X-Ray Detectors

Introduction

A large amount of our understanding of AGN comes from non-optical observations.

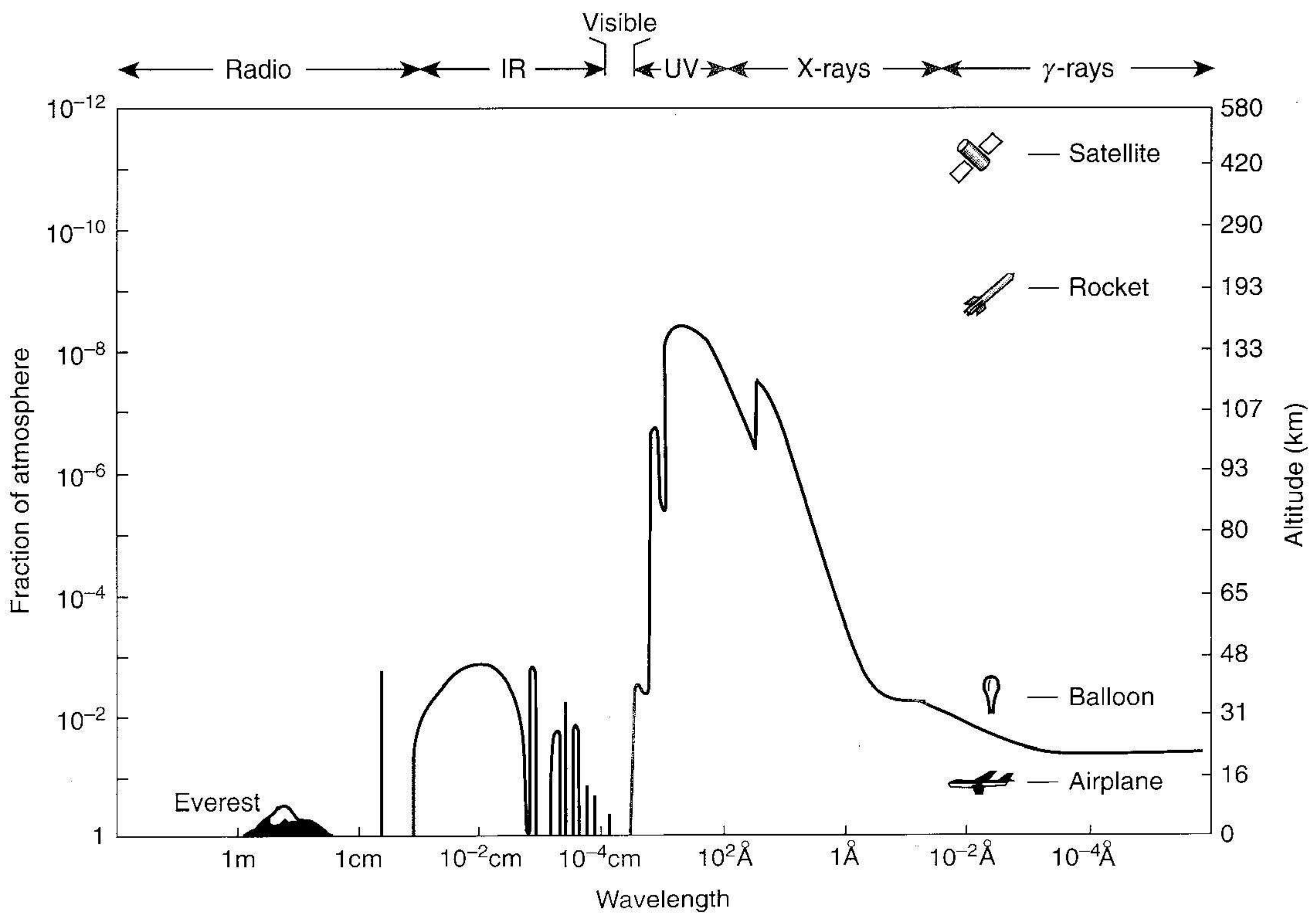
$\Longrightarrow$ we need to understand how these observations are made to be able to interpret their results.

$\Longrightarrow$ Will take a “side trip” into the world of X-ray detectors.

There are two main issues to deal with:

- X-ray Optics
- X-ray Detectors

Earth's Atmosphere



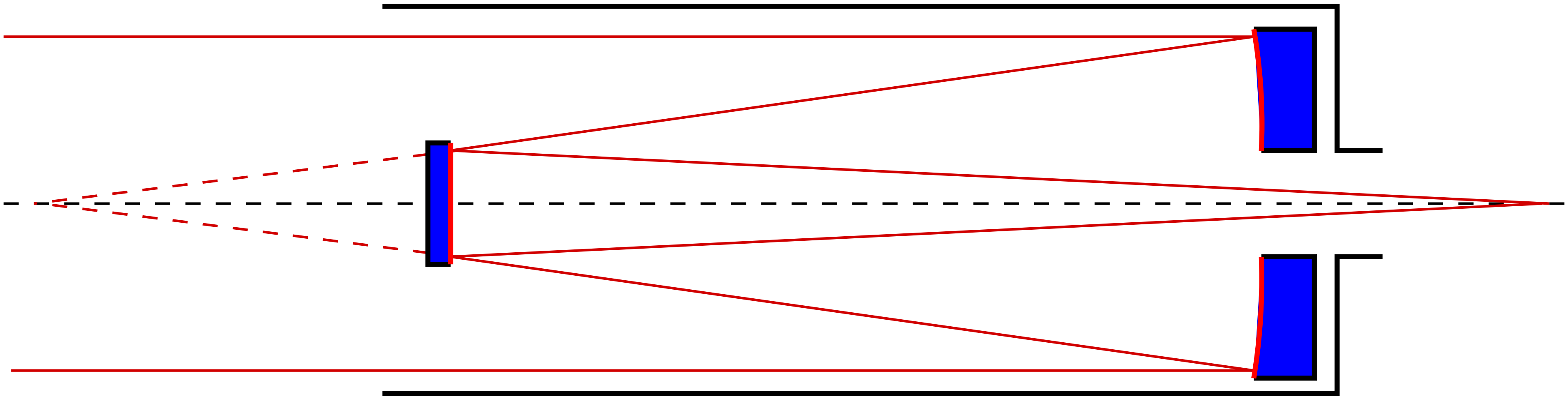
Charles & Seward, Fig. 1.12

Earth's atmosphere is opaque for all types of EM radiation except for optical light and radio.

Major contributer at high energies: photoabsorption ($\propto E^{-3}$), esp. from oxygen (edge at $\sim$500 eV).

$\Longrightarrow$ If one wants to look at the sky in other wavebands, one *has* to go to space!

Optical Imaging, I



Cassegrain telescope, after Wikipedia

Reminder: Optical telescopes are usually reflectors:

primary mirror (paraboloid) $\longrightarrow$ secondary mirror (often flat) $\longrightarrow$ detector

Main characteristics of a telescope:

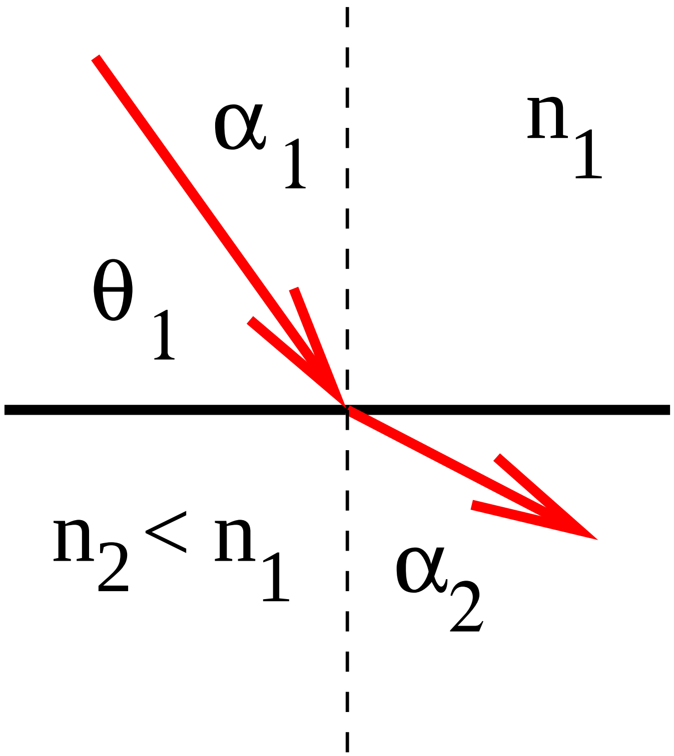
- collecting area (i.e., open area of telescope, $\sim \pi d^2/4$, where d: telescope diameter)
- for small telescopes: angular resolution,

$$\theta = 1.22\,\frac{\lambda}{d} \qquad (5.1)$$

but in the optical: do not forget the seeing!

Optical Imaging, II

Optical telescopes are based on principle that reflection "just works" with metallic surfaces.



Snell's law of refraction:

$$\frac{\sin\alpha_1}{\sin\alpha_2} = \frac{n_2}{n_1} = n \tag{5.2}$$

where n index of refraction, and $\alpha_{1,2}$ angle wrt. surface normal. If $n \gg 1$: Total internal reflection

Total reflection occurs for $\alpha_2 = 90^\circ$, i.e. for

$$\sin\alpha_{1,c} = n \iff \cos\theta_c = n \tag{5.3}$$

with the critical angle $\theta_c = \pi/2 - \alpha_{1,c}$.
Clearly, total reflection is only possible for $n < 1$.

Light in glass at glass/air interface: $n = 1/1.6 \Longrightarrow \theta_c \sim 50^\circ \Longrightarrow$ principle behind optical fibers.

Optical Imaging, III

X-rays: index of refraction vacuum versus material is (Aschenbach, 1985):

$$n = 1 - N_\mathrm{A} \frac{Z}{A} \frac{r_\mathrm{e}}{2\pi} \rho\lambda^2 =: 1 - \delta \qquad (5.4)$$

N_A: Avogadro's number, $r_\mathrm{e} = 2.8 \times 10^{-15}\,\mathrm{m}$, Z: atomic number, A: atomic weight ($Z/A \sim 0.5$), ρ: density, λ: wavelength (X-rays: $\lambda \sim 0.1$–$1\,\mathrm{nm}$).

