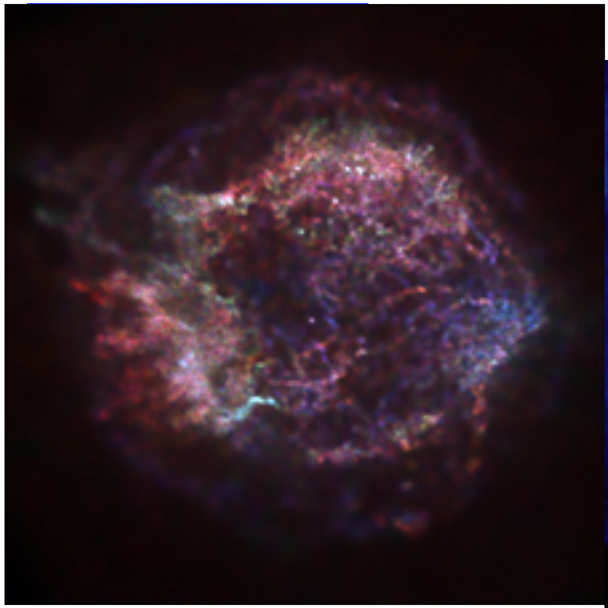
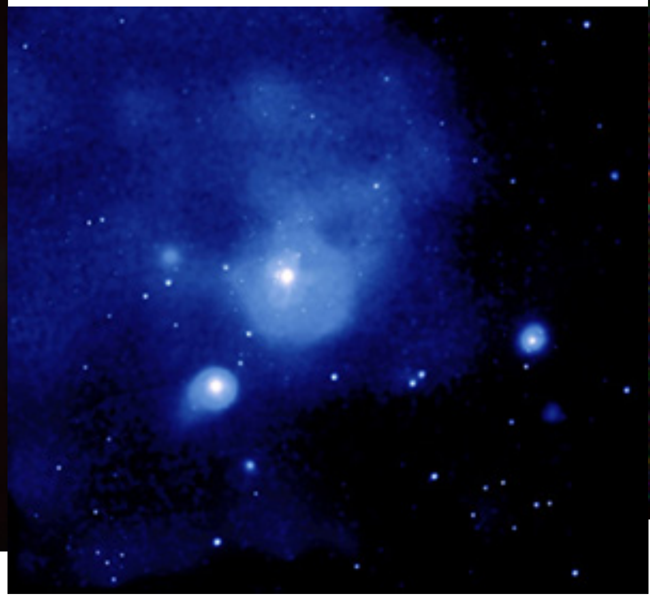
Insights into current/recent X-ray/ γ-ray missions

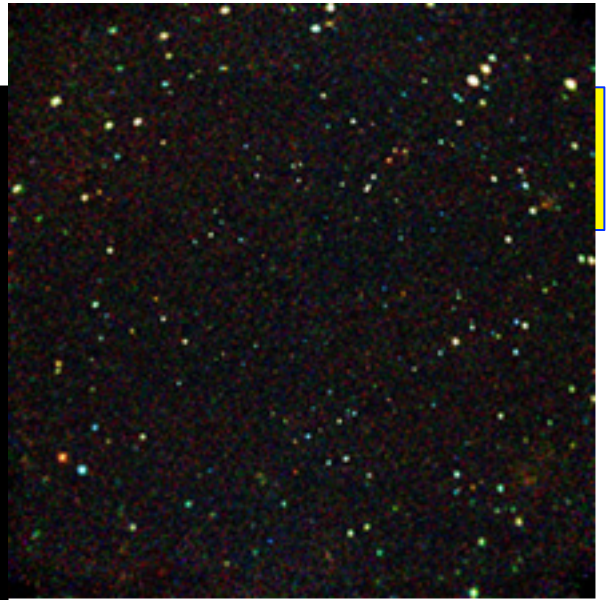
Since the birth of X-ray Astronomy in 1962, improvements were carried out in terms of

sensitivity, angular resolution, and energy bandpass

The importance of angular resolution

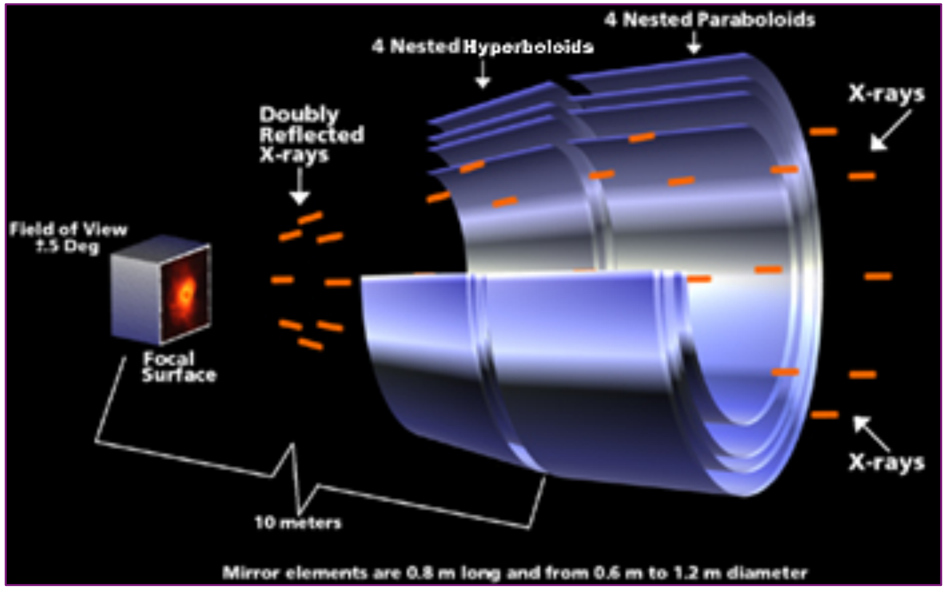






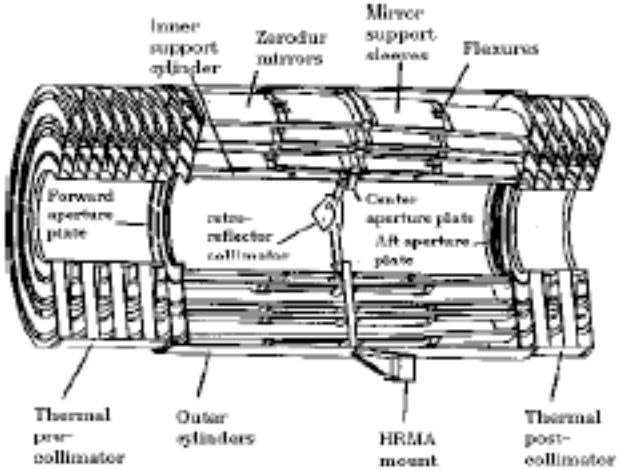
Chandra X-ray Observatory (NASA)

Chandra = angular resolution



Only four, robust shells
High-quality of shell production
to allow <arcsec on-axis angular
resolution (the best so far in X-rays)

High Resolution Mirror Assembly (HRMA)



Ottica Wolter Type-I

Mirror diameters: 1.23, 0.99, 0.87 0.65 m

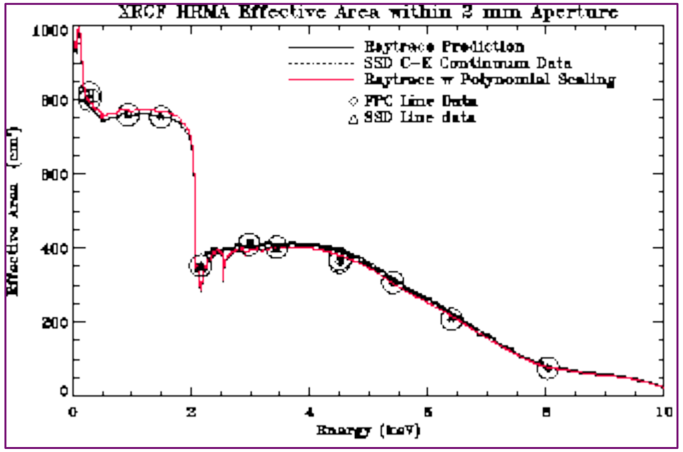
Mirror lengths: 84 cm

HRMA mass: 1500 kg

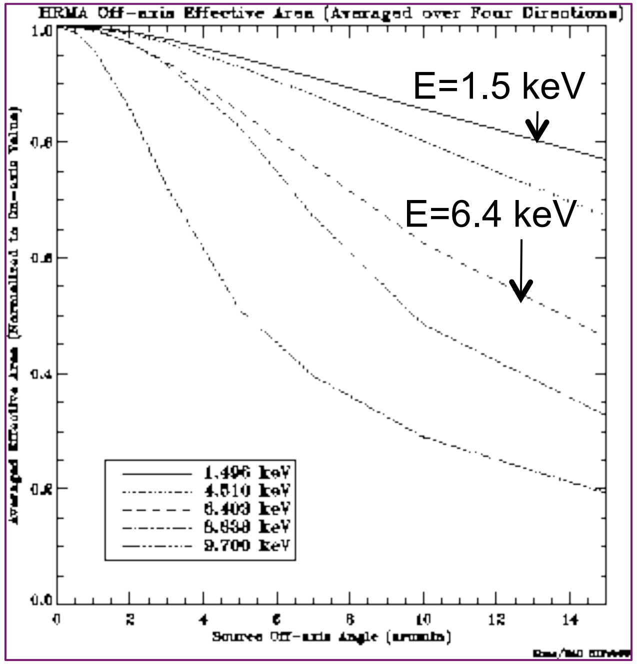
Focal length: 10 m

PSF FWHM: 0.5”

High Resolution Mirror Assembly (HRMA): Effective Area



Effective area vs. Energy



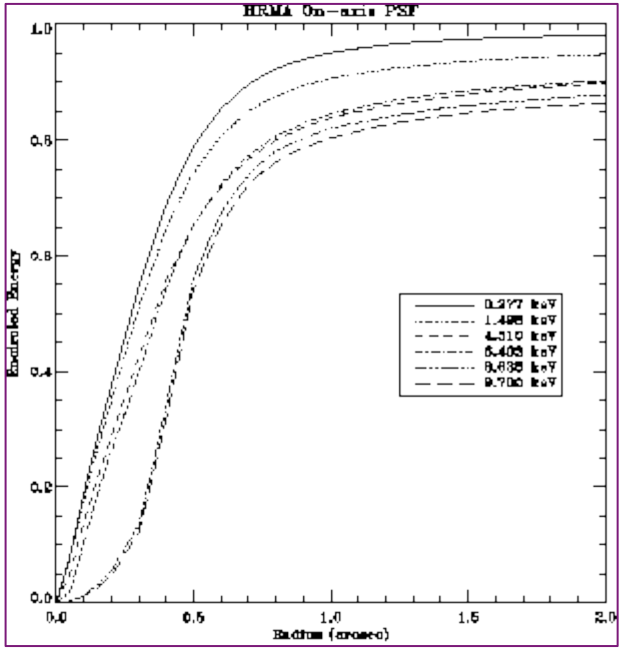
Effective area vs. off-axis angle at different energies

Effect of vignetting

Average effective area normalized to on-axis value

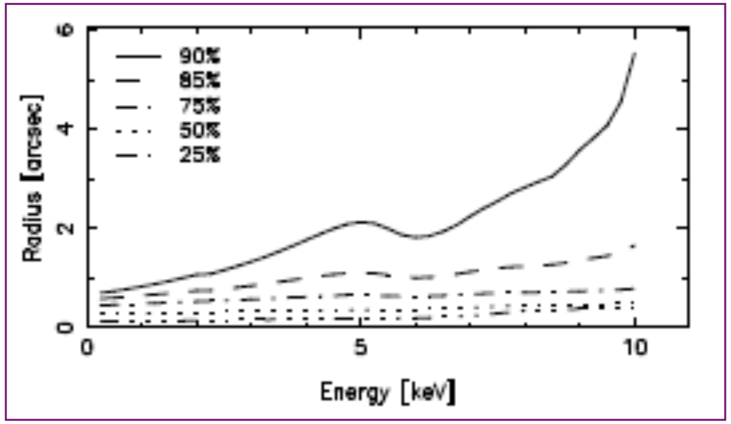
Decreasing performances at increasing off-axis angles

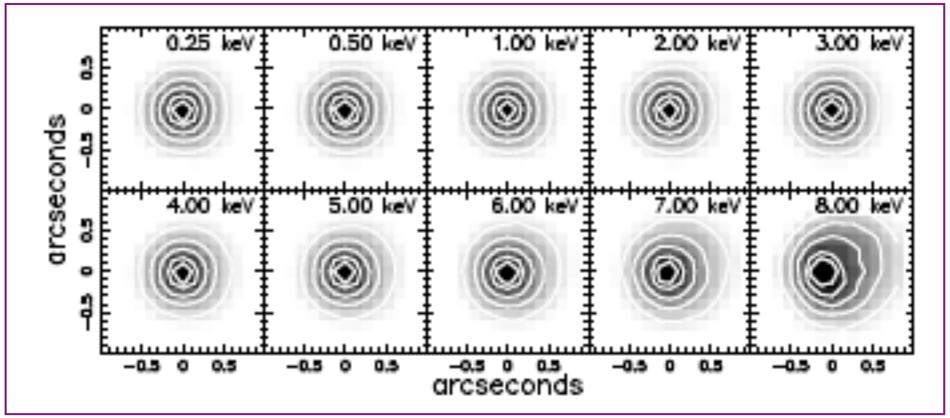
High Resolution Mirror Assembly (HRMA): On-axis PSF



Encircled energy vs. radius at different energies

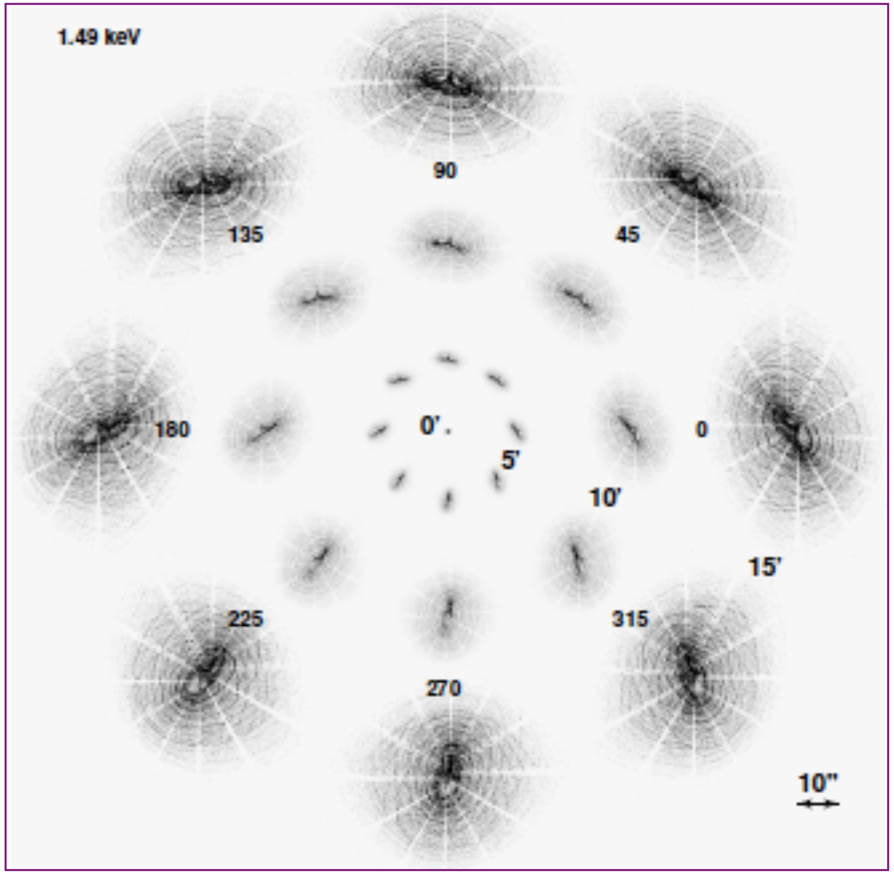
Radius encompassing NN% of the counts as a function of the energy

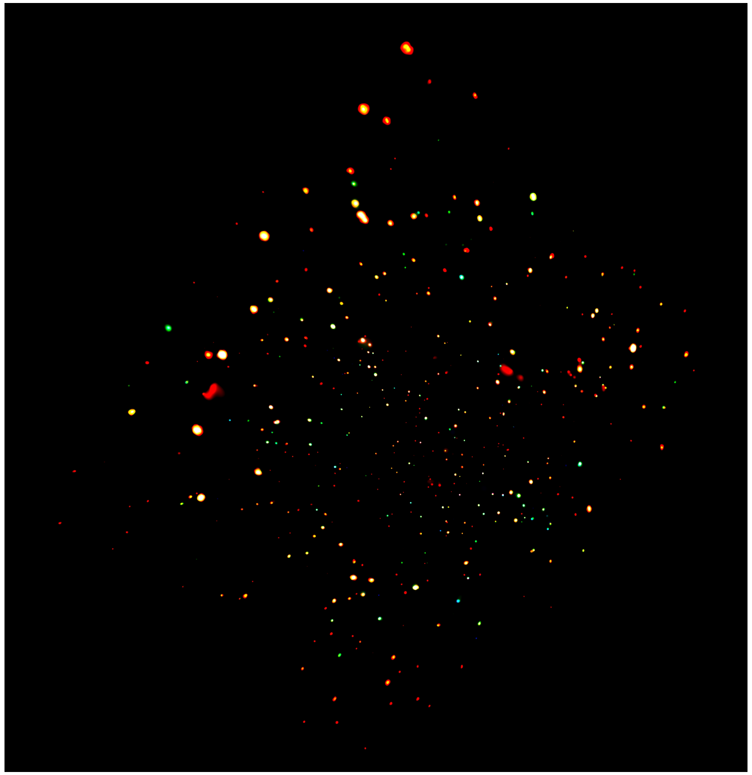




On-axis PSF size and shape

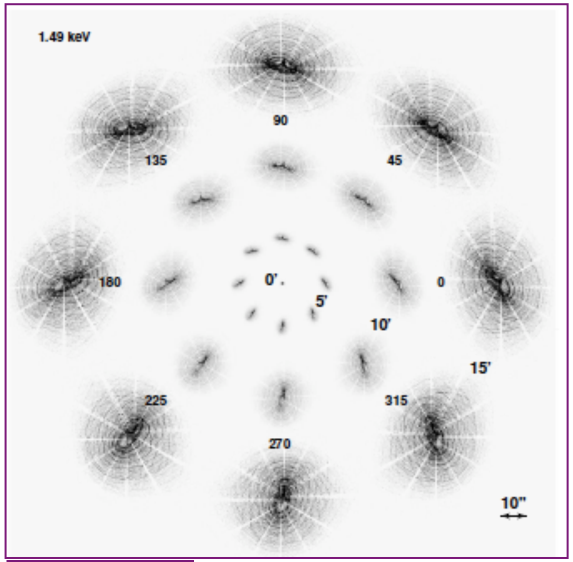
High Resolution Mirror Assembly (HRMA): Off-axis PSF



