ブラックホール天体の X線スペクトル観測

～わかってきたこと、まだわかっていないこと～

2024年3月1日

JAXA宇宙科学研究所

海老沢 研

今日の話の内容

- 1987年2月5日「ぎんが」衛星打ち上げ
  - Galactic Black Holes (GBH)、AGNの本格的なX線スペクトル観測の始まり
- 「ぎんが」打ち上げから今日まで、ブラックホール天体のX線スペクトルについて、わかってきたこと、わかっていないことを、脈絡なく話すつもりです。
  - 「わかってきたこと」はかなり私の主観が入っています。
  - 「私がわかったと思っていること」と言った方が良いかも。
- GBHとAGNのX線放射の、どこが共通で、どこが違うのか、まだ完全にわかっていない
  - 以下、GBHとAGNについて、ごっちゃに話します。
- まずは、わかってきたこと、次にまだわかっていないこと

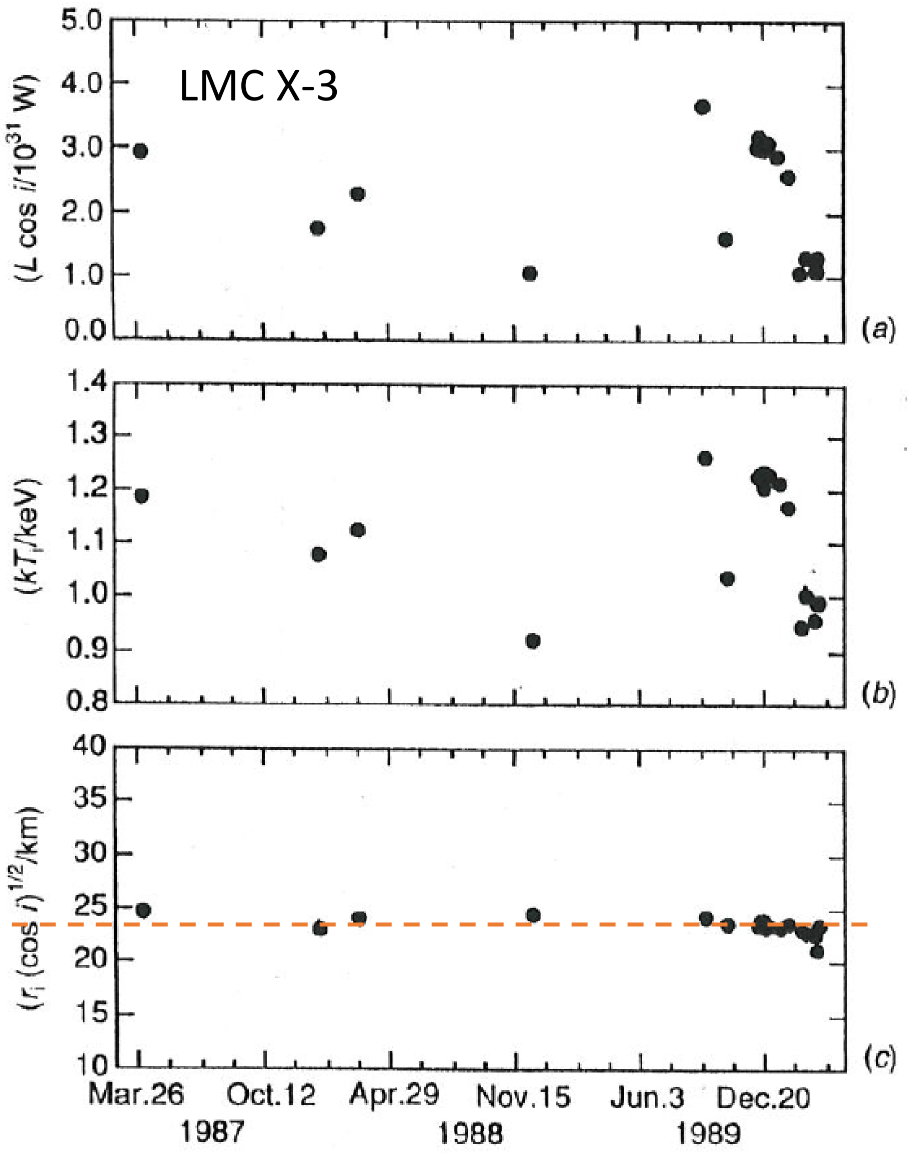
わかってきたこと1：標準降着円盤モデル

「ぎんが」
以前の状況

The theory of discs is in a much more primitive state than that of stars, because one essential constitutive relation is not understood, their rate ϵ of viscous heating. This resembles the problem of stellar structure prior to the development of nuclear physics in the 1930's. We may be worse off than this, because so few direct observations of discs are possible. What little data exist (for example, for discs around likely black holes like Cygnus X-1) indicates that real discs are not steady objects radiating from optically thick photospheres (as the theory assumes), but that they are wildly variable, release much of their energy in optically thin regions, and may have important nonthermal processes. It may be appropriate to compare our present understanding of discs to Galileo's understanding of sunspots and solar activity.

Katz, « High Energy Astrophysics » (1986)

- Longair, « High energy astrophyscs »(2^{nd} edition, 1994)



Inoue1993

「ぎんが」が、標準降着円盤スペクトルモデルを適用すると、円盤光度 (質量降着率)が変わっても、内縁半径が一定であることを発見した。

→光学的に厚い円盤の存在が確実になった

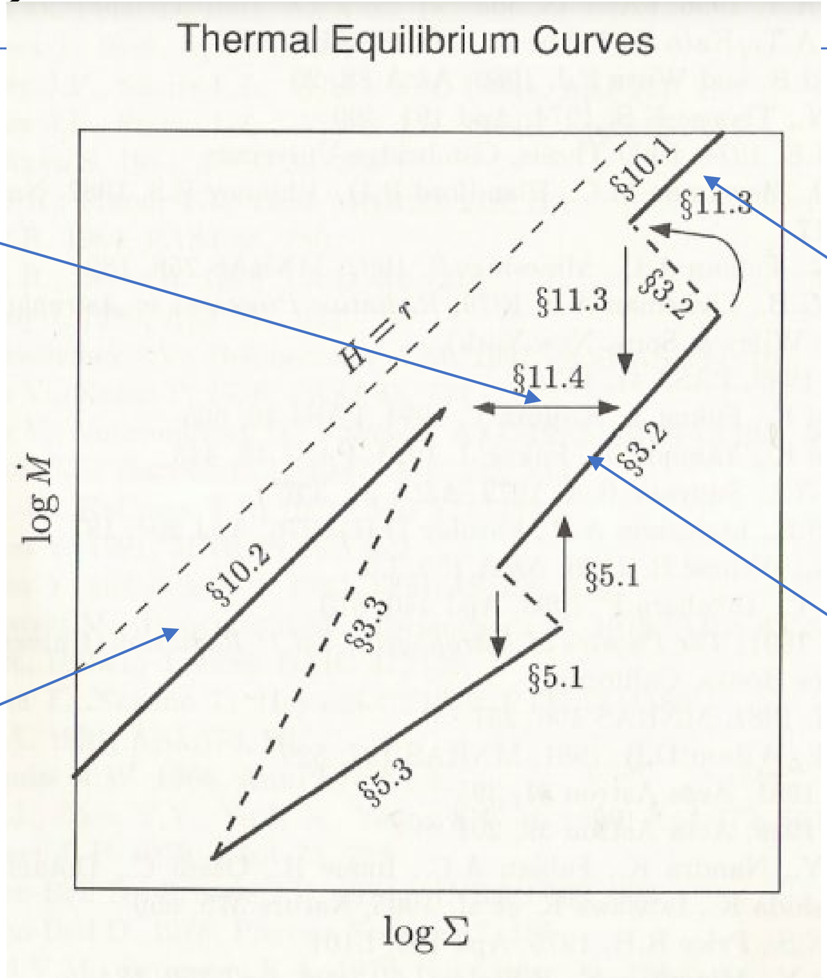
→内縁半径はInnermost Stable Circular Orbit(ISCO) に対応している