Critical angle for X-ray reflection:

$$\cos\theta_\mathrm{c} = 1 - \delta \qquad (5.5)$$

Since $\delta \ll 1$, Taylor ($\cos x \sim 1 - x^2/2$):

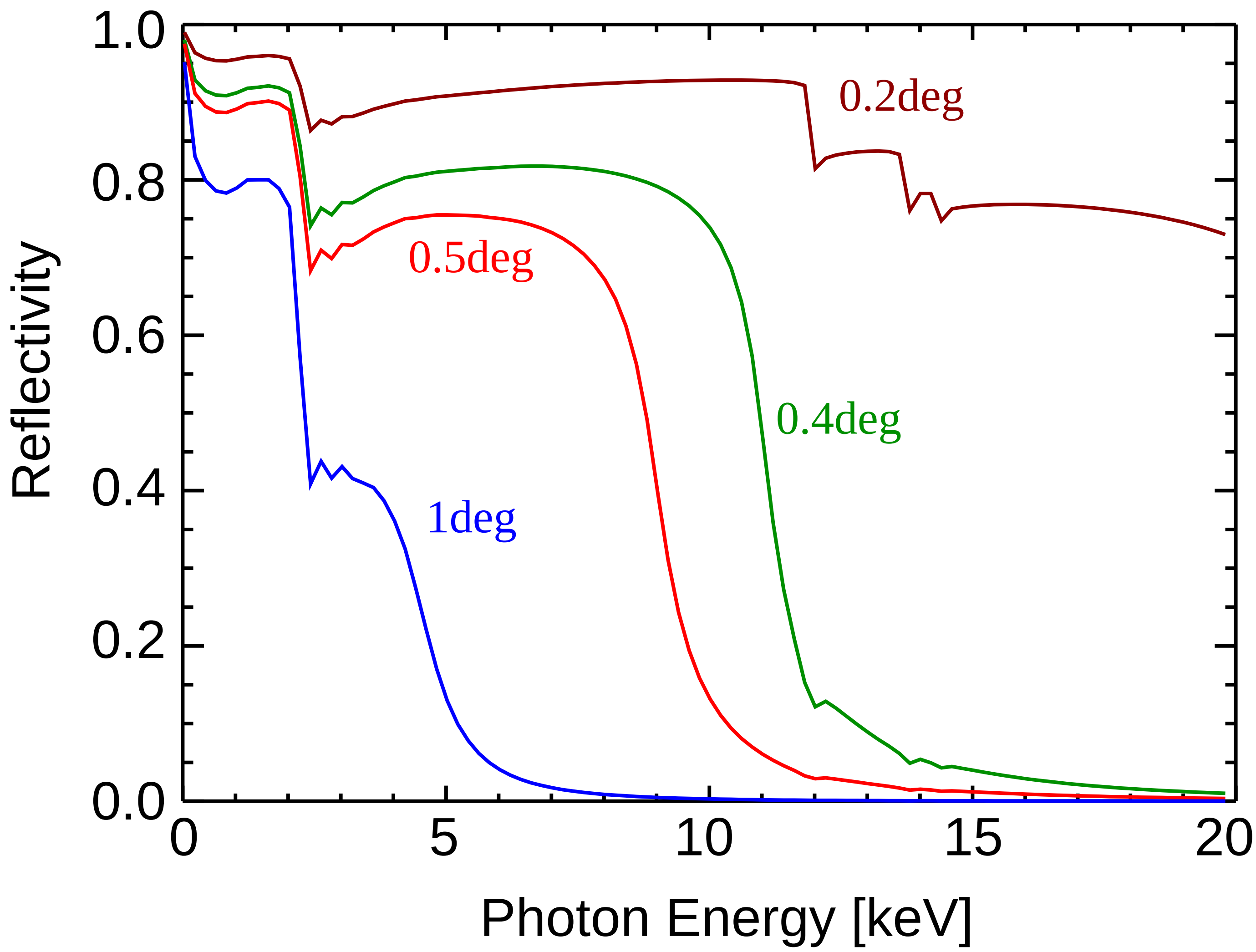
$$\theta_\mathrm{c} = \sqrt{2\delta} = 56'\rho^{1/2}\frac{\lambda}{1\,\mathrm{nm}} \qquad (5.6)$$

So for $\lambda \sim 1\,\mathrm{nm}$: $\theta_\mathrm{c} \sim 1^\circ$.

To increase θ_c: need material with high ρ

$\Longrightarrow$ gold (*XMM-Newton*) or iridium (*Chandra*).

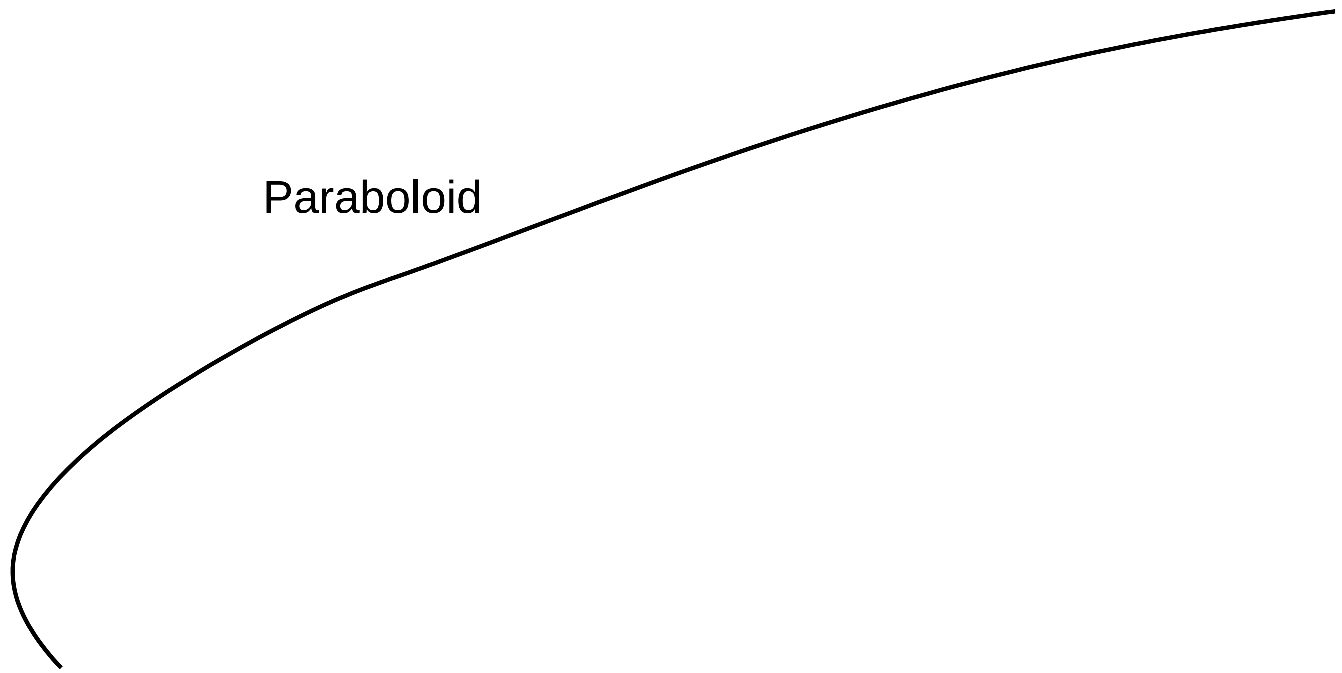
Optical Imaging, IV



Reflectivity for Gold

X-rays: Total reflection only works in the soft X-rays and only under grazing incidence $\Longrightarrow$ grazing incidence optics.

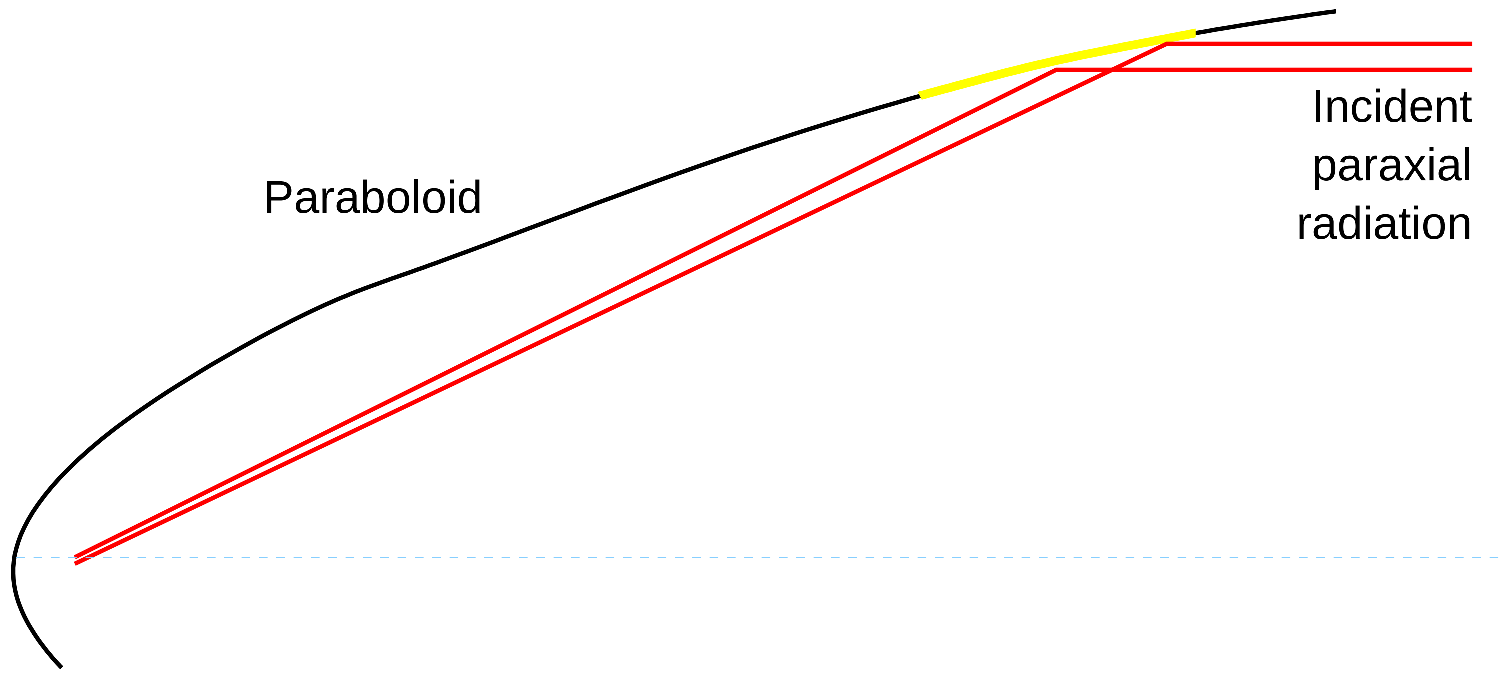
Wolter Telescopes, I



after ESA

Geometric optics: focusing with conic sections.

