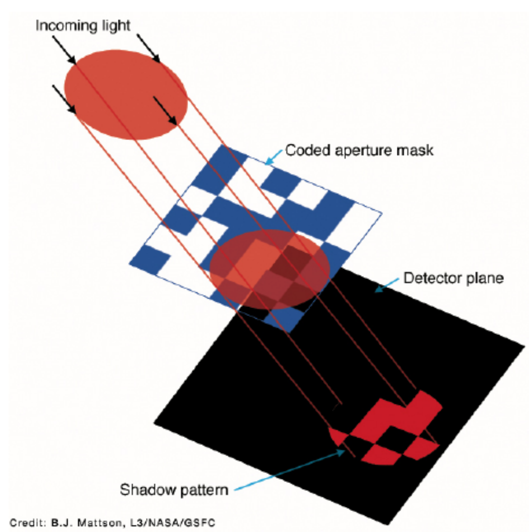
X-ray Telescopes
γ-rays 'have not been focused'

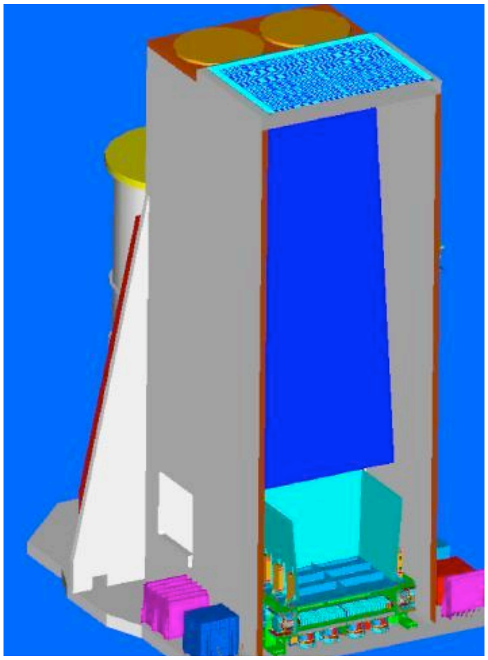
Almost X-ray Telescopes

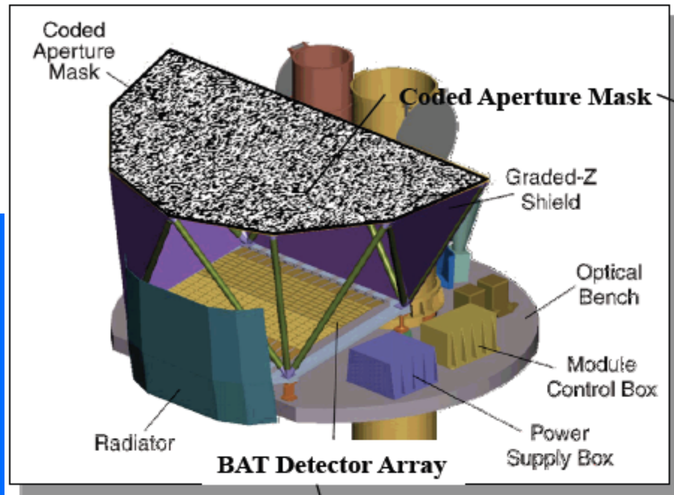
- one can make 'pseudo-imaging' telescopes using 'coded aperture masks' (shadowgrams) http://astrophysics.gsfc.nasa.gov/cai/
- Advantages- wide field of view, moderate angular resolution (~3') moderate sensitivity-works over a wide range in energy

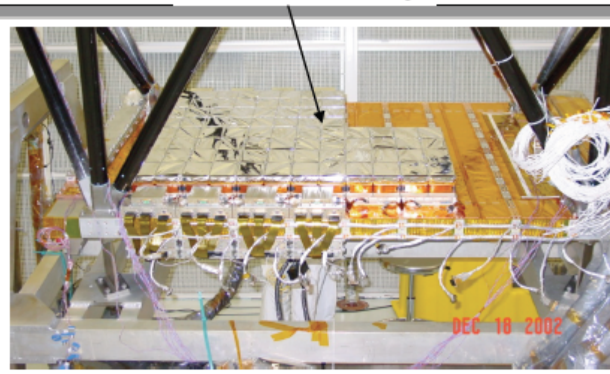
Used on INTEGRAL, Swift BAT- –
Detector -pixilated CdTe
BAT has 32,000 Detectors



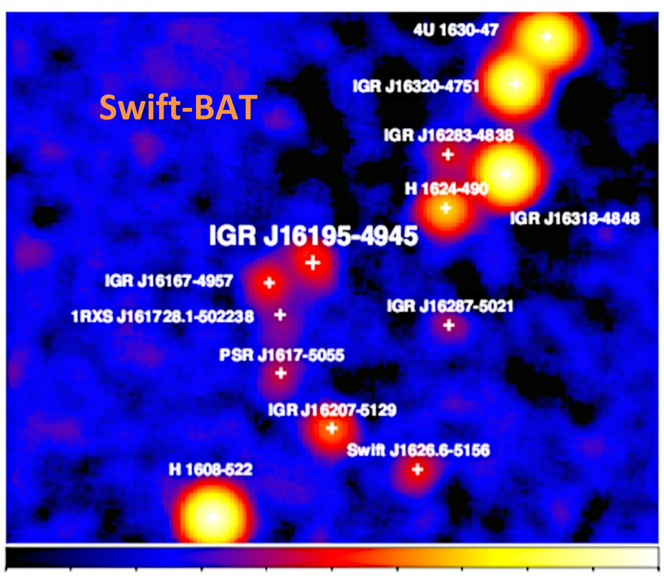
IBIS Instrument on Integral Satellite and BAT on Swift







Images From Shadow Masks



15-60kev image of sources in the galactic plane The source names are in RA and Dec and the color code is source significance

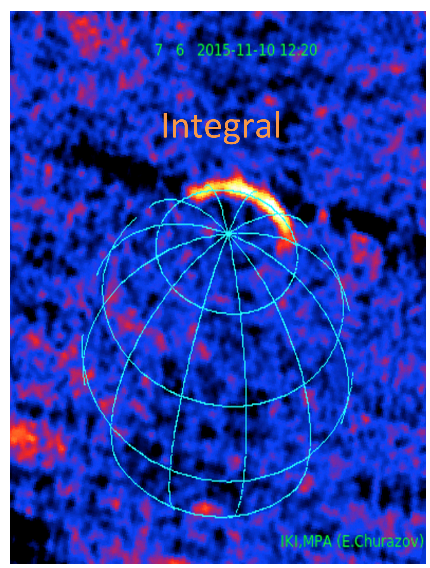


image of the high energy radiation produced by earth's aurora, charged particles from the sun that hit the earth's magnetic field and rapidly decelerate

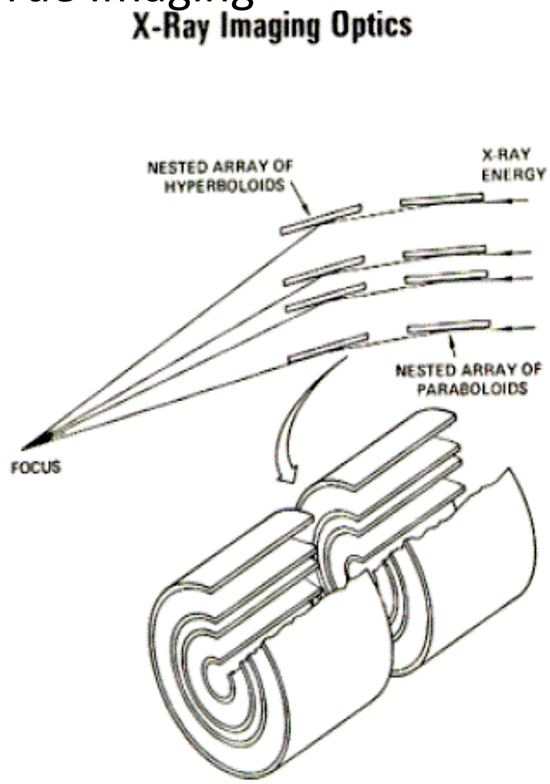
X-ray Telescopes- True Imaging

- 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

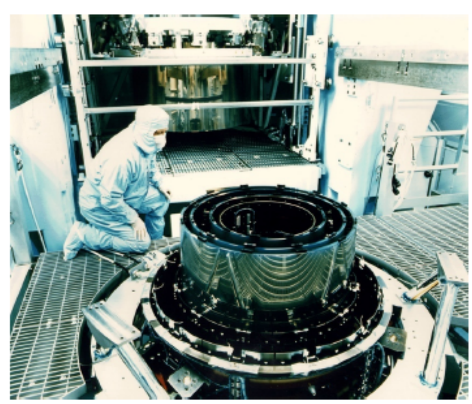
How to make the x-rays reflect and focus

