Hard X-ray Observations of Cosmic-ray Accelerators

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for the *Suzaku* team

X-ray Satellites

Chandra

Launch: 23 July 1999

Vehicle: Space Shuttle

Weight: 4.8 ton

XMM-Newton

Launch: 10 Dec 1999

Vehicle: Ariane 5

Weight: 3.8 ton

Suzaku

Launch: 10 July 2005

Vehicle: M-V

Weight: 1.7 ton

spatial resolution:

~0.5″

point-source sensitivity

~ 4e-15 erg/cm2/s

(100 ksec)

INTEGRAL

Hard X-ray & Gamma-rays

energy resolution:

7 eV (FWHM)

wide band:

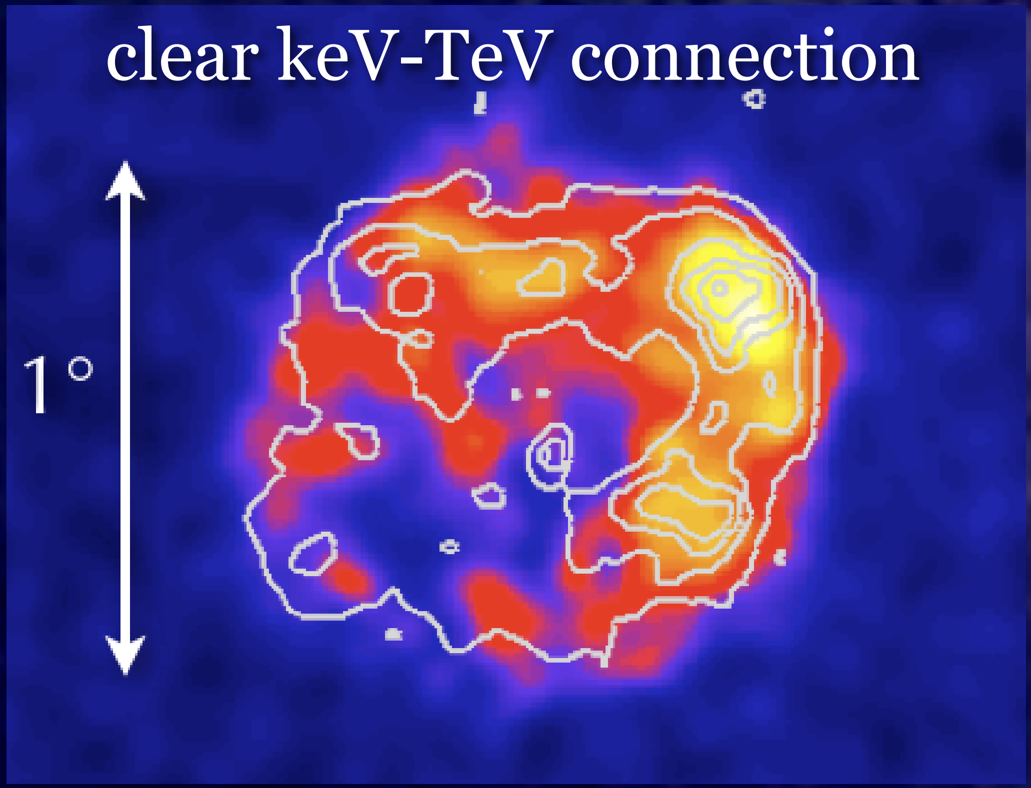
0.2 -- 300 keV

Why X-ray ?

Intimate connection between keV and TeV photons

(1) TeV gamma-rays require multi-TeV particles

(2) Multi-TeV electrons emit synchrotron X-rays



$$h\nu_{\rm syn} \simeq 5 \left(\frac{B}{10\mu{\rm G}}\right)\left(\frac{E_e}{100\ {\rm TeV}}\right)^2 \ {\rm keV}$$

PeV photons ⟶ Hard X-rays (This talk!)

- Superb spatial resolution (<1”) with *Chandra*
- Good sensitivities (< micro-Crab level)
- All-sky monitors (RXTE, *Swift*, *Maxi* in future)

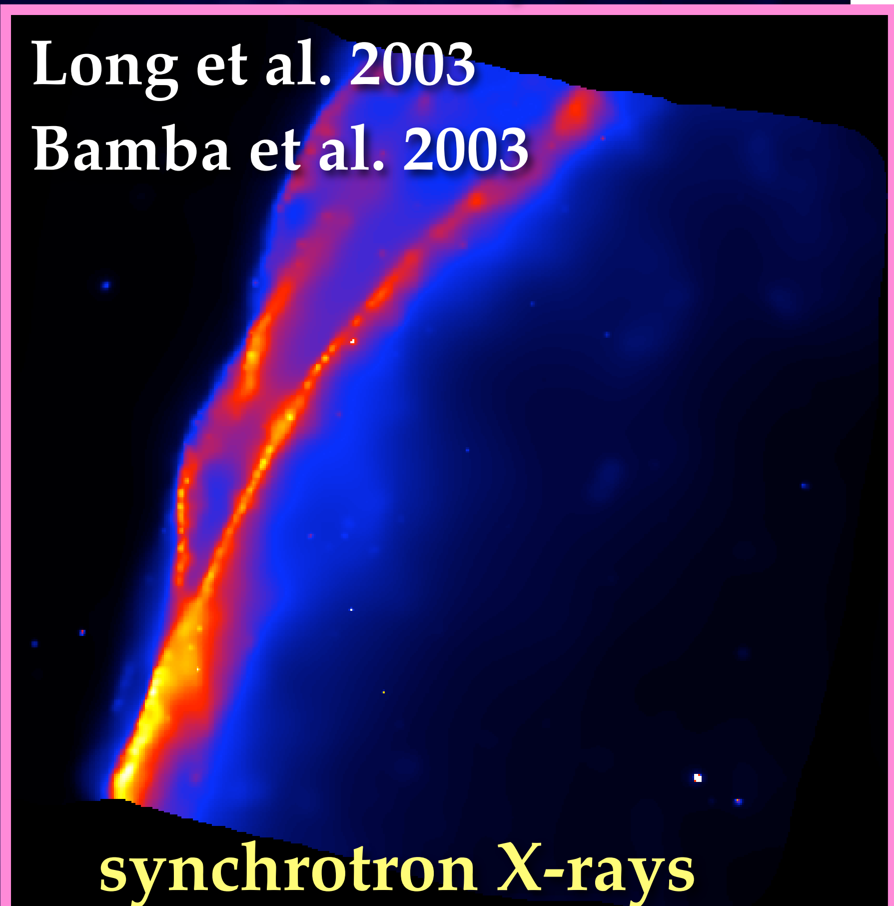
Outline

- *X-ray studies on Supernova Remnants (SNRs)*
  - Results from *ASCA & Chandra*
- *Suzaku X-ray satellite*
- *New results from Suzaku*
  - TeV SNRs: *RX J1713.7-3946 & Vela Jr.*
  - *unID* HESS sources
- *NeXT X-ray Satellite: to be launched ~2013*

SNRs (1) : The Remnant of SN 1006

“Anniversary”: Just 1000 years old

Chandra X-ray



(This is called SNR G327.6+14.6)

Simple morphology probably because this SNR is far from Galactic Plane

Shell filled with TeV electrons

Interior is cool and thermalized

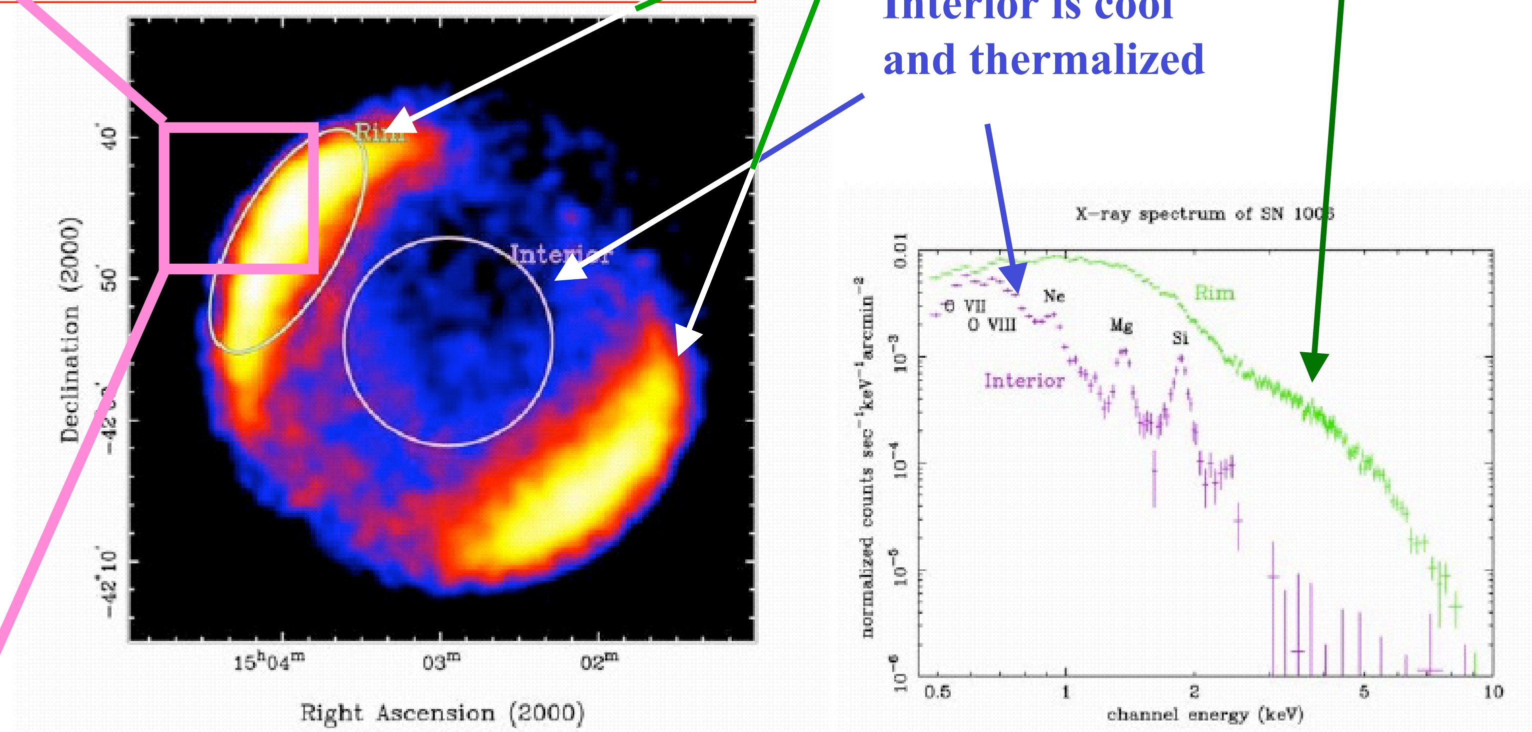


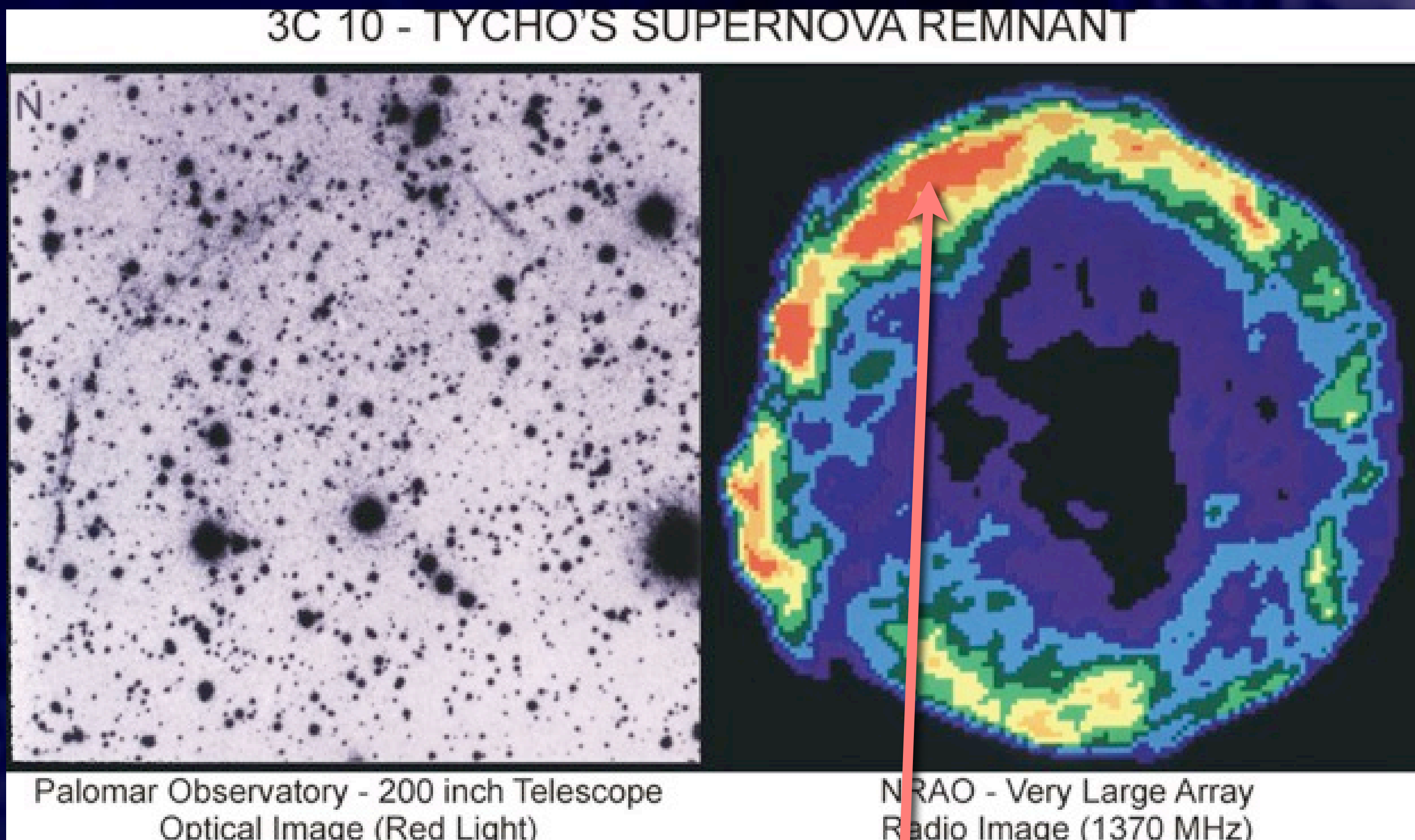
Figure 2.3: **(left)** X-ray *photograph* and **(right)** X-ray spectra of SN 1006 revealed by *ASCA* (after Koyama et al. 1995). Figures are provided by M. Ozaki.

Koyama et al (1995)

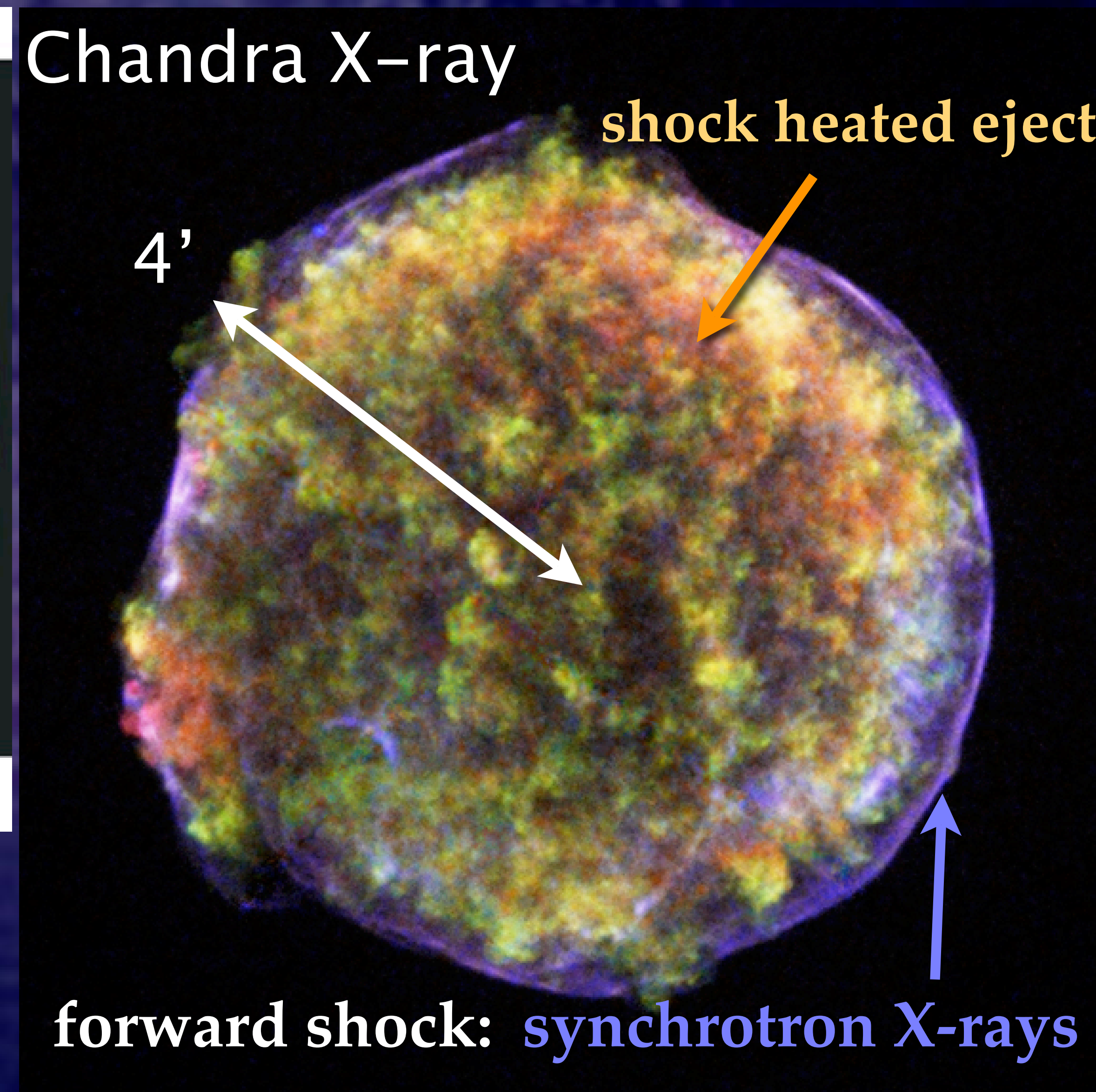
- This is the first evidence that forward shocks do accelerate electrons to “TeV” energies. (Koyama et al. 1995)
- Acceleration in “thin” filamentary structures (B-field amplification: Bell-Lucek hypothesis?)

SNRs (2) : Tycho's SNR

the debris of supernova explosion in the year 1572



reverse shock: synchrotron radio



shocked ISM region is quite "narrow"

R_contact / R_forwad = 0.93 !!

