Suzaku Observations of Hard X-ray Emission from Galaxy Clusters

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“The Suzaku X-ray Universe”
San Diego, 2007/12/10-12

Contents

Particle acceleration in galaxy clusters

Clusters of galaxies
are still evolving

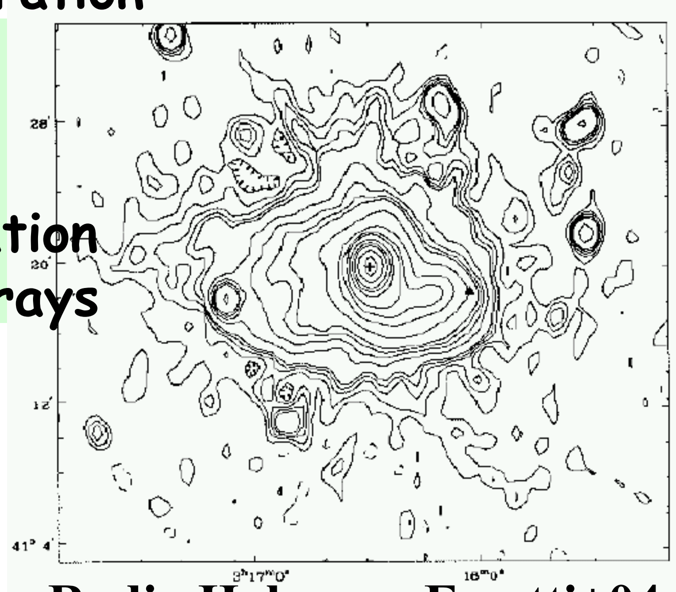
Merger, accretion of surrounding medium
Co-evolution with the cD galaxy and its massive black hole

Evolution → release of gravitational energy

Thernal energy (heating of ICM)
Nonthermal energy
Bulk motion of ICM
→ Particle acceleration

Entropy is small
Preserve the past information
Nonthermal pressure
Impacts on cluster mass estimation
Possible source of extragal. Cosmic-rays

Radio synchrotron emission
High energy electrons surely
exist in galacy clusers.



Radio Halo Feretti+04

Cluster Merger, Jets from AGNs

Bulk motion of ICM

Shock wave

and/or

Turbulent magnetic field

↓

Some accleration

Turbulence accleration (Fermi 2nd)

Shock acceleration (Fermi 1st) as SNR

High energy electrons

Short life time

($<10^{7-8}$year)

Decay soon

High energy protons

Long life time

↓

Interaction with ICM

Secondary electrons

shine for a long time

Possible acceleration cite of high energy particles

Large scale

Store accelerated particles (10$^{13-17}$eV particles can stay)

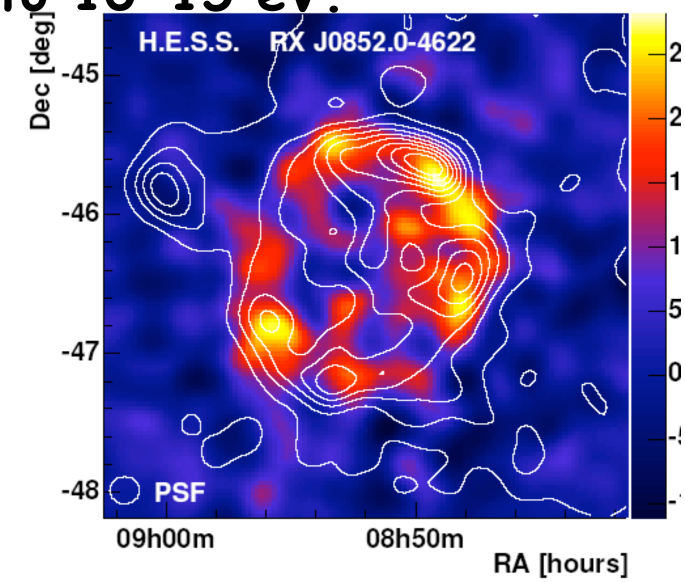
Large maximum energy of acceleration (up to 10^{18}eV)

Candidate of source of extragalctic cosmic-ray

Long life time

Slow acceleration by turbulence can grow up the particle energy up to 10^15 eV.

Observed shock wave in CL is not so strong unlike SNR, weak slow acceleration is possibly important.



Hard X-ray emission

Relativistic electrons with $\gamma = 10^4$

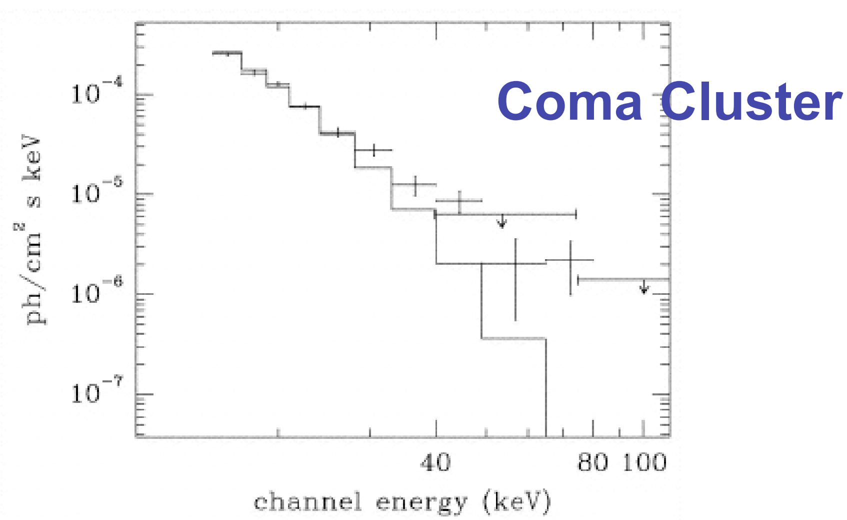
Synchrotron — Radio (GHz) for 1uG B

Inverse Compton of CMB — ~100keV X-ray

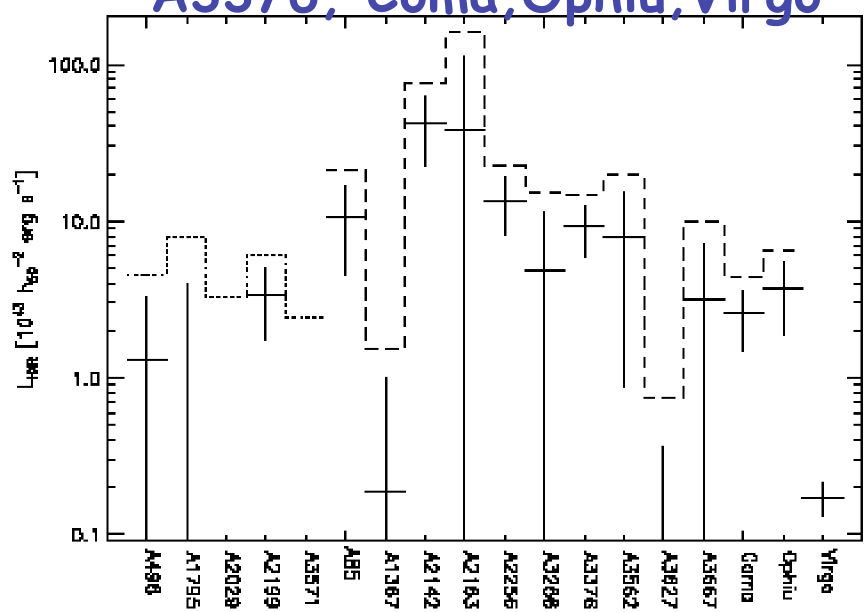
X-ray is important to constrain the energy of particles and B.

BeppoSAX/PDS have detected it from 7 clusters of galaxies (@2 σ level, Nevalainen et al. 2004)

A2142, A2199, A2256, A3376, Coma, Ophiu, Virgo



Fusco-Femiano+99 (BeppoSAX)



Hard X-ray is also reported with RXTE from several clusters.

(Rephaeli+99, A2256; +03, A2163: +06)

In some galaxy groups, Hard X-ray is also found with ASCA (Fukazawa+01, Nakazawa+06)

Problems:

Significance is still very low
(BGD subtraction is crucial)

Distinction from AGN is difficult

Spatial distribution is unkown

Further studies in hard X-ray is needed.

Expected development with Suzaku

The lowest baclground of HXD

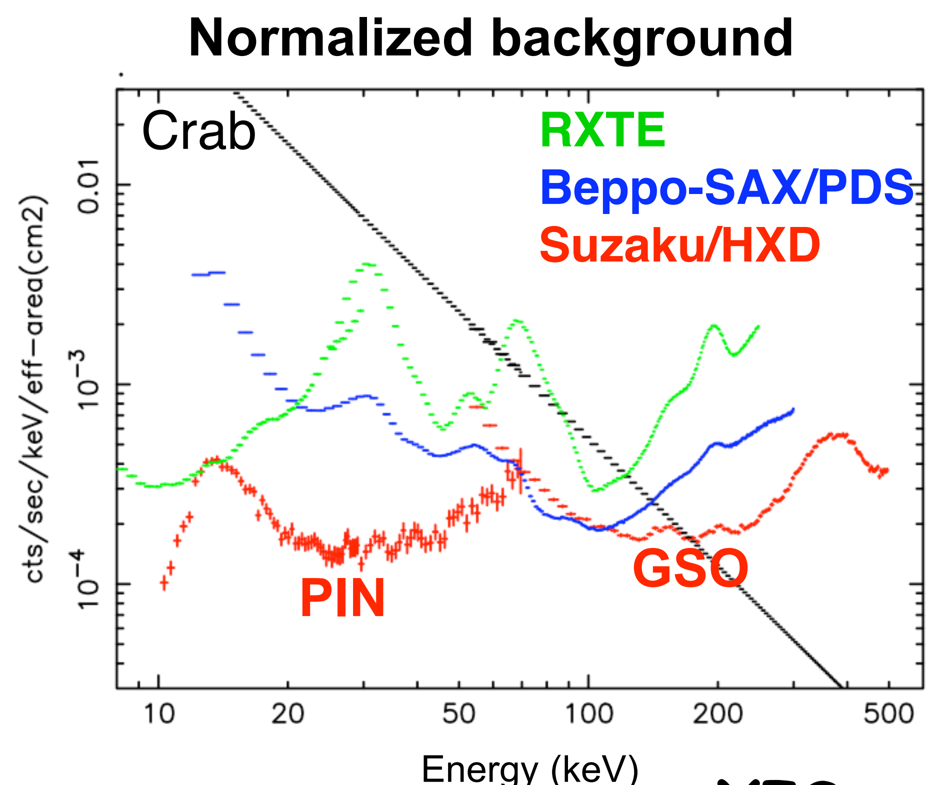
- Verification of hard X-rays observed with BeppoSAX
- Search for new hard X-ray emitting galaxy clusters

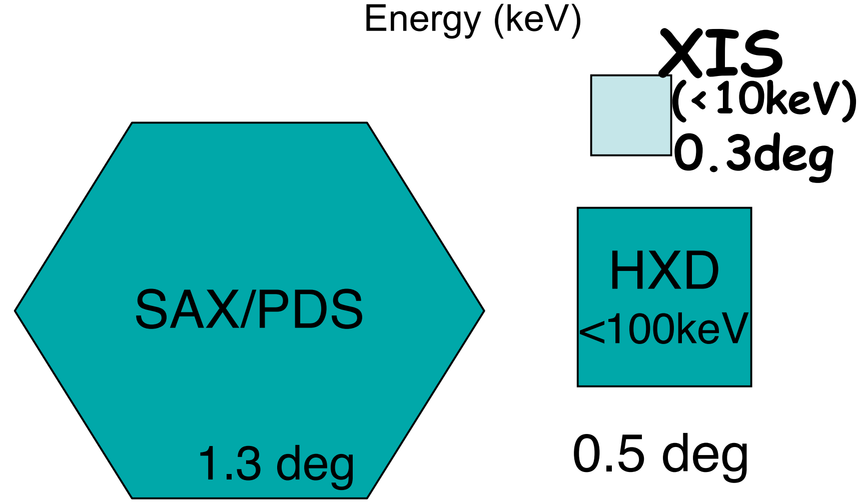
Narrow FOV of HXD

- Confirming the distribution of Hard X-ray emission
  by multi-pointing observation
  (Low contamination of AGN or other point source)

XIS

Give a tight upperlimit
on the narrow region
with good S/N for low-kT CL.
Image, Fe-K are also useful

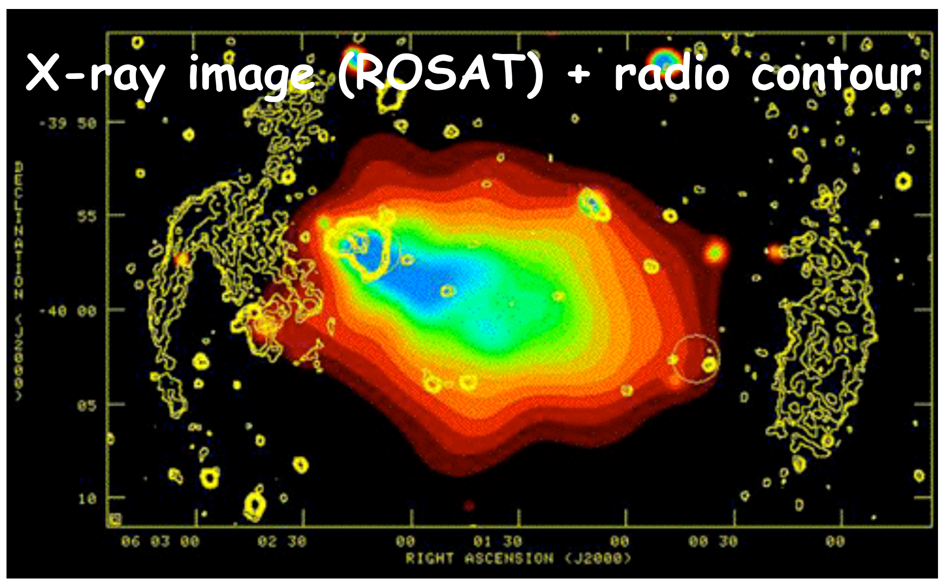




Abell 3376 : most promising galaxy cluster for HXD-PIN

Kawano, Fukazawa, Nakazawa+07 (z=0.046)

- Hard X-ray emission was detected with BeppoSAX
  (Nevalainen et al. 2004) 2.7σ highest
- Moderate ICM temperature (kT = 4keV)
  Efficient observation in most sensitive energy band of PIN
  (Nonthermal will appear above 10keV.)
- Large radio robe each side of X-ray peak Merging cluster



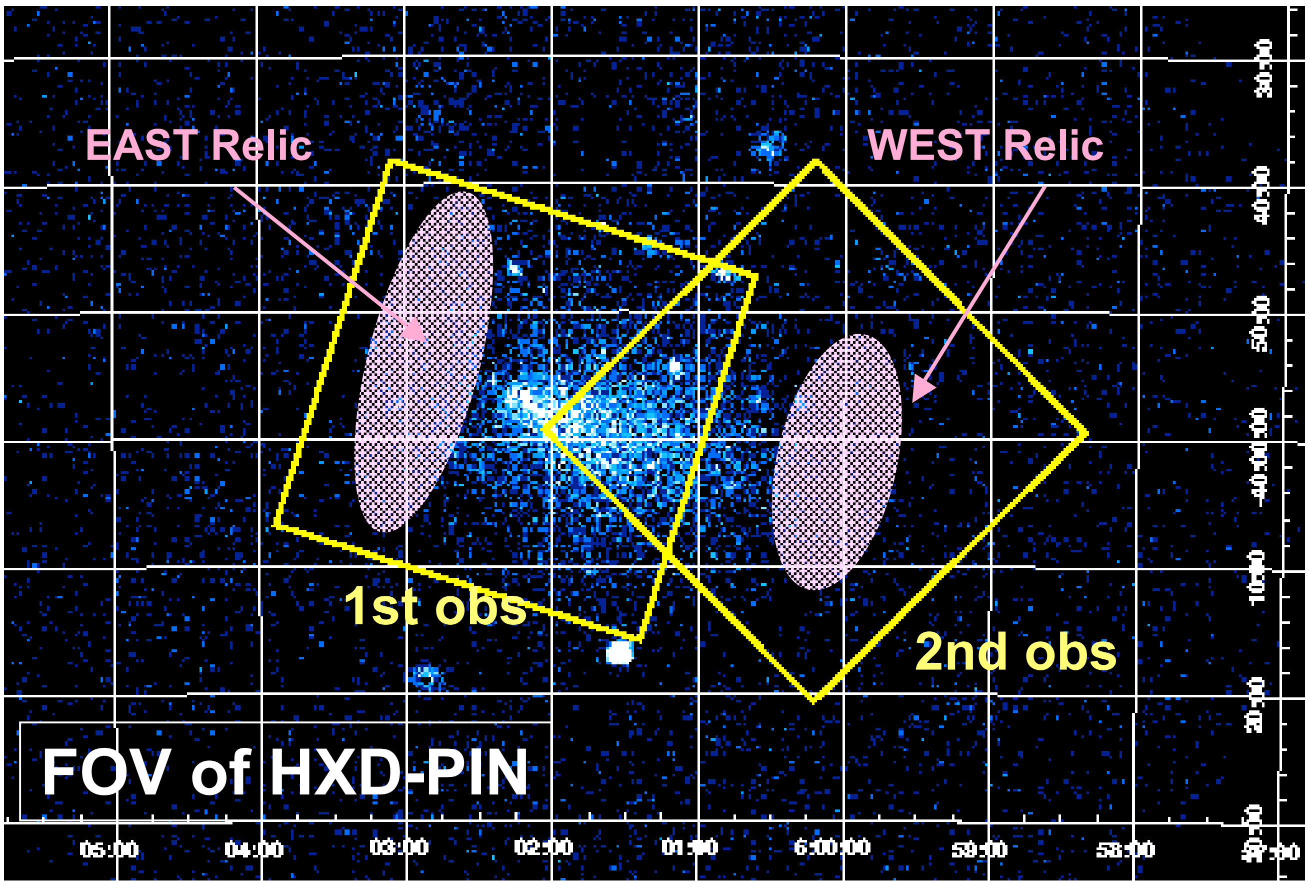
2Mpc

Observation with Suzaku

Abell 3376 was observed on 2005/10/06 and 2005/11/07.

First obs. : X-ray peak and East Relic (86 ksec)

Second obs. : West Relic (97 ksec)



Analysis of HXD-PIN data

Non X-ray Background

Use the public PIN background model, together with our own BGD model.

Comparing with the earth data,

BGD systematics is 6% in 3σ level.

