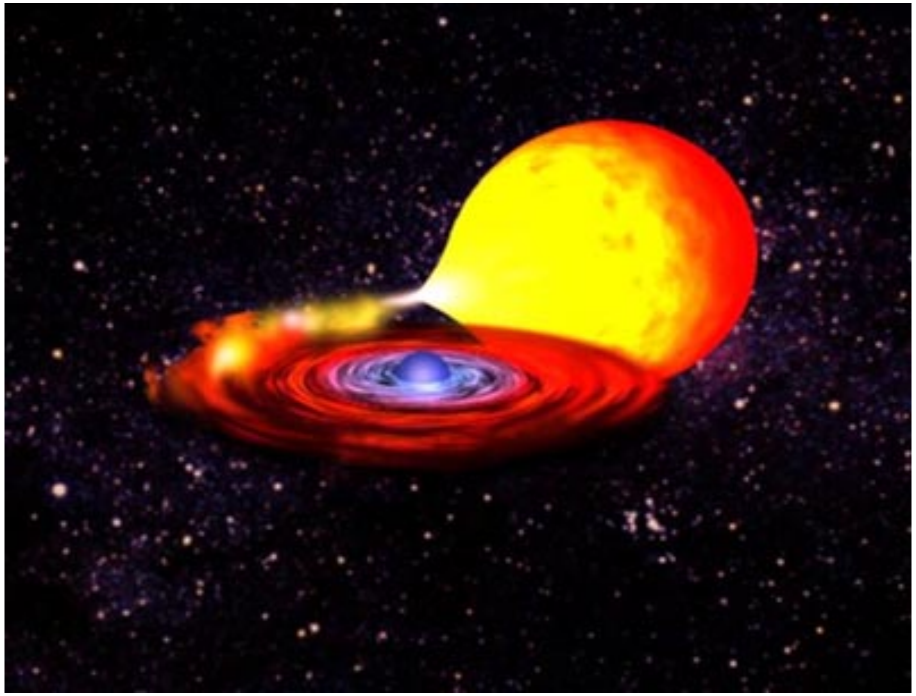
X-ray observations of the Galactic/Extragalactic Low-Mass X-ray Binaries

Hideyuki Mori

Outline:

1. Low-Mass X-ray Binaries？
2. X-ray emission mechanism of LMXBs in some states
3. Unidentified X-ray sources towards the Galactic bulge
4. X-ray observations of the unID X-ray sources
5. Luminosity function of the LMXBs

Low-Mass X-ray Binaries？



A binary system consisting of a compact object, which is an evolutional endpoint of a massive star, i.e., neutron star (NS) or stellar-mass black hole (BH), and a companion star (spectral type of G or K) with ~1 $M_{\odot}$.

Ex.：4U 1608-522, Aql X-1, GRO J1655-40

If the companion is a massive star with O or B spectral type, the system is called “High-Mass X-ray Binary” (HMXB).

Ex.：Cyg X-1 (Famous BH candidate、HD226868、O-type massive star)
GX 301-2 (Pulsar)

Catalogue:

LMXBs: Liu et al. 2001, A catalogue of low-mass X-ray binaries, A&A, 368, 1021L

HMXBs: Liu et al. 2000, A catalogue of high-mass X-ray binaries, A&AS, 147,25L

Topics of the LMXBs

Characteristics of the LMXBs (Hayakawa 1985),

- Weak magnetic field (< 10^9 G)
- Old age (> 10^9 yr)
- No eclipse/dip in their X-ray light curves
- Orbital period with 0.2 – 200 hours

etc.…

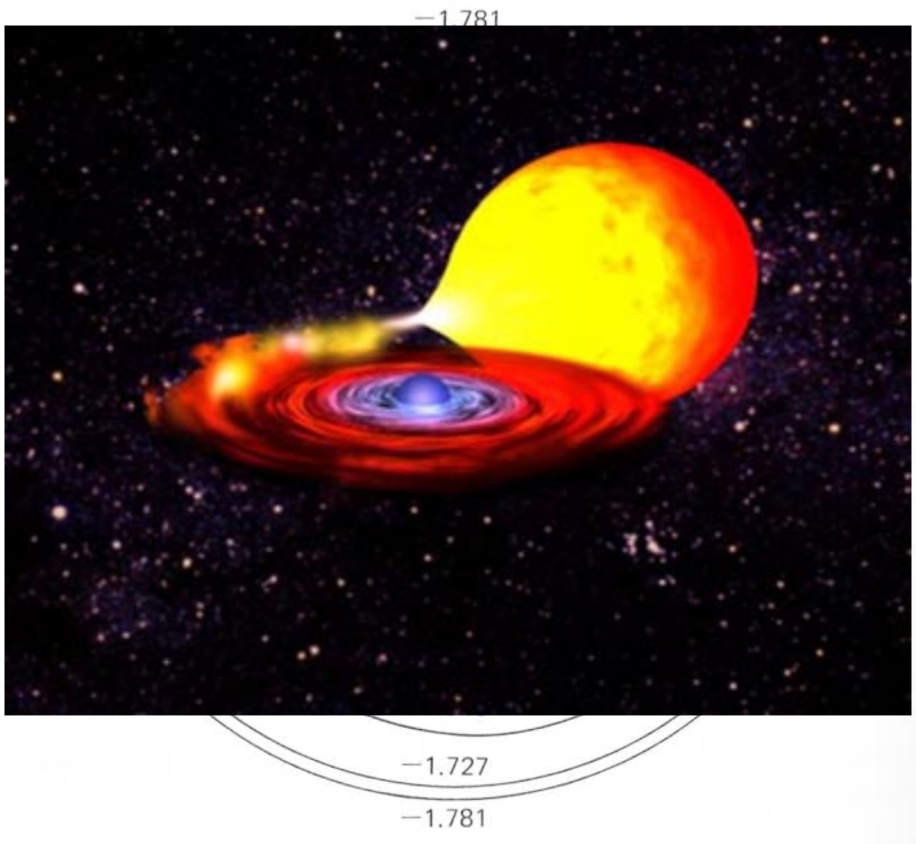
There are many topics for the LMXBs:

- ✓ X-ray emission mechanism
- ✓ Type-I X-ray bursts (Thermonuclear flush on the NS surface)
- ✓ Quasi-Periodic Oscillation (QPO：flux variation with a period of ~ Hz)
- ✓ Luminosity function
- ✓ Formation mechanism of the LMXBs

↓

X-ray emission mechanism/Luminosity function

Roche-lobe overflow



Equipotentials:
(Shapiro & Teukolsky 1983)

$$\Phi = -\frac{GM_1}{r_1} - \frac{GM_2}{r_2} - \frac{\omega^2 r_3^2}{2} = \text{const.}$$

When a companion star is evolved to fill its Roche lobe, the matter flows out via the Lagrange point (L1) to the compact object (Roche-lobe overflow).
The accreted matter has angular momentum with the orbital rotation of the binary system. Then, a stream of the matter forms an accretion disk around the compact object.

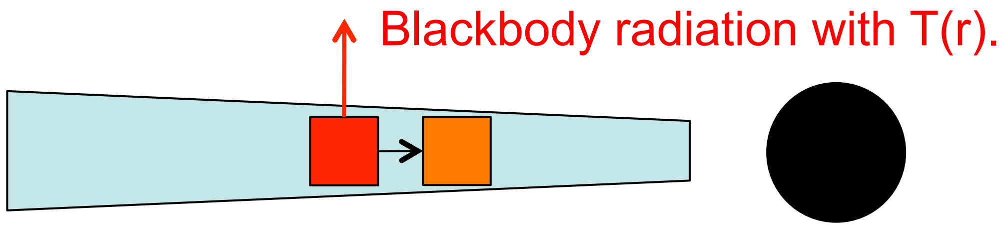
Gravitational energy is converted to the thermal X-ray radiation

$$L_X \sim \frac{GM\dot{M}}{R} = 10^{37}\left(\frac{M}{M_\odot}\right)\left(\frac{R}{10\,\mathrm{km}}\right)^{-1}\left(\frac{\dot{M}}{10^{17}\mathrm{g\,s^{-1}}}\right)\mathrm{erg\,s^{-}}$$

Eddington luminosity : $L_{\mathrm{Edd}} = 1.3 \times 10^{38}\left(\frac{M}{M_\odot}\right)\mathrm{erg\,s^{-1}}$

Standard disk model

Standard disk model proposed by Shakura & Sunyaev (1973)



Accreted matter loses its angular momentum via internal viscosity of the disk, and then falls into the inner disk. A part of the released gravitational energy is converted to the thermal X-ray emission.

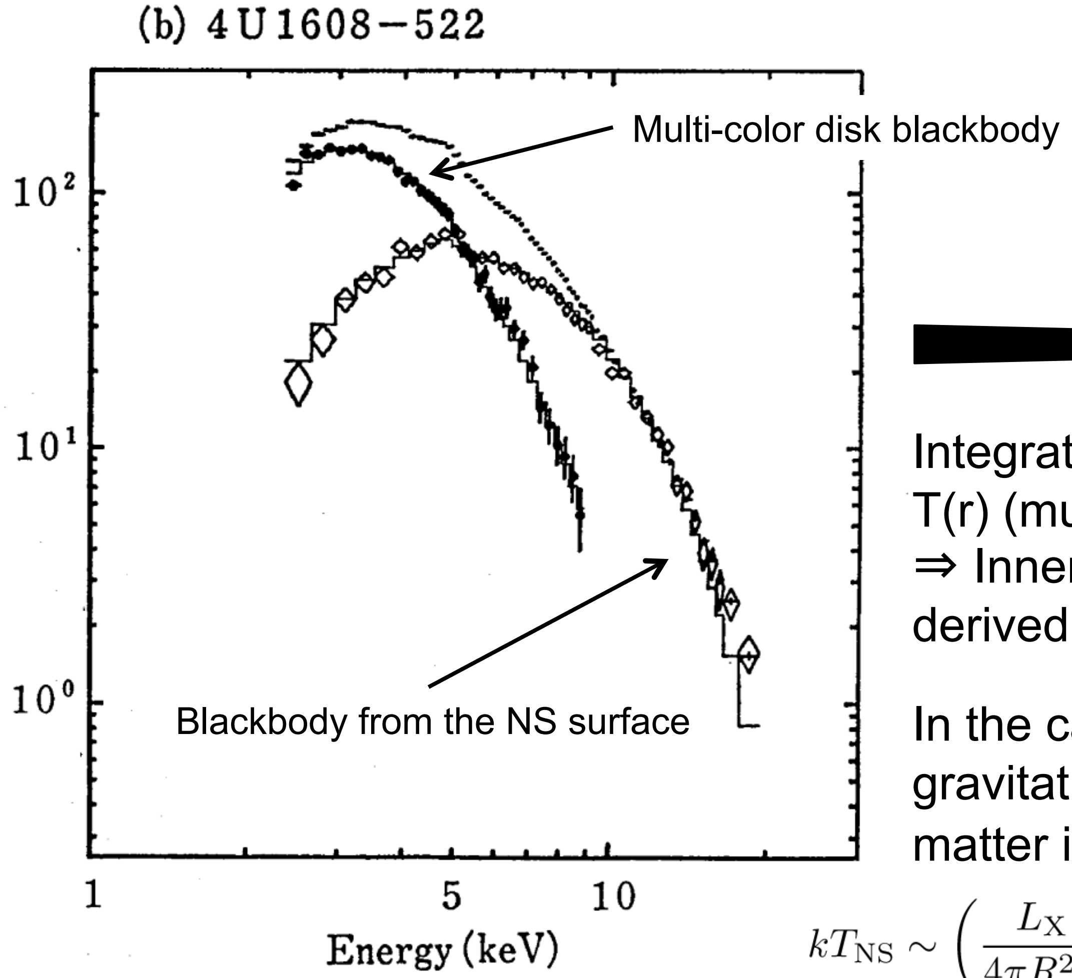
$$Q^{+} = \frac{3}{8\pi}\frac{GM\dot{M}}{r^3}\left(1-\sqrt{\frac{r_c}{r}}\right) = \sigma T(r)^4$$

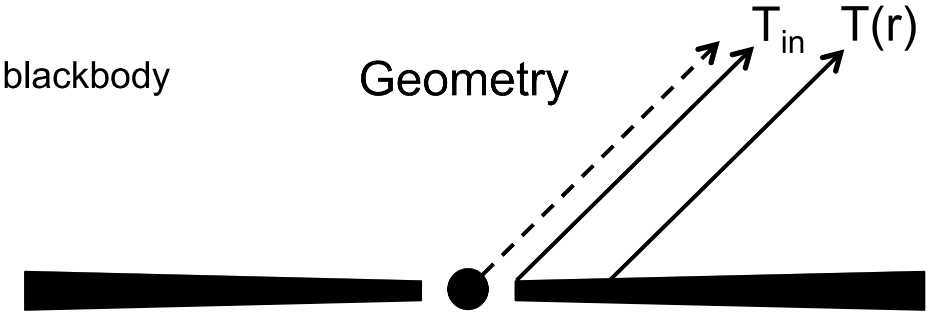
Optically-thick, geometrically-thin blackbody emission

Standard disk (α-disk) model ;
The internal viscosity is assumed to be proportional to the pressure, i.e., αP.

