

Probing the Vicinity of Supermassive Black Holes with State-of-the-Art X-ray Spectroscopy

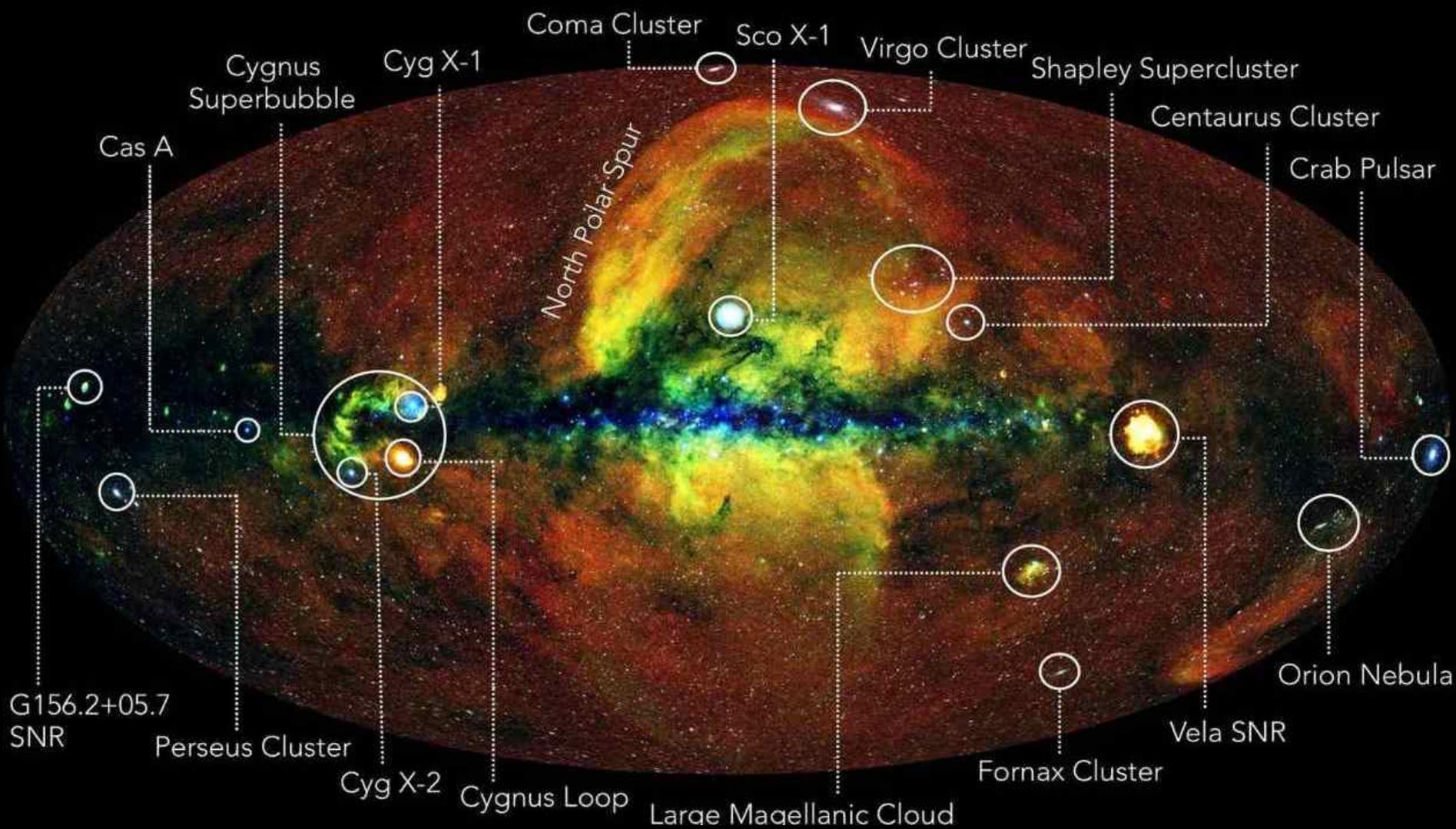
2026 Feb 10

Astronomical Institute, Tohoku Univ.

Hirofumi Noda

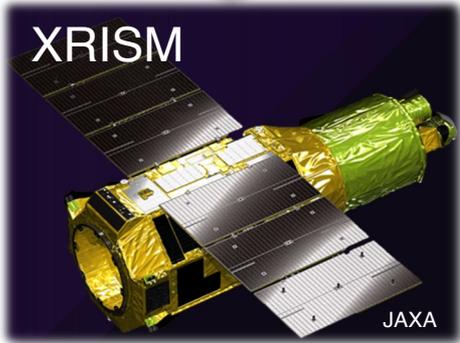
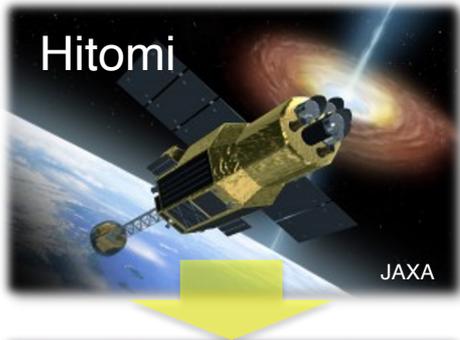


X-ray Universe

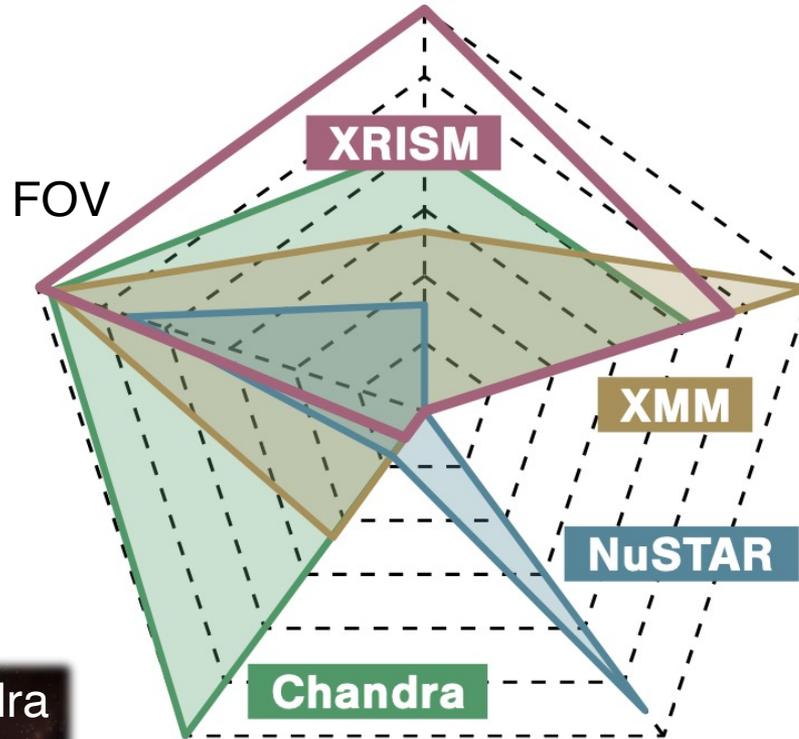


(credit) MPE

X-ray Observatories (Only Pointing Type)



Energy resolution@6 keV



Spatial resolution

Hard X-ray effective area @30 keV



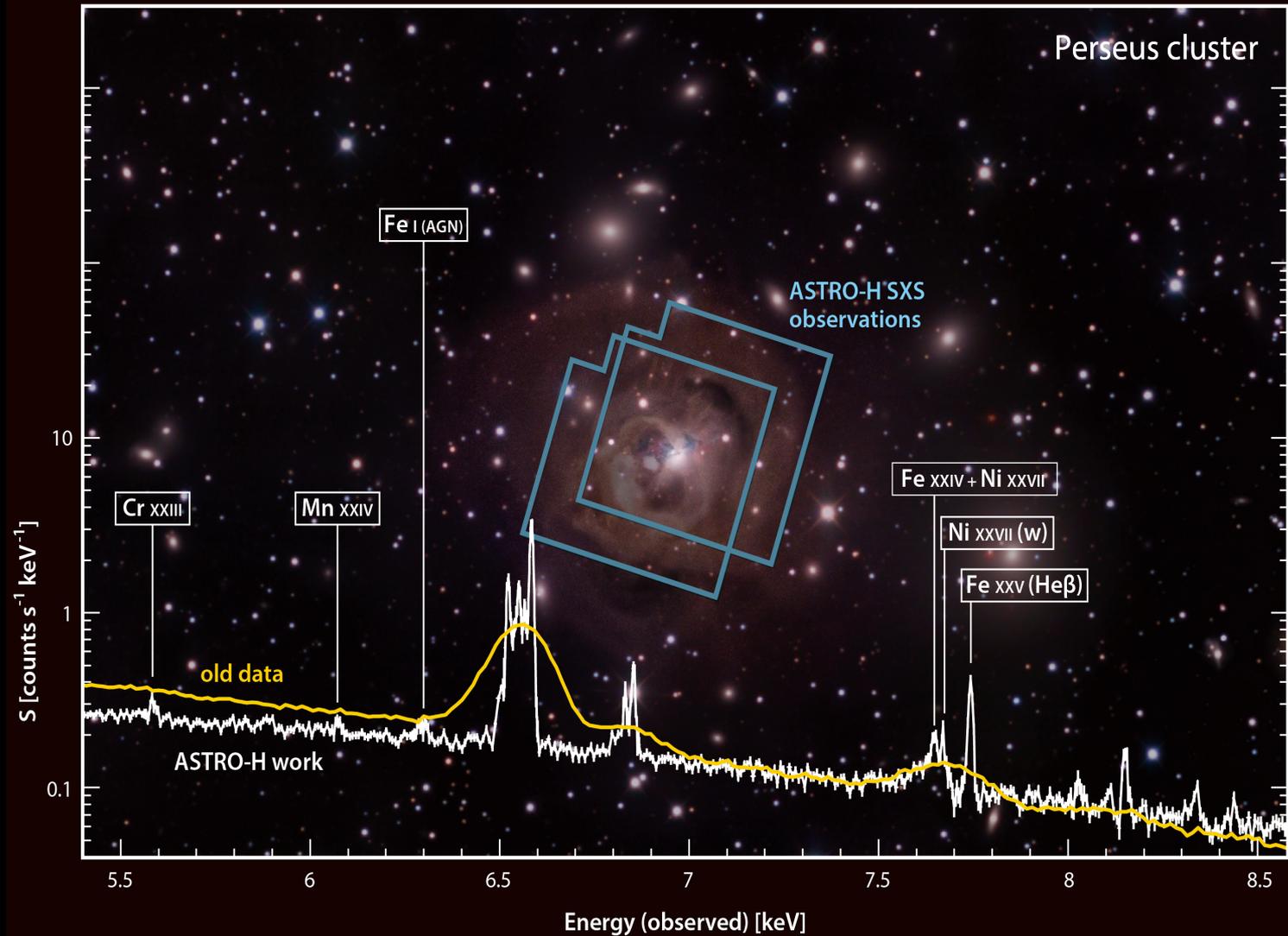
Soft X-ray effective area@1 keV



From XRISM press kit

First Precise X-ray Spectroscopy Realized by Hitomi

Hitomi collaboration (2016, 2018), Credit: JAXA/Ken Crawford (Rancho Del Sol Observatory)



However, the attitude control trouble occurred and the Hitomi operation was terminated just a month after the launch...

