The foundamental parameters of X-ray telescopes

INAF OAS BOLOGNA

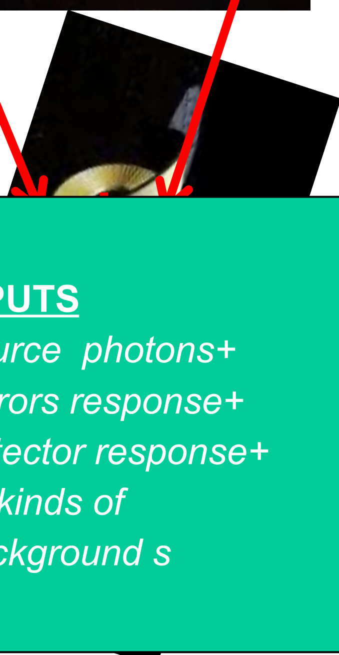
What happens

.. a X-ray source…

…mirrors, concentrators or collimators

board

ellites..



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

ctors

icrocal., etc.)

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

OUTPUTS
Images
Light Curves
Spectra

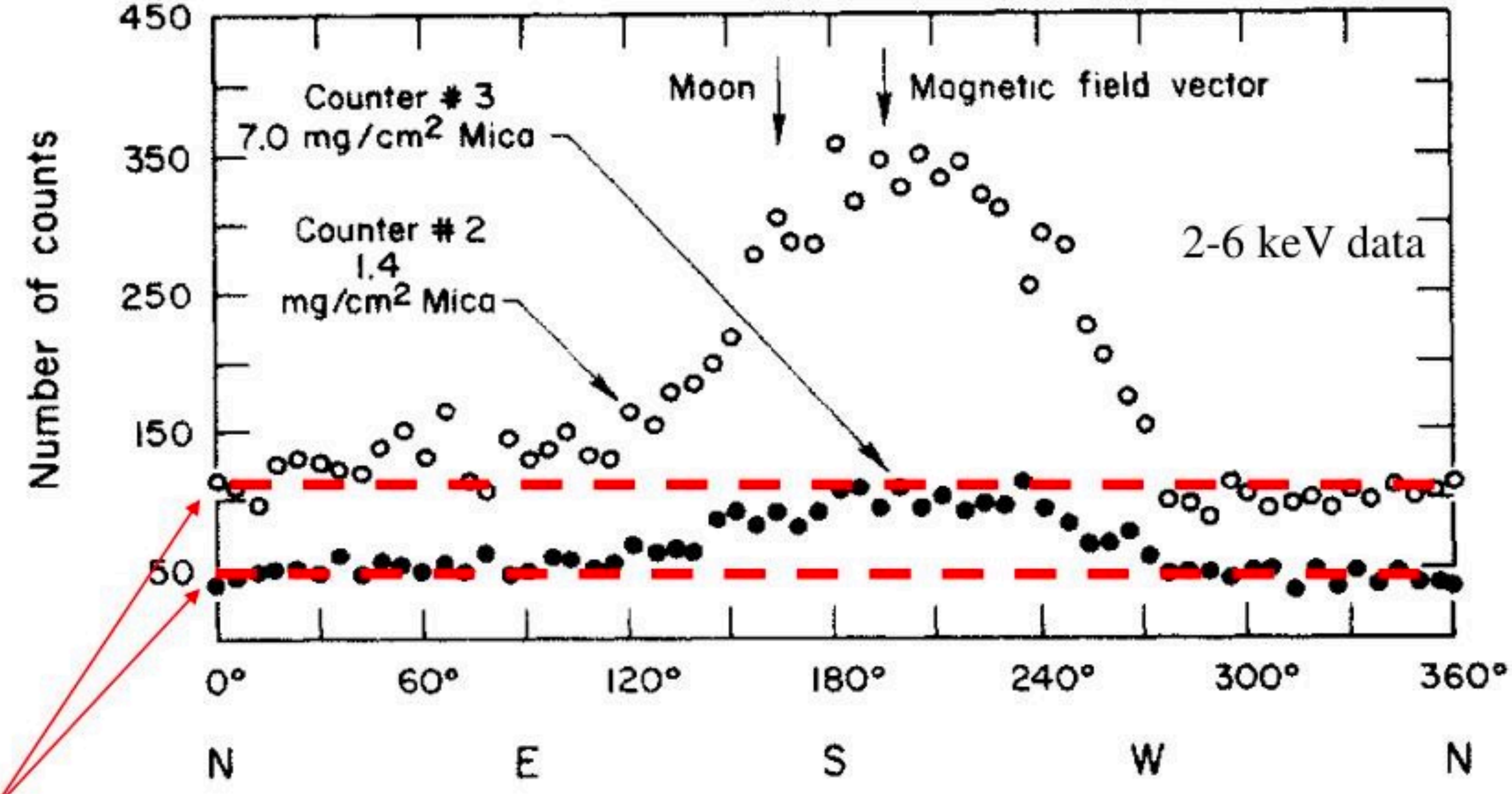
Take into account telescope response… and remaining bgds

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)

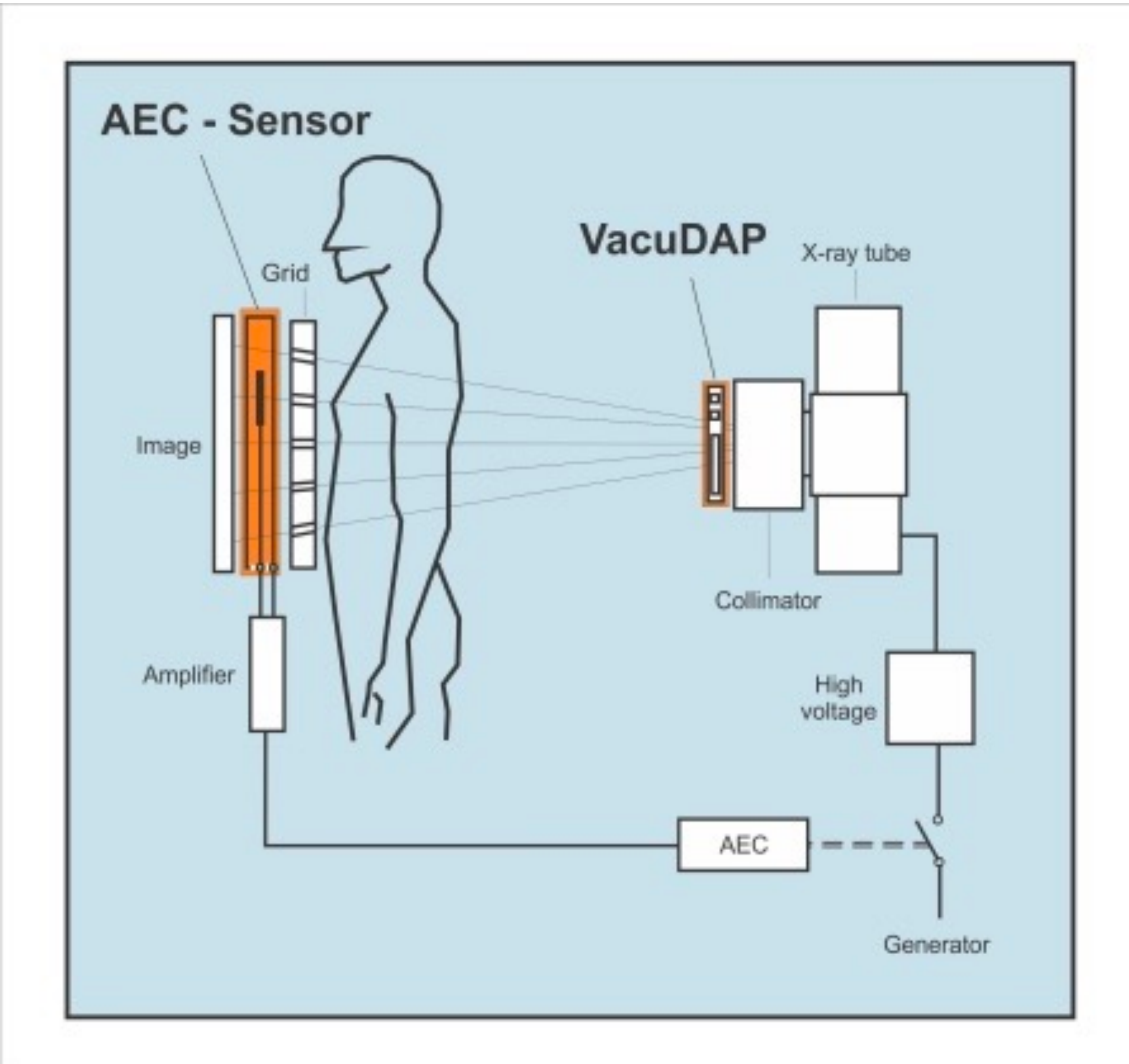
The discovery of the cosmic X-ray background (XRB)

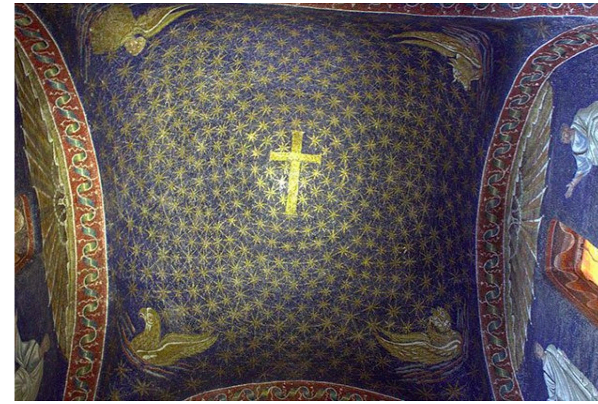


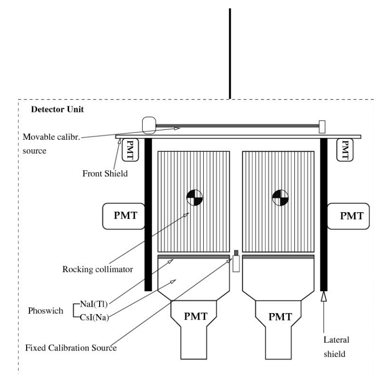
Counts > 0 from all directions → diffuse background radiation

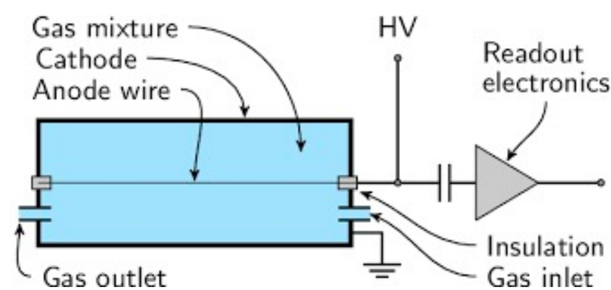
Giacconi et al. (1962). Nobel prize in 2002

