Blazars, radio galaxies, and radio lobes studied in X-rays with Suzaku, MAXI, and future Astro-H

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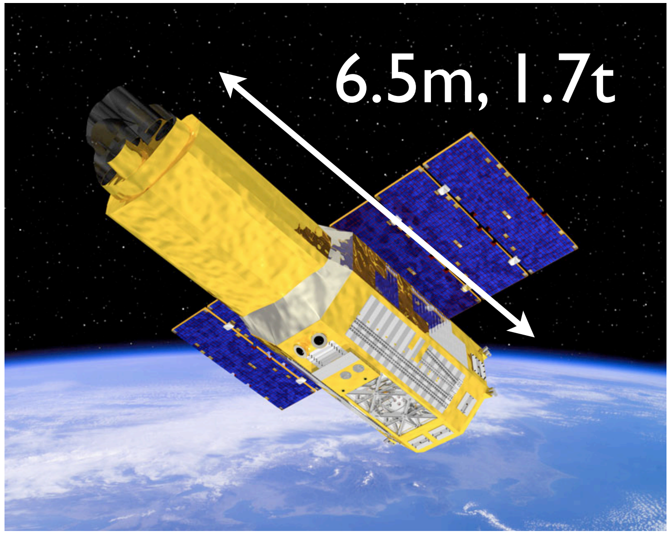
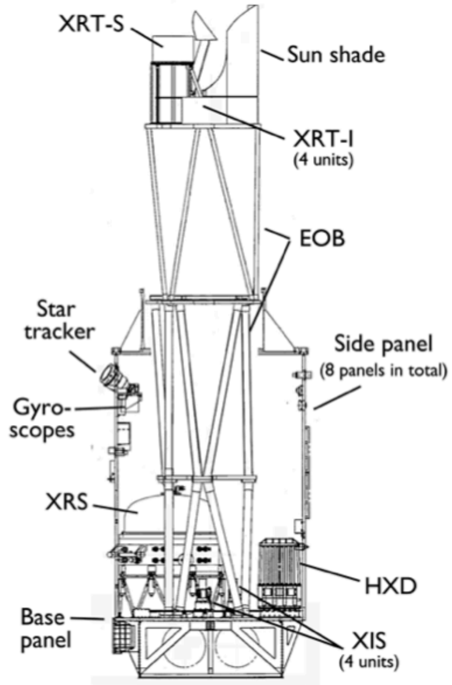
Outline

- Suzaku X-ray satellite and recent results
  - ✓ Fermi/LAT-detected radio galaxies
  - ✓ Thermal X-ray emission from radio lobes
- MAXI (all-sky X-ray monitor on ISS) and recent results
- Future Astro-H perspectives:
  - ✓ Soft gamma-ray polarimetry for bright blazars
  - ✓ Study "disk-jet-wind" connection using Ultra-high resolution (~7 eV) and wide-band spectroscopic capability (0.3-600 keV)

Suzaku X-ray satellite



Launched on 2005 July 10,
Low Earth Orbit (~550 km)

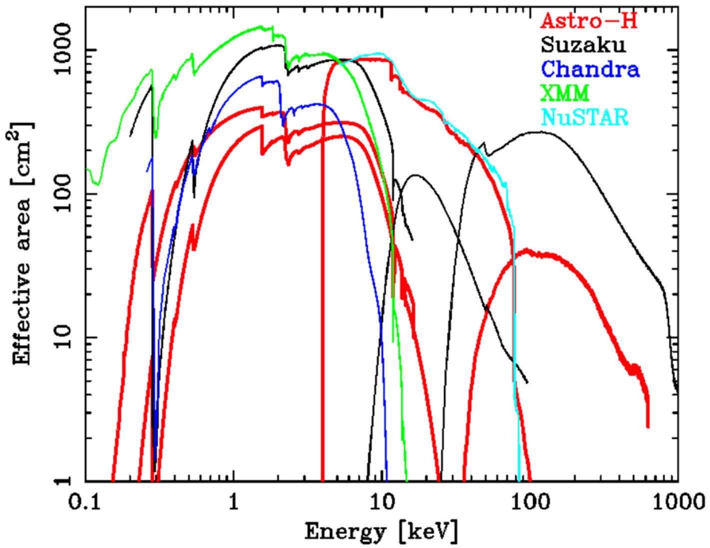


XIS: CCD, 0.3-10 keV
(3 CCDs are now working)

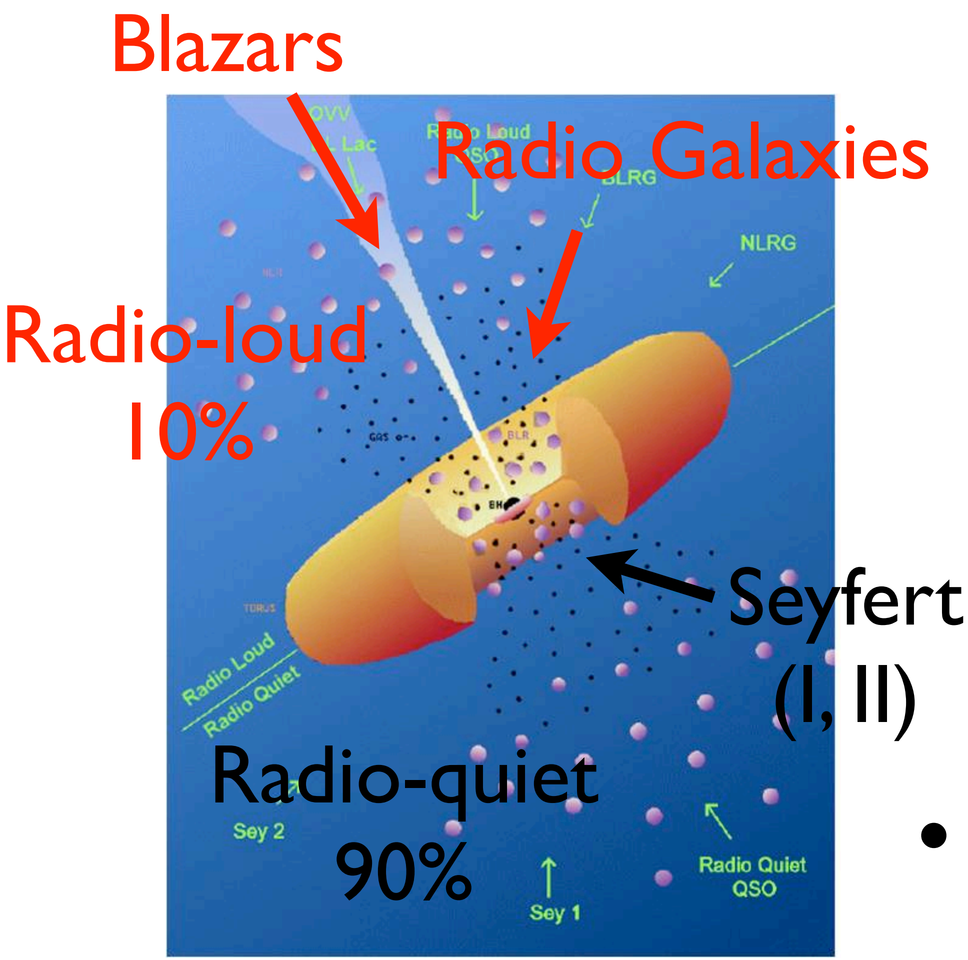
HXD: PIN and GSO
(cover 10-500 keV band)

XRS: micro-calorimeter
(Helium is lost before science observation)

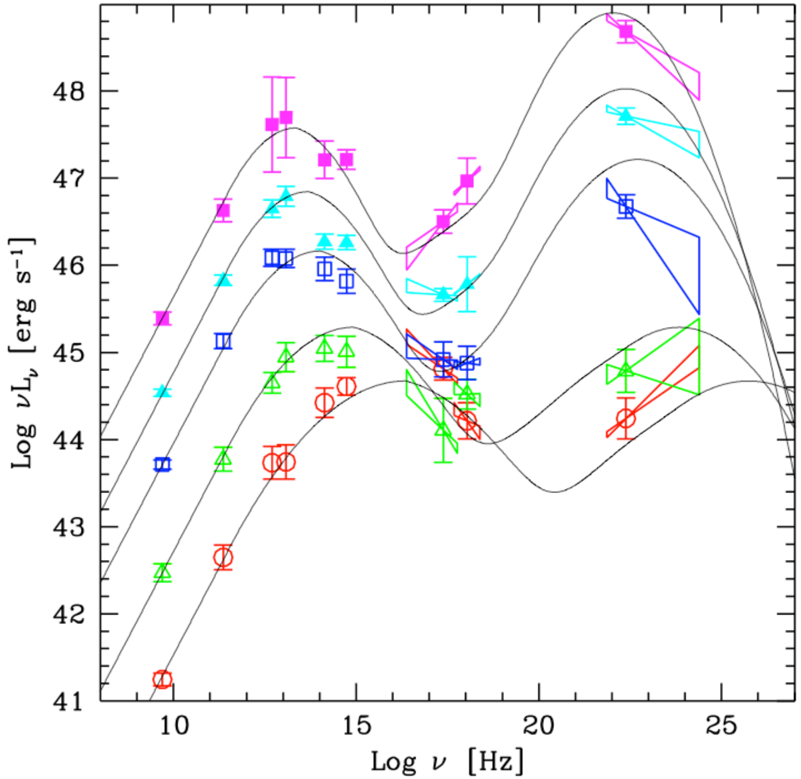
- Wide-band (0.3-500 keV) simultaneous spectroscopy with XIS+HXD
- XIS has larger effective area at E>~5 keV, suitable to study Fluorescence Fe K line at 6.4 keV
- Low and steady background of XIS, suitable to observe low surface-brightness spatially-extended emissions such as outskirts of galaxy clusters and thermal/nonthermal emission from radio lobes



AGN jets and Blazars



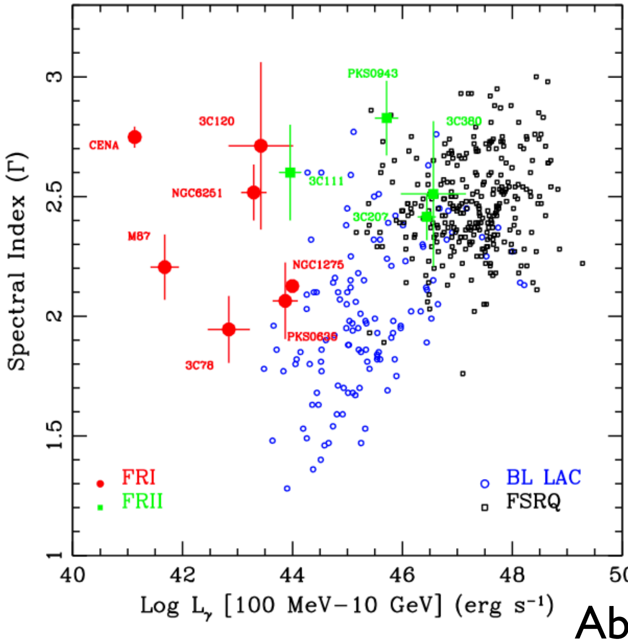
Unified model of AGN



e.g., Fossati+98, Kubo+98, Donate+01

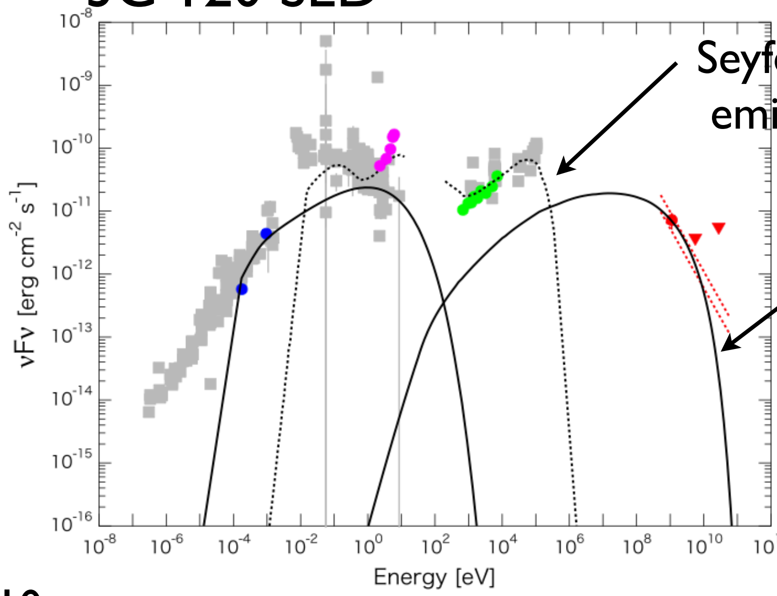
- Non-thermal emission dominates over the whole frequencies due to beaming effect
- Sync+IC emissions by high-E electrons

