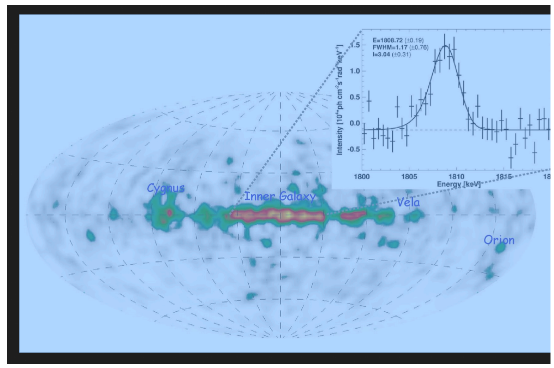
Gamma-Ray Spectroscopy Longair Sec 10.3

- Two types of nuclear processes producing γ -ray lines in astronomical sources:
  - the decay of radioactive species created in the processes of nucleosynthesis (e.g. ^{26}Al (1809 keV) and ^{60}Fe (see Diehl et al Nature 0601015.pdf and New Astron.Rev. 50 (2006) 534-539)
  - two main scenarios of planetary systems' formation: high-26Al systems, like our solar system, form small, water-depleted planets, whereas those devoid of ^{26}Al predominantly form ocean worlds arXiv:1902.04026 today

^{26}Al half life $T_{1/2}$~$7.2x10^5$ yrs created in SN

^{26}Al gamma-rays represent the massive star population

the amount of ^{26}Al, corresponds to a rate of supernovae from massive stars (i.e. "Types Ib/c and II") of two per100 years.



How Does One Obtain Spectral +Imaging Data

- What we observe depends on the instruments that one observes with !
- In x and γ-ray spectroscopy there are a wide variety of instruments with different properties
- In both fields one is driven by rather low fluxes (count rates) compared to radio-UV data and so <u>high quantum efficiency is a major goal</u>

γ-ray spectroscopy is dominated by continuum processes (lines are rare) the main stress is on broad band pass and high quantum efficiency

In the x-ray band there are numerous atomic transitions and so one wants good energy (wavelength) resolution in addition

- Another major difference from other energy bands is that many x-ray spectrometers are imaging, photon counting devices

- Thus one almost always get a 3d data 'cube' (e.g. every spatial element has spectral and timing data).

(As for any other energy band the properties of the telescopes are also very important)

see http://pulsar.sternwarte.uni-erlangen.de/wilms/teach/xray1 xray1chap3toc.html

Lots of 'Historical' Detectors

- Historically much of x-ray astronomy was performed with
  - Proportional counters
  - Imaging proportional counters
  - Channel plates
  - Scintillators
  - Etc etc

  - Most of these are not anticipated for use in future missions but some (Channel plates, scintillators in use today)

http://astronomy.nmsu.edu/tharriso/ast536/ast536week8.html

Recent High Energy Satellites- Basic Properties

Chandra (US)	High angular and high spectral resolution 0.3-8 keV - most sensitive
XMM **(ESA)**	High throughput and high spectral resolution 0.3-10 keV, best for x-ray spectra
Swift (US)	γ-ray bursts, hard x-ray survey, UV and x-ray flexible operations, wide field of view
*RXTE (US) **	x-ray timing best for x-ray timing of bright sources
Suzaku(Japan/US)	broad band x-ray imaging and timing
Integral **(ESA)**	hard x-ray imaging and timing
Fermi (US)	γ-ray (E>100 MeV) very wide field of view
NuStar	Hard x-ray (5-50 keV) imaging
Hitomi (Japan/US	X-ray calorimeter RIP
Nicer	X-ray Timing

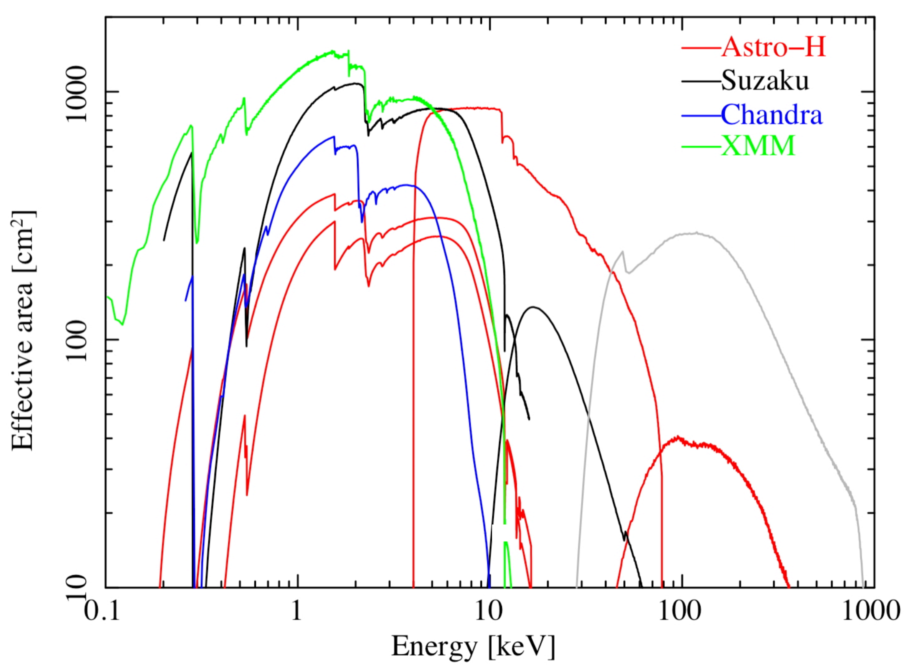
*RXTE, Hitomi, Suzaku are no longer operating

Historical X-ray Telescopes (see https://heasarc.gsfc.nasa.gov/)

- Skylab 42 cm^2 ~2 arcsec 0.2–2 First x-ray telescope; (1975) area) **solar** observations
- Einstein ~200 cm^2 at 1 keV 0.2–4.5keV First telescope observatory; discovered 7000+ sources 2.5 years of operation
- ROSAT 400cm^2 at 1 keV ~9 years of op's 0.1–2.4 4 Au coated Zerodur shells; (1990) discovered 150 000+ sources 5" angular resolution
- ASCA 1300 cm^2 at 1 keV, 174 0.5–10 Conical foil Al mirrors, (1993) 600cm^2 at 7 keV Au coat over lacquer, 4 separate telescopes 3' angular resolution- 7 years of ops
- BeppoSAX 330 cm^2 at 1 keV 60 0.1–10 Nickel-replicated conical (1996) optics, 30 nested shells- 6 years of ops
- Chandra 800 cm^2 at 1 keV 0.5" 0.1–10 Highest resolution, 4 shell Zerodor s, (1999) largest mirror 1.2 m diameter, transmission gratings
- XMM 4650 cm^2 at 1 keV, Nickel replicas, (1999) 1800cm^2 at 8 keV 3 telescopes, 58 shells each, reflection gratings
- Suzaku (2006) 4 x-ray telescopes, foil optics CCDs 10 years, microcalorimeter (failed due to spacecraft design error)- hard x-ray detector.

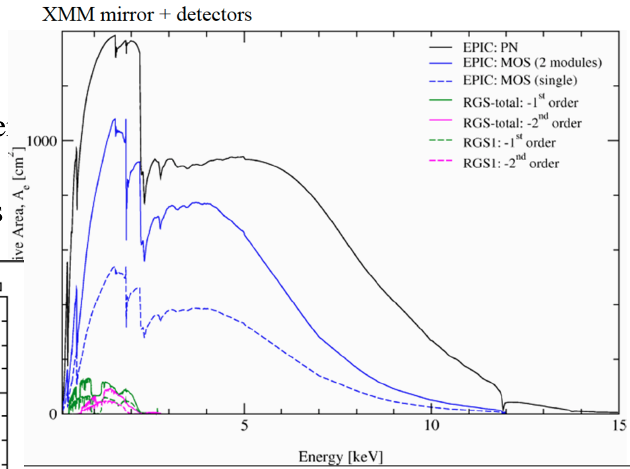
Collecting Area of X-ray Spectrometers

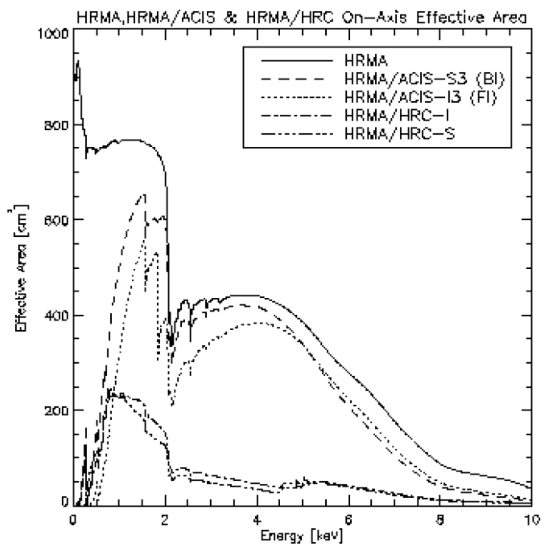
Notice area <1000cm^2 (14" telescope)



2 Examples

- XMM- Has 3 telescopes +3 image + 2 gratings
- Chandra has 3 imagers + 3 gratings





HRMA= x-ray telescope
each line represents one of the Chandra imagers

Proportional Counters Imaging or Otherwise (Uhuru, Heao-1, Einstein, Rosat, RXTE)

- X-ray proportional counters consist of a windowed gas cell, subdivided into a number of low- and high-electric field regions by an arrangement of electrodes.
- The signals induced on these electrodes provide the energies, arrival times, and positions of the photons.
- X-rays interact with gas molecules via the photoelectric effect, with the immediate release of a primary photo-electron, followed by a cascade of Auger electrons and/or fluorescent photons.

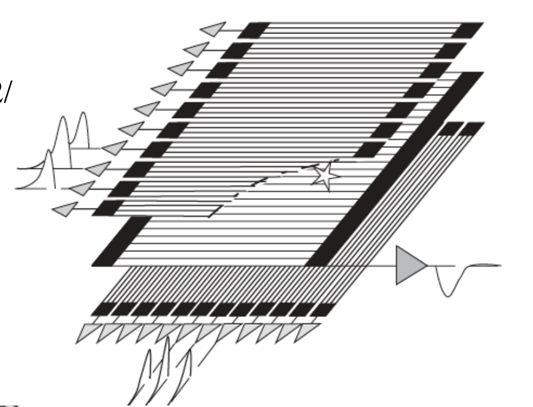
Photons deposit all of their energy within a short distance within the detector, so that only one cell is activated.

A charged particle ionizes the gas through collisions, hence leaving a trail of ionized particles through more than one cell.

The intrinsic timing resolution is ~ microsecond level.

Nobel Prize - Charpak 1992

https://www.nobelprize.org/prizes/physics/1992/charpak/facts/



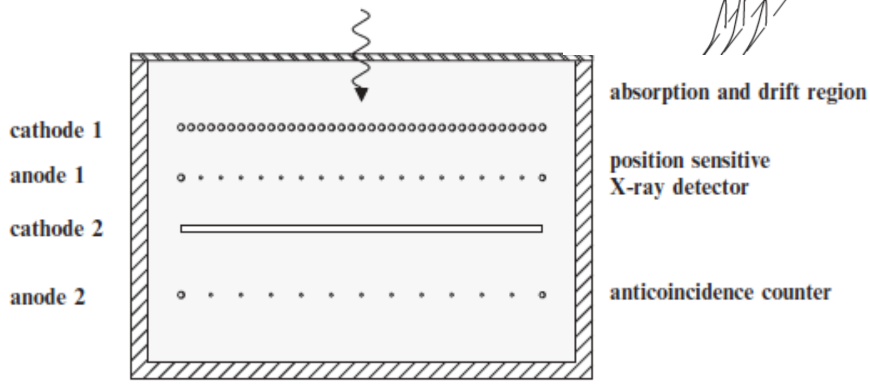
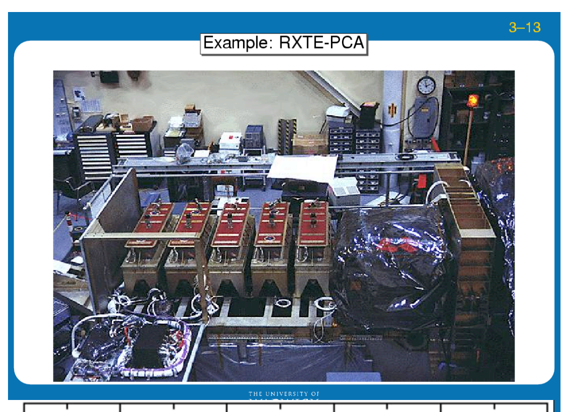


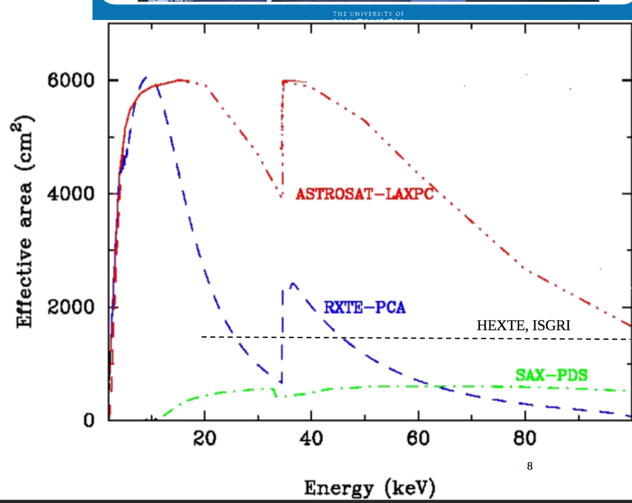
Fig. 4.1 Multiwire proportional counter for X-ray astronomy