The functioning of a X-ray telescope

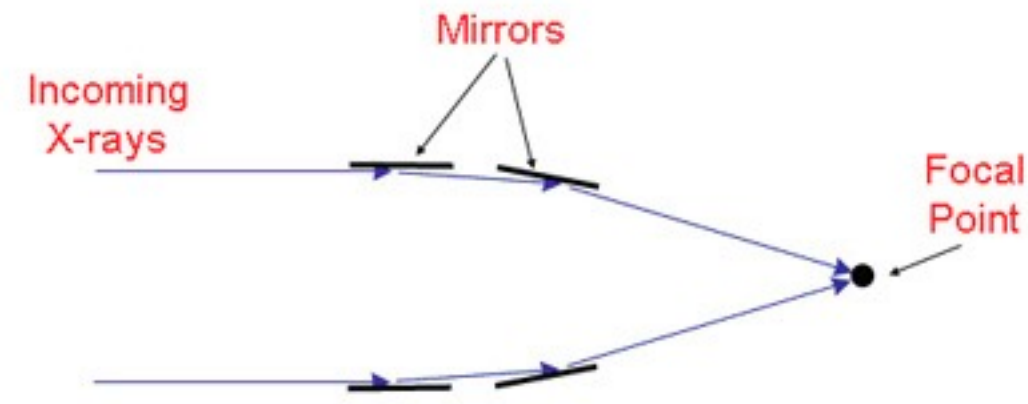




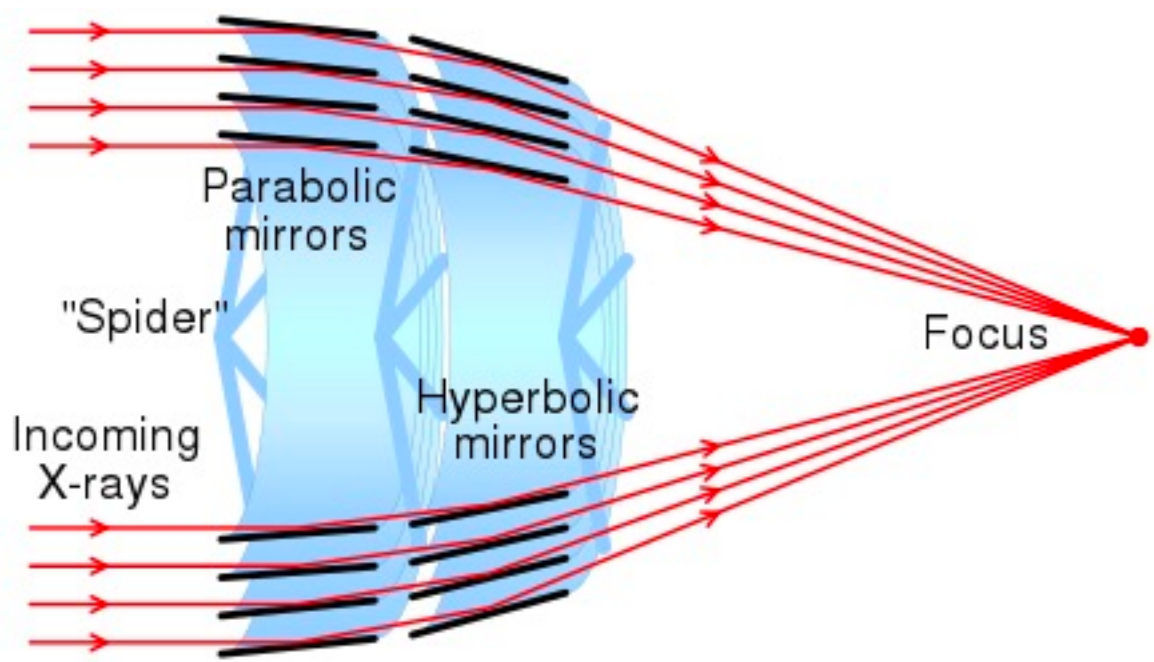




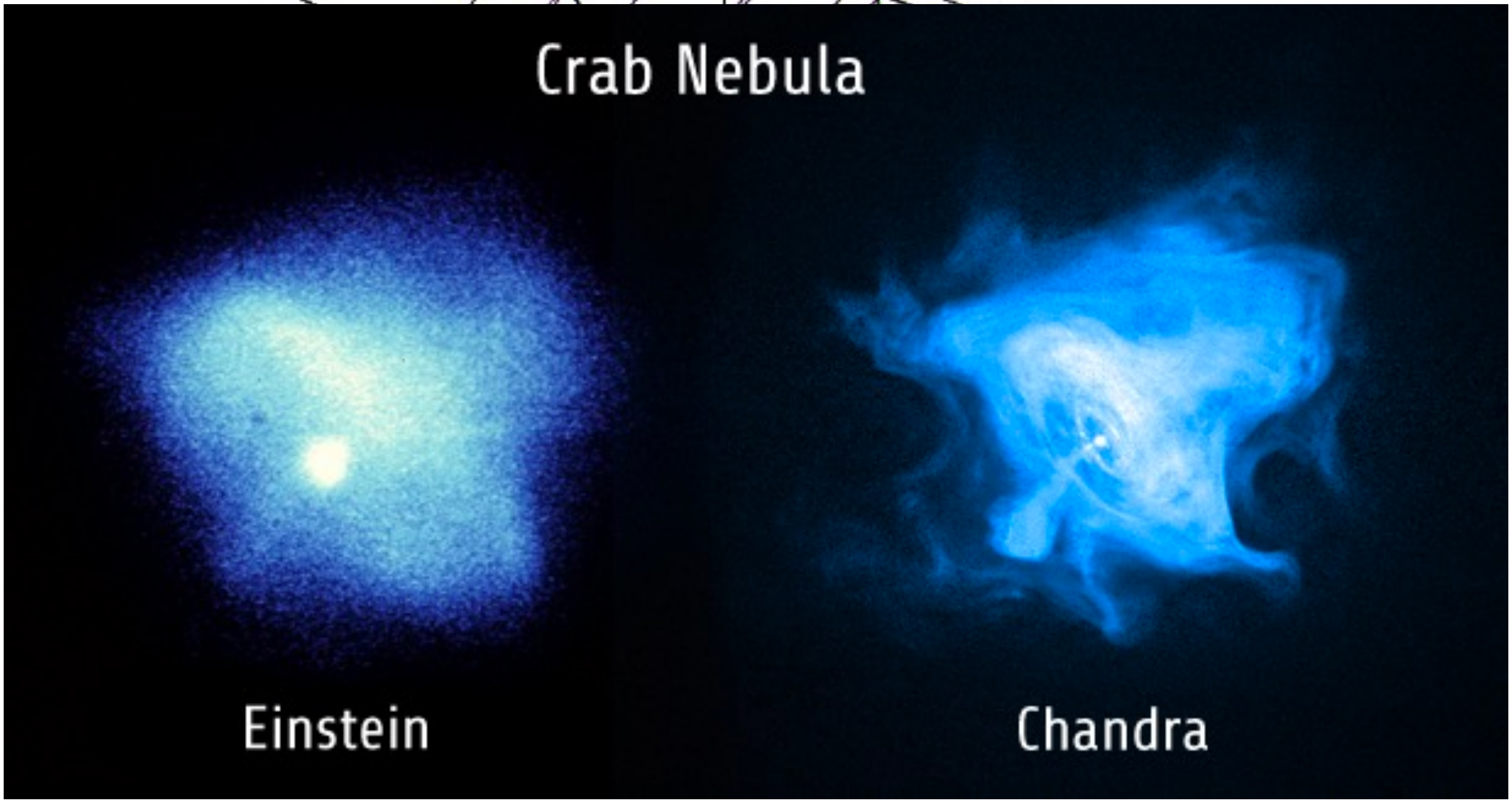
Grazing incidence



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



Einstein (HEAO-2): 1978-1981



What we are going to talk about…

….where we were in 1999.... and we are still there...

Chandra

XMM-*Newton*

Final note……

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

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

B_{sky}=Const x Sky region

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

$B_{rea\text{-}out(electronic)}$= Const x det. Reg.

How to increase the sensitivity….

Increasing the collecting/effective Area

$S = F \times A_{eff}$

S/N increases……

(….but sometime also the bgd increases)

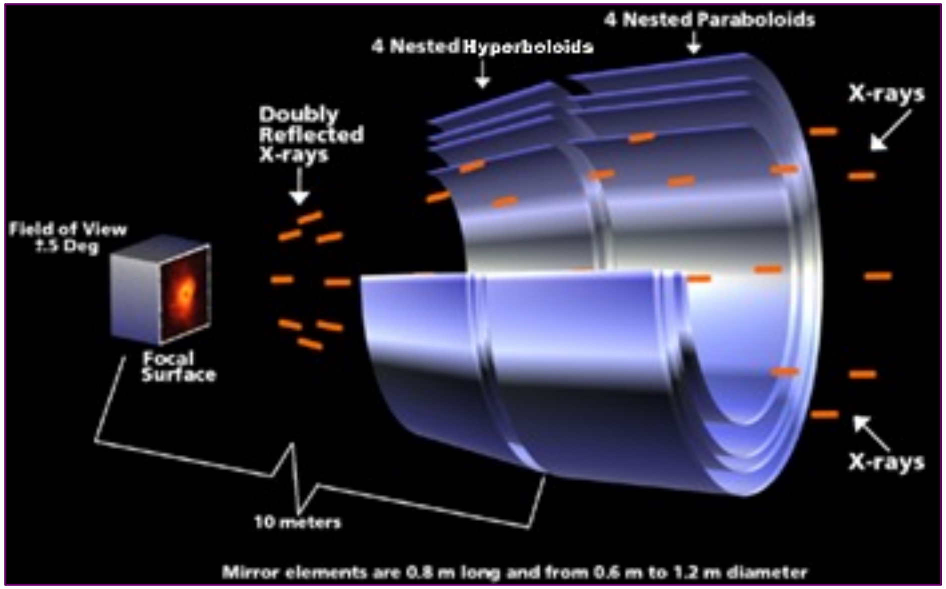
the ESA (XMM-Newton) way

Reducing the B.

S/N increases

the NASA (Chandra) way…

Chandra = “extreme” angular resolution

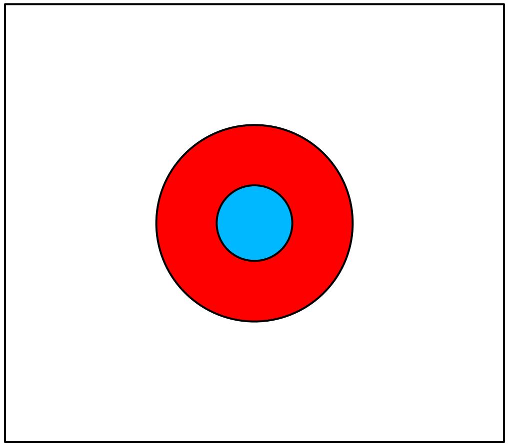


Only four, robust shells

High-quality of shell production

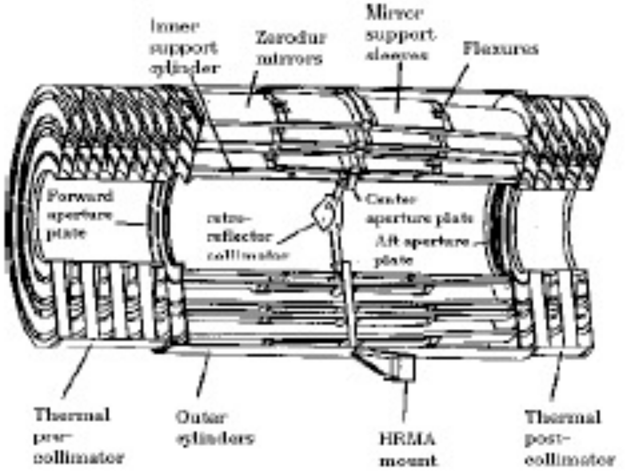
to allow <arcsec on-axis angular resolution (the best so far in X-rays)

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



Background “may depend” on the angular resolution...

High Resolution Mirror Assembly (HRMA)



Ottica Wolter Type-I

Mirror diameters: 1.23, 0.99, 0.87 0.65 m

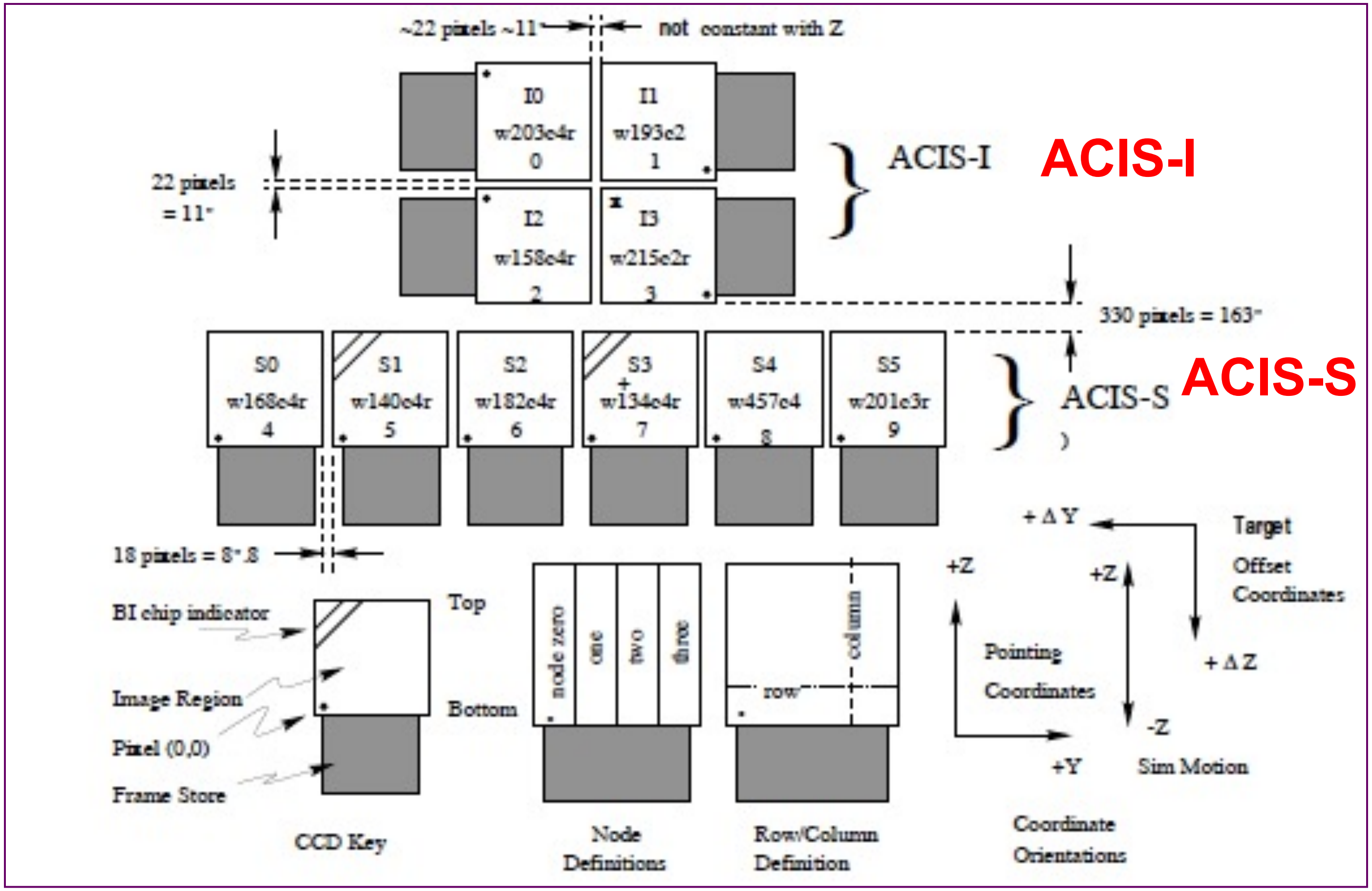
Mirror lengths: 84 cm

HRMA mass: 1500 kg

Focal length: 10 m

PSF FWHM: 0.5”