ISCOはBHのスピンに依るので、質量のわかっているBHについて、ISCOの観測からスピンに制限を付けられる

わかってきたこと2：GBHのstate transitionと降着円盤モデル

State transition

Slim disk

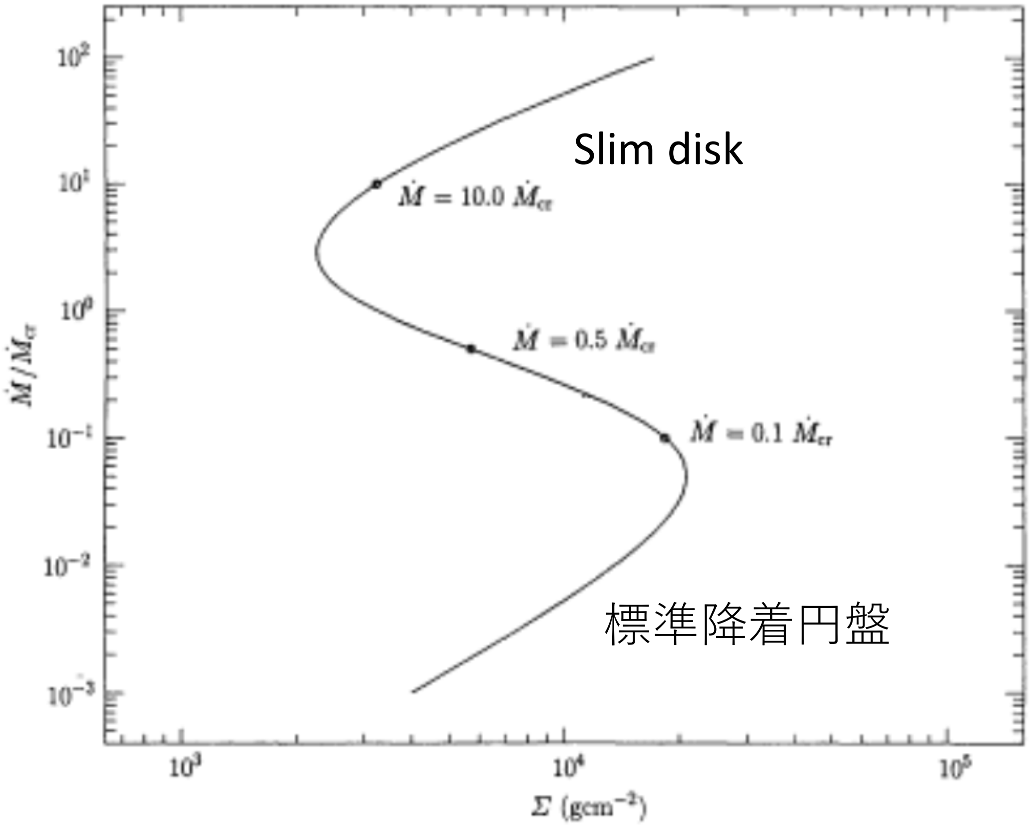


標準降着円盤
GBHのSoft state

ADAF
GBHのHard state

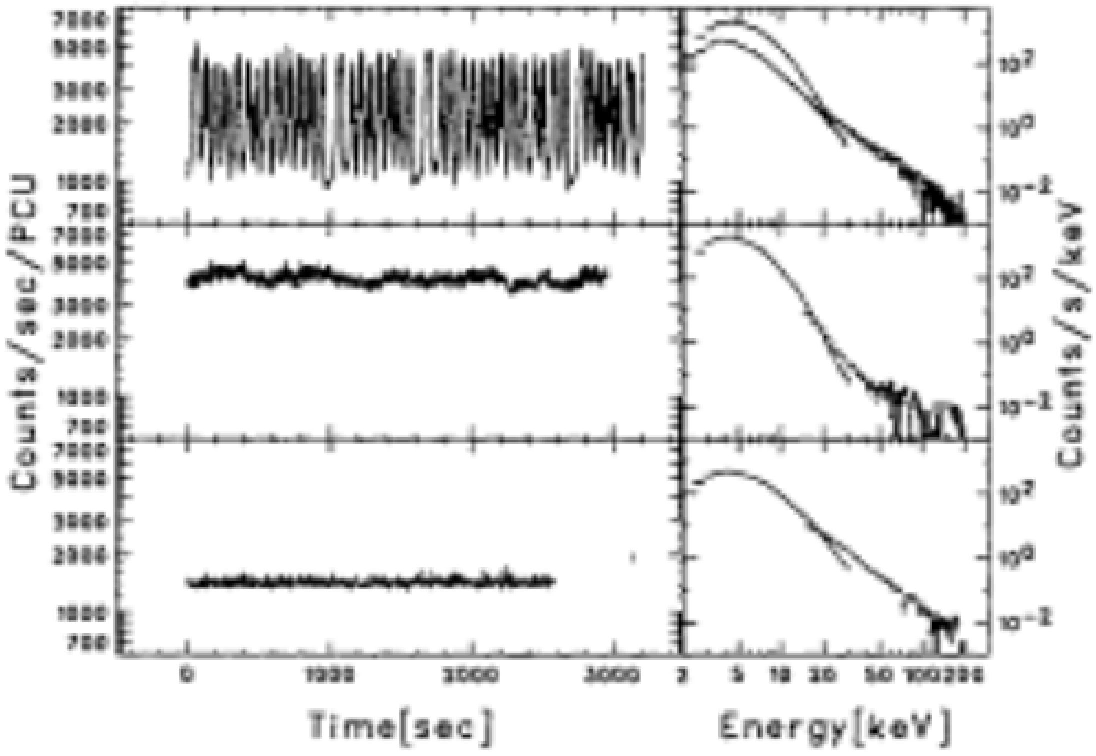
Kato, Mineshige and Fukue

わかってきたこと3：超臨界降着円盤



Honma et al. 1991

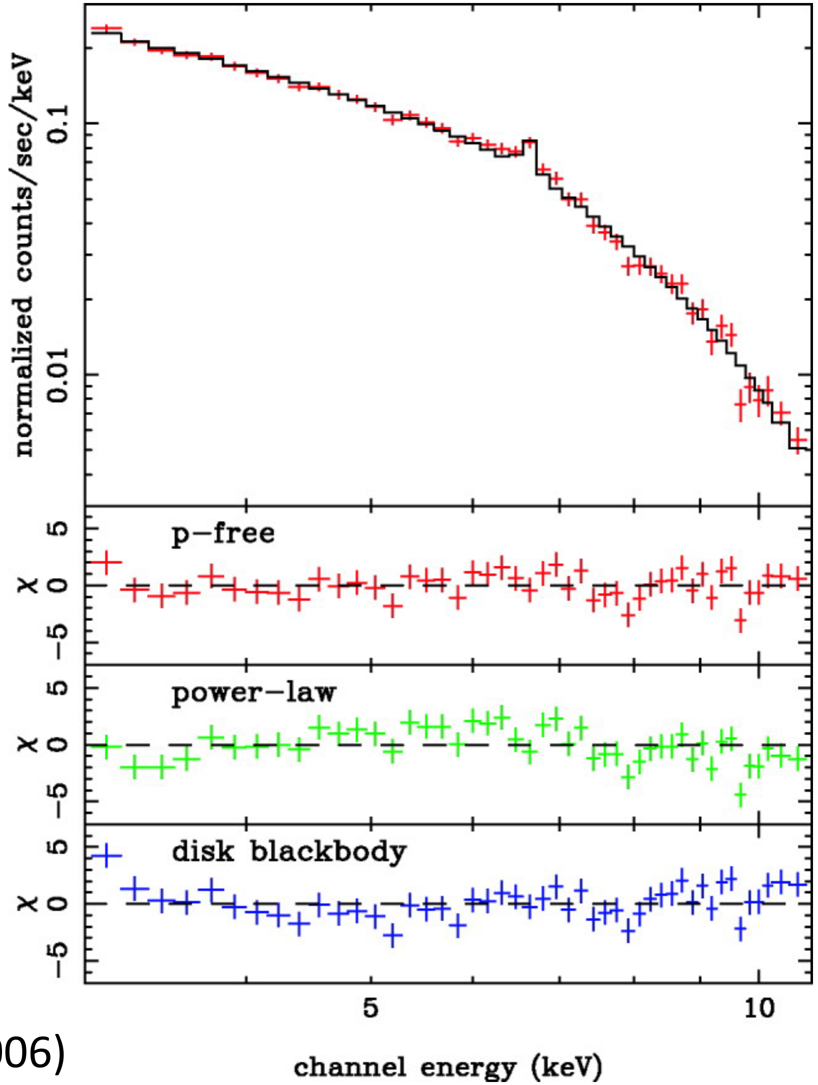
GRS1915+105



Yamaoka, Ueda and Inoue 2001

ULXは(少なくとも一部は)Slim diskで説明できる

M82 X-1



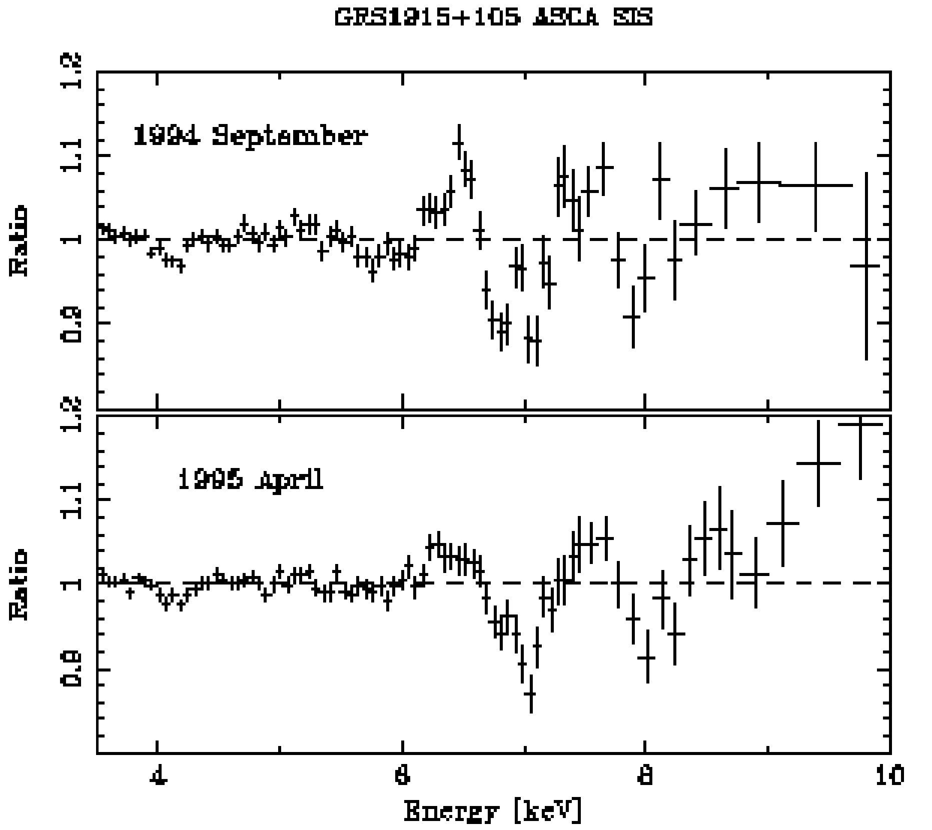
Slim disk モデルを
適用すると
BH質量は19-32 $M_\odot$

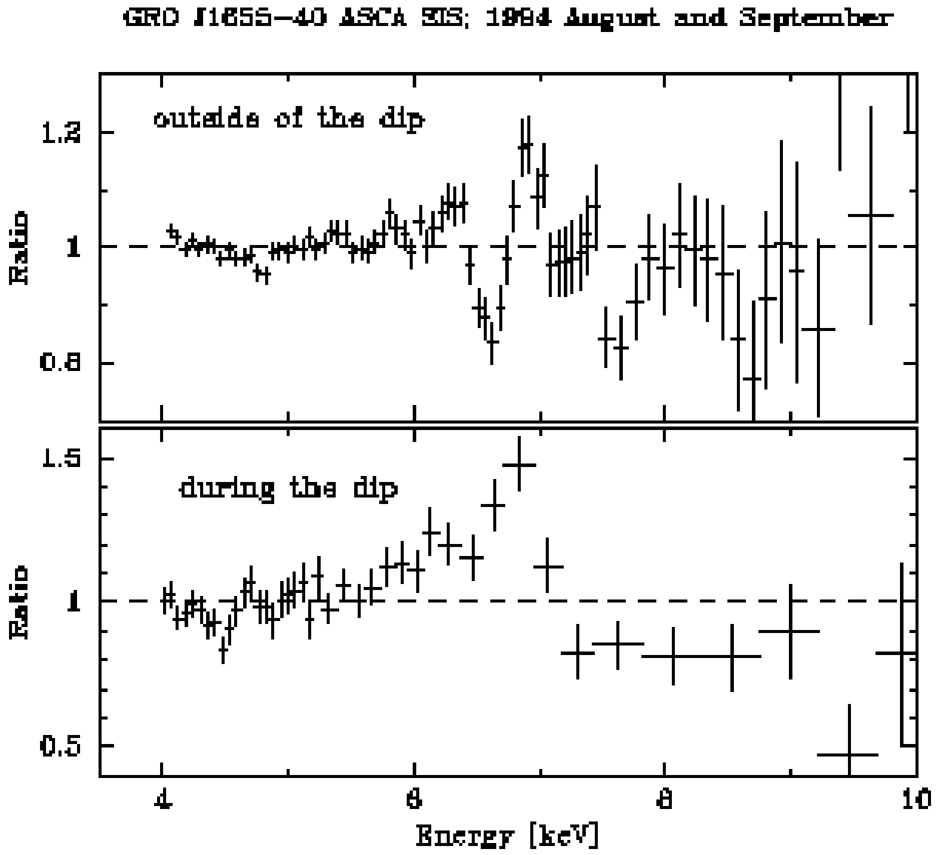
スペクトルの
curvatureはSlim diskに合う

Okajima, Ebisawa and Kawaguchi (2006)

わかってきたこと4：視線上の吸収物質

First Fe-K absorption line features in GBH GRS1915+105 and GRO J1655-40





「あすか」のCCDで初めてX線吸収線が観測された

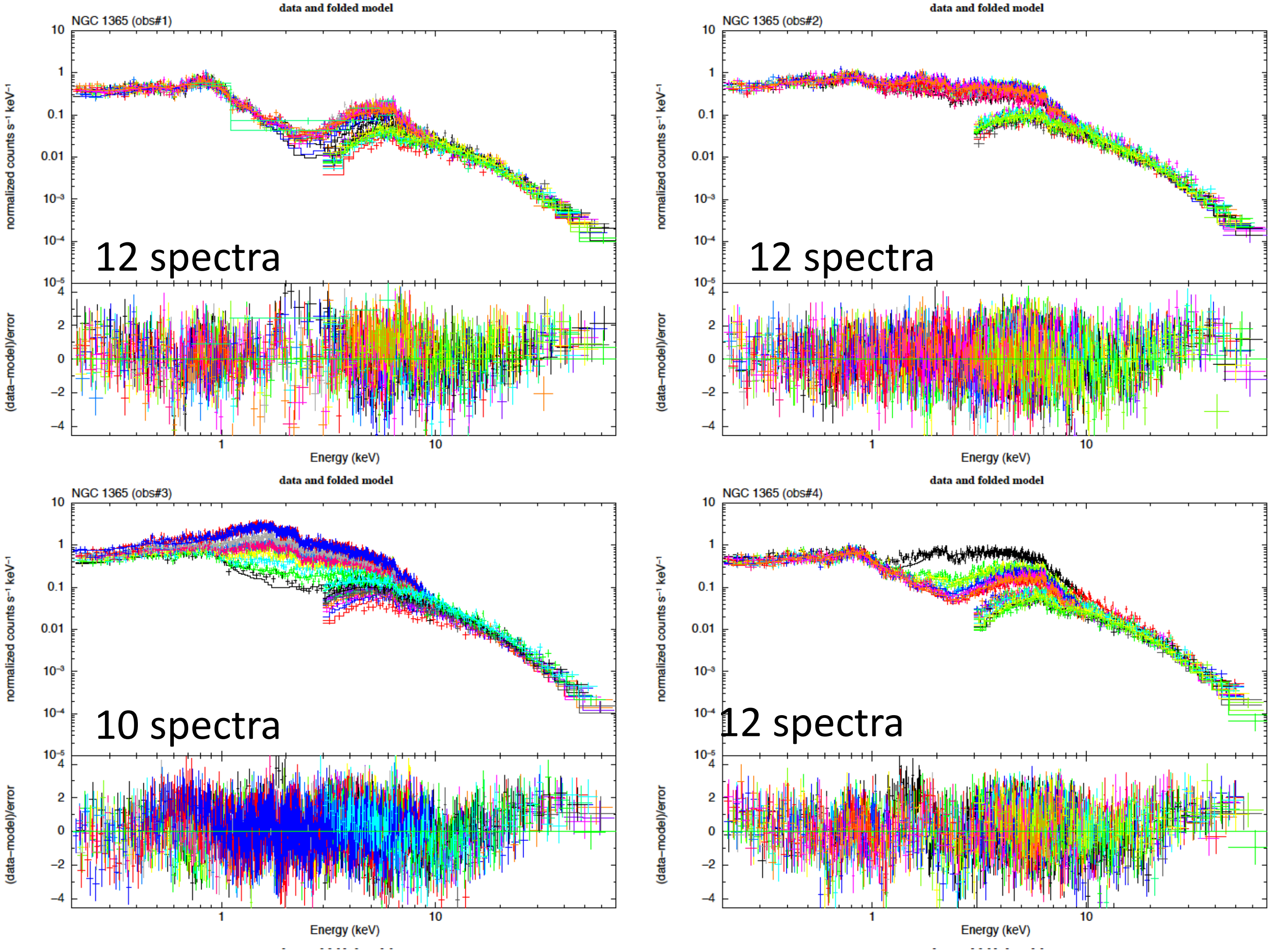
Ebisawa 1997xisc.conf..427E (Conference paper in 1996)

わかってきたこと5：AGNのスペクトル変化の起源

- 広帯域X線スペクトル(0.2-78 keV) の主な変化は、power-lawの normalization(N)と視線上を部分的に隠す吸収体の被覆率($0<\alpha<1$)の変化で説明できる
- Power-lawのべき、吸収体の電離度と柱密度の変化は、比較的小さい

Kusunoki Master thesis 2017

Time-slice spectra (NGC1365)



NGC 1365:
For each observation, the time-slice spectra are fitted simultaneously only varying α and N

Kusunoki Master thesis 2017

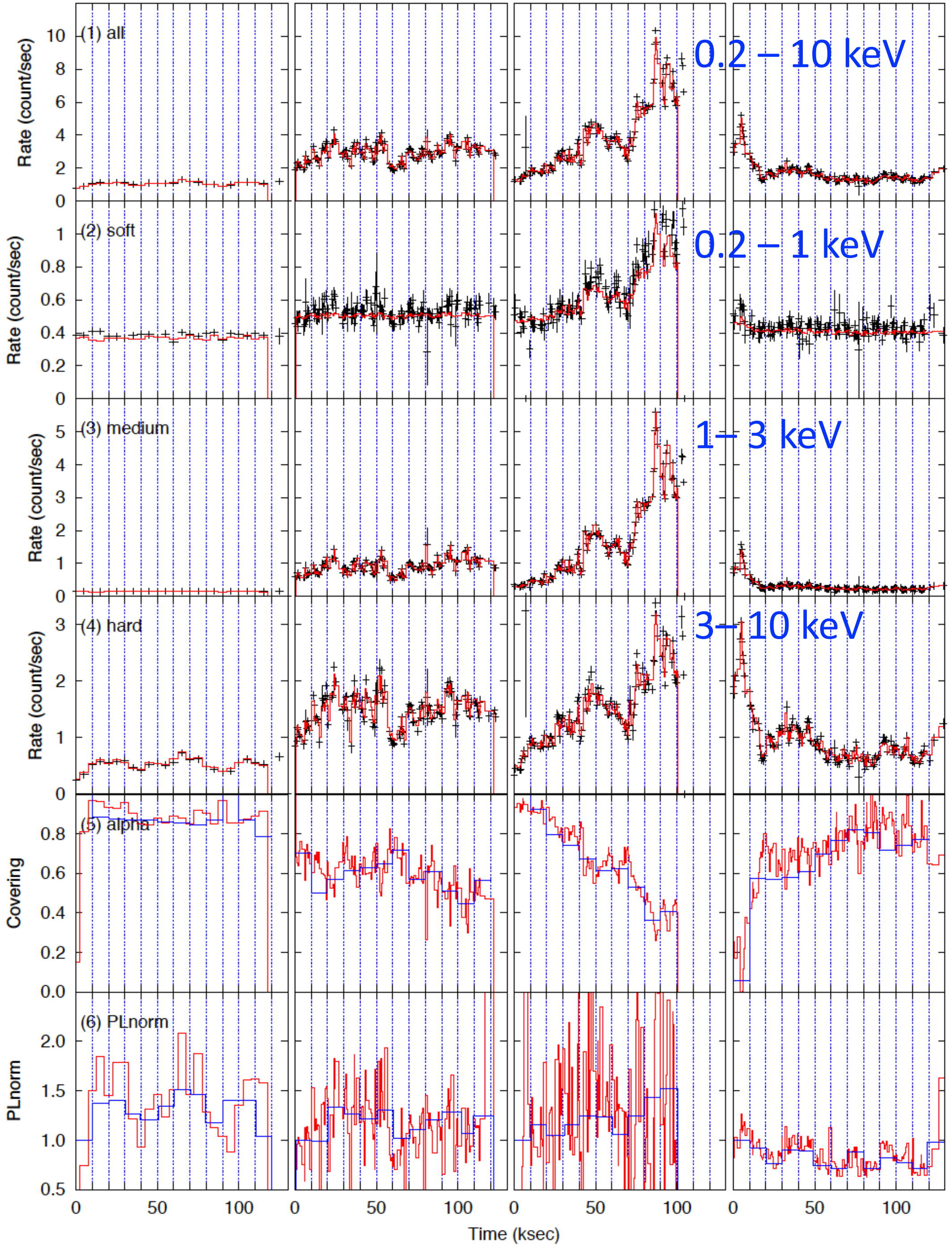
Light curves (NGC1365)

Light curve is made with 1ksec time-bin for different energy bands.

Model light-curve is made, where only α and N are varied to fit the light-curve.

