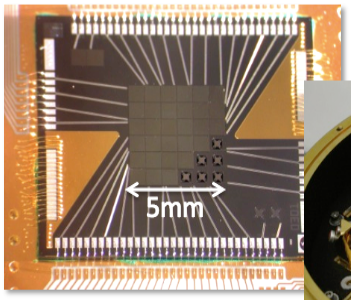
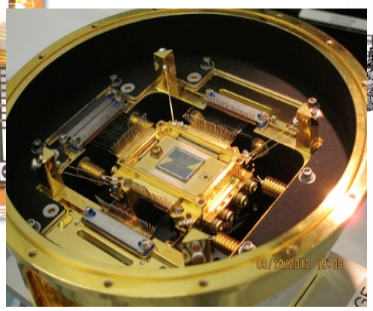
Gamma-ray Detectors and X-ray Telescopes

SXS: basic design

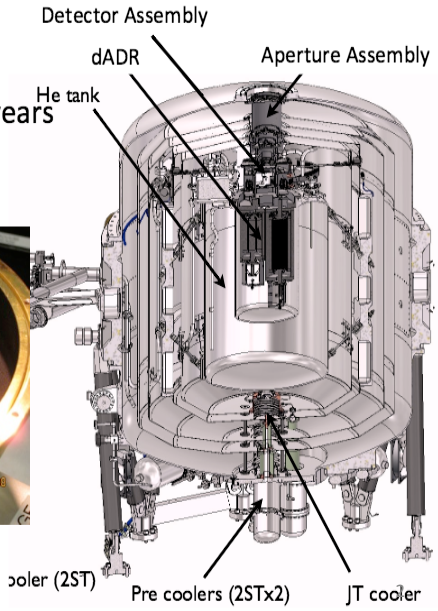
- X-ray micro-calorimeter spectrometer with energy resolution better than 7 eV (FWHM)
- 6 x 6 array with 3' x 3' field of view
- Operated at 50 mK
  - Nominal expected liquid He lifetime 3.3 years



Microcalorimeter array
NASA/GSFC

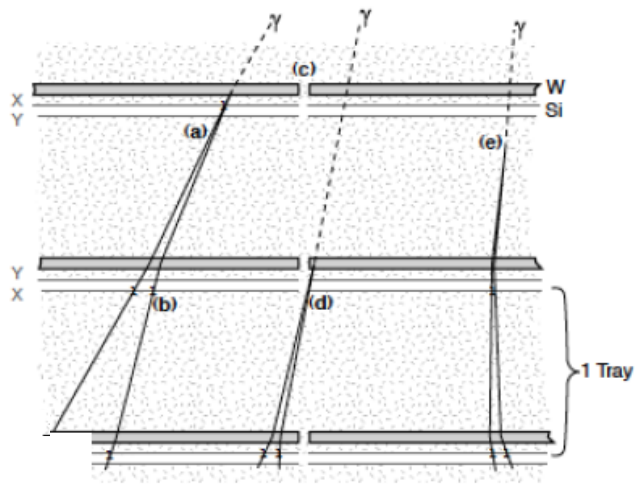


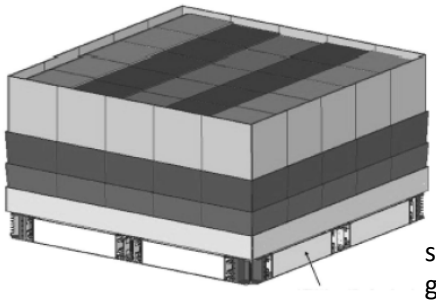
SXS detector assembly



γ-ray Detectors

- High-energy γ-rays "cannot" be reflected or refracted
- they are detected at E>30 Mev by their interaction via 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)





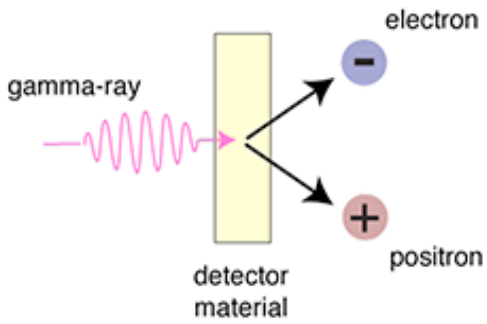
Full coverage of anti-coincidence detectors

see http://imagine.gsfc.nasa.gov/science/toolbox/gamma_detectors2.html

High Energy γ-Ray Detectors

At energies above about 30 MeV, pair production is the dominant photon interaction in most materials.

A pair telescope uses this process to detect the arrival of the cosmic photon through the electron/ positron pair created in the detector.



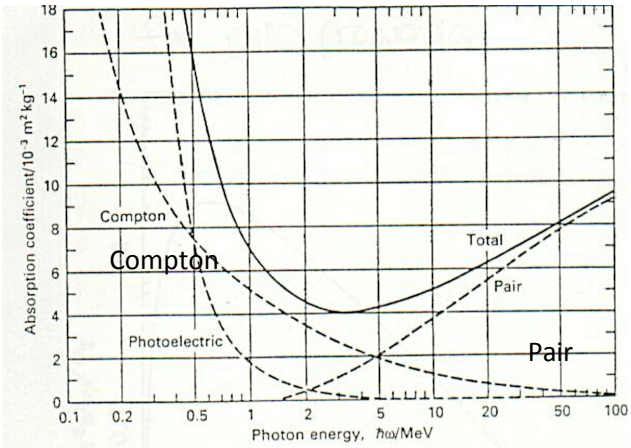


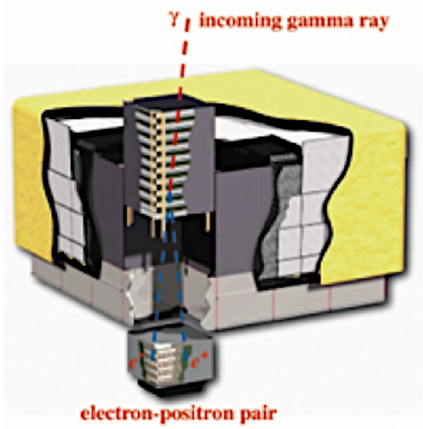
Figure 4.16. The total mass absorption coefficient for high energy photons in lead,

