Science and Instrumentation of ASTRO-H Mission

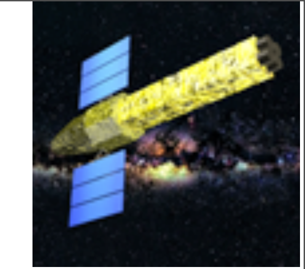
Hiroyasu Tajima
Kavli Institute for Particle Astrophysics and Cosmology
SLAC National Accelerator Laboratory

Outline

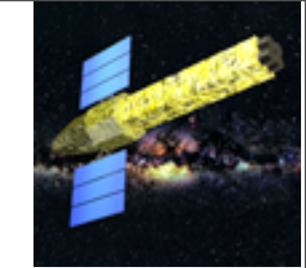
- ❖ Mission Overview
- ❖ Instruments
- ❖ SGD Science Drivers
- ❖ Technology Development
- ❖ Performance
- ❖ Roadmap

IPMU Seminar, University of Tokyo
December 15, 2008
Kashiwa, Japan

ASTRO-H Mission

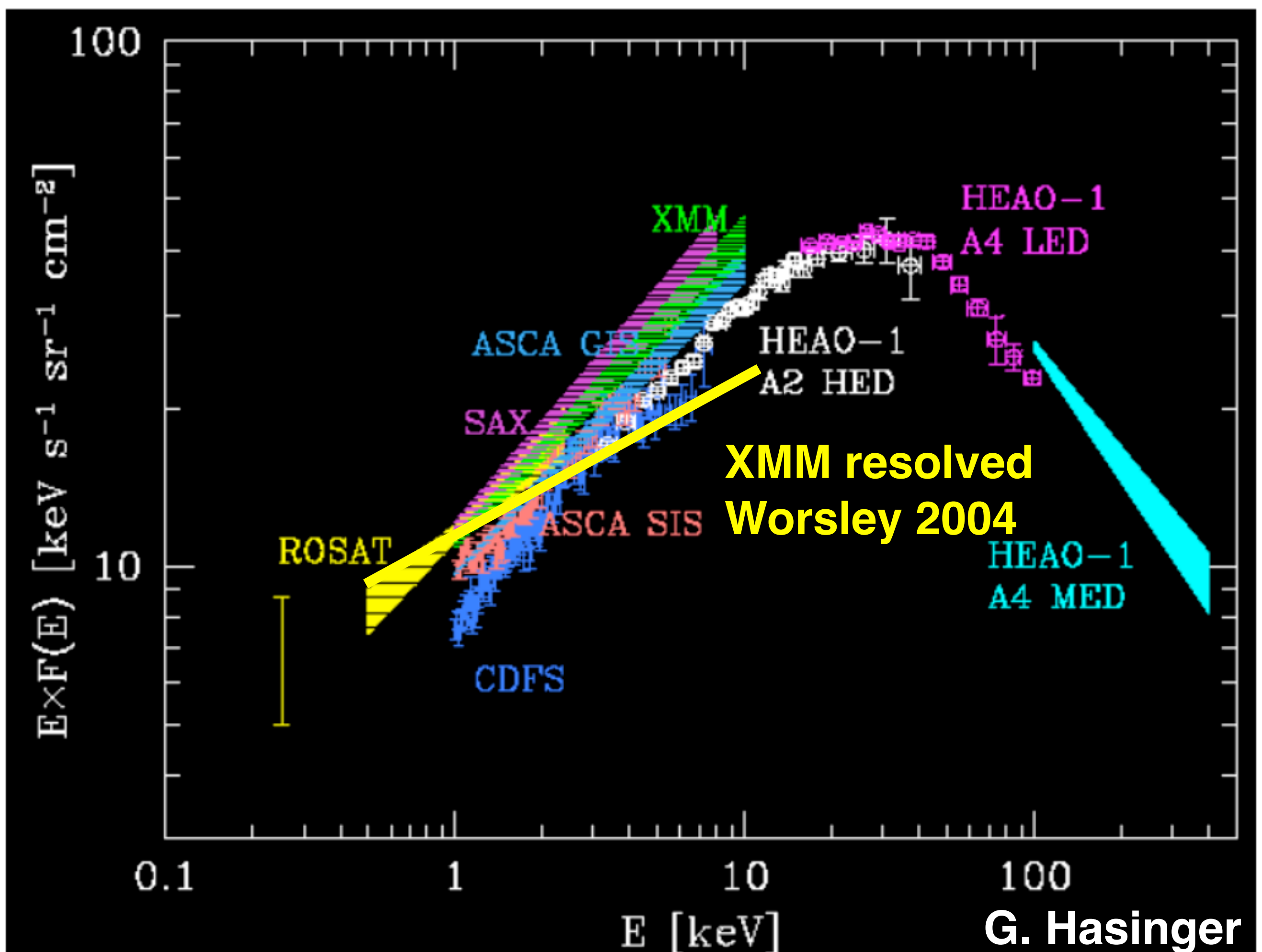


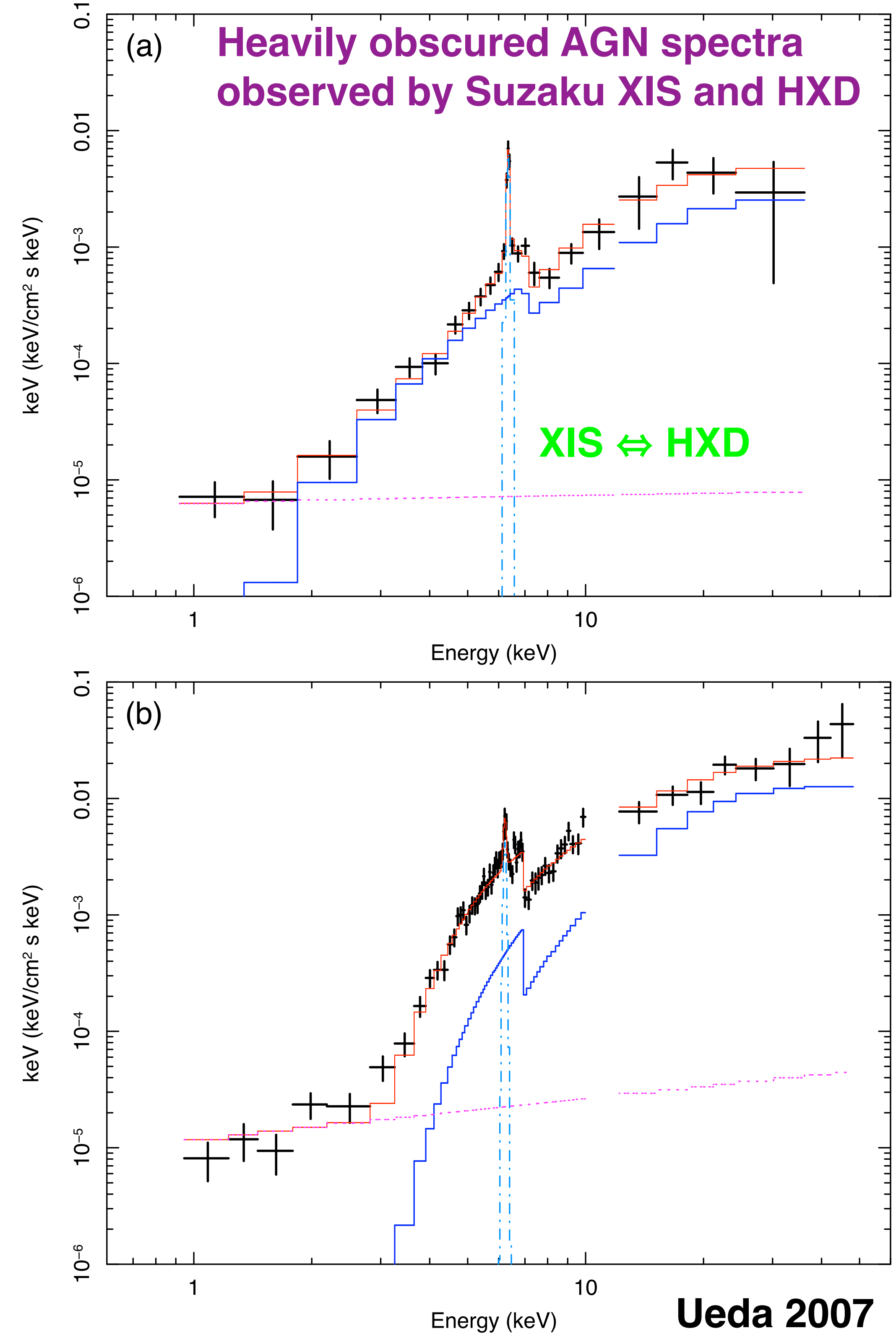
- Next Generation of Japanese X-ray Satellite Mission
  - Successor to Suzaku (Astro-E2)
- Recovery of Calorimeter Science
  - Lost due to failure of calorimeter onboard Suzaku
- Major Science Objectives
  - New probes of super-massive black holes
    - General Relativity effects near BHs
    - Obscured AGNs
  - Detailed Understanding of galaxy clusters
    - Better determination of cluster mass and other properties
      - Structure formation history of Universe
      - Properties of Dark Energy
  - Cosmic-ray accelerators



Obscured AGNs

- CXB (Cosmic X-ray Background)
  - CXB > 2 keV is not accounted for by point sources
  - Obscured AGN to rescue?

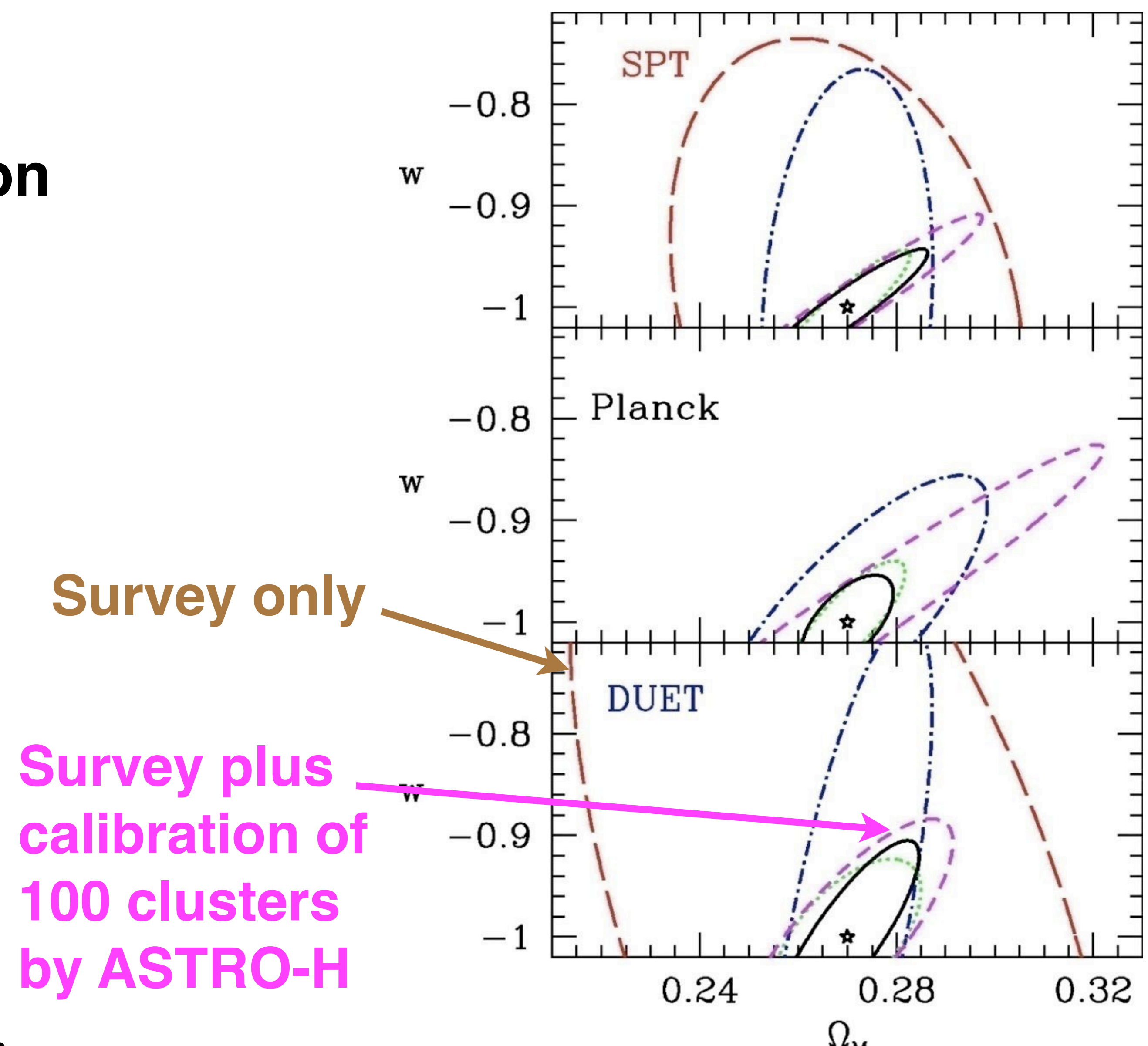




Ueda 2007

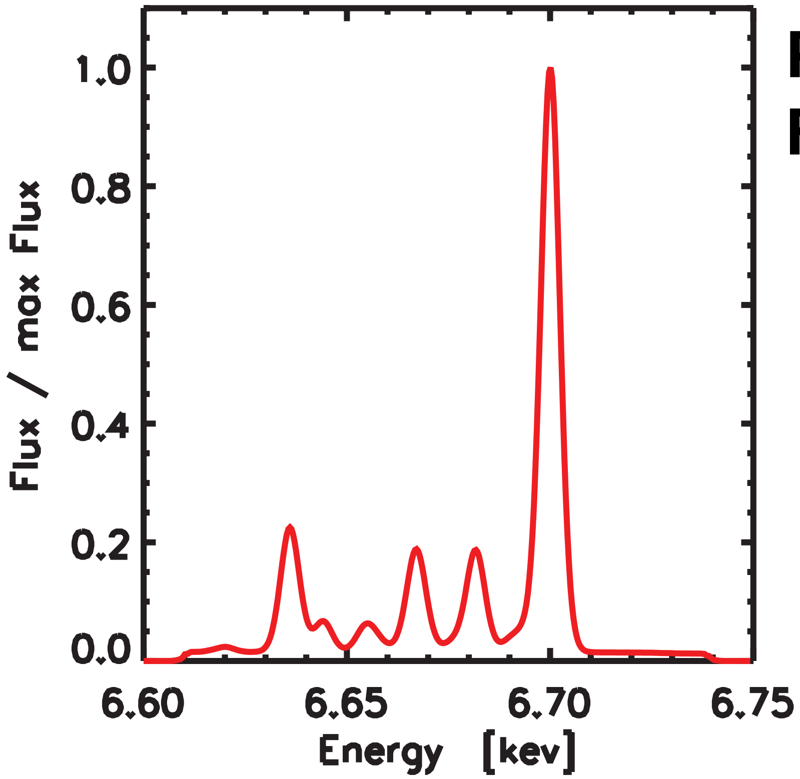
Dark Energy Science

- “The Cluster technique has the statistical potential to exceed the BAO and SN techniques.” (Dark Energy TF)
  - Largest systematic errors: relationship between cluster mass and observable
    - Precise X-ray line shape
      - Turbulence, velocity shear
      - Heat transport and dissipation
      - Thermal state of gas
      - Chemical abundance
    - Hard X-ray measurements
      - Magnetic field viscosity
        - Compton up-scattering + synchrotron (radio)
      - Cosmic-ray pressure
      - Radiative energy



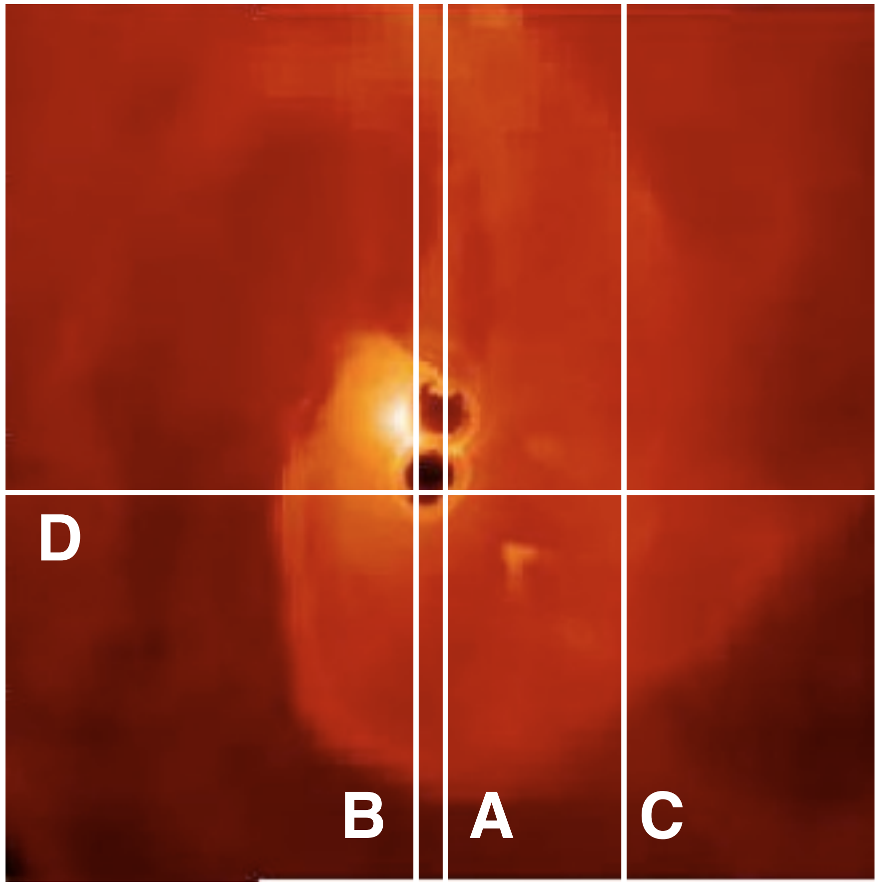
Turbulence in Galaxy Clusters

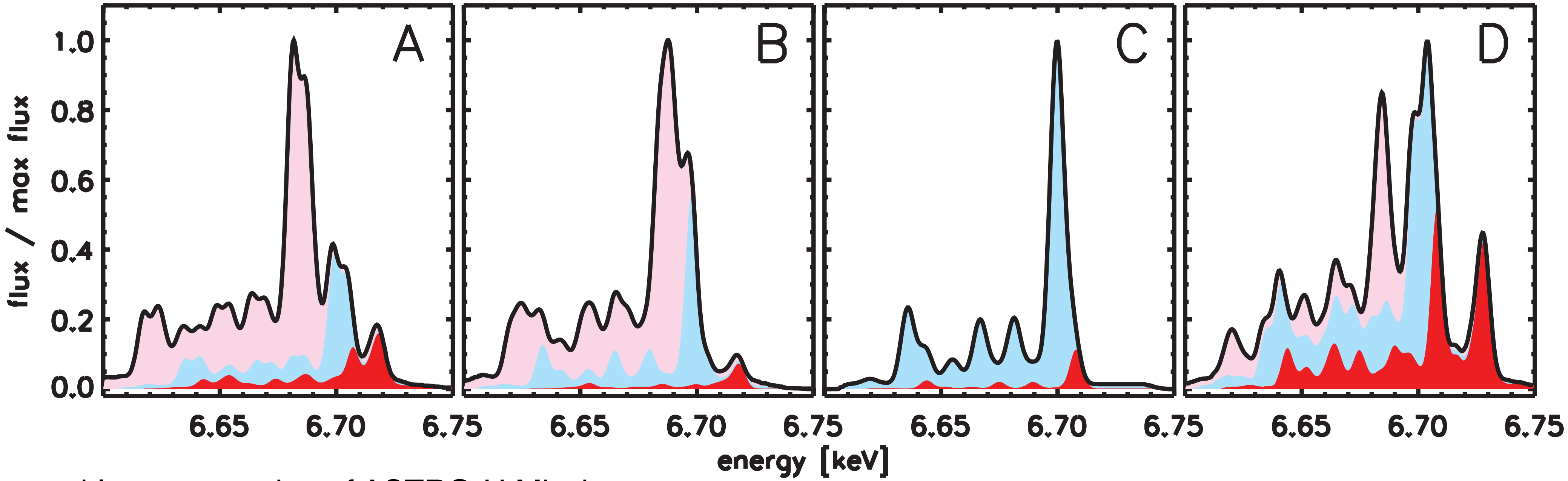
✤ **AGN induced turbulence in cluster.**



Pure thermal Fe emission

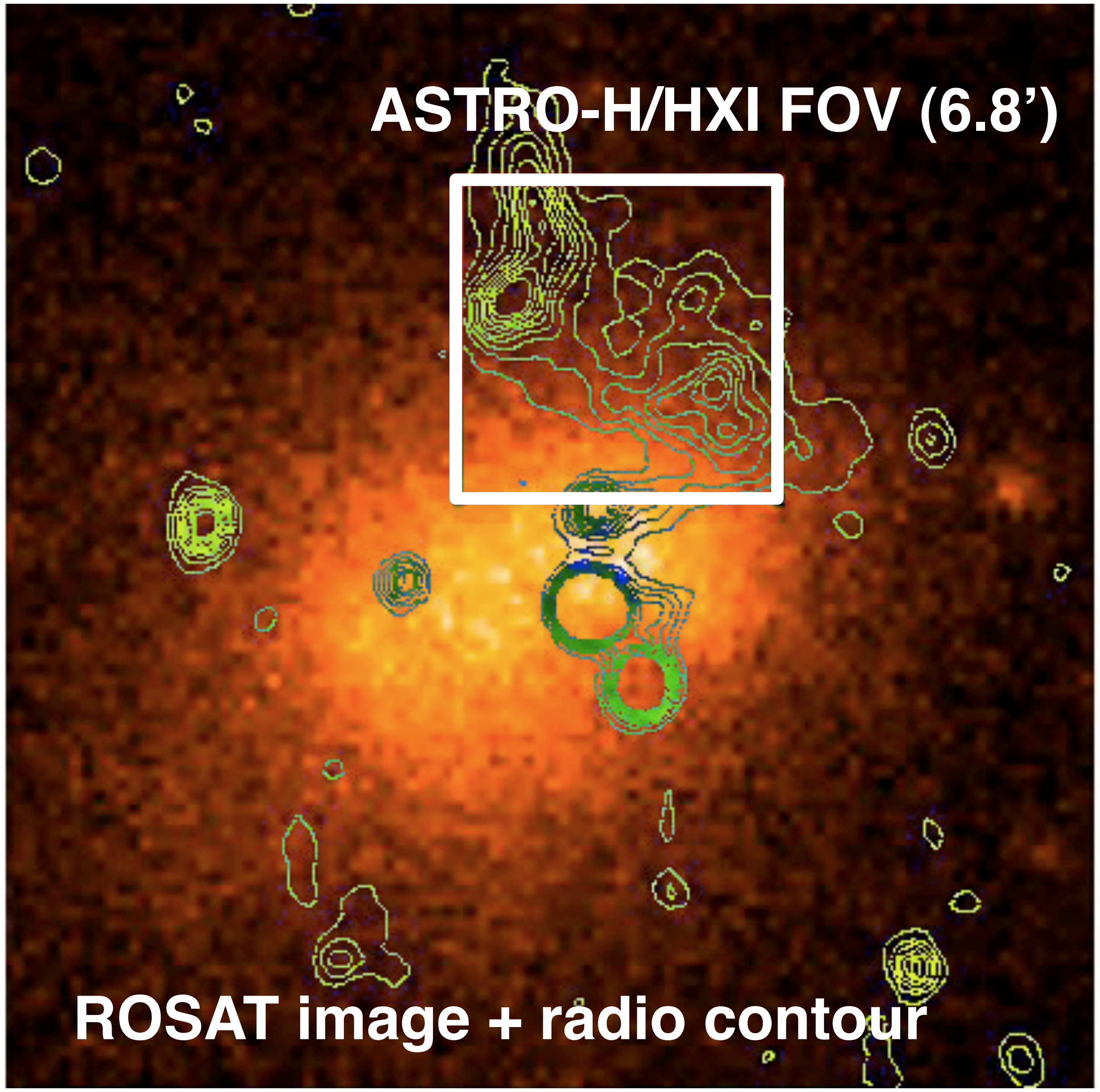
Simulation by Brueggen, Hoeft and Ruszkowski (2006)



