\nu d\nu}{4k\int_0^\infty L_\nu d\nu}$$

- gas is heated via Compton scattering up to Compton temperature $\mathbf{T_{IC}}$ and escapes as a wind when its kinetic energy overcomes the local gravity ($\mathbf{R_{IC}}$)

$$R_{IC} = GMm_p/kT_{IC}$$

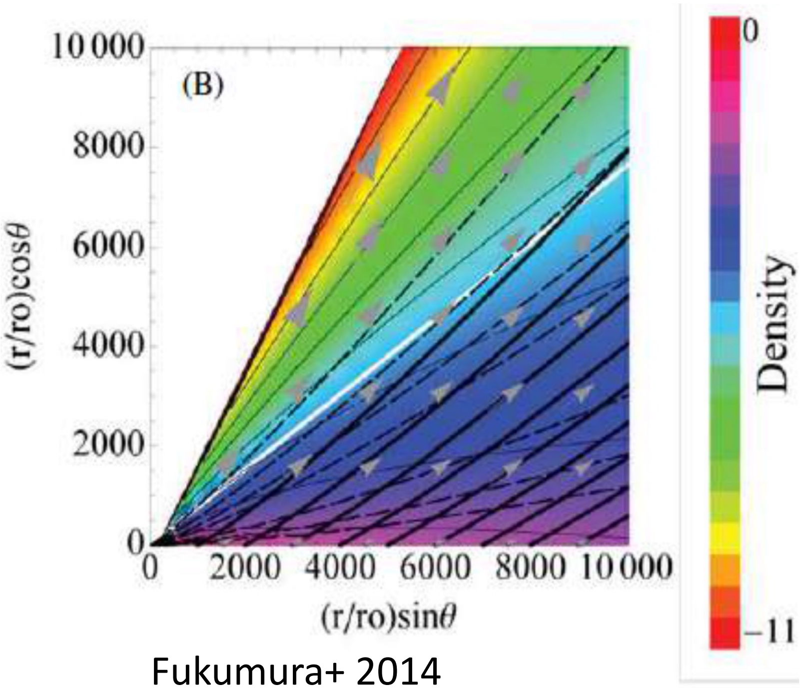
- In typical BHXBs, $T_{IC} \sim 10^7$ K, $R_{IC} = 10^{10} \sim 10^{11}$ cm (soft state)
- The heated gas expands at ~ sound speed ($v_{out} = 10^2 \sim 10^3$ km/s)



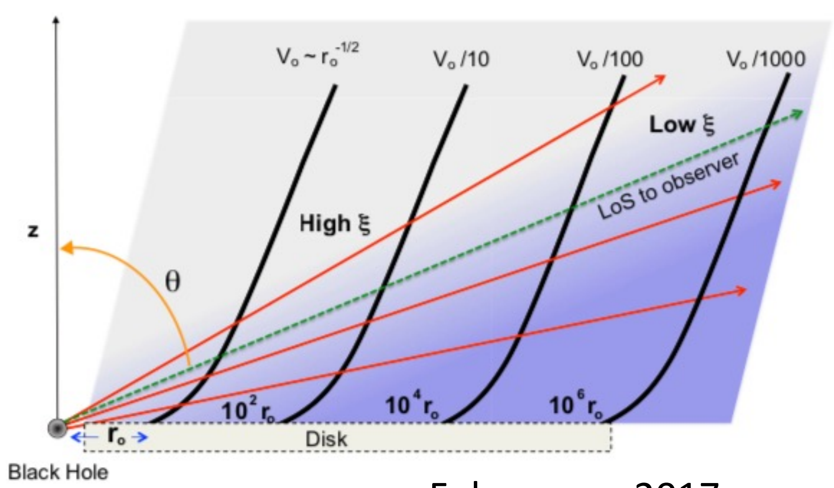
Possible launching mechanisms

(3) Magnetic driving

- models with self-similar structures can explain wind absorption lines (Fukumura+ 17)
- can launch at smaller radii with higher velocities than thermal driven winds (depending on the magnetic field structure)



Fukumura+ 2014

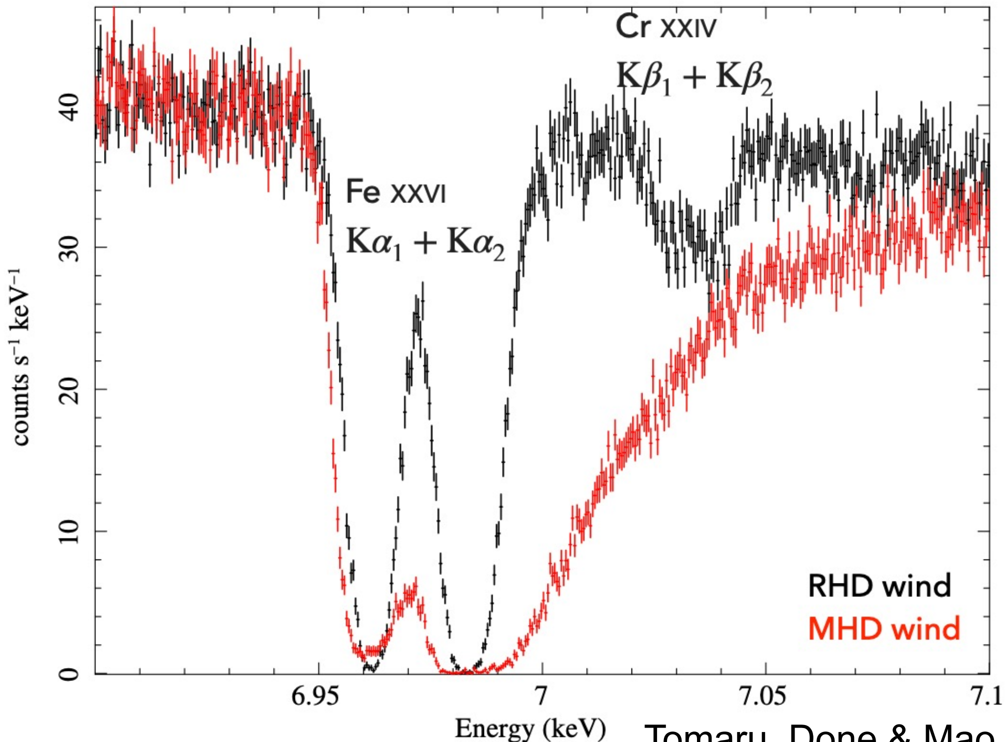


Fukumura+ 2017

Expected results from XRISM

Resolve (simulation)

thermal(-radiative) wind & magnetic wind



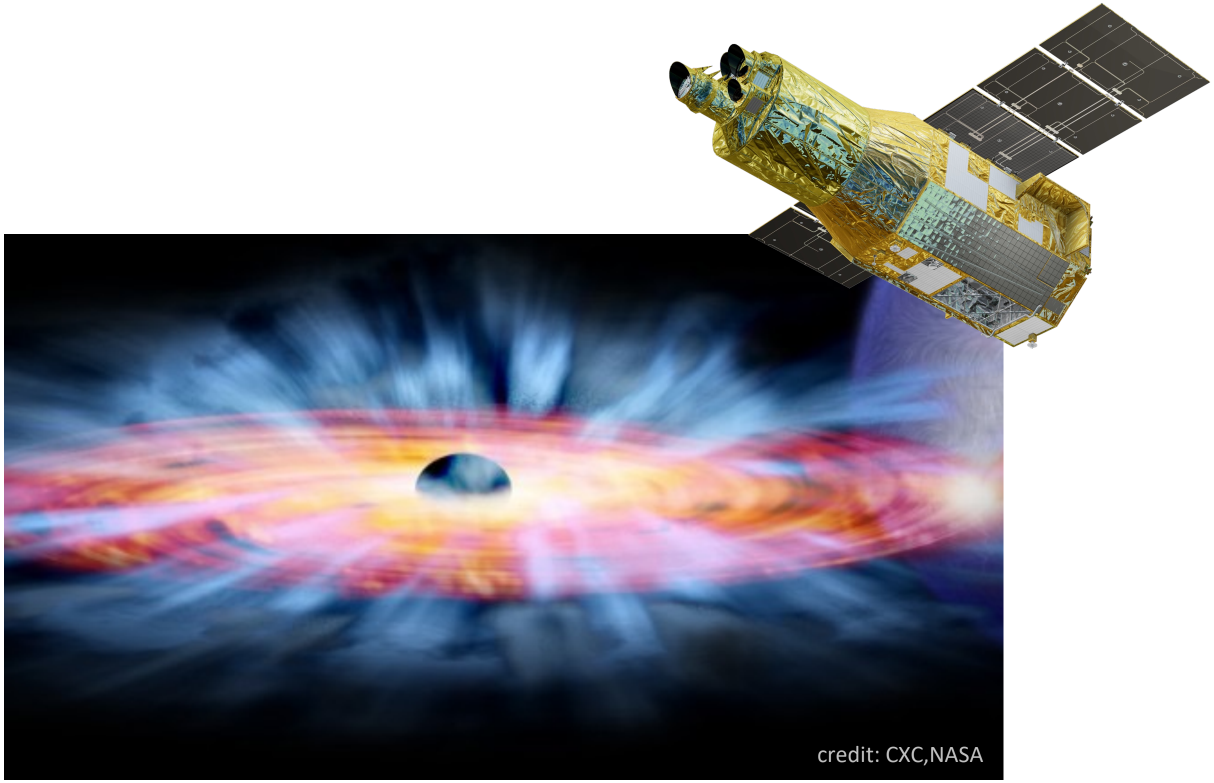
Tomaru, Done & Mao (2022)

Thanks to the high resolution (~5 eV) and high sensitivity around Fe Kα lines XRISM enables to study the profiles of absorption (& emission) lines in detail!