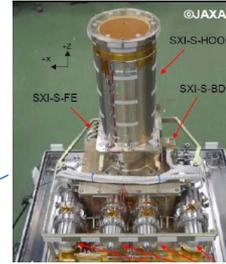
X-Ray Imaging and Spectroscopy Mission (XRISM)

A recovery mission of Hitomi (ASTRO-H), launched in 2016 Feb 17 and abandoned after a month

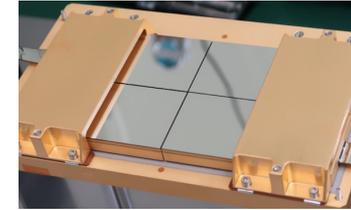
X-ray Mirror Assembly (XMA)



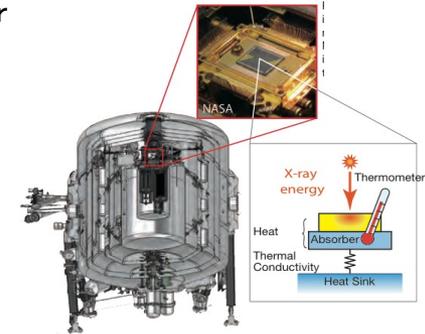
Xtend-Soft X-ray Imager



Noda et al. (2025)



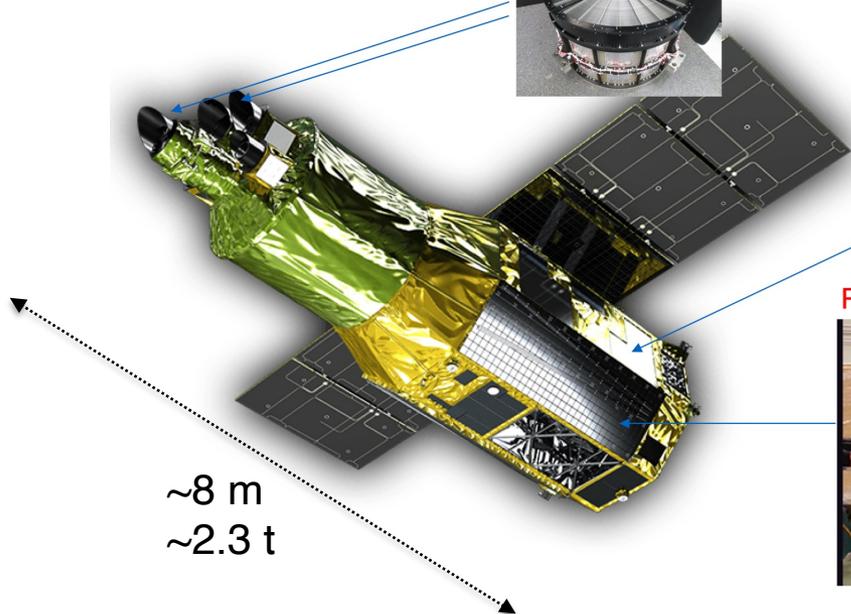
Kelley, +, Noda et al. (2025)



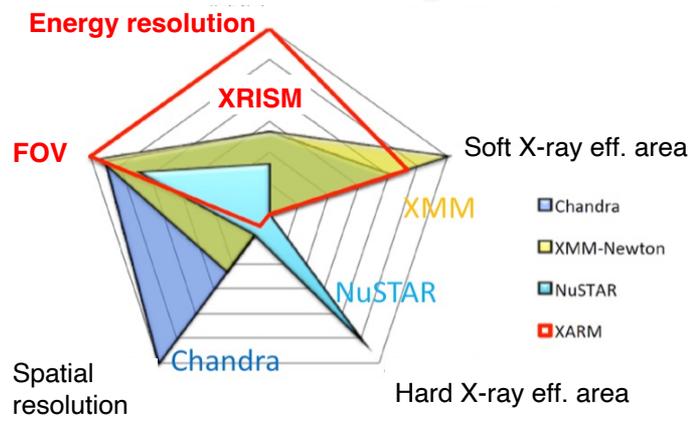
Resolve-Soft X-ray Spectrometer



XRISM quick reference



~8 m
~2.3 t



Instrument	FOV/pix	ΔE (FWHM at 6 keV)	E band
Resolve (X-ray mirror assembly + X-ray microcalorimeter)	2.9' \square / 6x6 pix	7 eV (goal 5 eV)	0.3–12 keV
Xtend (X-ray mirror assembly + X-ray CCD camera)	38' \square / 1280x12 80 pix	< 200 eV (BOL)	0.4–13 keV



宇宙航空研究開発機構



米国家航空宇宙局



欧州宇宙機関



首都大学東京



金沢大学



大阪大学



宮崎大学



埼玉大学



SRON(Netherlands Institute for Space Research)



University of Geneva



Canadian Space Agency



Gravitation AstroParticle Physics Amsterdam



Canadian Light Source Inc.



University of Chicago



中央大学



University of Durham



愛媛大学



European Southern Observatory



藤田医科大学



Harvard-Smithsonian Center for Astrophysics



広島大学



関東学院大学



近畿大学



関西学院大学



京都大学



Lawrence Livermore National Laboratory



Leiden University



University of Maryland



Massachusetts Institute of Technology



University of Michigan



名古屋大学



奈良教育大学



奈良女子大学



日本福祉大学



理化学研究所



立教大学



Saint Mary's University



芝浦工業大学



静岡大学



東北学院大学



東京大学



東京理科大学



早稲田大学



University of Waterloo

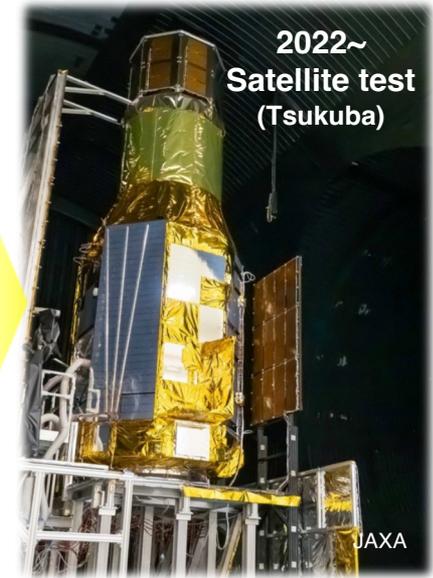
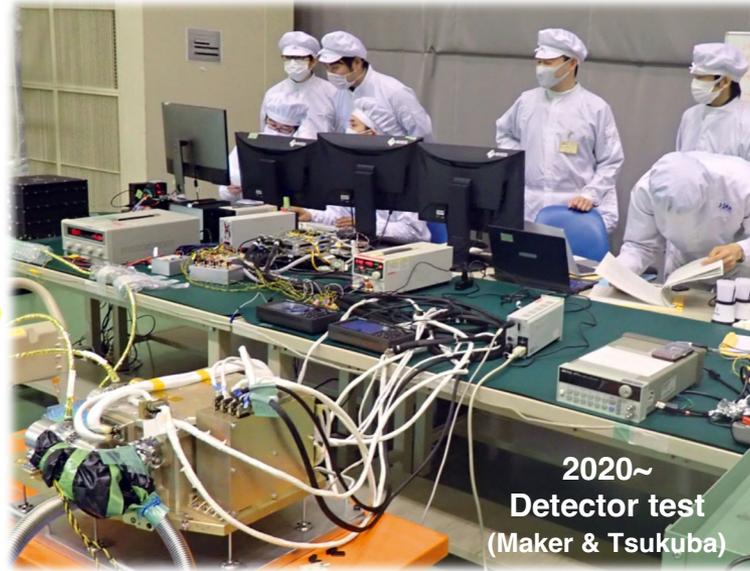


University of Wisconsin



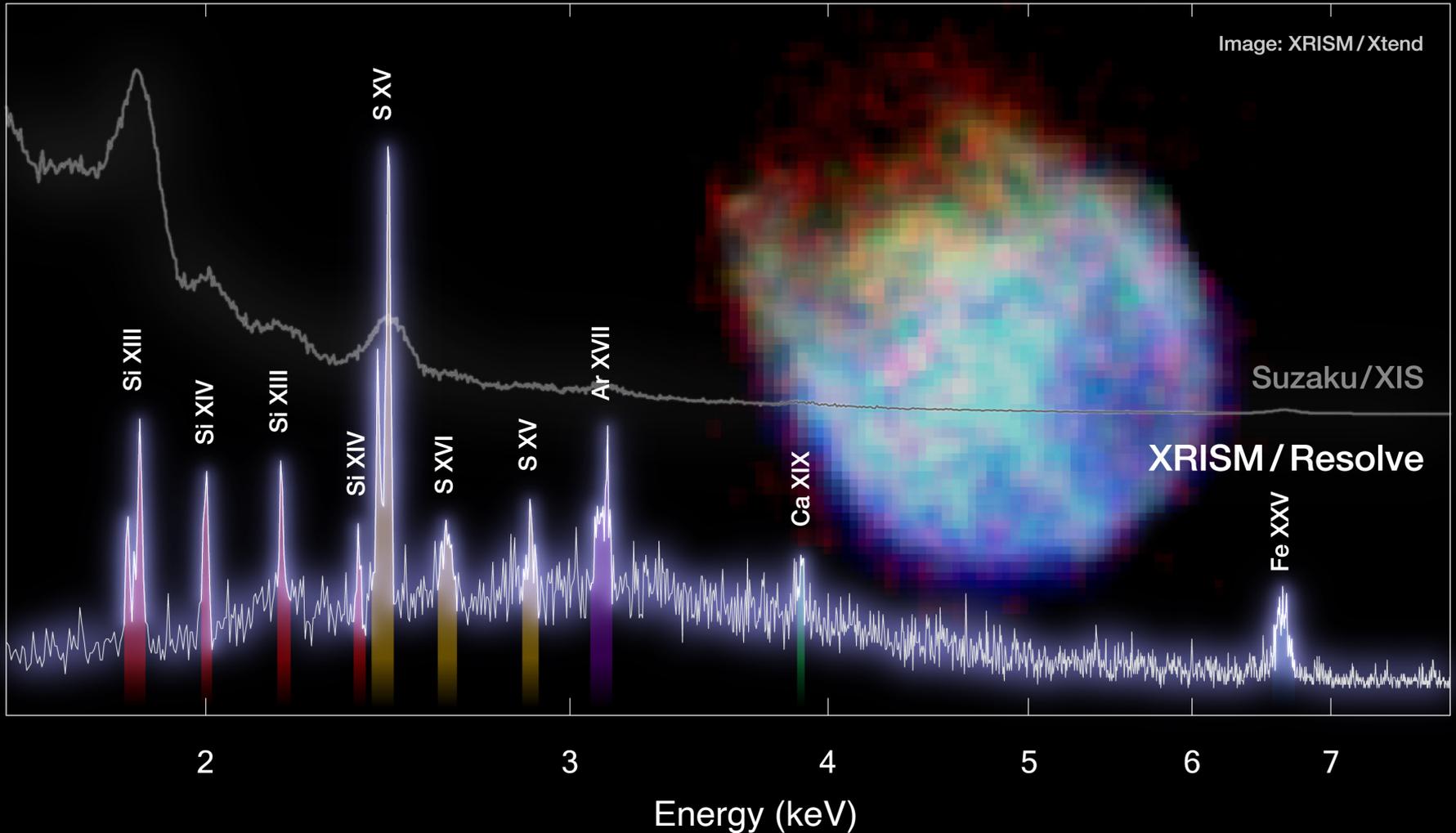
Yale University

Our Development of XRISM



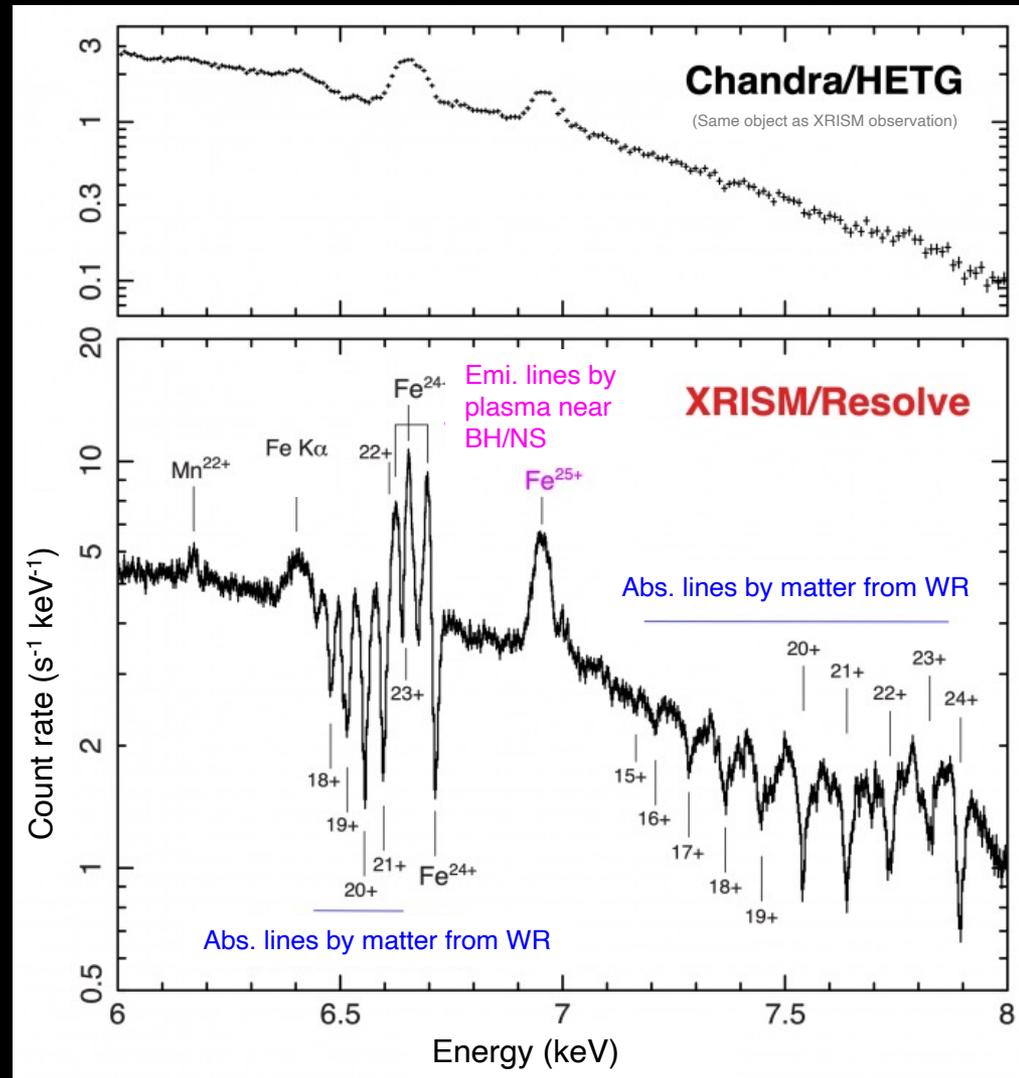
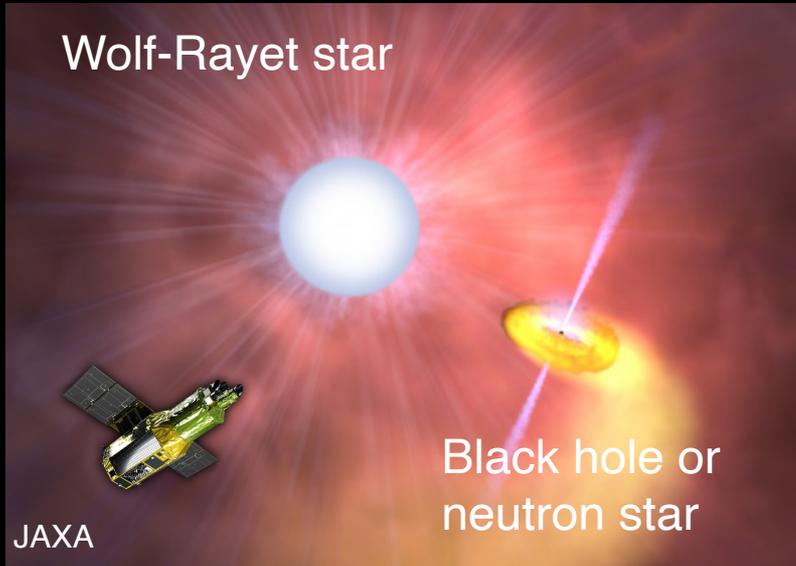