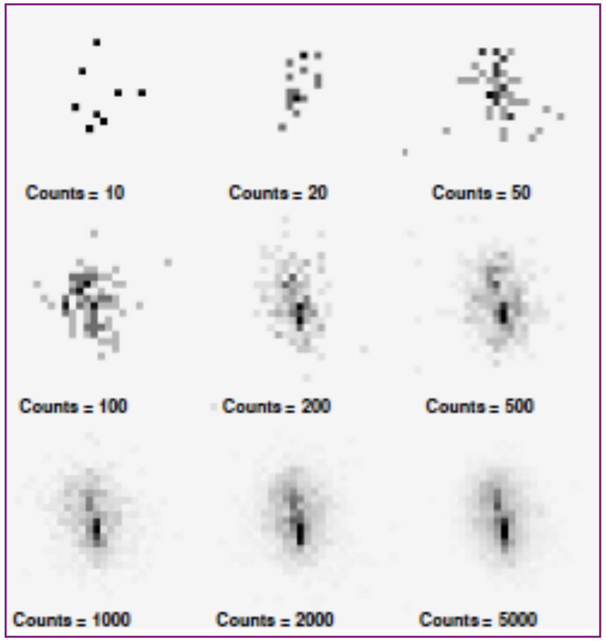


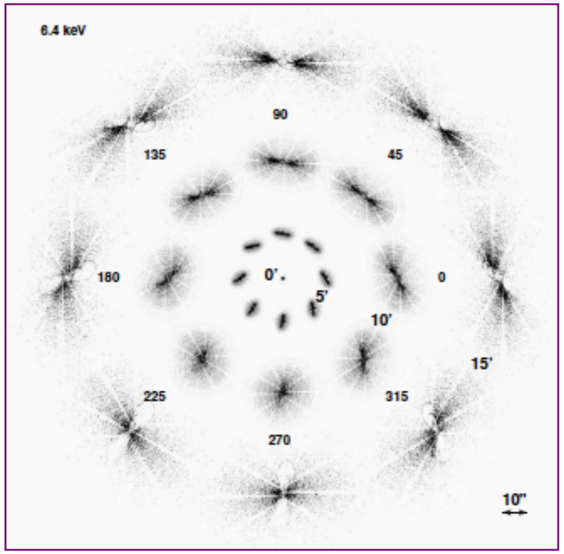
CDF-N 2Ms exposure

High Resolution Mirror Assembly (HRMA): Off-axis PSF



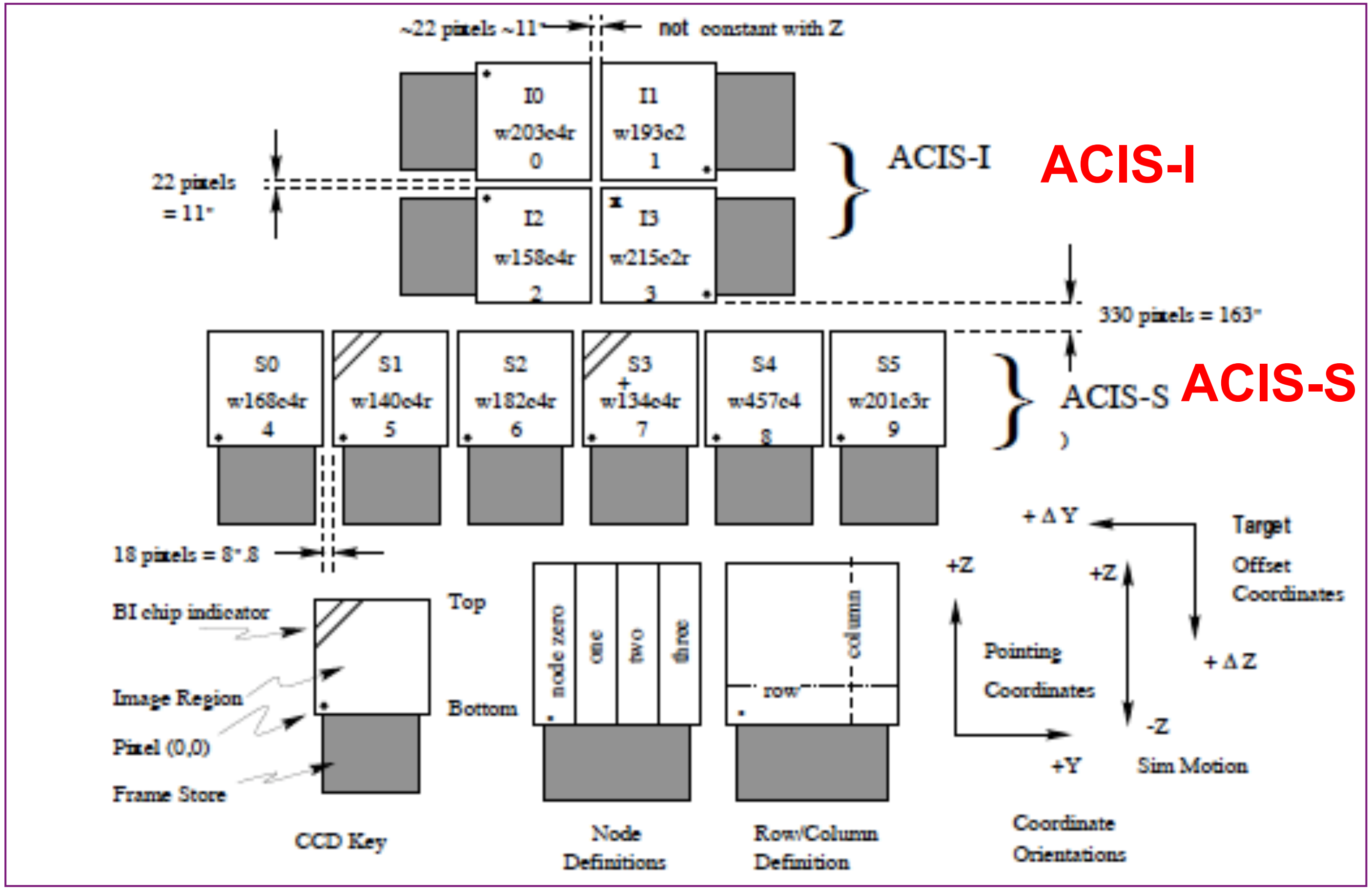
1.5 keV



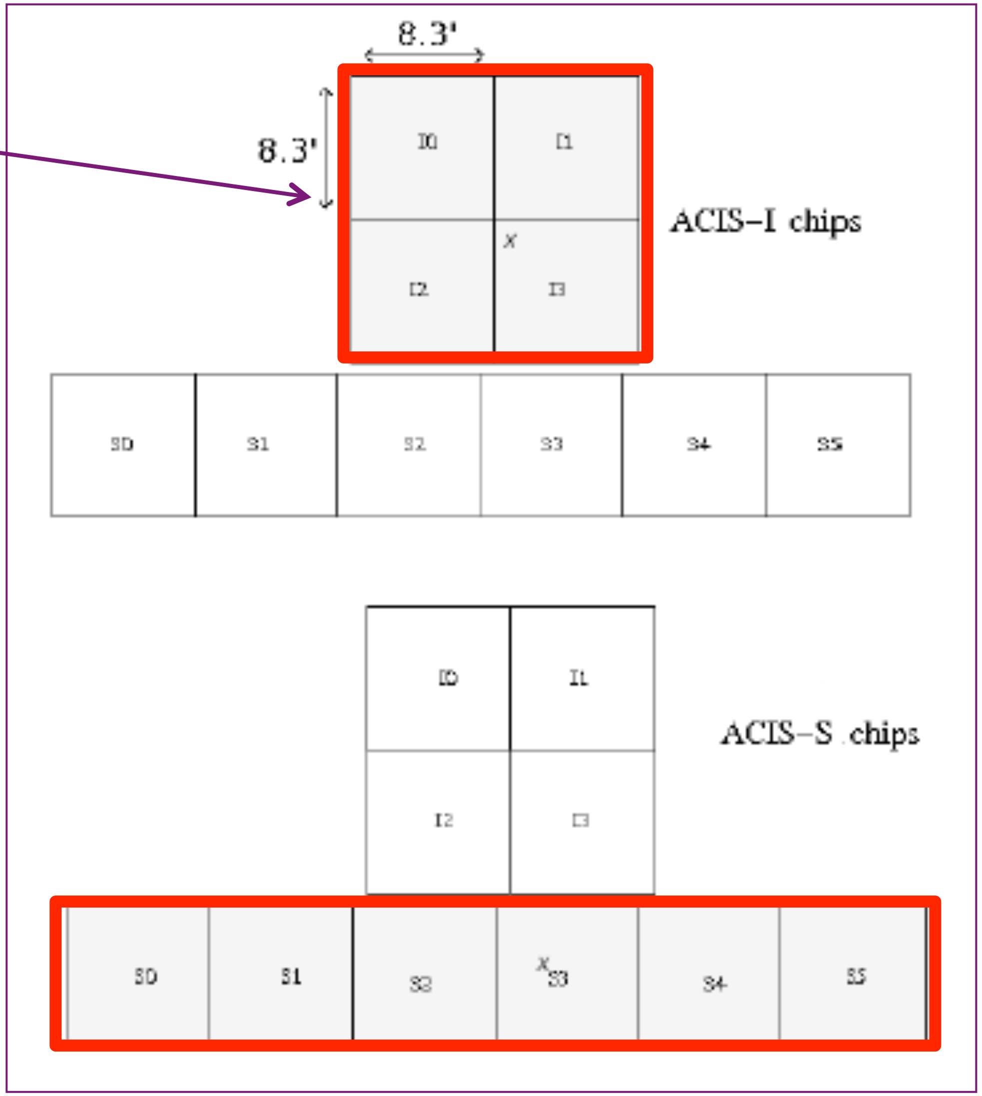


6.4 keV

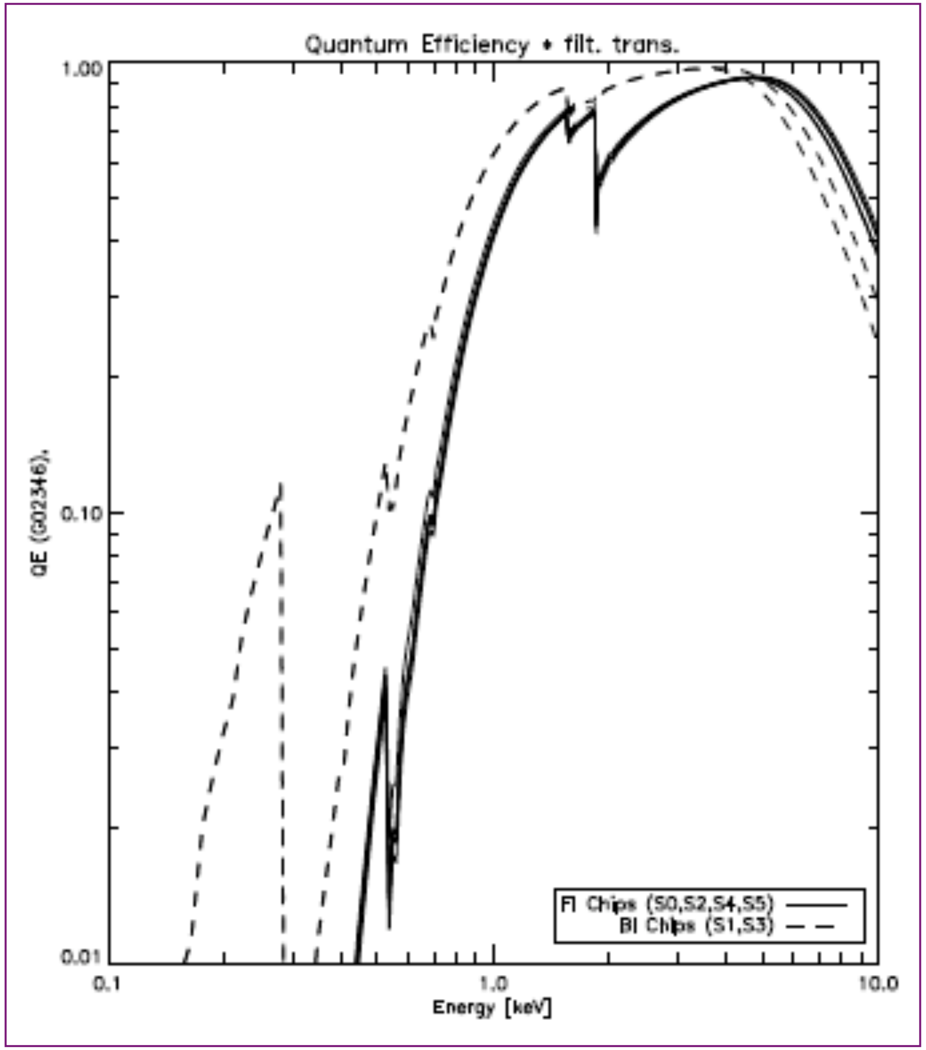
Chandra focal-plane detectors: CCDs



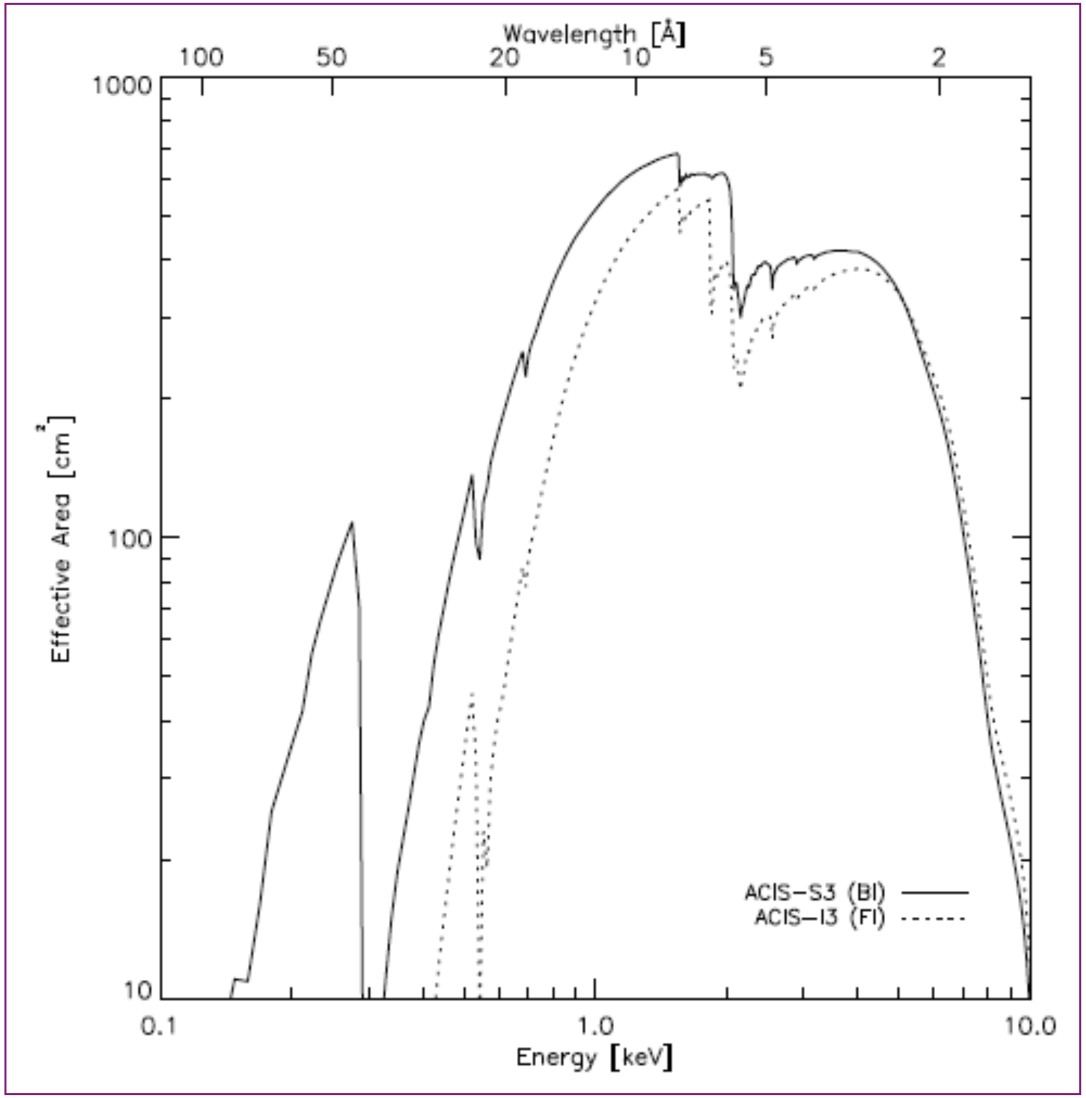
ACIS-I preferred for surveys



Chandra: quantum efficiency

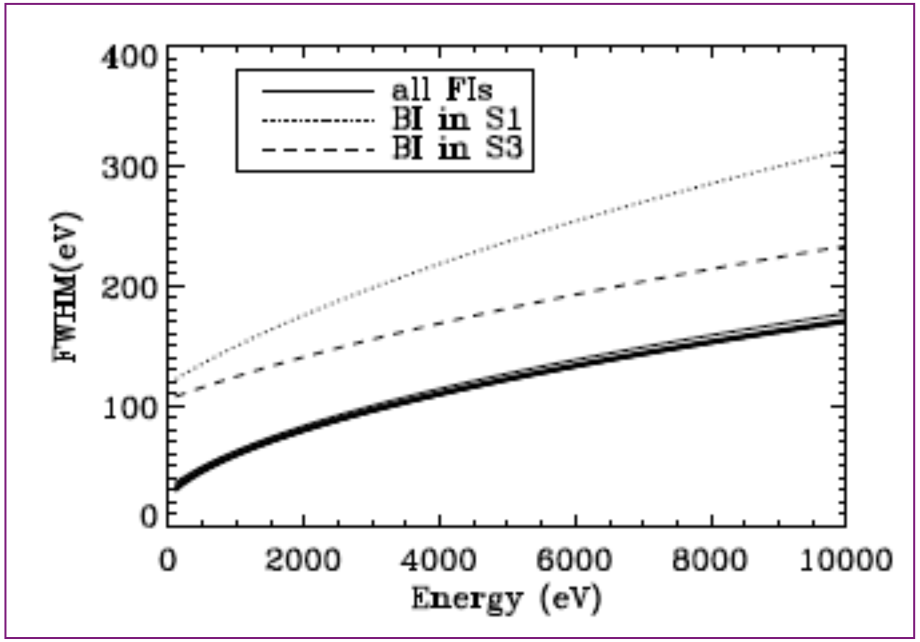


Chandra: effective area



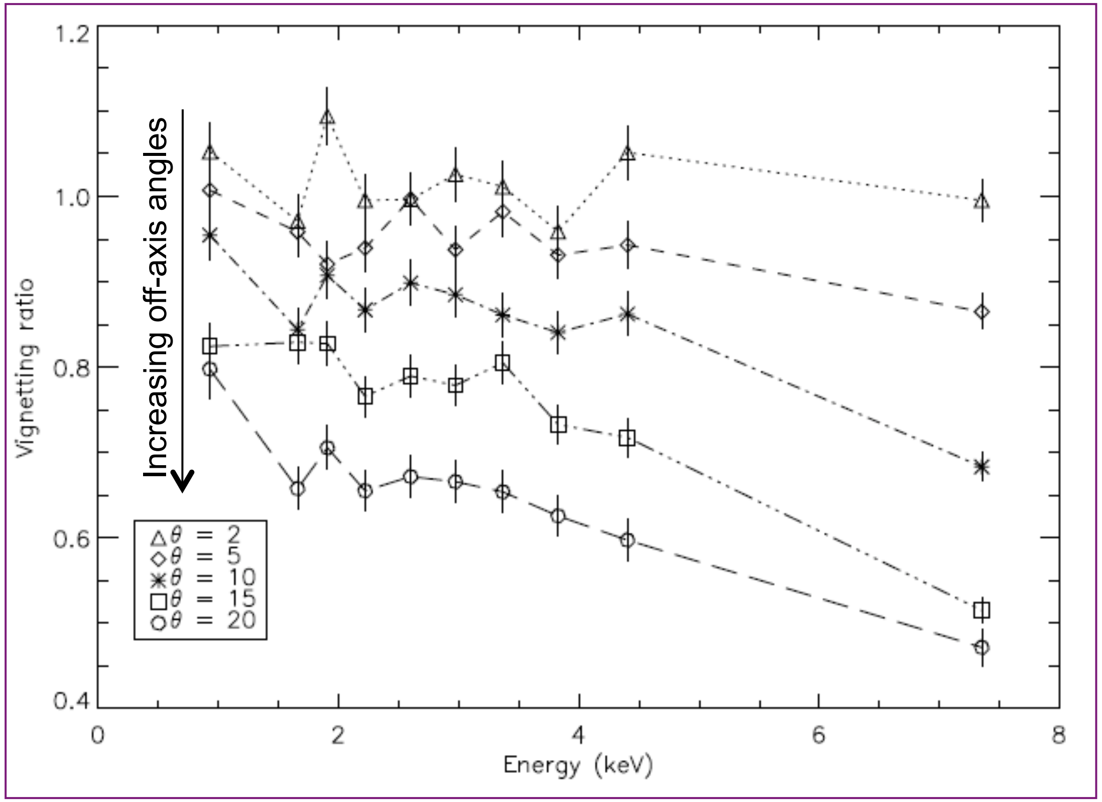
Chandra: energy resolution

Typical CCD resolution
100-150 eV



Chandra: vignetting

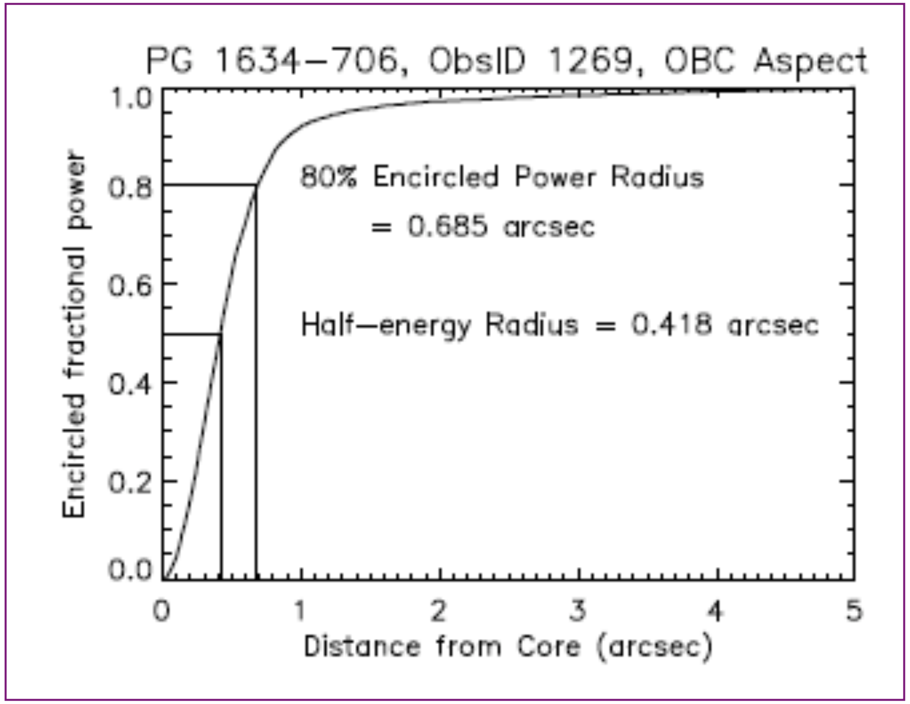
Vignetting ratio=ratio of the off-axis vs. on-axis counts at different off-axis angles



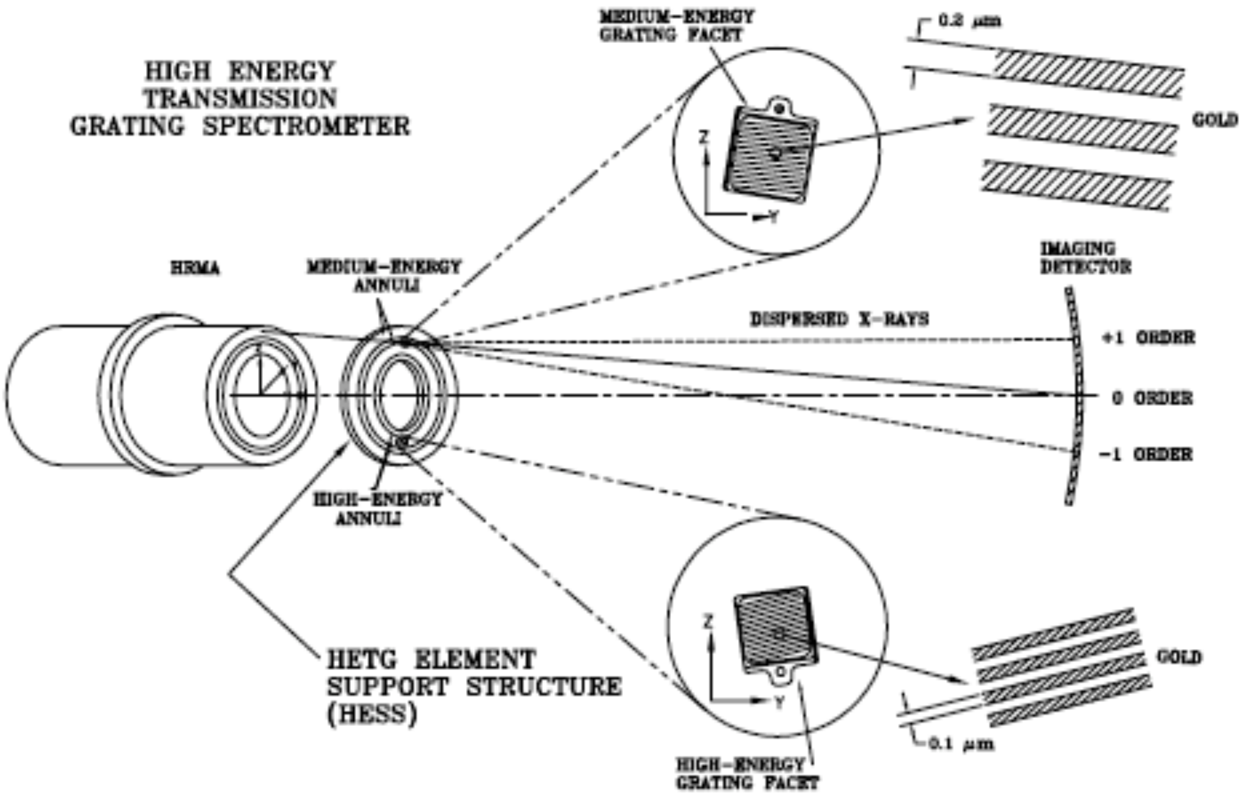
Hard X-ray photons are more difficult to focus

➔ **Vignetting**

Resulting image on the focal plane of ACIS

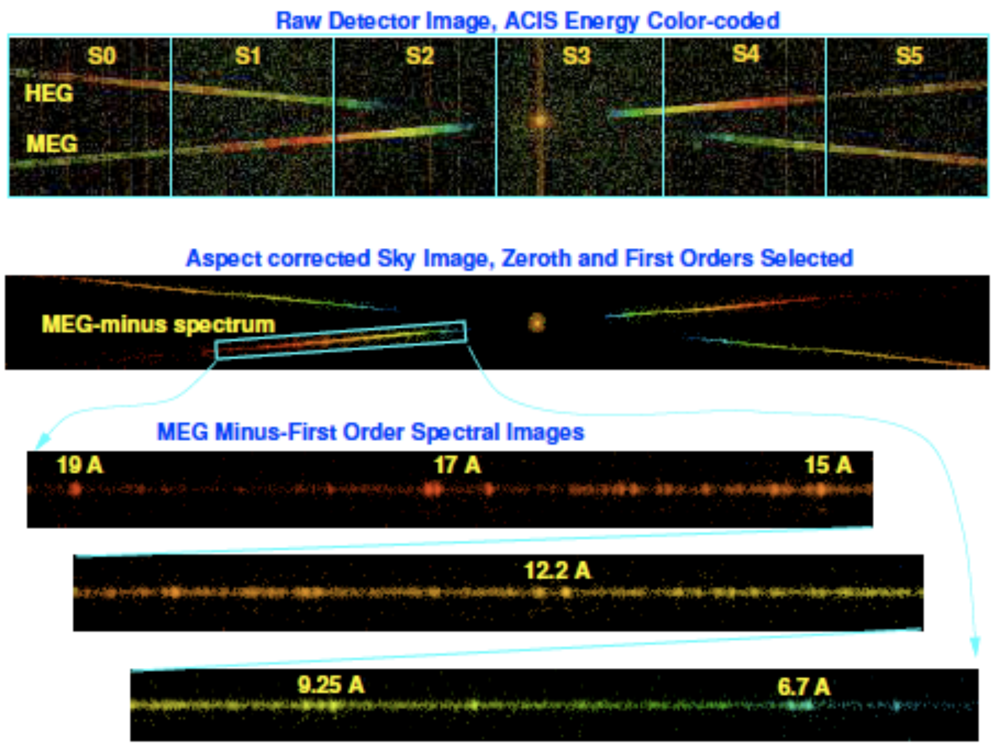


Chandra: the high-resolution spectrometers

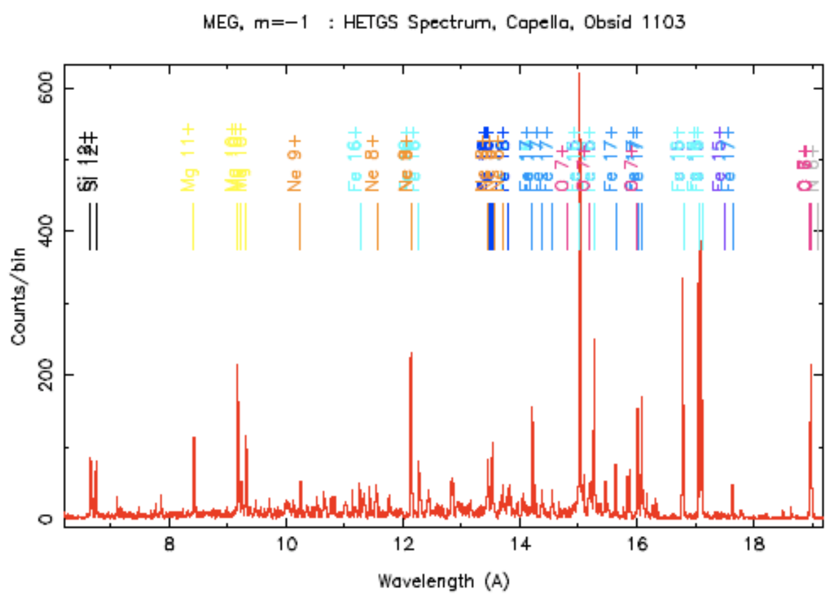


HETG: high-energy transmission gratings (HEG+MEG) - E/ΔE≈1000

Similar instrument at low energies (**LETG**)

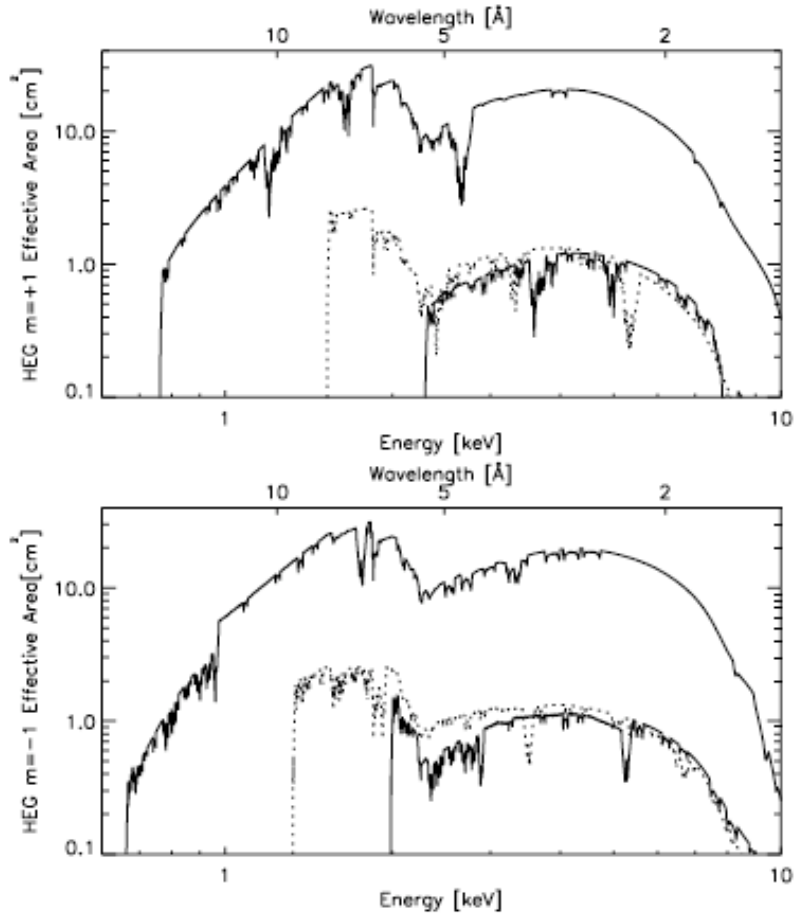


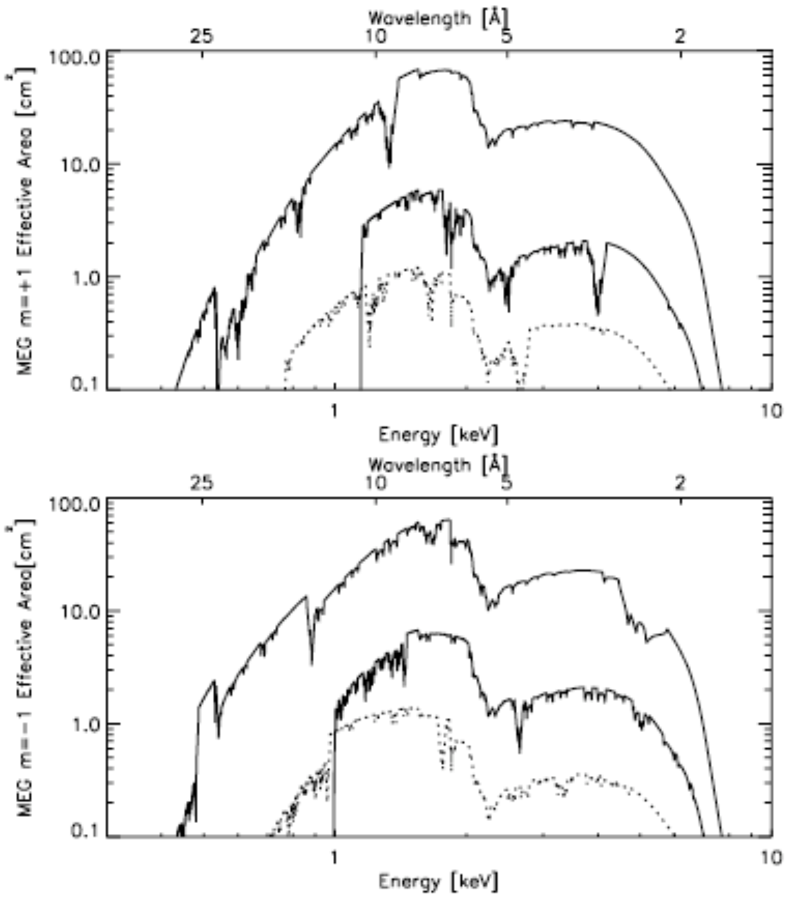
Capella X-ray spectrum



The spectrometers: effective area

Effective area: 200 cm^2 at most





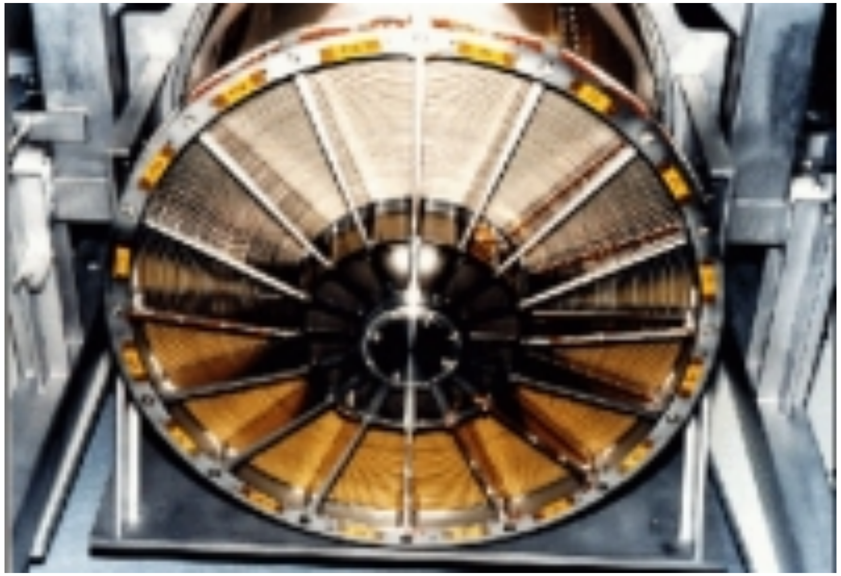
HEG: I, II and III orders (top panel: positive orders; bottom panel: negative)

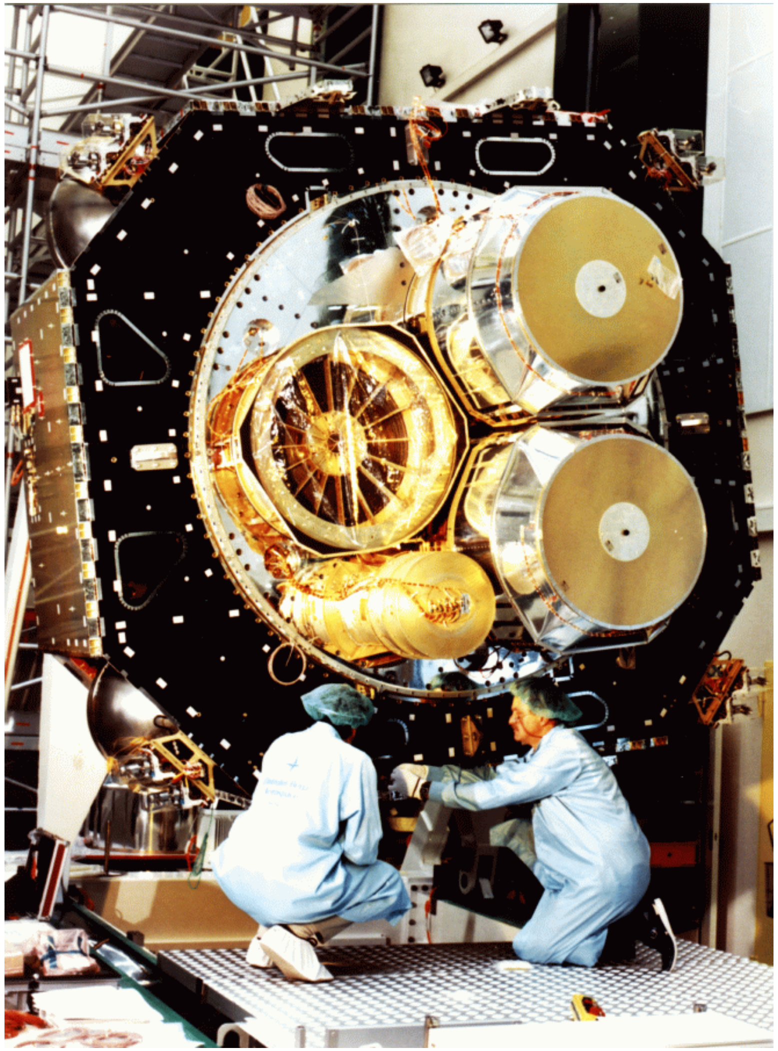
MEG: I, II and III orders (top panel: positive orders; bottom panel: negative)

XMM-*Newton* (ESA)

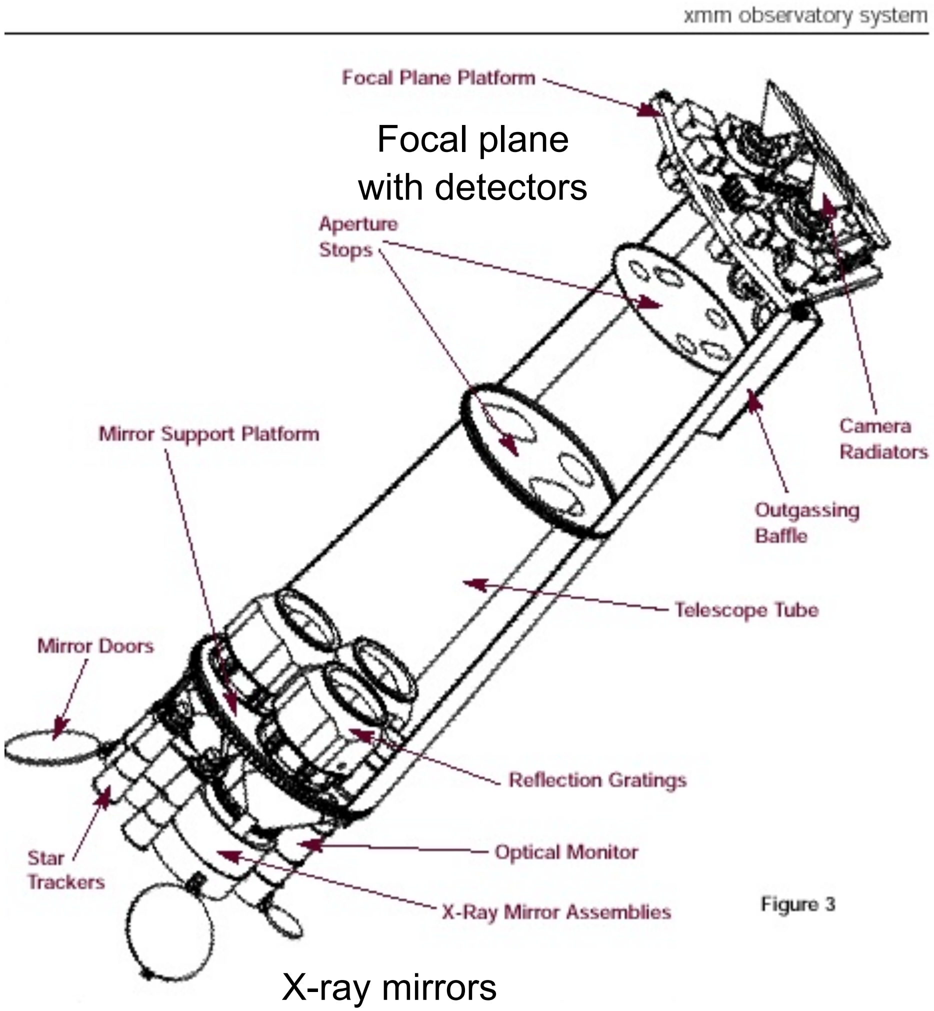
XMM-*Newton* = large effective area

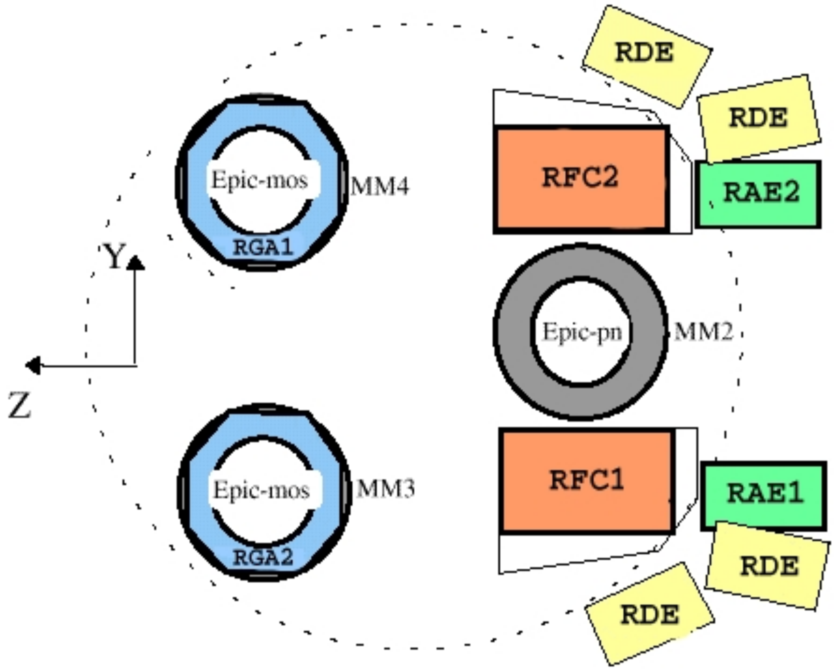
3 modules, 58 shells



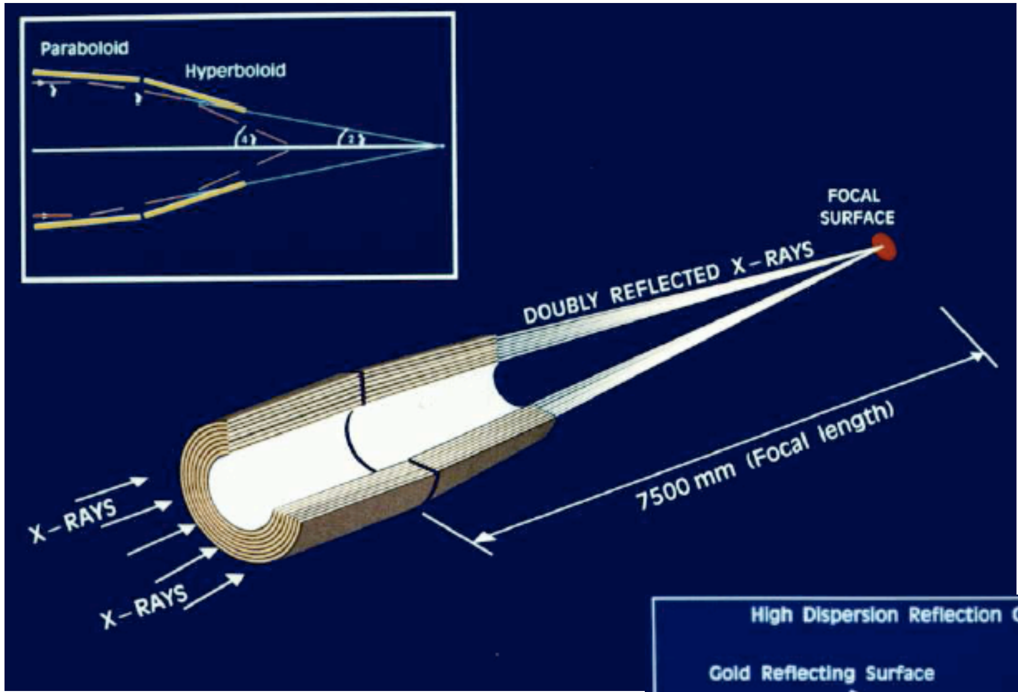


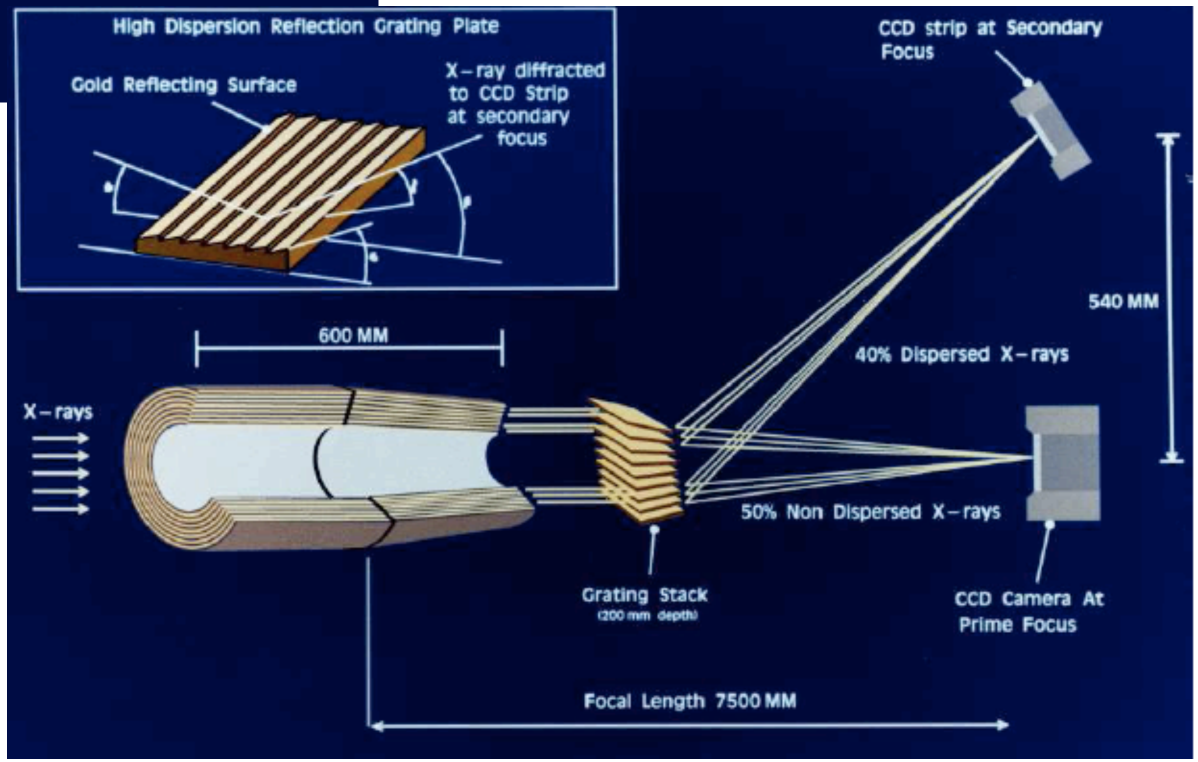
XMM-Newton: all instruments at work simultaneously