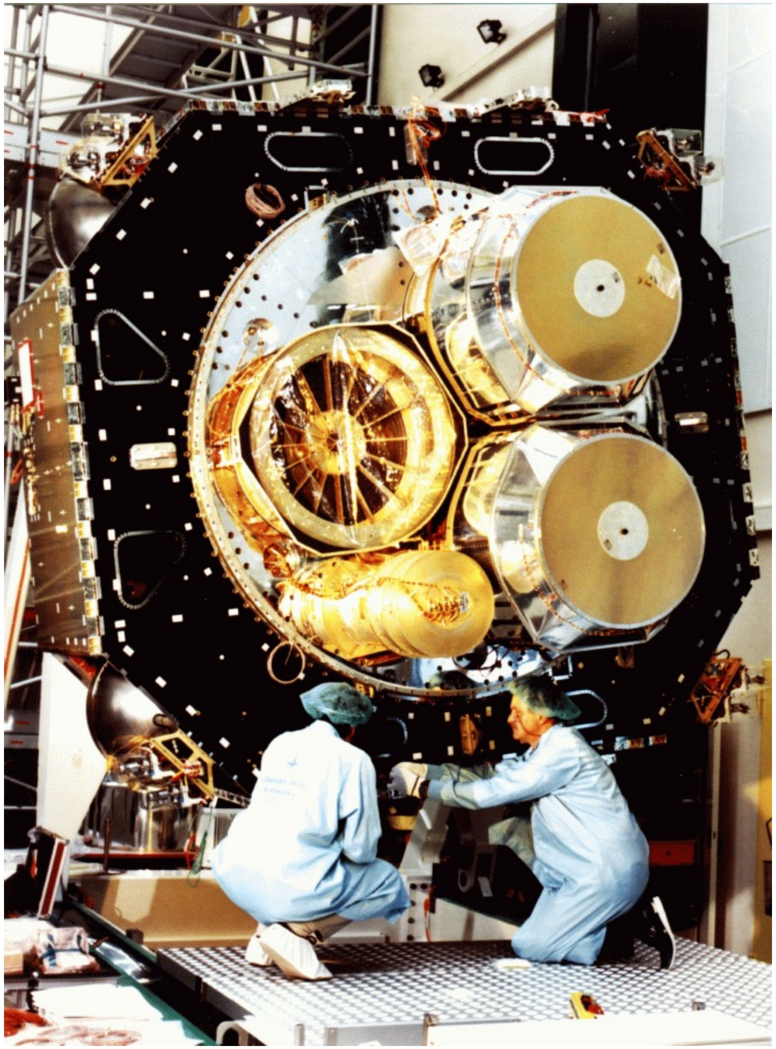
Chandra focal-plane detectors: CCDs



XMM-*Newton* = large effective area

3 modules, 58 shells

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



XMM-Newton: all instruments at work simultaneously

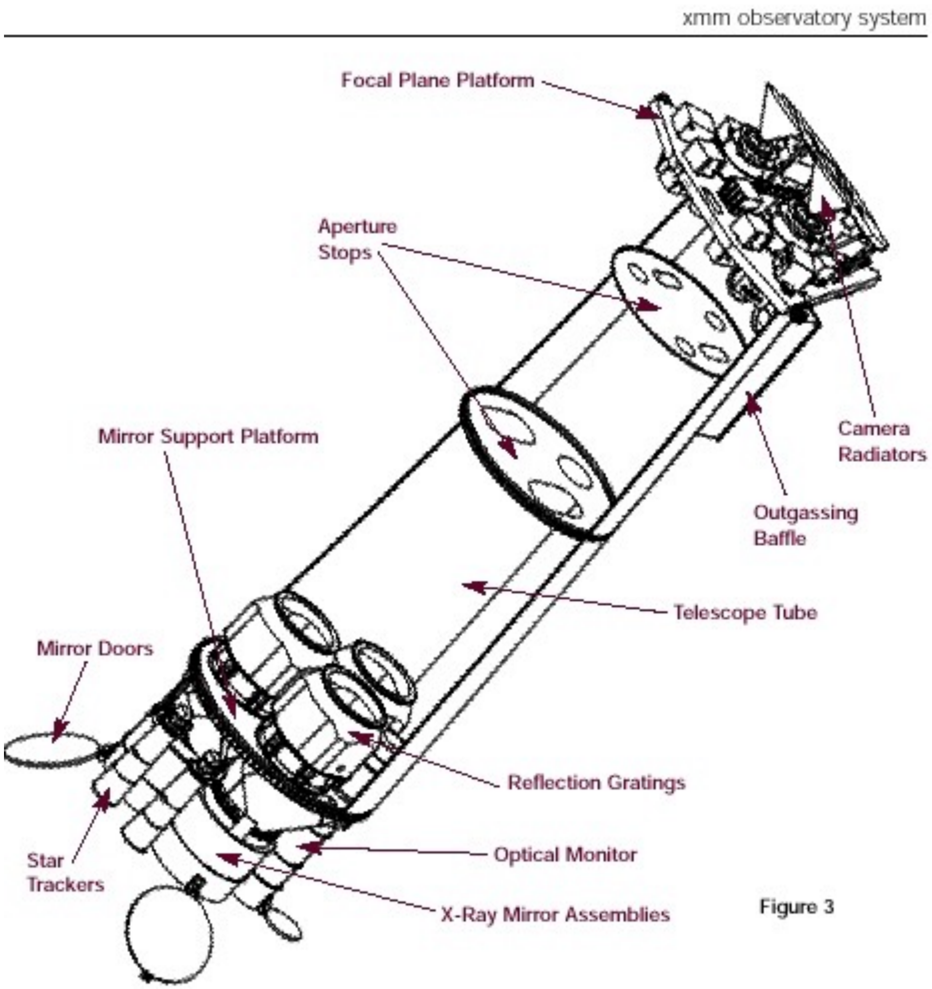
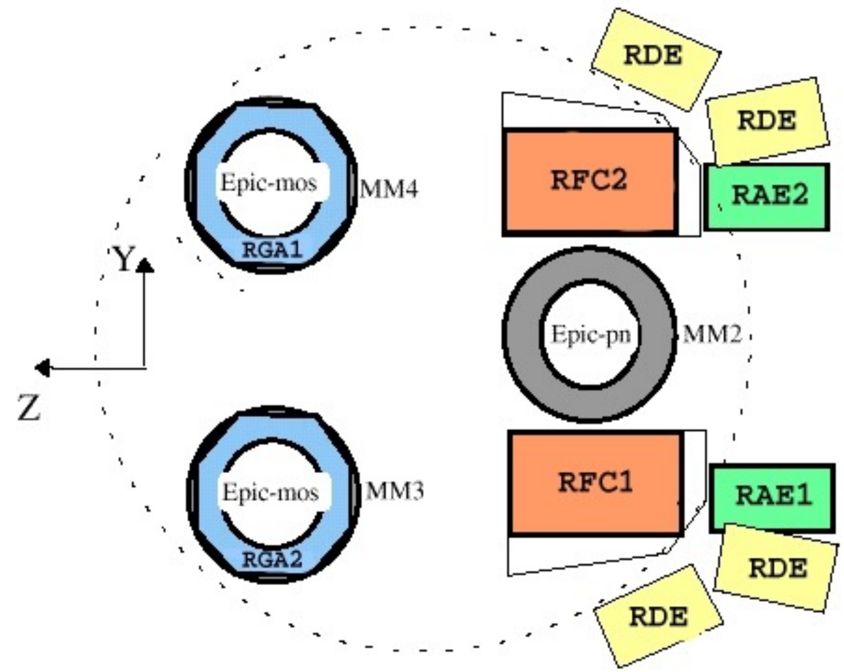
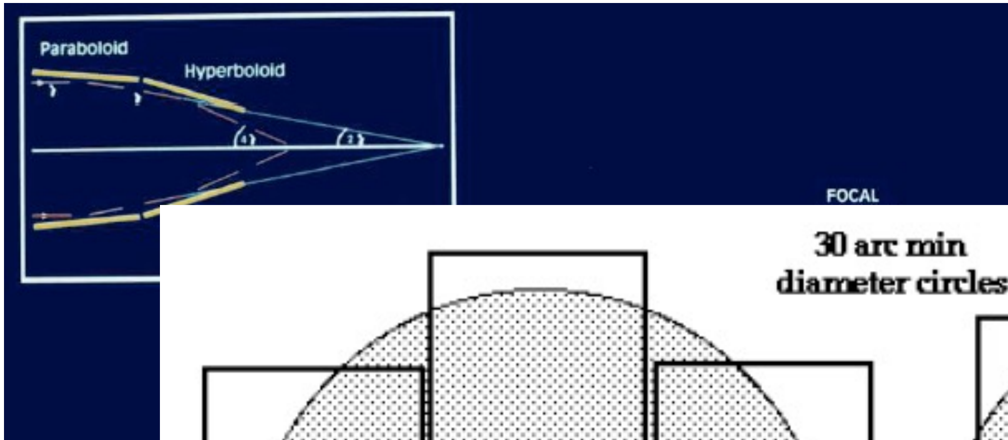
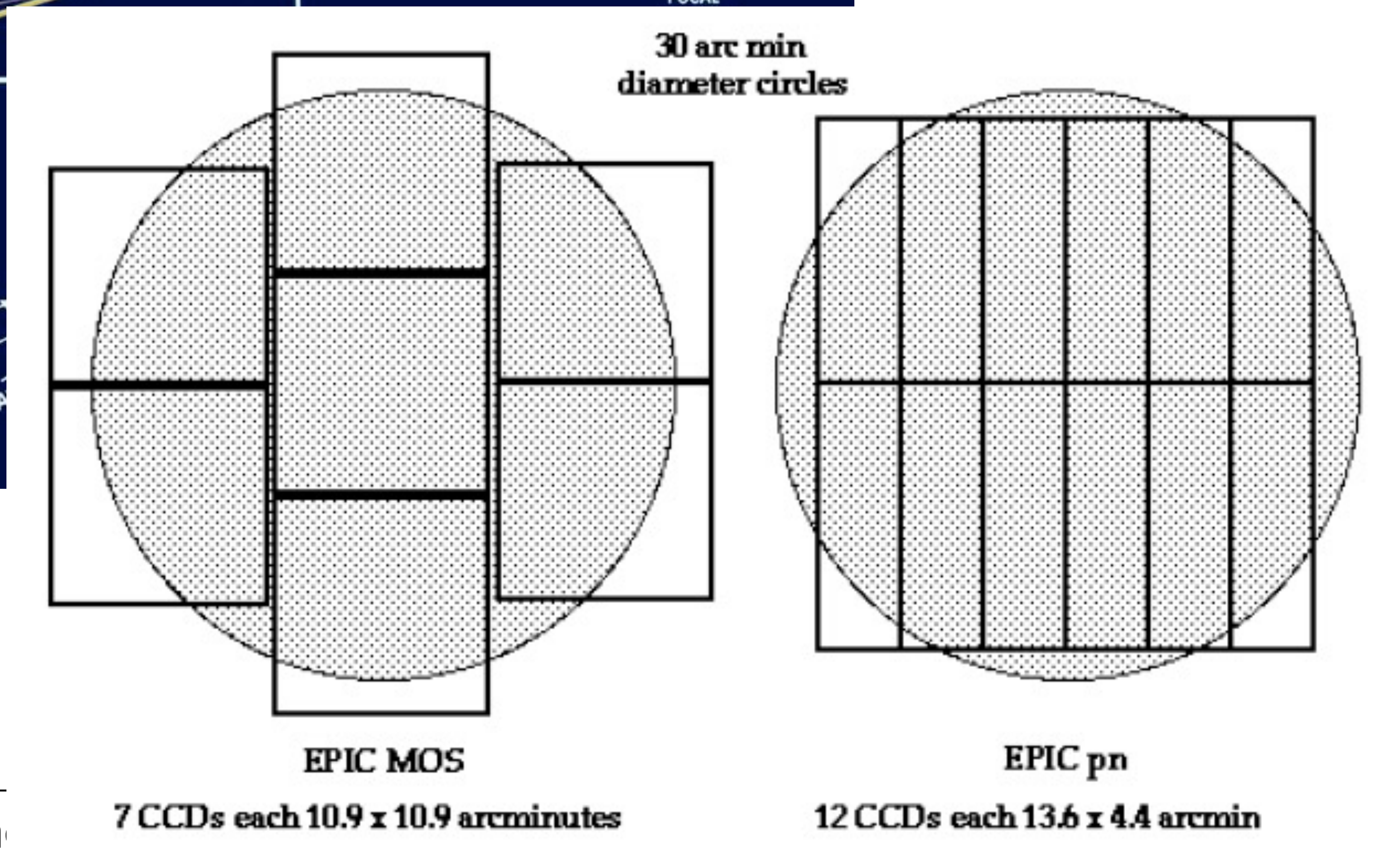


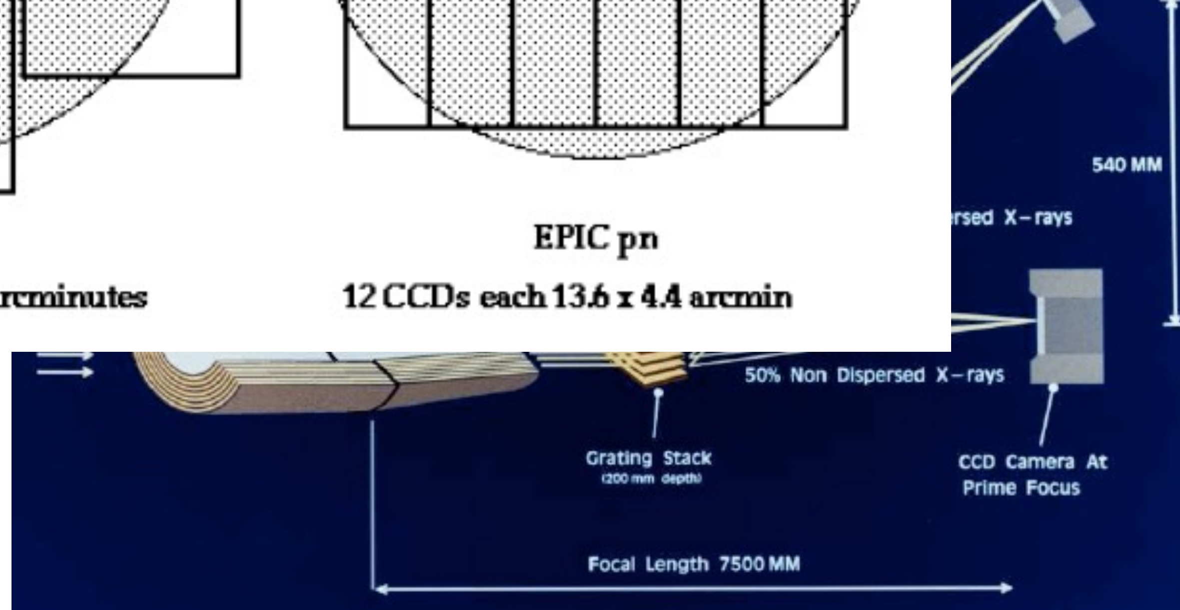
Figure 3





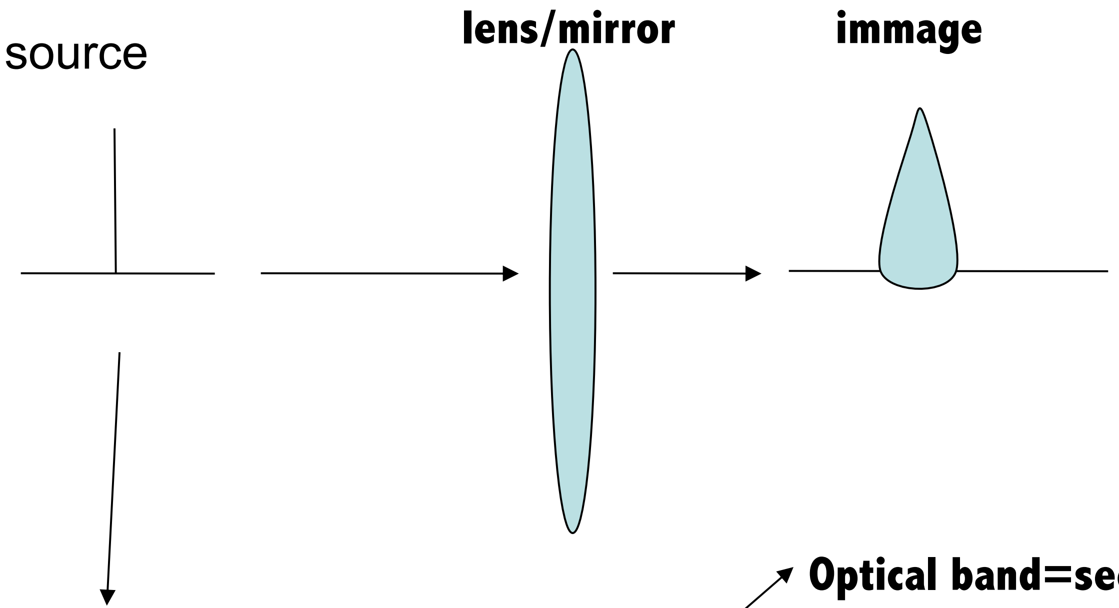
Wolter I solution

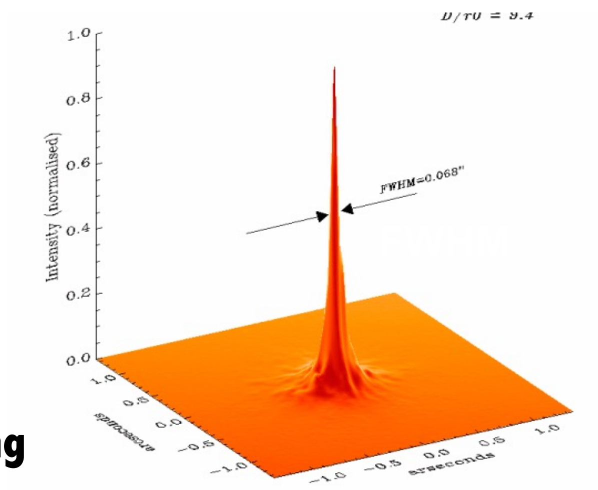




Full in
pn CCD, ≈50% to the MOS1-2, the rest to the grating spectrometers (RGS)

