「すざく」衛星の成果

立教大学理学部
北本俊二

目次

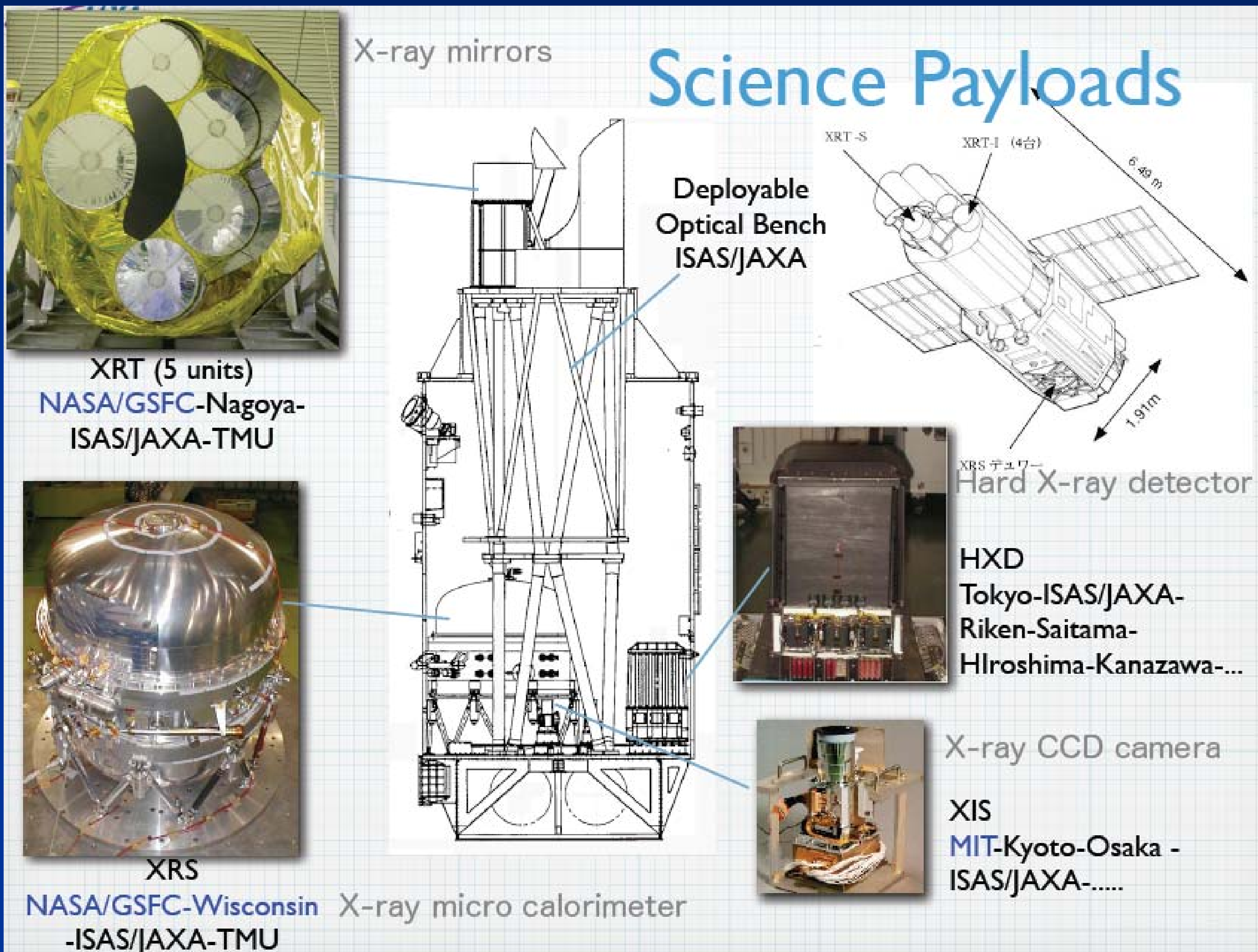
- X線天文衛星「すざく」
  - 拡散X線に強い「すざく」
  - 硬X線に強い「すざく」
- 宇宙高温ガスに迫る
  - 地球周辺からWHIMまで
- コンパクト星の中心に迫る
  - ブラックホールと中性子星
- 宇宙の粒子加速領域に迫る
- まとめ

X線天文衛星「すざく」

2005年7月10日

ISAS/JAXA-NASA

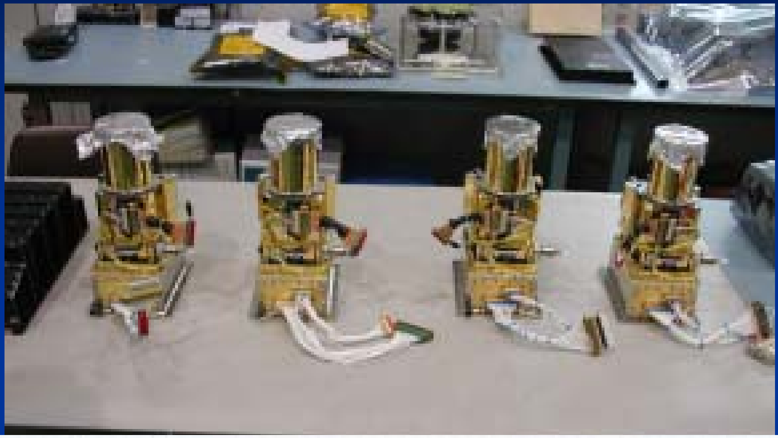
X線天文衛星「すざく」

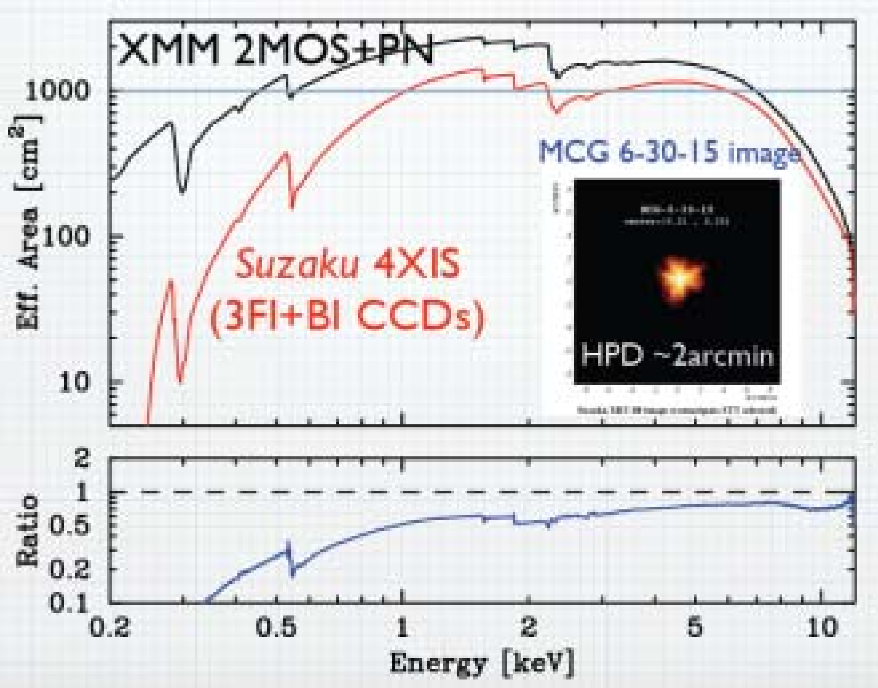

Science Payloads
X-ray mirrors
XRT (5 units)
NASA/GSFC-Nagoya-
ISAS/JAXA-TMU
Deployable
Optical Bench
ISAS/JAXA
XRT-S
XRT-I (4台)
6.49 m
1.91m
XRS デュワー
Hard X-ray detector
HXD
Tokyo-ISAS/JAXA-
Riken-Saitama-
HIroshima-Kanazawa-...
X-ray CCD camera
XIS
MIT-Kyoto-Osaka -
ISAS/JAXA-.....
XRS
NASA/GSFC-Wisconsin
-ISAS/JAXA-TMU
X-ray micro calorimeter

X線天文衛星「すざく」

- XIS
- 4台のCCDカメラ
  - FI　3台
  - BI　1台

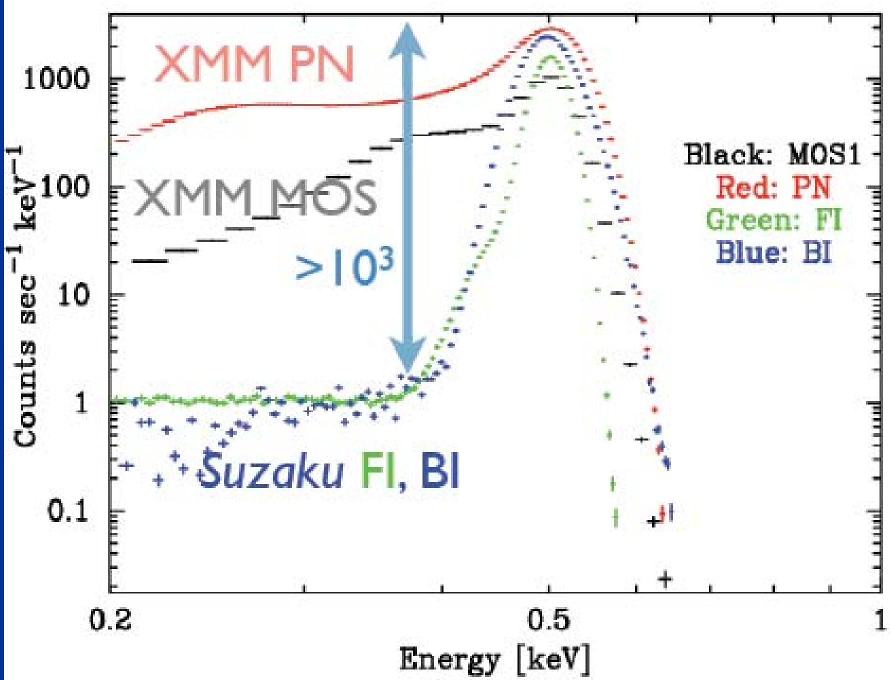
- 大面積
- 高エネルギー分解能
- 低バックグラウンド



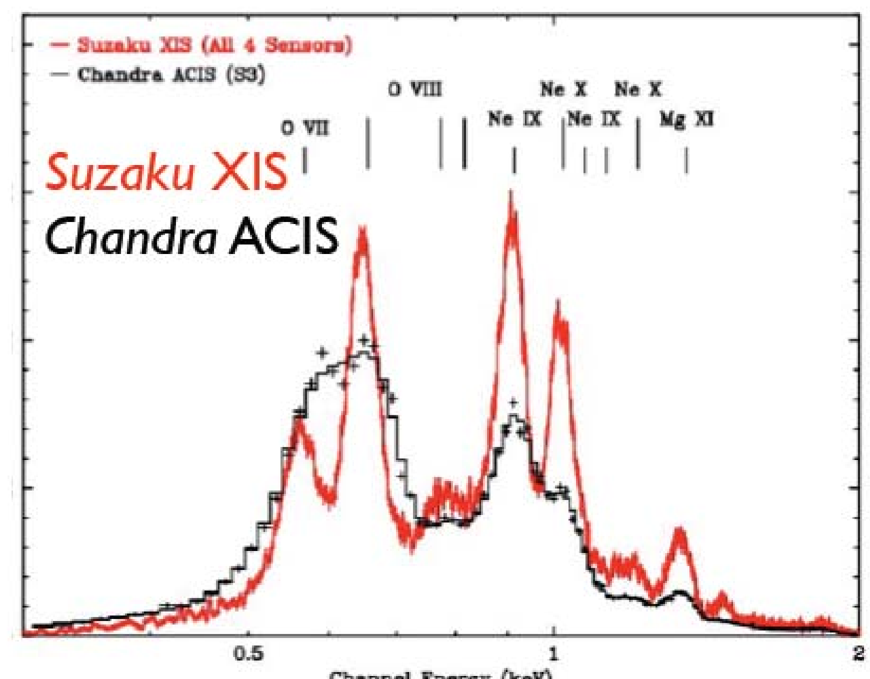


XIS:低エネルギーで高いエネルギー分解能

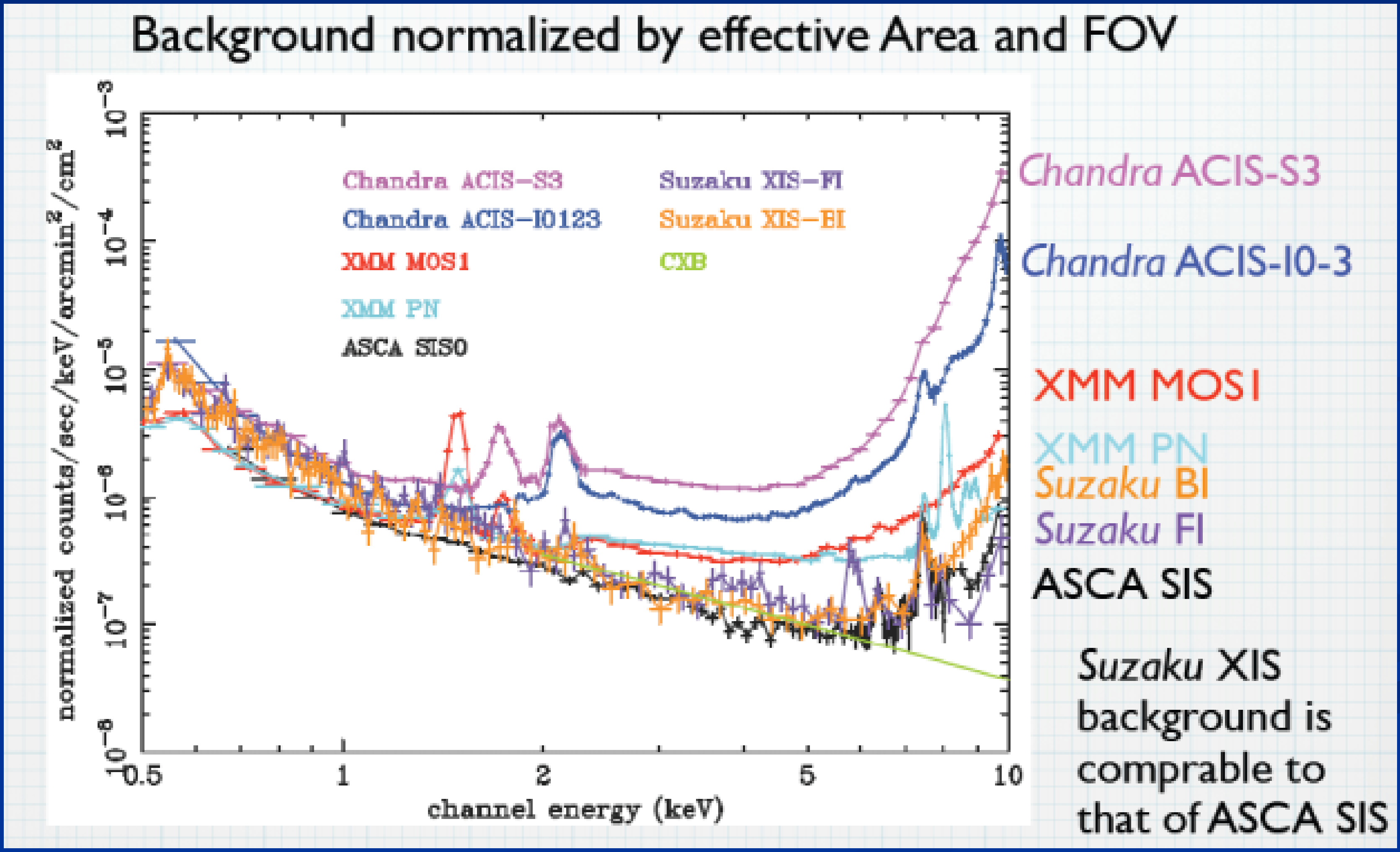
response for 0.5 keV monochromatic X-ray



Observed energy spectrum of the supernova remnant, E0102.2-729

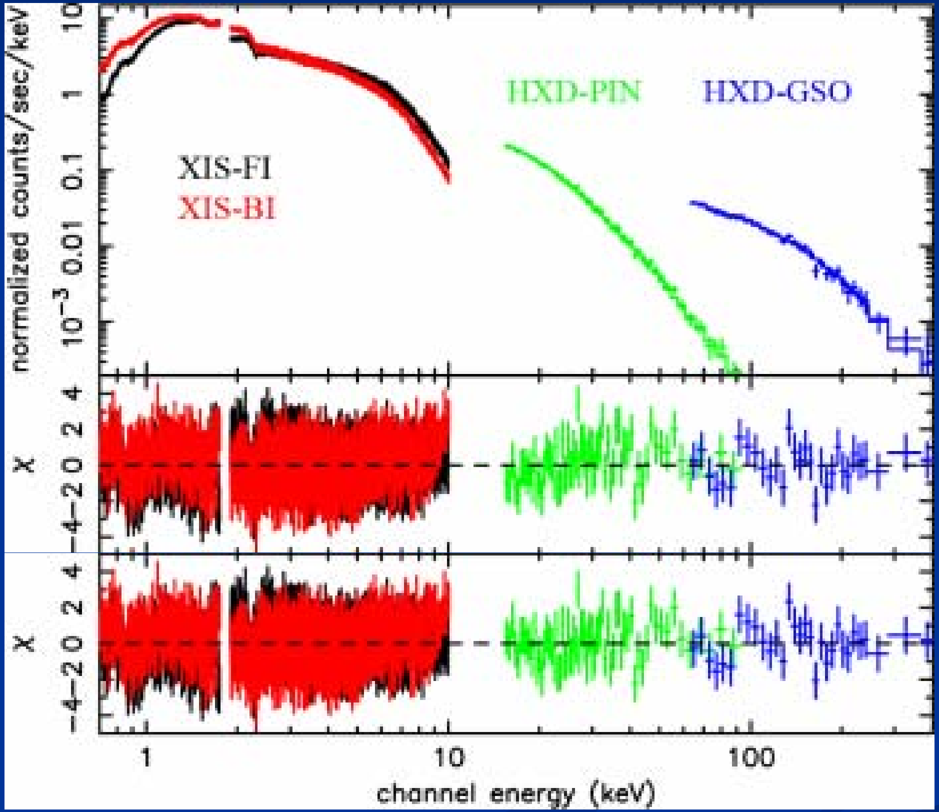


XIS：低バックグラウンド

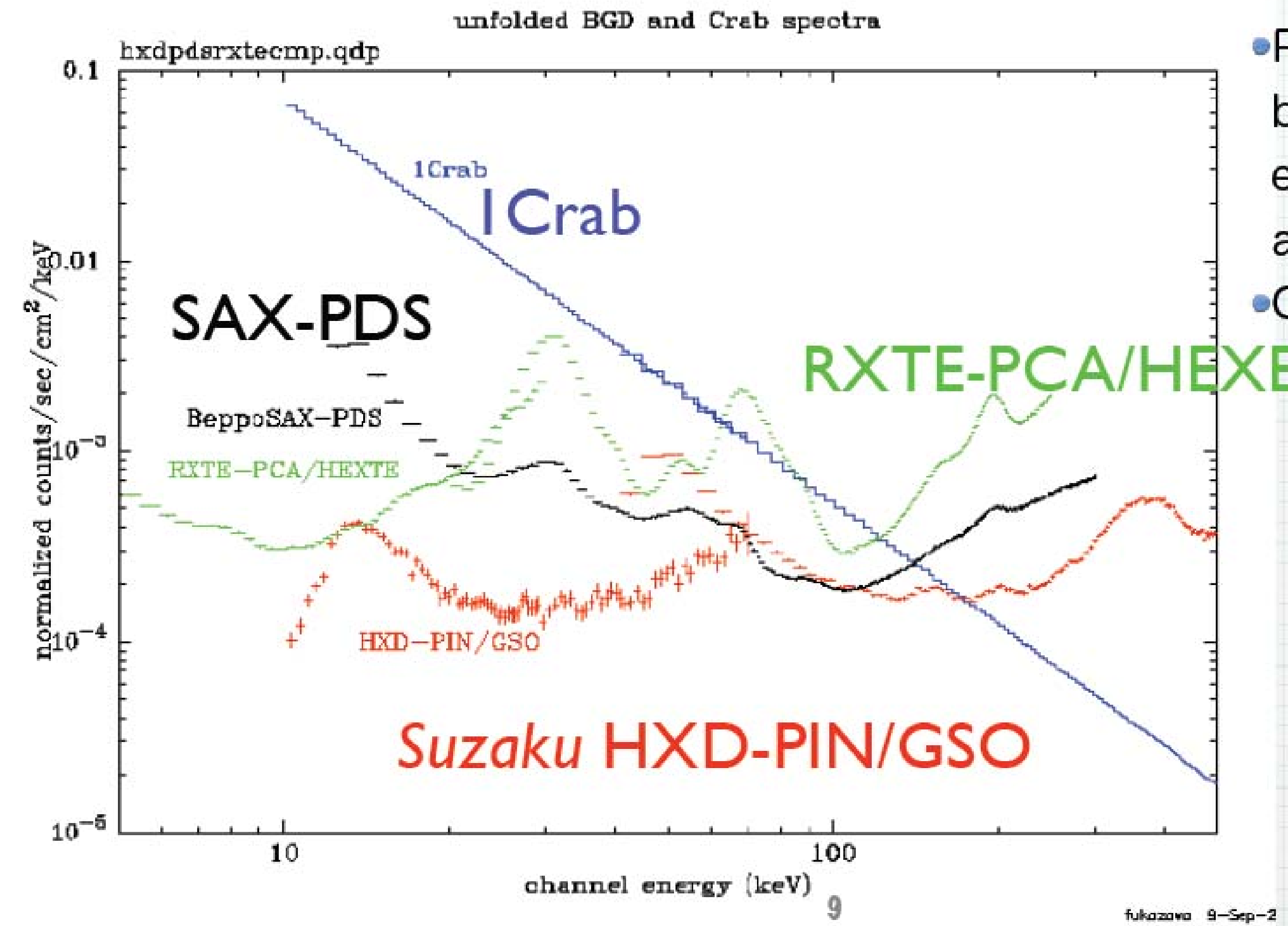


X線天文衛星「すざく」

- HXD
  - 広帯域
    - PIN　12-70 keV
    - GSO　50-600 keV
  - 低バックグラウンド
  - 小さいFOV (0.5x0.5)



HXD:低バックグラウンド



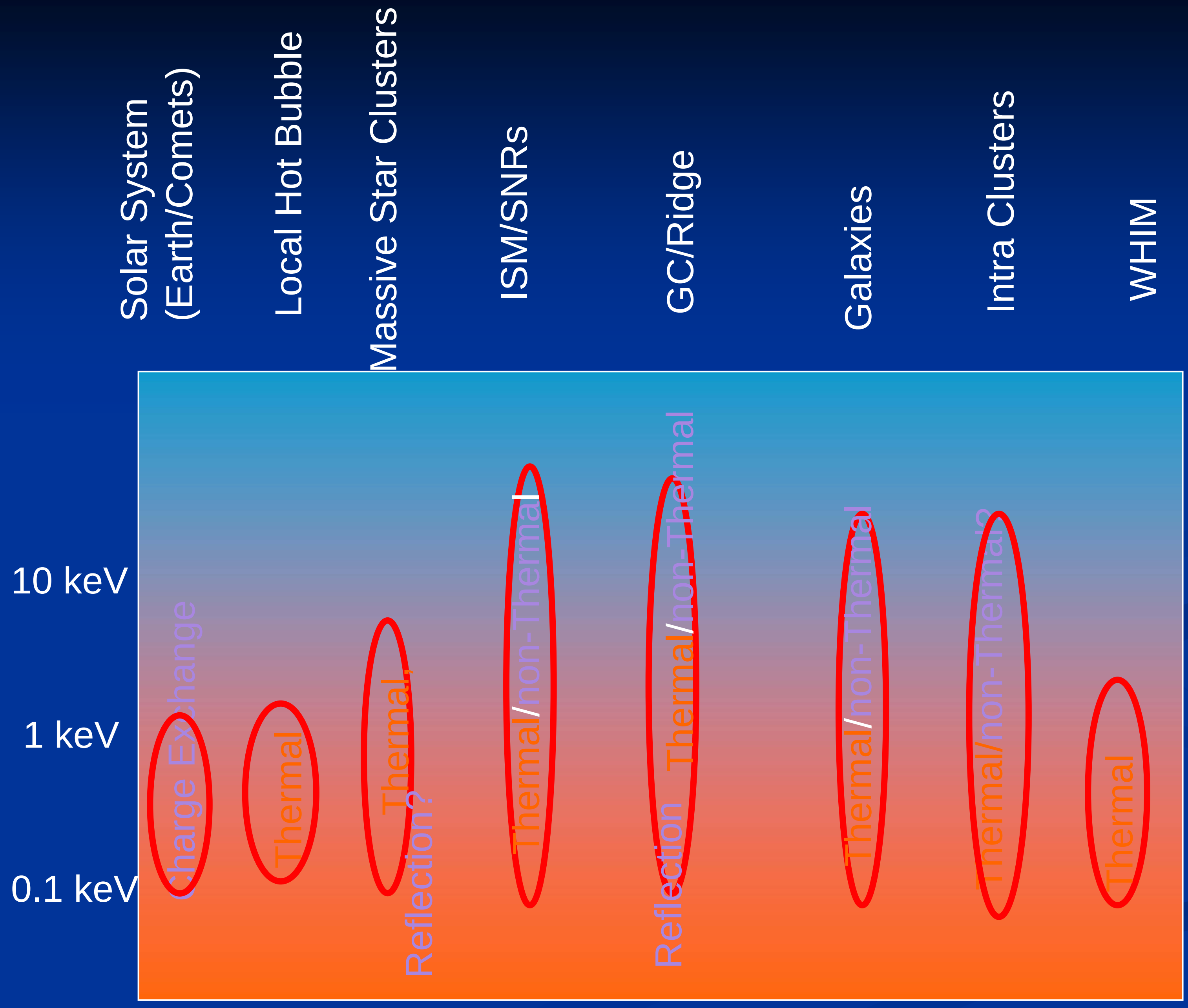
- Presently background can be estimated with an accuracy of 5%.
- Our goal is 1 %.