XRISM First Light – SNR N132D –



X-ray Binary Cygnus X-3

XRISM collaboration (2024), JAXA press release



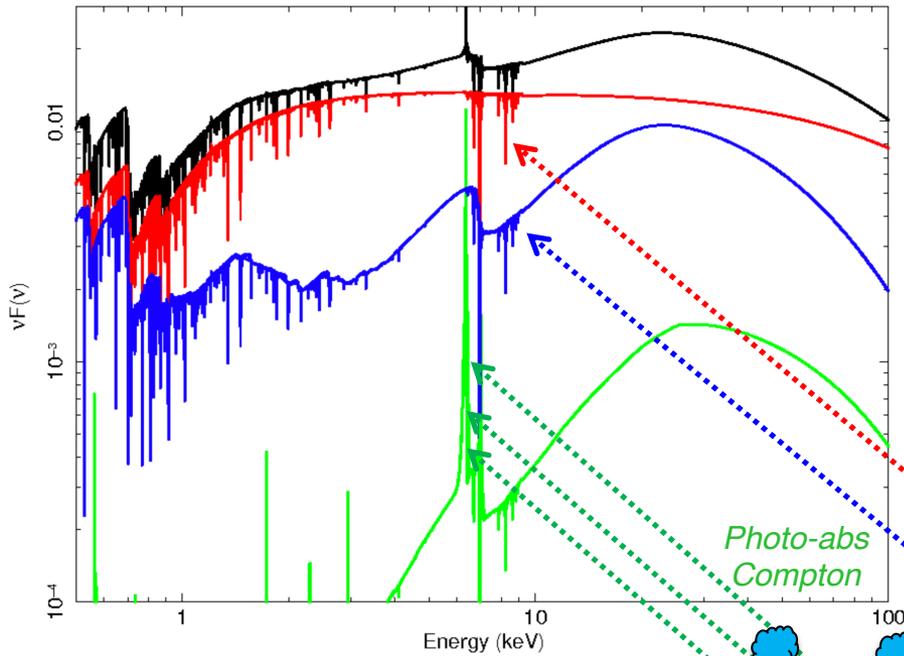
Enabling comprehensive detection of X-ray spectral lines from the vicinity of a black hole/neutron star

→ Detailed physical conditions and motions of hot plasmas near compact objects

Today, I focus Recent AGN results by XRISM

X-ray Spectral Features from AGNs

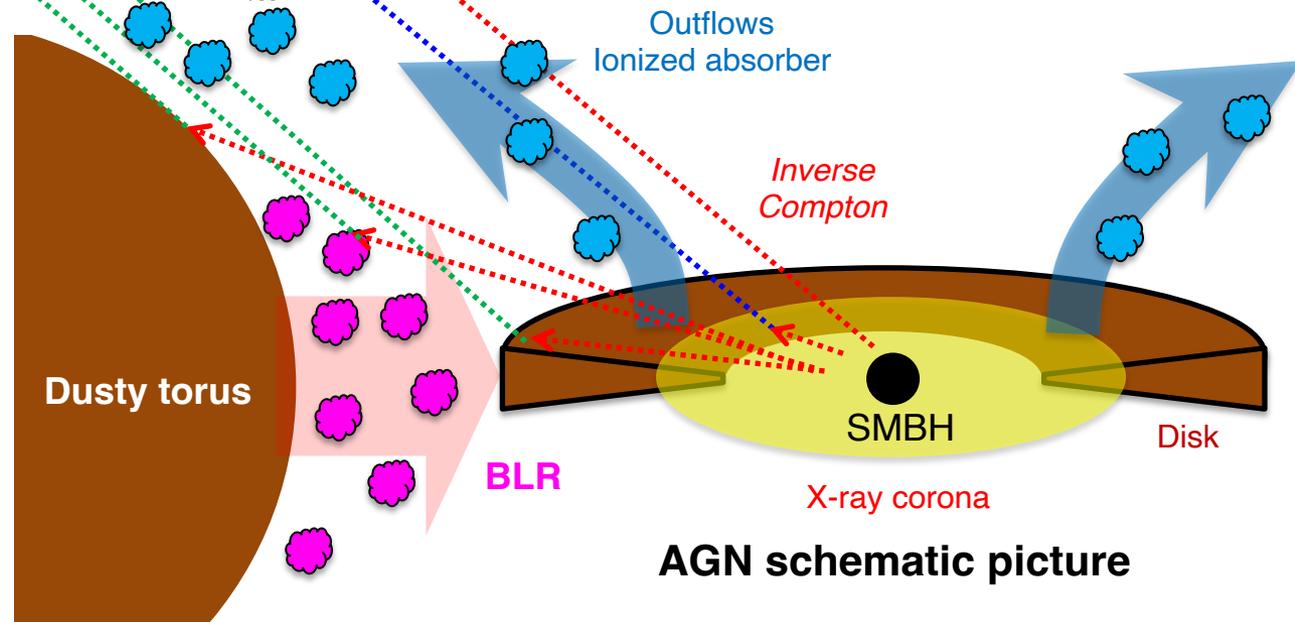
Example of X-ray spectral components (Reynolds 15)



- ☆ Consist of primary continuum, reflection, and lines
- ☆ Primary continuum is produced in corona near Super-Massive Black Hole (SMBH)
- ☆ Lines are caused by accretion disk, Broad-Line Region (BLR), outflows, & dusty torus etc

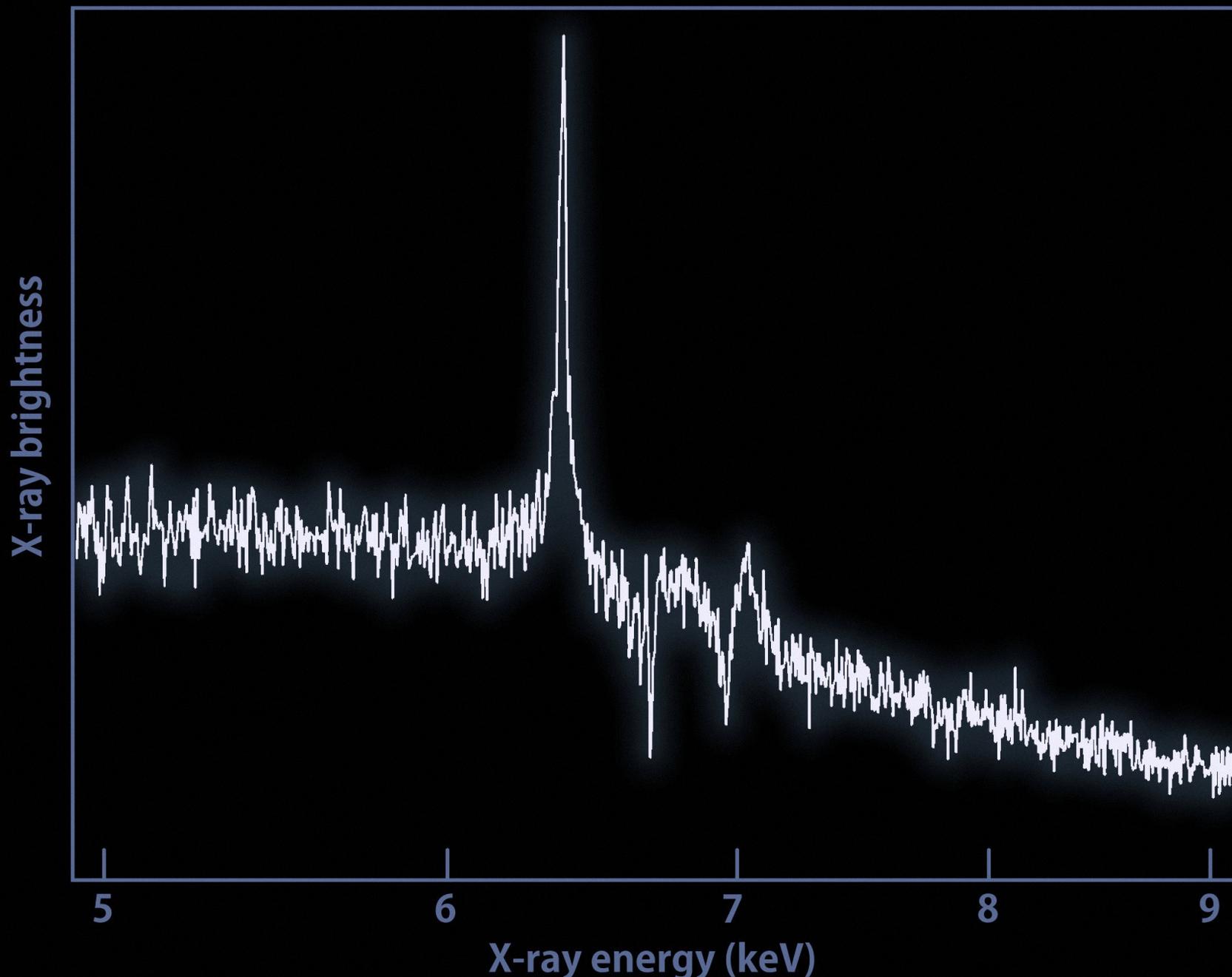
XRISM is effective in studying narrow lines at > 2 keV e.g.,