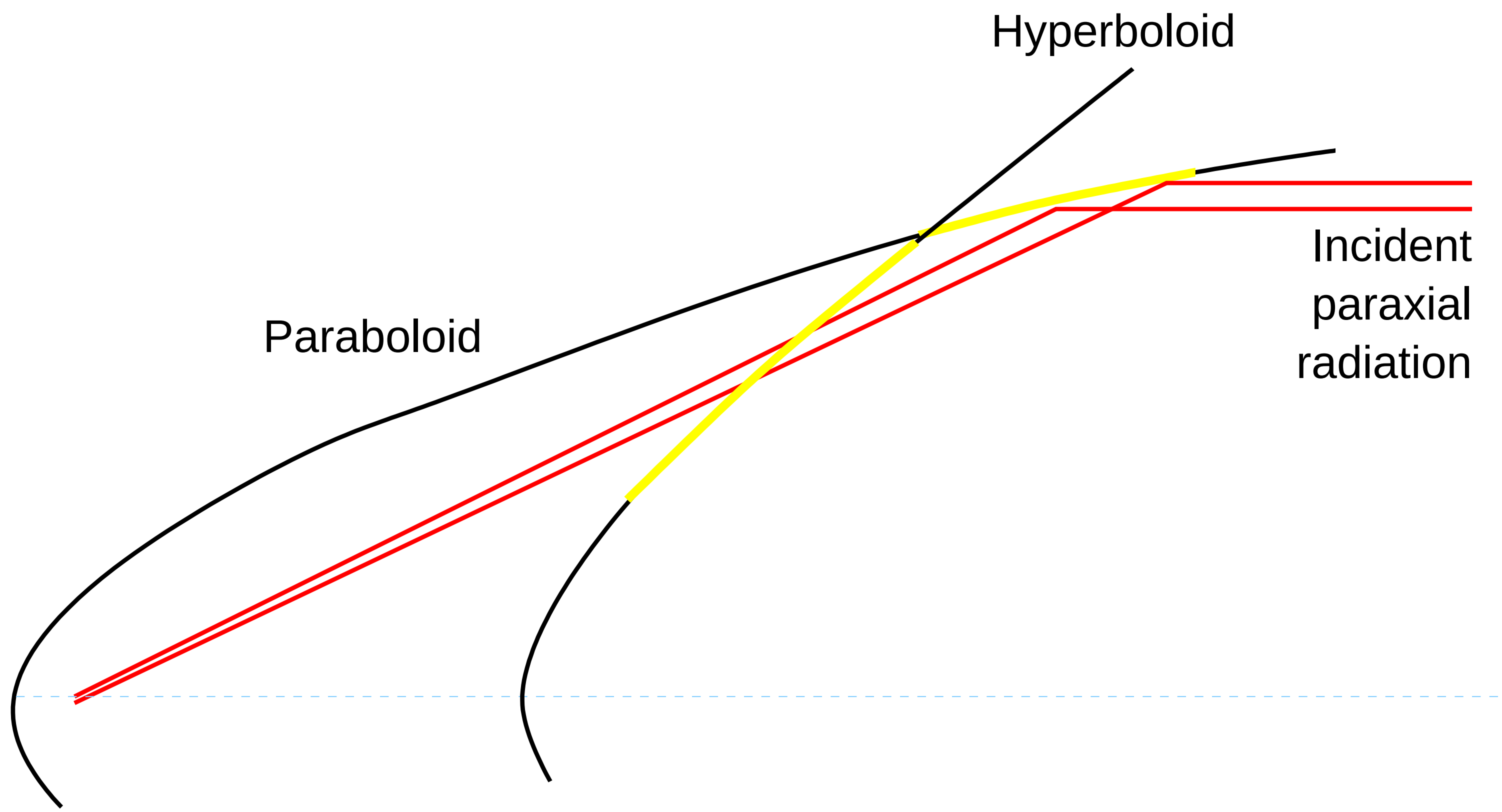
Wolter Telescopes, II



after ESA

Parabolic system alone: long focal length.

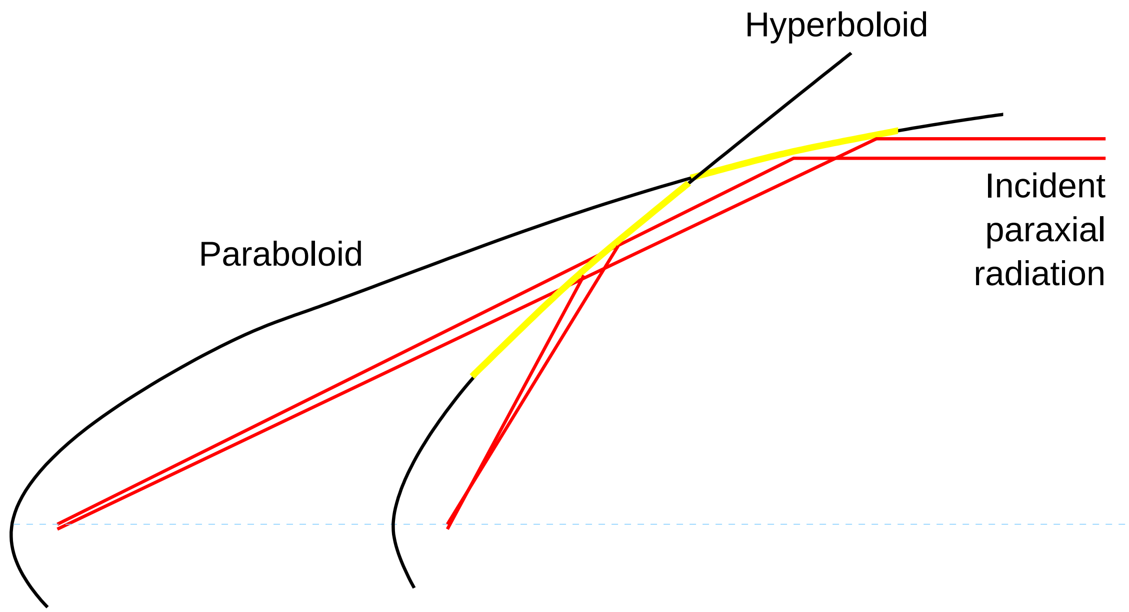
Wolter Telescopes, III



after ESA

Shorten system with combination of parabola and hyperboloid.

Wolter Telescopes, IV

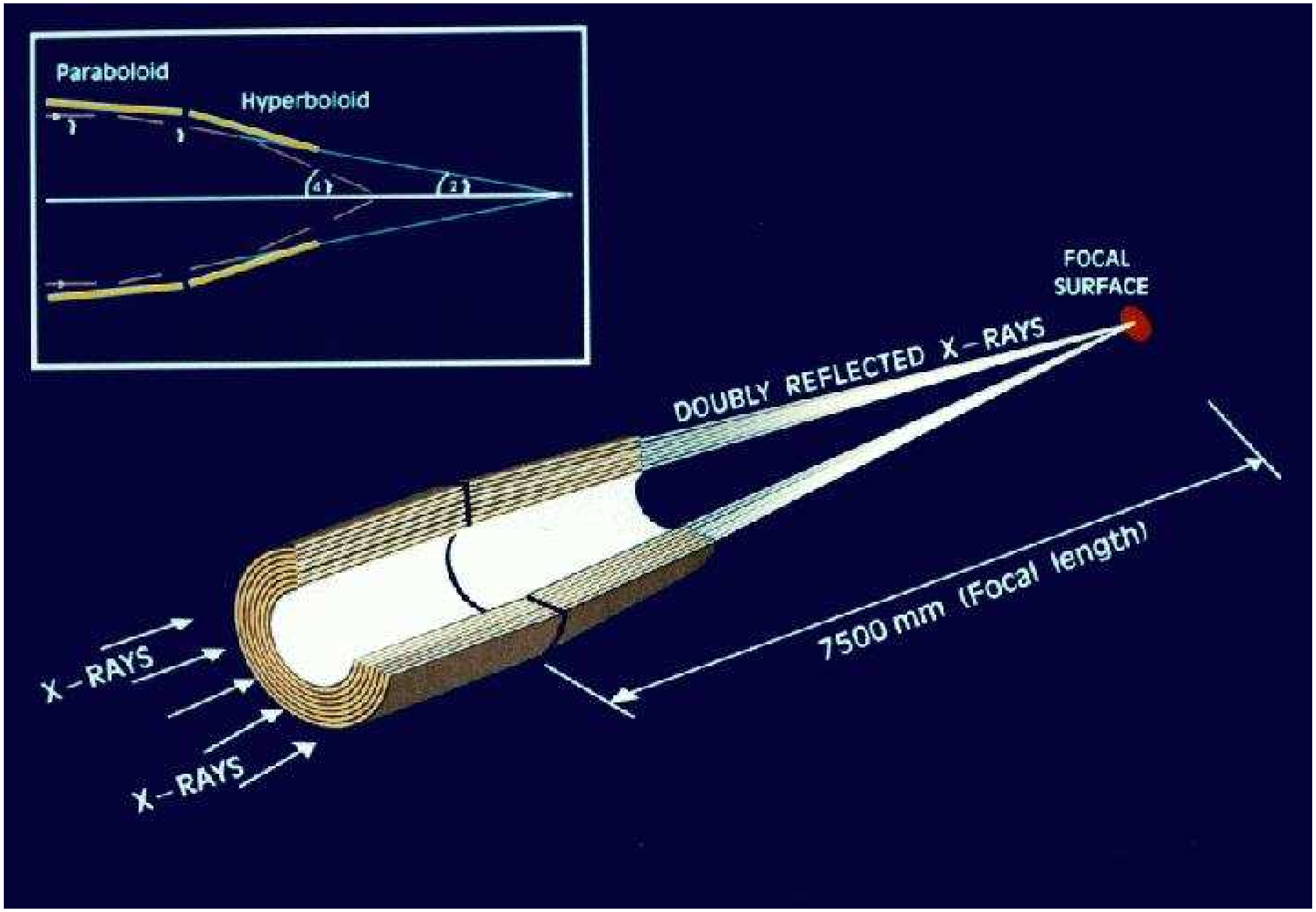


To obtain manageable focal lengths ($\sim$ 10 m), do imaging with telescope using two reflections on a paraboloic and a hyperboloidal mirror ("Wolter type I").

(Wolter, 1952, for X-ray microscopes, Giacconi, 1961, for UV- and X-rays).