Thermel emission

Almost negligible in the PIN band, thanks to low kT

Point source contribution

Estimating from the ROSAT PSPC catalog.

Also negligible

CXB

Past observations (Kirsch+05)

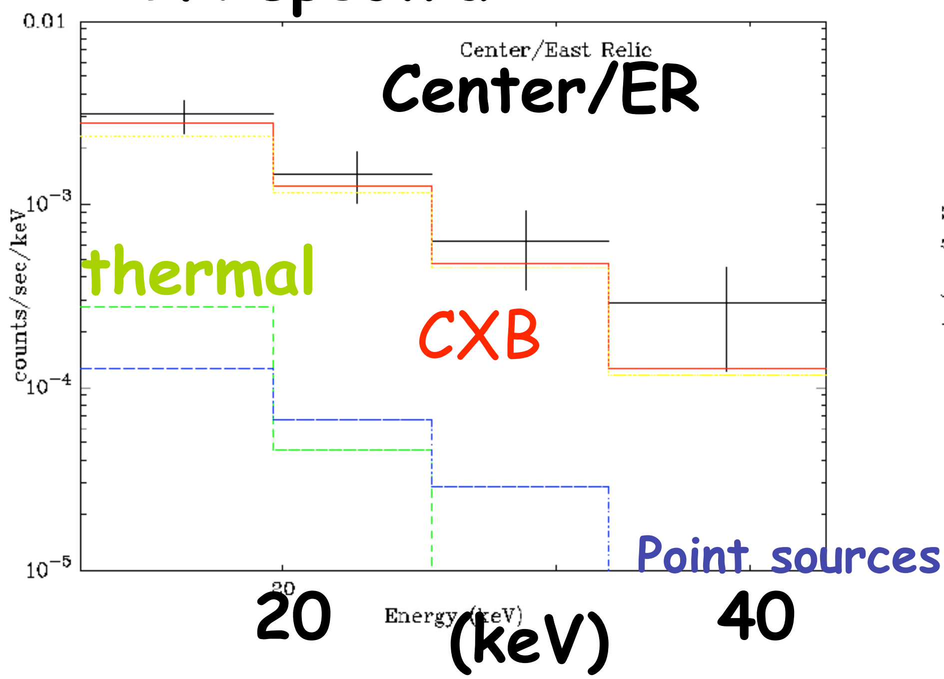
Derive 3σ upper limit in unit of erg/s/cm2 (15-50keV)

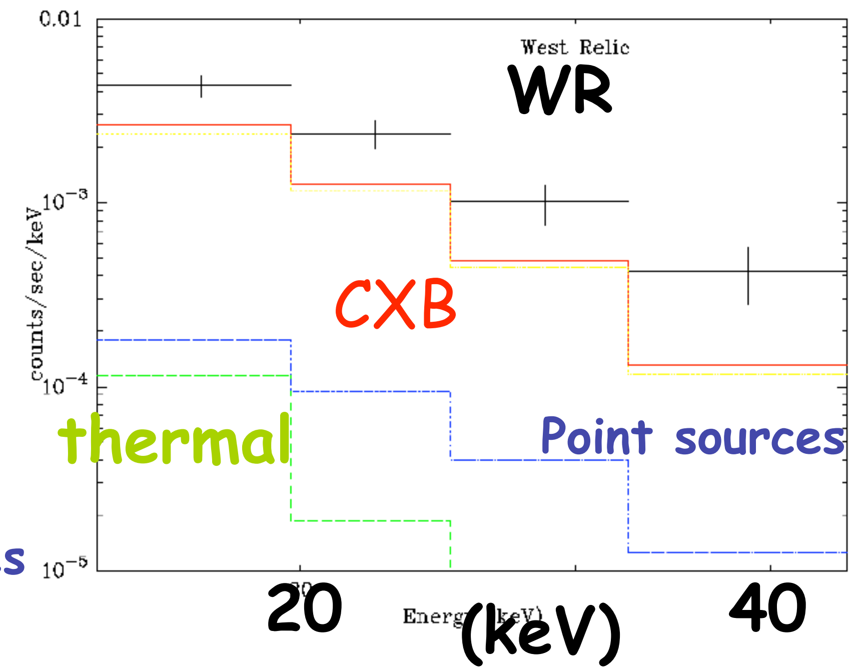
	stat sys	
ER	(0.0±2.4±5.5)E-12	< 7.9E-12
WR	(7.2±2.4±5.5)E-12	< 1.5E-11

almost dominated by BGD systematics

(c.f. BeppoSAX PDS 3σ (8.0±8.9)E-12)

PIN spectra

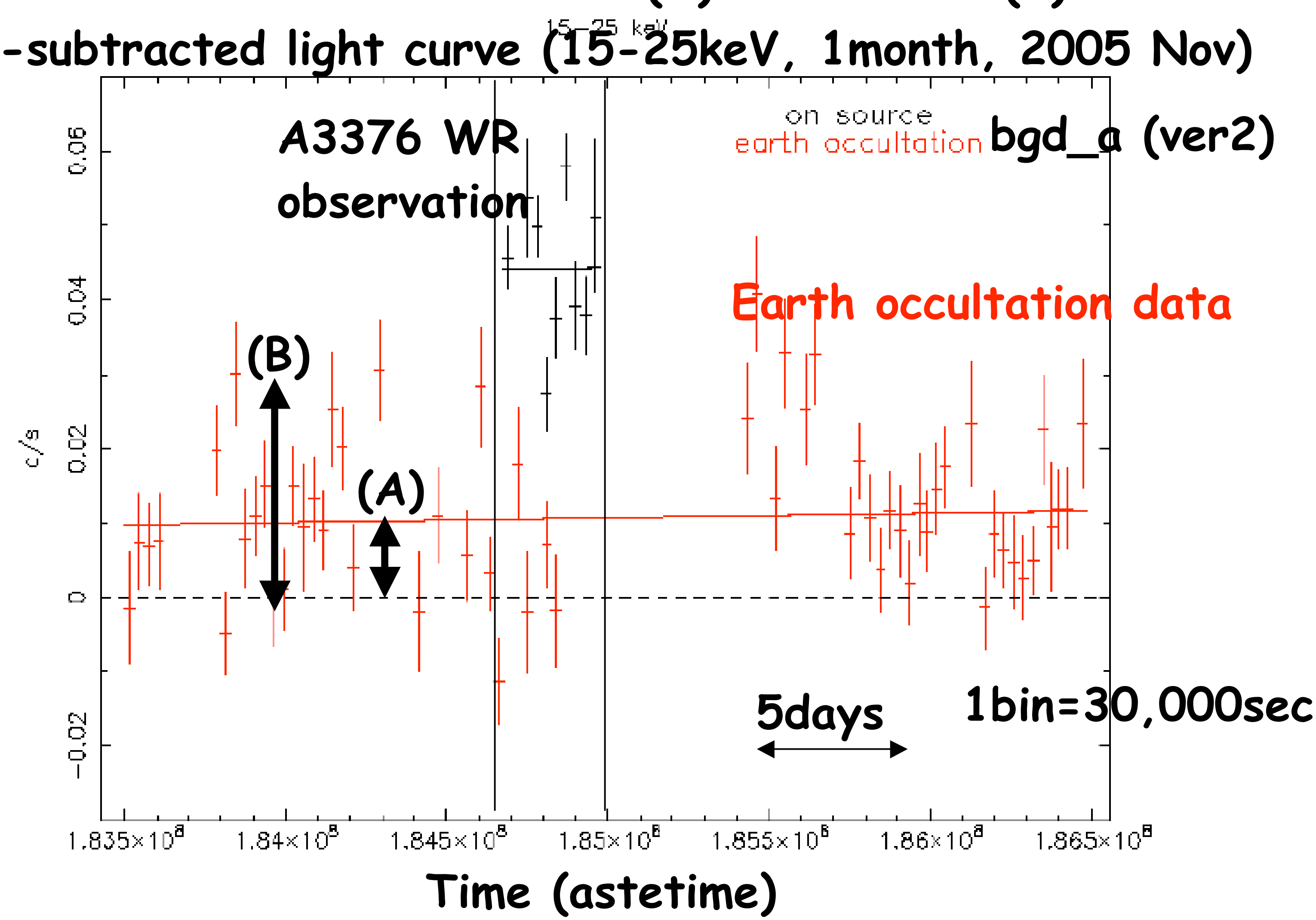




PIN-BGD systematics two components

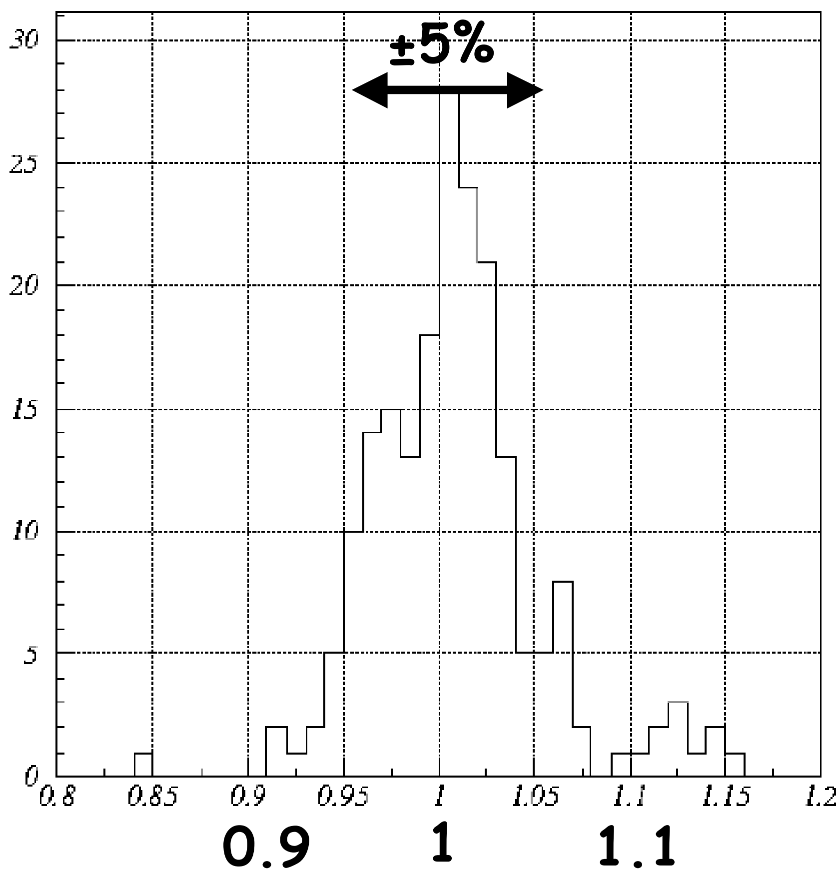
Residual with a time scale of long period and subday (A) (B)

BGD-subtracted light curve (15-25keV, 1month, 2005 Nov)



Error of (A) can be corrected, using earth data before/after the observation.

Earth data / BGD model Ratio



Current public BGD

90% sys. err 5%

undertainty

(A)long period

(B)sub-day

Corretion of (A) will improve.

HXD team is now preparing
a finer PIN BGD.

Both (A) and (B) will become small.

Preliminarily applied to A3376 WR

Upper limit becomes 4% (3 σ) of BGD.

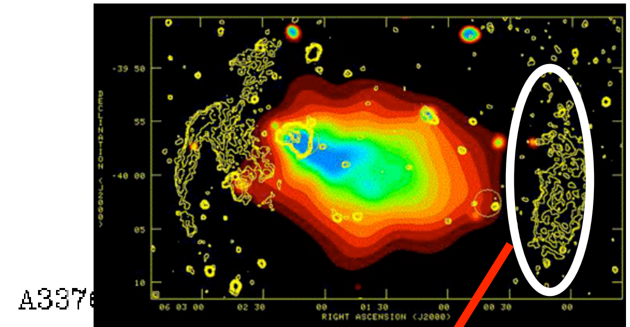
(or 2%=90% err)

90% level: F(PIN)<7E-12 F(SAX)=(8.0±4.5)E-12

Analysis of XIS spectra

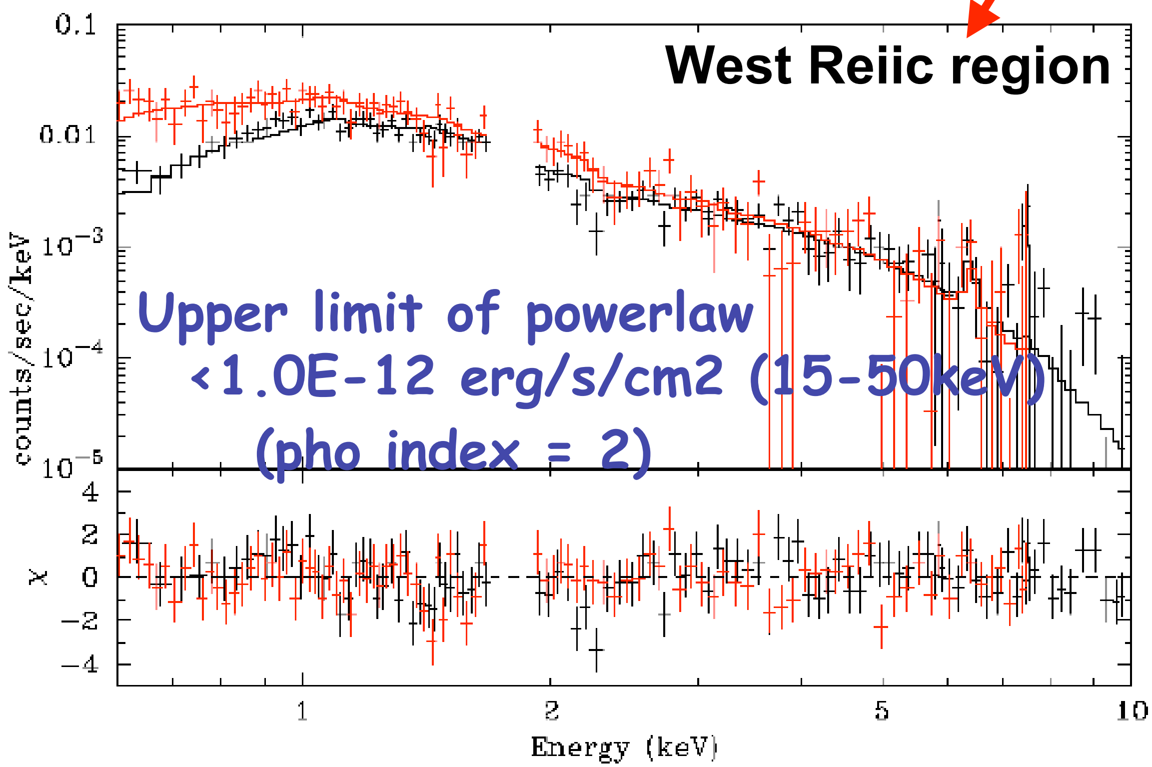
Model : wabs*apec (1kT)

- Temperature : 3.61 +/- 0.33 keV
- Abundance : 0.19 +/- 0.10 solar



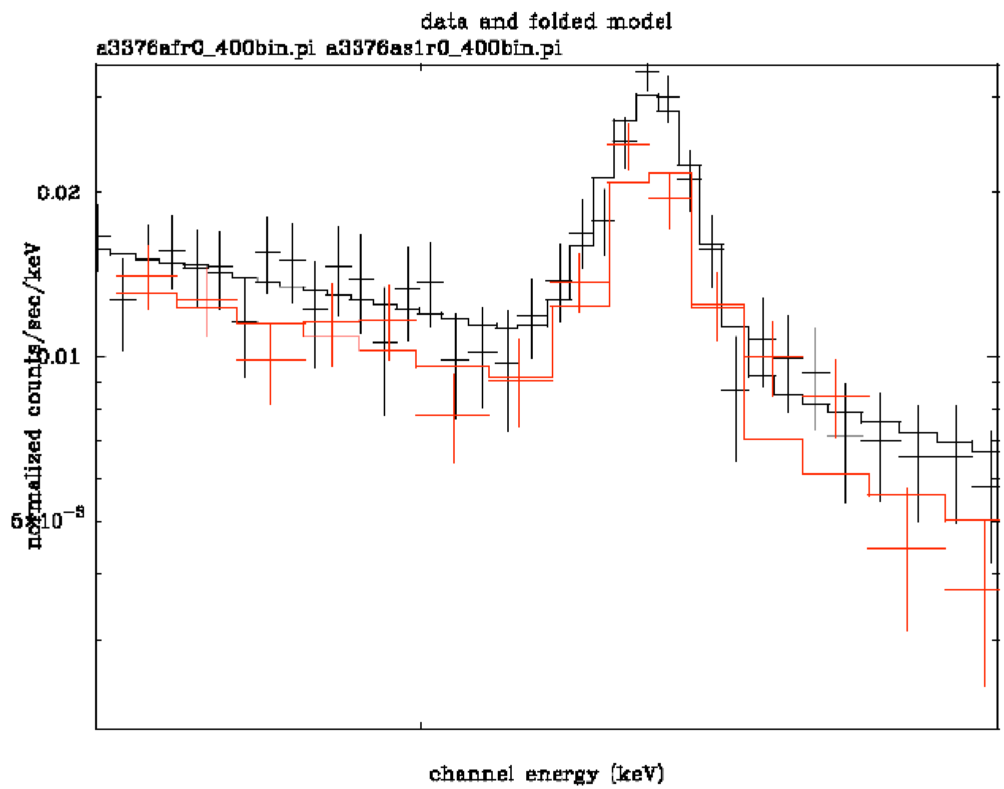
Roughly the same as
the center region
with ASCA and Newton.
(Fukazwa+04,Bagchi+05)

kT=3.98keV



(Upper limit of HXD/BeppoSAX : 1E-11)

Fe-Ka line around the Center/ER

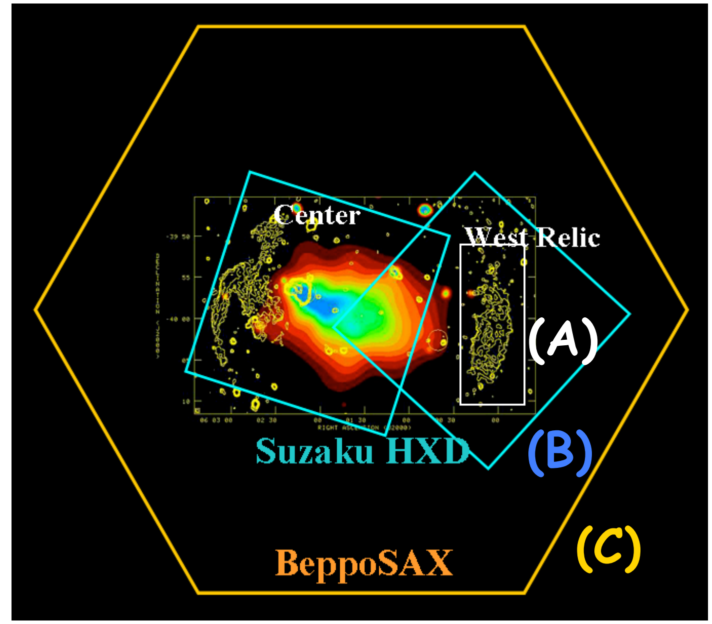


Upper limit of width
<40 eV (2000 km/s)

He/H-like Fe-K ratio gives consistent kT with the continuum.