- Fe-K α from disk, BLR, & dusty torus
- Ionized Fe lines by outflows

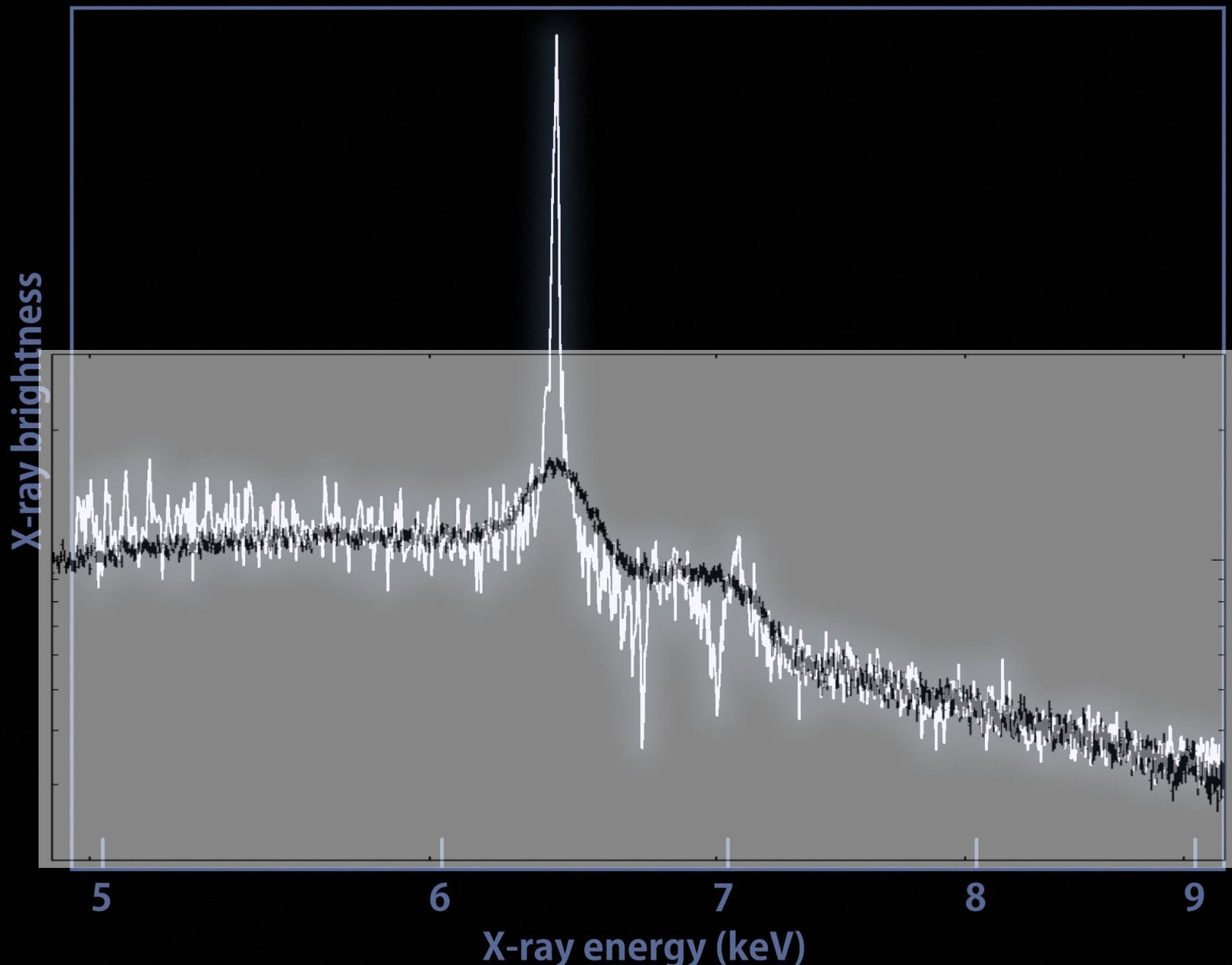


AGN schematic picture

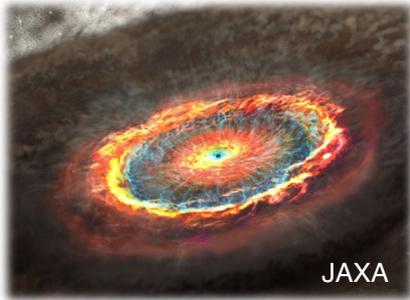
XRISM Resolve Spectrum of NGC 4151



XRISM Resolve Spectrum of NGC 4151



Important Questions Tackled with XRISM



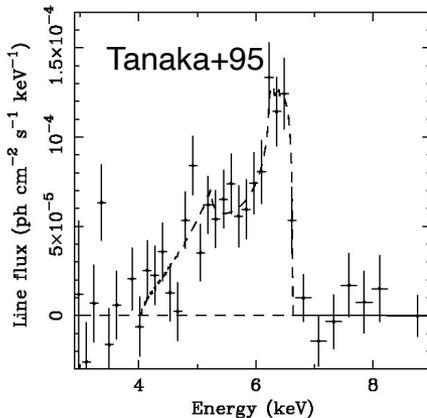
- I. How are outflows distributed around SMBH, and how is their impact on galaxy evolution?

e.g., **PDS 456, IRAS 05189-2524, NGC 3783**



- II. What are the properties and formation mechanisms of BLRs and dusty tori in AGNs?

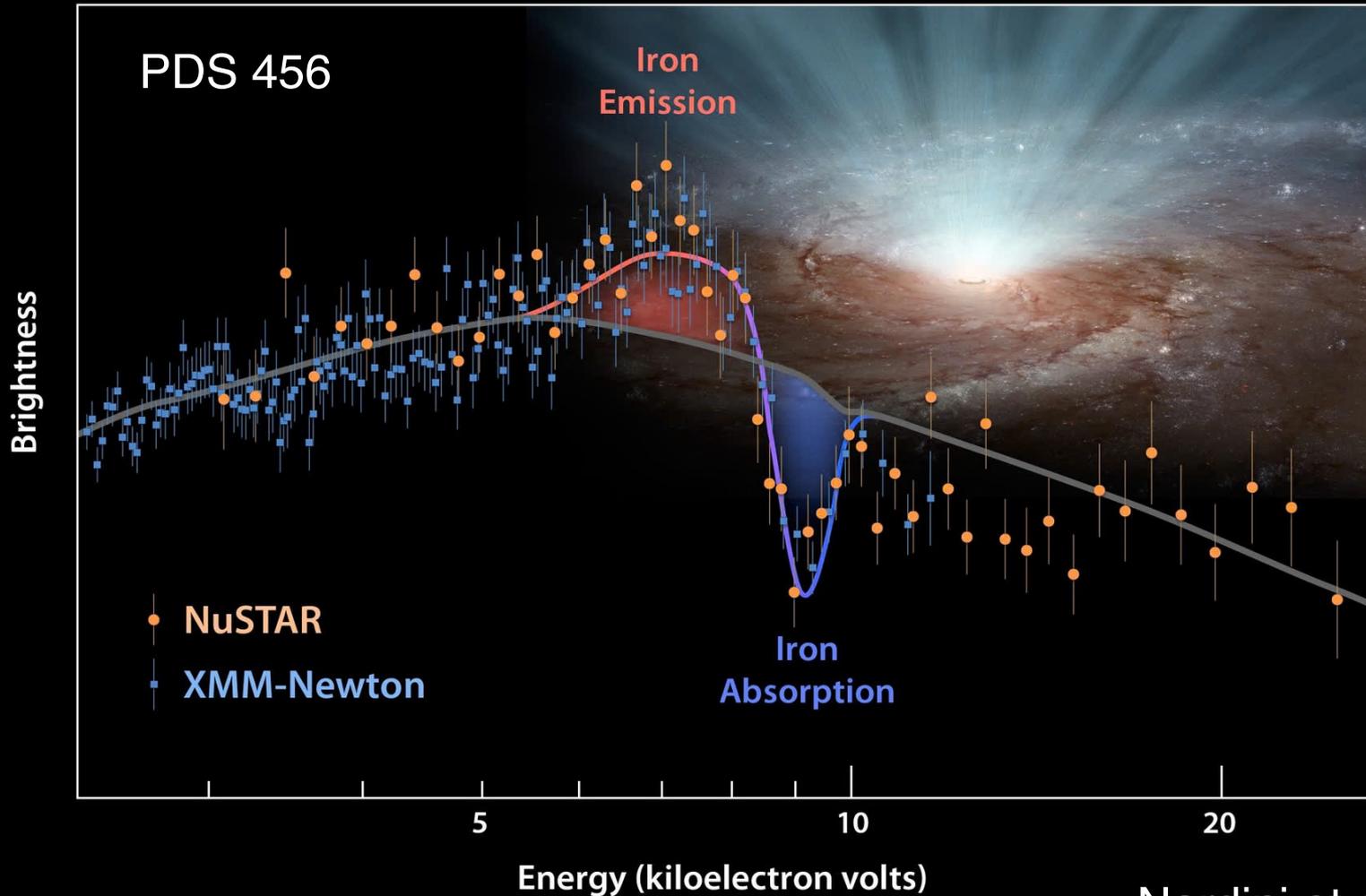
e.g., **NGC 4151, Centaurus A, M81***



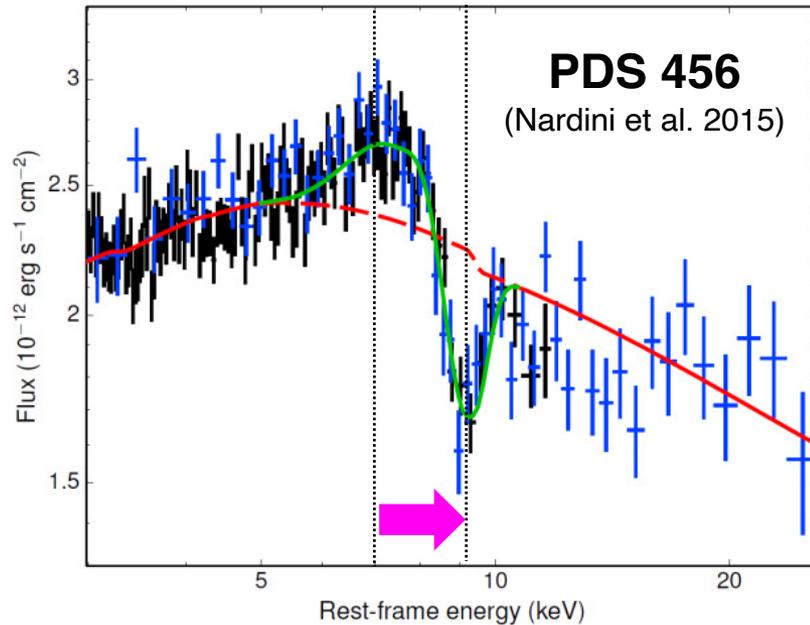
- III. How are relativistic Fe-K α features observed through high-resolution spectroscopy?

e.g., **MCG-6-30-15, 3C120**

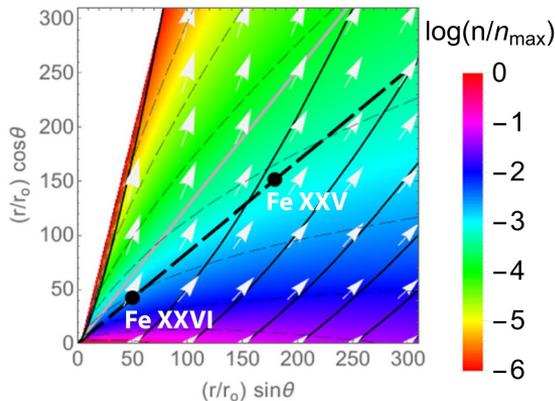
How are Outflows Distributed around SMBH, and How is Their Impact on Galaxy Evolution?



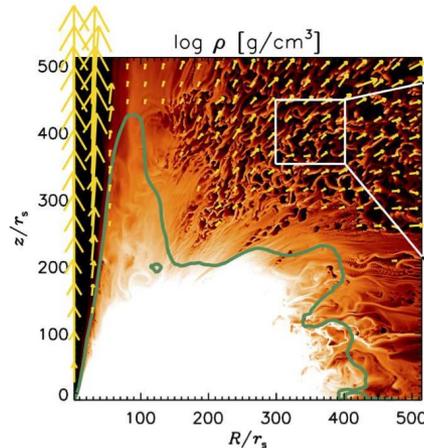
Ultra-Fast Outflow (UFO)



- ☆ Blueshifted Fe XXV/XXVI absorption lines
- ☆ Outflow velocity $v \sim 0.1-0.3c$
- ☆ Some studies reported that $\sim 40\%$ of nearby AGNs show UFOs (e.g., Tombesi et al. 2010)
- ☆ Acceleration mechanism



MHD wind
(Fukumura et al. 2015)



Radiation-driven wind
(Takeuchi et al. 2013)

YKIS2026a

- MHD-driven (e.g., Fukumura et al. 2015)
- Radiation-driven
 - Continuum (e.g., Takeuchi et al. 2013)
 - Line force (e.g., Nomura et al. 2020)

Powerful Clumpy UFOs in Quasar PDS 456

UFOs carry

$$\dot{M} \sim 60\text{--}300 M_{\odot}/\text{yr}$$

$$\dot{E} \sim 10^{47} \text{ erg/s}$$

$$\dot{P} \sim 10^{37} \text{ dyn}$$

($\gg \dot{E}$ & \dot{P} of galactic outflows)

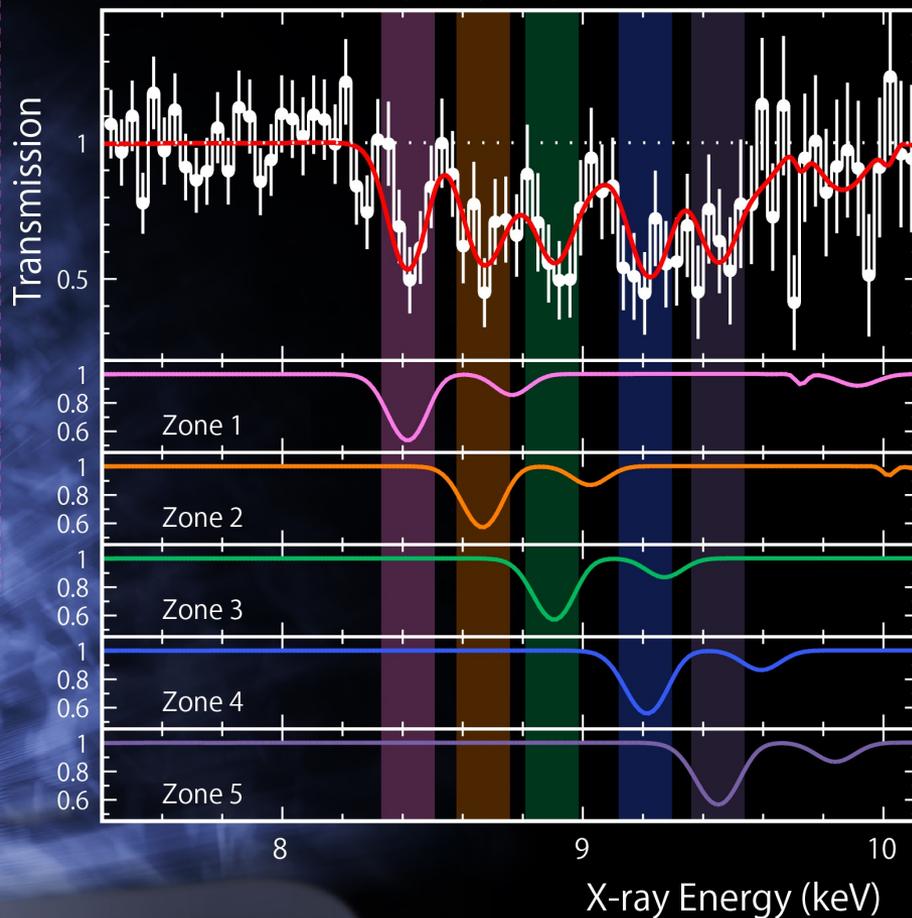
$\sim 200\text{--}600 R_g$

$\sim 2\text{--}16 R_g$

$v \sim 0.23\text{--}0.33c$

SMBH

Accretion disk



At Which Evolutionary Stage are Powerful UFOs Developed?