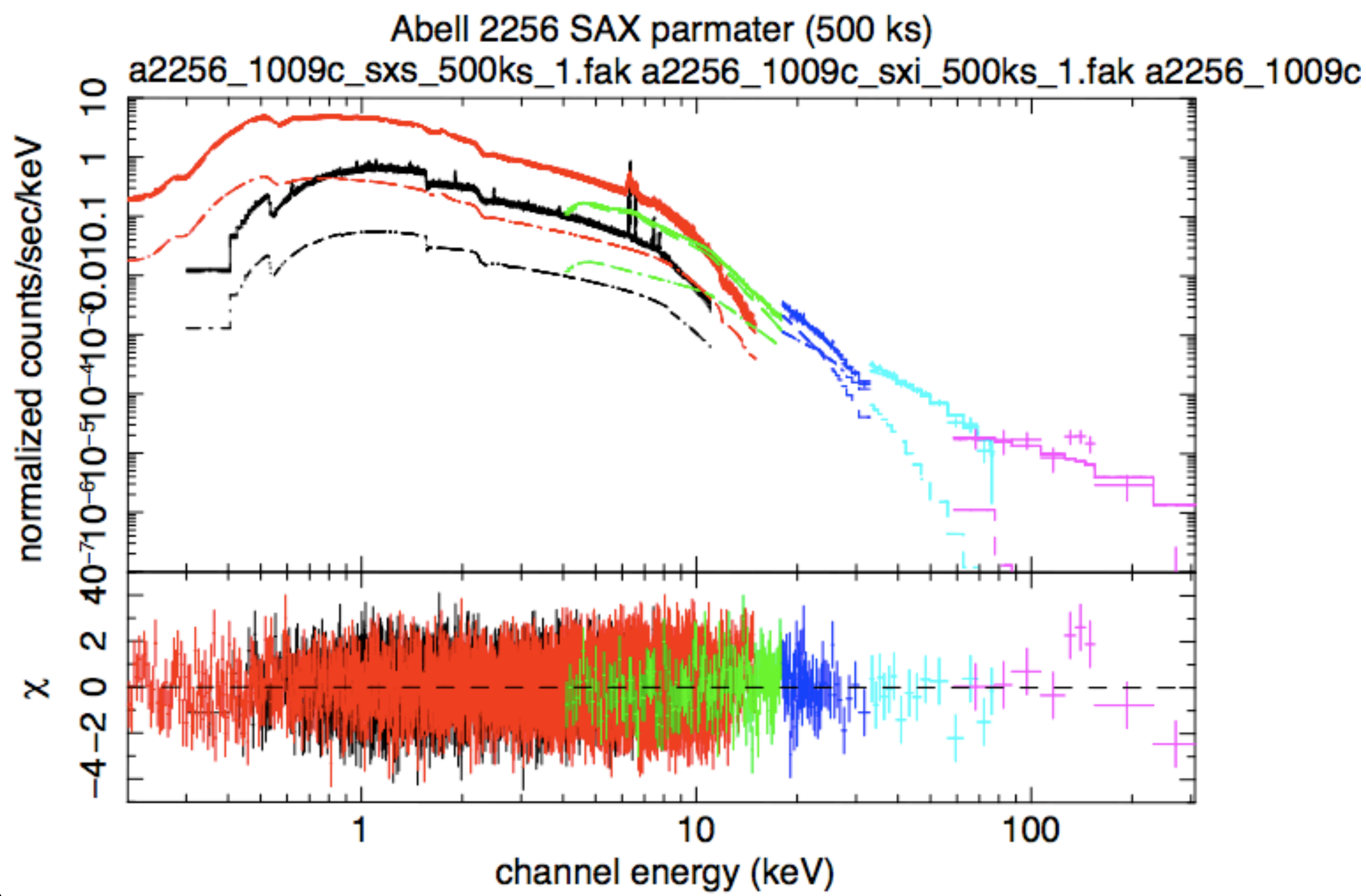


Non-Thermal Emission from Clusters

✤ A2256: Non-thermal emission claimed by Beppo-SAX

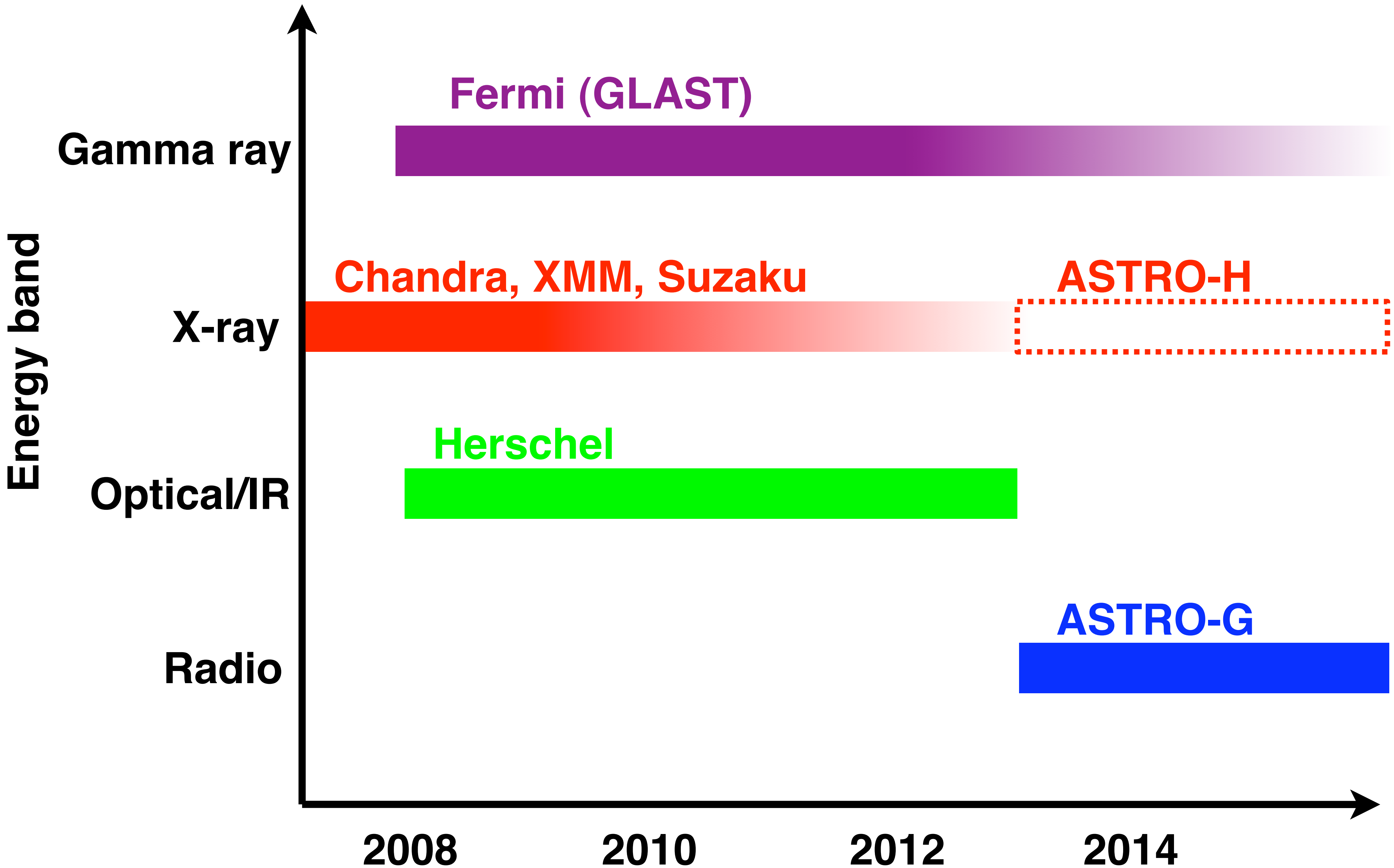


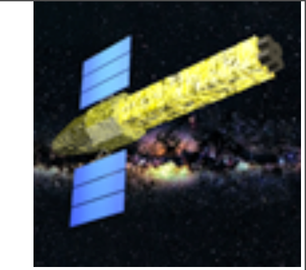
ASTRO-H simulation by Fukazawa/Nakazawa



Satellite Missions in Near Future

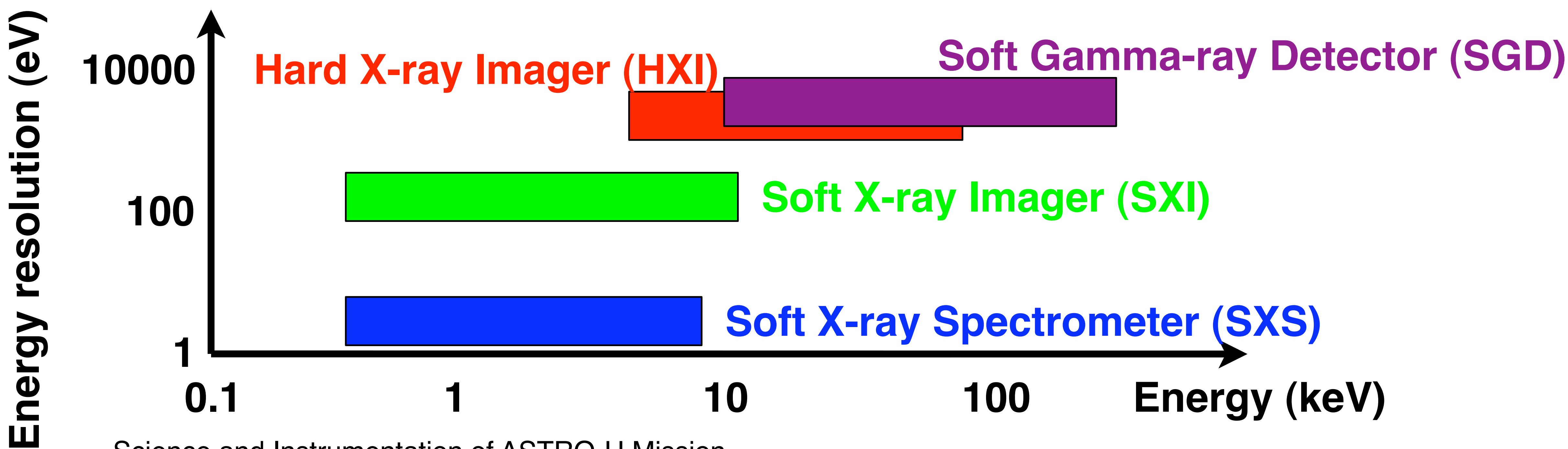
- Concerns on missing X-ray observatory from 2013





Instruments Onboard ASTRO-H

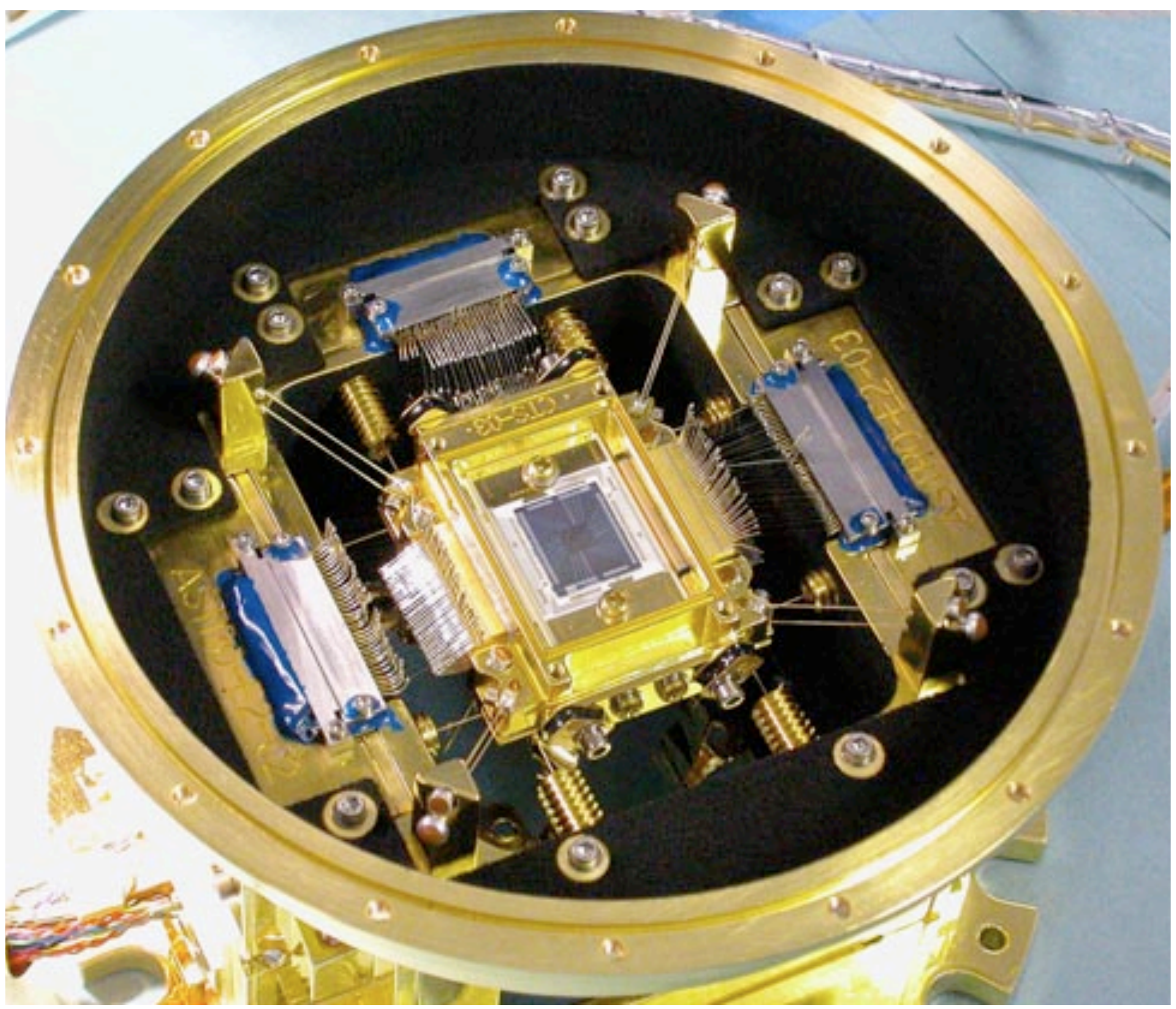
- **Soft X-ray Spectrometer**
  - Soft X-ray telescope + X-ray micro-calorimeter
- **Hard X-ray Imaging System**
  - Hard X-ray telescope + hard X-ray imager
- **Soft X-ray Imaging System**
  - Soft X-ray telescope + CCD
- **Soft Gamma-ray Detector**
  - Narrow field-of-view Compton camera

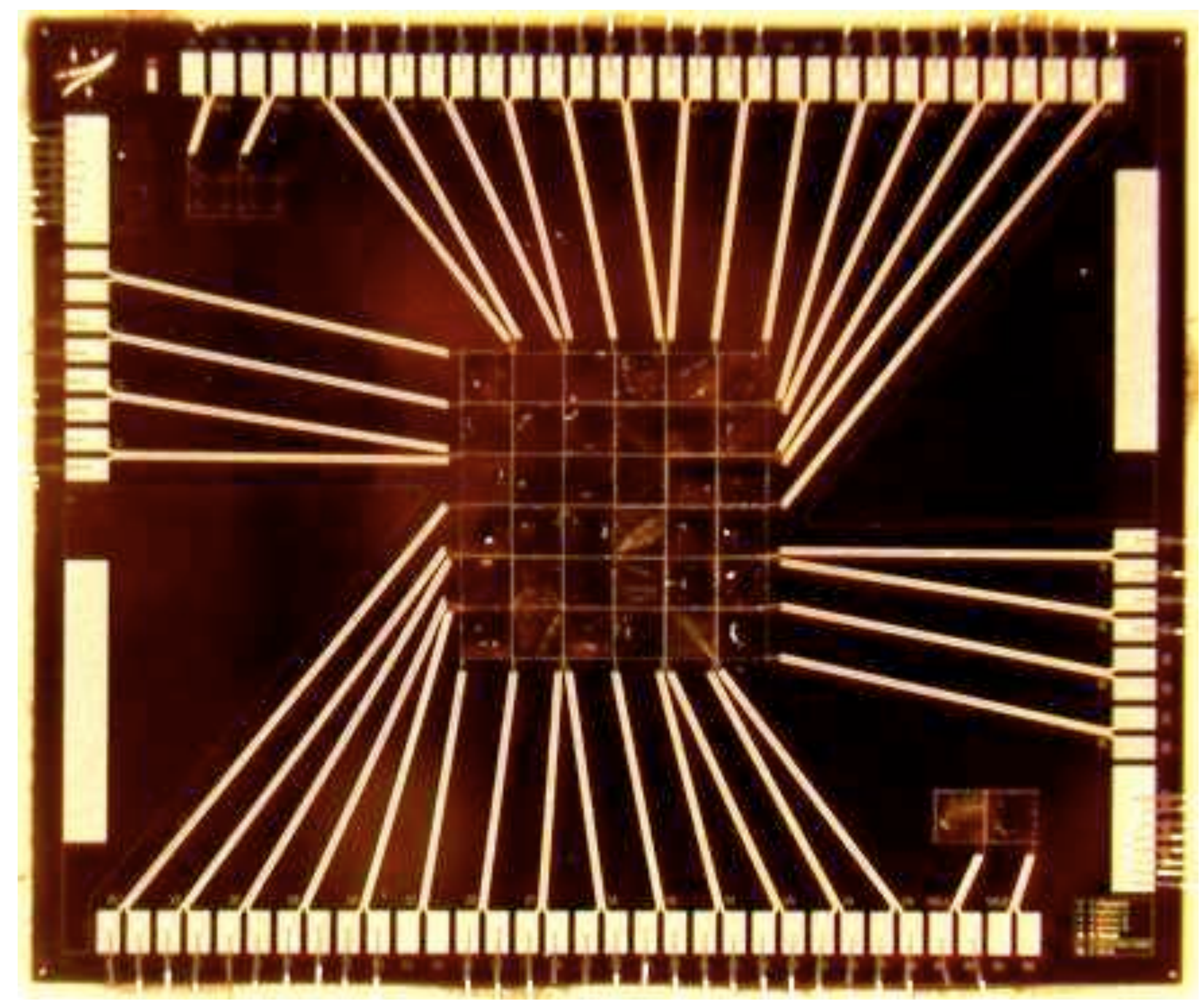


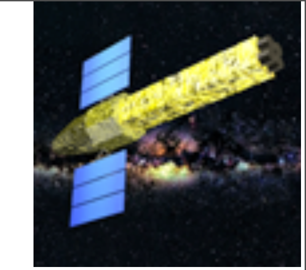
X-Ray Micro-Calorimeter

- Measure temperature rise due to absorption of X-ray
- Energy resolution ~ 6 eV
- 12 x 12 or 16 x 16 array

Suzaku XRS



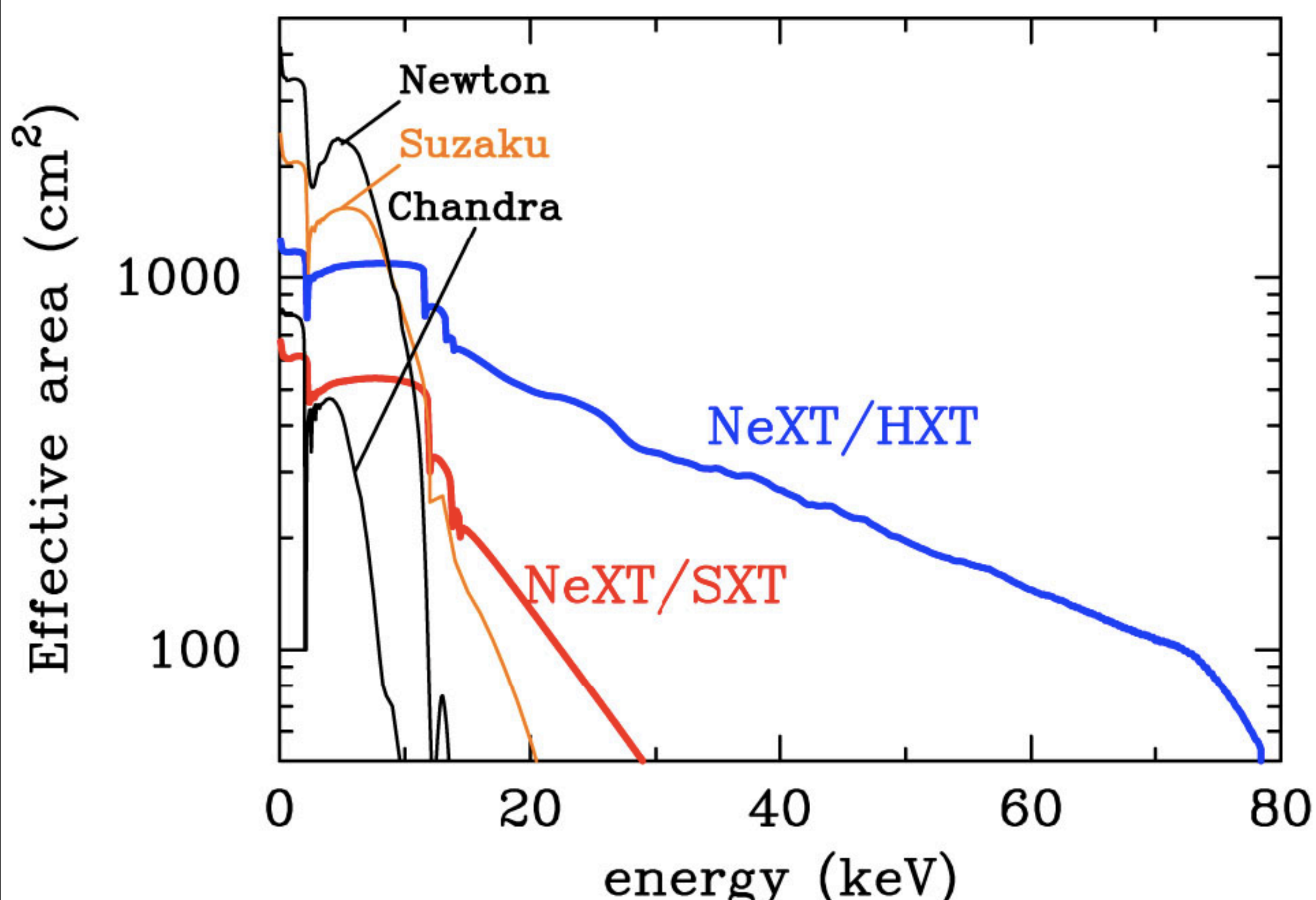


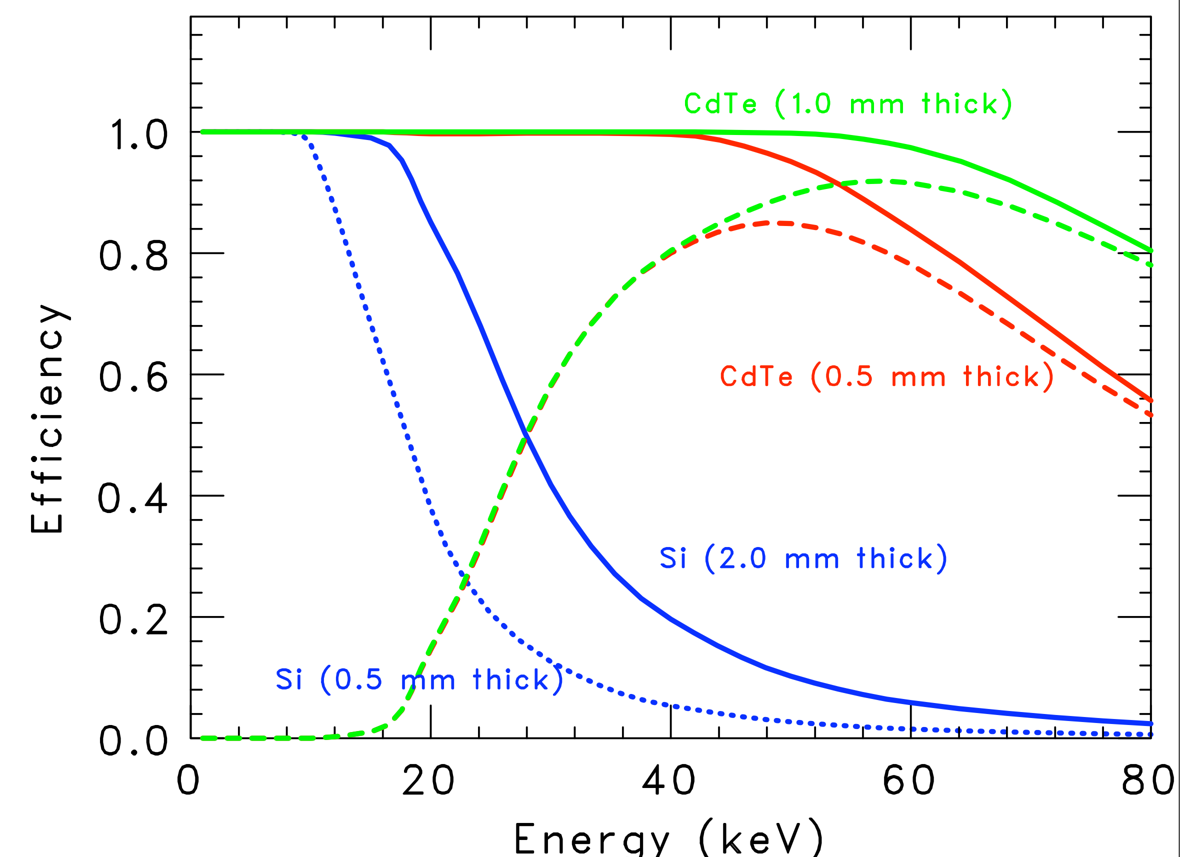


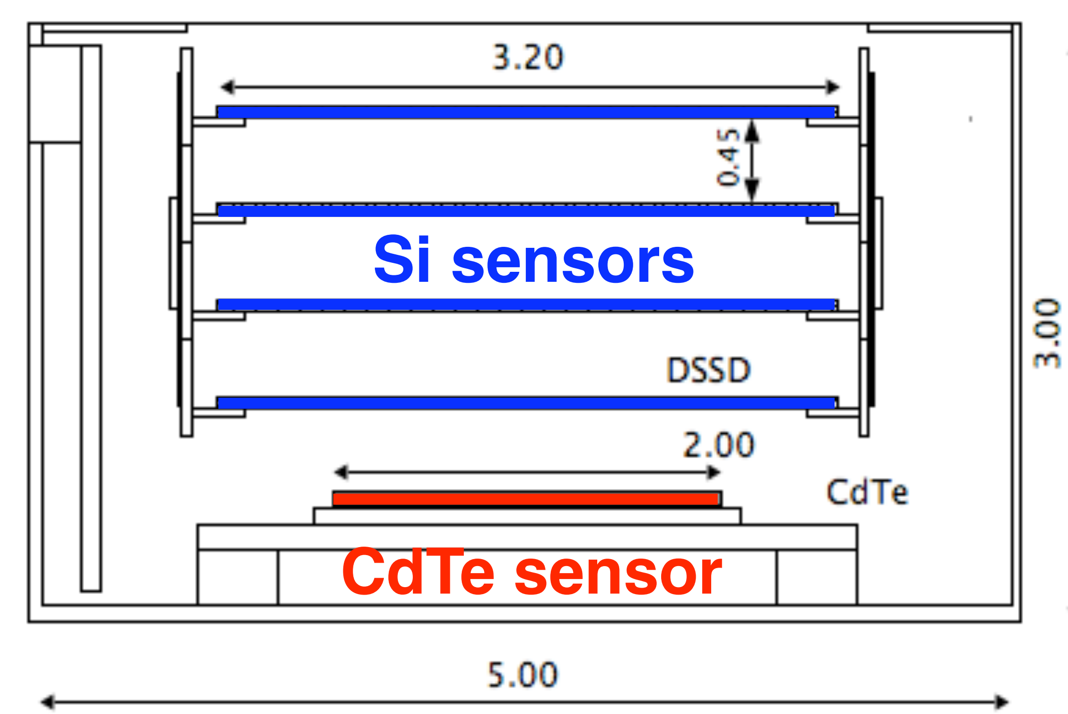
Hard X-Ray Imaging

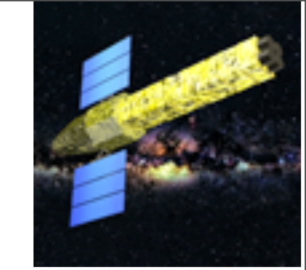
✤ Requirements

- **HPD: 60 arcsec**
- **Effective area: 340 cm^2 @ 30 keV**
- **Energy resolution: < 2 keV**
- **Pixel size: 0.25 – 1 mm**









SGD Concept and Requirements

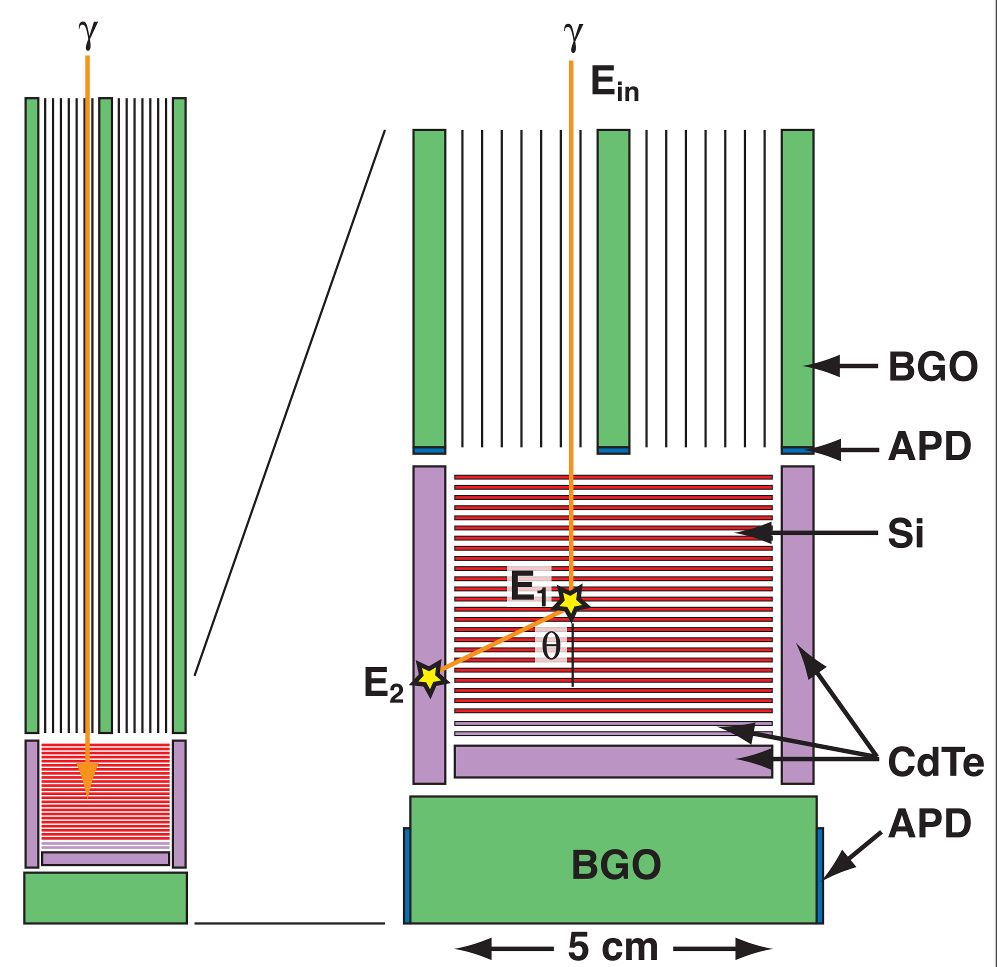
✤ Scientific drivers

- High-energy cut-off in SNR, BHB, AGN, Clusters
- Nuclear gamma-ray lines (nuclear synthesis in SNe)
- Soft gamma-ray polarization

✤ Requirements

- Spectral measurement down to 10^{-3} Crab sources @100ks
- Energy band: 10–600 keV
- 10 times better sensitivity than Suzaku/HXD @ 100 keV
- Energy resolution < 2 keV @ 40 keV

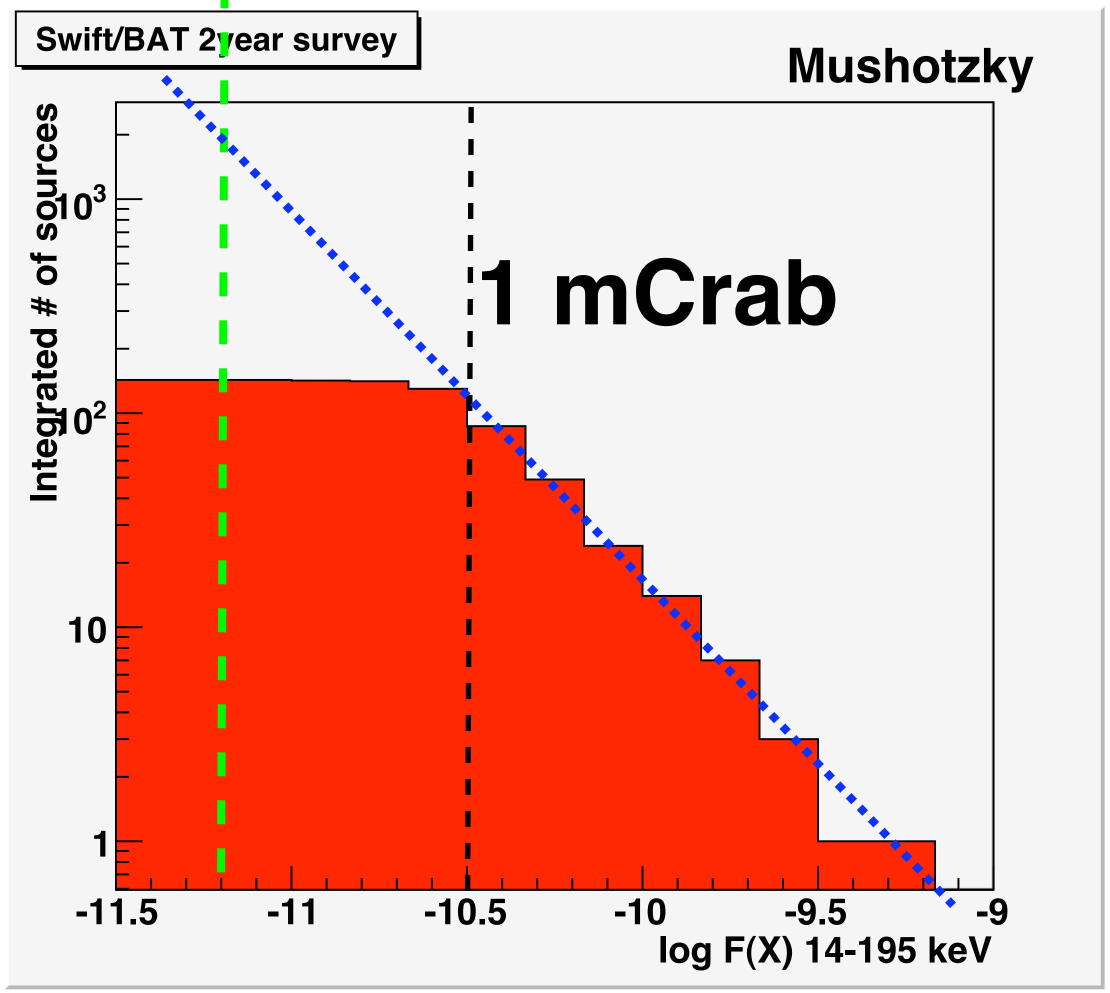
$$\cos\theta = 1 + \frac{m_e c^2}{E_1 + E_2} - \frac{m_e c^2}{E_2}$$