Consider the inverse Compton of CMB photons

$$L_{IC}/L_{sync} = U_{CMB}/U_B$$



Radio (WR) 0.085Jy (1.4GHz)

(A) Within WR (6' x 20')

XIS F<1.0E-12 B>0.17 uG

U_B>0.001eV/cm^3, Ue<0.2eV/cm^3

U_{ICM} 0.6eV/cm3

(B) HXD PIN(34' x 34') 2.7Mpc-Cubic region

PIN F<1.5E-11 Ue<0.2eV/cm^3

U_{ICM} 0.6eV/cm3

(C) BeppoSAX(1.3deg^2) F=8.9E-12

Ue=0.02eV/cm3

U_{ICM}~0.2eV/cm3

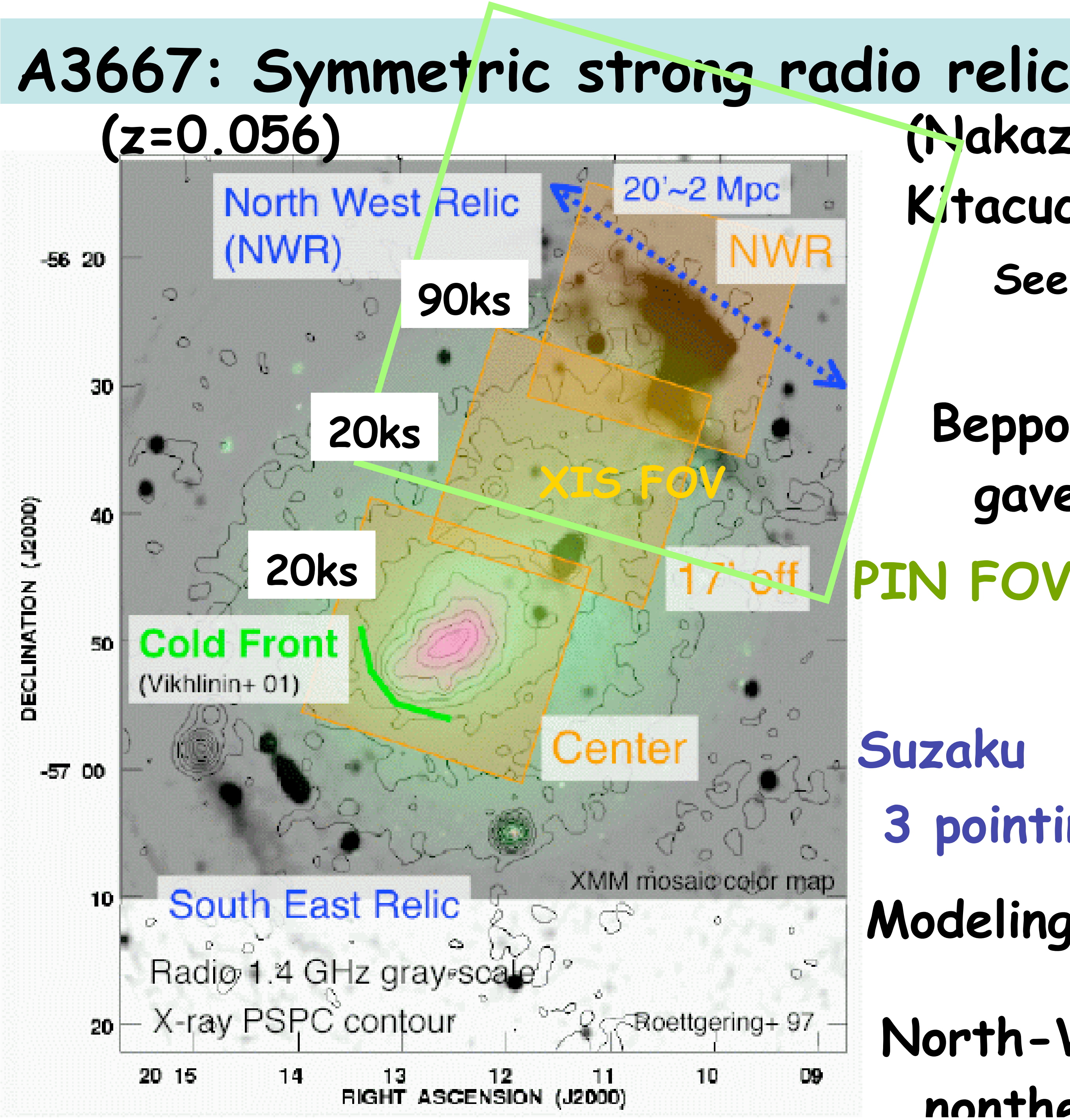
Nonthermal with 10% of themal pressure is permitted over cluster region.

A3667: Symmetric strong radio relic

(z=0.056)

(Nakazawa, Kawaharada, Kitacuchi, Okuyama)

See also Sarazion's talk



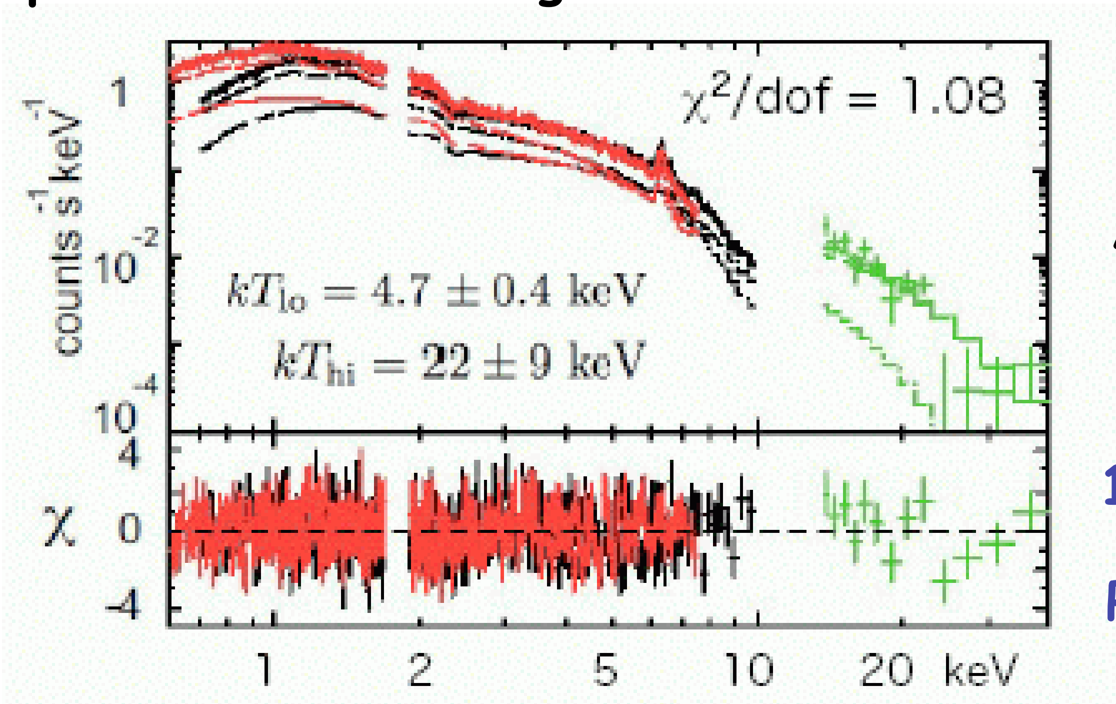
BeppoSAX/RXTE gave an upper limit

Suzaku 3 pointing observations

Modeling the thermal contribution.

North-Wesr Relic nonthermal emission

Spectra of center region



Arf response

XIS 17'x17'

HXD 34'x34'

Assume X-ray emission as ROSAT PSPC image

1kT fit is not acceptable.

PIN needs hotter one.

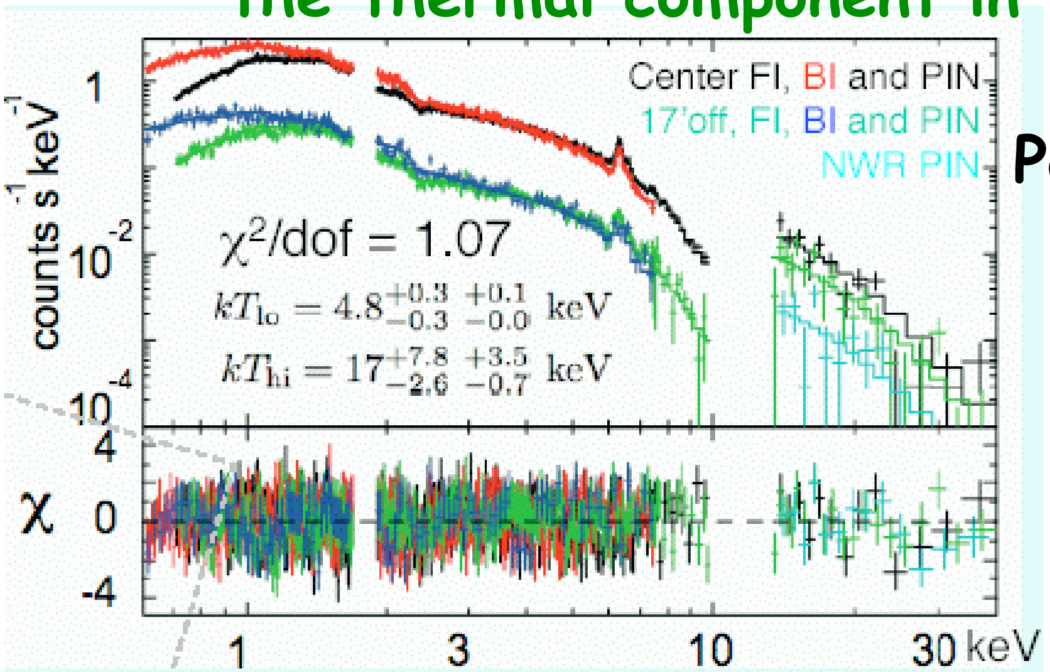
Very high kT components are needed for XIS/PIN spectra.

Merger-shock heated ICM?
Suprathermal electrons?

Past obs. kT=6.7keV

Search for nonthermal emission

Simultaneous fits of 3 pointing data, in order to cnstrain the thermal component in the PIN band accurately.



Powerlaw (photon index = 2)

Upper limit

4E-12 erg/s/cm2

(10-40keV)

(BeppoSAX < 7E-12)

Radio 3.7Jy (1.4GHz)

B>2uG Very strong Magnetic field is needed.

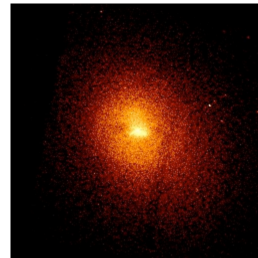
Amplified?

U_{ICM}=1.2eV/cm3

U_B>0.1eV/cm3, Ue<0.1eV/cm3

Other cluters

Bight Low-kT relaxed cD cluster

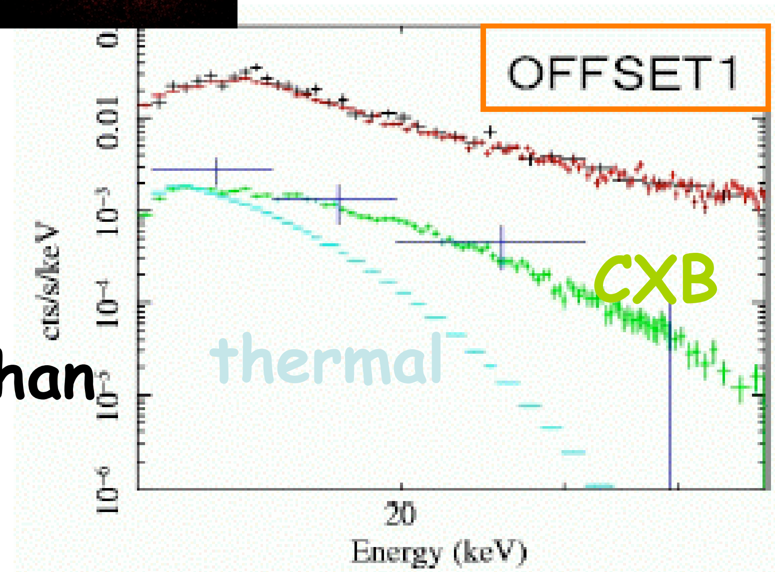


A2199 (kT=4keV)

(Kawaharada and Kitaguchi, poster)

Upper limit (1E-11 erg/s/cm2)

Consistent with/or slight lower than
BeppoSAX detected value



Centaurus cluster (kT=3.8 keV)

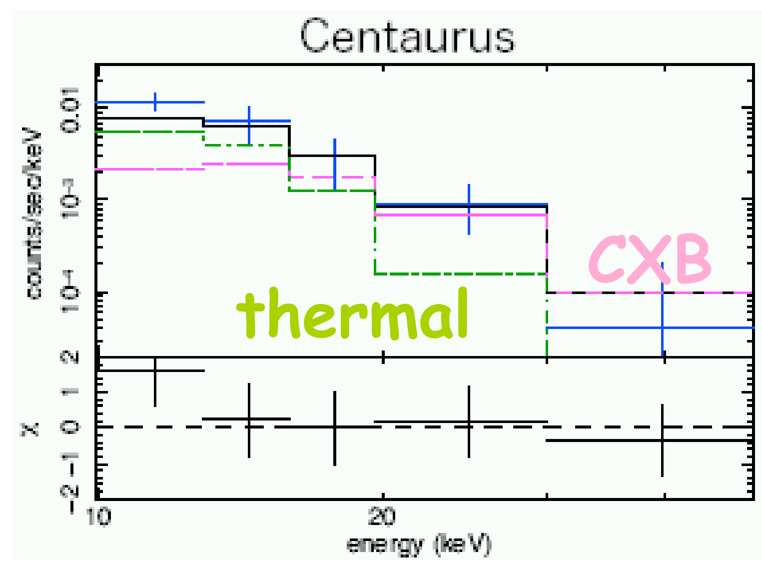
(Kitaguchi+)

Upper limit (1E-11 erg/s/cm2)

HCG62 (Tokoi+08) Not detected

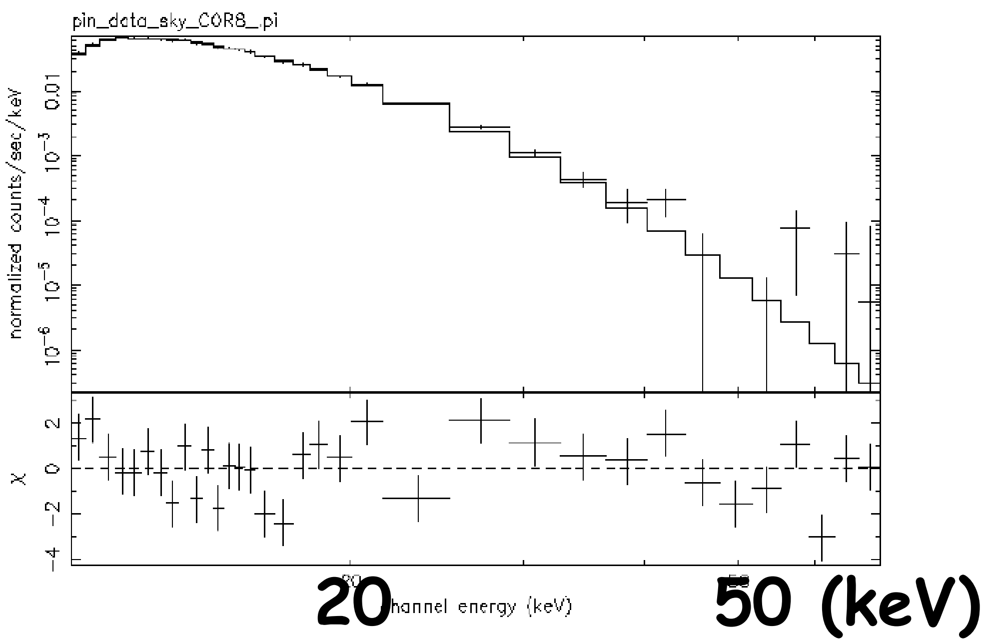
Small FOV than ASCA/GIS

Also,
no significant very hot componet
is needed



Rich cluster

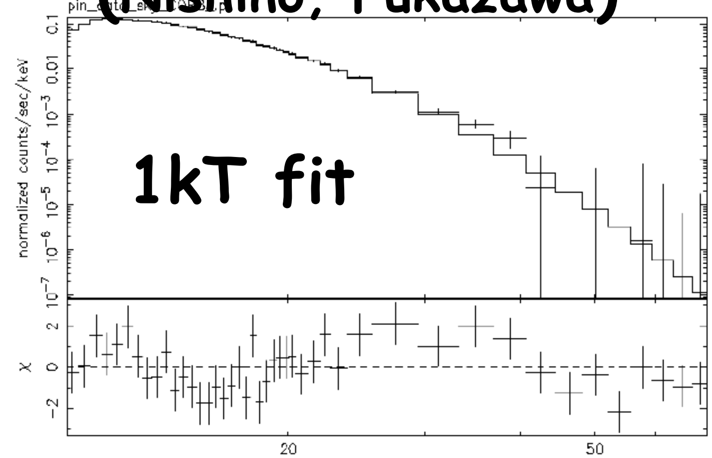
Coma cluster
(Wik, poster)

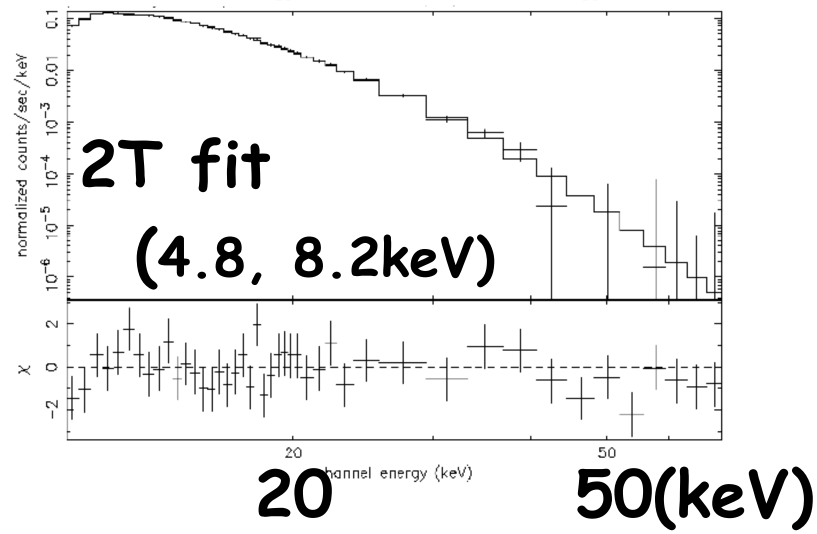


Almost consistent with thermal emission model.