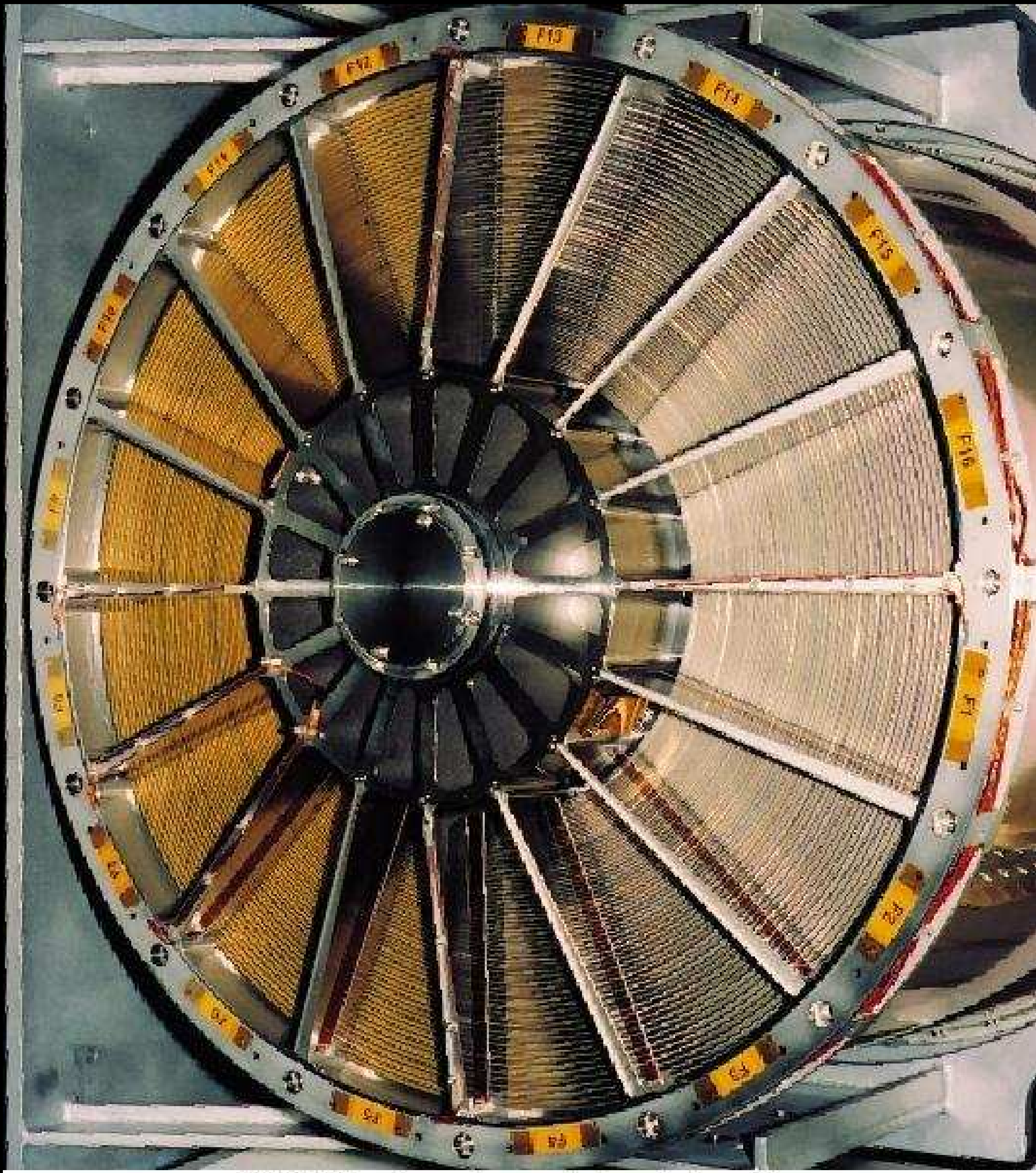
But: small collecting area ($A \sim \pi r^2 l / f$ where f: focal length)

Wolter Telescopes, V



ESA/XMM

Solution to small collecting area: nested mirrors.

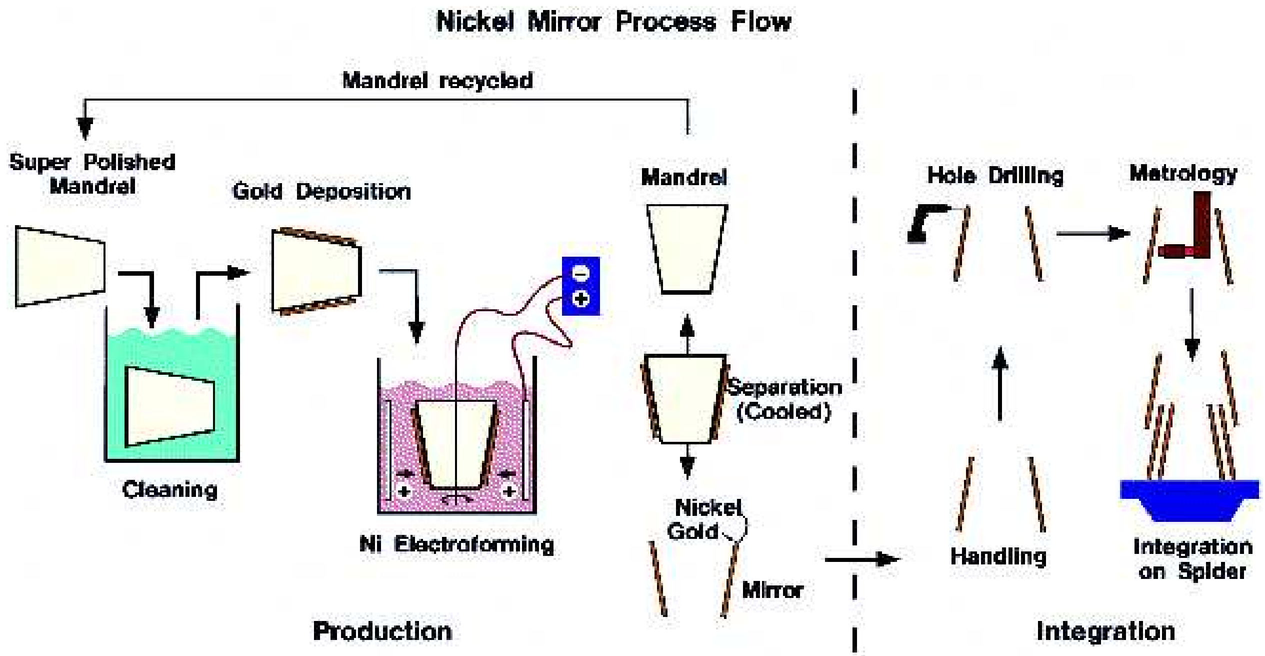


XMM-Newton mirrors during integration

Image courtesy of Dornier Satellitensysteme GmbH

European Space Agency

Mirror manufacture, I



Recipe for making an X-ray mirror:

1. Produce mirror negative (“Mandrels”): Al coated with Kanigen nickel (Ni+10% phosphorus), super-polished [0.4 nm roughness]).
2. Deposit 250 nm Au onto Mandrel
3. Deposit 1 mm Ni onto mandrel (“electro-forming”, 10 μm/h)
4. Cool Mandrel with liquid N. Au sticks to Nickel
5. Verify mirror on optical bench.

Total production time of one mirror: 12 d, for XMM: 3×58 mirrors.

Mirror manufacture, II

Gold plastered mandrel for one of the XMM mirrors before electroforming the Ni shell onto the gold.

ESA picture 96.05.006-070

Mirror manufacture, III

. . . insertion of Mandrel into electroforming bath

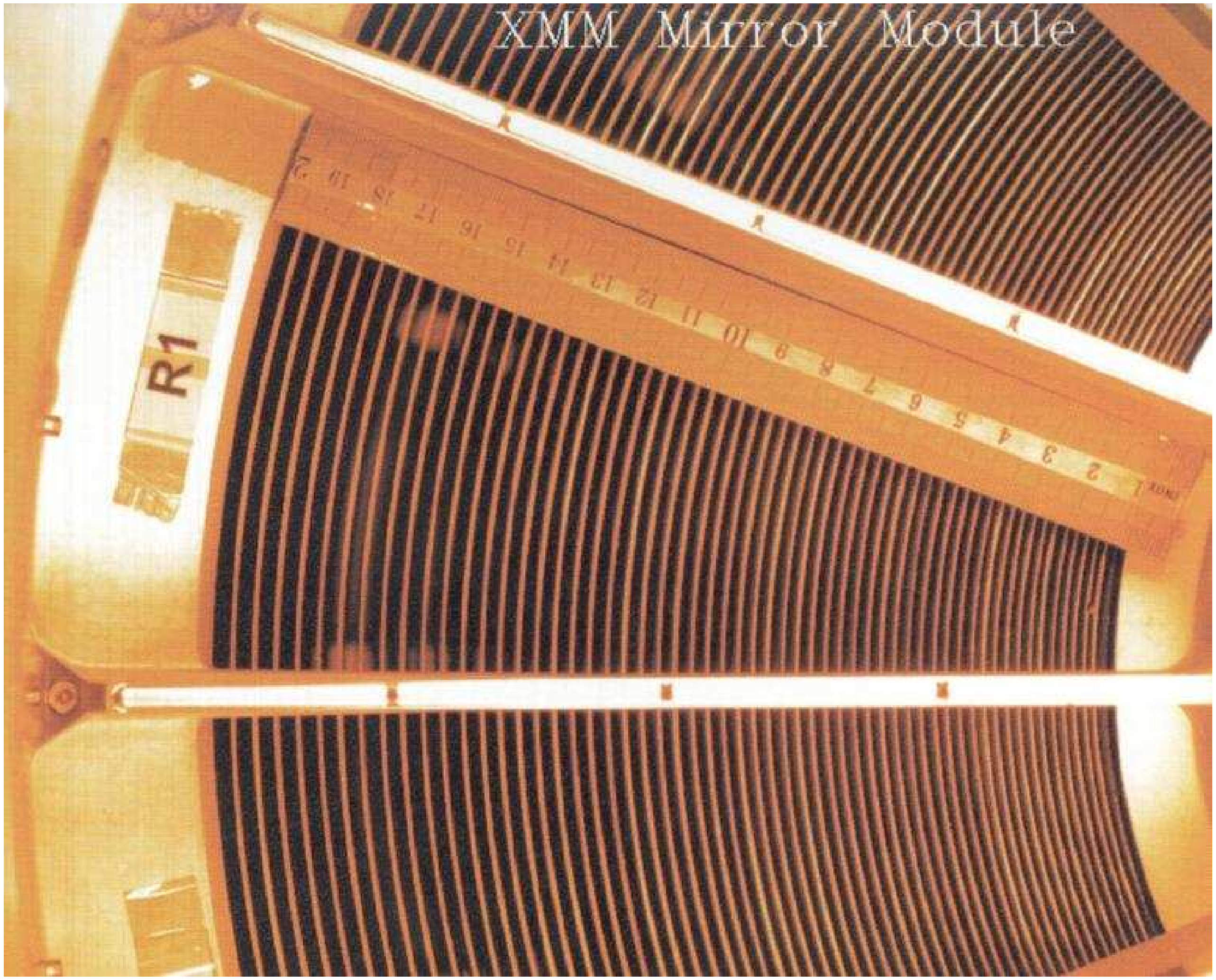
ESA picture 96.12.002-016

Mirror manufacture, IV

. . . and the mirror is done

ESA picture 96.12.002-093

XMM-Newton



Top of the XMM mirrors:

