Neutron star matter in view of nuclear experiments and astronomical observations
October 25, 2013

The ASTRO-H mission and prospects for constraining the mass-radius relation of a neutron star

T. Dotani (ISAS/JAXA)

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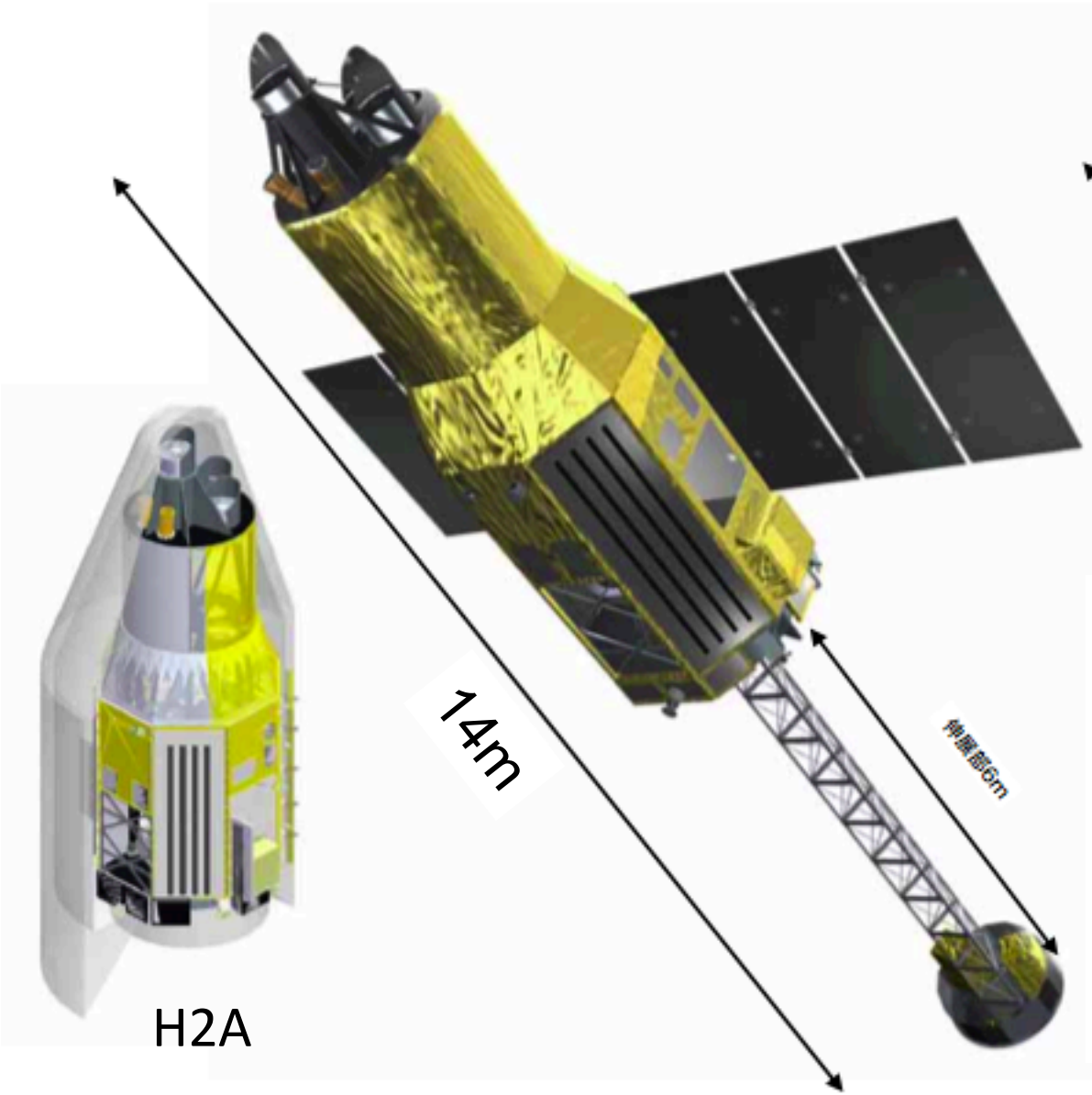
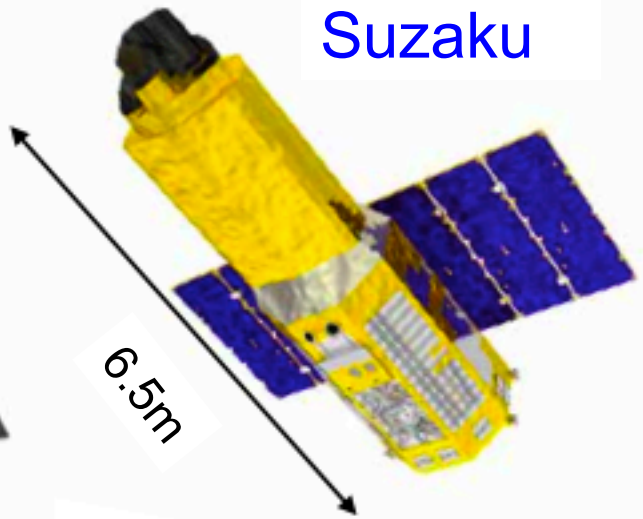
ASTRO-H





- Length :14 m
- Weight : 2.7 t
- Power : 3500 W
- Telemetry : 8Mbps (X-band)
- Data Recorder : 12 Gbits
- Launch : 2015
- Life : 3 year (requirement)
  5 year (goal)

ASTRO-H mission instruments

Sunshades

X-rays

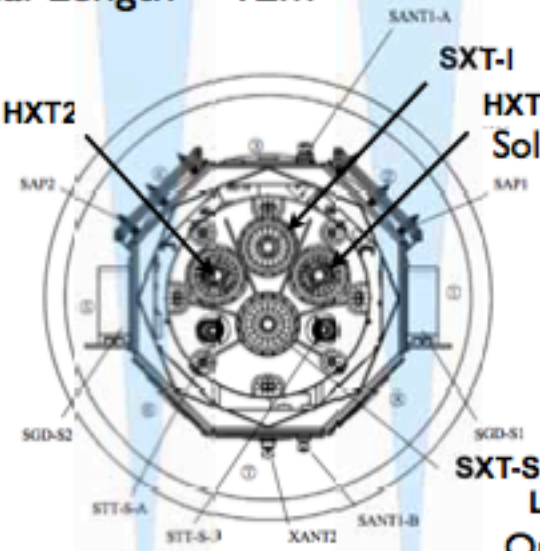
Hard X-ray Telescopes
(*HXT*)

Fixed
Optical
Bench

Soft X-ray Telescopes
(*SXT-S*, *SXT-I*)

Focal Length = 12m

Focal Length = 5.6 m

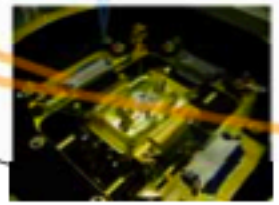


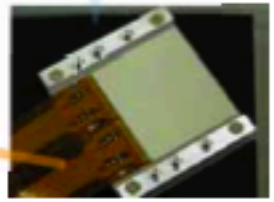
Solar power

Microcalorimater
(*SXS*)

X-ray CCD
(*SXI*)

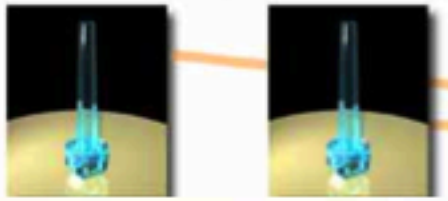
Radiator

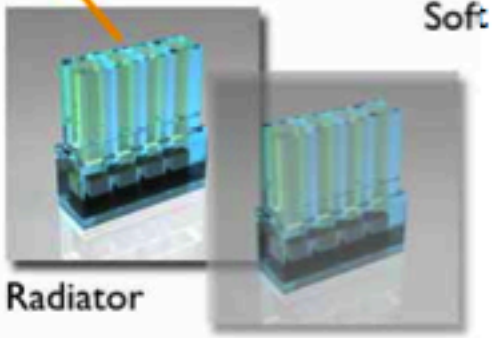




Deployable
Optical Bench

Hard X-ray Imagers
(*HXI*)

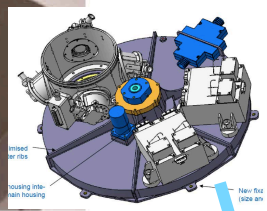




Soft γ-ray detectors
(*SGD*)

Radiator

Soft X-Ray Spectrometer (SXS)



Filter wheel

Soft X-Ray Telescope

5.6 m focal length – *fixed optical bench*

203 concentric shells (1624 individual reflectors)

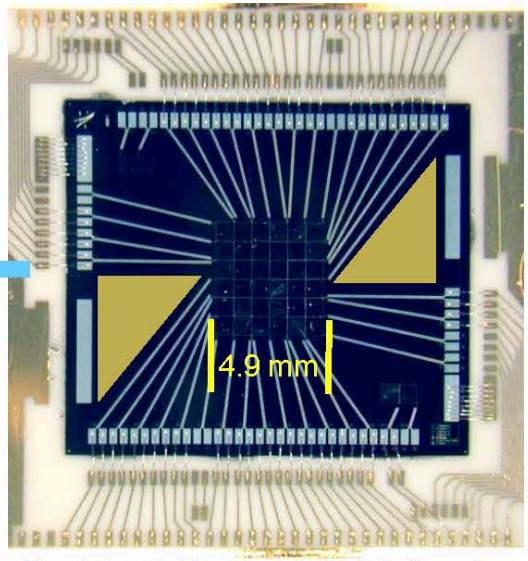
Outer Diameter: 45 cm
Mass: CBE = 46 kg

Half-Power Diameter of better than 1.7 arcmin

X-ray Calorimeter Spectrometer

SXS – energy resolution better than 7 eV at system level

6 x 6 array of 30” x 30” pixels (3 arcmin field of view)