Ultra-Luminous IR galaxy (ULIRG) IRAS 05189-2524

Quasar PDS 456

(c) Interaction/“Merger”



- now within one halo, galaxies interact & lose angular momentum
- SFR starts to increase
- stellar winds dominate feedback
- rarely excite QSOs (only special orbits)

(b) “Small Group”



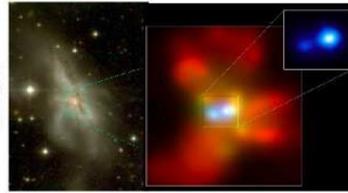
- halo accretes similar-mass companion(s)
- can occur over a wide mass range
- M_{halo} still similar to before: dynamical friction merges the subhalos efficiently

(a) Isolated Disk



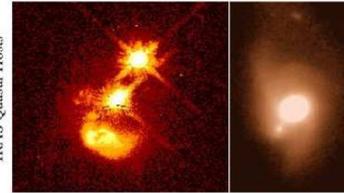
- halo & disk grow, most stars formed
- secular growth builds bars & pseudobulges
- “Seyfert” fueling (AGN with $M_{\text{e}} > -23$)
- cannot redden to the red sequence

(d) Coalescence/(U)LIRG



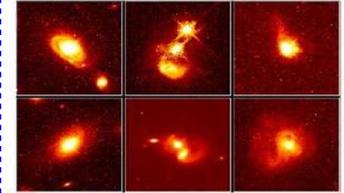
- galaxies coalesce: violent relaxation in core
- gas inflows to center: starburst & buried (X-ray) AGN
- starburst dominates luminosity/feedback, but, total stellar mass formed is small

(e) “Blowout”



- BH grows rapidly: briefly dominates luminosity/feedback
- remaining dust/gas expelled
- get reddened (but not Type II) QSO: recent/ongoing SF in host
- high Eddington ratios
- merger signatures still visible

(f) Quasar



- dust removed: now a “traditional” QSO
- host morphology difficult to observe: tidal features fade rapidly
- characteristically blue/young spheroid

(g) Decay/K+A

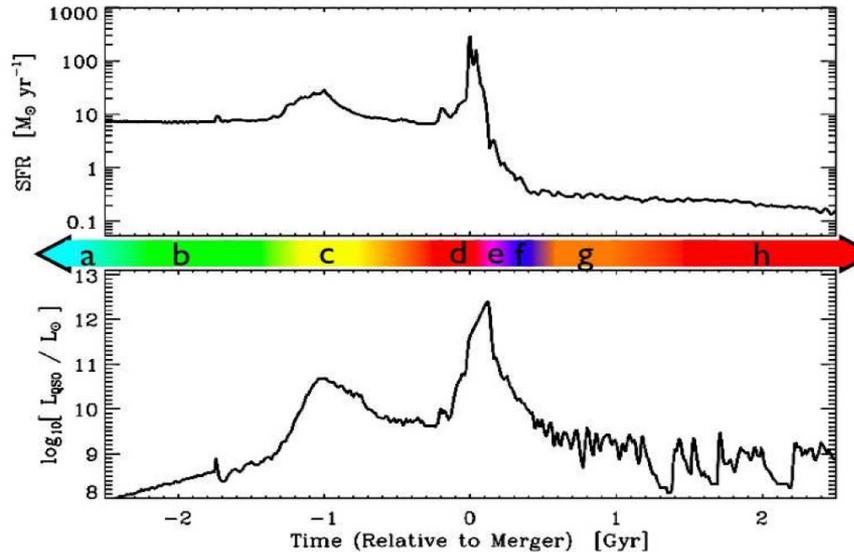


- QSO luminosity fades rapidly
- tidal features visible only with very deep observations
- remnant reddens rapidly (E+A/K+A)
- “hot halo” from feedback
- sets up quasi-static cooling

(h) “Dead” Elliptical



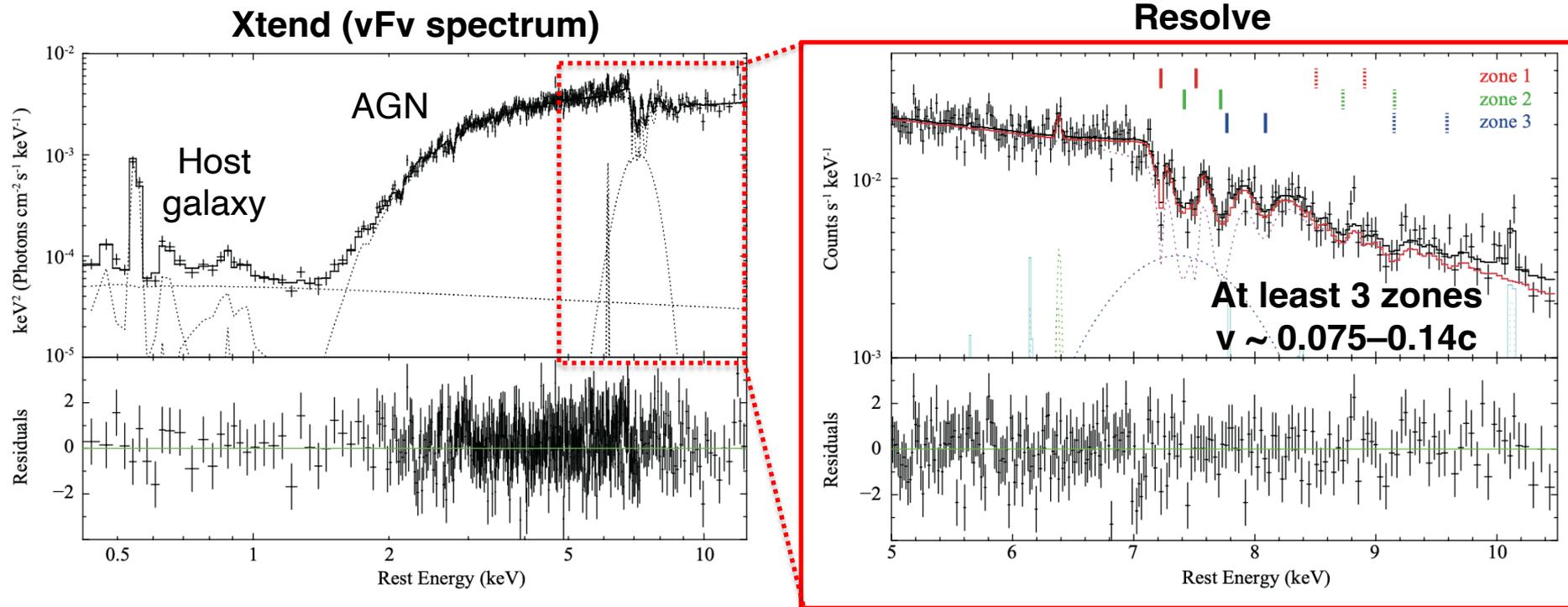
- star formation terminated
- large BH/spheroid - efficient feedback
- halo grows to “large group” scales: mergers become inefficient
- growth by “dry” mergers



Hopkins et al. (2008)

Discovery of Powerful UFOs in ULIRG IRAS 05189-2524

Noda et al. (2025), ApJL, 993, 53

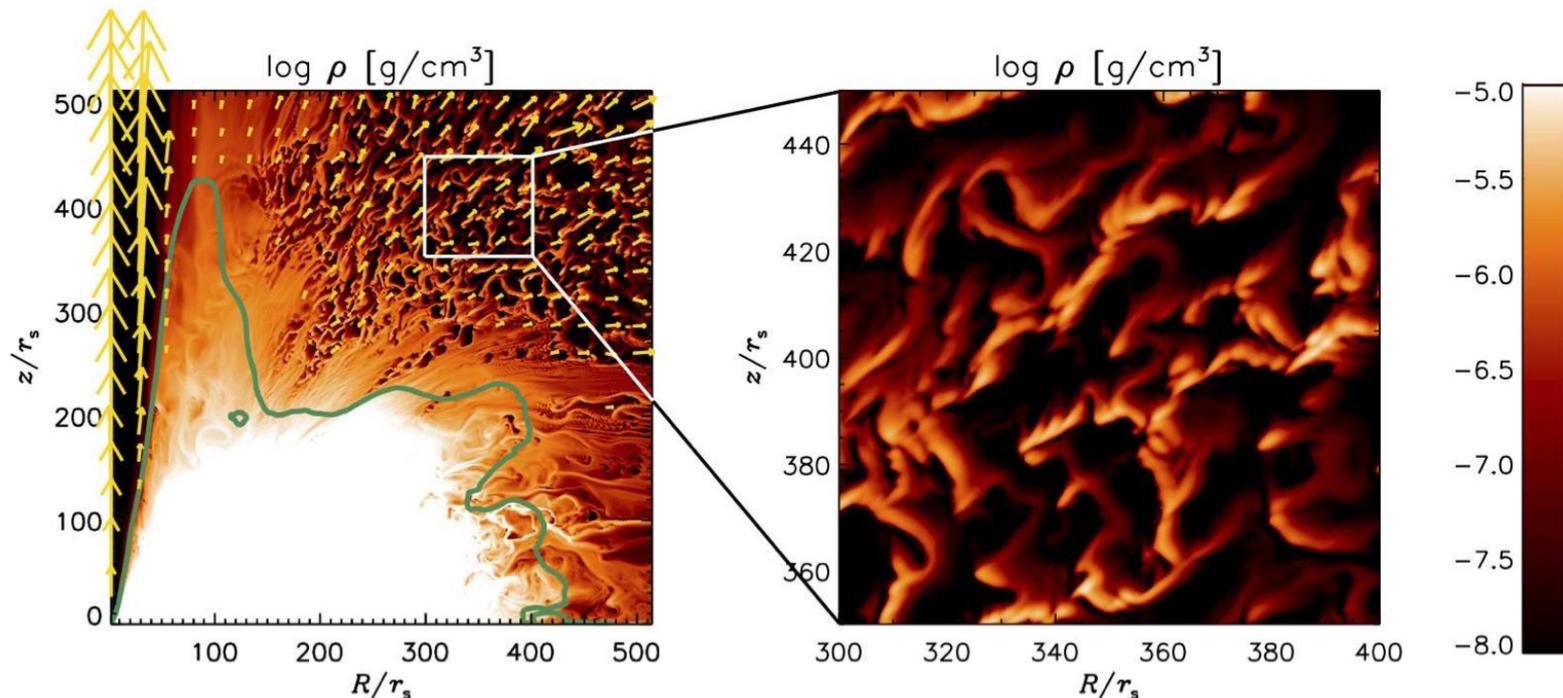


- ☆ $\dot{E} \sim 10^{46}$ erg/s, $\dot{P} \sim 10^{36}$ dyn: Orders of mag. higher than galactic outflows
- ☆ Powerful UFOs are found already developed in precursor stage of quasars

➔ Captured the short-lived stage where powerful UFOs are about to suppress the starburst activity, evolving into the quasar phase

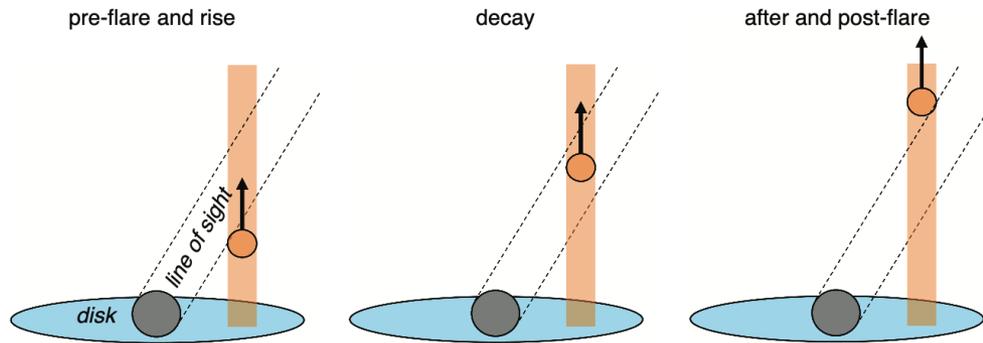
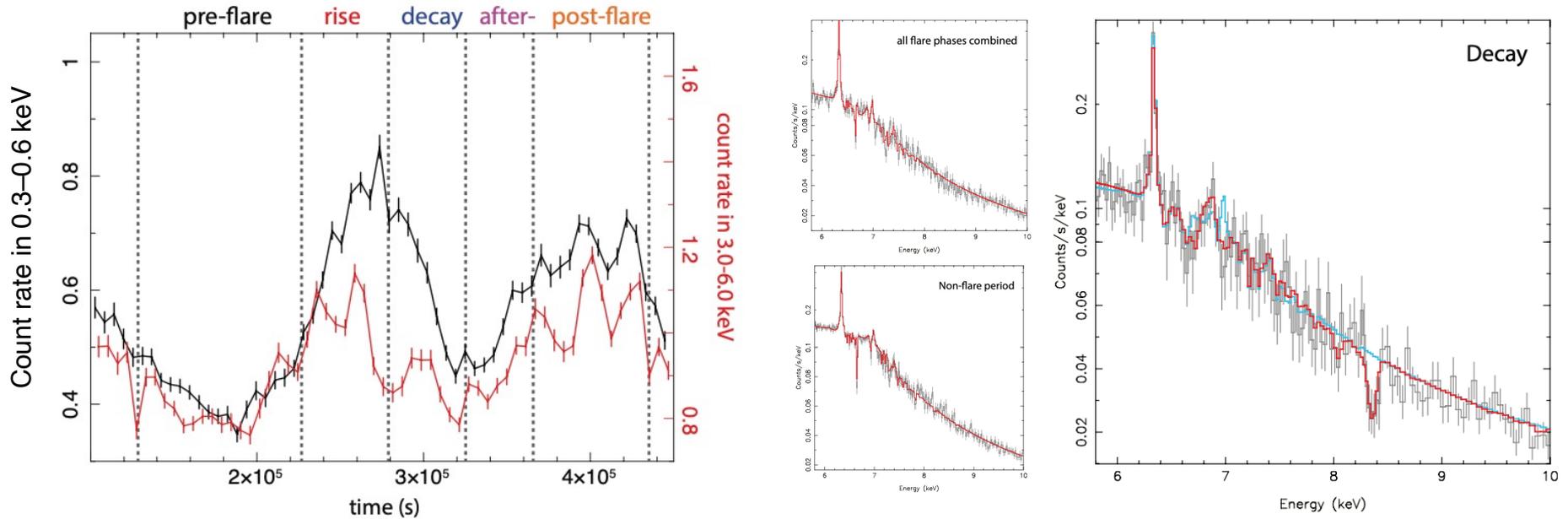
Clumpy UFO Formation Mechanism