X-ray spectrum

X-ray emission from the LMXBs in the bright state, which luminosity is near to the Eddington limit, can be reproduced by the multi-color disk blackbody + (blackbody emission from the NS surface)
(Mitsuda et al. 1984, Makishima et al. 1986)



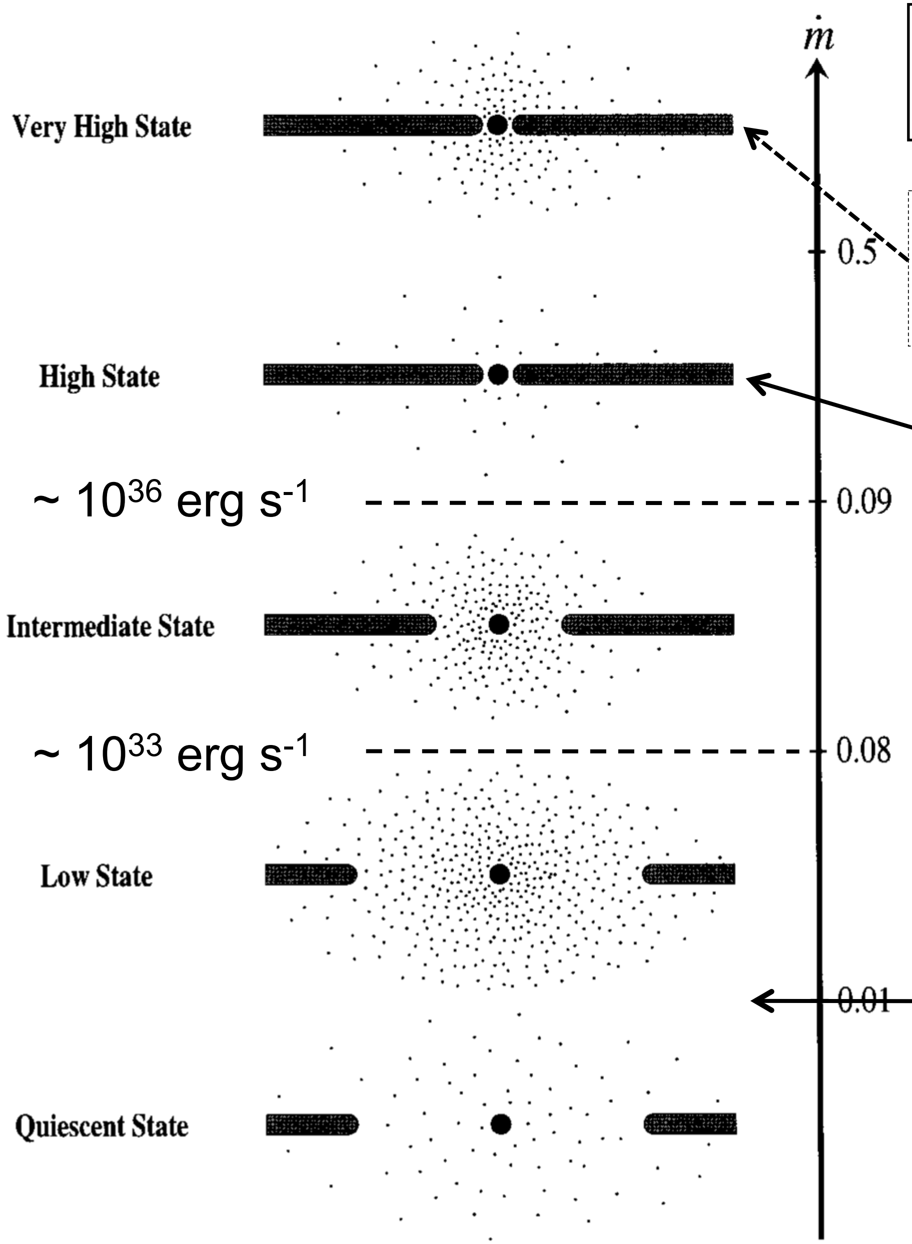


Integration of the blackbody emission with T(r) (multi-color disk BB)
⇒ Innermost disk radius, R_{in}, can be derived from T_{in}.

In the case of the NS, the residual gravitational energy of the accreted matter is thermalized on its surface.

$$kT_{\rm NS} \sim \left(\frac{L_{\rm X}}{4\pi R^2 \sigma}\right)^{1/4} \sim 1\,{\rm keV} \left(\frac{L_{\rm X}}{10^{37}{\rm erg\,s^{-1}}}\right)\left(\frac{R}{10\,{\rm km}}\right)^{-1/2}$$

State transition with the X-ray luminosity



X-ray luminosity ∝ Mass accretion rate
Classification by Esin et al. (1997)

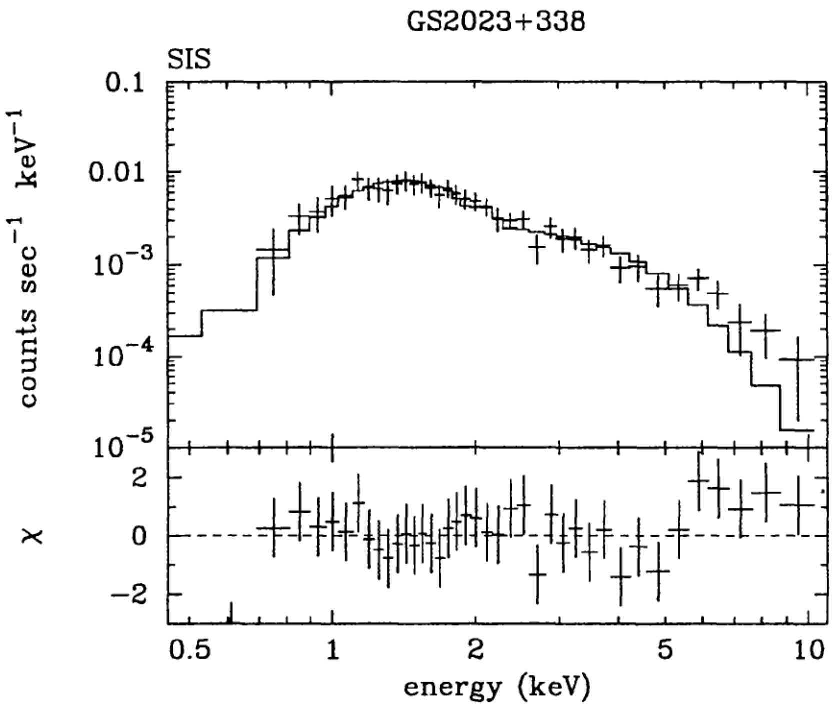
For the case of the very high state, where the mass accretion rate exceeds the Eddington limit, see Kubota & Done (2004).

High/Soft state:
Softening of the X-ray spectrum by the increase in the disk component.

? : X-ray spectral studies are limited; Yoshida et al. (1993), Barret et al. (2000).

Low/Hard state:
Decrease in the disk component. Emerge a hard (~10keV) tail.

X-ray spectrum in the Low/Quiescent state



X-ray spectrum of GS2023+338 (BH candidate) obtained with *ASCA* (Asai et al. 1998)
⇒ Power-law component with Γ = 1.7.

Recently, quiescent LMXBs in globular clusters have been studied with the *Chandra/XMM-Newton* observations. (Wijnands et al. 2002; Heinke et al. 2003; Wijnands et al. 2005)

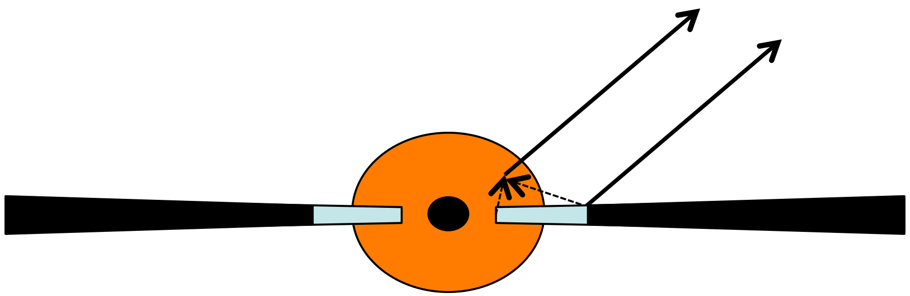
(Interpretation)
Mass accretion rate is too low to form the optically-thick, geometrically-thin accretion disk down to the NS surface or the innermost stable circular orbit of the BH.
⇒
The density in the accretion disk is sufficiently low so that the energy dissipation by the thermal emission is suppressed. The matter is fallen onto the compact object with its gravitational energy before it emits X-rays.
Advection-Dominated Accretion Flow, ADAF (Narayan & Yi 1995) or
RIAF (Radiative Inefficient Accretion Flow)

Eastern model vs Western model

Hard X-ray emission in the Low/Quiescent state is phenomenologically explained with a power-law or Comptonized blackbody spectrum.

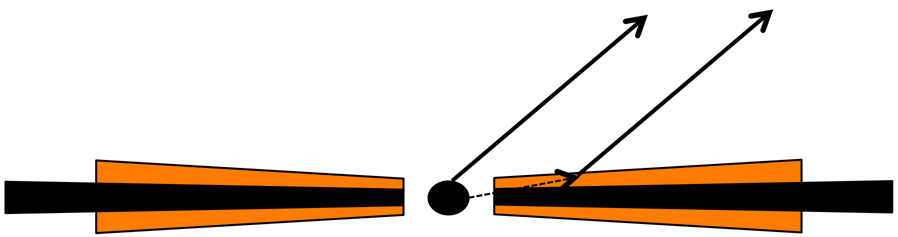
In the ADAF model, the hard X-ray emission is considered to be originated from an optically-thin, geometrically-thick corona of hot electrons (Accretion Disk Corona, ADC). However, its geometrical configuration is an open issue.

- Eastern model (e.g., Mitsuda et al. 1989, Done et al. 2002)



Comptonized hard X-ray emission by the ADC around the compact object (seed photons are provided from the disk) + multi-color disk blackbody

- Western model (e.g., Church & Balucinska-Church 2004)



Blackbody emission from the NS surface or neighborhood of the primary + Comptonized hard X-ray emission by the ADC on the accretion disk

X-ray emission in the intermediate state

There are few observations for this luminosity range (10^{34} – 10^{36} erg s^{-1}), where the state transition may occur between the Low/Hard state and the High/Soft state.

↓

The advent of *Chandra* (~0.5" angular resolution) allows us to detect the extragalactic LMXBs. However, the detection limit for these LMXBs is ~ 10^{36} erg s^{-1} (High/Soft state).