Proportional Counters

- Advantages
  - can be very large
  - robust
  - low background
  - can cover wide energy range (0.1-60 keV)
  - fast timing
  - not sensitive to radiation damage
- Drawbacks
  - low spatial and spectral resolution

http://pulsar.sternwarte.uni-erlangen.de/wilms/teach/astrospace/space0056.html





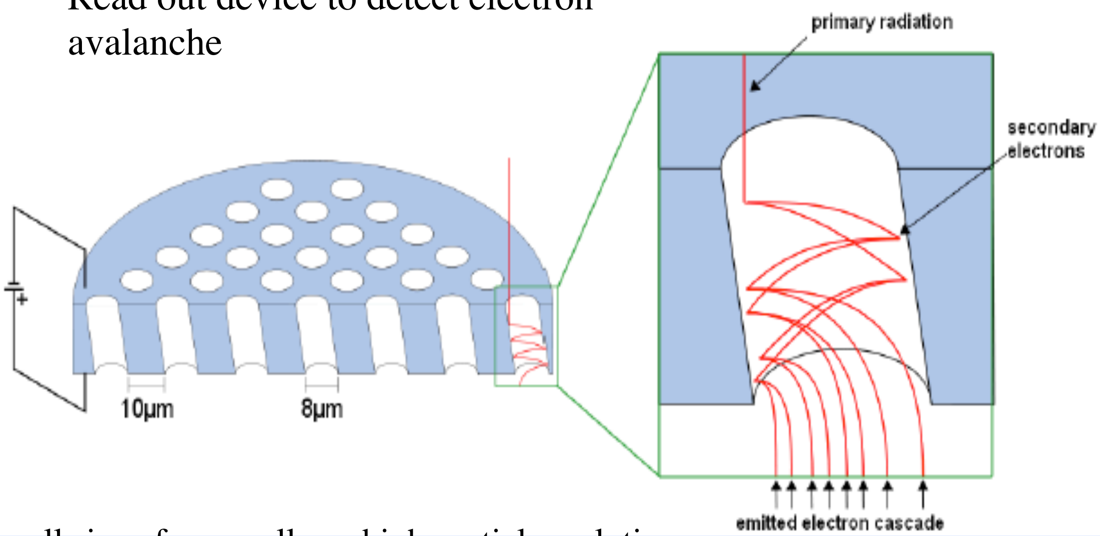
Microchannel plate (MCP)

Used on Galex, XMM optical monitor, Einstein, Rosat ,Chandra HRI

Electron avalanche is excited at the semiconducter walls

Emitted charge is **NOT** proportional to deposited energy

Read out device to detect electron avalanche



Small size of pores allows high spatial resolution

X-ray CCD

2009 Nobel Prize in Physics

- An x-ray photon is absorbed in the silicon of the CCD, producing multiple electron-hole pairs
- If this absorption occurs within the depletion region of the CCD, the electrons and holes are separated by the internal electric field, with the holes rapidly undergoing recombination while the electrons are 'trapped' in the pixel until being read-out

7 October 2009—Willard Boyle and George Smith, formerly of Bell Telephone Laboratories, in Murray Hill, N.J., shared half of the Nobel Prize in Physics "for the invention of an imaging semiconductor circuit-the CCD," the basis for digital imagery in everything from mobile phones to the Hubble Space Telescope.

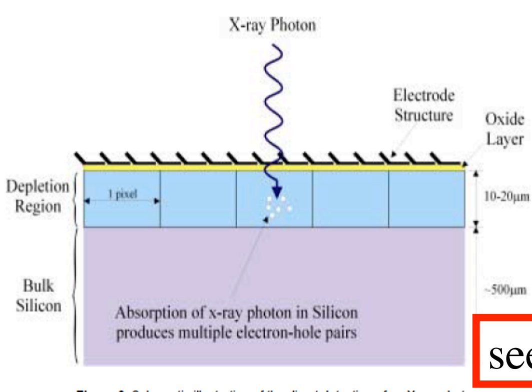


Figure 3: Schematic illustration of the direct detection of an X-ray photon.

www.lot-oriel.com/site/site_down/cc_notesxray_deen.pdf

see grant_ccds.pdf -class web pag

CCD Basic Physics

- In a semi-conductor there is an energy separation between the valence and conducting band of ~1 eV (energy of optical photon)- optical CCD
- Absorption of photons produces hole-electron pairs proportional to energy of photons (if rate is slow enough)- it takes 3.65 eV to create a hole-electron pair in Si x-ray CCD
  - 6 keV photon would create typically1640 electrons per X-ray interaction (as compared to only one electron per optical photon interaction).
- $N \sim h\nu/E_{gap} \sim 1$ for optical photon, ~300 for 1 kev x-ray
  - thus optical CCDs measure intensity, BUT x-ray CCDs measure individual photons

CCD = Charge--coupled device

- An array of linked ("coupled") capacitors
- Photons interact in a semiconductor substrate (usually silicon) and are converted into electron--hole pairs
- Applied electric field used to collect charge carriers (usually electrons) and store them in pixels
- Pixels are "coupled" and can transfer their stored charge to neighboring pixels
- Stored charge is transferred to a readout amplifier
- At readout amplifier, charge is sensed and digitized
- the detectors have to be 'cold' (T<-60C) to work- otherwise the electronic noise is too large
- X-ray CCDs single photon count: e.g. detect the charge deposited by one photon- thus the readout time has to be less than the anticipated rate to get more than one photon per pixel per readout time- otherwise get 'pile-up'

X-ray CCDs

- Modern detectors have 2048x2048 pixels, Size ~25μ

On Chandra/XMM the cameras have multiple CCD chips to cover a ~20' FOV

Timing resolution depends on mode but is typically a few secs-readout time of detector.

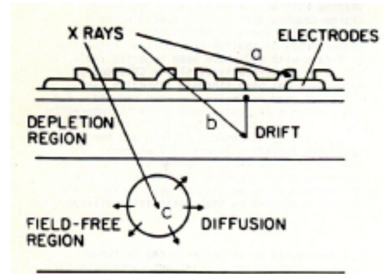
Quantum efficiency is set by physics

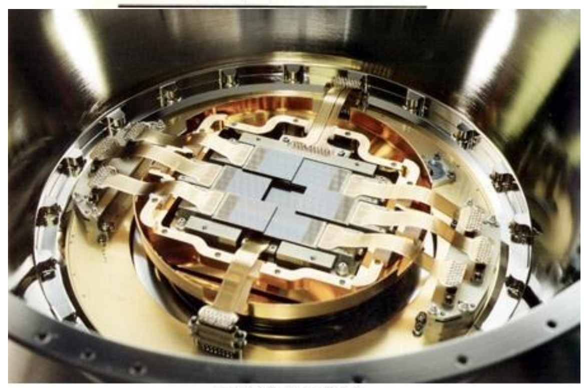
'dead' layer controls low E efficiency

Si thickness and photo-electron cross section high E efficiency

Typical devices operate in the 0.3-12 keV band (lowest energy set by electronic noise and absorption by UV blocking filters-highest energy set by how thick the Si can be and still recover charge)

Have very low background (Chandra 1 count/pixel/day)





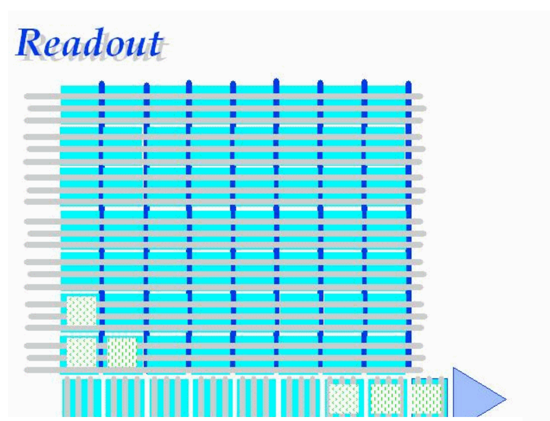
EPIC-MOS CCDs

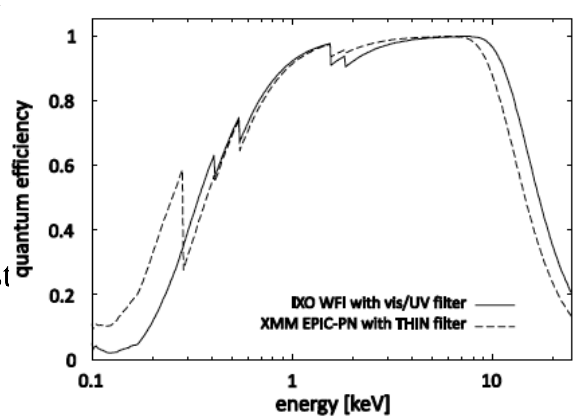
Image courtesy of Leicester University, University of Birmingham, CEA Service d'Astrophysique Saclay

European Space Agency

CCDs

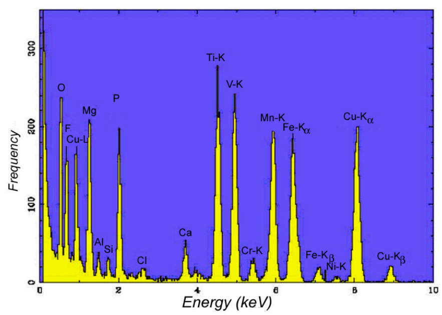
- X-ray CCD is fundamentally different from optical devices-
- Each photon generates charge (typically 1 e- per 3.7 ev of energy) Charge is 'read out' by shifting it from pixel to pixel until it reaches the readout register.
- Goal is to measure the amount of charge ~energy of incoming photon
- Which pixel it landed in (spatial resolution)
- And when it landed (timing info)
- Time resolution is set by how fast one can read it out- (power and electronics)



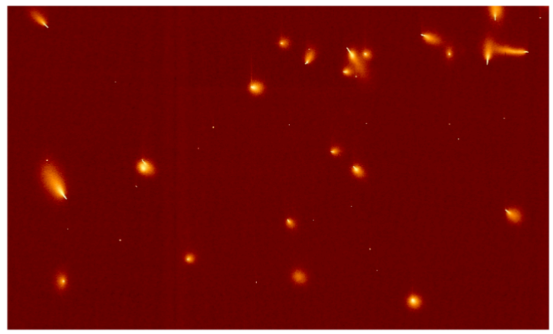


CCD Operation

- X-ray CCDs operated in photon-counting mode
- Spectroscopy requires ≤ 1 photon interaction per pixel per frametime
- Minimum frametime limited by readout rate
- Tradeoff between increasing readout rate and noise
- For Chandra, 100 kHz readout ⇒ 3.2 s frametime
- Frametime can be reduced by reading out subarrays
- Raw CCD frames must be processed on-board to find X-ray events and reject background



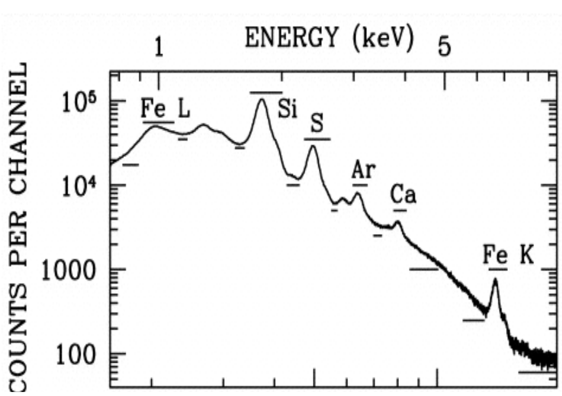
24.6: X-ray spectrum from a variety of elemental fluorescence lines



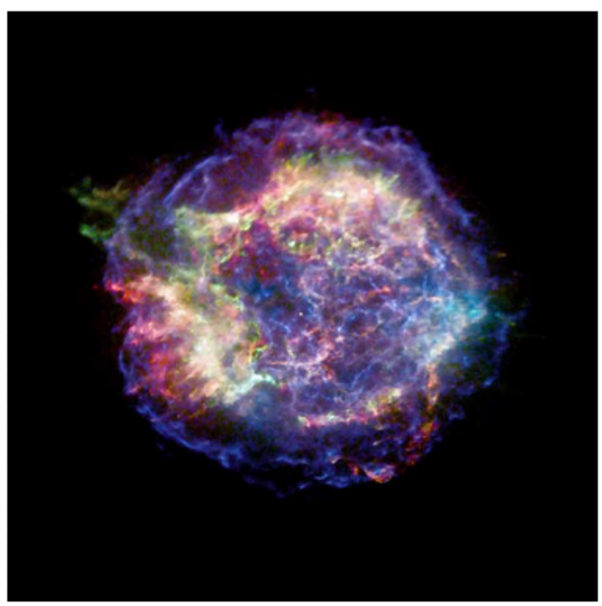
Blobs/streaks - charged particles. Small dots - X-ray events.

What Sort of Results from CCDs

- Chandra CCD image of a supernova remnant (Cas-A)-
- The color code is energy- blue is high, green is medium, red is low



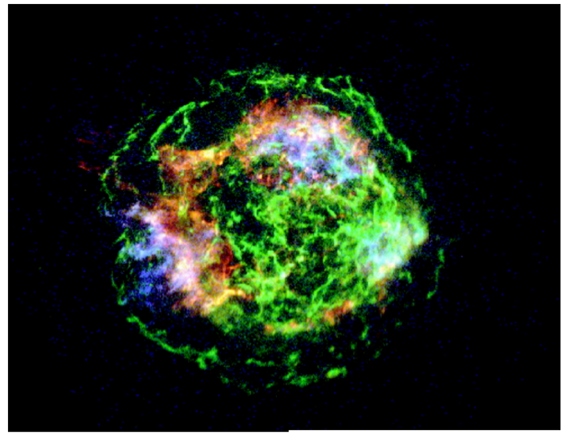
Lines from abundant elements have characteristic energies

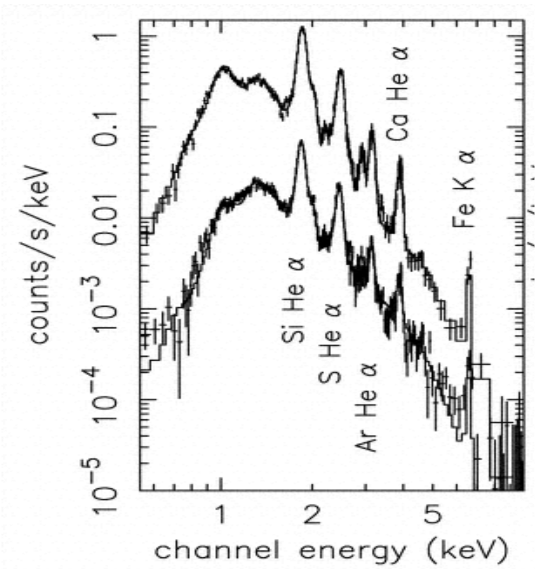


Credit: NASA/CXC/SAO/D.Patnaude et al.