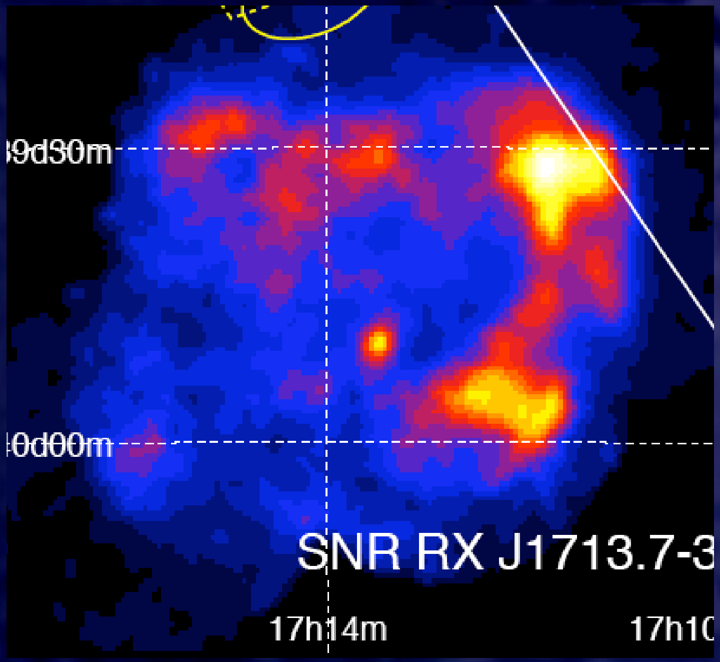
Hwang et al. 2002
Warren et al. 2005

- This is thinner than a hydrodynamic expectation.
- Suggests modified dynamics due to efficient cosmic-ray (protons) acceleration

SNRs (3) : Non-thermal SNRs

ASCA revealed a remarkable class of SNRs

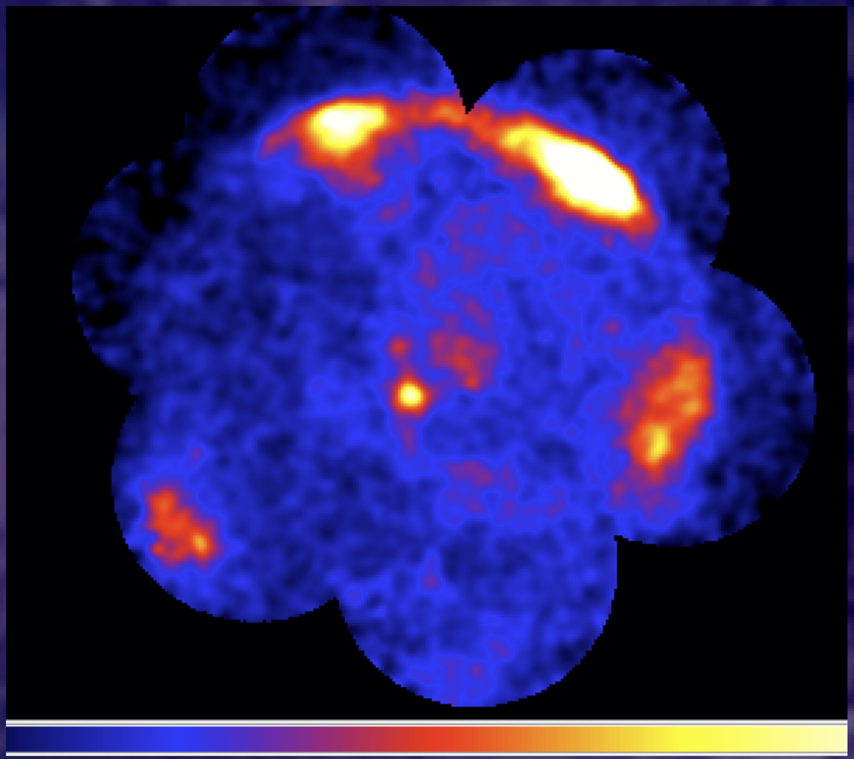
RX J1713.7-3946



ASCA X-ray

(Slane et al. 1999; Uchiyama et al. 2002)

Vela Jr.



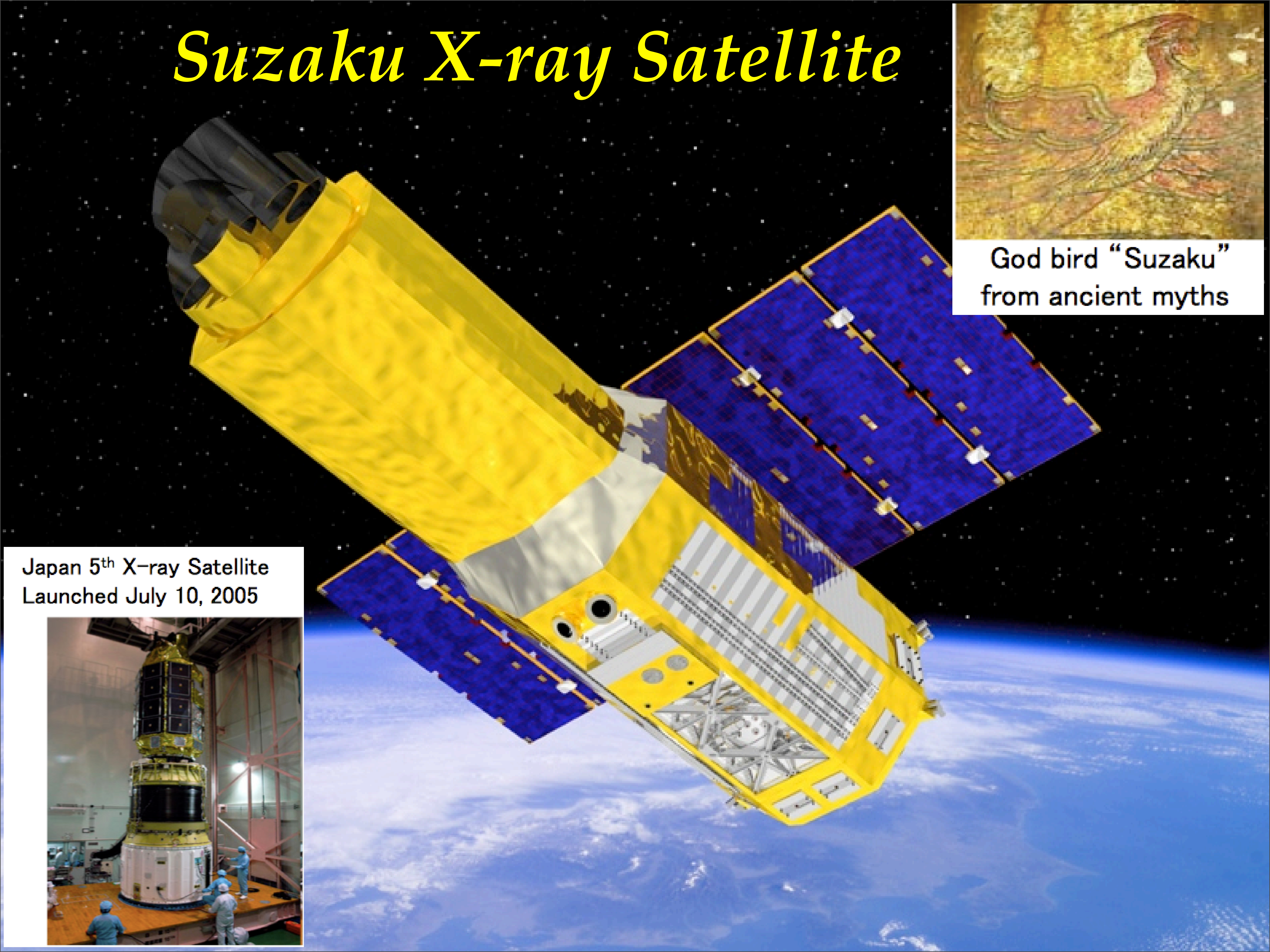
ASCA X-ray (Slane et al. 2001)

- **Only non-thermal (synchrotron) X-ray emission**
- **TeV Imaging shows a similar morphology (HESS)**

Ideal targets for ***Suzaku*** and indeed the objects of this talk:

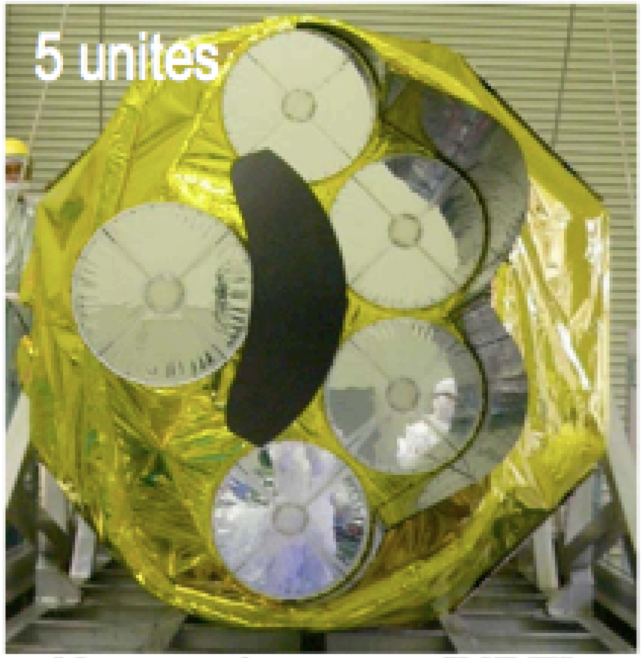
(1) XIS 0.3-10 keV with 1′ resolution

(2) HXD PIN 10-50 keV with 35′ aperture

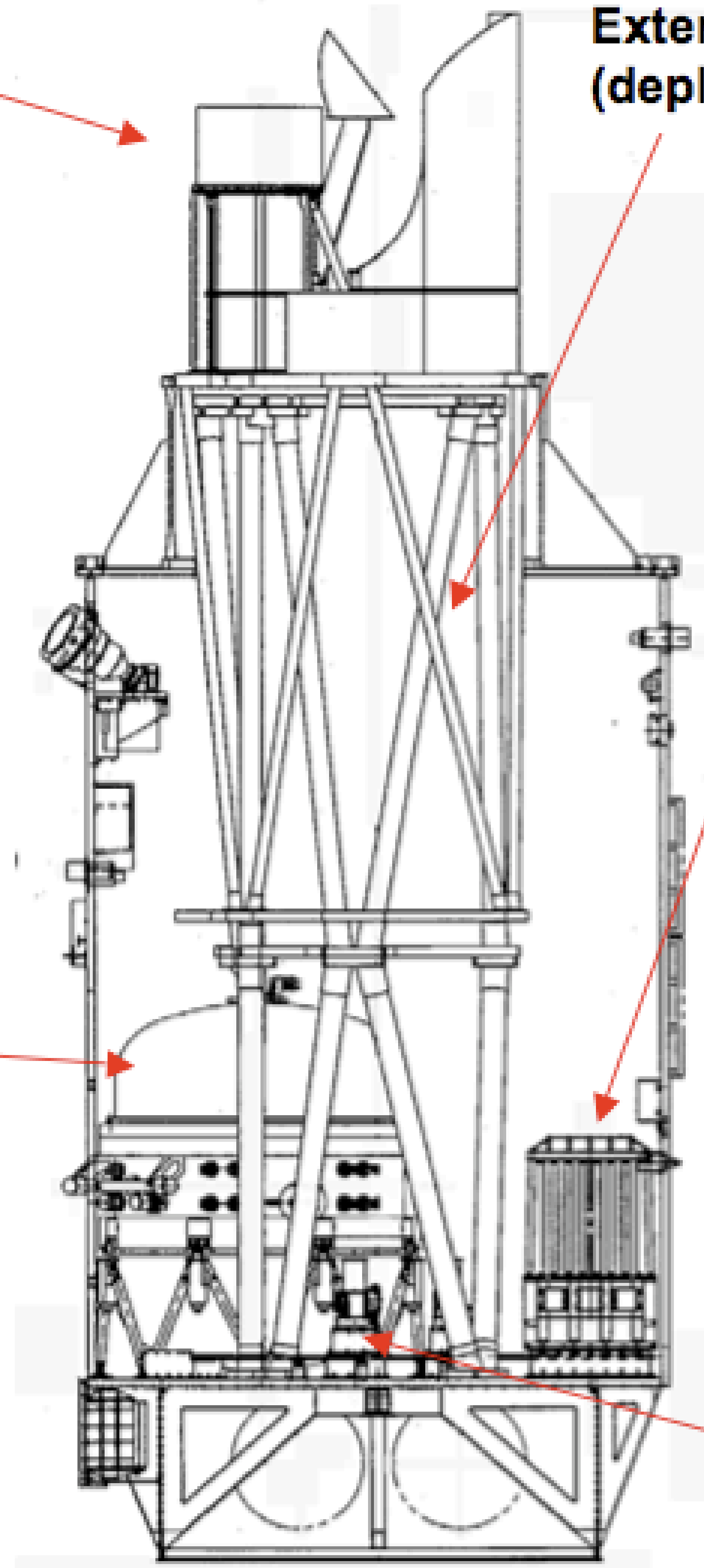

Suzaku X-ray Satellite
God bird "Suzaku" from ancient myths
Japan 5th X-ray Satellite
Launched July 10, 2005

Instruments onboard *Suzaku*

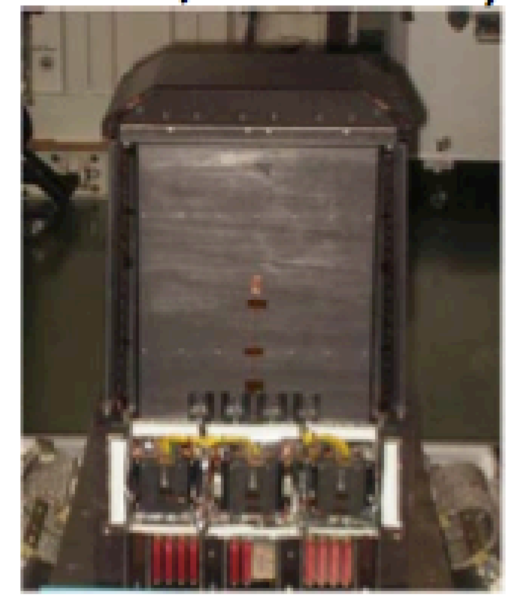
X-ray Mirror



X-ray telescope [XRT]
GSFC, Nagoya, ISAS/ISAS, TMU

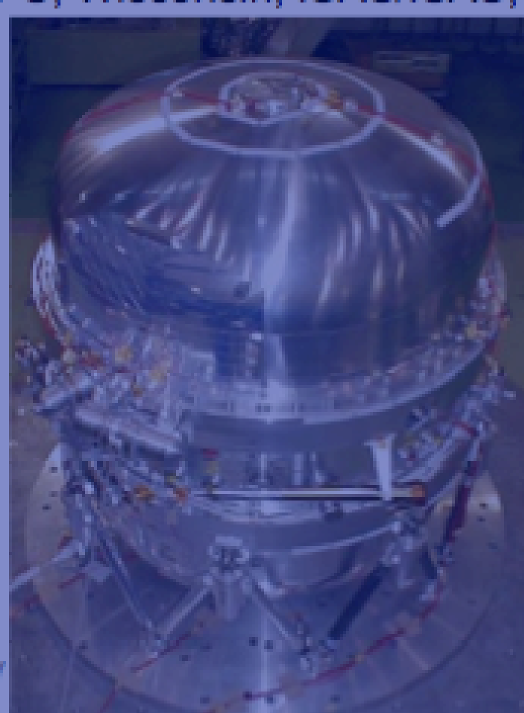


Extensible optical bench
(deployed in orbit, f=4.5-4.75m)

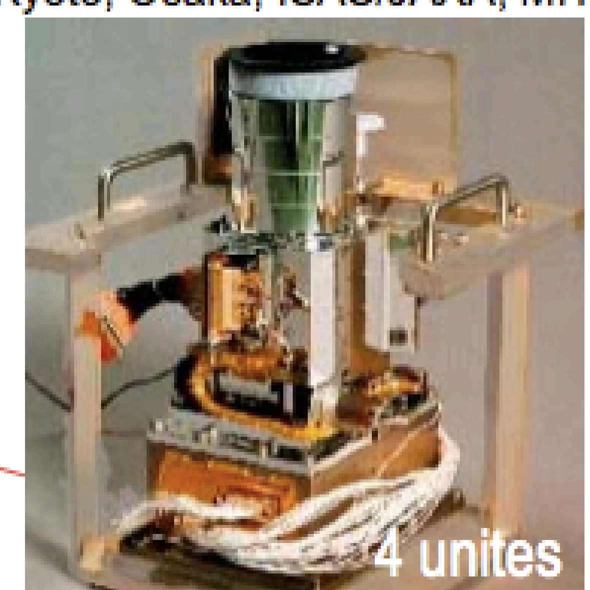


Hard X-ray Detector [HXD]
Tokyo, ISAS/JAXA, RIKEN,
Saitama, Hiroshima, Kanazawa, ...

X-ray spectrometer [XRS]
GSFC, Wisconsin, ISAS/ISAS, TMU

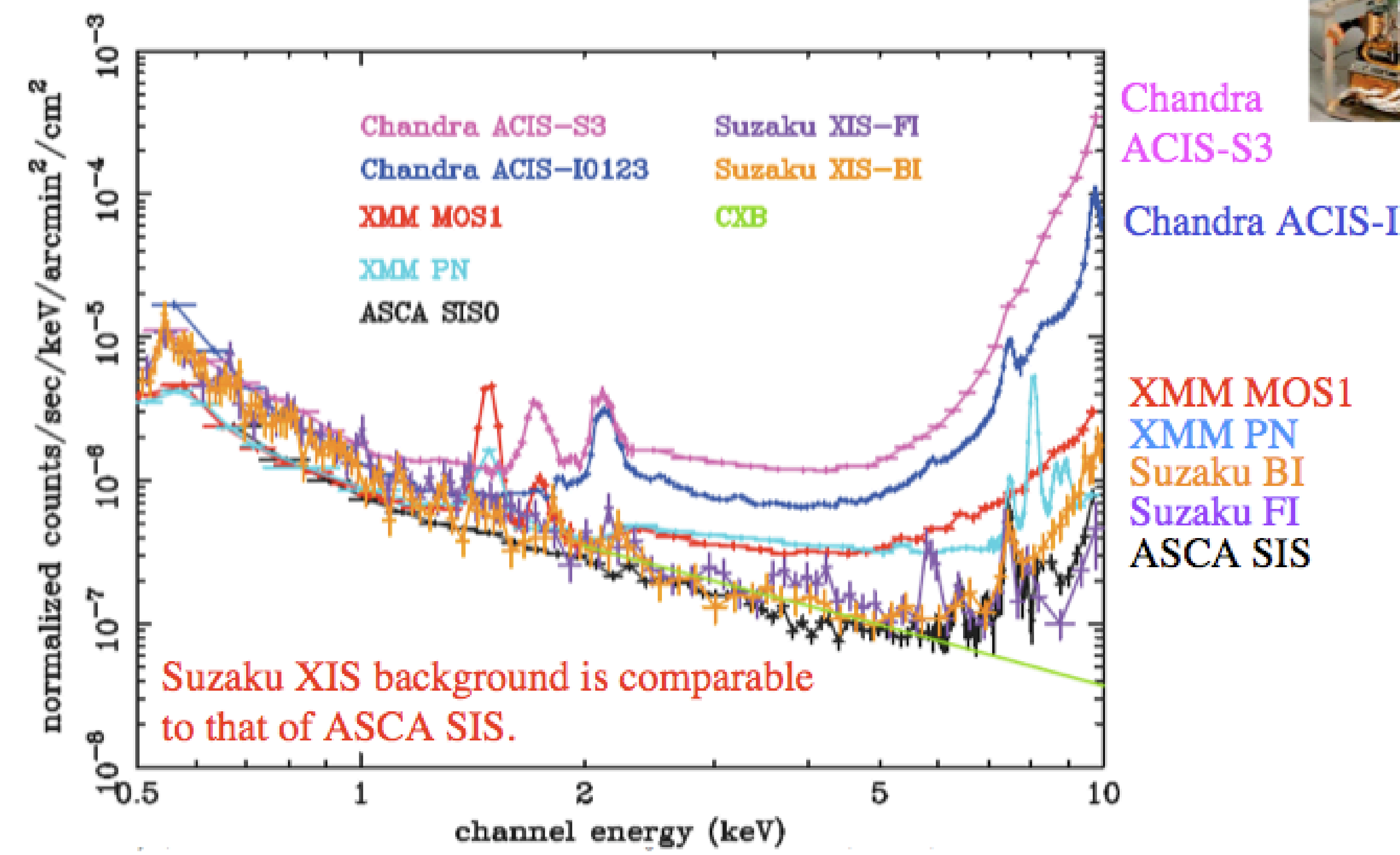


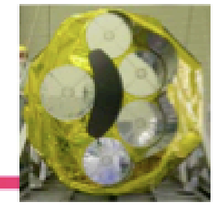
X-ray Imaging Spectrometer [XIS]
Kyoto, Osaka, ISAS/JAXA, MIT, ...



