The foundamental parameters of X-ray telescopes

M. Dadina, C. Vignali

What happens

.. a X-ray source…

INPUTS
Source photons+
~~*Mirrors response+*~~
~~*Detector response+*~~
~~*All kinds of*~~
~~*Background s*~~

OUTPUTS
Images
Light Curves
Spectra

Take into account telescope response… and remaining bgds

…mirrors,
concentrators
llimators n boar
tes..

INPUTS
Source photons+
Mirrors response+
Detector response+
All kinds of
Background s

ectors
Microcal., etc.)

Remove "some" backgrounds and malfunctioning

things to do

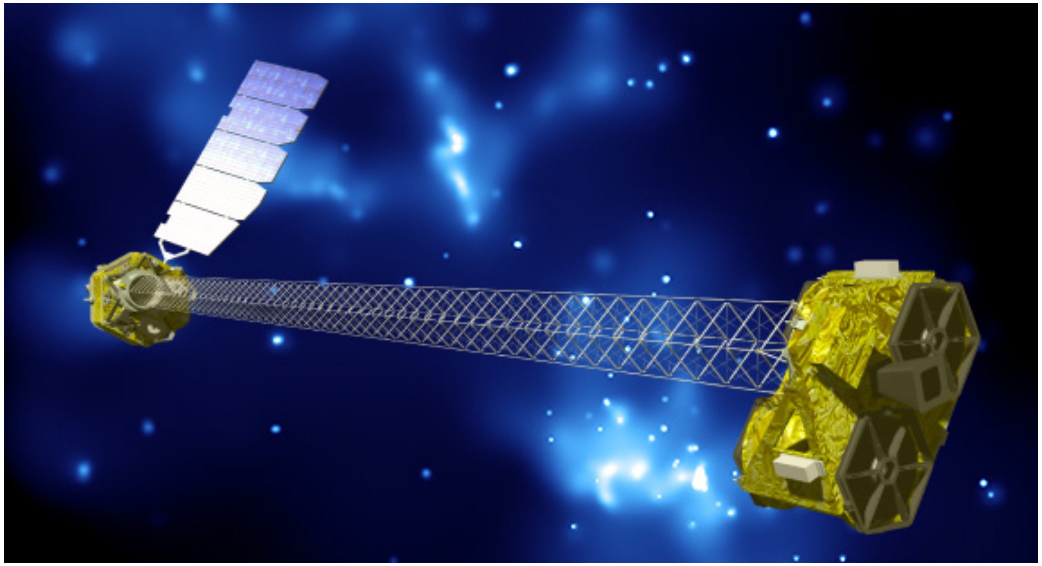
..since the birth of X-ray Astronomy in 1962, improvements were carried out in terms of sensitivity, angular resolution, energy resolution and energy bandpass

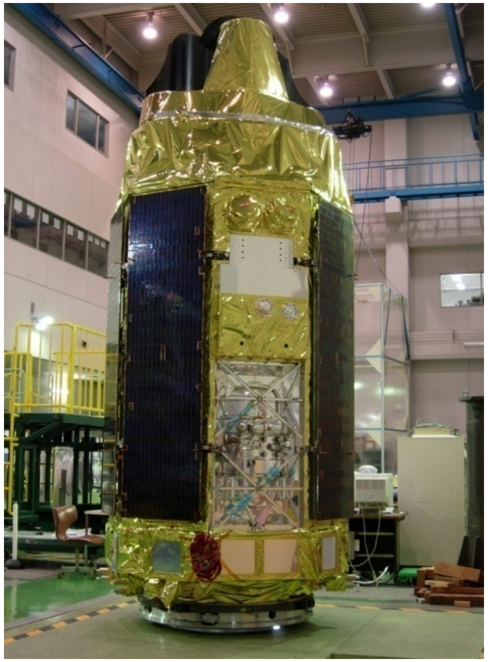
The Golden age of X-ray Astronomy

XMM-*Newton*

Chandra

NuSTAR





Suzaku

Final note……

Sensitivity:

$$S/N = S/(S+B)^{0.5} \longrightarrow \propto t^{0.5}$$

B_{sky}=Const x Sky region

$B_{dark\ current}$= Const x det. reg.

$B^2_{read\text{-}out\,(electronic)}$= Const x det. Reg.

$S^{0.5}$=Poisson Noise source counts

How to increase the sensitivity....

Increasing the collecting/effective Area

$S = F \times A_{eff}$

S/N increases......

(....but sometime also the bgd increases)

the ESA (XMM-*Newton*) way

Reducing the B.

S/N increases

the NASA (*Chandra*) way…

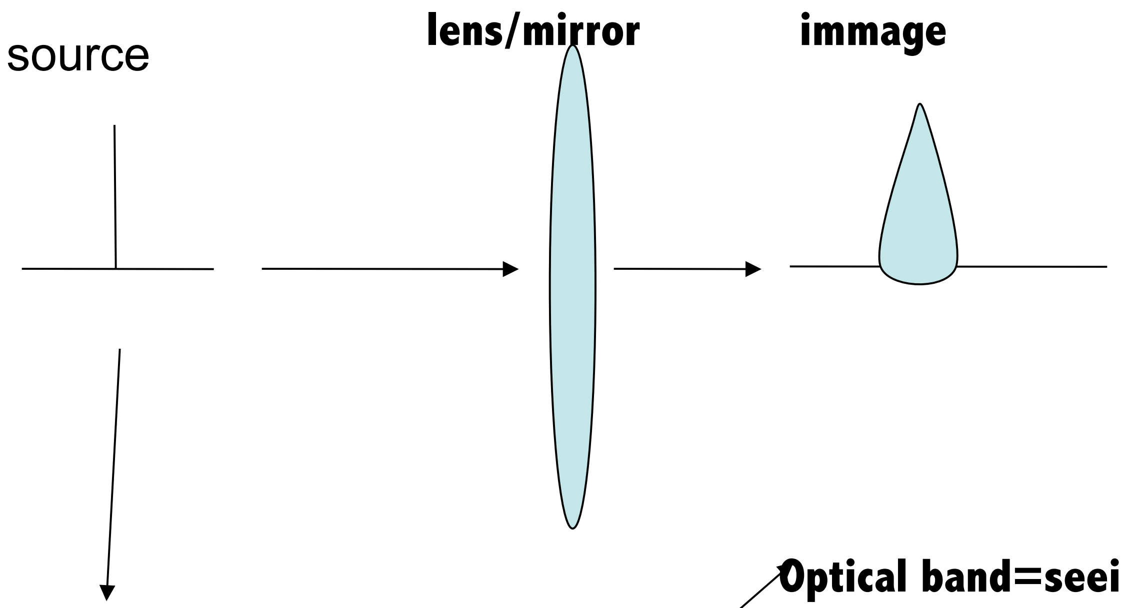
Chandra: very good spatial resolution and low backgroud

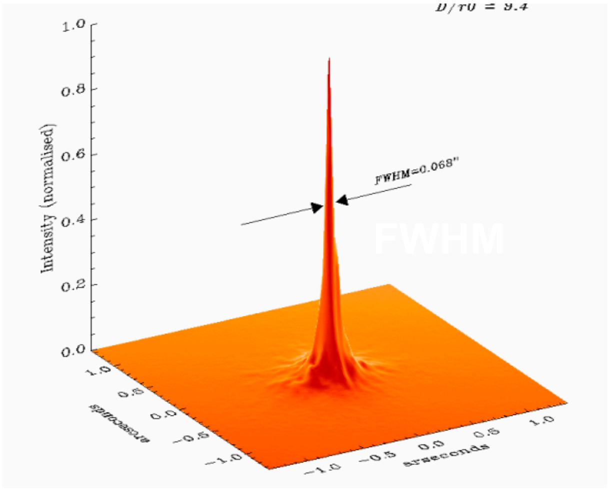
XMM-*Newton*: large effective area but worse PSF and higher background

Angular resolution

(PSF FWHM, on-axis vs. off-axis, . . .)

Mirrors and PSF





Intrinsic limit (θ=1.22 λ/D)
+ operations…

Optical band=seeing

X-rays= mirrors properties
+ mirror array assemply

Point Spread Function (PSF) – describes the response of an imaging system to a point source or point object.

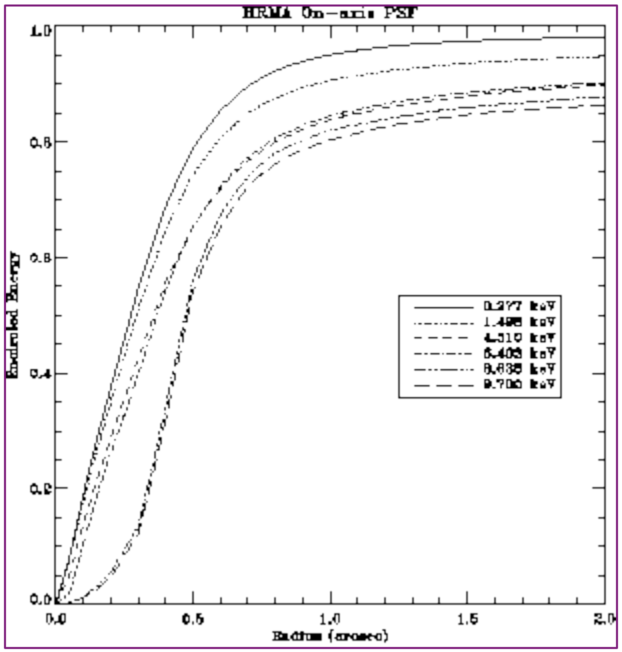
HEW (PSF), FWHM (PSF) = angular resolution

PSF = function of (x,y) or (r, ϑ).

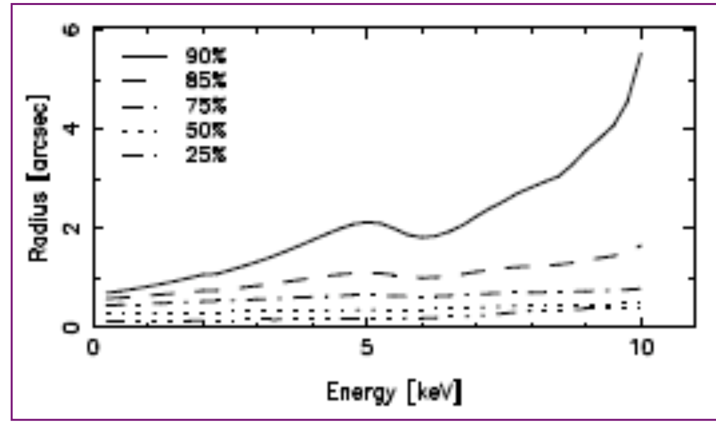
Chandra

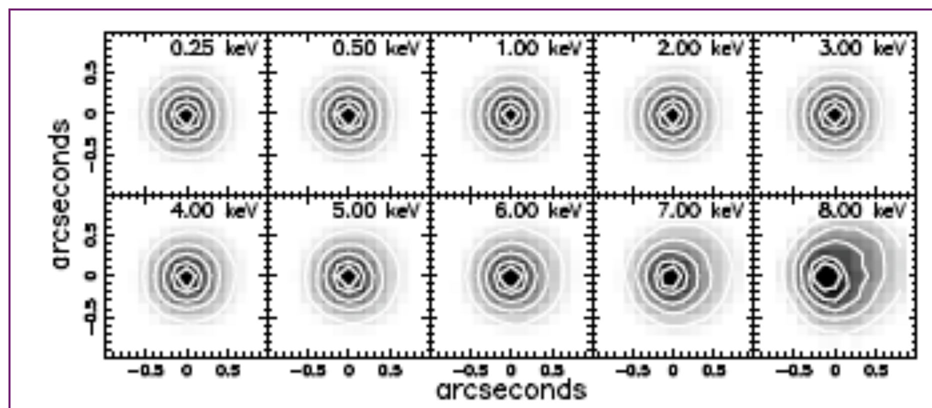
High Resolution Mirror Assembly (HRMA): On-axis PSF

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



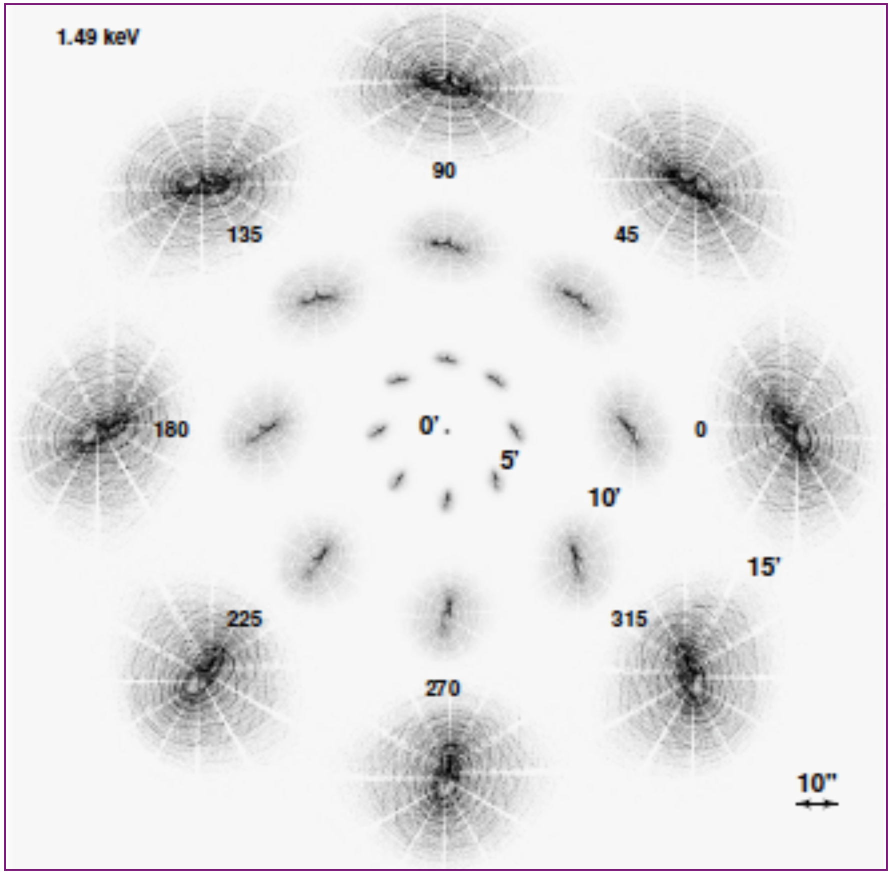
Encircled energy vs. radius at different energies