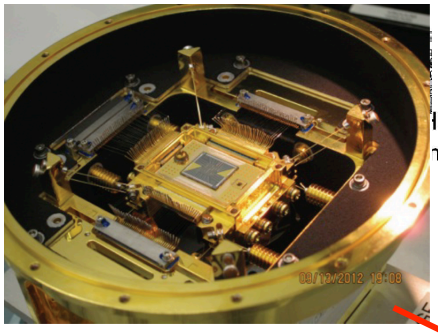


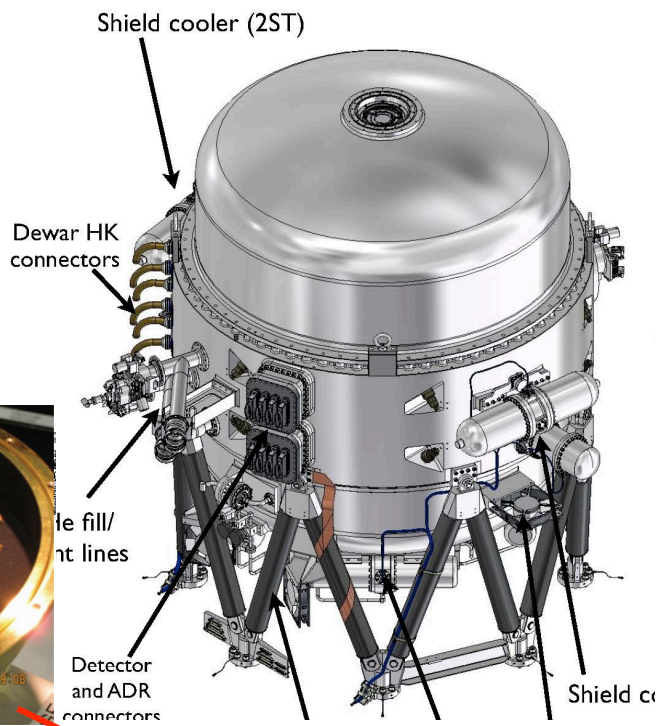
Goddard Space Flight Center

SXS: cooling chain

Cooling system

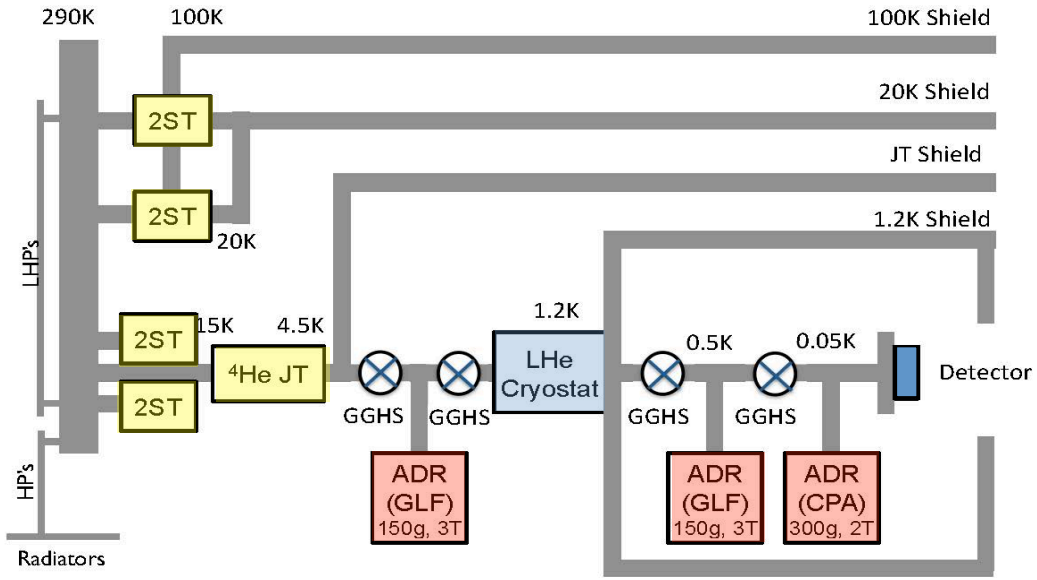
- Detector temp : 50 mK
- 2 ADR + LHe + JT + ST

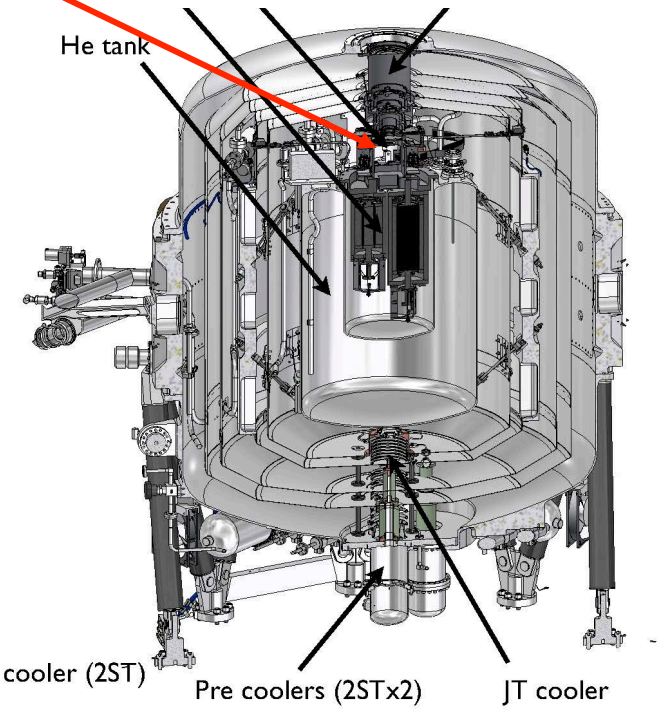




Life

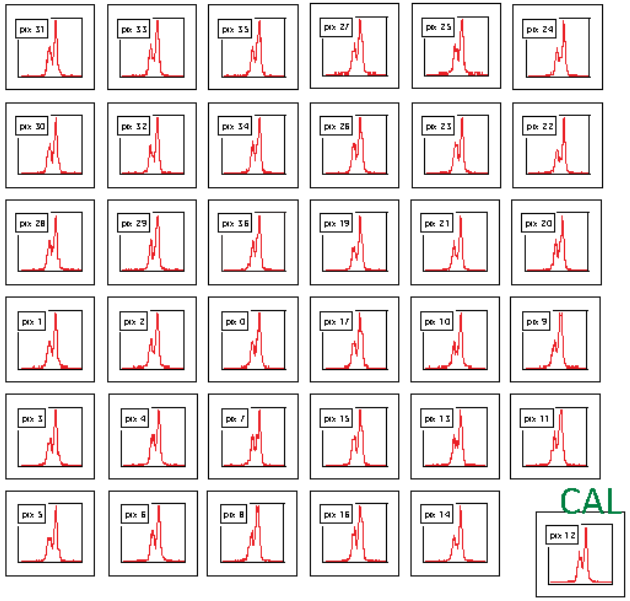
- 3 years with LHe
- 2 more years without LHe





