ASTRO-H and the search for keV sterile neutrino signatures

Daniel Maier on behalf of the Astro-H team
(project manager: Tadayuki Takahashi)

16. June 2016 Chalonge-de Vega Meudon Workshop 2016, Paris

Overview

- Introduction to the Astro-H satellite
  - Instrumentation → SXS
  - Motivation for the search of a line signal
  - Error report of the satellite

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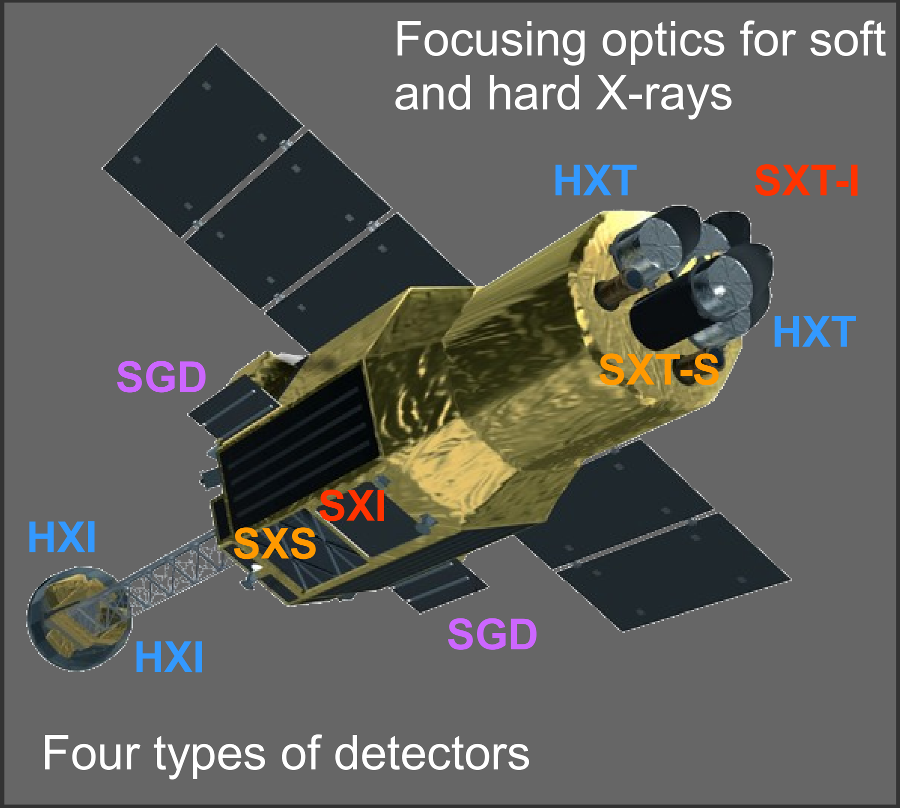
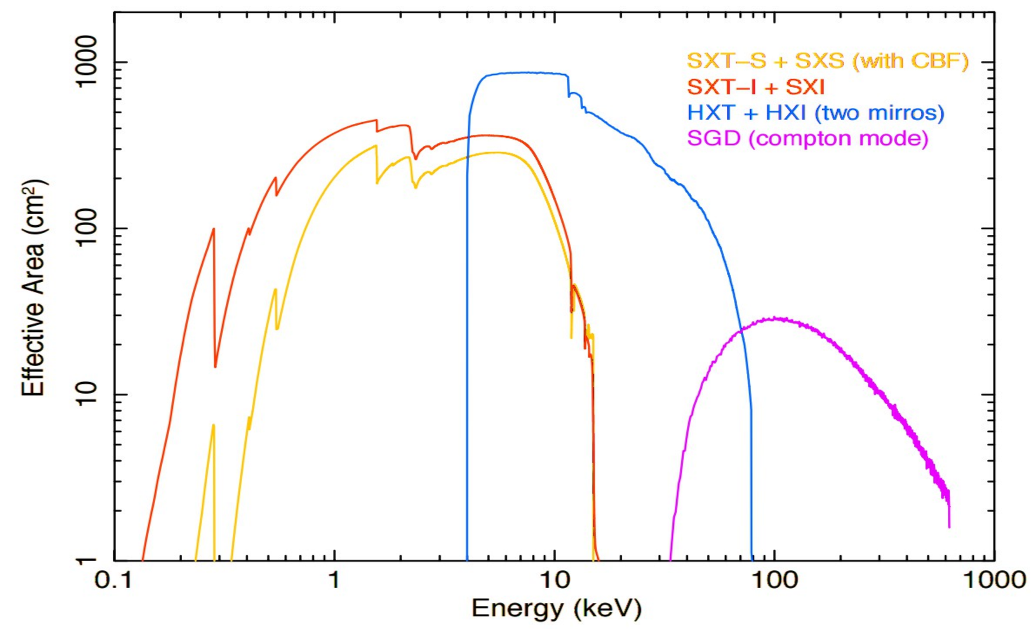
- Introduction to the Astro-H satellite
  - Instrumentation → SXS
  - Motivation for the search of a line signal
  - Error report of the satellite
- Observation: Perseus cluster
  - Mode of observation
  - ~~Results~~

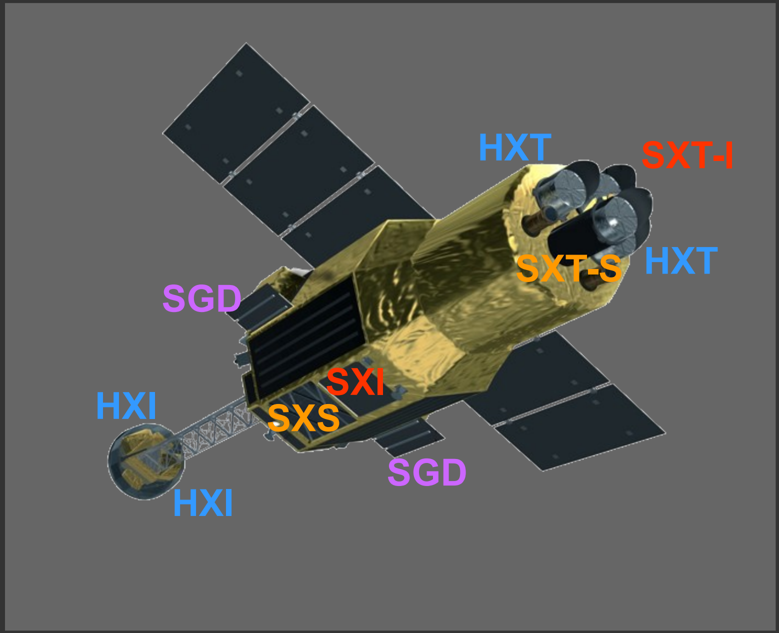
Astro-H:

- International X-ray satellite:
  JAXA/NASA mission

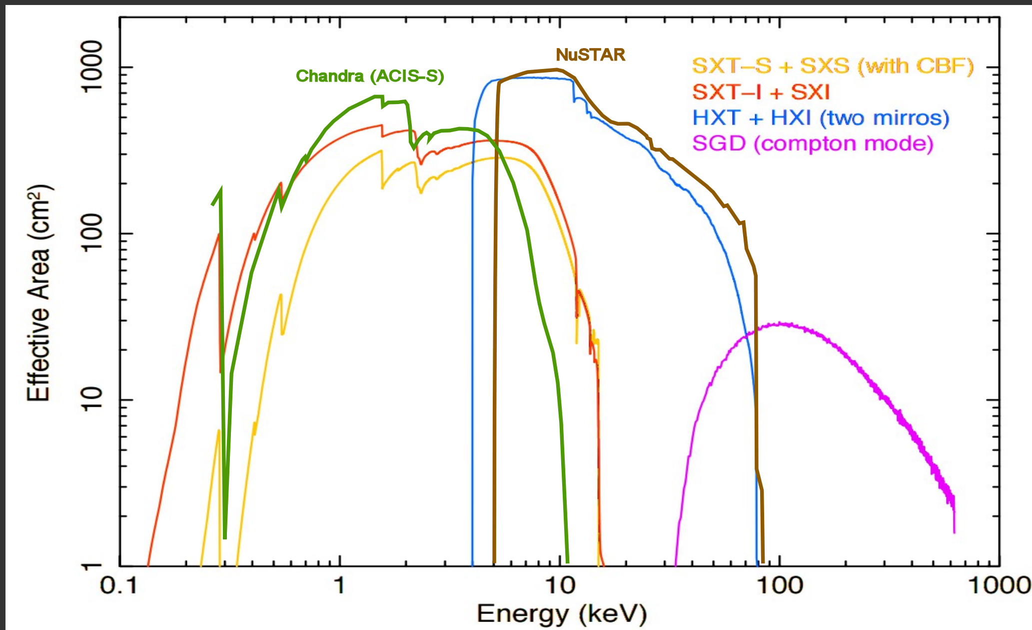
  ... and many more.
- Astro series: 6th X-ray satellite
- Launch: 17. Feb. 2016, JAXA H-IIA rocket, Tanegashima Space Center
- Orbit: 575 km, cricular, 31° incl., 96 min.
- Length: 14m; mass: 2.7 t, power: 3500 W
- Mission life: > 3 years → 38 d
- Energy resolution: <5 eV @ 6 keV
- Wide energy range: 0.3-600 keV
- Diverse science: large scale structure, matter in strong gravitational fields, CR acceleration, dark matter

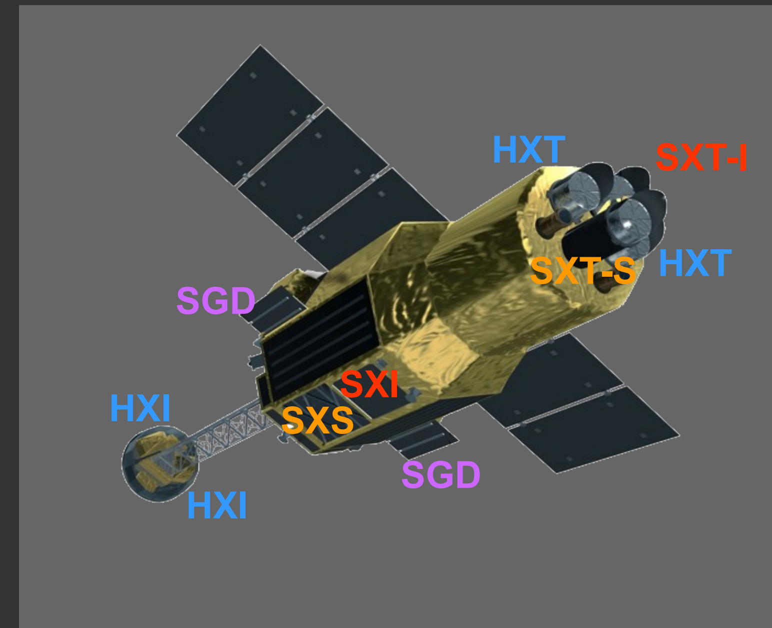






Properties	SXS	SXI	HXI	SGD (photo-abs)	SGD (Compton)
Effective area (cm^2)	50/225 (@0.5/6 keV)	214/360 (@0.5/6 keV)	300 (@30 keV)	150 (@30 keV)	20 (@100 keV)
Energy range (keV)	0.3-12.0	0.4-12.0	5-80	10-600	40-600
Angular resolution in HPD (arcmin)	1.3	1.3	1.7	N/A	N/A
Field of view ($arcmin^2$)	3.05x3.05	38x38	9x9	33x33 (<150 keV) 600x600 (>150 keV)	33x33 (<150 keV) 600x600 (>150 keV)
Energy resolution in FWHM (eV)	5	150 (@6 keV)	< 2000 (@60 keV)	2000 (@40 keV)	4000 (@40 keV)
Timing resolution (s)	$8x10^{-5}$	4	several x 10^{-5}	several x 10^{-5}	several x 10^{-5}
Instrumental background (/s/keV/FoV)	$2x10^{-3}/0.7x10^{-3}$ (@0.5/6 keV)	0.1/0.1 (@0.5/6 keV)	$6x10^{-3}/2x10^{-4}$ (@10/50 keV)[1] $2x10^{-3}/4x10^{-5}$ (@10/50 keV)[2]		$1x10^{-4}/1x10^{-5}$ (@100/600 keV)





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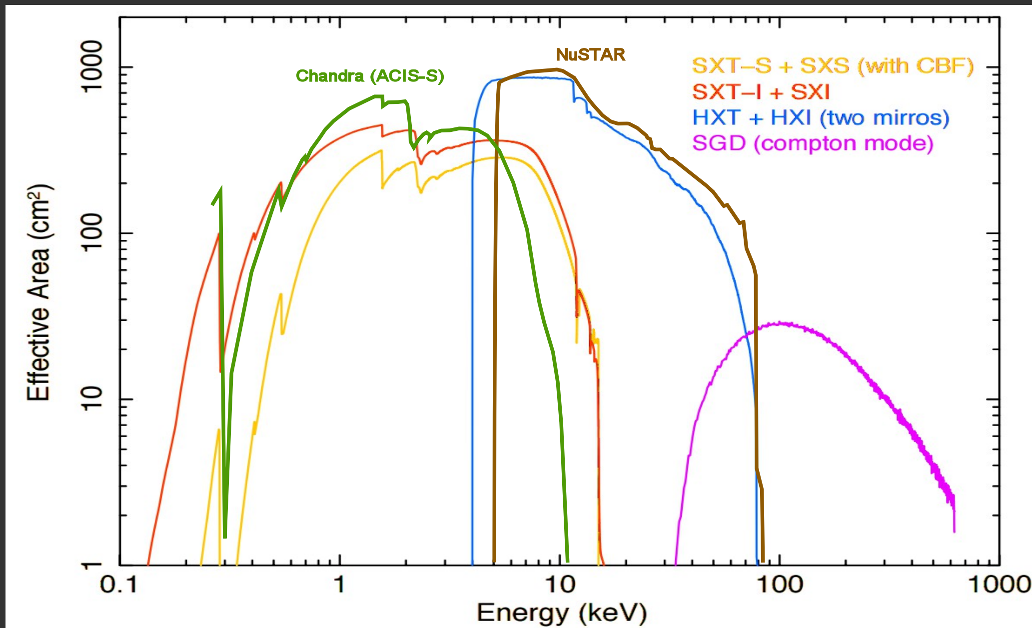