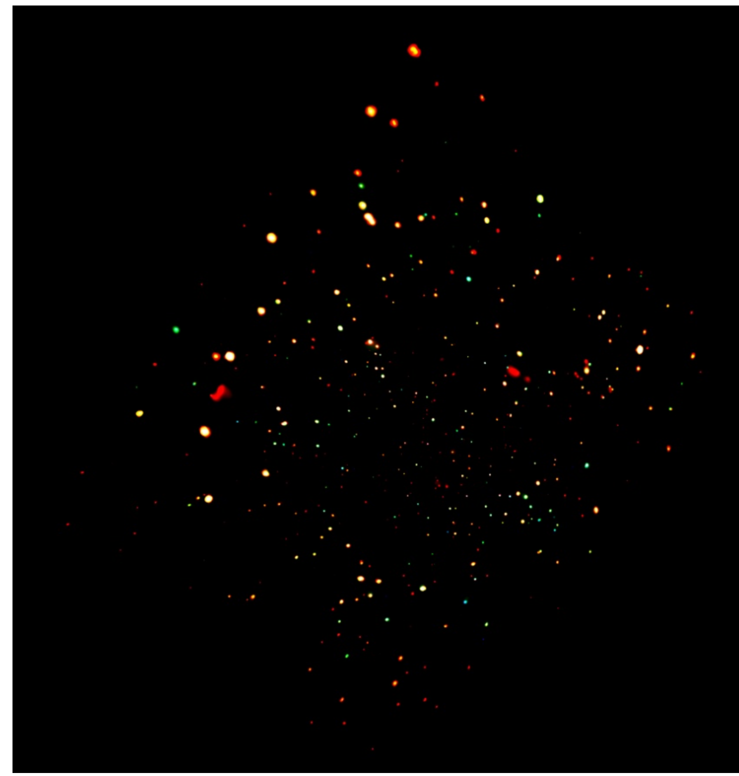




On-axis PSF size and shape

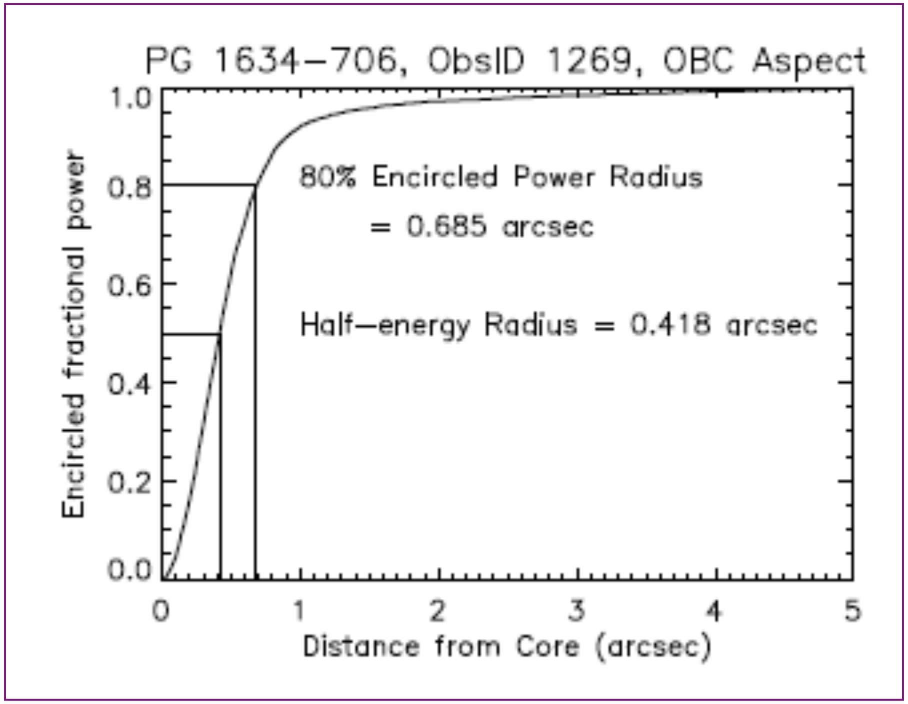
High Resolution Mirror Assembly (HRMA): Off-axis PSF



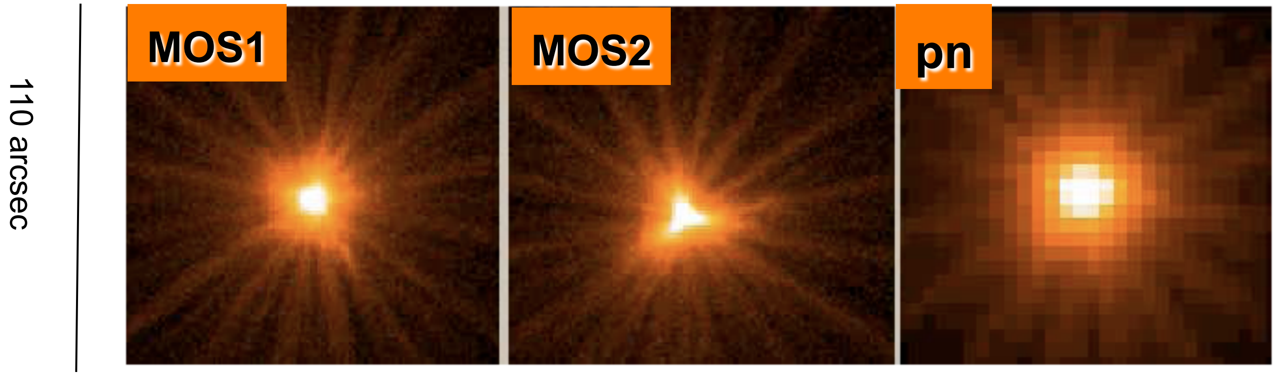


CDF-N 2Ms exposure

Resulting image on the focal plane of *Chandra*-ACIS



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

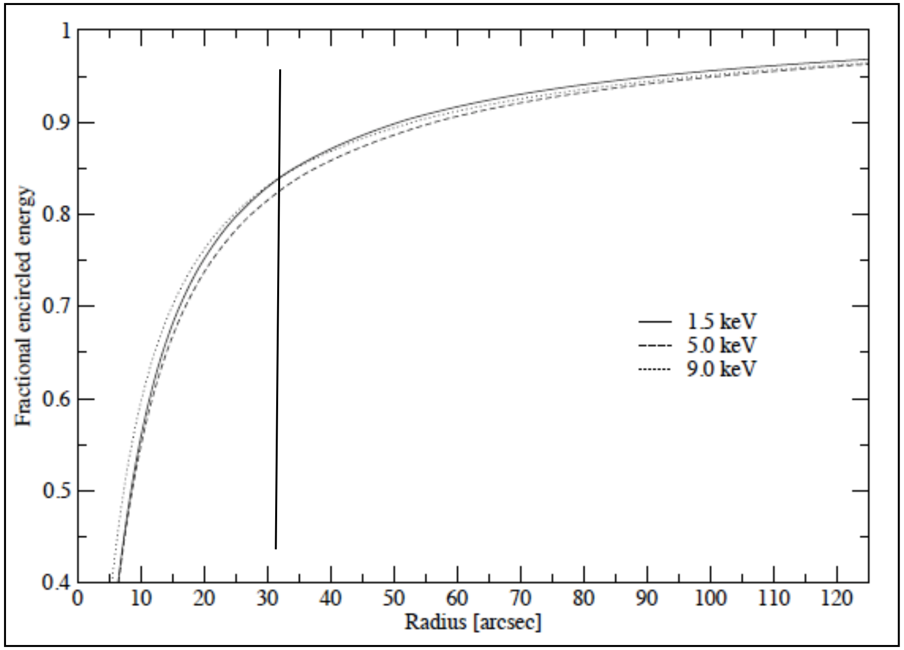


spider-like pattern due to the support of the Wolter I mirrors

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

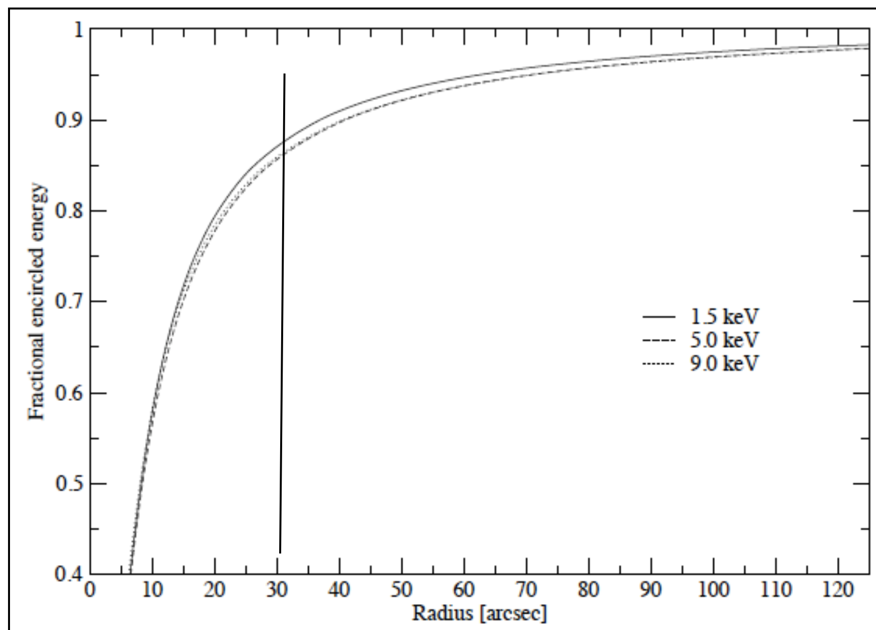
PSF FWHM higher than in *Chandra* but much larger effective area
Background (and confusion limit) can be an issue