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

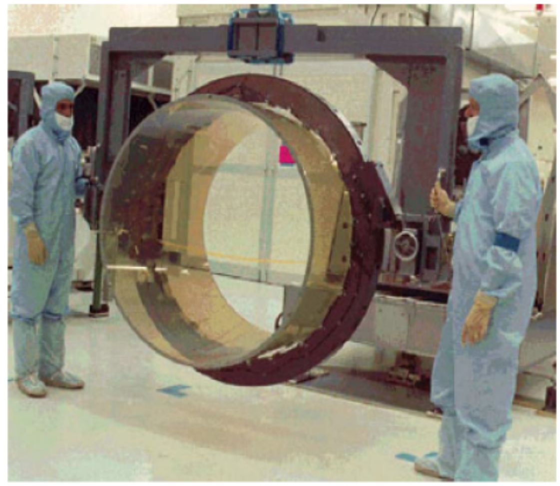


Chandra

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



Images of X-ray Optics



XMM Optics- 58 nested Shells, 0.5mm thick

1.2m diameter, 1 m long Chandra optic   one of 4 shells

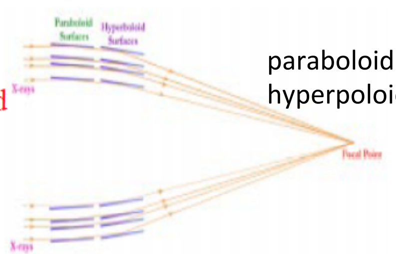
X-Ray Reflection: Zero Order Principles:

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



paraboloid then hyperpoloid

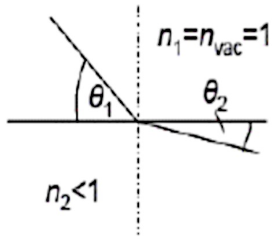
X-rays reflect at small grazing angles.

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

n= index of refraction



Snell's law:

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

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

For X-rays the refractive **index can be written as**

$\boxed{n = 1 - \delta - i\beta}$ δ describes the phase change and β accounts for the absorption

δ proportional to the atomic number Z

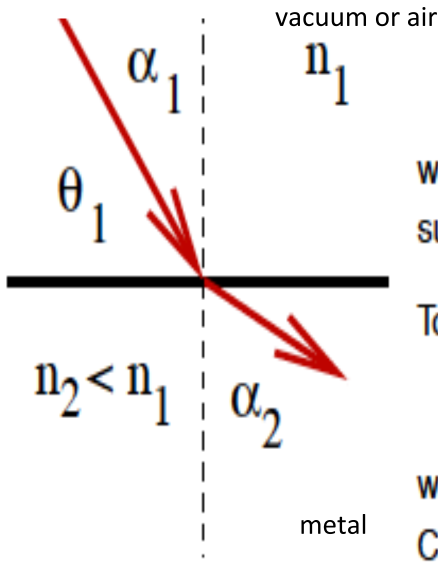
=> n small for heavy materials

Reflecting surface should be a heavy metal

Ni,Au and Pt have been used

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

Snells Law of Refraction



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

where n index of refraction, and $\alpha_{1,2}$ angle wrt. surface normal.

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

$$\sin\alpha_{1,c} = n \quad \Longleftrightarrow \quad \cos\theta_c = n$$

with the critical angle $\theta_c = \pi/2 - \alpha_{1,c}$.

Clearly, total reflection is only possible for $n < 1$

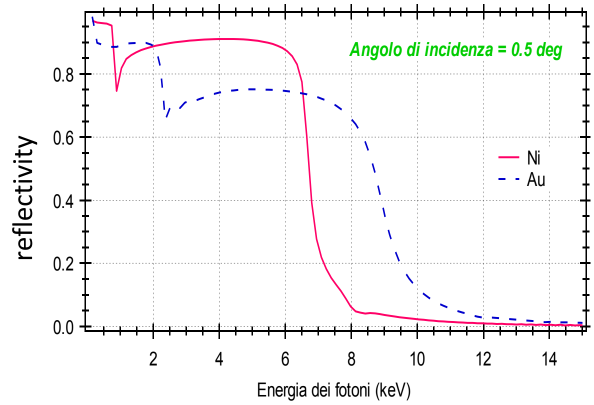
Light in glass at glass/air interface: $n = 1/1.6 \Longrightarrow \theta_c \sim 50° \Longrightarrow$ principle behind optical fibers.

I. Wilms

Total X-ray reflection at grazing incidence

- if vacuum is material #1 ($n_1 = 1$) ➔ the phase velocity in the second medium increases ➔ beam tends to be deflected in the direction opposite to the normal.

- Snell's law ($n1 \cos\theta_1 = n2 \cos\theta_2$) to find a critical angle for total reflection:



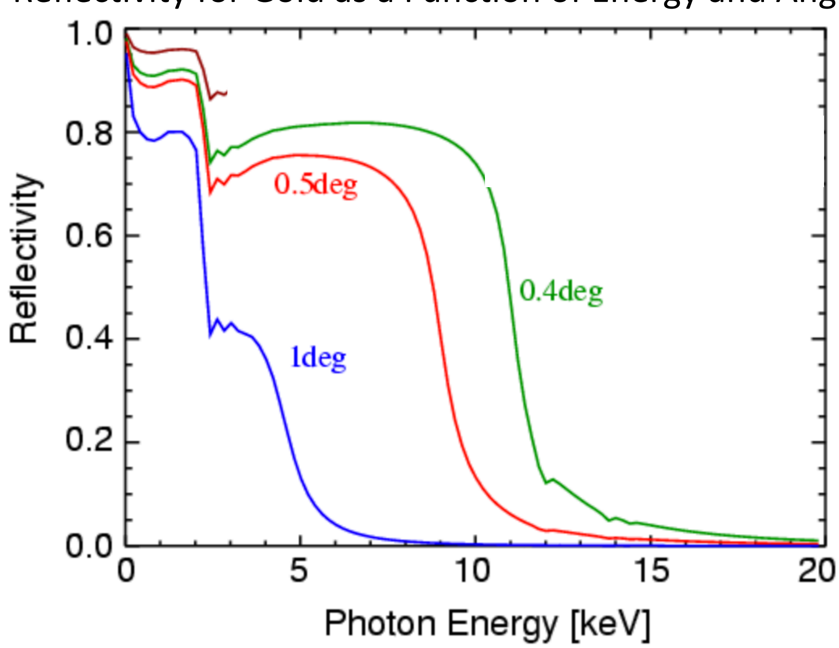
θ_{crit}(arc min)$=5.6\rho^{1/2}\lambda$(nm)
so for λ=1nm (~1 keV)
$\theta_{crit} = 1^0$

reflectivity for Ni or Au at a grazing angle of 0.5 deg as

a function of energy

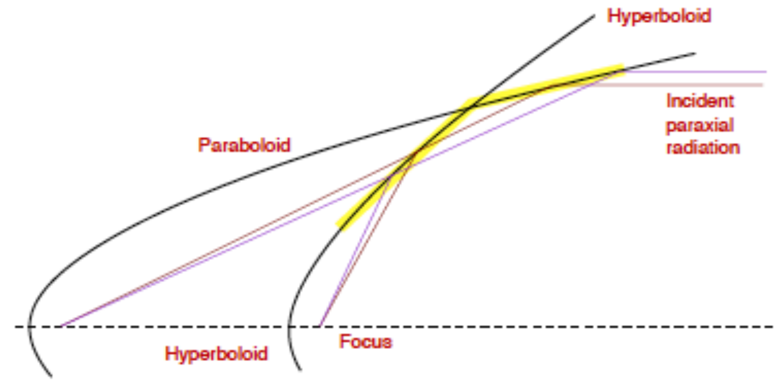
Pareschi 2003 λ = wavelength ρ = density A = atomic weight

