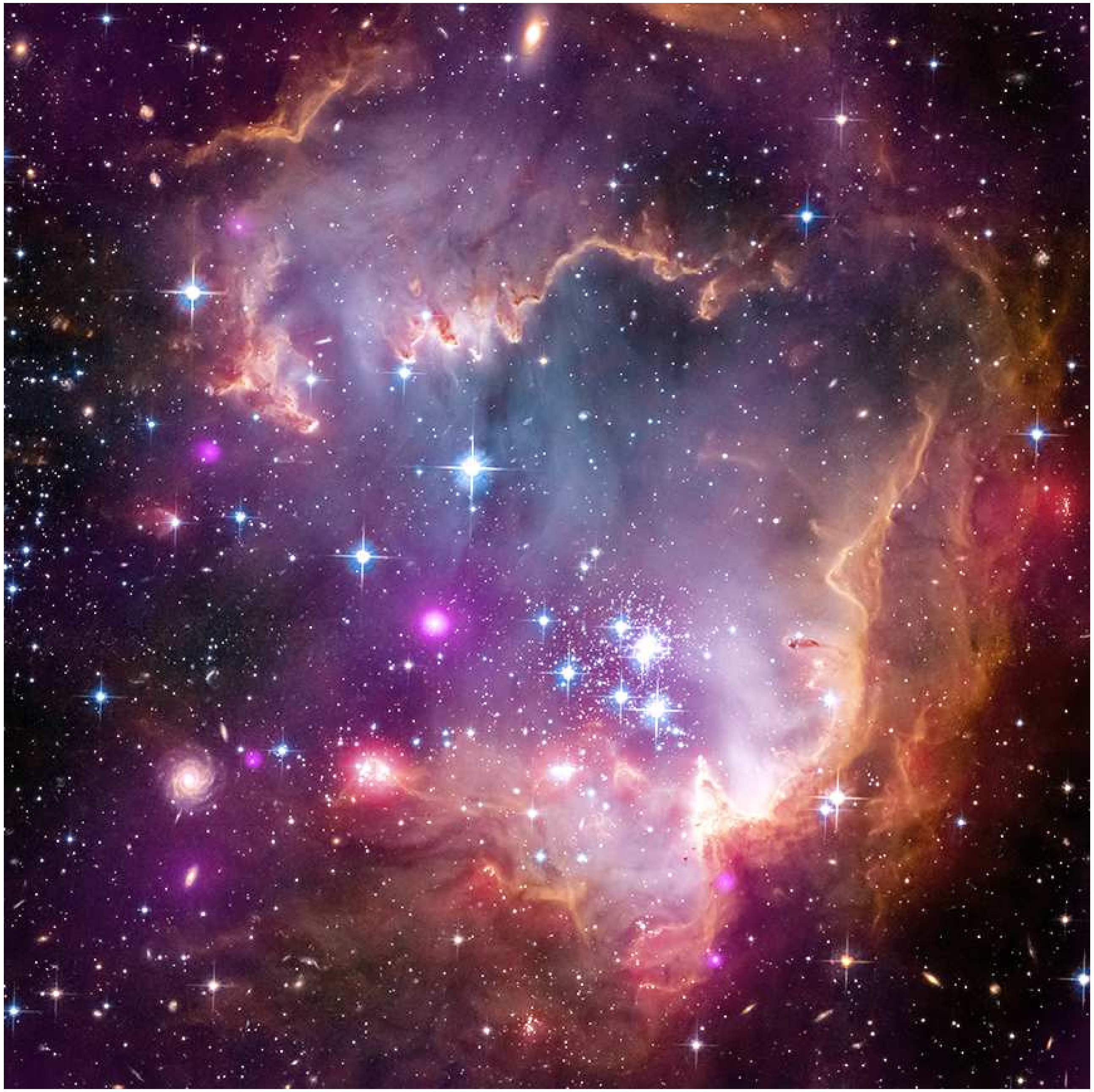
The X-Ray Universe



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astro.physik.uni-potsdam.de/~lida/x-ray.html

Chandra X-ray, HST optical, Spitzer IR
NGC602 in the SMC
d=60pc

II. X-ray Telescopes

http://chandra.harvard.edu/resources/

Introduction

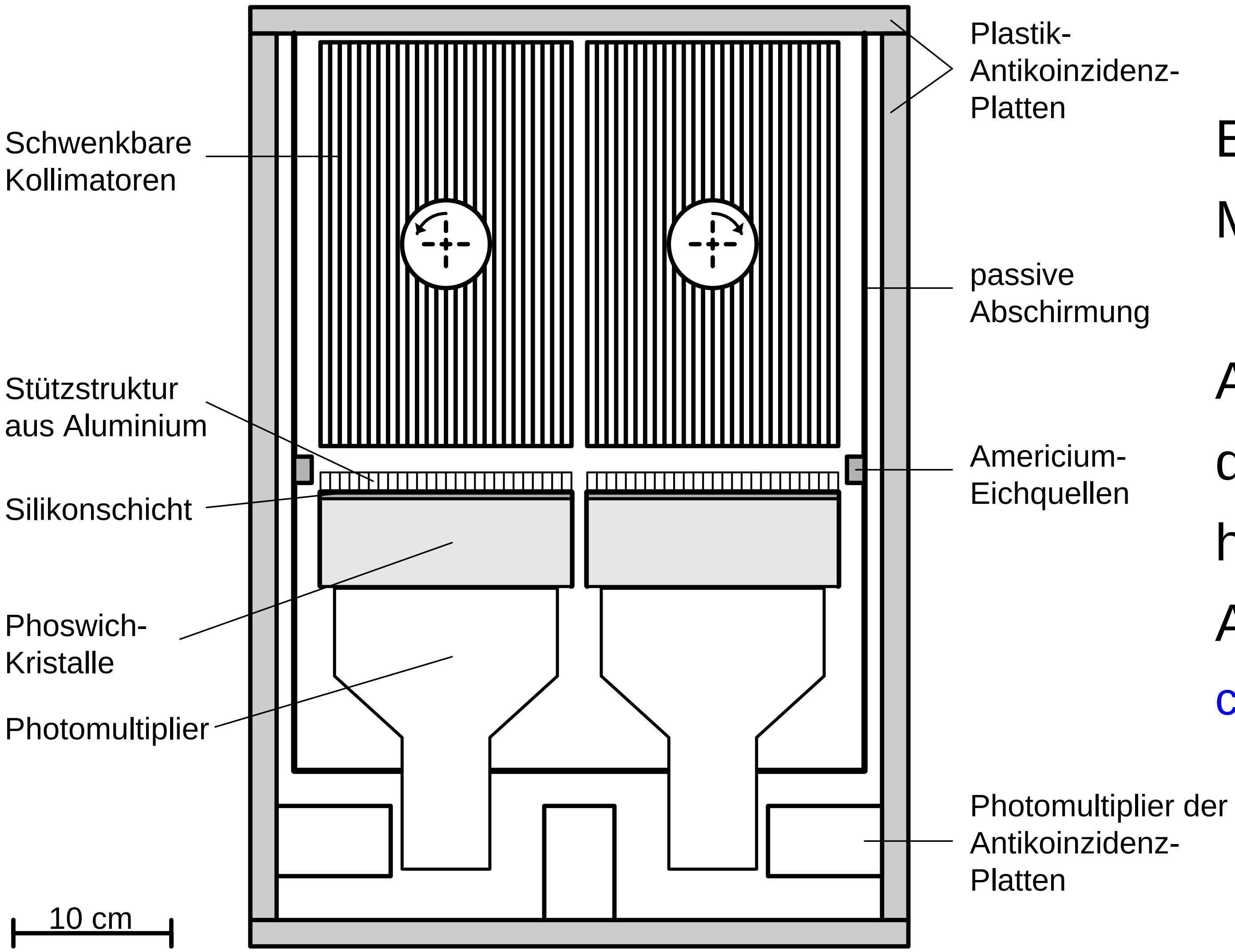
Before we look at astrophysical X-ray sources,
we need to understand how the images are formed
and how radiation is detected.

- Collimators
- Wolter Telescopes
- New generation of X-ray mirrors
- X-ray Detectors

Collimators

How to understand where the X-rays are coming from?

Simpliest: pinhole camera version honeycomb collimator



Example: Kvant modul

MIR station, 1987

Angular resolution $\sim d/h$,

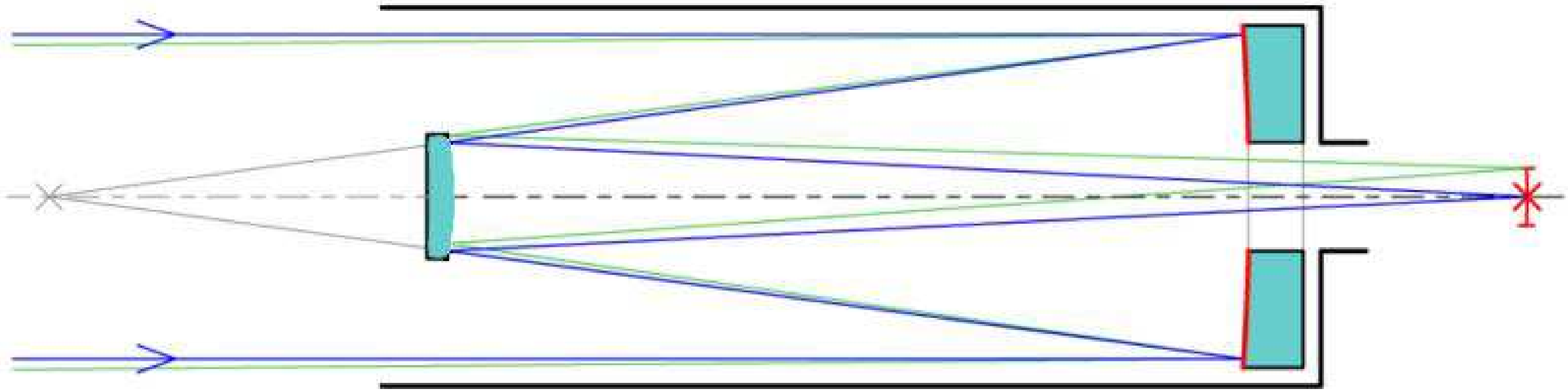
d is tube diameter,

h is tube length

Angular resolution - degrees

compare: Chandra: 0.5arcsec!

Reminder of optical telescopes

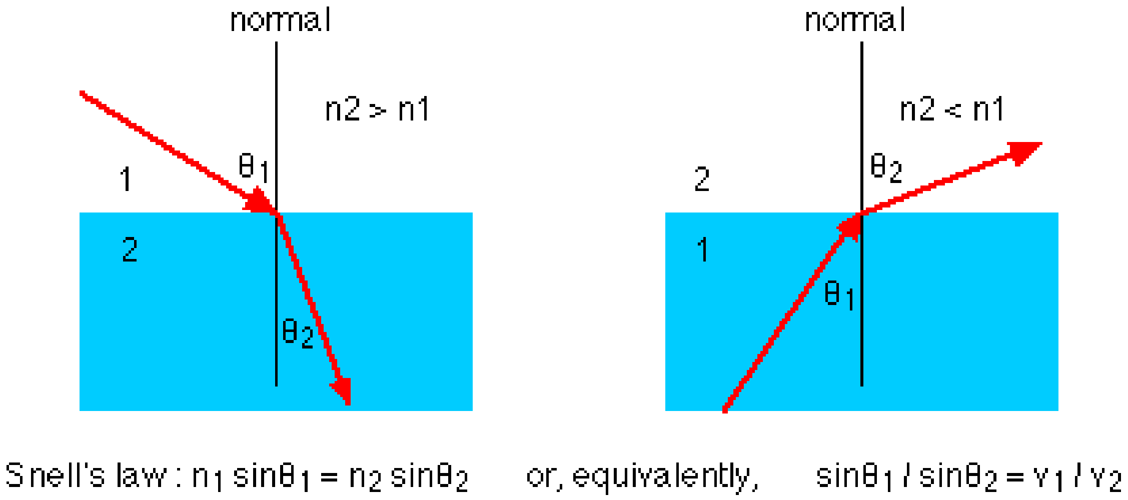


Cassegrian telescope (src. Wikipedia)

- Nowadays, optical telescopes are reflectors
- E.g. Primary mirror -> Secondary mirror -> Detector
- Main characteristics of a telescope
  - collecting area $\pi d^2/4$, where d is mirror diameter
  - angular resolution $\theta=1.22\lambda/d$ (perfect seeing)

Snell's law

The relationship between angles of incidence and refraction for a wave impinging on an interface between two media with different indices of refraction.



$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}$$

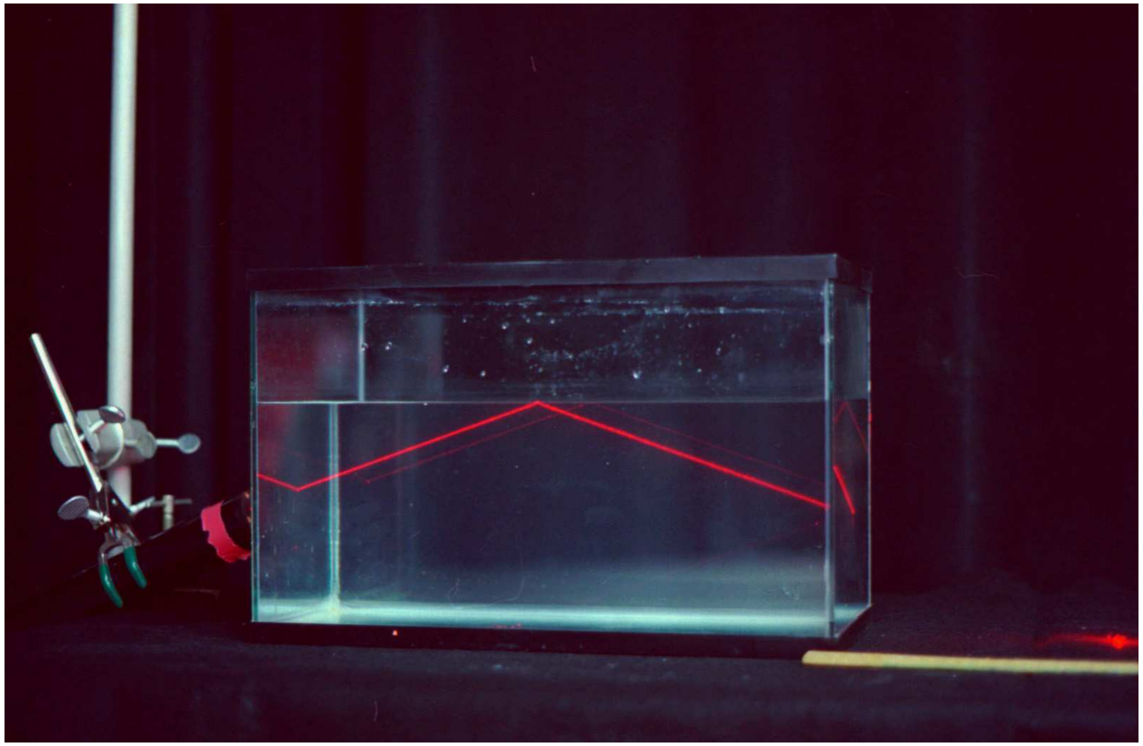
$$\sin\theta_2 = \frac{n_1}{n_2}\sin\theta_1$$

- Total internal reflection: $\theta_2 \geq 90^\circ$
- The incident angle θ_c: is the value of θ_1 for which $\theta_2 = 90^\circ$:
- for visual light n>1: n(air)=1.003, n(water ice)=1.31, n(gold)=2.1, n(diamond)=2.4, (silicon)=3.96, n(germanium)=4.01: Water/Air $\theta_c = 48.6^\circ$; Ge/Air $\theta_c \approx 14^\circ$

optical fibers, diamond cutting, mirrors

Reflection of X-rays

Total internal reflection



X-rays interact weakly with matter; X-ray refractive indices are thus extremely close to 1. X-rays cannot be reflected by “normal” mirror - they are passing through the material.

X-ray refractive indices are slightly smaller than 1, giving rise to total external reflection at sufficiently small angle. This can

Refraction of X-ray photons

• In optics, the index of refraction $n(E) = 1 + \delta(E) + i\beta(E)$: a real part is δ and an imaginary part is β, describing refraction and absorption, respectively.

• For X-rays the real part of the refractive index, dominated by Rayleigh scattering, is negative and converges to zero for higher energies.

