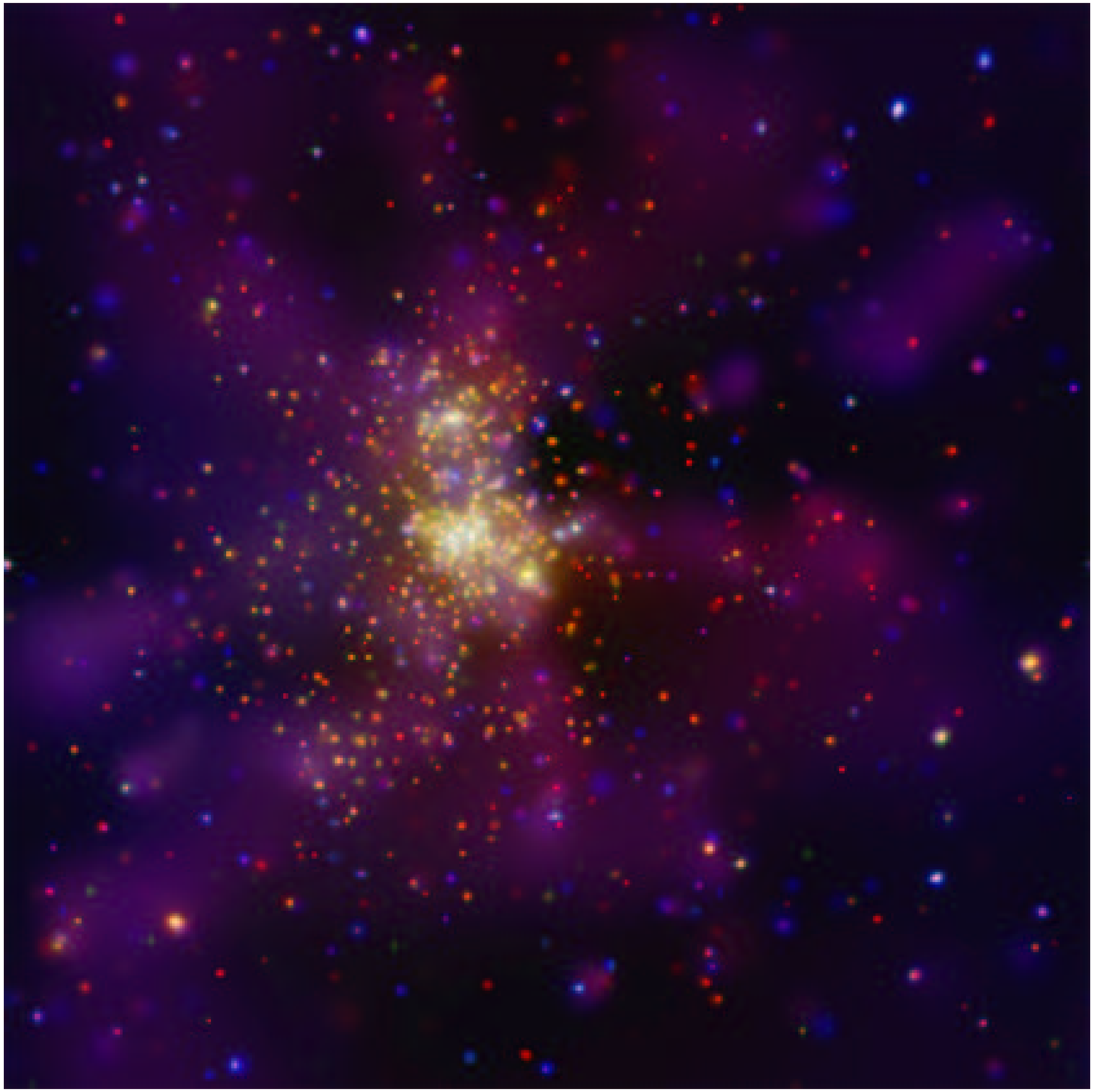
The X-Ray Universe



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

Chandra X-ray Observatory
Westerlund 2 - a young star cluster
d=2×10^4ly

II. X-ray Telescopes

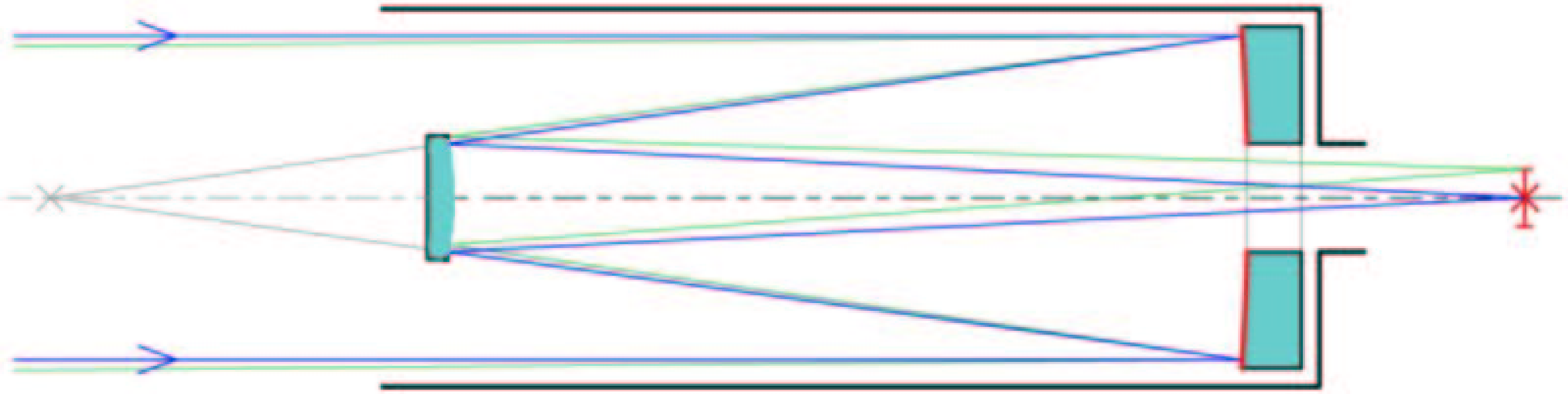
http://chandra.harvard.edu/resources/

II. 1. Introduction

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

- Wolter Telescopes (soft X-rays up to 15 keV)
- Lobster Eye Telescope
- Collimators
- Coded Mask Telescopes (hard X-rays)

II.2. Reminder of optical telescopes

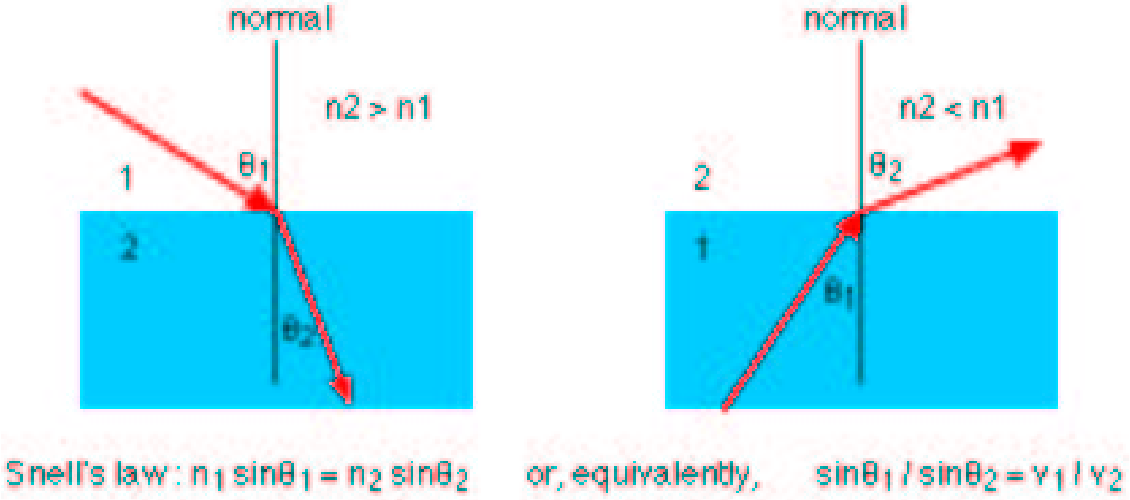


Cassegrian telescope (src. Wikipedia)

- 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)

II. 3. 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.



Snell's law: $n_1 \sin\theta_1 = n_2 \sin\theta_2$ or, equivalently, $\sin\theta_1 / \sin\theta_2 = v_1 / v_2$

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

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

- Total internal reflection: $\theta_2 \geq 90^\circ$
- The incident angle θ_c: $\frac{n_1}{n_2}\sin\theta_c \geq 1 \Rightarrow \theta_c = \arcsin\frac{n_2}{n_1}$
- n(air)=1, n(glass)=1.6, n(silver)=0.18, n(gold)=0.47, n(diamond)=2.4
- optical fibers, mirrors, diamond cutting

II. 4. Refraction of photons

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 mat

For free electrons, e.g. in metal,

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

ω_p - plasma frequency, ω=2πc/λ, n_e number density of electrons

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

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

II. 5. Critical angle

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

$$n = \sqrt{1 - \frac{n_\mathrm{e} r_\mathrm{e}}{\pi}\lambda^2} \approx 1 - \frac{n_\mathrm{e} r_\mathrm{e}}{2\pi}\lambda^2$$

electron number density $n_\mathrm{e} = \frac{\rho}{(Z/A)m_\mathrm{H}}$, where $m_\mathrm{H} = 1.66 \times 10^{-24}$ g

$$n \approx 1 - 5.4 \times 10^{10}\, \rho\, \lambda^2$$

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=$10^{\text{-8m}}$

$$1 - \frac{\alpha_\mathrm{c}^2}{2} = 1 - 5.4 \times 10^{10} \rho \lambda^2 \Rightarrow \alpha_\mathrm{c} \approx 5' \, \frac{\lambda}{1\,\text{Å}} \sqrt{\frac{\rho}{1\,\mathrm{g\,cm^{-3}}}}$$

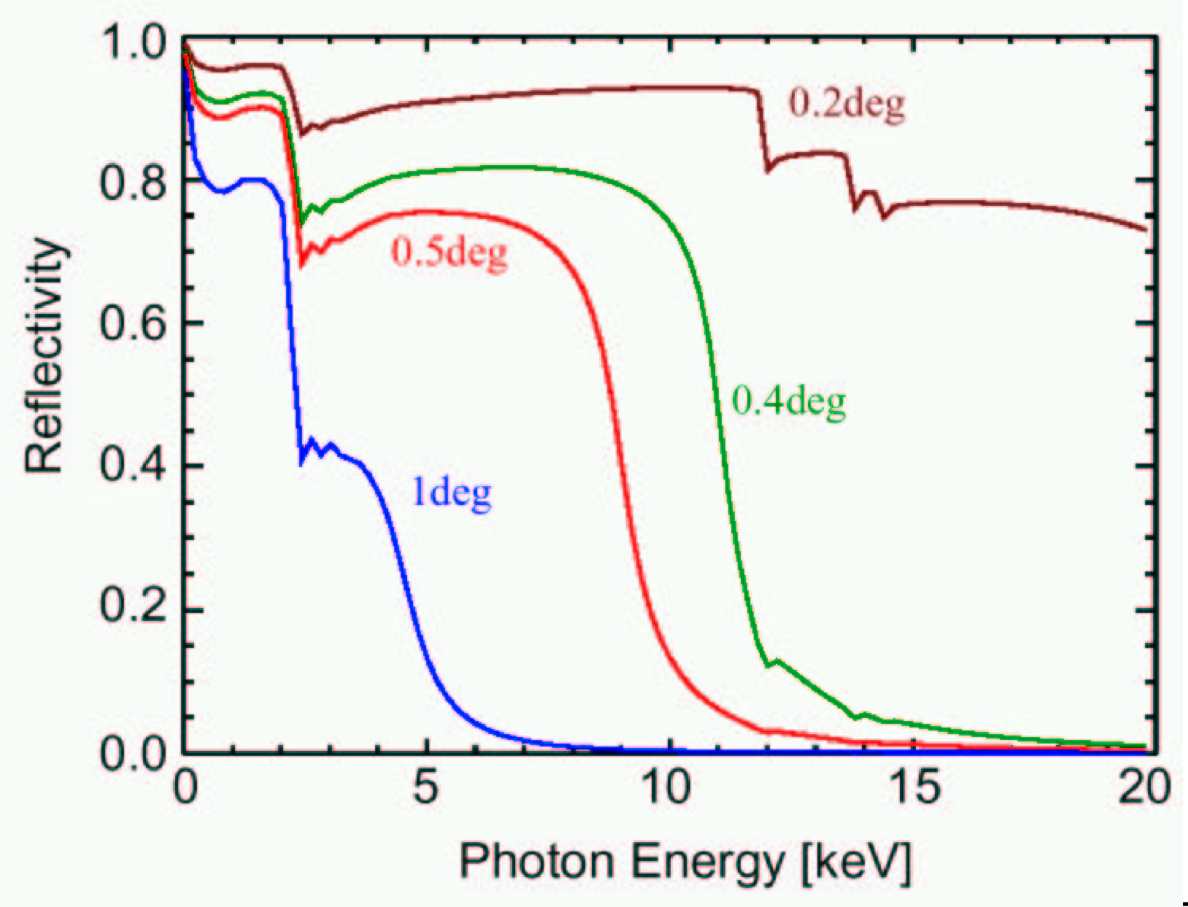
II. 6. Reflection of X-rays

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

Optical λ=6000Å $\Rightarrow \alpha_c \approx 50° \sqrt{\frac{\rho}{1\text{g cm}^{-3}}}$

X-ray λ=6Å $\Rightarrow \alpha_c \approx 3' \sqrt{\frac{\rho}{1\text{g cm}^{-3}}}$

Grazing!



