

X線で標準降着円盤はどこまで わかってきたか？

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話の内容

1. 標準降着円盤の観測
2. 広がったように見える鉄輝線の観測
3. まとめ

3.まとめ

- ブラックホール連星系において、標準降着円盤からのX線スペクトルが観測されている
 - 標準降着円盤のX線スペクトル観測から、ブラックホールの質量とスピンを推定することができる
- セイファート銀河のX線スペクトル中に、広がった鉄輝線のような構造が観測されている
 - 広がった鉄輝線のような構造は、(おそらく)ブラックホール近傍の降着円盤からの反射ではなく、視線上に存在する多くの吸収物質による部分吸収で説明できる

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1.標準降着円盤の観測

- Shakura and Sunyaev (1973)
 - X線天体の起源として、ブラックホール連星系の標準降着円盤を提案
 - 幾何学的に薄く、低温(≤ 1 keV)で、光学的に厚い円盤
- 一般に降着円盤の厚さを h , 中心からの距離を r とすると、ガスの熱エネルギー(kT)と粒子(ほとんど水素)1つあたりの重力エネルギーの比は、

$$\frac{kT}{GMm/r} \approx \left(\frac{h}{r}\right)^2$$

$$\frac{GMm_p}{r} < \frac{GMm_p}{r_S} = \frac{GMm_p}{2GM/c^2} \approx m_p c^2 \approx \text{GeV}$$

- 幾何学的に薄い降着円盤($h/r \ll 1$)は低温($\ll \sim \text{GeV}$)
- 幾何学的に厚い降着円盤($h/r \approx 1$)は高温($\approx \sim \text{GeV}$)

1.標準降着円盤の観測

- 実際、標準降着円盤の温度は

$$\lesssim 1 \text{ keV} \left(\frac{M}{10M_{\odot}} \right)^{-1/4}$$

- Hydrogenic ion(原子核と電子一個)の電離エネルギー

$$13.6 \times Z^2 \text{ eV}$$

シリコンの場合($Z=14$) 2.7 keV、鉄の場合($Z=26$)、9.2 keV

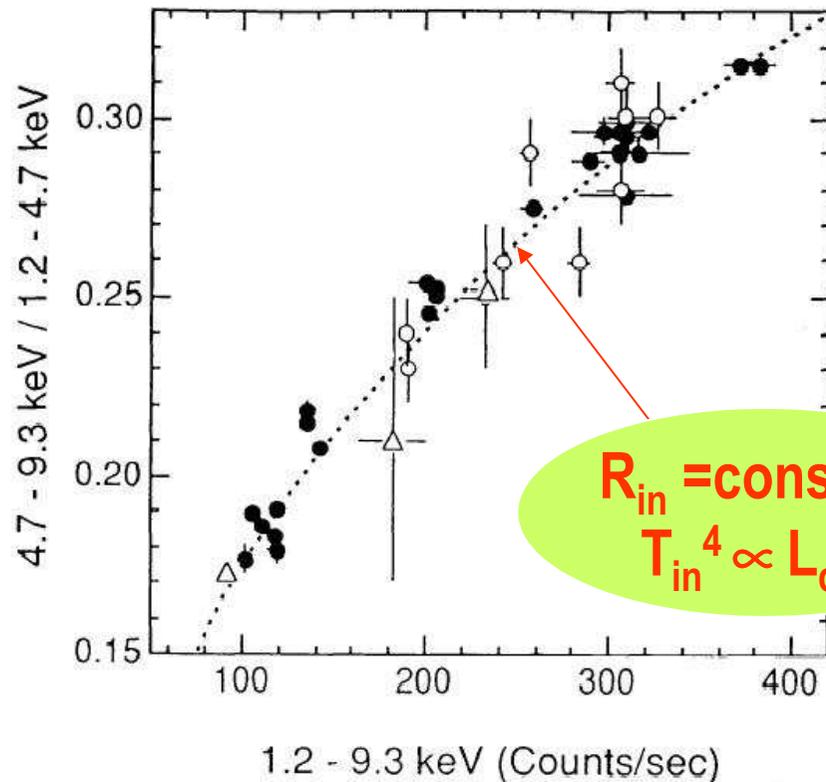
- ~1 keVでは重元素が完全電離しない→光電吸収が働く→
光学的に厚い

1.標準降着円盤の観測

- Katz “High Energy Astrophysics” (1986)より

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.

ぎんが衛星(1987年打ち上げ)による ブラックホール連星の観測



LMC X-3 GINGA

(Ebisawa et al. 1993)

強度と色(hardness-ratio)に相関

光学的に厚い円盤

$$L_{\text{disk}} \propto R_{\text{in}}^2 T_{\text{in}}^4$$

円盤の内縁半径は一定で、観測される強度変化は
円盤の温度変化だけで説明できる

LMC X-3 RXTE衛星による観測 (Kubota and Makishima 2005)

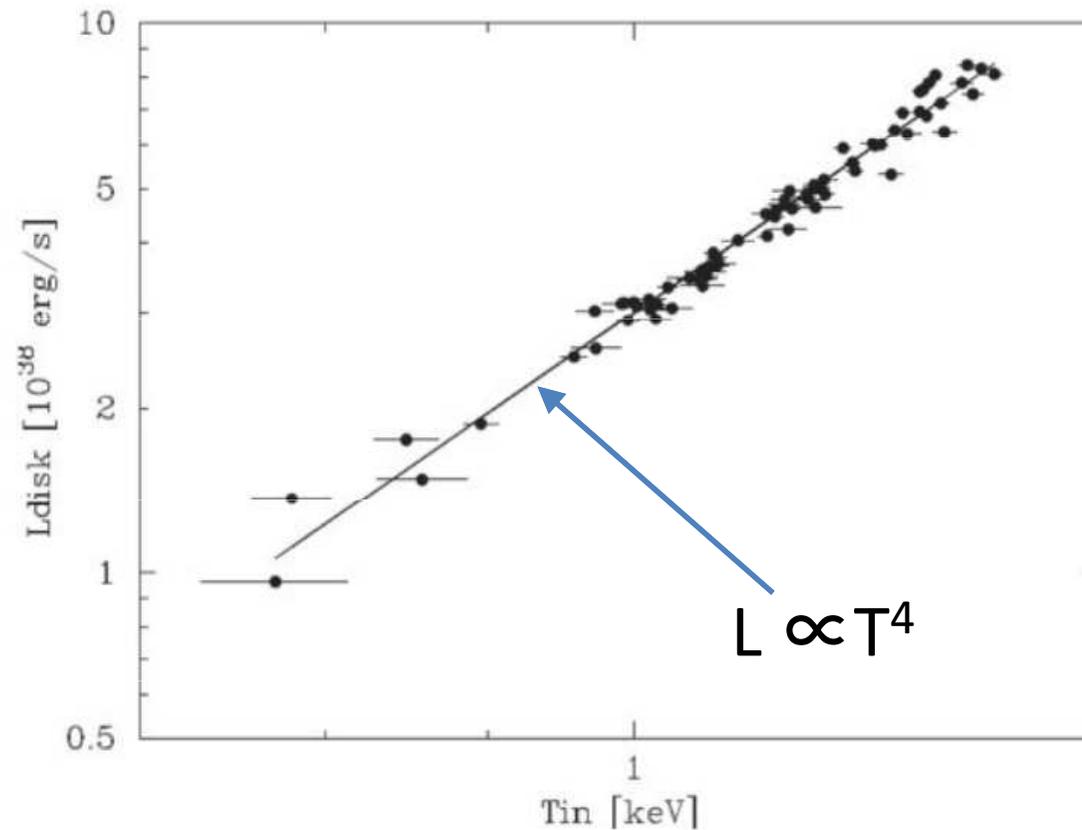
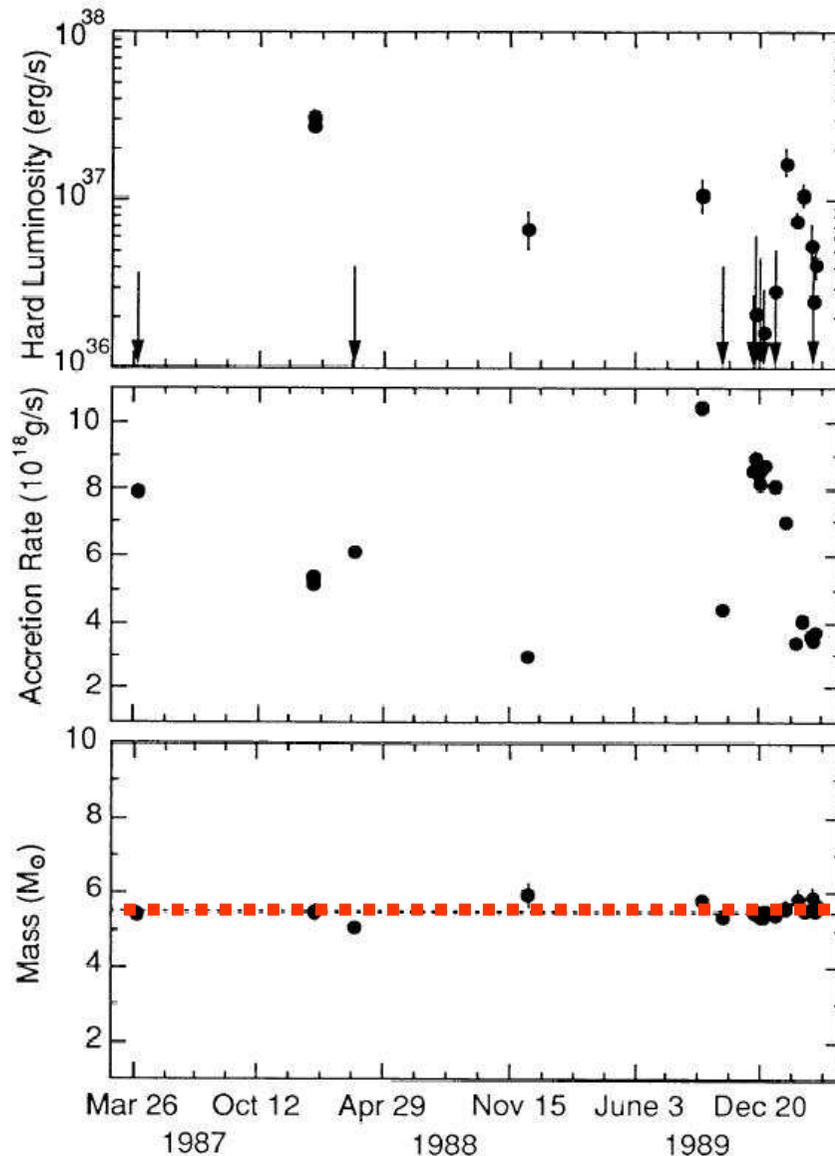


Fig. 14.26

The estimated thermal luminosity L_{disk} of LMC X-3 plotted against the observed temperature T_{in} . The distance and inclination are assumed to be $D = 50$ kpc and $i = 66^\circ$. The solid line is the relation $L_{\text{disk}} \propto T^4$ (Kubota and Makishima, 2005).

Longair 2011, "High Energy Astrophysics (third edition)" より

ぎんが衛星による標準降着円盤の観測



LMC X-3 GINGA

(Ebisawa et al. 1993)

回転していない
ブラックホールを仮定
 $R_{in} = 6GM/c^2$

距離、ディスク傾斜角を仮定、質量と質量降着率はフリーパラメーター

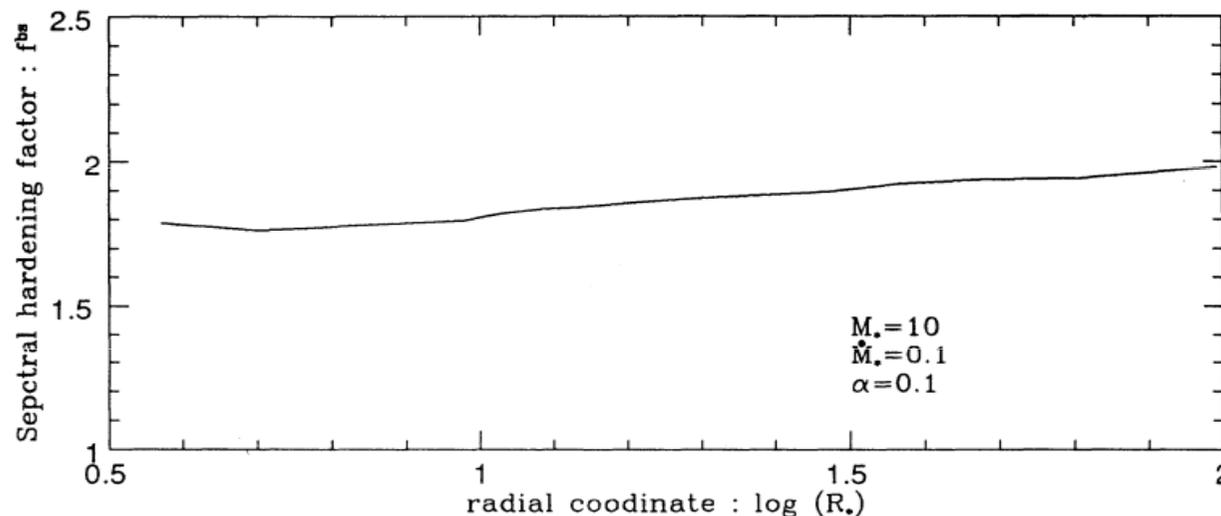
色温度と有効温度の補正:
 $T_{col}/T_{eff} \approx 1.9$ (一定)

ブラックホール質量 $\sim 6 M_{\odot}$

可視光による観測結果とほぼ一致

Color correction

- X線スペクトルフィットからわかるのは、降着円盤の**色温度** (T_{col})、内縁半径を決めるのは**有効温度** (T_{eff})
- 標準降着円盤の $T_{\text{col}}/T_{\text{eff}}$ は、光度と半径によらずにほぼ一定 (Shimura and Takahara 1995; ADSで322citation)

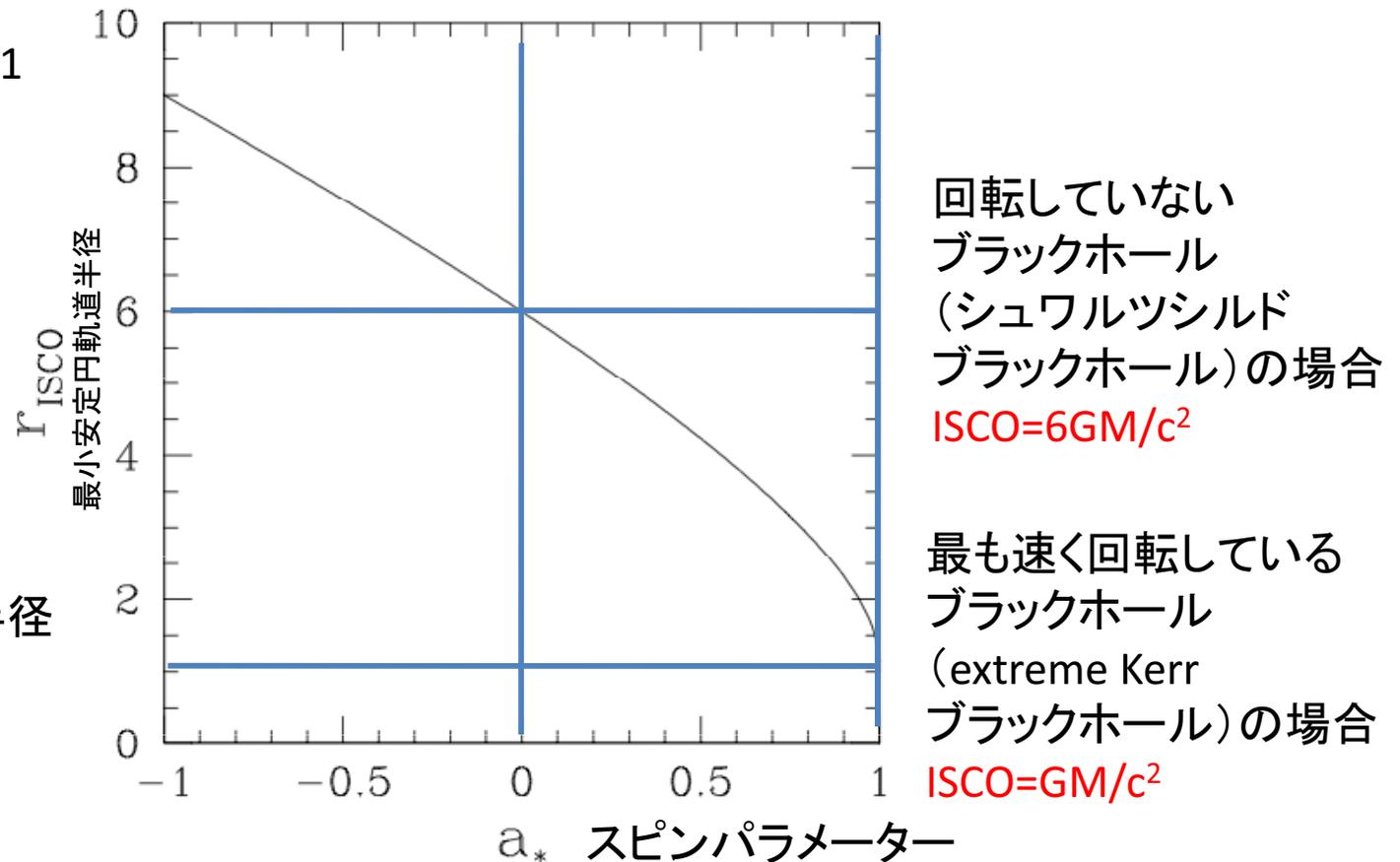


ブラックホールのまわりの最小安定円軌道半径 ISCO (Innermost Stable Circular Orbit)

McClontock 2011

GM/c²が単位

(シュワルツシルド半径
=2GM/c²)



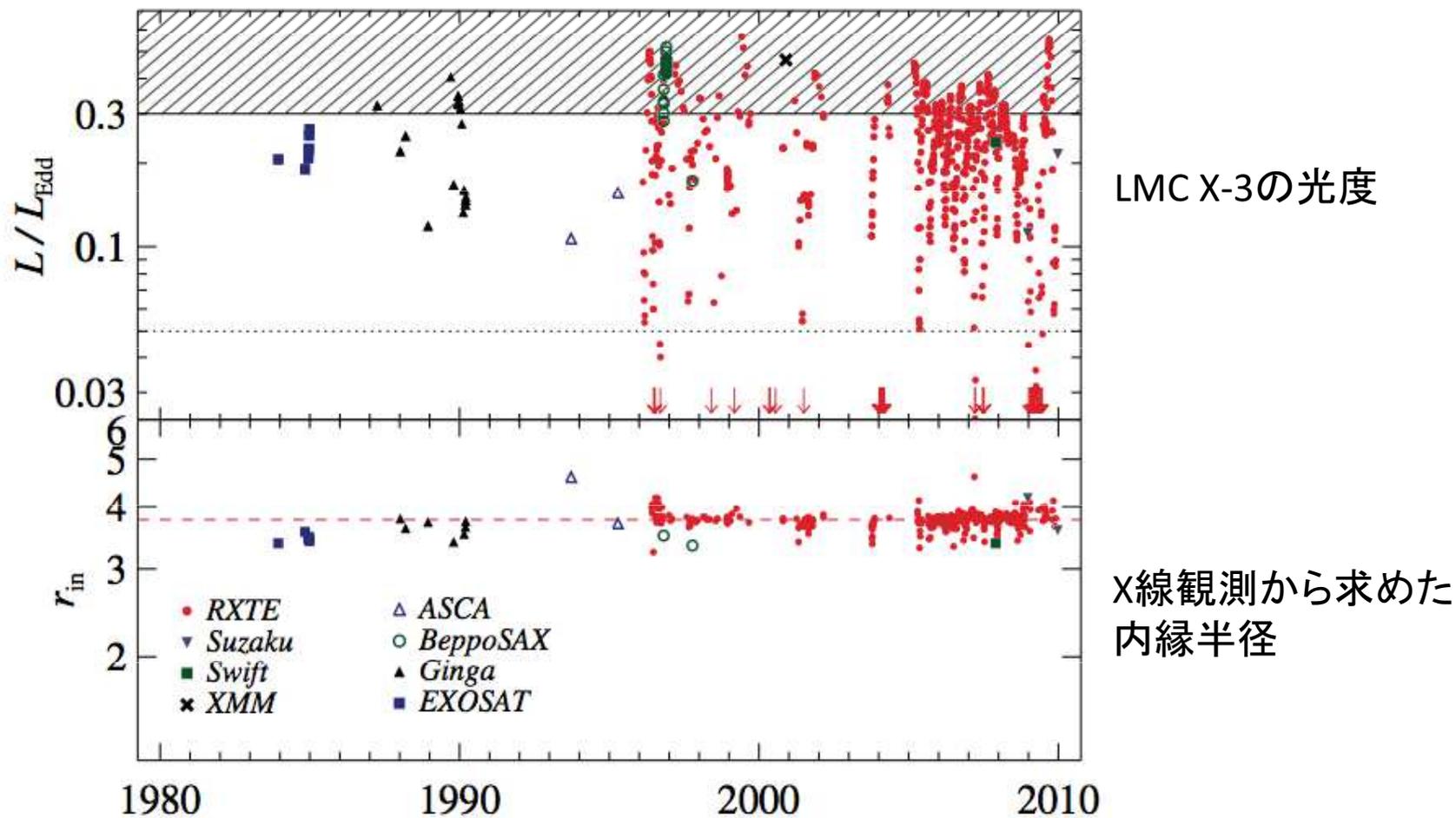
降着円盤の内縁がISCOに対応している

X線観測 → 降着円盤の内縁半径=ISCO(質量とスピンパラメーターの関数)

ISCOを測定し、質量とスピンパラメーターのどちらかを仮定すれば、もう片方が決まる 12

ISCOの安定性

Steiner et al. 2010



内縁半径は長期間にわたって一定
内縁半径がISCO(光度に依らない)に対応していることの証拠

標準降着円盤のX線スペクトル観測からスピンパラメータの推定

天体までの距離、ブラックホールの質量、円盤の傾きを仮定
 X線スペクトル $\rightarrow r_{\text{IN}} = \text{ISCO} \rightarrow a$ が推定できる

Table 1. Spin results to date for eight black holes^a.