First fundamental element of the telescope: PSF





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

Optical band=seeing

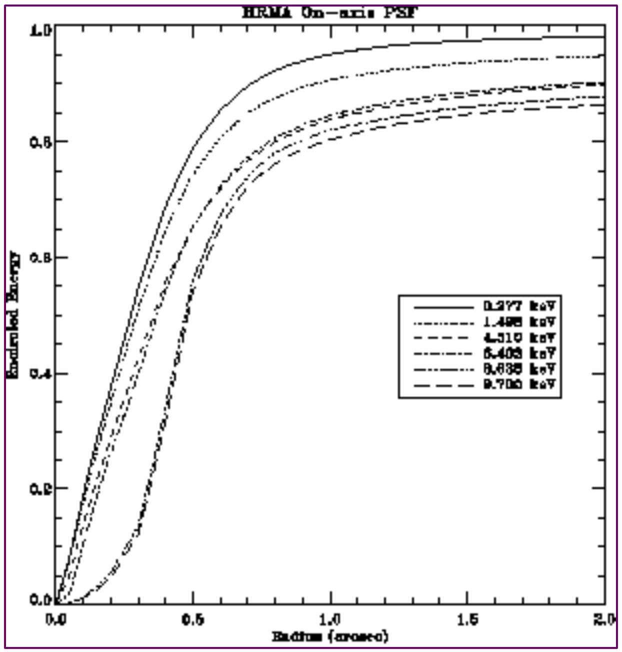
X-rays= mirrors properties
+ mirror array assembly

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

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

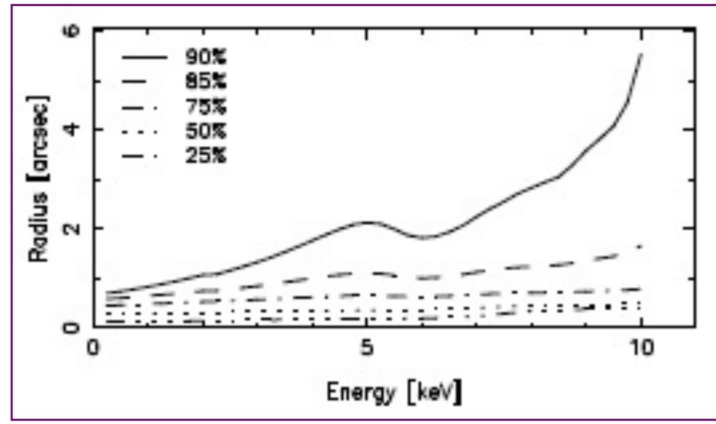
PSF = function of (x,y) or (r, ϑ) (...usually a couple of Gaussian/King profiles.....)

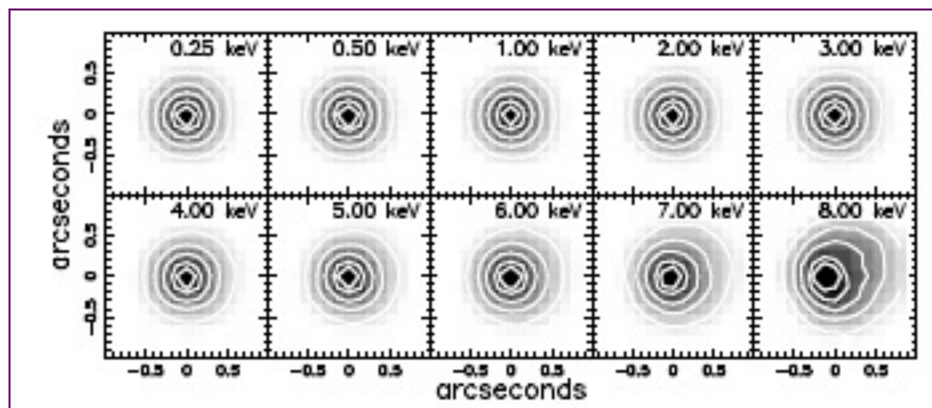
High Resolution Mirror Assembly (HRMA): On-axis PSF



Encircled energy vs. radius
at different energies

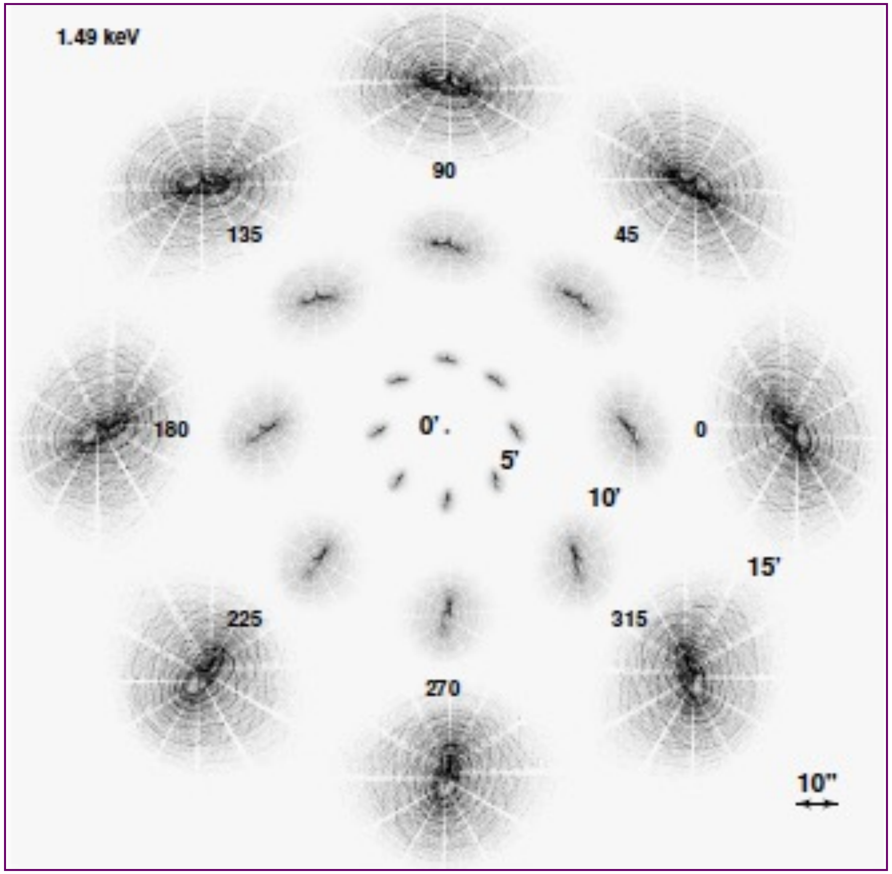
Radius encompassing NN% of the counts
as a function of the energy

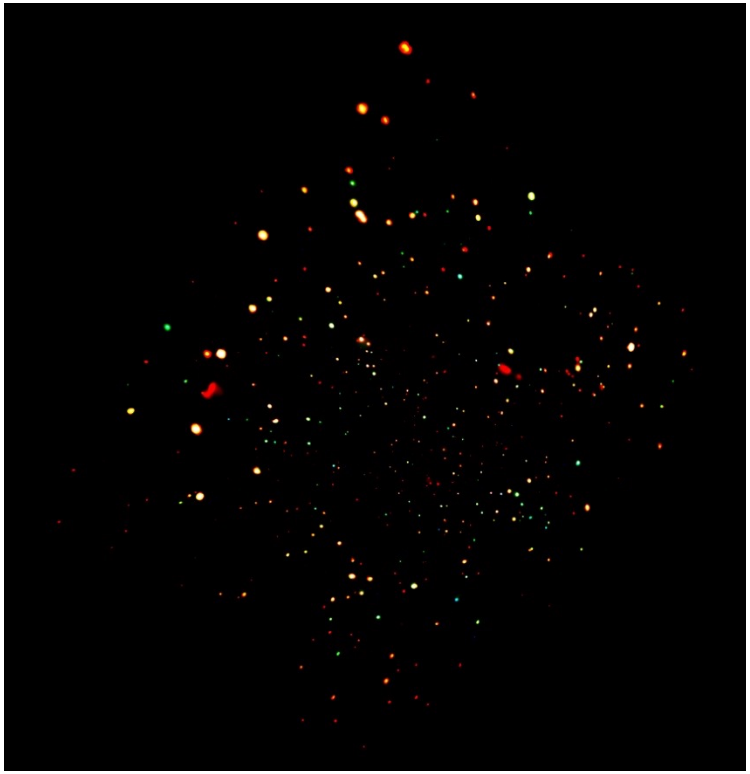




On-axis PSF size and shape

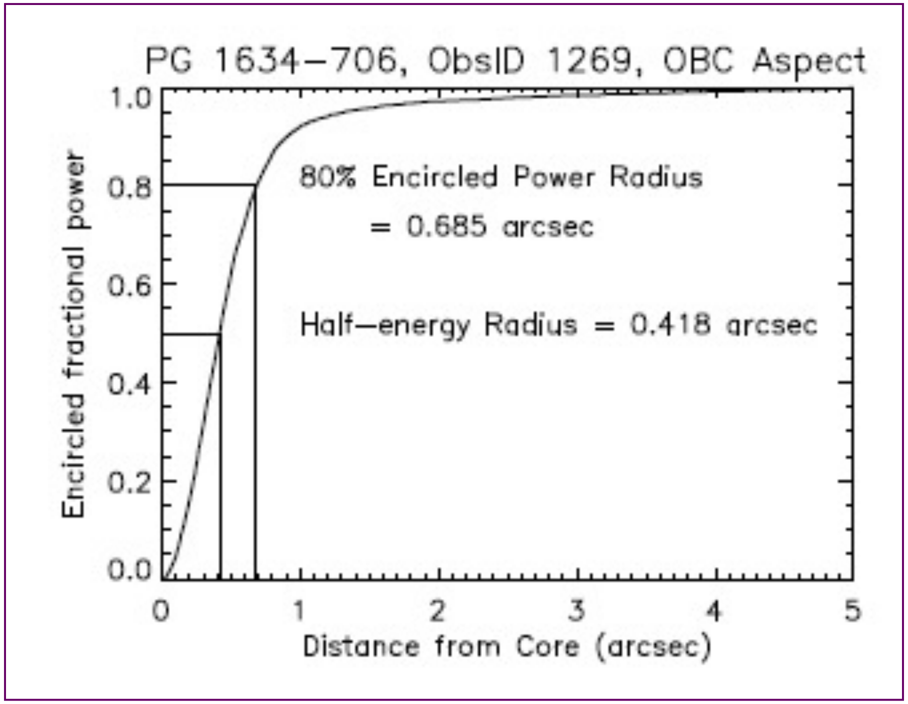
High Resolution Mirror Assembly (HRMA): Off-axis PSF



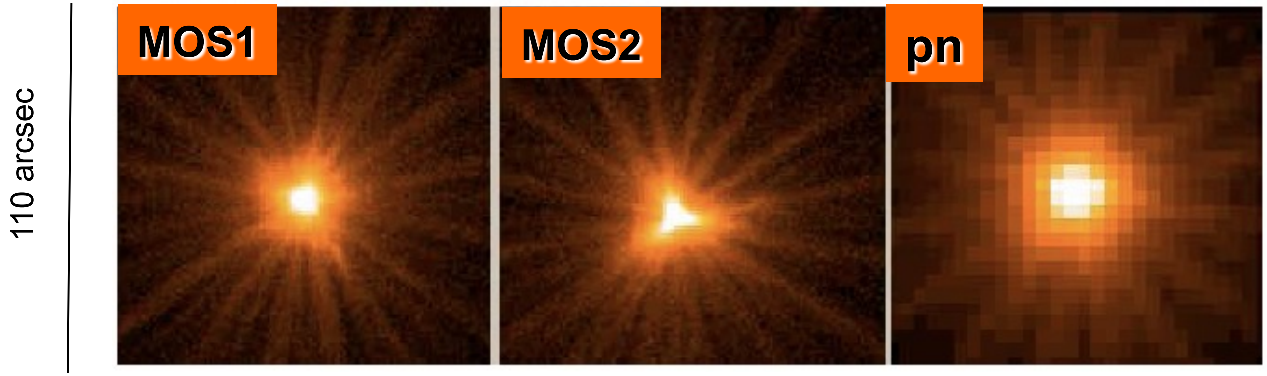


CDF-N 2Ms exposure

Resulting image on the focal plane of ACIS



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

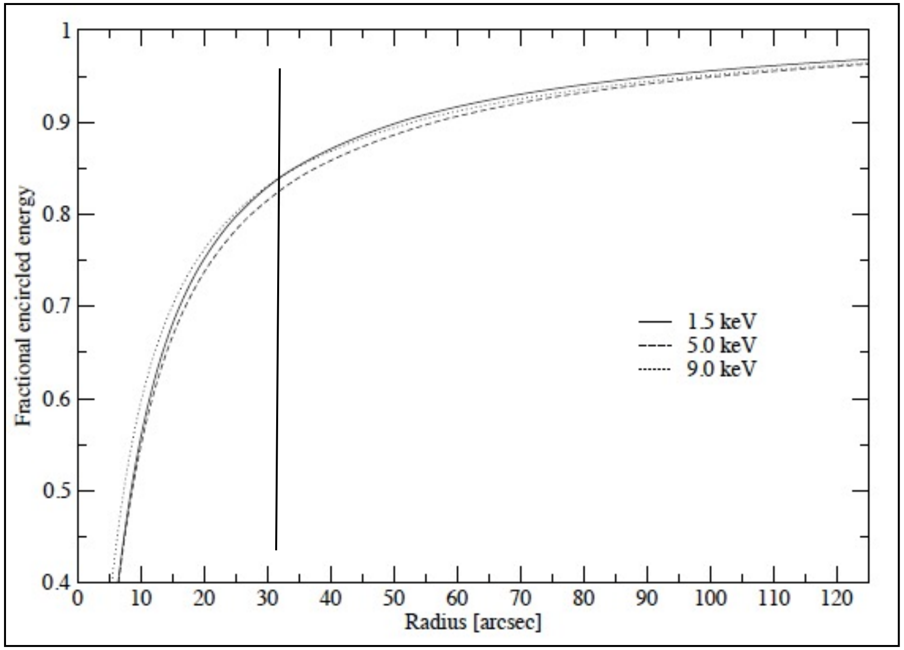


spider-like pattern due to the support of the Wolter I mirrors

Mirror module	2	3	4
Instr. chain[a]	pn orbit/ground	MOS-1+RGS-1 orbit/ground	MOS-2+RGS-2 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