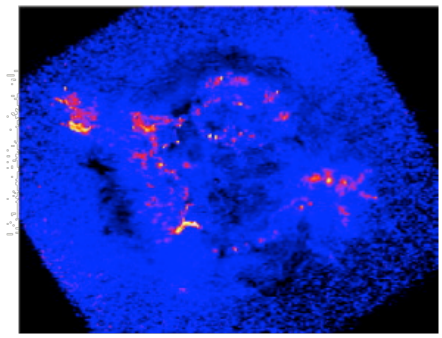
An Elemental Map of Cas-A- Exploded in ~1670 But not seen

- Red=He-like Si, blue=Fe complex; green= very hot gas
- Bottom right- ratio of Si to Fe





Spectrum of 2 regions in SNR

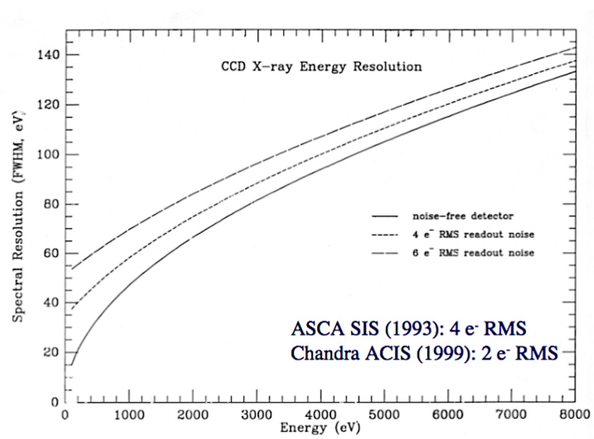


- Photoelectric interaction of a single X-ray photon with a Si atom produces "free" electrons:
- Spectral resolution depends on CCD readout noise and physics of secondary ionization:
- Need good charge collection and transfer efficiencies at very low signal levels–Low readout and dark-current noise (low operating temperature)

$N_e=E_X/w$ ($w\approx3.7$ eV/e−)

$\sigma_e^2=F\times Ne$ ($F\approx0.12$; not a Poisson process)

FWHM (eV)$=2.35\times w\times \text{sqrt}\,\sigma_e^2+\sigma^2_{read}$



CCDs- Pros and Cons

- Advantages
  - millions of of small pixels
  - 'good' energy resolution ($E/\Delta E \sim 50$ at 6 keV)
  - proven technology
  - low background
  - cover 0.1-12 keV
- Disadvantages
  - Need to cool to ~-90C
  - Slow readout- (e.g. ~100ms is best so far)
  - sensitive to radiation damage
  - 'low' maximum energy
  - sensitive to optical/UV light- need filter which reduces low E area

Types of Detectors/Spectrometers

- **Diffractive vs Non-diffractive Spectrometers**
  - **Diffractive Spectrometers: gratings, crystals**
  - **Non-diffractive spectrometers: CCD's, calorimeters**

- Non-diffractive spectrometers: convert energy of single photons into 'countable objects' (electrons, broken Cooper pairs, phonons)

•Example: Si CCD: ionization energy w, photon energy E:

#electrons $N = E/w$; variance on N: $\sigma^2 = FN$; F: Fano factor, < 1 (!!), so

$\Delta E/E = \Delta N/N = (wF/E)^{1/2}$

(Si: w = 3.7 eV, F = 0.12)

•Resolution ΔE, or resolving power $E/\Delta E$, slow function of E this is different to the case for absorption of visible / UV wavelengths which produce only one photoelectron per detected (i.e. absorbed) photon and thus have no energy resolution

Diffractive Spectrometers- Gratings

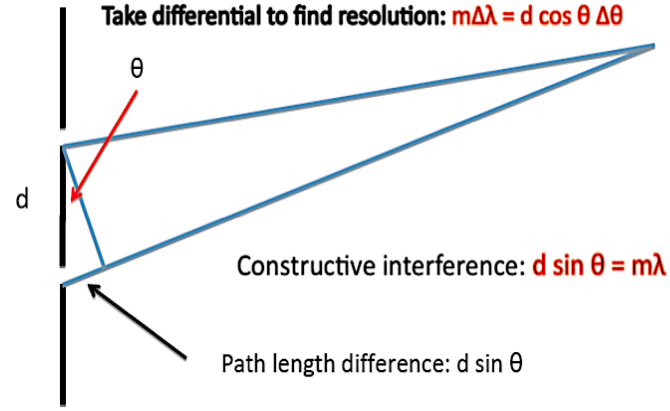
- Just like optical light, x-rays have a wave property and so can be diffracted
- The same wave equations- BUT the wavelength of x-rays is very small ~1-20Å and so there are great technical difficulties
  - Many of these have been solved and productive gratings were produced for Chandra and XMM

Diffractive spectrometers: constructive interference of light
cleverly chosen paths

Example: two slits:

Dispersion equation: $d \sin\theta = m\lambda$

Take differential to find resolution: $m\Delta\lambda = d \cos\theta\, \Delta\theta$



Resolving power: $\lambda/\Delta\lambda = \tan\theta/\Delta\theta \approx \theta/\Delta\theta$ (θ usually small)

'constant Δλ devices'

Spectrometer Complementarity

Non-Dispersive $E = h\nu$

Energy Standard (courtesy of nature)

IP, band gap, phonon energy…

$\delta E \sim$ eV

Instruments

- Prop Counters → IPC
- Gas Scint PC → IGSPC
- Si(Li) → CCD
- μCalorimeter
- STJ/TES

Properties

$\Delta E \sim$ fixed

Resolving Power = $E/\Delta E \sim E$

Dispersive $\lambda = c/\nu = hc/E$

Length Standard (courtesy of nature or engineering)

crystal lattice spacing (~ Å), grating period (~10^{2-3} Å)

$\delta x * \theta \sim$ 0.1-0.01 Å

Instruments

- Bragg spectrometers
- Transmission Gratings
- Reflection Gratings

Properties

$\Delta\lambda$~fixed

Resolving Power = $\lambda/\Delta\lambda \sim 1/E$

Canizares 2007

Chandra Gratings

Paerels and Kahn ARAA 41,291 2003

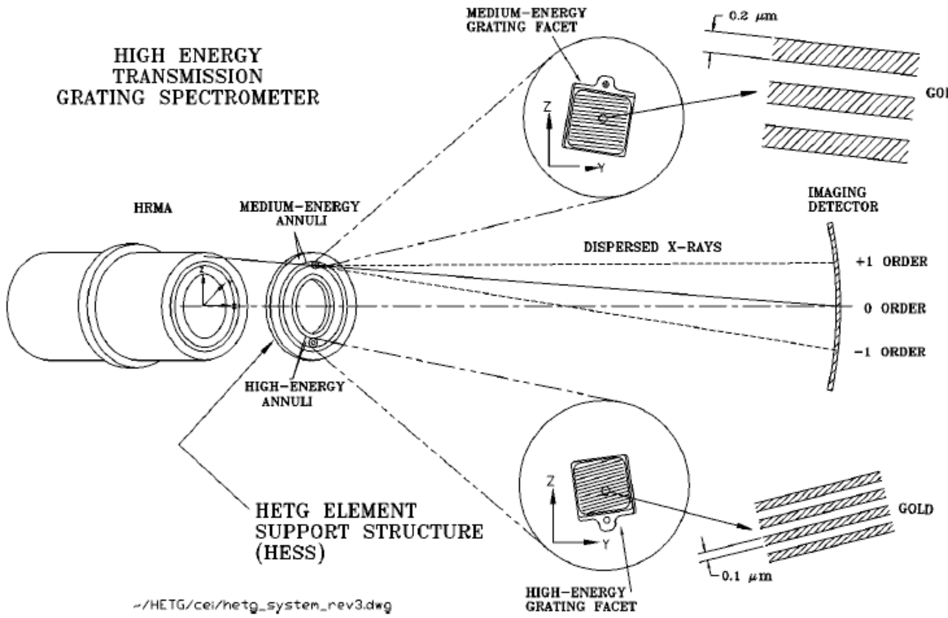
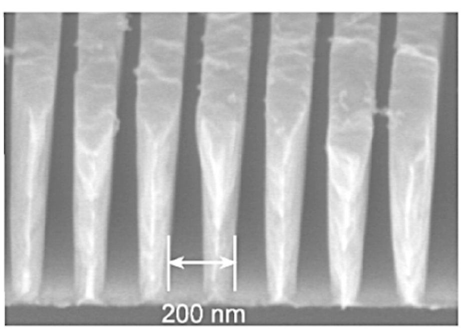
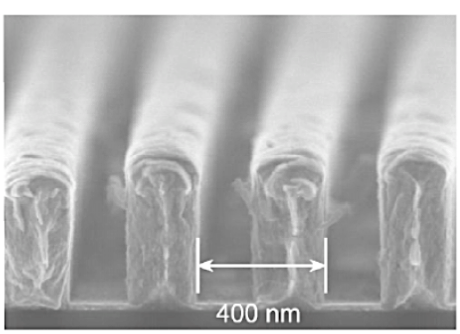


Figure 1 Geometry of the transmission grating spectrometers on *Chandra*.

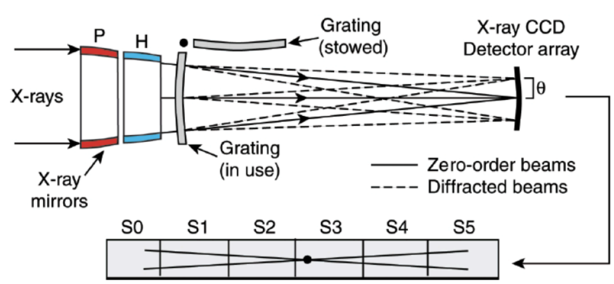
1. *Chandra* HETGS



(a) High Energy Grating (HEG).



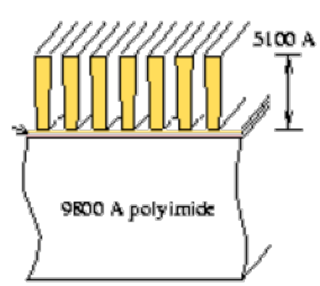
b) Medium Energy Grating (MEG).



Claude Canizares et al., *Publ. Astron. Soc. Pac.*, **117**, 1144 (2005)

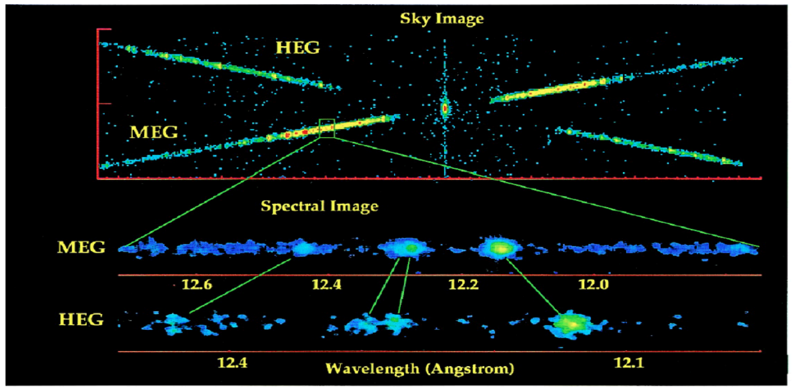
Dispersion equation: $\sin\theta = m\lambda/d$ (θ: dispersion angle, d: grating period, m: spectral order

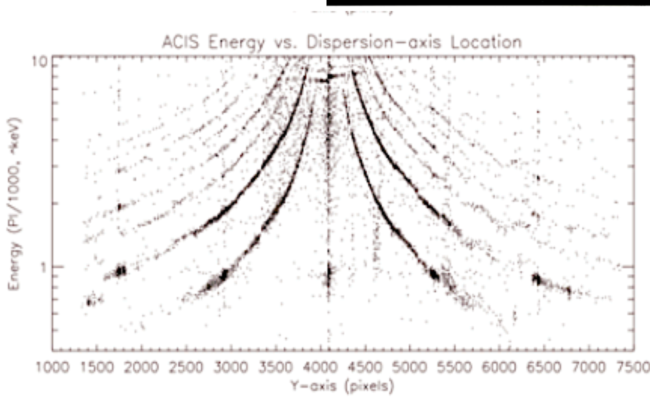
Spectral resolution: $\Delta\lambda = (d/m)\cos\theta\,\Delta\theta \cong (d/m)\Delta\theta$: dominated by telescope image (Δθ)



What the Data Look Like

Solution to need for broad band is three gratings HEG,MEG,LETG



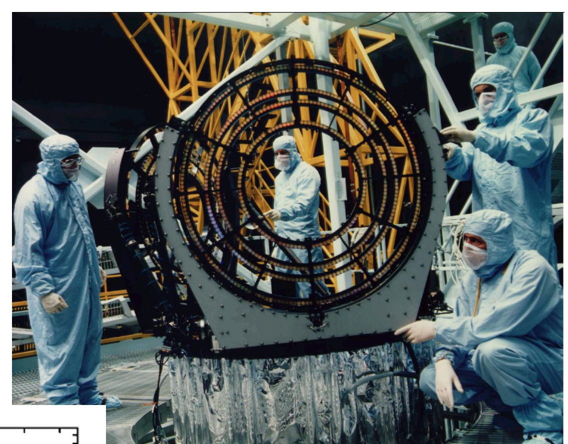


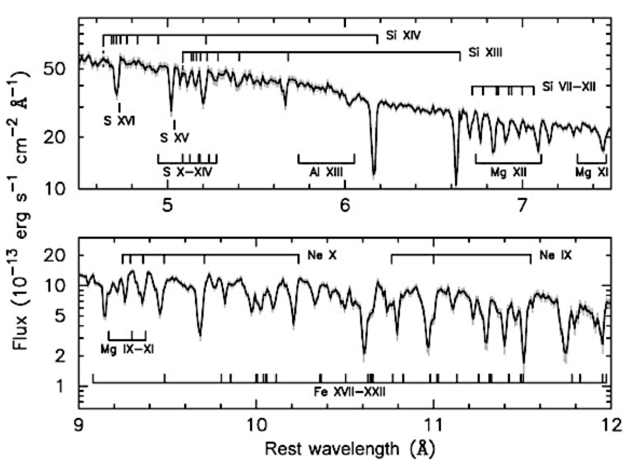
CCD/dispersion diagram ('banana')
NB: CCD energy resolution sufficient to separate spectral orders (m = ±1,±2, ...)

