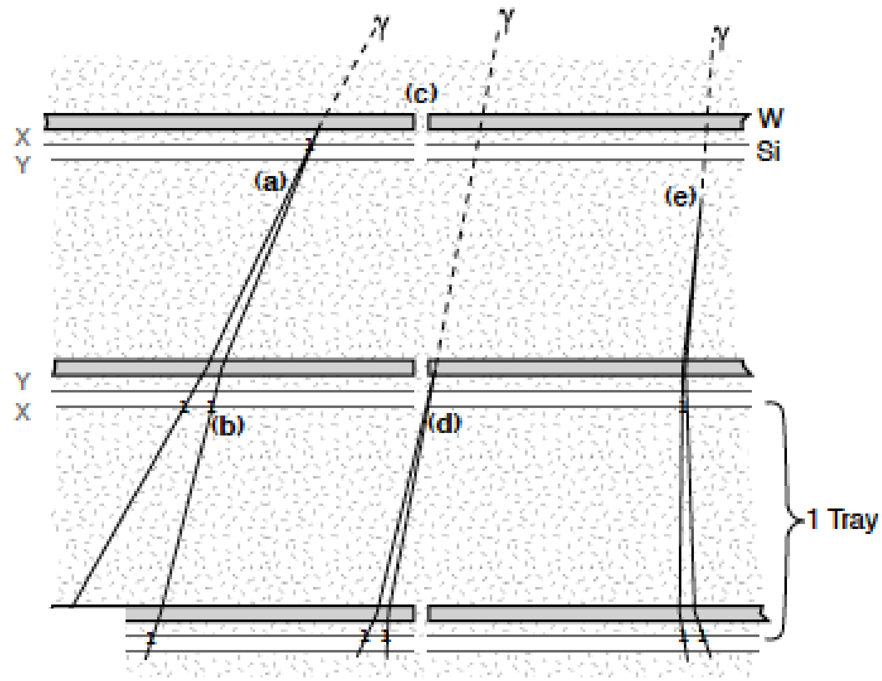
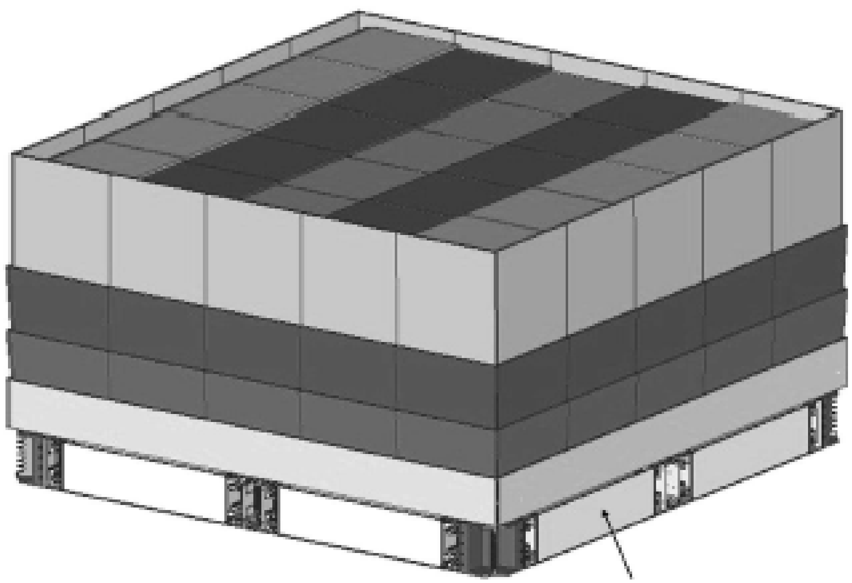
γ-ray Detectors and X-ray Telescopes

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)



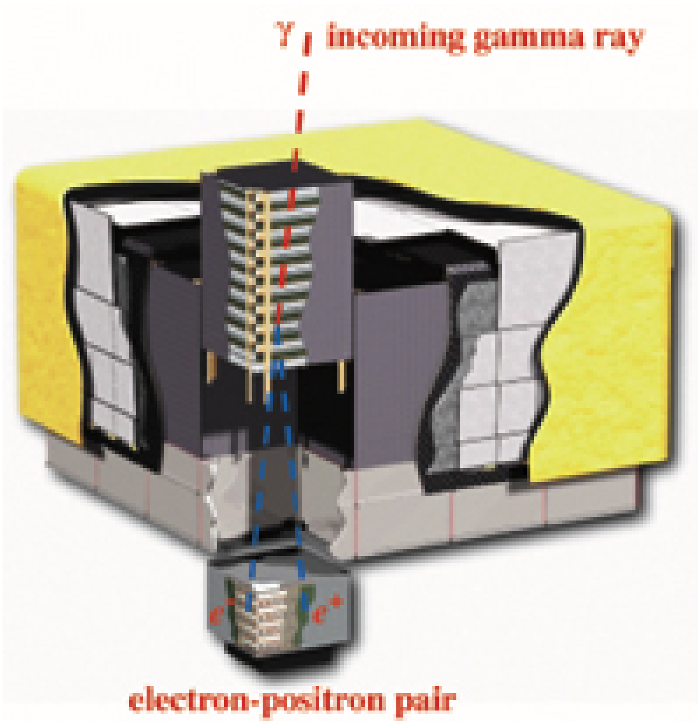


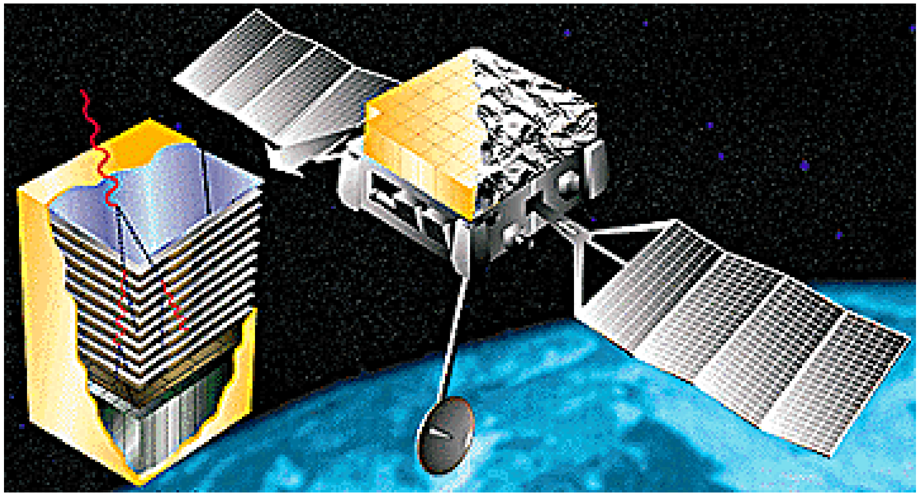
Full coverage of anti-coincidence detectors