→ **velocity structure and geometry of winds will be revealed!**

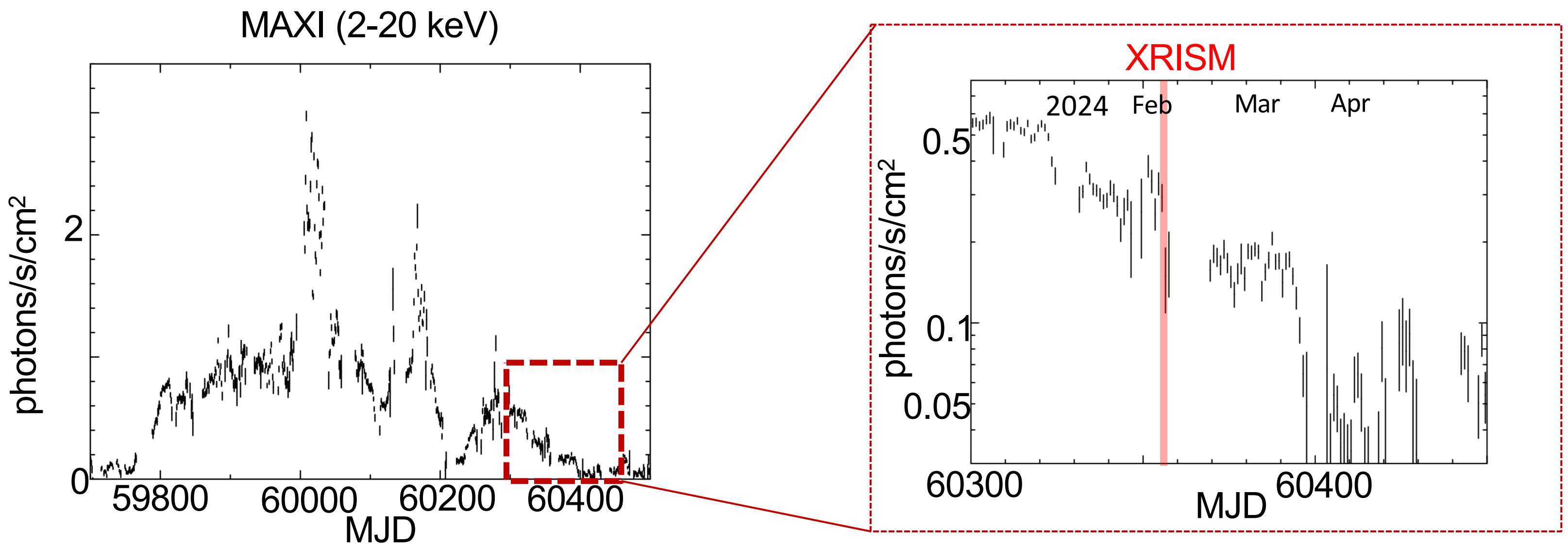
Key information for the wind launching mechanism and feedback effects

XRISM results



4U 1630-472

1st ToO observation of XRISM!



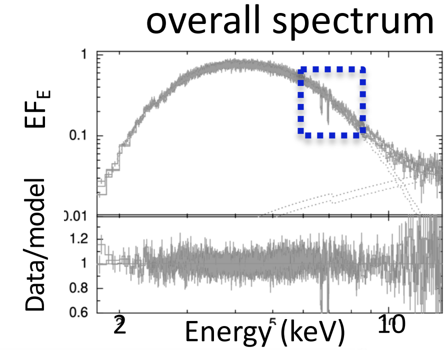
net exposure: ~50 ks

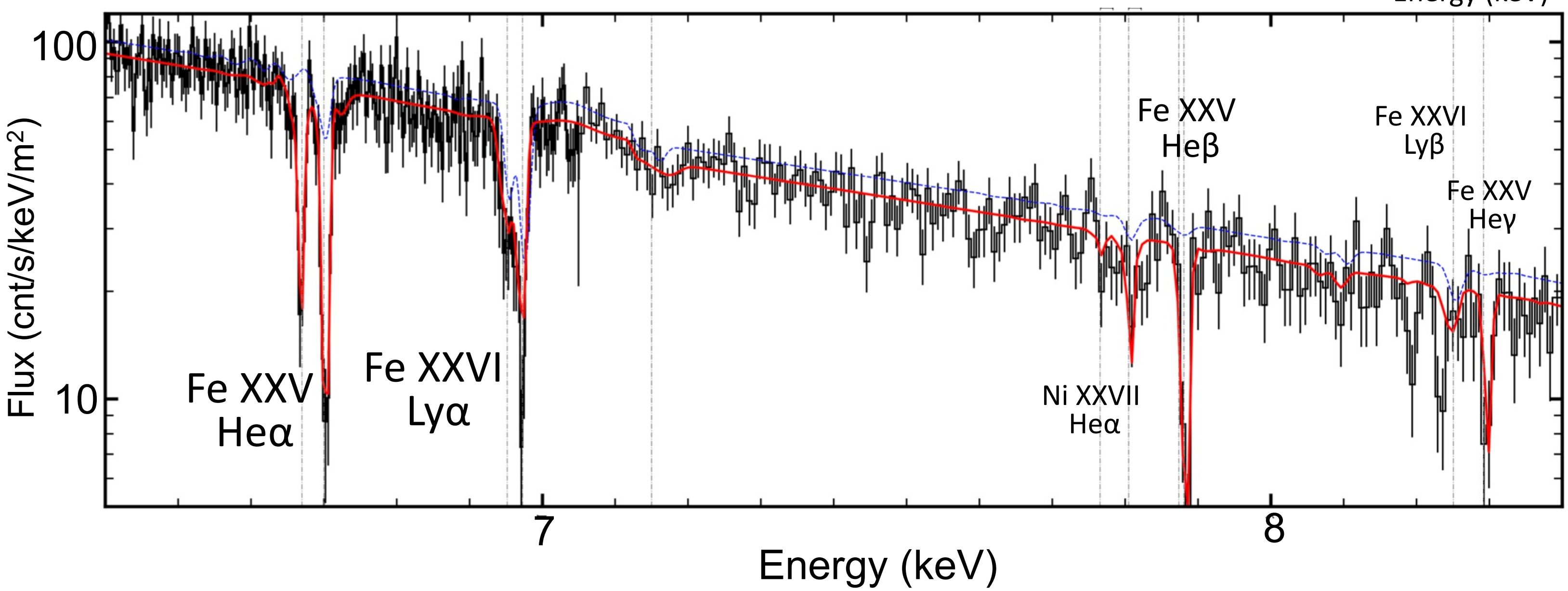
Miller, Mizumoto, Shidatsu+ (2025)

We were able to catch the last part of the decaying phase of the outburst

4U 1630-472 (soft state)

1st ToO observation of XRISM!