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

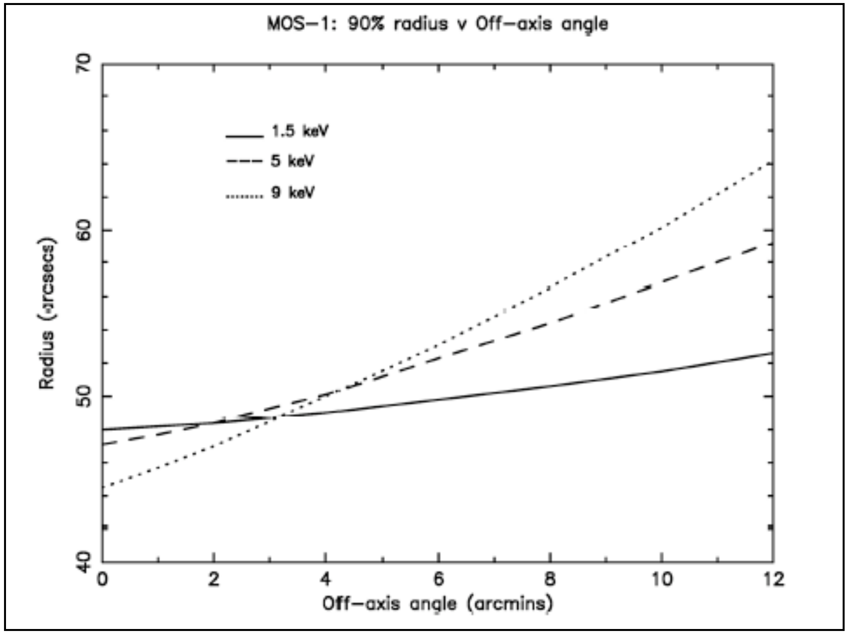


Encircled energy vs. radius
at different energies for the MOS1-2

Encircled energy vs. radius
at different energies for the pn

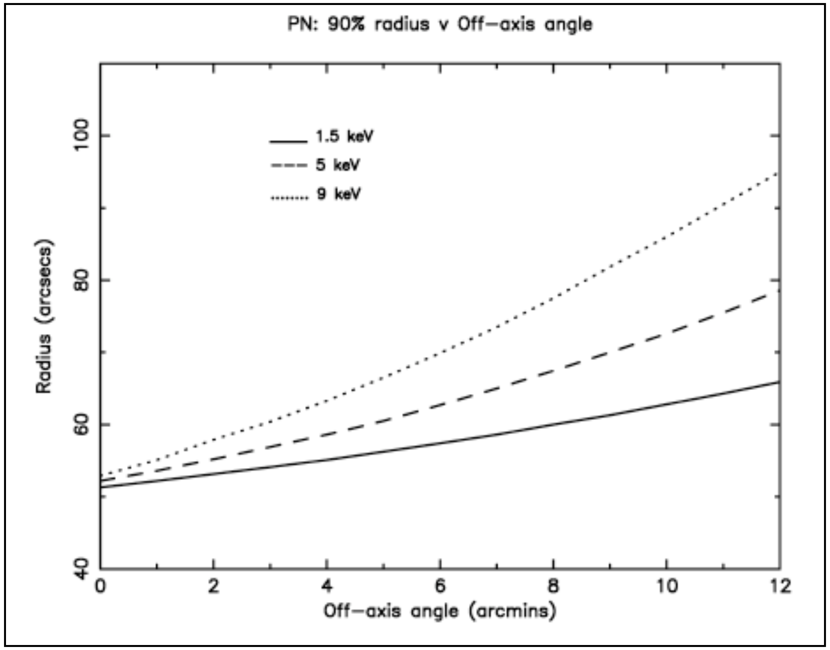


XMM-*Newton:* the EPIC off-axis PSF



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

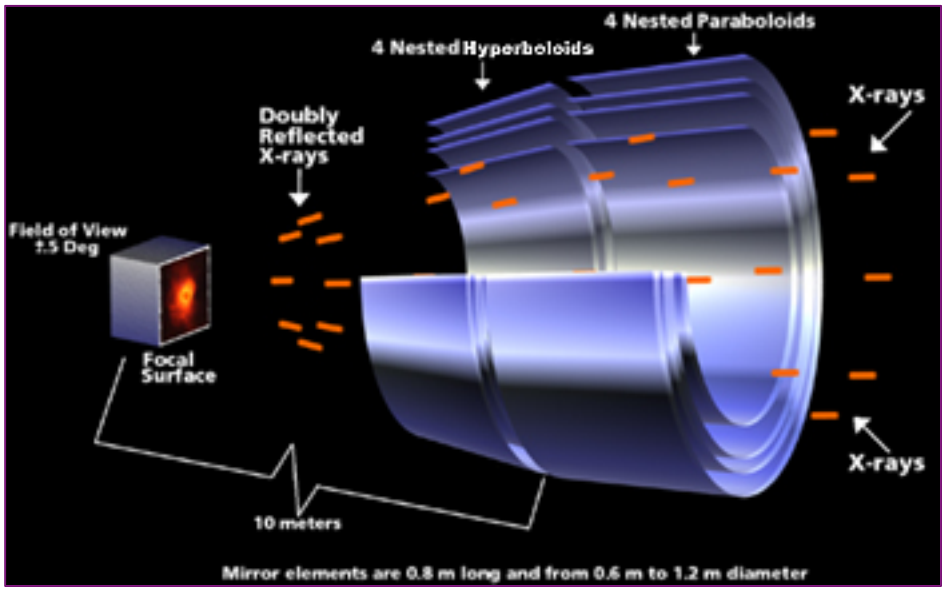
90% radius vs. off-axis angle for the pn at different energies



Chandra and XMM-*Newton*

(telescopes and CCD detectors)

Chandra = angular resolution

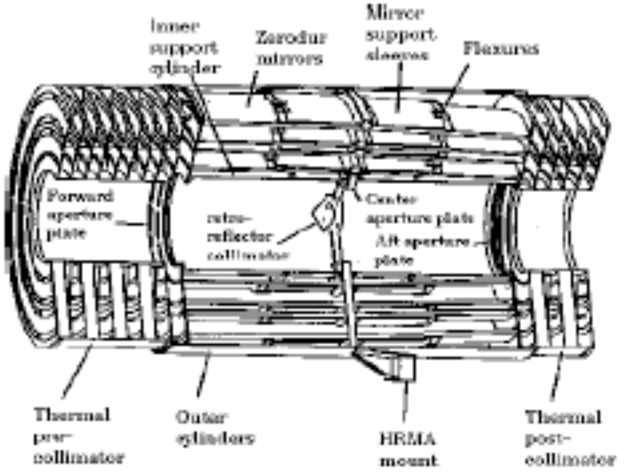


Only four, robust shells
High-quality of shell production
to allow <arcsec on-axis angular
resolution (the best so far in X-rays)

To focus X-rays, angles < critical angle for
total reflection are needed

$$\vartheta_{crit} \propto \frac{\sqrt{\rho}}{E}$$

High Resolution Mirror Assembly (HRMA)



Ottica Wolter Type-I

Mirror diameters: 1.23, 0.99, 0.87 0.65 m

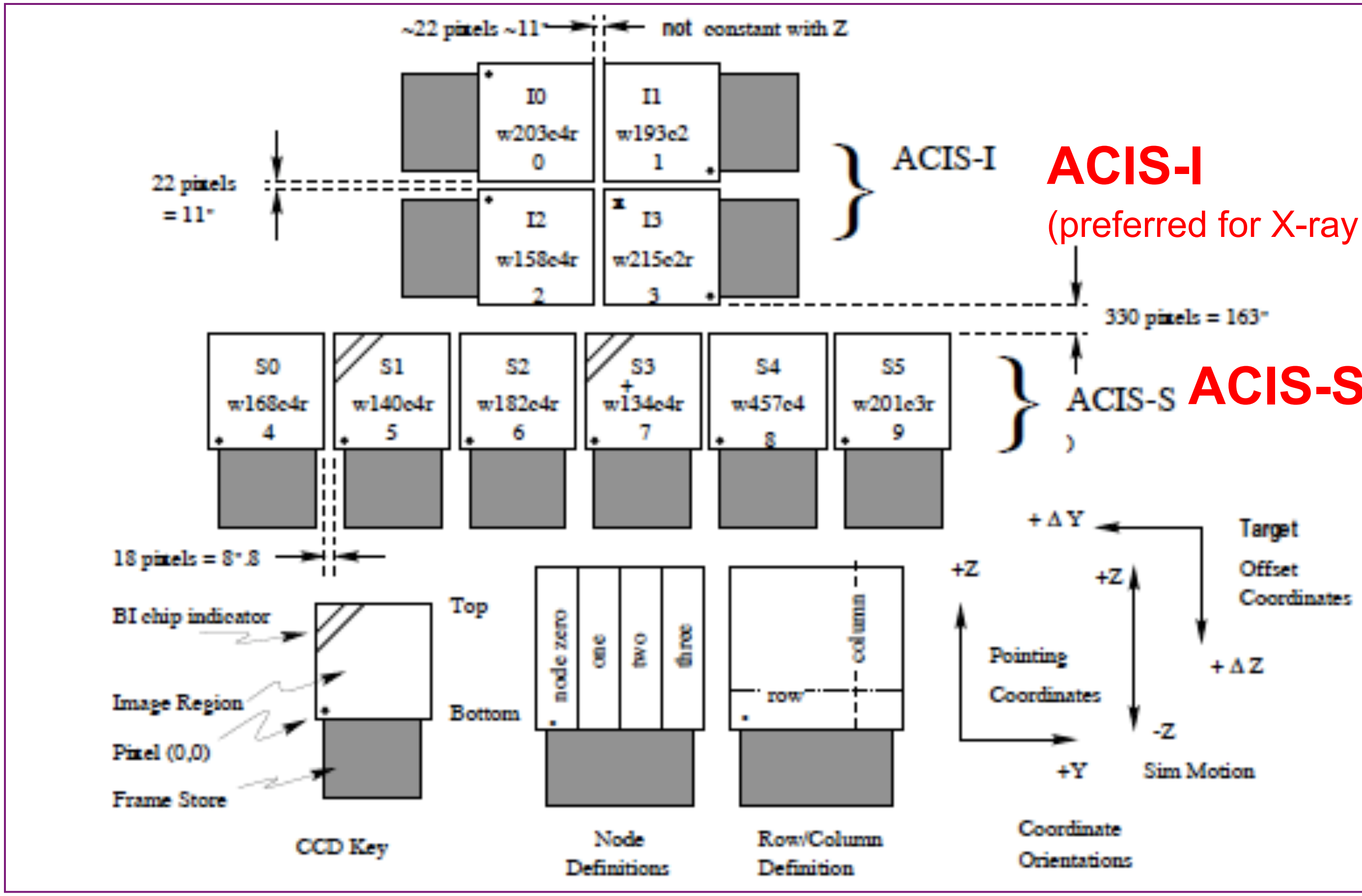
Mirror lengths: 84 cm

HRMA mass: 1500 kg

Focal length: 10 m

PSF FWHM: 0.5”

Chandra focal-plane detectors: CCDs



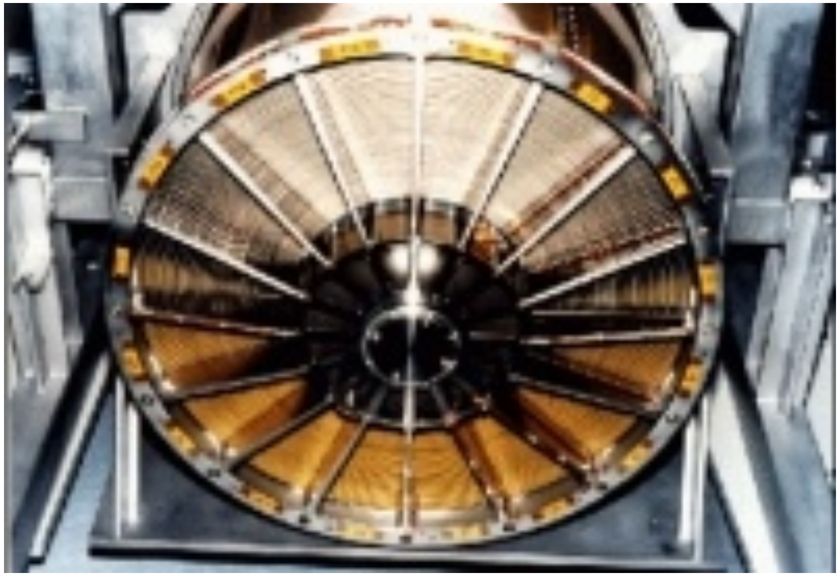
ACIS-I

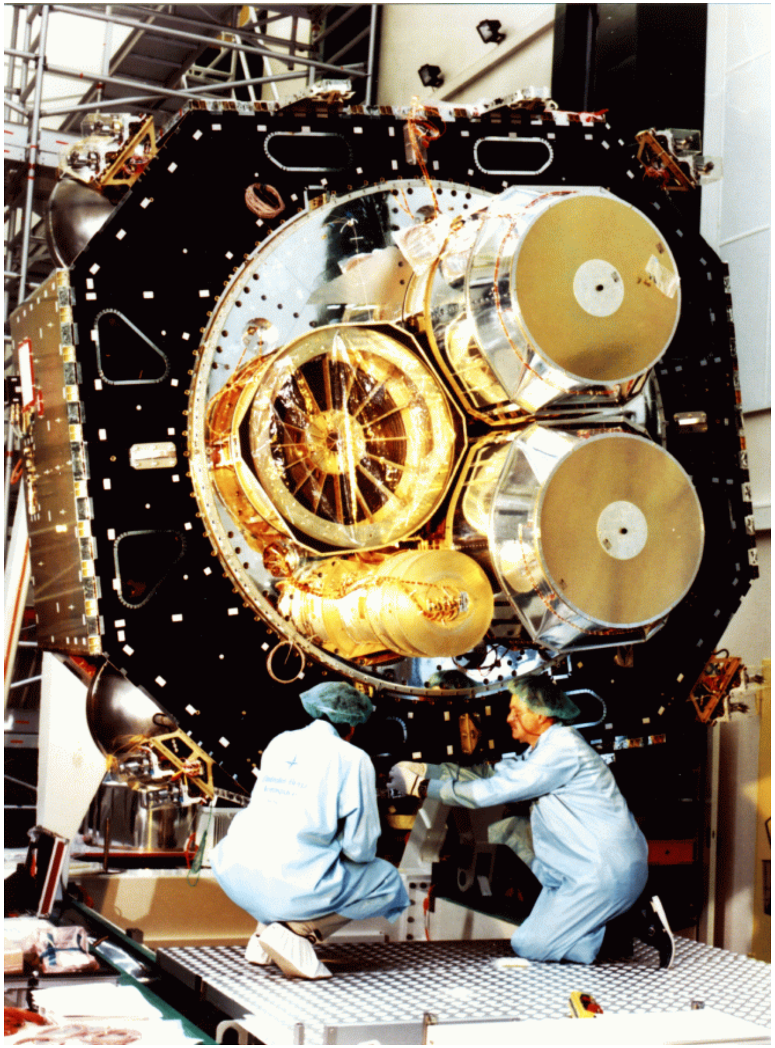
(preferred for X-ray surveys)