Wolter I solution

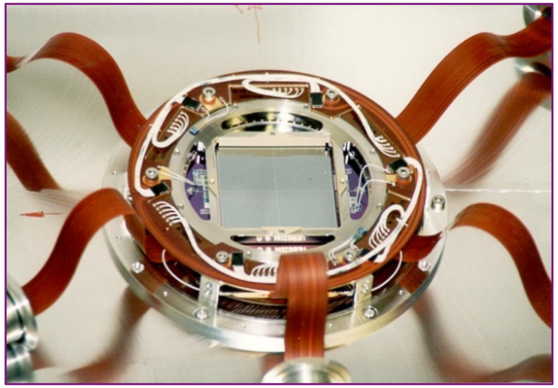


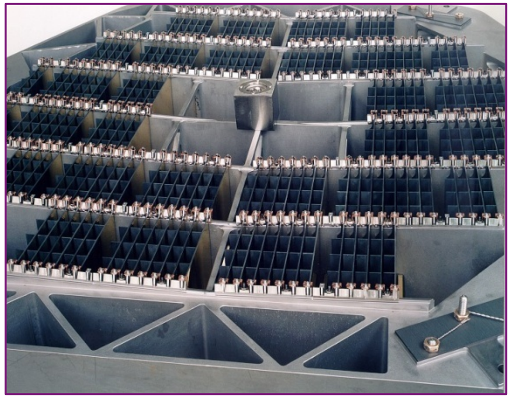


Full incident photons to the pn CCD, ≈50% to the MOS1-2, the rest to the grating spectrometers (RGS)

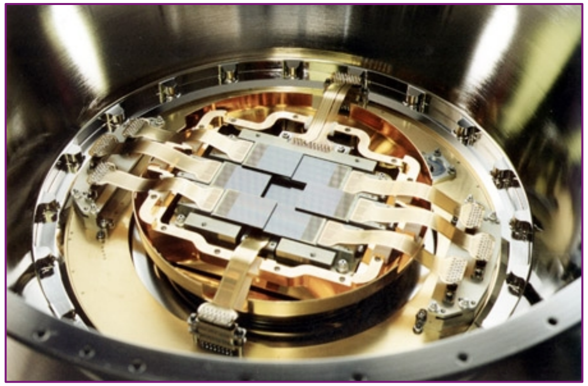
XMM-*Newton:* the EPIC (pn+MOS1-2) camera

pn

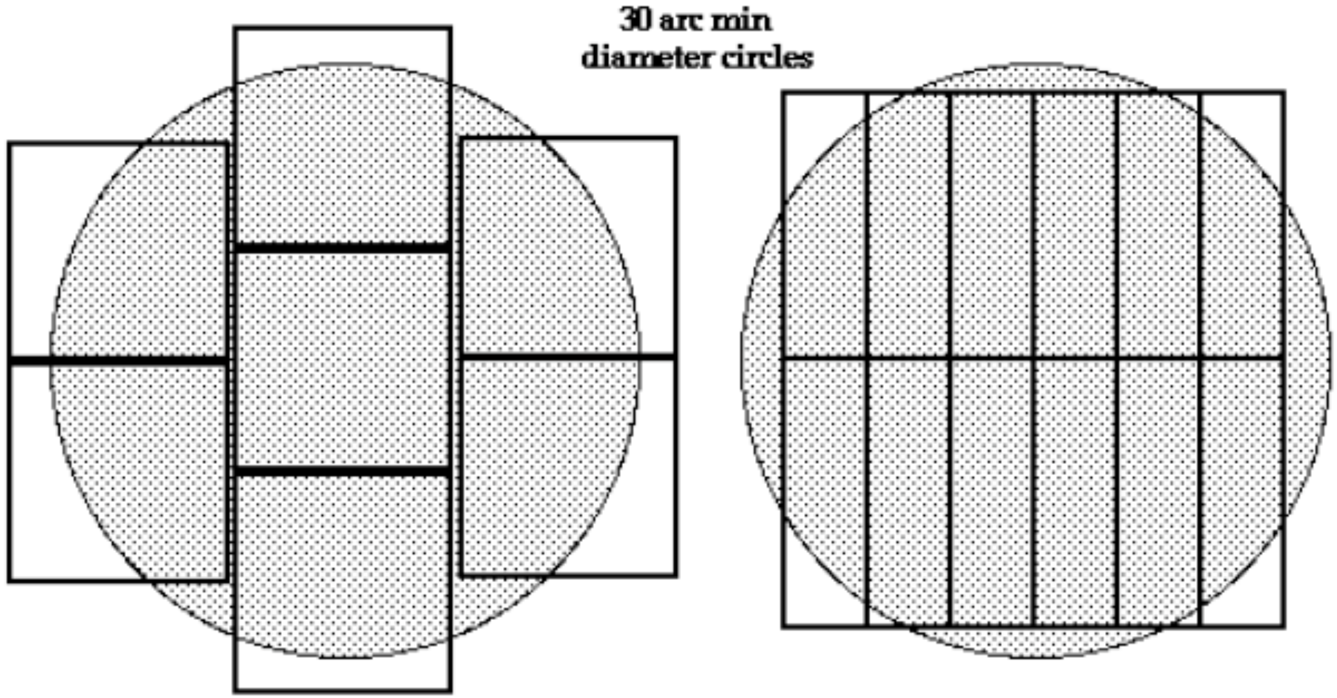




MOS1-2



XMM-*Newton:* the EPIC (pn+MOS1-2) camera



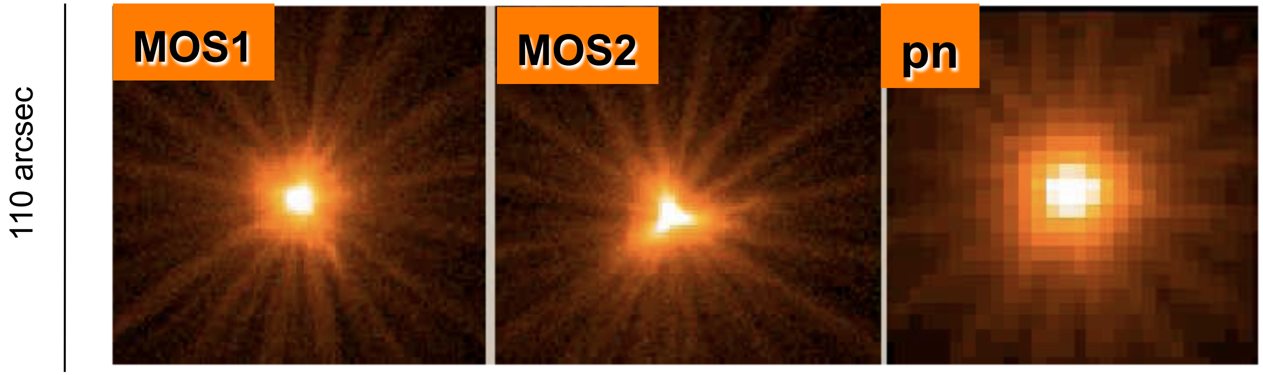
EPIC MOS

7 CCDs each 10.9 x 10.9 arcminutes

EPIC pn

12 CCDs each 13.6 x 4.4 arcmin

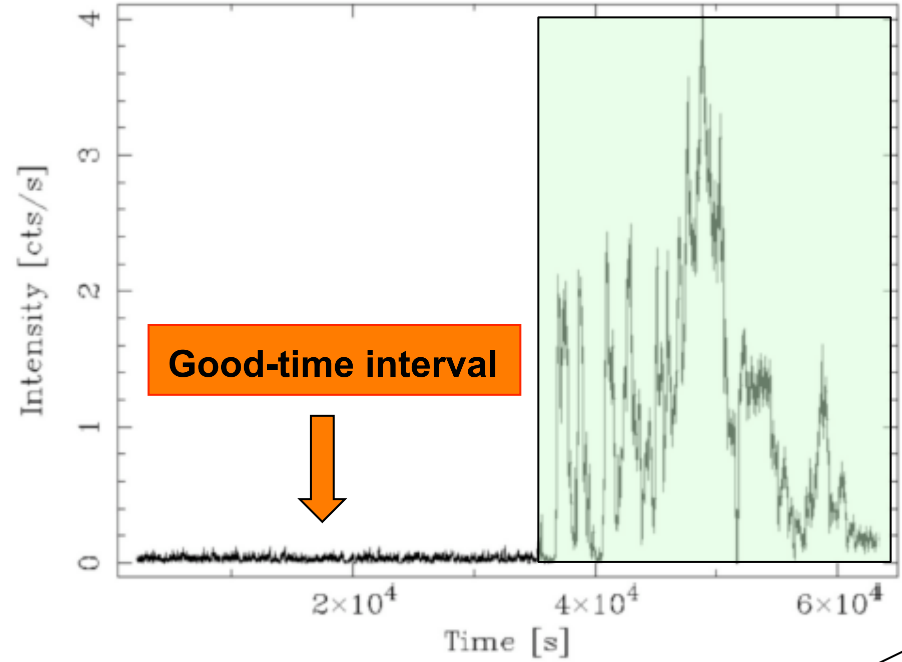
XMM-*Newton:* the EPIC on-axis PSF



spider-like pattern due to the support of the Wolter I mirrors

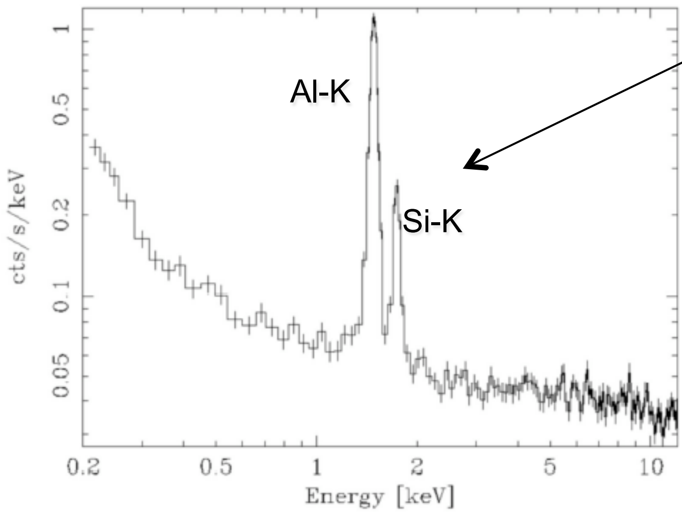
Mirror module	2	3	4
Instr. chain[a]	pn	MOS-1+RGS-1	MOS-2+RGS-2
	orbit/ground	orbit/ground	orbit/ground
FWHM [″]	$< 12.5^b/6.6$	4.3/6.0	4.4/4.5
HEW [″]	15.2/15.1	13.8/13.6	13.0/12.8

PSF FWHM larger than in *Chandra* but much higher effective area
Background (and confusion limit) can be an issue

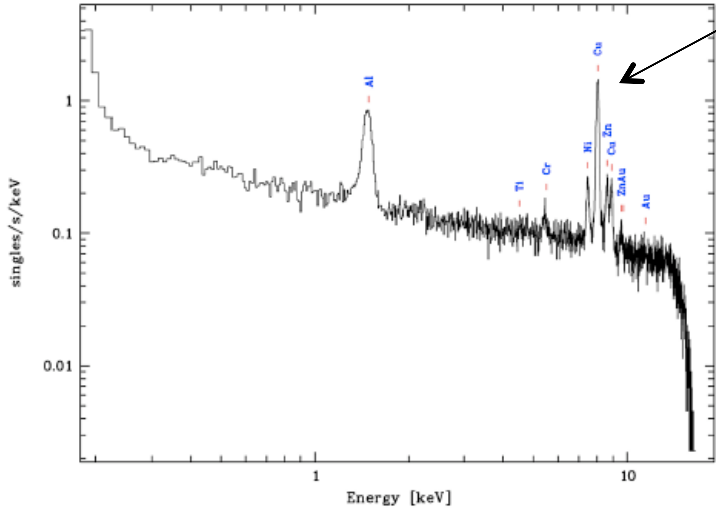


High-particle background due to proton flares (E ≈ few hundred keV) related to the XMM-*Newton* orbit.
Sometimes most of the observation is "lost"

Fluorescence emission lines due to interaction of high-energy (>100 MeV) particles with the structure of the detectors
➔ stable component + spatial distribution, needs removal of certain energy ranges

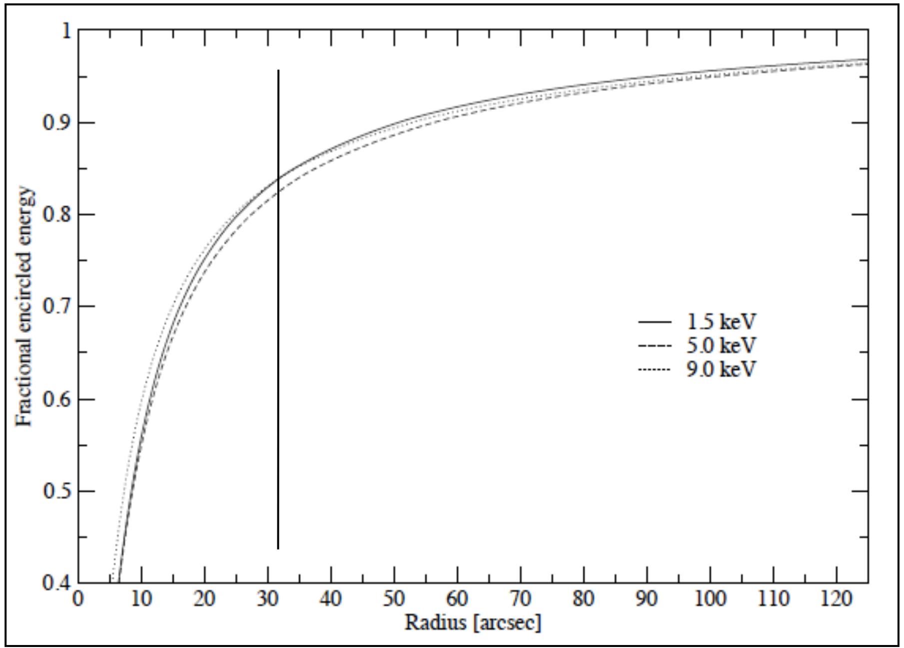


MOS



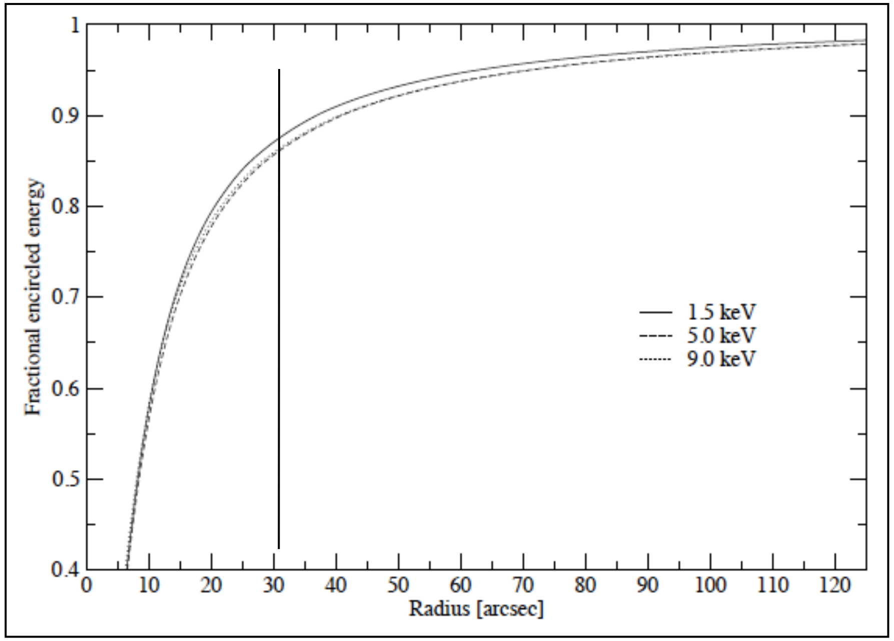
pn

XMM-*Newton:* the EPIC on-axis Encircled Energy Fraction

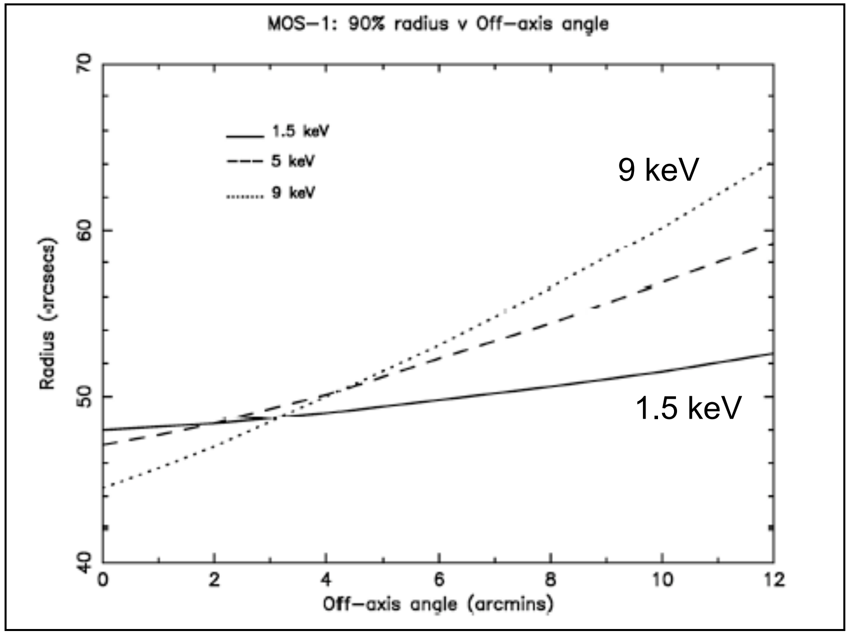


Encircled energy vs. radius
at different energies for the MOS1-2

Encircled energy vs. radius
at different energies for the pn

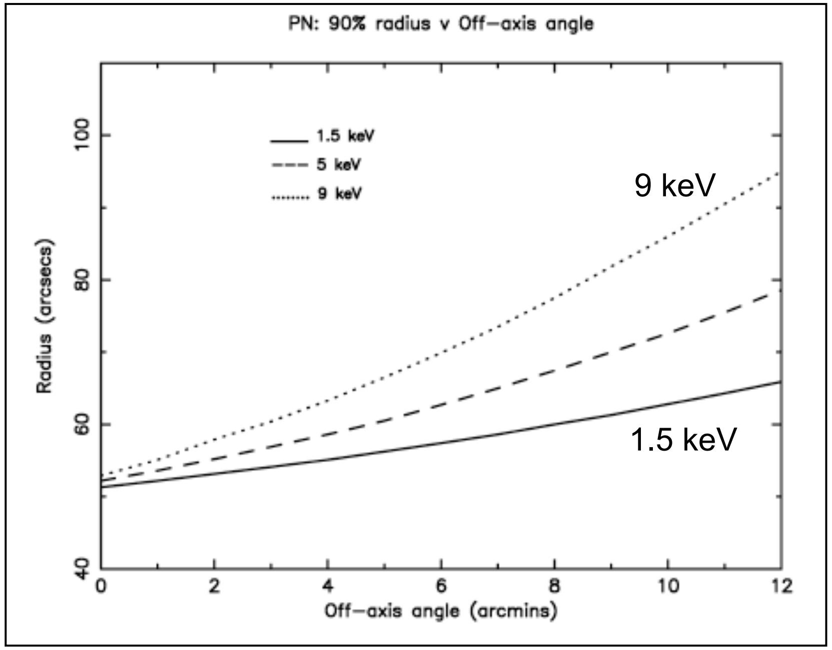


XMM-*Newton:* the EPIC off-axis PSF

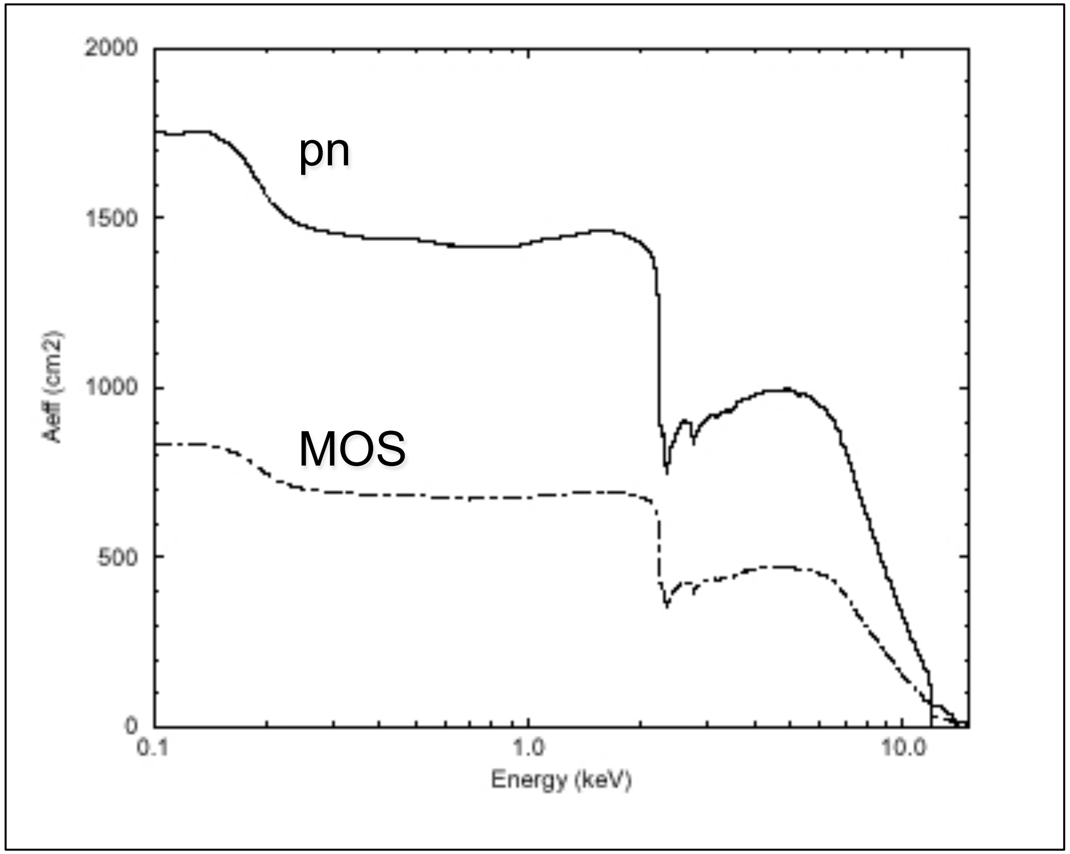


90% radius (radius encompassing 90% of the incoming photons) vs. off-axis angle for the MOS1-2 at different energies

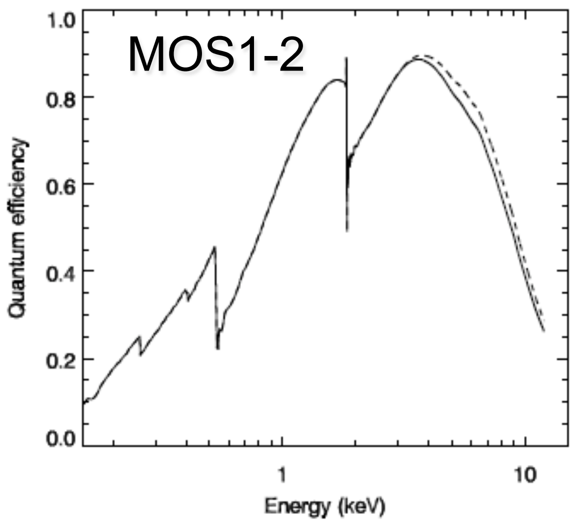
90% radius vs. off-axis angle for the pn at different energies

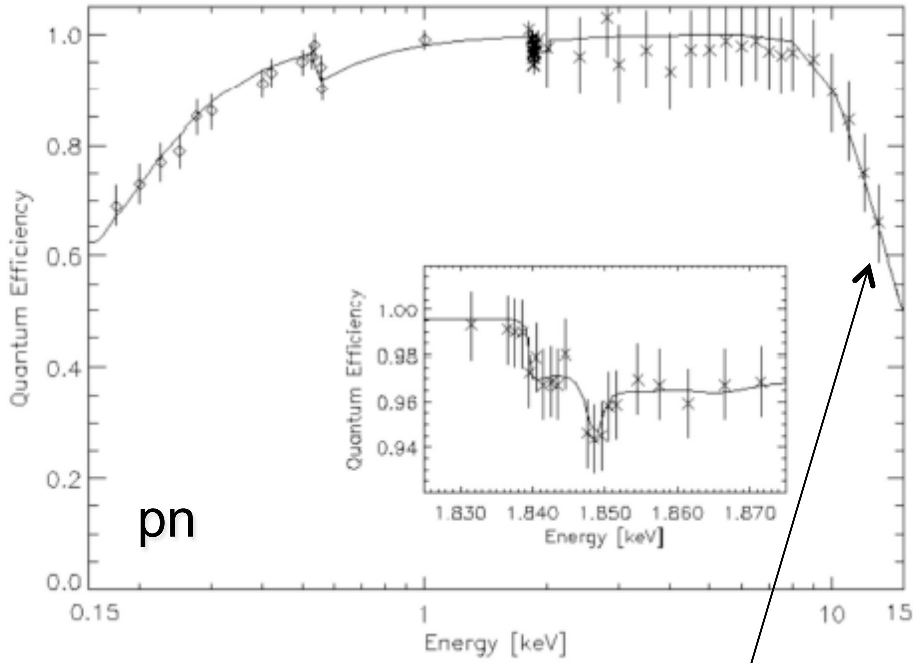


XMM-*Newton:* mirror effective (geometric) area



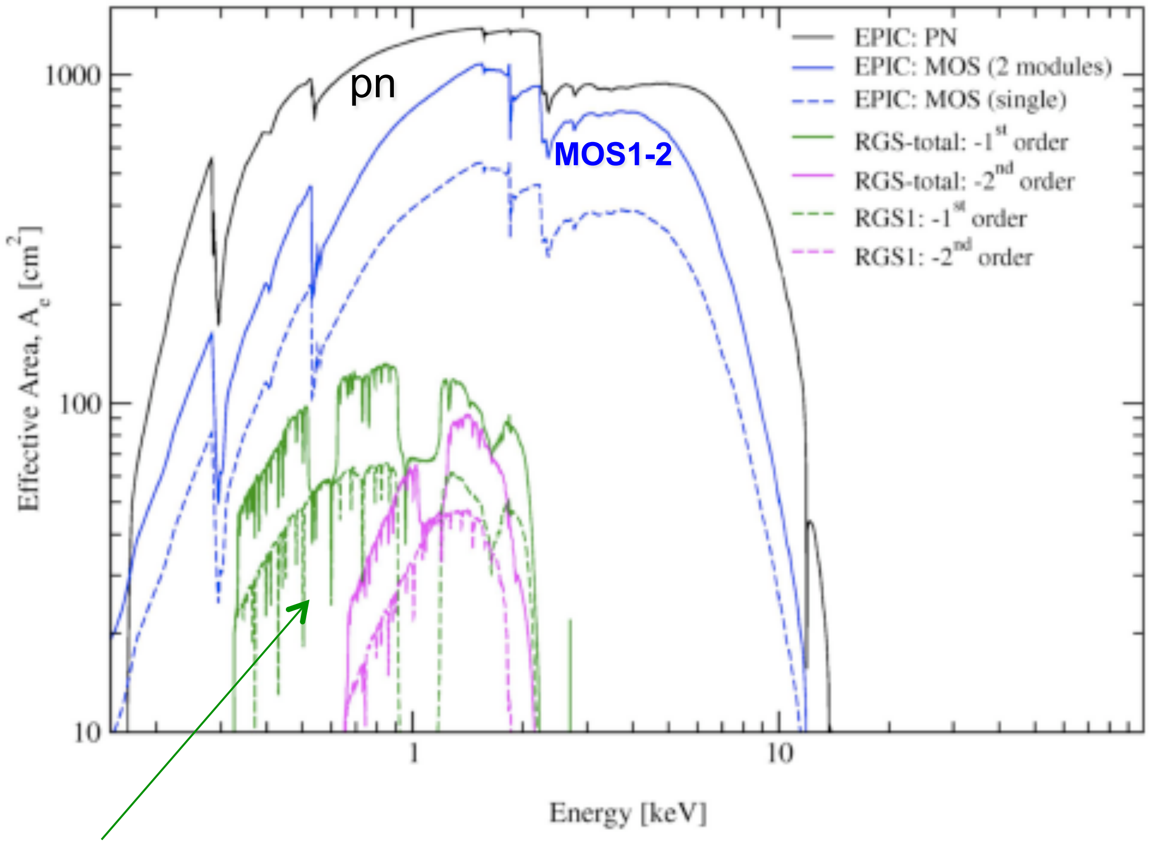
XMM-*Newton:* quantum efficiency





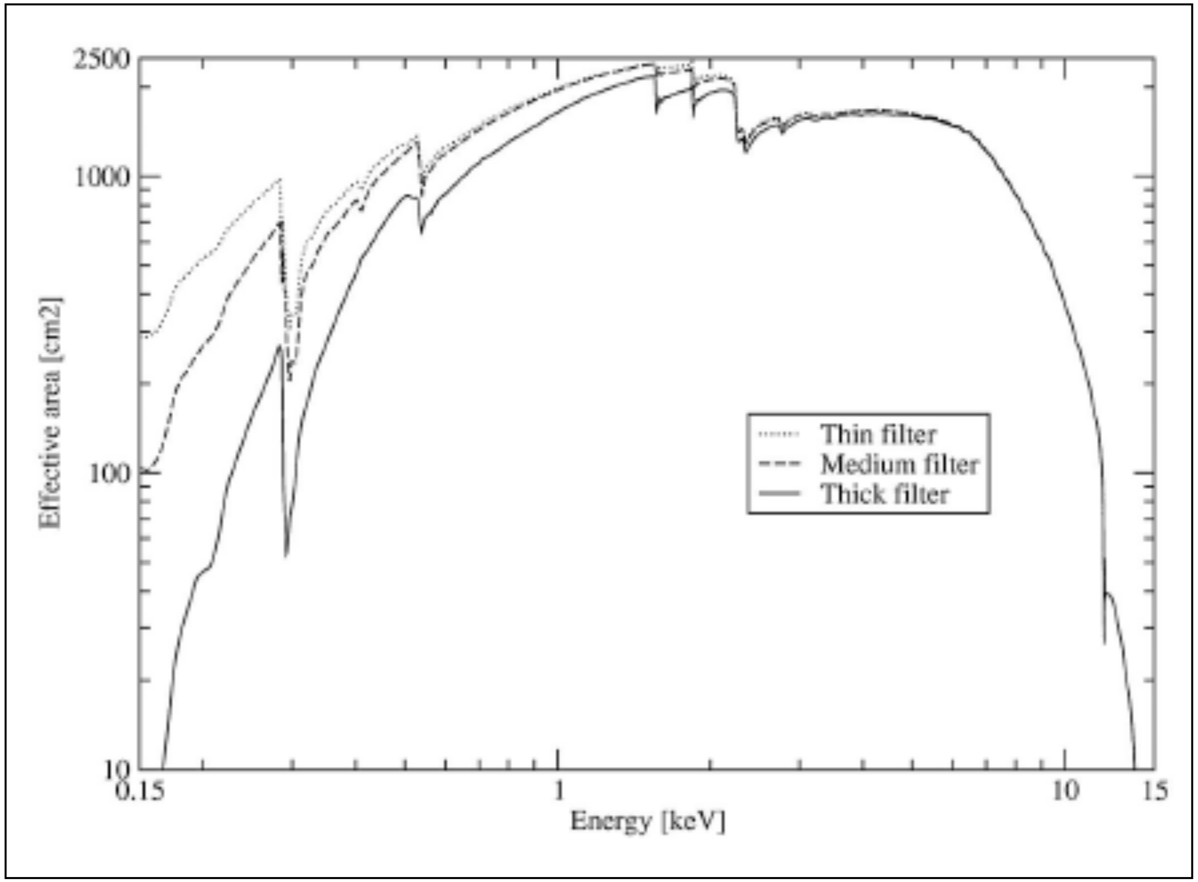
Strong decrease in the QE above 10 keV, where also the effective area due to the mirrors has a significant decrease