- ☆ XRISM revealed clumpy UFOs in PDS 456, IRAS 05189-2524, and PG1211+143, all of which are accreting near super-Eddington rates
 - ☆ RMHD simulations predict radiation-driven UFOs from super-Eddington accretion flows (e.g., Takeuchi et al. 2013; Kobayashi et al. 2018).
- ➔ **Clump sizes & locations are consistent with XRISM observations**
(Quantifying the contribution of magnetic driving remains subject to future work)



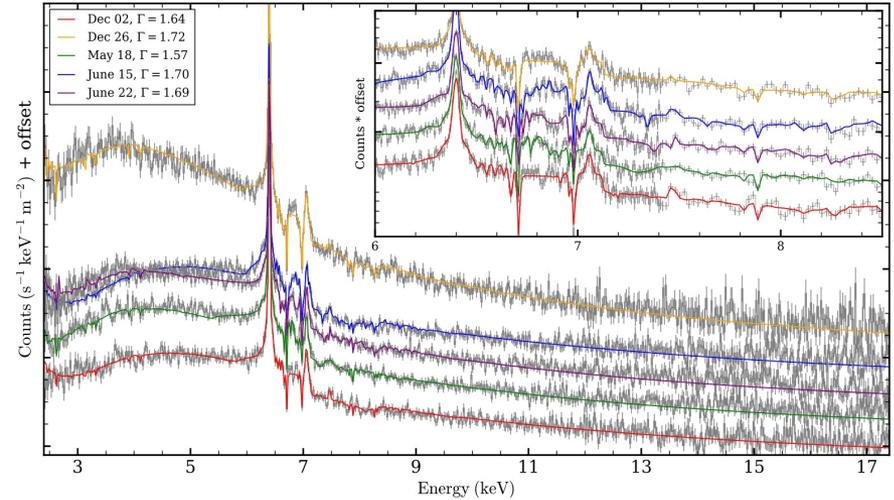
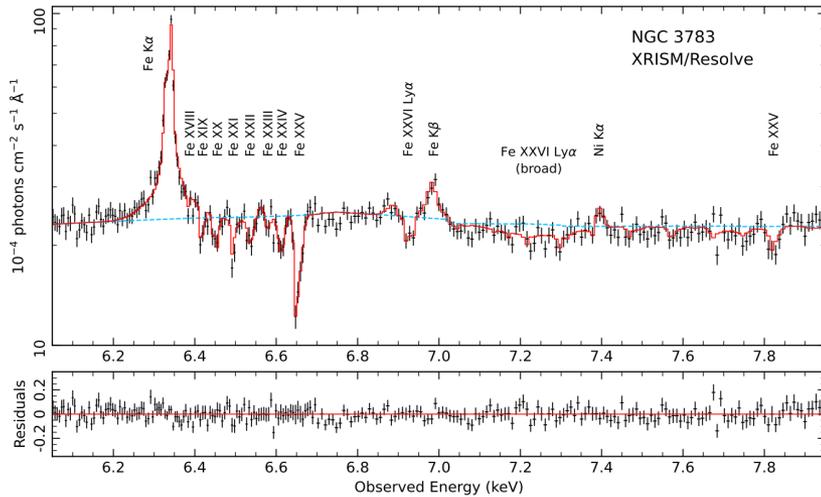
Capturing the UFO Launch in NGC 3783

Gu, + , Noda et al. (2025), A&A, 704, 146



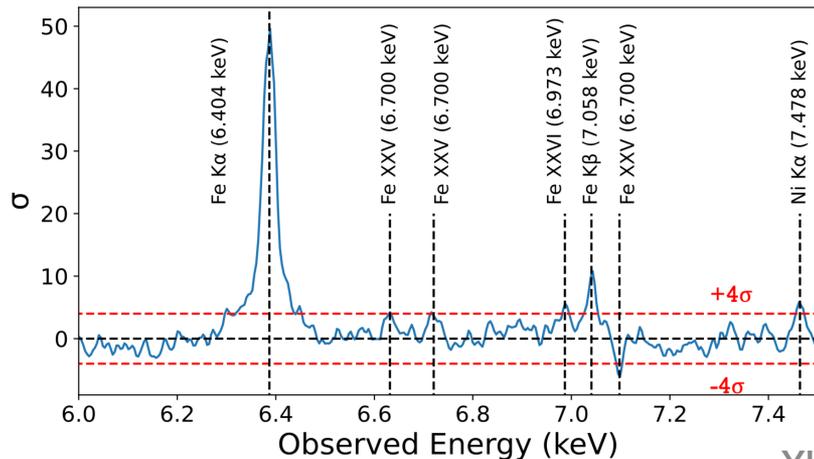
- ☆ Launch of UFO with $\sim 0.19c$ at the decay time of soft X-ray/UV flare
- ☆ Closely resembles the solar coronal mass ejection, implying magnetic driving?

Multi-Zone Outflows in Various AGNs



NGC 3783 (Mehdipour, +, Noda et al. 2025)

Multi-zone outflows with
 $v \sim 560\text{--}1170$ km/s



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NGC 4151 (Xiang, +, Noda et al. 2025)

Warm absorbers $v \sim 10^2\text{--}10^3$ km/s

Very fast outflows $v \sim 10^3\text{--}10^4$ km/s

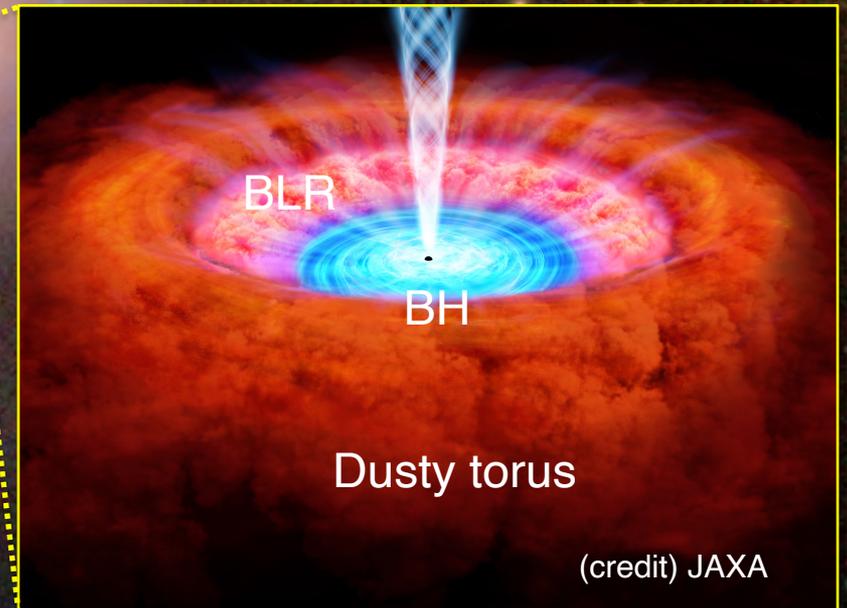
UFOs $v \sim 0.33\text{--}0.33c$

Centaurus A

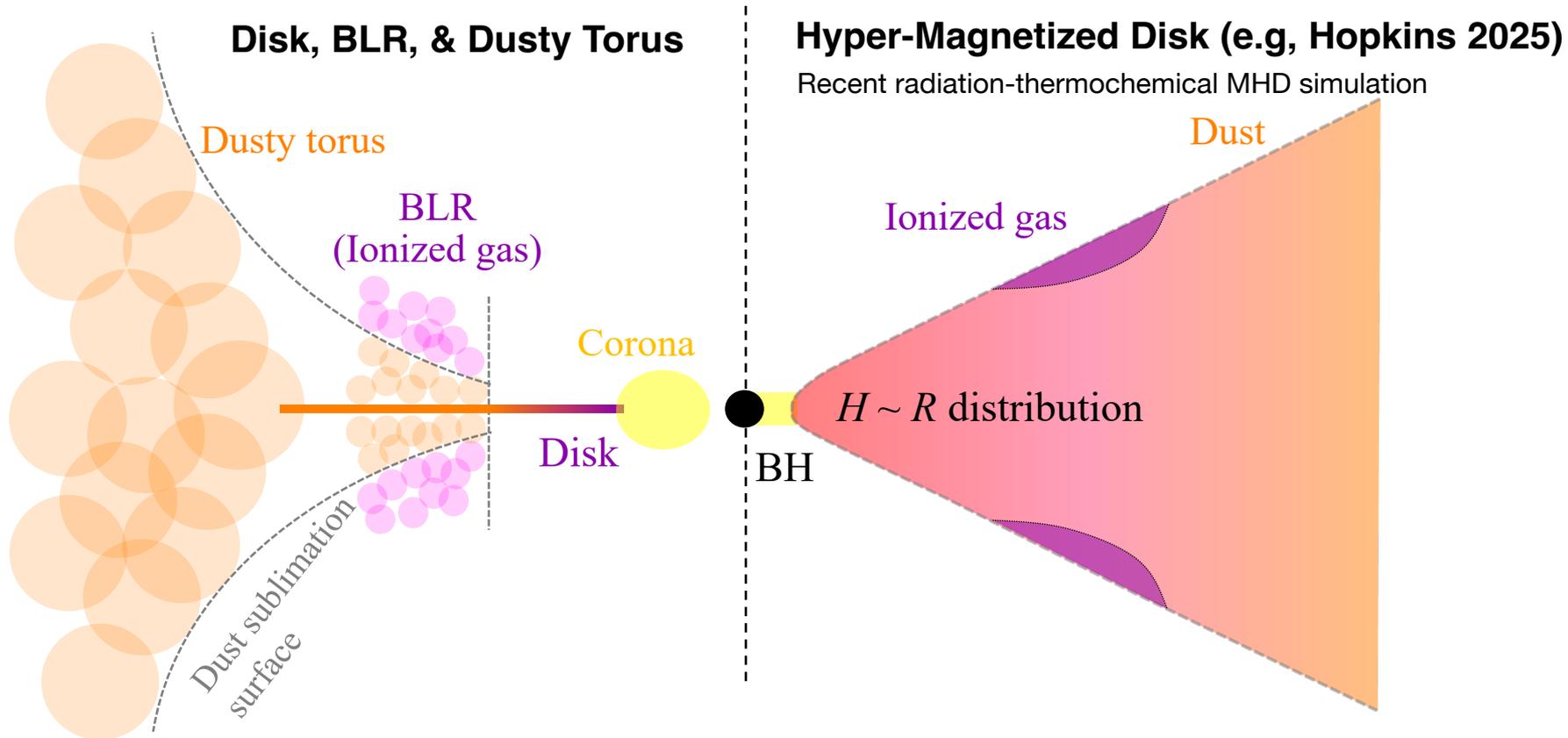
(Kayanoki, +, Noda et al. submitted)

Ionized emission line + UFO?

What are the Properties and Formation Mechanisms of BLRs and Dusty Tori in AGNs?