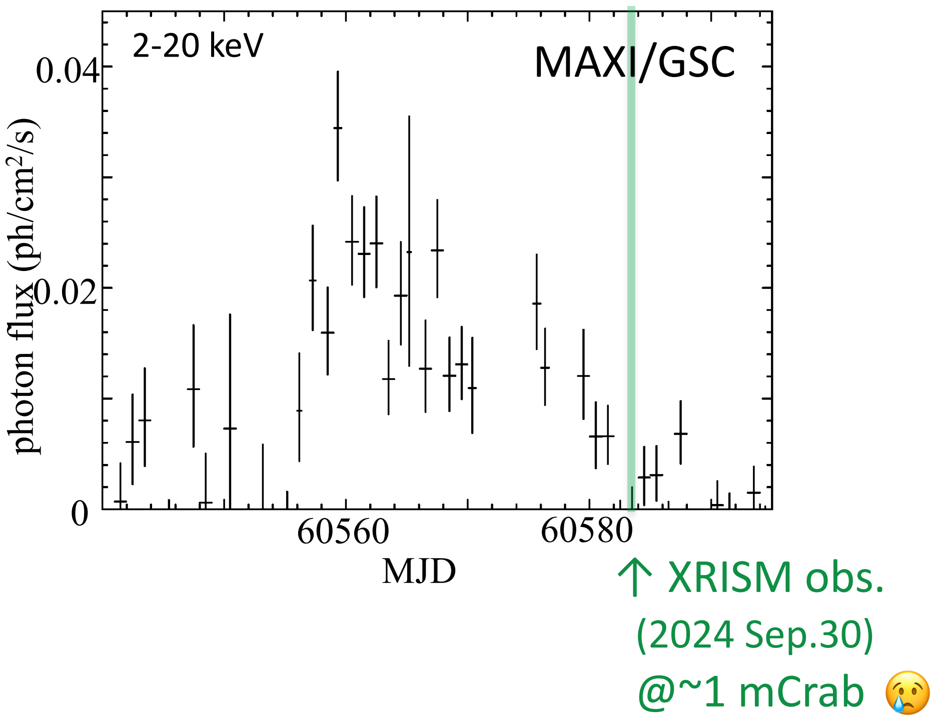


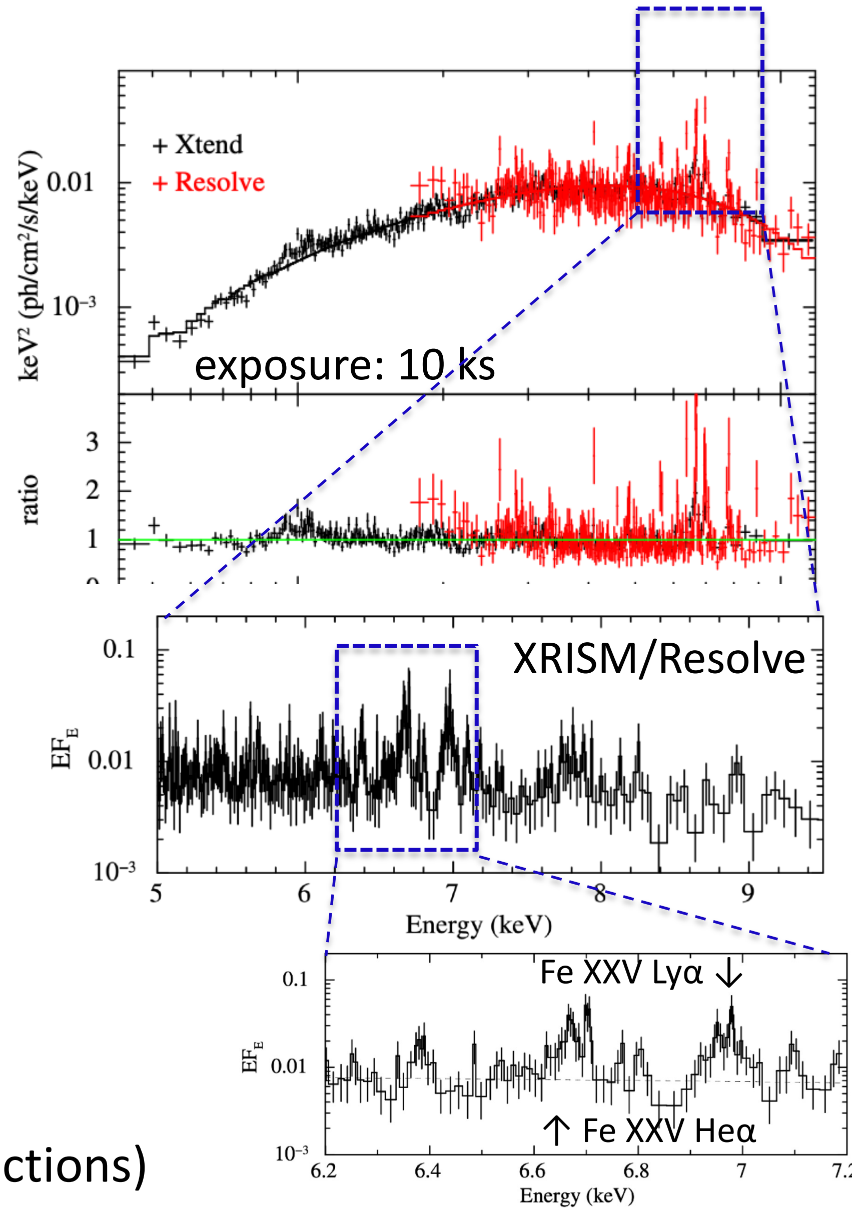
Miller, Mizumoto, Shidatsu+ (2025)

- **Lowest-luminosity detection** of absorption lines to date (~2% L_{Edd})
- **Slow line-of-sight velocity:** < ~200 km/s (below escape velocity)
  → structure bound on the disk

V4641 Sgr

1st DDT observation after the start of GO-phase



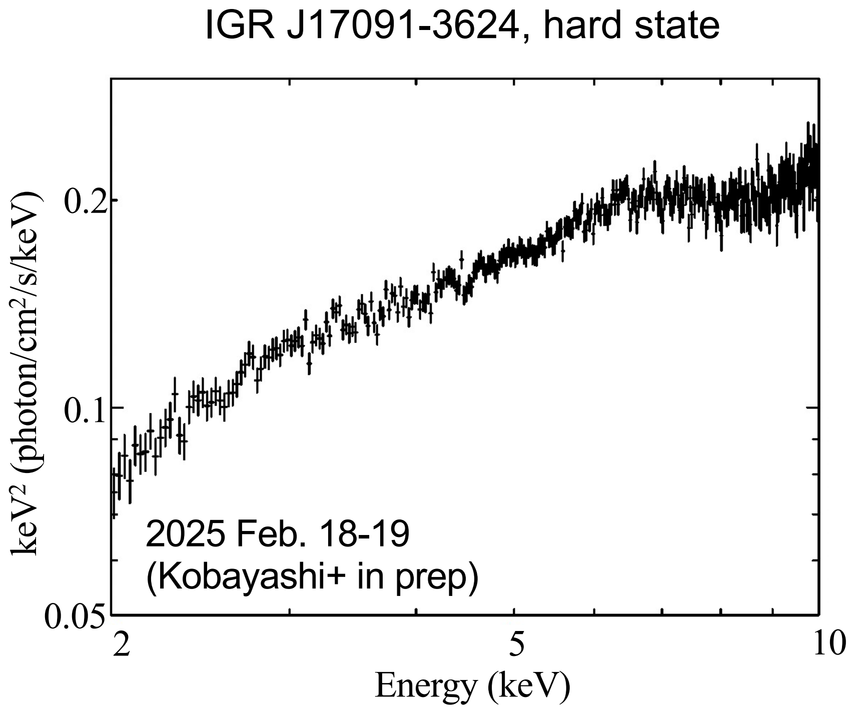


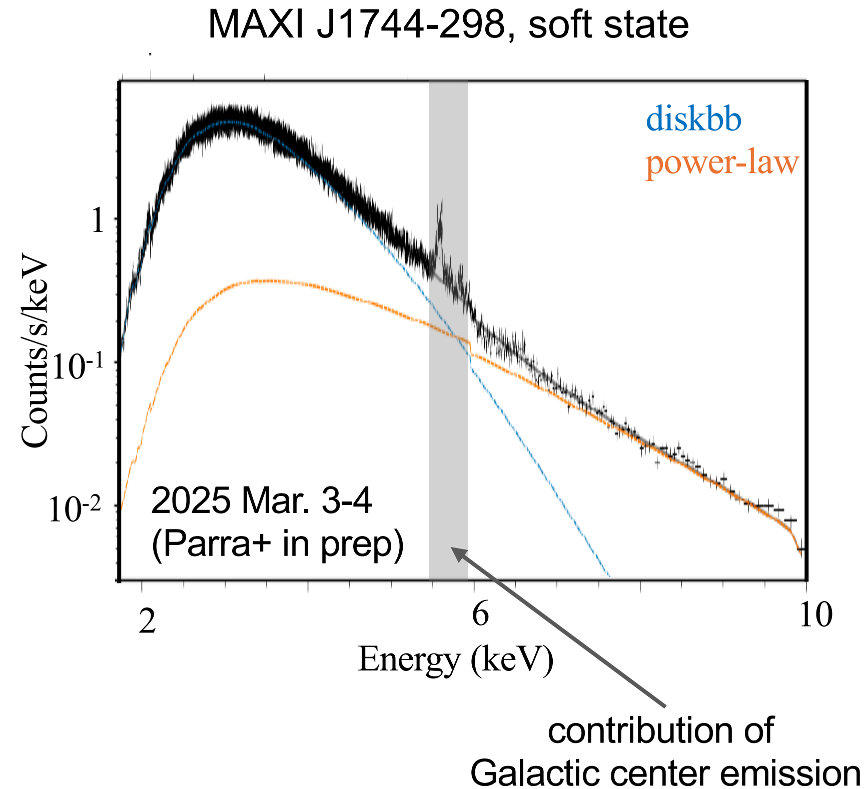
- dim (~ 10^{35} erg/s ~ 10^{-4} L_{Edd}) but disk blackbody-like spectrum
- Highly ionized Fe emission lines (see Shaw+ 2022 for previous Chandra detections)

→ inner disk region is heavily obscured??