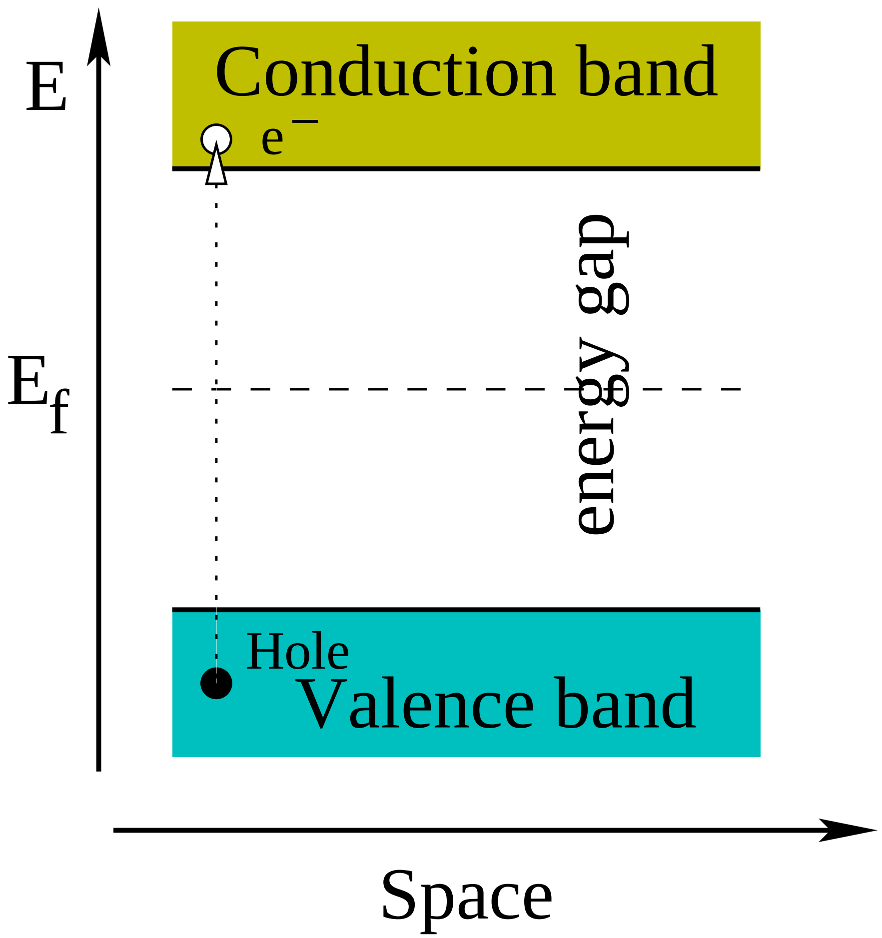
3 mirror sets, each consisting of 58 mirrors,

- Thickness between 0.47 and 1.07 mm
- Diameter between 306 and 700 mm,
- Masses between 2.35 and 12.30 kg,
- Mirror-Height 600 mm
- Reflecting material: 250 nm Au.

photo: Kayser-Threde

The *XMM-Newton* Spacecraft (photo: ESA)

Semi-Conductors



Semiconductors: separation of valence band and conduction band $\sim$1 eV (=energy of visible light).

Absorption of photon produces

$$N \sim \frac{h\nu}{E_{\text{gap}}} \quad (5.7)$$

electron-hole pairs.

For Si: $E_{\text{gap}} = 1.12\,\text{eV}$; 3.61 pairs created per eV photon energy [takes into account collective effects in semiconductor]

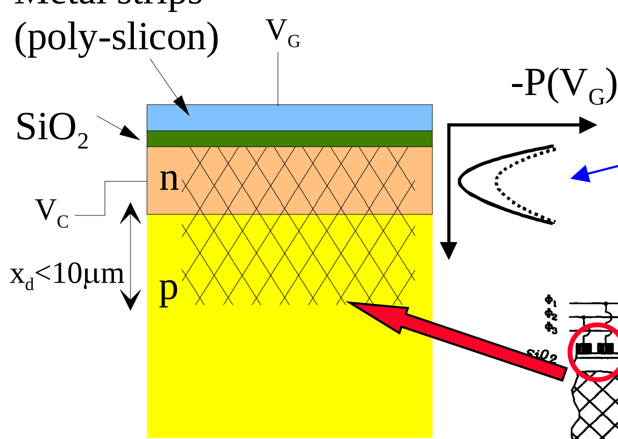
Note: band gap small $\Longrightarrow$ need cooling!

- optical light: $\sim$1 electron-hole pair
- X-rays (keV): $\sim$1000 electron-hole pairs

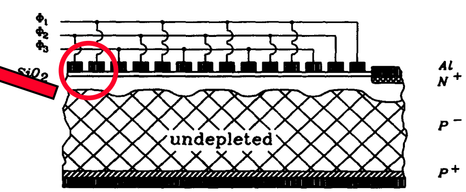
Problem: electron-hole pairs recombine immediately in a normal semiconductor $\Longrightarrow$ in practice, apply voltage to a "pn-junction" to separate electrons and pairs.

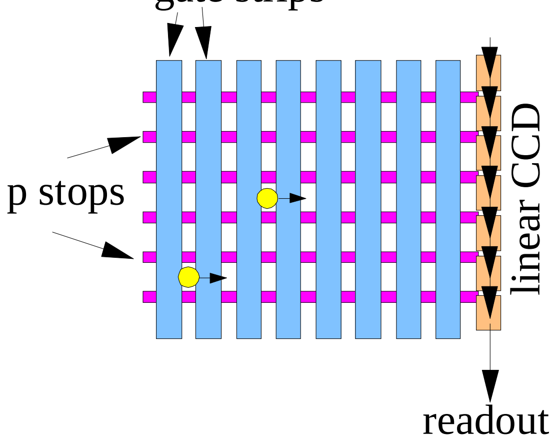
◆ Charge Coupled Devices (CCD)

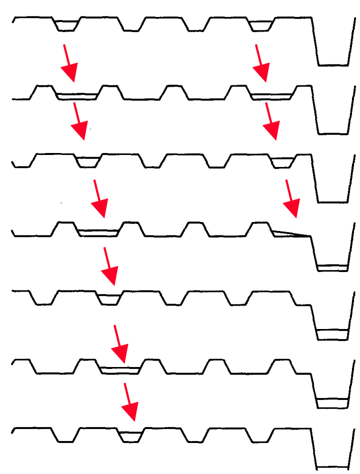
MOS structure with segmented metal layer



collect free electrons in a potential well, ca. 1µm below SiO_2 layer





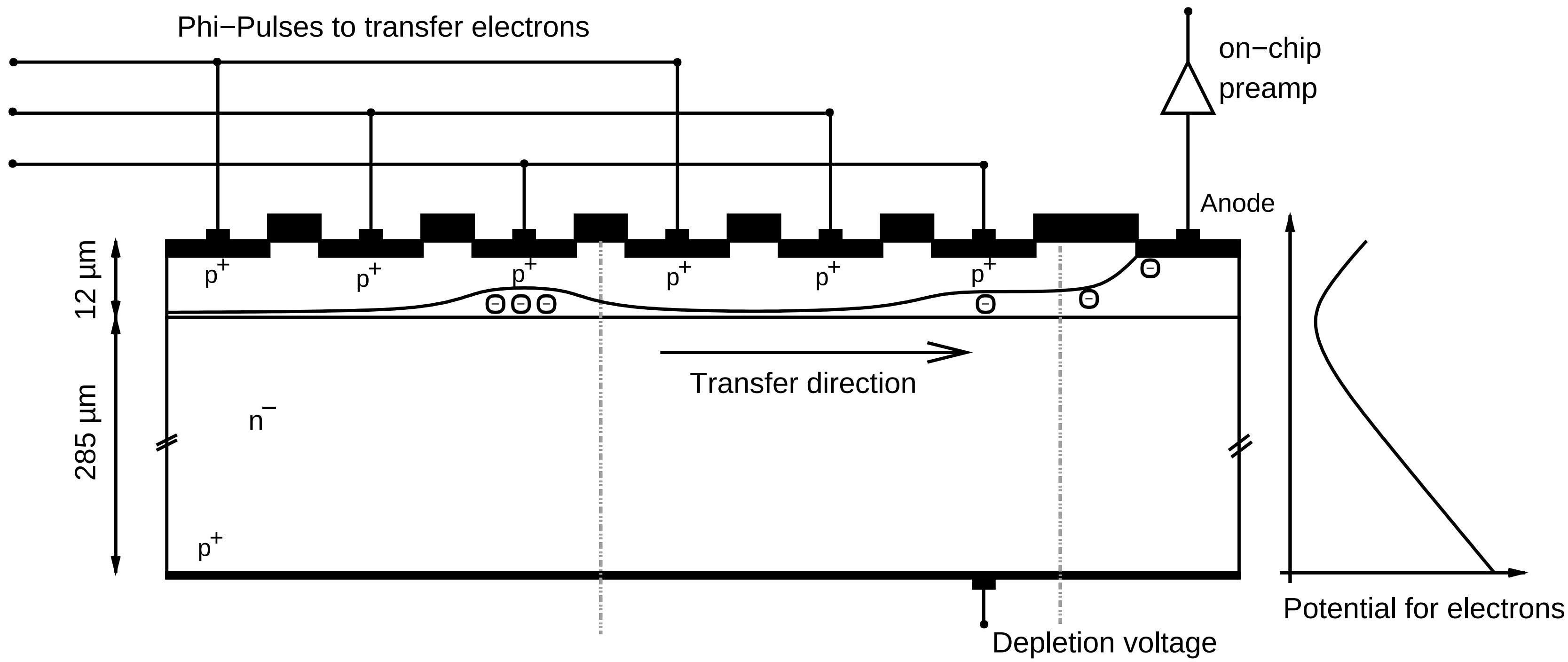


→ **all pixels are readout via one (few) output node(s)**

→ **very few electronic channels but long readout time!**

Charge transport by periodic change of gate voltage triplets (ϕ_1,ϕ_2,ϕ_3)

