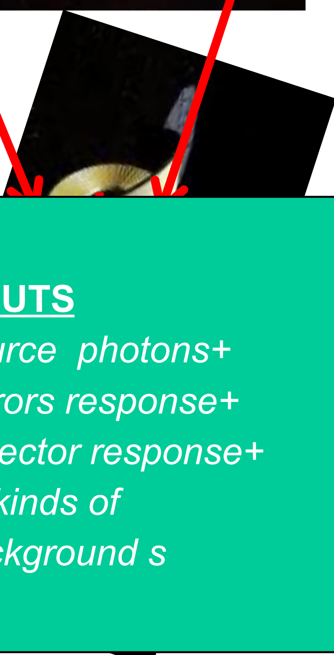
The foundamental parameters of X-ray telescopes

INAF OAS BOLOGNA

What happens



.. a X-ray source…

…mirrors, concentrators or collimators

board

ellites..

ctors

icrocal., etc.)

INPUTS

Source photons+

Mirrors response+

Detector response+

All kinds of

Background s

INPUTS

Source photons+

~~Mirrors response+~~

~~Detector response+~~

~~All kinds of~~

~~Background s~~

OUTPUTS

Images

Light Curves

Spectra

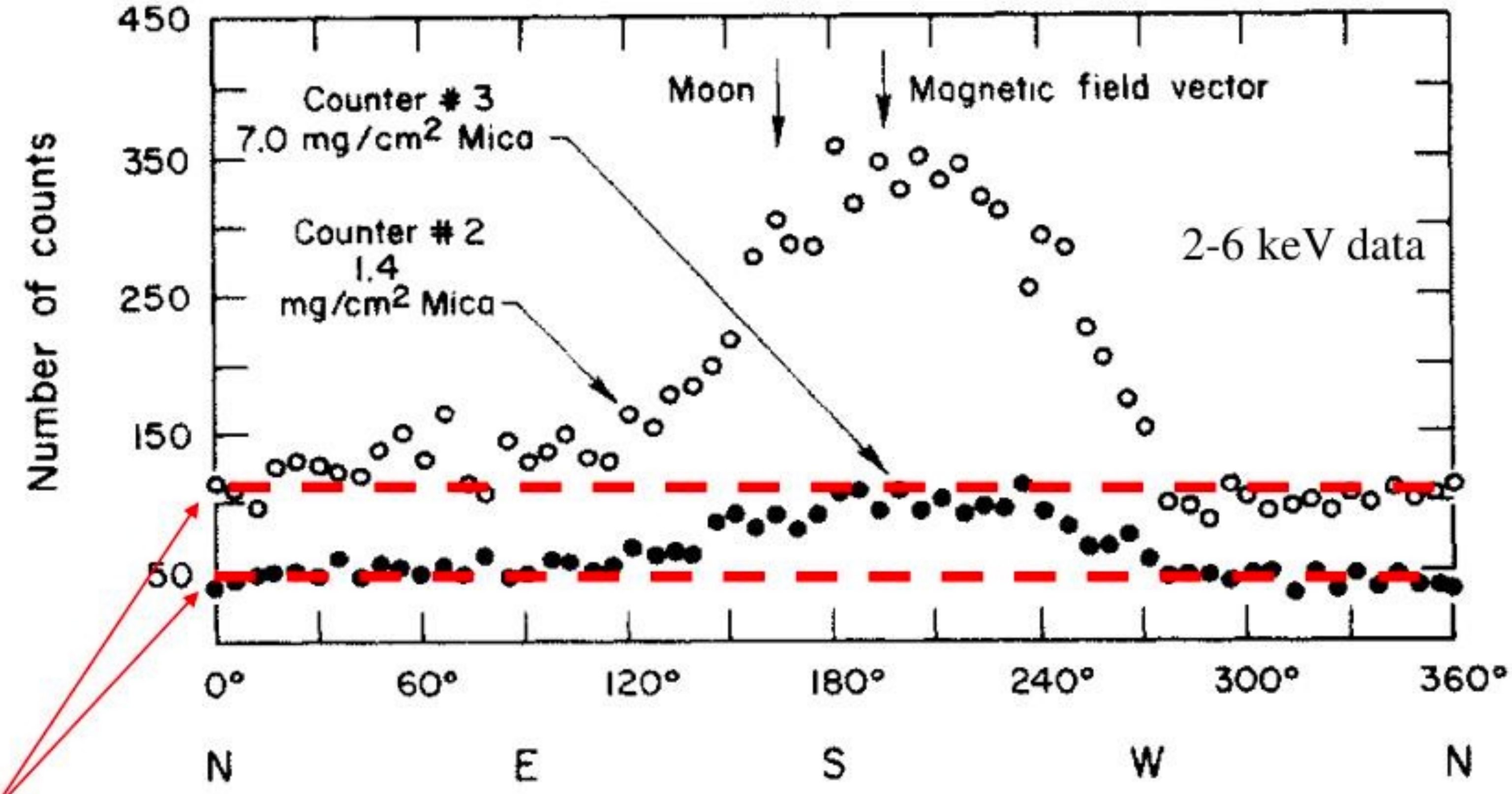
Take into account telescope response… and remaining bgds

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)

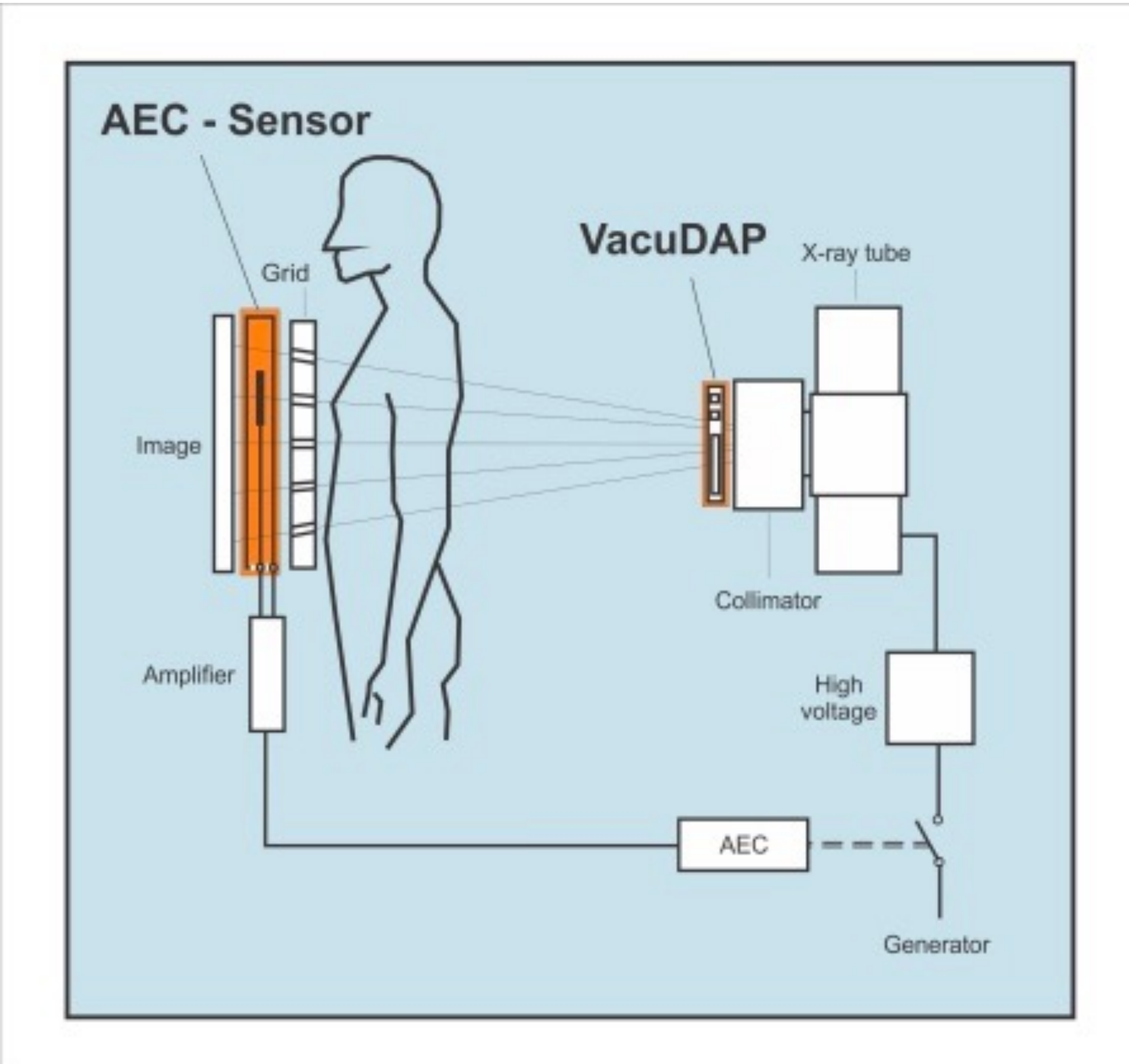
The discovery of the cosmic X-ray background (XRB)

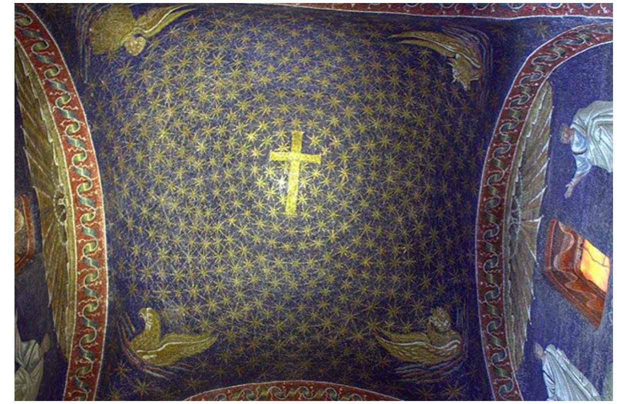


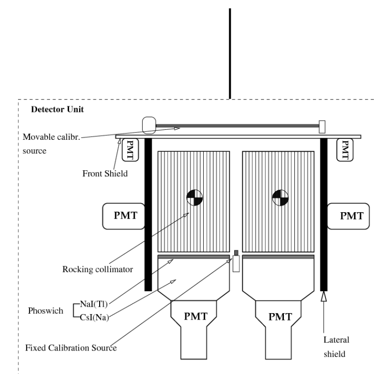
Counts > 0 from all directions ➔ diffuse background radiation

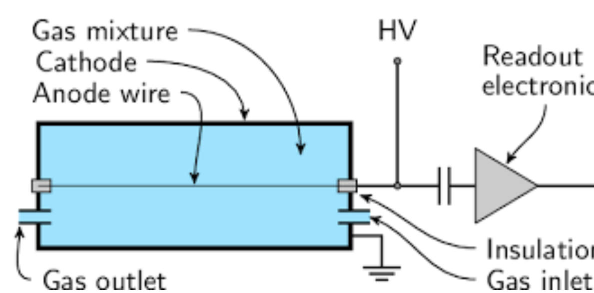
Giacconi et al. (1962). Nobel prize in 2002