McClintock 2011

	Source	Spin a_*	Reference
1	GRS 1915+105	>0.98	McClintock <i>et al</i> 2006
2	LMC X-1	$0.92^{+0.05}_{-0.07}$	Gou <i>et al</i> 2009
4	M33 X-7	0.84 ± 0.05	Liu <i>et al</i> 2008, 2010
3	4U 1543–47	0.80 ± 0.05	Shafee <i>et al</i> 2006
5	GRO J1655–40	0.70 ± 0.05	Shafee <i>et al</i> 2006
6	XTE J1550–564	$0.34^{+0.20}_{-0.28}$	Steiner <i>et al</i> 2010b
7	LMC X-3	$<0.3^b$	Davis <i>et al</i> 2006
8	A0620–00	0.12 ± 0.18	Gou <i>et al</i> 2010

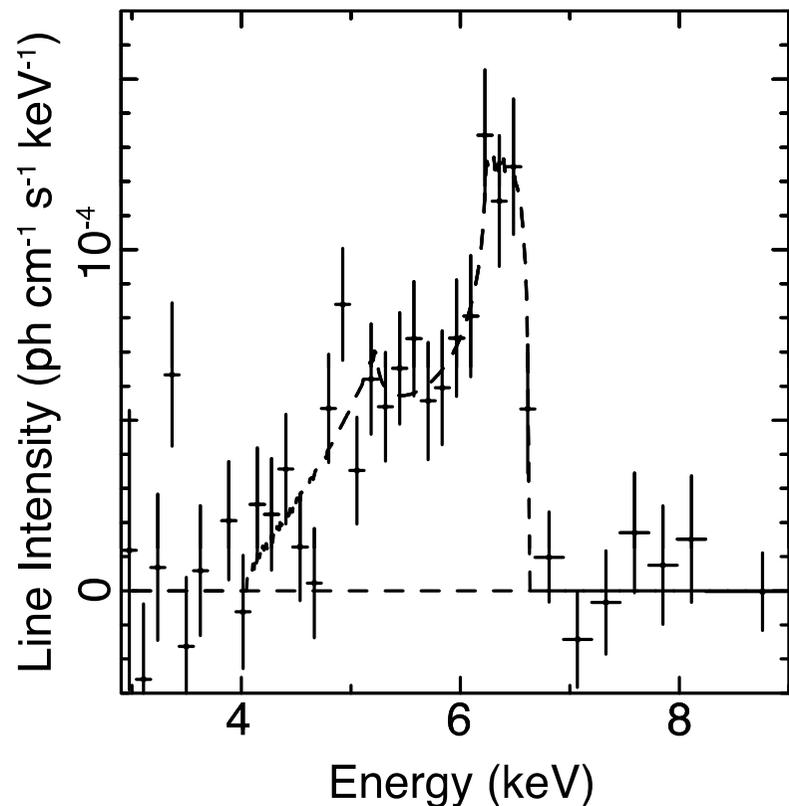
^a Errors are quoted at the 68% level of confidence.

^b Provisional result pending improved measurements of M and i .

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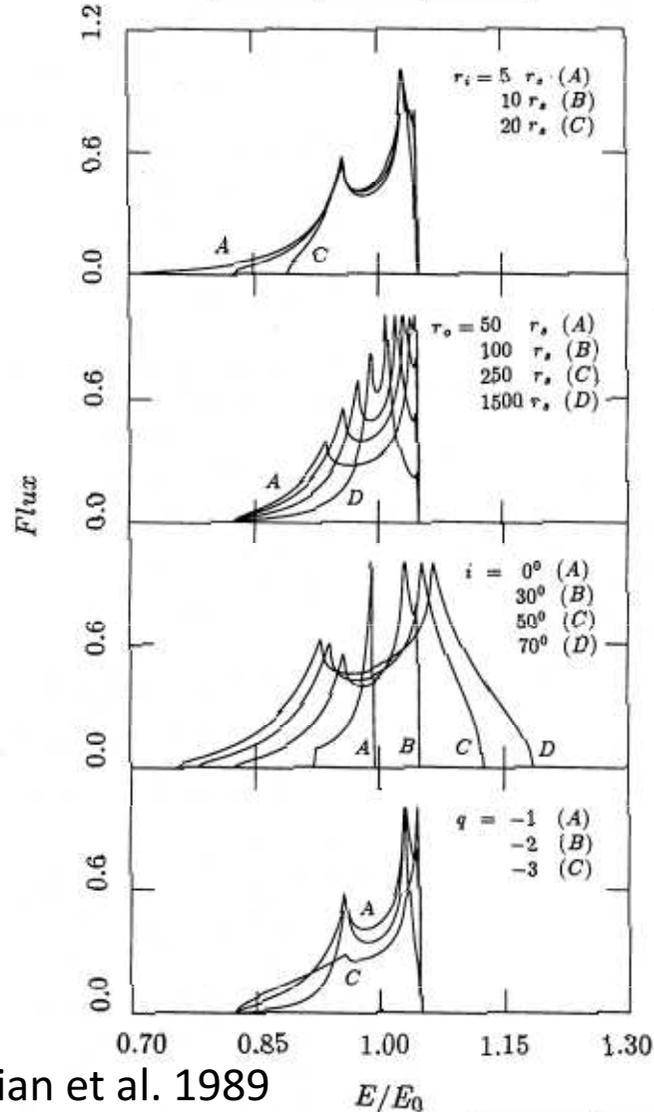
- ASCA MCG-6-30-15

(Tanaka+ 1995)

- 鉄のK-輝線が、相対論効果で広がっているように見える
- これを標準降着円盤内縁からの反射によるものとする解釈がある

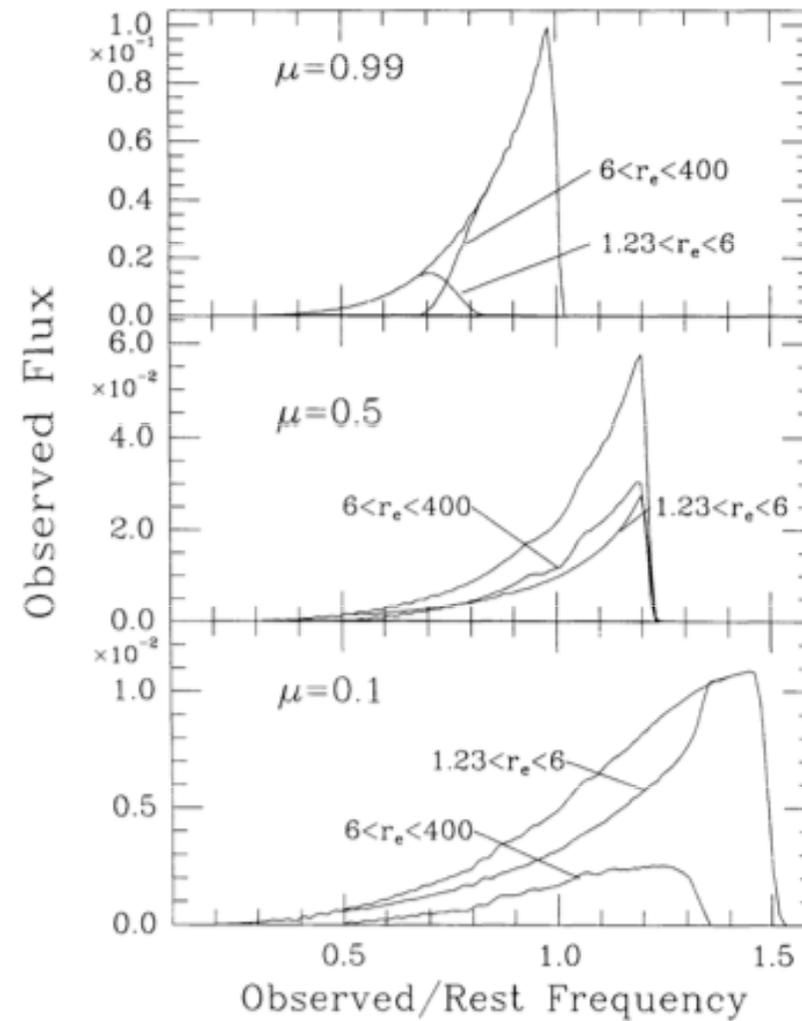
降着円盤内縁からの蛍光鉄輝線プロファイルの計算

シュワルツシルドブラックホールの場合



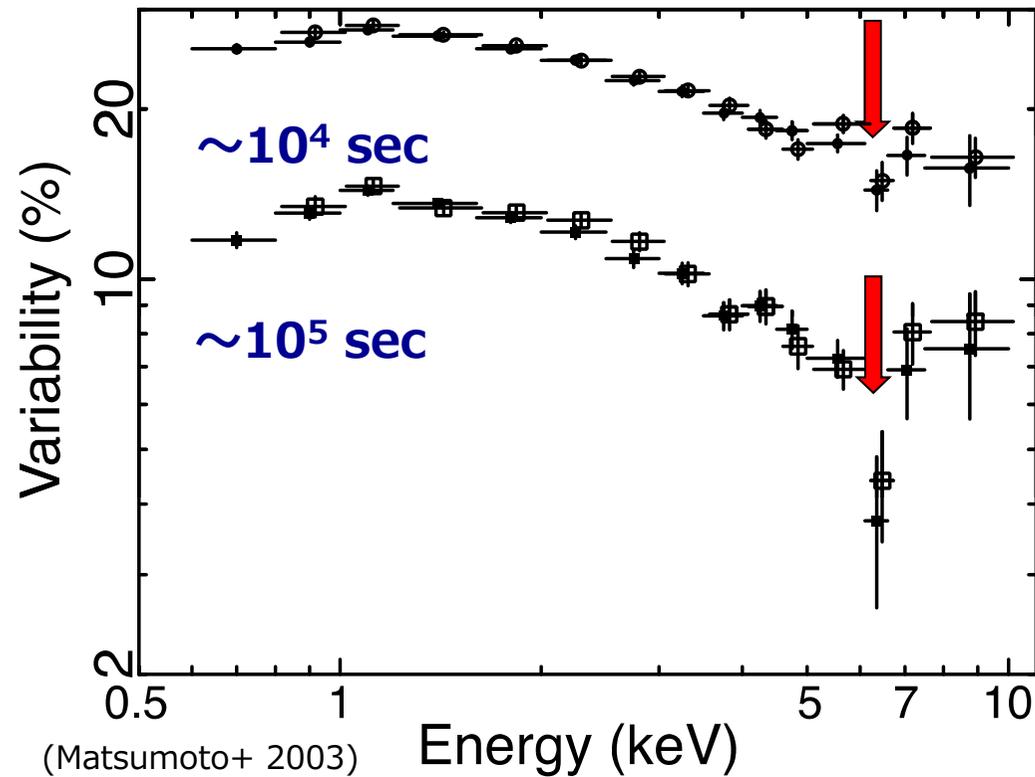
Fabian et al. 1989

Extreme Kerr ブラックホールの場合



Laor 1991

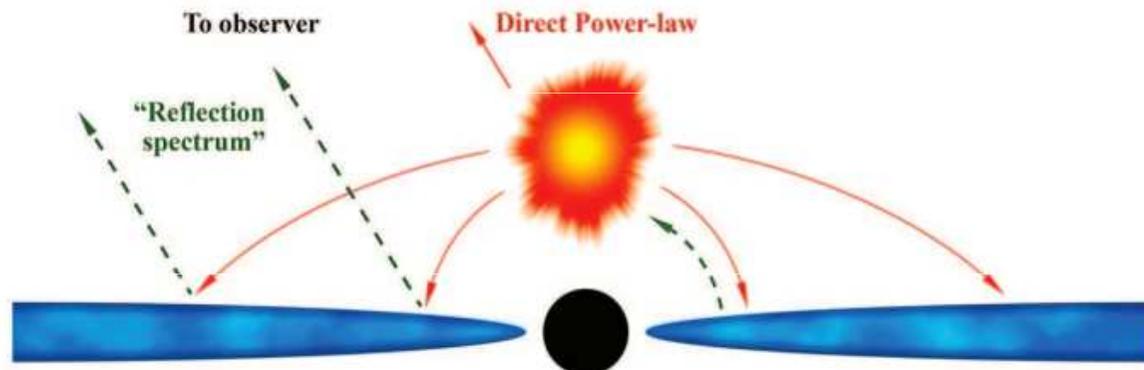
特徴的な時間変動



- MCG-6-30-15 with ASCA
Root Mean Square (RMS) 変化率のエネルギー依存性 (RMSスペクトル)
- 鉄のK輝線領域で、RMSスペクトルが急激に減少
- モデルに依存しない重要な結果

Light bendingモデル

- Miniutti and Fabian (2004)
 - ブラックホールの極近傍($\sim R_s$)で、ディスクが上からX線源 (“lump-post”)で照らされる
 - ディスクの内縁付近から広がった”ディスクライン”が観測される
 - Lump-postが強度を変えずに上下に動く
 - Lump-postからの直接成分は変動するが、“light-bending effect”によって、反射成分(鉄輝線)はあまり変動しない



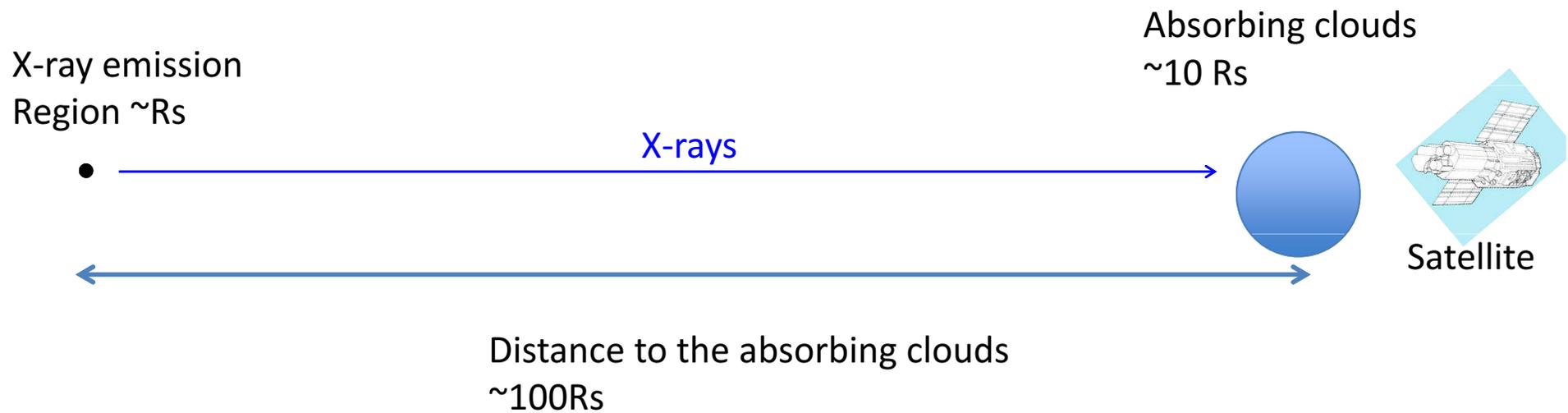
Fabian, Kara and Parker
(2014)

Variable Partial Coveringモデル

- AGNを説明する部分吸収(parial covering)のアイデア
e.g., Matsuoka+ (1990); McKernan and Yaqoob (1998);
Miller, Turner and Reeves (2008, 2009)
- **Variable Double Partial Coveringモデル** (Miyakawa,
Ebisawa and Inoue 2012; Mizumoto, Ebisawa and
Sameshima 2014; Yamasaki et al.2015, Iso et al. 2015)
 - 部分吸収体は、電離度の異なる二重構造を持つ
 - BHのまわりのX線源は広がっていて($\sim 20 R_s$)、あまり変動しない
 - 1~40 keVの強度/スペクトル変化は**部分吸収率(X線源が隠される割合)の変化**だけでほとんど説明できる

How can we distinguish the two models?