Upper limit of Hard X-ray 2E-11 (15-50keV)

Perseus cluster
(Nishino, Fukazawa)





2kT is necessary.
(due to strong kT gradient)
Upper limit (1E-11 erg/s/cm2)

Also Very hot componet is not needed.

Overall Properties

Merging cluster

Possible nonthermal emission, very hot ICM

Bulk motion of ICM

Relaxed cD cluster

No signature of nonthermal phenomena

Question?

Possible detection ⇔ Upper limit

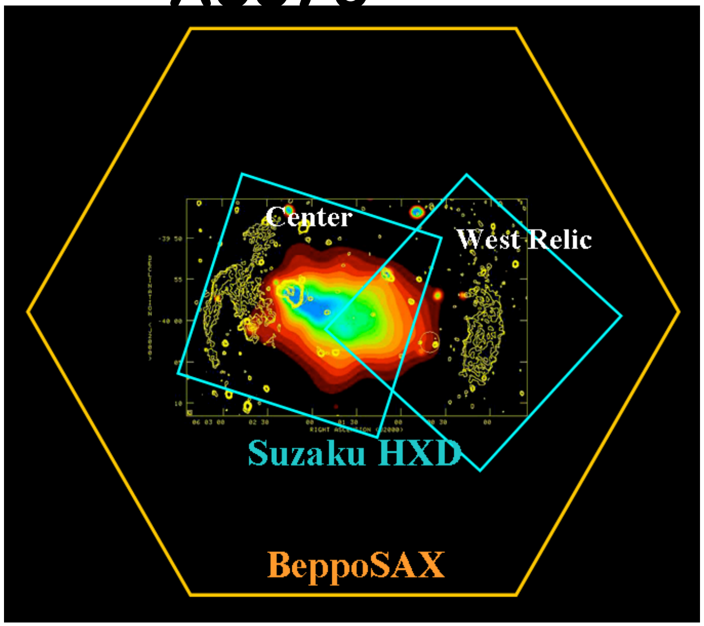
BeppoSAX, RXTE — Suzaku PIN/XIS

Large FOV — Narrow FOV

Indication

Nonthermal hard X-ray emission is very extended beyond PIN FOV?

A3376



Old protons scatter over cluster.

Small-scale merger occurs at the periphery.

Future missions

NeXT and GLAST are strong tools to study nonthermal emission from galaxy clusters.

NeXT/HXI detect the locally bright emission below 60keV

SGD detect largely extended emisson above 50keV

NeXT/SXS fine studies of Fe-K line probe nonthermal phenomena

GLAST(GeV Gamma-ray) is expected to detect some clusters

Summary and Conclusion

Suzaku has been developing our understanding of nonthermal phenomena in galaxy clusters.

Longer exposure is needed to constrain more tightly especially for high-kT clusters.

Suzaku gave a conservative upper limit on the nonthermal X-ray emission from galaxy clusters.

Narrower FOV detectors gives tighter constraint.
If the signal of BeppoSAX is nonthermal emission,
the emitting region might be very extended
over whole cluster.

Some radio relic has a strong magnetic field of >1uG.
Locally, the B field is amplified by cluster merger.

Some clusters contain a very hot ICM (>15keV).
Possible existence of suprathermal electrons.

NeXT HXI

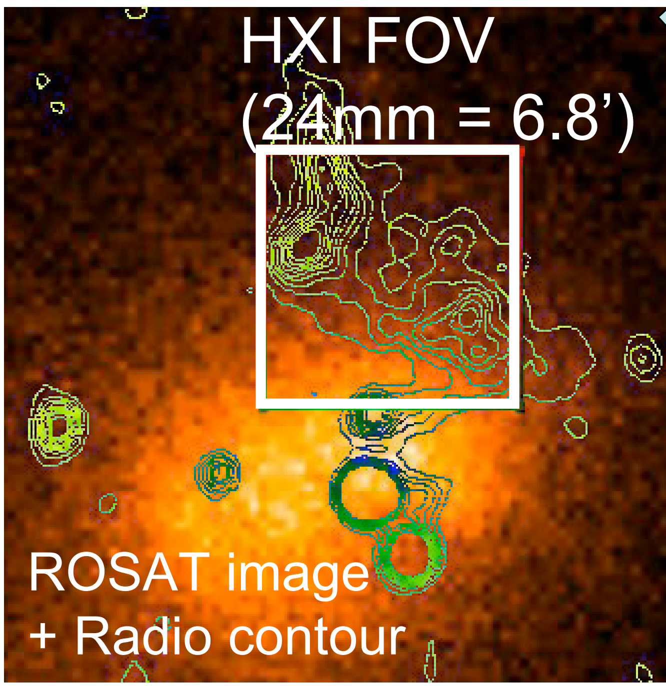
By Furuzawa, Nakazawa

Hard X-ray imaging (5-60 keV)

Tight constraint on the locally emitting region.

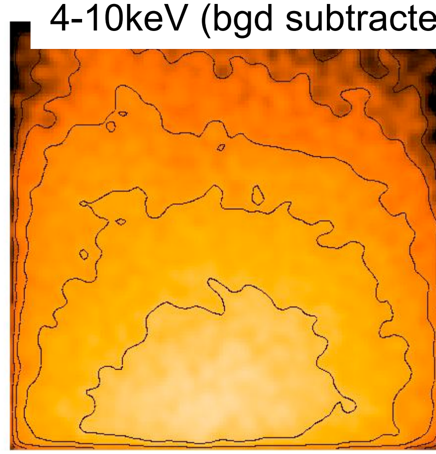
A2256

Cluster hard X-rays claimed by Beppo-SAX

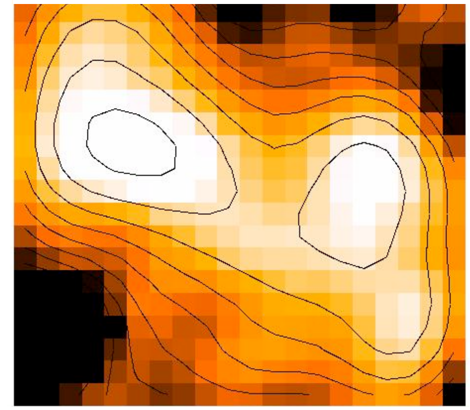


SAX x 1 case (9×10^{-12} cgs 20-80keV)

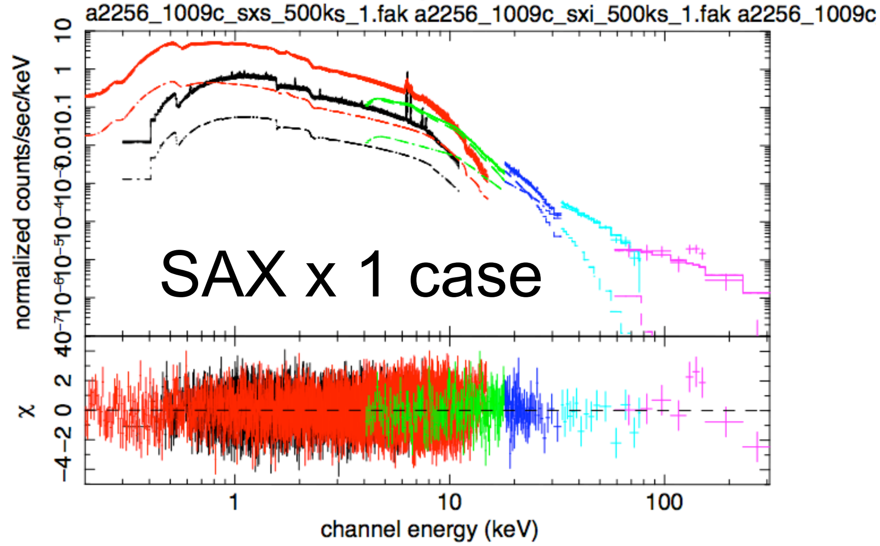
4-10keV (bgd subtracted)



30-80keV (bgd subtracted)



	4-10keV		30-80keV
thermal :	154240 cts	thermal :	111 cts
non-thermal:	17425 cts	non-thermal:	1012 cts
NXB:	22791 cts	NXB:	7995 cts

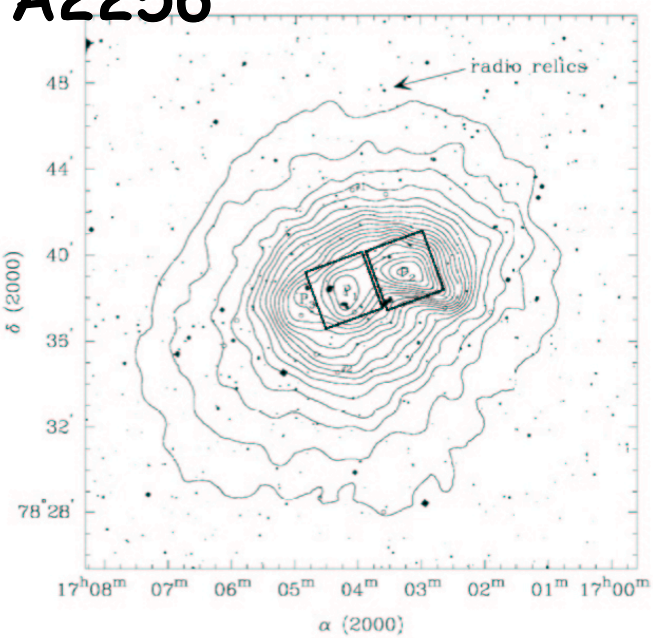


NeXT SXS (X-ray calorimeter)

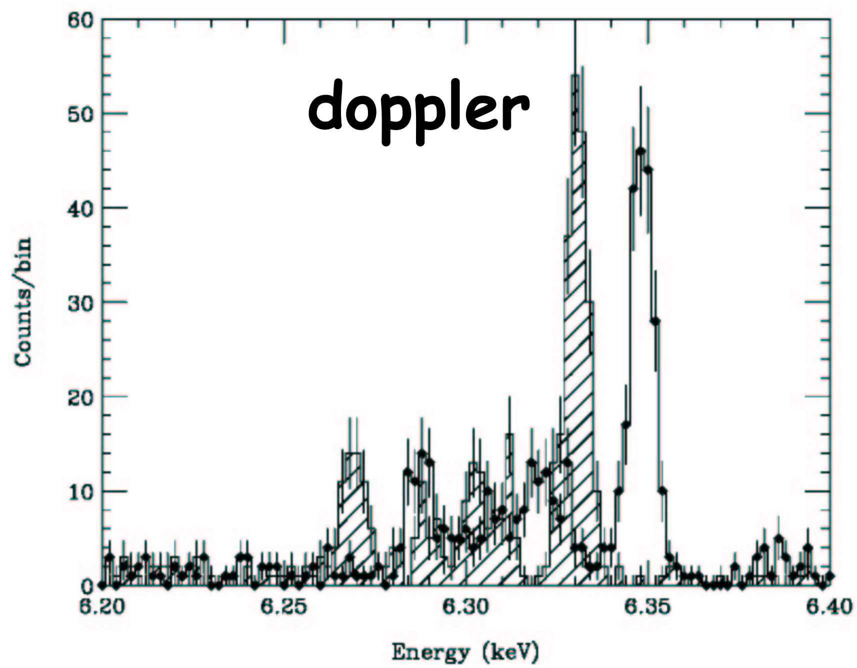
Fe-K line analysis

Doppler	bulk motion caused by merger
Line Broadening	Turbulence
Line ratio	nonthermal electrons

A2256

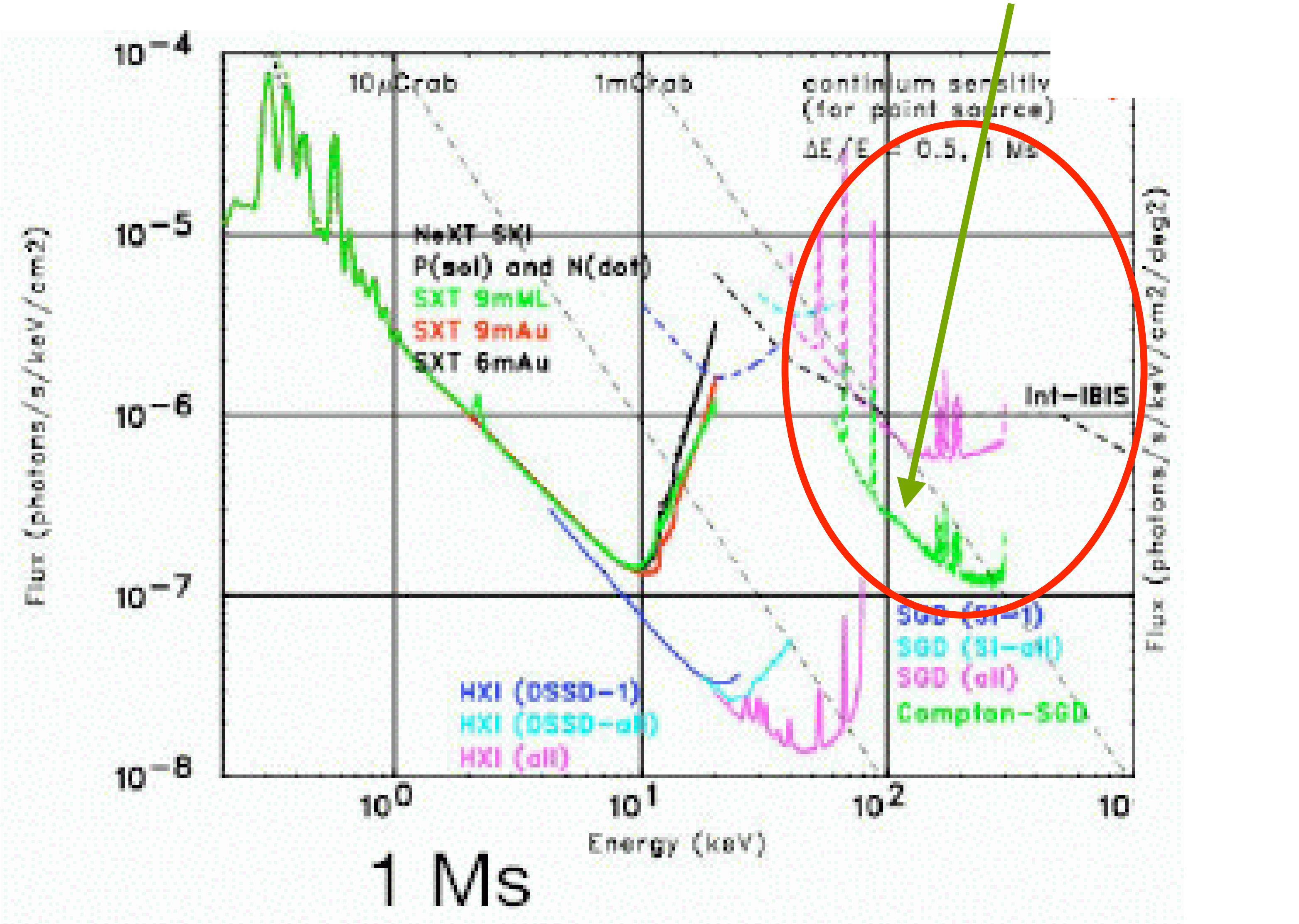


doppler



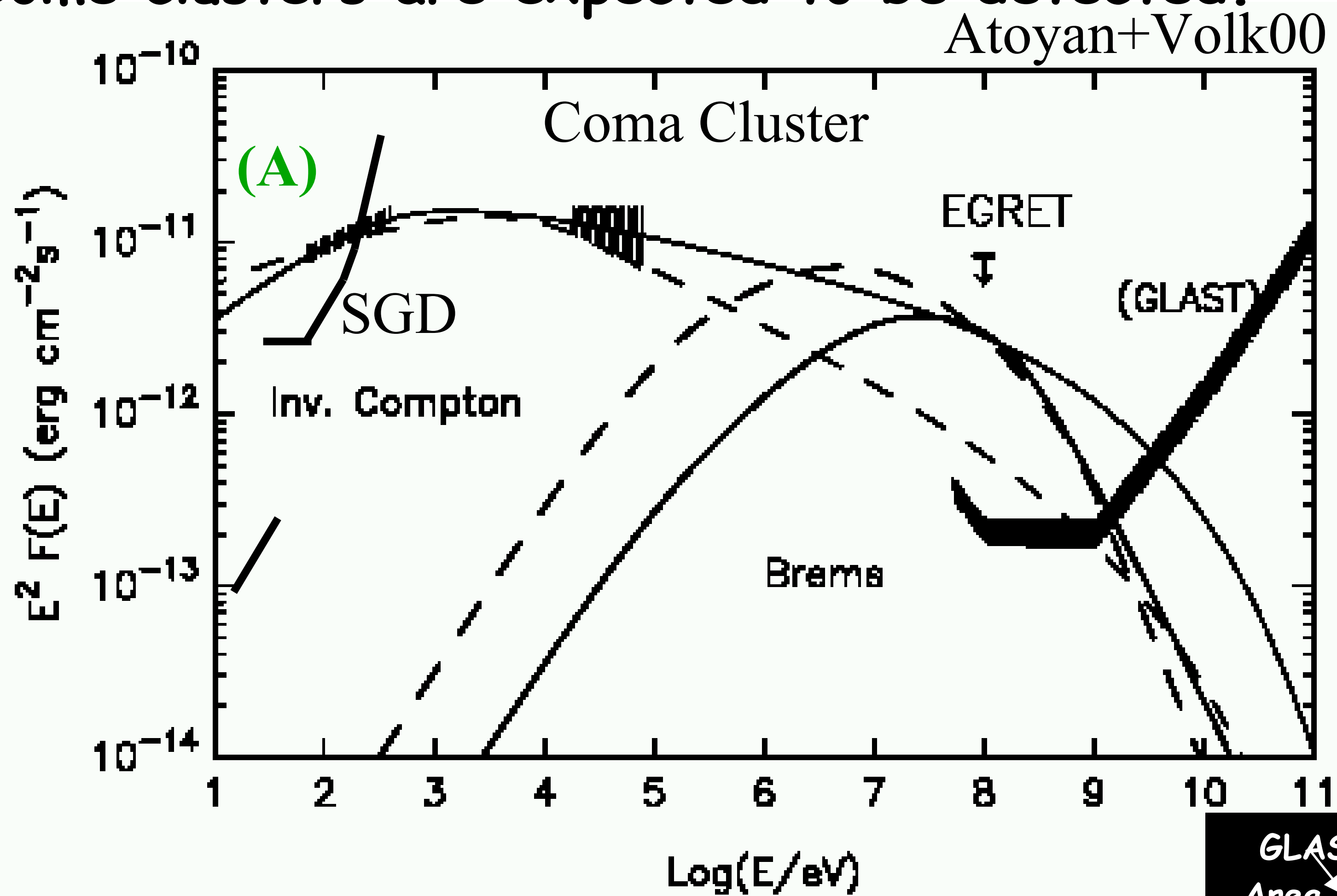
NeXT/SGD (Compton Camera)

More sensitive than BeppoSAX and PIN above 50 keV for extended hard emission beyond 30 arcmin.