The functioning of a X-ray telescope

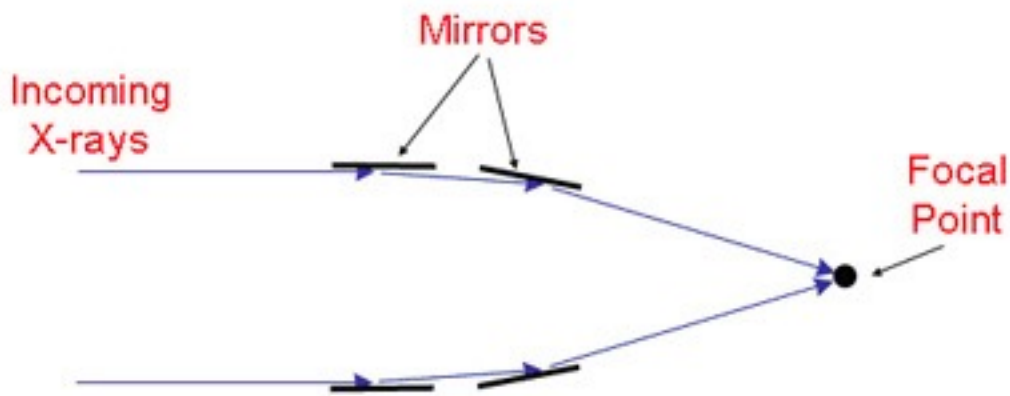




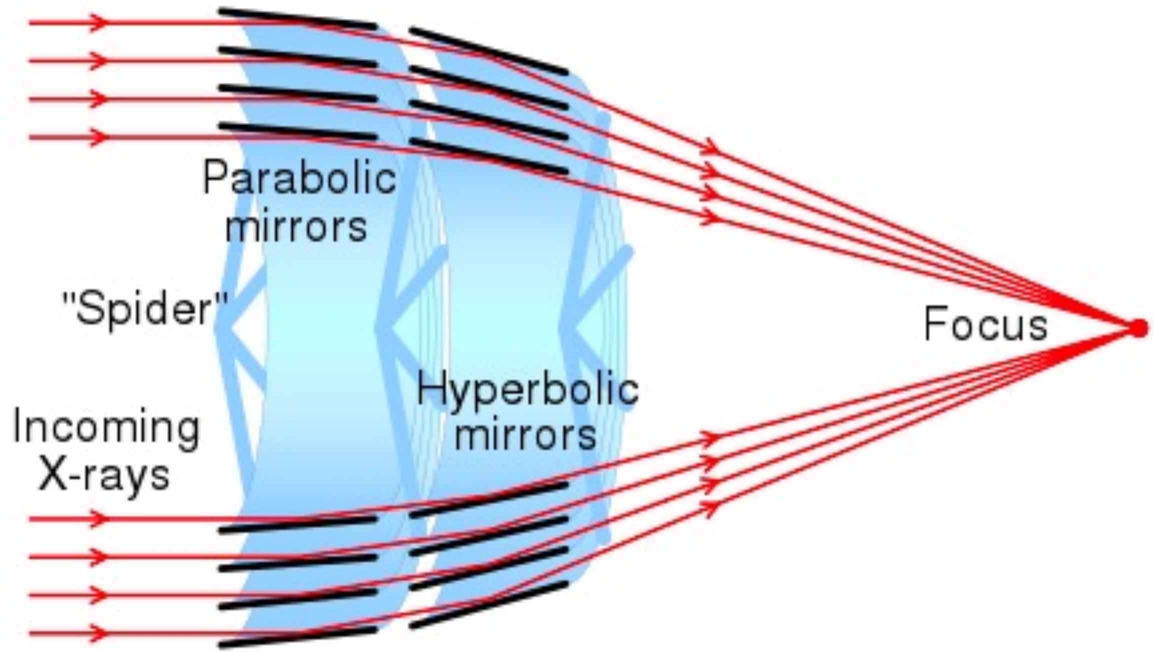




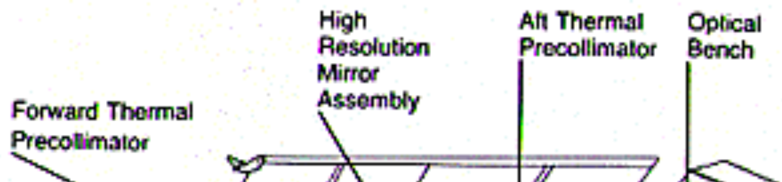
Grazing incidence

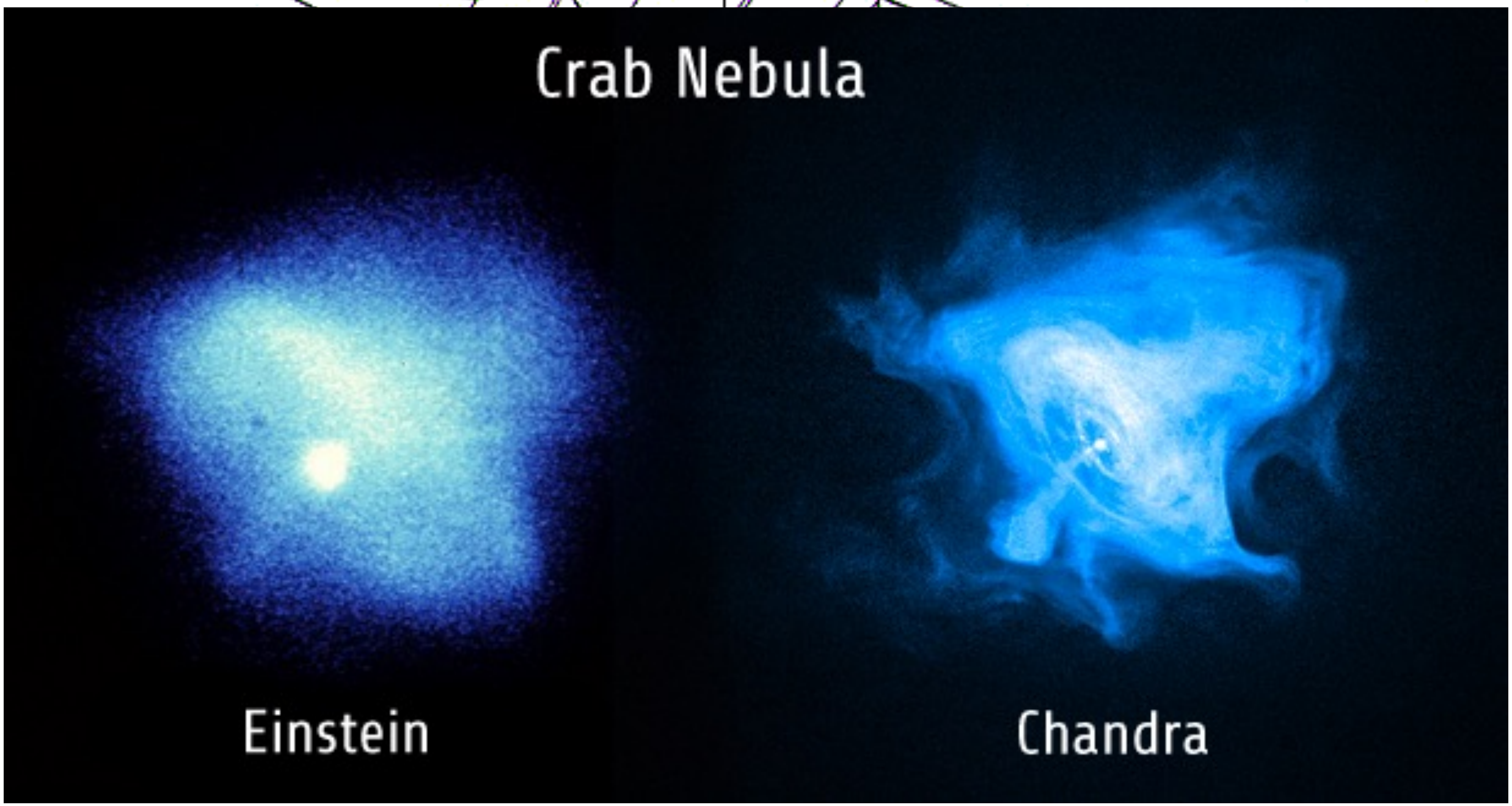


$$\vartheta_{crit} \propto \frac{\sqrt{\rho}}{E}$$



Einstein (HEAO-2): 1978-1981



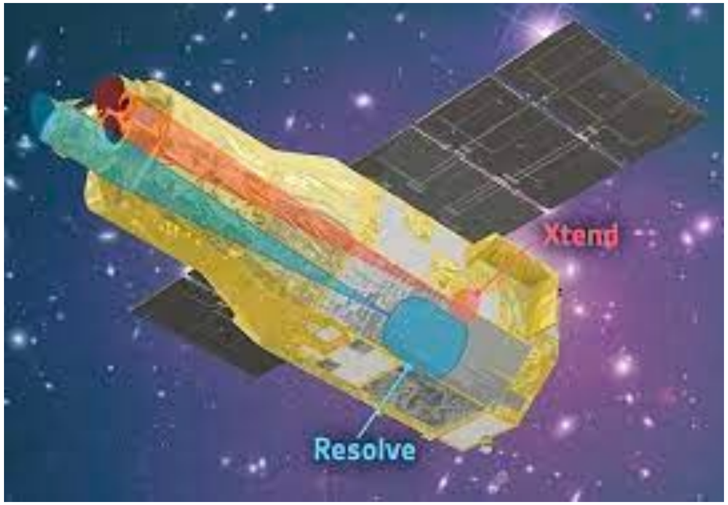


What we are going to talk about…

Chandra

XMM-*Newton*

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)

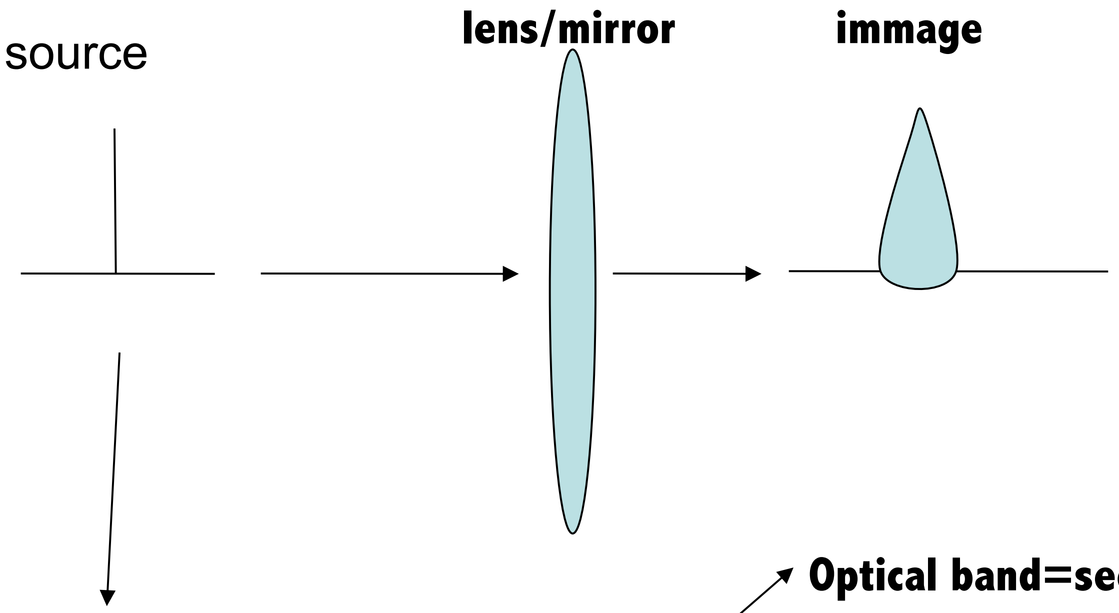
the ESA (XMM-Newton) way

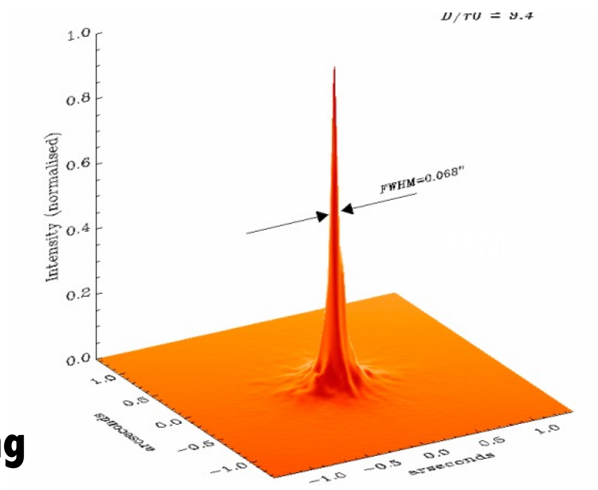
Reducing the B.

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

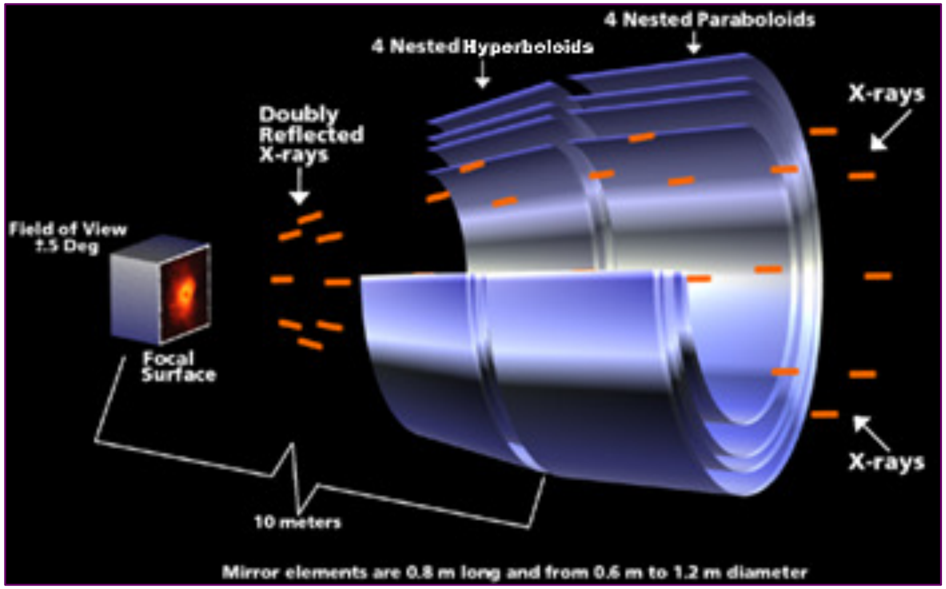
X-rays= mirrors properties
+ mirror array assembly

<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.....)

Chandra = "extreme" angular resolution



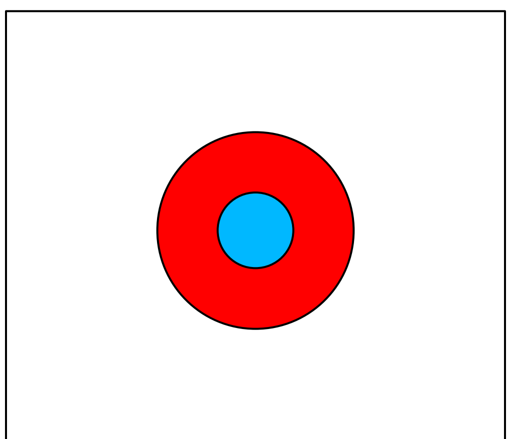
Only four, robust shells

High-quality of shell production

to allow <arcsec on-axis angular

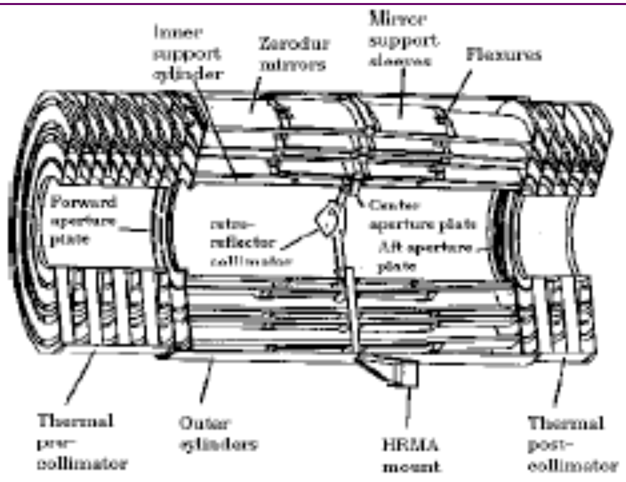
resolution (the best so far in X-rays)

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



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

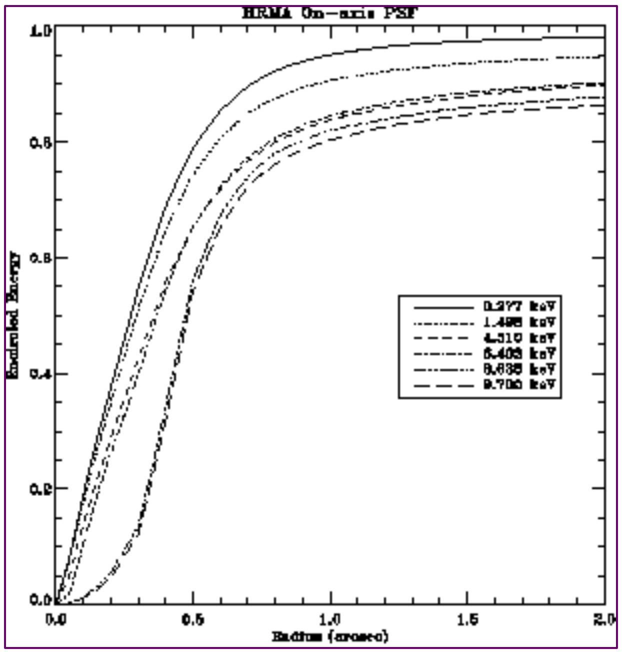
Mirror lengths: 84 cm

HRMA mass: 1500 kg

Focal length: 10 m

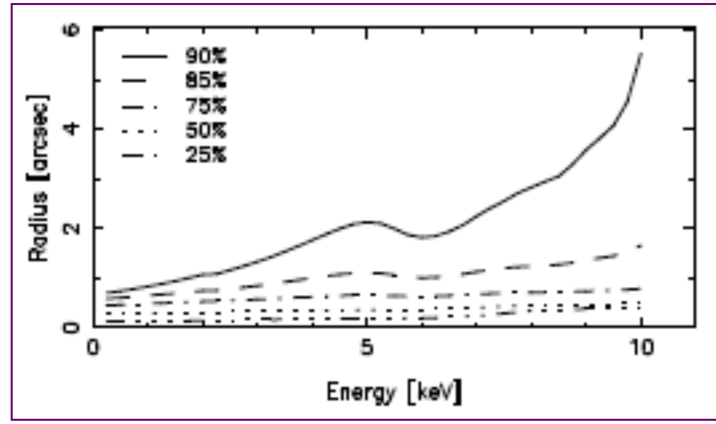
PSF FWHM: 0.5”

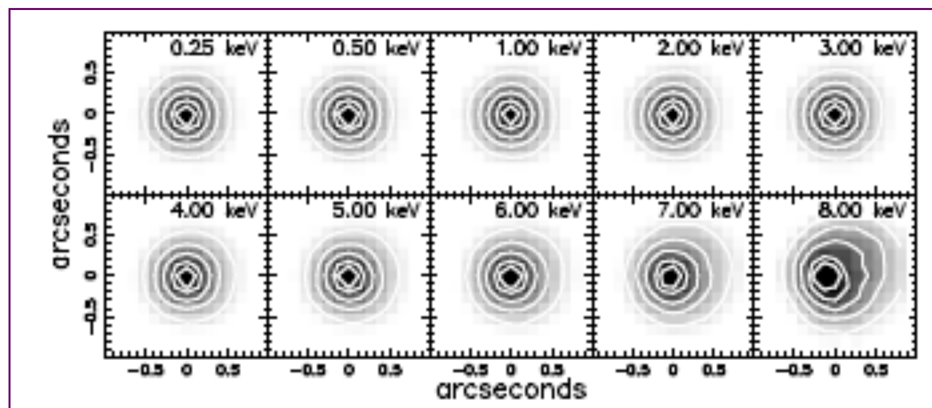
High Resolution Mirror Assembly (HRMA): On-axis PSF



Encircled energy vs. radius
at different energies

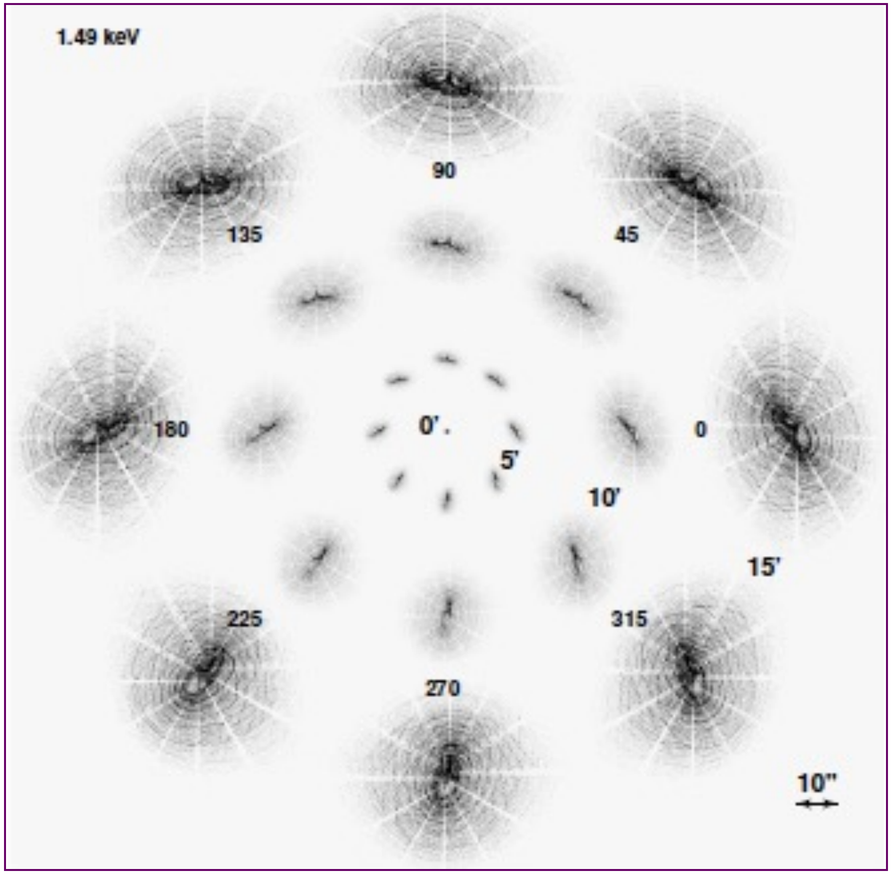
Radius encompassing NN% of the counts
as a function of the energy