- Position and wavelength are linearly related- have overlapping orders that are separated by the energy resolution of the readout detector (a CCD)

Chandra gratings

- Gratings have overlapping orders- uses energy resolution of CCD readout to separate them.
- Chandra gratings are good for point-like and small sources

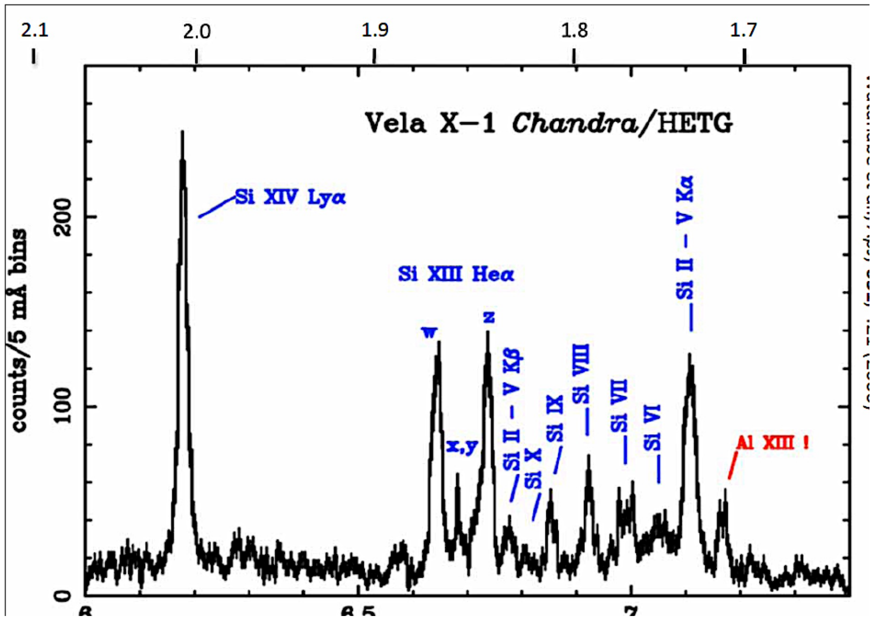




Very accurate wavelength scale: $\Delta v/c \sim 1/10{,}000$!

However small collecting area! typical exposure for AGN >100ks

See tgcat.mit.edu for processed data



Spectrum of x-ray binary in eclipse

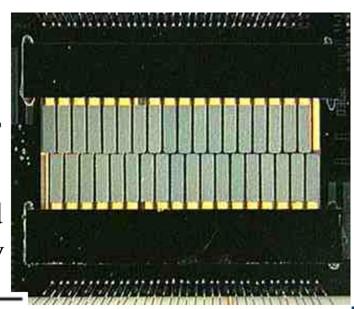
Calorimeter

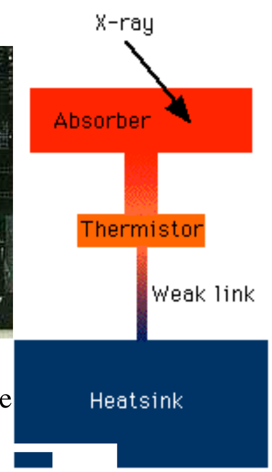
Single-photon calorimeters-Absorb a photon and measure the increase in T

- Work best at low T (60 milli-K), where thermal noise is low compared to the signal and heat capacity is very low .

$$\Delta E \sim \sqrt{(kT_b^2 C_b)} / |\alpha|$$

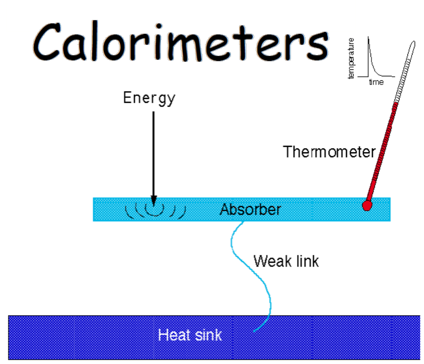
- Energy sensitivity very good because generate many phonons for each absorption.
- Energy range can be ~arbitrary devices have been optimized for the : 100 eV – 10 keV band
- Achieved energy resolution: 2.4eV
- Can be imaging, high quantum efficiency
- Physics Today, August 1999, pp 32-37.
- McCammon 2005 Cryogenic Particle Detection





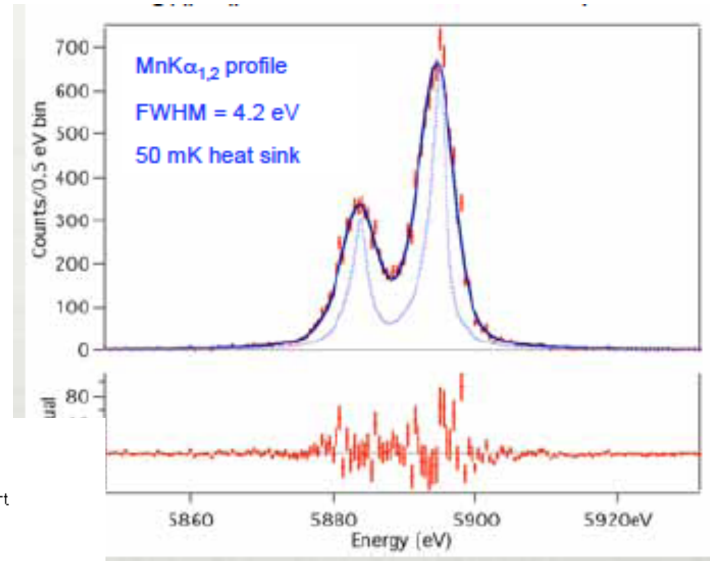
T_b=operating temperature

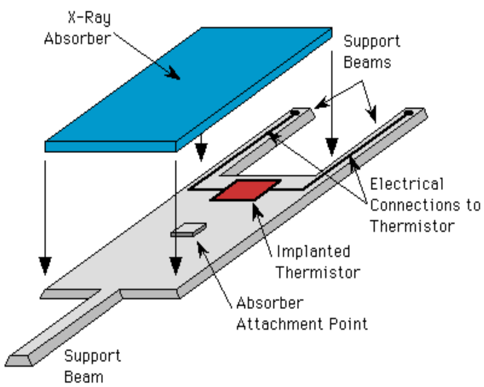
C_b=heat capacity



Calorimeter

- Lots of interesting physics and engineering (how to keep a detector at 60mK for long times)





Flew on Astro-H/Hitomi launched in Feb 2016 ! see Kelly et al 2016SPIE.9905E..0VK
Flown on several rocket flights

Calorimeter

- Major Challenge is the need to be very cold (dewar) - the cooling system regulates the detector temperature to 50mk with a 2μK rms
- The cooling chain is a 3-stage Adiabatic Demagnetization Refrigerator (ADR), superfluid liquid^{4}He , a ^{4}He Joule-Thomson (JT) cryocooler, and two-stage Stirling cryocoolers.

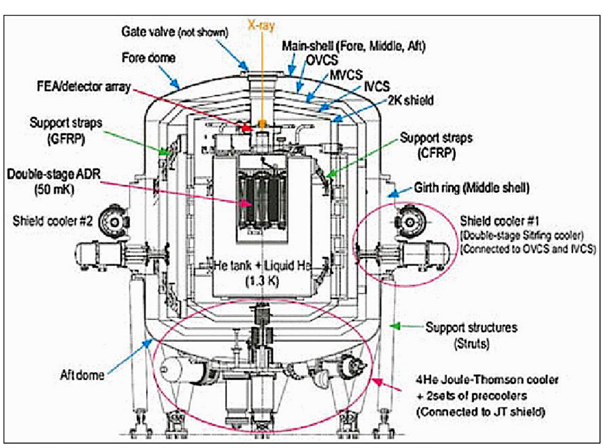
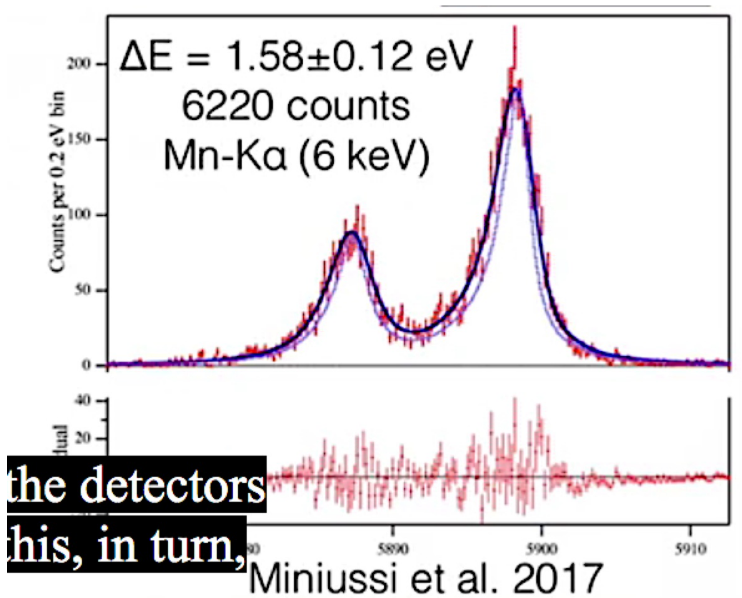


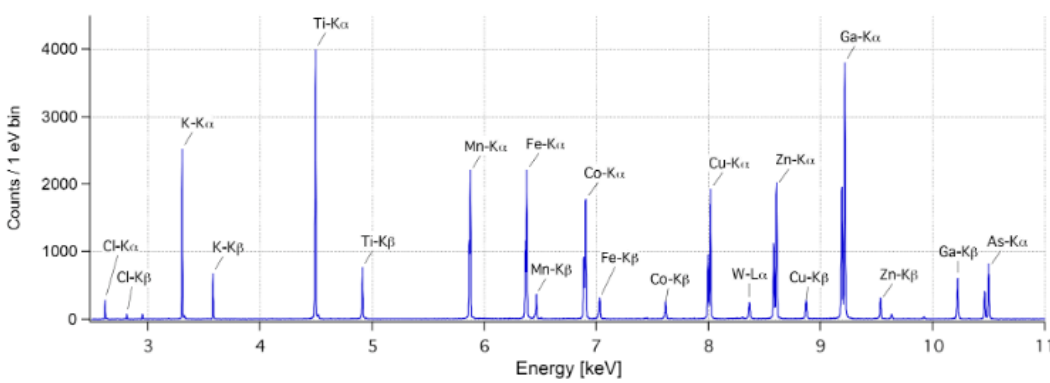
Figure 20: Cross-sectional view of the SXS Dewar (image credit: JAXA/ISAS)

Hitomi Cooler/Dewar

Best Performance...so far

- E/ΔE~3700 , 1024 pixels
  tested in lab
- Athena plans for 3840 pixels

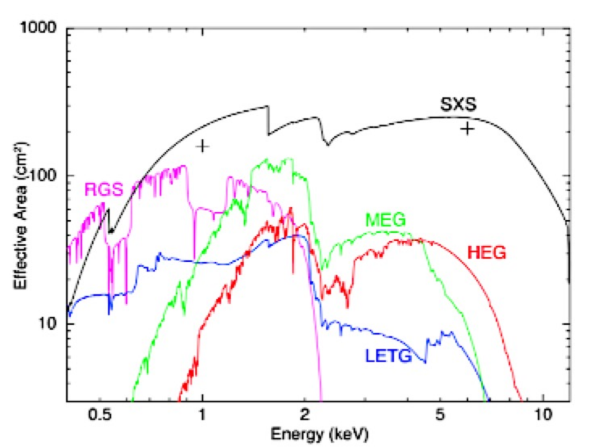




- Ability to observe over a broad band with high efficiency and very good spectral resolution.
- Calorimeter is SXS, Chandra

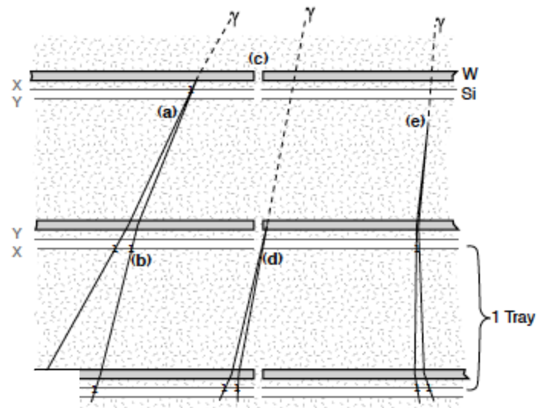
gratings are GHEG,MEG and LETG

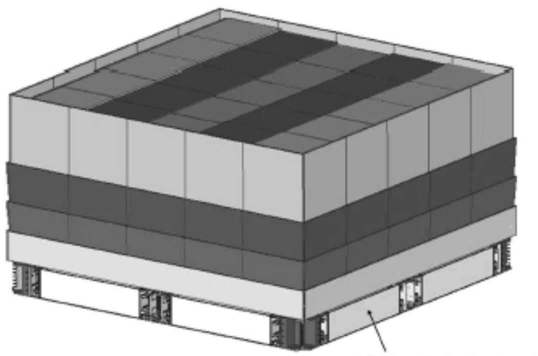
XMM gratings is RGS



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)



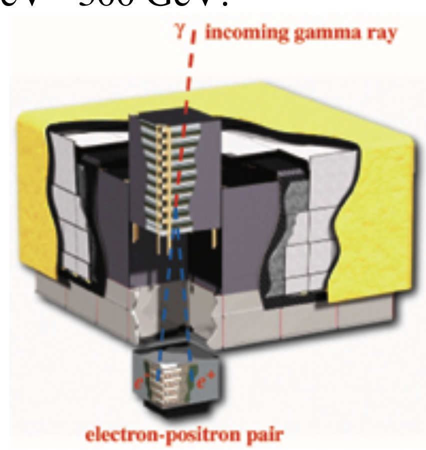


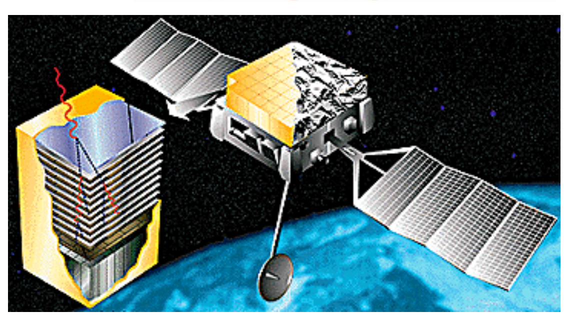
Full coverage of anti-coincidence detectors