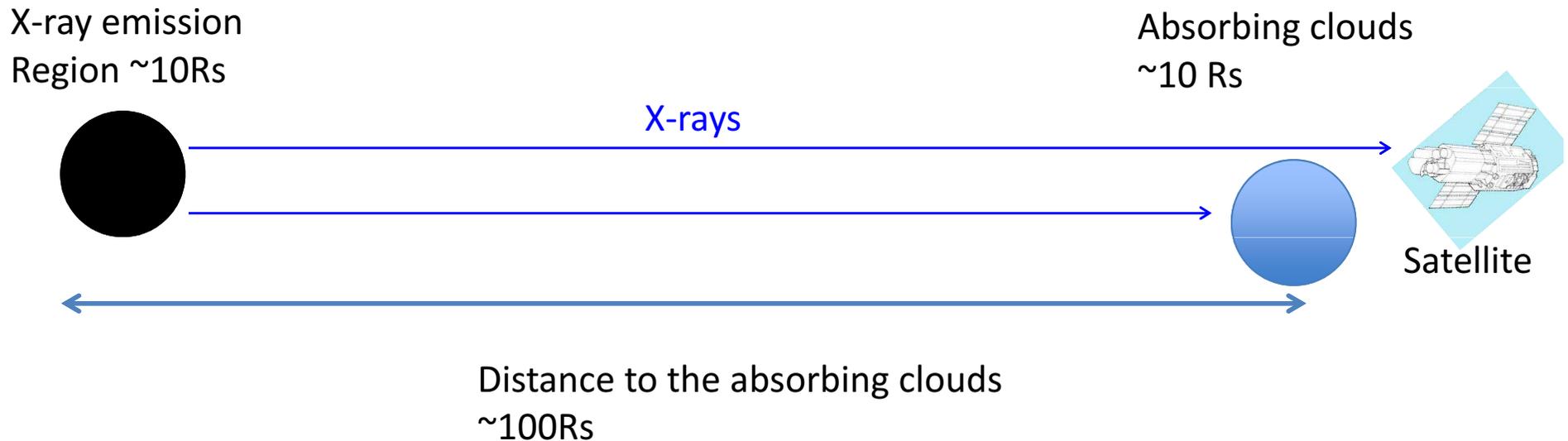
- Relativistic disk reflection model requires the X-ray emission region to be very compact



When the absorbing cloud size is larger than the X-ray source size, *partial covering does NOT take place (always full-covering)*

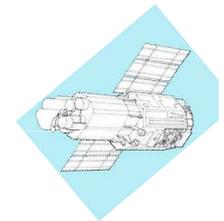
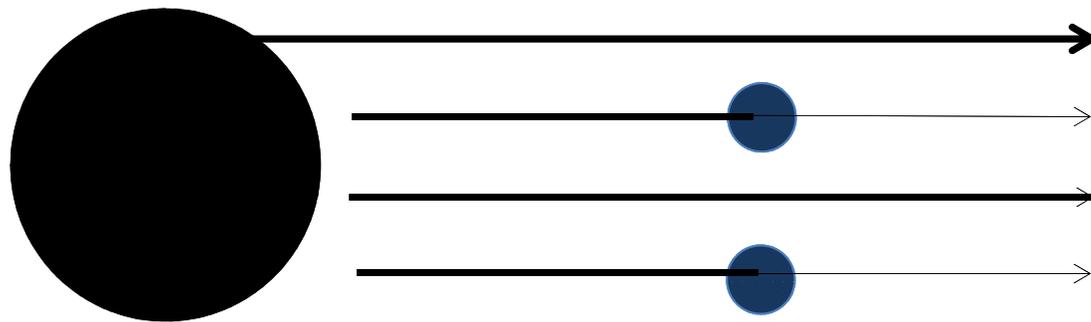
How can we distinguish the two models?

- Partial covering model requires the X-ray emission region extended



When the X-ray source size is greater than or comparable to the absorber size, *partial covering does take place*

2. Variable Double Partial Covering (VDPC) Model



Satellite

X-ray source

$$(1 - \alpha + \alpha \exp(-N_H^{(k)} \sigma(\xi_k)))$$

)

Partial covering by **thick**
and cold absorbers with the
partial covering fraction α

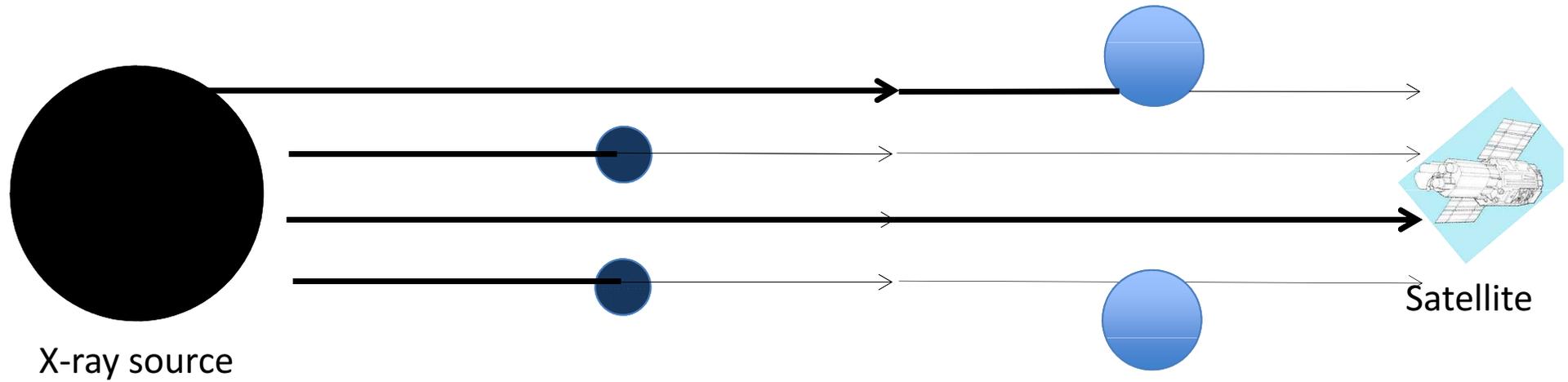


Responsible for iron K-edge

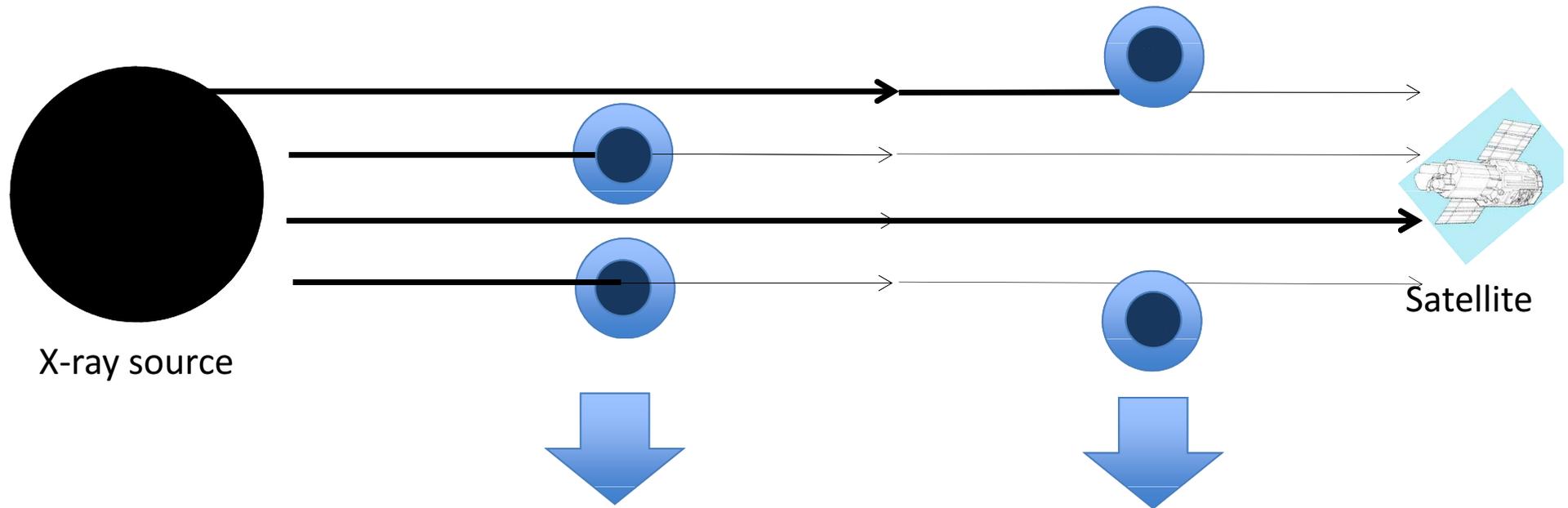


Responsible for iron L-edge

However, It is hard to imagine two separate layers with the same partial covering fraction so...



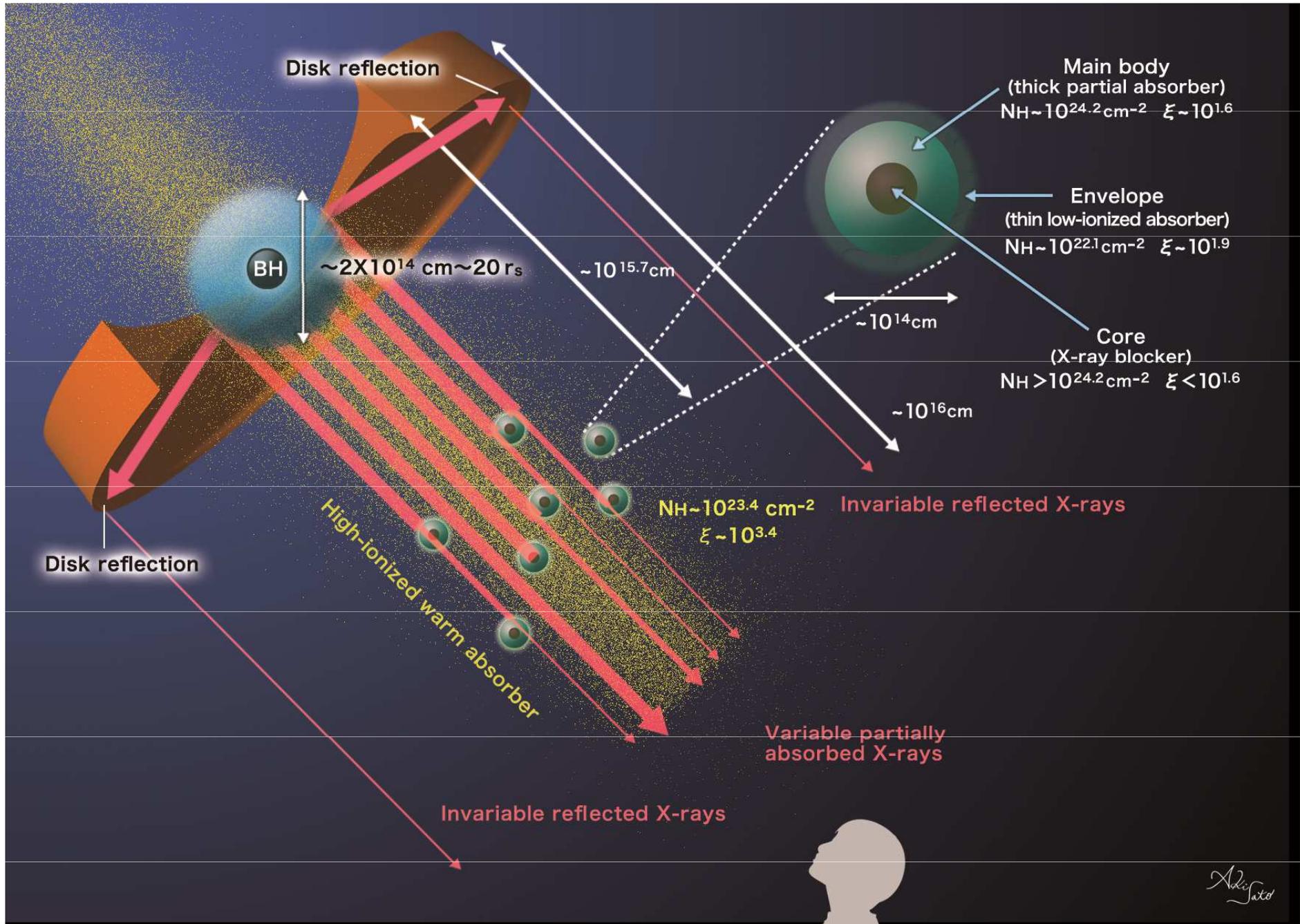
However, It is hard to imagine two separate layers with the same partial covering fraction so...



Thick and cold core responsible for the iron K-edge

Thin and hot envelope responsible for the iron L-edge

Presumably, the partial absorbers have inner structures; thick and cold core and thin and hot envelope

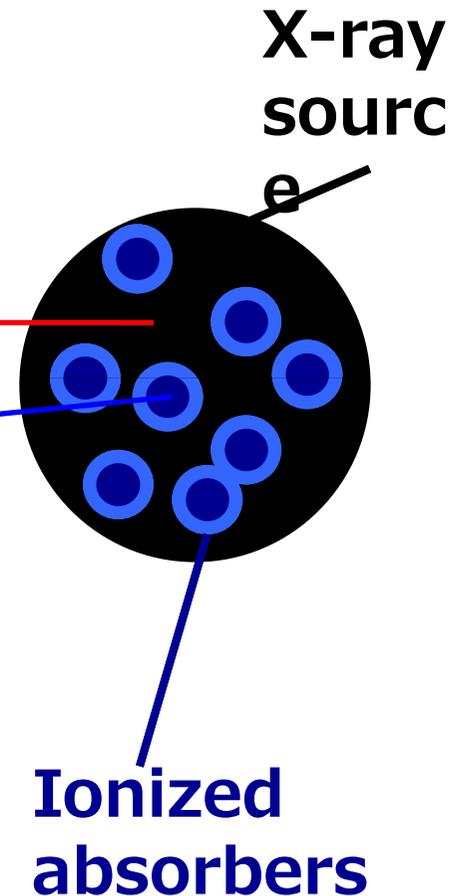
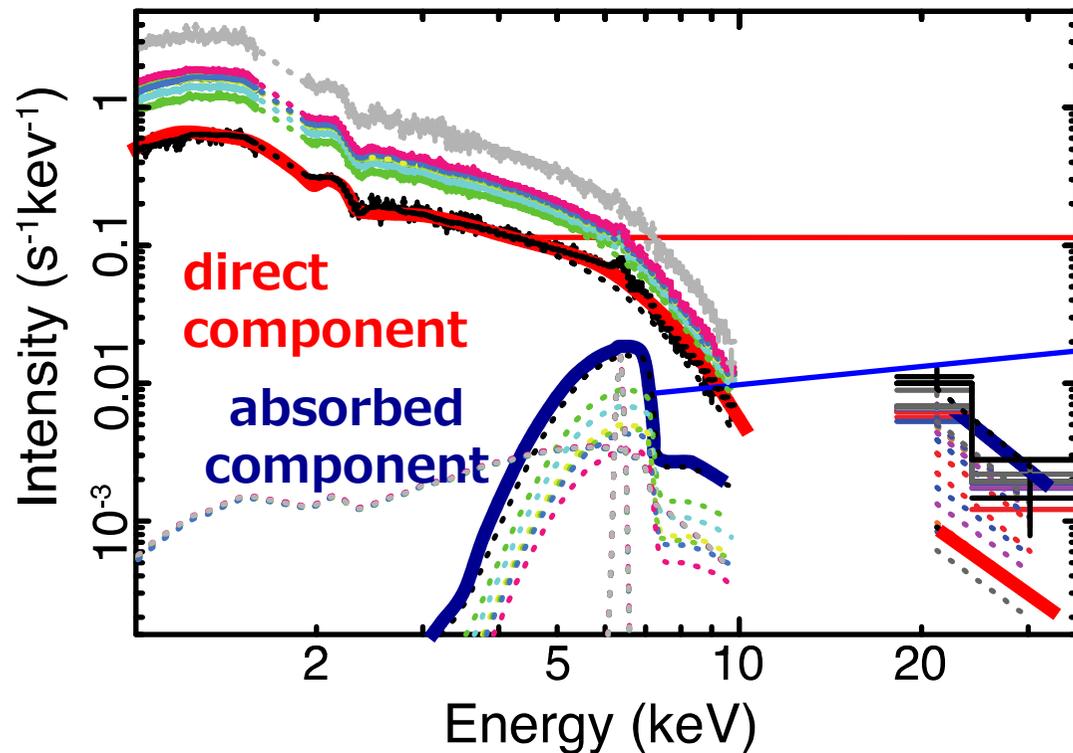


- Miyakawa, Ebisawa and Inoue (2012) (graphical work by Aki Sato)

Variable Partial Covering Model

(Miyakawa, Ebisawa and Inoue 20

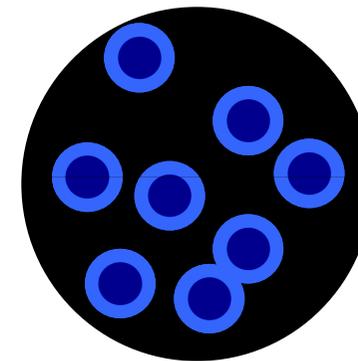
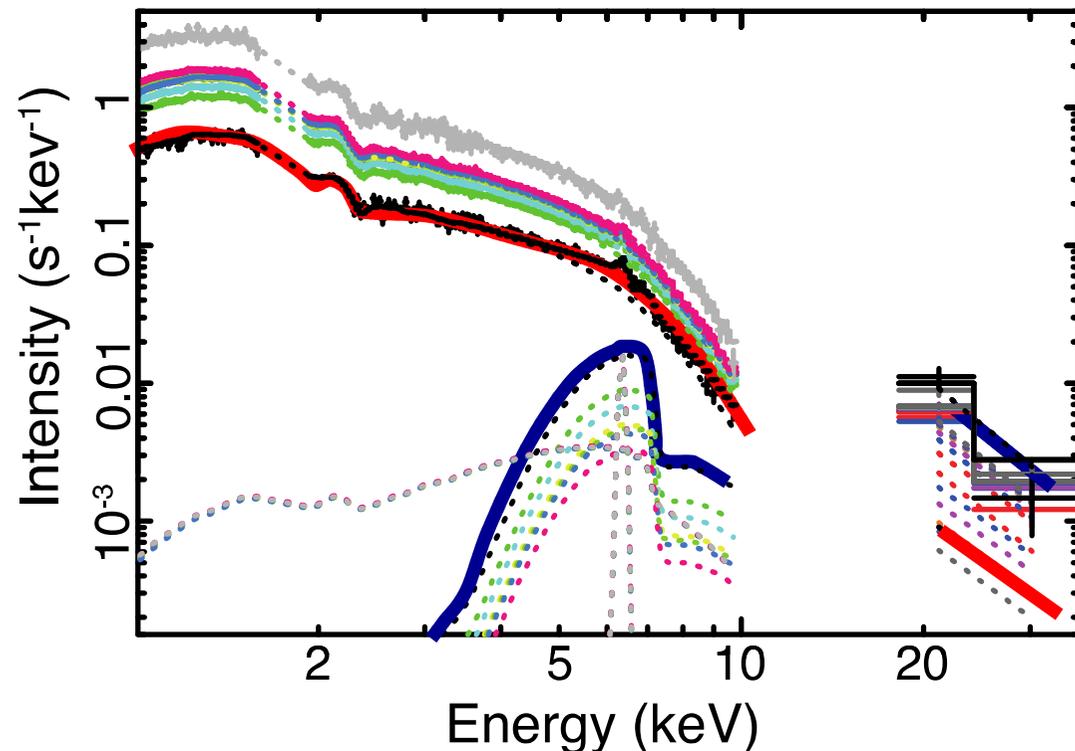
ブラックホールの光度はほとんど変動しない
部分吸収される割合(**covering fraction**)が大きく変動する



Variable Partial Covering Model

(Miyakawa, Ebisawa and Inoue 20

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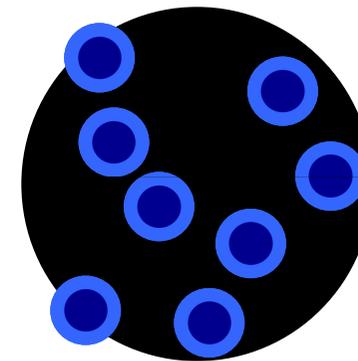
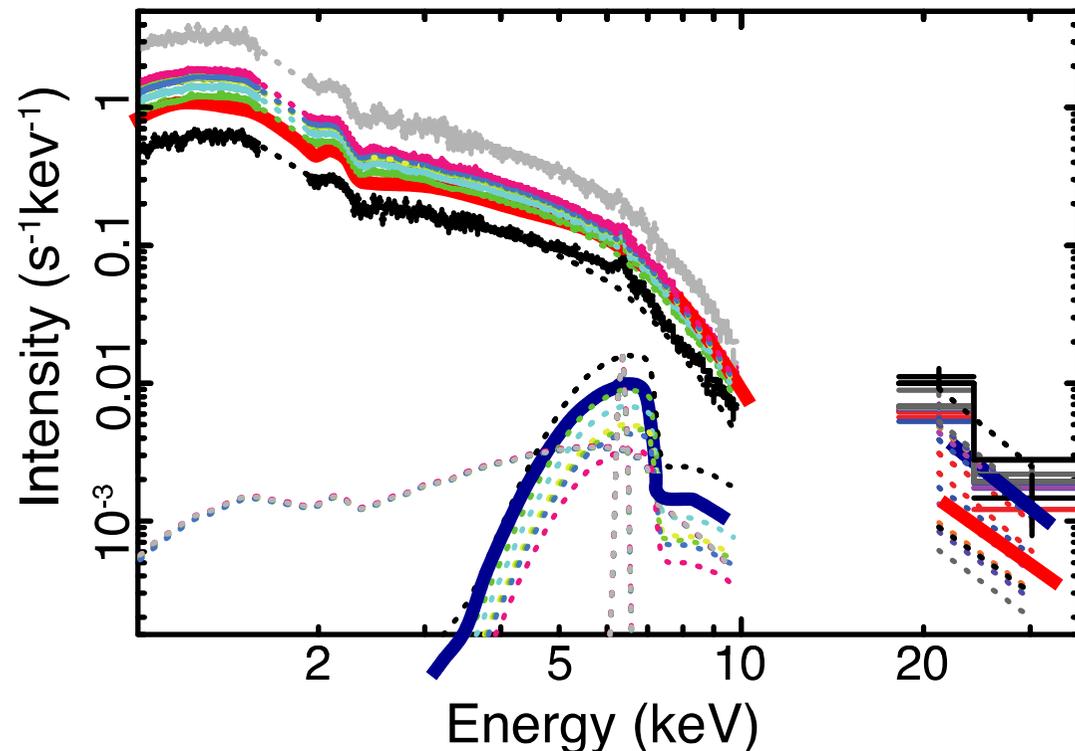