Reflectivity for Gold as a Function of Energy and Angle



to reflect at high energies need very shallow angles

Wolter Telescopes



after ESA

To obtain reasonable focal lengths need 2 reflections- on a parabolic and then hyperbolic source − 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)

J. Wilms

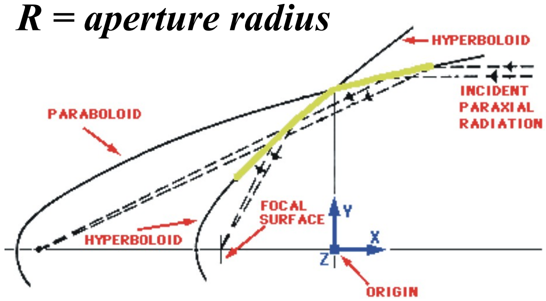
F= focal length = R / tan 4θ

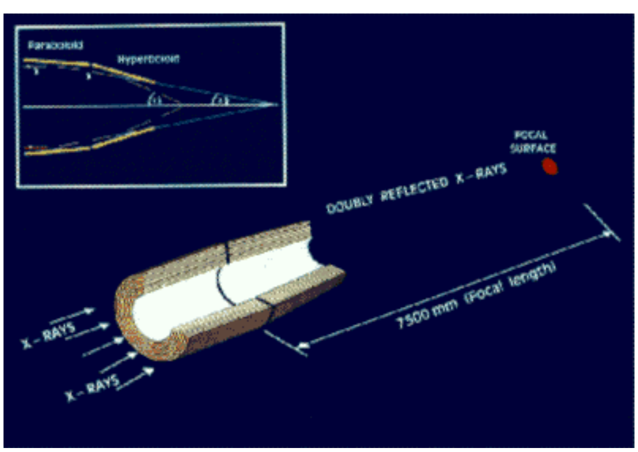
θ= *on-axis incidence angle*

R = aperture radius

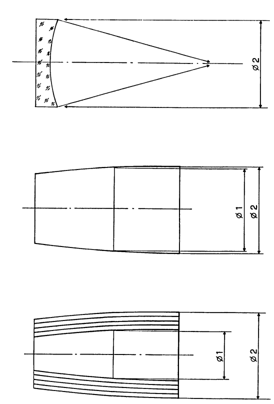
Wolter I mirror

- design has the minimum focal length for a given aperture
- it allows the nesting together of many confocal mirror shells
- Effective Area: **$8 \pi F L \theta^2 R^{2-}$ or**
- **A $\pi R^2 l/F$-**





optical telescope



$S_V = \frac{\pi \varnothing_2^2}{4}$

$S_1 = \frac{\pi (\varnothing_2 - \varnothing_1)^2}{4}$

single shell

$S_X = \frac{\pi (\varnothing_2 - \varnothing_1)^2}{4}$

many shells

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,

Chandra mirrors were ground and polished using classical techniques !

Rosat Telescope

XMM Optics

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.

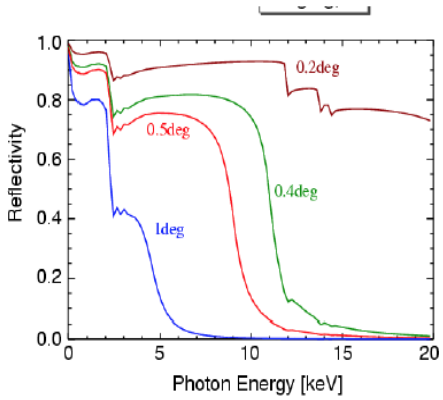
photo: Kayser-Threde

Imaging THE UNIVERSITY OF WARWICK 11

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

Long Focal Length

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



Reflectivity for Gold

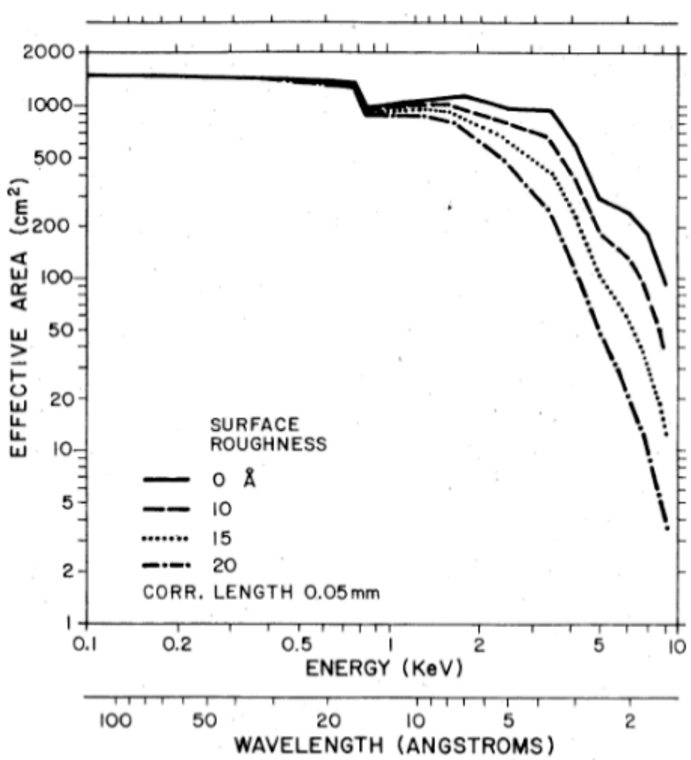
X-rays: Total reflection only works in the soft X-rays and only under grazing incidence
⟹ grazing incidence optics.

angle at which x-ray is reflected

17

Very Smooth Surface

- The rougher the surface the worse the reflectivity is, especially at high energies
- To achieve this smooth, precise surface the Chandra optics are ground and polished to 3Å precision into zerodur glass.
  - If the surface of the state of Colorado were as smooth, Pike's Peak would be less than 1 inch tall.
- Assembled, the Chandra mirror weighs more than 1 ton.



