Study of Galactic Diffuse Sources with Suzaku

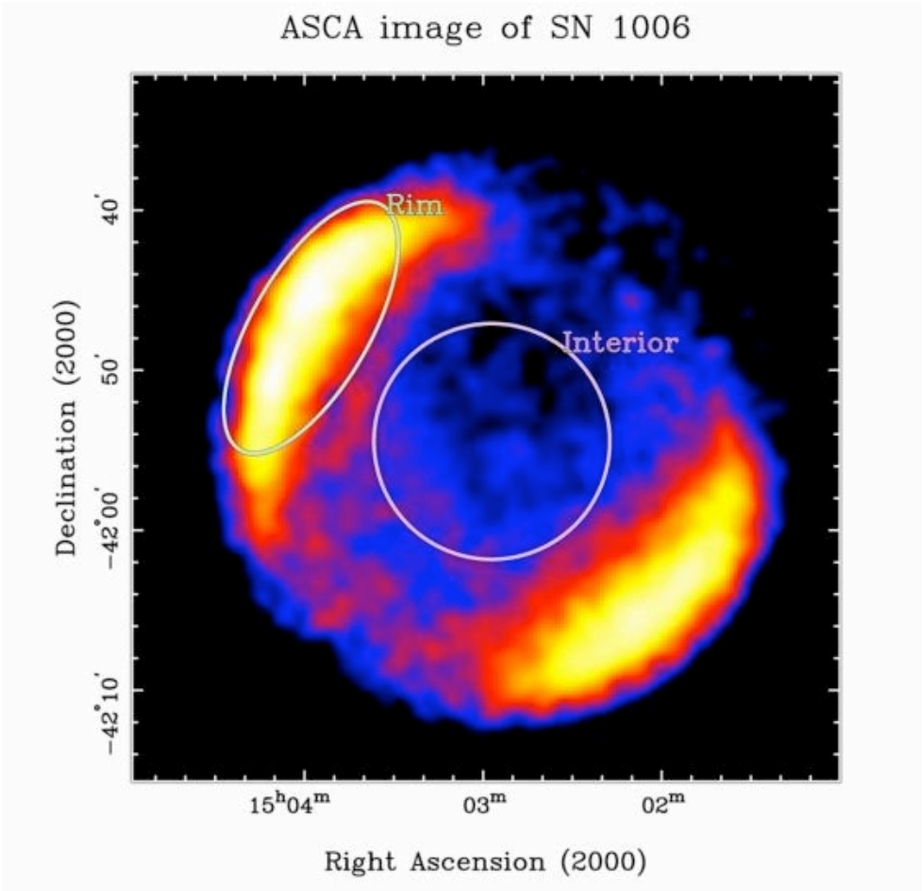
Tadayuki Takahashi
ISAS/JAXA

and the Suzaku team

From Supernova Remnants to Galactic Center Region

See also Talk by H. Tsunemi (35.07)
and R. Petre (59.04)

Supernova Remnants as the site of Cosmic-ray Acceleration



- ASCA discoveries of X-ray synchrotron emission from SN1006 (Koyama et al. 1995)

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

→ Existence of

high energy electrons with energy up to 10 - 100 TeV.

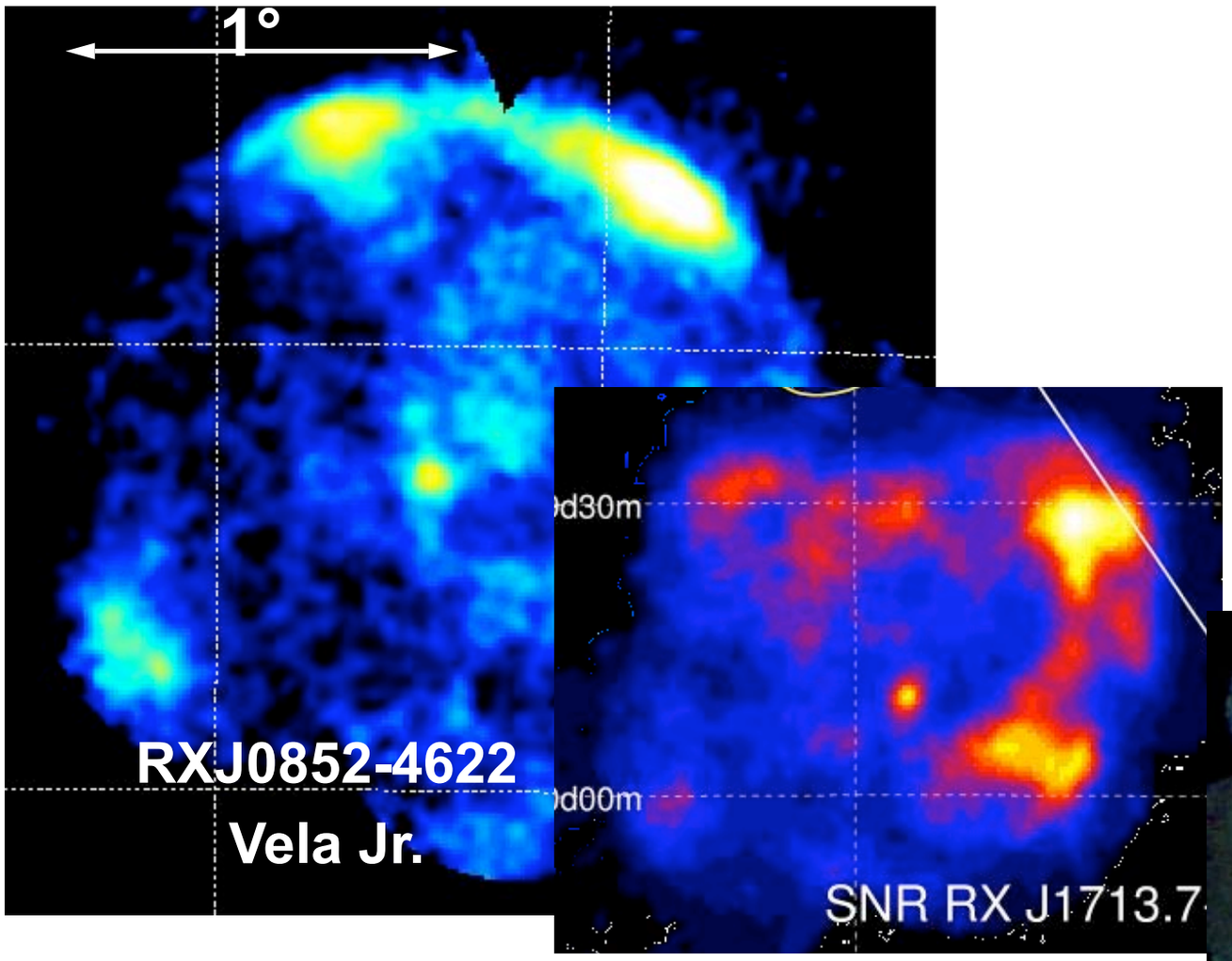
【Maximum Energy ($t_{acc} = t_{age}$)】

$$E_{max} = \frac{3}{20}\frac{1}{\eta}\left(\frac{V_s}{c}\right) eBR$$
$$= 460 \times \frac{1}{\eta}\left(\frac{V_s}{10^4\ \rm km/s}\right)\left(\frac{B}{10\mu G}\right)\left(\frac{R}{10\ \rm pc}\right)\ \ \rm TeV$$

Diffusive Shock Acceleration

maximum energy = Velocity x B filed x Region size

Non-thermal hard X-rays from Young Supernova Remnants



Rapid radiative losses of Synchrotron-X-ray-emitting electrons

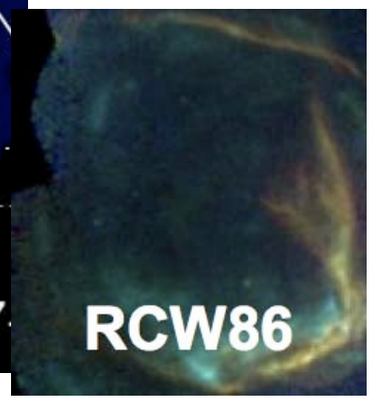
$$\tau_{\rm synch} = 880\,(B/10\mu{\rm G})^{-1.5}(\varepsilon/3{\rm keV})^{-0.5}\ {\rm yr}$$

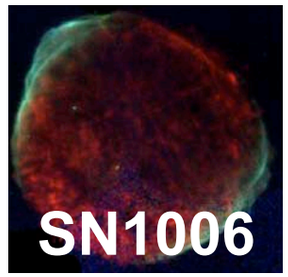
(= 10^{-5} of cooling time of radio-emitting-electrons)

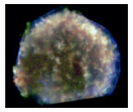
Multi-TeV electrons:

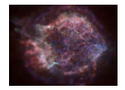
equilibrium between injection and radiation

X-ray brightness = injection rate

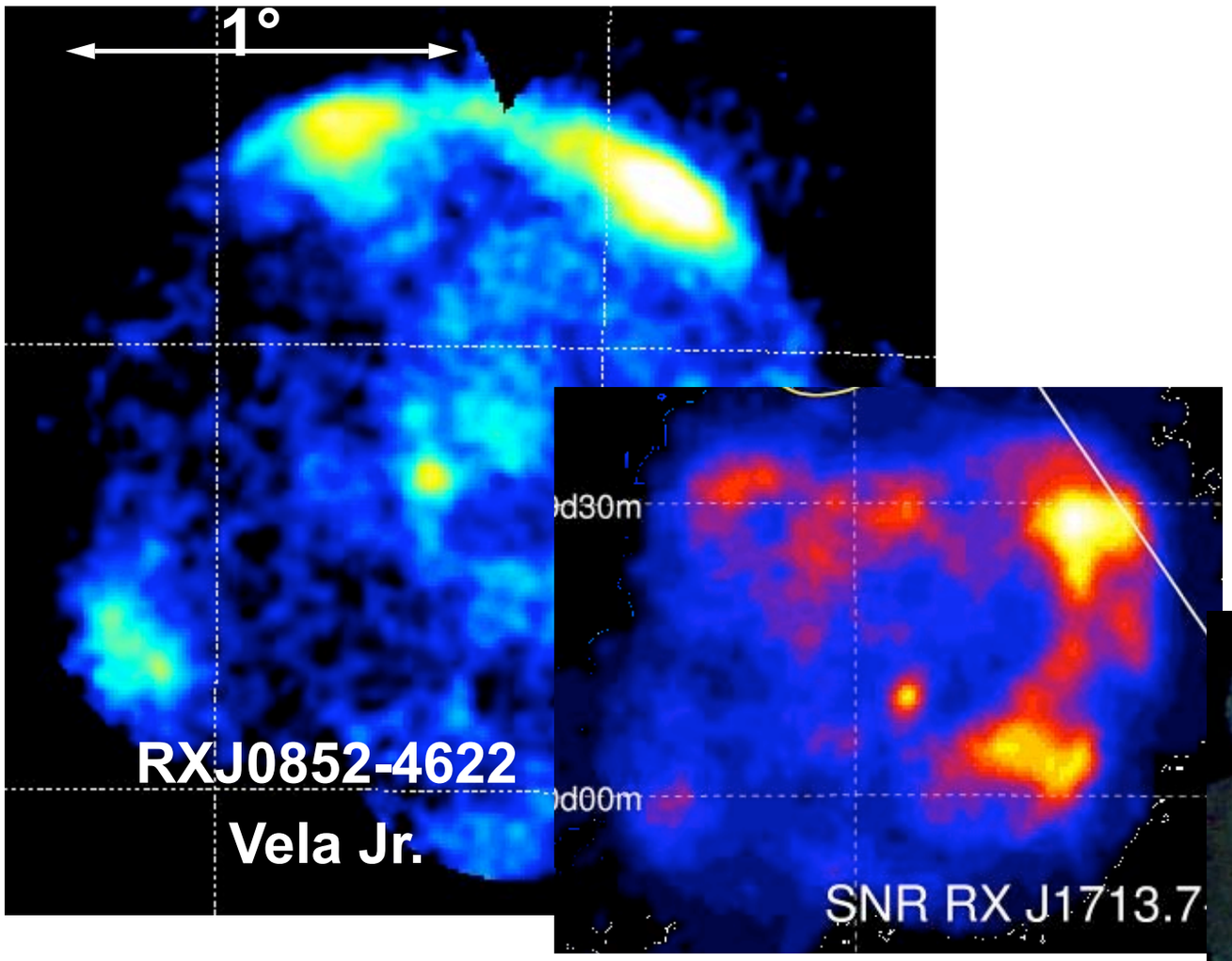








Non-thermal hard X-rays from Young Supernova Remnants



Rapid radiative losses of Synchrotron-X-ray-emitting electrons

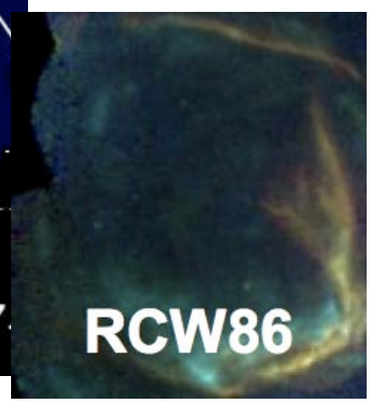
$$\tau_{\rm synch} = 880\,(B/10\mu{\rm G})^{-1.5}(\varepsilon/3{\rm keV})^{-0.5}\ {\rm yr}$$

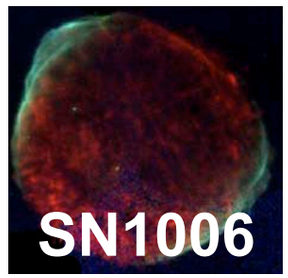
(= 10^{-5} of cooling time of radio-emitting-electrons)

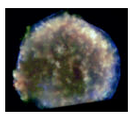
Multi-TeV electrons:

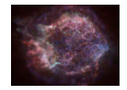
equilibrium between injection and radiation

X-ray brightness = injection rate





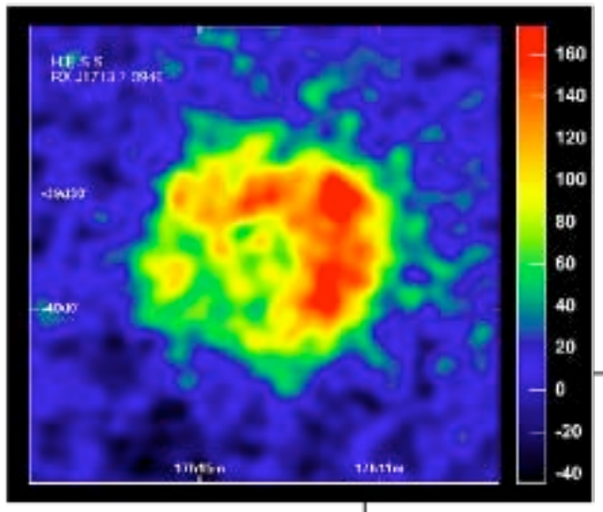




Q: Connection between Soft X-ray and Hard X-ray

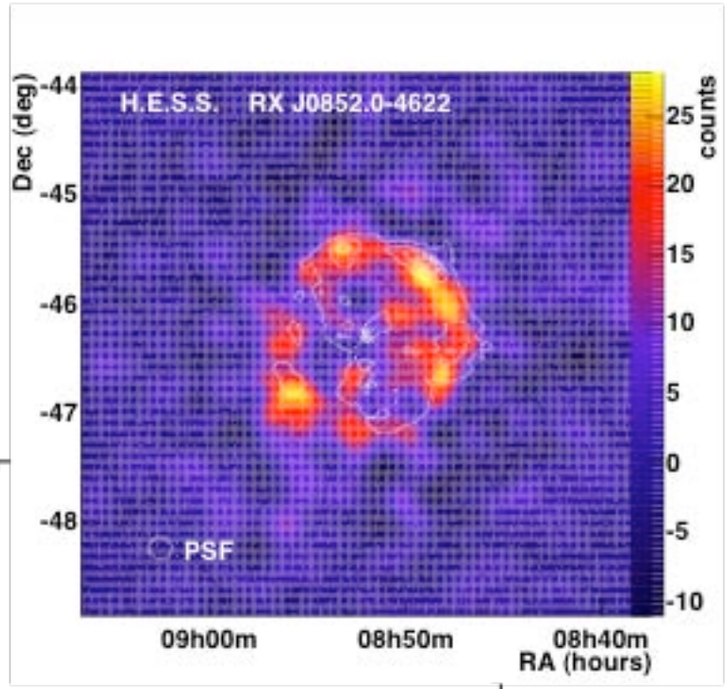
(Between Heating and Acceleration)

Energy Frontier = X/TeV

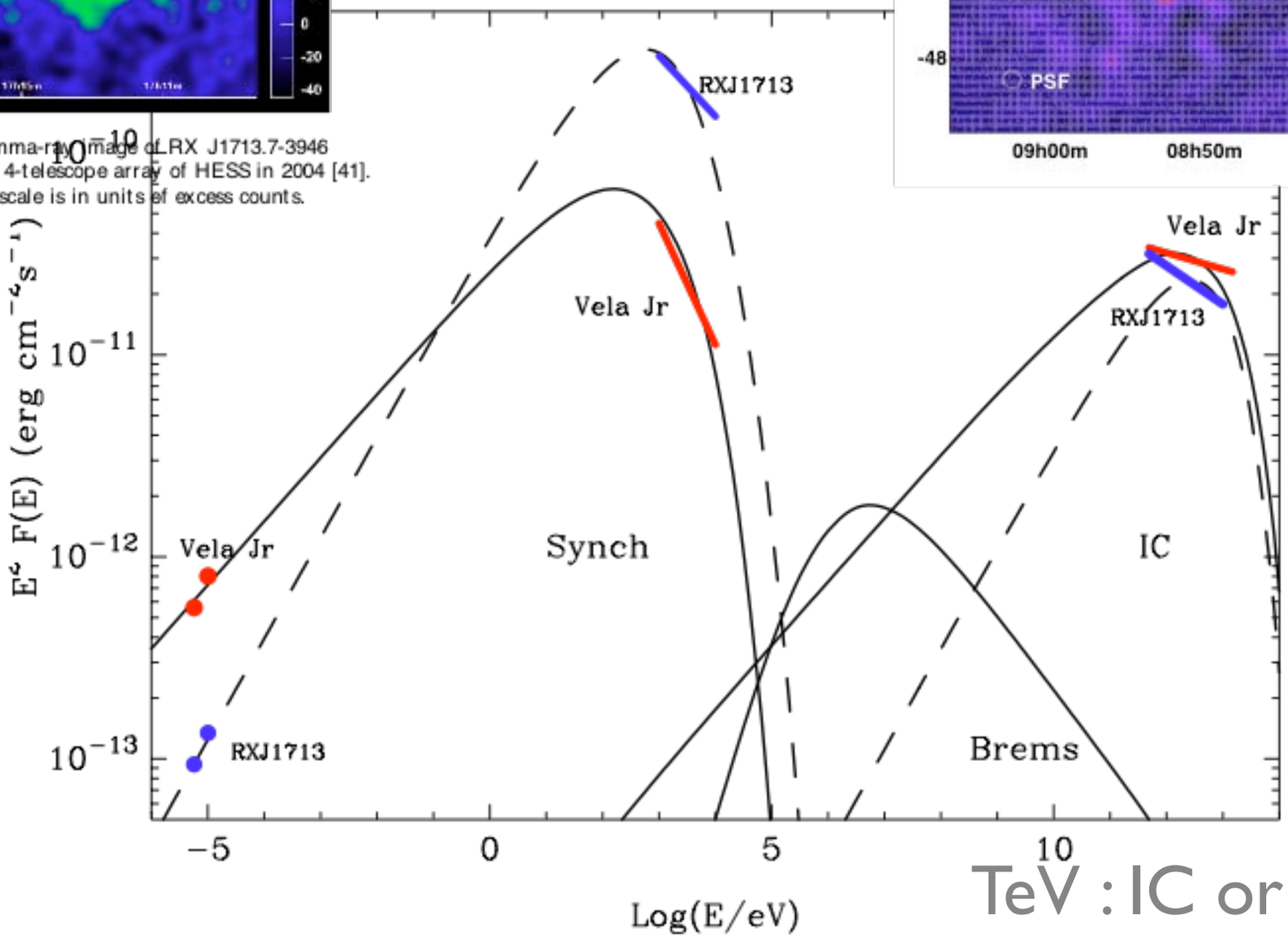


TeV Image
RXJ1713

Figure 2: The gamma-ray image of RX J1713.7-3946 obtained with the 4-telescope array of HESS in 2004 [41]. The linear colour scale is in units of excess counts.



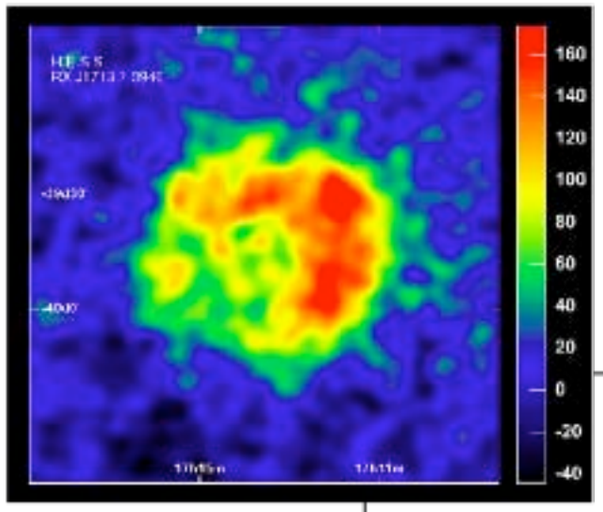
TeV Image
Vela Jr.



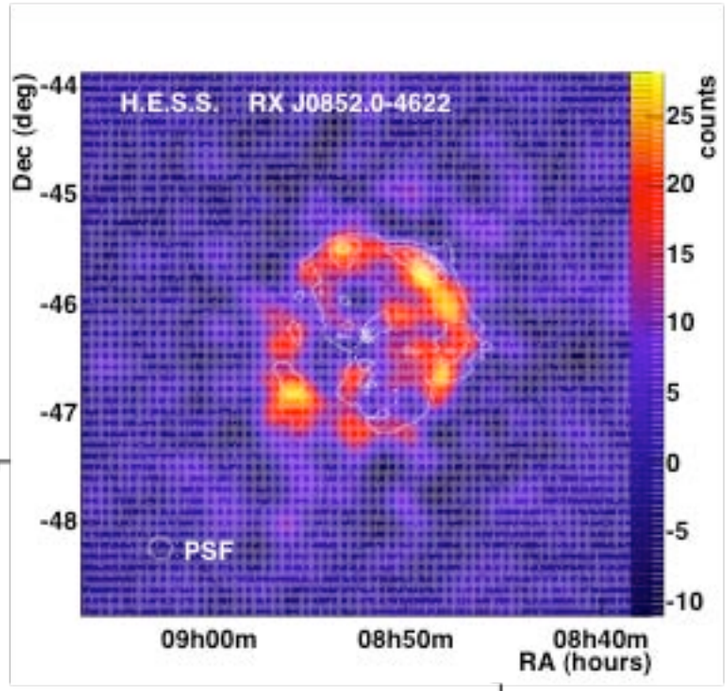
HESS

TeV : IC or Pi0

Energy Frontier = X/TeV

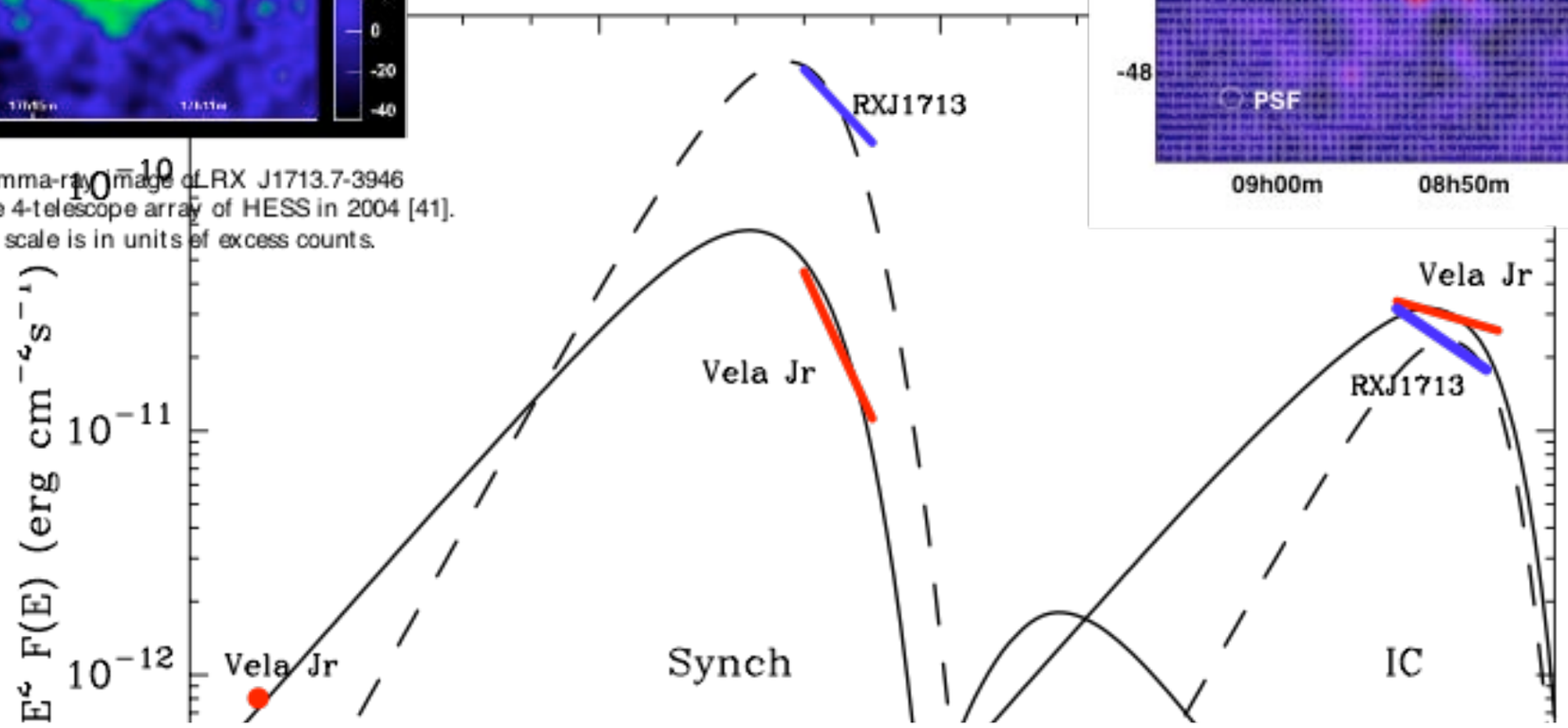


TeV Image
RXJ1713



TeV Image
Vela Jr.