Covering fraction maximum

Variable Partial Covering Model

(Miyakawa, Ebisawa and Inoue 20

ブラックホールの光度はほとんど変動しない
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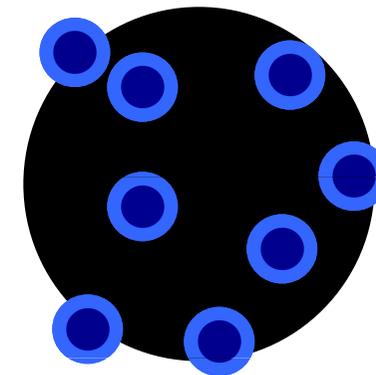
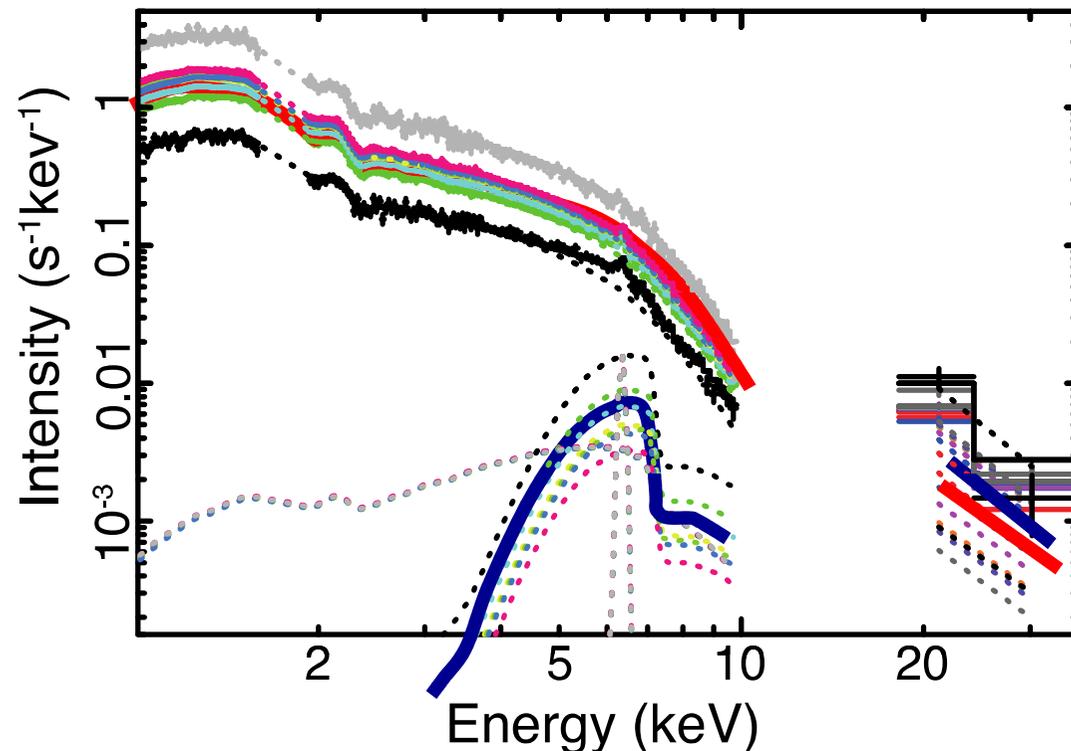


Covering fraction varies

Variable Partial Covering Model

(Miyakawa, Ebisawa and Inoue 20

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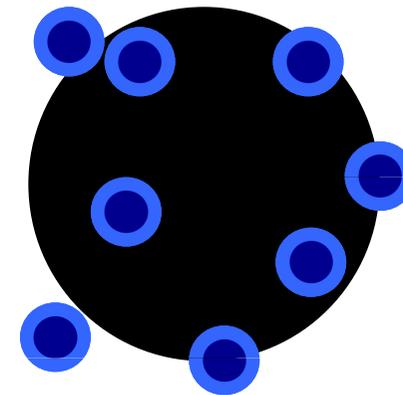
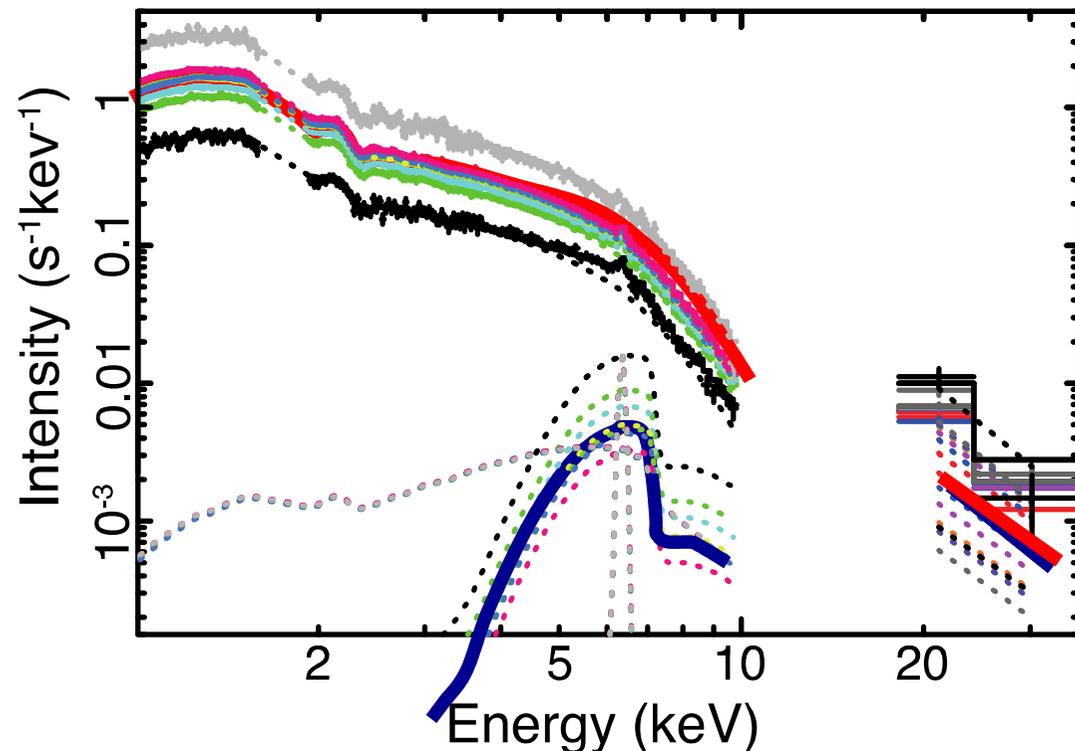


Covering fraction varies

Variable Partial Covering Model

(Miyakawa, Ebisawa and Inoue 20

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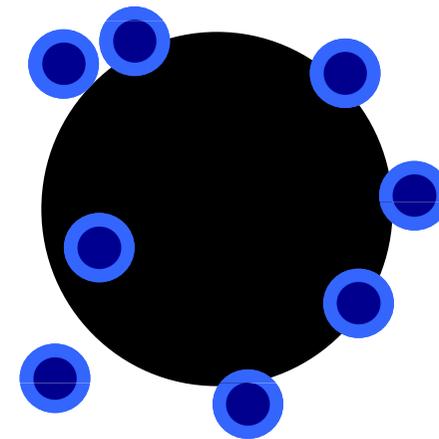
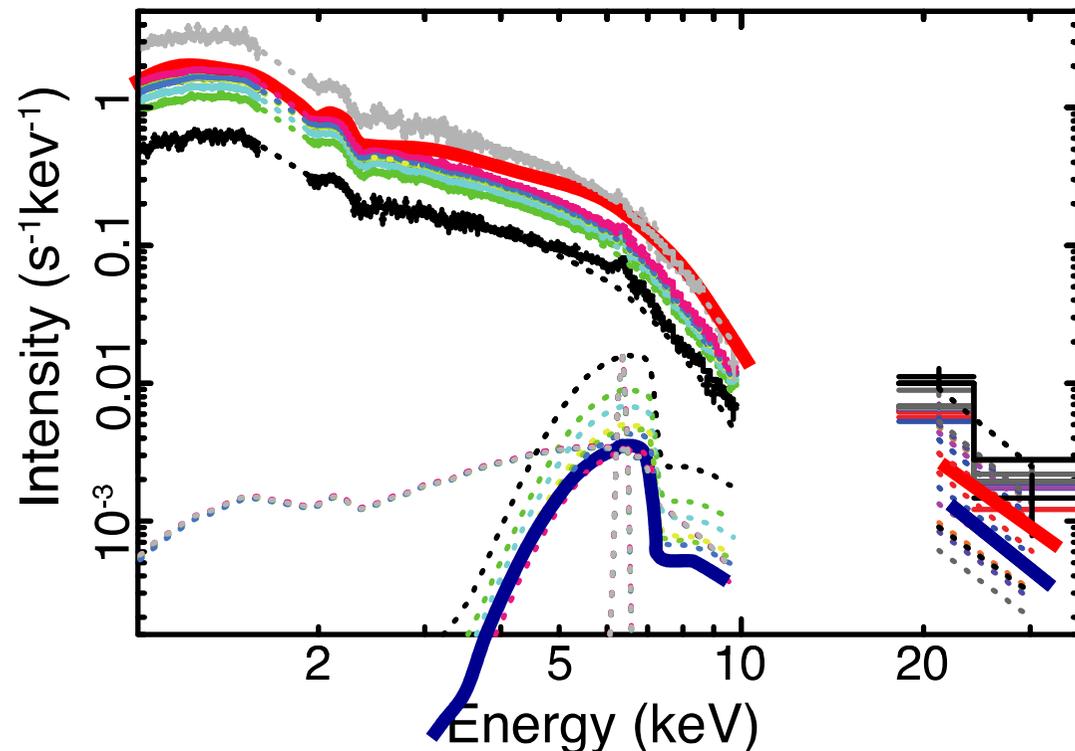


Covering fraction varies

Variable Partial Covering Model

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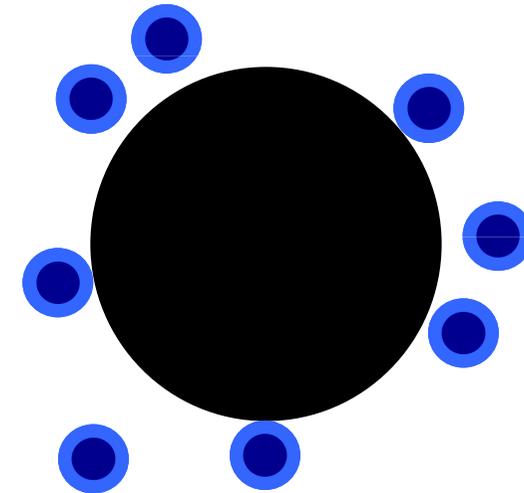
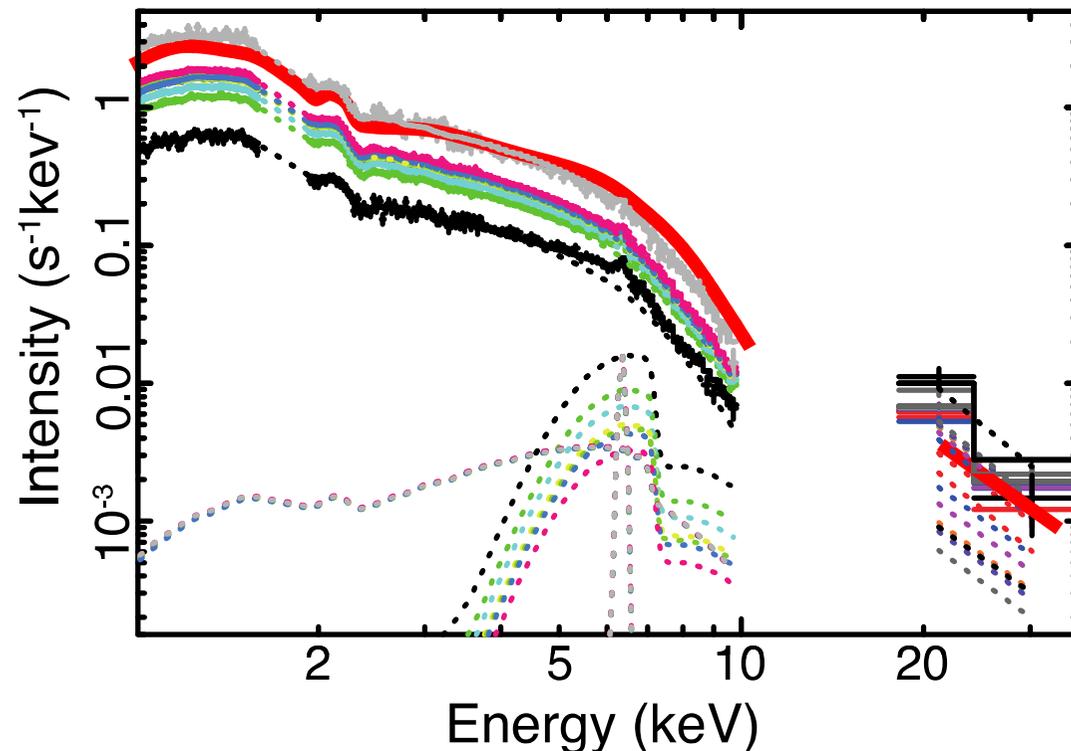


Covering fraction varies

Variable Partial Covering Model

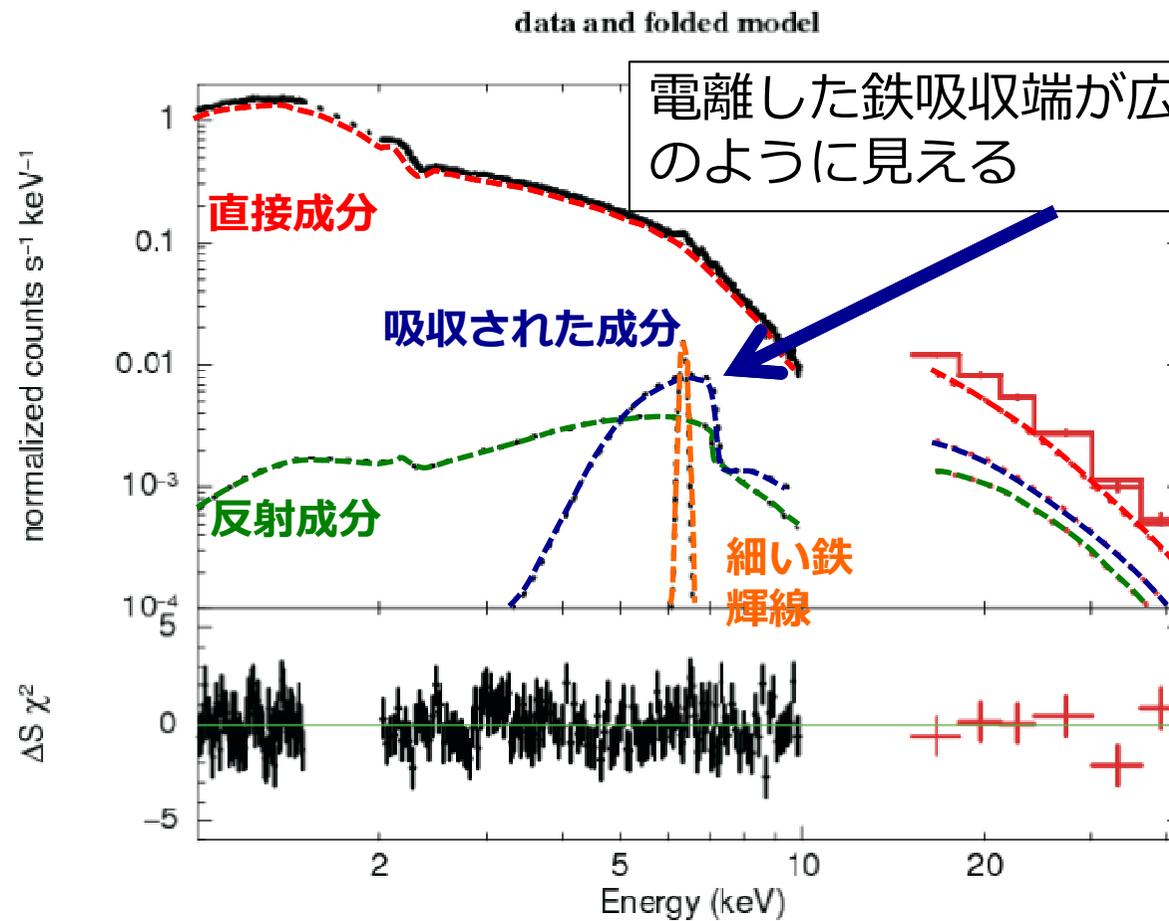
(Miyakawa, Ebisawa and Inoue 20

ブラックホールの光度はほとんど変動しない
部分吸収される割合(**covering fraction**)が大きく変動する



Covering fraction: Null

広がったように見える鉄輝線の説明

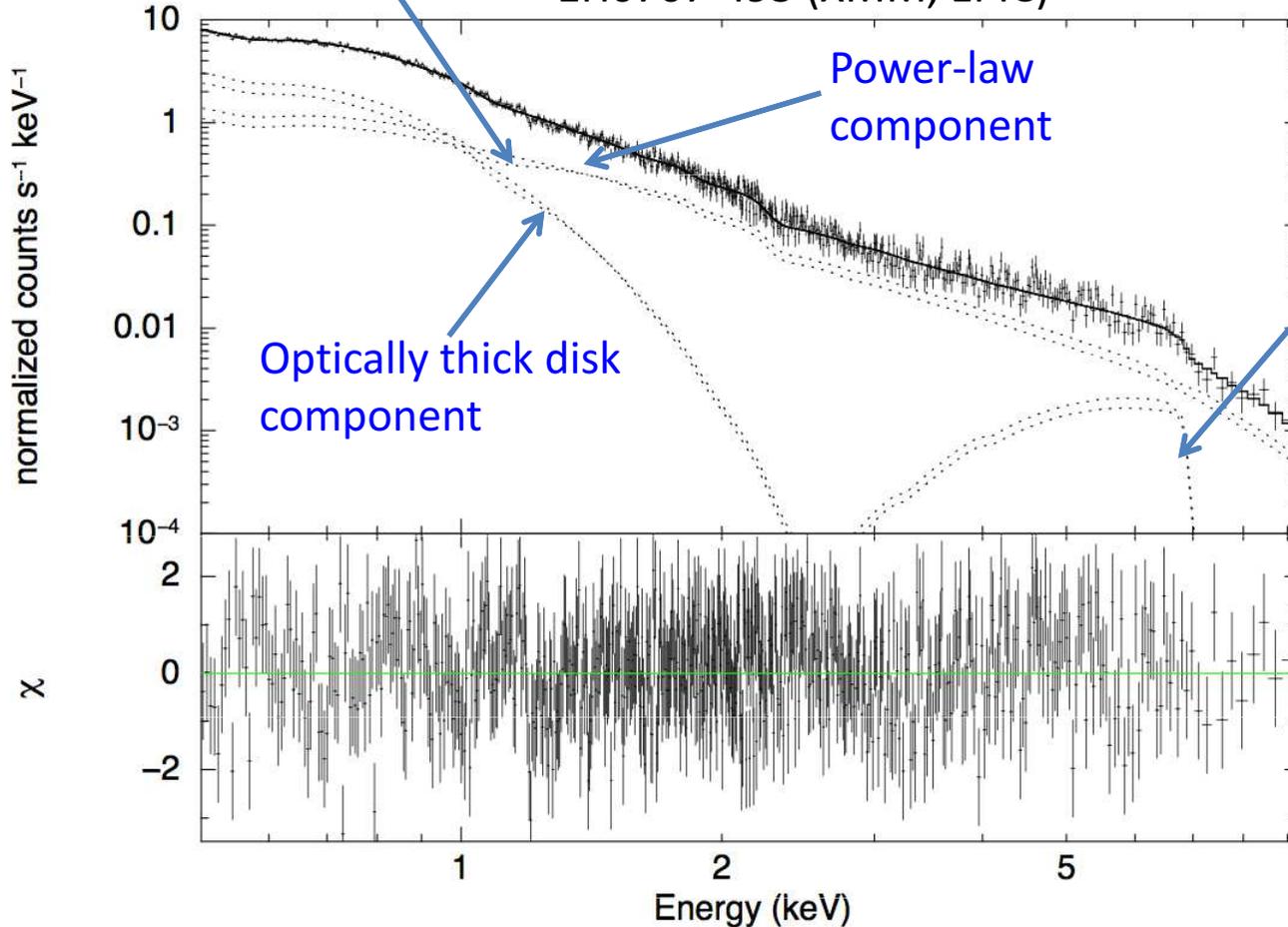


Suzaku MCG-6-30-15
Miyakawa, Ebisawa
and Inoue (2012)

