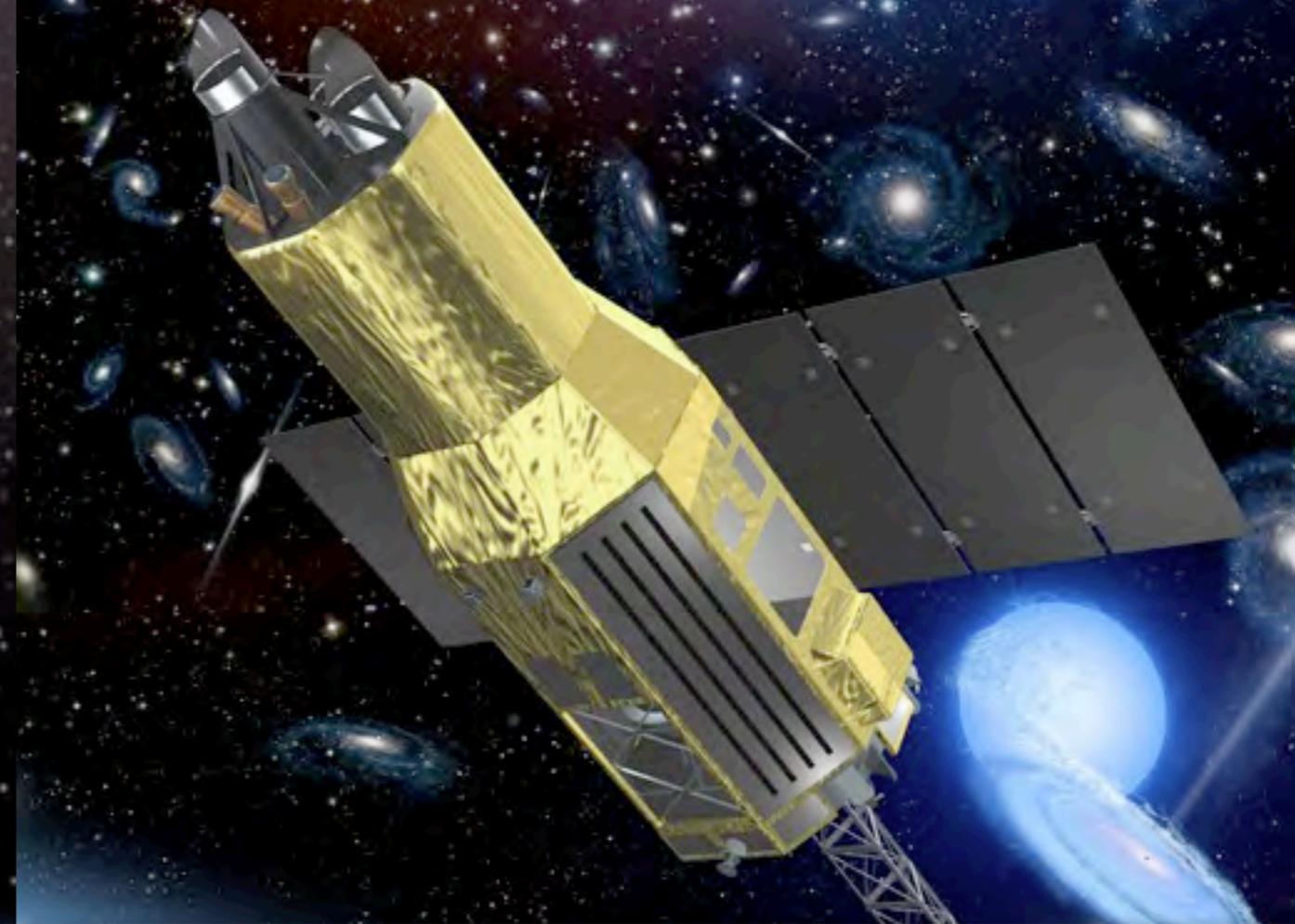


Study of the Galactic Center Region with X-ray Satellites



すざく衛星 2005年



ASTRO-H衛星 (NeXT) 2013年度

Takeshi Go TSURU Kyoto University, JAPAN

Why the center of the Milky Way Galaxy ?

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最近傍の巨大ブラックホール

⇒ 最も確実なブラックホール物理学

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⇒ 原子物理・輻射物理に立脚した確かな物理

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Why すざく ?

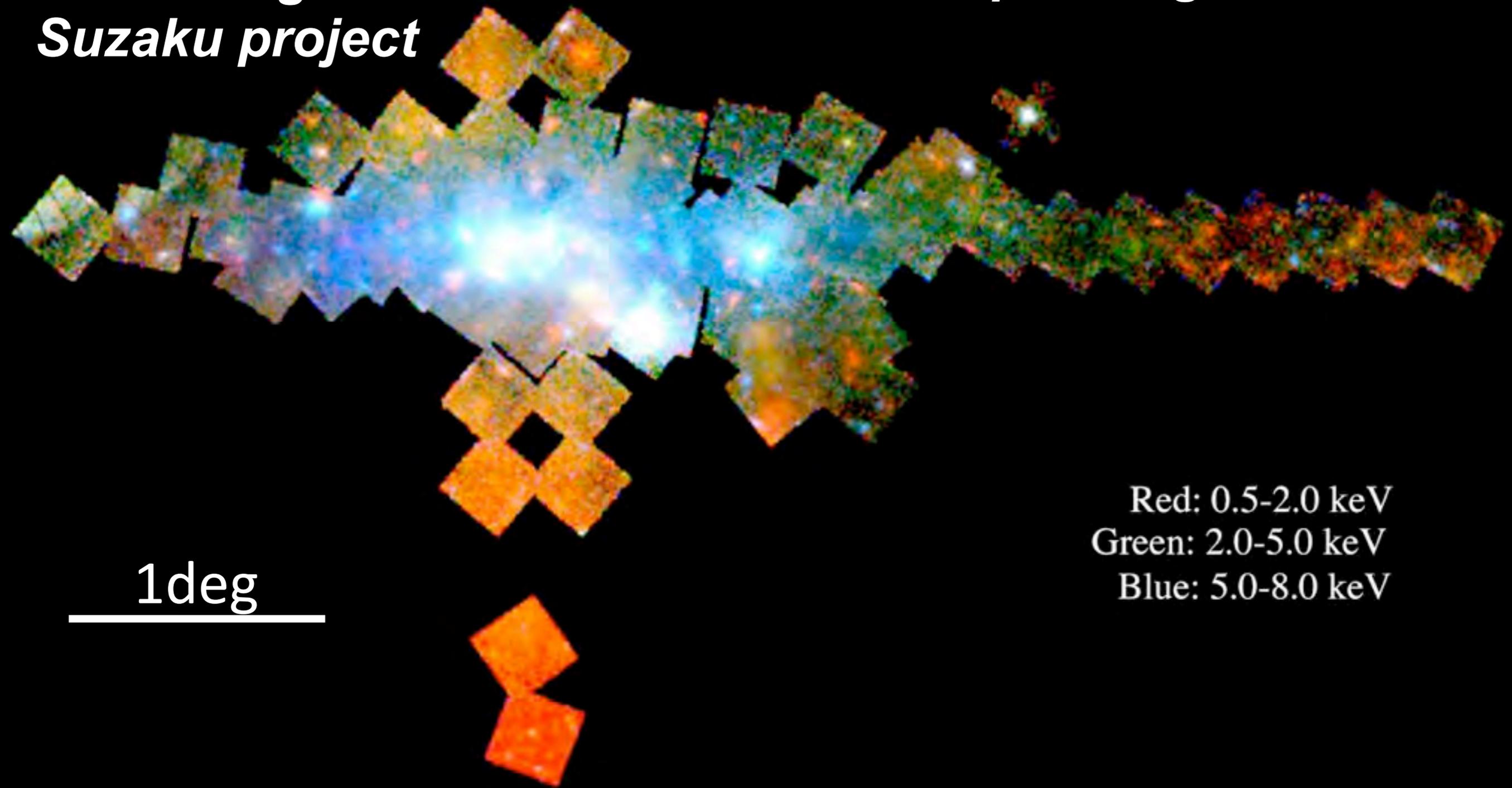
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新しい宇宙像の構築へ

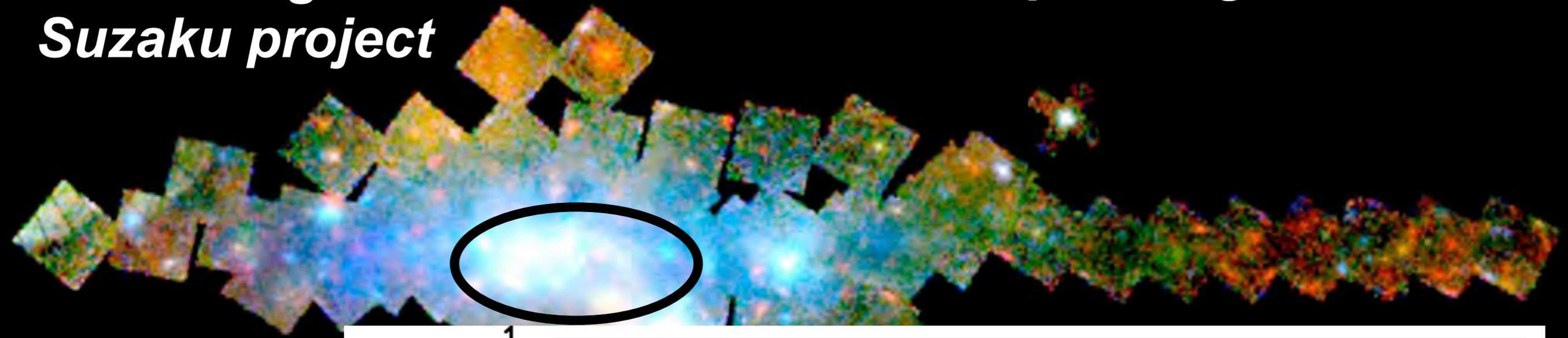
*the GC region
Suzaku project*

>60pointings, 3000ksec

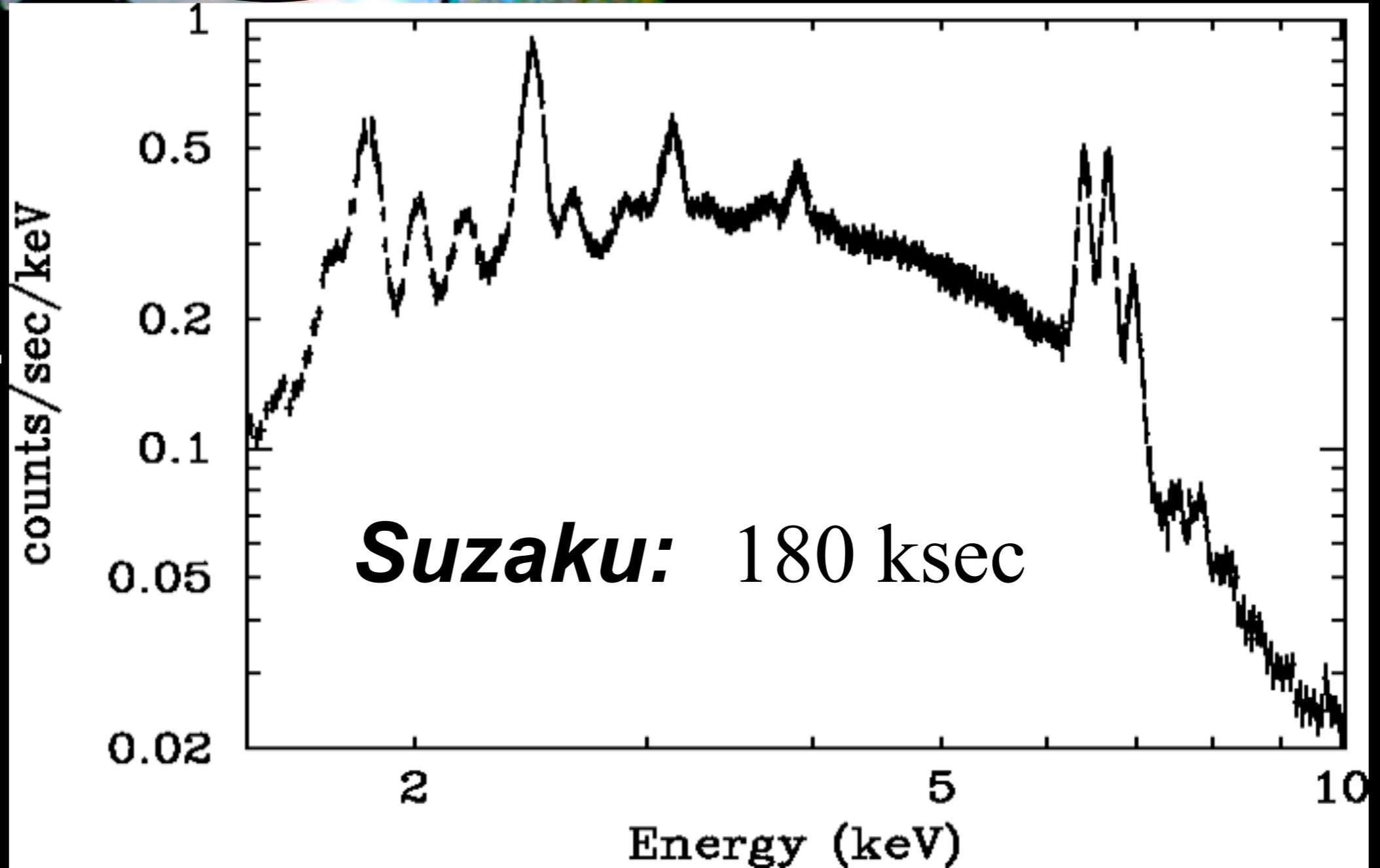


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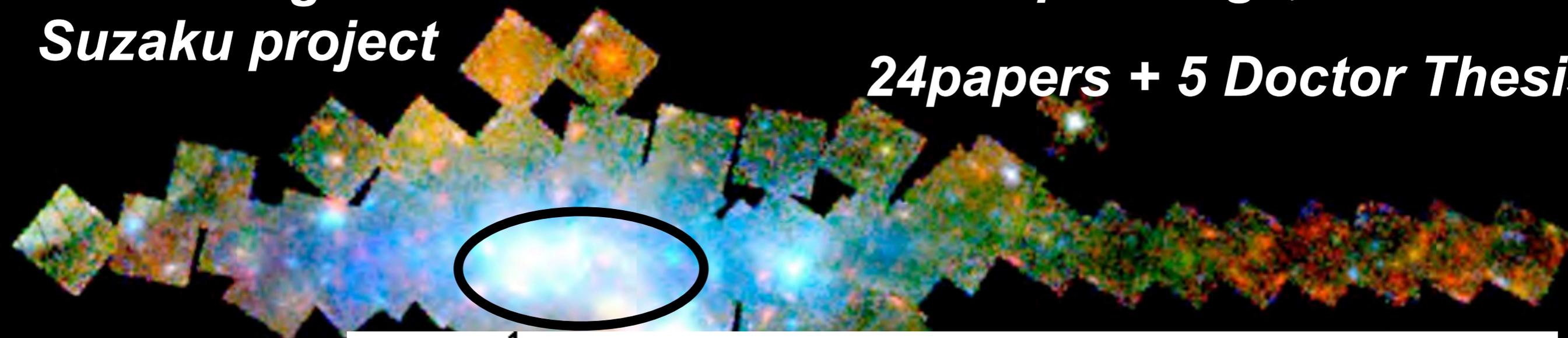


1deg

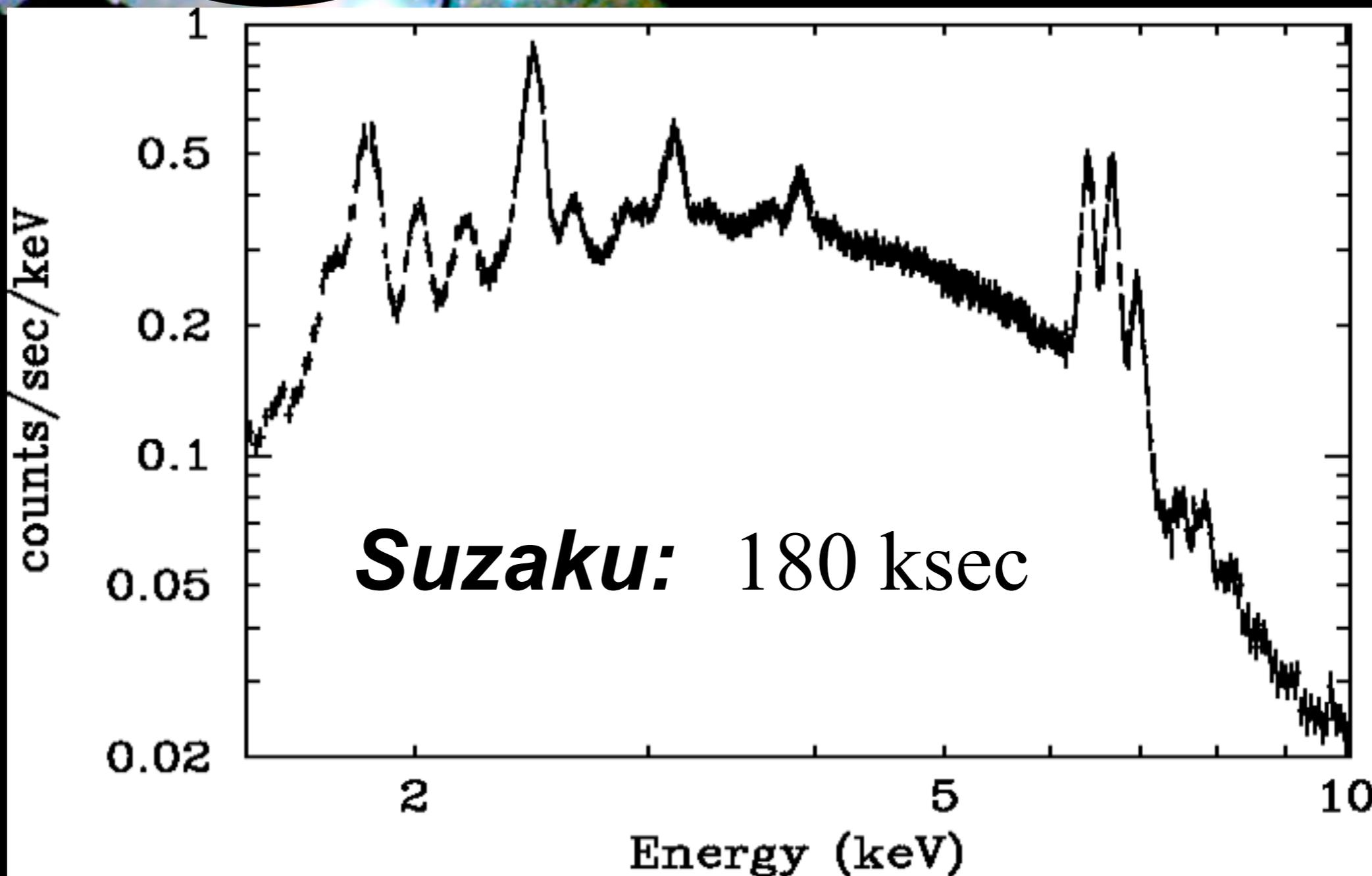


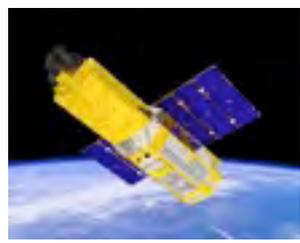
*the GC region
Suzaku project*

*>60pointings, 3000ksec
24papers + 5 Doctor Thesis*

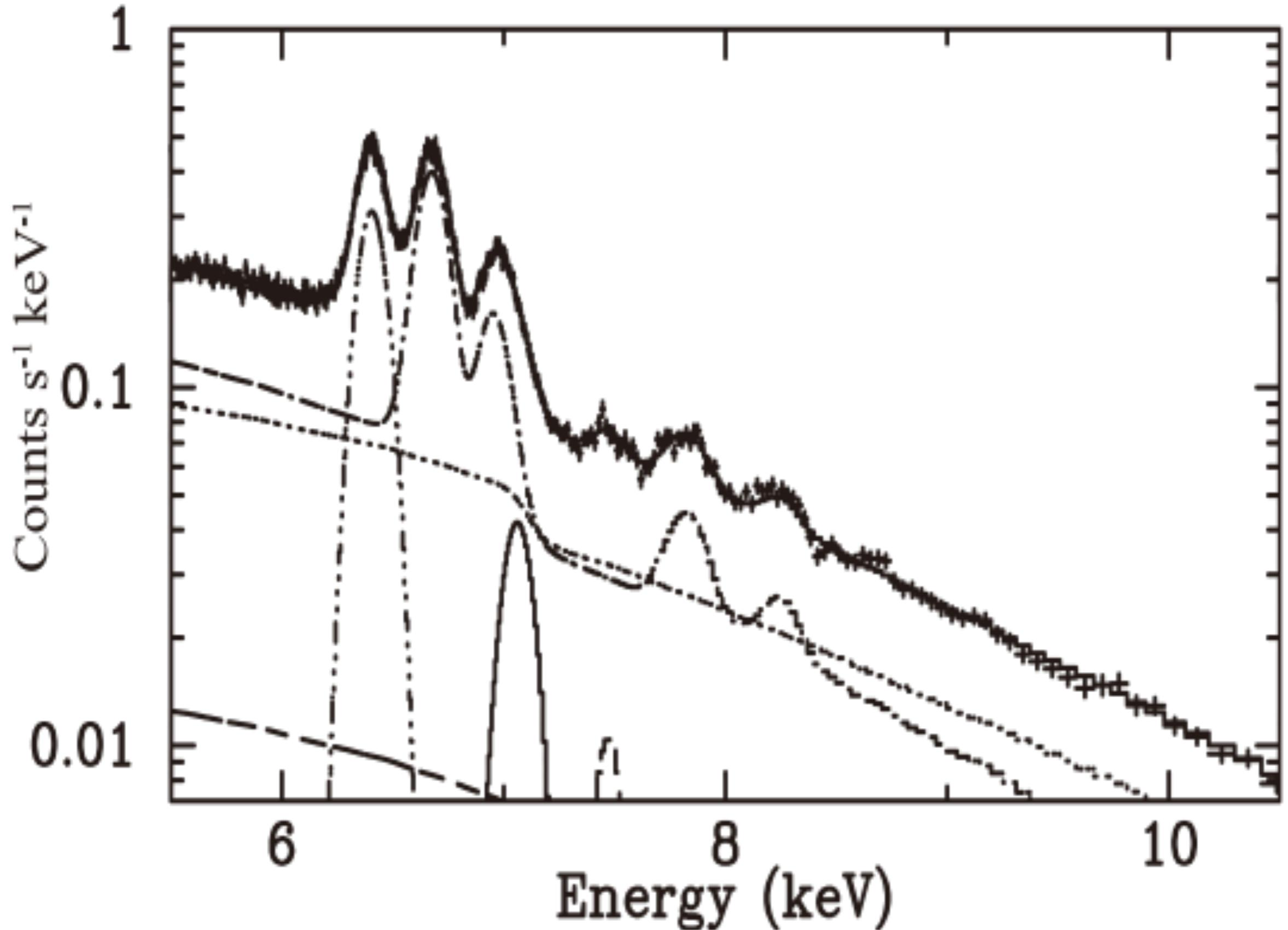


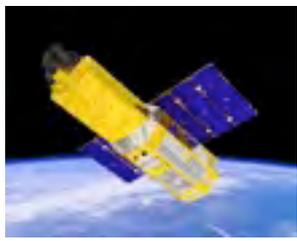
1deg



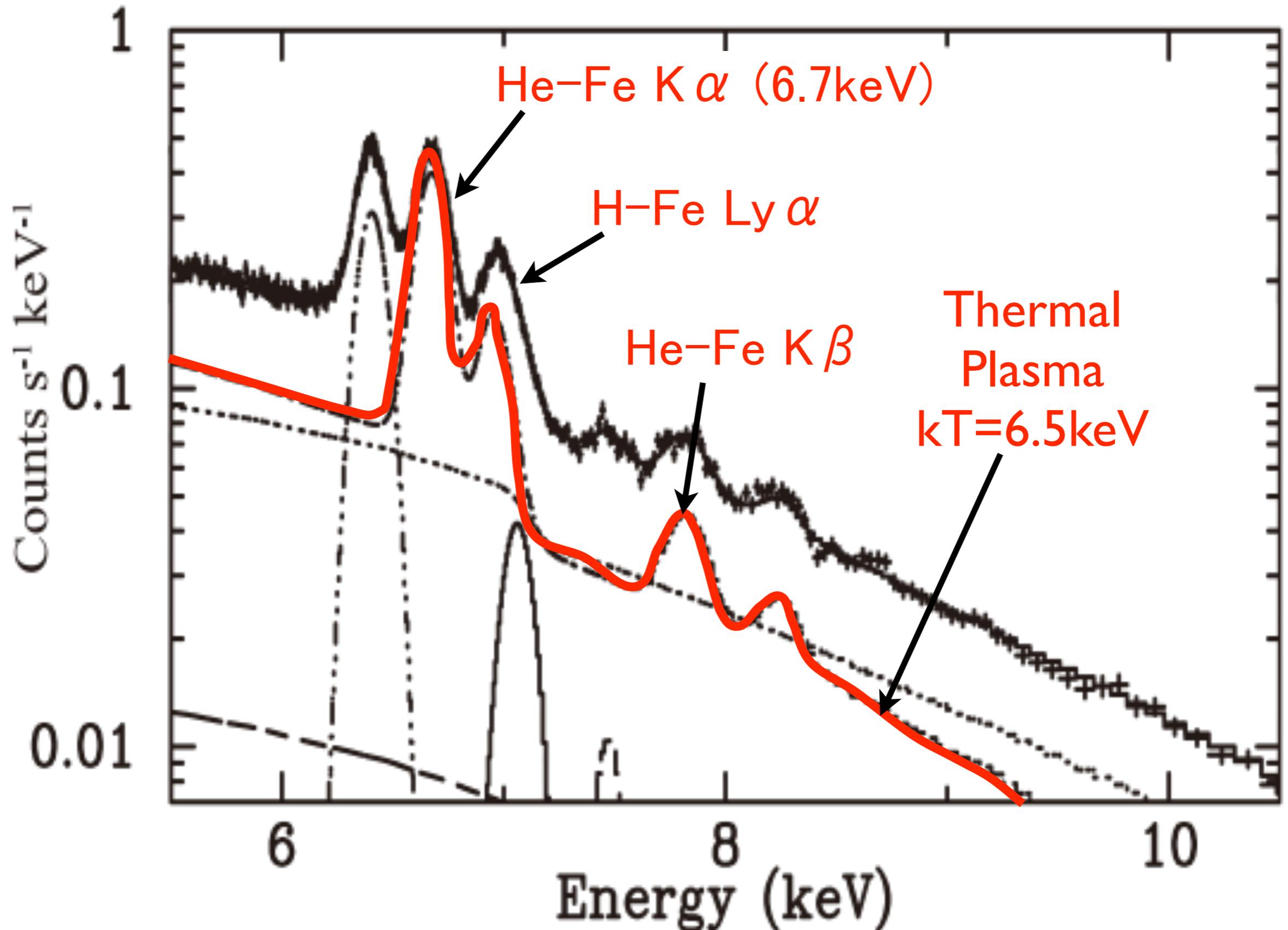


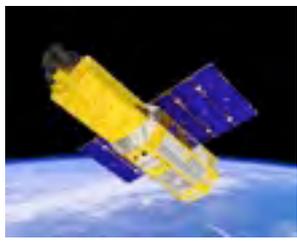
Suzaku Spectrum of the Galactic center region



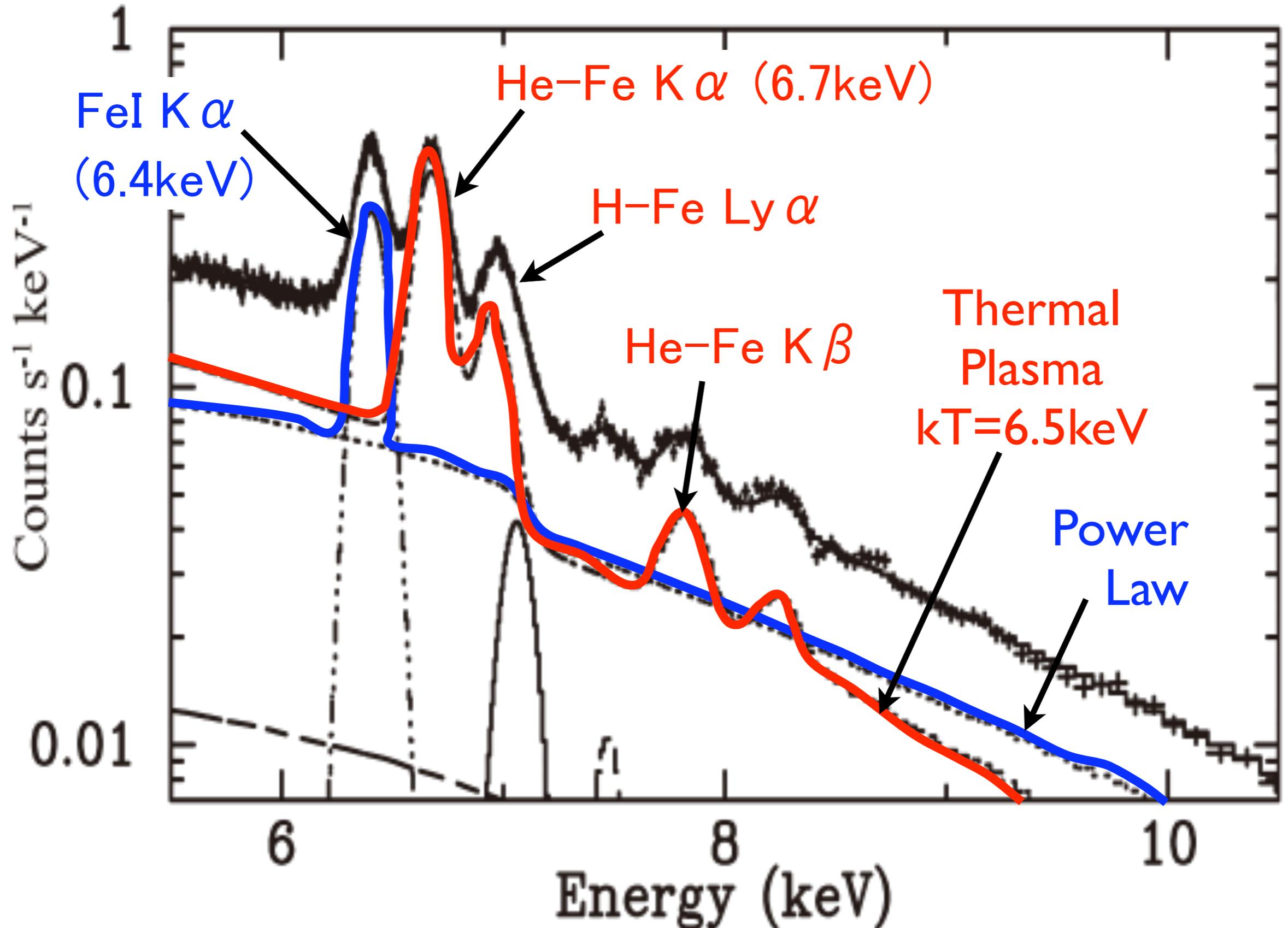


Suzaku Spectrum of the Galactic center region



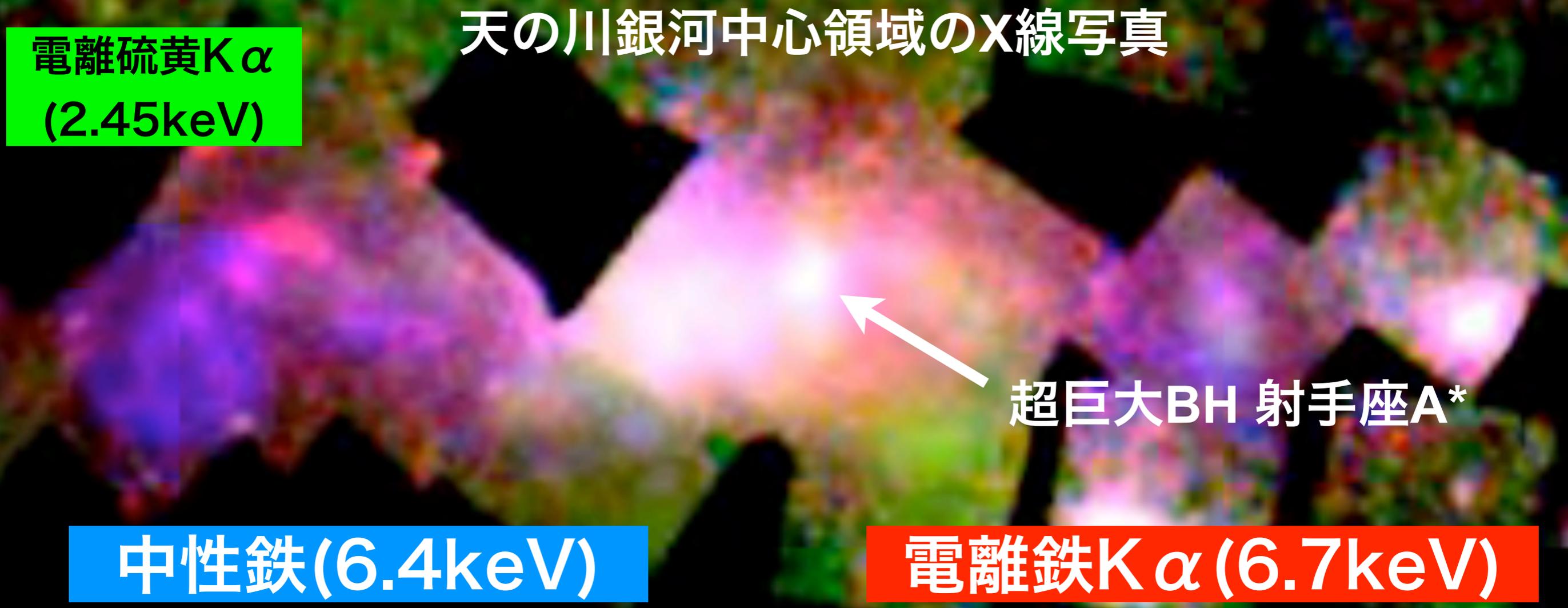


Suzaku Spectrum of the Galactic center region



天の川銀河中心領域のX線写真

電離硫黄K α
(2.45keV)



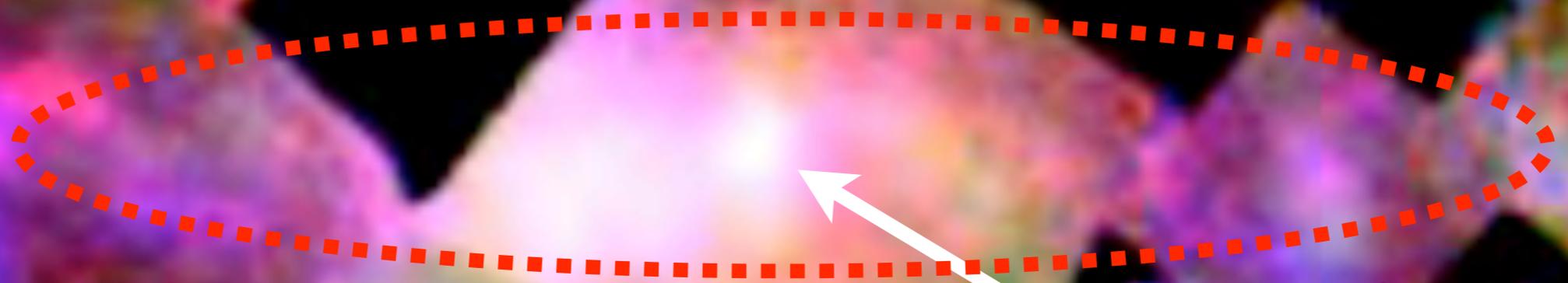
超巨大BH 射手座A*

中性鉄(6.4keV)

電離鉄K α (6.7keV)

天の川銀河中心領域のX線写真

電離硫黄K α
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超巨大BH 射手座A*

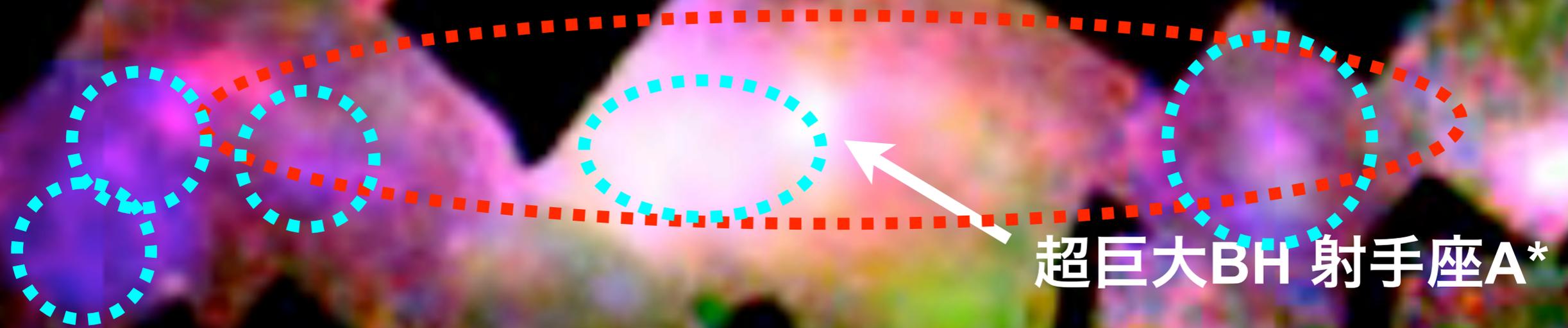
中性鉄(6.4keV)

電離鉄K α (6.7keV)

T $\sim 1 \times 10^8$ Kの
高温プラズマ

天の川銀河中心領域のX線写真

電離硫黄K α
(2.45keV)



超巨大BH 射手座A*

中性鉄(6.4keV)

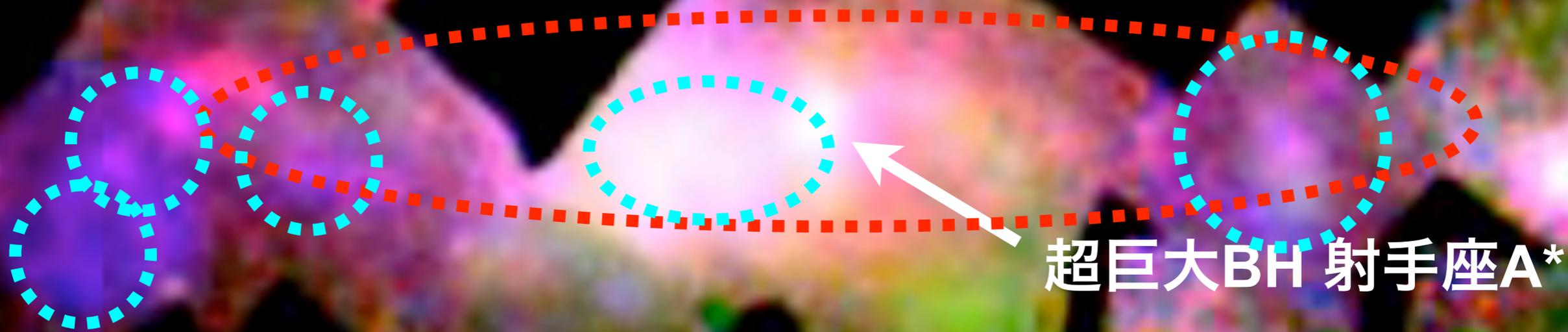
分子雲からの
蛍光X線

電離鉄K α (6.7keV)

T \sim 1 \times 10⁸Kの
高温プラズマ

天の川銀河中心領域のX線写真

電離硫黄K α
(2.45keV)



