The foundamental parameters of X-ray telescopes

INAF OAS BOLOGNA

What happens

.. a X-ray source…

INPUTS

Source photons+

~~*Mirrors response+*~~

~~*Detector response+*~~

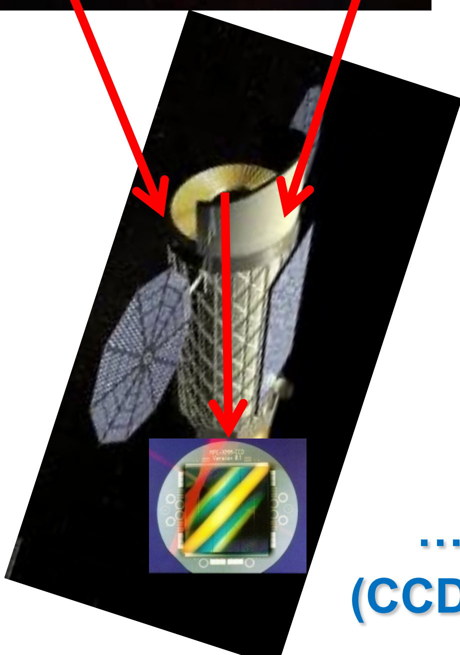
~~*All kinds of Background s*~~

OUTPUTS

Images

Light Curves

Spectra



…mirrors, concentrators or collimators on board satellites..

…detectors (CCDs, Microcal., etc.)

Take into account telescope response… and remaining bgds

Remove "some" backgrounds and malfunctioning

→ things to do

The foundamental parameters of X-ray telescopes

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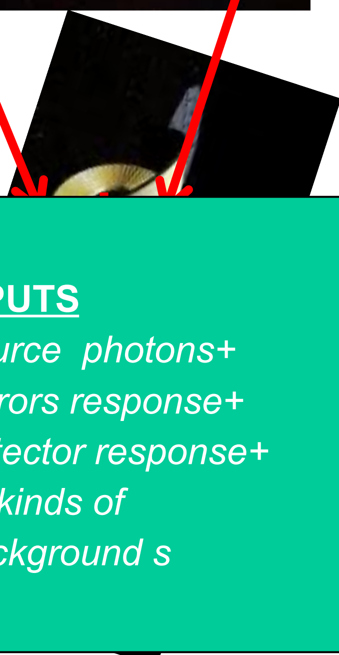

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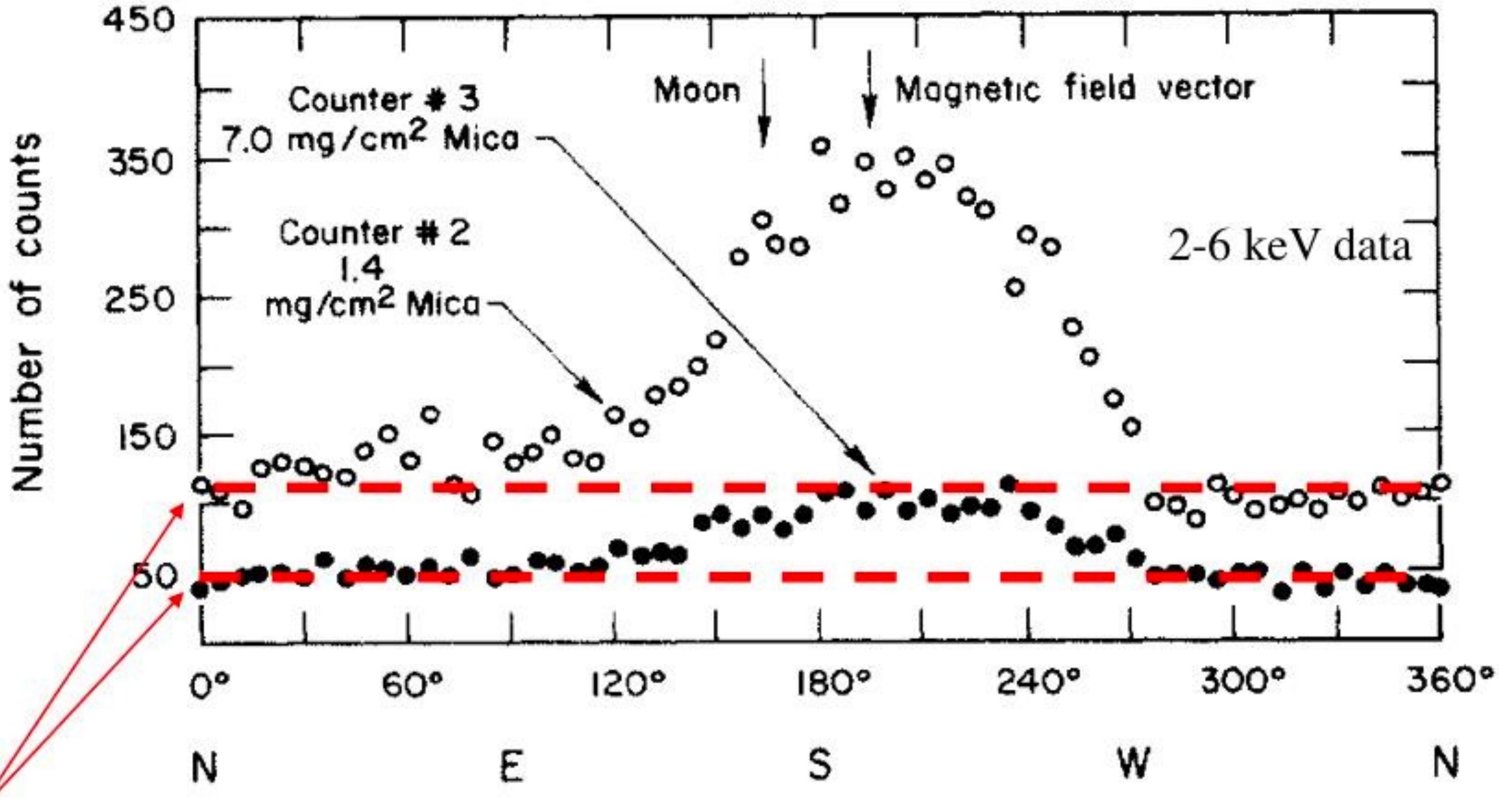
→ things to do

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

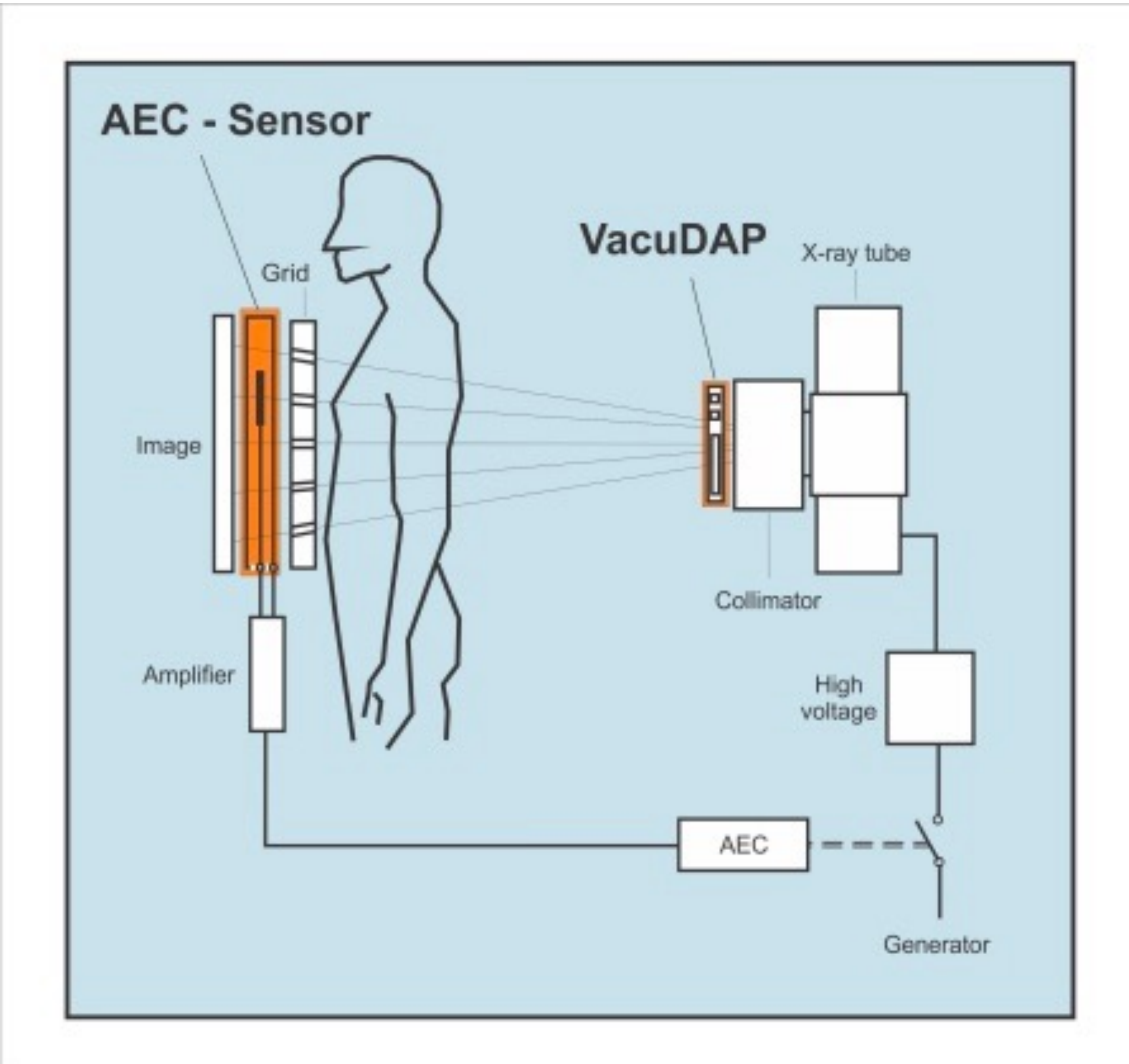
The discovery of the cosmic X-ray background (XRB)

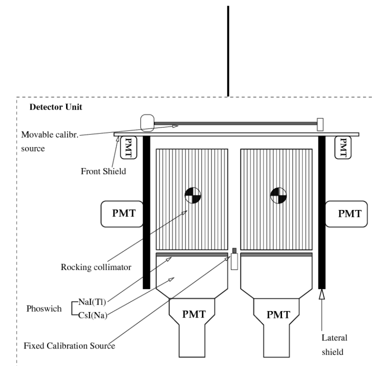


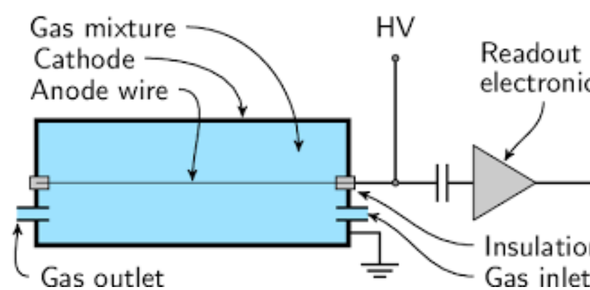
Counts > 0 from all directions ➔ diffuse background radiation