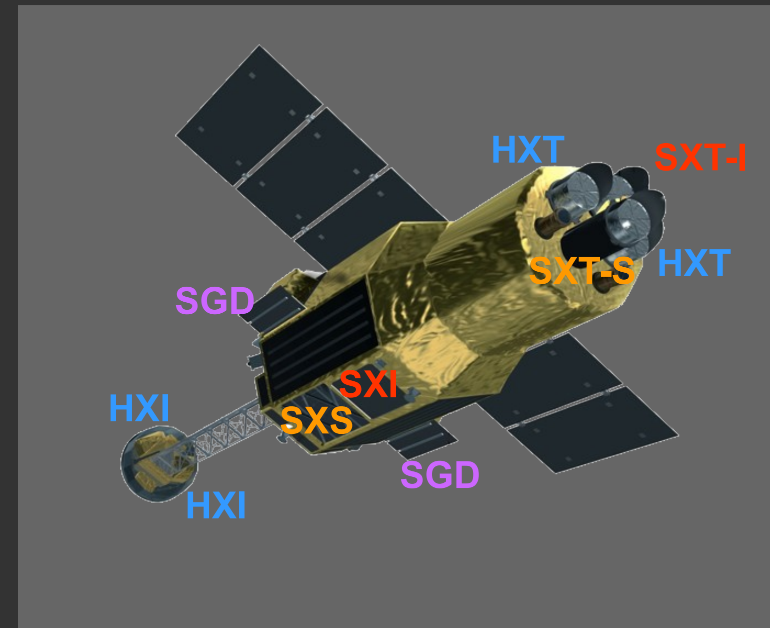

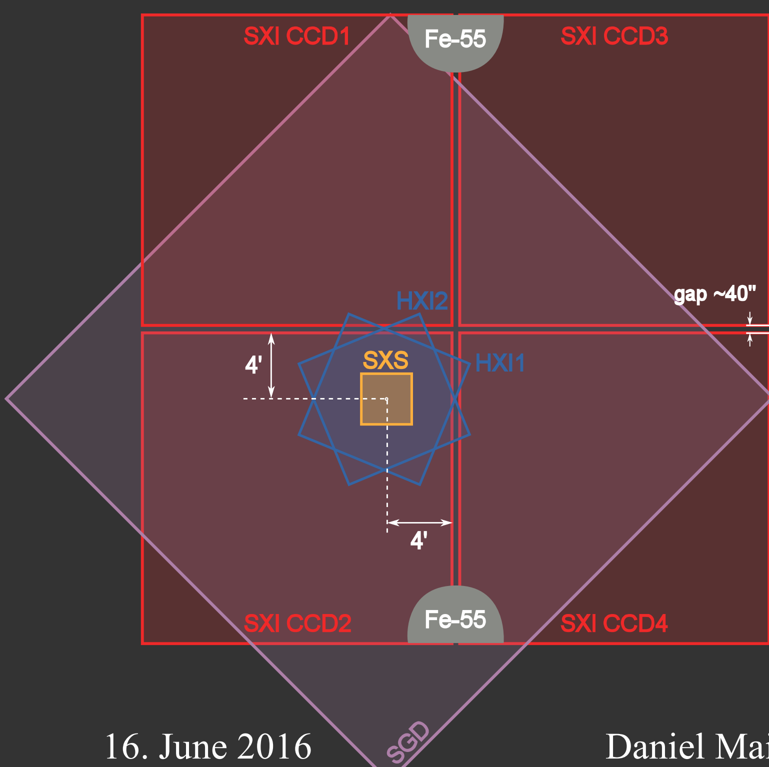

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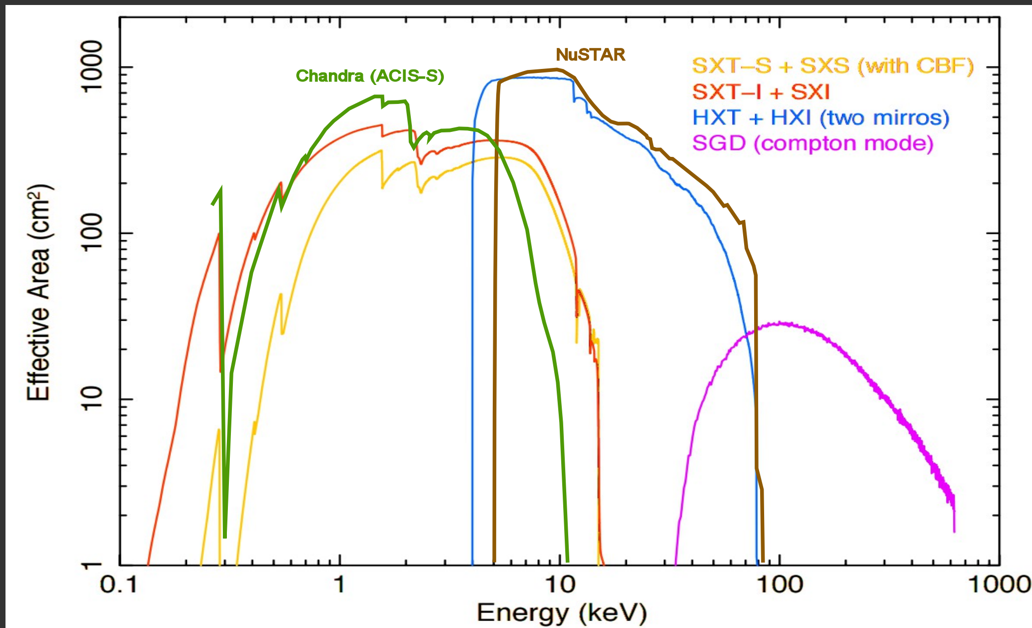

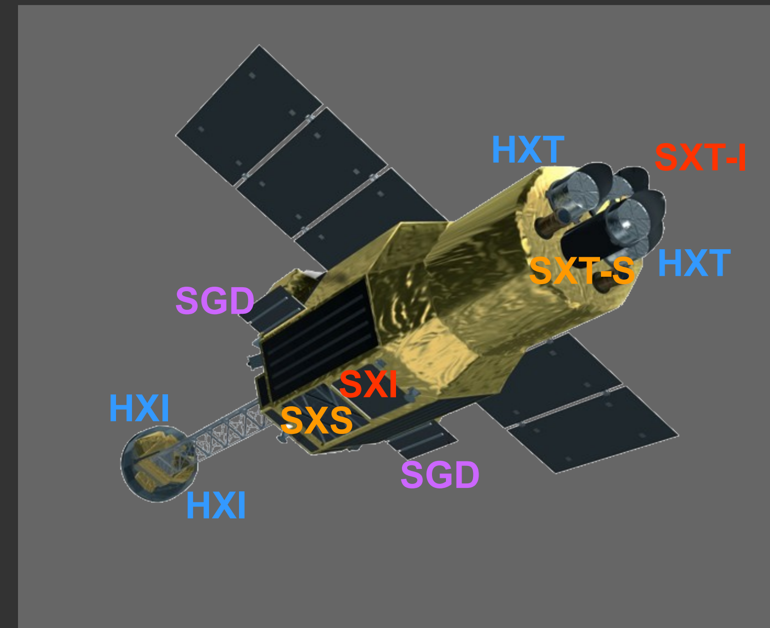

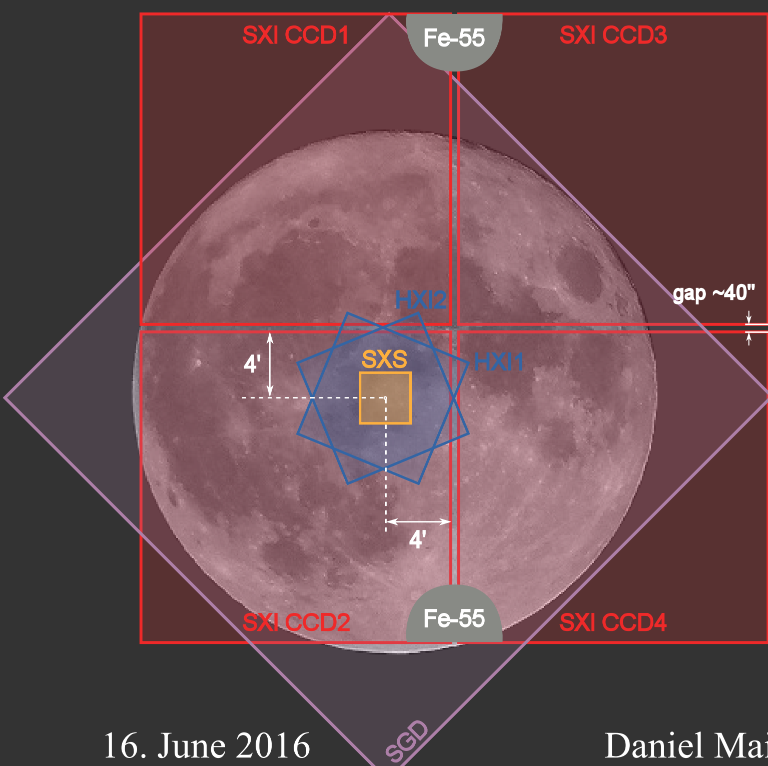

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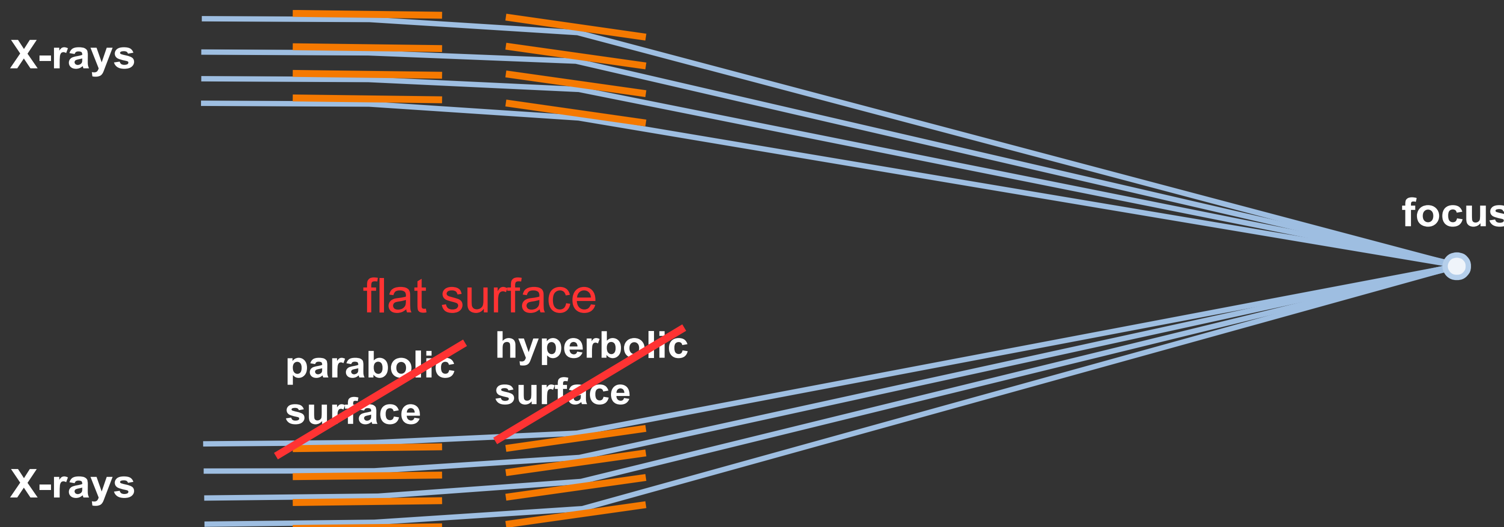
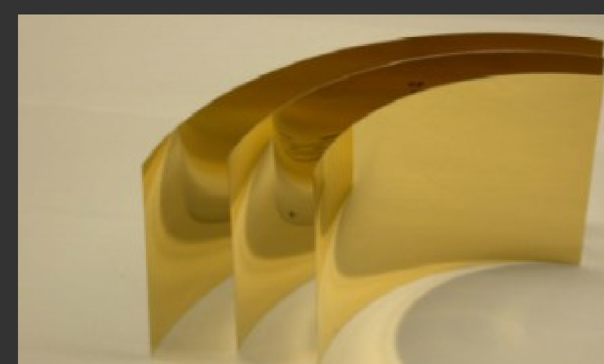
SXT : the soft X-ray telescope

A conical approximated Wolter-1 thin-foil mirror



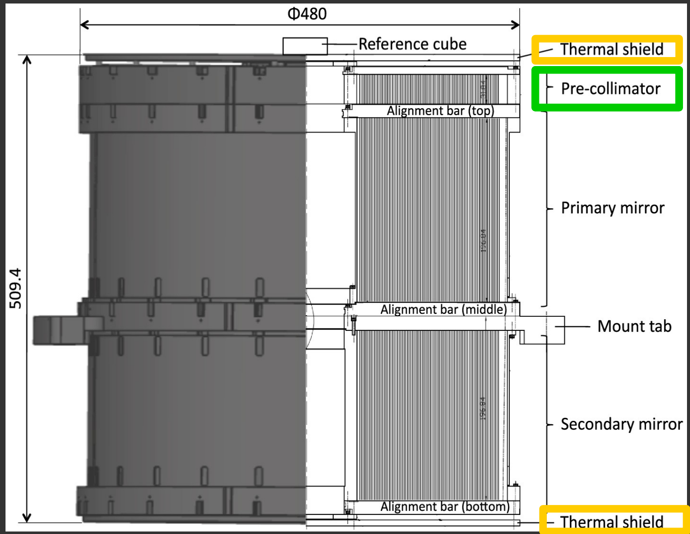
heat formed Al
~ 200 µm (20 x ordinary Al foil)