Backside Illuminated CCDs

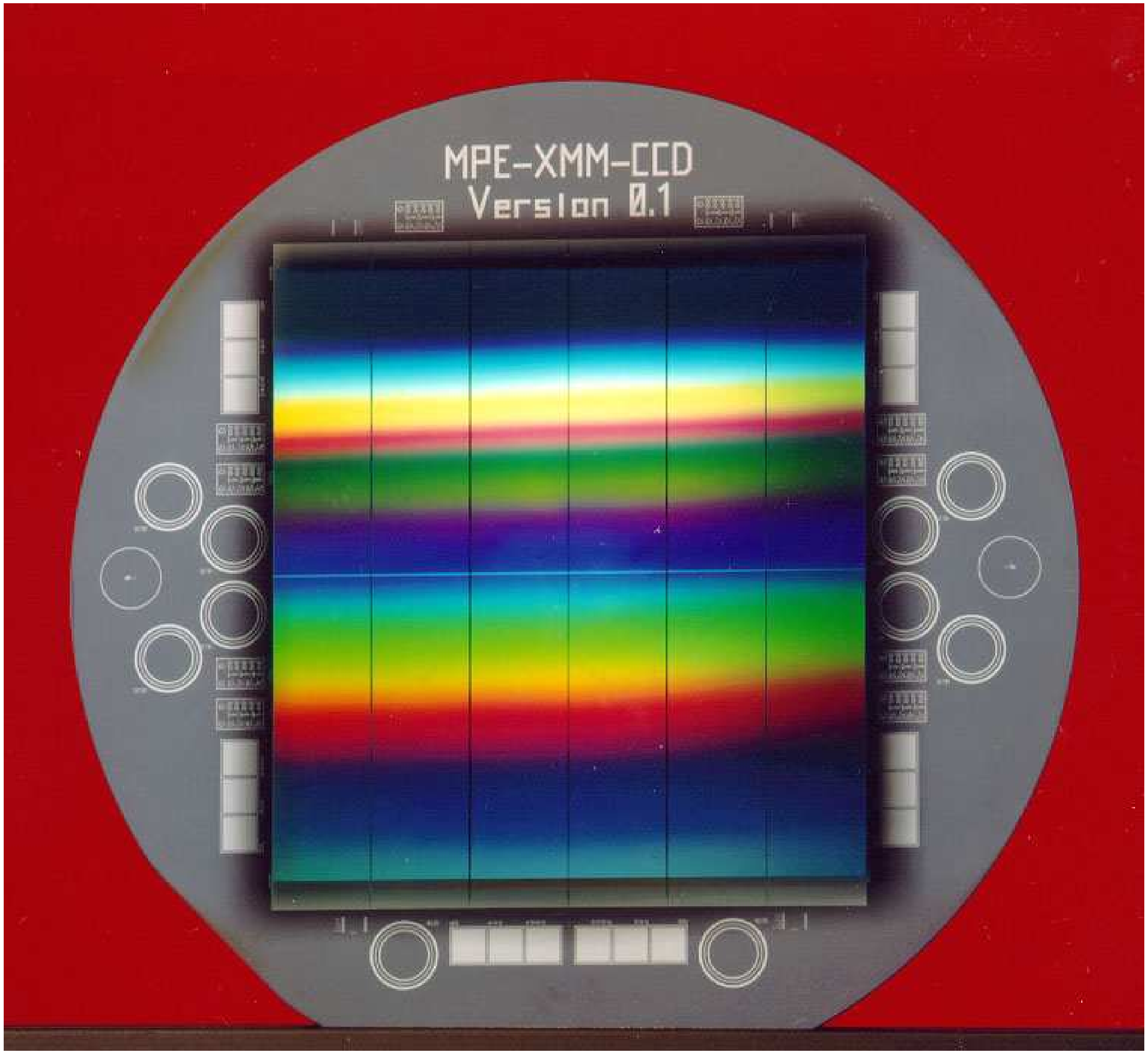


Schematic structure of the *XMM-Newton* EPIC pn CCD.

Problem: Infalling structure has to pass *through* structure on CCD surface $\Longrightarrow$ loss of low energy response, also danger through destruction of CCD structure by cosmic rays. . .

Solution: Irradiate the back side of the chip. Deplete whole CCD-volume, transport electrons to pixels via adequate electric field ("backside illuminated CCDs")

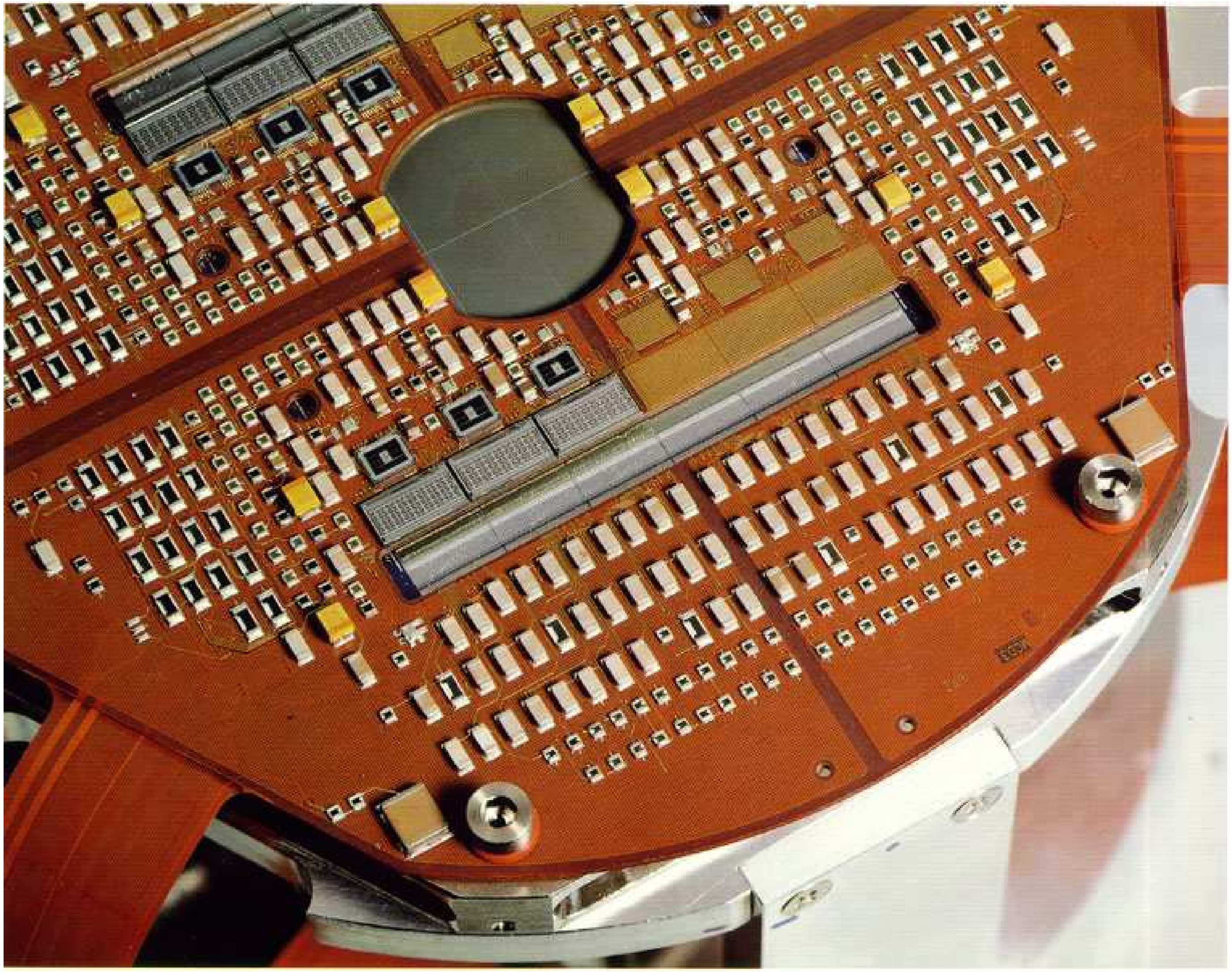
XMM-Newton: EPIC-pn CCD



XMM-Newton: Array of individual backside illuminated CCDs on one Silicon wafer $\Longrightarrow$ requires extreme care during production

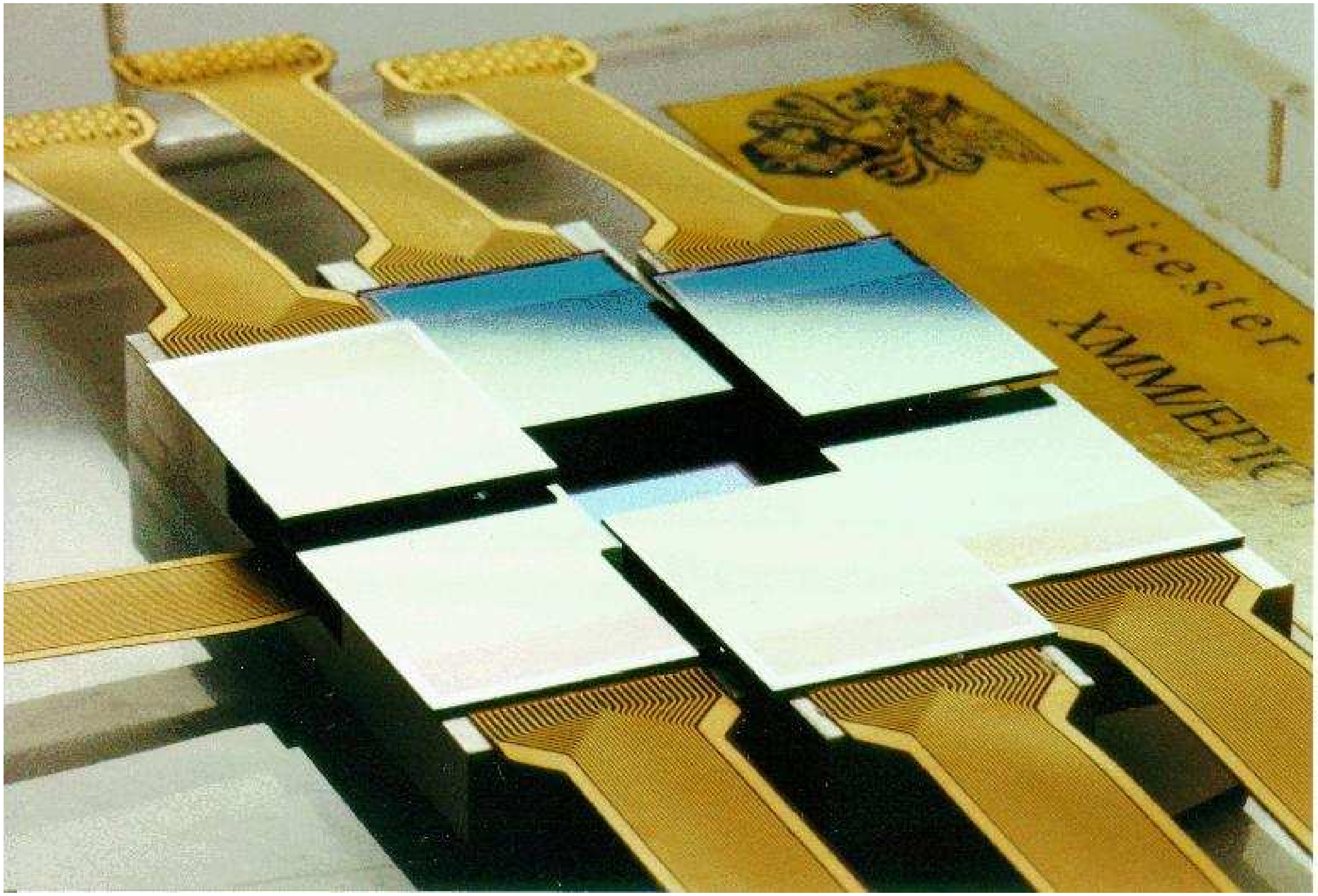
at the time of production one of the most complex Silicon structures ever made (diameter: 65.5 mm)