X線天文衛星「すざく」

- 10keV以下
  - 拡散成分には最高の感度とエネルギー分解能
- 10keV以上
  - 最高の感度

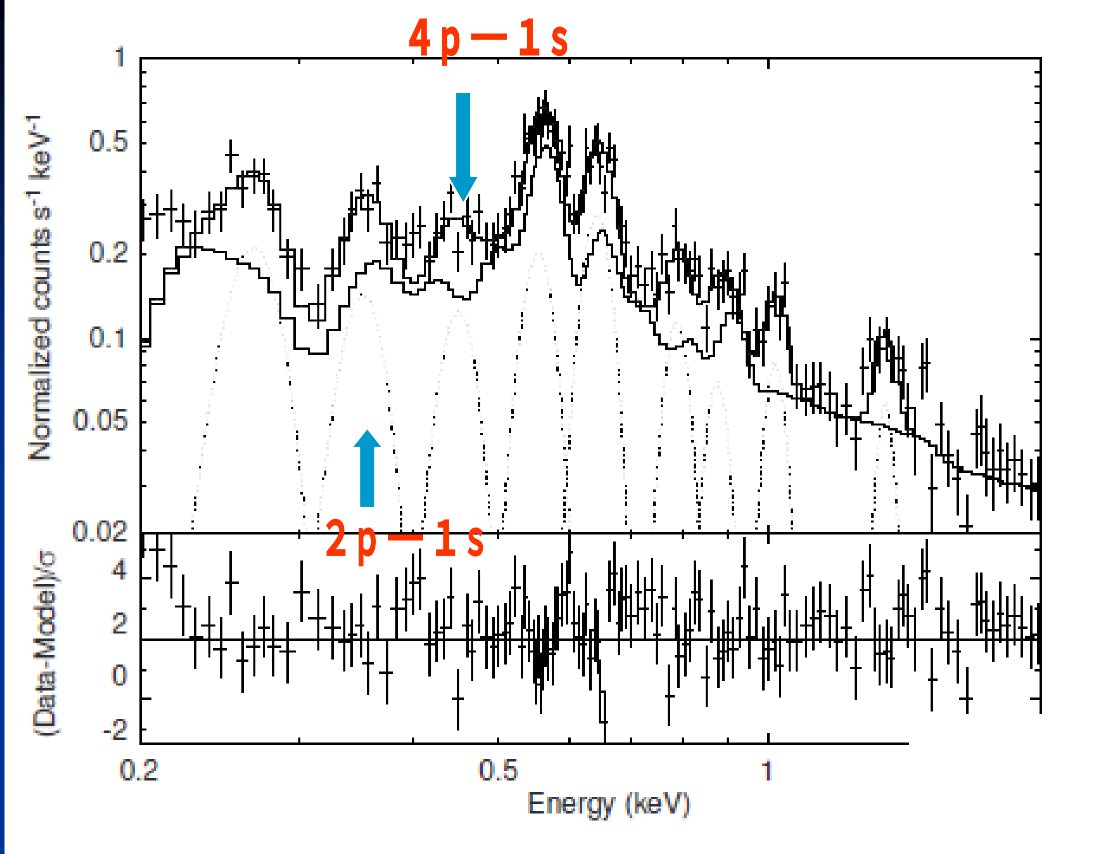
宇宙高温ガスに迫る

- 宇宙高温ガスに迫る
  - 地球周辺からWHIMまで
- Line Diagnostics
  - 放射機構に迫る
  - 元素組成比を求める　(ガスの起源に迫る)
- Thermal / non-thermal ?


Solar System
(Earth/Comets)
Local Hot Bubble
Massive Star Clusters
ISM/SNRs
GC/Ridge
Galaxies
Intra Clusters
WHIM
10 keV
1 keV
0.1 keV
Charge Exchange
Thermal
Thermal,
Reflection?
Thermal/non-Thermal
Thermal/non-Thermal
Reflection
Thermal/non-Thermal
Thermal/non-Thermal
Thermal

Solar Wind Charge-Exchange X-ray Emission (Fujimoto et al. 2006 PASJ)

- mysterious Soft X-ray Emission by ROSAT
  - LTEs (Long Term Enhancement)
    - Snowden et al. (1994)
- Soft X-ray Emission from Comets by ROSAT

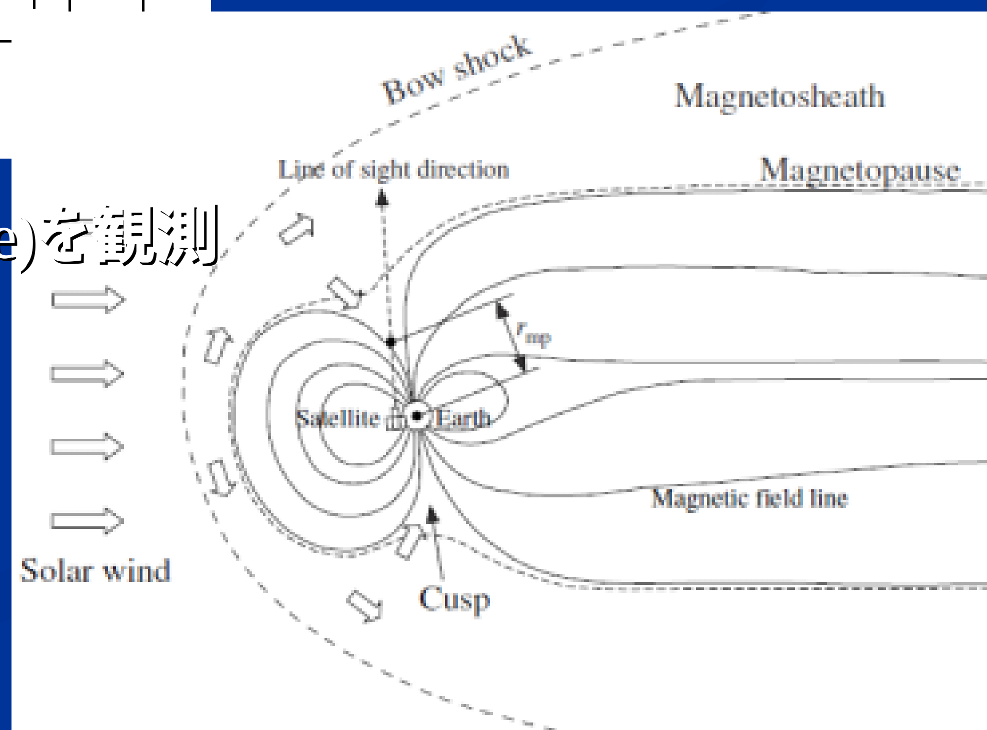


CVI 4p—1s: 459eV

Strong Evidence of Charge Exchange

- Suzaku でNEP(north ecliptic pole)を観測

  Fujimoto et al. 2006 PASJ



Massive Star Clusters

- Massive Stars:
  - SNRs
  - Violent Stellar Wind
    - Shock/collisions
- Arches Cluster
- Carina Nebulae
- M17

η Carinae （Hamaguchi et al. 2006 PASJ）

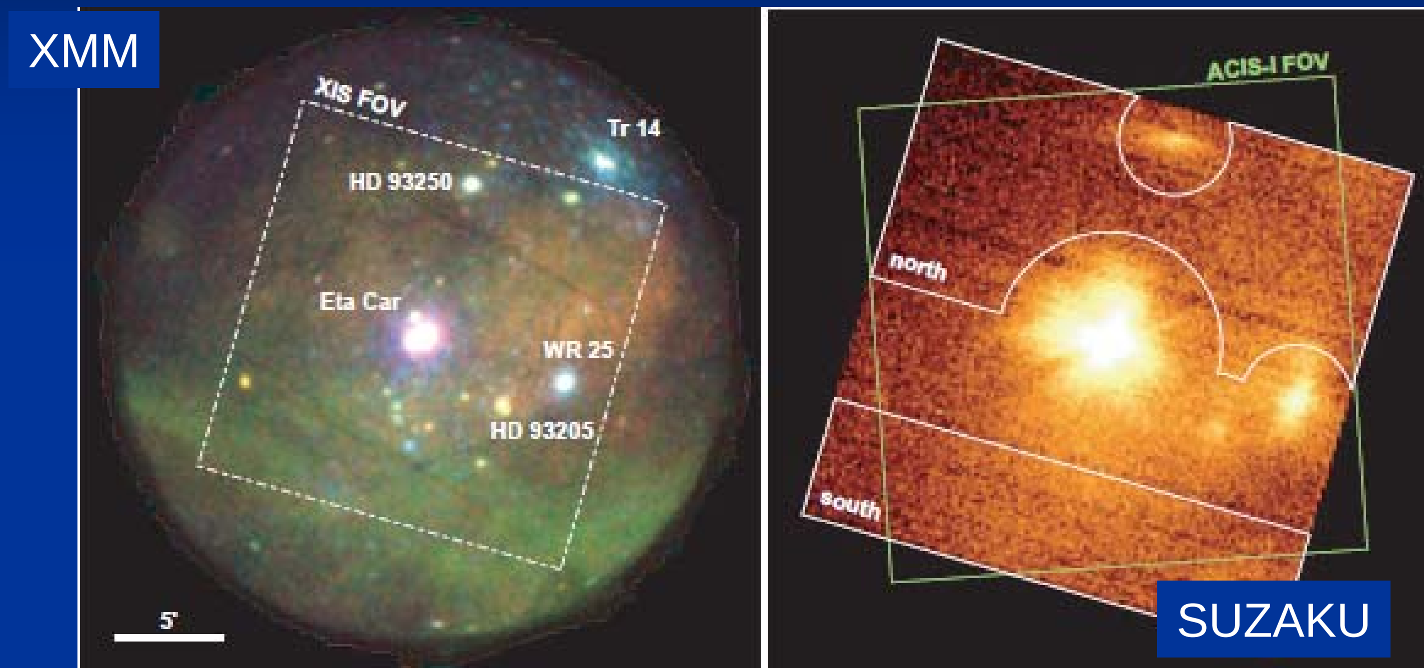
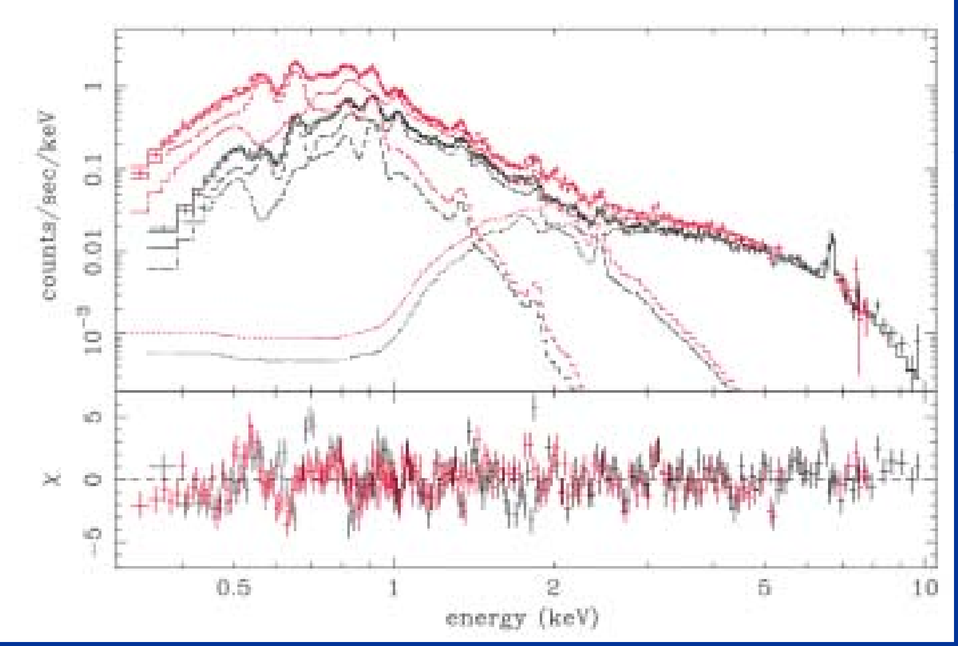
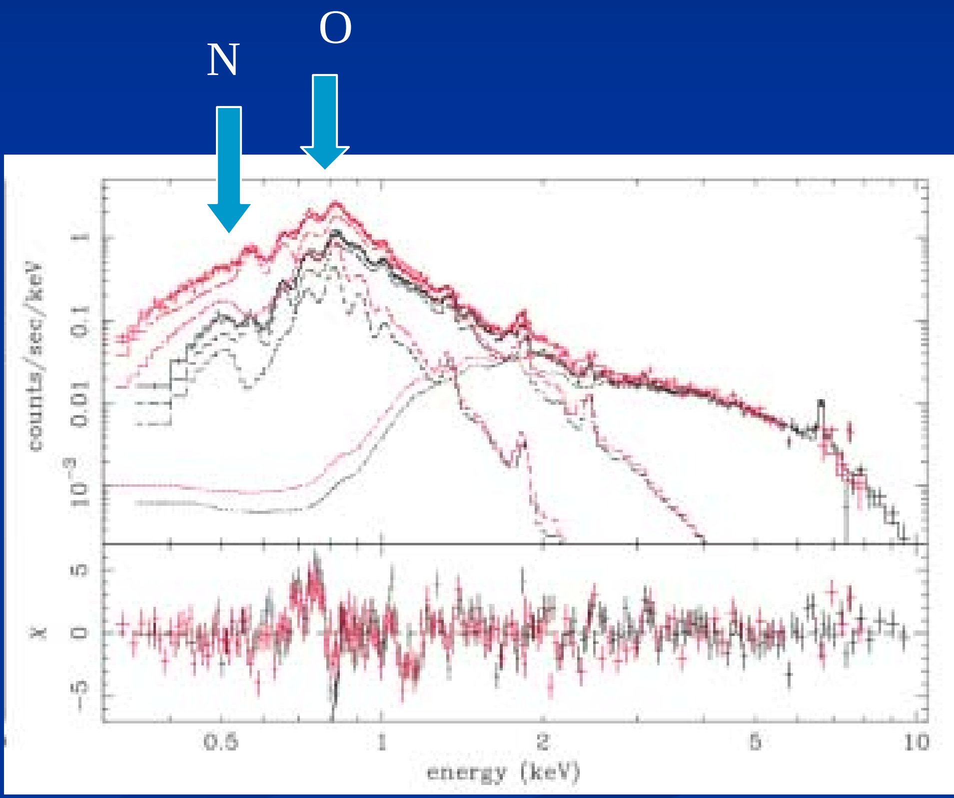


Fig. 1.— *Left*: *XMM-Newton* EPIC MOS image color-coded to represent the soft band (0.2–0.6 keV) to red, medium band (0.6–1.2 keV) to green and hard band (1.2–10 keV) to blue. The bar-dot lines show the XIS FOV in the 2005 Aug. 29 observation. *Right*: *Suzaku* XIS1 image of the 2005 Aug 29 observation. The solid white lines show event extraction regions, and the solid green lines show the *Chandra* FOV in the 1999 September observation. Both images are drawn with logarithmic scale. The vignetting effect is not corrected.

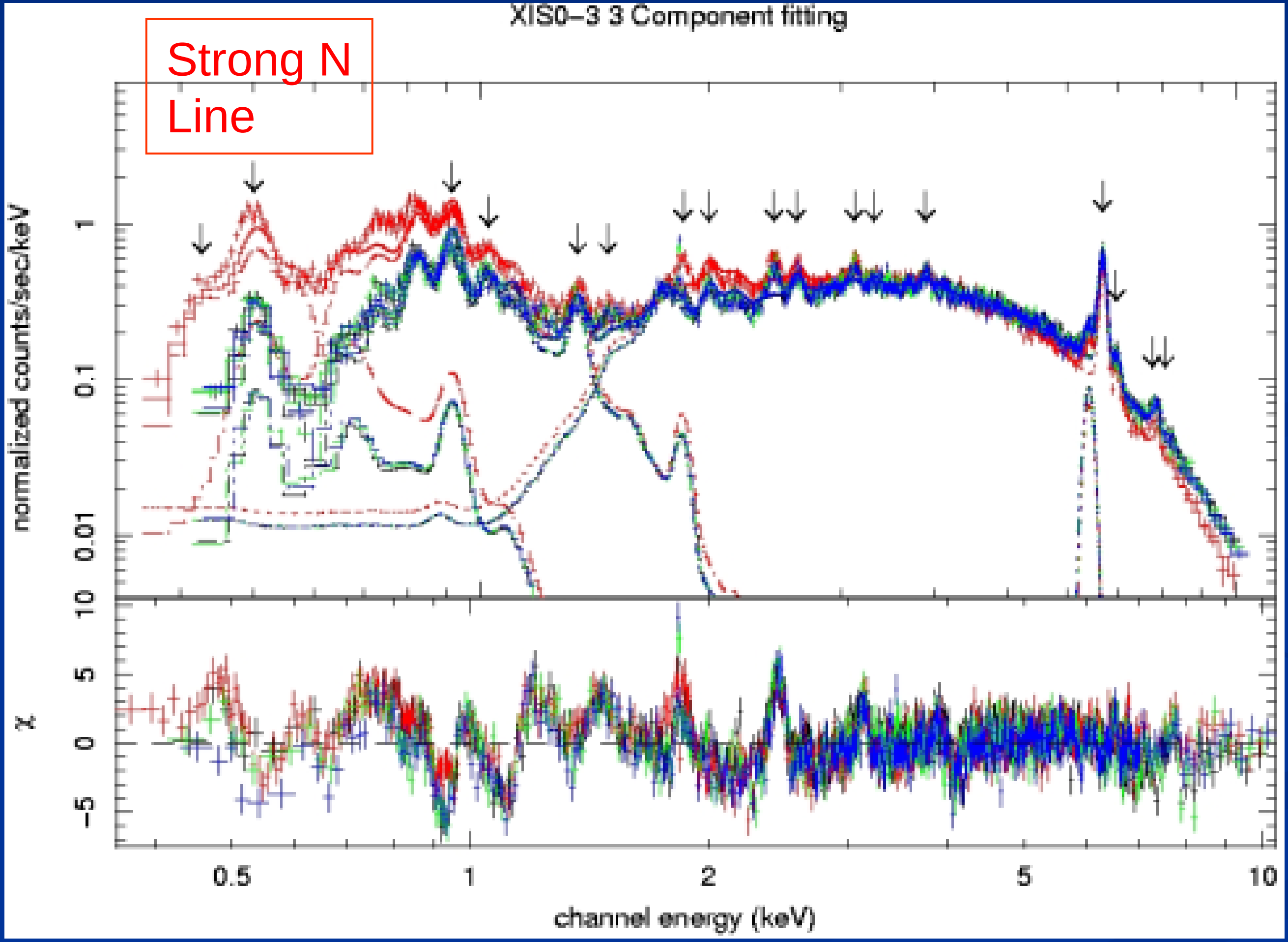
0.2 keV, 0.6keV & 5 keV Thermal -> Abundance Study

N/O<0.4 l : not the wind from early type stars
but from multiple SNRs?