Performance of SXS

All 36 channels by location

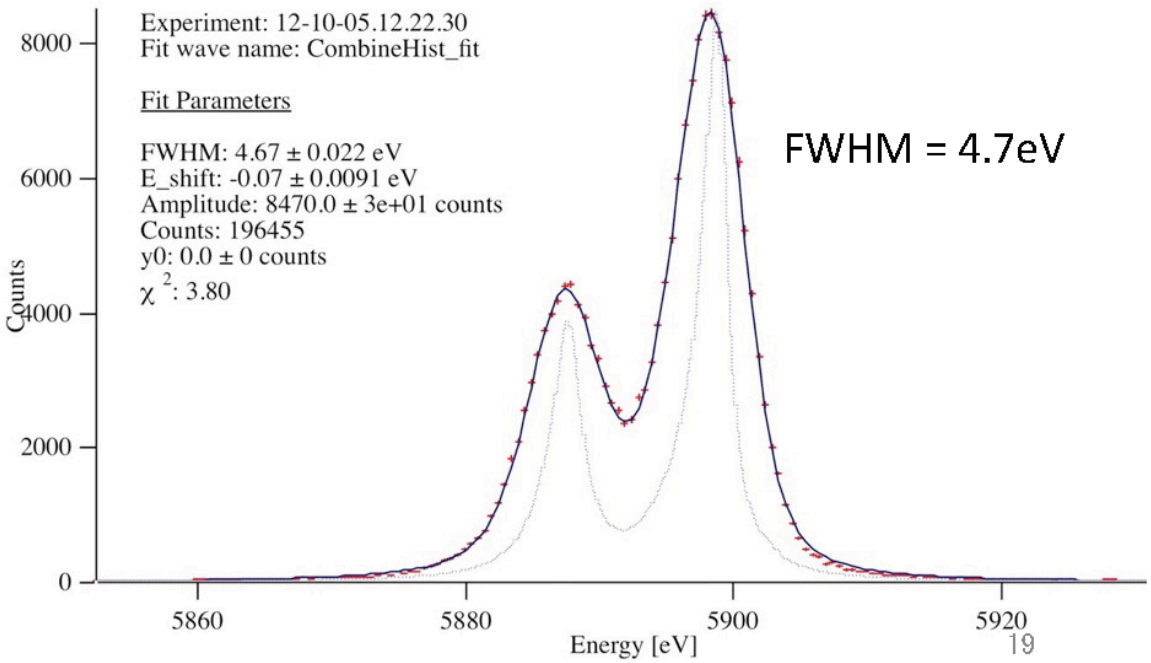


- FM detector system calibration campaign

Oct 2012 – Feb 2013, GSFC/NASA

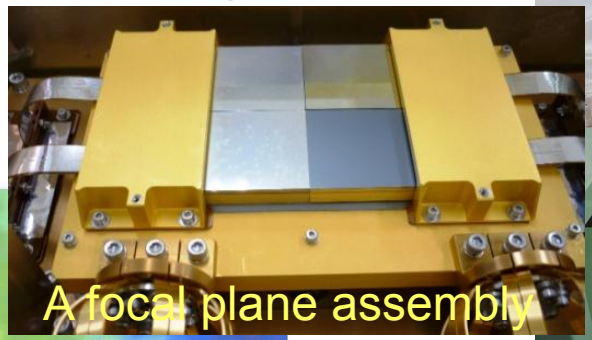
All pixels meet requirement < 7eV

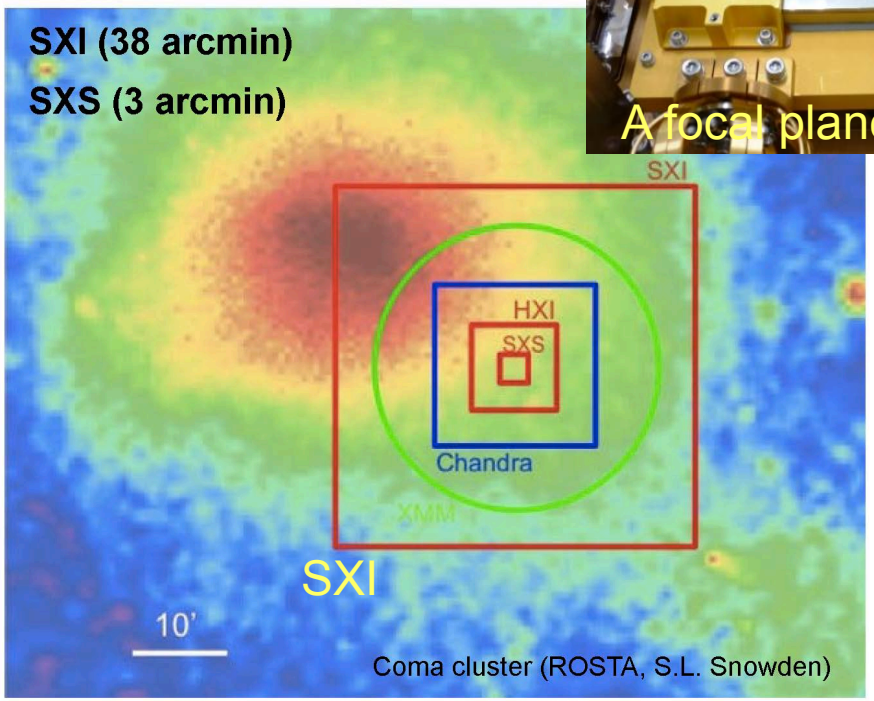
Composite fit to all 36 channels



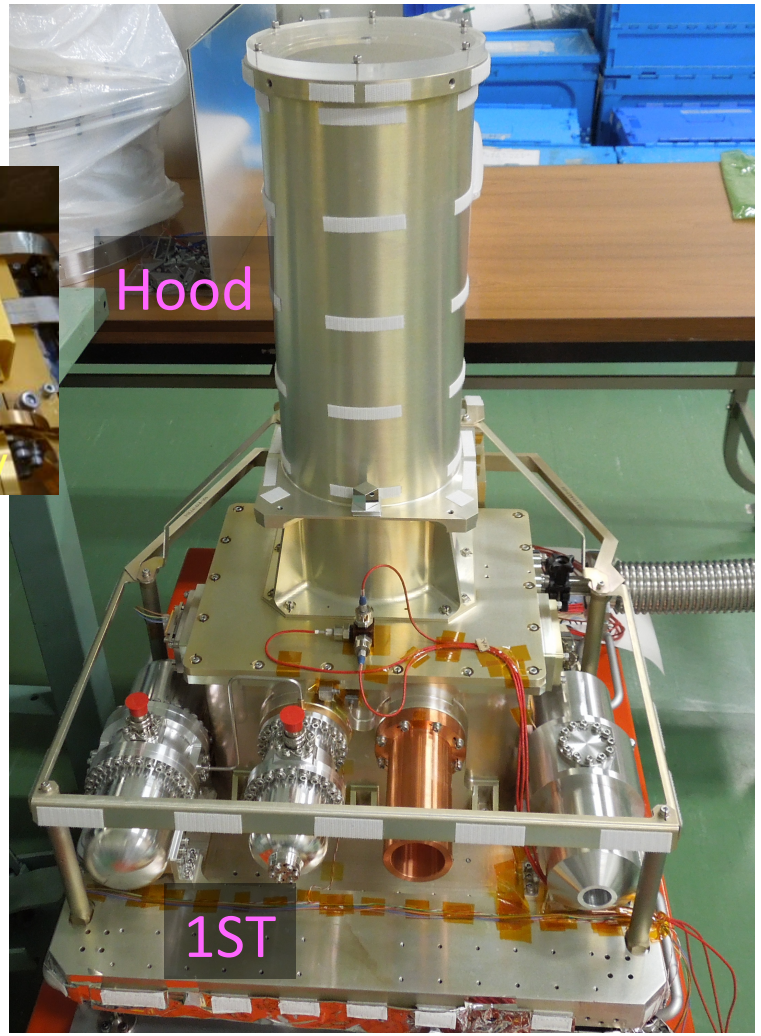
SXI: X-ray CCD camera

- 4 CCD chips with 31x31mm
- Depletion layer: 200μm
- Type: Back-illumination
- Operating temp.: -120 - -100 degC
- Exposure time: 4 sec
- FOV: 38x38 arcmin

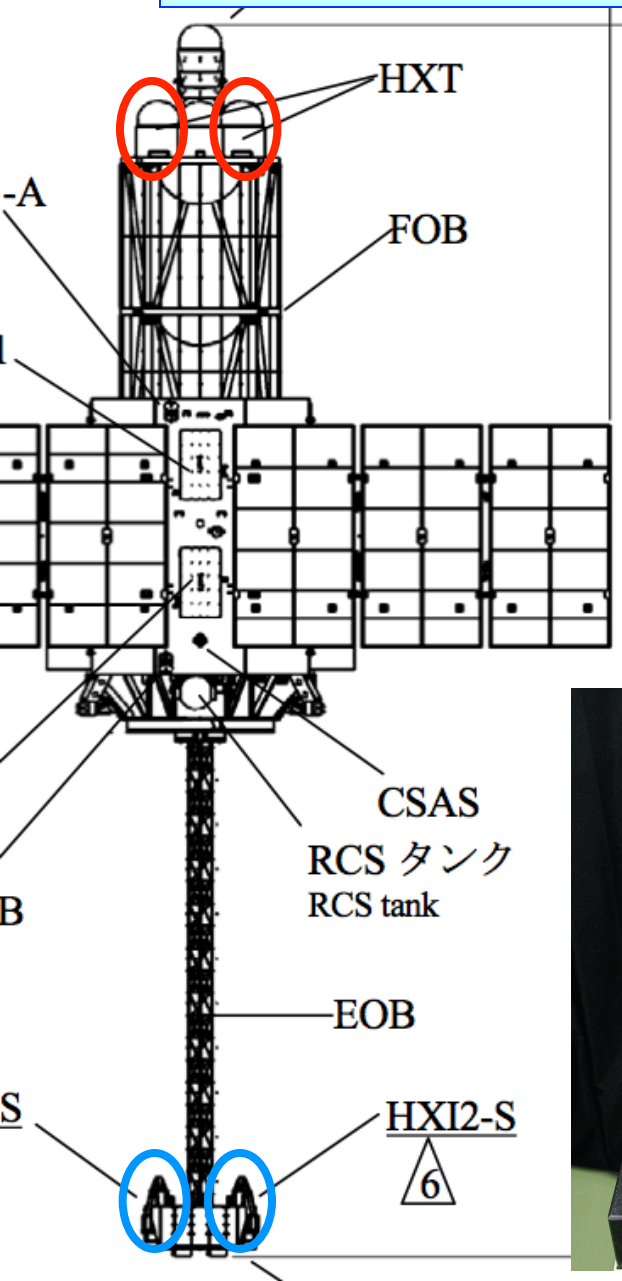




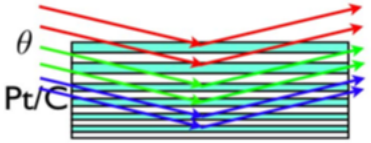
Engineering model



Hard X-ray telescopes & imagers

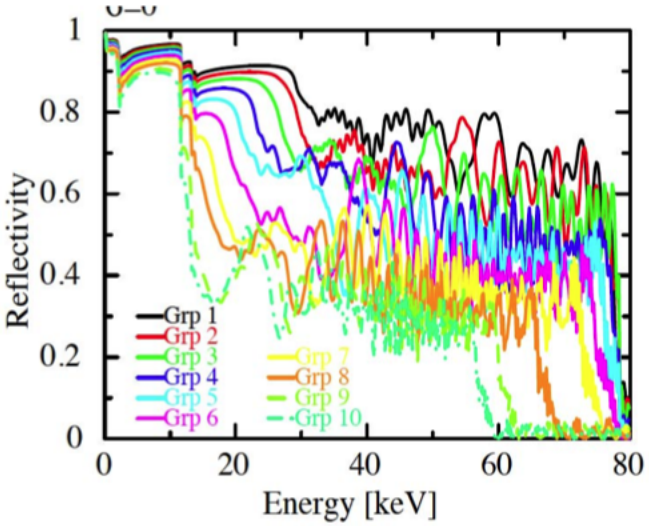


HXT principle

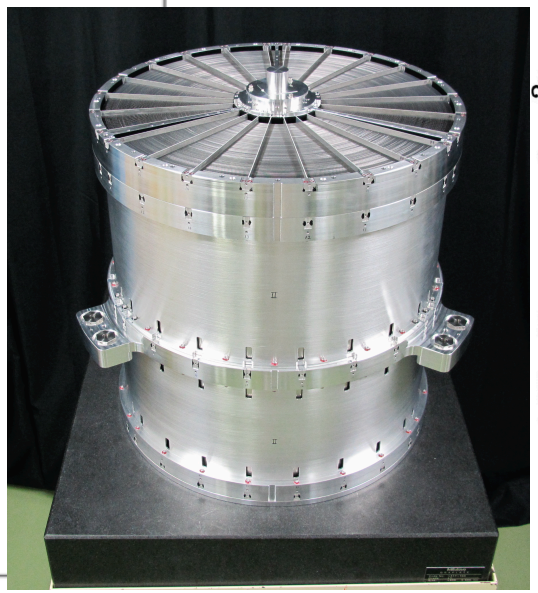


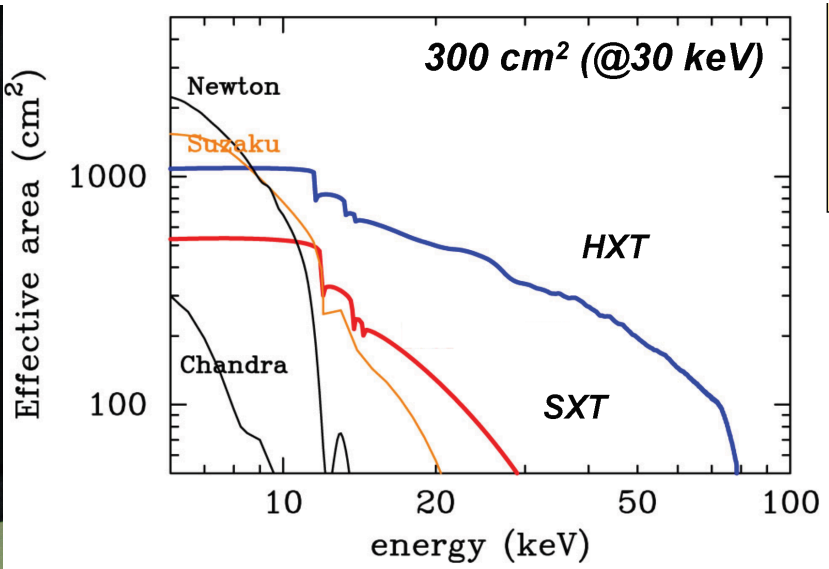
Depth-graded multilayer Bragg reflection