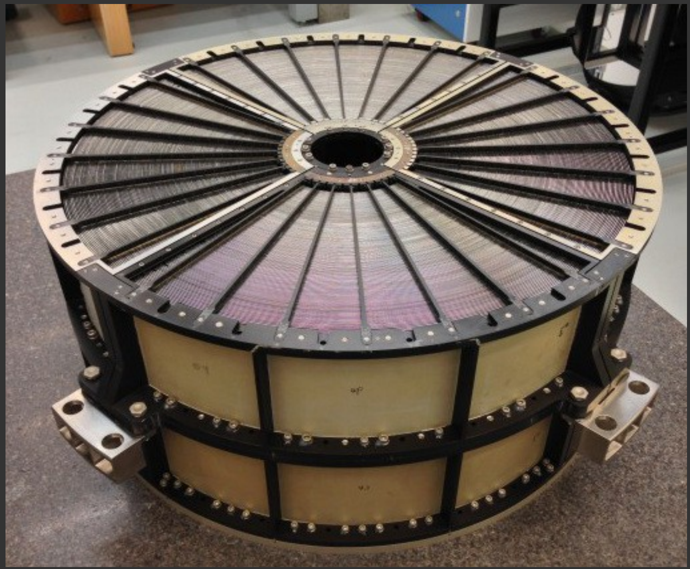
+ epoxy
+ gold



SXT : the soft X-ray telescope

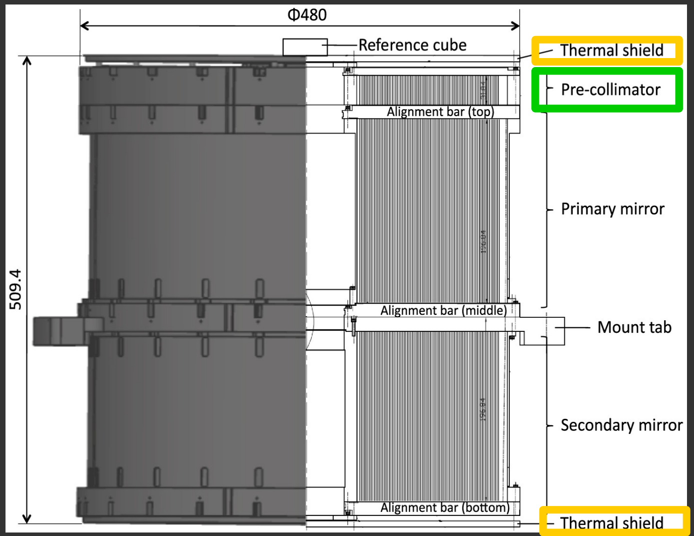
- Thermal shield: T = 20°C
- Stray ligth baffle
- Conical approximated Wolter-1 thin-foil mirrors:
  - 4 segments, nesting: 203
  - 11.6 cm < Ø < 45 cm
  - 5.6 m focus, 0.4-12 keV
  - Ang. res. 1.3' (Suzaku: 2', but in theory: > 0.2')
  - Assambly imprecisions
  - Roundness & figure errors





HXT : the hard X-ray telescope

- Thermal shield: T = 20°C
- Stray ligth baffle
- Conical approximated Wolter-1 thin-foil mirrors:
  - 3 segments, nesting: 213
  - 12 cm < Ø < 45 cm
  - 12 m focus, 4-78 keV
  - Ang. res. 1.9' @ 30 keV
    1.5' @ 70 keV



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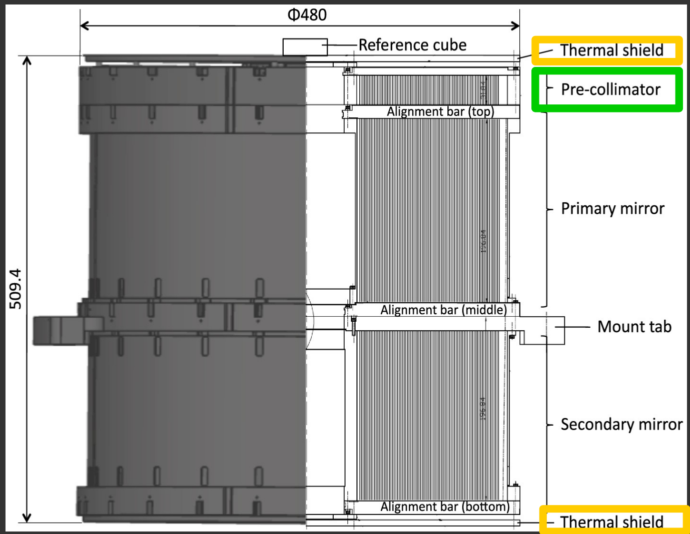
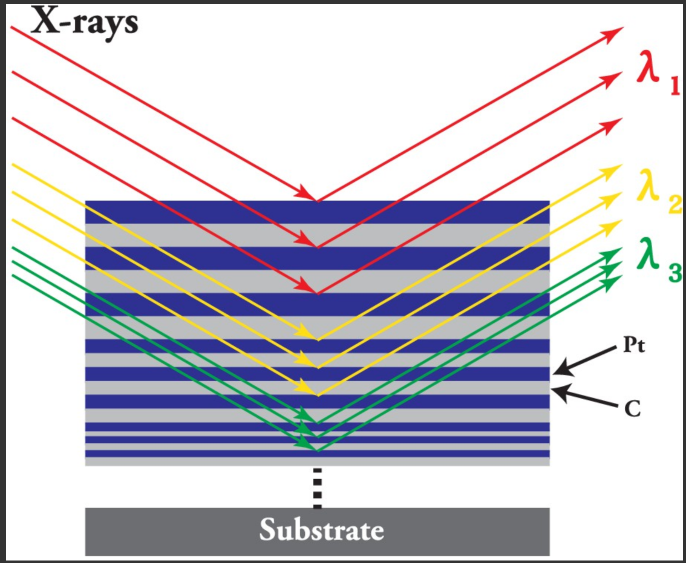
    1.5' @ 70 keV
  - Pt/C depth-graded multilayer
    – Bragg refl. $n\lambda = 2d \sin(\theta)$





SXS: the soft X-ray spectrometer

- 6x6 bolometer array
- Basic definition of energy: $\Delta E = C \cdot \Delta T$
- E = 6 keV ≈ 10^{-15} J → $\Delta T = 2.4\ 10^{-16}$ K

  illustrative example

  for 1 g H_2O @ 20°C

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- Freeze-out: C → 0 for $T \to 0$ Debye model: $C \sim T^3$
- HgTe pixel @ T = 50 mK, → C = 0.11 pJ/K

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- Freeze-out: C → 0 for $T \rightarrow 0$ Debye model: $C \sim T^3$
- HgTe pixel @ T = 50 mK, → C = 0.11 pJ/K
- E = 6 keV ≈ 10^{-3} pJ → ΔT = 9 mK

  Astro-H SXS — for 46 µg HgTe @ 50 mK

SXS: the soft X-ray spectrometer

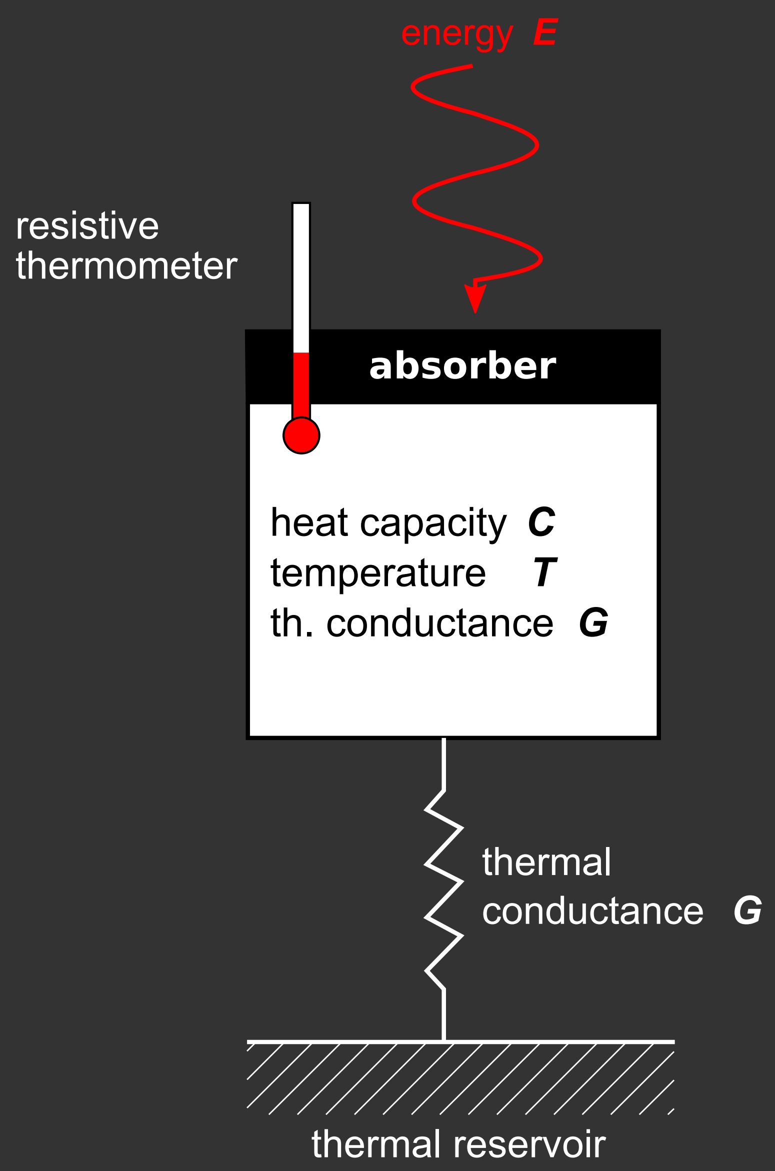
1) **Absorber**

HgTe: 814 x 814 x 8.5 μm^3

97 % absorption efficiency @ 6 keV

2) Thermometer

3) Heat sink & thermal reservoir



SXS: the soft X-ray spectrometer

1) Absorber

HgTe: 814 x 814 x 8.5 μm^3

97 % absorption efficiency @ 6 keV

2) **Thermometer**

thermistor = temp. dependent resistor

silicon doped with phosphorus:

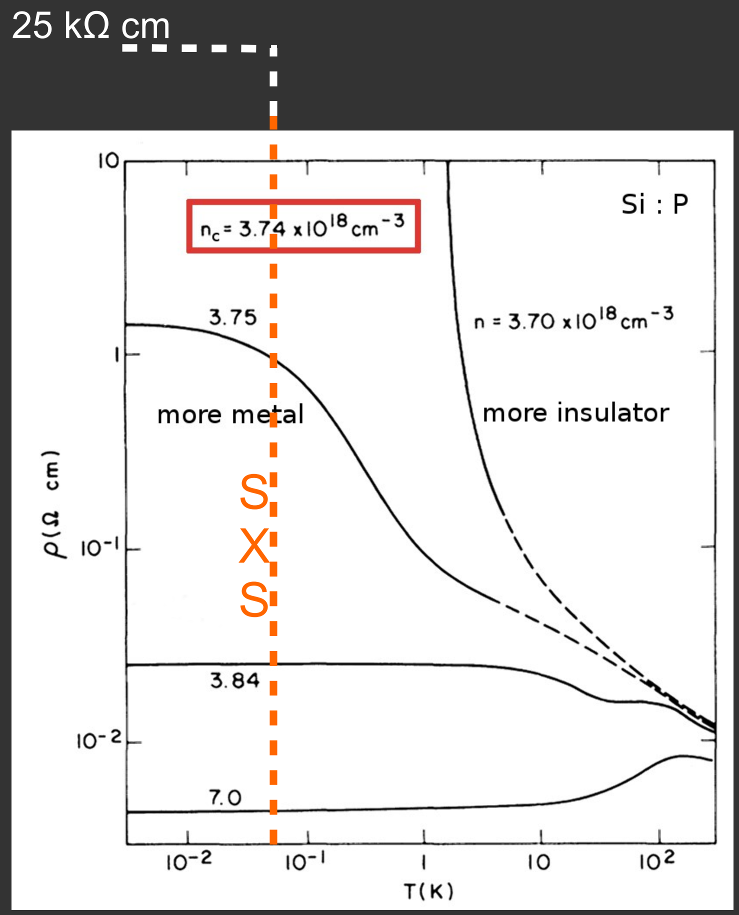
just below the metal-insulator transition

very high temperature coefficient:

$d(\log R) / d(\log T) = -7$ at R = 30 MΩ

$\Delta R = -20$ MΩ for $\Delta T = 9$ mK ($E = 6$ keV)

drop of resistance is sampled by an external FET



Rosenbaum et al., 1983, Phy. Rev. B

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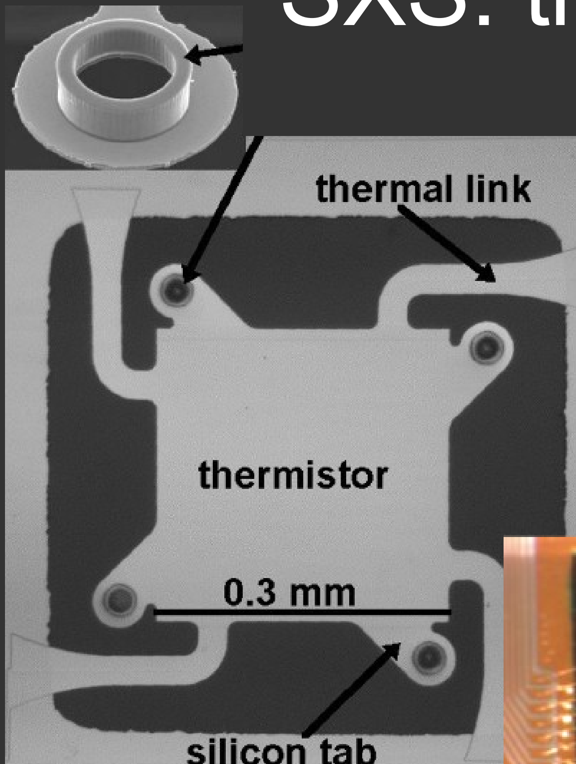
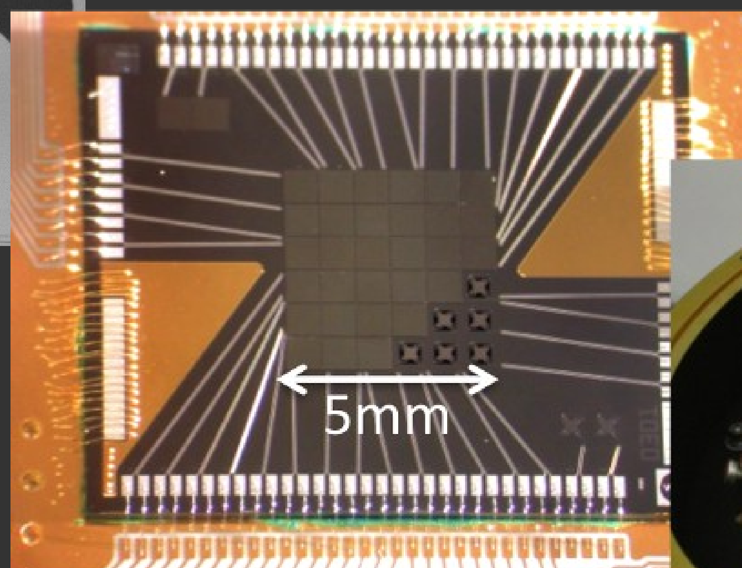
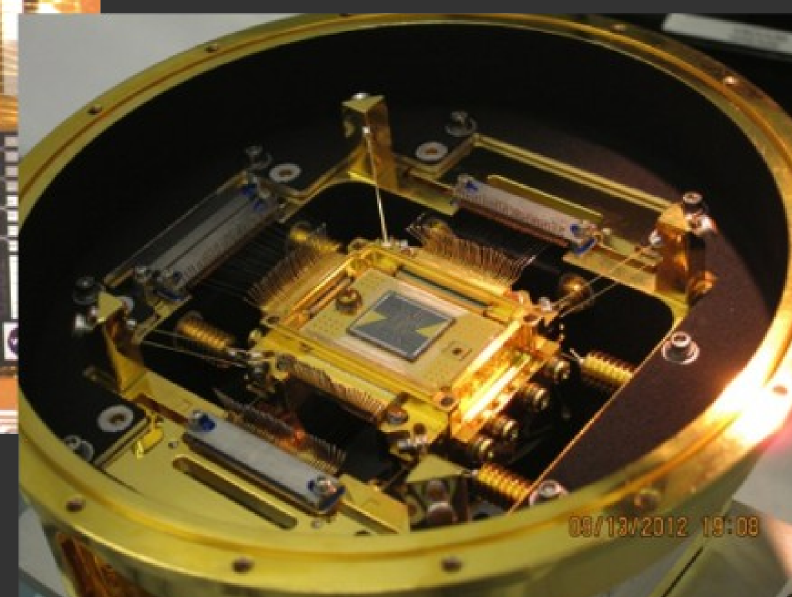






