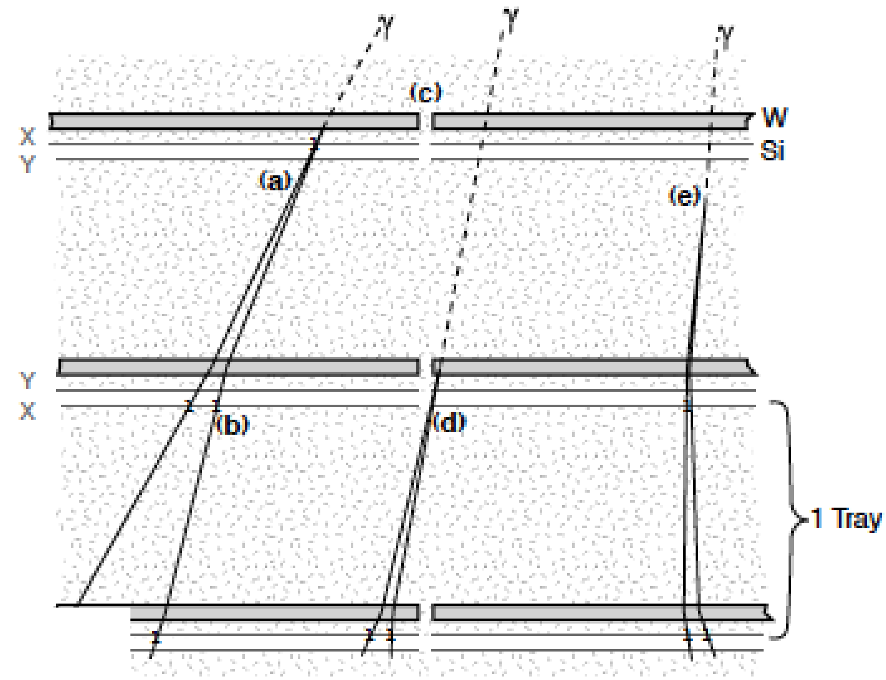
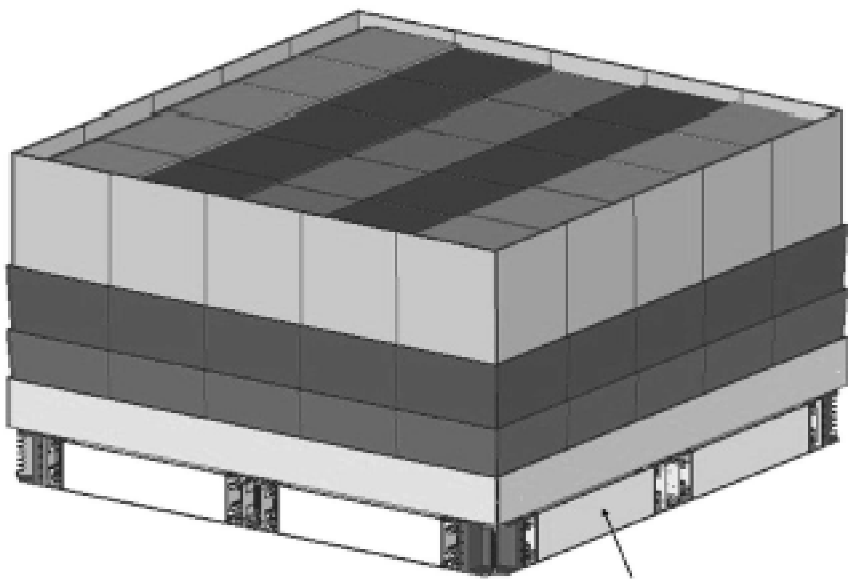
γ-ray Detectors

- High-energy γ-rays cannot be reflected or refracted; they interact by the conversion of the γ-ray into an e^+e^- pair
- A major concern is rejecting the much larger number of cosmic rays (need 0.9997 efficiency in rejection)



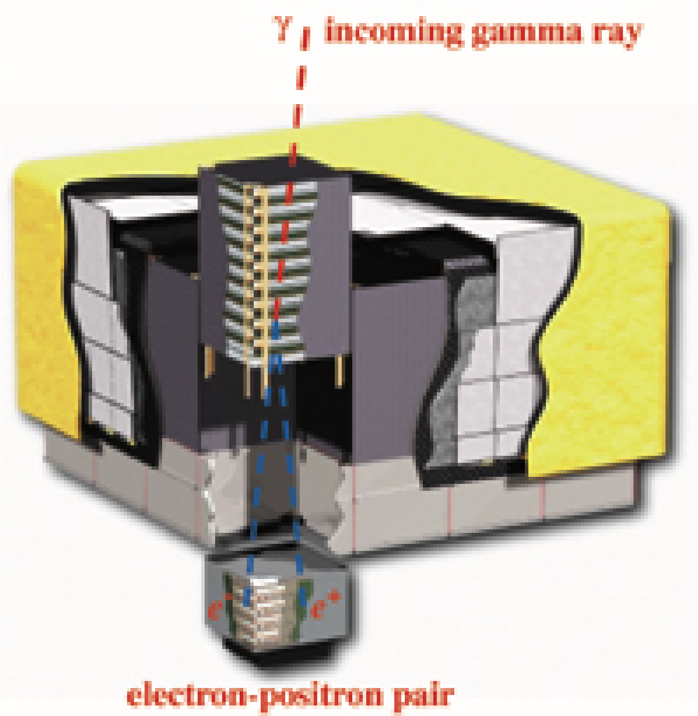


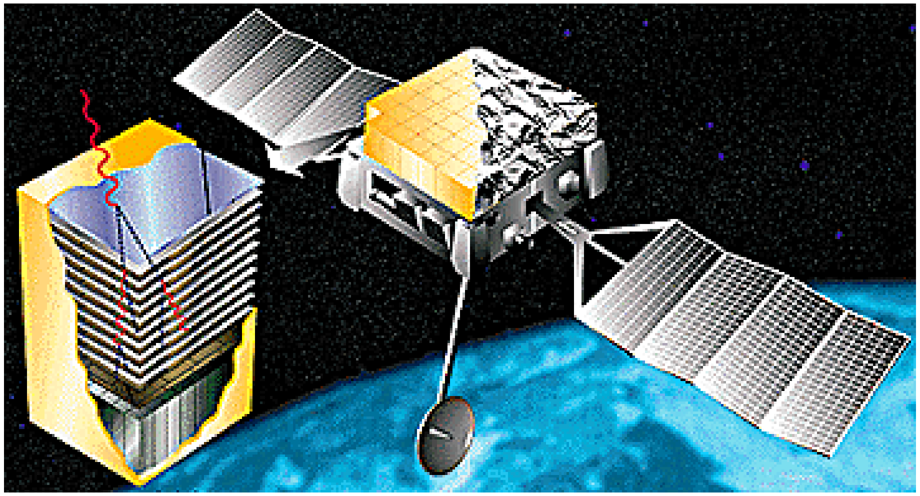
Full coverage of anti-coincidence detectors

γ-ray Detectors

Fermi energy range from 20 MeV - 300 GeV.