↓

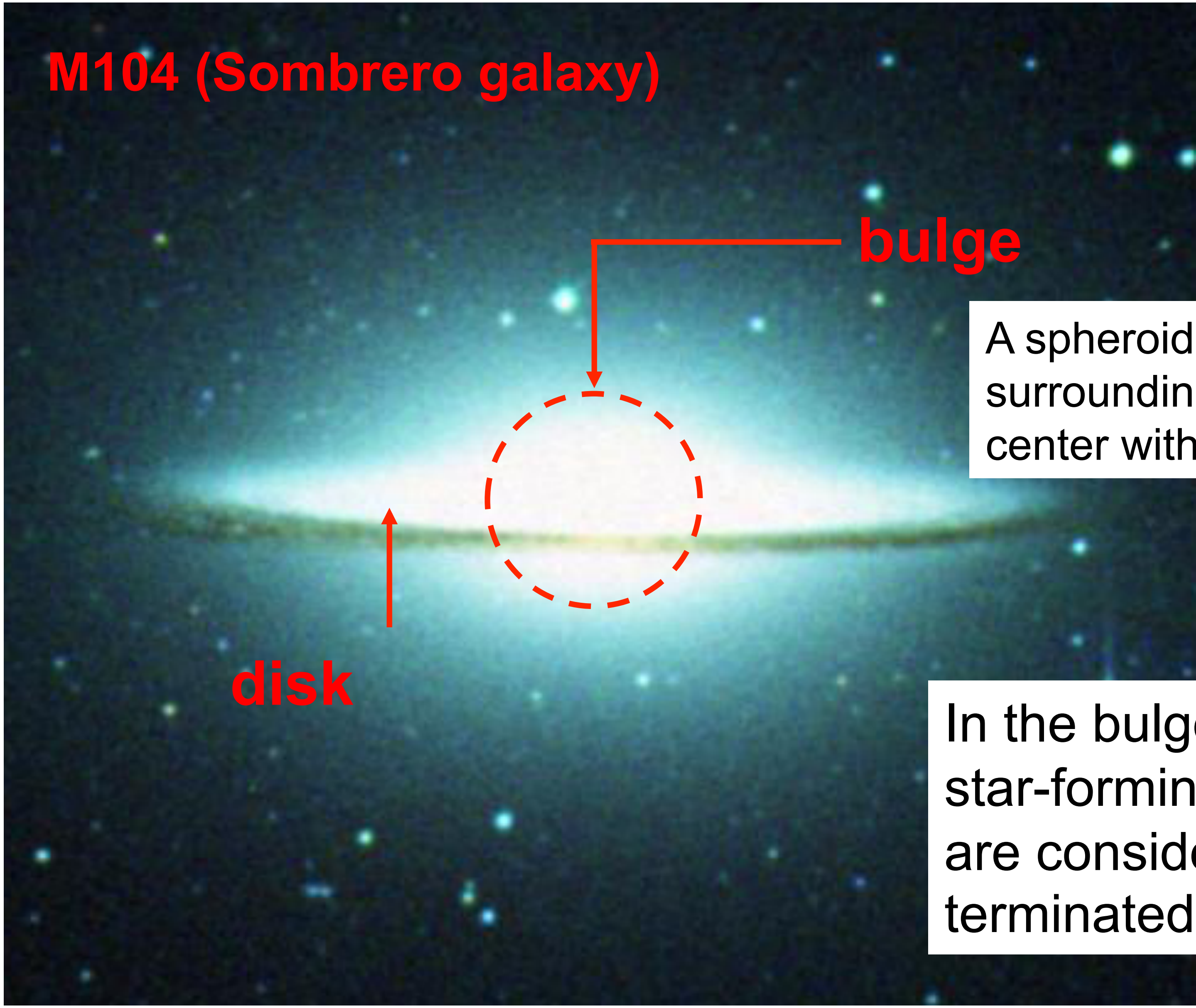
Search relatively dim (new class) LMXBs in our Galaxy!

The Galactic bulge: a reservoir of the LMXBs?

(The spatial distribution of the LMXBs in our Galaxy is different from that of HMXBs. Most of the HMXBs exist in the Galactic disk. This fact reflects that the age of the OB supergiants is typically ~ 10^{6} yr, which requires star-formation activity.)

X-ray fluxes of the Galactic bulge sources are Fx = 10^{-12} – 10^{-11} erg s^{-1} cm^{-2}

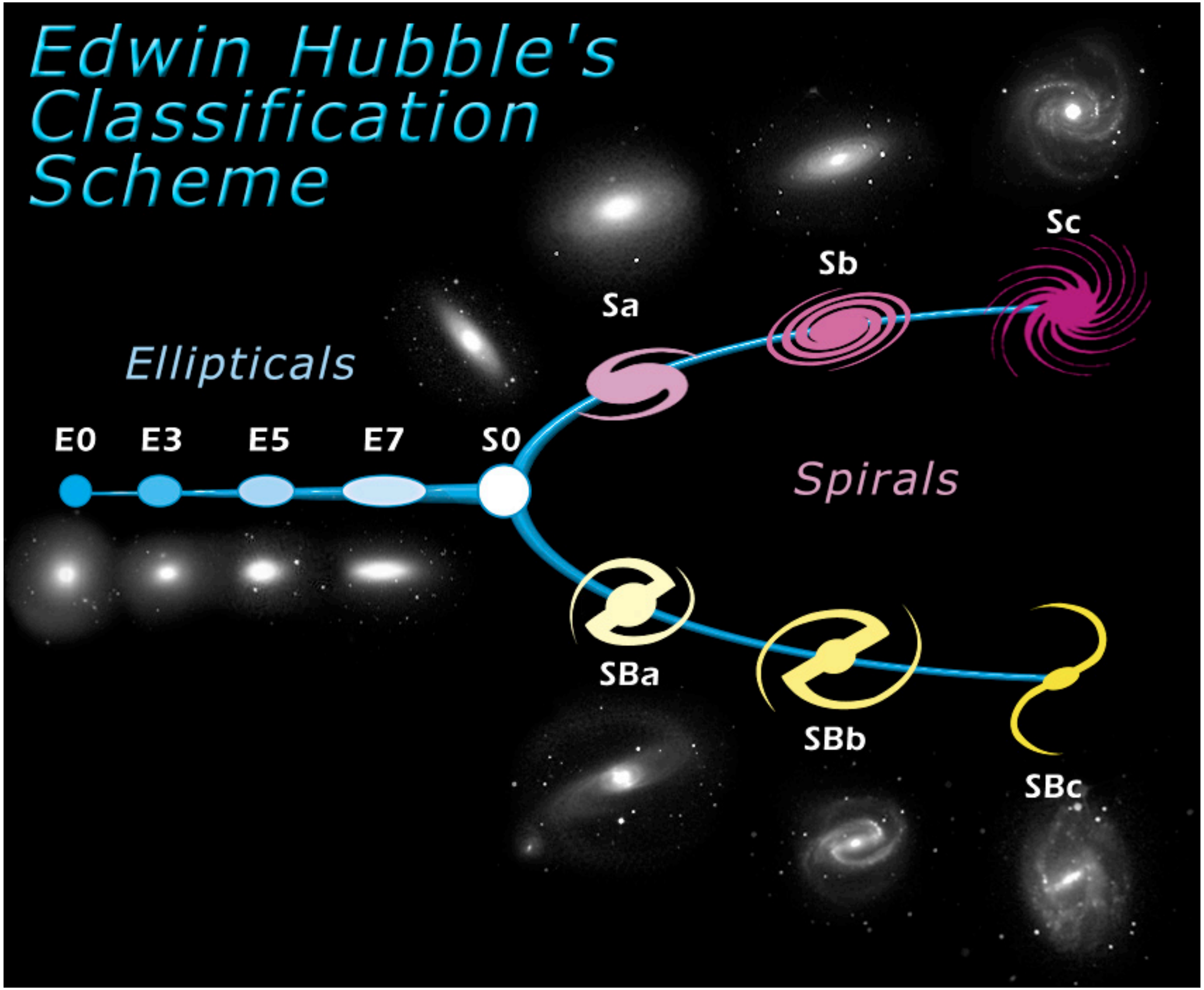
Galactic bulges



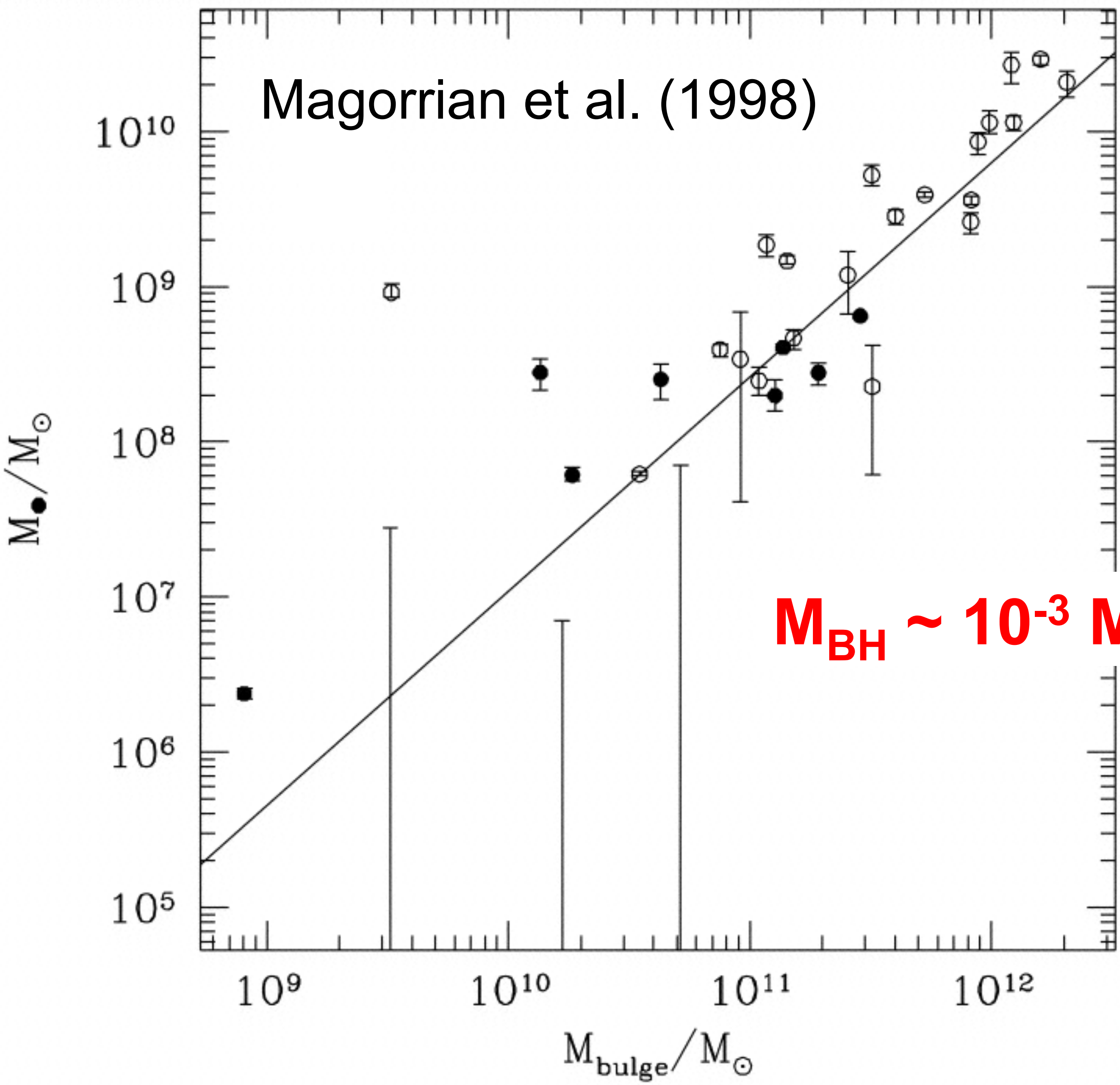
A spheroidal component surrounding the galactic center with ~1kpc.

In the bulges, the star-forming activities are considered to be terminated.

Hubble sequence



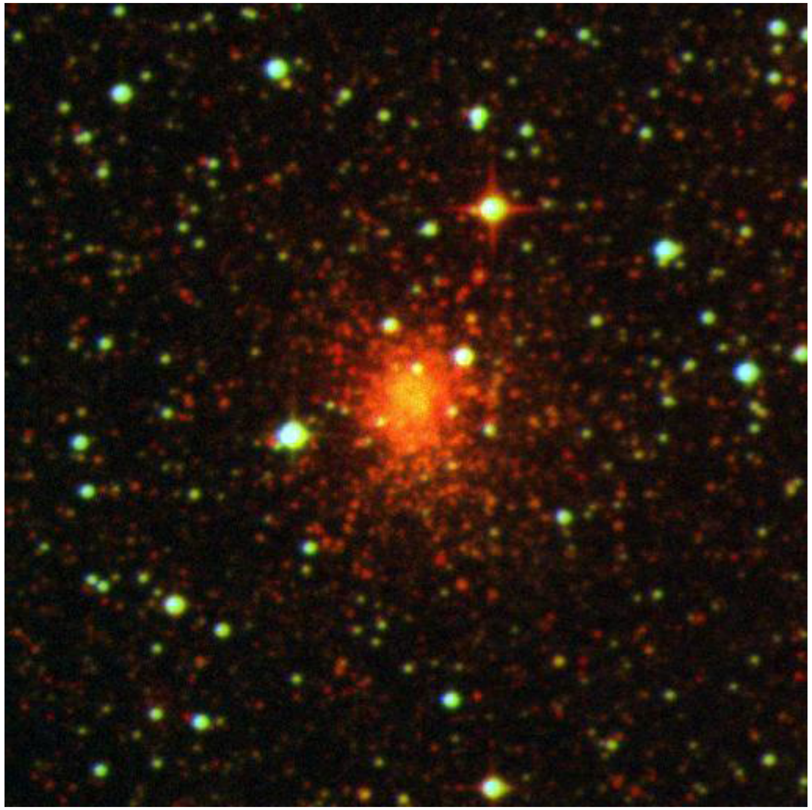
M_{BH}–M_{Bulge} relation



$M_{BH} \sim 10^{-3}\, M_{Bulge}$

Population in the bulges

Age of the galactic bulges = 10^8~10^9 yr
→ There are many old-age stars, called "Population II".