広がったように見える鉄輝線の説明

Iron L-feature

due to thin/hot absorber 1H0707-495 (XMM, EPIC)



Iron K-feature due to thick/cold absorber

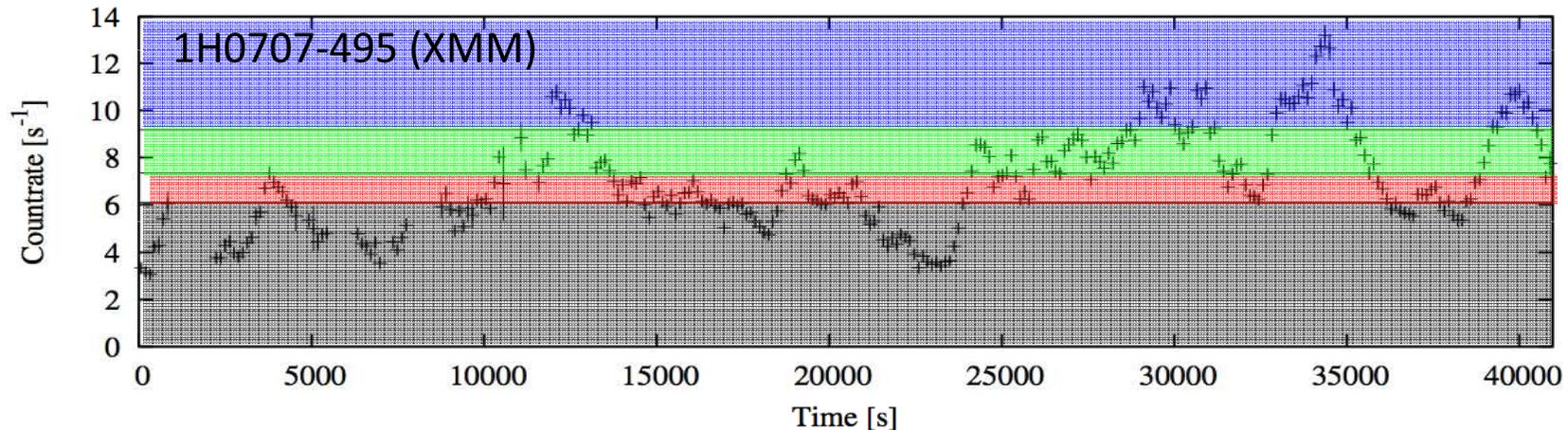
Thick/cold absorber:
 $N_H \sim 10^{24} cm^{-2}$, $\xi \sim 10^{0.1-0.3}$

Thin/hot absorber:
 $N_H \sim 10^{23} cm^{-2}$, $\xi \sim 10^3$

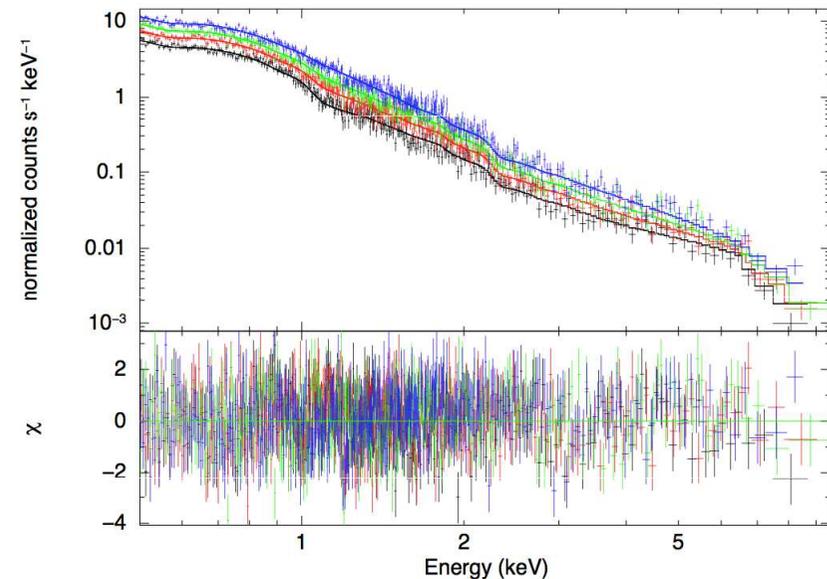
Mizumoto, Ebisawa and Sameshima (2014)

スペクトル変化の説明

強度でソートしたスペクトル



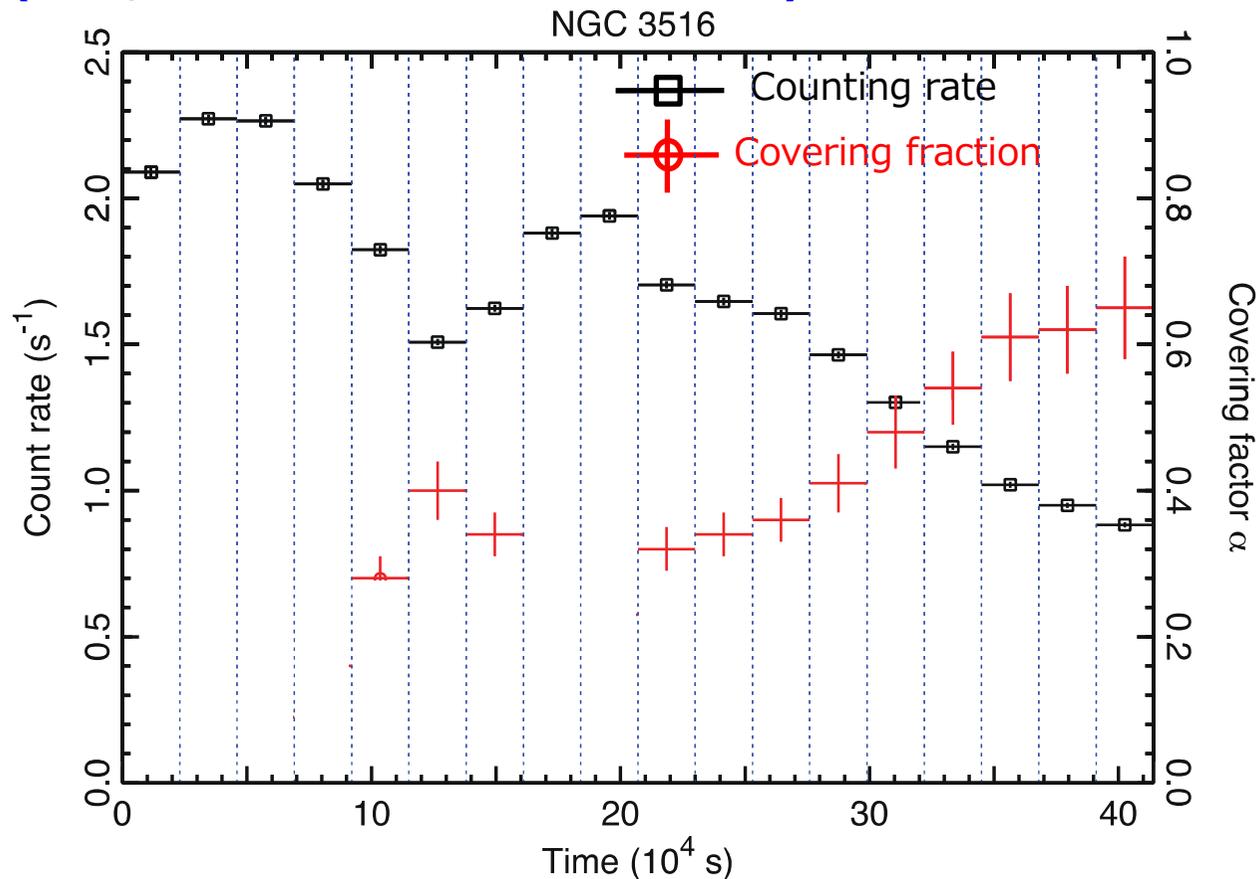
- Observation within \sim a day is divided into four different flux levels
- Flux-sorted spectra are fitted simultaneously **only varying the partial covering fraction.**



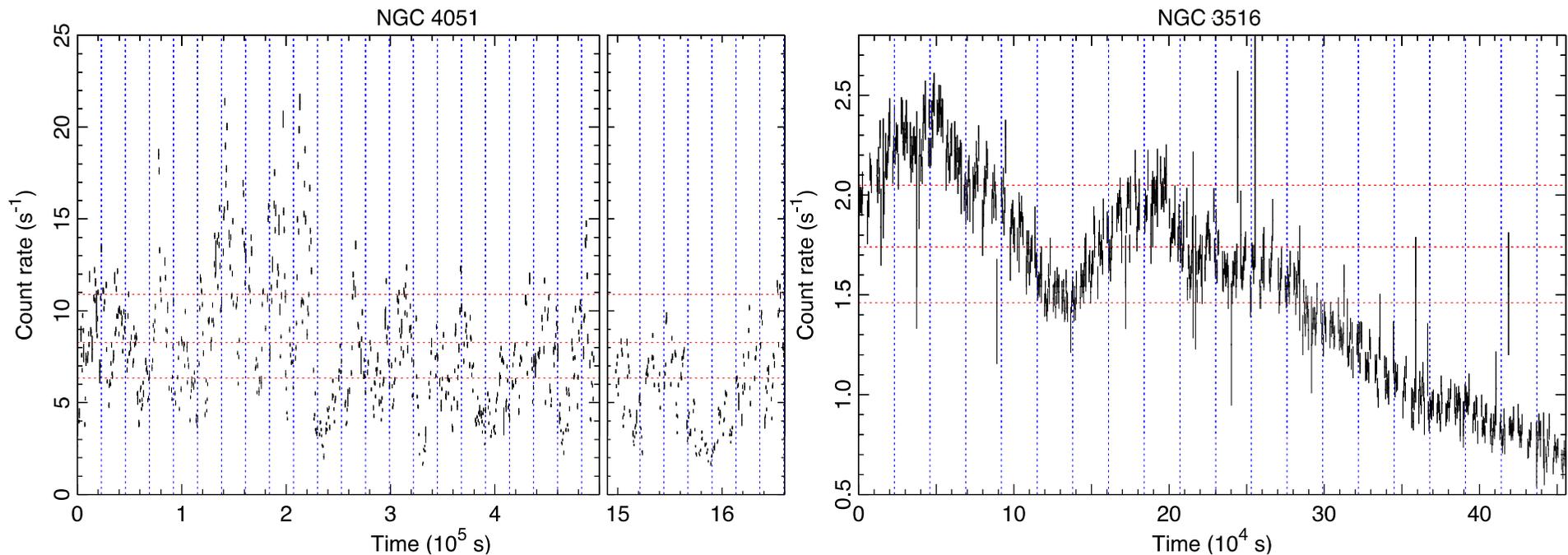
Mizumoto, Ebisawa and Sameshima (2014)

AGNの強度変動の説明

Flux variation of 21 Seyfert galaxies observed with Suaku, explained by only change of the covering fraction (Iso, Ebisawa et al. 2015)