GLAST (GeV Gamma-ray)

Some clusters are expected to be detected.



Electrons are primary or secondary?
How much are protons?

Size of >1 reg can be resolved.

Other information, related with nonthemal emission
(poster, PASJ issue)

Hayashida+ Bulk motion in merging cluster A2256
Fe-K line energy shift (~2000km/s)

Ota+07 no significant doppler in the cD cluster
<1500km/s Cen Cluster

Made j ski+ Bullet cluster (RXJ0658-55)
Possible hard/very hot component?

Werner+ S159-03 Soft excess
Thermal or nonthermal?

Fitted with CXB and powerlaw model of photon index = 2,
the flux of non-thermal emission is…

In first observation

***** $egr/sec/cm^2$

***** $egr/sec/cm^2$

In second observation

***** $egr/sec/cm^2$

***** $egr/sec/cm^2$

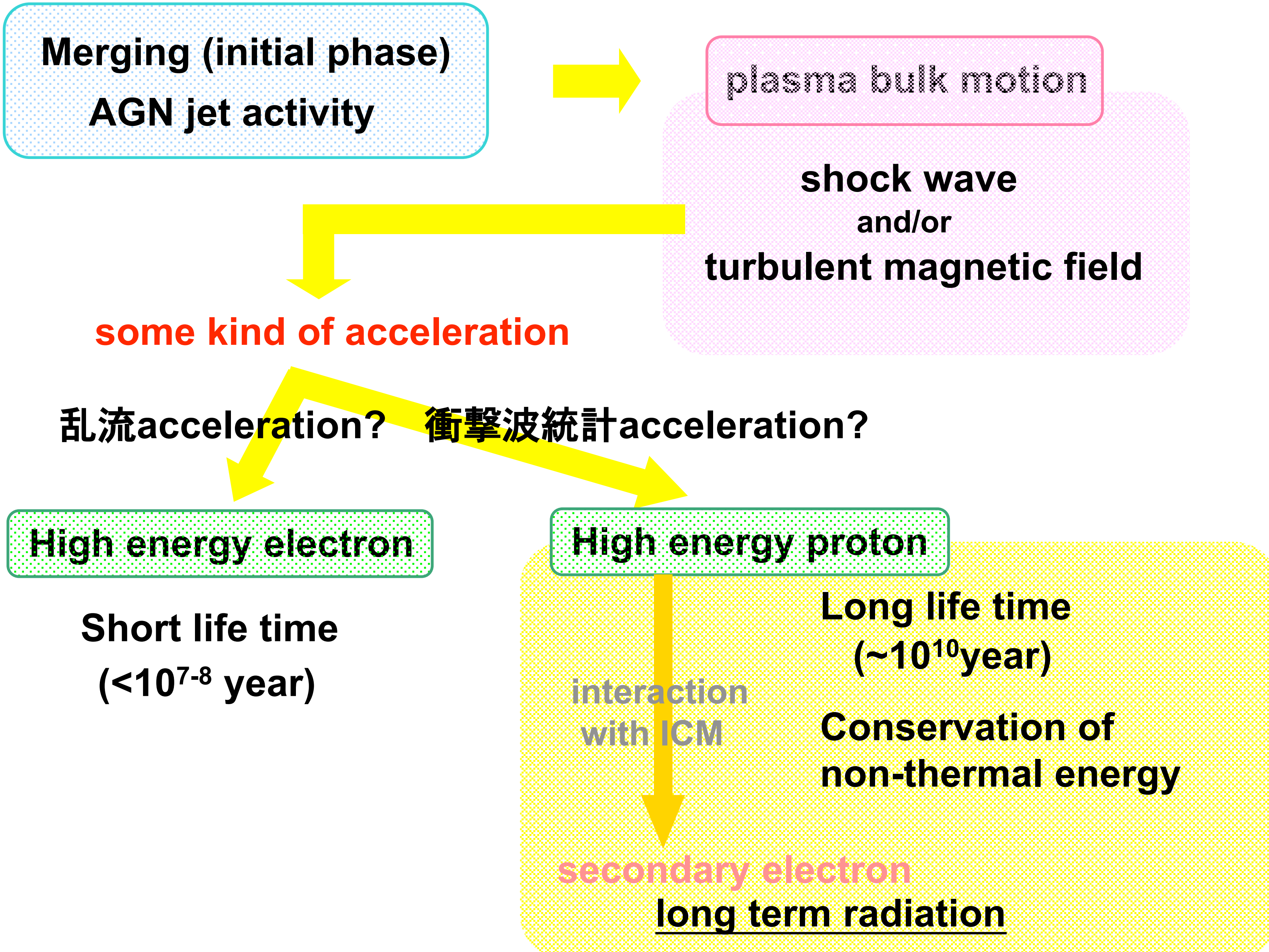
CXB flux is assumed as **** $egr/sec/cm^2$

If origin of hard X-ray is AGN,

hard X-ray flux in the second observation is almost zero.

Separation between each aim point is ~30'.

FOV of PIN is ~34'.

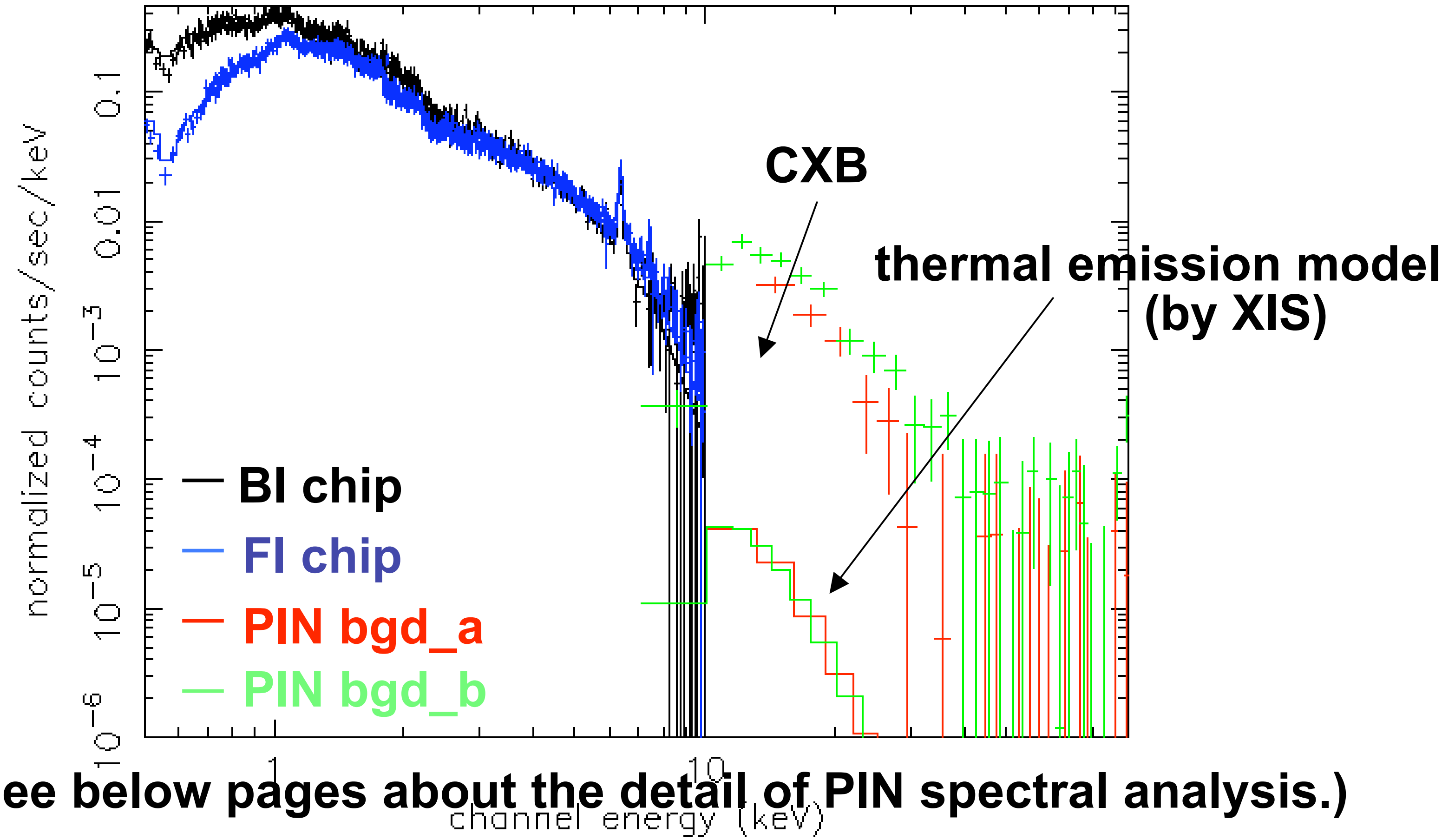


Merging (initial phase)
AGN jet activity
plasma bulk motion
shock wave
and/or
turbulent magnetic field
some kind of acceleration
乱流acceleration?
衝撃波統計acceleration?
High energy electron
Short life time
(<10^7-8 year)
High energy proton
Long life time
(~10^10year)
interaction
with ICM
Conservation of
non-thermal energy
secondary electron
long term radiation

Wide-band spectra

The models show the thermal emission XIS data.

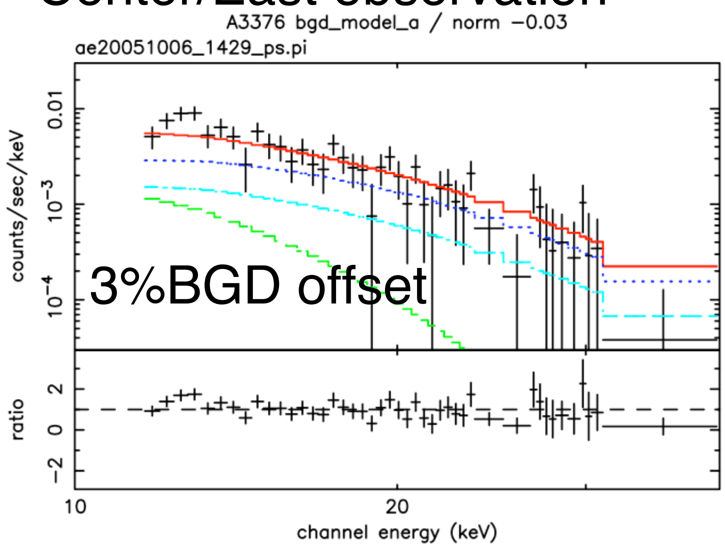
Excess emission from thermal component is seen.



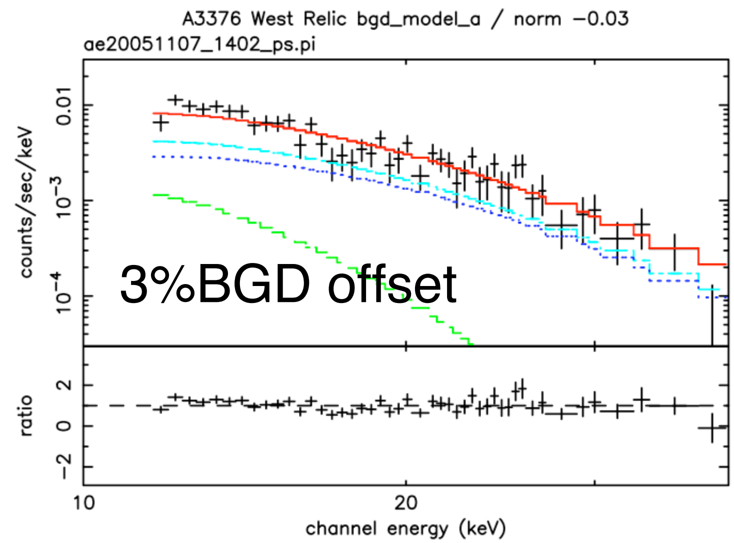
(See below pages about the detail of PIN spectral analysis.)

Suzaku observations of A3376 cluster

Center/East observation



West Relic observation



Data / Model (thermal / non-thermal / CXB)

	20-80 keV flux with Γ = 2.0 PL [erg/s/cm2]
Center/East	$< \quad 1.0 \times 10^{-12} \quad \pm 4.3 \times 10^{-12}$ / 3% BGD offset
West Relic	$6.4^{+1.2}_{-1.2} \times 10^{-12} \quad \pm 4.3 \times 10^{-12}$ / 3% BGD offset
SAX/PDS	$10.0^{+6.0}_{-**} \times 10^{-12}$

Much strict upper limit will be derived. NOTE: LESS CONTAMINATION

CXB is modeled :: another science !!

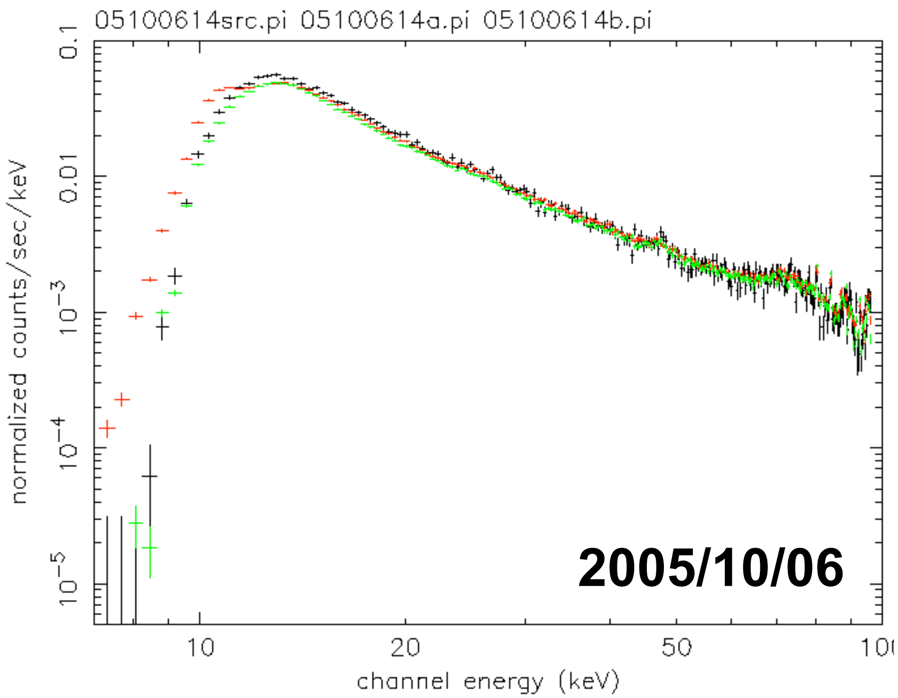
PIN Spectra

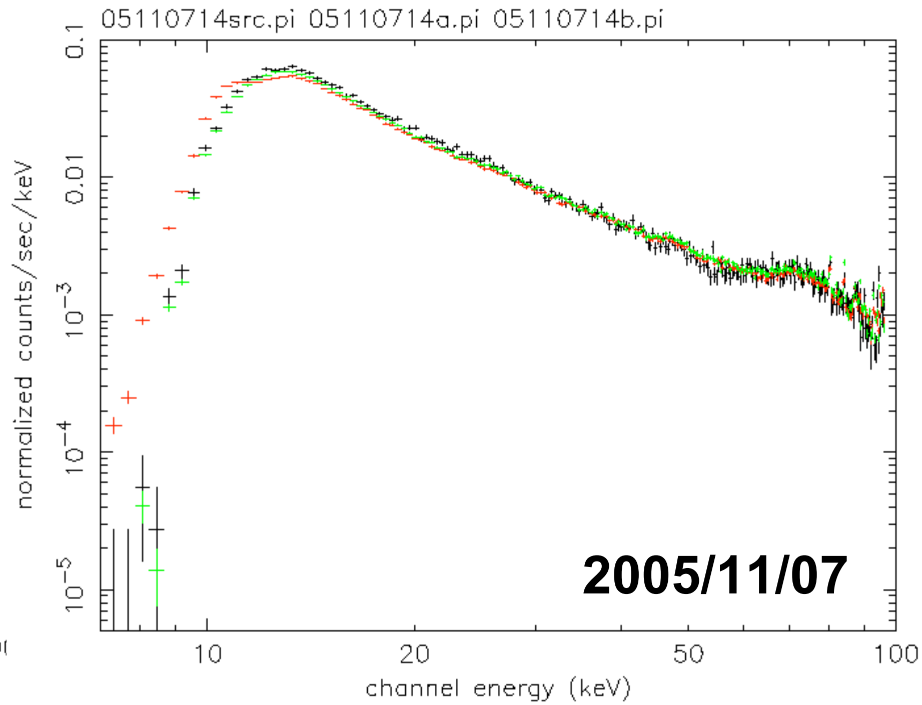
(i) Comparison of data and background spectra

Both spectra show excess X-ray above background in 15~30 keV.

→ CXB + non-thermal emission?

Background level between bgd_a and bgd_b is somewhat different.