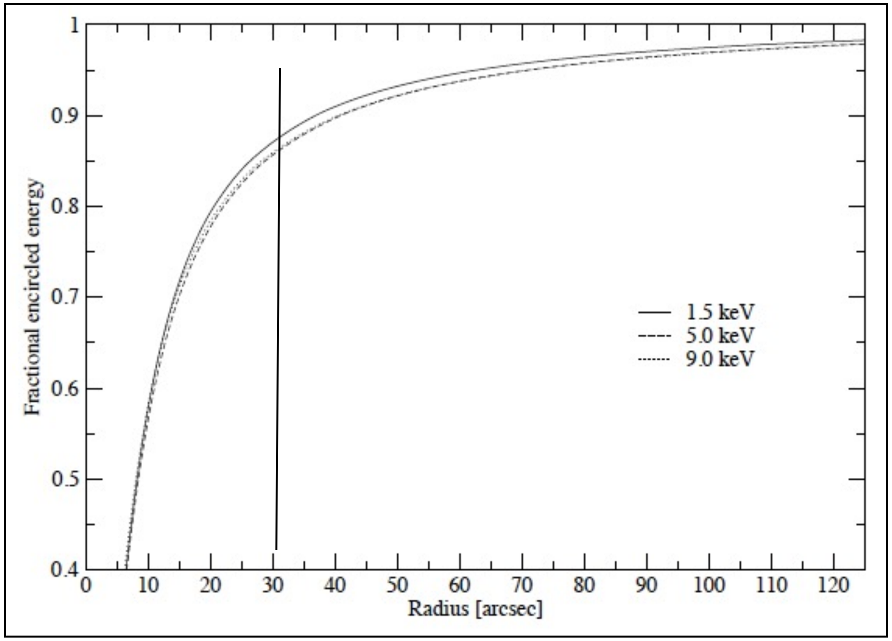
PSF FWHM higher than in *Chandra* but much larger effective area
Background (and confusion limit) can be an issue

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

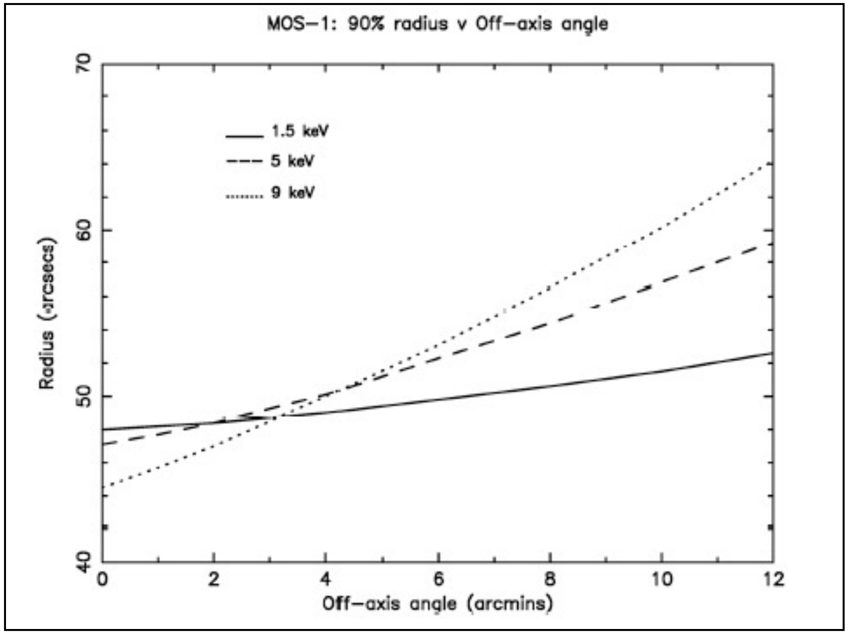


Encircled energy vs. radius
at different energies for the MOS1-2

Encircled energy vs. radius
at different energies for the pn

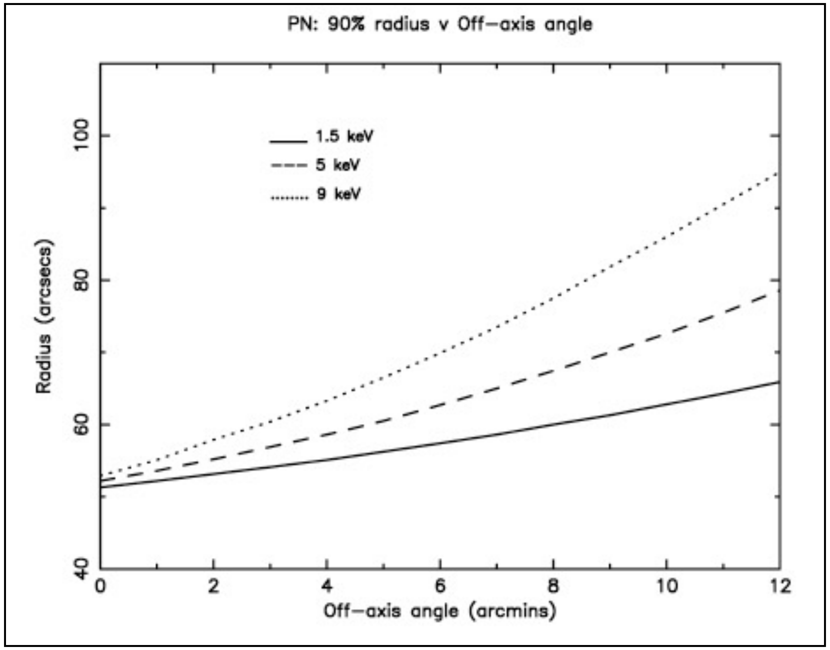


XMM-*Newton:* the EPIC off-axis PSF



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



Second fundamental element of the telescope: mirrors and detector
Effective Area

Mirrors — Detector

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

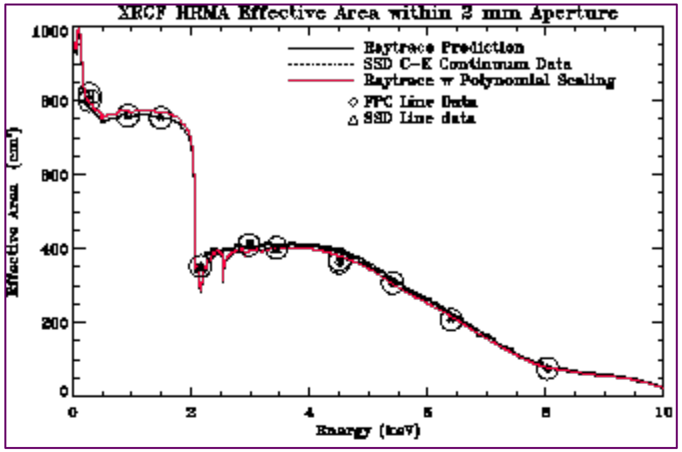
Effective area — Geometric area — Reflectivity — Vignetting — Quantum Efficiency

Most quantities in X-rays depend on the energy of the photons

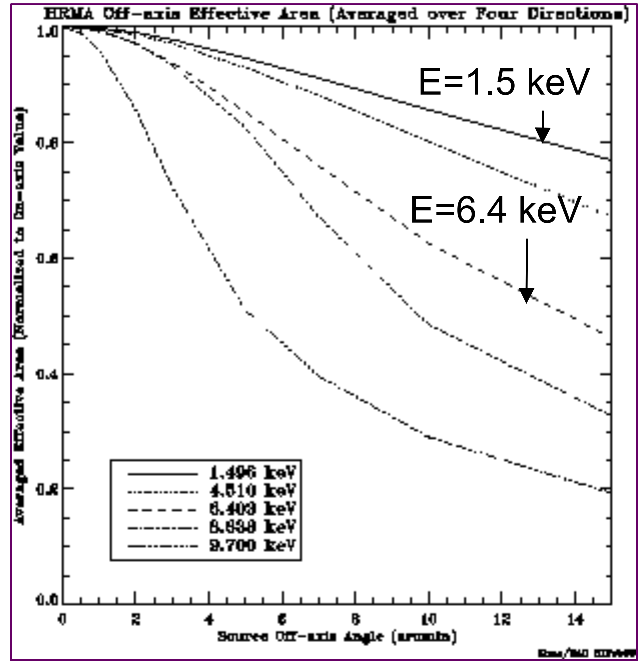
- **Effective area** – in cm^2
- **Geometric area** – 'cross section' of the telescope
- **Reflectivity** – fraction of photons reflected by the mirrors
- **Vignetting** – fraction of photons lost as a function of the distance wrt. the optical axis (ϑ)
- **Quantum Efficiency** – fraction of incident photons registered by the detector. (x,y) represents the position on the detector

The effective area represents the capability of the telescope+detector to collect photons

Chandra: High Resolution Mirror Assembly (HRMA): Effective Area



Effective area vs. Energy

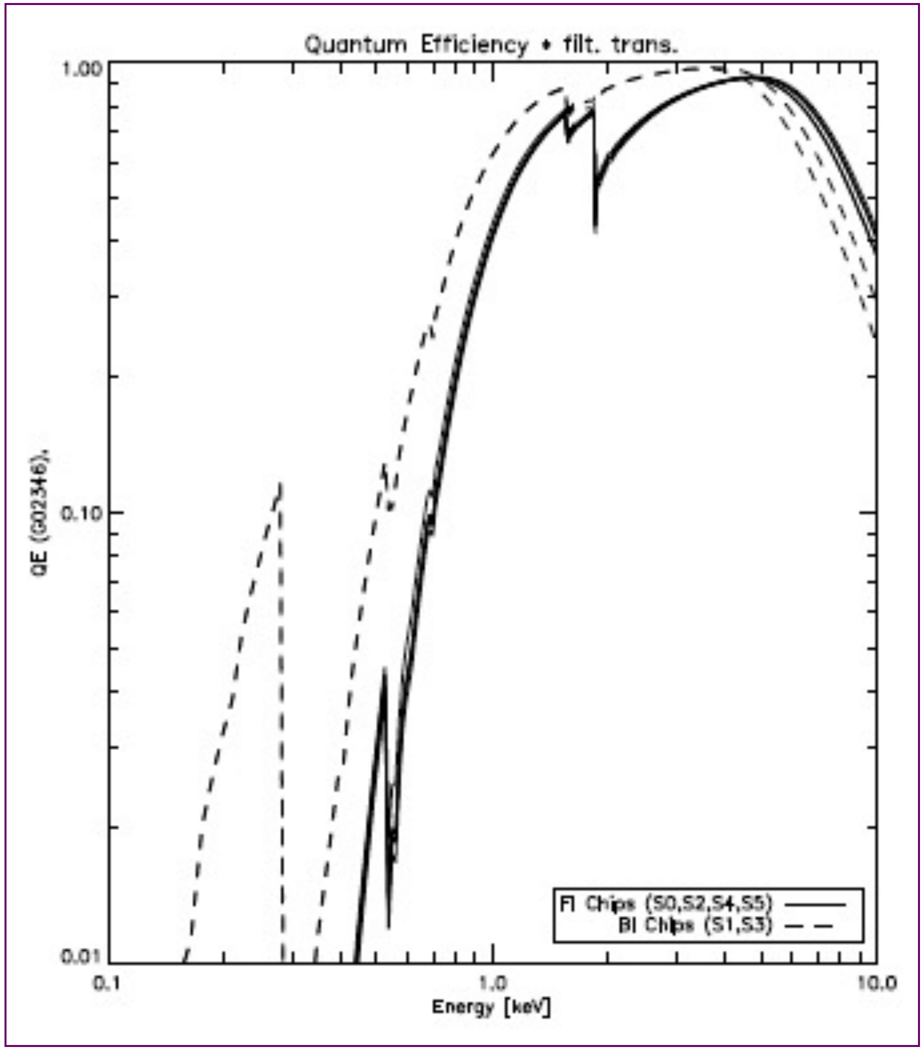


Effect of vignetting

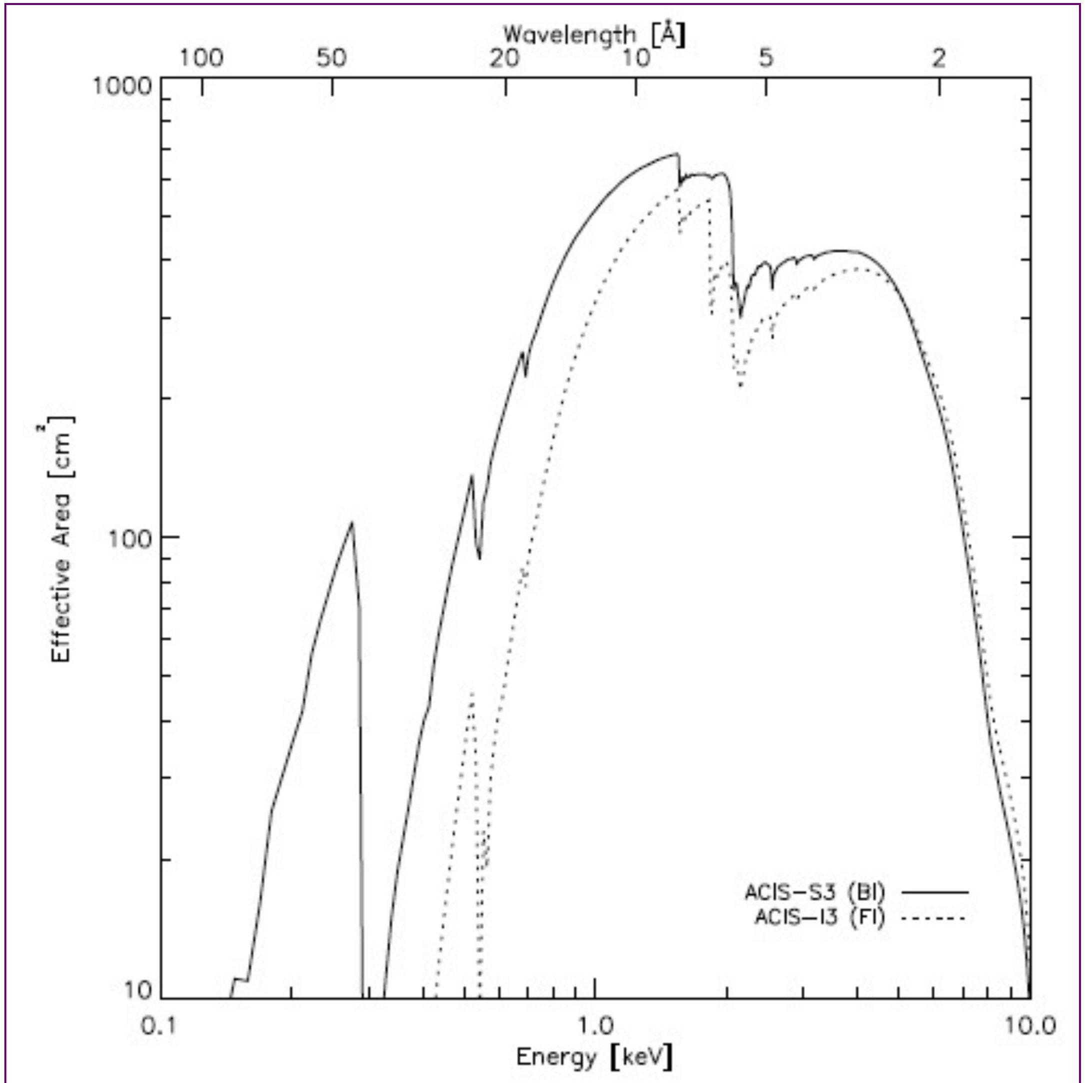
Effective area vs. off-axis angle at different energies