XMM-Newton: EPIC-pn CCD



Backside of the EPIC-pn camera head

XMM-Newton: EPIC-pn CCD



XMM-Newton (EPIC-MOS; Leicester): 7 single CCDs with 600 $\times$ 600 pixels, mounting is adapted to curved focal plane of the Wolter telescope.

Data Analysis

optical CCDs: mesure intensity $\Longrightarrow$ need *long* exposures

X-ray CCDs: measure individual photons $\Longrightarrow$ need fast readout

bright sources: several 1000 photons per second $\Longrightarrow$ readout in μs!

In X-rays: spectroscopy possible. Typical resolution reached today:

$$\frac{\Delta E}{E} = 2.355\sqrt{\frac{3.65\,\mathrm{eV}\cdot F}{E}} \tag{5.8}$$

with $F \sim 0.1 \Longrightarrow \sim 0.4\%$, so much better than gas detectors.

Energy $\propto$ number N of initial photoelectrons $\Longrightarrow$ Energy resolution (Poisson statistics!):

$$\frac{\Delta E}{E} \propto \frac{\Delta N}{N} = \frac{N^{1/2}}{N} = \frac{1}{N^{1/2}} \propto E^{-1/2} \tag{5.9}$$

For both optical and X-rays: sensitivity close to 100%

Si-based CCDs are currently the best available imaging photon detectors for optical and X-ray applications.

Data Analysis

Finite resolution of X-ray detectors has major implications for X-ray data analysis.

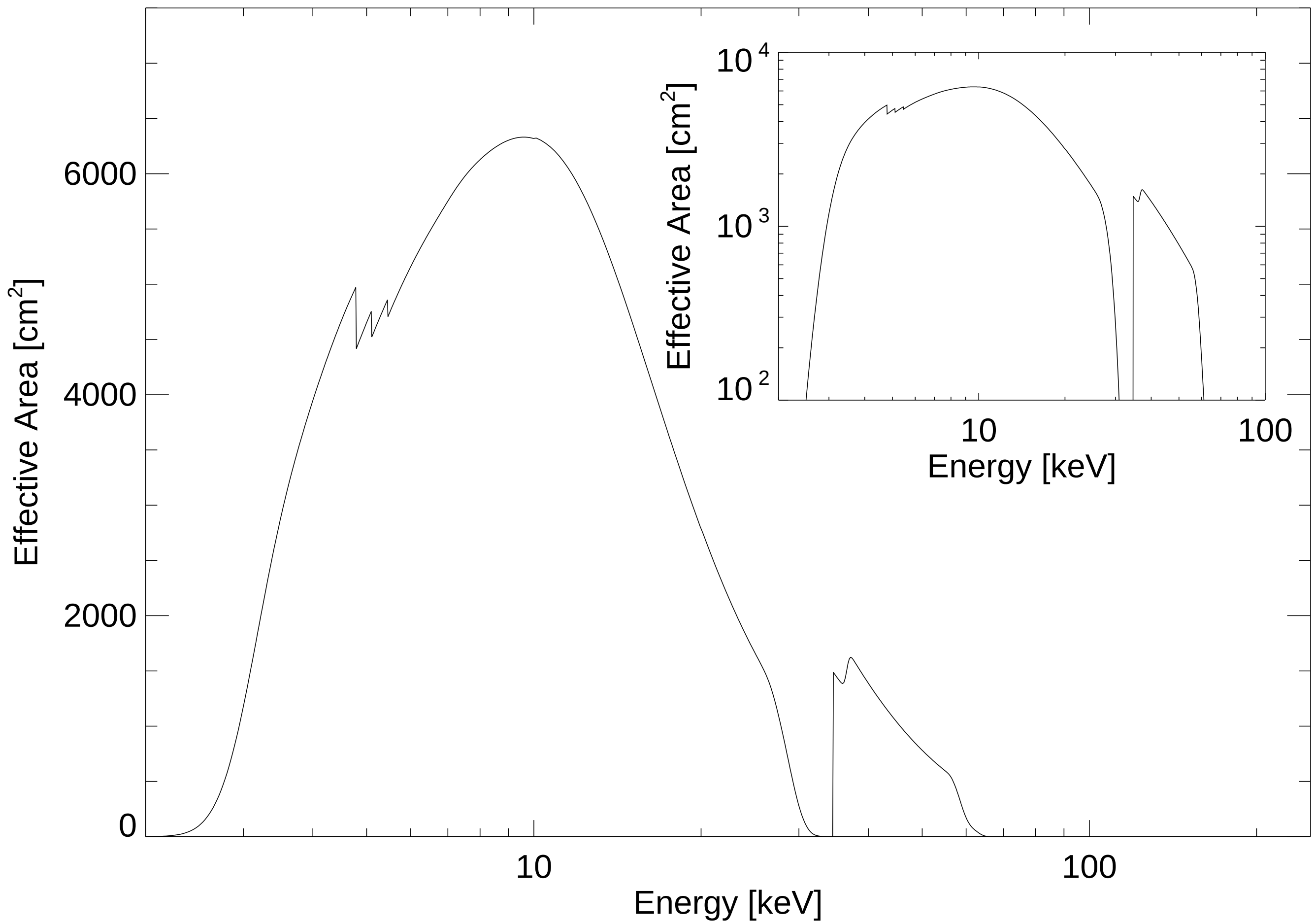
Mathematical description of the X-ray measurement process:

$$n_{\text{ph}}(c) = \int_0^\infty R(c, E) \cdot A(E) \cdot F(E)\, dE \tag{5.10}$$

where

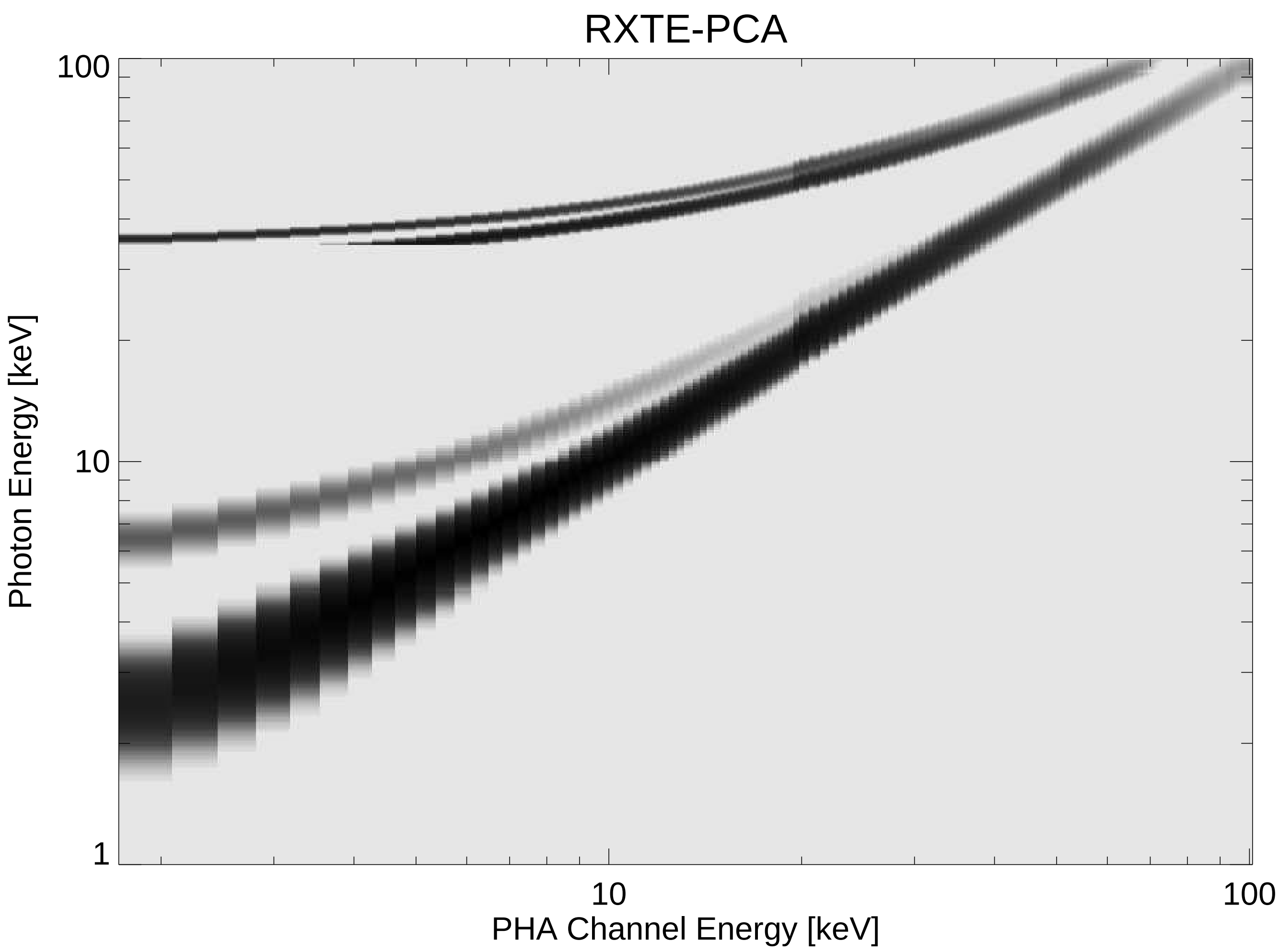
- $n_{\text{ph}}(c)$: source count rate in channel c (counts s^{-1}),
- $F(E)$: photon flux density (ph cm^{2} s^{-1} keV^{-1}),
- $A(E)$: effective area (units: cm^2),
- $R(c, E)$: detector response (probability to detect photon of energy E in channel c).