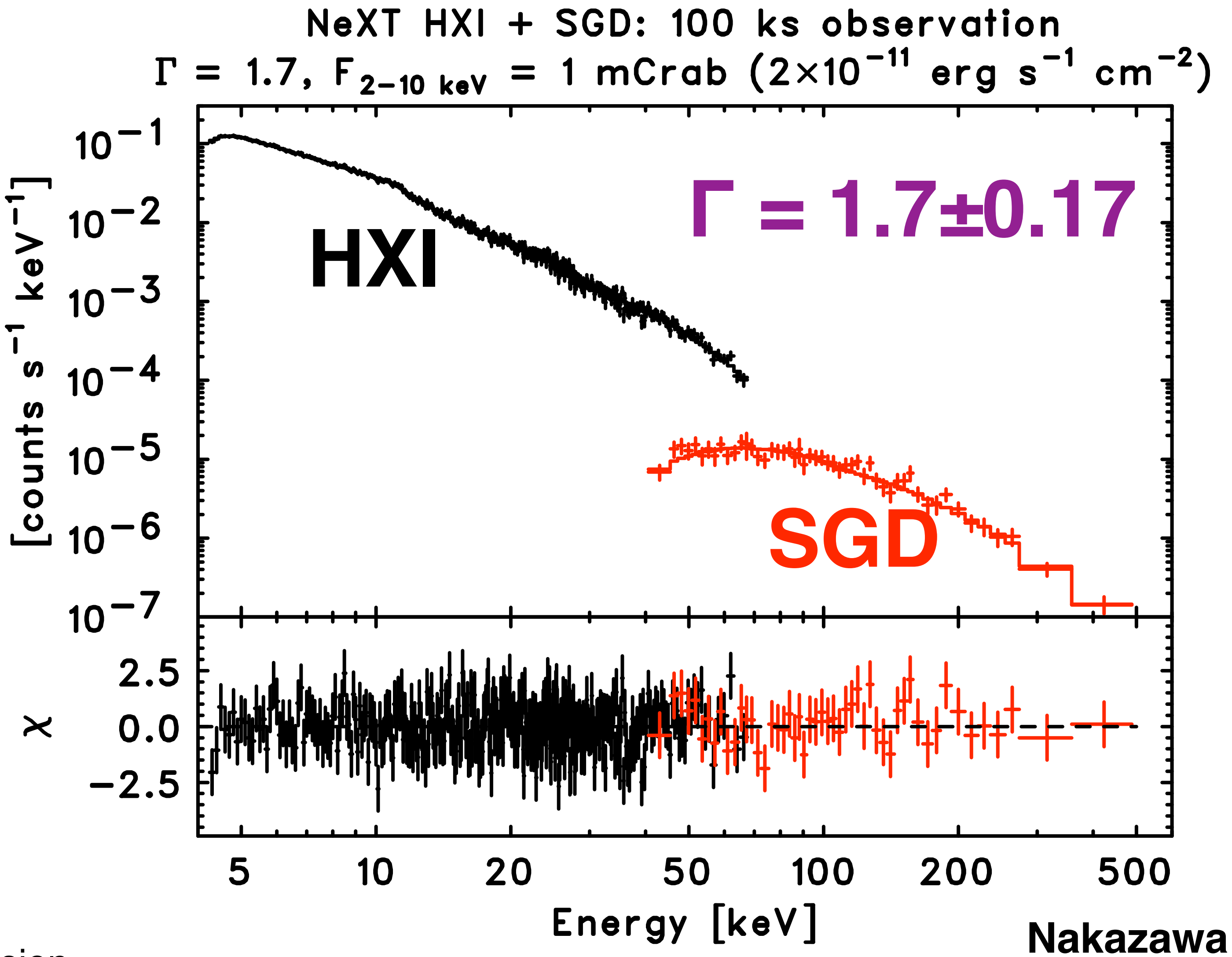
AGN

- Spectral Measurements for ~100 AGNs (10^{-3} Crab)
- Detect >500 AGNs (0.2×10^{-3} Crab) with 100 ks observation

SGD sensitivity @100ks

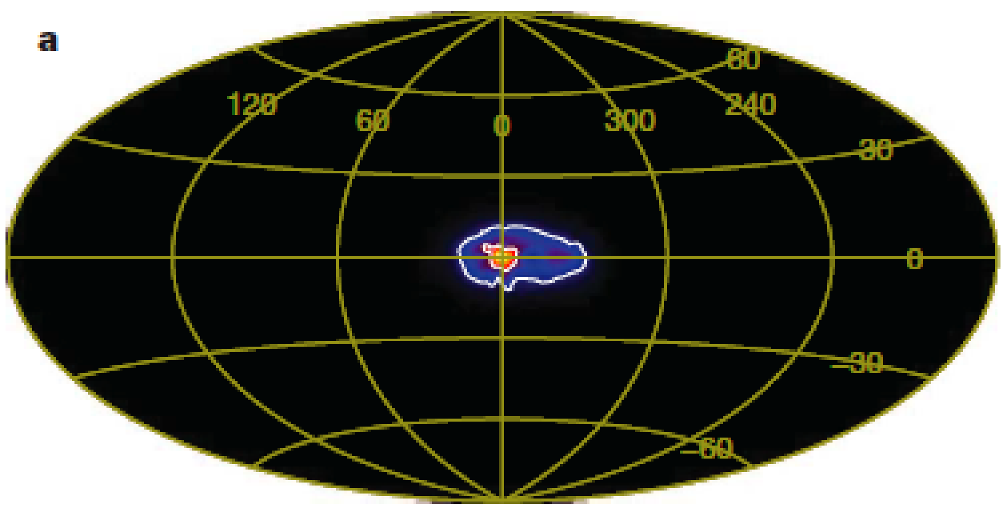


10^{-3} Crab @100ks

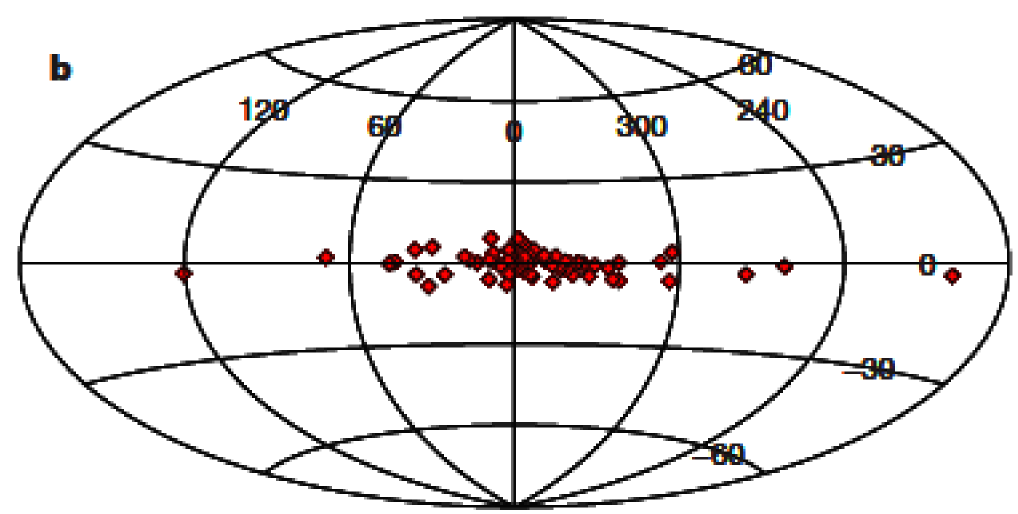


Mystery of 511 keV Emission

- **Origin is not well known for 30 years.**
  - **Sgr A*: Totani 2007**
  - **SN Ia: Knodlseder 2005**
  - **LMXB (low-mass X-ray binary): Weidenspointner et al. 2008**
  - **Low-mass dark matter**
- **Recent INTEGRAL measurement indicates spatial asymmetry**
  - **Correlation with distribution of LMXB**

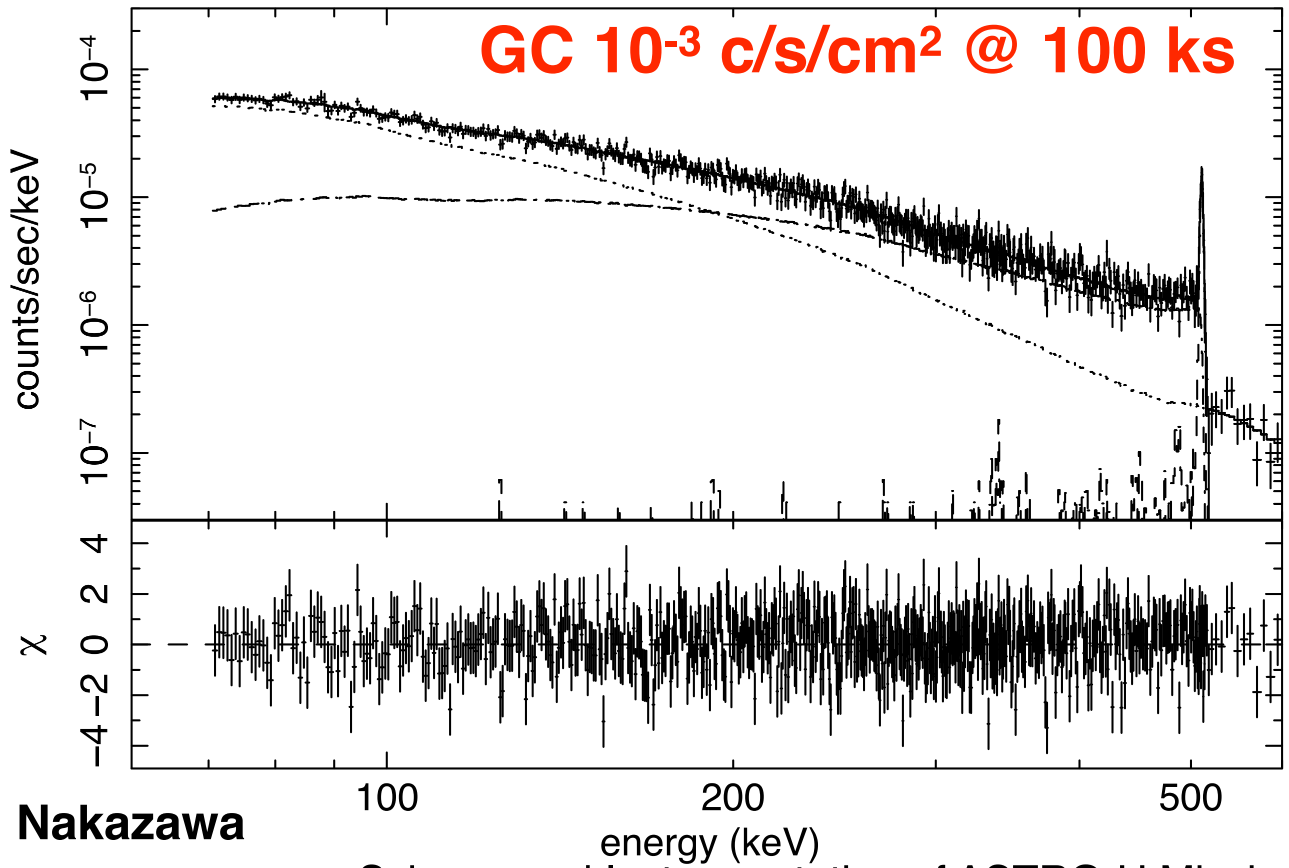


Weidenspointner et al. 2008



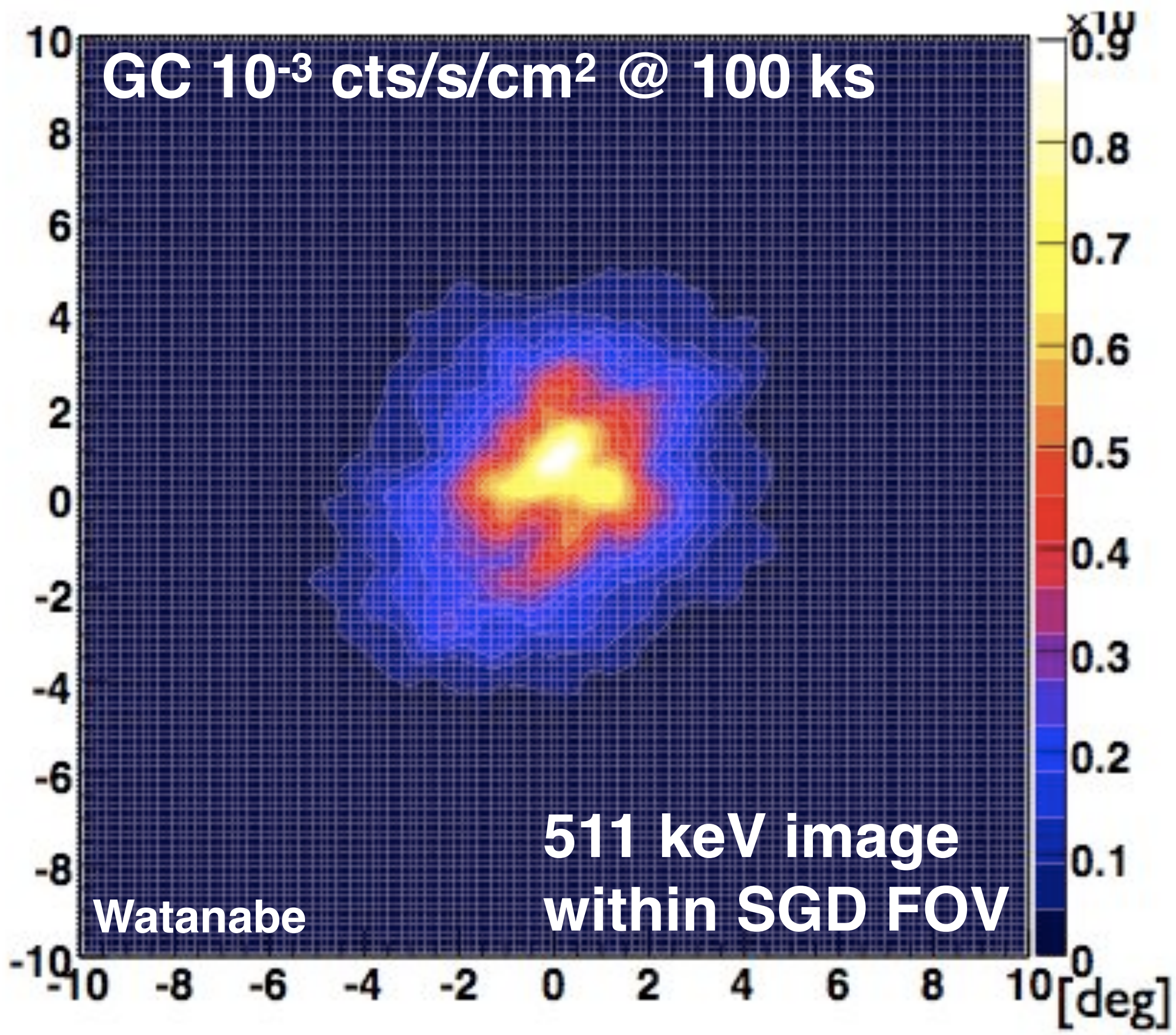
511 keV Annihilator with SGD

- **Competitive against OSSE and INTEGRAL**
  - Low BG due to narrow FOV (10° x 10°)
    - Good sensitivity: 10^{-5} cts/s/cm^2
  - Imaging with Compton reconstruction within FOV
    - Could be useful to identify signal against flat BG
  - Energy resolution: ~ 5 keV
    - probe condition of emission site



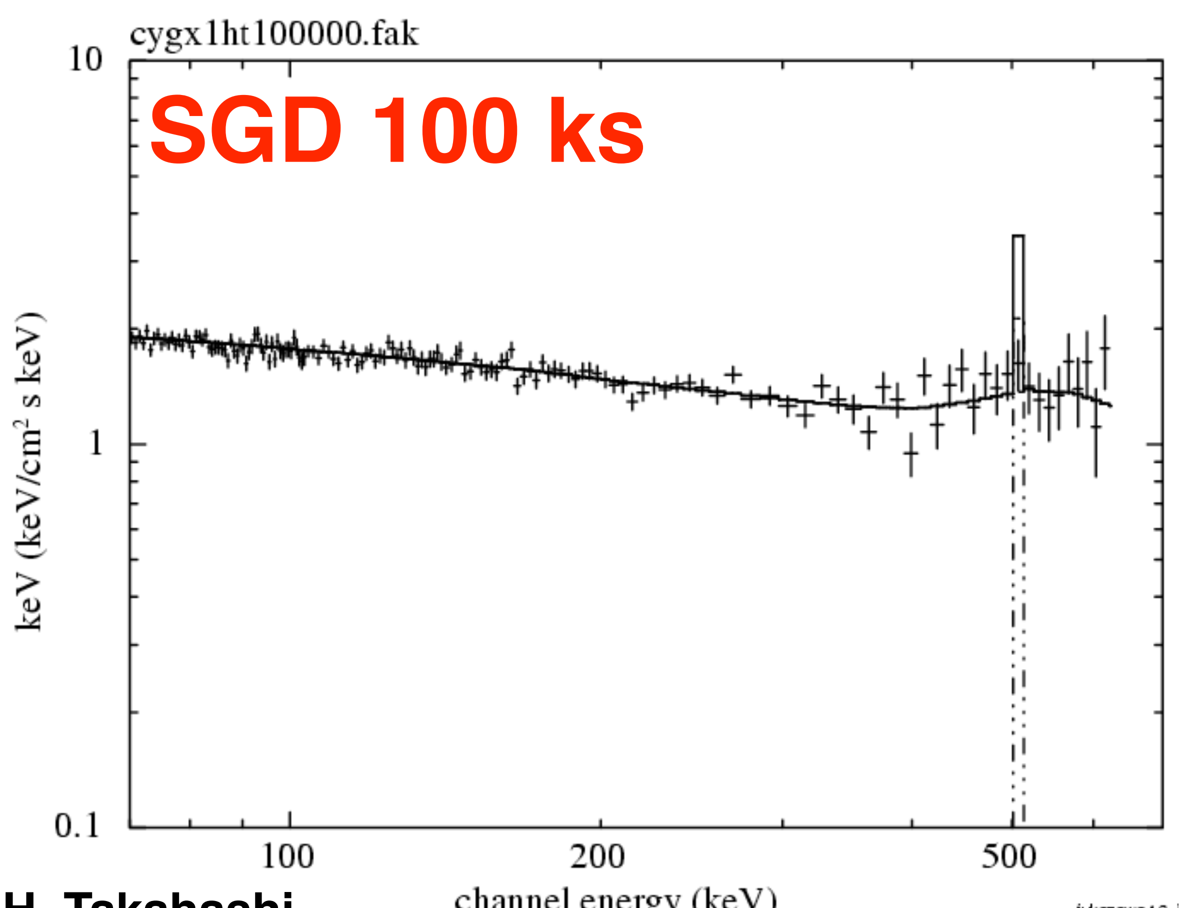
Nakazawa

Science and Instrumentation of ASTRO-H Mission, H. Tajima, IPMU Seminar, December 15, 2007

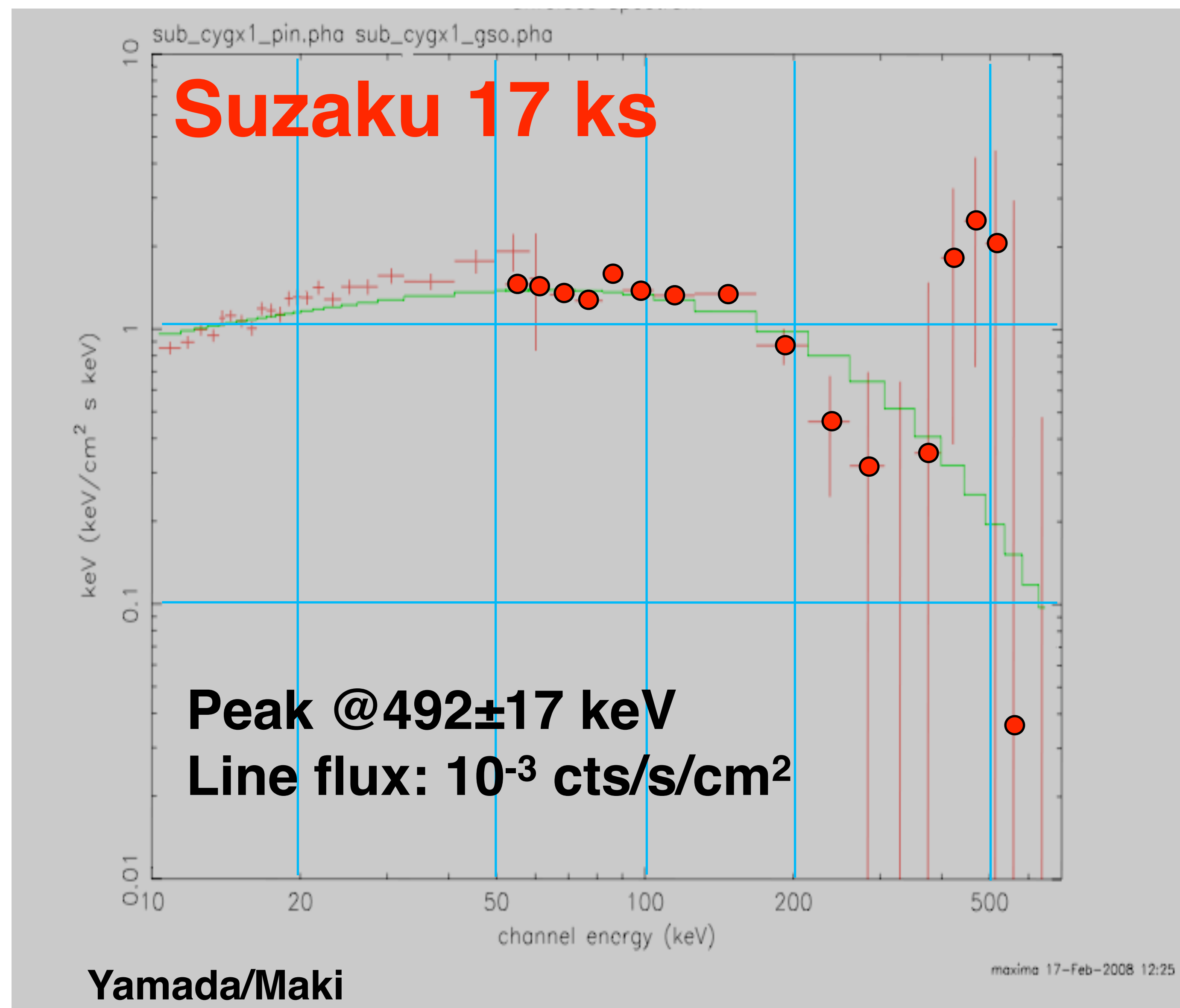


511 keV from Cygnus X-1

- 2.5σ (stat) evidence by Suzaku/HXD (Makishima et al. 2008)
  - Difference between bright/faint period by XIS
  - Systematic error due to BG is canceled to <1%
- Origin of 511 keV @ GC?
- Emission mechanism?



H. Takahashi

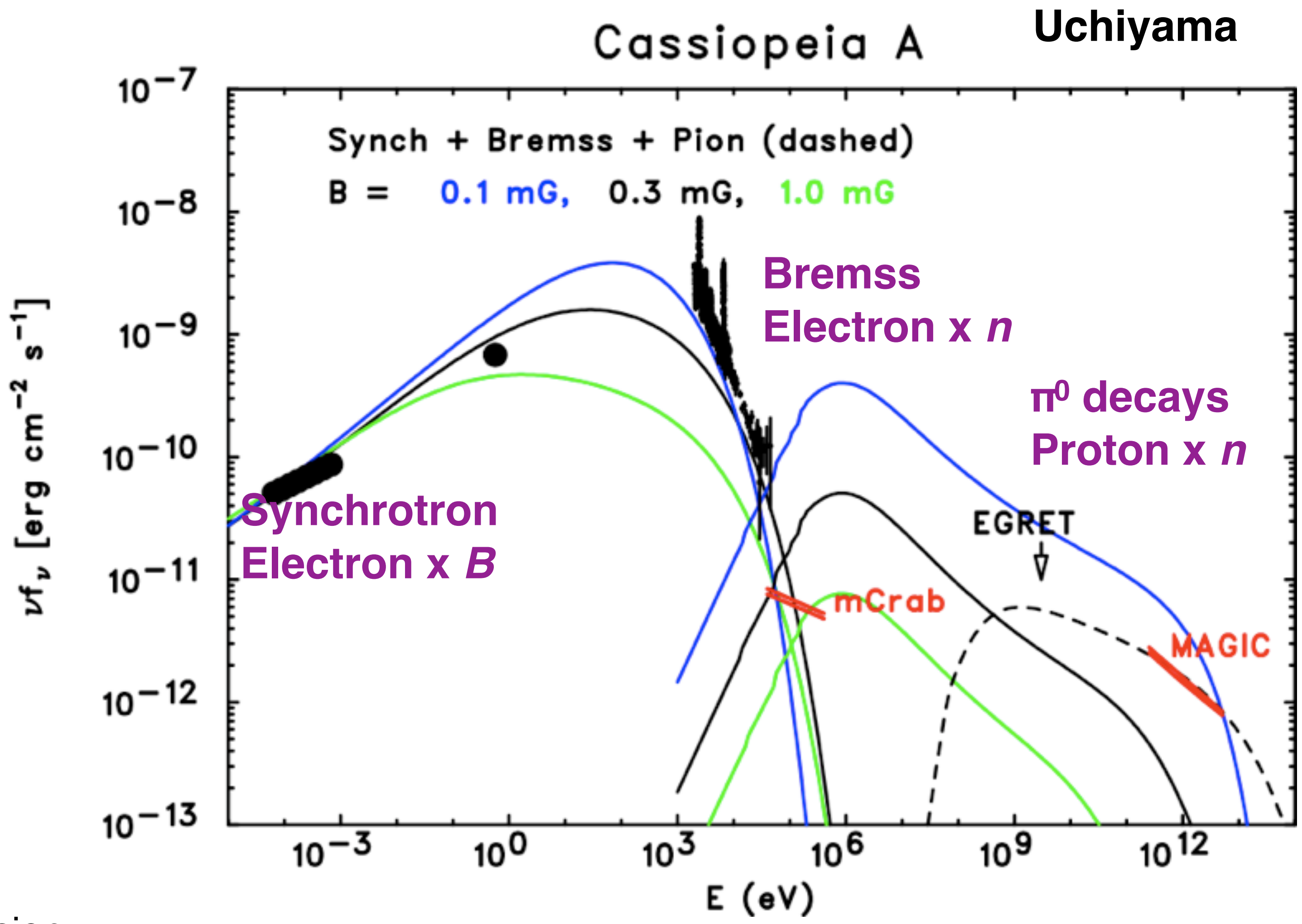


Yamada/Maki

Non-Thermal Bremsstrahlung

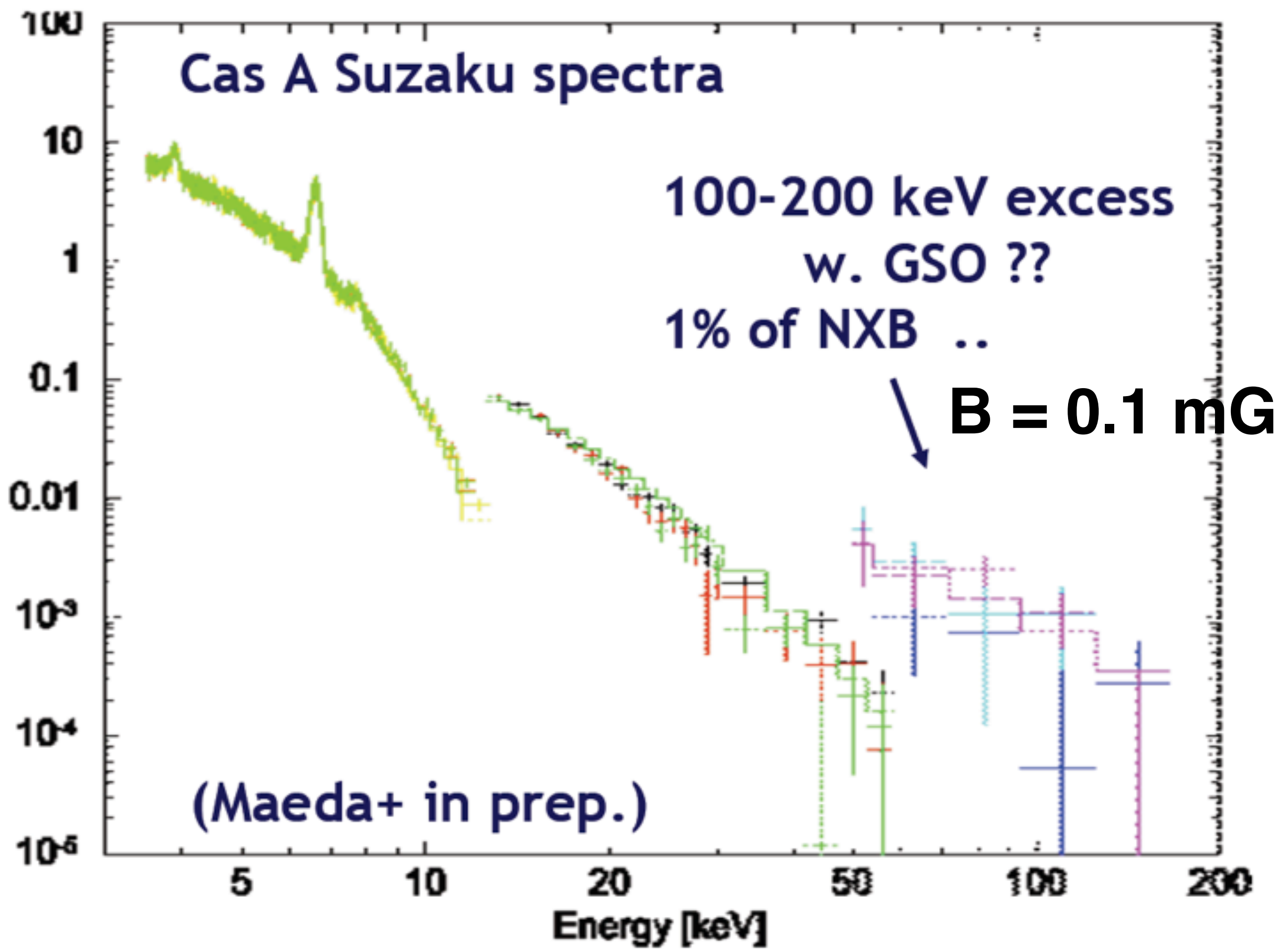
- **First detection of non-thermal Bremsstrahlung by SGD**
  - Characteristic Γ~1 spectrum determined by Coulomb loss
  - New probe for cosmic-ray acceleration
    - ✦ Energy budget in sub-GeV cosmic rays
    - ✦ Interstellar medium heating
- **Prime candidate: Cassiopeia A**
- **Other sources**
  - SNR, Molecular clouds
    - ✦ ~0.1 mG
  - Broad Iron lines
    - ✦ ~ 400 eV
    - ✦ Synergy with SXS