In general, the index of refraction is given by the Maxwell relation:

$$n = \sqrt{\epsilon\mu}\,,$$

where ε is the dielectrisity constant; $\mu \sim 1$ is permeability of the material

For free electrons, e.g. in metal,

$$\epsilon = 1 - \left(\frac{\omega_{\rm p}}{\omega}\right)^2 \text{ with } \omega_{\rm p}^2 = \frac{4\pi n_{\rm e} {\rm e}^2 Z}{m_{\rm e}}\,,$$

$\omega_{\rm p}$ - plasma frequency, $\omega=2\pi c/\lambda$, n_e number density of electrons

$$\epsilon = 1 - \frac{n_{\rm e}{\rm e}^2 Z}{\pi m_{\rm e} c^2}\lambda^2 = 1 - \frac{n_{\rm e} r_{\rm e} Z}{\pi}\lambda^2,$$

where $r_{\rm e} = \frac{{\rm e}^2}{m_{\rm e}c^2} \approx 2.8 \times 10^{-13}$ cm - the classical electron radius

Critical angle

The index of refraction from a metal surface of photons with λ

$$n = \sqrt{1 - \frac{n_e r_e Z}{\pi}\lambda^2} \approx 1 - \frac{n_e r_e Z}{2\pi}\lambda^2 =$$

electron number density $n_e = \frac{\rho}{\mu m_H}$

$$n \approx 1 - \text{const} \cdot \rho\, \lambda^2$$ for $\lambda \sim$ Å n<1

Critical angle for reflection θ_c, $\sin\theta_c = n_2/n_1$ lets $\theta_c = 90 - \alpha_c$ ⇒

$\cos\alpha_c = n_2$ when $n_1 = 1$ (e.g. vacuum)
remember $\cos\alpha \sim 1 - \alpha^2/2$, also λ in Å, 1Å=$10^{-8}$ cm

$$1 - \frac{\alpha_c^2}{2} \approx 1 - 5 \times 10^{10} \rho\lambda^2 \Rightarrow \alpha_c \approx 0.5' \frac{\lambda}{1\text{Å}} \sqrt{\rho[\text{g cm}^{-3}]}$$

Total External Reflection

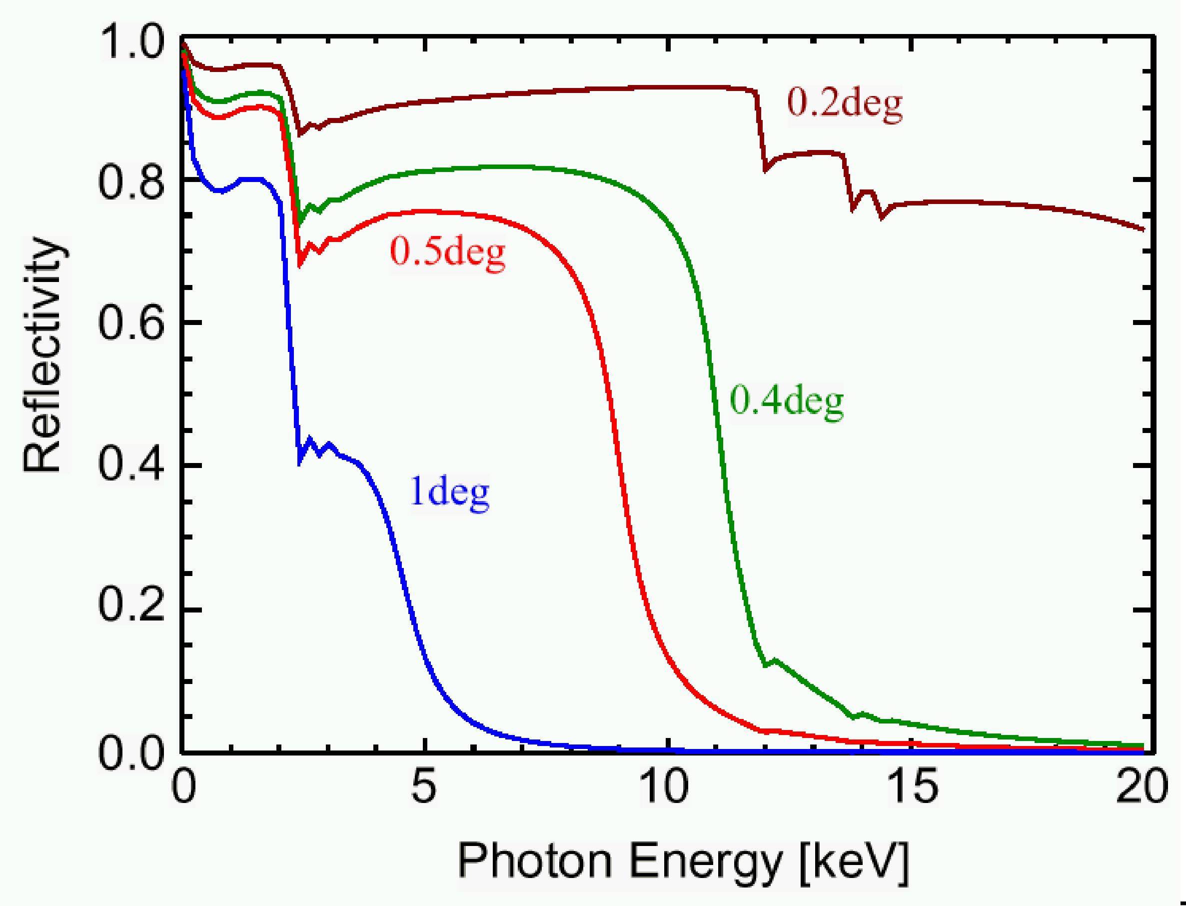
Reflection of X-rays

Grazing angle $\alpha_c \approx 0.5' \frac{\lambda}{1\text{Å}} \sqrt{\frac{\rho}{1\,\text{g cm}^{-3}}}$

Gold ρ=19.3 g cm^{-3}

X-ray λ~1Å $\Rightarrow \alpha_c \approx 2'$

Grazing!



To increase α_c need high ρ

XMM-Newton: gold

Chandra: iridium

see Ais-Nielsen & McMorrow, 2004, Elements of modern X-rays physics

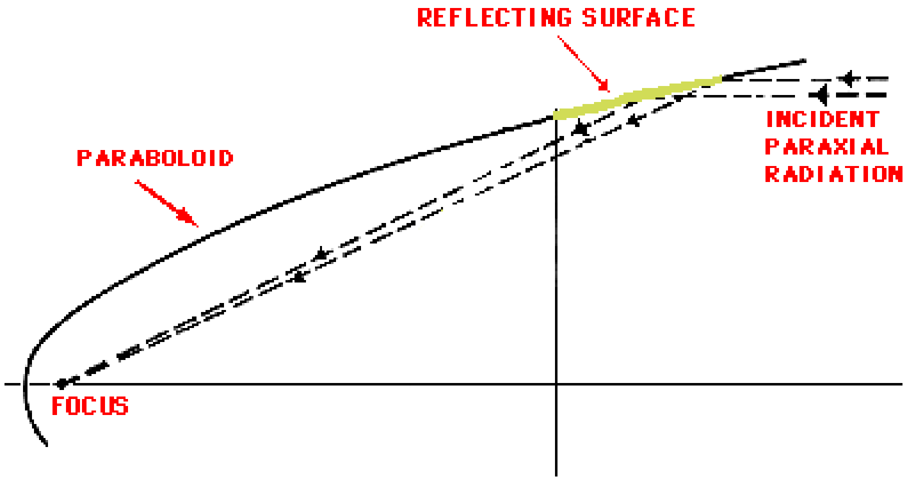
Bragg's Effect:

X-ray diffraction (XRD)

direct evidence for the periodic atomic structure of crystals

Nobel Prize in physics in 1915

Simple X-ray telescope



Same idea as
optical telescope primary

1960 R. Giacconi & B. Rossi

Only paraxial rays parallel
to the optical axis are focused:
Abbe sine condition not fulfilled

In optical telescopes:
secondary mirror

Abbe sine condition:

Ernst Karl Abbe (1840-1905)

Germany, University of Jena

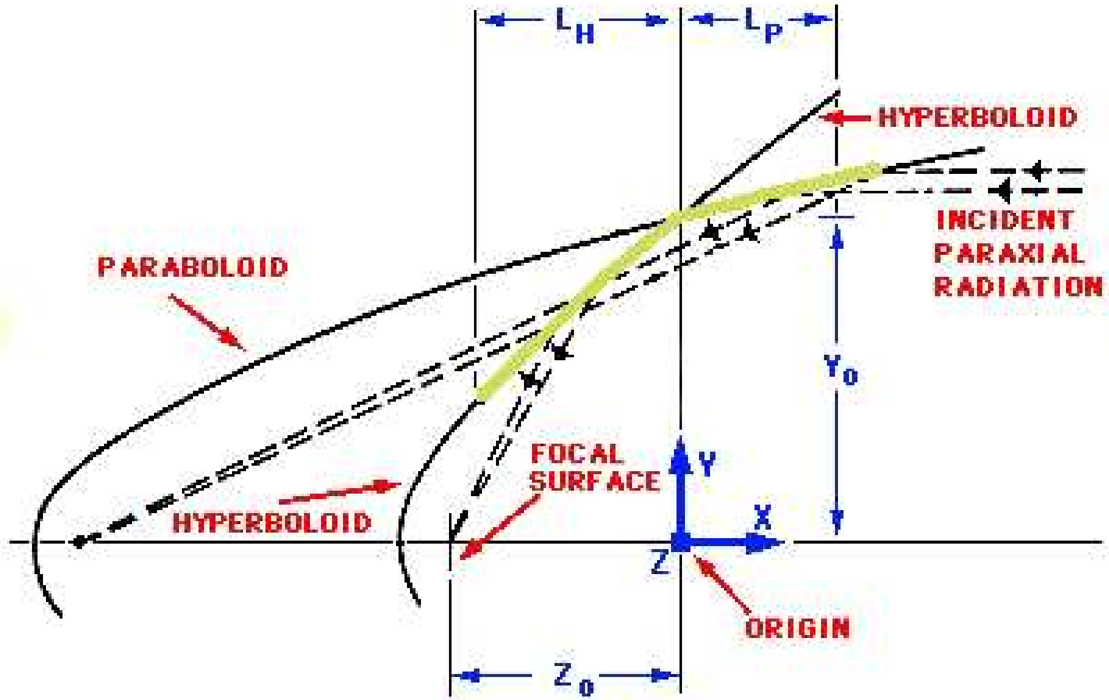
must be fulfilled by optical system in order for it
to produce sharp images of off-axis as well as on-axis objects:

$$\frac{\sin u'}{\sin U'} = \frac{\sin u}{\sin U}$$

u, U angles of any two rays as they leave the object

u', U' angles of any two rays as they leave the object

Wolter I telescope



Hans Wolter (1911 - 1978)

Germany

1952 X-ray focusing optics that satisfies Abbe condition

Three types, practical Type I developed for microscopes

1961 R. Giacconi & B. Rossi X-ray telescopes

Collecting area $A \propto \frac{\pi r^2 l}{f}$

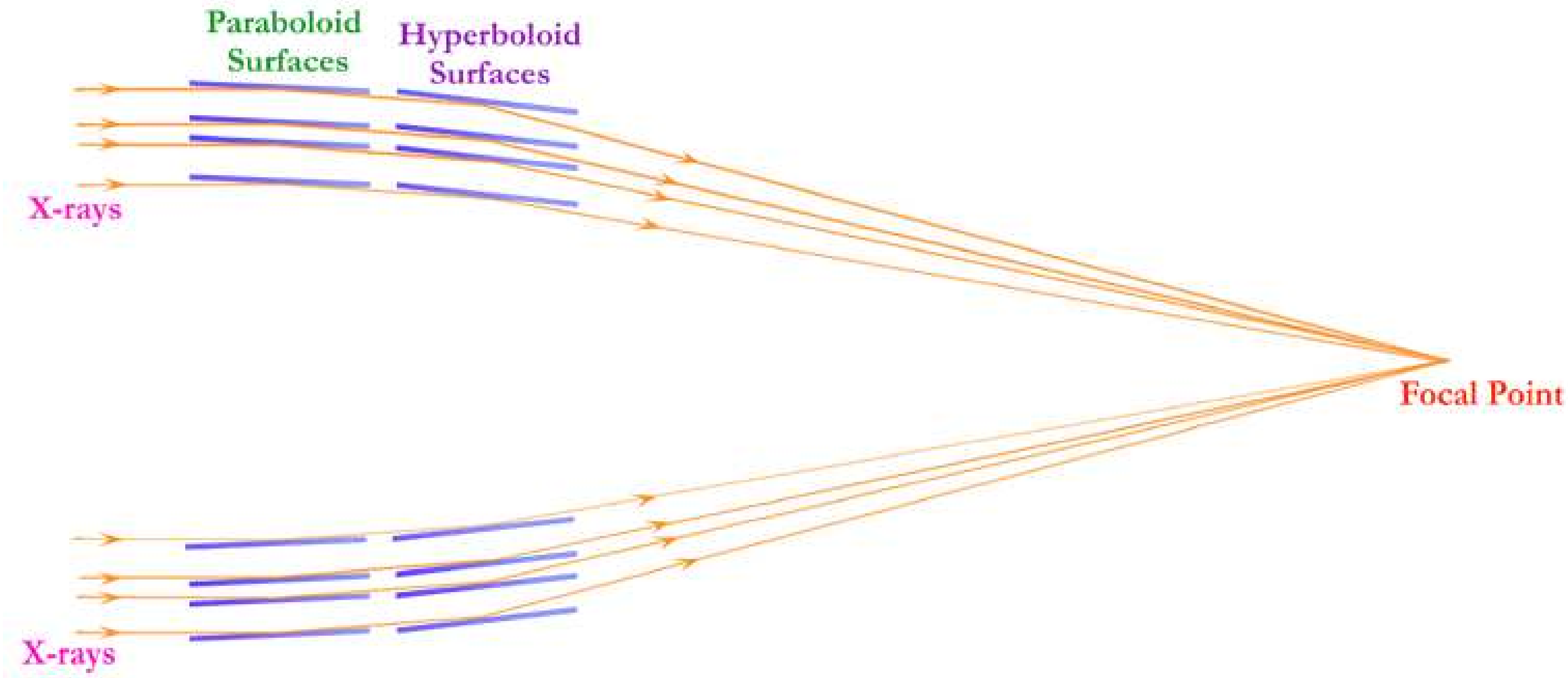
where f is focal length

Small collecting area of a mirror

Astrophysical X-ray sources are weak.

How to increase collecting area?

Nested mirrors



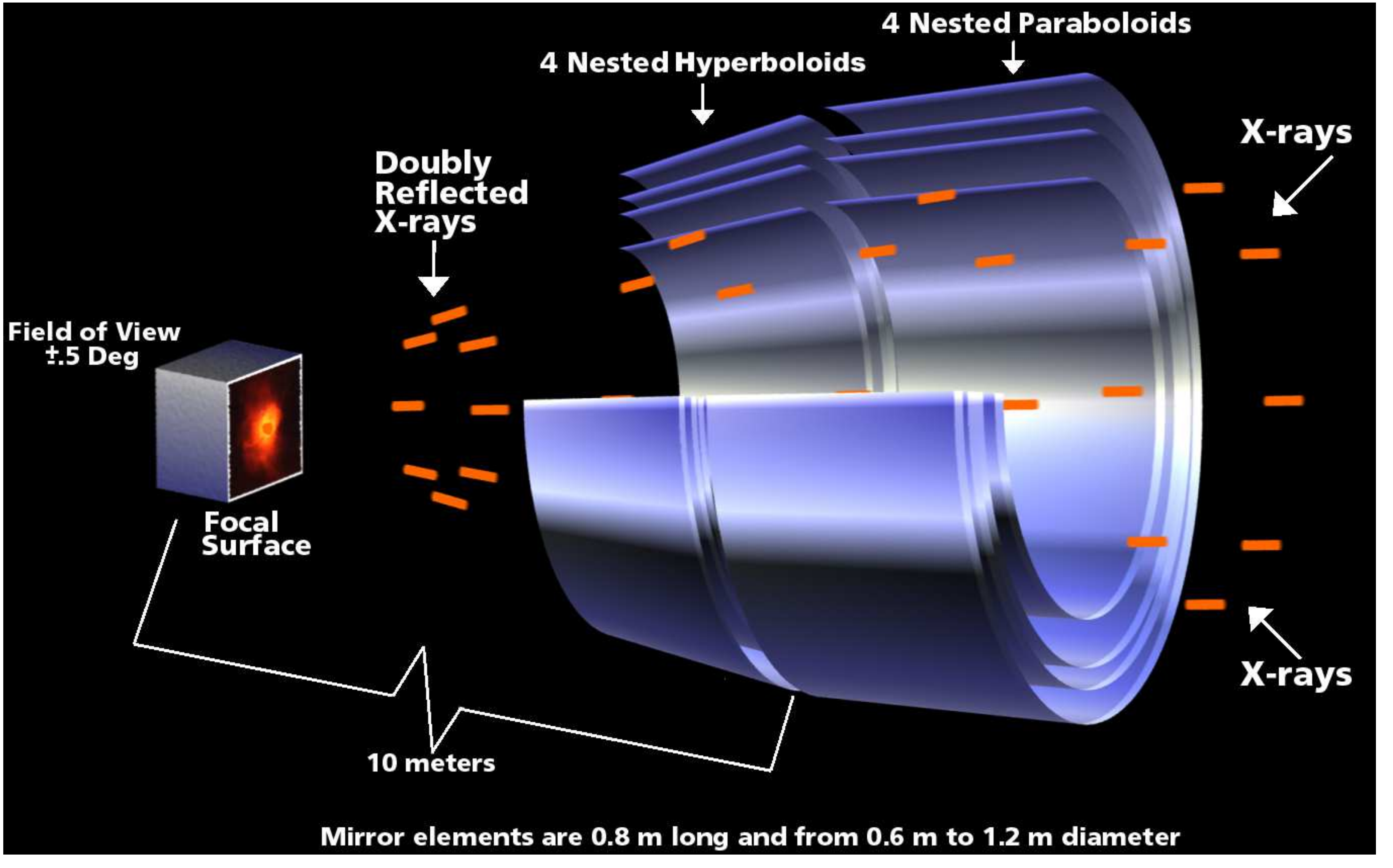
Chandra: four nested pairs of mirrors

Two reflections are required to make an image.