Data Analysis



Effective Area of the Rossi X-ray Timing Explorer's Proportional Counter Array (Xe gas detector).

Data Analysis



Response Matrix of the RXTE-PCA. Note the secondary peaks in the response caused by escaping Xe Kβ and Xe Lα photons.

Data Analysis

To analyze data: discretize Eq. (5.10):

$$S_{\mathrm{ph}}(c) = \Delta T \sum_{i=0}^{n_{ch}} A(E_i) R(c,i) F(E_i) \Delta E_i \tag{5.11}$$

where $N_{\mathrm{ph}}(c)$: total source counts in channel c, ΔT: exposure time (s), x$A(E_i)$: effective area in energy band i ("ancilliary response file", ARF), $R(c,i)$: response matrix (RMF), $F(E_i)$: source flux in band (E_i, E_{i+i}), ΔE_i: width of energy band.

Because of background $B(c)$ (counts), what is measured is

$$N_{\mathrm{ph}}(c) = S_{\mathrm{ph}}(c) + B(c) \tag{5.12}$$

So estimated source count rate is

$$\tilde{S}_{\mathrm{ph}}(c) = N_{\mathrm{ph}}(c) - B(c) \tag{5.13}$$

with uncertainty (Poisson!)

$$\sigma \tilde{S}_{\mathrm{ph}}(c) = \sqrt{N_{\mathrm{ph}}(c)^2 + B(c)^2} \tag{5.14}$$

Data Analysis

To get physics out of measurement, need to find $F(E_i)$.

Big problem: In general, Eq. (5.11) is *not invertible*.

$\Longrightarrow$ χ^2-minimization approach

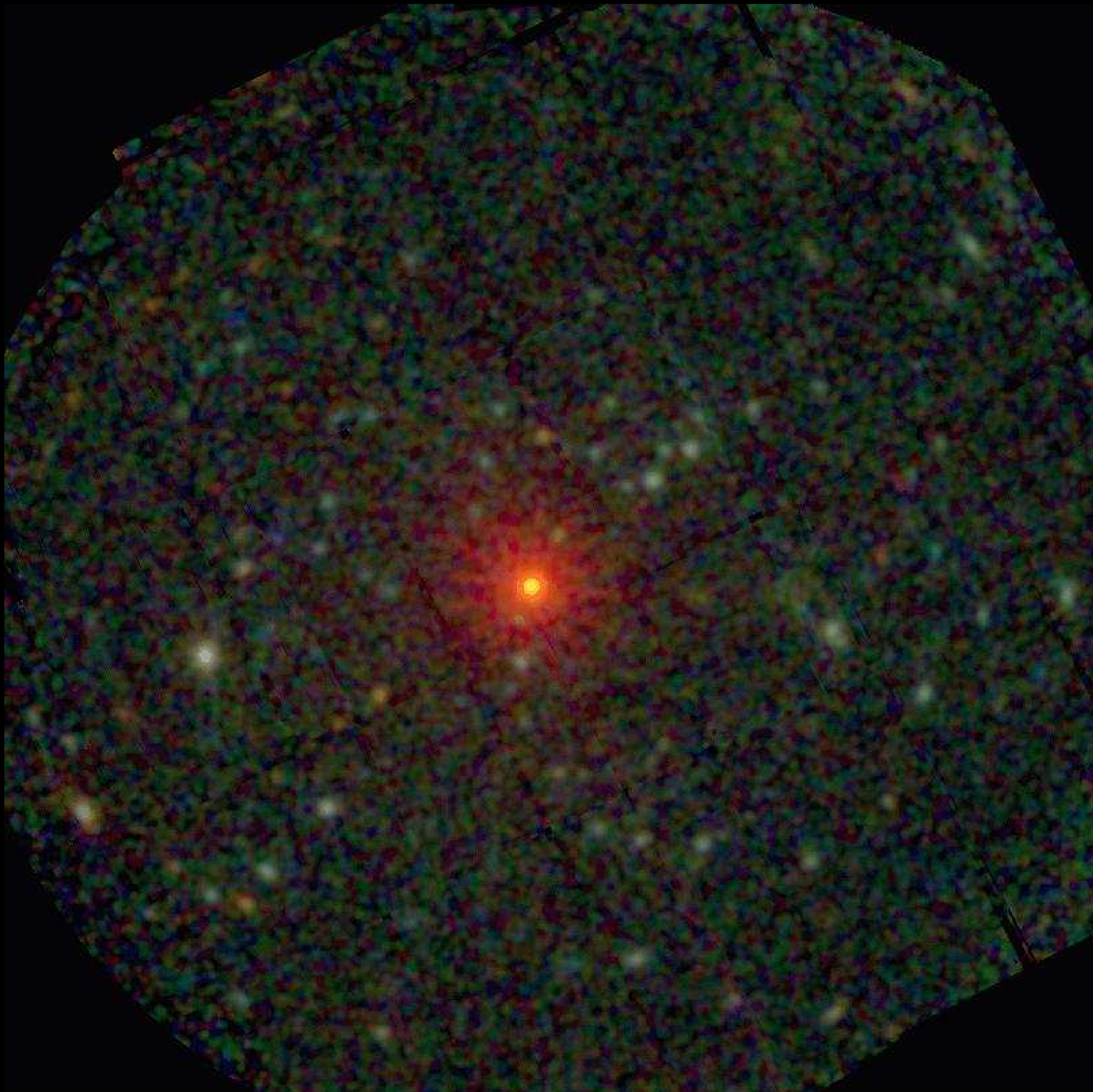
Use a model for the source spectrum, $F(E;\mathbf{x})$, where $\mathbf{x}$ vector of parameters (e.g., source flux, power law index, absorbing column,...), and calculate predicted model counts, $M(c;\mathbf{x})$, using Eq. 5.11).

Then form χ^2-sum:

$$\chi^2(\mathbf{x}) = \sum_c \frac{\left(\tilde{S}_{\text{ph}}(c) - M(c;\mathbf{x})\right)^2}{\sigma\tilde{S}_{\text{ph}}(c)^2} \tag{5.15}$$

Then vary $\mathbf{x}$ until χ^2 is minimal and perform statistical test based on χ^2 whether model $F(E;\mathbf{x})$ describes data.

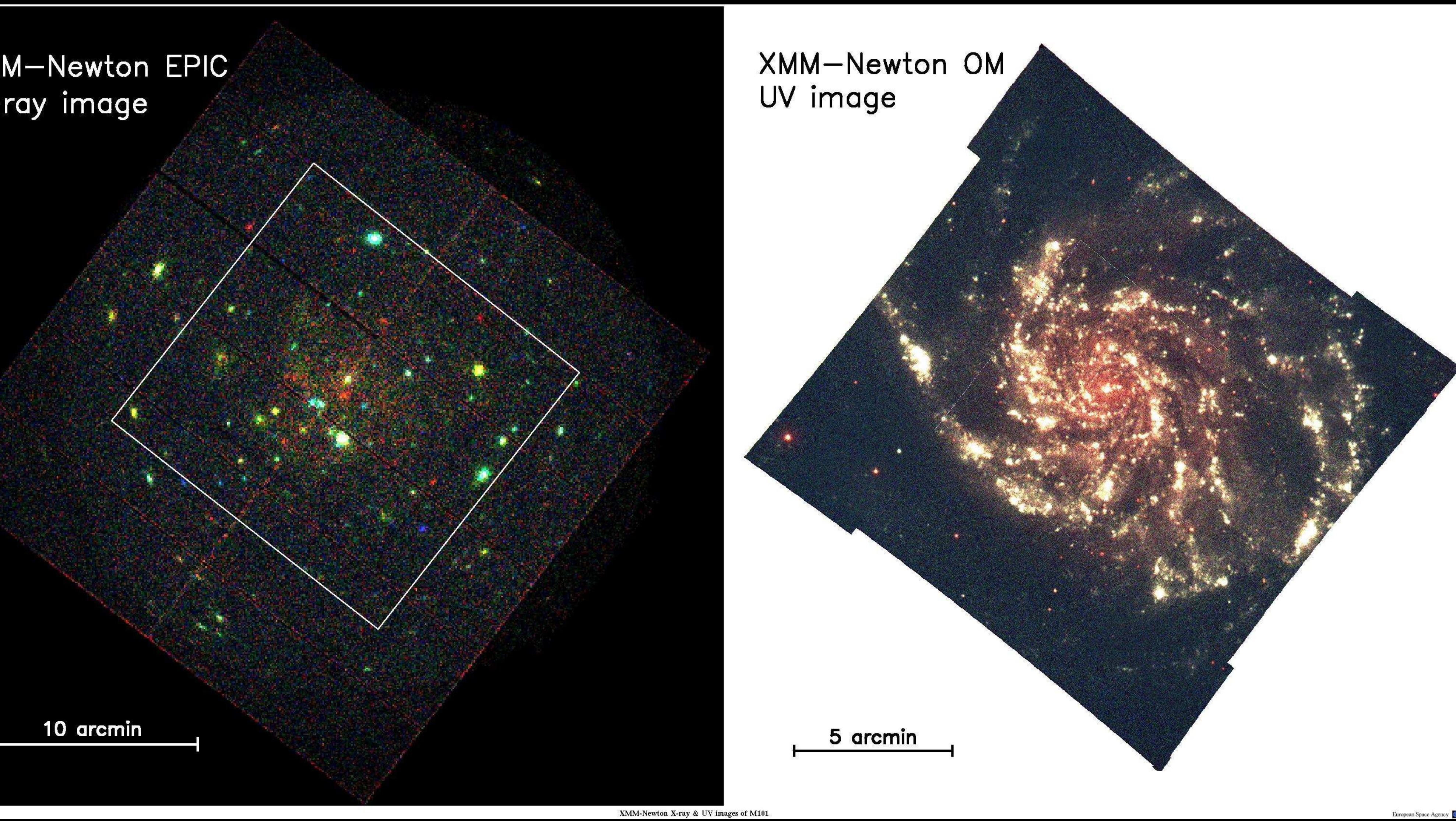
Programs used: `XSPEC`, `ISIS`



The isolated neutron star RX J0720.4-3125

Image courtesy of F. Haberl

European Space Agency



Point sources: Accreting stellar-mass systems in M101.

Lockman-Hole with *XMM-Newton*: The Universe is full of AGN!

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Aschenbach, B., 1985, Rep. Prog. Phys., 48, 579