ACIS-S

XMM-*Newton* = large effective area

3 modules, 58 shells





XMM-Newton: all instruments at work simultaneously

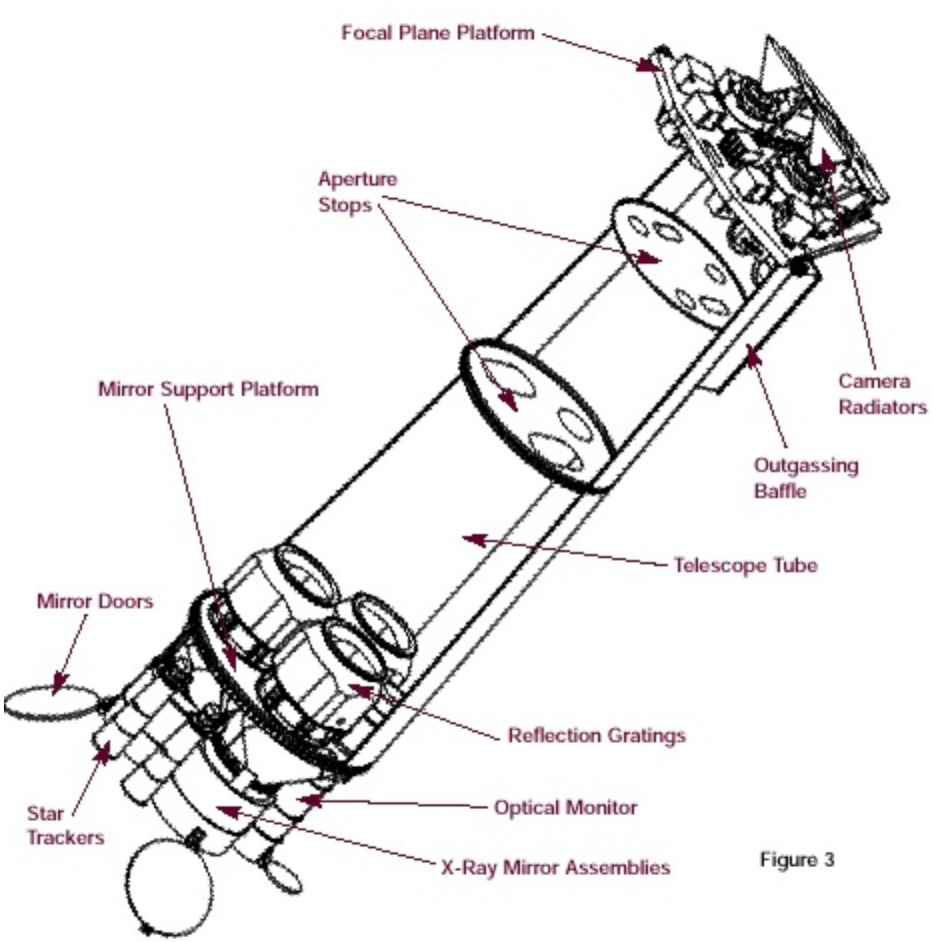
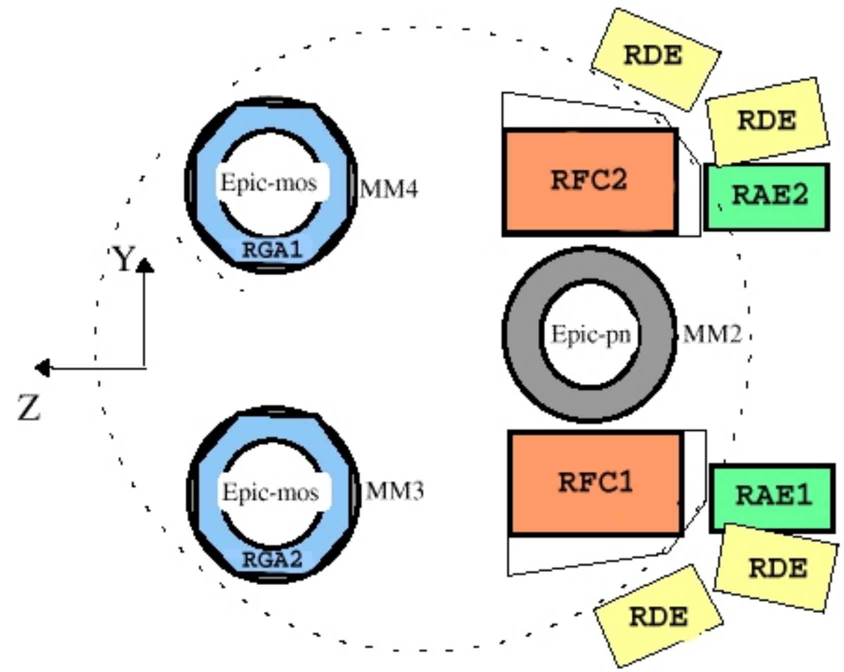
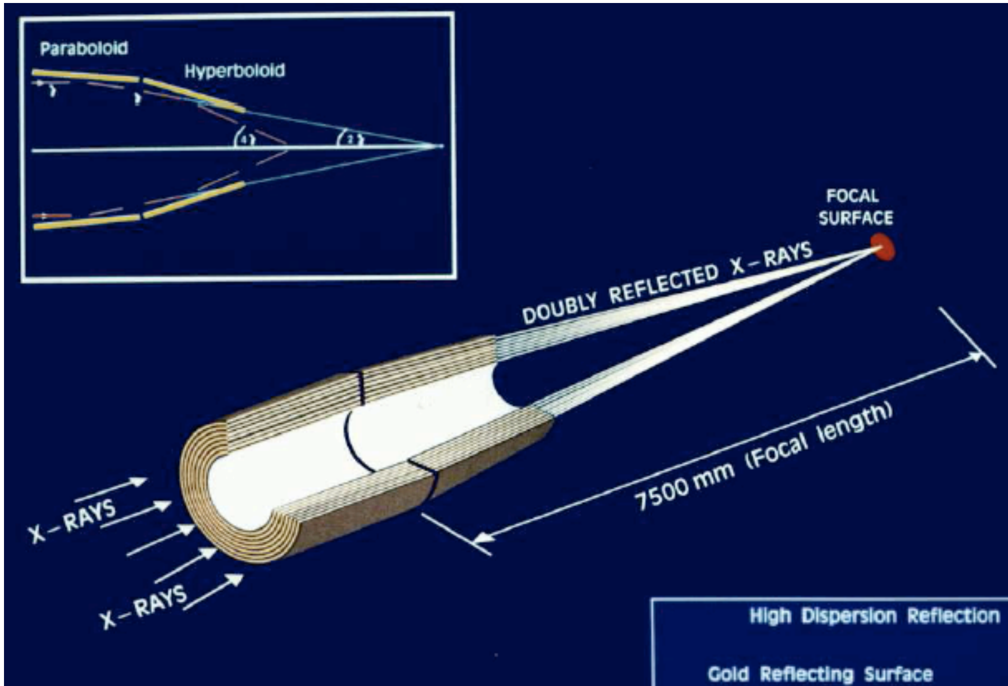
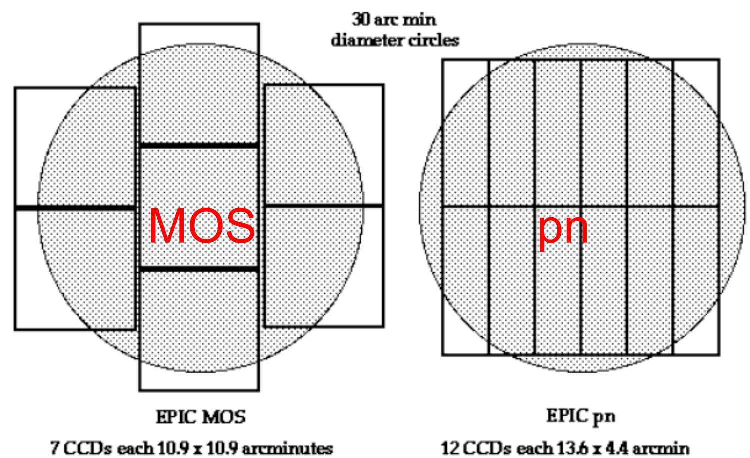


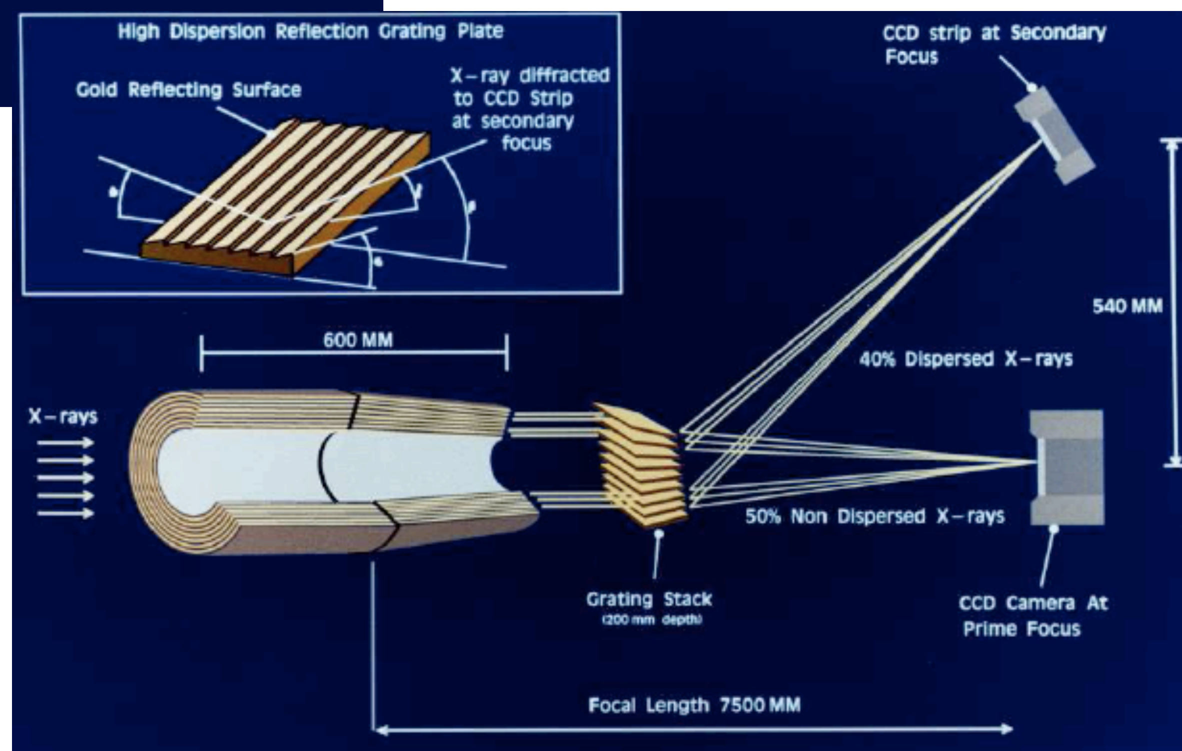
Figure 3



Wolter I solution







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

Effective area

(and its dependencies)

Mirrors and Effective Area

$$A_{effective}(E,\theta,x,y) = A_{geometric} \times R(E) \times V(E,\vartheta) \times QE(E,x,y)$$

Effective area

Geometric Area

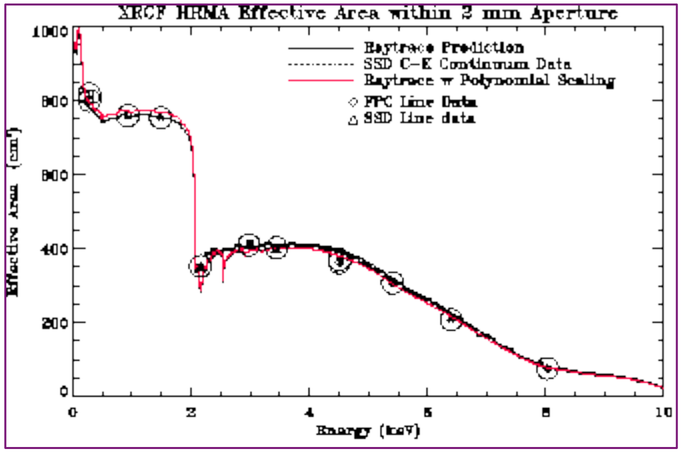
Reflectivity

Vignetting

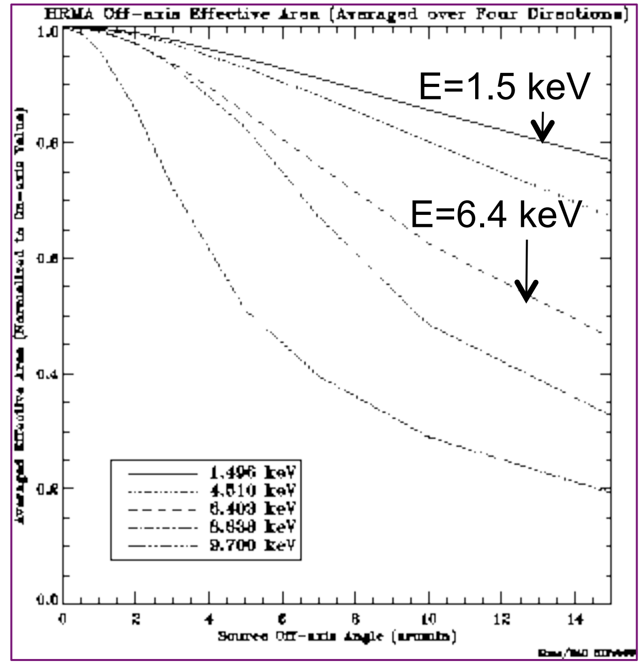
Quantum Efficiency

- **Effective area** – it is the area “encoded” in the ARF [cm^2]
- **Geometric area** – “cross-section” of the telescope
- **Reflectivity** – fraction of photons reflected by the mirros (function of energy)
- **Vignetting** – quantifies the fraction of “lost” photons (function of the off-axis angle from the optical axis, ϑ, and the energy of the incoming photon)
- **Quantum Efficiency** – fraction of incident photons on the detector actually registered by the detector. In the case of CCD, QE=f(energy, position on the detector)