X-ray CCD camera

Suzaku XIS (0.3-10 keV)

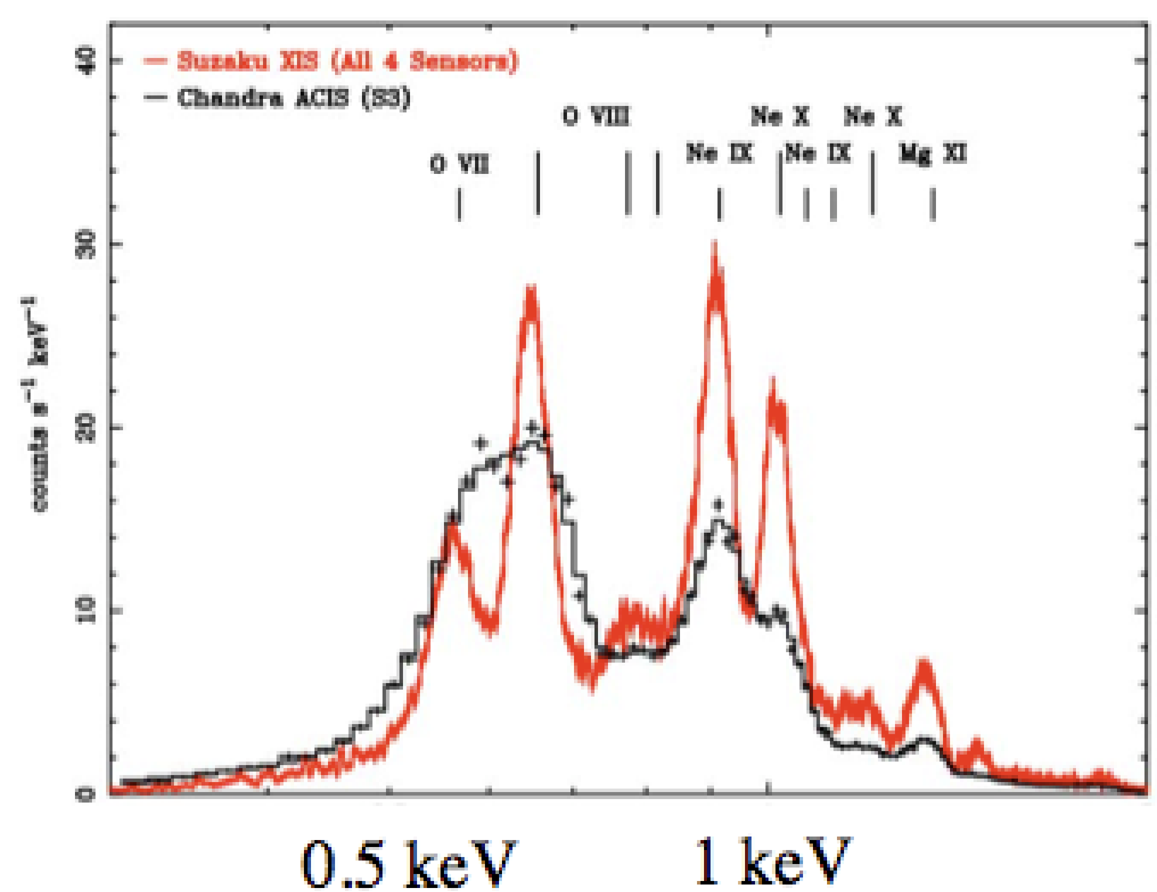




Koyama et al. (in press)

Good energy response (< 1 keV)

Observed energy spectrum of SNR E0102.2-729



Low instrumental background thanks to low Earth orbit

Suzaku HXD (10 - 600 keV)

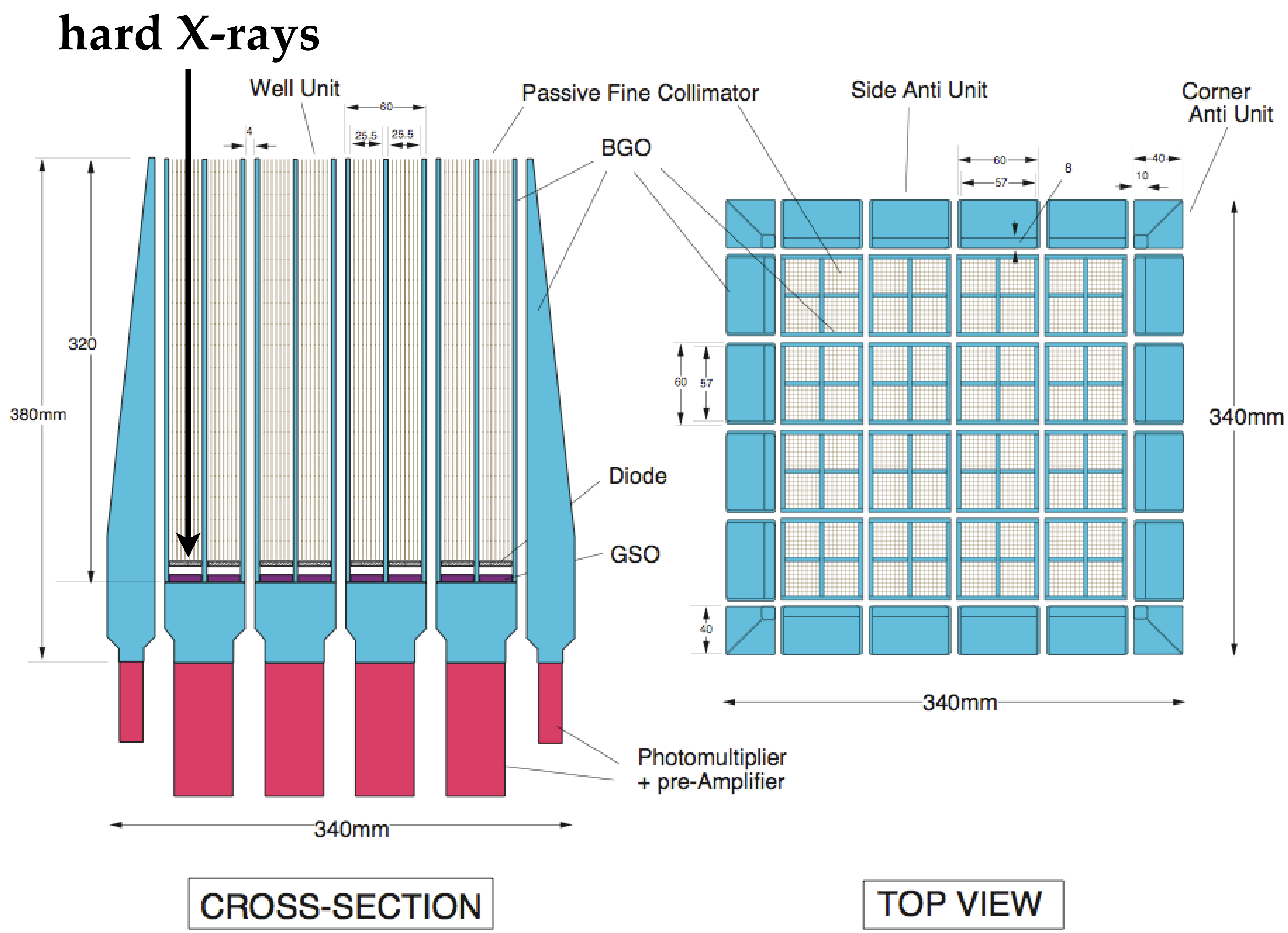
Takahashi et al. (in press)

Compound–Eye Well–type Phoswich Detector

PIN 10–60 keV (FOV 35' x 35')

GSO 30–600 keV (FOV 4 deg x 4 deg)

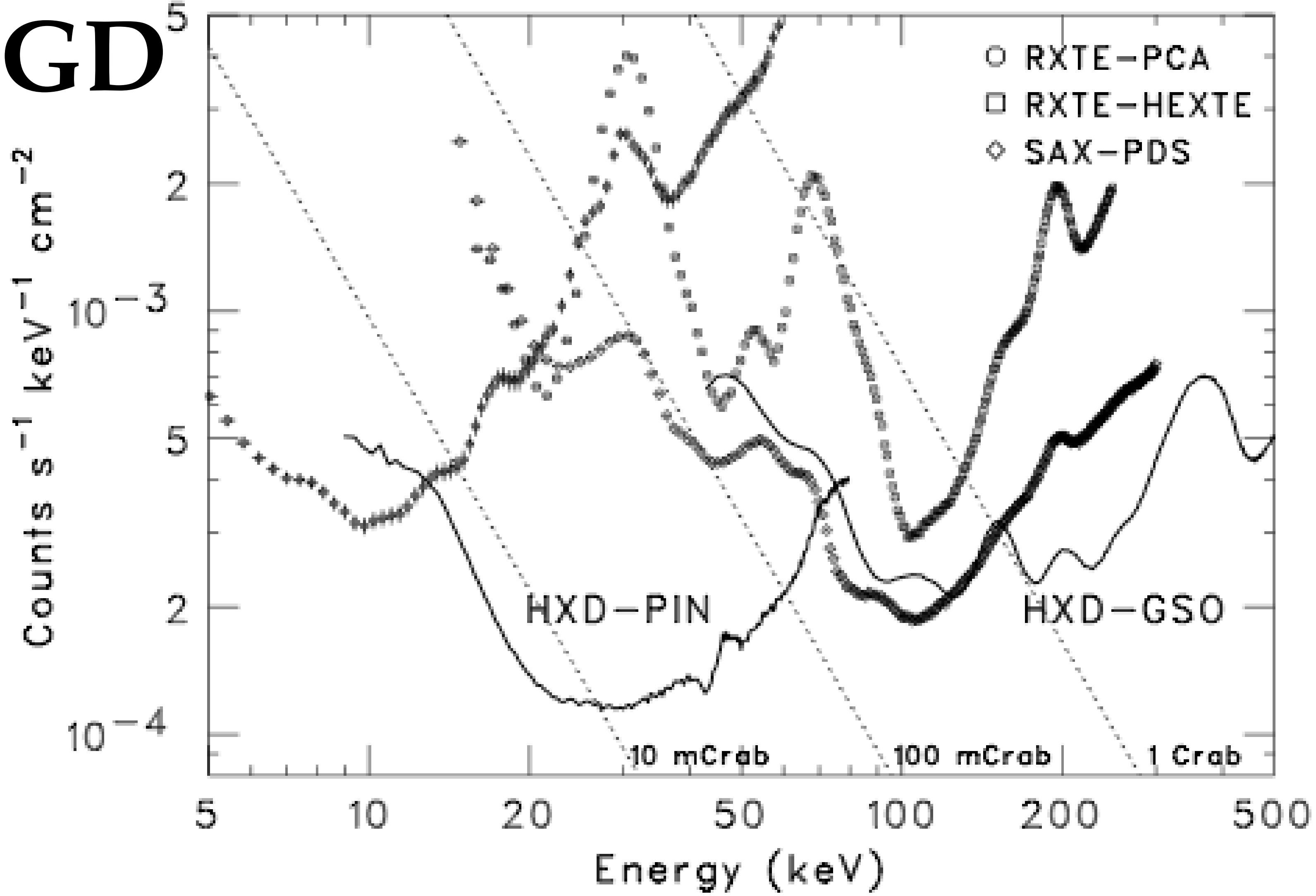
Non-Imaging



Suzaku HXD (10 - 600 keV)

Lowest background thanks to (BGO) active shields and narrow FOV

BGD

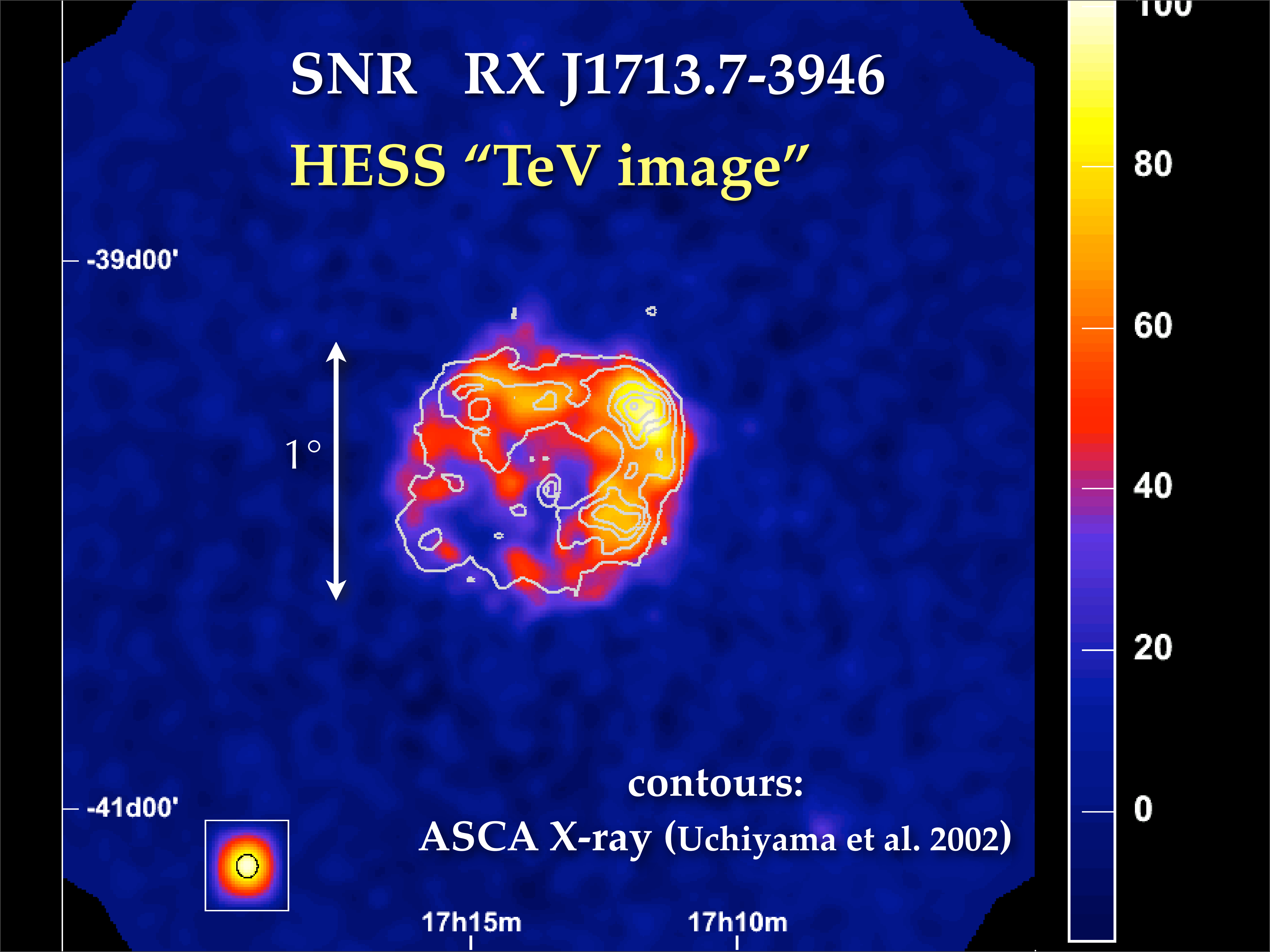


Kokubun et al. (in press)

Outline

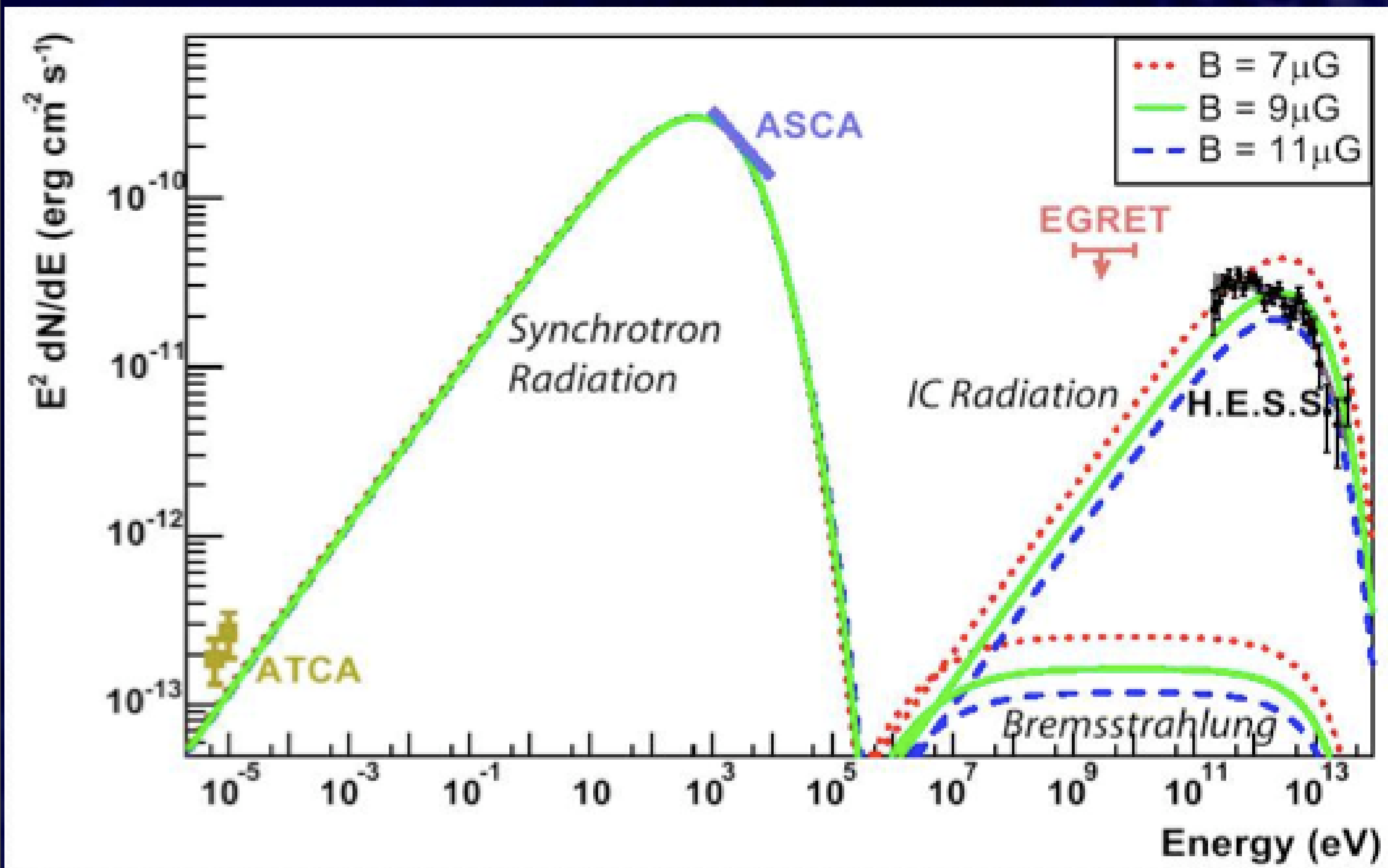
- *X-ray studies on Supernova Remnants (SNRs)*
  - Results from *ASCA & Chandra*
- *Suzaku X-ray satellite*
- *New results from Suzaku*
  - TeV SNRs: *RX J1713.7-3946 & Vela Jr.*
  - *unID* HESS sources
- *NeXT X-ray Satellite:*