XMM-*Newton:* effective area



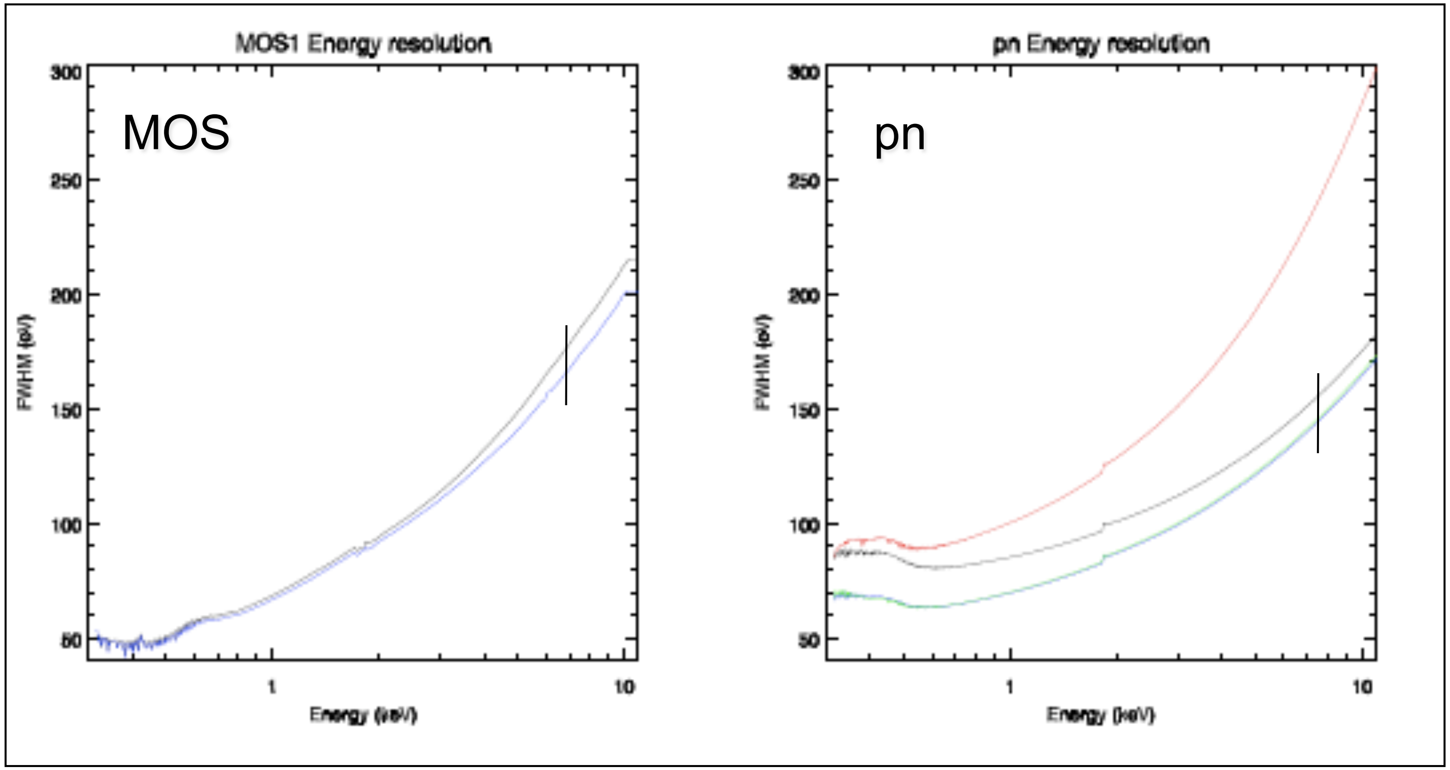
High-resolution spectrometers (up to 2.5 keV) have much lower effective area than the EPIC camera instruments (pn and MOS1-2)

XMM-*Newton:* effective area dependence on the filter choice

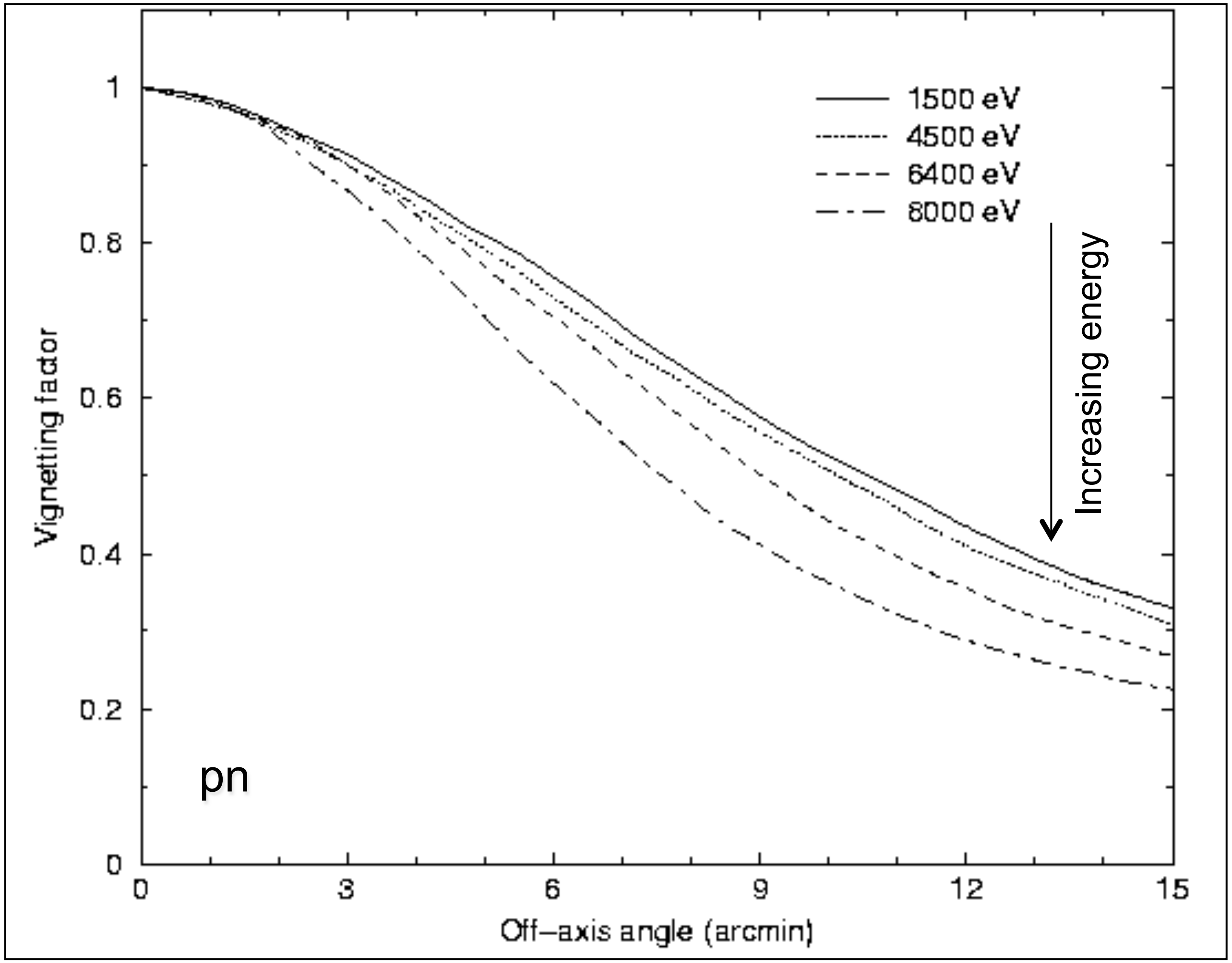


To avoid contamination from bright, soft objects (e.g., stars), a medium/thick filter is adopted

XMM-*Newton:* energy resolution



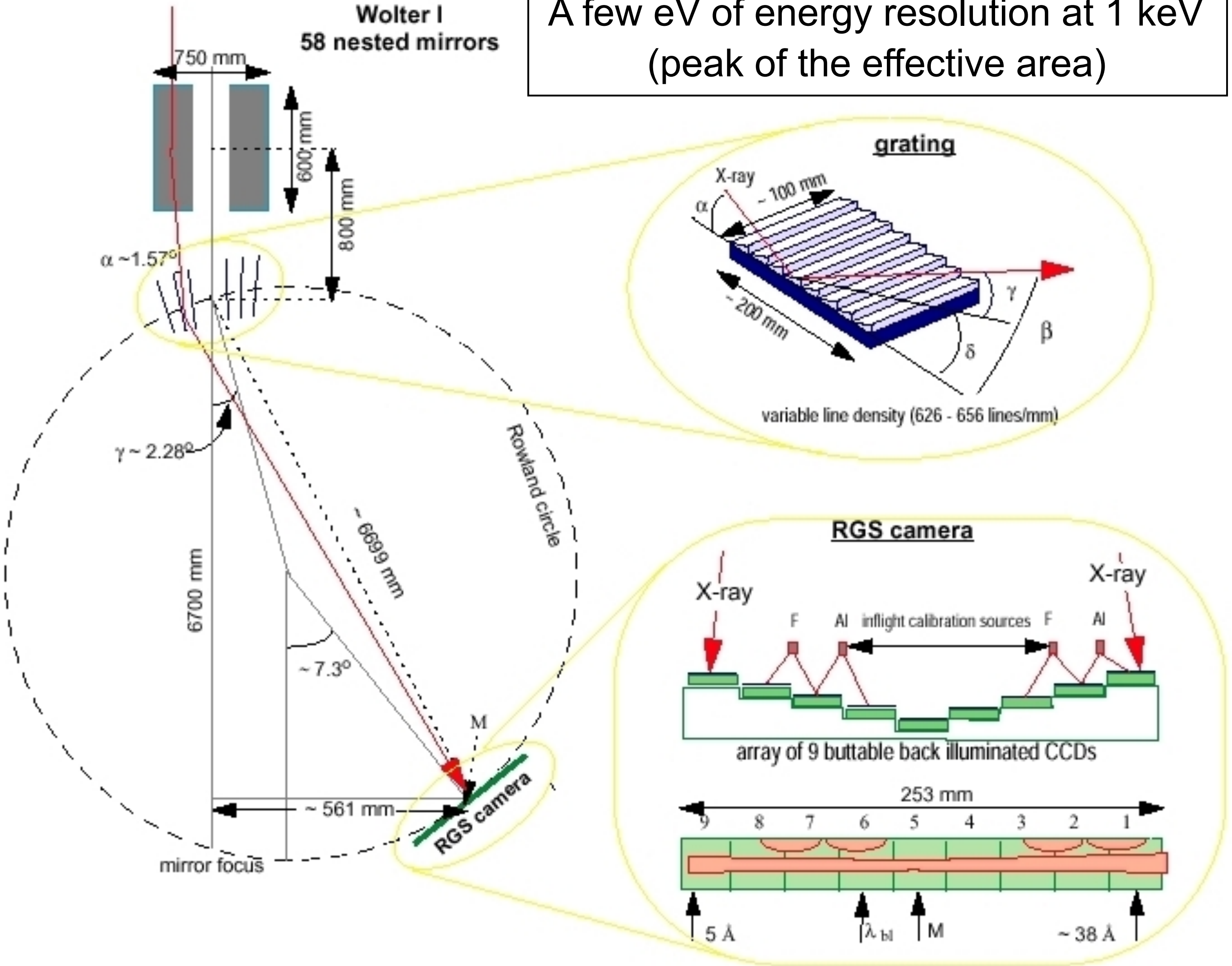
Energy resolution of ≈150 eV at 6 keV typical of X-ray CCDs

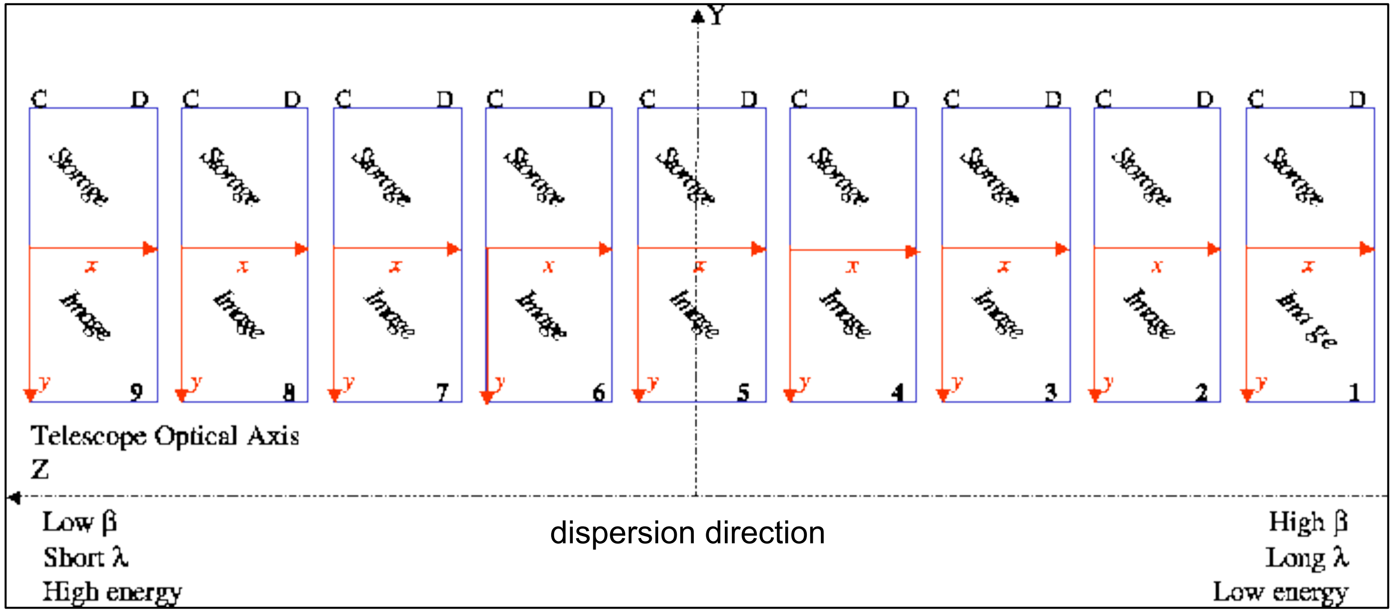


Strong vignetting (as expected) for high-energy photons,
partly compensated by the large effective area (e.g., wrt. *Chandra*)

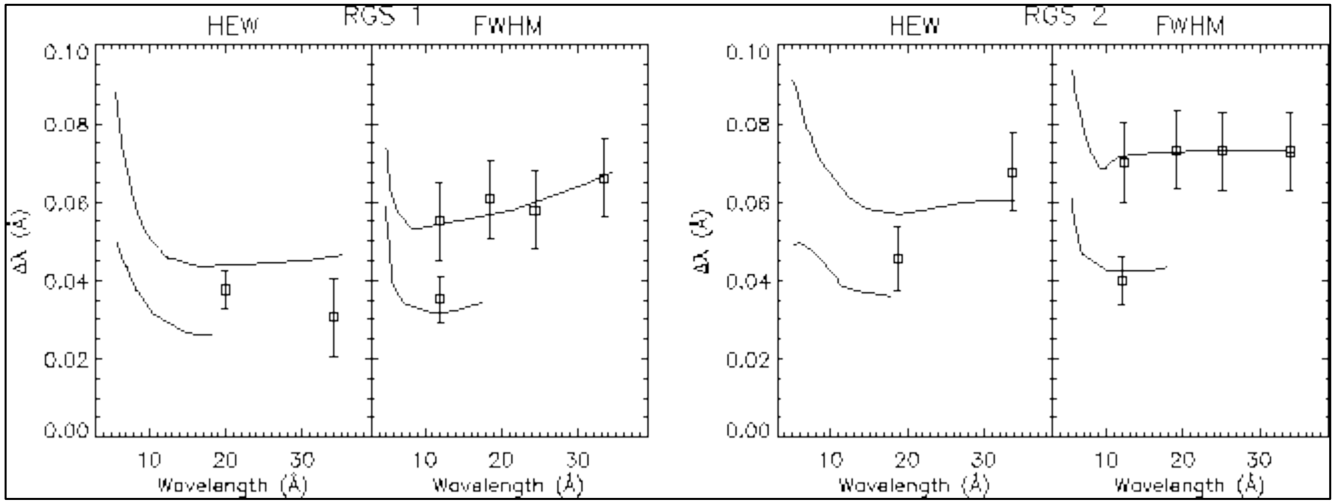
XMM-*Newton:* the RGS instrument

A few eV of energy resolution at 1 keV
(peak of the effective area)





Y
C D
Storage
Image
x
y
9 8 7 6 5 4 3 2 1
Telescope Optical Axis
Z
Low β
Short λ
High energy
dispersion direction
High β
Long λ
Low energy



RGS 1
HEW
FWHM
RGS 2
Δλ (Å)
0.00
0.02
0.04
0.06
0.08
0.10
10
20
30
Wavelength (Å)

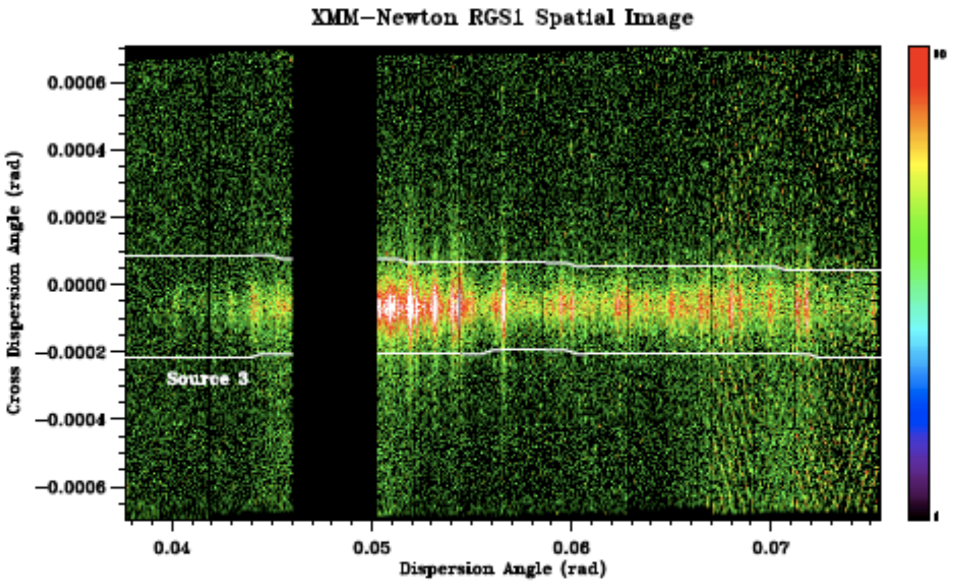
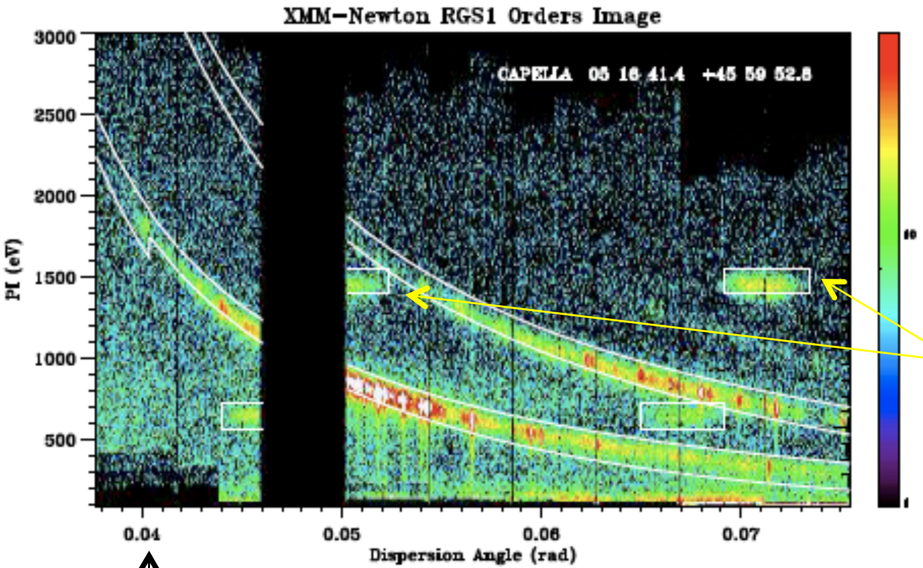


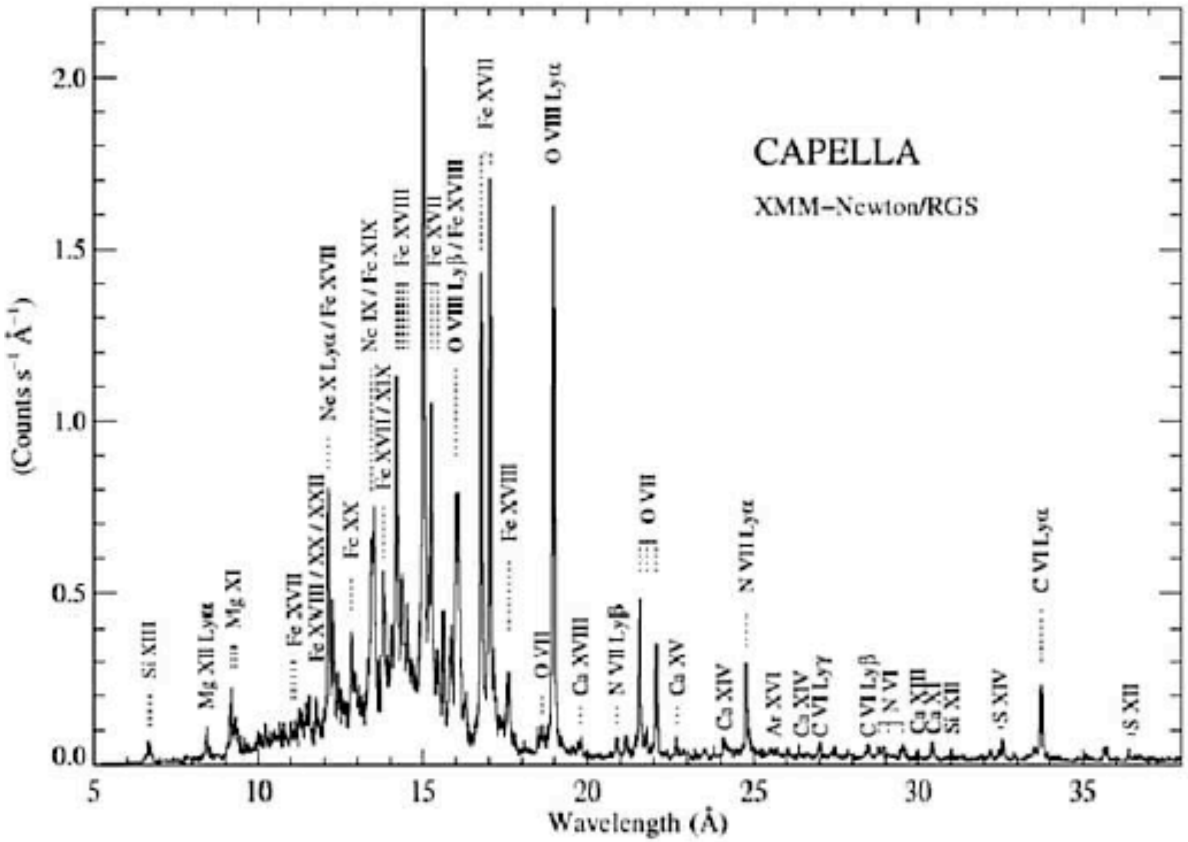
Image of the dispersed light in the detector



Order selection plane as a function of energy

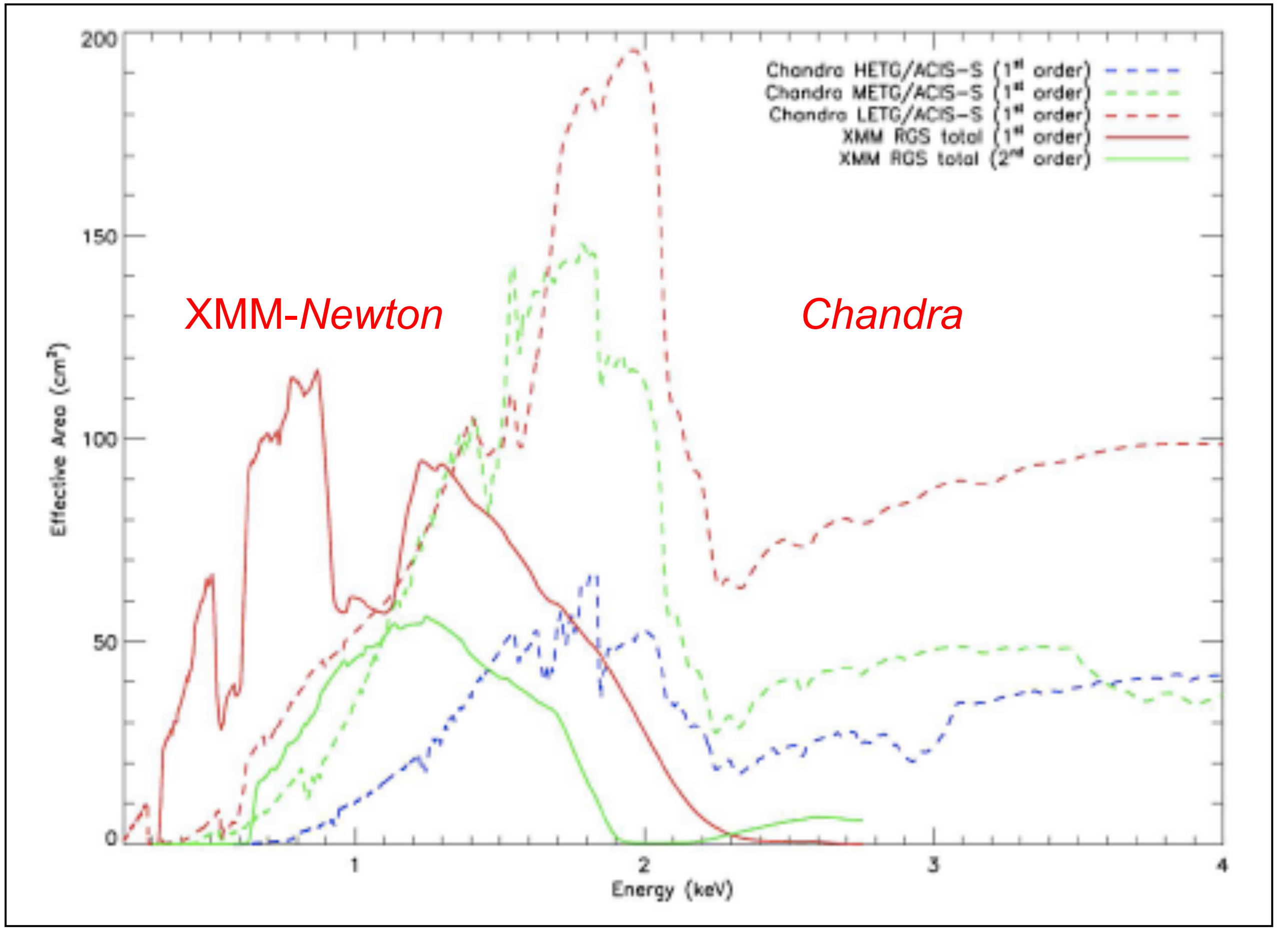
calibration sources

short wavelengths, high energies



Resulting high-resolution spectrum of Capella

XMM-*Newton* high-resolution spectrometers vs. those onboard *Chandra*

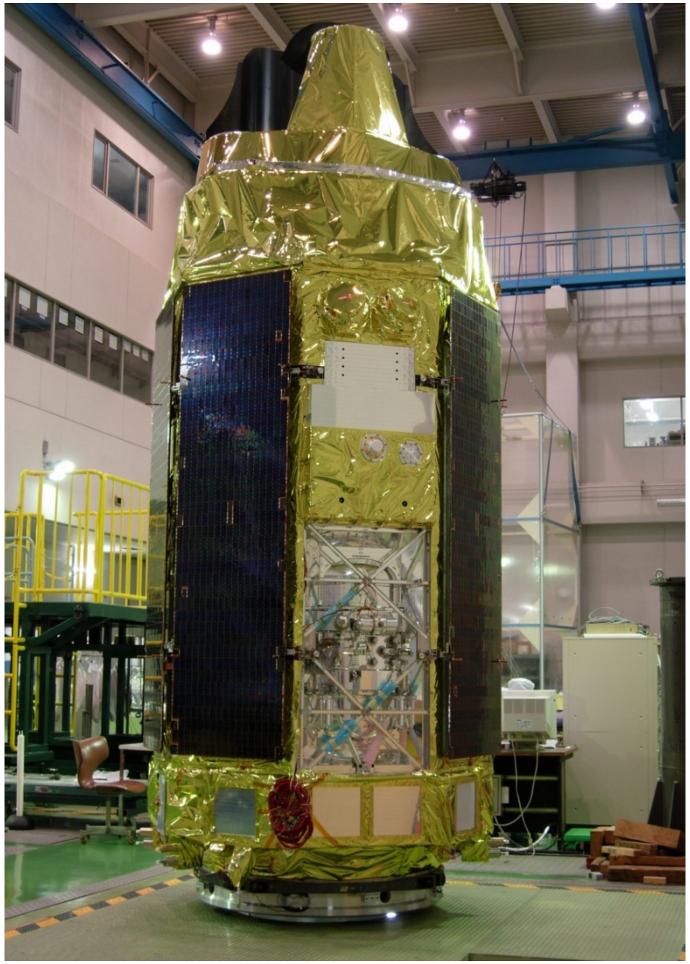


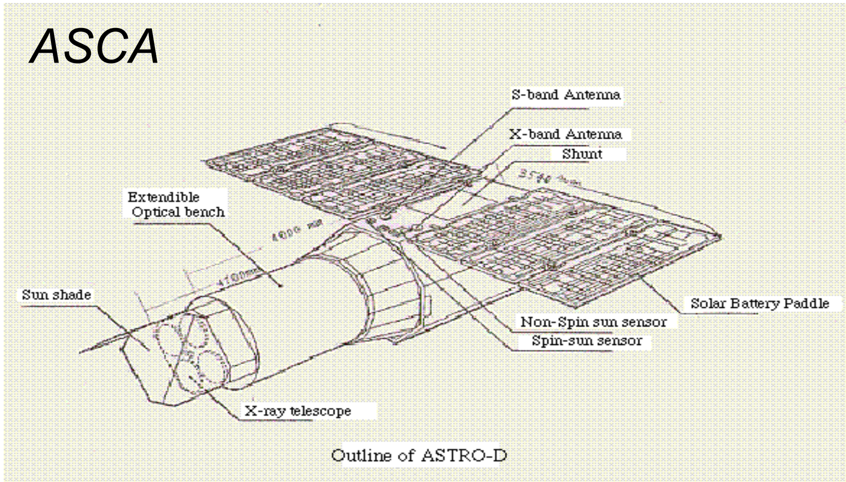
At very low energies (soft X-rays), XMM-*Newton* RGS have no "counterparts" in *Chandra*
Detector choice based on energy band pass, effective area and spectral resolution