Viewing angles for radio galaxies are larger than blazars, hence jet emission is not enhanced like blazars



Abdo+10

3C 120 SED



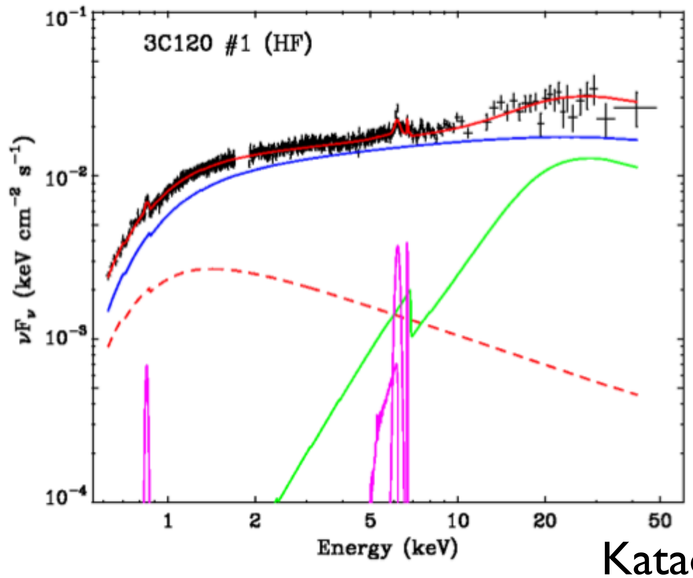
Seyfert-like disk/corona emission (dashed line)

Sync+SSC jet emission (solid line)

Tanaka+15, Kataoka+11

Cen A, NGC 1275, M87, NGC 6251,
3C 111, 3C 120, 3C 78, PKS 0625-354

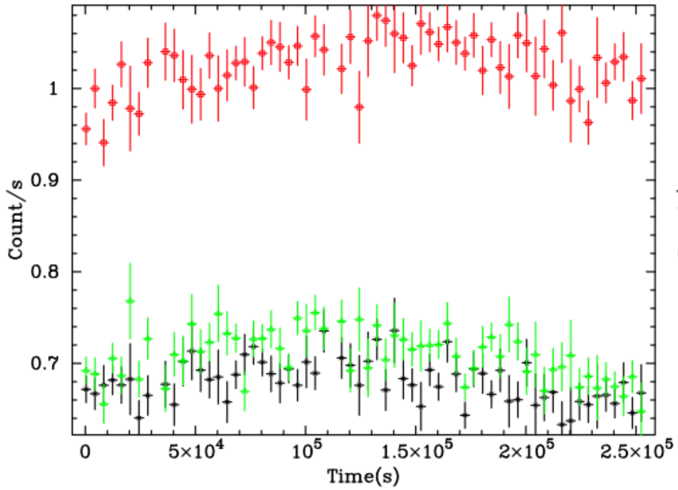
- PKS 0625-354 and 3C 78 are not well studied in X-ray band
- Disk/corona or jet origin?
- PL index, variability, and EW of Fe K-line are useful to reveal the X-ray origin



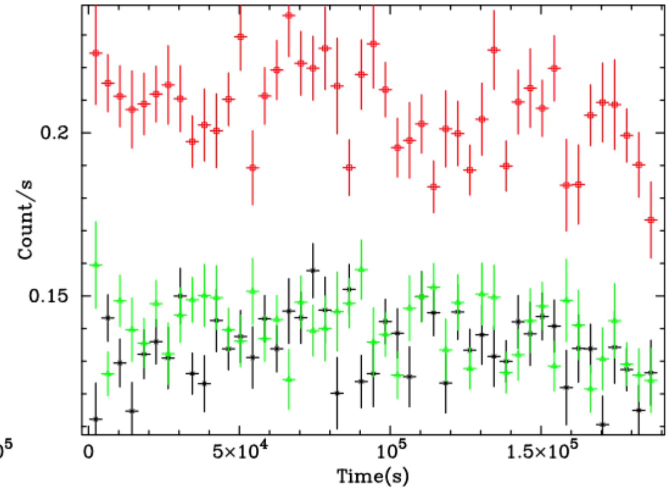
Kataoka+07

0.45-8 keV light curve and spectrum

PKS 0625-354

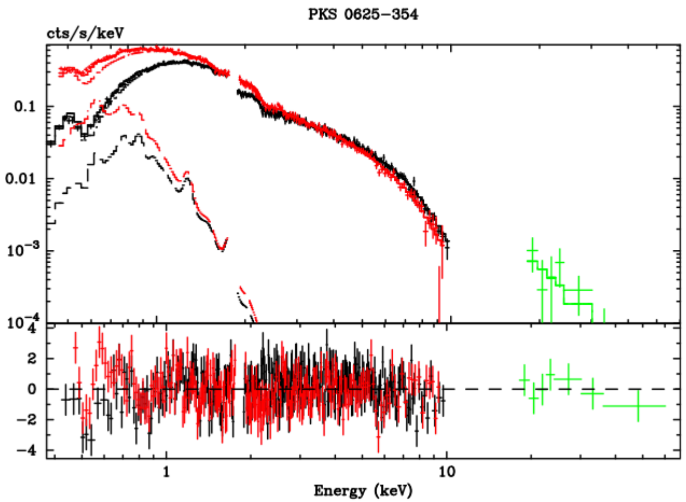


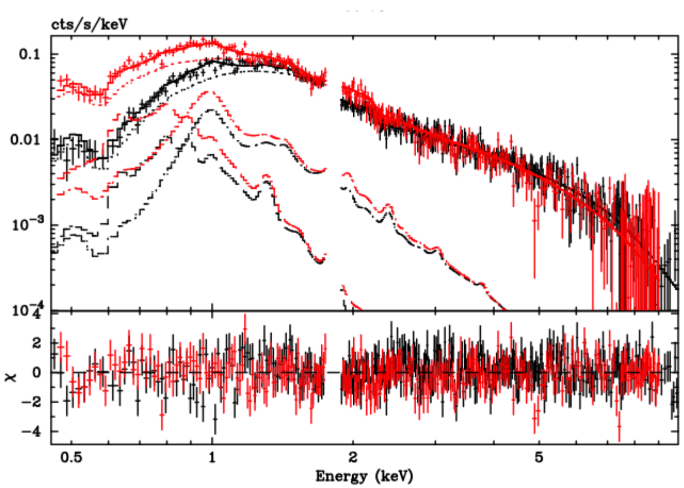
3C 78



XIS1 (BI), XIS0 (FI), XIS3 (FI)

- No significant rapid flux change
- Small (~10%) flux variation in dayscale for PKS 0625, while no significant change for 3C 78





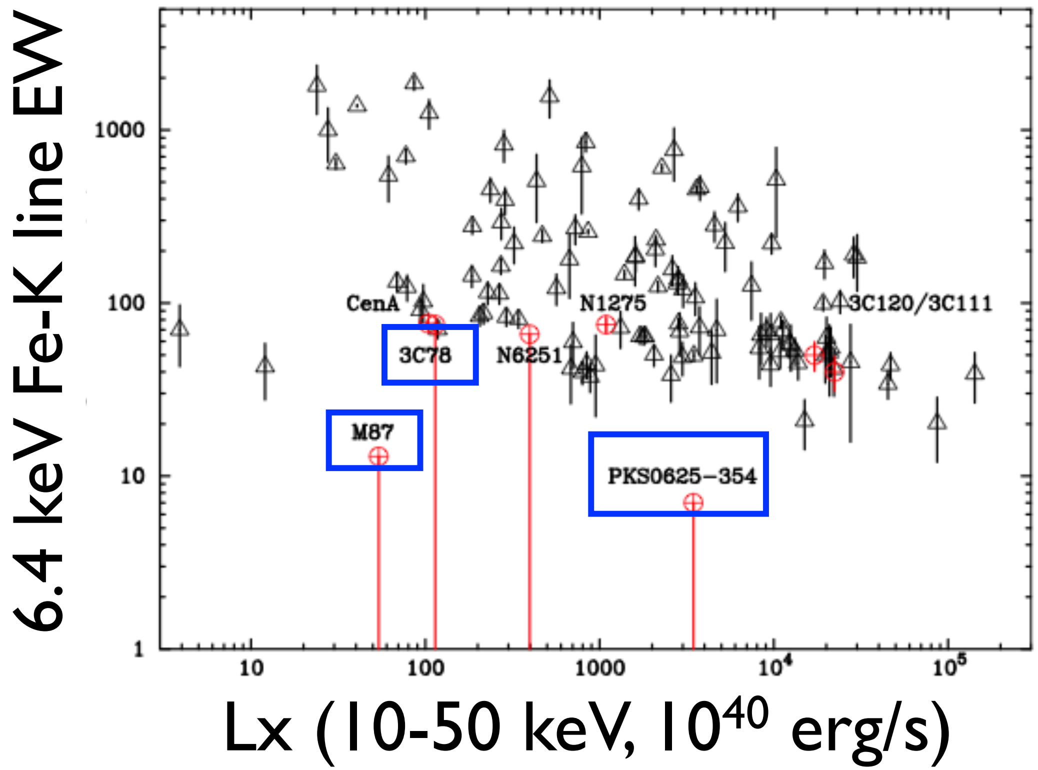
- Fluorescence Fe-K lines are common features in Seyferts (dominated by disk emission), but no sign of fluorescence Fe-K lines (EW<7 and 75 eV for PKS 0625 and 3C 78)

Γx=2.25+/-0.02, Lx=4.9E+43

Γx=2.32+/-0.04, Lx=2.0E+42

Fukazawa, YTT, 2014

Fe K-line EW vs hard X-ray luminosity for seyfert galaxies and radio galaxies



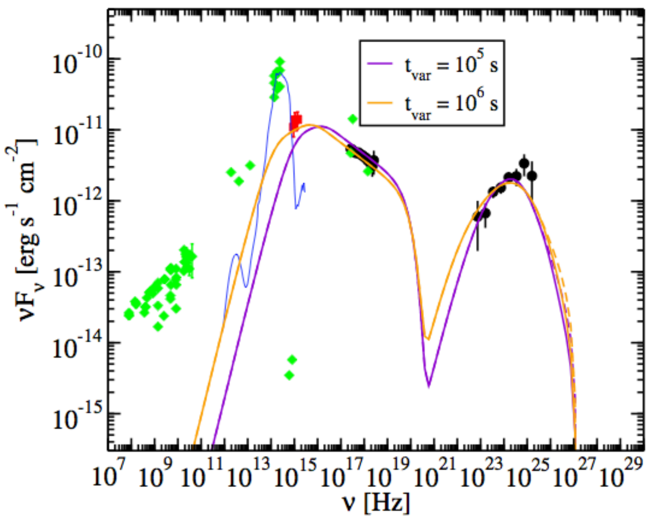
- Some RGs (e.g. Cen A and 3C 120) locate at the same region as Seyfert, suggesting disk/corona origin for X-rays
- Strong ULs for M87, PKS 0625, and 3C 78 indicate that X-rays are jet origin, rather than Seyfert-like disk/ corona origin

Source (1)	N_H (10^{20} cm^{-2}) (2)	kT (keV) (3)	Z ($Z_\odot$) (4)	$L_{0.5-10\,keV}$ (10^{42} erg s^{-1}) (5)	Γ_X (6)	$L_{2-10\,keV}$ (10^{42} erg s^{-1}) (7)	EW (eV) (8)	χ^2/dof (9)
M87	10 ± 6 (1.9)	1.79 ± 0.02	1.4 ± 0.8	13	2.42 ± 0.03	0.7	<13	674/572
		2.28 ± 0.03	1.4 ± 0.2					
PKS 0625−354	9 ± 1 (6.36)	0.24 ± 0.02	$0.3^{(f)}$	9.6	2.25 ± 0.02	49	<7	640/486
3C 78	14 ± 2 (9.51)	0.29 ± 0.04	$0.3^{(f)}$	1.0	2.32 ± 0.04	2.0	<75	572/567
		1.07 ± 0.06	$0.3^{(f)}$					
NGC 6251					$1.82^{+0.04}_{-0.05}$	2.86	<66	
3C 111					1.65 ± 0.02	259	40 ± 9	
3C 120					$1.75^{+0.03}_{-0.02}$	100	50 ± 10	
NGC 1275					1.73 ± 0.03	7.7	75 ± 7	
Cen A					1.73 ± 0.03	10	76 ± 3	