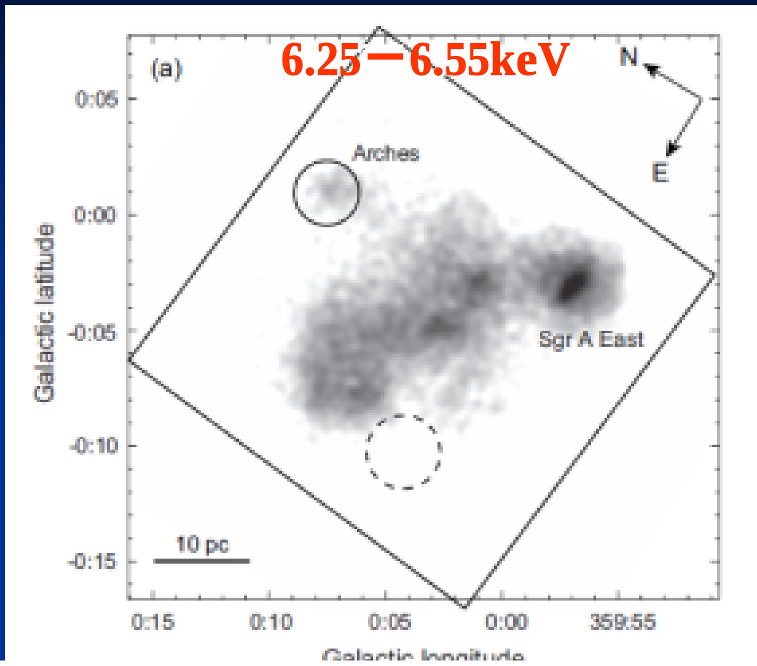


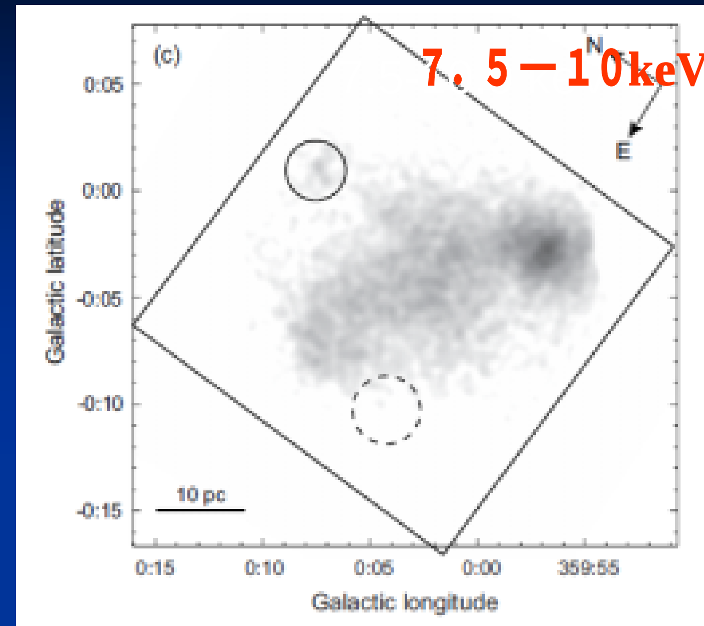
η Carinae
(Sekiguchi et al. Preliminary / Hamaguchi et al. 2006, PASJ)

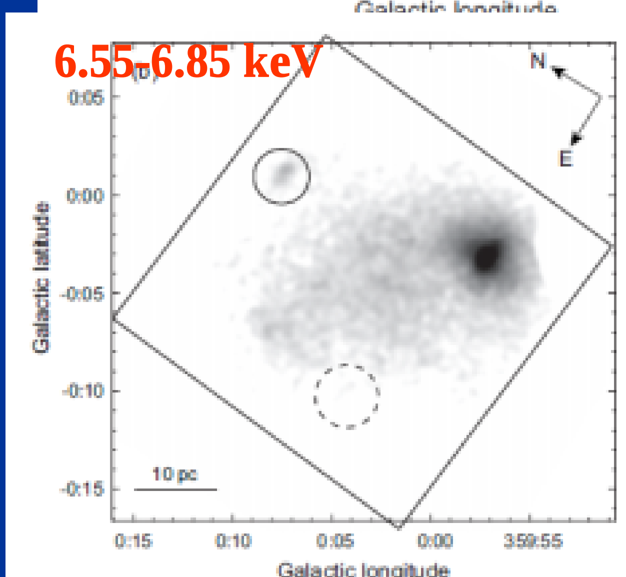


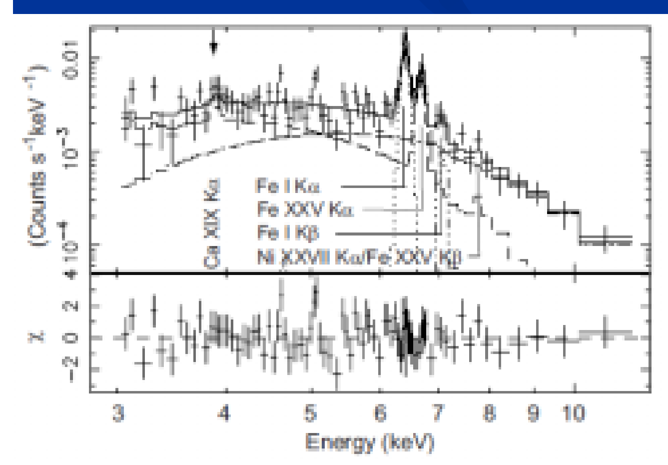
大質量星近傍ではNの過剰

Arches Cluster ;Tsujimoto et al. 2006 PASJ









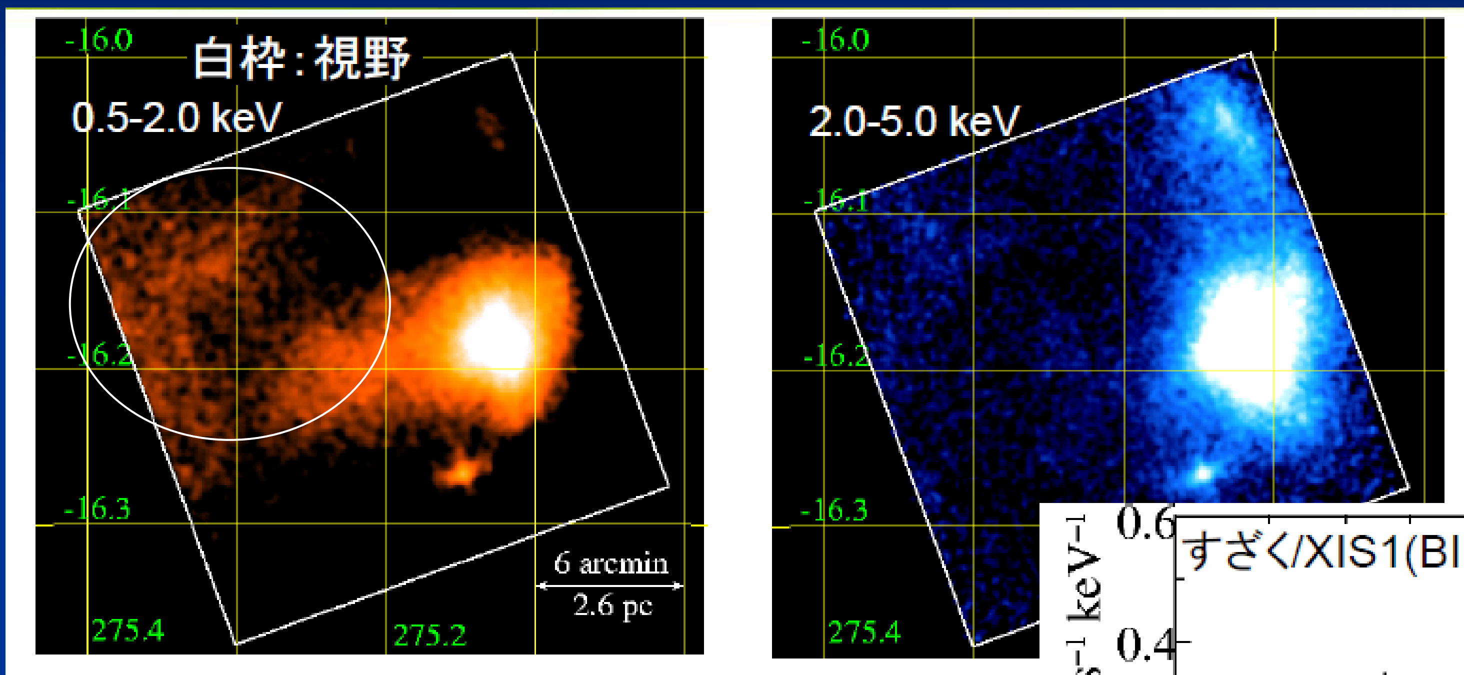
Thermal Emission

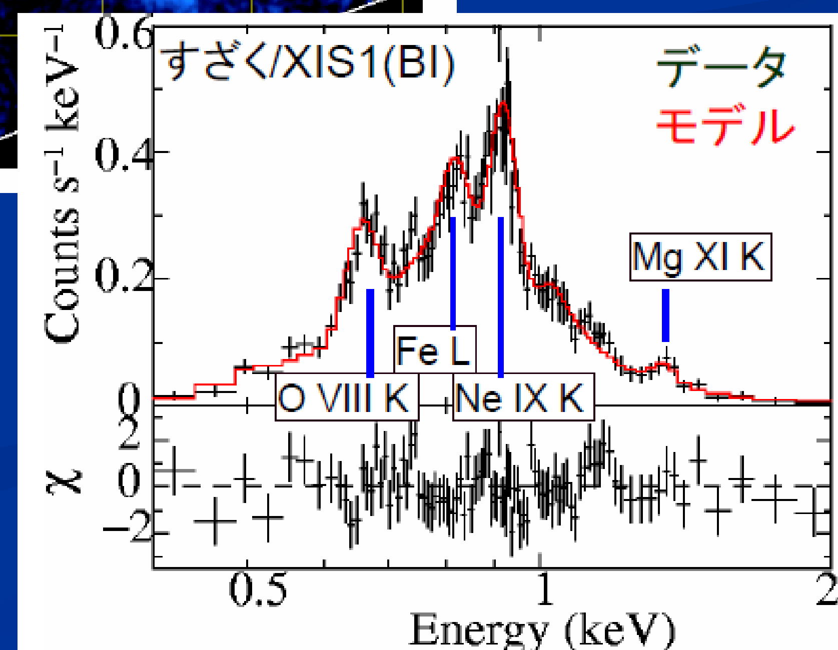
+

6.4 keV line + Hard Reflection & Scattering

M17

- Diffuse Soft Component (Hyodo et al. Preliminary)

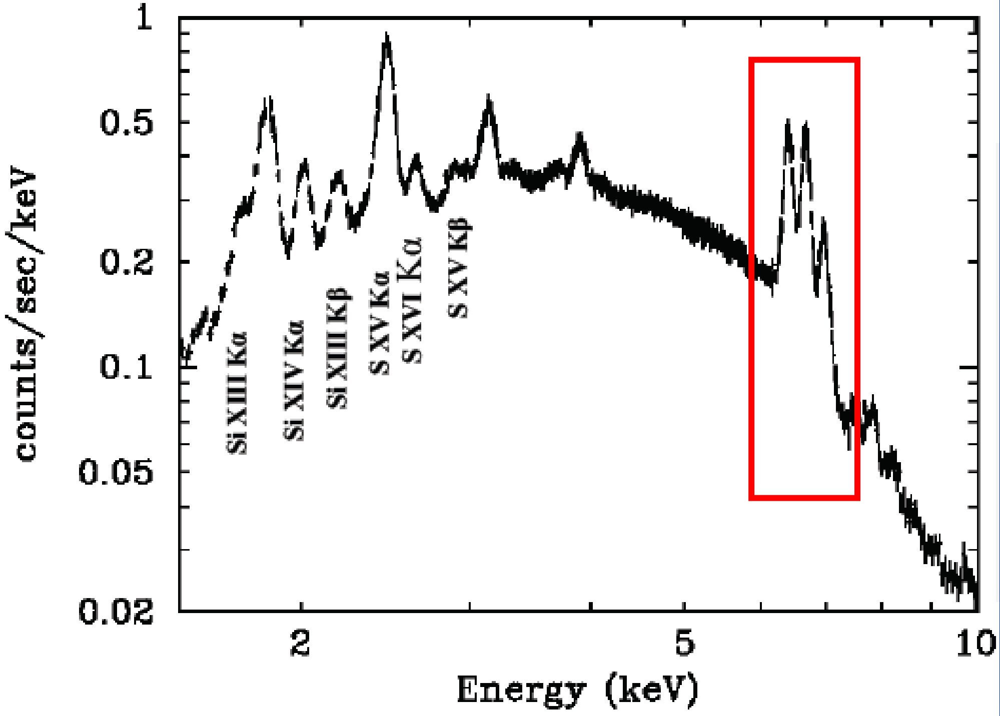




kT~0.25 keV
Abundance; 0.1~0.3
N_H~4x10^{21}

Galactic Center

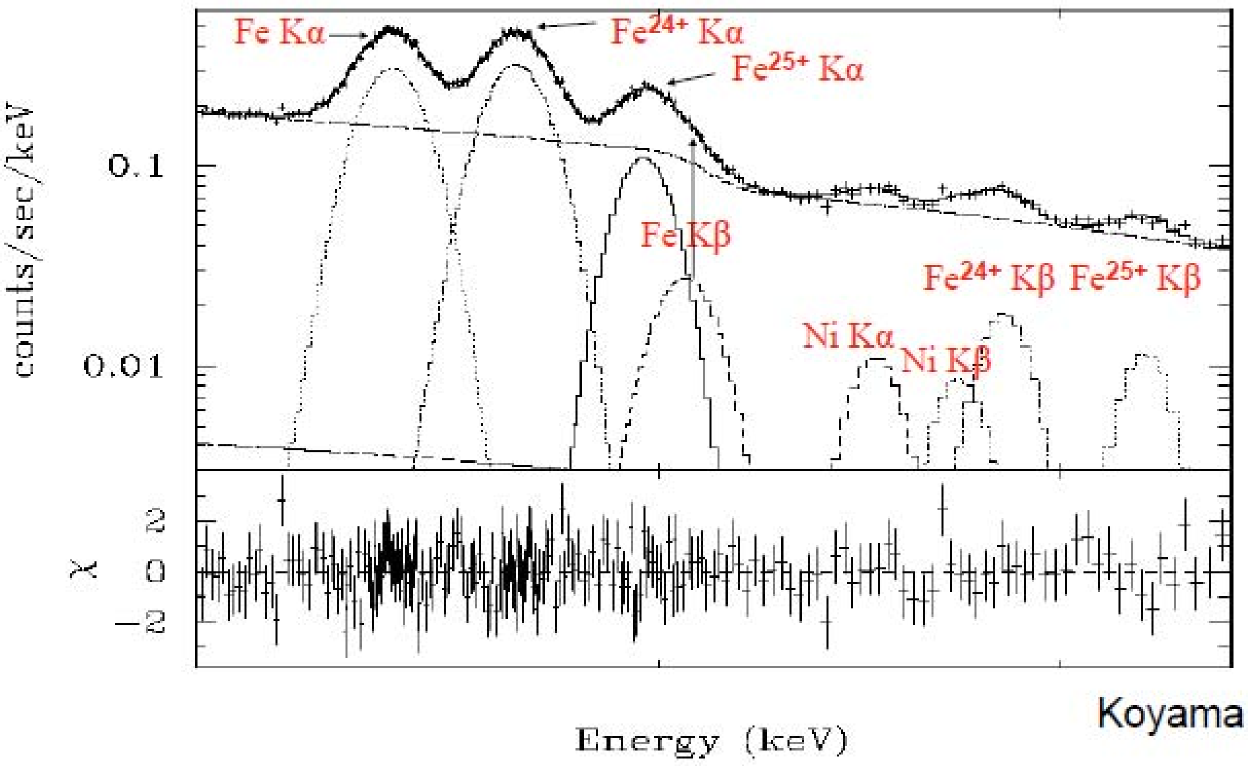
- Iron Line Spectroscopy



Suzaku: 180 ksec Observation

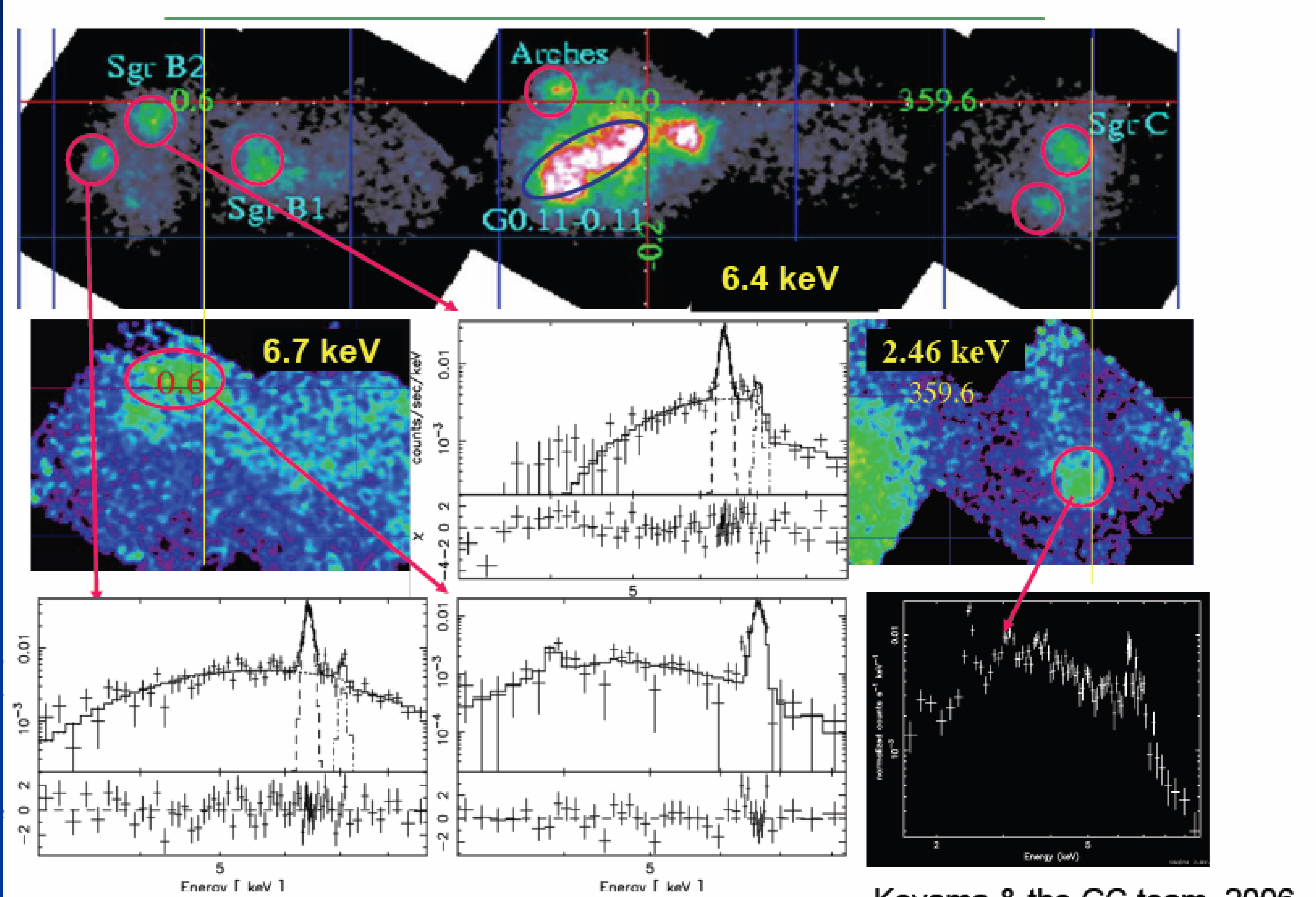
Koyama & the GC team, 2006

- <~5eVの精度でエネルギーを決定
- He-like Fe Ka=6679(+1.3,-0.9) eV
  - Collisional Excitation(6685eV)
    - (cf. Electron Capture (6666eV)ではない)



Koyama & the GC team, 2006

Line Mapping で反射星雲、SNR?

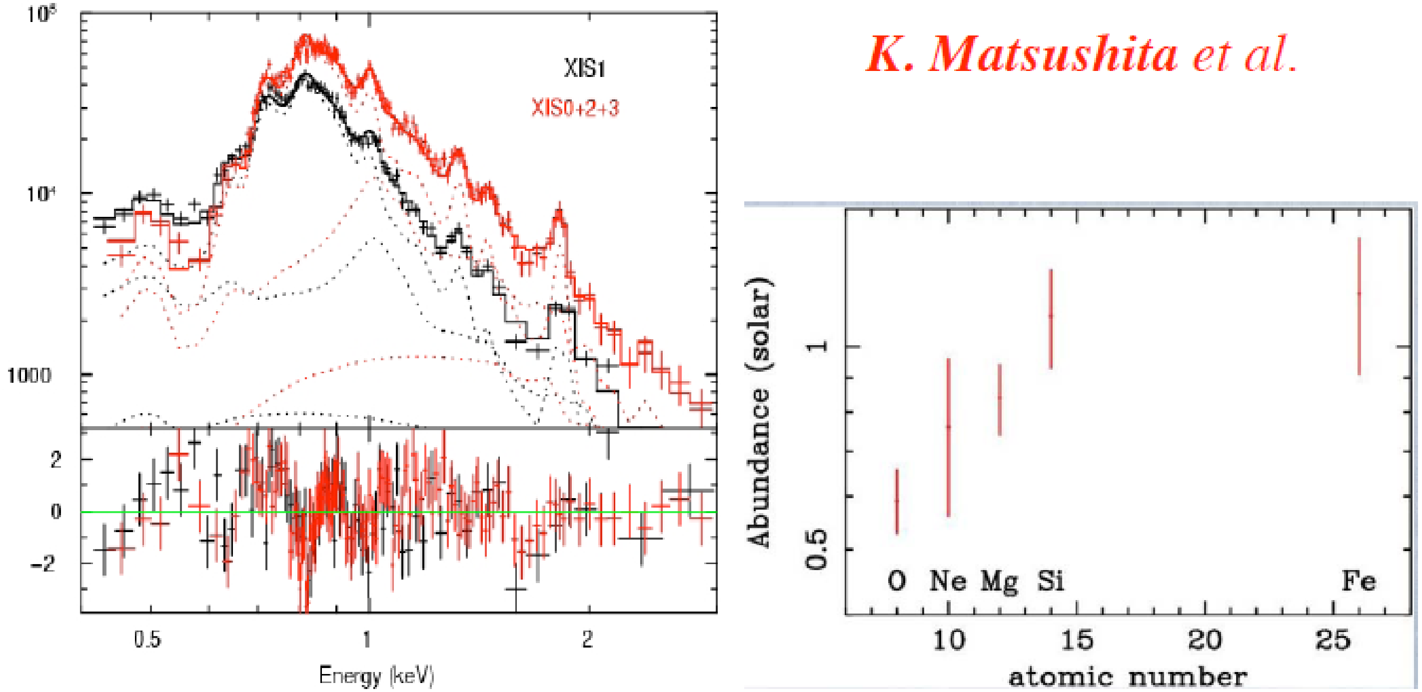


Koyama & the GC team, 2006

Galaxies / Clusters
(Fronax Cluster ・NGC 1404)

Matsushita et al. 2006 PASJ

- Abundance Determination

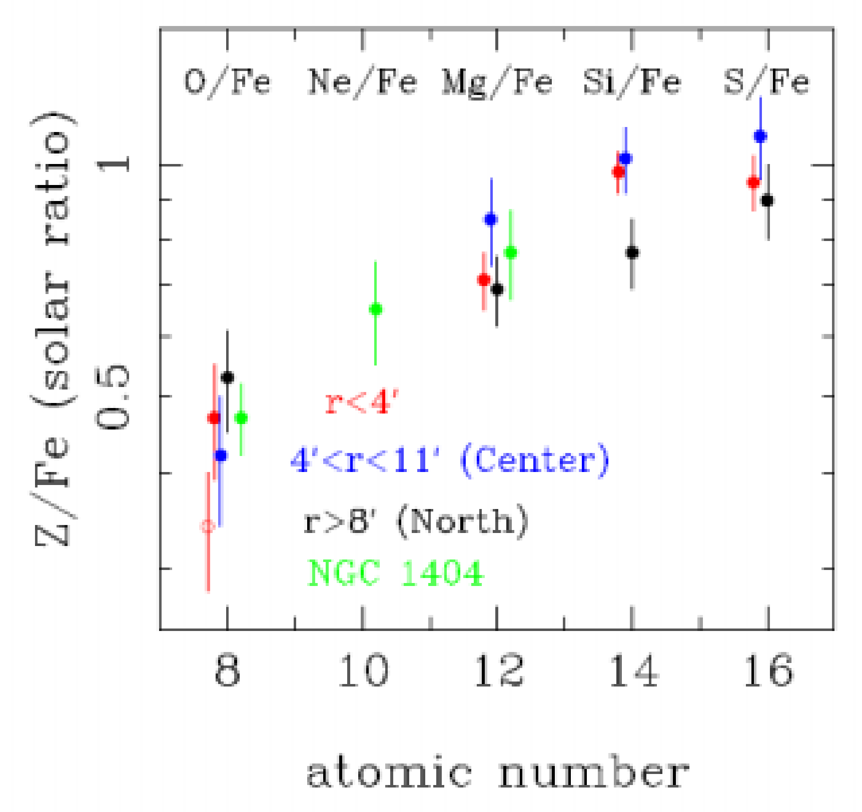


• Si & Fe ~ solar ; O/Fe ~ 1/2; O, Ne, Mg ~ stellar metallicity

• SNIa must contribute Si, possibly with enhanced Si/ Fe ratio

(cf M87, Mitsushita et al., 2003)

Fornax Cluster (Matsushita et al. 2006,PASJ)