Mirror Collecting Area

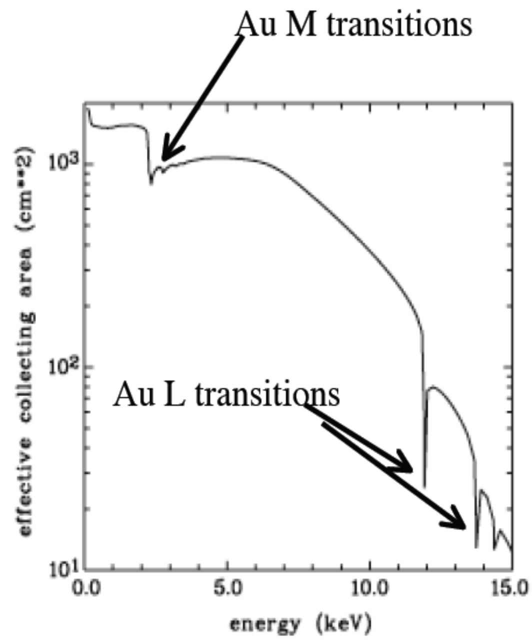
- Depends on mirror diameter, number of shells, focal length and coating of mirror (e.g. which metal coats the substrate)
- XMM mirror- the 'bumps and wiggles' are due to the atomic transitions of gold (the coating material)

- 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

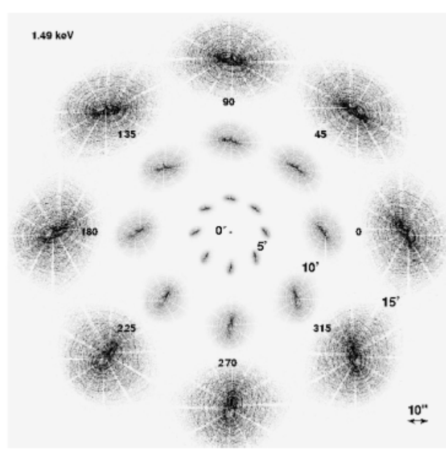


Some Issues

- 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 (10m for Chandra)

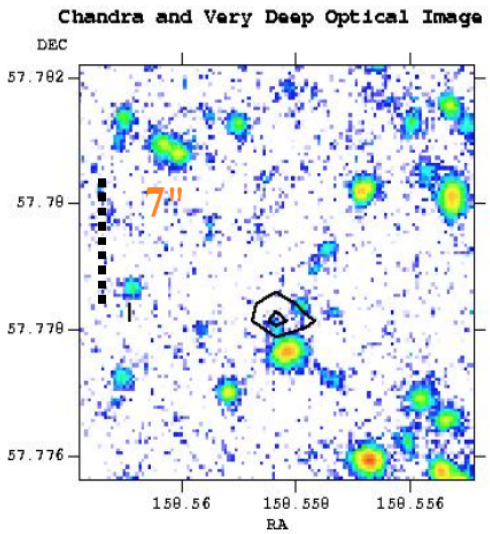
The point-response functions of the Chandra mirrors on axis and at 5, 10 and 15 arcminutes off axis (radial separations not to scale).

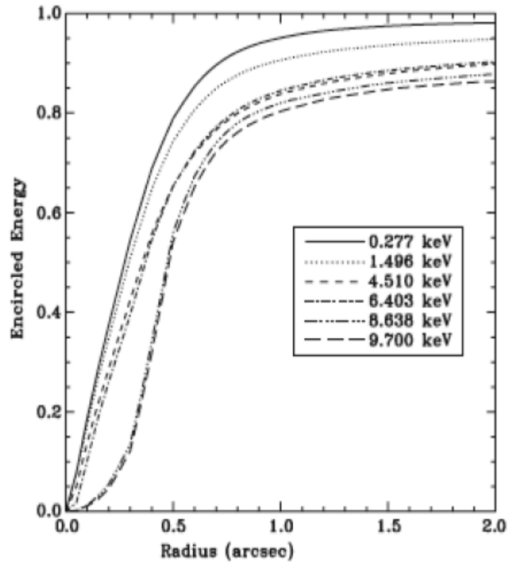


Point spread function (PSF)
As a function of off axis angle

Can Get Pretty Good Images

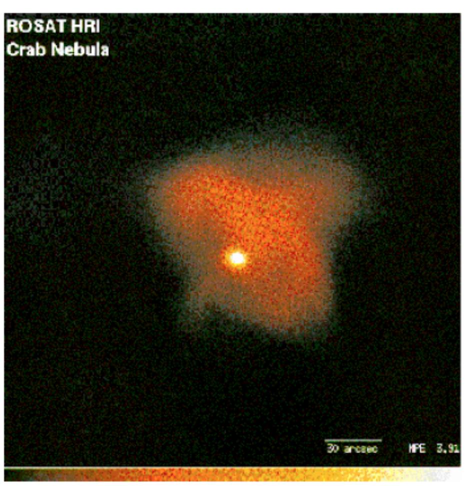
- Chandra Images are as good as the best images that can be obtained from the ground



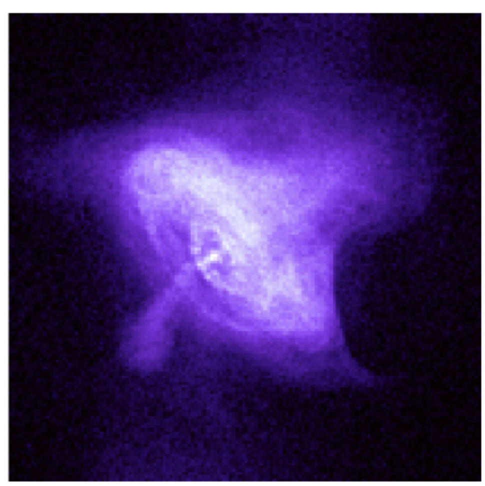


Chandra- fraction of energy inside an inscribed circle on axis

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



Rosat: HPD = 3 arcsec



Chandra: HPD = 0.5 arcsec

Manufacturing techniques utilized so far

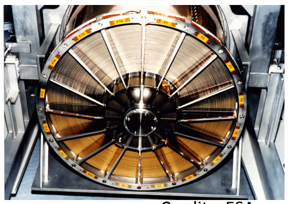

Credits: NASA

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

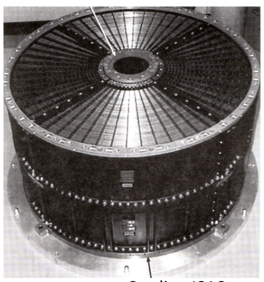
2. Replication

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

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,*** Hitomi

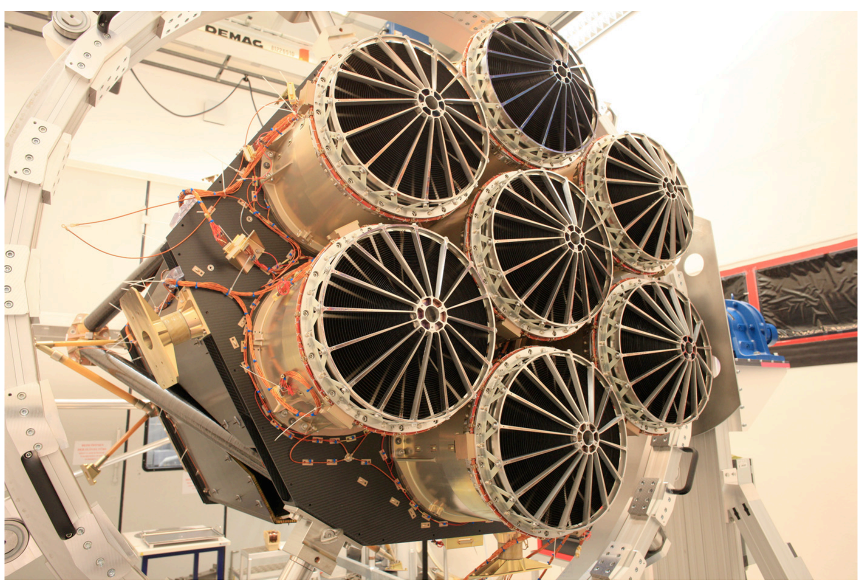
Advantages: *high mirror "nesting" possibility, low mass/geom. area ratio (the foils are made of Al), cheap process*