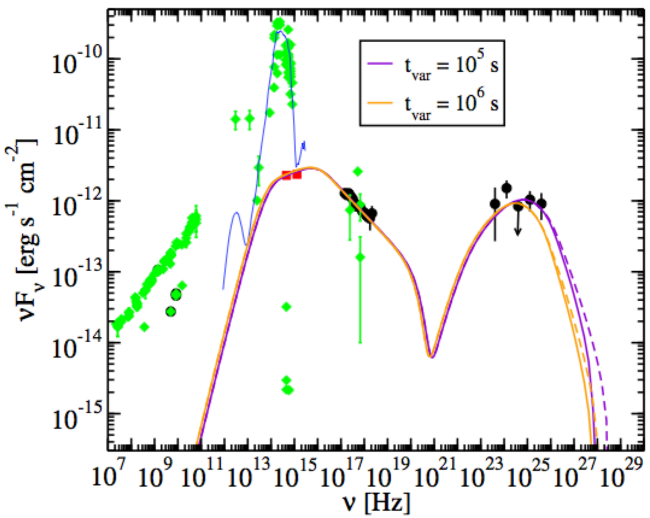
Fukazawa, YTT, 2014

One-zone Sync+SSC modeling

PKS 0625-354



3C 78



- X-ray emission, found to be dominated by jet emission, is included in SED modeling
- Bulk Lorentz factor and beaming factor are ~5, comparable to other LAT-detected RGs, and lower than BL Lac objects

Table 5
SED Model Parameters of Radio Galaxies

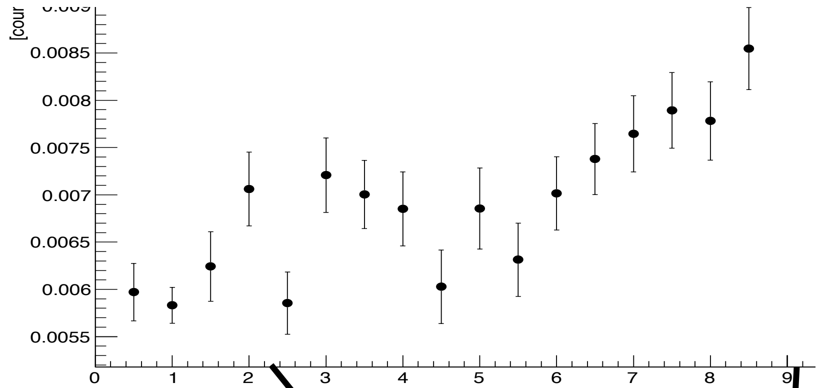
	PKS 0625−354		3C 78		Cen A	M87	NGC 1275	NGC 6251
Γ	5.8	5.7	2.93	5.75	7.0	2.3	1.8	2.4
δ	5.8	5.8	2.92	5.75	1.0	3.9	2.5	2.4
θ (deg)	10	19	20	20	30	10	25	25
B (G)	0.82	0.11	0.77	0.02	6.2	0.055	0.05	0.04
t_v (Ms)	0.1	1	0.1	1	0.1	1.2	30	1.7
R_b (10^{16} cm)	1.6	16	0.85	17	0.3	1.4	200	12
p_1	2.5	2.5	2.7	2.7	1.8	1.6	2.1	2.75
p_2	3.5	3.5	3.7	3.7	4.3	3.6	3.1	4.0
γ_{min}	6×10^3	6×10^3	1×10^3	1×10^4	3×10^2	1	8×10^2	250
γ_{max}	2×10^6	6×10^6	2×10^7	2×10^7	1×10^8	1×10^7	4×10^5	4.4×10^5
γ_{brk}	2.9×10^4	4.6×10^4	7.3×10^4	1.4×10^5	8×10^2	4×10^3	9.6×10^2	2.0×10^4
$P_{j,B}$ (10^{42} erg s^{-1})	43	740	0.3	2.5	65	0.02	230	0.4
$P_{j,e}$ (10^{42} erg s^{-1})	2	10	0.6	13	31	7	120	160

Variable X-ray emission from NGC 1275

- Perseus cluster center is one of calibration targets for Suzaku and the central galaxy NGC 1275 is always located at the CCD center
- 40 ks exposure every half an year (Feb. and Aug.)

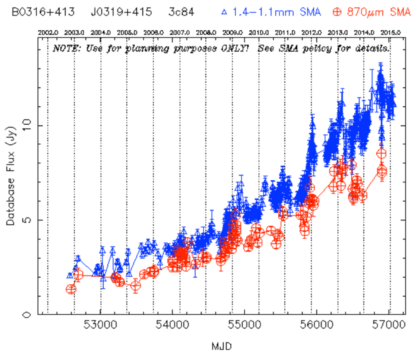
2006-2014 Suzaku light curve shows possible increasing trend

First evidence of X-ray variability from NGC 1275



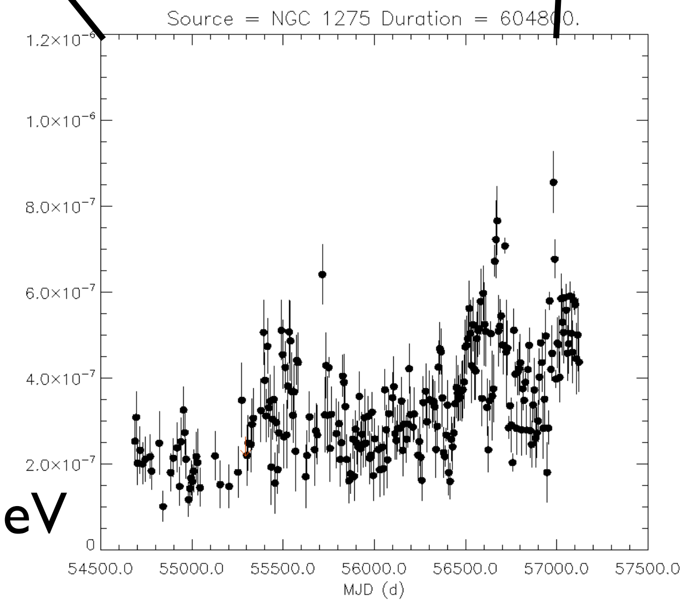
Edahiro, YTT 2015, Fermi sympo. Proc. arXiv: 1503.02890

SMA sub-mm light curve
1.4-1.1 mm and 870 um



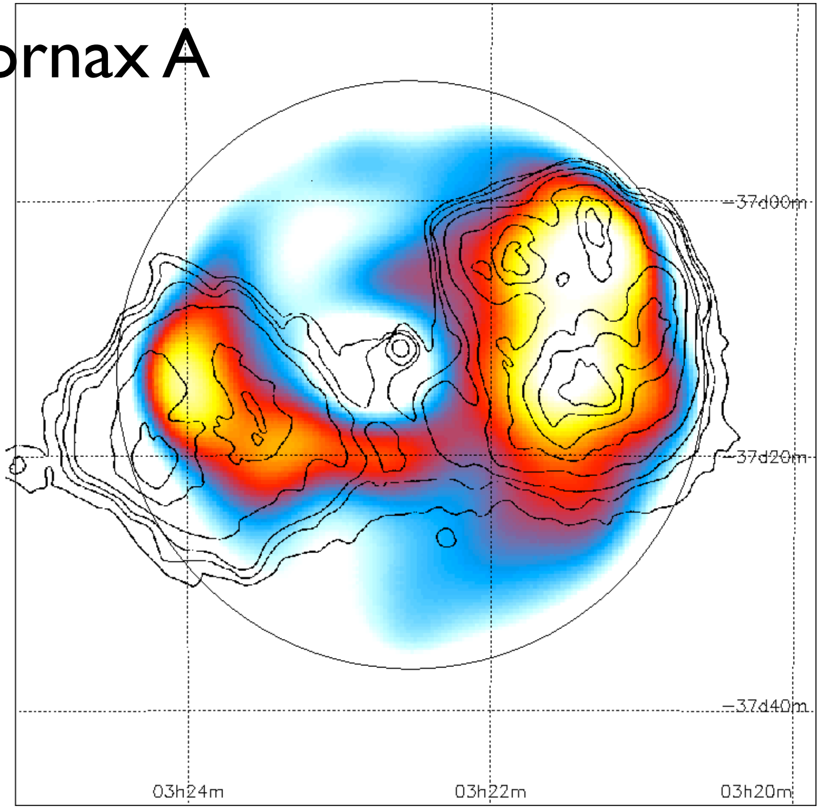
Possible correlation with GeV and sub-mm flux increase may suggest X-rays are jet origin? (but disk origin is still viable)

LAT 0.1-300 GeV



Extended non-thermal hard X-ray emission

Fornax A

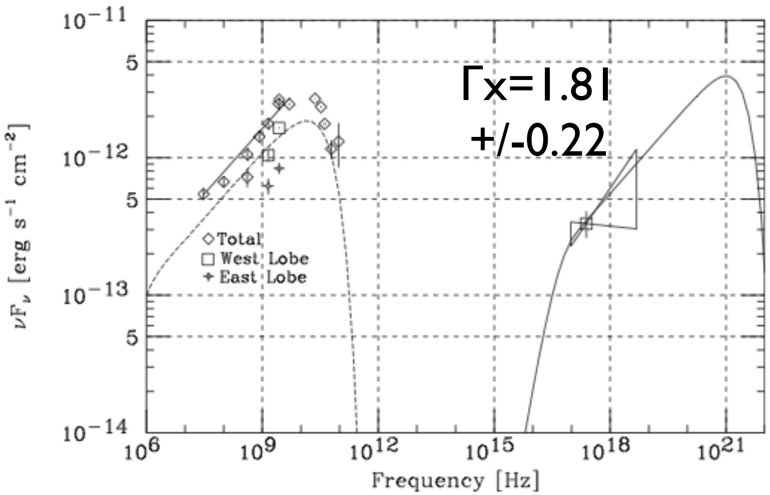


ASCA 2-10 keV image with VLA contour (Kaneda+95)

Radio-emitting relativistic electrons inside the lobe can produce IC X-rays by upscattering CMB photons

$$\nu_{\rm sync} \simeq 1 \left(\frac{B}{1\ \mu{\rm G}}\right) \left(\frac{\gamma}{10^{4.5}}\right)^2\ {\rm GHz}$$

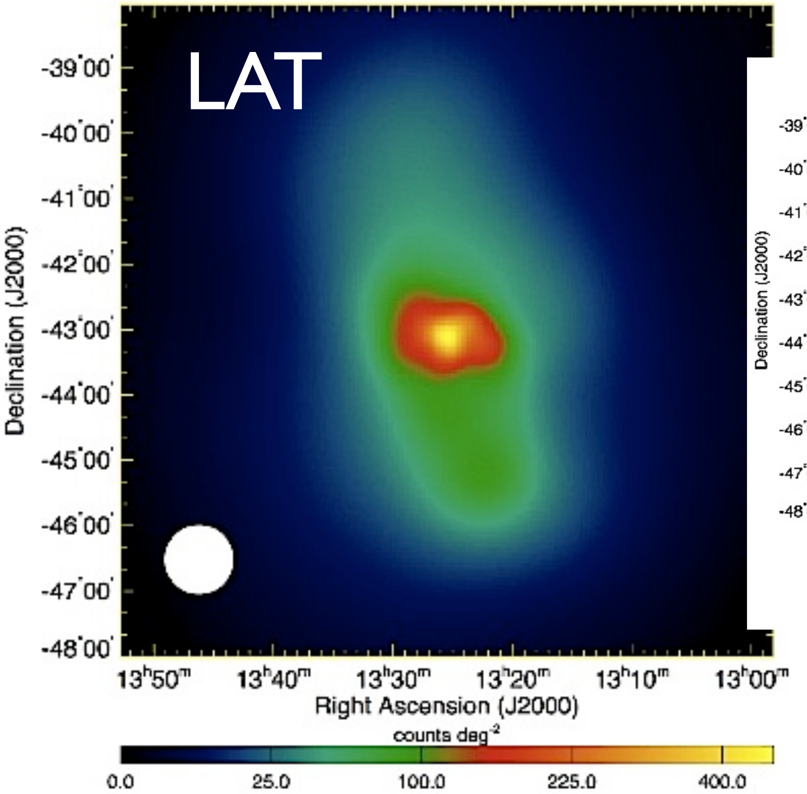
$$h\nu_{\rm IC} \simeq 20 \left(\frac{\gamma}{10^{4.5}}\right)^2 \left(\frac{h\nu}{3\ {\rm K}}\right)\ {\rm keV}$$