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



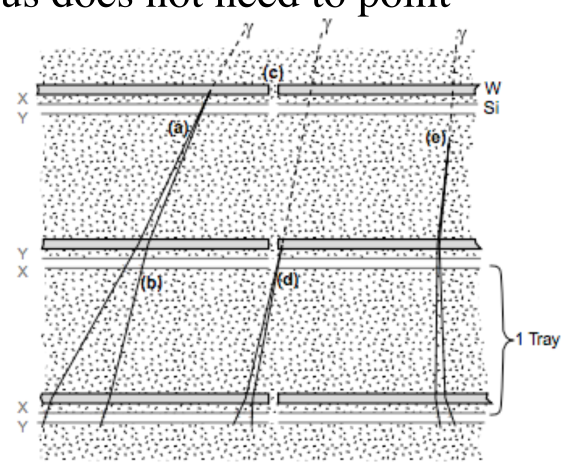


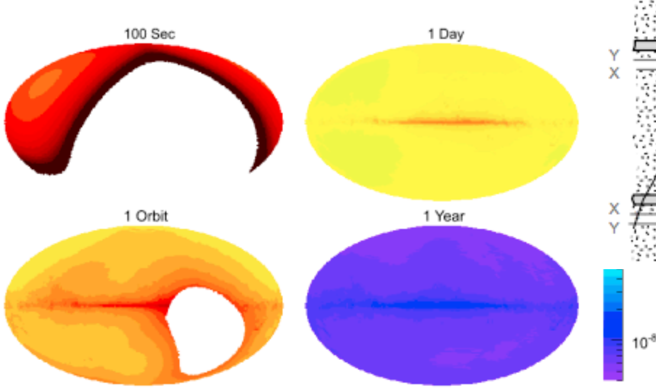
γ-Ray Detectors

- The direction of the incoming gamma ray is determined by tracking the direction of the cascading particles back to their source
- 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.
  - 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



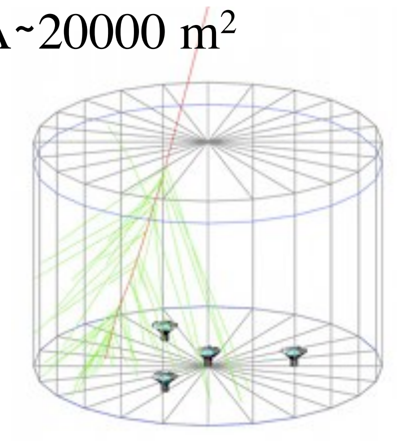


ensitivity for exposures on various timescales. Each map is an Aitoff projection in galactic coordinates. In stand
is achieved every 2 orbits, with every region viewed for ~30 min every 3 hours.

Cerenkov Telescopes-HAWC

- Cherenkov production is relatively efficient in water due to its high index of refraction. The Cherenkov light is emitted into a forward cone that surrounds the direction of motion of the charged particle
- The water is dense (relative to air), and so a gamma-ray produces an e+e- (electron/ positron) pair once it enters the tank.
- Very large FOV, long observing time, low sensitivity per unit time.

A~20000 m^2



Cerenkov Telescopes- HESS https://www.mpi-hd.mpg.de/hfm/HESS/pages/about/telescopes/

- A high-energy gamma ray interacts high up in the atmosphere and generates an air shower of secondary particles.
- The shower particles move at essentially the speed of light, emitting *Cherenkov light* (when a particle moves faster than the speed of light in a medium)
- The Cherenkov light is beamed in the direction of the incident primary particle
  - on the ground it illuminates an area of about 250 m diameter,
- a primary photon at Tev energy (10^{12} ev), produces 100 photons per m^2 on the ground. Within, a few nanoseconds.
- Have a small (few sq degrees FOV)

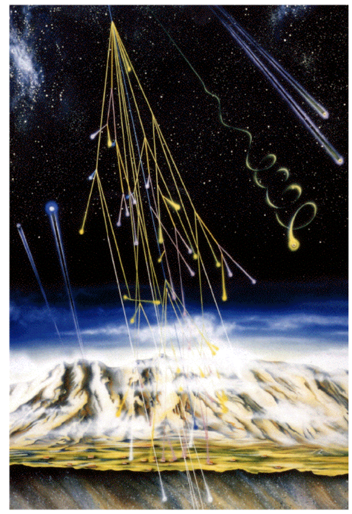
Need large

- collecting area
- very fast detectors
- multiple telescopes to stereoscopically locate air shower

Cerenkov Atmospheric Telescopes
Pareschi 2003

• Atmospheric Cherenkov Telescopes allow observations of astronomical objects emitting in gamma-rays with energies from 50 GeV up to several TeV from the ground

• The showers extend over many kilometers in length and few tens to hundreds of meters in width and have their maximum located at around 8-12 km altitude. Electrons and positrons in the shower core, moves with ultra-relativistic speed and emits Cherenkov light.



• This radiation is mainly concentrated in the near UV and optical band and can therefore pass mostly unattenuated to ground and detected by appropriate instruments.

• Light flashes from showers have a very short duration, typically 2-3 ns in case of a g shower.

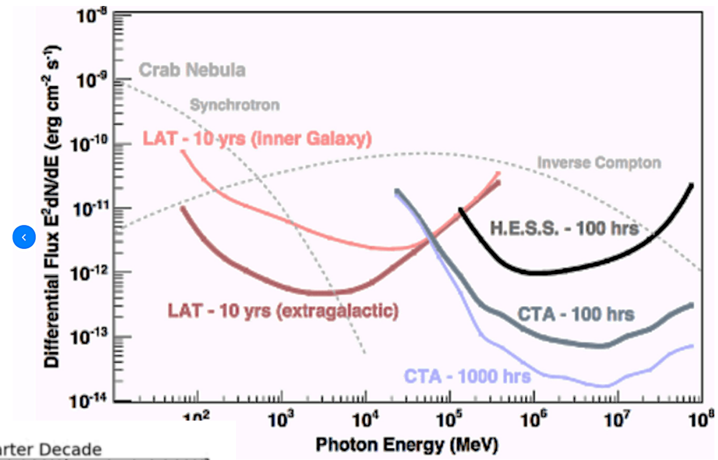
Imaging Atmospheric Cherenkov Telescopes

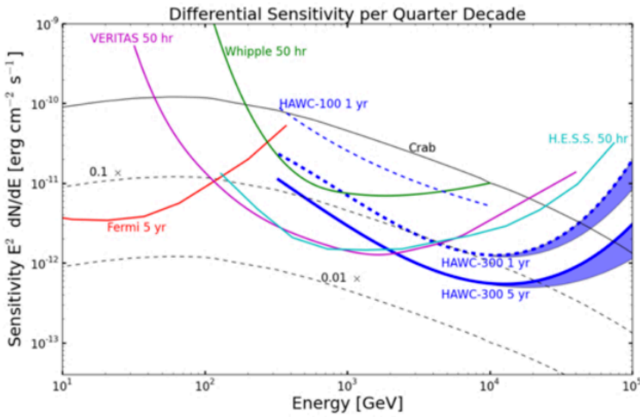
- IACTs consist of telescopes with large mirrors
  - (mirror area > 100 m^2) to collect enough photons,
- pixelated cameras with >500 photomultipliers, sophisticated trigger systems and fast electronics.
- Using several telescopes and stereoscopic techniques allows the reconstruction of the direction of the incoming gamma ray; its energy can be estimated by the signal size.

- Sensitive in 20-70 GeV to 30 TeV band
- detect a source with a flux of 1% of the Crab Nebula in ~20-40 hours.
- an energy resolution of 15-20% and angular resolution of 0:1 deg.
- field of view of IACTs is 3-5 deg wide
- duty cycle is low, restricted to dark nights ~ 1200 hours of observations per year.

Relative Sensitivity

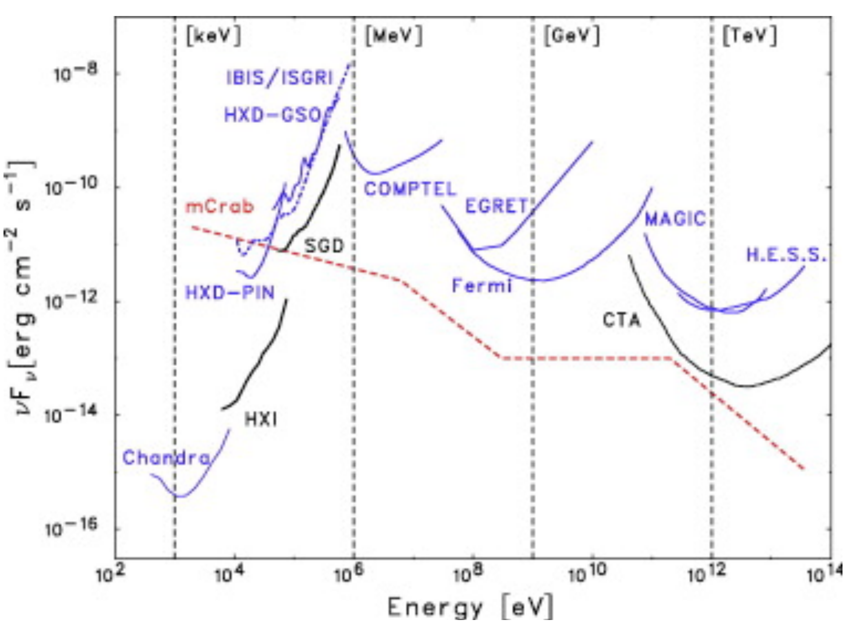
- Use Crab Nebulae as a 'standard candle'





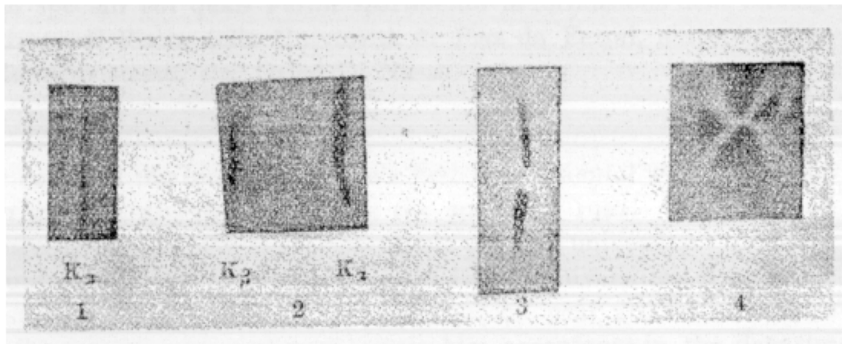
HESS sensitivity is for 100 hours, Fermi 10 years-and HAWC for 5 years however ratio of solid angles is ~ 5000 so for ALL Sky Fermi ~60x more sensitive

X-ray and Gamma-ray Sensitivity



- X-ray missions ~4 orders of magnitude more sensitive than present day gamma-ray observatories for most sources.

Imaging experiments using Bragg reflection from "replicated" mica pseudo-cylindrical optics



E. Fermi – Thesis of Laurea, "Formazione di immagini con i raggi Roentgen" ("Imaging formation with Roentgen rays"), Univ. of Pisa (1922)

Thanks to Giorgio Palumbo!

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)

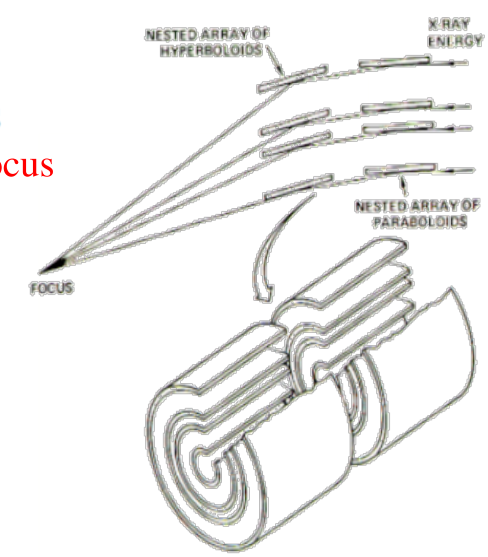
X-Ray Optics

Have to make the x-rays reflect and focus

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

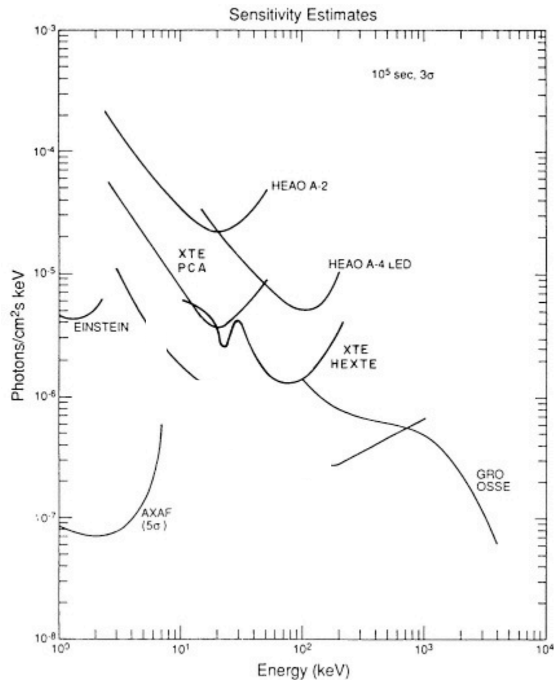
See schwartz_optics.pdf

X-Ray Imaging Optics



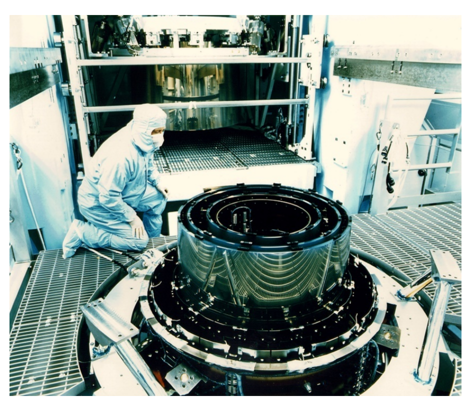
Improvement in Sensitivity

- The advent of x-ray imaging telescopes improved sensitivity and angular resolution by ~10^4



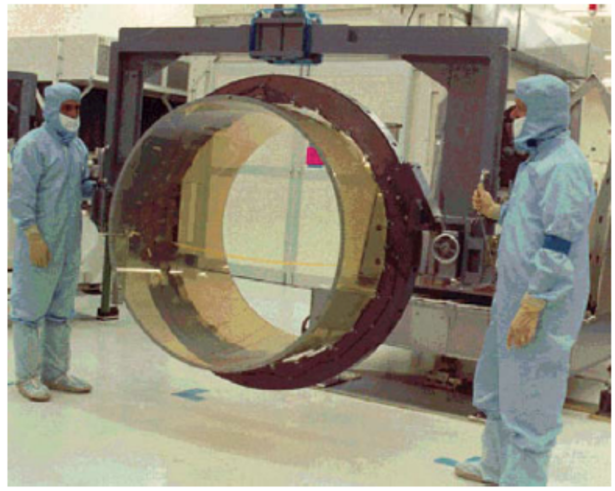
Chandra

- 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



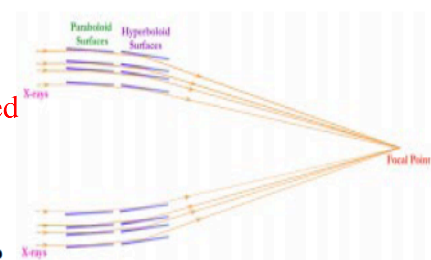
1.2m diameter, 1 m long Chandra optic

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

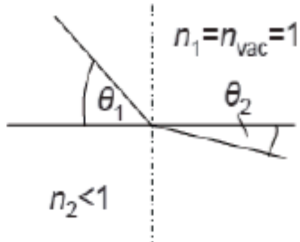


X-rays reflect at small grazing angles.