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

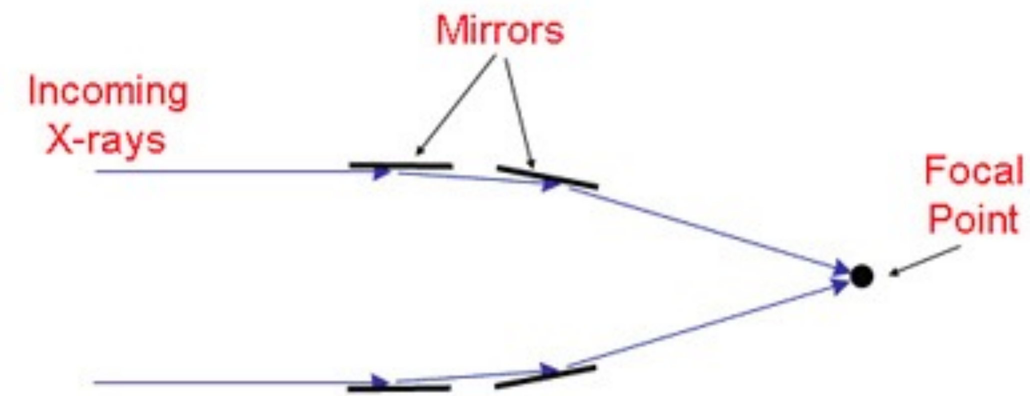
The functioning of a X-ray telescope



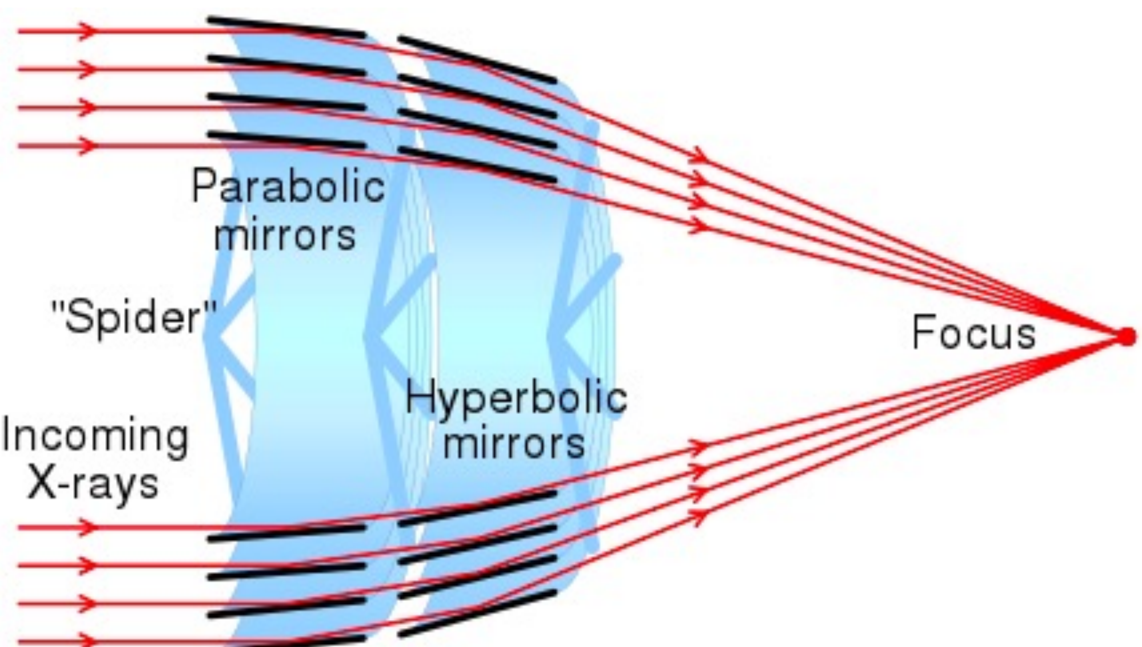




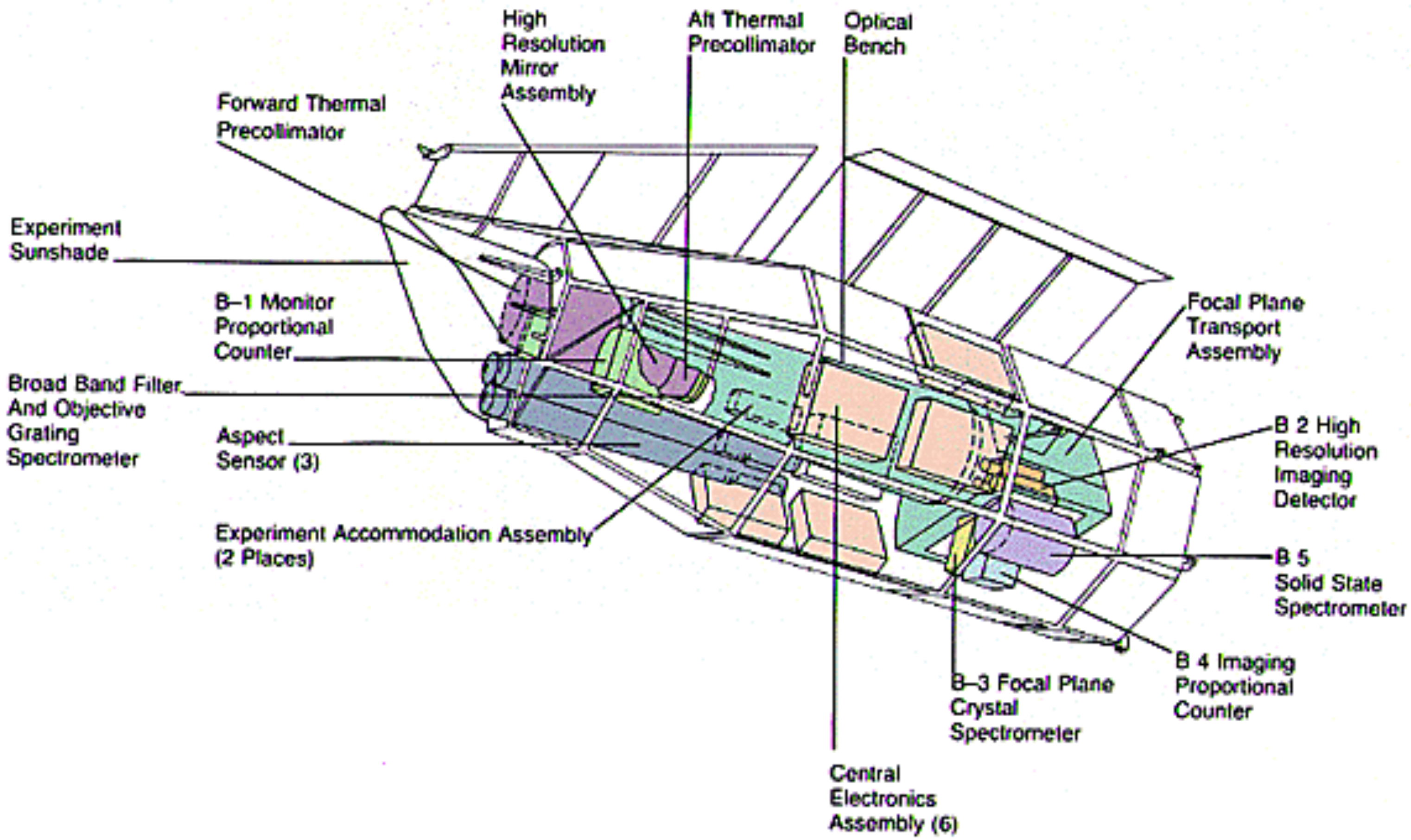
Grazing incidence



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



Einstein (HEAO-2): 1978-1981



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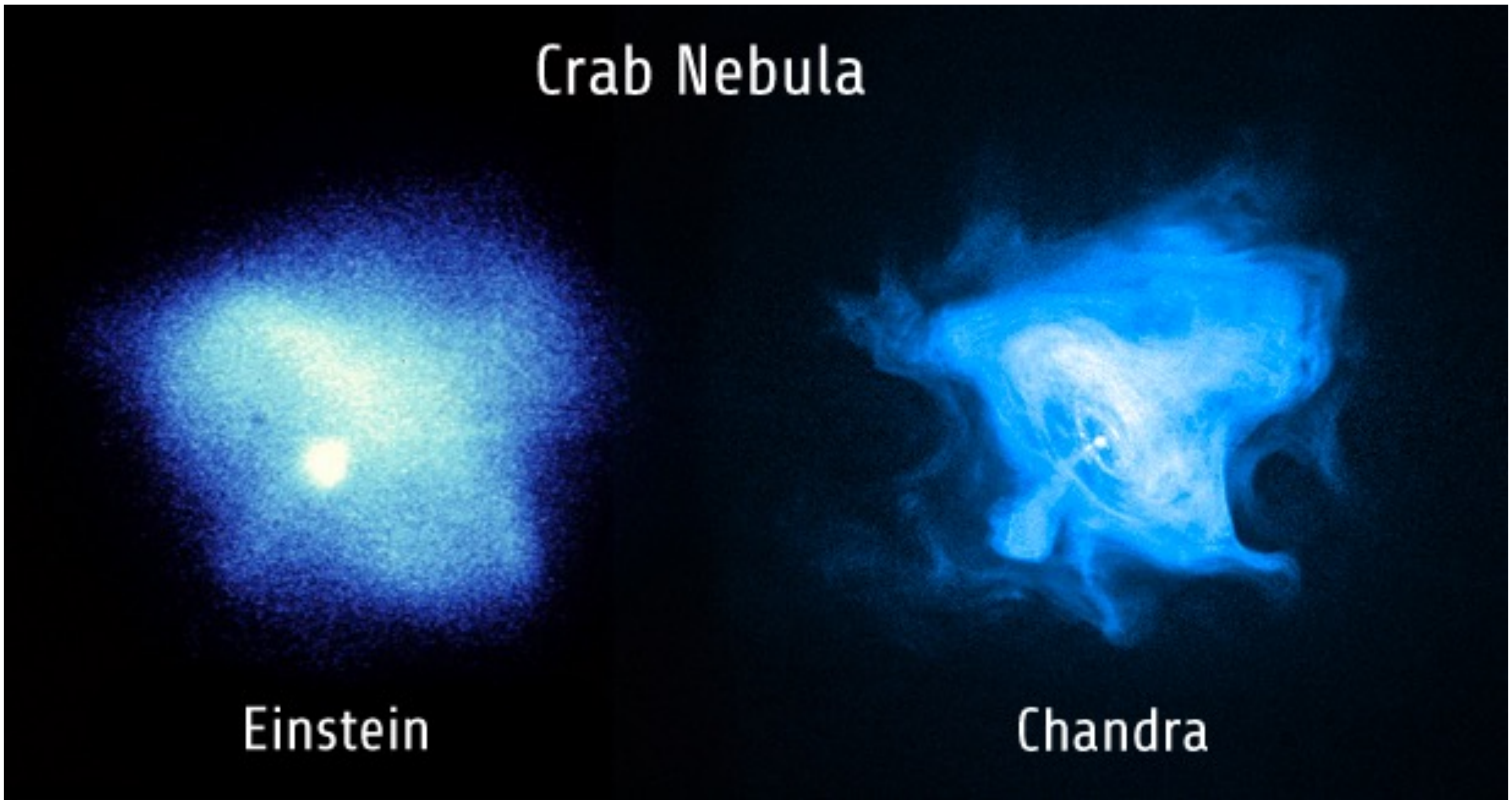


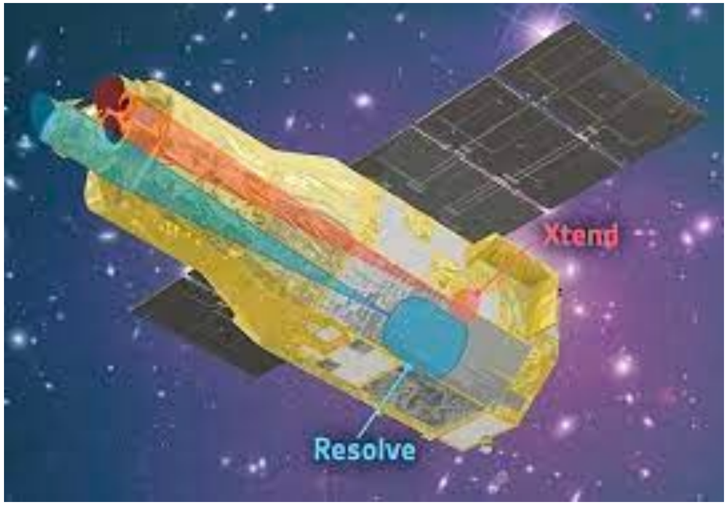
What we are going to talk about…

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

XMM-*Newton*

Chandra

From September the 7, 2023
Xrism (Jaxa-Nasa)



A foundamental concept……

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.

$B^2_{rea\text{-}out(electronic)}$= Const x det. reg.

These terms depend on the "real" regions of the detector where the source counts are collected -> PSF

How to increase the sensitivity….

Increasing the collecting/effective Area

$S = F \times A_{eff}$

S/N increases……

(….but sometime also the bgd increases)

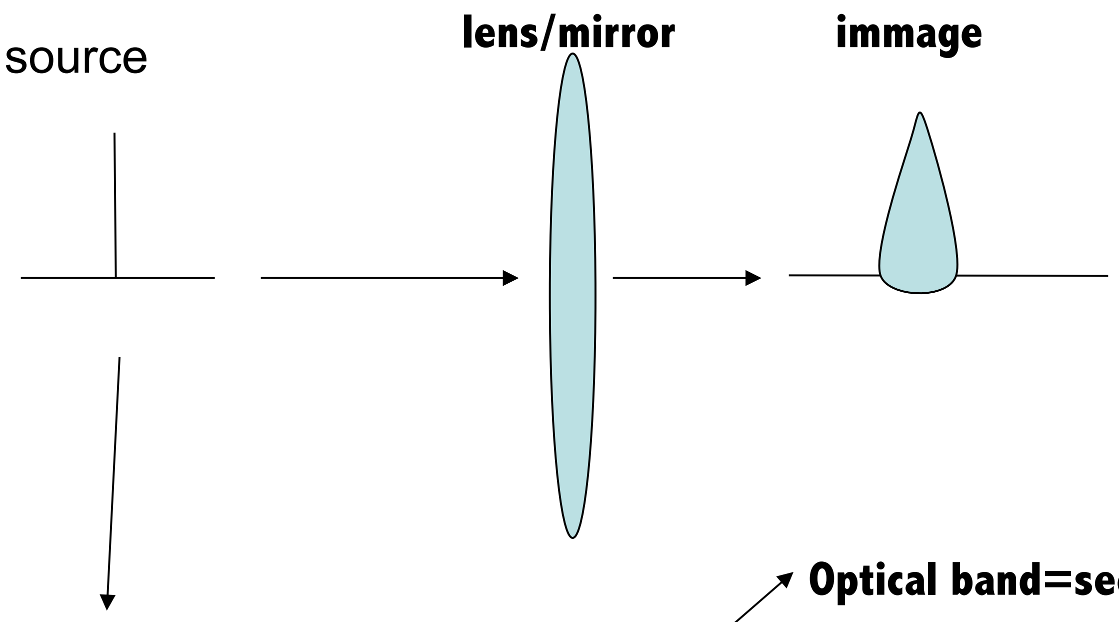
the ESA (XMM-Newton) way

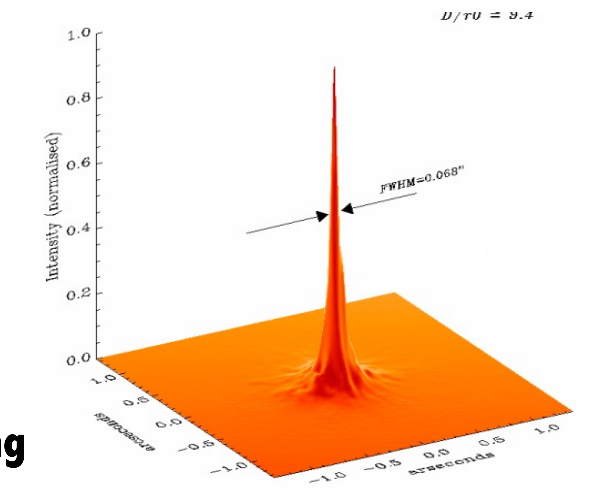
Reducing the B.

S/N increases

the NASA (Chandra) way…

First fundamental element of the telescope: PSF





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

Optical band=seeing

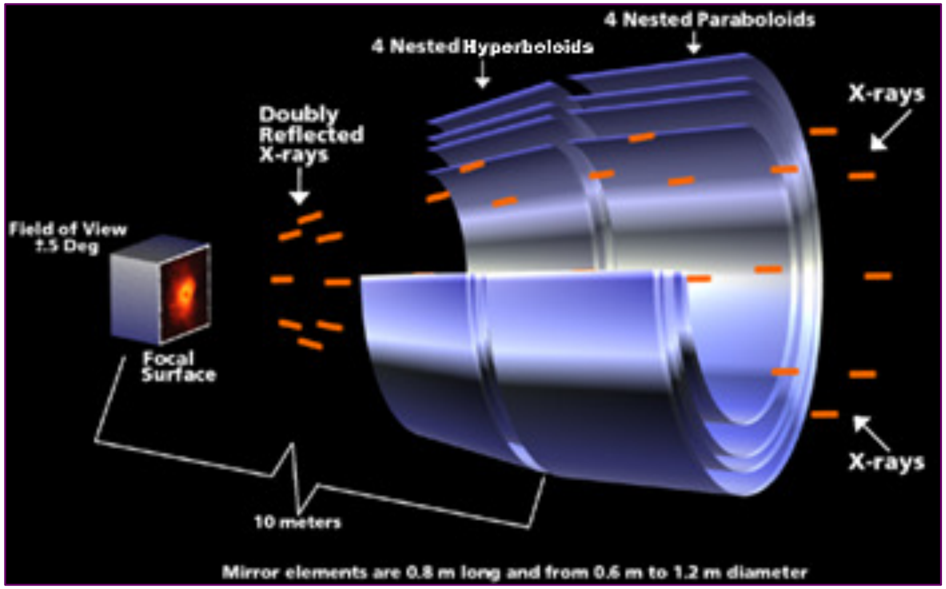
X-rays= mirrors properties
+ mirror array assembly

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) (...usually a couple of Gaussian/King profiles.....)

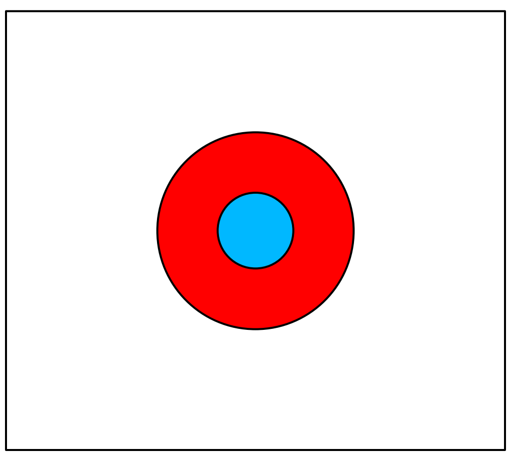
Chandra = "extreme" angular resolution



Only four, robust shells

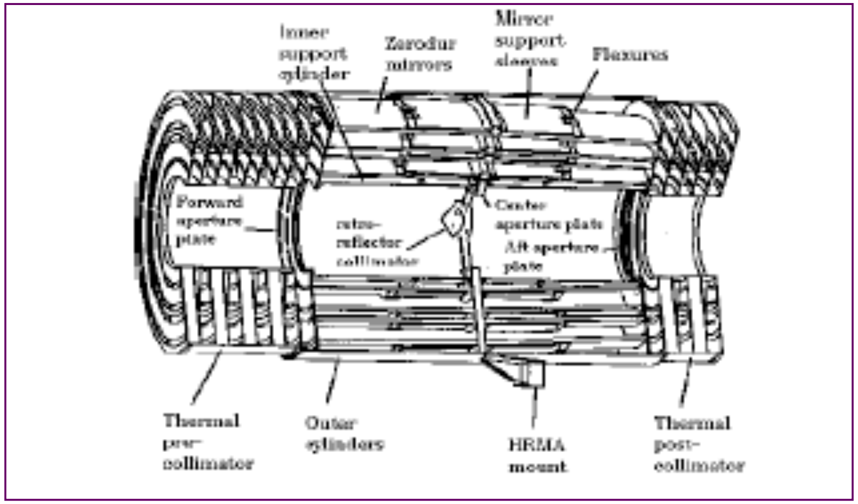
High-quality of shell production to allow <arcsec on-axis angular resolution (the best so far in X-rays)

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



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

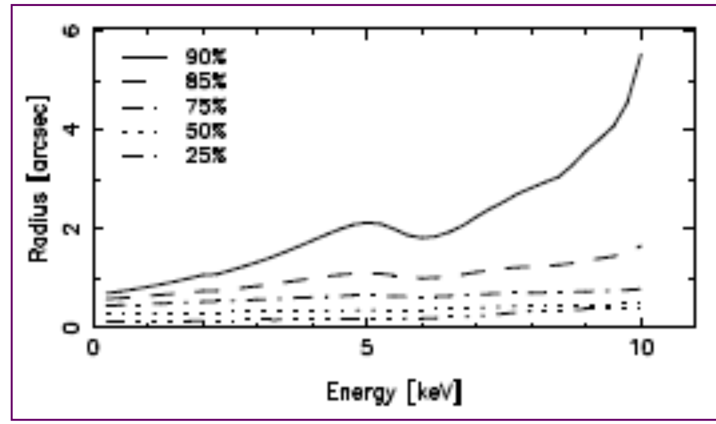
HRMA mass: 1500 kg

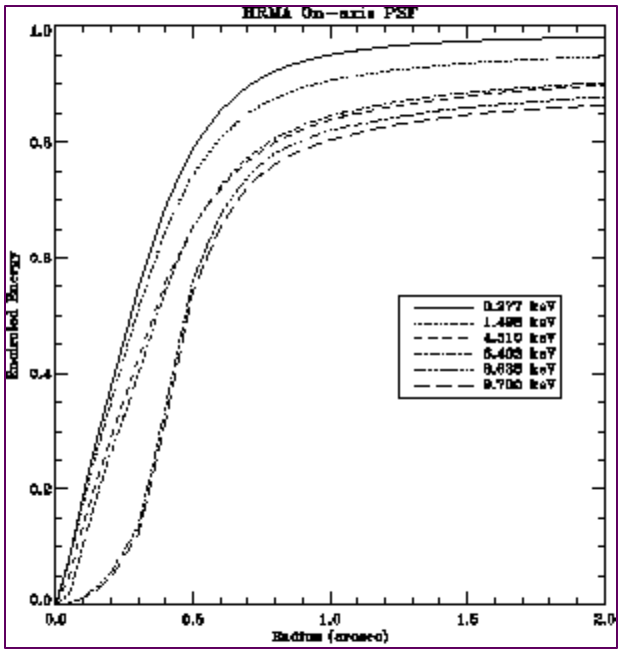
Focal length: 10 m

PSF FWHM: 0.5”

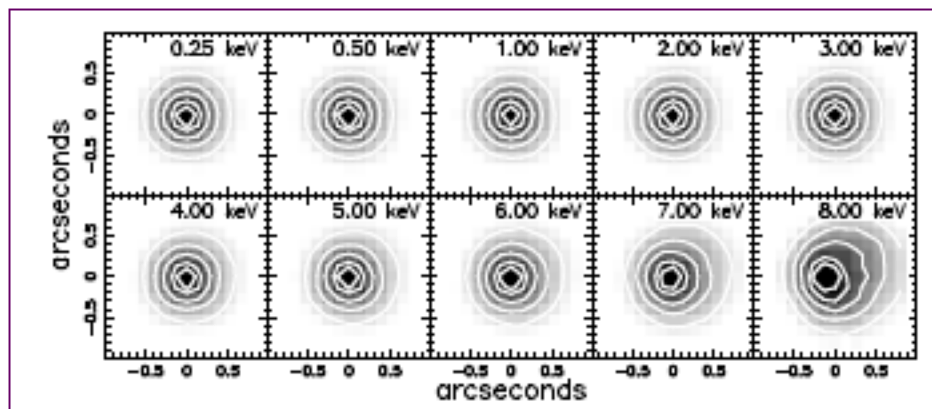
High Resolution Mirror Assembly (HRMA): On-axis PSF