The grazing angle: 3.5 degrees for the outer pair

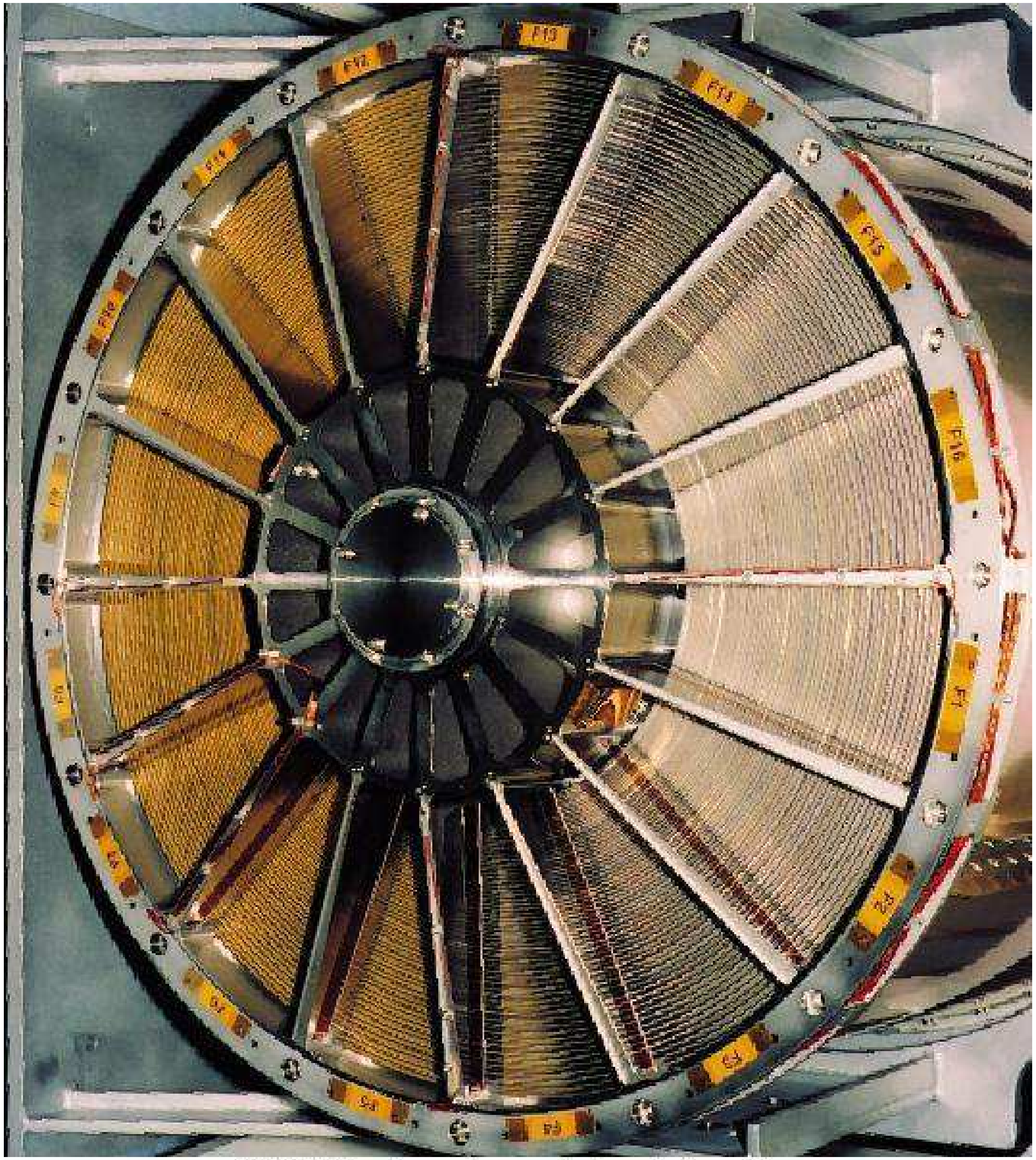
The grazing angle: 2 degrees for the inner pair.

High Resolution Mirror Assembly (HRMA) on Chandra.



Chandra: four nested pairs of mirrors

XMM-Newton mirrors



XMM-Newton mirrors during integration

Image courtesy of Dornier Satellitensysteme GmbH   European Space Agency

Optics:

Wolter Type-I

Nested mirrors:

58

Mirror coating:

gold

Mirror outer diameters:

3.5,...,1.5 m

Focal length

7.5m

PSF FWHM (with detector):

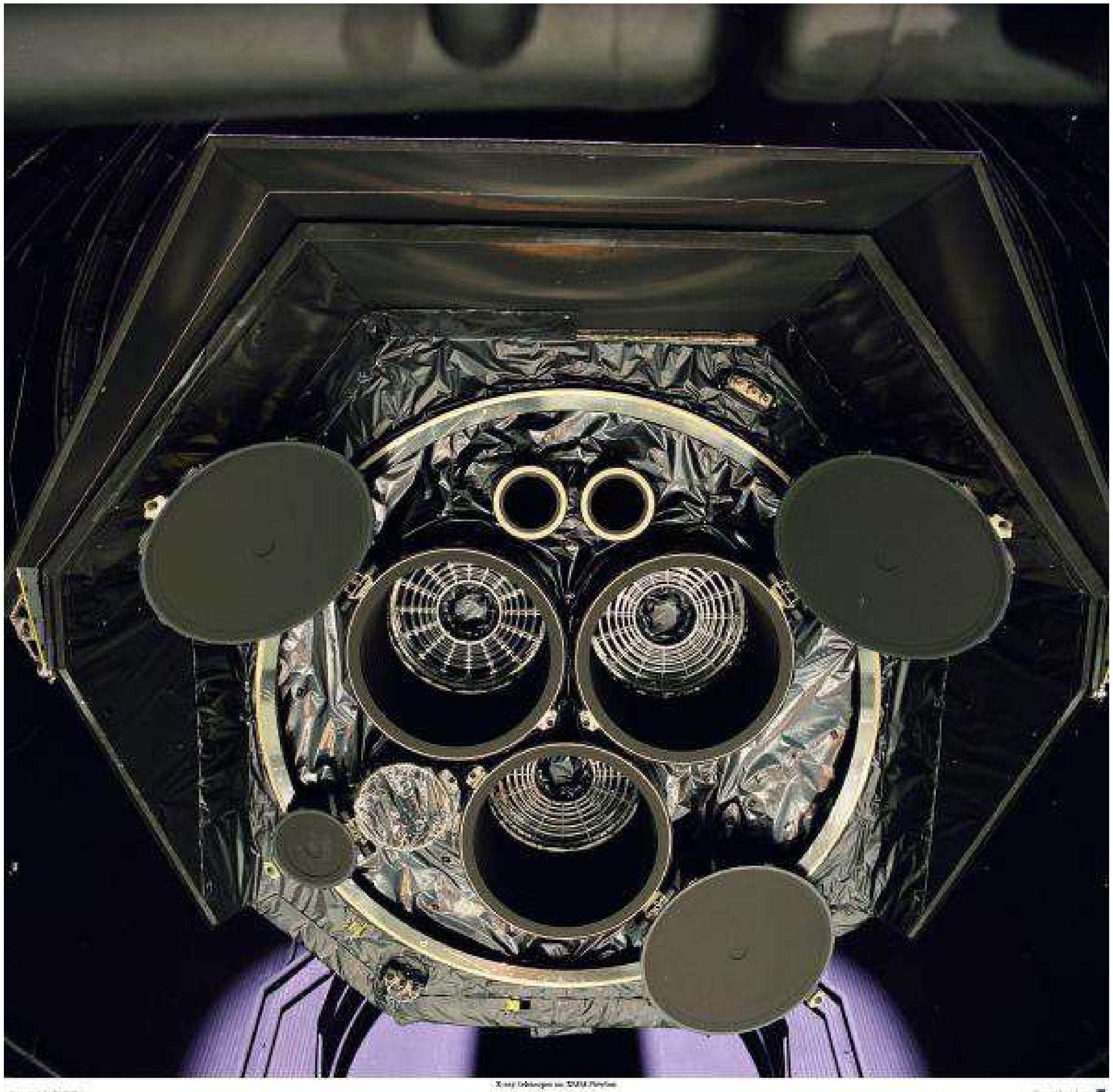
4 arcsec !!!

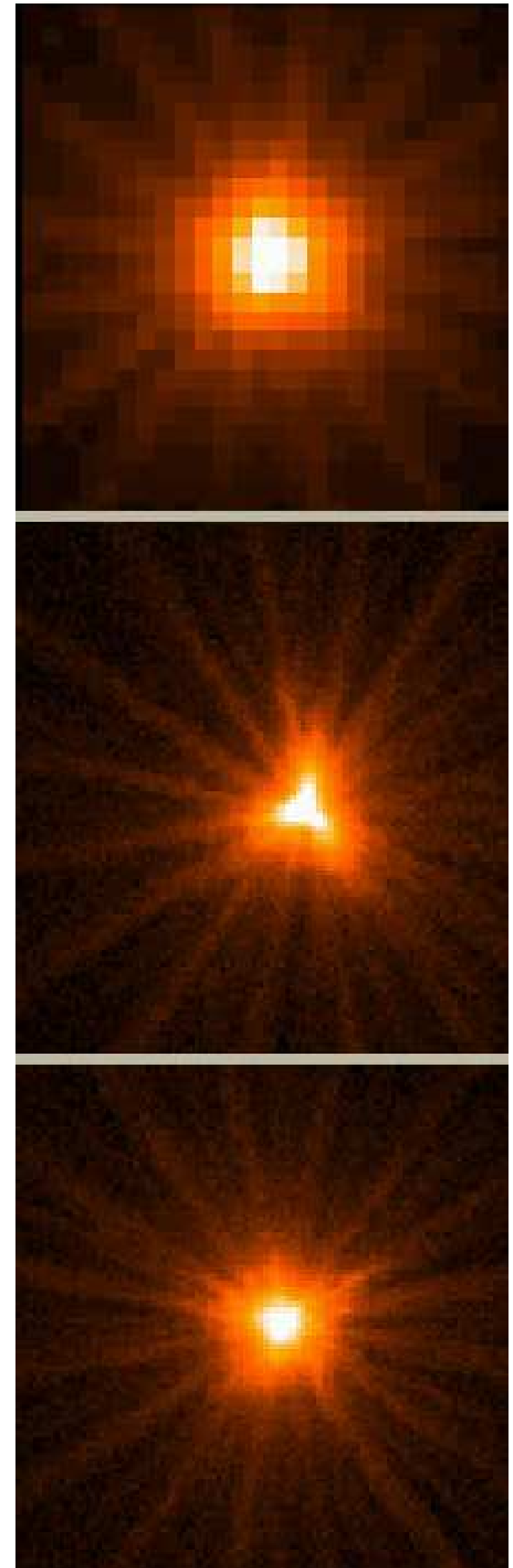
Effective area:

1 keV:2000 cm^2, 8.0 keV:1600 cm^2

Three telescopes of XMM-Newton

Image of the on-axis PSF for the three telescopes



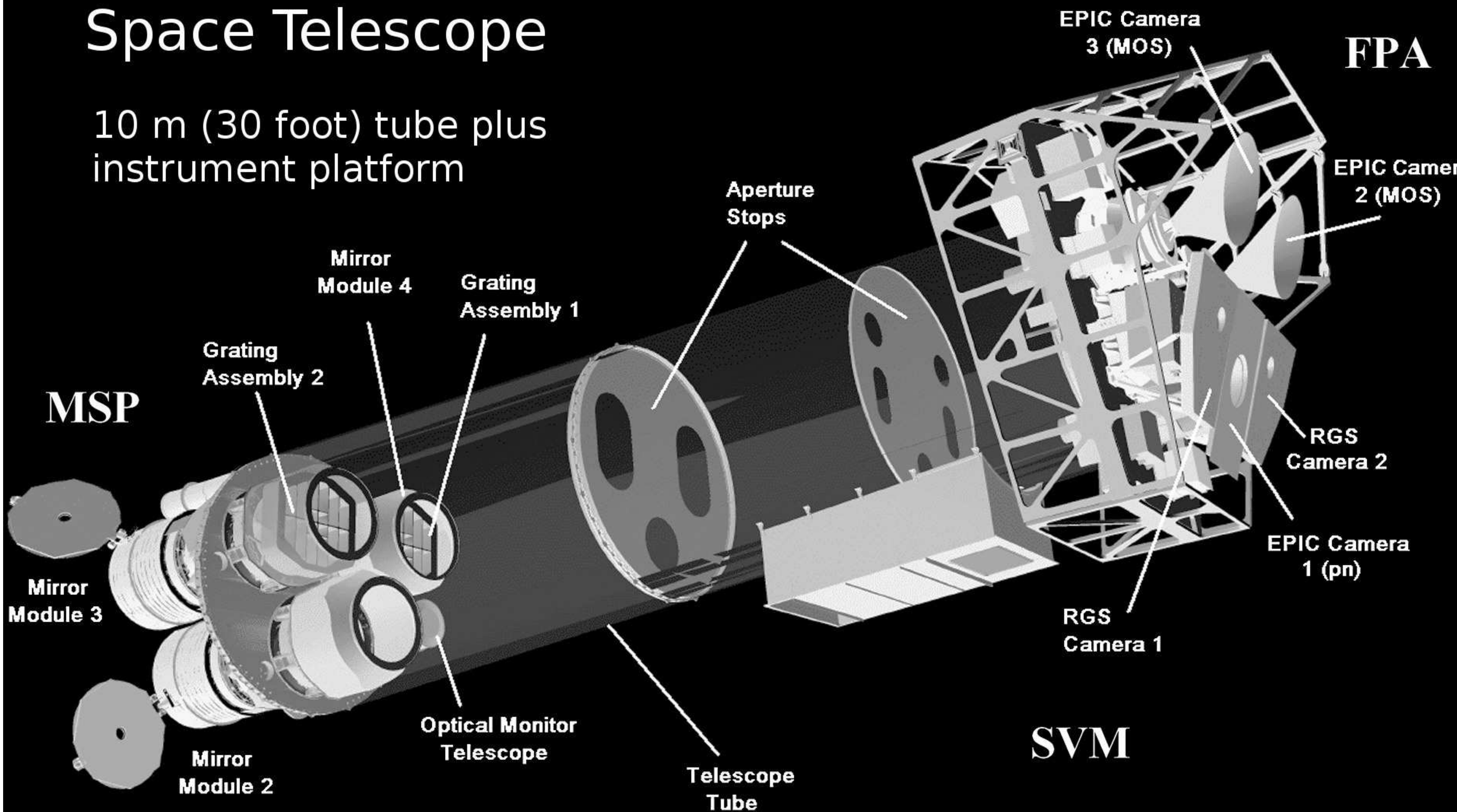


100" × 110"