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



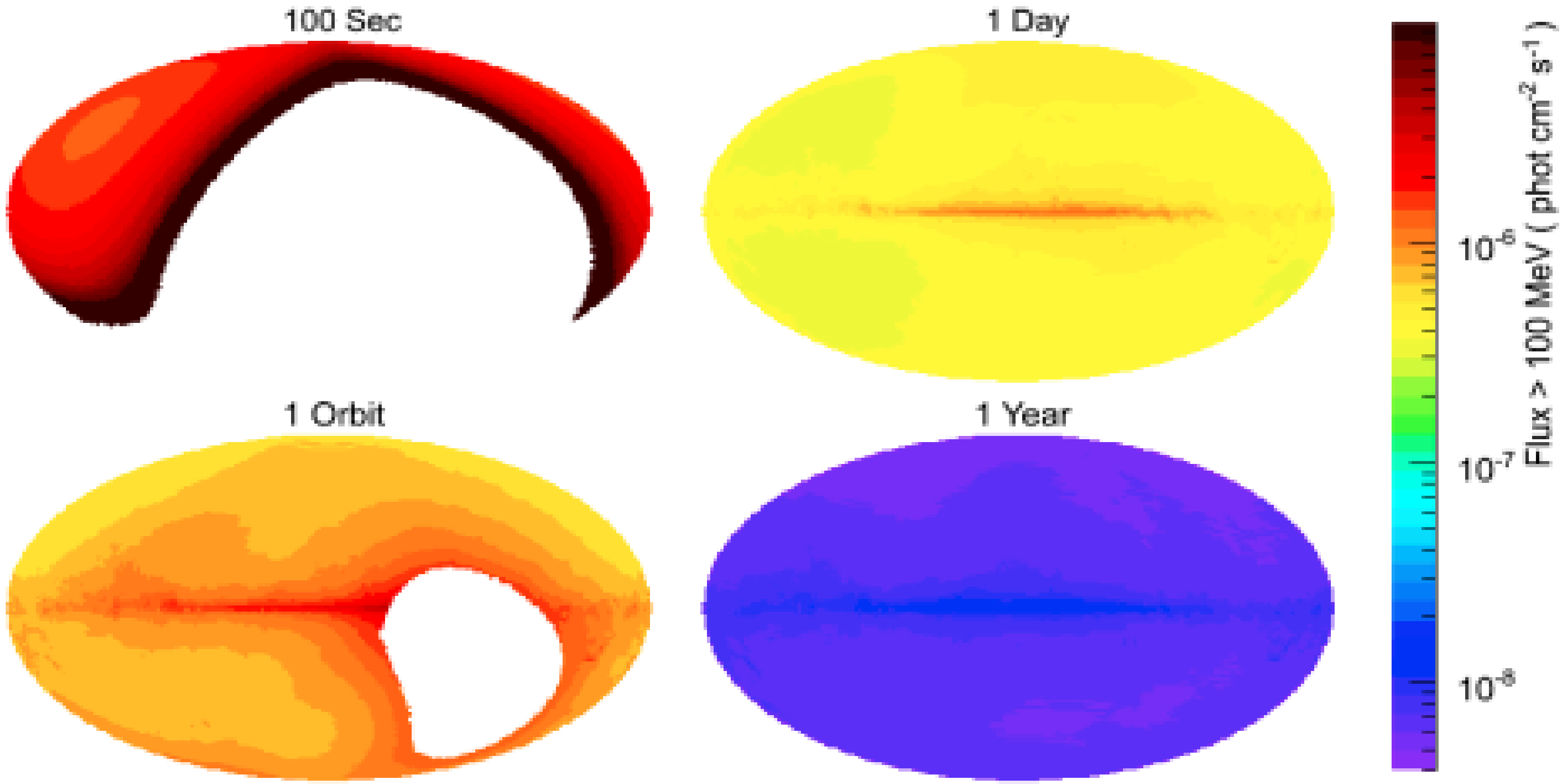


γ-Ray Detectors

- Fermi uses 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
- The direction of the incoming gamma ray is determined by tracking the direction of the cascading particles back to their source by reconstructing the tracks of the charged pair as it passes through the vertical series of trackers, the γ-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

γ-Ray

- The Fermi detector (called LAT) has a very large field of view ~2π ster-radians and thus does not need to point



ensitivity for exposures on various timescales. Each map is an Aitoff projection in galactic coordinates. In stand
s achieved every 2 orbits, with every region viewed for ~30 min every 3 hours.

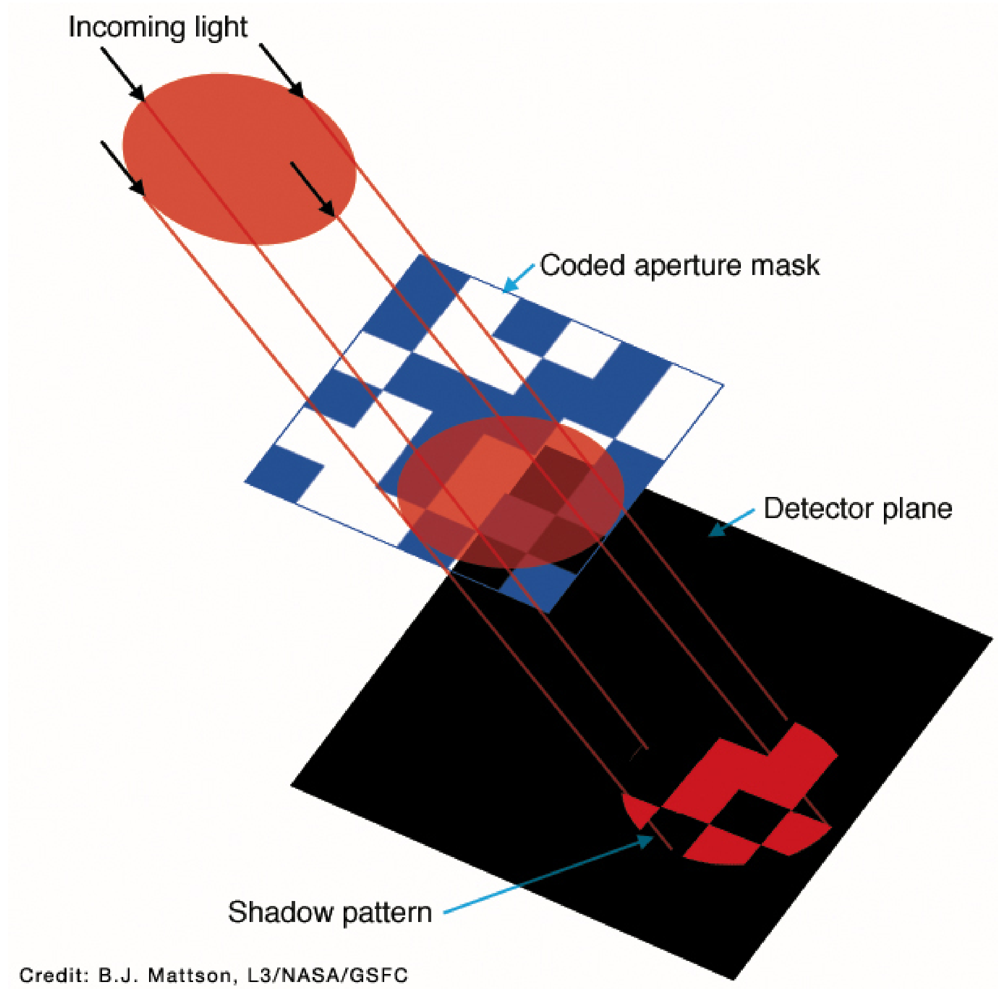
Other Detectors

- I do not have time to talk about
  - Compton detectors (e.g Comptel on GRO or the SGD on Astro-H)
  - Pixilated CdTe (e.g. BAT and Integral)
  - NaI, CsI scintillators (HEXTE on RXTE) or other scintillators (the HXD on Suzaku)
  - Gas scintillators (EXOSAT, Tenma)
  - Bragg crystal spectrometers (Einstein)
  - etc etc

High Energy Telescopes

- At higher energies one can make 'pseudo-imaging' telescopes using 'coded aperature masks' (shadowgrams) http://astrophysics.gsfc.nasa.gov/cai/

Used on INTEGRAL, Swift BAT



High Energy Telescopes

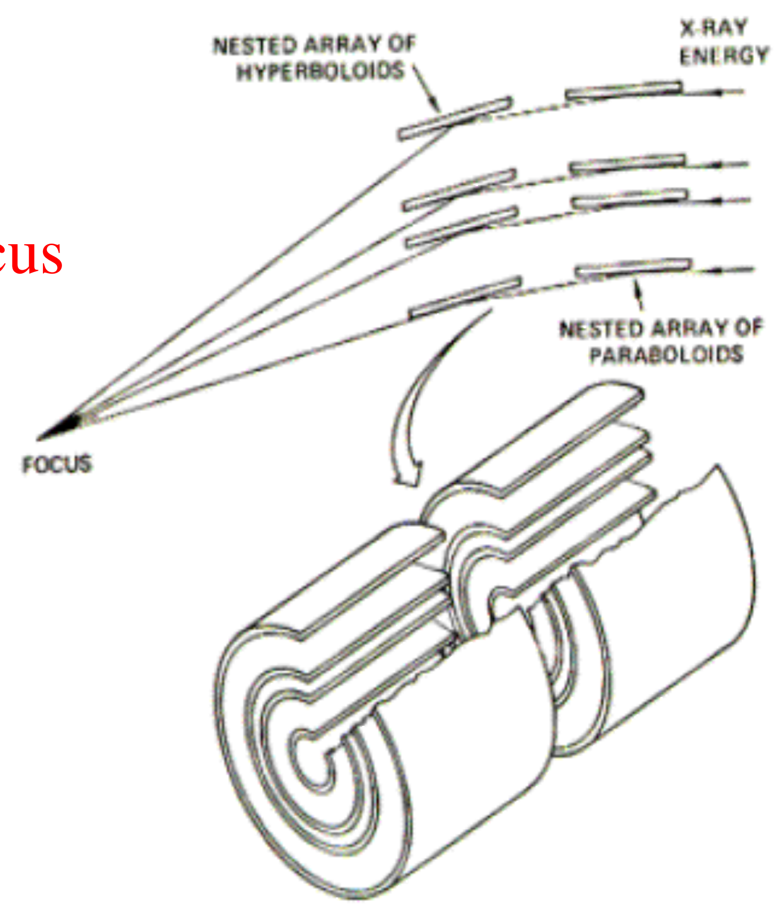
- 'true' imaging telescopes
- X-rays can be reflected at 'grazing' incidence (phenomenon of total external reflection at a surface where the index of refraction changes)