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

from Pareschi 2008

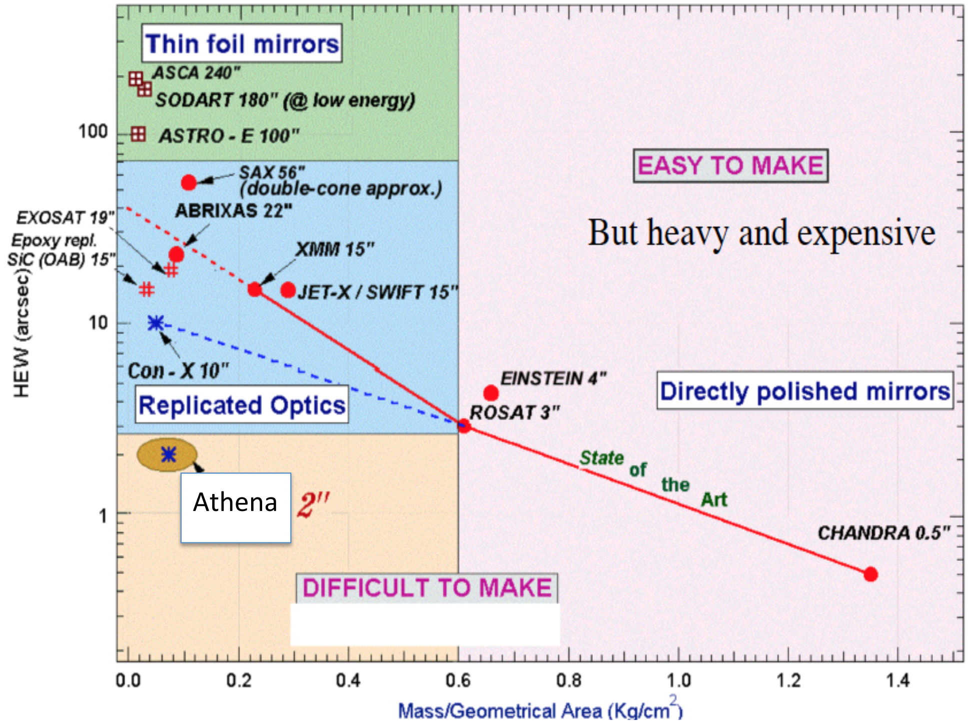
eRosita- launched July 2019

- Ni replicated 54 shells in each of 7 telescopes



Present Astronomical optics technologies: HEW Vs Mass/geometrical area

from Pareschi 2008

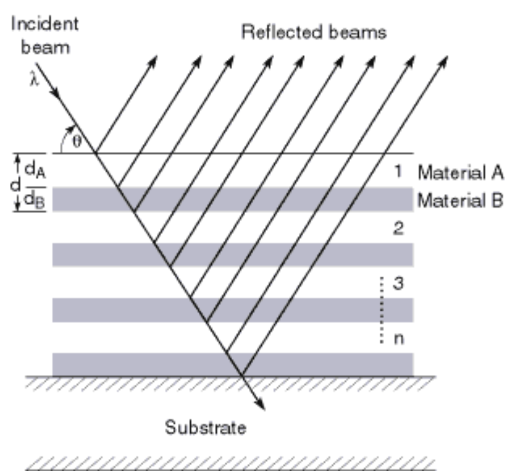


Multilayer Reflection- D. Schwartz

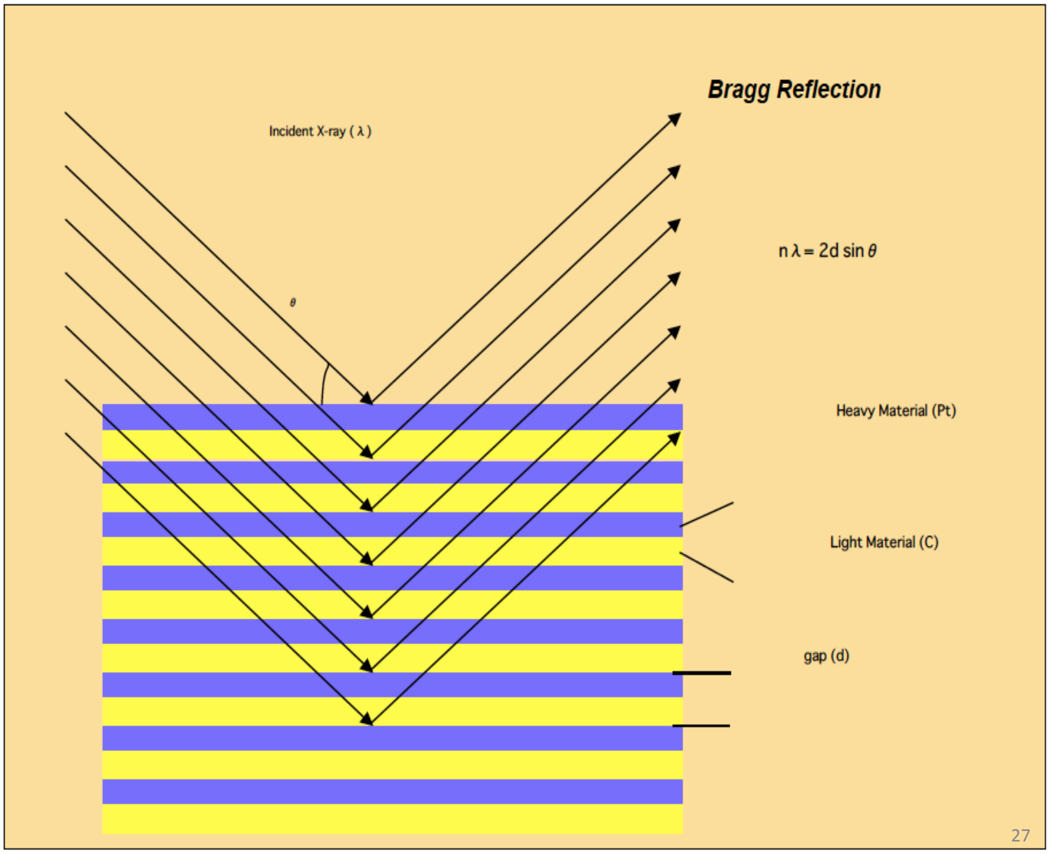
- Underwood, J.2001, X-ray data
- booklet, sect. 4.1 (http://xdb.lbl.gov)
- Near normal incidence, reflectivity of soft X-rays is ~ 10^{-4} because the X-rays penetrate the material until they are absorbed.