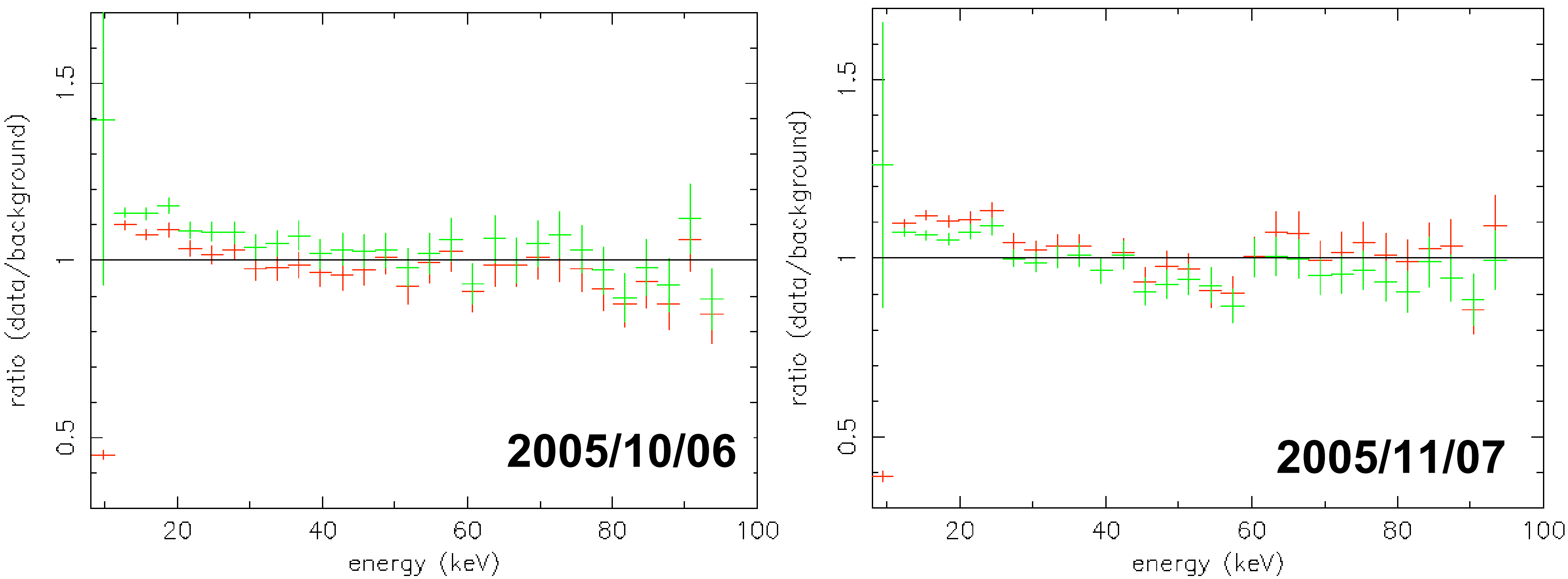
data : black, bgd_a : red, bgd_b : green

(ii) Background systematic error

Ratio of data/background

Significant signal below 30 keV with both background.

Systematic error of PIN background is ~5% at least.

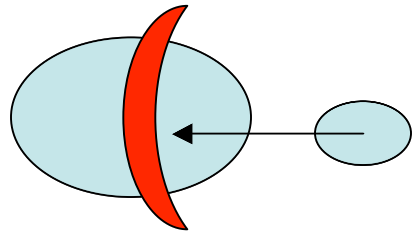


data/bgd_a : red, data/bgd_b : green

①銀河団合体・形成に伴う衝撃波

理論計算

滝沢さん



フェルミの１次加速

距離大　　高いエネルギーまで加速可能

Emax BVL

$$E^e_{max} \approx 6.3 \times 10^4 B_\mu^{1/2} v_8 g(r)^{-1/2}\ GeV,$$

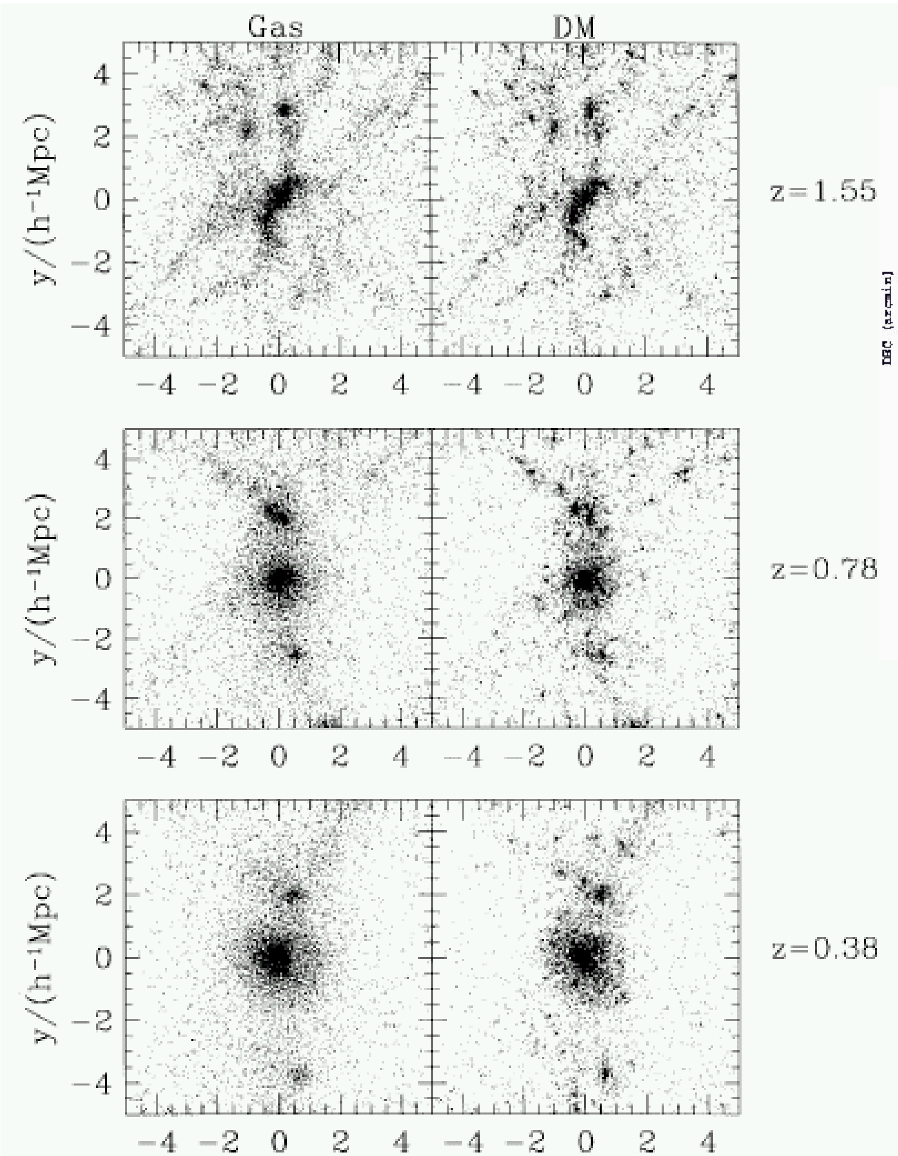
$$E^p_{max} \approx 3 \times 10^9 B_\mu v_8^2 g(r)^{-1}\ GeV.$$

Chandraの観測　　cold frontが多い　　亜音速合体

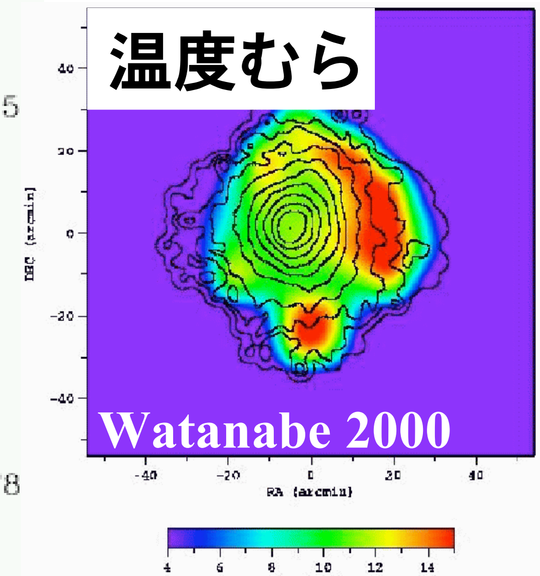
②銀河団の進化に伴う粒子加速

CDM,ボトムアップ

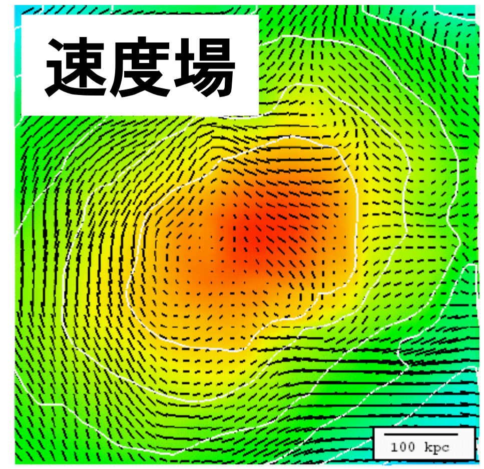
Eke et al. 1997



熱的



非熱的



Norman et al. 1998

銀河団全体に、
ガスの乱れが残る

↓

フェルミの２次加速

銀河団は、巨大
長い年齢

加速領域から逃げにくい
長い加速時間が可能

③中心銀河の進化と粒子加速

巨大BHへの質量降着

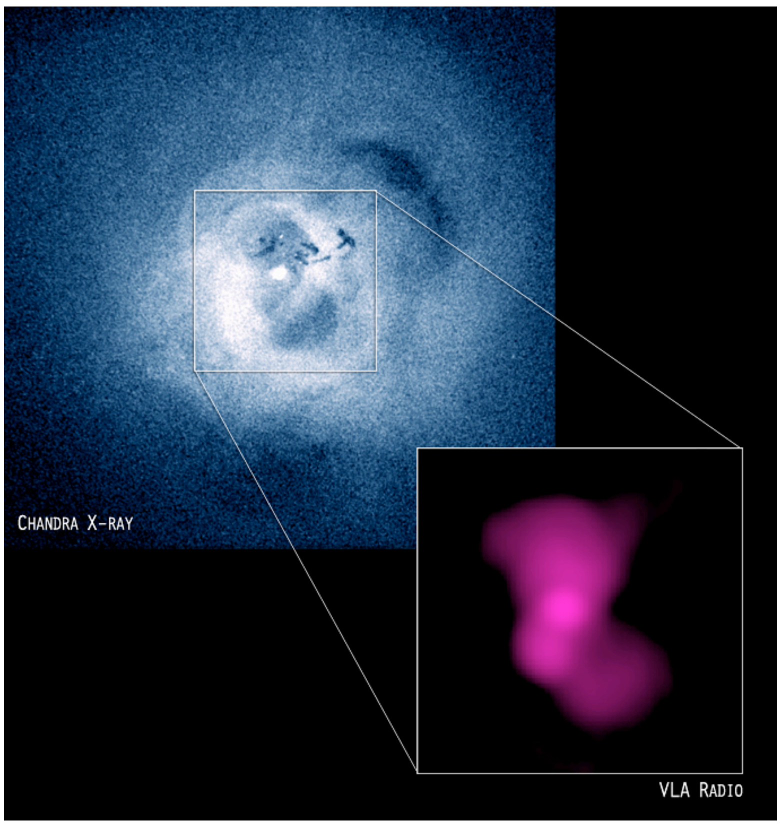
宇宙最大ジェットの放出

↓

非熱的粒子の発生

一次的（BH近傍）

二次的（ジェットと高温ガスの相互作用）



何らかの大量の加速粒子の存在が期待される

電子　　シンクロトロン放射、逆コンプトン散乱

ほとんどは、10^6-7年以下で cooling
１次粒子は加速直後しか生きていない

陽子　銀河団プラズマとの相互作用
Cooling time >> 宇宙年齢

期待されるガンマ線放射の概算

粒子密度　　1eV/cm3

銀河団全体で高エネルギー粒子　10^62 erg

宇宙年齢で生成すると $W_p = 2\times10^{44}$ erg/s の粒子生成

巨大銀河団、明るいAGNで可能

ガンマ線放射率

$$L_\gamma / W_p = 1/3\left(t_{pp}/t_H\right)^{-1} = 0.03\left(\frac{n_{ICM}}{10^{\wedge-3}cm^{-3}}\right)$$

Coma銀河団　2E-12 erg/s/cm2

銀河団の非熱的放射の多波長観測

１次加速か２次加速か？

加速される粒子、磁場のエネルギー分配は？

電波（低い周波数側の情報不足）

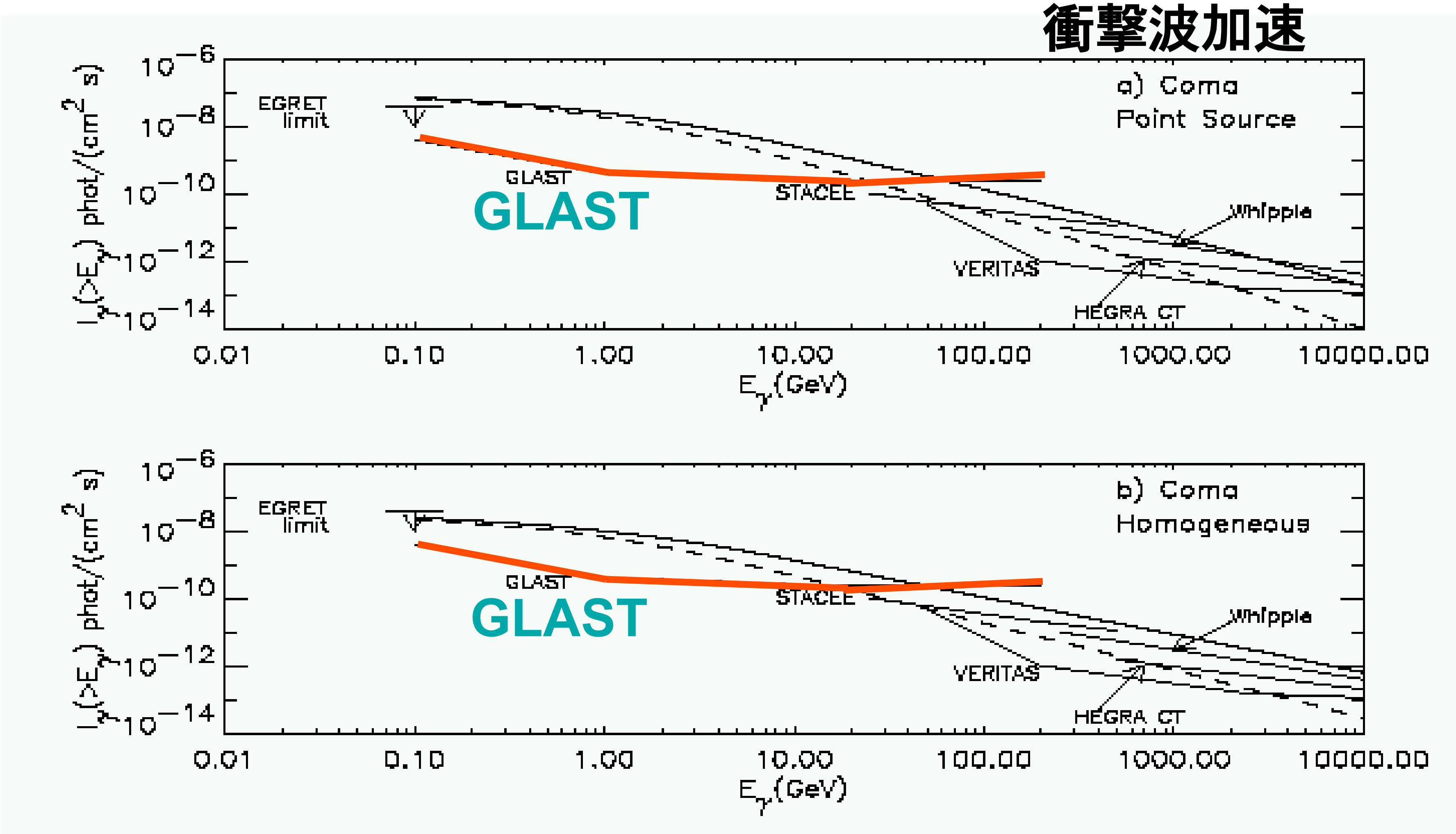
硬X線（はっきりした検出例不足）
中沢君講演

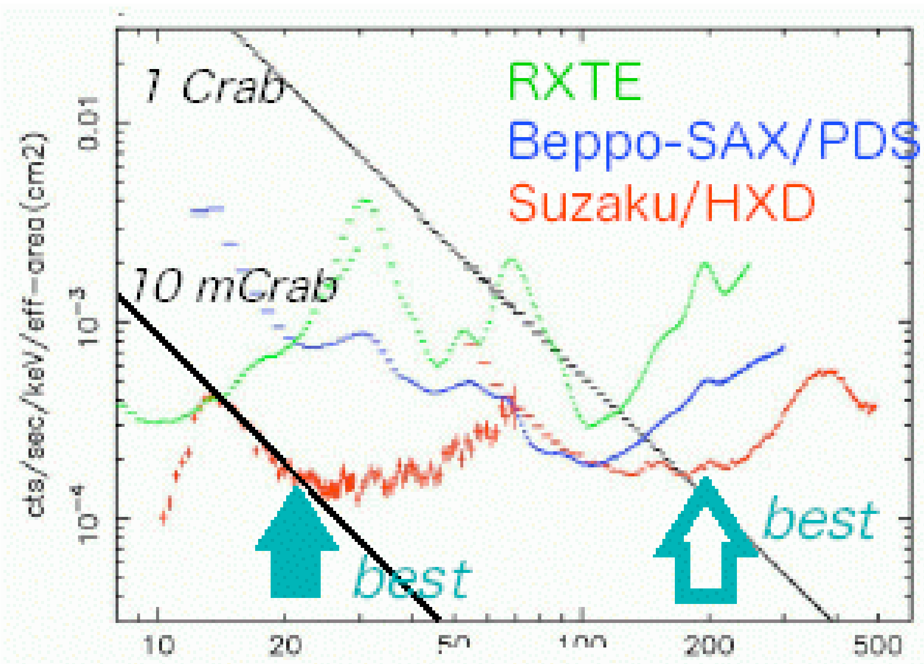
ガンマ線（検出例なし）

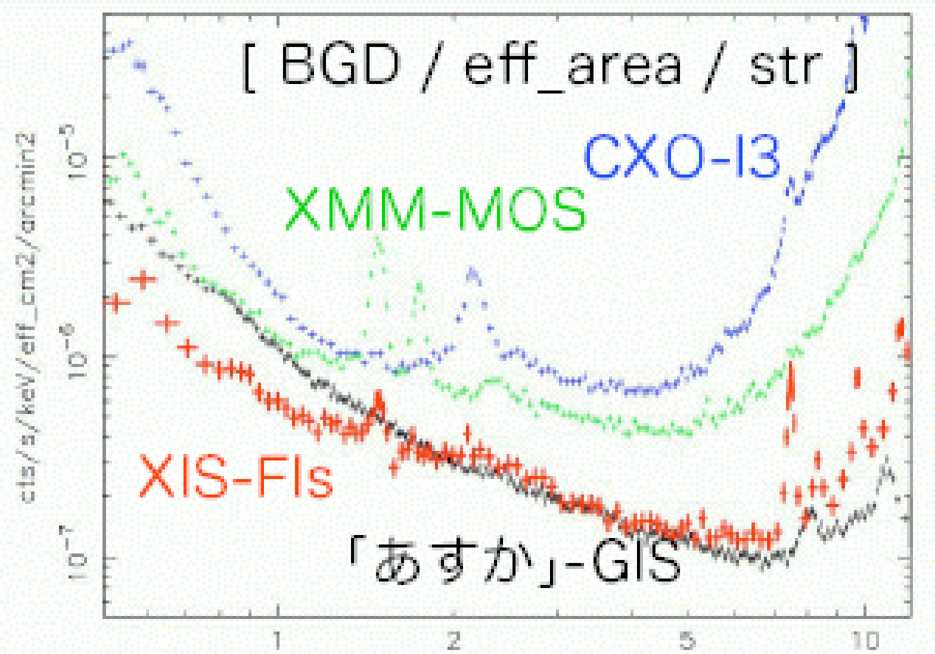
多くの予想は、衝撃波加速では、EGRET感度ぎりぎり

GLASTに期待！

Blasi et al.
衝撃波加速




1 Crab
RXTE
Beppo-SAX/PDS
Suzaku/HXD
10 mCrab
best
best
cts/sec/keV/eff−area(cm2)


[BGD / eff_area / str]
CXO-I3
XMM-MOS
XIS-FIs
「あすか」-GIS
cts/s/keV/eff_cm2/arcmin2