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

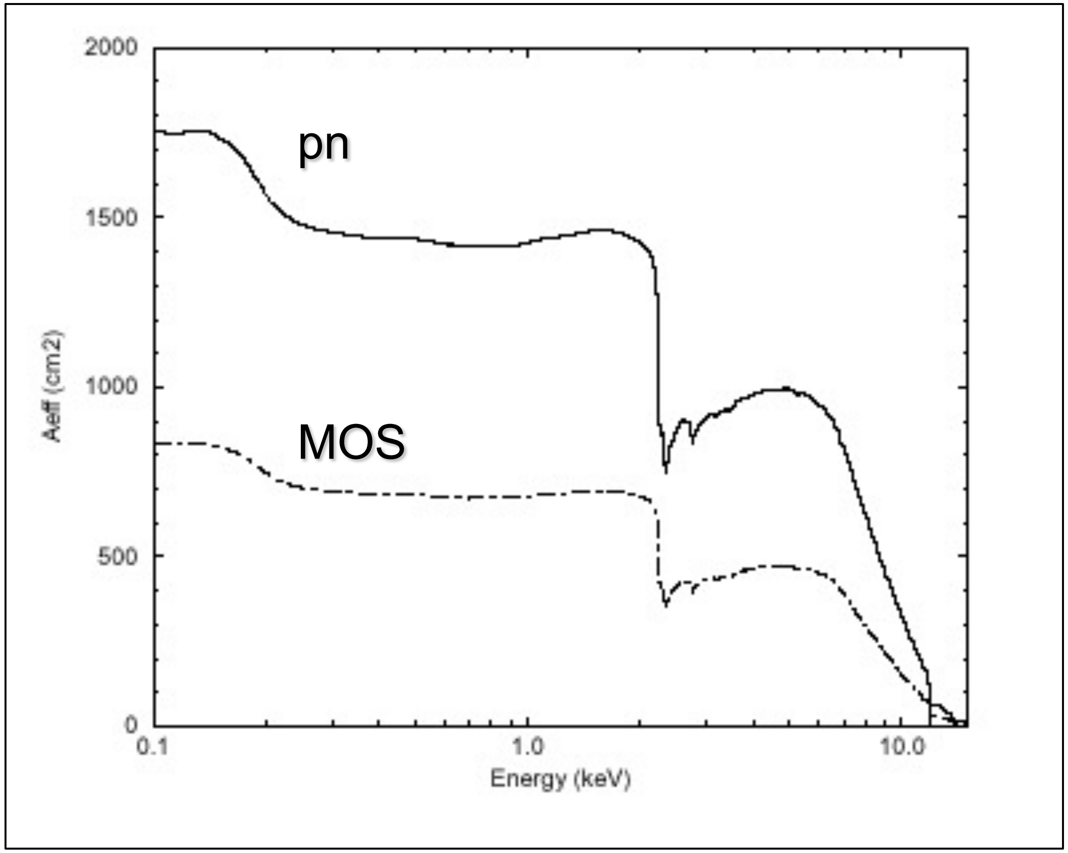
Chandra: quantum efficiency



Chandra: effective area

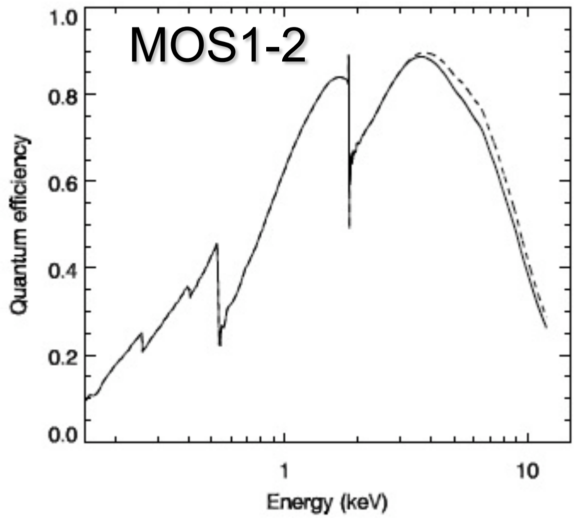


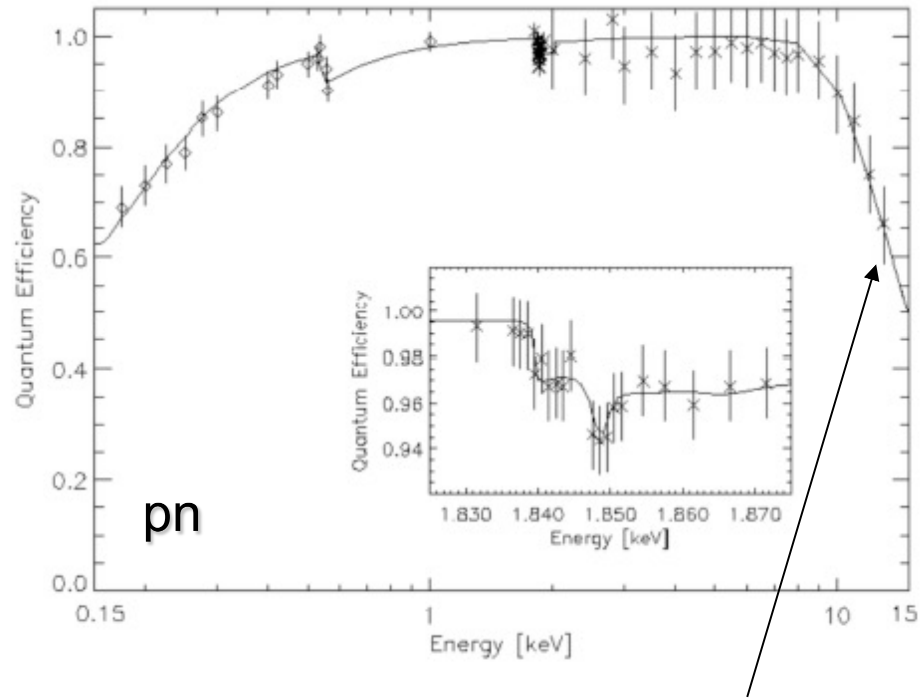
XMM-*Newton:* mirror effective (geometric) area



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

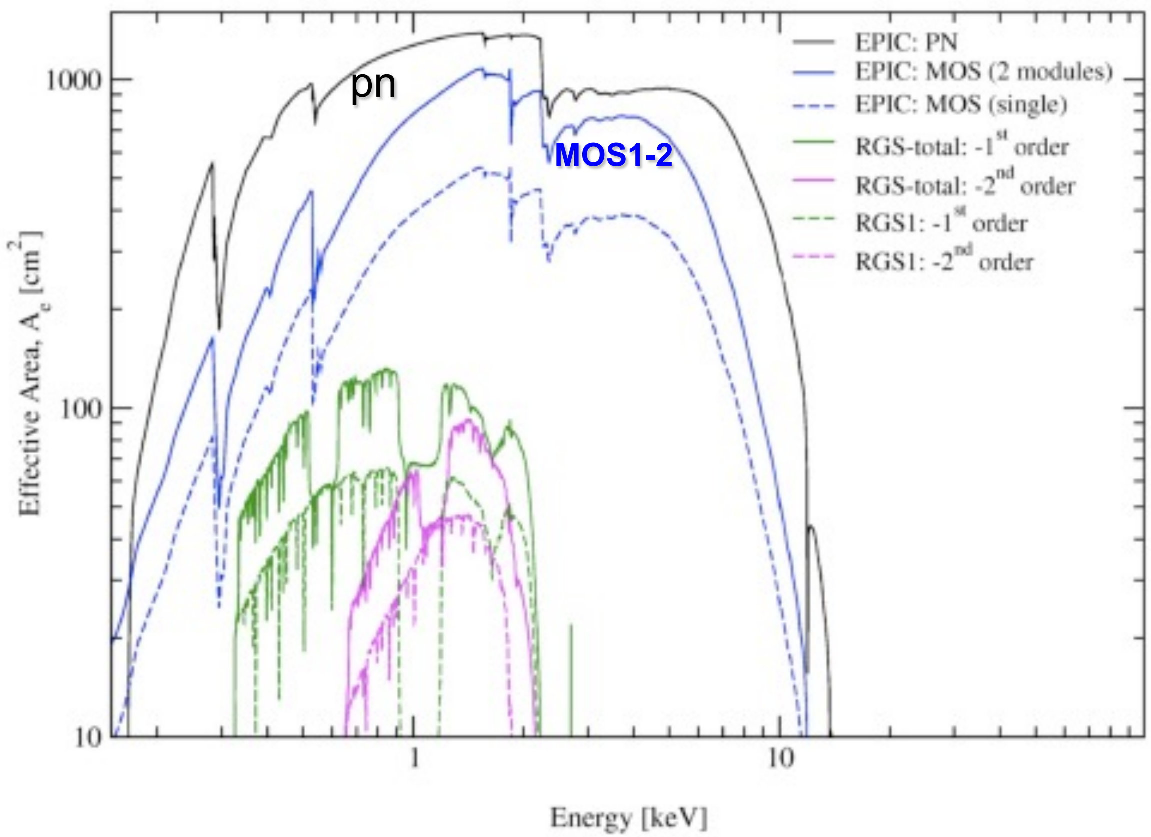
XMM-*Newton:* quantum efficiency



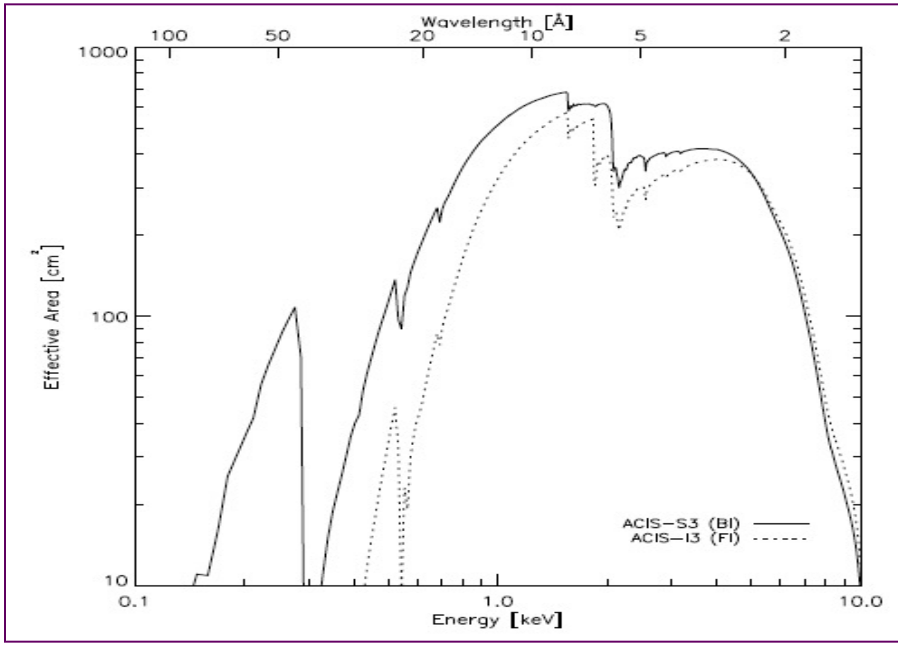


Strong decrease in the QE above 10 keV, where also the effective area due to the mirrors has a significant decrease