X-Ray Optics

Have to make the x-rays reflect and focus

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

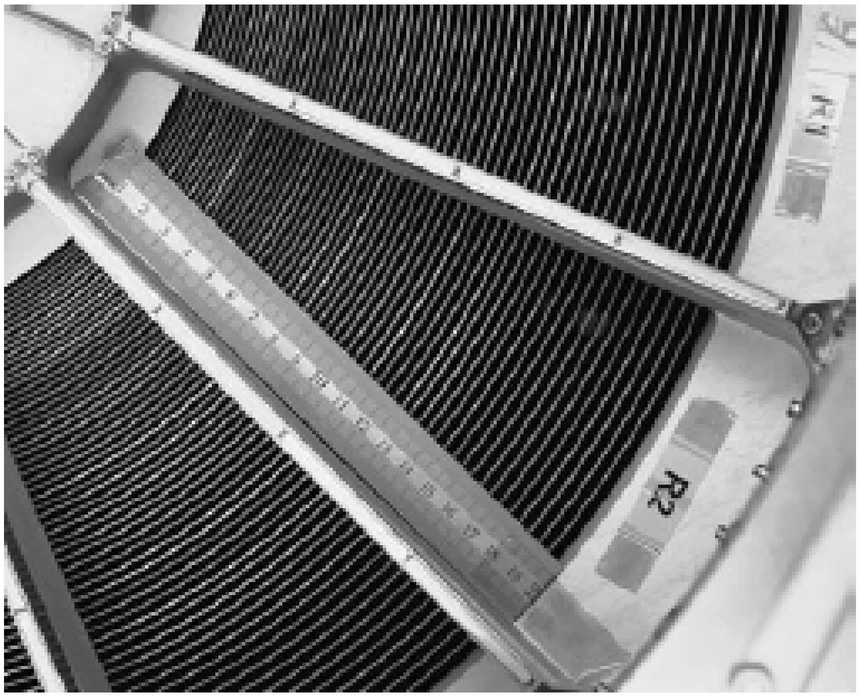
X-Ray Imaging Optics

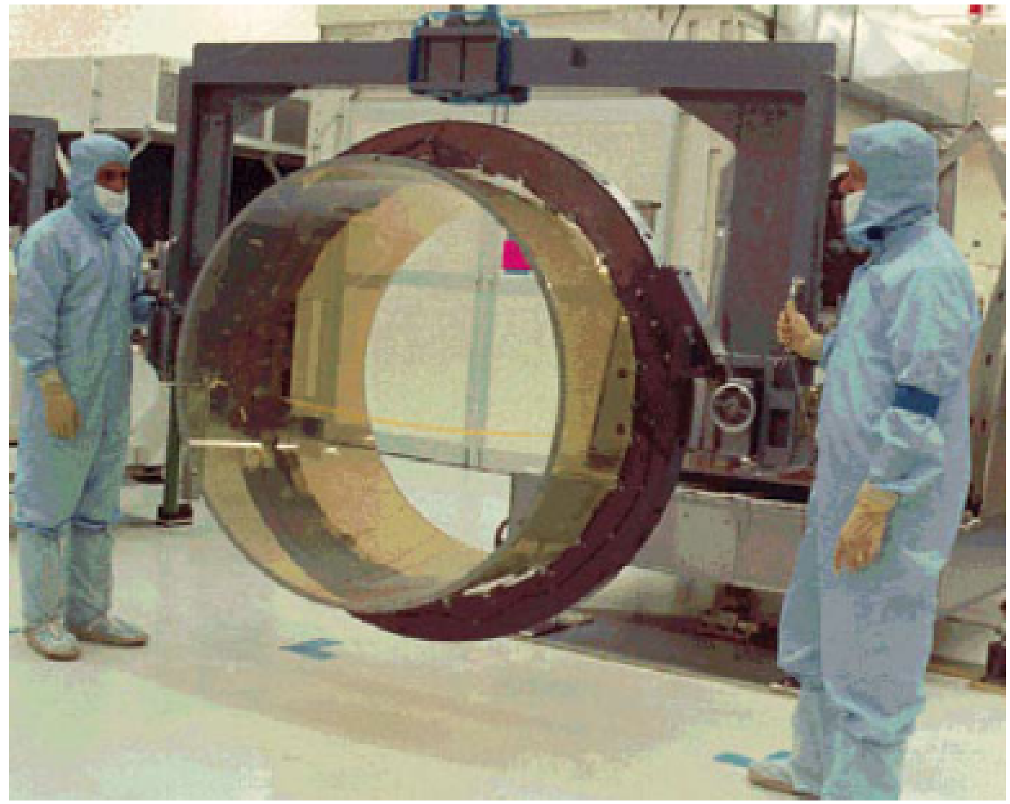


Chandra

- 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

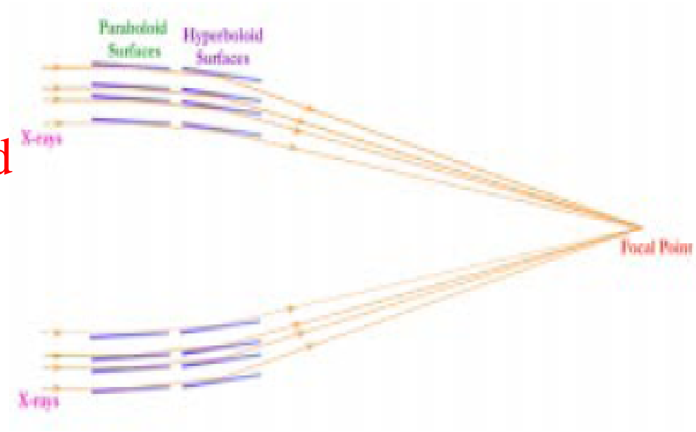
1.2m diameter, 1 m long Chandra
optic

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. * very detailed

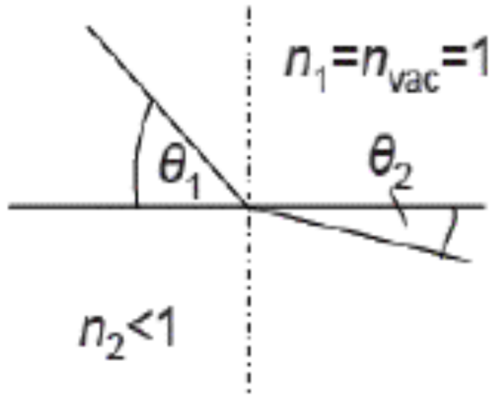


X-rays reflect at small grazing angles.

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 describes the phase change and β accounts for the absorption

δ proportional to the atomic number Z

=> n small for heavy materials

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

X-ray optical constants

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

ñ = n + iβ = 1 - δ + iβ

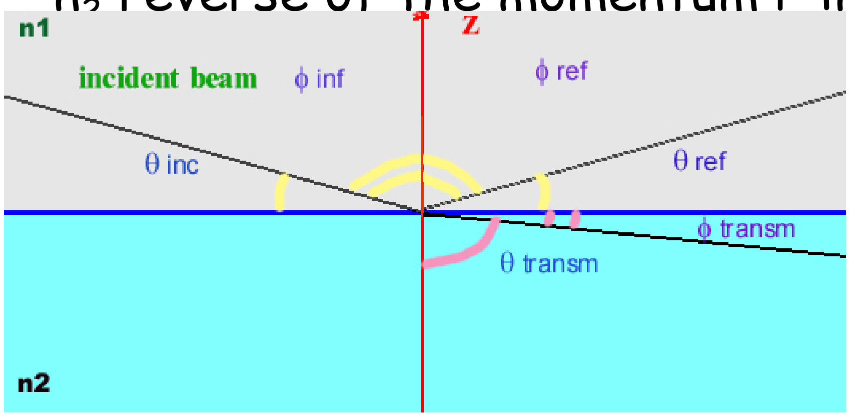
(μ = 4 π β/λ *cm* $^{-1}$)

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:



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

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

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

momentum transfer

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

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

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

Grazing Incidence (Aschenbach 1984)

- the refraction angle measured from the surface normal is > 90º for the real part of the index of reflection

  $n_r = 1 - \delta < 1$,
- total external reflection occurs for grazing-incidence angles $\alpha \leq \alpha_t$:

  $\cos\alpha_t = 1 - \delta$ .....for $\delta << 1$ $\alpha_t = \sqrt{2\delta}$.
- The index of refraction or the optical constants can be computed from anomalous dispersion theory.
- For wavelengths or photon energies sufficiently far from any electron binding energy a coarse estimate of δ is

  $\delta = (r_e/2\pi)(N_0\, \rho/A)Z\lambda^2$
- 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 $\delta << 1$ can be estimated to:

  $\alpha_t = 5.6\lambda\sqrt{\rho}$ – *high energies short* λ

  α_t in arcmin, λ in Å and ρ in g/cm3.

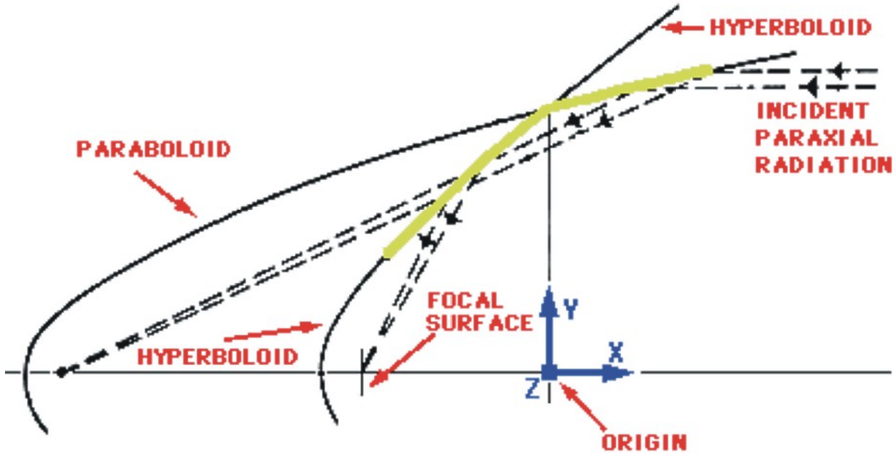
  So high density materials Au, Pt, Ir are best for reflection coatings