Uchiyama



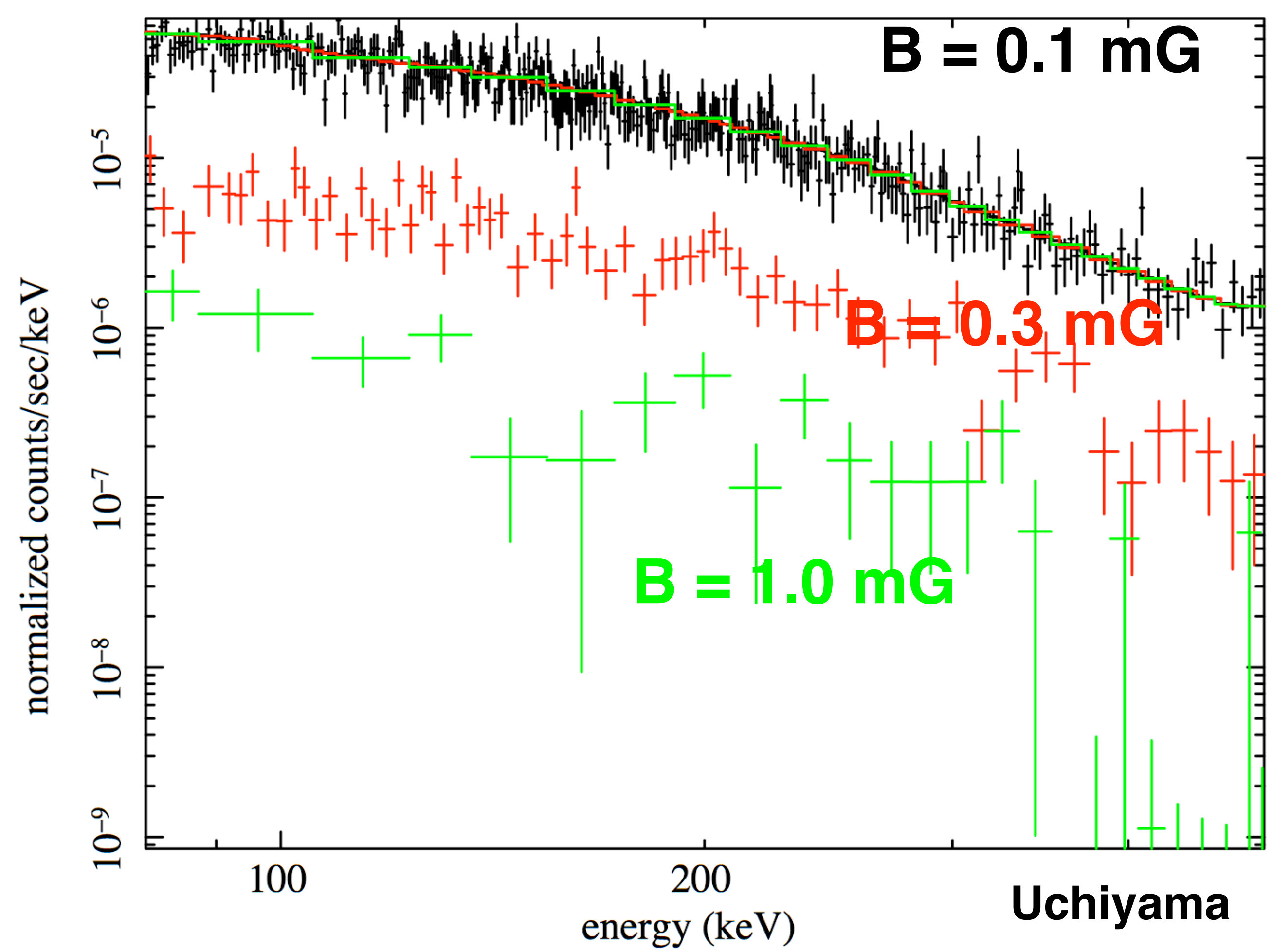
SGD Observation of Cas-A

- **Constraints on**
  - Electron spectrum
  - Magnetic field
    - Equipartition: B = 0.3 mG
    - Synchrotron cooling: B = 0.5 mG
  - sub-GeV electron/proton population



Science and Instrumentation of ASTRO-H Mission,
H. Tajima, IPMU Seminar, December 15, 2007

SGD 100 ks

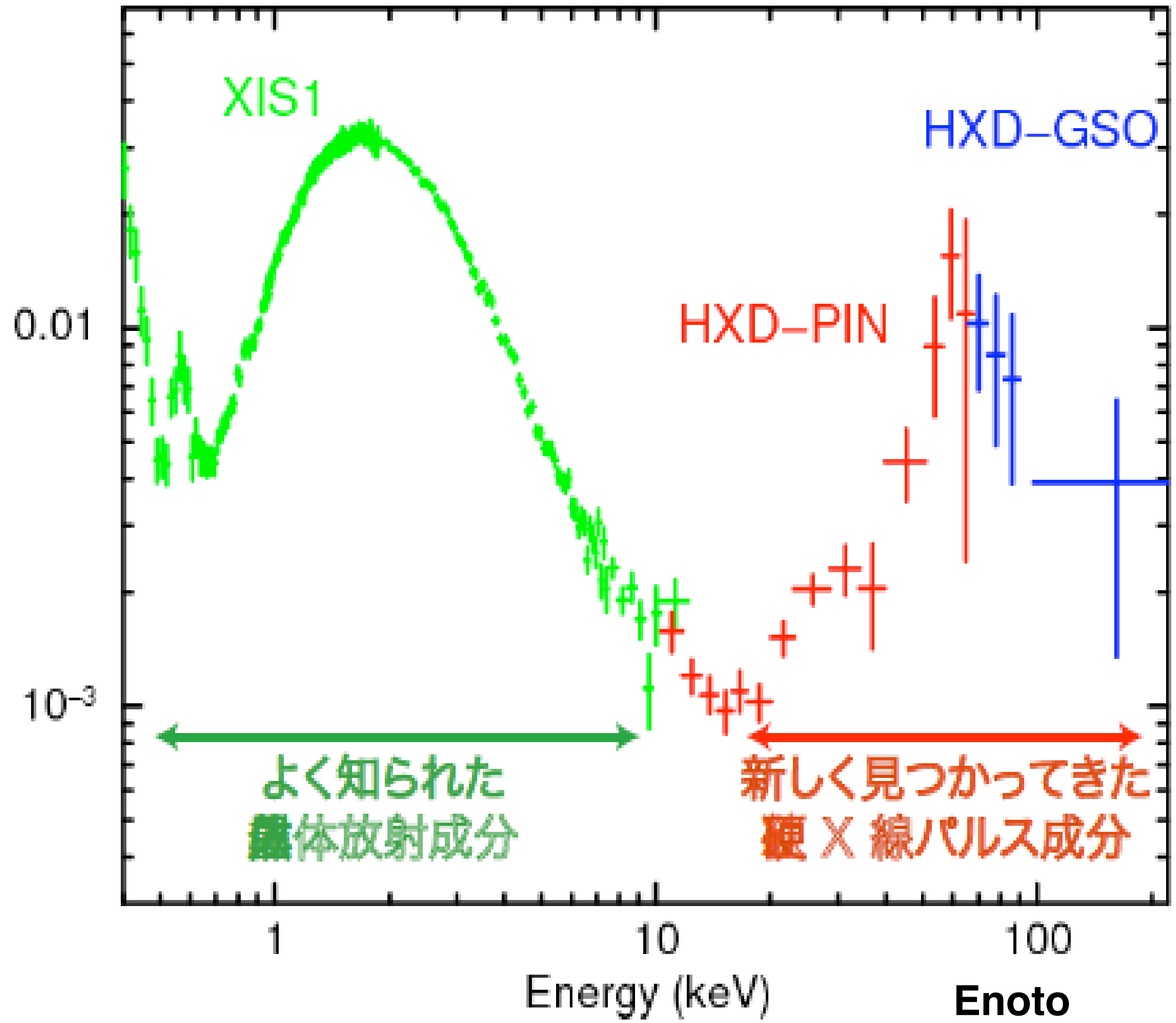


Uchiyama

AXP 4U0142+63

✤ Non-thermal Bremsstrahlung from Magnetar

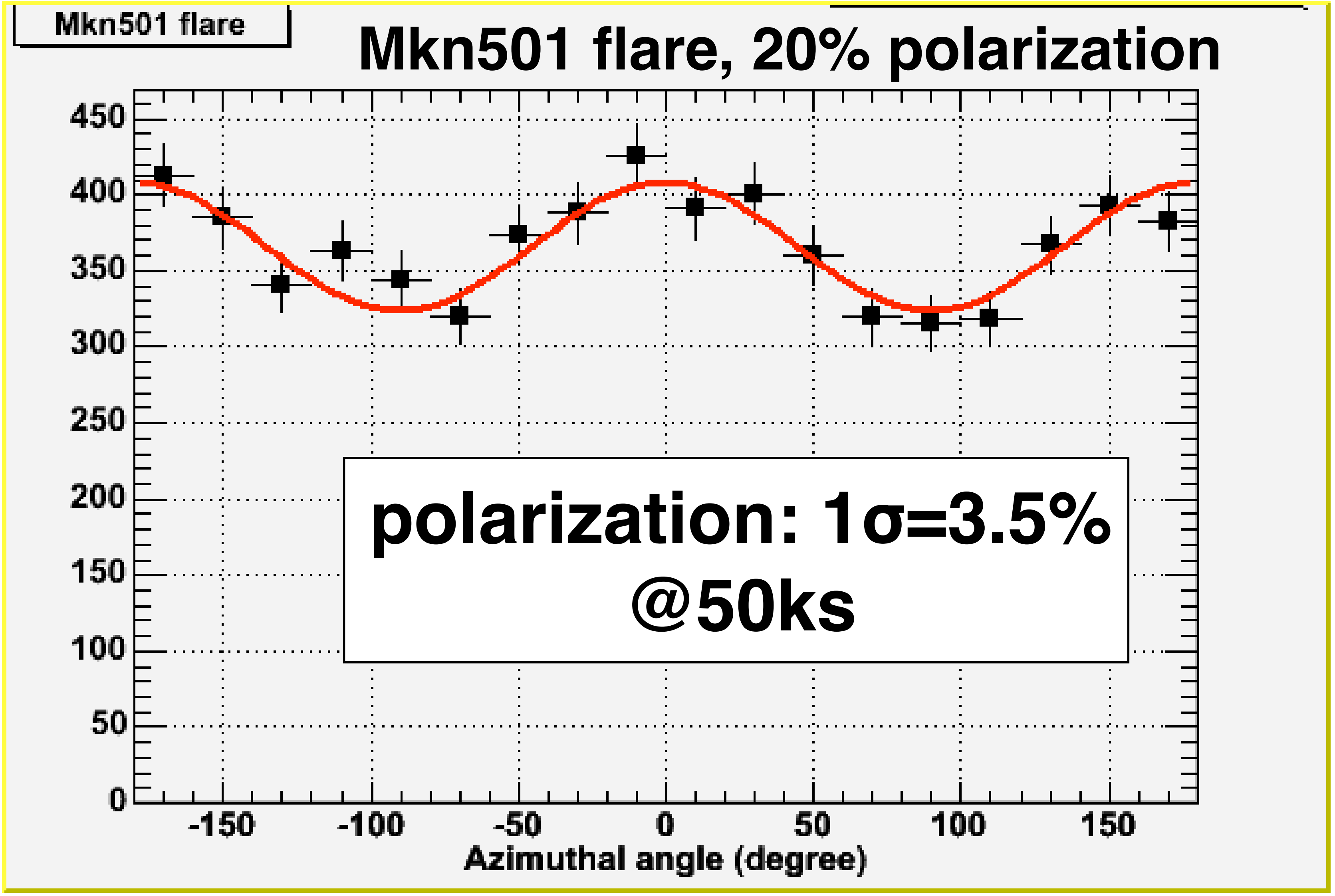
- e^+e^- pairs created around Magnetar are accelerated along magnetic field
- e^+e^- pairs emit non-thermal Brems when reaching the pole and Compton scatter at Magnetar surface
- e^+ should emit 511 keV
  - ✦ Gravitational redshift!

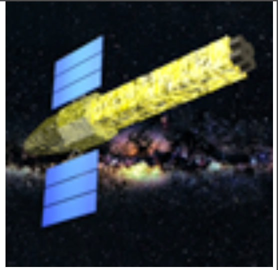


Enoto

Polarization: New Frontier

- Geometrical information on magnetic field & accretion disk
  - Polarization is only probe
- SGD is only instrument which is sensitive for <1/10 Crab
  - Pulsar emission model, cyclotron resonance
  - AGN jet
  - BHB reflection
- Constraints on Lorentz Invariance Violation



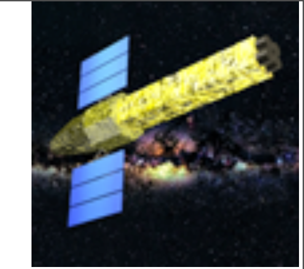


Summary of Polarization Performance

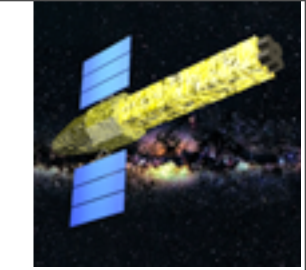
- **SGD sensitivity can be parameterized as**
  - 1σ sensitivity = 4.0% / sqrt(t_{obs}*F_{Crab})
    - t_{obs}: observation time in ks
    - F_{Crab}: flux in Crab in in 40–200 keV

Source	Observation time	N_γ	Polarization 1σ sensitivity
Crab	5 ks	235,000	1.8%
Cygnus X-1 soft state	25 ks	272,000	1.6%
X0115+63	25 ks	219,000	2.4%
Mk501 flare	100 ks	152,000	2.1%

Summary of SGD Science

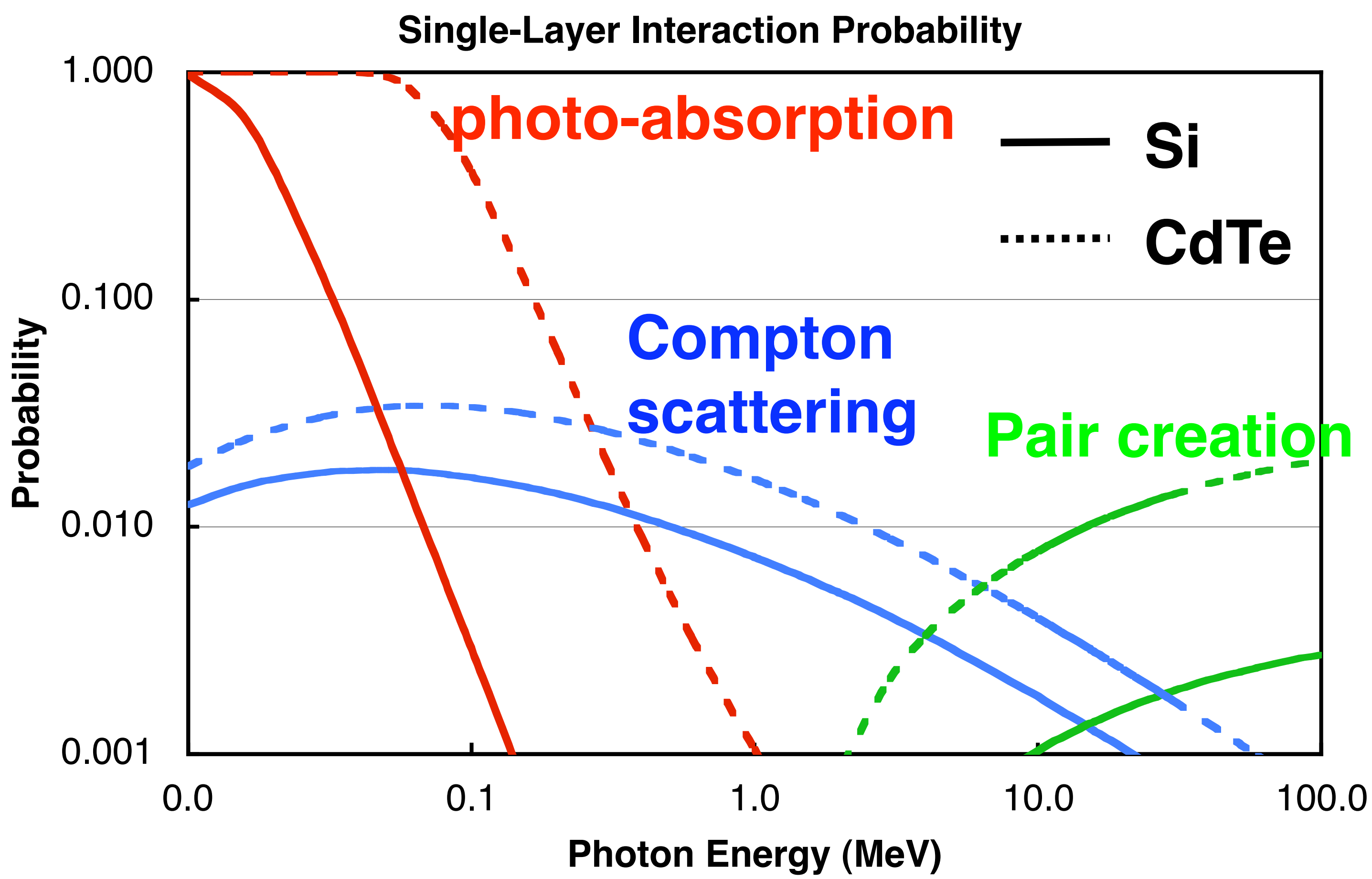


- **More than 10 papers**
  - **Seyfert, radio quiet Quasar, High-z Quasar (Blazar)**
  - **X-ray pulsar, Magnetar**
  - **CXB**
- **Less than 10 papers.**
  - **TeV Blazar**
  - **ULX (Ultra Luminous X-ray source), LMXB, gamma-ray binary**
  - **Rotation-powered pulsar**
  - **SNR (Supernova Remnant)**
  - **GC (Galactic center), Galactic ridge**
- **High impact.**
  - **511 keV from GC, SNR, BHC, LMXB or AXP**
  - **Non-thermal Bremsstrahlung from Cas-A**
  - **Polarization in BHC, pulsar or TeV blazar**

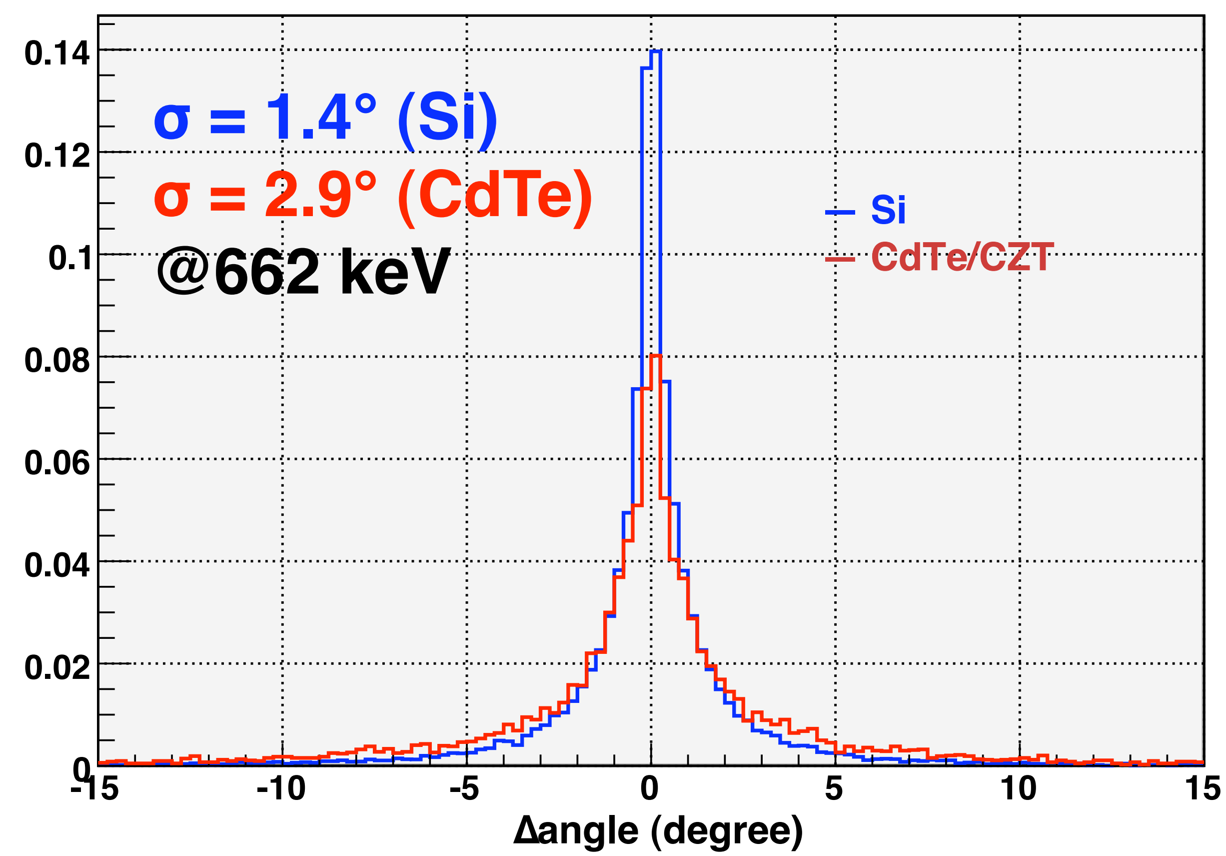


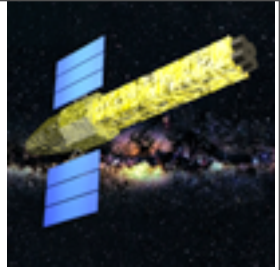
Si/CdTe Hybrid Design

- ✤ **Low-Z sensor (Si) is a good scatterer:**
  - **Compton scattering dominant for Si at lower energies**
    - ✦ **Diamond (C) is even better if low energy threshold possible**
  - **Smaller Doppler broadening effect**
- ✤ **High-Z sensor (CdTe/CZT/Ge) is a good absorber**
  - **Photon absorption is dominant to 300 keV**



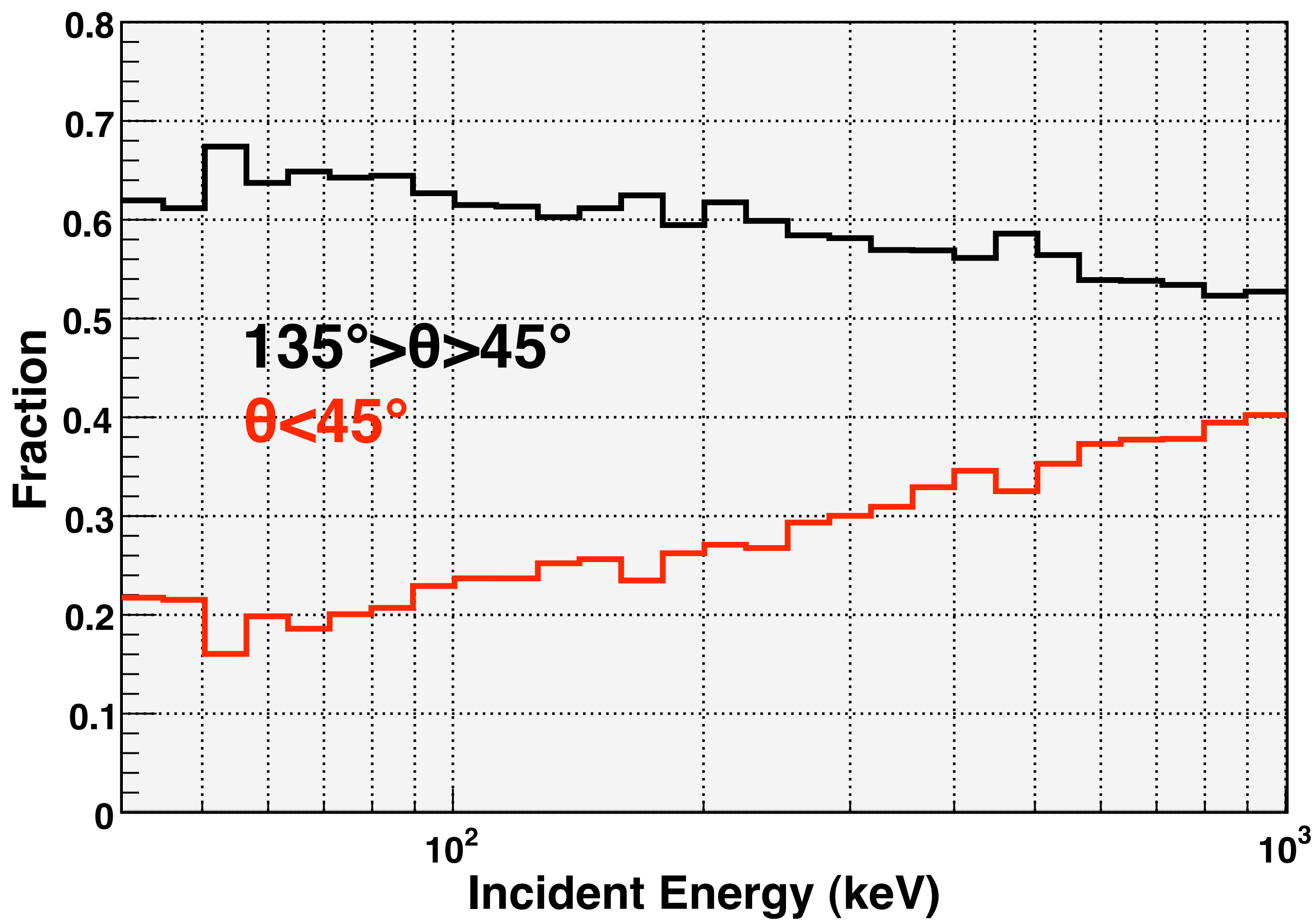
Science and Instrumentation of ASTRO-H Mission,
H. Tajima, IPMU Seminar, December 15, 2007

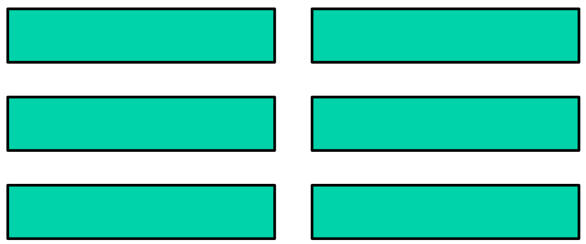




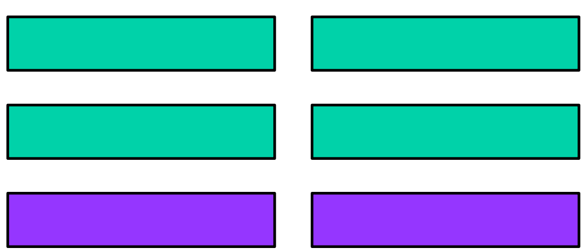
Detector Configuration

- **Single sensor type**
  - **Simpler structure, readout**
- **Hybrid type**
  - **Low-Z scatterer and high-Z absorber**
  - **Simple stacking or sounding absorber**
    - **Photons tend to be scattered horizontally**