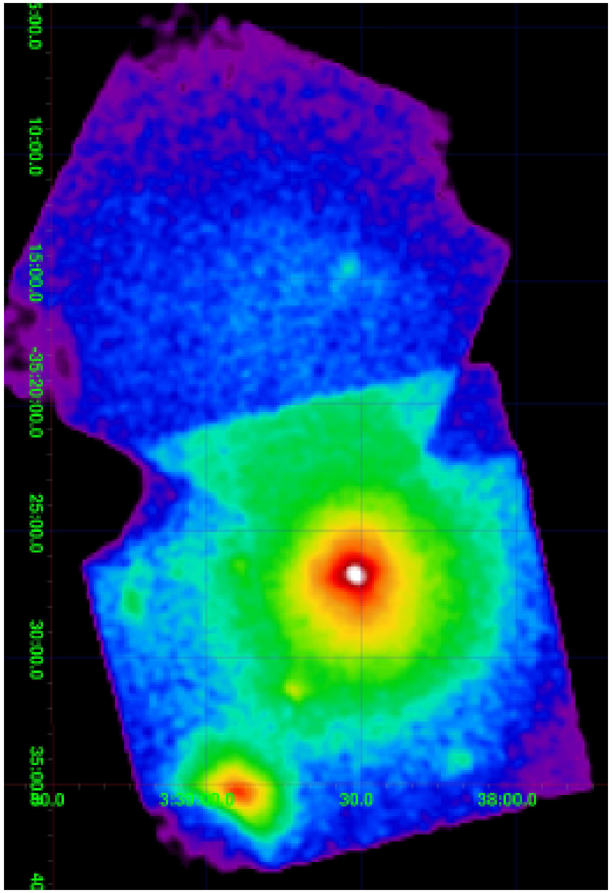
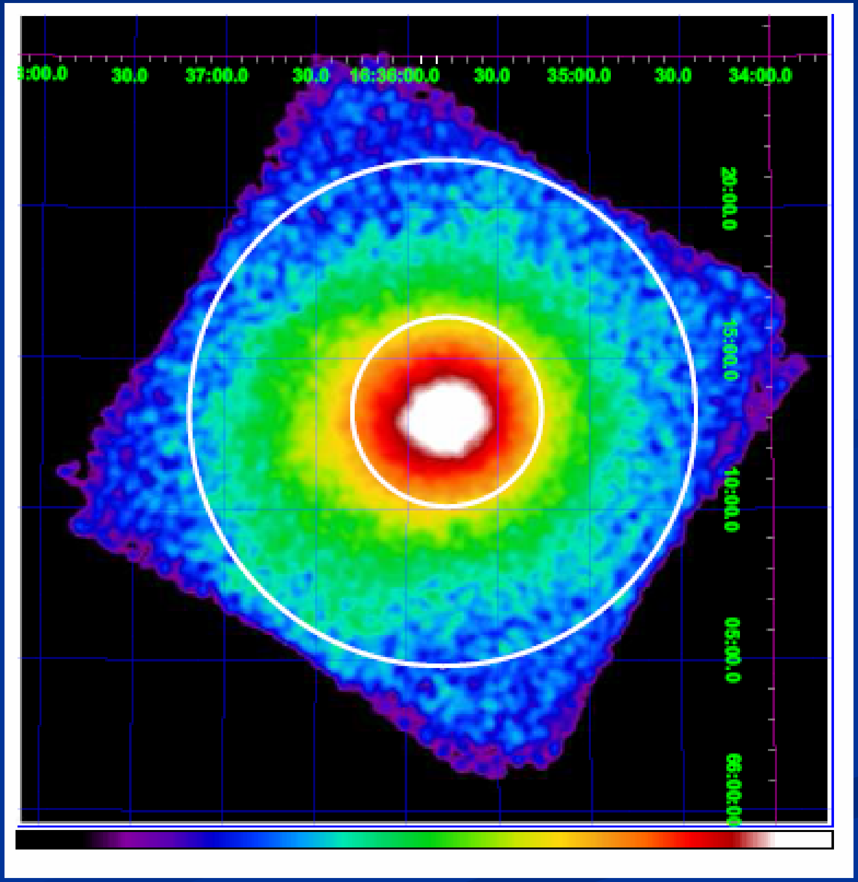


Fig. 1. The 0.3-4.0 keV Suzaku XIS image of the Fornax cluster. Data from the BI and FI detectors were combined

元素分布を精密決定

WHIMの観測
Takei et al. 2006 PASJ

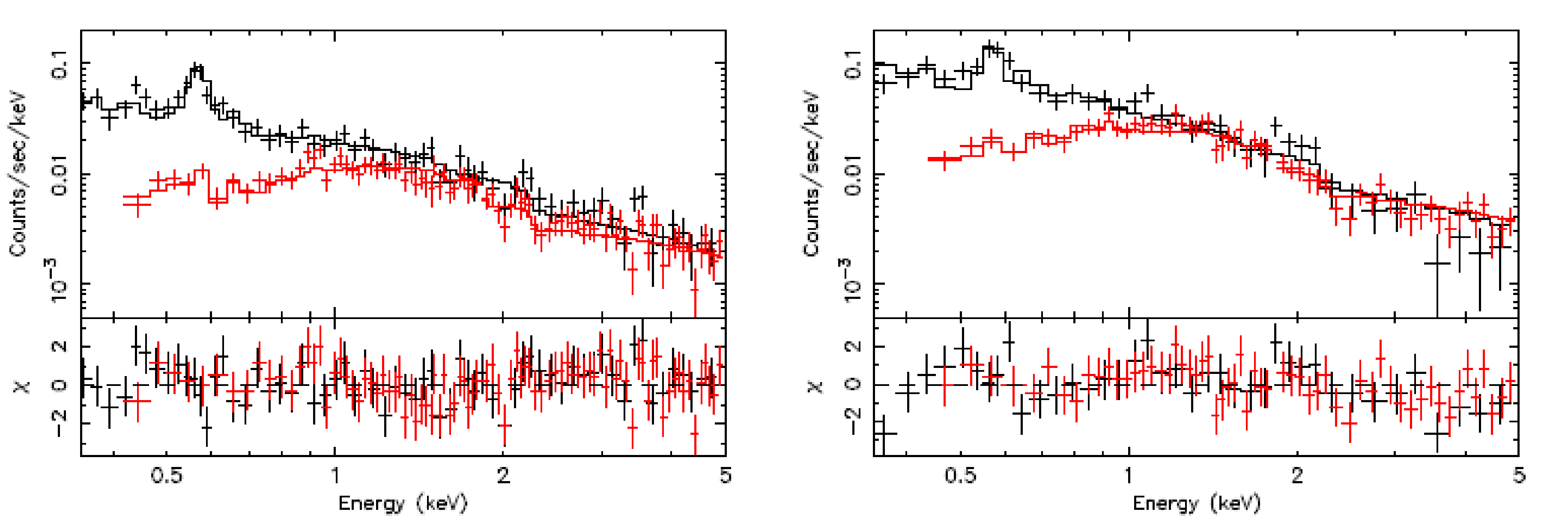
- A2218(z=0.1756)の周辺のwarm-hot intergalactic mediumの探索
  - missing baryons
  - $10^{5\sim7}$K



- 赤方偏移した高電離酸素(OVII, OVIII)の探索

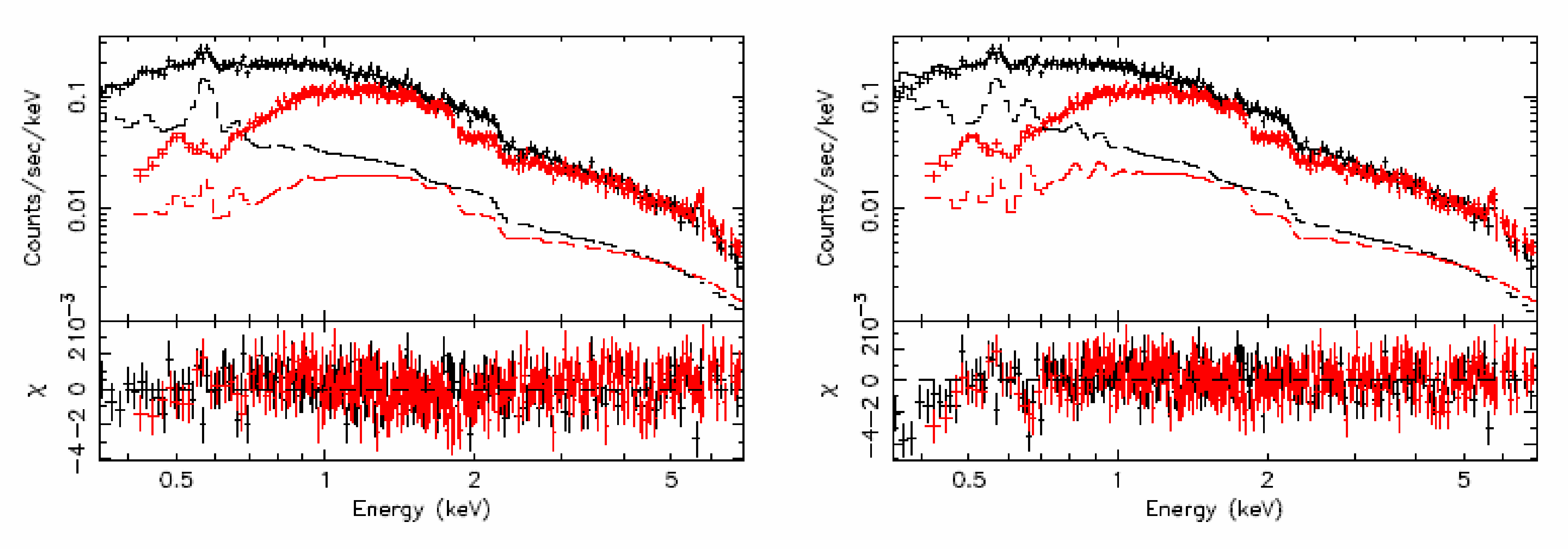
WHIMの観測

- BG(offset region)の観測
  - Local Hot Babble (LHB)
  - Milky Way halo (MWH)
  - CXB



WHIMの観測

- A2218(z=0.1756)の周辺(3'-8' region)
  - BG+ HotGas (Intra Cluster Gas　~6keV)
  - この中でOVII, OVIII line (z=0.1756) (WHIMからの放射) 探索　(488.22, 555.99 eV)

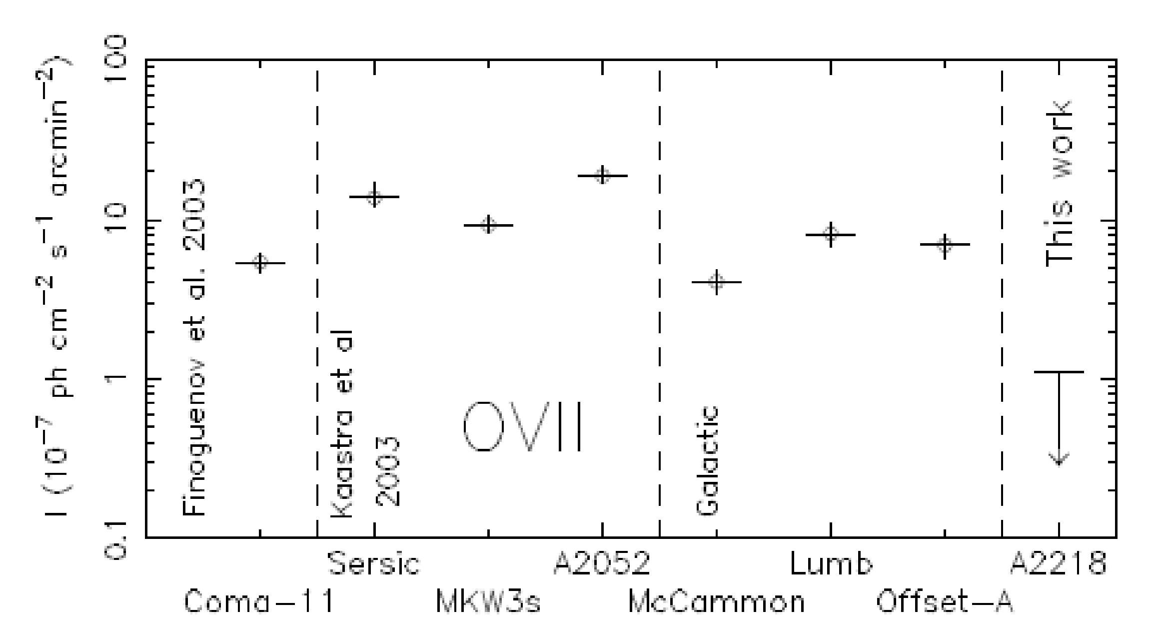


WHIMの観測

- 上限値

$$n_H < 7.8\times10^{-5}\,cm^{-3}\left(\frac{Z}{0.1Z_{\otimes}}\right)^{-1/2}\left(\frac{L}{2Mpc}\right)^{-1/2}$$

$$\delta = \frac{n_H}{\bar{n}_H} < 270\left(\frac{Z}{0.1Z_{\otimes}}\right)^{-1/2}\left(\frac{L}{2Mpc}\right)^{-1/2}$$



where $\bar{n}_{\rm H} = X\Omega_{\rm b}\rho_{\rm crit}(1+z)^3/m_{\rm p} = 1.77\times10^{-7}\ (1+z)^3\ {\rm cm}^{-3}$ is the mean hydrogen density in the universe, in which $X =$ 0.71 is the hydrogen-to-baryon mass ratio, $\Omega_{\rm b} = 0.0457$ is the baryon density of the universe, $\rho_{\rm crit} = 9.21\times10^{-30}$ g cm^{-3} is the critical density of the universe, and $m_{\rm p}$ is the proton mass. Even though this level of overdensity is much higher

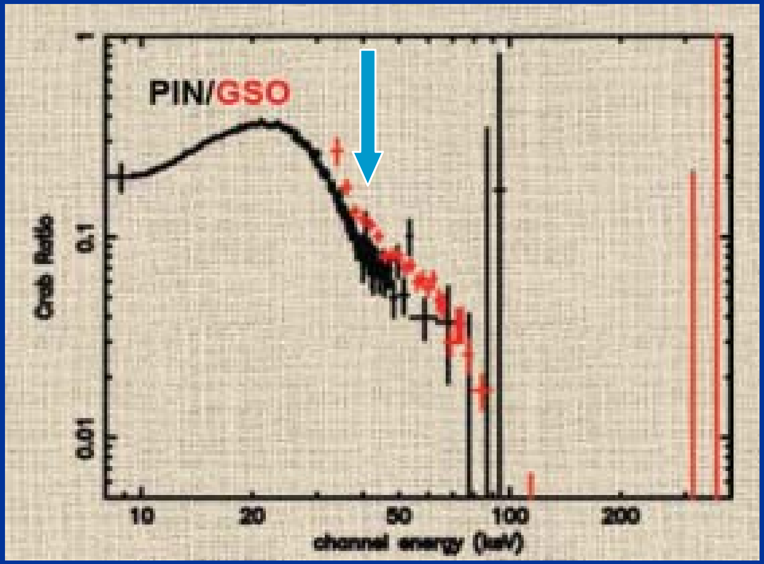
コンパクト星の中心に迫る

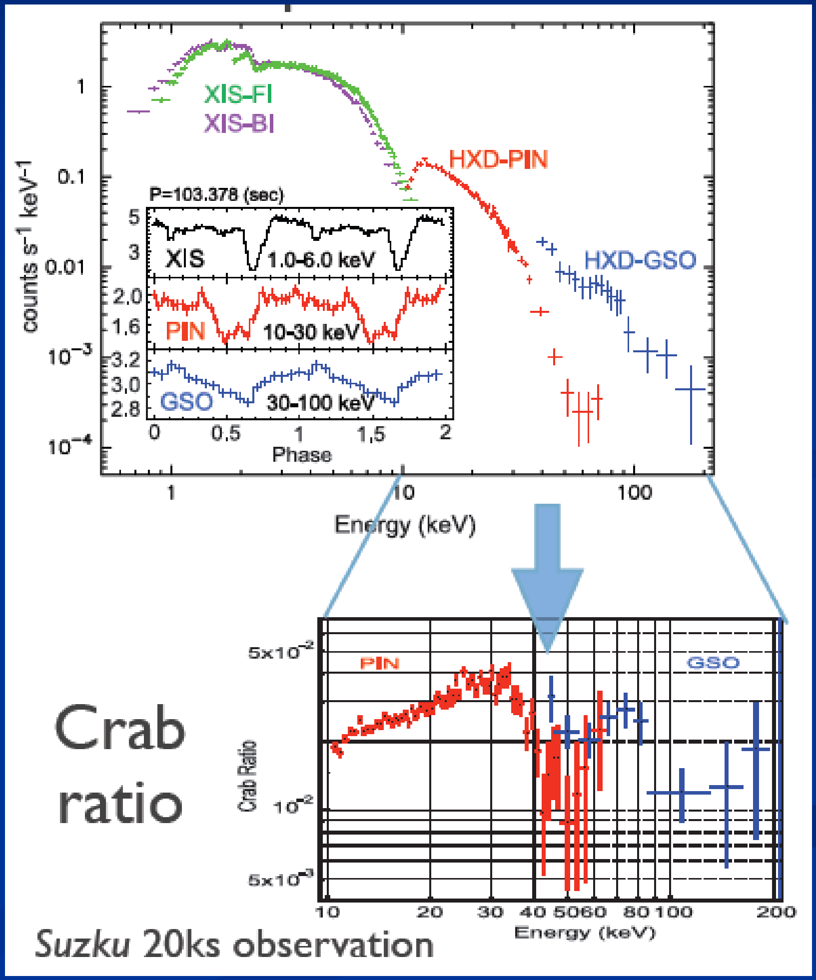
- 1.中性子星の磁場
  - サイクロトロン吸収構造
- 2.降着円盤に診断 (特に low/hard state)
  - コロナの温度
  - 円盤の構造

中性子星の磁場

- E_{res}~11.6 (B/10^8T) keV
  - A0535+26 (Terada et al. ApJ, 2006)
  - Her X-1 (Terada et al.2006)

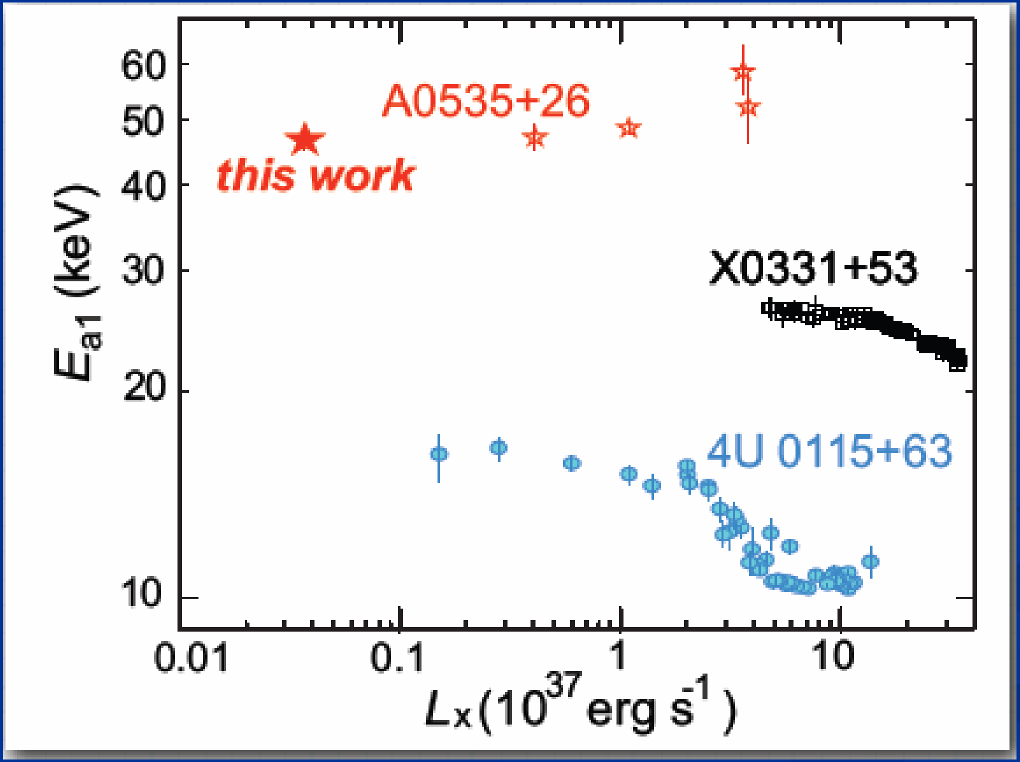
Her X-1 : Crab ratio





中性子星の磁場

- 低高度でエネルギー高：表面磁場を反映
  - ある光度でTransition?

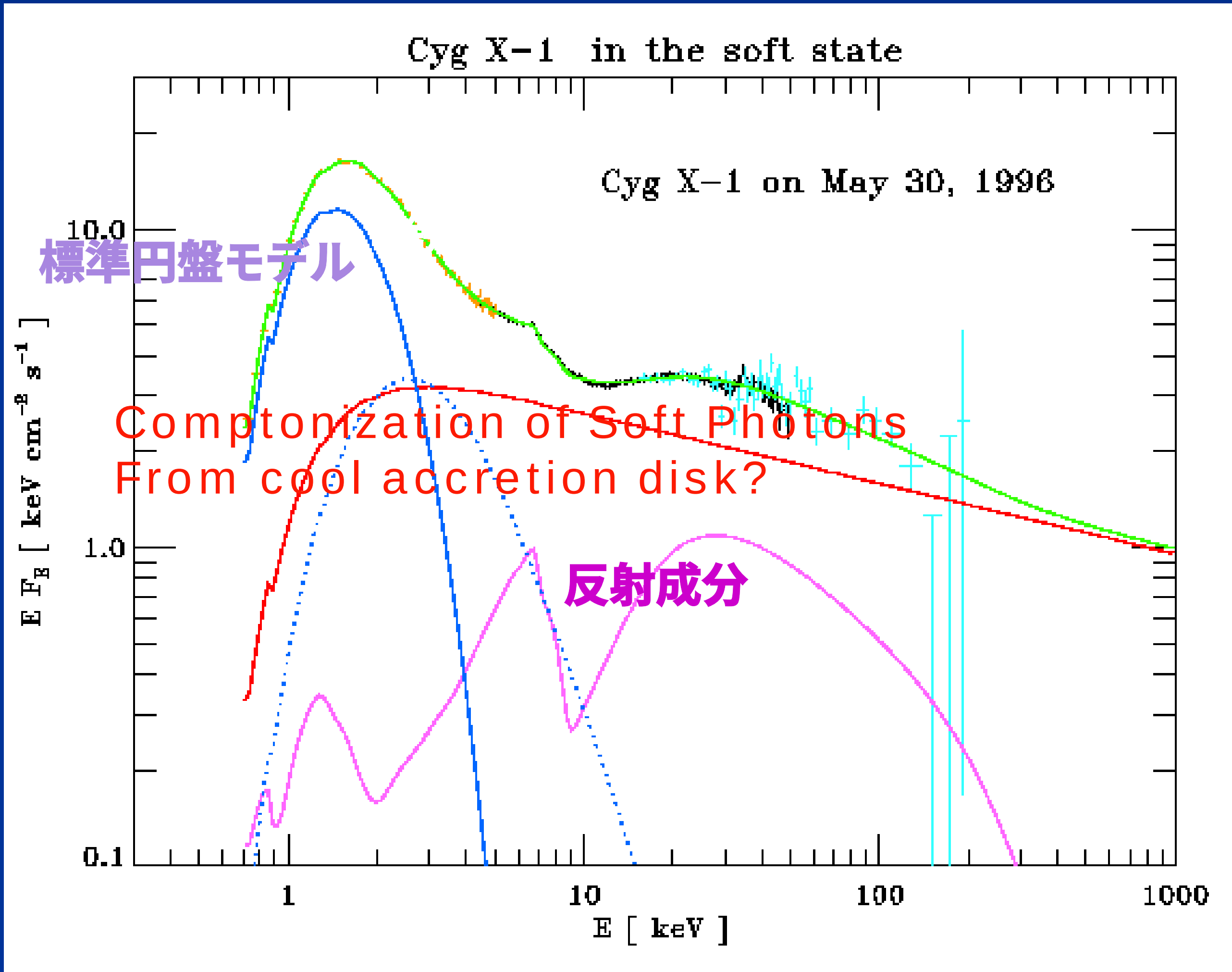


Terada et al. 2006, ApJ: cf, Nakajima et al. 2006

ブラックホール候補星のステート

- High/Soft State

主成分;標準円盤
コンプトン散乱された成分？
up to MeV?