Chandra High Resolution Mirror Assembly (HRMA): Effective Area



Effective area vs. Energy



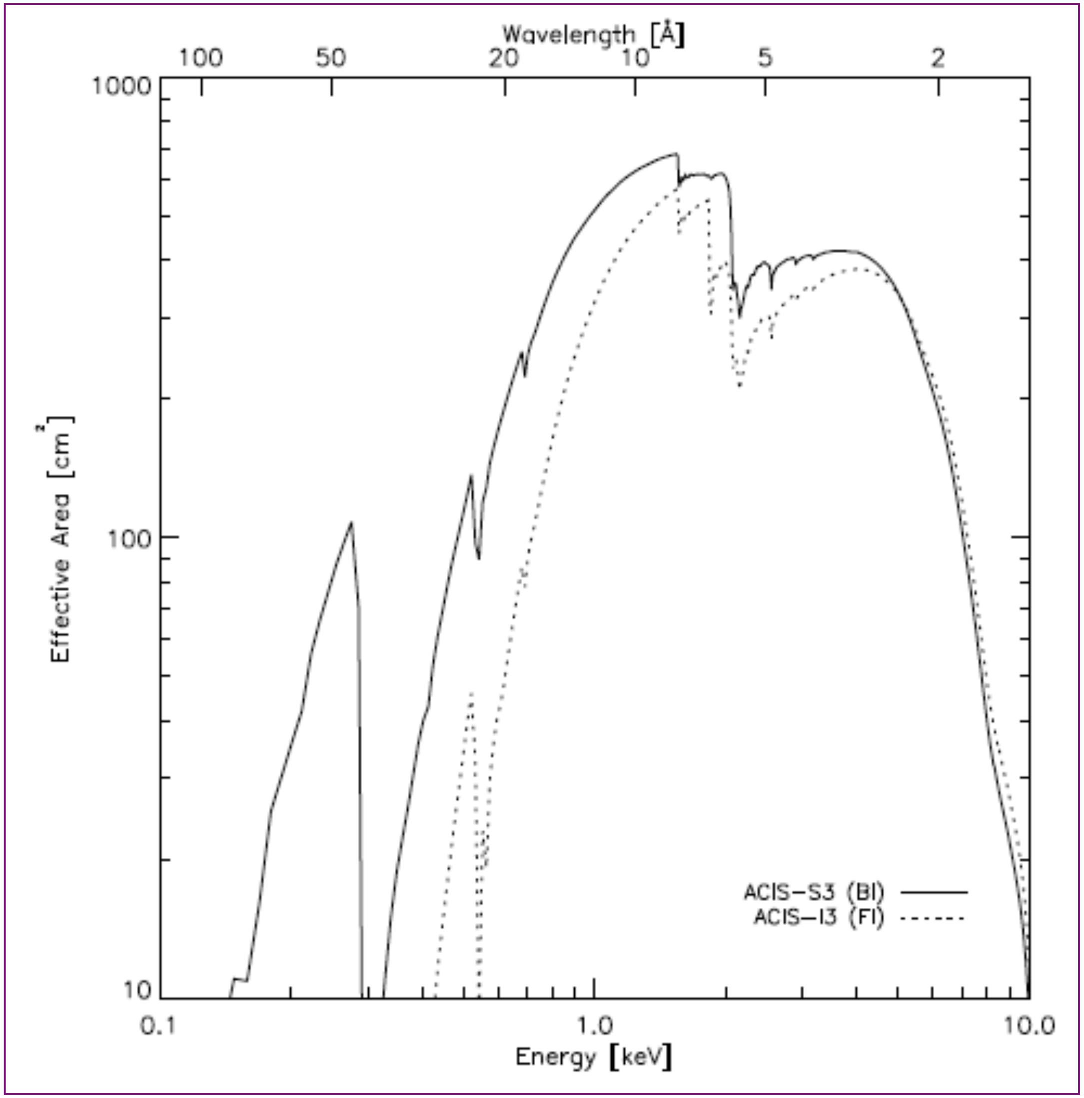
Effective area vs. off-axis angle at different energies

Effect of vignetting

Average effective area normalized to on-axis value

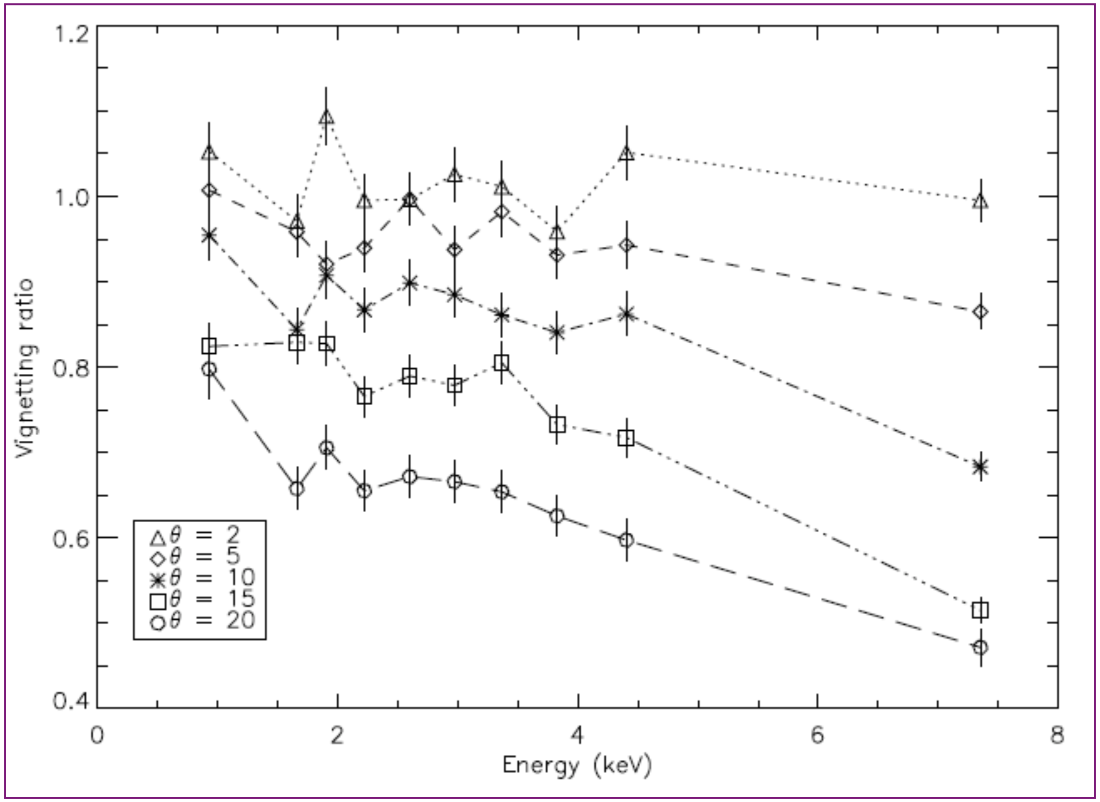
$$\vartheta_{crit} \propto \frac{\sqrt{\rho}}{E}$$