EPIC PN camera
larger pixels

XMM-Newton X-Ray Space Telescope

10 m (30 foot) tube plus instrument platform

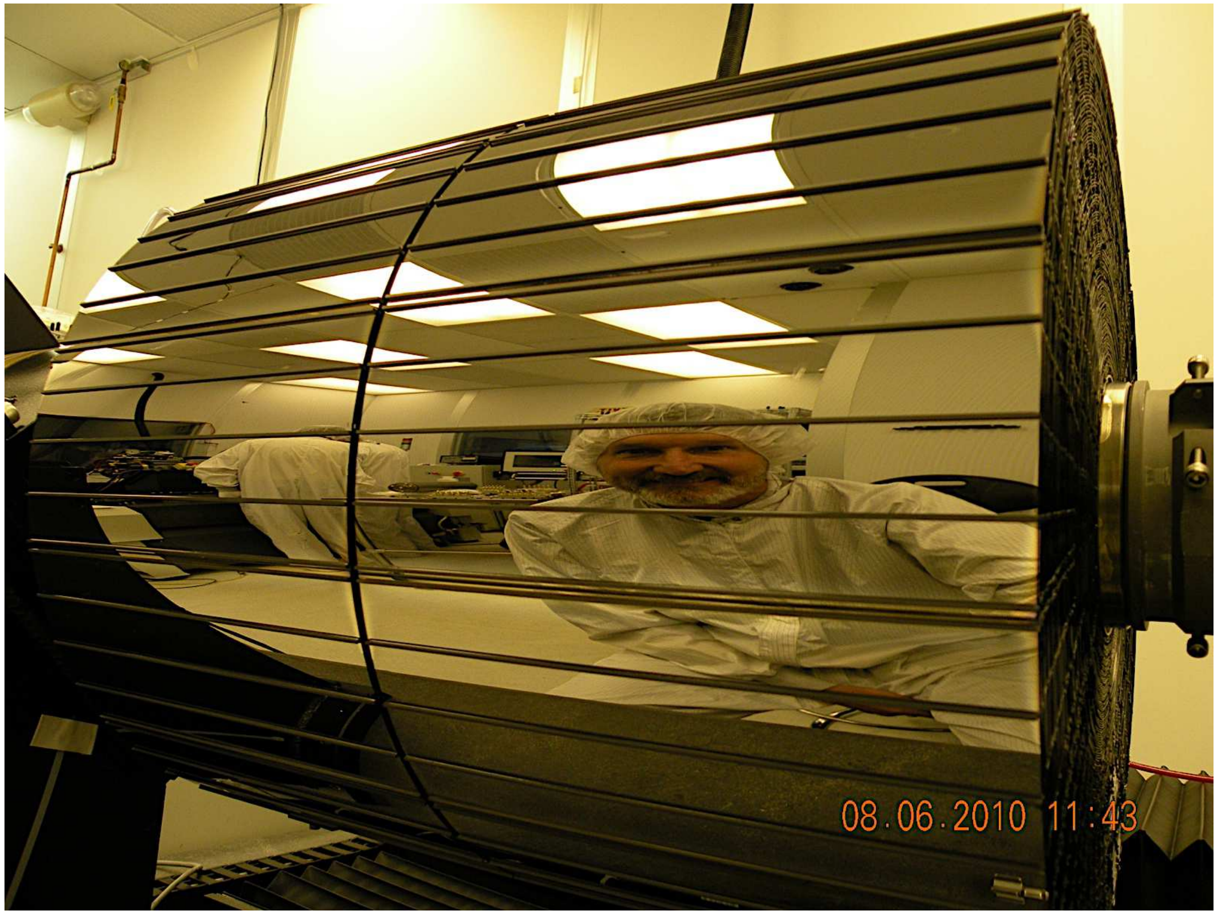


NuSTAR Telescope (2010) 3-79keV

Multilayer Mirror Coatings

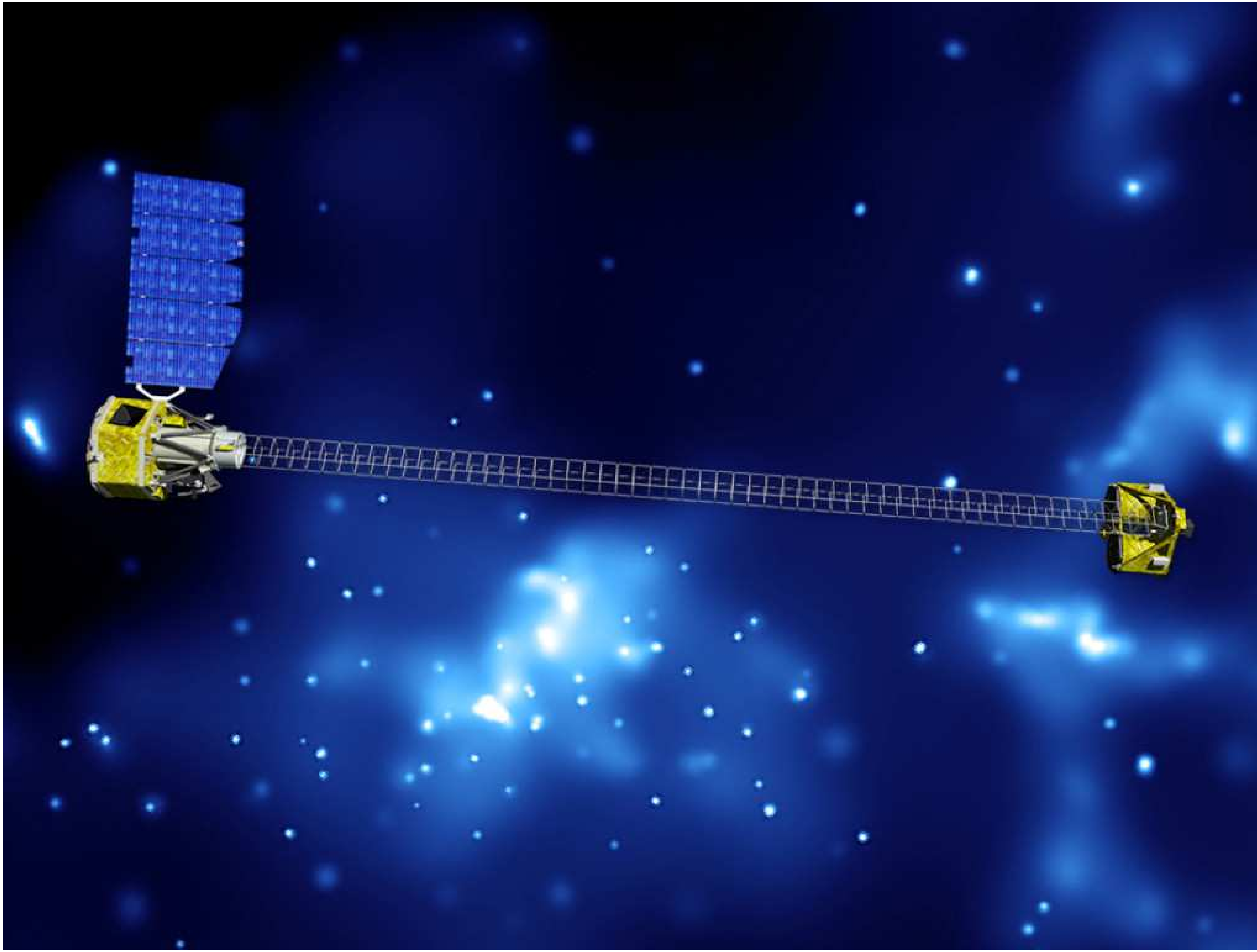
- "Depth-graded multilayers": thin coatings of two alternating materials (low and high density) deposited one on top of the other
- A typical multilayer has 200 pairs of coatings: high-density Tungsten (W) and Platinum (Pt), low density layers are Si, Siliconcarbite (SiC)

130 concentric mirror shells

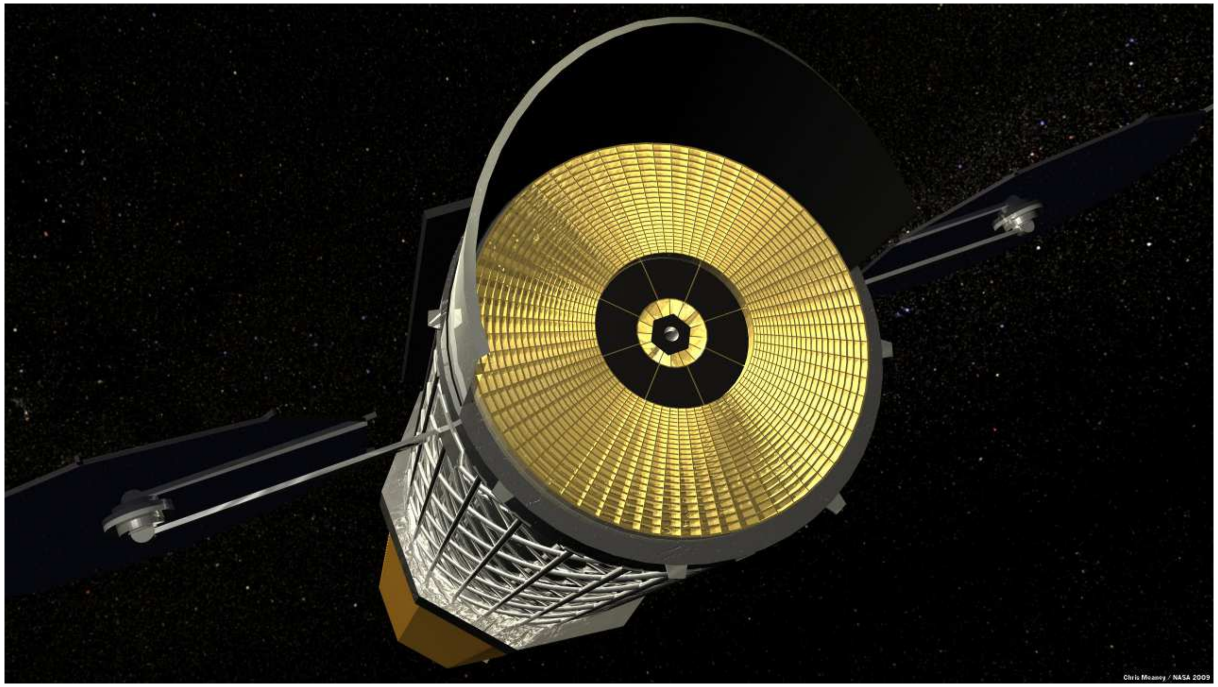


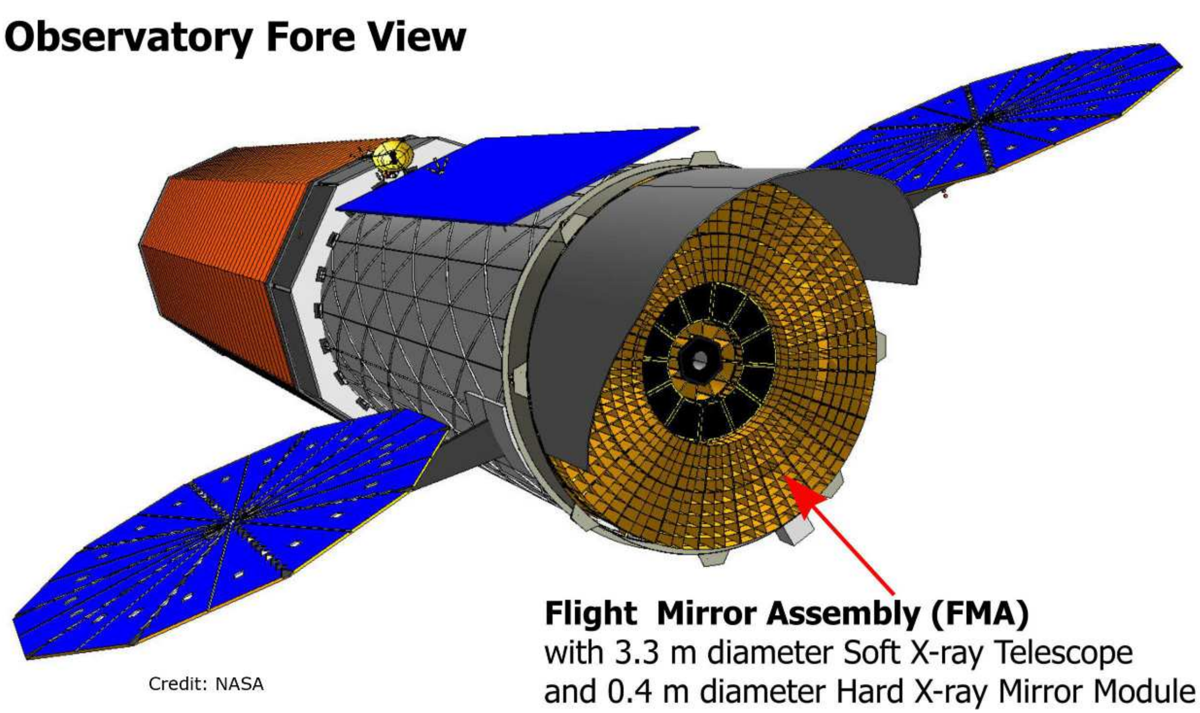
The multilayer stack acts as a crystal lattice and constructive interference creates enhanced reflectivity at high energies up to 79 keV

Conical approximation to parabolic mirror, angular resolution 18”



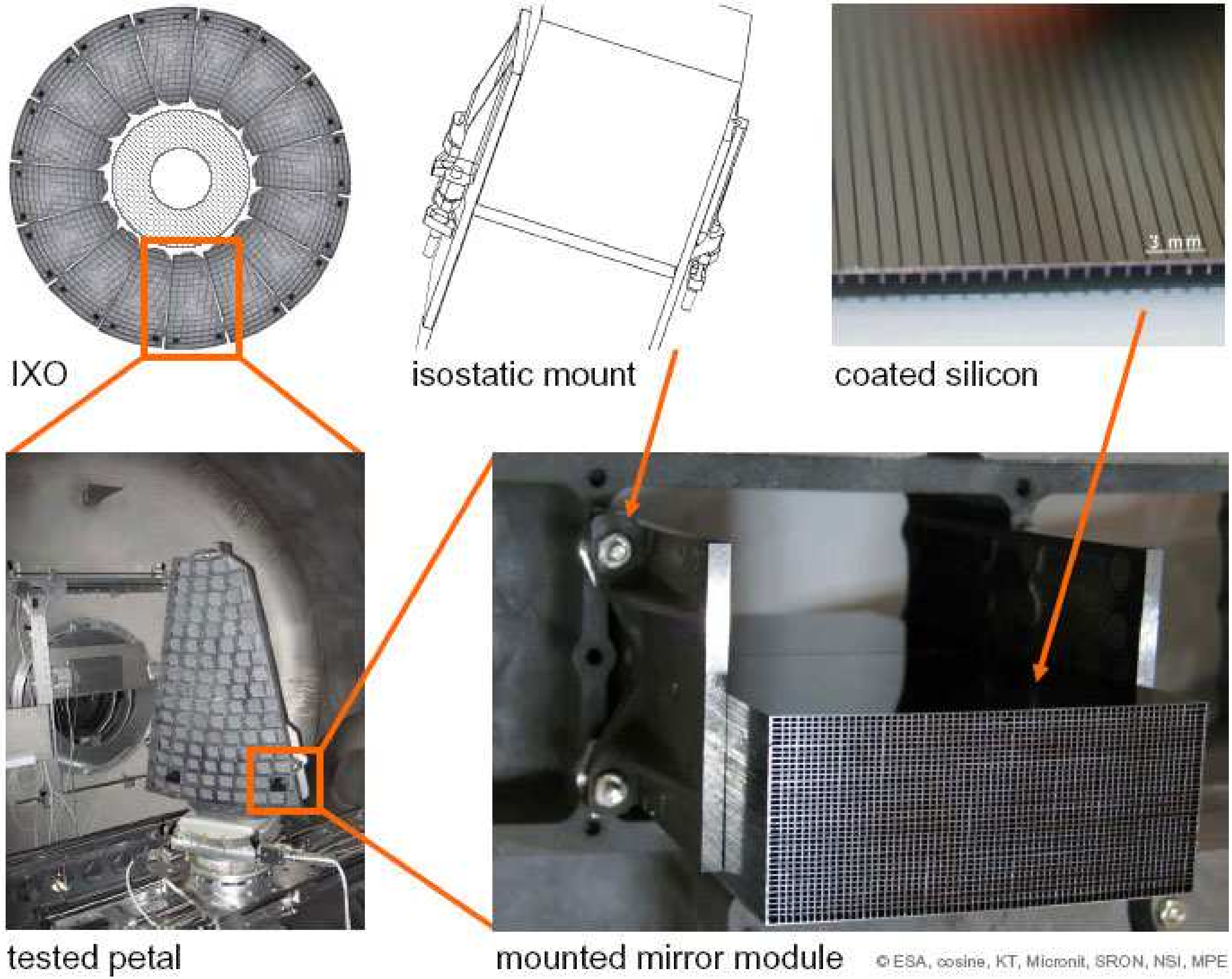
Athena Next Generation X-ray Observatory