Images: R. Kelley, 2007

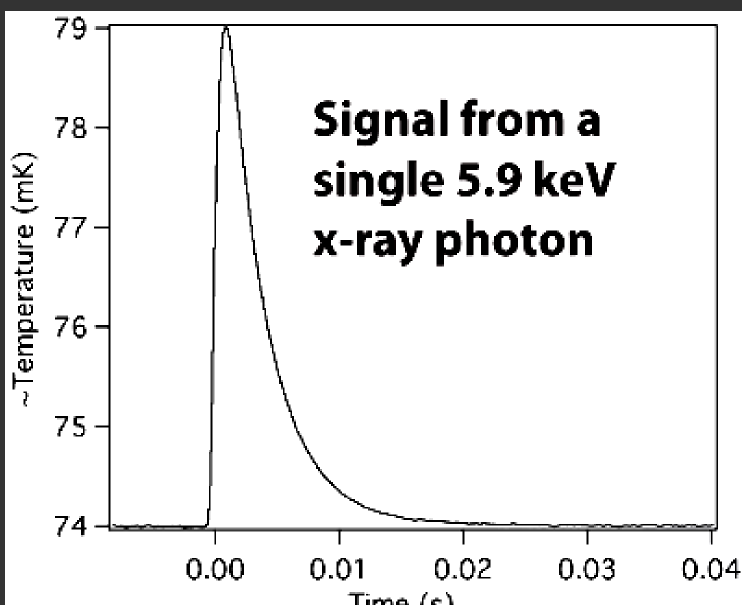
SXS: the soft X-ray spectrometer

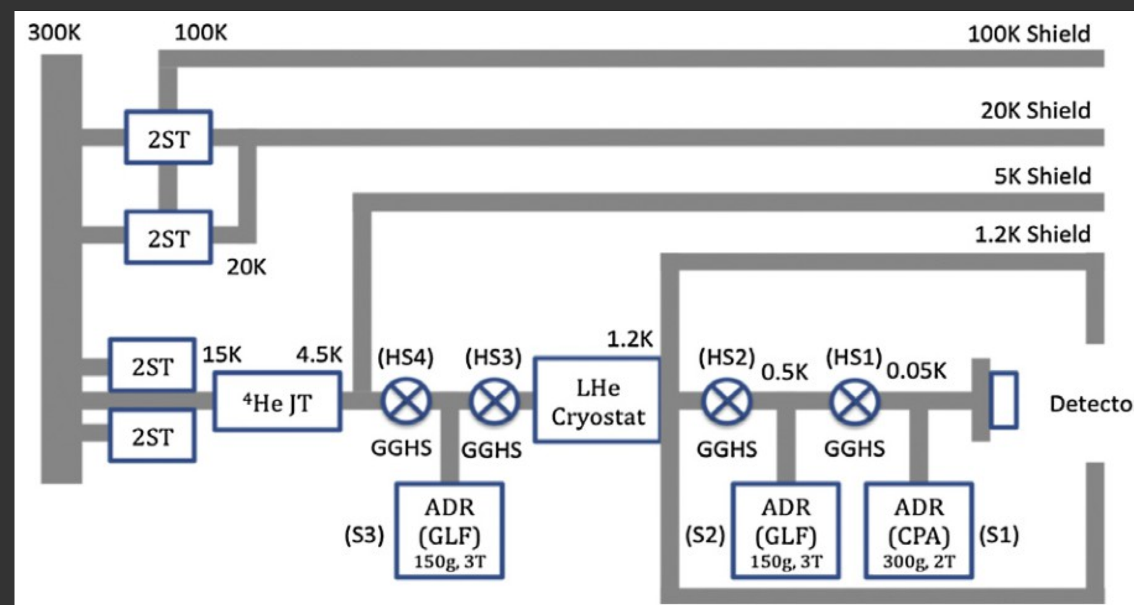
1) Absorber

2) Thermometer

3) **Heat sink & thermal reservoir**
- Life time (mech. cooler, liquide He)
- Redundancy
- Power management (540 W)
- Stability of operation: 90h / 32h

Thermal coupling
- Signal decay
- Count rate capability: 150 cnt/s





SXS: the soft X-ray spectrometer

1) Absorber

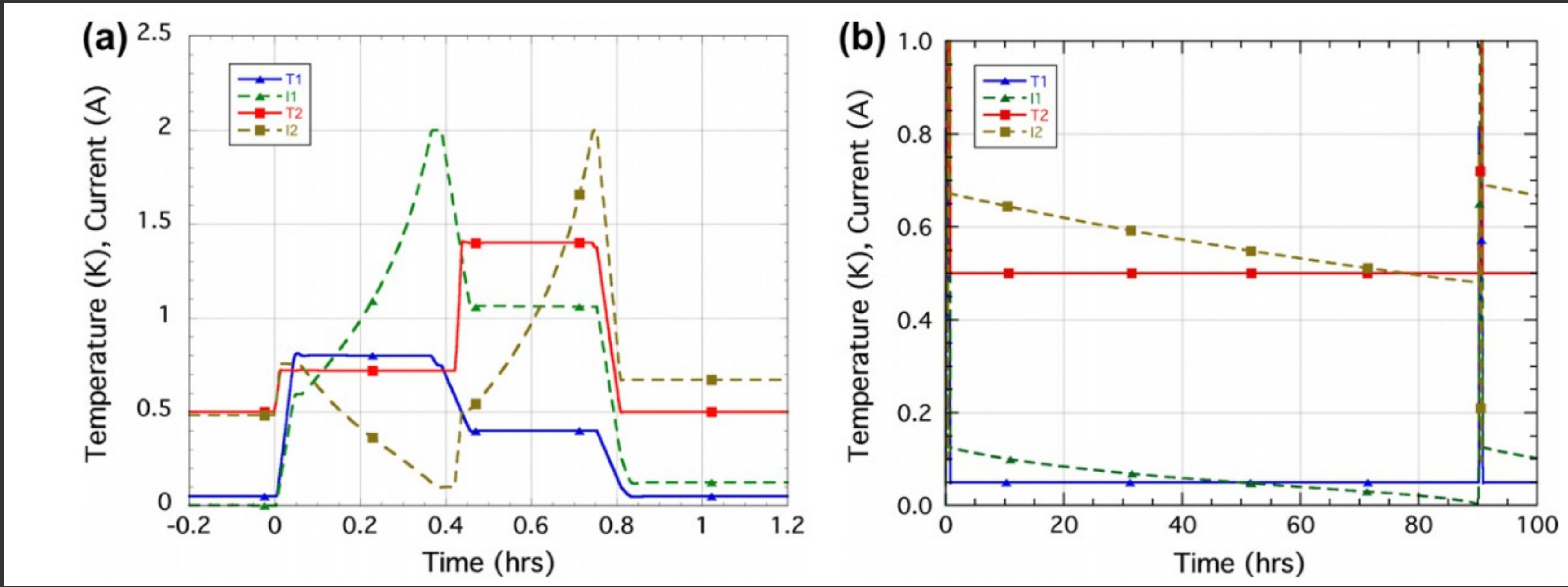
2) Thermometer

3) **Heat sink & thermal reservoir**

- Life time (mech. cooler, liquide He)
- Redundancy
- Power management (540 W)
- Stability of operation: 90h / 32h

Thermal coupling

- Signal decay
- Count rate capability: 150 cnt/s



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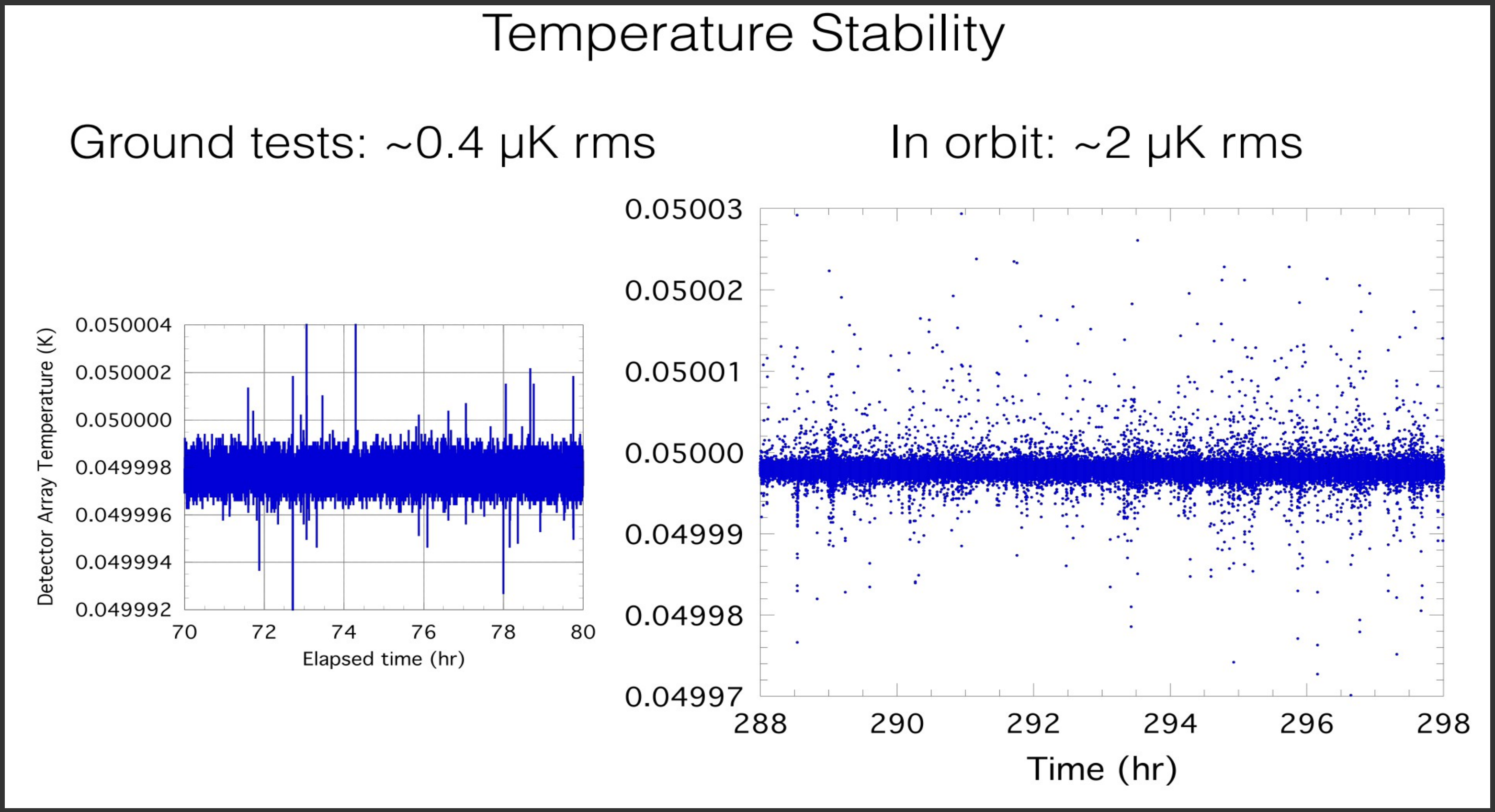
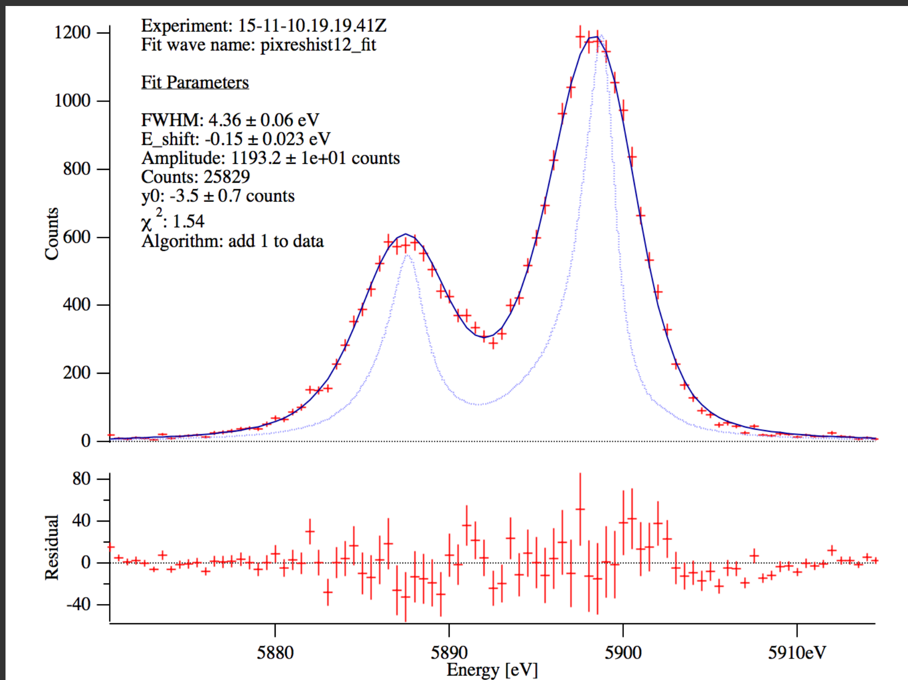
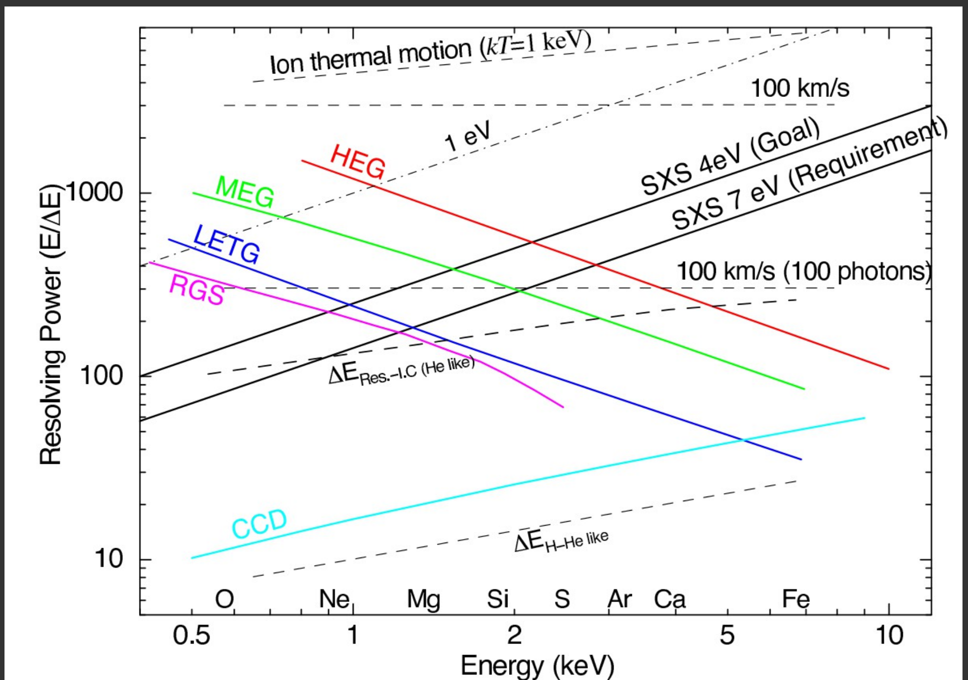