Figure 2: The gamma-ray image of RX J1713.7-3946 obtained with the 4-telescope array of HESS in 2004 [41]. The linear colour scale is in units of excess counts.



HESS

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

(Between Magnetic Field and CMB photons

or

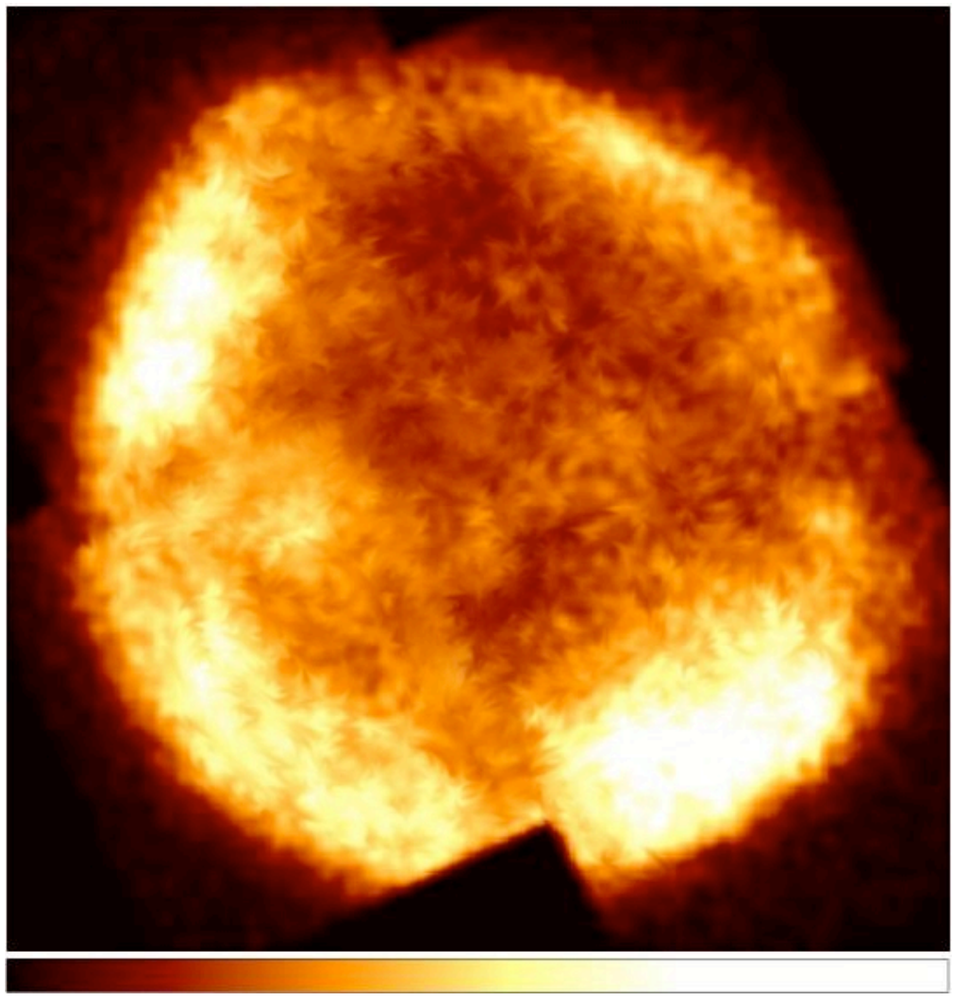
electrons and protons)

Suzaku - Initial Results

- SN 1006
- Un-identified HESS TeV sources
- RXJ1713-3946
- Galactic Diffuse Emission, near GC
  - Newly discovered SNRs