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



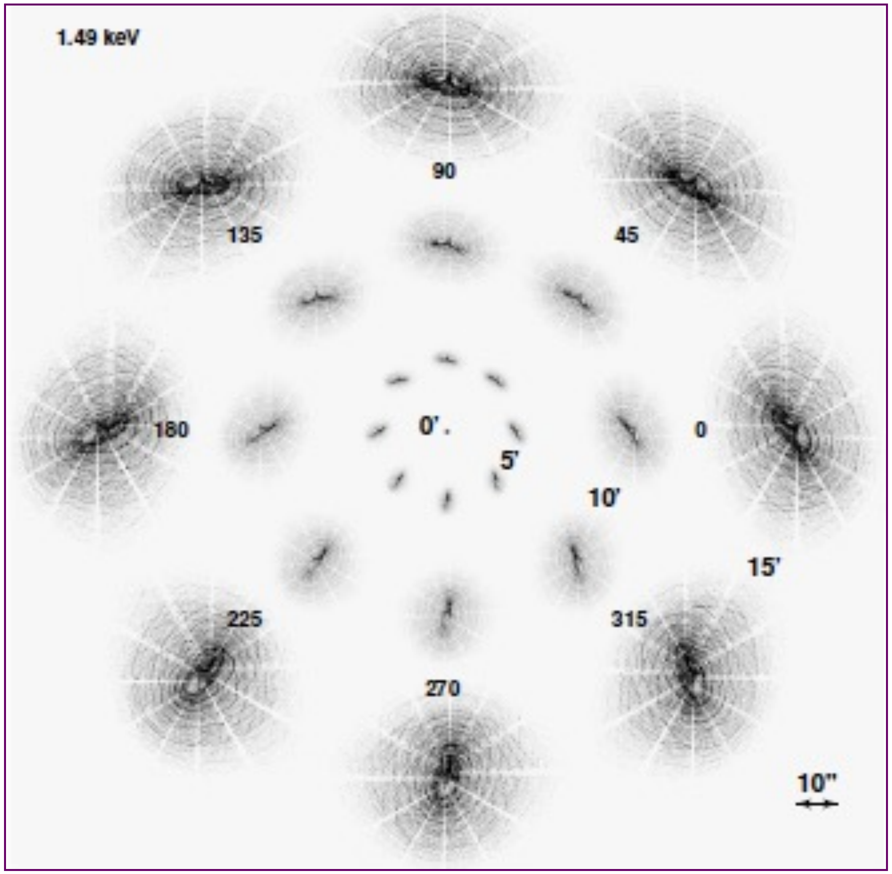


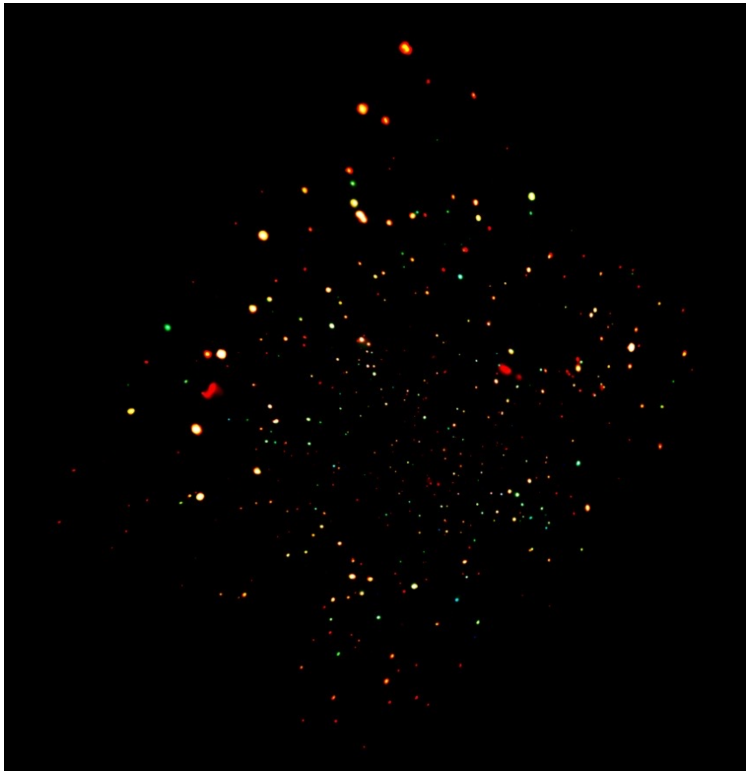
Encircled energy vs. radius at different energies



On-axis PSF size and shape

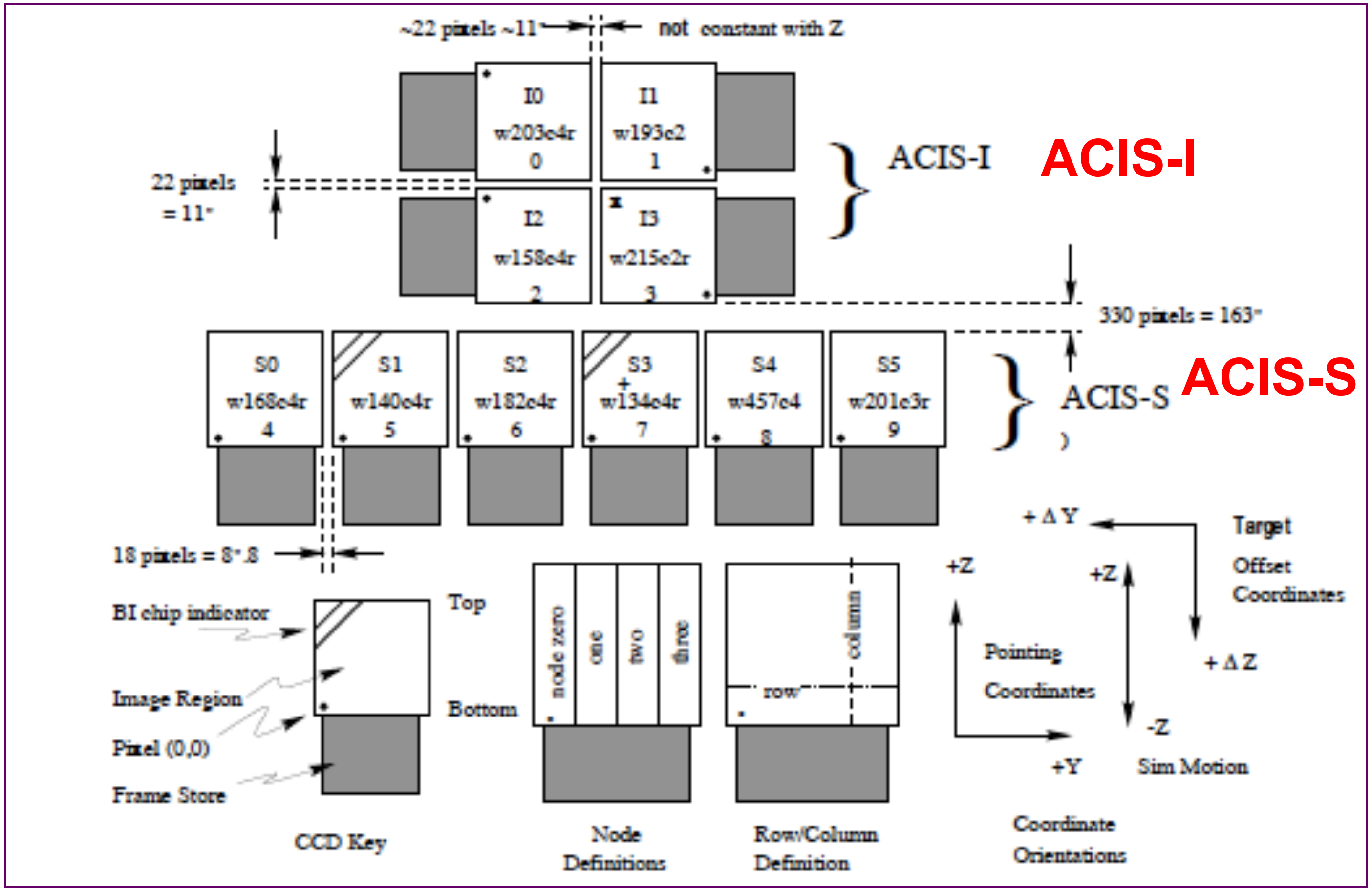
High Resolution Mirror Assembly (HRMA): Off-axis PSF





CDF-N 2Ms exposure

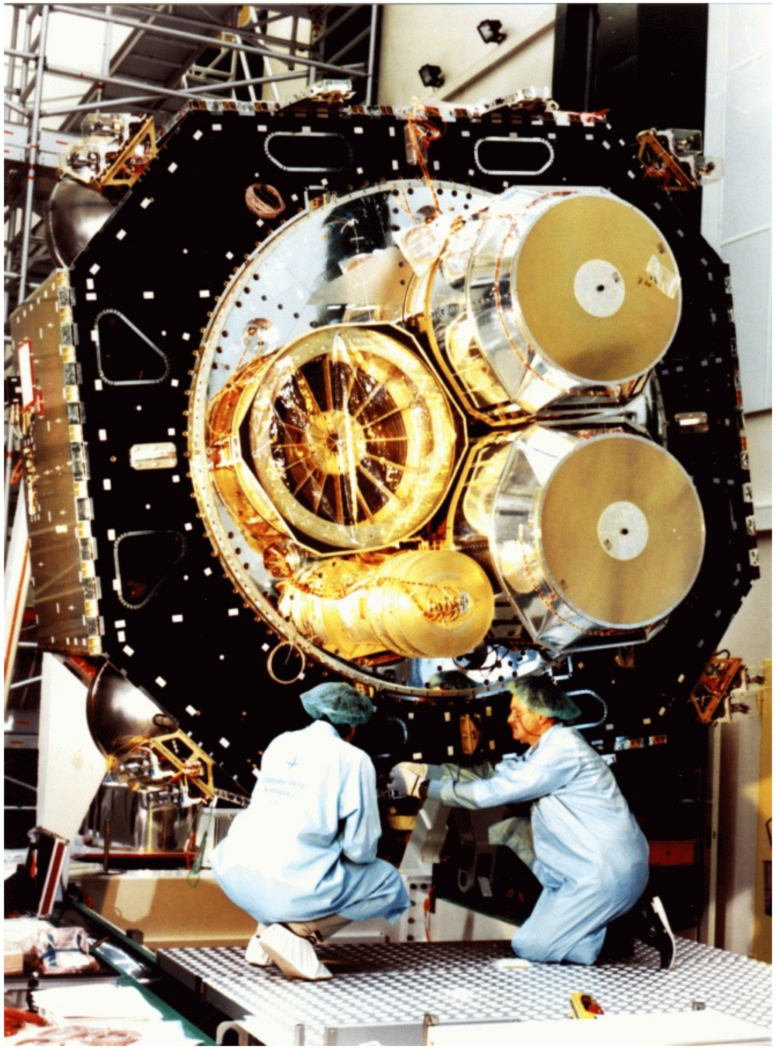
Chandra focal-plane detectors: CCDs



XMM-*Newton* = large effective area

3 modules, 58 shells

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



XMM-Newton: all instruments at work simultaneously

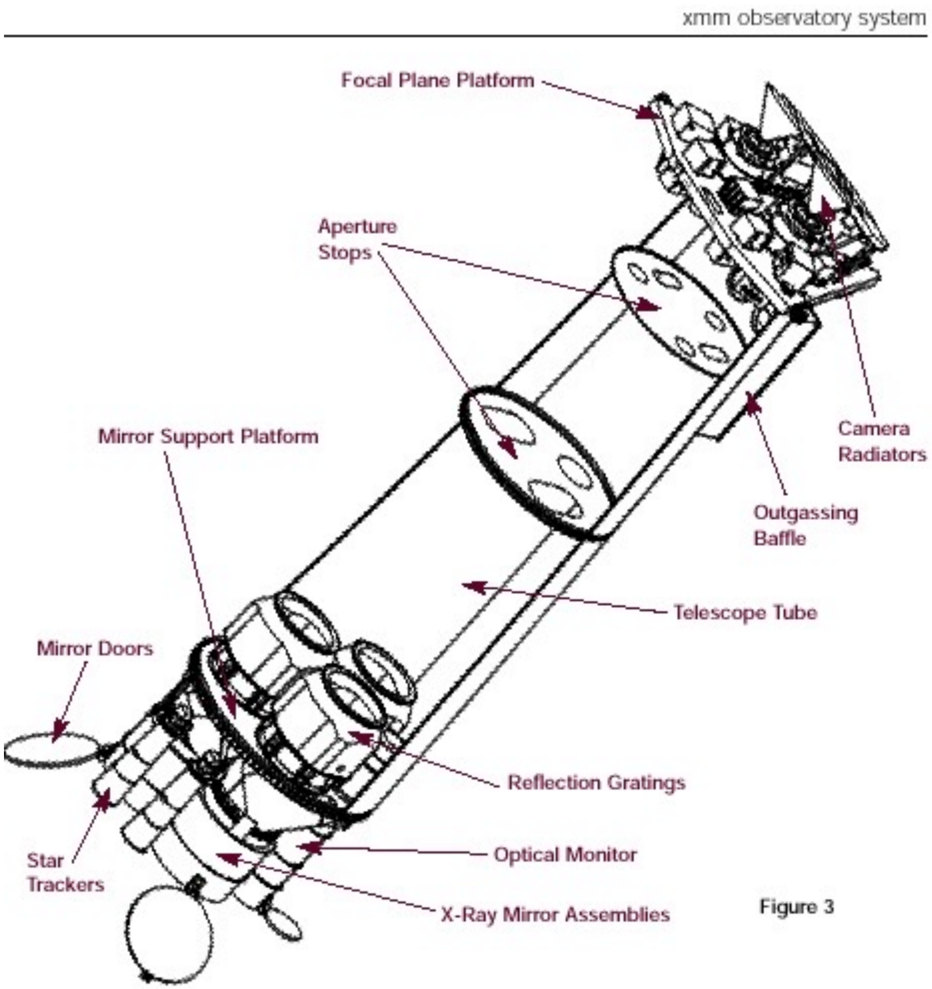
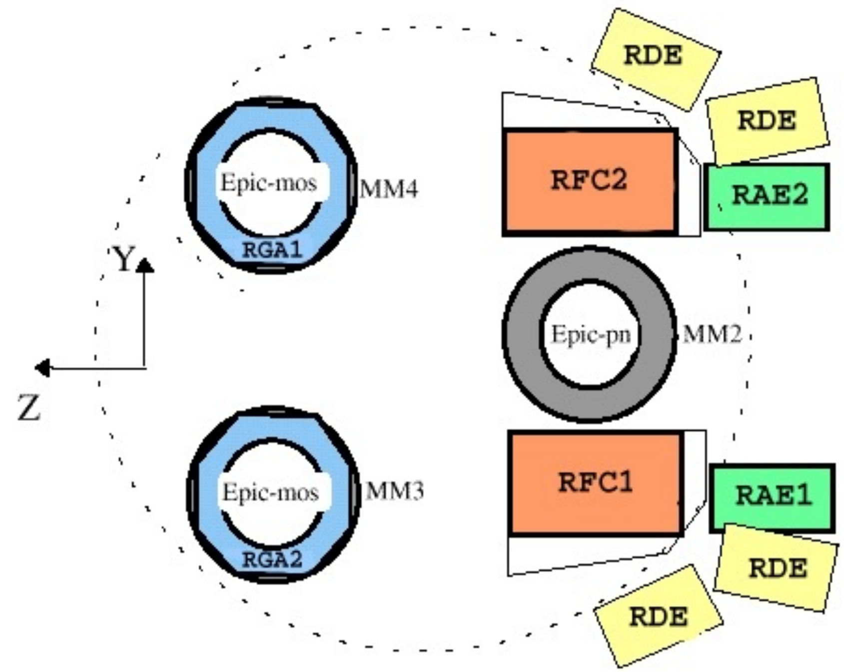
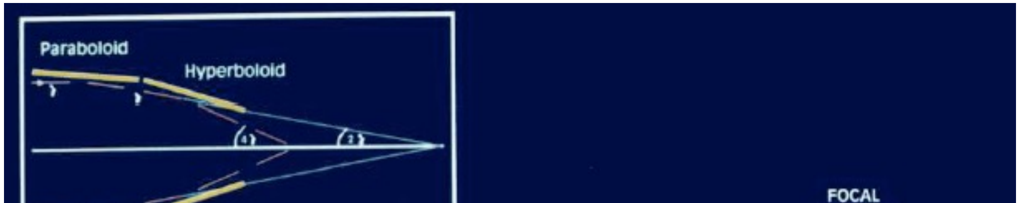
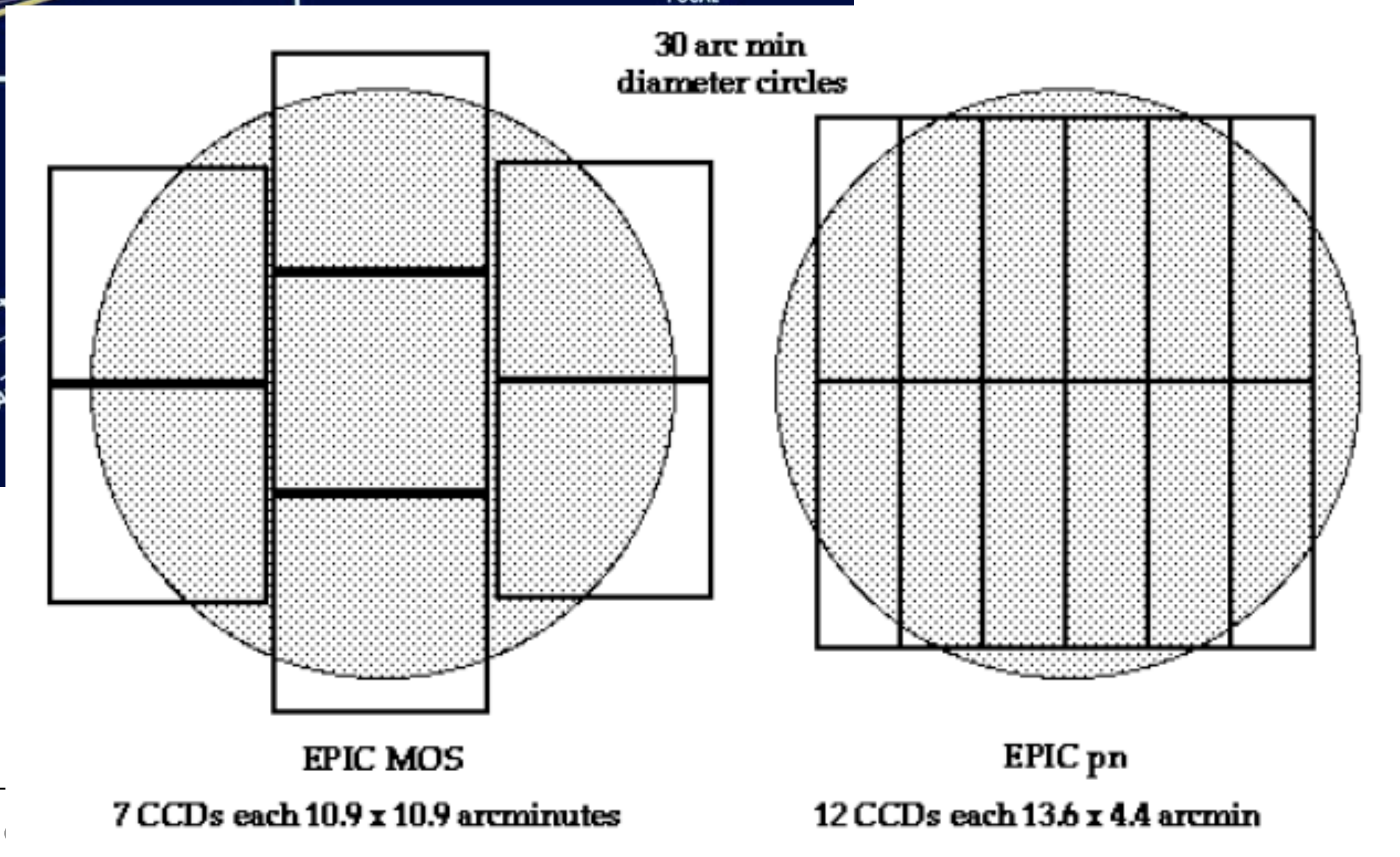