SXS: performance

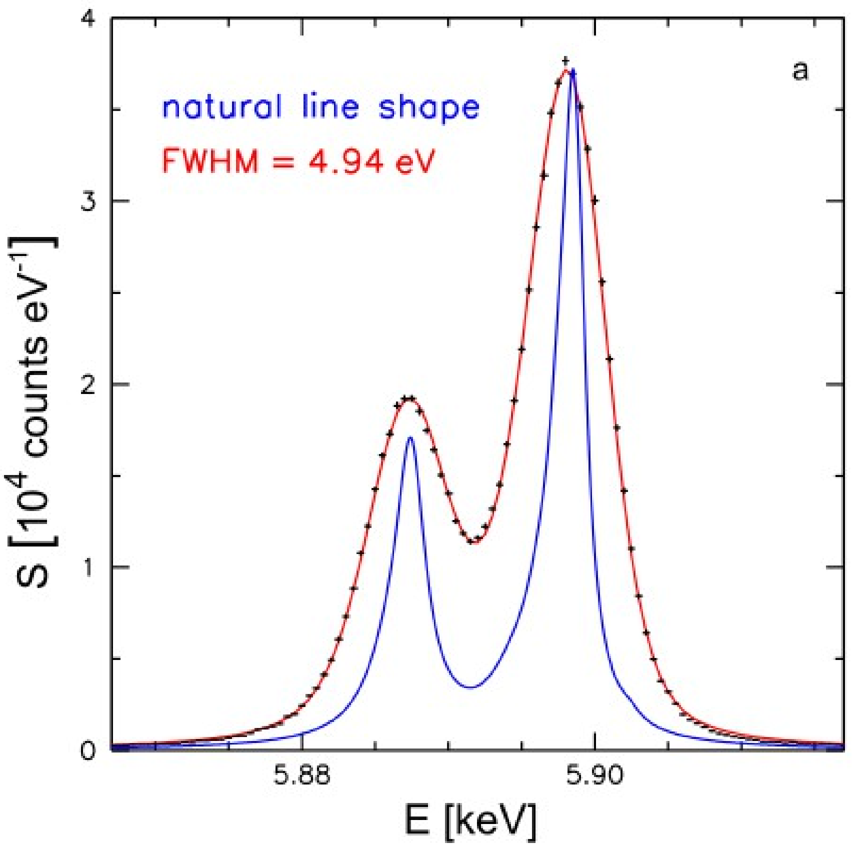


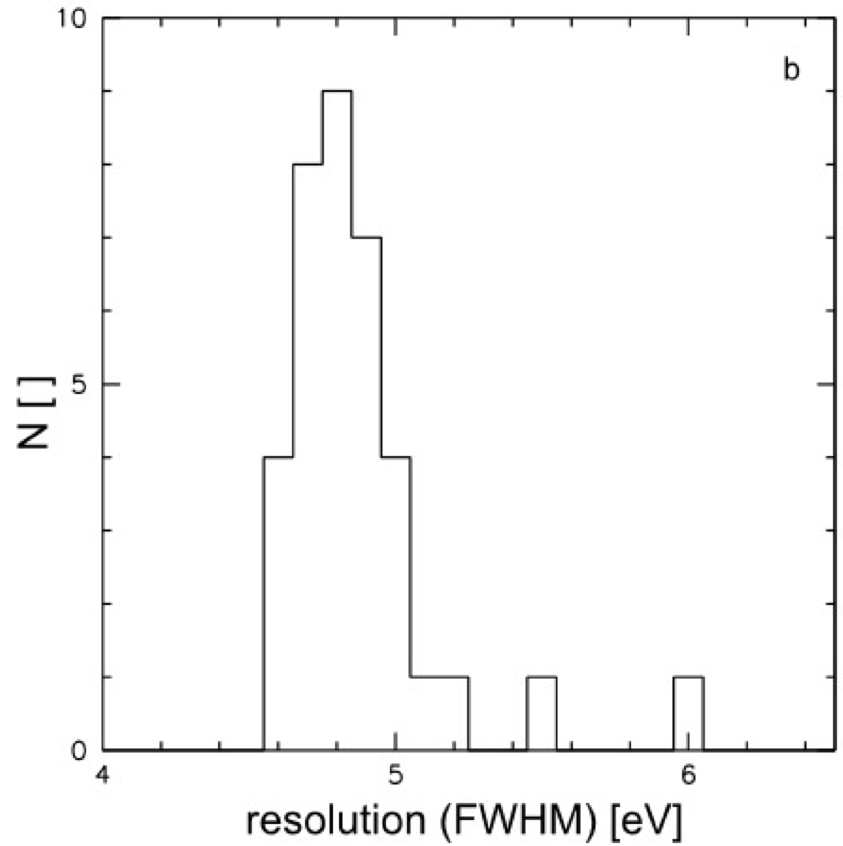


Spectroscopic resolution:
4.36 eV @ 5.9 keV

Unique spectroscopic capability in X-ray astronomy:
- High energy resolution
- High quantum efficiency
- Imaging

SXS: in-flight performance



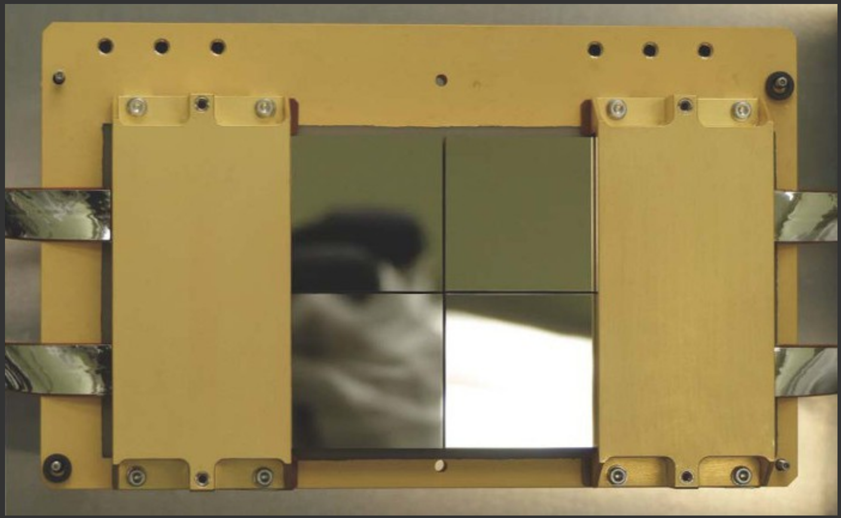


Spectroscopic resolution:
4.94 eV @ 5.9 keV

Two pixel show a slightly worse performance compared to laboratory measurements

SXI: the soft X-ray imager

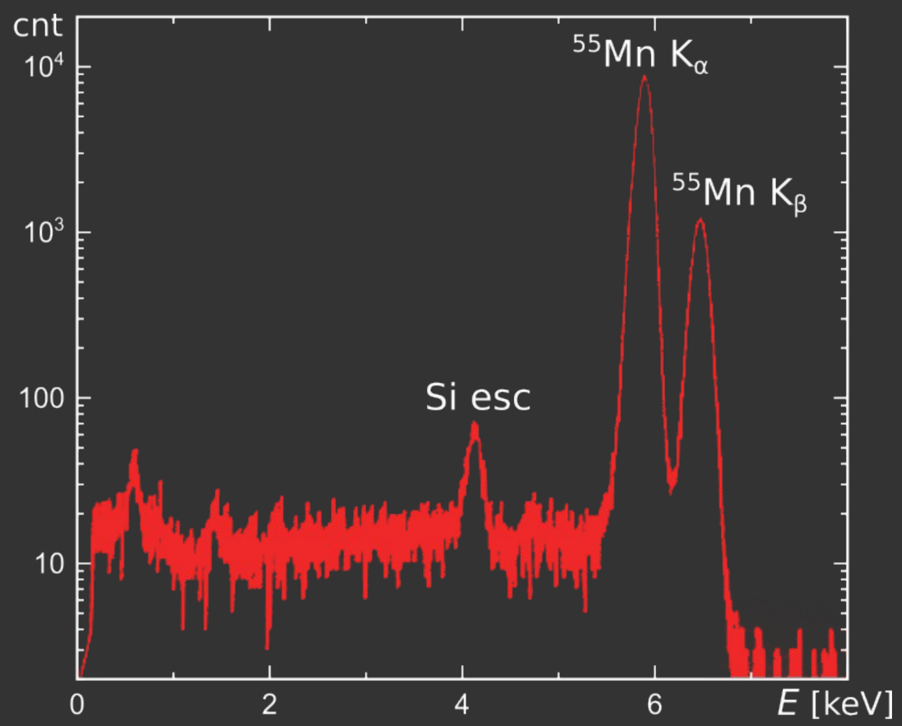
- Frame-store CCD camera 0.4-12 keV:
  - 4 CCD chips each 31 x 31 mm²
    - 1280 x 1280 pixel
    - 640 x 640 pixel (2x2 on-chip binning)
  - P-channel, back-illuminated
  - 200 µm Si
  - Frame time 4 s
  - T = -120°C
  - Wide FoV: 38' x 38'
  - 41 kg
  - SCI: spaced-row-charge injection: CTI = 10^{-5}



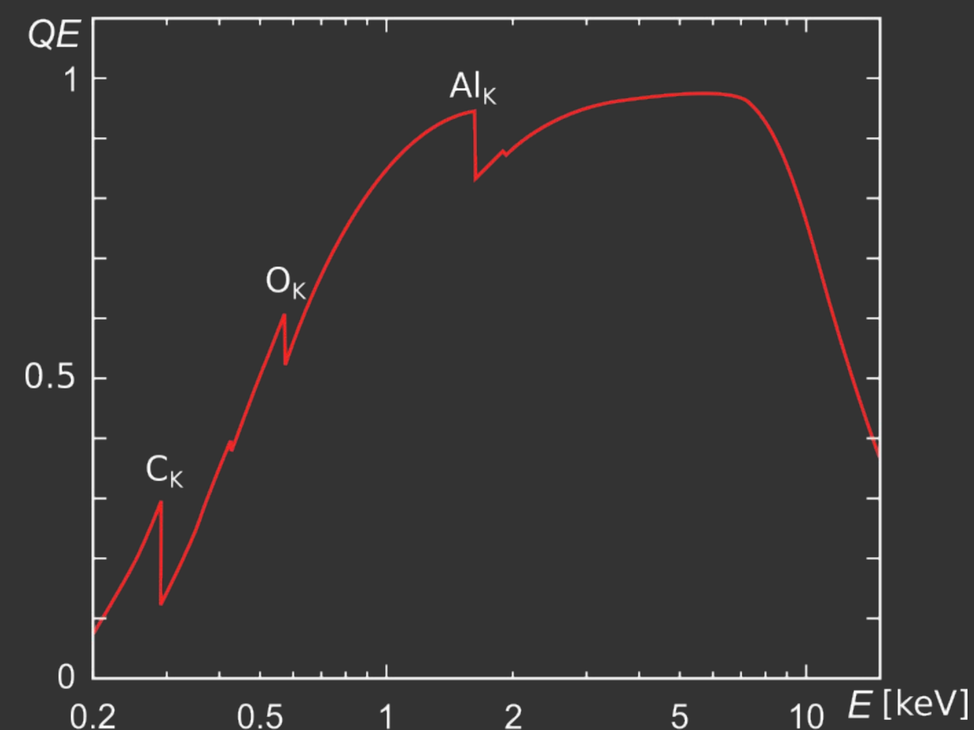
SXI: performance

- Reduced low energy tail
- Fully depleted substrate + thin entrance window
  → good response at low energies