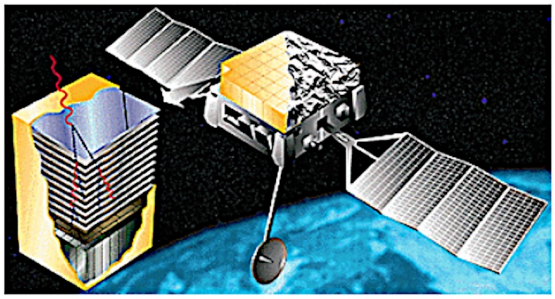
γ-ray Detectors
Fermi energy range from 20 MeV - 300 GeV.

- 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



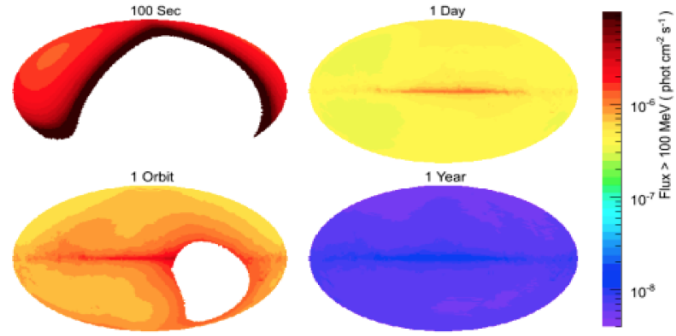


γ-ray Detectors

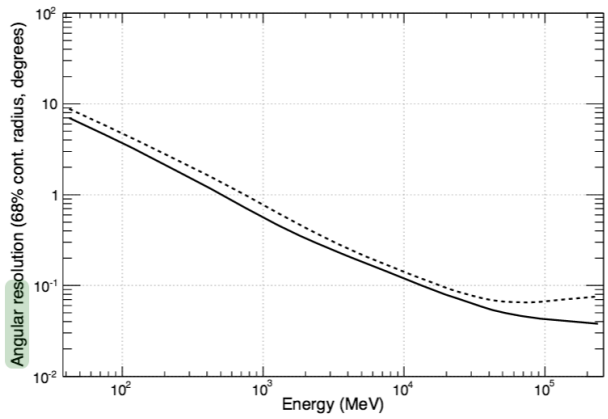
- Fermi uses silicon detectors consisting of two planes of silicon one oriented in the "x"-direction, the other plane has strips in the "y"-direction. The position of a particle passing through these two silicon planes can be determined
- The direction of the incoming γ-ray is determined by tracking 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 Detectors

- The Fermi detector (called LAT) has a very large field of view ~2π ster-radians and thus does not need to point
- Angular resolution function of energy E>10Gev 0.15°, 1 Gev 0.6°, 100 Mev 3.5°



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- see http://web.mit.edu/iachec/meetings/2013/Presentations/Ota.pdf) for details of Astro-H instrumentation)- basic idea is that

  – In a Compton camera, events involving the incident γ-ray are scattered (similar to Fermi) and then and fully absorbed by CdTe detectors which give a 'Compton image'.

  – The direction of the γ-ray is calculated by solving the Compton kinematics with information concerning deposit energies and interaction positions recorded in the detectors.

  – NaI, CsI scintillators (HEXTE on RXTE) or other scintillators (the HXD on Suzaku)

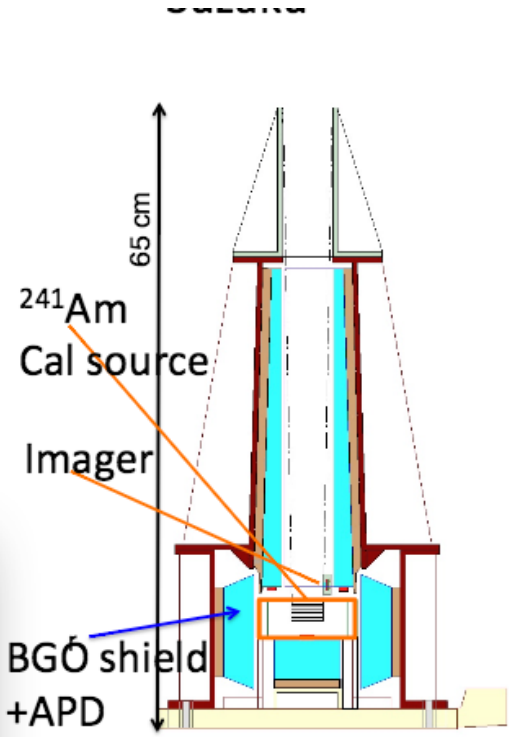
Older technology X-ray detectors

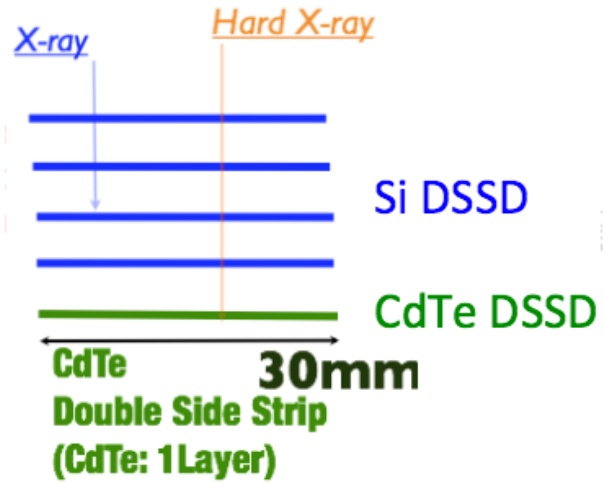
Gas scintillators (EXOSAT, Tenma)