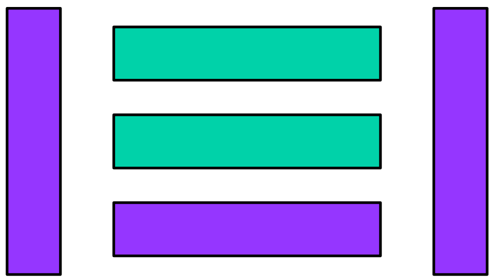




Nuclear Compton Telescope GRIPS



Some of Advanced Compton telescope options



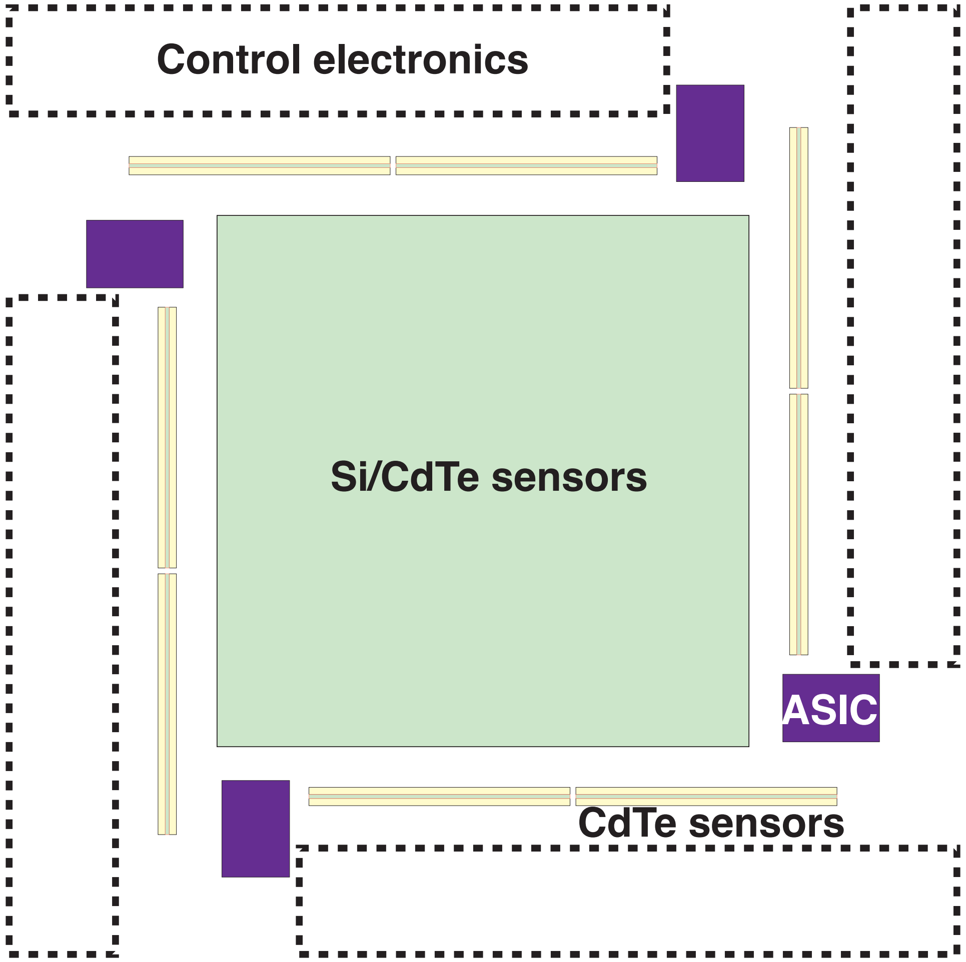
ASTRO-H/SGD

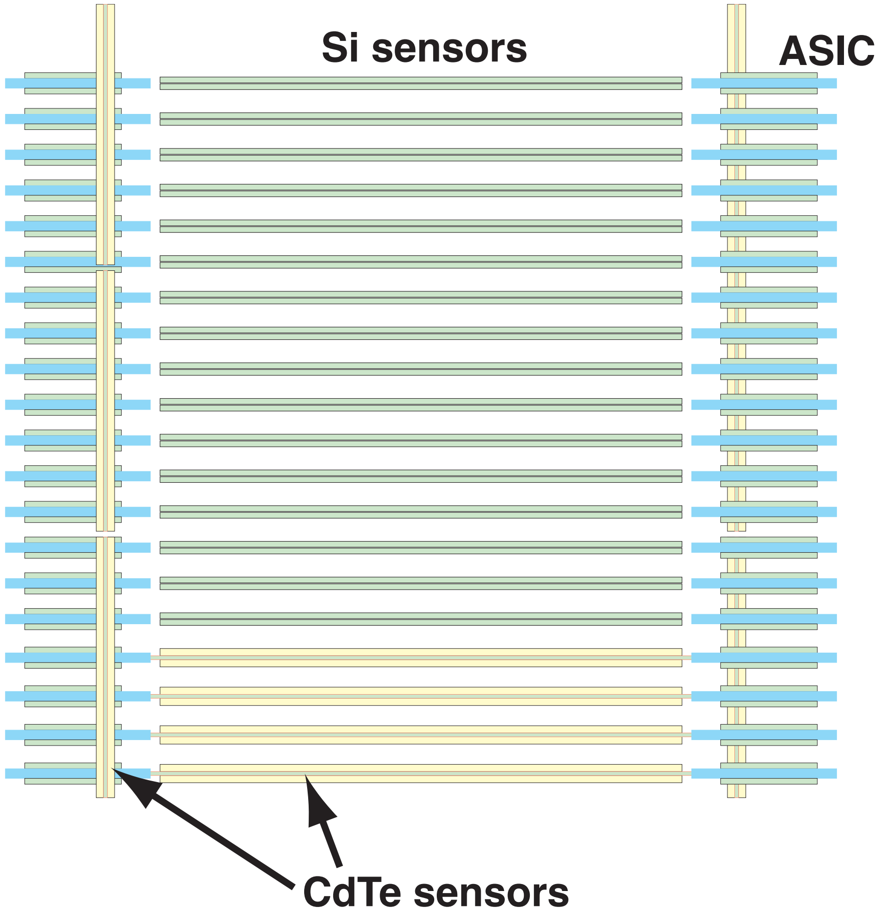
Compton Camera Design

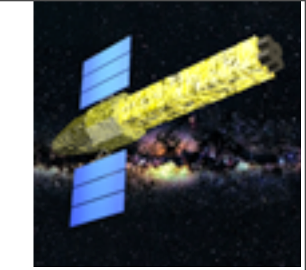
✤ Compton Camera Baseline Design

- 32 layers of 0.6 mm thick Si Pad
- 8 layers of 0.75 mm thick bottom-CdTe
- 2 layers of 0.75 mm thick side-CdTe
- 2 layers/module to reduce # of mechanical elements

✤ Placement of ASICs to maximize hermeticy of CdTe sensors







Development of Key Technologies

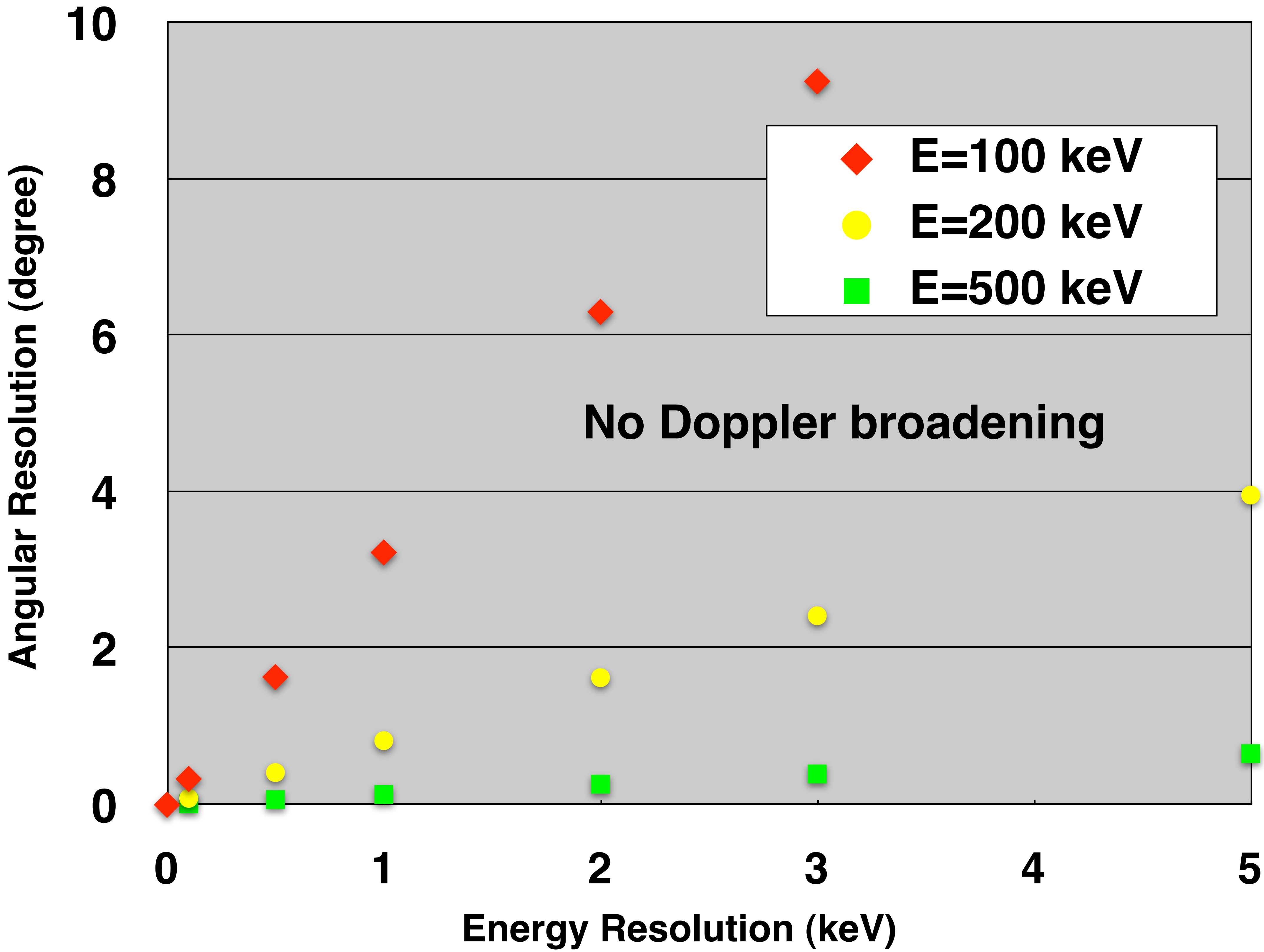
✤ Key Technologies with good progress

- Si sensor
  - ✦ Well developed and understood technology
  - ✦ Reliable manufacturer: Hamamatsu Photonics (HPK)
- High-Z semiconductor (CdTe/CZT) sensor
  - ✦ Long development history, well understood
- Front-end electronics
  - ✦ Low noise: ~ 1 keV (FWHM)
    - ❖ Good energy and angular resolution
    - ❖ Background rejection
    - ❖ Low energy threshold
  - ✦ Low power
    - ❖ Total # of channels: ~280k
  - ✦ Highly-integrated functionality

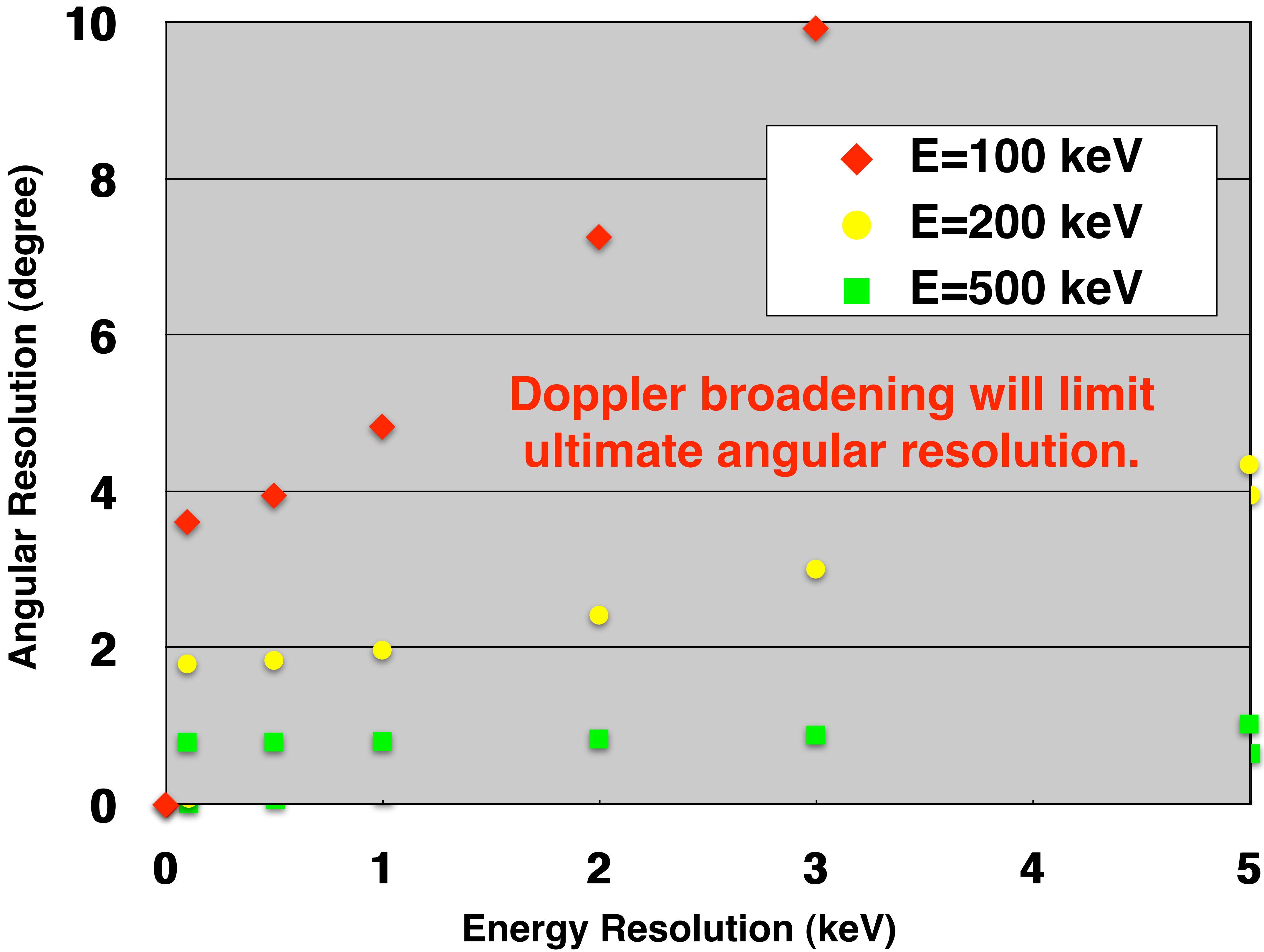
✤ Challenging technology

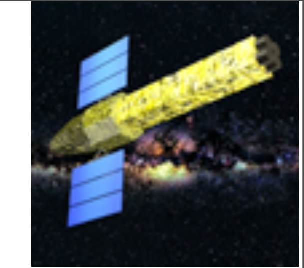
- Compact assembly (but extremely complex)

Angular Resolution



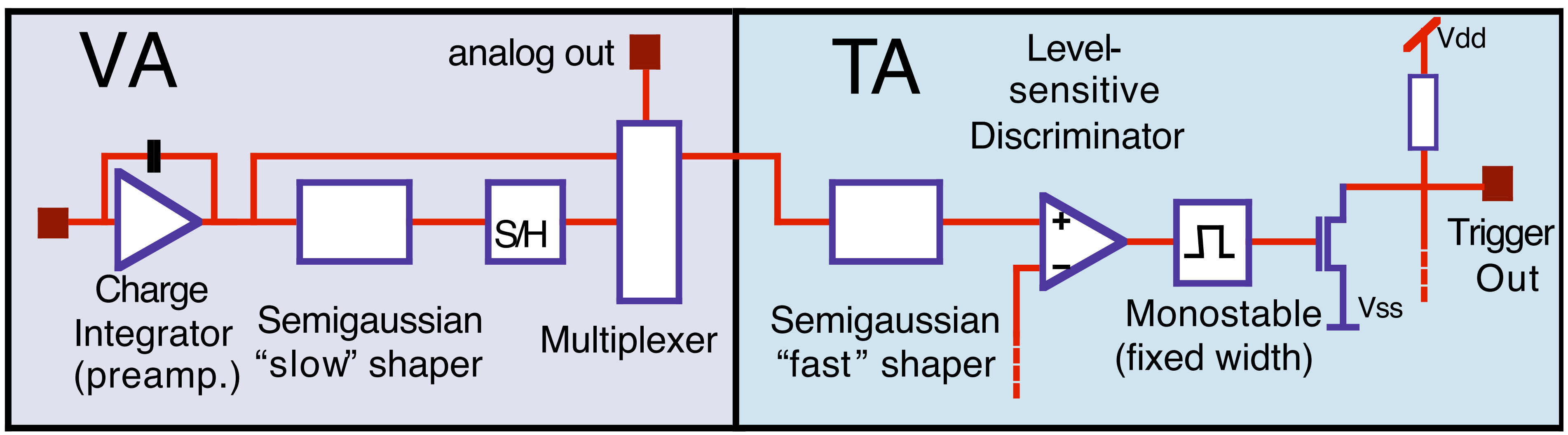
Angular Resolution



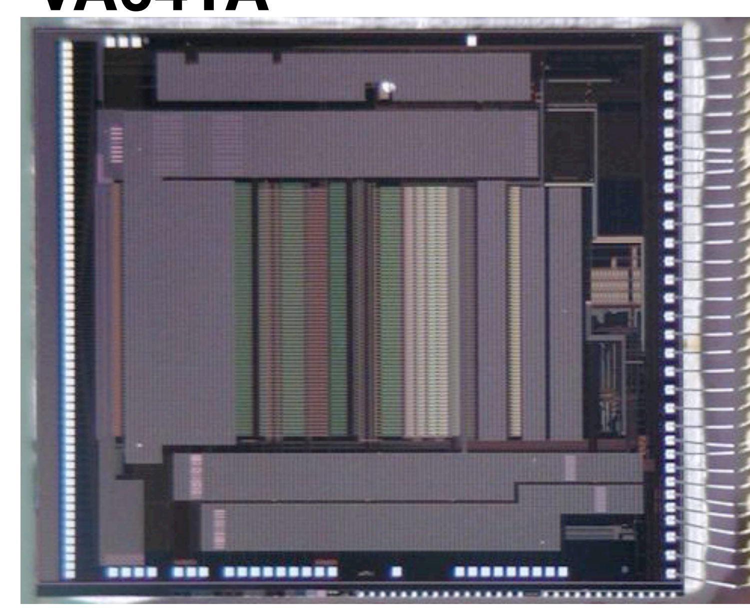


VATA: Low Noise Front-end ASIC

- **Low noise and low power consumption**
  - **Front-end MOSFET geometry optimized for small capacitance.**
  - **VA32TA: 2 mW/channel, shaping time 2 μs** $(45 + 19 \times C)/\sqrt{\tau}\ [e^-]$ (RMS)
  - **VA32TALP: 0.2 mW/channel, shaping time 4μs, 110 e^- @ 6 pF.**
  - **VA64TA1: 0.2 mW/channel, shaping time 4μs** $(76 + 24 \times C)/\sqrt{\tau}\ [e^-]$ (RMS)
  - **VA32TA5: VA64TA1 + integrated ADC**
    - **Common mode noise detection.**
- **Fast shaper for self-trigger. (75–600 ns)**

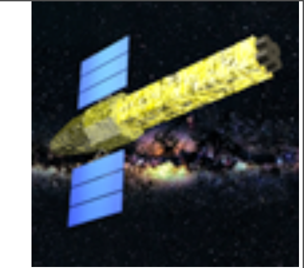


VA64TA



Ideas ASA

- **Internal DAC (4-bit trim DAC, bias).**
- **Radiation hard to 20 MRad (due to 0.35 μm process).**
- **SEU (single event upset) tolerant design. (>70 MeV/μm^2)**



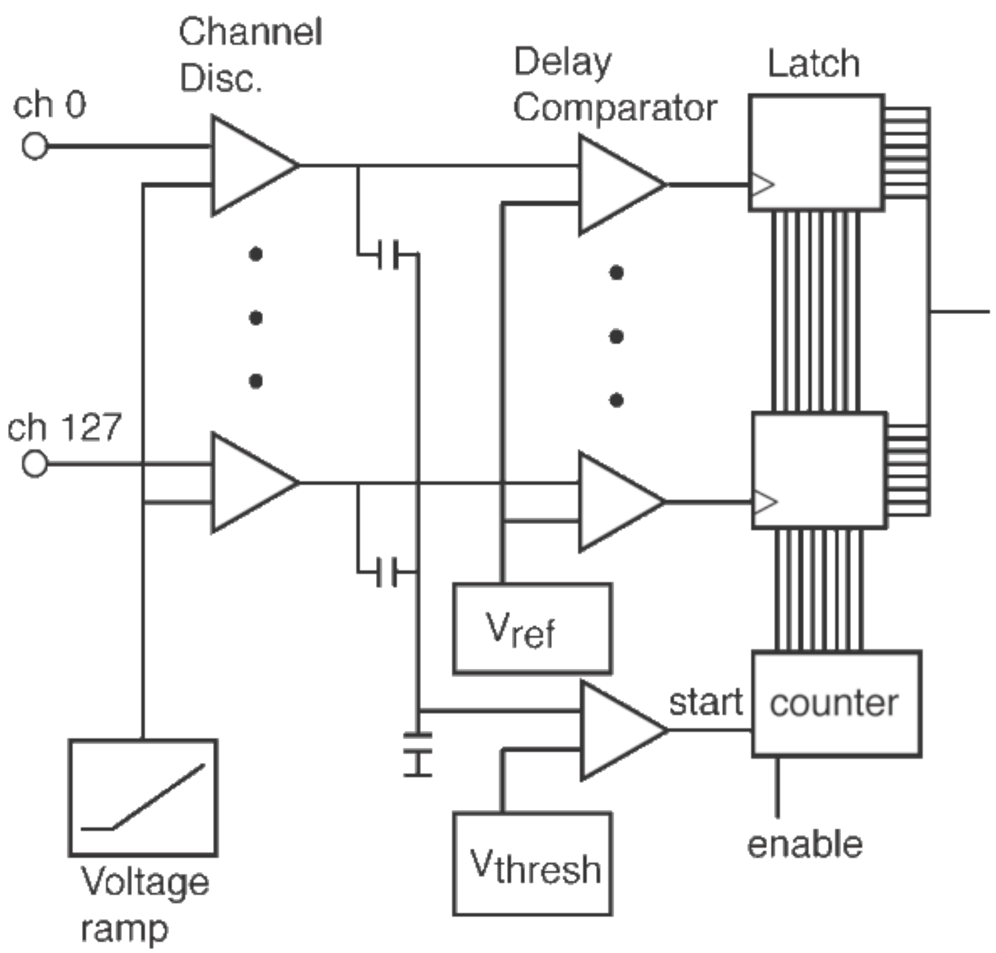
Integrated Analog-to-Digital Converter

✤ **High integration of functions to reduce electric components.**

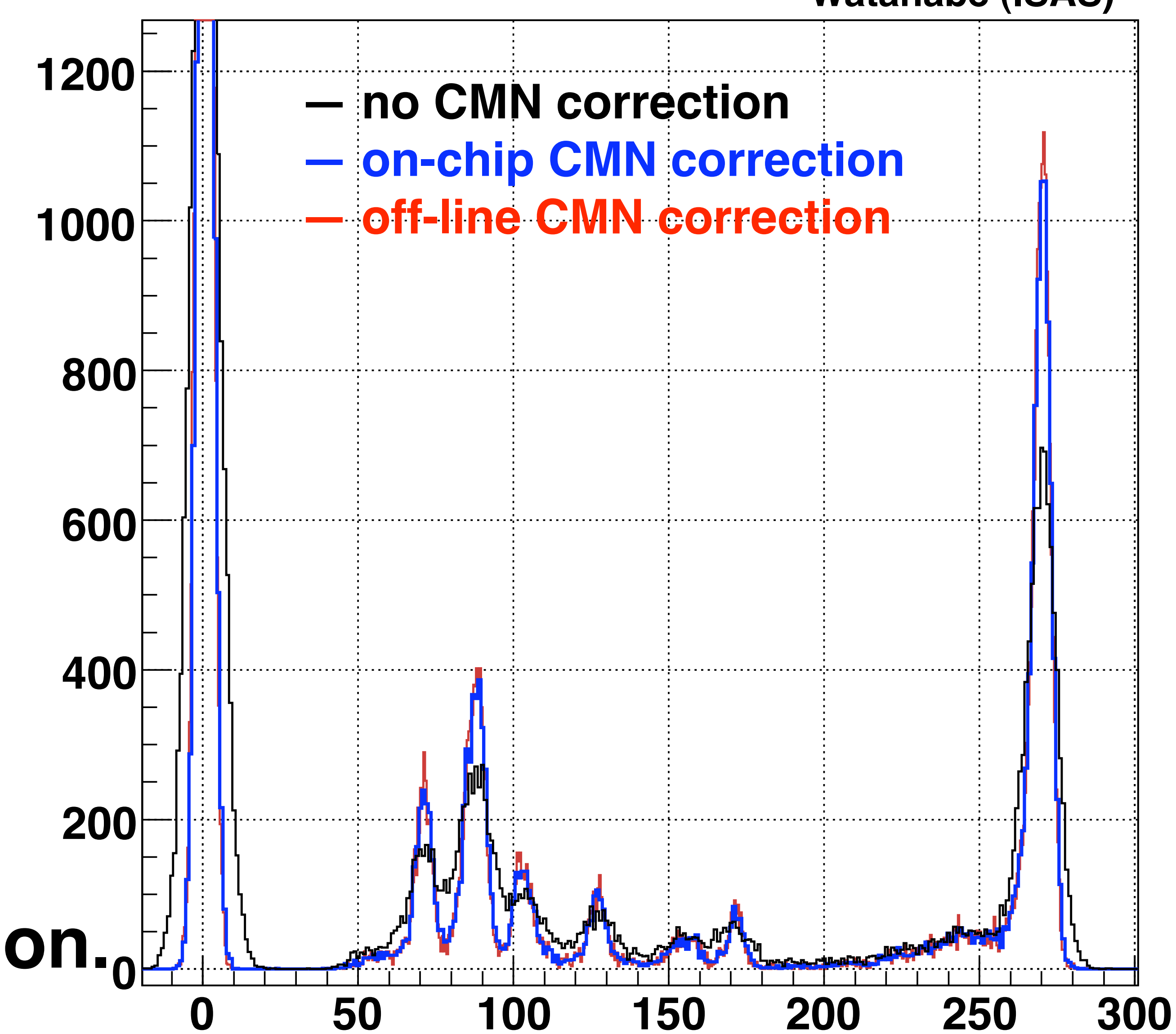
- **Integrated Wilkinson-type ADC**
- **Common mode noise detection**

Integrated ADC with on-chip common mode noise detection

Al-pixel/CdTe/Pt
1.4 mm pixel
0.75 mm thick
@-20°C, -400V

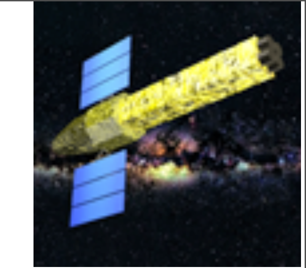


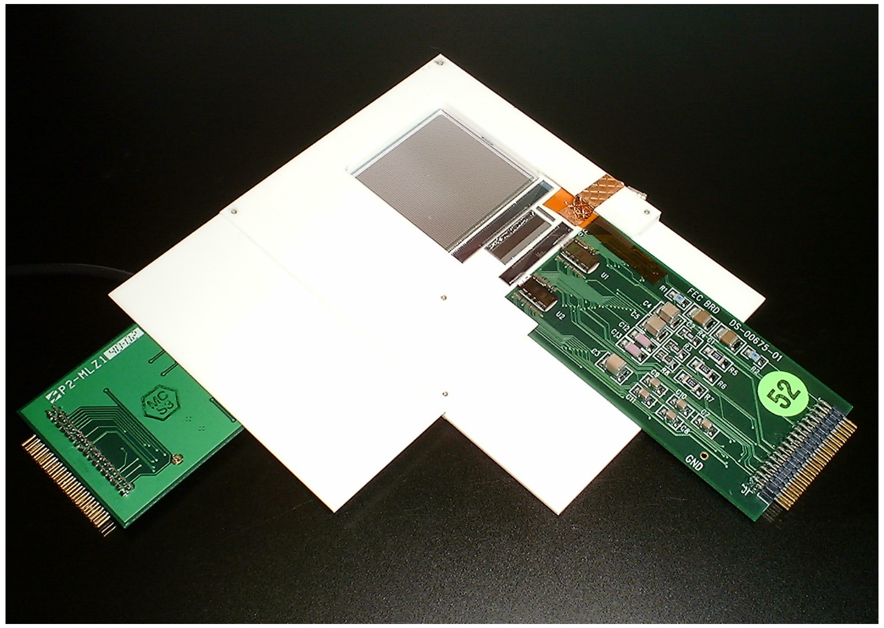
Watanabe (ISAS)