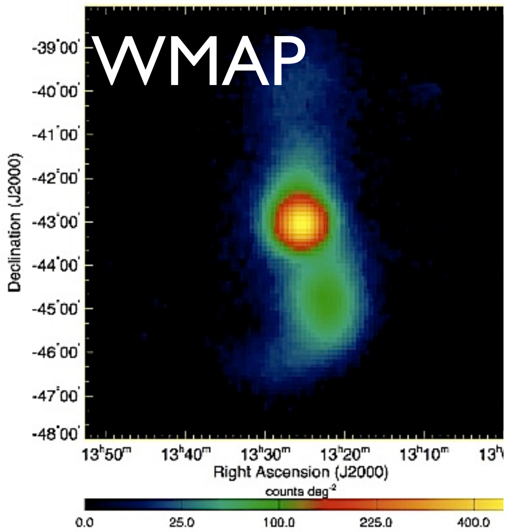


B=1.3 uG
Ue/Um=7.5
(Tashiro+09)

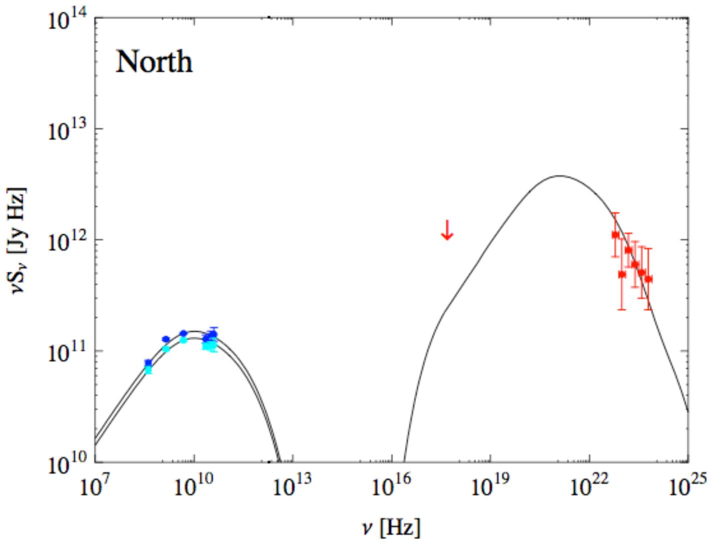
- IC X-rays from radio lobes were detected from many sources by Chandra/XMM/Suzaku, and Ue/Um=1-100 is found (e.g., Croston+05, Konar+10, Isobe+11)

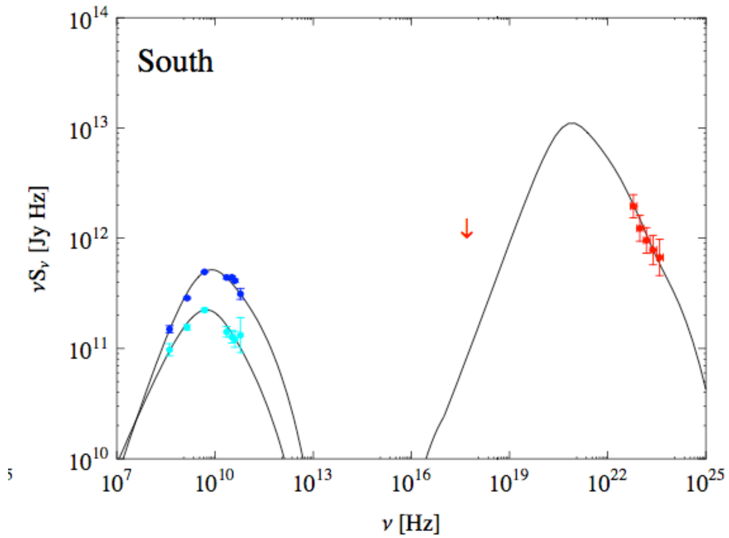
Fermi-LAT resolved giant gamma-ray lobe





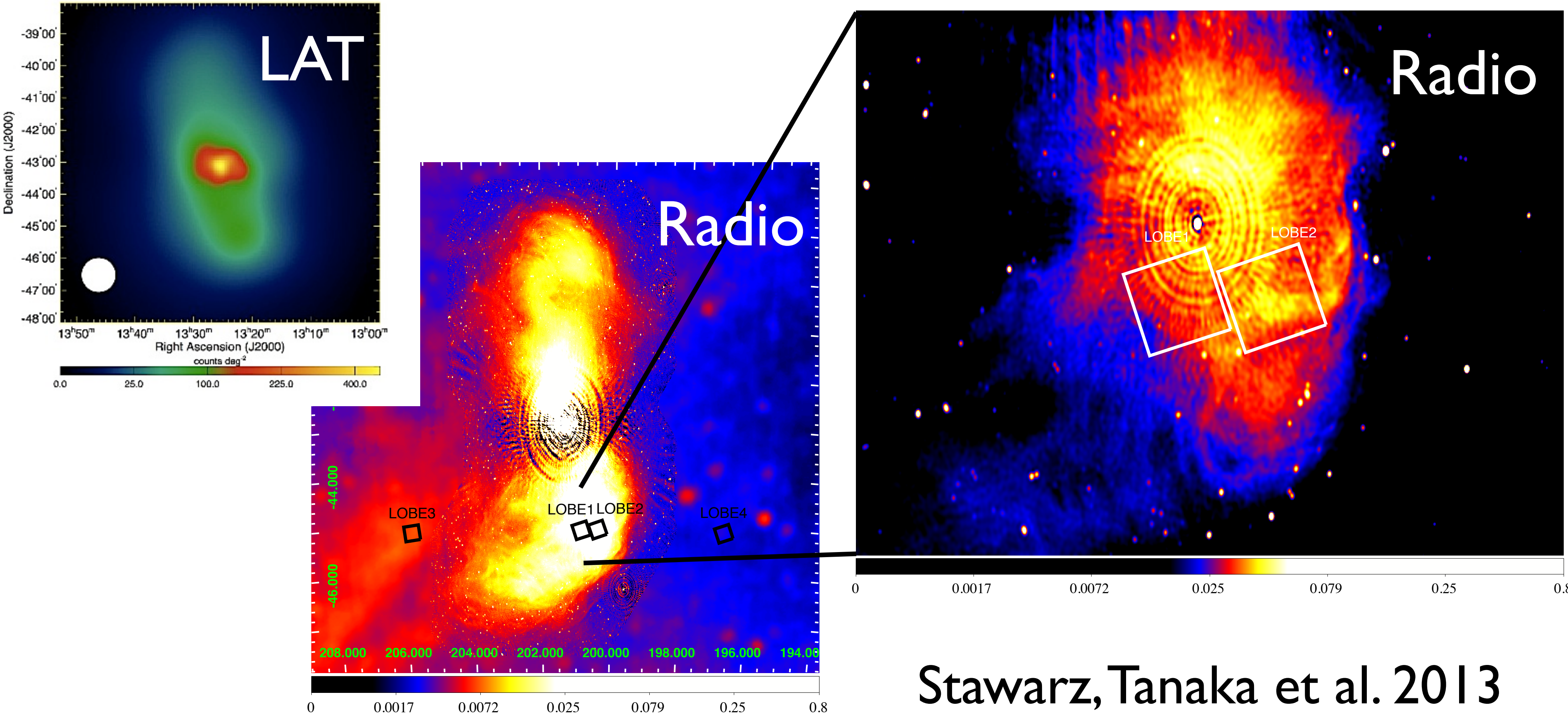
Abdo+11





- Fermi-LAT resolved Cen A giant lobe at E>100 MeV
- Gamma-rays are produced through IC of CMB, EBL etc
- Northern lobe: B=0.89 uG, Ue/UB=4.3
- Southern lobe: B=0.85 uG, Ue/UB=1.8

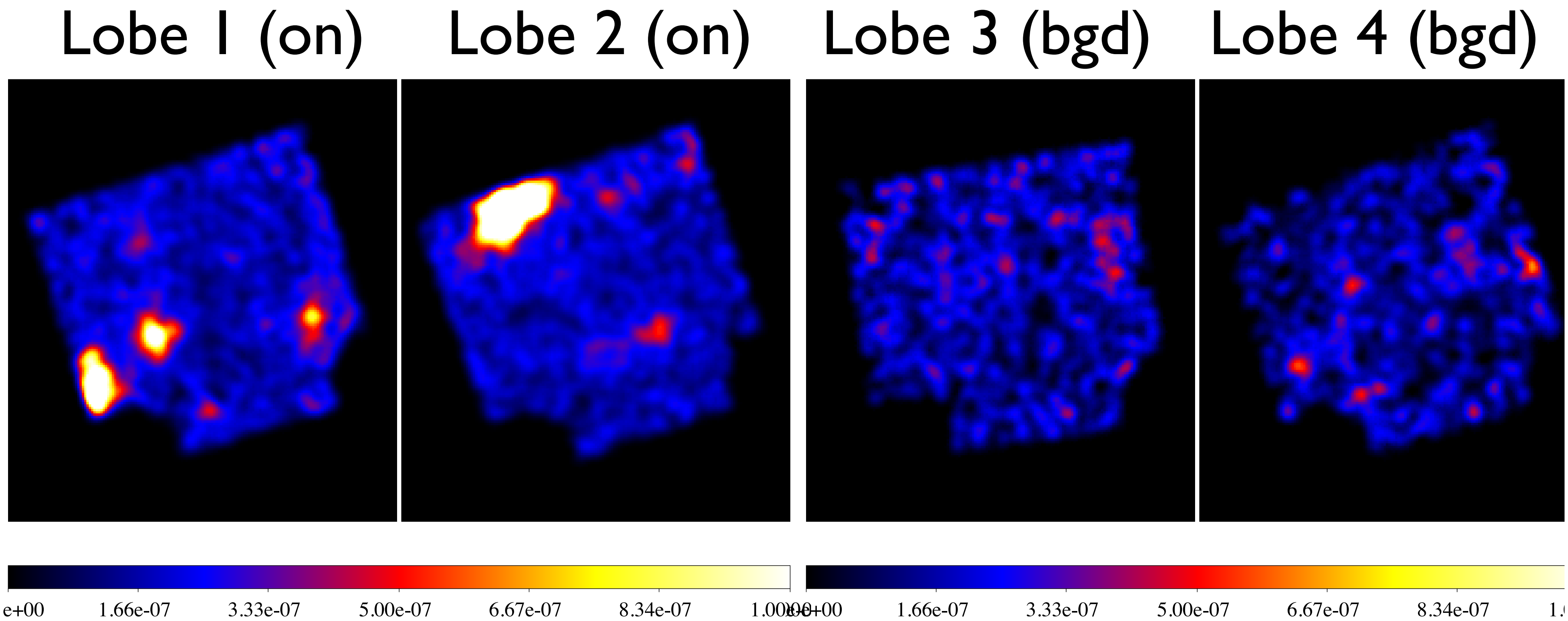
Suzaku X-ray pointings in 2011



Stawarz, Tanaka et al. 2013

- Suzaku is suited to observe faint diffuse emission thanks to low non X-ray background
- Gamma-ray intense region (80 ks x 2, BGD: 20 ks x 2)

Exposure-corrected NXB-subtracted XIS1 images (0.5-2 keV)



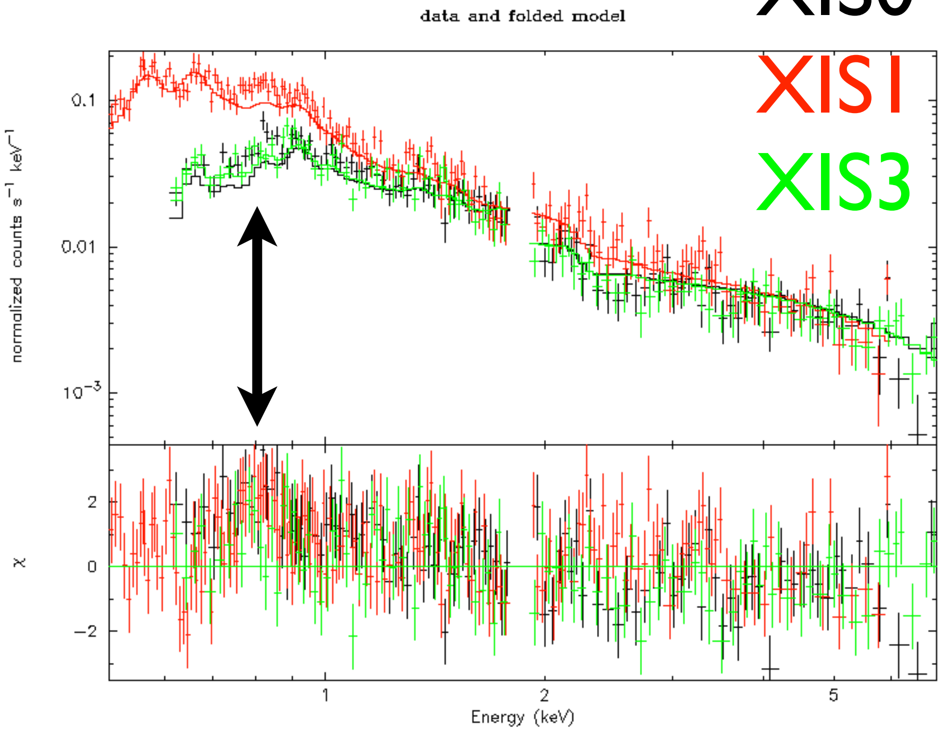
Color bars are the same range and scale

The unit is [counts/s/64pixels]