Light-curve within ~day is explained variations of only α and N

Kusunoki Master thesis 2017



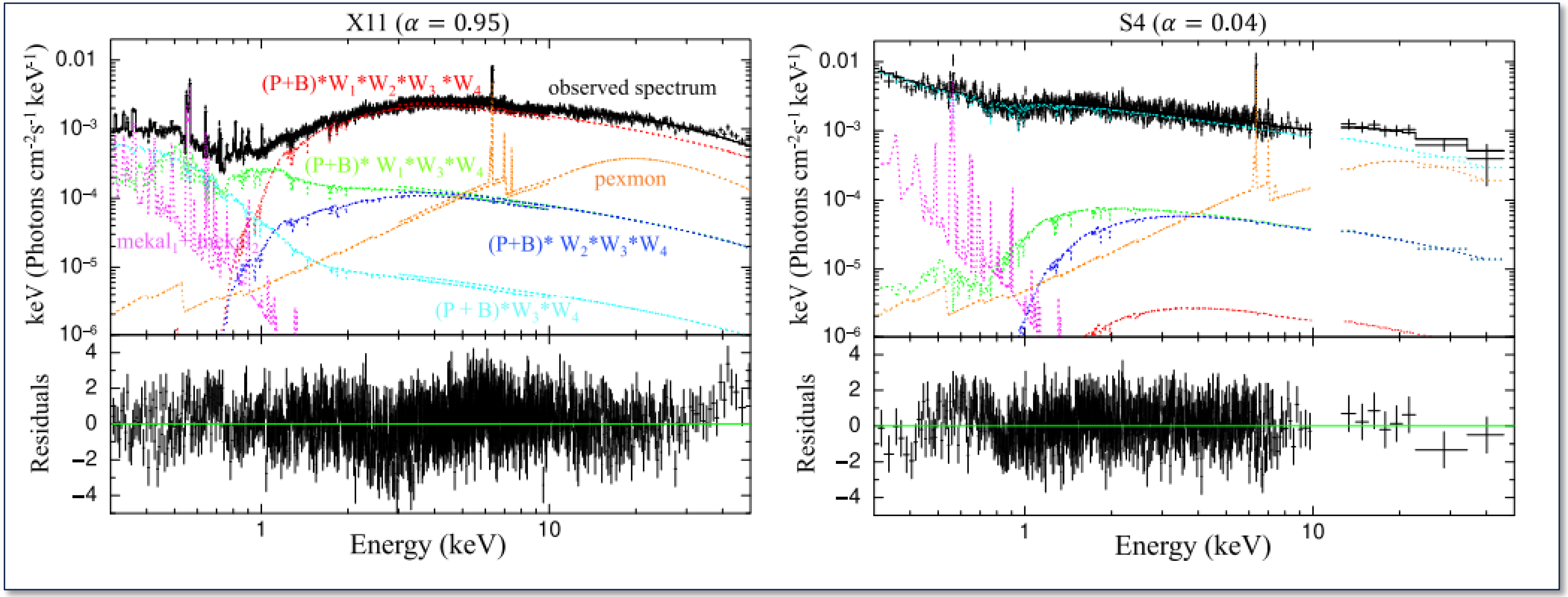
Black: data
Red: model

Partial covering fraction α

Power-law normalization N

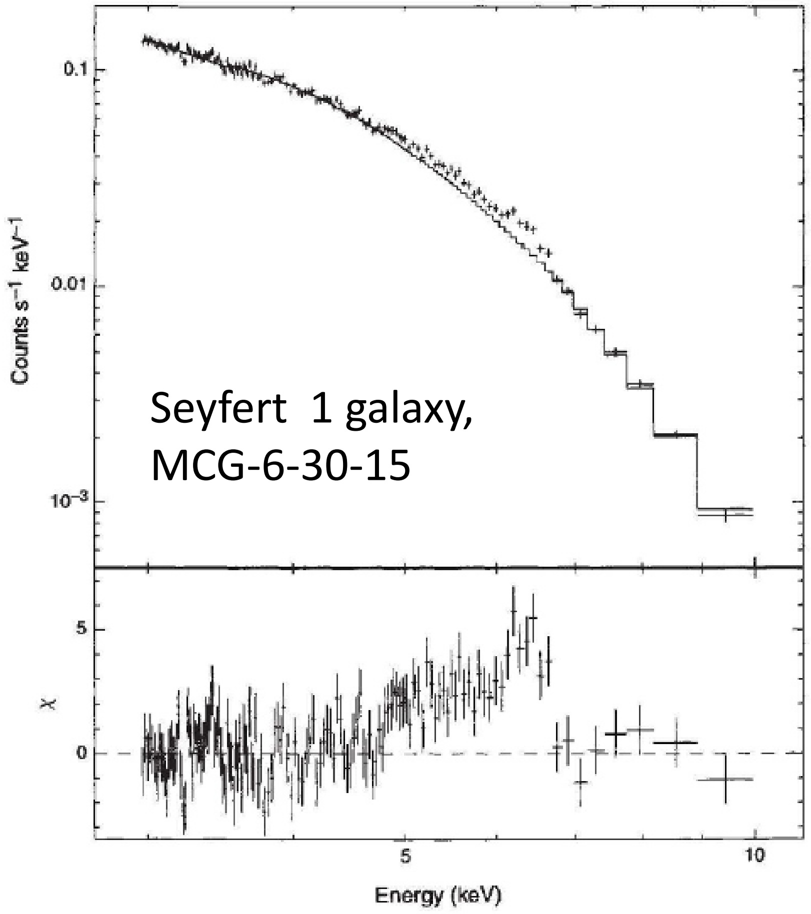
NGC5548

顕著なスペクトル変化をNとαの変化だけで説明できる



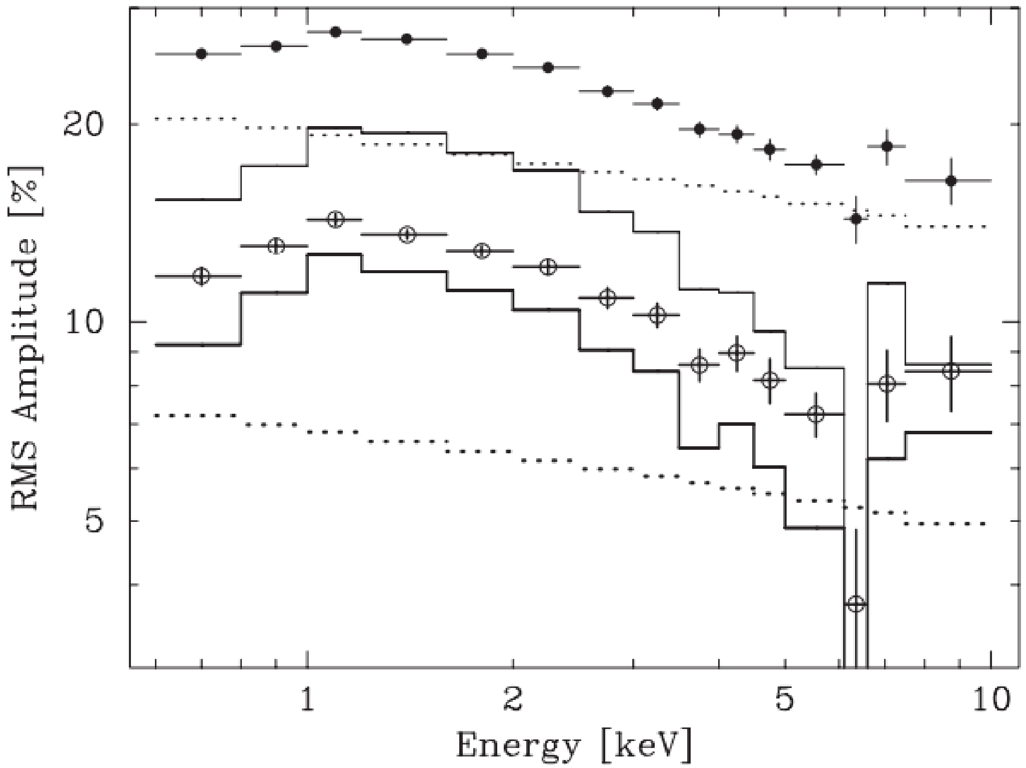
Midooka et al. 2022, MNRAS, 513, 5020

わかってきたこと6："disk line"の起源



Tanaka et al. 1995Natur.375..659T

Relativistic disk line model proposed



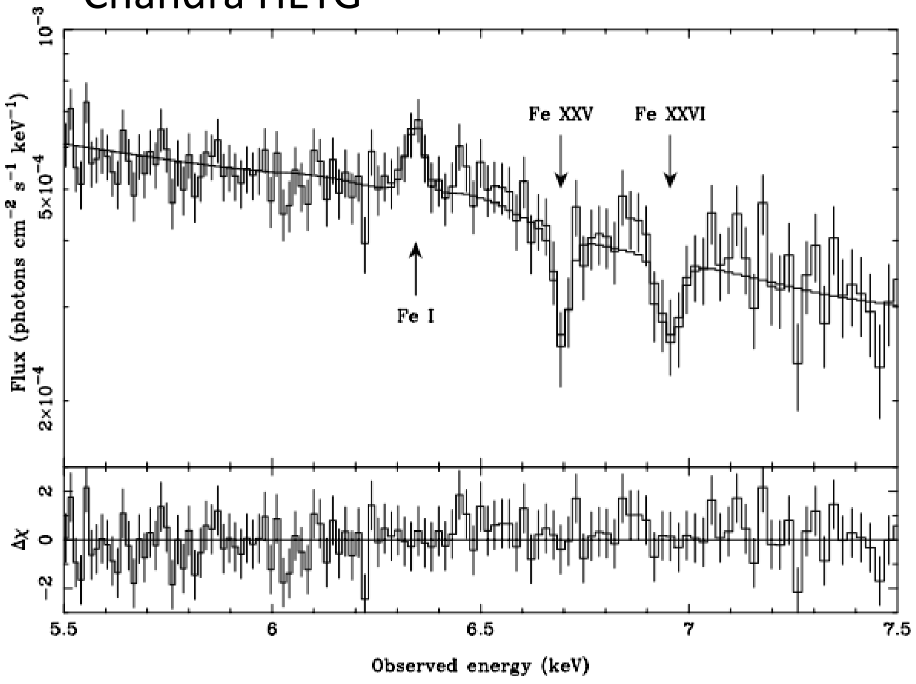
Significant reduction of the variability in the Fe-K band

→ Variation of the absorption in the line-of-sight

Inoue and Matsumoto 2003PASJ...55..625I

MCG-6-30-15 by Chandra and Suzaku

Chandra HETG

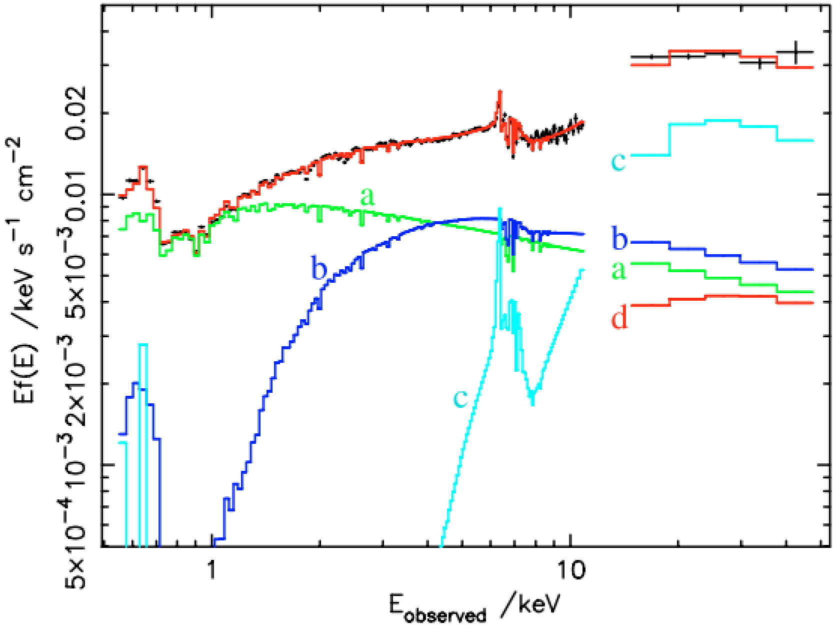


Young et al. 2005, ApJ, 631, 733

視線上に電離吸収体が存在

An absorption origin for the X-ray spectral variability of MCG–6-30-15

L. Miller[1], T. J. Turner[2,3], and J. N. Reeves[4]

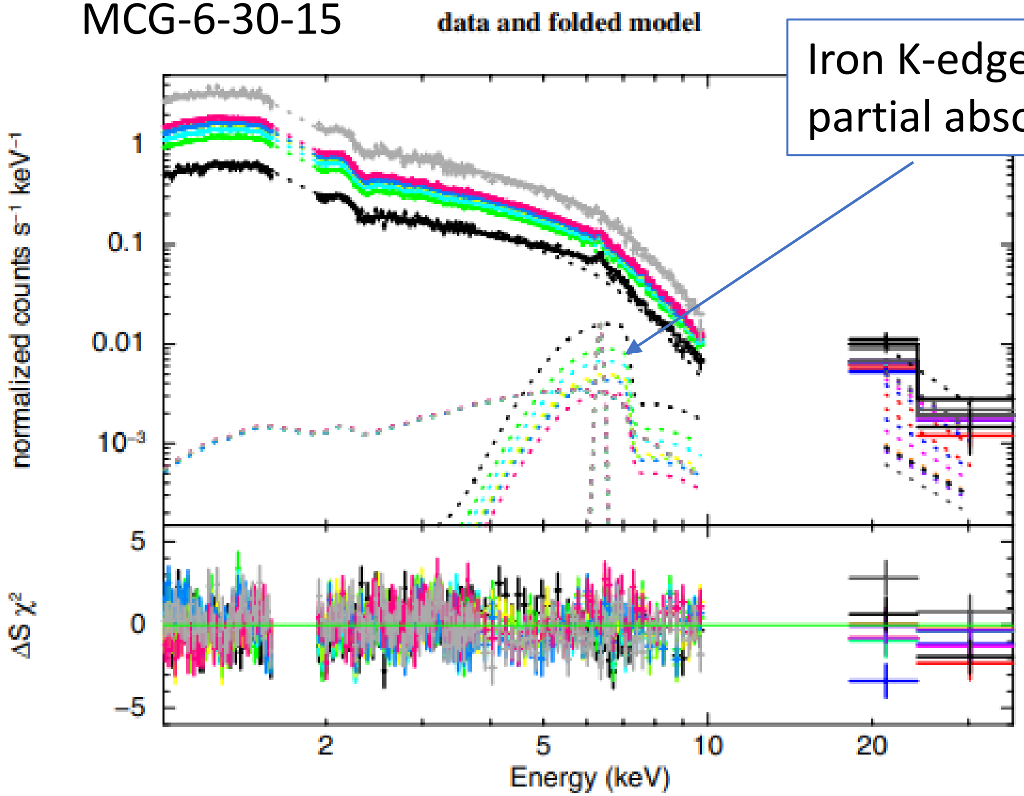


2009MNRAS.399L..69M

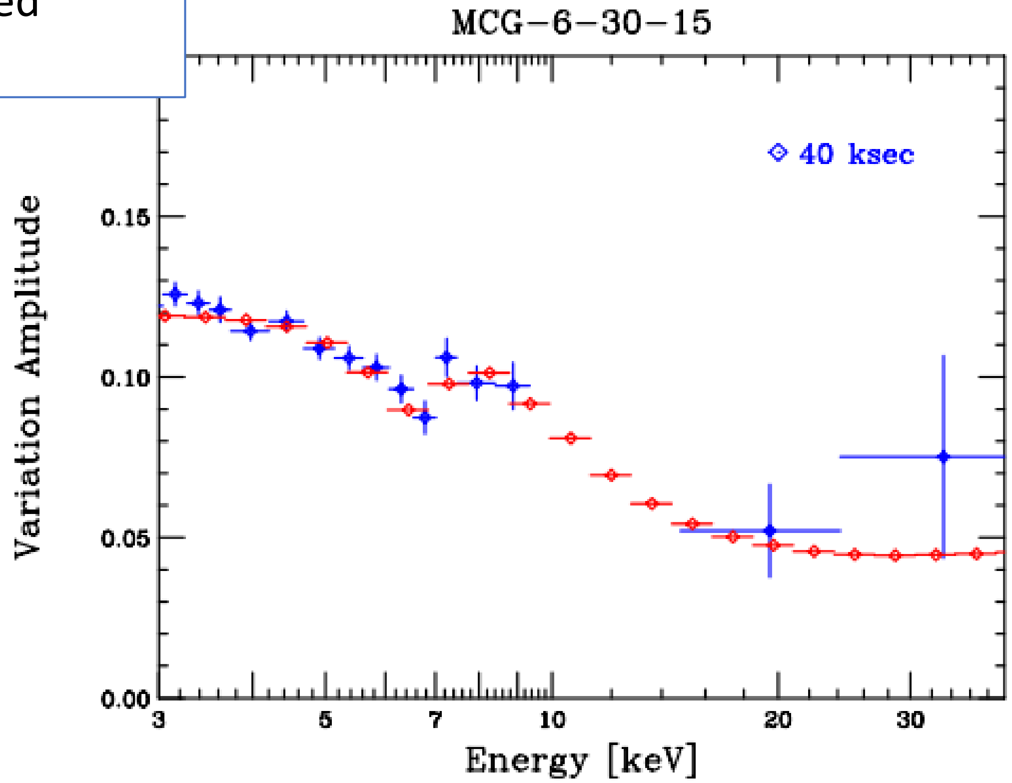
複数の電離部分吸収体でスペクトルを説明

Variation of the partial covering fraction explains most of the observed spectral variations

MCG-6-30-15



Iron K-edge of ionized partial absorber



Miyakawa, Ebisawa and Inoue 2012, PASJ, 64, 140

Spectral variation < 10 keV due to variation of outer cold clumps

- **Variation of the *partial covering fraction* explain most of the spectral variations below ~10 keV in Suzaku.**

MCG-6-30-15 (Miyakawa, Ebisawa and Inoue 2012)