Globular cluster Terzan 5

✓ A low-mass star (< $1M_\odot$)
  → Late-Type star
  → Infrared observation
✓ A massive star
  → Rapid evolution (~10^7 yr) to NS or BH
  → X-ray objects, esp., LMXBs
✓ Globular cluster

In the Galactic bulge, the nearest bulge to the Sun, relatively dim X-ray sources can be detected.
⇒ Ideal site to search the LMXBs in the intermediate state.

Comparison of the X-ray satellites

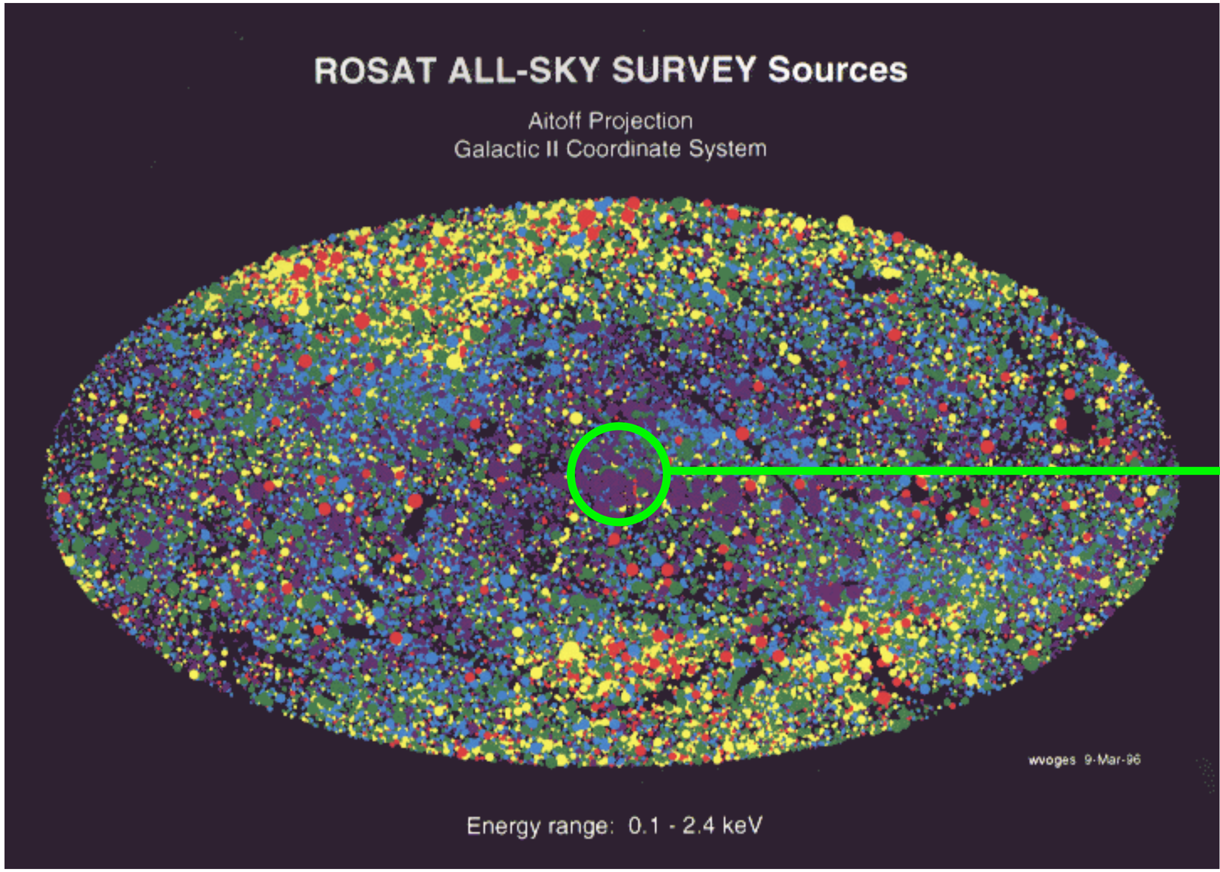
Satellites Detector (FOV)	Energy (keV)	Angular resolution	Survey
ROSAT PSPC (2° × 2°)	0.1 - 2.4	~10”	All sky
ASCA GIS (r = 25’)	0.7 - 10.0	3’	Limited sky
RXTE ASM SSC (6° × 90°)	1.5 - 12.0	3’ ×15’	All sky
Chandra ACIS-S (8.3’ × 50.6’)	0.2 - 10.0	0.5”	Limited sky
XMM-Newton pn (27’ × 26’)	0.15 – 15.0	15”	Limited sky
Suzaku XIS (19’ × 19’)	0.3 – 12.0	1.9’	Limited sky

ROSAT satisfies
- ✓All-Sky survey which covers the Galactic bulge
- ✓High angular resolution to determine the X-ray source position
- ✓Energy band sensitive to the X-ray absorption

ROSAT All-Sky Survey

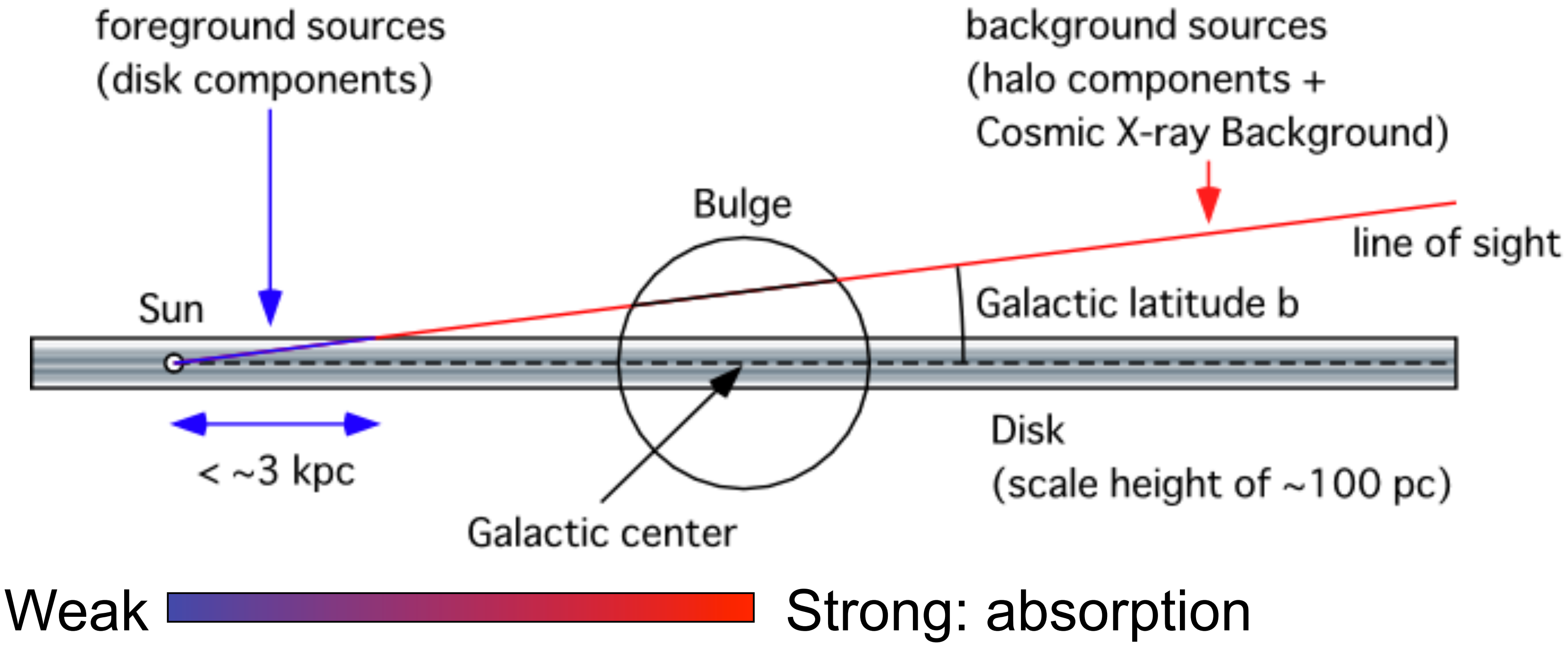
All-Sky survey performed in the initial phase

⇒ Catalogue for the detected bright point sources:
ROSAT Bright Source Catalogue
(RBSC: Voges et al. 1999)



Flux-limited sample of the Galactic bulge (r ~ 12°) constructed by an X-ray optics

Cross-section of the Galaxy

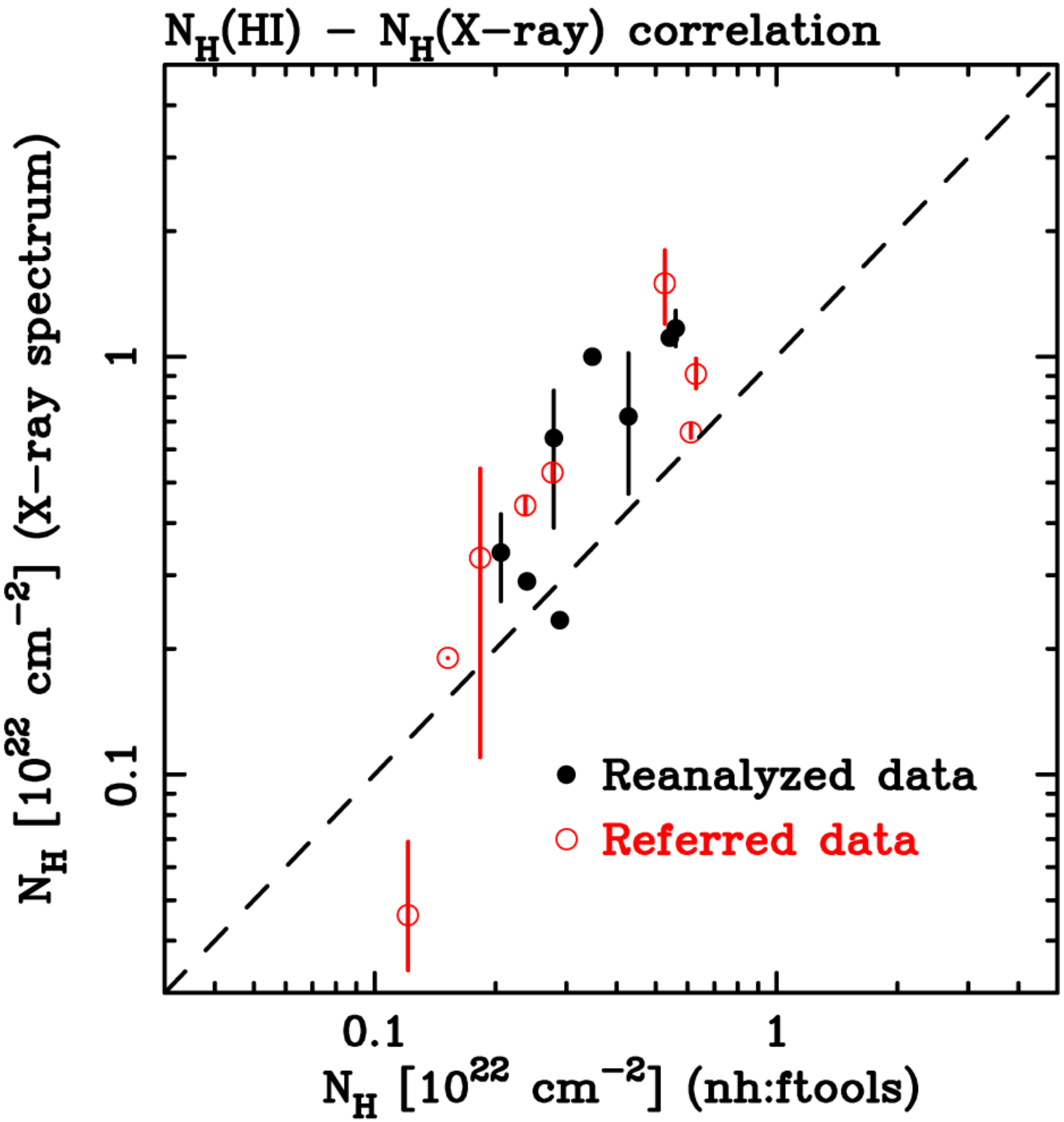


X-ray sources in the Galactic center are suffered from the heavy absorption (~10^{22} cm^{-2}). On the other hand, the absorption for the foreground sources is low.

Distance to the source can be estimated by the X-ray absorption.