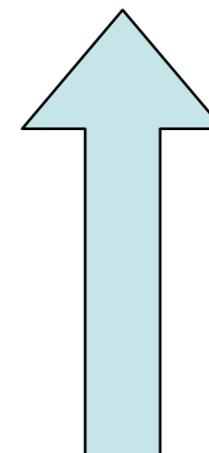
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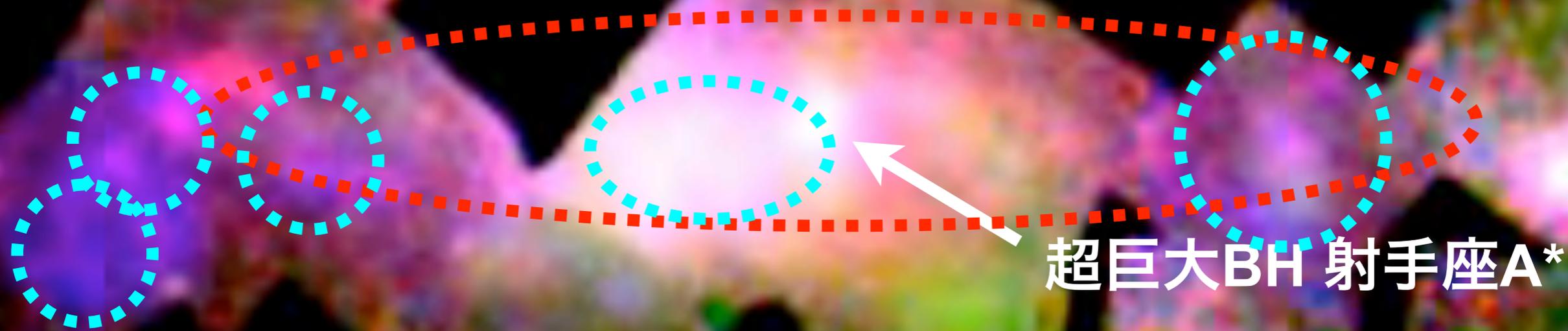
T $\sim 1 \times 10^8$ Kの
高温プラズマ



連鎖的な超新星爆発

天の川銀河中心領域のX線写真

電離硫黄K α
(2.45keV)



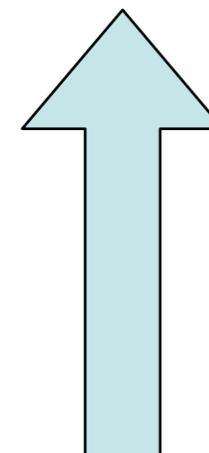
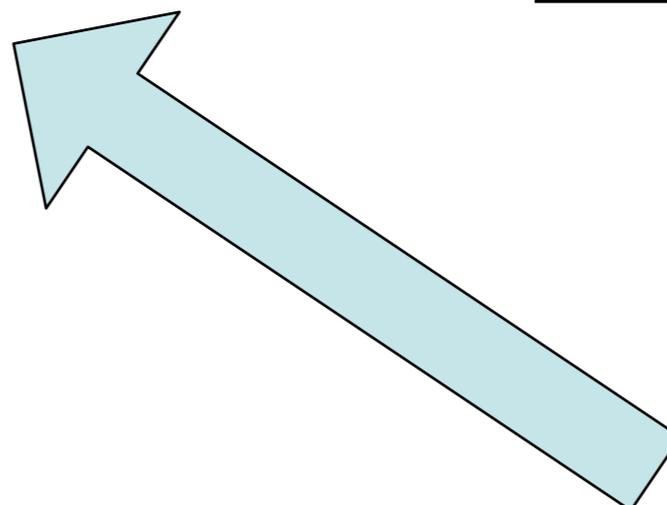
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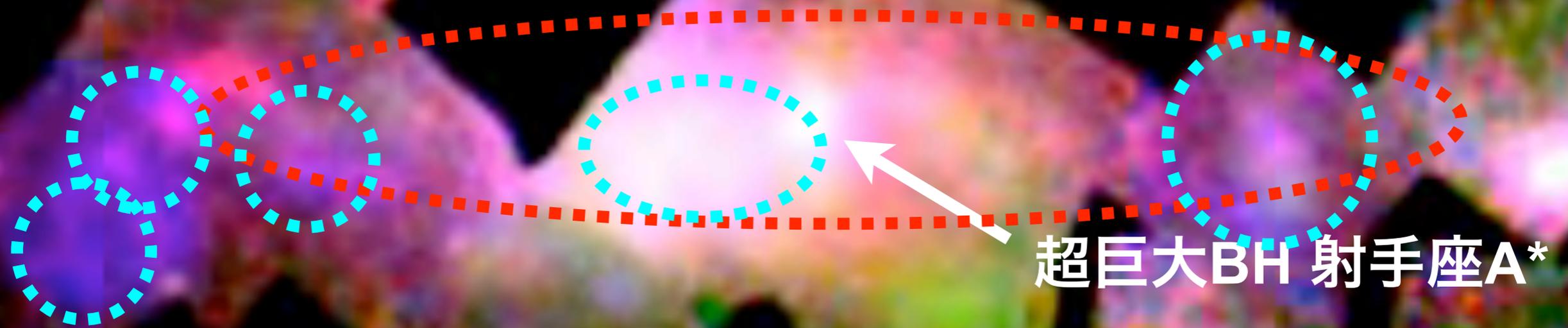
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天の川銀河中心領域のX線写真

電離硫黄K α
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超巨大BH 射手座A*

中性鉄(6.4keV)

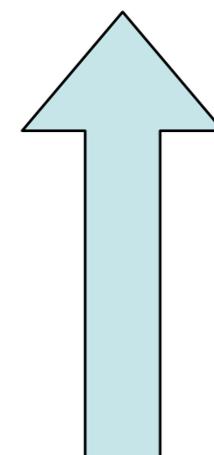
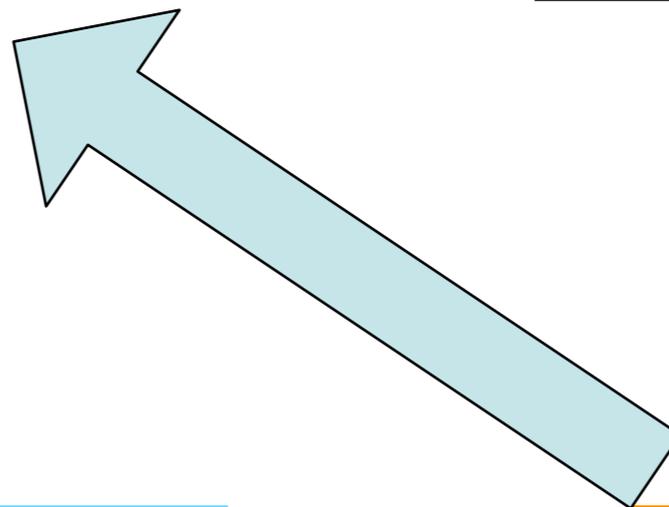
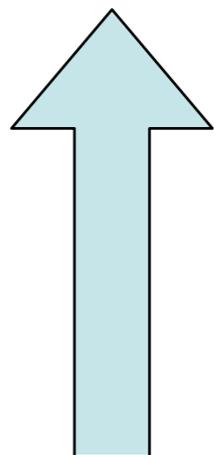
電離鉄K α (6.7keV)

分子雲からの
蛍光X線

T $\sim 1 \times 10^8$ Kの
高温プラズマ

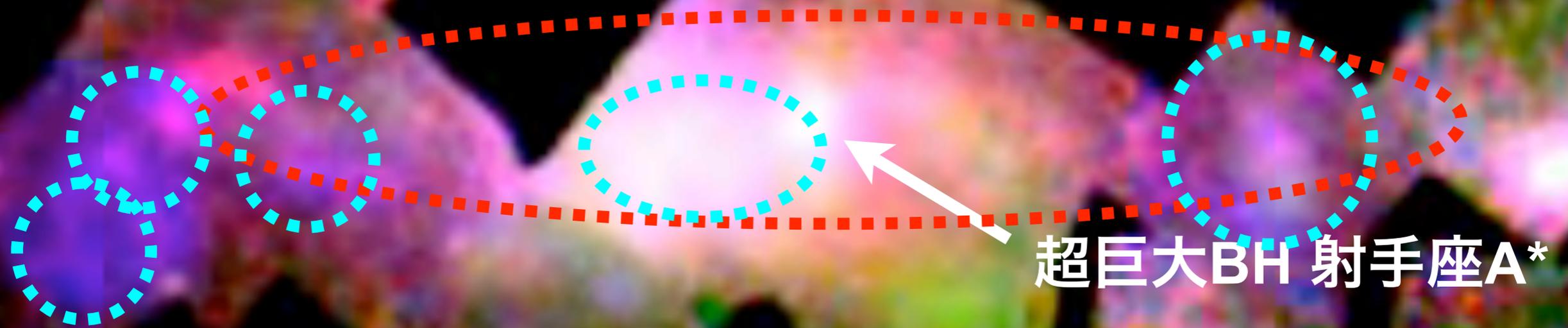
射手座A*の過去の大爆発

連鎖的な超新星爆発



天の川銀河中心領域のX線写真

電離硫黄K α
(2.45keV)



超巨大BH 射手座A*

中性鉄(6.4keV)

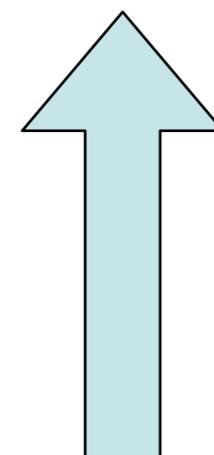
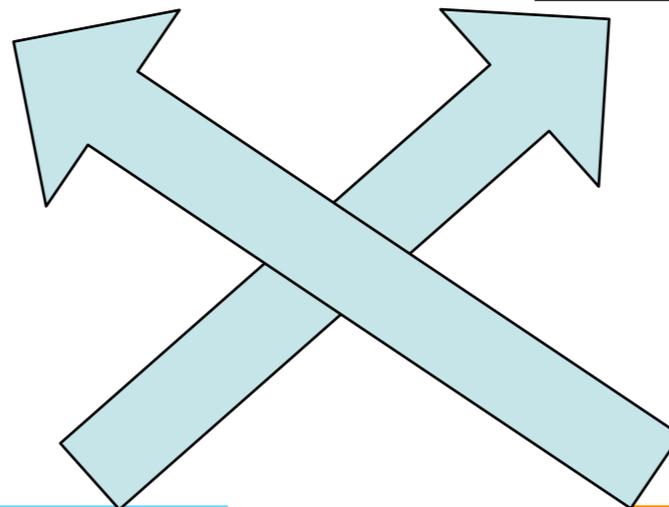
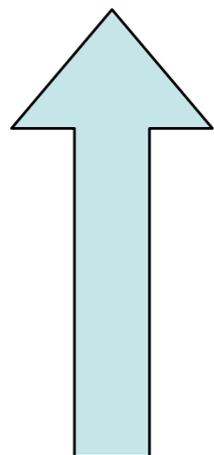
電離鉄K α (6.7keV)

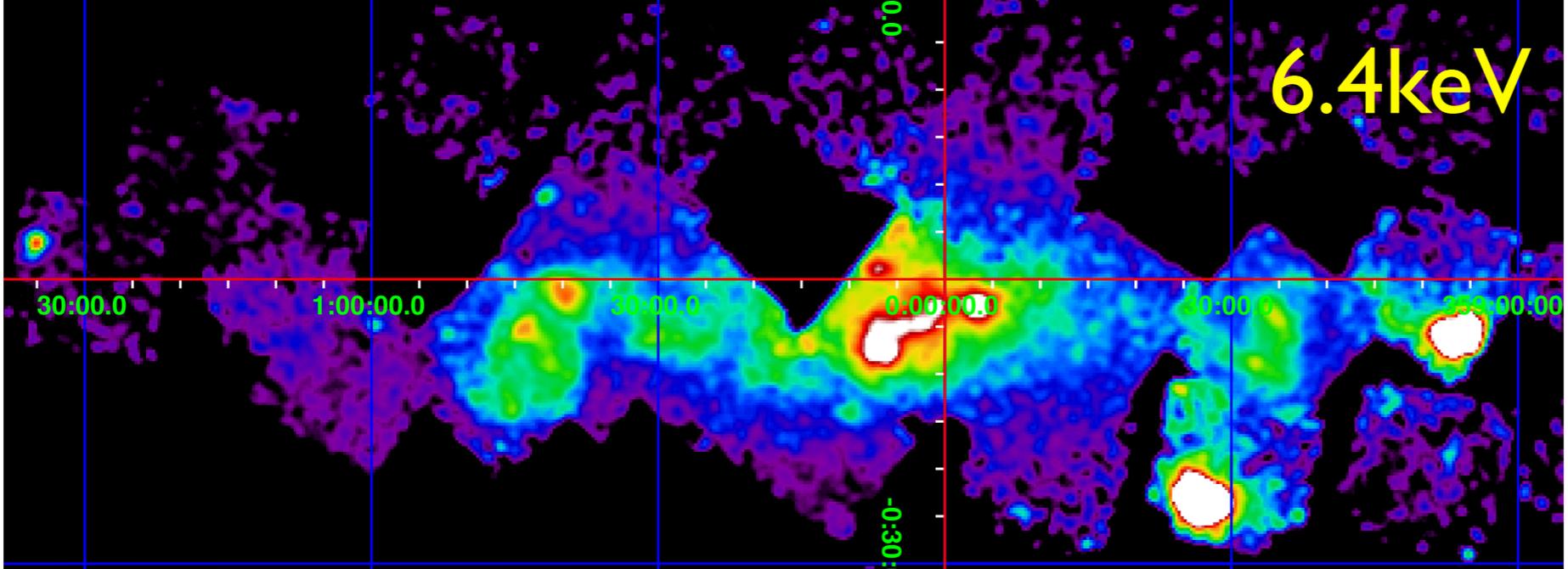
分子雲からの
蛍光X線

T $\sim 1 \times 10^8$ Kの
高温プラズマ

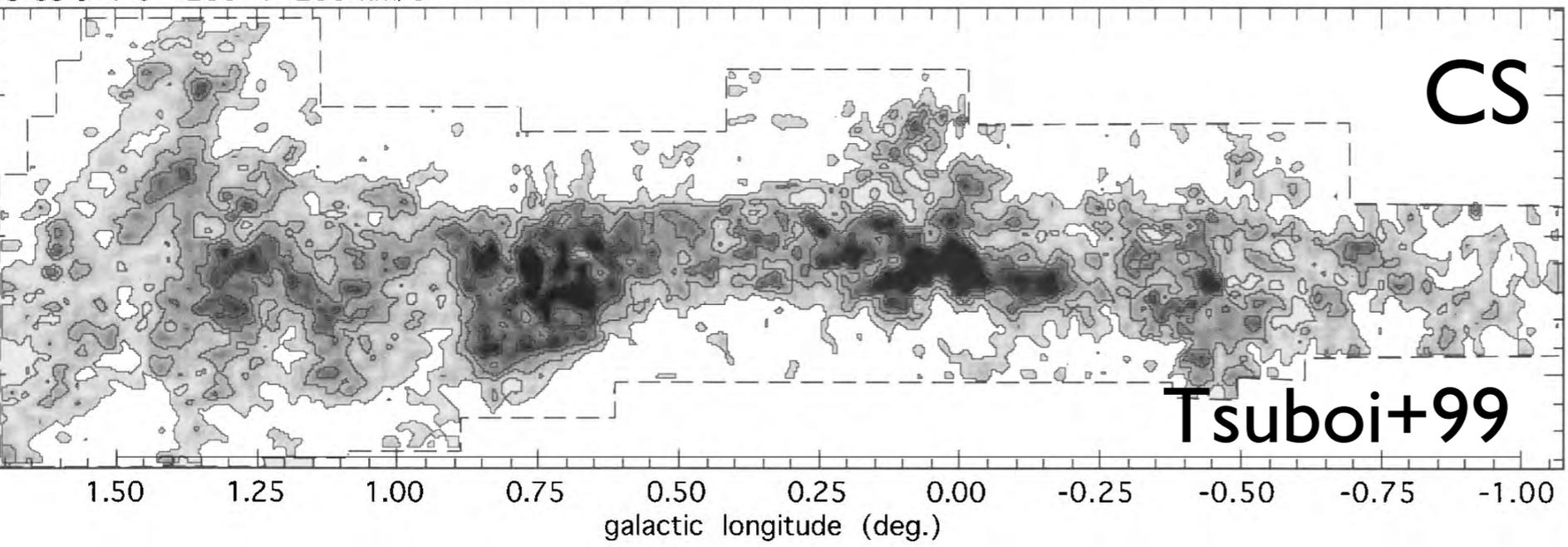
射手座A*の過去の大爆発

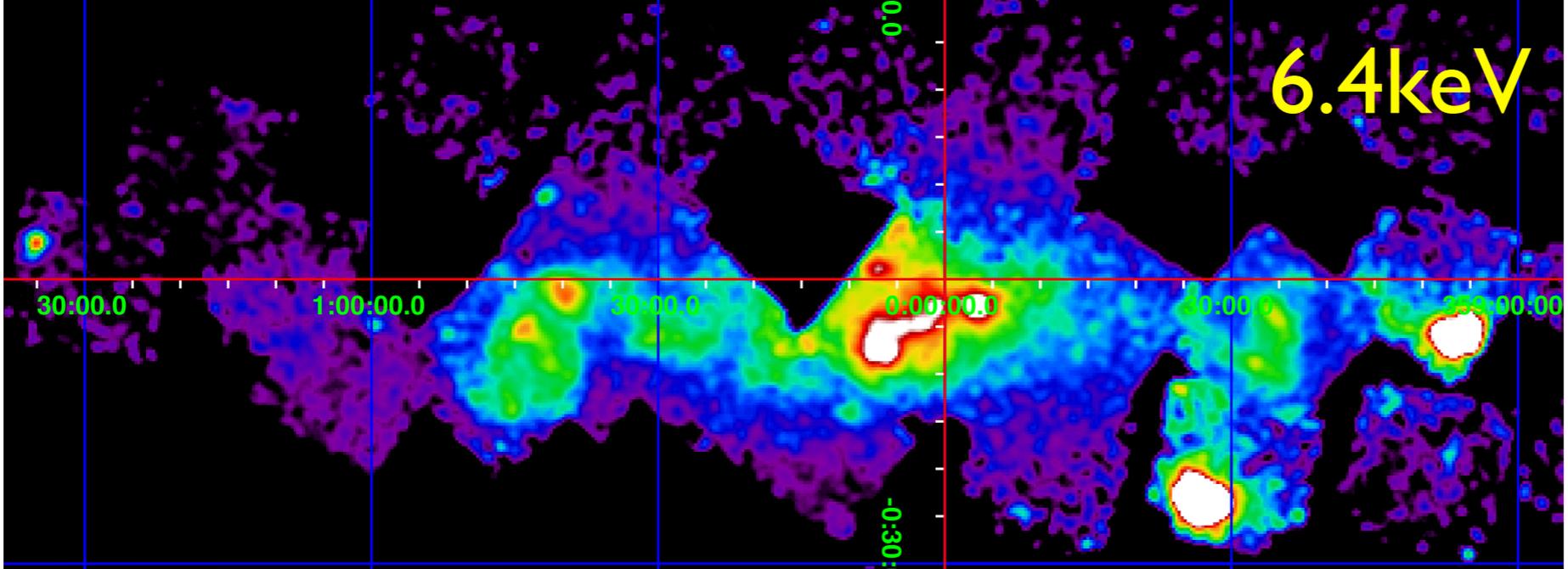
連鎖的な超新星爆発



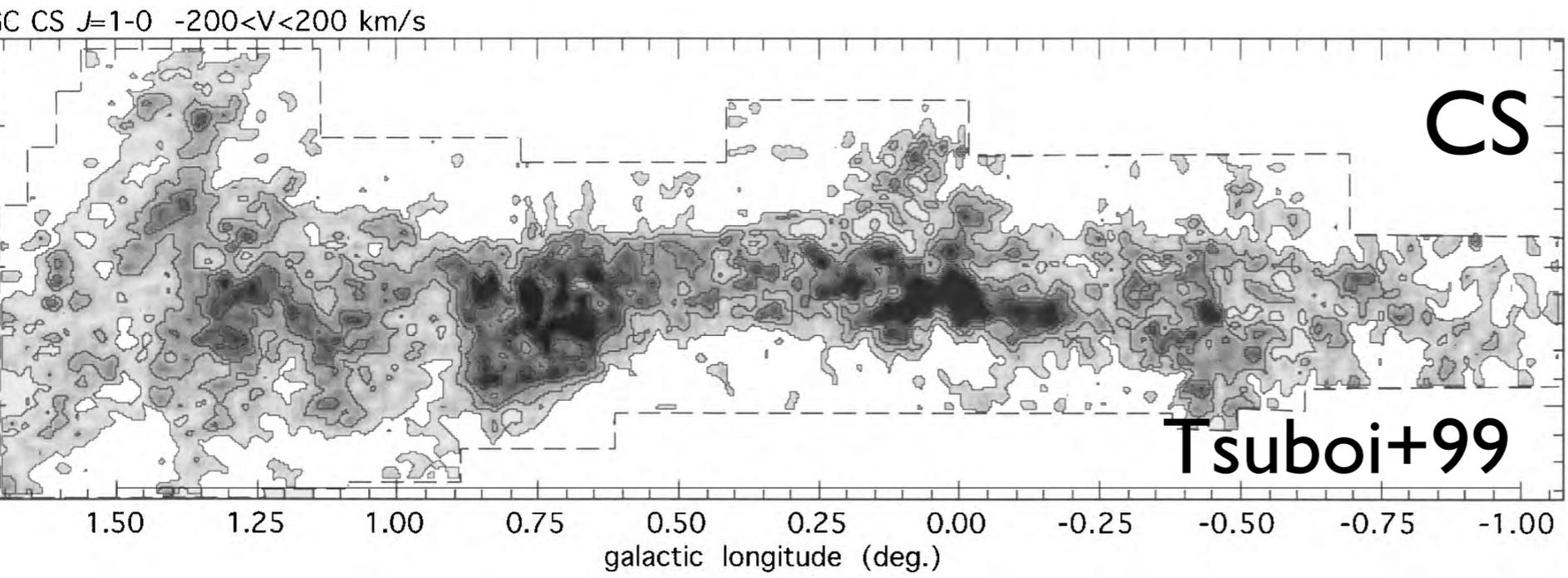


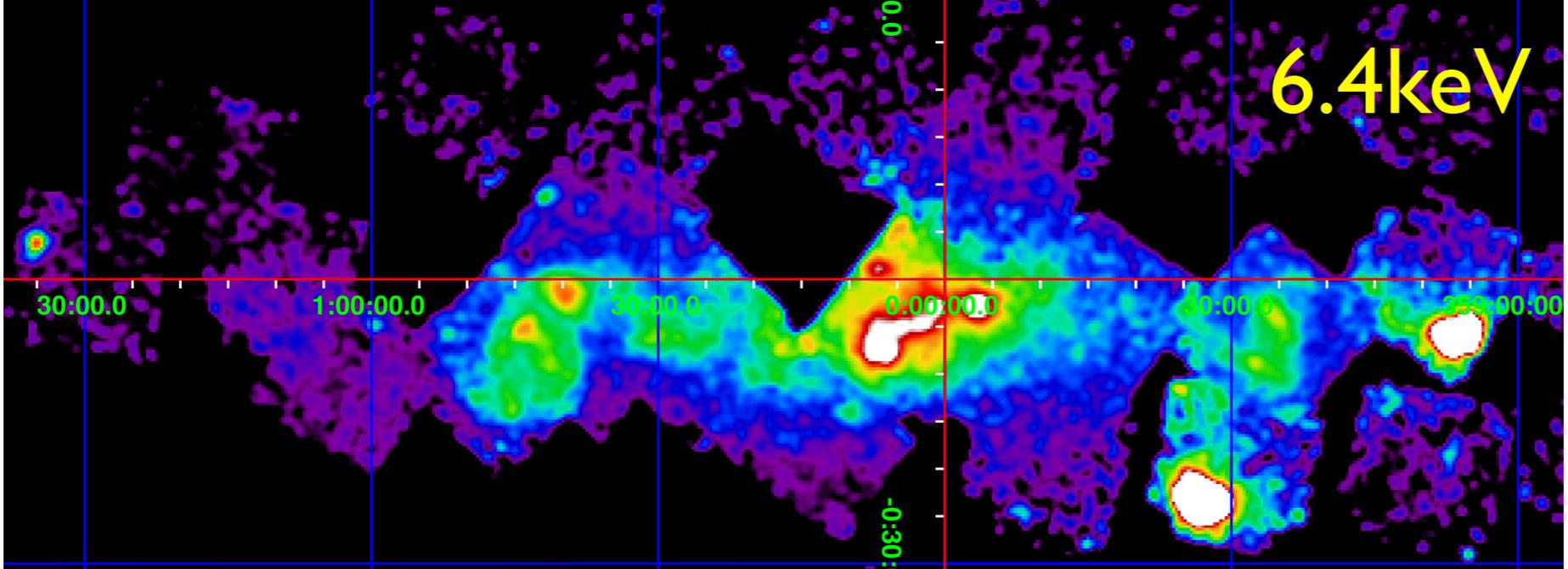
C CS $J=1-0$ $-200 < V < 200$ km/s



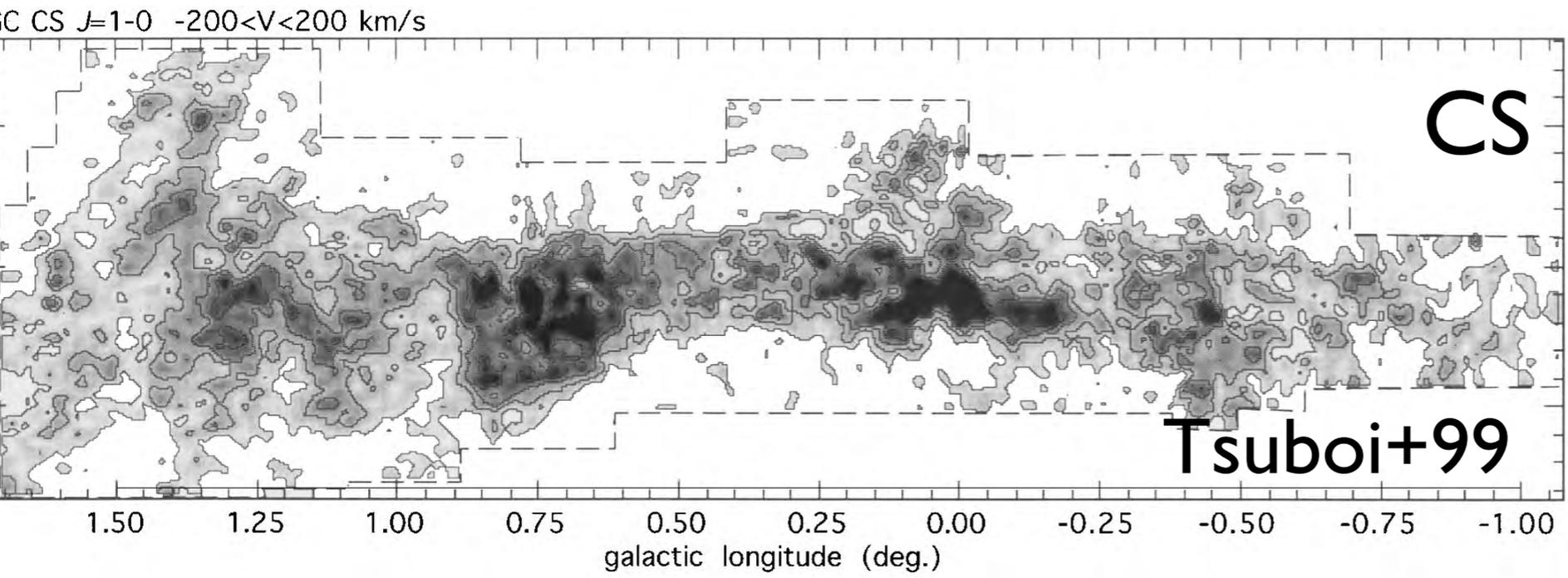


6.4keV line traces the distribution of the molecular clouds (MC).

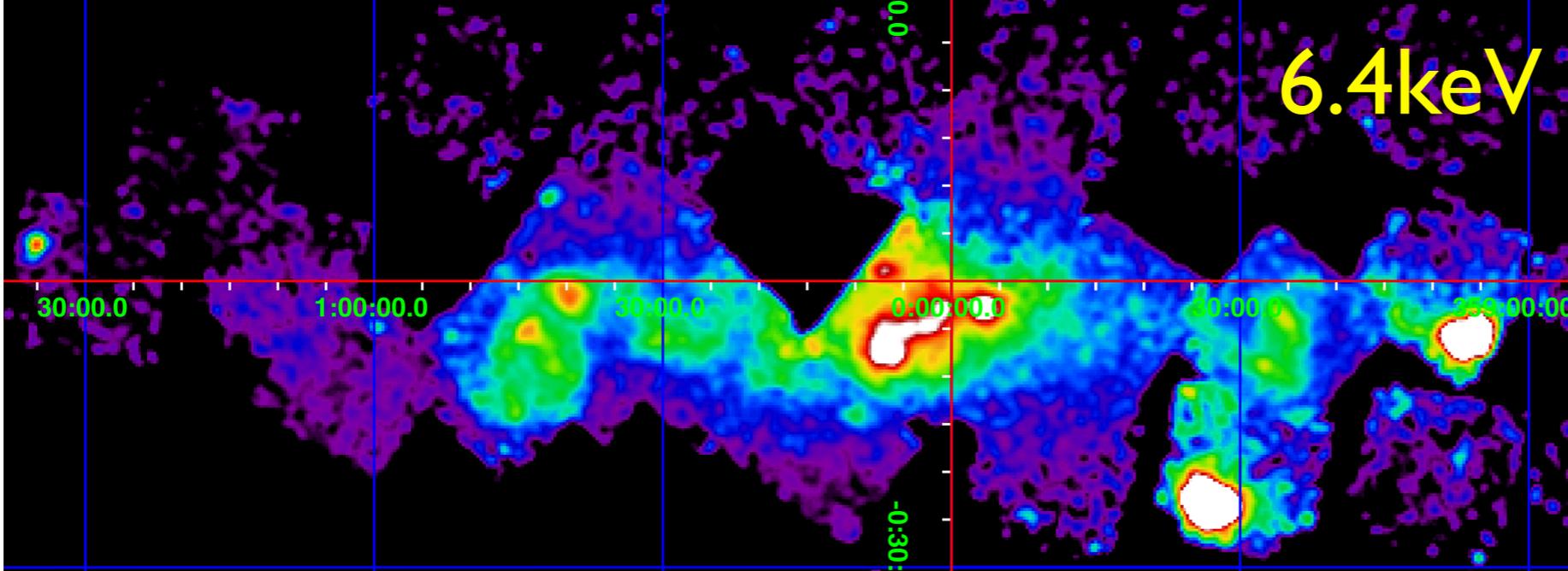




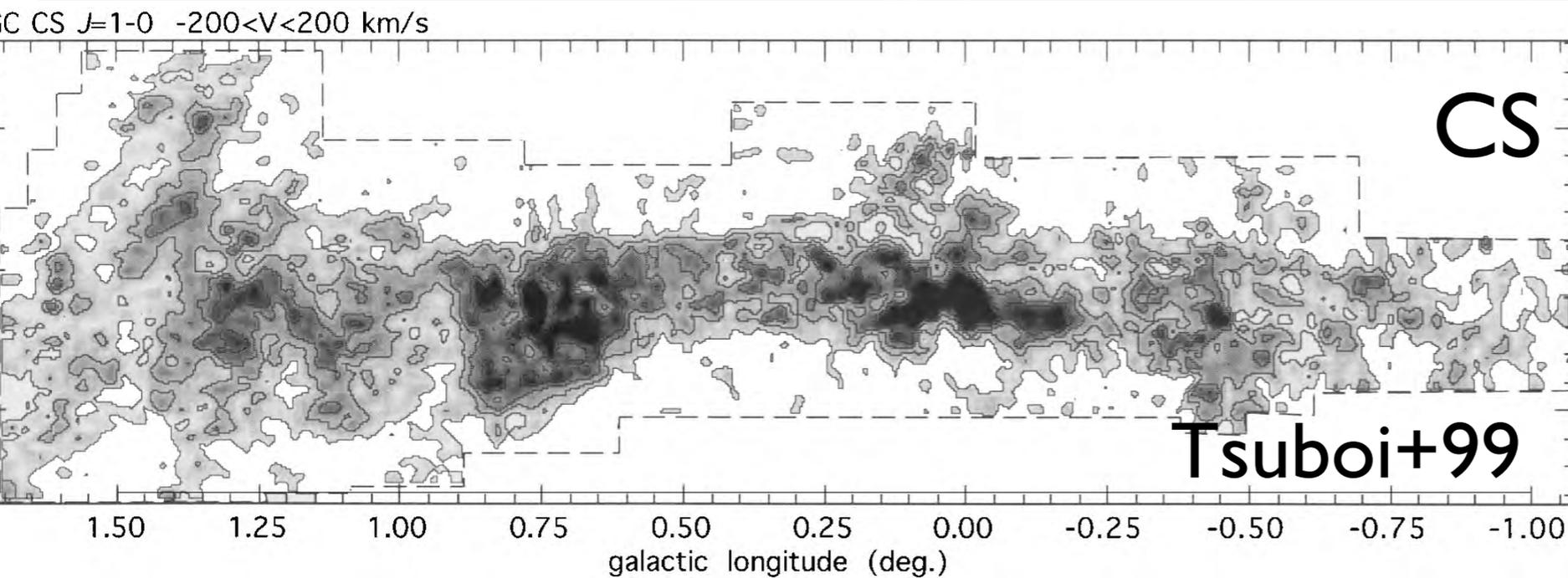
6.4keV line traces the distribution of the molecular clouds (MC).



6.4keV fluorescence line is emitted from MC.

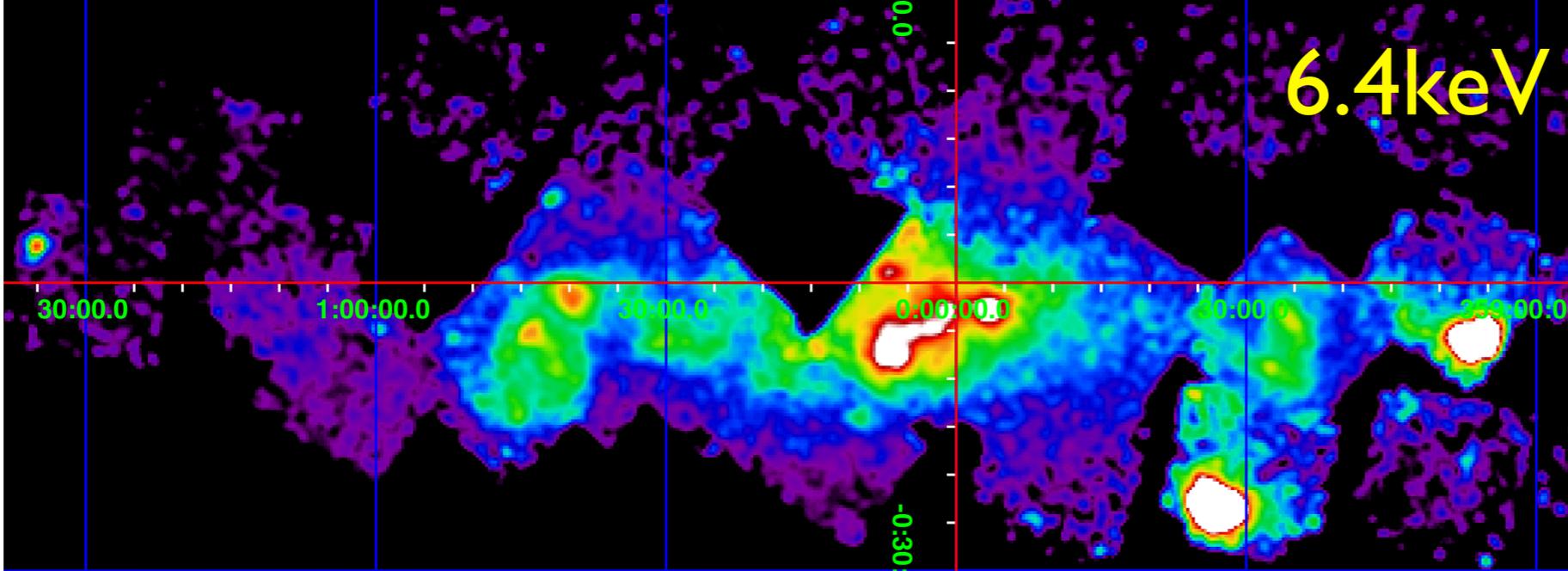


6.4keV line traces the distribution of the molecular clouds (MC).

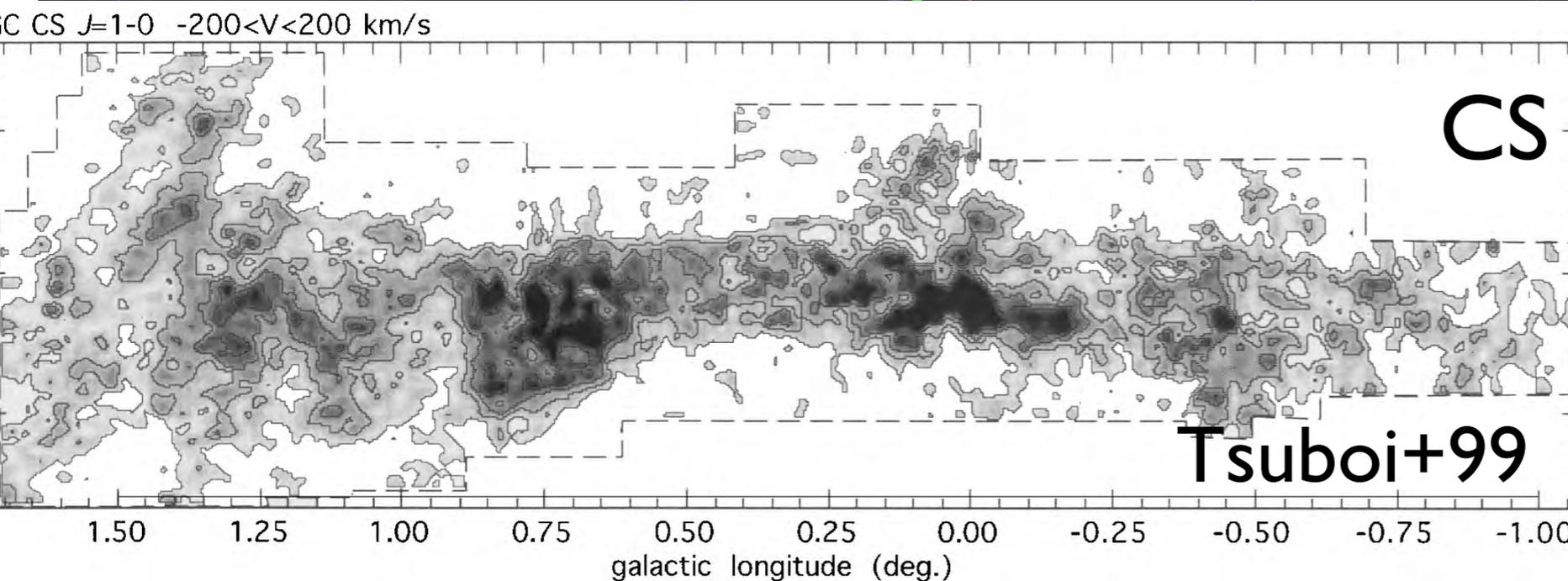


6.4keV fluorescence line is emitted from MC.

Big Question: What is the ionizing particle ?



6.4keV line traces the distribution of the molecular clouds (MC).