Bragg crystal spectrometers (Einstein)

– etc etc

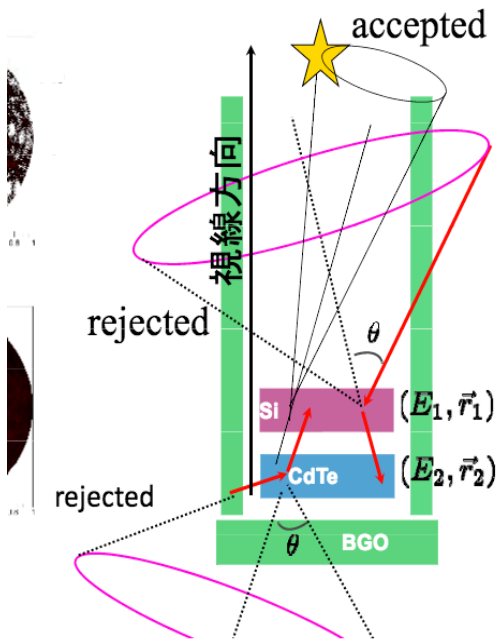
Hard x-ray imager on Astro-H





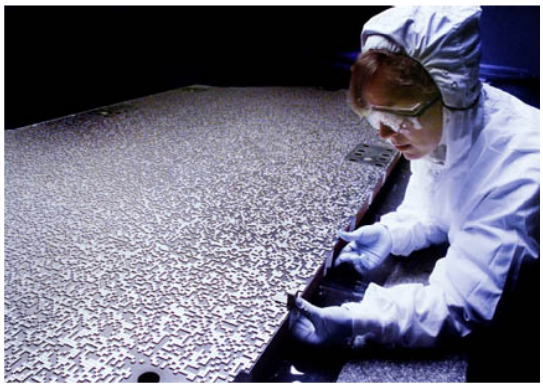
A Compton Camera

$$\cos\theta = 1 + \frac{m_e c^2}{E_1 + E_2} - \frac{m_e c^2}{E_2}$$

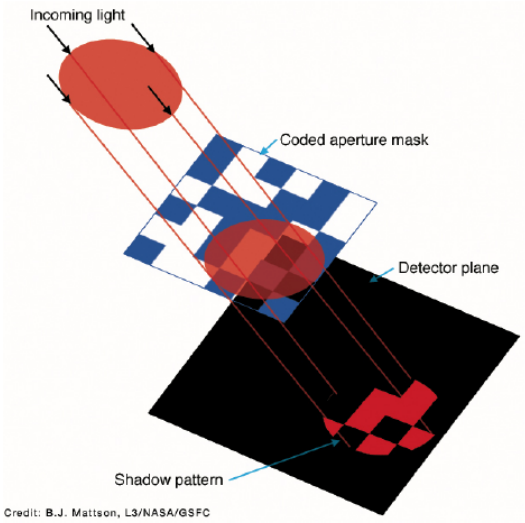


X-ray Telescopes

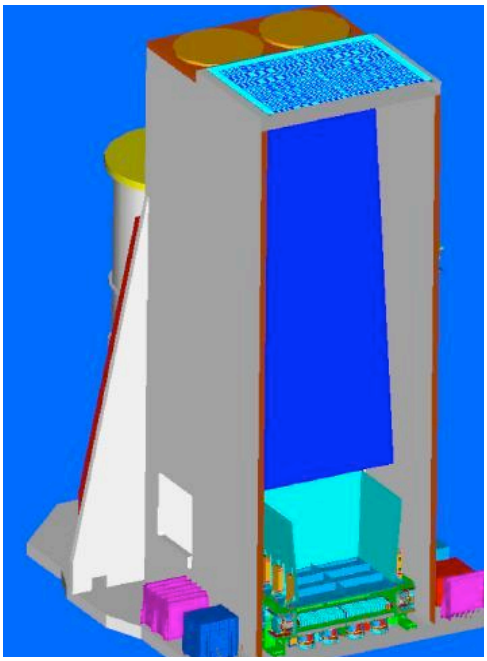
- one can make 'pseudo-imaging' telescopes using 'coded aperture masks' (shadowgrams) http://astrophysics.gsfc.nasa.gov/cai/
- Advantages- wide field of view, moderate angular resolution (~3') moderate sensitivity-works over a wide range in energy