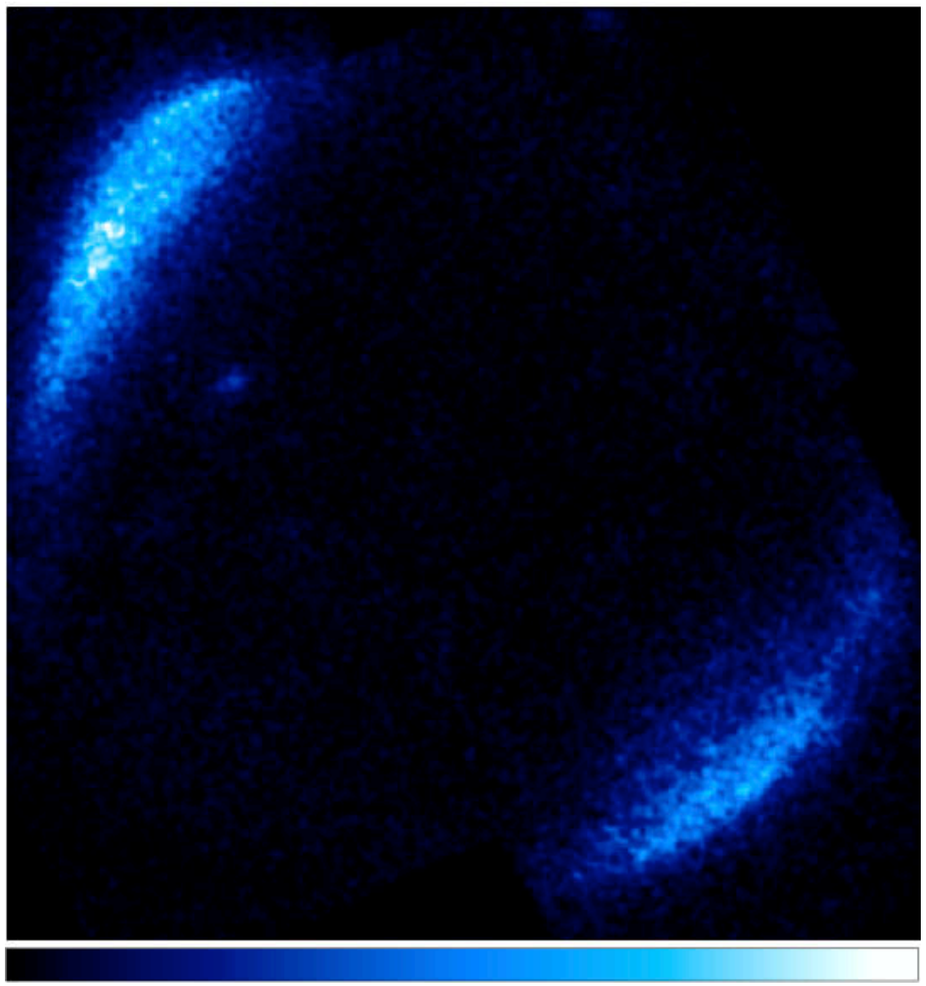
SN1006

A map of line X-rays
of He-like and H-like Oxygen



O VII line band

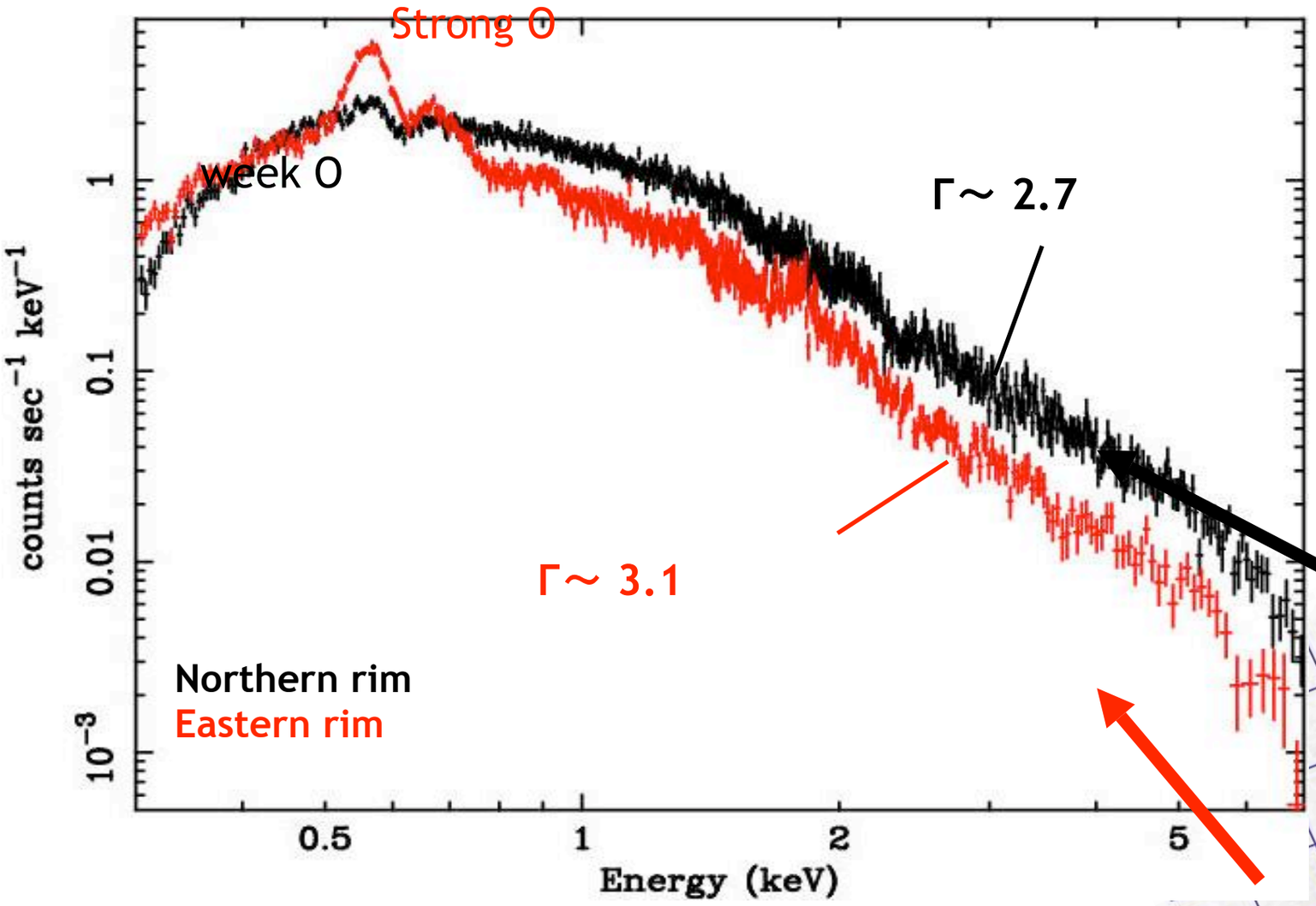
A map of
non-thermal X-rays

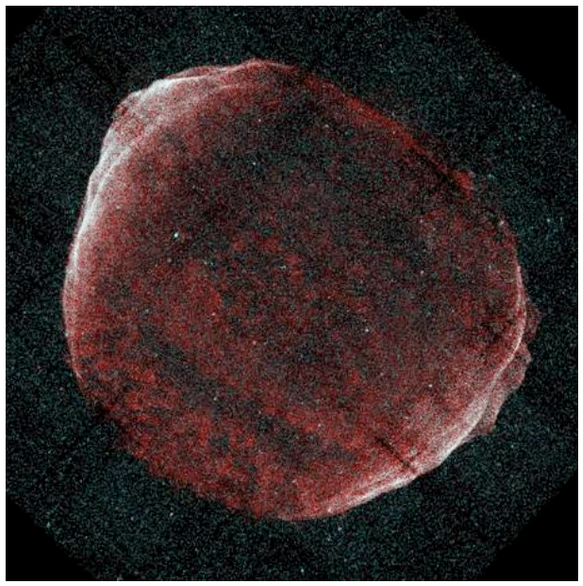


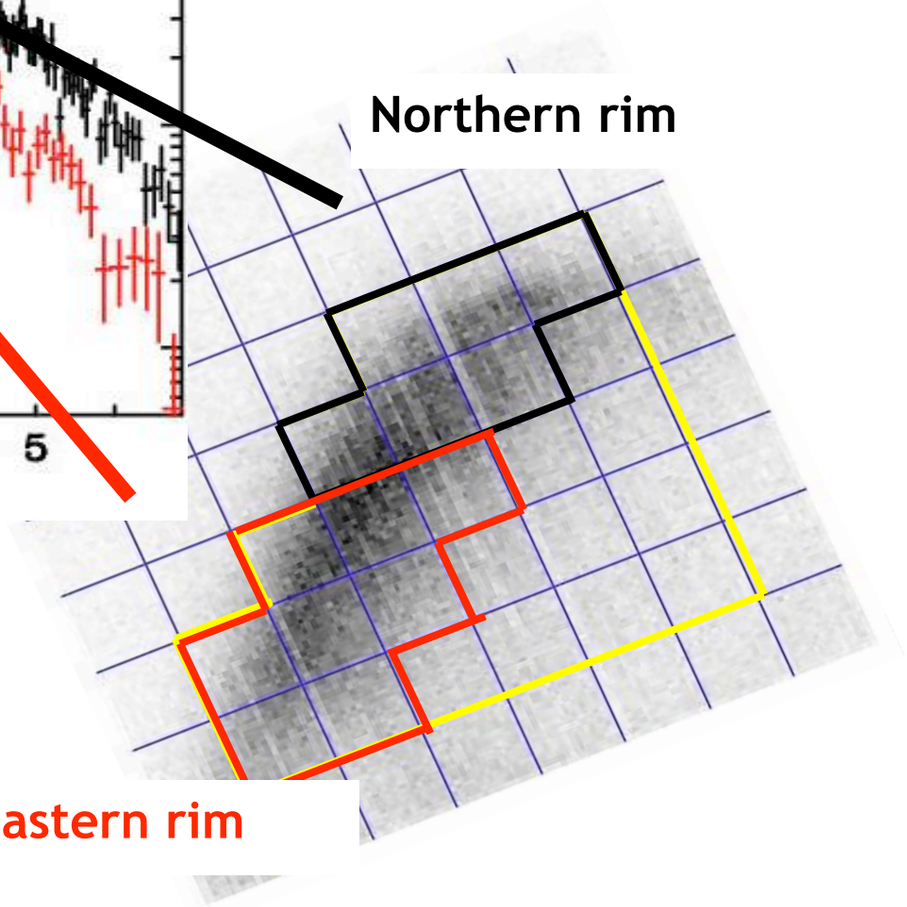
3 - 5 keV band

A. Bamba et al. 2006

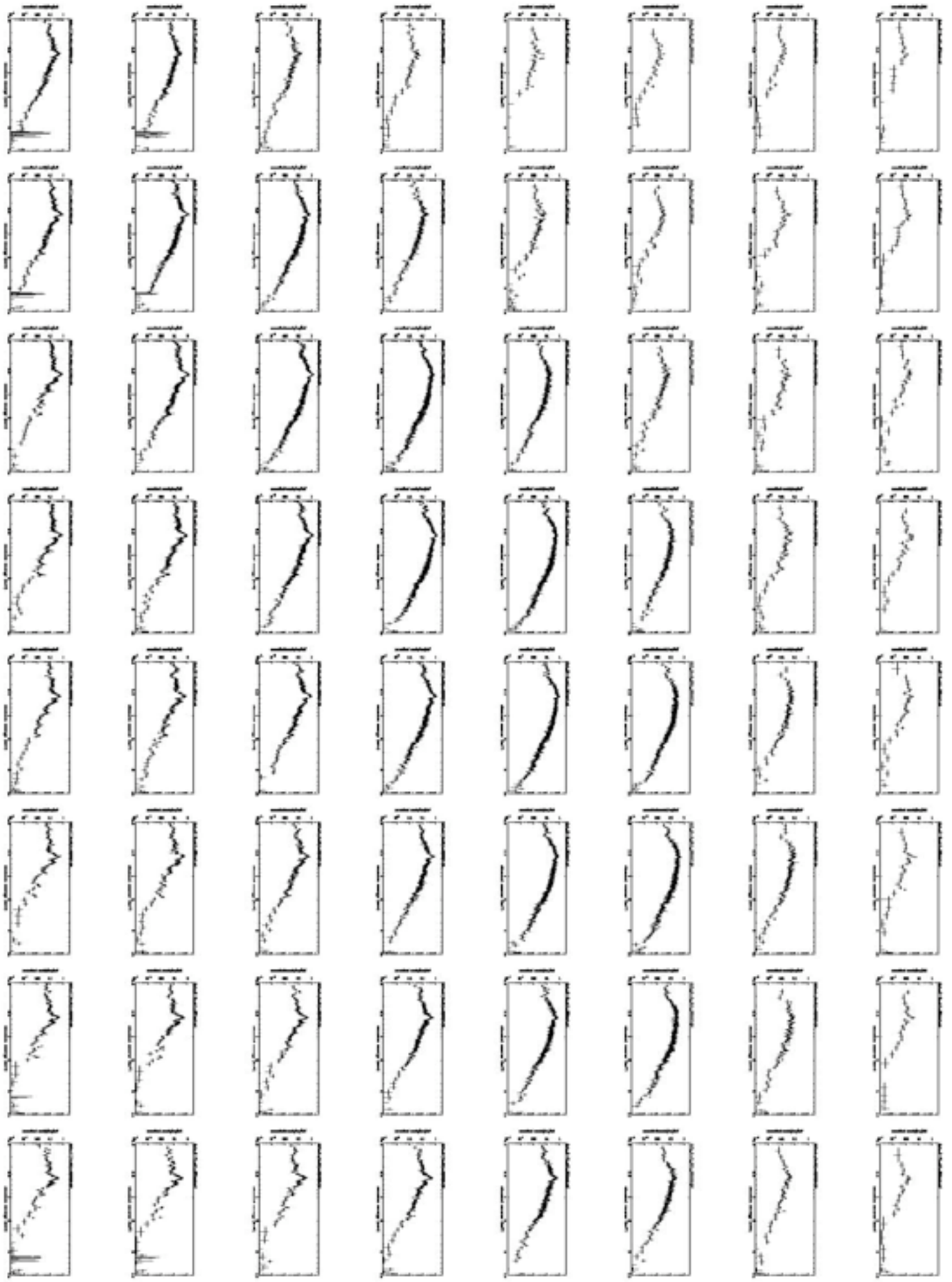
Thermal Plasma vs Non-thermal Emission



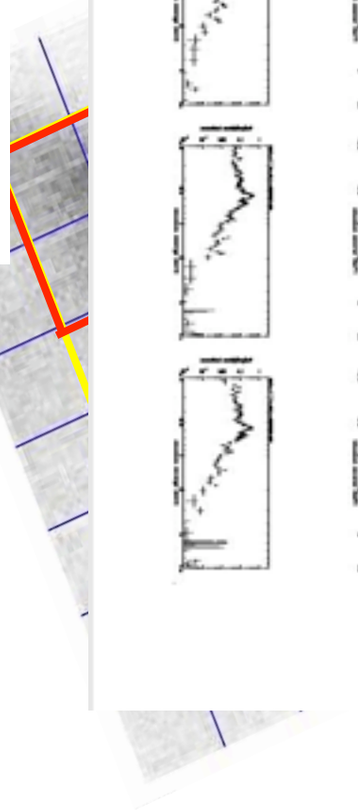




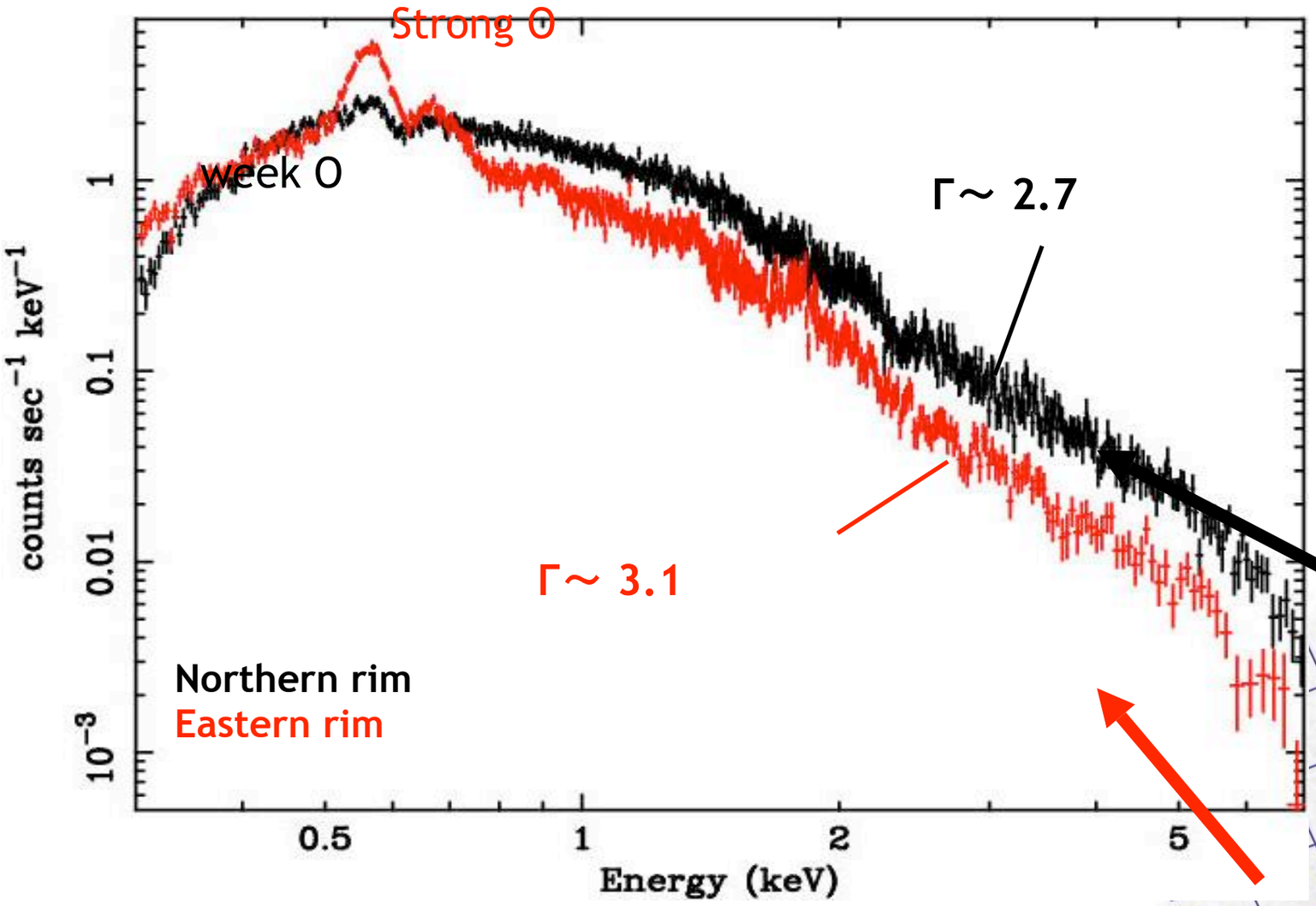
counts sec^{-1} keV^{-1}

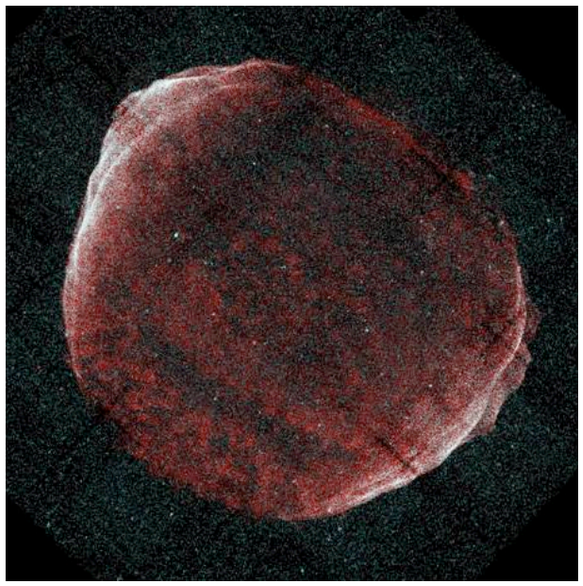


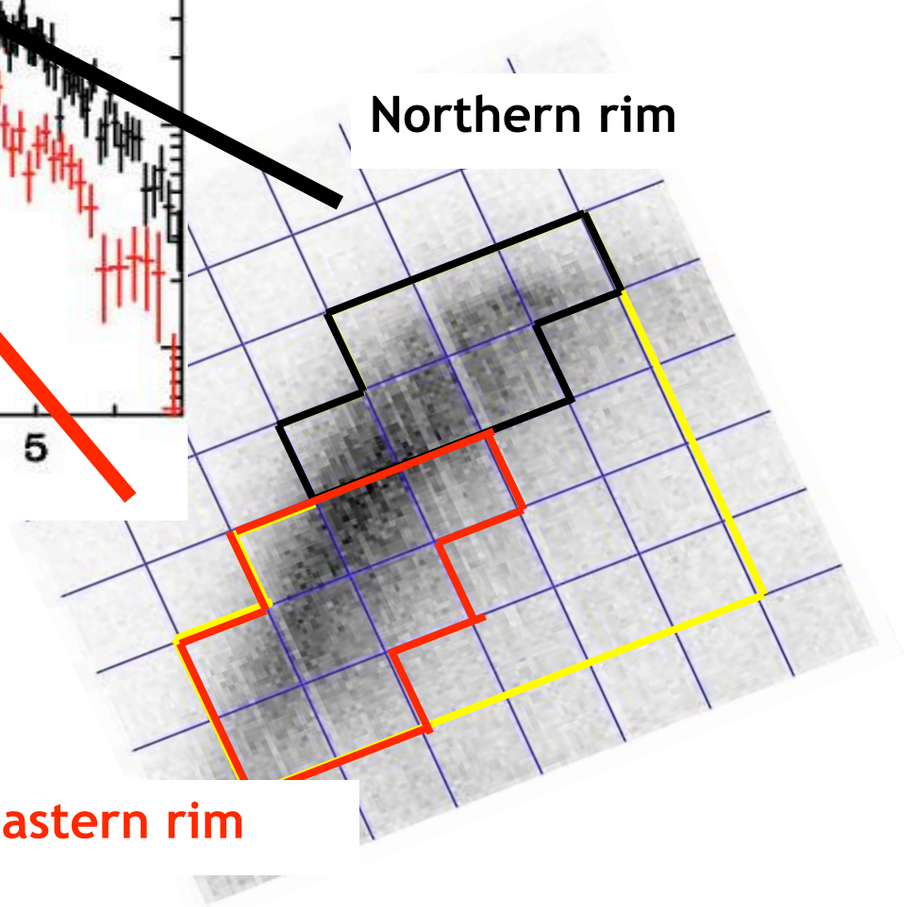
Eastern rim



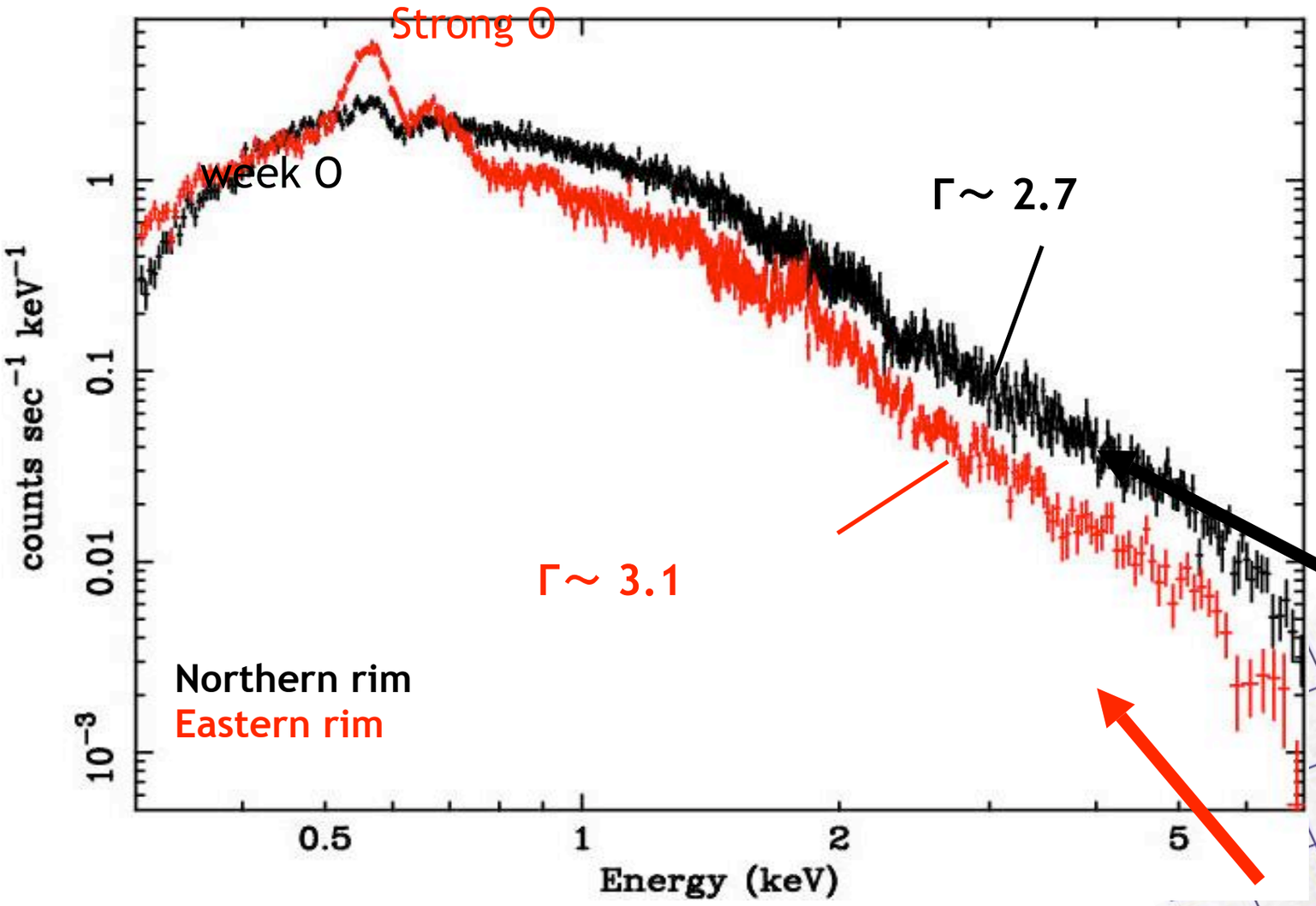
Thermal Plasma vs Non-thermal Emission

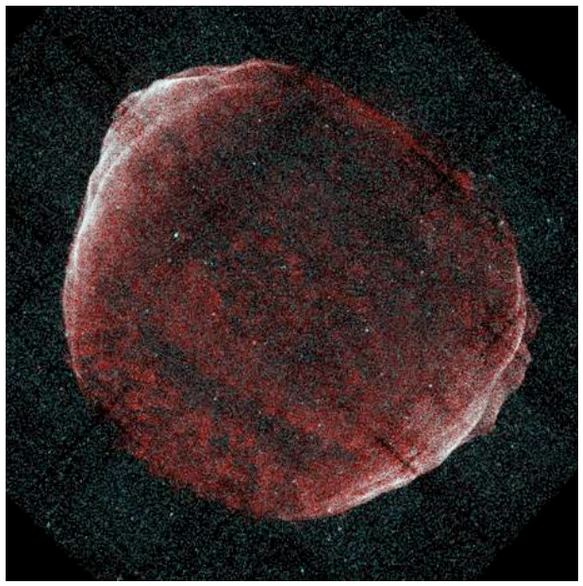


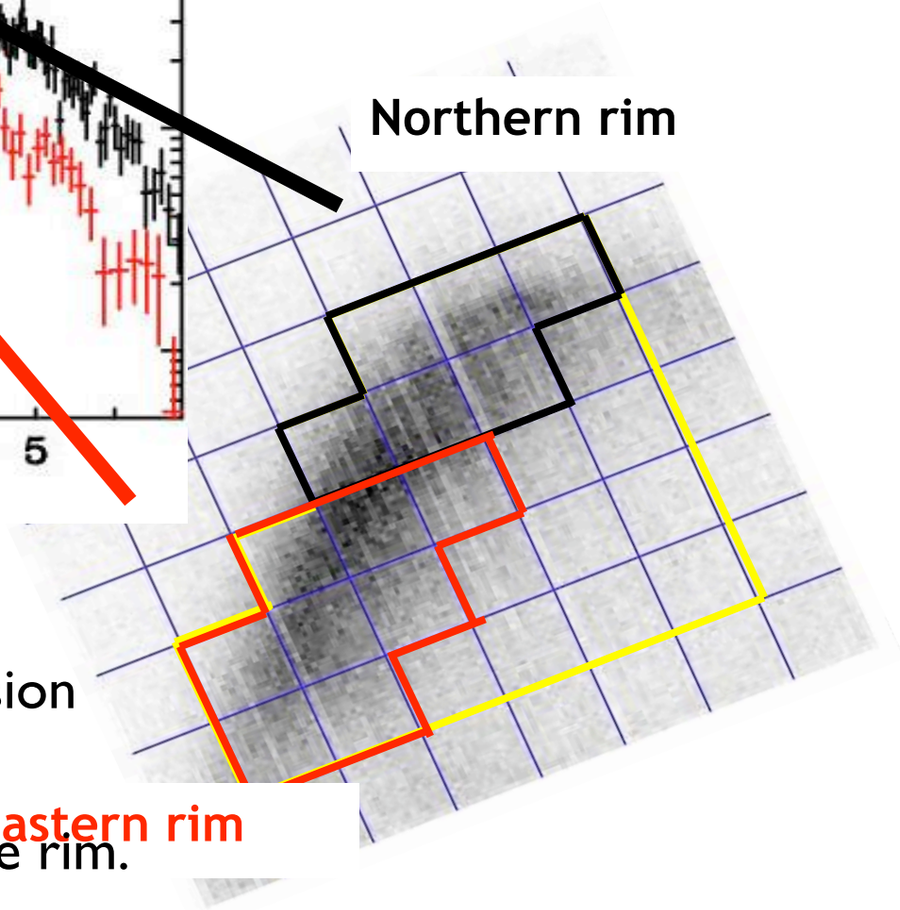




Thermal Plasma vs Non-thermal Emission





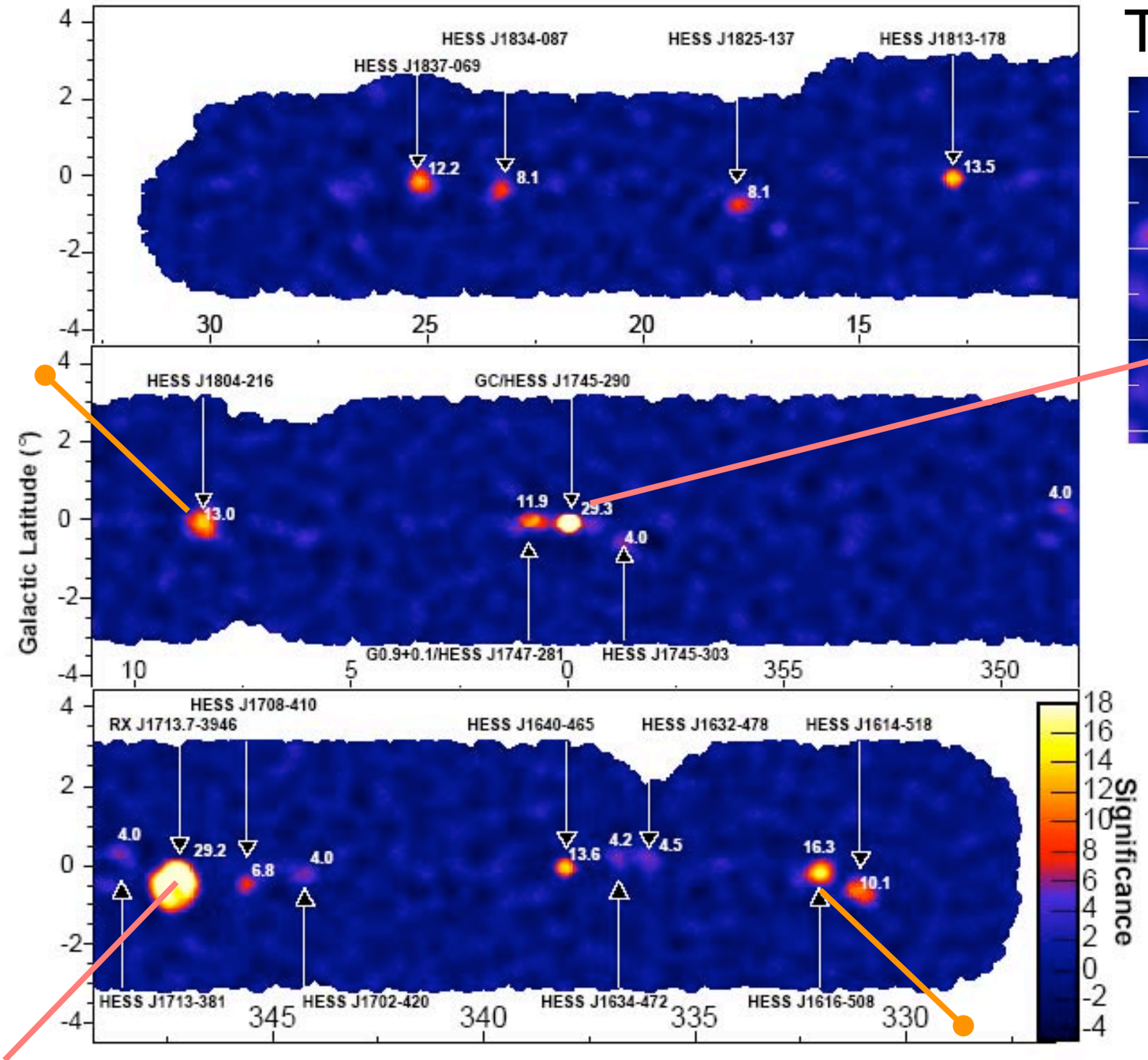


Weak Oxygen Line ⇔ Strong (Hard) Non Thermal Emission

The ratio between He-like/H-like Oxygen looks same in the rim.
(indicate same temperature)

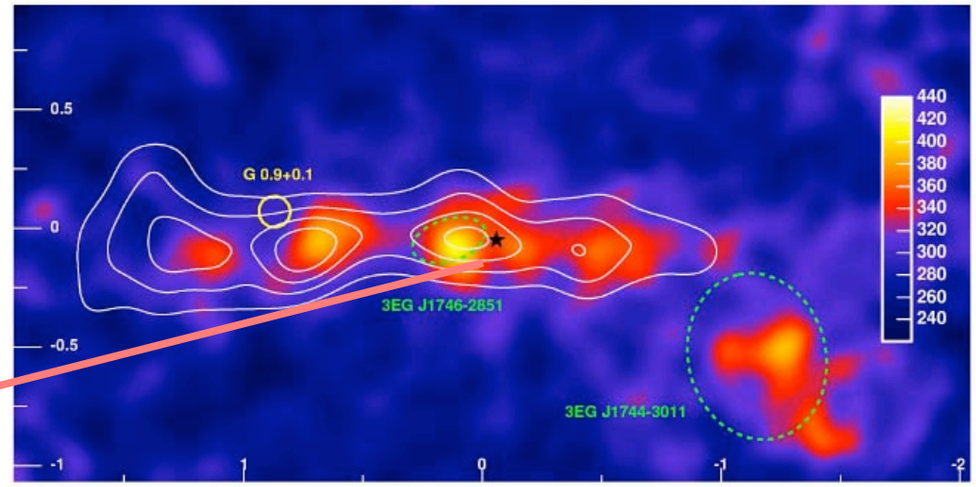
Unidentified TeV sources

Only 5 sources, out of 22, have firm identification.



RXJ1713-3946

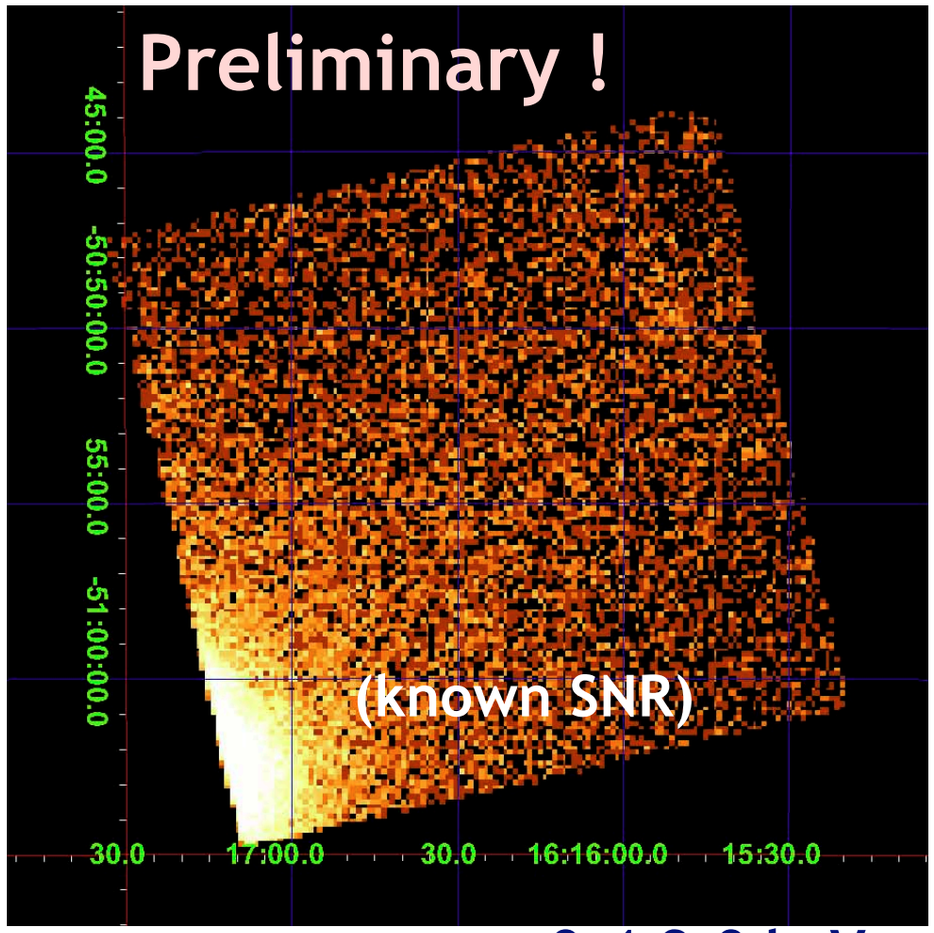
TeV Diffuse near GC



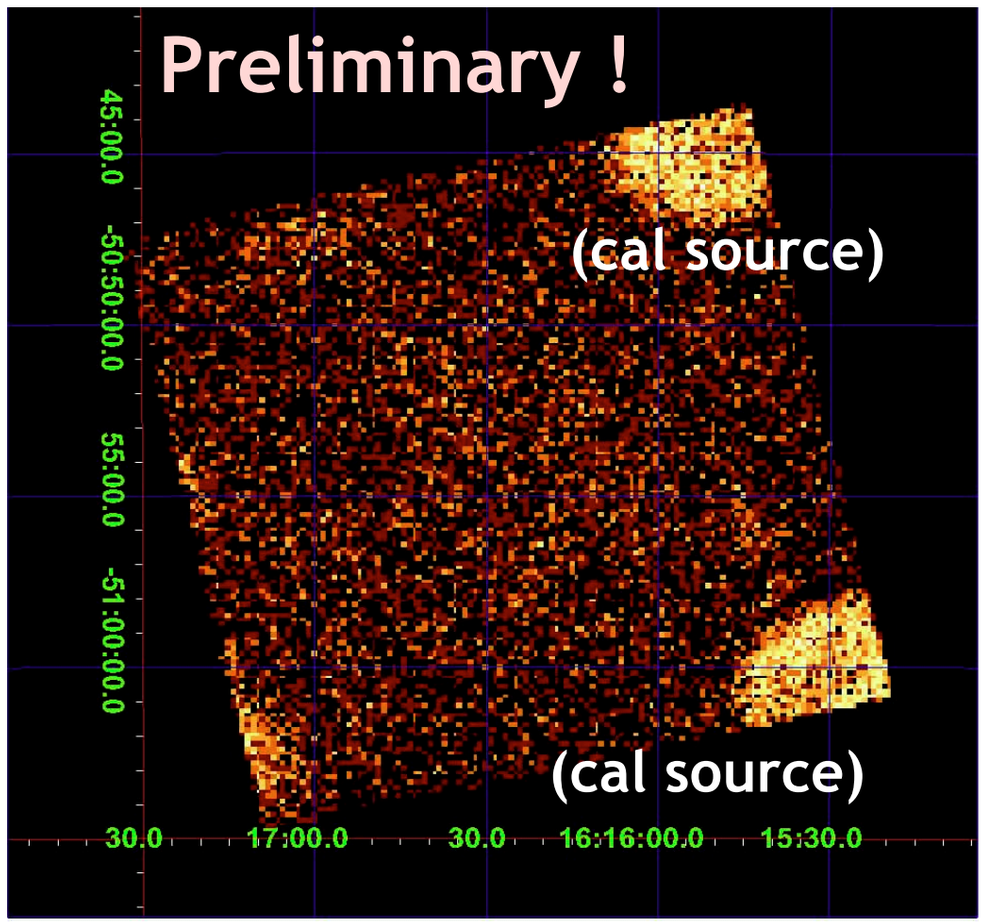
H.E.S.S. Cherenkov TeV telescope

HESS collaboration, 2005/2006

HESS J1616-508



0.4-2.0 keV



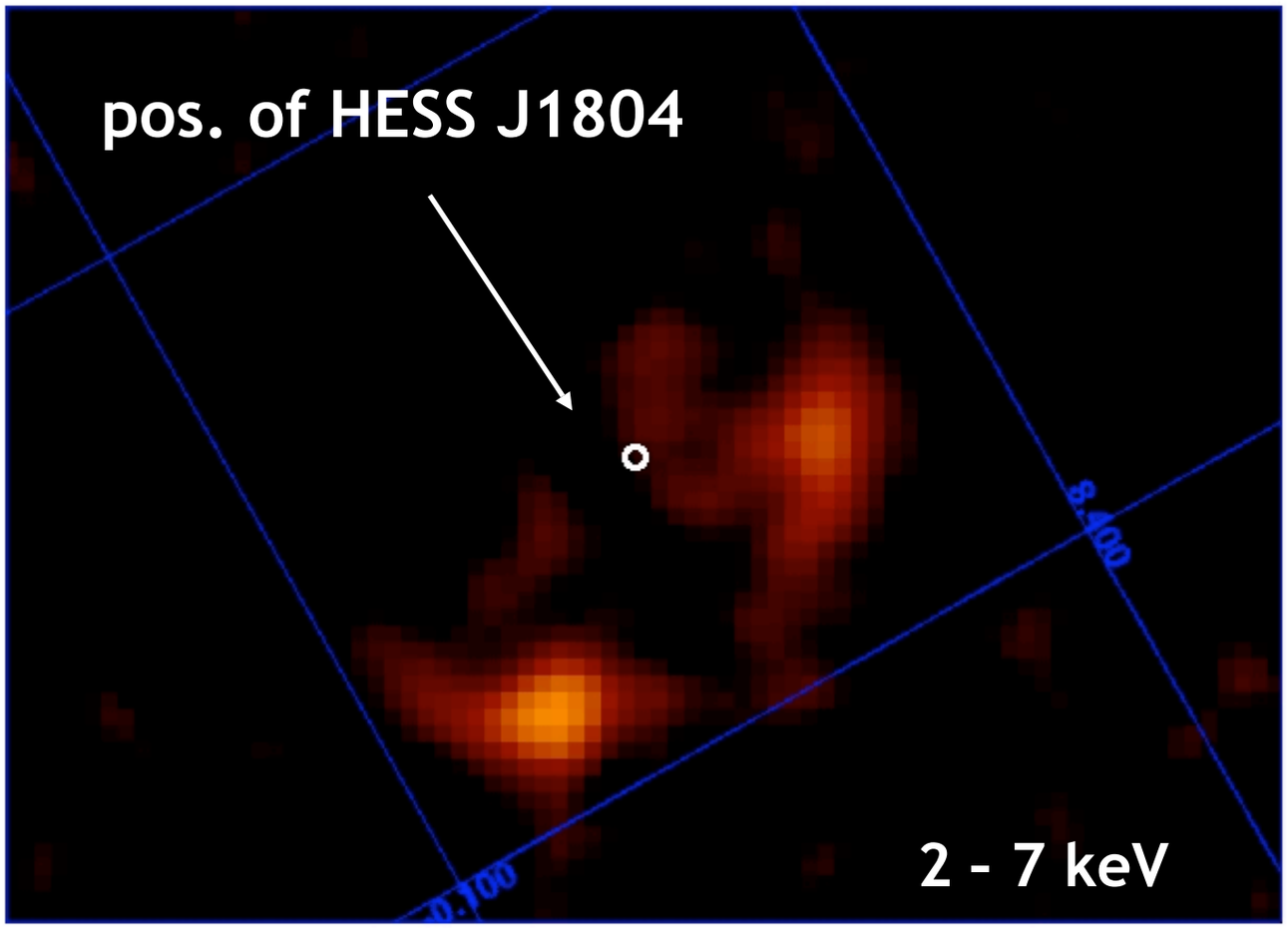
2.0-10.0 keV

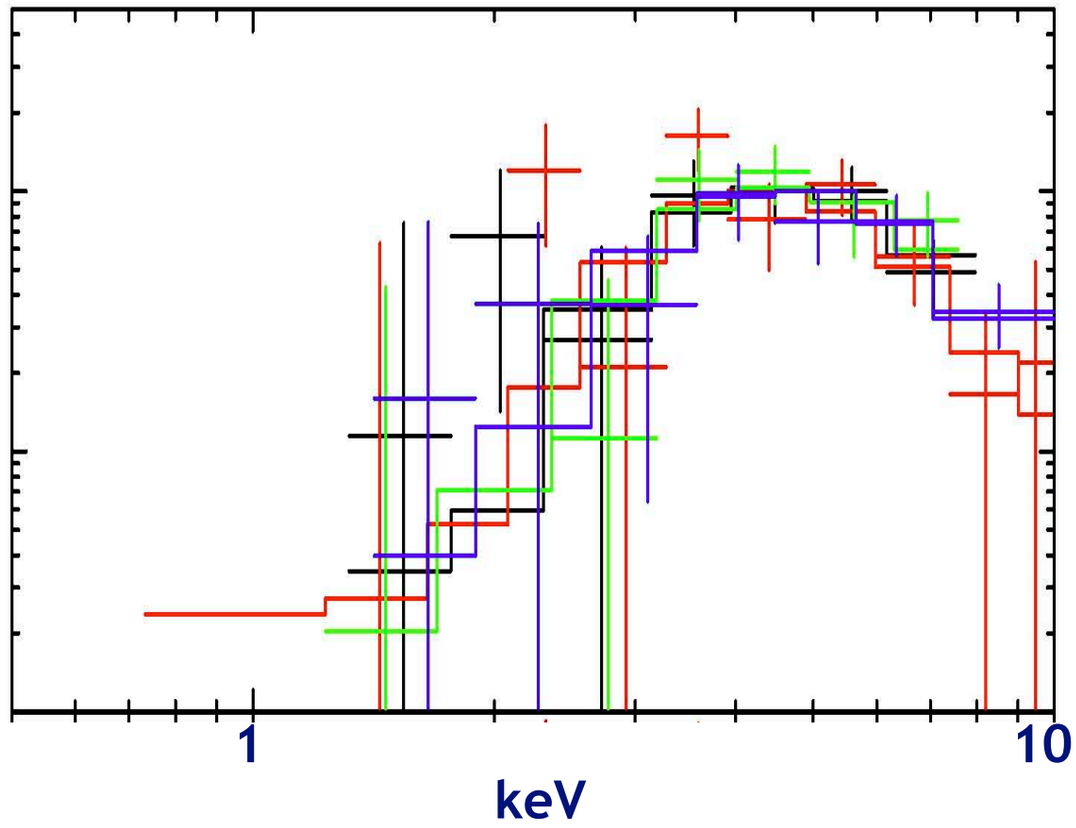
No bright X-ray source.
Maybe electrons, which can be responsible for X-rays, already died out, and TeV is emitted from protons? → Old SNR?