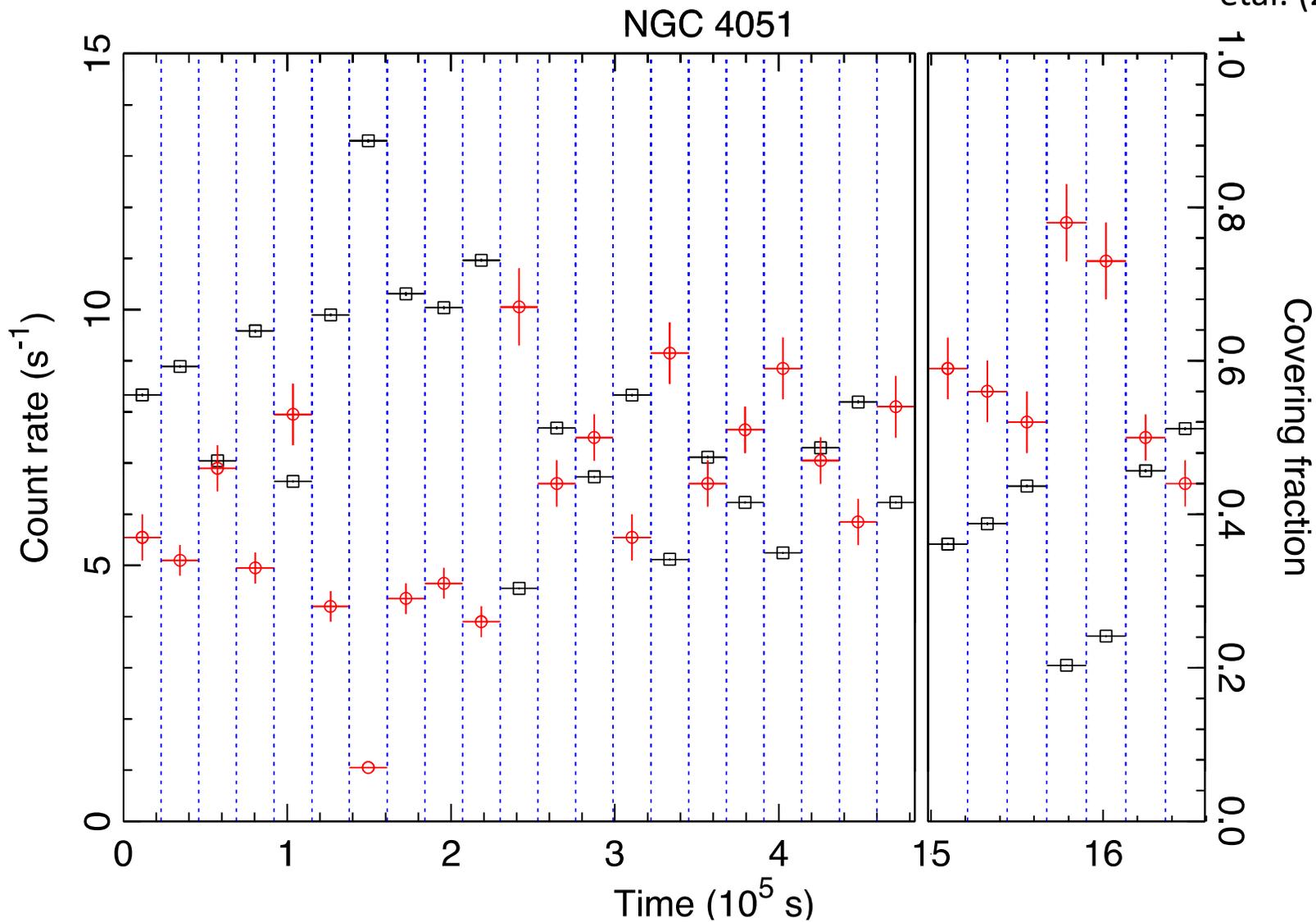


AGNの強度変動の説明



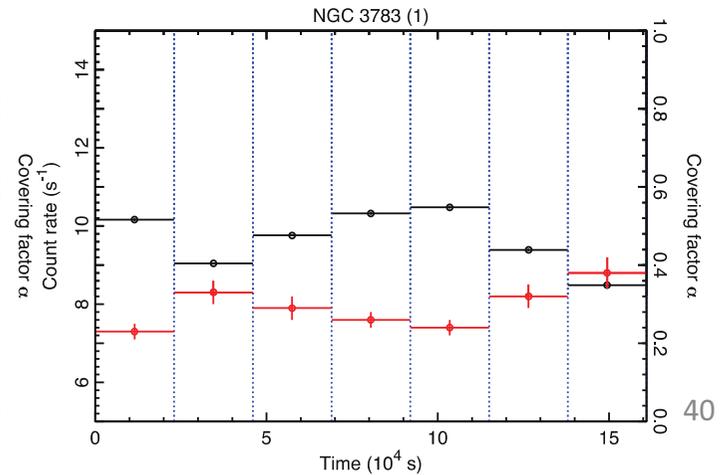
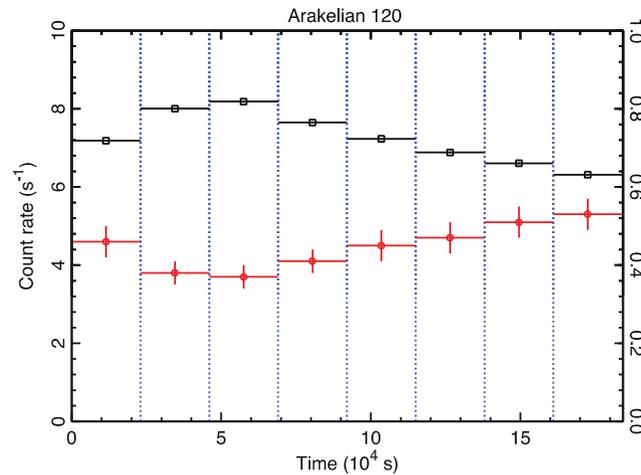
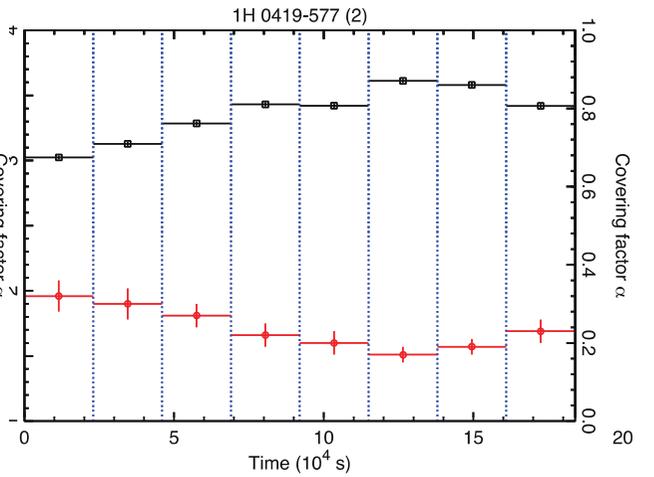
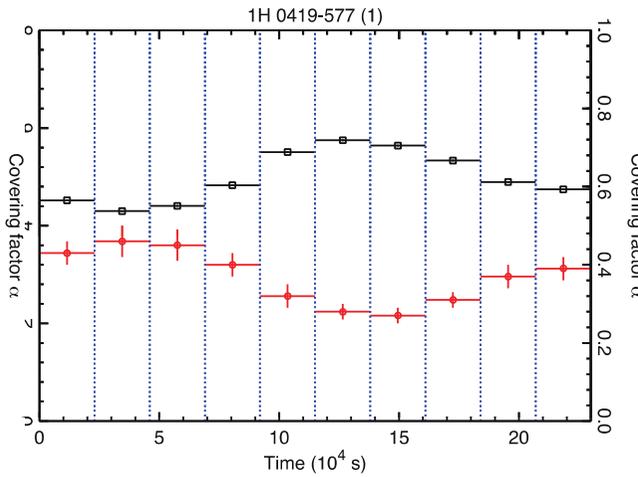
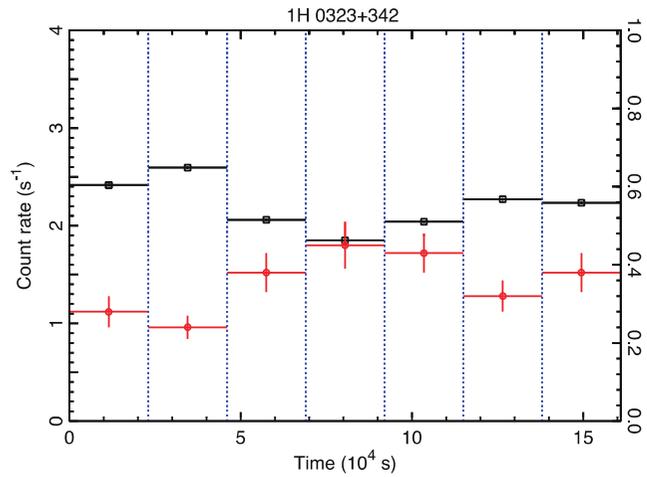
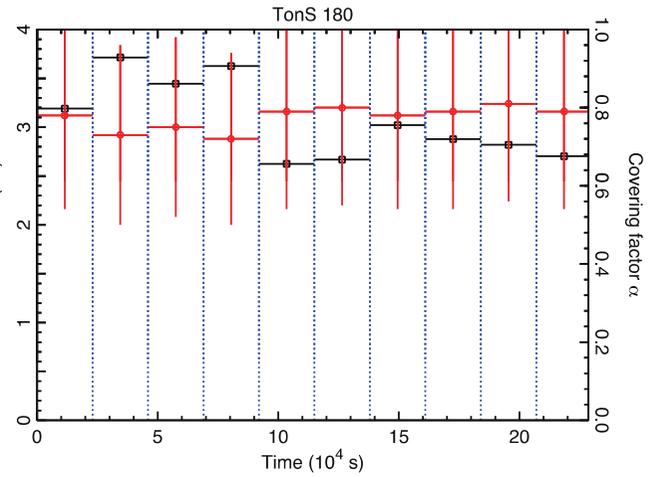
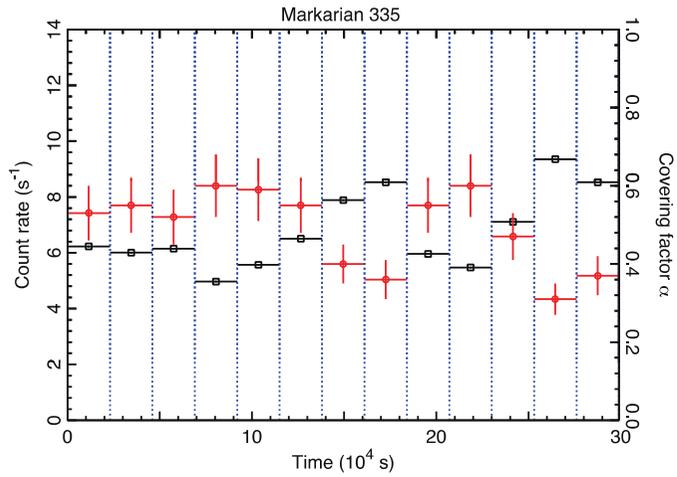
Suzaku observations of NGC4051 and NGC3516
(0.2—12 keV, 1bin=512sec)

Significant and aperiodic variations in various time-scales



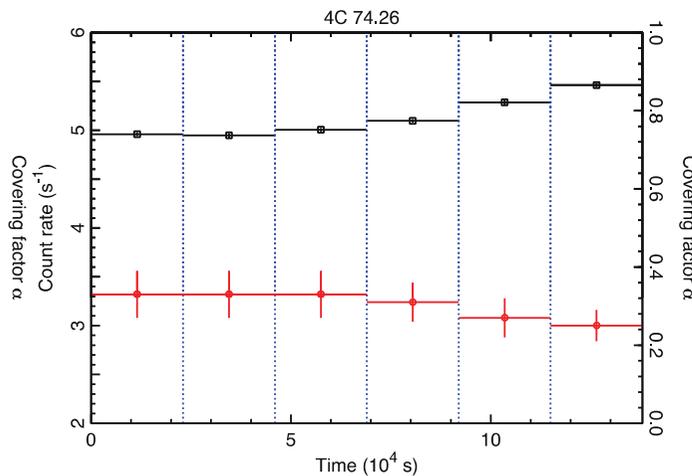
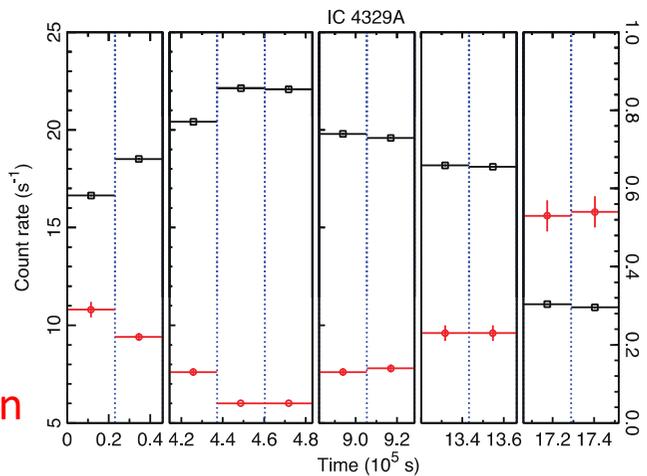
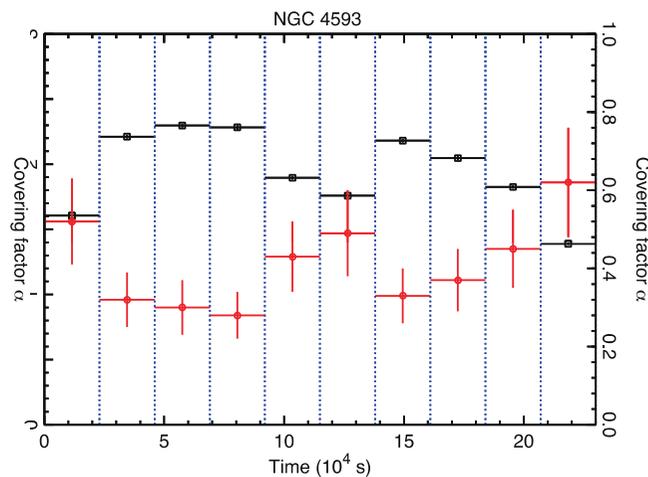
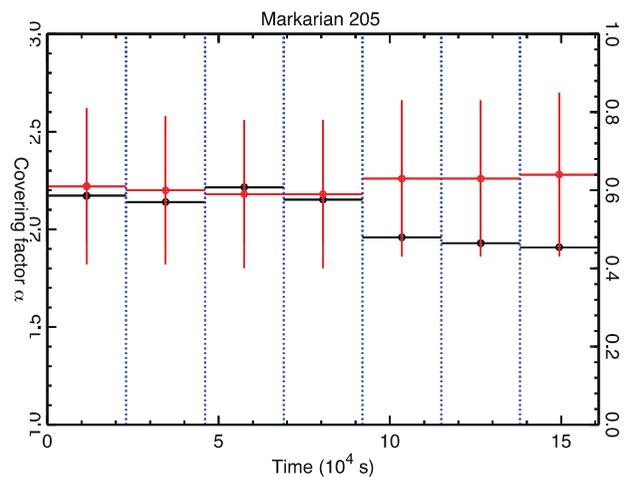
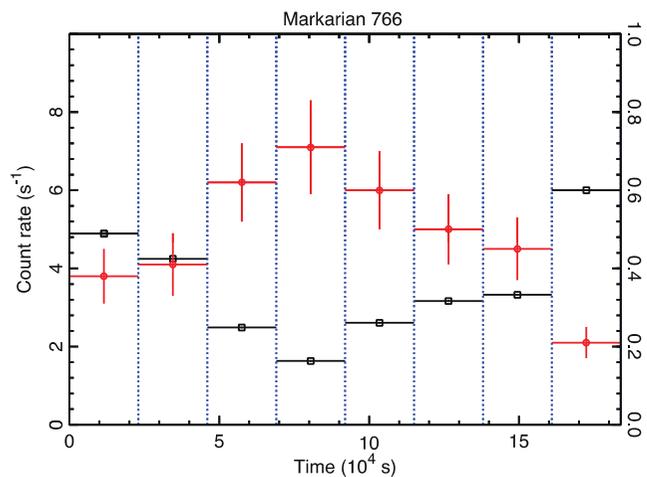
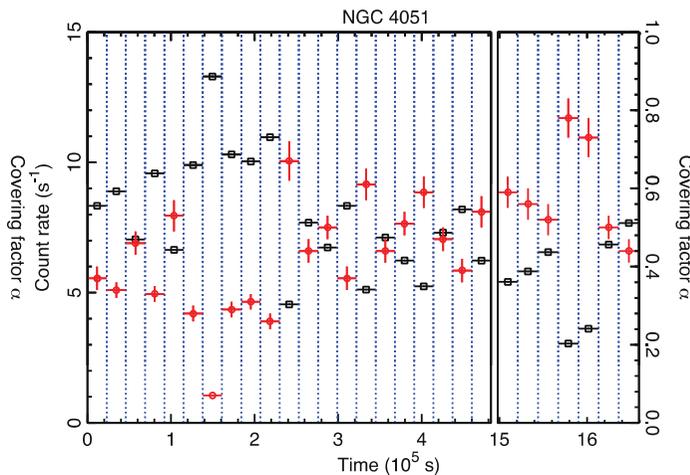
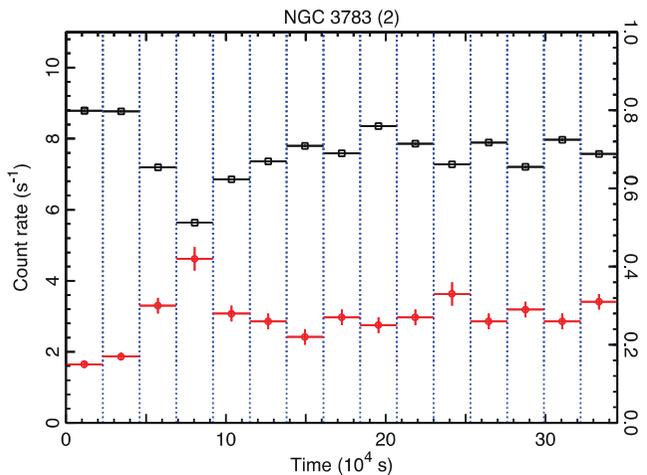
Observed flux variations explained by “constant black hole
luminosity and variable covering fraction”.

Iso, Ebisawa
etal. (2015)

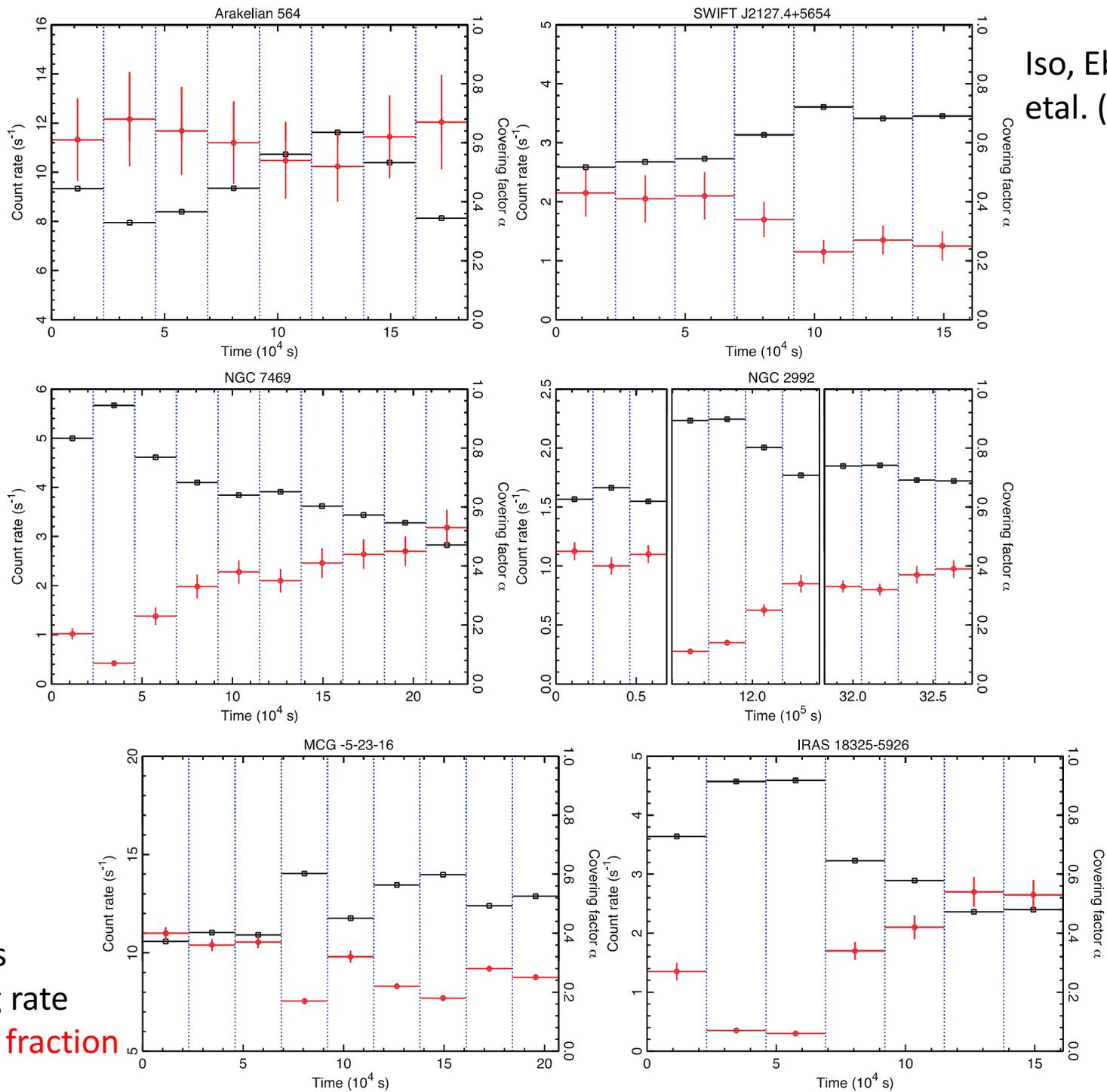


Example of
other sources
Black:countig rate
Red:covering fraction

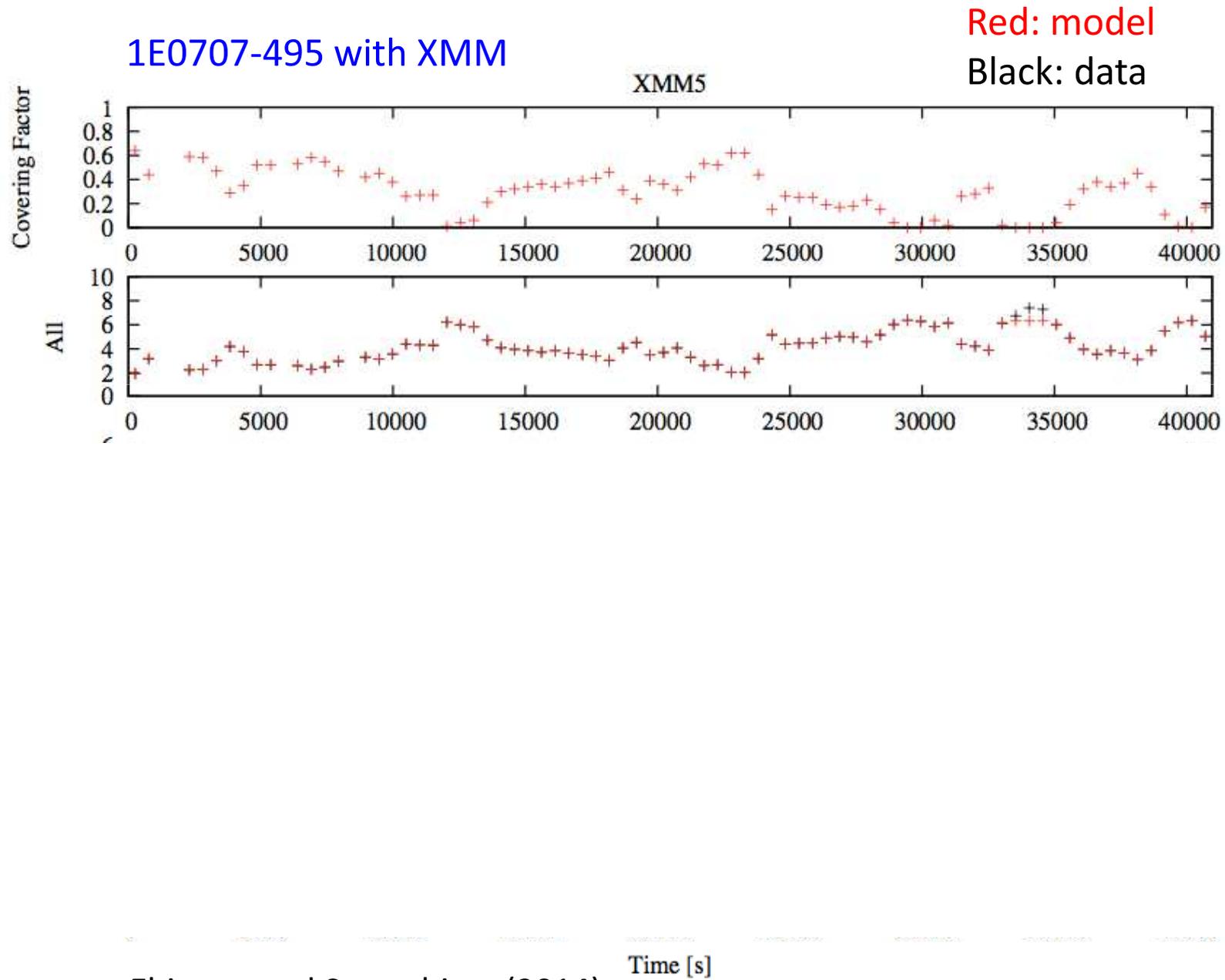
Iso, Ebisawa
etal. (2015)