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 $\theta < \theta_1$

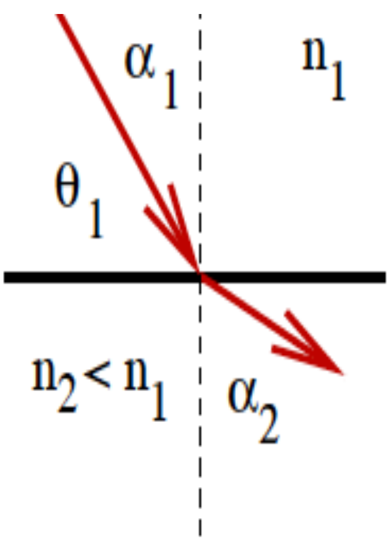
critical angle (θ_1) decreases as sqrt(Z)E^{-1}

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

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. If $n \gg 1$: Total internal reflection

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.

J. Wilms

X-ray optical constants

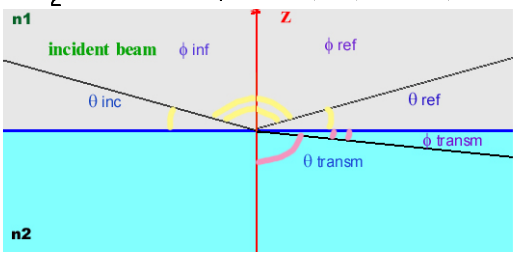
- complex index of refraction to describe the interaction X-rays /matter:

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

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



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

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

momentum transfer

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

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

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.

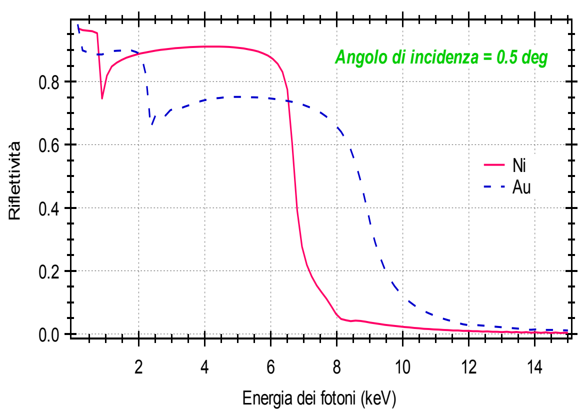
- Snell's law ($n1 \cos\theta_1 = n2 \cos\theta_2$) to find a critical angle for total reflection:

$$\theta_{crit} \approx \sqrt{2\delta} = \sqrt{\frac{r_0 \lambda^2 \rho N_{Av} f_1}{A\pi}}$$

λ = wavelength ρ = density
A = atomico weight f_1 = scattering coeff.
r_0 = classical electron radius

- For heavy elements Z/A ≈ 0.5:

$$\theta_{crit}(arc\min) \approx 5.6\lambda(A)\sqrt{\rho}$$



Pareschi 2003

X-ray optical constants

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

($\mu = 4\pi\beta/\lambda$ cm^{-1}) ← *Linear abs. coeff.*

δ → changes of phase
β → absorption

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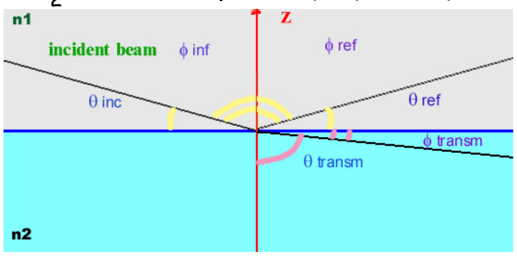

$\vec{p}_1 = \frac{h}{2}\vec{k}_1$

$|\vec{k}_1| = \frac{2}{\ } n_1$

⇒ $2p_z \propto \frac{4}{\ } n_1 \sin_{inc}$

momentum transfer

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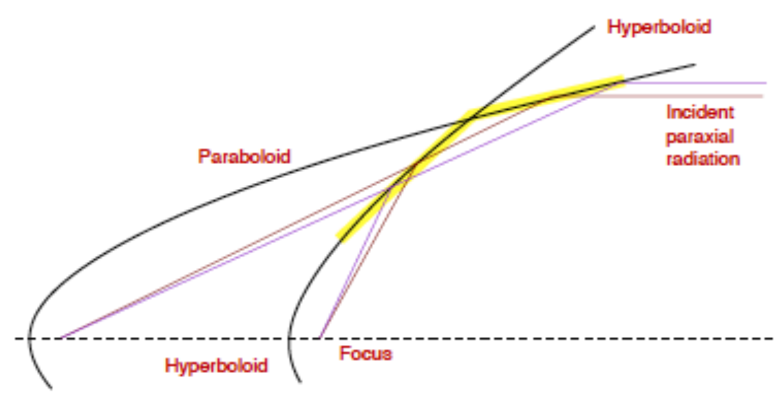
Wolter Telescopes



after ESA

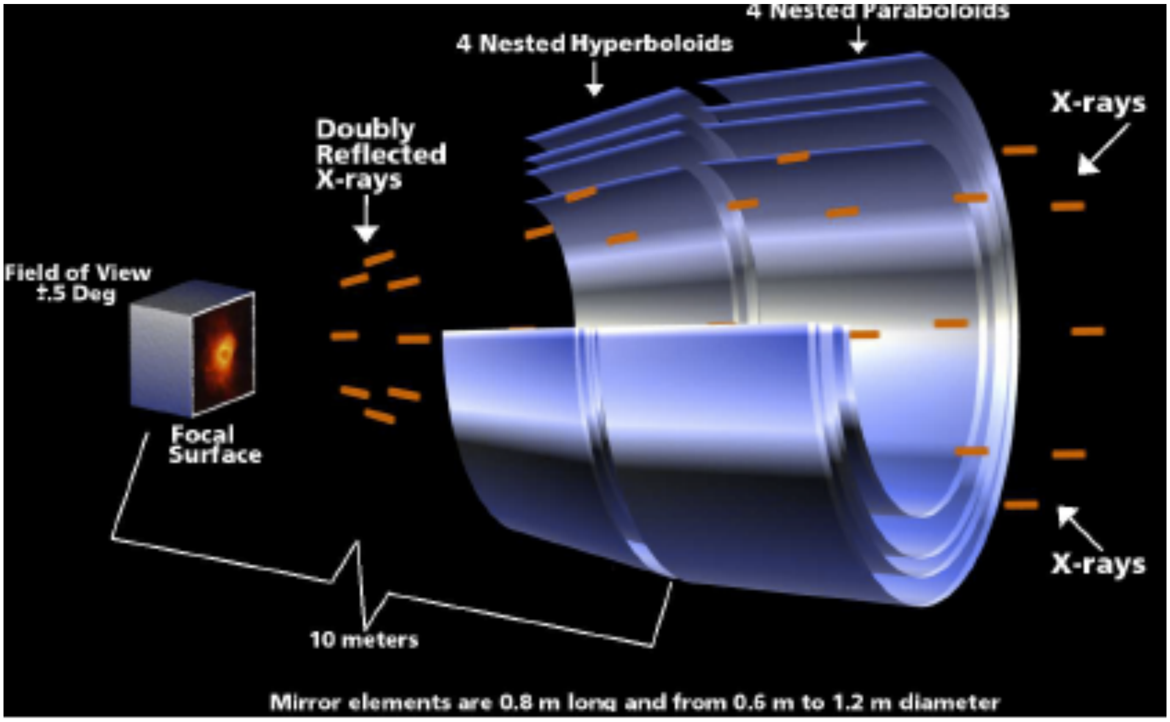
To obtain reasonable focal lengths need 2 reflections- on a parabolic and then hyperbolic surce − Wolter tyoe I

(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

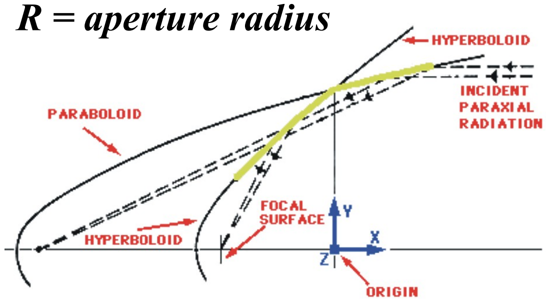
Chandra Mirror



F= focal length = R / tan 4θ

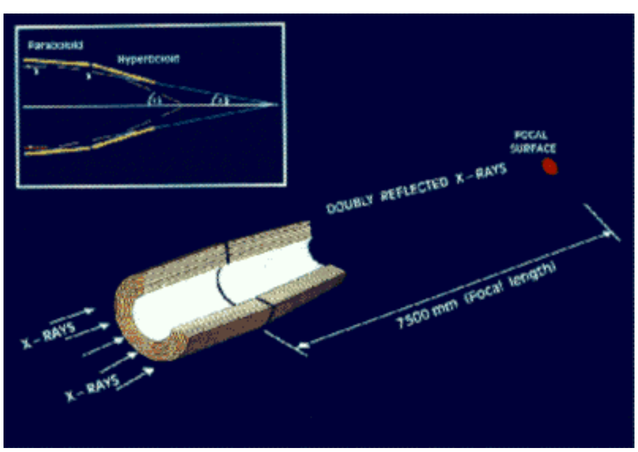
θ= *on-axis incidence angle*

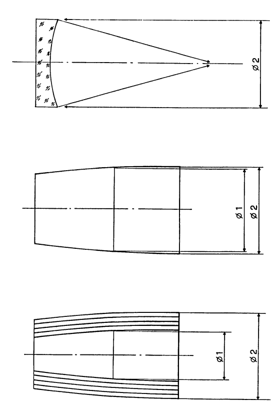
R = aperture radius



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 π F L θ^2 R^{2-} or**
- **A $\pi R^2 l/F$-**





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

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

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

Design criteria

There is a strong interdependence between f-number, grazing angle, telescope diameter and focal length

large diameter telescopes working at high energies need long focal distances,

the highest photon energy which one want to image defines the optimum grazing angle and the nature of the reflecting surface since the incidence angle of total reflection is α_t=5.6$\lambda\sqrt{\varrho}$ with α_t in arcmin , λ in Å and ϱ in g/cm^3.
However the smaller the grazing angle the smaller the field of view

For high-resolution telescopes, the controling factor is the surface shape

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≈0.5, the incidence angle of total reflection for $\delta \ll 1$ can be estimated to:

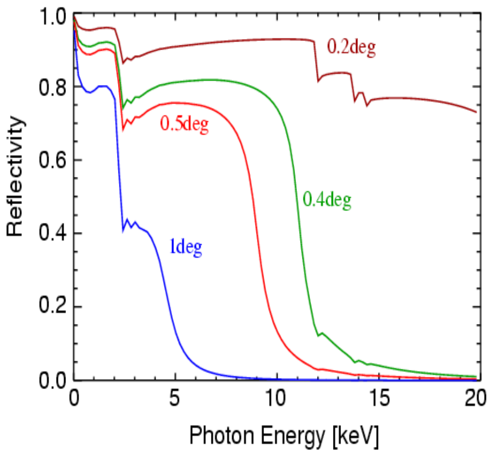
$$\alpha_t = 5.6\,\lambda\,\sqrt{\rho} \qquad (7)$$

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, v

- Higher Z materials reflect higher energies, for fixed grazing angles
  Higher Z materials have a larger critical angle at any energy.