H.Matsumoto et al. 2006

HESS J1804-216

HESS J1804-216 XIS image and Spectra





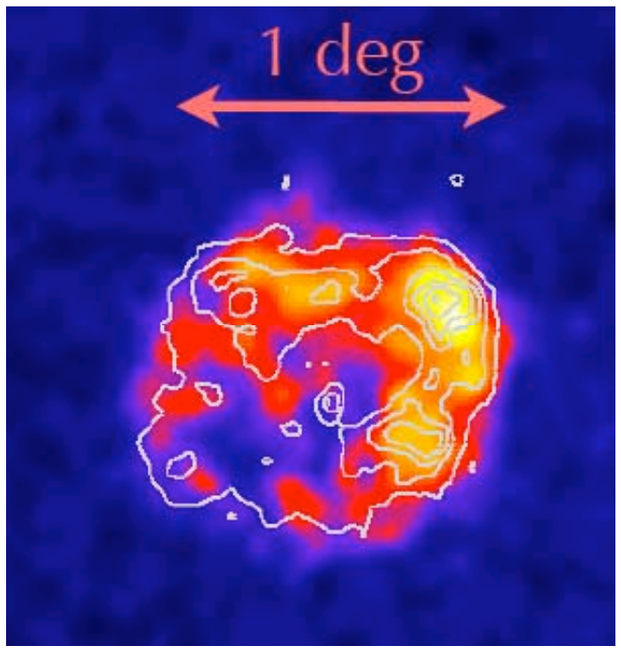
Suzaku discovered the possible counterpart !
The spectrum is very hard and strongly absorbed.

A. Bamba et al. 2006

RXJ1713.7-3946

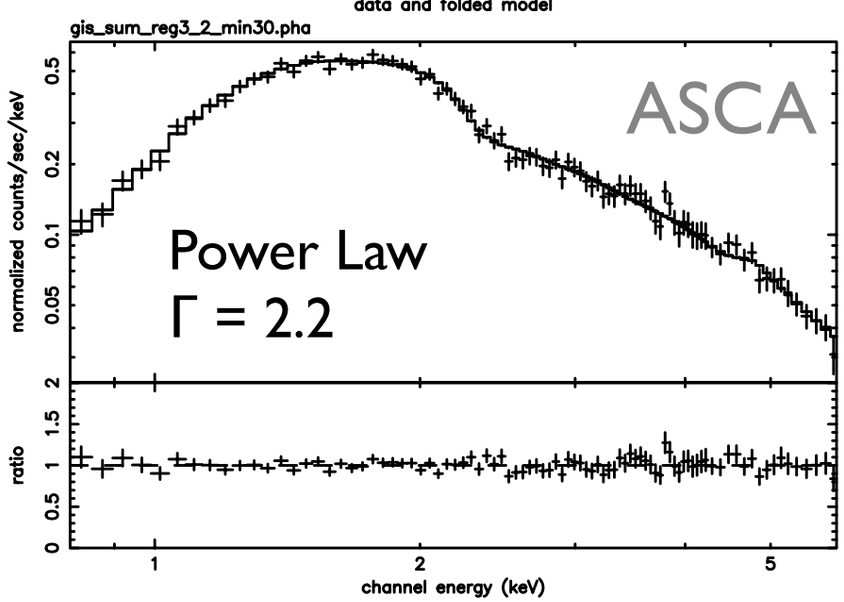
- Brightest Non-thermal SNR in the sky, both in X-ray and TeV gamma-ray

TeV Image vs
ASCA X-ray Contour



Age thought to be ~1000 yrs

Detector response included



Q1. Ecut (Maximum Energy)?
Q2. How can we explain it?

synchrotron cooling

【Loss limited maximum energy ($t_{acc} = t_{sync}$) 】

$$E_{max} = 67 \times \left(\frac{B}{10\mu G}\right)^{-\frac{1}{2}} \left(\frac{V_s}{2000\ \mathrm{km/s}}\right) \eta^{-\frac{1}{2}}\ \mathrm{TeV}$$

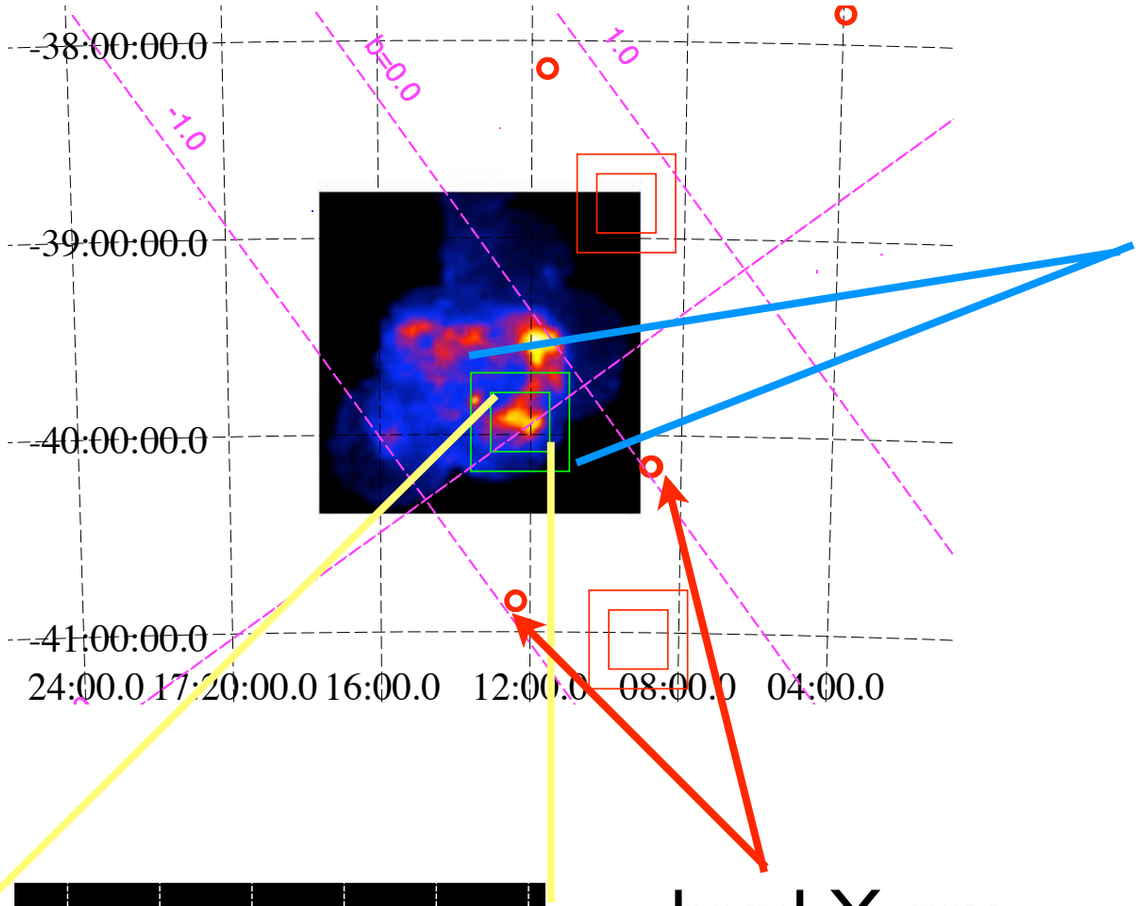
If Cutoff > 10 keV, very high Vs is required?

【Synchrotron cutoff】

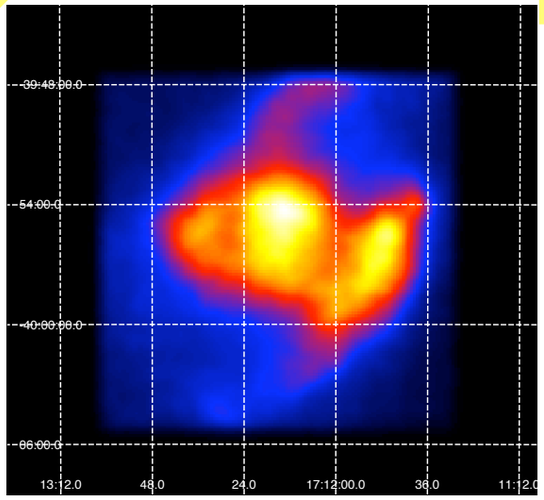
$$\epsilon_0 = 2.0 \times \left(\frac{V}{2000\mathrm{km/s}}\right)^2 \times \eta^{-1} keV$$

independent of B

Observation



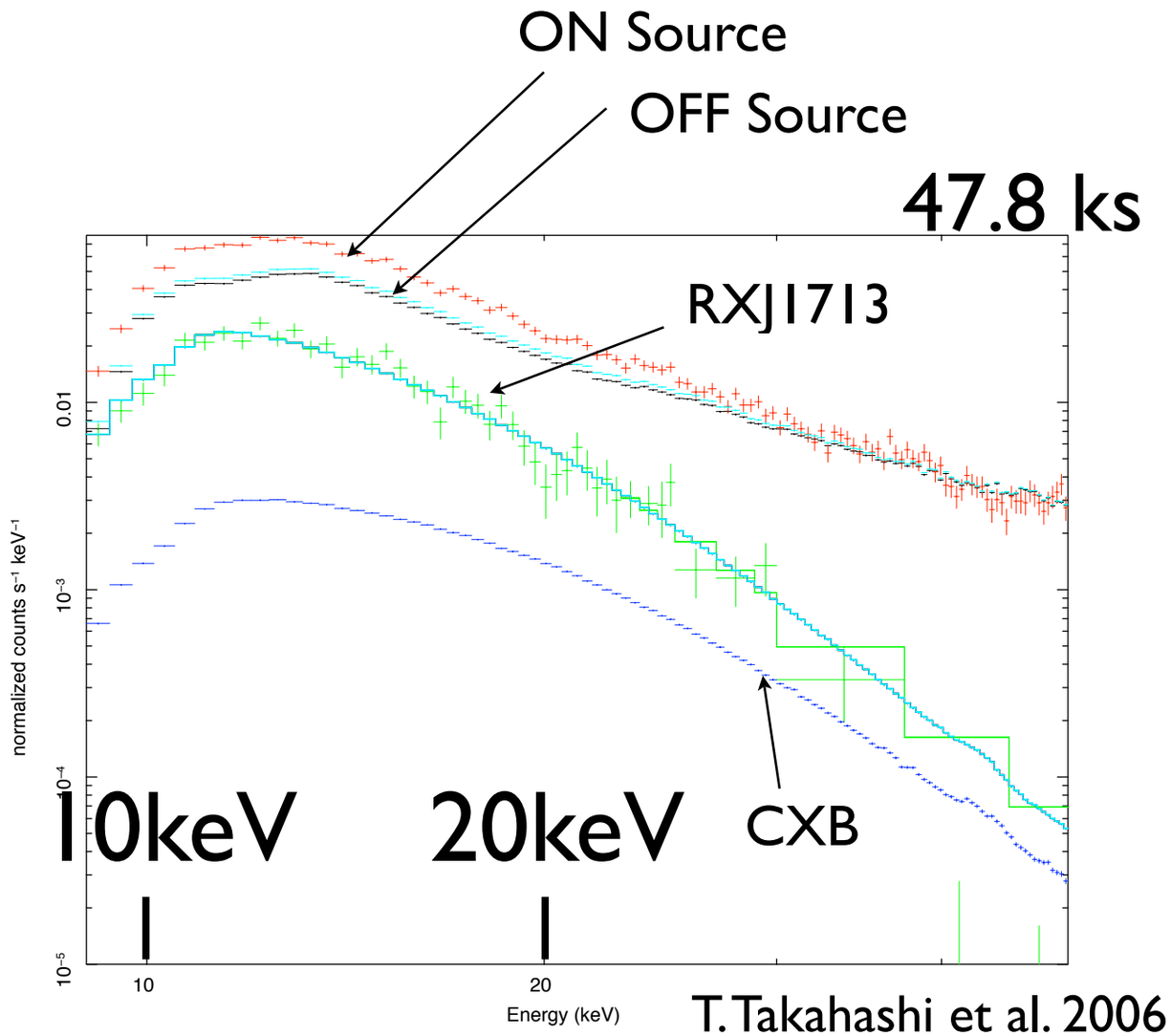
hard X-ray sources



XIS Image

Hard X-ray Detector (HXD)

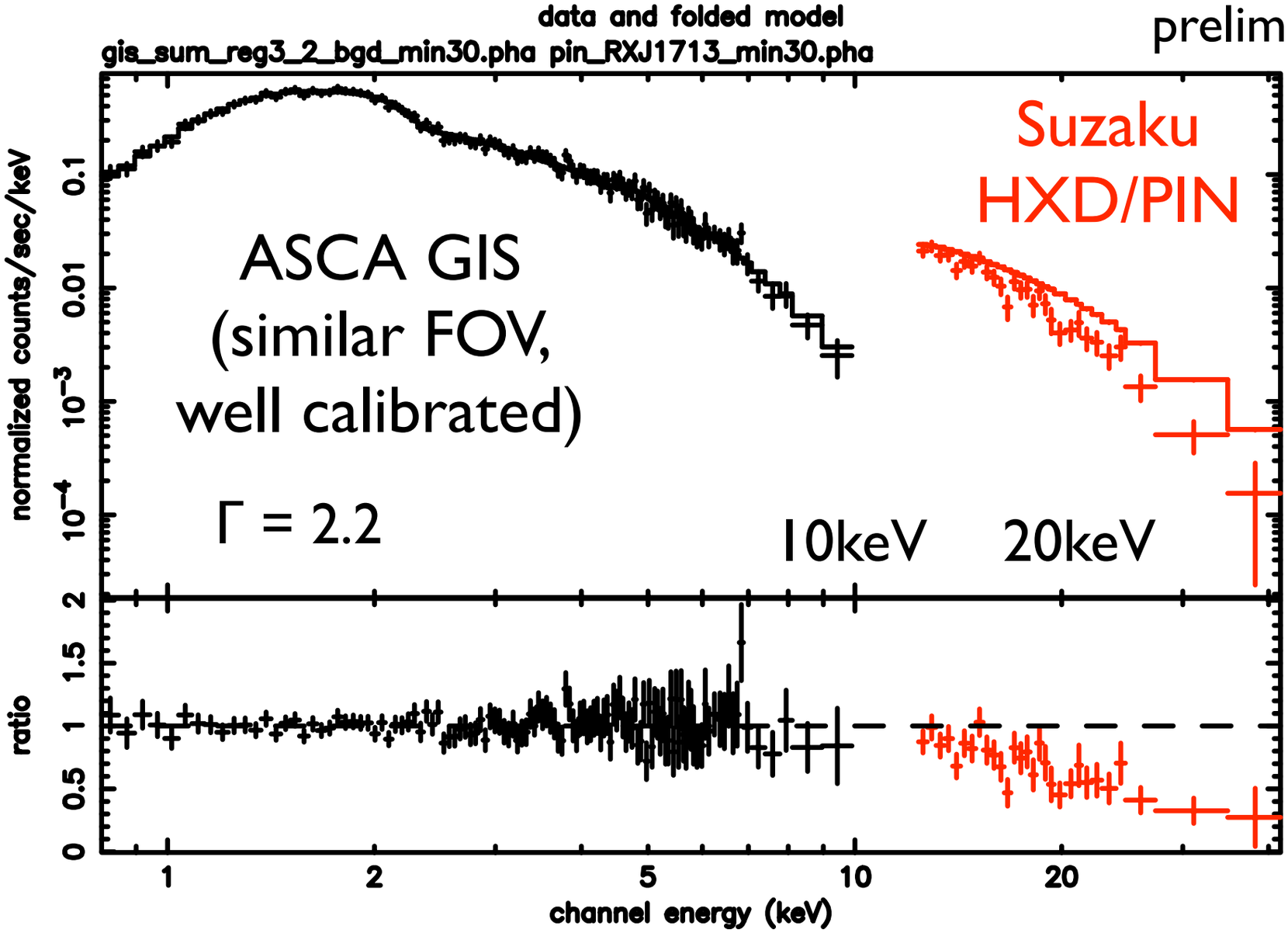
- Japan's answer for the "high sensitivity Gamma-ray" detector
- Low Background by the Well-type Shield
- Small FOV (1/4 of SAX, 0.5 deg. x 0.5 deg)



T. Takahashi et al. 2006

Results

First reliable detection up to 40 keV,
with a signature of break at ~15 keV.



T. Takahashi et al. 2006

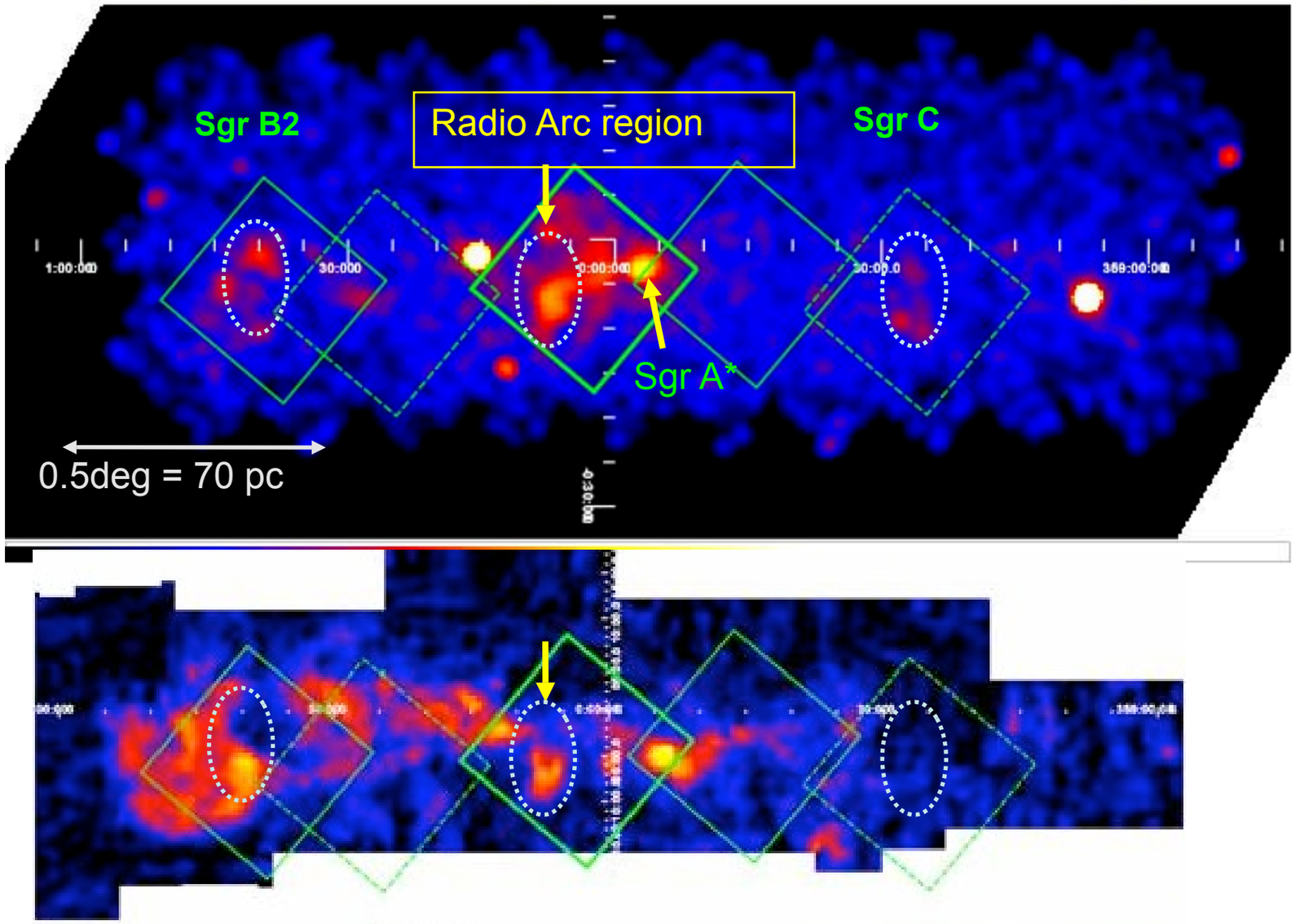
Galactic Diffuse Emission, near GC

Fe I Ka (6.4 keV)
Chandra GC survey

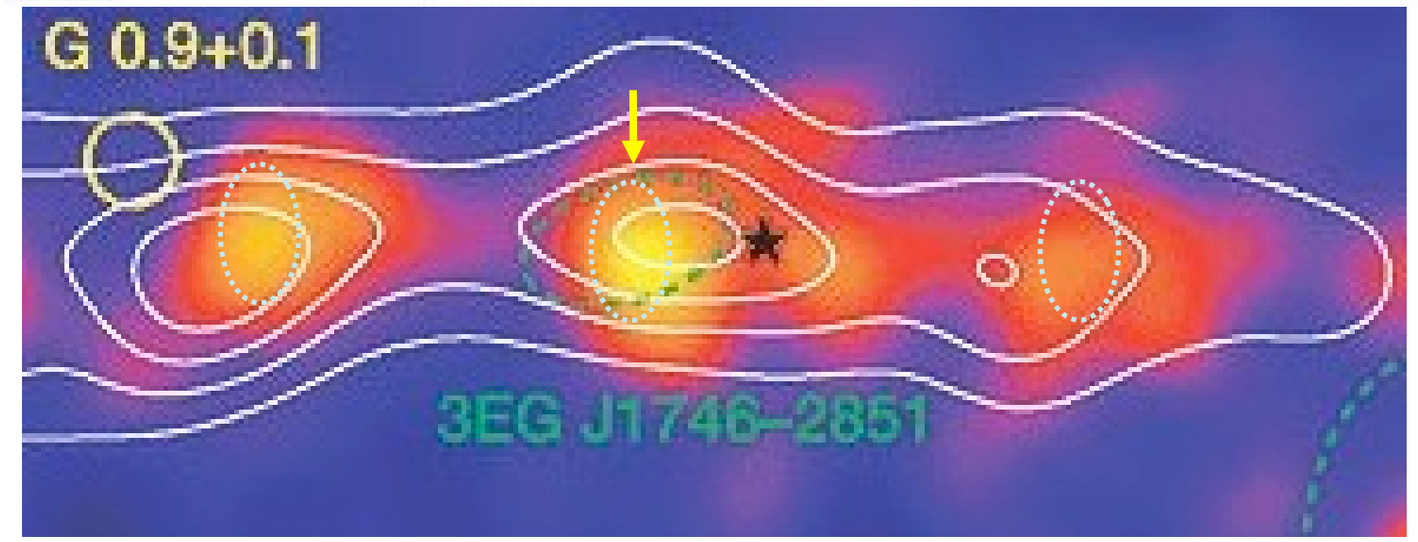
Suzaku Fe-K edge

Embedded in MC

Likely fluorescence by hard X-rays from a past active SMBH (Koyama 1994)



Molecular Cloud
NRO CS J=1-0
20 km/s < v < 30 km/s
(Tsuboi et al. 1999)

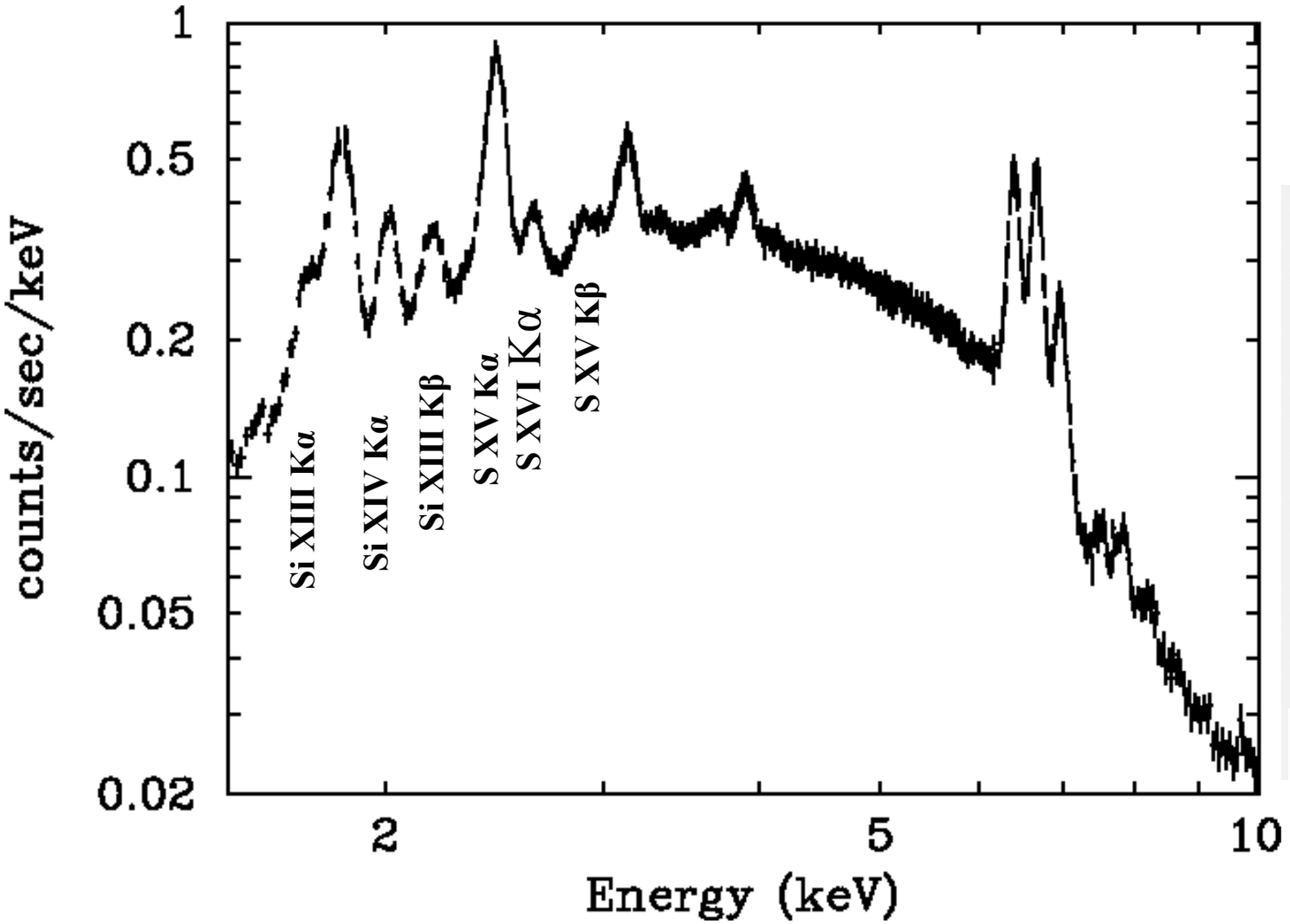


Diffuse VHE γ-rays
HESS
(Aharonian et al. 2006)

VHE proton bomberment?