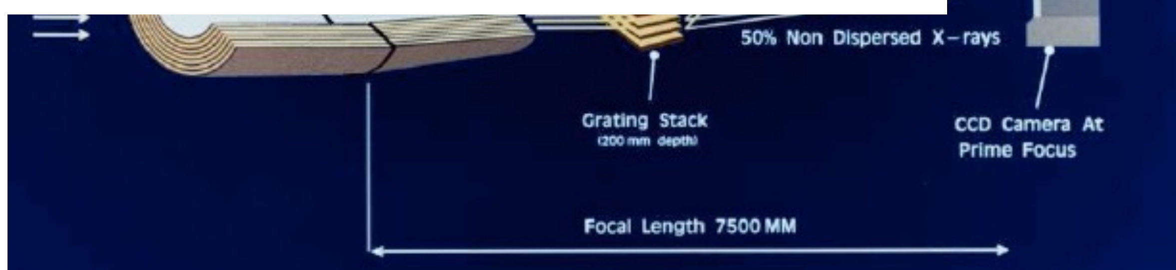
Figure 3



Wolter I solution

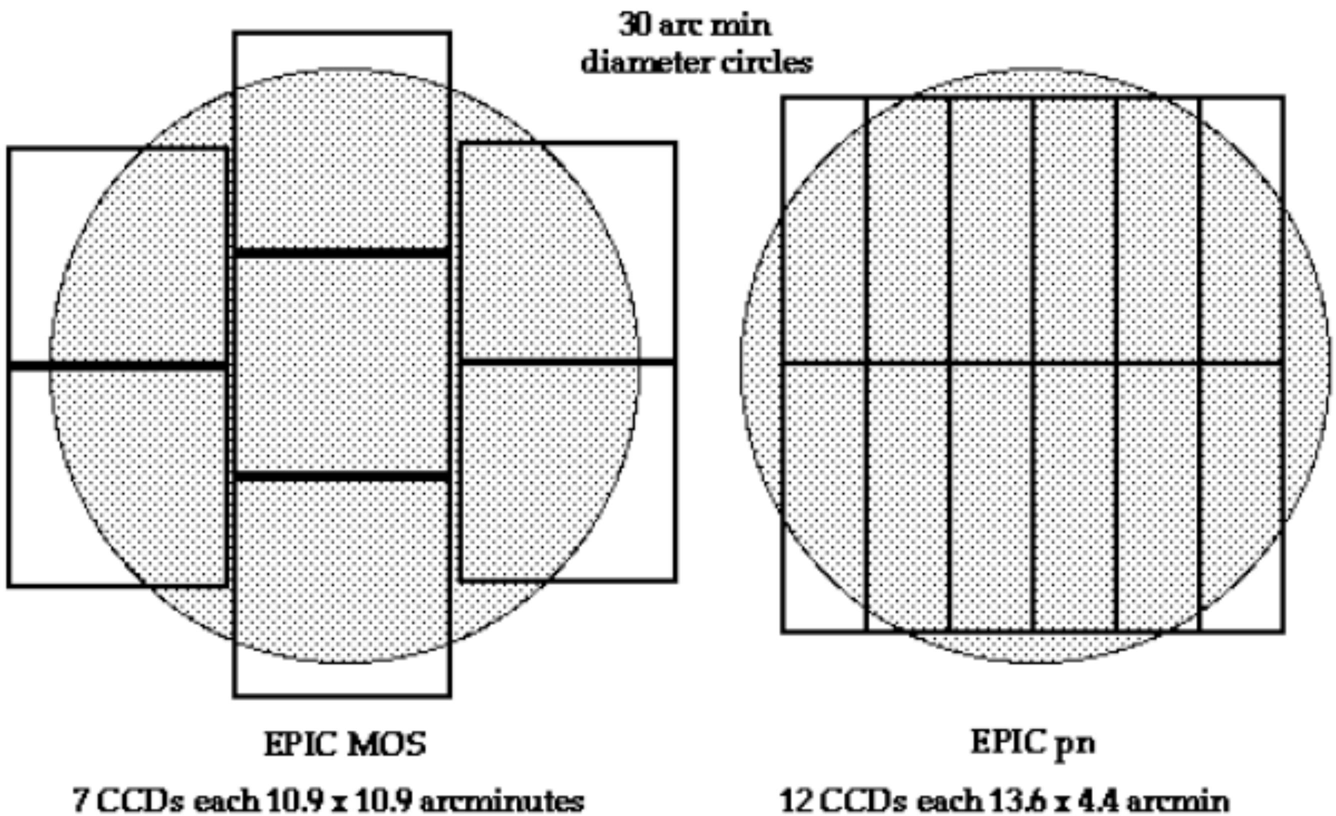






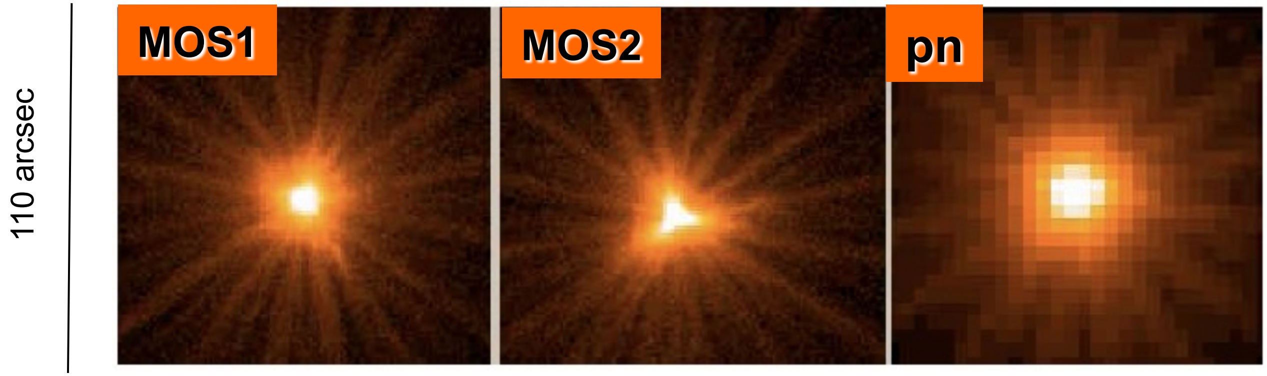
Full in
pn CCD, ≈50% to the MOS1-2, the rest to the grating spectrometers (RGS)

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 on-axis PSF

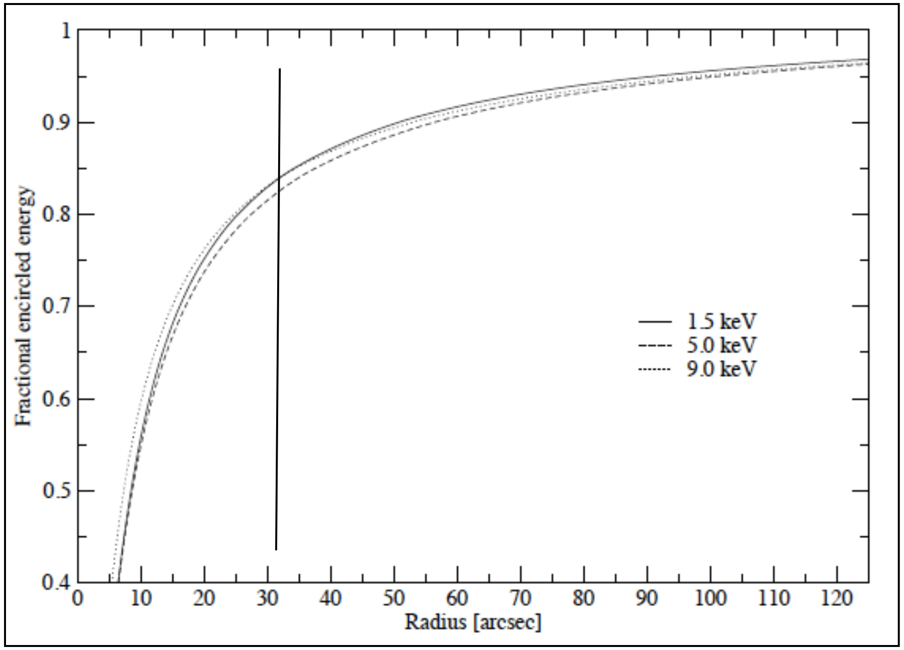


spider-like pattern due to the support of the Wolter I mirrors

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

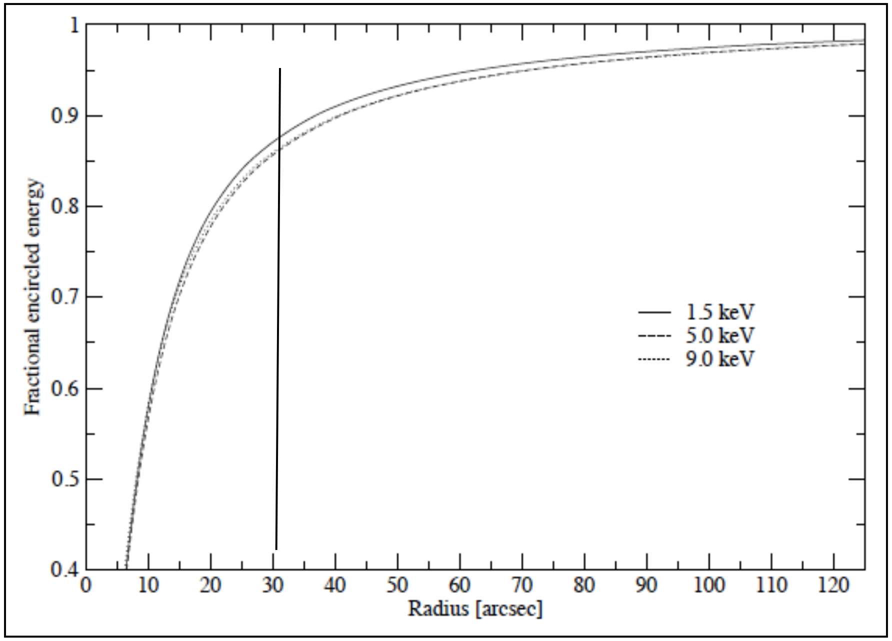
PSF FWHM higher than in *Chandra* but much larger effective area
Background (and confusion limit) can be an issue

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



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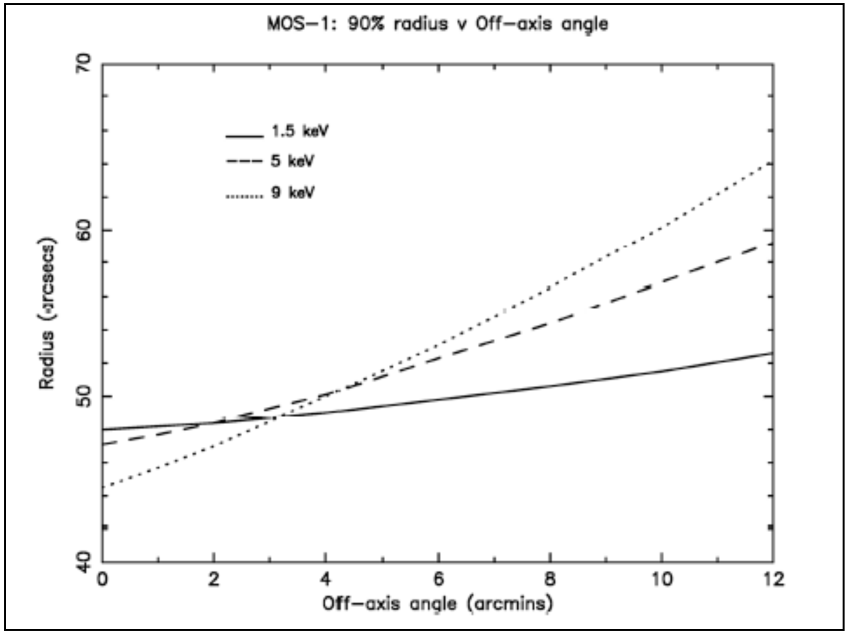
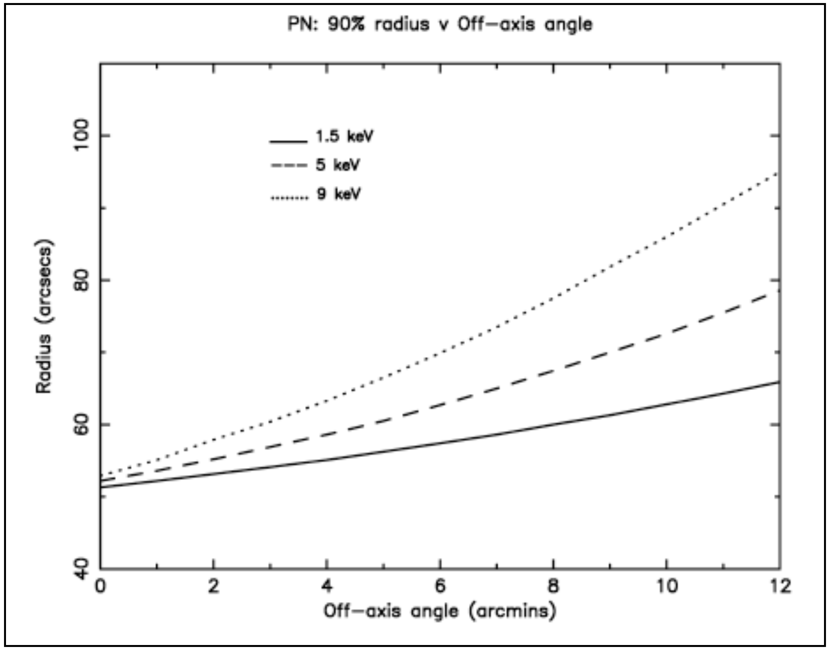


90% radius (radius encompassing 90% of the incoming photons) vs. off-axis angle for the MOS1-2 at different energies