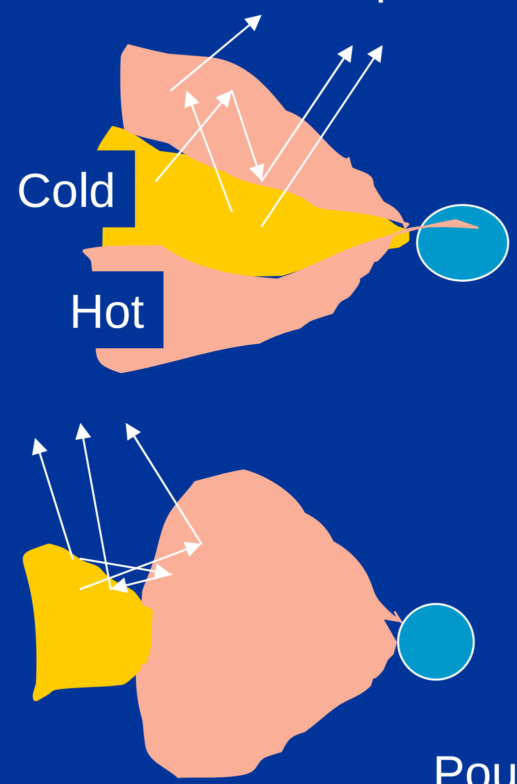


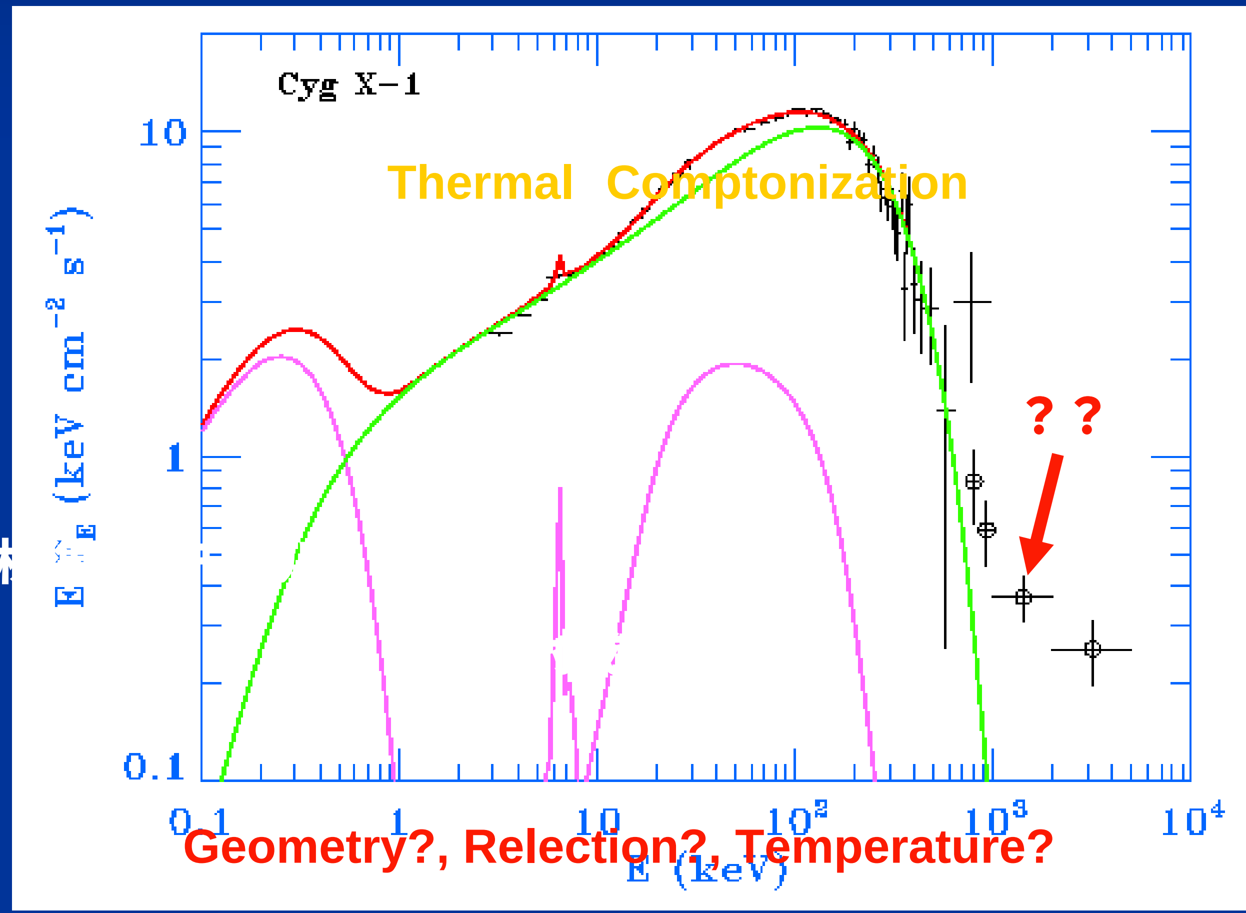
Poutanen & Coppi 1998

ブラックホール候補星のステート

- Low/hard State

100keV当たりが主成分
Thermal Comptonization





Poutanen and Svenson 1996, ApJ, 470, 249-268

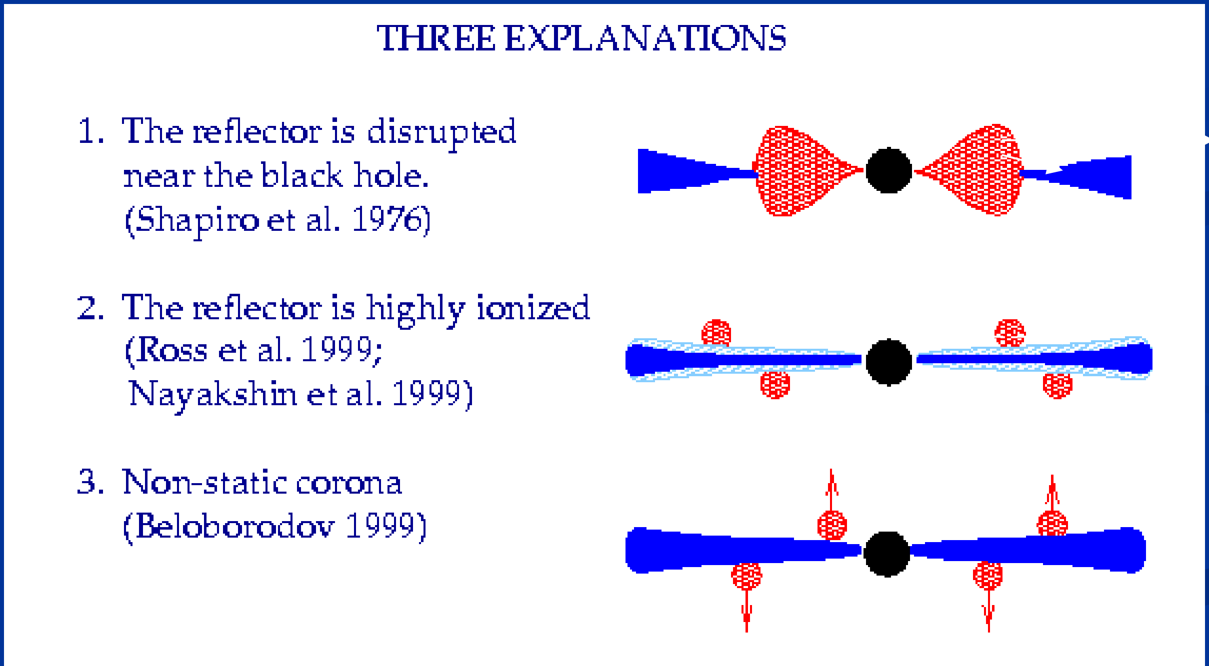
反射成分

Compton Reflection Component

$$R = \frac{\Omega}{2\pi}$$

Cyg X-1の場合

$$R \sim 0.3$$

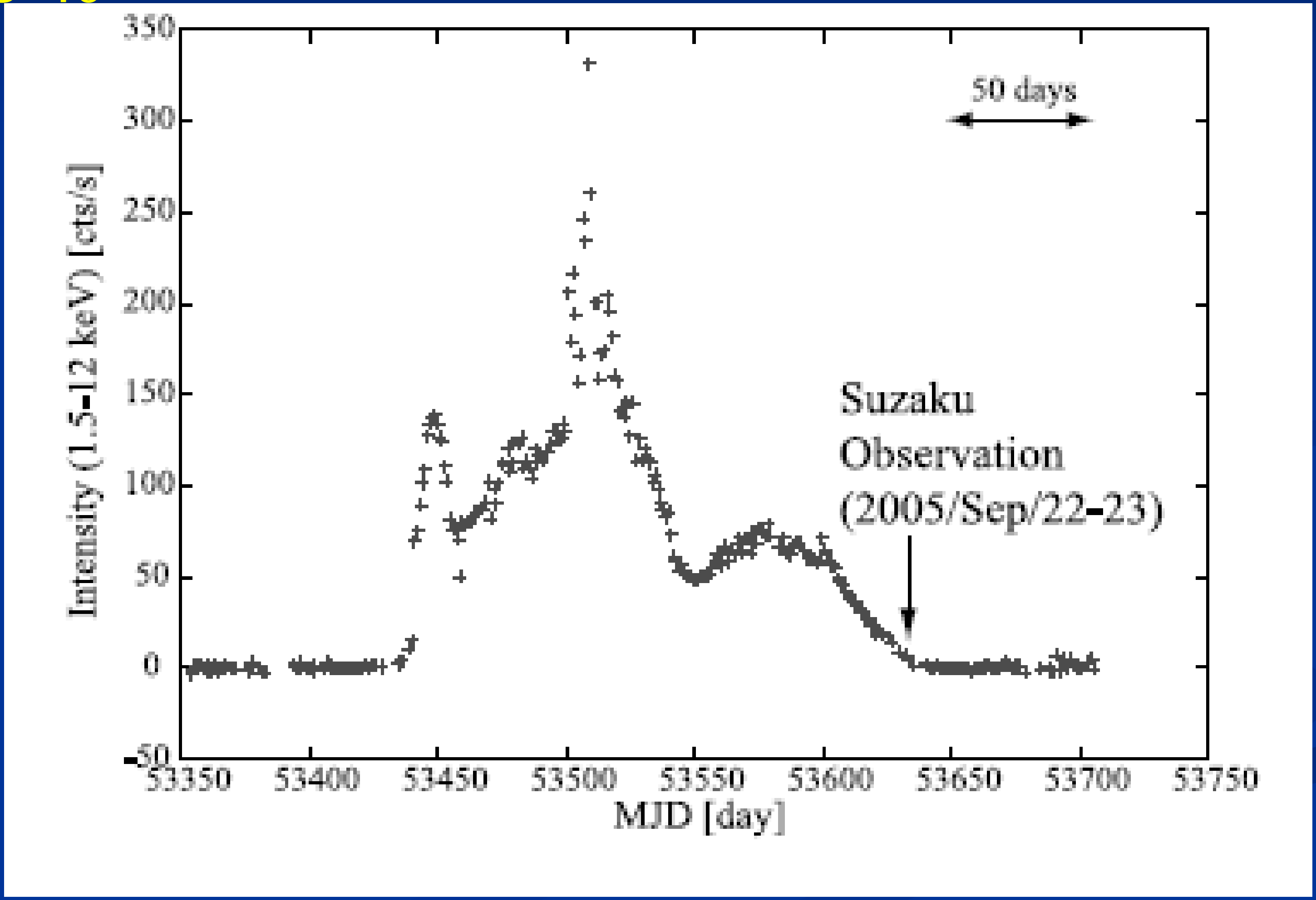


降着円盤の診断

- GRO J1655-40 (Takahashi et al. 2006; PASJ submitted)
- Cyg X-1 (Kubota et al.)

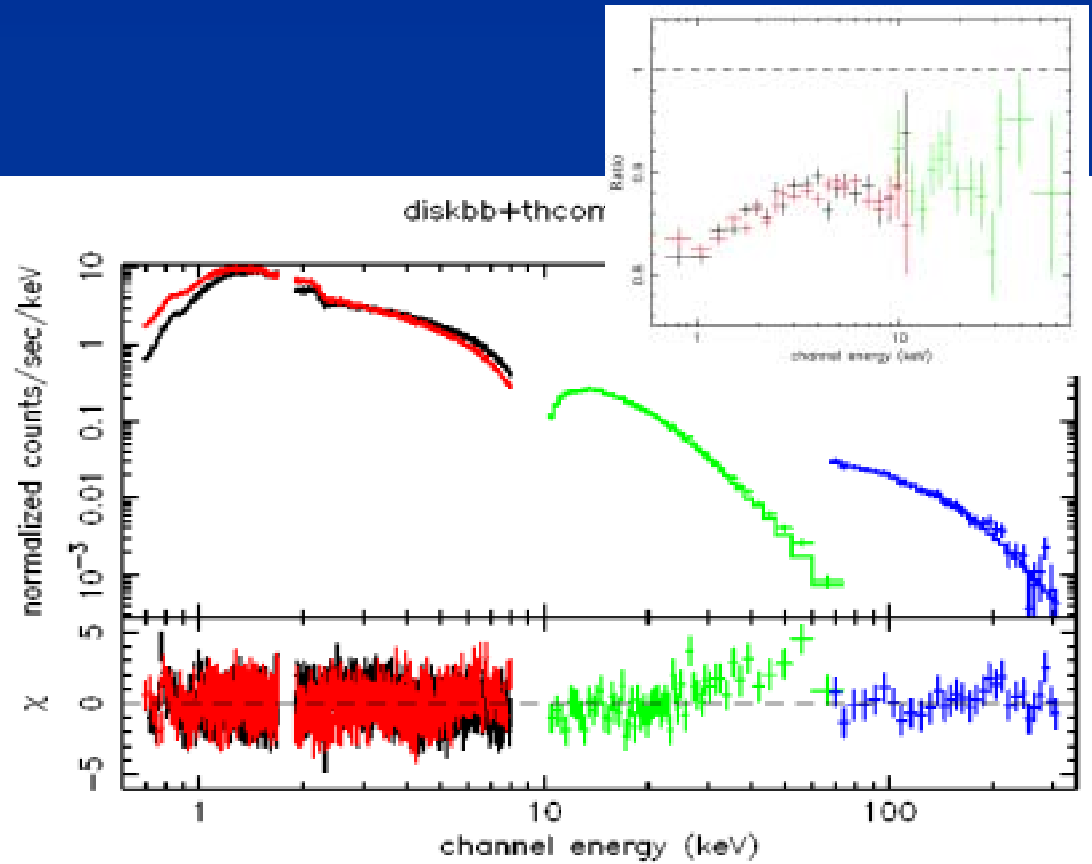
「すざく」による降着円盤の診断

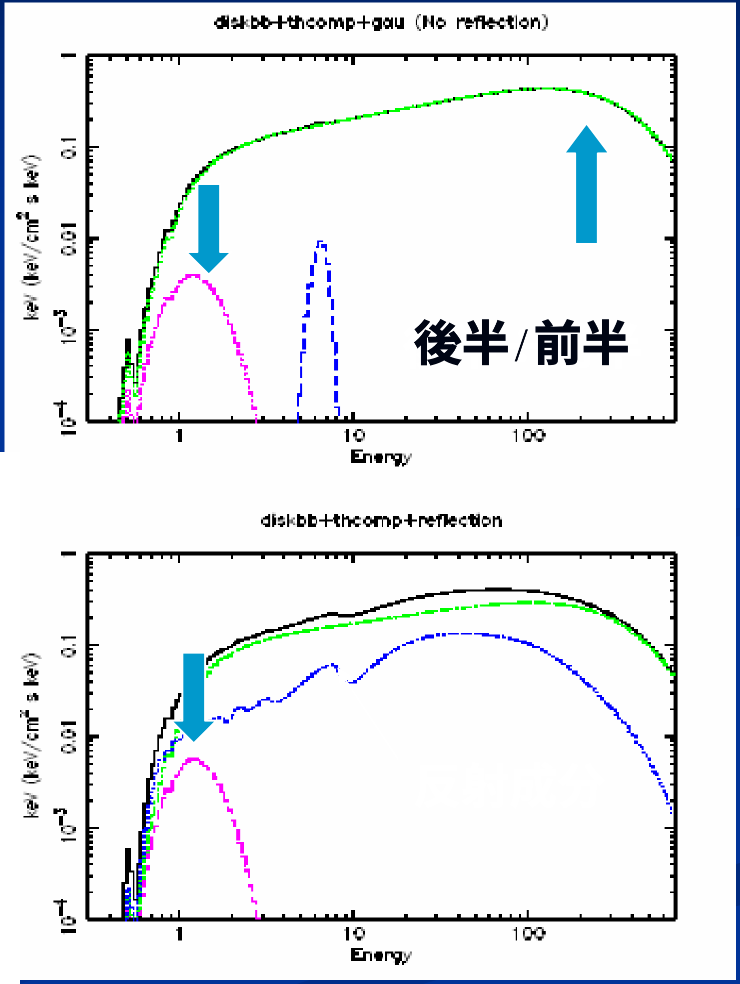
GRJ1655-40



「すざく」によるＧＲＯＪ１６５５－４０　の観測
Takahashi et al. 2007(PASJ submitted)

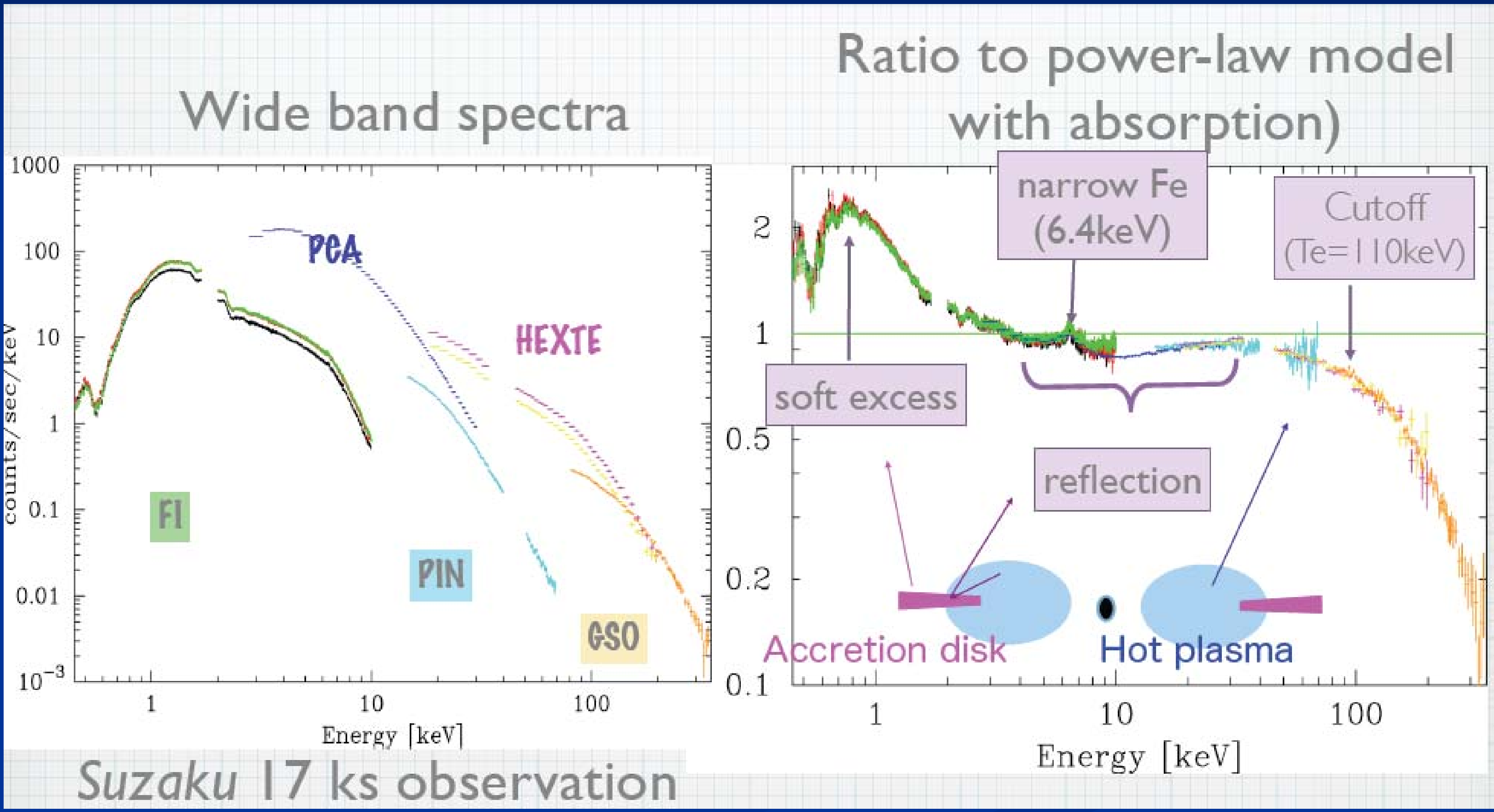
～２００　keVの折れ曲がり
　　電子温度、反射成分
低エネルギー側での別成分
　(スタンダード降着円盤　~0.2 keV ~30 km)





Ω~０．０５－１．０　(Preliminary)

「すざく」によるCyg X-1　の観測
Kubota et al. preliminary

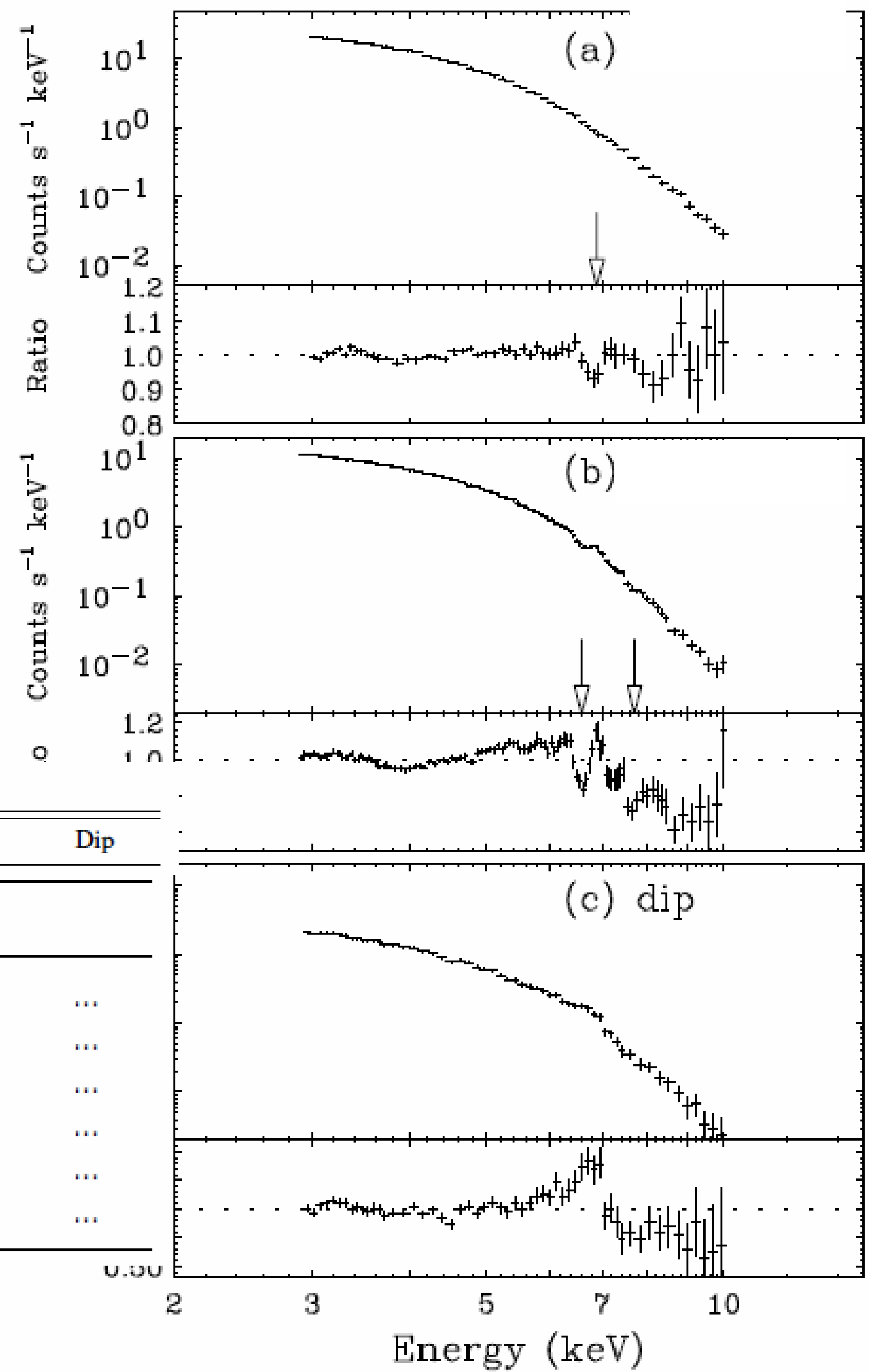


6.吸収線

Ueda et al. 1998
「あすか」で発見

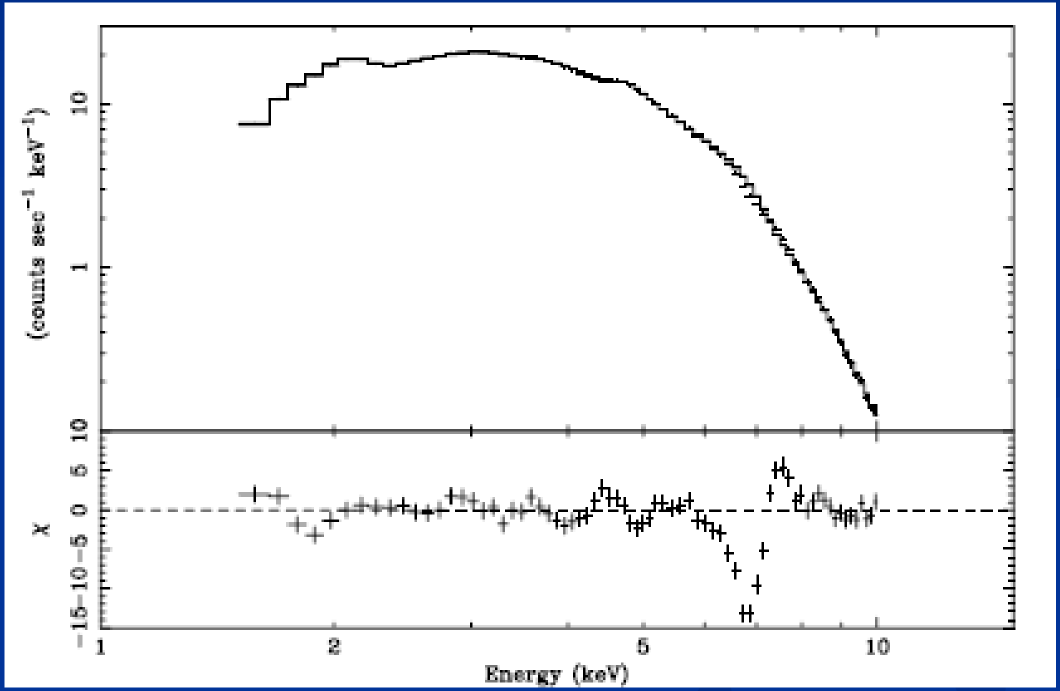
Spectral Fits in the 1.2–10 keV Band

Parameters	High State	Low State	Dip
Spectral Features in the Iron K Band[c]			
Absorption-line energy (keV)[d]	6.95 ± 0.10	6.63 ± 0.07/7.66 ± 0.13	...
1 σ line width (eV)...................	<150	<75/<130	...
Equivalent width (eV)...............	25^{+13}_{-11}	$61^{+15}_{-13}/35^{+30}_{-29}$	...
Identification	Fe xxvi Kα	Fe xxv Kα/Fe xxv Kβ	...
Edge energy (keV)	...	8.81 ± 0.12	...
Optical depth	...	0.38 ± 0.07	...