Parra & Shidatsu+ submitted

Other BHXBs





No clear absorption lines from winds are visible

Summary of XRISM observations

see Maxime's talk for more details

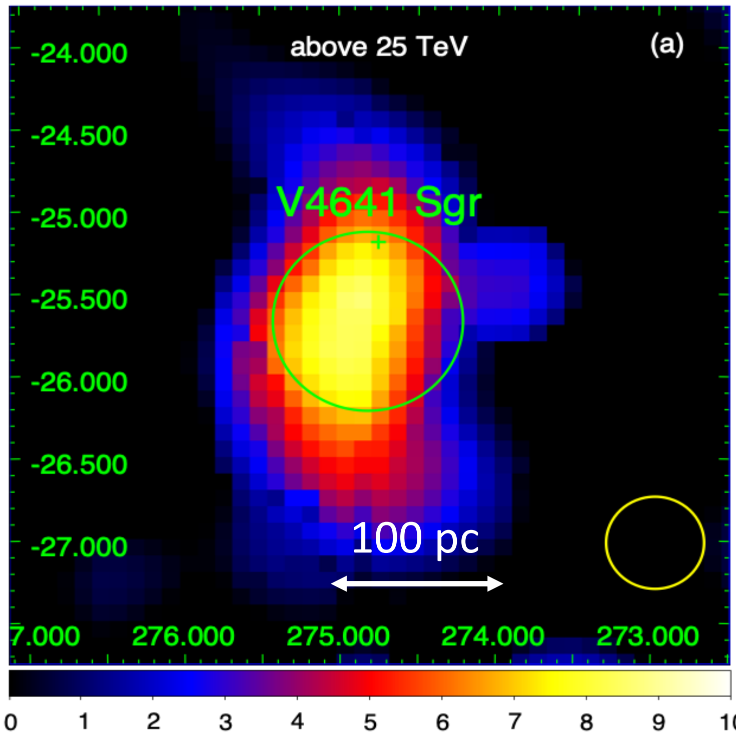
We have found:

- strong absorption lines (but unlikely to originate from winds) at very low L_{Edd} (~2%)
- narrow emission lines from an obscured source
- absence of clear absorption lines
  - in the soft sate of low inclination sources
  - in the hard state of high inclination sources

Observations conducted so far have been limited to unusual sources or sources/states where absorption lines from winds are not expected

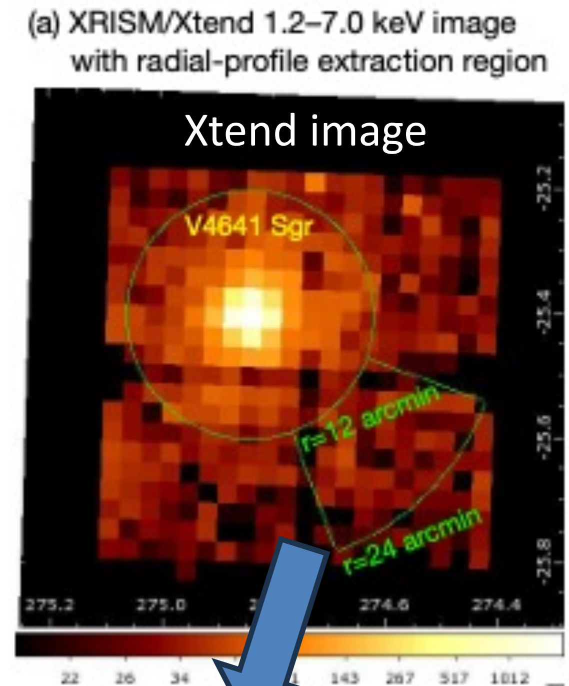
to understand disk winds, more observations of high inclination sources with winds are needed

Diffuse source emission around V4641 Sgr

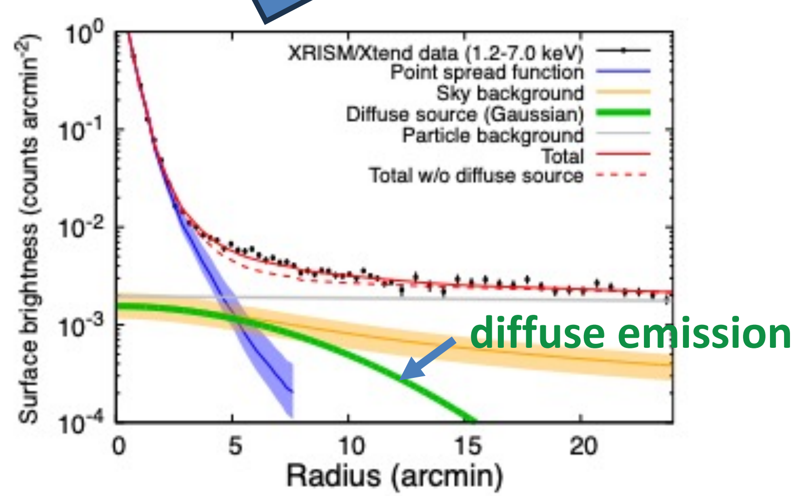


Ultra high energy (>1 TeV) gamma-rays have been detected (LHASSO Collaboration 2024, Nature)

X-ray (XRISM/Xtend)



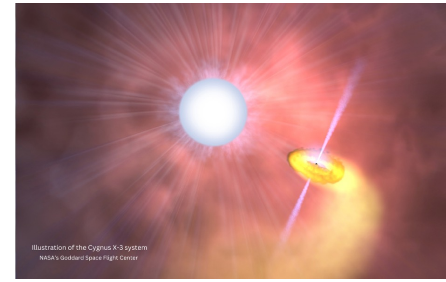
exposure ~10 ks

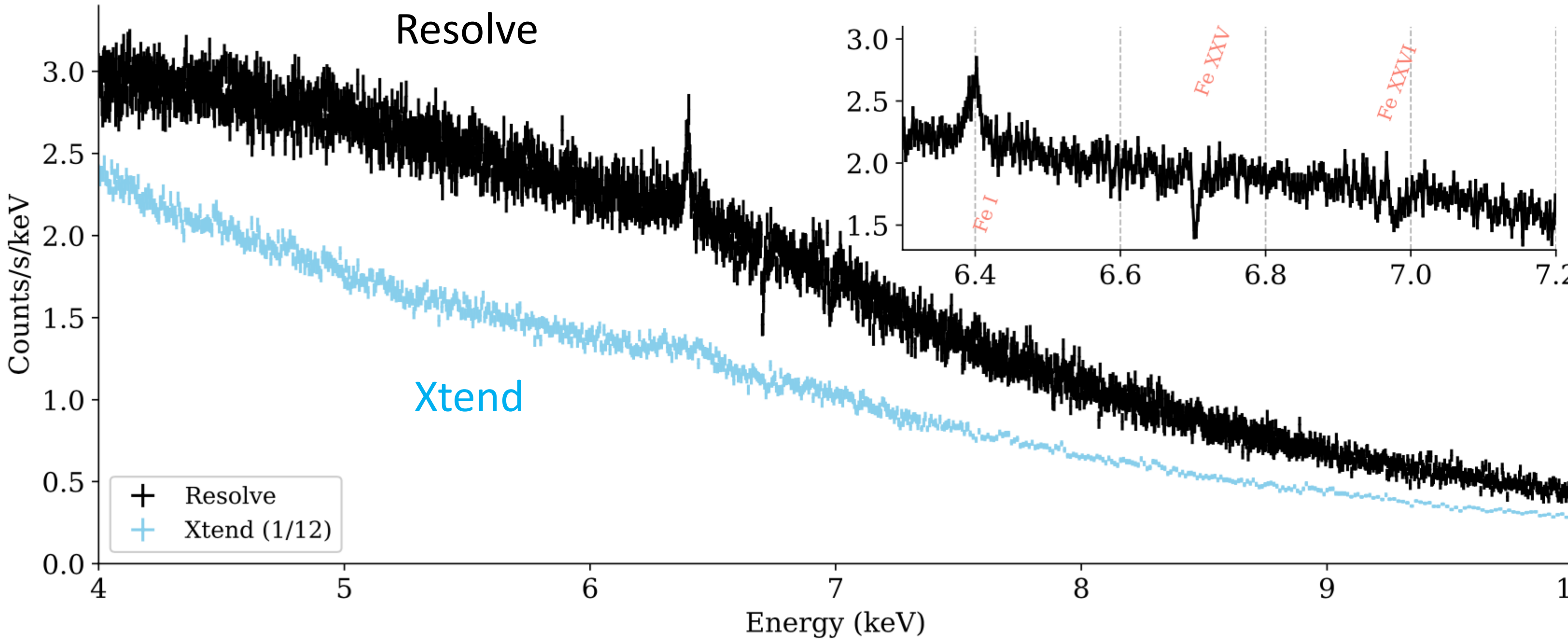


Suzuki+ (2025)

Extended X-ray emission was detected using XRISM's wide-field X-ray CCD Xtend!

High-mass X-ray binaries
Cyg X-1





Yamada, Hell+ (2025), PASJ accepted

see Michael McCollough's talk for Cyg X-3

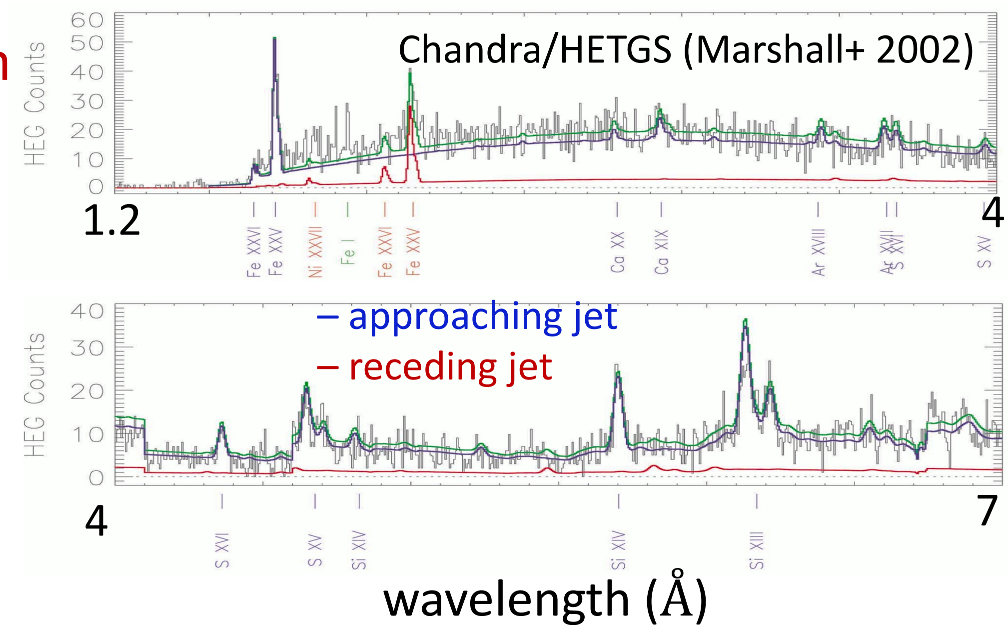
high-resolution X-ray spectroscopy of jets in SS 433