Long Focal Length

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



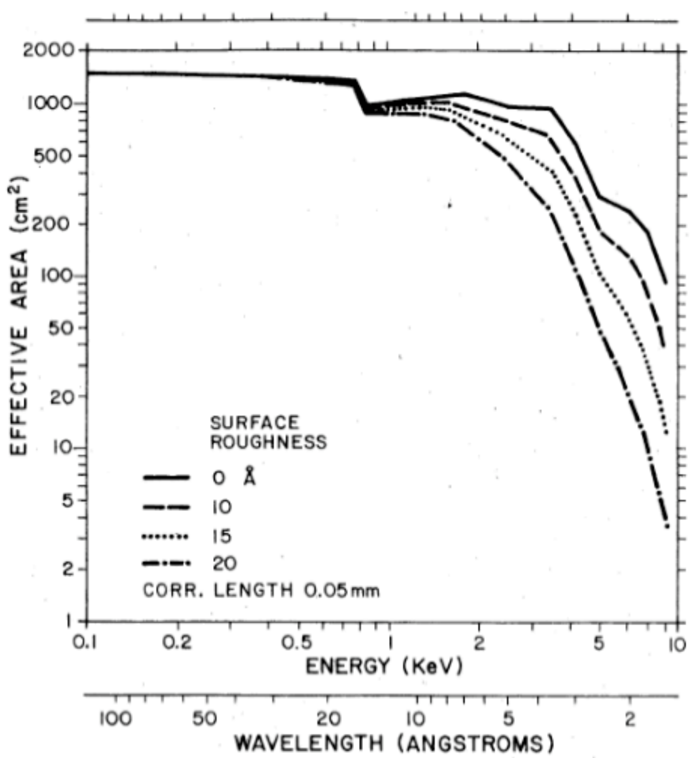
Reflectivity for Gold

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

angle at which x-rays are reflected

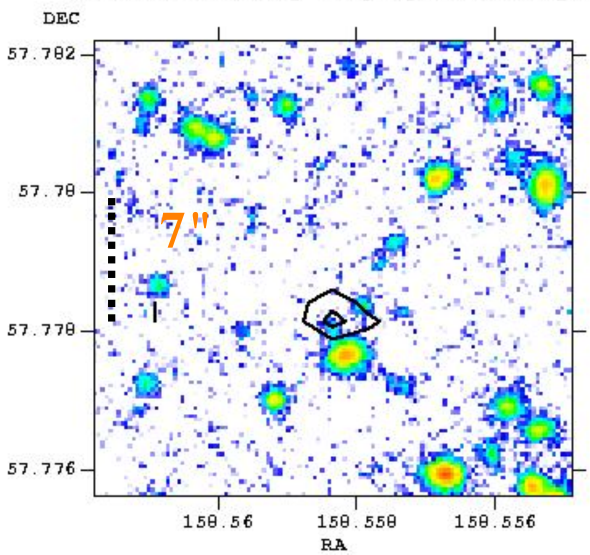
Very Smooth Surface

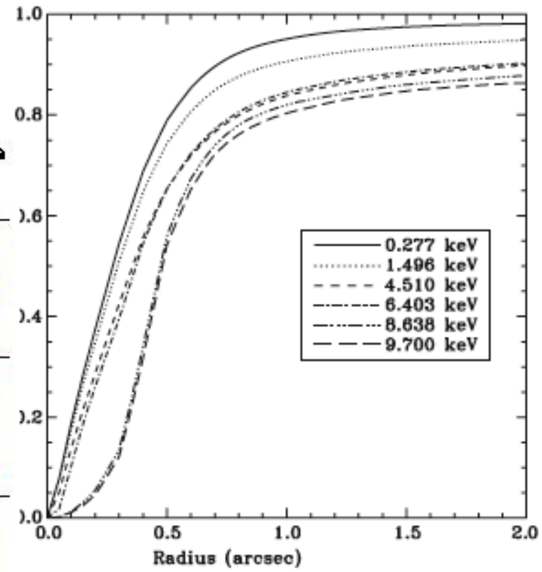
- The rougher the surface the worse the reflectivity is, especially at high energies
- To achieve this smooth, precise surface the Chandra optics are ground and polished to 3Å precision into zerodur glass.
  - If the surface of the state of Colorado were as smooth, Pike's Peak would be less than 1 inch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



Can Get Pretty Good Images

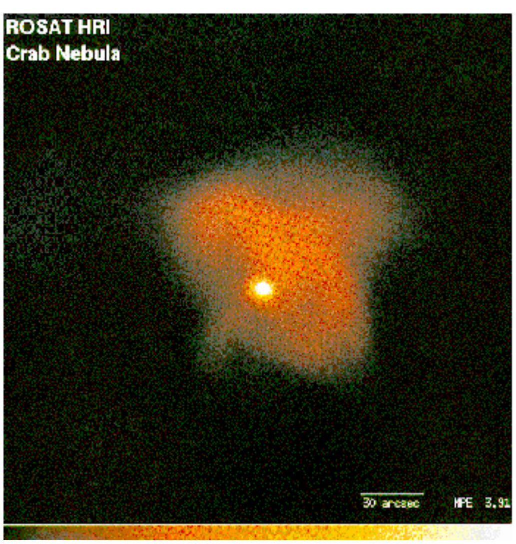
- Chandra Images are as good as the best images that can be obtained from the ground



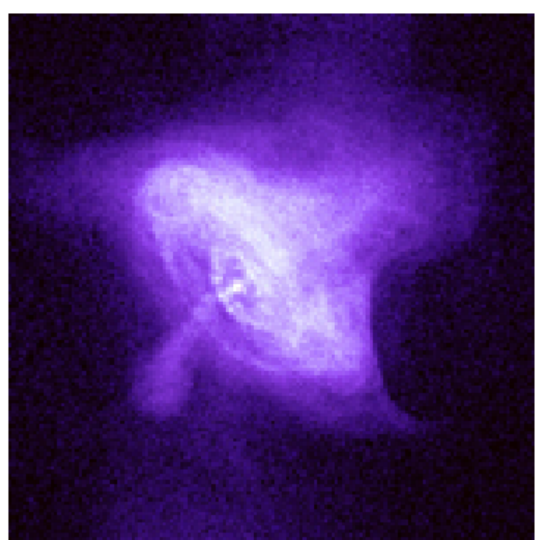


Chandra- fraction of energy inside an inscribed circle on axis

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



Rosat: HPD = 3 arcsec



Chandra: HPD = 0.5 arcsec

Mirror Collecting Area

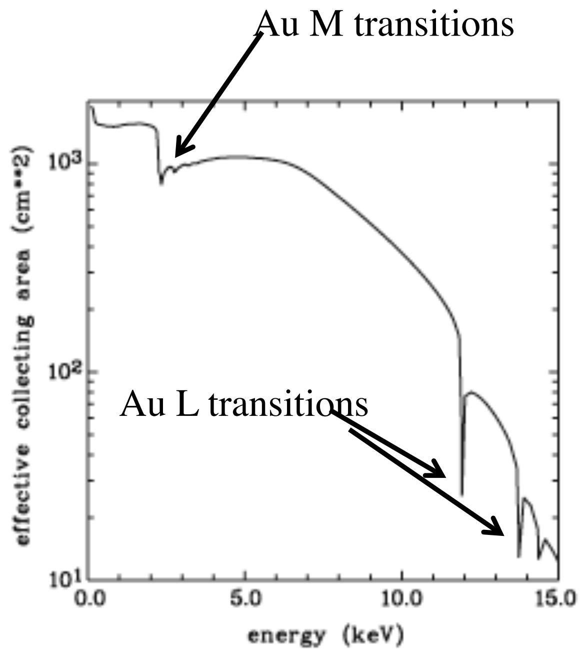
- Depends on mirror diameter, number of shells, focal length and coating of mirror (e.g. which metal coats the substrate)
- XMM mirror- the 'bumps and wiggles' are due to the atomic transitions of gold (the coating material)

- 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 $\sigma<\lambda$

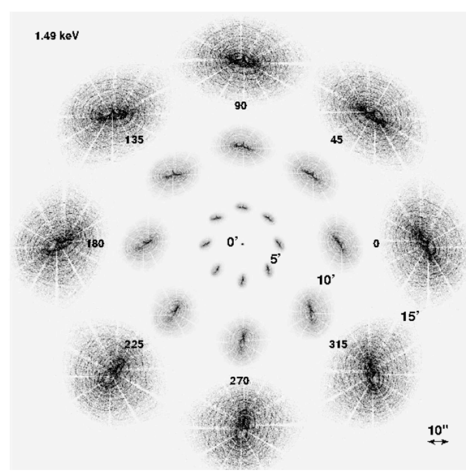
If want <10% scattered at 10Å with α=1deg σ<9Å



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 (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 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

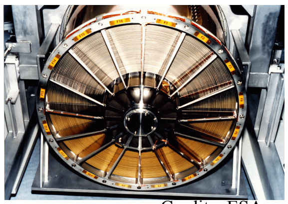
Credits: NASA

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***



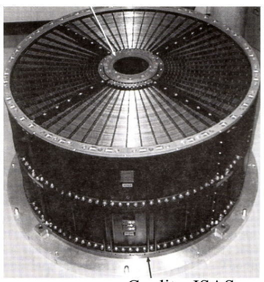
Credits: ESA

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"

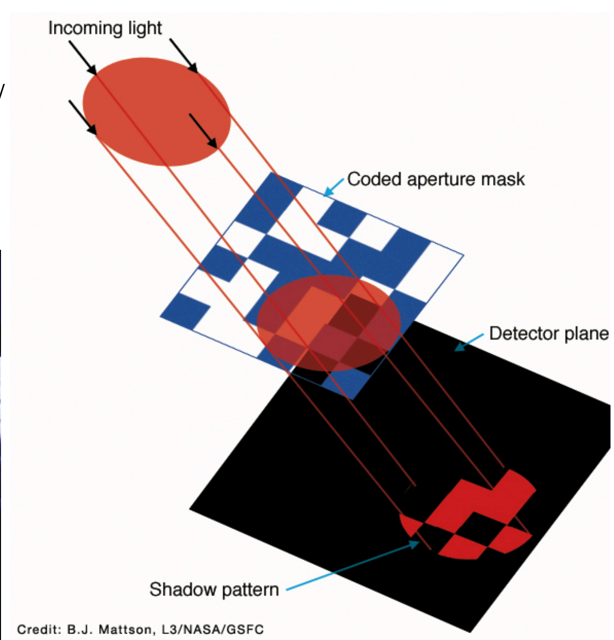
Projects: **BBXRT, *ASCA, Suzaku , ASTRO-H***

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)*

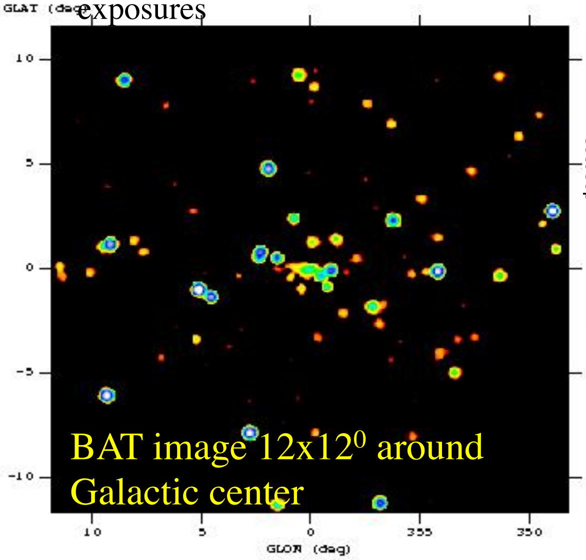
High Energy Telescopes

- 'true' imaging telescopes in the 0.1-70 keV band (NuStar, Astro-H)
- At higher energies one can make 'pseudo-imaging' telescopes using 'coded aperture (Swift BAT Integral ISGRI) masks' (shadowgrams) http://astrophysics.gsfc.nasa.gov/cai/

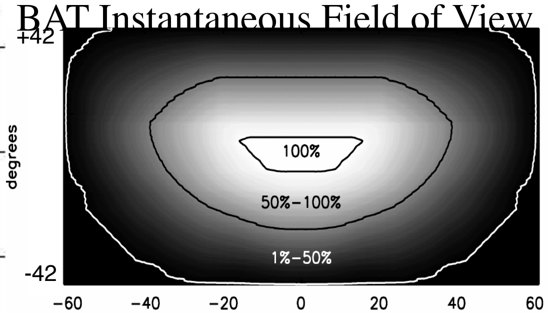


Swift BAT and Integral ISGRI

- The Swift BAT - ‘all sky’ instrument sensitive 15-150 keV band
- - covers ~20% of the sky at any time ~ 50% of the sky each day relatively uniform sky coverage
- Extensive follow-up of sources by the two other telescopes on SWIFT (UVOT- (a ultraviolet-optical telescope) and XRT (a x-ray telescope)) with short exposures



BAT Instantaneous Field of View

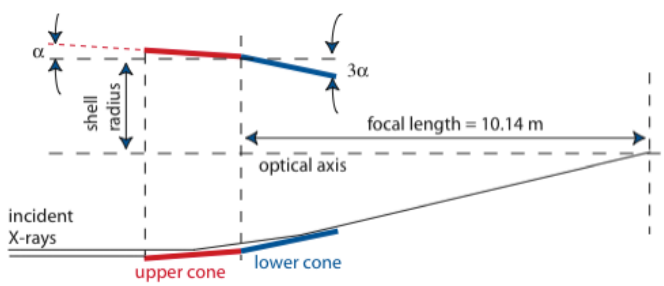


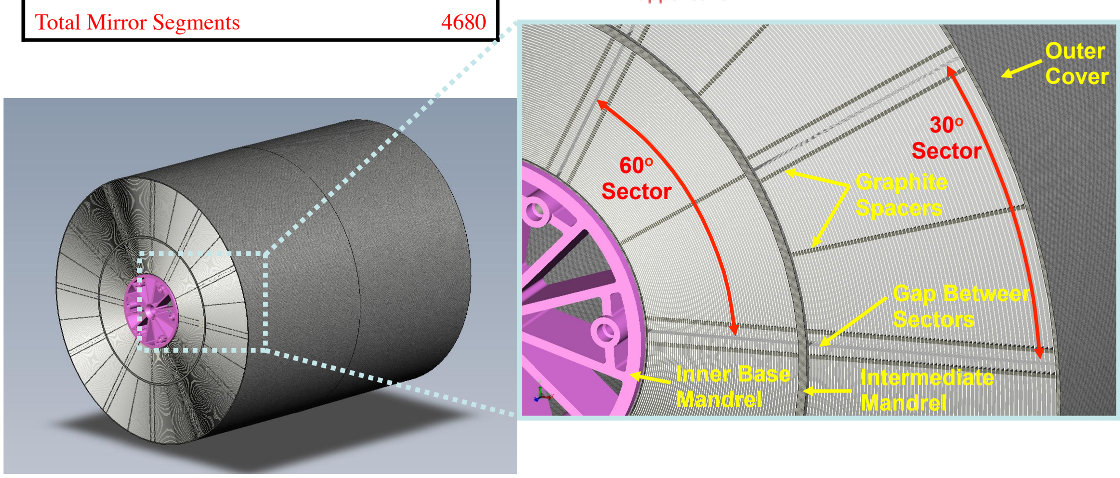
Degrees

Closeness and brightness of sample allows extensive follows with moderate sized telescopes and good x-ray S/N

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





Multi-Layers

- when the X-ray beam impinges onto the multilayer, they are reflected by each of the reflection layers due to the differences in refractive indexes between the reflection and the spacer layers.
- When these reflected X-ray beams satisfy the interference condition (or Bragg condition), strong reflected intensities are obtained similar to those of a diffraction peak when the Bragg condition is satisfied: $n \bullet \lambda = 2d \cdot \sin\theta$
  - where n is a positive integer; λ wavelength , d period of the multilayer or
- In a multilayer, each interface between a heavy-element layer and a light-element layer with significant difference in refractive indexes forms a reflection plane. A major advantage of a multilayer is that it can be made with desired layer materials and layer spacing, d

(Kazuhiko and Omote The Rigaku Journal, 24(1), 2008)

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*

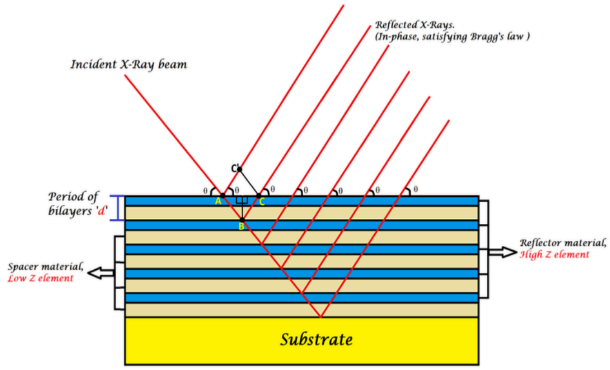
$$\vartheta_{crit} \propto \frac{\sqrt{\rho}}{E}$$

Multi-Layer

a high density contrast between the two materials is needed, and common high density materials are Tungsten (W) and Platinum (Pt), while common materials for the low density layers are Silicon (Si), Carbon (C), and Silicon Carbide (SiC).