Comparison with BGD spectrum

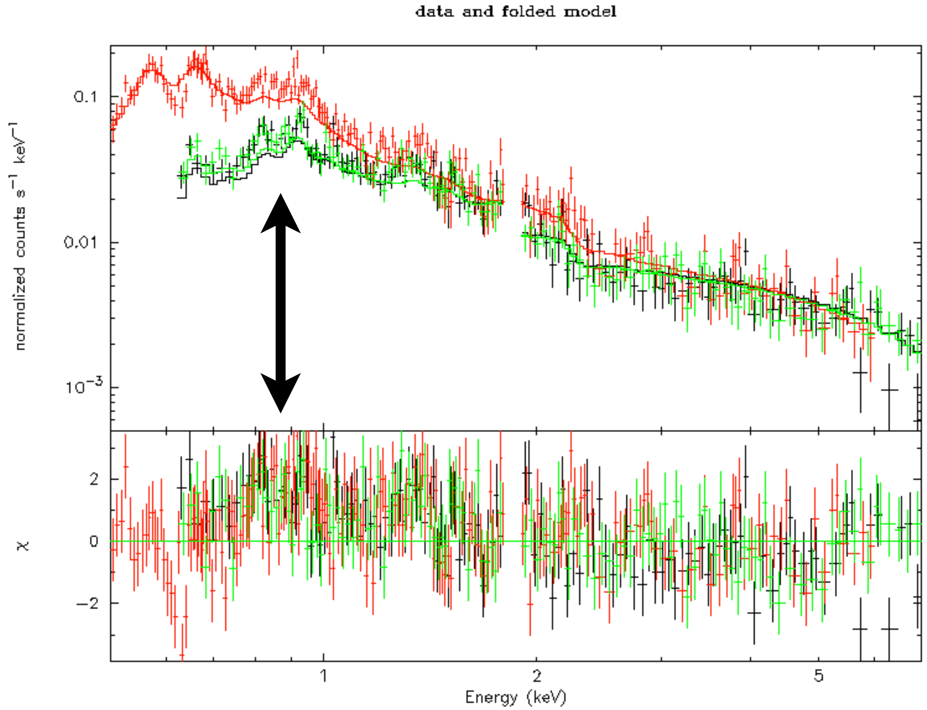
Lobe 1

XIS0
XIS1
XIS3



Reduced chi/dof=1.524/446

Lobe 2



Reduced chi/dof=1.512/517

- Lines show background emissions produced by using best fit parameters from background observation (Lobe3)
- Excess soft emissions are seen around 0.8 keV

Additional thermal component

- In the model, additional mekal component is added (which represents lobe-related thermal emission), namely mekal+wabs*(mekal+pow+mekal)
- Parameters of 3 BGD components are fixed to those obtained from Lobe3 data fitting
- And then, Lobe 1 and 2 data were fitted

Model	Parameter	Lobe1	Lobe2
	BGD	Lobe3	Lobe3
Thermal 1	kT [keV]	0.20 (fixed)	
(LHB)	Z	1.0 (fixed)	
	Norm $[10^{-3}]$	3.30 (fixed)	
Absorption	$N_{\rm H}$	0.0707 (fixed)	
Thermal 2	kT [keV]	0.70 (fixed)	
(GH)	Z	1.0 (fixed)	
	Norm $[10^{-4}]$	3.79 (fixed)	
Power-law	Γ	1.41 (fixed)	
(CXB)	Norm $[10^{-3}]$	1.04 (fixed)	
Thermal 3	kT [keV]	$0.46^{+0.08}_{-0.11}$	0.64 ± 0.05
(Lobe)	Z	1.0 (fixed)	
	Norm $[10^{-4}]$	$3.10^{+1.11}_{-0.53}$	$2.91^{+0.34}_{-0.35}$
	Flux (absorbed, 0.5-2 keV)	5.84E-13	5.83E-13
	$\chi^2_\nu/d.o.f$	1.20/444	1.13/515

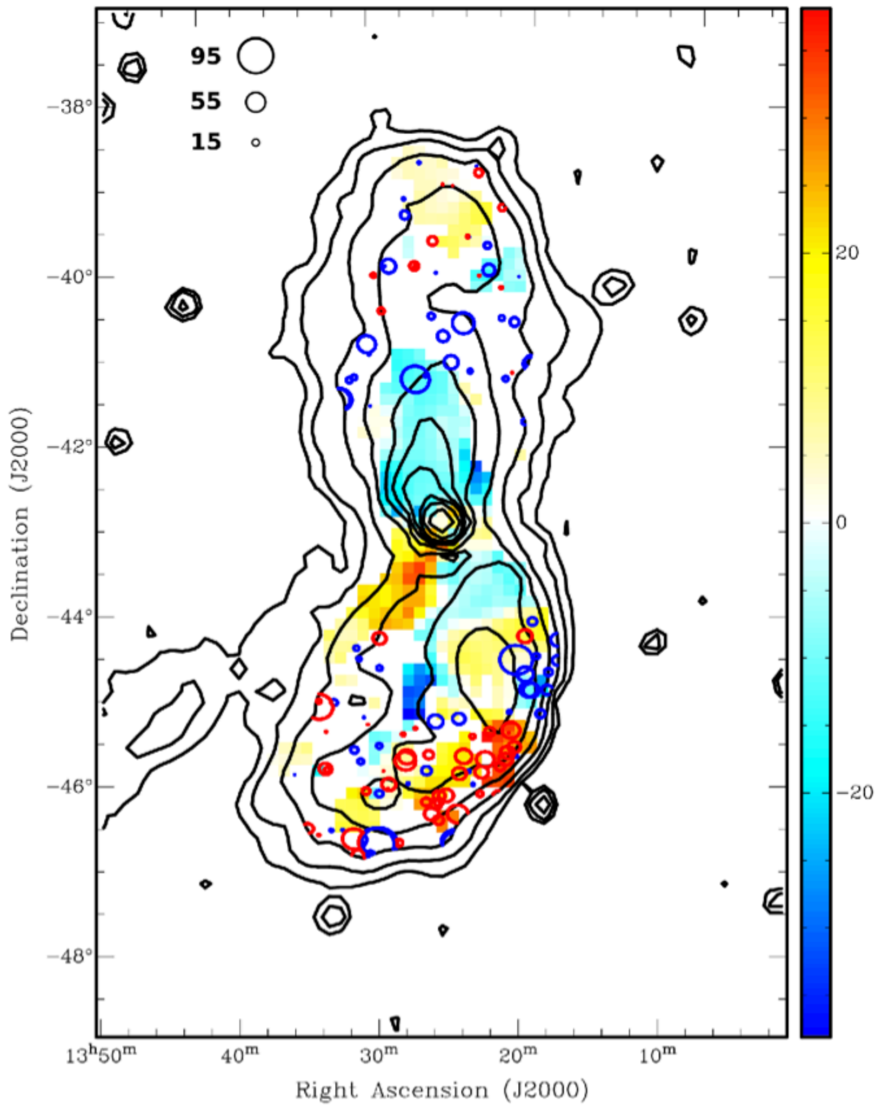
TABLE 3. The best fit model parameters. Flux unit is $[{\rm erg/cm^2/s/0.35deg^2}]$.

Thermal gas pressure

Mekal norm $$K = \frac{10^{-14}}{4\pi(D(1+z))^2} \int n_e n_H dV$$

- Assuming that the the lobe has a size of 130 kpc (=2 deg for D=3.7 Mpc) along the line of sight and thermal plasma uniformly distributes over the cylindrical volume, Ne~(1-2)x10^{-4} cm^{-3}
- Thermal gas pressure is P_g=nkT~8x10^{-14} erg/cm^3. This is almost comparable to non-thermal pressure of P_B+P_{rel} (In other words, plasma beta=P_g /P_B~1 inside radio lobe)

Latest radio observation of Rotation Measure



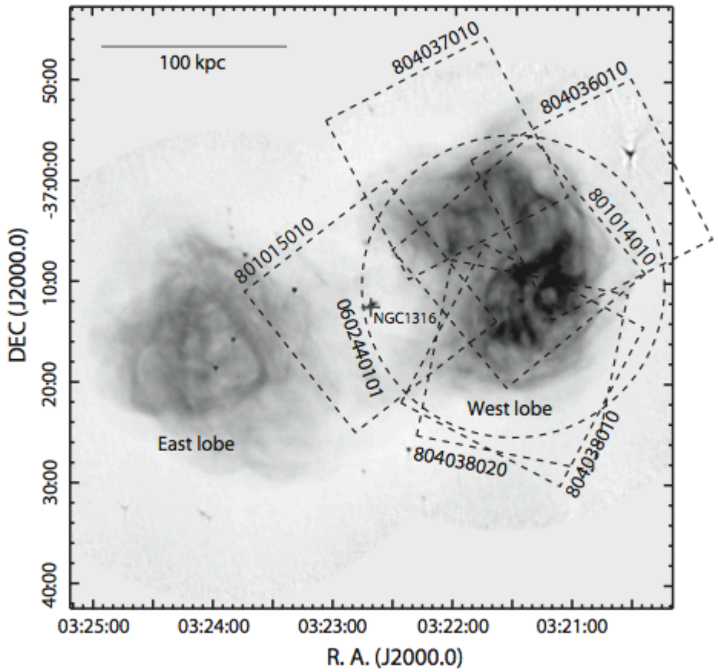
Residual RM map of Cen A lobe

(O'Sullivan+13)

$$\phi(L) = 0.81 \int_L^0 n_e B_{||} dl \ \ \text{rad m}^{-2},$$

A mean residual RM of ~12 rad m^{-2}, which corresponds to n_e~10^{-4} cm^{-3} (B~1uG, L~100 kpc)

The case of Fornax A west lobe



Fornax A exposures

Table 1. Suzaku and XMM-Newton data sets for For A.

Observatory	Sequence ID	Aiming position (J2000.0) R. A.	DEC	Observation start date	t_{exp}* (ks)
Suzaku	801015010	$03^h22^m40^s.4$	−37°12′10″	2006-12-22	86.7
	801014010	$03^h21^m40^s.4$	−37°09′52″	2006-12-23	42.9
	804036010	$03^h20^m53^s.3$	−37°02′03″	2009-06-08	54.8
	804037010	$03^h22^m05^s.5$	−37°58′03″	2009-06-09	55.5
	804038010	$03^h21^m25^s.9$	−37°18′39″	2009-06-30	47.0
	804038020	$03^h21^m25^s.7$	−37°18′40″	2009-08-02	39.6
XMM-Newton	0602440101	$03^h21^m29^s.3$	−37°11′30″	2009-06-25	59.5

* The mean exposure time of the three XIS sensors for Suzaku and the two MOS and one PN sensors for XMM-Newton.

Nearby BGD exposures

Table 2. Suzaku data sets for the comparison regions in the Fornax cluster.

Sequence ID	Position (J2000.0) R. A.	DEC	Observation start date	Dist.* (arcdeg)	t_{exp}† (ks)^b
703038010	$03^h31^m06^s.3$	−38°24′05″	2008-06-16	3.30	24.3
802037010	$03^h13^m10^s.4$	−37°40′25″	2007-06-28	5.55	15.0
802040010	$03^h19^m57^s.4$	−32°03′58″	2007-06-29	5.13	19.7

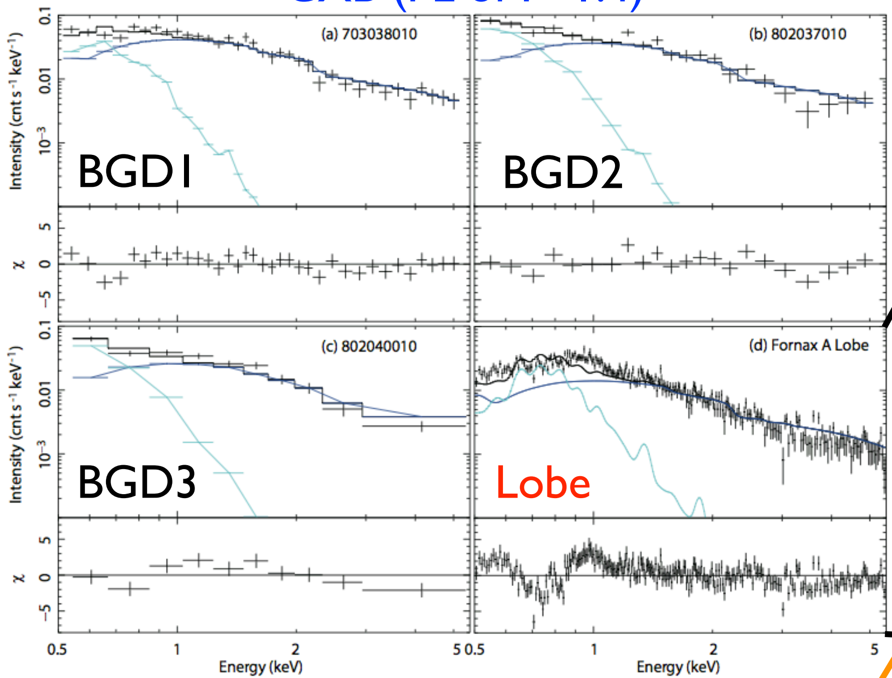
* The distance from the center of the Fornax cluster at (R. A., Decl.)=($03^h38^m30^s.9$, −35°27′16″).
† The mean exposure time of the three XIS sensors.