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



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

$$A_{effective}(E,q,x,y) = A_{geometric} x R(E) x V(E,x,y) x QE(E,x,y)$$

Detector

Mirror

Effective area

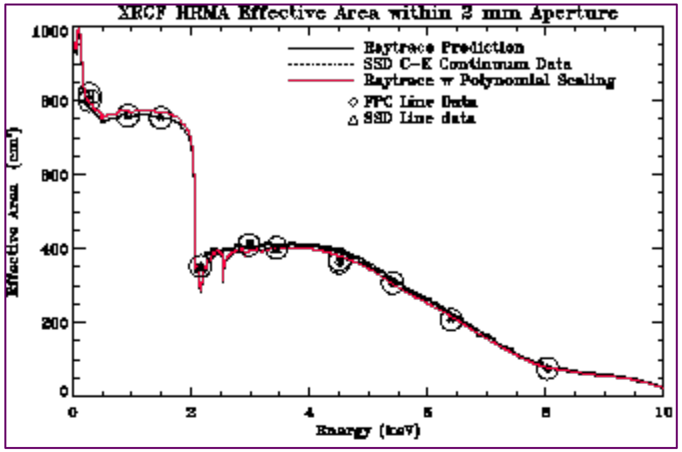
Geometric Area

Reflectivity

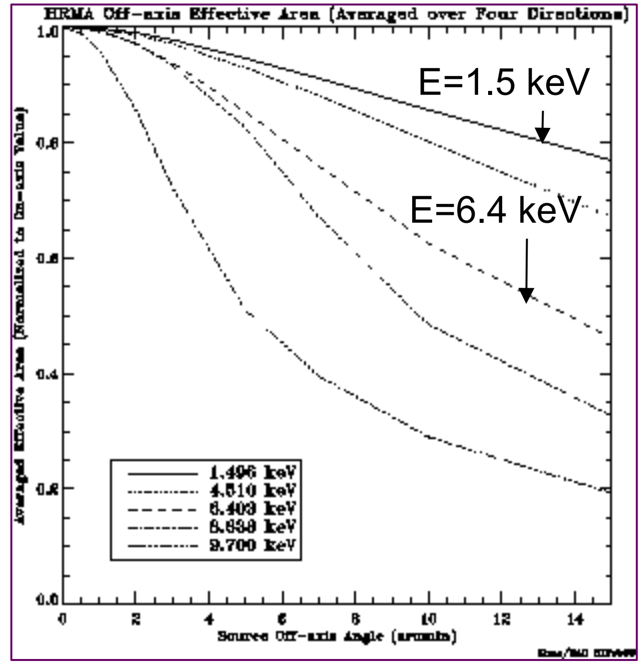
Vignetting

Quantum Efficiency

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



Effective area vs. Energy

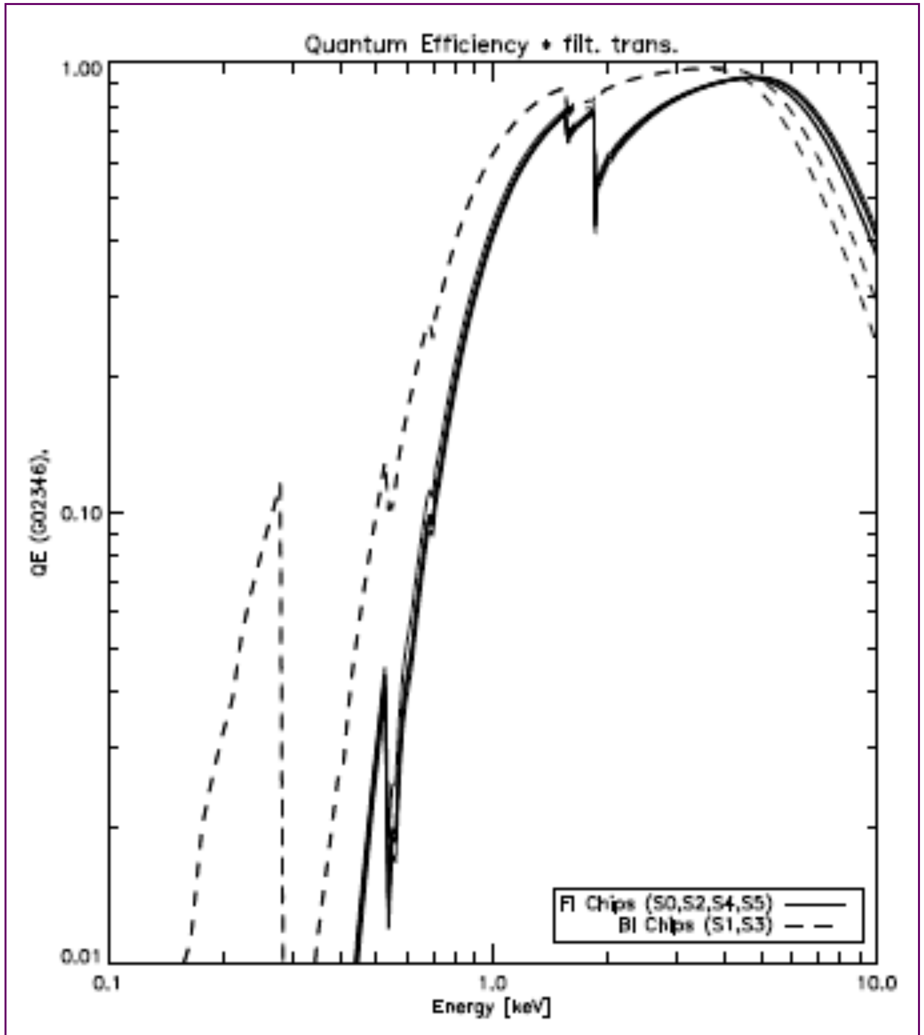


Effective area vs. off-axis angle at different energies

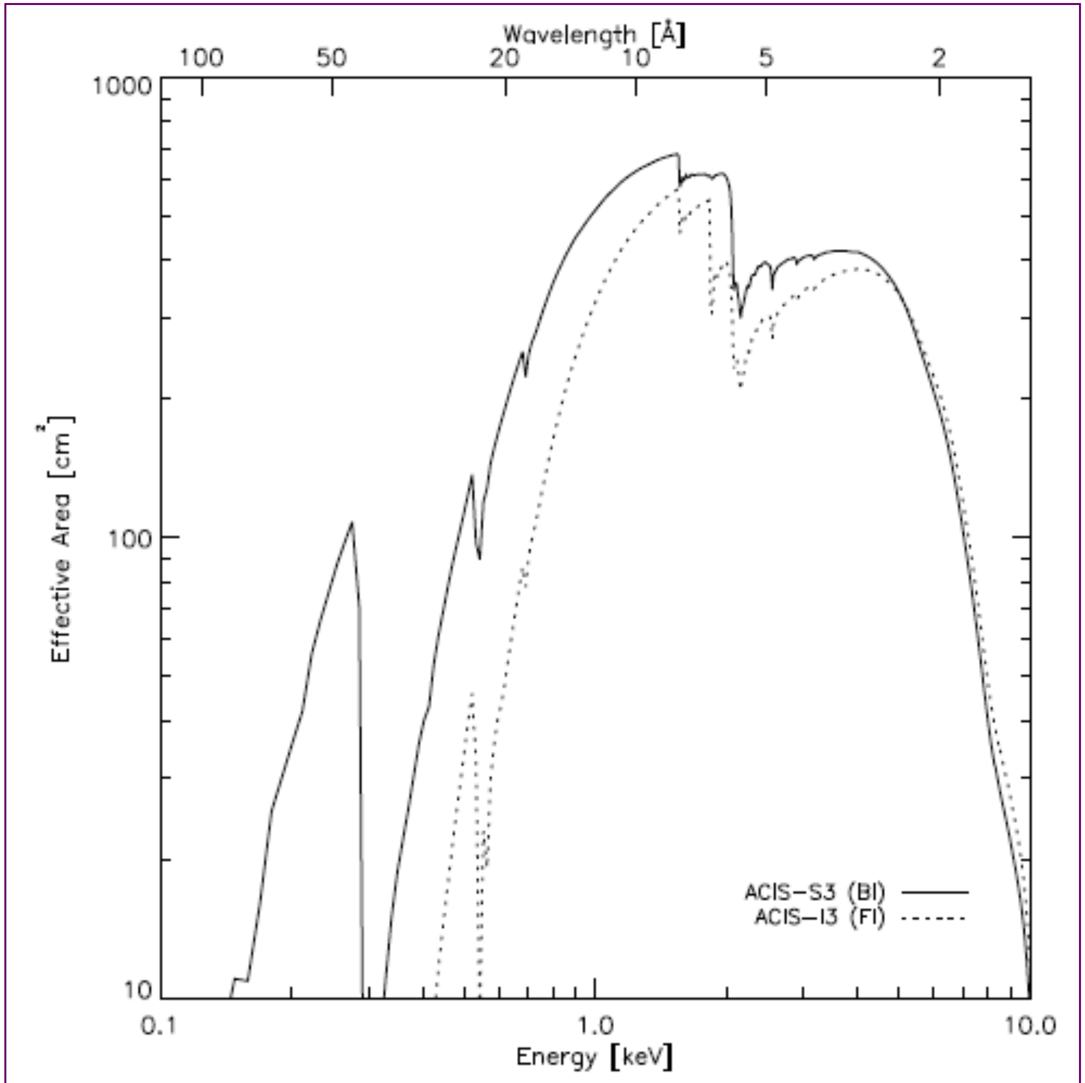
Effect of vignetting

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

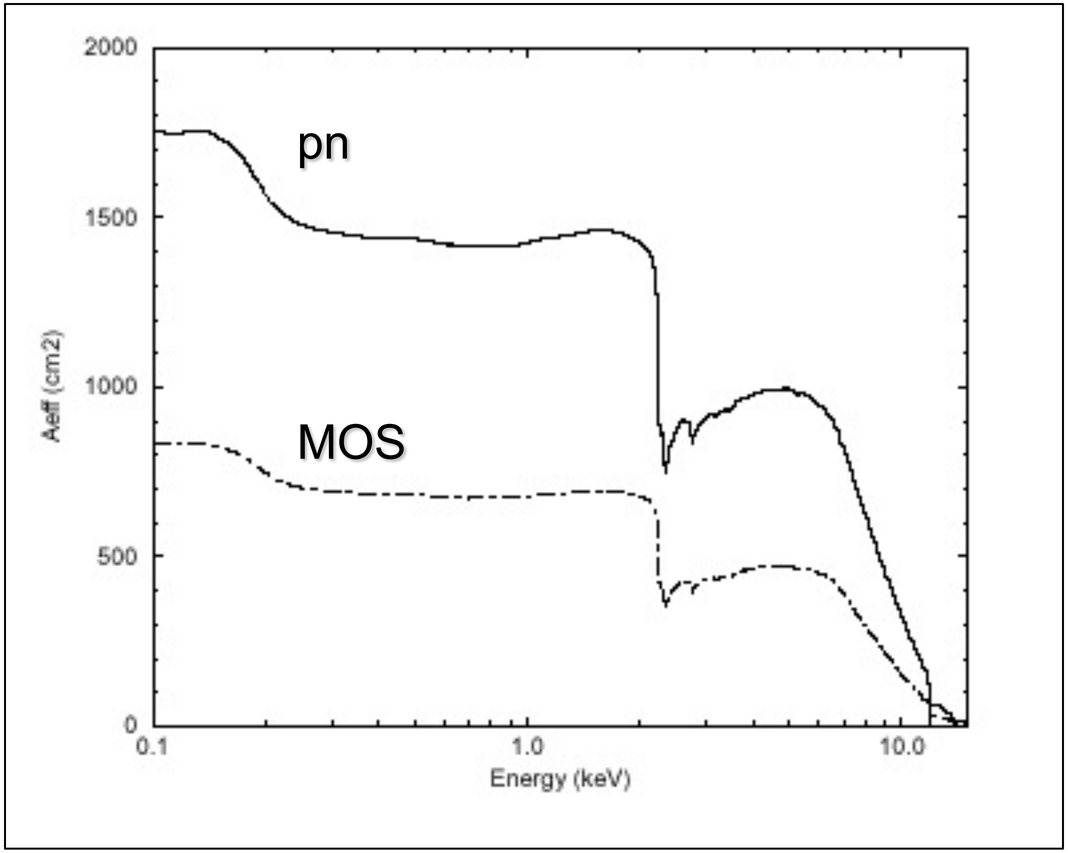
Chandra: quantum efficiency



Chandra: effective area



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



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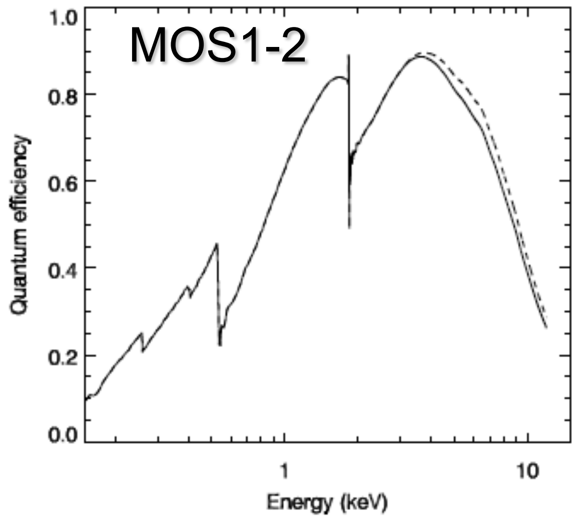
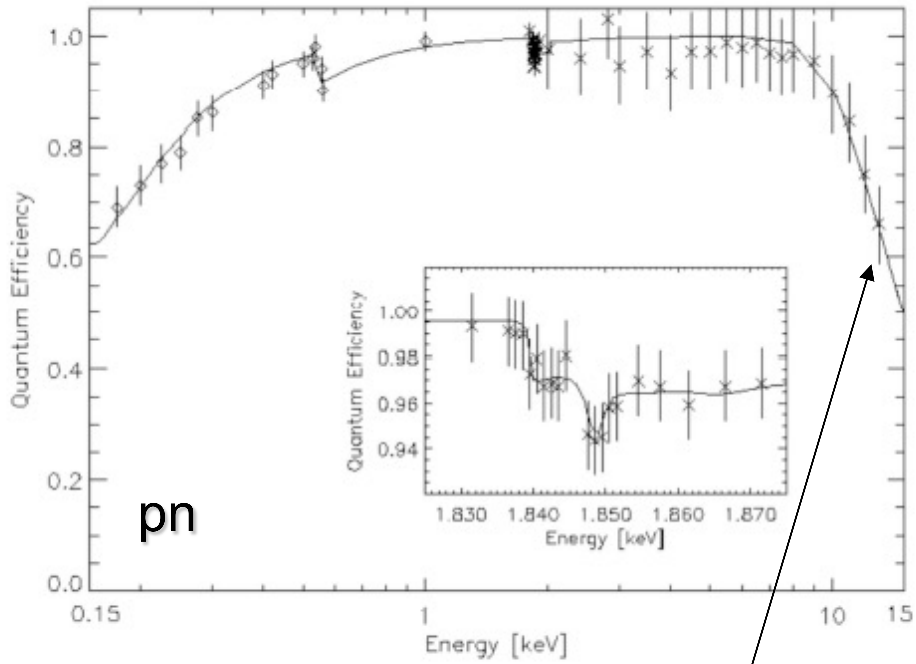
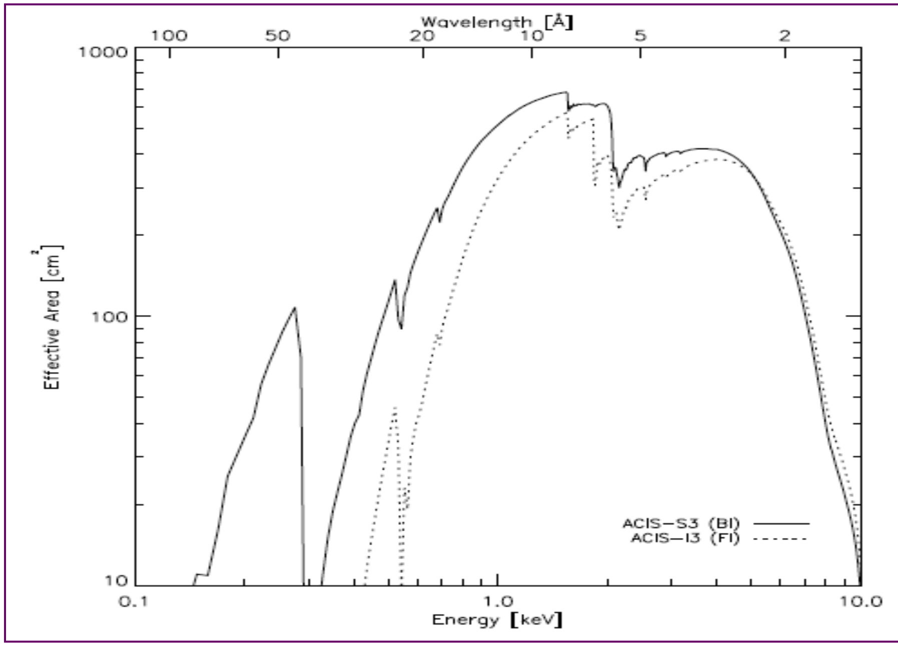
XMM-*Newton:* quantum efficiency



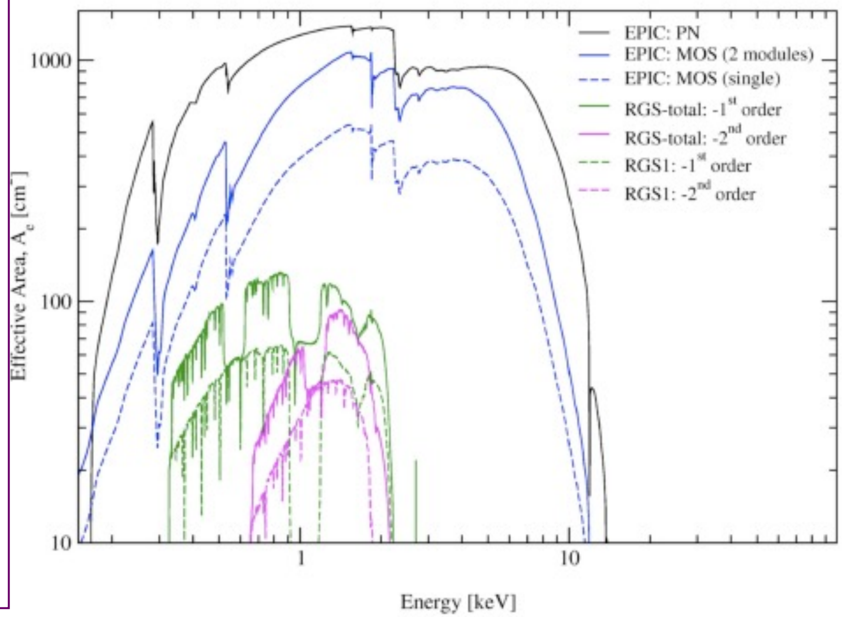


Strong decrease in the QE above 10 keV, where also the effective area due to the mirrors has a significant decrease