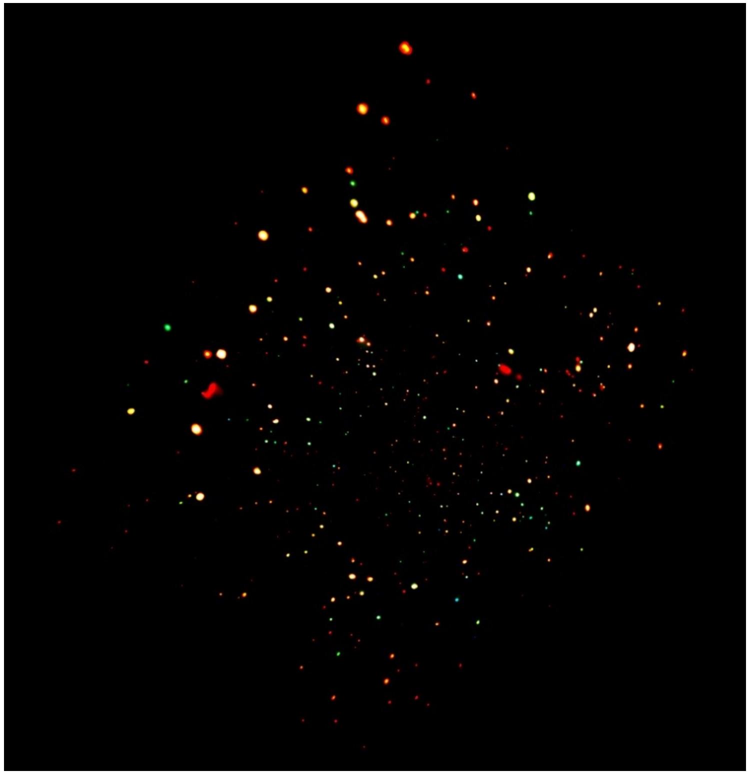




On-axis PSF size and shape

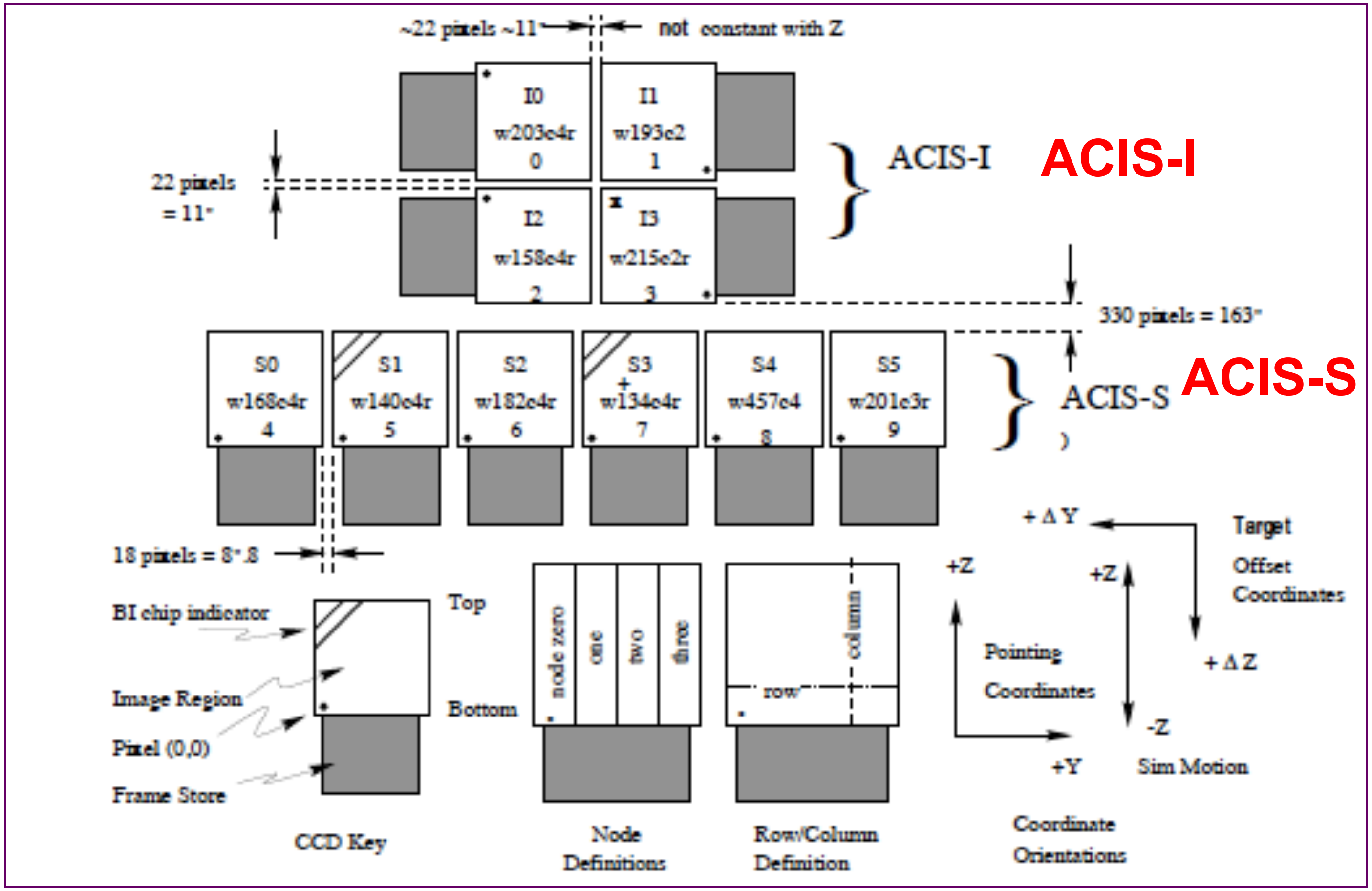
High Resolution Mirror Assembly (HRMA): Off-axis PSF