$$2d[\text{Å}]\sin\theta = m\frac{12.39}{E[\text{keV}]}$$



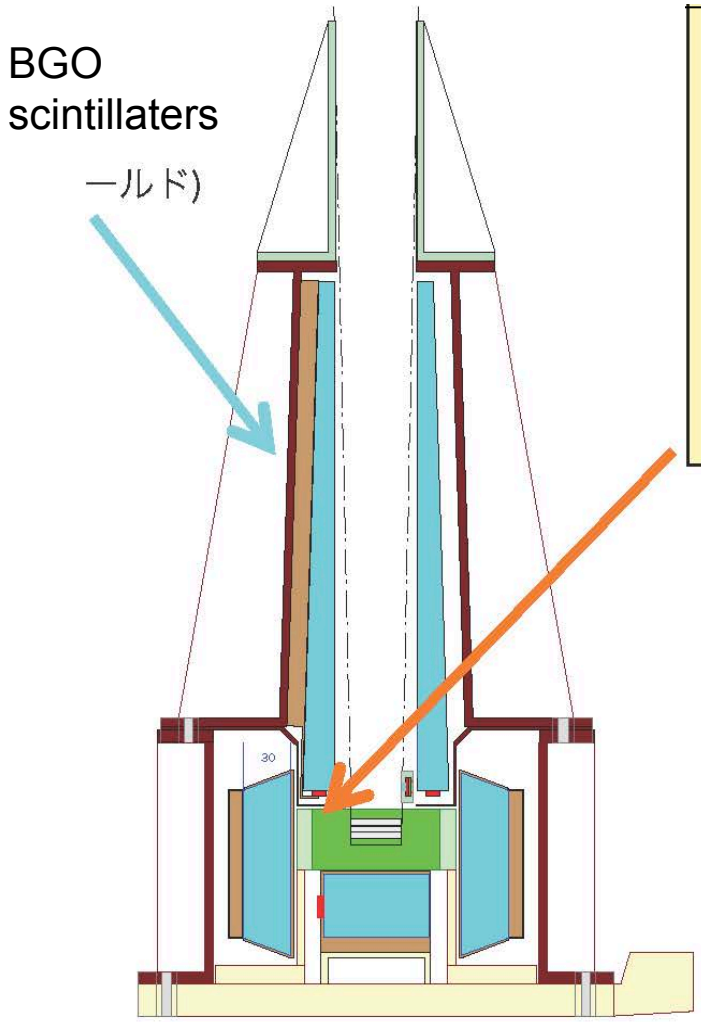
Super mirror

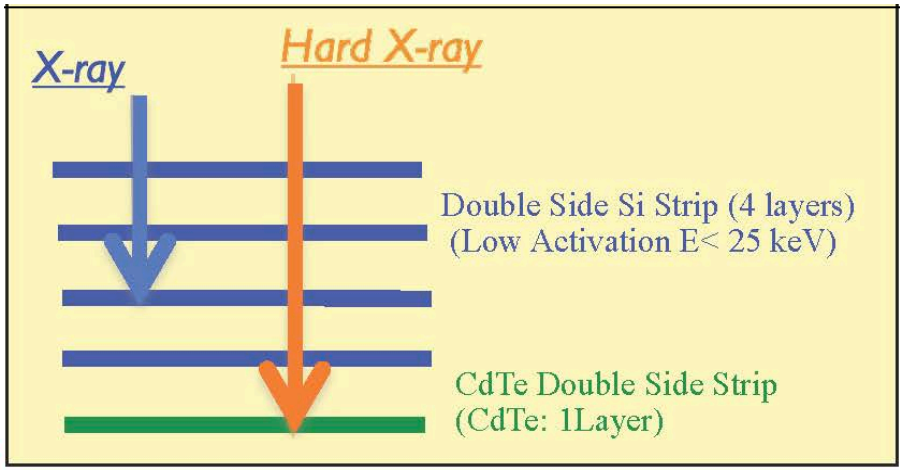




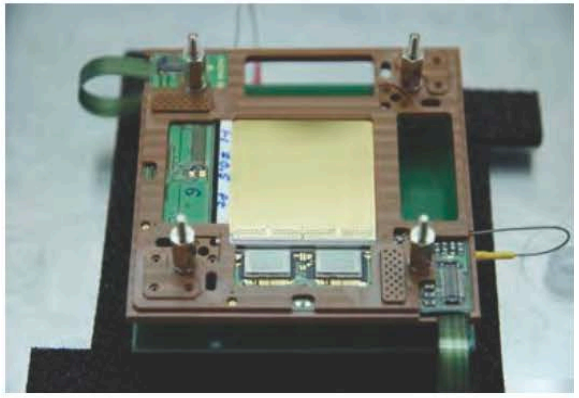
HXI: hard X-ray imagers

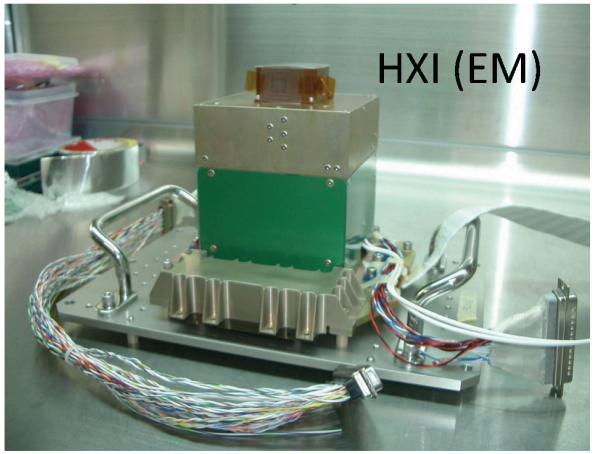
Si + CdTe hybrid imager sensitive in 5−80 keV