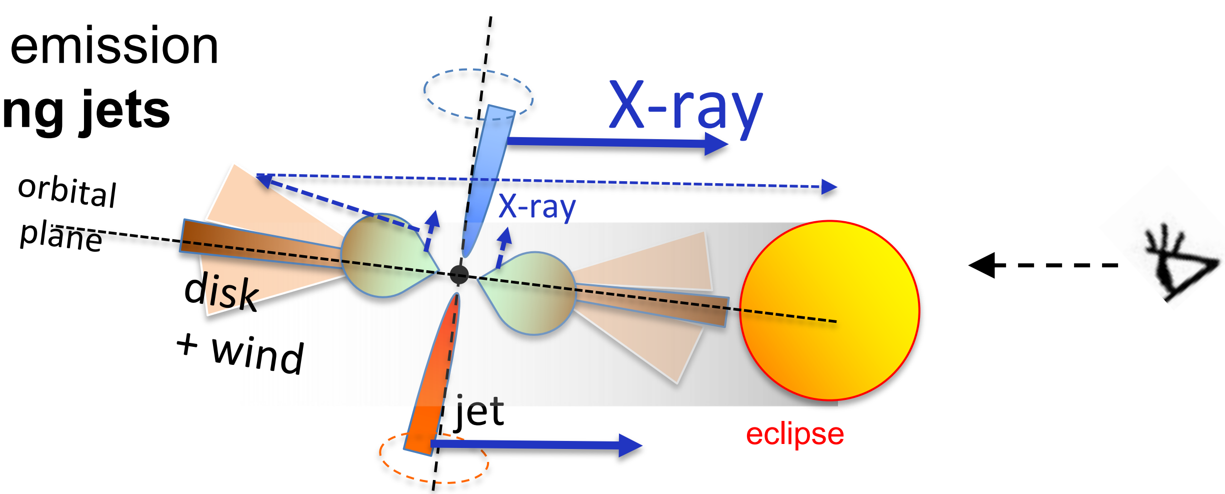
SS 433

a unique X-ray binary with
- persistent supercritical accretion (L_{UV} ~ 1e40 erg/s)
- persistent bipolar baryonic jets with a ~162-day precession and nodding motions

high inclination angle (~78 deg)
-> inner disk is obscured

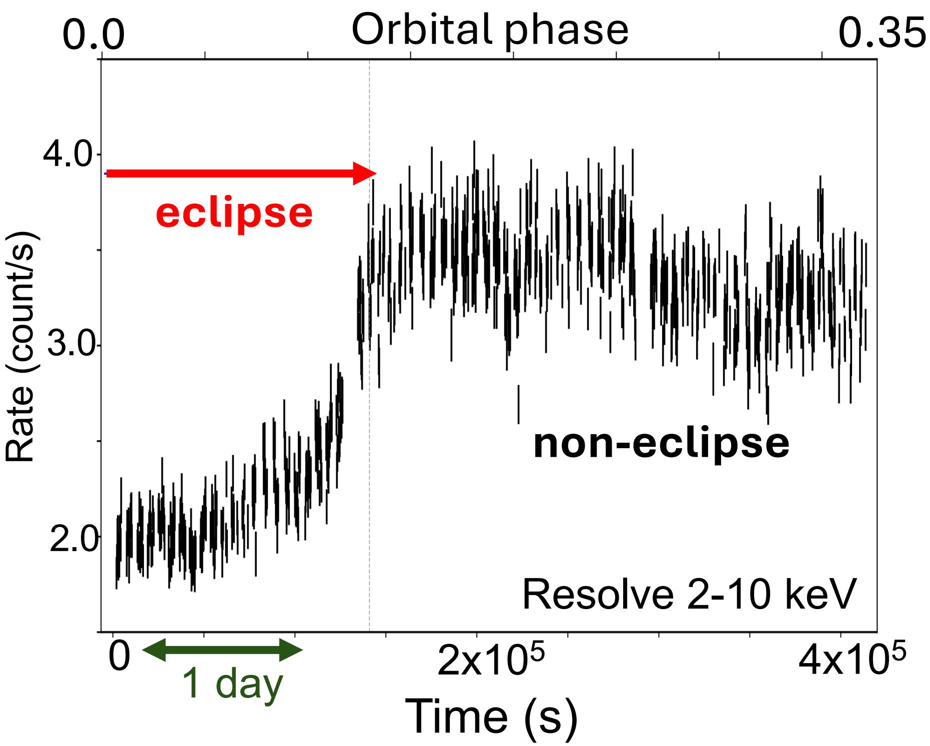
the X-ray spectrum is dominated by thin thermal plasma emission from **bipolar, precessing jets**





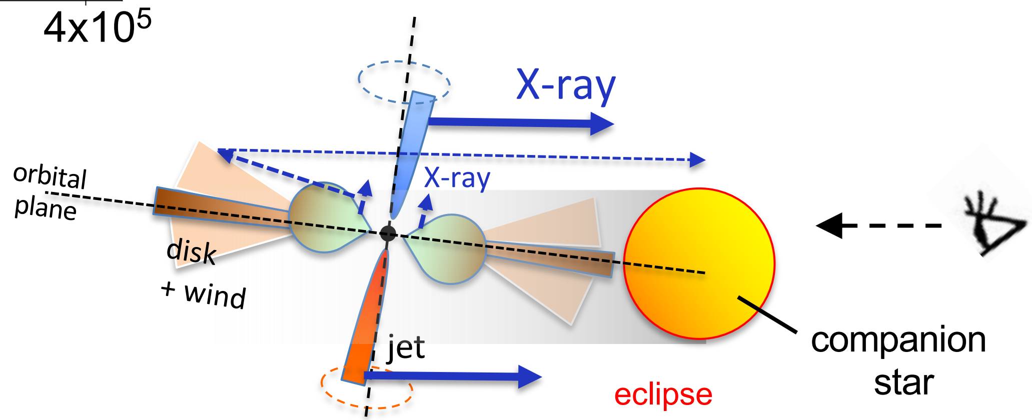
XRISM observation (overview)

Period: 2024 Apr. 10-15 (PV phase)
Net exposure: ~200 ks
Orbital phase: 0.0 ~ 0.35

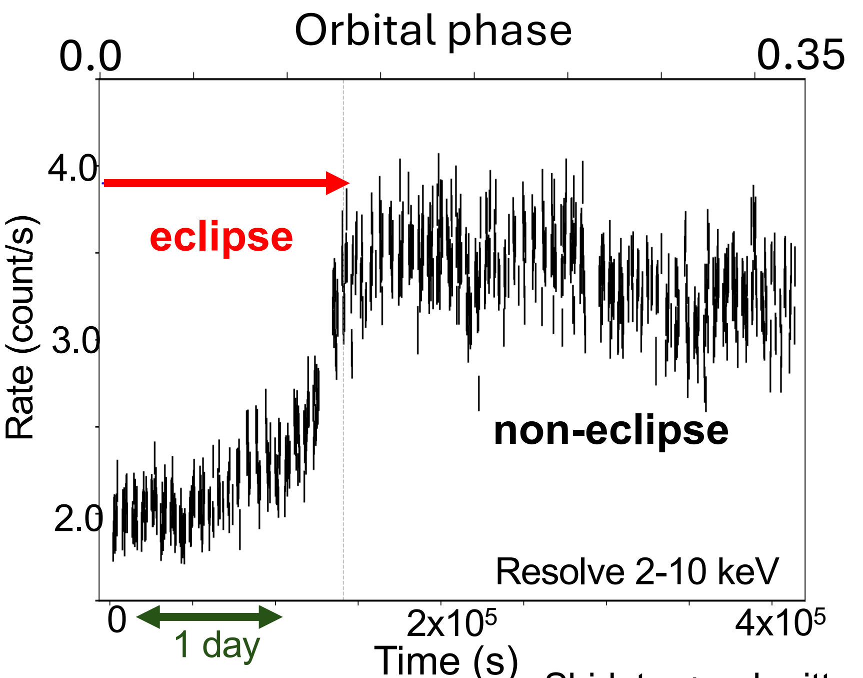


lower flux in eclipse phase
due to obscuration of innermost, hottest part of the jets
(e.g., Kawai+ 1989)