To increase α_c need high ρ

XMM-Newton: gold

Chandra: iridium

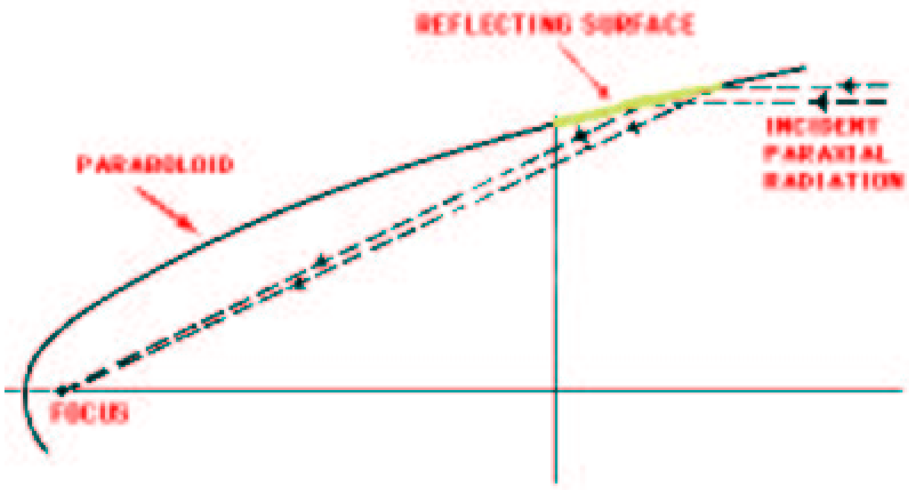
see Ais-Nielsen & McMorrow, 2004, Elements of modern X-rays physics

for hard X-rays: **Bragg's Effect**

Multilayered mirrows,

not yet in produciton

II. 7. 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

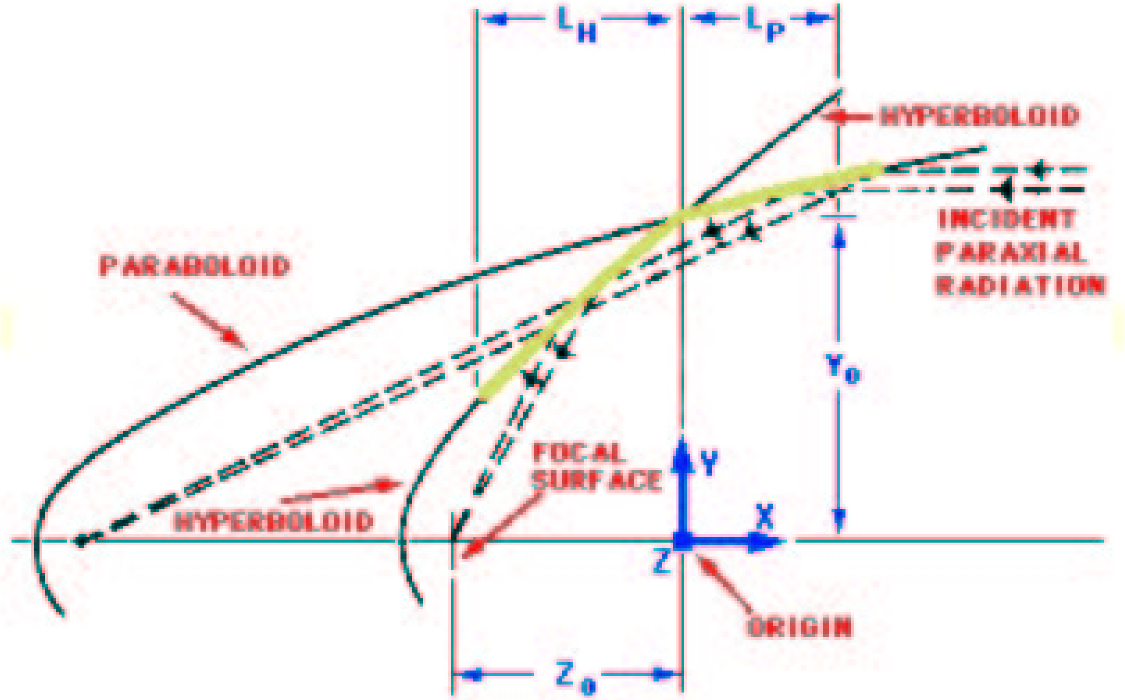
to produce sharp images of off-axis as well as on-axis objects:

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

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

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

II. 8. 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

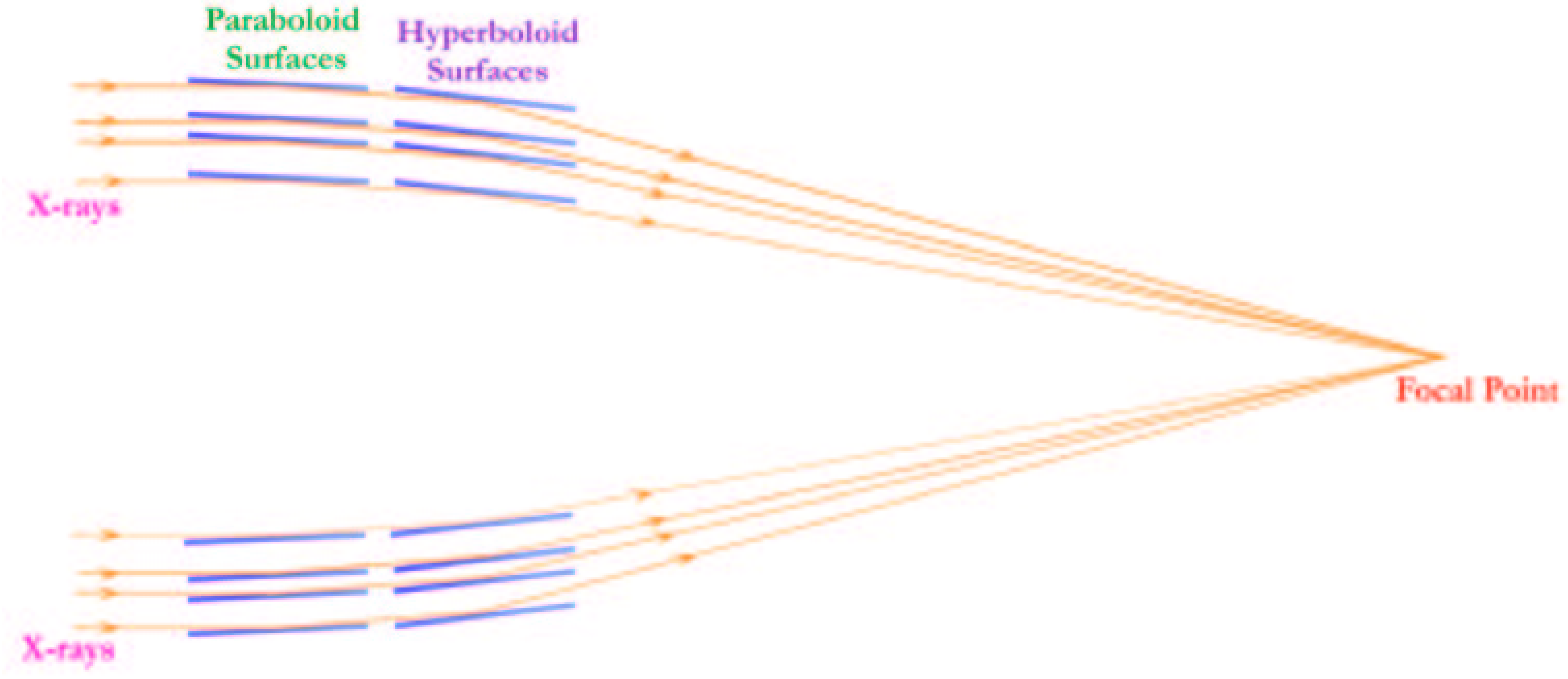
1961 R. Giacconi & B. Rossi X-ray telescopes

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?

II. 9. Nested mirrors



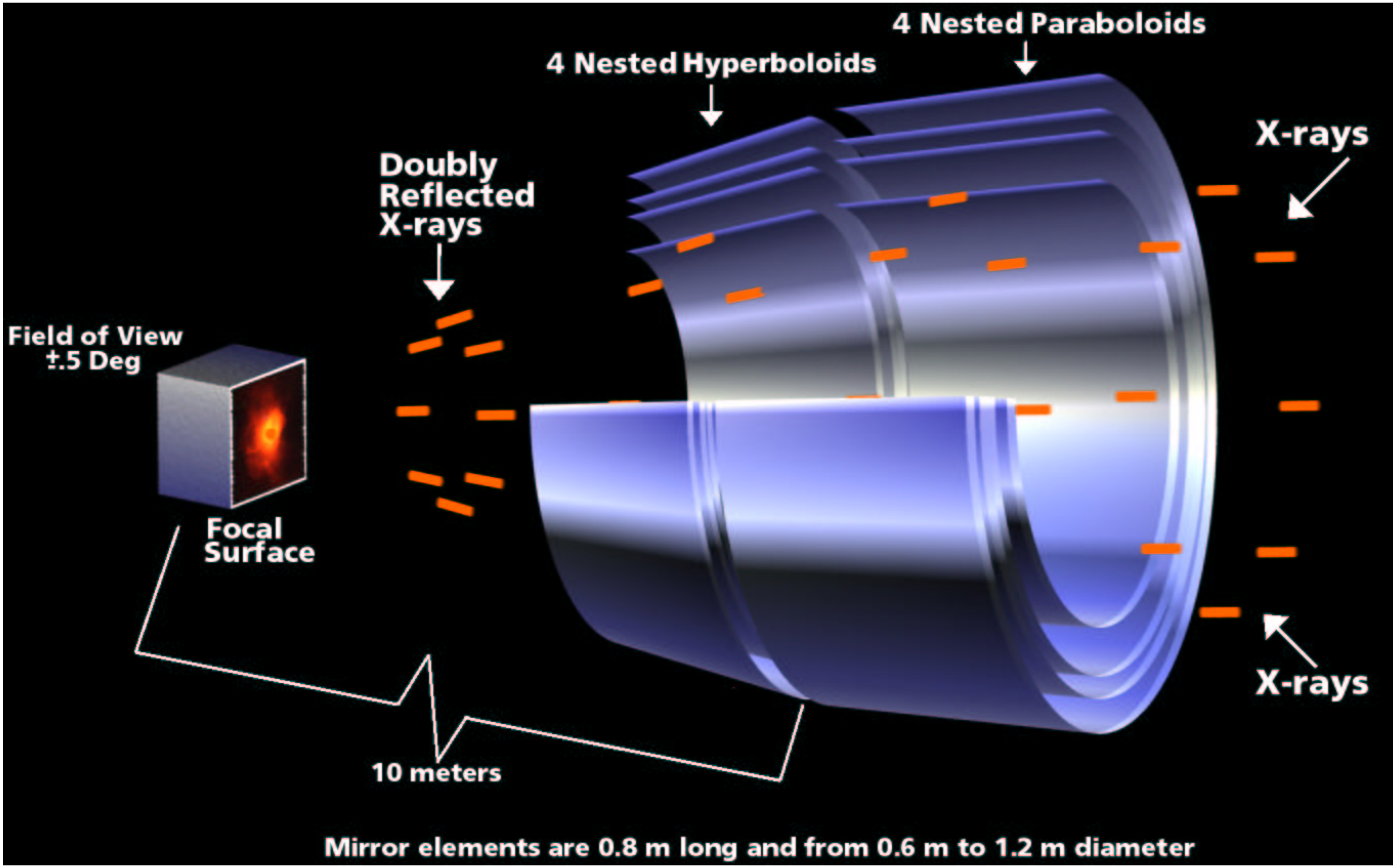
Chandra: four nested pairs of mirrors

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.