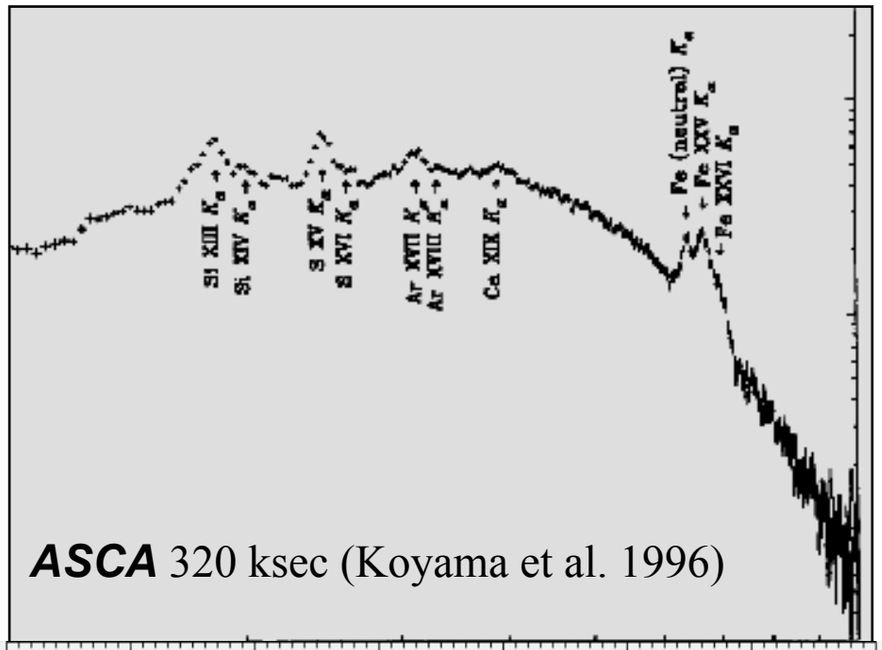
Complied by
Y. Maeda

Iron line spectroscopy

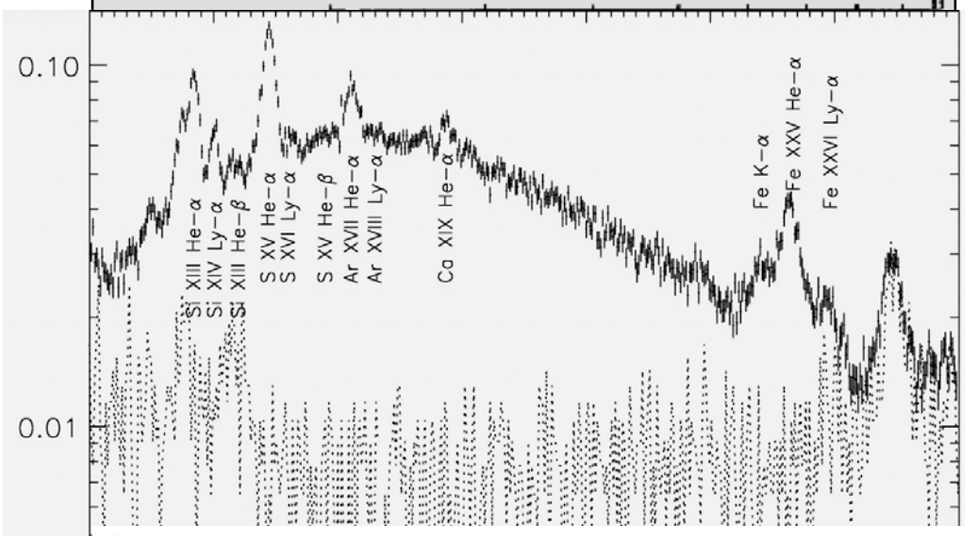


Suzaku: 180 ksec Observation

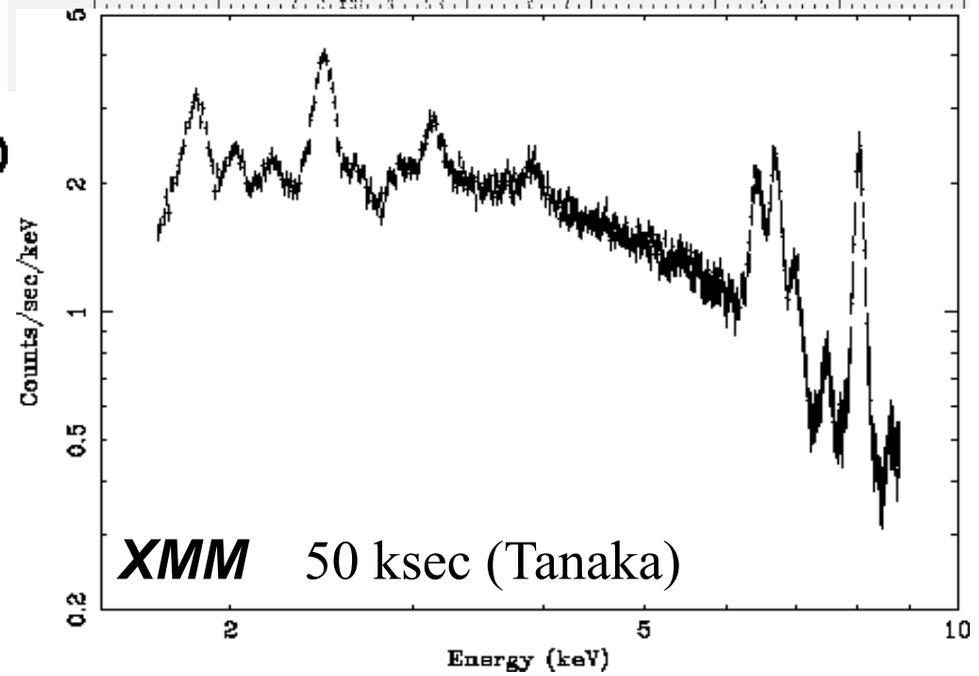
Koyama & the GC team, 2006



ASCA 320 ksec (Koyama et al. 1996)

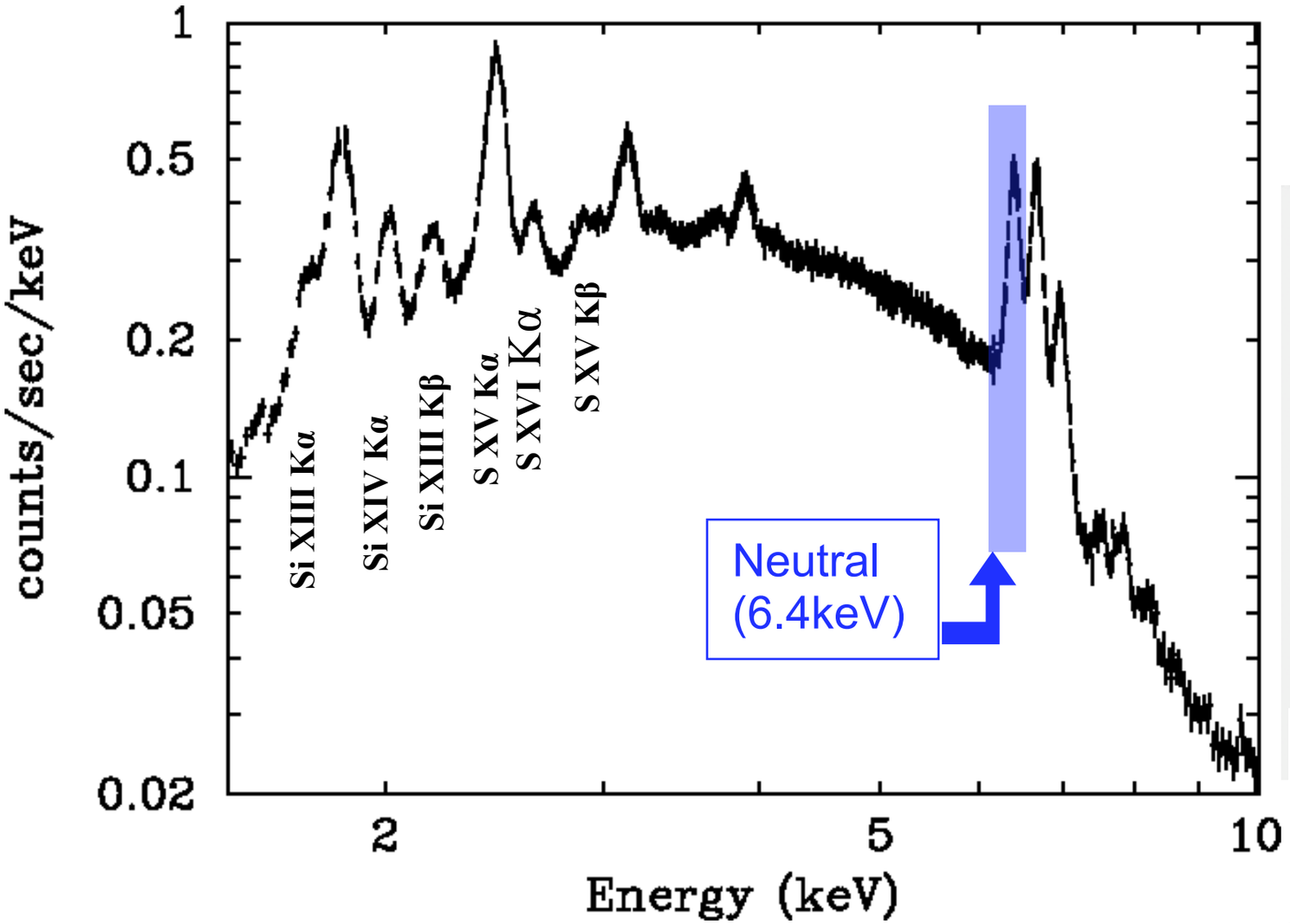


Chandra 600ksec (Muno et al. 2004)



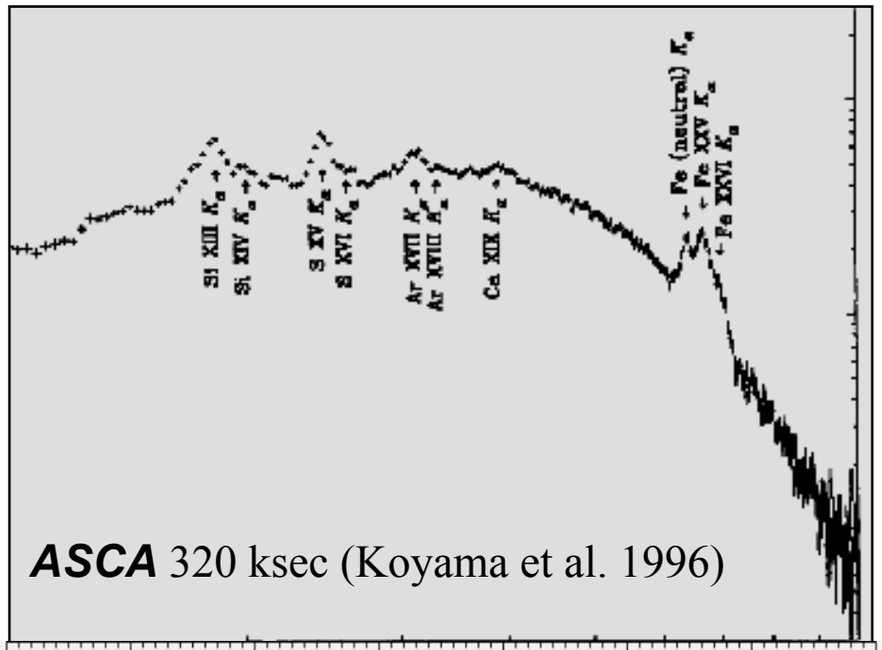
XMM 50 ksec (Tanaka)

Iron line spectroscopy

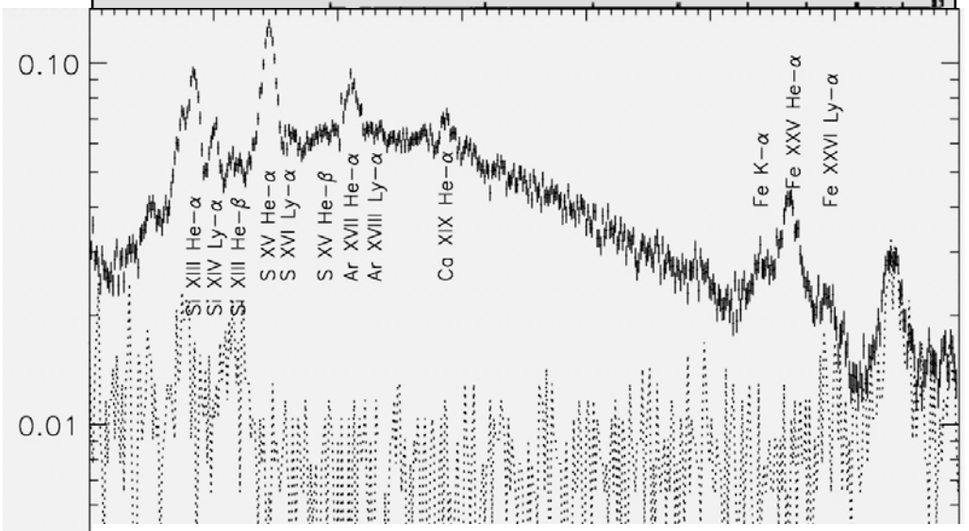


Suzaku: 180 ksec Observation

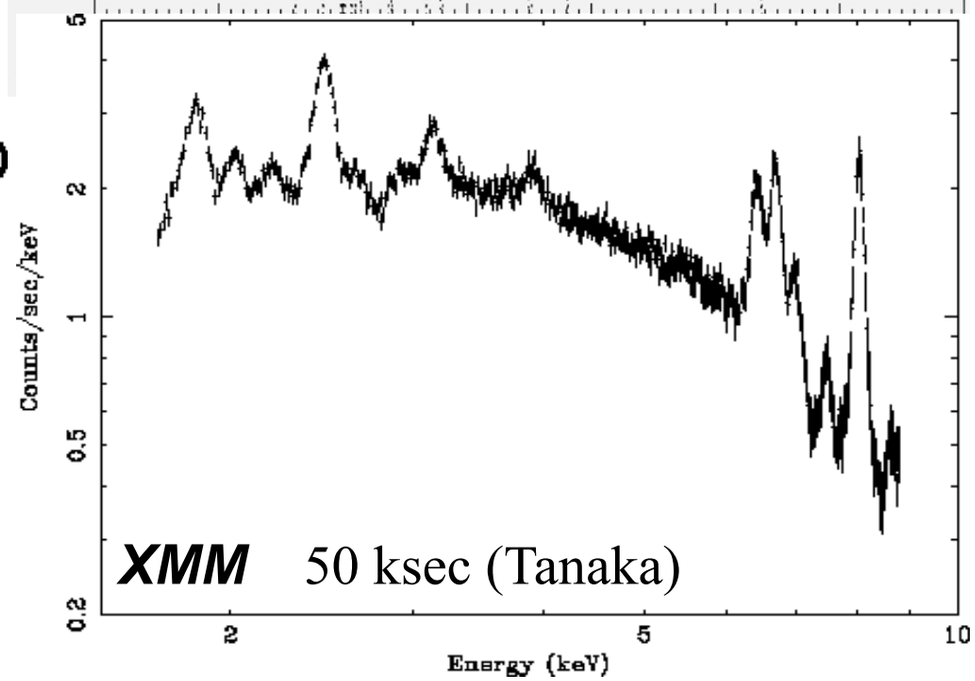
Koyama & the GC team, 2006



ASCA 320 ksec (Koyama et al. 1996)

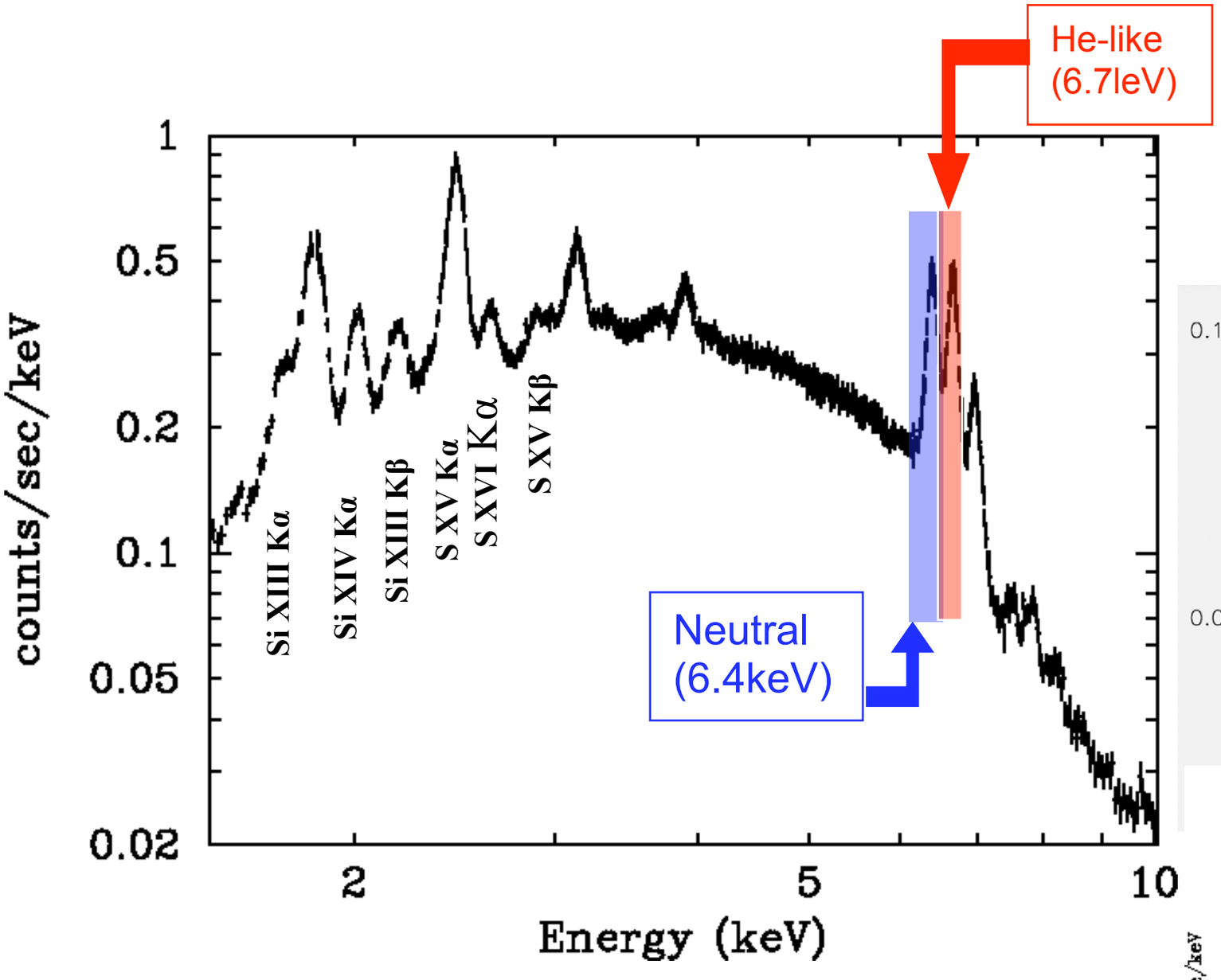


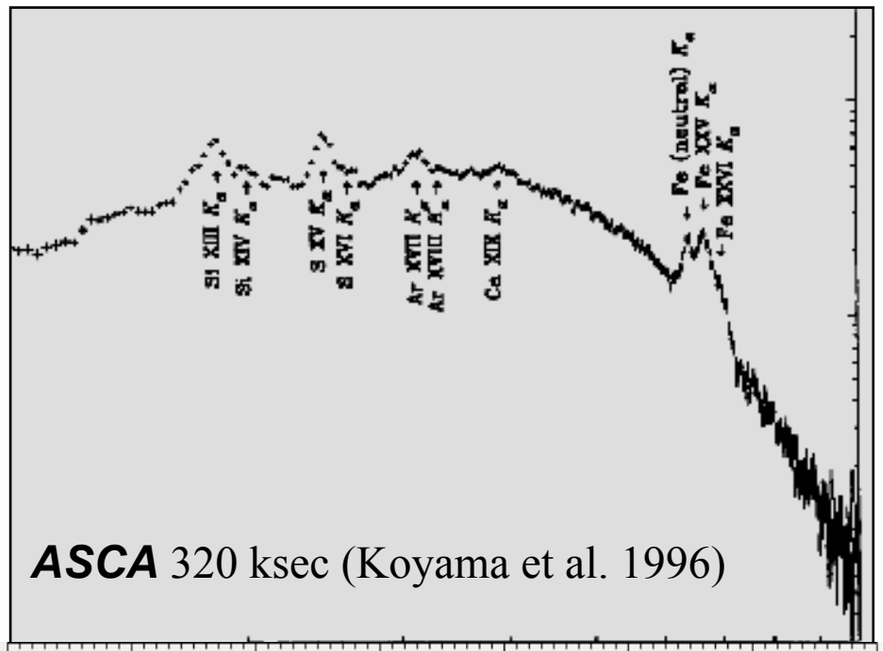
Chandra 600ksec (Muno et al. 2004)



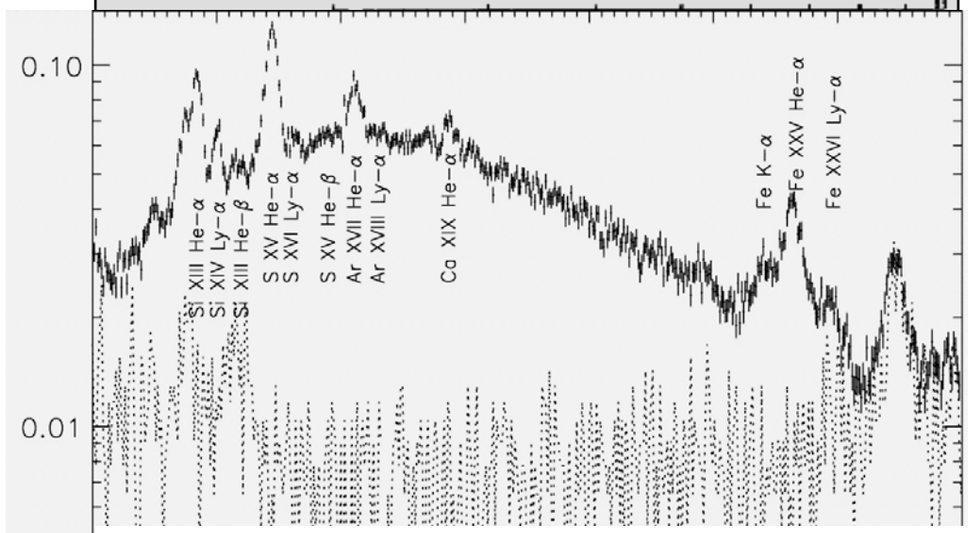
XMM 50 ksec (Tanaka)