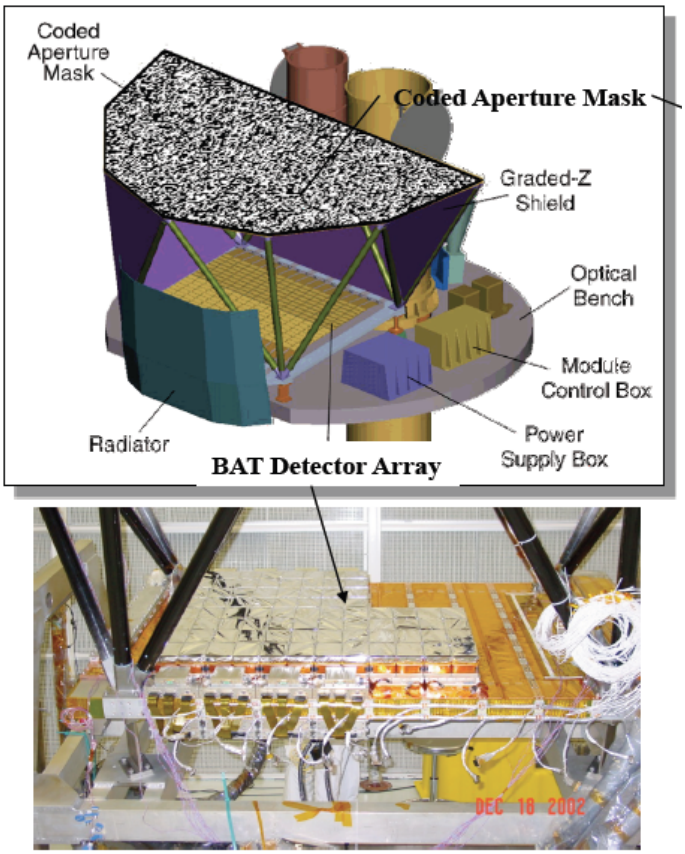


Used on INTEGRAL, Swift BAT- uses – Pixilated CdTe (e.g. BAT and Integral) BAT has BAT 32,000 CZT Detectors

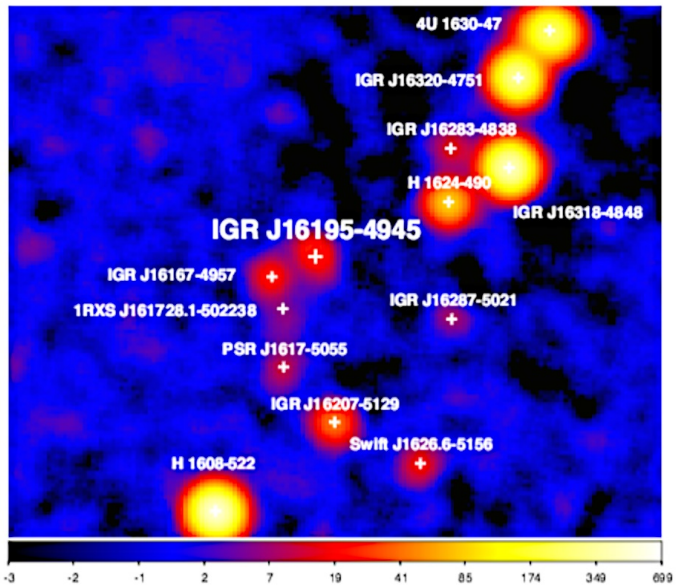


IBIS Instrument on Integral Satellite and BAT on Swift





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 signifigance

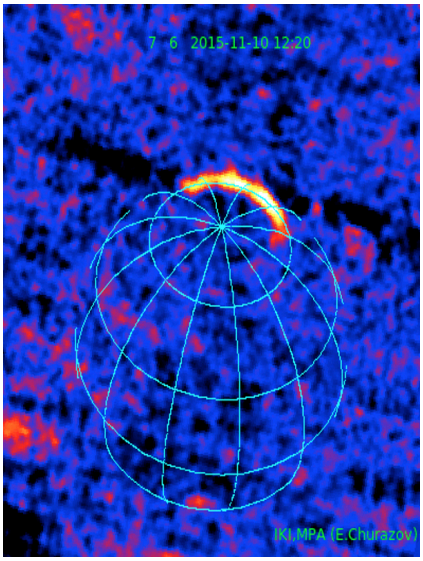


image of the high energy radiation produced by earth's aurora, charged particles from the sun that hit the earth's magnetic field and rapidly decelerate. The earth itself emits no high-energy emission

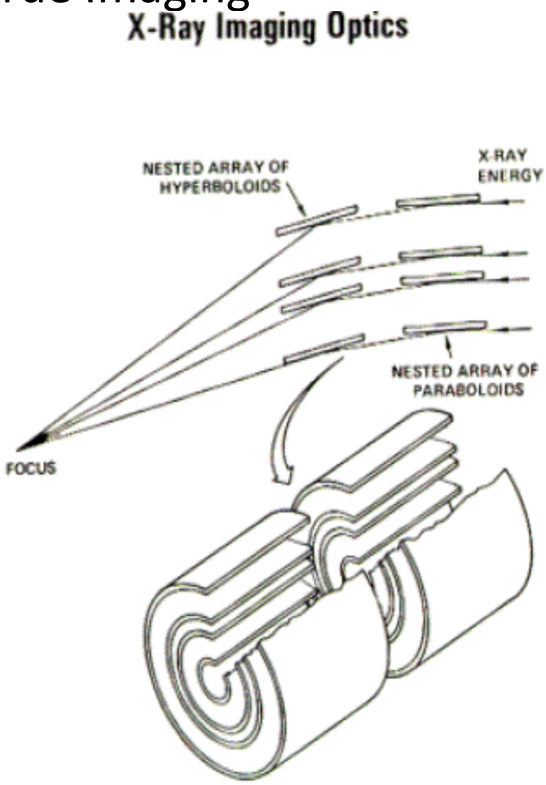
X-ray Telescopes- True Imaging

- 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

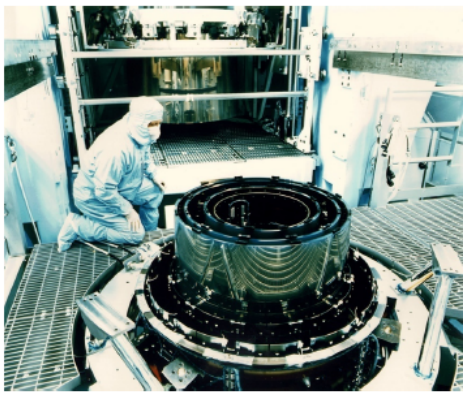
How to make the x-rays reflect and focus