II. 10. High Resolution Mirror Assembly (HRMA) on Chandra.



Chandra: four nested pairs of mirrors

II. 11. High Resolution Mirror Assembly (HRMA) on Chandra.

CXO Mirror Being Assembled at Eastman-Kodak

(Photo: Eastman-Kodak)

Optics:

Wolter Type-I

Mirror coating:

Iridium

Mirror outer diameters:

1.23, 0.99, 0.87, 0.65 m

HRMA mass:

1484 kg

θ_c:

3.42, 2.75, 2.42, 1.80 degrees

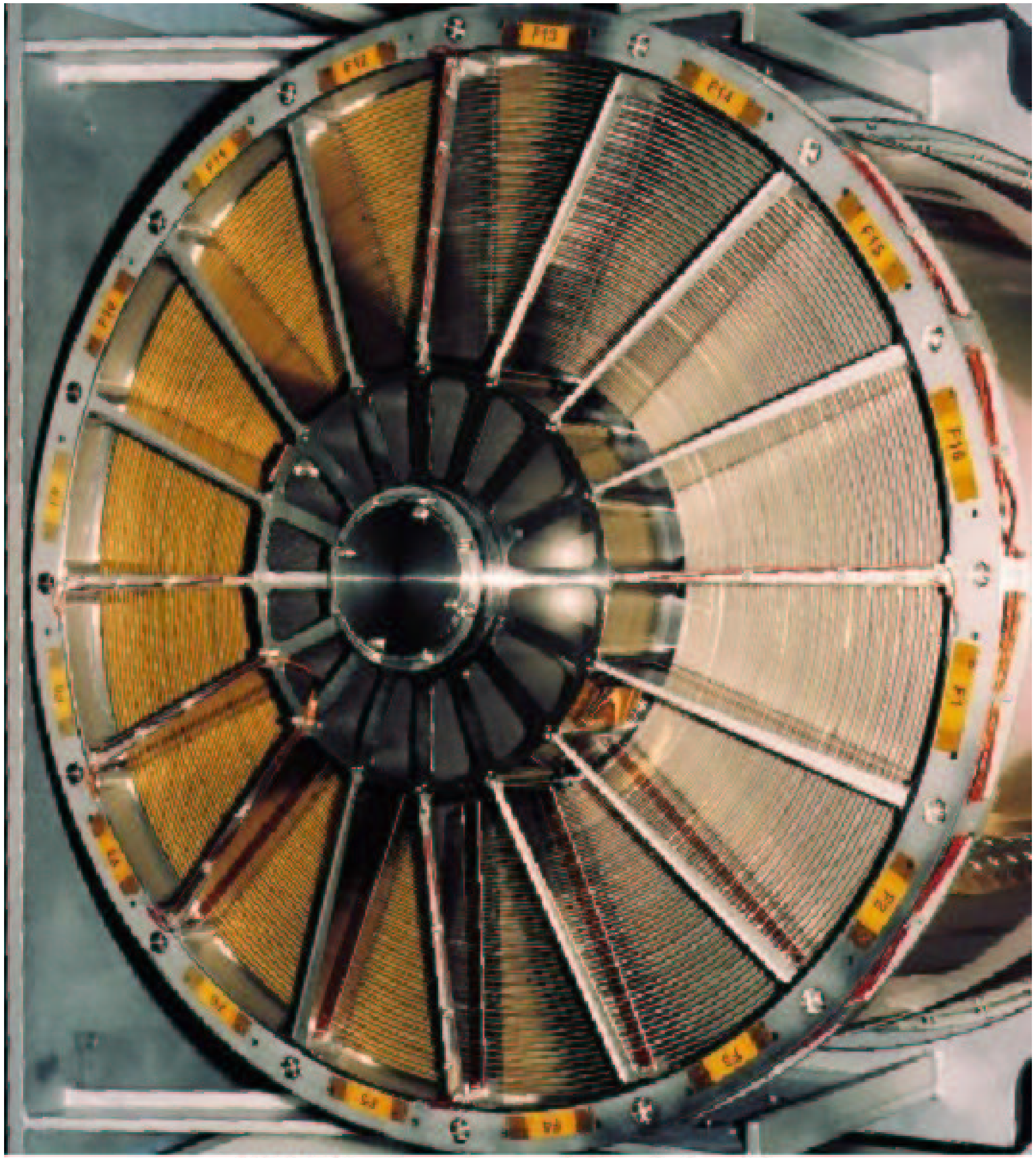
PSF FWHM (with detector):

0.5 arcsec !!!

Effective area:

0.25 keV:800 cm^2, 8.0 keV:100 cm^2

II. 12. 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):

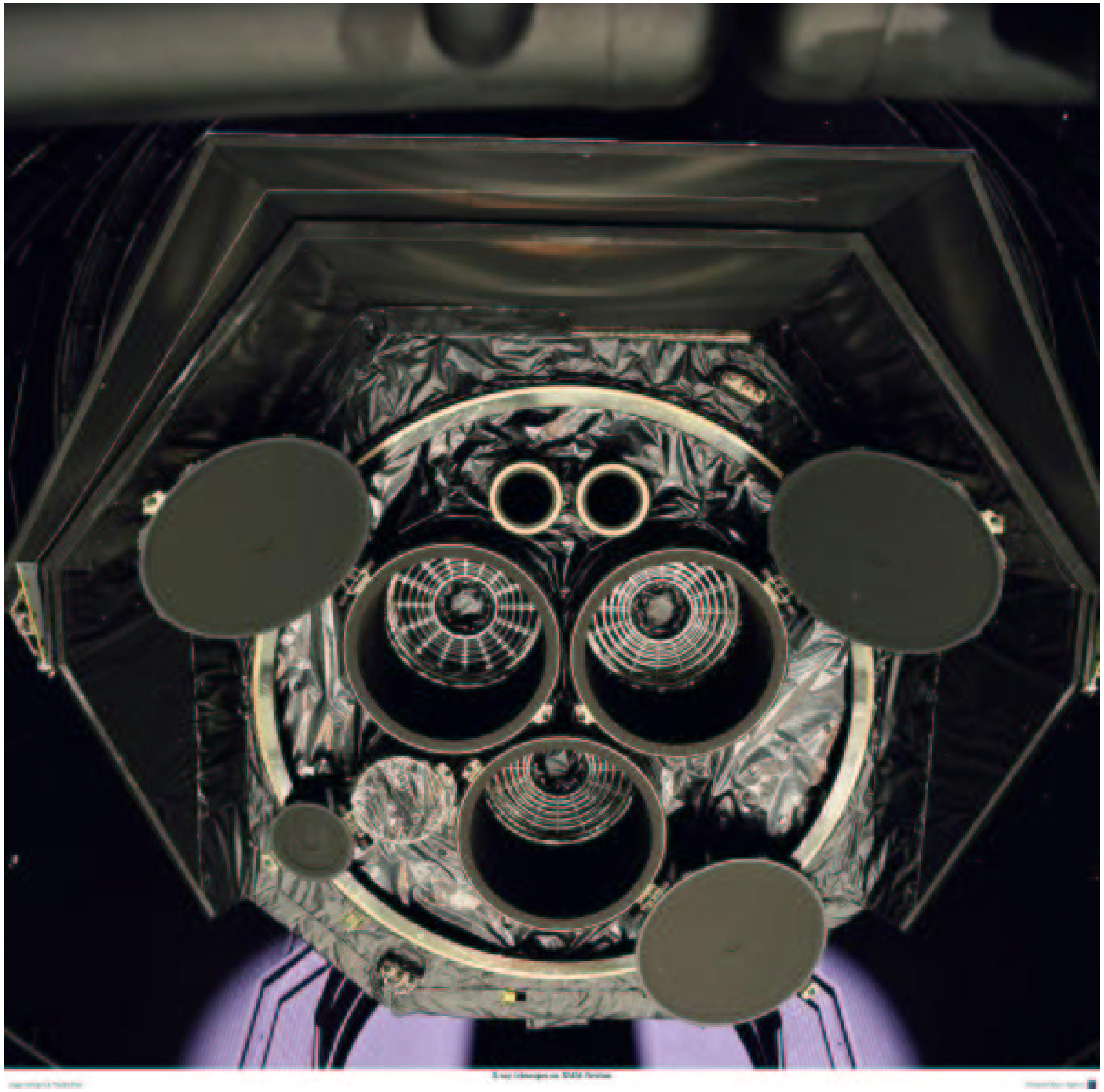
4 arcsec !!!

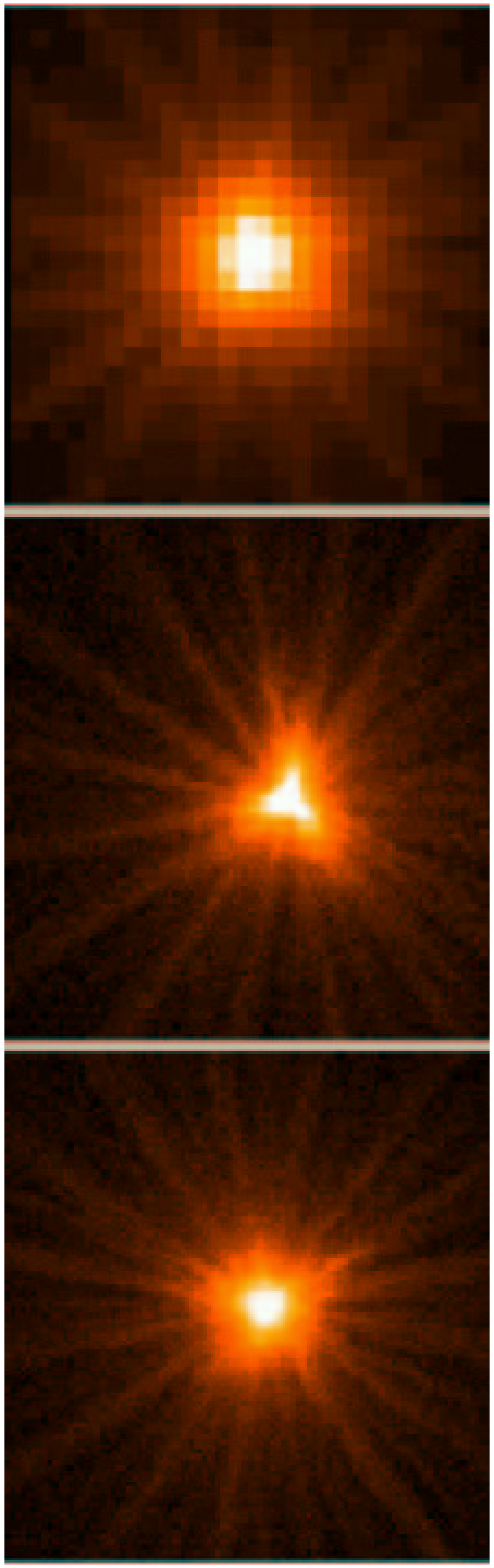
Effective area:

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

II. 13. Three telescopes of XMM-Newton

Image of the on-axis PSF for the three telescopes





100” × 110”

EPIC PN camera
larger pixels

II. 14. Lobster Eye Telescopes

Wolter I telescopes are inefficient:

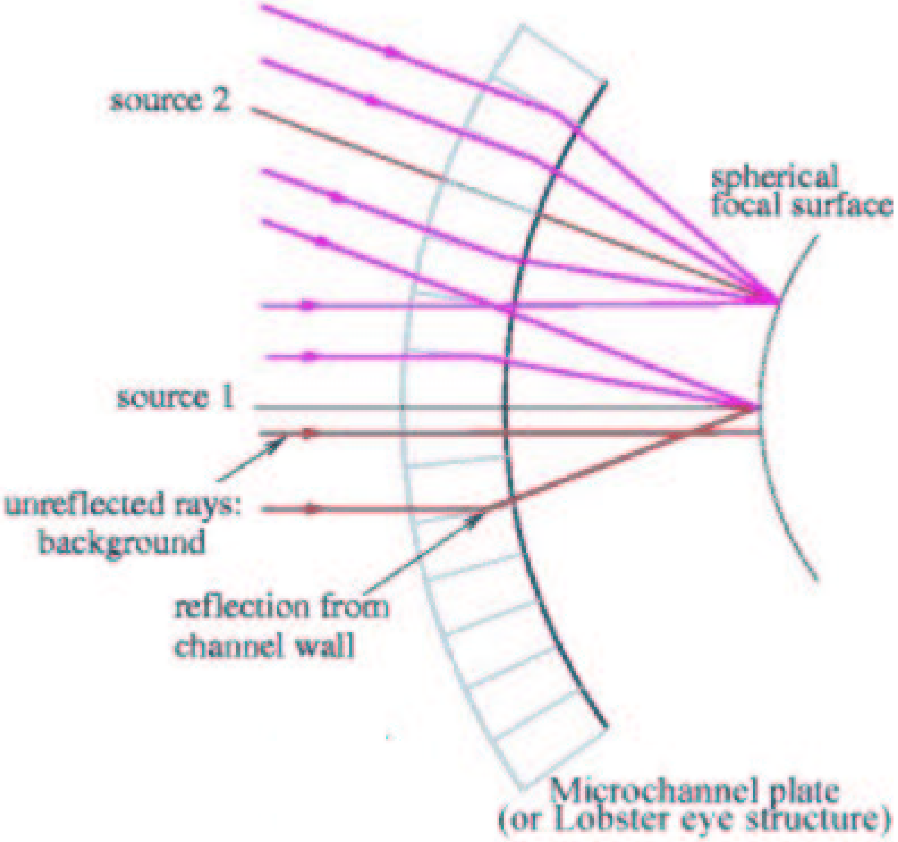
mirrors are used nearly edge-on

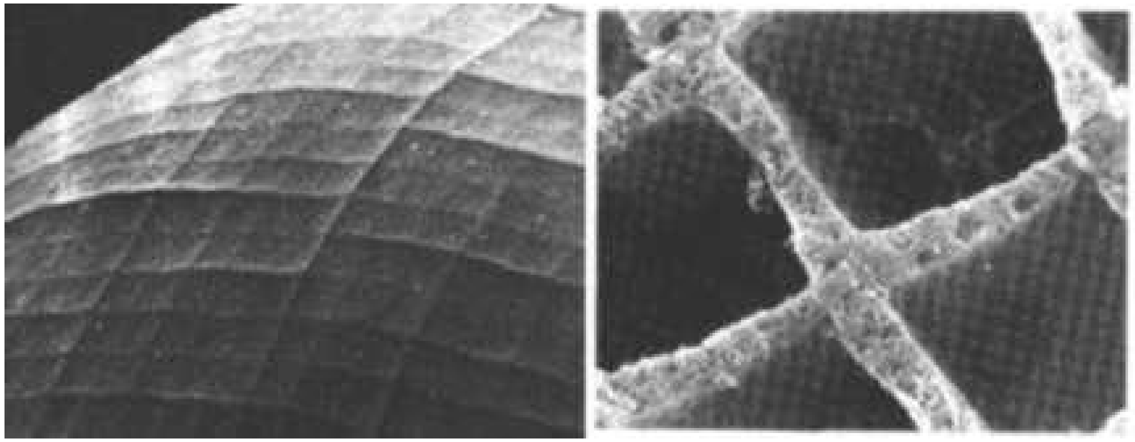
Heavy, exepnsive

The FoV is small, half-degree XMM

Need for many pointings

Lobster Eye





Lobster eye uses grazing incidence

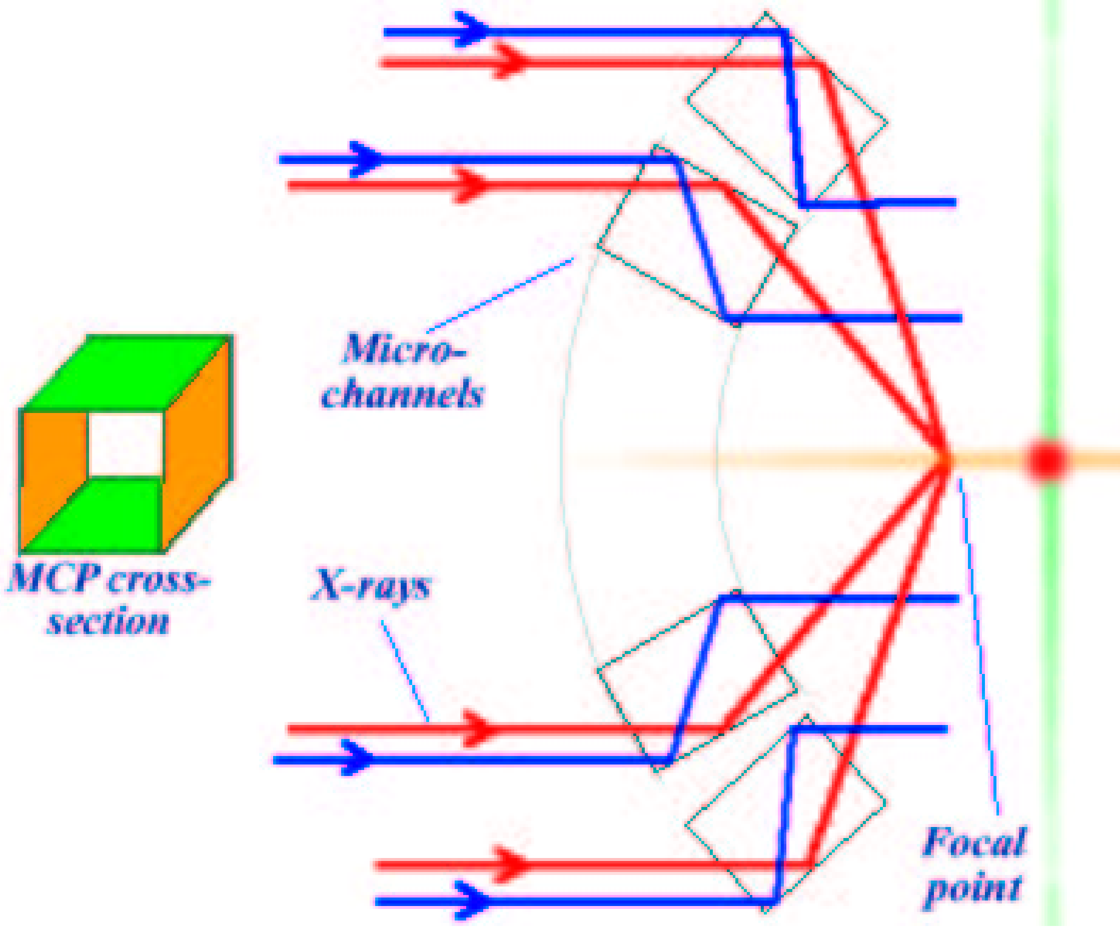
in optical

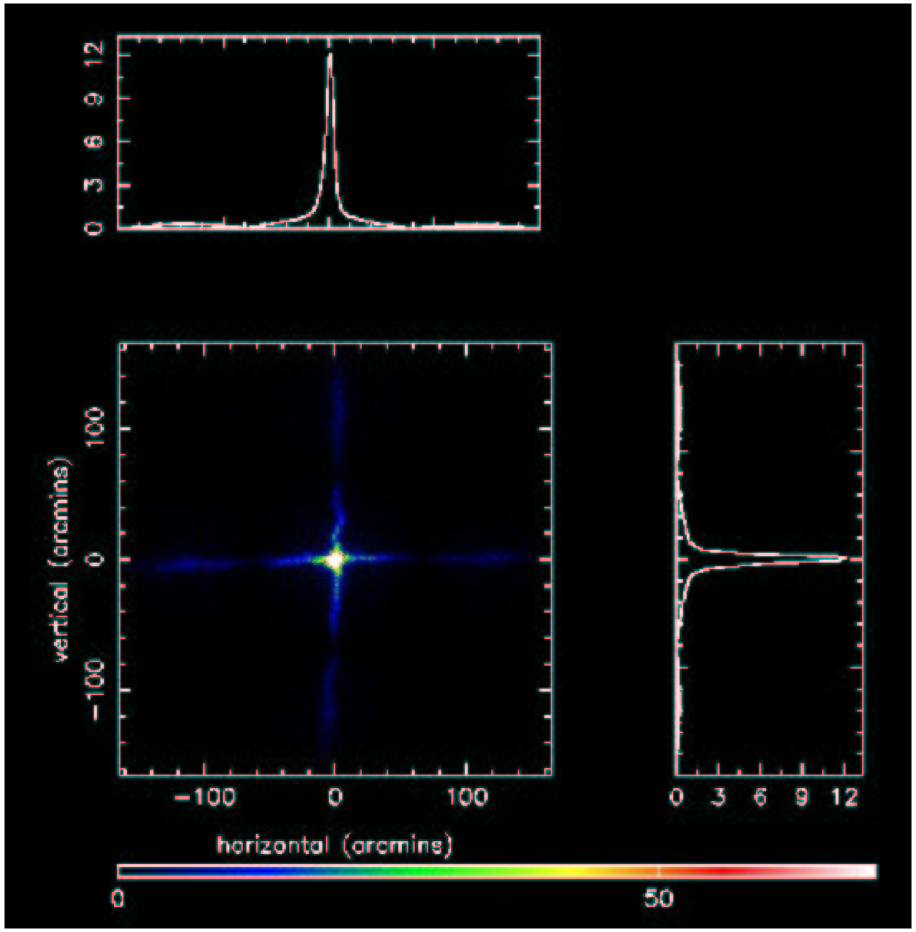
10^6 channels, approx. 20 micron

II. 15. Lobster-ISS

Will be flown onto ISS

now in stage of development





Rays with odd number of reflections in both vertical and horisontal planes arrive in the central focus