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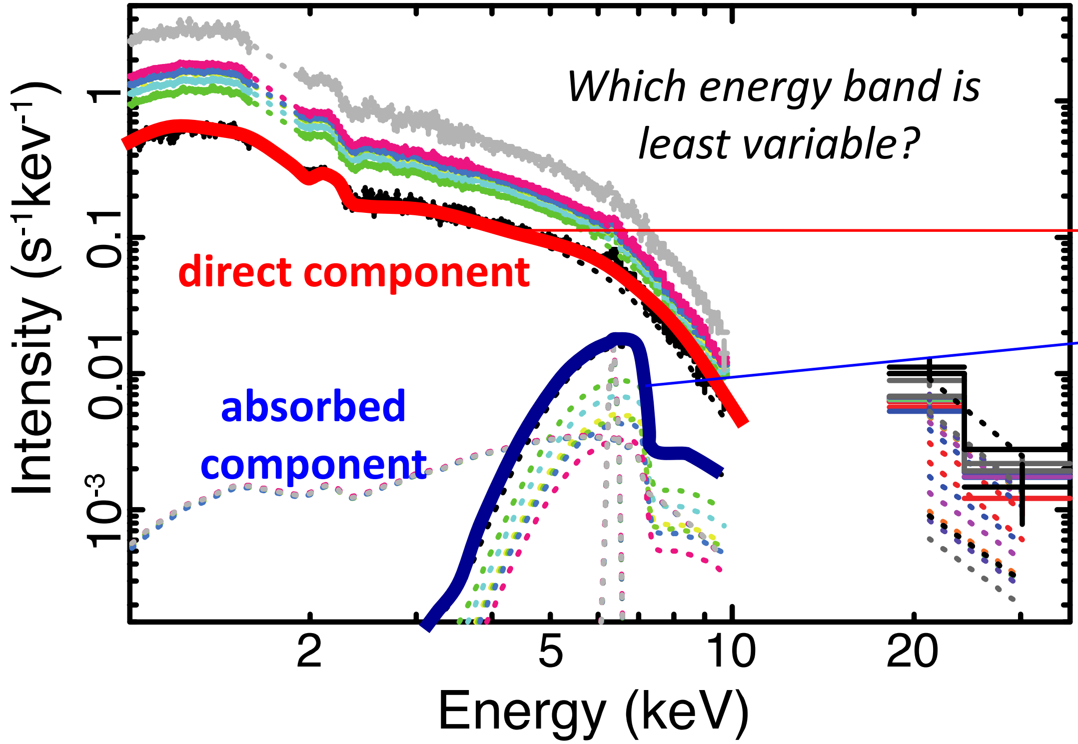

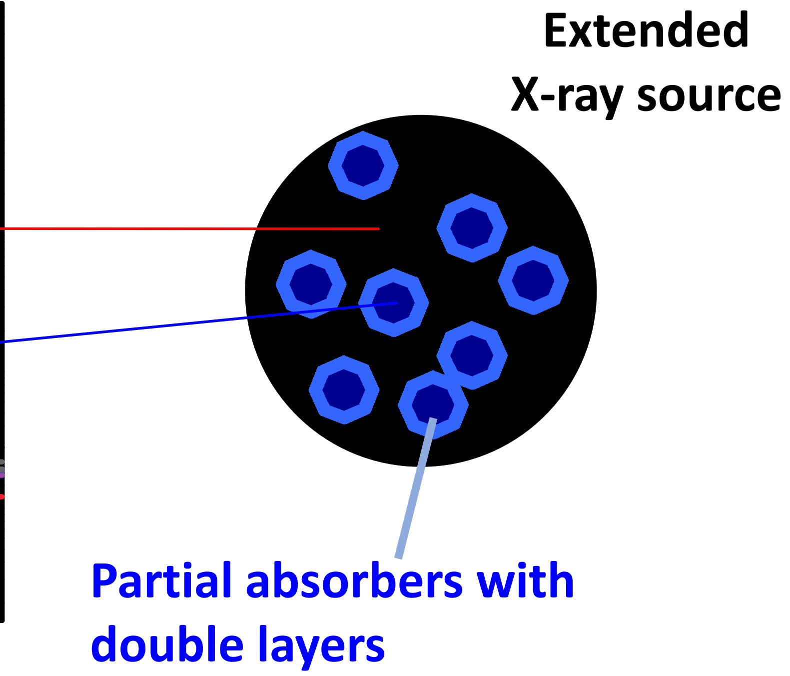

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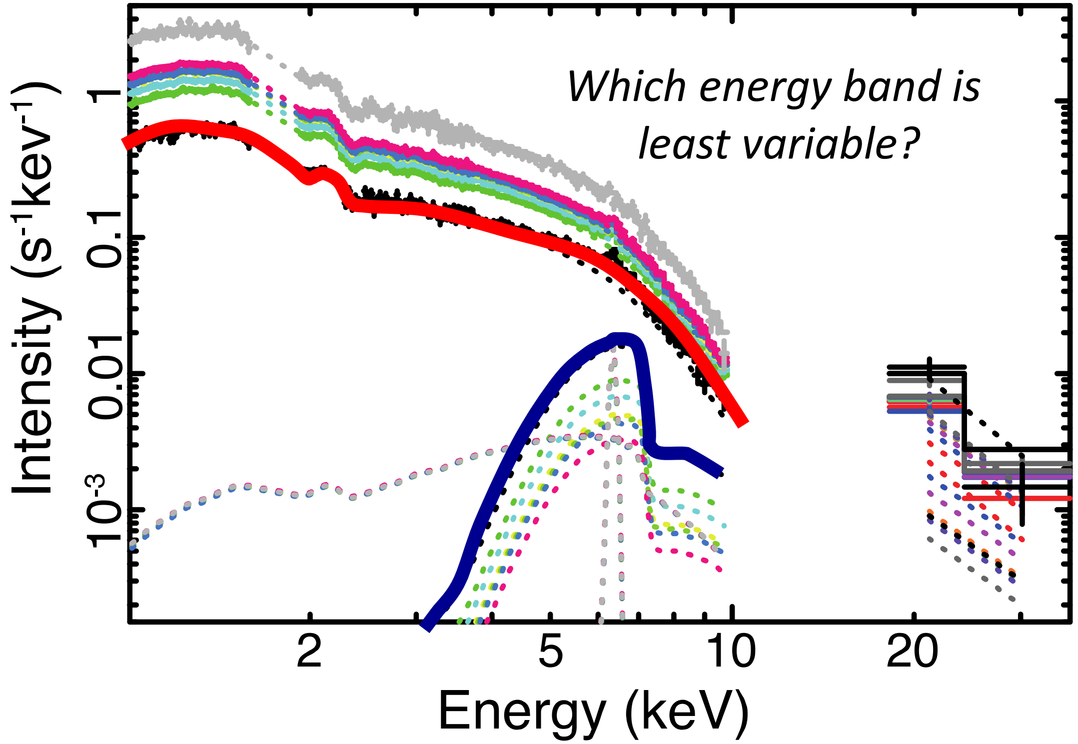

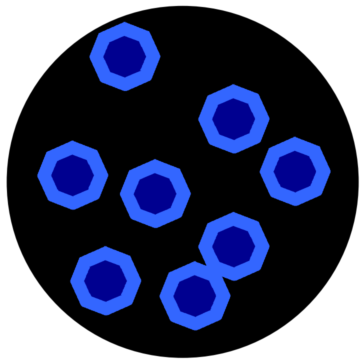

Covering fraction varies

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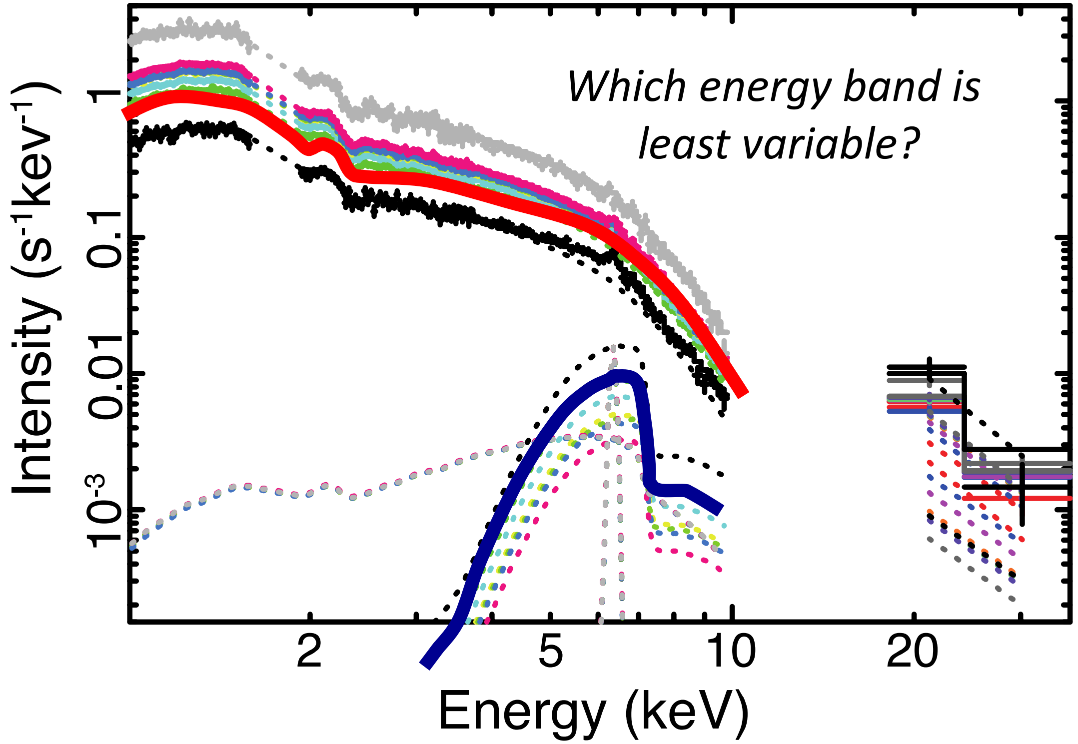
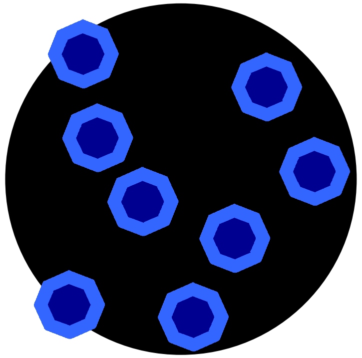
MCG-6-30-15 (Miyakawa, Ebisawa and Inoue 2012)





Covering fraction varies

Spectral variation < 10 keV due to variation of outer cold clumps

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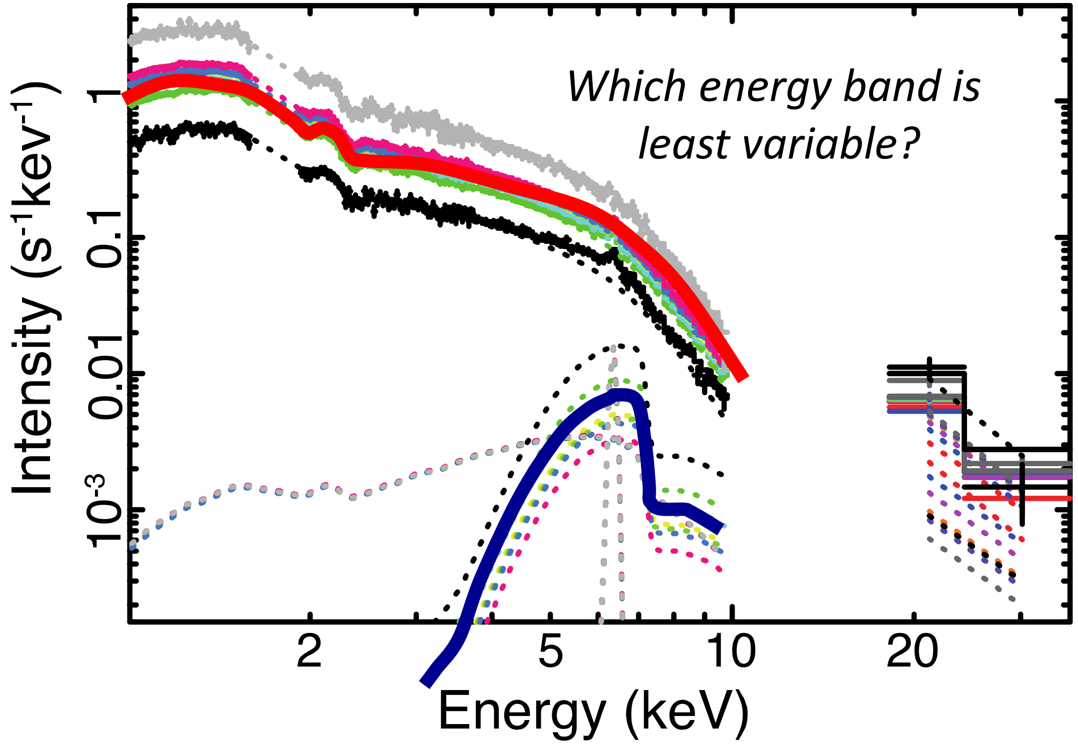

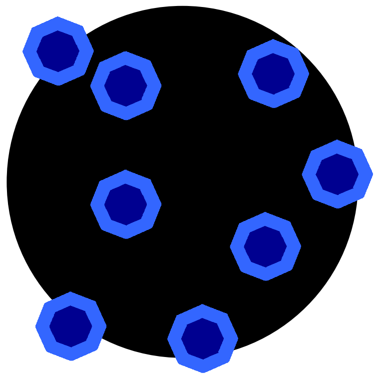

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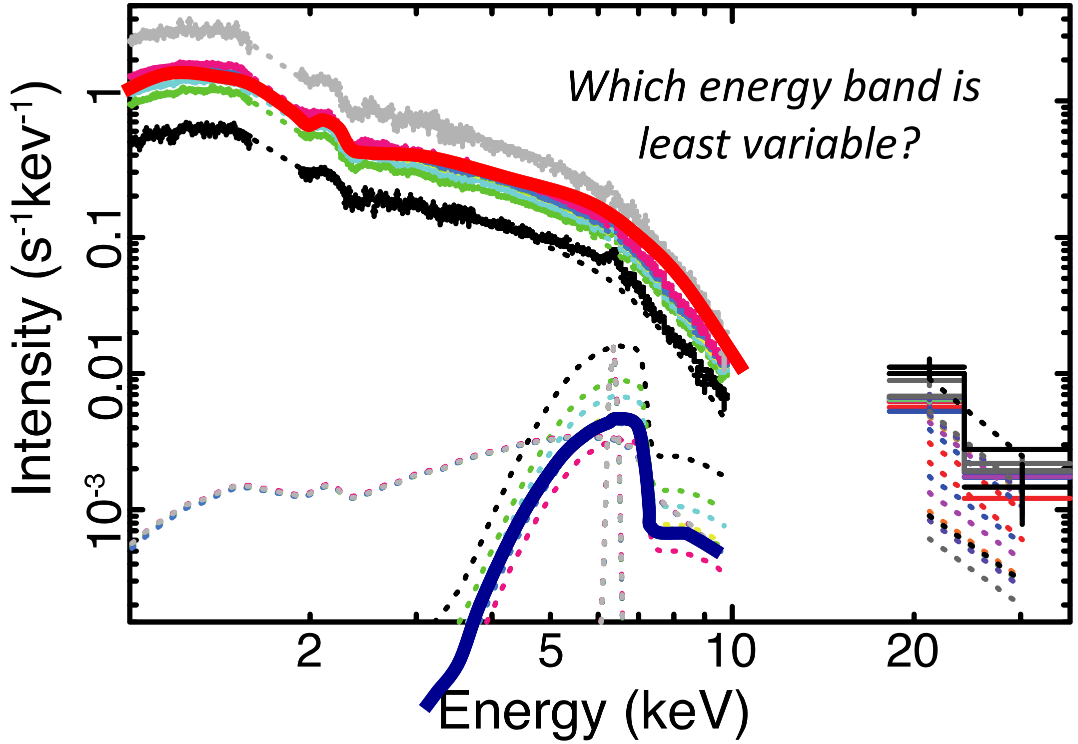