F= focal length = R / tan 4θ

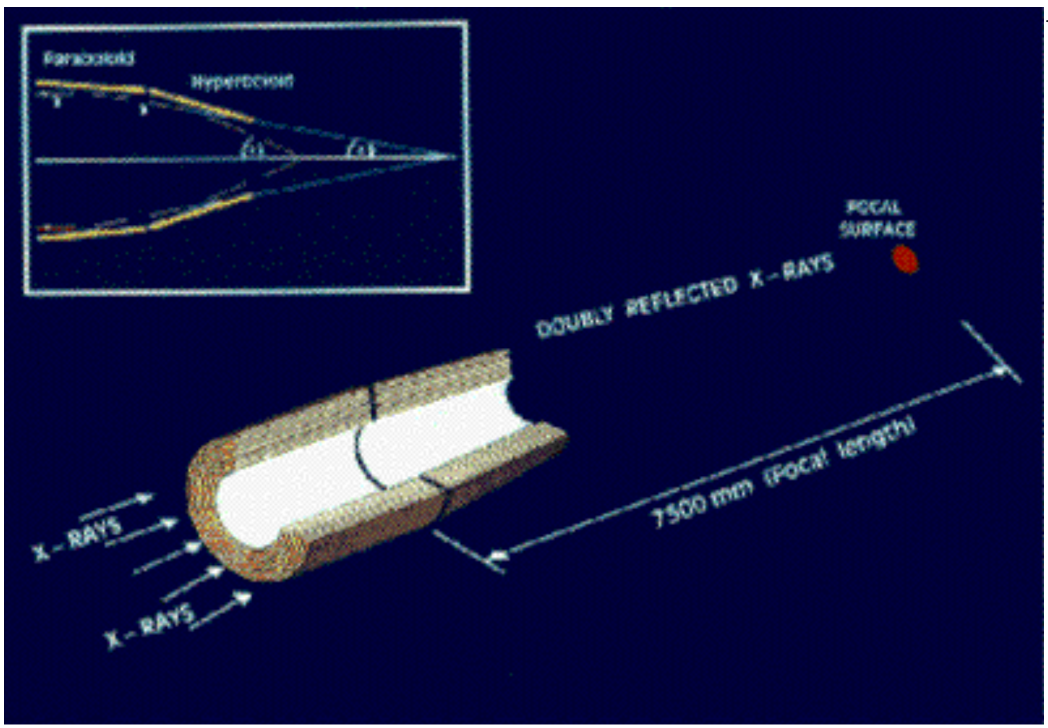
θ= *on-axis incidence angle*

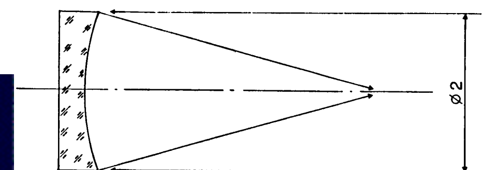
R = aperture radius

Wolter I mirror

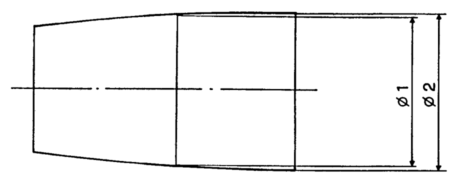


- minimum focal length for a given aperture
- it allows the nesting together of many confocal mirror shells
- Effective Area: **8 π F L θ² Refl.²**

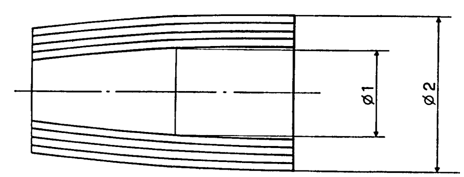




$$S_V = \frac{\pi \phi_2^2}{4}$$

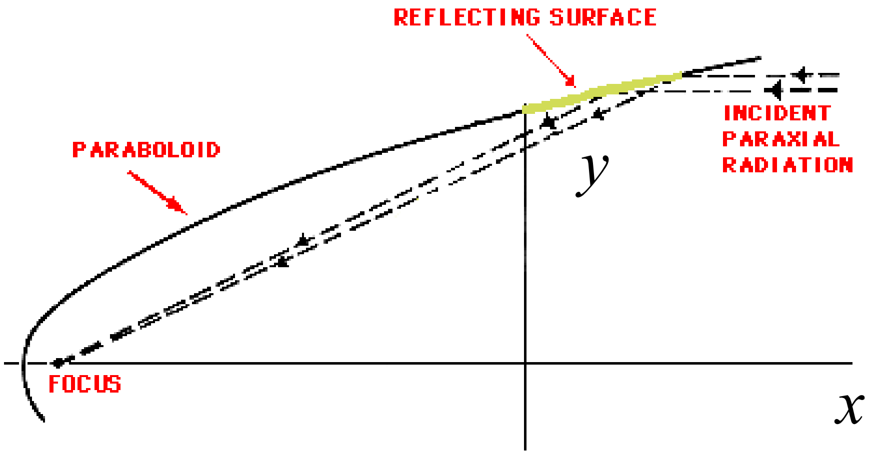


$$S_1 = \frac{\pi (\phi_2 - \phi_1)^2}{4}$$



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

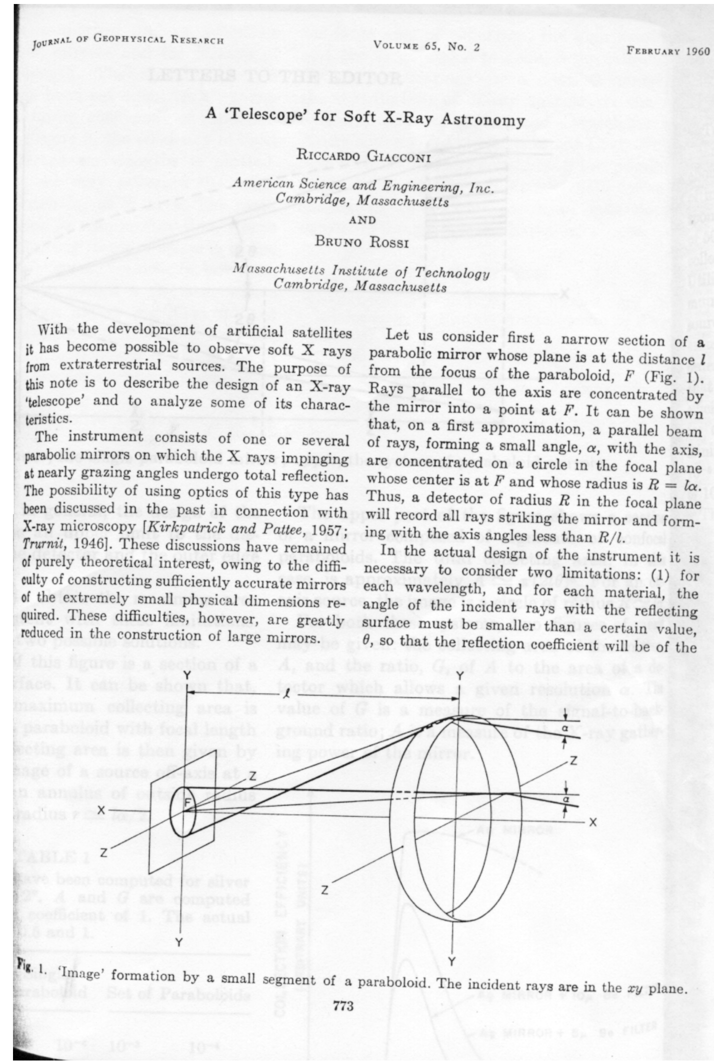
X-ray mirrors with parabolic profile



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

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

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



Journal of Geophysical Research Volume 65, No. 2 February 1960

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.

At grazing incidence, imaging of an extended source or imaging over some extended field requires at least two reflections, i.e. two reflecting surfaces

Reflection of X-rays

the f-number is inversely proportional to the angle of total reflection which decreases linearly with increasing photon energy

- telescopes optimized for the low-energy regime (<2 keV) have lower f values (are faster- better for surface brightness)

- Because of the interdependence between f-number, grazing angle, telescope diameter and focal length, large diameter (collecting area) telescopes working at high energies require long focal lengths,

Rosat Telescope

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:

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

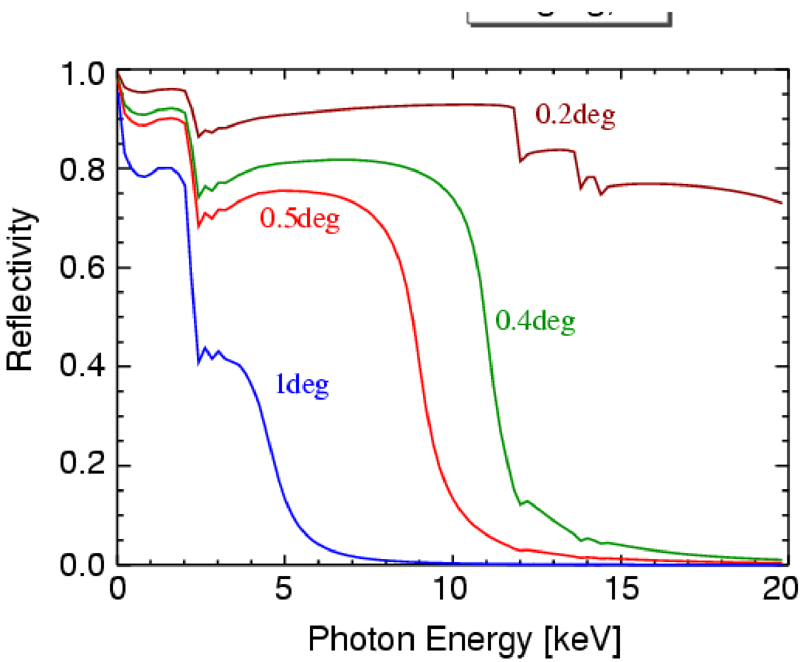
where N_0 is Avogadro's number, r_e is the classical electron radius, Z and A are the atomic number and weight, respectively, and ρ is the mass density. For heavy elements for which $Z/A \approx 0.5$, the incidence angle of total reflection for $\delta \ll 1$ can be estimated to:

$$\alpha_t = 5.6 \lambda \sqrt{\rho} \qquad (7)$$

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, w

Long Focal Length

- To get reasonable collecting area at E>2 keV need long focal length- big satellites !