Chandra: Effective area



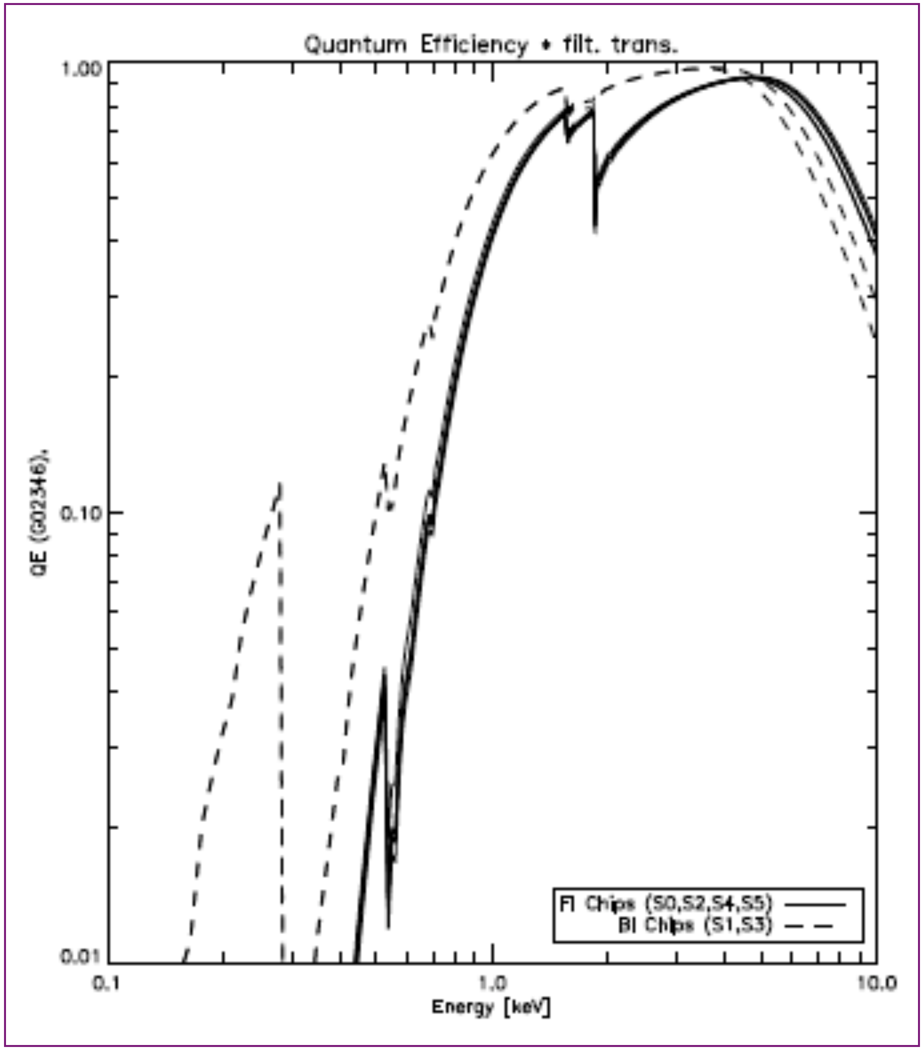
Chandra: vignetting

Ratio of the off-axis vs. on-axis counts at different off-axis angles

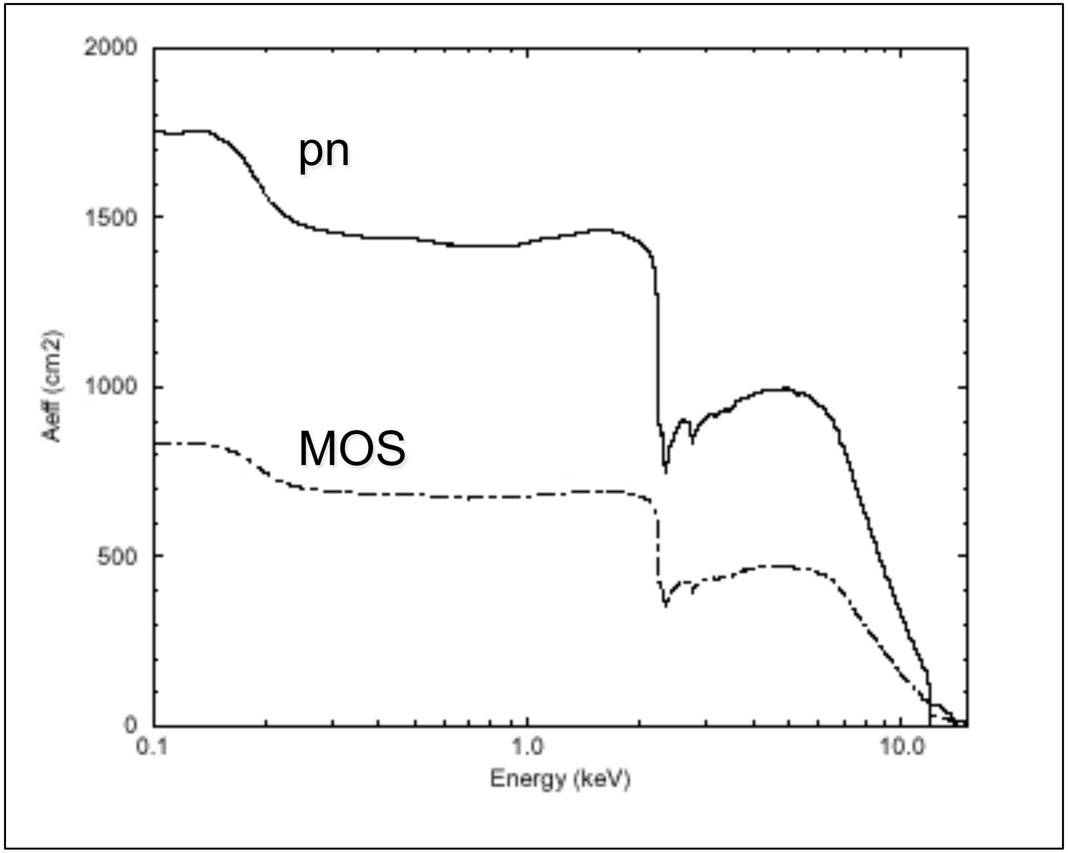


Hard X-ray photons are more difficult to focus
➔ **Vignetting**

Chandra: Quantum efficiency

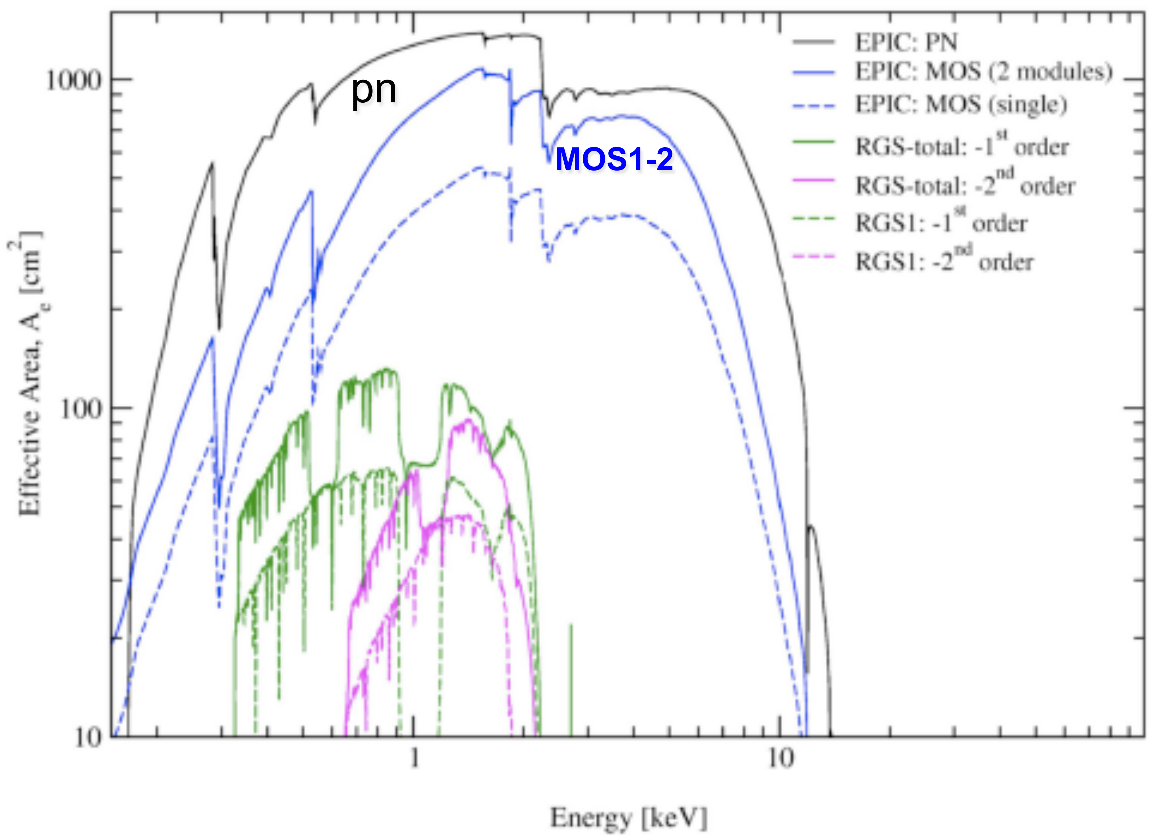


XMM-*Newton:* mirror effective (geometric) area

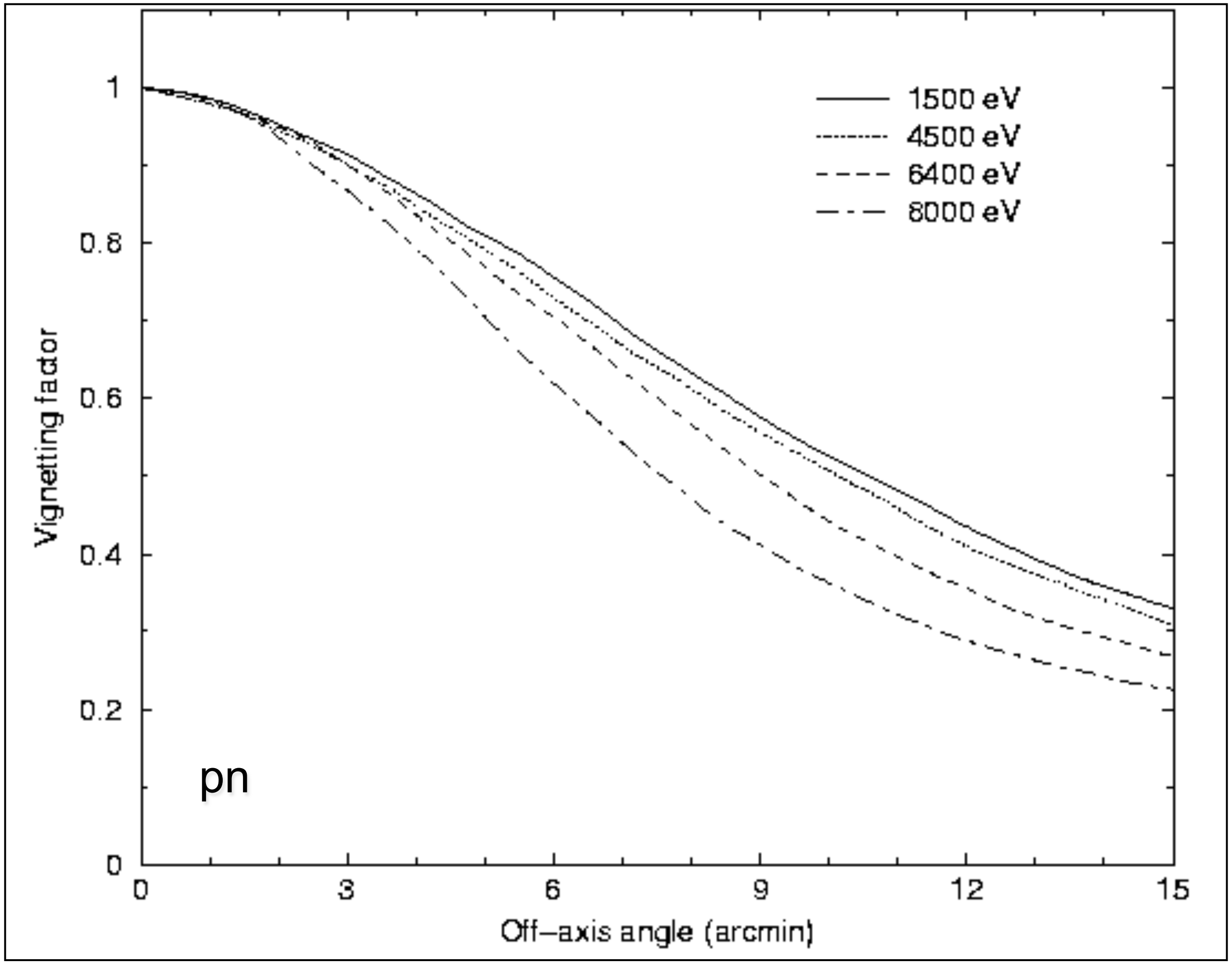


$$\vartheta_{crit} \propto \frac{\sqrt{\rho}}{E}$$

XMM-*Newton:* effective area

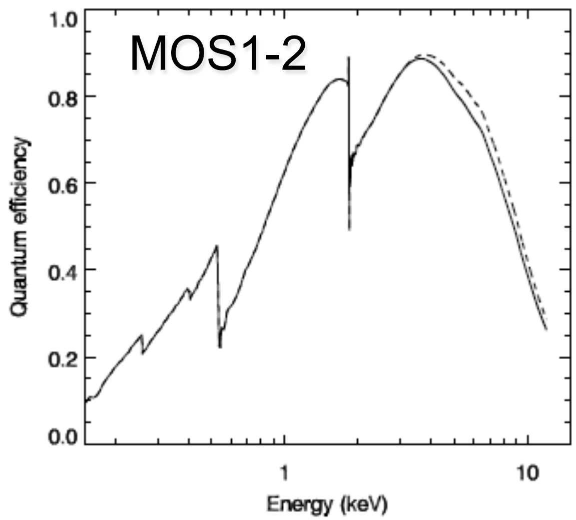


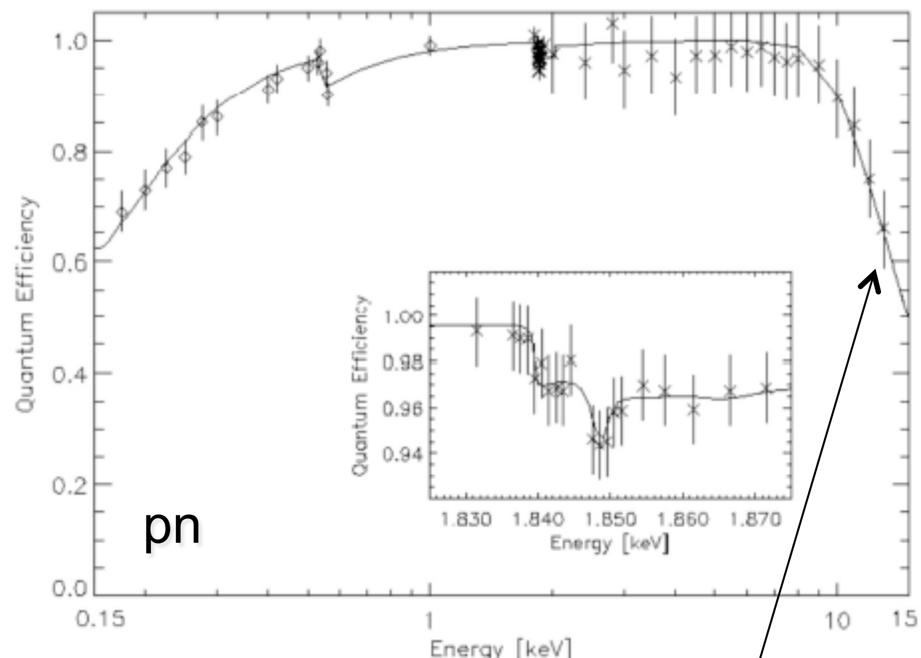
XMM-*Newton:* vignetting



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

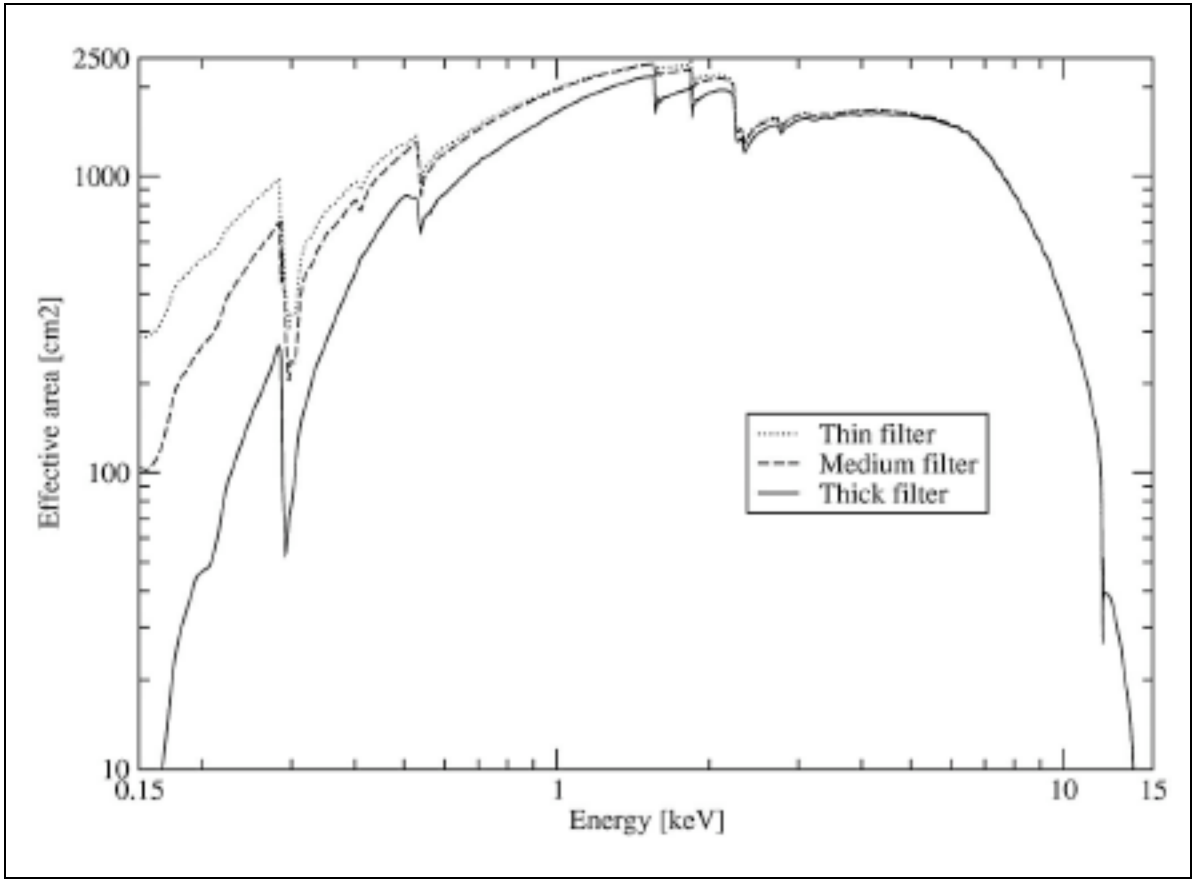
XMM-*Newton*: quantum efficiency





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

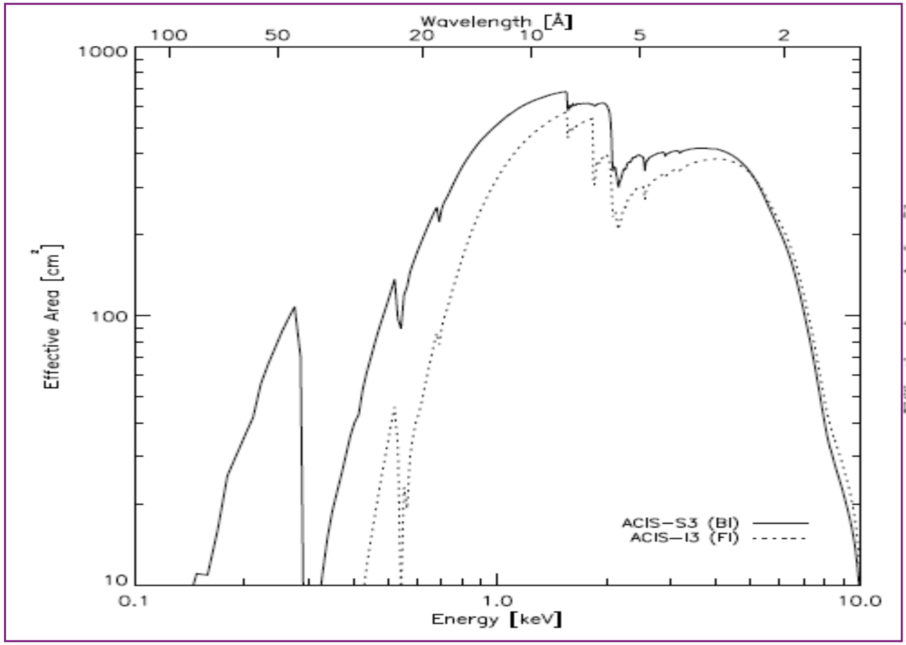