CDF-N 2Ms exposure

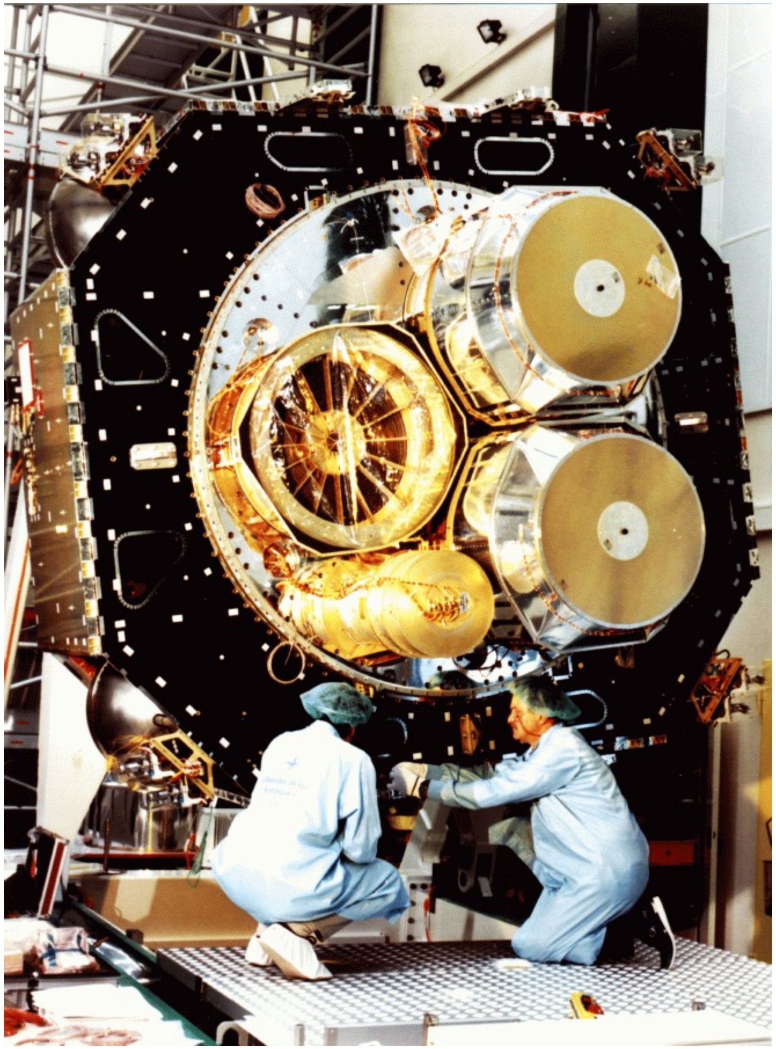
Chandra focal-plane detectors: CCDs



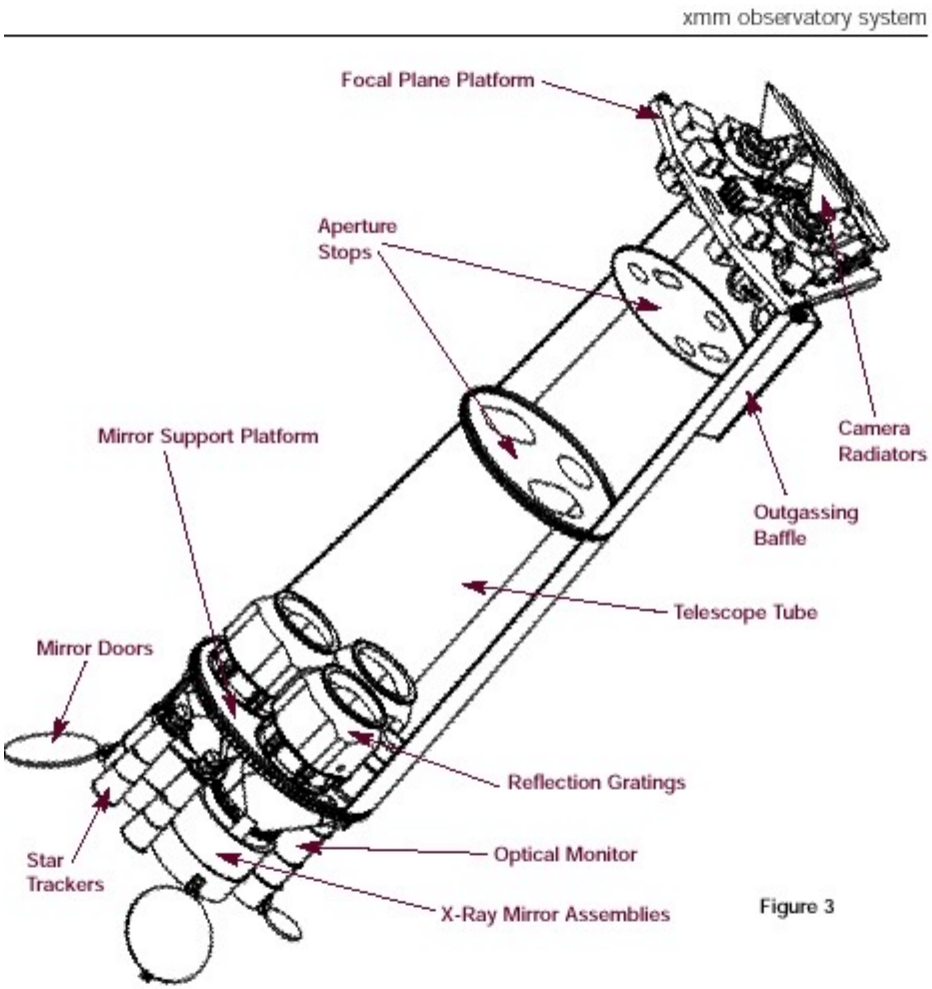
XMM-*Newton* = large effective area

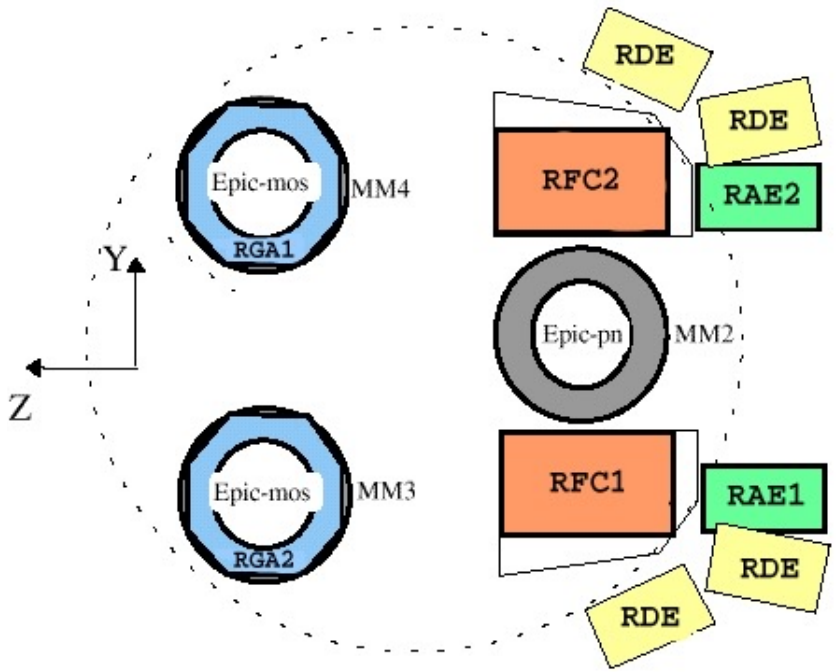
3 modules, 58 shells

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

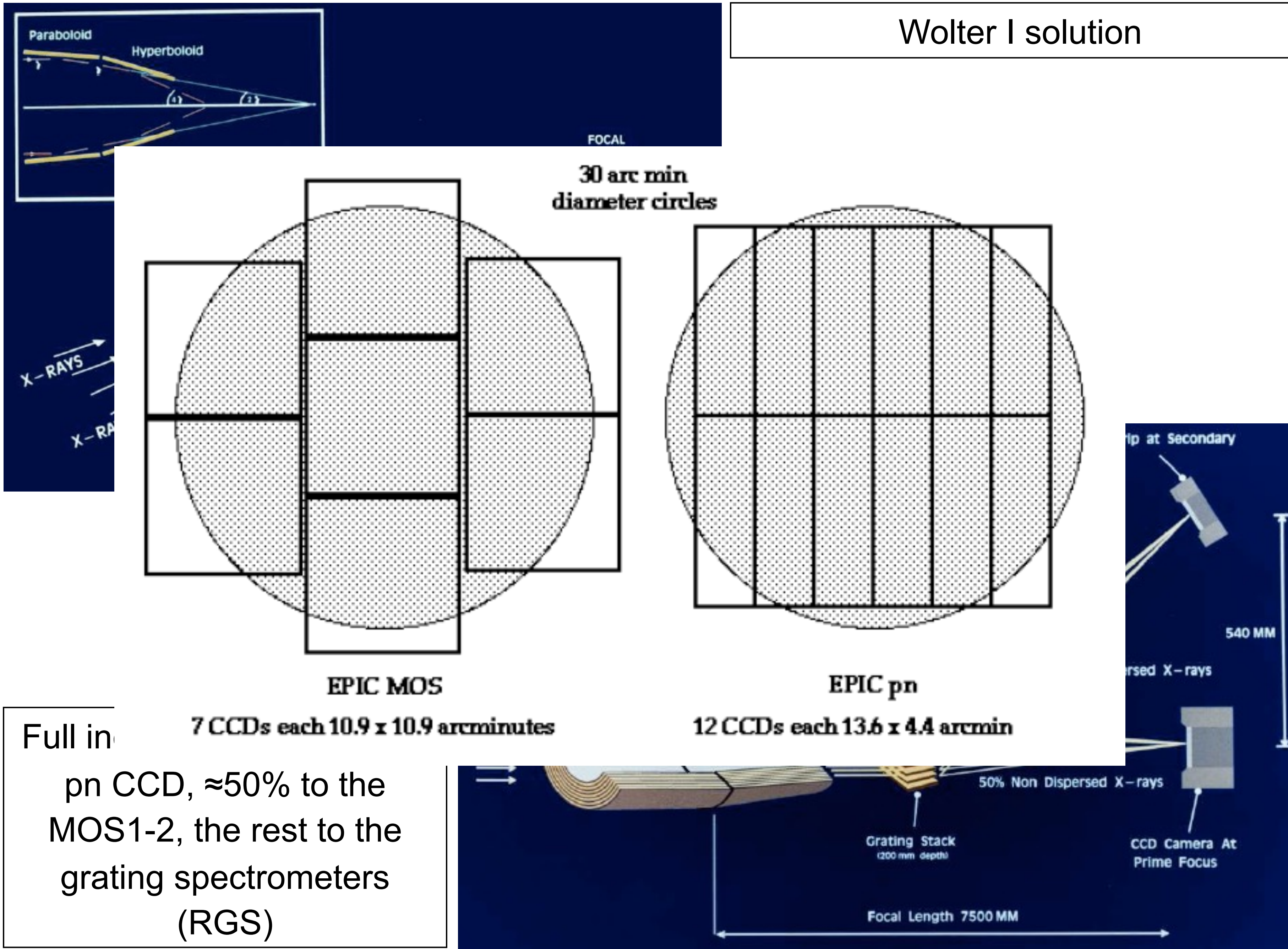


XMM-Newton: all instruments at work simultaneously



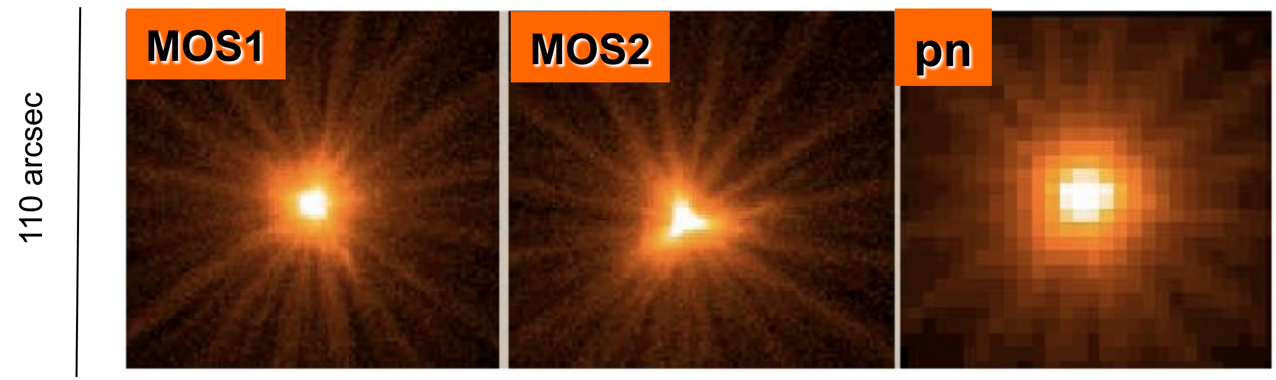


Wolter I solution



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

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

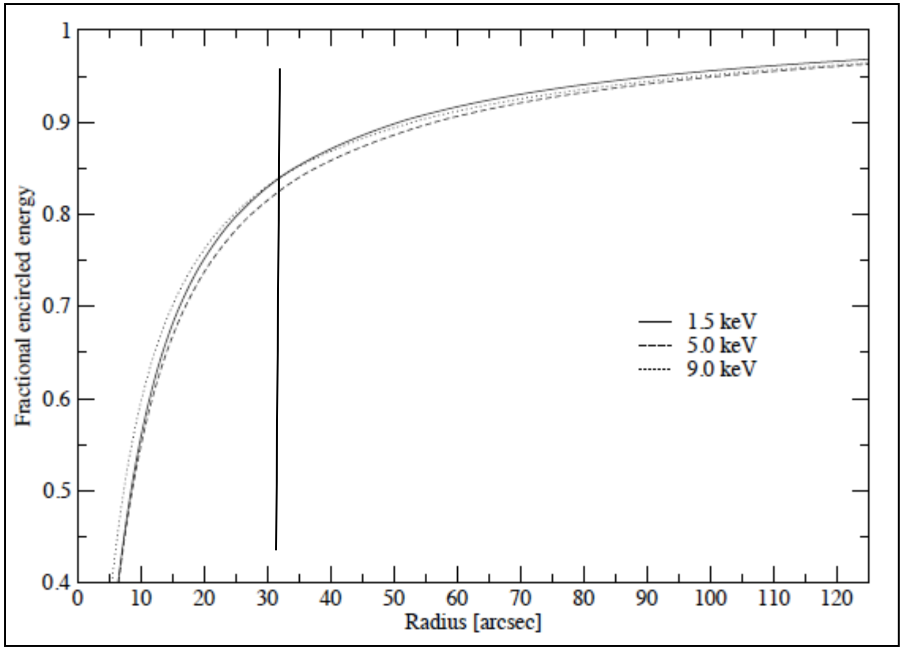


spider-like pattern due to the support of the Wolter I mirrors

Mirror module	2	3	4
Instr. chain[a]	pn	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

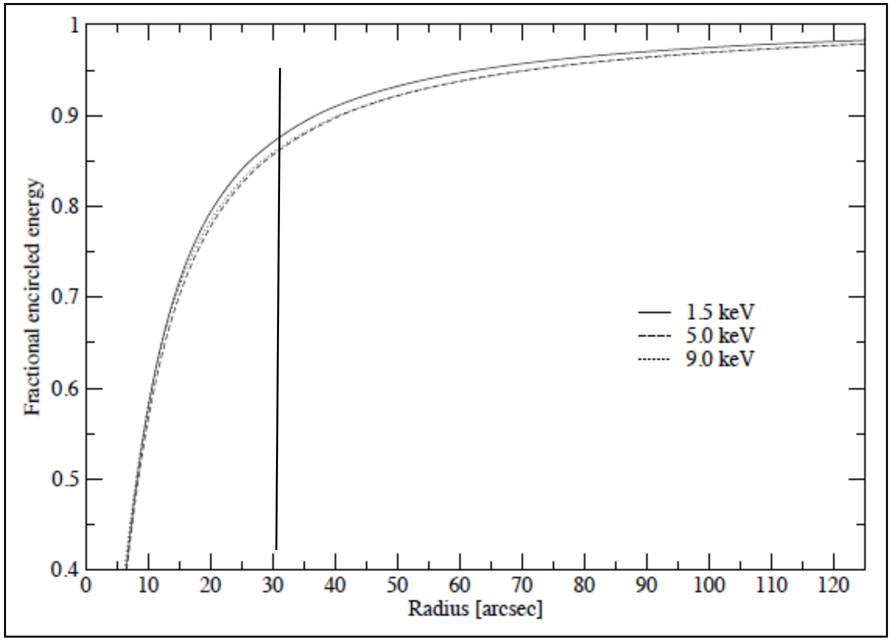
PSF FWHM higher than in *Chandra* but much larger effective area
Background (and confusion limit) can be an issue

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

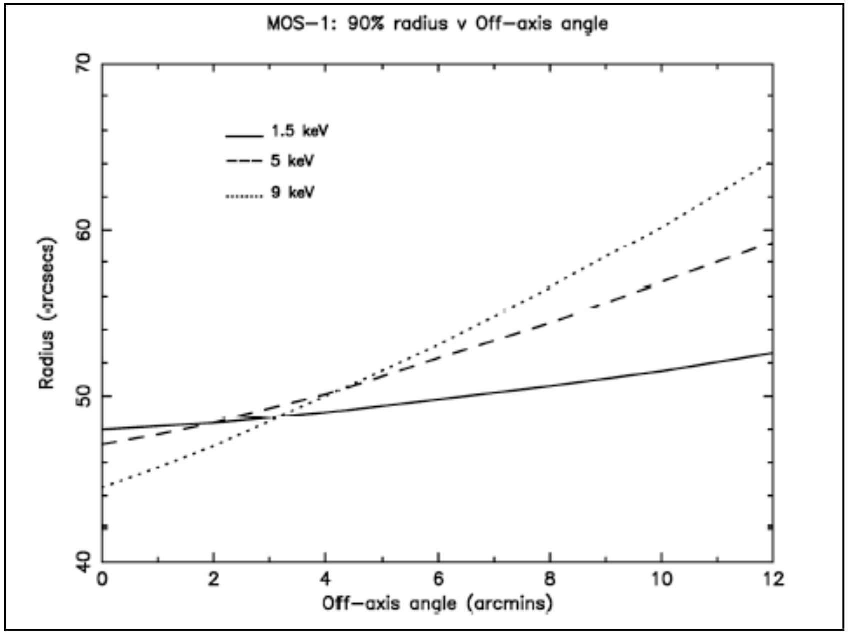


Encircled energy vs. radius
at different energies for the MOS1-2

Encircled energy vs. radius
at different energies for the pn

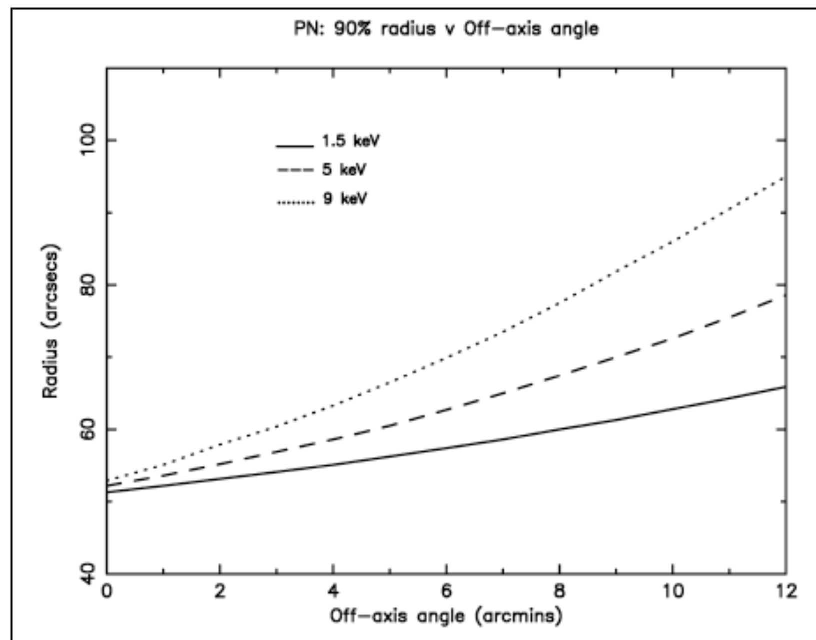


XMM-*Newton:* the EPIC off-axis PSF



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



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

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

Detector

Mirror

Effective area

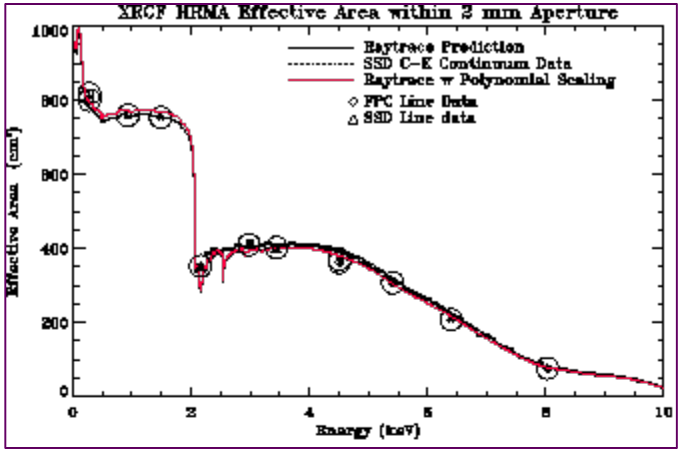
Geometric Area

Reflectivity

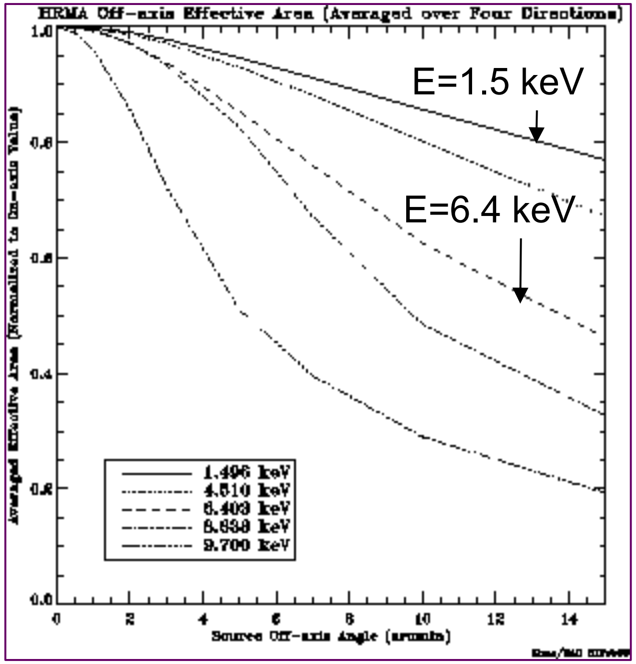
Vignetting

Quantum Efficiency

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



Effective area vs. Energy

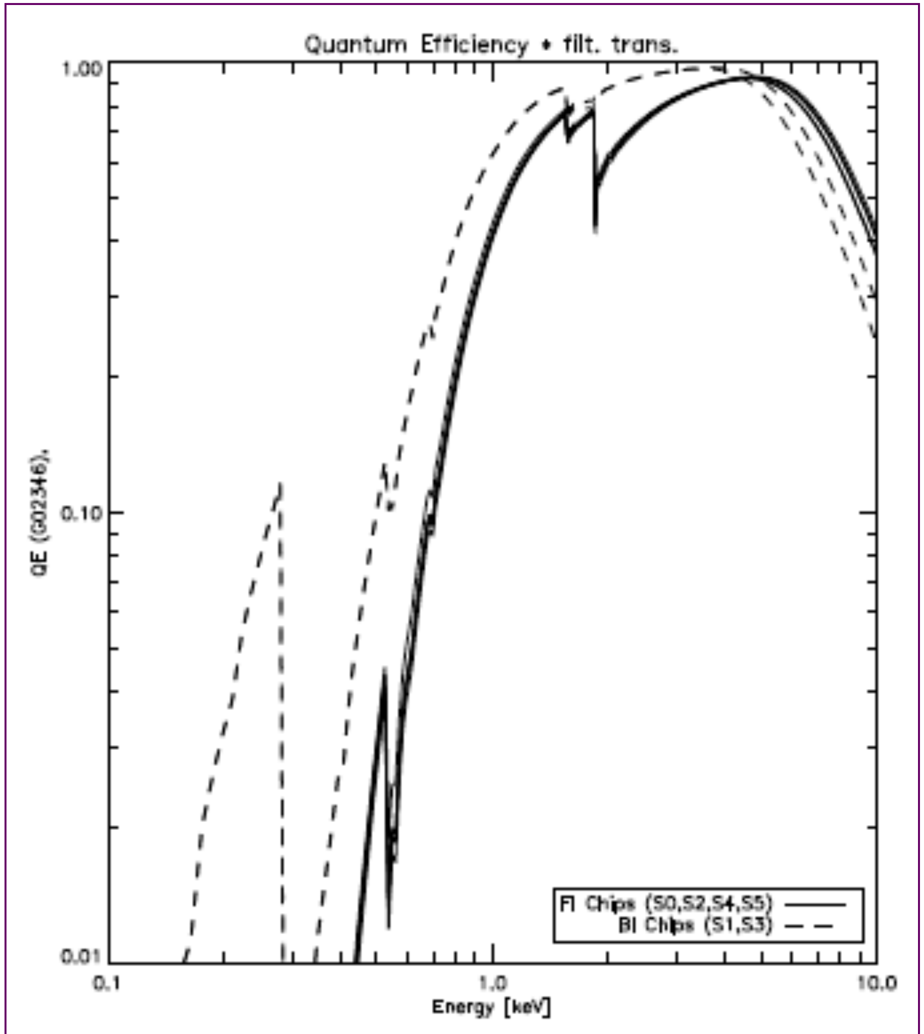


Effect of vignetting

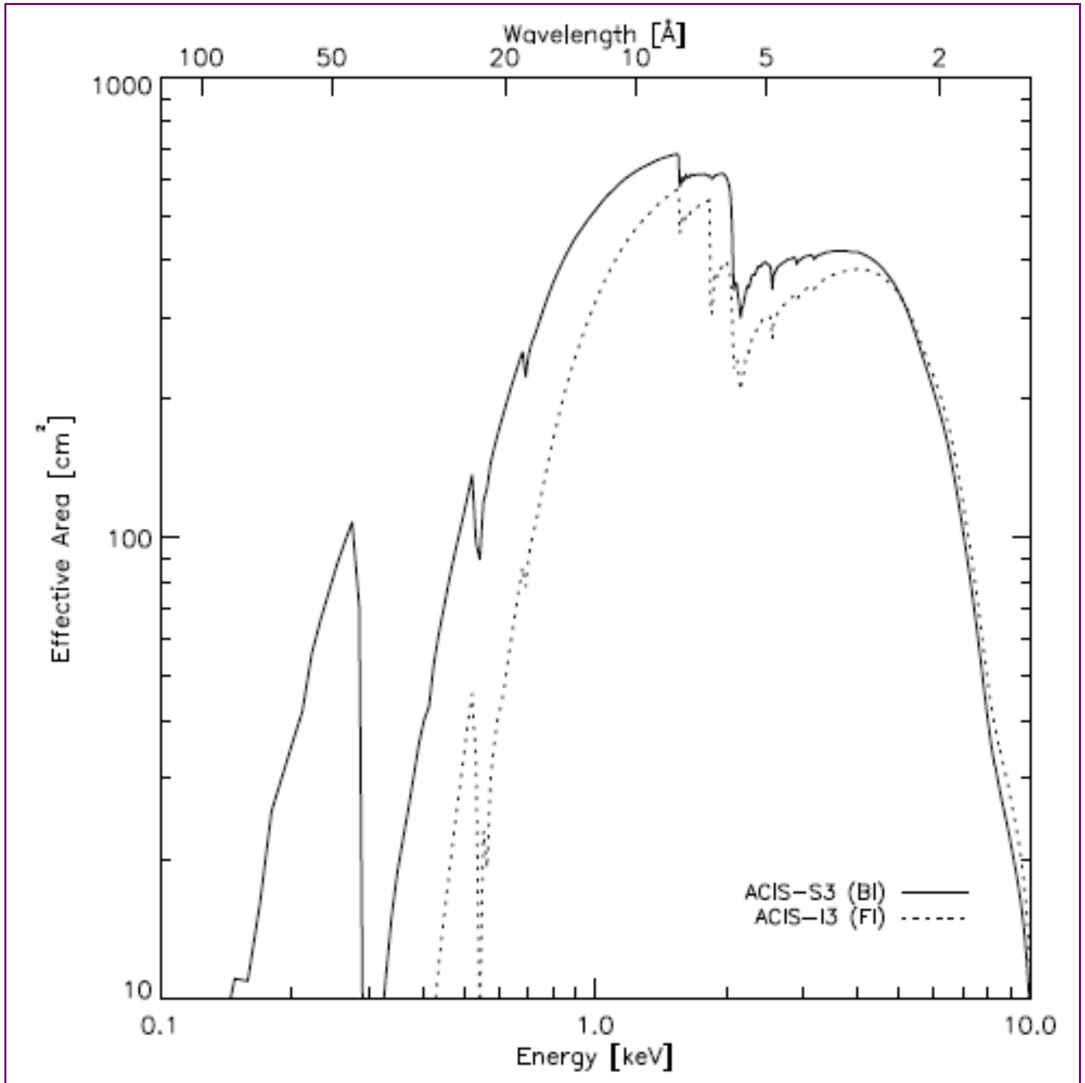
Effective area vs. off-axis angle at different energies