6.吸収線

- Kotani et al. 2000
  - 「あすか」で発見
- GRS J1915-105
  - ＢＨ，Superliminal Motion
  - i~70度

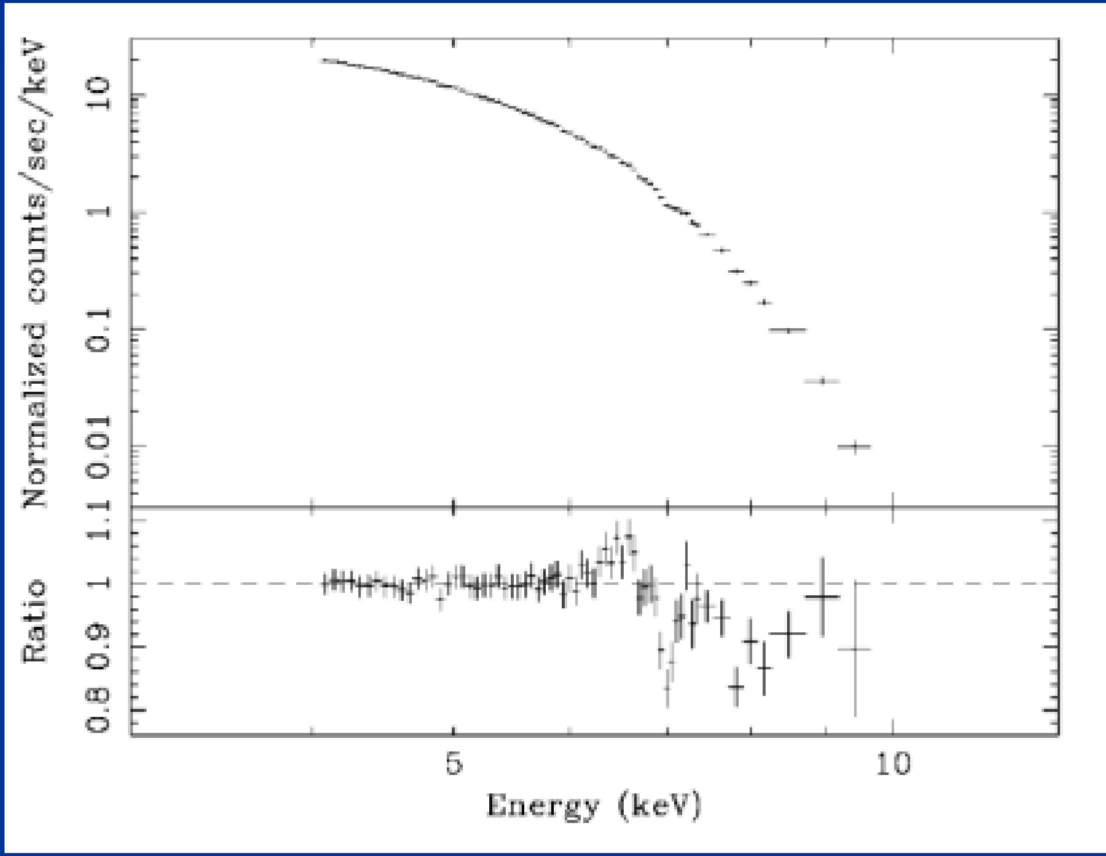


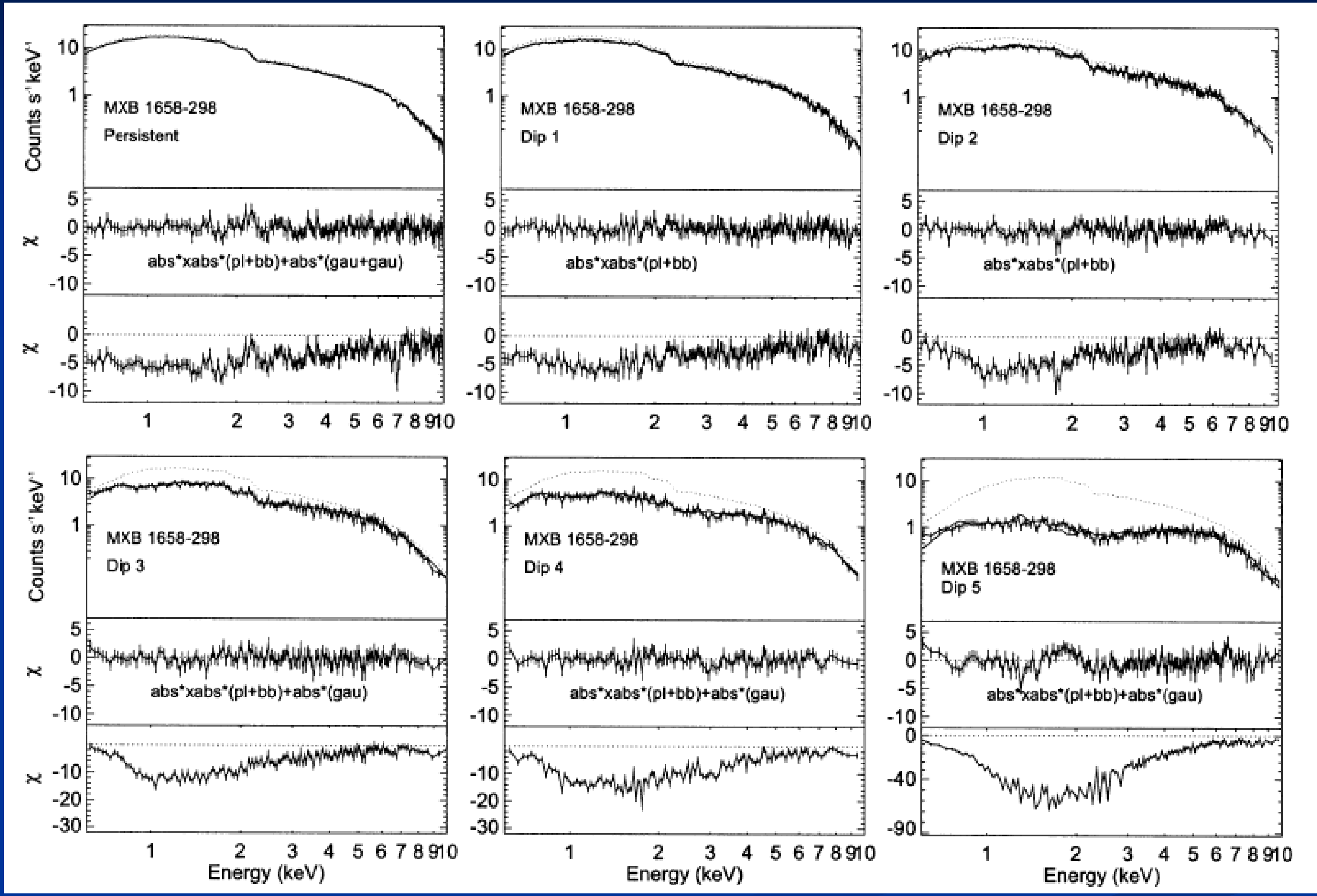
6.吸収線

- Ueda et al. 2001
- GX13＋1
- NS, i:不明

TABLE 1
RESULTS OF THE SPECTRAL FIT

Parameter	Best-Fit Value
Spectral Features in the Iron K Band (SIS)	
Emission-line energy	6.42 ± 0.08 keV
1 σ line width	<220 eV
Equivalent width	19 ± 8 eV
Absorption-line energy	7.01 ± 0.03 keV
1 σ line width	<70 eV
Equivalent width	35 ± 8 eV
Edge energy	7.61 ± 0.13 keV
Optical depth	0.13 ± 0.05
χ^2/degrees of freedom[b]	74.4/98





Diaz-Trigo et al. 2006, A&A, 445, 179

たくさんのLMXRB (Dipping source) で吸収構造あり

6.吸収線

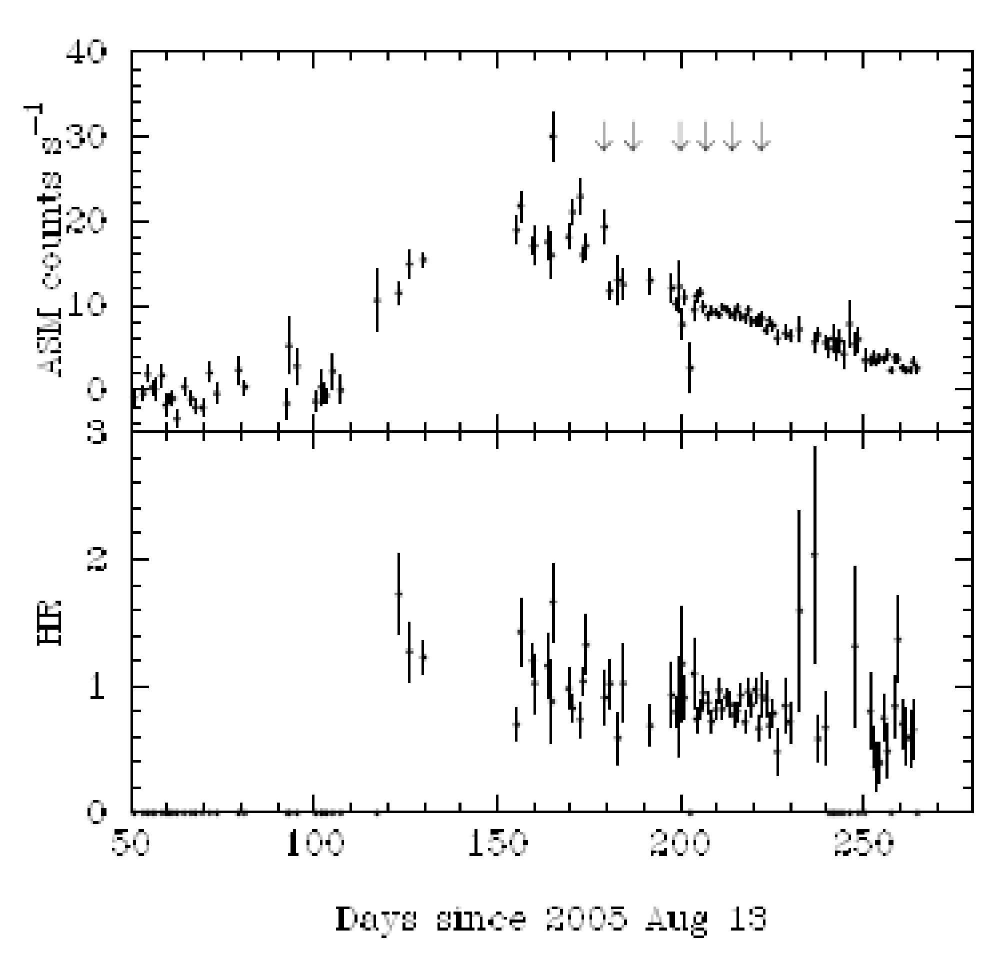
- Inclination の大きい系で吸収が見つかる
  - ＧＲＯ　Ｊ１６５５－４０　i~70
  - GRS J1915-105　i~70
  - ＧＸ１３＋１　i~不明

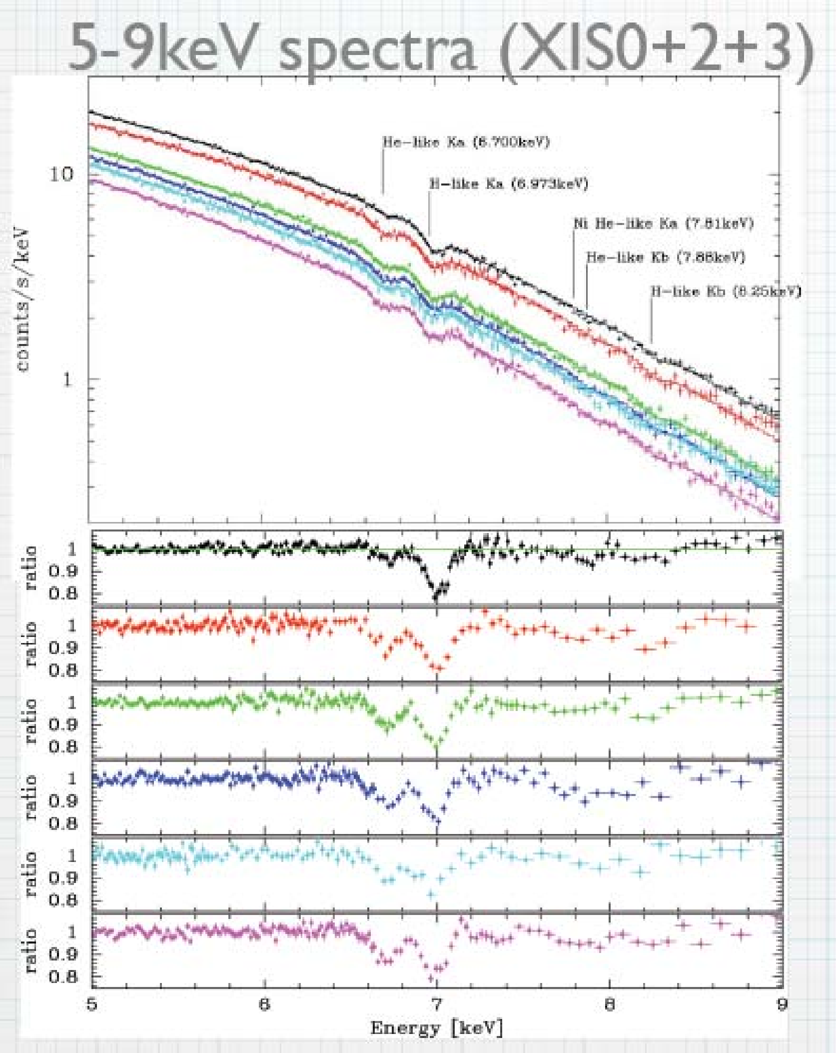
  - 降着円盤の外側?内側？のコロナ？
    - 光電離

「すざく」による降着円盤の診断

4U1630-47

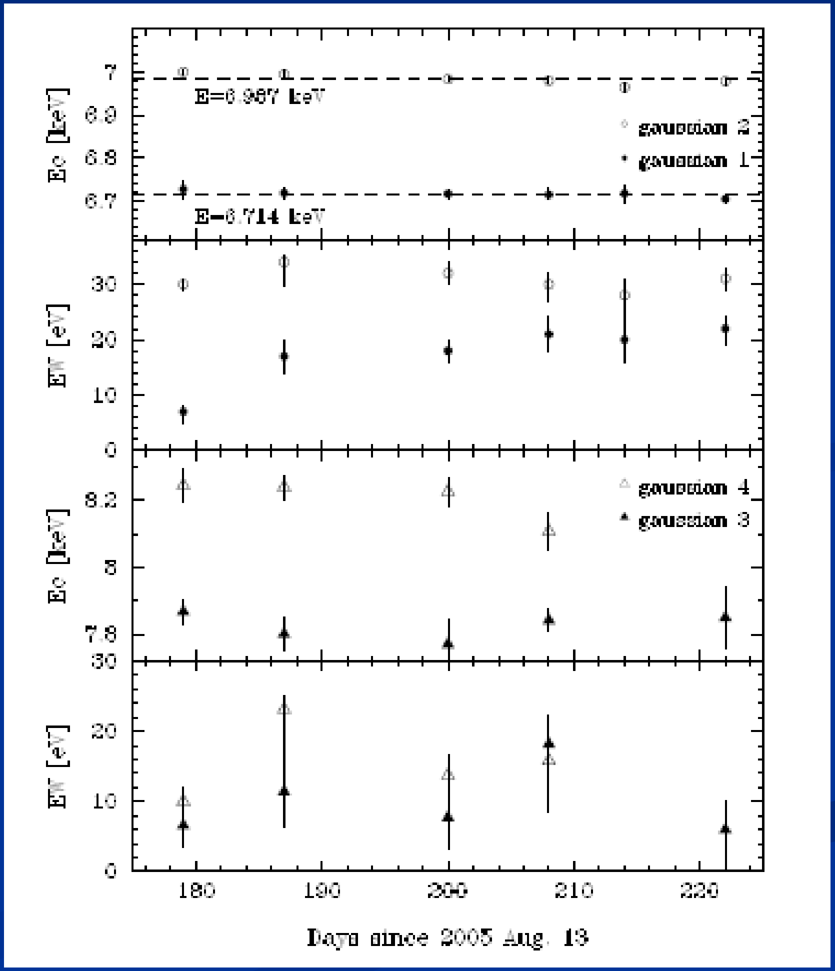
Kubota et al. 2006 PASJ





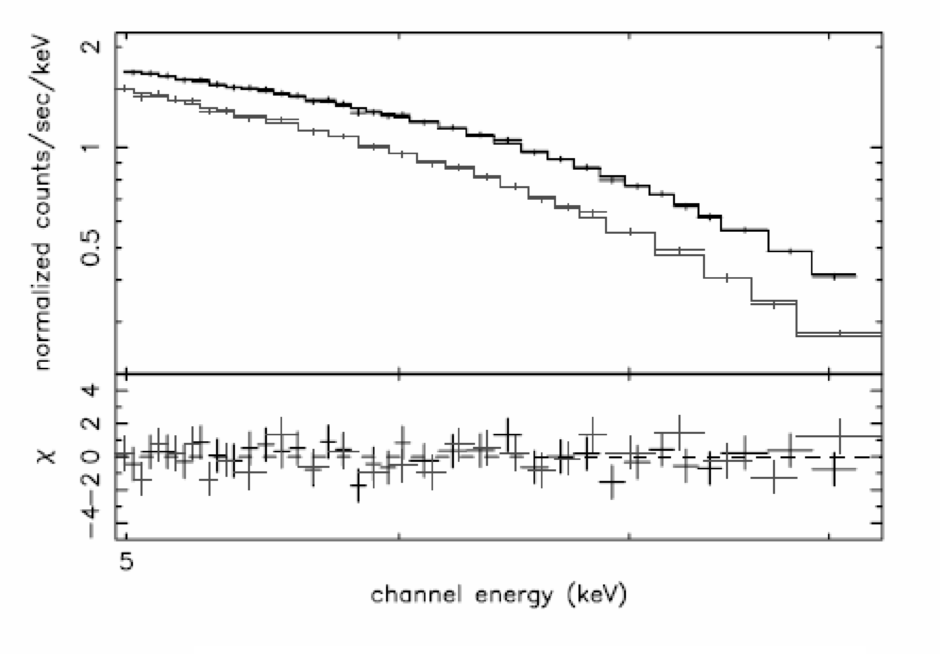
「すざく」による降着円盤の診断

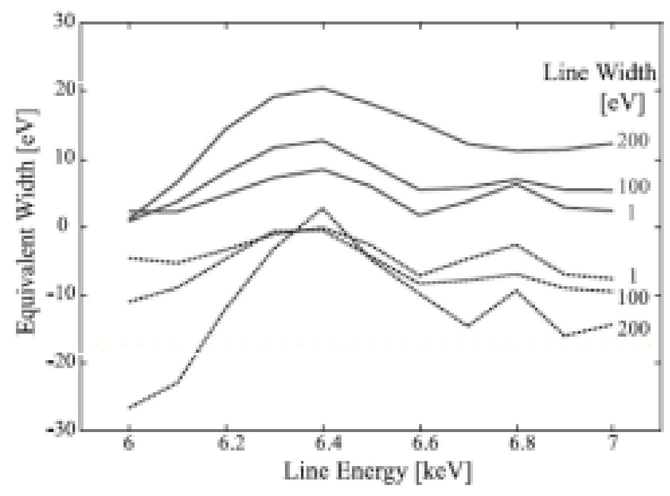
- **鉄の吸収線構造**
  - X1630-47 Kubota et al. 2006 PASJ
  - He-like, H-like
  - Blue shift ~1000km s-1
  - $\xi = L/(nr^2)$, optical depth
    - Radius (Photo ionization)
      - $(0.2\text{-}5)\times10^{10}\ D_{10}^{2}$cm
    - Density
      - $\sim10^{12}\ D_{10}^{-2}$cm^{-2}



「すざく」による降着円盤の診断

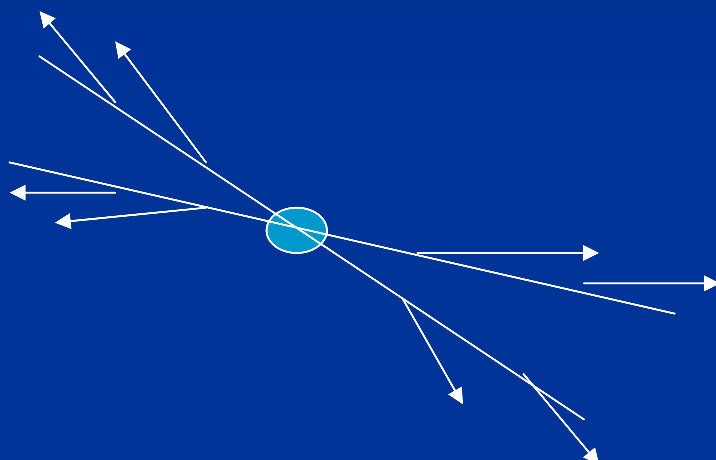
- GROJ1655-40
  (Takahashi et al. 2007)
  - No narrow line
- **吸収線はすべて**
  - High/Soft State
    - inclination **の大きいもの**
  - Low/Hard State **では見えない**
    - **１６５５－４０　(有意に小さい)**
    - High/Soft state: 70~120 eV
    - Low/Hard state: <20 eV