Engineering model





SGD

BGO fov

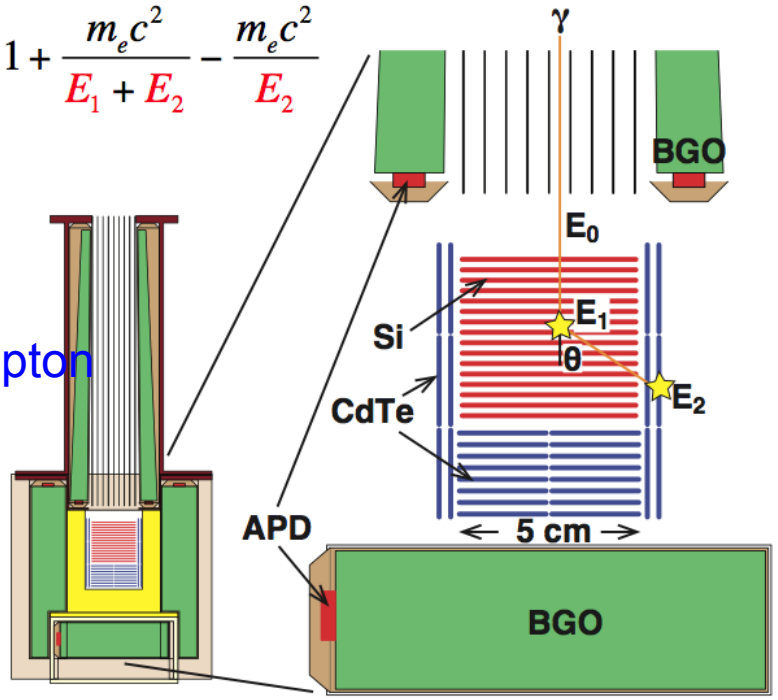
Fine collimator fov

SGD

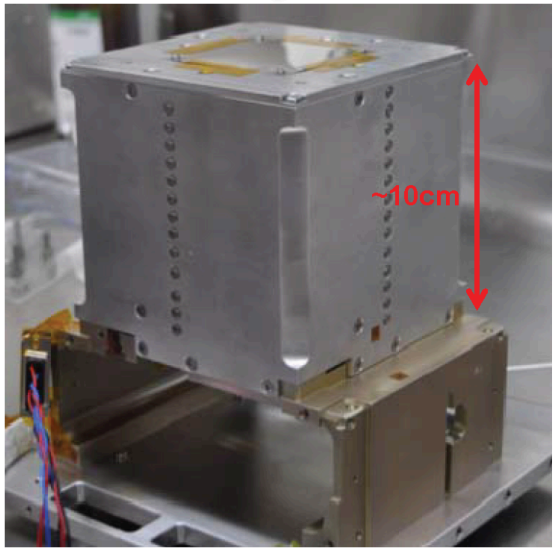
Principle

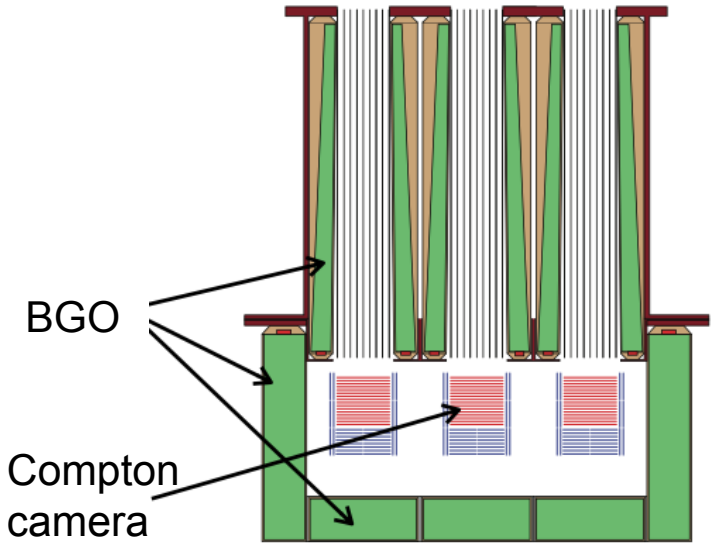
Narrow field Compton camera

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



Engineering model





SXS performance compared with existing observatories

Effective area

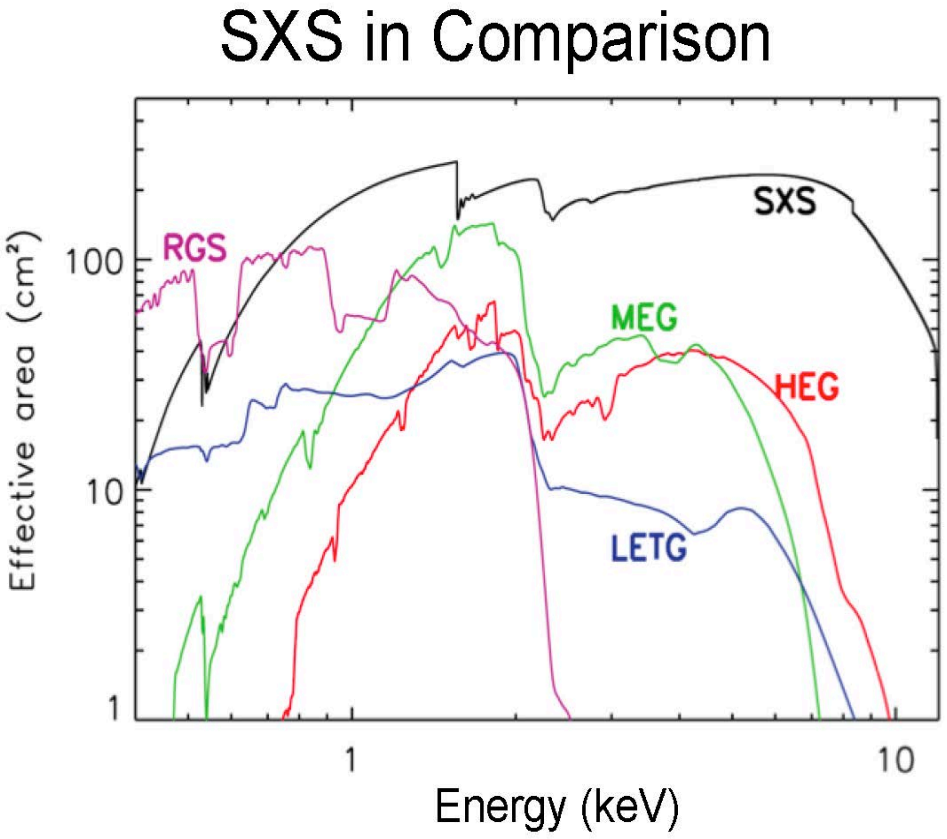
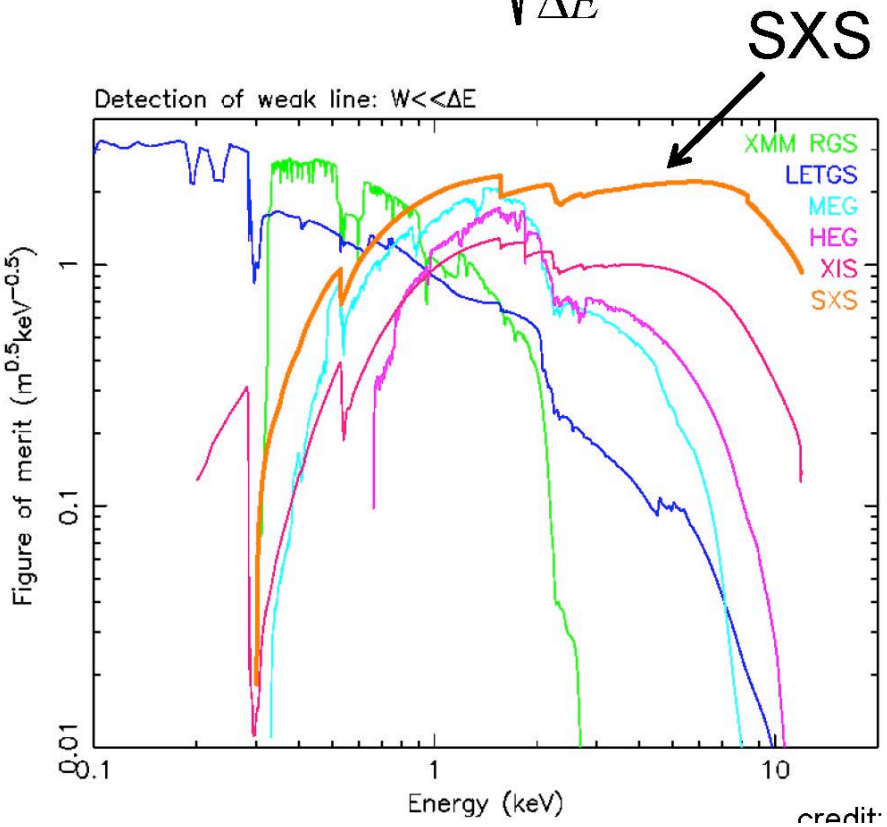
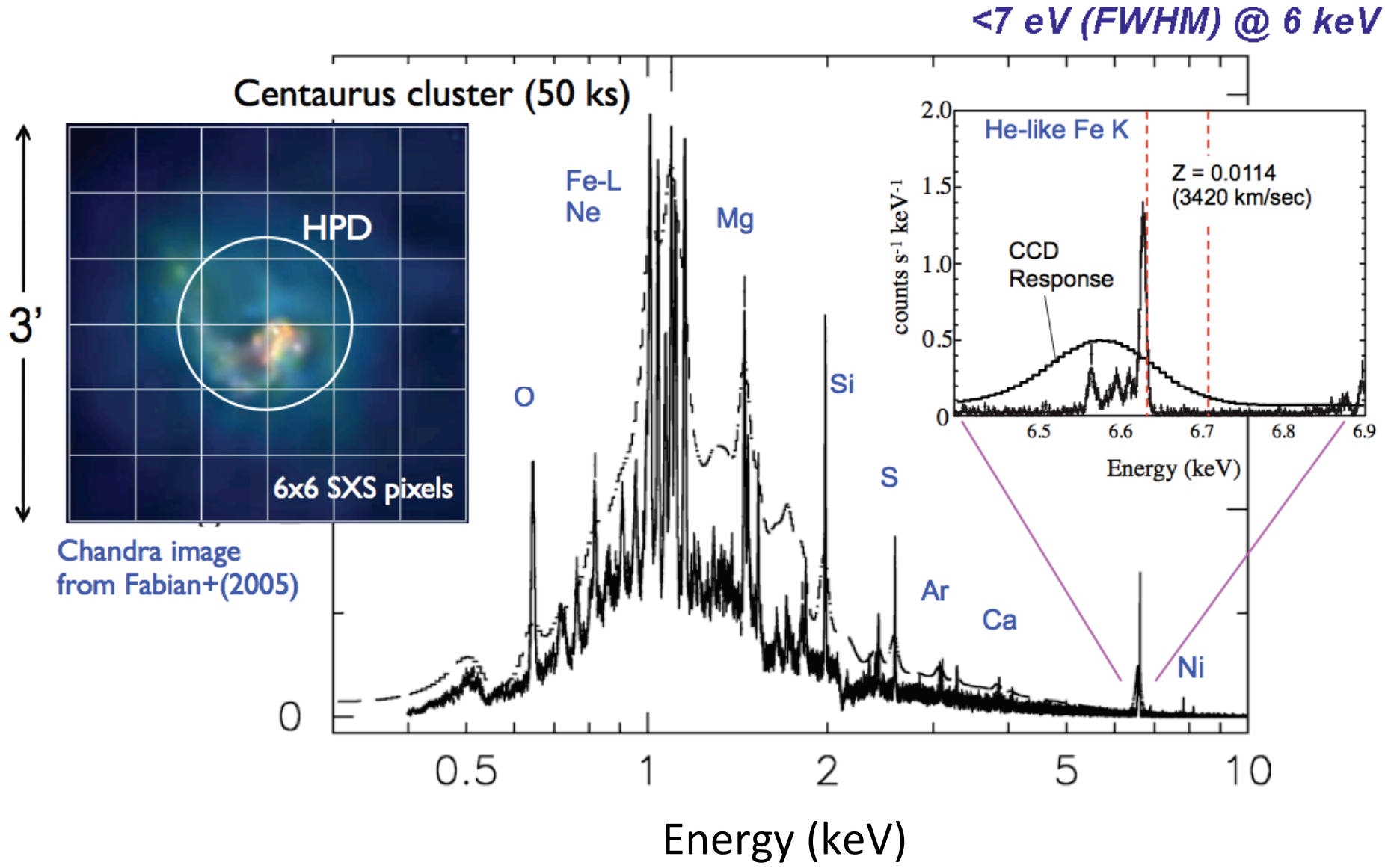


Figure of merit

$$FOM \sim \sqrt{\frac{A}{\Delta E}}$$

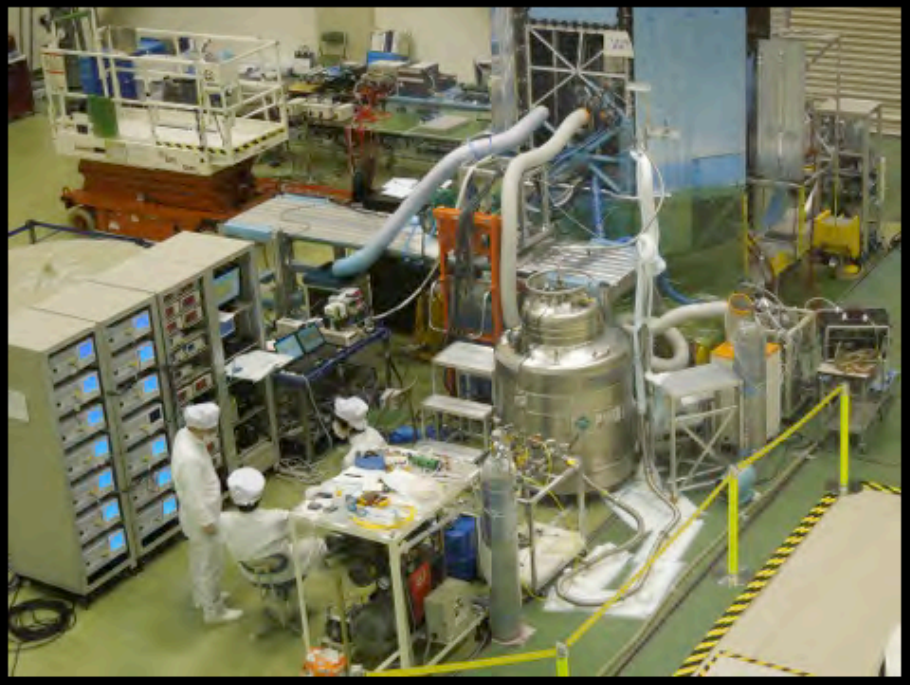


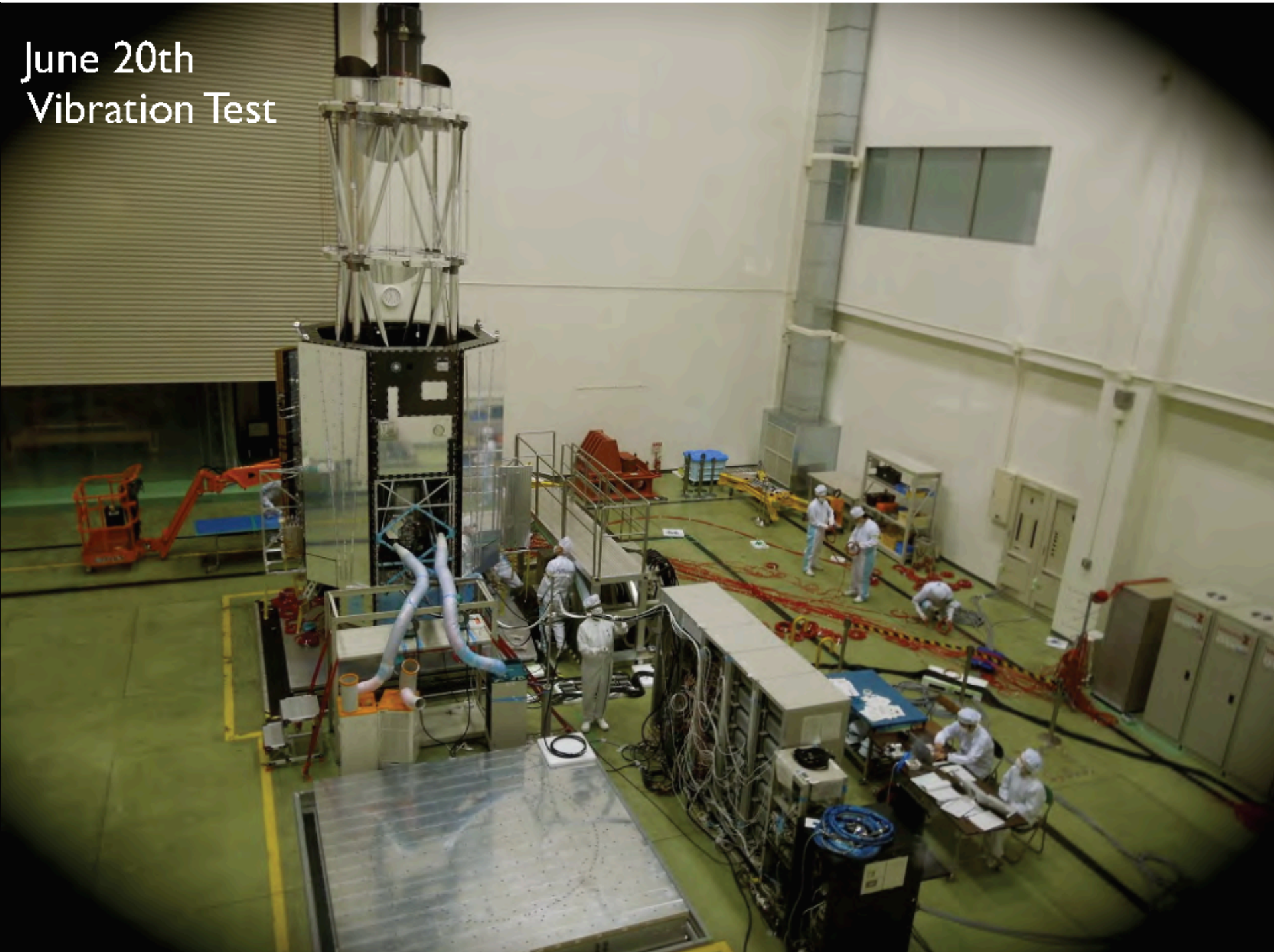
Example of the SXS spectrum : cluster of galaxies