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

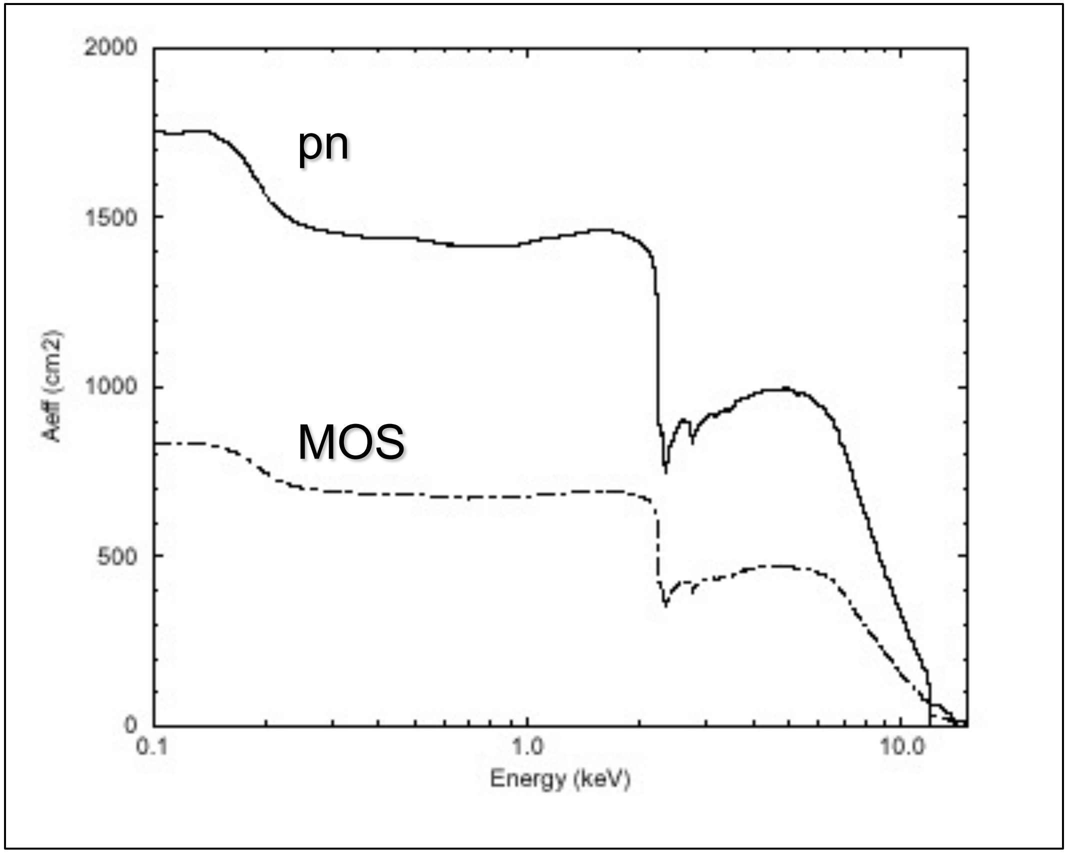
Chandra: quantum efficiency



Chandra: effective area

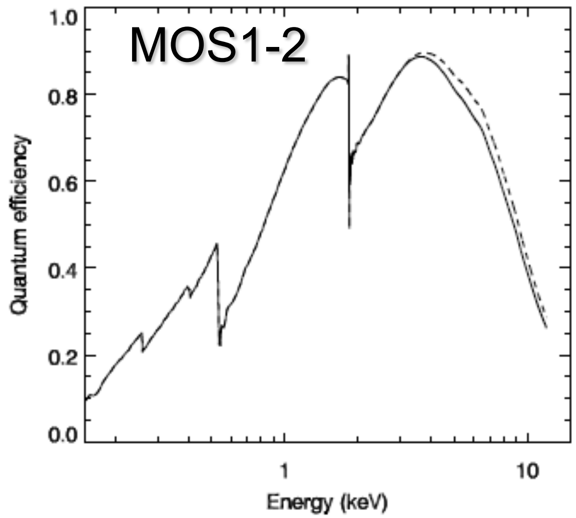


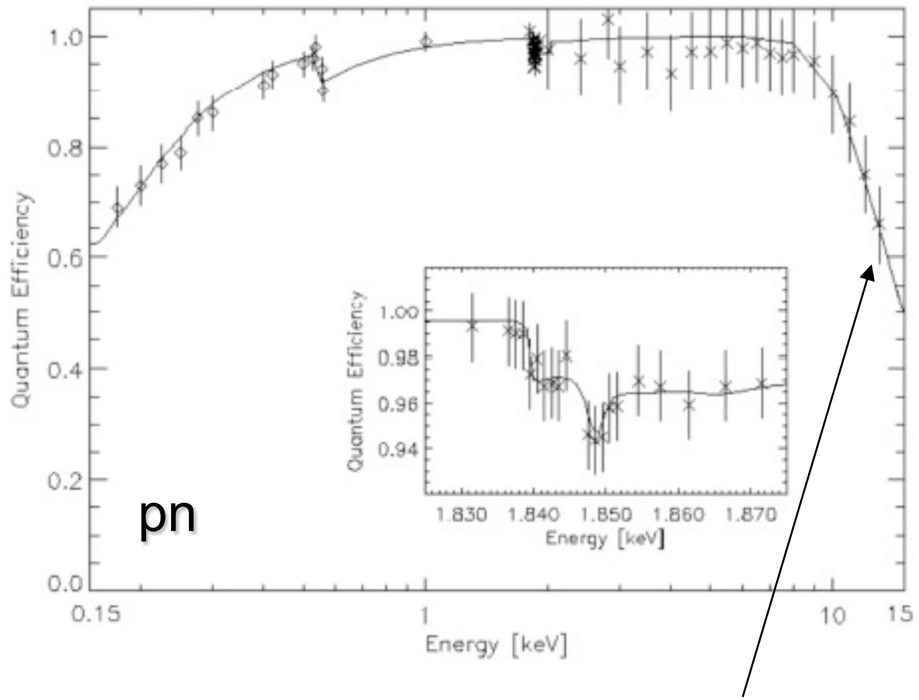
XMM-*Newton:* mirror effective (geometric) area



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

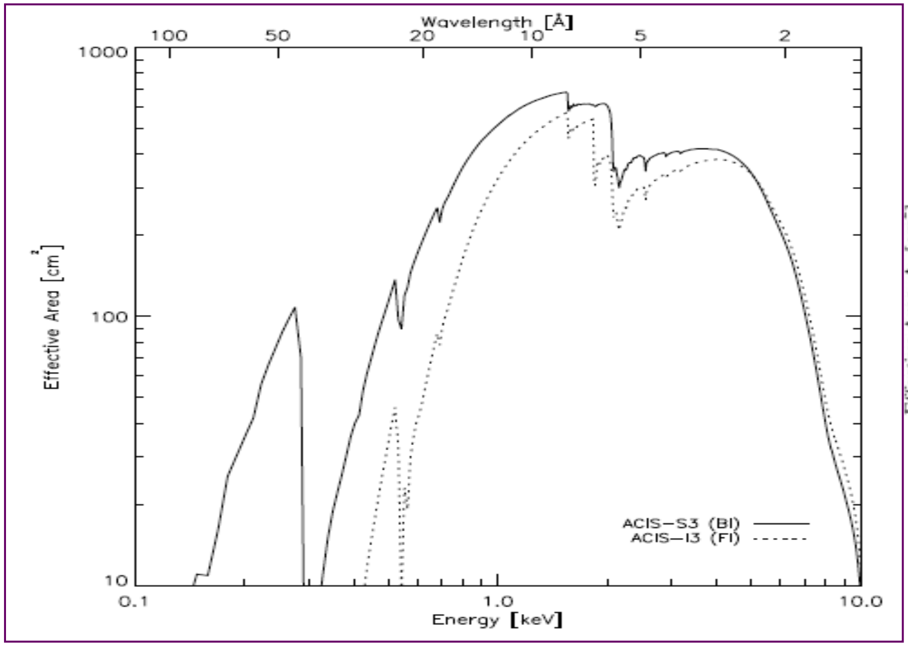
XMM-*Newton:* quantum efficiency



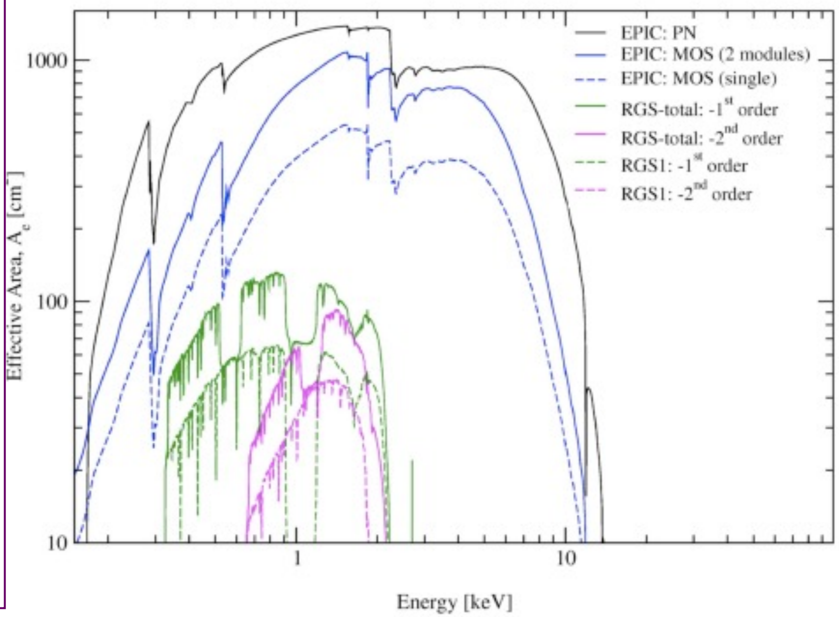


Strong decrease in the QE above 10 keV, where also the effective area due to the mirrors has a significant decrease

Chandra



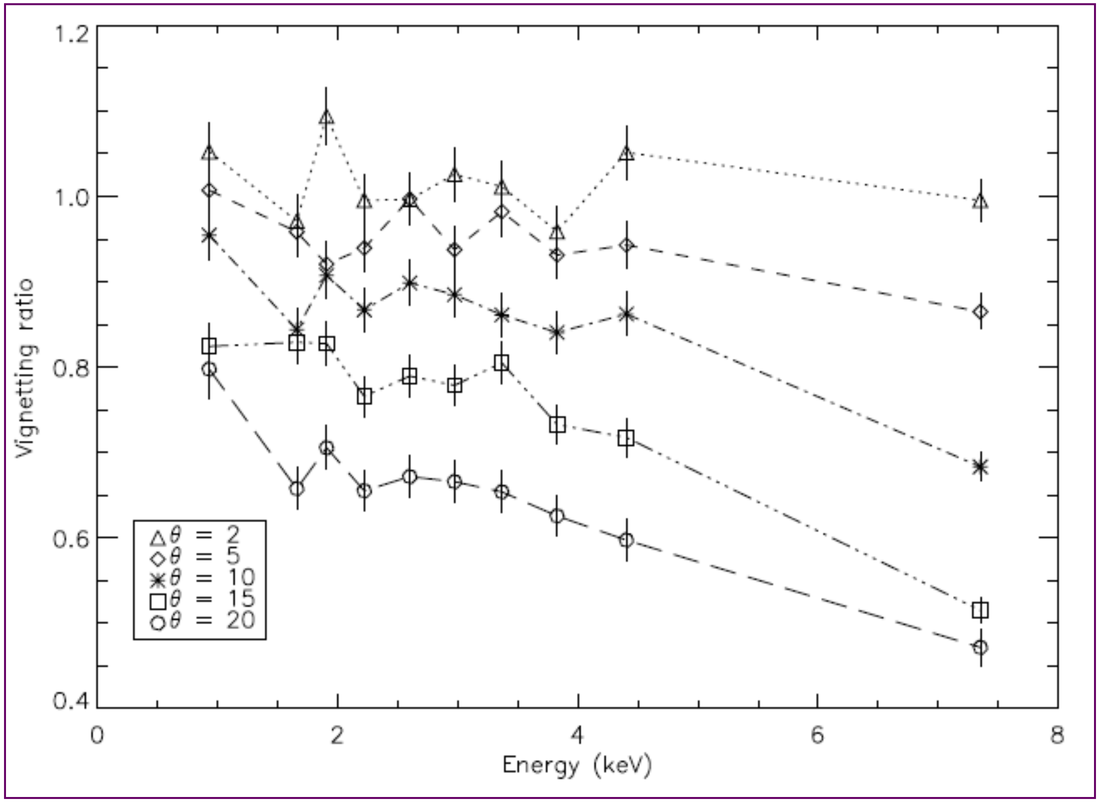
XMM-Newton



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

Chandra: vignetting

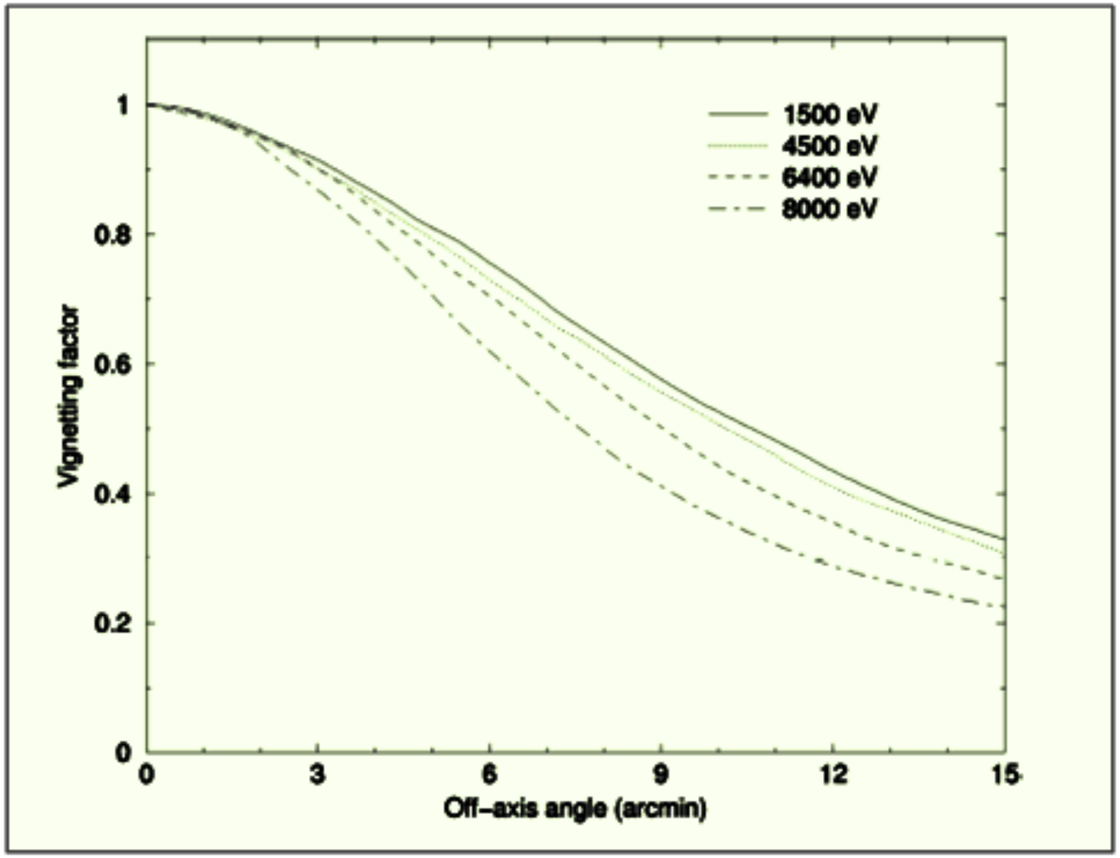
Ratio of the off-axis vs. on-axis counts at different off-axis angles



Hard X-ray photons are more difficult to focus

➔ **Vignetting**

XMM-*Newton:* vignetting



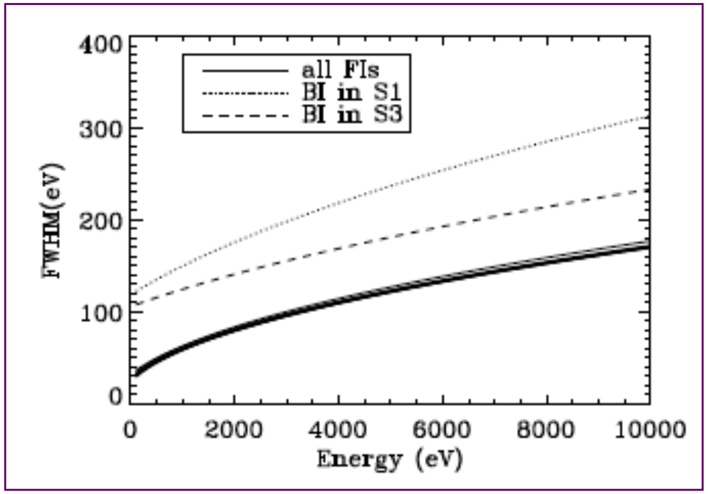
Strong vignetting (as expected) for high-energy photons, partly compensated by the large effective area (e.g., wrt. *Chandra*)

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

Last but not least….