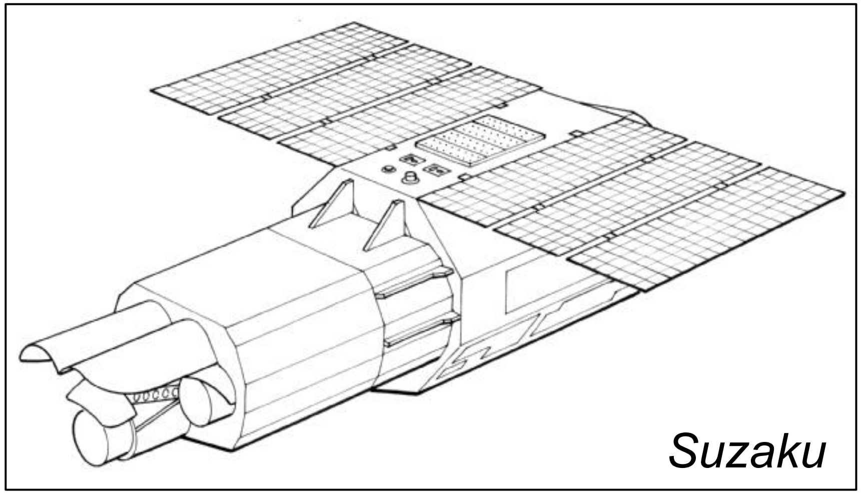
Gamma/X-ray satellites in a nutshell

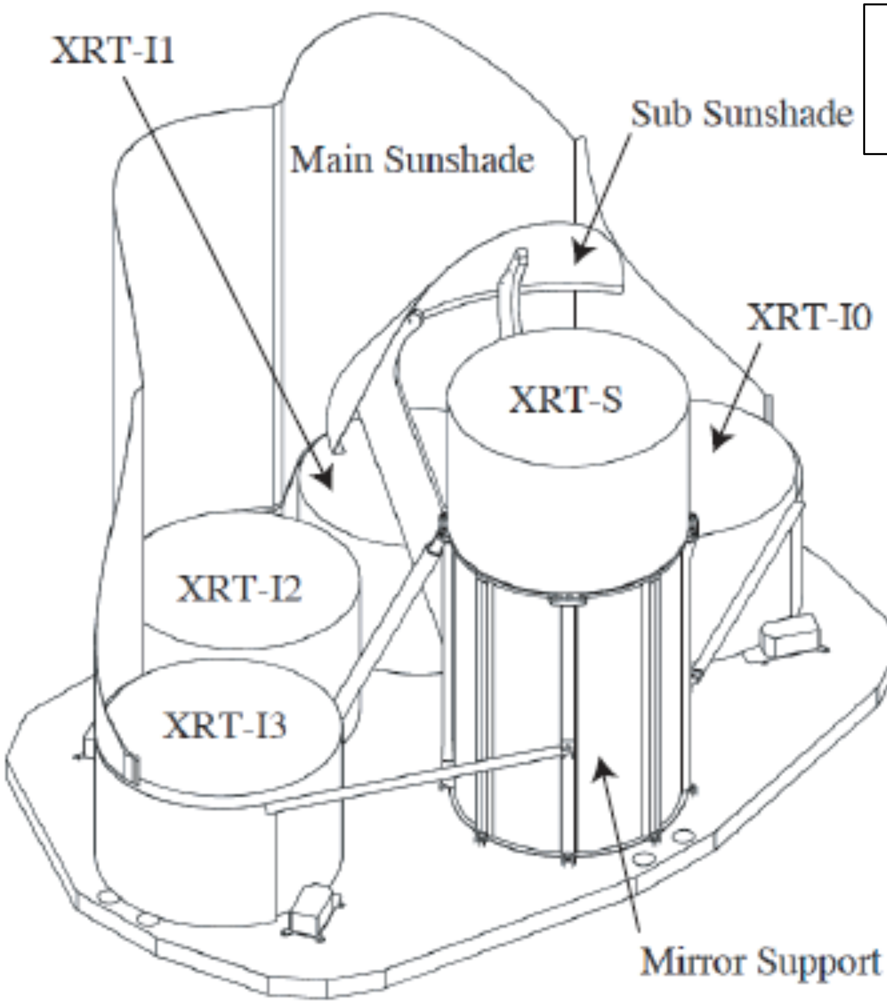
Suzaku (JAXA+NASA)

Suzaku = high-energy (non-imaging) instrument









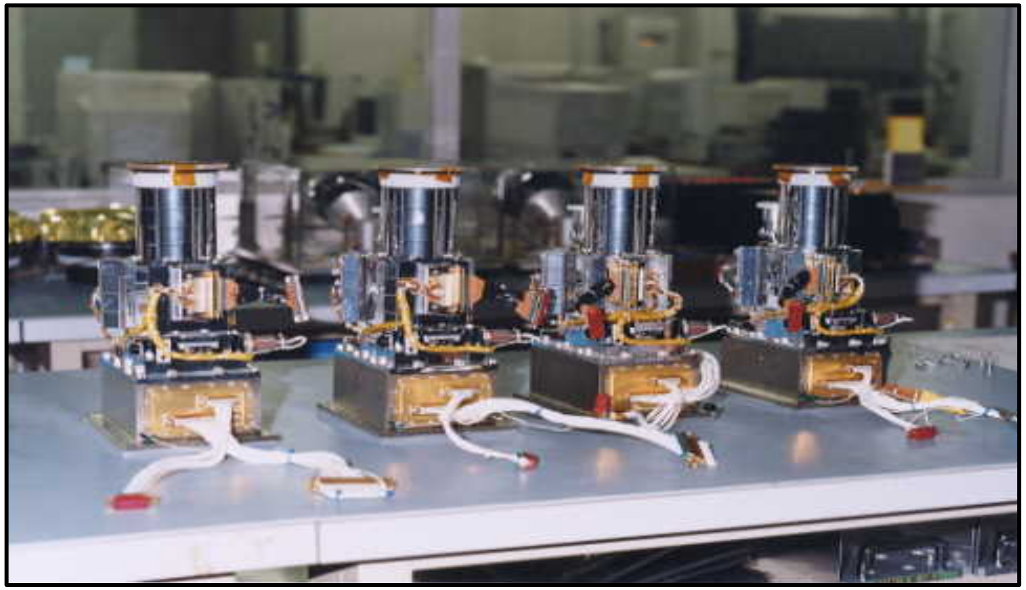
XRT (4 units):
low-resolution spectrometers

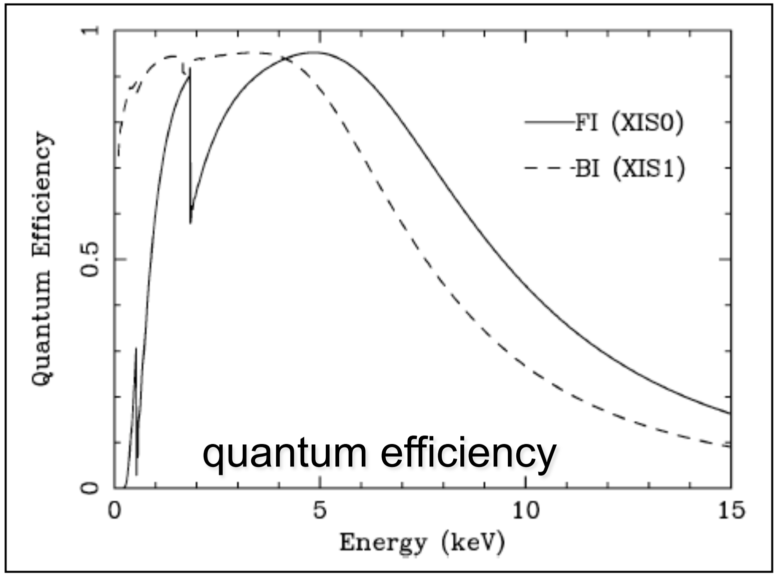
XRS: calorimeter
failure at the beginnings

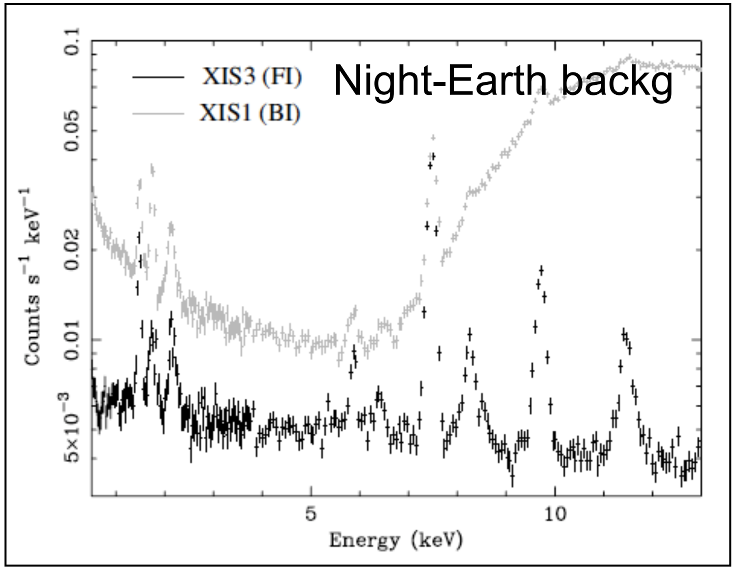
+

pin/GSO detectors at
high energies [15-300
(600) keV]

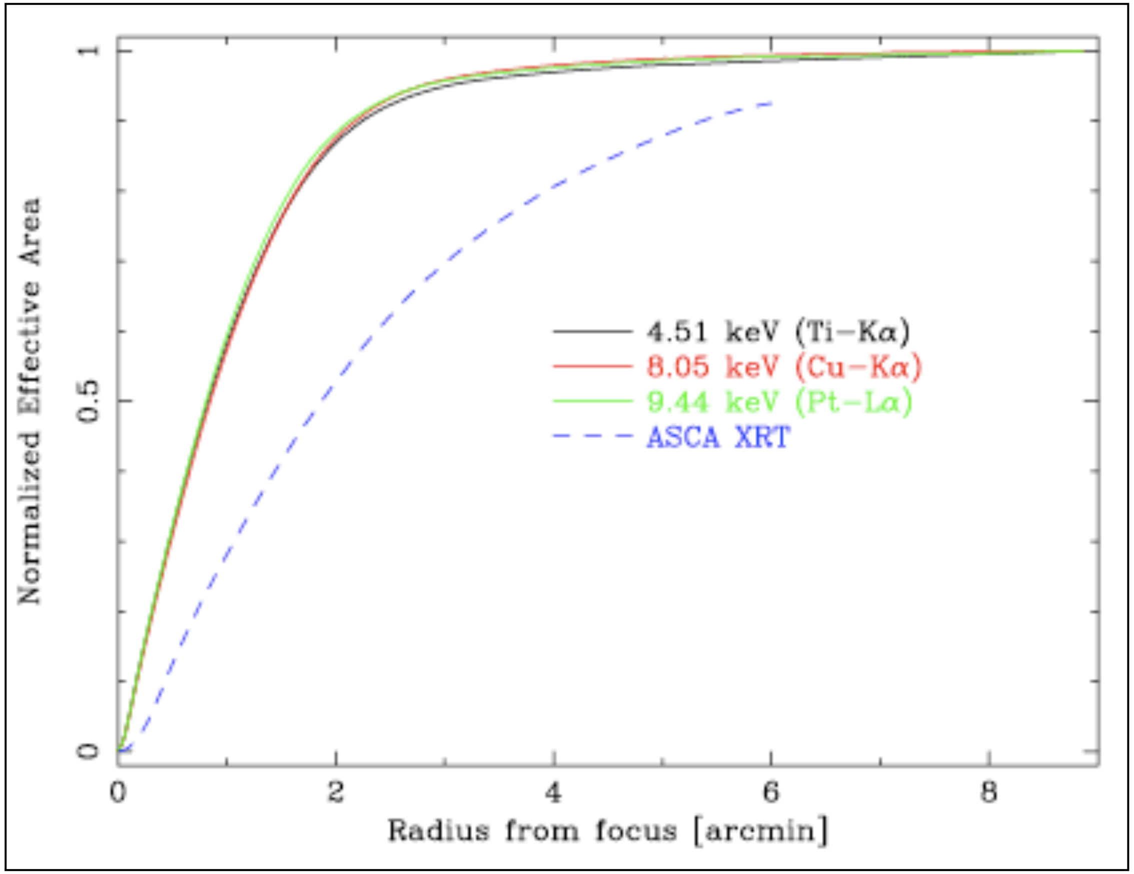
Suzaku: the X-ray imaging spectrometers (XIS)



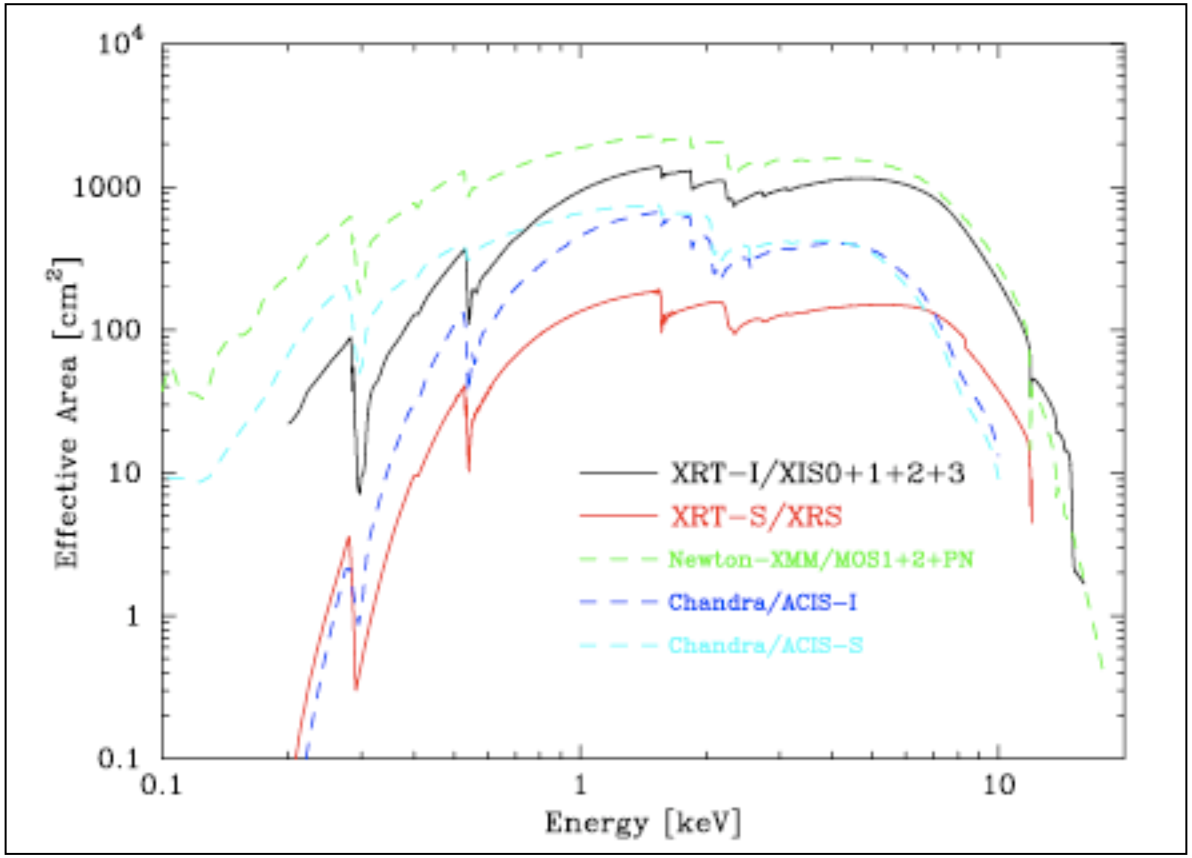




Suzaku: normalized effective area vs. ASCA

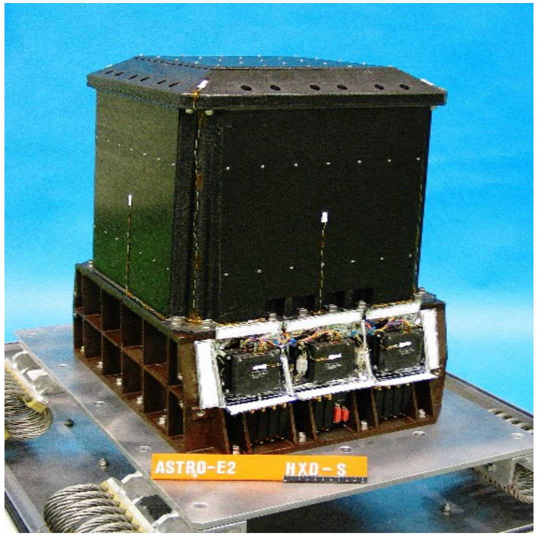


Suzaku: comparison of effective area wrt. other X-ray satellites

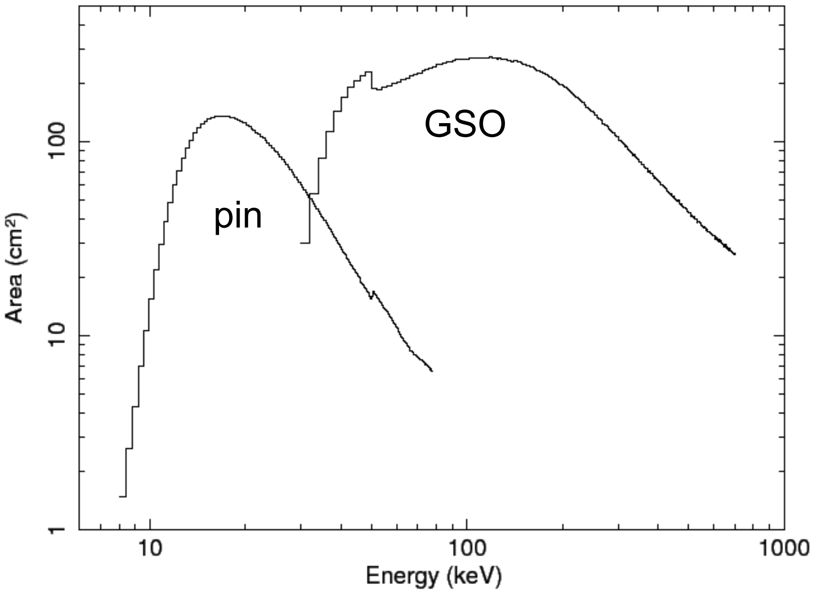


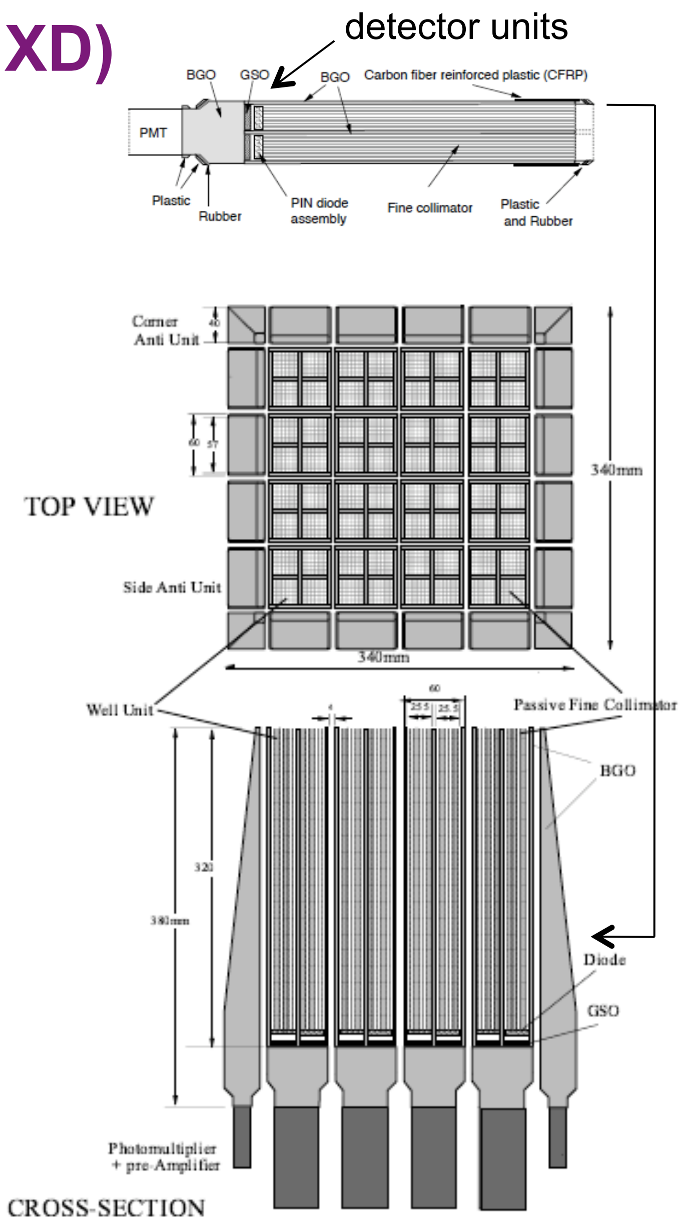
Effective area larger than *Chandra* but smaller than XMM-*Newton*

Suzaku: hard X-ray detector (HXD)



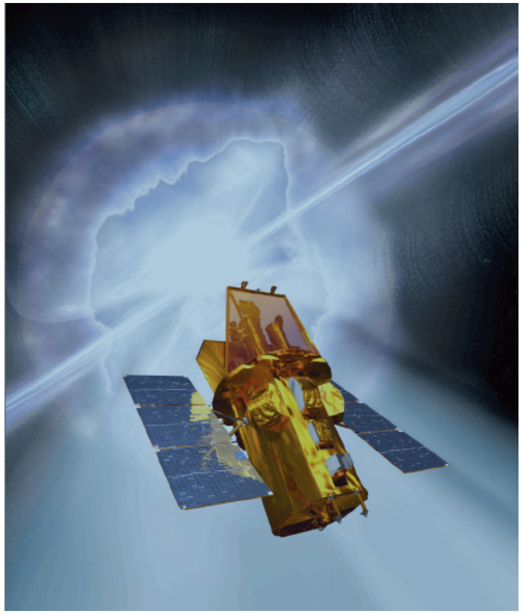
Hard X-ray Detector (HXD)





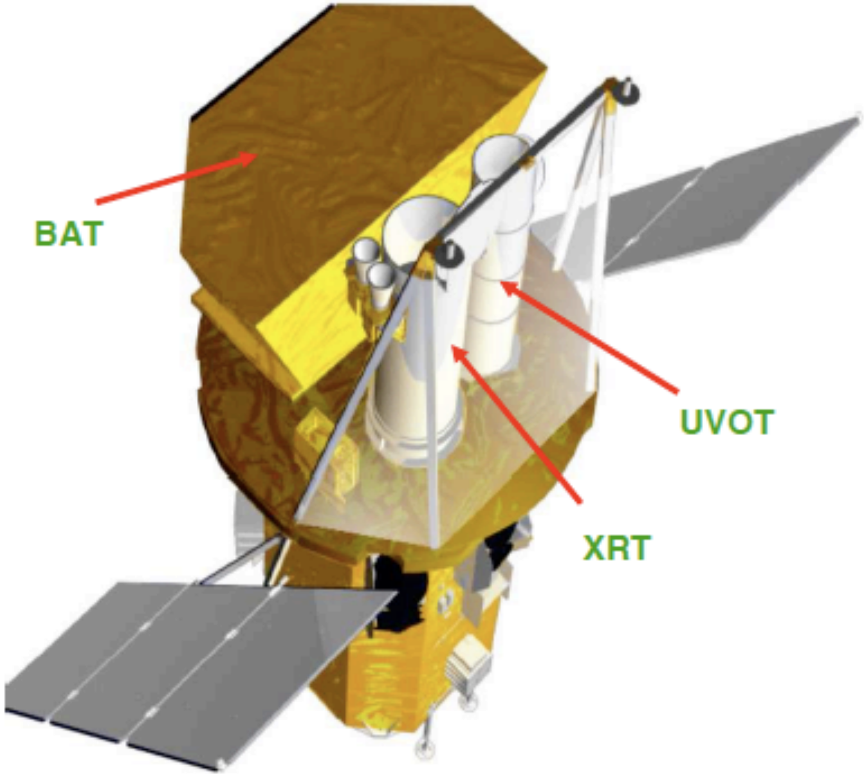
Swift (NASA)

Swift: 0.2-200 keV



Launched on 20th Nov, 2004
Medium explorer NASA
Science focused on the search and study of GRBs
and rapid pointing (20-75 sec reaction time)

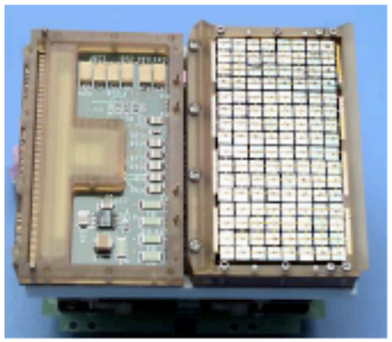
Instruments onboard Swift

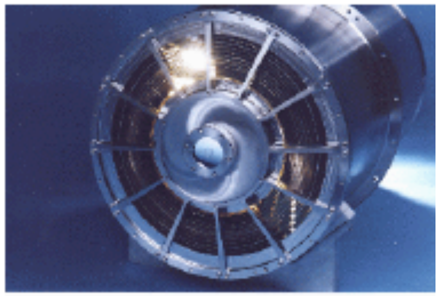


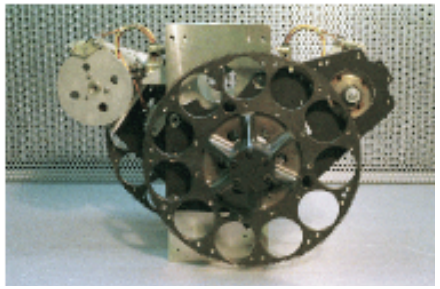
BAT (burst alert telescope)
Coded-mask telescope (see next)
Up to 150-200 keV

XRT (X-ray Wolter-I telescope)
Follow-up instrument for GRB positioning
0.2-10 keV band
PSF HPD=18 arcsec

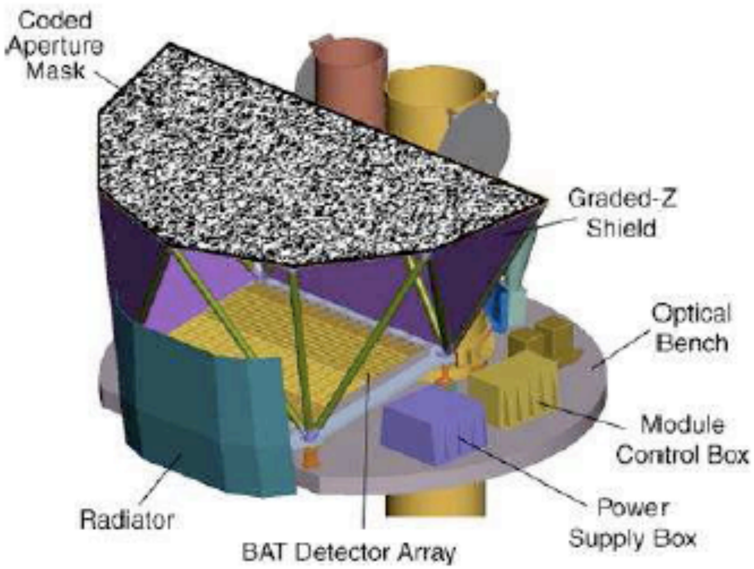
UVOT (ultra-violet optical telescope)
To study the UV/optical counterparts
Band=1700-6000Å
Resolution=0.9 arcsec