ΔE = 160 eV @ 5.9 keV

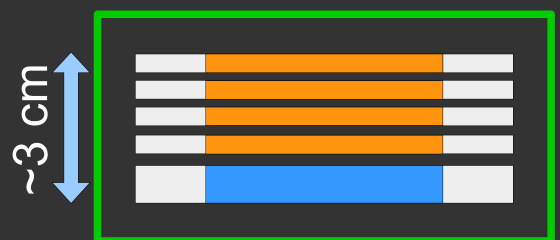


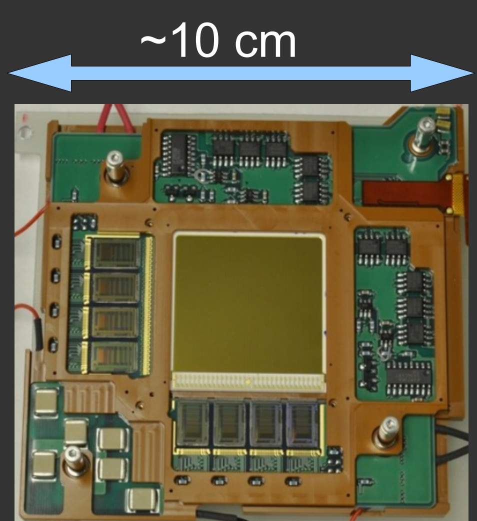
QE = 77% @ 10 keV

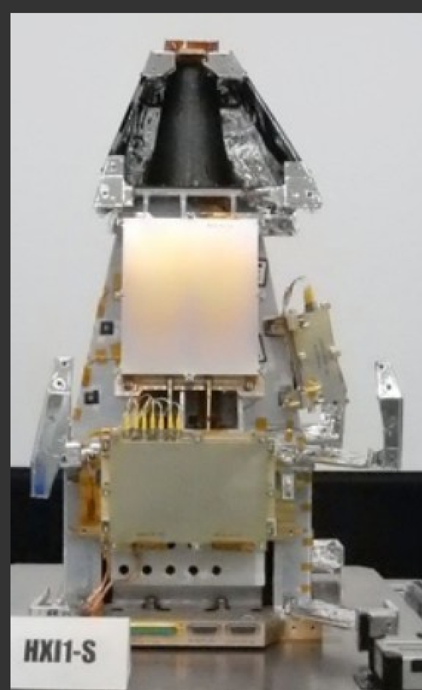


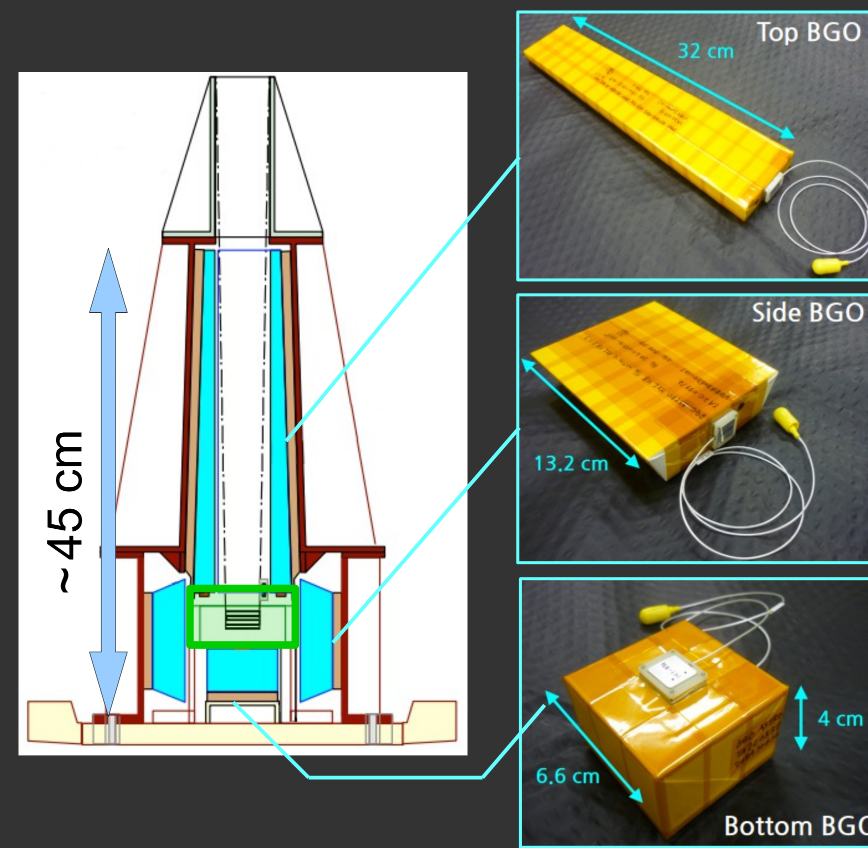
HXI: the hard X-ray imager

- A Si-CdTe detector stack 4-78 keV
  - 4 x 500 μm Si + 750 μm CdTe
  - Low background: BGO shield + APDs









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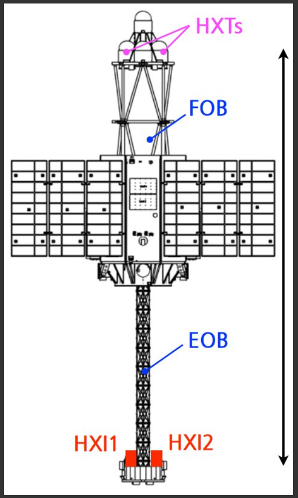
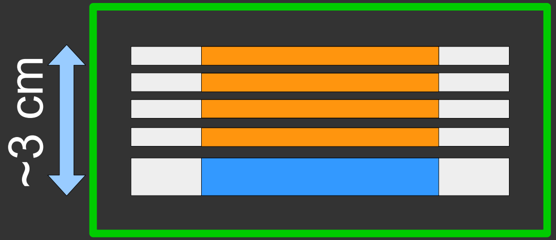
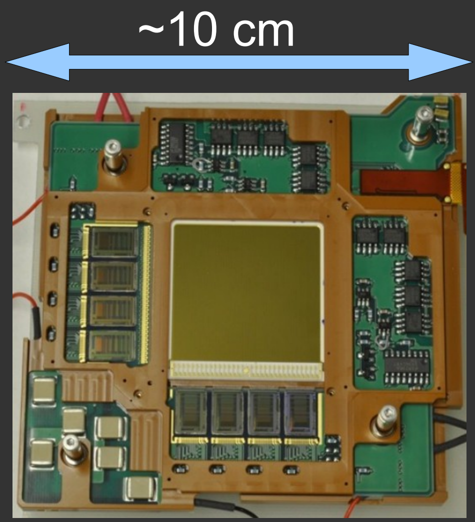
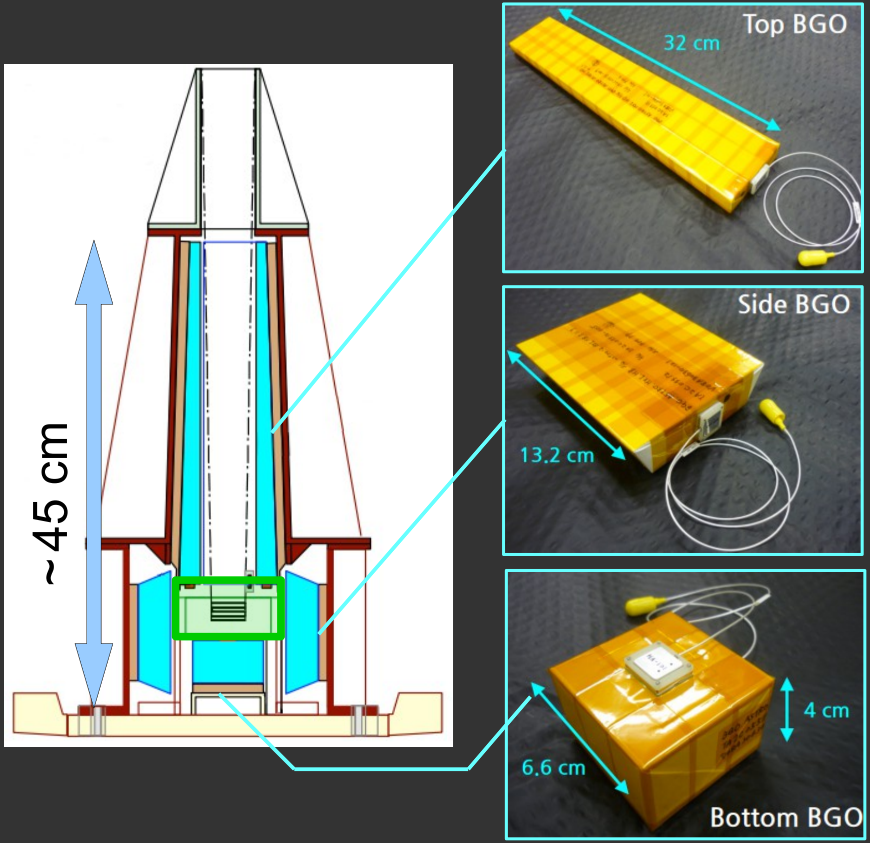