Example of
other sources
Black:count rate
Red:covering fraction



Example of
other sources
Black:countig rate
Red:covering fraction



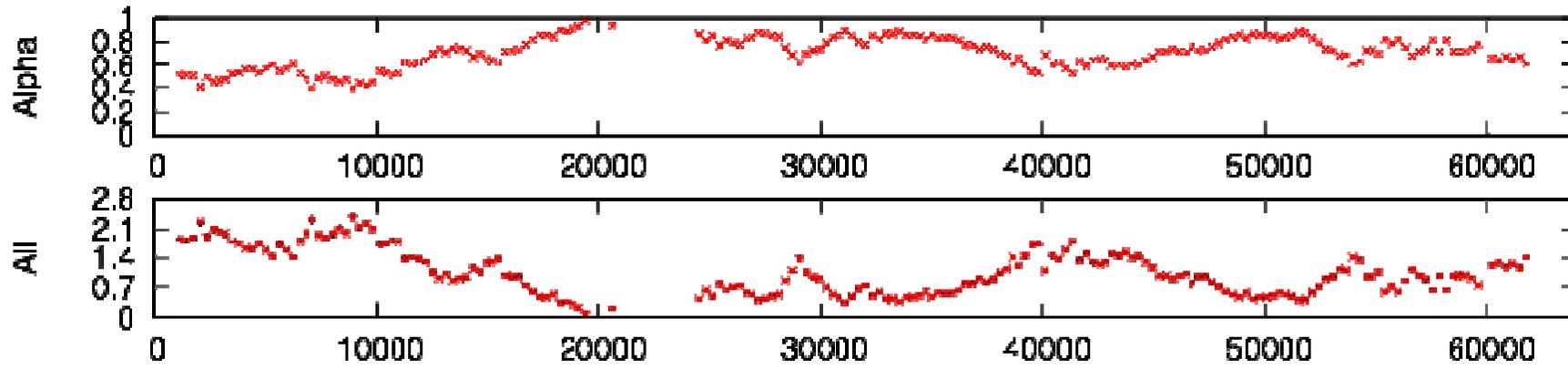
Mizumoto, Ebisawa and Sameshima (2014)

IRAS13224-3809 with XMM

XMM1

Red: model

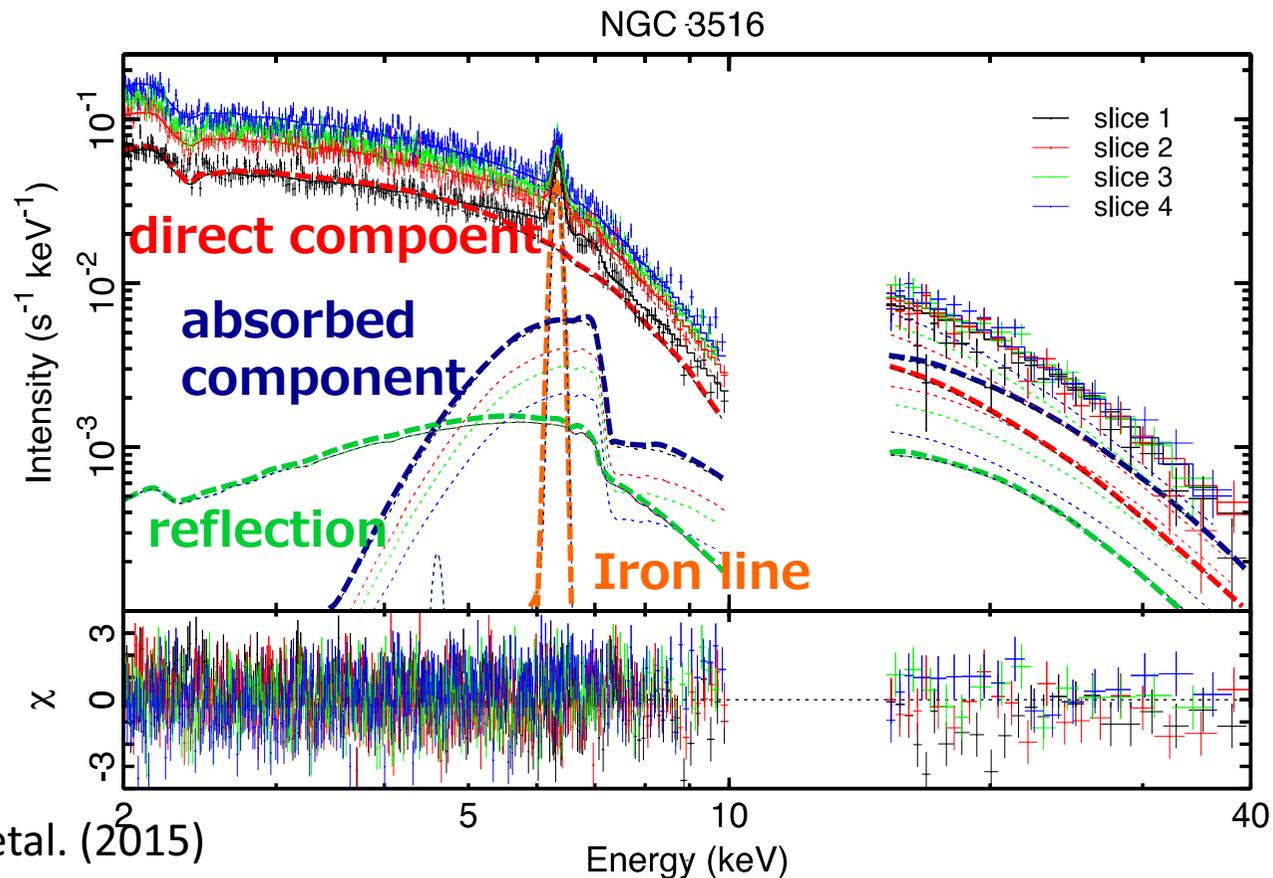
Black: data



Yamasaki et al. (2015)

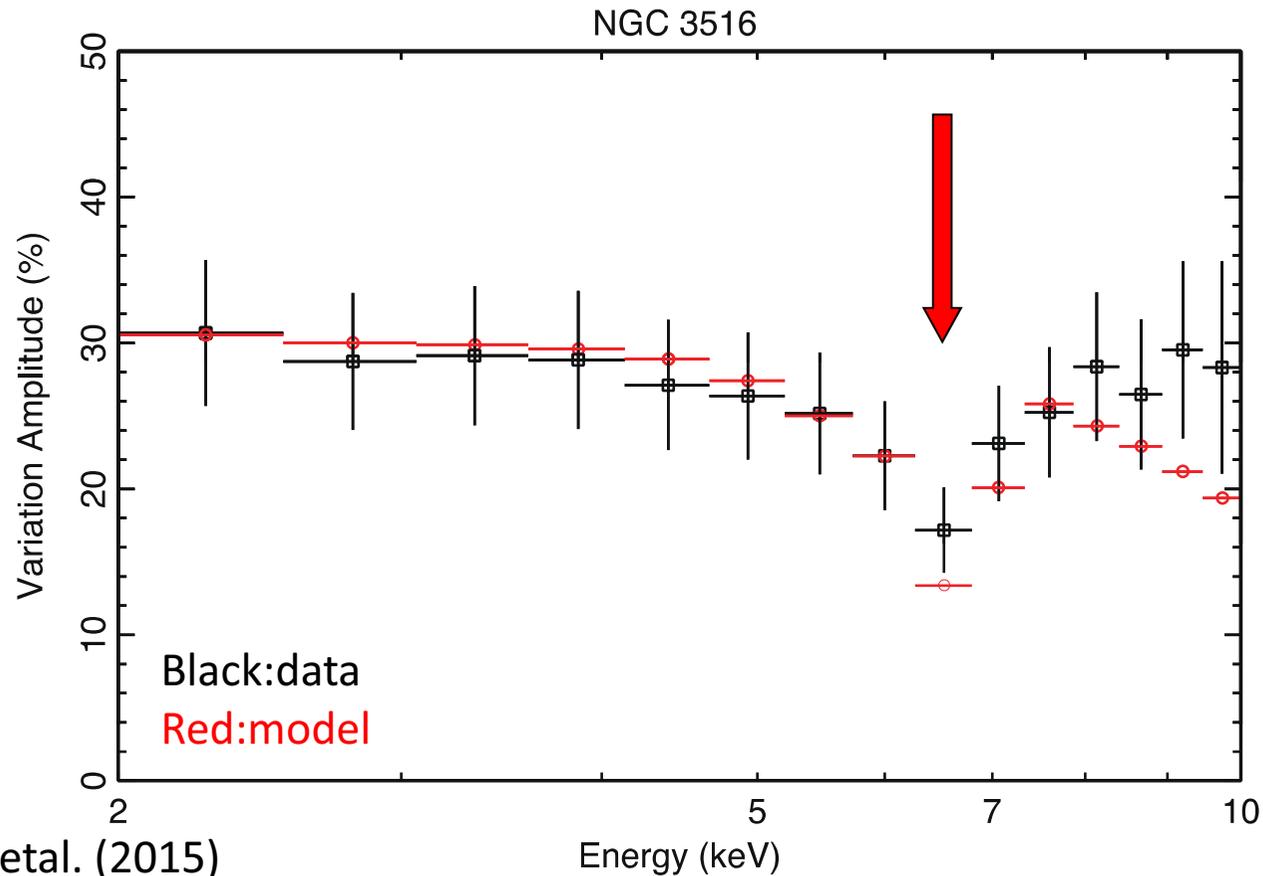
鉄K輝線領域の時間変動の説明

- Variable Partial Coveringモデル **直接成分と吸収成分の変化は逆相関を示す**
- **鉄のKバンドで打ち消し合う**

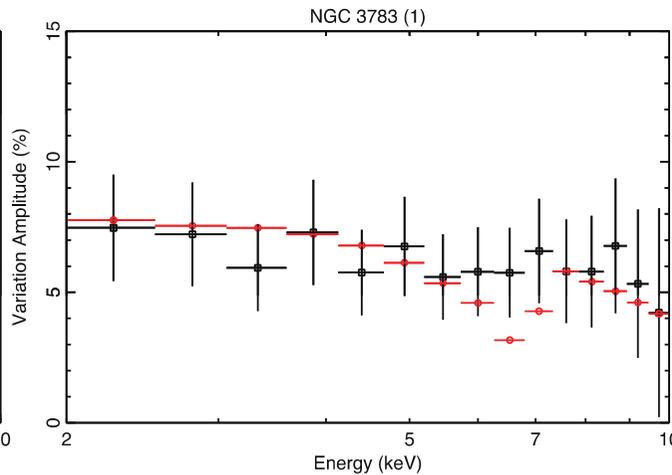
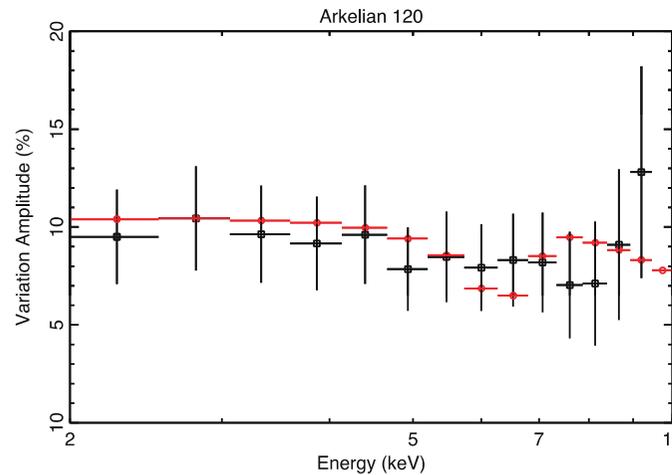
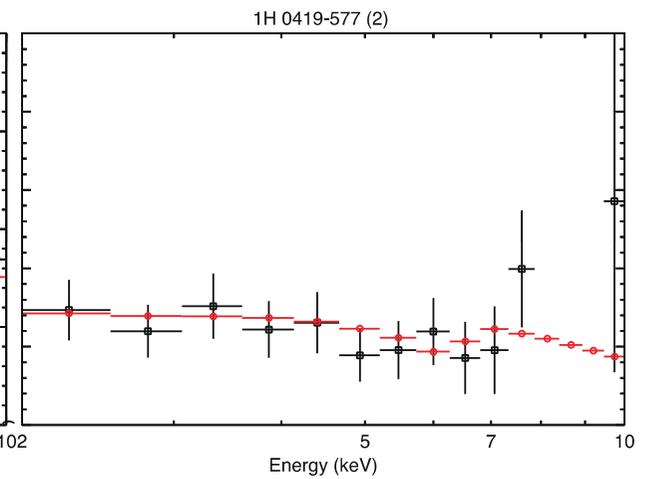
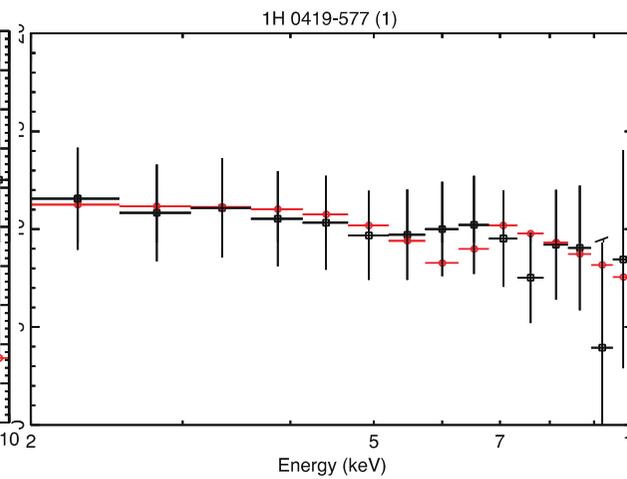
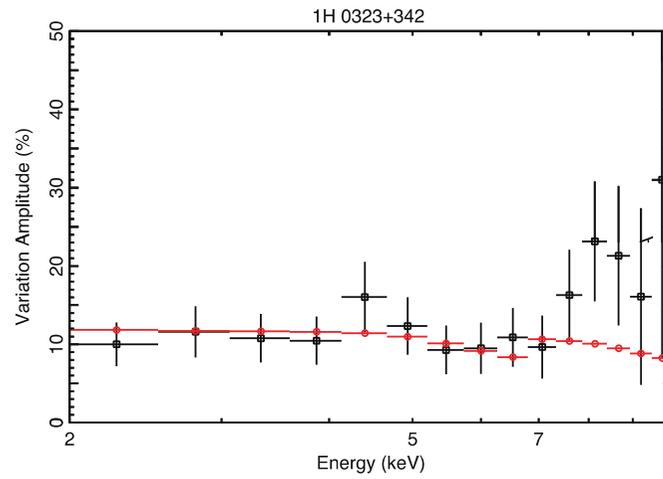
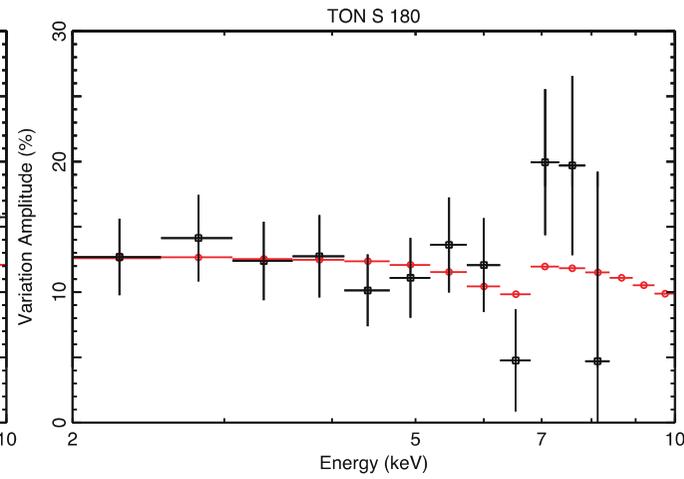
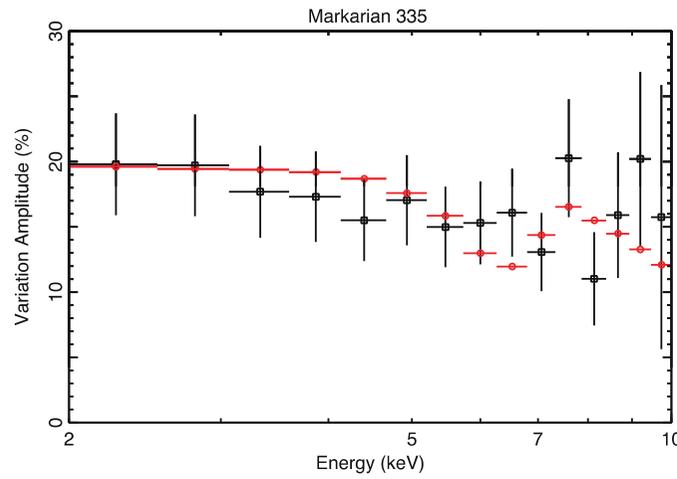


鉄K輝線領域の時間変動の説明

- Observed Root Mean Square spectrum is explained by only variation of the covering fraction