What is the column density towards the Galactic bulge？

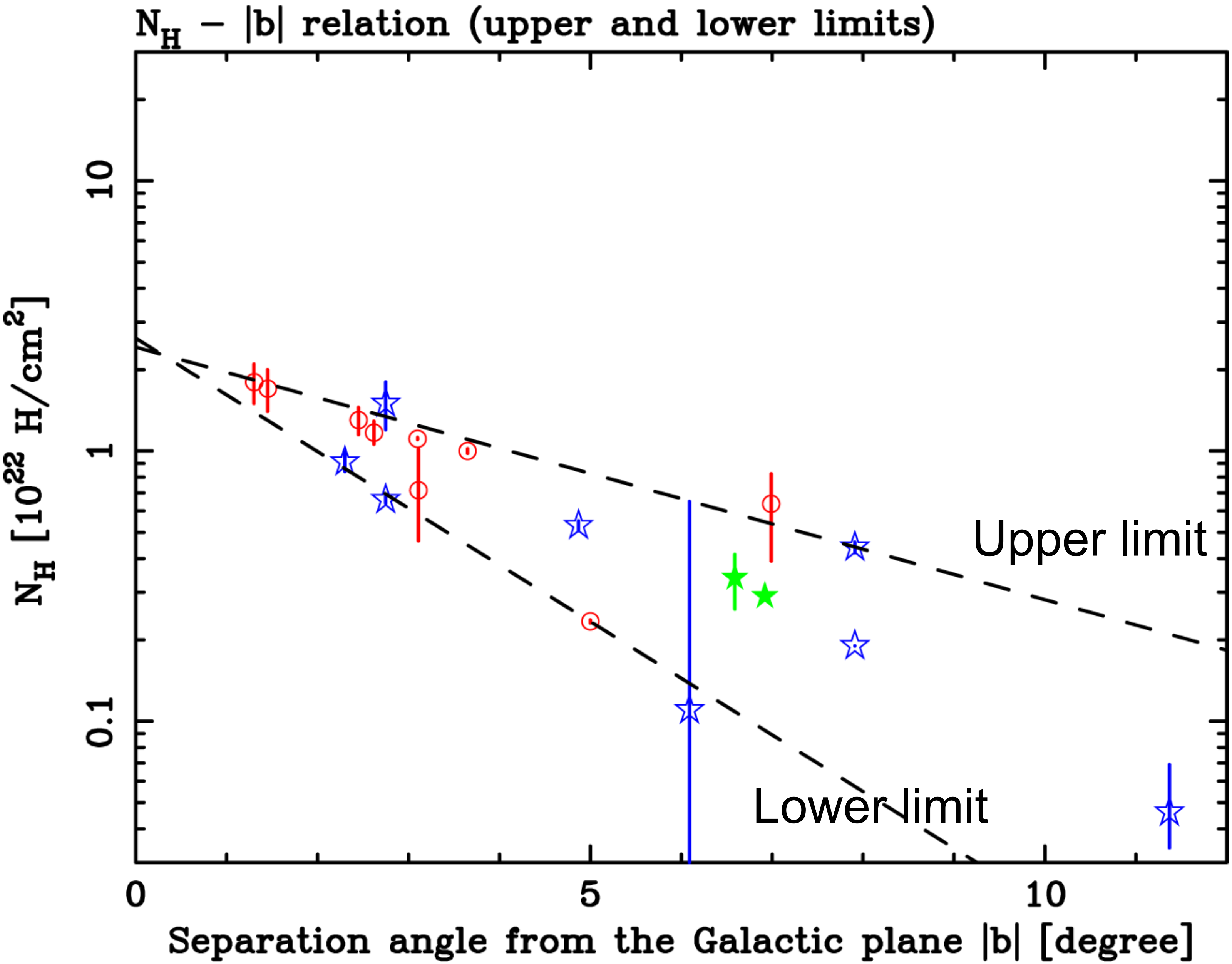
Absorption column density



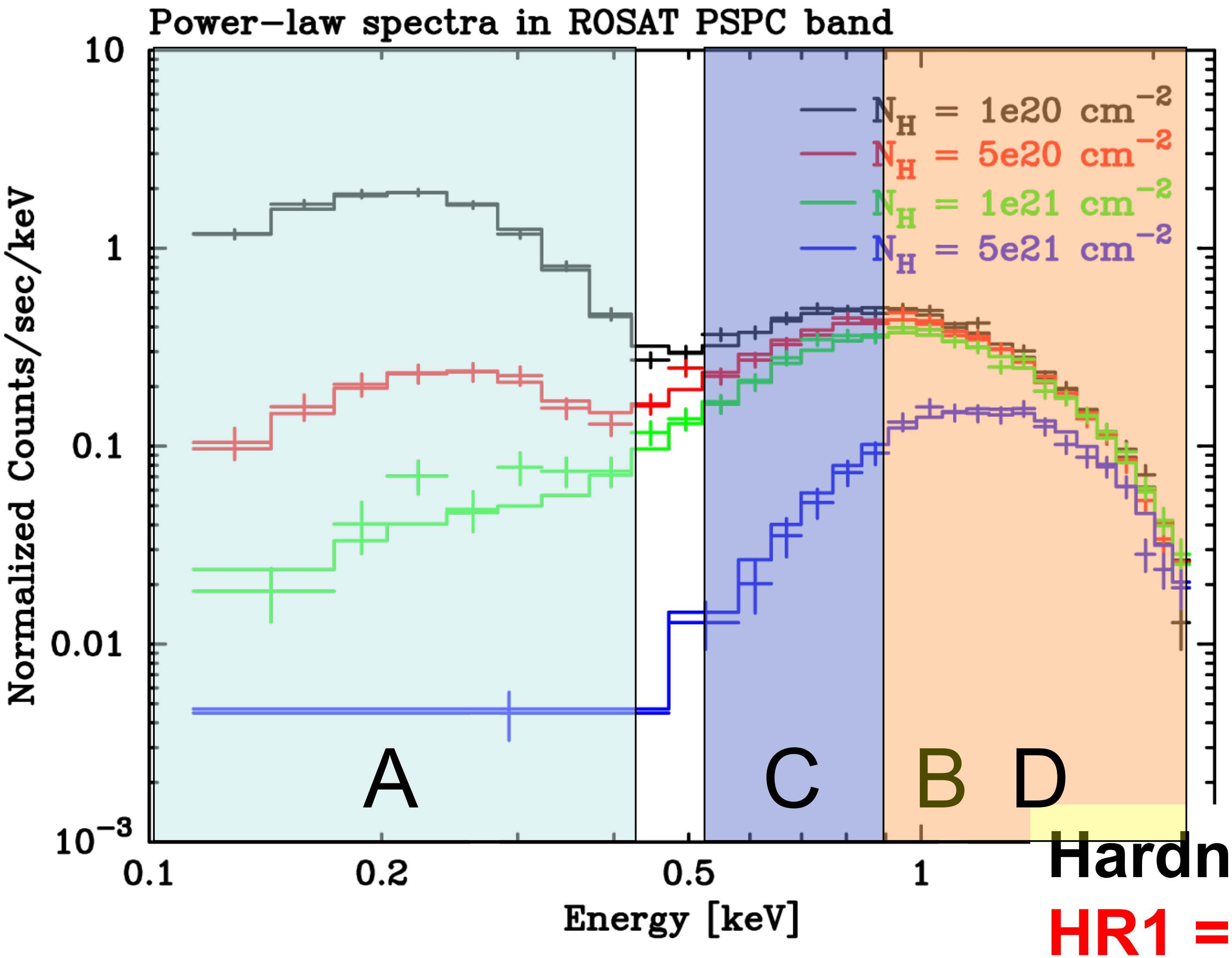
(Horizontal axis)
HI column density derived from the 21cm emission line (Dickey & Lockman 1990)

(Vertical axis)
Absorption column density derived from the X-ray spectral analysis of the Galactic bulge LMXBs.

|b|-dependence of the column density



Hardness ratio



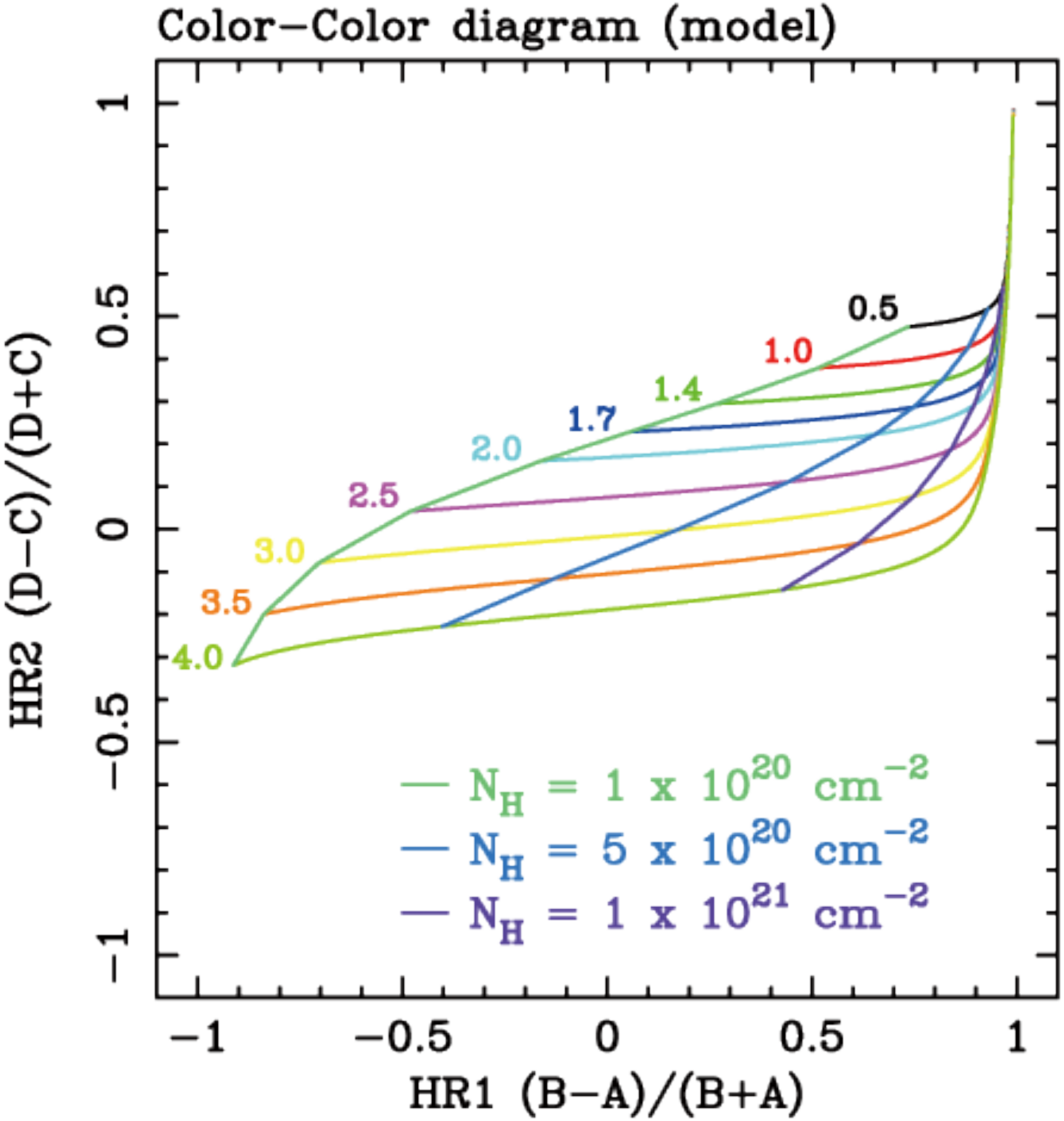
Power-law spectrum with Γ = 1.7 is assumed.