Bright TeV SNR (1)
RX J1713.7-3946

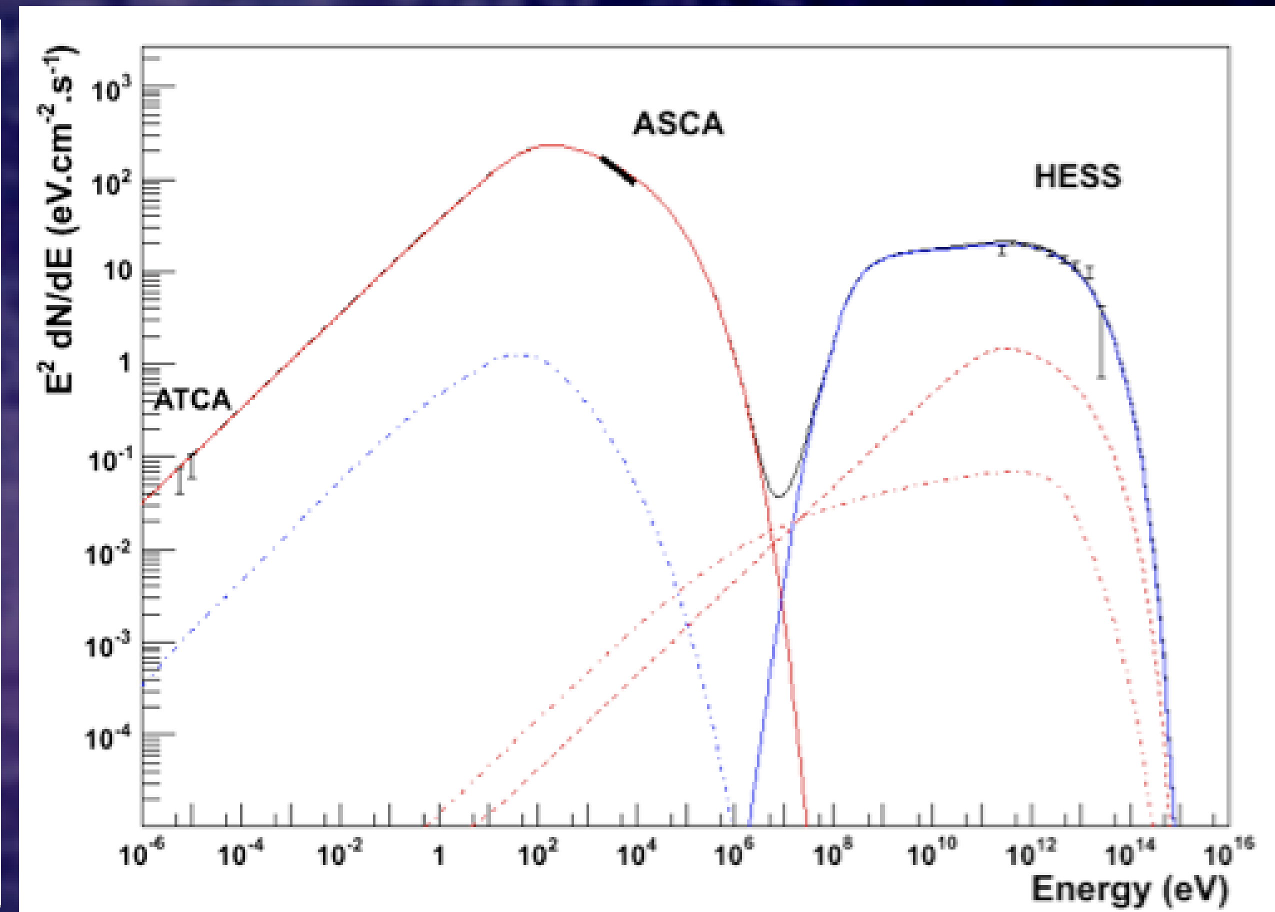

SNR RX J1713.7-3946
HESS "TeV image"
-39d00'
-41d00'
1°
contours:
ASCA X-ray (Uchiyama et al. 2002)
17h15m
17h10m
100
80
60
40
20
0

Broadband Spectrum

Synchrotron + Inverse-Compton



Synchrotron + pion-decay



From Horns's talk

Advantages: similar morphology

Disadvantages:
- small B-field with large Emax
- TeV spectrum unmatched

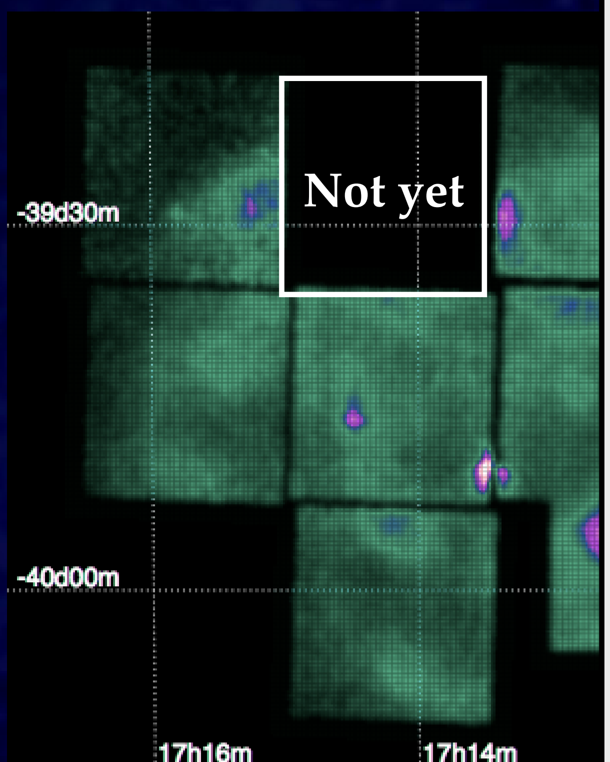
Advantages:
- a good fit to the spectrum
- energetically OK

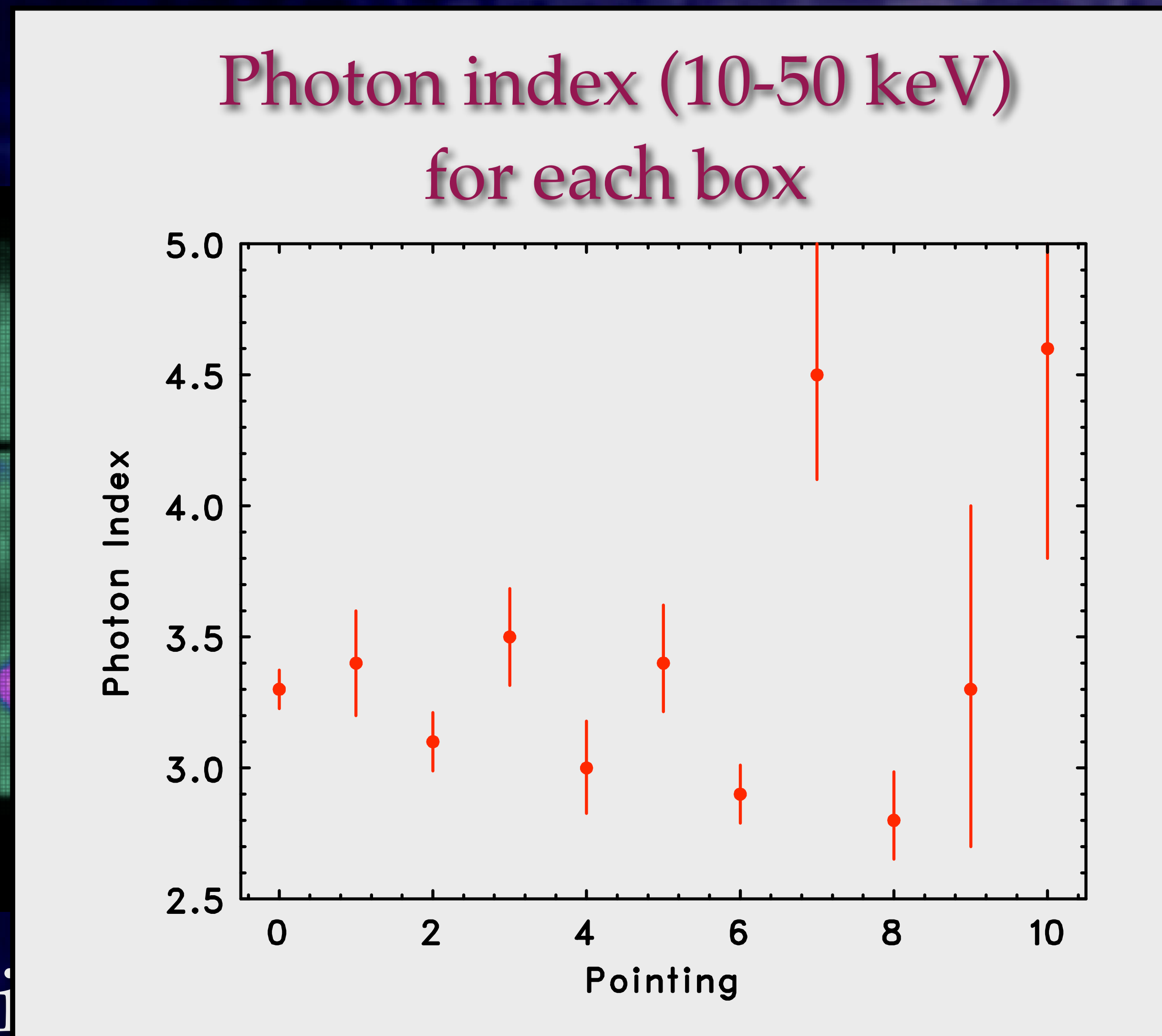
Disadvantages:
- why morphology so similar?

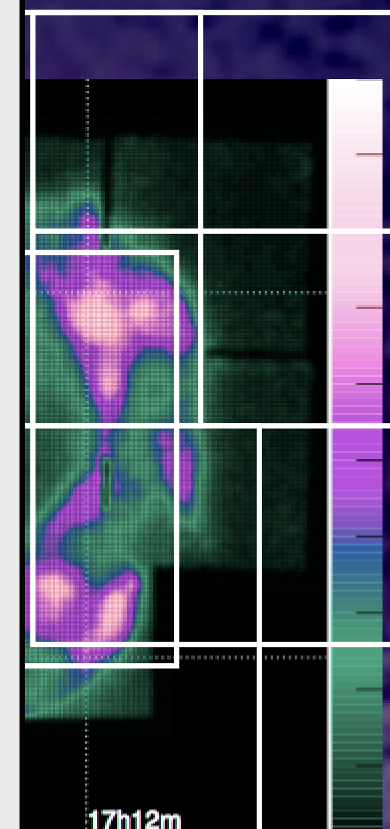
New keys: ***Suzaku*** hard X-ray (up to 50 keV) observations

Suzaku hard X-ray Observations

We have observed RX J1713.7-3946 in September 2006 with a total of 200 ks exposure. (Tanaka et al. in prep)







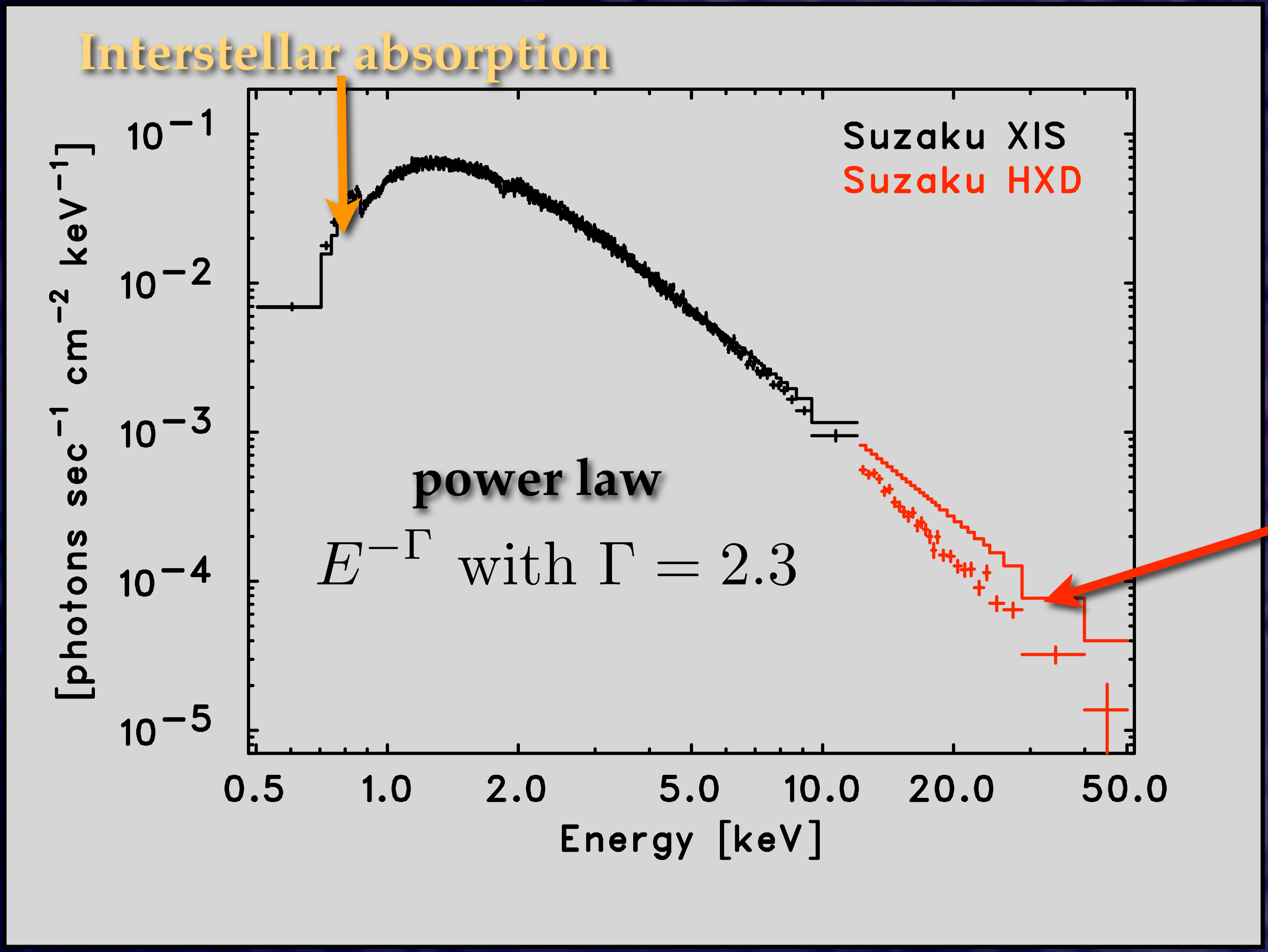
Suzaku XIS i

(0.5 - 5 keV)

Suzaku HXD PIN (10-50 keV) measurements have been made in each 11 boxes (34′x34′).

Suzaku Wide band spectrum

Integrated over the entire remnant (energy range: 0.5 - 50 keV)

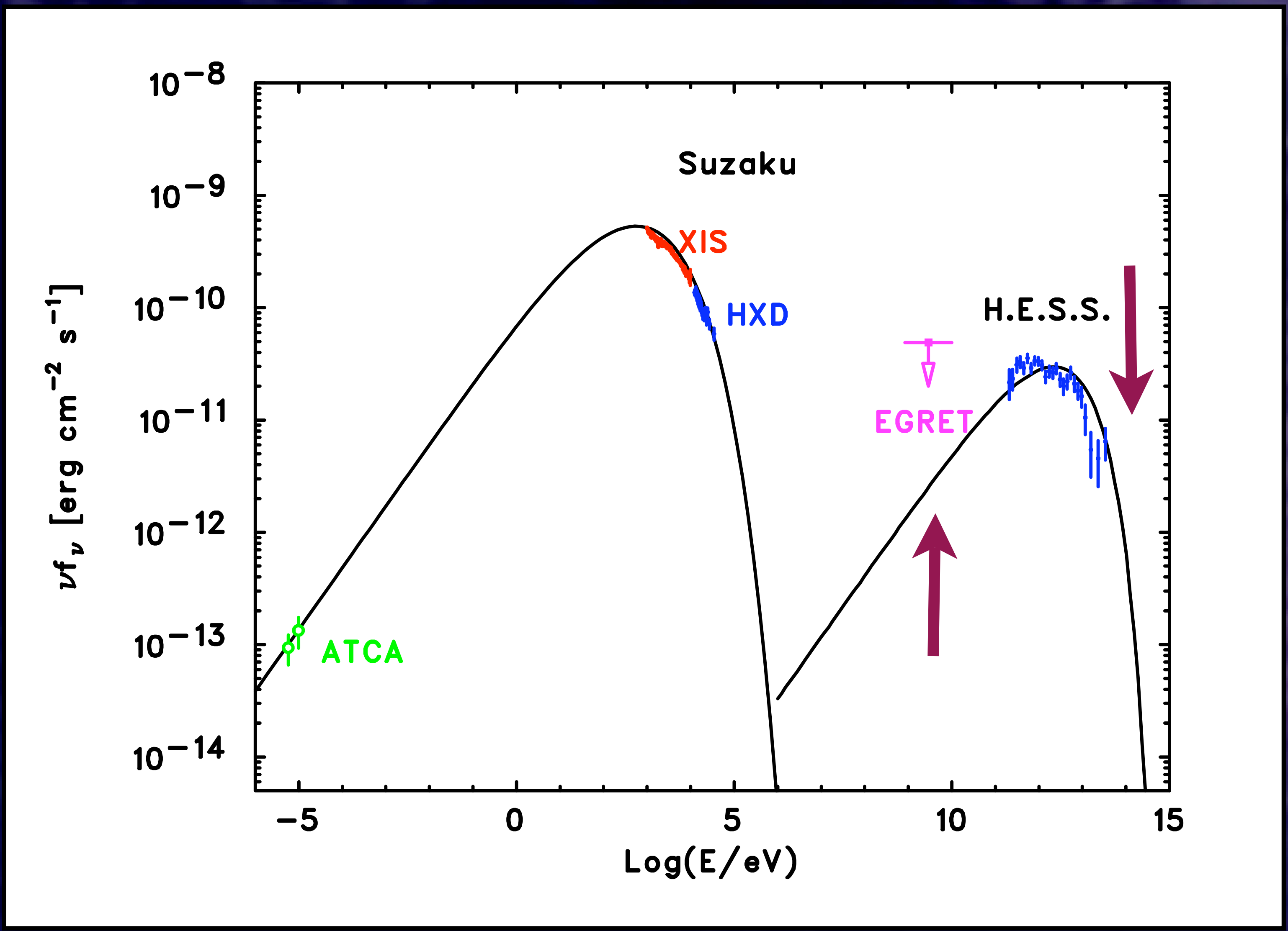


steepening!!
(break at ~10 keV)