Chandra



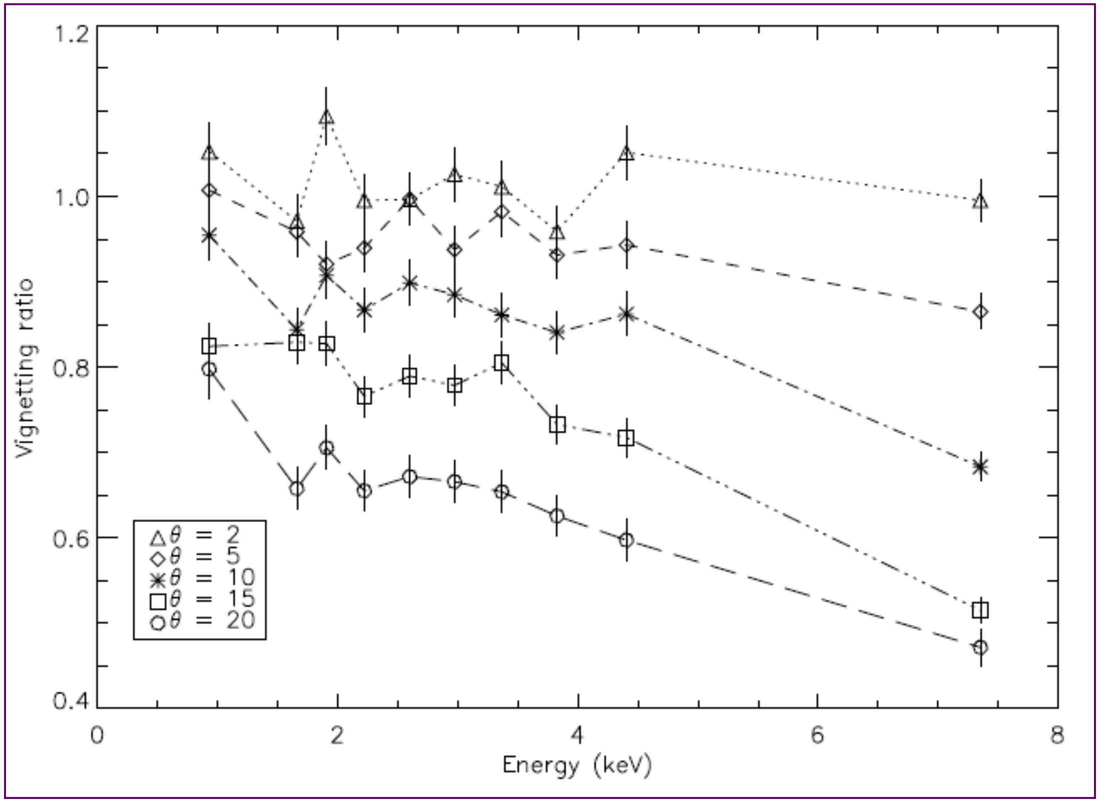
XMM-Newton



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

Chandra: vignetting

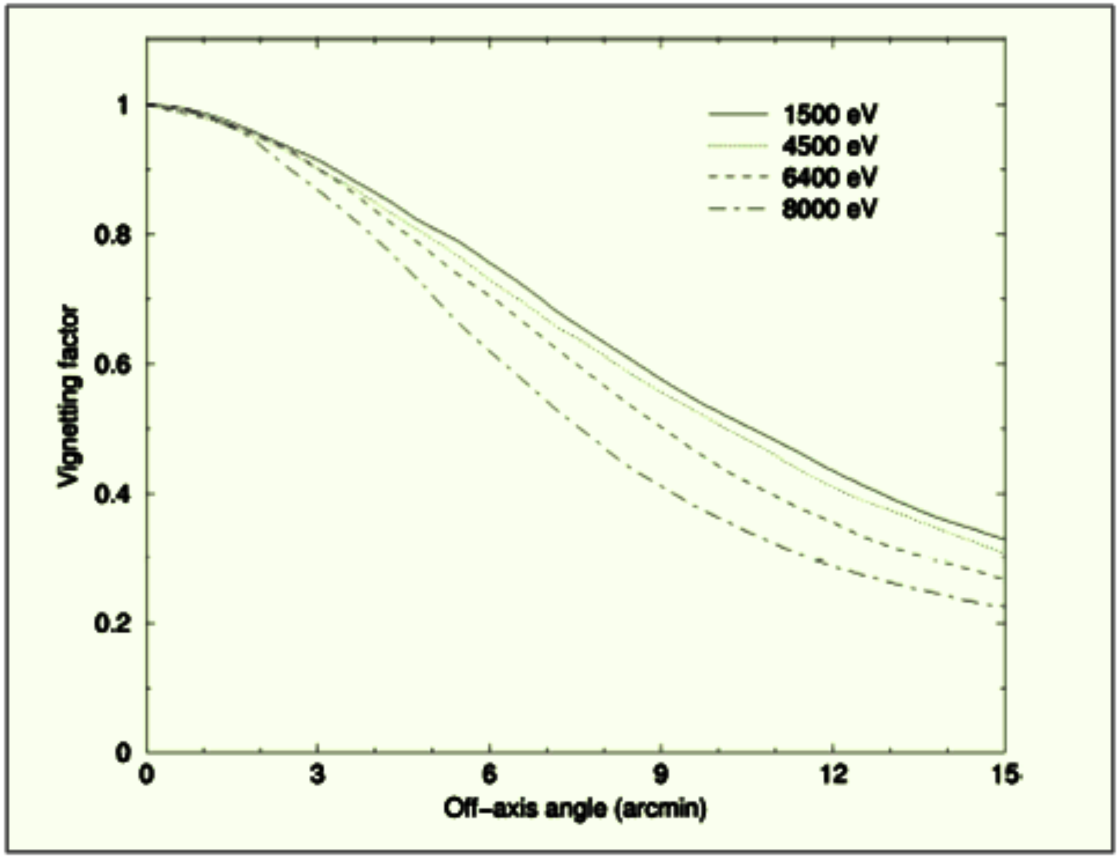
Ratio of the off-axis vs. on-axis counts at different off-axis angles



Hard X-ray photons are more difficult to focus

➔ **Vignetting**

XMM-*Newton:* vignetting



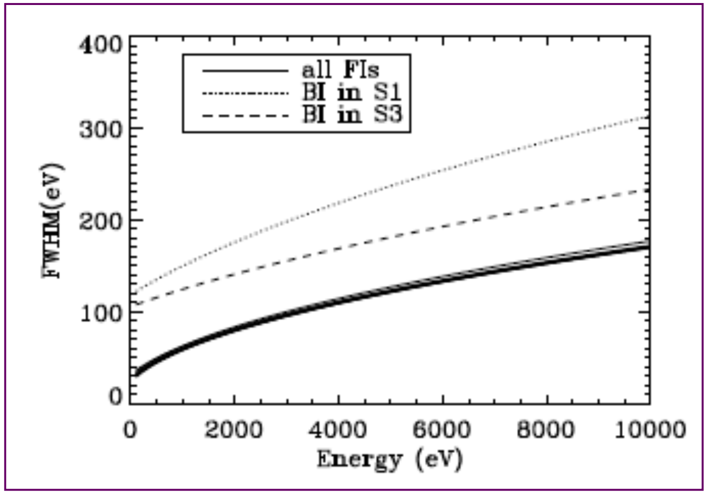
Strong vignetting (as expected) for high-energy photons,
partly compensated by the large effective area (e.g., wrt. *Chandra*)

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

Last but not least….

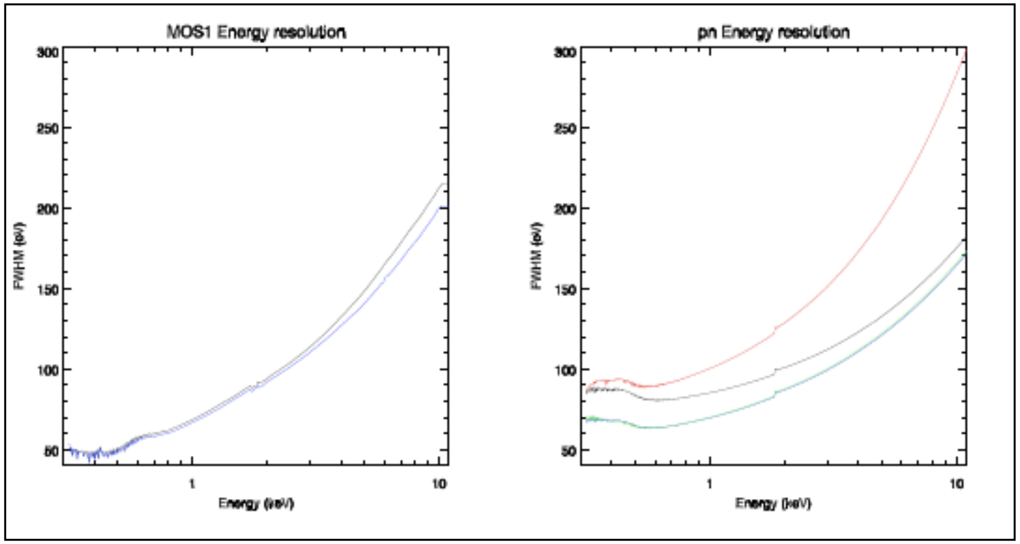
Energy resolution

Chandra: energy resolution



Typical CCD resolution
100-150 eV

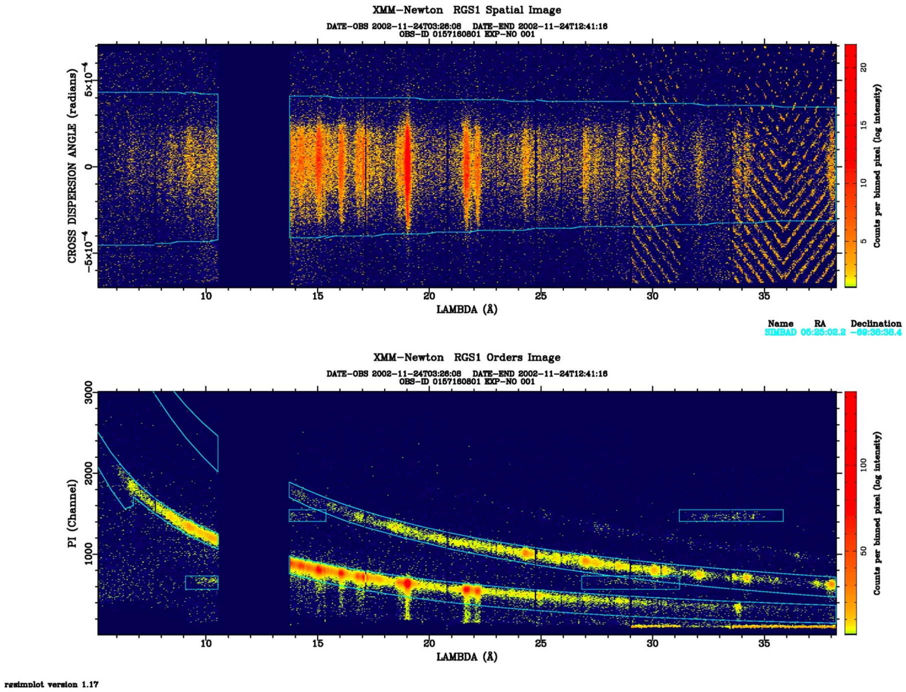
XMM-*Newton:* energy resolution

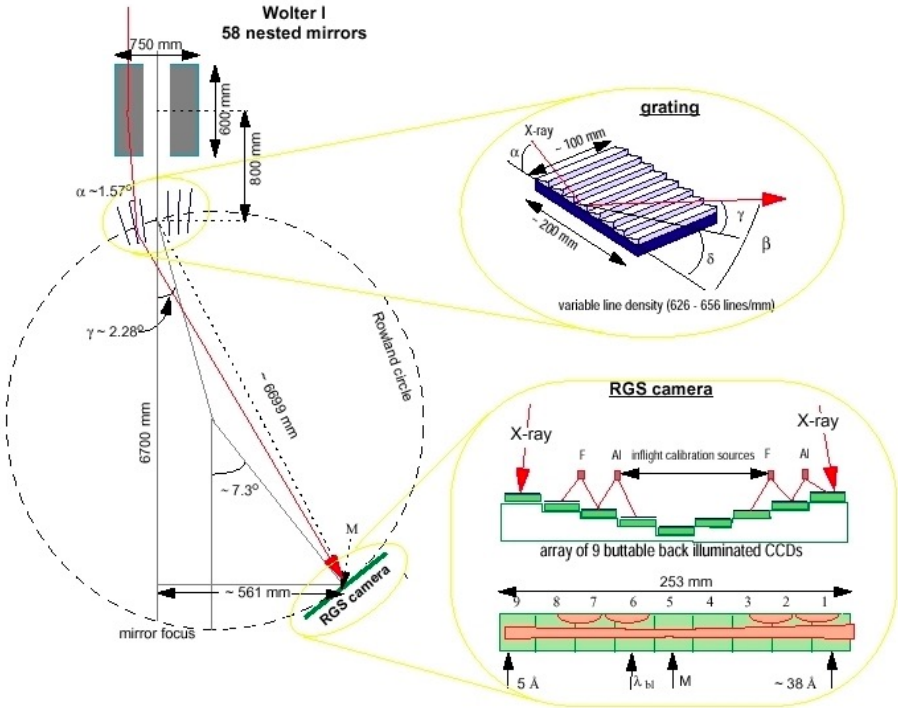


$\Delta E(FWHM)/E \propto E^{-1/2}$ (E in keV)

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

What about high-resolution Spectrospcopy?

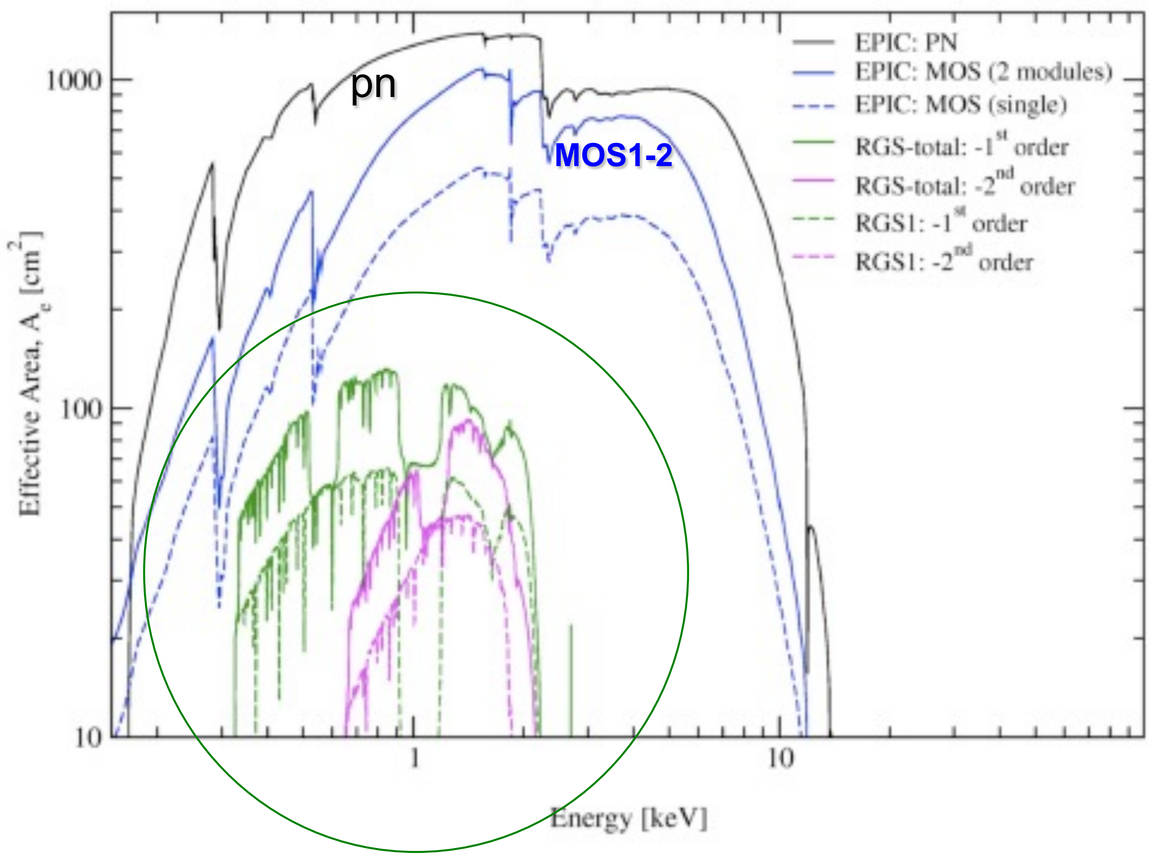




Resolution R ~ 100-500 (FWHM)

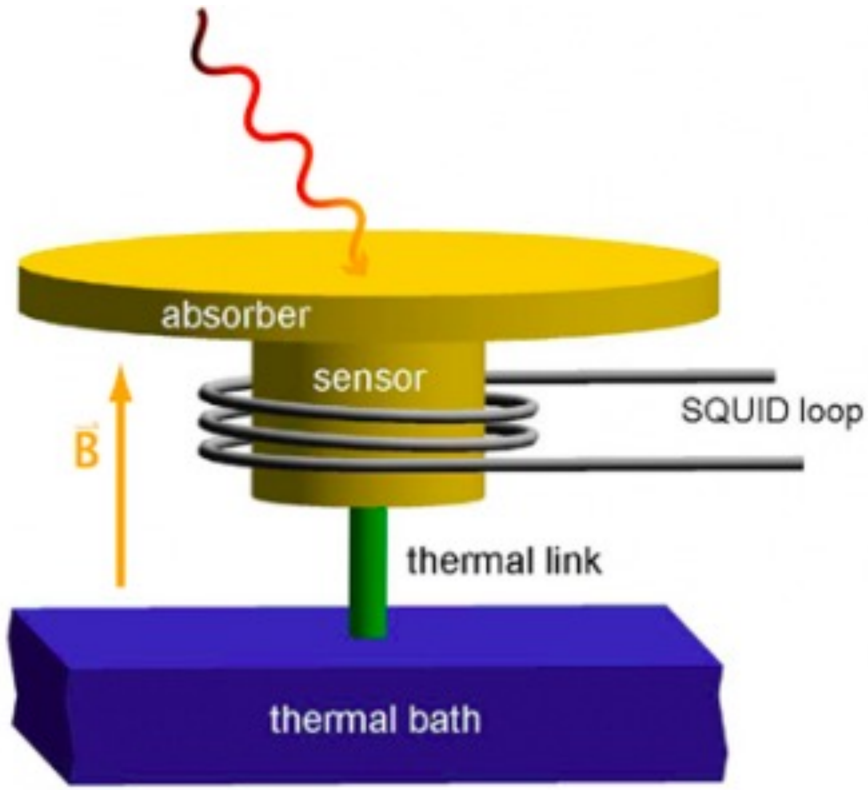
What's missing?