Silicon Pore Optics

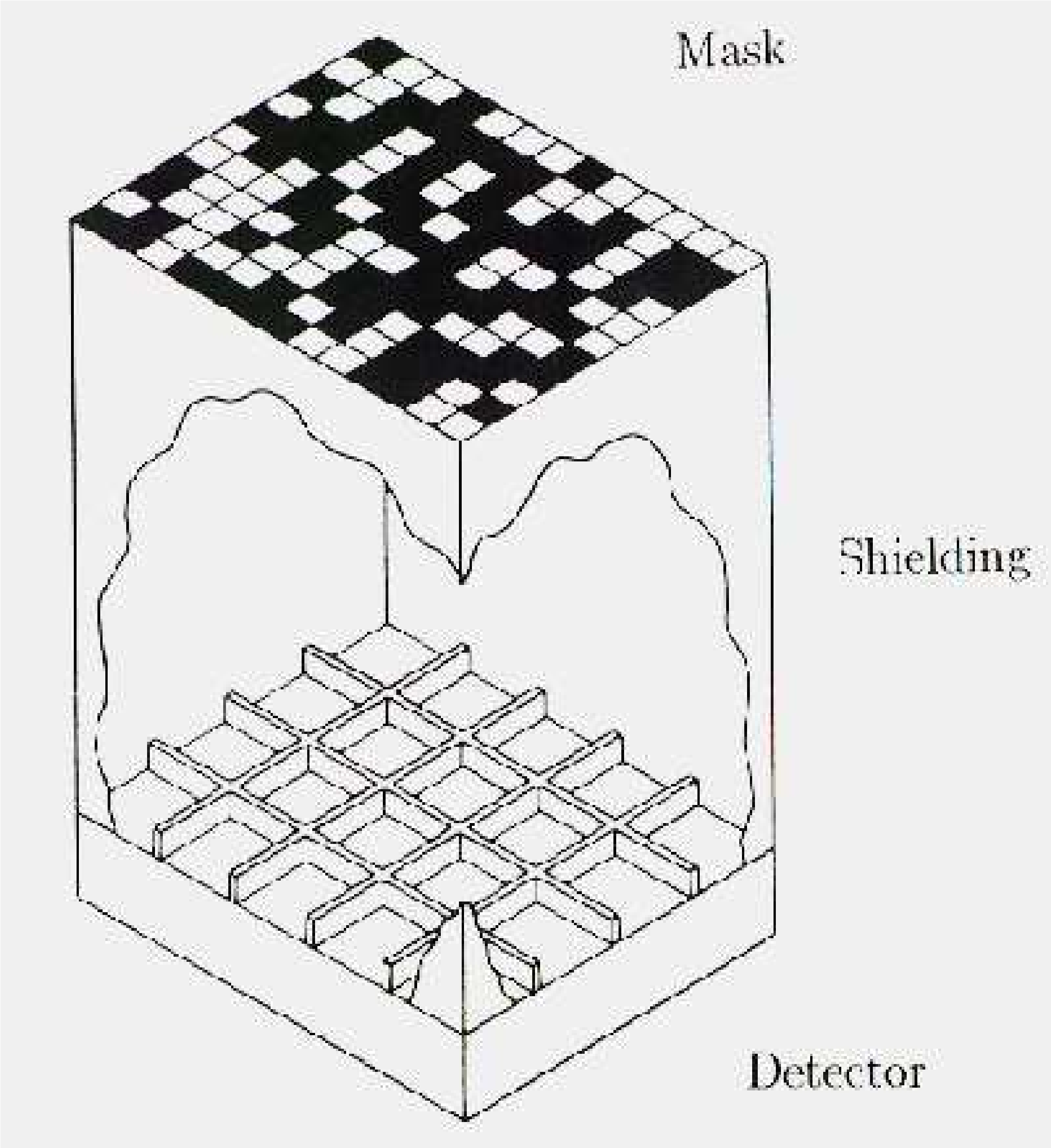
Silicon Pore Optics



Coded Mask Telescopes

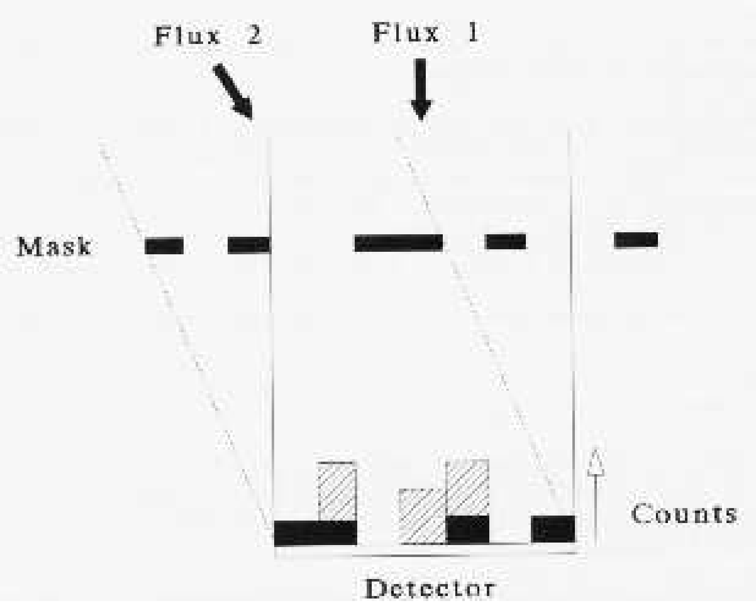
Collimators have no imaging capabilities

Coded Masks: imaging for hard X- and γ-rays



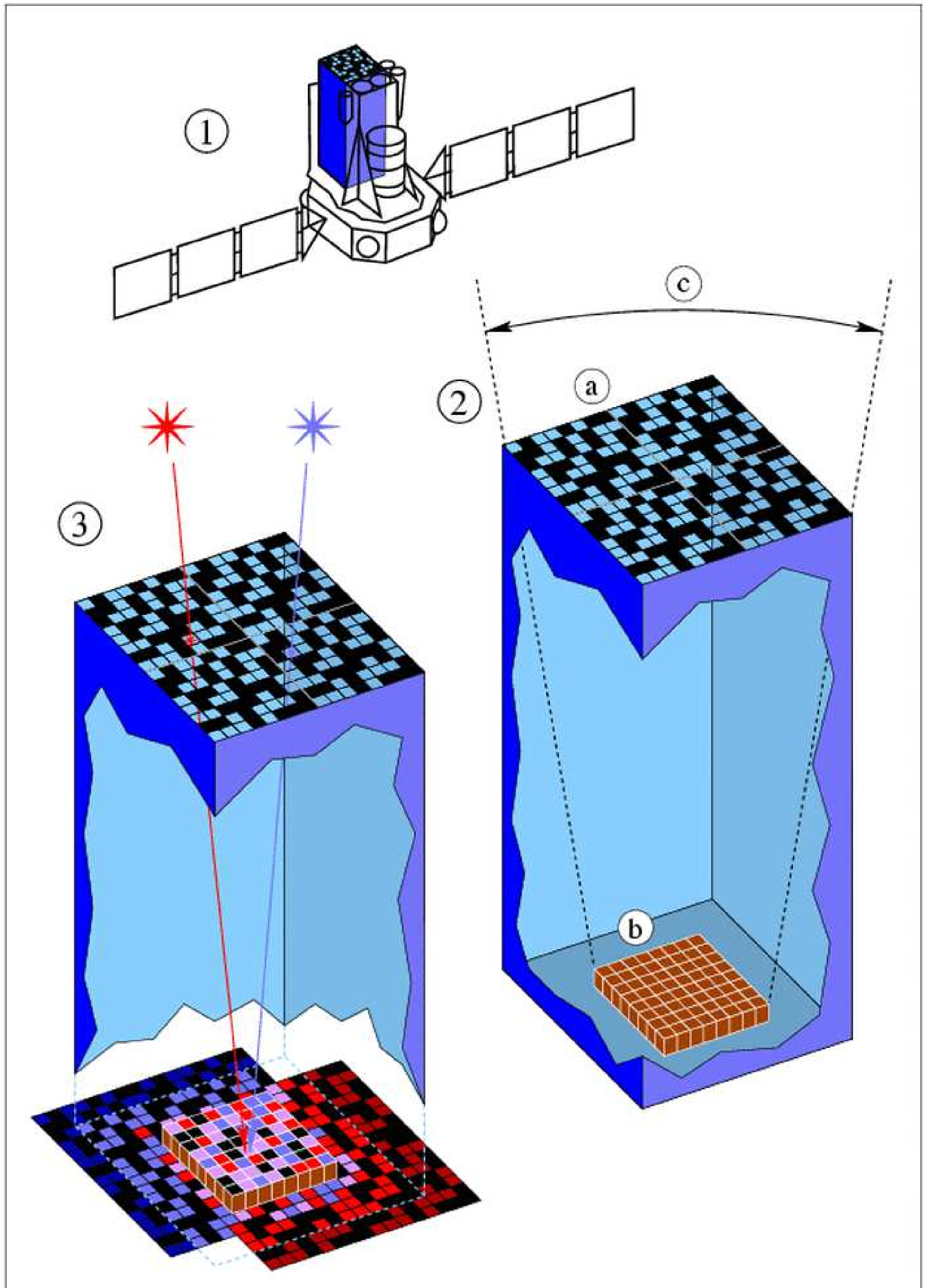
Shift of the projected shadow relative the telescope axis.

For multiple sources: image deconvolution.



http://isdc.unige.ch/Outreach/

IBIS on board of INTEGRAL



http://isdc.unige.ch/Outreach/

Principle iof image reconstraction:
mask shadow on detector plane:

Detector: pixel at (x,y) with "responce"

$R(x,y) = C(x,y) - \langle C \rangle$,

C(x,y): measured signal in the pixel

$\langle C \rangle$ average signal in the detector

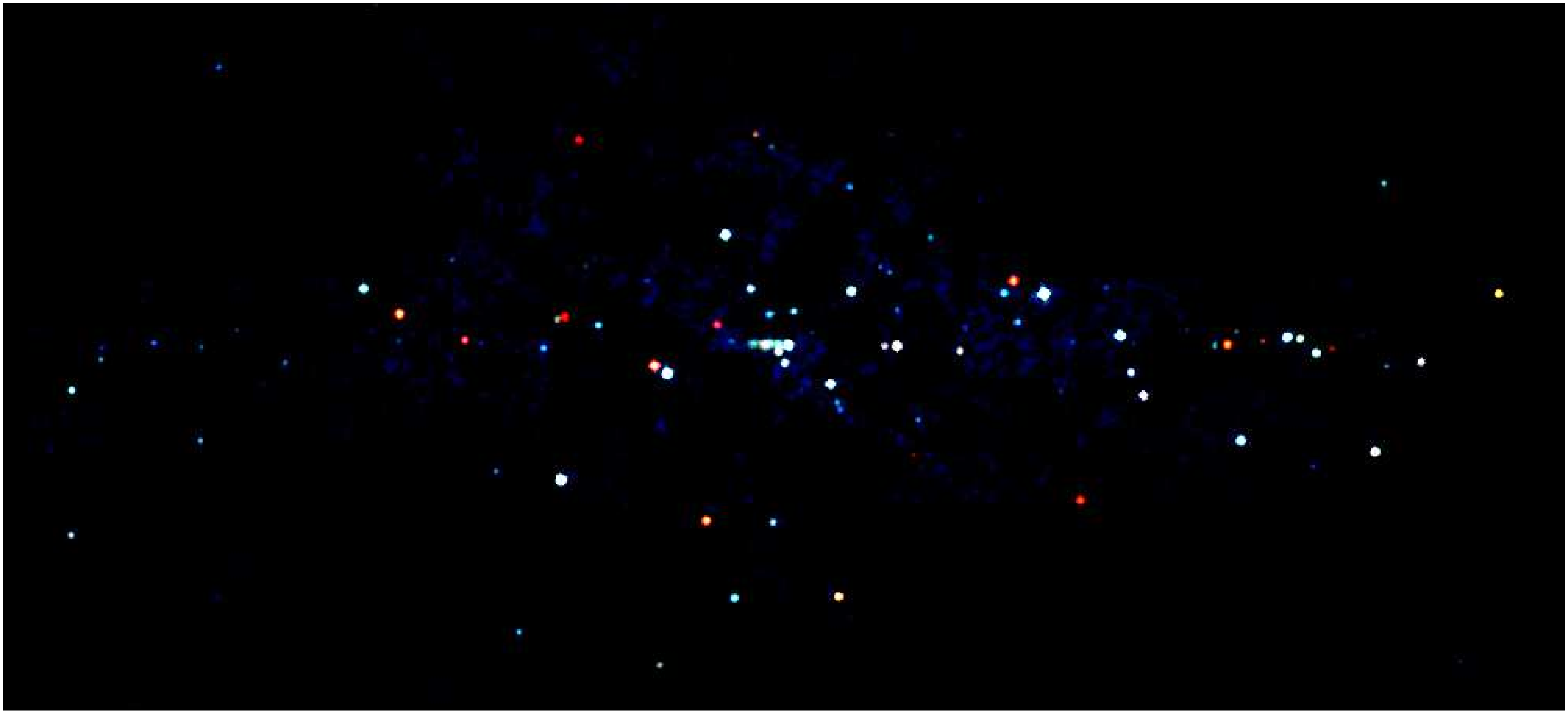
Compare R(x,y) to response expected
if there were a source at α, δ on the sky
using cross-correlation function CCF(α,δ)

CCF(α,δ)= $\int\int R(x,y)R(x,y;\alpha,\delta)\mathrm{d}x\mathrm{d}y$

CCF has peak if match with real source

Subtract this source and repeat
"IROS" iterative removal of sources

Milky Way with Integral



http://www.sciops.esa.int/

mainly stellar remnants: black holes and neutron stars

Swift X-ray Telescope (2004)

- Coded Mask (BAT) 15-150 keV, one steradian, position 4 arcmin within 15 sec
- Walter I (XRT) 12 nested mirrows, 0.2-10 keV, position with 2”
- Cassegran UVOPT (1700-6500 Å)

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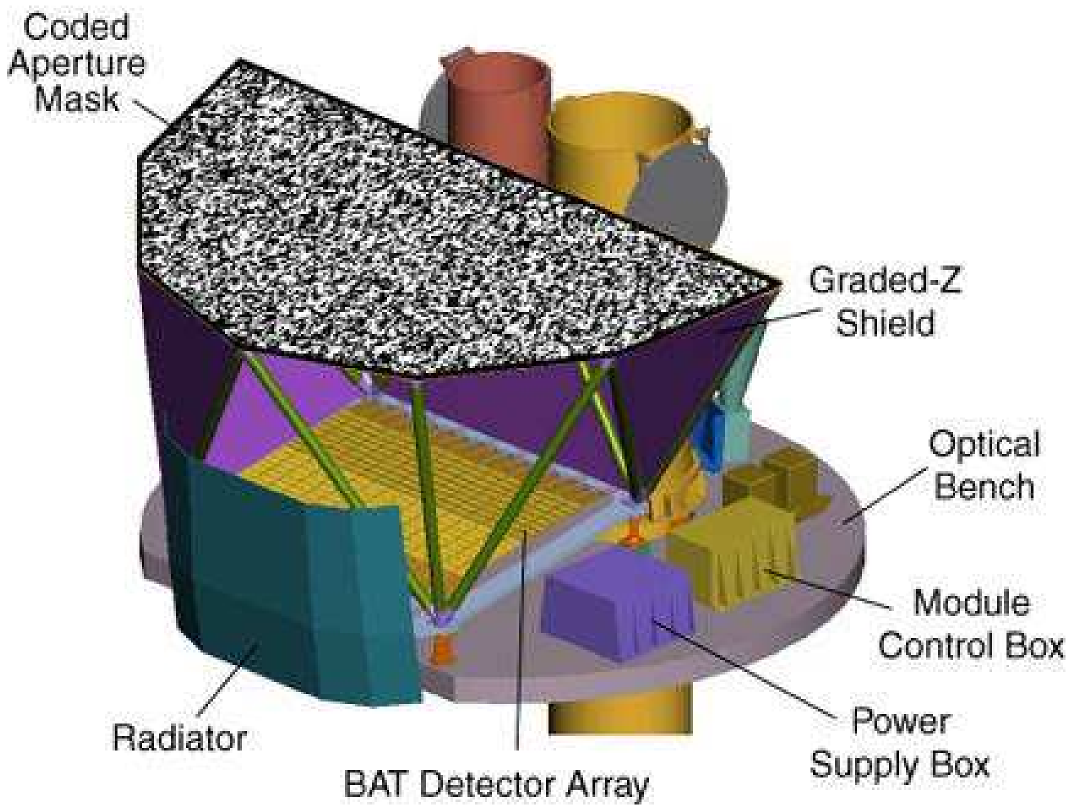
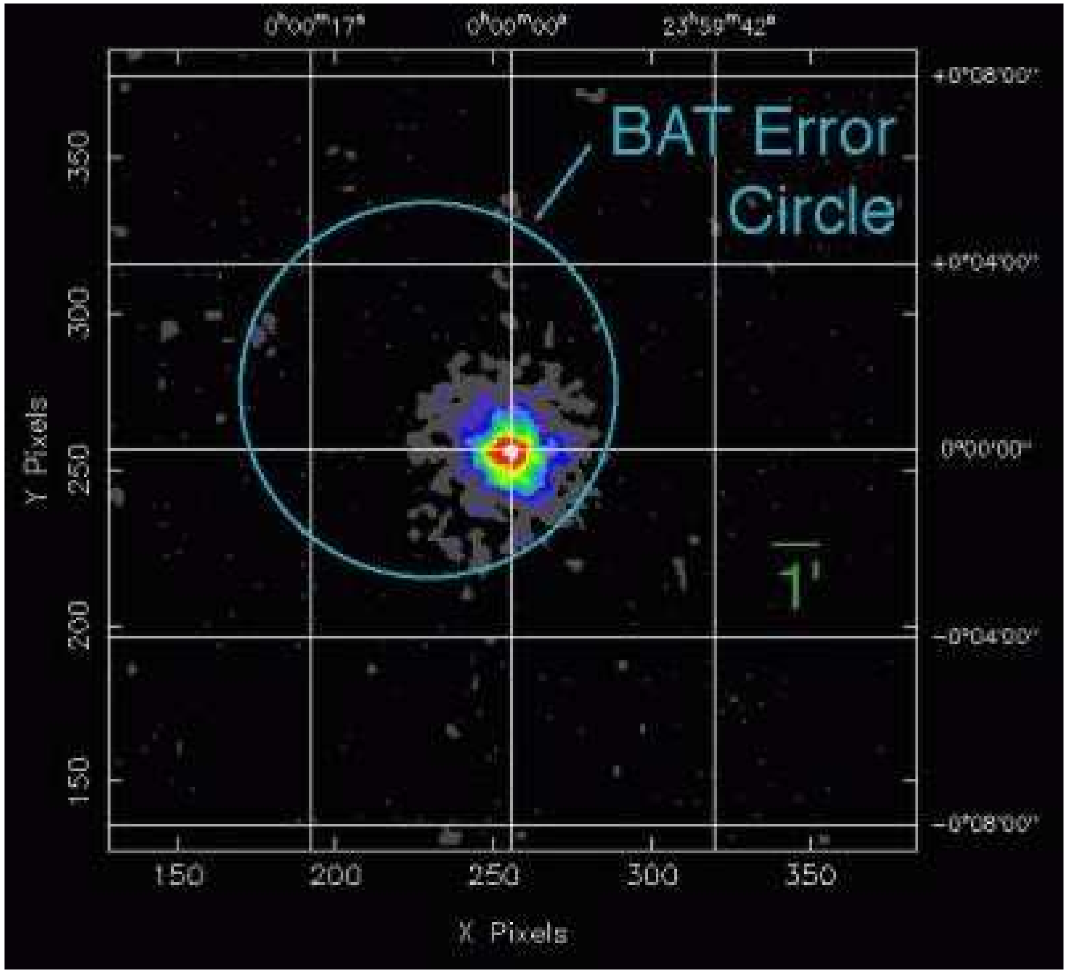
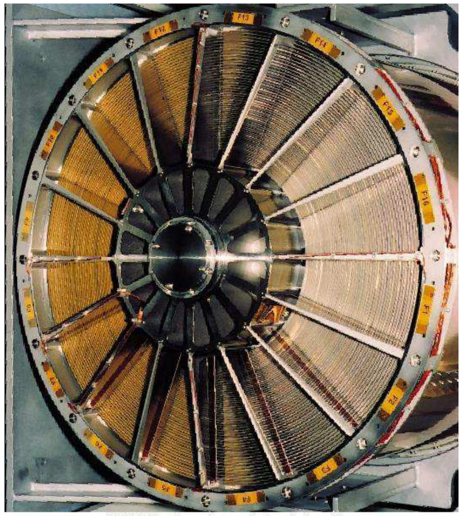