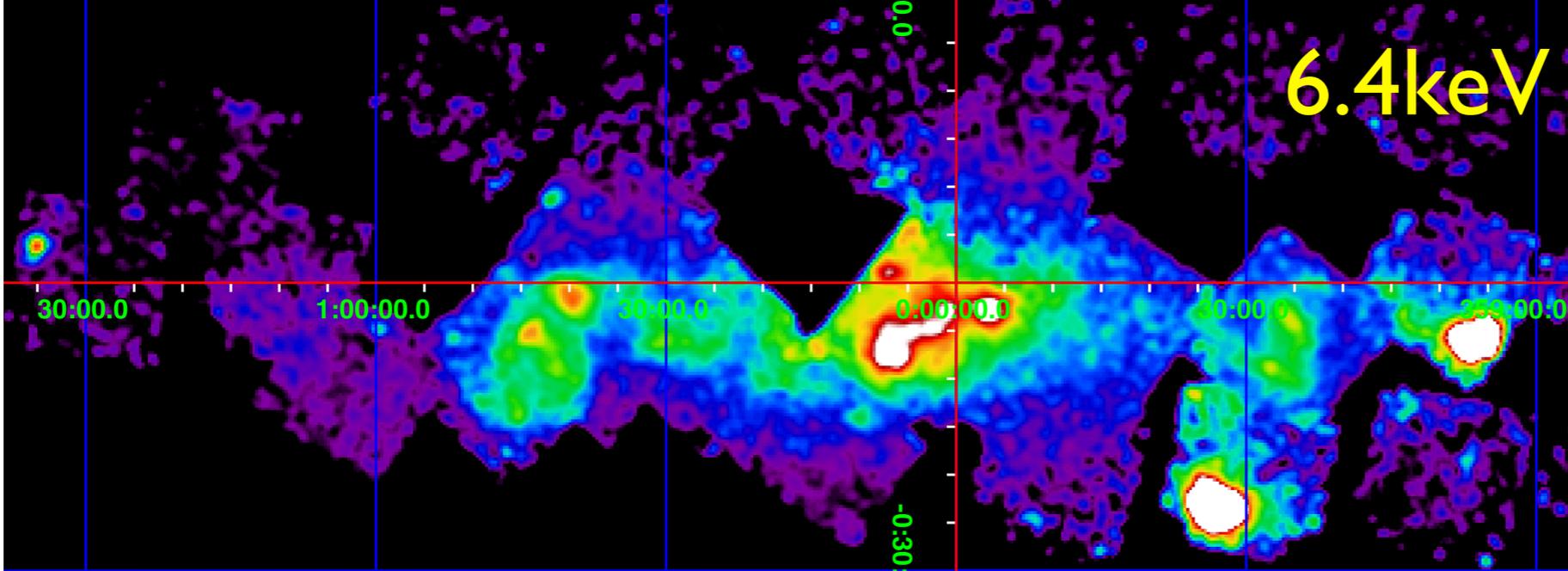


6.4keV fluorescence line is emitted from MC.

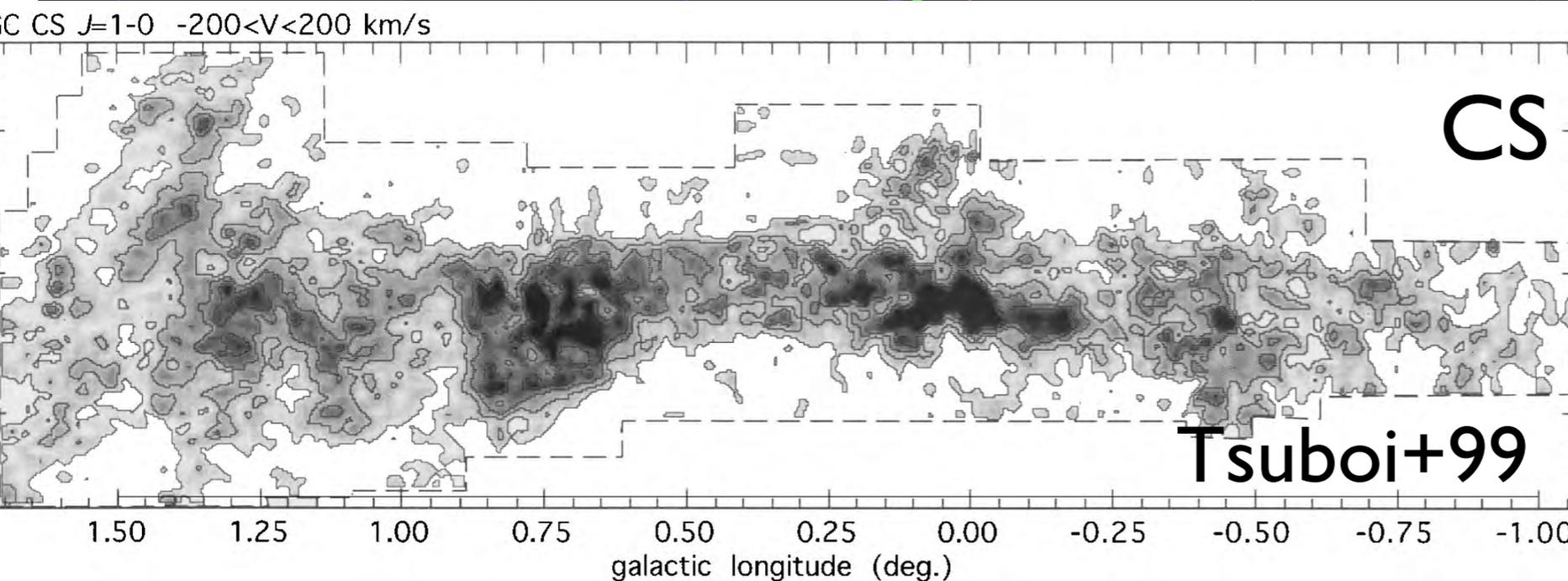
Big Question: What is the ionizing particle ?

X-rays

electrons



6.4keV line traces the distribution of the molecular clouds (MC).

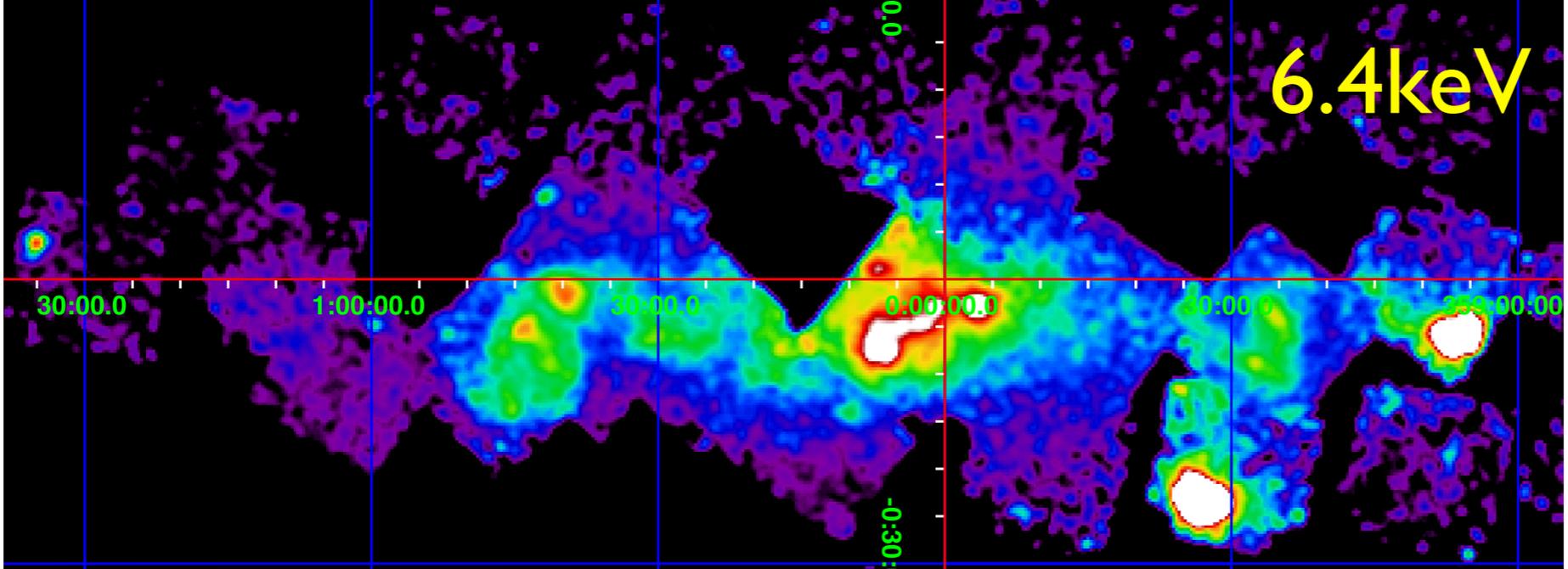


6.4keV fluorescence line is emitted from MC.

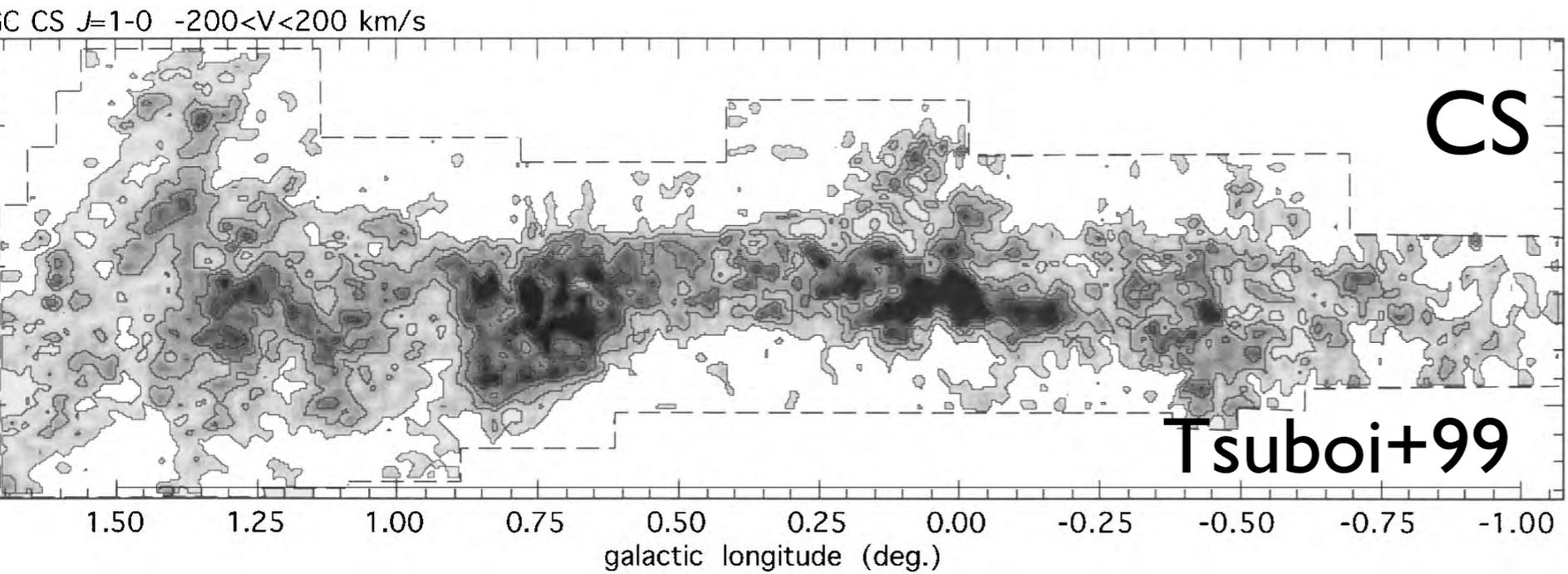
Big Question: What is the ionizing particle ?

X-rays → 6.4keV - Photoelectric absorption
 Continuum - Thomson Scatter

electrons



6.4keV line traces the distribution of the molecular clouds (MC).

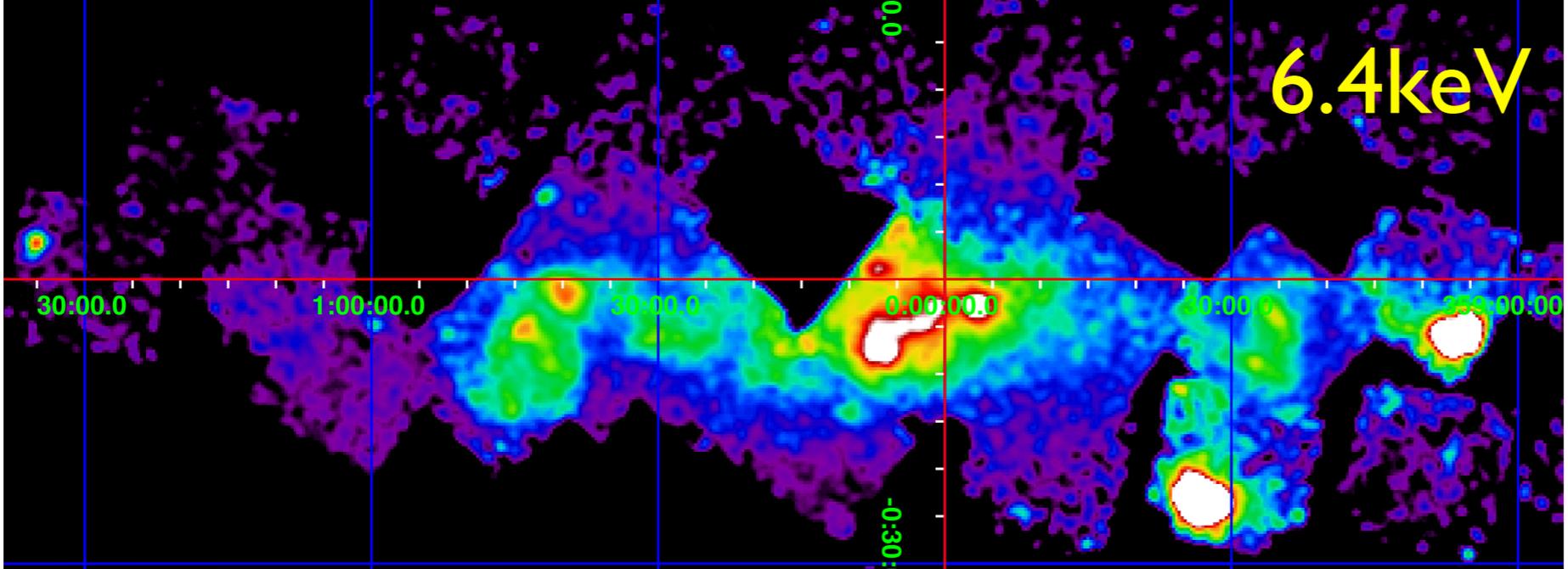


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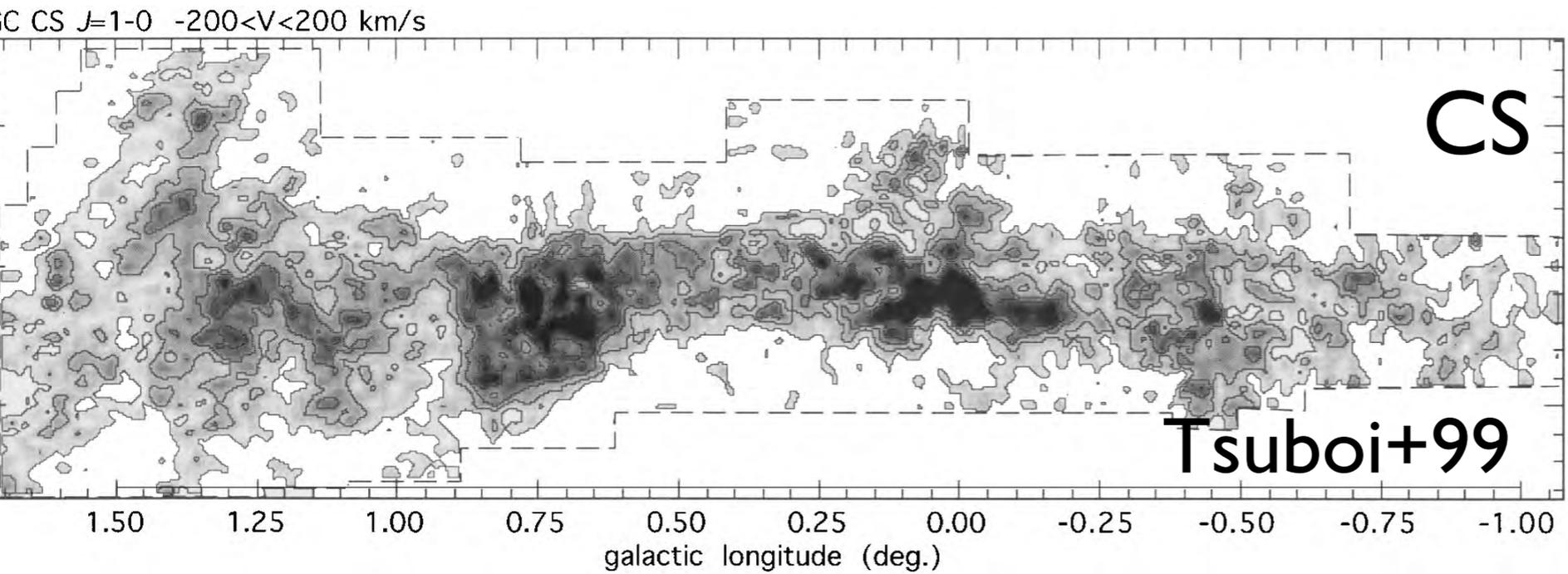
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X-rays → 6.4keV - Photoelectric absorption
 Continuum - Thomson Scatter

electrons → 6.4keV - Inner shell ionization
 Continuum - Bremsstrahlung



6.4keV line traces the distribution of the molecular clouds (MC).

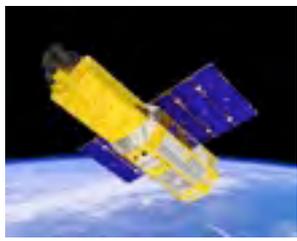


6.4keV fluorescence line is emitted from MC.

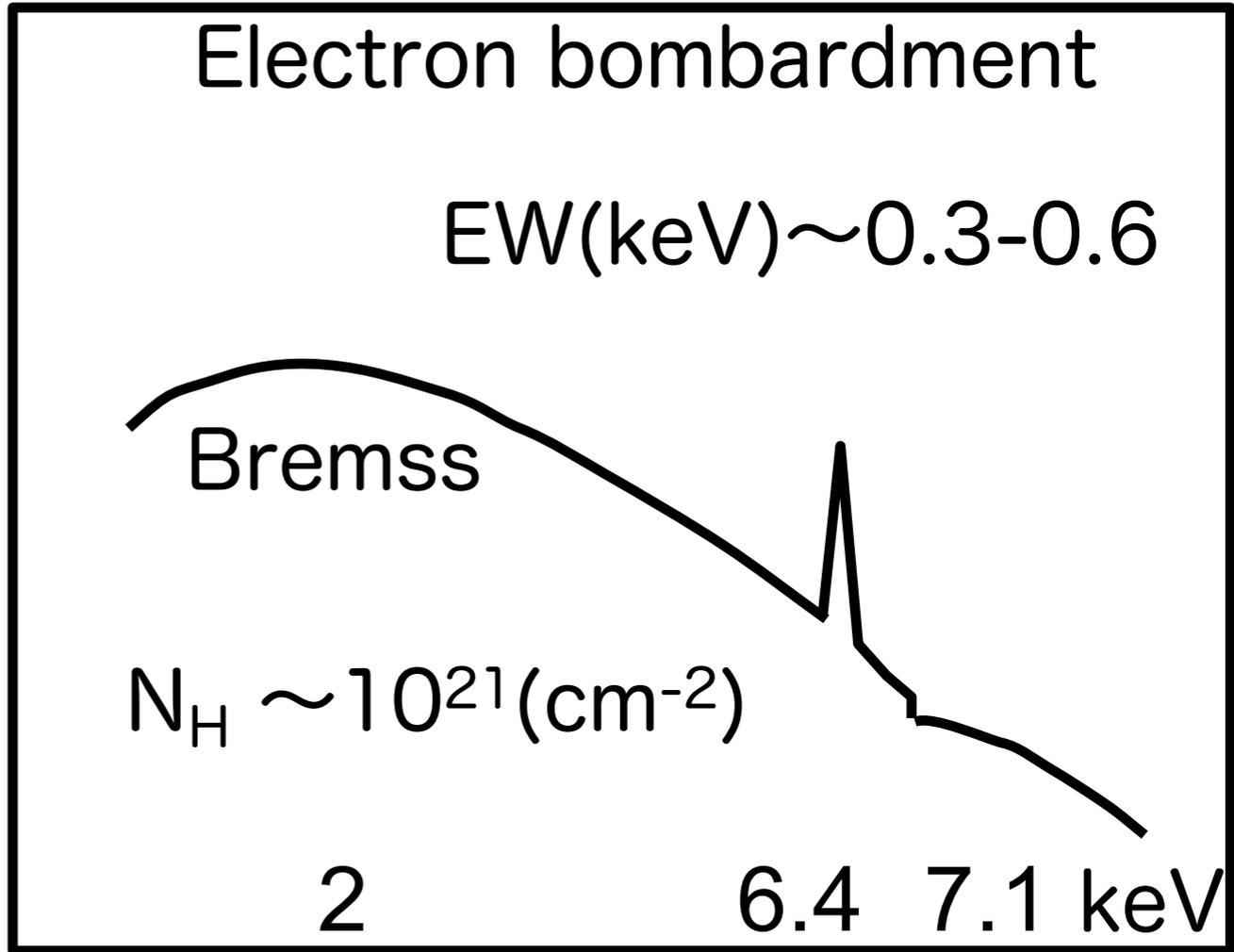
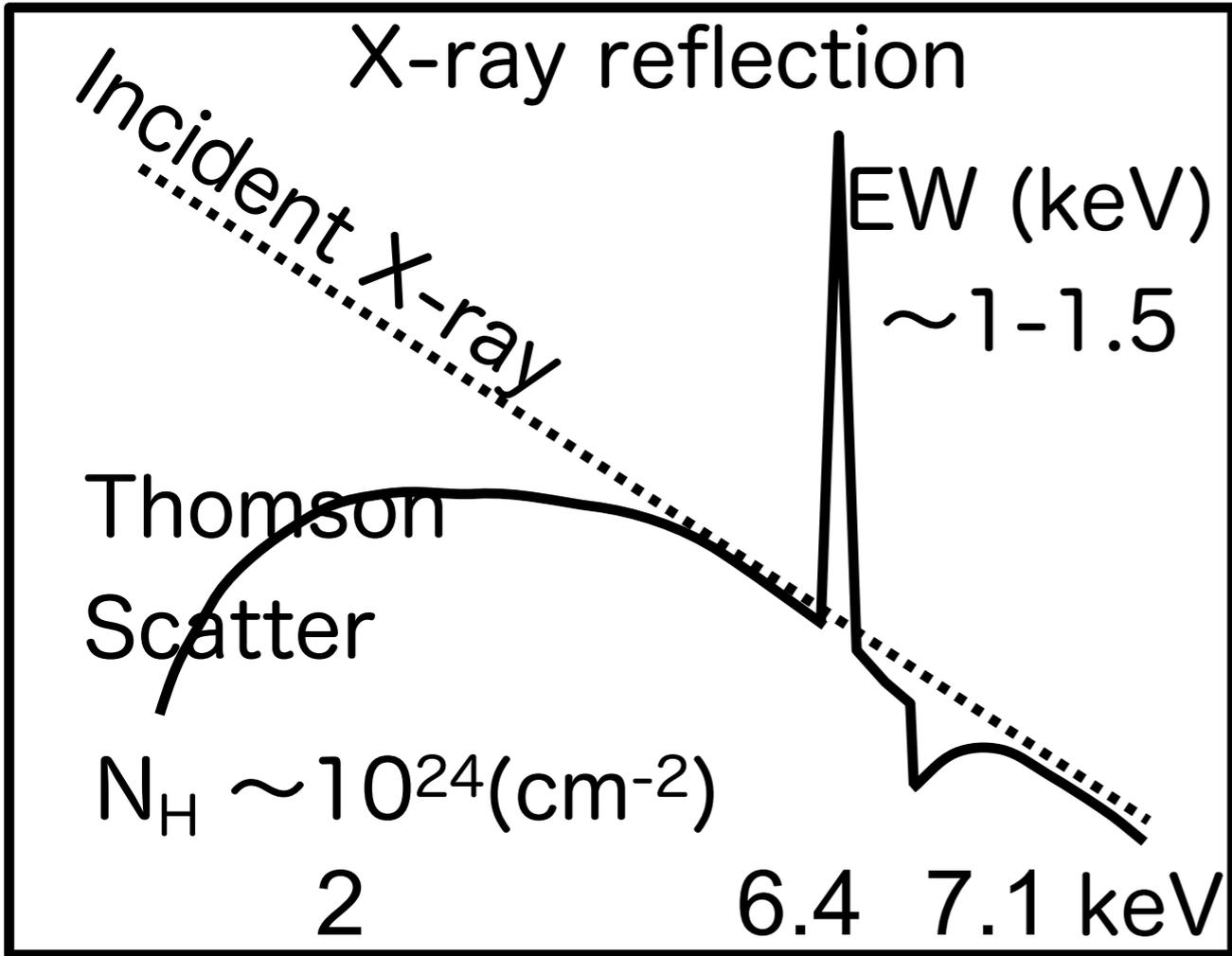
Big Question: What is the ionizing particle ?

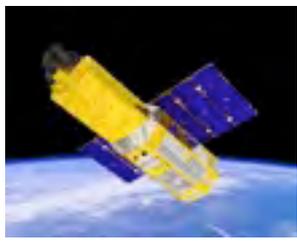
X-rays → 6.4keV - Photoelectric absorption “X-ray reflection”
 Continuum - Thomson Scatter

electrons → 6.4keV - Inner shell ionization “Electron bombardment”
 Continuum - Bremsstrahlung

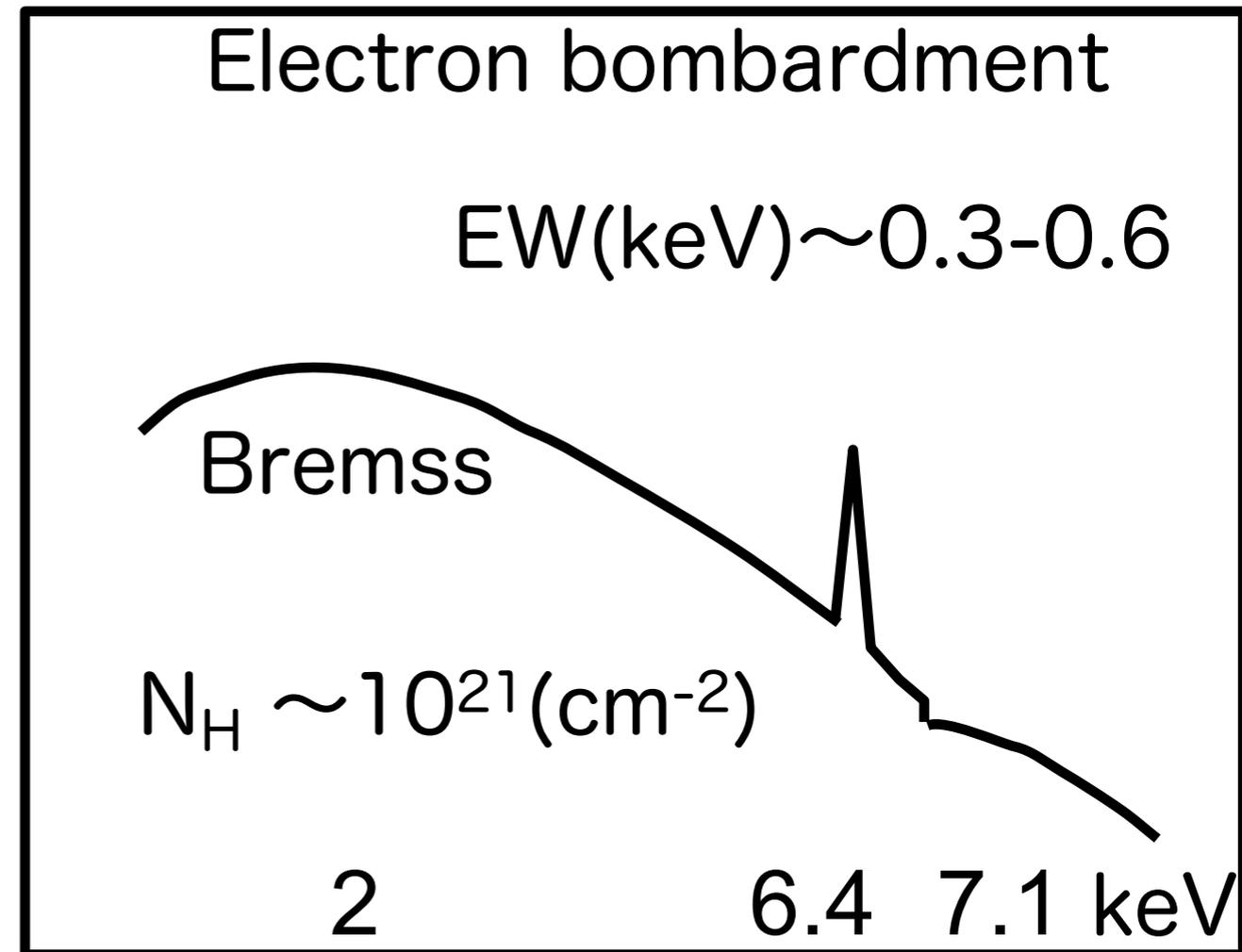
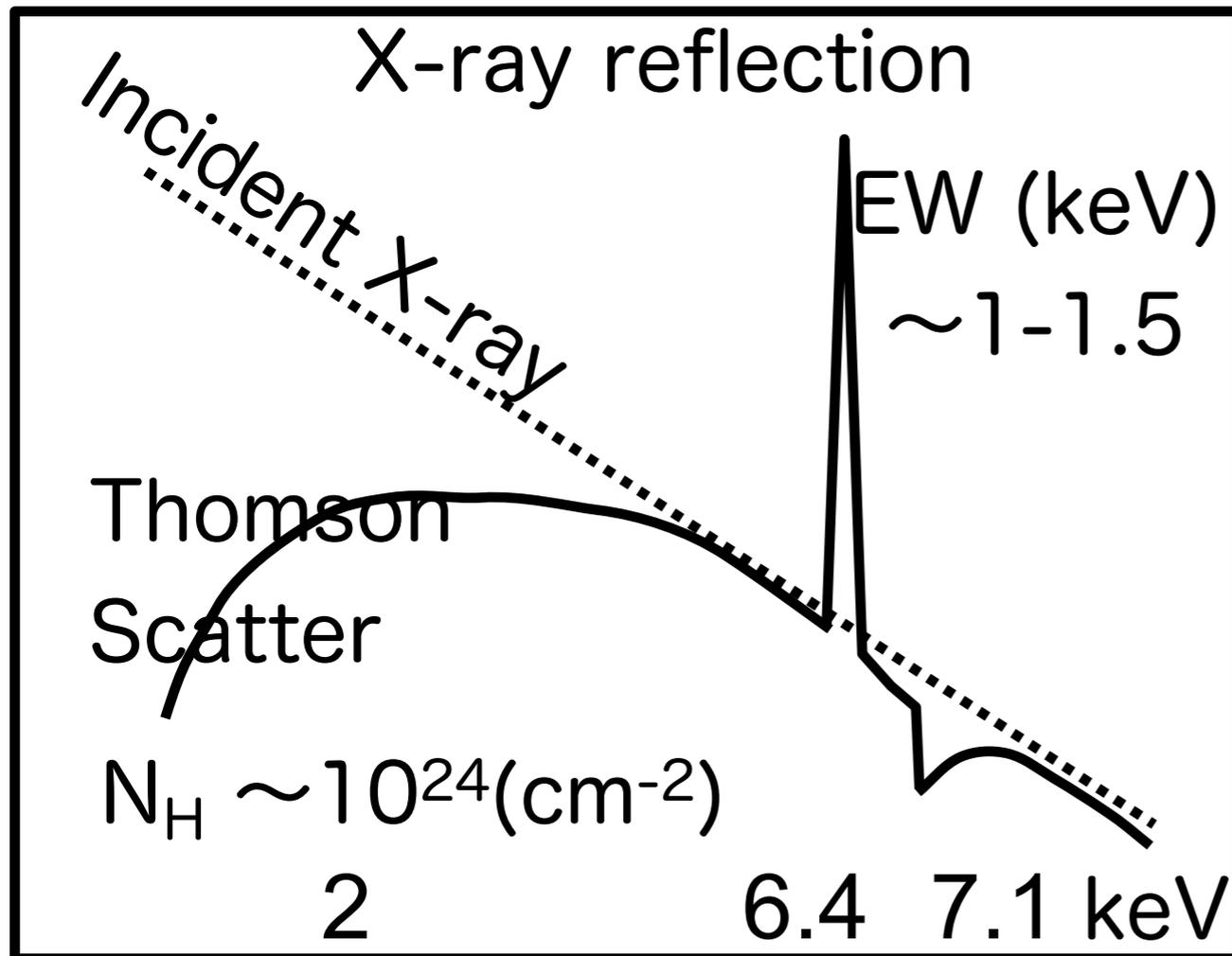


X-ray reflection vs. Electron bombardment

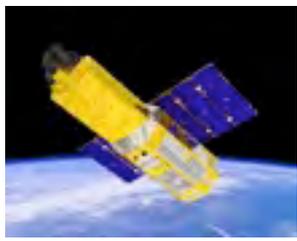




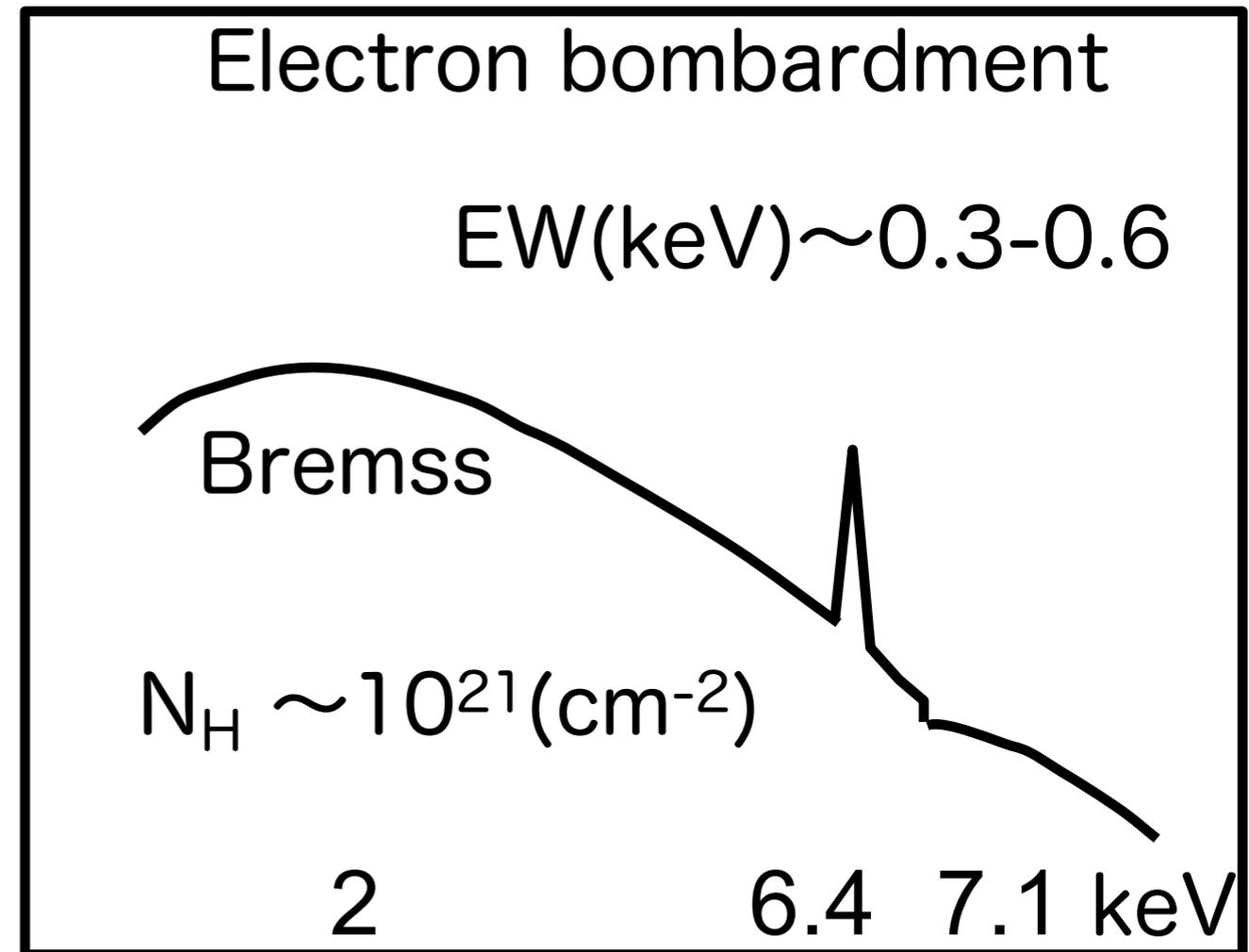
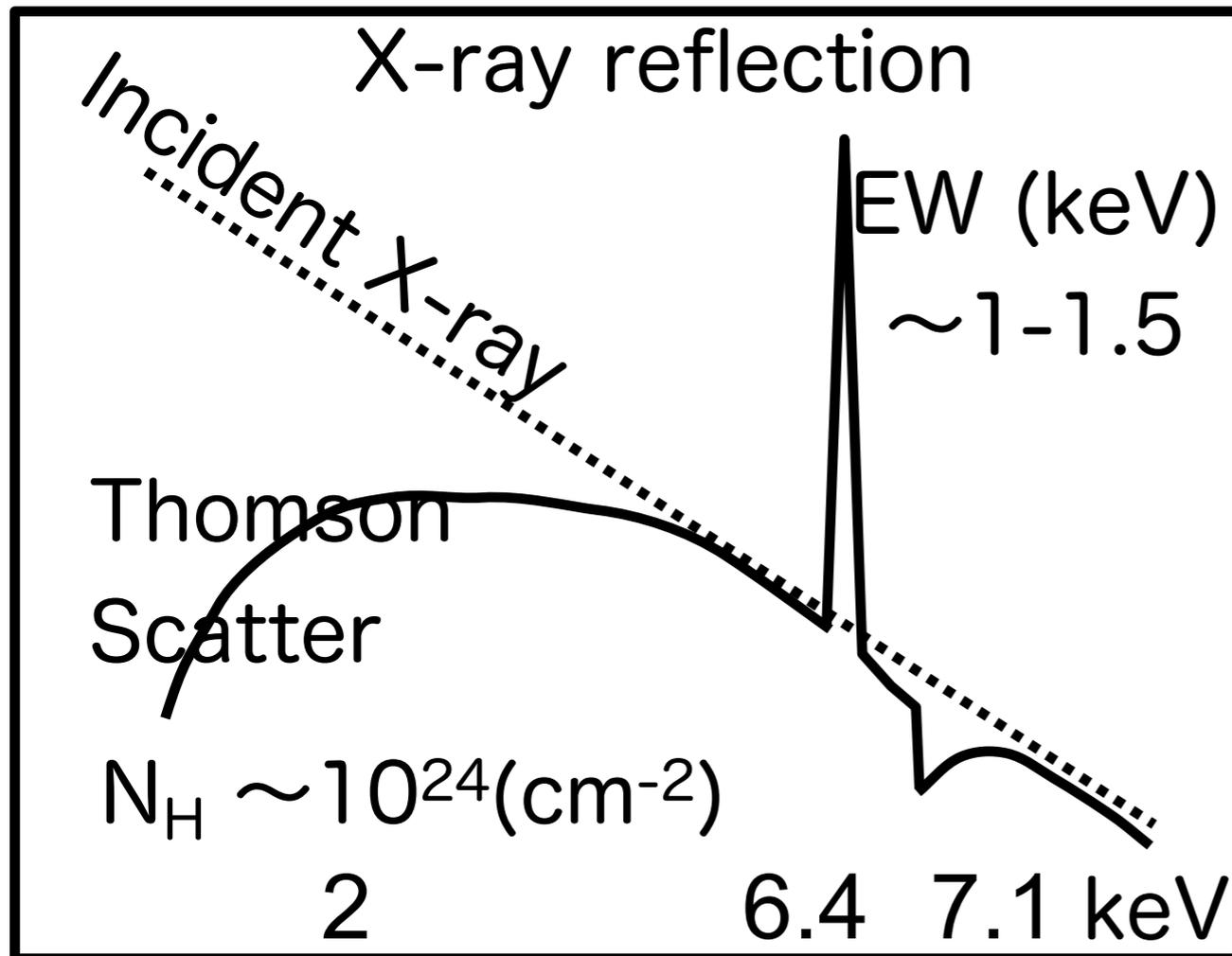
X-ray reflection vs. Electron bombardment