- **Zero-suppression in final version.**

Si Sensor Energy Resolution



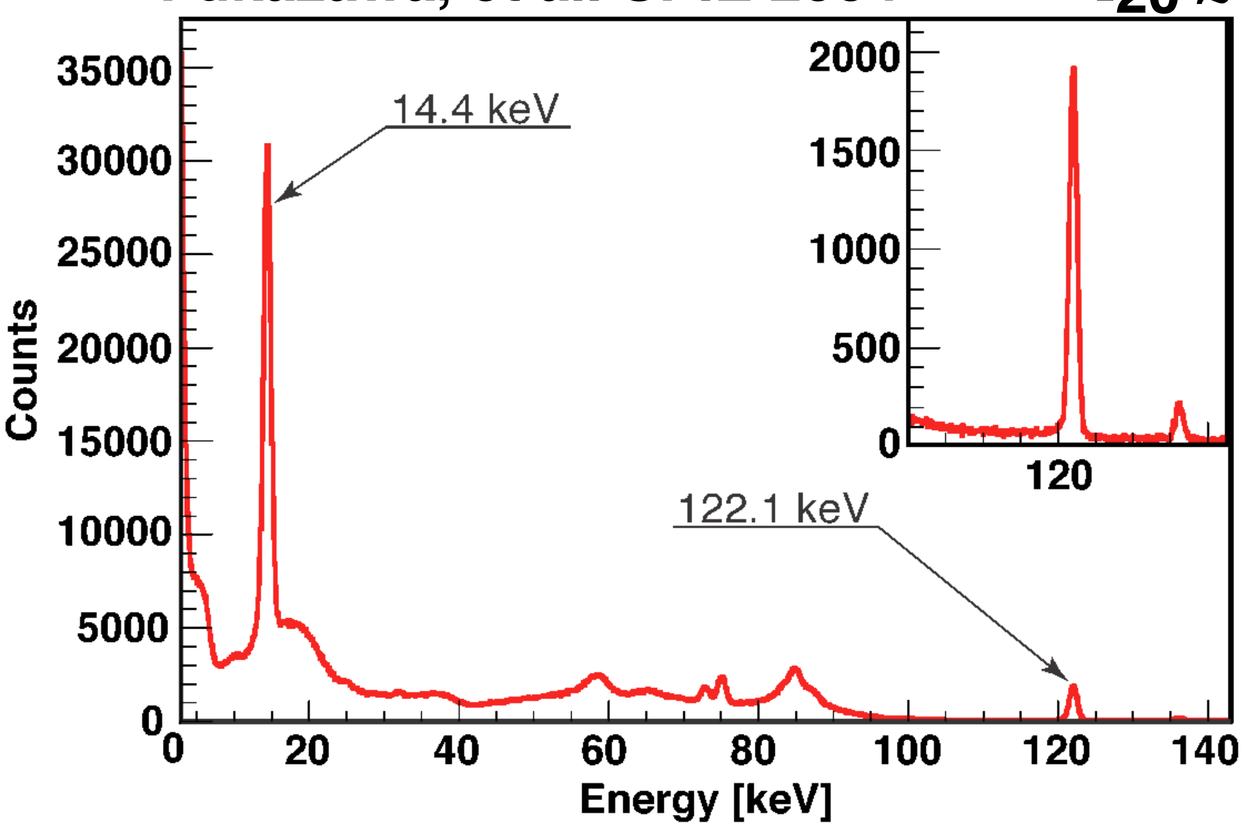


Double-sided
Si-Strip Detector
(DSSD)
2.56x2.56 cm^2
0.4 mm pitch
0.3 mm thick

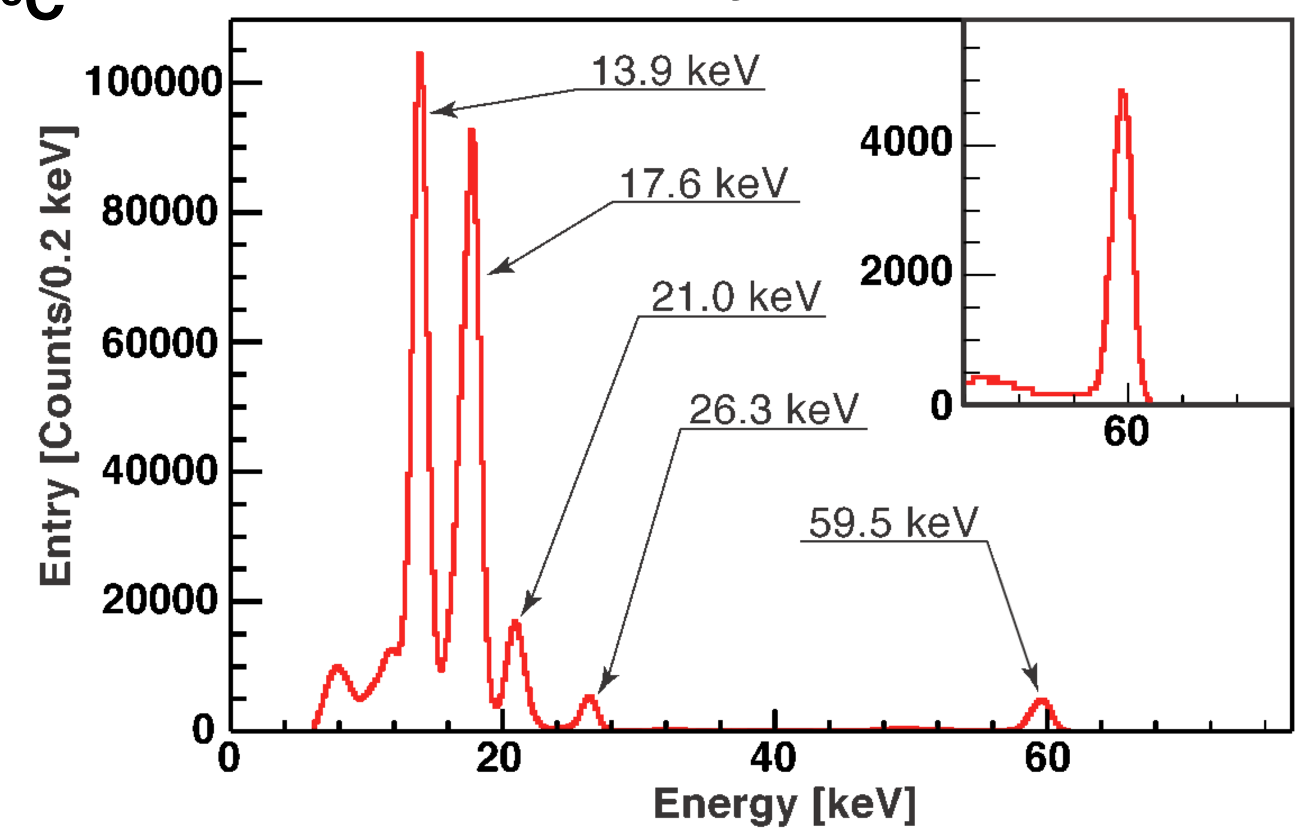
Energy	Resolution (FWHM)
13.9 keV	1.1 keV
14.4 keV	1.1 keV
60 keV	1.3 keV
122 keV	1.3 keV

Operation temperature
-20 ~ 0 °C

Fukazawa, et al. SPIE 2004



H. Tajima, et al. SPIE 2002

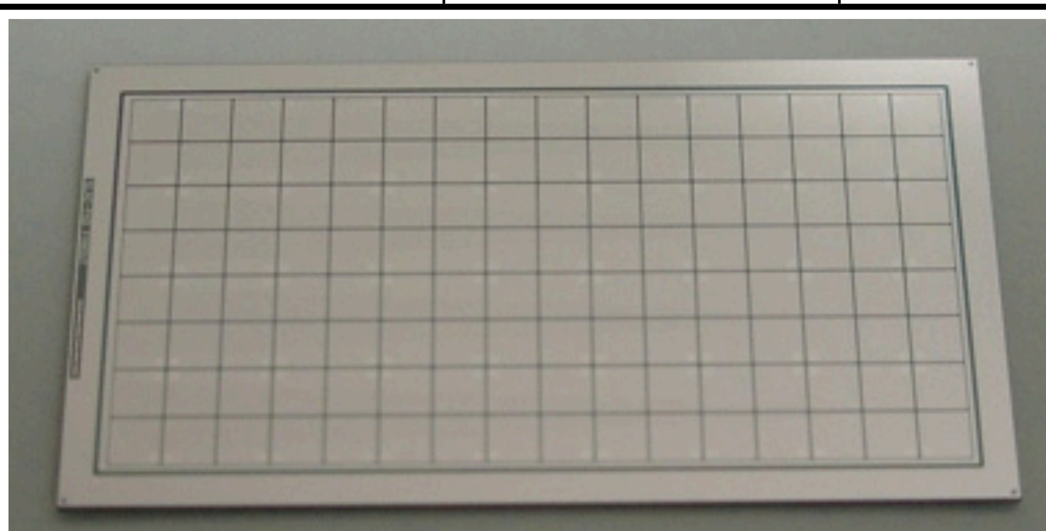


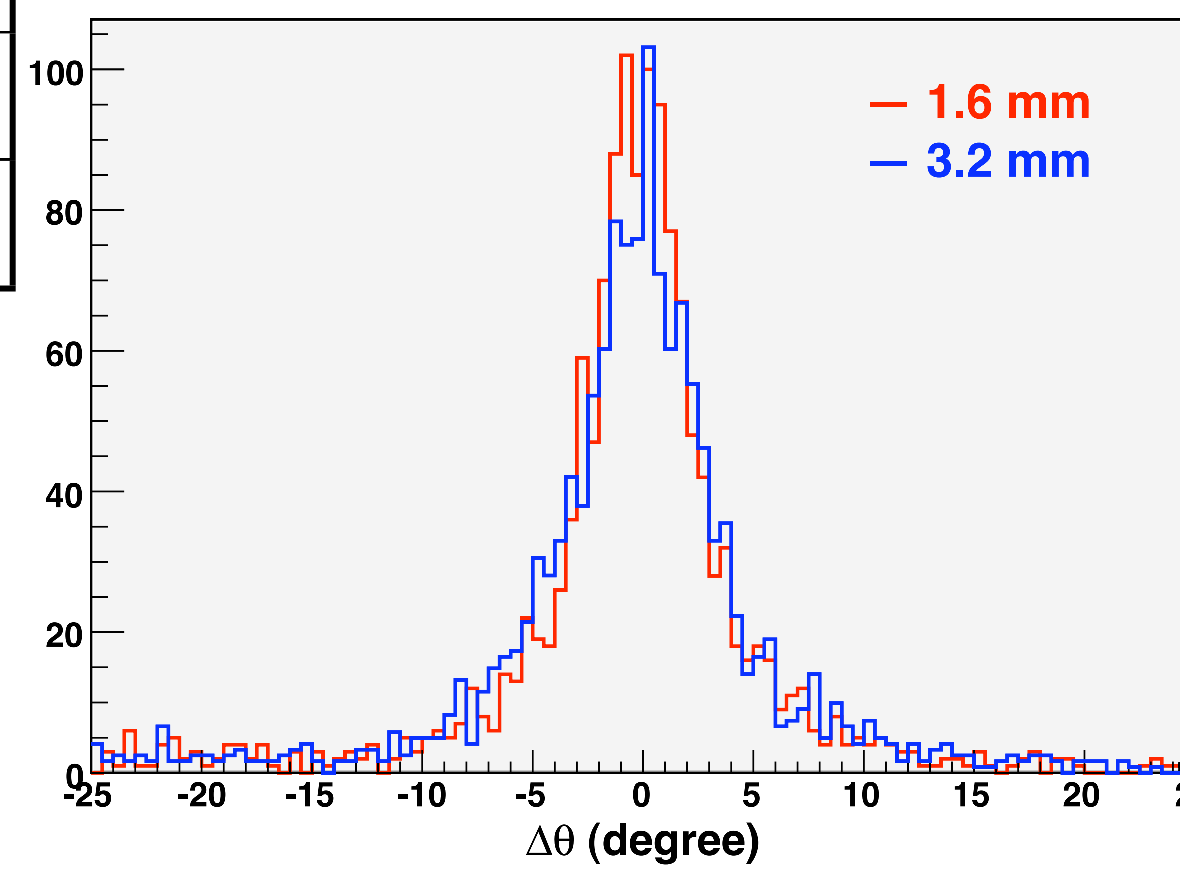
Optimization of Pixel Size.

- **Larger pixel is preferred to reduce channel count**
  - **Lower power**
  - **Easier assembly due to smaller number of ASIC**
- **Contributions to angular resolution (68% containment)**

	1.6 mm	3.2 mm
Doppler broadening	2.0°	2.0°
Geometrical error	2.2°	3.0°
Energy resolution	0.9°	0.9°
Total	3.5°	4.1°

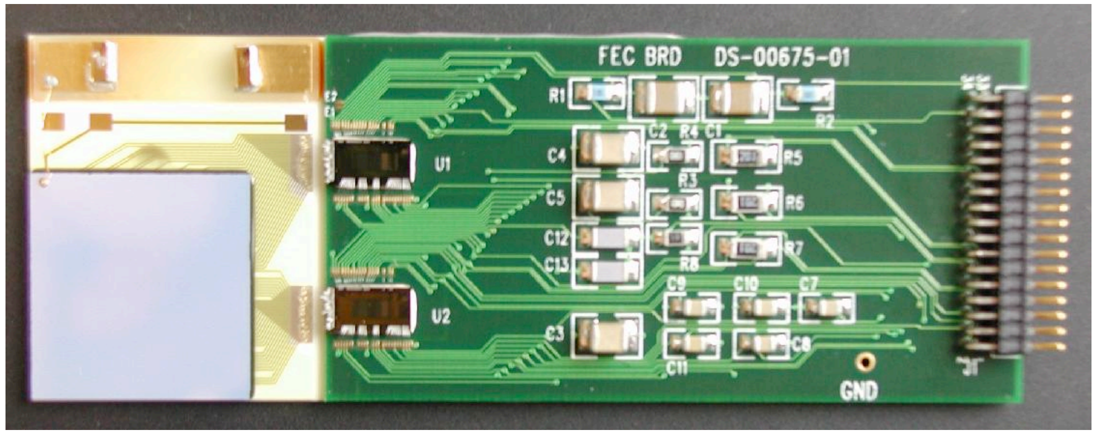
pixel size



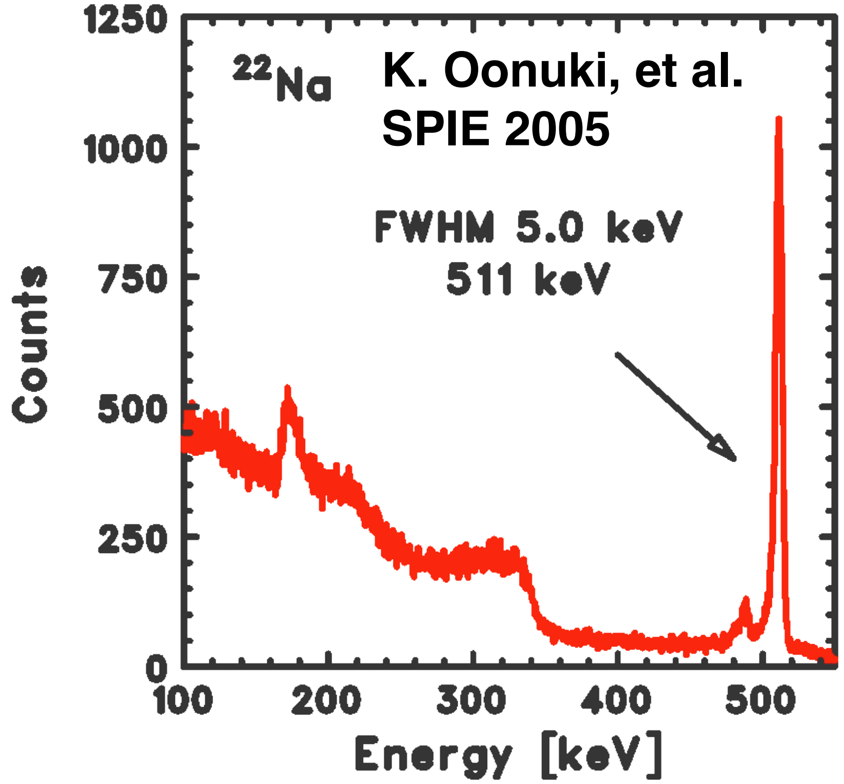


Science and Instrumentation of ASTRO-H Mission,
H. Tajima, IPMU Seminar, December 15, 2007

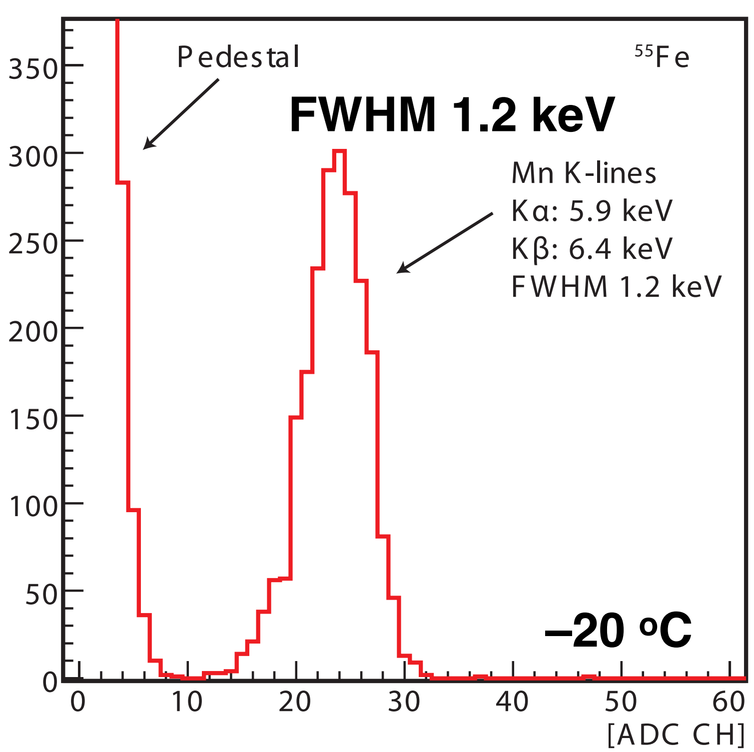
CdTe Energy Resolution



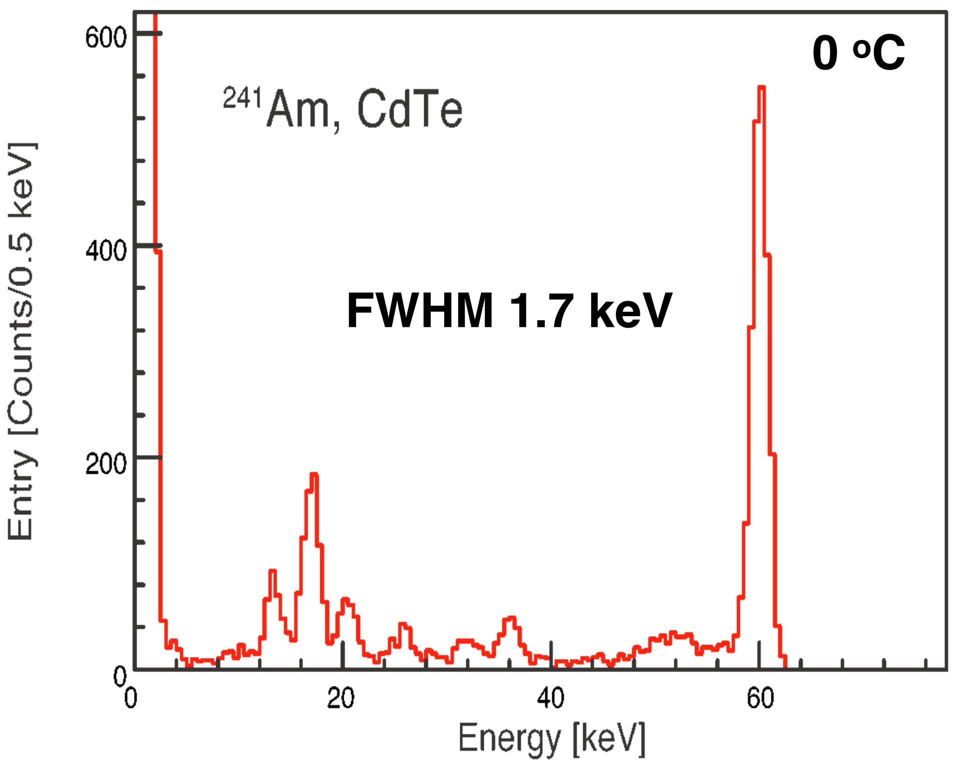
CdTe pixel
1.6x1.6 cm²
2x2 mm² pixel
0.5 mm thick

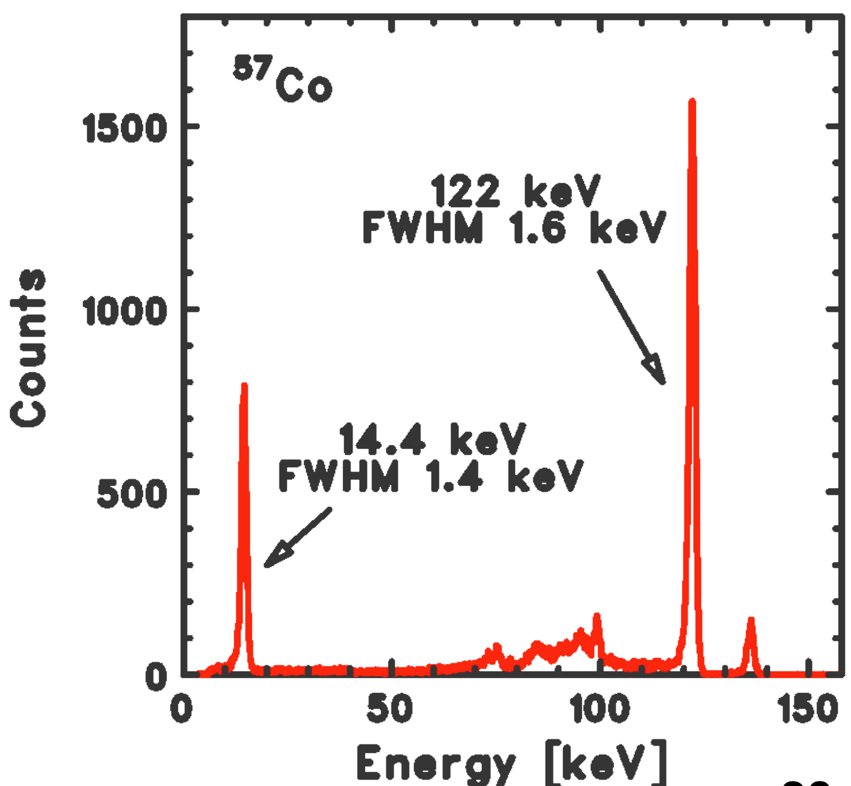


S. Watanabe, et al. IEEE TNS 2008



T. Mitani, et al. IEEE TNS 2004



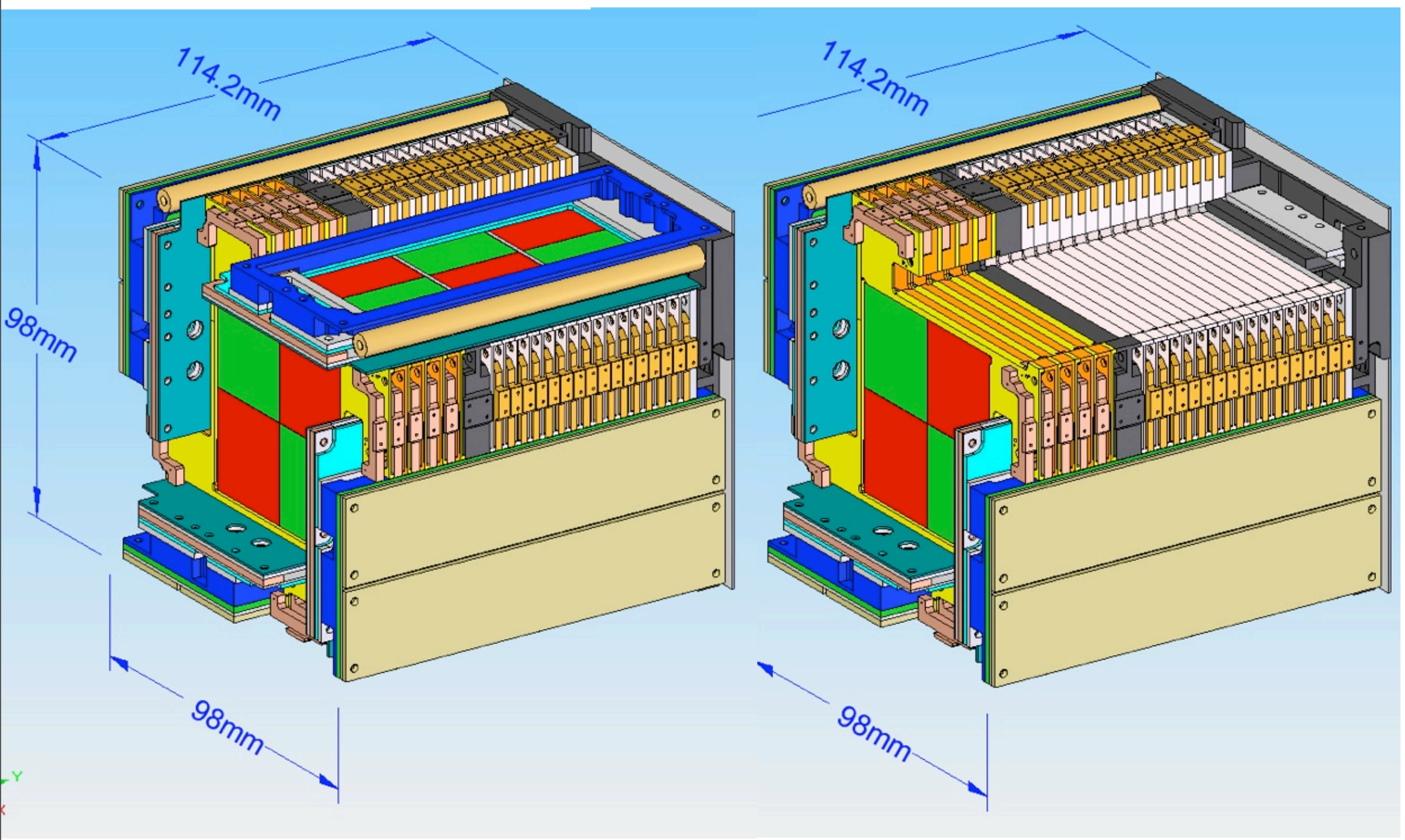


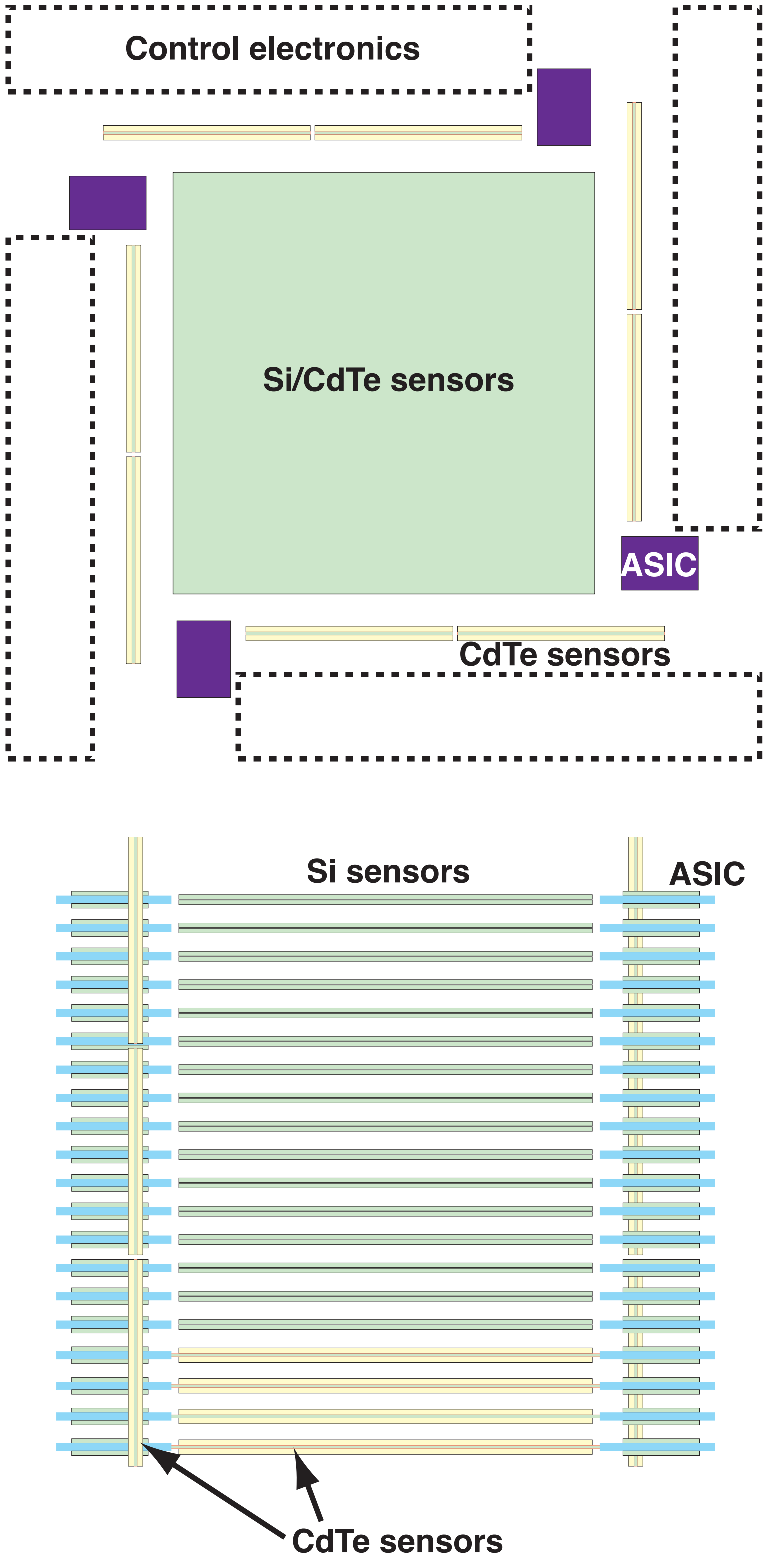
–20 °C

Science and Instrumentation of ASTRO-H Mission,
H. Tajima, IPMU Seminar, December 15, 2007

Compact Assembly

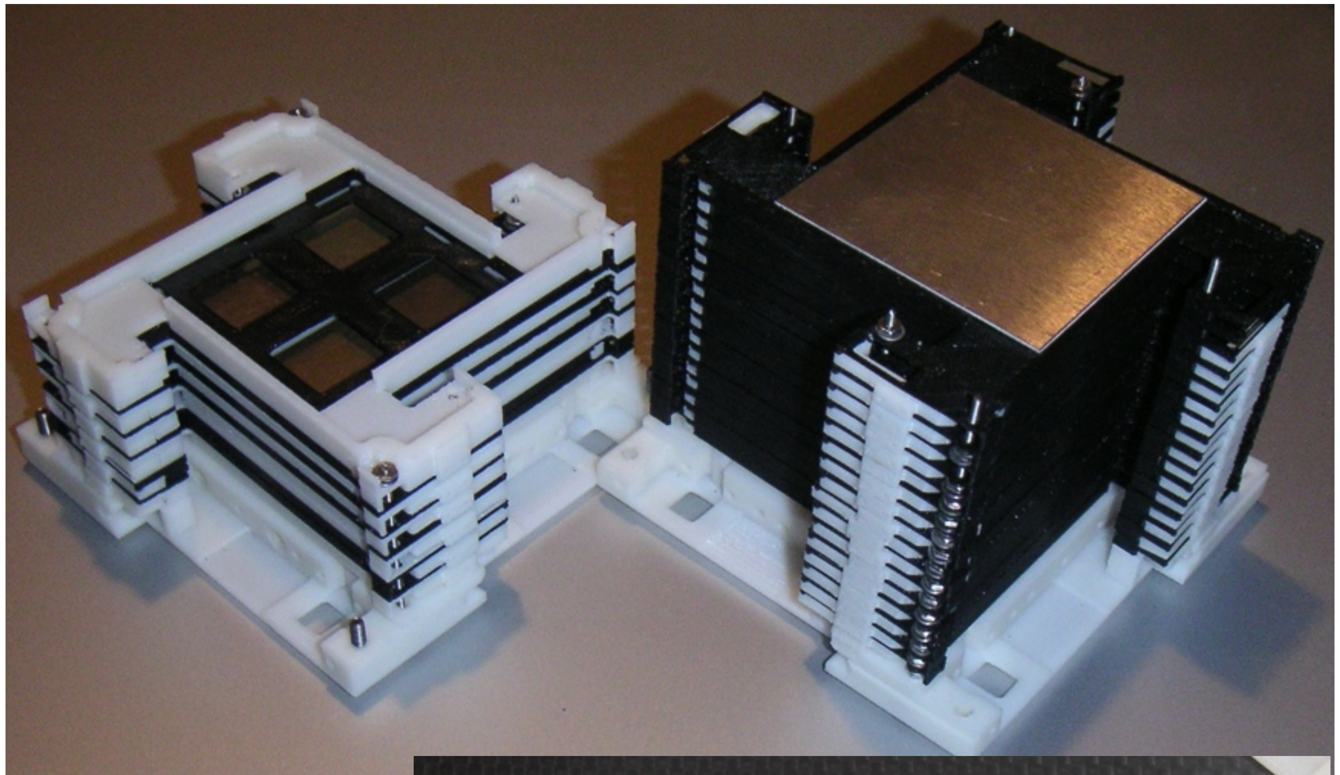
- ✤ **Detailed design in progress.**
  - **Electronics behind sensors.**
  - **Side-CdTe closer to Si sensors.**
- ✤ **Fabrication of mechanical mockup.**