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



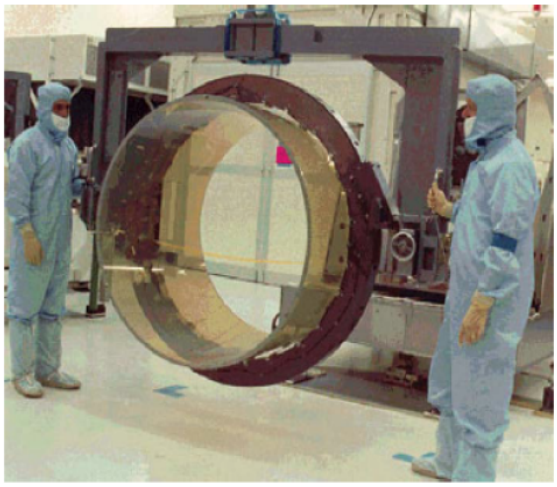
Chandra

- 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

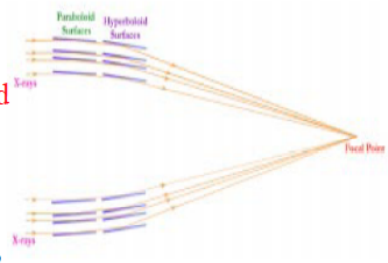
X-Ray Reflection: Zero Order Principles:

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

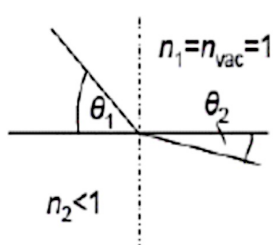


X-rays reflect at small grazing angles.

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, $\phi_i = \phi_0$.

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

Reflecting surface should be a heavy metal

Ni,Au and Pt have been used

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

X-ray optical constants

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

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

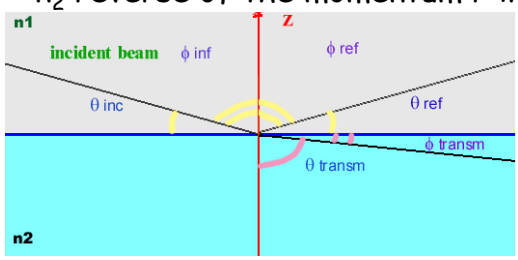
$(\mu = 4\pi\beta/\lambda \;\; cm^{-1})$

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 amplitude of reflection is described by Fresnel's equations:

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

Grazing Incidence (Aschenbach 1984)

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

  $nr = 1 - \delta < 1$,

- 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 $\delta \sim (re/2\pi)(N_0\, \rho/A)Z\lambda^2$ where N_0 is Avogadro's number, r_e is the classical electron radius, Z and Aare the atomic number and weight, respectively, and ρ is the mass density.

- For heavy elements for which Z/A≈0.5, the incidence angle of total reflection for $\delta << 1$ is
- $\alpha_t = 5.6\lambda\sqrt{\rho}$– high energies short λ ; α_t in arcmin, λ in Å and ρ in g/cm^3.
- **high density materials Au, Pt, Ir are best for reflection coatings**

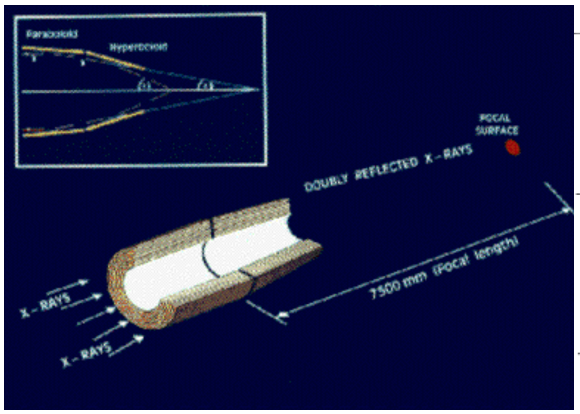
- F= focal length = R / tan 4θ
  - θ= *on-axis incidence angle*
  - *R = aperture radius*

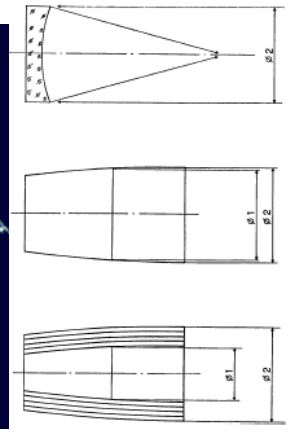
Wolter I mirror

• minimum focal length for a given aperture

• it allows the nesting together of many confocal mirror shells

• Effective Area: **8 π F L θ² ε**



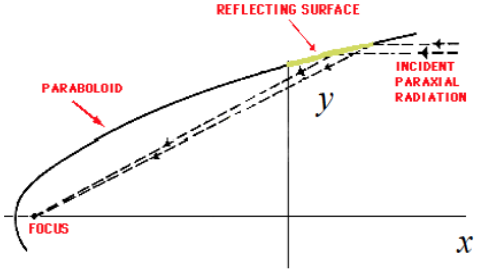


$$S_V = \frac{\pi \phi_2^2}{4}$$

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

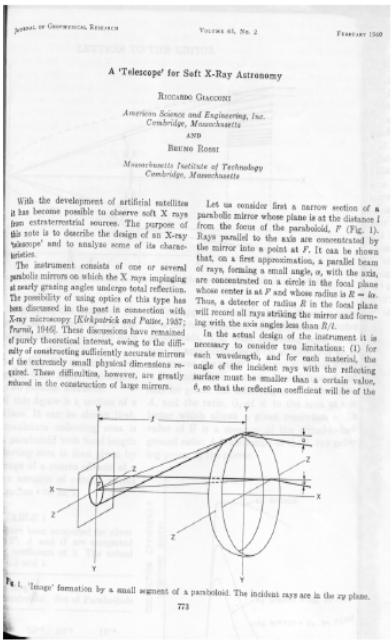
$$S_X = \frac{\pi (\phi_2 - \phi_1)^2}{4}$$