Iron line spectroscopy

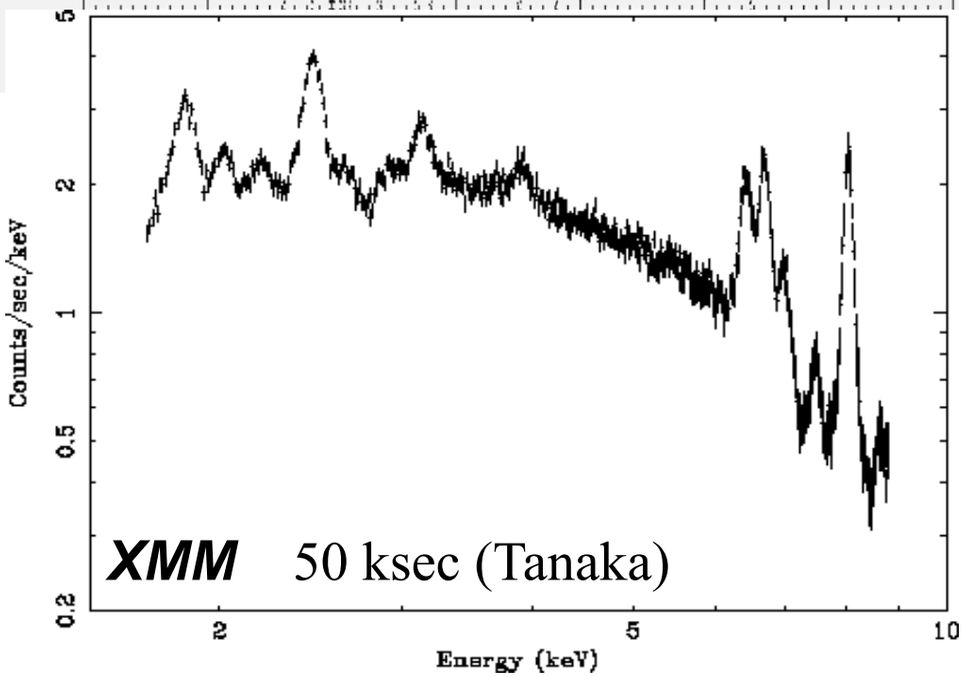




ASCA 320 ksec (Koyama et al. 1996)



Chandra 600ksec (Muno et al. 2004)

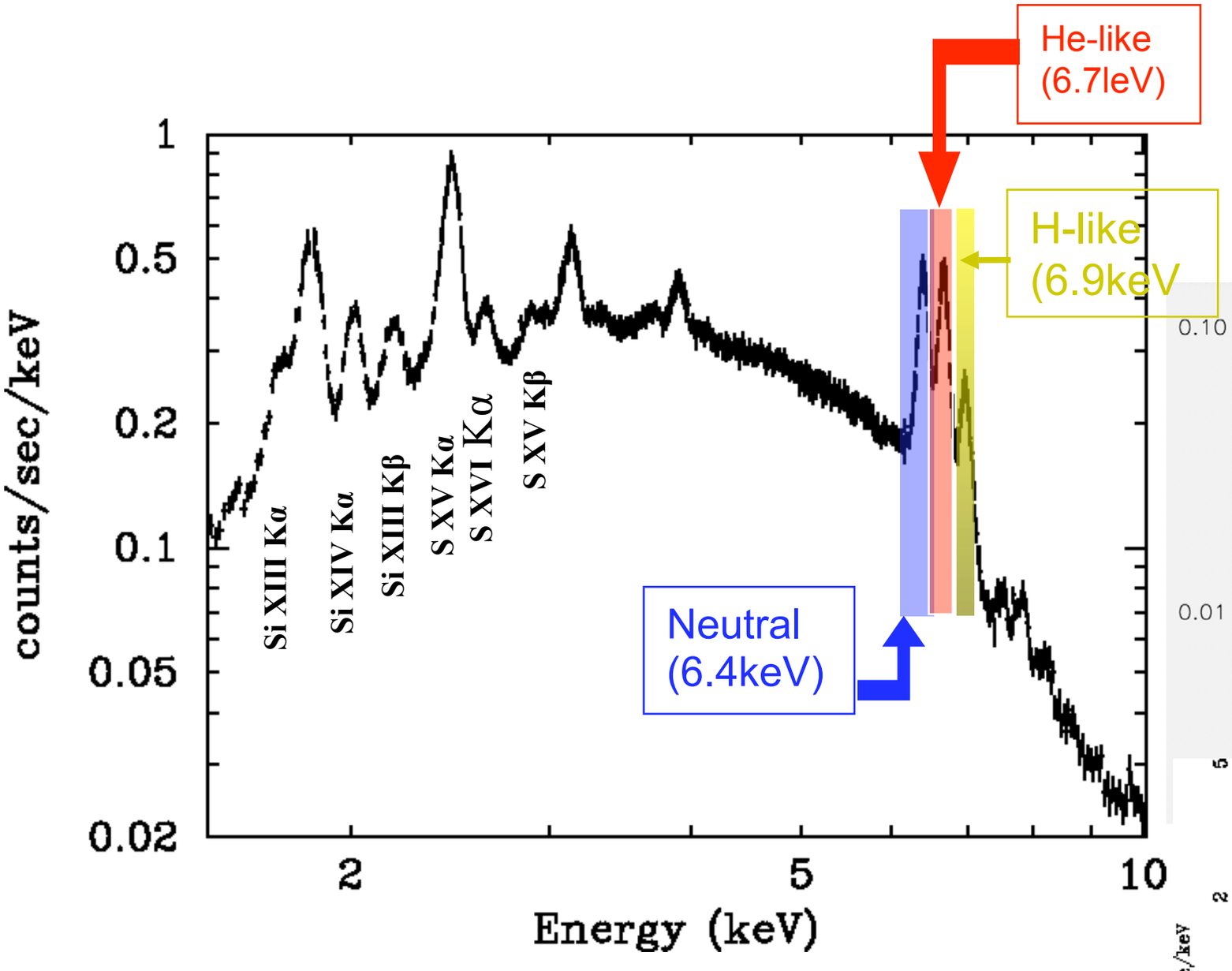


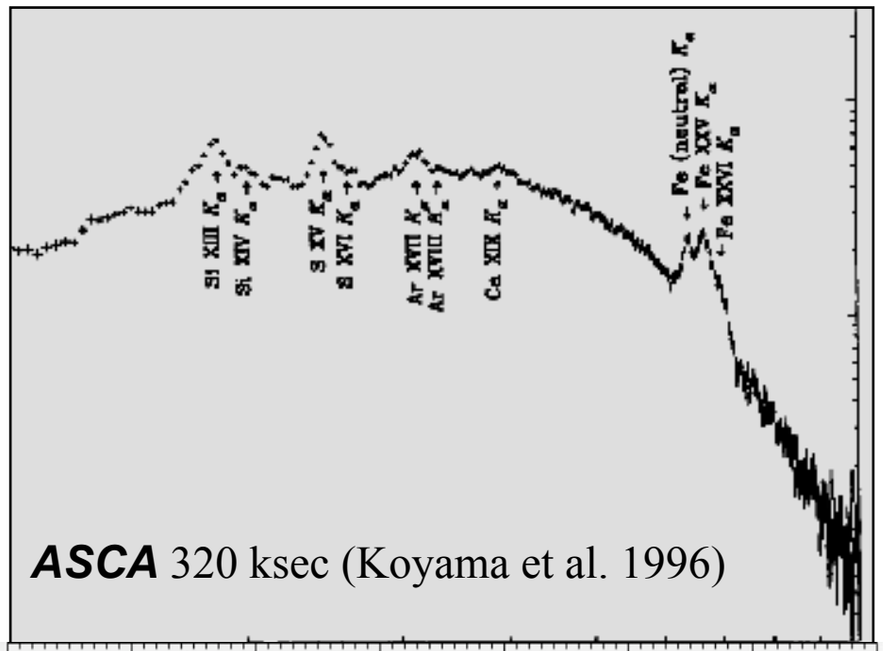
XMM 50 ksec (Tanaka)

Suzaku: 180 ksec Observation

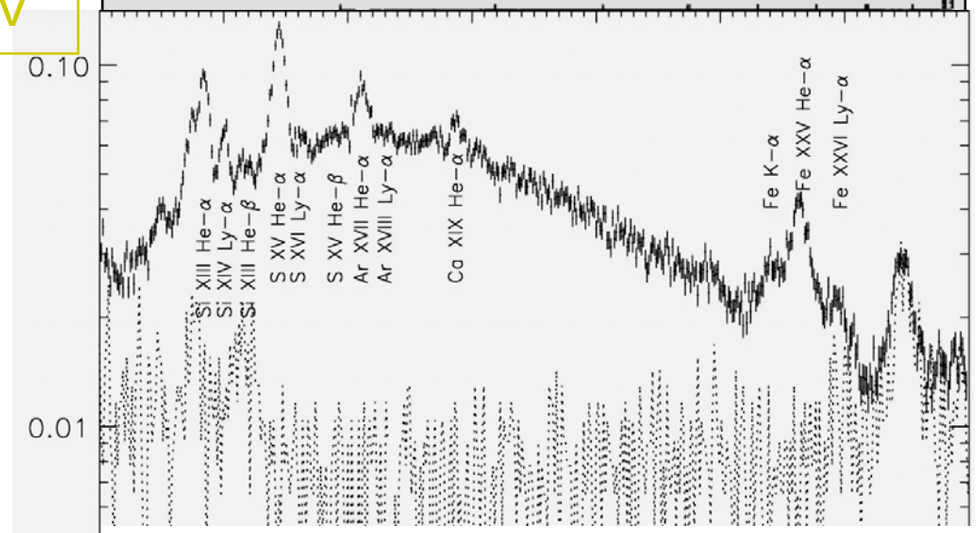
Koyama & the GC team, 2006

Iron line spectroscopy

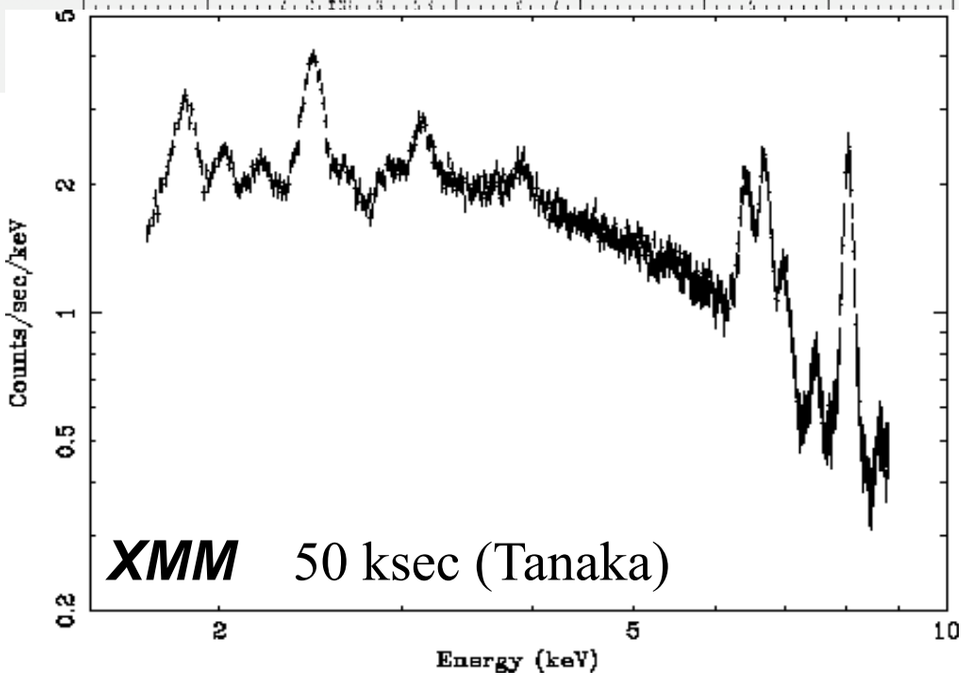




ASCA 320 ksec (Koyama et al. 1996)



Chandra 600ksec (Muno et al. 2004)

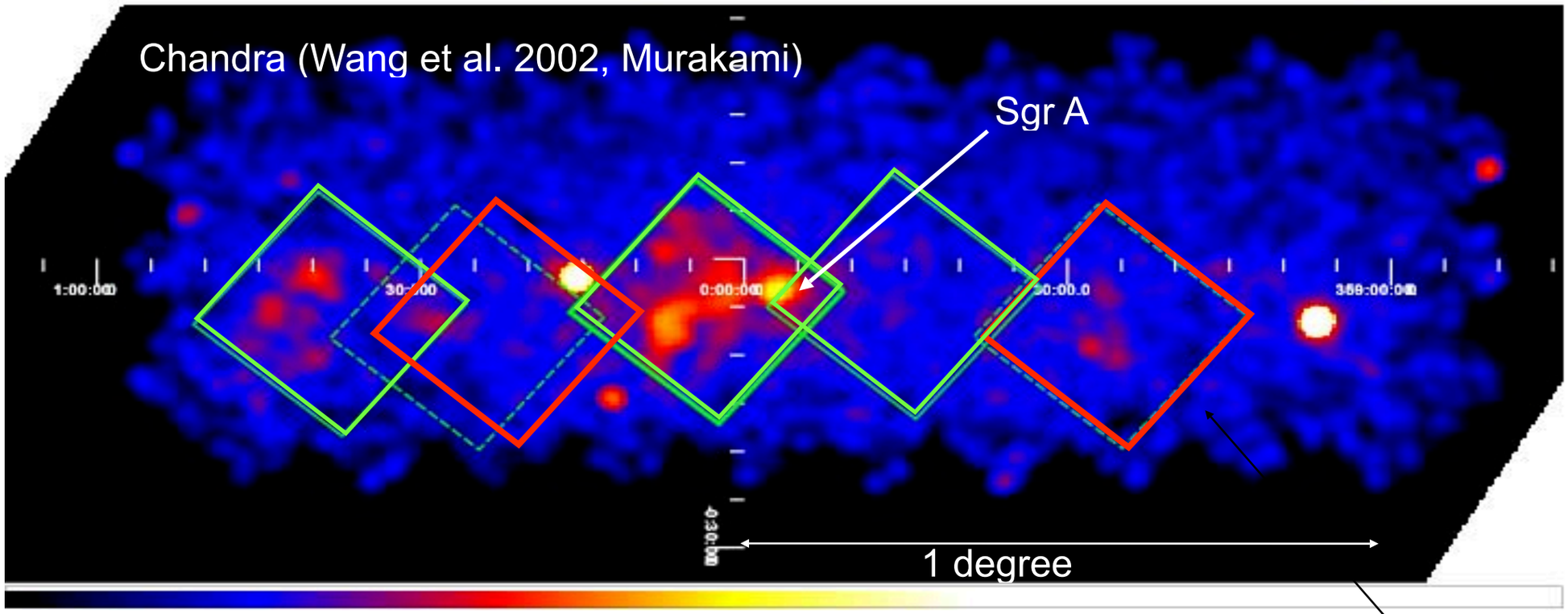


XMM 50 ksec (Tanaka)

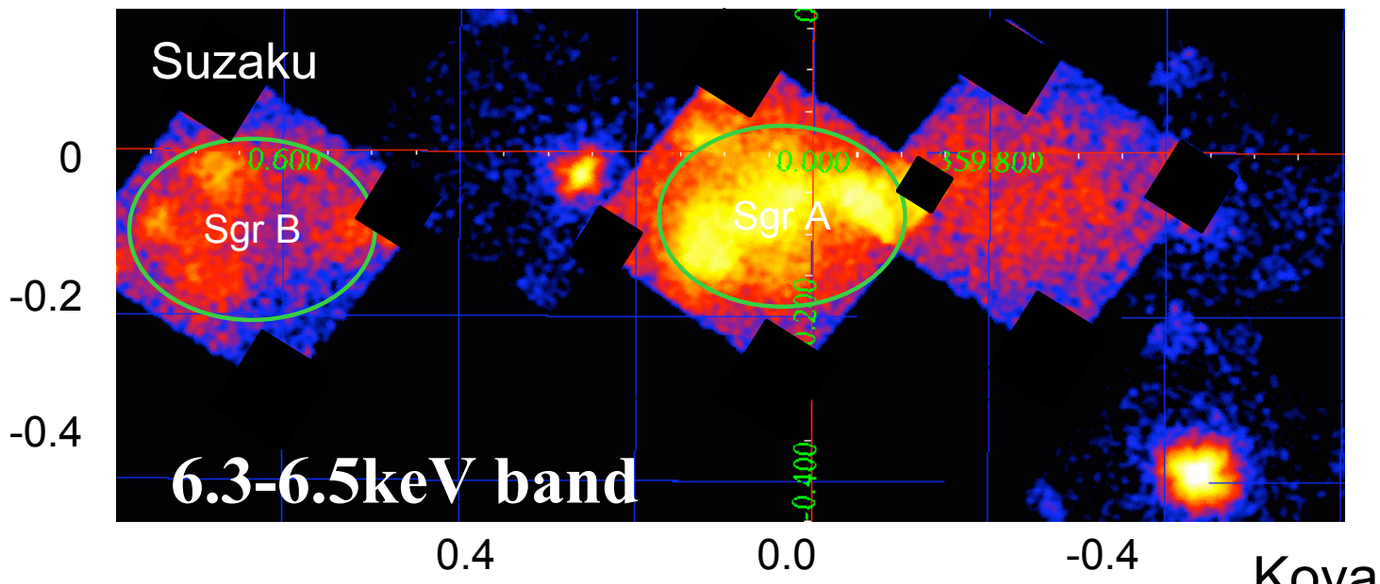
Suzaku: 180 ksec Observation

Koyama & the GC team, 2006

Galactic Diffuse Emission, near GC



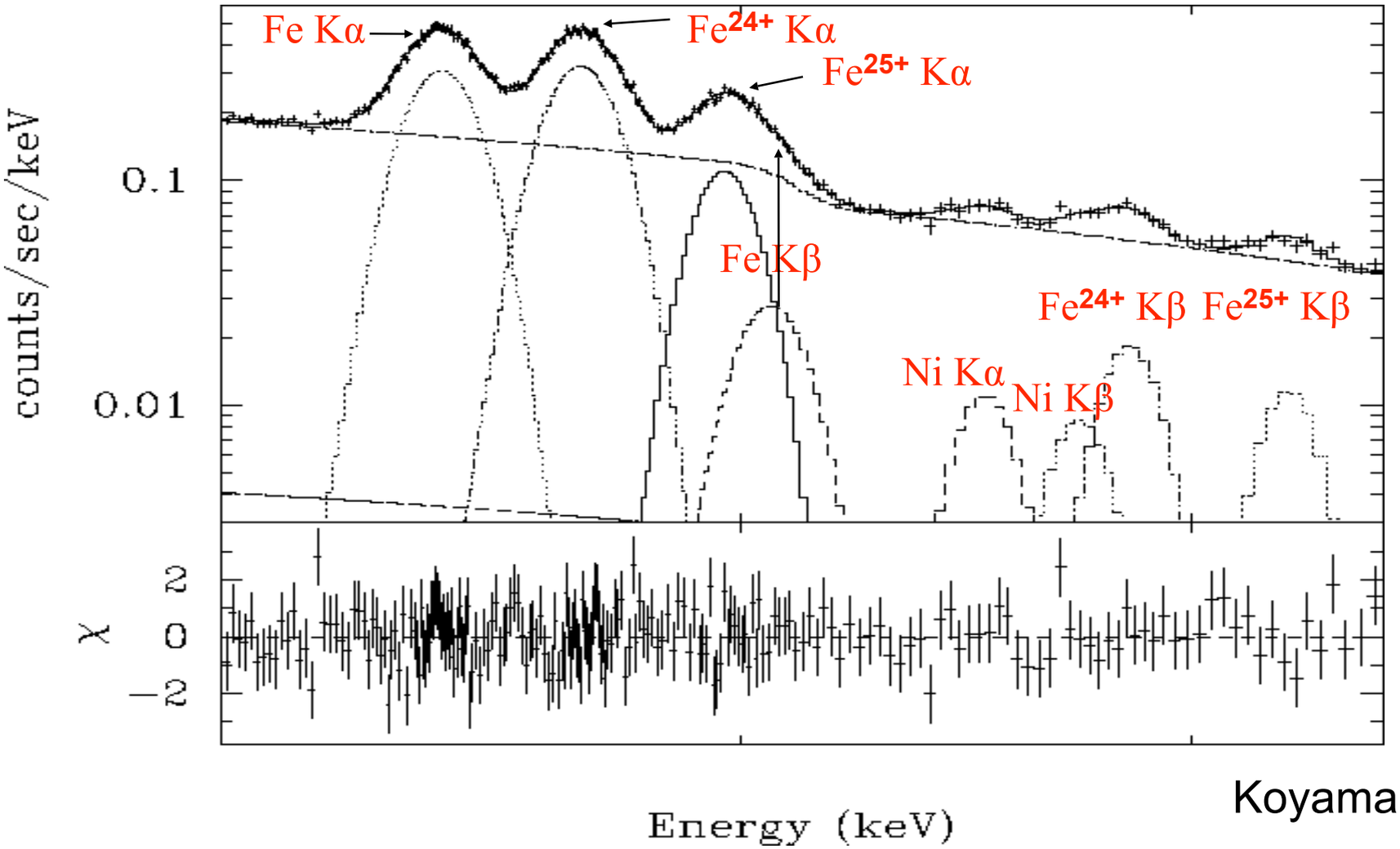
XIS FOV
Green: Finished
Red: Scheduled



6.4 keV diffuse emission is clearly resolved.

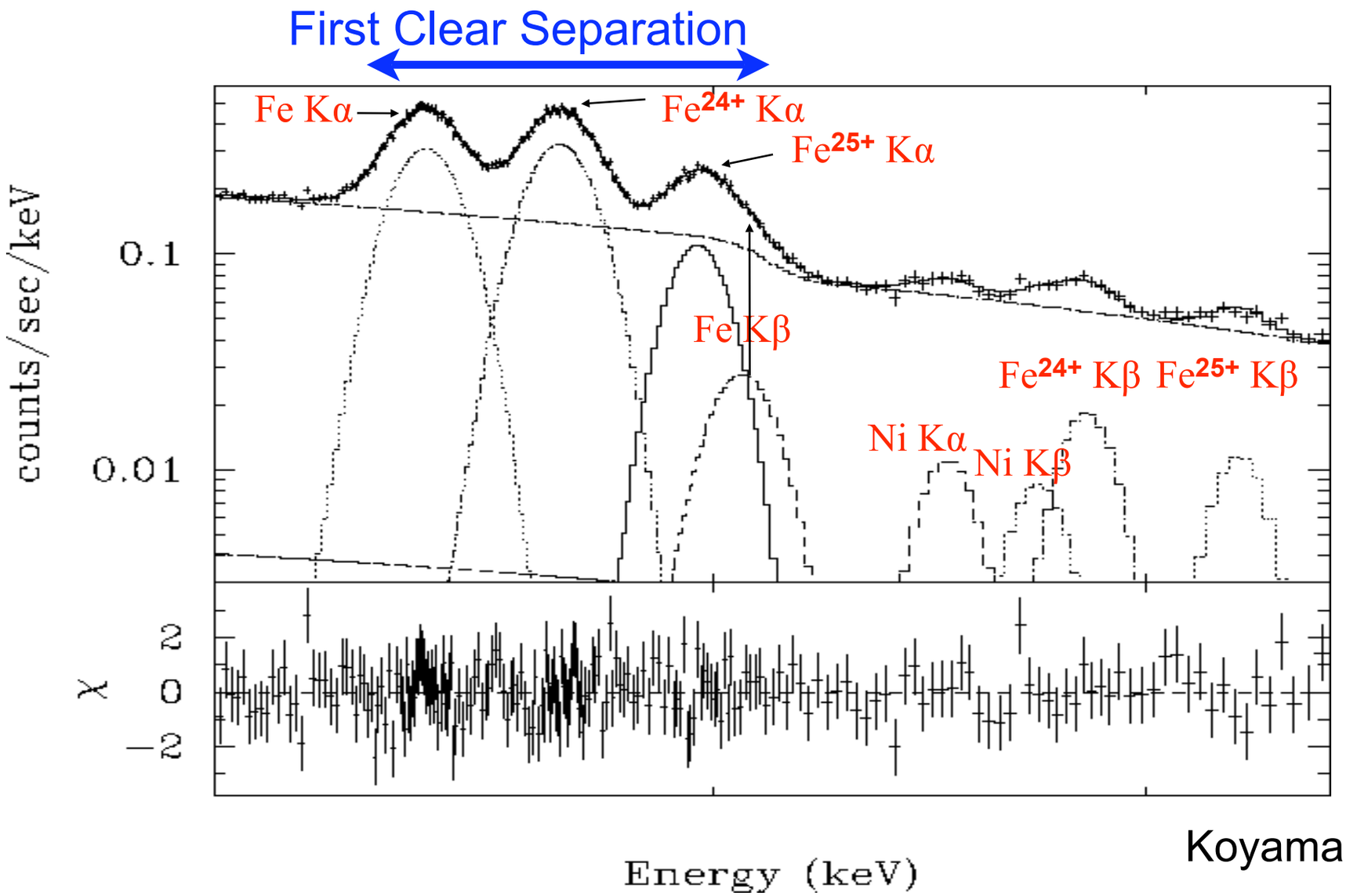
Koyama & the GC team, 2006

Power of Suzaku : Center Energy can be determined with an accuracy of a few eV (systematics ~ 5 eV)