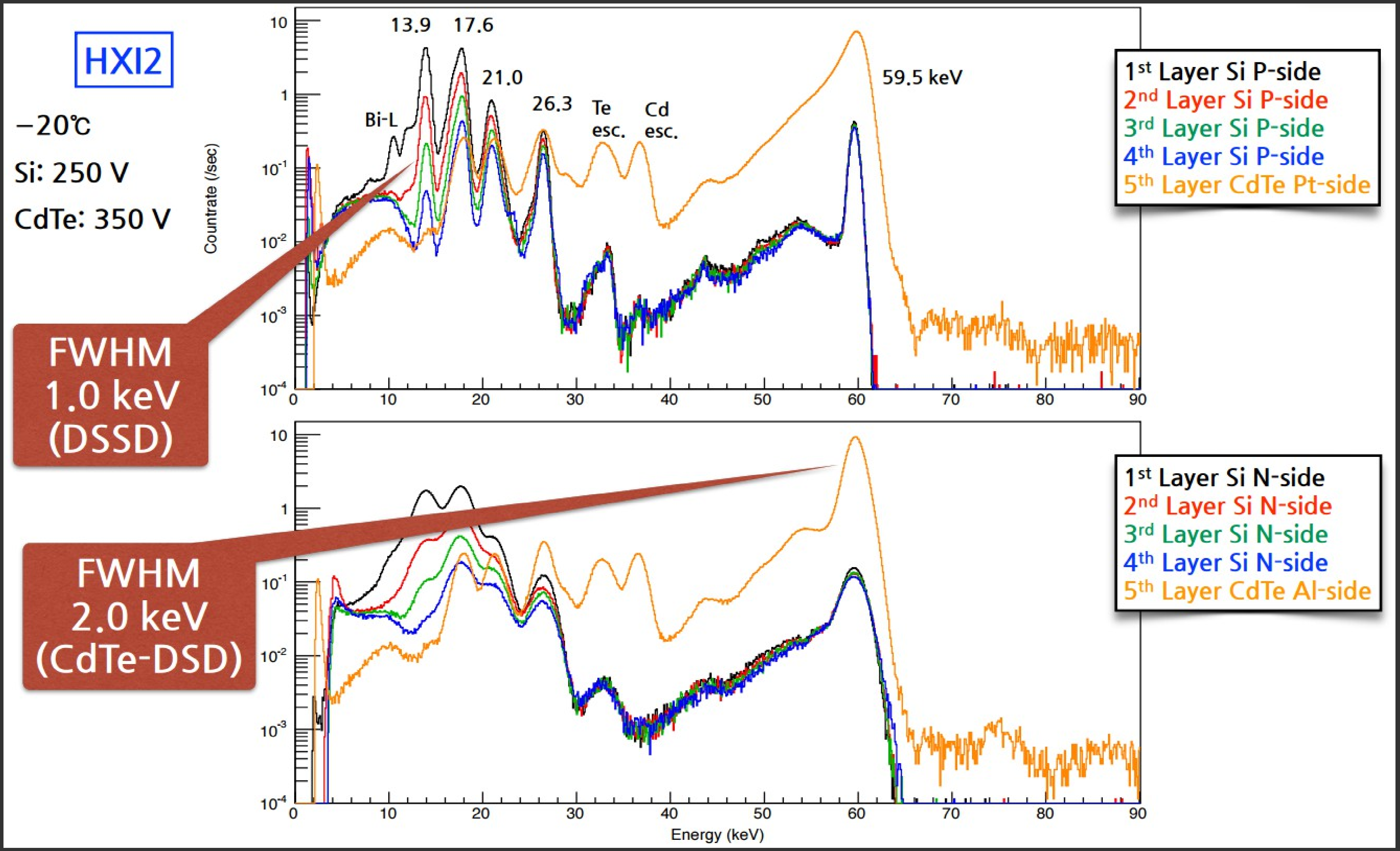






HXI: performance

^{241}Am

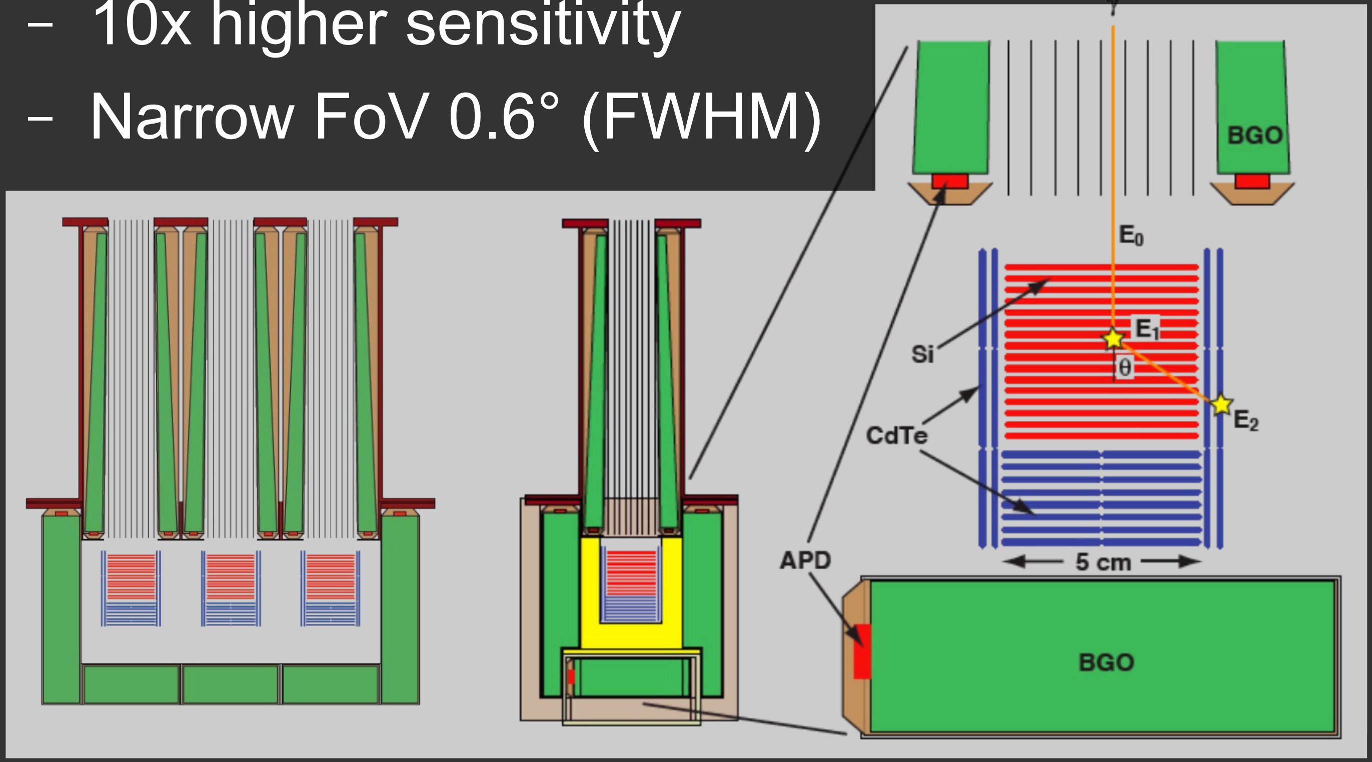


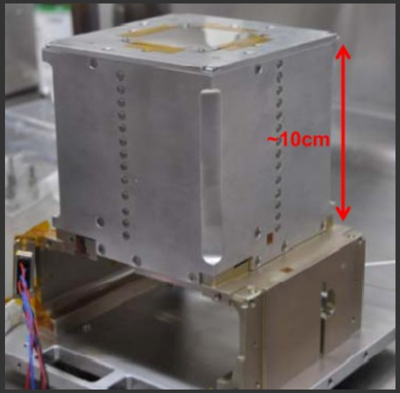
Sato et al., 2014

SGD: the soft gamma-ray detector

A multilayer Si-CdTe Compton telescope 60-600 keV

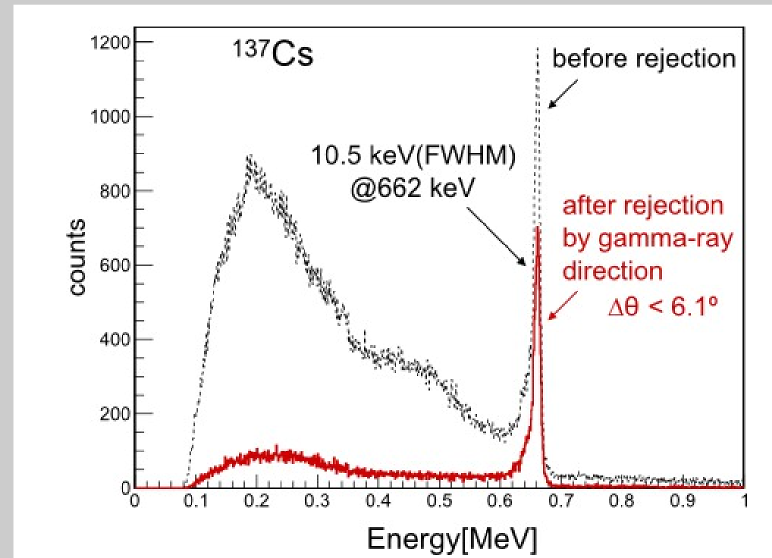
- Collimator + active shield (BGO+APDs) + Compton kinematics
  - Reduced background ~100 times less than HXD on Suzaku
  - 10x higher sensitivity
  - Narrow FoV 0.6° (FWHM)

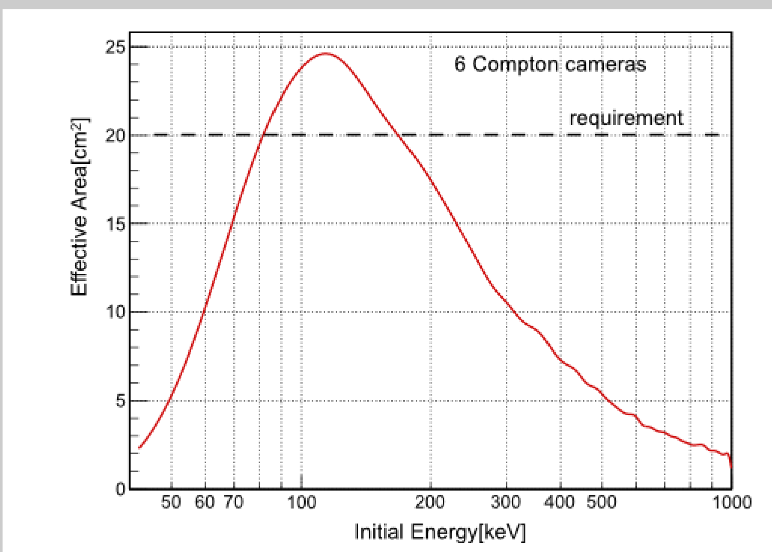




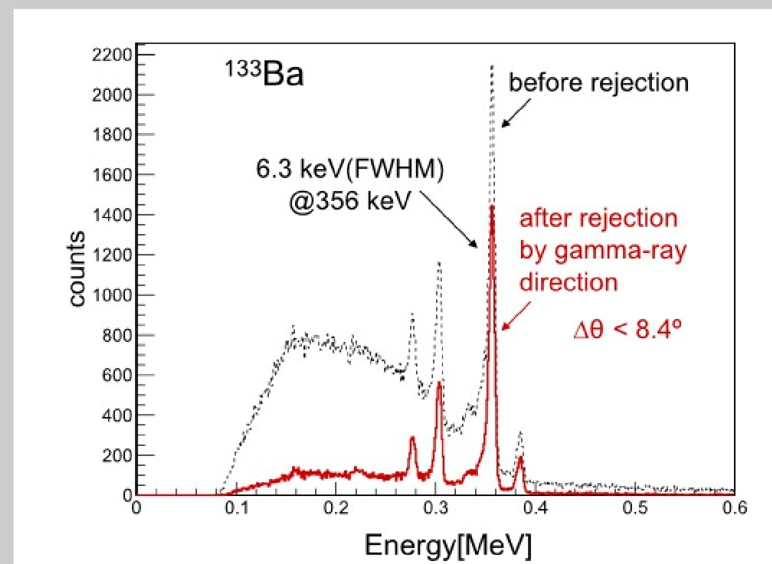
SGD: performance

- Broad band imaging spectrometer with low noise (< 2%) and low background
- Efficiency: 15% and 3% for 100 keV and 511 keV
- Spec. res.: 1-2 keV @ 60 keV
  1.6-2.5 keV @ 122 keV
  Compt. mode: 6.3 keV @ 356 keV





Fukazawa et al., 2014



Astro-H: instrumentation summary

- SXS: X-ray bolometer → RESOLUTION
- SXI: CCD → FIELD OF VIEW
- HXI: focusing hard X-rays → SENSITIVITY
  → POLARIMETRY
- SGD: narrow field Compton camera
  low background → SENSITIVITY
  stacked detector → POLARIMETRY

A spectroscopic search for dark matter

- Sterile neutrino is one candidate to look for
- Decay with a very long lifetime
  → (weak) X-ray emission line → intensity I; energy width ΔE; centroid energy E

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→ I:

Kitayama et al. 2014

$$I = \frac{\Sigma_{dm}}{4\pi(1+z)^3}\frac{\Gamma}{m_{dm}}$$

$$9.3 \times 10^{-5} \mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1} \frac{1}{(1+z)^3} \frac{\Sigma_{dm}}{10^3 M\ \mathrm{pc}^{-2}} \frac{\Gamma}{10^{-32}\ \mathrm{s}^{-1}} \frac{m_{dm}}{\mathrm{keV}}^{-1}$$

Σ_{dm} mass column density
m_{dm} mass of dm particle
Γ decay rate
z redshift

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$$\Delta E_0 = 7.9\,\mathrm{eV}\;\frac{\sigma_{dm}}{1000\,\mathrm{km/s}}\;\frac{E_0/(1+z)}{\mathrm{keV}}$$

$$\Delta E = \Delta E_0 * \Delta E_{det}$$

Σ_{dm}	mass column density
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Kitayama et al. 2014

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→ E:

$$E_0 = 0.5\, m_{dm}\, c^2$$

$$E = E_0 / (z+1)$$

Σ_{dm}	mass column density
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σ_{dm}	velocity dispersion

DM search: sources

Milky Way

+ 'strong' decay signal
+ moderate velocity dispersion
- high absorption colum density
- bright background X-ray emission near GC
- uncertainty in the dark matter mass profile towards the GC

Astro-H PV phase:
- GC

(nearby) Galaxy clusters

+ 'strong' decay signal
+ better knowledge of mass profile
+ lower absorption colum densities
+ test different redshifts
o large velocity disperisions
- bright thermal X-ray emission from Intracluster plasma

Astro-H PV phase:
- Perseus
- Coma
- Virgo

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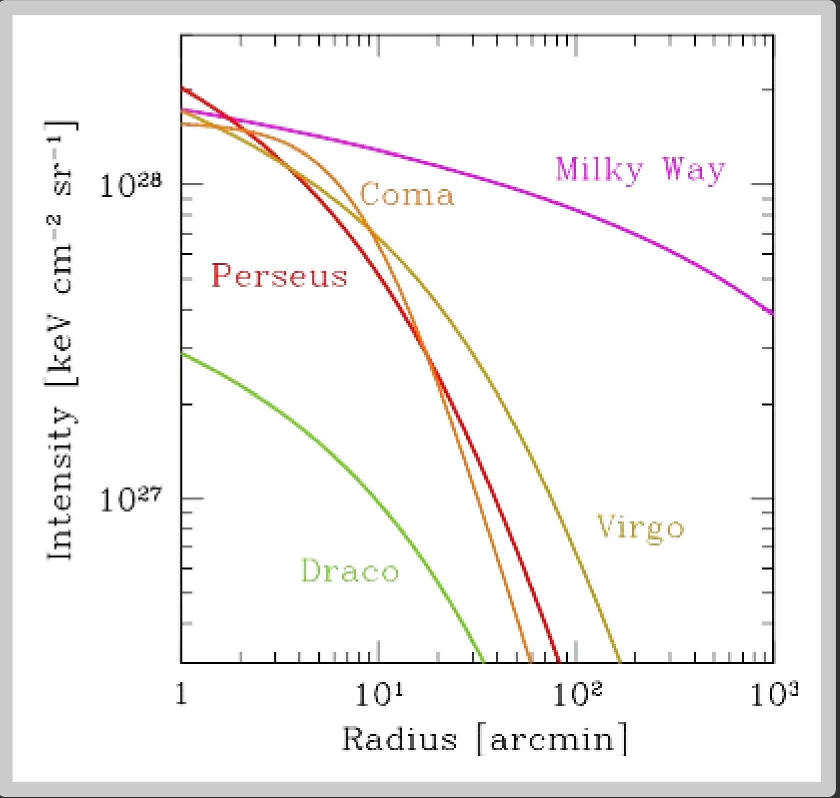
Astro-H PV phase:
- GC

Dwarf spheroidal sattelite galaxies of the MW

+ low velocity dispersion
+ no background plasma emission
- weak decay signal



Kitayama et al. 2014

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Astro-H PV phase:
- Perseus
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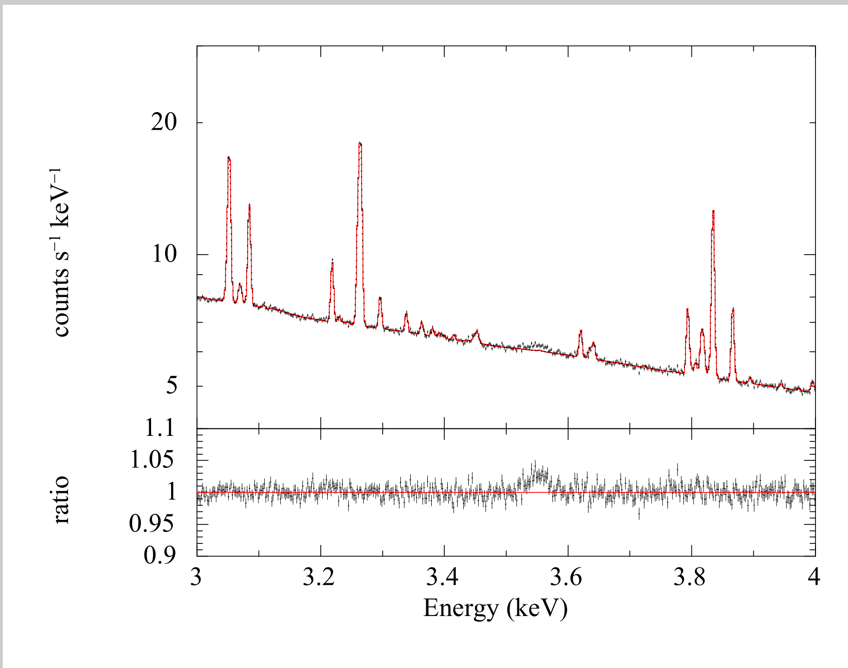
DM search: simulations

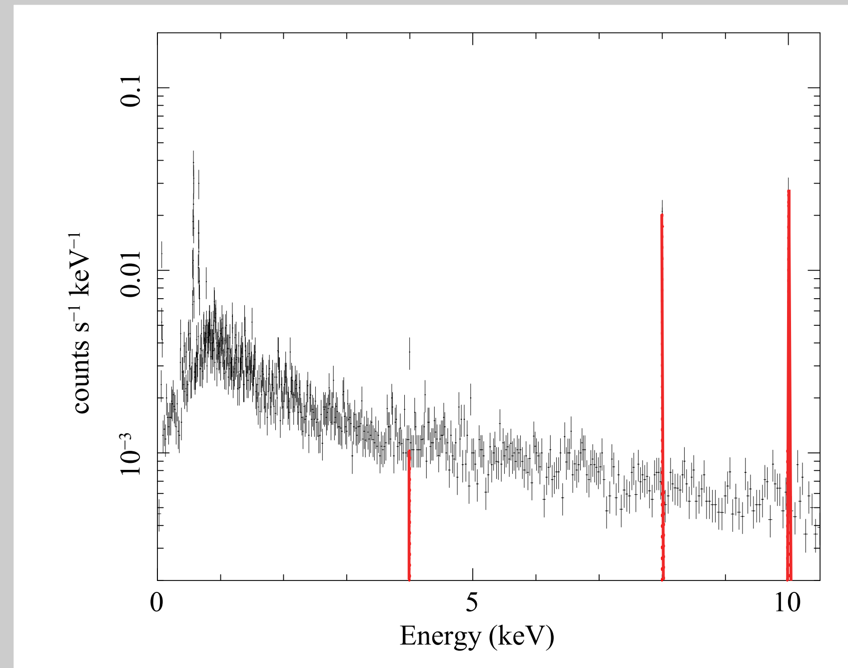
Perseus cluster (z=0.0178)



Kitayama et al. 2014

Simulation:
1 Ms exposure SXS
E_0 = 3.55 keV with
F = $3*10^{-5}$ ph/s/cm²
σ = 1300 km/s → ΔE_0 = 35 eV