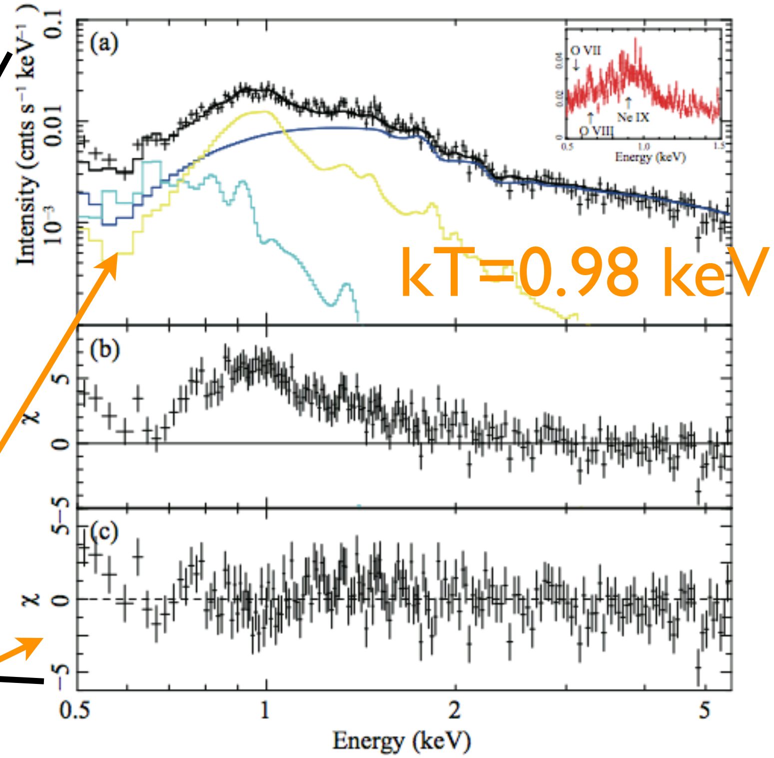
- Seta et al. (2013) analyzed archival Suzaku and XMM data to search for thermal emission from Fornax A West lobe
- Analysis method is quite similar: Comparison with BGD observations and search for excess thermal emission

Thermal emission from Fornax A west lobe

Fit by foreground Galactic thermal emission (Apec)

+CXB (PL of Γ=1.4)





Residuals disappeared by adding another Apec

Seta+13

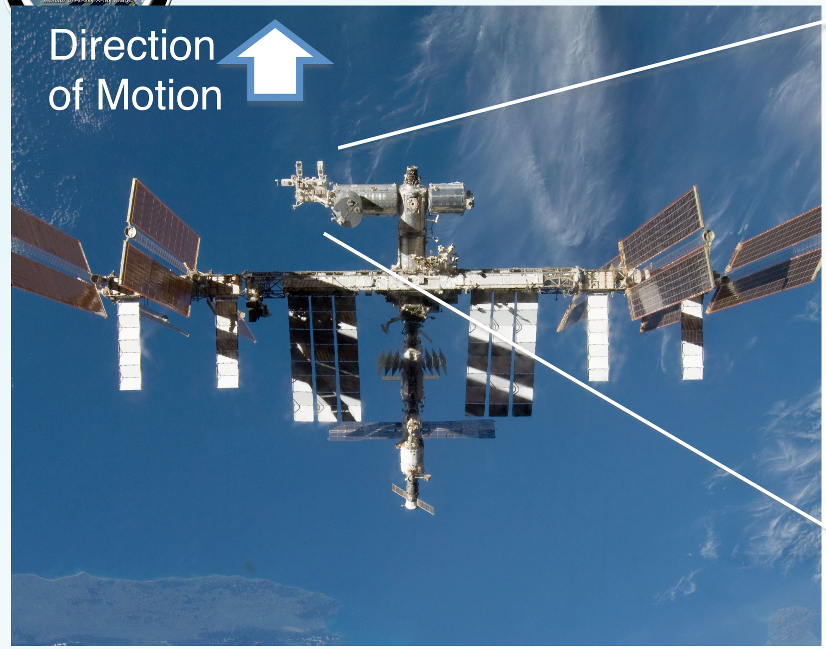
Object	n_e (cm^{-3}) (1)	k_BT (keV) (2)	V (cm^3) (3)	ϵ_T (erg cm^{-3}) (4)	ϵ_{mag} (erg cm^{-3}) (5)	$\epsilon_{NT,e}$ (erg cm^{-3}) (6)	R (7)
For A†	3.0×10^{-4}	1.0	3.4×10^{70}	1.4×10^{-12}	6.7×10^{-14}	5.0×10^{-13}	2.5
Cen A‡	0.9–2.5×10^{-4}	0.5	2.0×10^{71}	2.4×10^{-13}	4.0×10^{-14}	5.2×10^{-14}	2.6

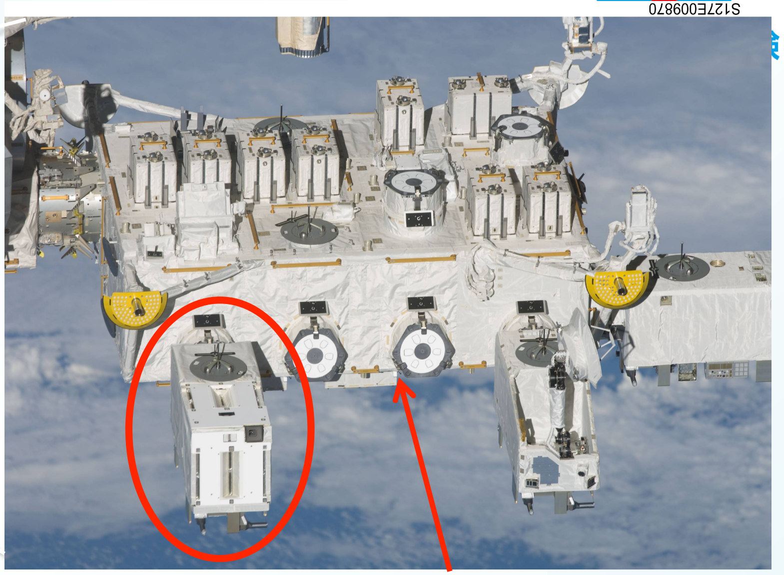
* The parameters are (1) electron density, (2) temperature, and (3) emitting volume (cm^3) assuming a volume filling factor of unity for the lobe thermal emission. The energy densities of (4) the thermal emission, (5) magnetic field, and (6) non-thermal electrons. (7) The ratio of energies in thermal to non-thermal components defined as $\epsilon_T/(\epsilon_{mag}+\epsilon_{NT,e})$.

Total mass of entire lobe is~10^{10}M_sun for both

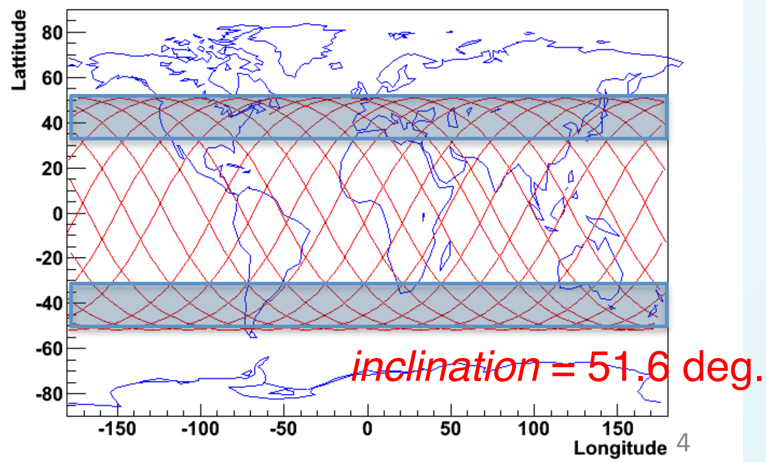
- Thermal/Non-thermal ratio is ~1, quite similar to Cen A lobe

MAXI (Monitor of All-sky X-ray Image) on ISS





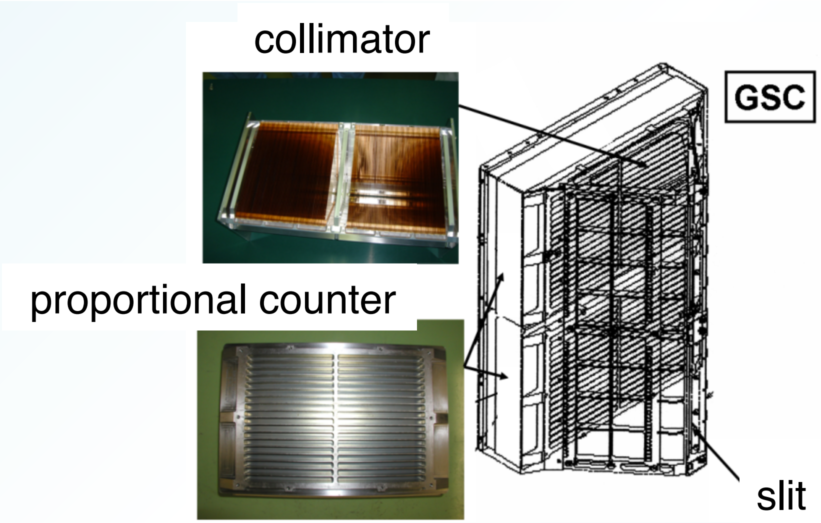
- The first astronomical mission on ISS
- Transported by Space Shuttle (Endeavour) on July16, 2009
- Installed on JEM (Japanese Experimental Module, KIBO) EF (Exposed Facility) on July 23.
- First Light on August 15.

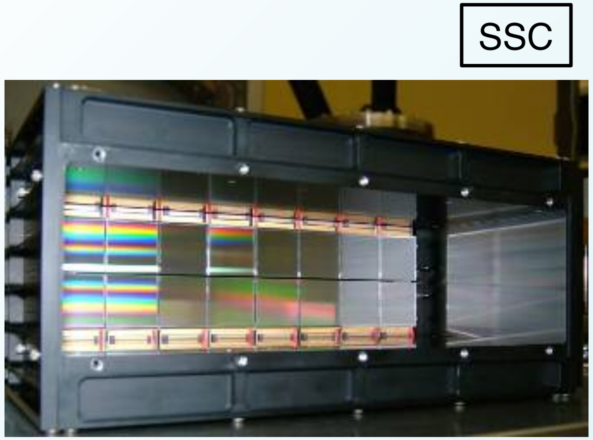


Taken from N. Kawai's slide at MAXI workshop in 2010

Detectors

	GSC (X-ray Gas Camera)	SSC (X-ray CCD Camera)
Detector	Gas(Xe) prop. counter x12	CCD 16 chips x 2 camera
Energy range (Q.E.>10%)	2−30 keV	0.5−12 keV
Energy resolution (FWHM)	15.7%(at 8.0keV)	< 2.5%(150eV) (at 5.9keV)
Time resolution & accuracy	<200μsec	~6 sec
Instantaneous sky coverage	2.4 % of the whole sky (160 deg x 3 deg x 2 sets)	1.4% of whole sky (90 deg x 3 deg x 2 sets)
Point Spread Function	1.5 degree	1.5 degree
sensitivity	2 mCrab (week)	5 mCrab (week)





Taken from N. Kawai's slide at MAXI workshop in 2010

“First light” MAXI-GSC all-sky X-ray image over one ISS orbit (~90 min)