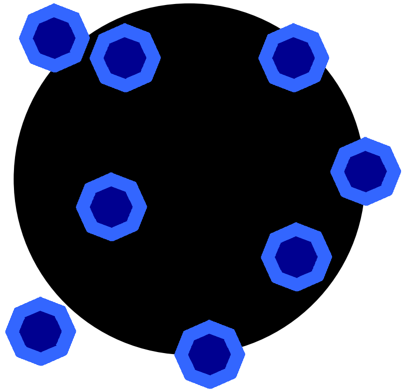

Covering fraction varies

Spectral variation < 10 keV due to variation of outer cold clumps

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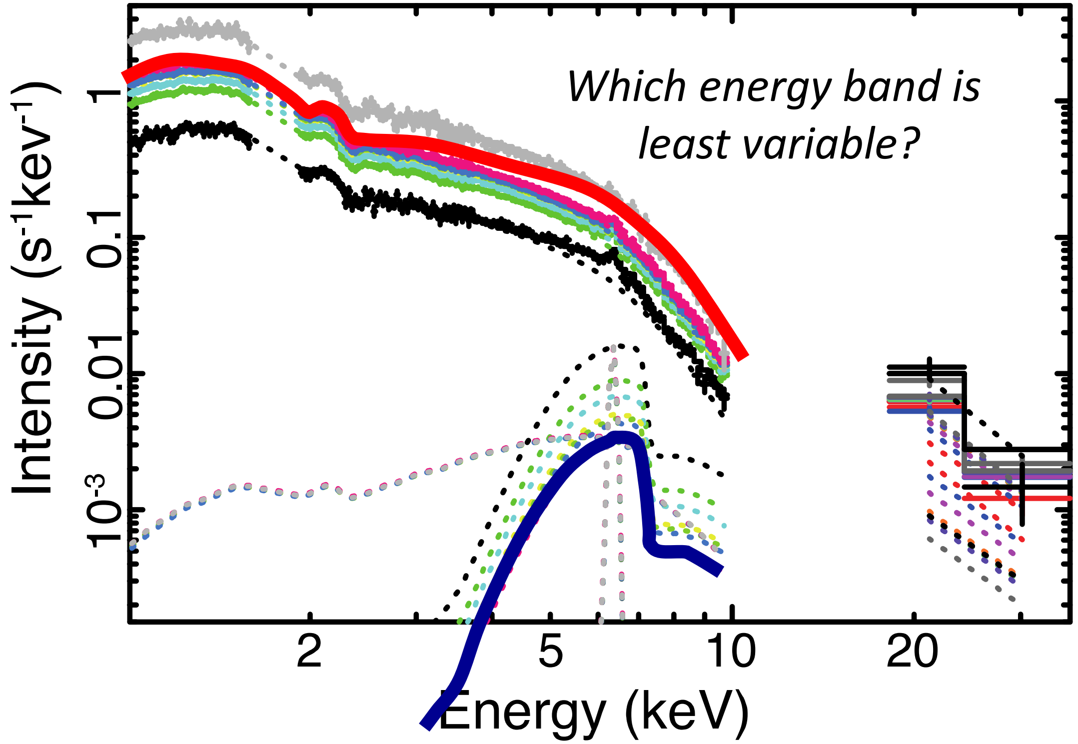
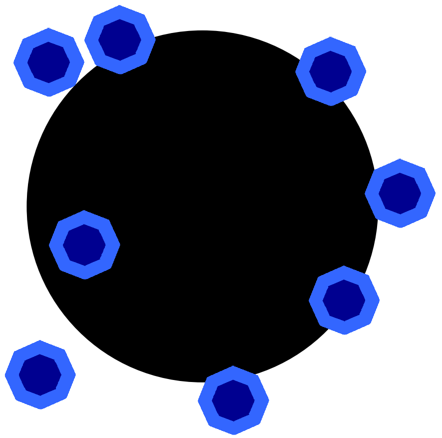
MCG-6-30-15 (Miyakawa, Ebisawa and Inoue 2012)





Covering fraction varies

Spectral variation < 10 keV due to variation of outer cold clumps

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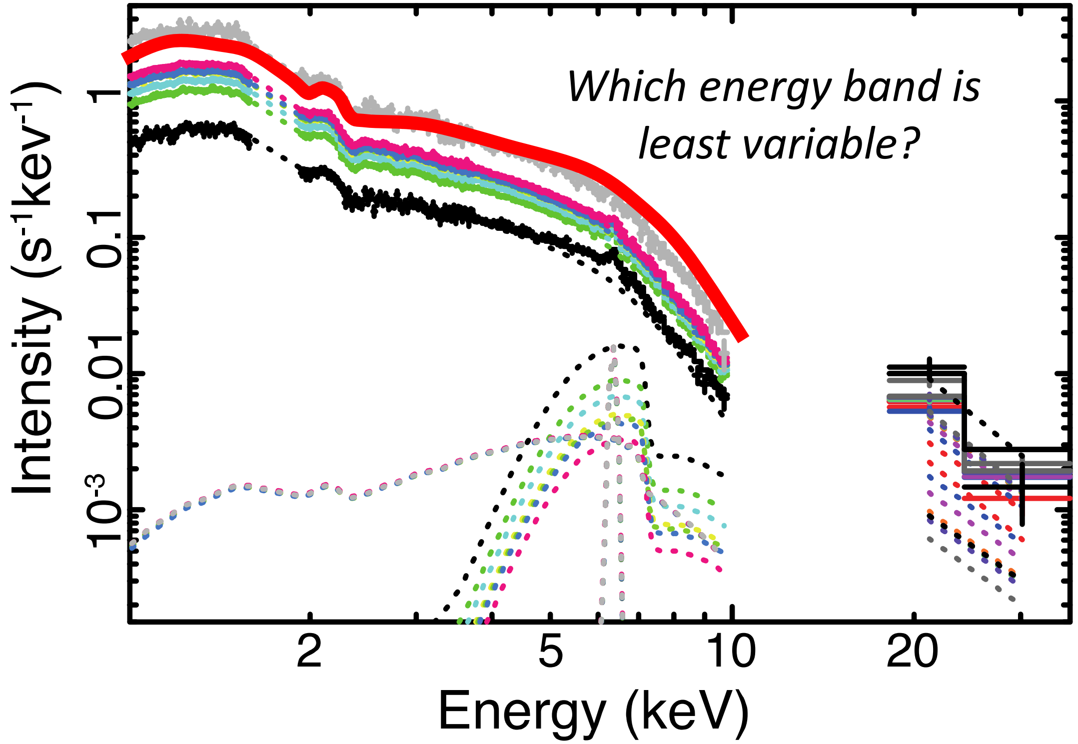
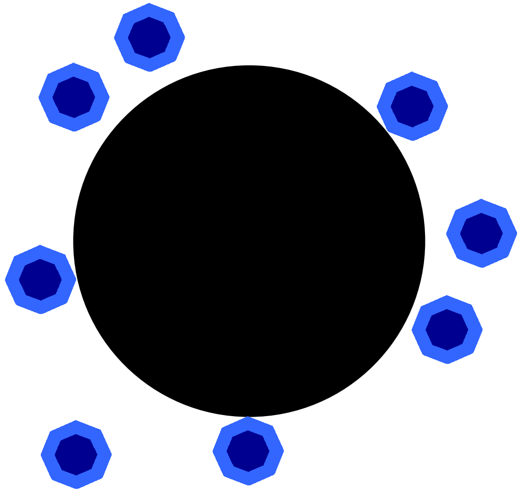
MCG-6-30-15 (Miyakawa, Ebisawa and Inoue 2012)

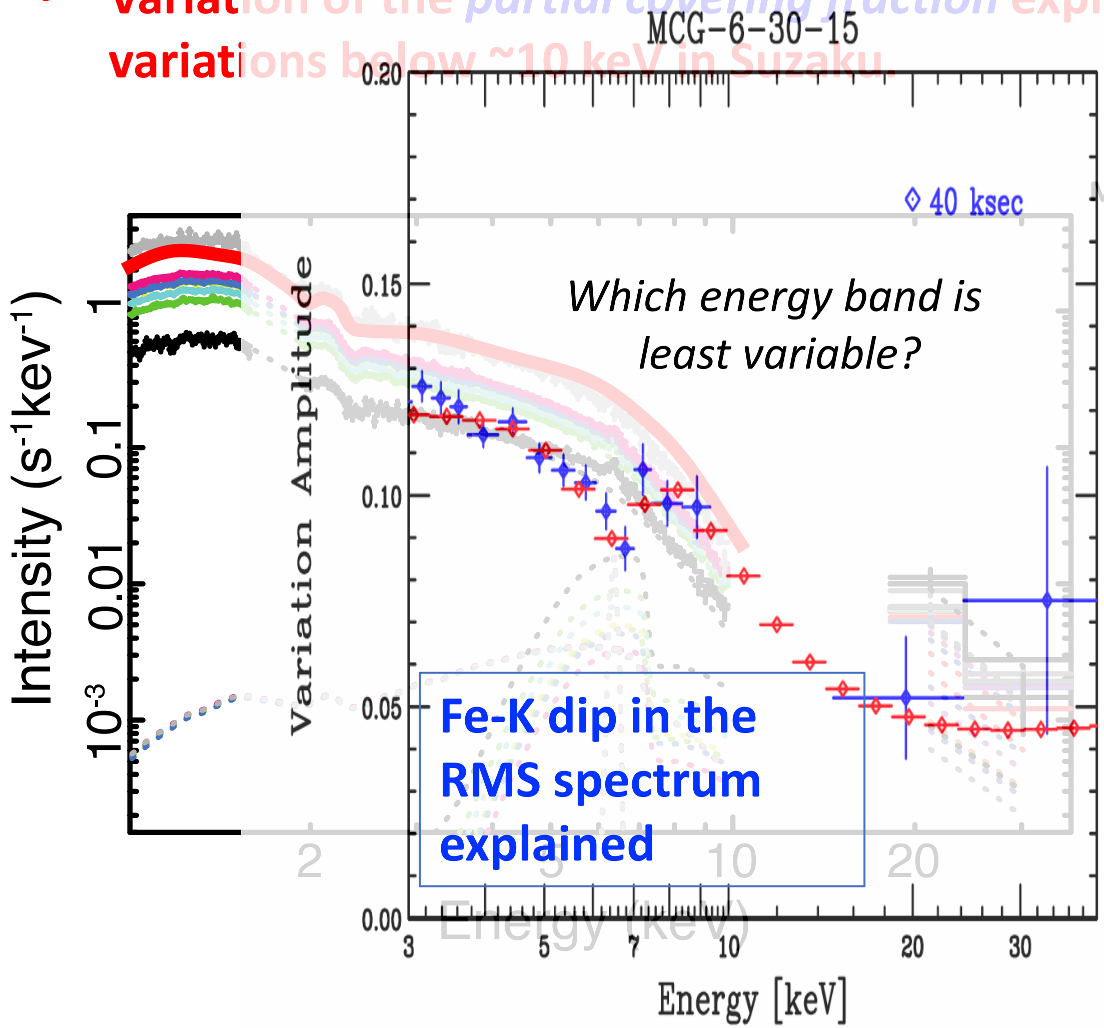




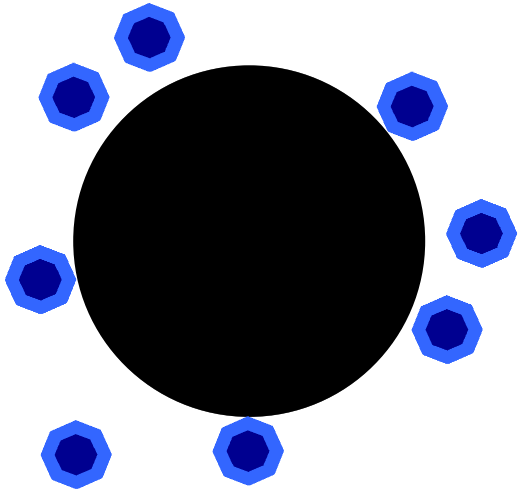
Covering fraction: Null

Spectral variation < 10 keV due to variation of outer cold clumps

- **Variation of the *partial covering fraction* explain most of the spectral variations below ~10 keV in Suzaku.**

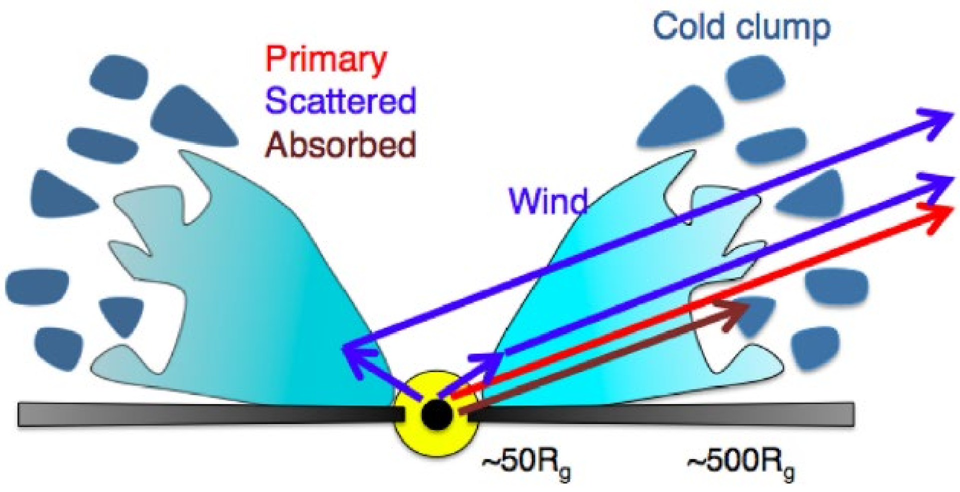


MCG-6-30-15 (Miyakawa, Ebisawa and Inoue 2012)