Hardness ratio:

HR1 = (B-A)/(B+A)

HR2 = (D-C)/(D+C)

Color-Color diagram



HR1: Absorption
HR2: Power-law index

Galactic latitude of each RBSC source

↓

Upper/Lower limit of the hydrogen column density towards the Galactic bulge

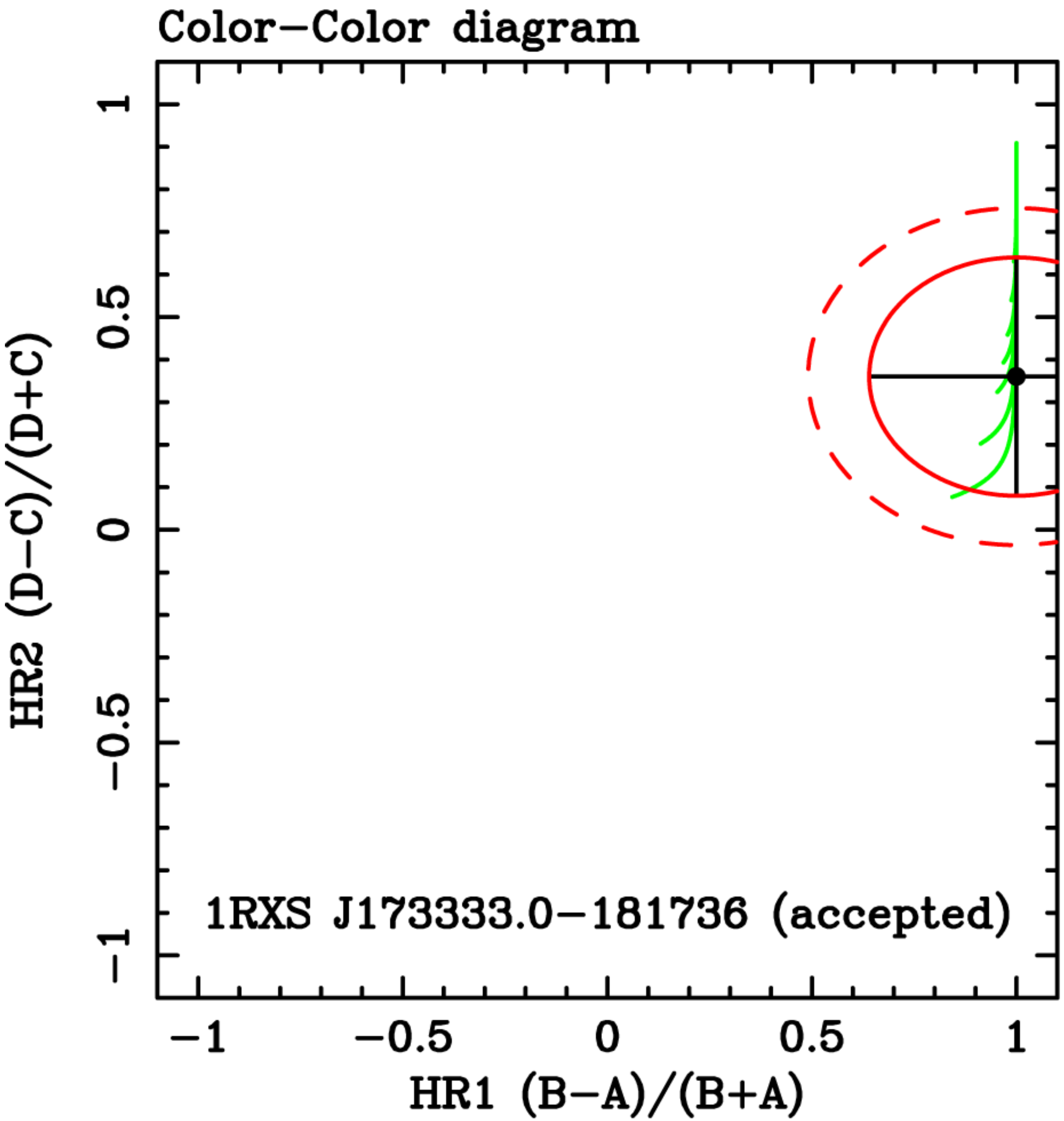
↓

Assumption of the power-law index

↓

Region in the color-color diagram

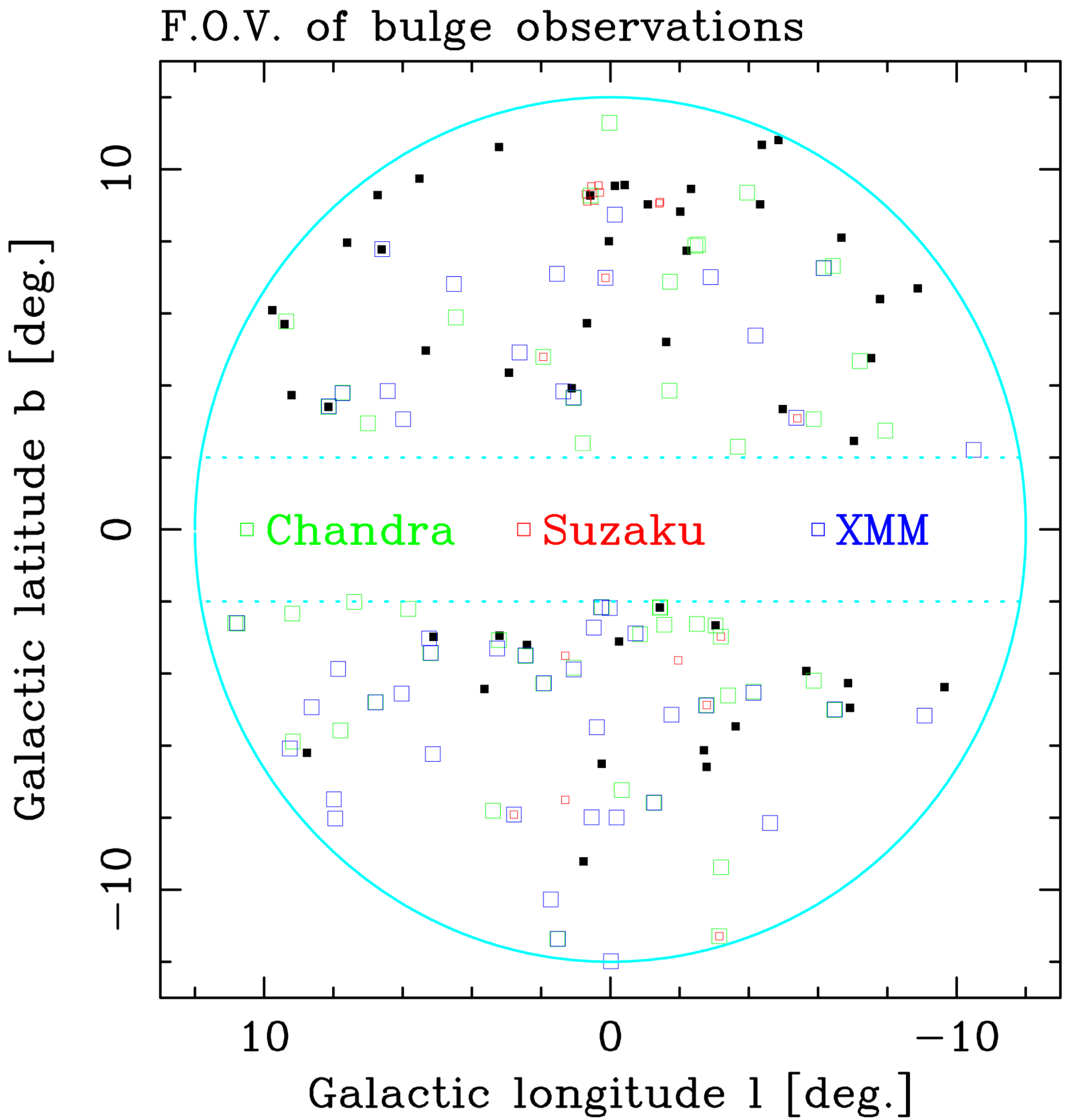
Source selection



X-ray sources with the separation angle from the Galactic center of > 12°, and |b| > 2°: 149 objects

Selected sources: (Candidates of the Galactic bulge sources) 68 objects

Previous observations



Among the 68 objects, the identified sources are as follows:

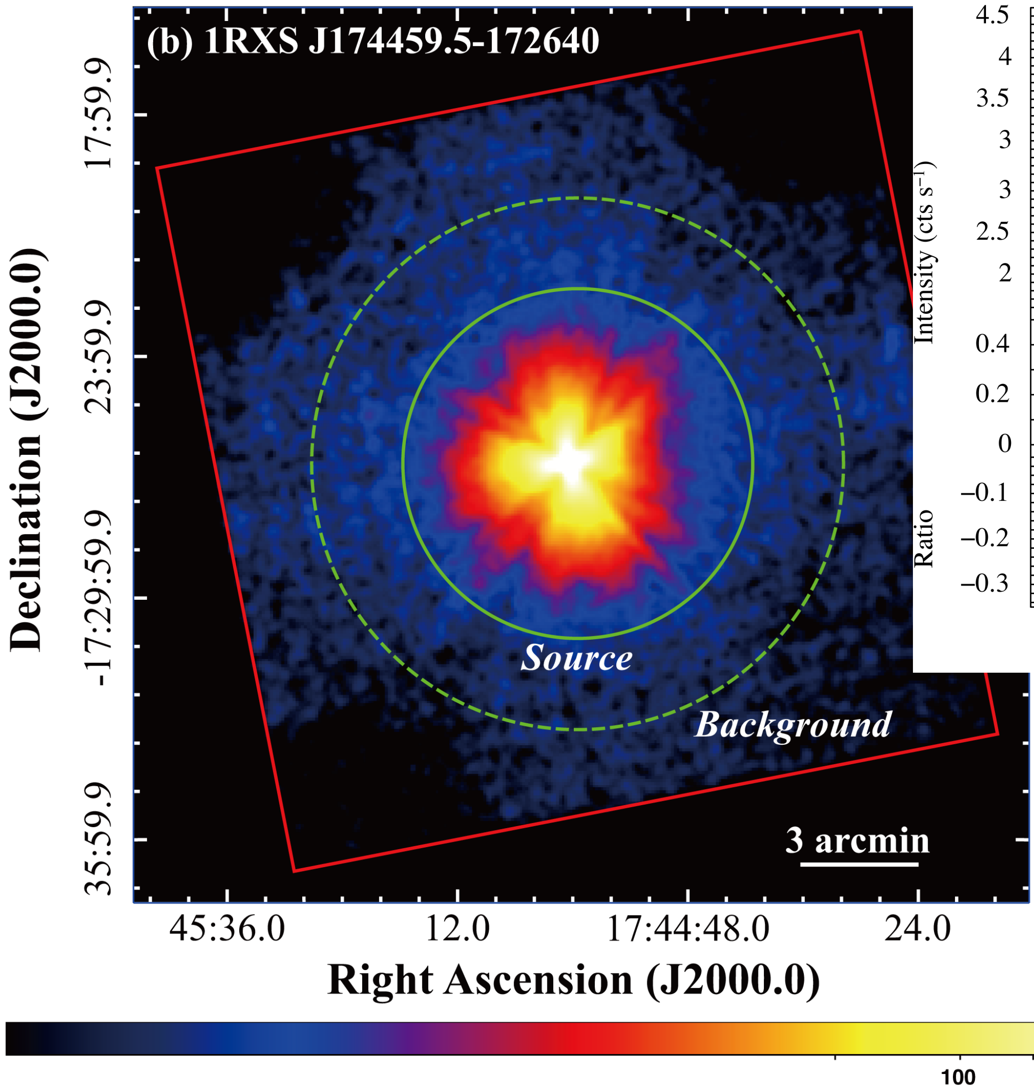
- NS LMXBs : 16
- Cluster of galaxies : 1
- Supernova remnants : 1
- Cataclysmic variable : 1
- T-Tauri star : 1

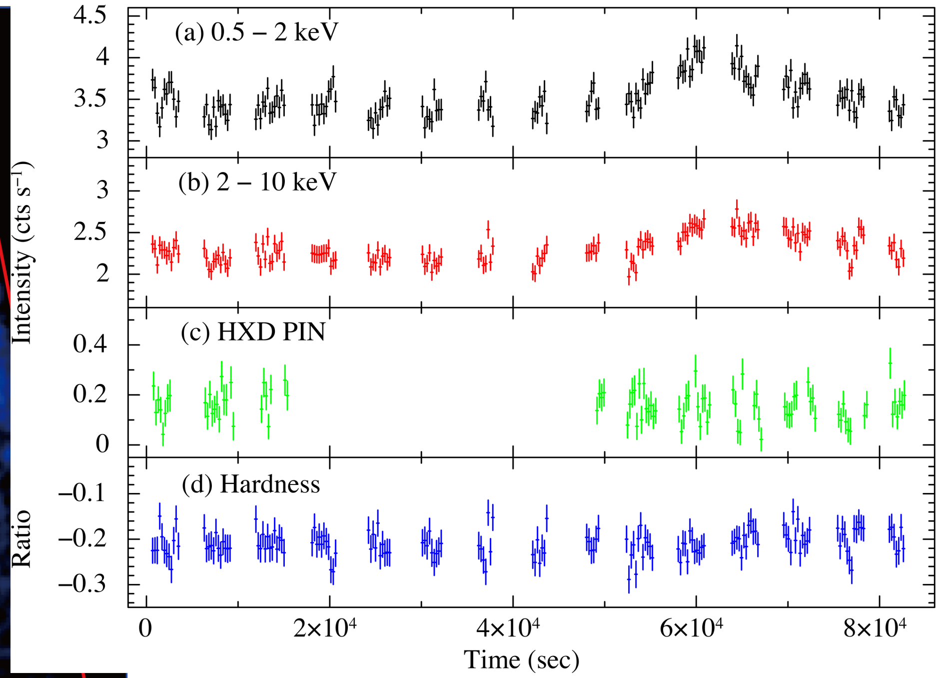
Unknown : 48
(filled black squares)