BAT

XRT


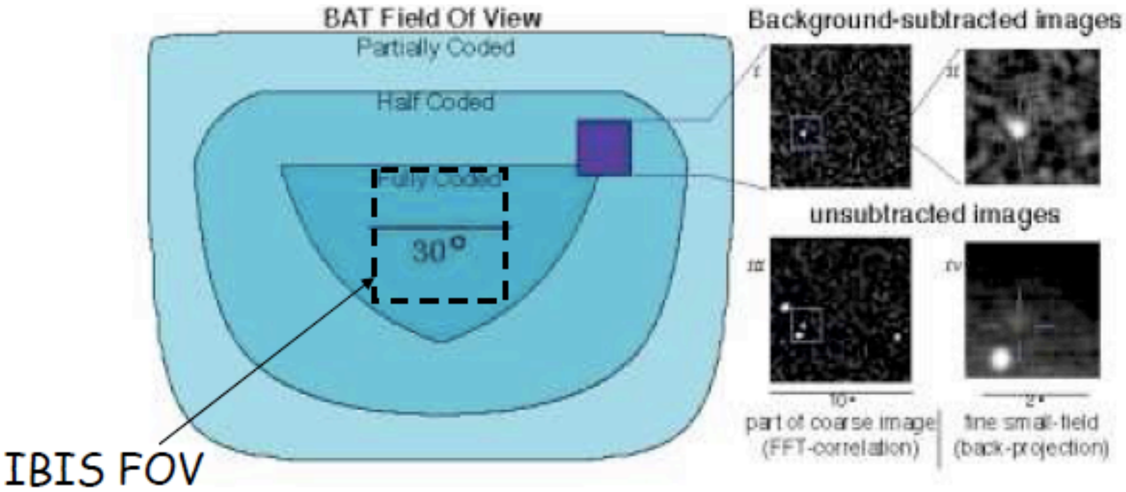

UVOT

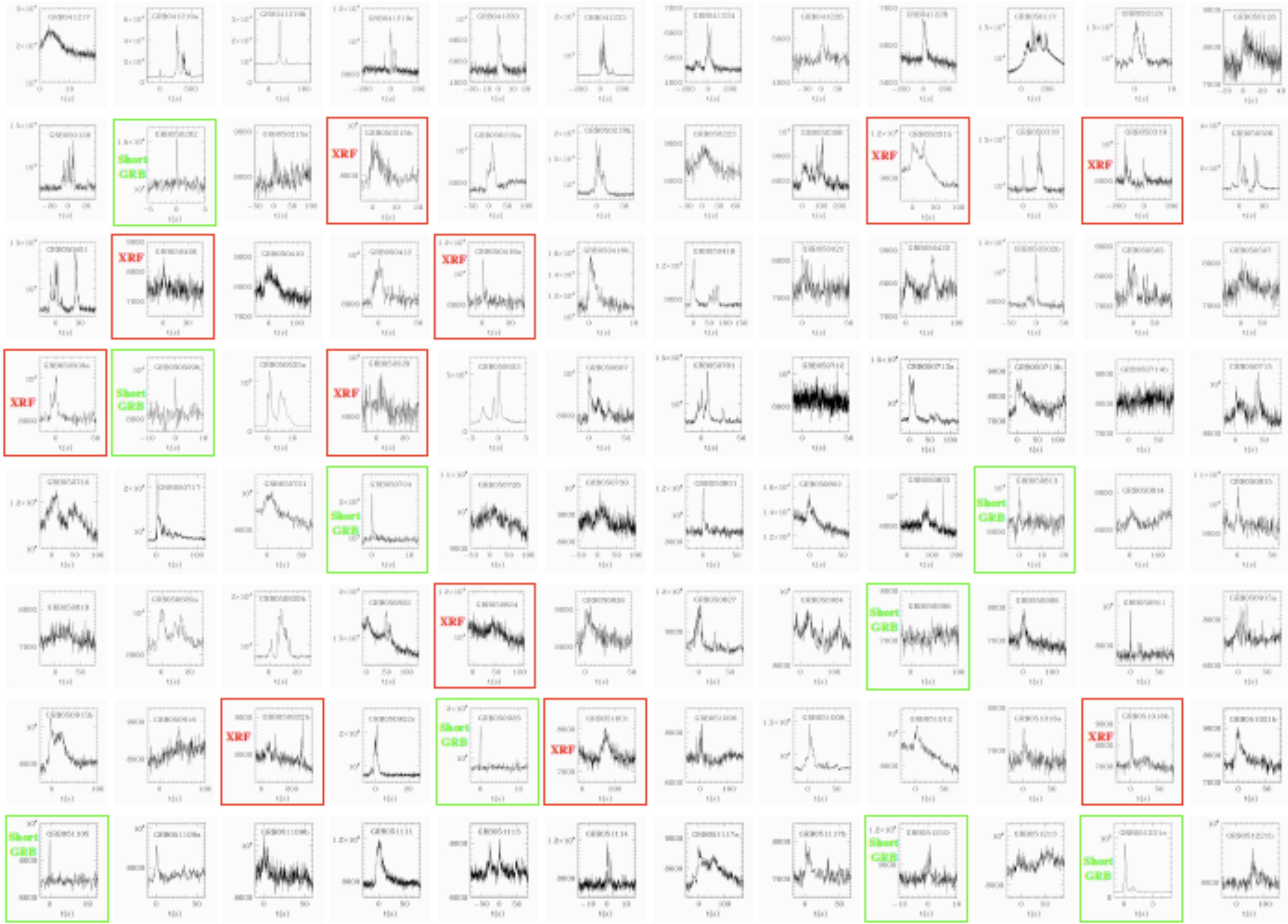
BAT and the coded mask



CZT detector
Random-mask theme (50% open)
FoV≈100°×60° (half coded)
≈160°×80° (PCFOV)

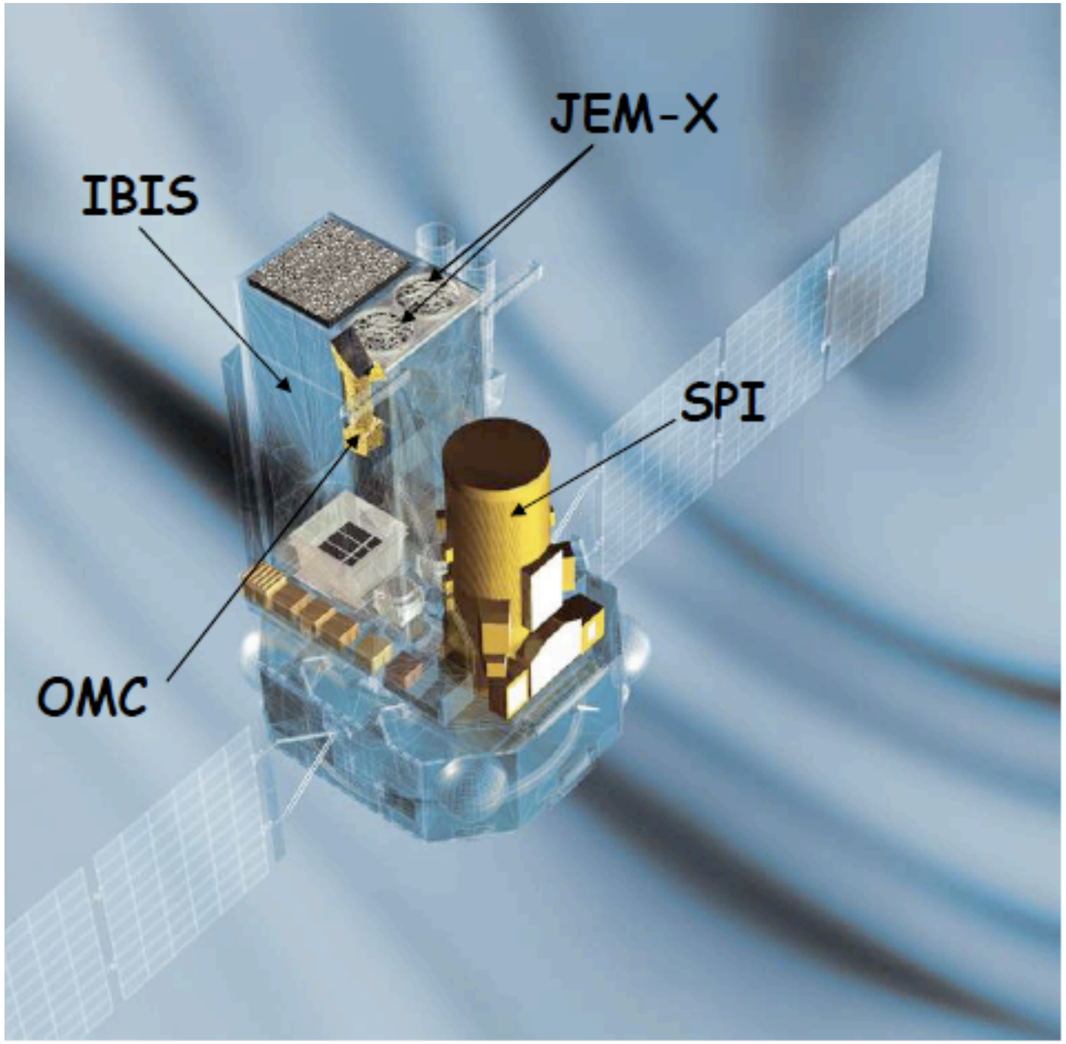
Band=15-200 keV
Angular resolution=17 arcmin
Coded-mask telescope (see next)

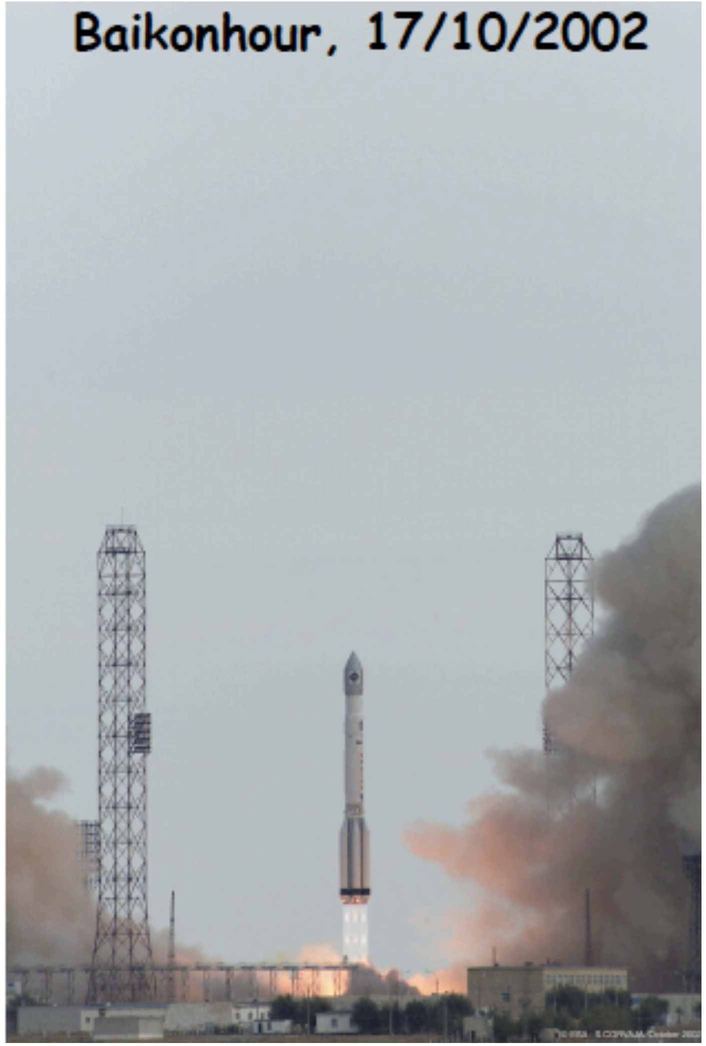



Short GRB
XRF
XRF
XRF
XRF
XRF
XRF
Short GRB
XRF
Short GRB
Short GRB
XRF
Short GRB
XRF
Short GRB
XRF
XRF
Short GRB
Short GRB
Short GRB

Integral (ESA)

Integral: 0.03-10 MeV

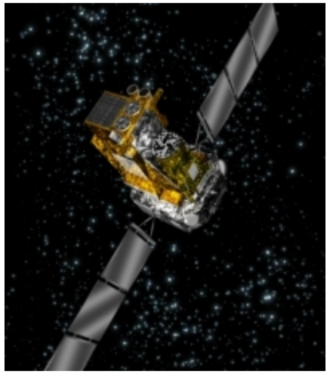




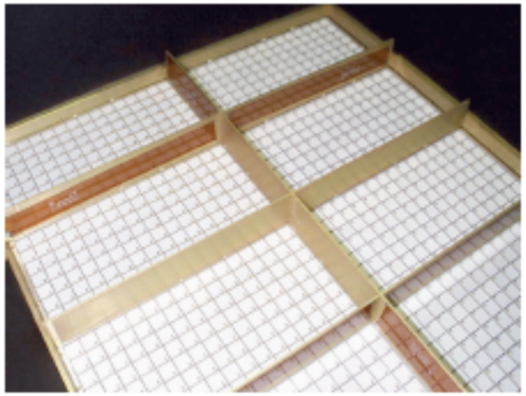
IBIS: Imaging through coded-masks

“The Coded-Mask Technique is the worst possible way of making a telescope…
…except when you can’t do anything better!”

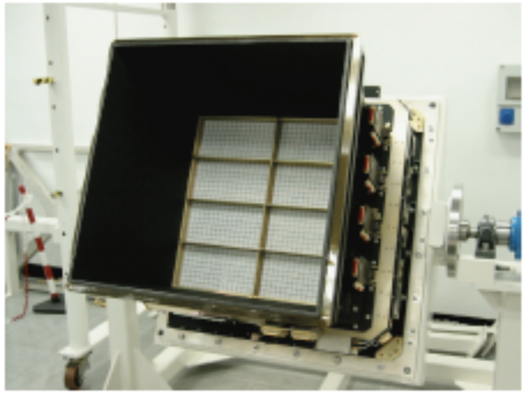
(Gerry Skinner, one of the fathers of the high-energy Astronomy through coded masks)



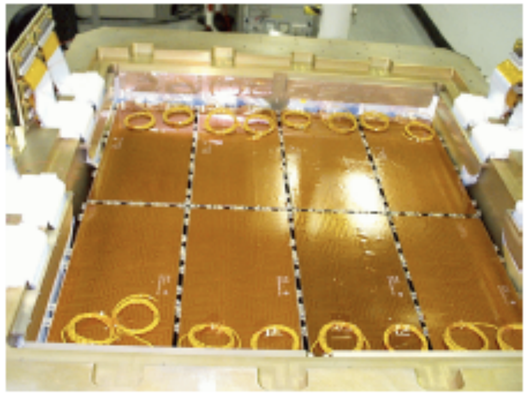
IBIS: 12’ resolution FoV=29°×29°, moderate energy resolution



ISGRI: CdTe detector,
15 keV-1 MeV

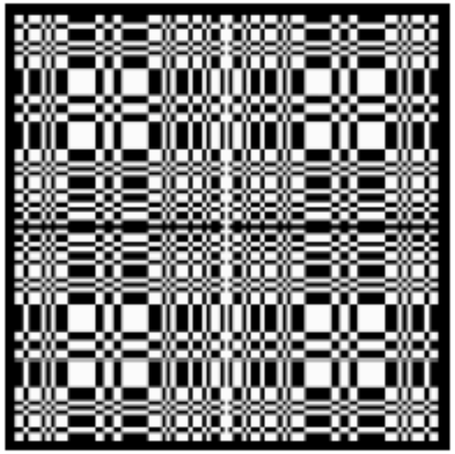


ISGRI + PICsIT=**IBIS**

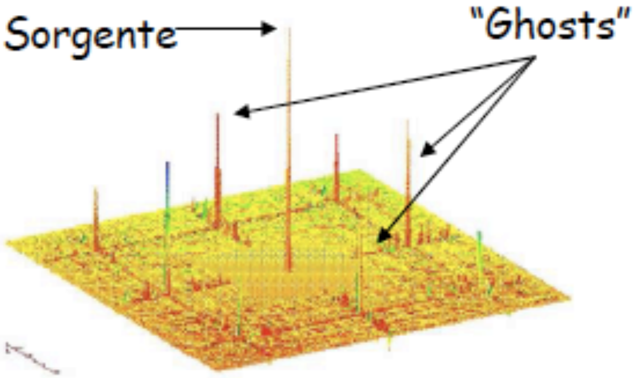


PICsIT: CsI detector,
175 keV-10 MeV

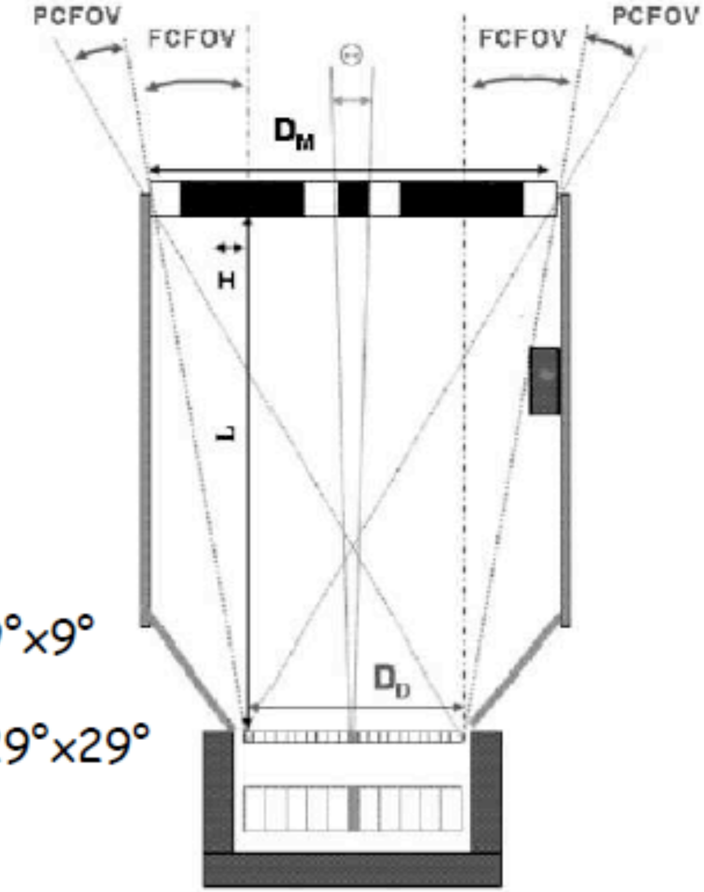
IBIS adopts a Modified Uniformly Redundant Array CODED MASK, proper to reconstruct point-like sources



Nero = Chiuso
Bianco = Aperto



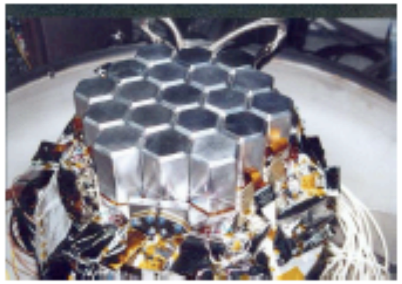
Point Spread Function (PSF)



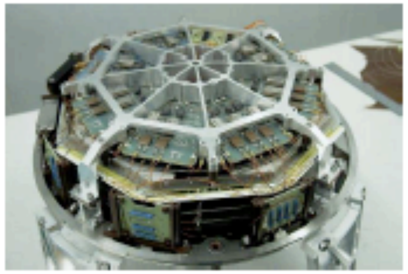
Fully Coded FOV
FCFOV = $\arctan[(D_M-D_D)/L] = 9°\times9°$
Partially Coded FOV
PCFOV = $\arctan[(D_M+D_D)/L] = 29°\times29°$
Risoluzione Angolare
$\Theta = \arctan(H/L) = 12'$

The other instruments onboard *Integral*

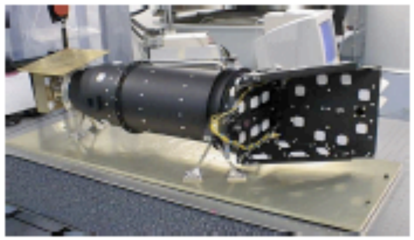
SPI (spectrometer on Integral)
2.2 keV FWHM @ 1.3 MeV
FoV=16°×16°
Band=0.02-8 MeV
angular resolution 2.5°



JEM-X (X-ray imaging/spectrometer)
Follow-up instrument
Band=3-35 keV
angular resolution 3 arcmin



OMC (optical monitor camera)
V band, to study optical counterparts
of X-ray/Gamma-ray sources
angular resolution 25 arcsec



Fermi (*GLAST*, NASA)

GLAST (Fermi)

major step to disclose the γ-ray sky (10 keV - 300 GeV)

LAT Specifications and Performance Compared with EGRET

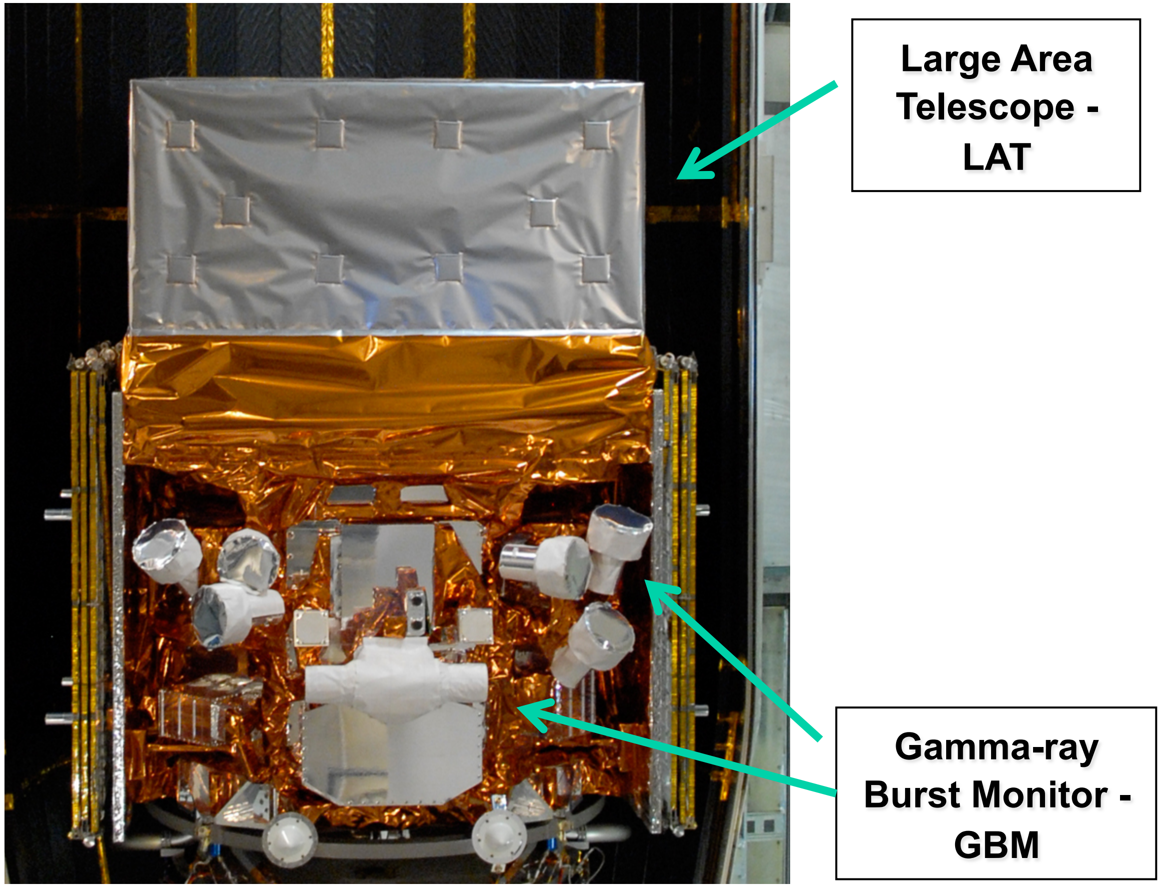
LAT

Quantity	LAT (Minimim Spec.)	EGRET
Energy Range	20 MeV - 300 GeV	20 MeV - 30 GeV
Peak Effective Area[1]	> 8000 cm^2	1500 cm^2
Field of View	> 2 sr	0.5 sr
Angular Resolution[2]	< 3.5° (100 MeV) < 0.15° (>10 GeV)	5.8° (100 MeV)
Energy Resolution[3]	< 10%	10%
Deadtime per Event	< 100 μs	100 ms
Source Location Determination[4]	< 0.5'	15'
Point Source Sensitivity[5]	< 6×10^{-9} cm^{-2} s^{-1}	~ 10^{-7} cm^{-2} s^{-1}

GBM

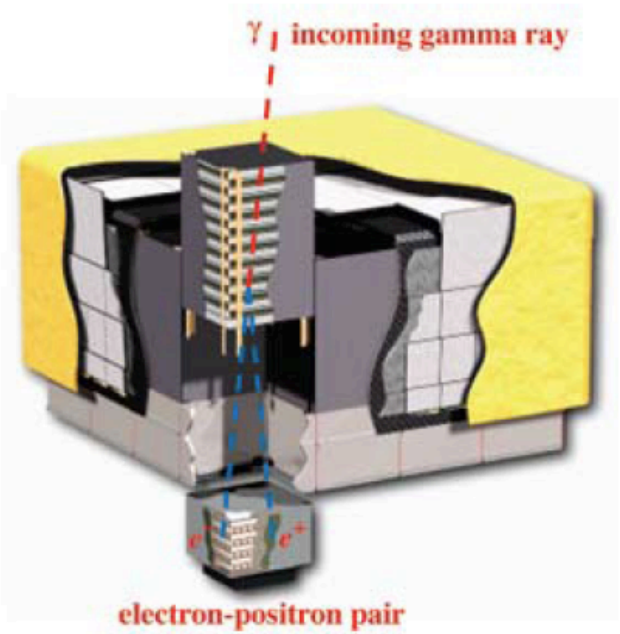
	GLAST Burst Monitor (GBM) Requirements	BATSE
Energy Range	8 keV to > 25 MeV	25 keV to 10 MeV
Field of View	> 8 sr	
Energy Resolution[1]	< 10%	< 10%
Deadtime per Event	< 10 μs	
Burst Sensitivity[2]	< 0.5 cm^{-2} s^{-1}	0.2 cm^{-2} s^{-1}
Alert GRB Location[3]	~15° (goal)	~ 25°
Burst Sensitivity On-board Trigger[4]	< 1.0 cm^{-2} s^{-1}	0.3 cm^{-2} s^{-1}

Successors to EGRET and BATSE on the Compton Gamma Ray Observatory


Large Area Telescope - LAT
Gamma-ray Burst Monitor - GBM

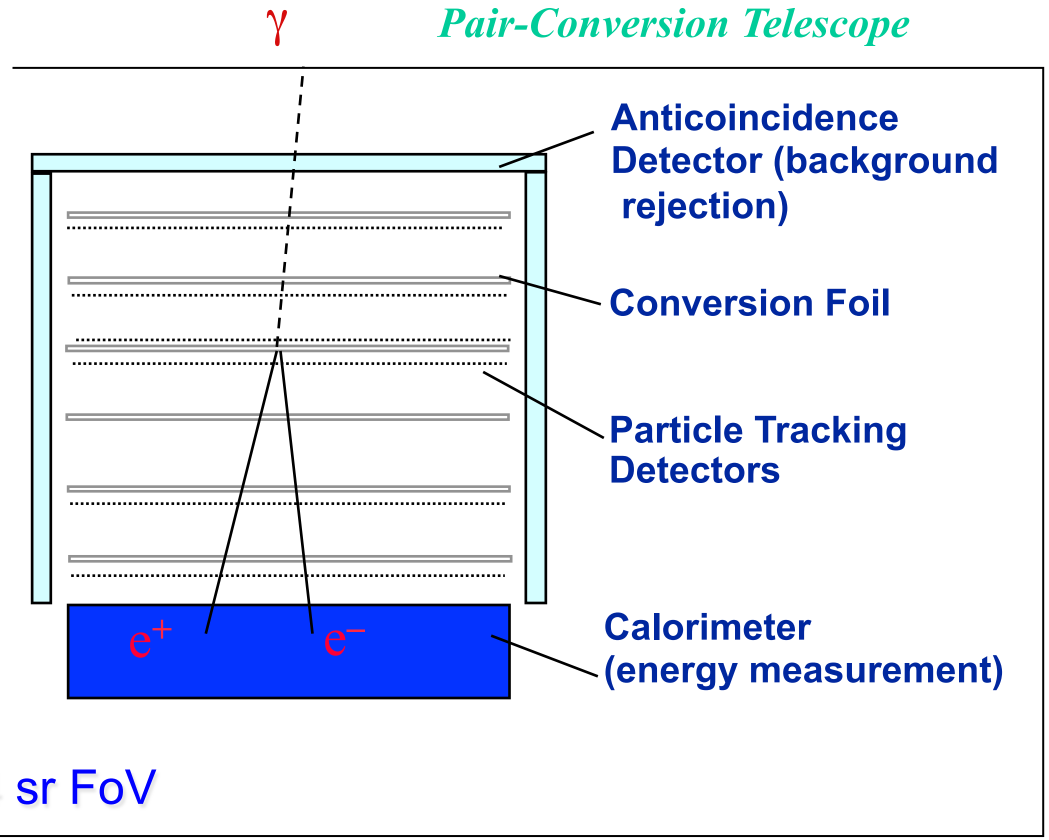

Cape Canaveral, 11st June 2008
USAF
ULA
DELTA
GLAST

Fermi: the LAT instrument (20 MeV – 300 GeV)



LAT

4x4 array of identical
towers with 880,000
silicon strip detector channels

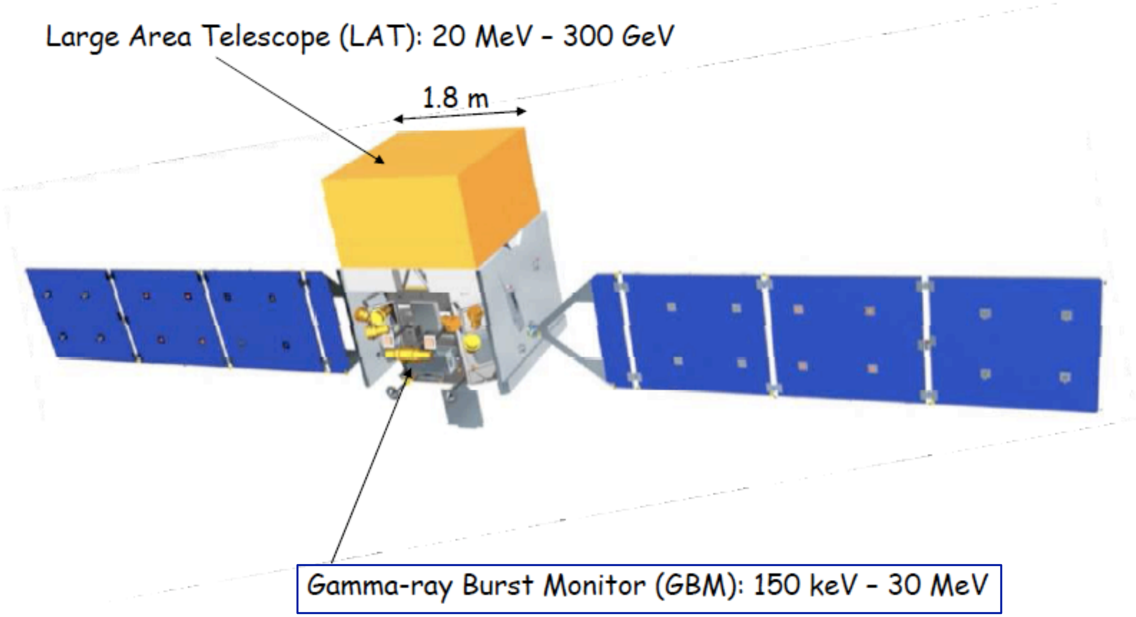


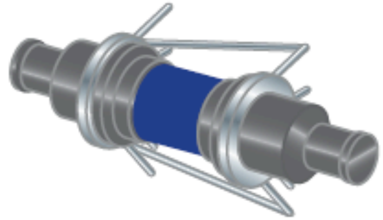
Gamma rays interact by pair production, the conversion of the gamma-ray energy into two particles – an electron and a positron (really an antiparticle); LAT is a particle detector.
LAT has four sub-systems: a *solid-state detector pair-conversion tracker* for Gamma-ray detection and direction measurement, a *calorimeter* for measurement the energies, a *plastic scintillator anti-coincidence system* to reject the background of charged particles, and *a trigger system*.

Fermi: the GBM instrument (≈150 keV – 30 MeV)

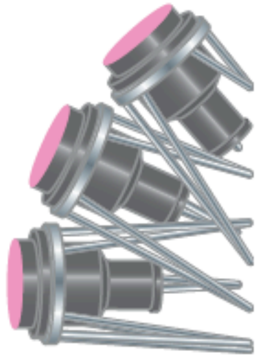
GBM has 12 NaI scintillators and two BGO scintillators mounted on the sides of the spacecraft.

The GBM will view the entire sky not occulted by the Earth (few keV – 30 MeV).