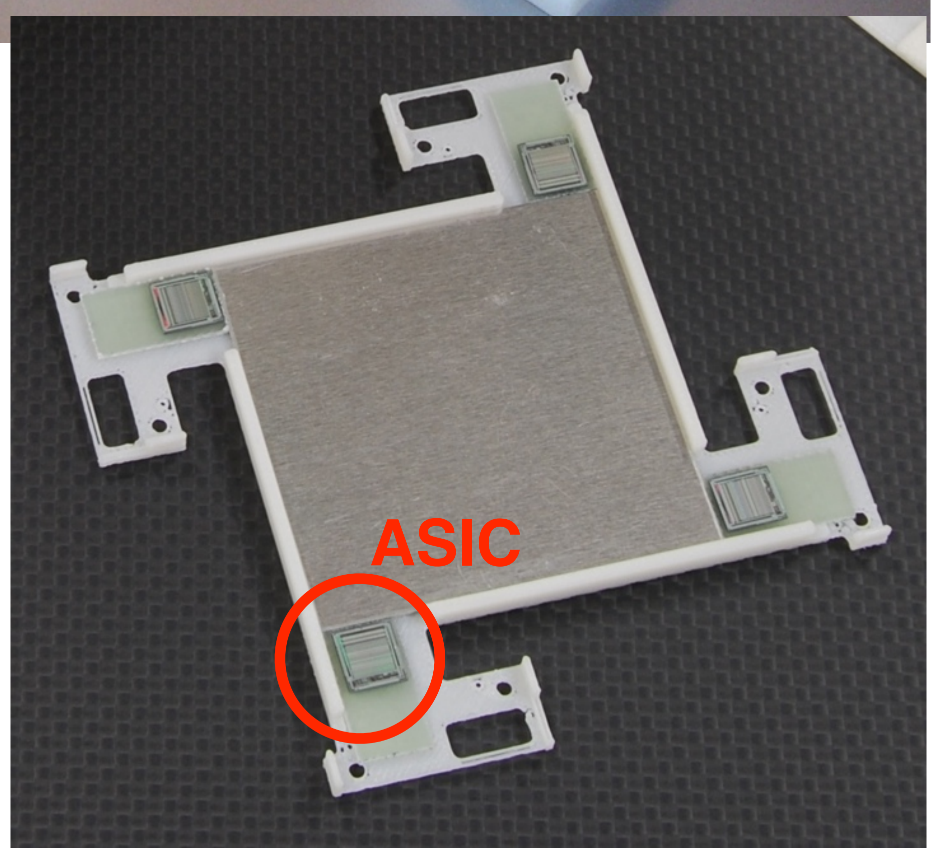


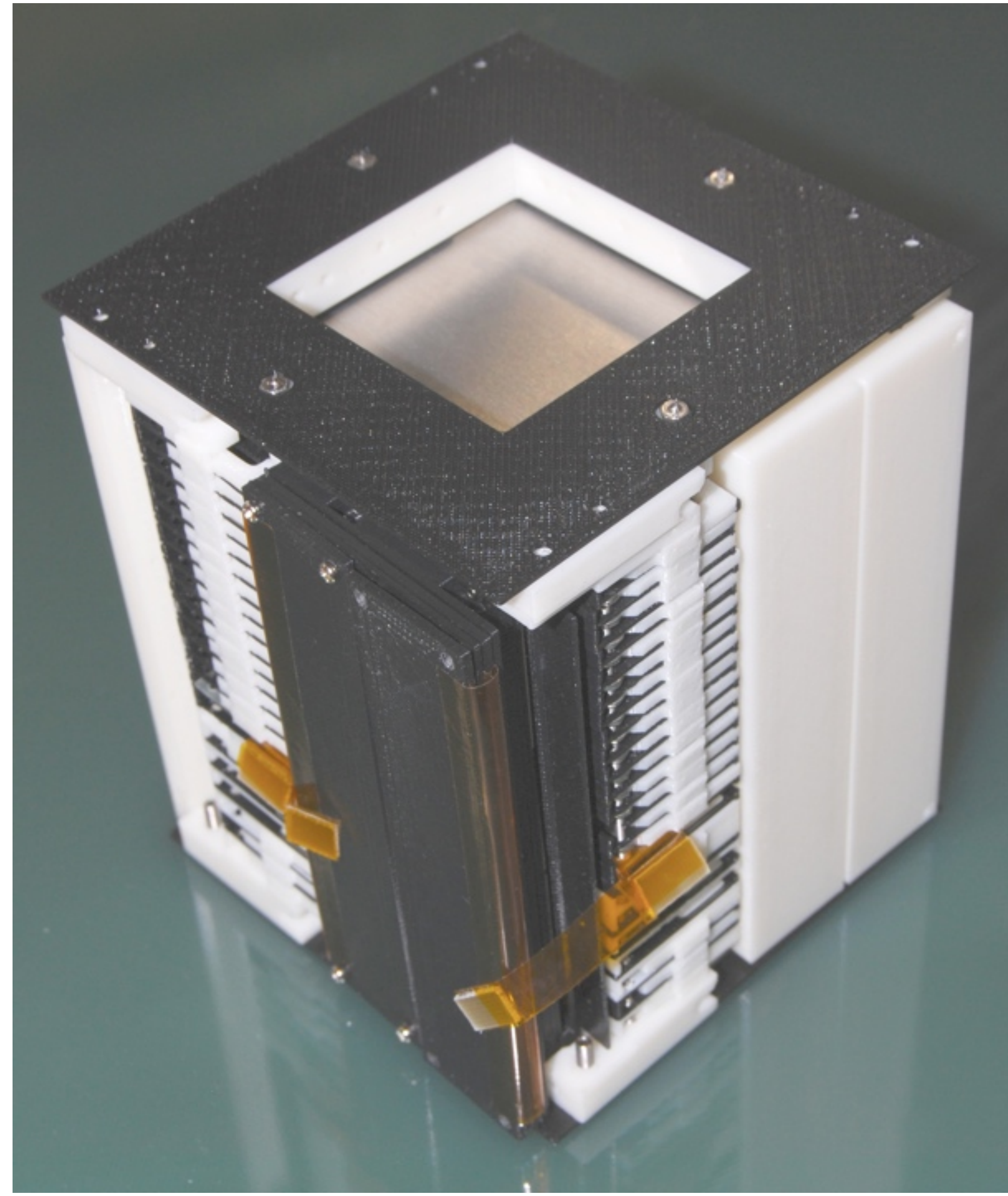


Baseline design by MHI.