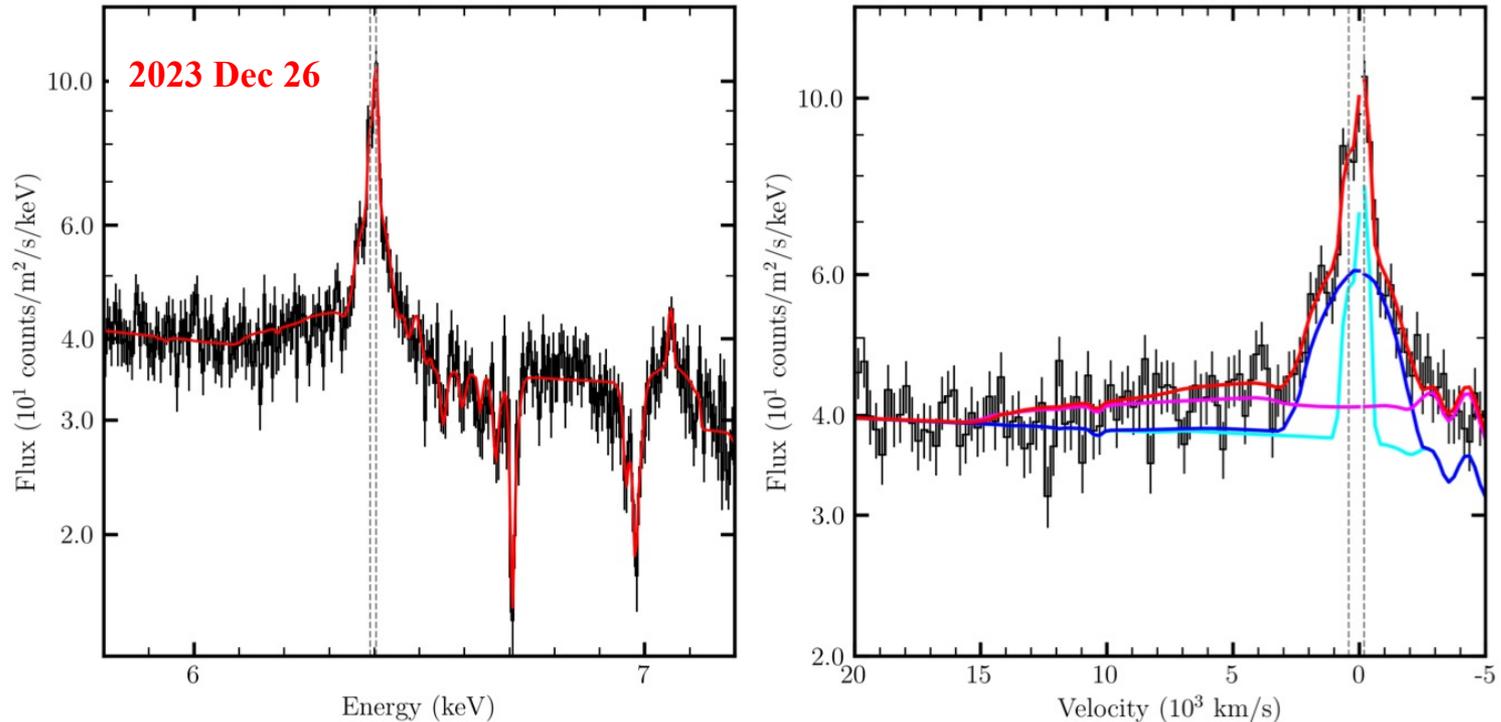
Recent Discussion on the Structure of AGN



- ☆ The formation mechanism of BLR & dusty torus is under much debate
 - (i) Dusty **outflows** (e.g., Czerny & Hryniewicz 2011; Wada 2012, Kudoh et al. 2023)
 - (ii) Continuous **inflow** with different ionization states (Hopkins 2025)
- ☆ With only optical spectroscopy, it is difficult to distinguish them...

Decomposition of Narrow Fe-K α Line in NGC 4151

NGC 4151 (XRISM Collaboration 2024)



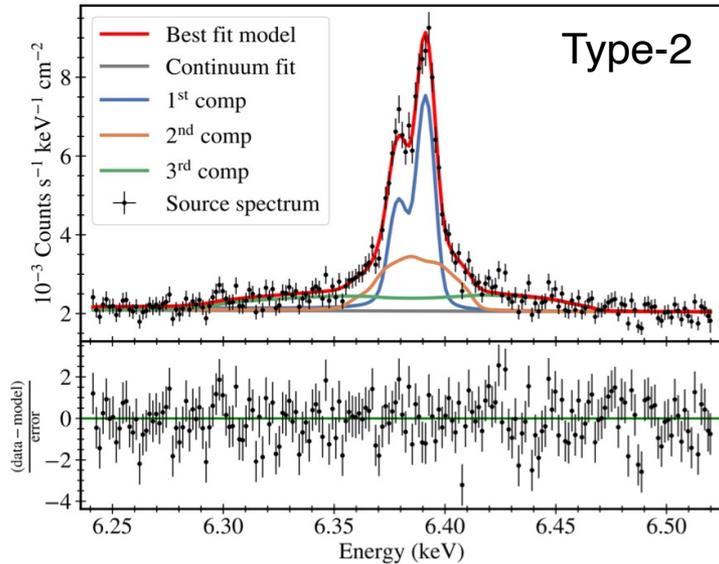
☆ Narrow Fe-K α , K β em. & Fe XXV/XXVI abs. lines are detected

☆ **Fe-K α is resolved into at least 3 components for the first time:**

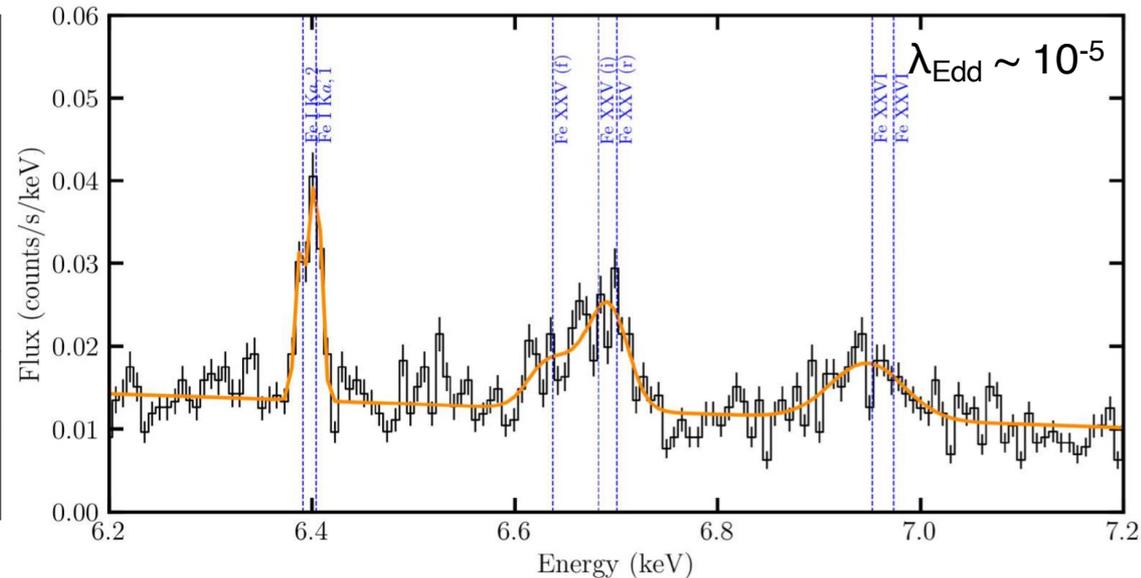
- **Broad** : $R_{\text{in}} \sim 100 R_g \rightarrow$ Accretion disk
- **Intermediate** : $R_{\text{in}} \sim 3000 R_g \rightarrow$ BLR (focused in the next page)
- **Narrow** : $R_{\text{in}} \sim 10000 R_g \rightarrow$ Dusty torus

Properties of BLRs & Tori in Various Types of AGNs

Radio Galaxy Centaurus A
(Bogensberger, +, Noda et al. 2025)



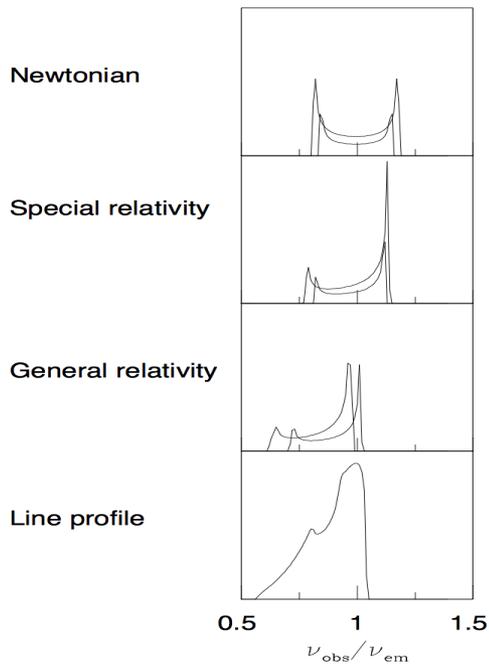
Low-Luminosity AGN M81*
(Miller et al. 2025)



- ☆ **Probing X-ray BLR** via multi-components of Fe-K α in type-2 Centaurus A
- ☆ **Remnant torus** associated with waning mass accretion in M81*
- ➔ Studies on the difference of the structure by inclination & Eddington ratio are ongoing (e.g., NGC 4051, NGC 4388, MCG-5-23-16, etc)

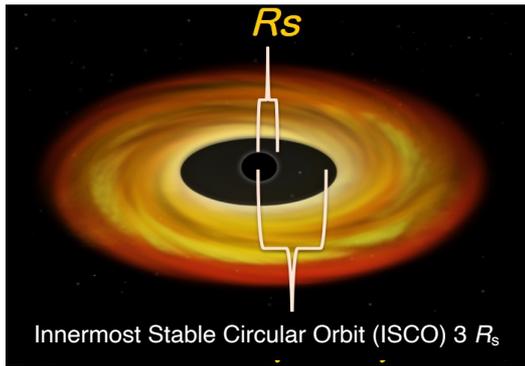
How are the relativistic Fe-K α features observed through high-resolution spectroscopy?

Fabian et al. (2000)

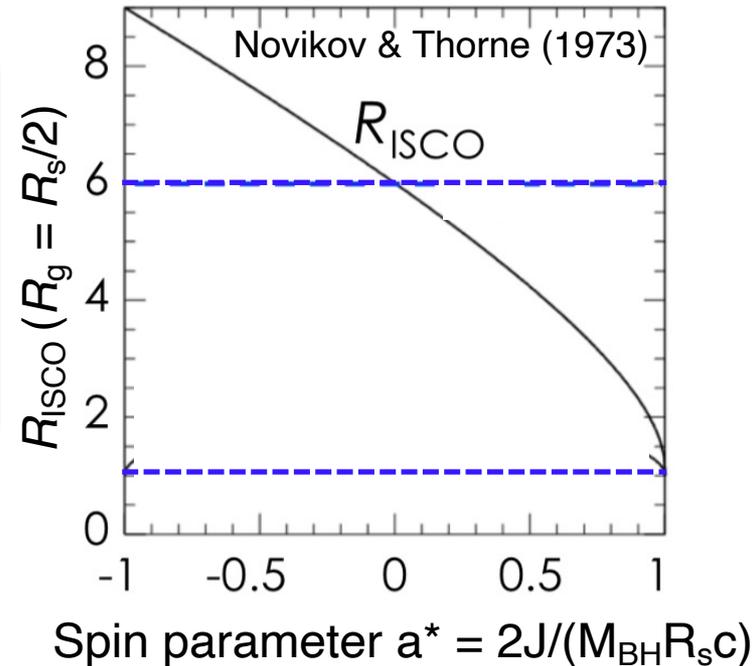
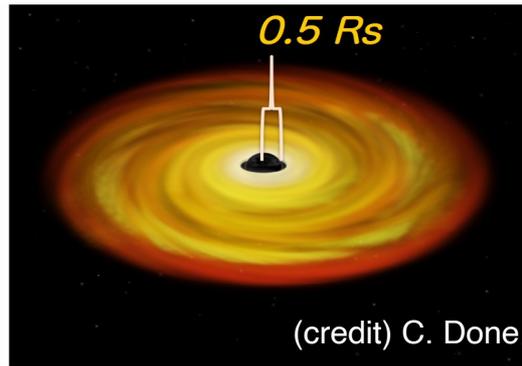


BH Spin & Relativistic Fe-K α Profile

Schwarzschild BH

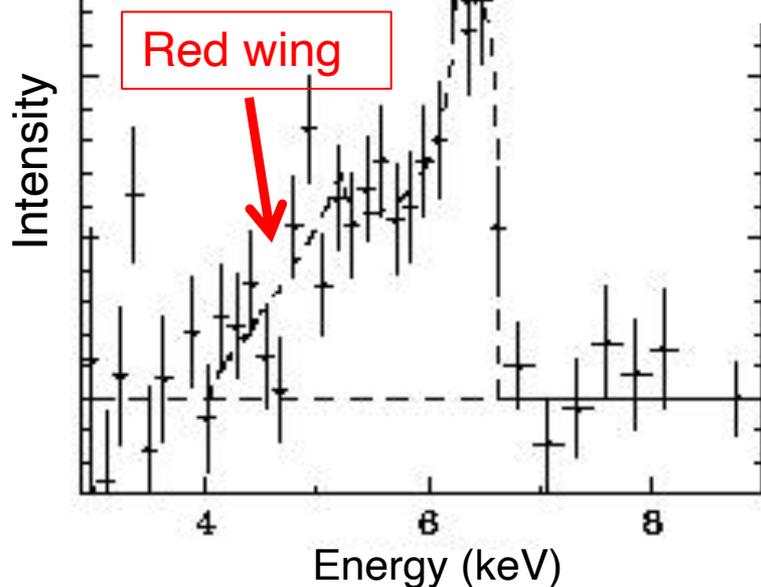


$a^* \sim 1$ Kerr BH



MCG-6-30-15
(Tanaka et al. 1995)