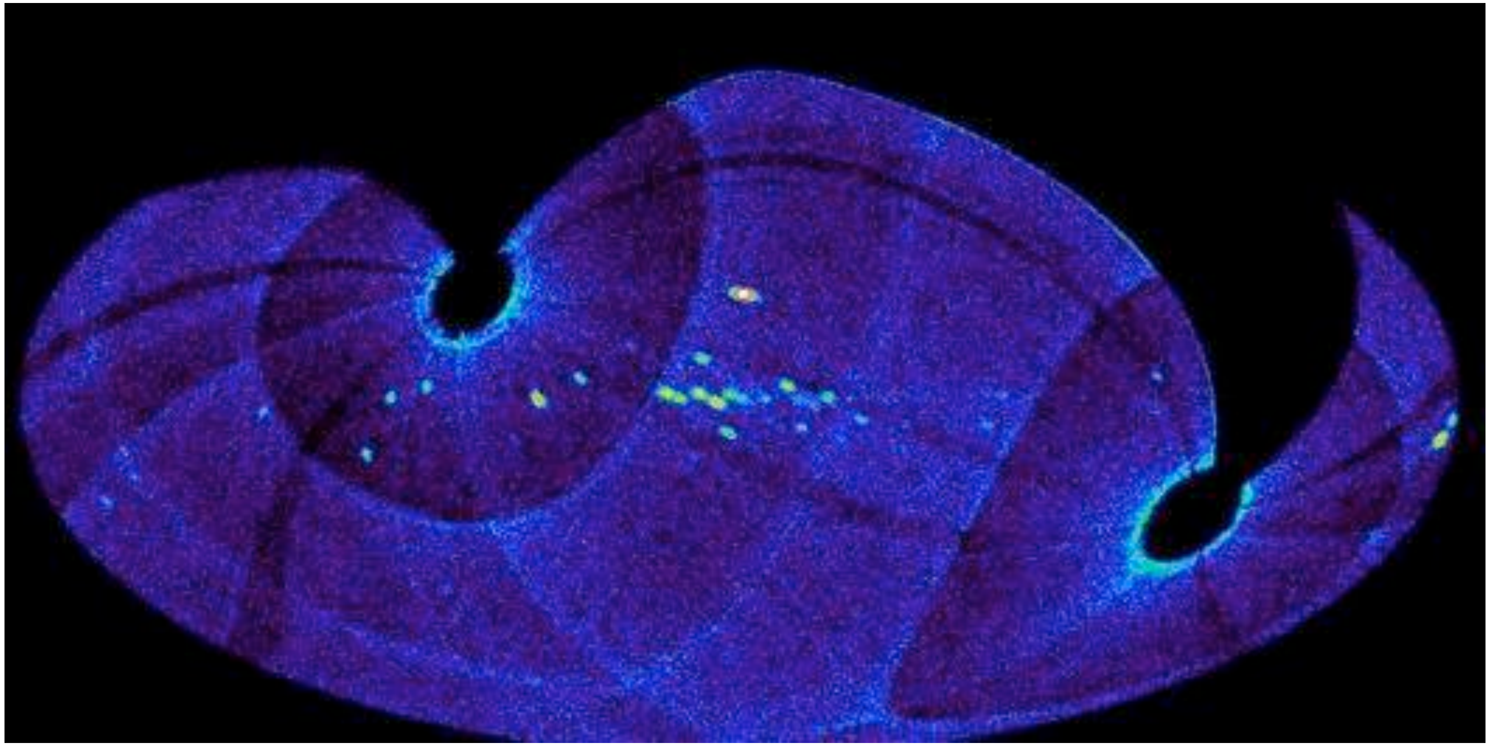
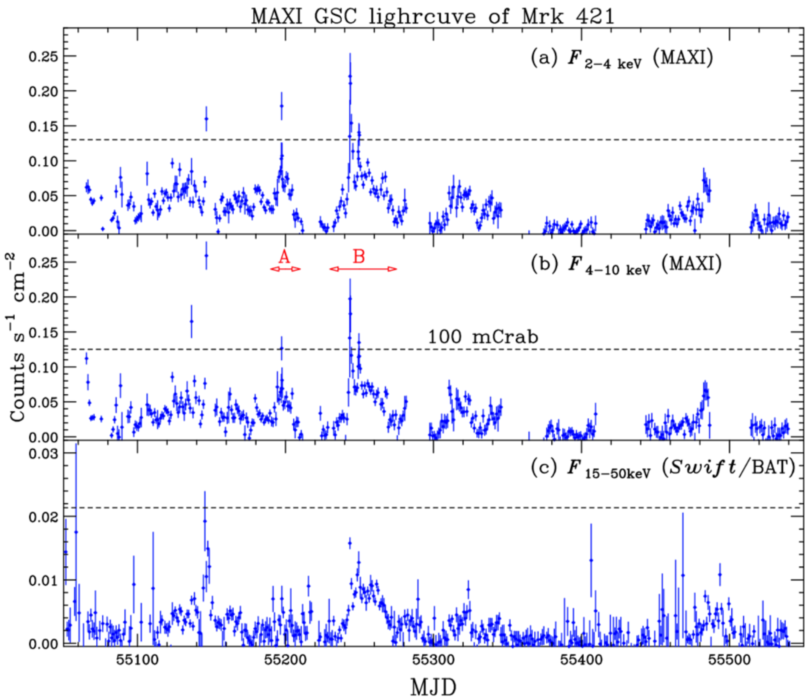
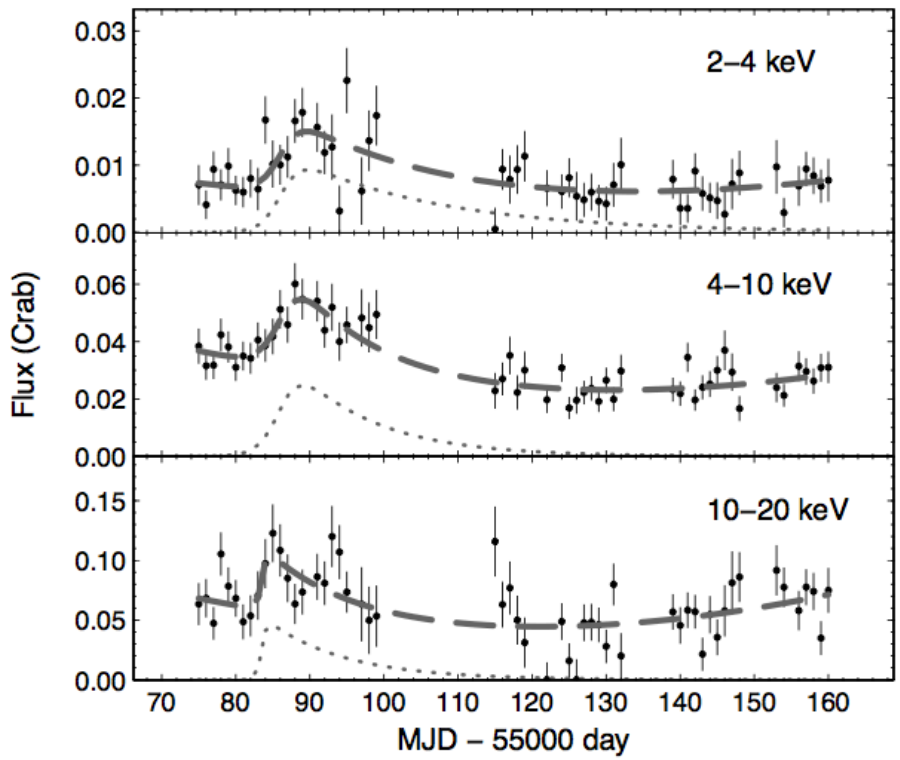


Image courtesy of Japan Aerospace Exploration Agency (JAXA)

Long-term light curves from bright sources such as Mrk 421 and Cen A



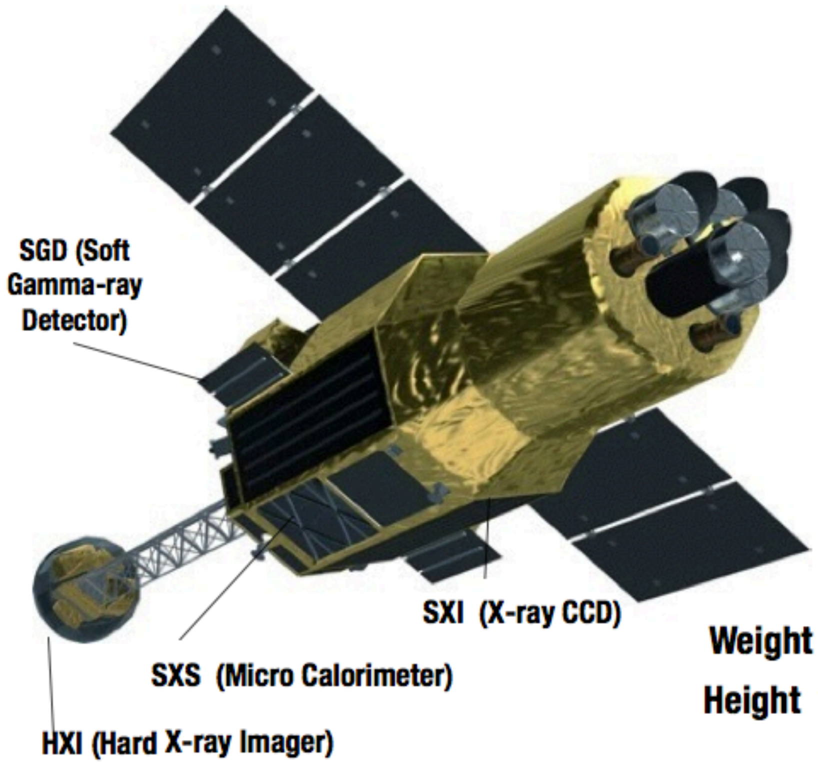
Isobe+11



Tachibana+15, arXiv: 1504.03208

- Bright X-ray flares from Mrk 421
- Soft X-rays are delayed w.r.t hard X-rays by ~5-10 days

2. ASTRO-H Mission



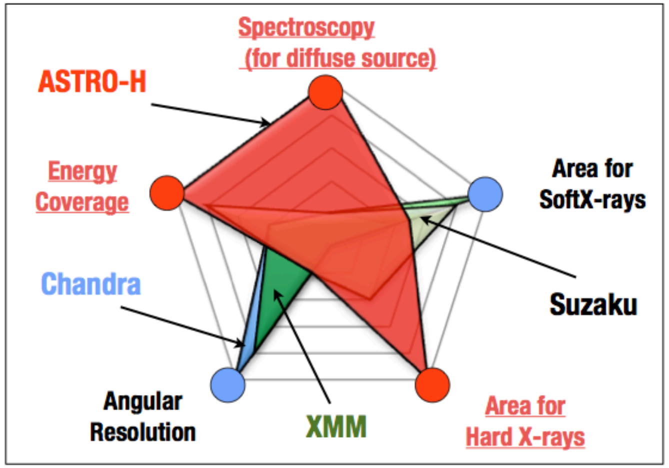
Weight 2.7 t

Height 14 m

- Orbit Altitude: 550km
- Orbit Inclination: ~31 degrees
- Launch : 2015 (JFY)