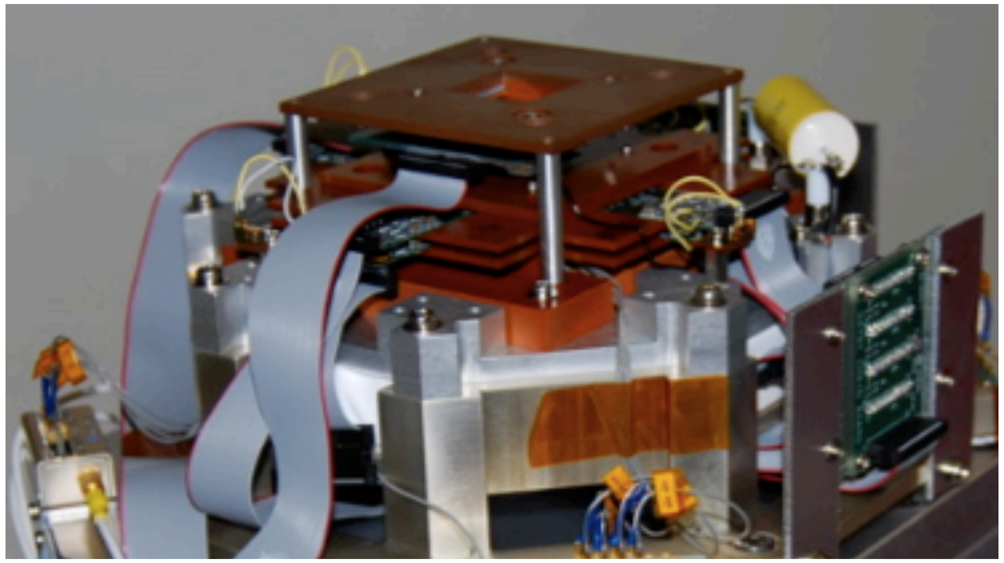
Compton Camera Mechanical Model

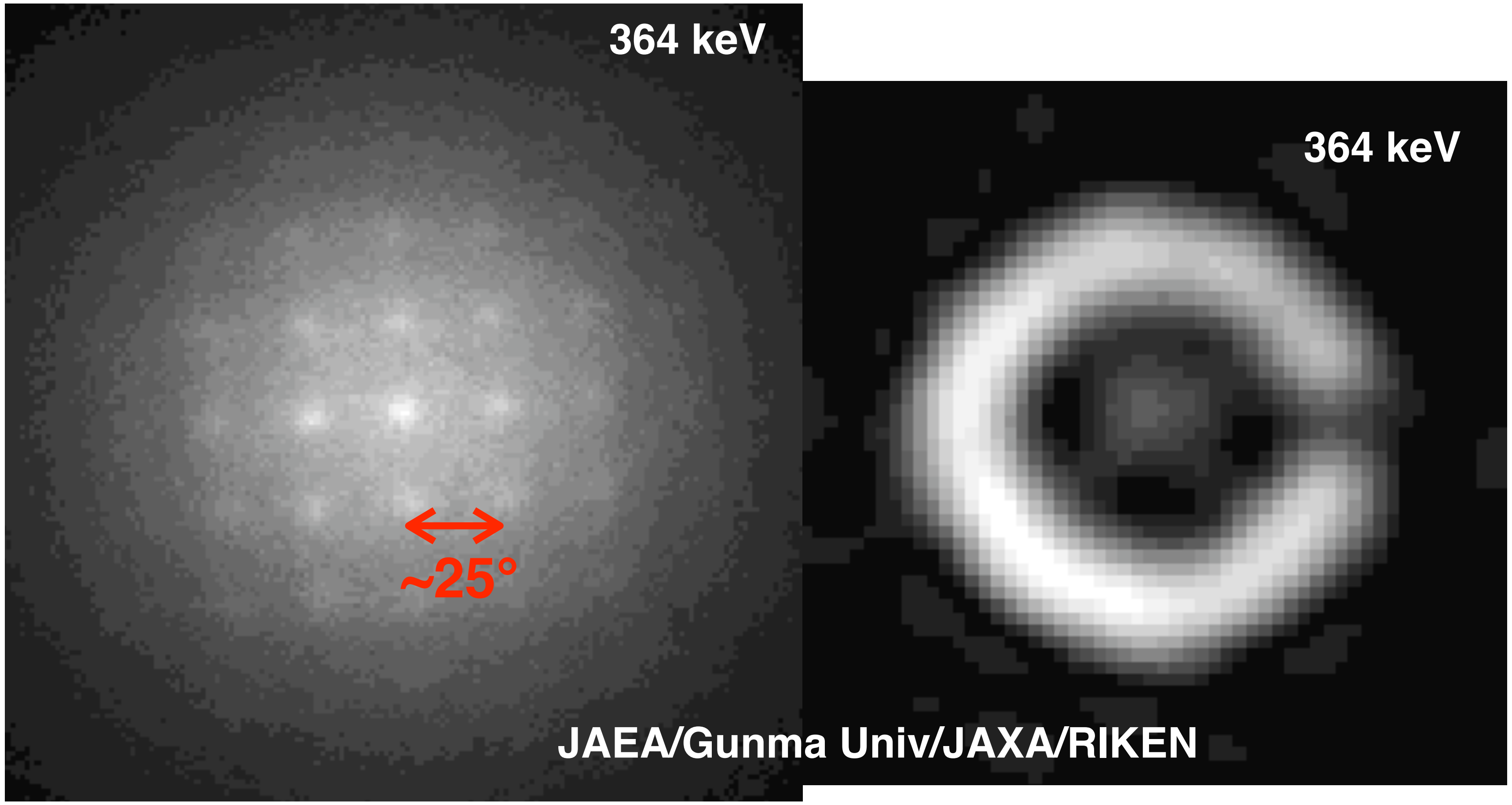


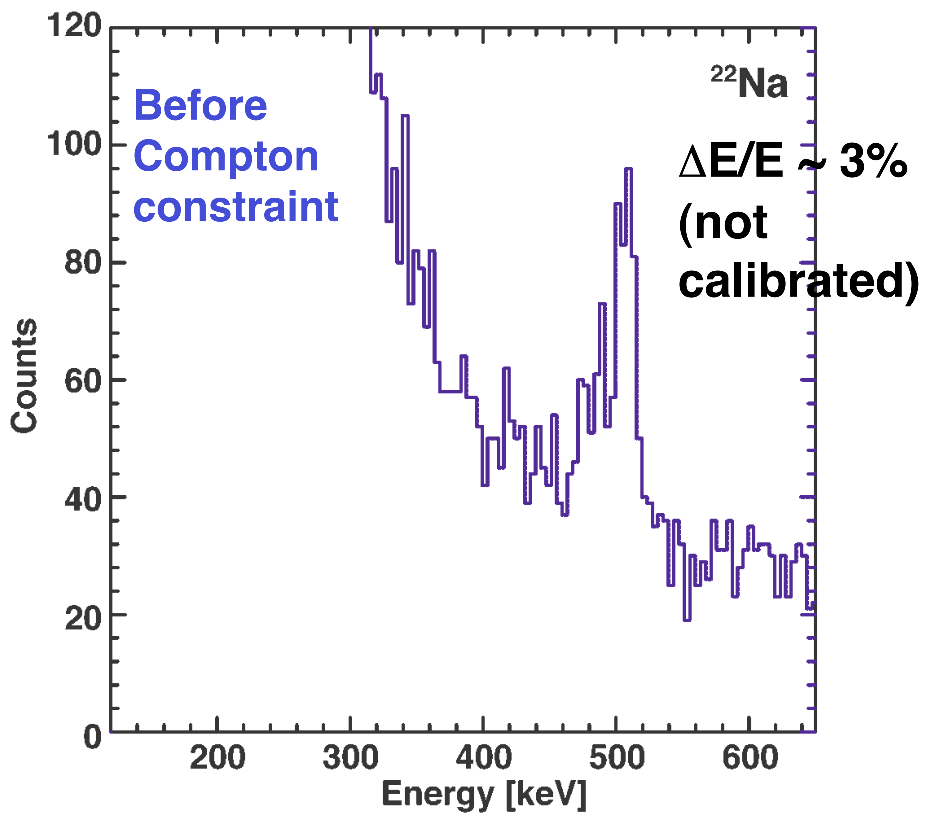




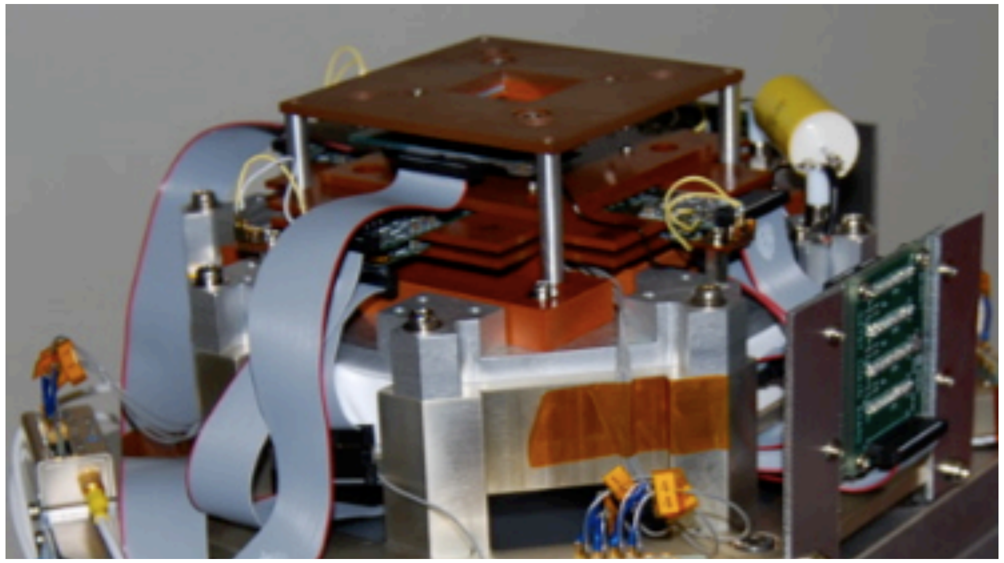
Experimental Test of Compton Camera

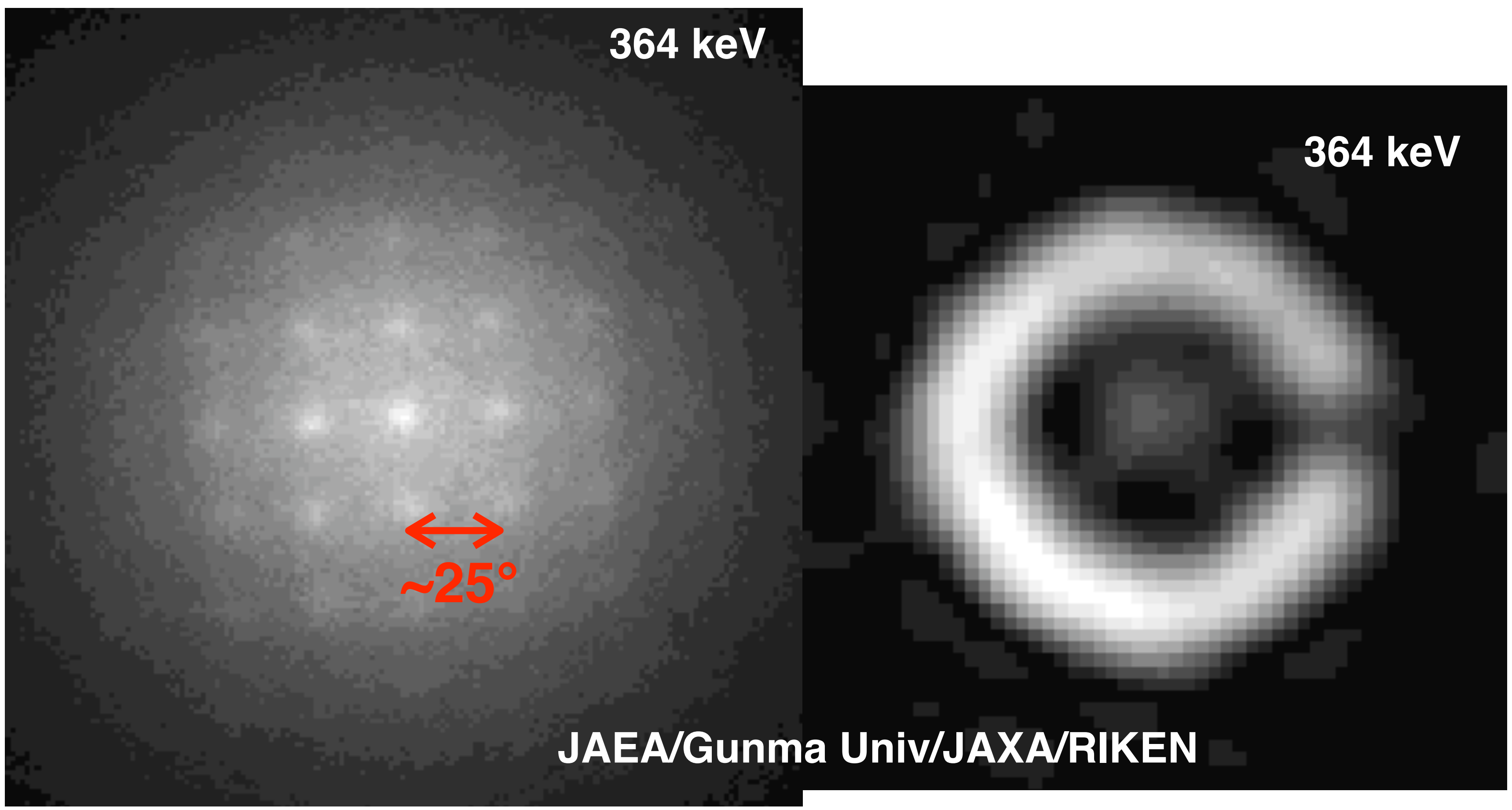


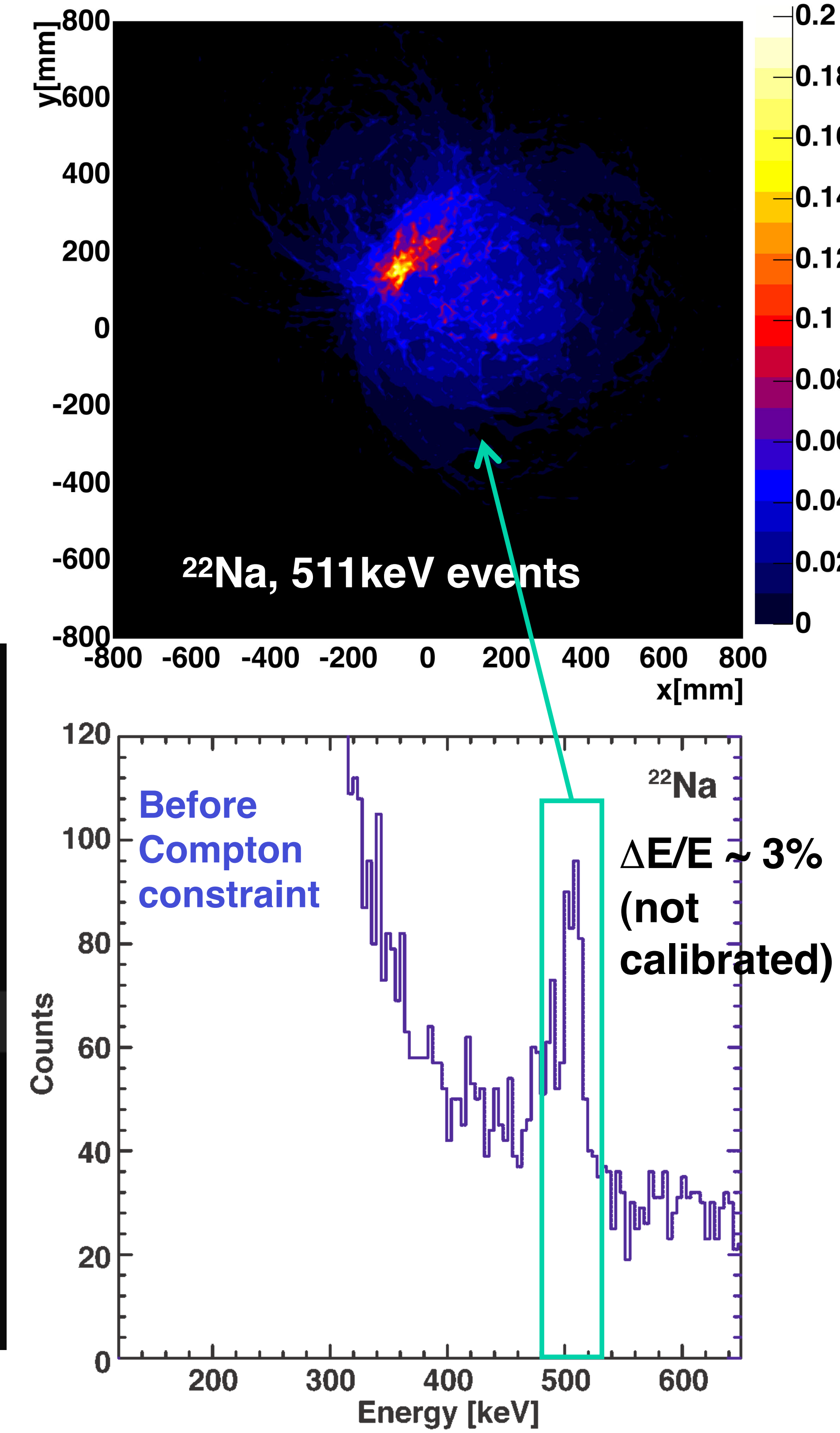




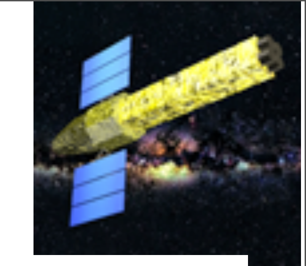
Experimental Test of Compton Camera

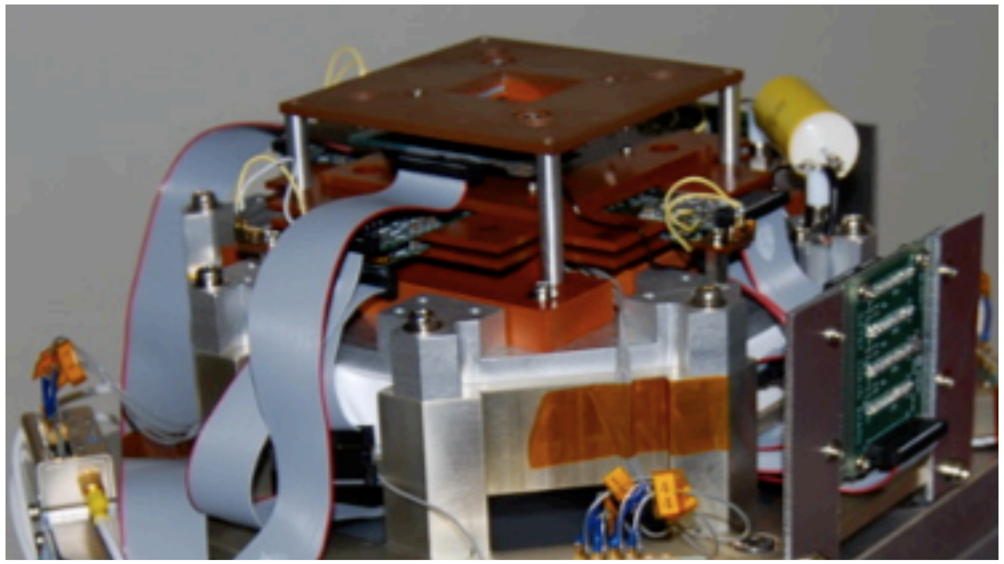


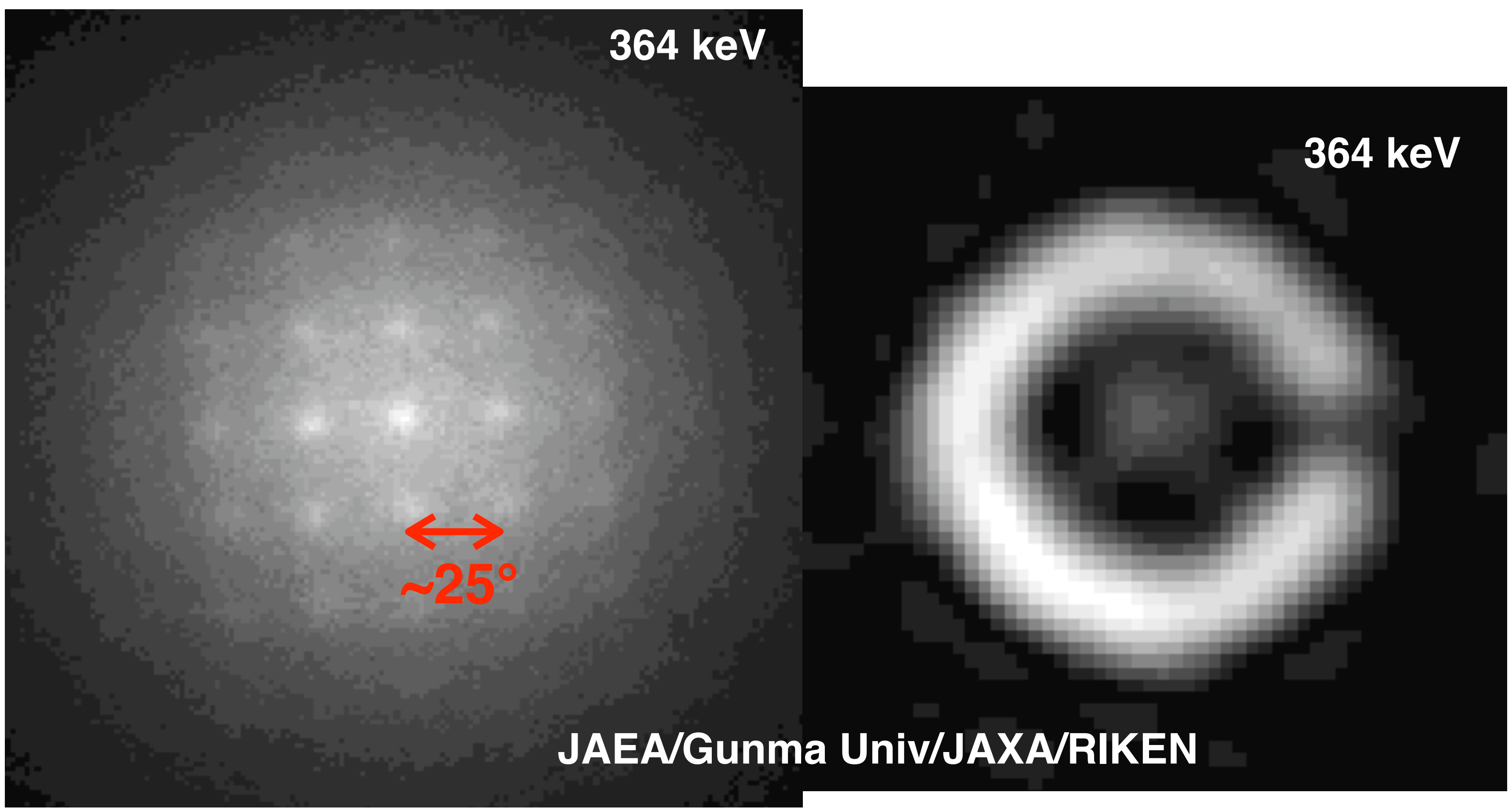


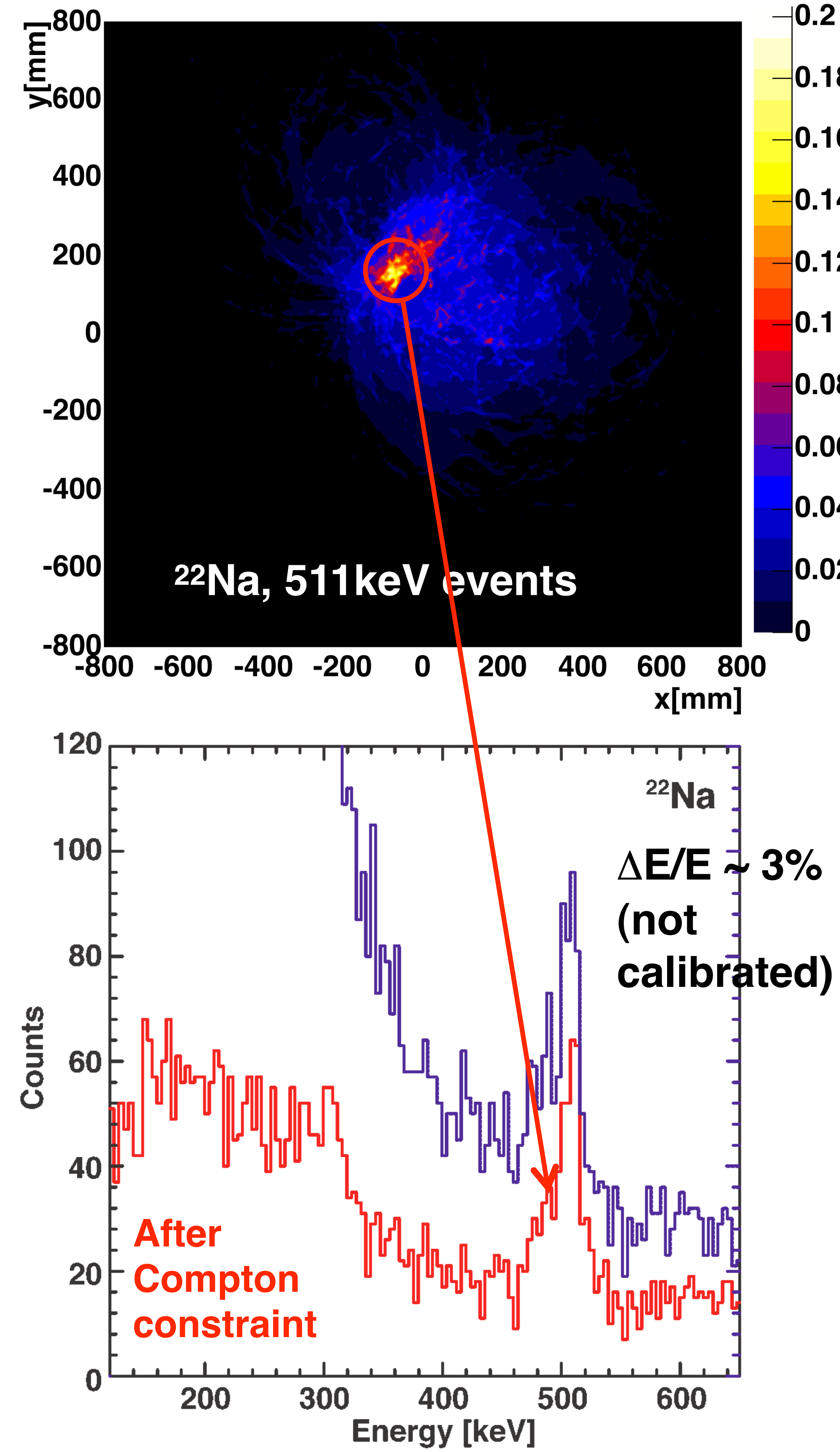


Experimental Test of Compton Camera



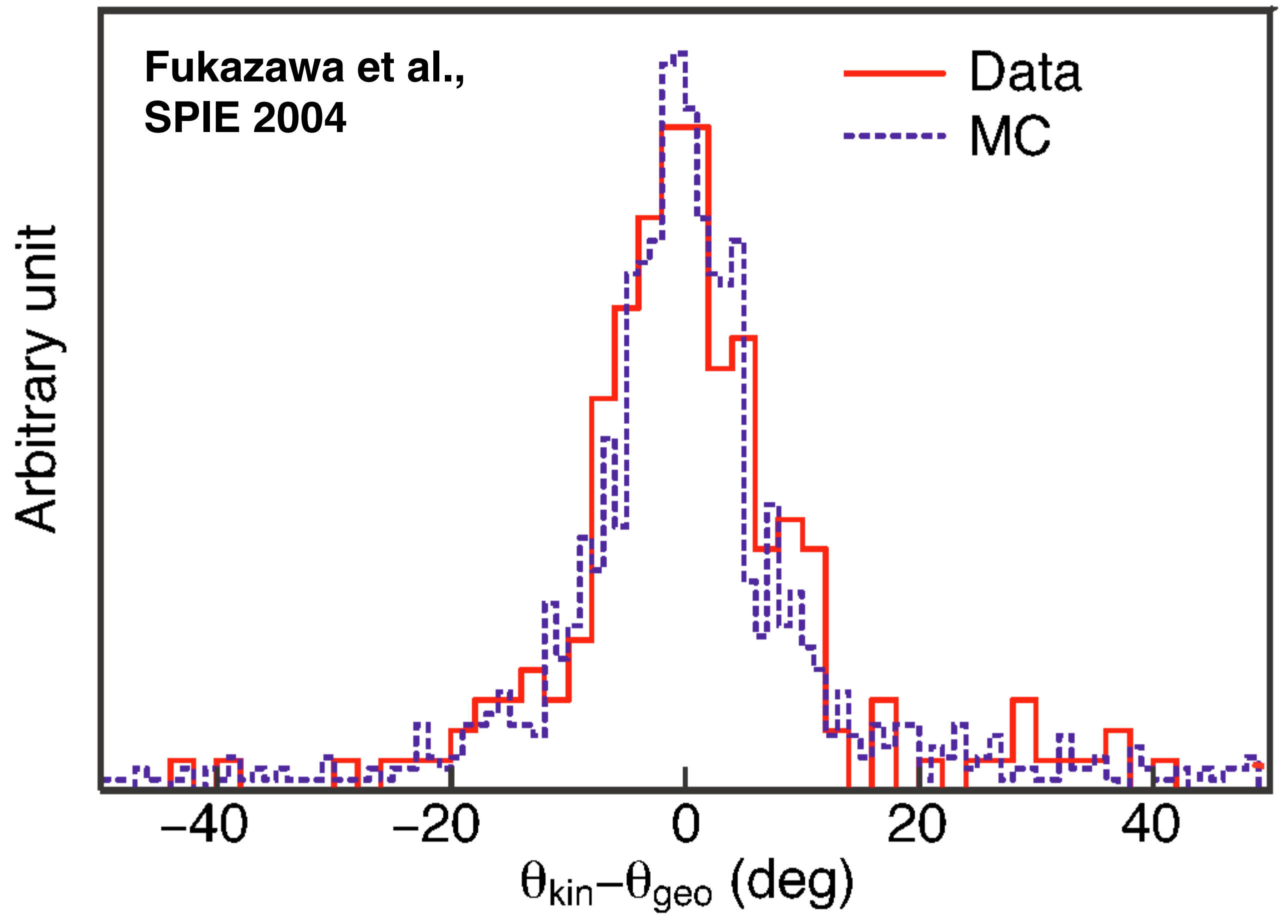






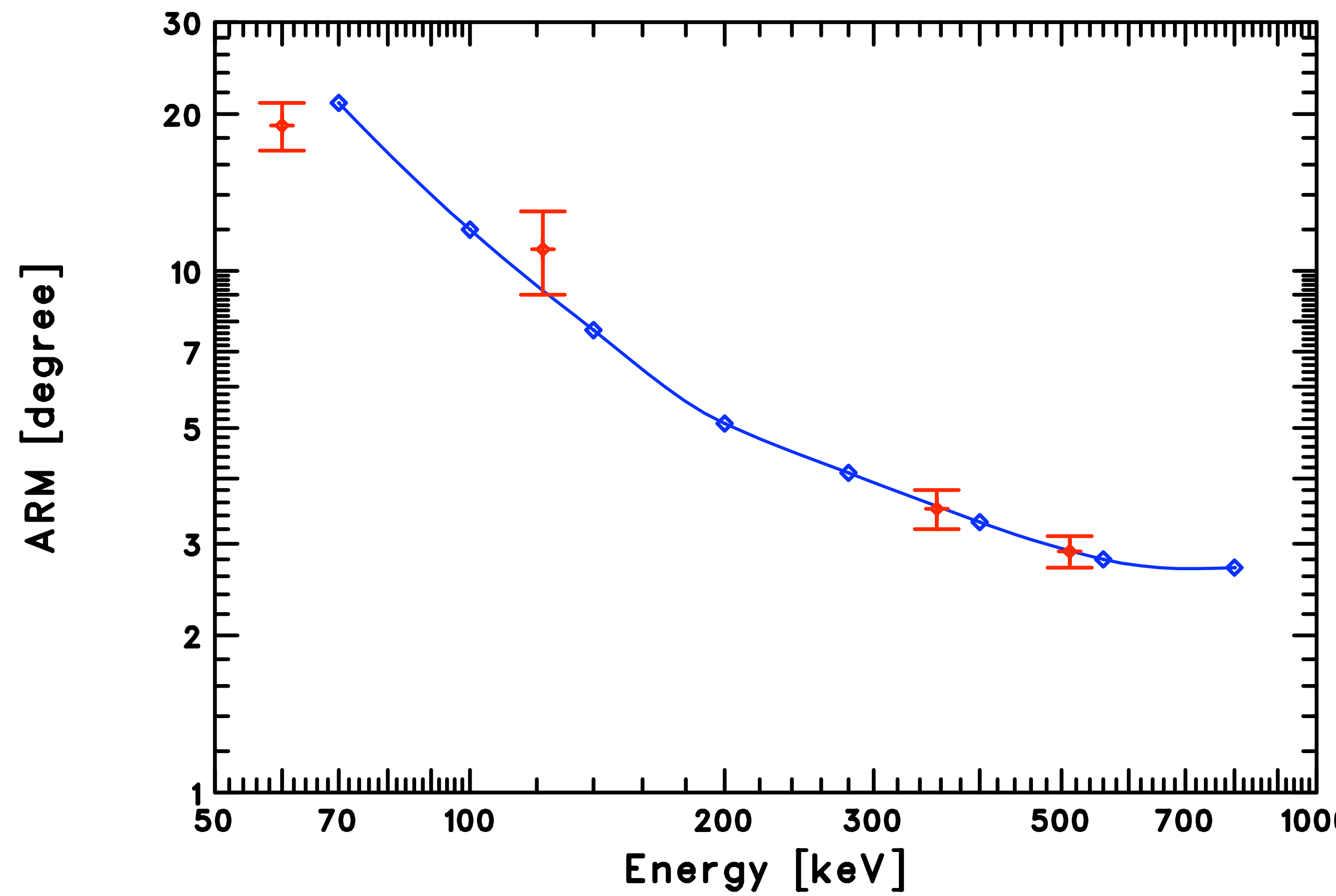
Angular Resolution of Compton Camera

Scattering angle resolution @ 122 keV



Experimental angular resolution is dominated by Doppler broadening.

Energy dependence

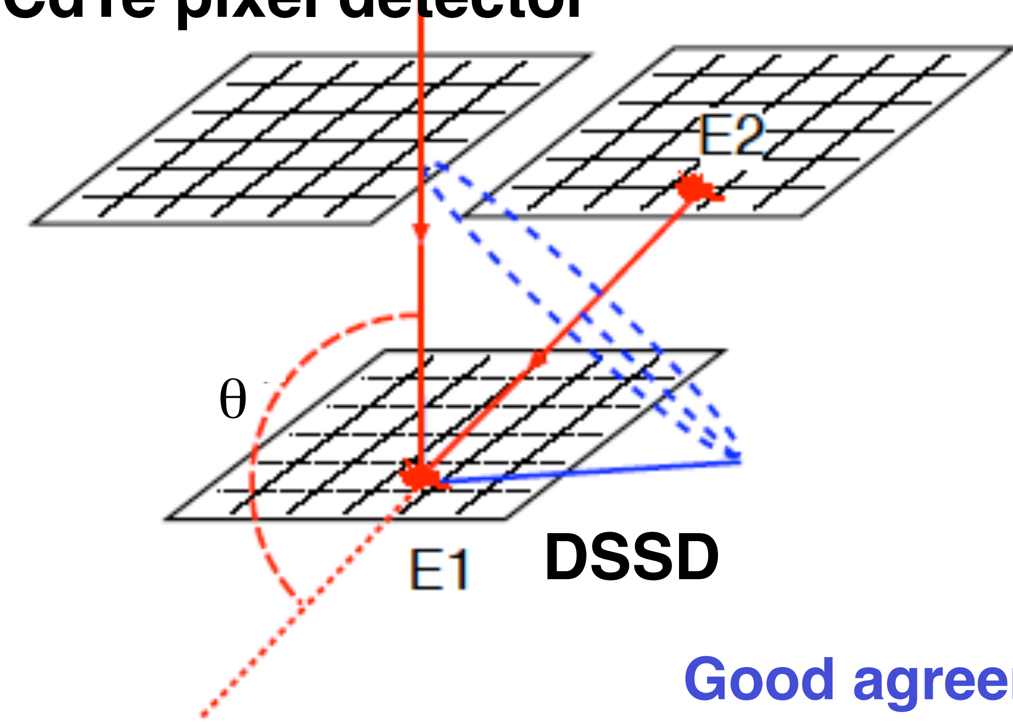


Watanabe (ISAS)

Energy resolution
pixel size } Good enough

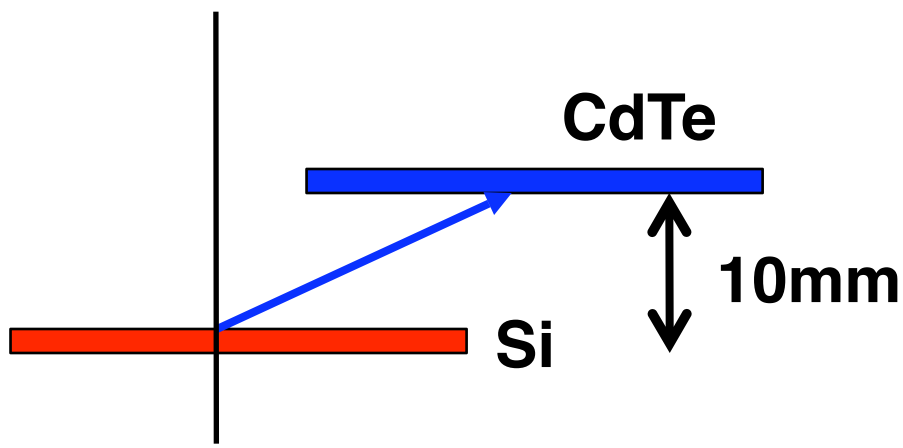
Polarization Measurement @SPring-8

CdTe pixel detector

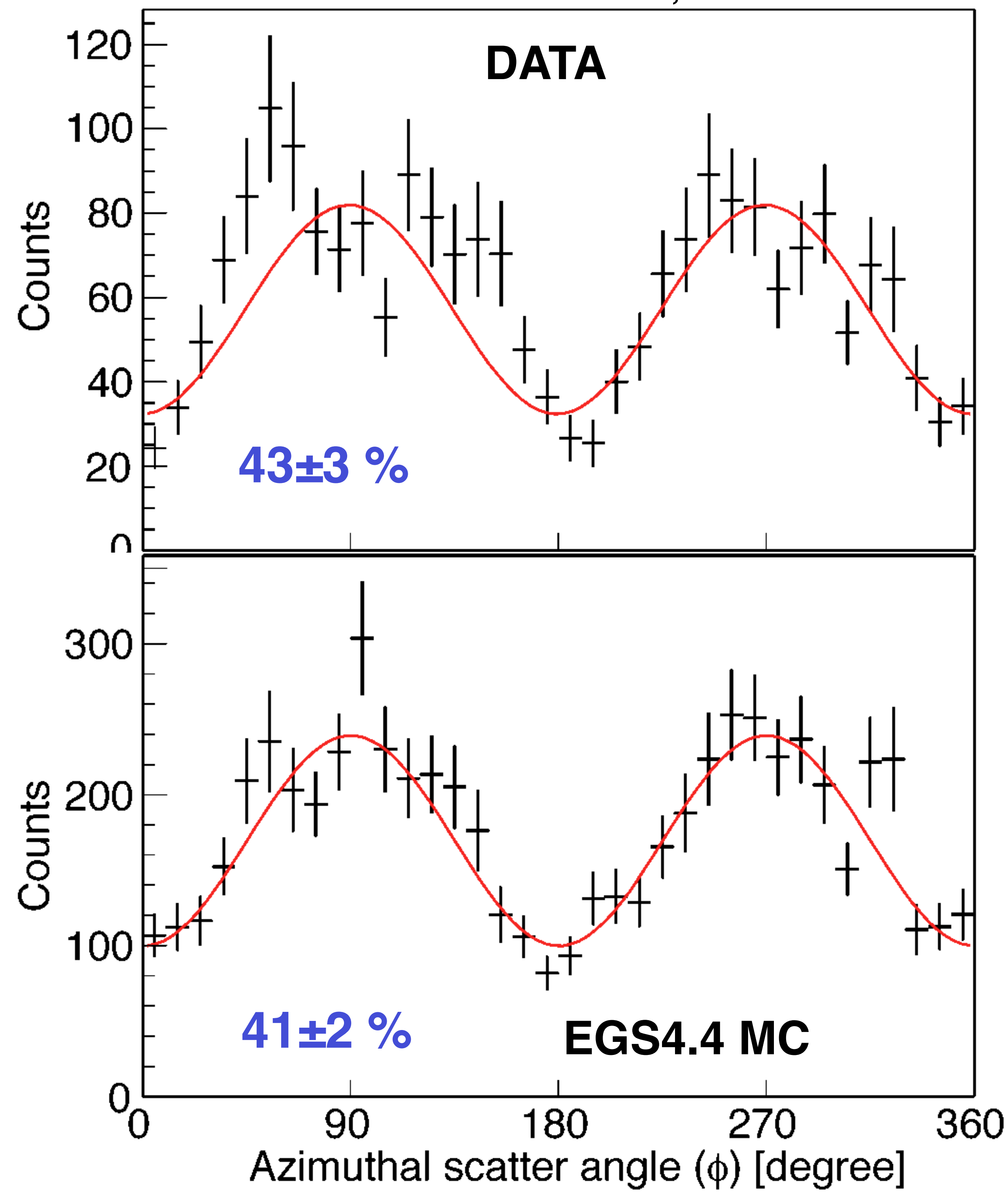


Good agreement between data and MC

177 keV polarized photon

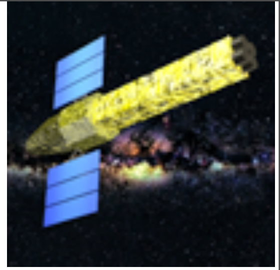


Mitani et al., IEEE TNS 2003



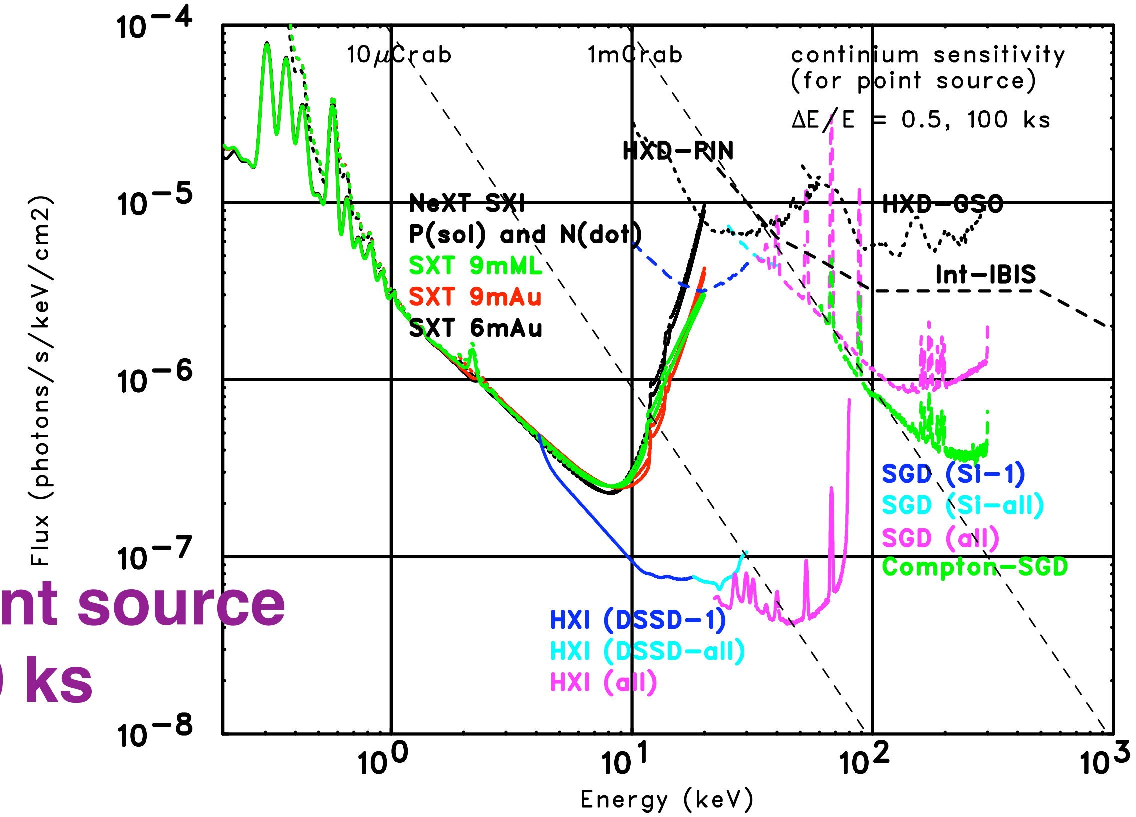
Azimuth Scattering Angle (deg)

HXI/SGD Sensitivity

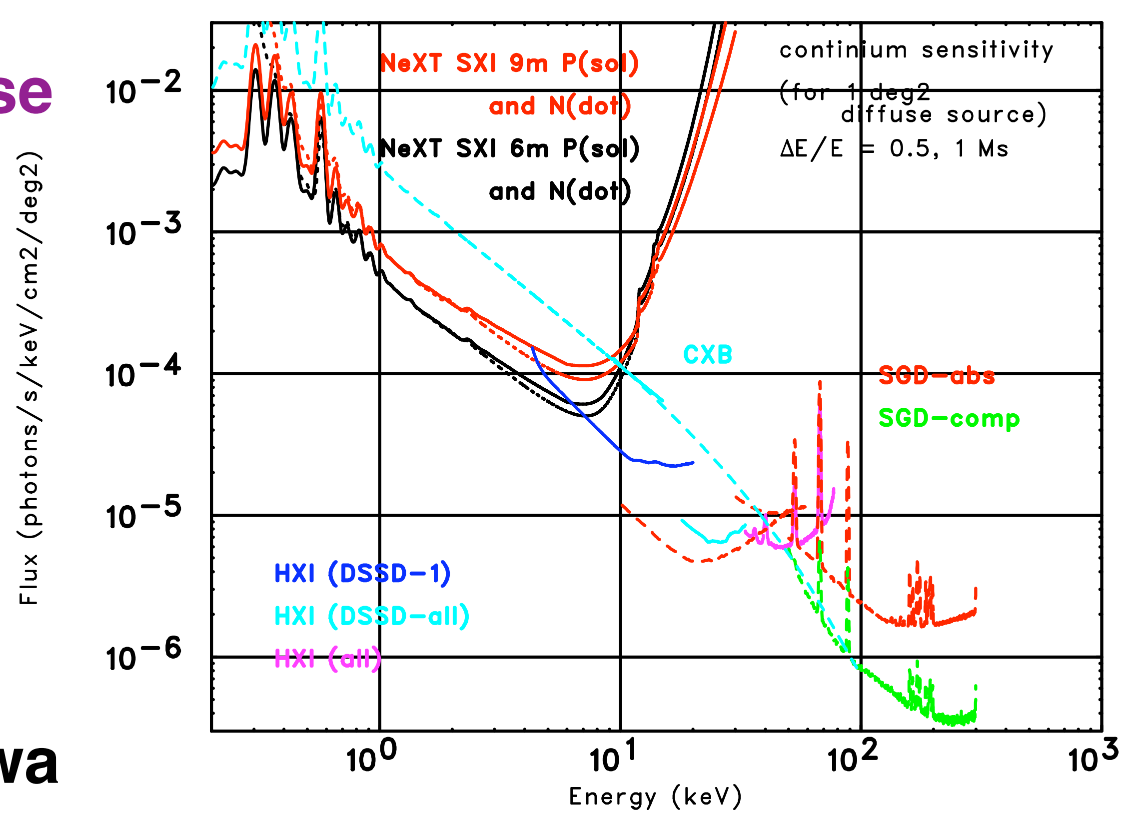


- SGD sensitivity is competitive for diffuse sources.
  - Compton mode is photon limited.
    - Better sensitivity by longer exposure or larger effective area.

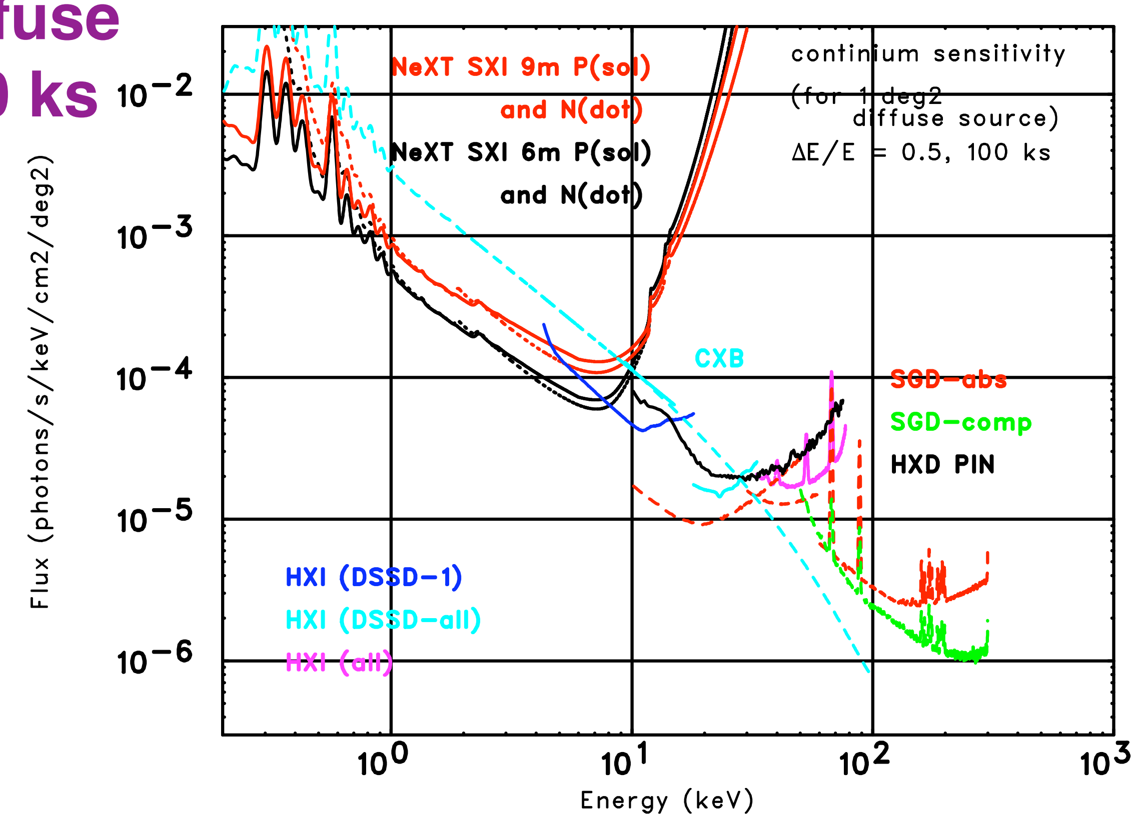
Point source 100 ks



Diffuse 1 Ms



Diffuse 100 ks

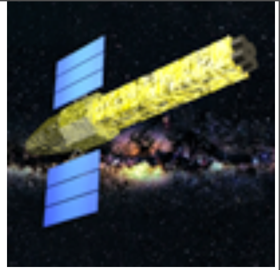


Nakazawa

Summary

- ASTRO-H Science
  - Super-massive black holes
  - Galaxy clusters
    - Structure formation history, dark energy
  - Cosmic-ray accelerators
- SGD Technology Development
  - Good progress on Si/CdTe sensors and ASIC technologies
  - Some technologies still require further development
    - Compact Assembly Technique with minimum material

ASTRO-H Mission Roadmap



- ASTRO-H was approved as a JAXA official mission
- Currently in phase B