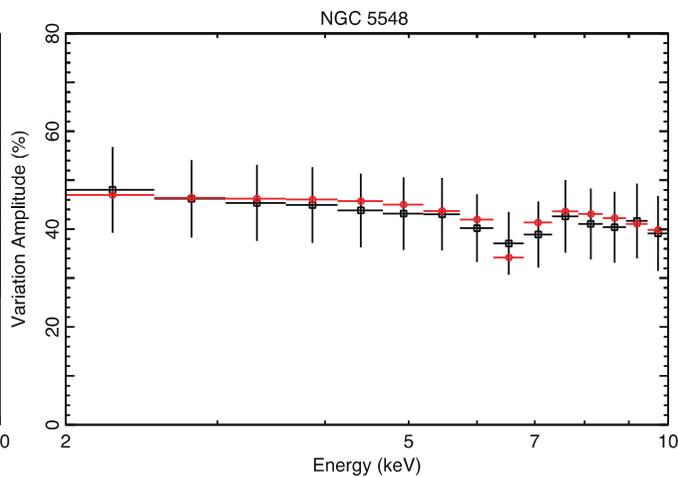
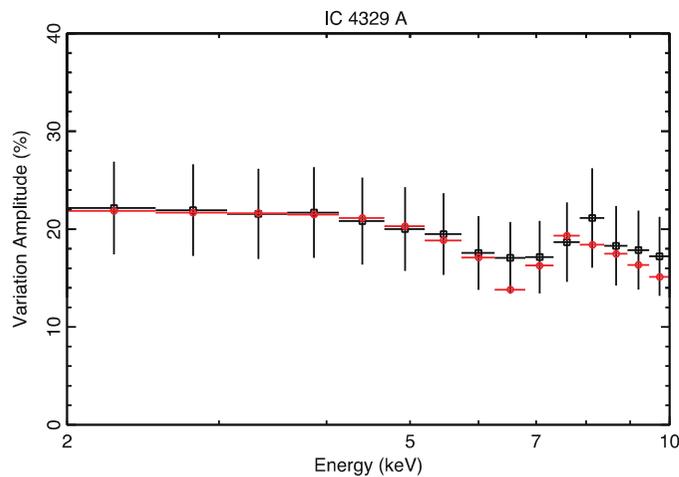
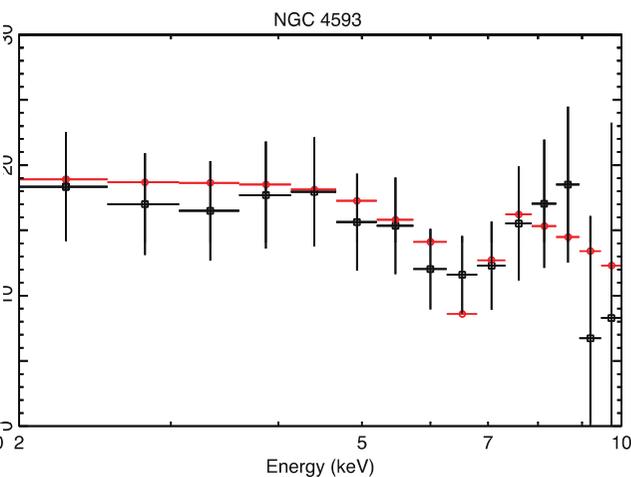
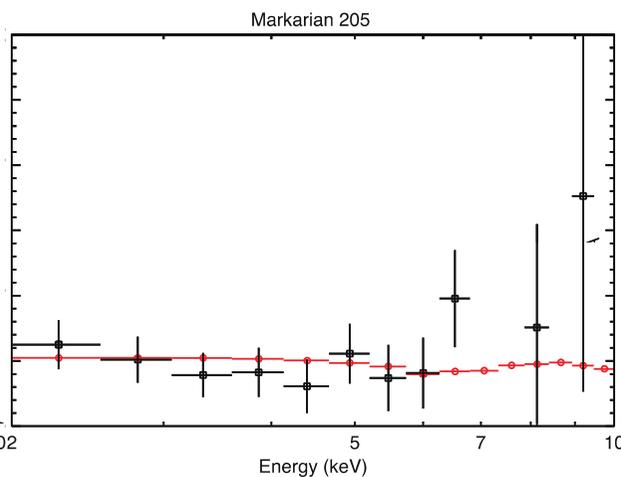
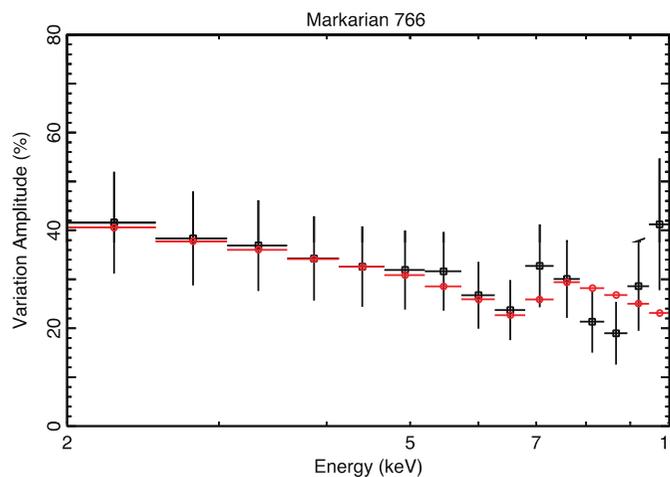
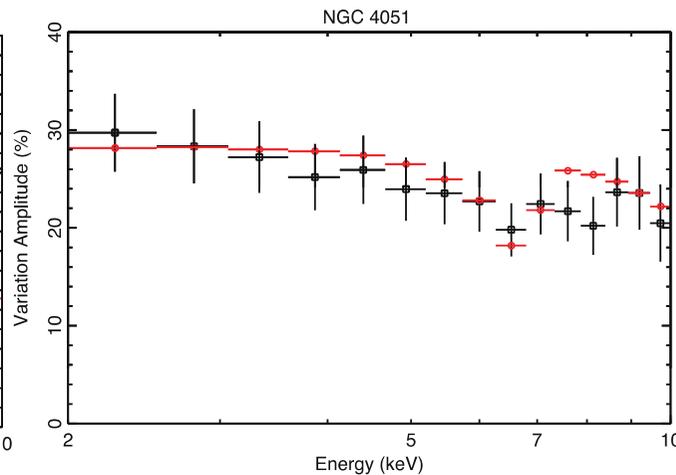
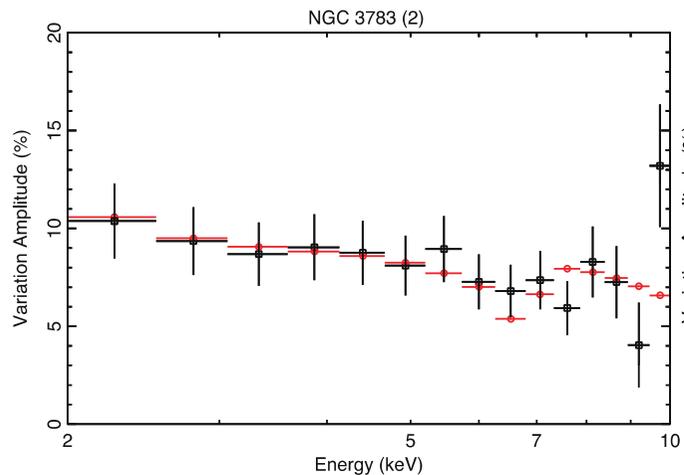


Iso, Ebisawa
etal. (2015)



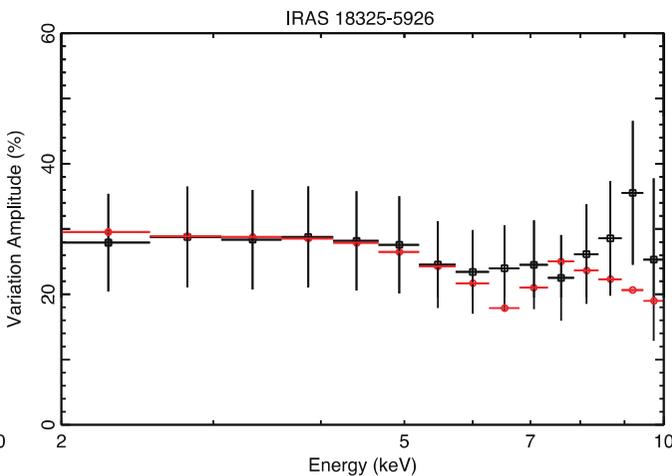
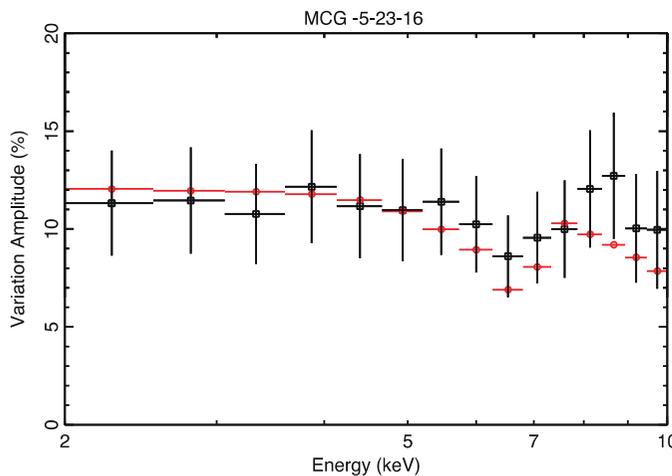
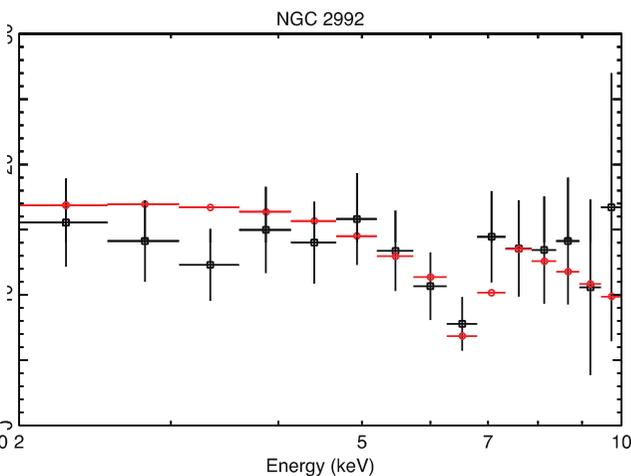
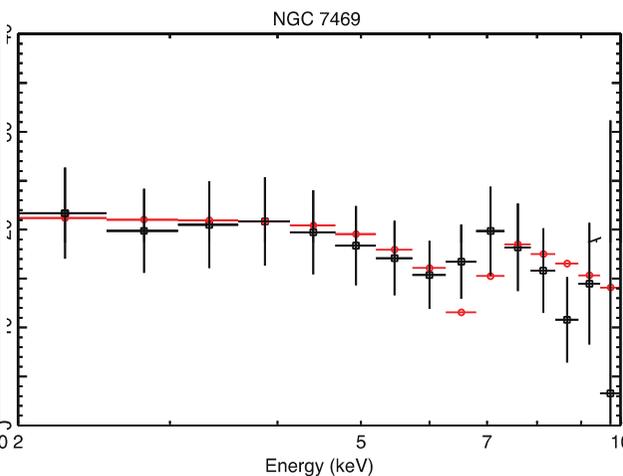
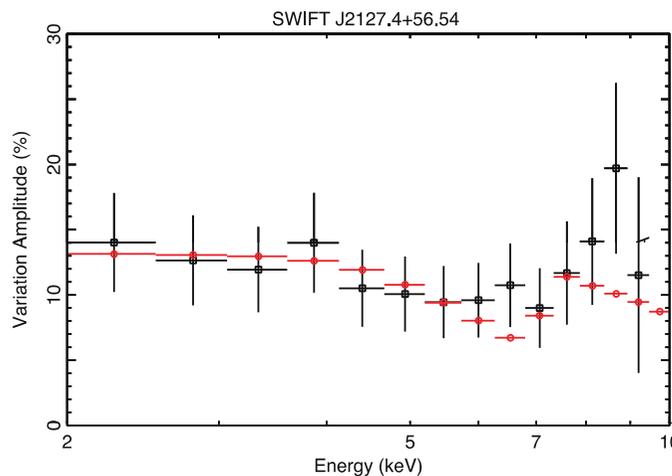
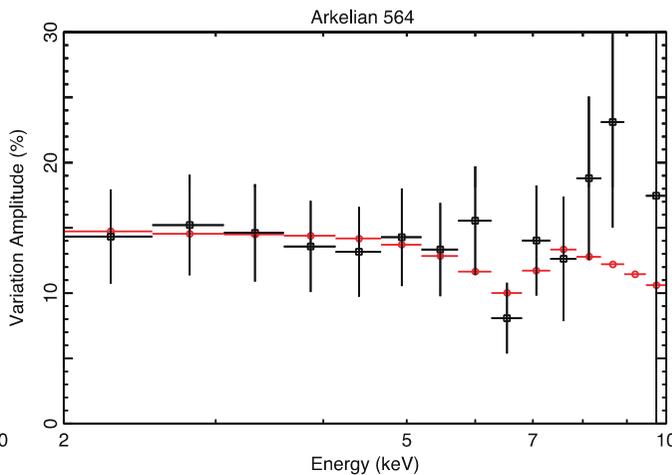
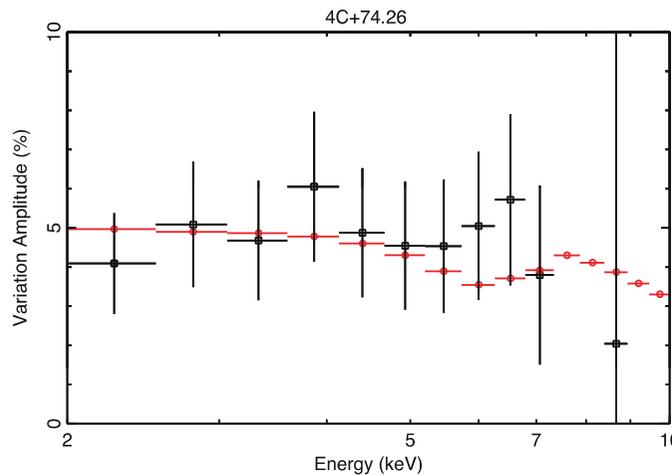
Example of
other sources
Black:data
Red:model

Iso, Ebisawa
etal. (2015)



Example of
other sources
Black:data
Red:model

Iso, Ebisawa
etal. (2015)

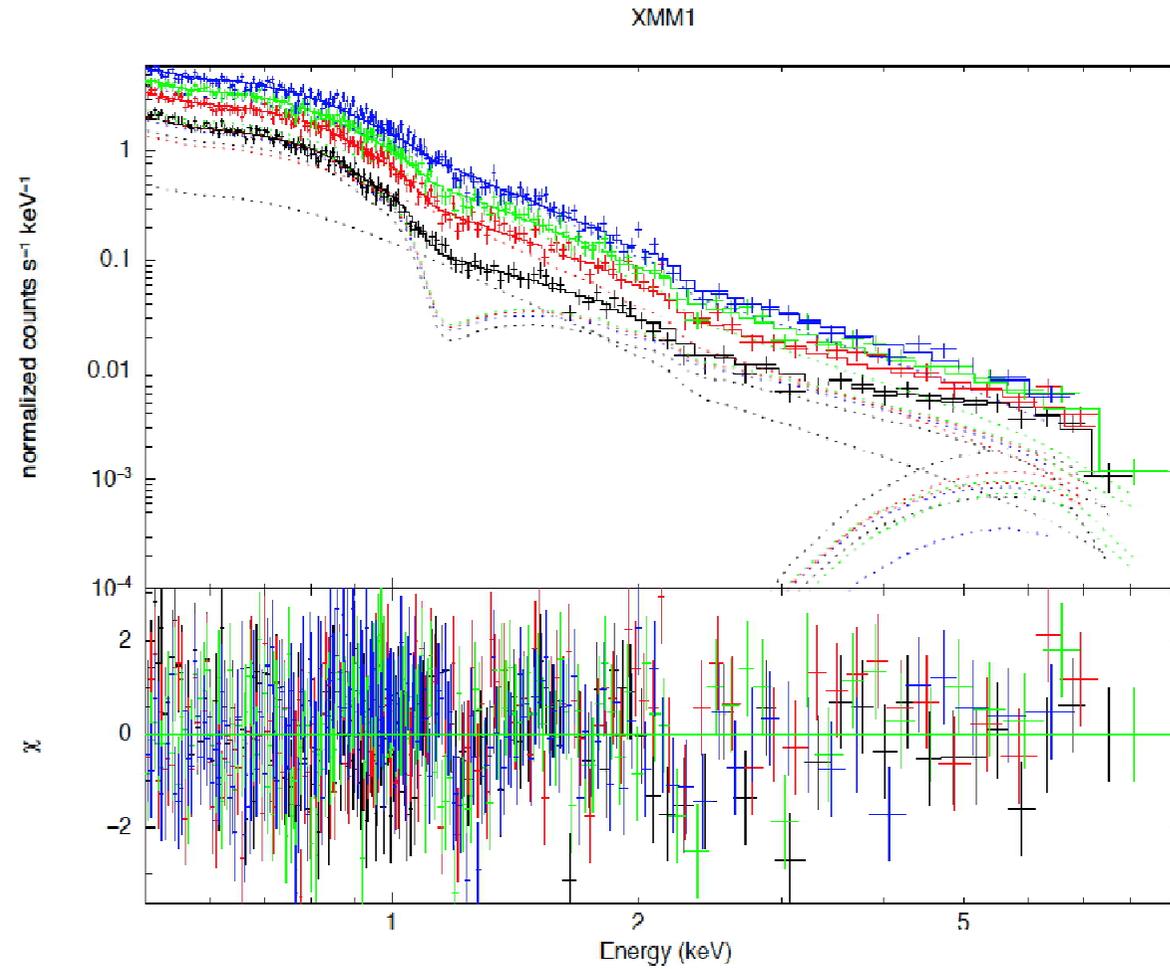


Example of
other sources
Black:data
Red:model

鉄L輝線領域の時間変動の説明

- Iron L-peaks are seen in the RMS spectra when iron L-absorption edges are particularly strong.
- Naturally explained with the VDPC model, where the fluxes of the direct component and the absorbed component exhibit anti-correlation.
- The fractional variation peaks at the energy where the flux separation between the two spectral components is the widest.

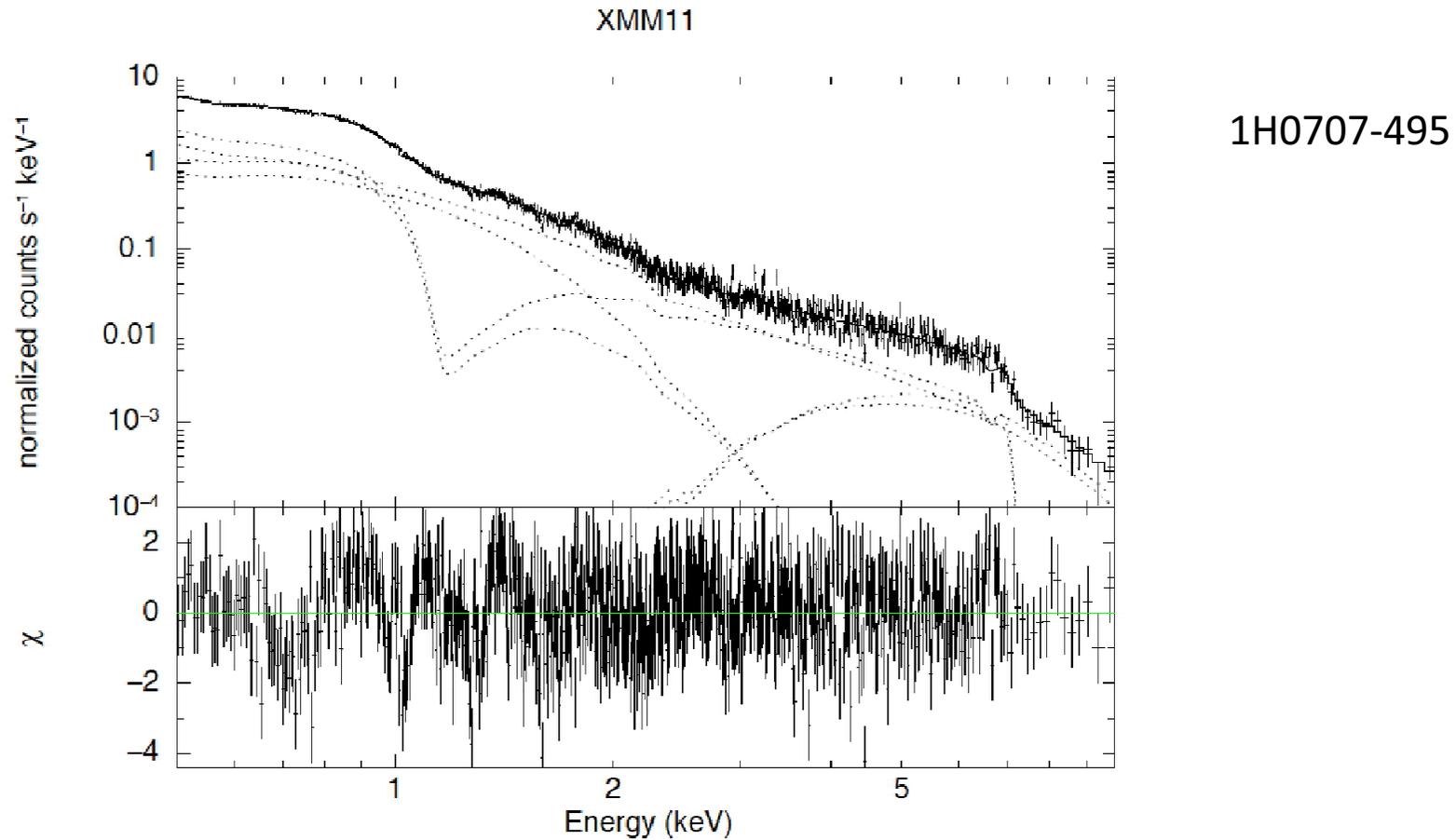
Characteristic iron-L feature in the RMS spectra



RAS13224-3809

.....ki et al. (2015)

Characteristic iron-L feature in the RMS spectra



Yamasaki et al. (2015)

話の内容

1. 標準降着円盤の観測
2. 広がったように見える鉄輝線の観測
3. まとめ

3.まとめ

- ブラックホール連星系において、標準降着円盤からのX線スペクトルが観測されている
 - 標準降着円盤のX線スペクトル観測から、ブラックホールの質量とスピンを推定することができる
- セイファート銀河のX線スペクトル中に、広がった鉄輝線のような構造が観測されている
 - 広がった鉄輝線のような構造は、(おそらく)ブラックホール近傍の降着円盤からの反射ではなく、視線上に存在する多くの吸収物質による部分吸収で説明できる