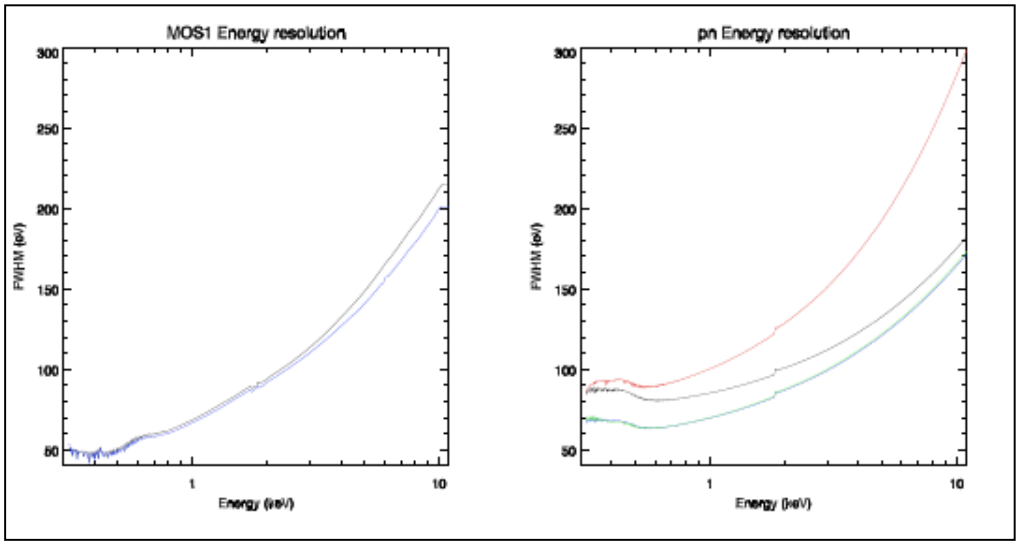
Energy resolution

Chandra: energy resolution



Typical CCD resolution
100-150 eV

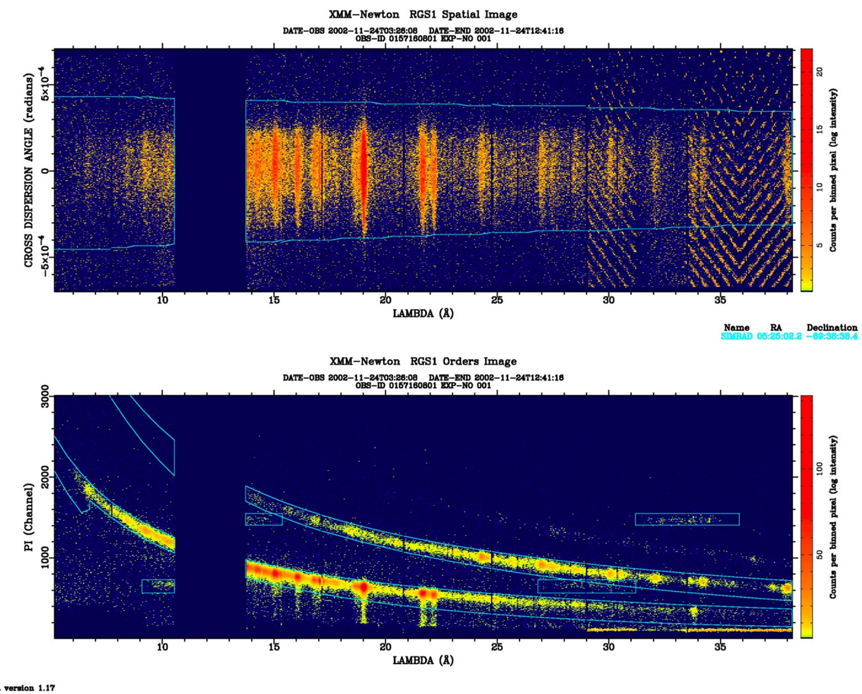
XMM-*Newton:* energy resolution

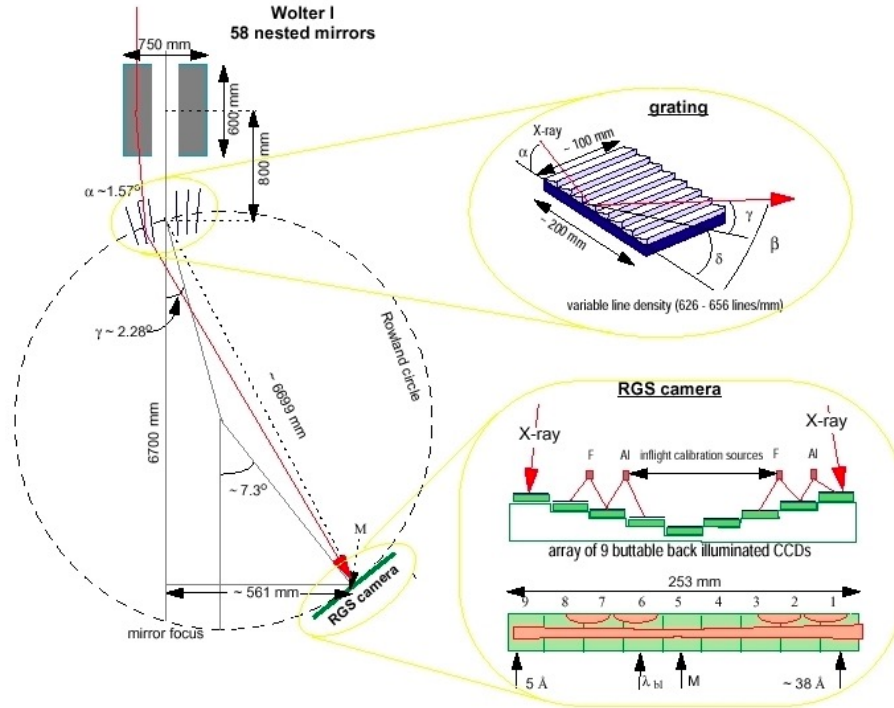


$\Delta E(FWHM)/E \propto E^{-1/2}$ (E in keV)

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

What about high-resolution Spectrospcopy?

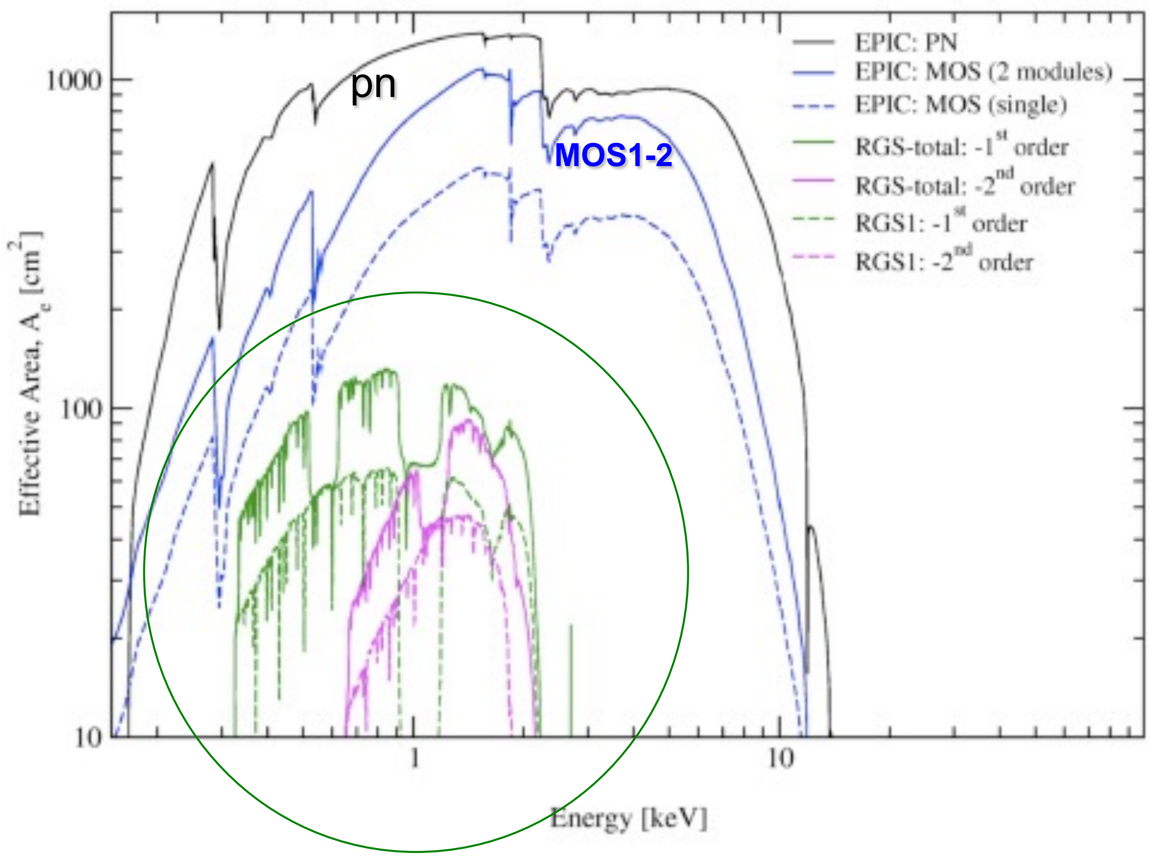




Resolution R ~ 100-500 (FWHM)

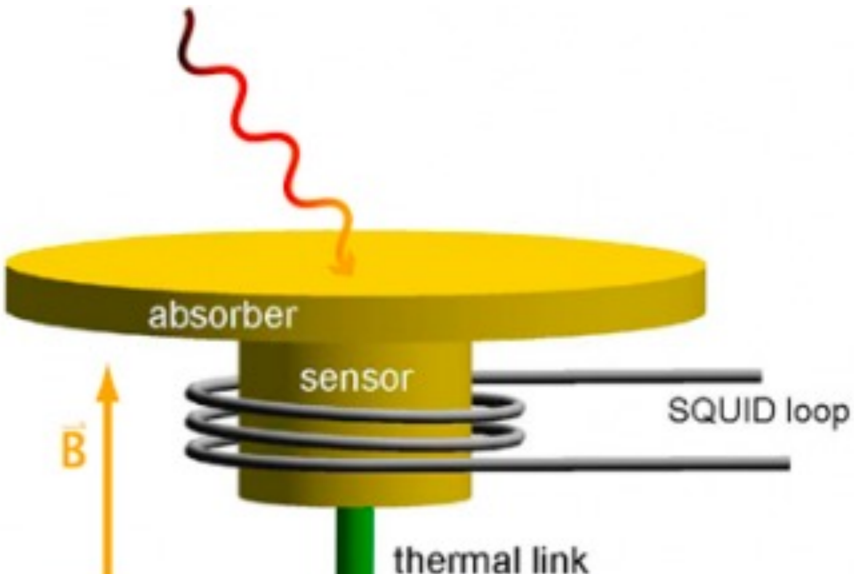
What's missing?

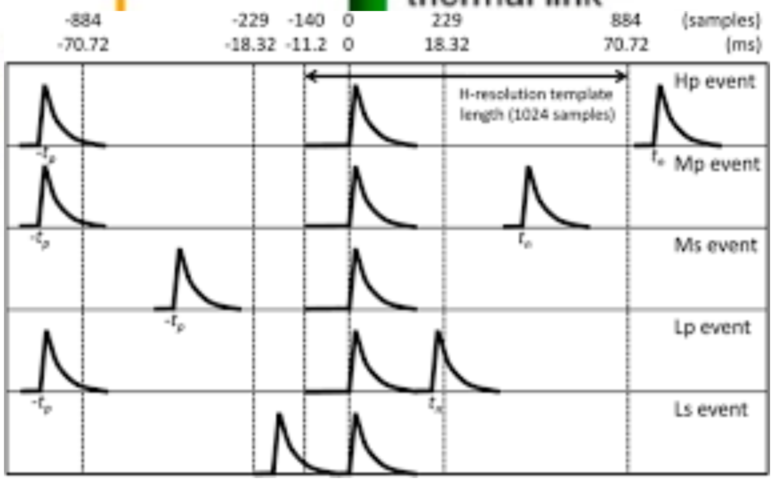
XMM-*Newton:* effective area

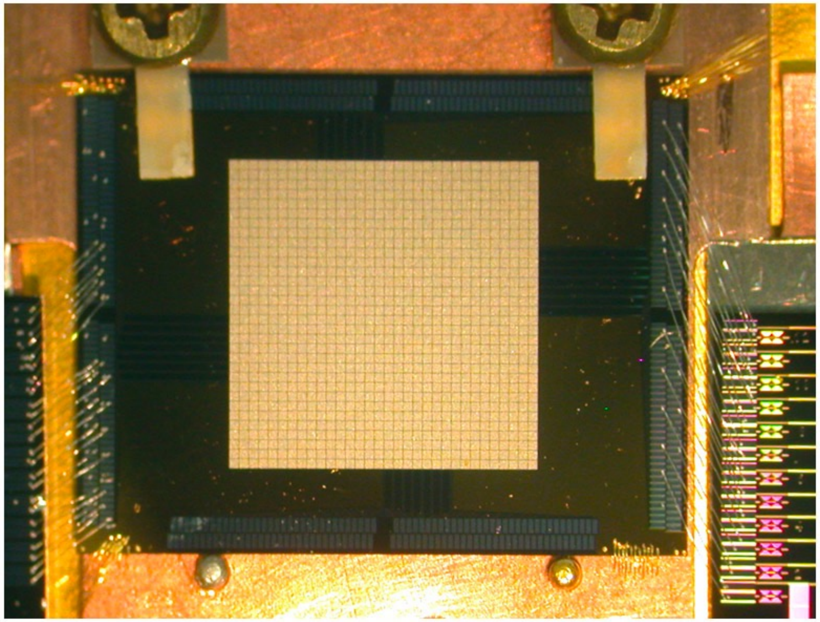


Reflection gratings for high-resolution spectrposcopy -> very small effective area -> “to be used only with bright sources!”

New tech! -> Transition Edge Arrays (microcalorimeters)