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**

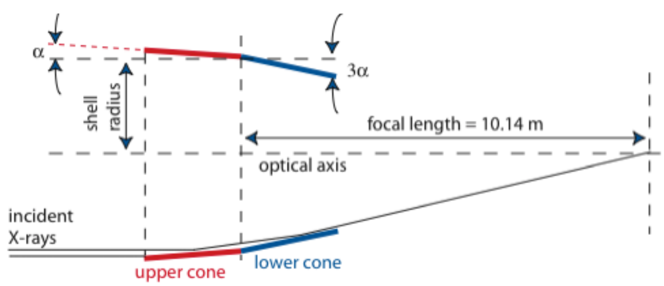


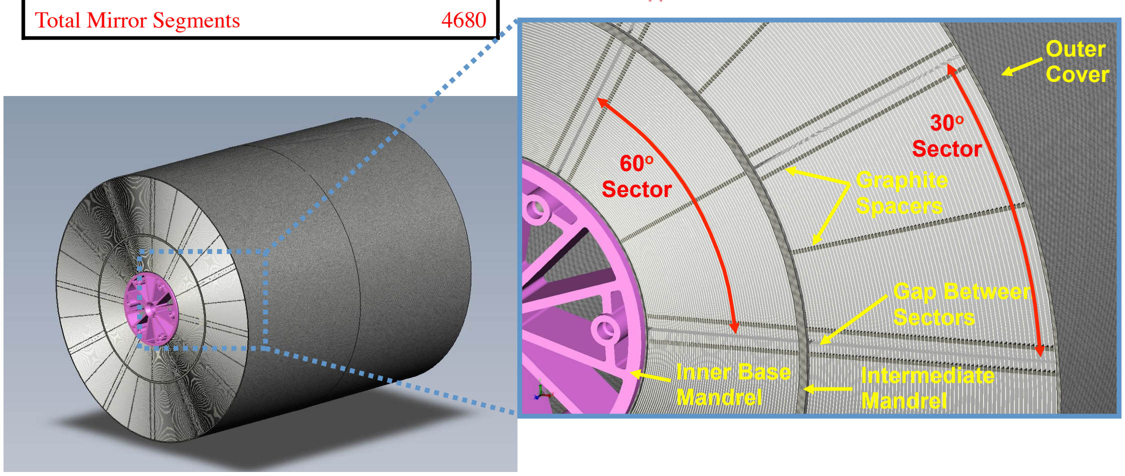
built for NuStar and Astro-H



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

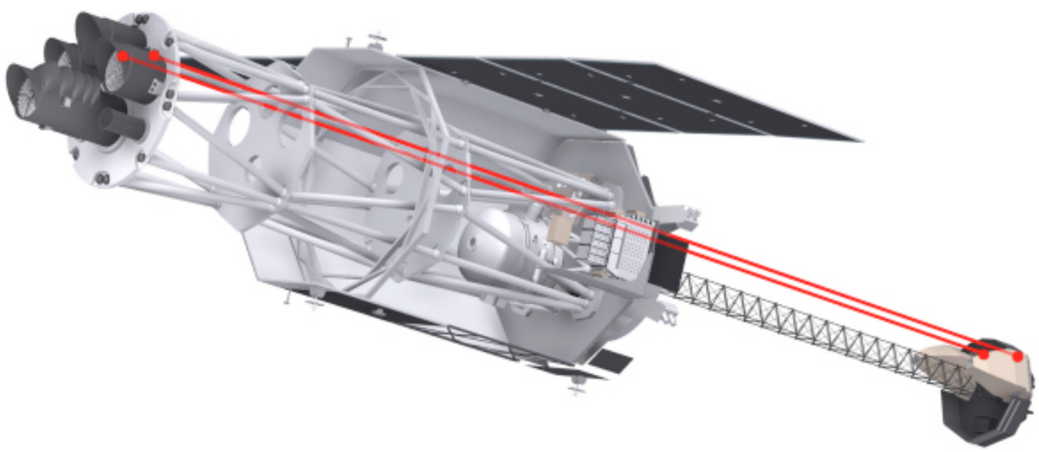
Parameter	Value
FocalLength	10.14 m
Shell Radii	54-191 mm
Graze Angles	1.3-4.7 mrad
Shell Length	225 mm
Mirror Thickness	0.2 mm
HPD Performance	40”
Total Shells Per Module	130
Total Mirror Segments	4680





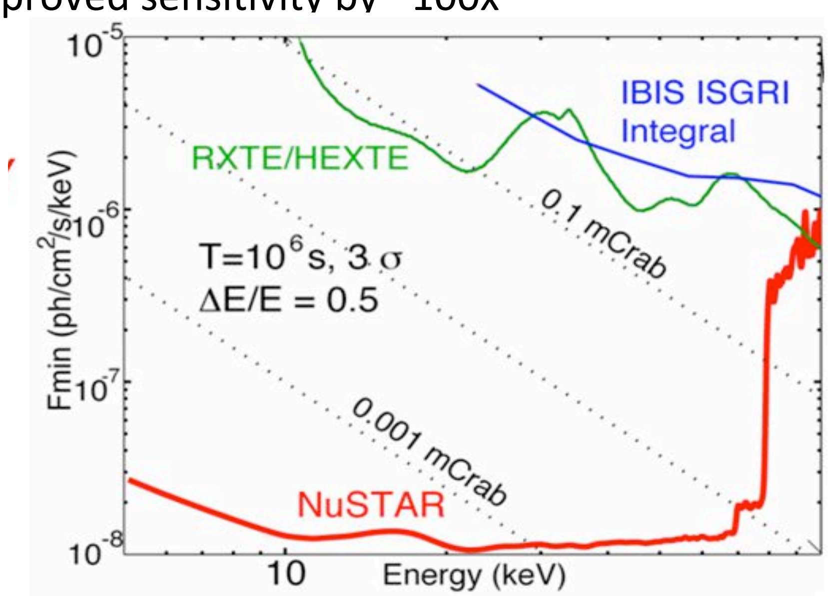
Hard x−ray Imaging

- require very long focal length- on Nustar and Hitomi this was achieved with an extendable optical bench
- The mirror substrates on Nustar are thin sheets of flexible glass as opposed to the Chandra thick zerodur



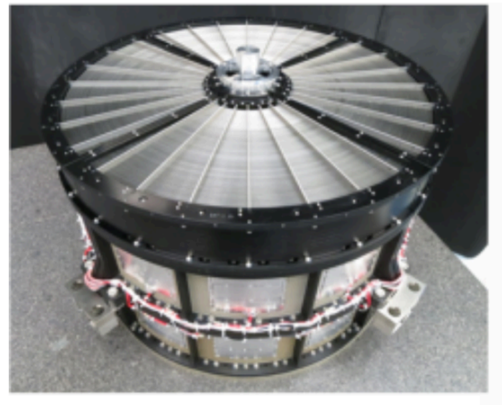
The Imaging Advantage

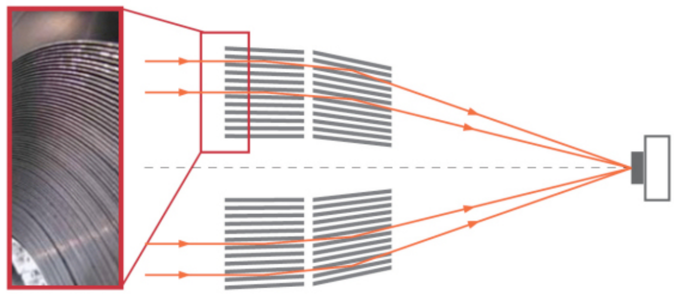
- Before 2010 there were no 'hard' (E> 10 keV) imaging x-ray satellites
- NuStar has improved sensitivity by ~100x



'Cheap' Telescopes

- To get an opportunity to fly in space mass and cost are very important
- A high resolution telescope is expensive and heavy (Chandra mirror mass was ~1500kg)
- Thus the European and Japanese programs have used 'light weight' 'low cost' optics with large collecting area but poorer angular resolution on XMM, Suzaku and Hitomi
- The design allows many thin (~1mm) shells (203 in Hitomi, 58 in XMM)