Suzaku XIS+HXD spectrum ***0.5 - 50 keV!! (high quality)***

Spectral steepening > 5 keV
from a photon index $\Gamma = 2.3$

Multifrequency Spectrum with *Suzaku*/HESS



Synchrotron + IC Model
(electron cooling taken into account)

In the Sy+IC hypothesis, it is now possible to obtain physical parameters:

electron index = 1.9

B = 10 uG

Emax = 100 TeV

(similar to Aharonian et al. 2005)

Bohm diffusion required

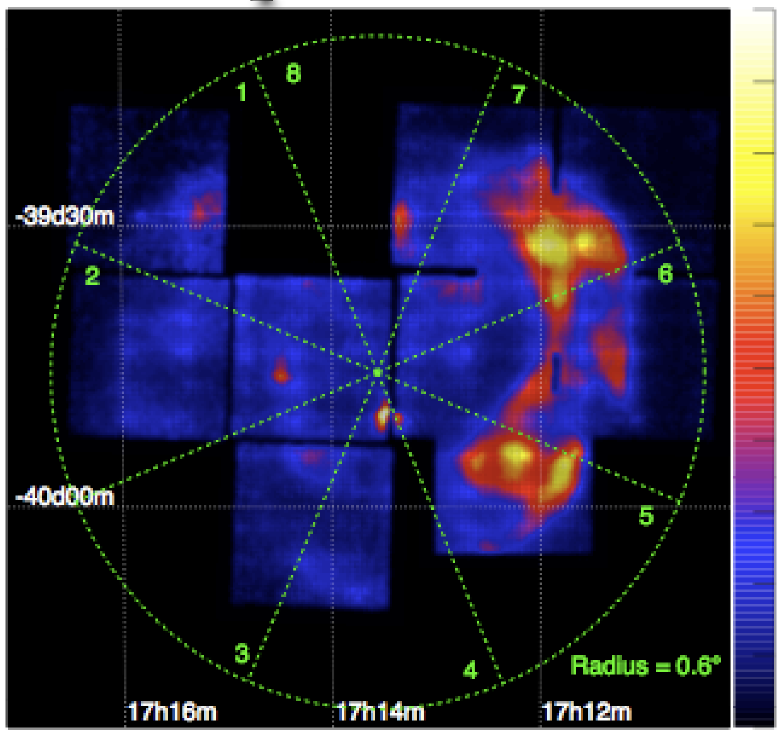
- One-zone is OK?
  Yes (as shown later)

- B-field seems too low (c.f. Voelk et al. 2005)

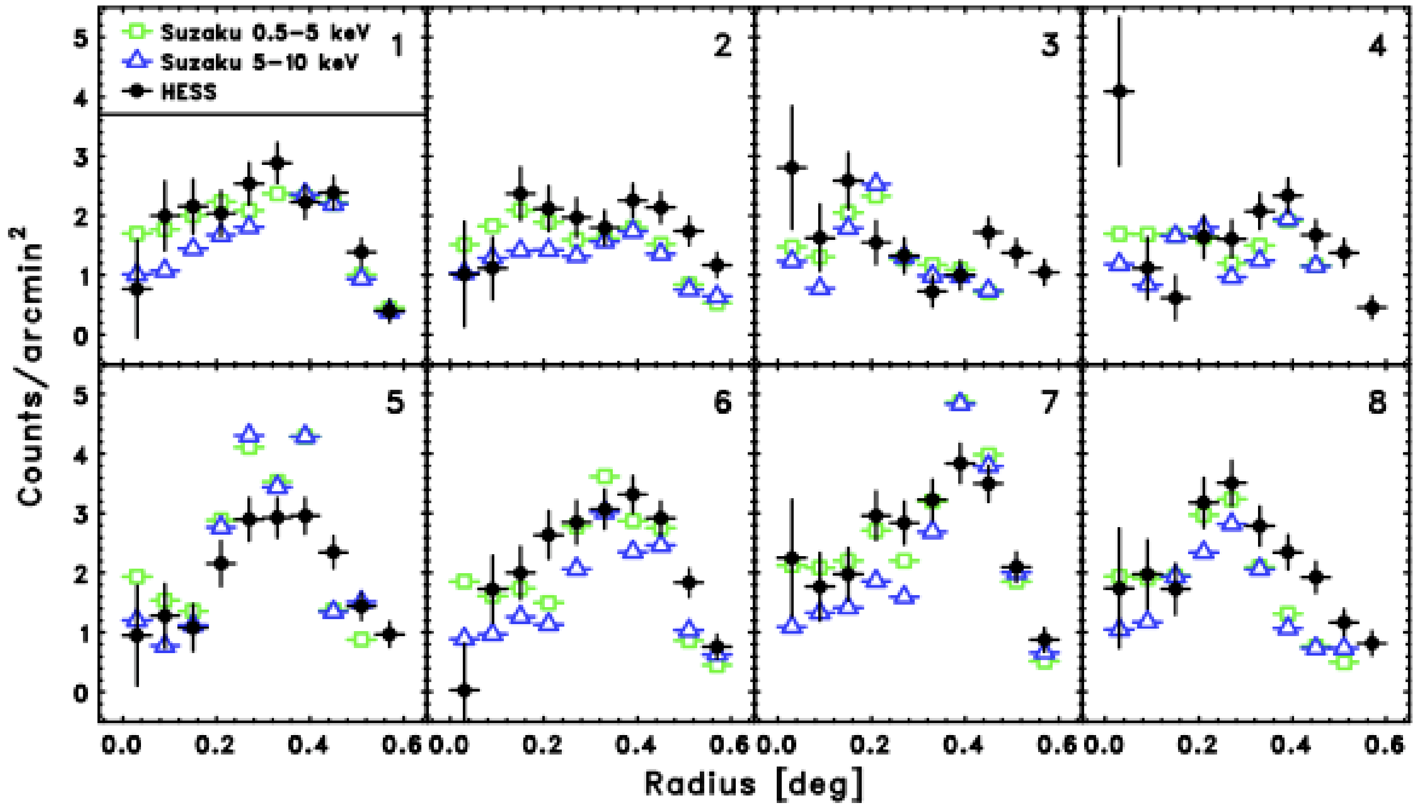
To test this hypothesis, (1) GLAST measurements
(2) good statistics at ~ 100 TeV (= Emax) to see *Klein-Nishina* suppression

keV-TeV Comparison

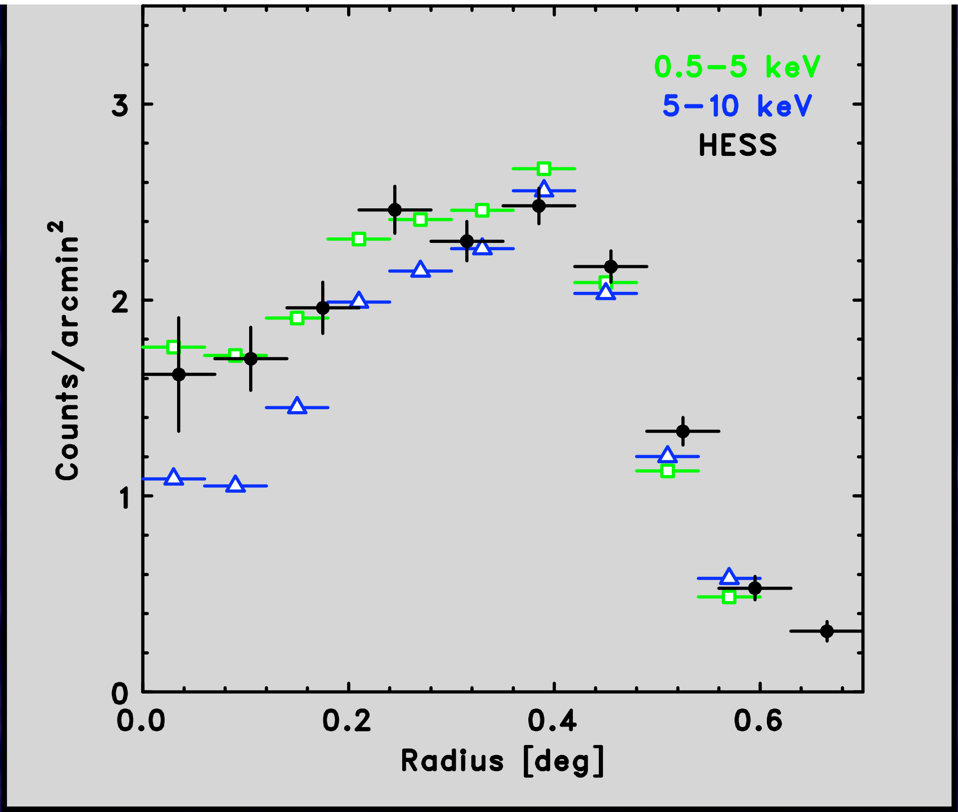
radial profiles



Suzaku vs HESS

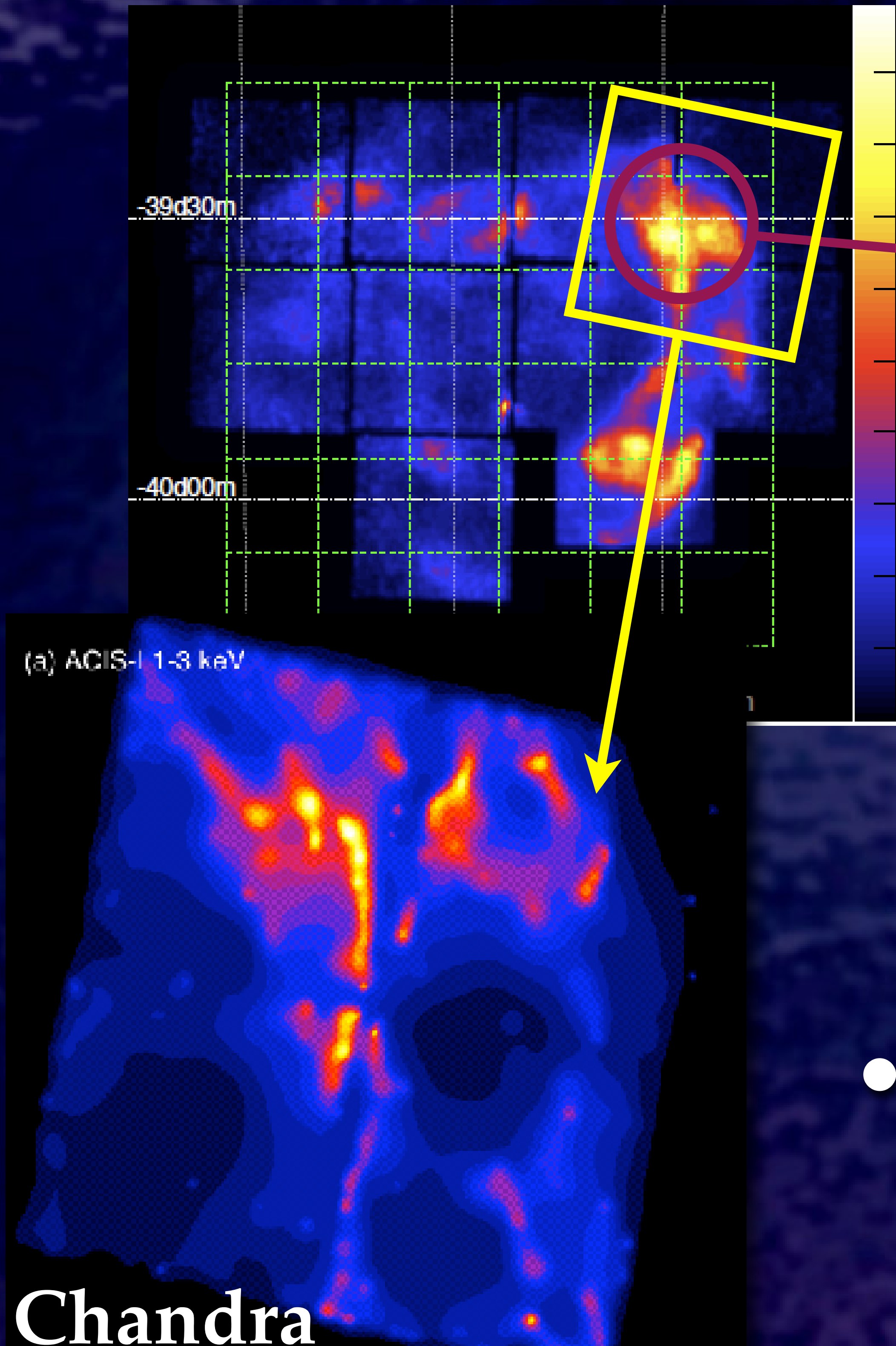


pies 1-8 integrated:

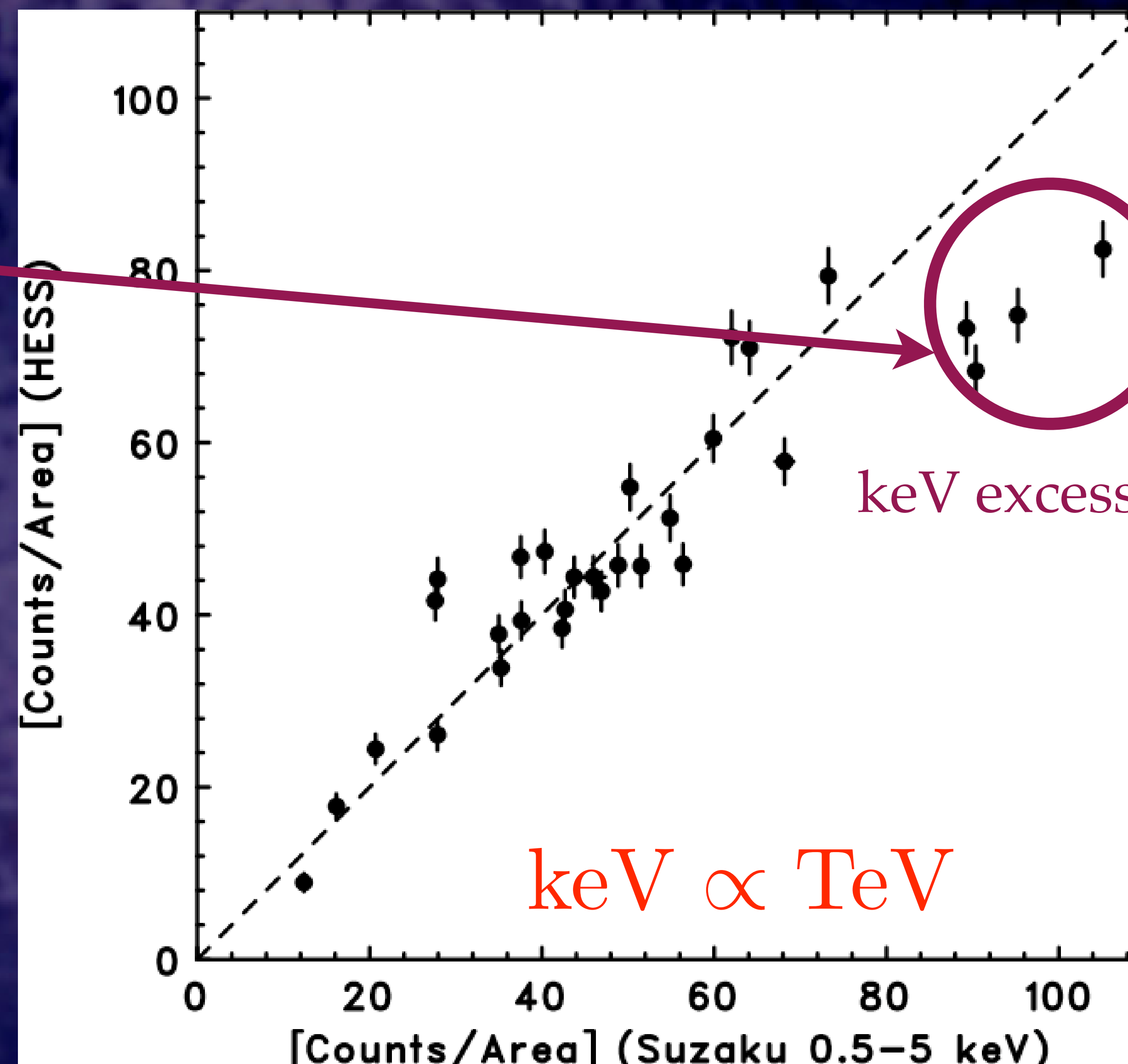


consistent with the ASCA results

keV-TeV Surface Brightness Relation



Uchiyama et al. 2003



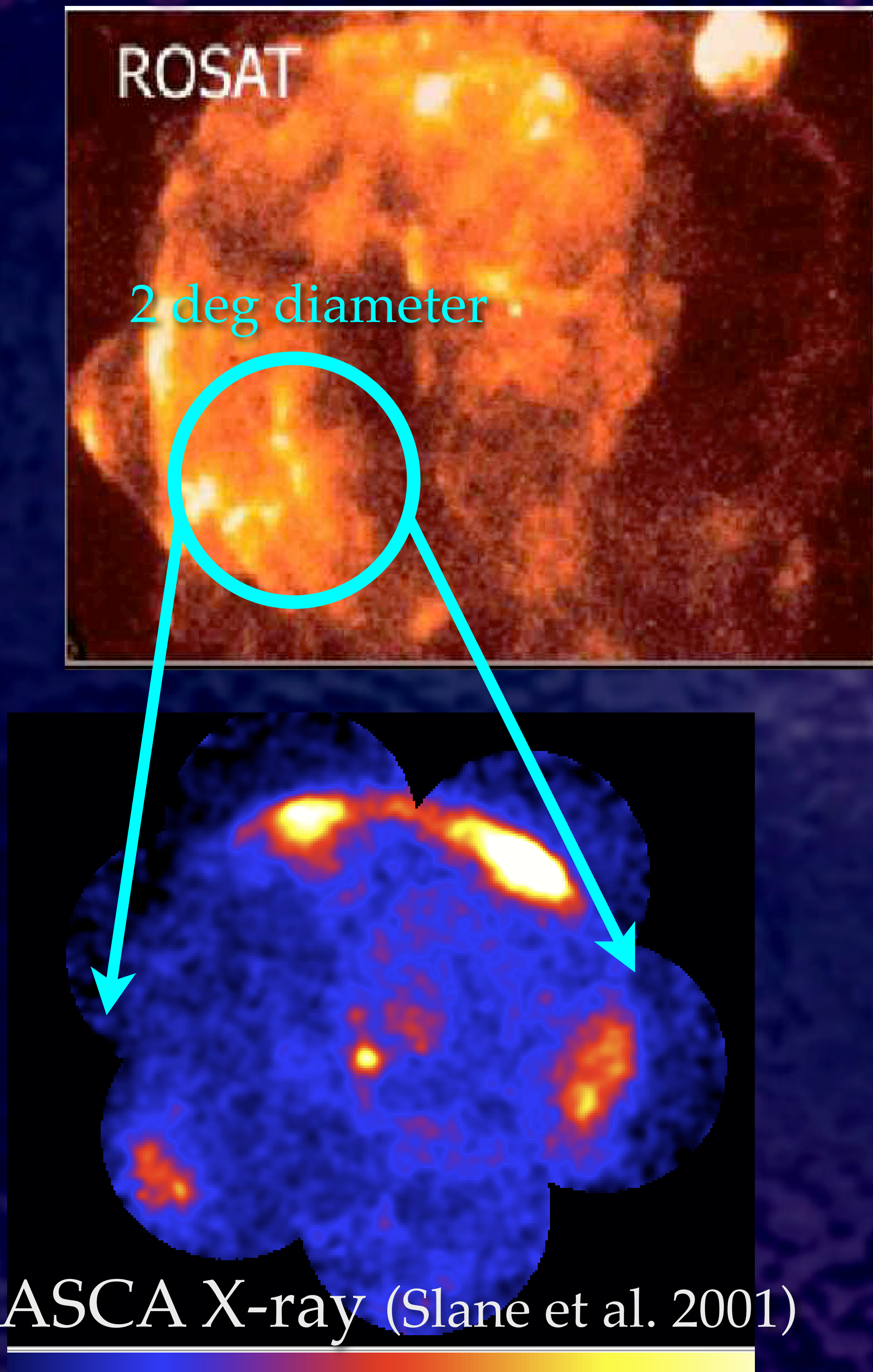
- "keV excess" in NW and SW rims
  - Compact features (like filaments) would account for the excess.