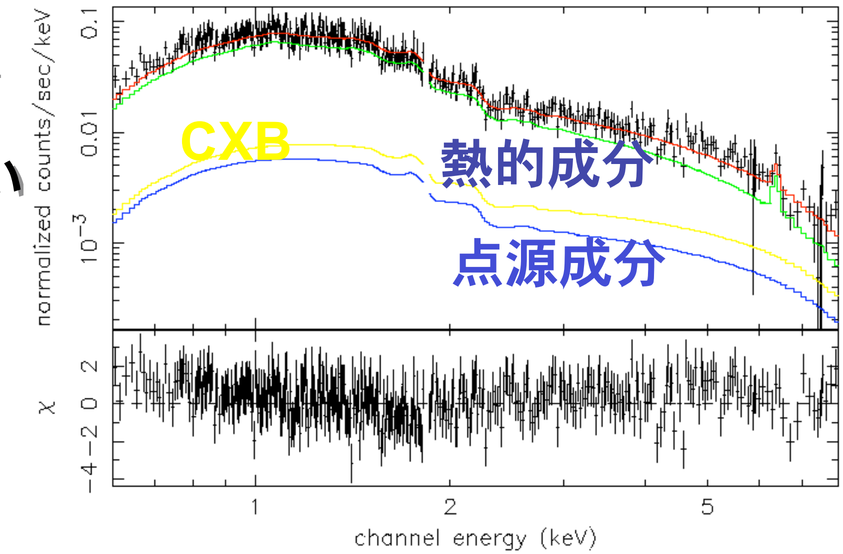
A3376WR からの硬X線放射の広がり

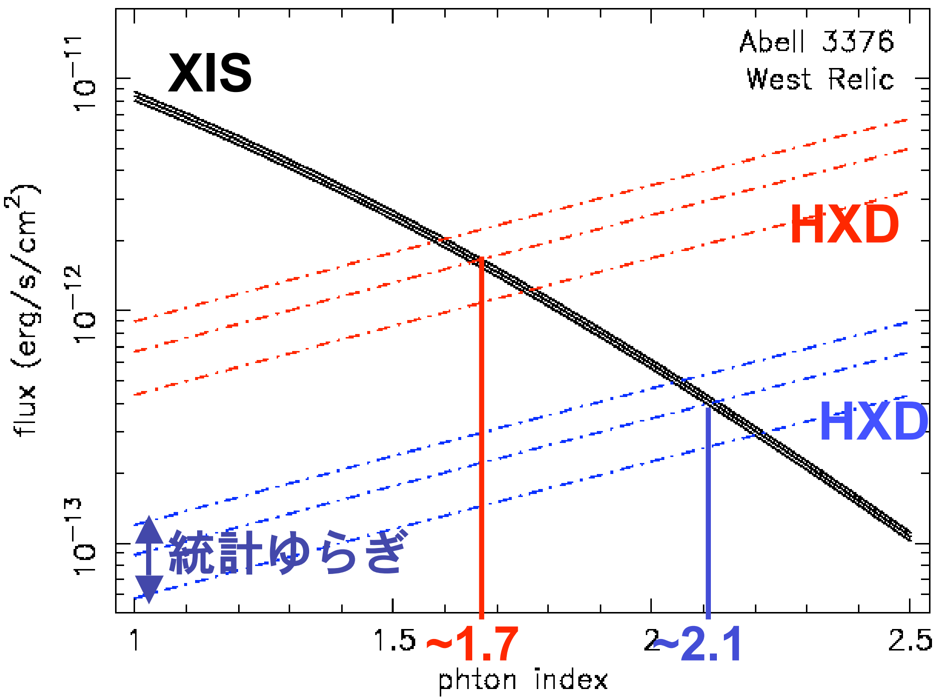
XIS は他検出器に比べ NXB が非常に低い

4~8 keV で硬X線 flux を見積もると、

Fx : 5.7 ± 0.3 ± 2.9　x10^{-13}　erg/s/cm^2

(1σ error、ベキ=2.0)





放射領域 ~ XIS 視野 (15')

ベキ 1.7

放射領域 ~ HXD 視野 (60')

ベキ 2.1

BeppoSAX の観測より、ベキは ~2.0

広がりは ~15-60 分角と予想される

電波Relic よりやや広がっている?

Background subtracted spectra of HXD-PIN

Compared with CXB…

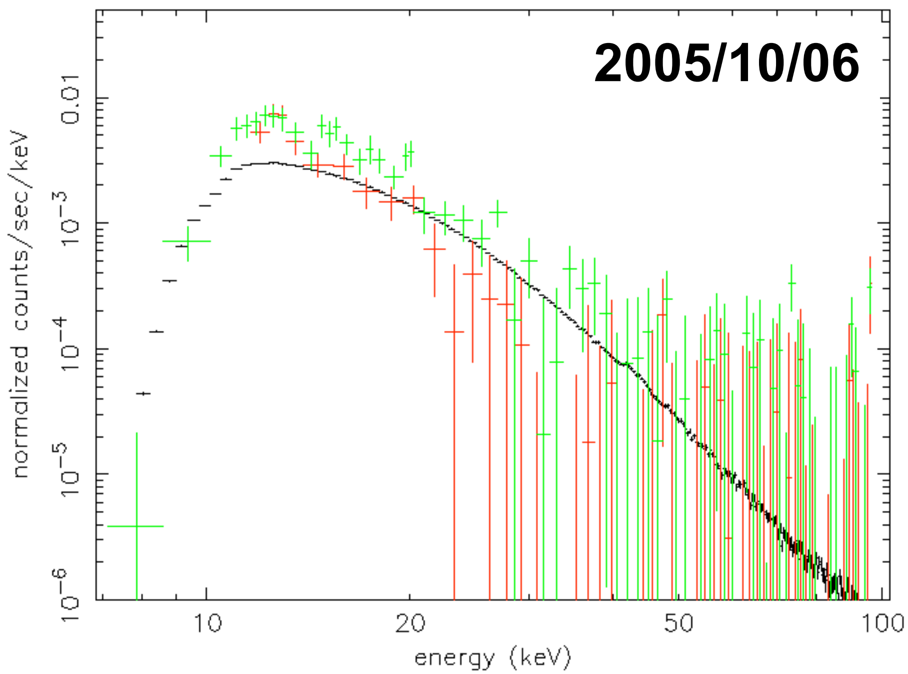
In the first observation,

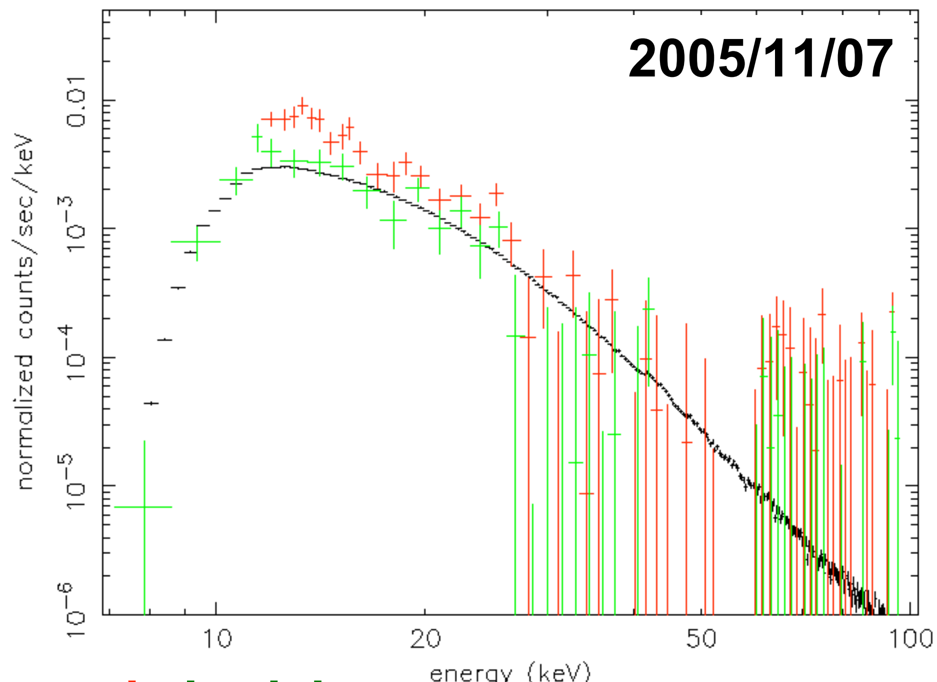
hard X-ray emission above CXB appears.

Upper limit … 1E-11 erg/s/cm2 (20-80keV)

(photon index is assumed to be 2)

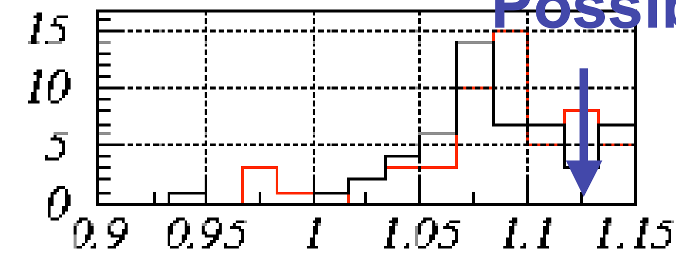
almost the same as that of BeppoSAX PDS



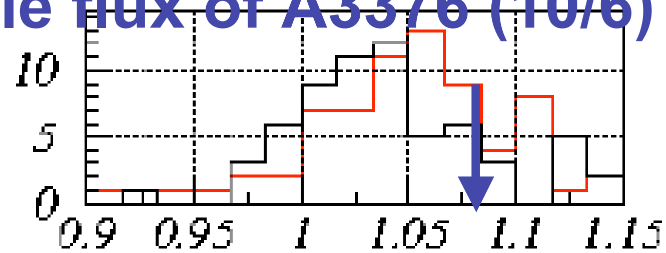


CXB : black, bgd_a : red, bgd_b : green

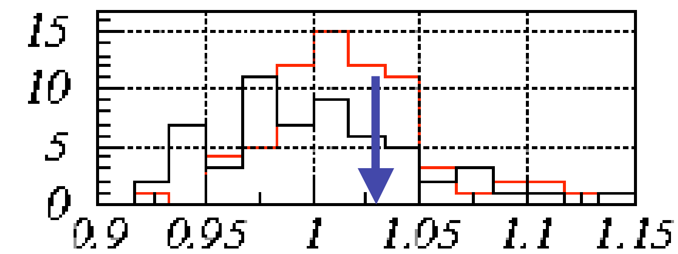
Possible flux of A3376 (10/6)



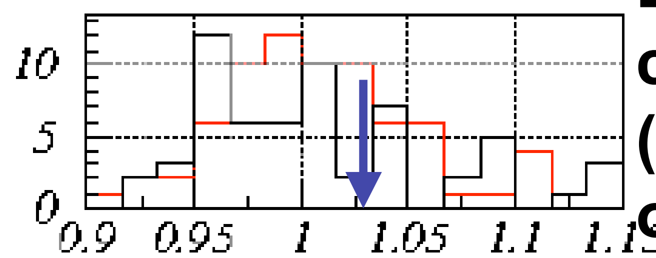
12-24keV



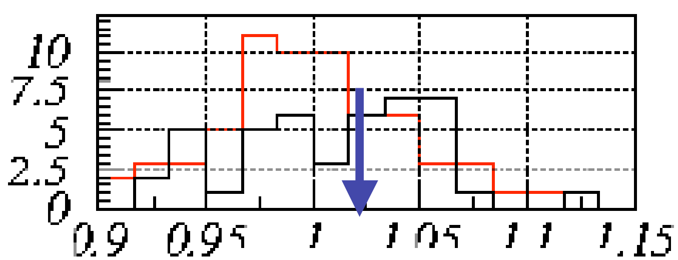
24-36keV



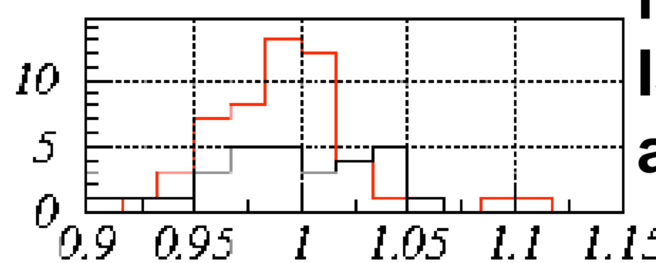
36-48keV



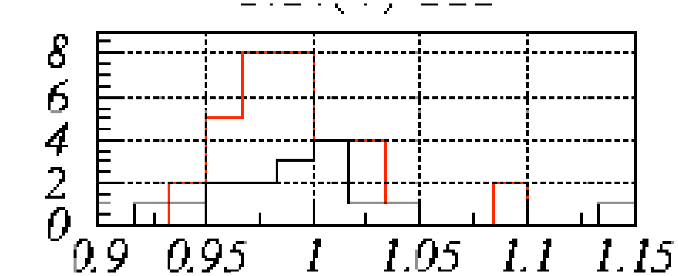
48-60keV



60-72keV



72-84keV



84-96keV

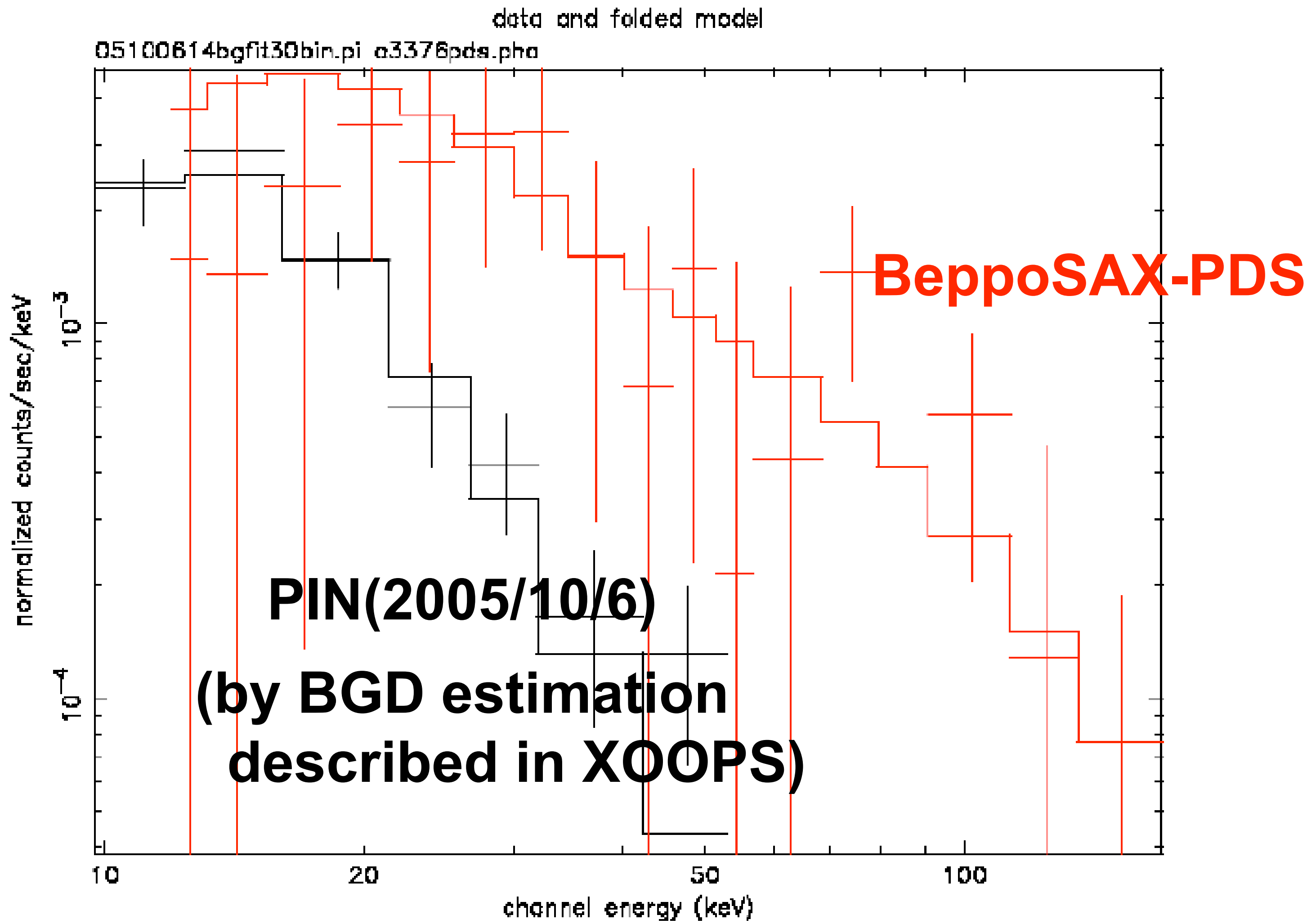
Distribution of count ratio of (on source)/BGD of all the obs.

Now the excess Is not significant above 3sigma.