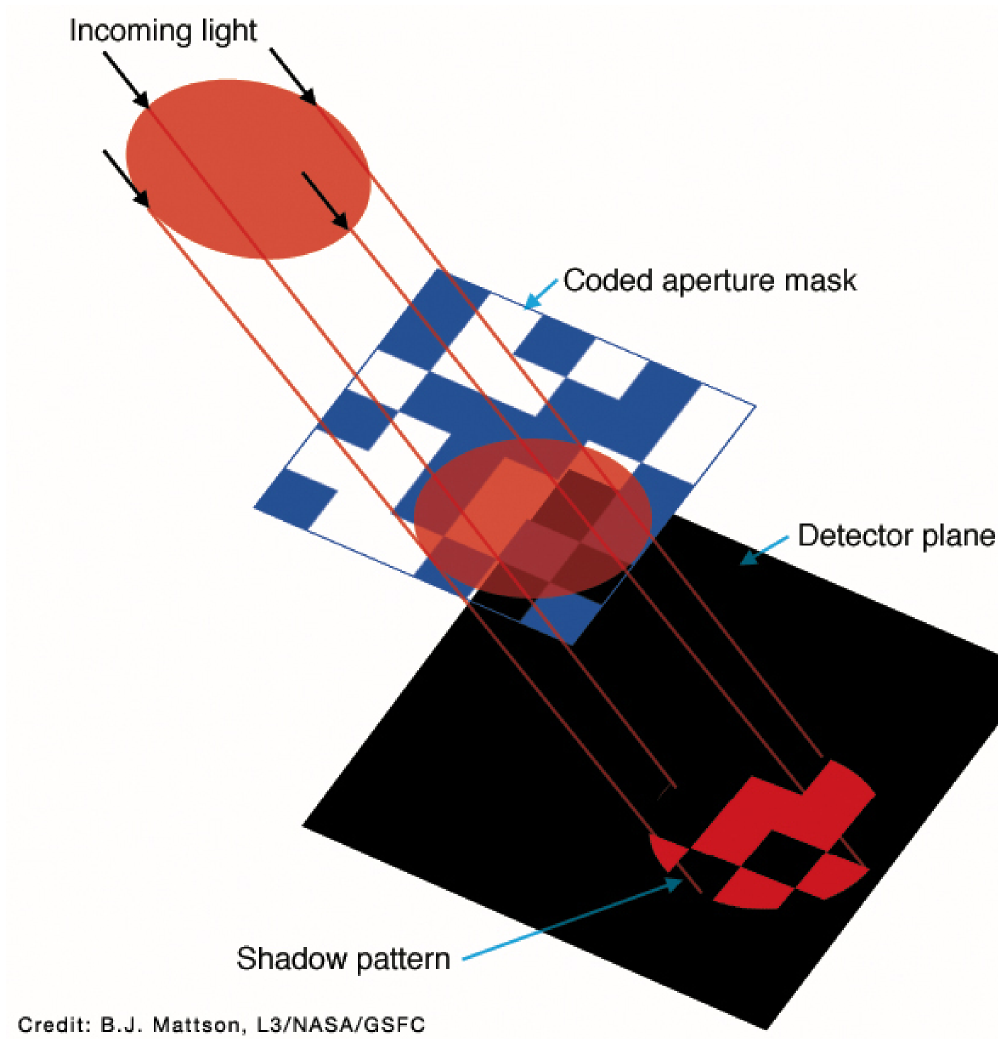
- A layered telescope, with converter layers interleaved with tracking material.
  - The converter is a high Z material (ex. Tungsten in Fermi) providing the target for creating a $e^{+/-}$ pair
- These particles in turn hit another, deeper layer of tungsten, each creating further particles etc
- The direction of the incoming gamma ray is determined by tracking the direction of these cascading particles back to their source using silicon detectors consisting of two planes of silicon one oriented in the "x"-direction, the other plane has strips in the "y"-direction. The position of a particle passing through these two silicon planes can be determined
- By reconstructing the tracks of the charged pair as it passes through the vertical series of trackers, the gamma-ray direction and therefore its origin on the sky are calculated. the absorption of the pair by a scintillator detector or a calorimeter after they exit the spark chamber, determines the total energy of the γ-ray





High Energy Telescopes

- A present can construct 'true' imaging telescopes in the 0.1-70 keV band
- At higher energies one can make 'pseudo-imaging' telescopes using 'coded aperature masks' (shadowgrams) http://astrophysics.gsfc.nasa.gov/cai/



High Energy Telescopes

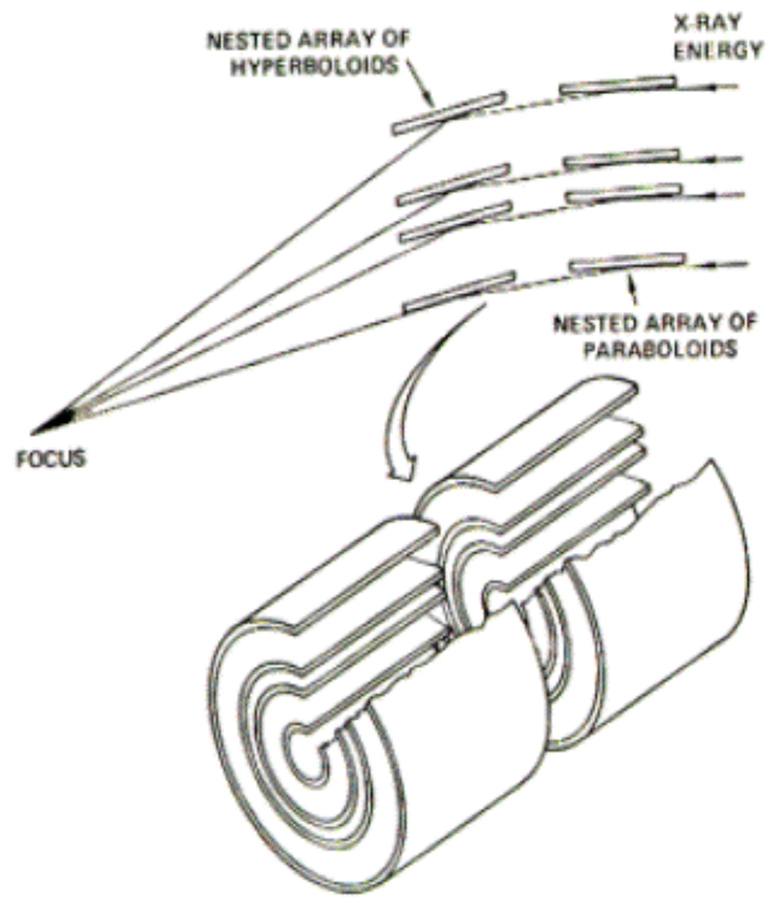
- 'true' imaging telescopes
- X-ray can be reflected at 'grazing' incidence (phenomenon of total external reflection at a surface where the index of refraction changes)