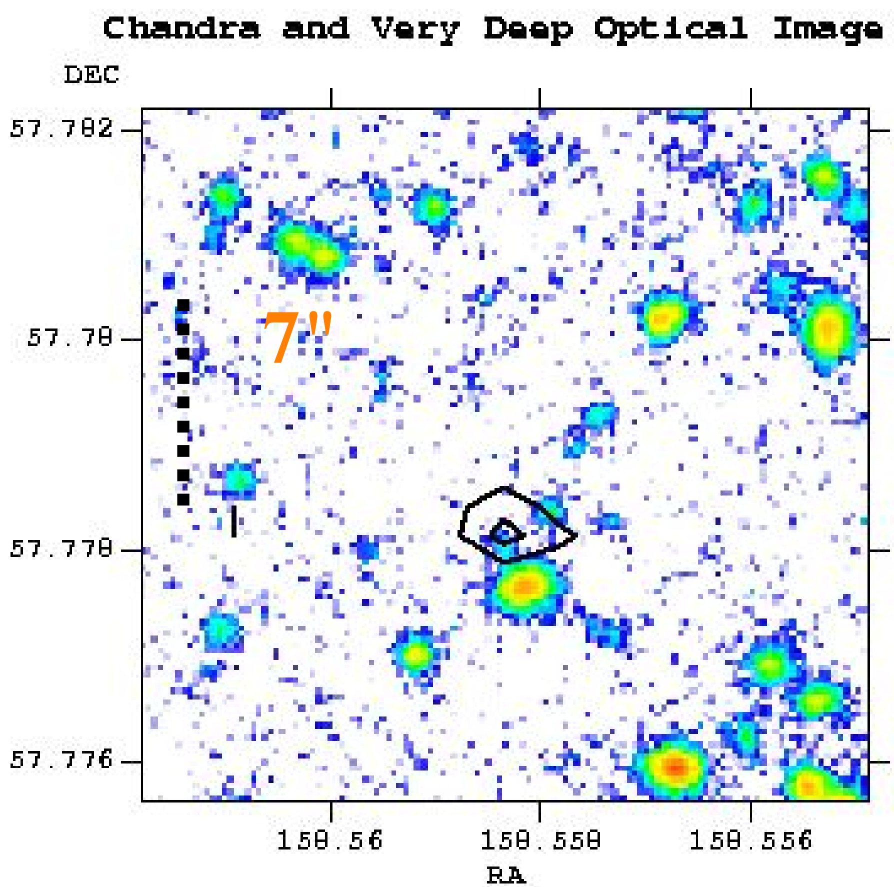
Reflectivity for Gold

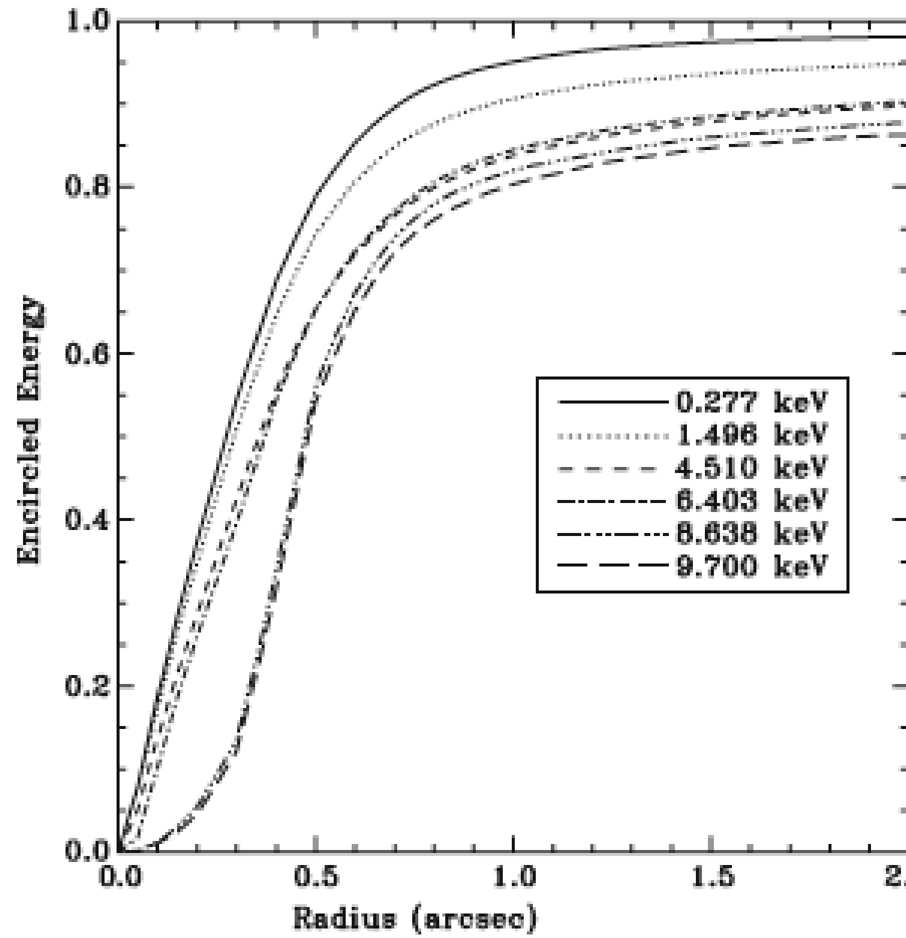
X-rays: Total reflection only works in the soft X-rays and only under grazing incidence
⟹ grazing incidence optics.

angle at which x-ray is reflected

Can Get Pretty Good Images

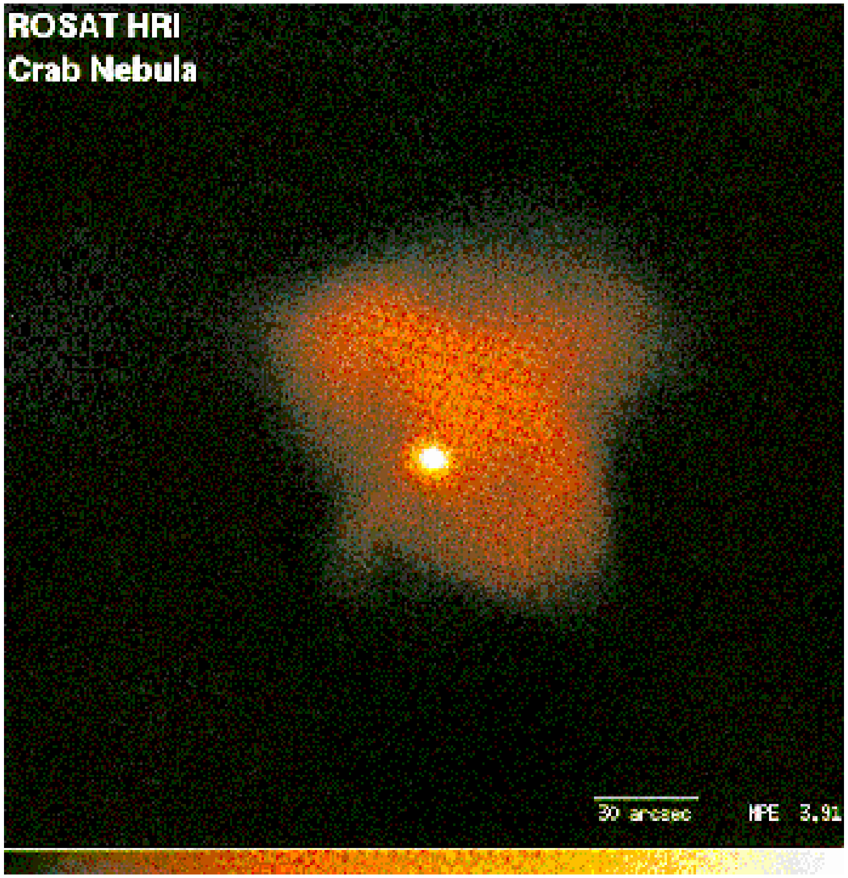
- Chandra Images are as good as the best images that can be obtained from the ground