Typical local dwarf spheroidal



Kitayama et al. 2014

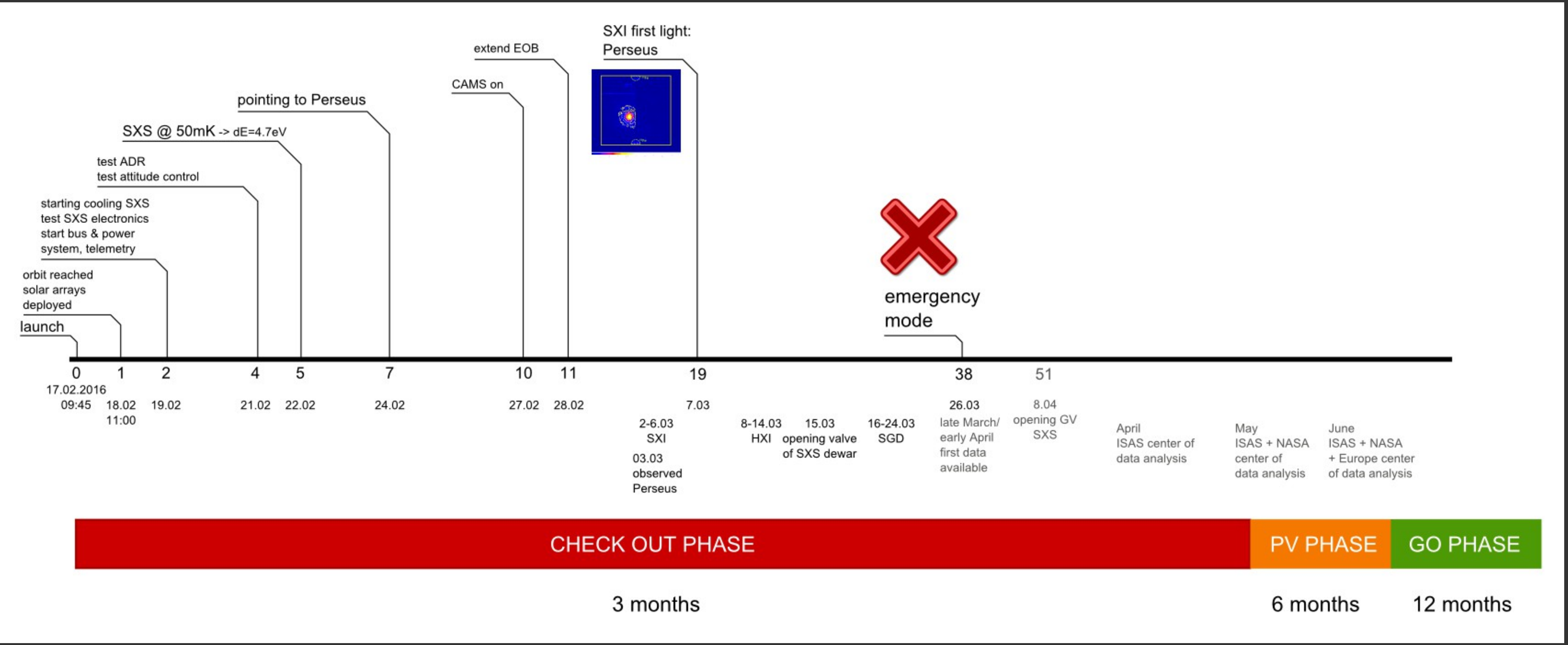
Simulation:
1 Ms exposure SXS
E_0 = 4 / 8 / 10 keV with
F = 0.04 / 0.65 / 1.6 $*10^{-6}$ ph/s/cm²
σ ≈ 20 km/s → ΔE_0 ≈ 1 eV

Status: Astro-H -> Hitomi

- Launch: 17. Feb. 2016, Tanegashima Space Center

Status: Astro-H -> Hitomi

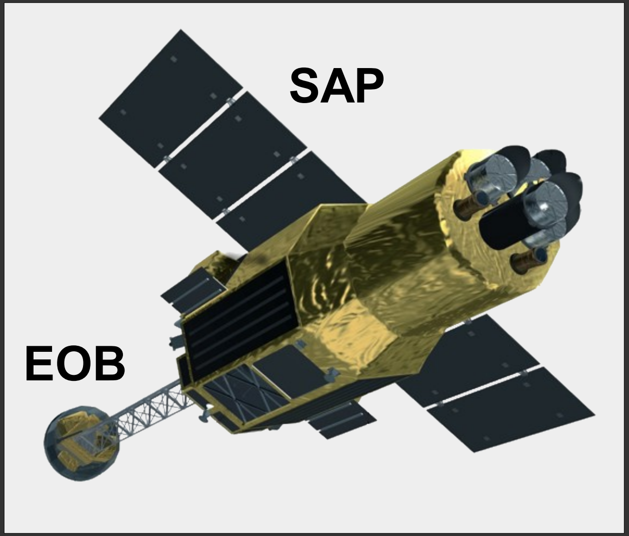
- Launch: 17. Feb. 2016
  - 3 months check out
  - 6 months PV + 12 months GO



Hitomi: failure scenario

- What happend?

  Rotation anomaly caused the separation of the Solar Array Paddles and Extendable Optical Bench



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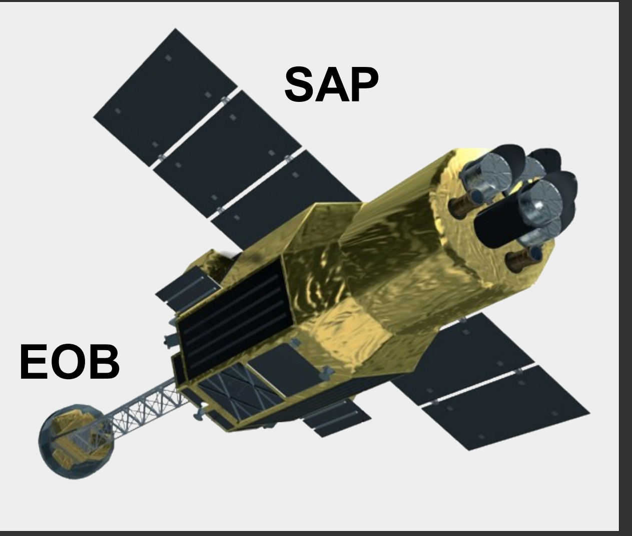
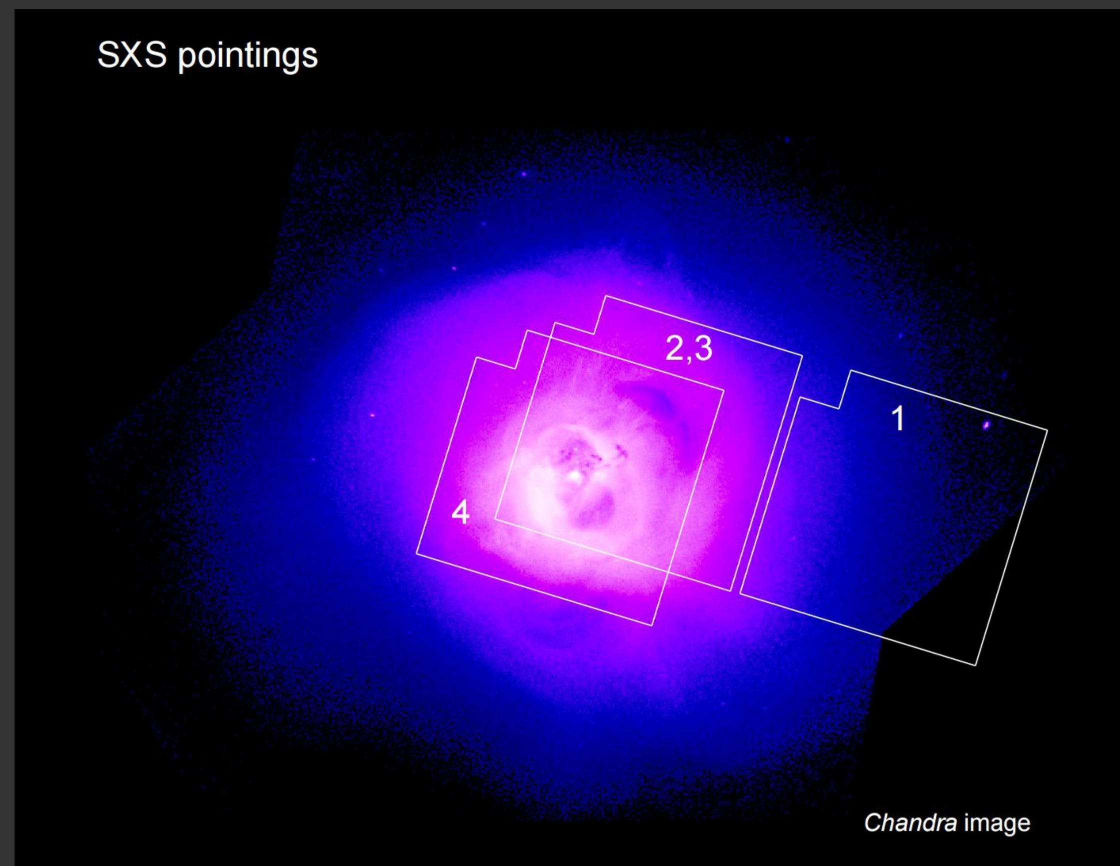


- Why? Attitude Control System error
  - Incorrect determination of the attitude (~20°/h) → correction (reaction wheels) caused actual rotation
  - Safe mode: ACS sets inappropriate truster commands → rotation accelerates until separation of SAP and EOB

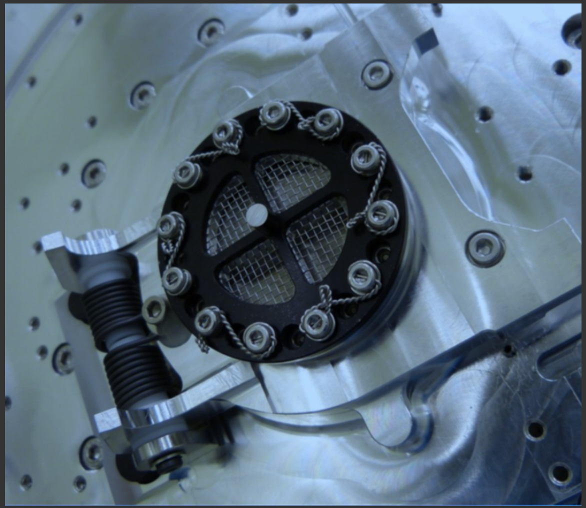
Perseus observation:

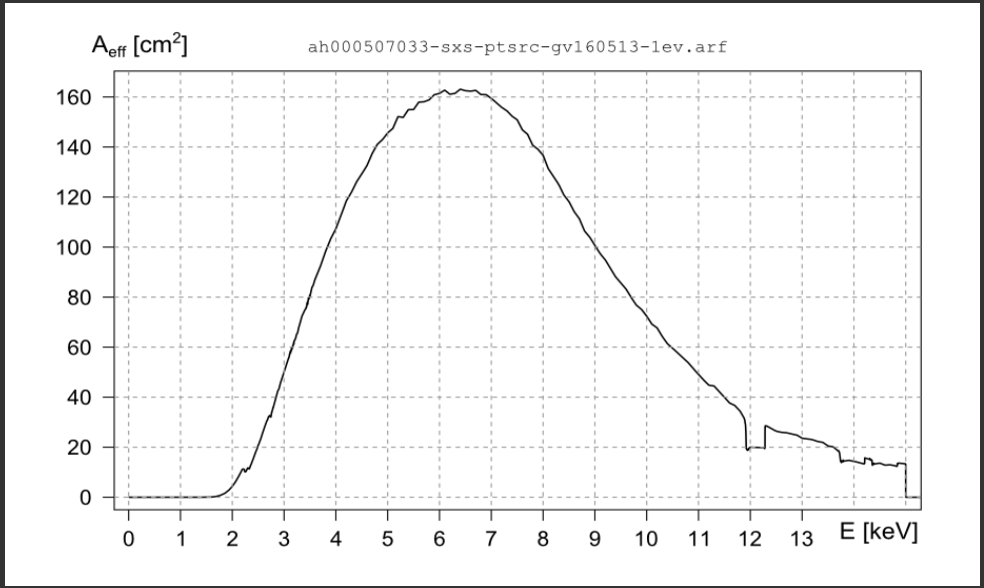
- 4 times during calibration phase of Astro-H:
  - Obs 1: missalignment
  - Obs 2 + 3:
    - 236 ks in total
    - 60 ks effective @ 3.5 keV because of closed gate valve
  - Obs 4: 70 ks (18 ks effective)

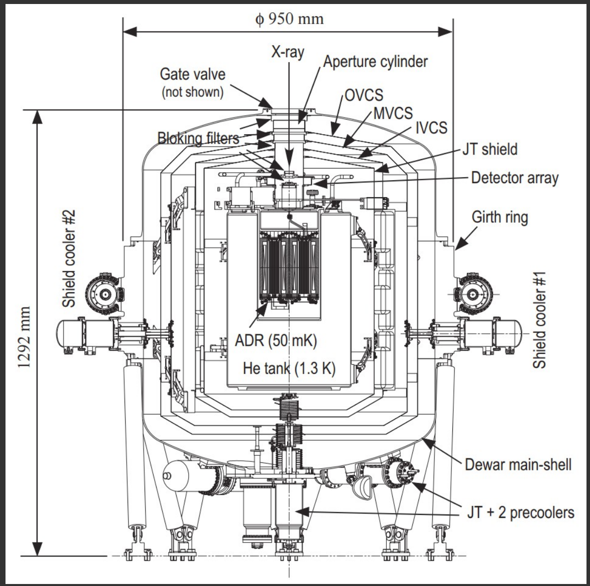


Perseus observation: we are looking through the gate valve!

- Gate valve
  - Protecting the cold inner parts of the SXS from condensation of out-gasing material at the beginning of the mission.
  - New model using Crab + G21.5 observations: 300 um ⟶ 270 um thick Be window







Summary

- All instruments were working very well during the check out phase of ASTRO-H
- ASTRO-H cannot be recovered
- There are ~60 ks of Perseus data

Additional informations:

- Instruments:
  - The ASTRO-H X-ray Astronomy Satellite, Takahashi et al., 2014, SPIE
  - ASTRO-H Soft X-ray Telescope (SXT), Soong et al., 2014, SPIE
  - ASTRO-H Hard X-ray Telescope (HXT), Awaki et al., 2014, SPIE
  - Soft x-ray Spectrometer (SXS): the high-resolution cryogenic spectrometer onboard ASRTO-H, Mitsuda et al., 2014, SPIE
  - The Suzaku High Resolution X-Ray Spectometer, Kelley et al., 2014, PASJ
  - Soft X-ray Imager (SXI) onboard ASTRO-H, Hayashida et al., 2014, SPIE
  - The Hard X-ray Imager (HXI) for the ASTRO-H mission, Sato et al., 2014, SPIE
  - Soft Gamma-ray Detector (SGD) onboard ASTRO-H, Fukazawa et al., 2014, SPIE
- Science:
  - 16 Astro-H white papers:
    - Kitayama et al., 2014: Cluster of Galaxies and related science