X-Ray Optics

1. We must make the X-rays Reflect

- **Total External Reflection**
- **Fresnel's Equations**

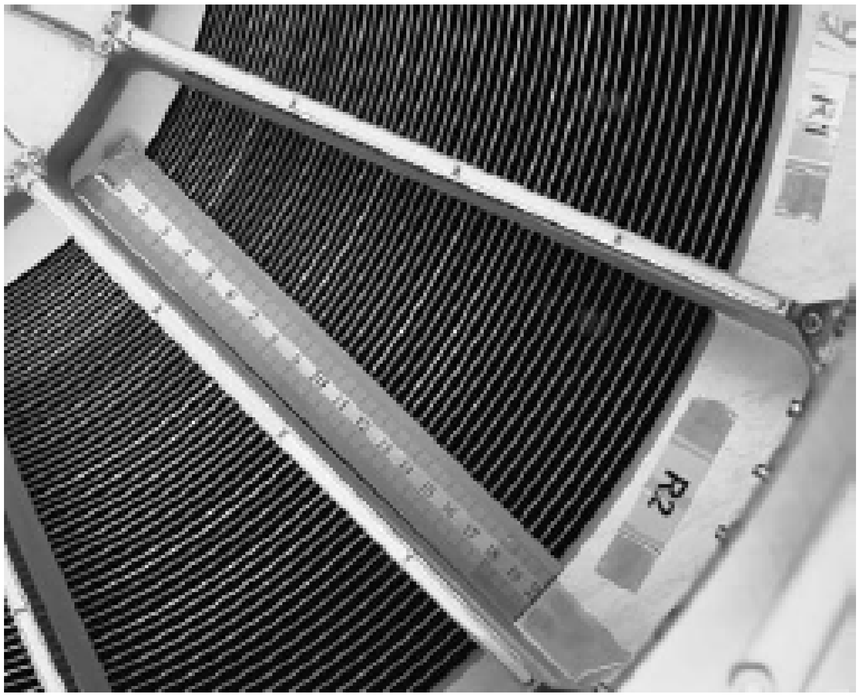
X-Ray Imaging Optics



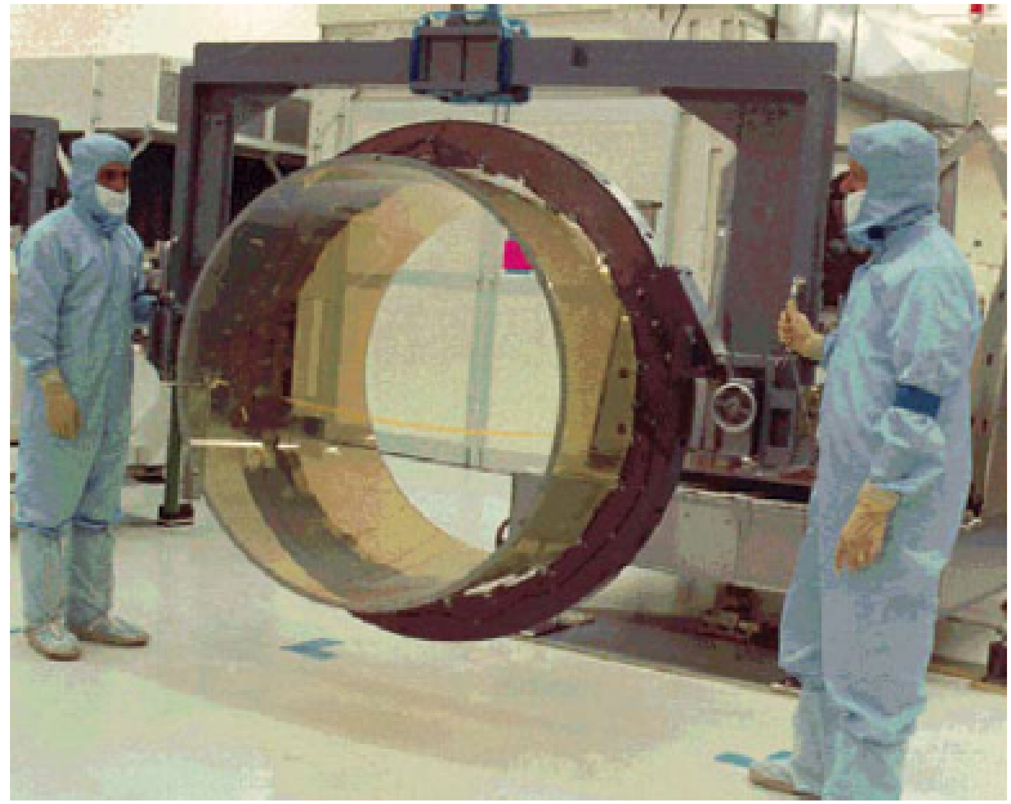
Chandra

- Focal length = 10 m
- 1 module, 4 shells
- Coating = Iridium
- Angular Resolution = 0.5 arcsec HPD

Images of X-ray Optics



XMM Optics- 58 nested
Shells, 0.5mm thick



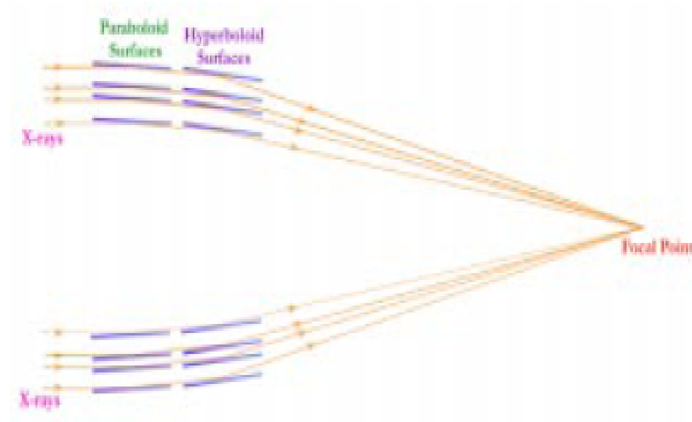
1.2m diameter, 1 m long Chandra
optic

X-Ray Reflection: Zero Order Principles:

Refs:

Gursky, H., and Schwartz, D. 1974, in "X-Ray Astronomy," R. Giacconi and H. Gursky eds., (Boston: D. Reidel) Chapter 2, pp 71-81;

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

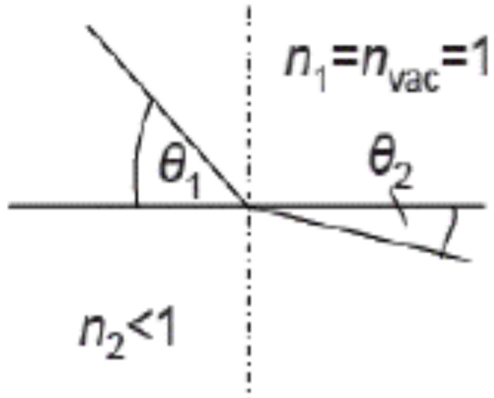


X-rays reflect at small grazing angles.