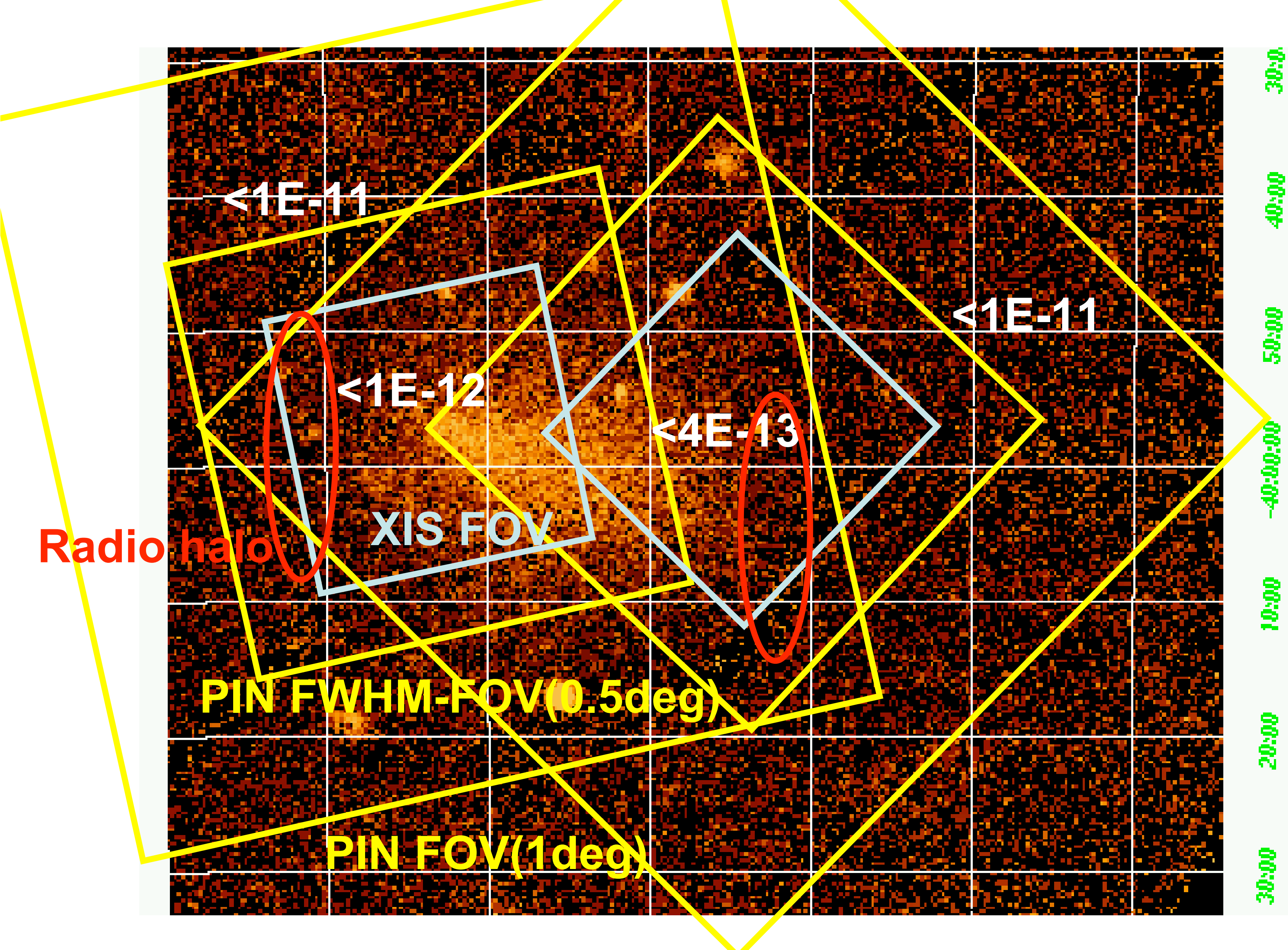
BGD systematics and Significance of A3376 signal

4% systematics ???

Photon index = 1.75
1.0E-11 erg/s/cm2 (20-80keV)



Upper Limit Map of nonthermal X-rays



Summary

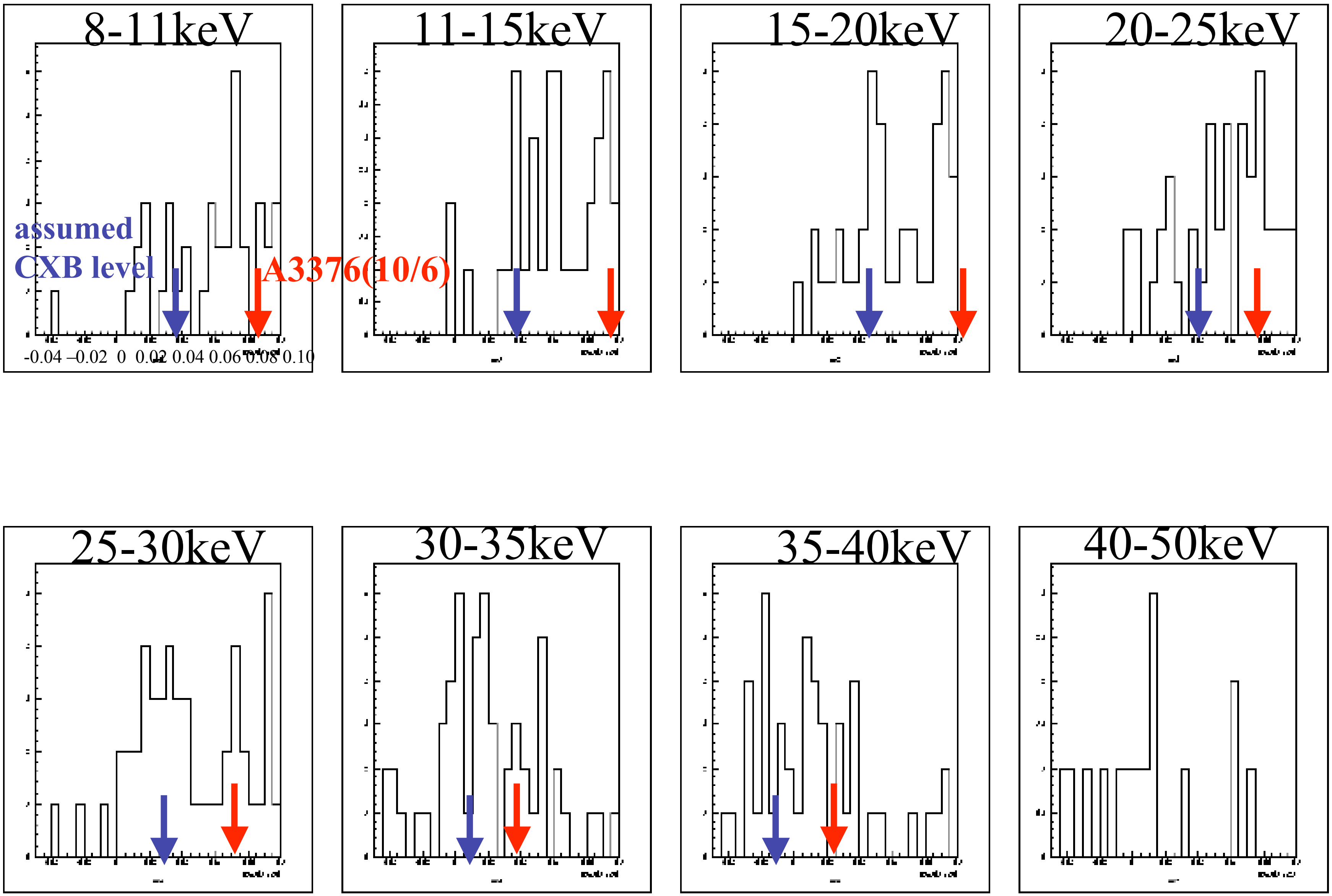
Now, HXD can set the upper limit of nonthermal emission
1E-11 erg/s/cm2 (20-80keV)
consistent with that of BeppoSAX PDS

If the nonthermal emission exists, it would be around the outer cluster region beyond the radio lobe.

Further works

Improvements of PIN-BGD estimation
More constraint of doppler broadening of Fe-K (to constrain the merging motion)

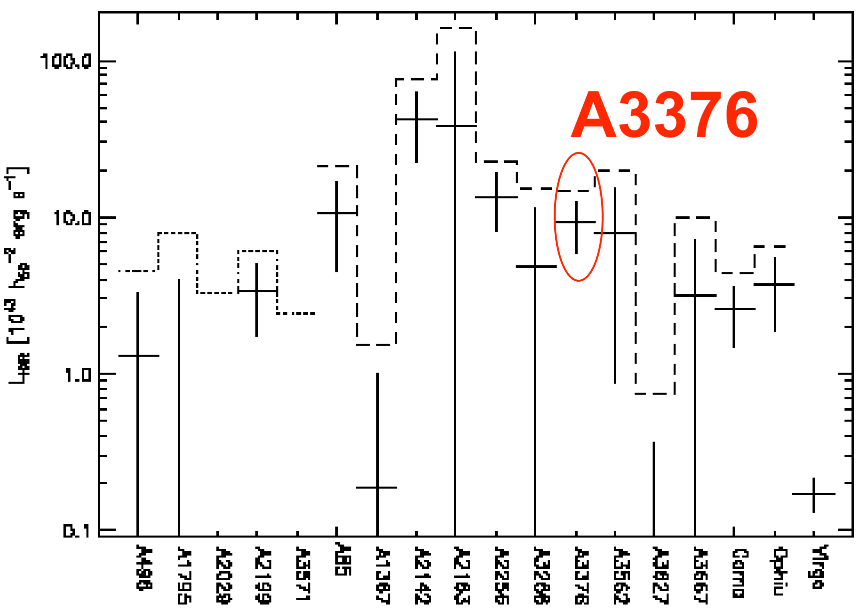
Significance of A3376 signal for method described in XOOPS



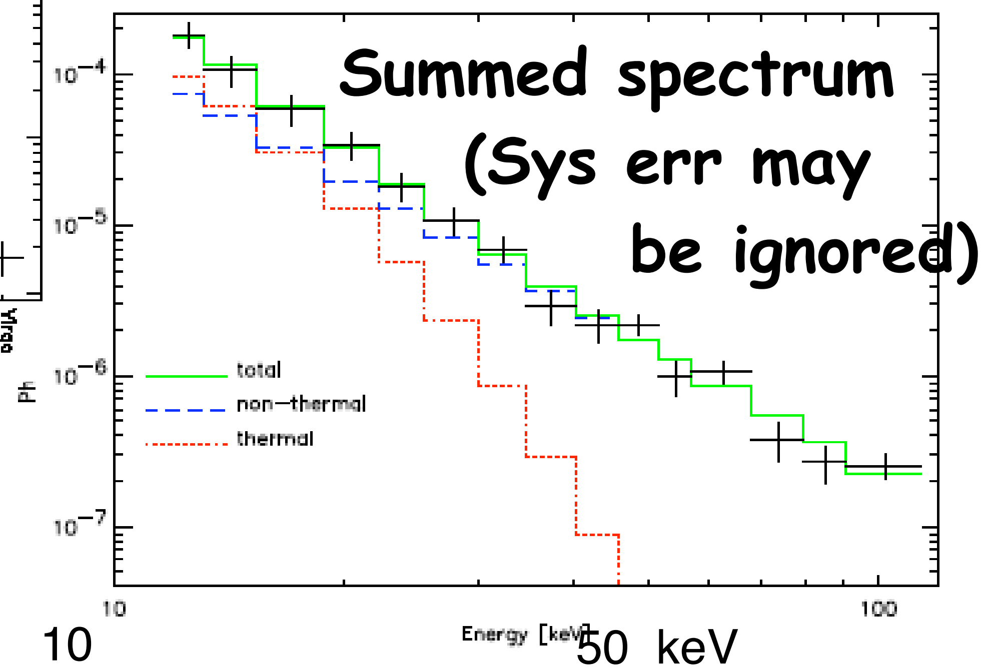
Hard X-ray Emission from Clusters with BeppoSAX PDS

A2142, A2199, A2256, A3376, Coma, Ophiu, Virgo

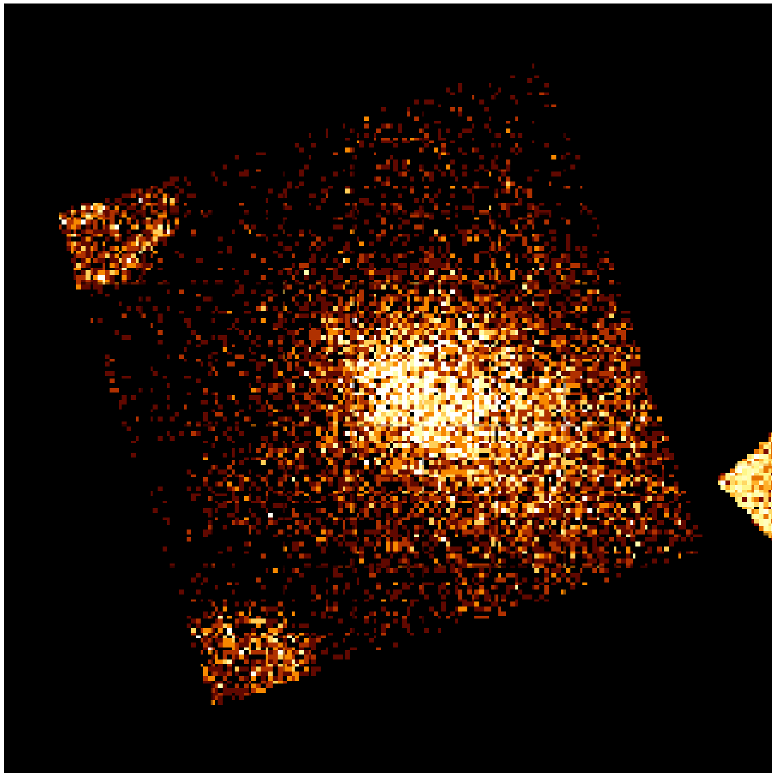
Nevalinen et al. 2004



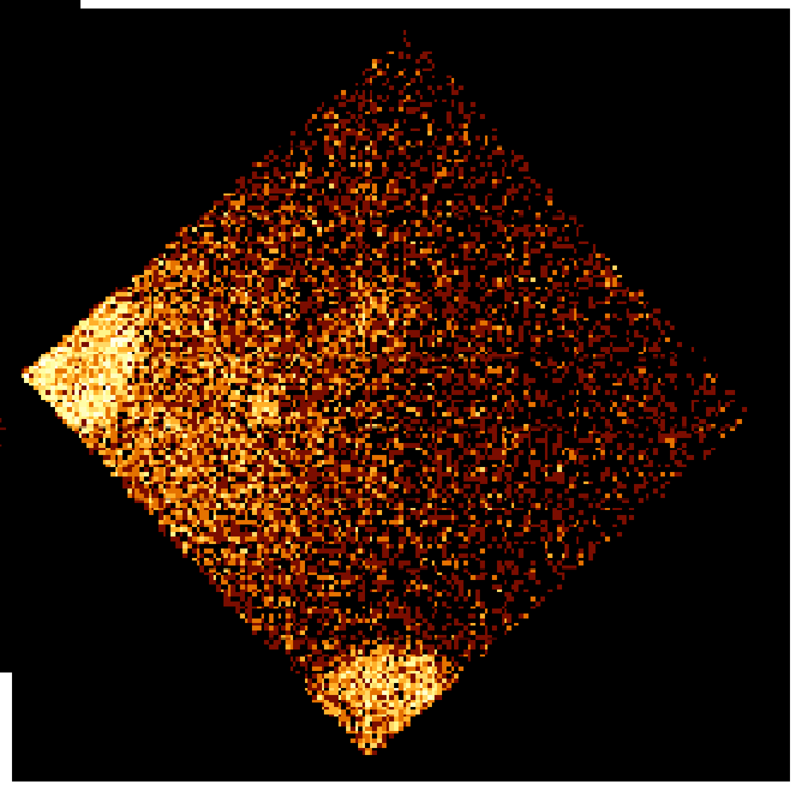
BeppoSAX/PDS
systematic analysis



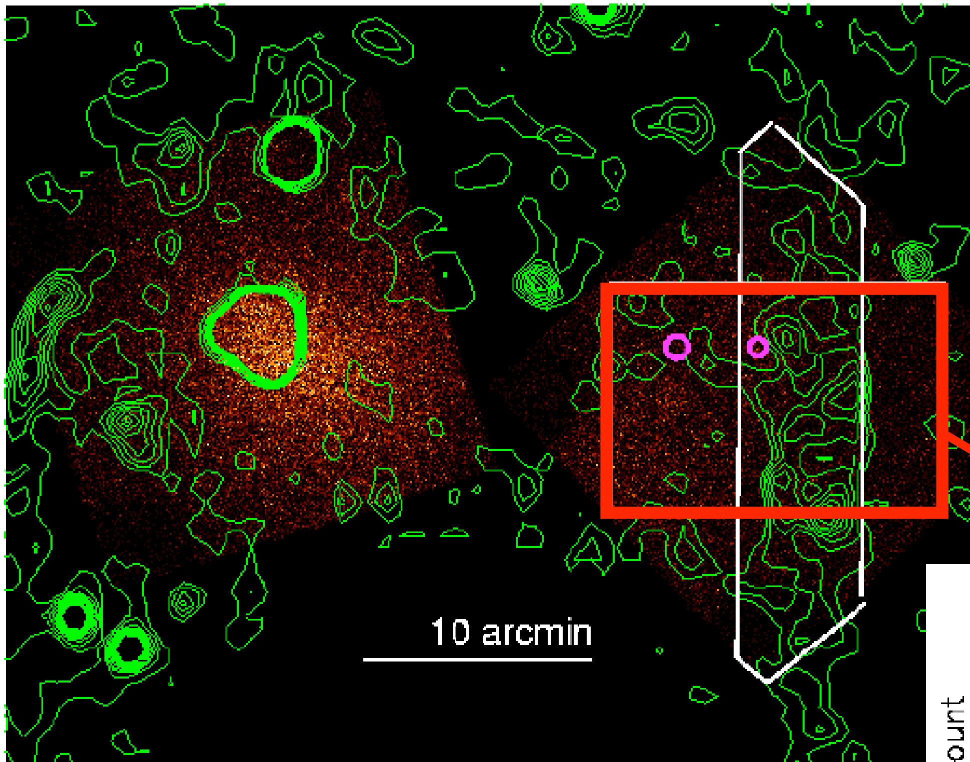
XIS images



fainter (<1/5)



X-ray image and Radio contour



No significant X-ray hole

Nonthermal pressure is
not so strong as ICM pressure.