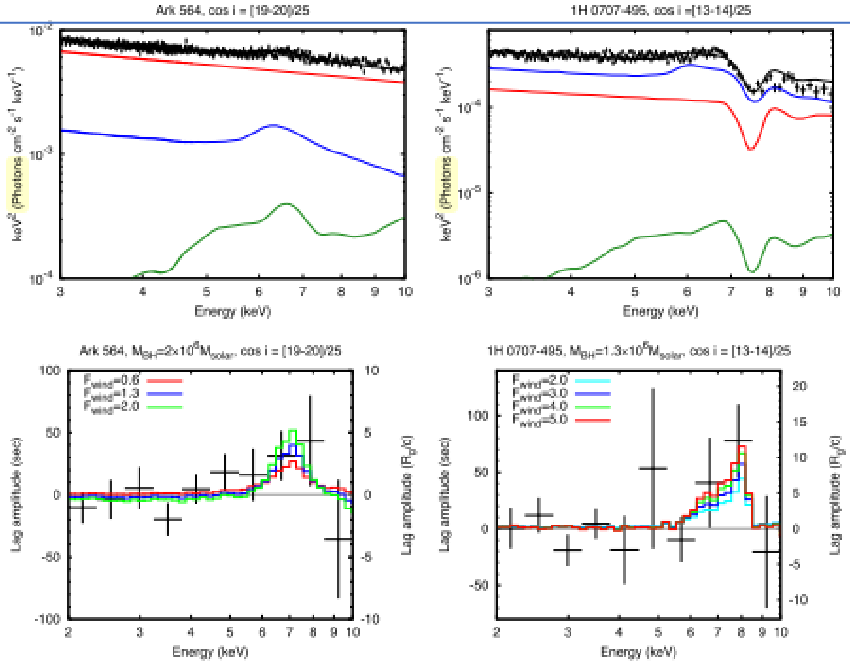


Covering fraction: Null

わかってきたこと7：視線外の物質、 鉄輝線のラグの説明

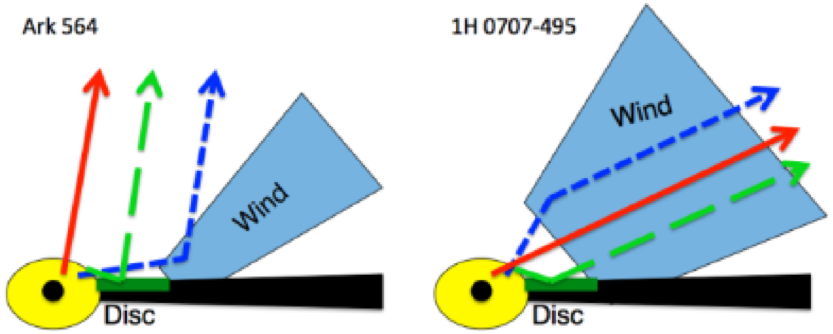


Hot-inner and clumpy-outer wind model



Fe line profiles explained

Fe line reverberation lags explained

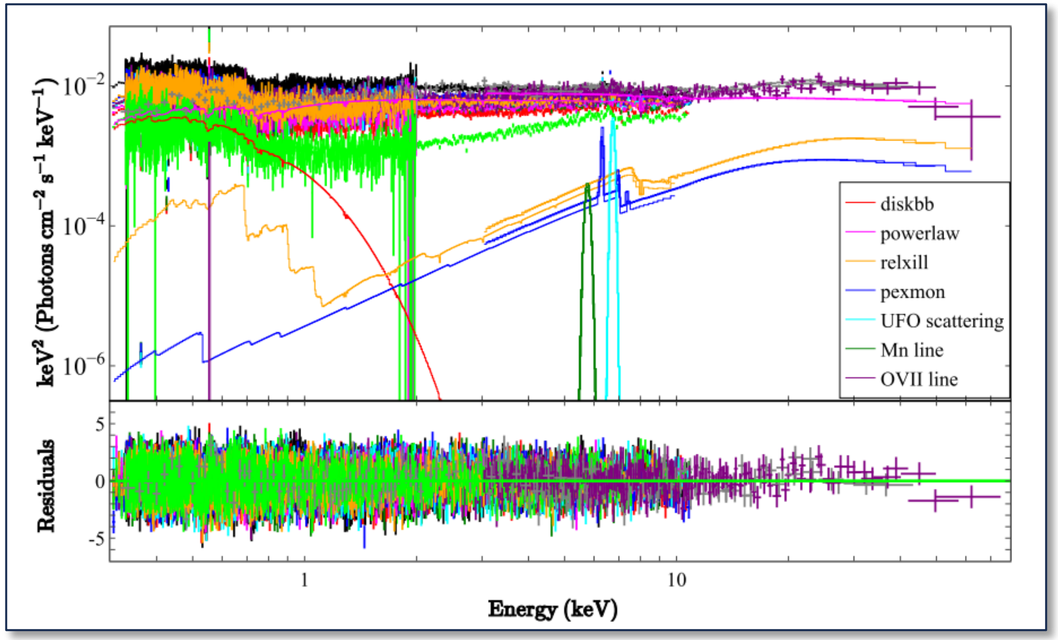


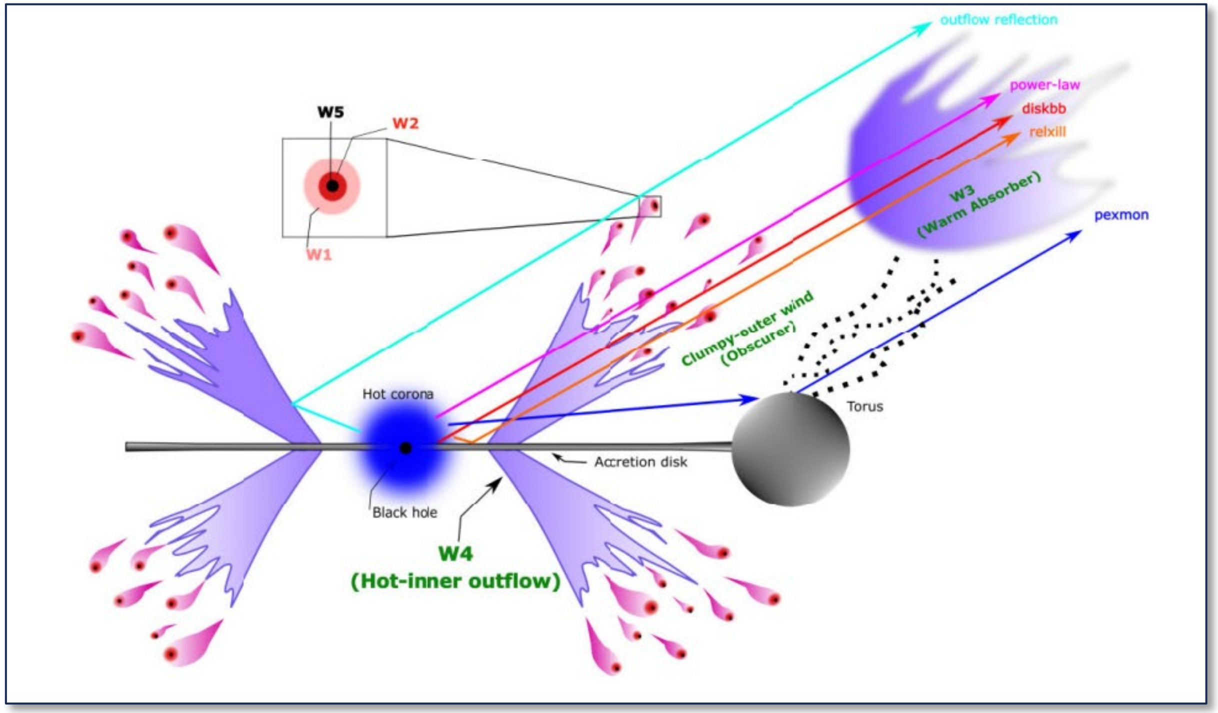
Difference in geometry

Mizumoto et al. 2019, MNRAS, 482, 5316

わかってきたこと8：Outflowの構造

Hot-inner and clumpy-outer wind model works!



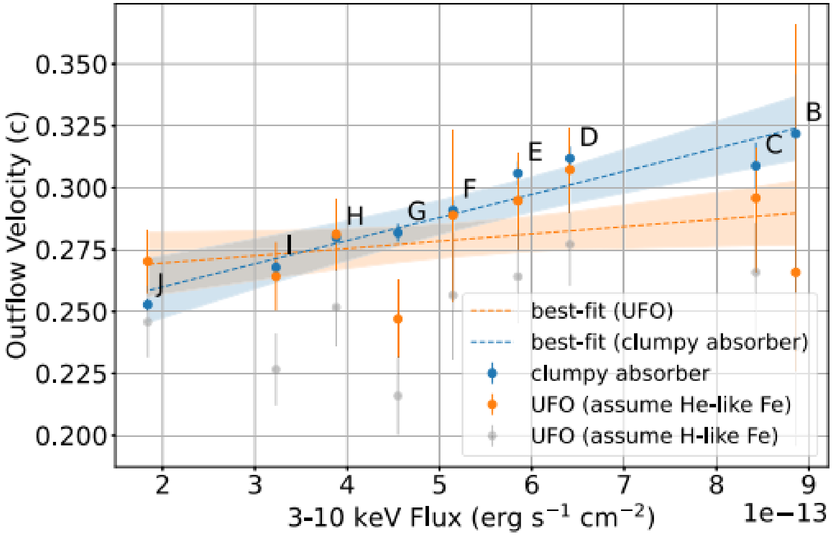


Mrk 766

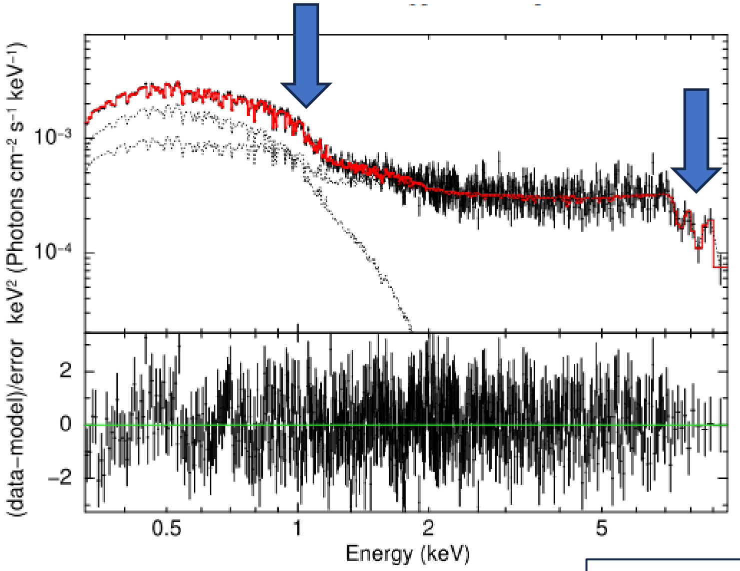
Mochizuki, Mizumoto and Ebisawa 2023, MNRAS, 2023, MNRAS, 525, 922

Discovery of the very fast outflowing clumpy wind

IRAS13224-3809

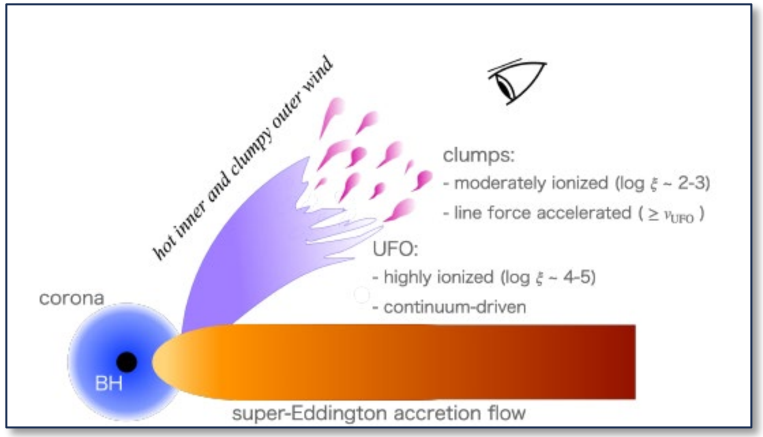


Fe-L edge feature due to the clumpy-outer winds is blue-shifted



UFO (blue-shifted Fe-K absorption lines)

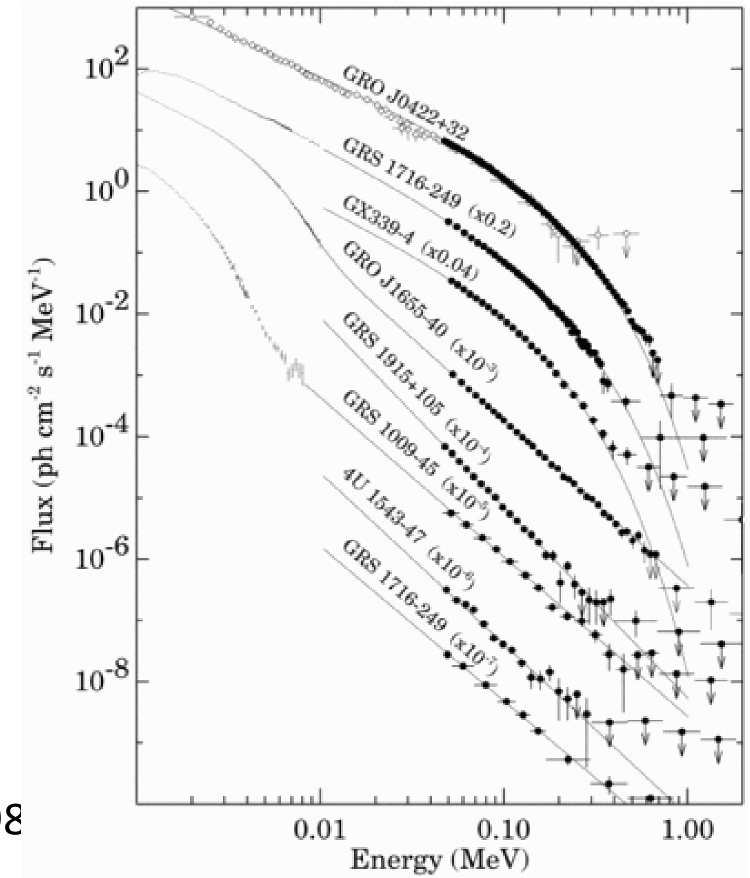
Midooka doctoral thesis, 2023



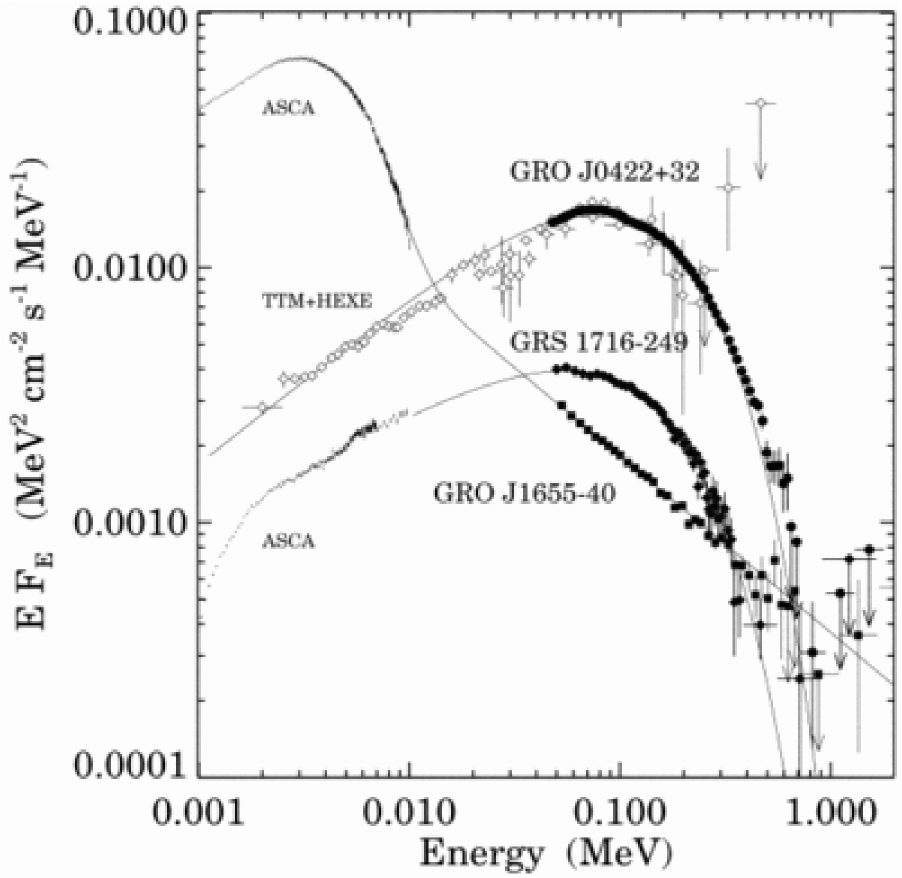
First evidence that the clumpy-outer wind has a similar high velocity as the hot-inner flow (UFO)

Midooka, Mizumoto and Ebisawa 2023, ApJ, 954-47

まだわかっていないこと1：GBHのSoft stateのhard-tailの起源



Grove et al. (1998



Hard state (low state)はThermal Compton, Soft state (high state)のhard tailはnon-thermal

Soft stateでHard-tail(> 5 keV)がsoft componentと独立にパタパタ変動

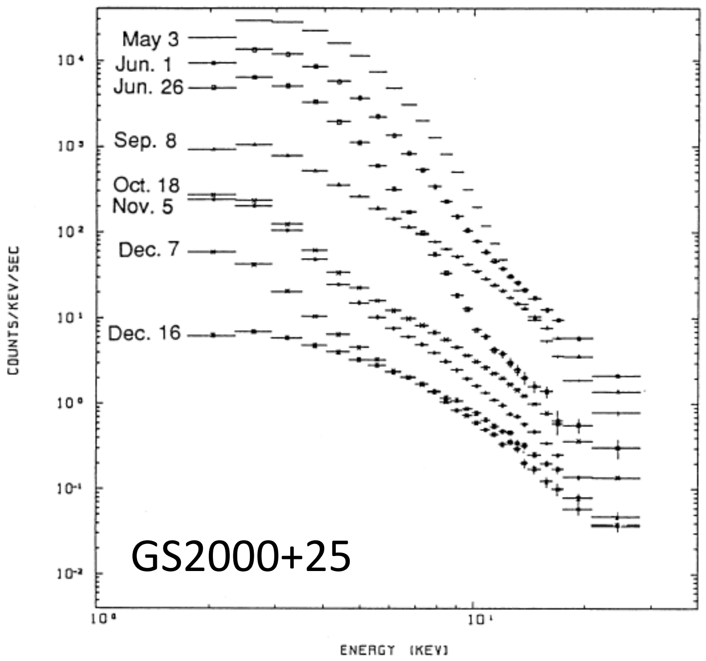


Figure 5.16: Energy spectra of GS2000+25 from May 3 to Dec. 16 in 1988. Note that intensity at lower energies decreases with time continuously whereas that at higher energies does not.

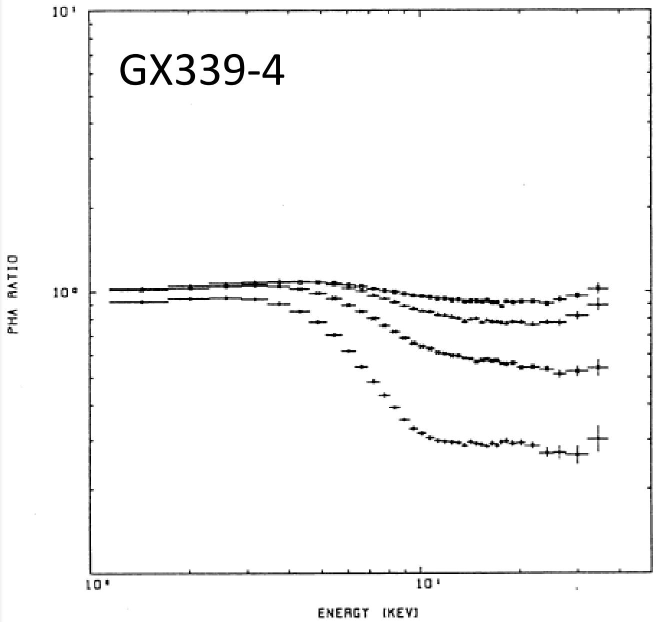


Figure 5.29: PHA ratios of the spectra of branch 2 – 5 in figure 5.28 to the spectrum of branch 1.