X-ray telescopes: Summary

Collimators (RXTE)


XMM-Newton mirrors during integration
Image courtesy of Dornier Satellitensysteme GmbH European Space Agency

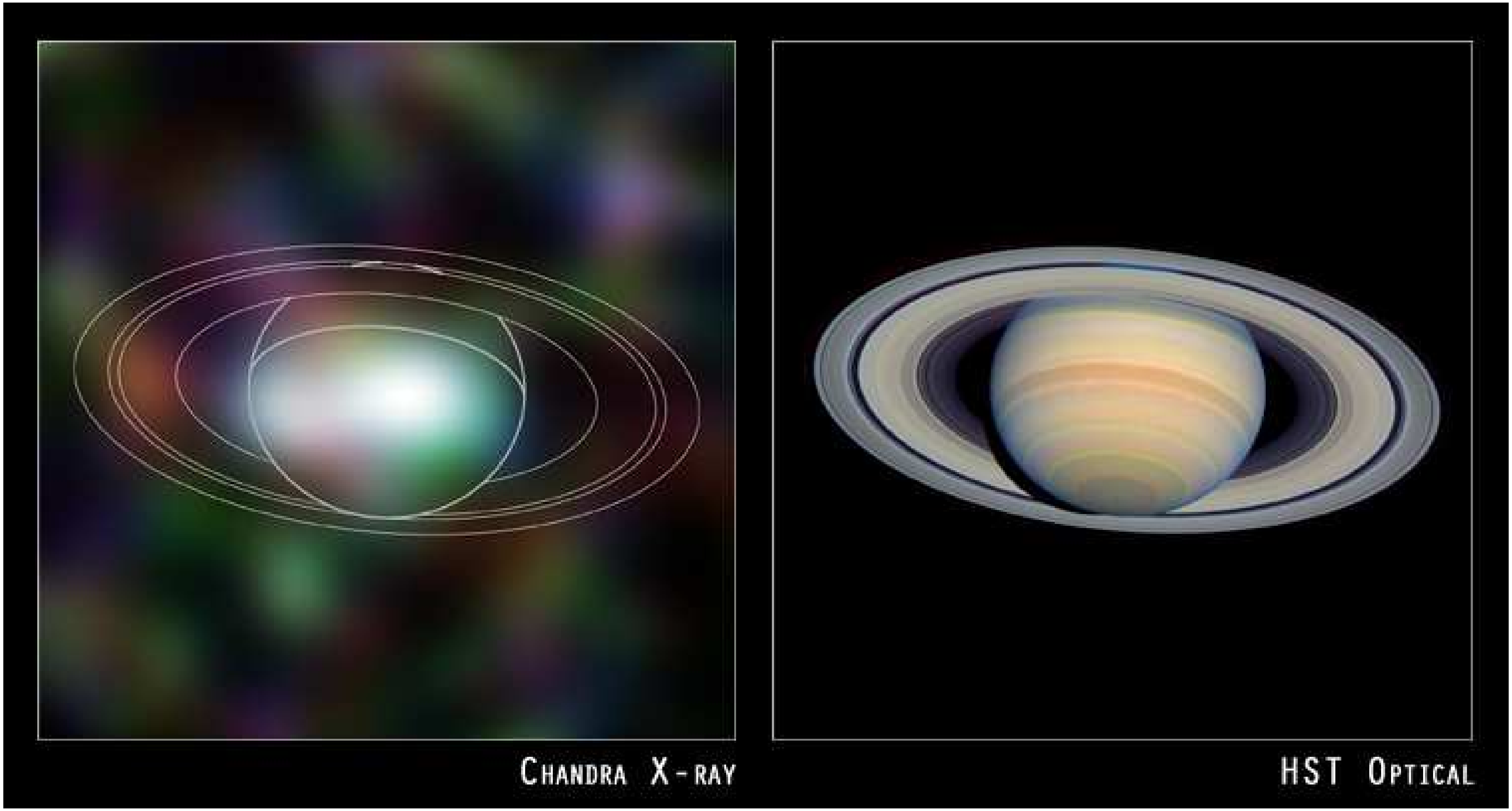
Wolter I mirrors

XMM-Newton, Chandra, SWIFT, SUZAKU

New Technology: Multylayer, Silicon Pore Optics

FUTURE MISSIONS: eROSITA, ASTRO-H, ATHENA, ...

III. X-ray Detectors



http://chandra.harvard.edu/resources/

Introduction

Ideal detector for satellite-borne X-ray astronomy?

- High spatial resolution
- Large useful area
- Excellent temporal resolution
- Good energy resolution
- Broad bandwidth
- Stable on timescales of years
- Very low internal background
- Immune to damage by the in-orbit radiation
- Require no consumables
- Simple and cheap
- Light in weigh
- A minimal power consumption
- No moving parts
- Low data rate

Such a detector does not exist!

from "X-ray Detectors in Astronomy" G.W.Fraser

Types of X-ray detectors

We want to detect a weak source against a fairly strong background.

1 ph with E 1..10 keV per 1 cm^2 per s is a strong X-ray source

Integrating detectors (such as film) not much useful

Source detection is done on a photon-by-photon basis.

Non-imaging and imaging detectors

Ionization detectors: X-ray hits detector and ionizes an atom:

Photo-electric absorption

Resulting free electron will create secondary electrons

Electric field: the electrons can be collected and counted.

Mesured charge is proportional to the deposited energy

Microcalorimeters: Exited electorns go back to the original energy

Returning to ground state they loose energy to heat

Measured heat is proportional to the deposited energy

Background.

Background results from:

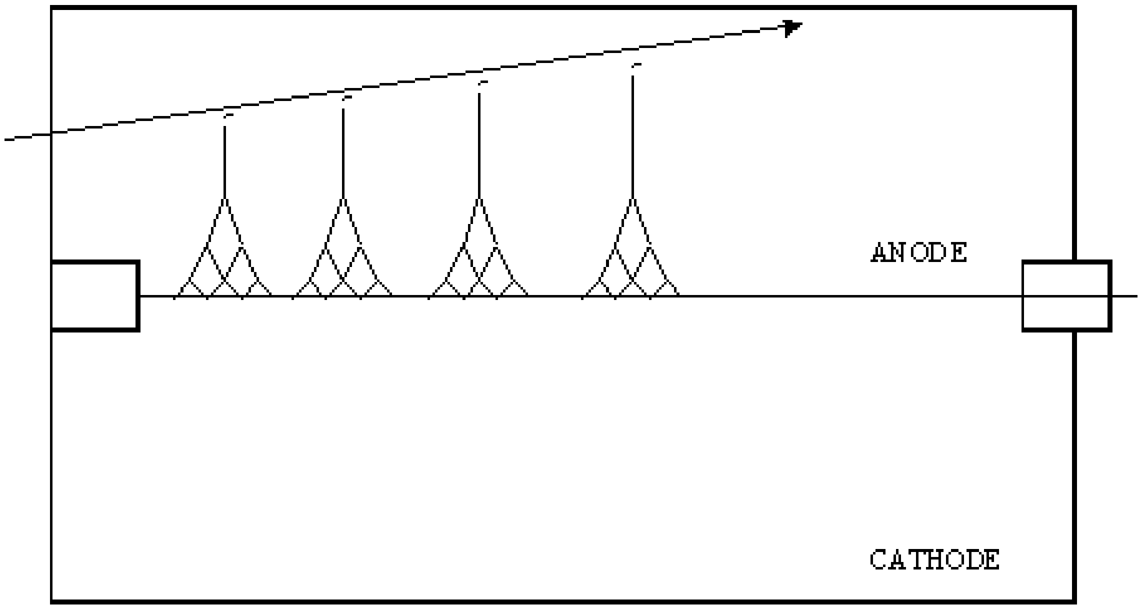
* Particles and Photons
* Particles: cosmic rays, inreplanetary rays, radiation belts around Earth
* radioactivity of detector, trapped electrons, solar activity..
* Cosmic X-ray background, unresolved sources, secondary UV photons
* optical leakage, et cet...

Understanding the background is key to correct intrpreatation ofthe data

Non-Imaging Instruments: how to reject background?

- energy selection: reject events with non X-ray energies
- rise-time discrimination
- ...

Proportional counters - Non-imaging



www.orau.org/ptp/

The Size of the Pulse:

1. Operating Voltage.
The higher the operating voltage, the larger each avalanche and the larger the pulse.

2. Energy of X-ray photon.
The greater the energy of photon the larger the number of primary ions the larger the number of avalanches, and the larger the pulse.

Measured voltage:

$$\delta U = -\frac{eN}{C} \cdot A$$

A is amplification factor ($10^4 ... 10^6$)

A is constant, voltage puls $\propto eN$ $\propto$ energy

Propotional counter.

Photoelectric Absorption

Photoelectric interaction of X-ray with Si atoms generates electron-hole pairs.

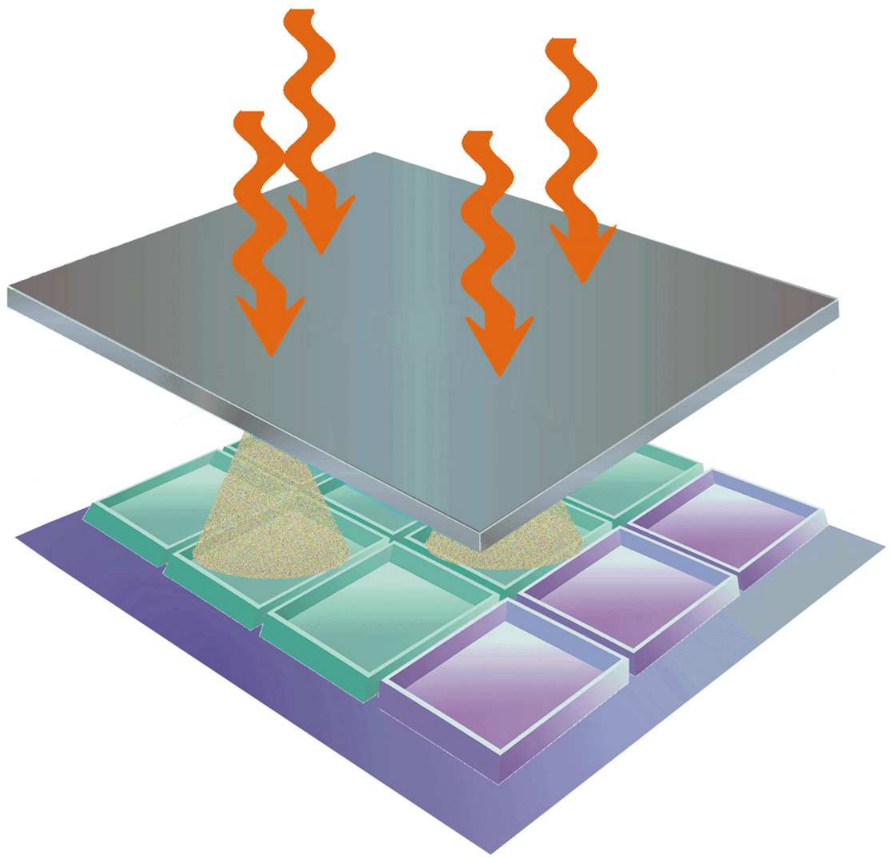
On average: $Ne = E_X/w$, Ne = number of electrons, E_X = energy of X-ray photon
W ~ 3.7 eV/e- (temperature dependent)

X-ray creates a charge cloud which can diffuse and/or move under influence of an electric field

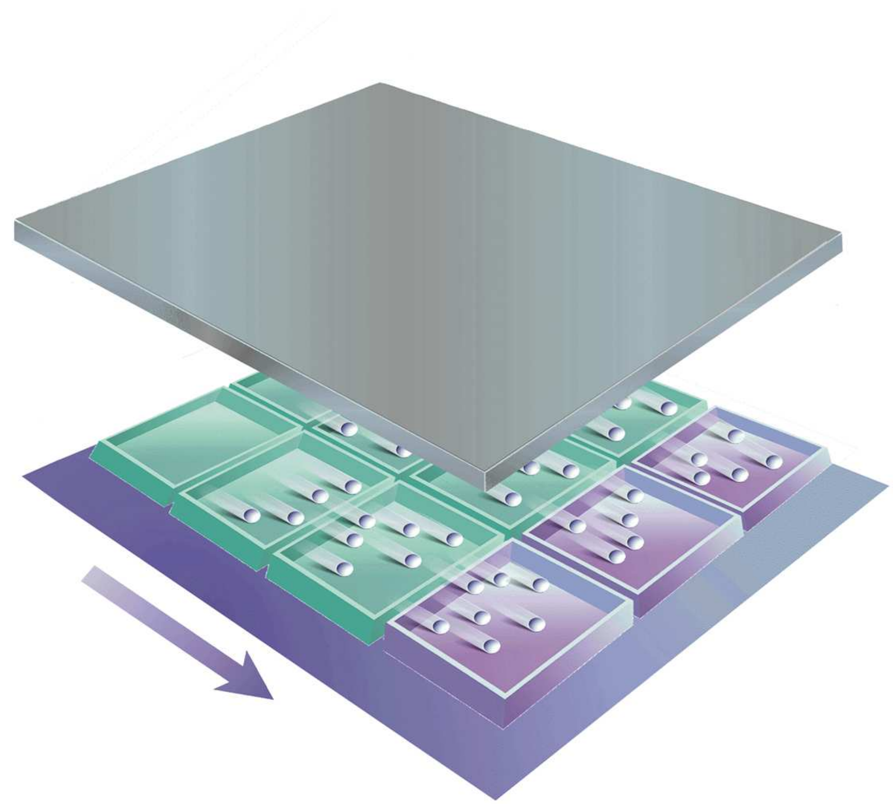
A single metal-oxide-semiconductor (MOS) storage well, the basic element in a CCD

- X-ray CCDs operated in photon-counting mode
- Spectroscopy requires 1 photon interaction per pixel per frametime
- Minimum frametime limited by readout rate
- Tradeoff between increasing readout rate and noise