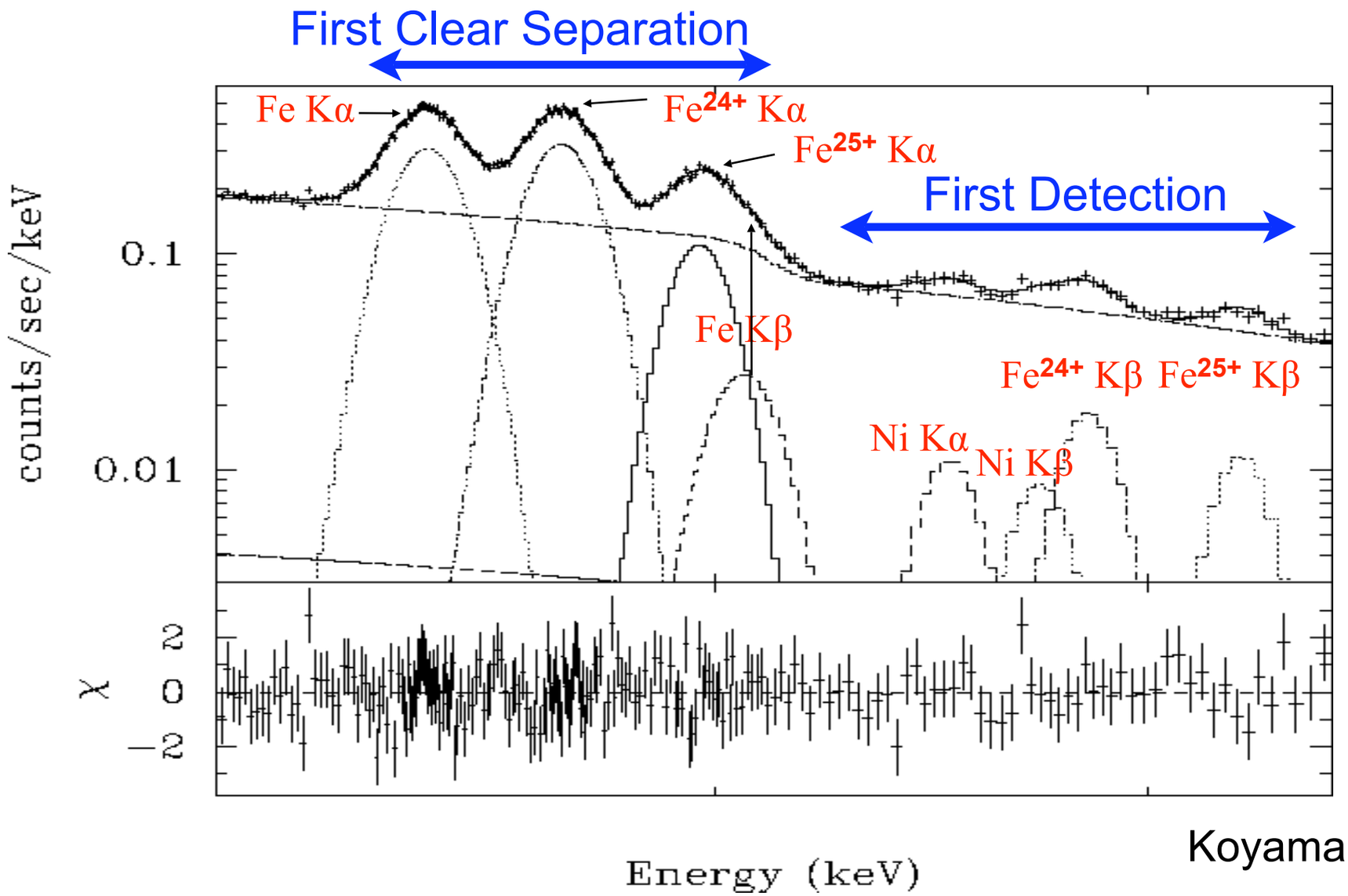
Koyama & the GC team, 2006

Power of Suzaku : Center Energy can be determined with an accuracy of a few eV (systematics ~ 5 eV)



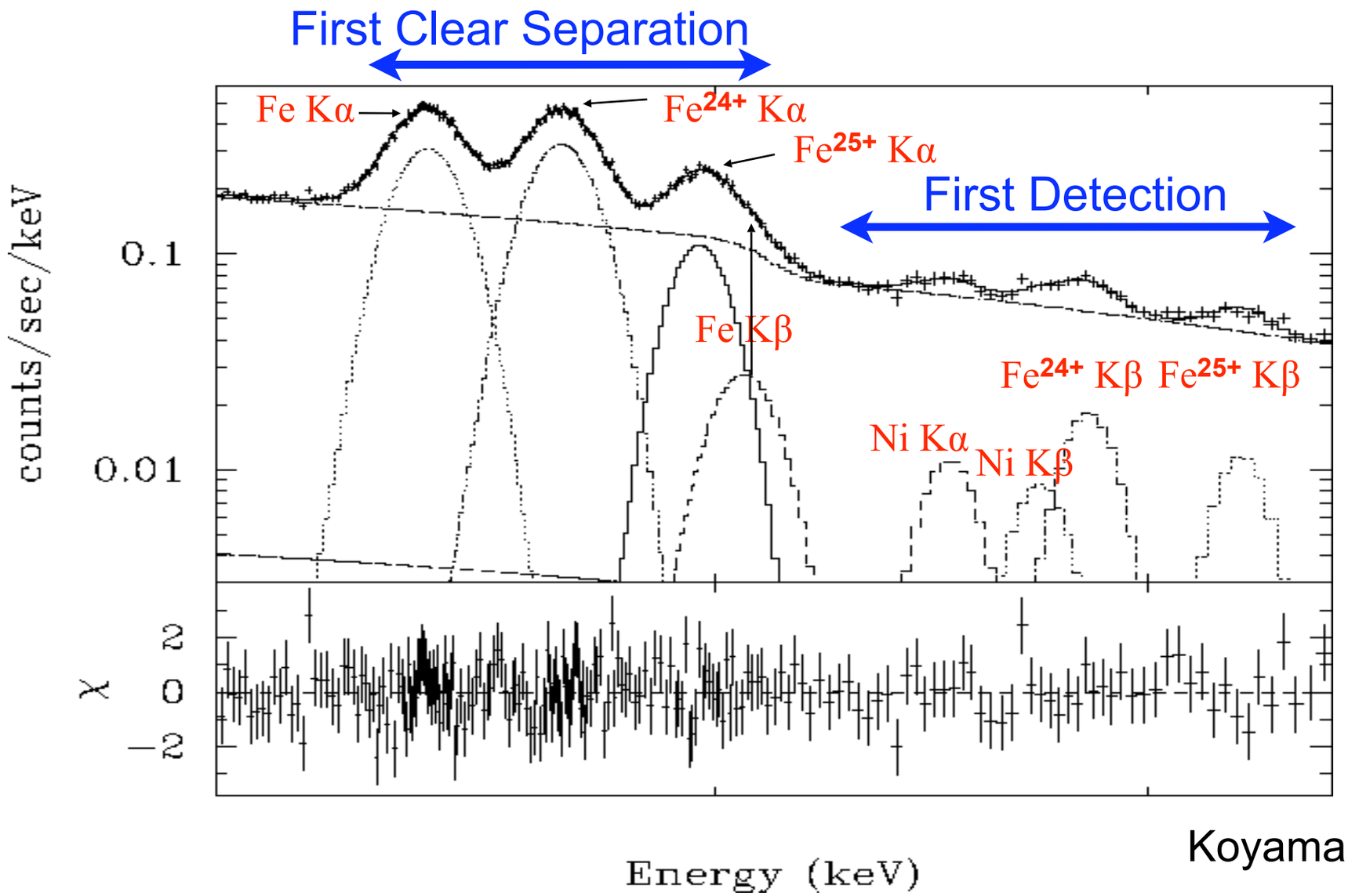
Koyama & the GC team, 2006

Power of Suzaku : Center Energy can be determined with an accuracy of a few eV (systematics ~ 5 eV)



Koyama & the GC team, 2006

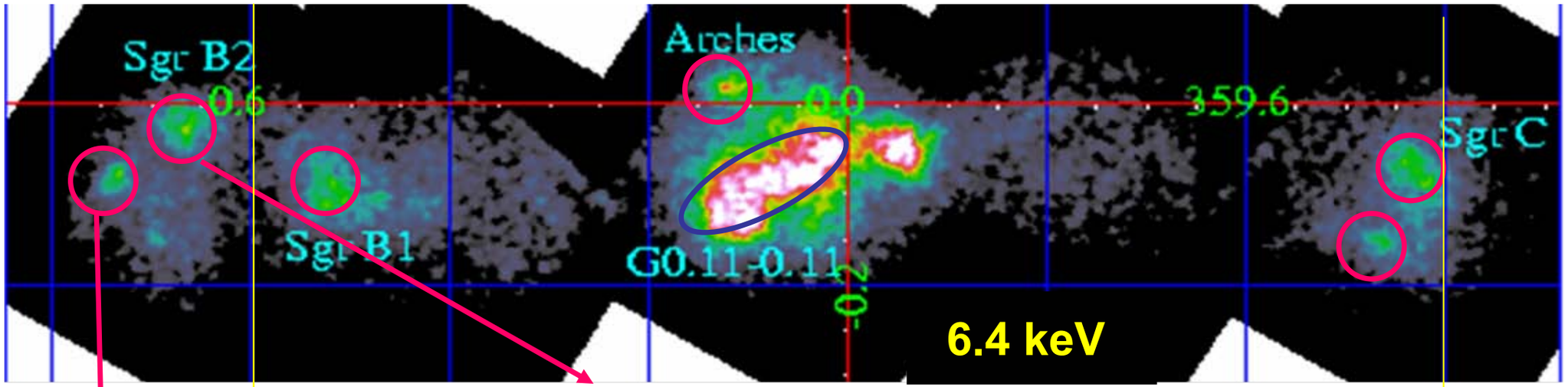
Power of Suzaku : Center Energy can be determined with an accuracy of a few eV (systematics ~ 5 eV)

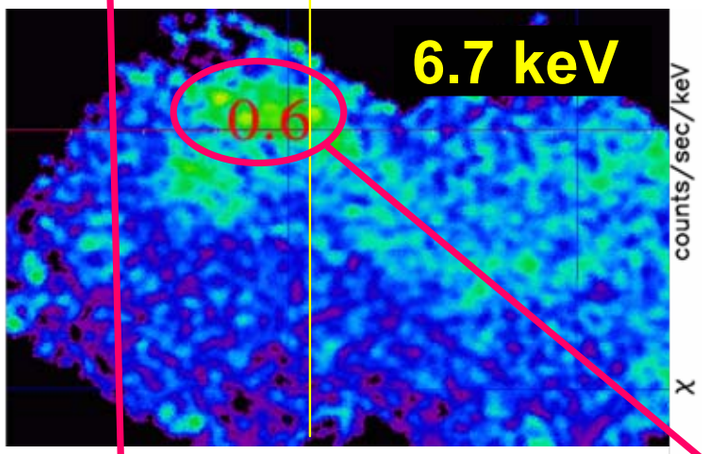


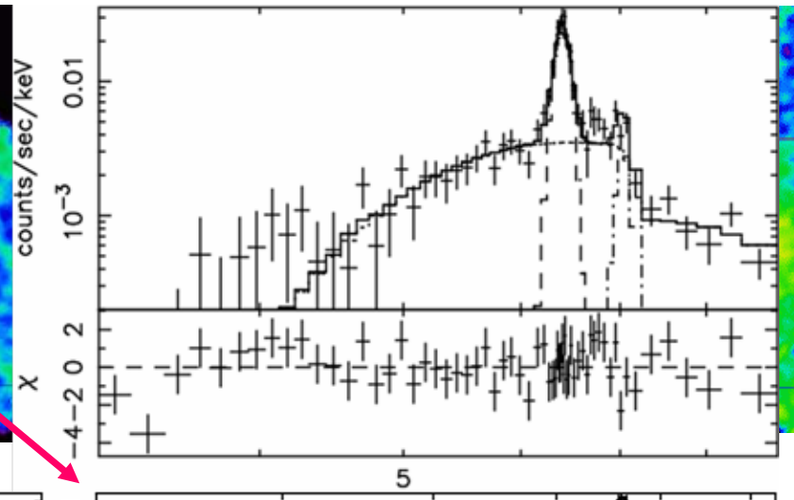
Koyama & the GC team, 2006

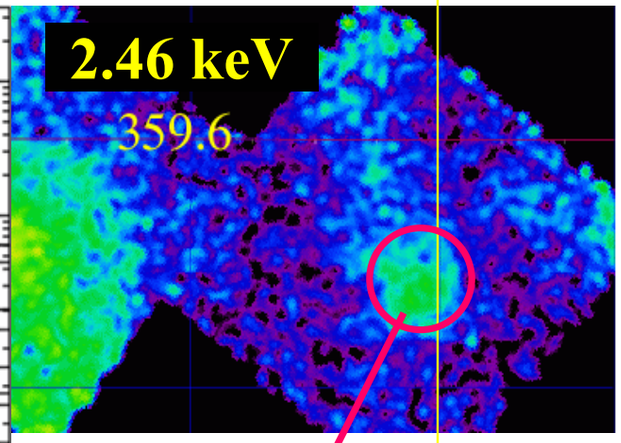
He-like Fe Kα =6679 (+1.3-0.9) eV:
Close to 6685eV, expected from Collisional excitation rather than Electron capture (6666 eV)
Similar values of ~6.5 keV are derived for
Ionization Temperature (He-/H-like Kα)
and Electron Temperature (Kβ/Kα)

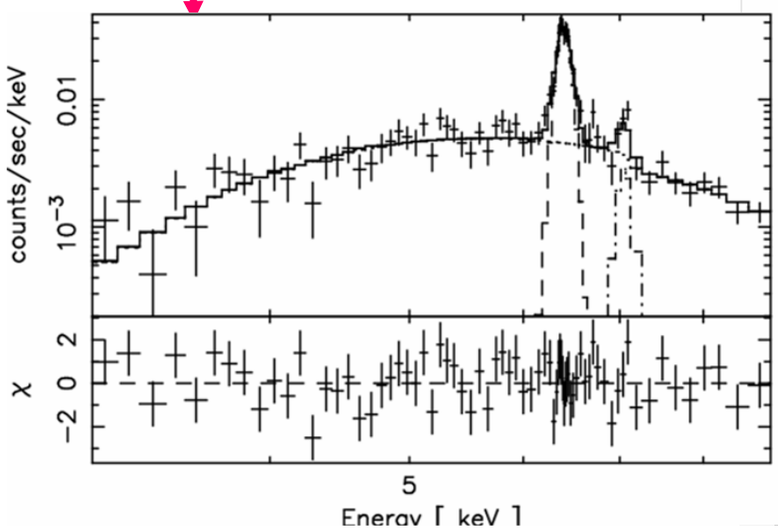
New Sources in the Sgr B & C regions from “Map of Line X-rays”

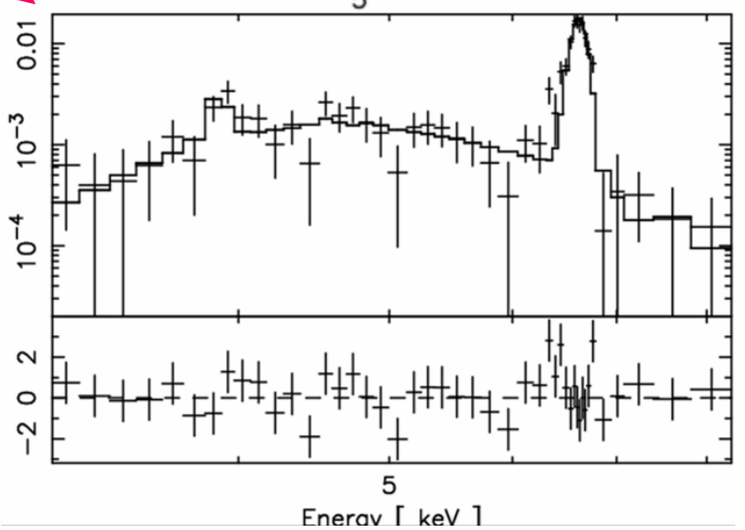


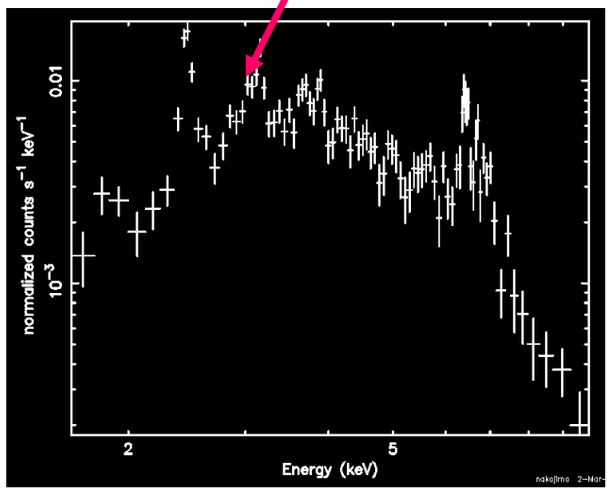










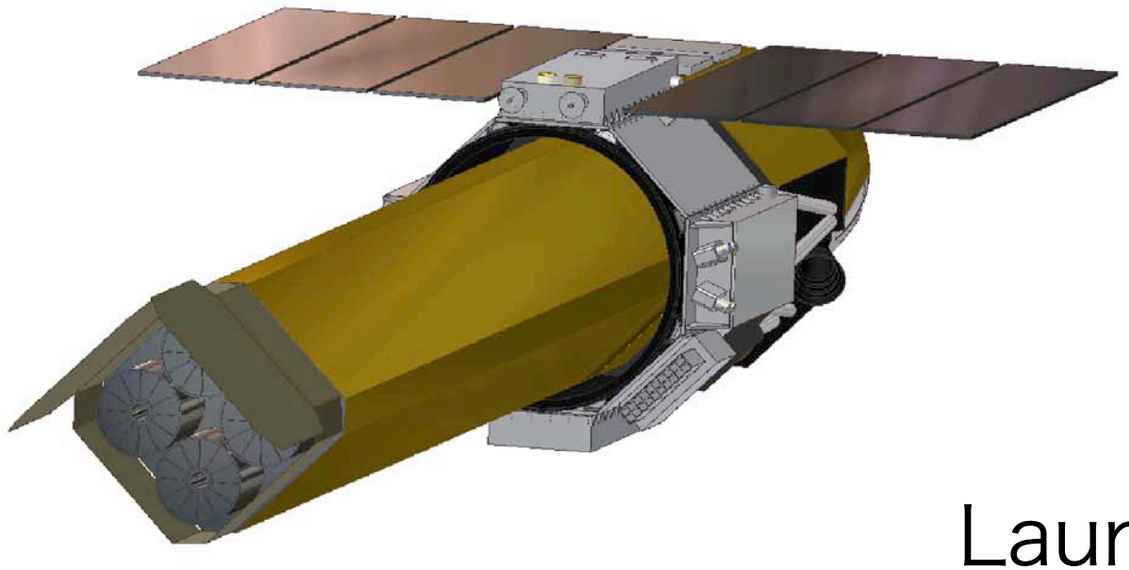


Koyama & the GC team, 2006

Summary

- Power of Suzaku
  - Low background and High Resolution of the XIS
  - Low background and Small FOV of the HXD/PIN
- Especially suitable for the study of diffuse sources.
- Suzaku has already discovered 6 new sources in the Sgr B & C regions.
- With Suzaku, we will be able to study the origin of the non-thermal emission and its connection with thermal plasma

NeXT Mission

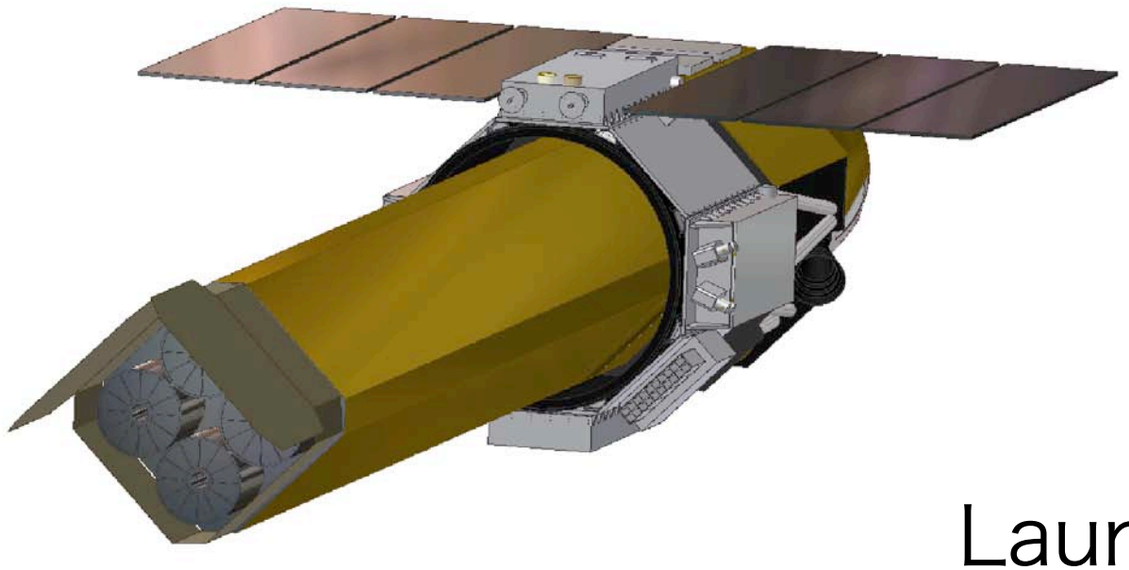


Based on the proposal 2005-Oct,
"Completion of pre-phase A" approved
Waiting for the transition to Phase A/B

Launch 2012-2013

inclination 31deg
altitude 550 km
weight 1.7t

NeXT Mission



Based on the proposal 2005-Oct,
"Completion of pre-phase A" approved
Waiting for the transition to Phase A/B

Launch 2012-2013

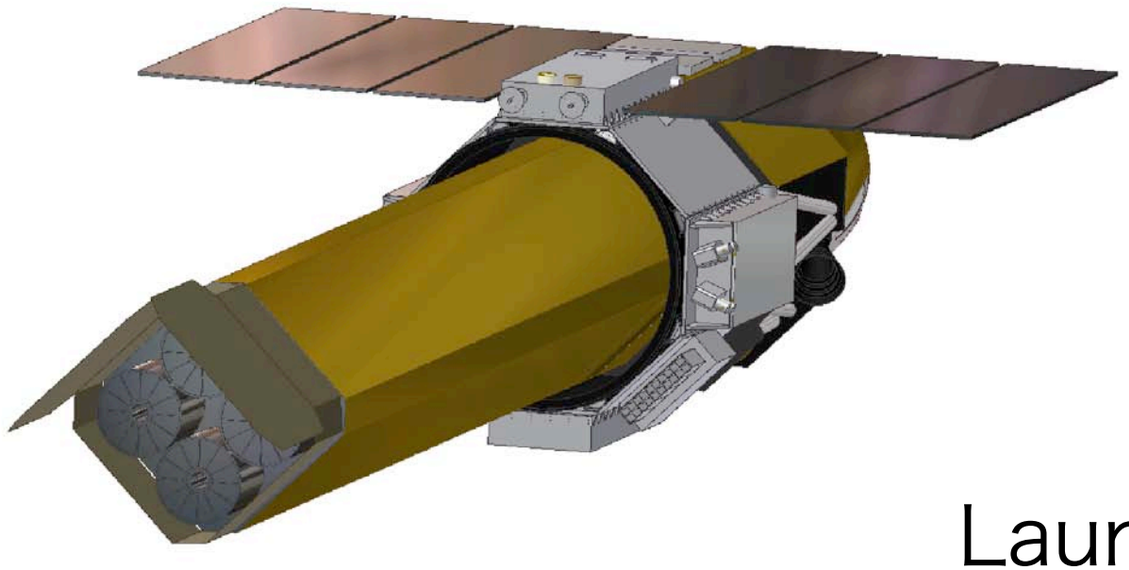
inclination 31deg

altitude 550 km

weight 1.7t

- First Hard X-ray Imaging Observation (10 keV - 80 keV)
- Wide band observation (0.3 keV - 300 keV)
- High Resolution X-ray observation of Diffuse Sources

NeXT Mission

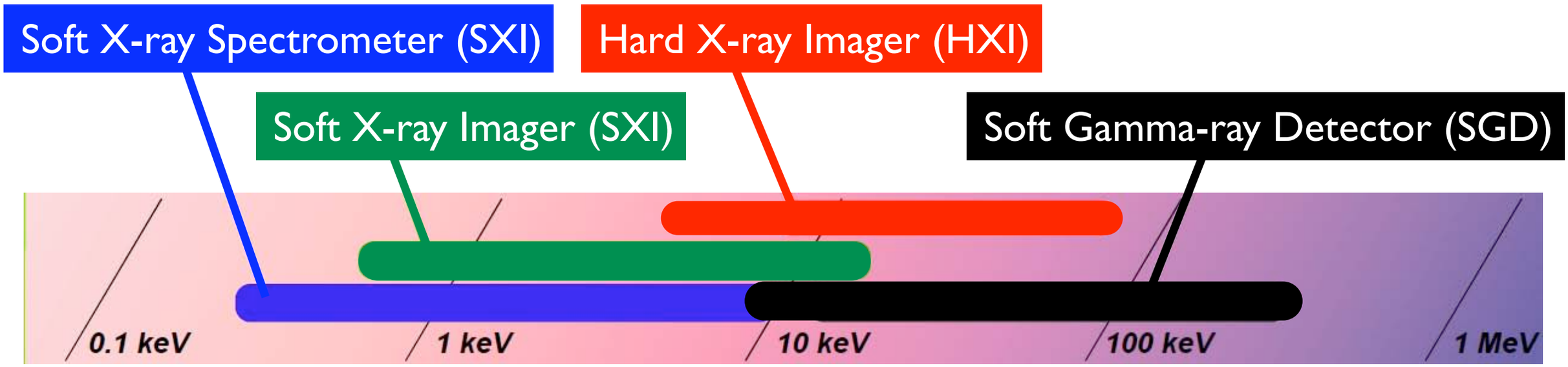


Based on the proposal 2005-Oct,
"Completion of pre-phase A" approved
Waiting for the transition to Phase A/B

Launch 2012-2013

inclination 31deg
altitude 550 km
weight 1.7t

- First Hard X-ray Imaging Observation (10 keV - 80 keV)
- Wide band observation (0.3 keV - 300 keV)
- High Resolution X-ray observation of Diffuse Sources