Larger EW of 6.4 keV line is expected for X-ray reflection
 $\sigma(\text{Thomson scatter}) < \sigma(\text{bremss by electron})$



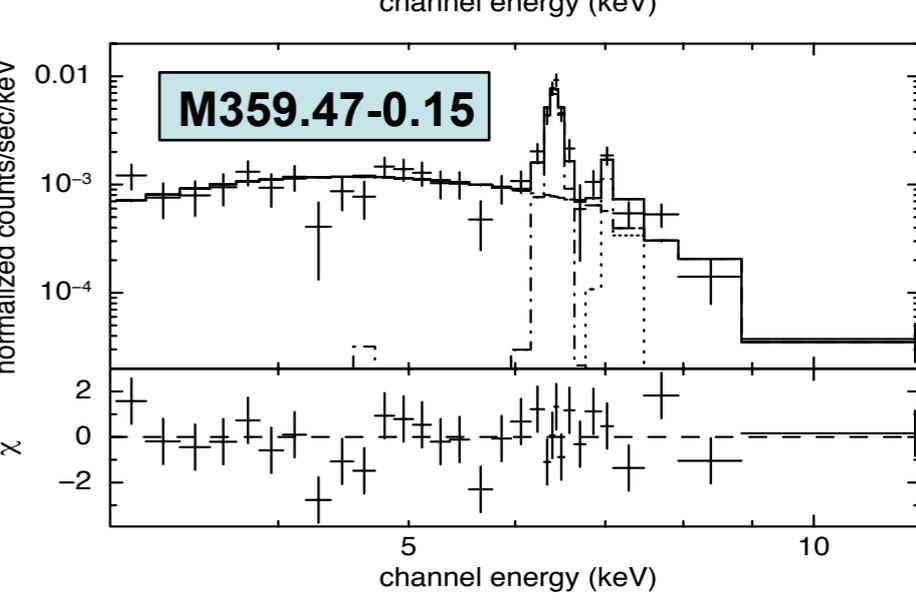
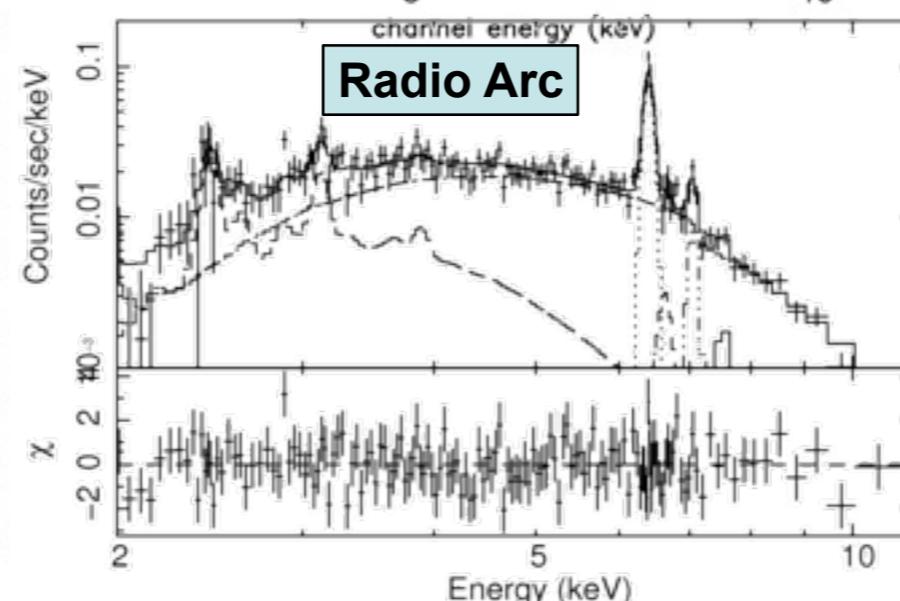
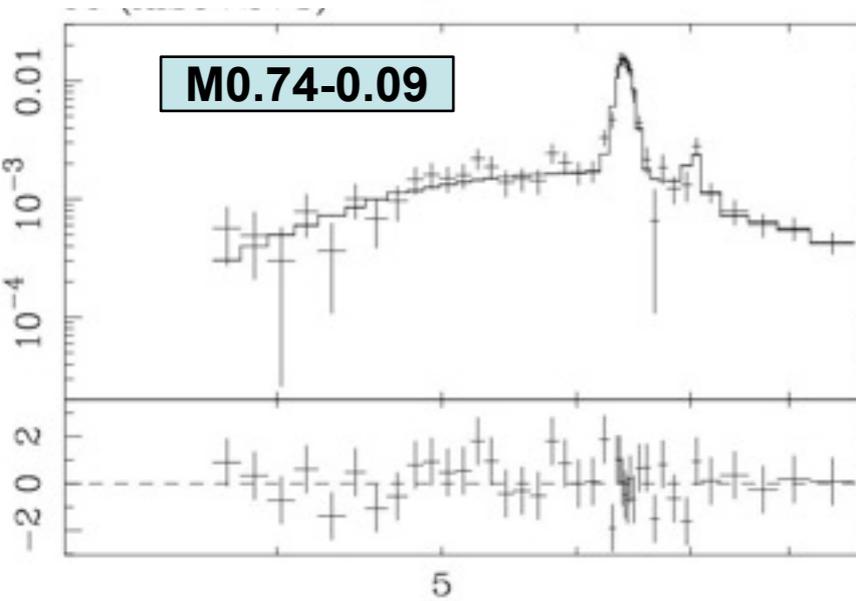
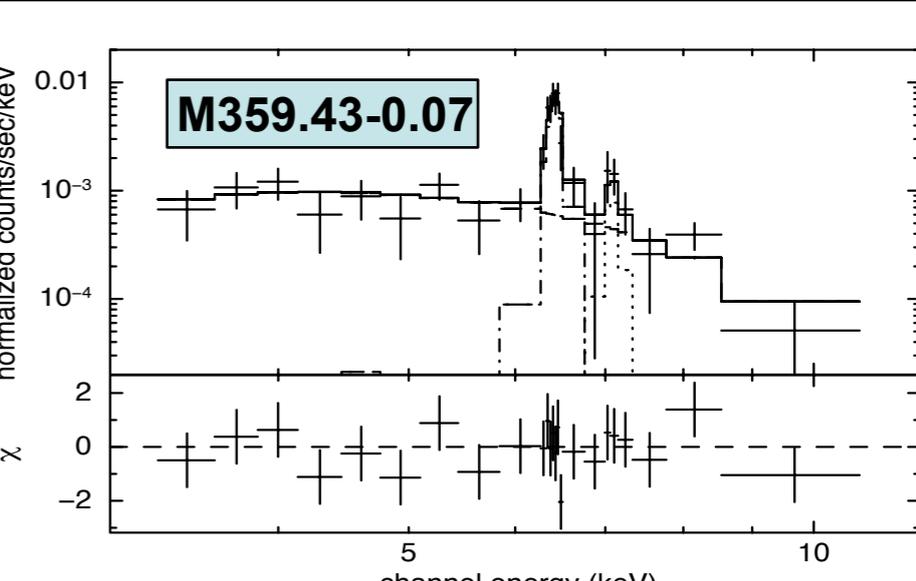
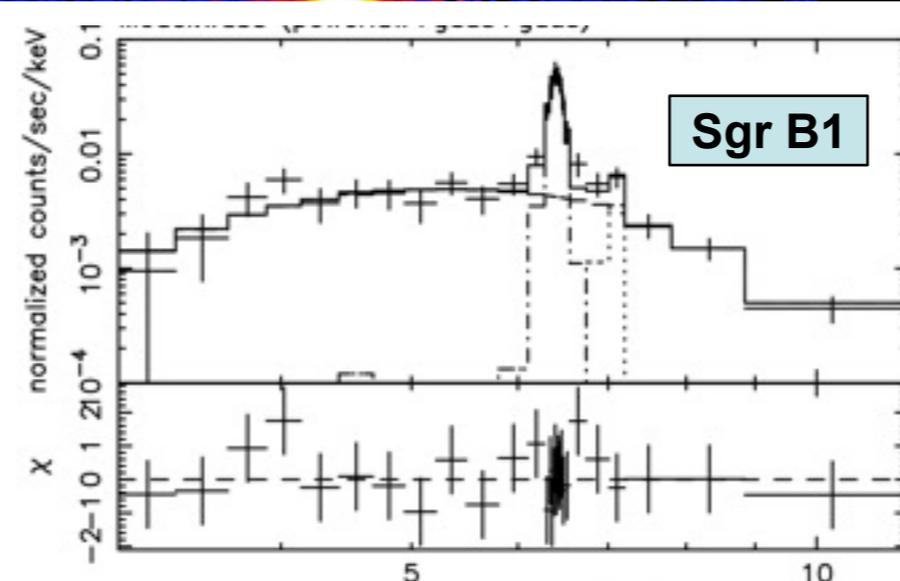
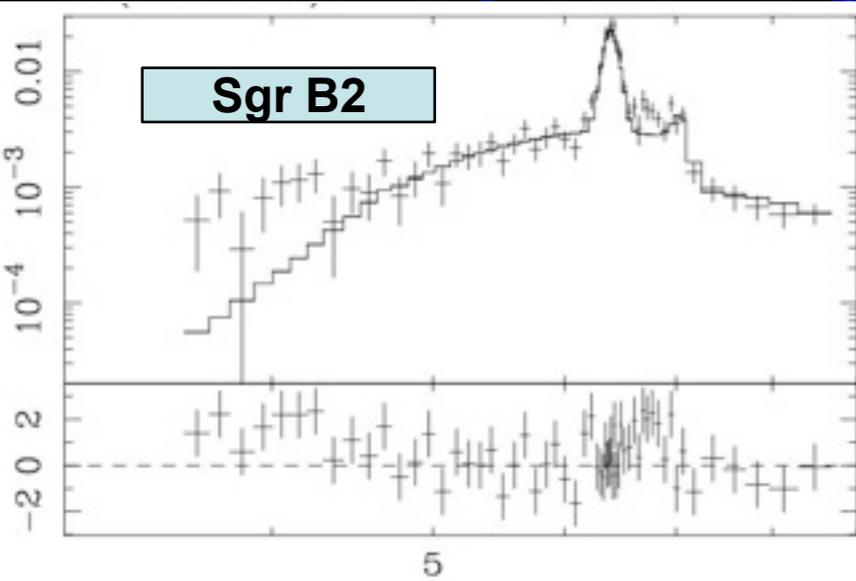
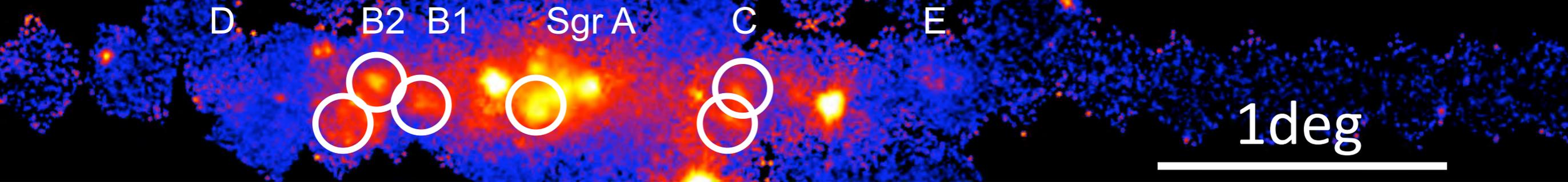
X-ray reflection vs. Electron bombardment

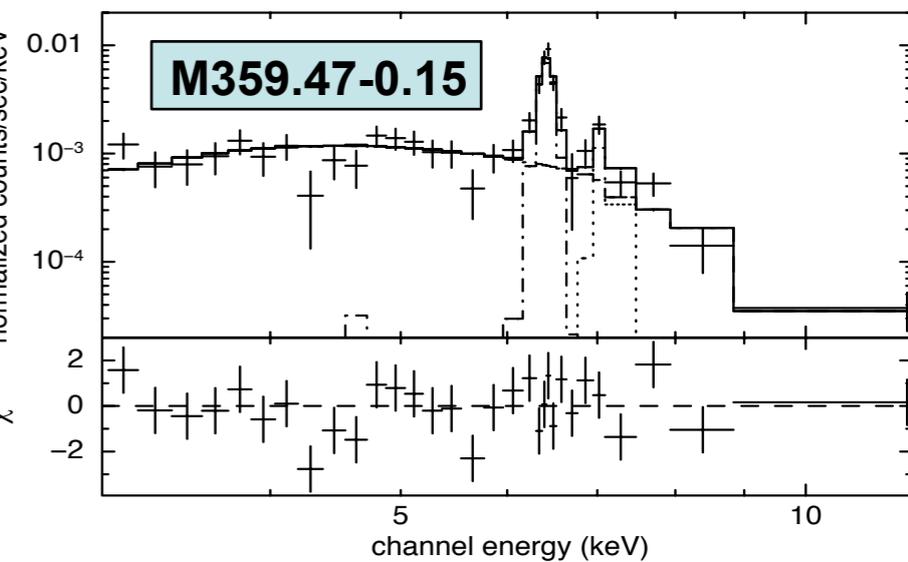
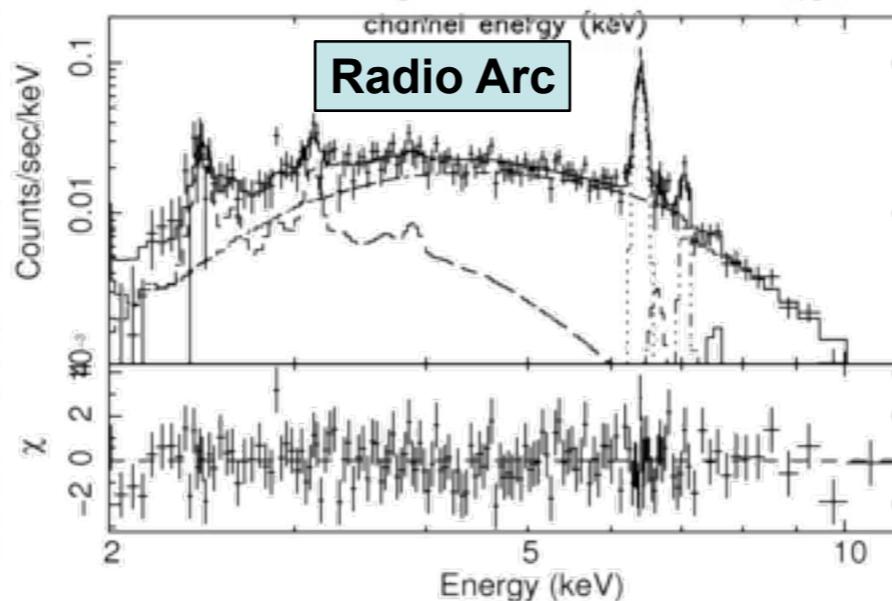
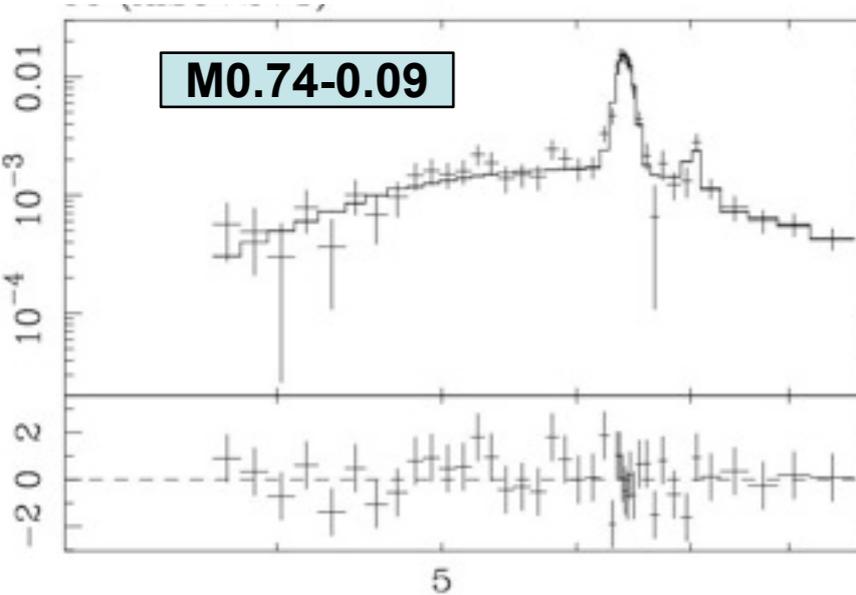
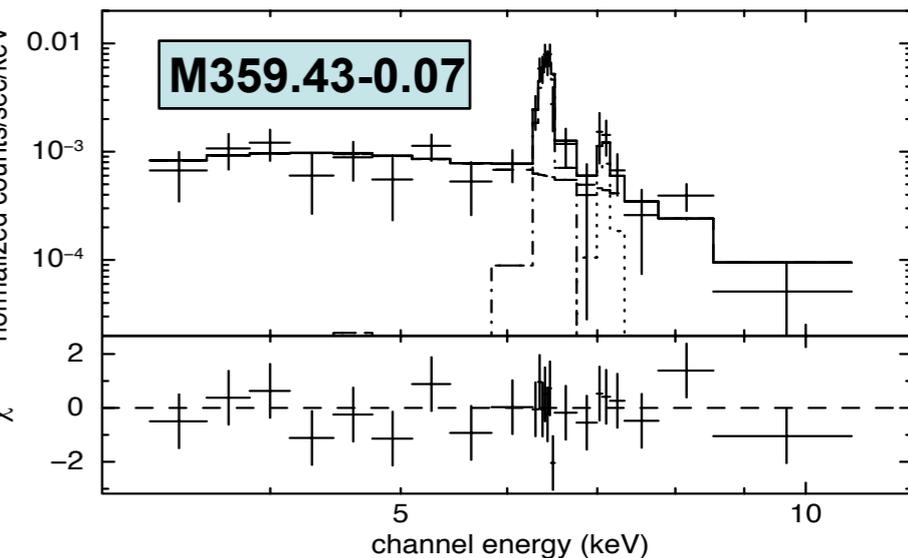
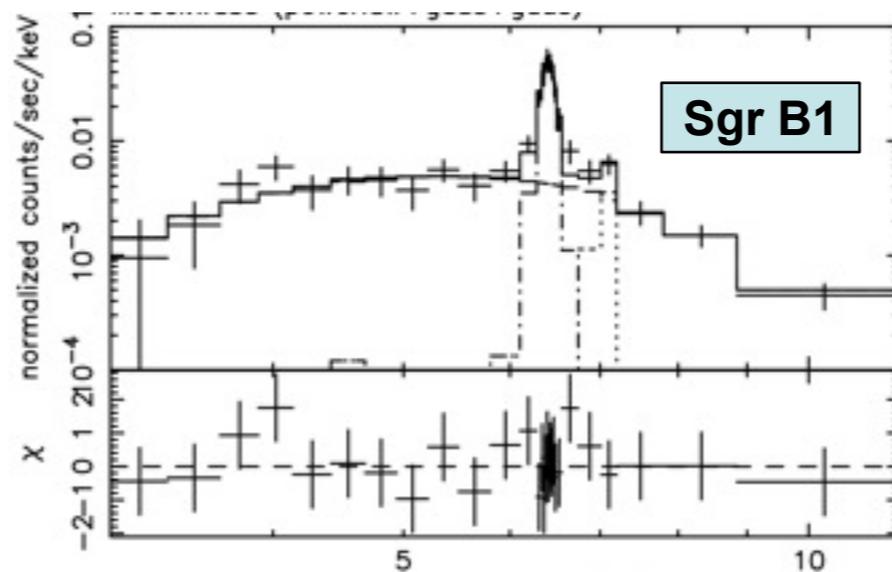
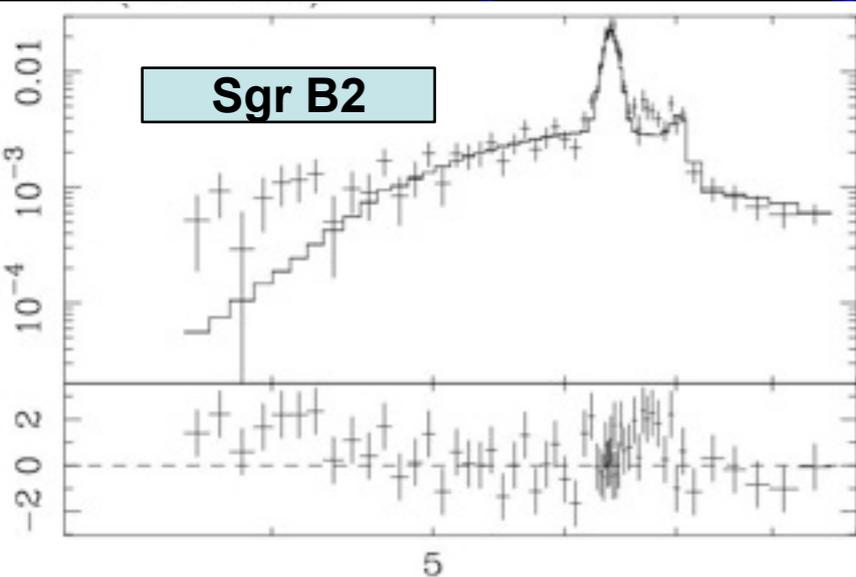
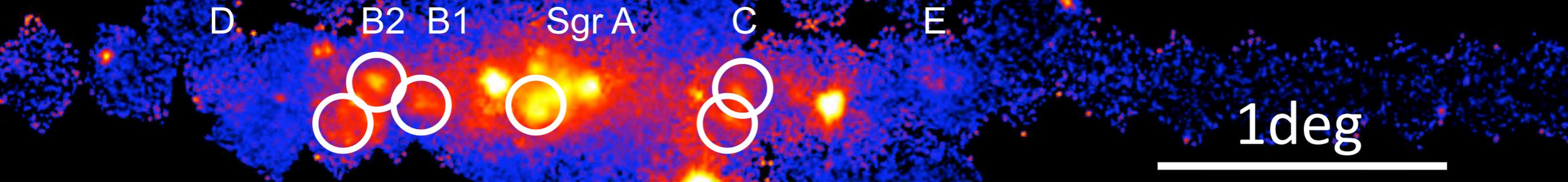


Larger EW of 6.4 keV line is expected for X-ray reflection
 $\sigma(\text{Thomson scatter}) < \sigma(\text{bremss by electron})$

Larger absorption $N_H (\text{cm}^{-2})$ for X-ray reflection

Electrons stop at the surface of MC due to ionization loss.





$$K\alpha / K\beta = 0.1$$

E.W: 1.1 – 2.1 keV

K-edge: $1.8 - 9.6 \times 10^{23} \text{ cm}^{-2} \gg 1 \times 10^{23} \text{ cm}^{-2}$

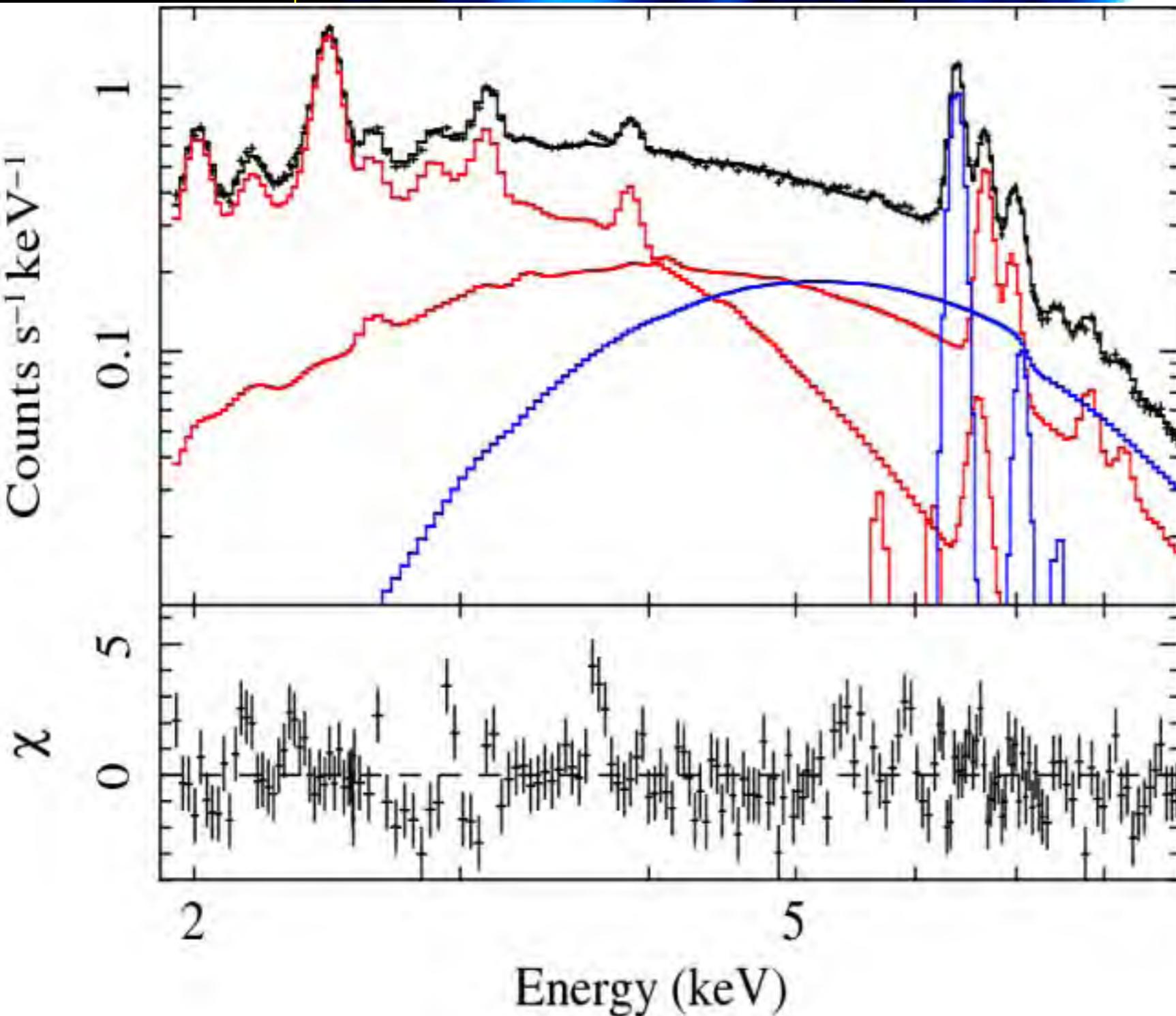
X-ray reflection is more likely.

Nakajima, Inui, Hyodo, Uchiyama,
Takikawa, Nobukawa, Tsuru et al.

6.4 keV map

Sgr A East
(SNR)

selected
region

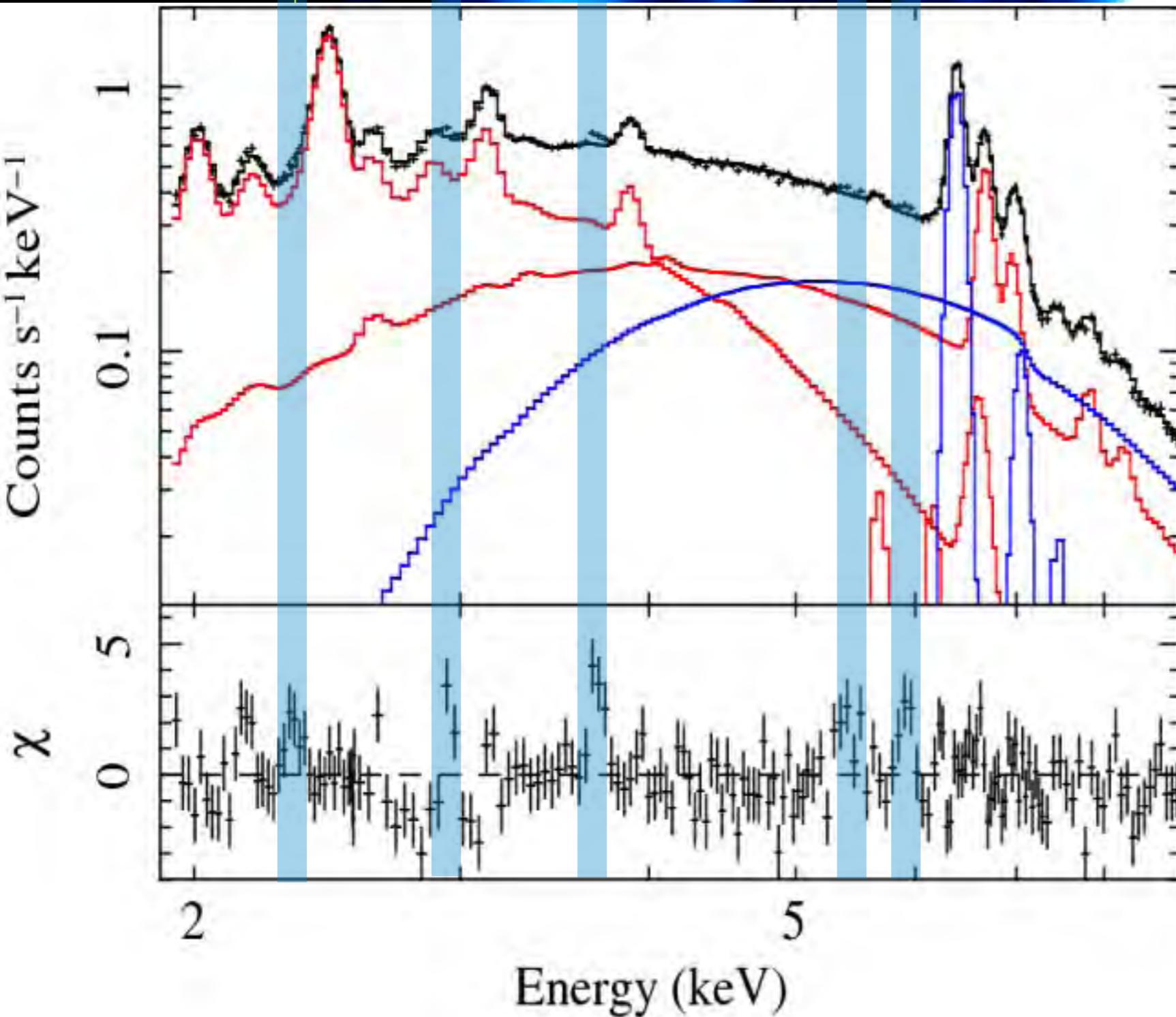


Nobukawa +10

6.4 keV map

Sgr A East
(SNR)

selected
region



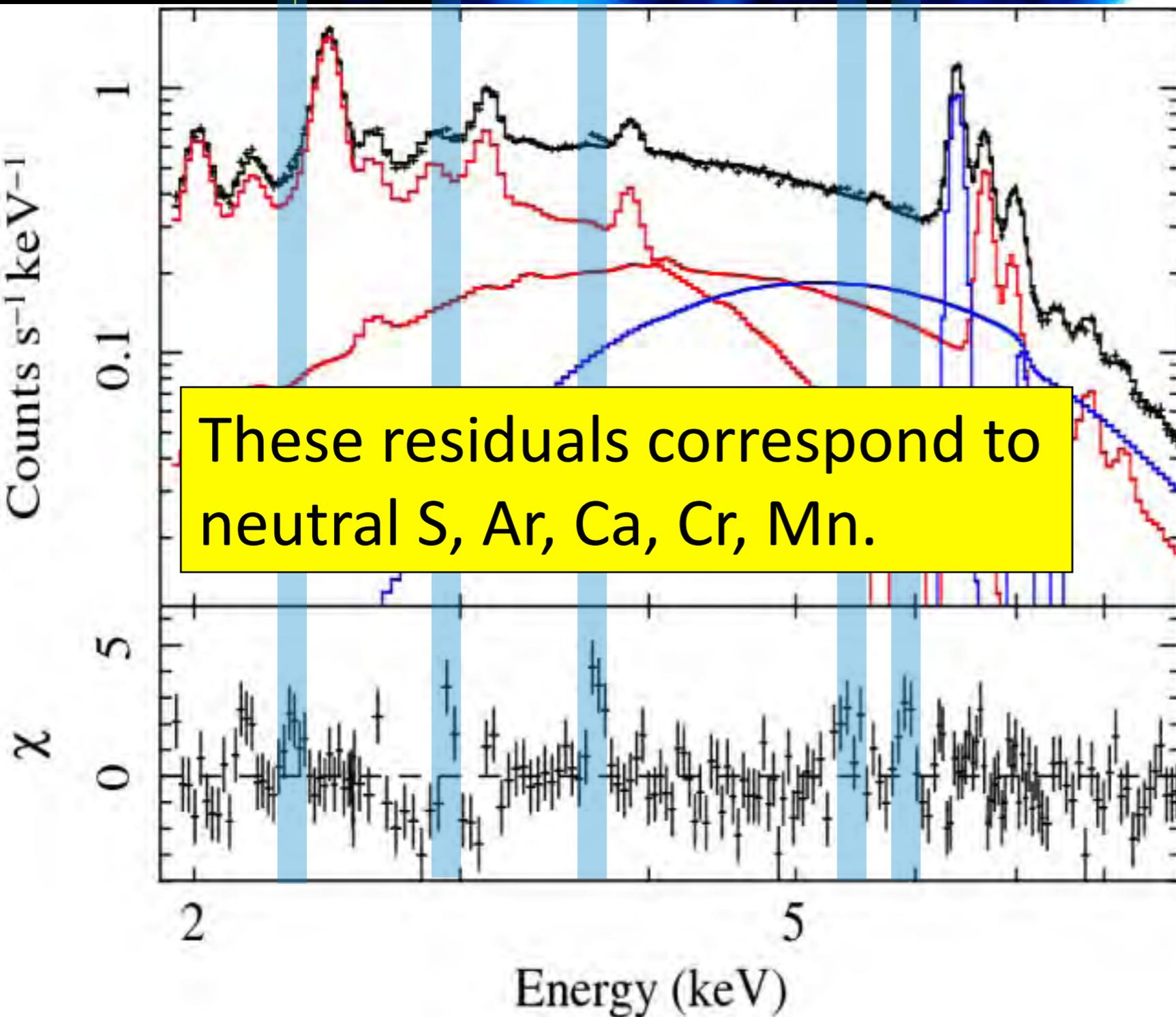
Nobukawa +10

6.4 keV map

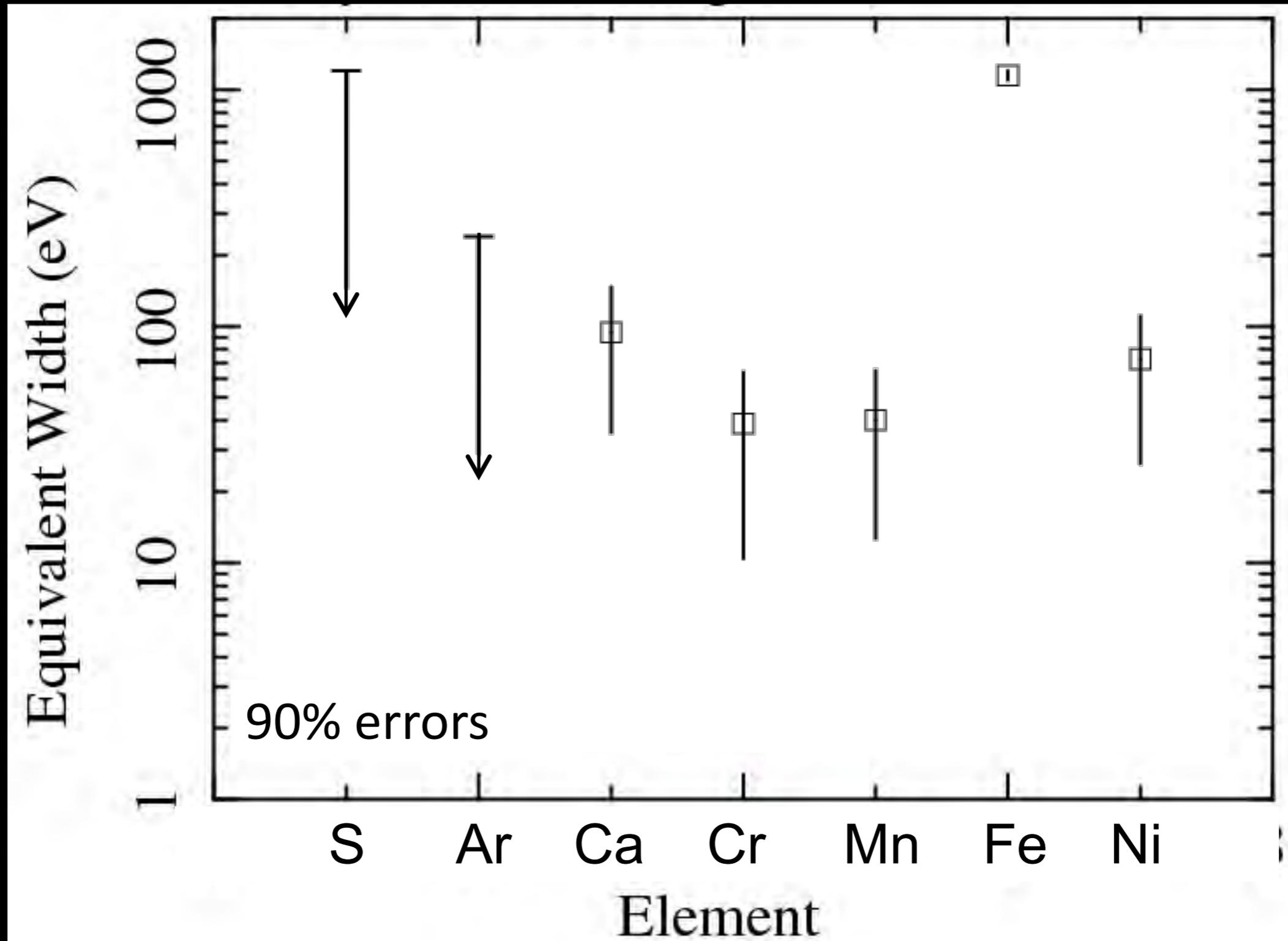
S Ar Ca Cr Mn

Sgr A East
(SNR)