Schematic illustration of Chandra CCD



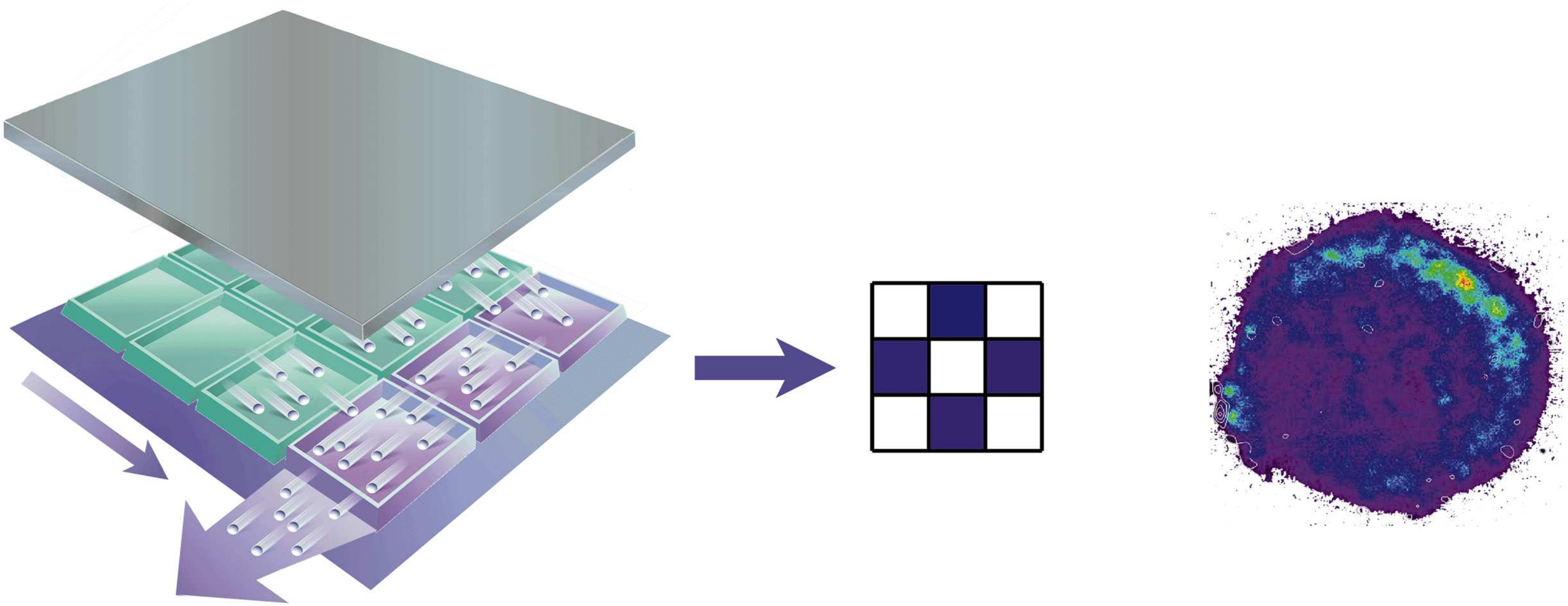
(1) Incident x-ray produces shower of electrons in selected pixels



(2) Voltage moves electrons to the right to "count-out" row

http://chandra.harvard.edu/resources/illustrations/instrumentsSchema.html

Schematic illustration of Chandra CCD



(3) Clocked voltage moves electrons out of count-out row

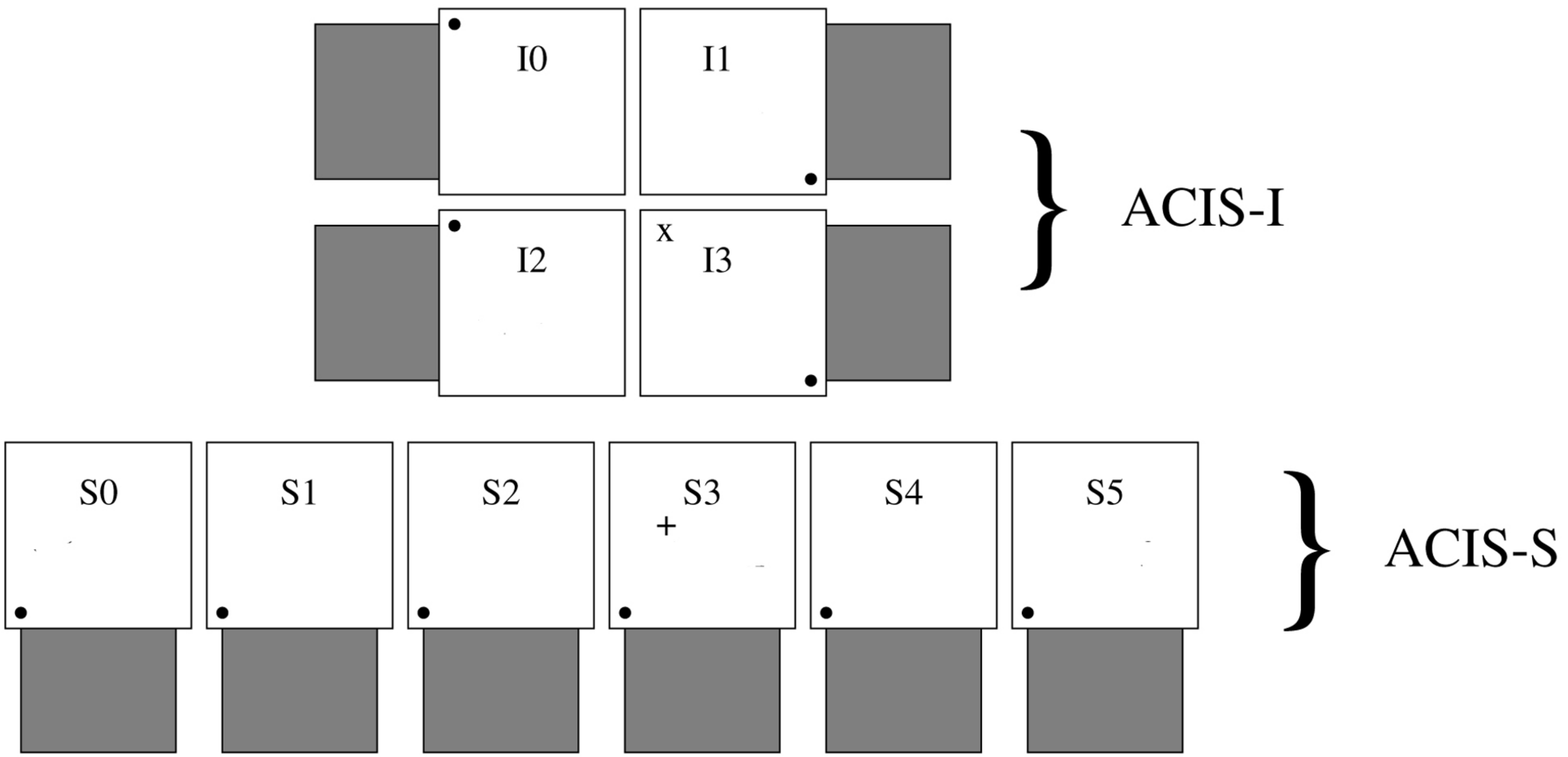
(4) Computer reconstructs image (9 pixels)

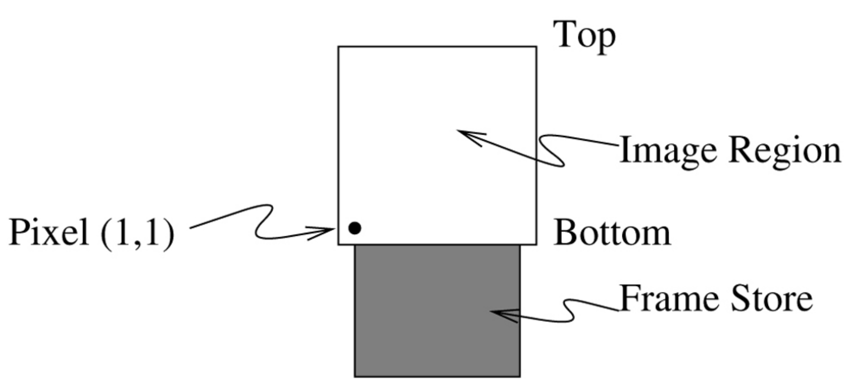
AXAF CCD's will have ~ 1 million pixels

http://chandra.harvard.edu/resources/illustrations/instrumentsSchema.html

Chandra ACIS: Advanced CCD Imaging Spectrometer

ACIS FLIGHT FOCAL PLANE





10 chips, 8 FI, 2 BI

Each CCD 1024 x 1024 pixels

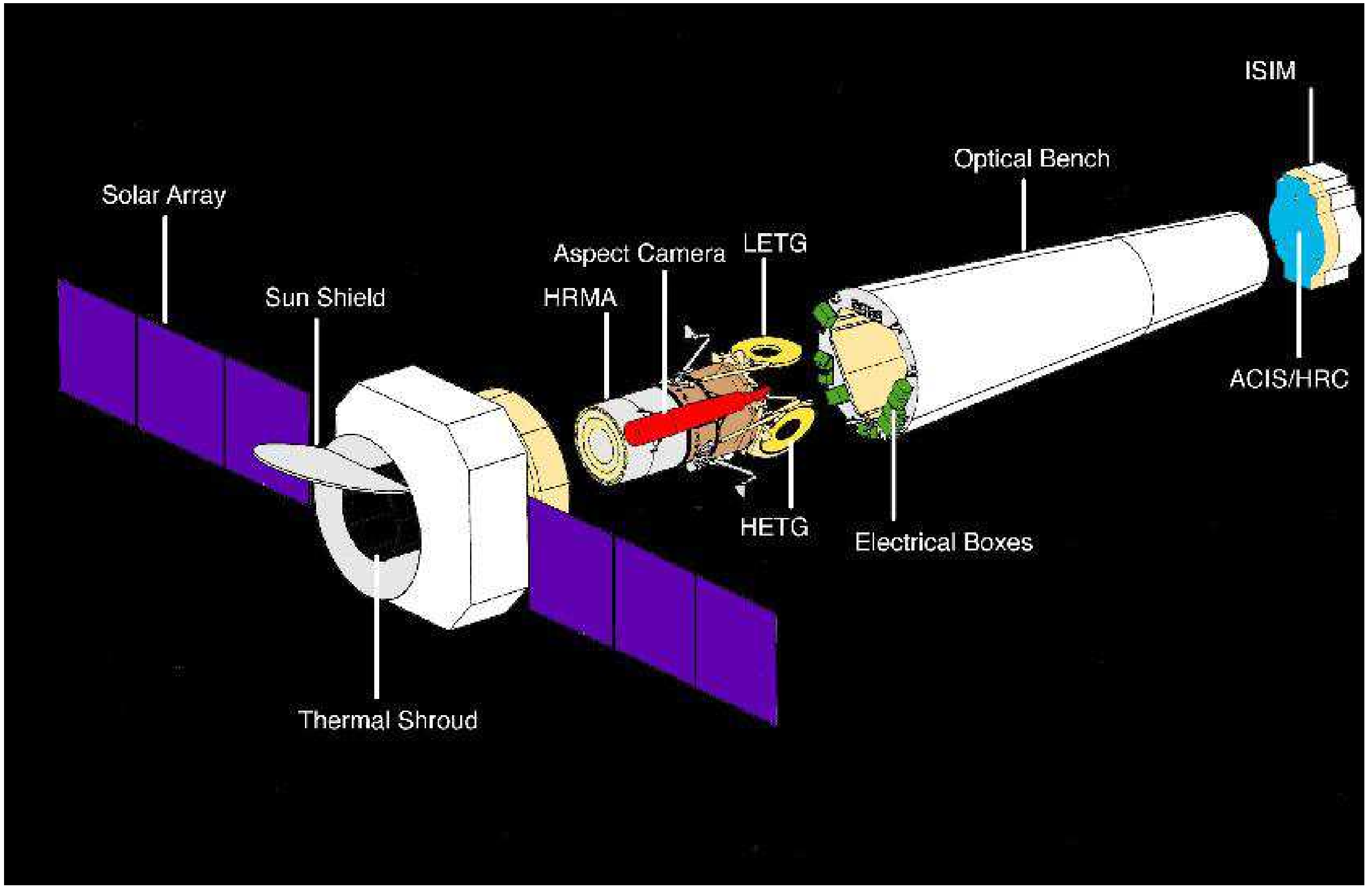
Pixel size 24 micron (0.5 arcsec)