Central circle a.3 arcmin; 0.93 keV

from www.src.le.ac.uk/projects/lobster/ov_optics.htm

All others make cross structure and background

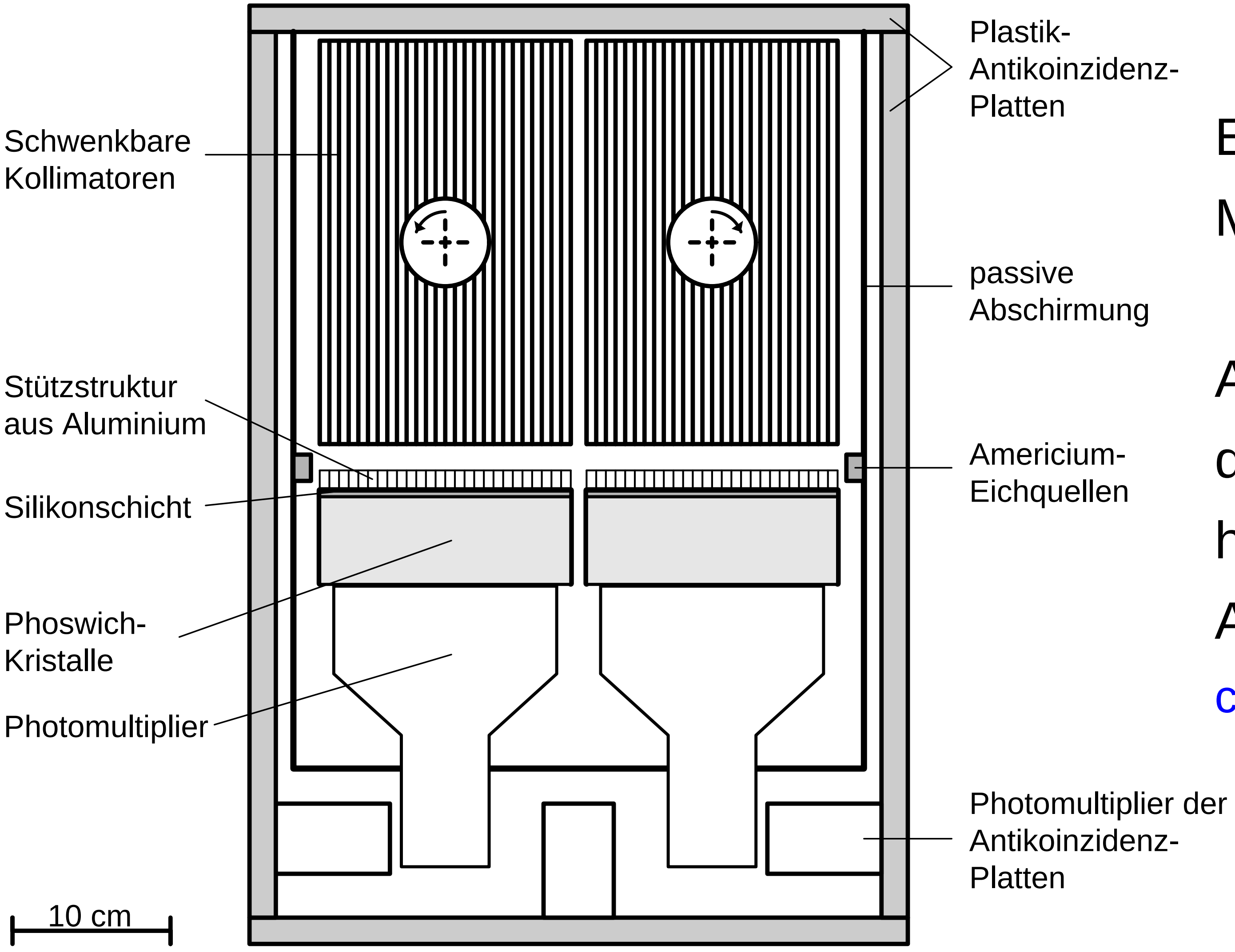
II. 16. Collimators

At energies above 10 keV, imaging with mirrors is not possible

(..development of multilayer mirrors)

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

Simpliest: pinhole camera version honeycomb collimator



Example: Kvant modul

MIR station, 1987

Angular resolution $\sim d/h$,

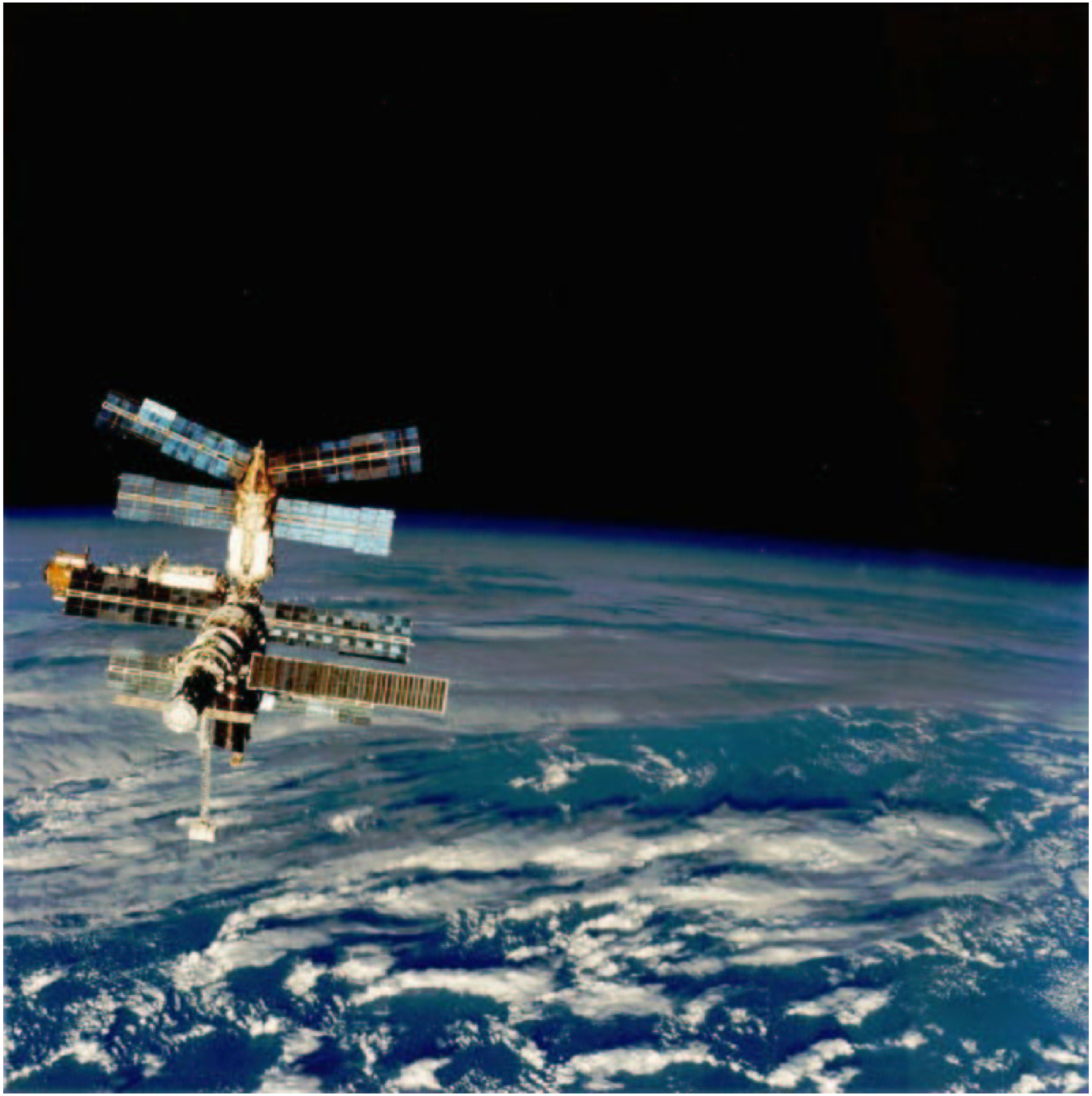
d is tube diameter,

h is tube length

Angular resolution - degrees

compare: Chandra: 0.5arcsec!

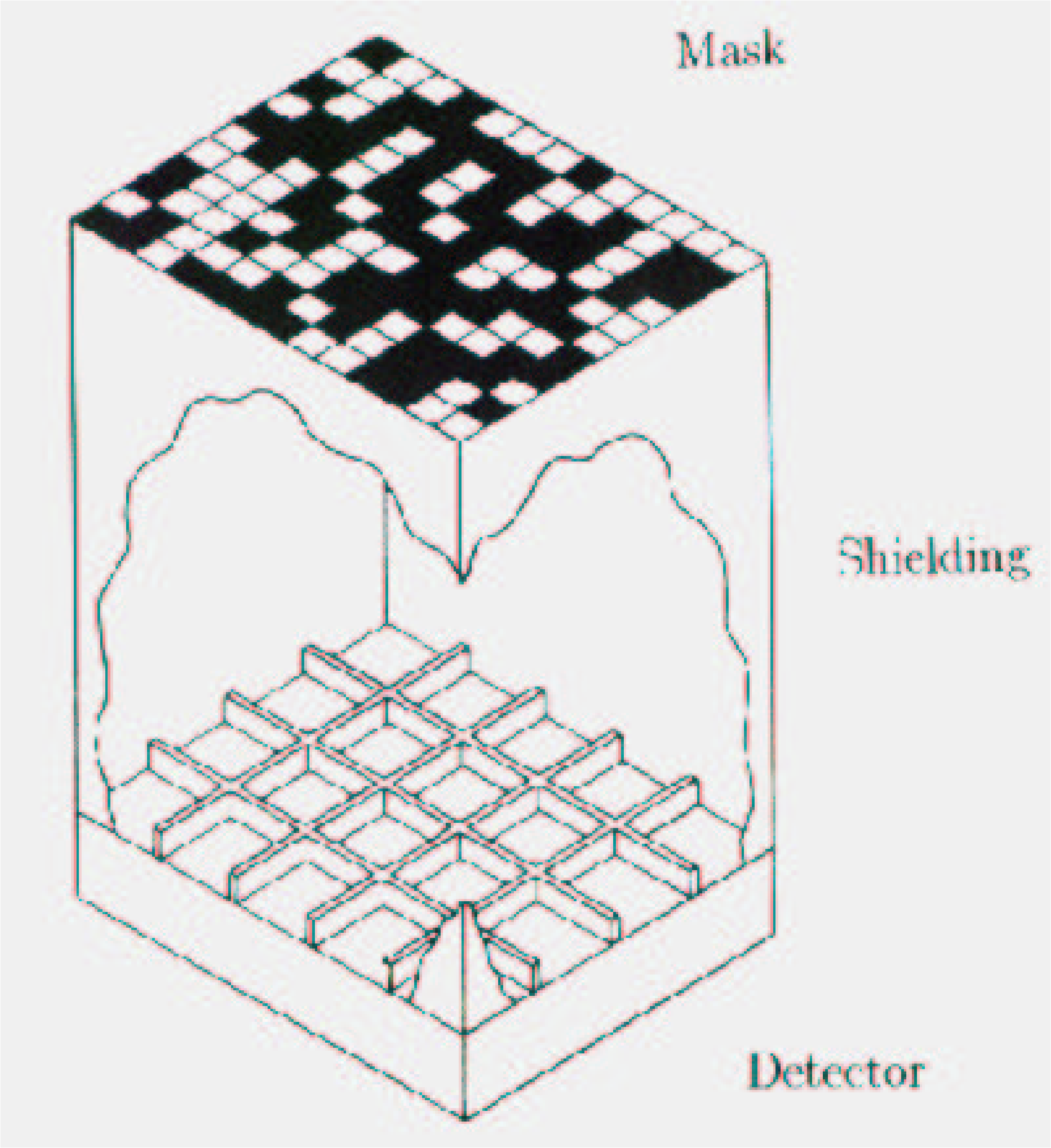
II. 17. The Mir space station in 2000 with the Kvant attached.



II. 17. Coded Mask Telescopes

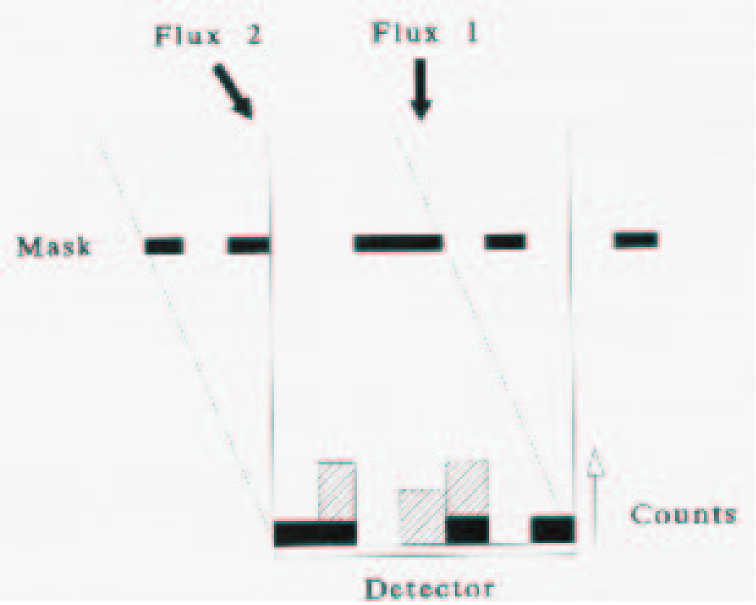
Collimators have no imaging capabilities