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**

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

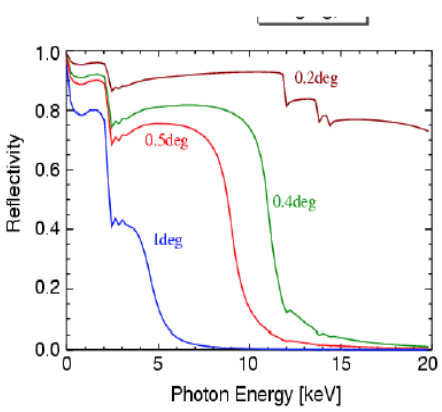
- telescopes optimized for the low-energy regime (<2 keV) have lower f values (are faster- better for surface brightness)

- 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

Long Focal Length

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



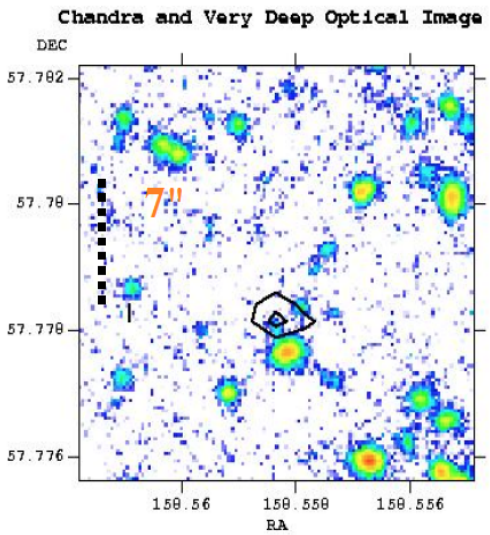
Reflectivity for Gold

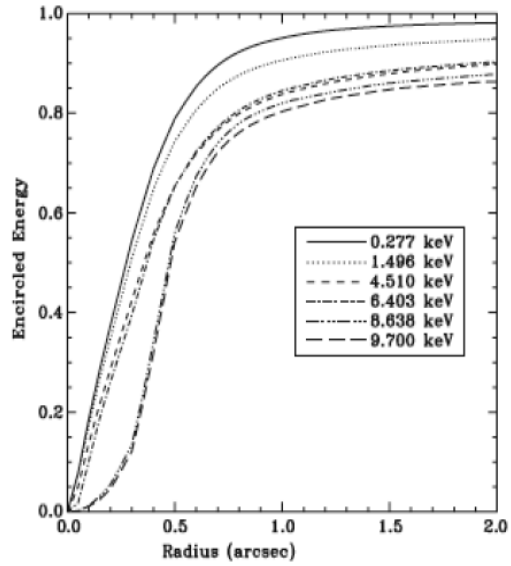
X-rays: Total reflection only works in the soft X-rays and only under grazing incidence
⟹ grazing incidence optics.

angle at which x-ray is reflected

Can Get Pretty Good Images

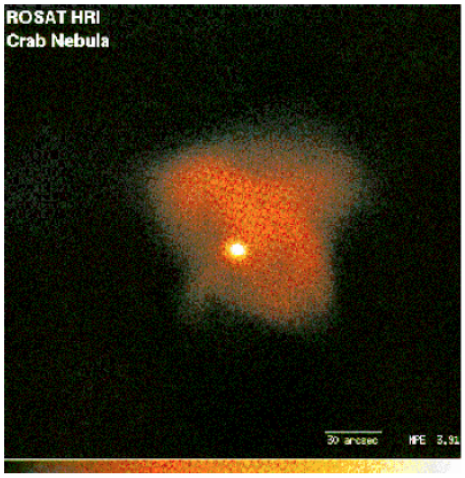
- Chandra Images are as good as the best images that can be obtained from the ground

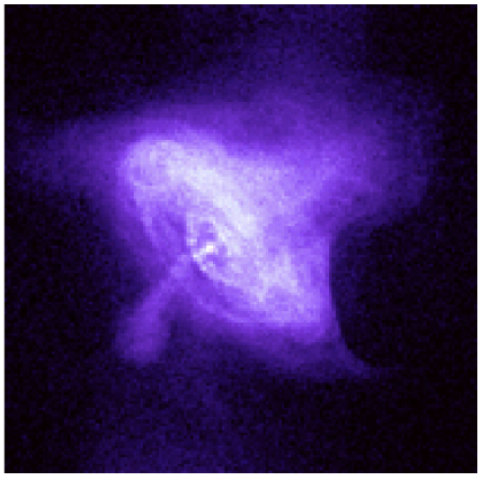




Chandra- fraction of energy inside an inscribed circle on axis

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





Rosat: HPD = 3 arcsec

Chandra: HPD = 0.5 arcsec

Mirror Collecting Area

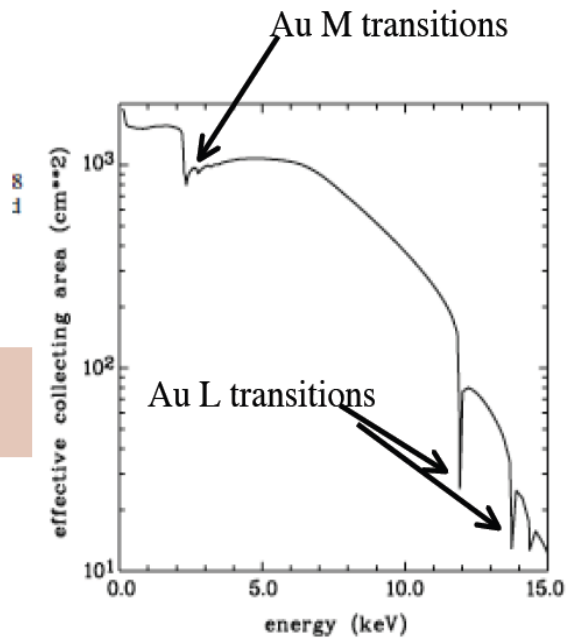
- Depends on mirror diameter, number of shells, focal length and coating of mirror (e.g. which metal coats the substrate)
- XMM mirror- the 'bumps and wiggles' are due to the atomic transitions of gold (the coating material)