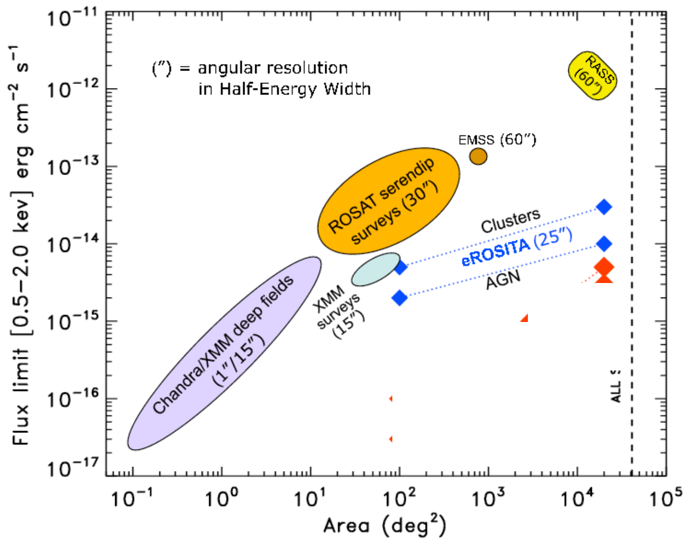


It Works-58" HPD

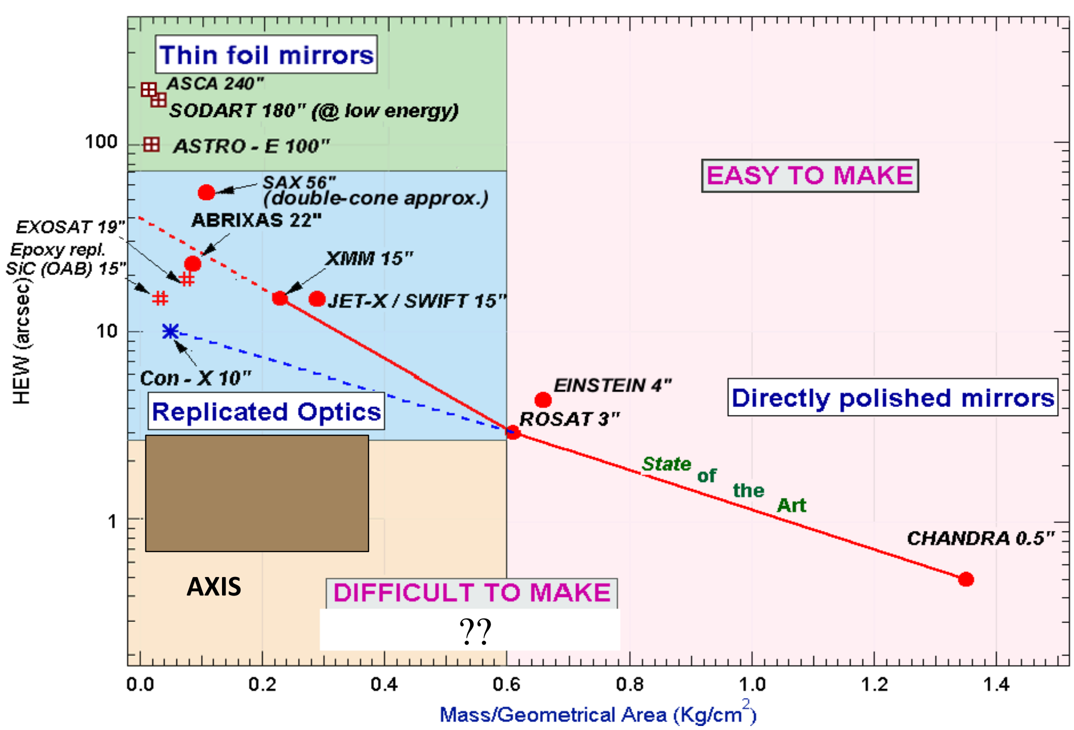
- NuStar Image of Cas-A in x-ray colors
  - 10 < E< 20 KeV blue;
  - 8 < E< 10 KeV green;
  - 4.5 < E< 5.5 keV red.
  - E<10 keV overlaps with NASA's high-resolution Chandra X-ray Observatory.
  - The outer blue ring is where the shock wave from the supernova blast is interacting with ISM
- (white is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

Relative Sensitivity for Surveys

- One of the main goals of a high energy mission is to find and characterize sources
- This is called a survey
- The sensitivity of a survey depends on the collecting area, background, angular resolution, solid angle of the telescope (etc etc)

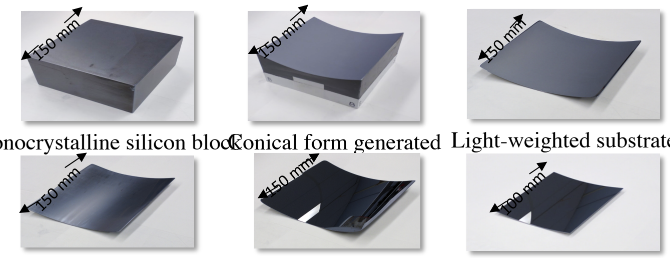


Present Astronomical optics technologies: HEW Vs Mass/geometrical area



Future of X-ray Optics

New technology allows ~10x the Chandra collecting area with similar angular resolution for ~1/10th the mass and cost of the Chandra optics



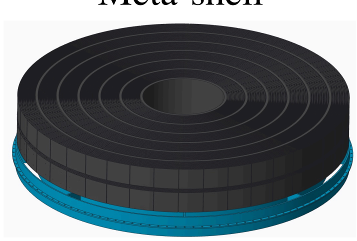
Monocrystalline silicon block | Conical form generated | Light-weighted substrate

Etched substrate | Polished mirror substrate | Trimmed mirror substrate

The Meta-Shell Paradigm

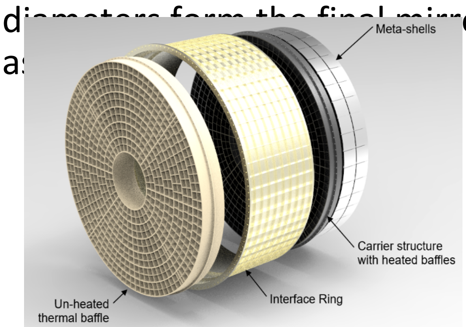
Mirror Segment

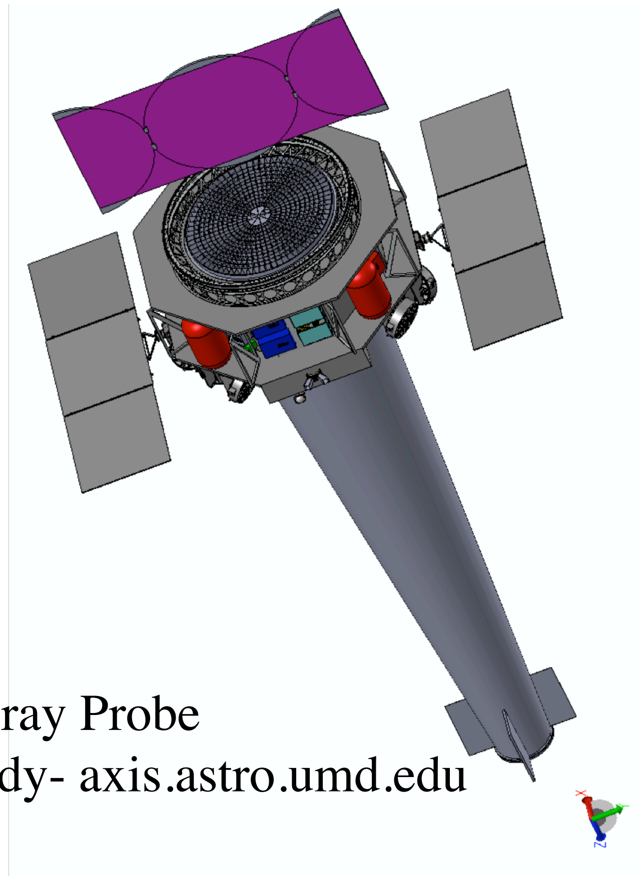
Meta-shell



Mirror Assembly

- Each mirror segment is fabricated, qualified, and then aligned by and bonded to four spacers which kinematically constrain it.
- Several hundred mirror segments are aligned and bonded to form a meta-shell.
- A dozen or so meta-shells of different diameters form the final mirror assembly