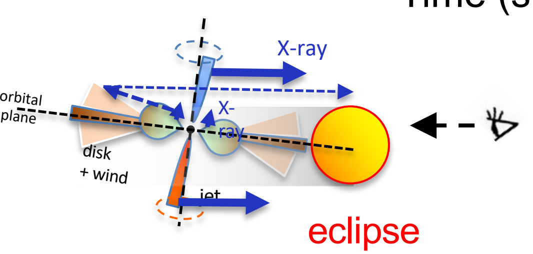
Shidatsu+ submitted



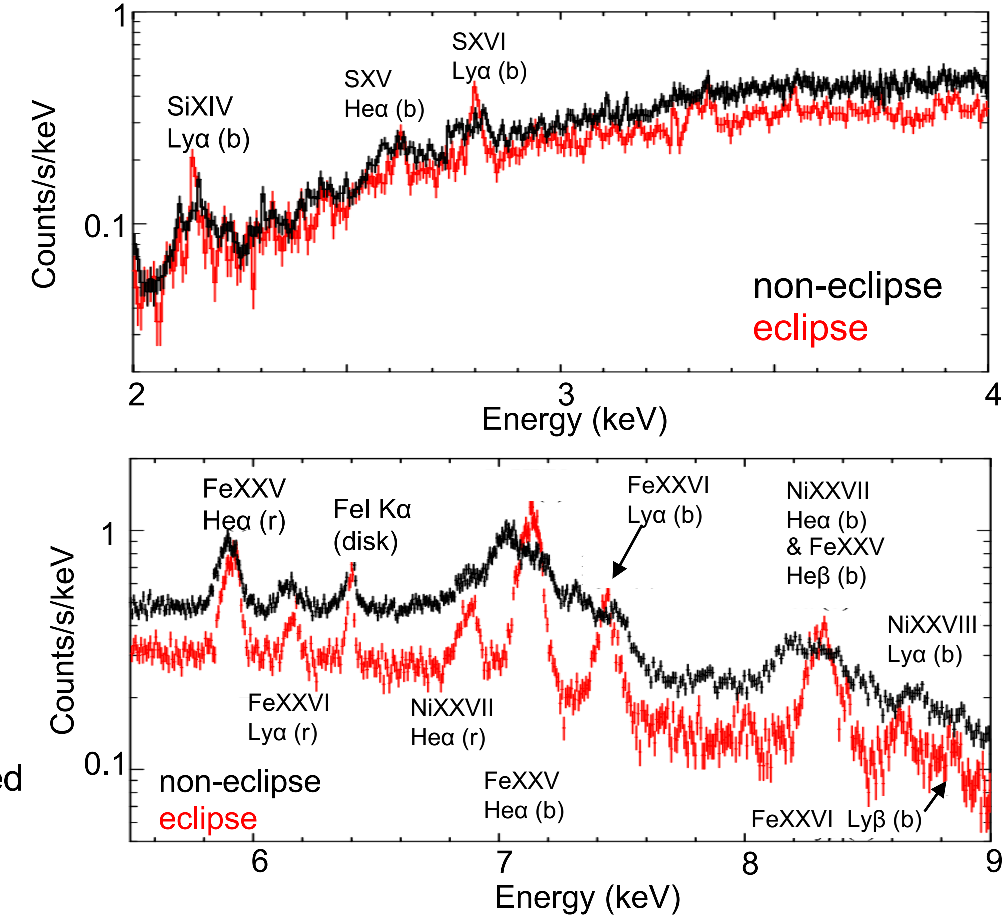
XRISM observation (overview)



Shidatsu+ submitted



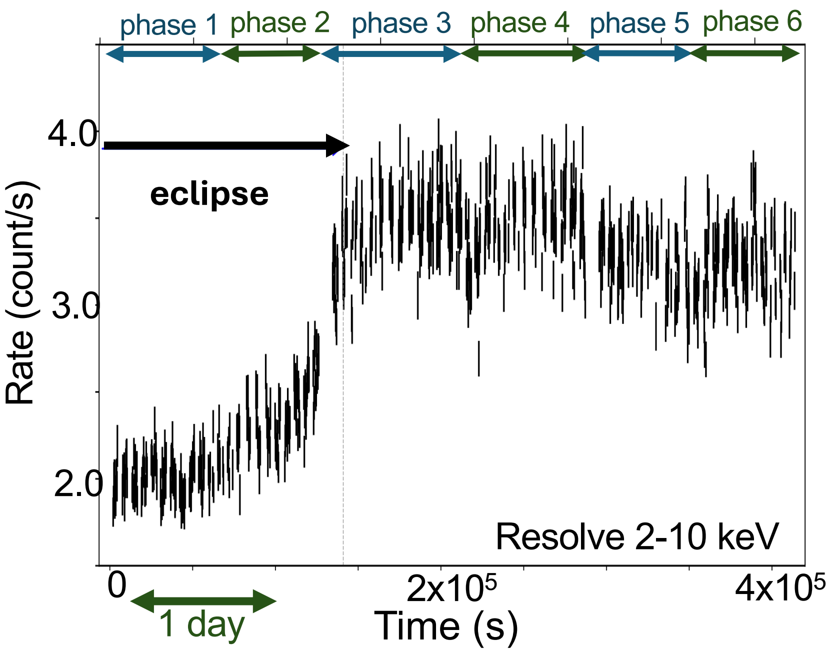
Resolve spectra

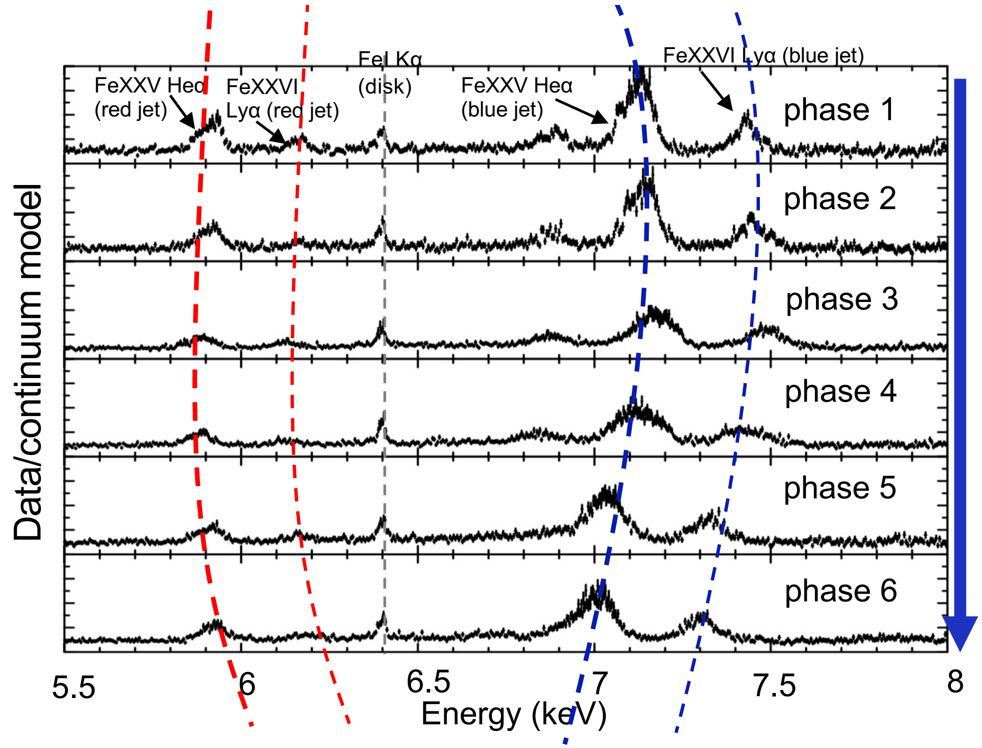


(b): approaching jet
(r): receding jet

lines are significantly broadened by the jet precession…

Resolve data





Shidatsu+ submitted

Broad lines from the precessing bipolar jets
+ a narrow FeI Ka line from the disk were detected

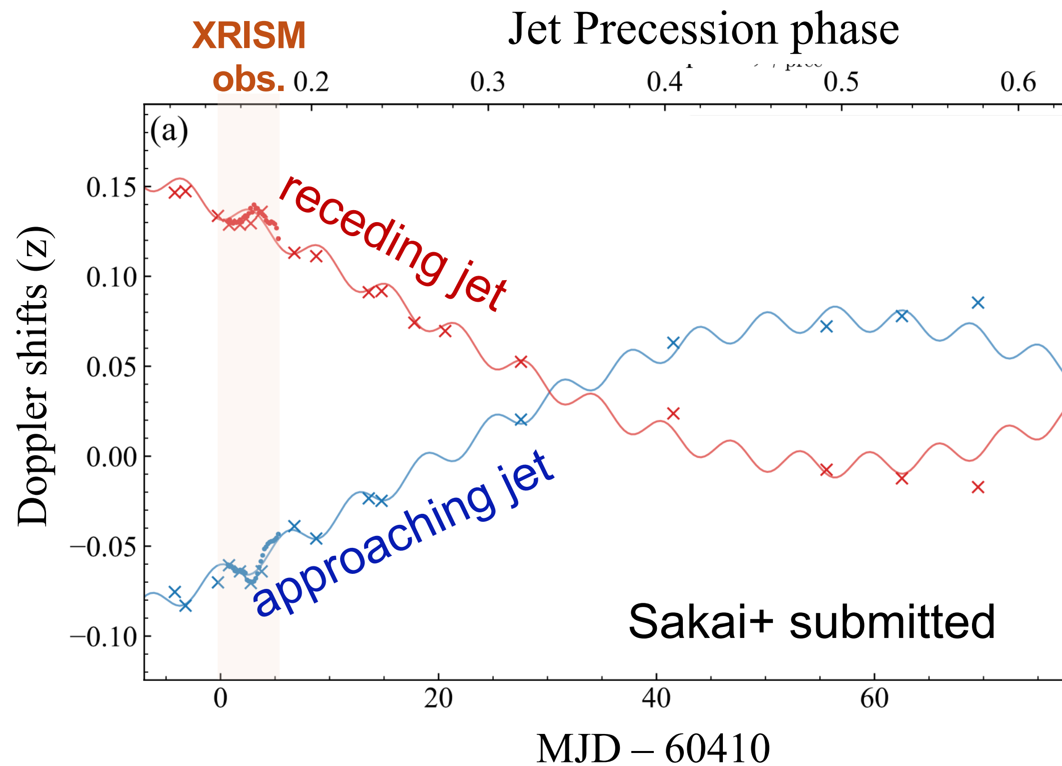
Precession & nodding motion

Optical spectroscopic monitoring was also carried out

Doppler shift variations measured from XRISM/Resolve is consistent with those from optical Hα lines