- 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 $\sigma \sim \lambda$

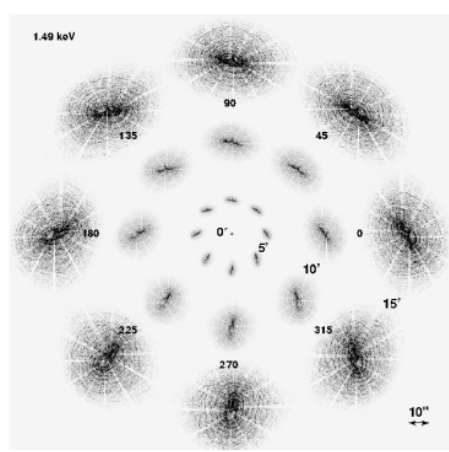
If want <10% scattered at 10A with α=1deg σ<9A



Some Issues

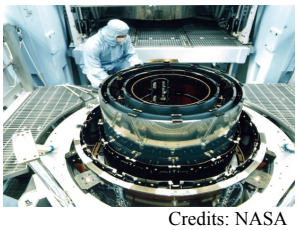
- The reflecting surfaces have to be very smooth- if they are rougher than the wavelength the photons hit 'mountains' and scatter (not reflect)
- A 'Wolter type I' optic focuses 'perfectly' at the center of the field of view
  - off axis the angular resolution degrades-due to coma aberration, astigmatism 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

Manufacturing techniques utilized so far


Credits: NASA

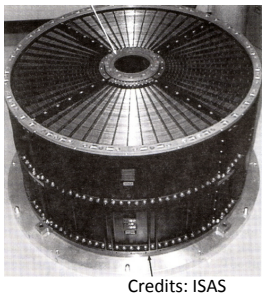
1. Classical precision optical polishing and grinding

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

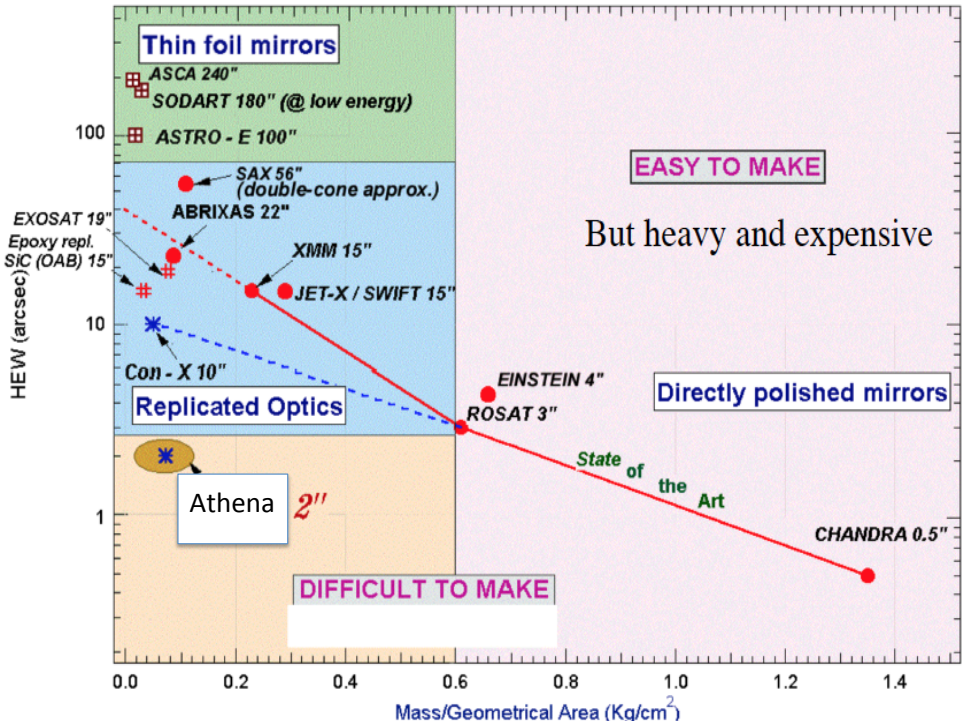
3. "Thin foil mirrors"