Our proposal of the X-ray poiting observations to obtain the X-ray spectrum has been accepted for
XMM-Newton : 5 sources
Chandra : 11 sources
Suzaku : 5 sources

UnID X-ray source observed with Suzaku

1RXS J174459.5-172640 (l,b) = (+9.77°, +6.09°)

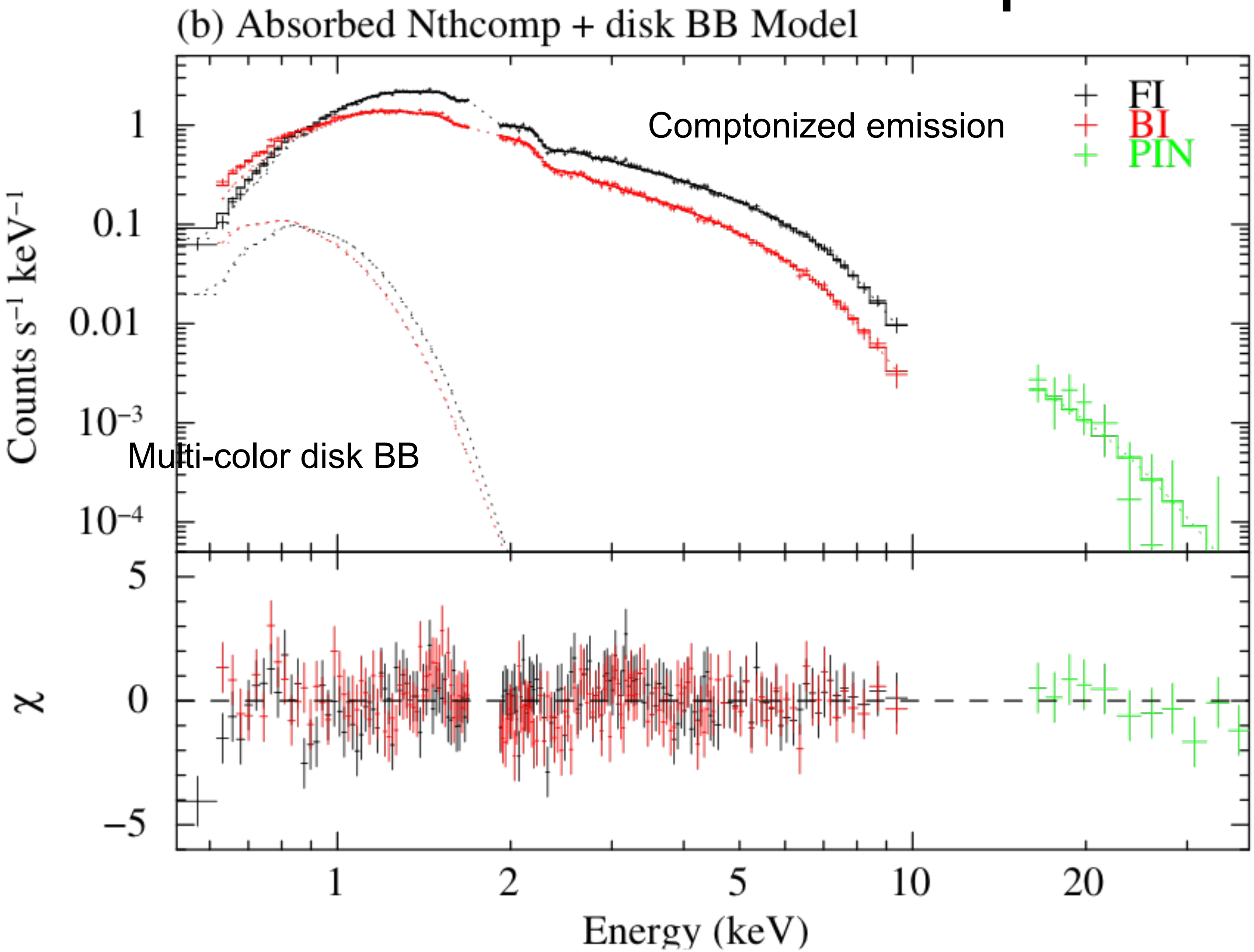




(Left) X-ray image in the 0.5 – 10 keV band obtained with the X-ray telescope + X-ray CCD camera. (Right) X-ray light curves, including the one obtained with the Hard X-ray Detector.

Mori et al. (2012)

1RXS J174459.5-172640 spectrum



Discussion

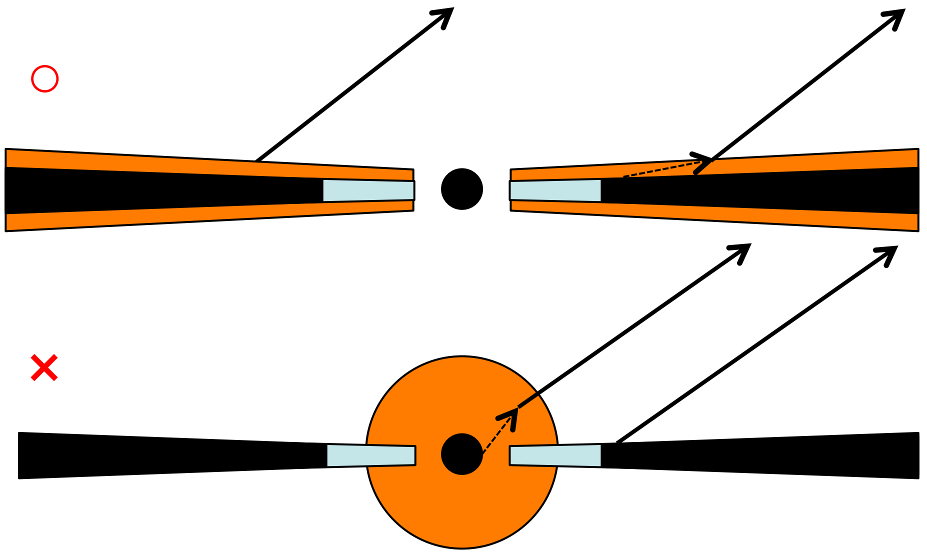
- ➢ Hydrogen column density (N_H) is larger than that of HI (2.6×10^{21} cm^{-2}).
⇒ Not a foreground source.
- ➢ No emission line characteristic of optically-thin thermal plasma ⇒ × Active binary.
- ➢ No Fe-K emission line ⇒ × Cataclysmic variable or AGN.
- ➢ No pulsation was detected. ⇒ × Pulsar/Pulsar wind nebula.

Optical counterpart, 2MASS J17445953-1726397, was found. Its magnitudes in the J, H, and K bands suggests that the companion star is a yellow-white (A or F) giant star.

↓

A new LMXB with a luminosity of Lx(0.5-10keV) = 2×10^{35} $(d/8.5kpc)^2$ erg s^{-1}

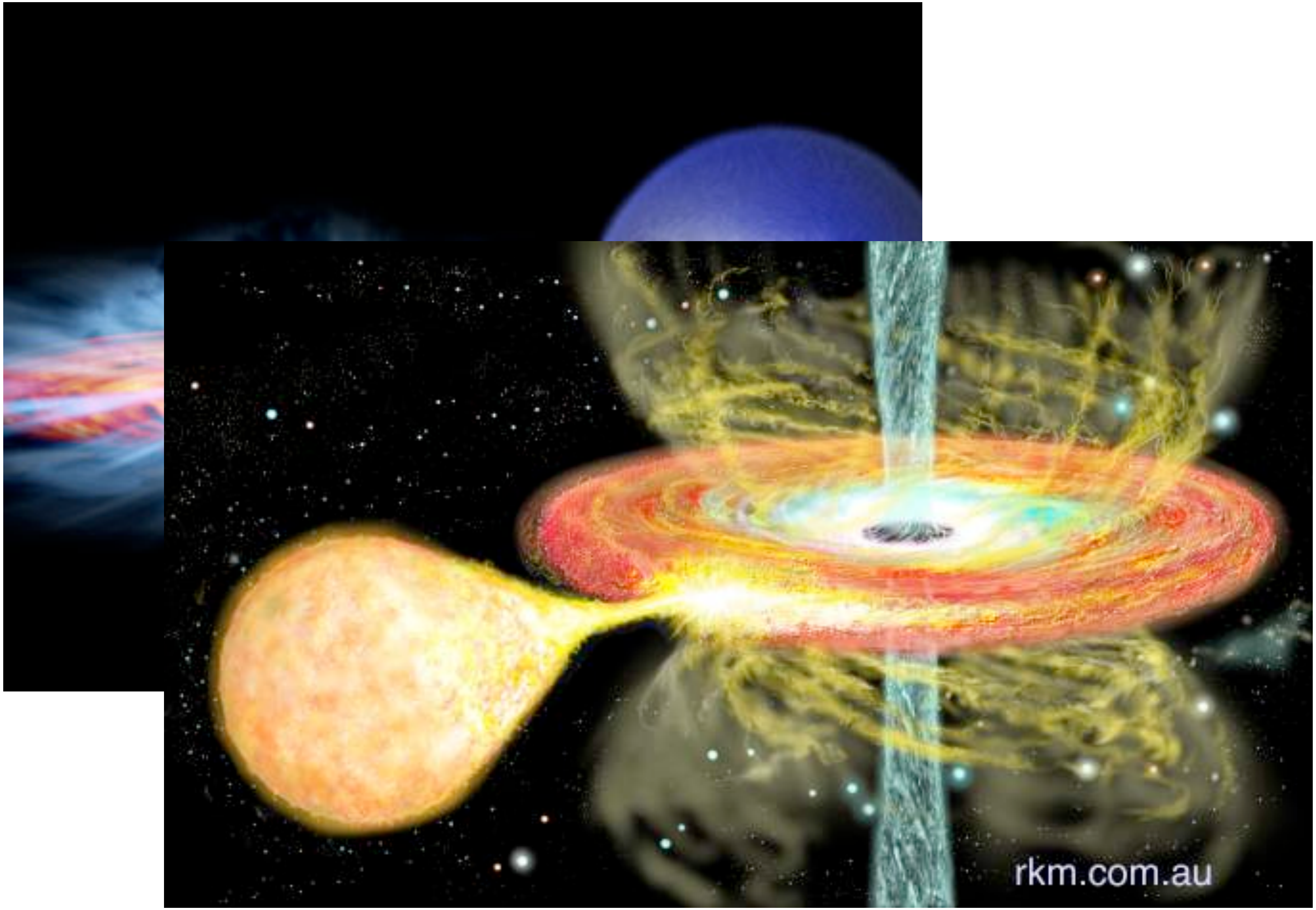
Possible geometry



The disk blackbody emission (kT ~ 0.1 keV) from the accretion disk is up-scattered by the hot plasma with kT ~ 7 keV. The innermost disk radius can be estimated to be ~ 140 – 200 km (i.e., truncated disk).