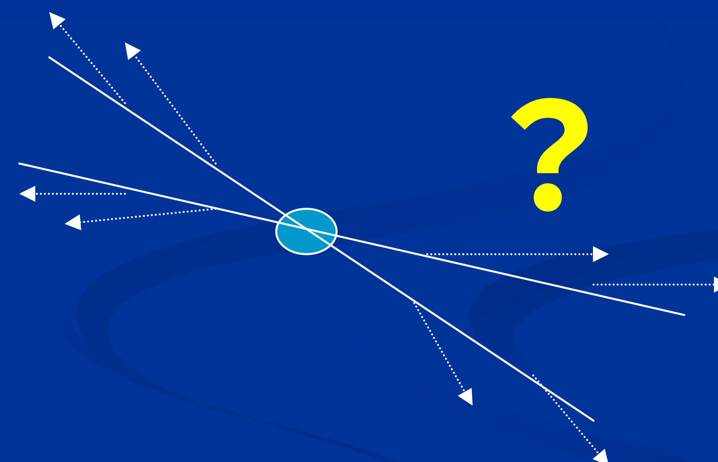


「すざく」による降着円盤の診断

- High/Soft State



Low/Hard State

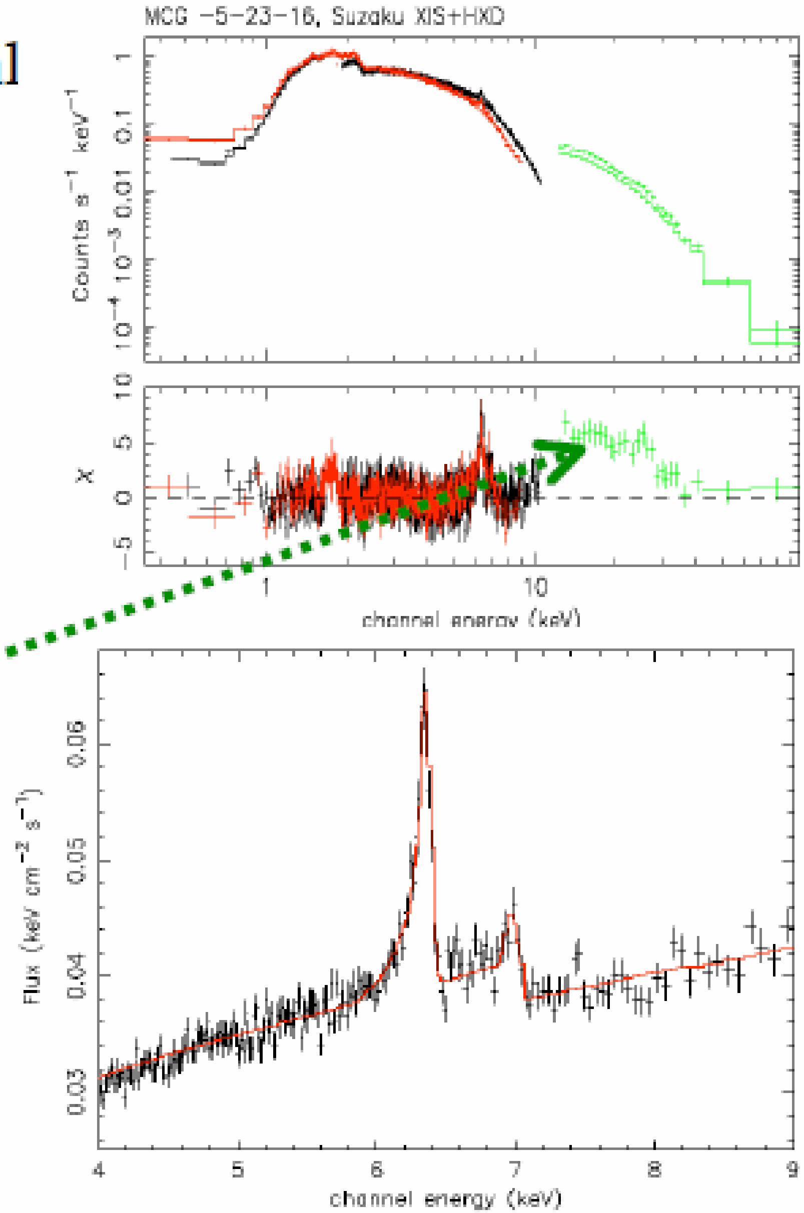


No (Thin) Wind?
ADAF?
Violent Motion?

スタンダード的な降着円盤の存在？

MCG-5-23-16- J. Reeves et al

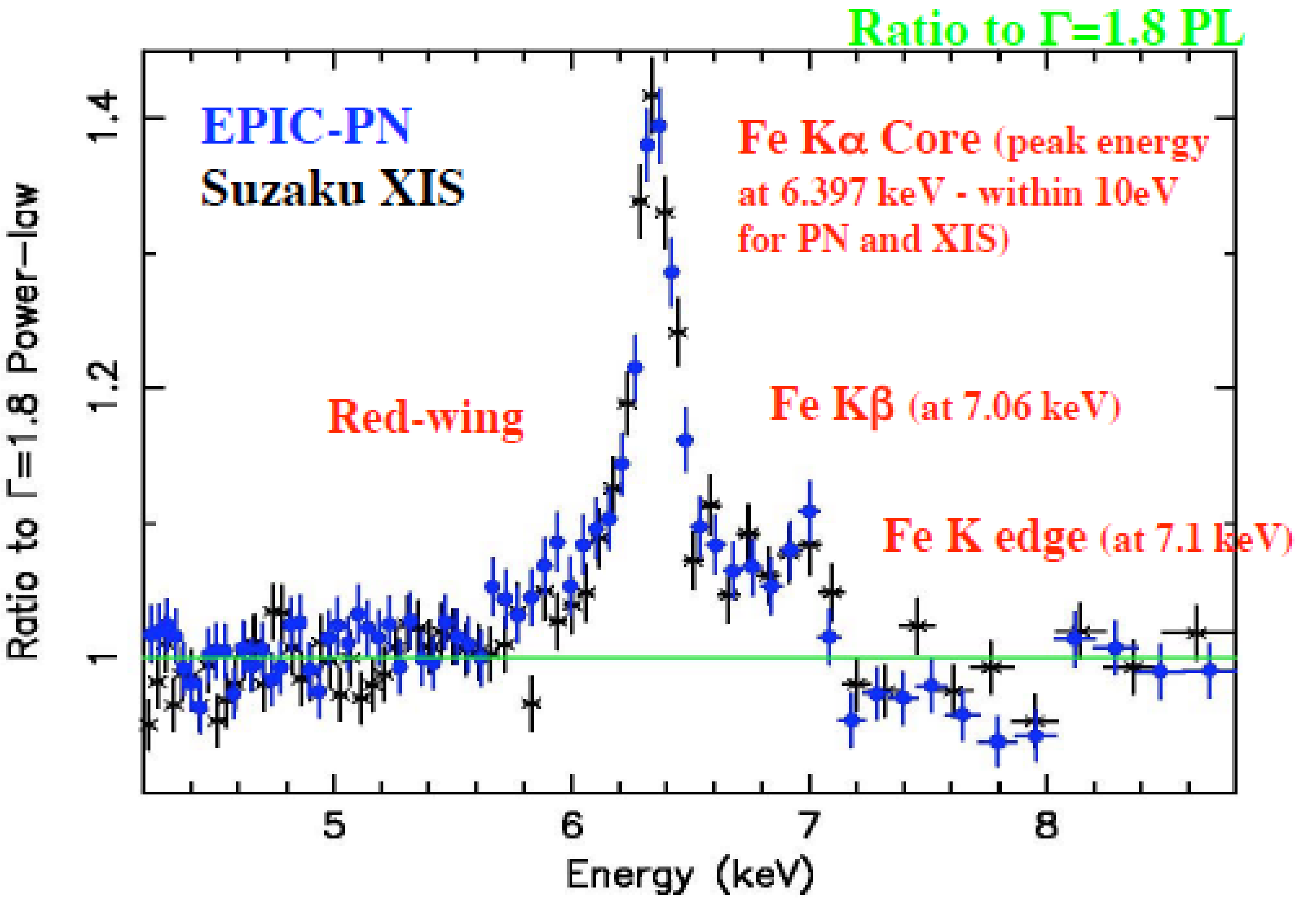
- Fe K line needs two components, a narrow core and a broad diskline or gaussian component to fit the red-tail below 6.4 keV
- . The reflection component is well constrained with R=1.3, with an Fe abundance of 0.6x solar.
- The edge at 7.1 keV and the Compton hump allows us to determine both parameters.



AGN

Simultaneous Suzaku and XMM Observation- *notice the excellent agreement on Fe K line shape*

Iron line Profile of MCG -5-23-16

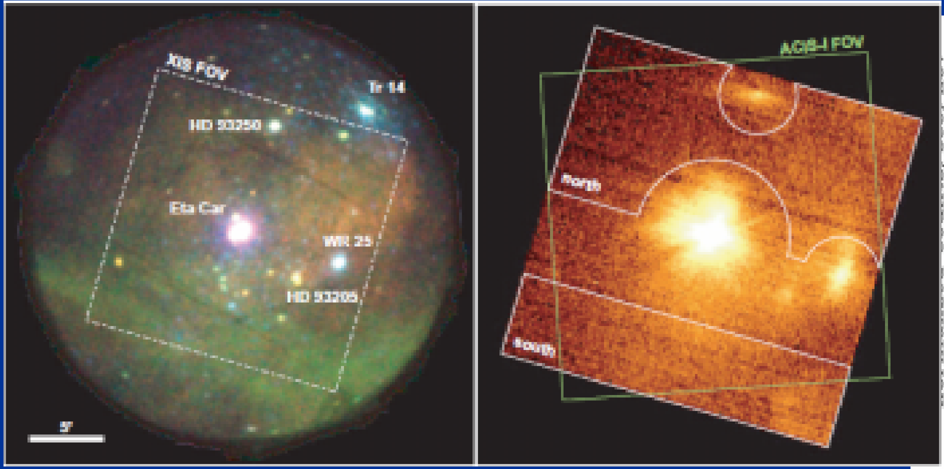


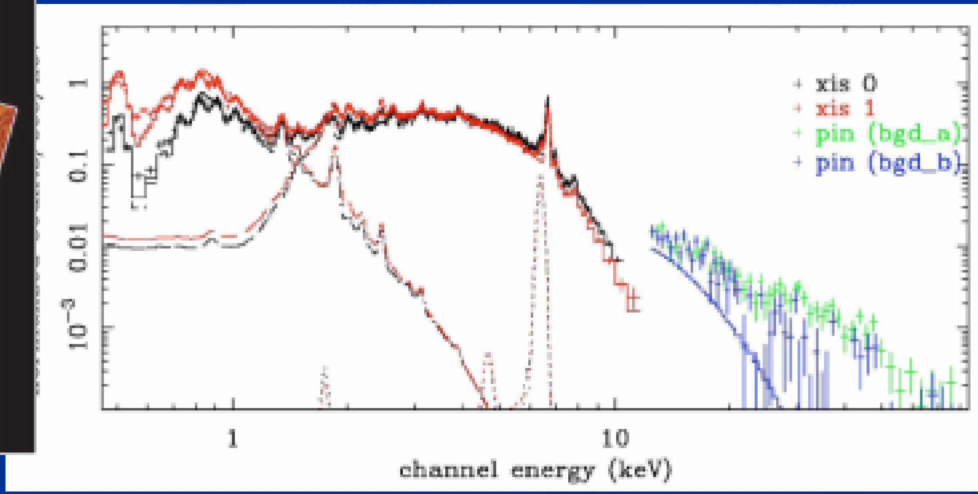
宇宙の加速領域に迫る

- 1. 大質量星
- 2. SNR
- 3. HESS　Sources

Non-thermal Component Search

- 大質量星
  - ηCar　(LBV)　(Sekiguchi et al. Preliminary)
  - Carina　Nebura　(Hamaguchi et al. 2006, PASJ)





ηCar:　5．6yr Binary
Wind-Wind collision　ー>　Non thermal comp?

Non-thermal Component Search

- SNRs
  - SN1006 (Koyama et al. 1995)
  - Diffusive Shock 加速

$$E_{max} = 460 \times \frac{1}{\eta} \left(\frac{V_s}{10^4\ \mathrm{km/s}} \right) \left(\frac{B}{10\mu G} \right) \left(\frac{R}{10\ \mathrm{pc}} \right)\ \mathrm{TeV}$$

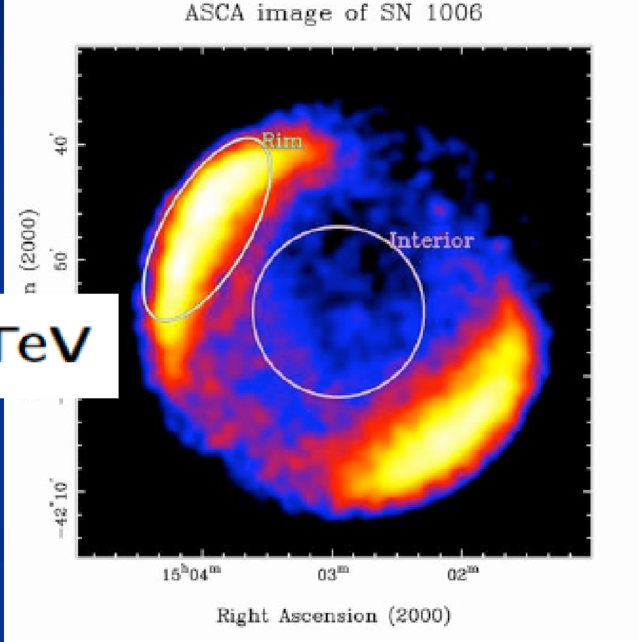
  - Synchrotron emission

$$h\nu_{\mathrm{synch}} = 5.3\ E^2_{100\,\mathrm{TeV}} B_{10\,\mu\mathrm{G}}\quad [\mathrm{keV}]$$

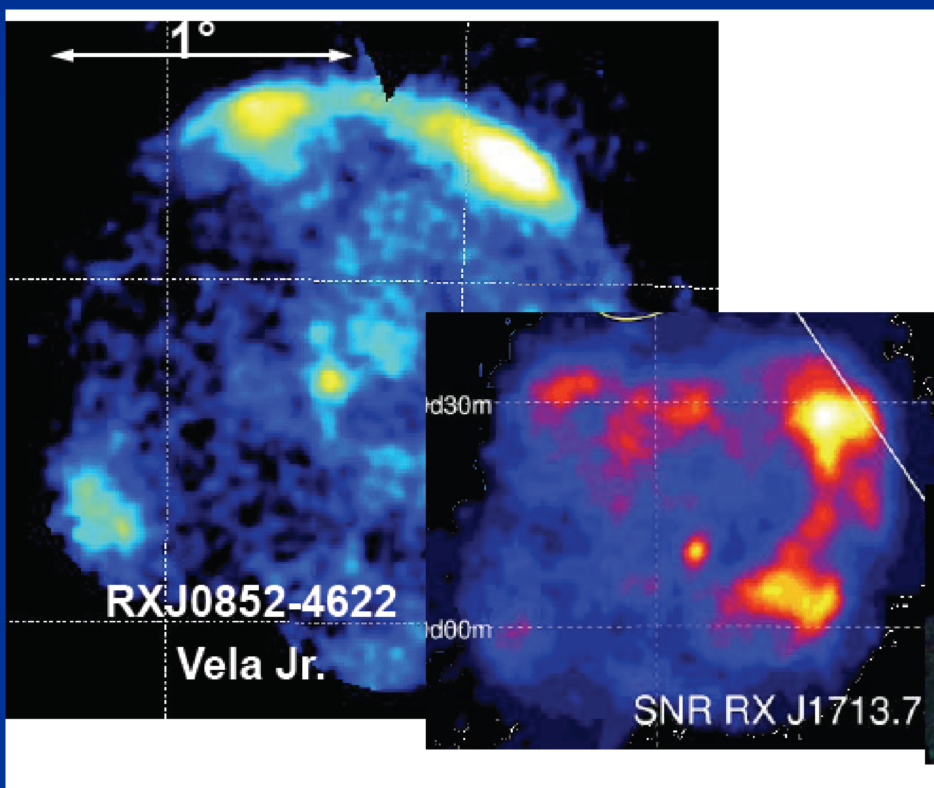
  - Radiative loss by synchrotron emission

$$\tau_{\mathrm{synch}} = 880\ (B/10\mu\mathrm{G})^{-1.5} (\varepsilon/3\mathrm{keV})^{-0.5}\ \mathrm{yr}$$

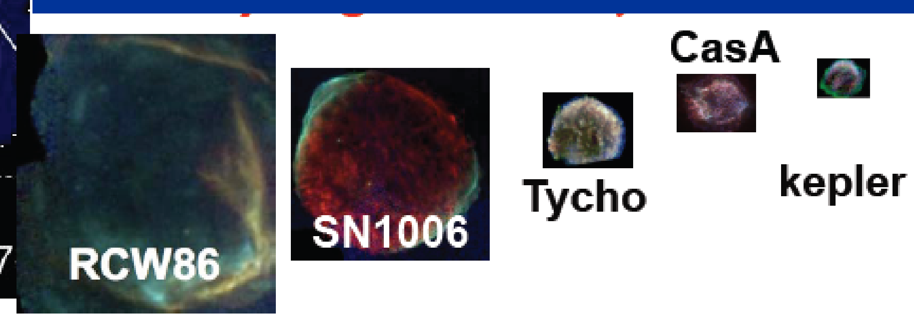
  - TeV electron の存在
    - 常時加速



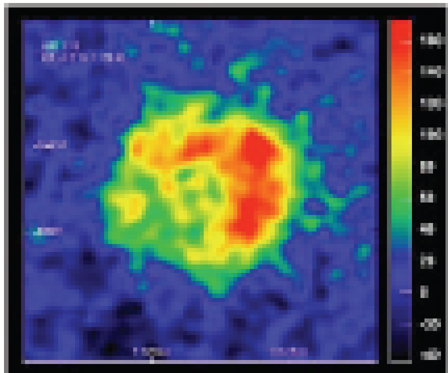
Non-thermal Component Search in young SNRs



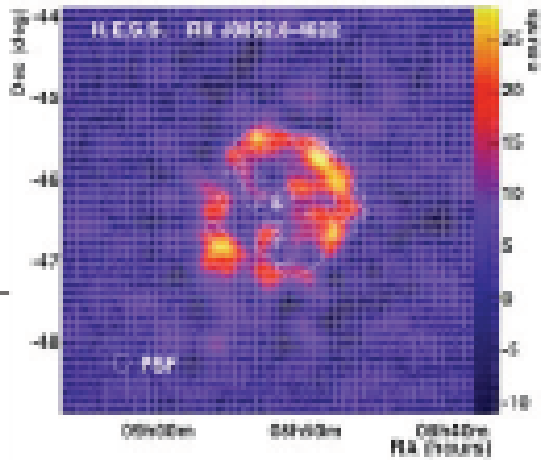
Non−thermal
Emissions
from Young SNRs



Energy Frontier = X/TeV

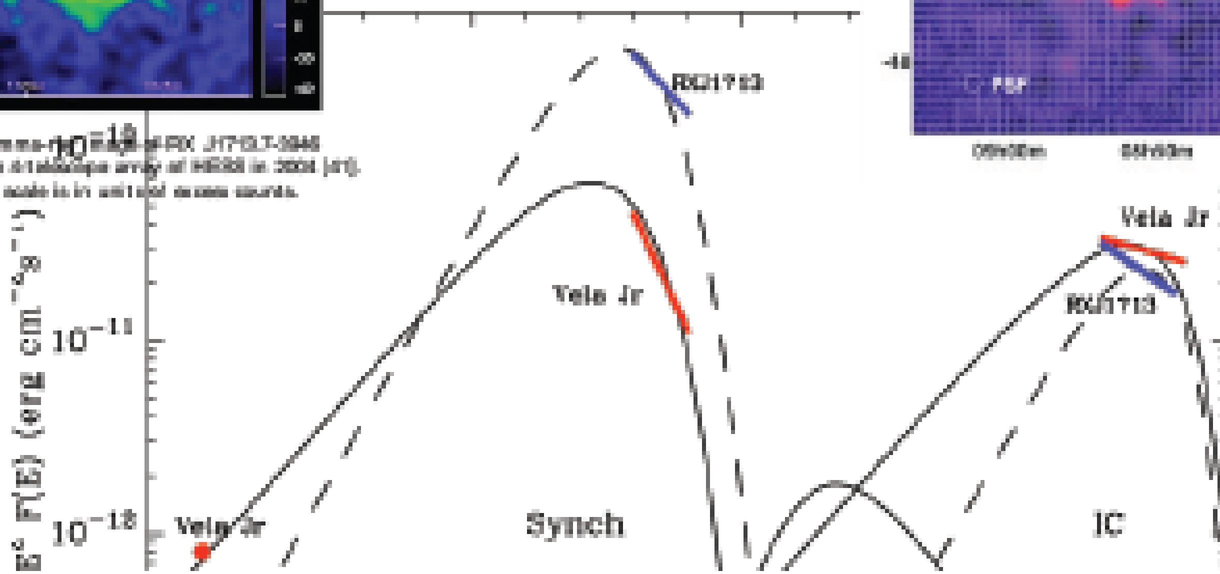


TeV Image
RXJ1713



TeV Image
Vela Jr.