0.5′ TeV imaging is needed to test this.

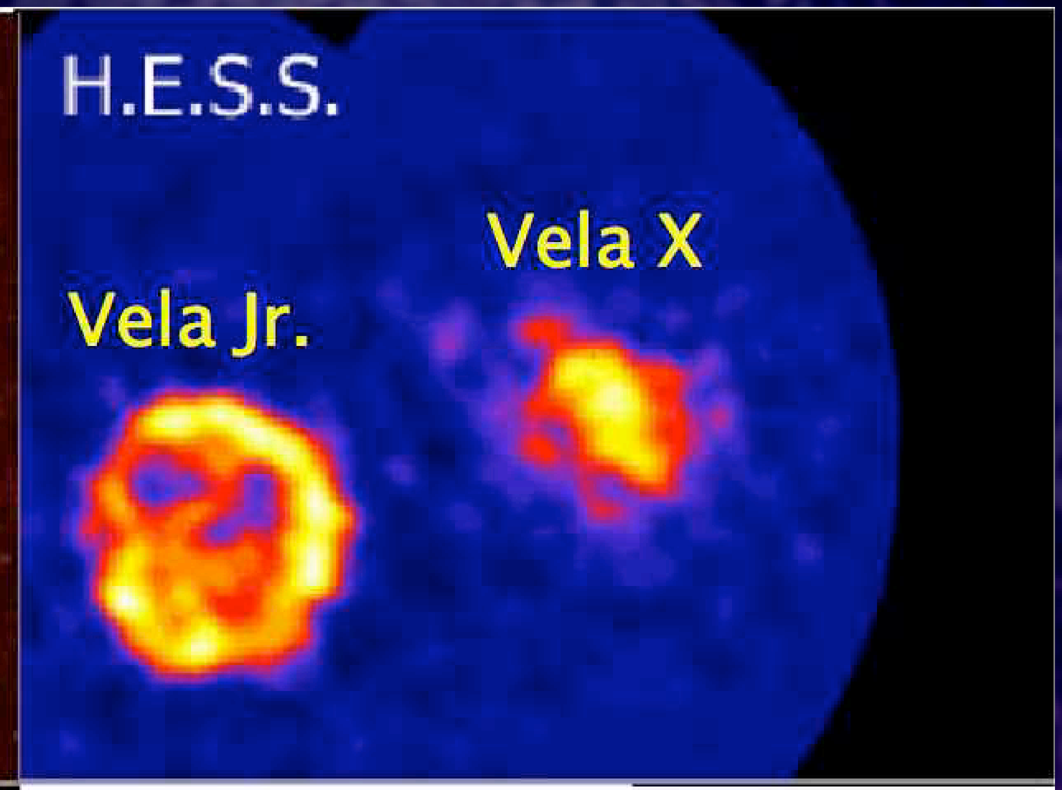
Bright TeV SNR (2)
Vela Jr. (RX J0852.0-4622)

Vela Jr. (RX J0852.0-4622)

young remnant of core-collapsed SN hidden in the old Vela SNR



ASCA X-ray (Slane et al. 2001)



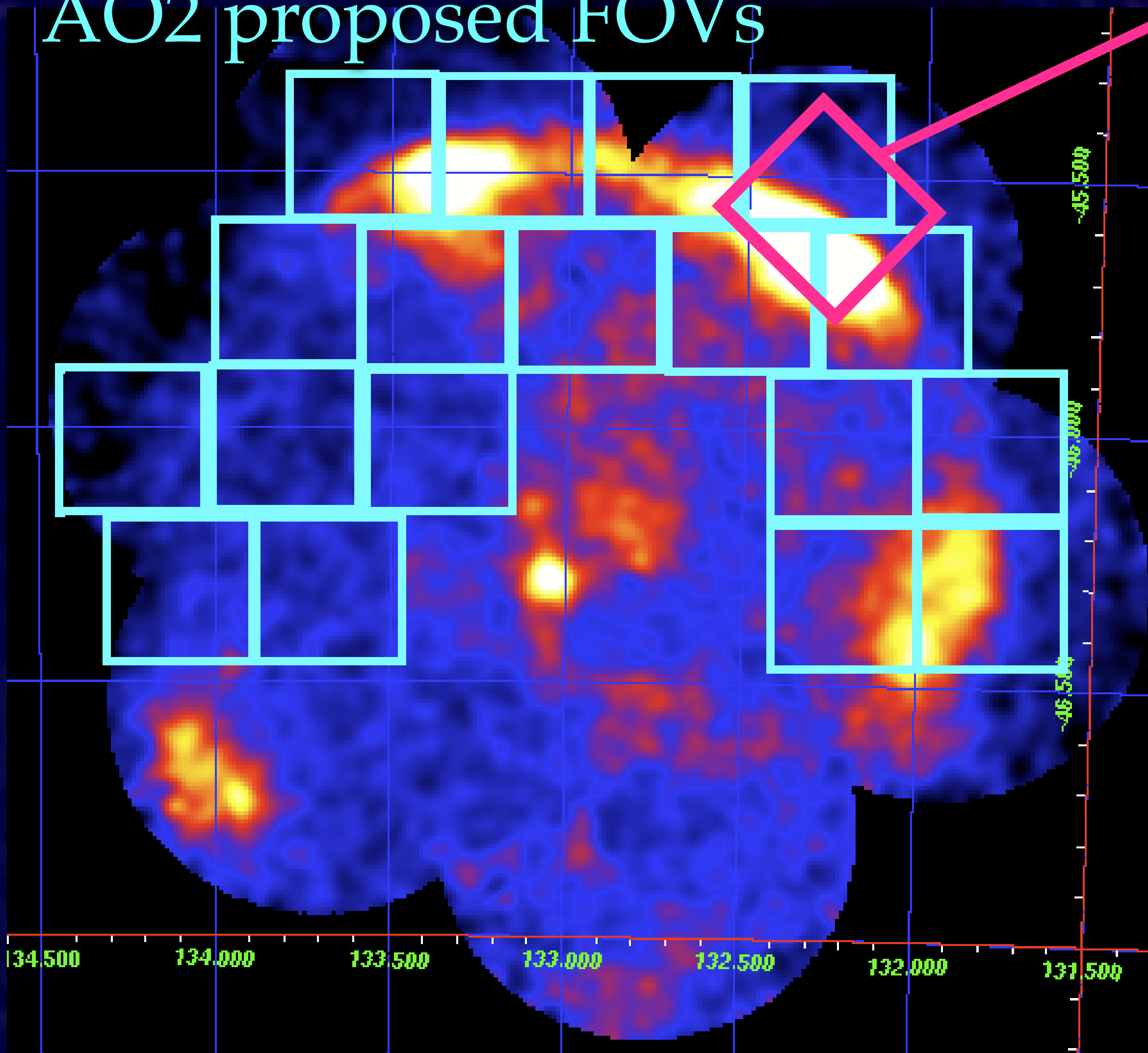
X-ray = Synchrotron

TeV = IC / pion-decay

Distance: uncertain 0.2 - 1 kpc

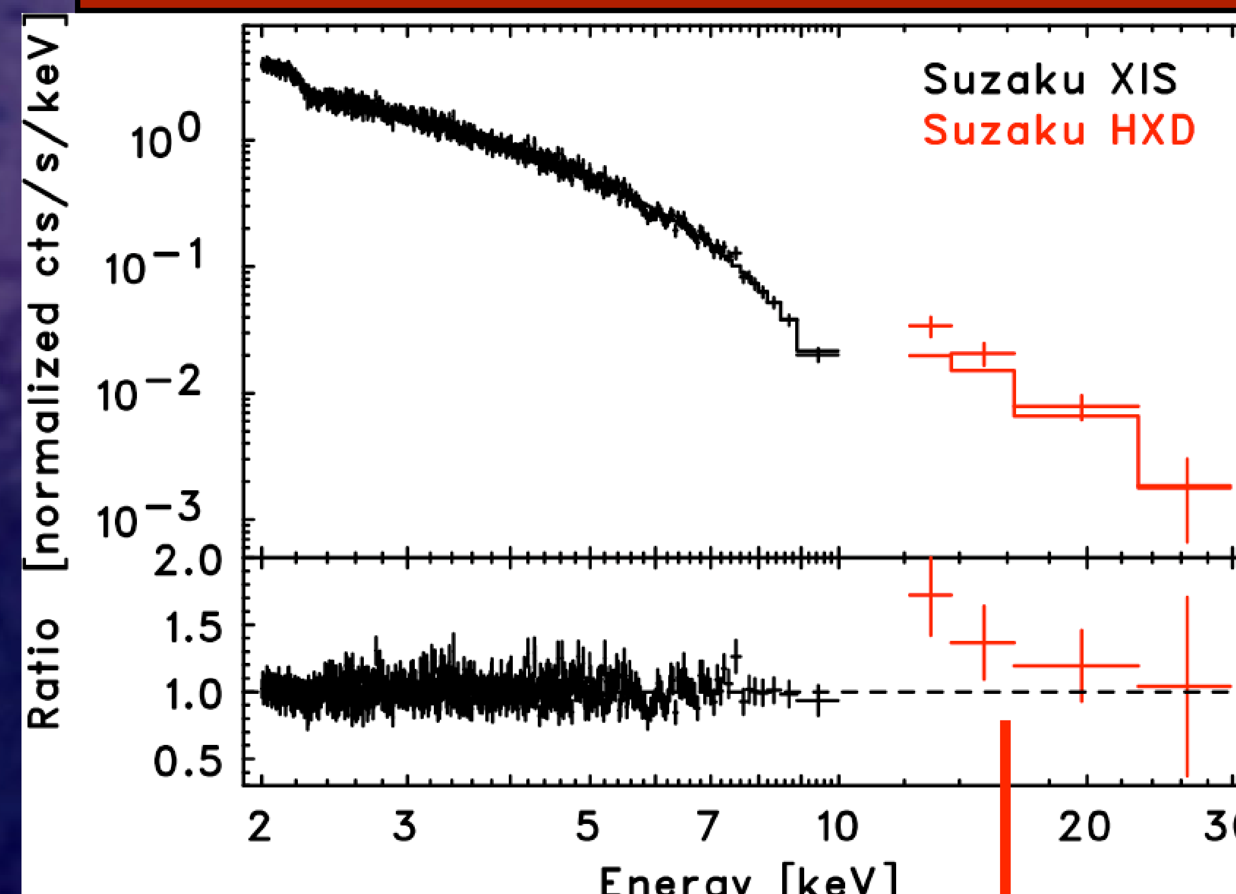
Suzaku hard X-ray Observations

AO2 proposed FOVs



Only a "pilot" observation has been performed.

A power law up to 30 keV has been measured $\Gamma \simeq 2.8$



HXD PIN: ~ sensitivity limits

We need mapping observations to conduct keV-TeV comparisons as we did for RX J1713.7-3946.

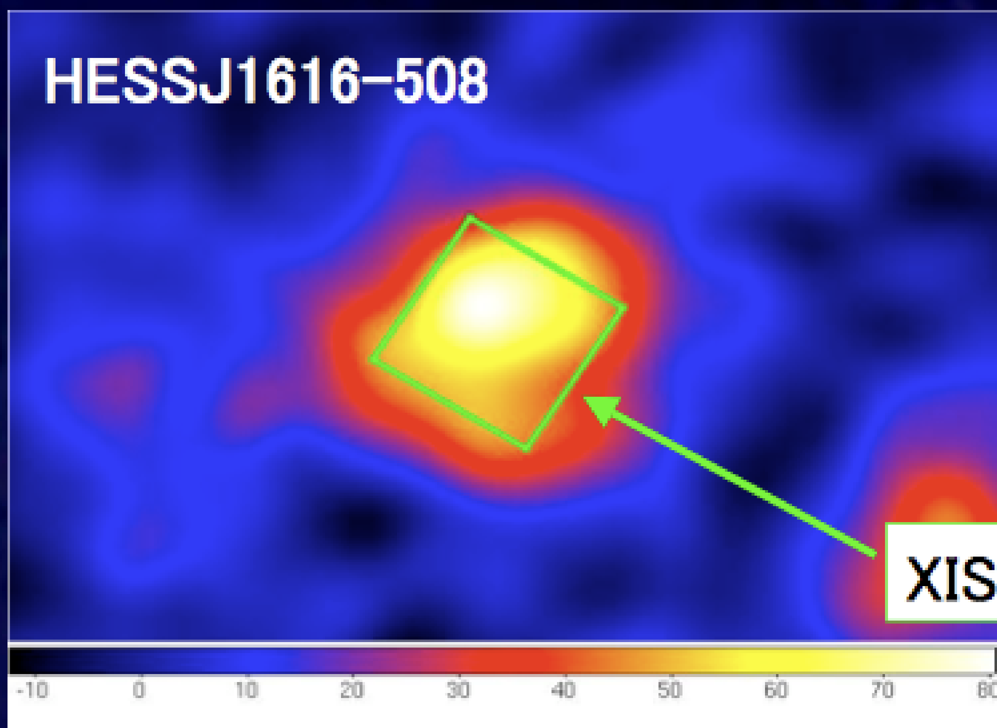
→ AO2 proposal (PI: Uchiyama)

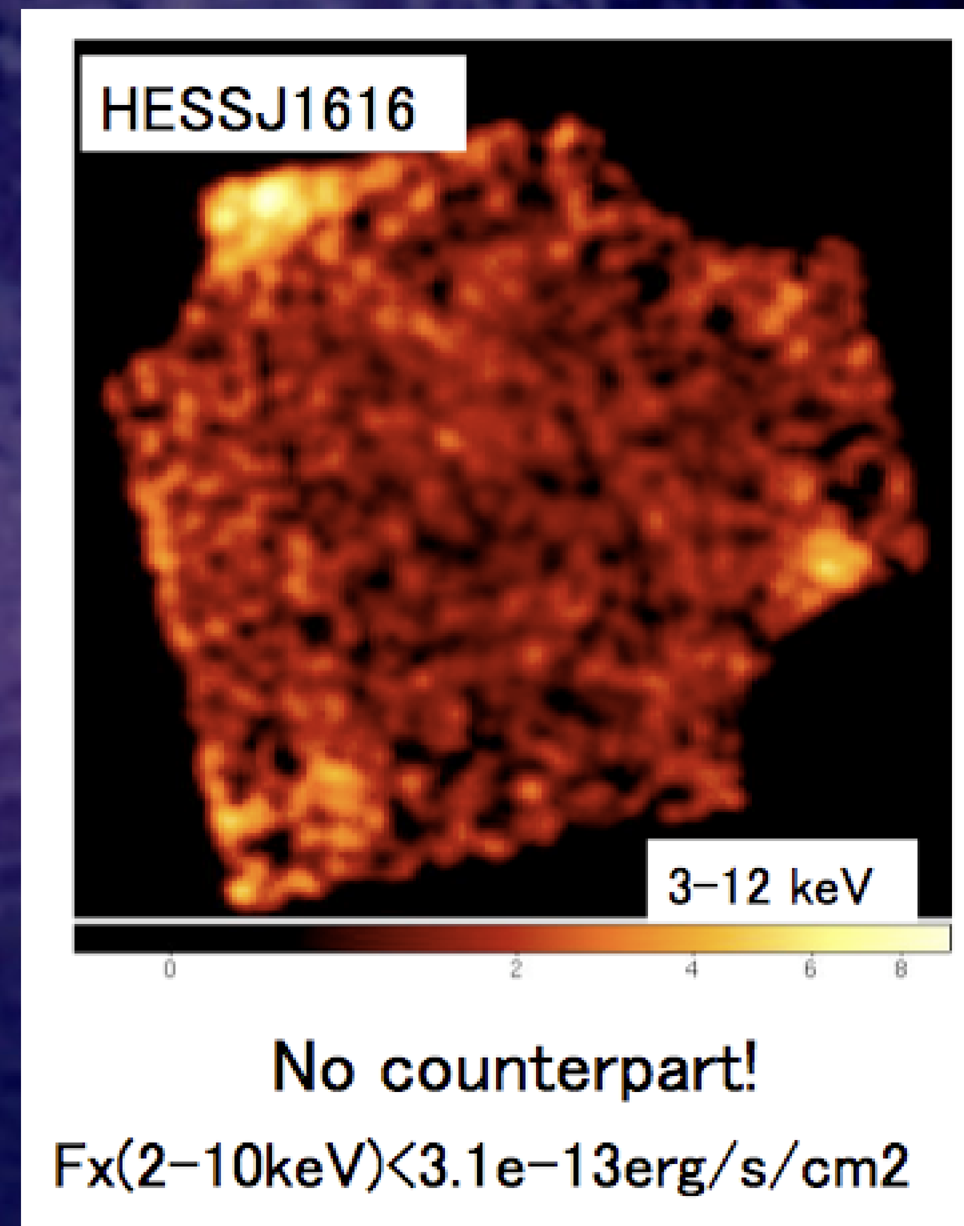
Unidentified TeV Sources

Suzaku Observation of HESS J1616-508

Matsumoto et al. 2006 (in press)