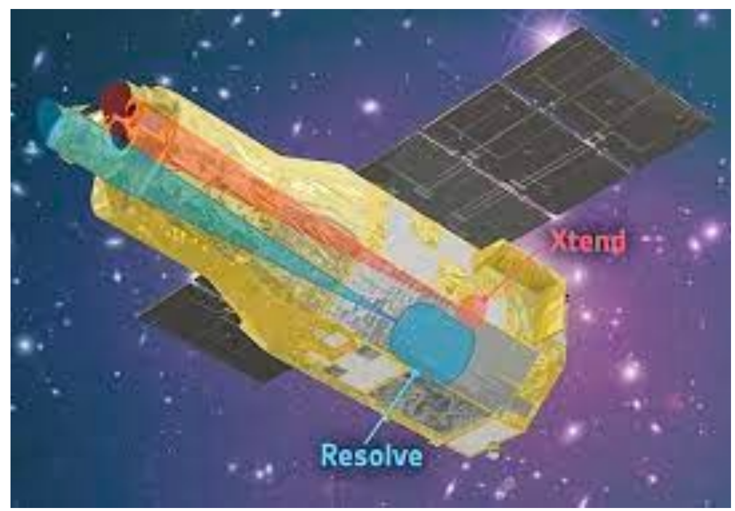


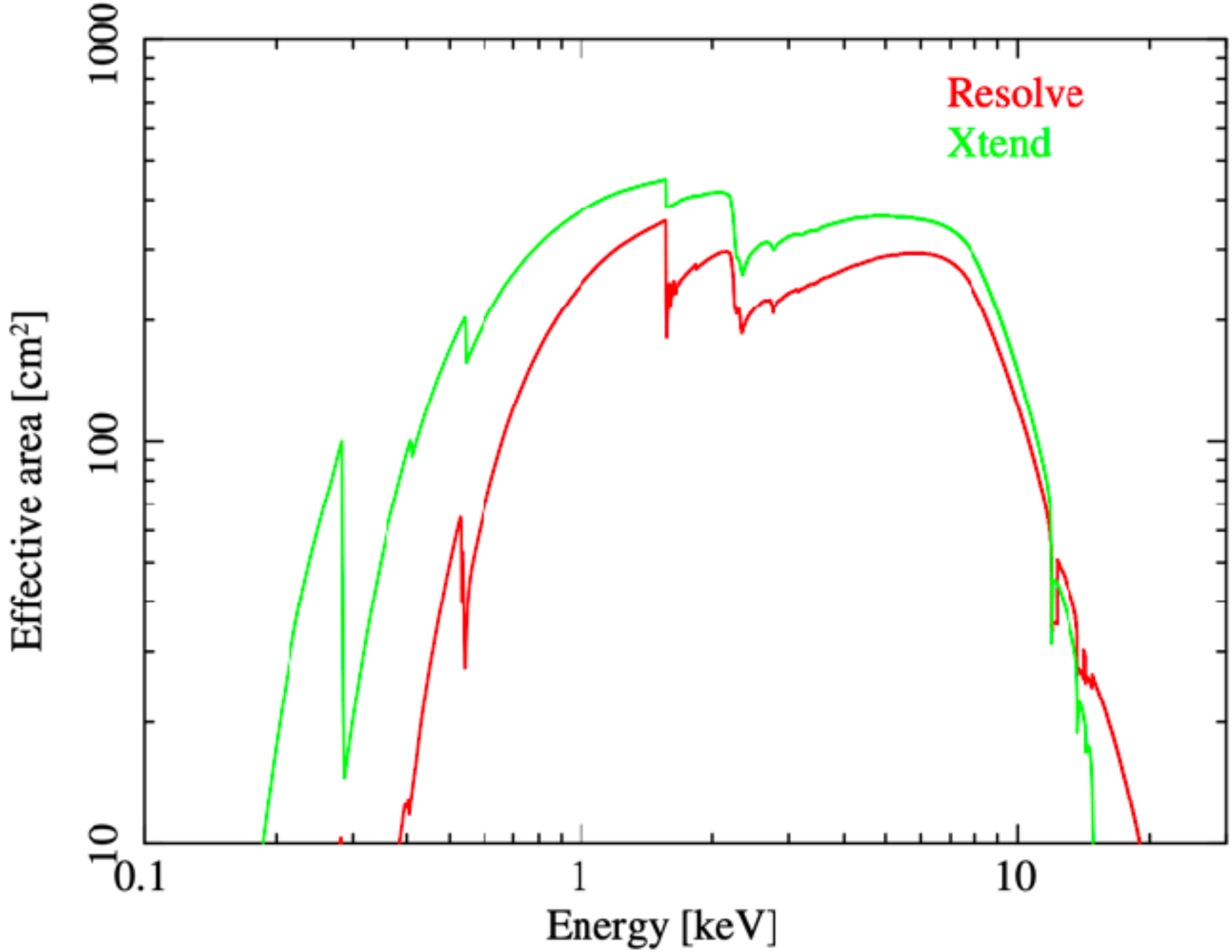
What we are going to talk about…

XMM-*Newton*

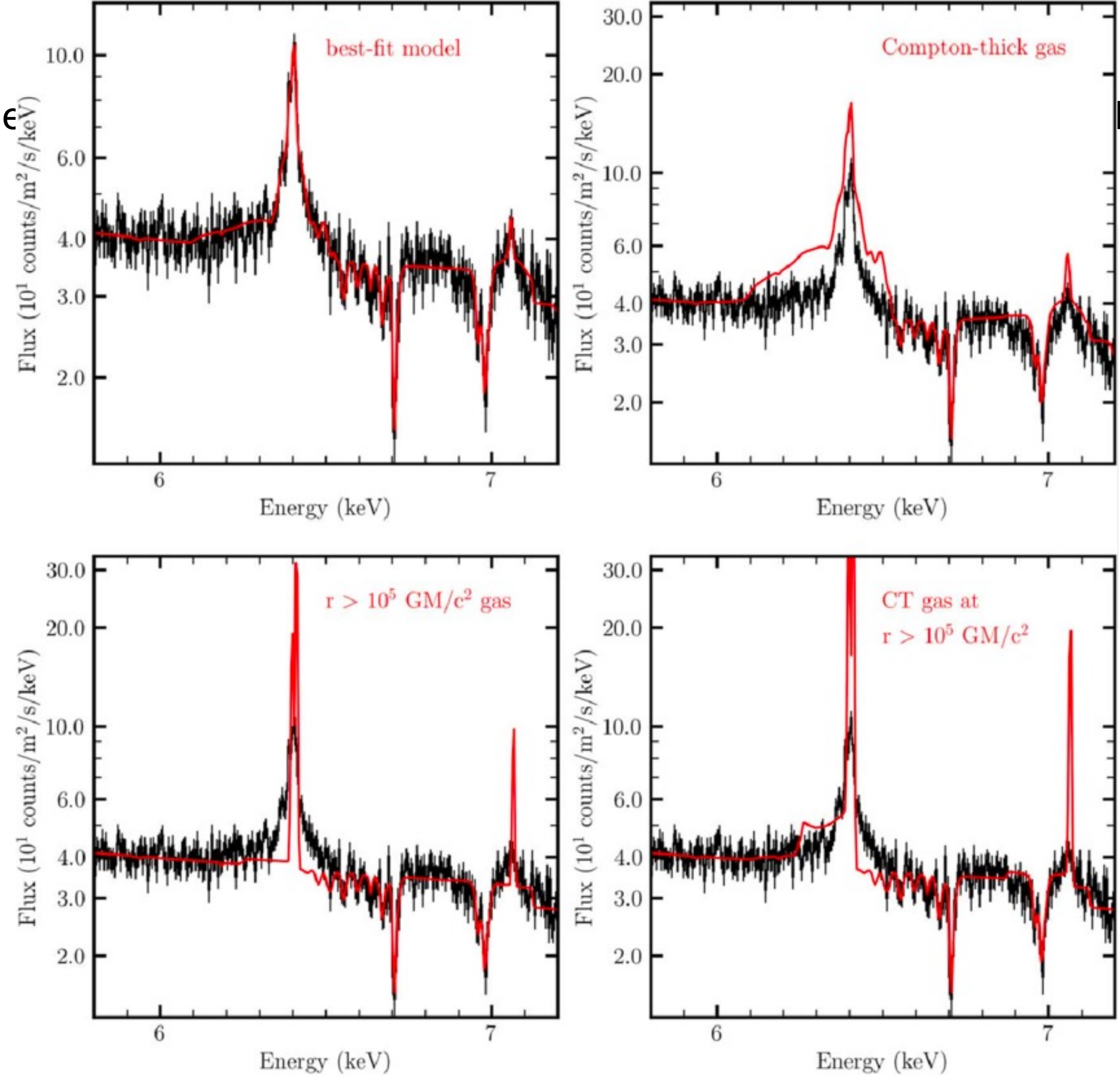
Chandra

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

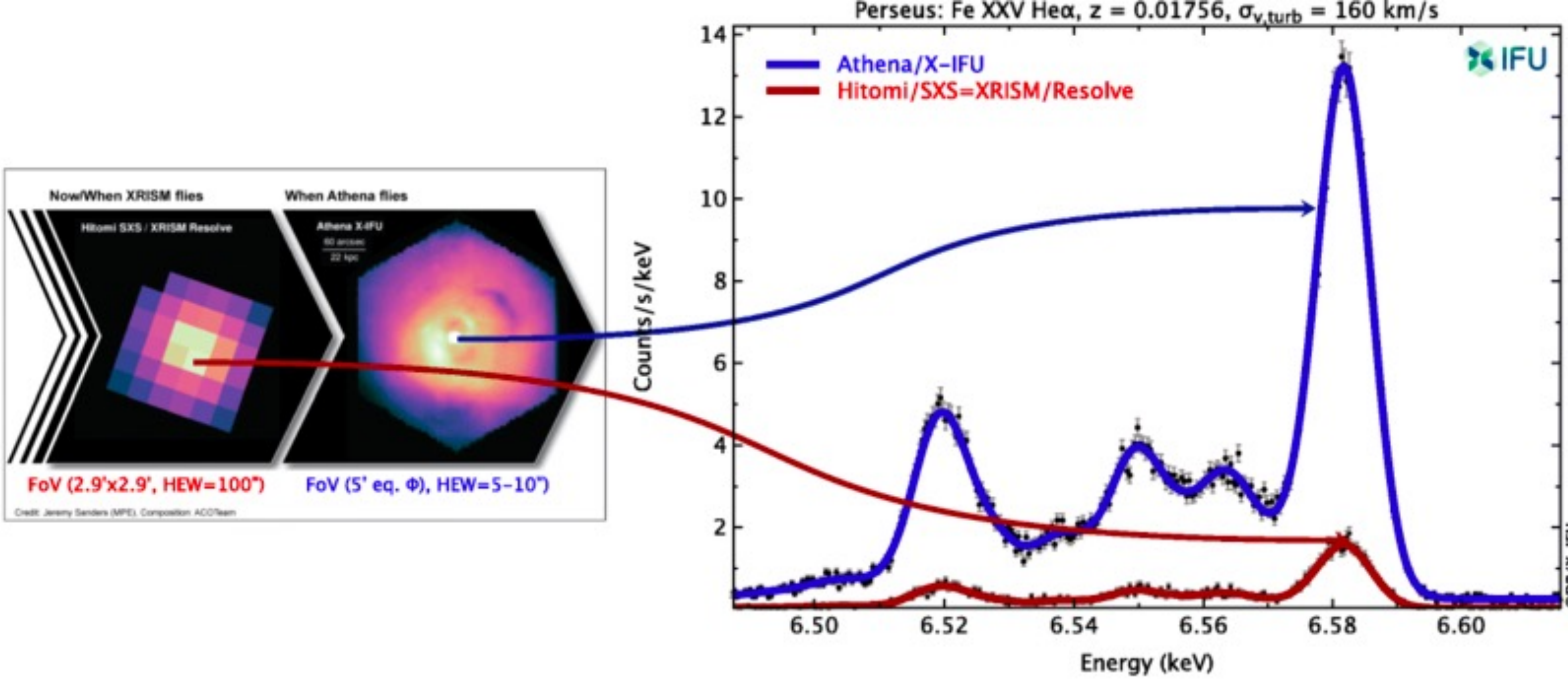


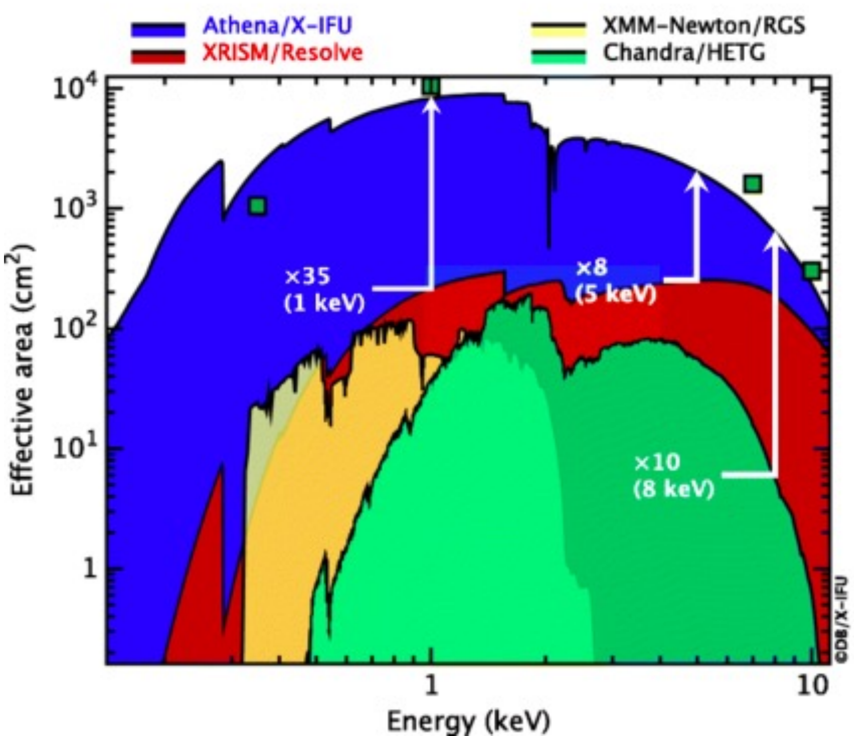

Resolve
Xtend
Effective area [cm2]
1000
100
10
0.1
1
10
Energy [keV]
ea

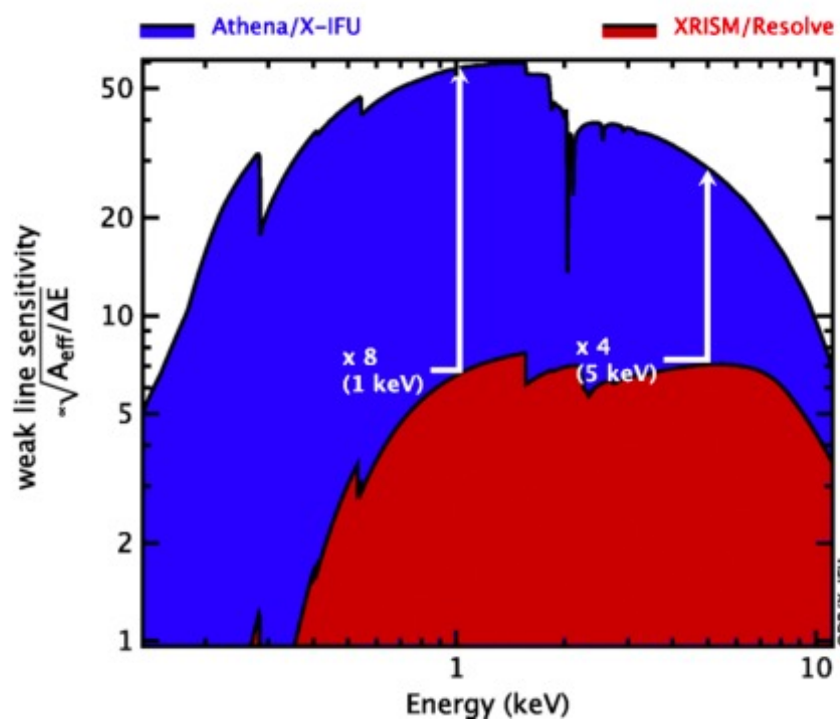
ΔE≈5 e ... ke detectors



ESA: Athena (2037-…)

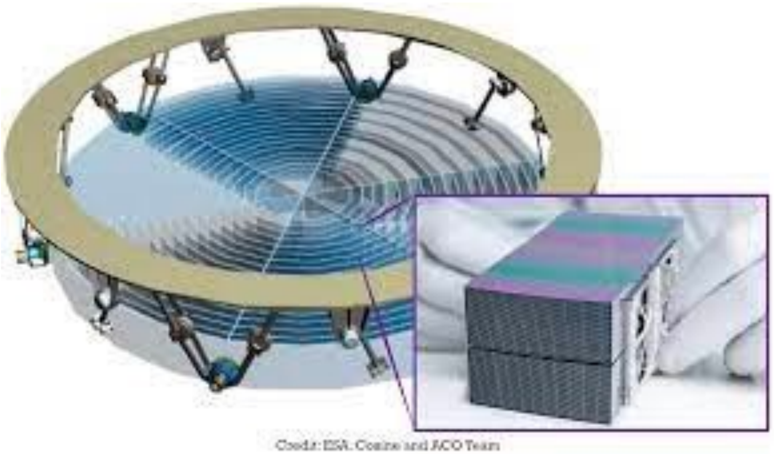

Perseus: Fe XXV Heα, z = 0.01756, σv,turb = 160 km/s
Athena/X-IFU
Hitomi/SXS=XRISM/Resolve
IFU
Now/When XRISM flies
When Athena flies
Hitomi SXS / XRISM Resolve
Athena X-IFU
FoV (2.9'x2.9', HEW=100")
FoV (5' eq. Φ), HEW=5-10")
Counts/s/keV
Energy (keV)
©DB/X-IFU

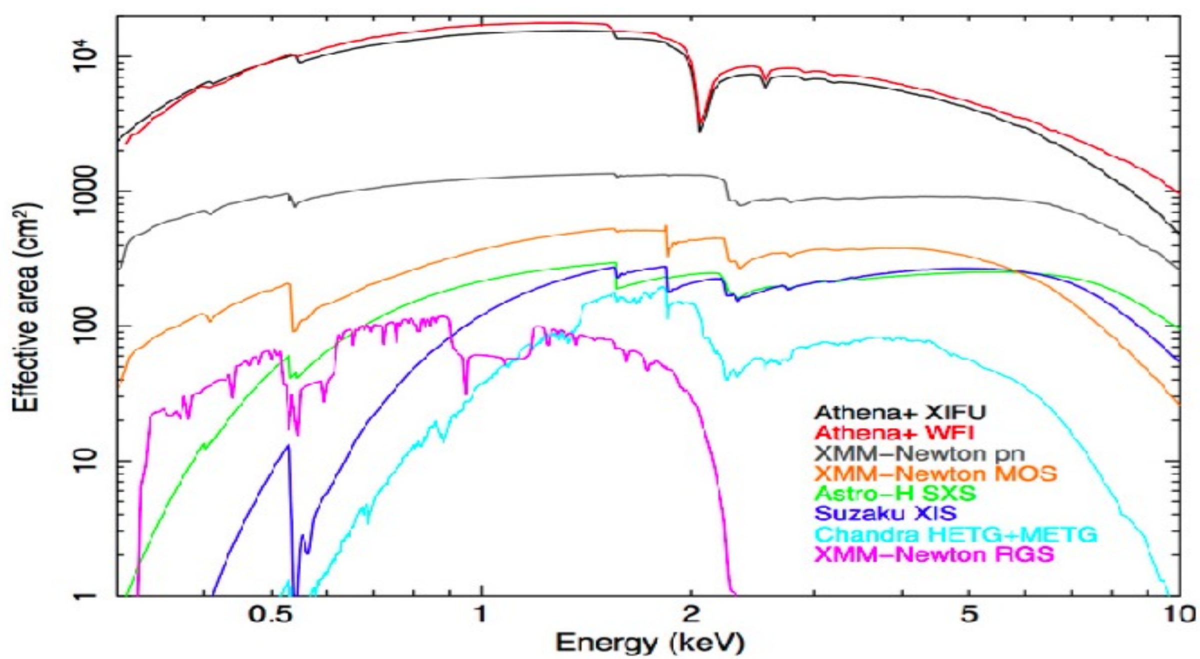

Athena/X-IFU
XRISM/Resolve
XMM-Newton/RGS
Chandra/HETG
Effective area (cm2)
×35
(1 keV)
×8
(5 keV)
×10
(8 keV)
Energy (keV)
©DB/X-IFU