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



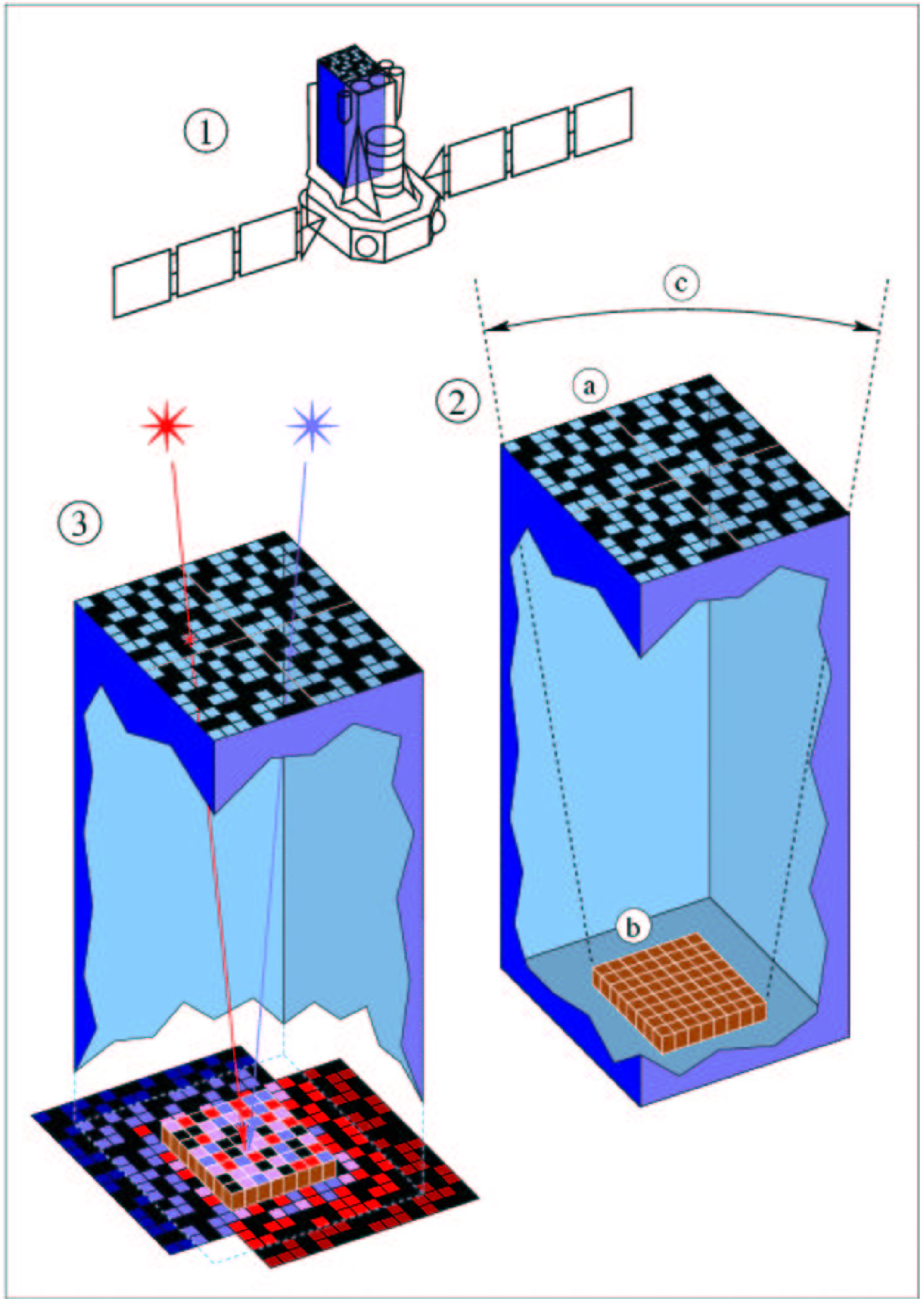
Shift of the projected shadow relative the telescope axis.

For multiple sources: image deconvolution.



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

II. 17. 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

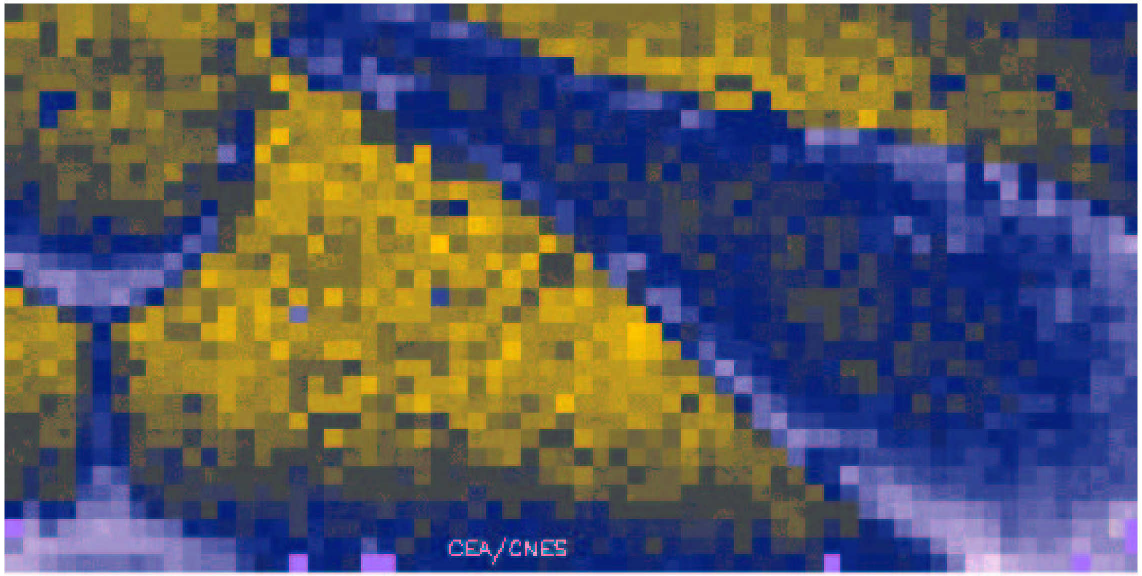
Compare R(x,y) to response expected if there were a source at α, δ on the sky using cross-correlation function CCF(α,δ)