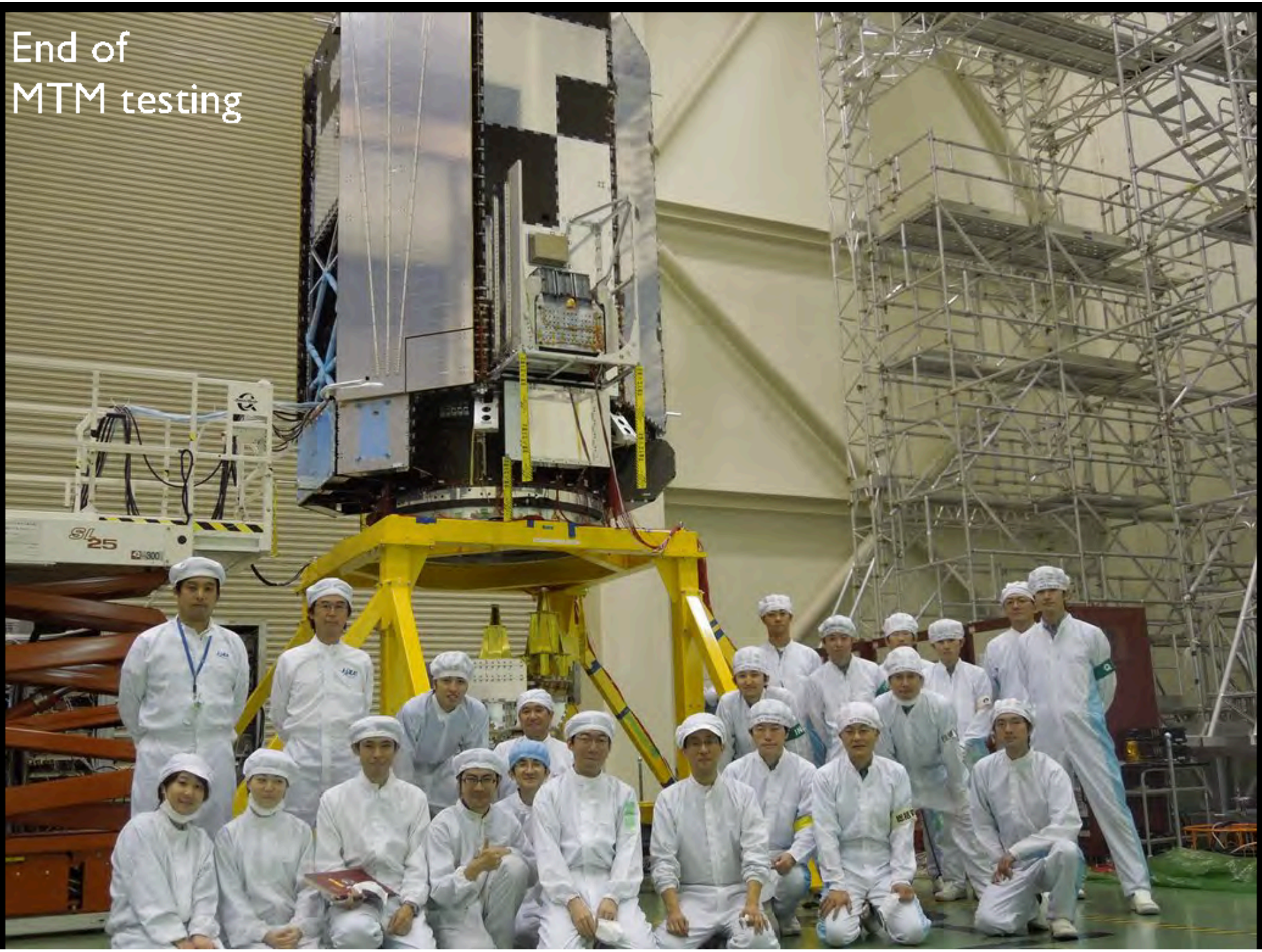


March 16th

Micro Vibration Test




June 20th
Vibration Test


End of
MTM testing

Radius-related observables of a NS

Lattimer & Prakash, 2007, Phys Rep., 442, 109.
Bhattacharayya, 2010, Adv. Space Res., 45, 949.

1. Gravitational redshift
    1. Absorption lines of the NS atmosphere
    2. Eddington limit of the photospheric radius expansion bursts
2. Pulse profile of a millisecond pulsars

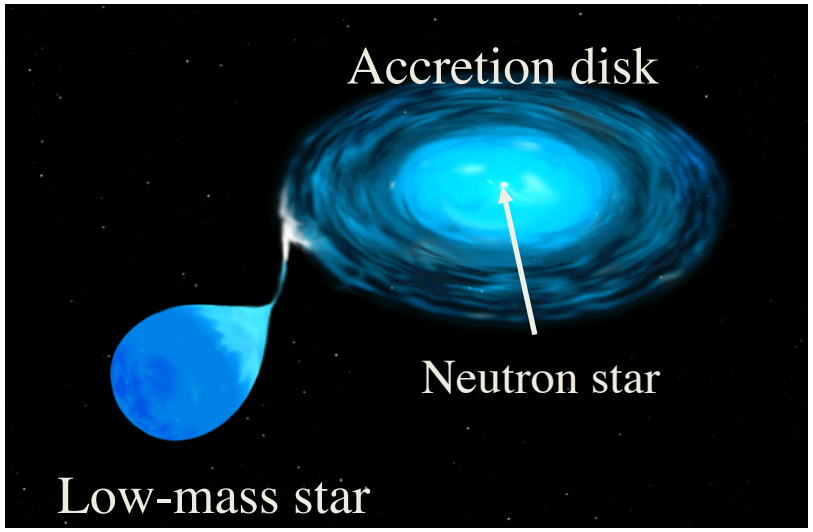
    Gravitational light bending and Doppler boosting
    1. Rotation-powered millisecond pulsars
    2. Burst oscillations
    3. Accretion-powered millisecond pulsars
3. Quasi-periodic oscillations

    X-ray modulation at the ISCO frequency
4. Thermal emission from the quiescent LMXBs
5. Broad relativistic iron line from the accretion disk

Low-mass X-ray binaries (LMXBs)

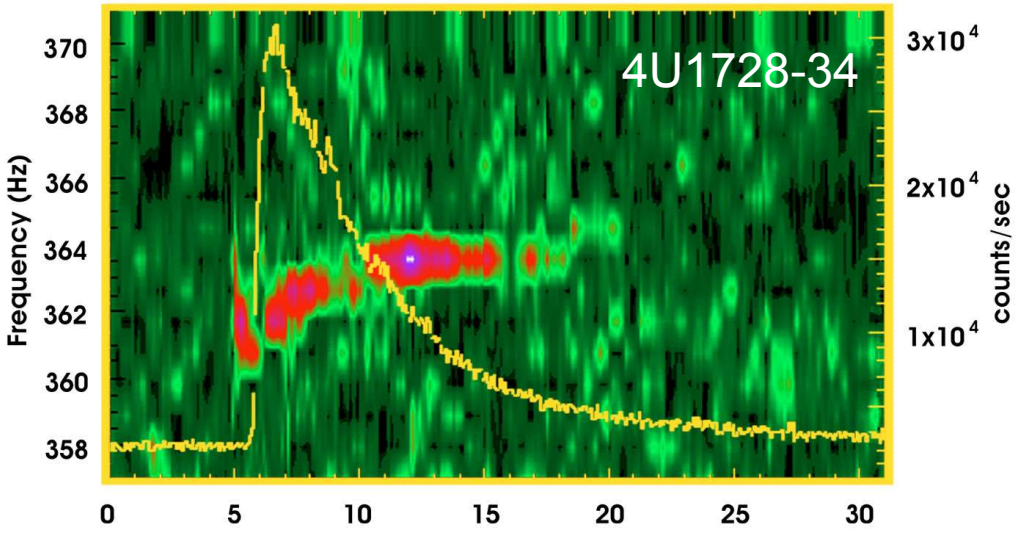
Properties of the NS in LMXBs

- $B_s < 10^9$-10^{10} G
- F_{spin} ~ 200-600 Hz
- T_s <0.1 - 2 keV
- Persistent / Transient



X-ray bursts

Run-away burning of He (H) on the NS surface.



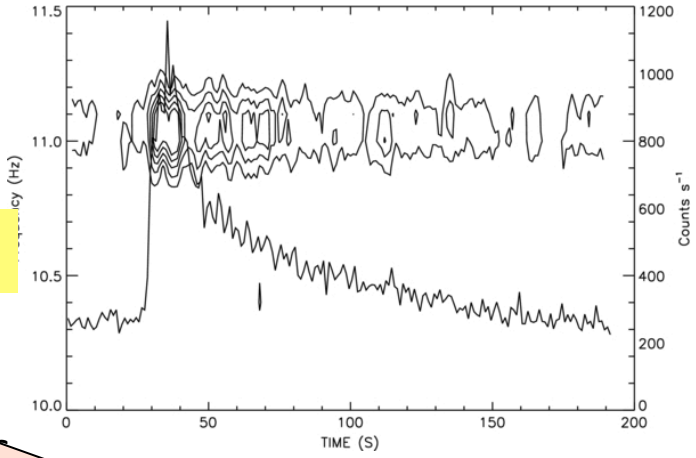
- Duration : ~10-100 sec
- Interval : hours ~ days
- Luminosity : ≤Eddington limit ~10^{38} erg/s

Burst oscillation is used to infer the spin frequency.

A unique LMXB : Terzan 5 X2

- A transient source in the globular cluster Terzan 5.
- Spin frequency : 11 Hz
- Magnetic field : 10^9-10^{10} G

Cavecchi et al. 2011, ApJ, 740, L8



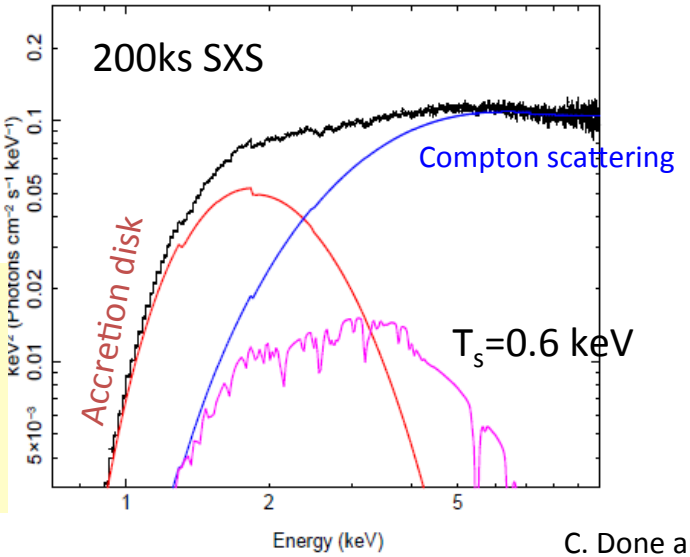
Narrow lines are expected from the NS atmosphere.