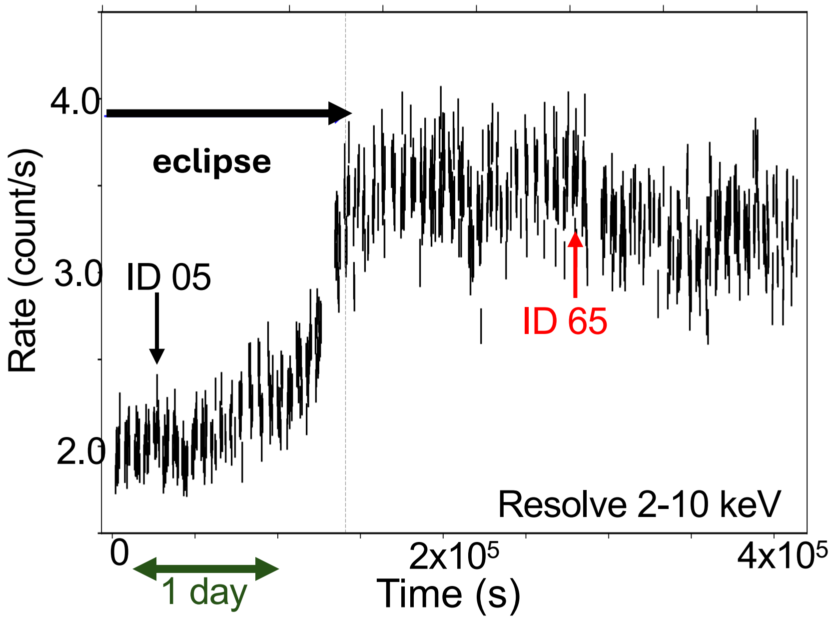
→ jet speed is not significantly decelerated from X-ray to optical emitting regions

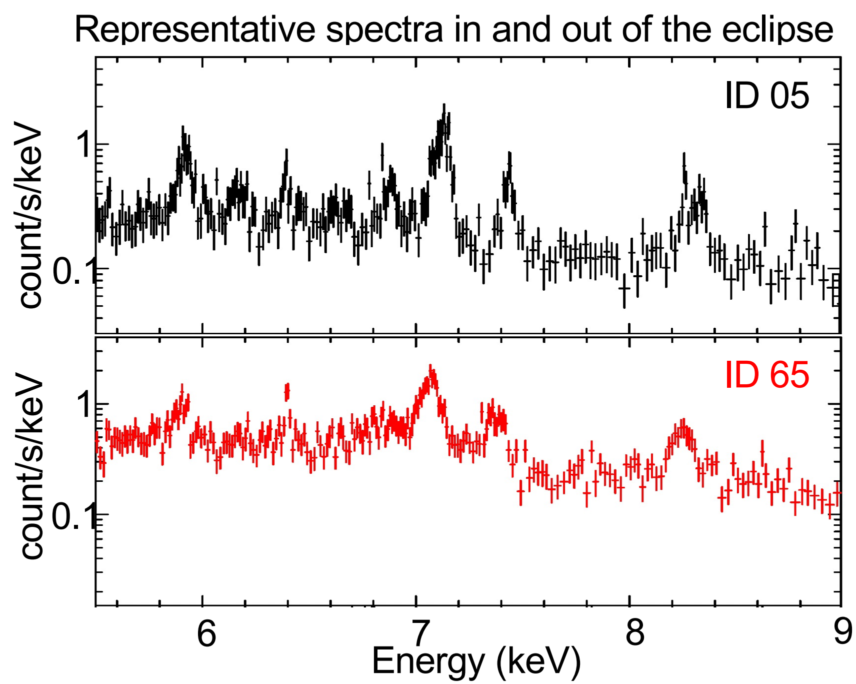
(consistent with previous works; Kubota+ 2010, Marshall+ 2013)



● X-ray (XRISM/Resolve)
× optical (Hα, Seimei Telescope, Japan + LCO, Hawaii)
– model (Gies+ 2002, Davydov+ 2008)

Time variation of Resolve spectrum





Shidatsu+ submitted

To reduce the line broadening
due to the jet precession, we divided the data into the individual orbits

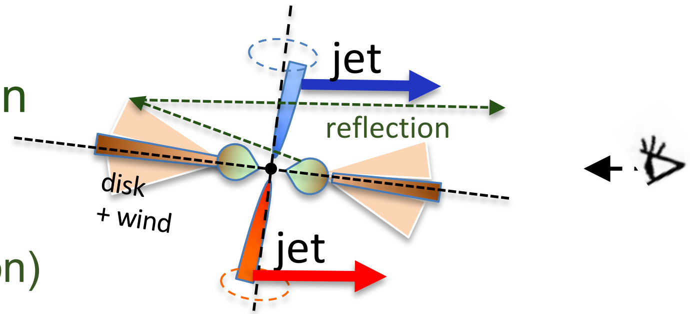
number of data segment: 95, averaged exposure: ~ 3500 s / orbit
=> line broadening by precession: 100~200 km/s (Gies+ 2002)
(= 2-4 eV @ 7 keV)

Modeling the Resolve spectra

Energy range: 5.5-9.0 keV

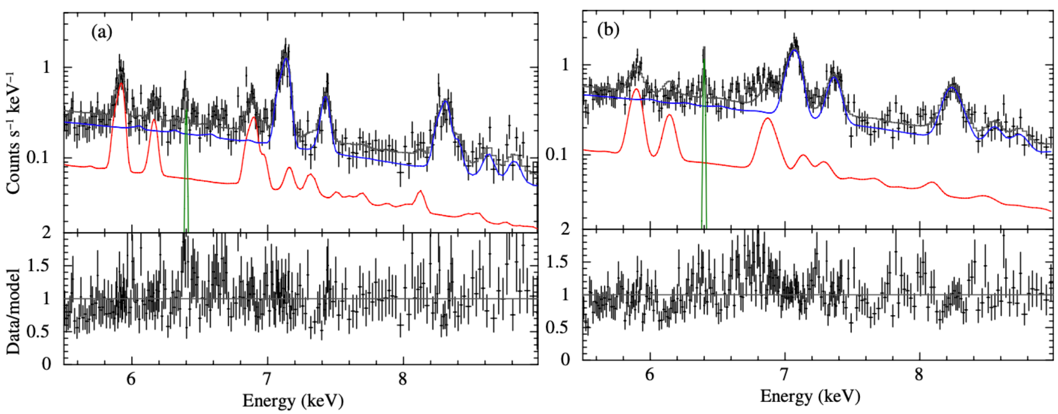
Model: gsmooth * (vapec + vapec) + Gaussian

- gsmooth ↑ line broadening (Gaussian)
- vapec ↑ approaching jet
- vapec ↑ receding jet
- Gaussian ↑ FeI Kα (reflection)



eclipse (ID=05)

non-eclipse (ID=65)