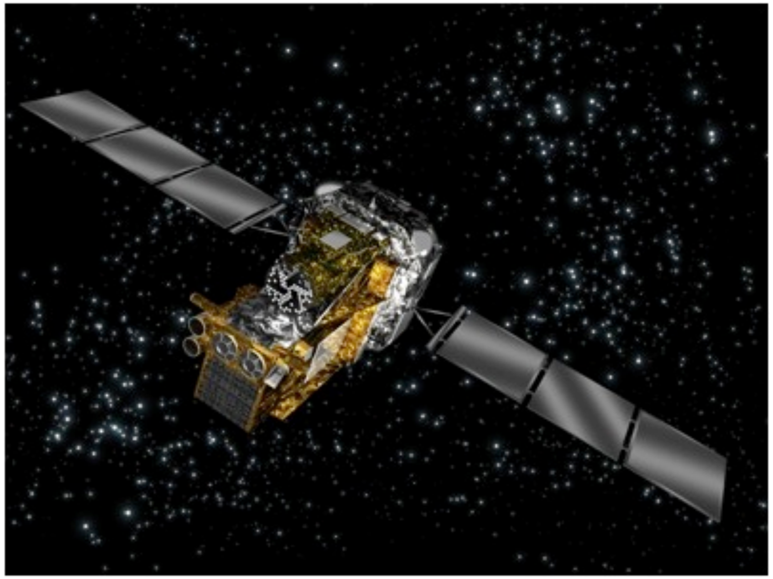
GBM - HE BGO
(1 of 2)

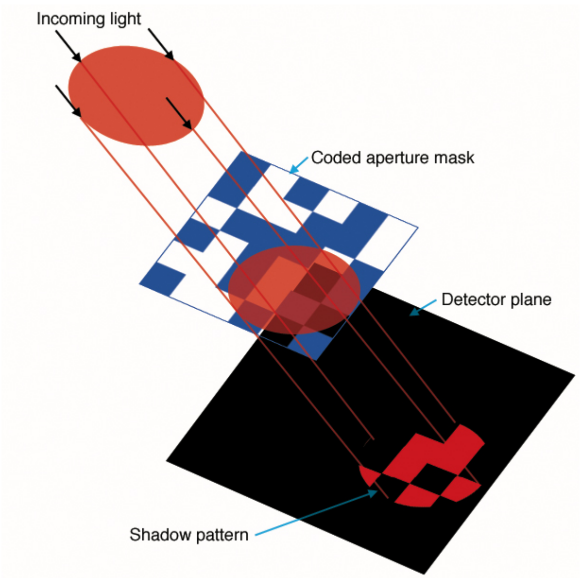


GBM - LE NaI
(3 of 12)

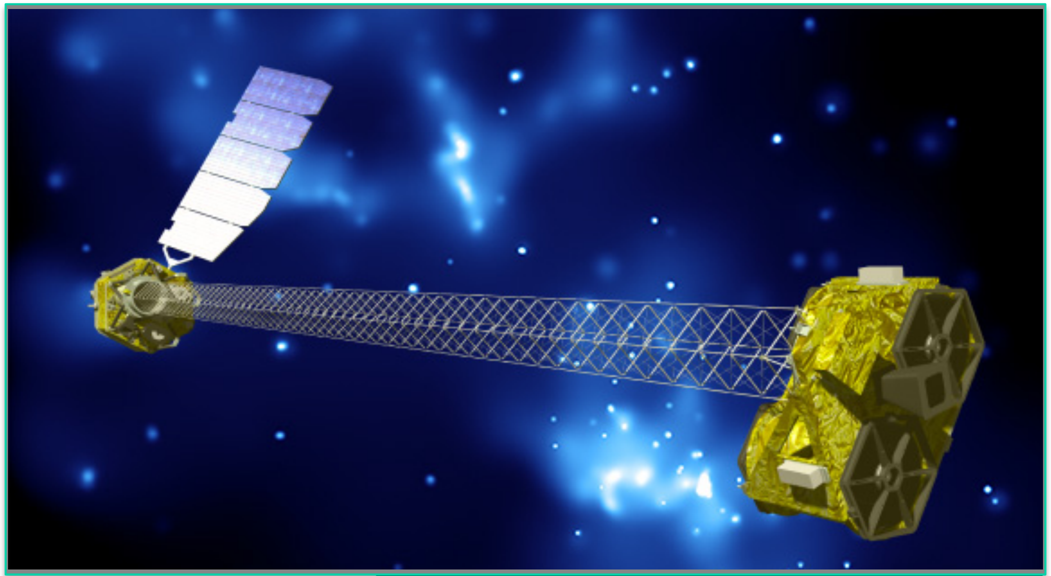
NuSTAR (NASA) – small mission

INTEGRAL, *Swift* BAT

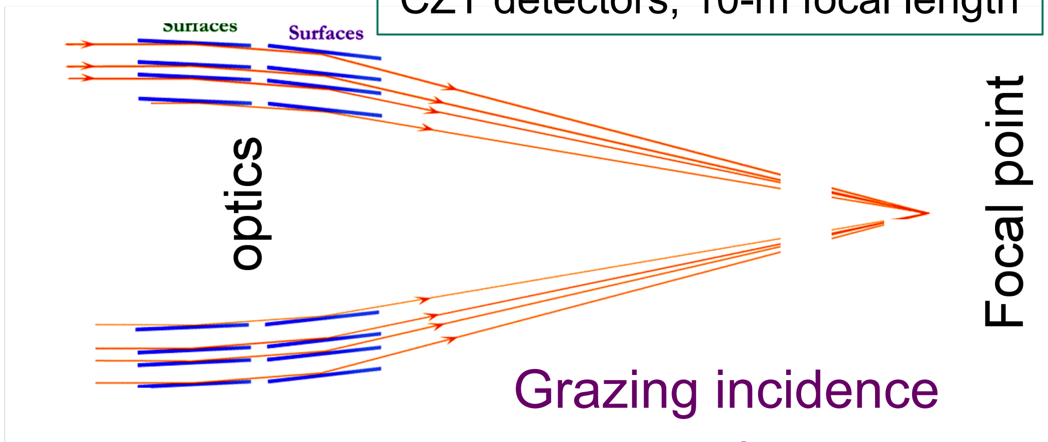




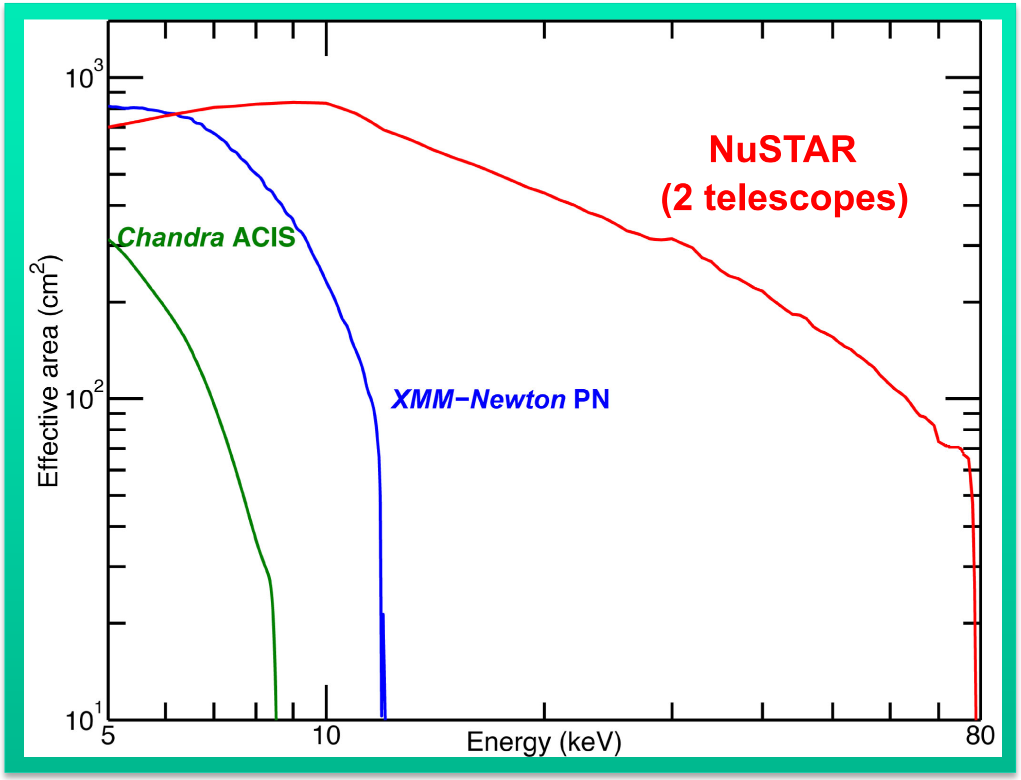
NuSTAR



Two multilayer coded optics,
CZT detectors, 10-m focal length



Grazing incidence optics



Satellite (instrument)	Sensitivity
INTEGRAL (ISGRI)	~0.5 mCrab (20-100 keV) with >Ms exposures
Swift (BAT)	~0.8 mCrab (15-150 keV) with >Ms exposures
NuSTAR	1 μCrab (10-40 keV) in 1 Ms

Sensitivity comparison

1 Ms Sensitivity

3.2×10^{-15} erg/cm^2/s (6 – 10 keV)

1.4×10^{-14} (10 – 30 keV)

Timing

relative 100 microsec

absolute 3 msec

Imaging

HPD 58”

FWHM 16”

Localization 2” (1-sigma)

Spectral response

energy range 3-79 keV

threshold 2.0 keV

ΔE @ 6 keV 0.4 keV FWHM

ΔE @ 60 keV 1.0 keV FWHM

Field of View

FWZI 12.5’ x 12.5’

FWHI 10’ @ 10 keV

8’ @ 40 keV

6’ @ 68 keV

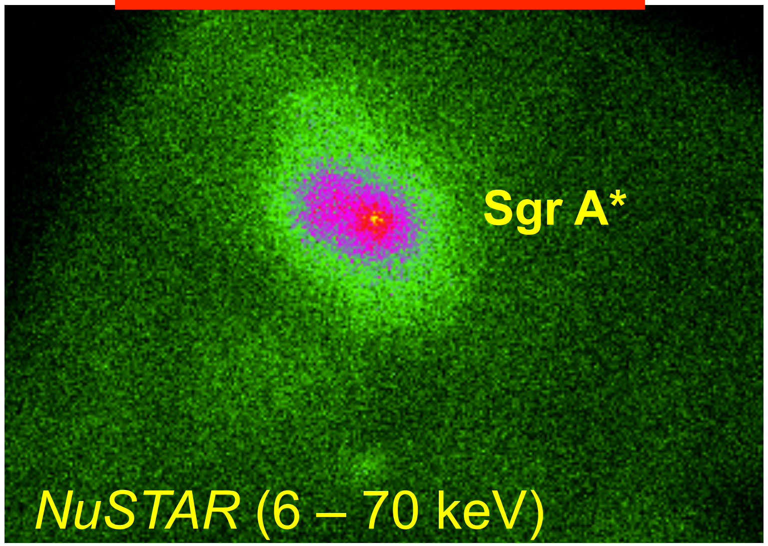
Target of Opportunity

response <24 hr (reqmt)

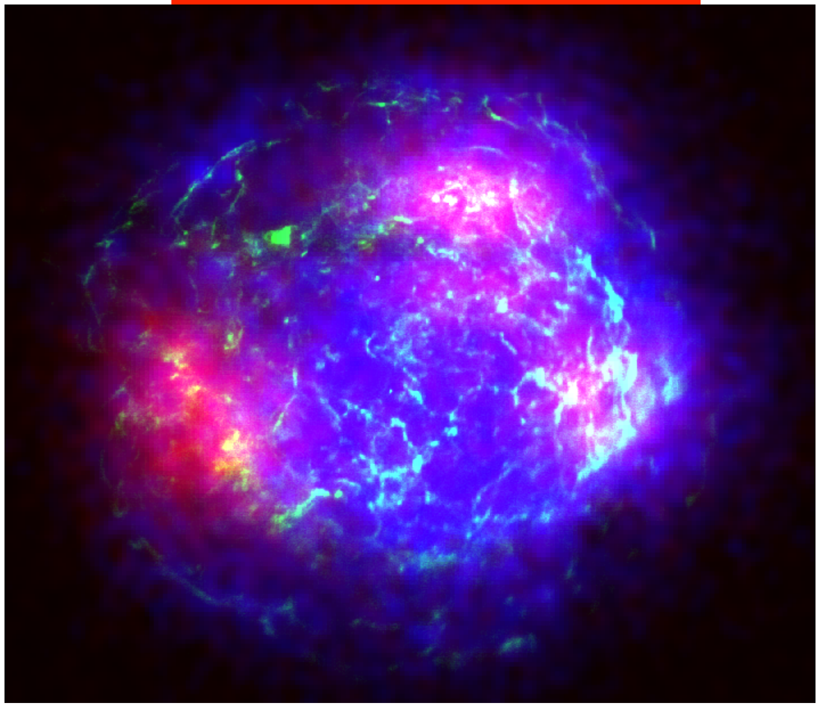
typical 6-8 hours

80% sky accessibility

Sgr A*



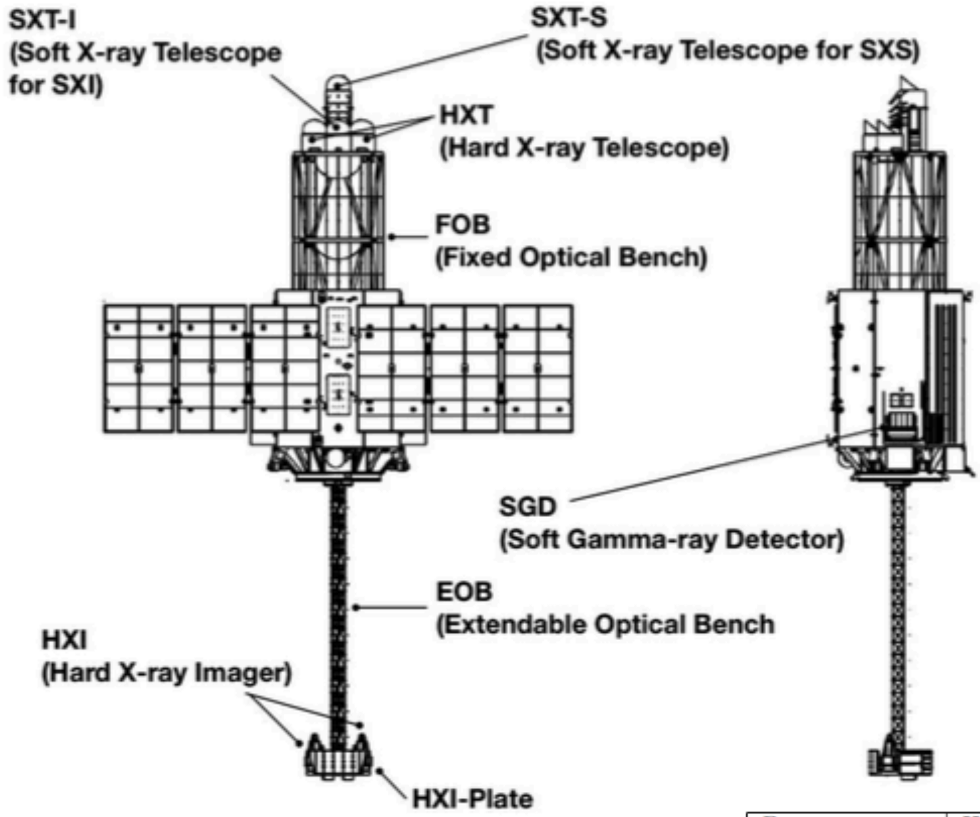
Cassiopeia A



Red: *NuSTAR* Fe
Blue: *NuSTAR* 10-25 keV
Green: *Chandra* 4-6 keV

ASTRO-H (*Hitomi*, Jaxa)

failed after few measurements



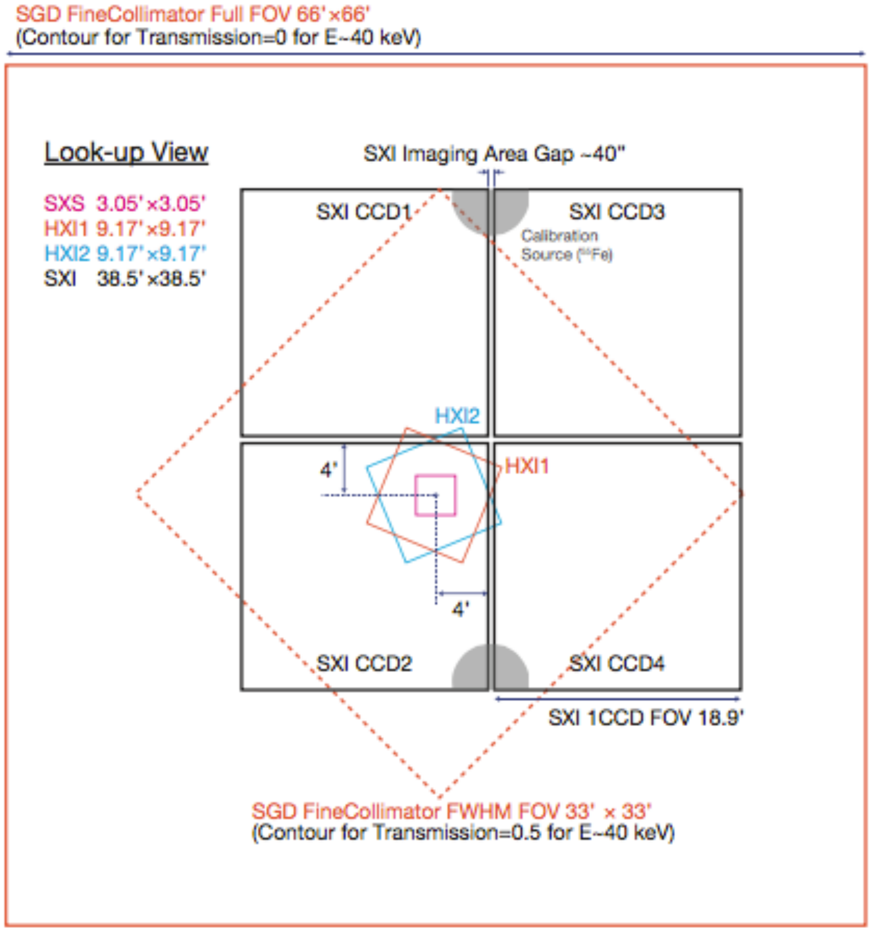
Multi-layer coatings

Up to ~80 keV

High spectral resolution

Limited angular resolution

Parameter	Hard X-ray Imager (HXI)	Soft X-ray Spectrometer (SXS)	Soft X-ray Imager (SXI)	Soft γ-ray Detector (SGD)
Detector technology	Si/CdTe cross-strips	micro calorimeter	X-ray CCD	Si/CdTe Compton Camera
Focal length	12 m	5.6 m	5.6 m	–
Effective area	300 cm^2@30 keV	210 cm^2@6 keV 160 cm^2 @ 1 keV	360 cm^2@6 keV	>20 cm^2@100 keV Compton Mode
Energy range	5 –80 keV	0.3 – 12 keV	0.4 – 12 keV	40 – 600 keV
Energy resolution (FWHM)	2 keV (@60 keV)	< 7 eV (@6 keV)	< 200 eV (@6 keV)	< 4 keV (@60 keV)
Angular resolution	<1.7 arcmin	<1.3 arcmin	<1.3 arcmin	–
Effective Field of View	$\sim 9 \times 9$ arcmin^2	$\sim 3 \times 3$ arcmin^2	$\sim 38 \times 38$ arcmin^2	0.6×0.6 deg^2 (< 150 keV)
Time resolution	25.6 μs	5 μs	4 sec/0.1 sec	25.6 μs
Operating temperature	−20°C	50 mK	−120°C	−20°C



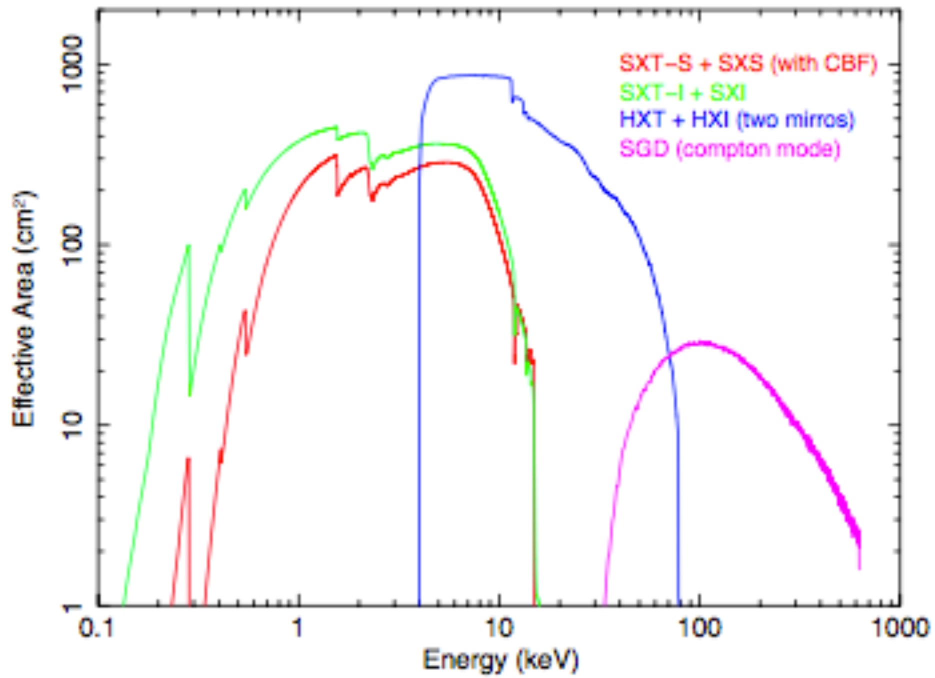
The center of the SGD FOV is designed to match the SXS FOV center.

HXI: hard X-ray Imager
5−80 keV, 9×9 arcmin^2, <1.7 arcmin resol.

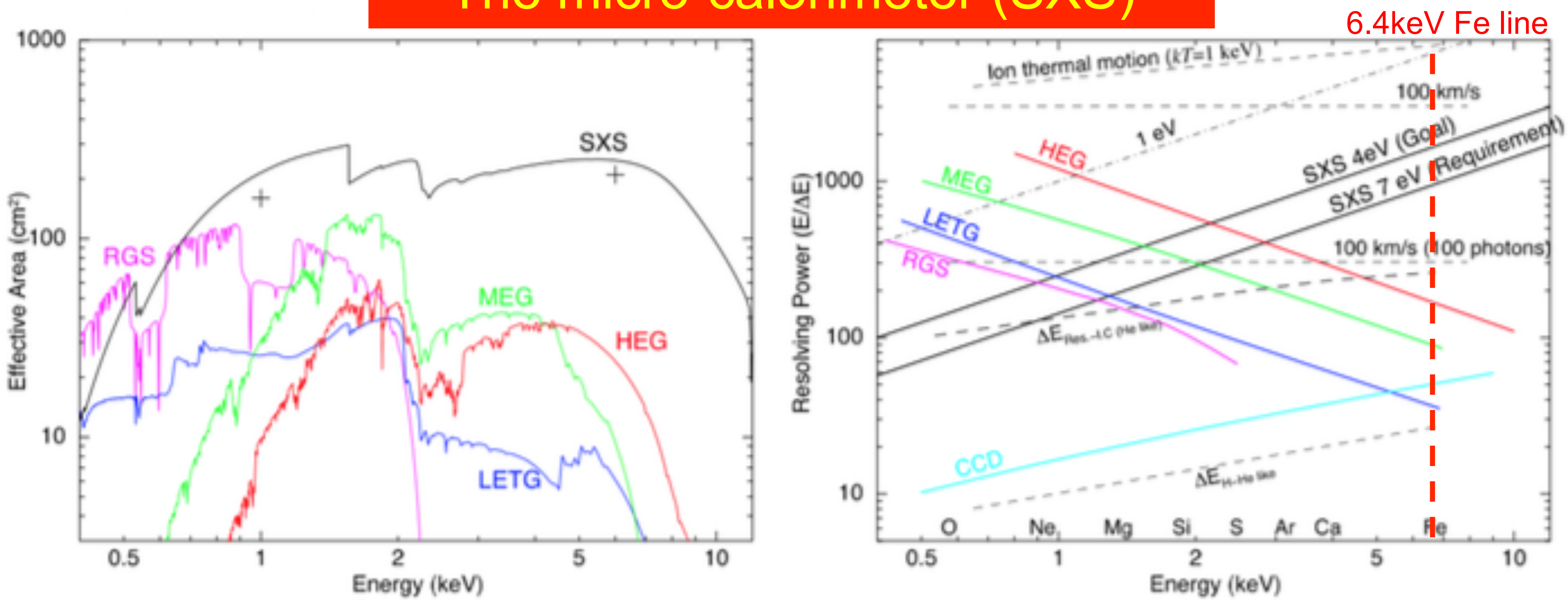
SXS: Soft X-ray Spectrometer
microcalorimeter, <7 eV resolution,
0.3−12 keV, 3×3 arcmin^2, <1.3 arcmin resol.

SXI: Soft X-ray Imager
CCD, 0.4−12 keV, 38×38 arcmin^2,
<1.3 arcmin resol.

SGD: Soft Gamma-ray Detector
40−600 keV, 0.6×0.6 deg^2, Compton telescope

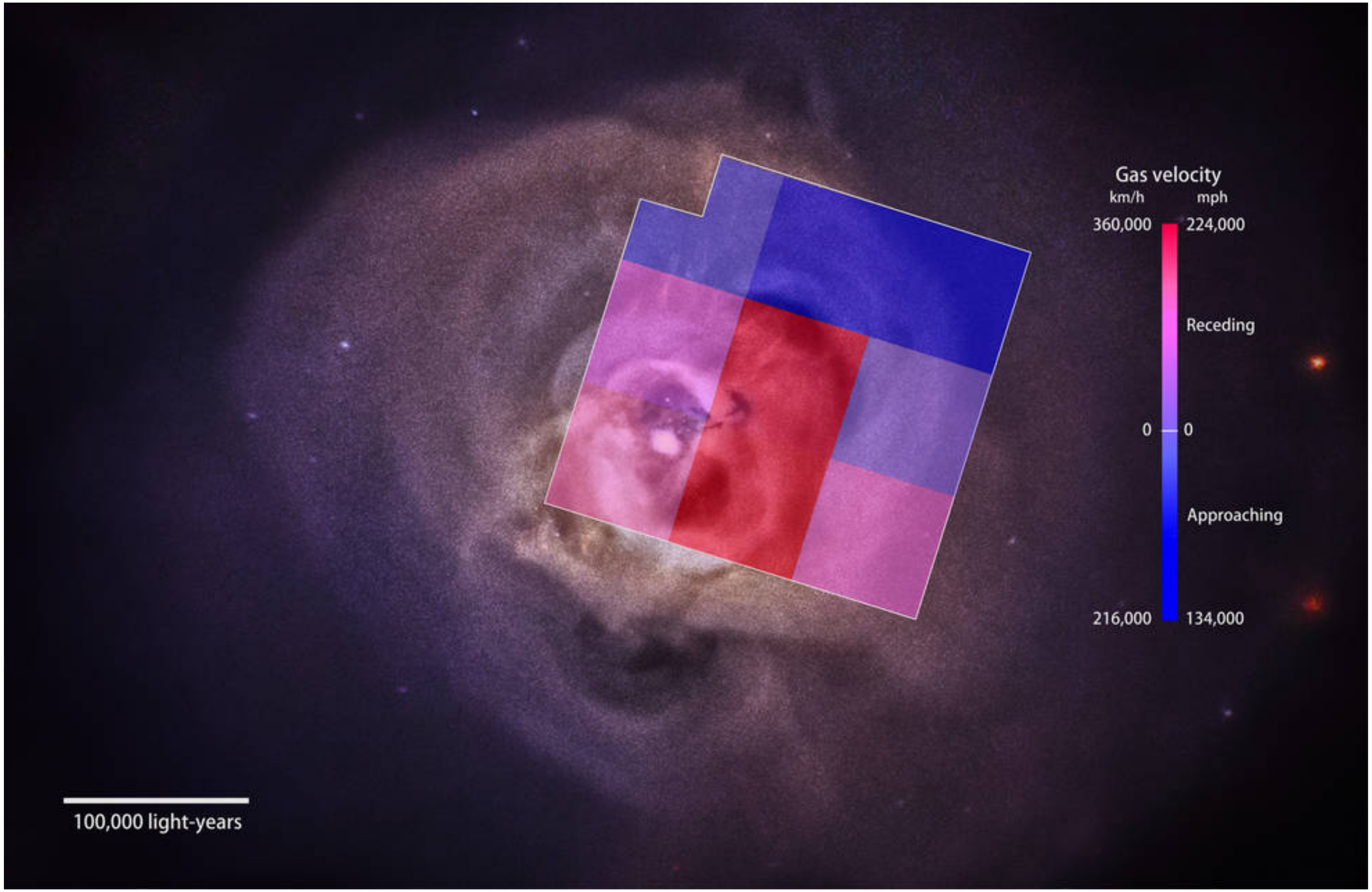


The micro-calorimeter (SXS)

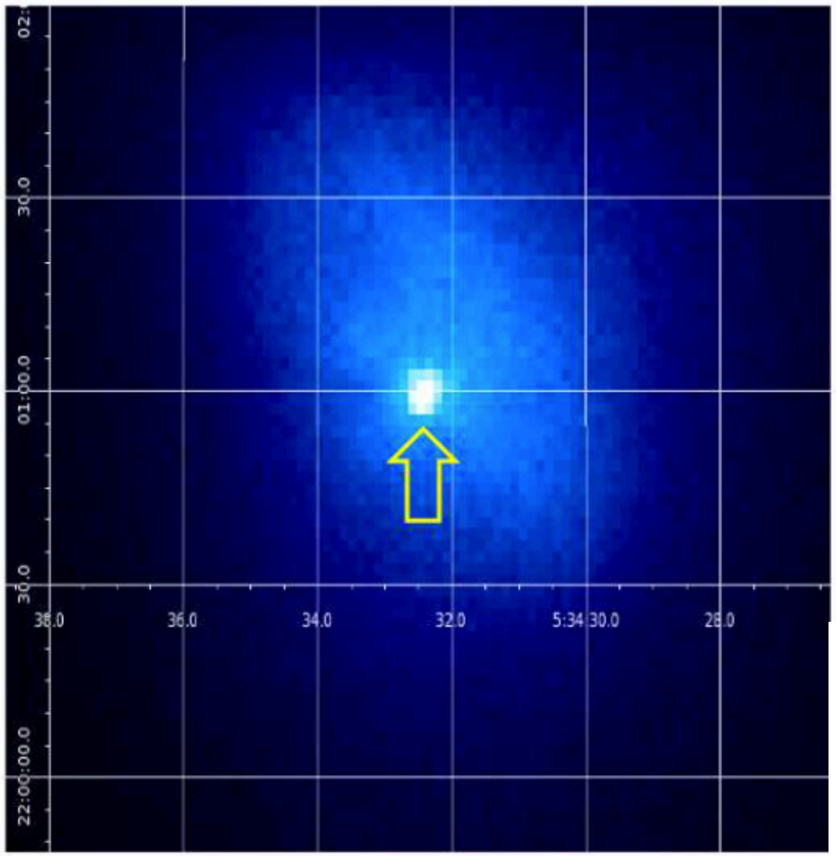


Takahashi et al. 2013

Hitomi, Perseus cluster (Hitomi collaboration, Nature, 2016)

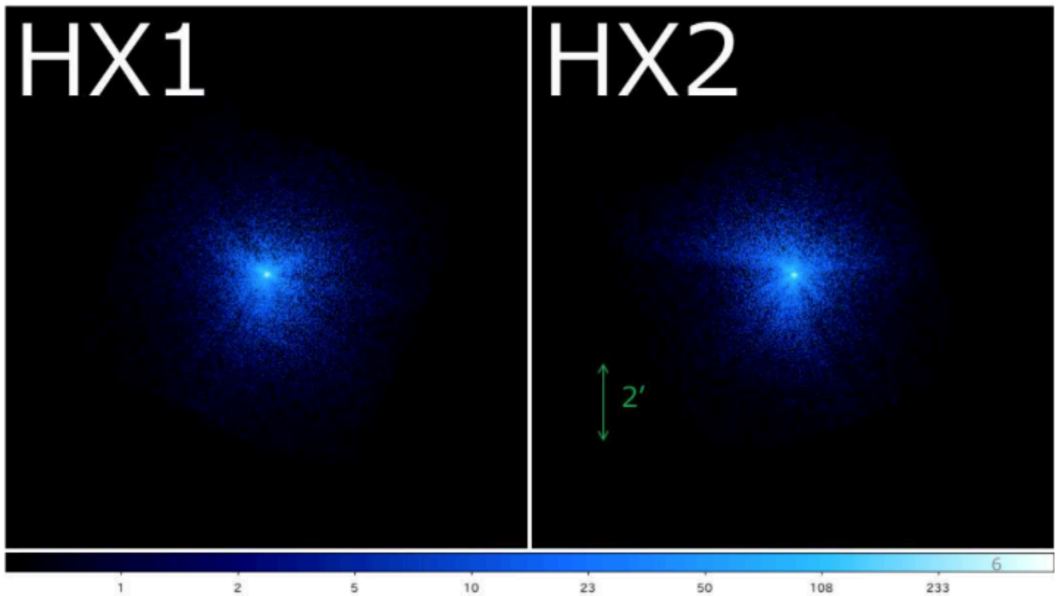


The hard X-ray detector (HXT)