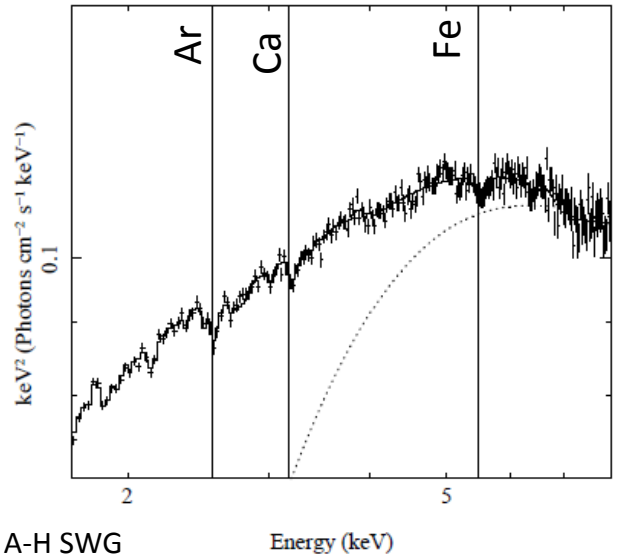
- Clean and clear results are expected:
  Independent of distance, radiation isotropy, details of the emission region, continuum models
- Caveat
  T5X2 is a transient source.

High accuracy

Simulated 200ks SXS spectrum of T5X2.

SXS can significantly detect absorption lines from He-like Ar, Ca and Fe.





C. Done and A-H SWG

Bursts with photospheric radius expansion (PRE)

Eddington limit : gravitational acceleration ~ radiation pressure

When $L_{burst} \sim L_{edd}$ ⇒ Photosphere expands largely

$L_{burst} \approx L_{Edd}$ (for local observer)

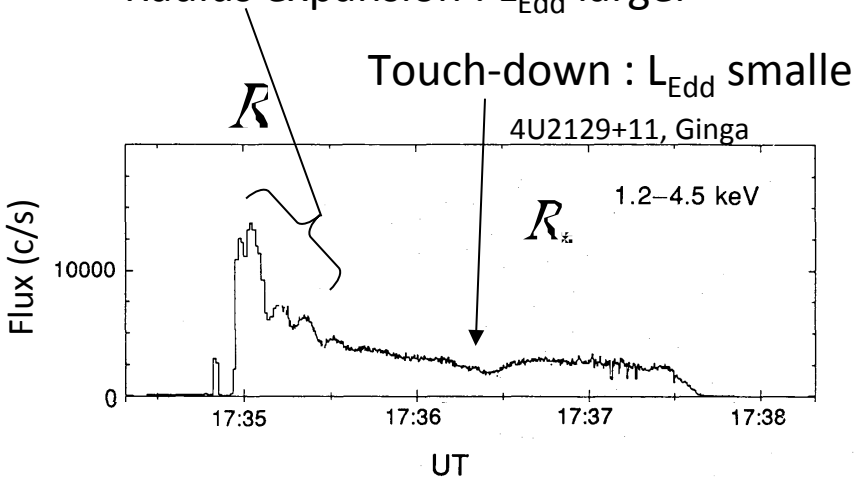
For distant observer, L_{Edd} changes depending on the radius of the photosphere.

$$L_{Edd} = \frac{4\pi G M_{\infty} c}{\kappa}\left(1 - \frac{2GM_{\infty}}{Rc^2}\right)^{1/2}$$

κ : opacity

Radius expansion : L_{Edd} larger

Touch-down : L_{Edd} smalle



Van Paradijs et al. PASJ, 42, 633 (1990)

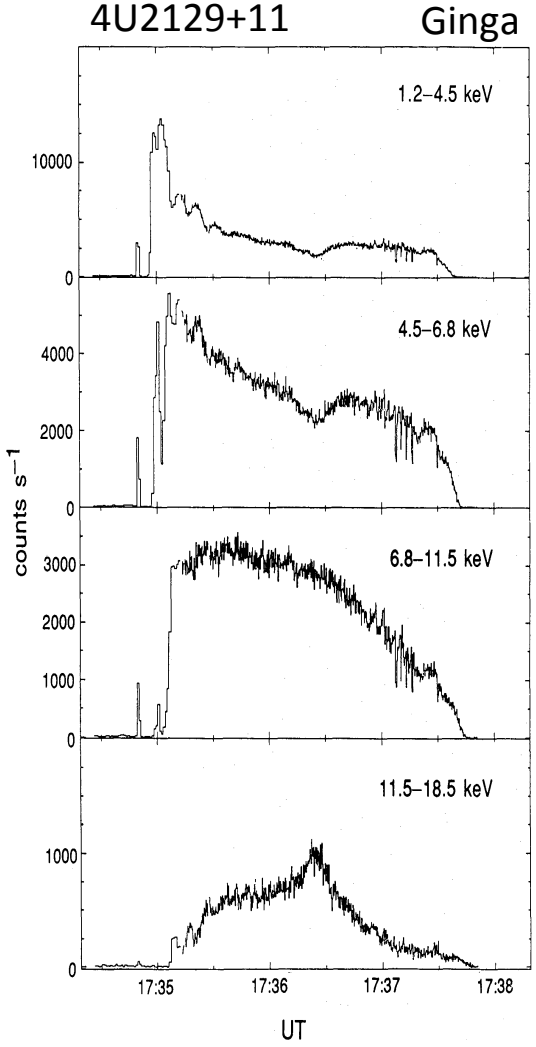
Gravitational redshift may be calculated from the apparent flux and radius ratios.

$$(1+z)^2 = \frac{\varsigma_\infty^2 - \chi^{-1}}{1-\chi^{-1}} \qquad \begin{cases} \varsigma_\infty = F_{Edd}(R > R_\infty)/F_{Edd}(R = R_\infty) \\ \chi = R/R_\infty \end{cases}$$

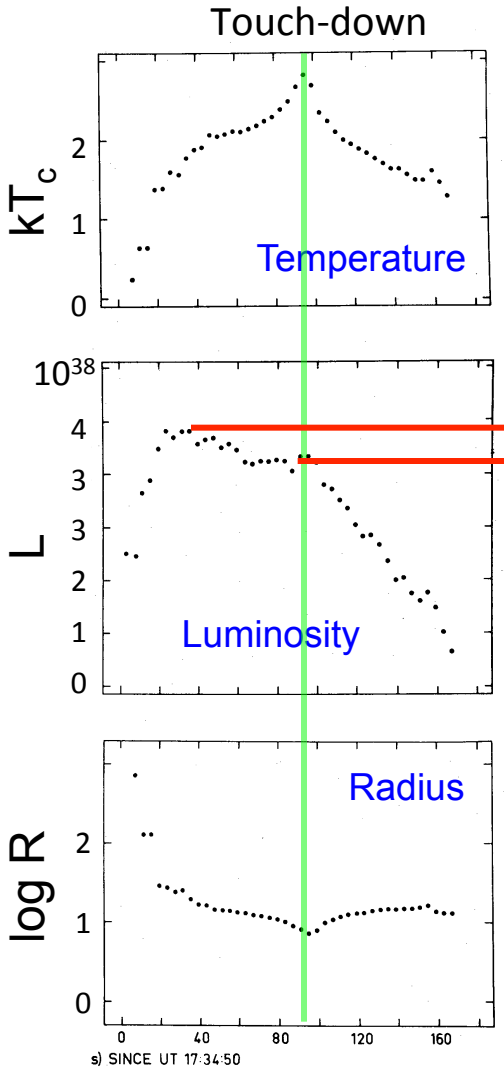
Merits

Mostly independent of the source distance, spin frequency, composition, unisotropy (if constant).

X-ray bursts with PRE : past result



Van Paradijs et al. PASJ, 42, 633 (1990)



$$(1+z) = \begin{cases} 1.15-1.27 & \text{Color correction1} \\ 1.29-1.46 & \text{Color correction2} \end{cases}$$

Corr1 : constant color correction
Corr2 : color correction from the decay phase

$$L_{\rm Edd}(R > R_*)$$
$$L_{\rm Edd}(R = R_*)$$

Caveat

1. Deviation from blackbody
   $T_c / T_{\rm eff} \approx 1.7$
2. Soft band coverage to estimate the bolometric luminosity.
3. Local structures in the energy spectrum

ASTRO-H SXS may improve items 2 and 3.

Pulse-profile of millisecond pulsars

Rotation-powered millisecond pulsars (MSPs)

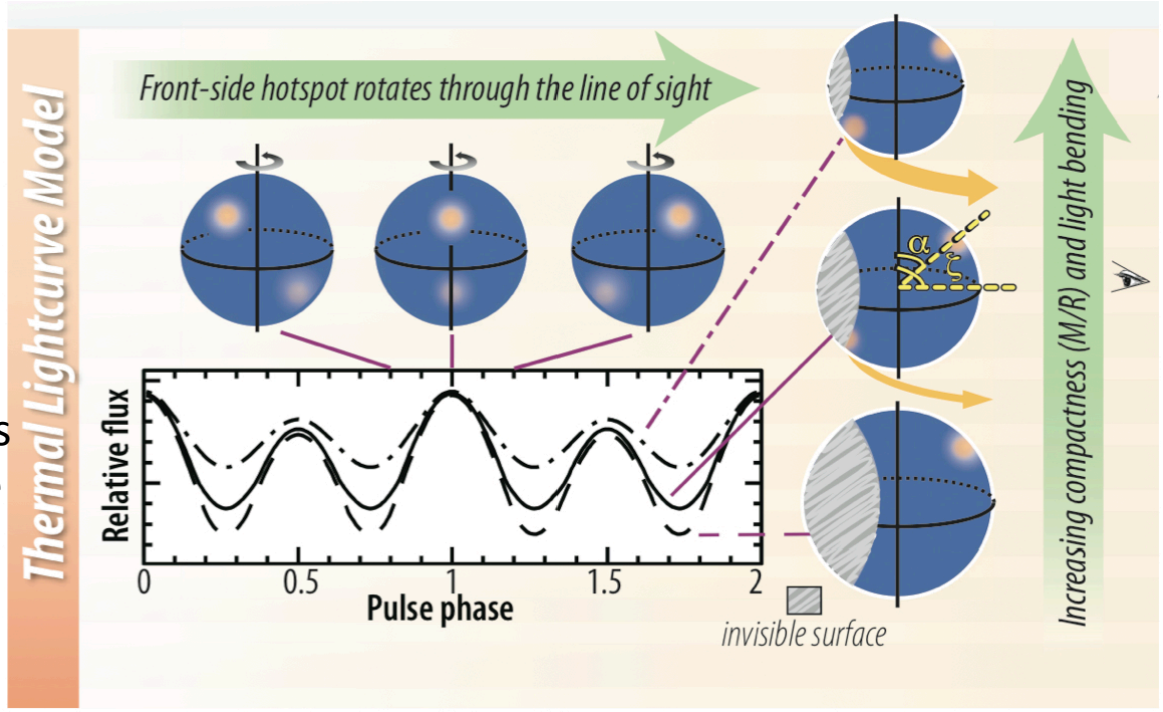
Weakly magnetized (~10^8-10^9G), rapidly spinning (≤30 ms) neutron star. An evolutionary descendant of LMXB. About 200 MSPs are known.