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

II. 19. Shadowgram



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

ISGRI detector

Pre-flight model

122 keV

INTEGRAL

The International Gamma-Ray

Astrophysics Laboratory

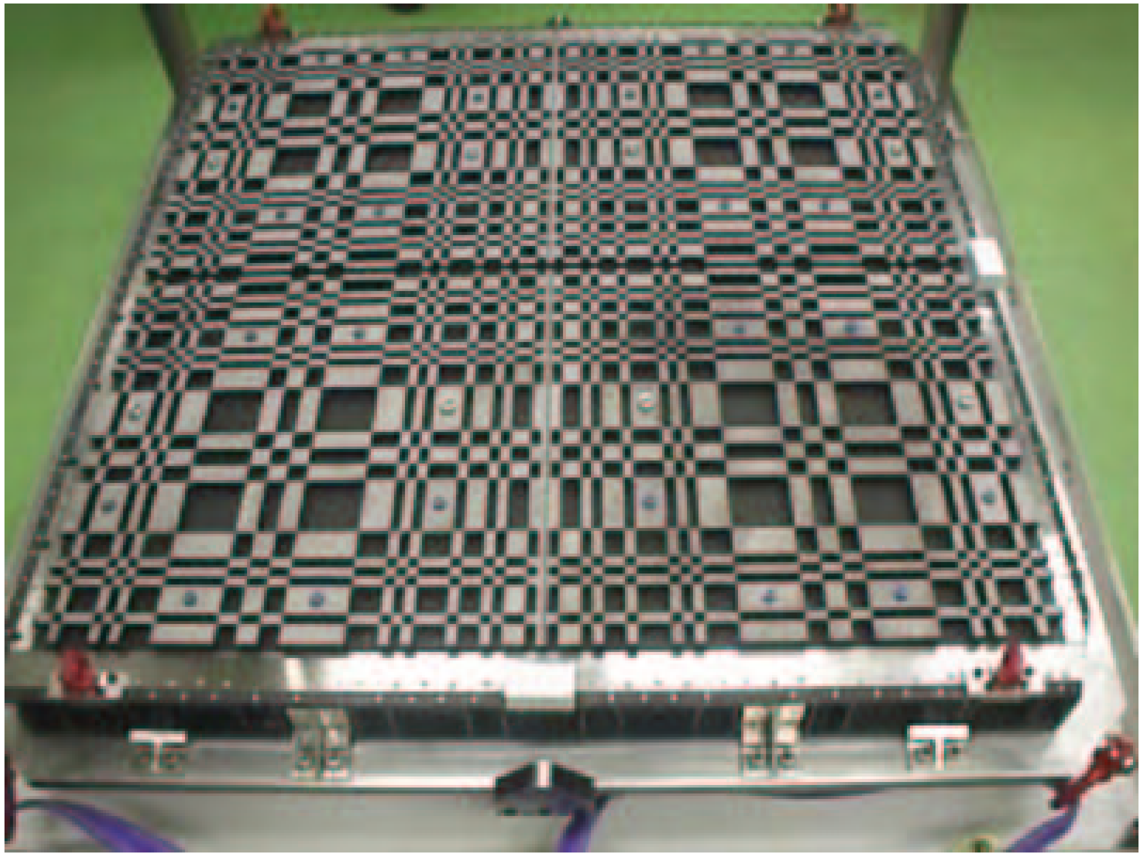
ESA’s Horizon 2000

3 keV - 10 MeV

Angular resolution FWHM 12 arcmin

FOV 8 x 8 degrees

II. 19. IBIS



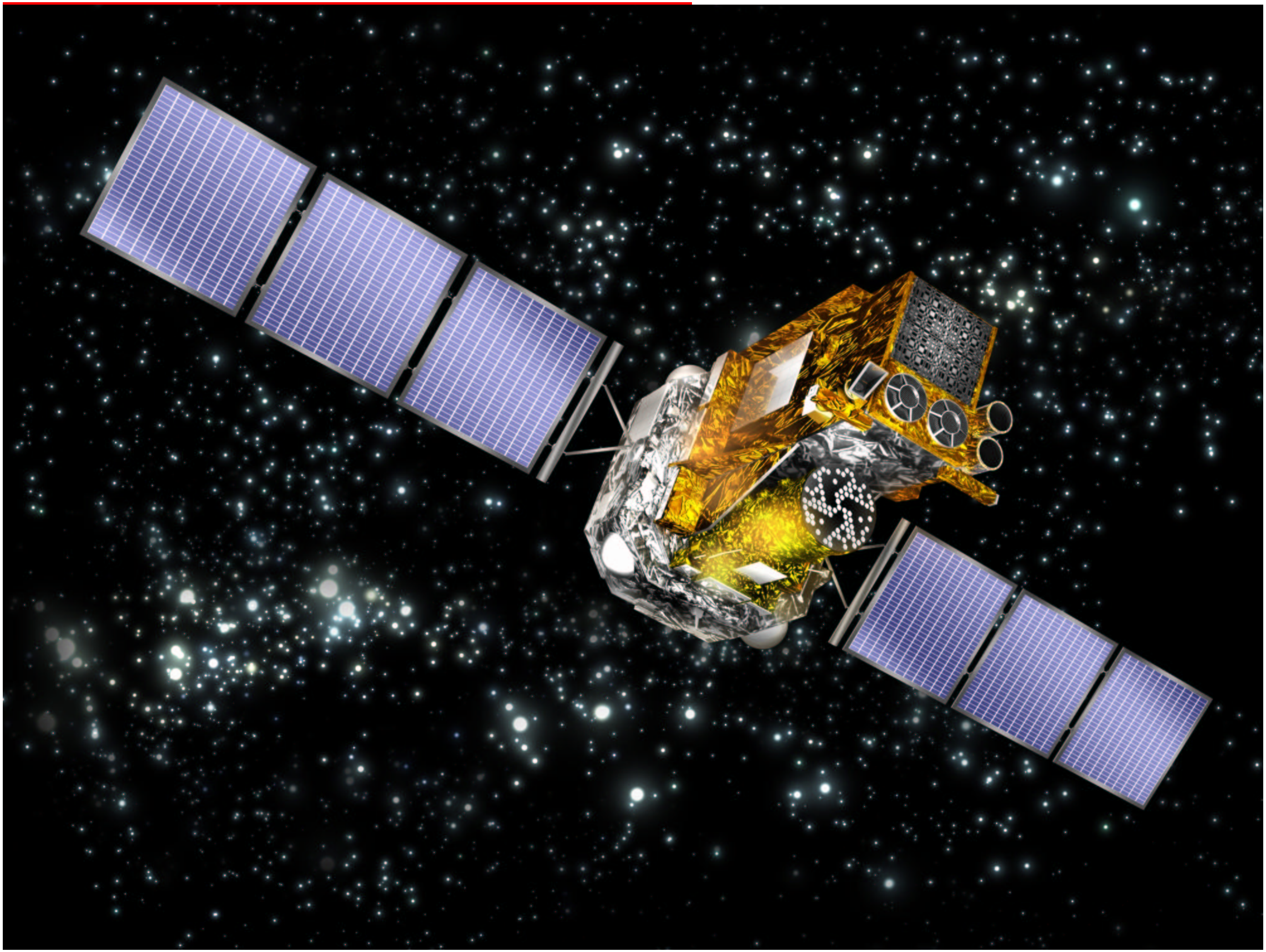
http://pollux.uv.es/integral/Masks/

ISGRI detector

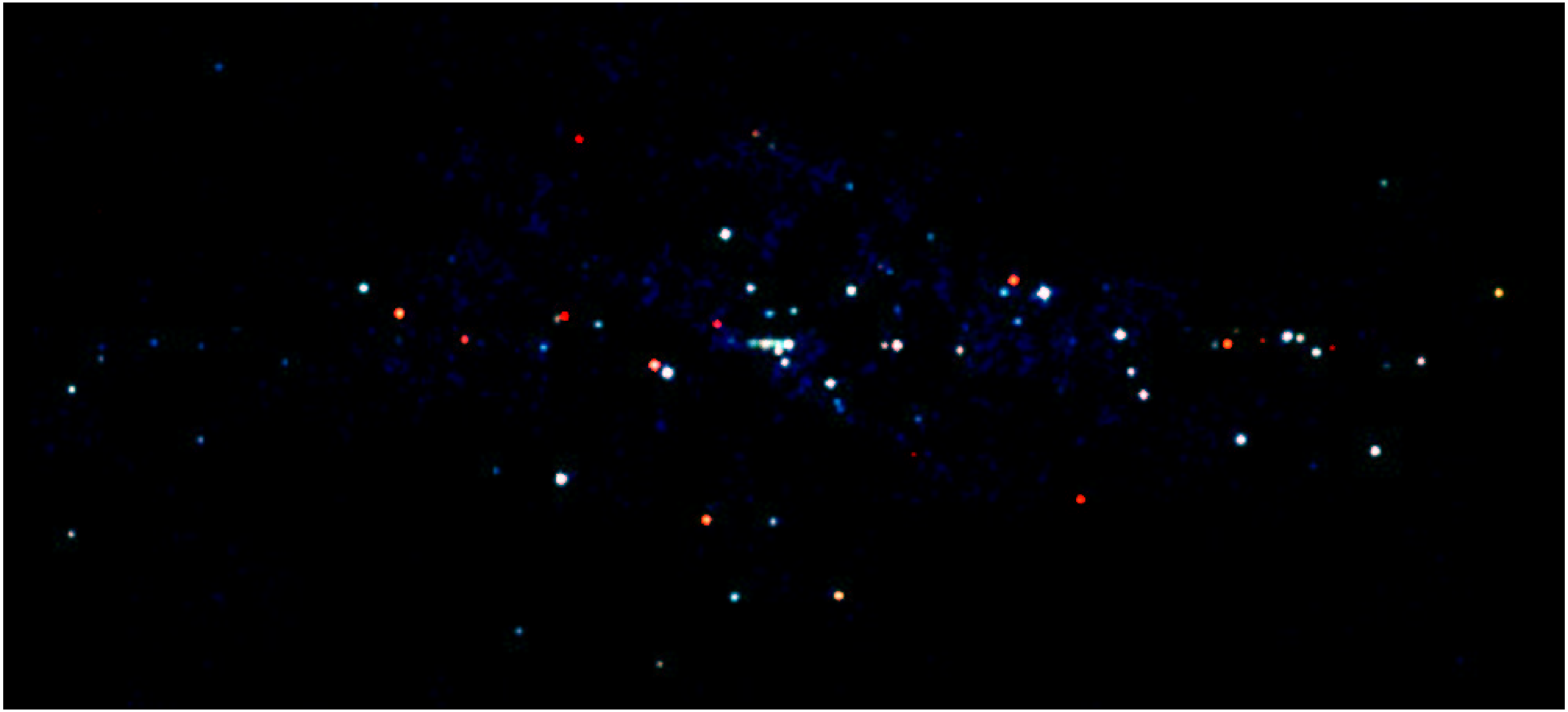
IBIS

(Imager on Board INTEGRAL Satellite)

II. 20. INTEGRAL launched October 2002



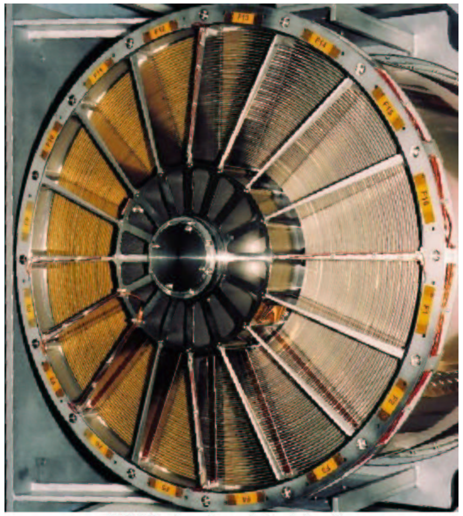
II. 21. Milky Way with Integral



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

mainly stellar remnants: black holes and neutron stars

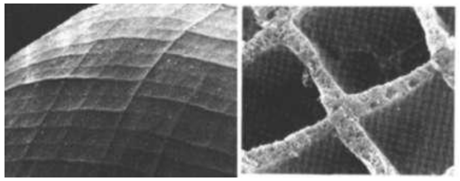
II. 22. X-ray telescopes: Summary



XMM-Newton mirrors during integration

Image courtesy of Dornier Satellitensysteme GmbH European Space Agency

Wolter I mirrors (XMM-Newton, Chandra)

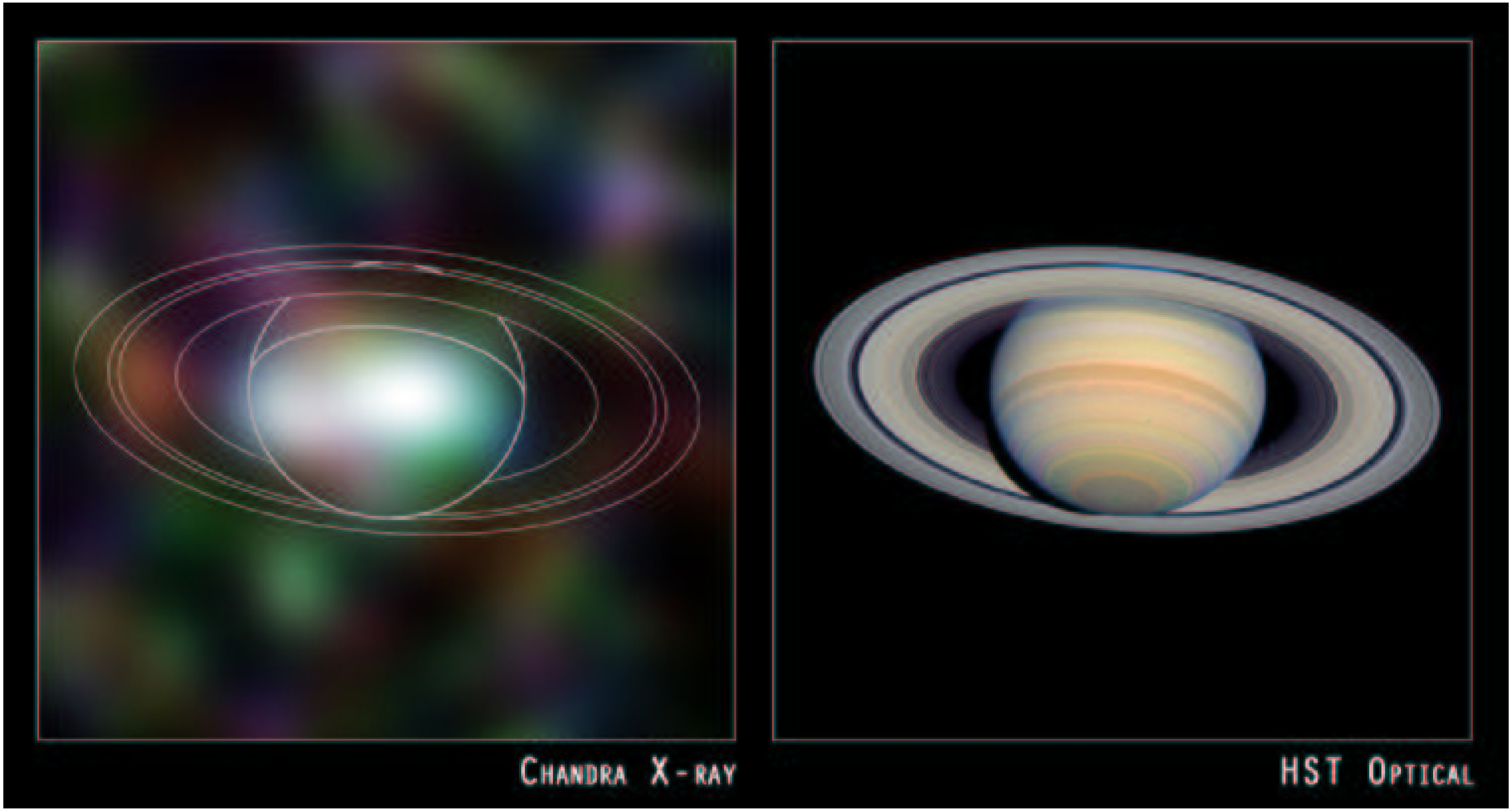


Lobster Eye (LOBSTER-ISS)

Collimators (RXTE)

Coded Mask (Integral)

III. X-ray Detectors



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

III. 1. 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

III. 2. 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

NB Dualism! X-ray quantum is both particle and wave

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.

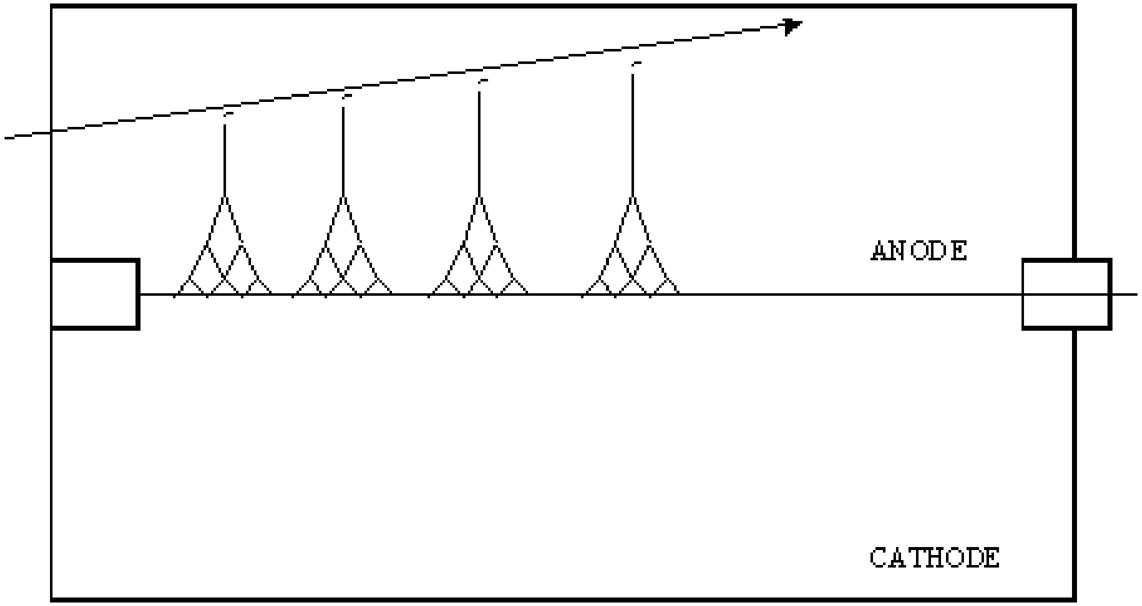
Mesured charge is proportional to the deposited energy