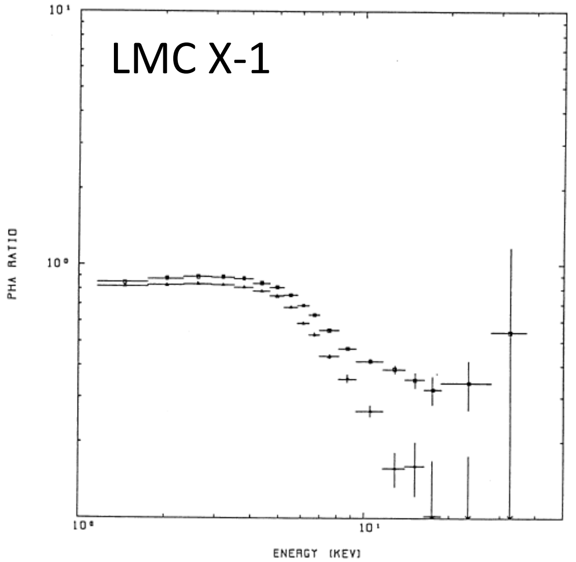


Figure 5.24: PHA ratios of LMC X-1. The ratios of the spectrum in July (crosses with squares) and in September (crosses with triangles) to that in April are shown together.

Ebisawa 博士論文191

まだわかっていないこと2：Spectal branchと QPO

なぜこのような 「一次元」 のbranchができる？

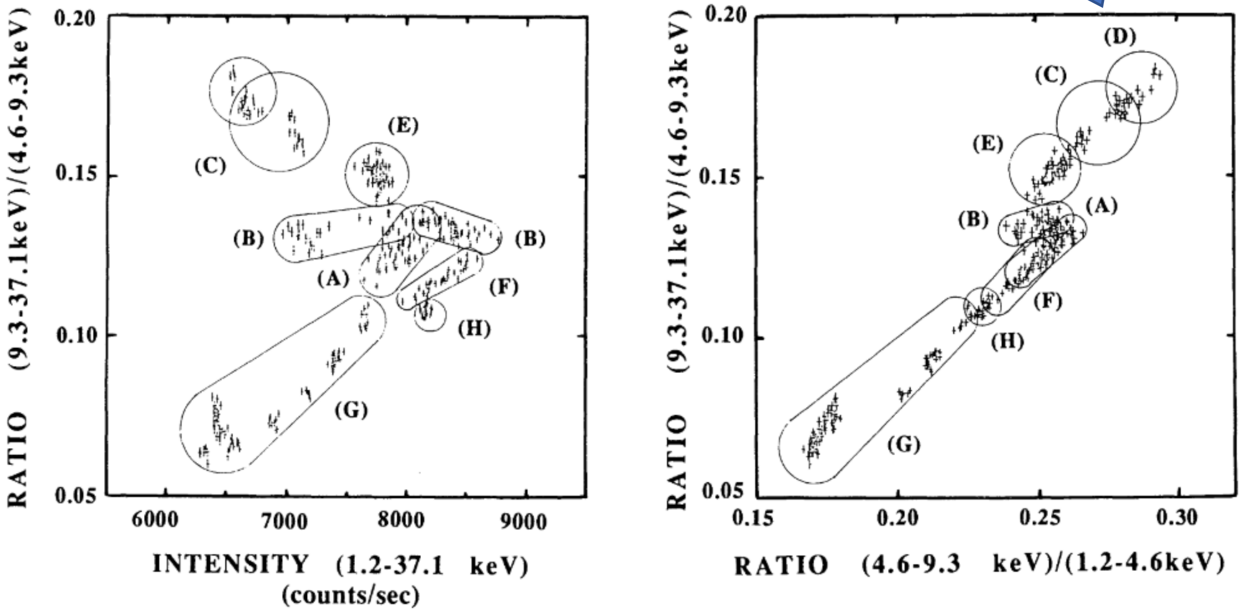
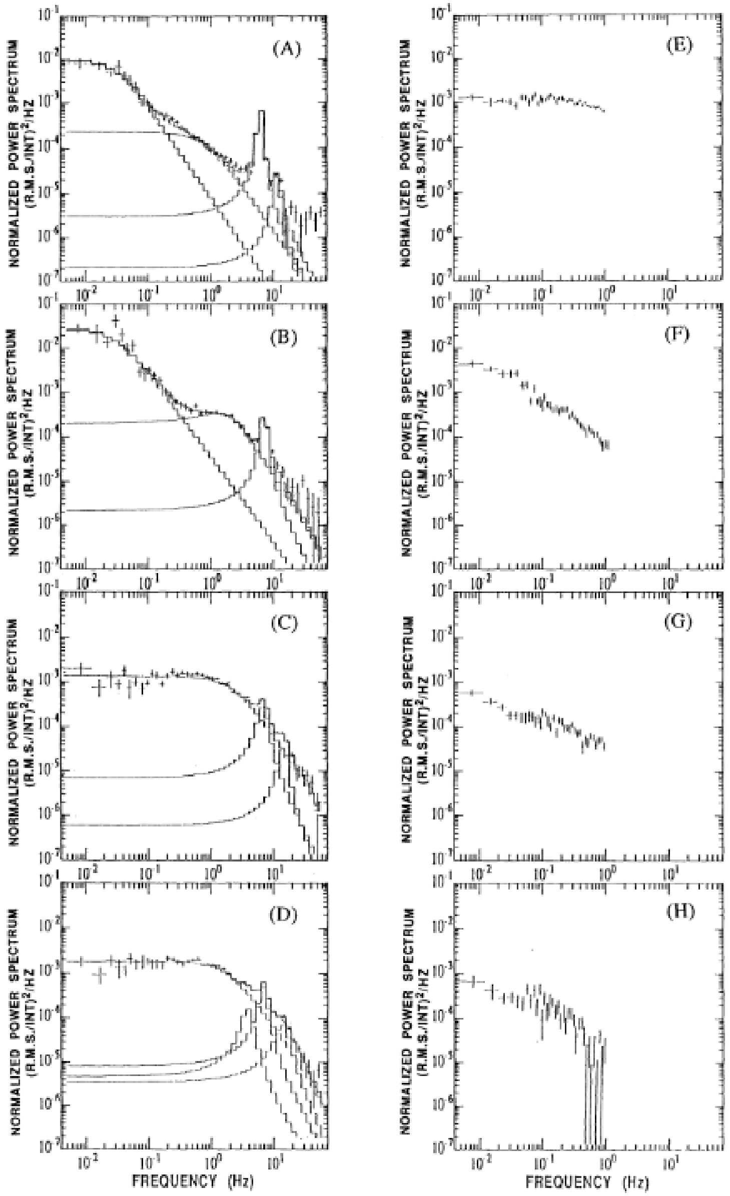


FIG. 5.—A color-intensity and a color-color diagram. The power spectral states are also shown.

Miyamoto et al. (1991), Ginga , GX339-4 very high state



なぜbranch上の場所によって、QPOの様子が異なる？

こんなのもある。Branch上でジャンプする

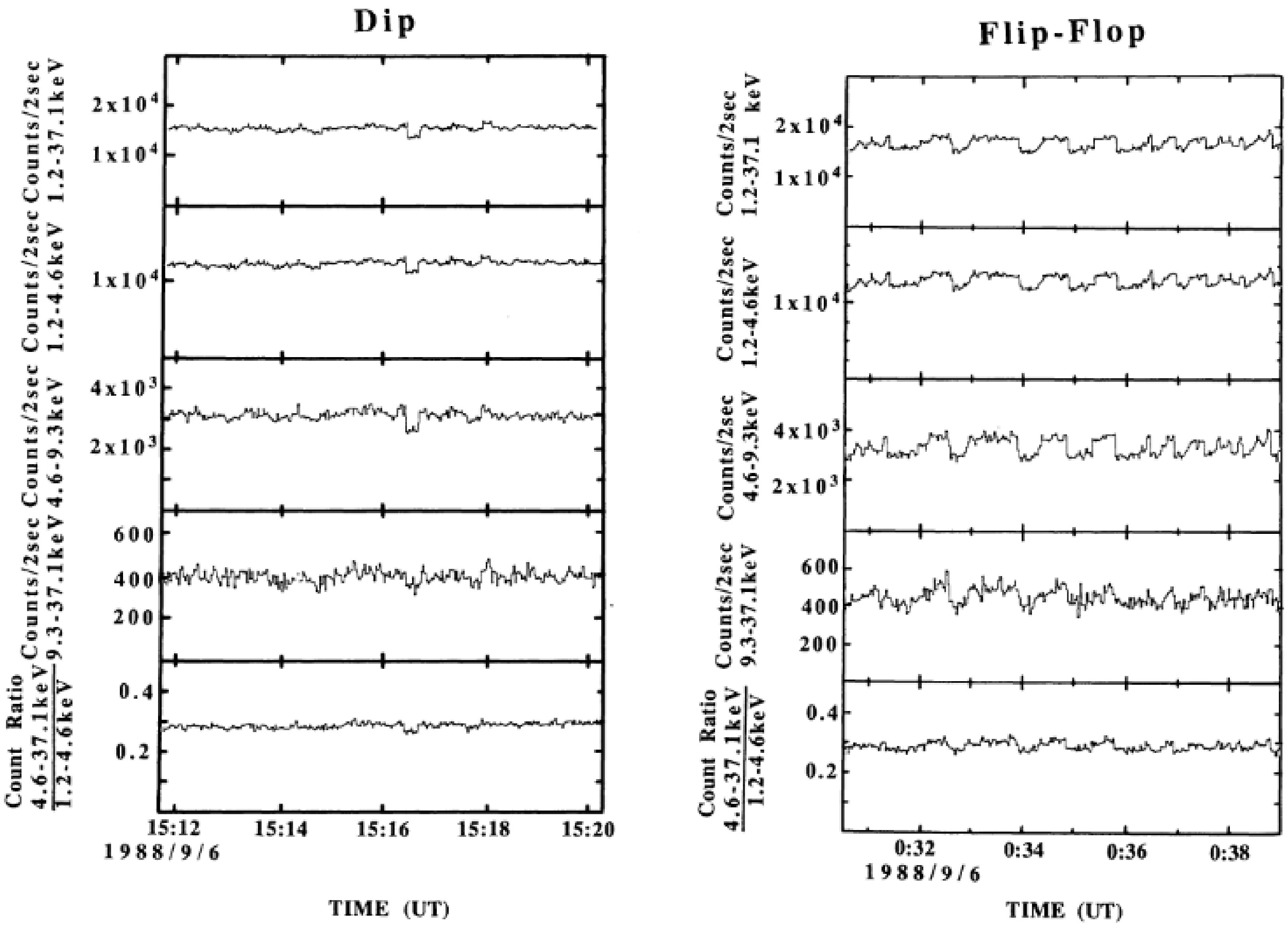
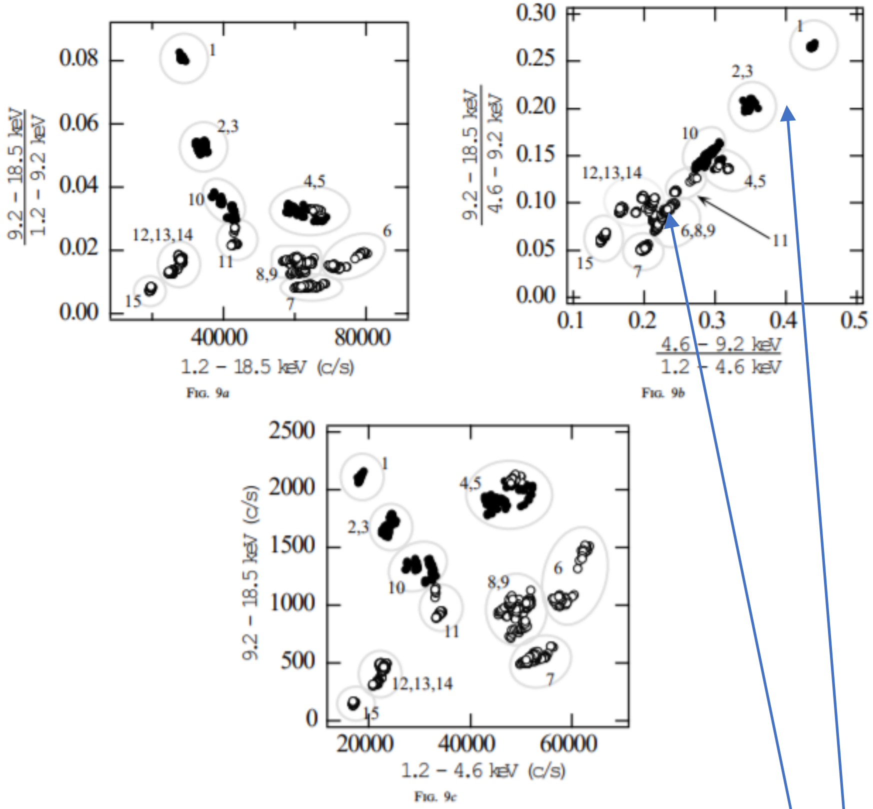
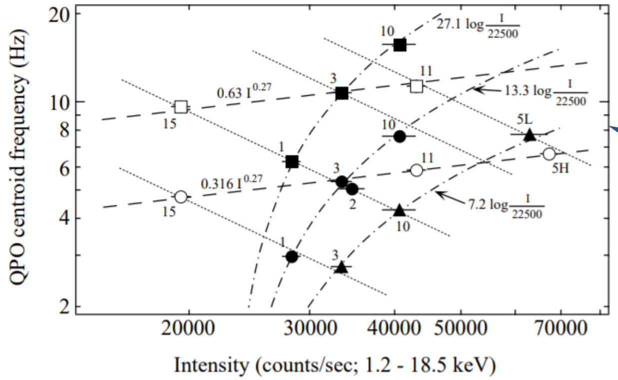
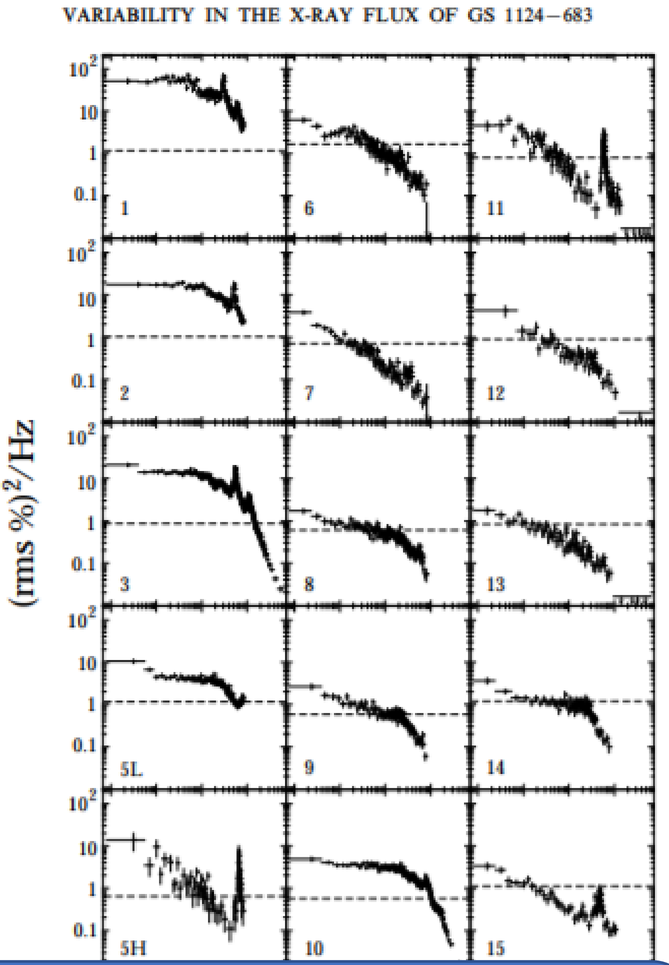