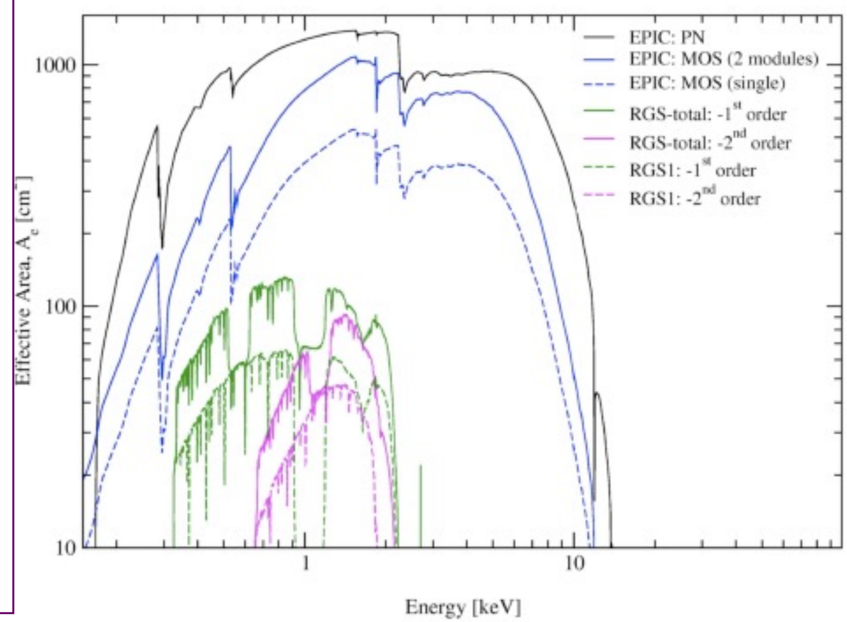
XMM-*Newton:* effective area



Chandra



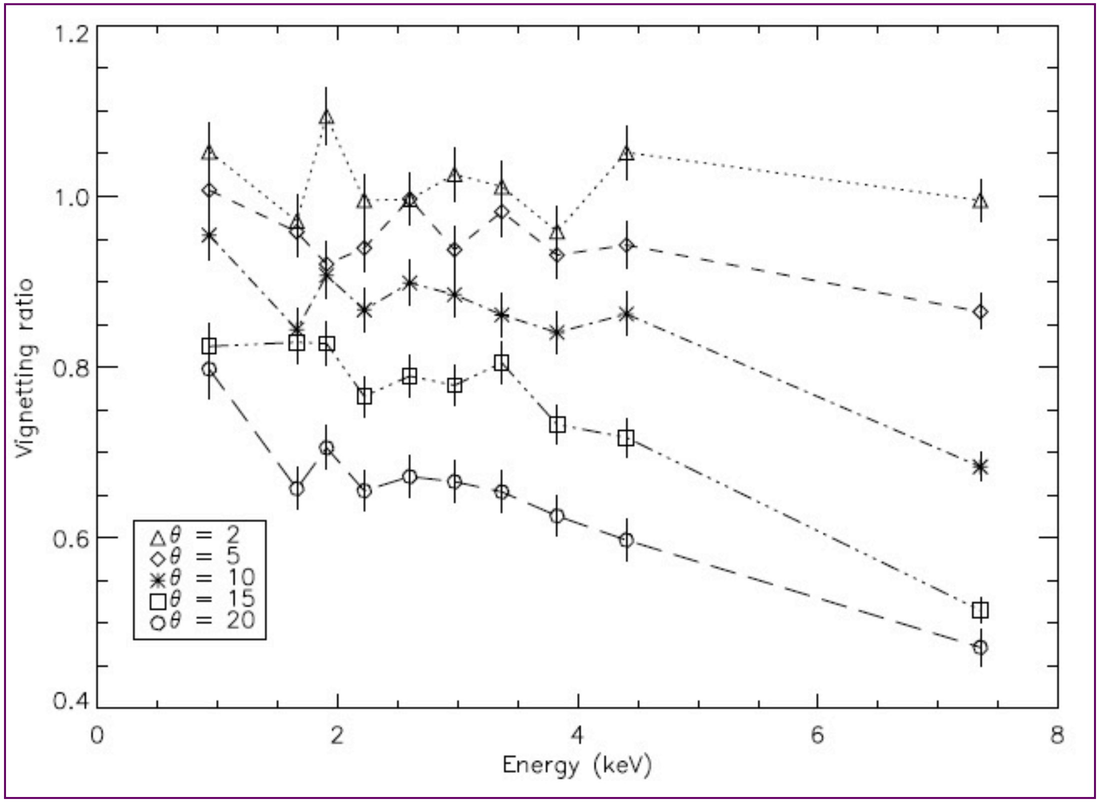
XMM-Newton



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

Chandra: vignetting

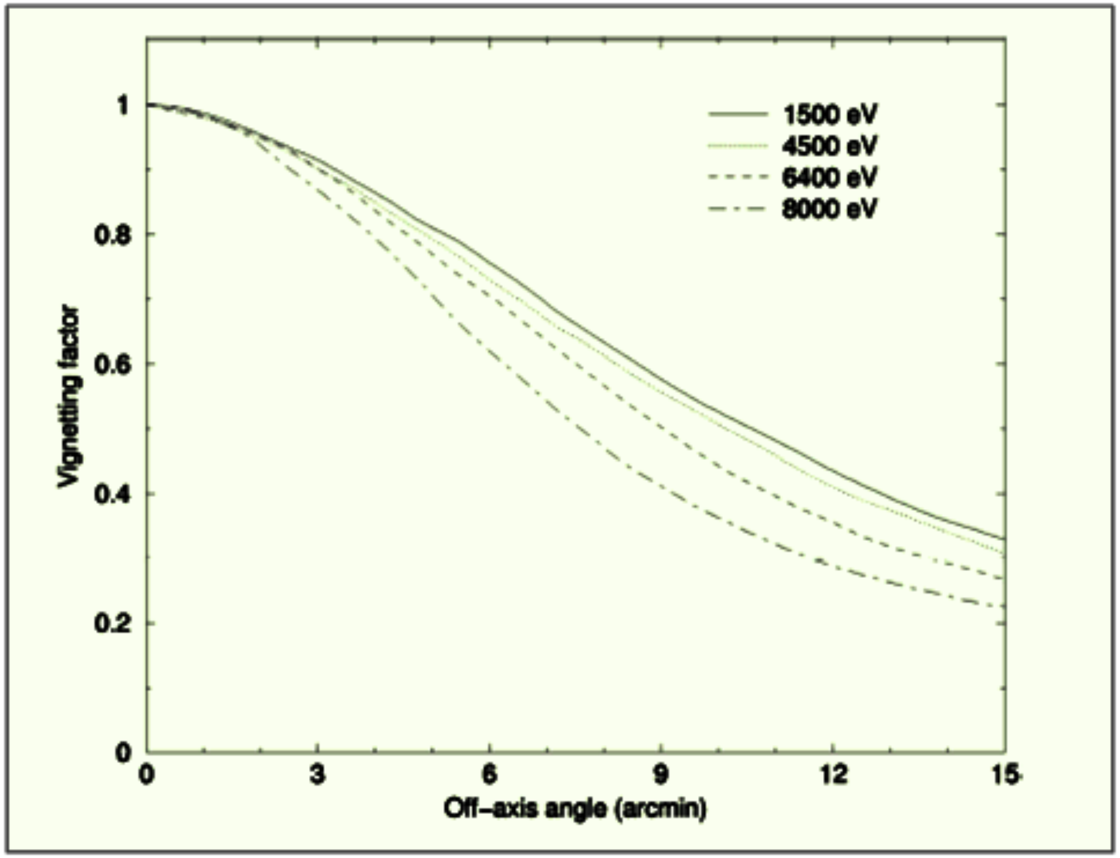
Ratio of the off-axis vs. on-axis counts at different off-axis angles



Hard X-ray photons are more difficult to focus

➔ **Vignetting**

XMM-*Newton:* vignetting



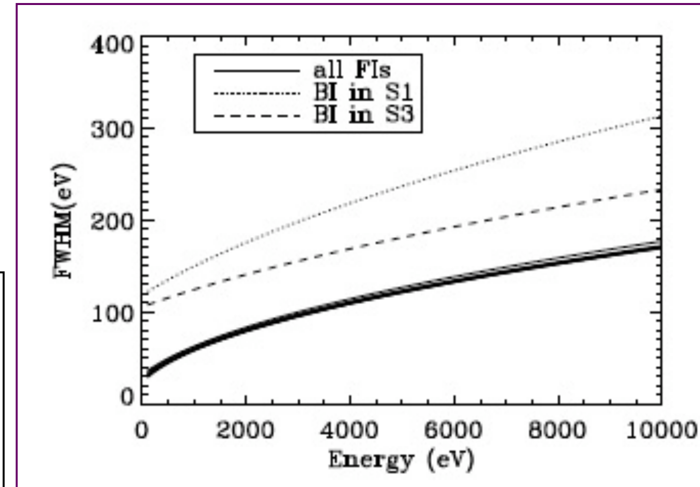
Strong vignetting (as expected) for high-energy photons, partly compensated by the large effective area (e.g., wrt. *Chandra*)

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

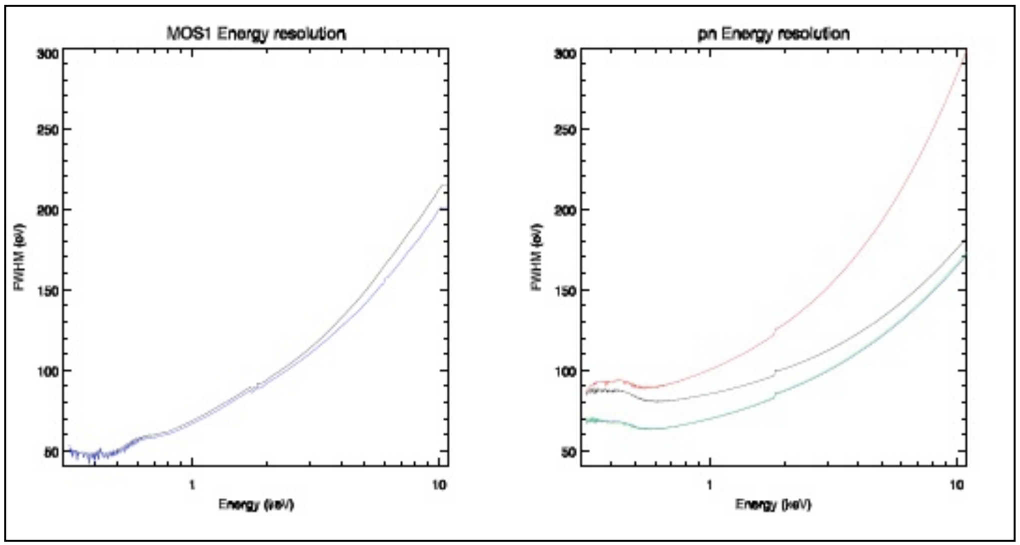
Last but not least….

Energy resolution

Chandra: energy resolution



XMM-*Newton:* energy resolution

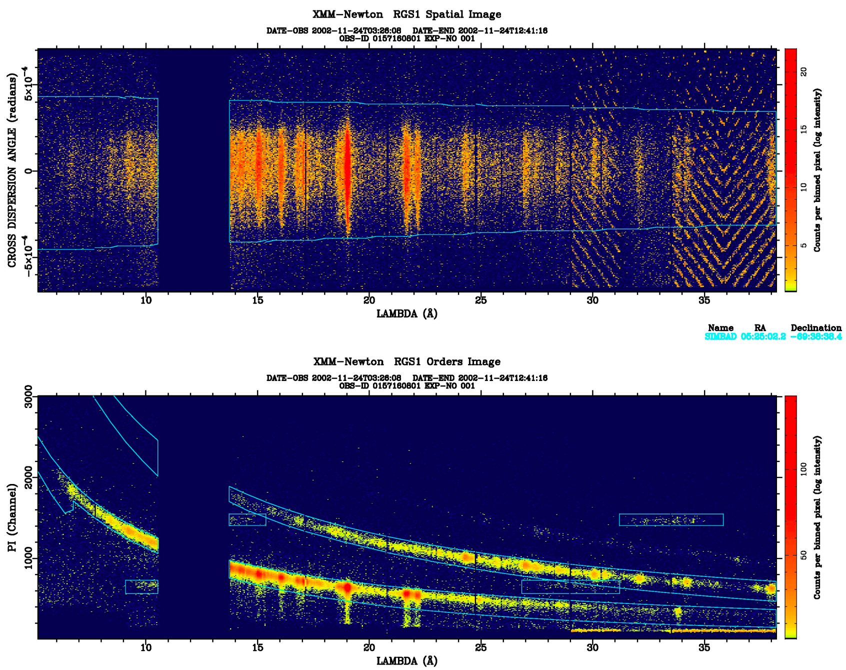


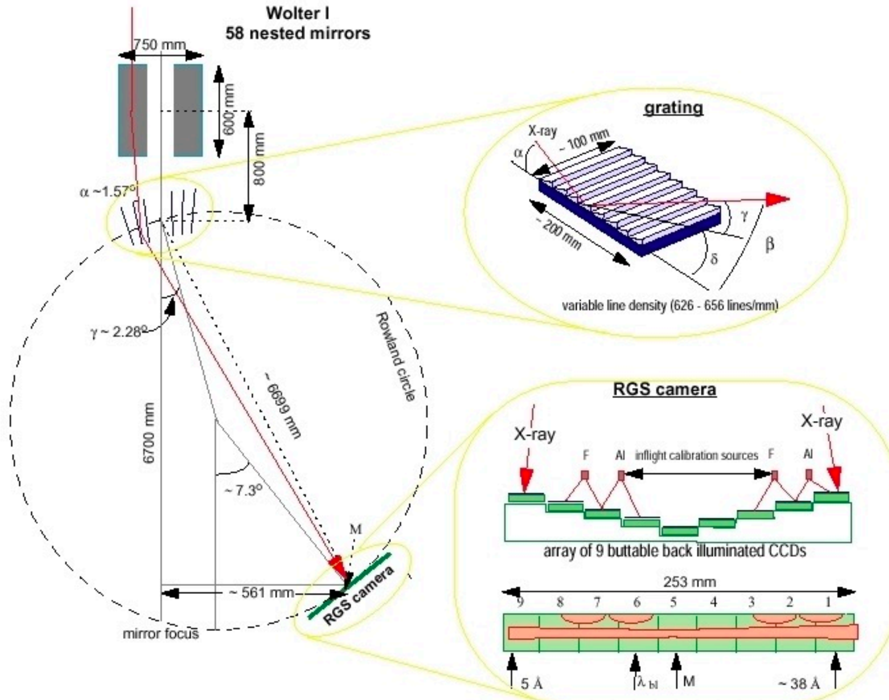
Typical CCD resolution
100-150 eV

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

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

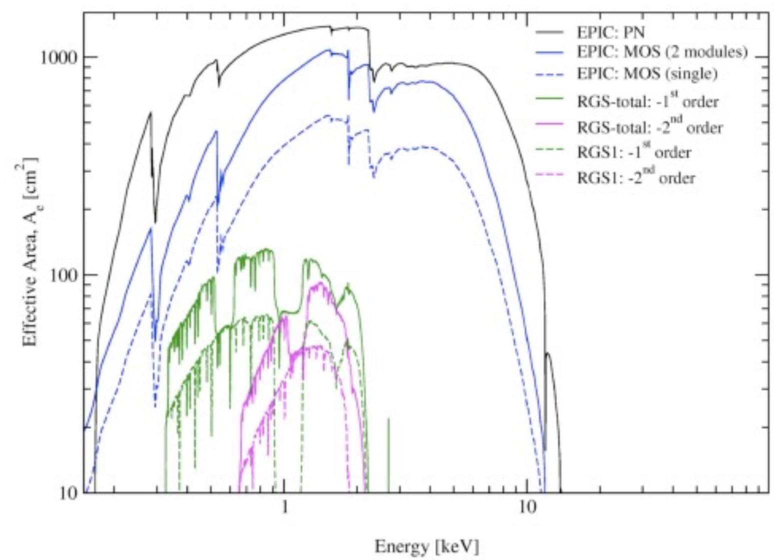
What about high-resolution Spectroscopy?