Array size 17 x 17 arcmin

Nominal frame time 3.2s

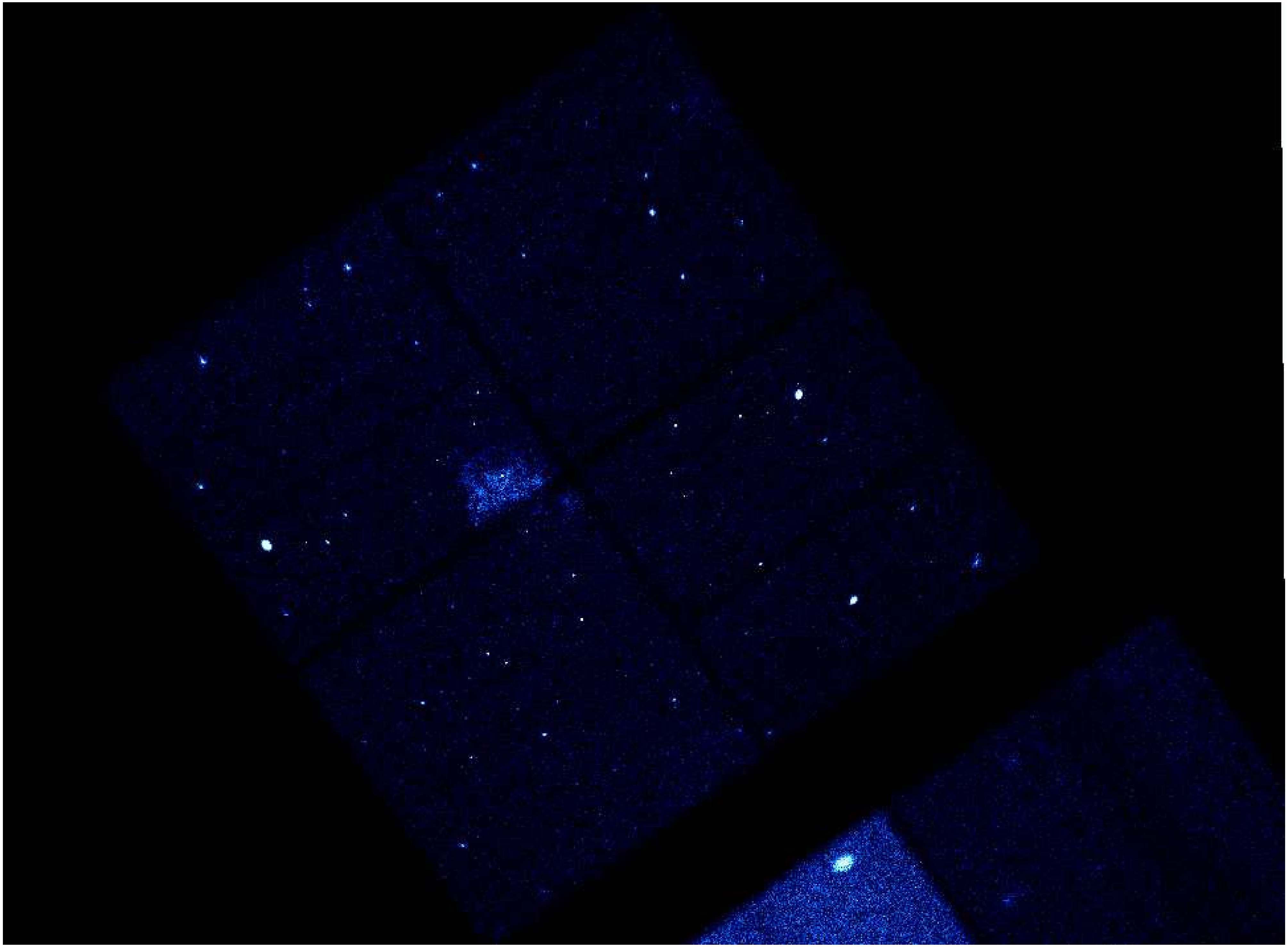
http://asc.harvard.edu/proposer/POG/

Chandra Spacecraft

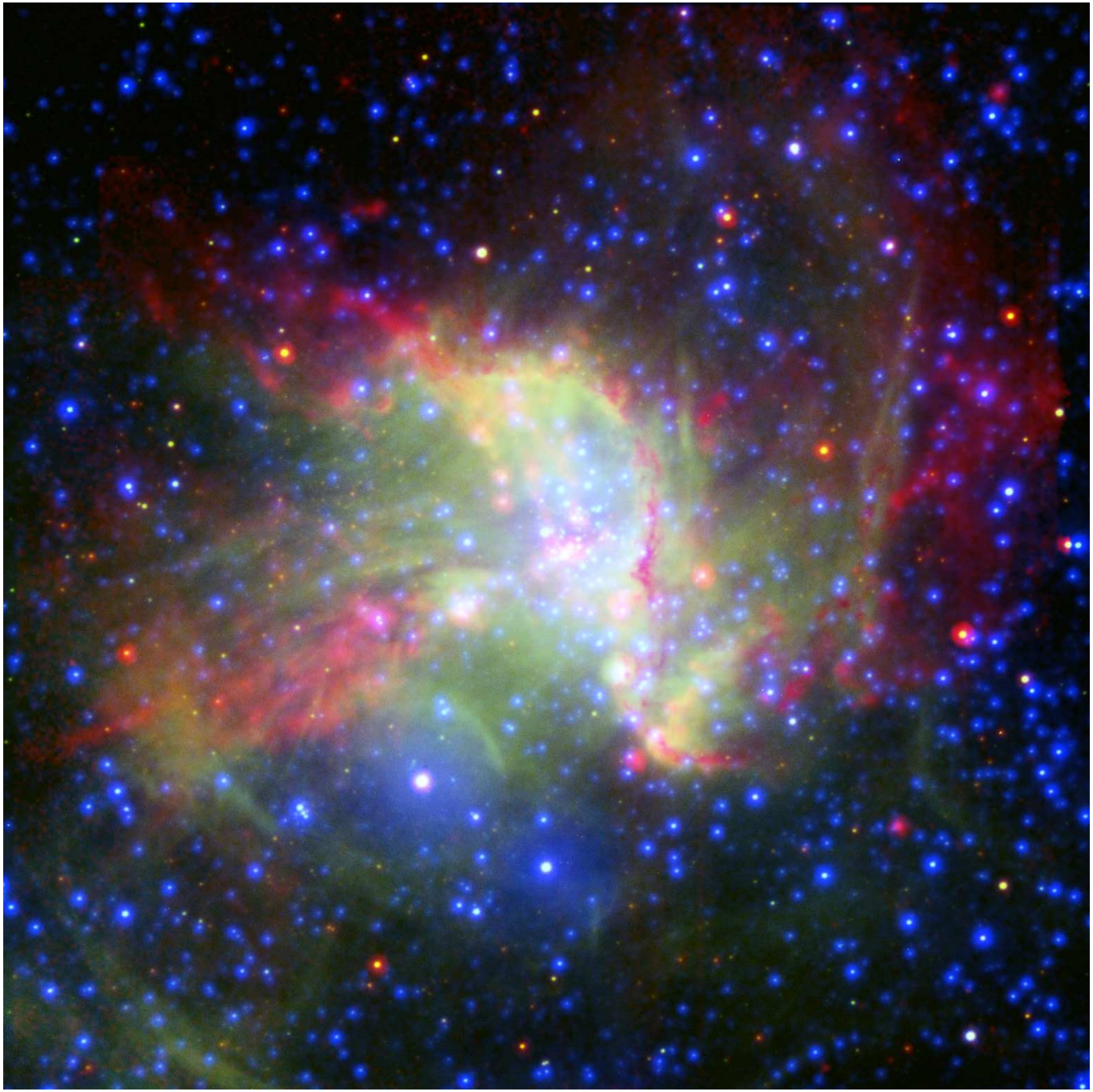


http://chandra.harvard.edu/resources

ACIS image of NGC346 in the SMC



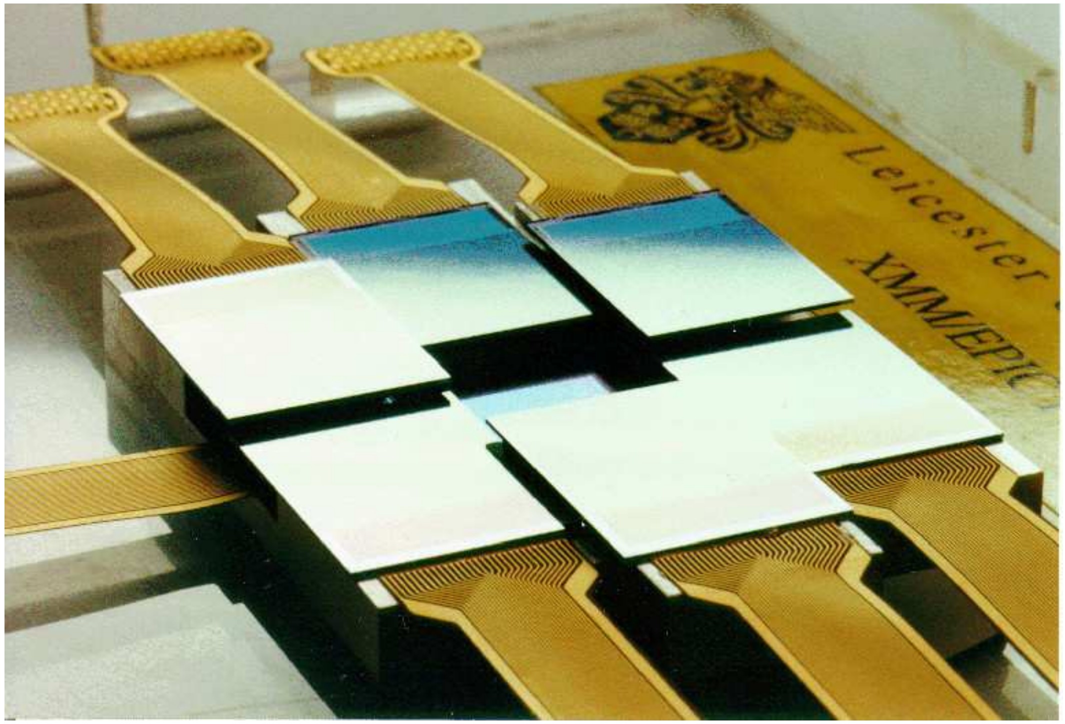
NGC346: X-ray + optic + IR

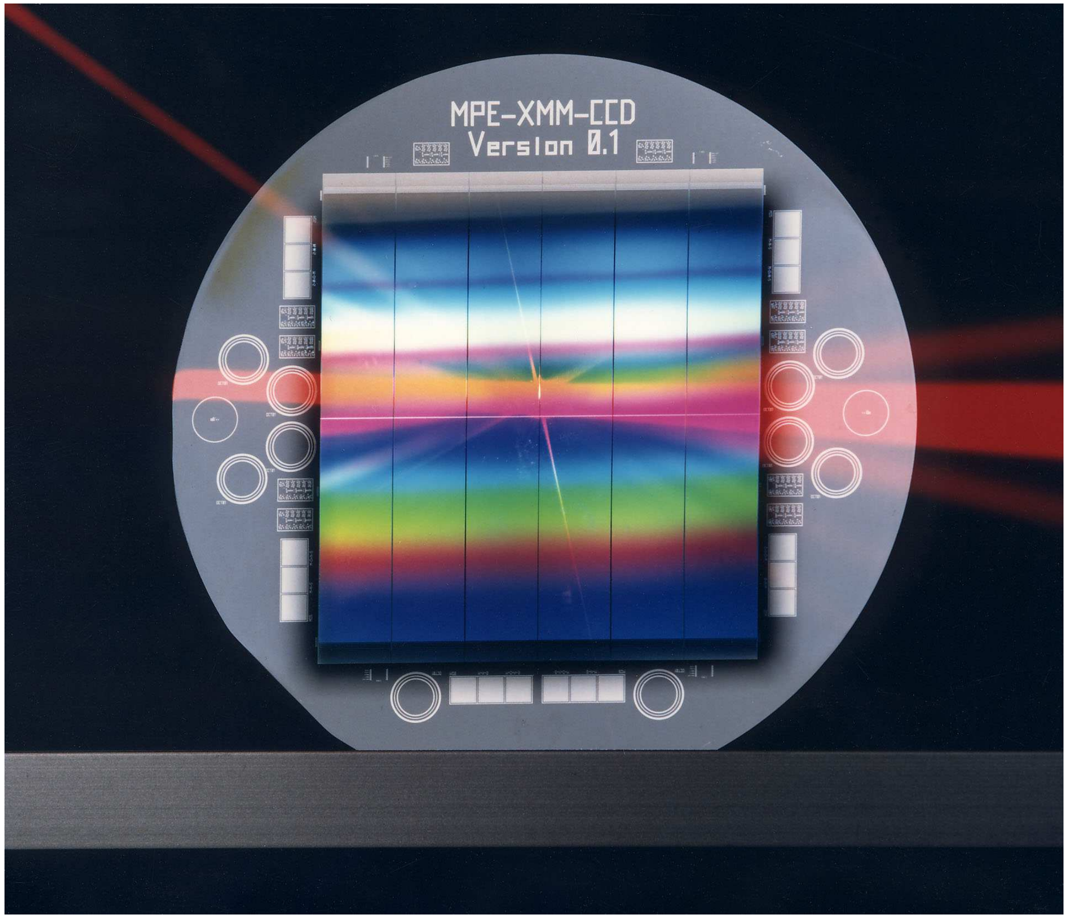


XMM-Newton has 5 cameras

- MOS1,2 and PN = EPIC

RGS1 and RGS2





XMM-Newton has 5 cameras

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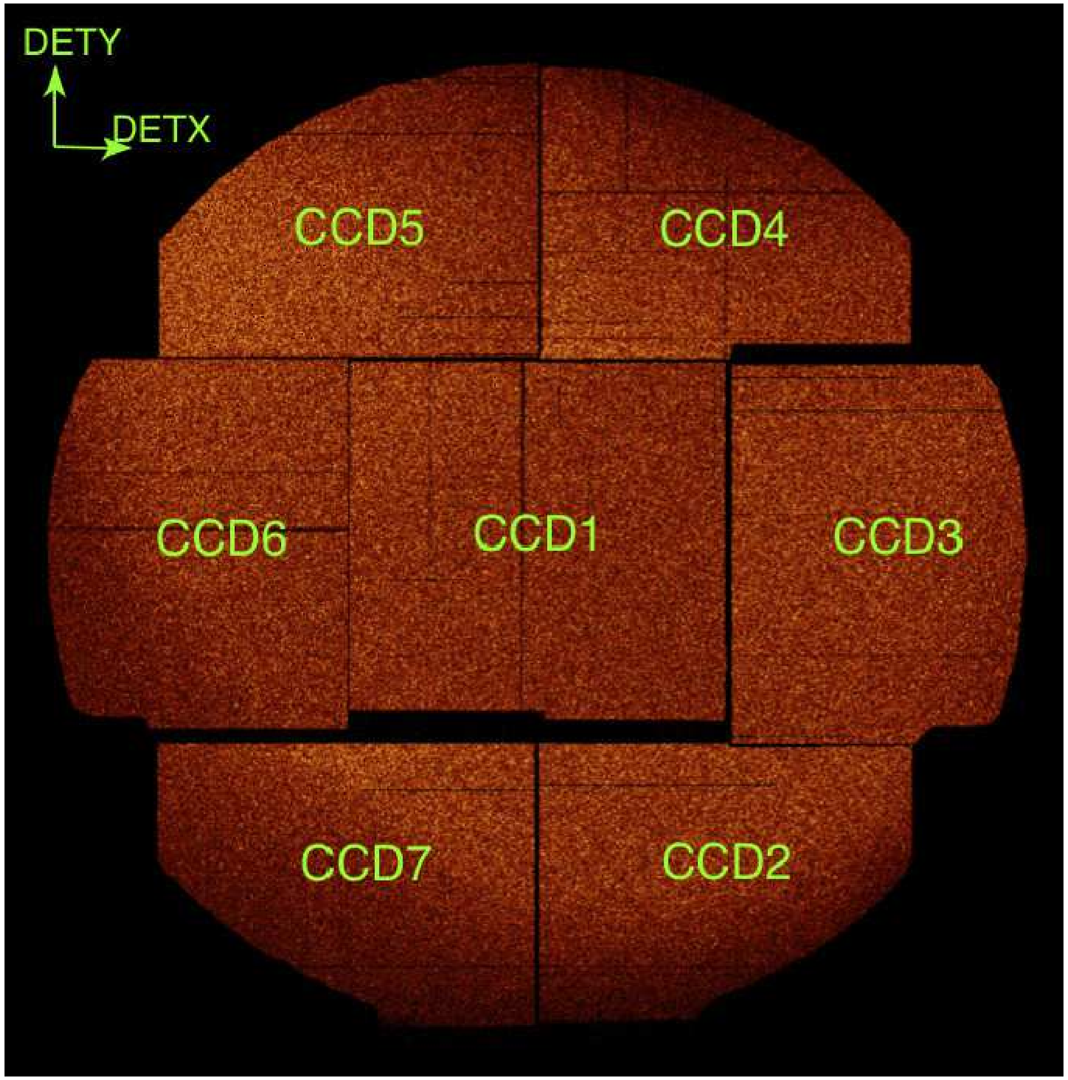

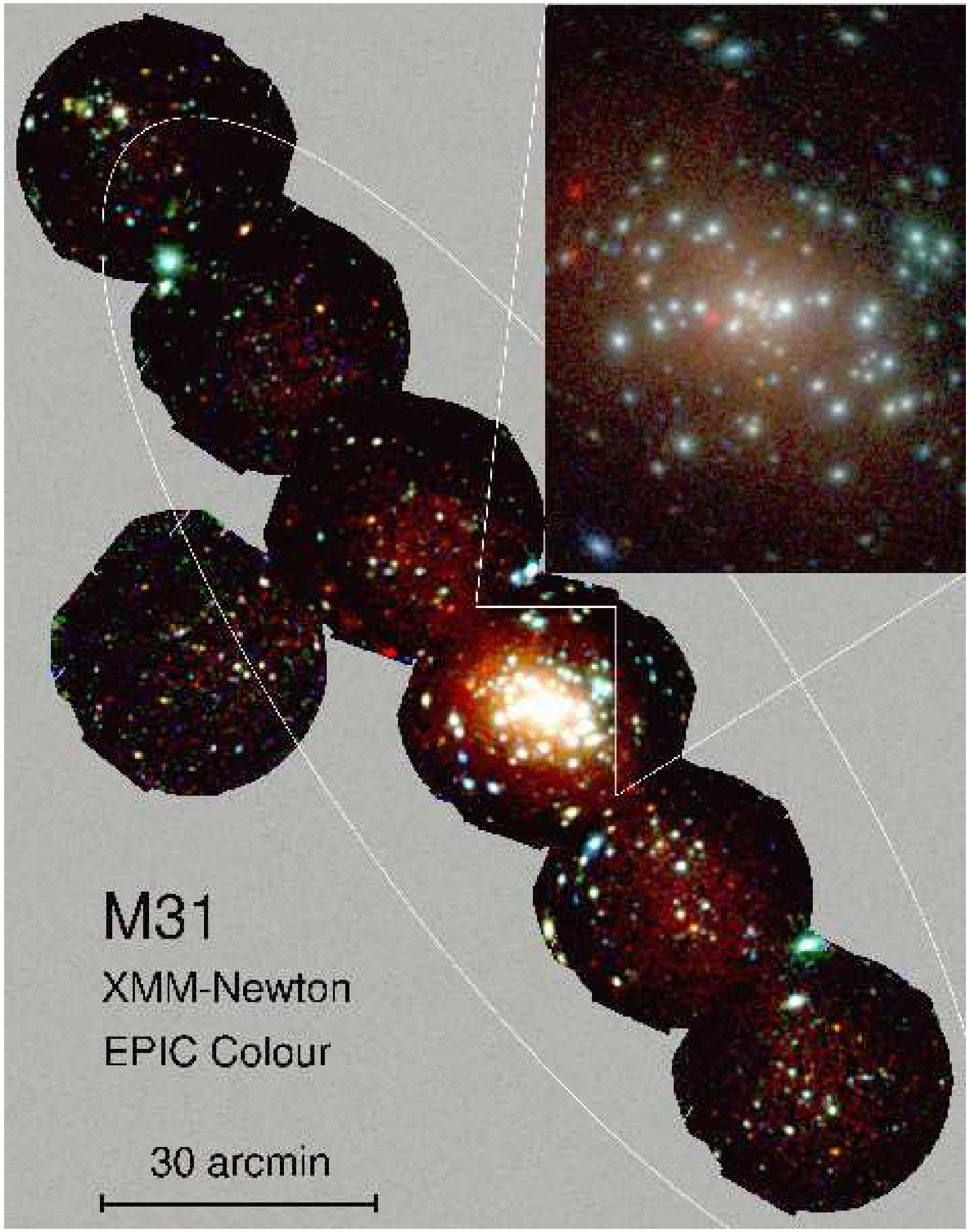

Summary

- Mirrows: Walter I
- Instruments: could be grating
- Detectors: CCD (future microcalorimetrs)