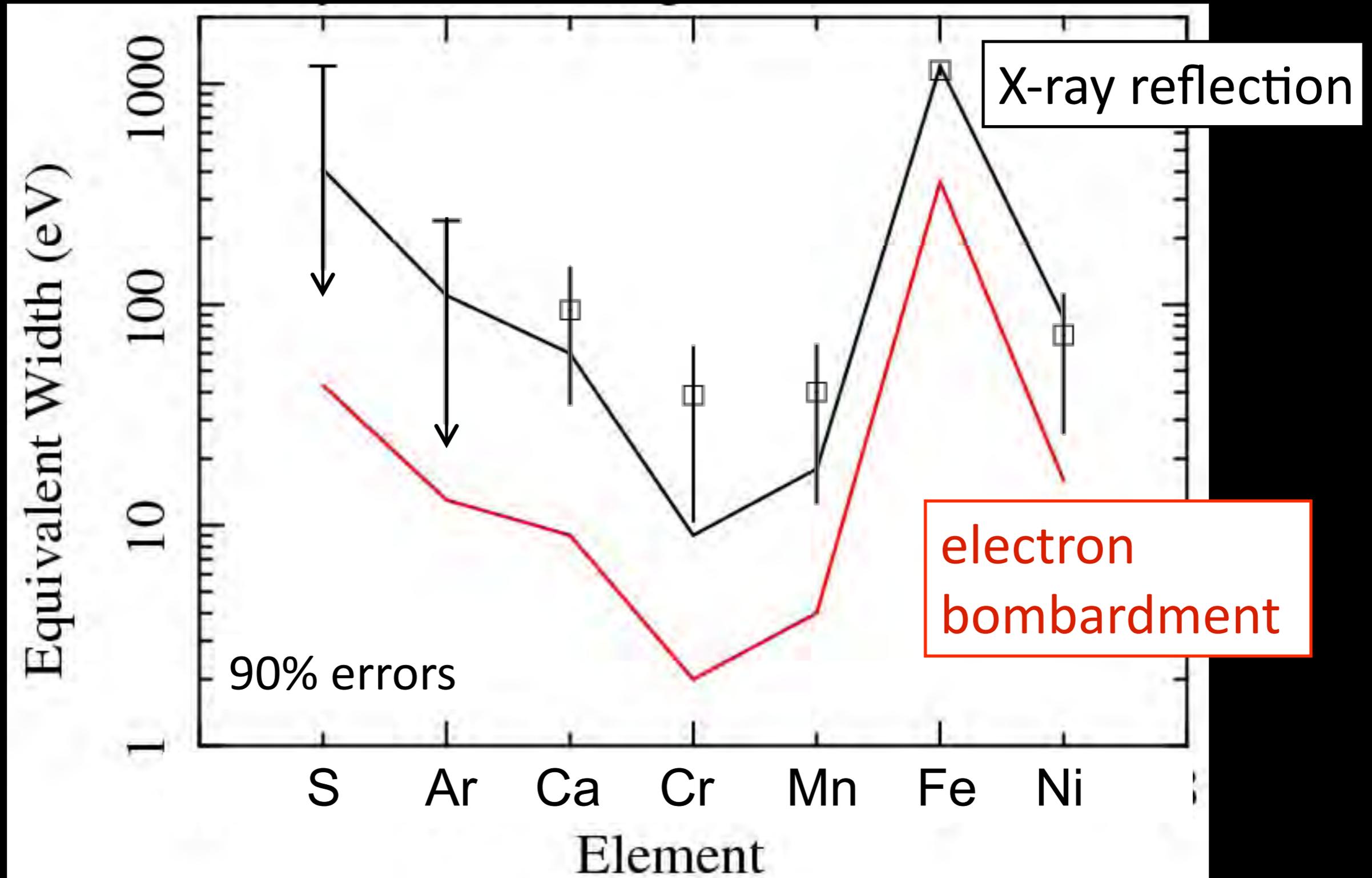
selected
region



Equivalent width and the origin Nobukawa +10

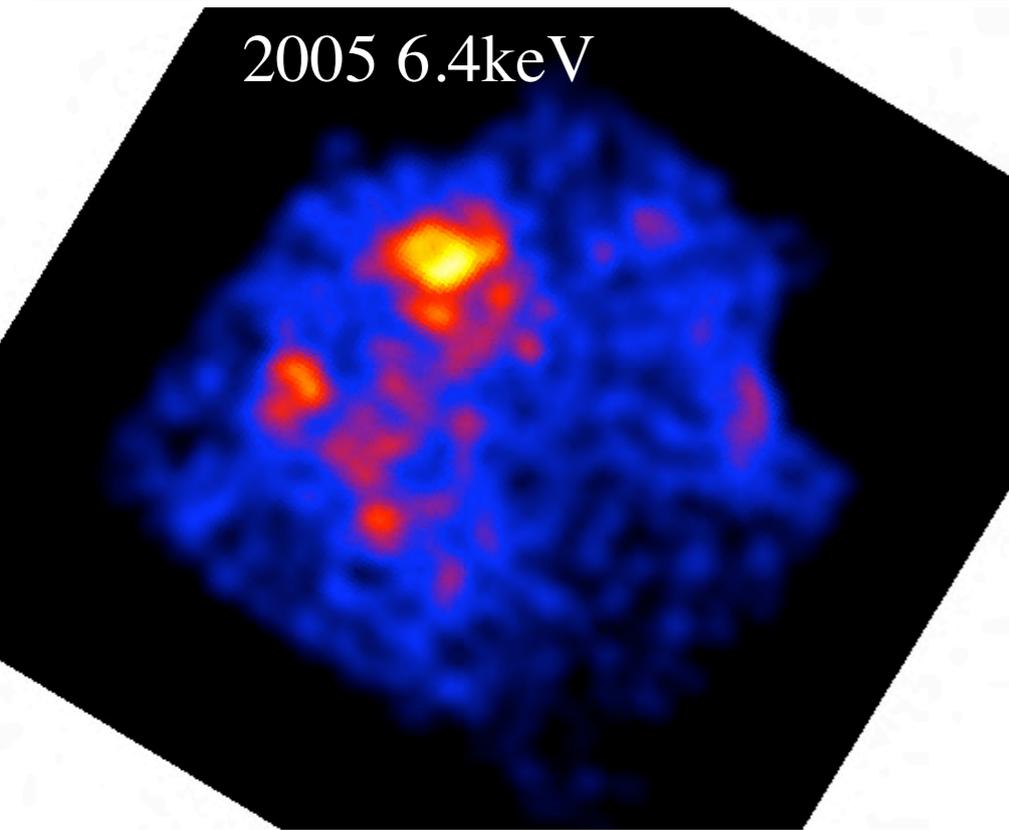


Equivalent width and the origin Nobukawa +10





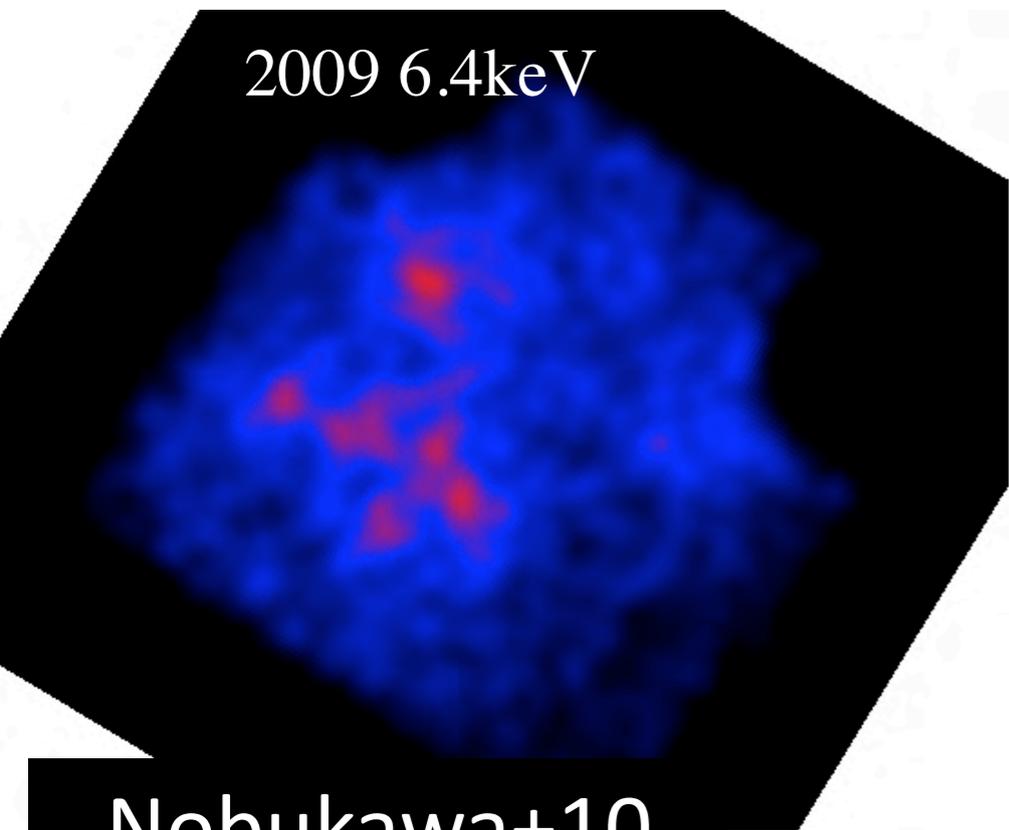
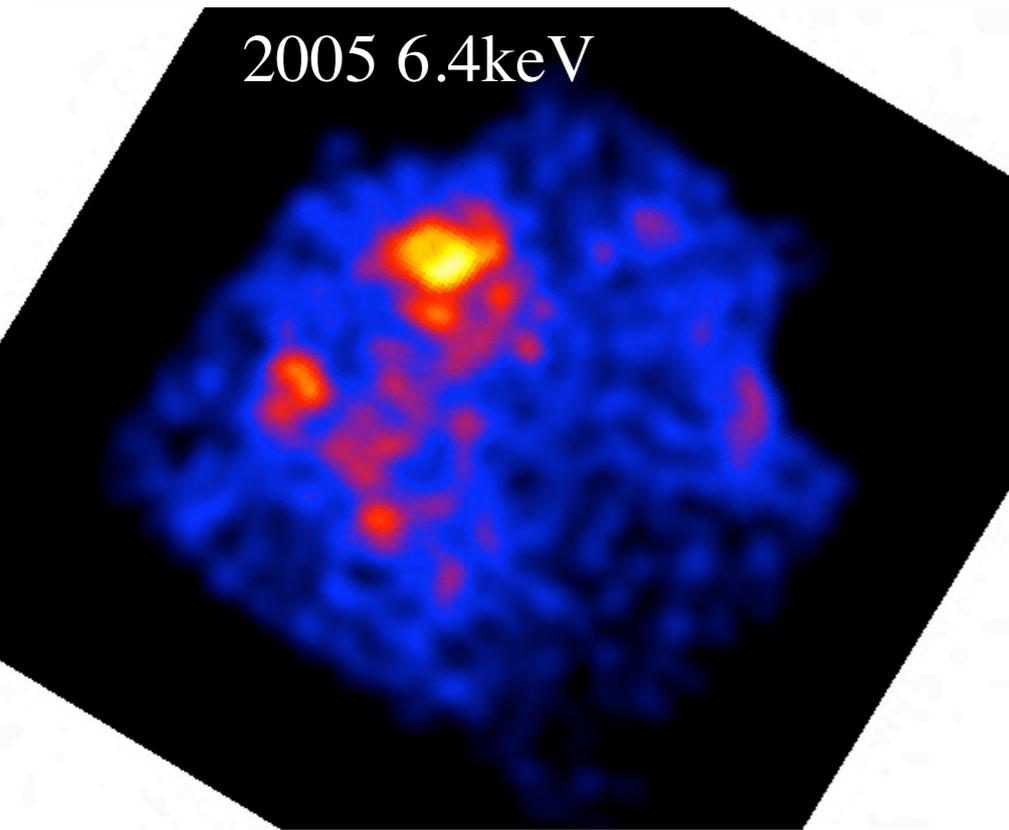
Sgr B2 Cloud -- Time Variable Diffuse 6.4keV emission : only with Suzaku



2005 6.4keV



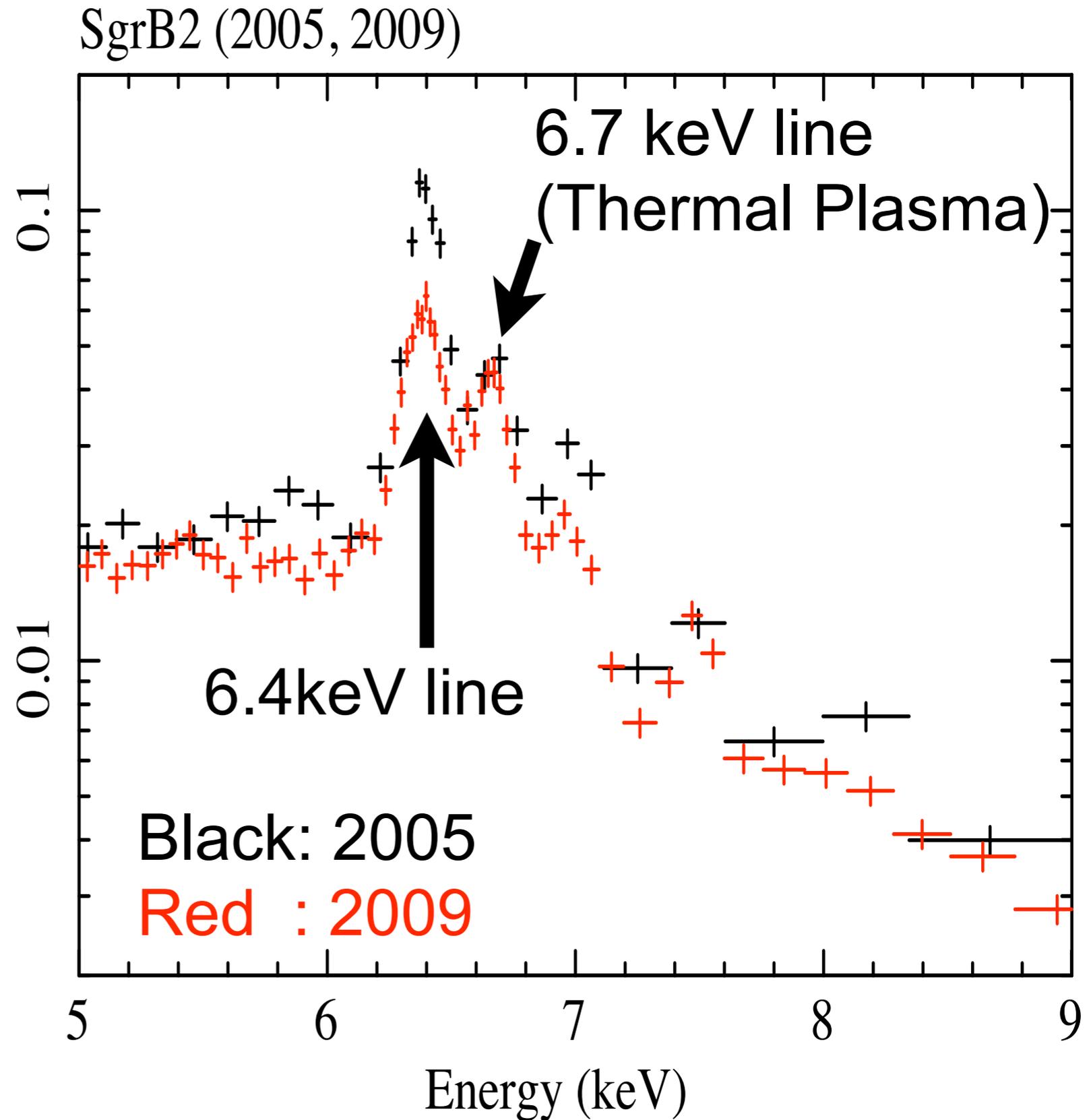
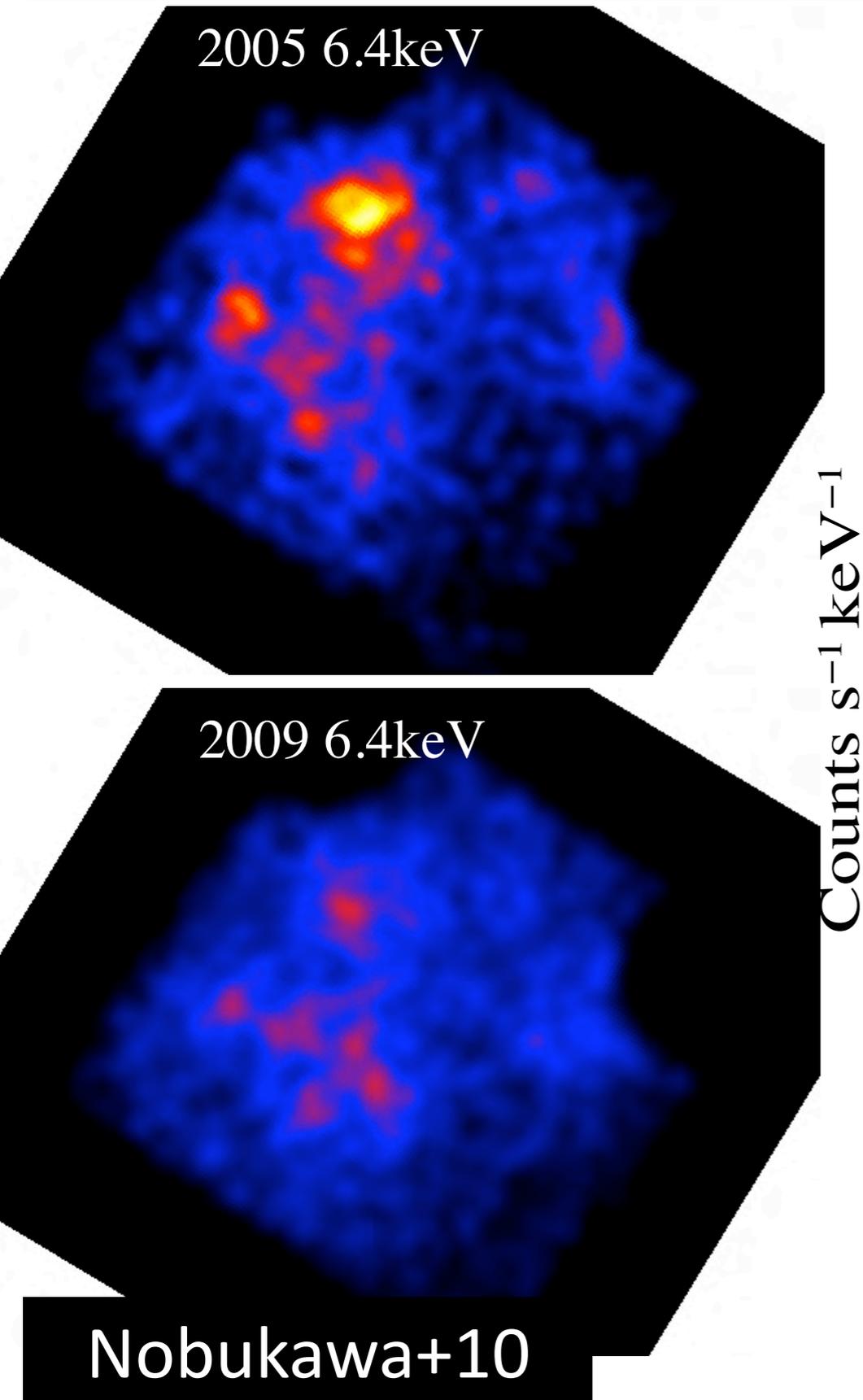
Sgr B2 Cloud -- Time Variable Diffuse 6.4keV emission : only with Suzaku



Nobukawa+10

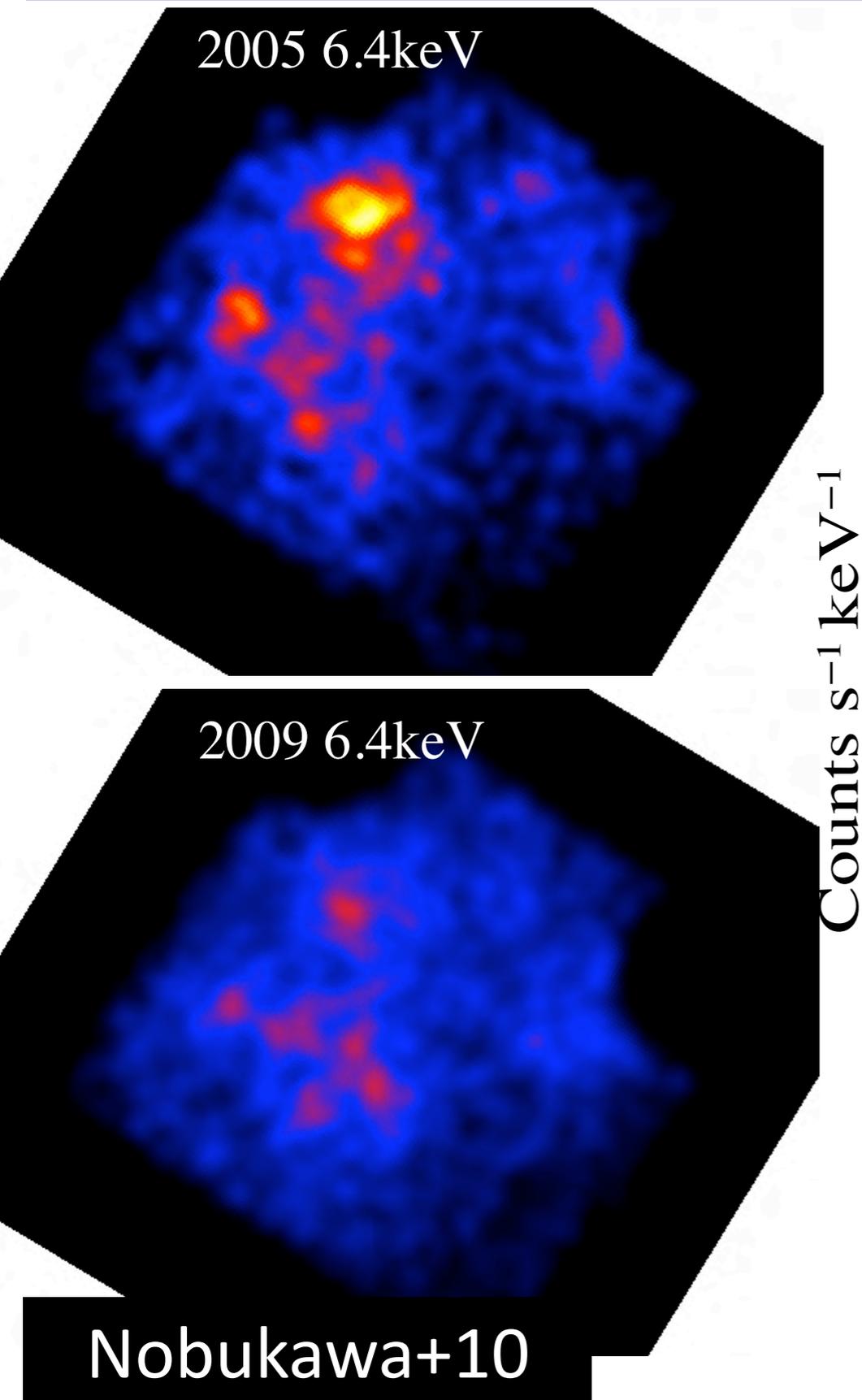


Sgr B2 Cloud -- Time Variable Diffuse 6.4keV emission : only with Suzaku

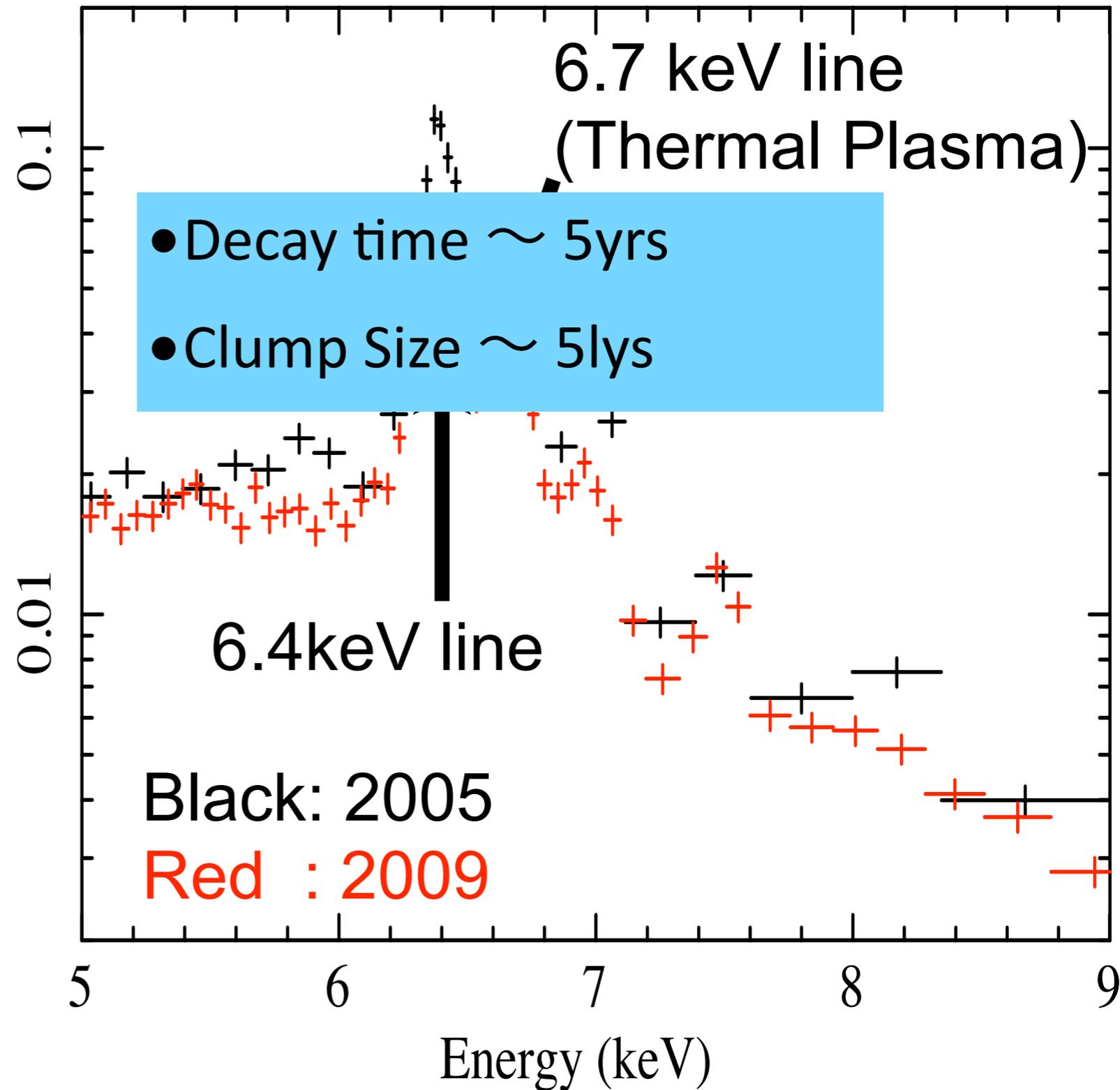


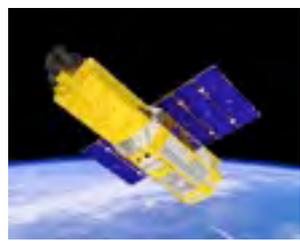


Sgr B2 Cloud -- Time Variable Diffuse 6.4keV emission : only with Suzaku

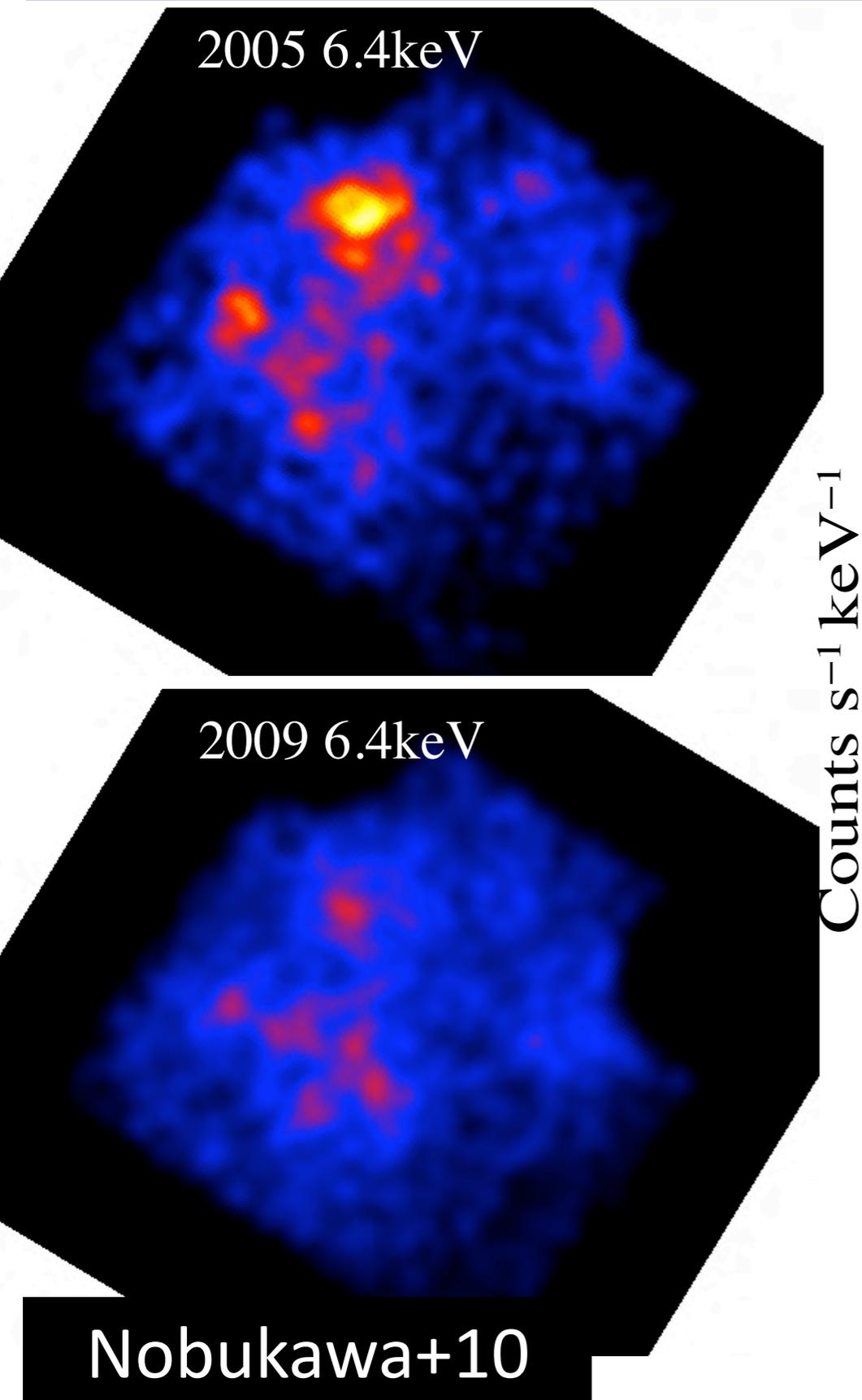


SgrB2 (2005, 2009)

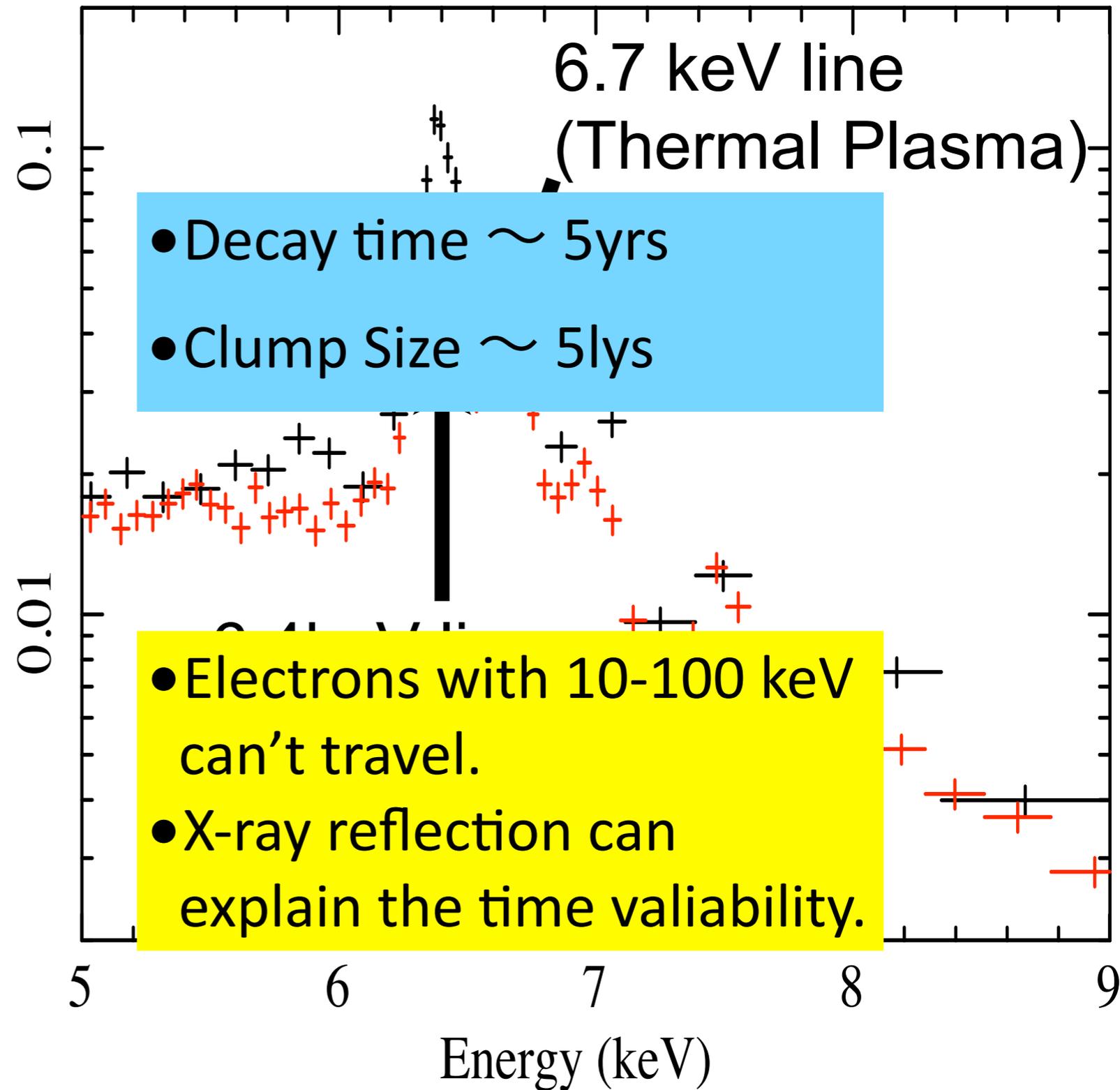




Sgr B2 Cloud -- Time Variable Diffuse 6.4keV emission : only with Suzaku



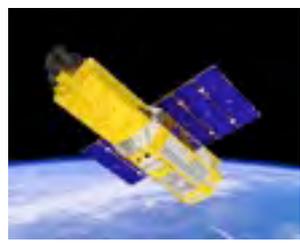
SgrB2 (2005, 2009)





Xray Reflection Nebula

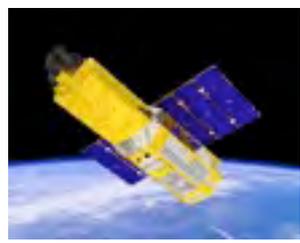




Xray Reflection Nebula



- X線反射星雲 = 「X-ray Reflection Nebula (XRN)」 と命名



Xray Reflection Nebula



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- 照射源には明るさ $\sim 10^{39-40}$ ergs/s必要



Xray Reflection Nebula



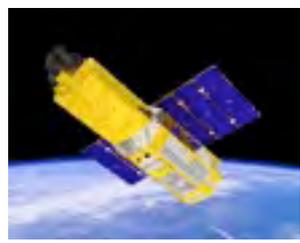
- X線反射星雲 = 「X-ray Reflection Nebula (XRN)」 と命名
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 - 最大光度は「エディントンリミット」 $\sim 10^{38}$ ergs/s を超えない。



Xray Reflection Nebula



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 - 他の銀河 : $\sim 10^{39-40}$ ergs/s は「楽勝」



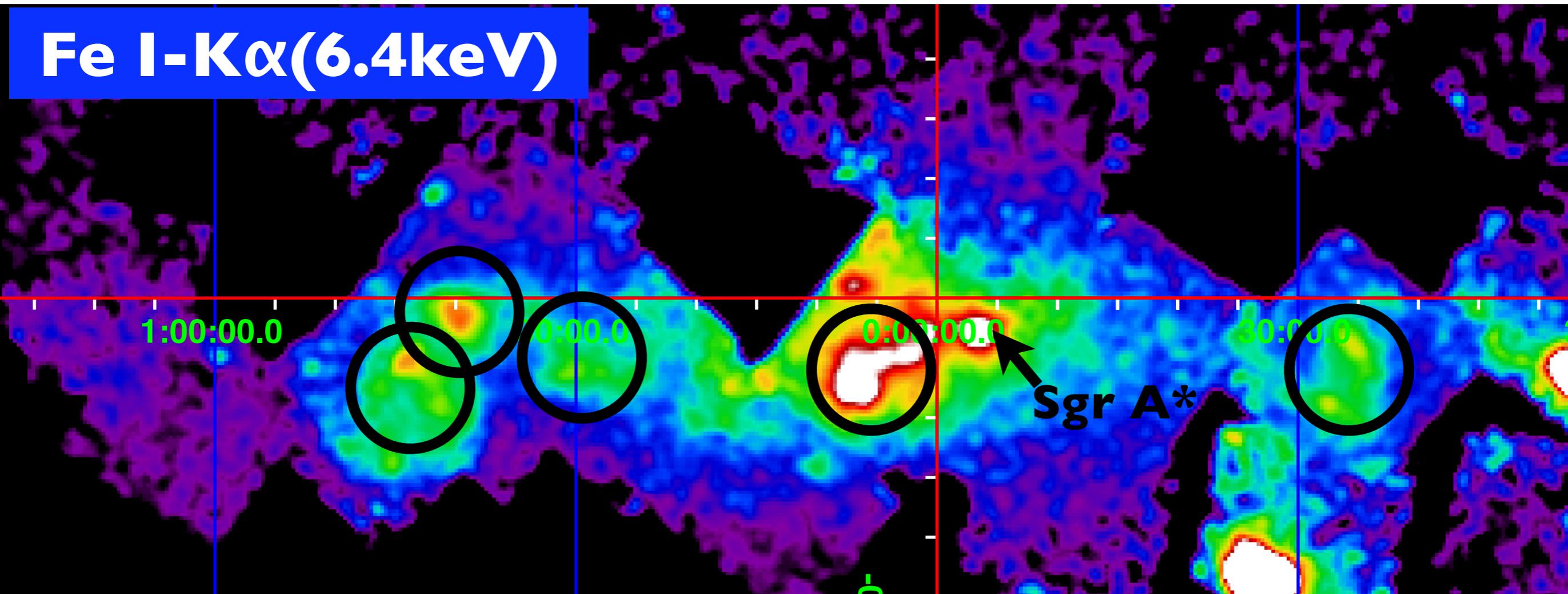
Xray Reflection Nebula

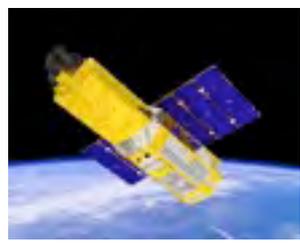
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- Sgr A* の過去の活動性



Past Activity of Sgr A*

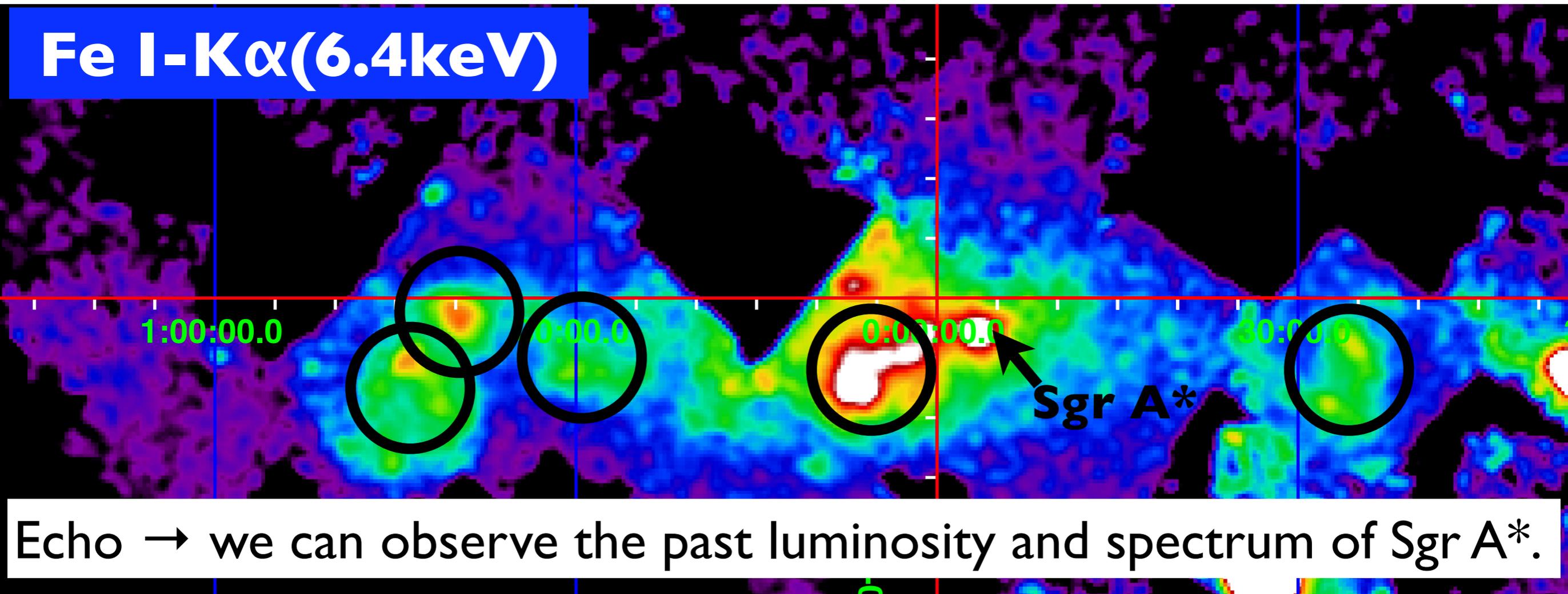
Fe I-K α (6.4keV)



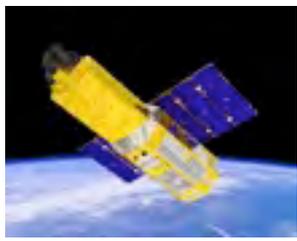


Past Activity of Sgr A*

Fe I-K α (6.4keV)

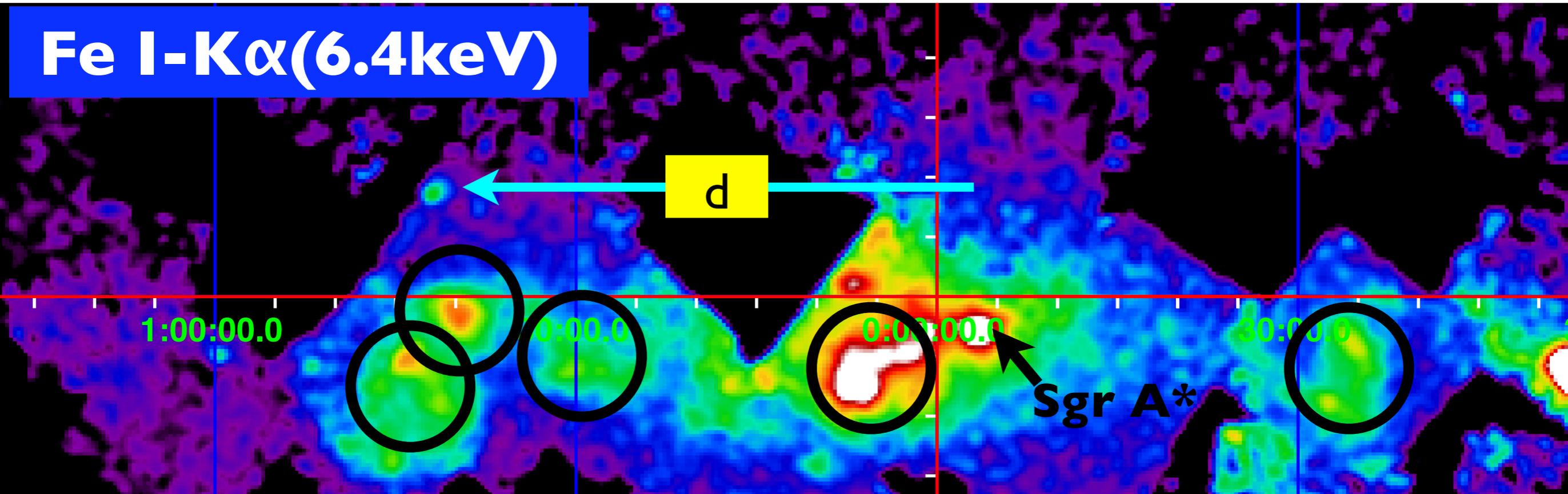


Echo → we can observe the past luminosity and spectrum of Sgr A*.