XMM-*Newton:* effective area dependence on the filter choice

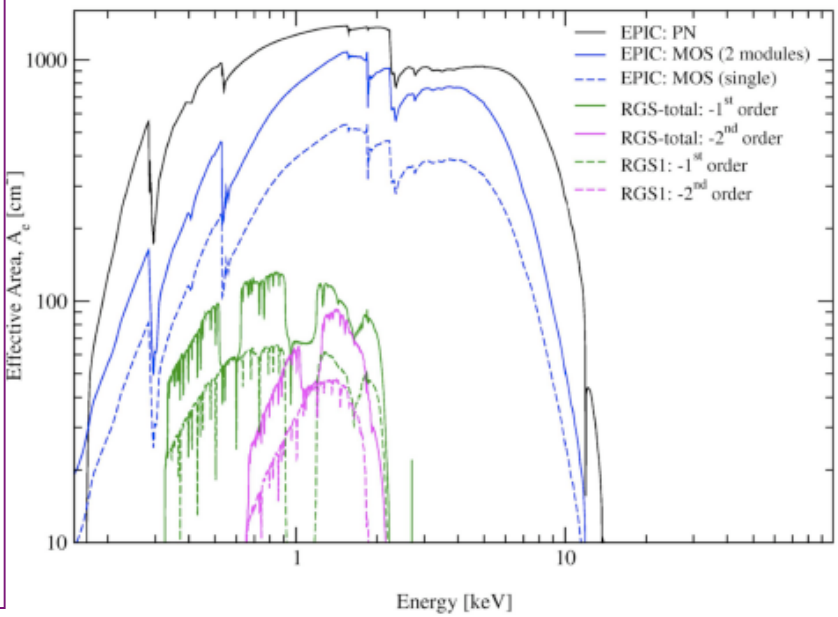


To avoid contamination from bright, soft objects (e.g., stars), a medium/thick filter is adopted

You willl account for all this information creating a file named arf (ancillary response file)

Chandra **XMM-*Newton***

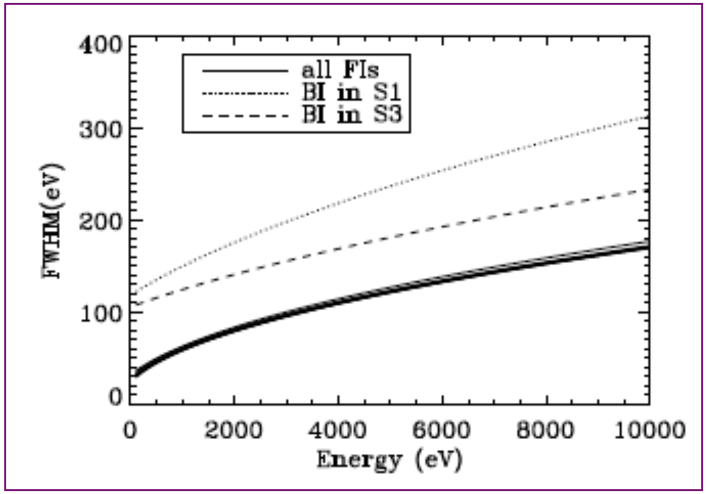




$$\vartheta_{crit} \propto \frac{\sqrt{\rho}}{E}$$

Spectral (energy) resolution

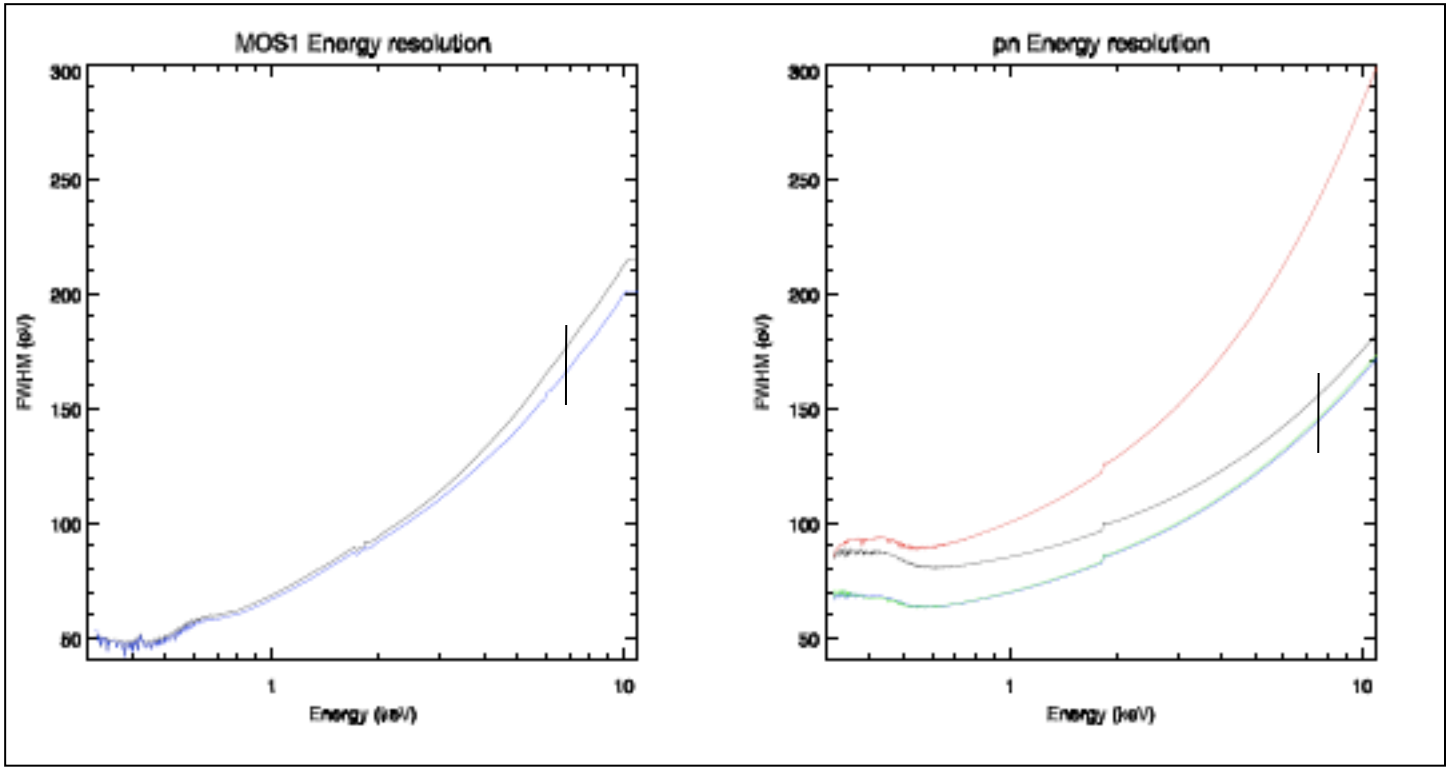
Chandra: energy resolution



Typical CCD resolution
100-150 eV at 6 keV

$\Delta E(FWHM)/E \propto E^{-1/2}$ (E in keV)

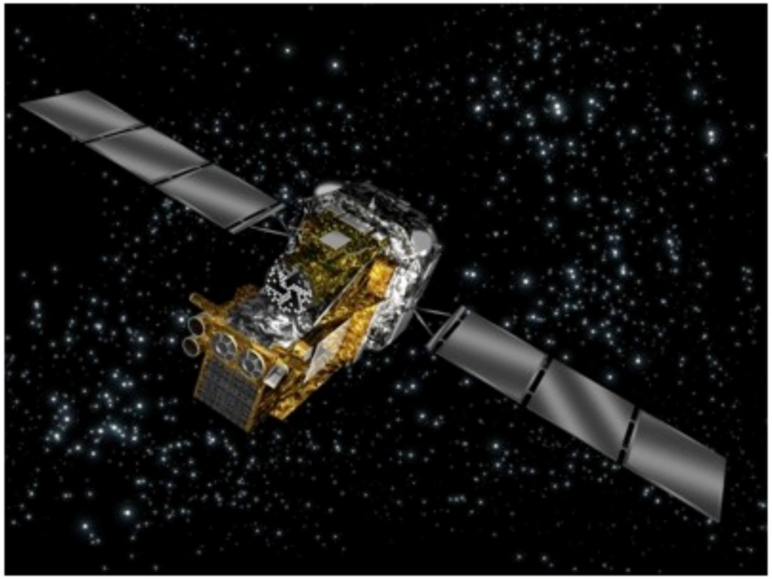
XMM-*Newton:* energy resolution

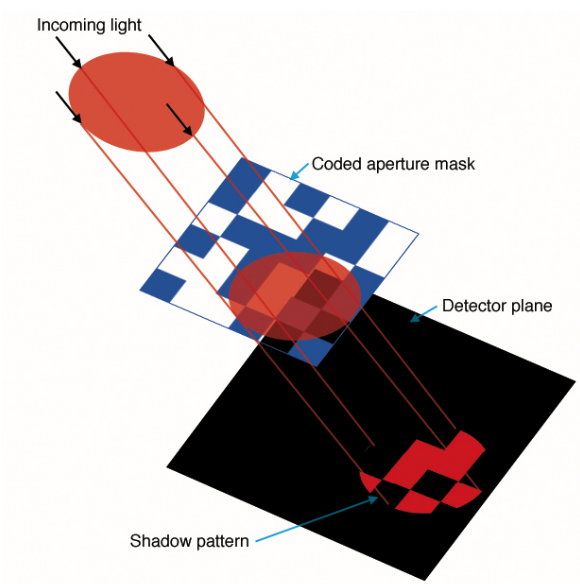


You willl account for all this information creating a file named rmf (redistribution matrix file)