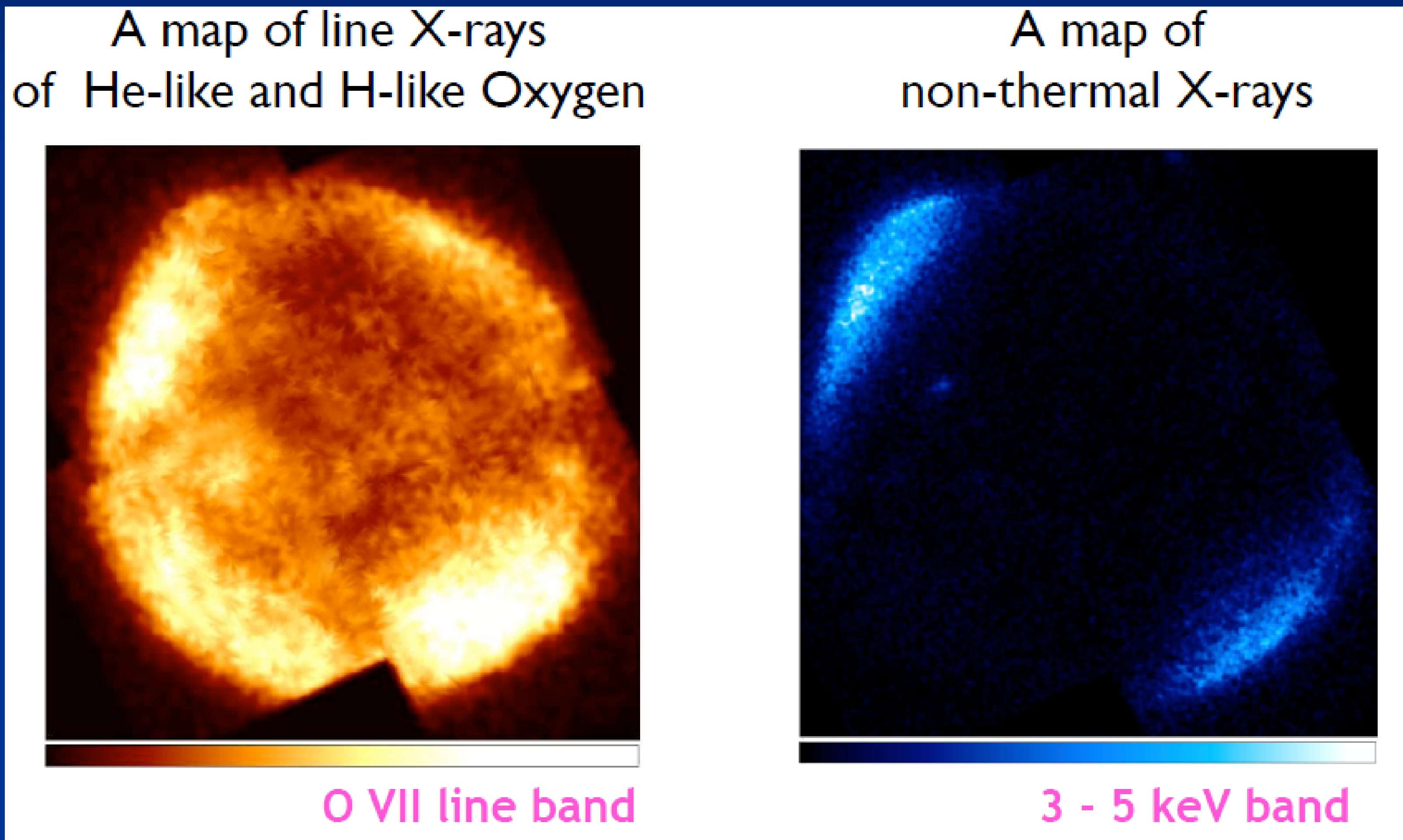
HESS



Q.Connection between X-ray and TeV gamma-ray

(Between Magnetic Field and CMB photons
or
electrons and protons)

加速領域の特定



熱的放射

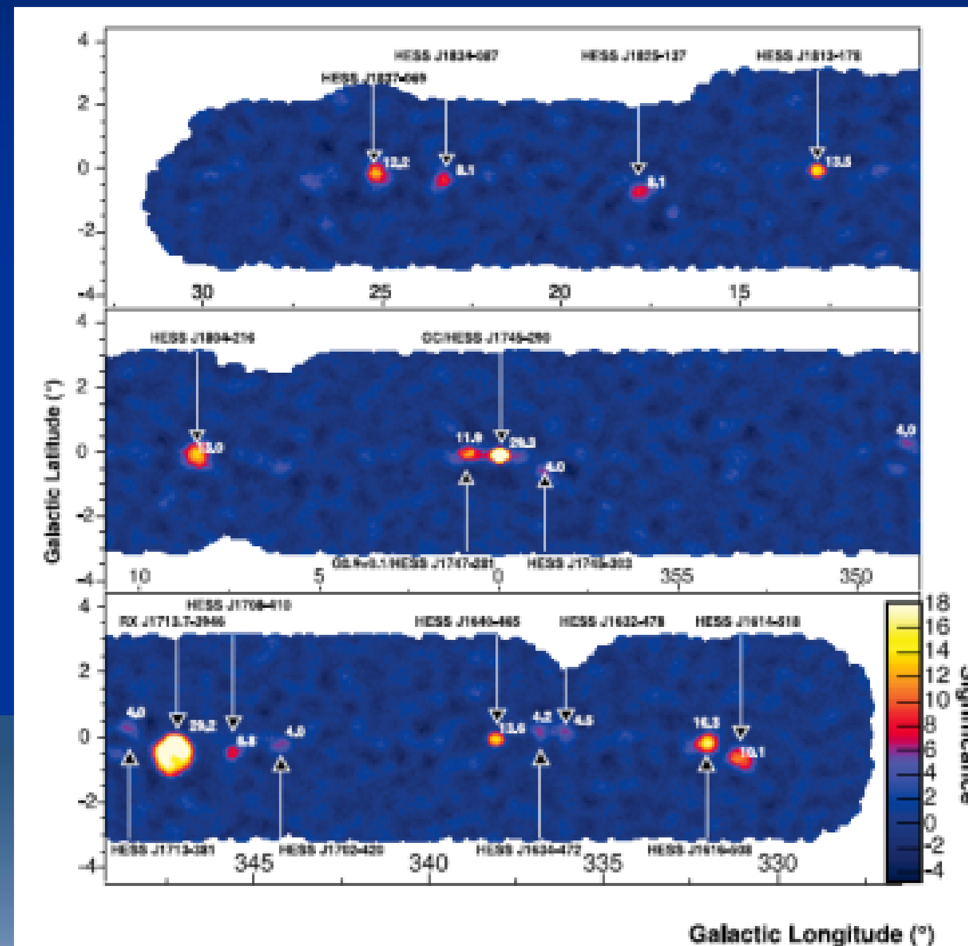
非熱的放射

Un-identified TeV Sources

Significance Map of the HESS Galactic plane survey

HESS
Cherenkov Telescope
E>200GeV

Imaging Technique
Galactic Plane Survey
(500 pointing, 230hr)



Namibia 1800m above sea level

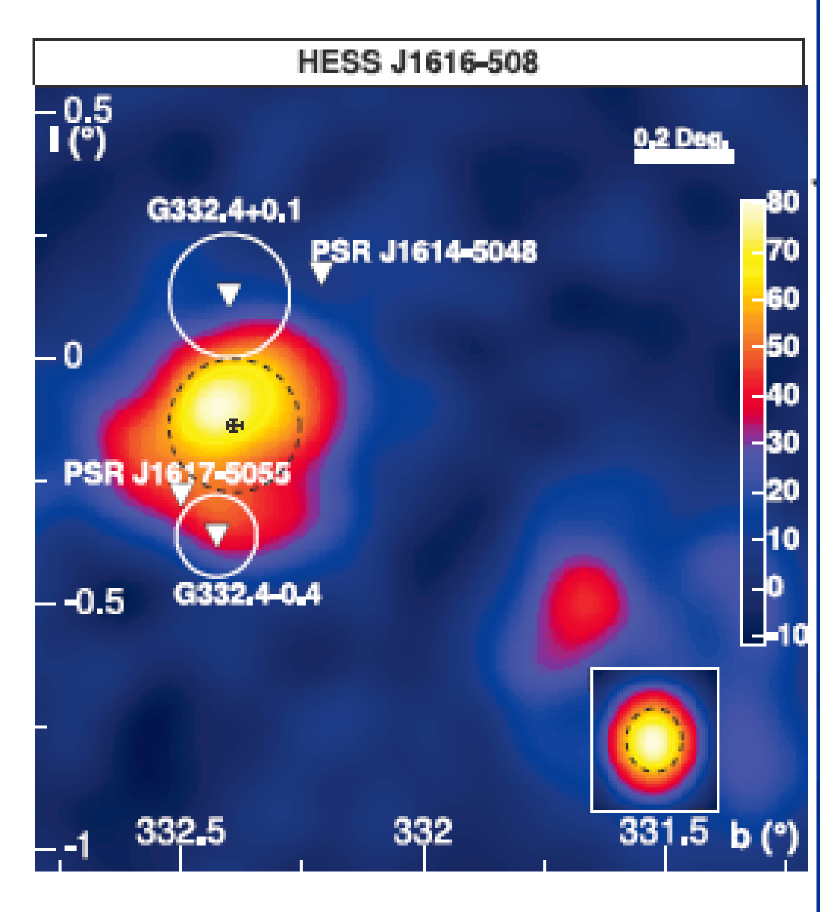
TeV sources

TABLE 5
SUMMARY OF POSSIBLE COUNTERPARTS TO THE H.E.S.S. VHE GAMMA-RAY SOURCES IN THE INNER GALAXY

Name	Possible Counterpart	Class	Offset (arcmin)	Distance (kpc)	Luminosity (10^{34} ergs s^{-1})
J1614–518.............	...	...	...	...	...
J1616–508.............	PSR J1617–5055	PWN	10.4	6.5	20.2
J1632–478.............	IGR J16320–4751	XRB	3	...	...
J1634–472.............	IGR J16358–4726/G337.2+0.1	XRB/SNR	13/10	.../14	.../28.3
J1640–465.............	G338.3–0.0/3EG J1639–4702	SNR/UID	0/34	8.6	16.2
J1702–420.............	...	...	...	...	...
J1708–410.............	...	...	...	...	...
J1713–381.............	G348.7+0.3	SNR	0	10.2	5.2
J1713–397.............	RX J1713.7–3946 (G347.3–0.5)	SNR	0	1	1.2
J1745–290.............	Sgr A East/Sgr A*	SNR/BH	0	8.5	12.8
J1745–303.............	3EG J1744–3011	UID	10	...	...
J1747–281.............	G0.9+0.1	PWN	0	8.5	4.4
J1804–216.............	G8.7–0.1/PSR J1803–2137	SNR/PWN	21/10.8	6/3.9	16.5/7.0
J1813–178.............	G12.82–0.02	SNR	0	4	3.1
J1825–137.............	PSR J1826–1334/3EG J1826–1302	PWN/UID	11/43	3.9/...	6.1/...
J1834–087.............	G23.3–0.3	SNR	0	4.8	4.4
J1837–069.............	AX J1838.0–0655	UID	6	...	...

TeV ガンマ線Sources
HESS J1616-508

Ahoronian et al. 2006, ApJ 636, 777-797



TeV ガンマ線Sources HESS J1616-508

- Suzaku: No detection
  - High L_{TeV}/L_x
- proton origin (π^0 decay)

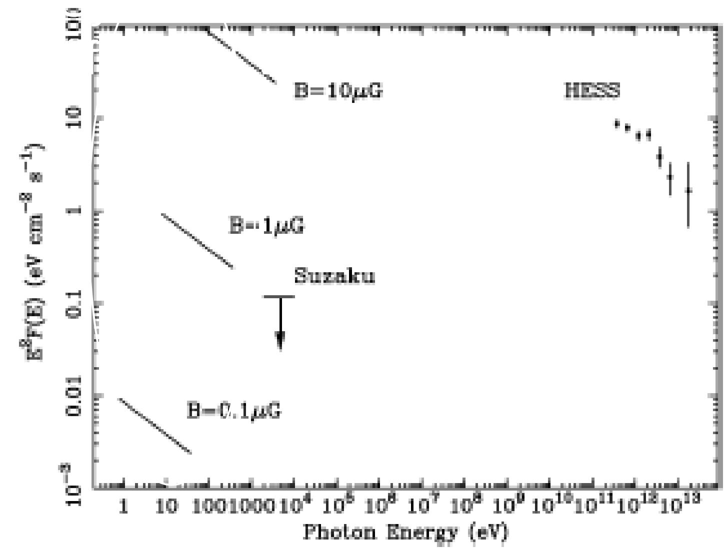


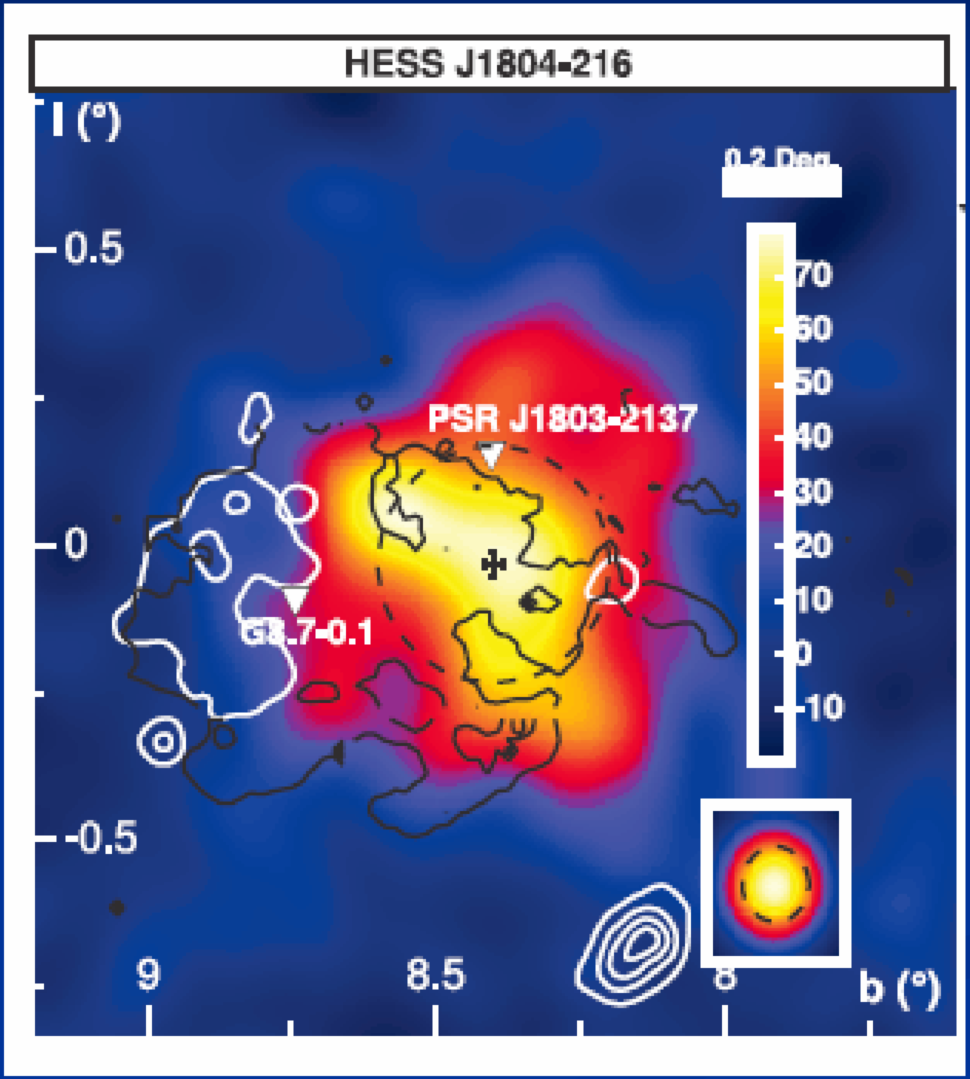
Fig. 9. Spectral energy distribution of HESS J1616 from the X-ray to TeV γ-ray band. The synchrotron radiation from accelerated electrons, which boost the 3 K background up to the TeV energy range, is plotted toward the left for three different values of the magnetic field.

Table 3. Spatially extended VHE objects with X-r

Name	Possible counterpart	Type[a]	Γ^b_{TeV}	f^c_{TeV}	N^d_H	Γ^e_X	f^f_X	f_{TeV}/f_X	Reference[g]
HESS J0852−463	RX J0852−4622	SNR	2.1	6.9	4	2.6	∼10	∼ 0.7	1, 2, 3
HESS J1303−631	—	?	2.4	1.0	20	2.0	<0.64	> 1.6	4, 5
HESS J1514−591	PSR B1509−58	PWN	2.3	1.6	8.6	2.0	3.2	0.5	6, 7
HESS J1632−478	AX J1631.9−4752	HMXB?	2.1	1.7	210	1.6	1.7	1.0	8, 9
HESS J1640−465	G338.3−0.0	SNR	2.4	0.71	96	3.0	0.30	2.4	8, 10
HESS J1713−397	RX J1713.7−3946	SNR	2.2	3.5	8	2.4	54	0.065	11, 12
HESS J1804−216	Suzaku J1804-2142	?	2.7	0.48	2	-0.3	0.025	19	8, 13
HESS J1804−216	Suzaku J1804-2140	?	2.7	0.48	110	1.7	0.043	11	8, 13
HESS J1813−178	AX J1813−178	?	2.1	0.89	110	1.8	0.70	1.3	8, 14
HESS J1837−069	AX J1838.0−0655	?	2.3	1.4	40	0.8	1.3	1.1	8, 15
TeV J2032+4130	—	?	1.9	0.20	?	?	<0.20	>1.0	16
HESS J1616−508	—	?	2.4	1.7	4.1	2.0	<0.031	>55	This work

Matsumoto et al. 2006、PASJ in press

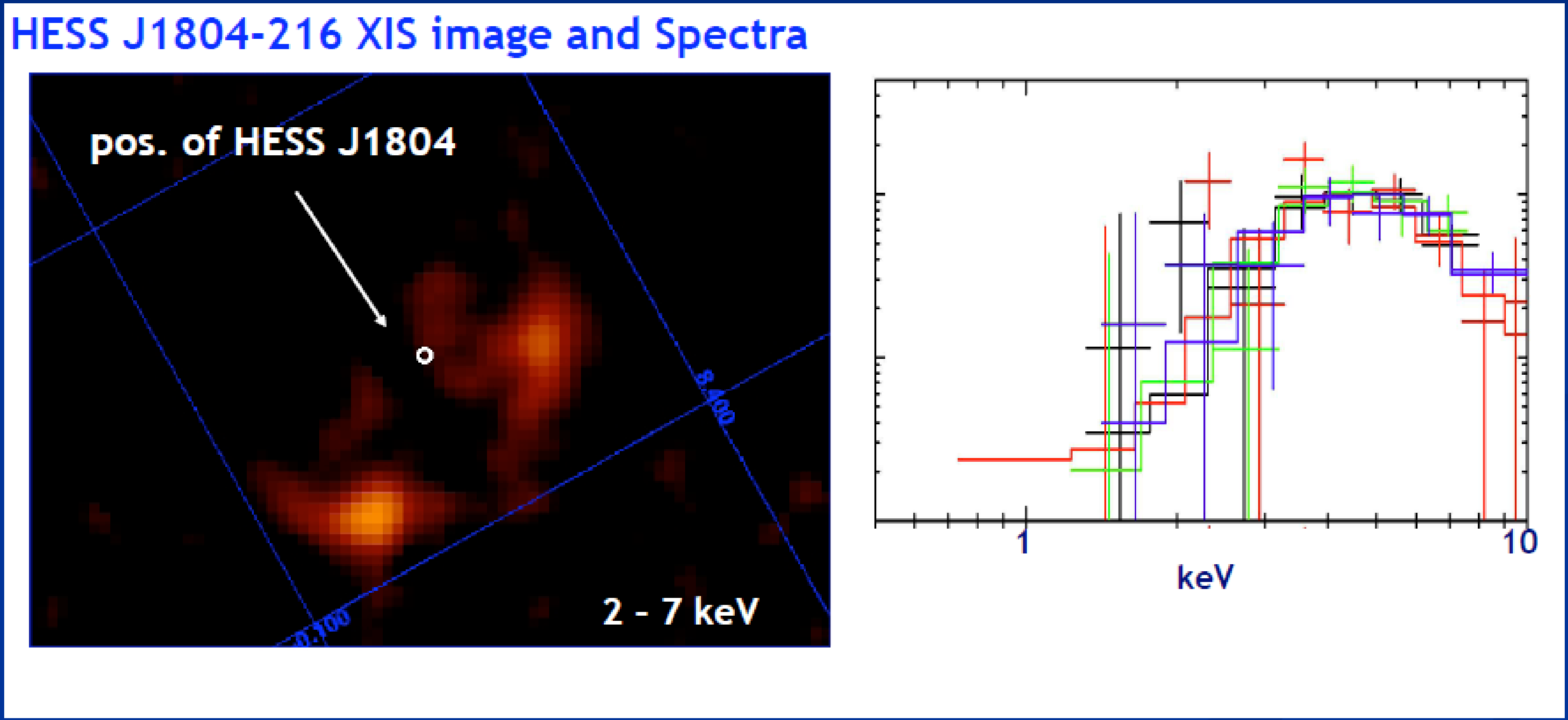
TeV ガンマ線Sources HESS J1804-216



Black: 20cmm RADIO
white; ROSAT
SNR G8.7-0.1

Ahoronian et al. 2006, ApJ 636, 777-797

TeV ガンマ線Sources
HESS J1804-216



Bamba et al. 2006 PASJ in press

Possible Counterpart Search

- HESS J 1616-508 (Matsumoto et al, 2006, PASJ)
  - No bright X-ray souce
- HESS J 1804-216 (Bamba et al. 2006 PASJ)
  - Possible diffuse source

まとめ
X線天文衛星「すざく」

- 10keV以下
  - 拡散成分には最高の感度とエネルギー分解能
    - 太陽系内からWHIMまで

- 10keV以上
  - 最高の感度
    - 宇宙の加速領域
    - コンパクト星や極限領域に迫る

J.M.Miller et al. 2006, Nature

- GRO J1655-40
- Chandra HETGS
- X-ray absorbing wind must be powered by a magnetic process

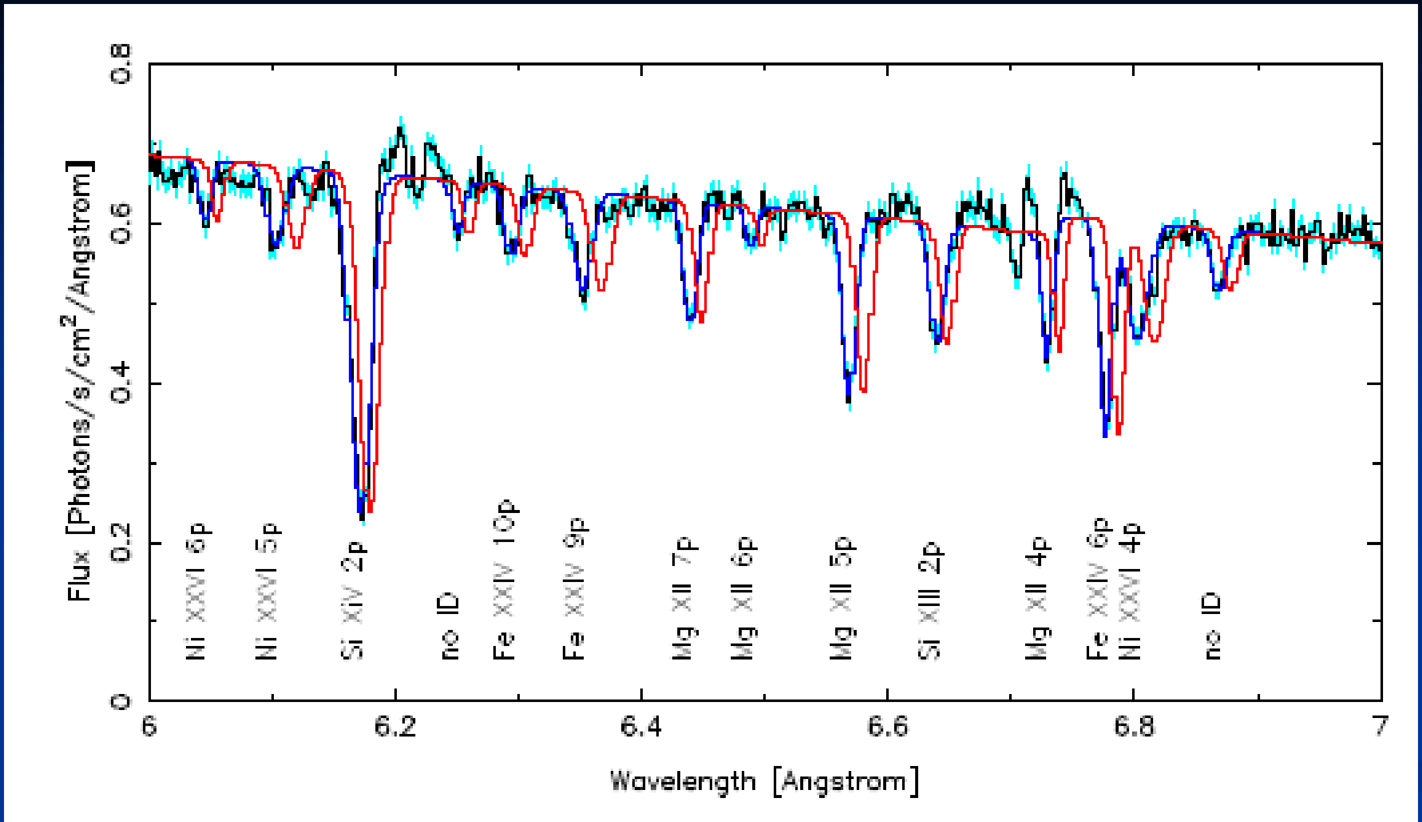
GRO J1655-40

7.0Mo BH + F3IV~F6IV (2.3Mo) 2.6day orbital period

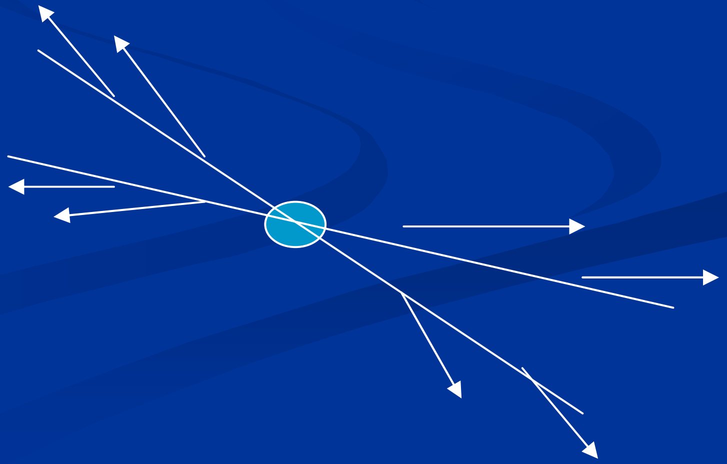
inclination of 67-85 (nearly edge-on)

$L=3.3x10^{37}$ erg s^{-1} (d=3.2kpc)

(4% Eddington limit of 7Mo)



90 absorption lines (＞5σ)
Lines show blue-shifts in the 300-1600 km s^{-1}
Spectra contain no strong emission lines



幅は～300km sec^{-1}