A

サンシェード

X-ray Te;escope

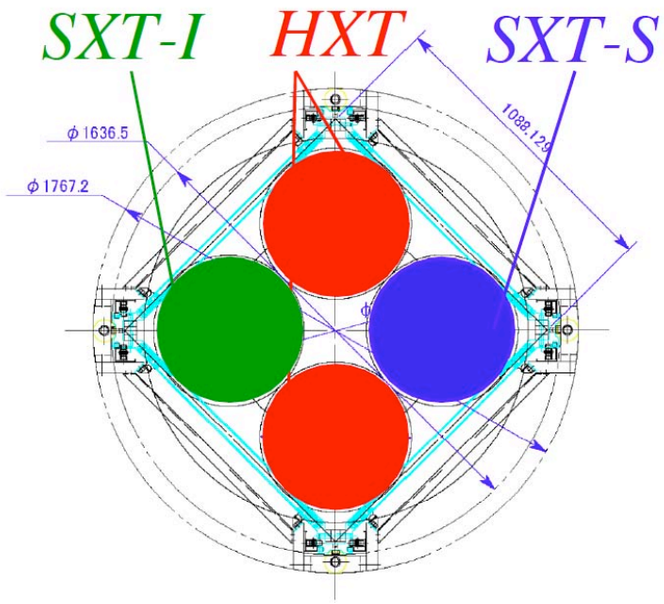
(SXT)

(HXT)

EOB

Focal Length
12m

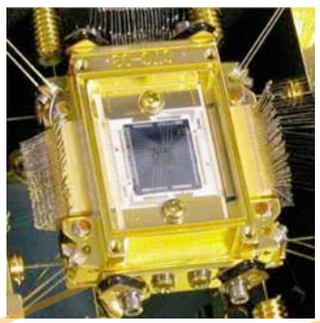
Focal Length
9m

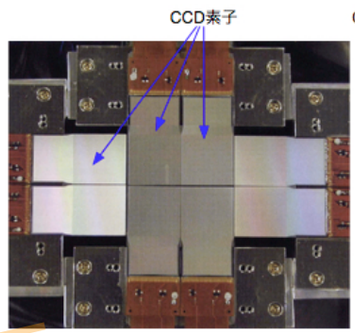


MLI

(SXS)

(SXI)





ラジエータ

ＳＧＤ－Ｓ

光

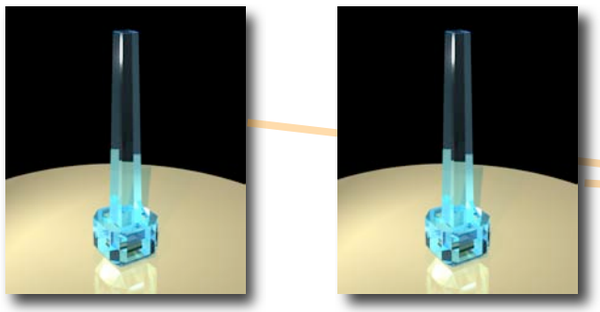
ラジエータ

(SGD)

ＭＬＩ

ＳＸＳ－Ｓ

(HXI)

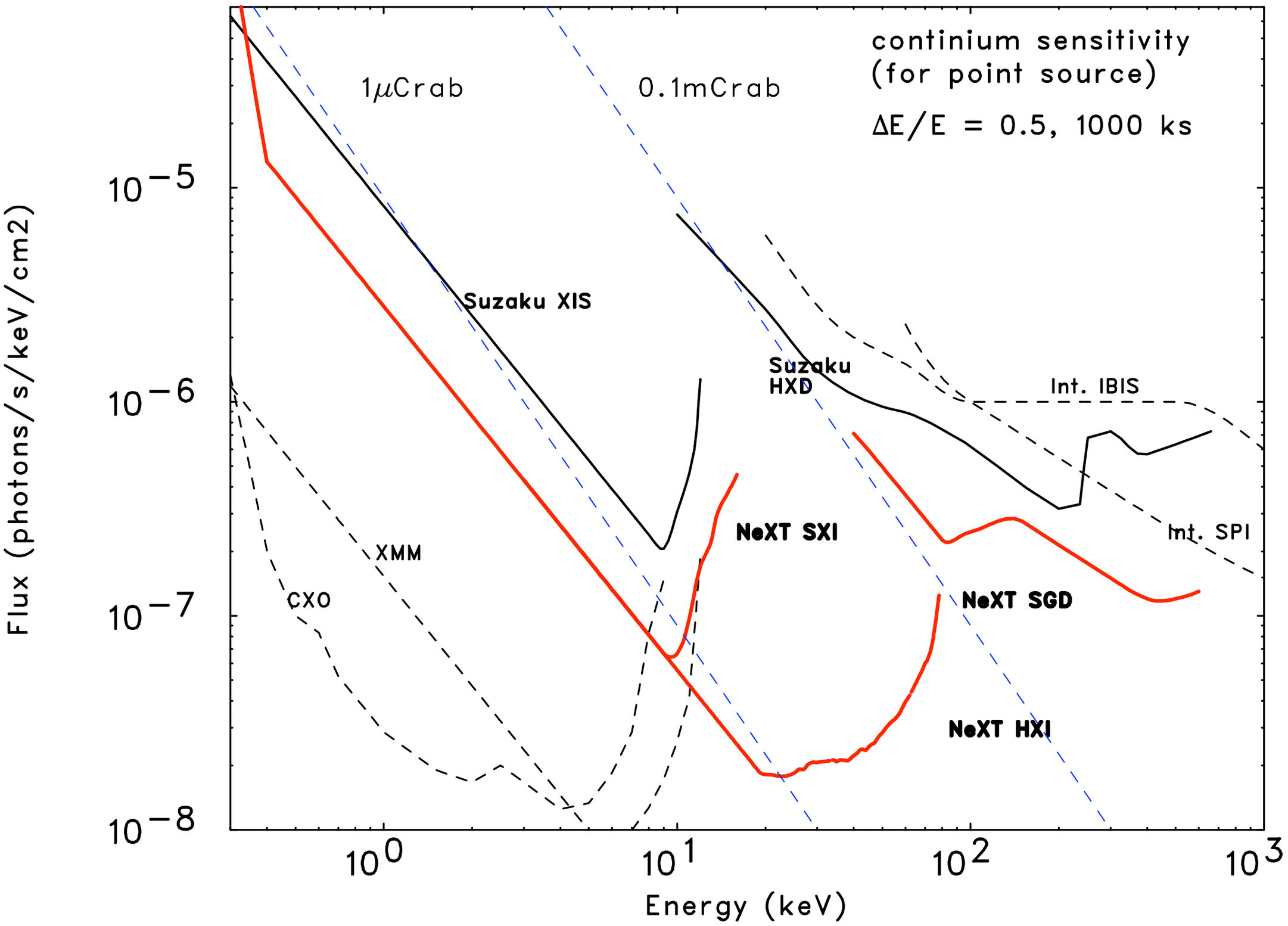


HXI-S

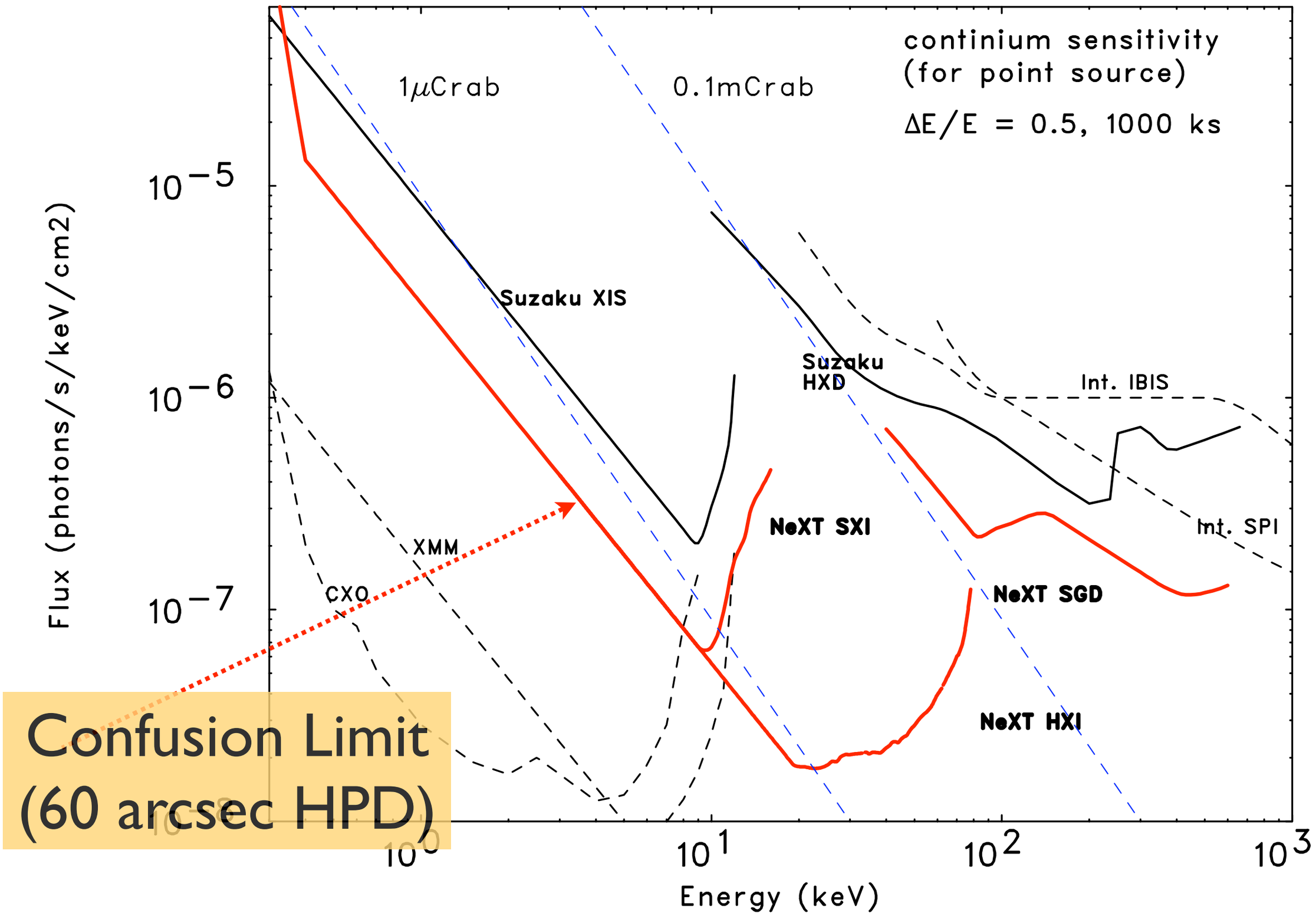
ラジエータ

サンシェード

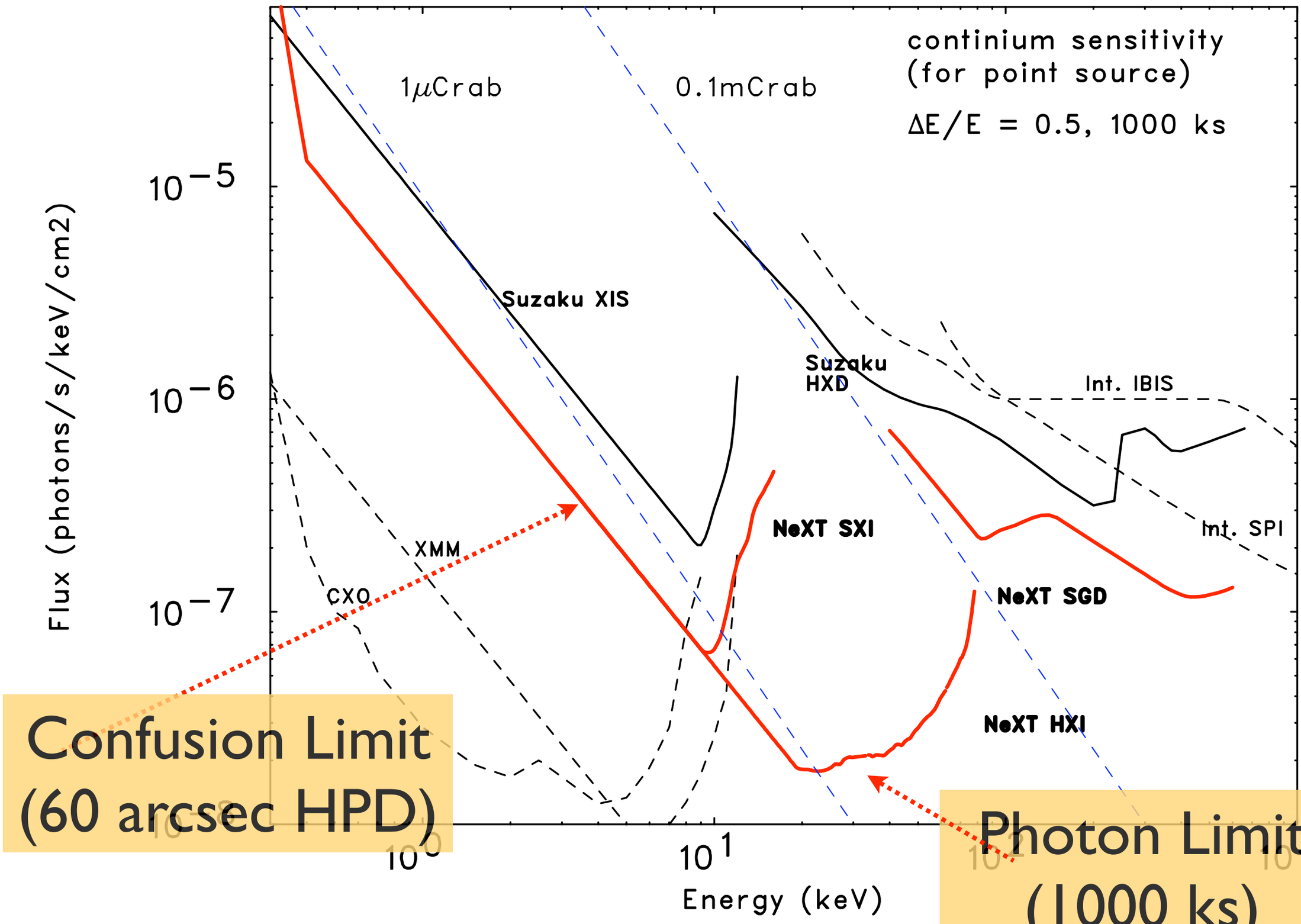
High Sensitivity from 0.3-300 keV



High Sensitivity from 0.3-300 keV



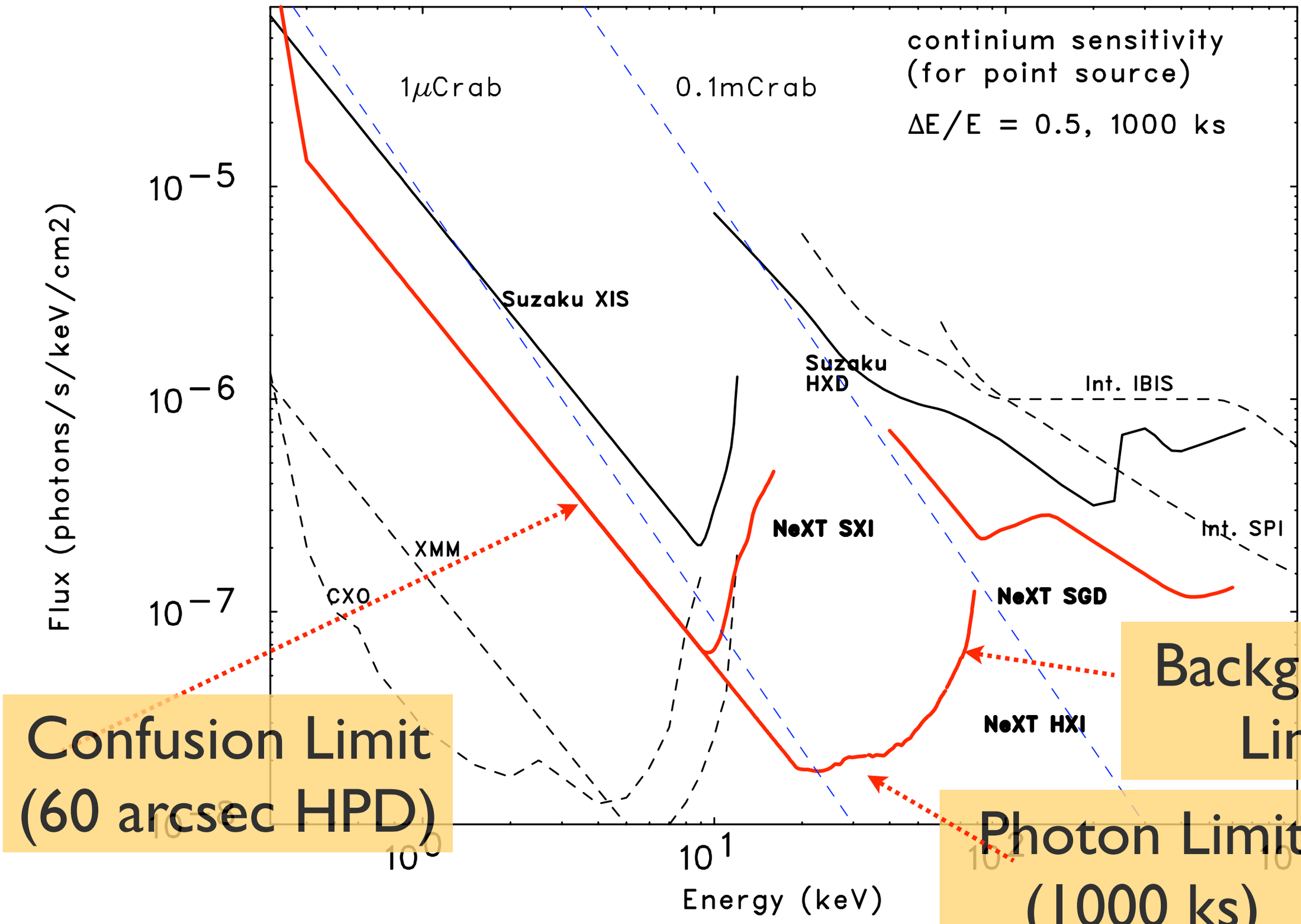
High Sensitivity from 0.3-300 keV



Confusion Limit (60 arcsec HPD)

Photon Limit (1000 ks)

High Sensitivity from 0.3-300 keV

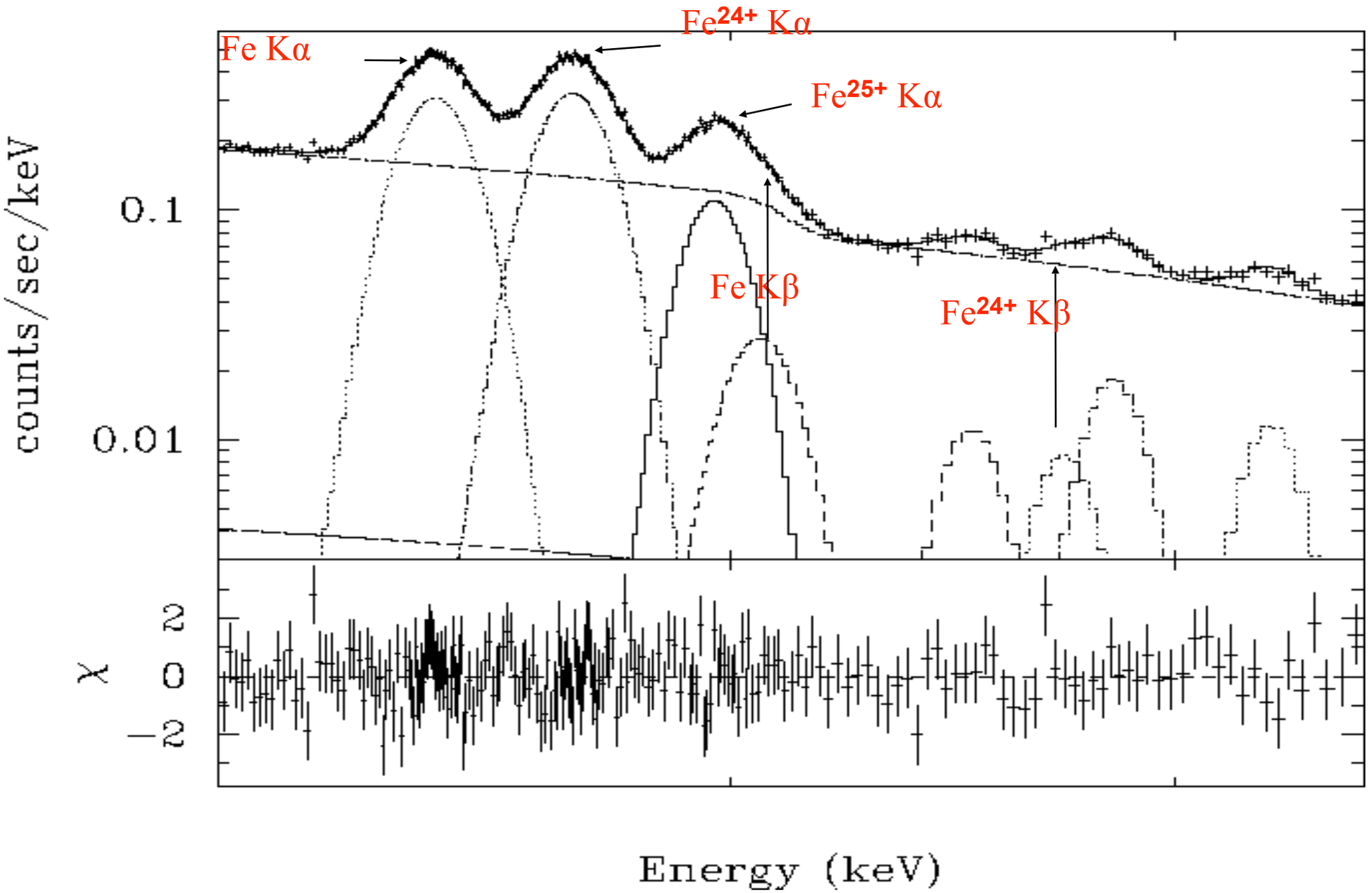


Confusion Limit (60 arcsec HPD)

Background Limit

Photon Limit (1000 ks)

Center Energy can be determined with an accuracy of a few eV (systematics ~ 5 eV)



Center Energy can be determined with an accuracy of a few eV (systematics ~ 5 eV)

Center Energy (eV)	Identification Line	Identification Energy (eV)	Width (eV)	Intensity (photons s^{-1} cm^{-2})
$1858.5^{+0.4}_{-1.2}$	Si XIII Kα	1839.4—1864.9	16	$2.56^{+0.06}_{-0.07} \times 10^{-3}$
$2004.4^{+1.7}_{-2.2}$	Si XIV Kα	2005.5	24	$9.13^{+0.20}_{-0.38} \times 10^{-4}$
$2182.1^{+2.5}_{-4.2}$	Si XIII Kβ	2182.6	23	$3.31^{+0.25}_{-0.08} \times 10^{-4}$
$2301.0^{+3.5}_{-4.2}$	S I† Kα		0 (fixed)	$1.44^{+0.07}_{-0.20} \times 10^{-5}$
$2380.7^{+2.5}_{-2.0}$	Si XIV Kβ	2376.3	0 (fixed)	$2.23^{+0.10}_{-0.17} \times 10^{-4}$
$2459.1^{+0.7}_{-0.6}$	S XV Kα	2430.3—2460.5	20	$1.25^{+0.02}_{-0.02} \times 10^{-3}$
$2622.4^{+3.0}_{-2.7}$	S XVI Kα	2621.6	31	$2.15^{+0.06}_{-0.13} \times 10^{-4}$
$2870.9^{+4.1}_{-6.7}$	S XV Kβ	2870	0 (fixed	$7.96^{+0.40}_{-0.94} \times 10^{-5}$
$2971.1^{+7.3}_{-4.9}$	Ar I† Kα		0 (fixed)	$4.32^{+0.72}_{-0.42} \times 10^{-5}$
$3130.2^{+2.1}_{-1.4}$	Ar XVII Kα	3104.0—3139.5	33	$2.48^{+0.05}_{-0.05} \times 10^{-4}$
$3315.6^{+9.3}_{-6.3}$	Ar XVIII Kα	3321.3	0 (fixed)	$3.17^{+0.40}_{-0.48} \times 10^{-5}$
3696.8^{+15}_{-13}	Ar XVII Kβ	3690	0 (fixed)	$1.83^{+0.29}_{-0.42} \times 10^{-5}$
$3897.4^{+3.8}_{-3.5}$	Ca XIX Kα	3861.1—3902.2	14	$5.96^{+0.43}_{-0.28} \times 10^{-5}$
4112.9^{+13}_{-12}	Ca XX Kα	4104.9	0 (fixed)	$1.37^{+0.34}_{-0.28} \times 10^{-5}$
$6408.8^{+0.8}_{-1.5}$	Fe I† Kα		36	$2.29^{+0.04}_{-0.03} \times 10^{-4}$
$6678.7^{+1.3}_{-0.9}$	Fe XXV Kα	6636.4—6700.2	38	$2.57^{+0.03}_{-0.03} \times 10^{-4}$
$6969.5^{+2.8}_{-2.1}$	Fe XXVI Kα	6965.7	17	$8.37^{+0.28}_{-0.27} \times 10^{-5}$
7765^{+44}_{-23}	Ni XXVII Kα	7735—7805	0 (fixed)	$9.87^{+3.11}_{-2.86} \times 10^{-6}$
7855[a]	Fe XXV Kβ	7881	0 (fixed)	$2.67^{+0.36}_{-0.26} \times 10^{-5}$
Intrinsic line				
$5899.6^{+1.7}_{-0.4}$	Mn I Kα	5895.1	34	
$6491.1^{+2.5}_{-1.6}$	Mn I Kβ	6490.4	37	
$7486.6^{+4.5}_{-3.2}$	Ni I Kα	7472.4	25	

The errors are at 90% confidence level.
† or low ionization state
[a] fixed to Fe XXVI Kα line energy +90

Ionization Temperature (He-/H-like Kα) and Electron Temperature (Kβ/Kα)