An analogy is skipping stones on water.

Scattering of any wave by an ensemble of electrons is coherent only in very special directions; namely, the familiar Angle of Incidence equals Angle of Reflection, $\phi_i = \phi_o$.

Principle of grazing incidence



Snell's law:

$$\frac{\cos\theta_1}{\cos\theta_2} = \frac{n_2}{n_1} \quad \Rightarrow \cos\theta_1 = n_2$$

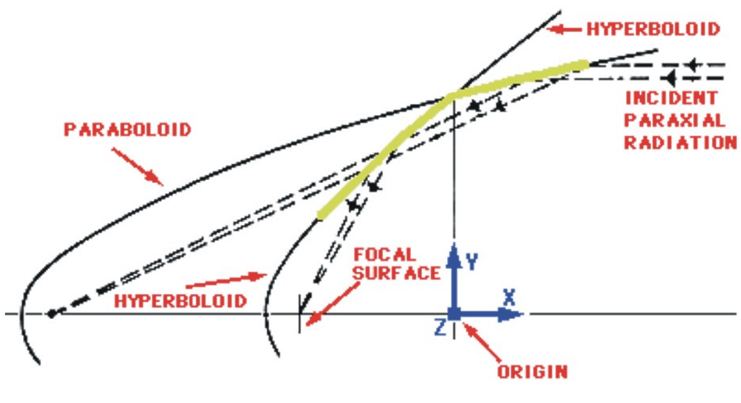
=> total reflection for $\theta < \theta_1$

For X-rays the refractive index can be written as
$n = 1 - \delta - i\beta$

δ proportional to the atomic number Z
=> n small for heavy materials

From Atwood 1999 http://www.coe.berkeley.edu/AST/sxreuv

The Wolter I mirror profile for X-ray astronomy applications

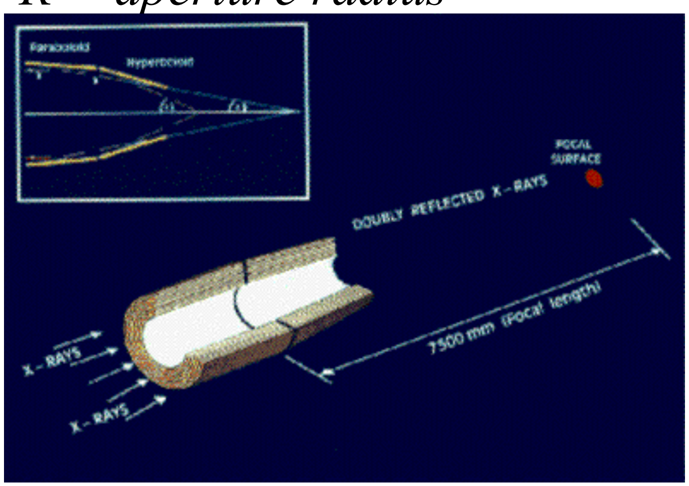


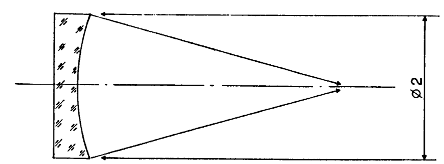
- it guarantees the minimum focal length for a given aperture
- it allows us to nest together many confocal mirror shells
- Effective Area: **$8 \pi F L \theta^2 \text{Refl.}^2$**