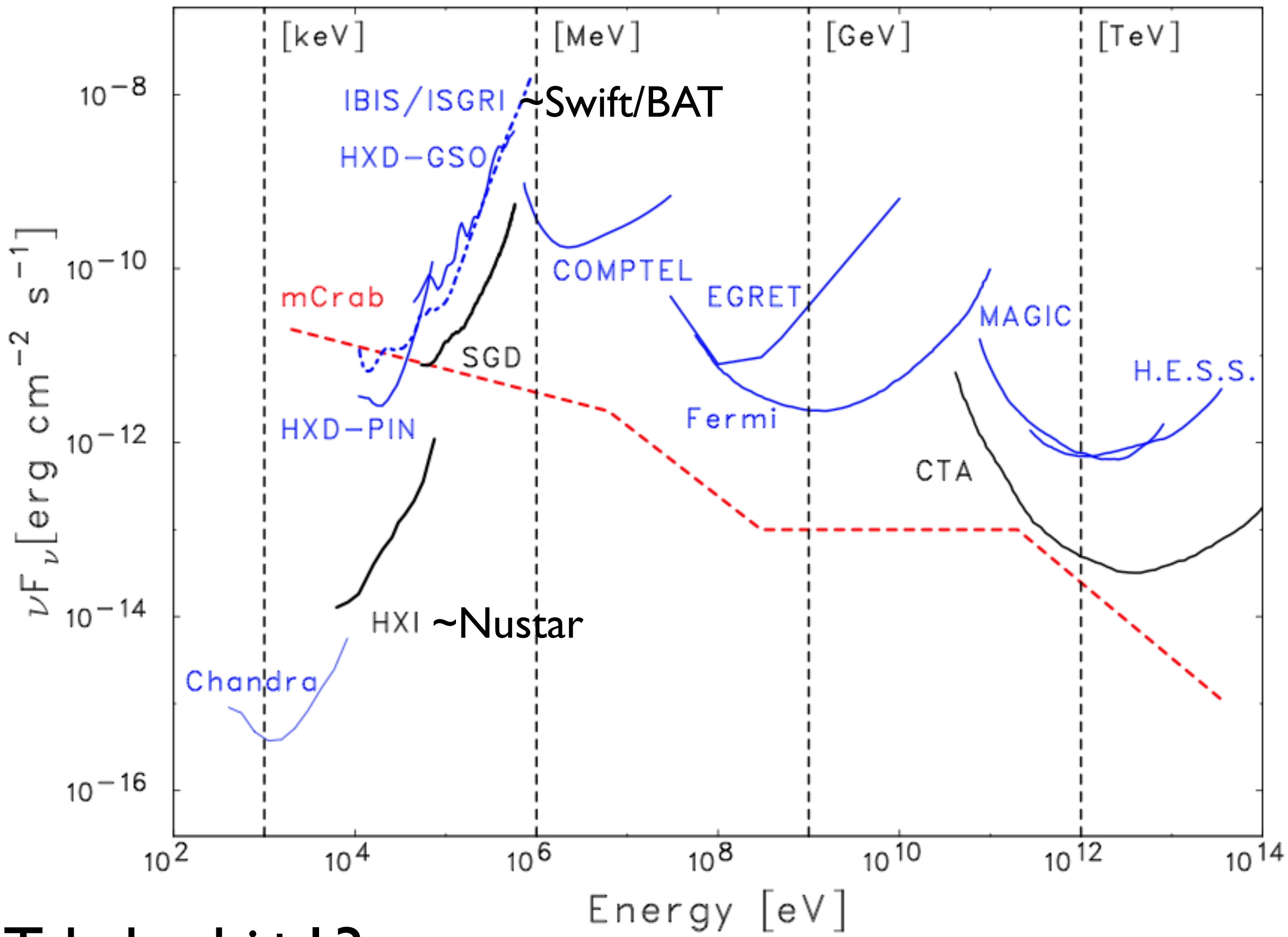
International Contribution

NASA	Micro Calorimeter Array/ADR Two soft X-ray Telescopes Eight Science Advisors Pipeline Analysis
SRON & U. of Geneva	Filter Wheel/MXS for SXS
CEA/DSM/IRFU	Contribution to BGO Shield/ASIC test
ESA	Three Science Advisors Contribution to mission instruments User support in Europe
CSA	Metrology System



Taken from T.Takahashi's Slide at Fermi symposium 2014

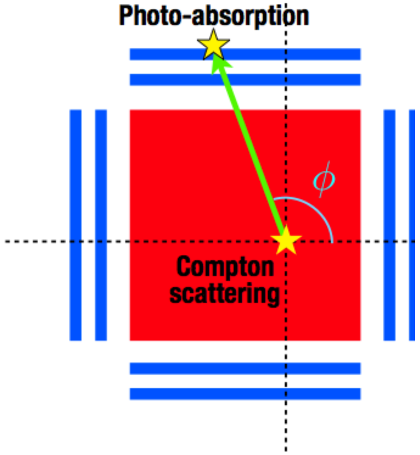
Astro-H/HXI and SGD 3σ sensitivities (100 ks exposure is assumed)



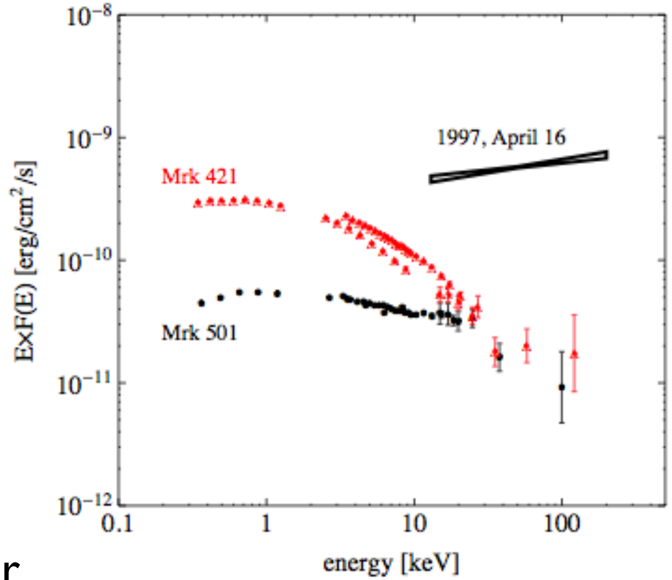
Takahashi+13

- Swift/BAT (15-300 keV)~IBIS/ISGRI
- COMPTEL & EGRET: all life-time
- Fermi: 5σ detection for 1-year data
- MAGIC, HESS, CTA: 50h exposure
- HXI sensitivity is comparable to Nustar
- SGD has the highest sensitivity above Nustar and HXI bands (E>~80 keV)

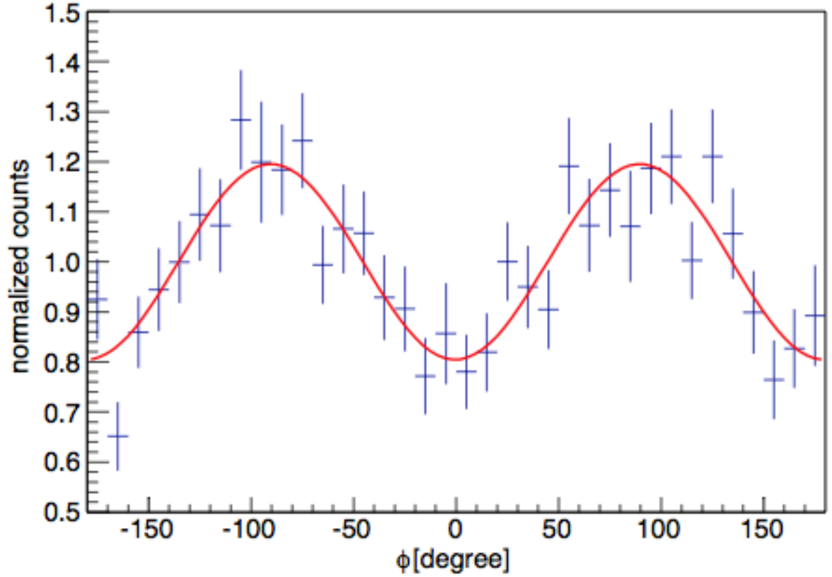
Soft Gamma-ray Polarimetry by SGD



Astro-H White Paper (Broadband Spectroscopy and Polarimetry, Coppi et al. arXiv: 1412.1190)



100 ks exposure

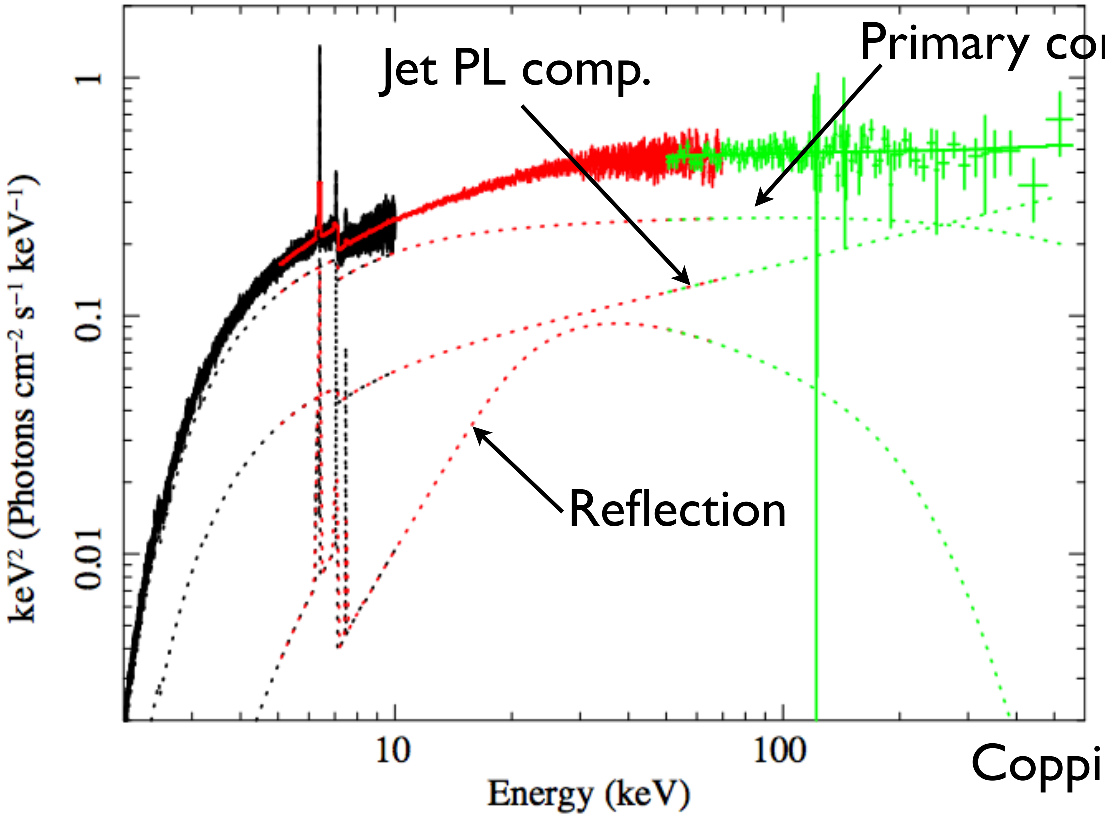


Simulation of bright X-ray flare from Mrk 501 in 1997 ($F_{13\text{-}200\ keV}$=15.9E-10 erg/cm2/s, Γ=1.84, 30% polarization degree is assumed)

- Crab nebula is also a promising target for polarimetry
- Continuous monitoring with Swift/BAT, MAXI, Fermi, and IACTs are important to trigger SGD TOO observation

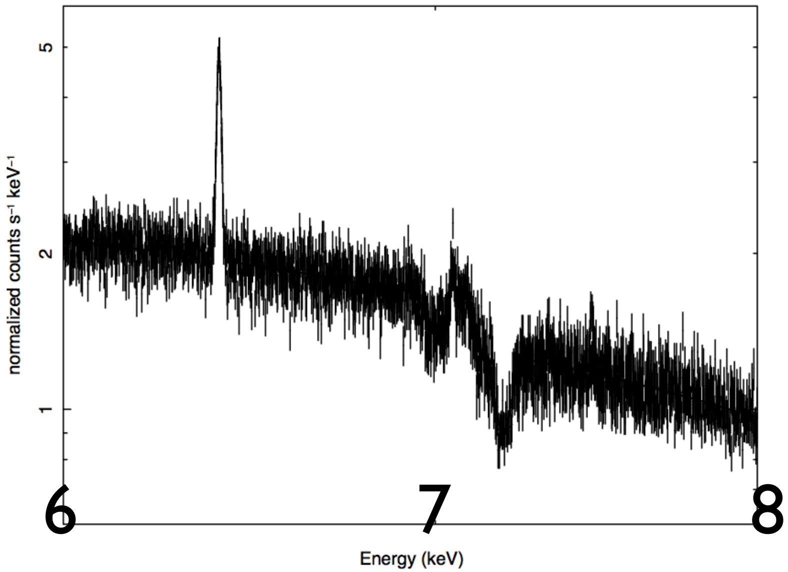
Wide-band spectroscopy by SXS+SXI+HXI+SGD

100 ks Cen A simulation spectrum



Coppi+14

100 ks SXS simulation



- Detection up to ~600 keV is promising!
- Search for cutoff in soft gamma-ray band for primary corona PL component
- Independent confirmation of blue-shifted absorption features (Ultra-fast outflow) by SXS and SXI for Cen A, 3C 120 etc
- First attempt to study "disk-jet-wind" connection using simultaneous Fermi-LAT and radio data

Summary

- Suzaku's larger effective area at E>~5 keV and low background is still useful to study
  - ✓ "Jet" X-ray emission from radio galaxies
  - ✓ Faint extended "thermal" emission from radio lobes: Thermal and non-thermal pressure (energy density) ratio is ~1
- MAXI: All-sky X-ray monitor
  - ✓ Daily X-ray light curve for bright X-ray sources such as Mrk 421 and Cen A
- Astro-H as a new powerful instrument to investigate AGN jets
  - ✓ Soft gamma-ray polarimetry at E>50 keV
  - ✓ Ultra-high energy resolution (~7 eV) and wide-band spectroscopy allow a first attempt to investigate "disk-jet-wind" connection