HESS TeV image





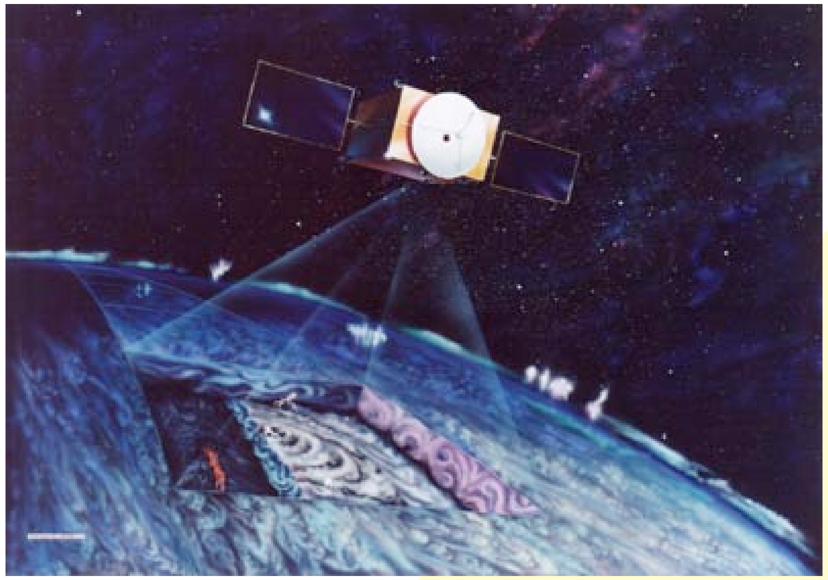
Non-detection in X-rays favors "hadronic" origin of TeV gamma-rays
(TeV IC without X-ray requires B < a few uG)

Fx << Ftev

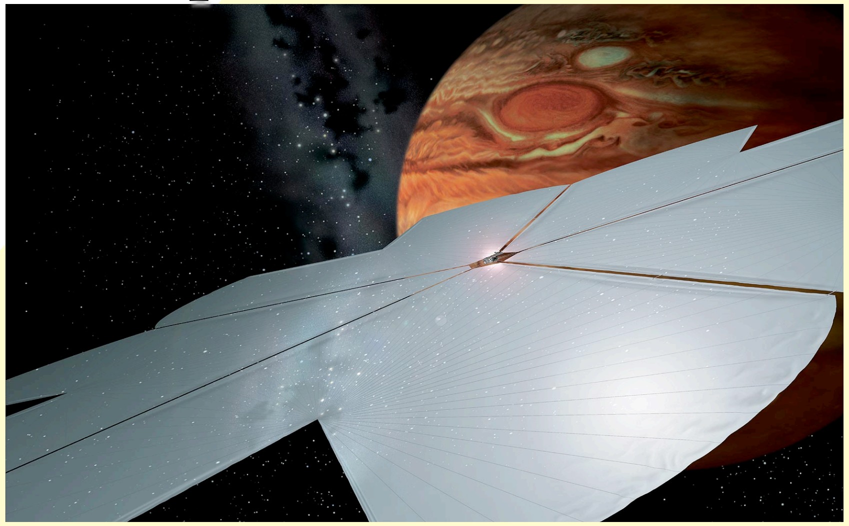
The Japanese "NeXT" mission

Within about 10 years (Defined in ISAS's Long Term Vision)

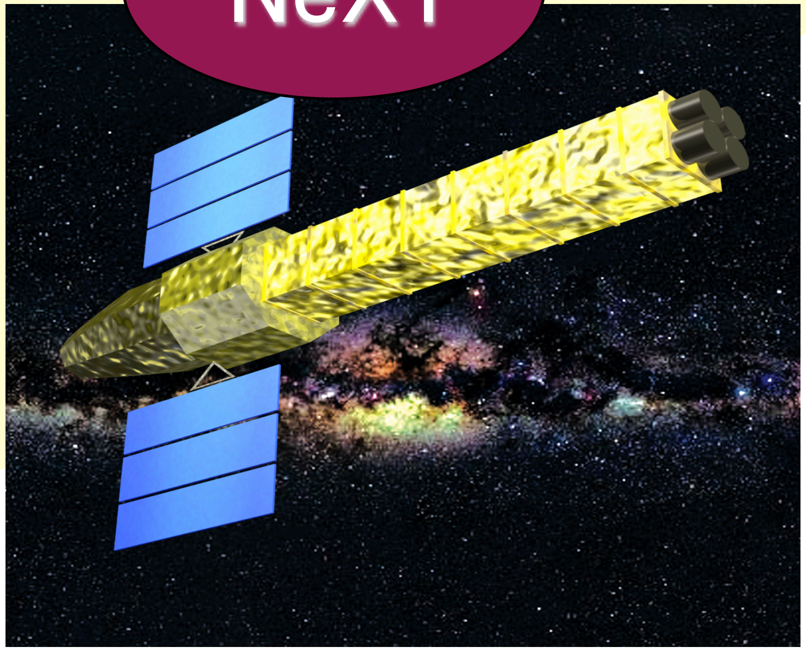
Venus Exploration
「PLANET-C」



Solar-powered Sail

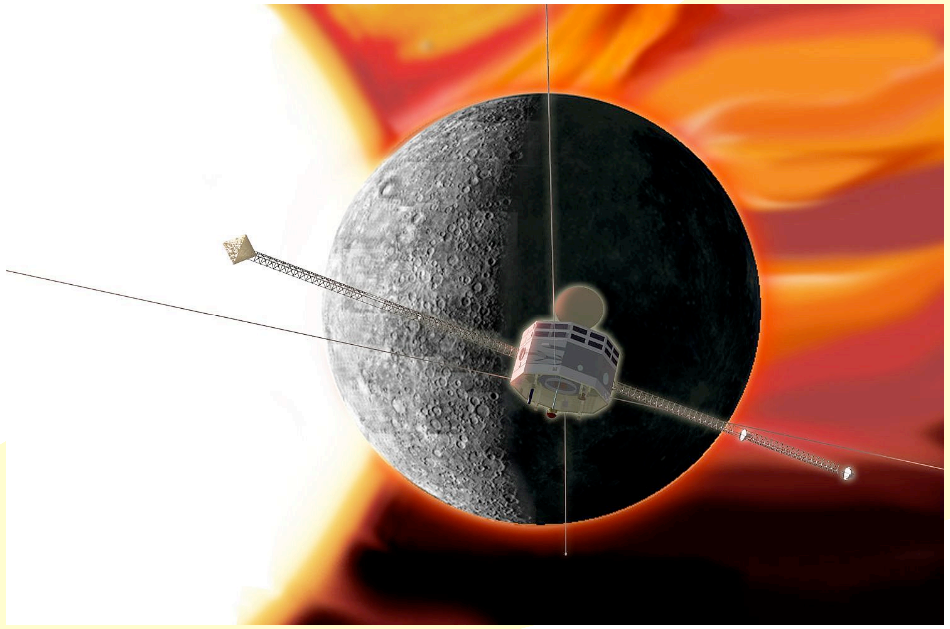


NeXT

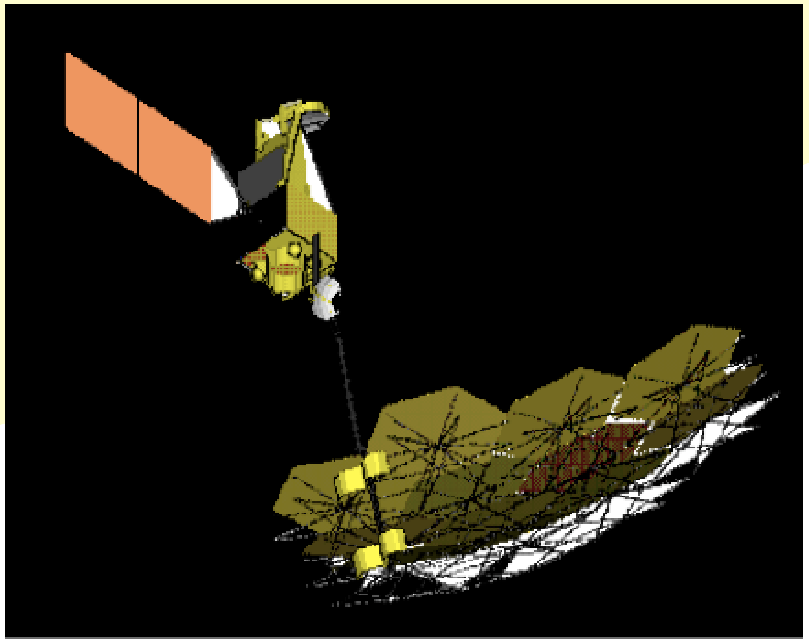


First Hard X-ray Focusing
with
the finest X-ray spectrum

Mercury Exploration
「BepiColombo/MMO」

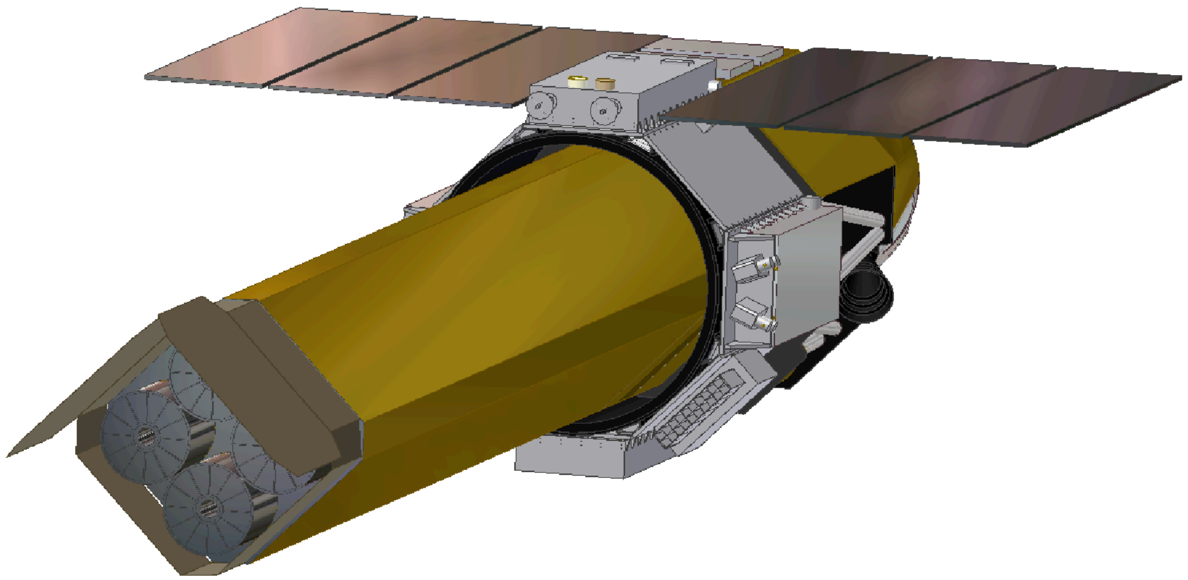


VSOP2



Finest resolution by Space VLBI

NeXT Mission **Launch ~2013**

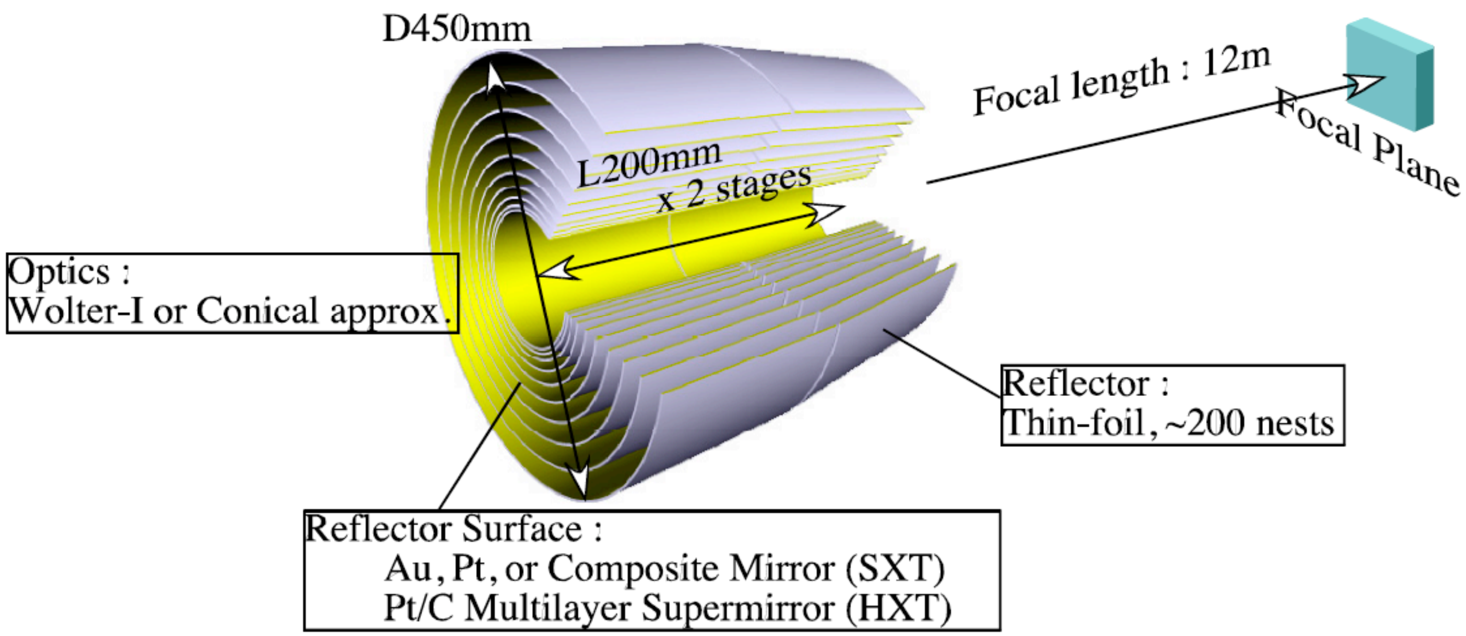


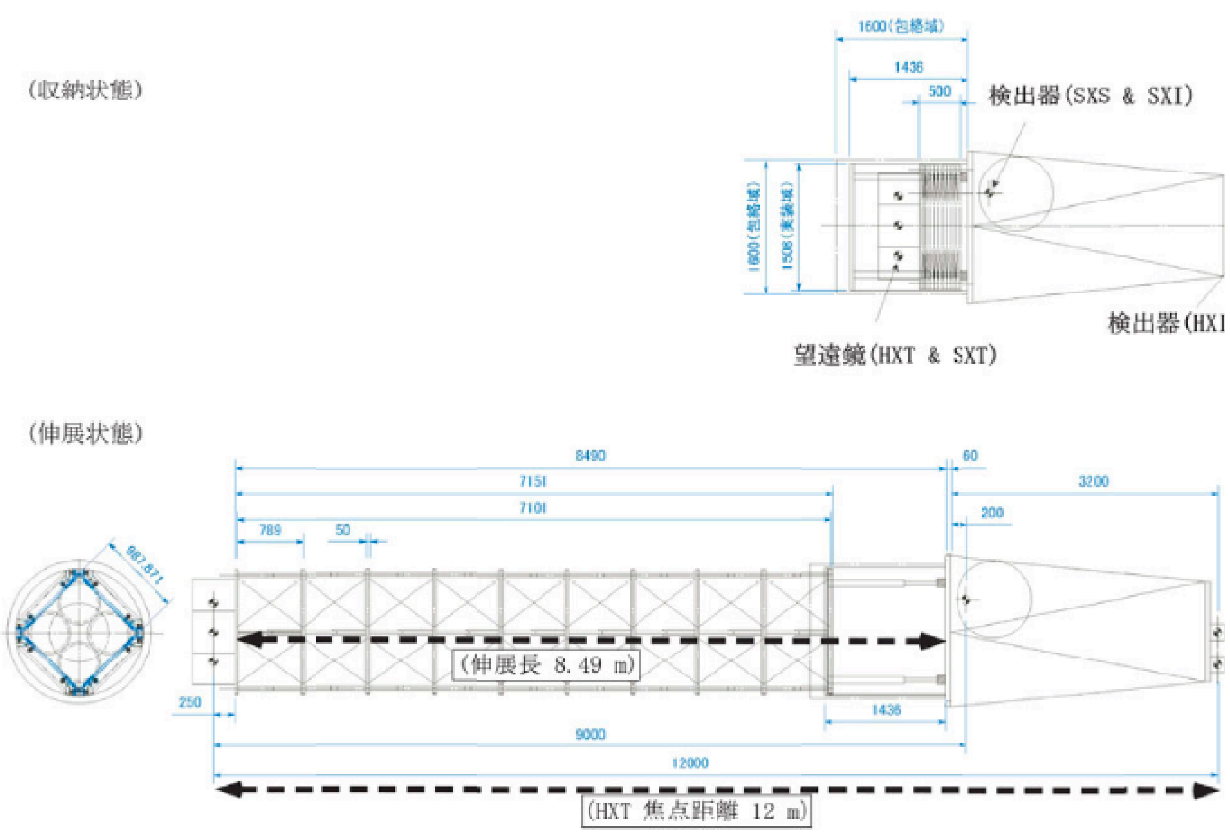
Based on the proposal 2005-Oct,
Approved “Completion of pre-phase A”
Waiting for the transition to Phase A/B

inclination 31 deg
altitude 550 km
weight 1.7t

- **First Hard X-ray Focusing Observation (10 - 80 keV)**
- **Wide band observation (0.3 - 300 keV) with high sensitivity**
- **High Resolution (7 eV) X-ray spectroscopy (0.3 - 10 keV) of diffuse sources**