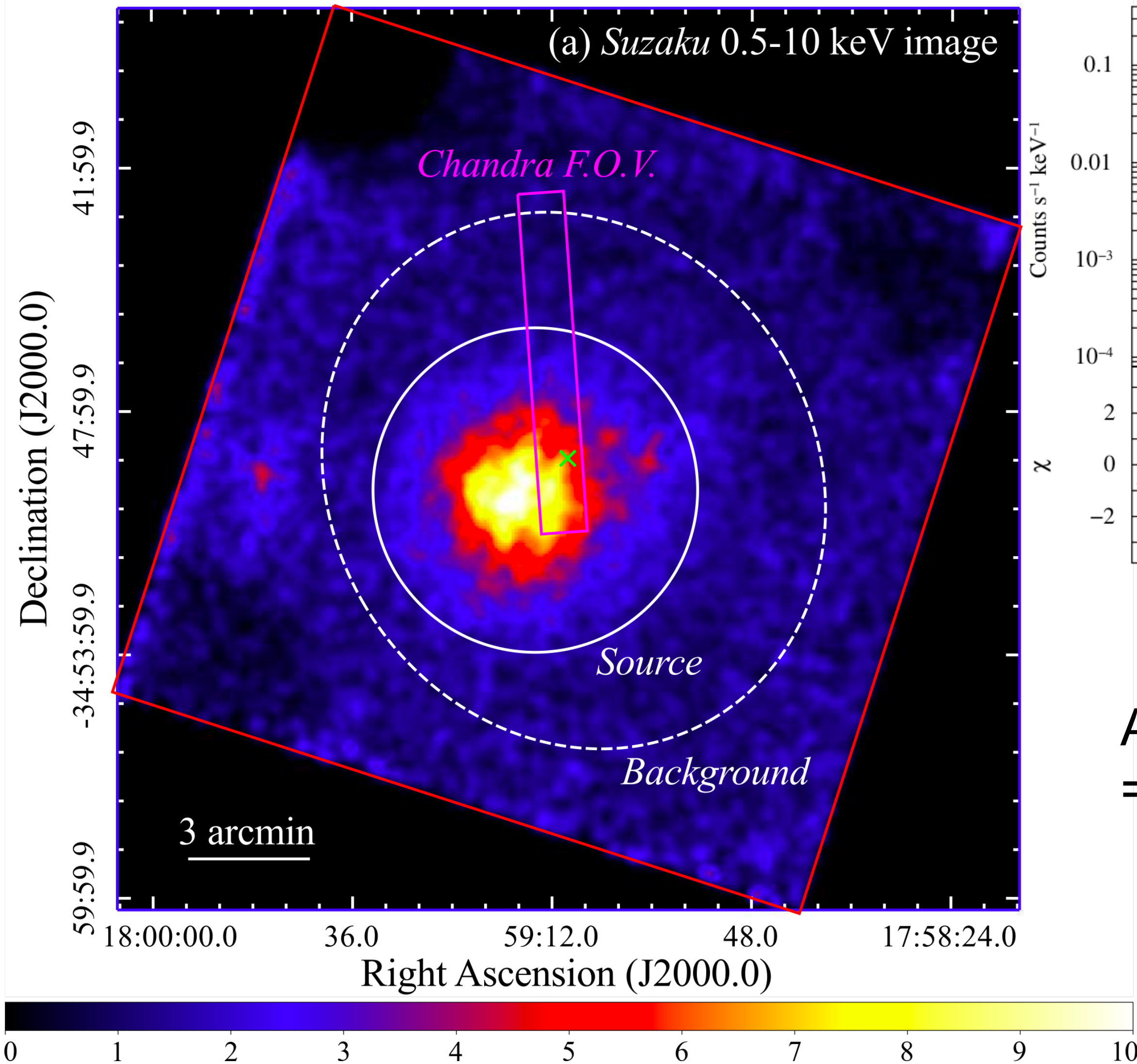
The plasma may be blowing out from the disk surface, such as disk wind.

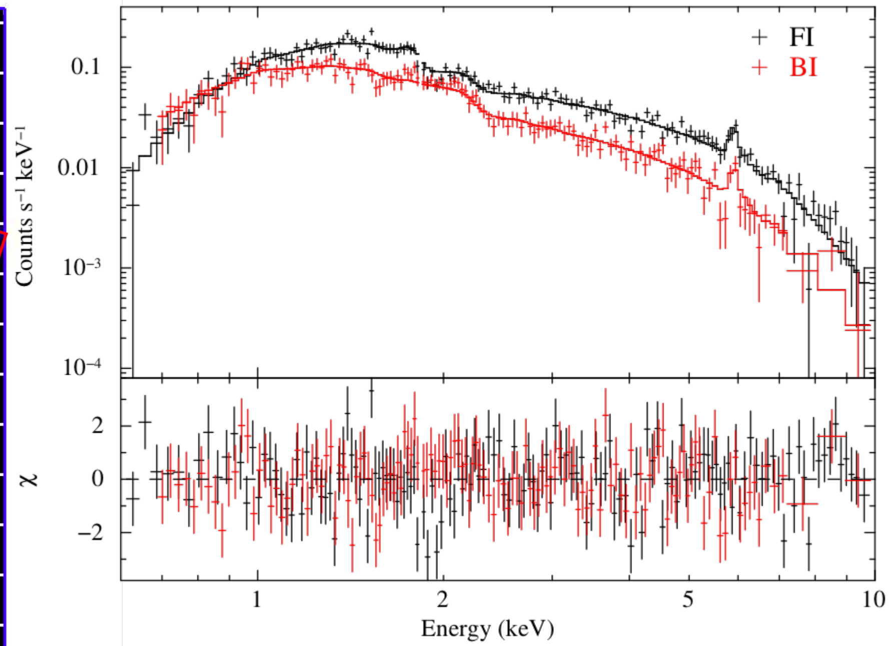
Discussion



Another example of the unID source

1RXS J175911.0-344921 (l,b) = (-3.62°, -5.46°)



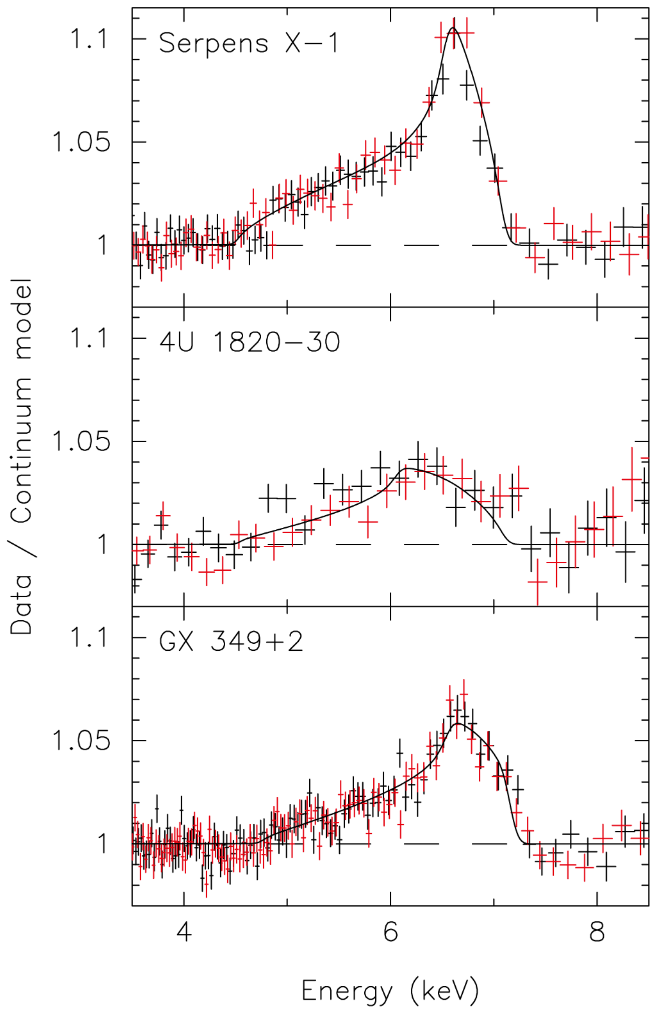


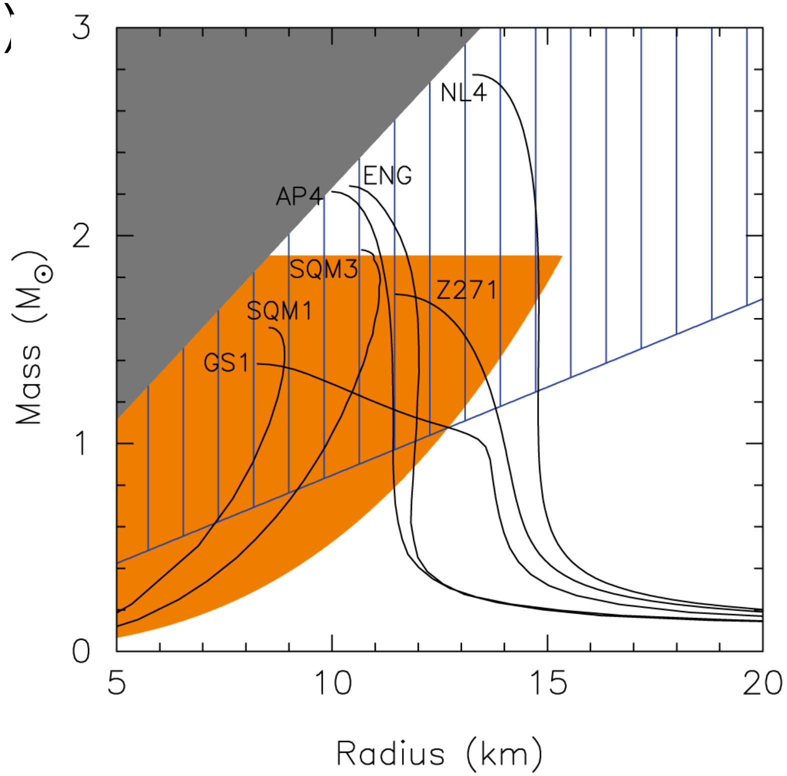
A new cluster of galaxies at z = 0.13 was found!

Mori et al. submitted

Broadening of Fe-Kα emission line

Recently, in some NS LMXBs, the broad Fe-K emission lines distorted by the gravitational redshift was detected (e.g., Bhattacharyya & Strohmayer 2007, Cackett et al. 2008)

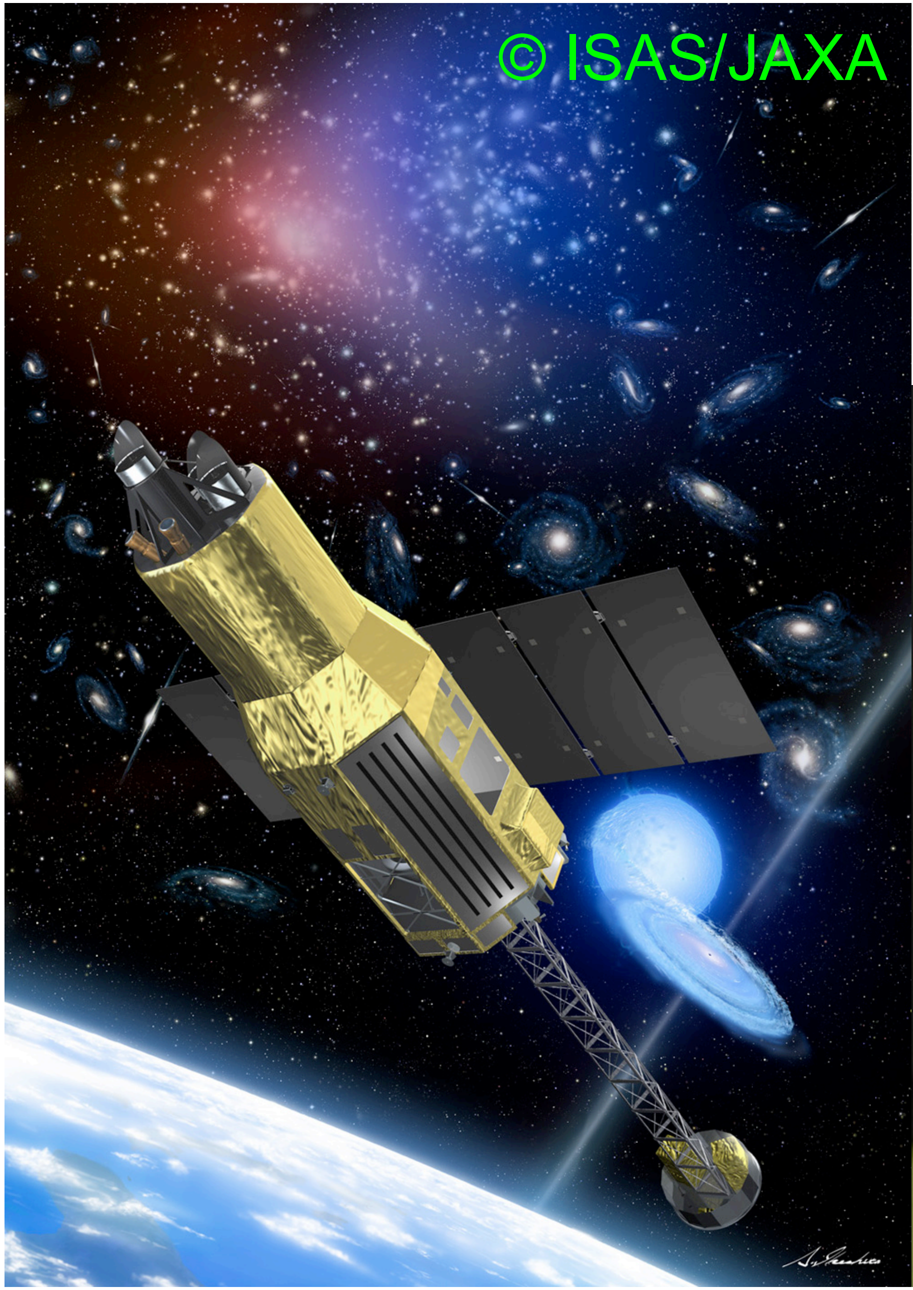




Gravitational redshift parameter $z = GM/Rc^2$ gives a relation between M and R (blue region in the figure) ⇒ Constrain the NS Euqation of State.

One of the scientific goals of ASTRO-H!

ASTRO-H



⌘ High energy resolution with Soft X-ray Telescope + X-ray micro-calorimeter
⌘ Wide energy band with Hard X-ray Telescope + Hard X-ray Imager