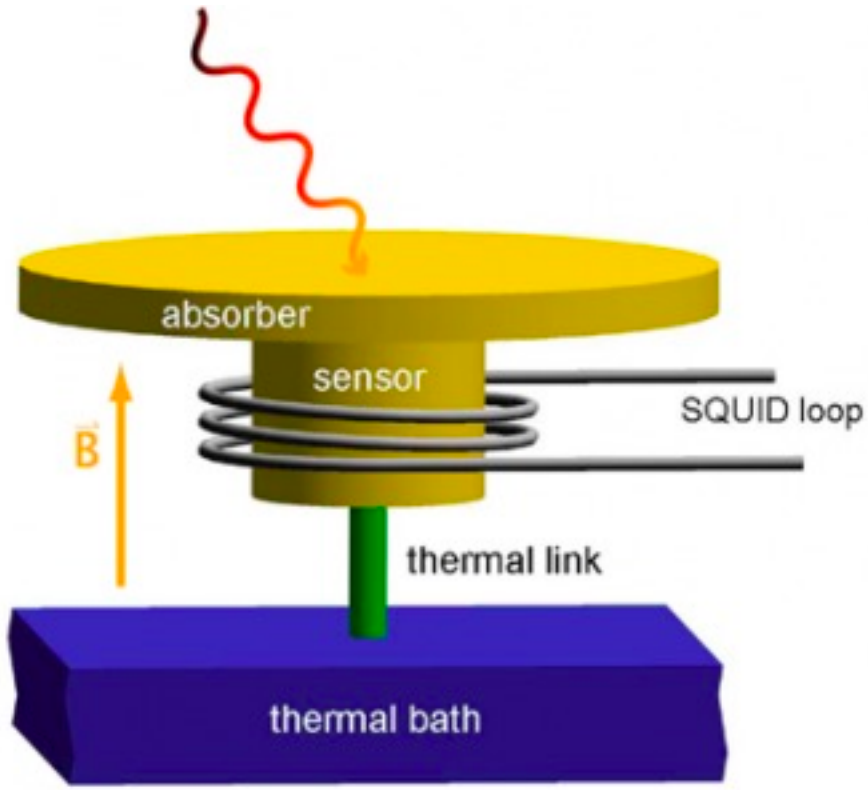


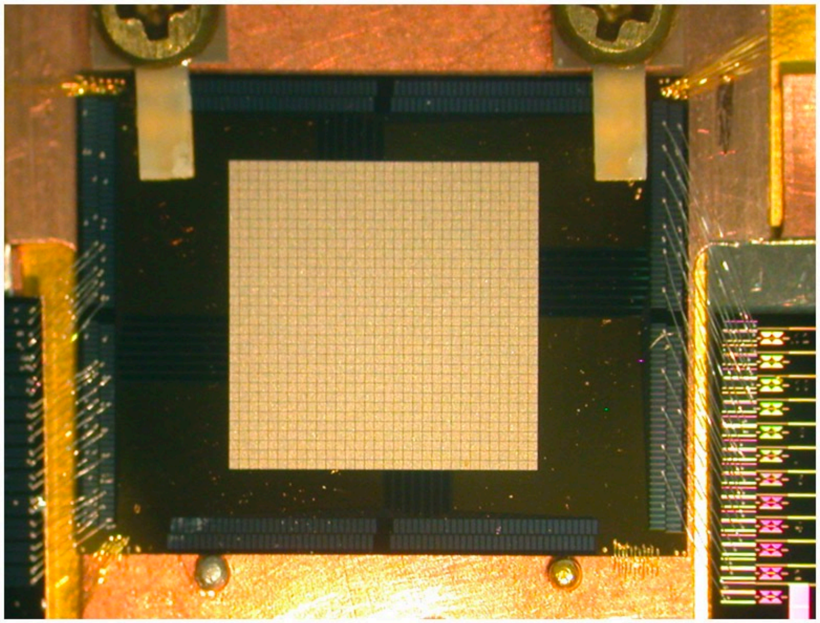
Resolution~100-500 (FWHM)

What's missing?

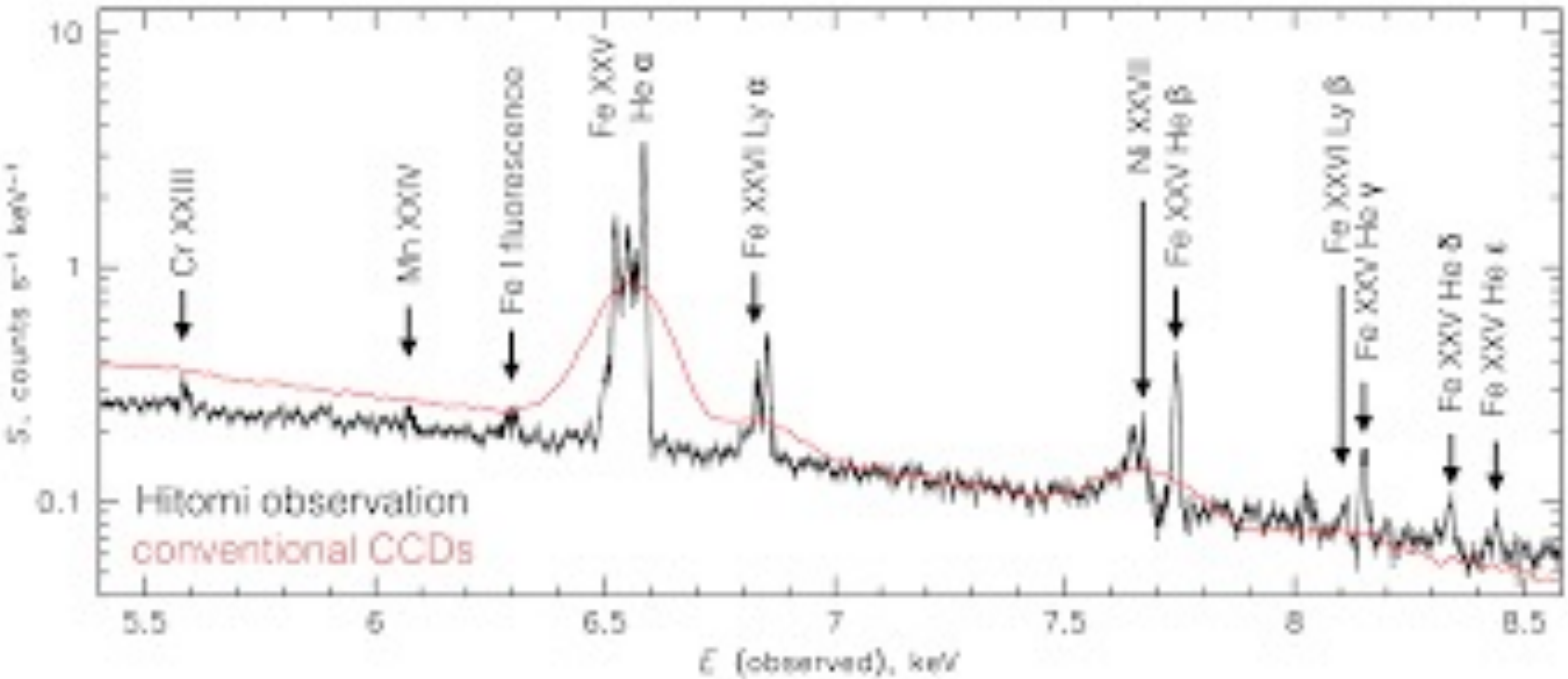


Transition Edge Arrays (microcalorimeters)

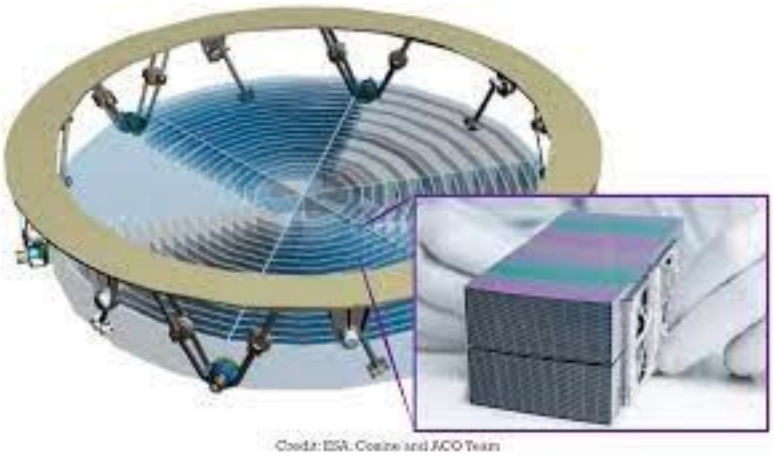


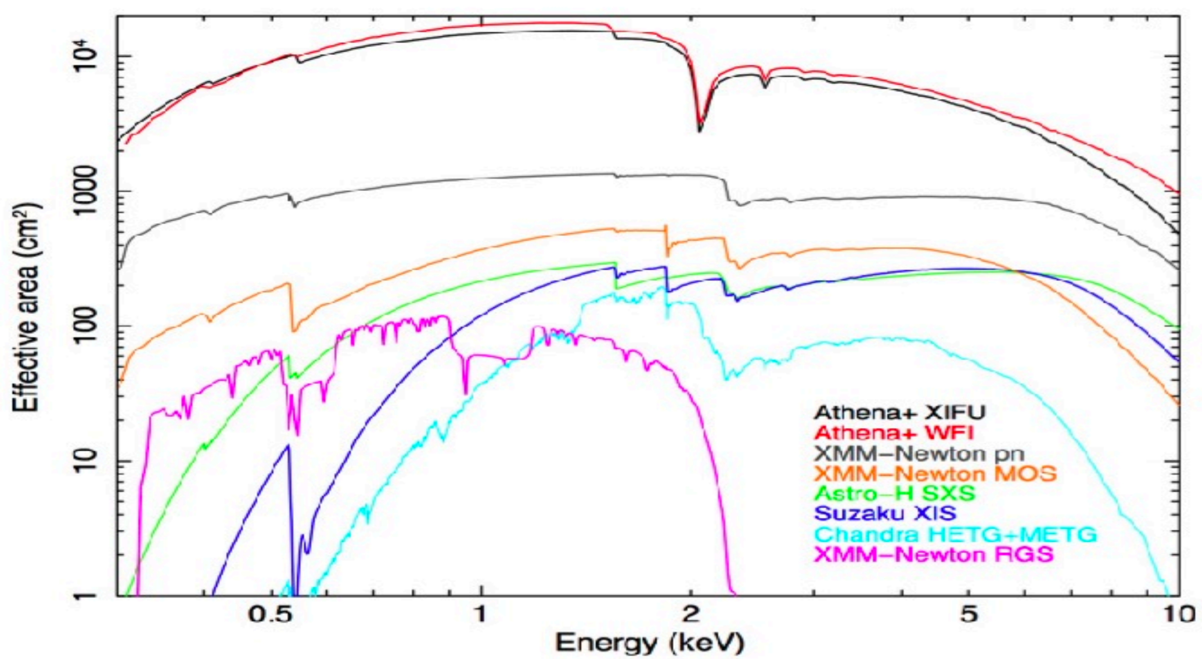


Xrism/Resolve (2023)

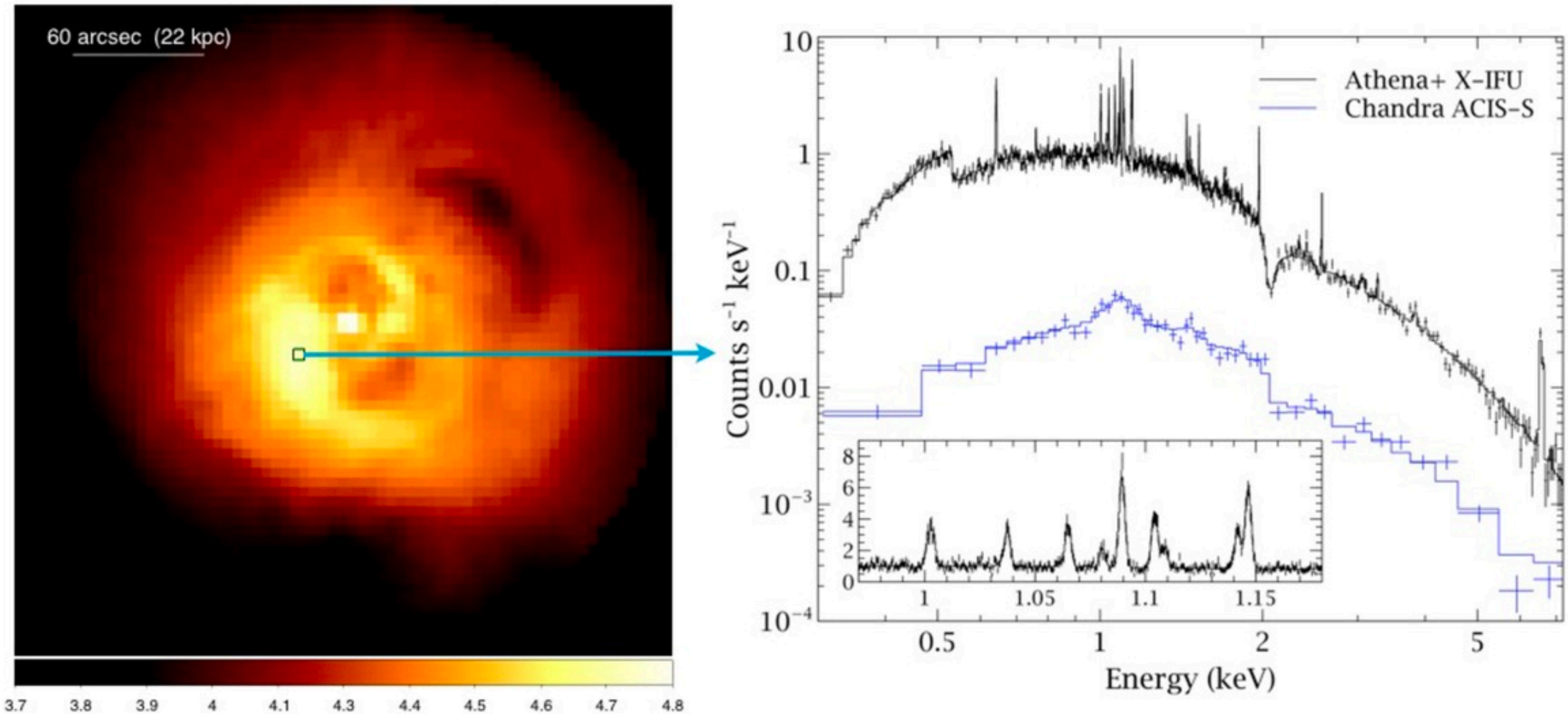


Athena X-IFU (2034)





Athena X-IFU (2034)



In the future, when microcalorimeter will be functioning...
Athena X-IFU (energy resolution 2.5eV, 10ks) simulation.