Past Activity of Sgr A*

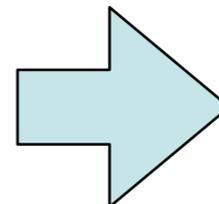
Fe I-K α (6.4keV)



Echo \rightarrow we can observe the past luminosity and spectrum of Sgr A*.

- $L(\text{Sgr A}^*) \propto L(\text{XRN}) \times d^2$

- Distance “d” between XRN and Sgr A*
 \rightarrow Look back time of echo



Collecting XRNe
 Long Term ($\sim 1000\text{yr}$)
 Light Curve of Sgr A*

Easier said than done 言うが易し, 行うが難し

Easier said than done 言うが易し, 行うが難し

In order to
obtain an
accurate light
curve...

Easier said than done 言うが易し, 行うが難し

In order to
obtain an
accurate light
curve...

Need to obtain the
distance to the MC
along the line of sight.

Easier said than done 言うが易し, 行うが難し

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obtain an
accurate light
curve...

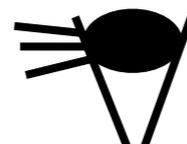
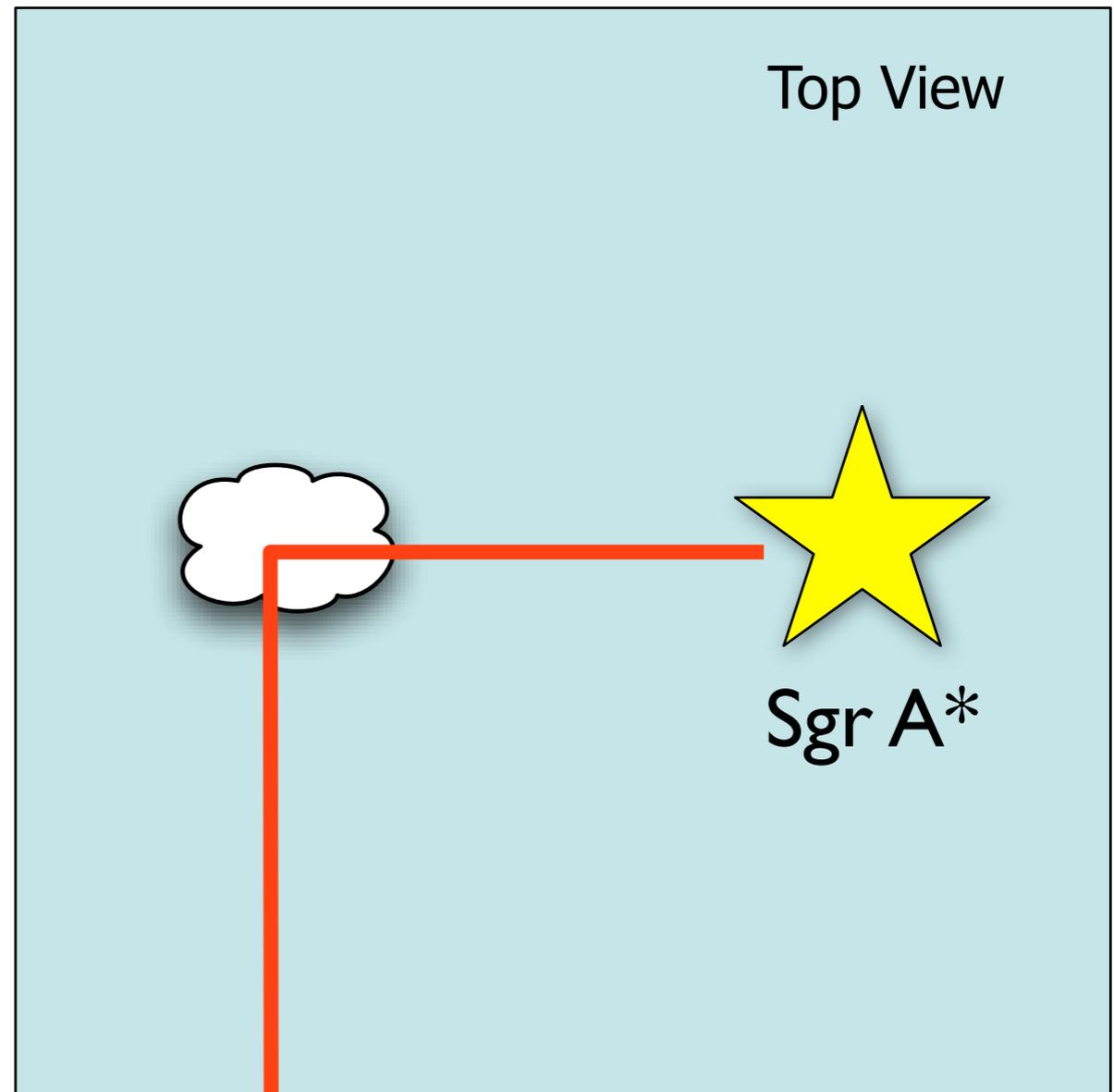


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along the line of sight.

Easier said than done 言うが易し, 行うが難し

In order to obtain an accurate light curve...

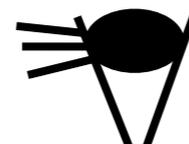
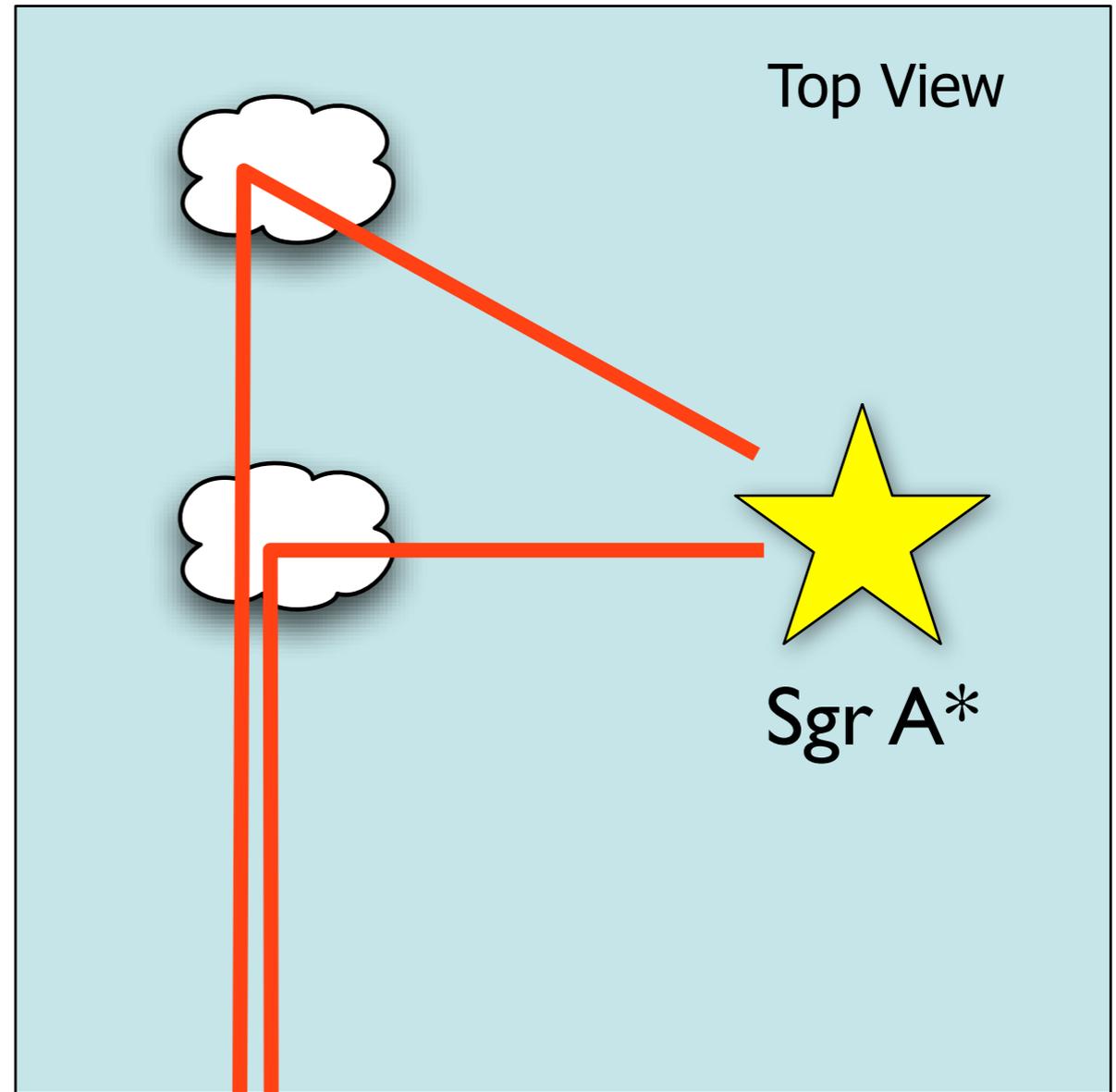
Need to obtain the distance to the MC along the line of sight.



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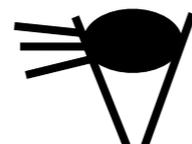
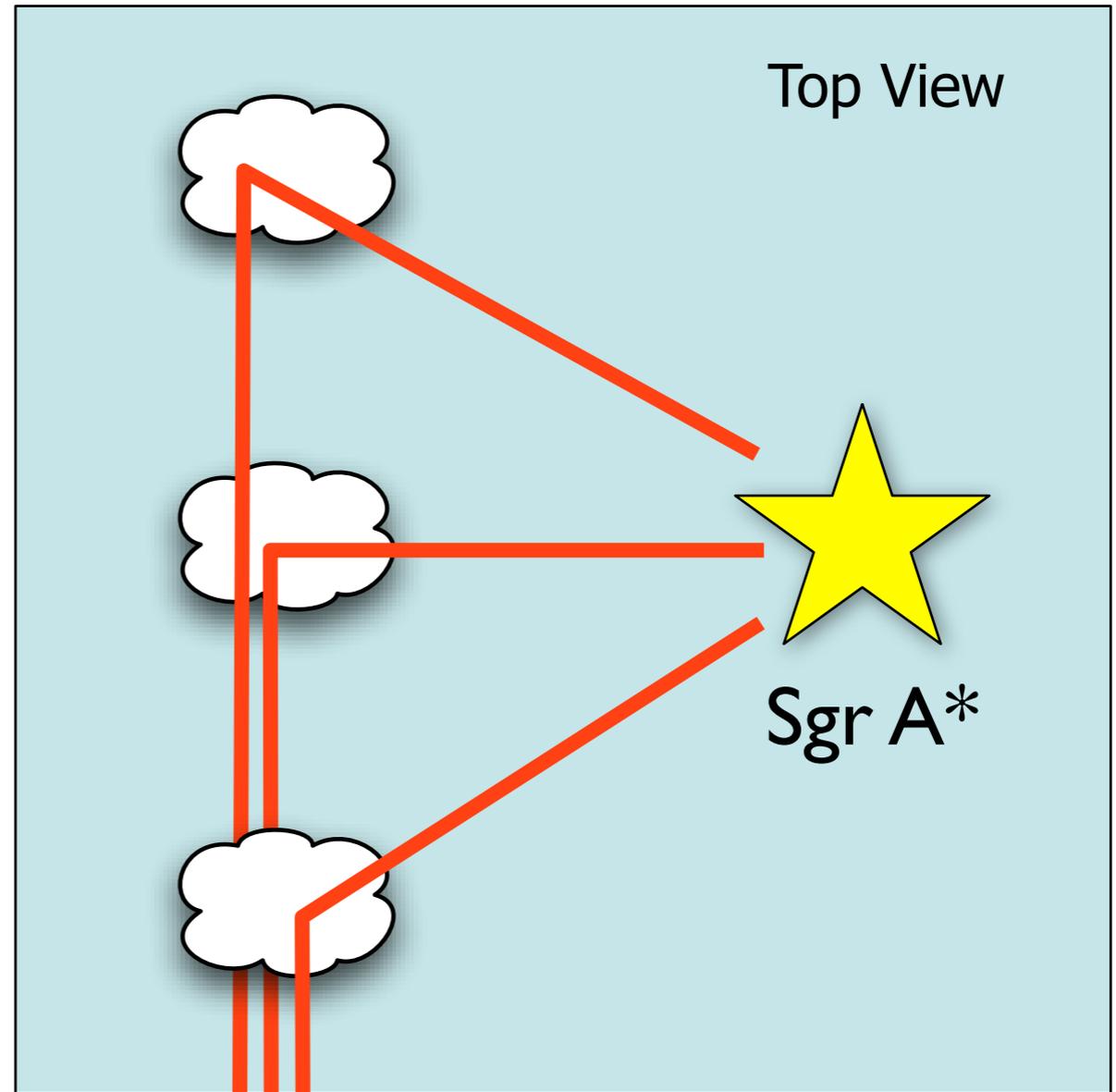
Need to obtain the distance to the MC along the line of sight.



Easier said than done 言うが易し, 行うが難し

In order to obtain an accurate light curve...

Need to obtain the distance to the MC along the line of sight.



奥行き方向の情報を得るには...

←東

西→

超高温プラズマからの連続X線

平面分布

100光年



巨大質量
ブラックホール

冷たい分子雲からの特性X線

平面分布

100光年



巨大質量
ブラックホール

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明るい



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巨大質量
ブラックホール

100光年

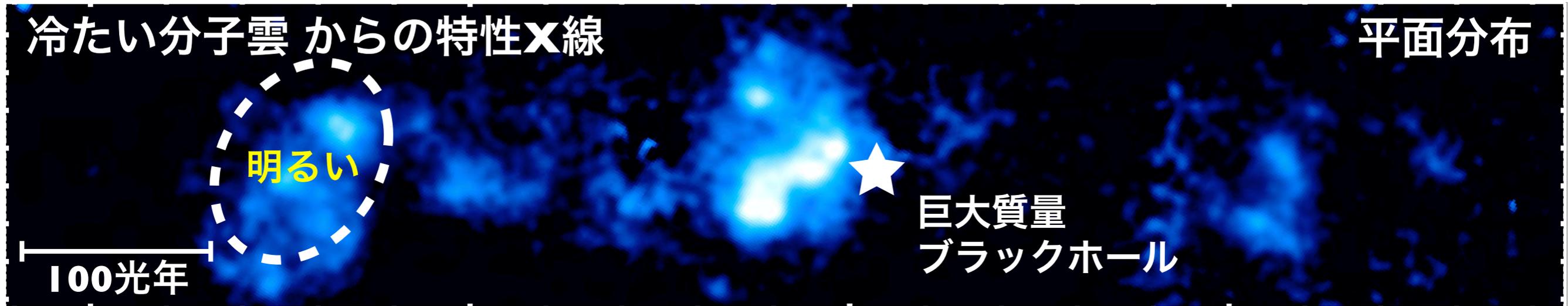
冷たい分子雲からの特性X線

平面分布

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巨大質量
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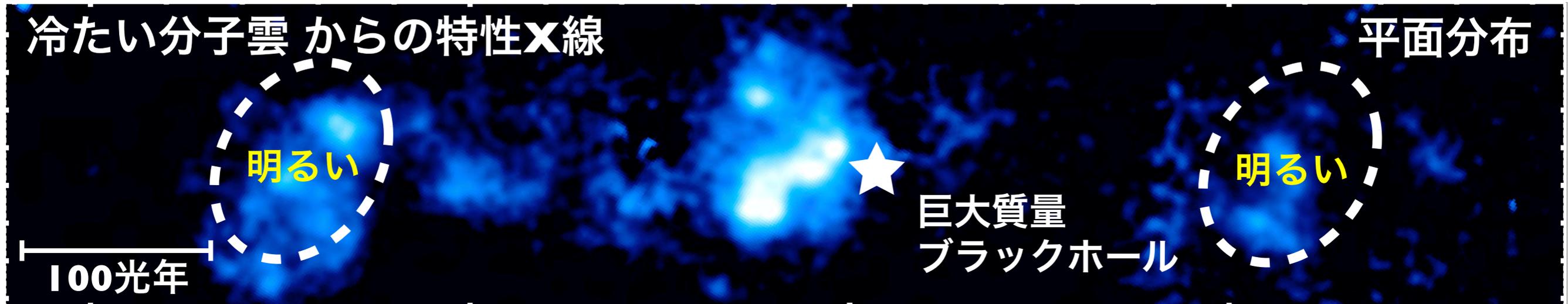
平面分布

明るい

巨大質量
ブラックホール

100光年

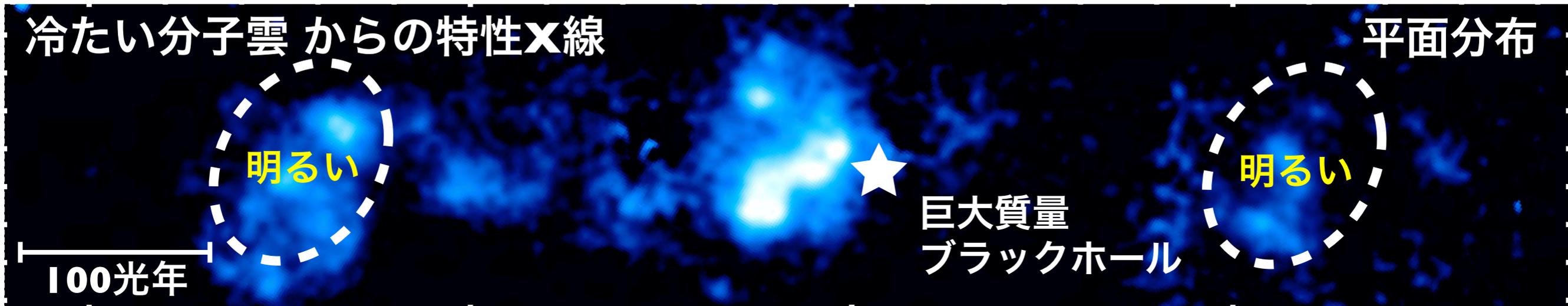
明るい



奥行き方向の情報を得るには...

←東

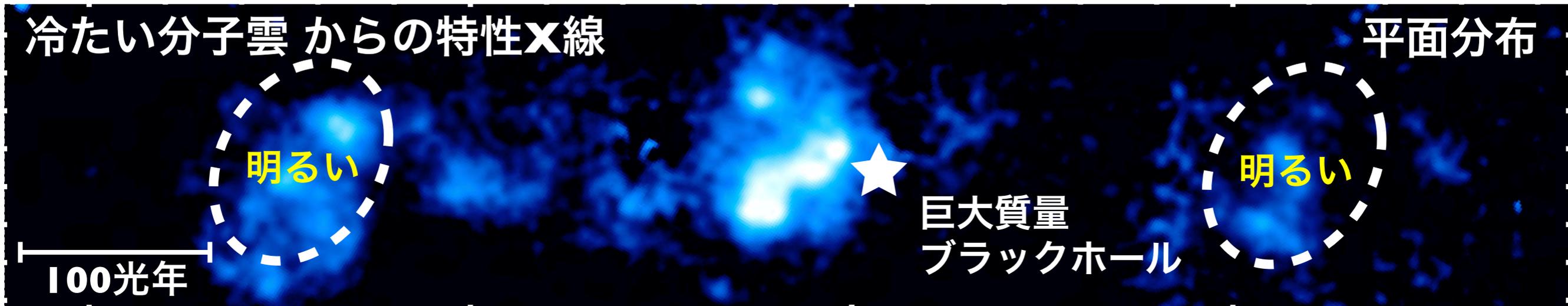
西→



奥行き方向の情報を得るには...

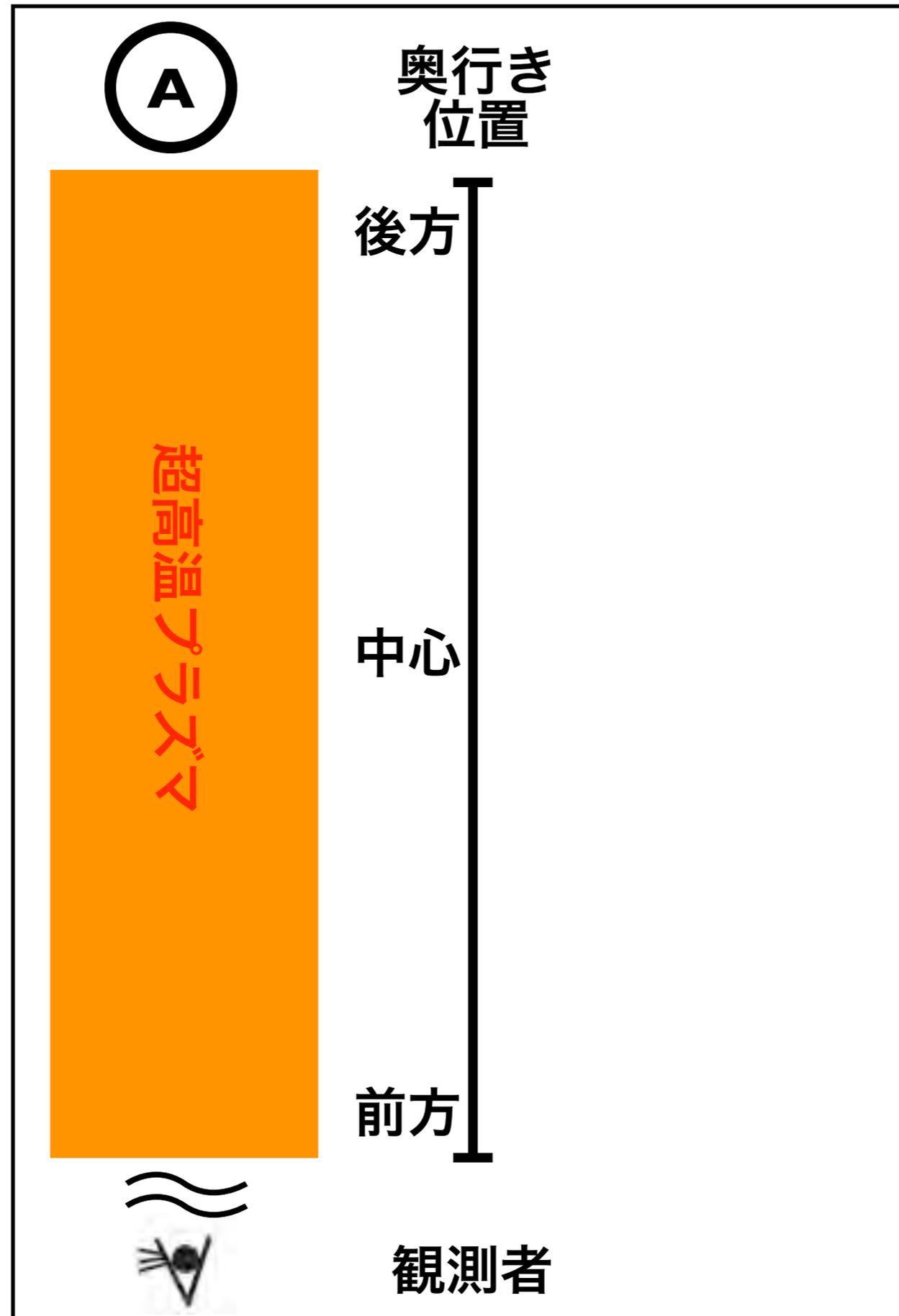
←東

西→

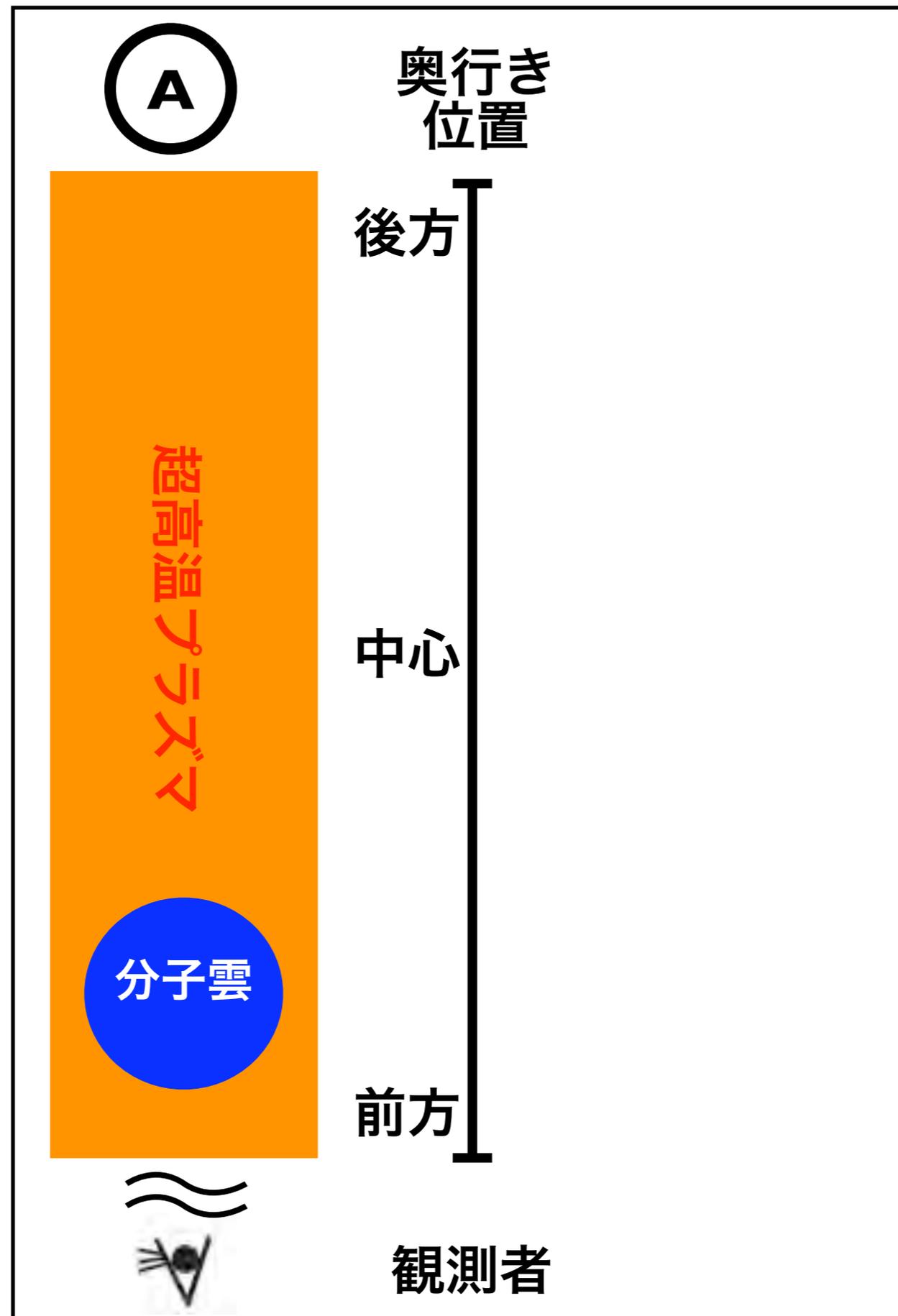


これをうまく利用できないか?