Radio : magnetospheric emission

X-Ray : thermal emission from the polar caps (NS surface) heated by the back-flow from the magnetosphere.

Pulse profile of MSPs

- Gravitational light bending (M/R)
  Far side of hot spot becomes more visible for compact NS.
- Doppler boosting (R)
  Approaching hot spot becomes brighter than the receding one due to relativistic beaming.

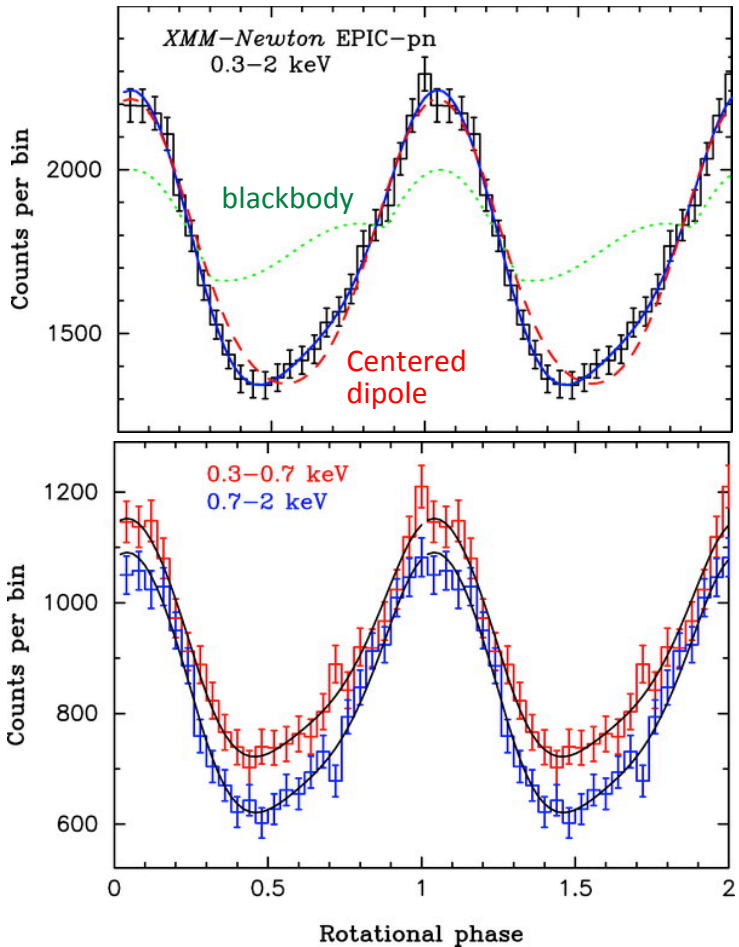


Gendreau, K. C. et al. 2012, SPIE, 8443, 844313

The closest MSP PSR J0437-4715 : XMM-Newton obs.

PSR J0437-4715

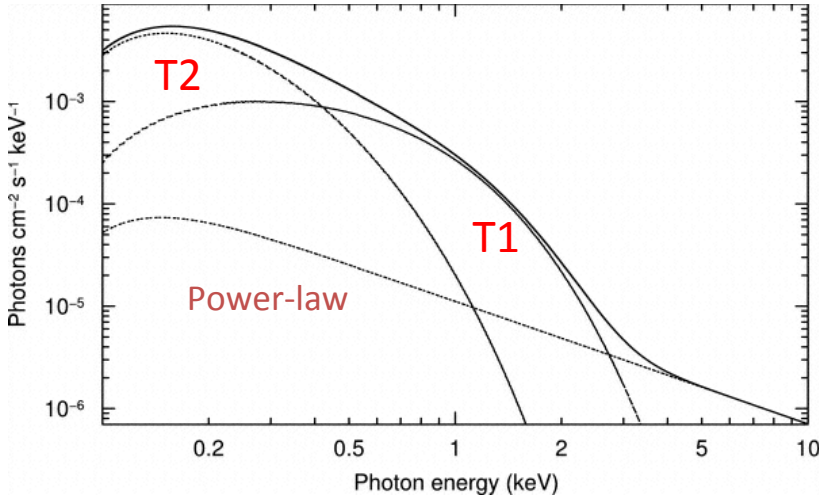
- Spin period : 5.76 ms
- Distance : 156 pc



Analysis & results

Spectrum: Hydrogen atmosphere model
Geometry : off-center dipole
Hot spot1 : T1=1.4-1.85 MK, R1=0.1-0.36 km
Hot spot2 : T2=0.4-0.54 MK, R2=2.0-3.5 km
Radius : 6.8-13.8 km for 1.4 M_{solar}

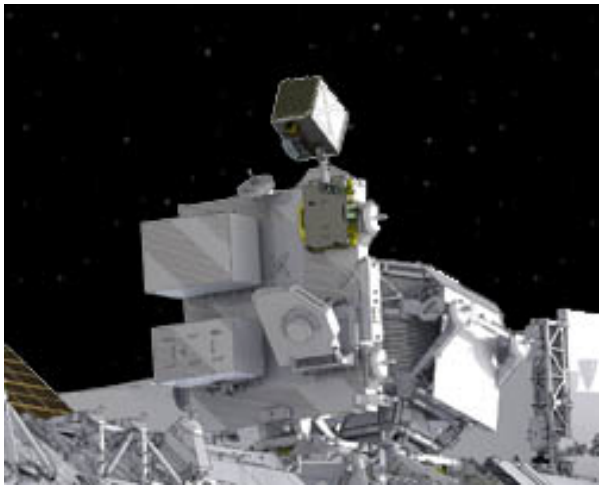
XMM-Newton: Accuracy limited by the time assignment and calibration errors.
ASTRO-H : can give more accurate temperature and better time assignment.

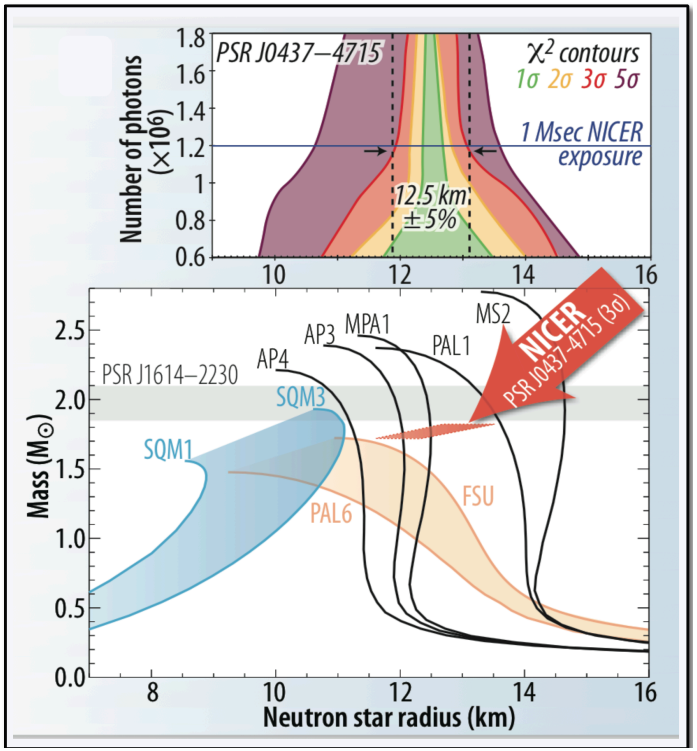


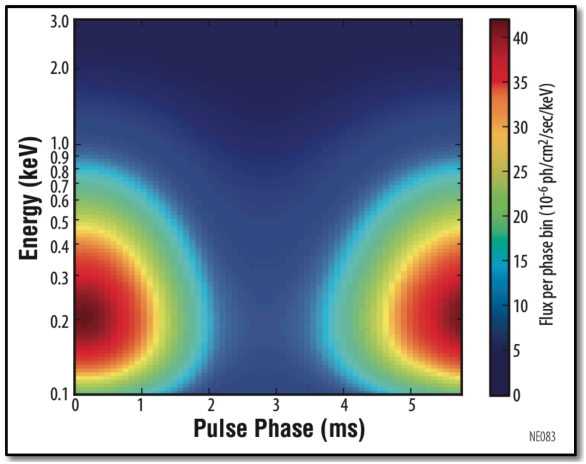
Bogdanov, S. et al. 2007, ApJ, 670, 668

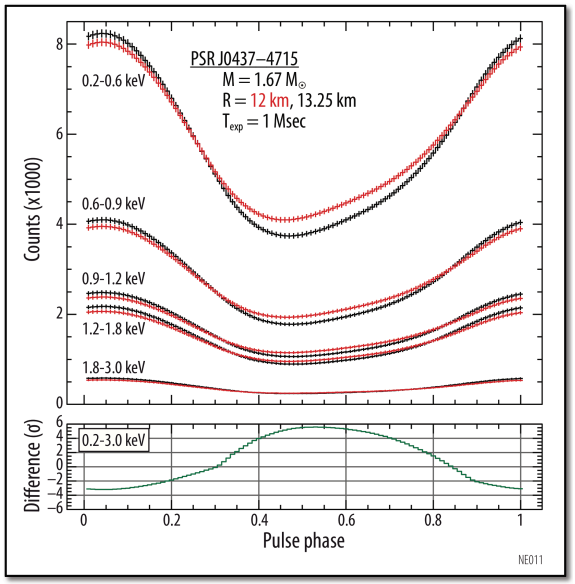
NICER

- An approved NASA explore mission of opportunity.
- An x-ray timing and spectroscopic instrument as an attached payload aboard the ISS.
- Launch : late 2016
- Detectors
  - Bandpass : 0.2-12 keV
  - Effective area : >2000cm2 @1.5 keV
    600cm2 @ 6 keV
  - Energy resolution : 85 eV @ 1 keV
    137 eV @ 6 keV
  - Time tagging accuracy : <300 nsec









http://heasarc.gsfc.nasa.gov/docs/nicer/

Summary

- The ASTRO-H mission
  - 4 mission instruments: SXS, SXI, HXI, SGD
  - The micro-calorimeter (SXS) is the most powerful instrument for X-ray line spectroscopy.
  - Launch schedule: late 2015
- Possible observations of A-H to constrain the M-R relation of a NS.
  - Absorption lines from the photosphere of a NS.
  - Change of the Eddington limit during the photospheric radius expansion bursts.
  - Pulse profile of thermal X-ray emission from MSPs.