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)*

from Pareschi 2008

Present Astronomical optics technologies: HEW Vs Mass/geometrical area

from Pareschi 2008

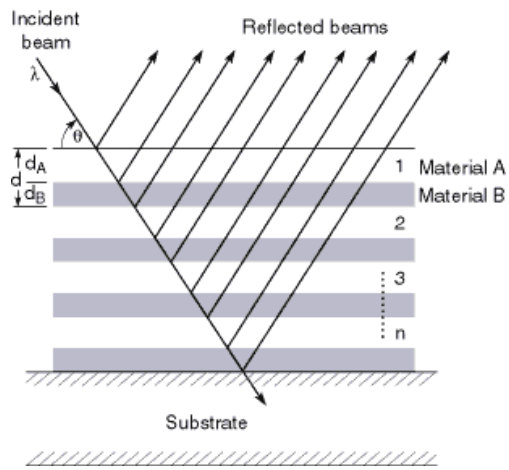


Multilayer Reflection- D. Schwartz

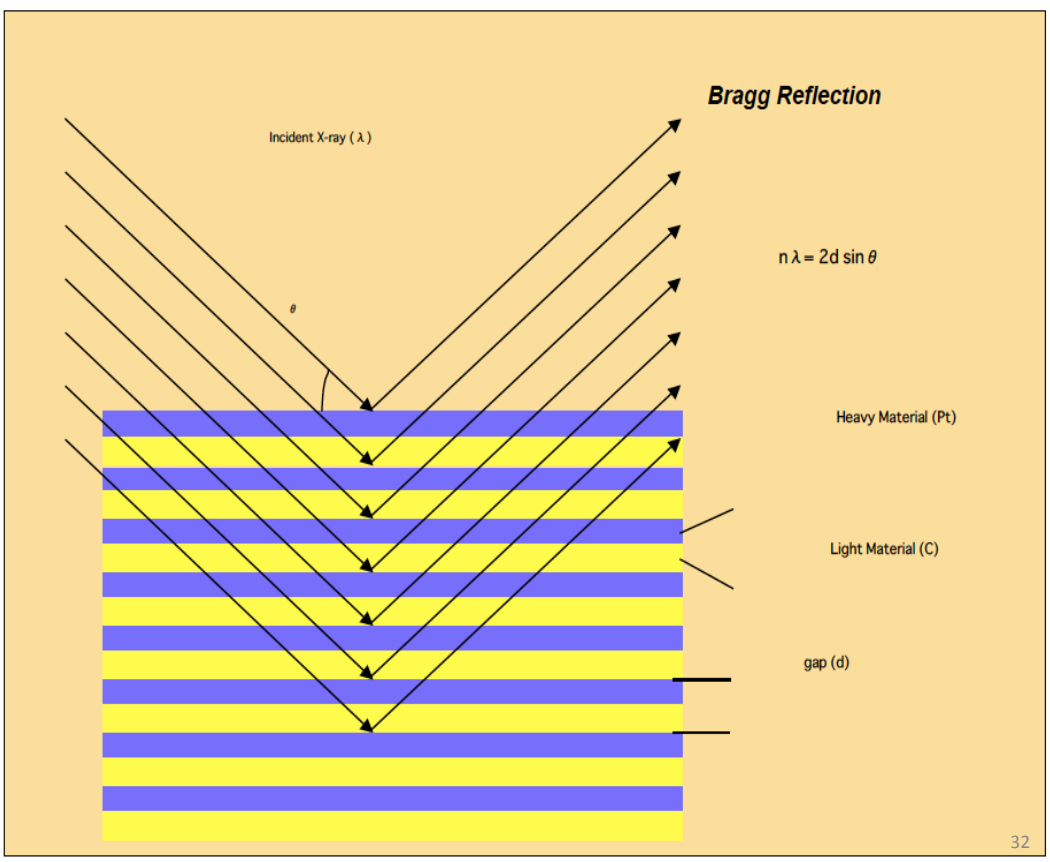
- Underwood, J.2001, X-ray data
- booklet, sect. 4.1 (http://xdb.lbl.gov)
- Near normal incidence, reflectivity of soft X-rays is ~ 10^{-4} because the X-rays penetratethe material until they are absorbed.
- BUT 10_{-4} reflectivity means a reflected amplitude of 10^{-2}

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**

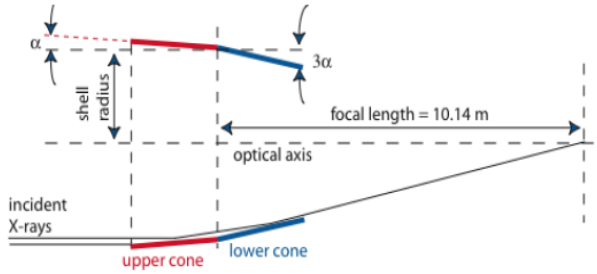


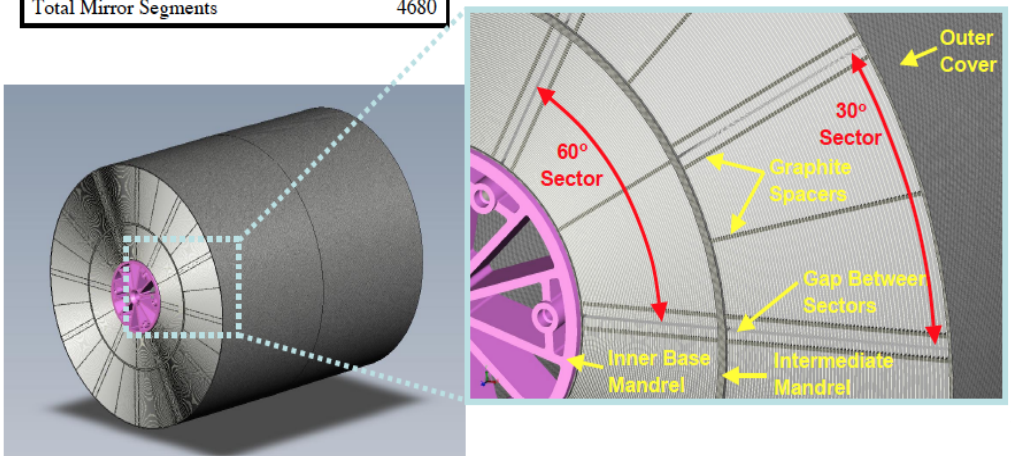
built for NuStar and Astro-H



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





Astro-H Hard X-ray Telescope

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)