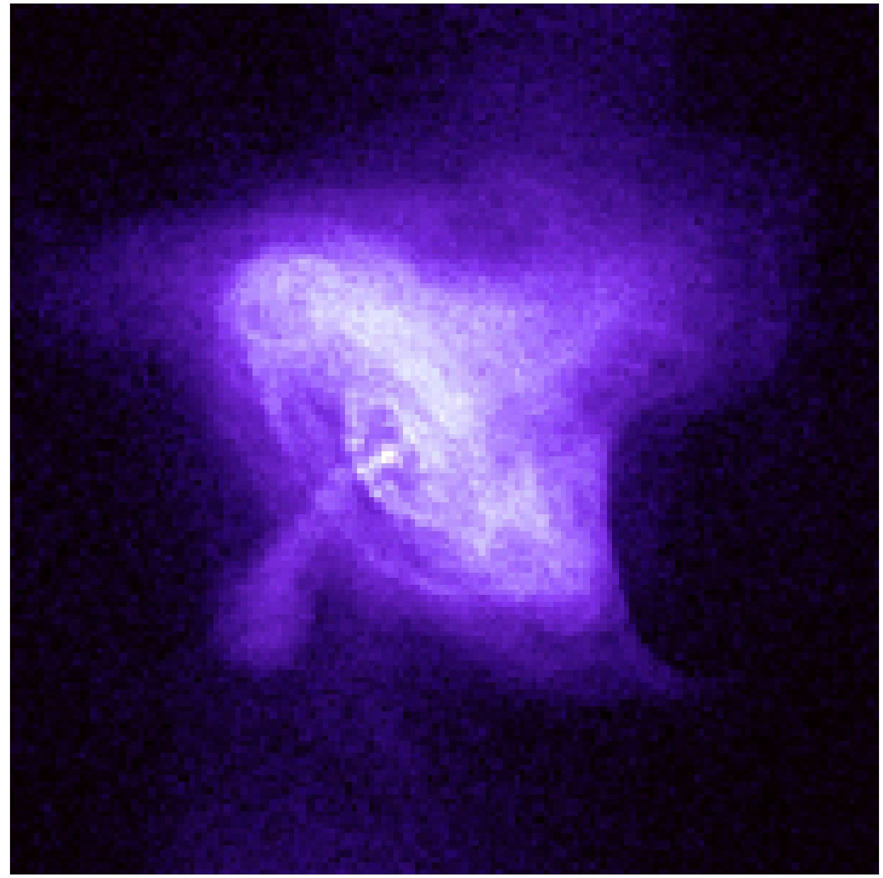


Chandra- fraction of energy inside an inscribed circle on axis

The Central Region of of the Crab Nebula in X-rays



Rosat: HPD = 3 arcsec



Chandra: HPD = 0.5 arcsec

Mirror Collecting Area

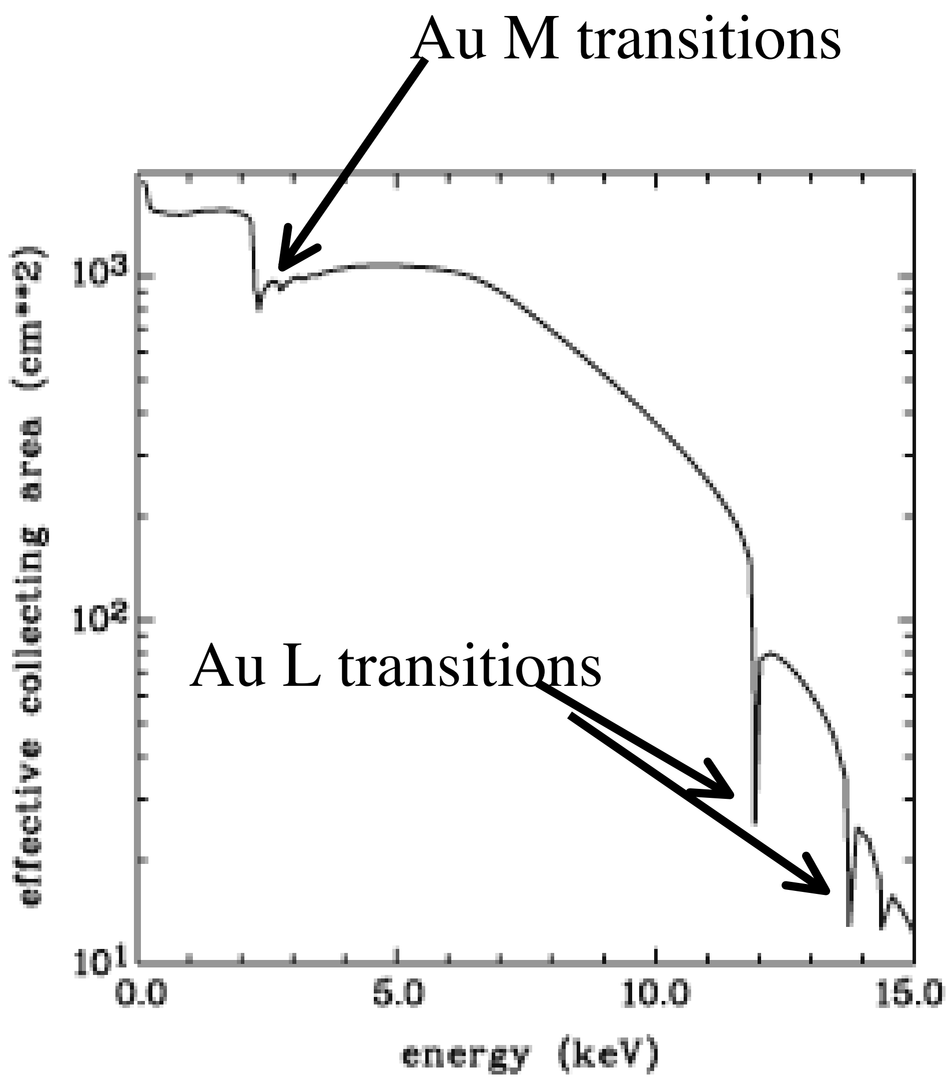
- Depends on mirror diameter, number of shells, focal length and coating of mirror (e.g. which metal coats the substrate)
- XMM mirror- the 'bumps and wiggles' are due to the atomic transitions of gold (the coating material)

- 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

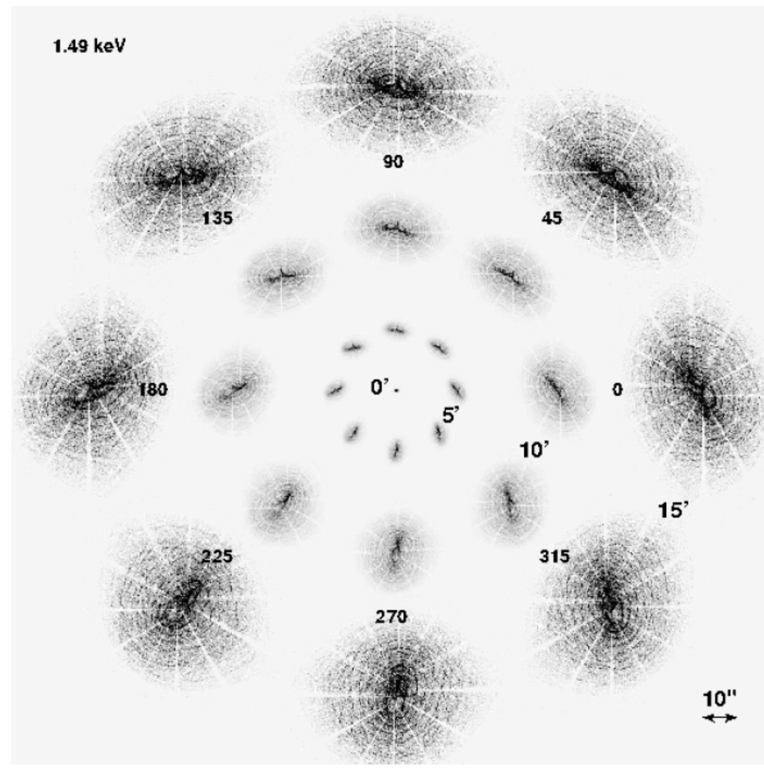
If want <10% scattered at 10A with α=1deg σ<9A



Some Issues

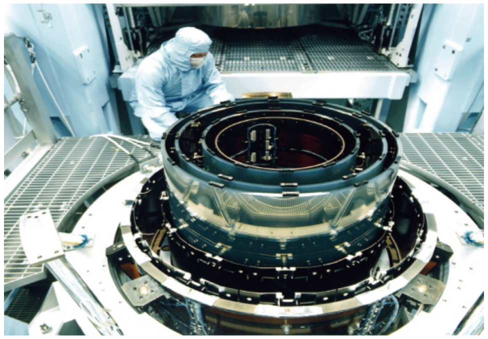
- The reflecting surfaces have to be very smooth- if they are rougher than the wavelength the photons hit 'mountains' and scatter (not reflect)
- A 'Wolter type I' optic focuses 'perfectly' at the center of the field of view- off axis the angular resolution degrades-due to coma aberration, astigmatism and field curvature.
- The actual collecting area is much smaller than the polished surface (sine 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 require long focal lengths

The point-response functions of the Chandra mirrors on axis and at 5, 10 and 15 arcminutes off axis (radial separations not to scale).