F= focal length = R / tan 4θ

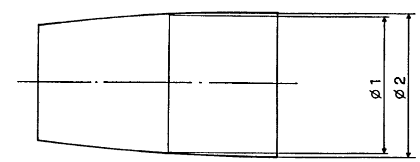
θ= *on-axis incidence angle*

R = aperture radius

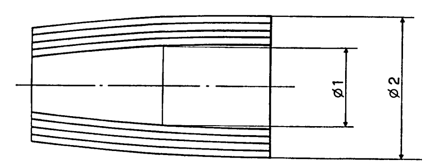




$$S_V = \frac{\pi \, \phi_2^2}{4}$$

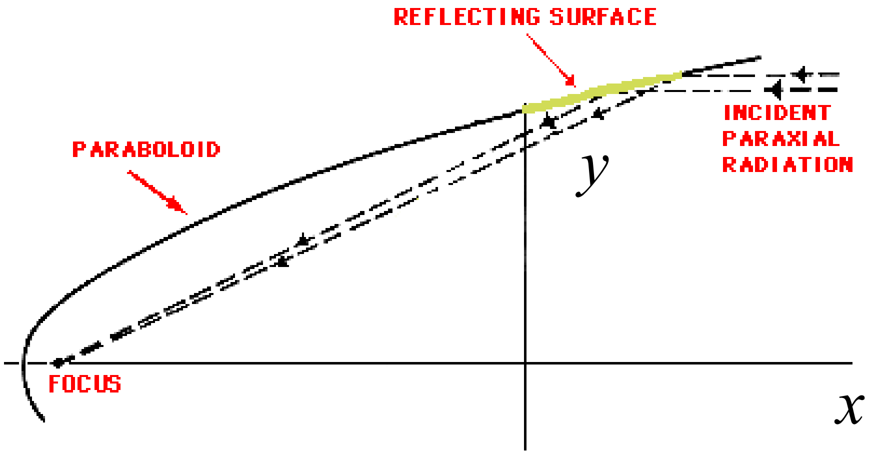


$$S_1 = \frac{\pi \, (\phi_2 - \phi_1)^2}{4}$$



$$S_X = \frac{\pi \, (\phi_2 - \phi_1)^2}{4}$$

X-ray mirrors with parabolic profile

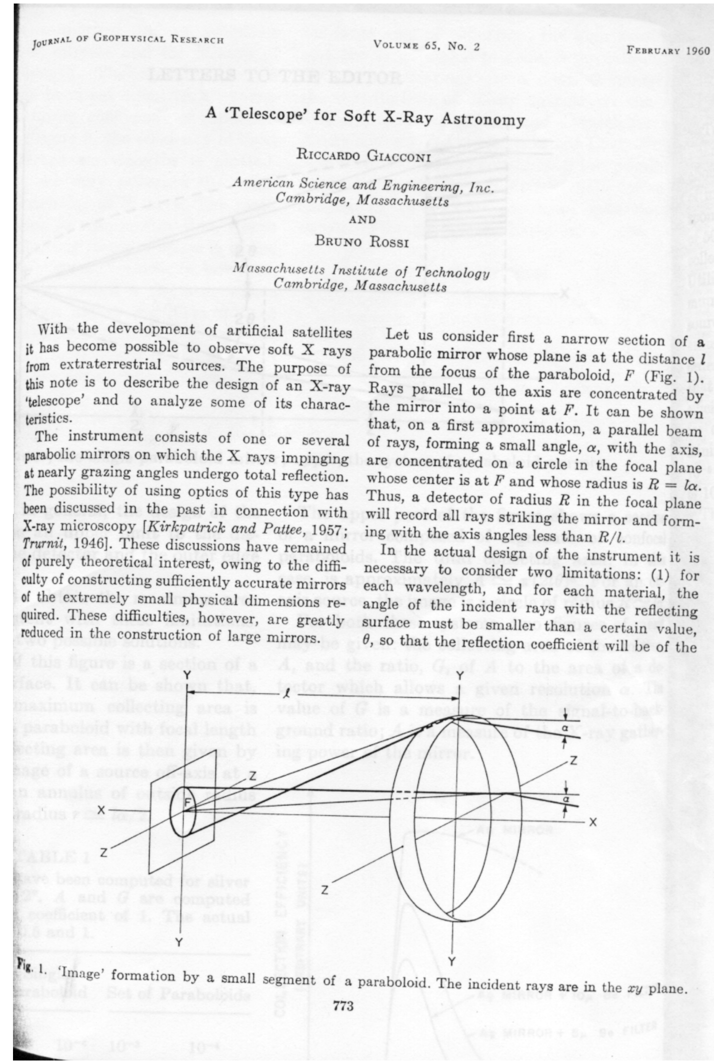


$$y^2 = 2\,p\,x$$

$$p = 2 * dist.\ focus\text{-}vertex$$

- perfect on-axis focusing

- off-axis images <u>strongly </u>affected by **coma**



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A 'Telescope' for Soft X-Ray Astronomy

RICCARDO GIACCONI

American Science and Engineering, Inc.
Cambridge, Massachusetts

AND

BRUNO ROSSI

Massachusetts Institute of Technology
Cambridge, Massachusetts

With the development of artificial satellites it has become possible to observe soft X rays from extraterrestrial sources. The purpose of this note is to describe the design of an X-ray 'telescope' and to analyze some of its characteristics.

The instrument consists of one or several parabolic mirrors on which the X rays impinging at nearly grazing angles undergo total reflection. The possibility of using optics of this type has been discussed in the past in connection with X-ray microscopy [*Kirkpatrick and Pattee*, 1957; *Trurnit*, 1946]. These discussions have remained of purely theoretical interest, owing to the difficulty of constructing sufficiently accurate mirrors of the extremely small physical dimensions required. These difficulties, however, are greatly reduced in the construction of large mirrors.

Let us consider first a narrow section of a parabolic mirror whose plane is at the distance l from the focus of the paraboloid, F (Fig. 1). Rays parallel to the axis are concentrated by the mirror into a point at F. It can be shown that, on a first approximation, a parallel beam of rays, forming a small angle, α, with the axis, are concentrated on a circle in the focal plane whose center is at F and whose radius is $R = l\alpha$. Thus, a detector of radius R in the focal plane will record all rays striking the mirror and forming with the axis angles less than R/l.

In the actual design of the instrument it is necessary to consider two limitations: (1) for each wavelength, and for each material, the angle of the incident rays with the reflecting surface must be smaller than a certain value, θ, so that the reflection coefficient will be of the

Fig. 1. 'Image' formation by a small segment of a paraboloid. The incident rays are in the xy plane.

Reflection of X-rays

The index of refraction or the optical constants can be computed from anomalous dispersion theory. For wavelengths λ or photon energies sufficiently off-set from any electron binding energy a coarse estimate of δ can be made:

$$\delta = \frac{r_e}{2\pi} \frac{N_0 \rho}{A} Z \lambda^2 \tag{6}$$

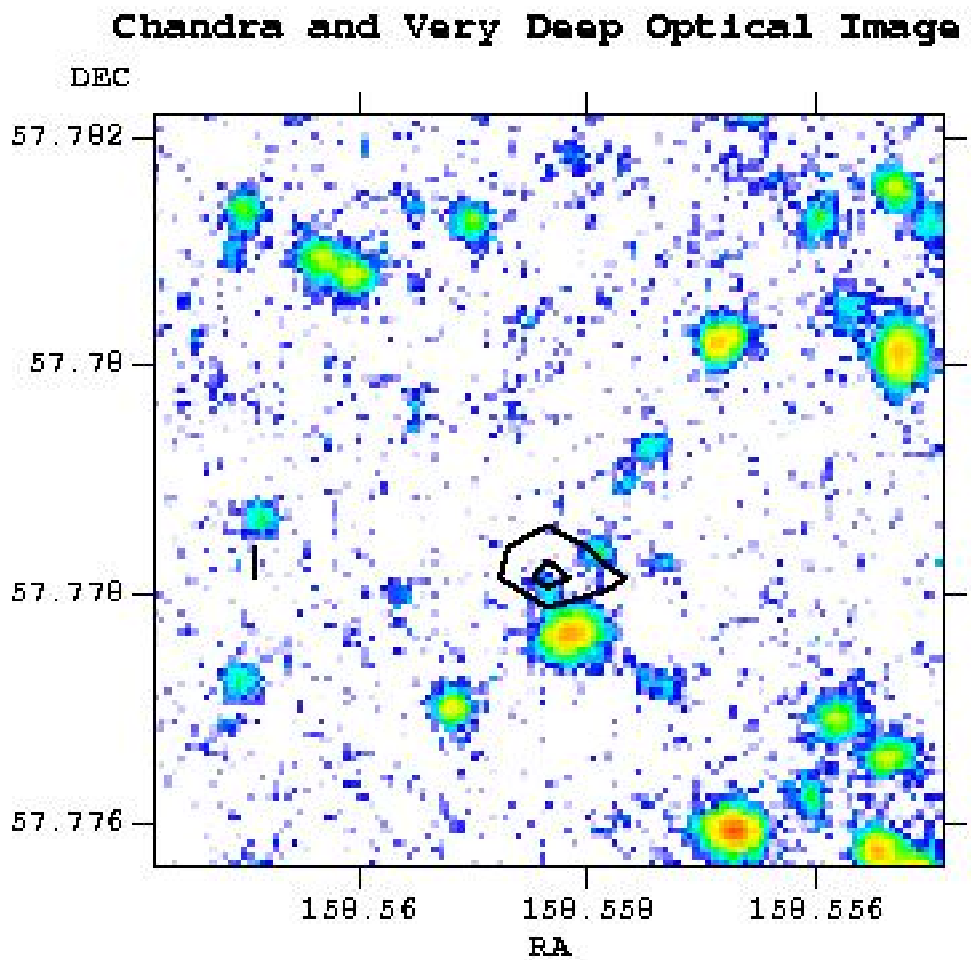
where N_0 is Avogadro's number, r_e is the classical electron radius, Z and A are the atomic number and weight, respectively, and ρ is the mass density. For heavy elements for which $Z/A \approx 0.5$, the incidence angle of total reflection for $\delta \ll 1$ can be estimated to:

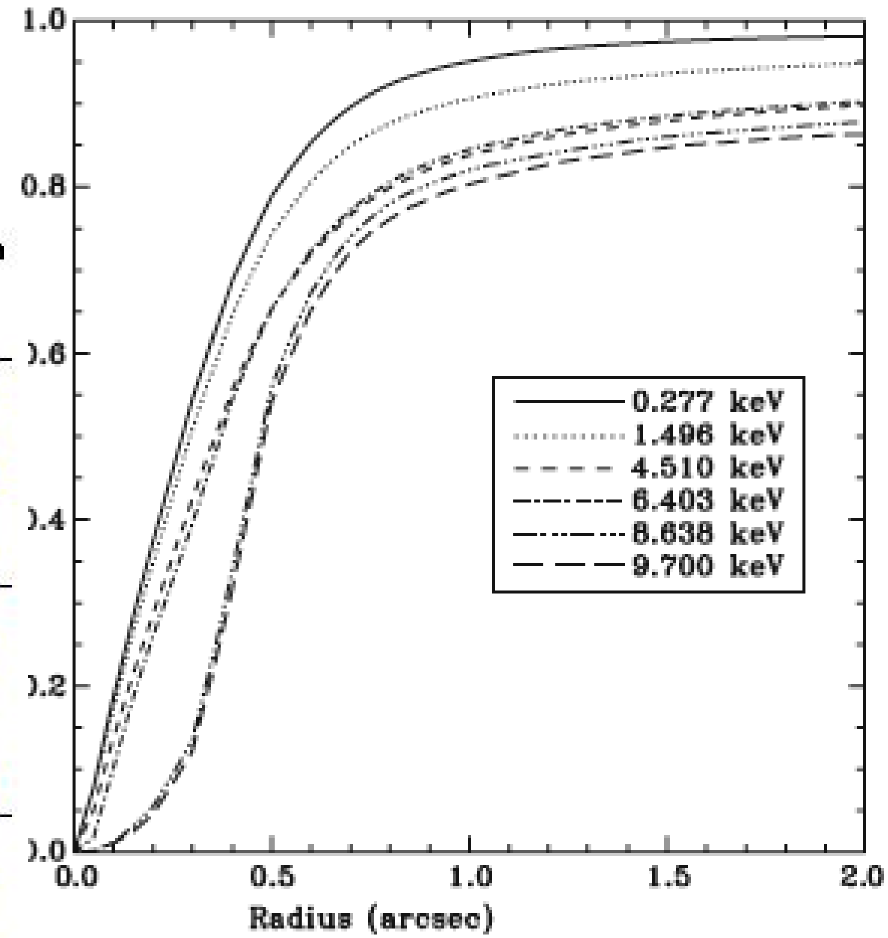
$$\alpha_t = 5.6 \lambda \sqrt{\rho} \tag{7}$$

with α_t in arcmin, λ in Å and ρ in g/cm^3. For X-rays, with λ of a few Å, α_t is about one degree. Equation (7) suggests the most dense materials as reflective coatings like gold, platinum or iridium, v

Can Get Pretty Good Images

- Chandra Images are as good as the best images that can be obtained from the ground





Chandra- fraction of energy inside an inscribed circle on axis

Mirror Collecting Area

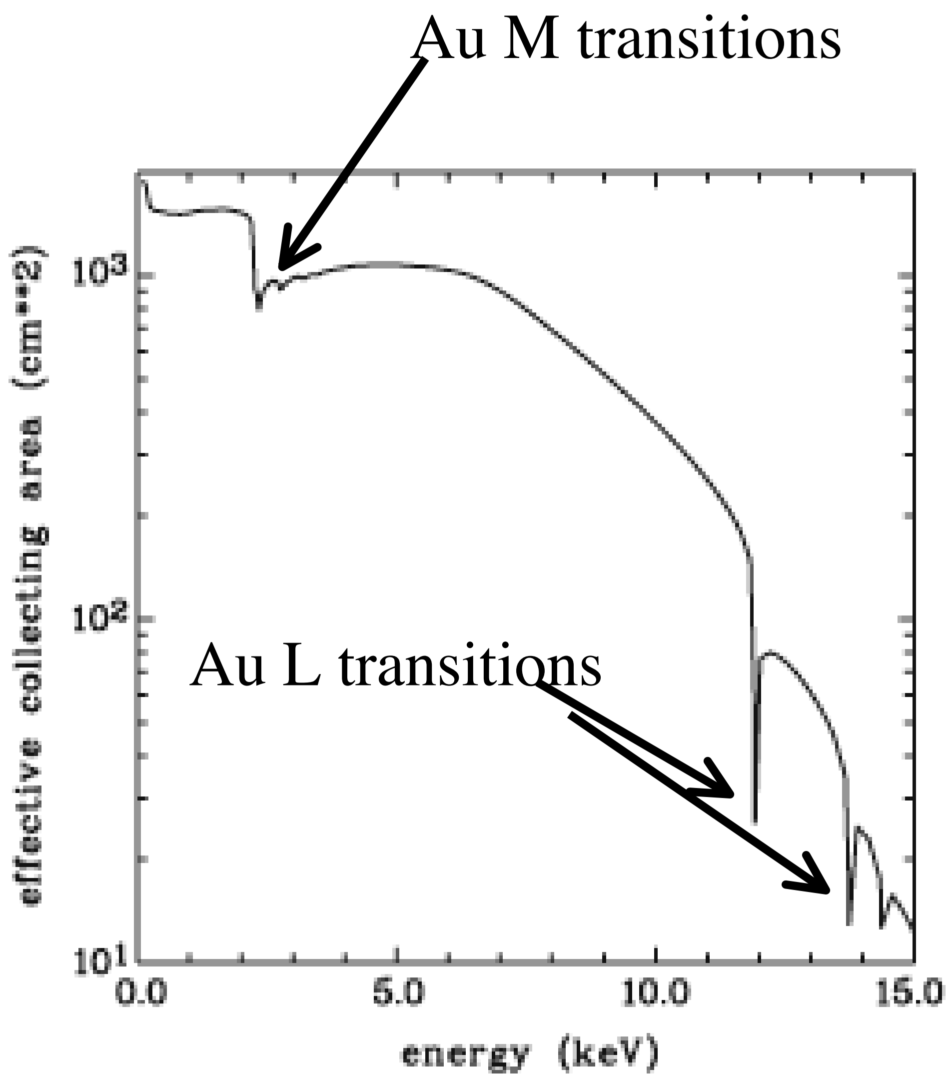
- Depends on mirror diameter, number of shells, focal length and coating of mirror (e.g. which metal coats the substrate)
- XMM mirror- the 'bumps and wiggles' are due to the atomic transitions of gold (the coating material)