Shidatsu+ submitted

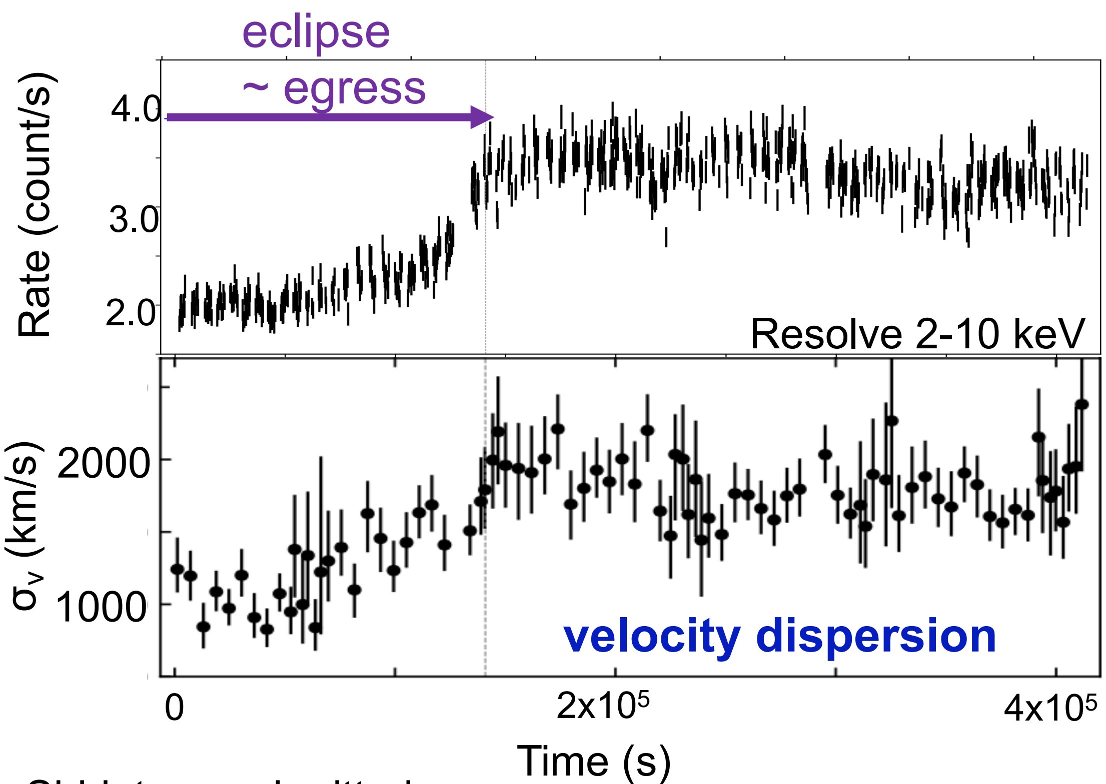
	eclipse	non-eclipse
ID	05	65
Jet parameters (vapec)		
kT (keV)	6.3 ± 0.4	$7.2^{+0.4}_{-0.3}$
A_{Ni}	8^{+2}_{-1}	8 ± 1
z_b (10^{-2})	-6.20 ± 0.05	-5.44 ± 0.05
z_r (10^{-2})	13.0 ± 0.1	13.4 ± 0.1
Line broadening (gsmooth)		
σ (km/s)	1000 ± 100	1800 ± 200

FeI Kα: E=6.4 keV (fixed), σ = 10 eV (fixed)

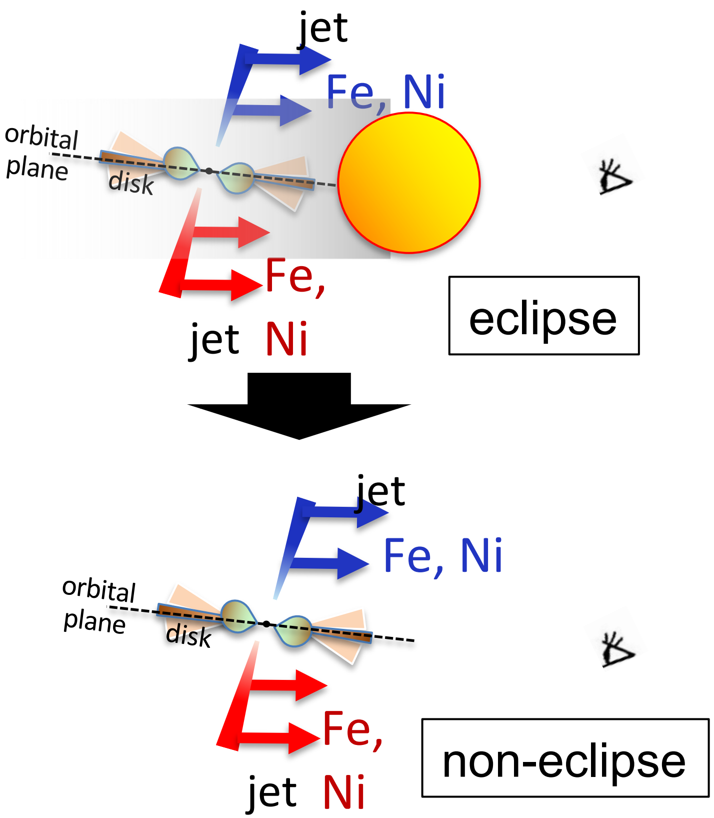
A_{Ni}: Ni abund. (/solar)

Note: all the parameters except for the line shift of the two jet components are linked

Variation of velocity dispersion (line width)



Shidatsu+ submitted

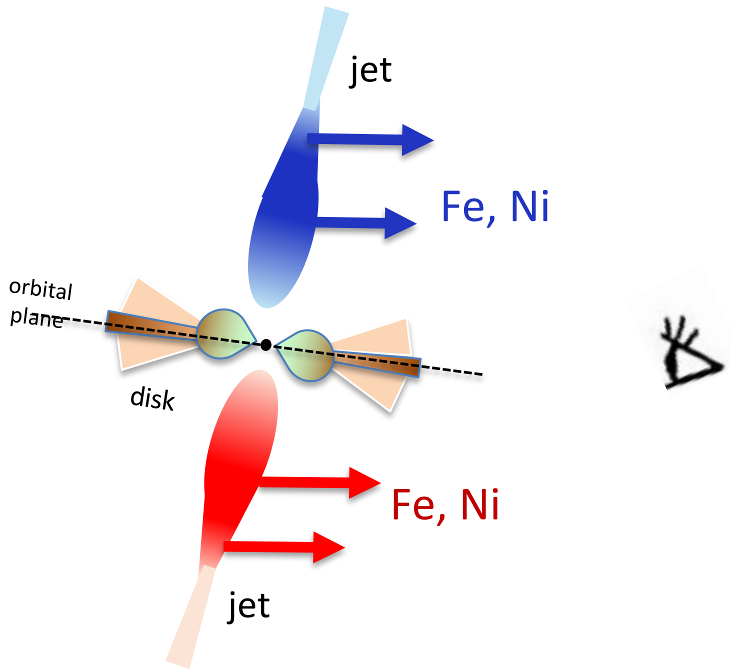


The velocity dispersion (= line width) gradually increases during egress

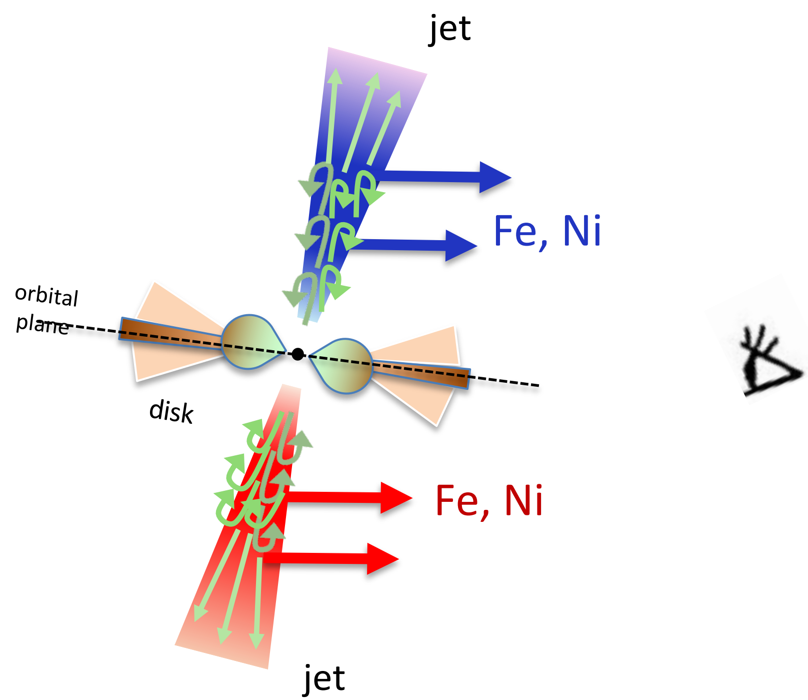
= velocity dispersion decreases as jet plasma travels outward

What causes the decrease of σ_v?

- Progressive jet collimation? (Namiki et al. 2003)



- Jet becomes laminar?



X-ray emitting region: ~10^{12} cm (Kotani+ 1998)

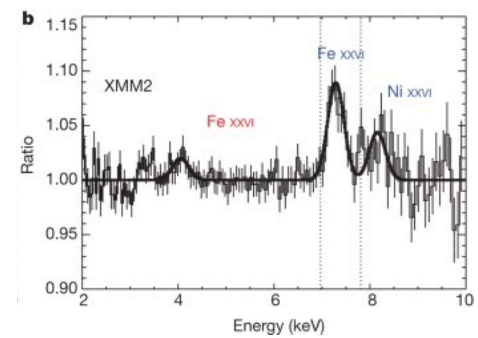
Comparison with simulations is needed!

Summary of SS 433$_+$

XRISM/Resolve has enabled a time-resolved investigation of the plasma properties and dynamics in the jets

More works are in progress!!

- multi-wavelength campaign (Sakai+ submitted)
- modelling FeI Kα line, Ni/Fe abundance ratio (Takagi+ submitted)
- variation of X-ray & optical line profiles (Usuki+ in prep)
- search for diffuse emission (Suzuki+ in prep)
- abundance measurement (Uenishi, Yoshimoto+ in prep), etc.



Diaz Trigo+ (2013)

Baryonic jets in normal BHXBs at brightest phases?
(4U 1630-472; Diaz Trigo+ 2013)

→ XRISM monitoring of hard-to-soft transition
(where powerful transient jets are observed) may be valuable

Summary

- High resolution X-ray spectroscopy is a powerful tool to probe plasma properties and dynamics around BHs
- XRISM/Resolve is driving great progress in our understanding of the outflows.
- more observations (including monitoring observations covering hard-to-soft state transitions) are needed to uncover the launching mechanism/feedback effects/ evolution of winds and search for baryonic jets