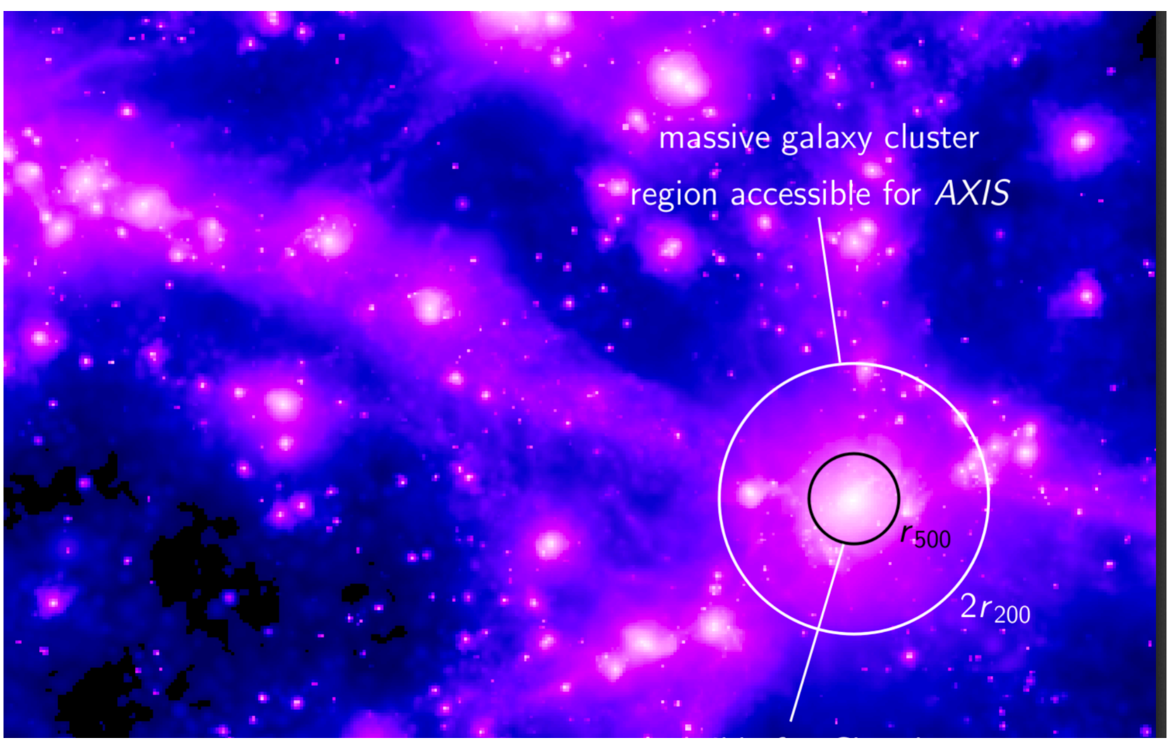


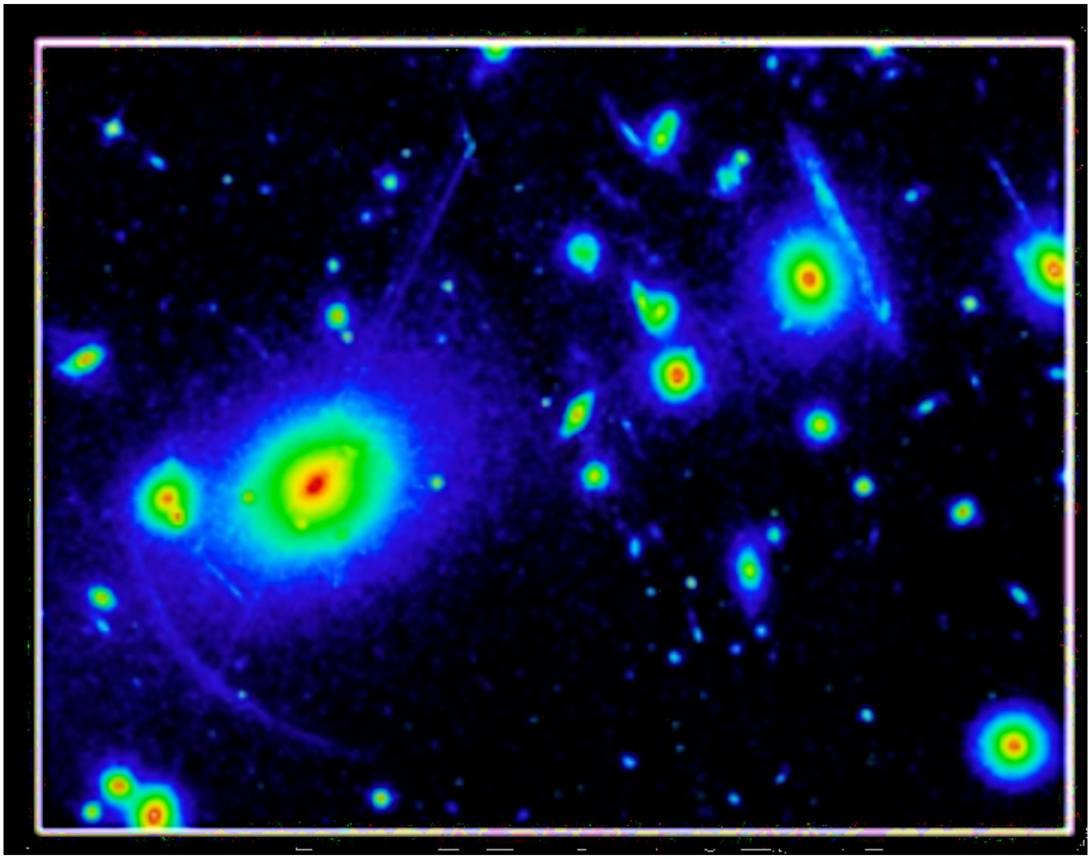


AXIS an x-ray Probe
mission study- axis.astro.umd.edu

Onto clusters of galaxies !

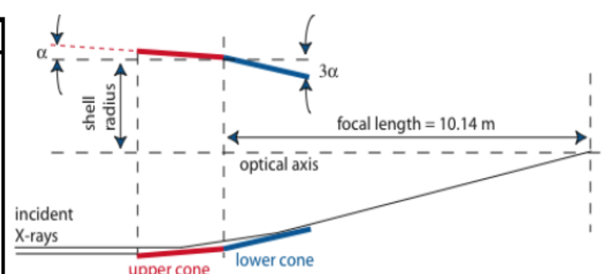
End of Telescopes and Detectors

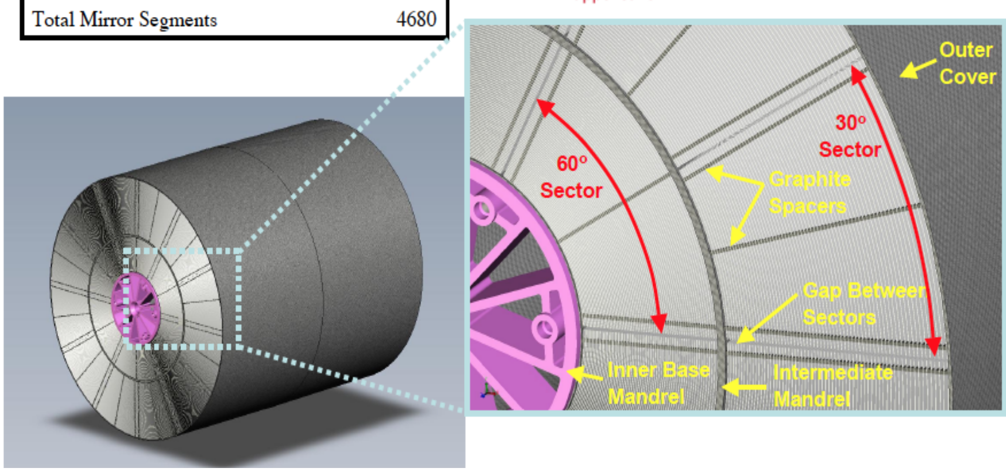




Each NuSTAR optic is comprised of 130 conic approximation Wolter-I shells

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





Grazing Incidence (Aschenbach 1984)

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

  nr = 1 - δ < 1,

- total external reflection occurs for grazing-incidence angles $\alpha \leq \alpha_t$:

$\cos\alpha_t = 1 - \delta$ .....for δ<< 1 $\alpha_t = \sqrt{2\delta}$.

$\delta \sim (r_e/2\pi)(N_0\, \rho/A) Z \lambda^2$ 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 the incidence angle α_t of total reflection for δ << 1 is
- $\alpha_t = 5.6\lambda\sqrt{\rho}$– α_t in arcmin, λ in Å and ρ in g/cm³.
- **high density materials Au, Pt, Ir are best for reflection coatings**

Hard X-ray Imaging

- *At photon energies > 10 keV the cut-off angles for total reflection are very small also for all 'simple' metals- so need very long focal length*
- *Solution* *Wide band multilayers*

$$\boxed{\vartheta_{crit} \propto \frac{\sqrt{\rho}}{E}}$$