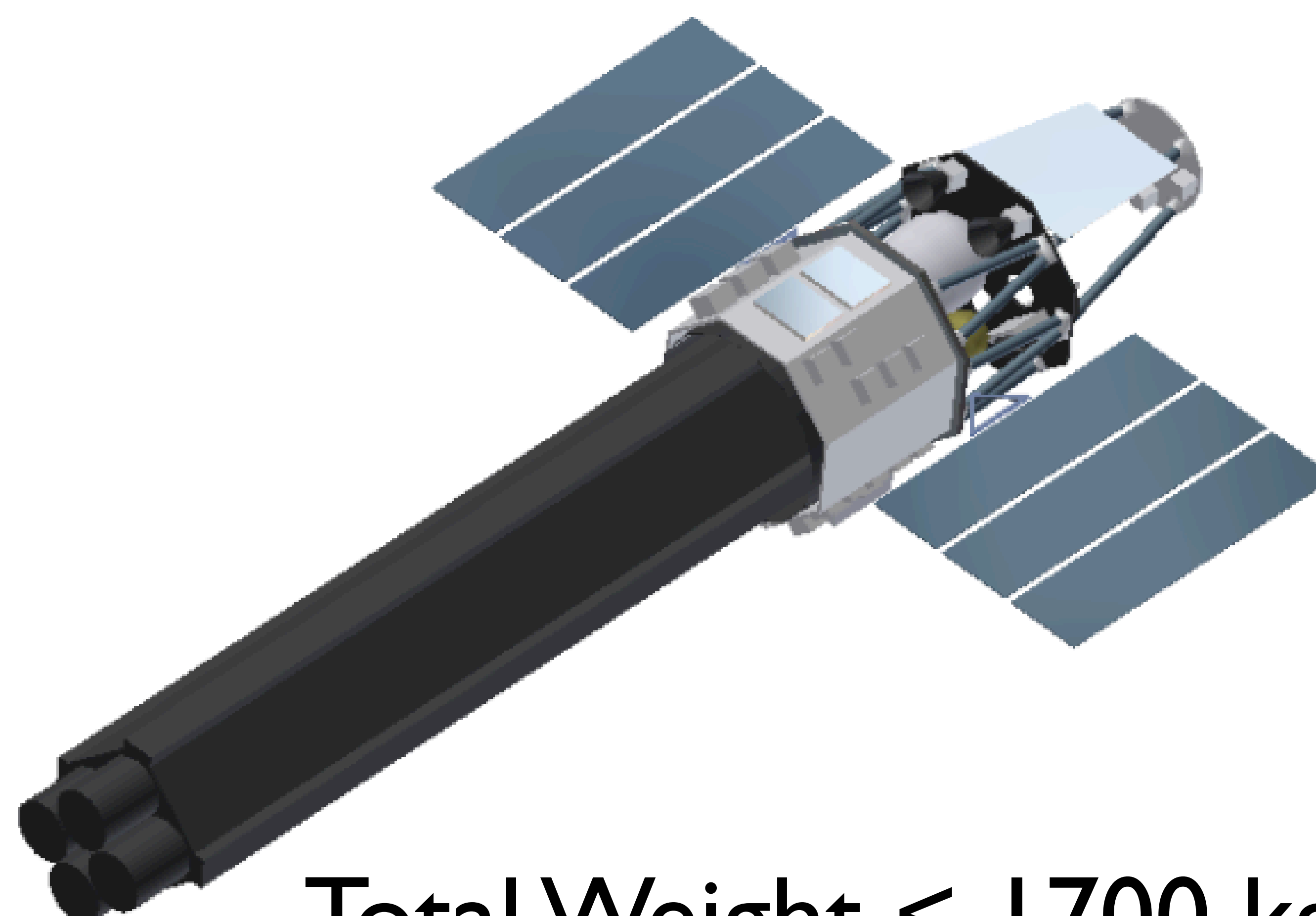
Hard X-ray Imaging





Multilayer Super Mirror:
using *Bragg* reflection

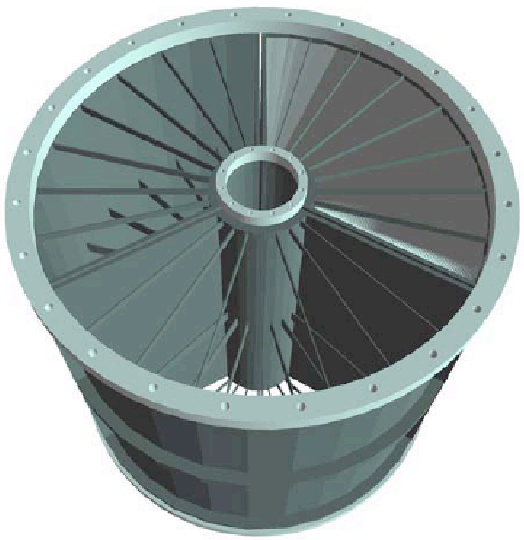
**Super Mirror +
Hard X-ray Imager**

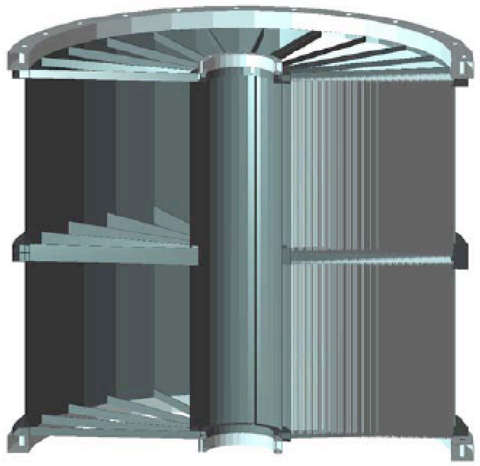


Total Weight < 1700 kg

Large Area/Light Weight Mirror

with ASCA/Suzaku Style

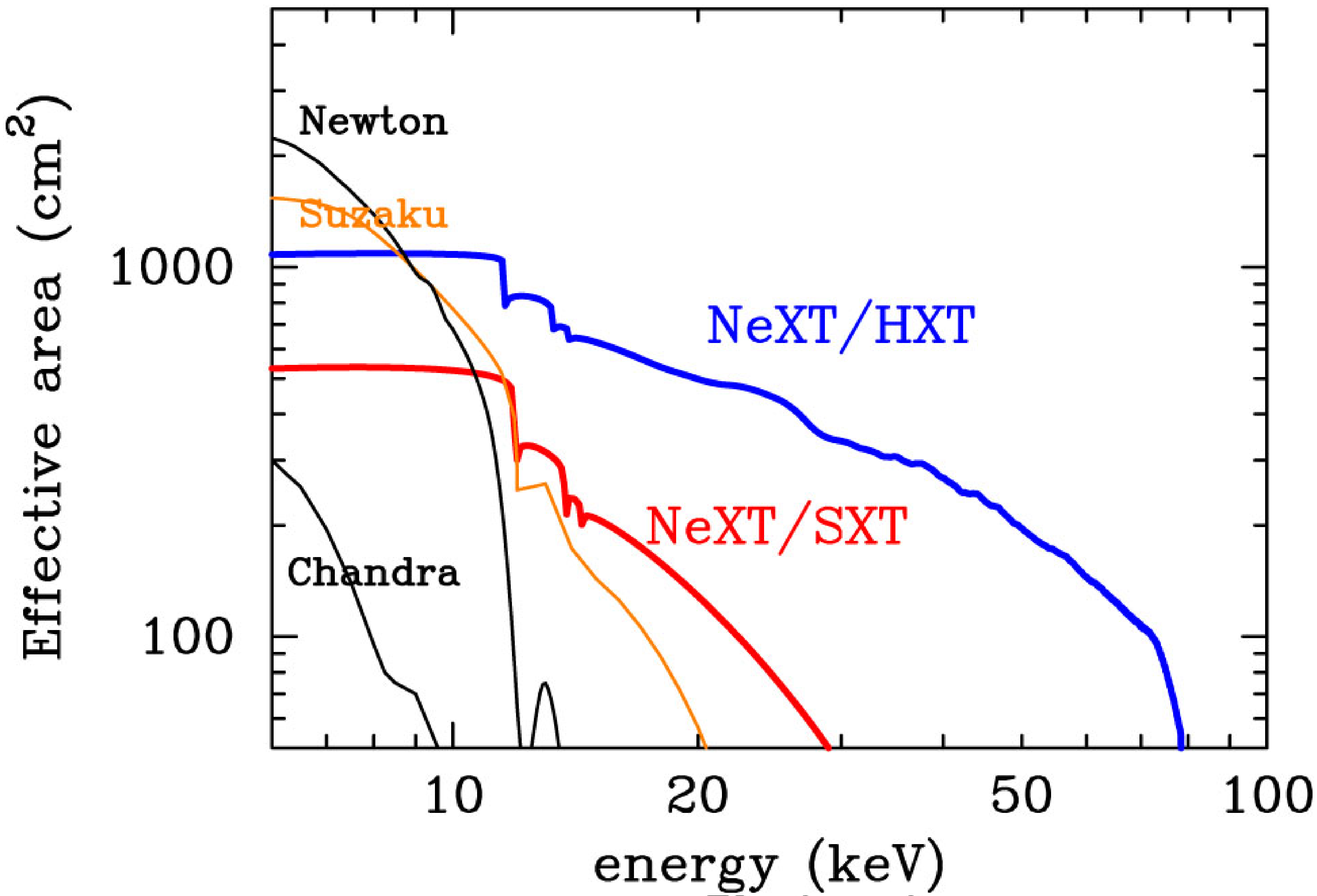




Pt/C multilayer super mirror
(Nagoya U.)

Mirror weight/telescope

Chandra	**1500 kg**
XMM	**440 kg**
Suzaku	**20 kg**
NeXT HXT	**65 kg**



Breakthrough brought by Hard X-ray Focusing Telescope

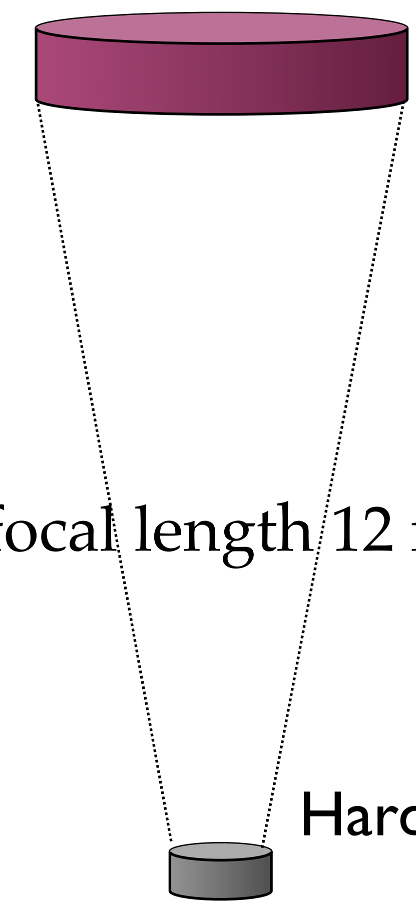
Hard X-ray region is detector background dominated:

Rule of thumb

Detector Background ∝ Detector Volume

Focusing Telescope

NeXT

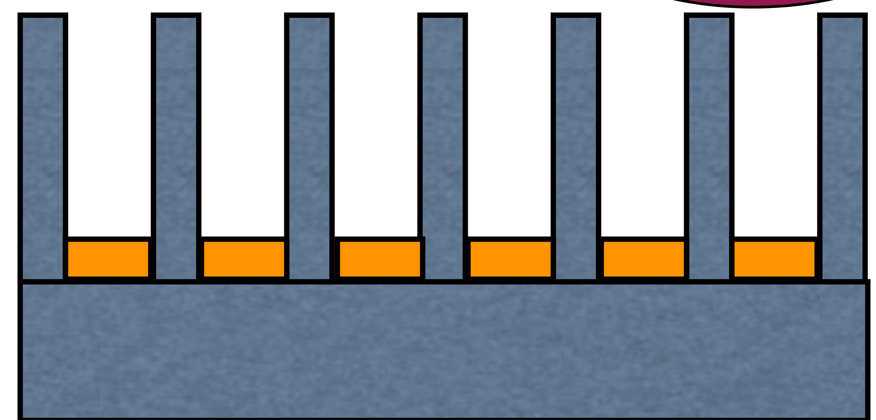


Sensitivity ◎

Sensitivity △

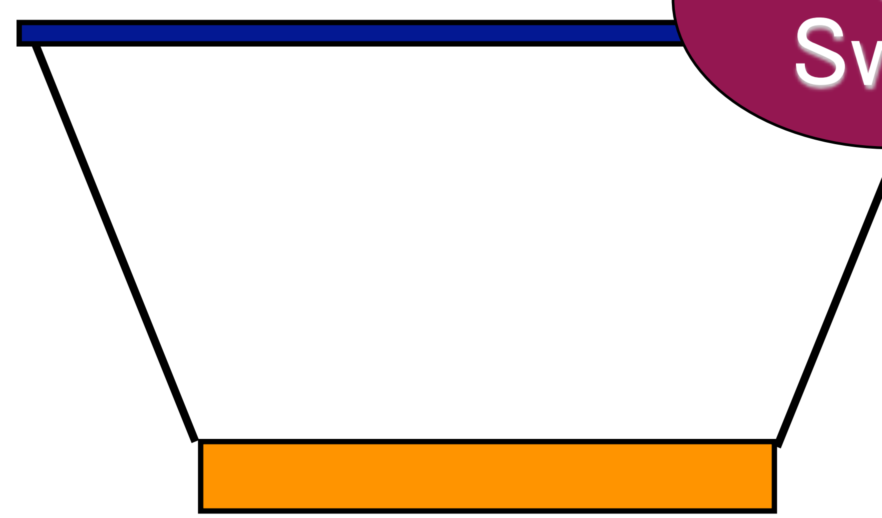
Collimator

Suzaku



Coded-Mask

Integral/ Swift



Effective Area >> Detector Area

Effective Area = Detector Area

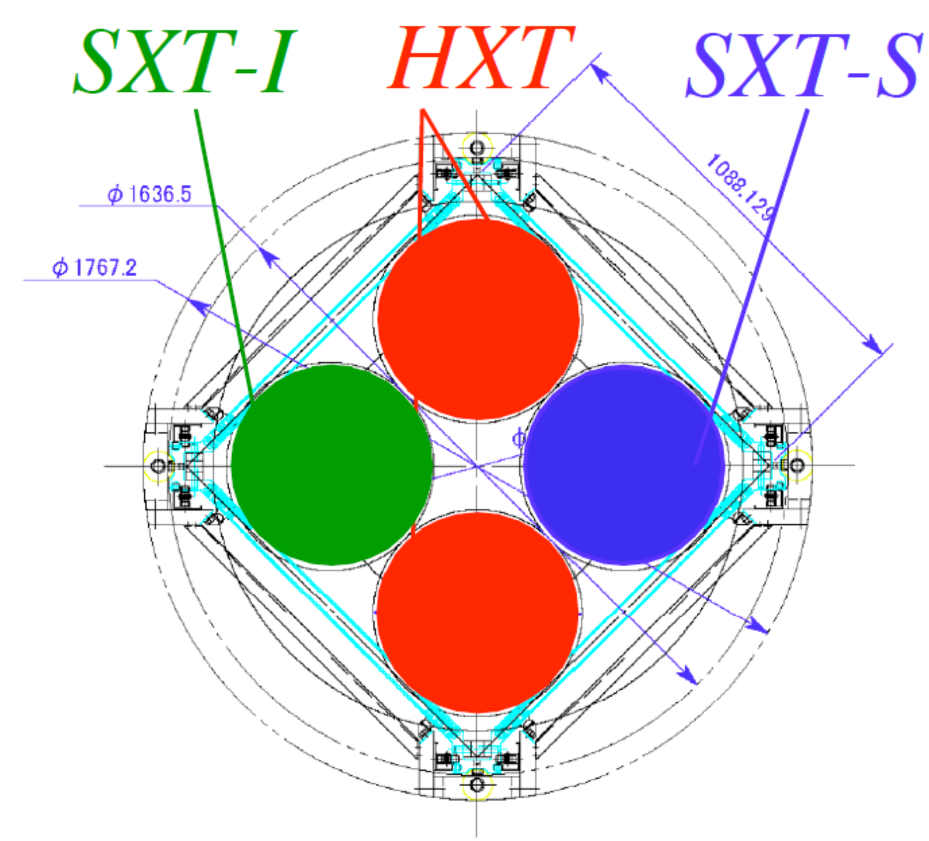
Expected Performance
baseline design

For Hard X-ray Imager (HXT)

Focal Plane	Hard X-ray Imager (HXI)
Energy Range	< 80 keV
Effective Area	~300 cm^2 at 30 keV
Imaging Quality	~ 60 arcsec (HPD)
Effective FOV	~ 8 arcmin

For Soft X-ray Instruments (SXT)

Focal Plane	Soft X-ray Spectroscopy/Imager
Energy Range	< 12 keV
Effective Area	~500 cm^2 at 30 keV
Imaging Quality	~ 60 arcsec (HPD)
Effective FOV	~ 12 arcmin

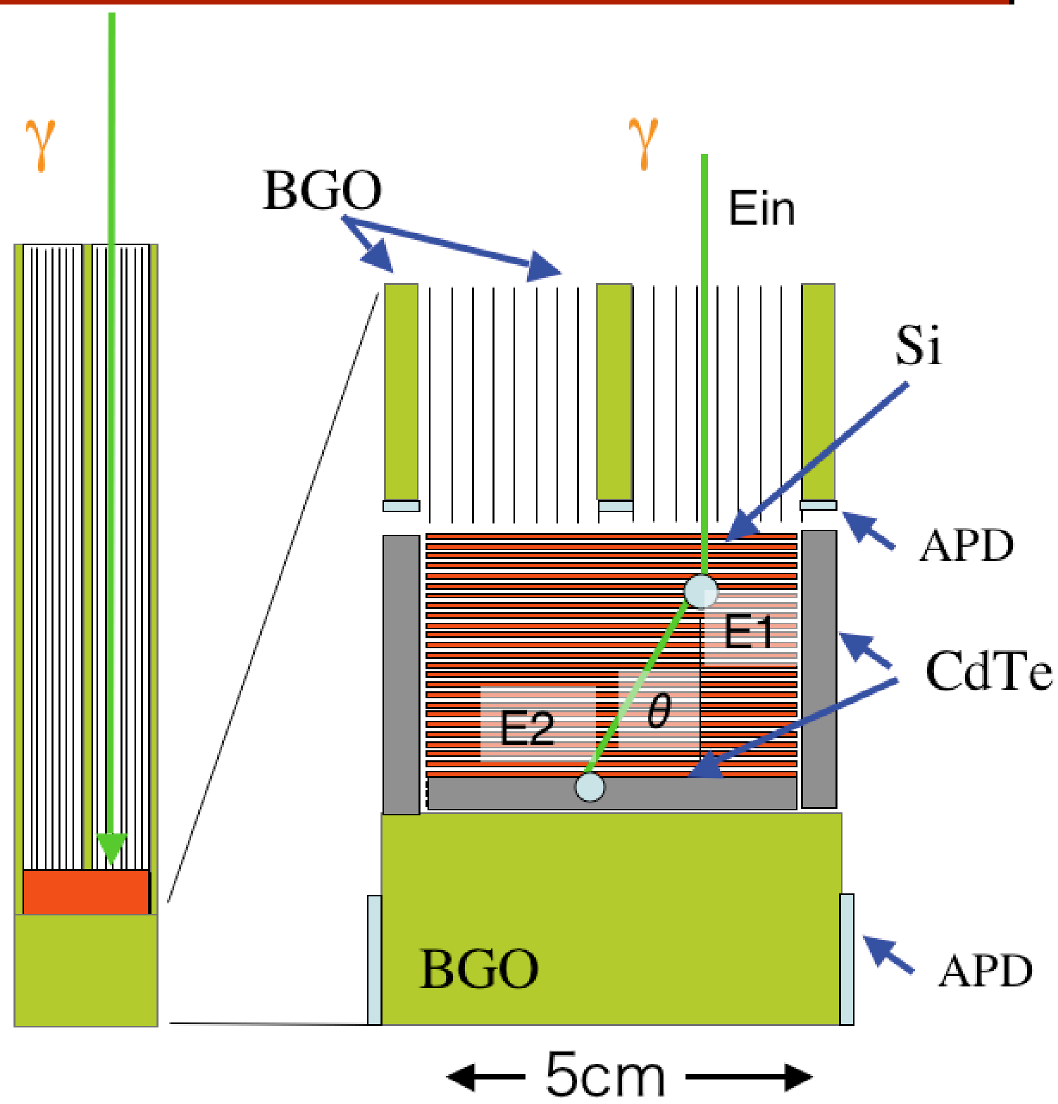


SGD (Soft Gamma-ray Detector)

New Concept:

Narrow Field of View Compton telescope

Takahashi, Makishima, Kamae, 2001
Takahashi et al. SPIE, 2002



Compton kinematics inside the BGO WELL is the key to reduce the internal background

1. Select two-hits events
(e.g. one in Si and one in CdTe)
2. Calculate the direction of "incident" gamma-ray by using Compton Eq.
3. Accept events only if the ring intercepts the FOV (0.5 deg for <100 keV, ~ 4 deg at 500 keV)

DSSD 0.5mm thick, 400 micron pitch 24 layers
CdTe Pixel Wall, 5-6 mm thick, 1-2 mm pitch

Conclusions

- *Suzaku is suited for X-ray studies on TeV sources*
- *"NeXT" will realize the first **Hard X-ray Focusing Telescope** up to 100 keV (with 1′ resolution)*
- *We hope the realization of TeV imaging with < 1′ resolution to be compared with X-ray and hard X-ray images*