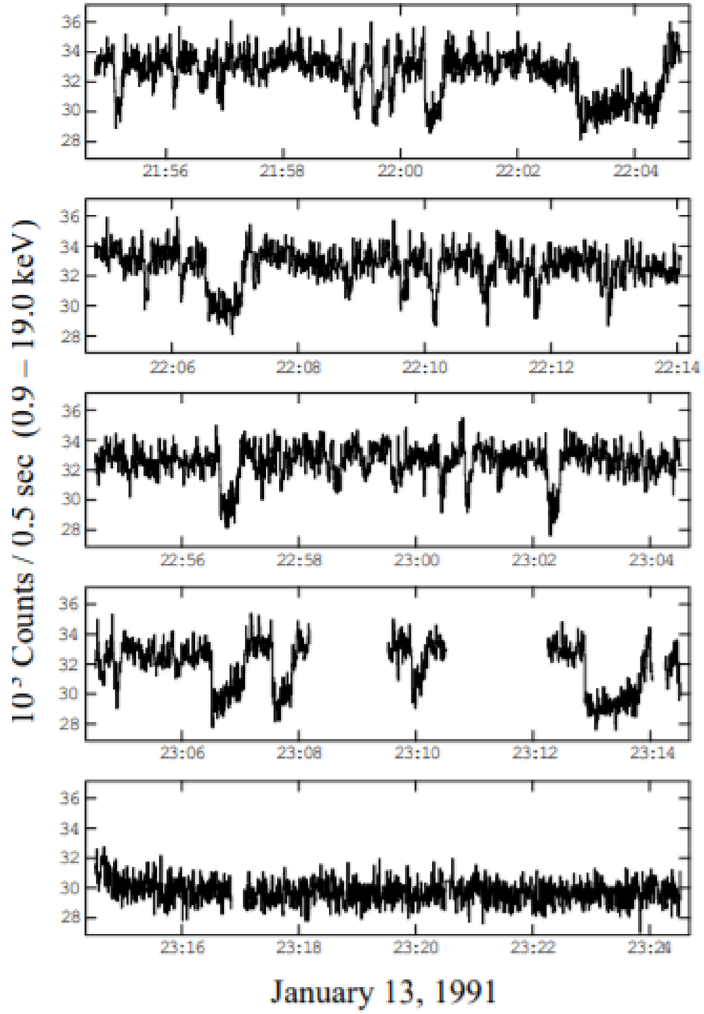
FIG. 7.—Some examples of the dip and flip-flop







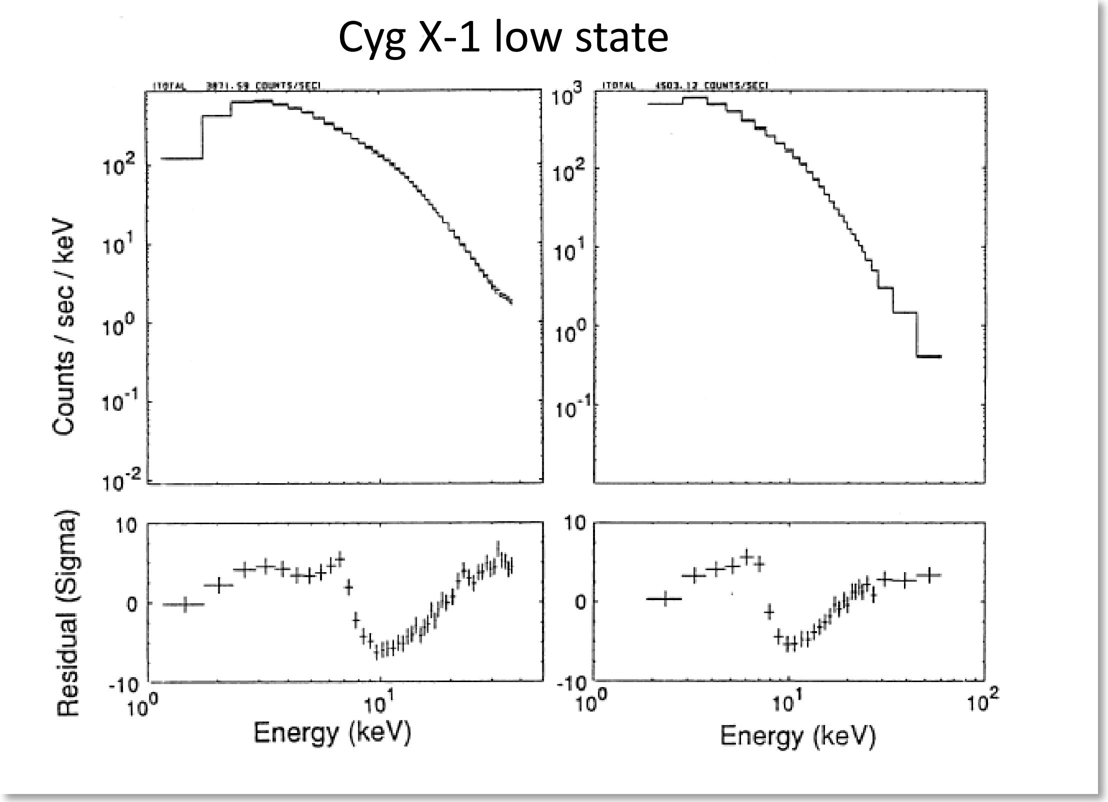
Region 間のflip-flop



Color-color diagram上で2つ
の「region」がある。
QPO frequencyの強度依存性が異なる

Takizawa et al. (1997), Ginga , GS1124-68 very high state

まだわかっていないこと3：どれだけ(部分)吸収、どれだけ円盤反射？



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幅の広い鉄K輝線または吸収端のような構造がある

Reflection model

Partial covering model

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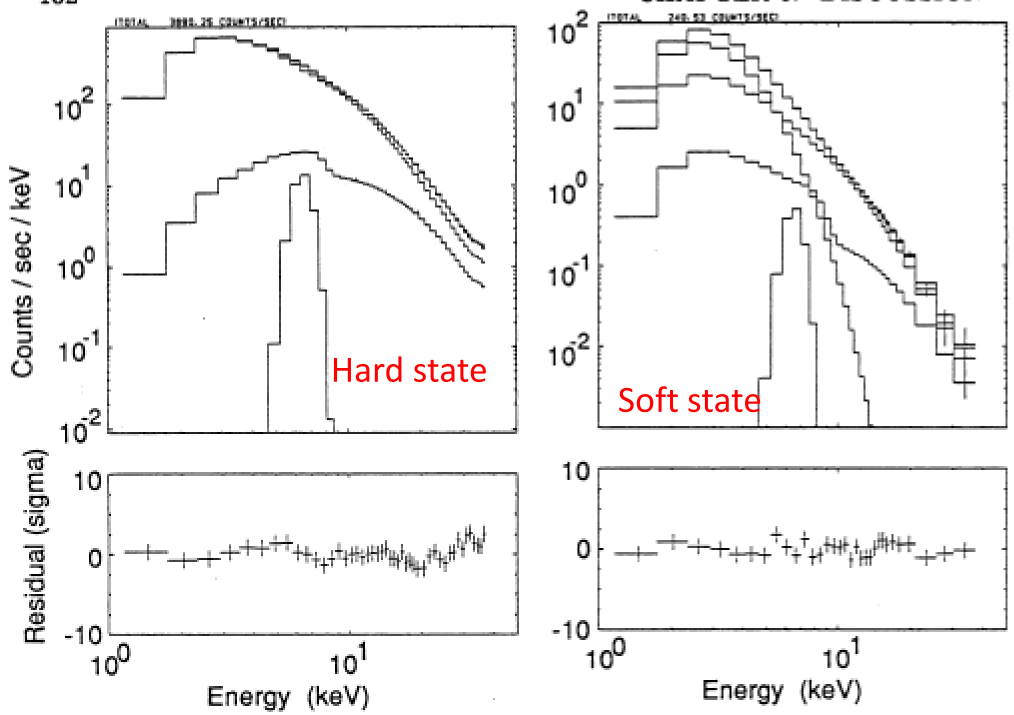


Figure 6.2: Examples of the fits with the reflection model to the hard state spectrum (left; Cyg X-1, 1987) and to the soft state spectrum (right; LMC X-1, 1987 April). Iron emission lines are included at 6.4 keV in the both fits. In the fit for LMC X-1, the multicolor disk model is included to represent the the soft component.

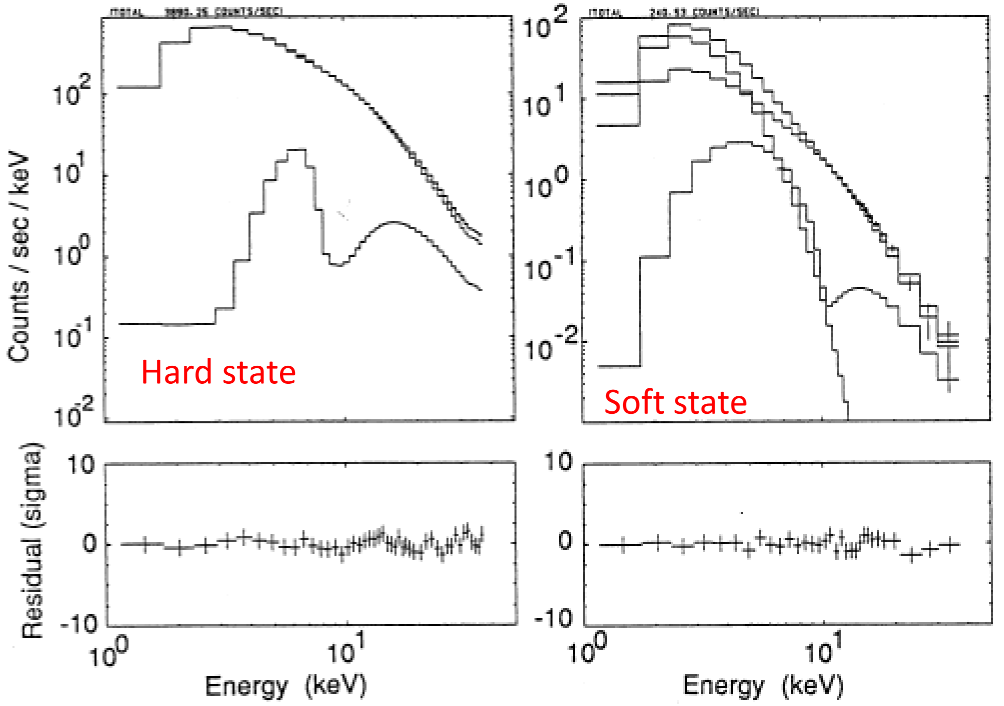
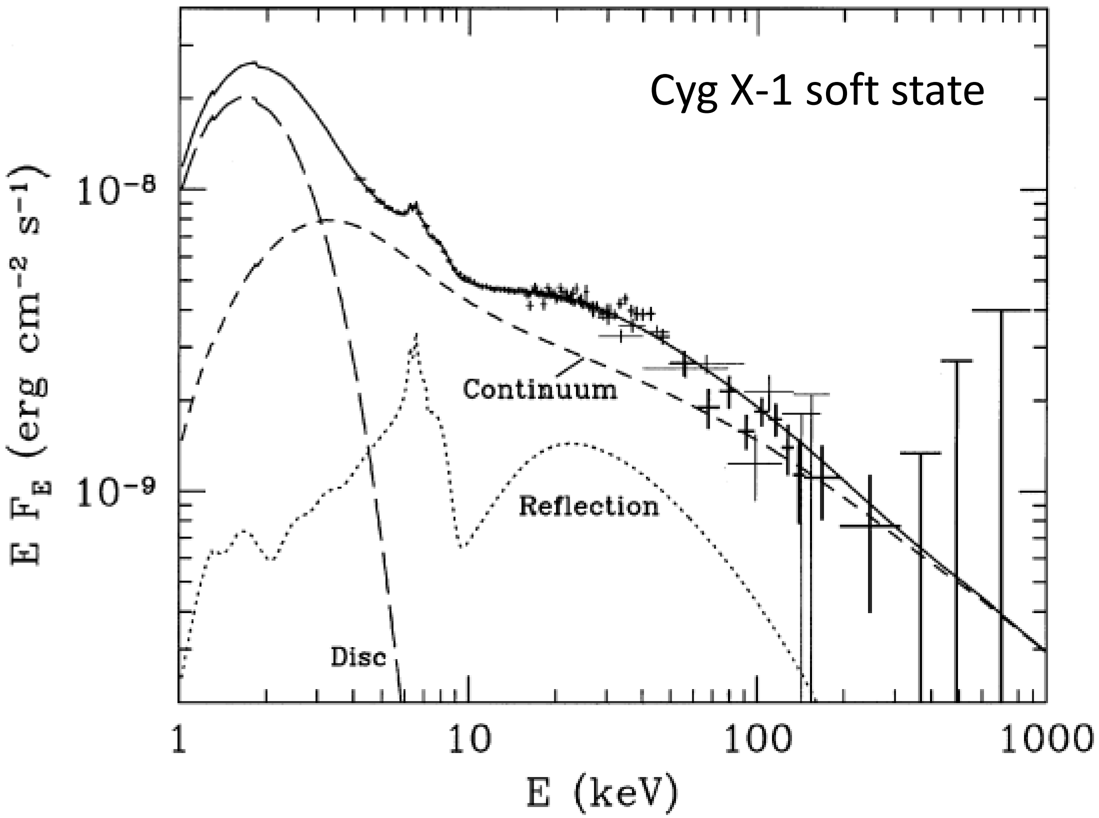


Figure 6.3: Examples of the fits with the partial absorption model (with the ionized absorber, see text) to the hard state spectrum (left; Cyg X-1, 1987) and to the soft state spectrum (right; LMC X-1, 1987 April). In the fit for LMC X-1, the multicolor disk model is included to represent the soft component.

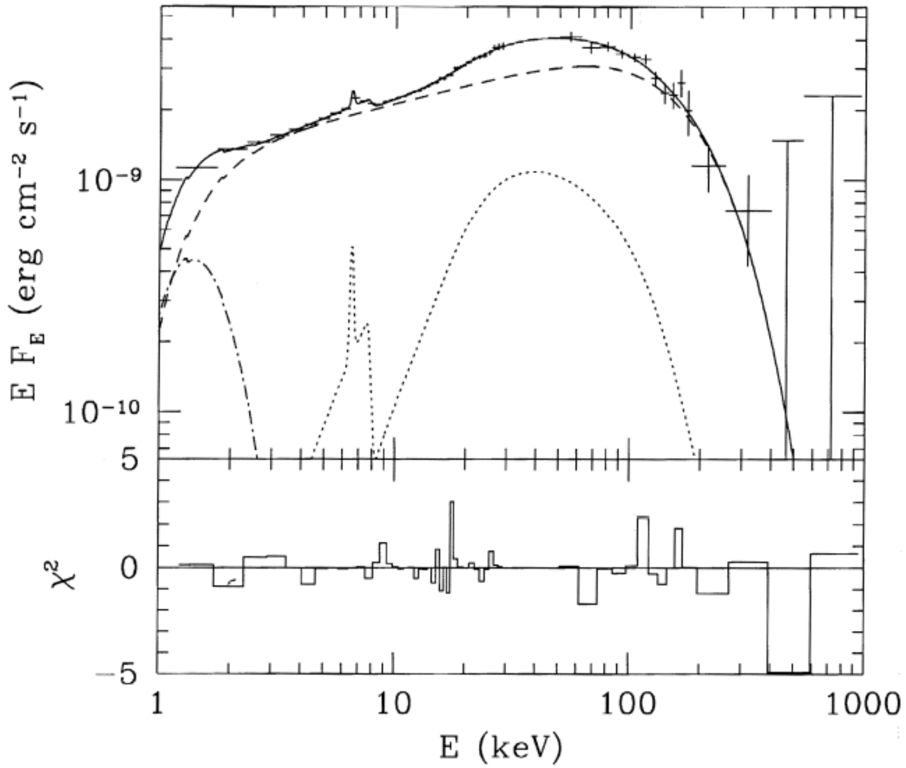
円盤反射モデルでも部分吸収モデルでも説明できる
どちらがもっともらしい？両方存在する？

円盤反射モデルでGBHを説明できるが…



Gierlinski et al. (1999)

GX339-4 hard state



Zdziarski et al. (1998)