Point spread function (PSF)
As a function of off axis

Manufacturing techniques utilized so far



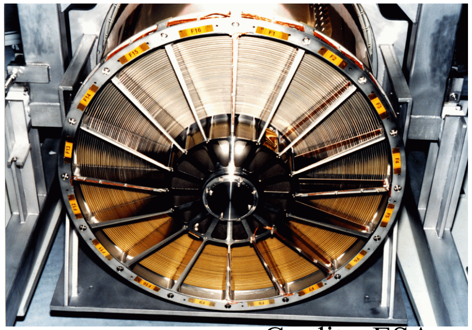
Credits: NASA

1. Classical precision optical polishing and grinding

Projects: ***Einstein, Rosat, Chandra***

Advantages: *superb angular resolution*

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



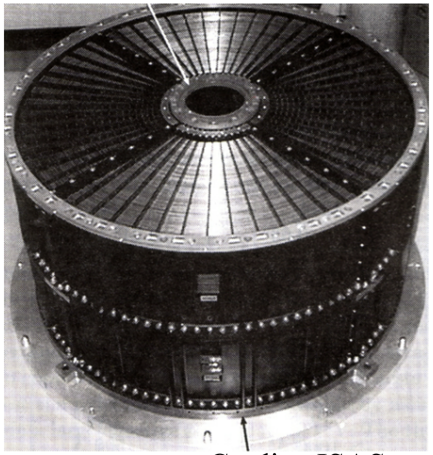
Credits: ESA

2. Replication- mostly electroforming so far

Projects: ***EXOSAT, SAX, JET-X/Swift, XMM, eRosita***

Advantages: *good angular resolution, high mirror "nesting" ,cheaper than precision polishing*

Drawbacks: *; high mass/geom. area ratio (if Ni is used) but less than polished optics.*



Credits: ISAS

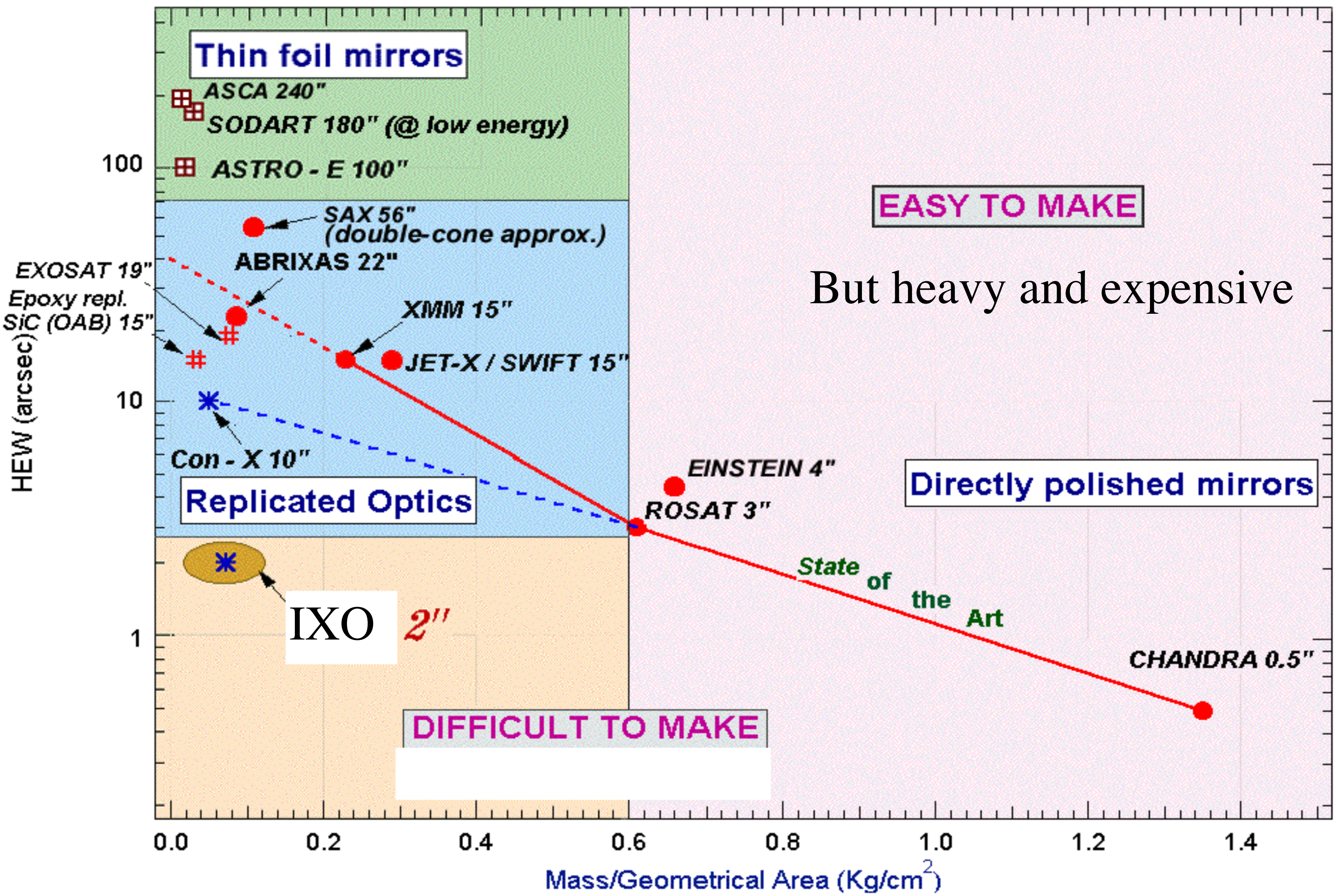
3. "Thin foil mirrors"