ASCA spectrum of
relativistic Fe-K α

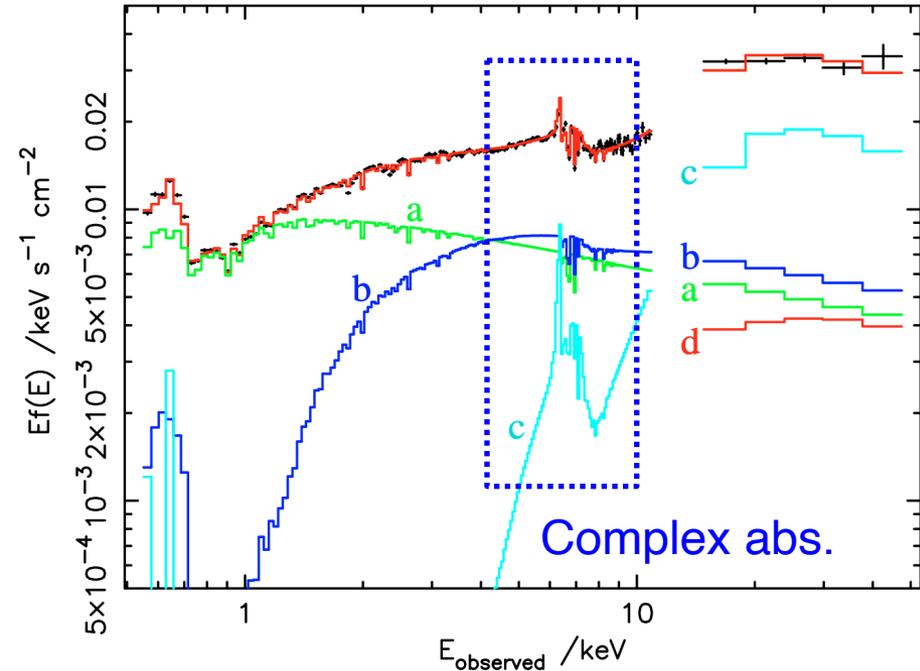
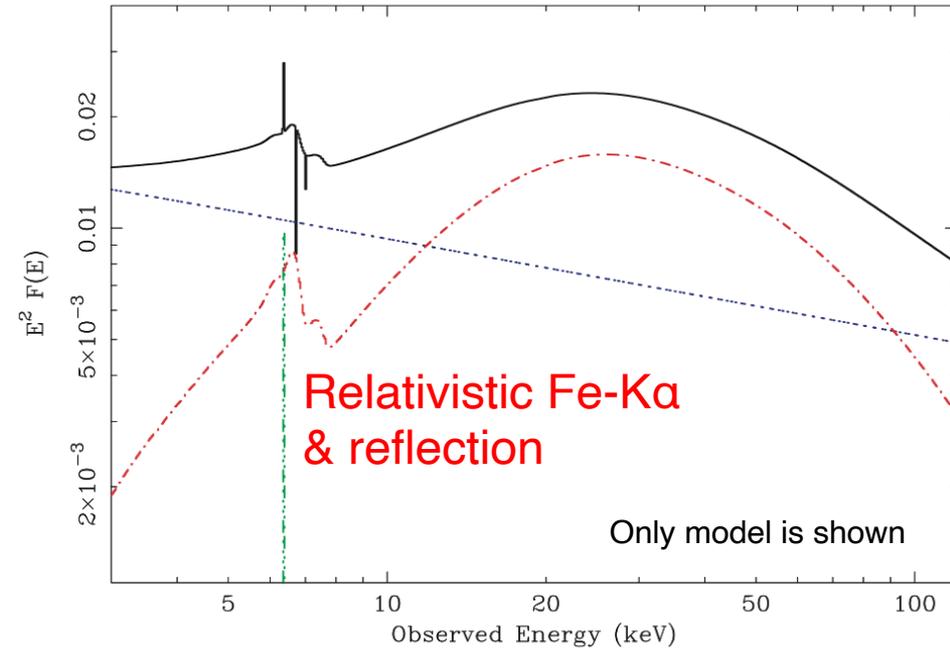


- ☆ Fe-K α is broadened by **relativistic Doppler effects + gravitational redshift**
 $\rightarrow R_{\text{in}} \rightarrow R_{\text{ISCO}} \rightarrow a^*$
- ☆ X-ray satellite ASCA reported for the first time, and MCG-6-30-15 has been discussed to have $a^* \sim 1$

Difficulty in BH Spin Measurement by Fe-K α So Far

Suzaku MCG-6-30-15 spectrum reproduced by the extreme Kerr BH model (Miniutti et al. 2007)

Suzaku MCG-6-30-15 spectrum reproduced without relativistic Fe-K α (Miller et al. 2008)



- ☆ BH spins have been measured in tens of AGNs (e.g., Reynolds 2019). However, the identical data can be also reproduced by complex absorption effects (e.g., Miller et al. 2008)

→ Kerr BH ($a^* \sim 1$) & Schwarzschild BH ($a^* = 0$) are degenerate

- ☆ One of the main causes is lack of E resolution in X-ray spectroscopy

XRISM/Resolve Spectroscopy of MCG-6-30-15

Brenneman, +, Noda, et al. (2025), ApJ, 995, 200

☆ Relativistic reflection

(e.g, Fabian et al. 1989; Reynolds & Nowak 2003)

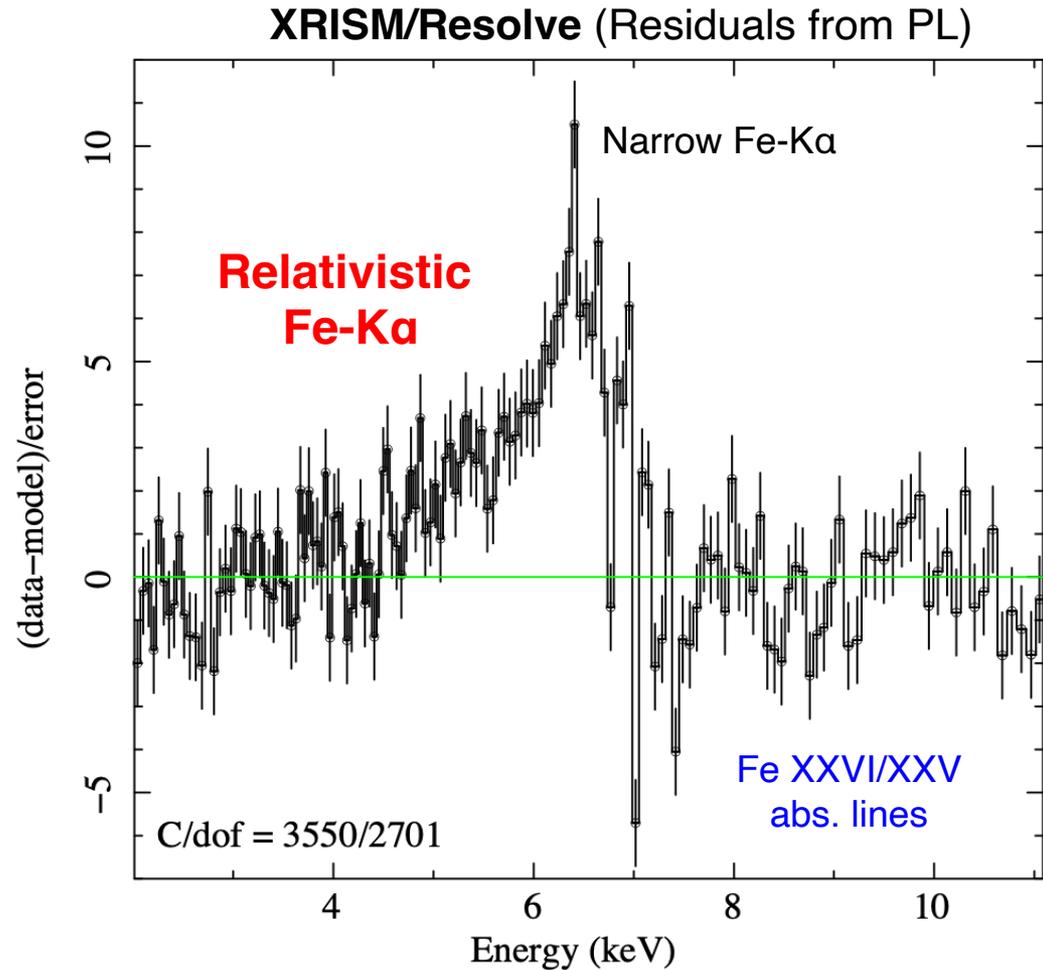
Complex absorption

(e.g., Miller et al. 2008; Miyakawa et al. 2012)

are degenerate so far

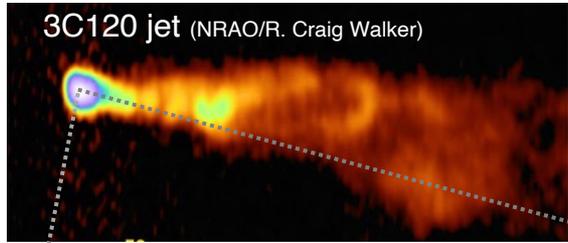
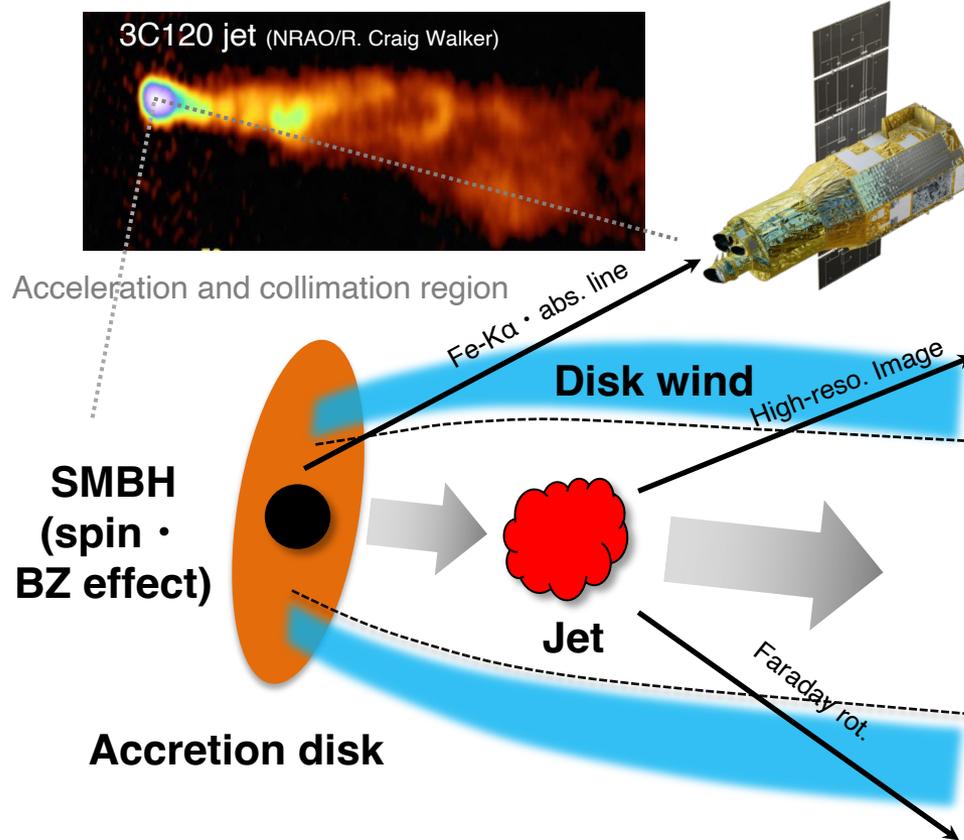
☆ With the X-ray microcalorimeter, the **relativistic Fe-K α line** is confirmed, modified by some **ionized absorption lines**

☆ The spin constraint is highly dependent on the continuum shape. Further studies, including variability, are ongoing.



Our Ongoing Project Related to Relativistic Fe-K α

XRISM & EHT Collaboration



XRISM

(BH Spins · winds)

EHT / GMVA / EAVN / VLBA

(Jet power · structure · Faraday rotation)



- ☆ The AGN jet production is a longstanding question in astrophysics. Deeply related to the **BH spin, inner disk structure, & disk wind**
- ☆ Acc./outflow at BH vicinity → **Precise X-ray spectroscopy (XRISM)**
- Jet production region → **Ultra-high reso. mm imaging (EHT etc)**

Summary

- ☆ XRISM was successfully launched on September 7, 2023, and achieved precise X-ray spectroscopy in orbit.
- ☆ XRISM is effective in studying lines by accretion disks, BLRs, outflows, and dusty tori in AGNs. During the XRISM performance verification phase, ten AGNs have been successfully observed.
- ☆ Various key results to important questions of AGNs, as follows.
 - I. **UFOs are clumpy, carrying a huge amount of energy and momentum. They were significantly developed in ULIRG phase.**
 - II. **XRISM decomposed Fe-K α into multiple components, which give unprecedented constraints to BLR and dusty torus structures.**
 - III. **With the X-ray microcalorimeter, the relativistic Fe-K α line is confirmed, modified by some ionized absorption lines.**