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

III. 3. 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:

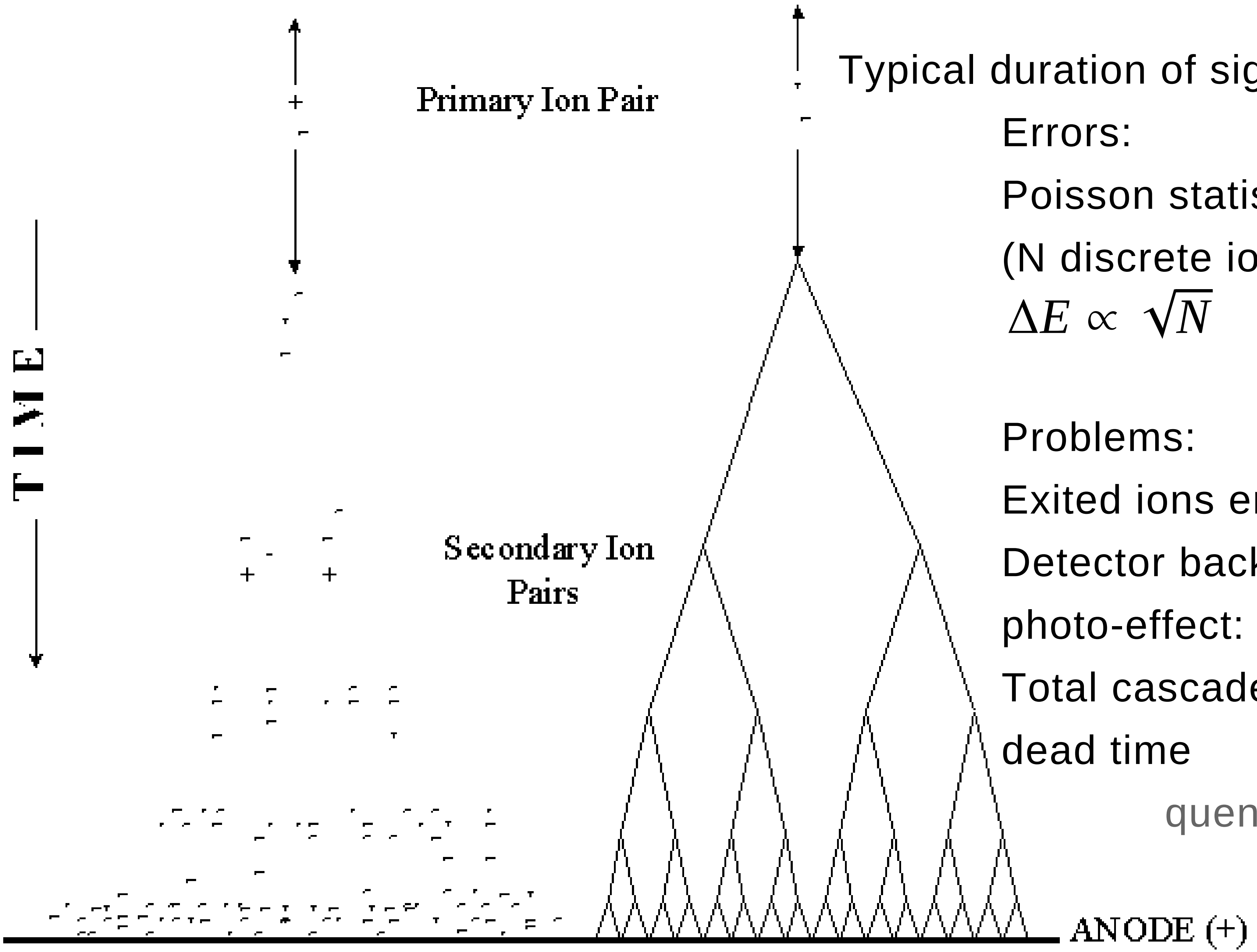
$$\delta U = -\frac{\mathrm{e}N}{C} \cdot A$$

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

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

Propotional counter.

III. 4. Proportional counters. Avalanche.



Typical duration of signal 100µs

Errors:

Poisson statistics

(N discrete ion pairs)

$\Delta E \propto \sqrt{N}$

Problems:

Exited ions emit UV ph

Detector background:

photo-effect: avalanches

Total cascade takes time:

dead time

quenching

www.orau.org/ptp/

III. 5. 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 intrpreatationofthe data

Non-Imaging Instruments: how to reject background?

Energy Selection:

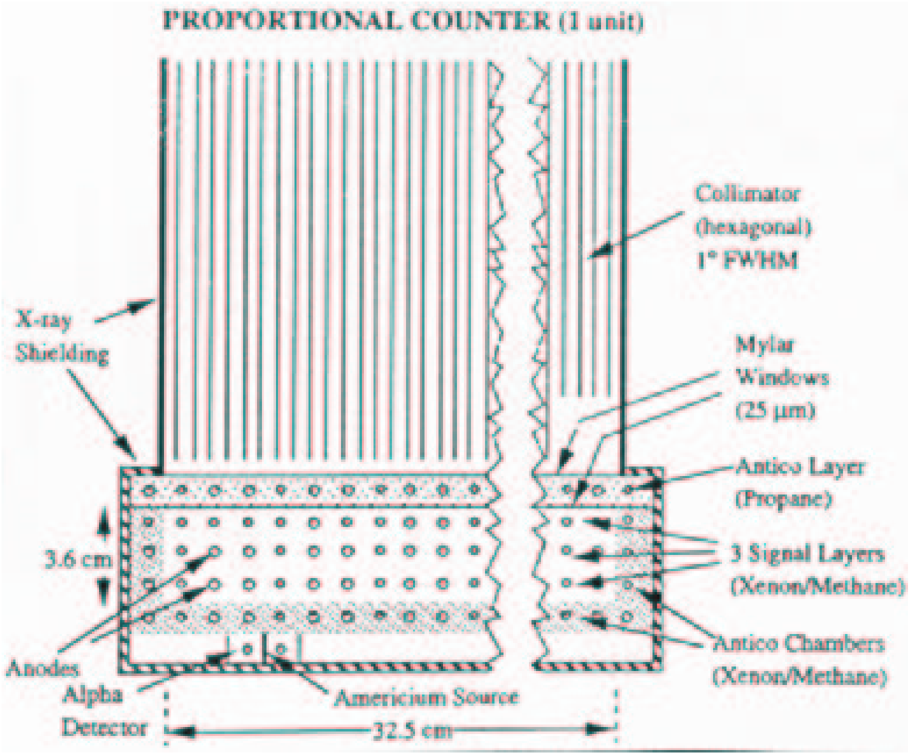
rejecting all events which deposit energies outside the X-ray bandpass

rise-time discrimination

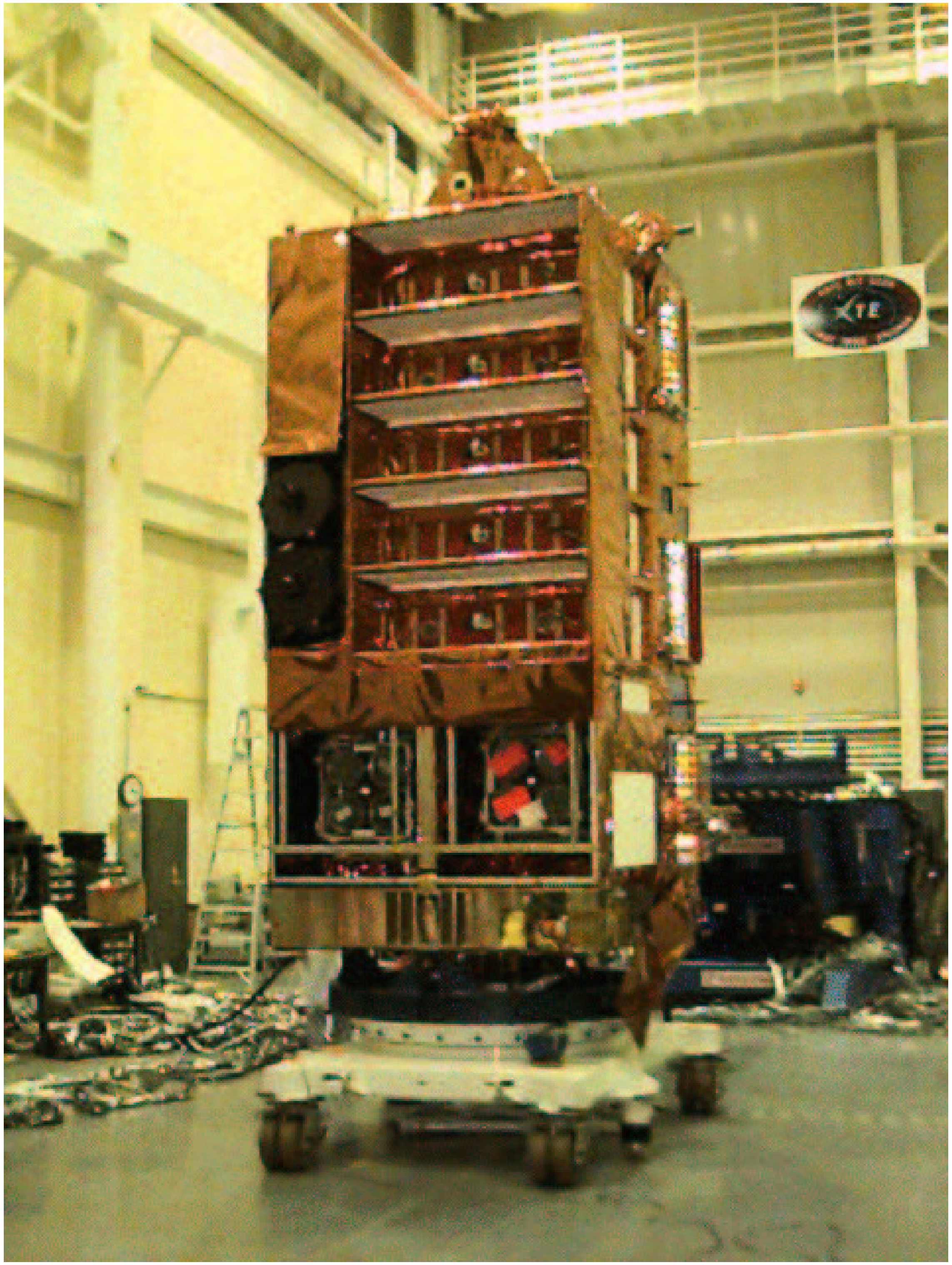
anti-coincidence within a sub-divided gas cell

Reducing backgruond by factor 100!

III. 6. The Rossi X-ray Timing Explorer Mission (1995-present)



http://heasarc.gsfc.nasa.gov/docs/xte/xtegof.html



NASA, 2 to 250 keV

Proportional Counter Array

High-energy X-ray timing experiment

All Sky Monitor

µsec resolution, it is all about timing

Blach Holes, pulsars, etc...

III. 7. CCD: Charge Coupled Devices - Imaging

- An array of linked ("coupled") capacitors

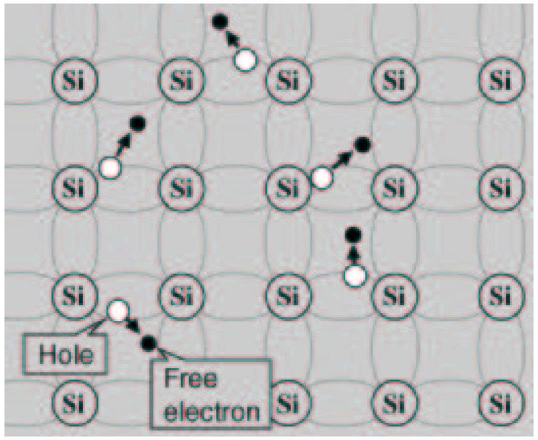
- Photons interact in a semiconductor substrate
and are converted into electrons

- An applied electric field collects
and stores the electrons in pixels

- Pixels are "coupled" and can transfer their stored charge
to neighboring pixels

- Stored charge is transferred to a output amplifier and read out

III. 8. Reminder: What is Semiconductor?



A silicon crystal is different from an insulator

- T>0: finite probability that an electron in the lattice
- is knocked loose from its position
- behind is an electron deficiency called a "hole"
- voltage: both the electron and the hole contribute to small cu

The Doping of Semiconductors

The addition of a small percentage offoreign atoms in the regular crystal lattice of silicon or germanium changes their electrical properties producing n-type and p-type semiconductors.

see http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html

-Atoms with 5 valence electrons produce n-type semiconductors by contributing extra electrons.

-Atoms with 3 valence electrons produce p-type semiconductors by producing a "hole" or electron deficiency.

III. 9. 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

To be continued...