Projects: **BBXRT, *ASCA, Suzaku , ASTRO-H***

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

Drawbacks *low imaging resolution (1-3 arcmin)*

Present Astronomical optics technologies: HEW Vs Mass/geometrical area

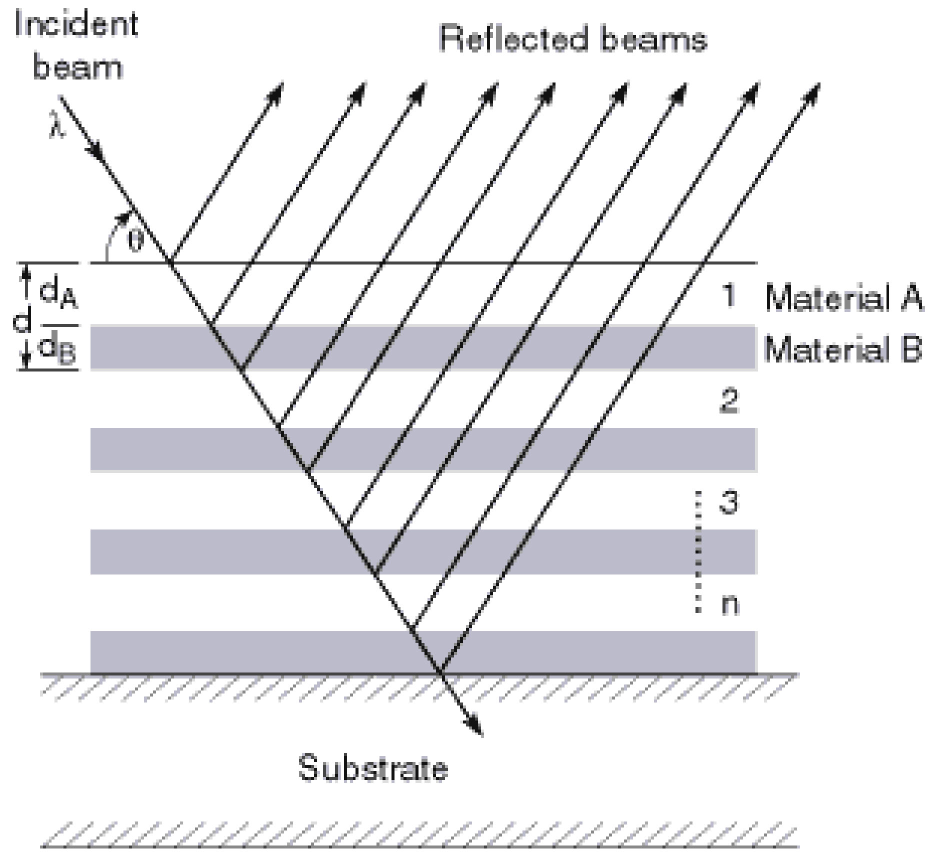


Multilayer Reflection- D. Schwartz

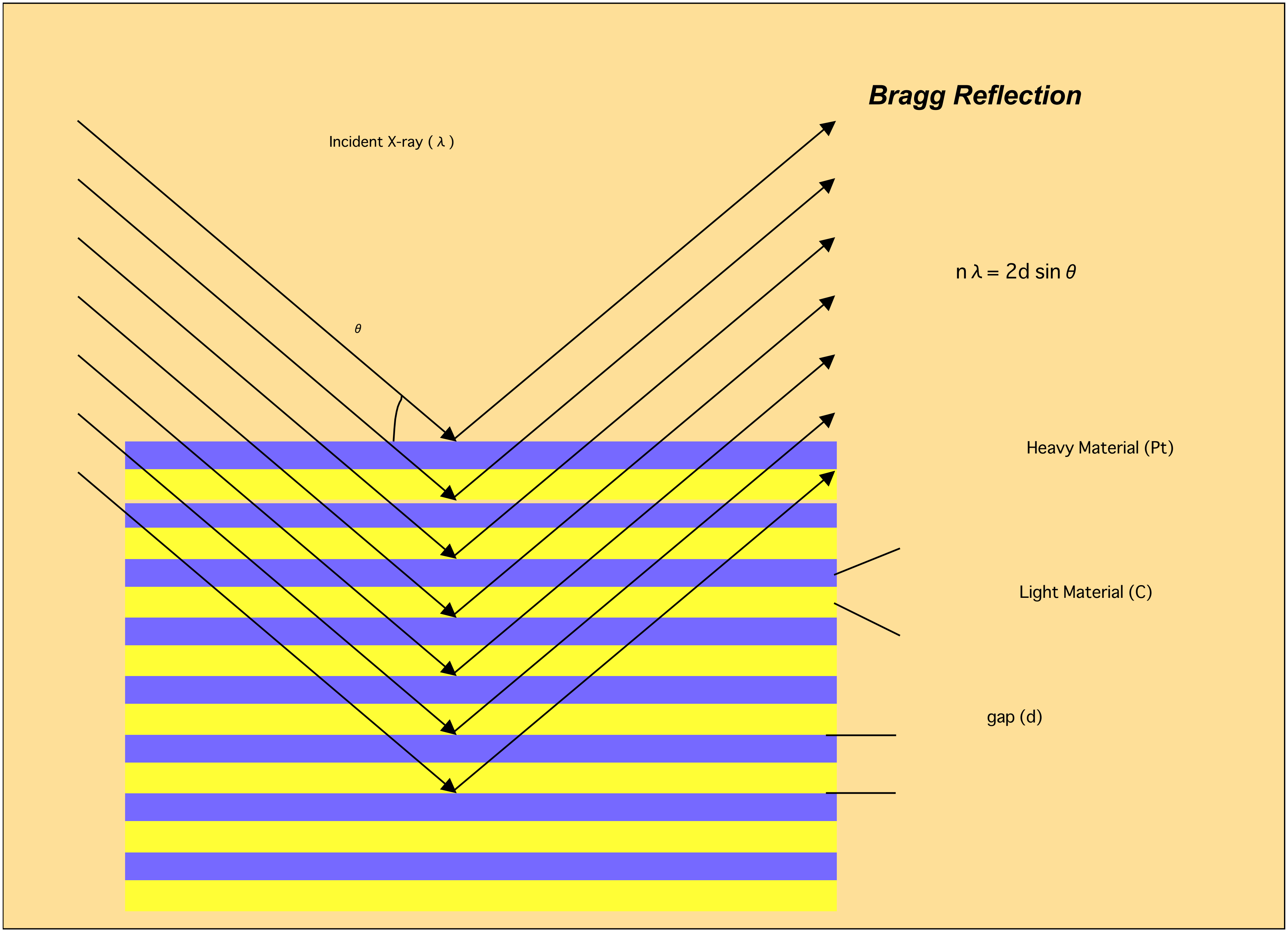
- Underwood, J.2001, X-ray data booklet, sect. 4.1 (http://xdb.lbl.gov)

Near normal incidence, reflectivity of soft X-rays is ~ 10^{-4}.

- This is because the X-rays penetrate the material until they are absorbed.
- 10^{-4} reflectivity means a reflected amplitude of 10^{-2}
- so if we can get ~ 100 layers to add coherently we can achieve significant reflection probability.
- **This has been realized with alternate layers of high Z material, to provide a high electron density for reflection, and low Z material, to provide a phase shift with minimal absorption**



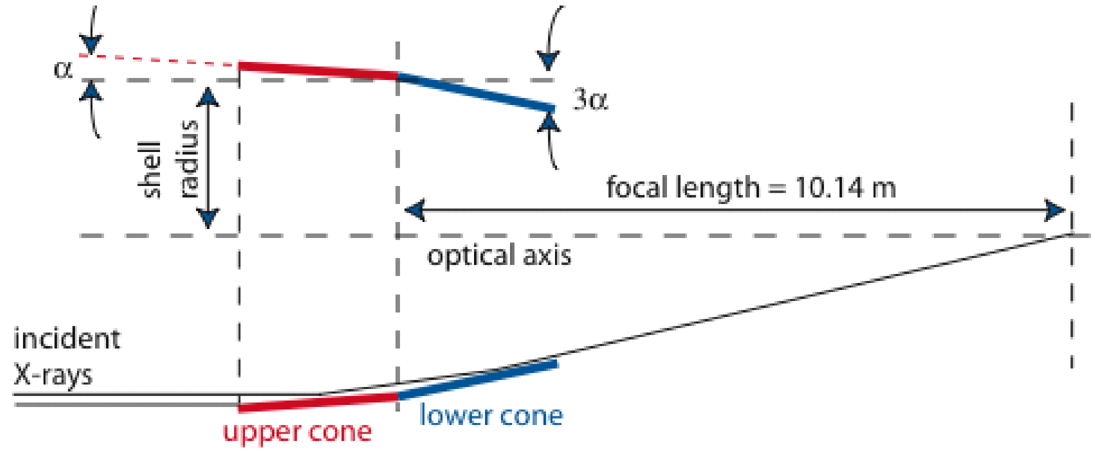
Now being built for NuStar and Astro-H

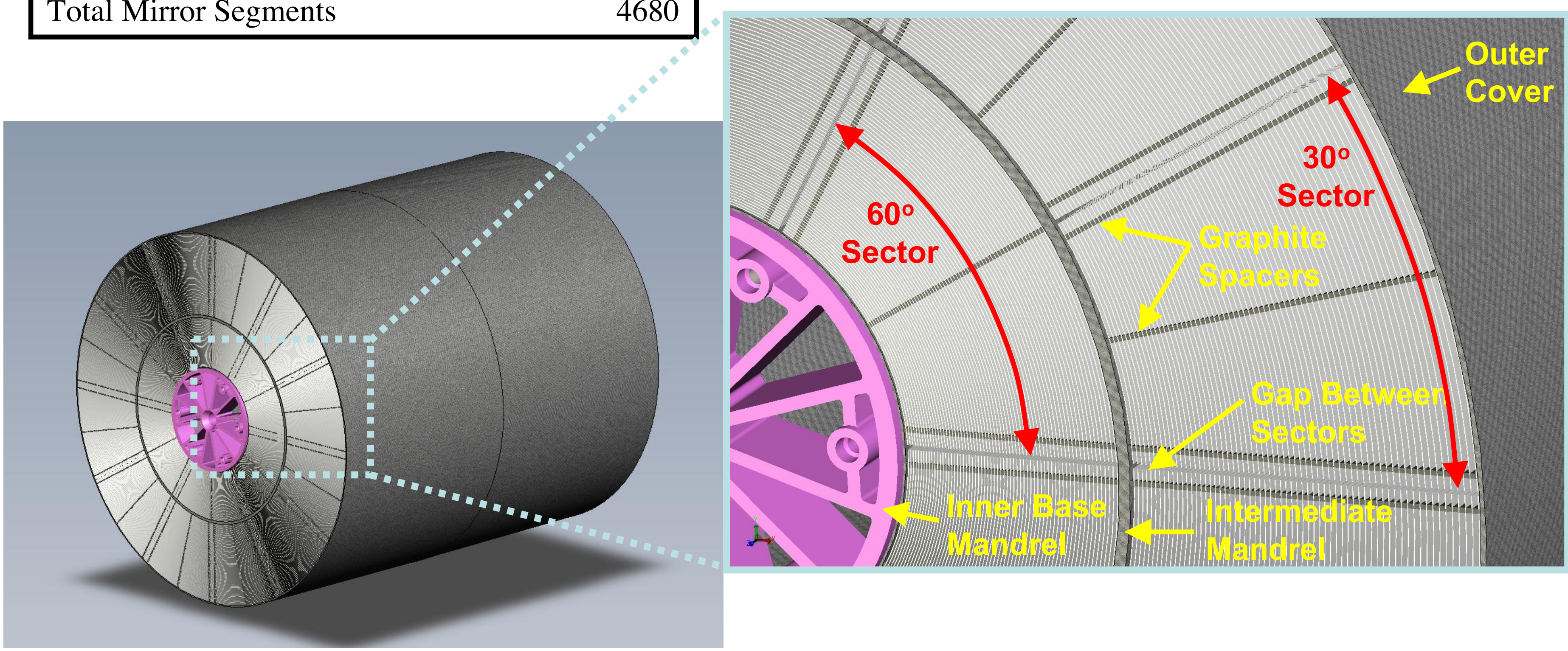


Bragg Reflection
Incident X-ray (λ)
θ
n λ = 2d sin θ
Heavy Material (Pt)
Light Material (C)
gap (d)

Each NuSTAR optic is comprised of 130 conic approximation Wolter-I shells

Parameter	Value
FocalLength	10.14 m
Shell Radii	54-191 mm
Graze Angles	1.3-4.7 mrad
Shell Length	225 mm
Mirror Thickness	0.2 mm
HPD Performance	40”
Total Shells Per Module	130
Total Mirror Segments	4680





It Works-58" HPD

- NuStar Image of Cas-A in x-ray colors
  - 10 < E< 20 KeV blue;
  - 8 < E< 10 KeV green;
  - 4.5 < E< 5.5 keV red.
  - E<10 keV overlaps with NASA's high-resolution Chandra X-ray Observatory.
  - The outer blue ring is where the shock wave from the supernova blast is interacting with ISM
- (white is optical image)