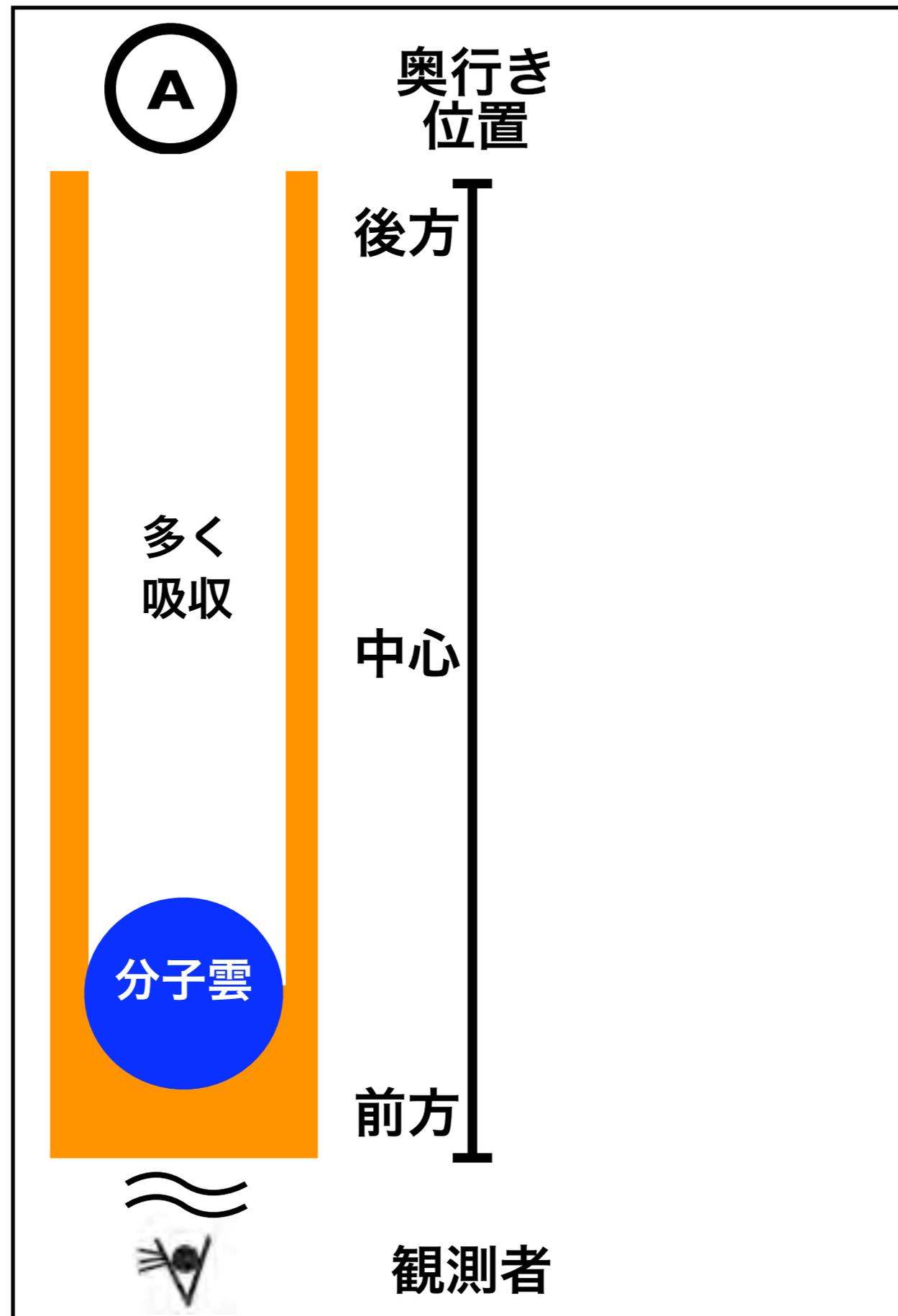
X線トモグラフィの開発：X線吸収の利用



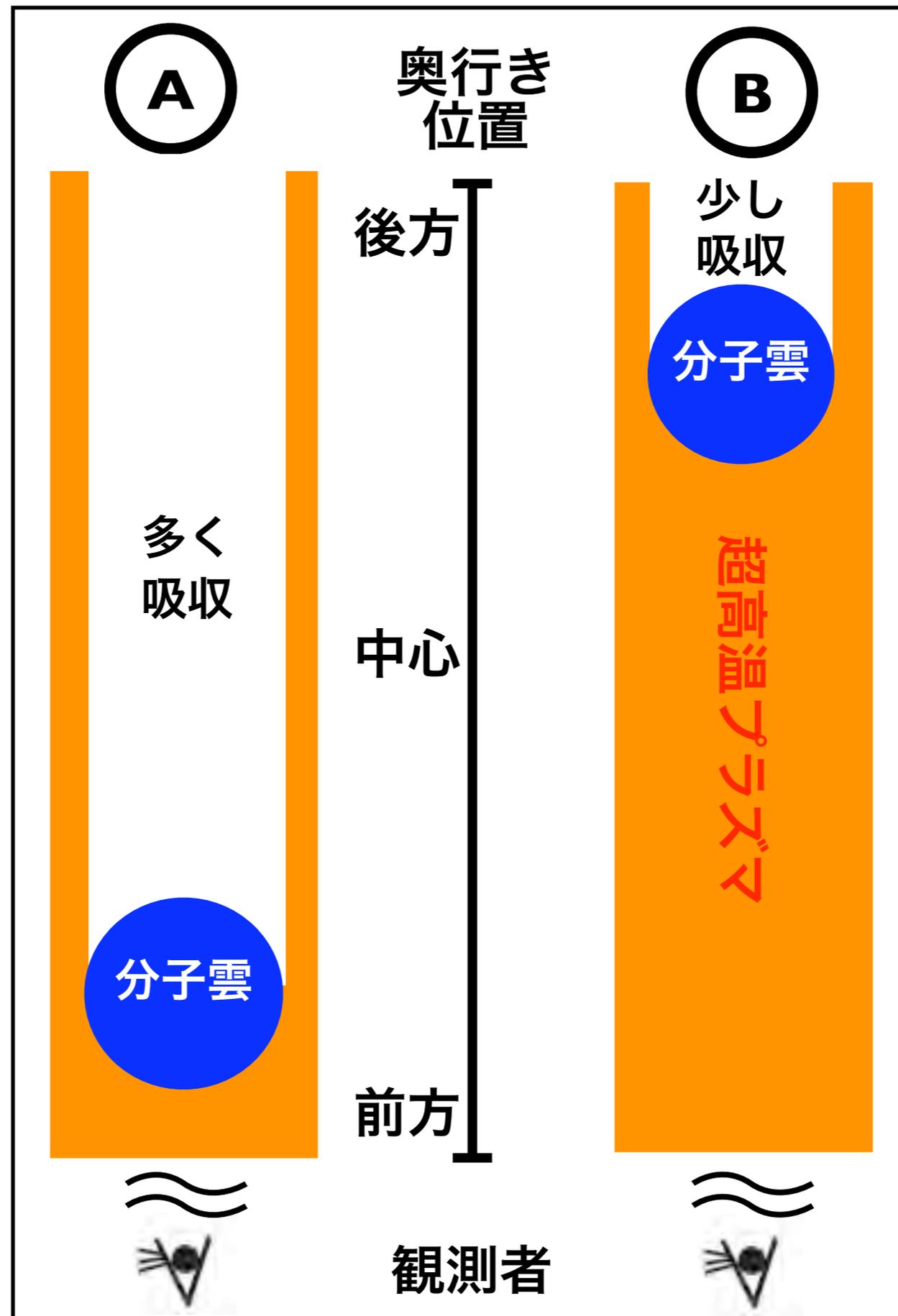
X線トモグラフィの開発：X線吸収の利用



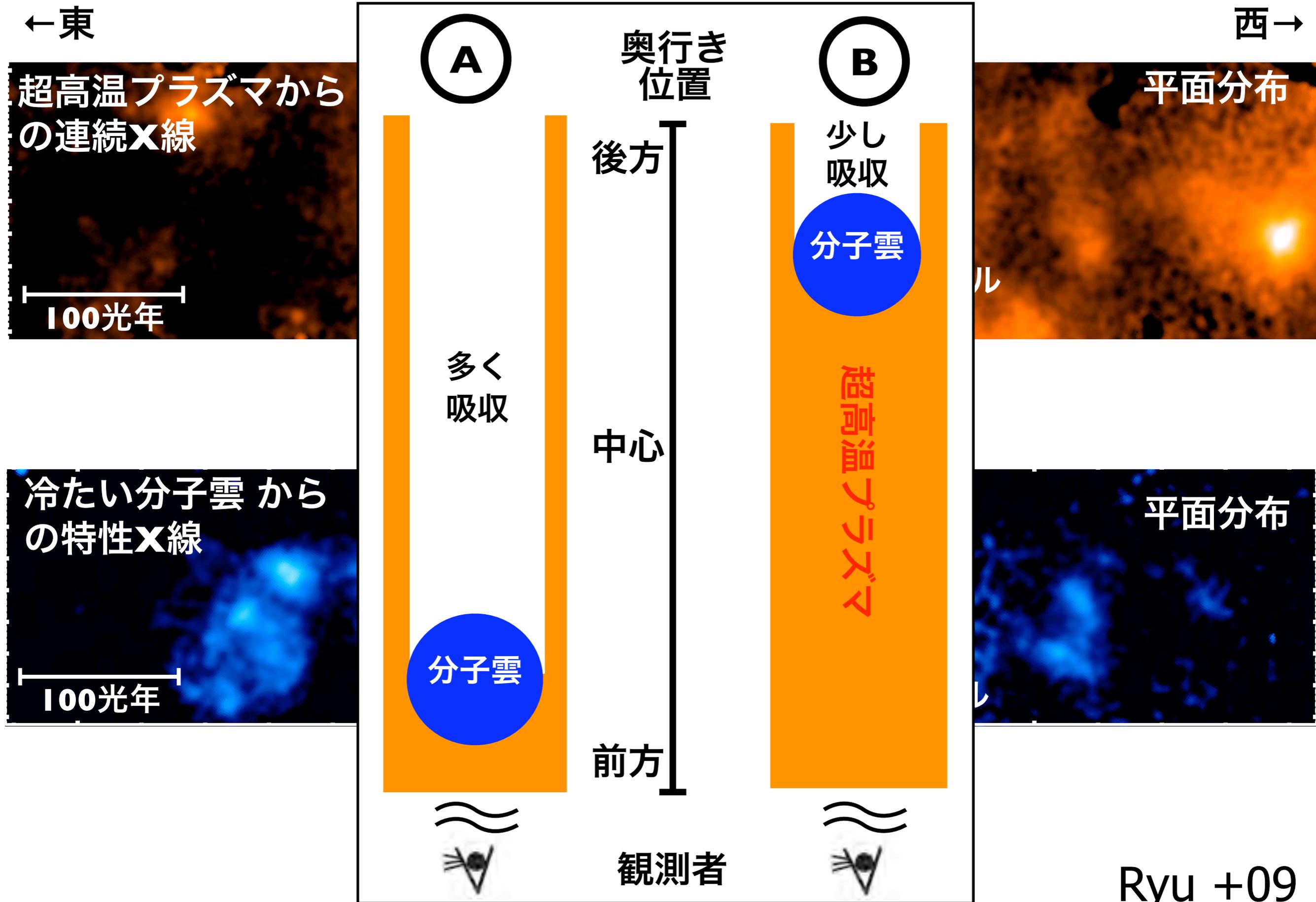
X線トモグラフィの開発：X線吸収の利用



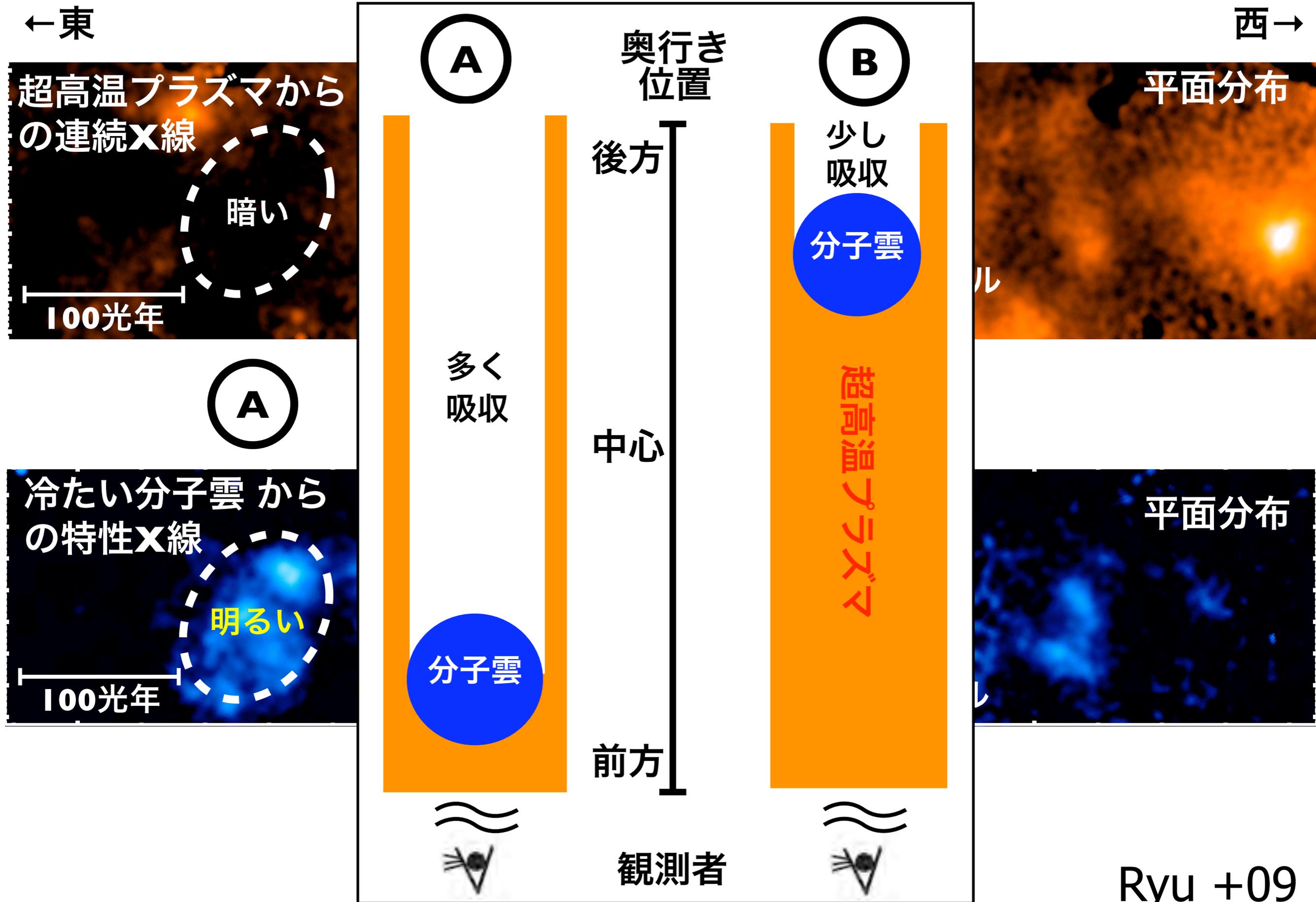
X線トモグラフィーの開発：X線吸収の利用



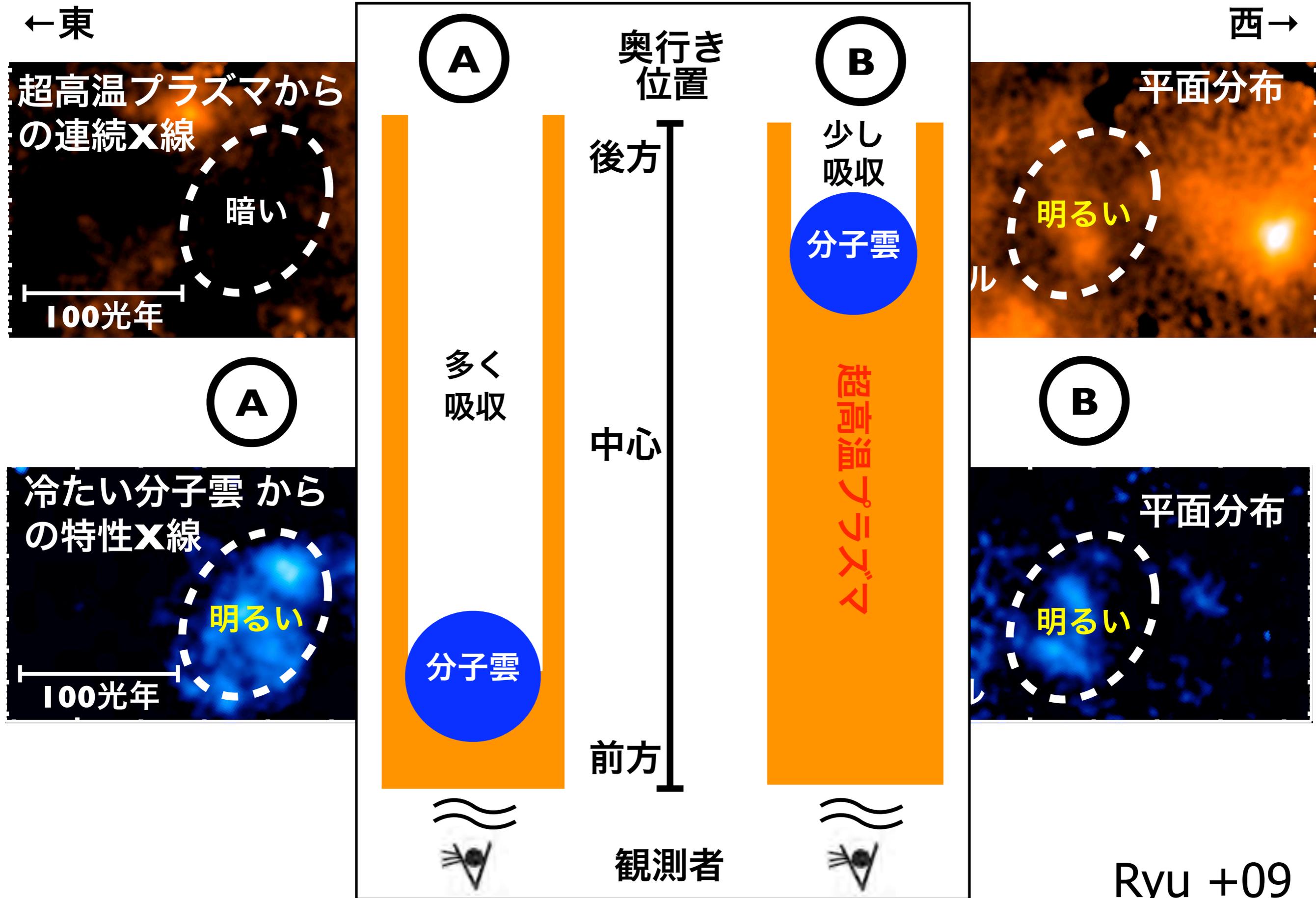
X線トモグラフィーの開発：X線吸収の利用



X線トモグラフィーの開発：X線吸収の利用

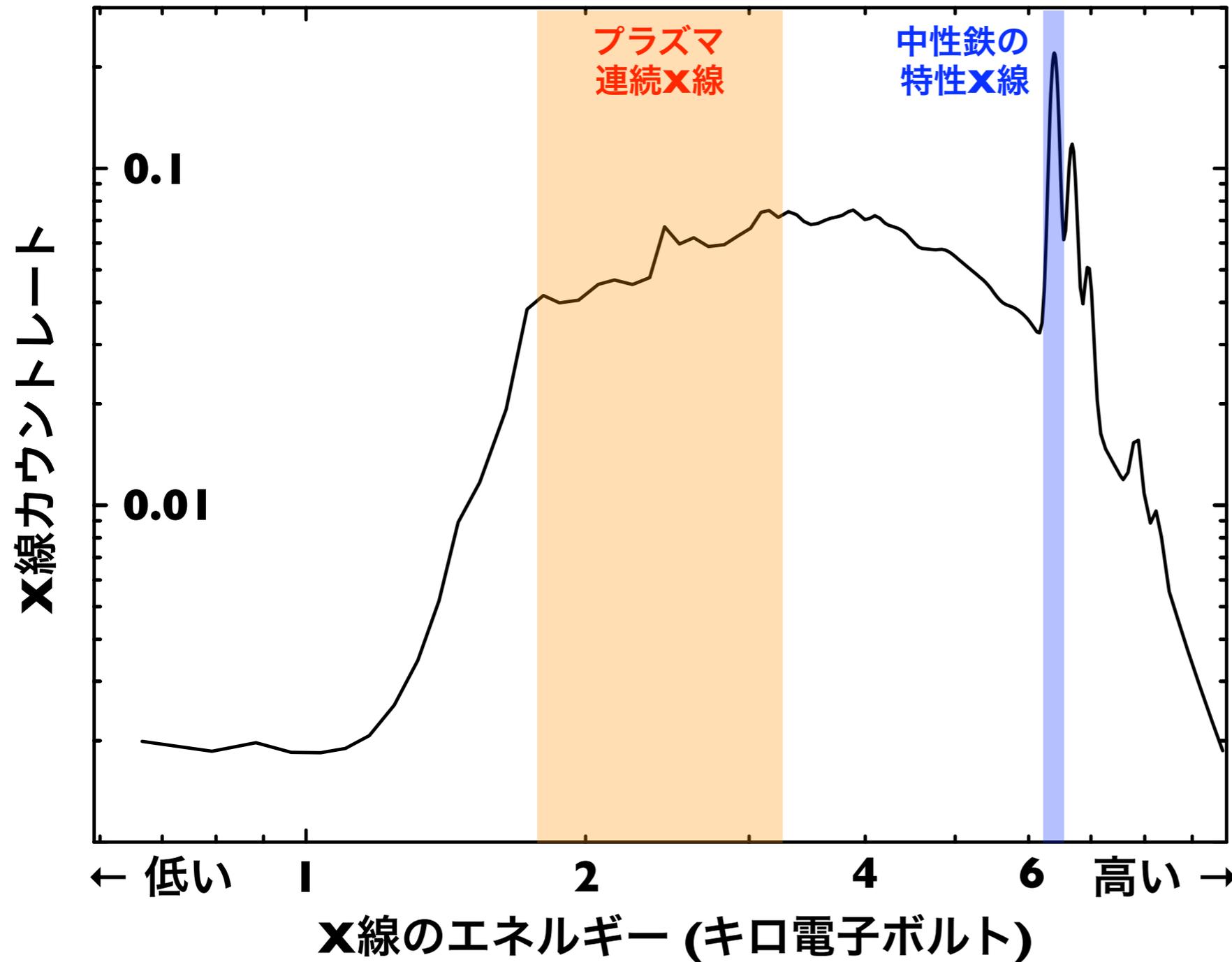


X線トモグラフィーの開発：X線吸収の利用



X線スペクトル・トモグラフィー

分子雲の奥行き位置 によるスペクトルの変化



奥行き方向

プラズマ内の位置

後方

中心

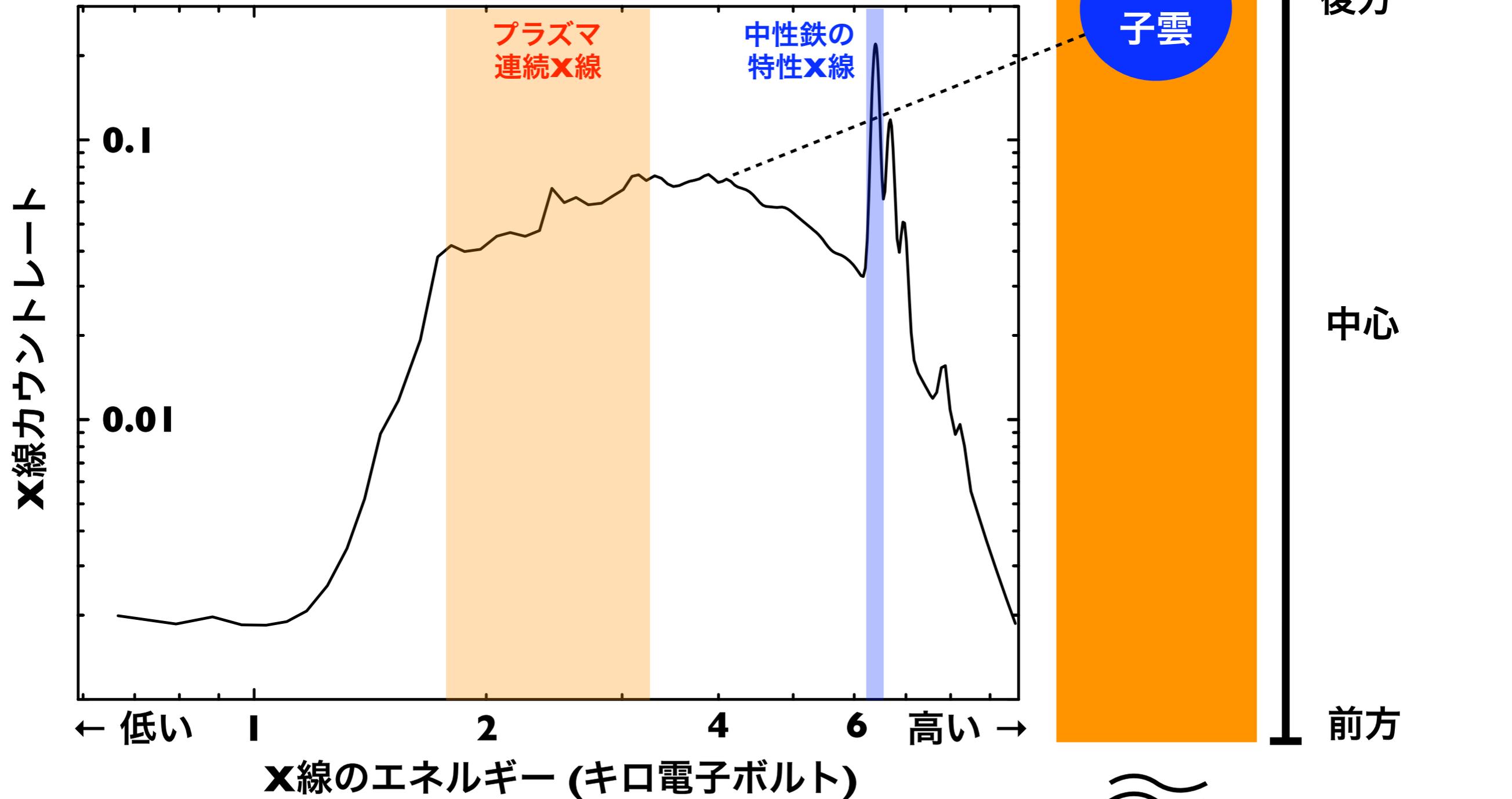
前方



観測者

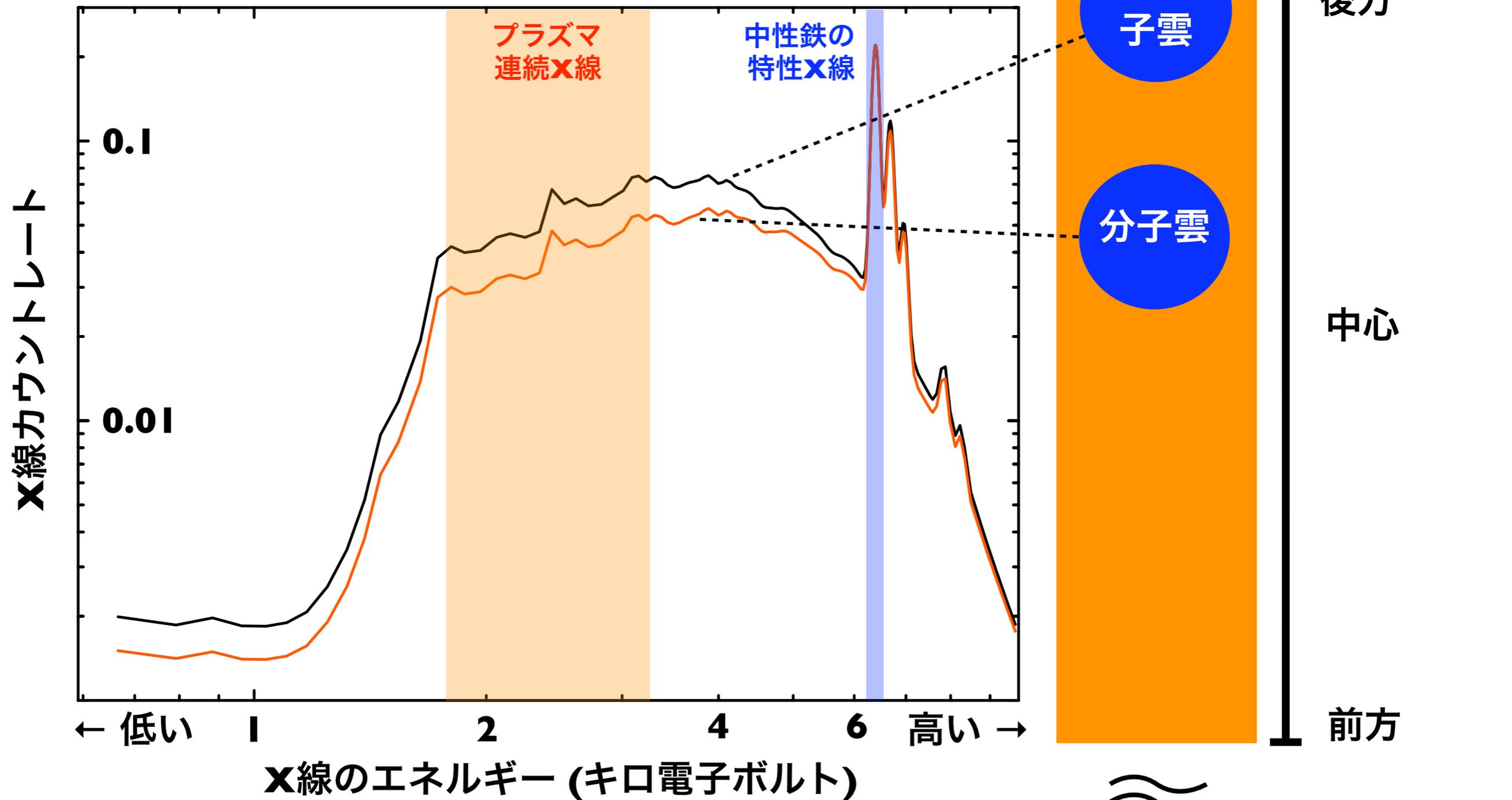
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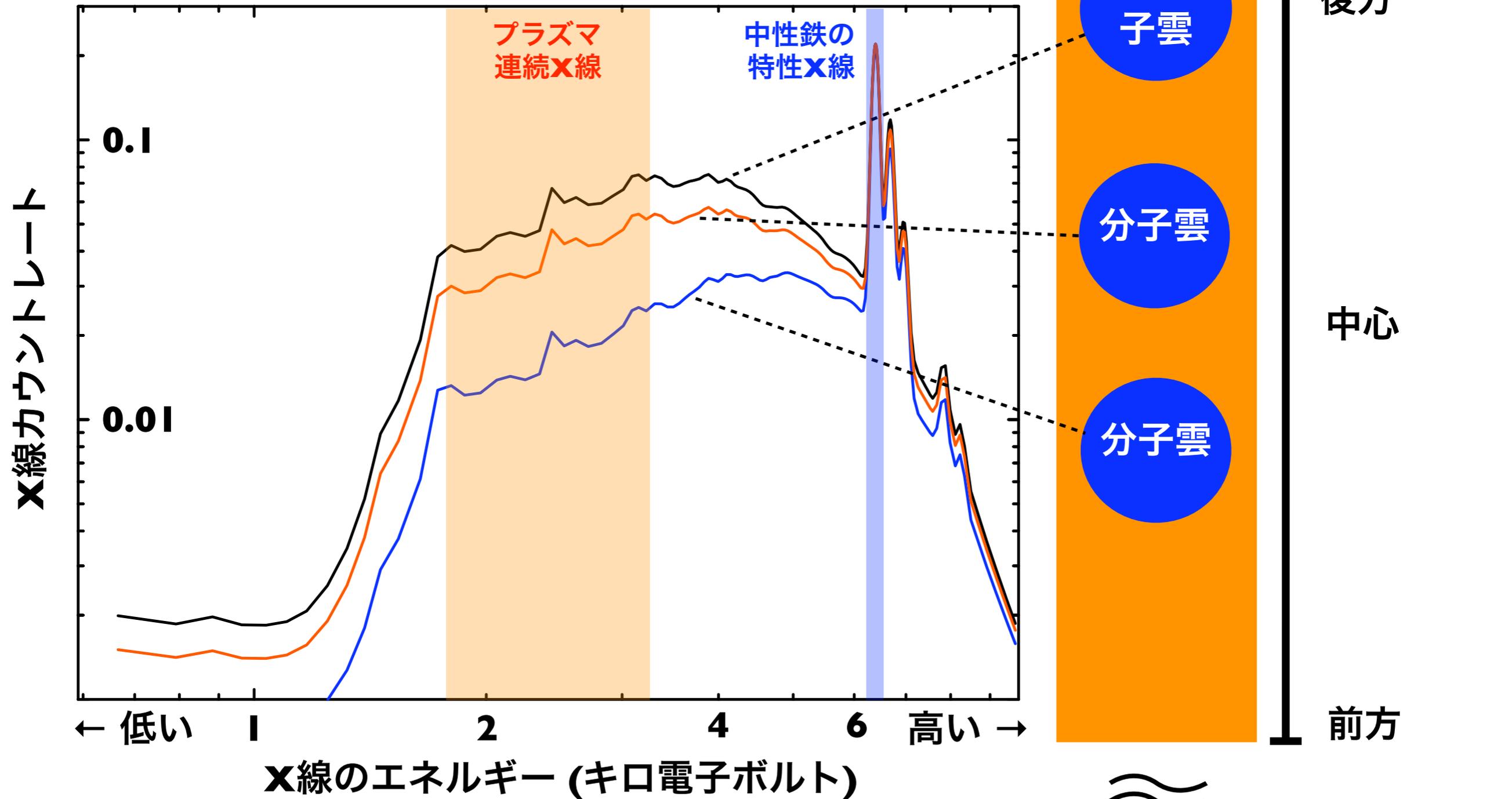
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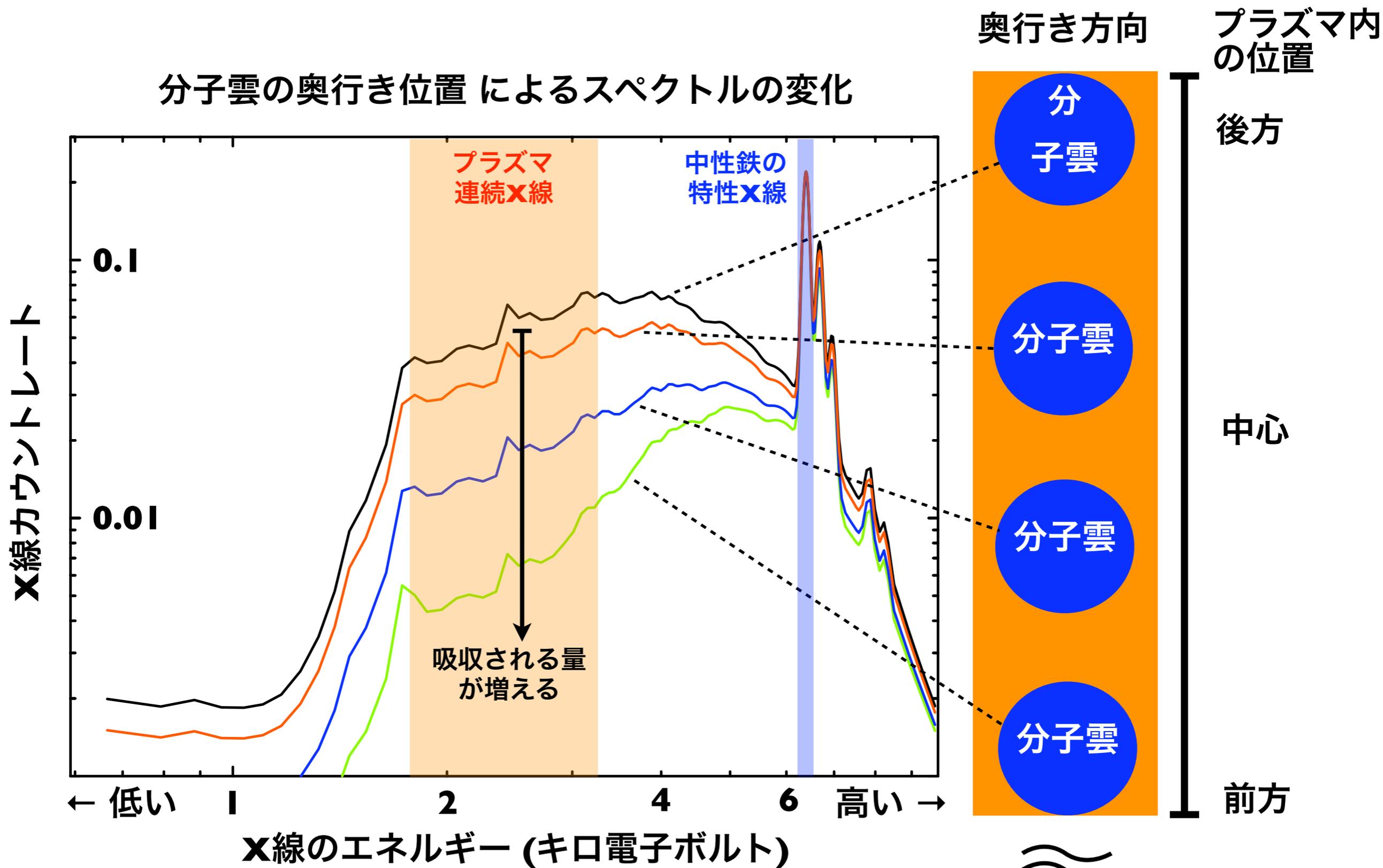
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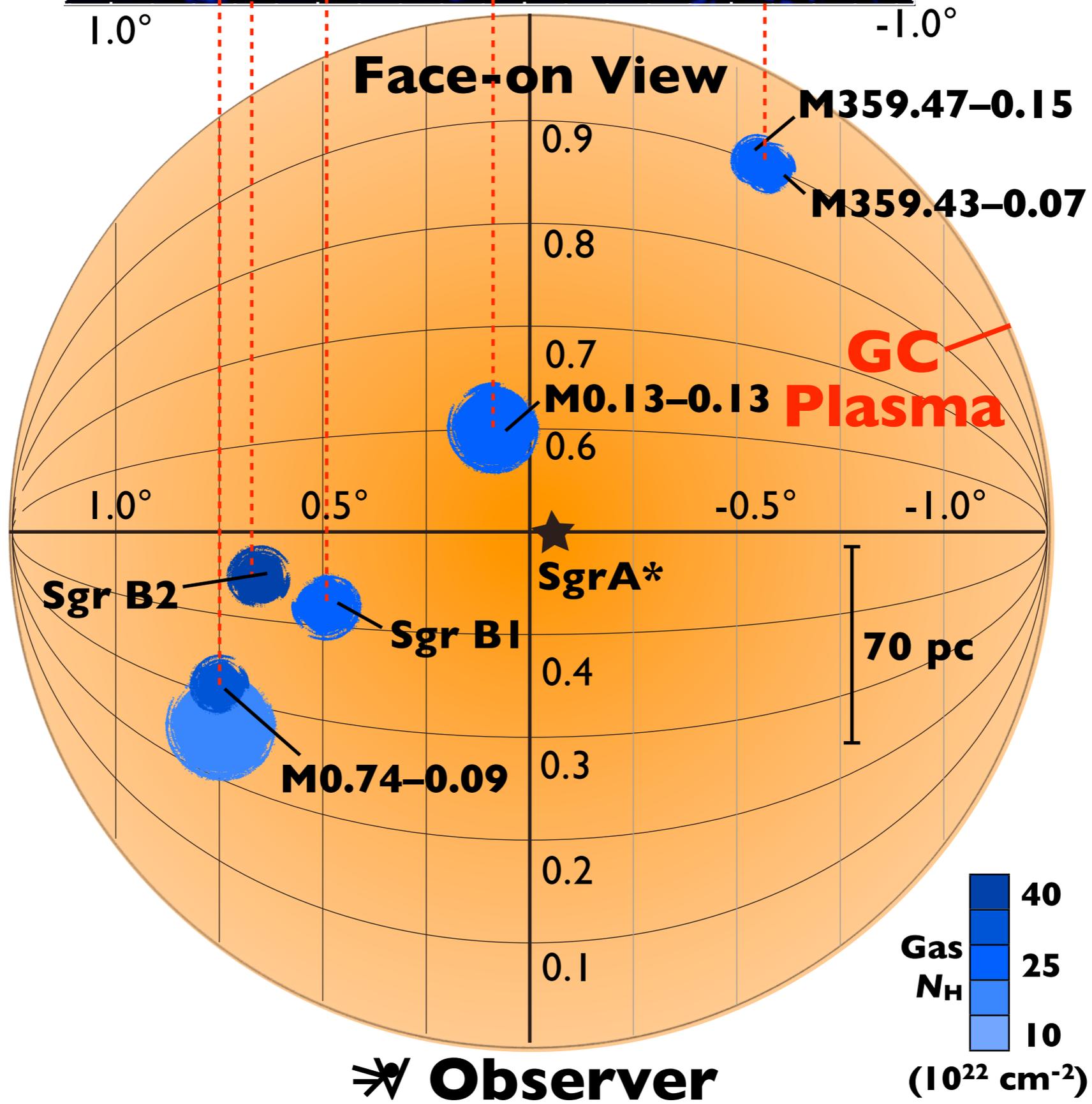
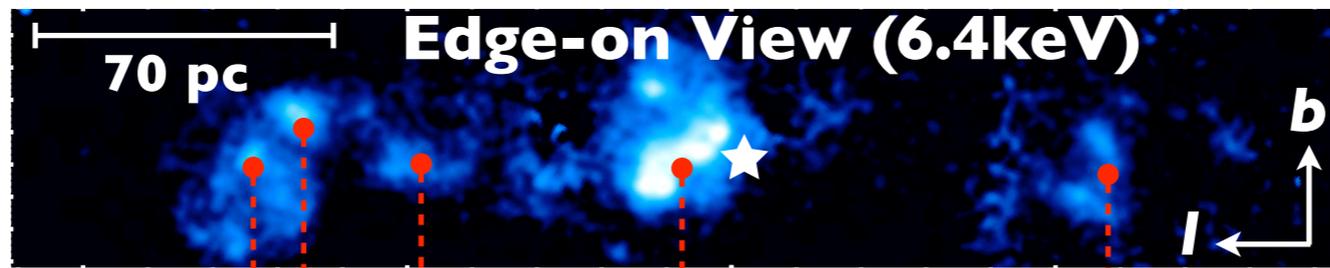
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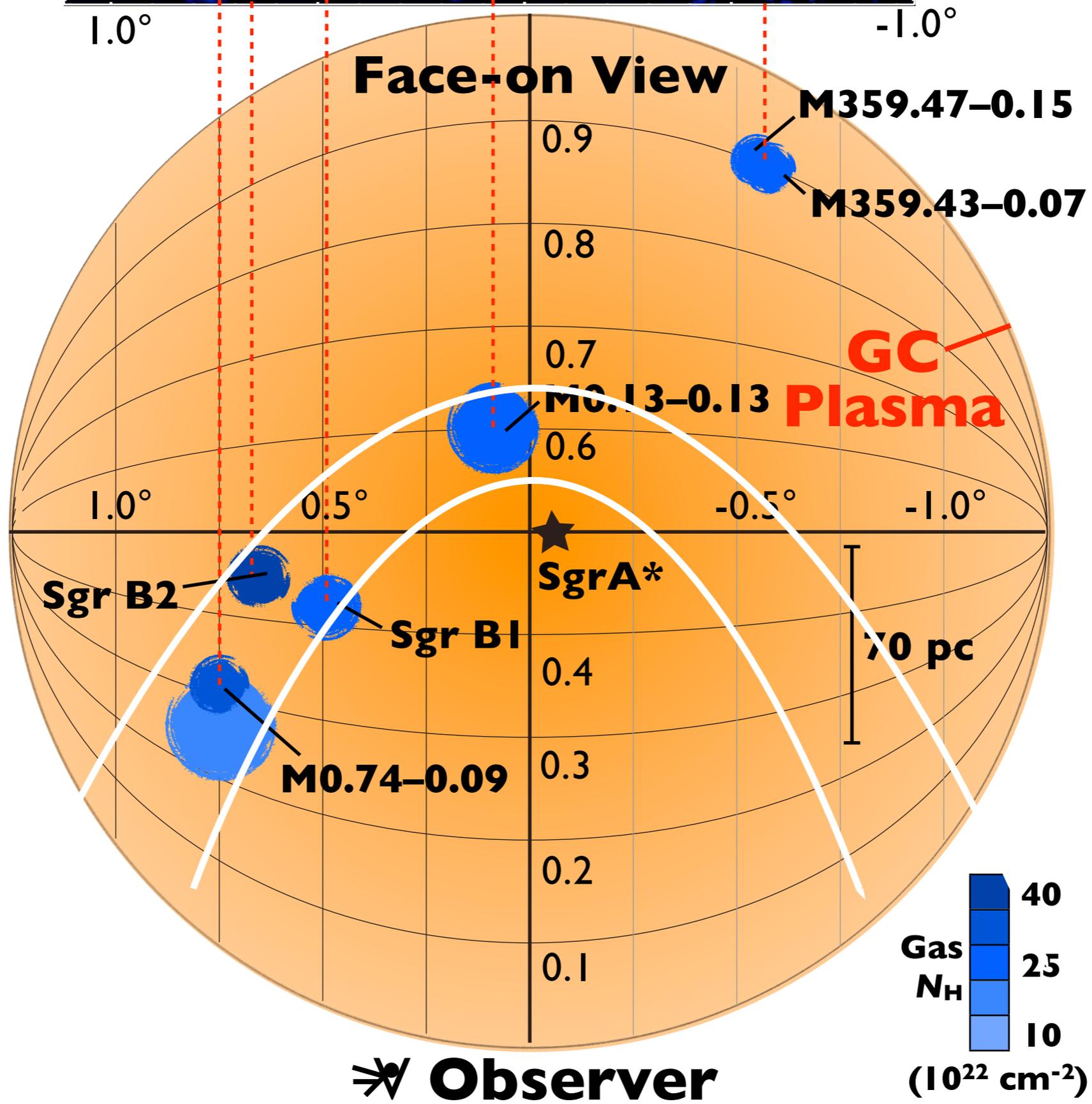
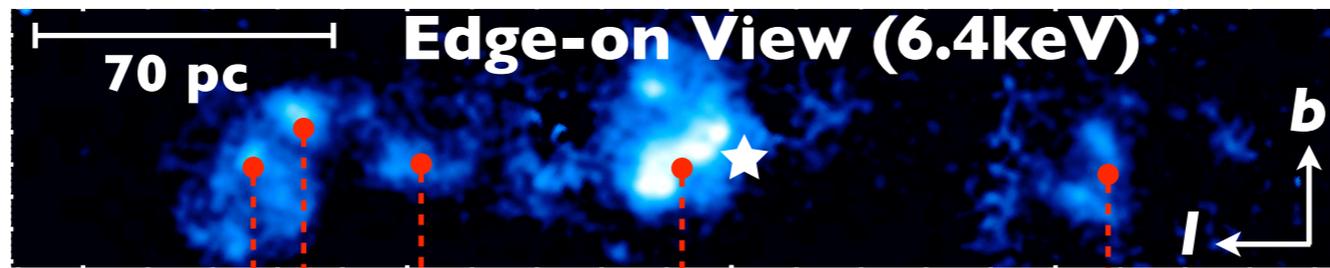
X線スペクトル・トモグラフィ