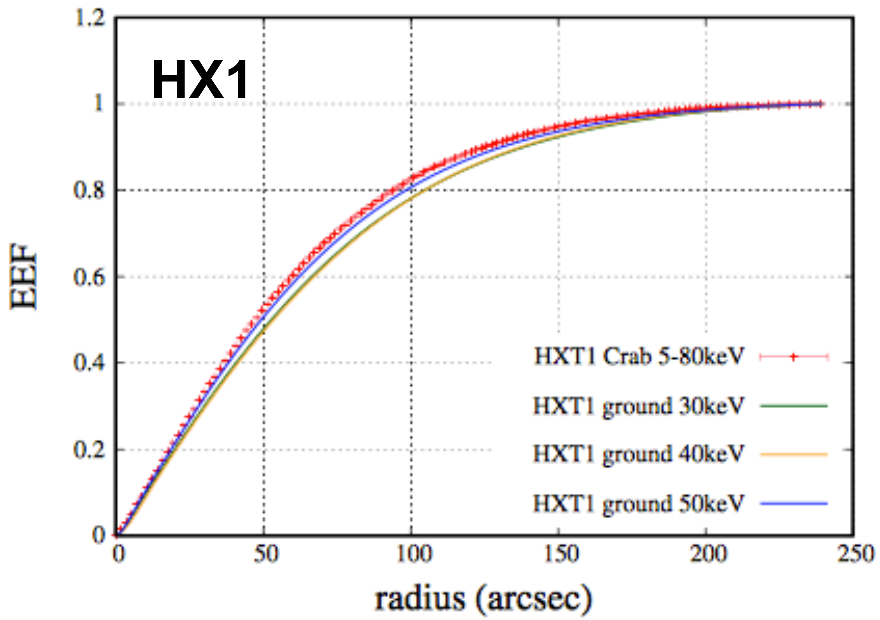
Crab Nebula, 5−80 keV

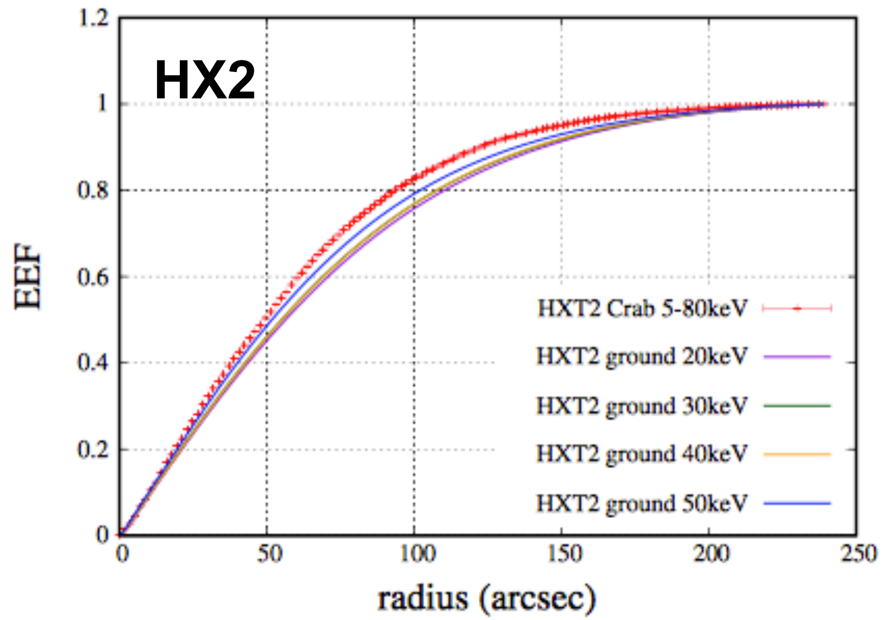
Matsumoto et al. 2018



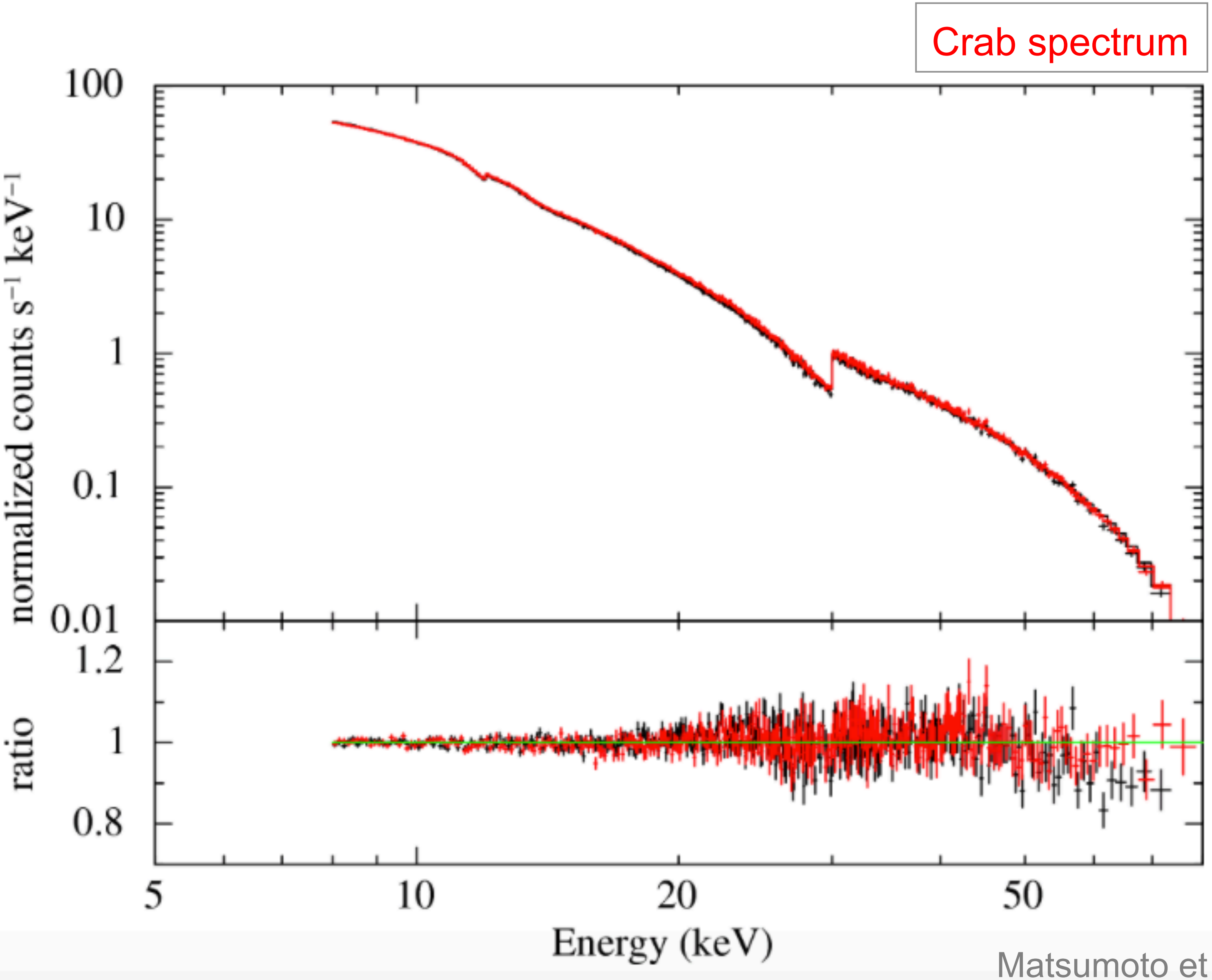
HPD≈1.6 arcmin

In-flight vs. ground calibrations





Matsumoto et al. 2018



Matsumoto et al. 2018

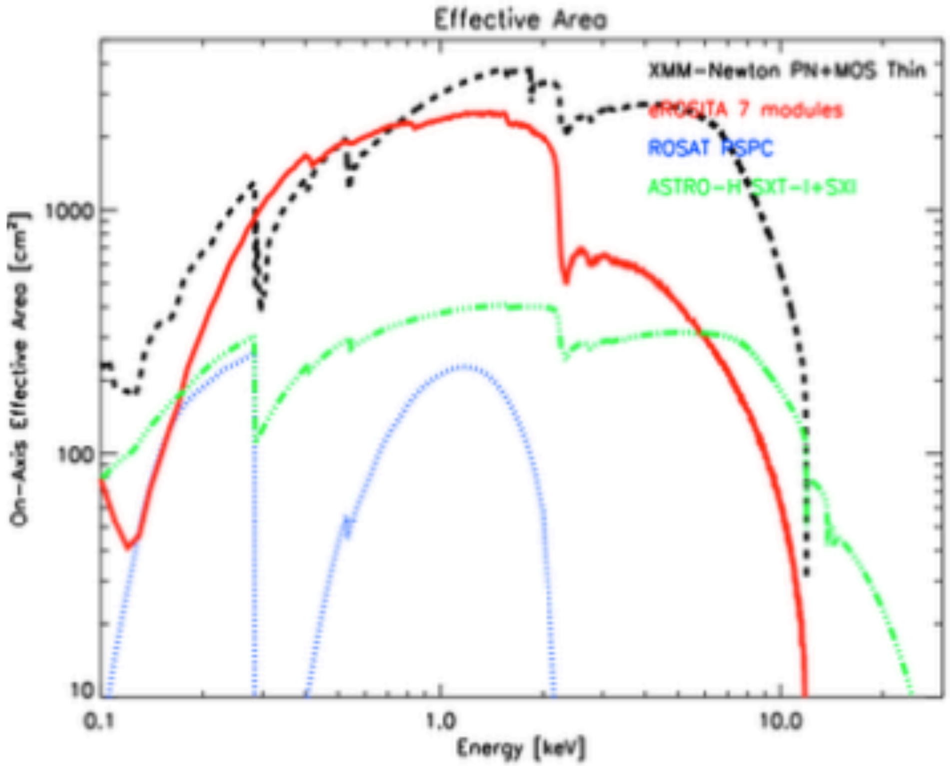
eROSITA (Germany+Russia)

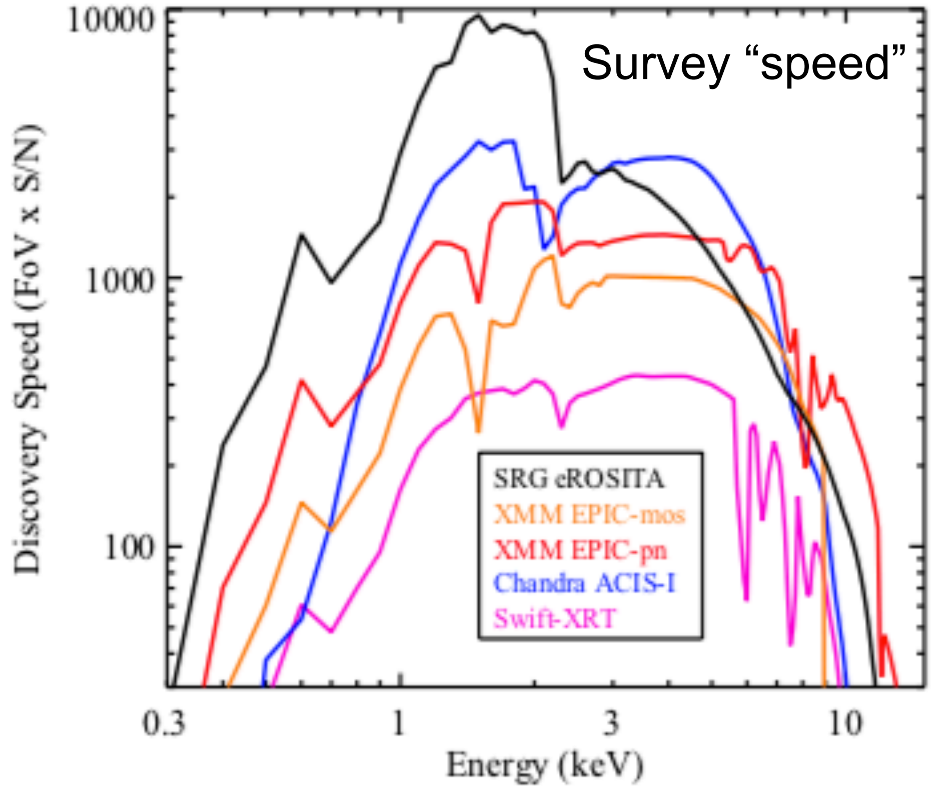
Actually, Spectrum-Roentgen Gamma (SRG)


Baikonur, July 13th, 2019
Satellite thought for X-ray surveys (large FoV), L2 position
8 public releases, one every 6 months
Providing the first hard (2-10 keV) survey in X-rays (ROSAT: <2 keV)
2 instruments: ART-XC (5-30 keV, 0.3 sq. deg, HPD~30” at 8 keV Russia)
+ eROSITA (0.3-10 keV, 1 sq. deg., 27” average HEW, Germany)

eROSITA performances

Effective Area: ~1700 cm² (FoV avg. @1keV)

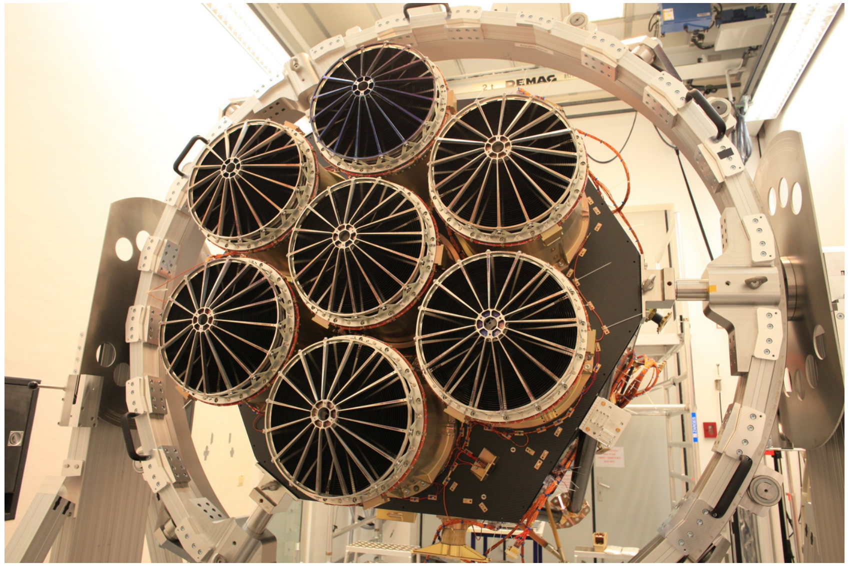




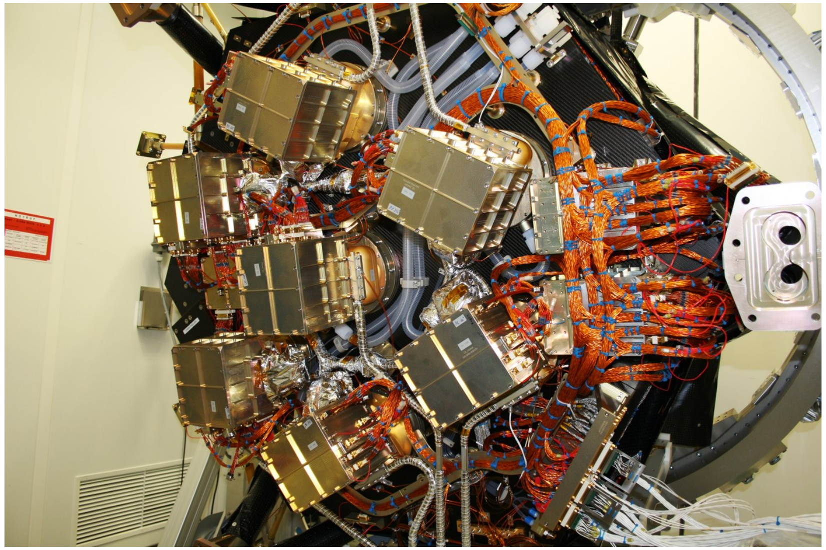
- FoV=1 deg^2 diameter
- Factor ~5-6 higher survey speed
- HEW~18" (on axis), ~27" (average over the FoV)
- Spectral resolution FWHM~80 eV @1.5 keV
- Good detector uniformity, no CCD gaps

eROSITA mirror modules (“telescopes”)

7 mirror modules, each with 54 shells

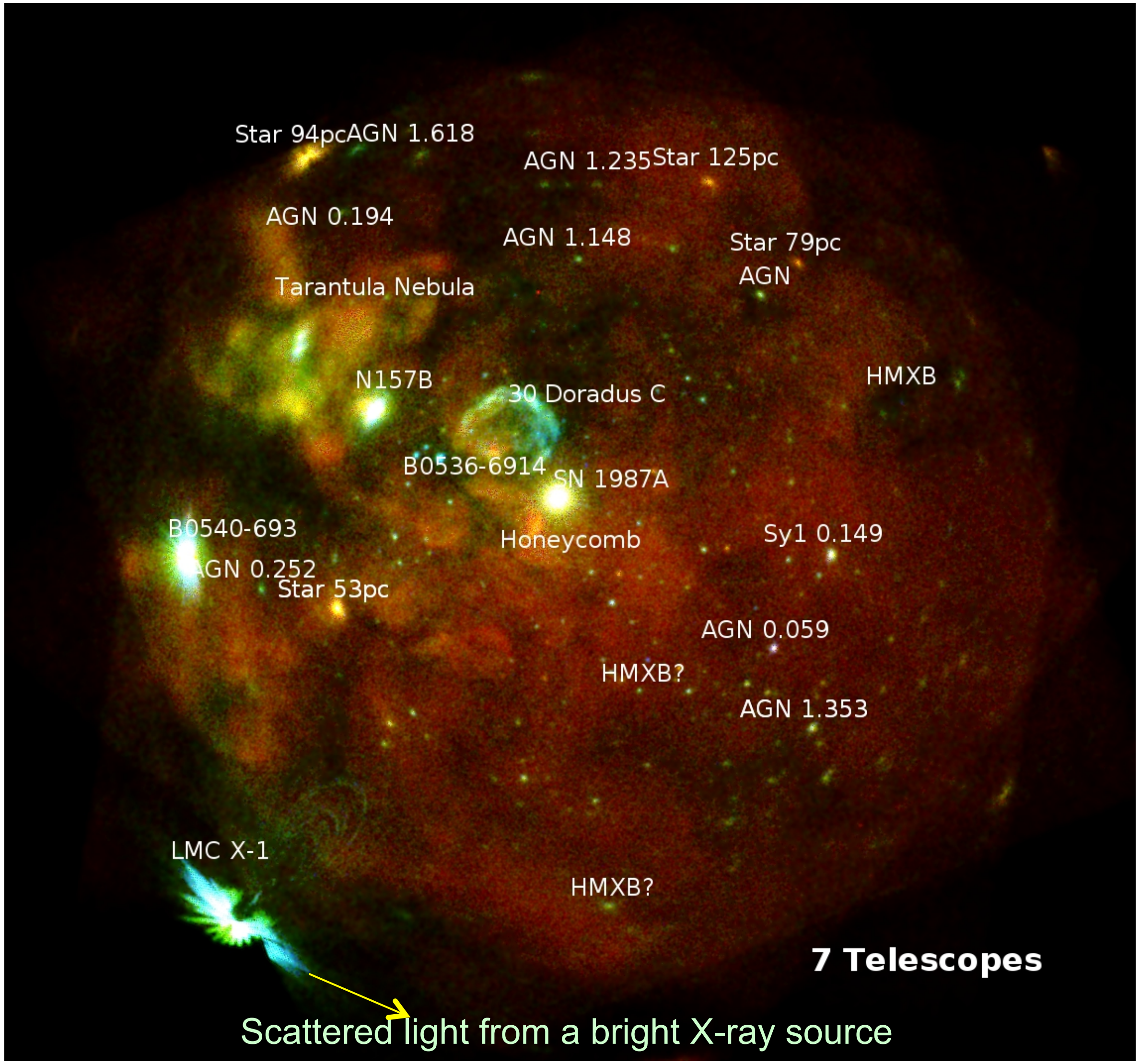


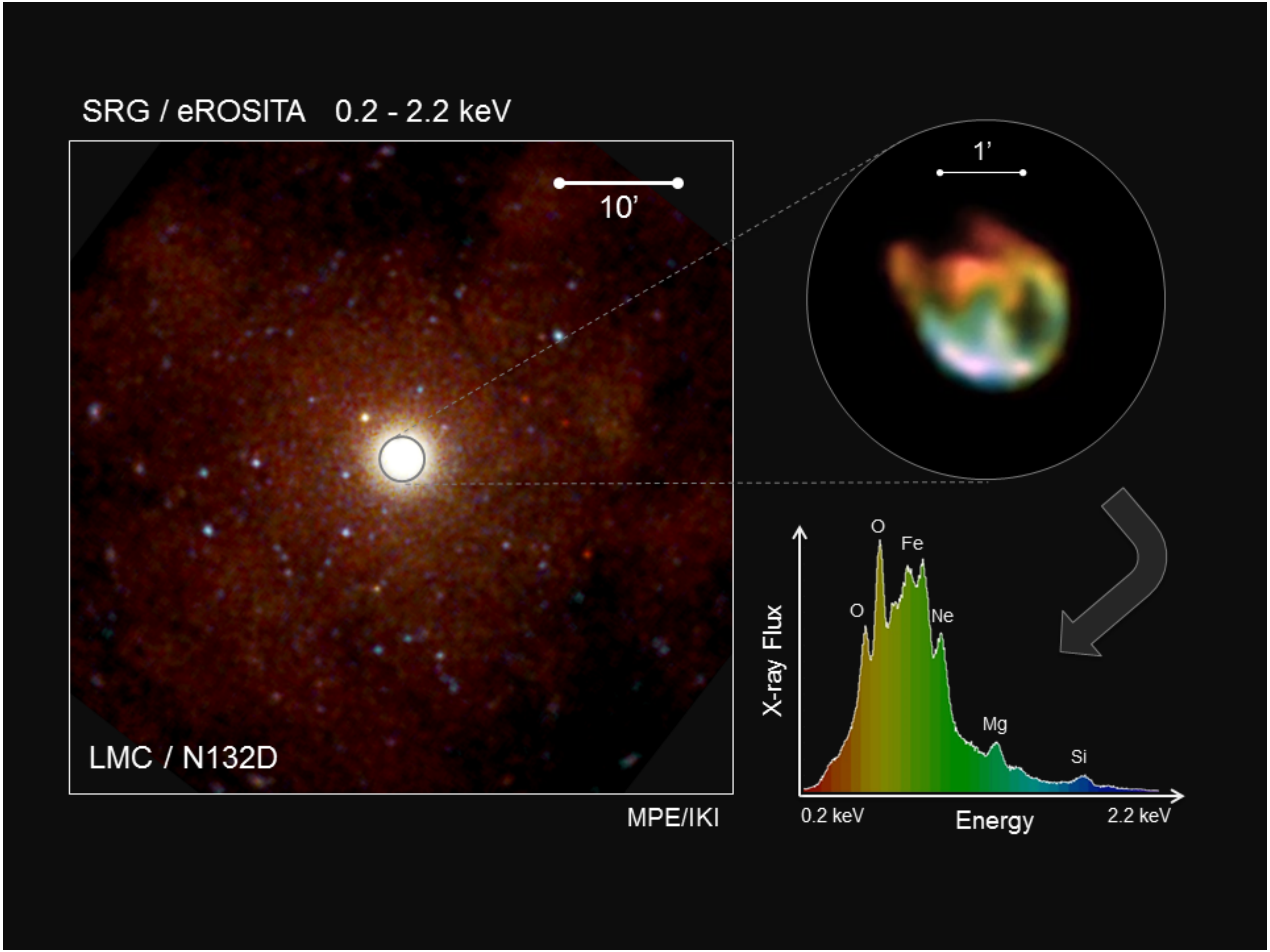
7 cameras, one for each module



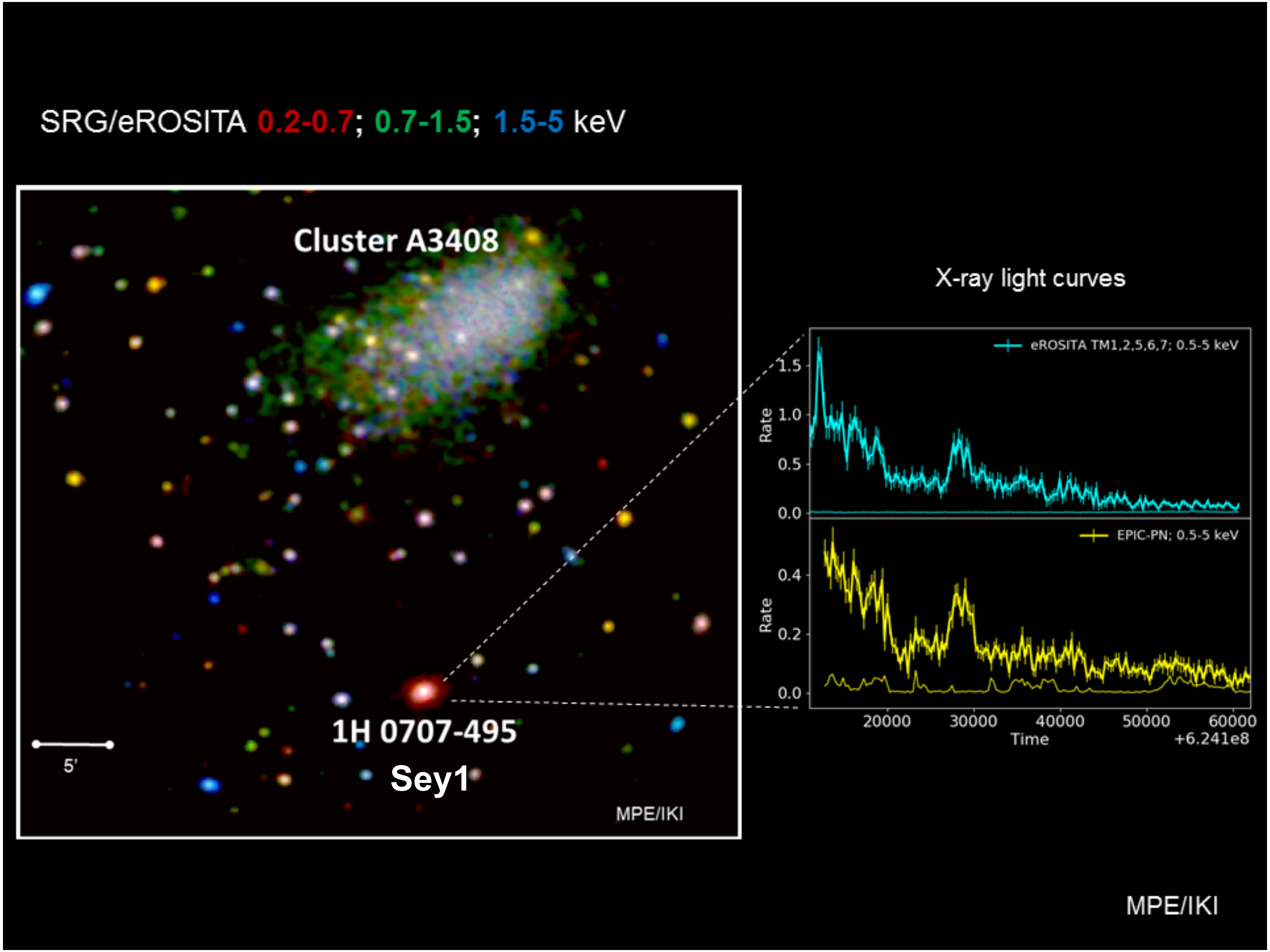
Some nice pictures for the press release

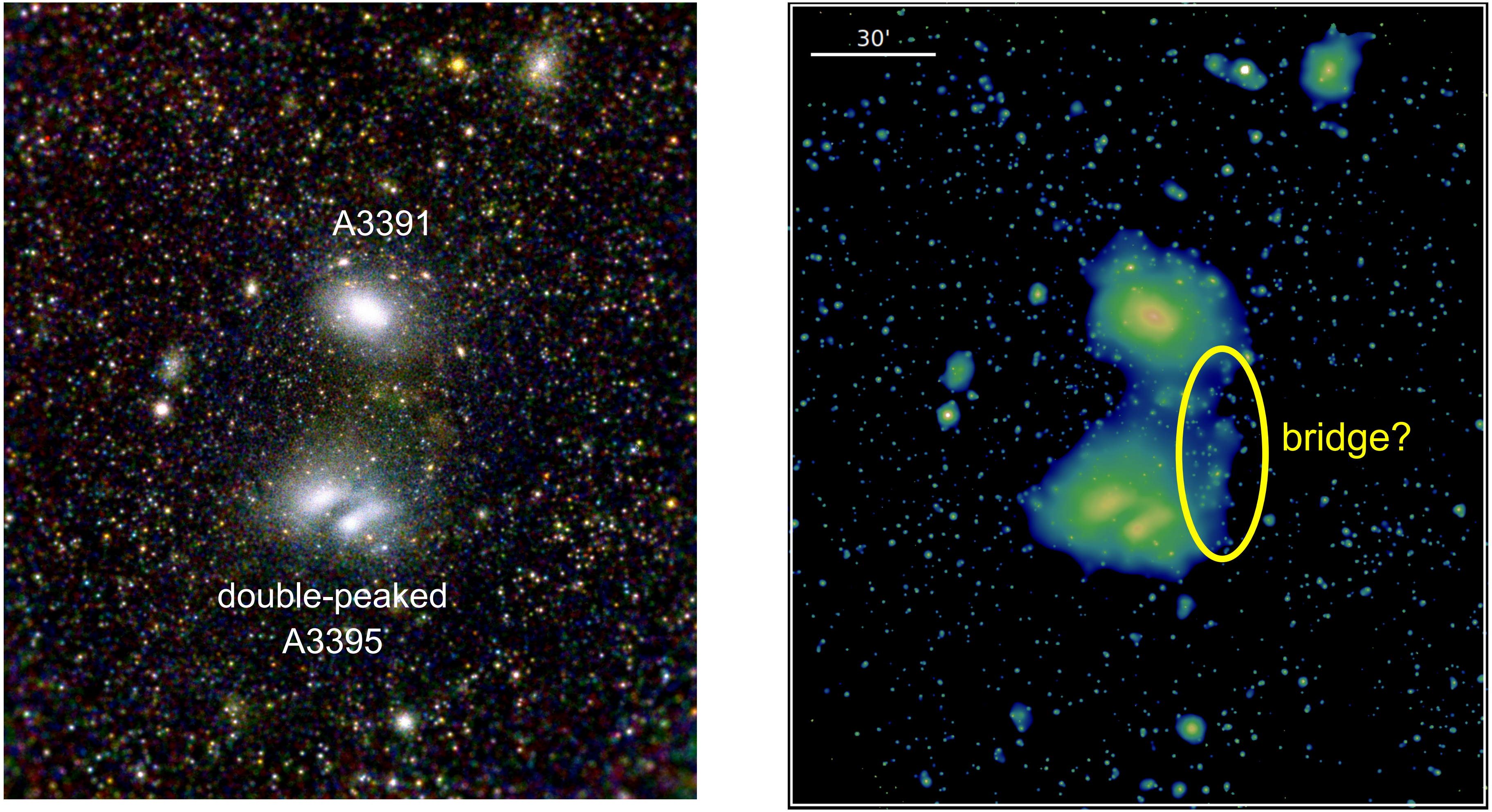
LMC
including SNR1987A





SRG / eROSITA 0.2 - 2.2 keV
10'
1'
LMC / N132D
MPE/IKI
O
Fe
O
Ne
Mg
Si
X-ray Flux
0.2 keV
Energy
2.2 keV


SRG/eROSITA 0.2-0.7; 0.7-1.5; 1.5-5 keV
Cluster A3408
1H 0707-495
Sey1
5'
MPE/IKI
X-ray light curves
eROSITA TM1,2,5,6,7; 0.5-5 keV
EPIC-PN; 0.5-5 keV
Rate
Time
+6.241e8
MPE/IKI


A3391
double-peaked
A3395
30'
bridge?