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

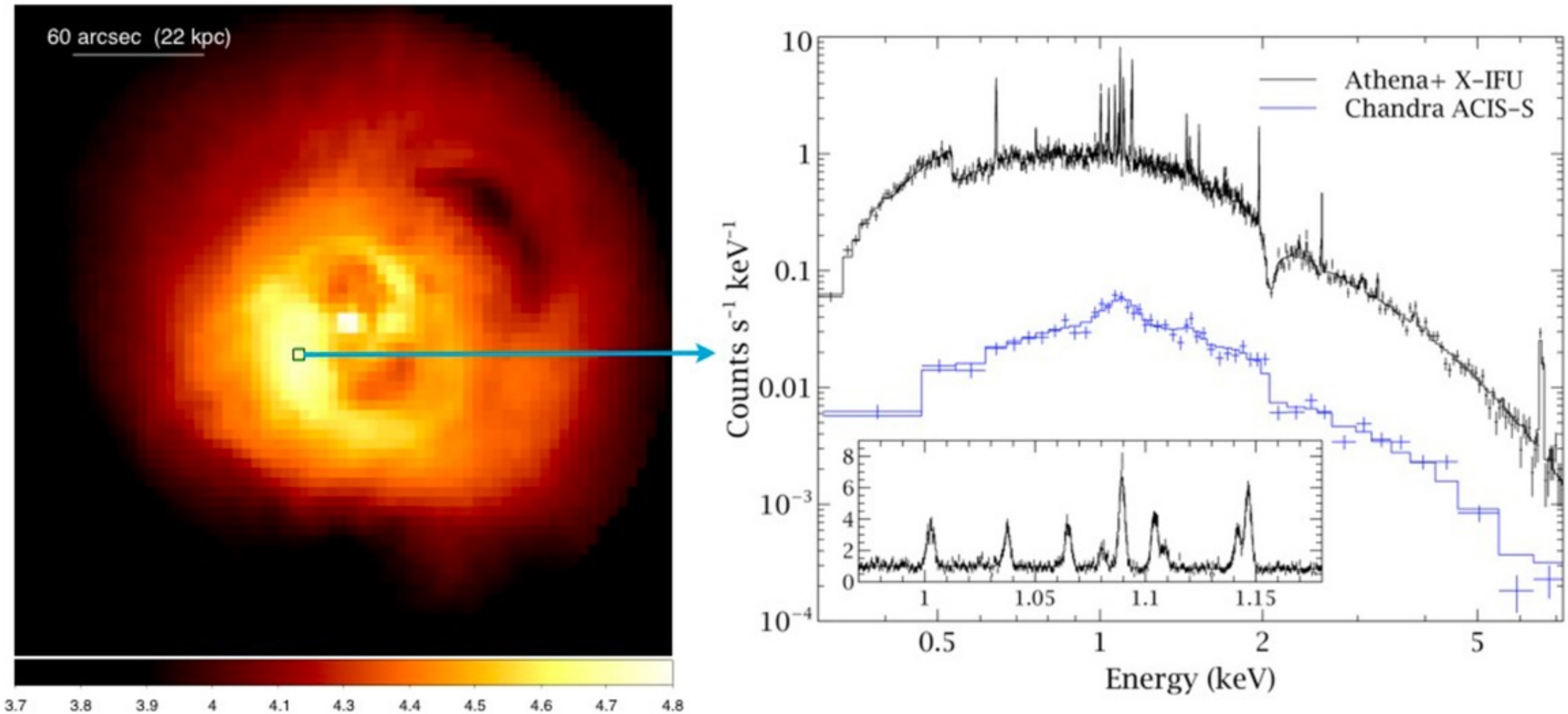
a

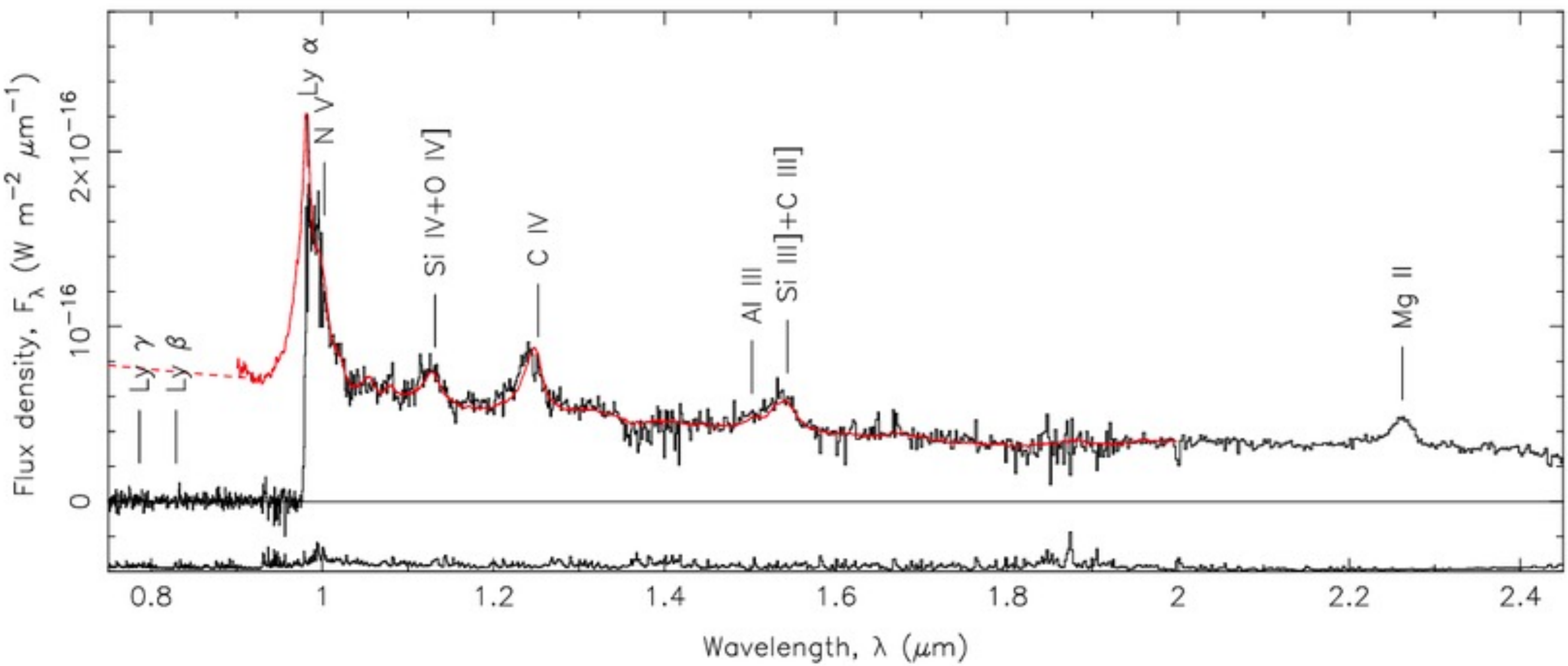
Athena X-IFU (2037…)



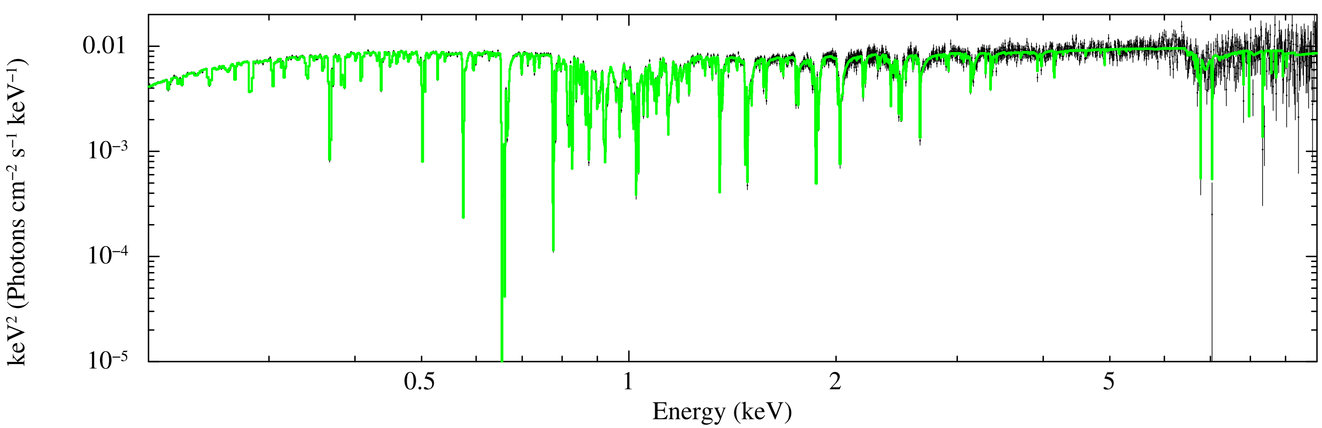


Athena XIFU ΔE≈4 (3!) eV (FWHM) to be compared with ΔE≈5 eV (FWHM) for Resolve





Flux density, F_λ (W m^{-2} μm^{-1})
0
10^{-16}
2×10^{-16}
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)

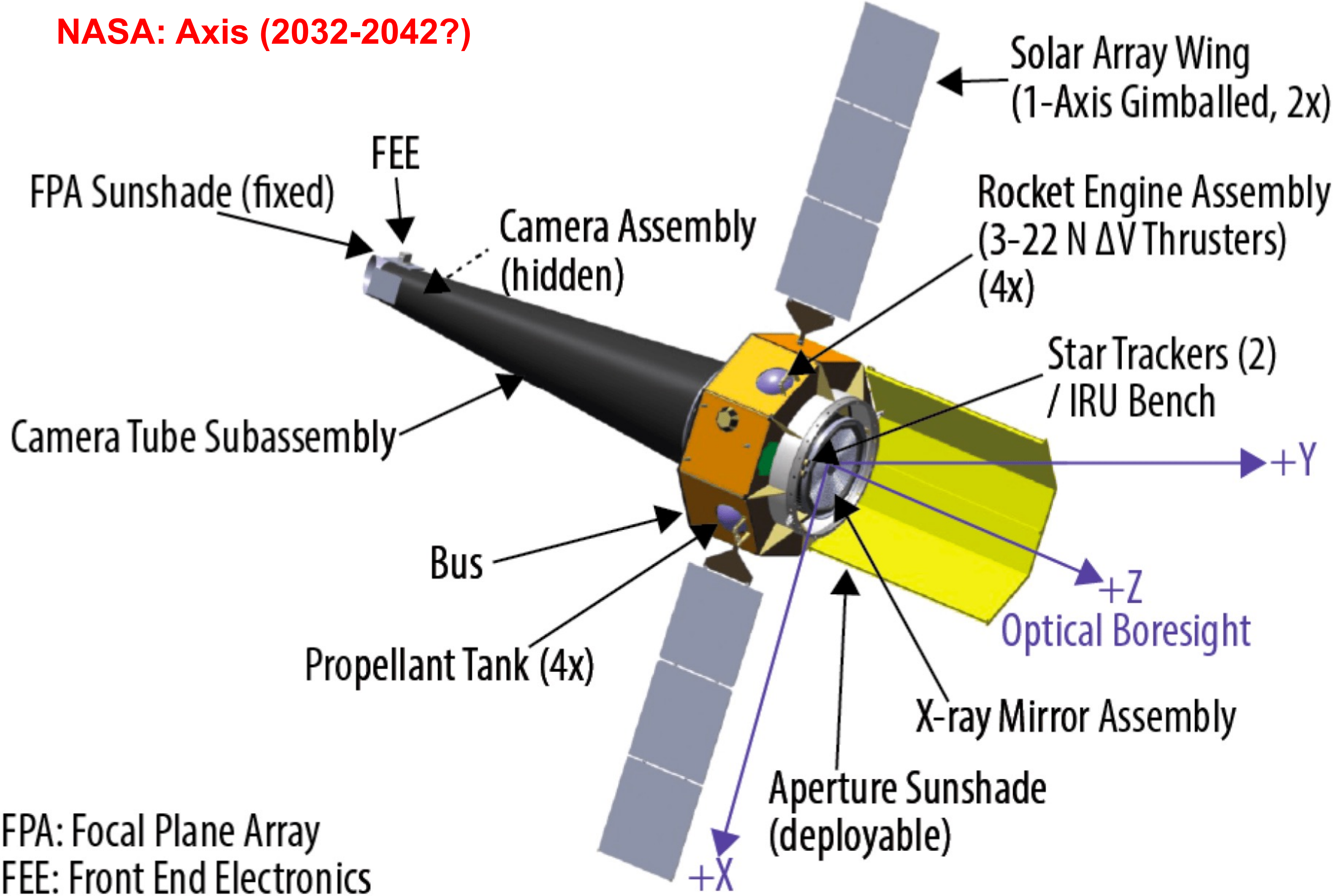


keV^2 (Photons cm^{-2} s^{-1} keV^{-1})
0.01
10^{-3}
10^{-4}
10^{-5}
0.5
1
2
5
Energy (keV)

	Athena X-IFU	XRISM Resolve
Energy range	0.2-12 keV	0.3-12 keV
Spectral resolution	4 eV (design goal of 3 eV)	5 eV
Pixel size	~5 arcsec	1 arcmin
Pixels	~1500	~36
Field of view	4'	3'
1 keV effective area	~5800 cm2	~220 cm2
7 keV effective area	~880 cm2	~230 cm2
Maximum source int.	1 Crab	0.2 Crab

PSF similar to XMM-Newton (≈9" HEW)

NASA: Axis (2032-2042?)



FPA: Focal Plane Array
FEE: Front End Electronics
IRU: Inertial Reference Unit

AX009

AXIS is a huge leap forward

AXIS vs Chandra

- 5-10x larger effective area
- 6x better FoV-ave PSF

AXIS vs Swift

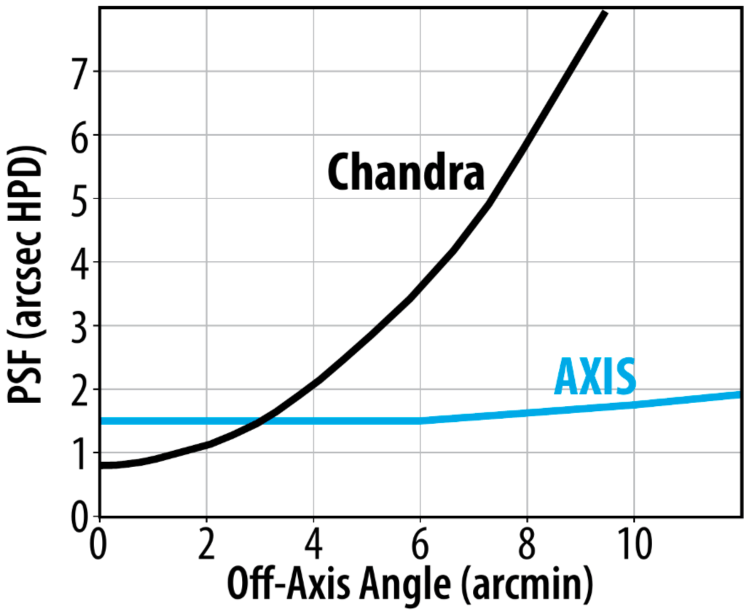
- Same fast ToO Response Time
- 60x better sensitivity

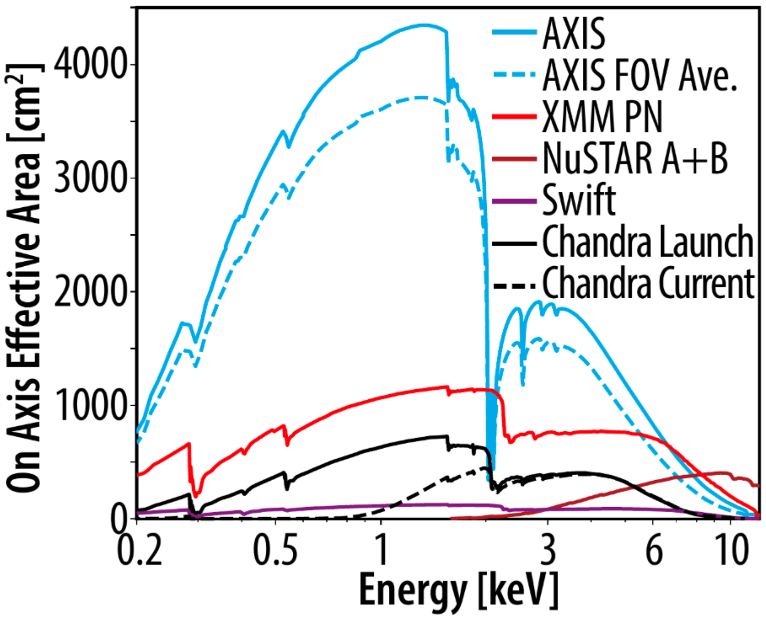
AXIS vs XMM-Newton

- 4x larger area below 2 keV
- 10x better PSF

AXIS vs NuSTAR

- Superior area below 8 keV
- 40x better PSF





AXIS has 70x the survey grasp (FoV x area) at 1.6″ than Chandra

enabling surveys that probe *further, wider,* and *faster*