- Effect of scattering:ratio of scattered to incident light

$$I_s/I_0 = 1 - \exp\left[-(4\pi\,\sigma\,\sin\alpha\,/\,\lambda)^2\right]$$

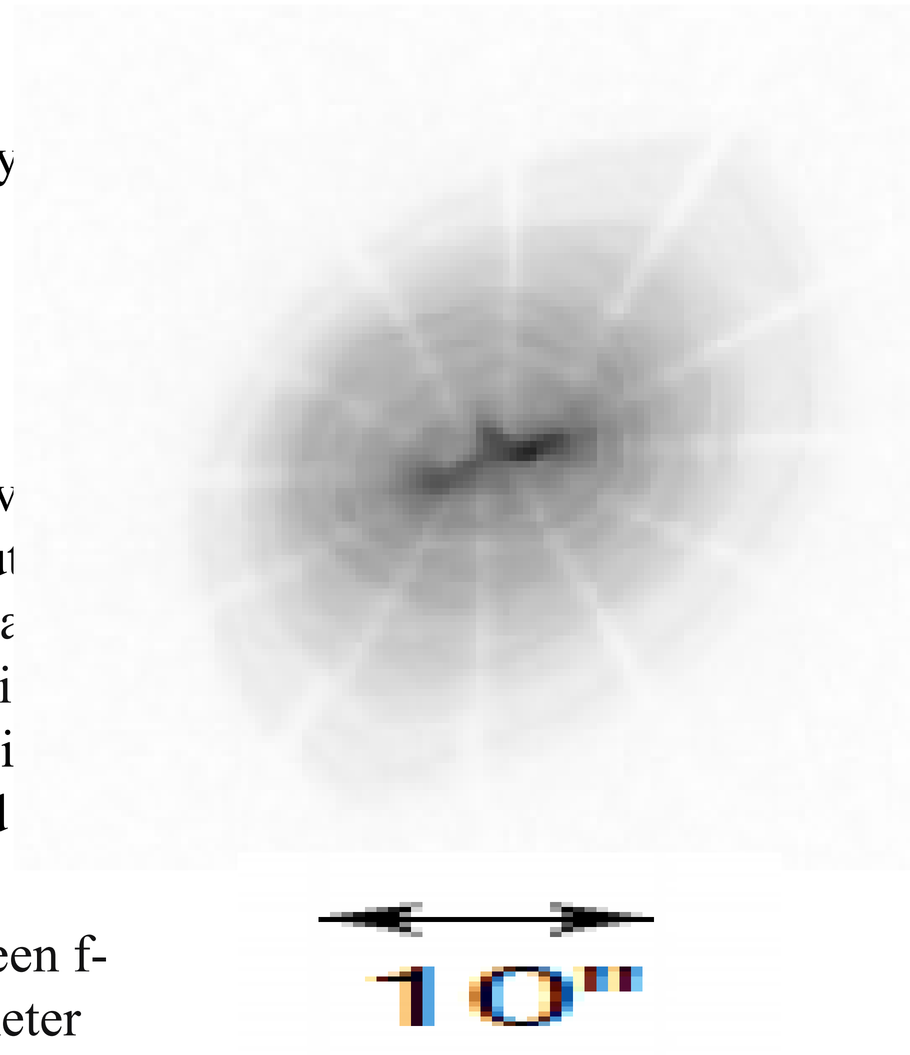
λ=wavelength of x-rays, α= incident angle for reflection, σ= 'average roughness' - so want σ~λ

If want <10% scattered at 10A with α=1deg σ<9A



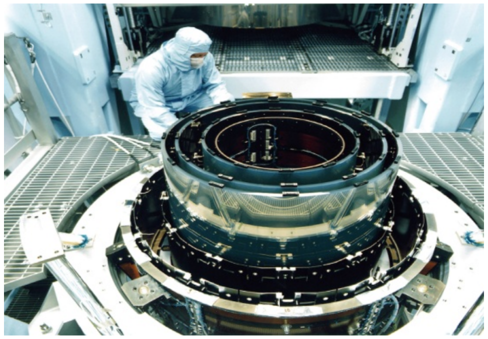
Some Issues

- The reflecting surfaces have to be very smooth- if they are rougher than the wavelength then the photons hit 'mountains' and scatter (not reflect)
- A 'Wolter type I' optic only focuses 'perfectly' at the center of the field of v as one goes off axis the angular resolut degrades-while free of spherical aberra suffer from coma aberration, astigmati and field curvature. The actual collecti area is much smaller than the polished surface (sin of a small angle)
- Because of the interdependence between f-number, grazing angle,telescope diameter and focal length, large diameter telescopes working at high energies can be constructed only with long focal lengths



Point spread function (PSF)
10' off axis

Manufacturing techniques utilized so far

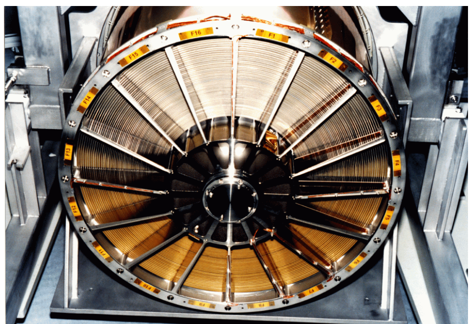

Credits: NASA

1. Classical precision optical polishing and grinding

Projects: **Einstein, Rosat, Chandra**

Advantages: *superb angular resolution*

Drawbacks: *high mirror walls ➔ ➔ small number of nested mirror shells, high mass, high cost process*

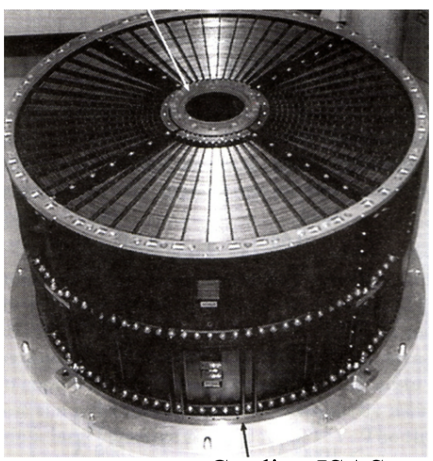

Credits: ESA

2. Replication

Projects: ***EXOSAT, SAX, JET-X/Swift, XMM, ABRIXAS*** ***(➔ examples follow hereafter)***