分子雲の奥行き位置 によるスペクトルの変化



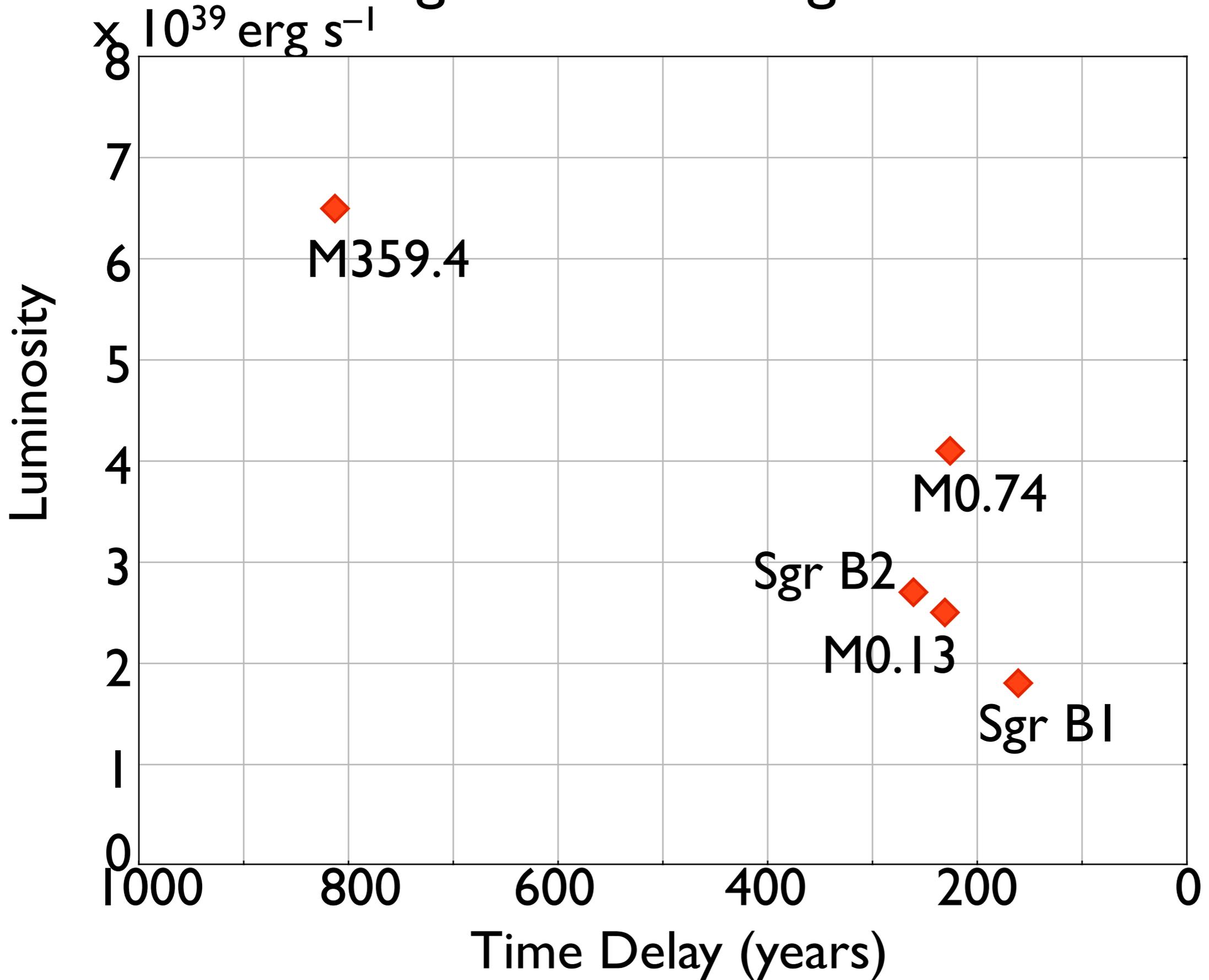


Ryu +09

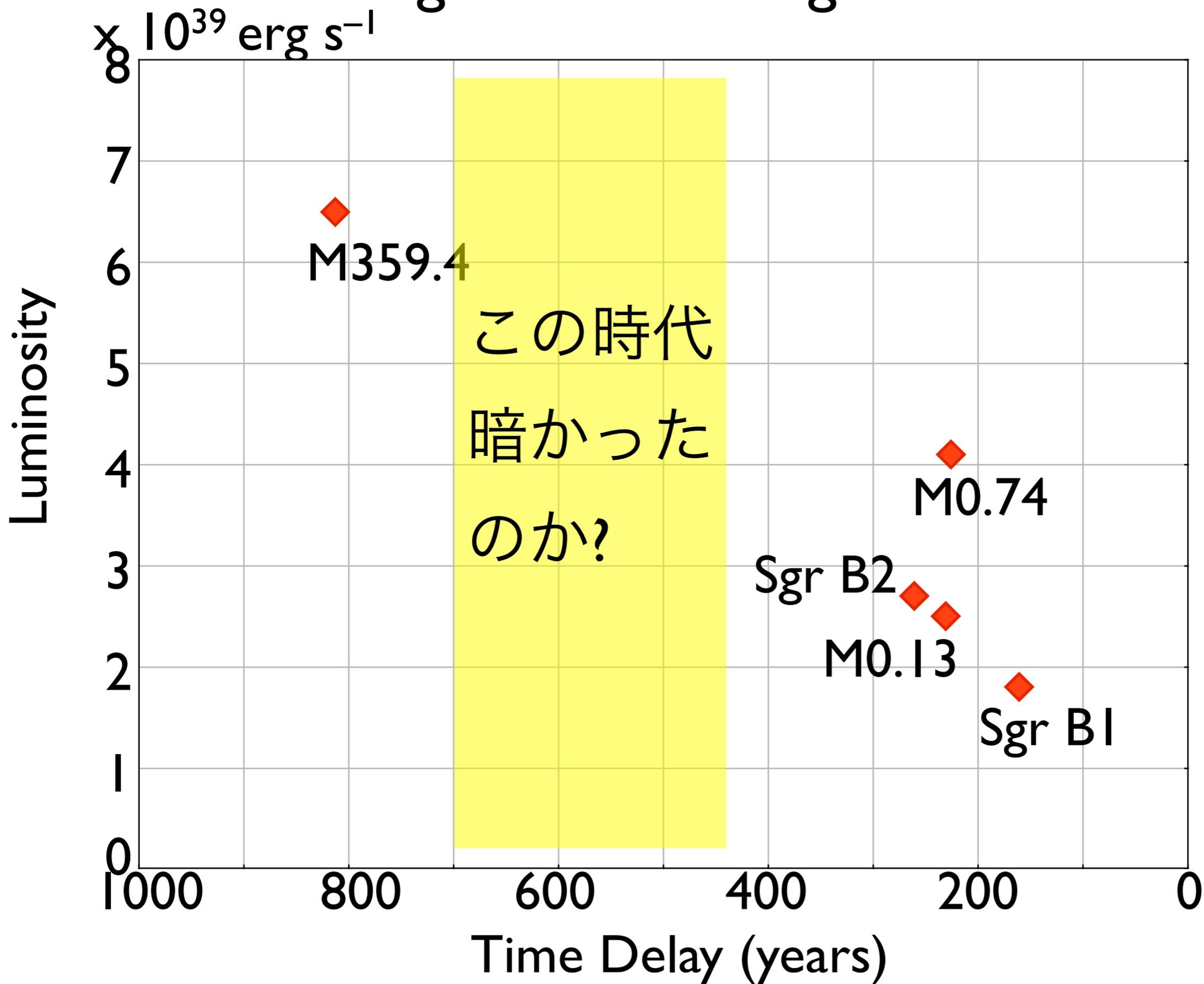


Ryu +09

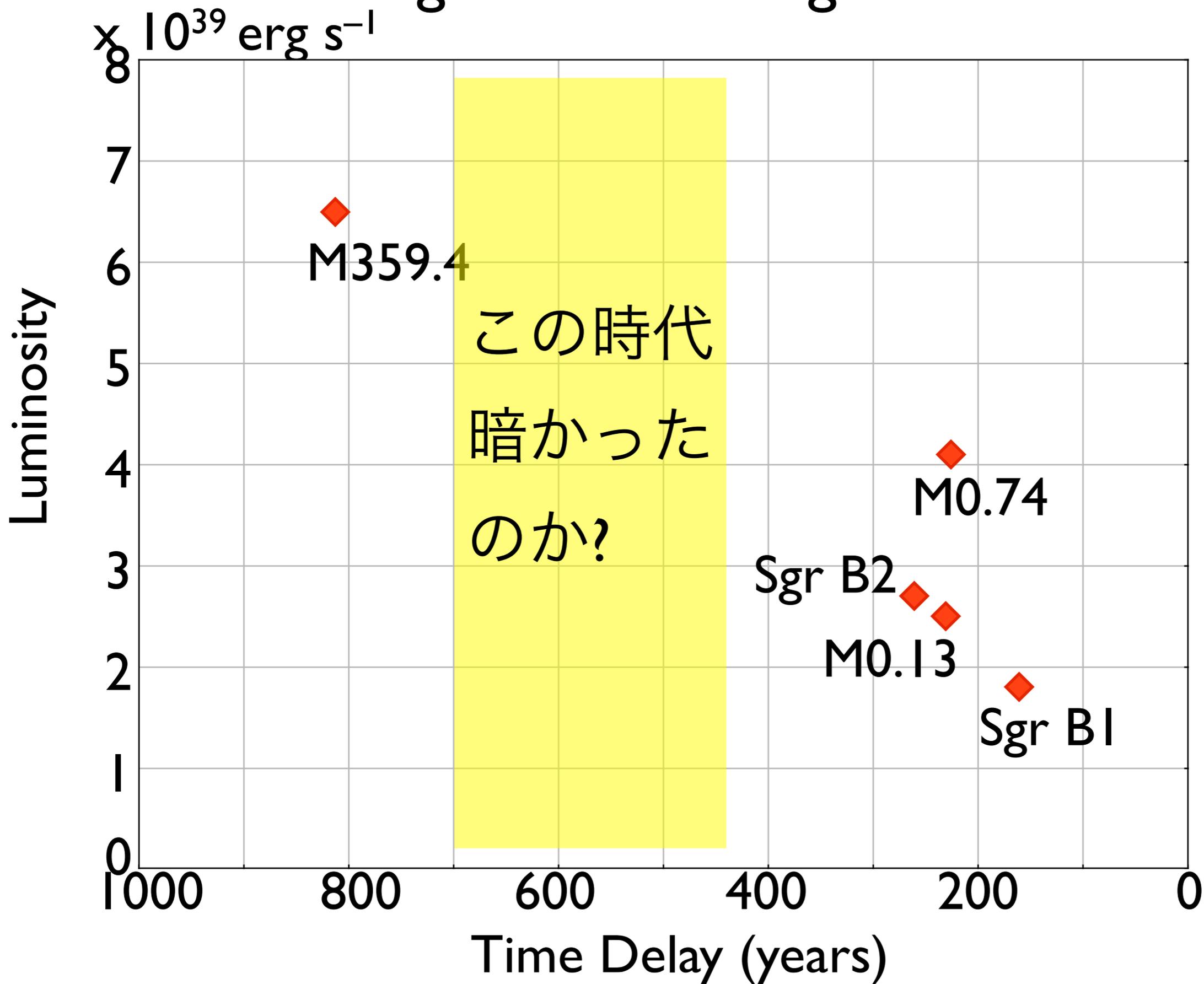
Light Curve of Sgr A*



Light Curve of Sgr A*

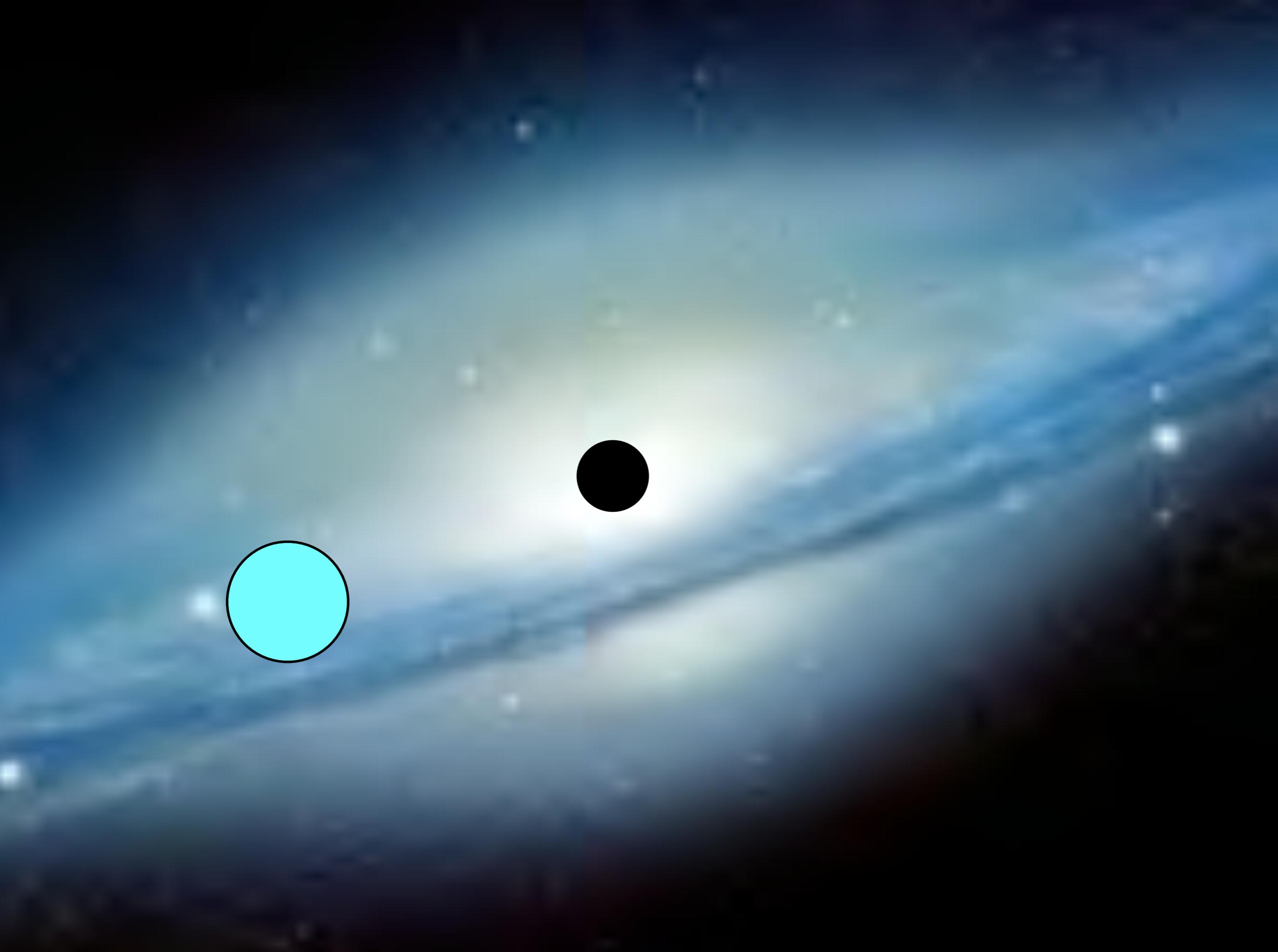


Light Curve of Sgr A*

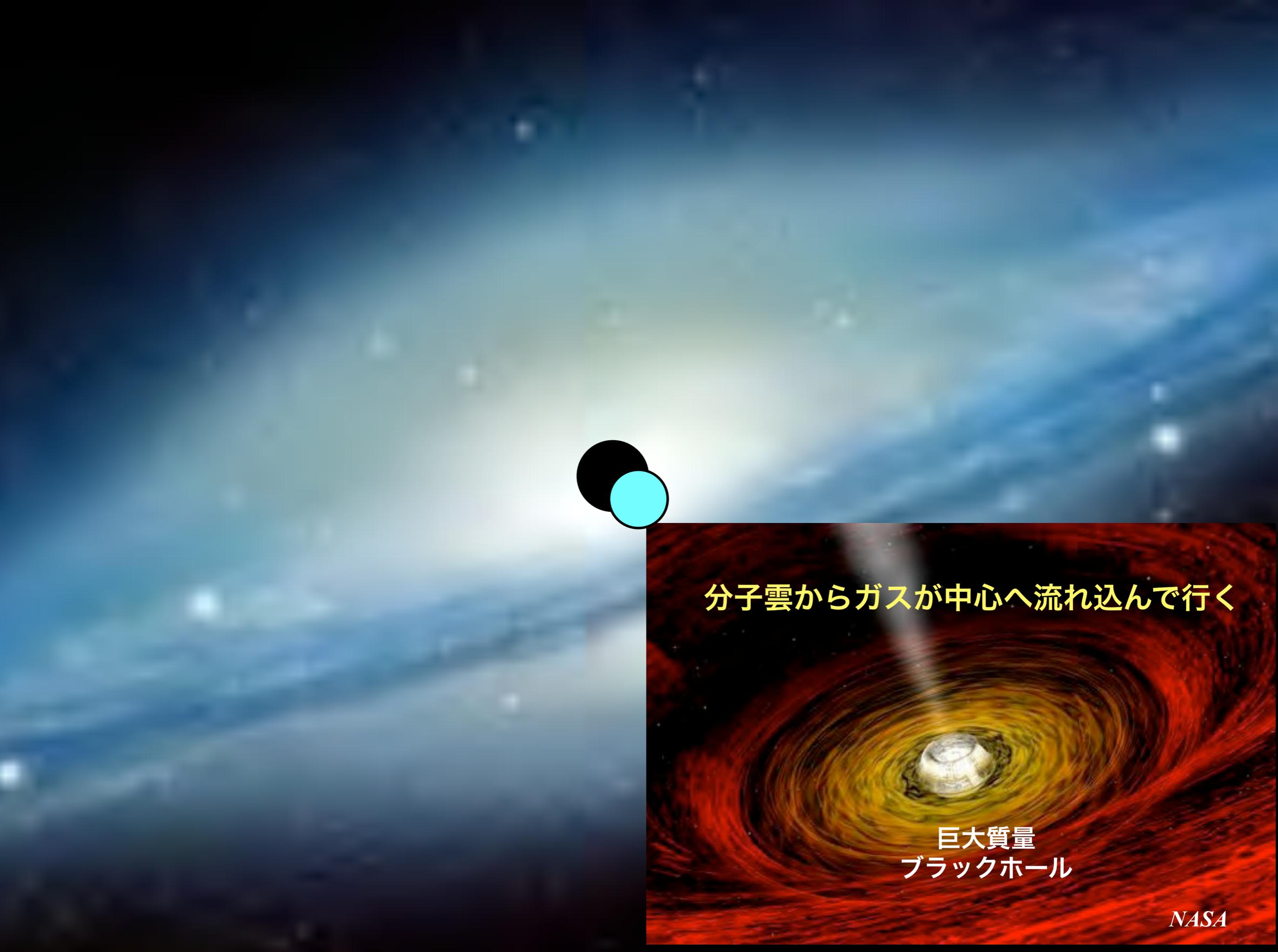


この先
どうなる?









分子雲からガスが中心へ流れ込んで行く

巨大質量
ブラックホール

爆発!

分子雲から... 巻き込んで行く

次の爆発を予測する

爆発!

分子雲から... 流れ込んで行く

分子雲から、たくさん
「太陽」が生成される

次の爆発を予測する

巨大質量
ブラックホール

NASA

爆発!

分子雲から... 流れ込んで行く

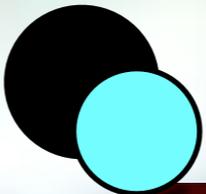
NASA



次の爆発を予測する

爆発!

爆発!

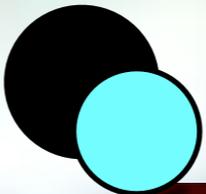




次の爆発を予測する

爆発!

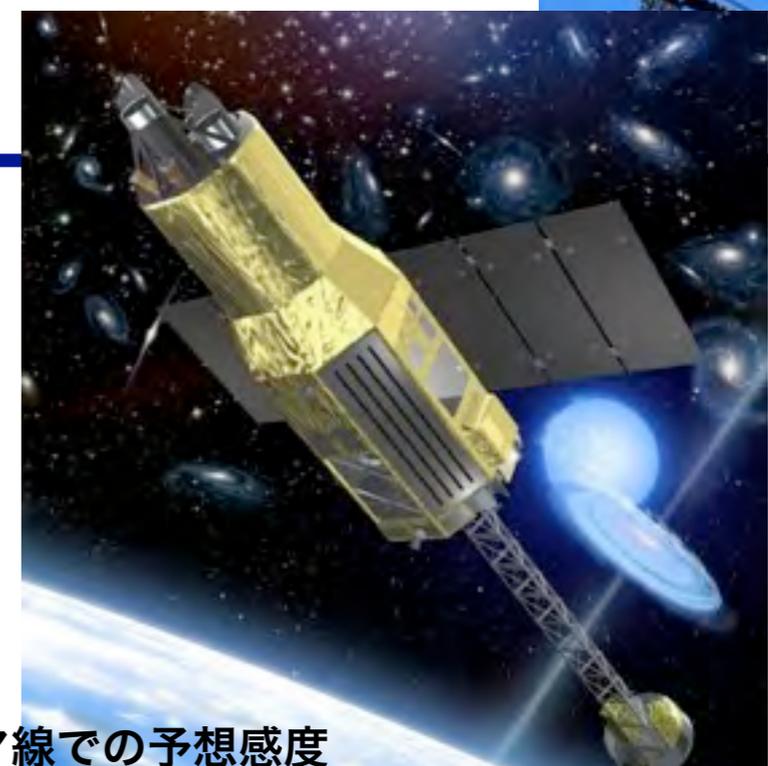
爆発!



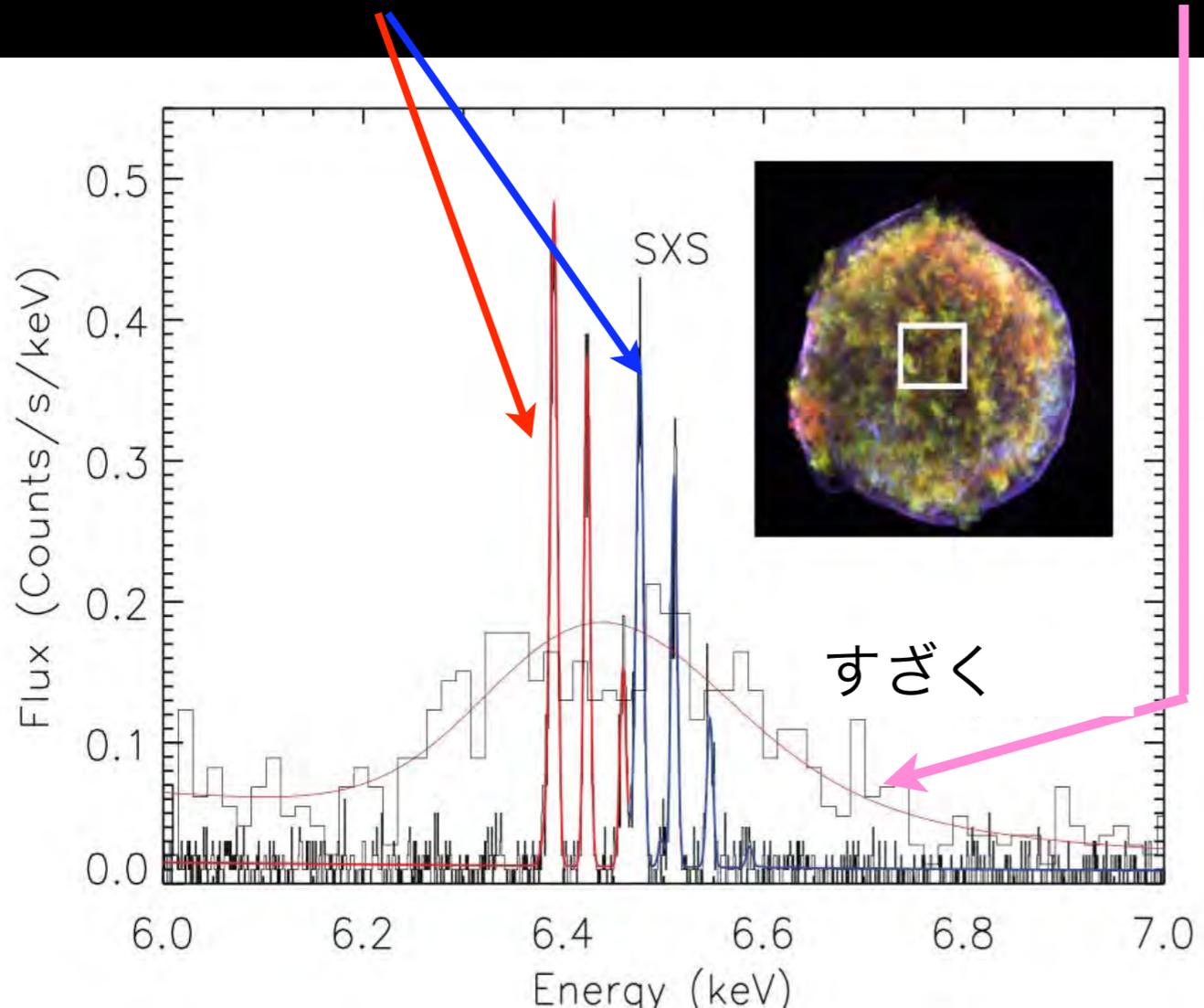
BH・銀河進化の解明

Astro-H

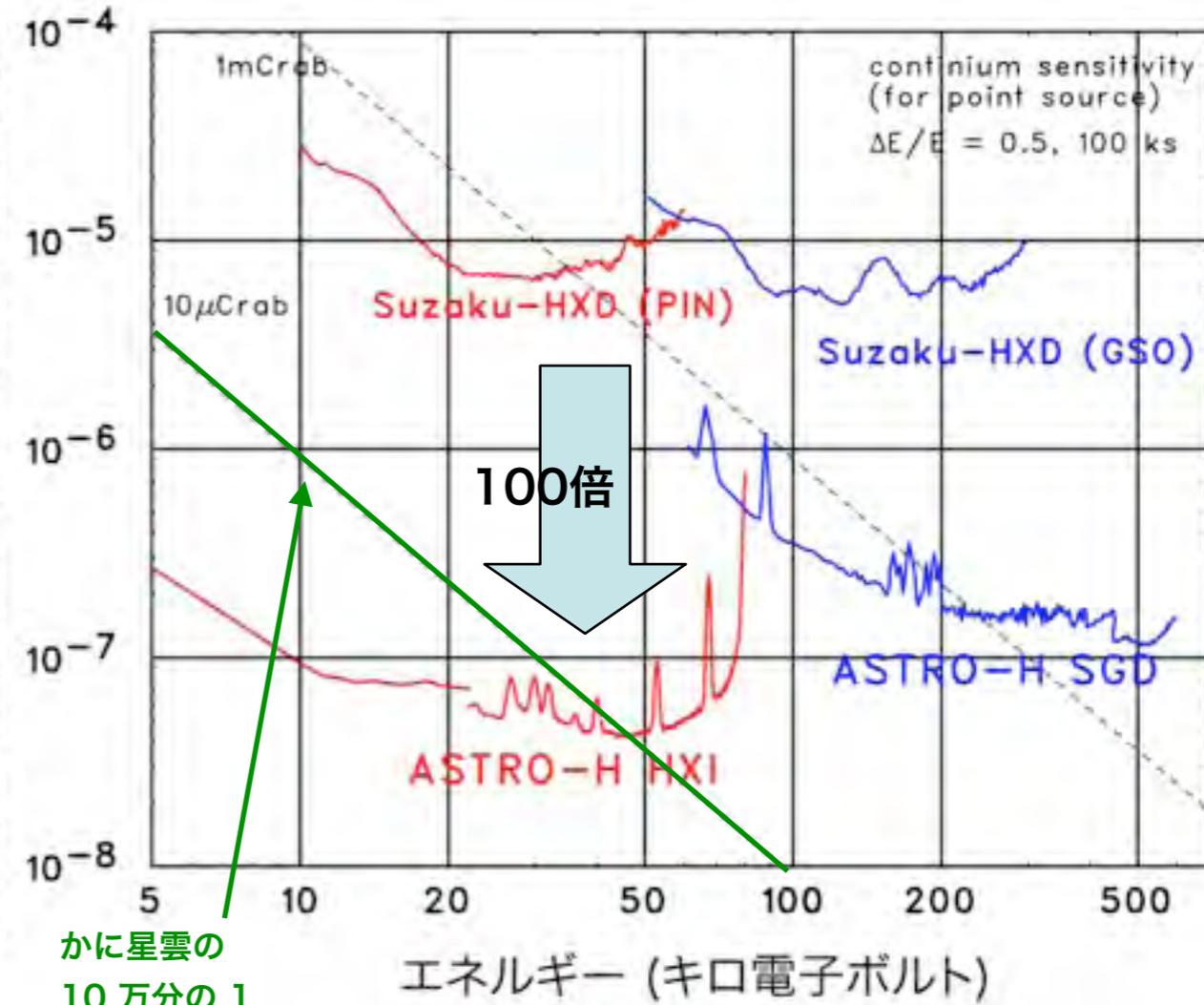
- 2013年度打ち上げの日本主導の国際共同プロジェクト
- 250億円: 日本(80%)、アメリカ(20%)



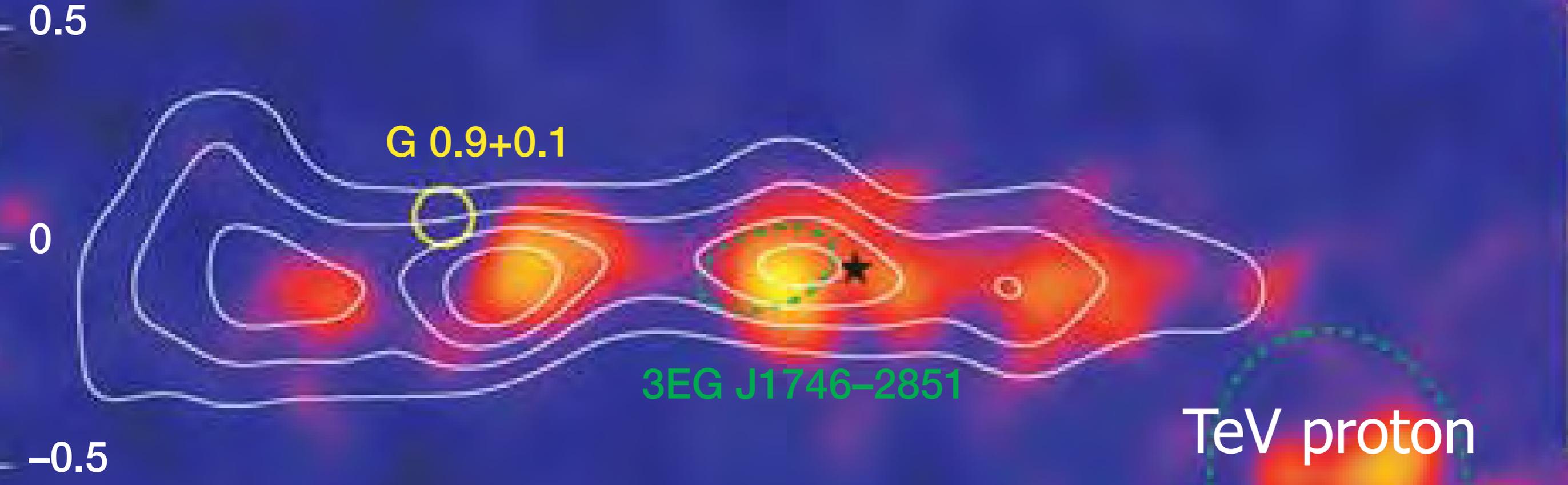
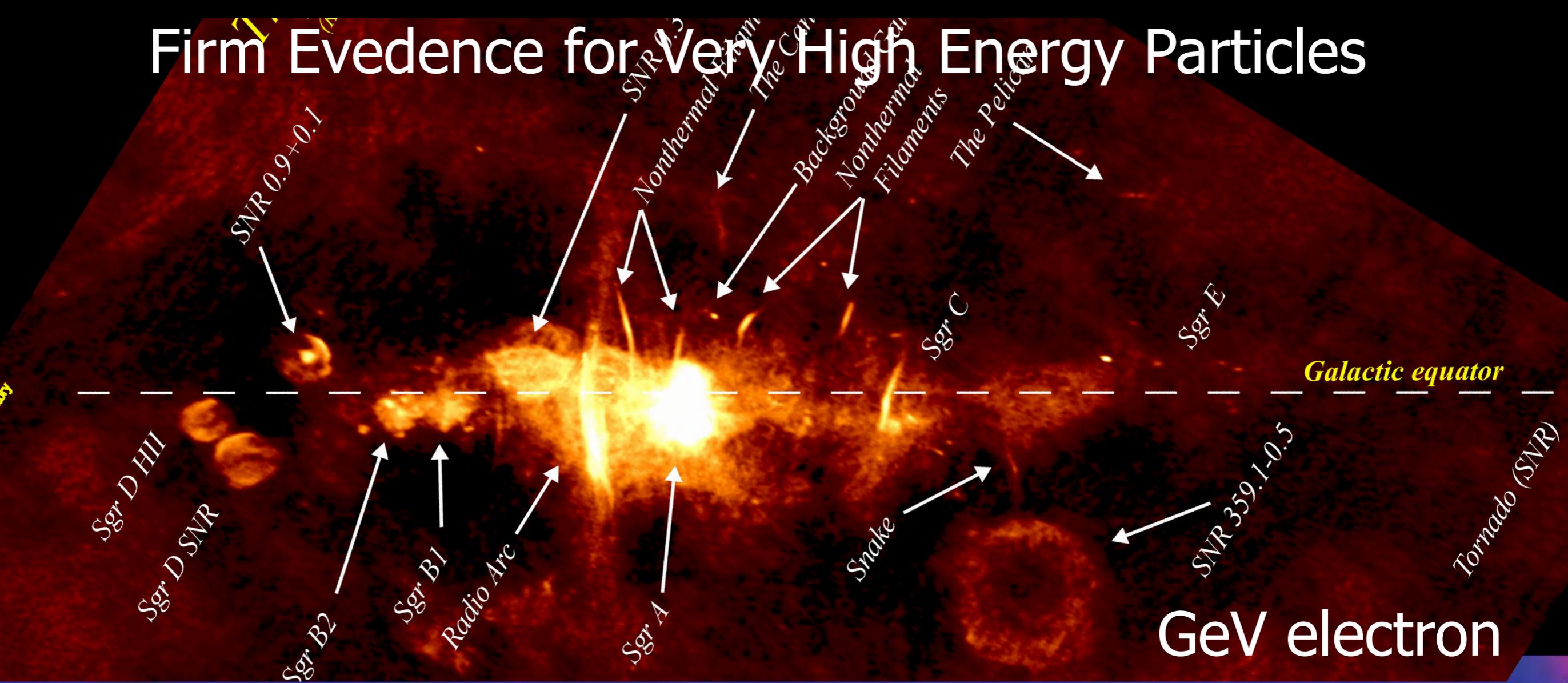
ASTRO-H at 6 keV Suzaku at 6 keV



硬X線、軟ガンマ線での予想感度



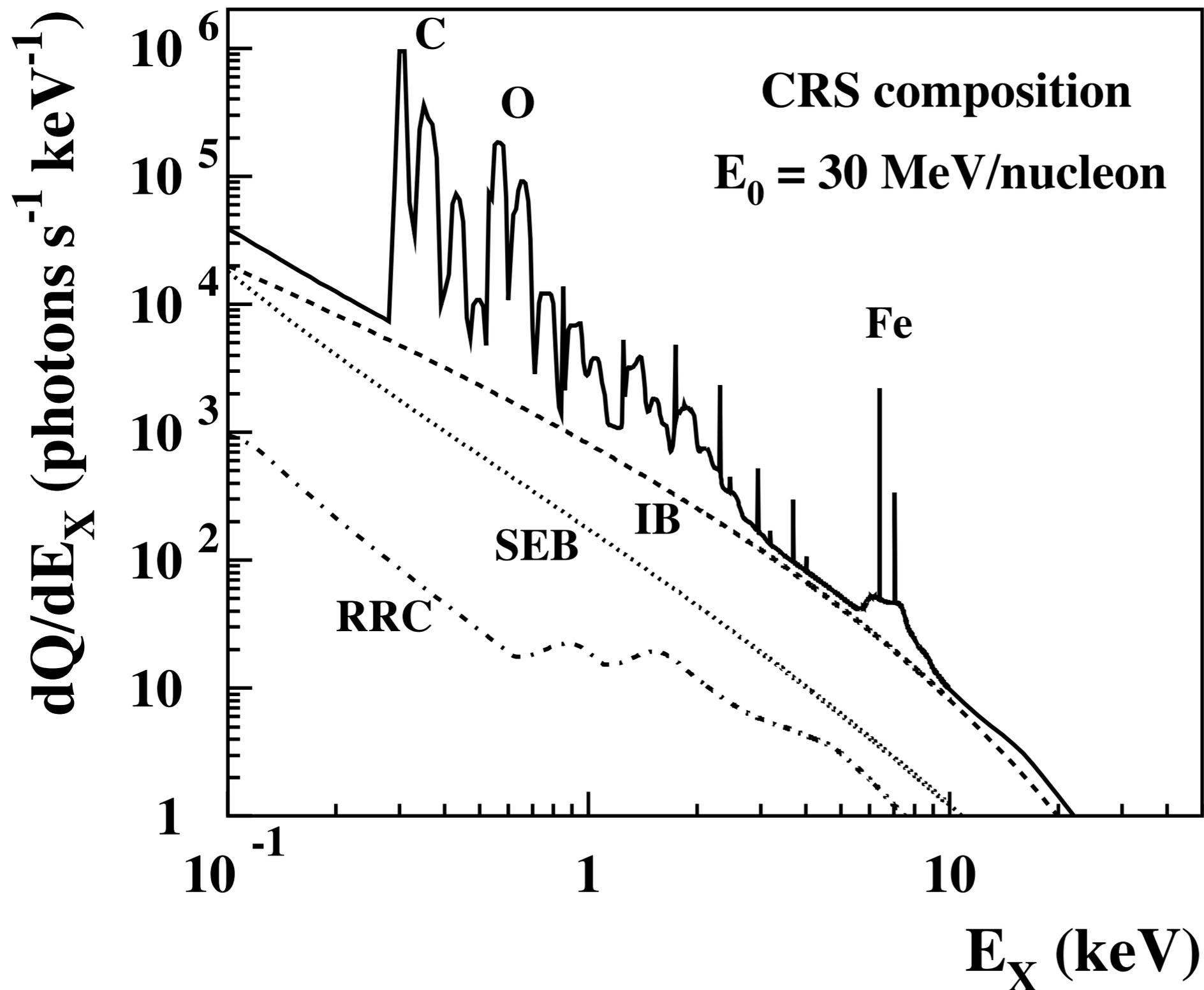
Firm Evedence for Very High Energy Particles





Electron impact vs Ion/proton impact

X線を出していないはずはない。



加速天体は？

まとめ

中性鉄輝線 6.4keV を用いた 天の川銀河中心領域の活動性の解明

X線反射星雲の発見

Sgr A*の過去の活動

X線トモグラフィ 分子雲の三次元分布

Sgr A* 1000年の活動→将来の活動の予想へ

高エネルギー粒子起源はないのか?→Astro-H衛星