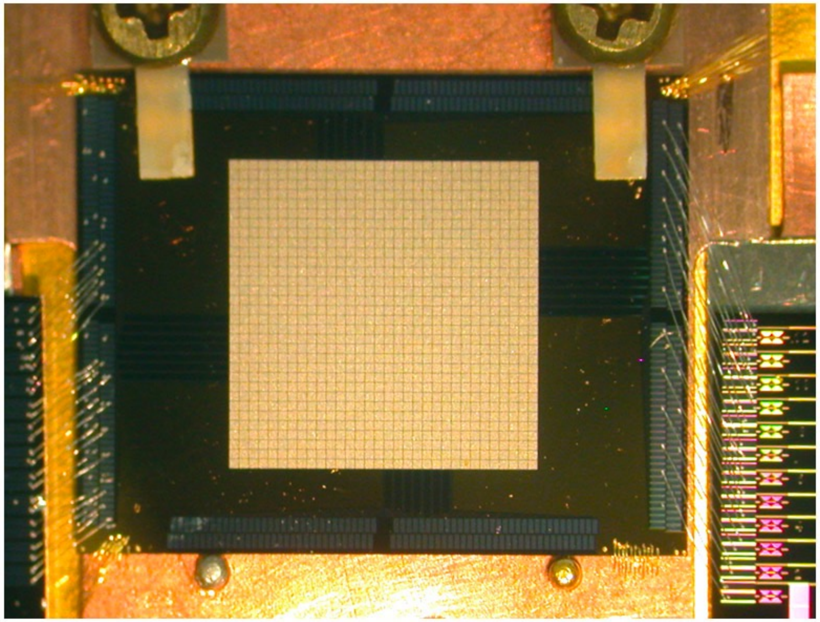
XMM-*Newton:* effective area

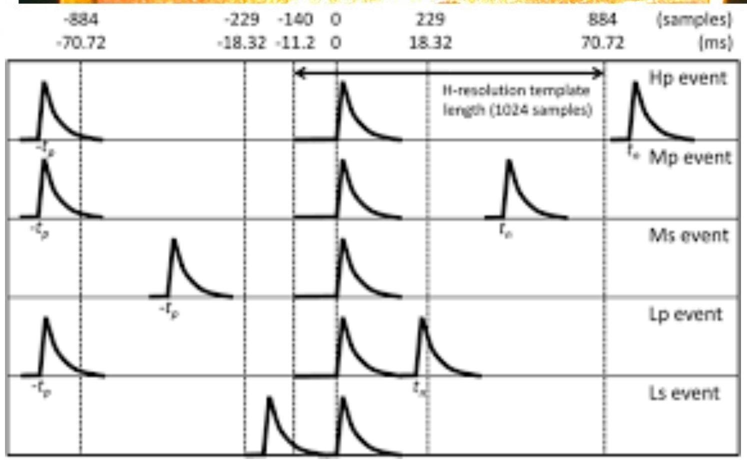


Reflection gratings for high-resolution spectrposcopy -> very small effective area -> “to be used only with bright sources!”

New tech! -> Transition Edge Arrays (microcalorimeters)





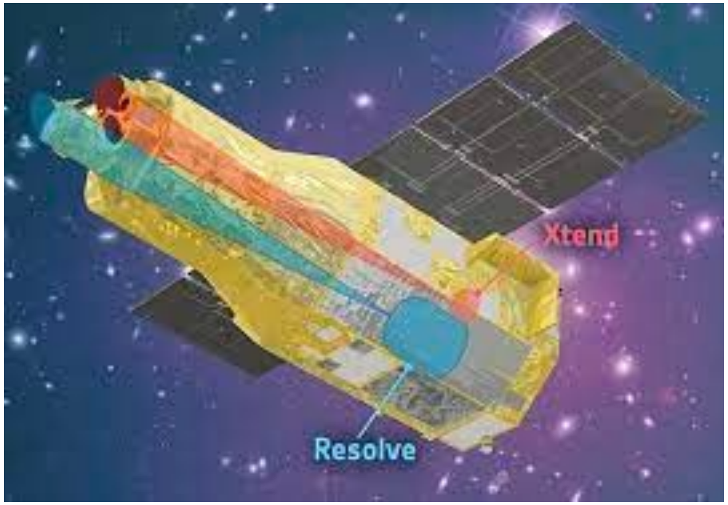


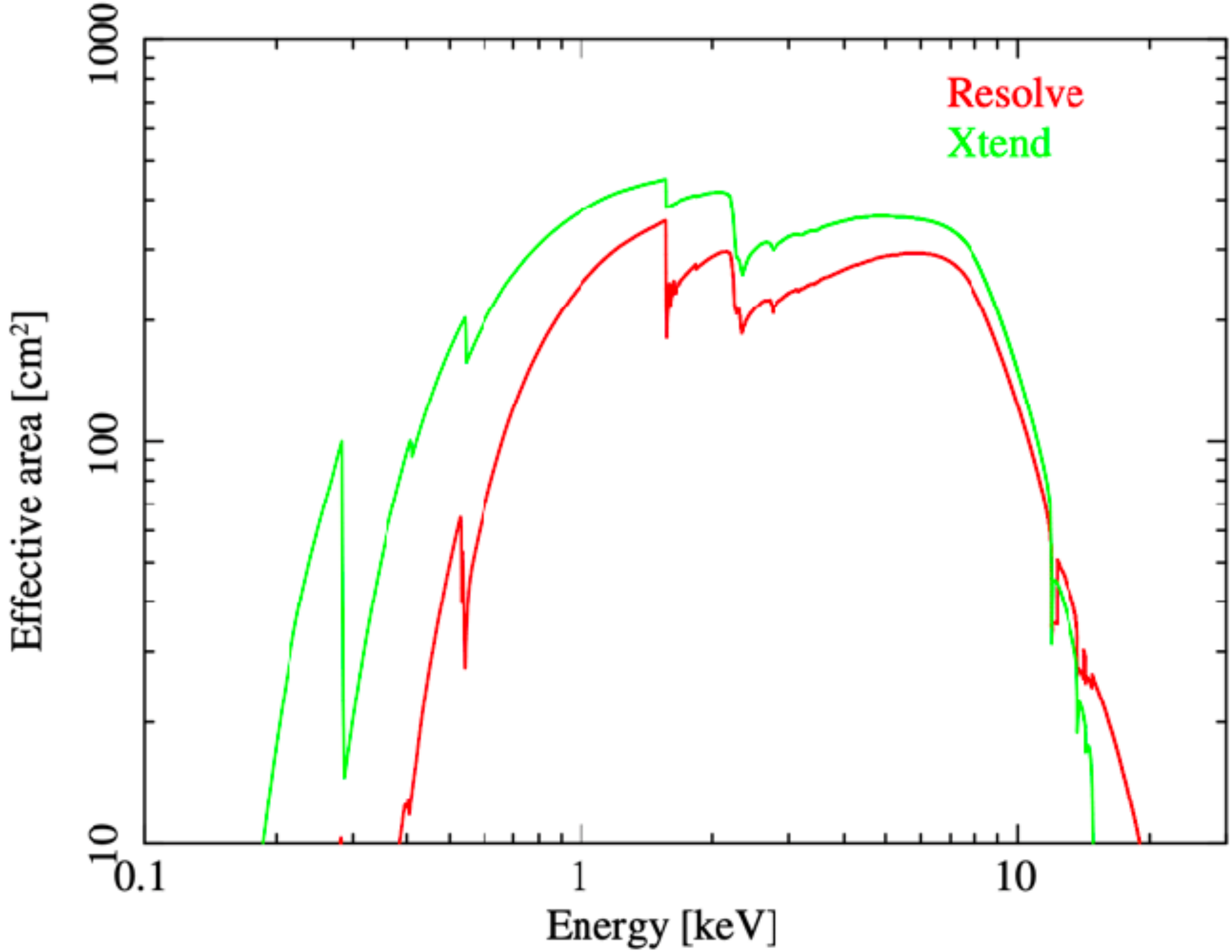
What we are going to talk about…

XMM-*Newton*

Chandra

From September the 7, 2023
Xrism (Jaxa-Nasa)

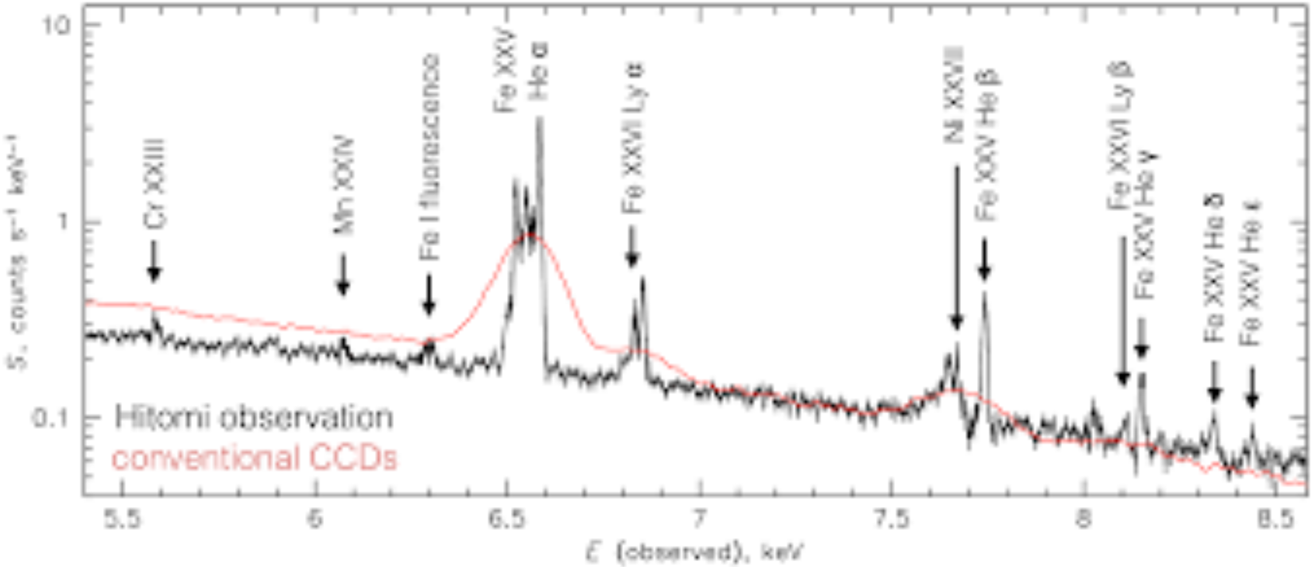


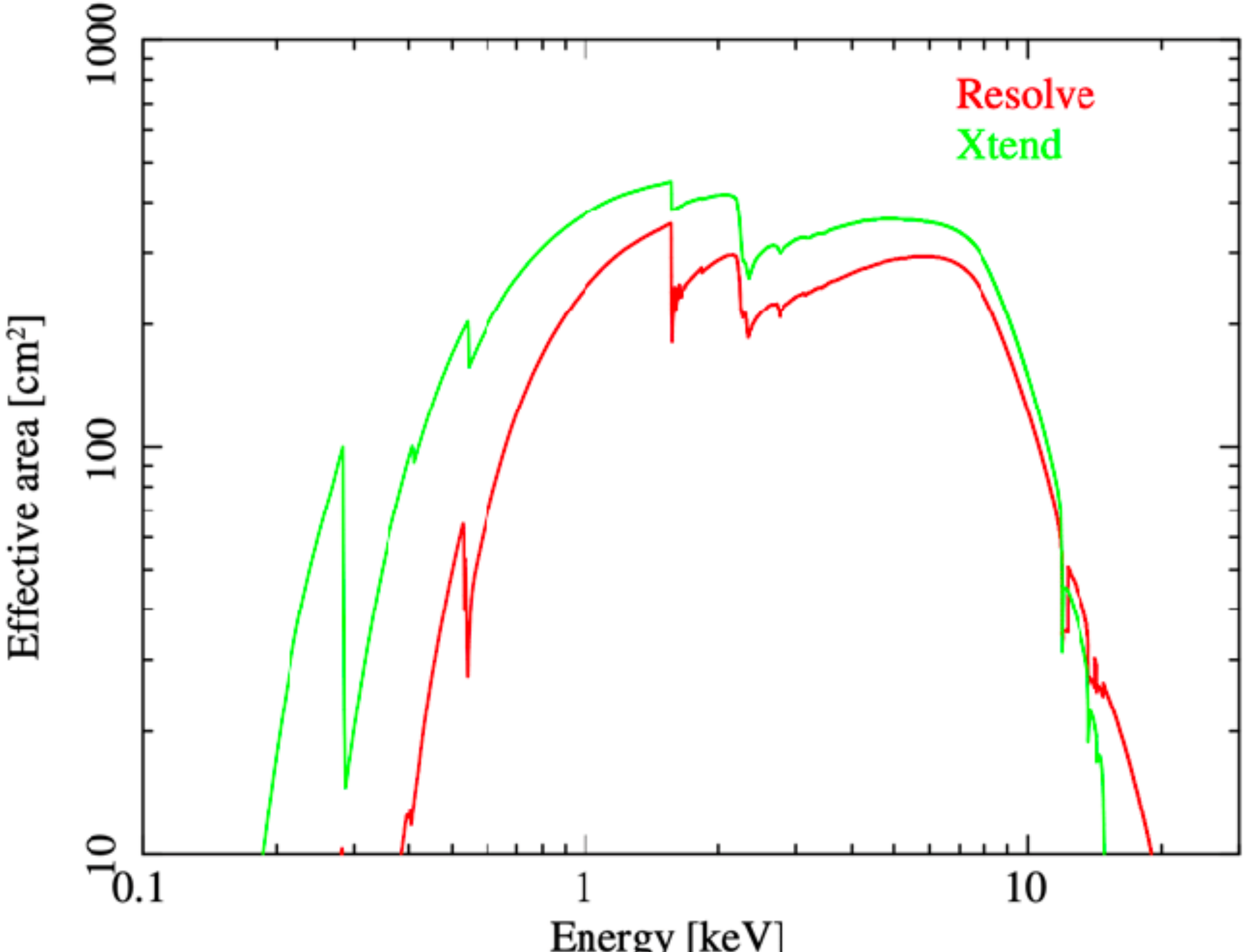


Resolve
Xtend
Effective area [cm²]
1000
100
10
0.1
1
10
Energy [keV]

ea

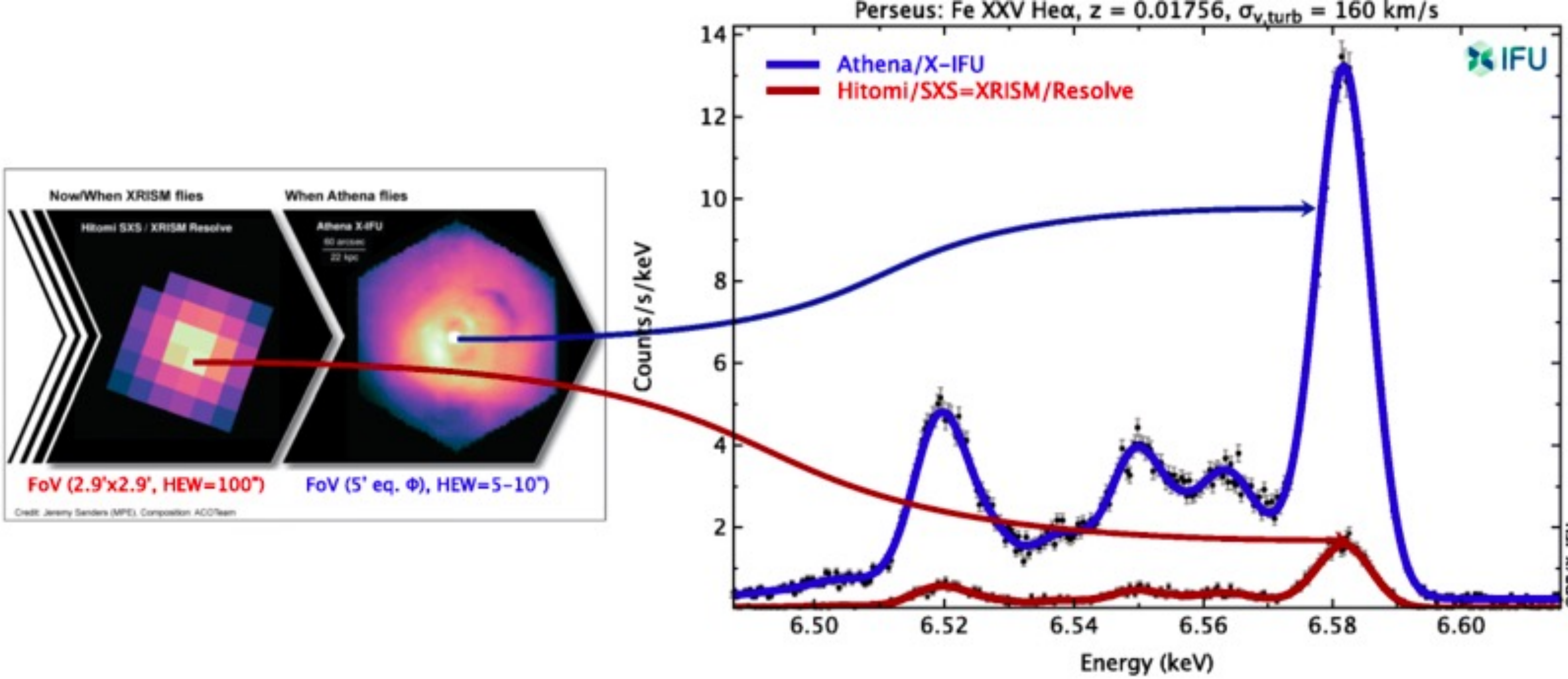
ΔE≈5 eV (FWHM) to be compared with ΔE≈200 eV (FWHM)for CCD-like detectors