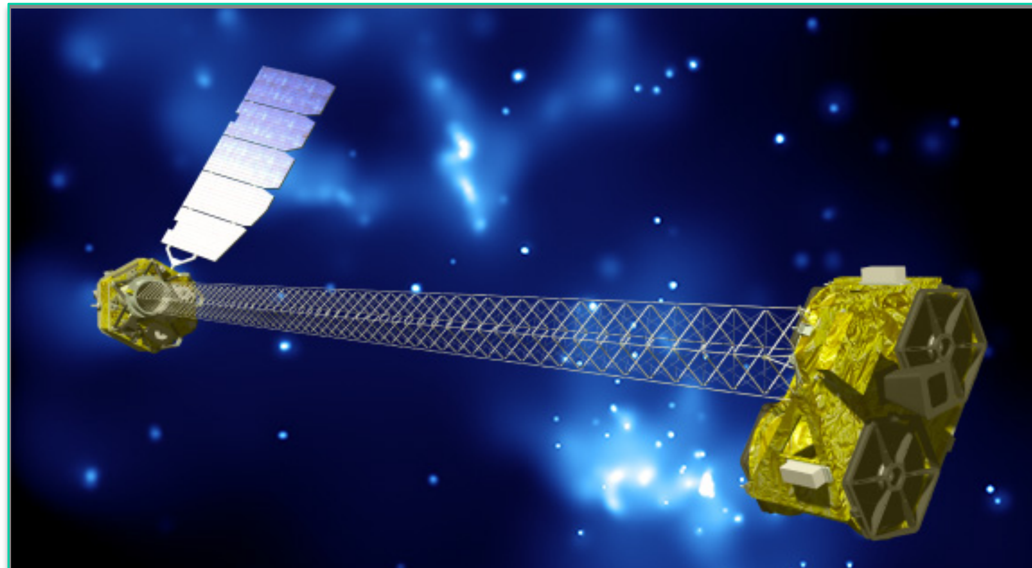
NuSTAR

INTEGRAL, Swift BAT

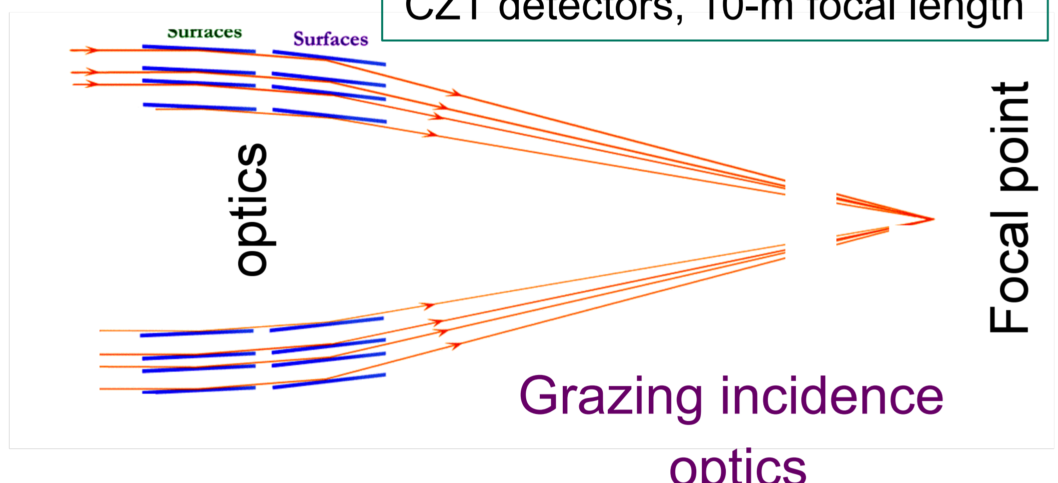


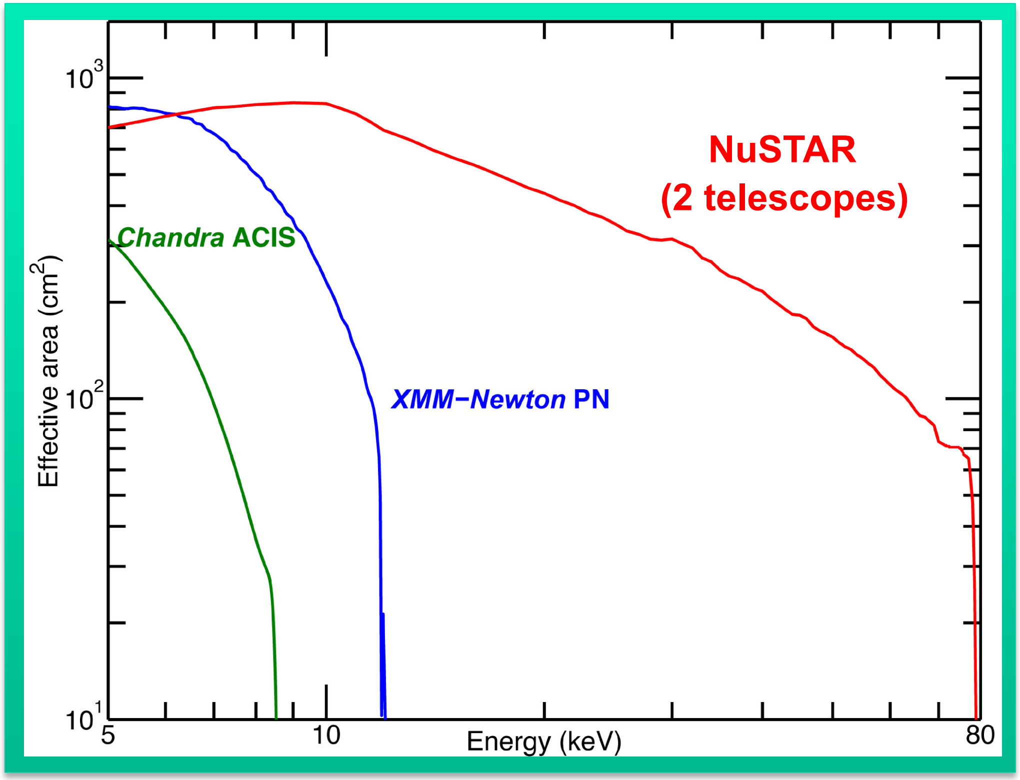


NuSTAR



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





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)

Imaging

HPD 58”

FWHM 16”

Localization 2” (1-sigma)

Field of View

FWZI 12.5’ x 12.5’

FWHI 10’ @ 10 keV

8’ @ 40 keV

6’ @ 68 keV

Timing

relative 100 microsec

absolute 3 msec

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

Target of Opportunity

response <24 hr (reqmt)

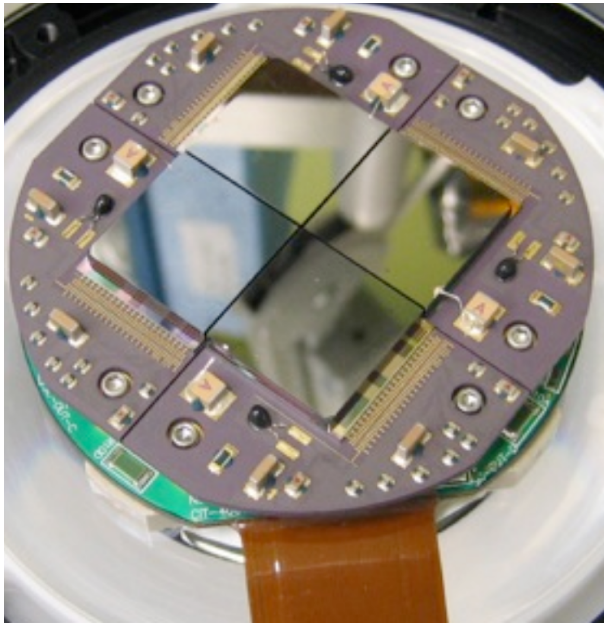
typical 6-8 hours

80% sky accessibility

Focal Plane Detector

Focal Plane Parameter	Value
Detector Anode	32 pixel x 32 pixel
Pixel Size	0.6 mm/12.3''
Focal Plane Size	12' x 12'
Energy threshold	2 keV
Time resolution	2ms
Dead time fraction (at threshold)	5%
Max processing rate	400 events s^{-1} $module^{-1}$
Max. flux meas. rate	10^4 counts s^{-1}

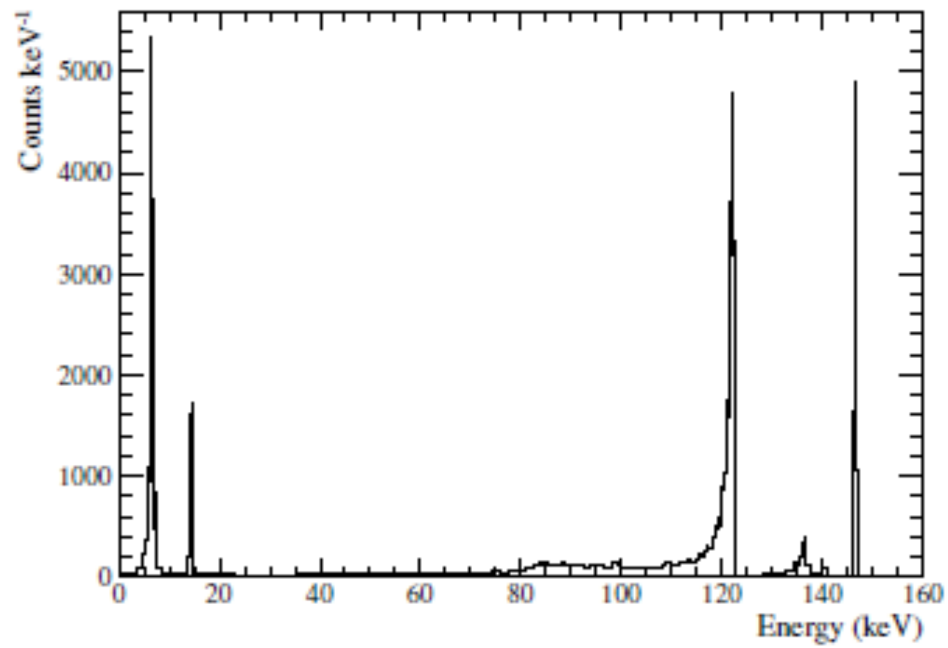
Number of FPDs: 2
Material: CdZnTe
1 FPD ⇨ 4 detectors (2x2 array)
Detector area =2 x 2 cm
Detector thickness = 2 mm



Focal Plane Detector

^{57}Co spectrum of one CZT pixel (gamma-ray lines at 6.40, 7.06, 14.4, 122 and 136 keV).

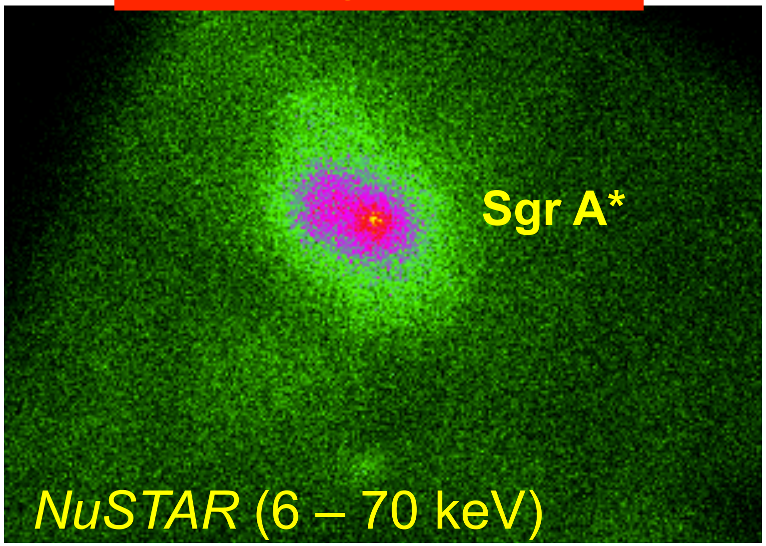
The 146 keV peak is produced by the test pulser.



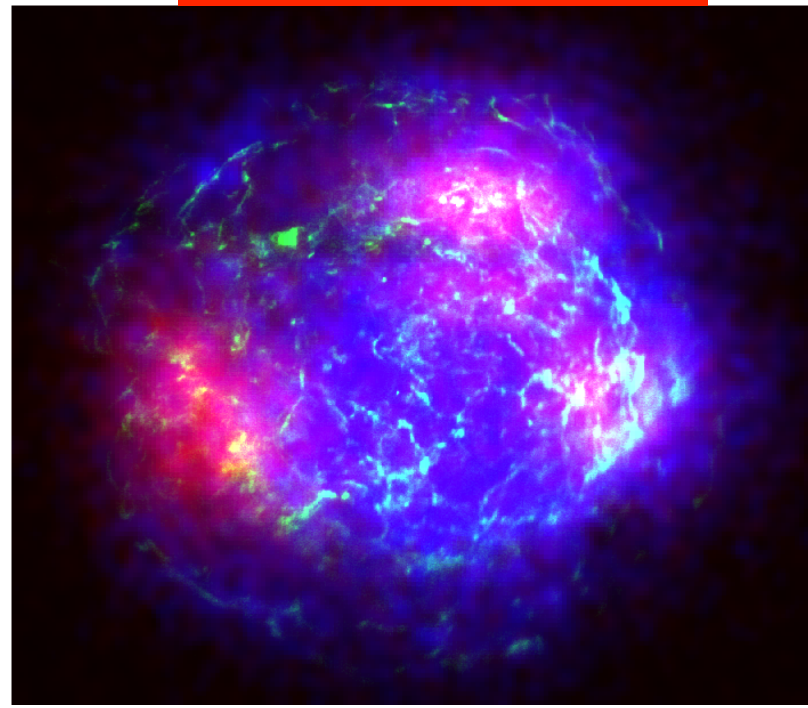
Operating settings: Temperature = 278 K
High voltage= -450 V
Acquisition time = one day

Energy resolution:
@ 14.4 keV = 0.5 keV
@ 122 keV = 0.9 keV

Sgr A*



Cassiopeia A



Red: *NuSTAR* Fe

Blue: *NuSTAR* 10-25 keV

Green: *Chandra* 4-6 keV