Advantages: *good angular resolution, high mirror "nesting"*
the same mandrels for many modules

Drawbacks: *relatively high cost process; high mass/geom. area ratio (if Ni is used).*


Credits: ISAS

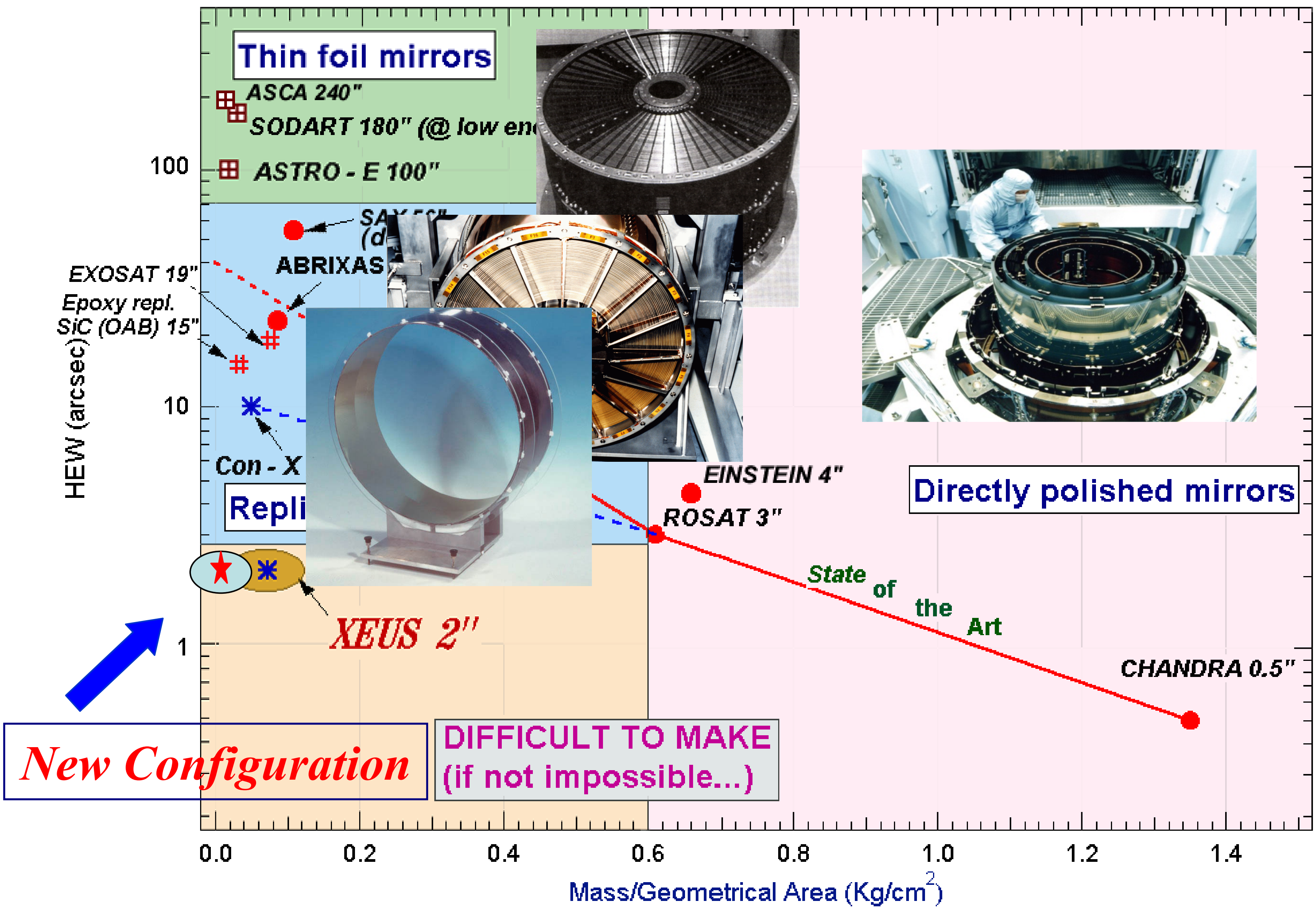
3. "Thin foil mirrors"

Projects: **BBXRT, *ASCA, SODART, ASTRO-E***

Advantages: *high mirror "nesting" possibility, low mass/geom. area ratio (the foils are made of Al), cheap process*

Drawbacks: *until now low imaging resolutions (1-3 arcmin)*

Present Astronomical optics technologies: HEW Vs Mass/geometrical area



X-ray optical constants

- complex index of refraction to descrive the interaction X-rays /matter:

$$\tilde{n} = n + i\beta = 1 - \delta + i\beta$$

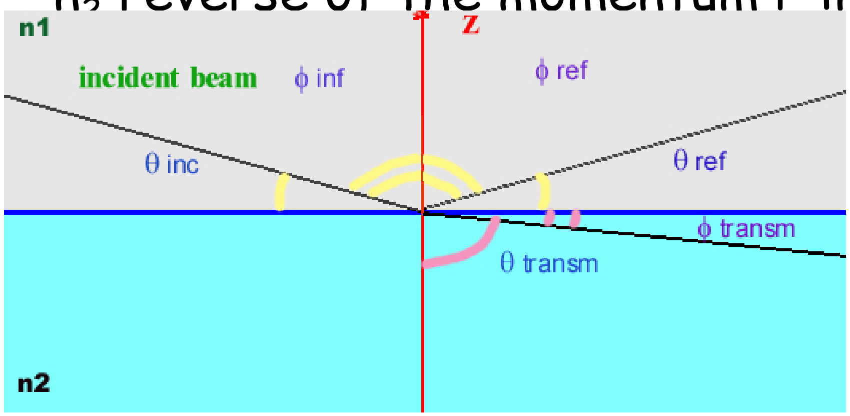
$$(\mu = 4\pi\beta/\lambda \;\; cm^{-1})$$

Linear abs. coeff.

δ → changes of phase

β → absorption

- at a boundary between two materials of different refraction index n_1, n_2 reverse of the momentum P in the z direction:



$$\vec{p}_1 = \frac{h}{2\pi}\vec{k}_1$$

$$\left|\vec{k}_1\right| = \frac{2\pi}{\lambda} n_1$$

$$2p_z \propto \frac{4\pi}{\lambda} n_1 \sin\theta_{inc}$$

momentum transfer

- the amplitute of reflection is described by the Fresnel's equations:

$$r_{12}^{s} = \frac{n_1 \sin\theta_1 - n_2 \sin\theta_2}{n_1 \sin\theta_1 + n_2 \sin\theta_2}$$

$$r_{12}^{p} = \frac{n_1 \sin\theta_2 - n_2 \sin\theta_1}{n_1 \sin\theta_2 + n_2 \sin\theta_1}$$