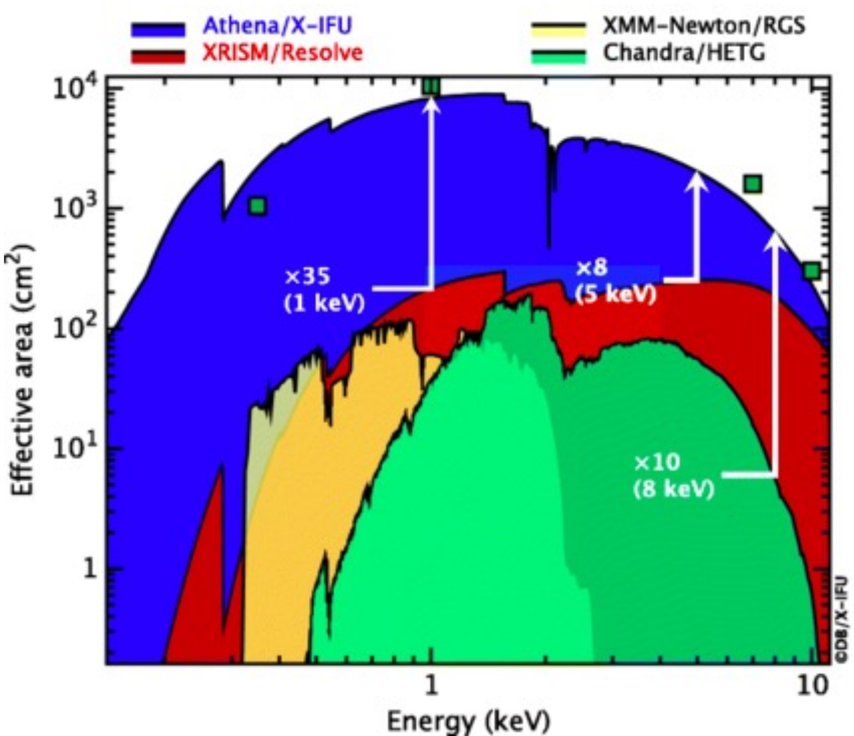


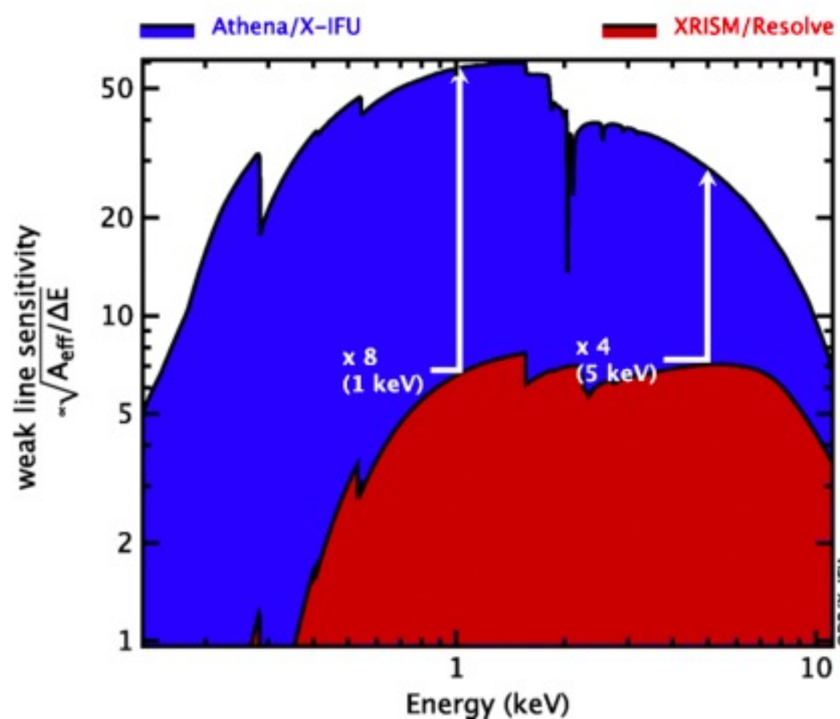


Resolve
Xtend
Effective area [cm²]
1000
100
10
0.1
1
10
Energy [keV]

ea

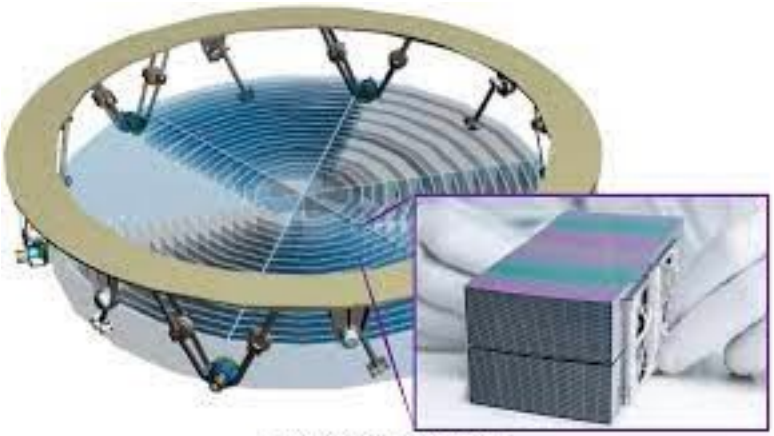

Perseus: Fe XXV Heα, z = 0.01756, σv,turb = 160 km/s
Athena/X-IFU
Hitomi/SXS=XRISM/Resolve
IFU
Now/When XRISM flies
When Athena flies
Hitomi SXS / XRISM Resolve
Athena X-IFU
FoV (2.9'x2.9', HEW=100")
FoV (5' eq. Φ), HEW=5-10")
Credit: Jeremy Sanders (MPE), Composition: ACOTeam
Counts/s/keV
Energy (keV)
©DB/X-IFU

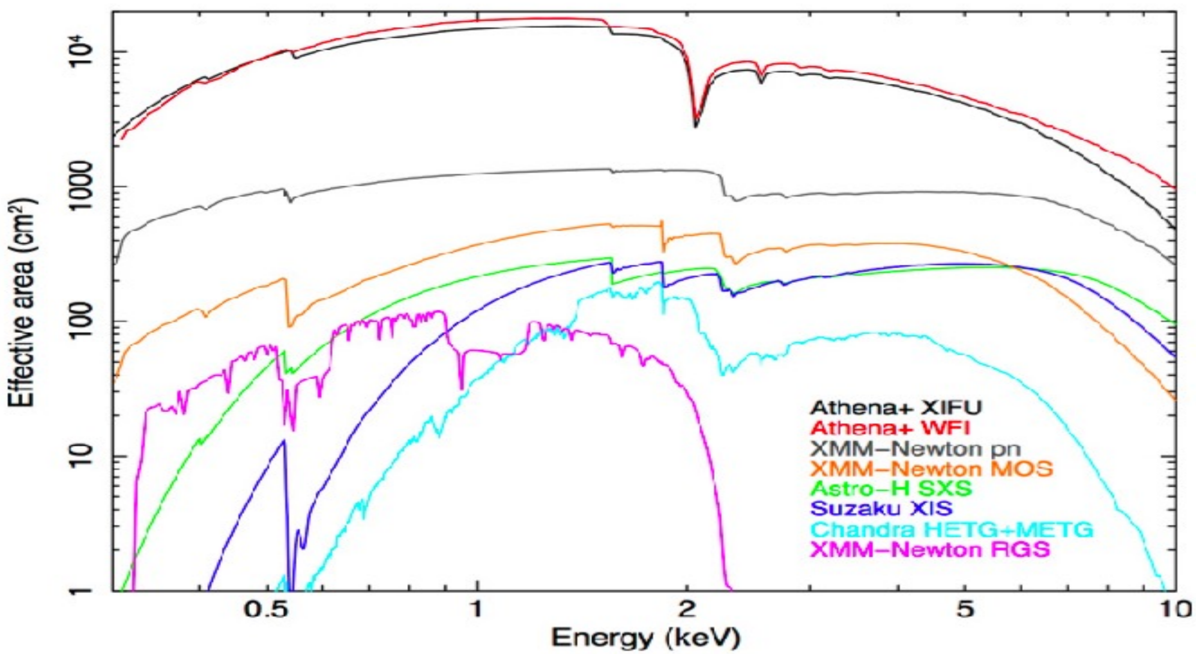

Athena/X-IFU
XRISM/Resolve
XMM-Newton/RGS
Chandra/HETG
×35
(1 keV)
×8
(5 keV)
×10
(8 keV)
Effective area (cm²)
Energy (keV)
©DB/X-IFU


Athena/X-IFU
XRISM/Resolve
x 8
(1 keV)
x 4
(5 keV)
weak line sensitivity
∝√Aeff/ΔE
Energy (keV)
©DB/X-IFU

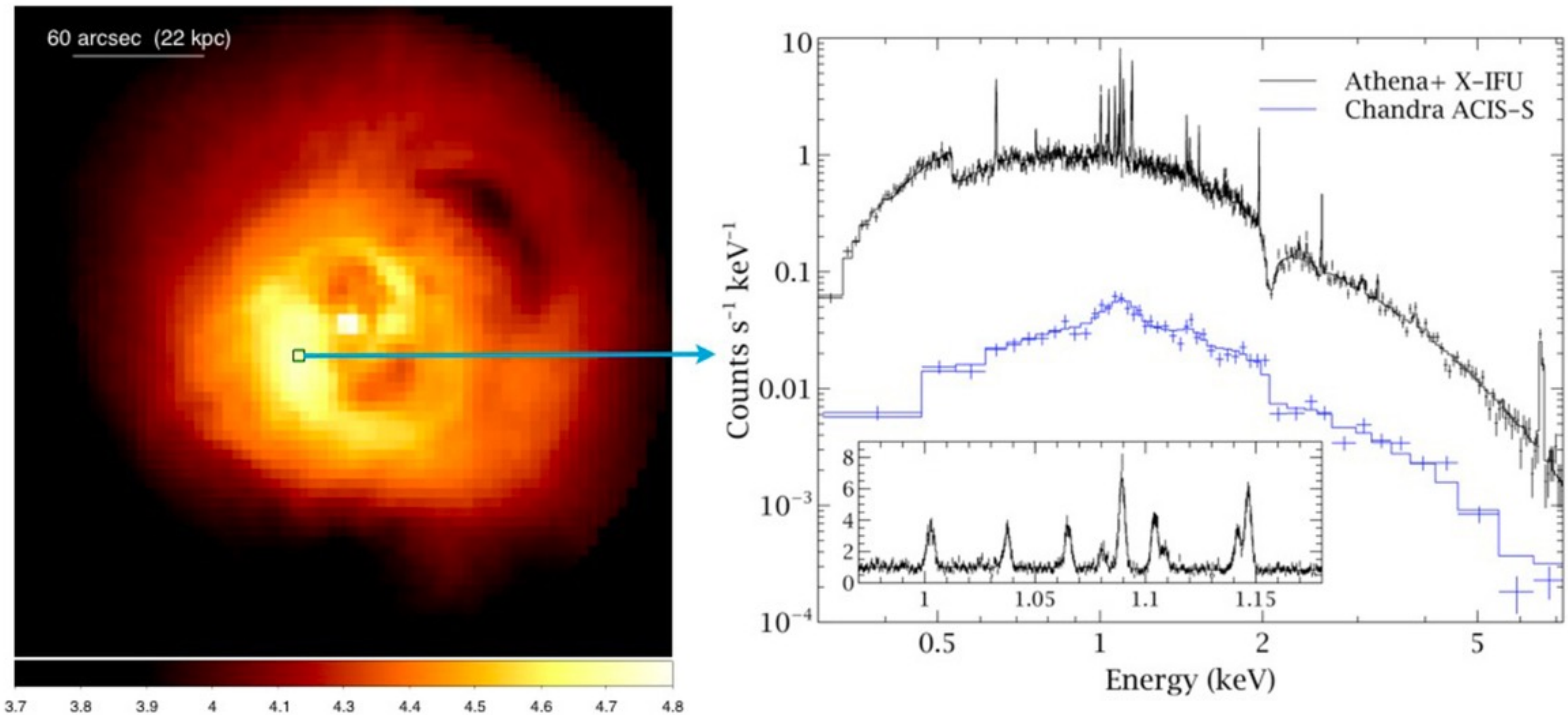
a

Athena X-IFU (2037…)



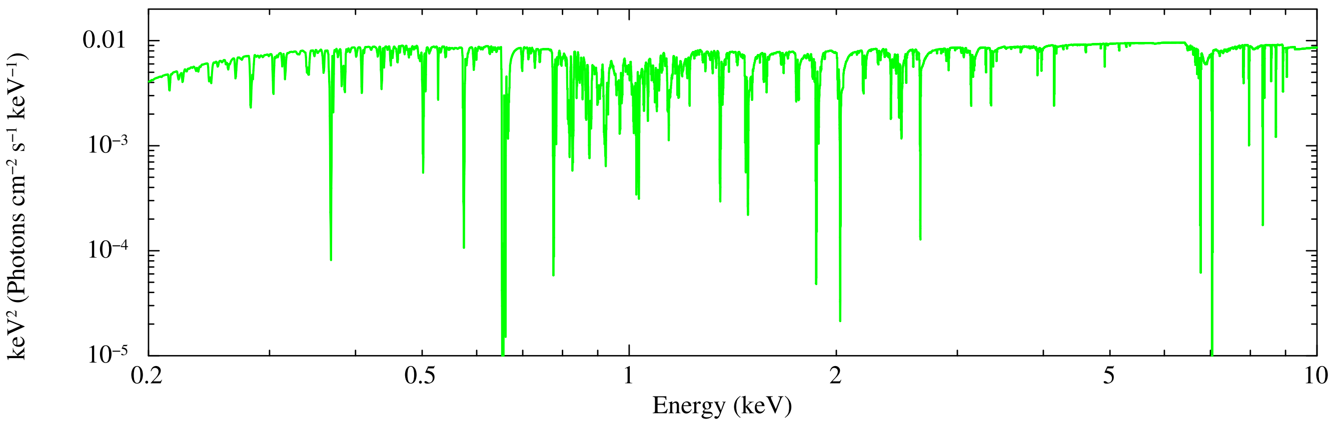


Athena XIFU ΔE≈4 (3!) eV (FWHM) to be compared with ΔE≈5 eV (FWHM) for Resolve

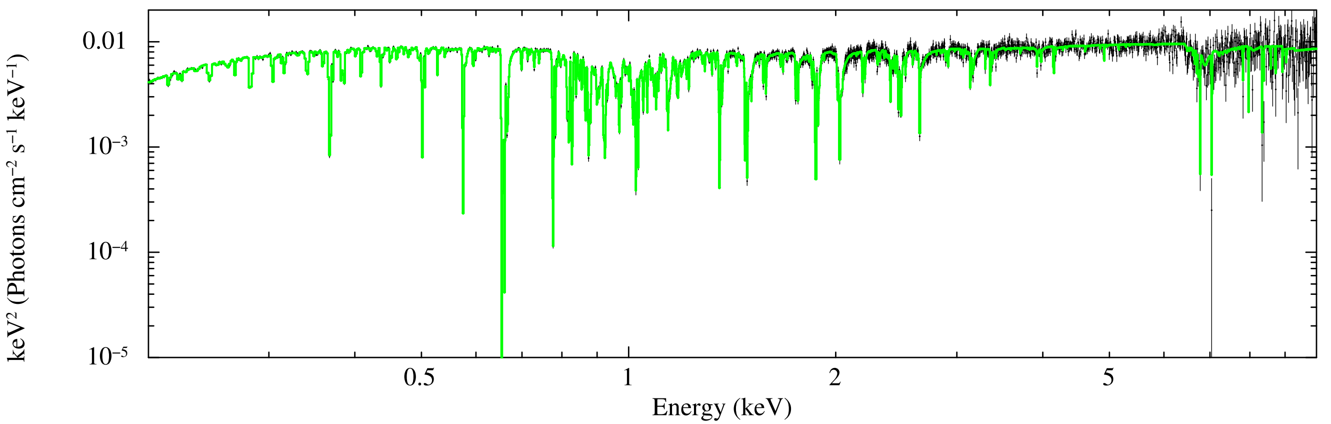


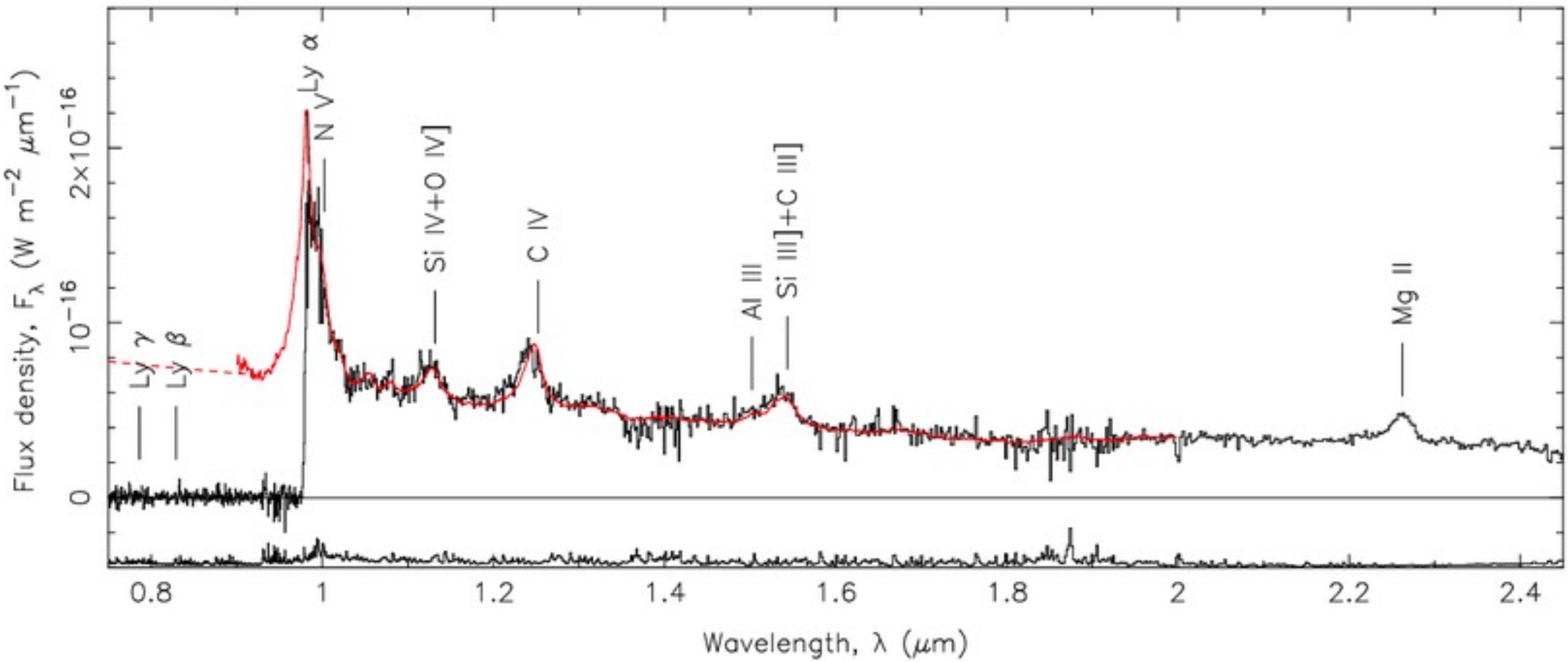
In the future, when microcalorimeter will be functioning...
Athena X-IFU (energy resolution 2.5eV, 10ks) simulation.

Theoretical Model ($F_{2-10\,keV}=2\times10^{-11}$ erg s^{-1} cm^{-2})



Simulated X−IFU spectrum ($T_{exp.}$=10ks)





Flux density, F_λ (W m^{-2} μm^{-1})
2×10^{-16}
10^{-16}
0
Ly α
N V
Si IV+O IV]
C IV
Al III
Si III]+C III]
Mg II
Ly γ
Ly β
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
Wavelength, λ (μm)