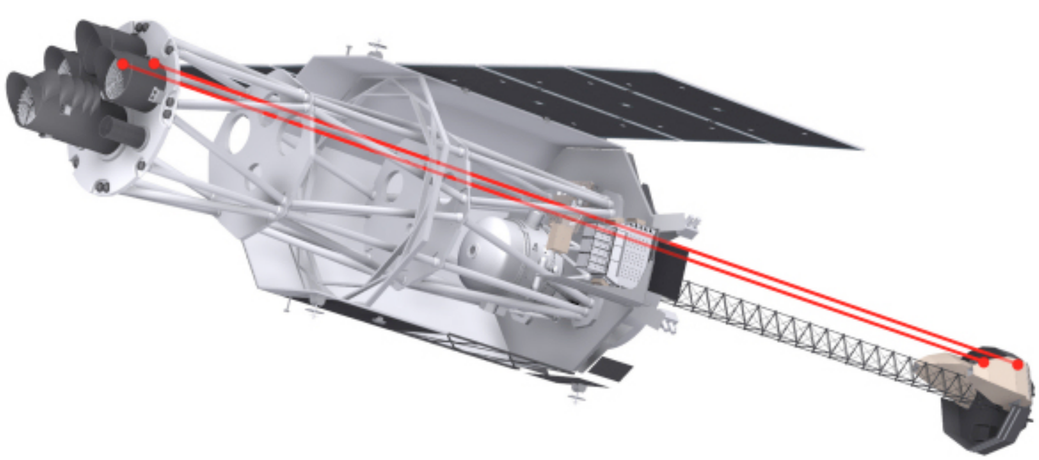
the multilayer stack acts as a crystal lattice and constructive interference creates enhanced reflectivity

- Instead of a coating of a high z material (Au, Ir) the Nustar optics have a multi-layer reflection
- Multilayers are thin coatings of two alternating materials deposited on top of the other. - A typical multilayer has 200 pairs of coatings.
- Reflects well up to ~70 keV



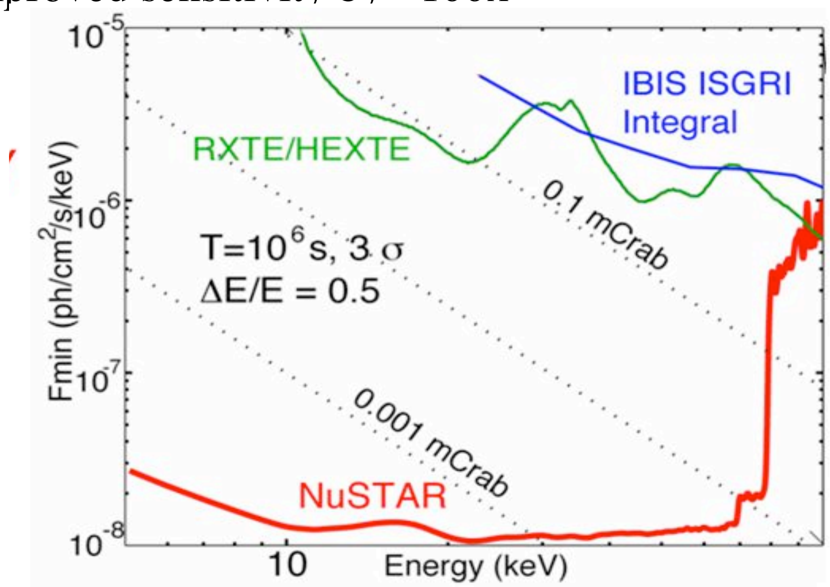
Hard x-ray Imaging

- require long focal length- on Nustar and Hitomi this was achieved with an extendable optical bench
- The mirror substrates 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

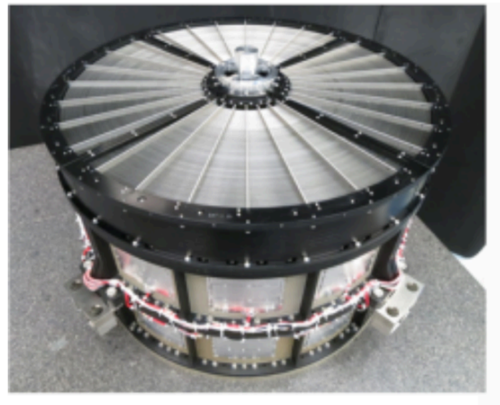


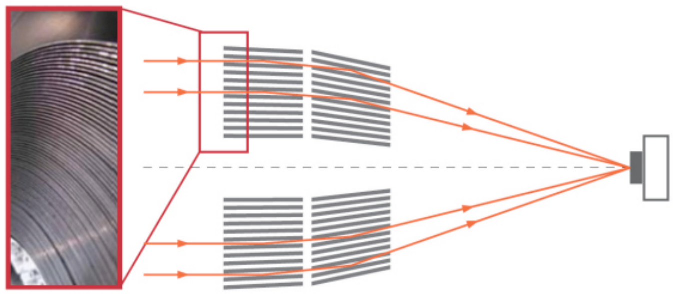
It Works-58" HPD

- 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)

'Cheap' Telescopes

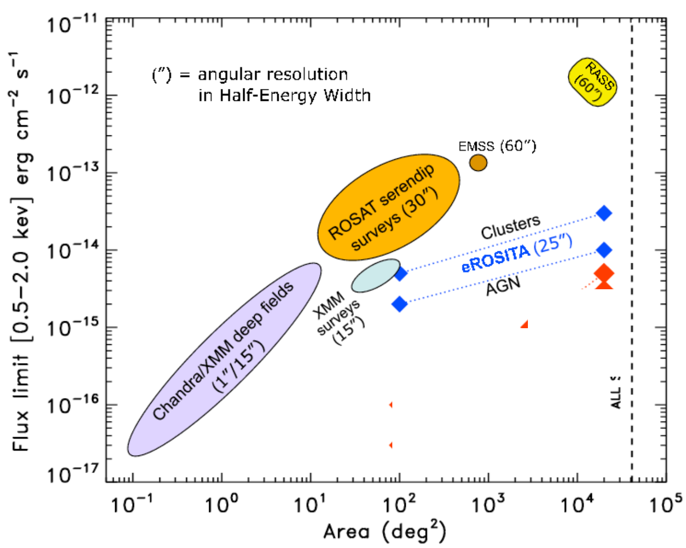
- To get an opportunity to fly in space mass and cost are very important
- A high resolution telescope is expensive and heavy (Chandra mirror mass was ~1500kg)
- Thus the European and Japanese programs have used 'light weight' 'low cost' optics with large collecting area but poorer angular resolution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





Relative Sensitivity for Surveys

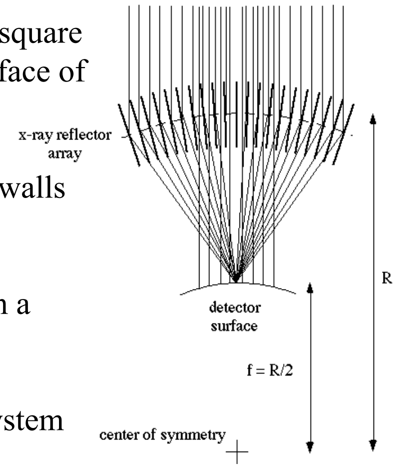
- One of the main goals of a high energy mission is to find and characterize sources
- This is called a survey
- The sensitivity of a survey depends on the collecting area, background, angular resolution, solid angle of the telescope (etc etc)



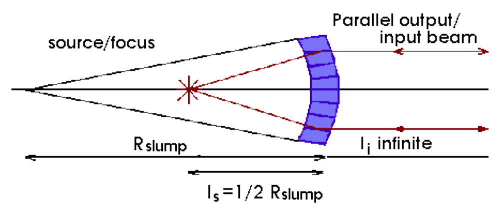
Lobster-Eye optics- Very wide FOV

Lobster-Eye Optics Geometry (1-dimensional)

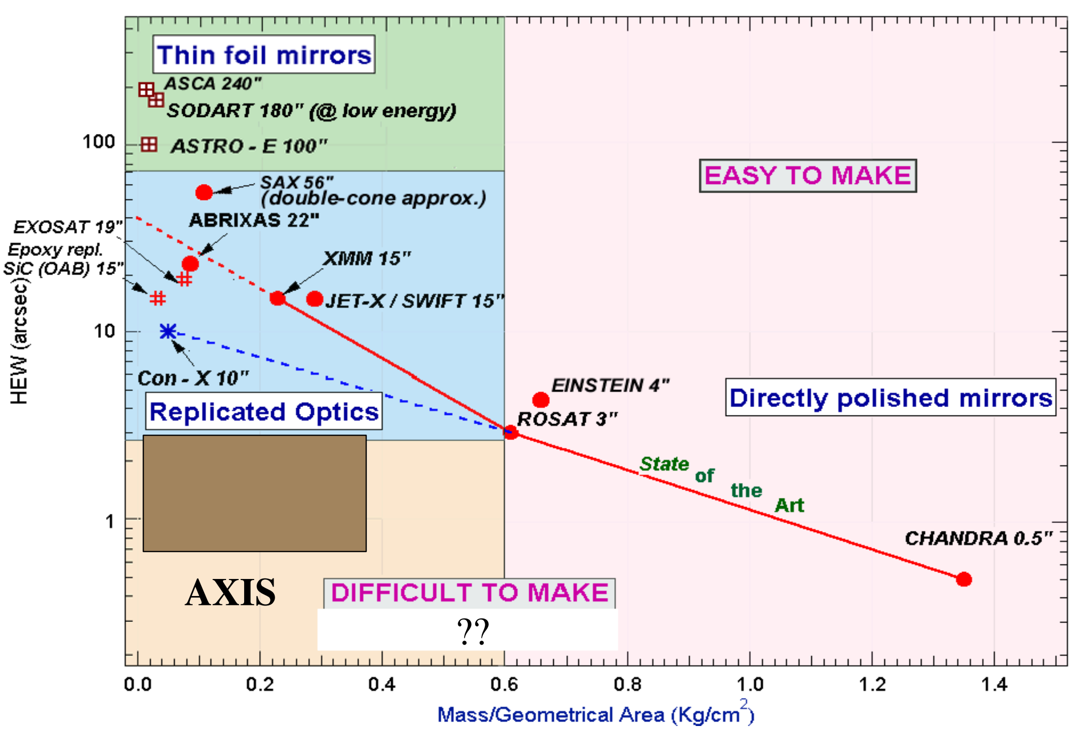
- the pupil is formed by a system of channels with square section uniformly distributed around a spherical surface of radius R.
- To be focused need reflection by two orthogonal walls of same channel;
- the photons are focused onto points distributed on a spherical surface of radius R/2;
- a preferential optical axis does not exist ➔ the system field of view can be as large as 4 p with the same Effective Area for every direction- perfect for γ-ray bursts



Pareschi 2003

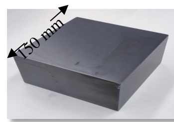


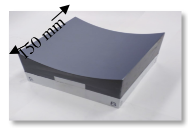
Present Astronomical optics technologies: HEW Vs Mass/geometrical area

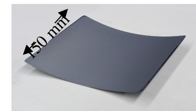


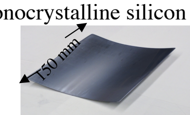
Future of X-ray Optics

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

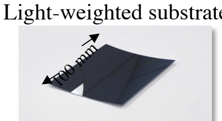

Monocrystalline silicon block


Conical form generated

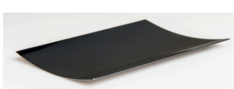

Light-weighted substrate


Etched substrate

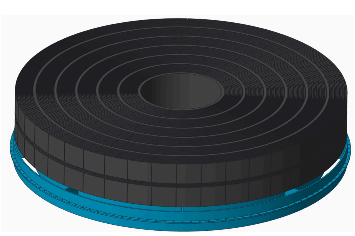

Polished mirror substrate


Trimmed mirror substrate

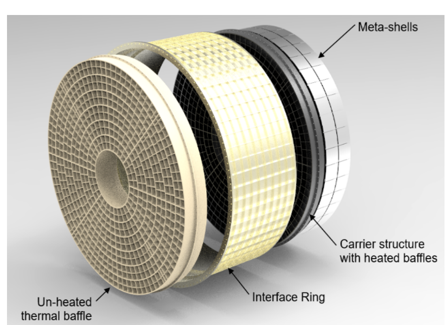
The Meta-Shell Paradigm

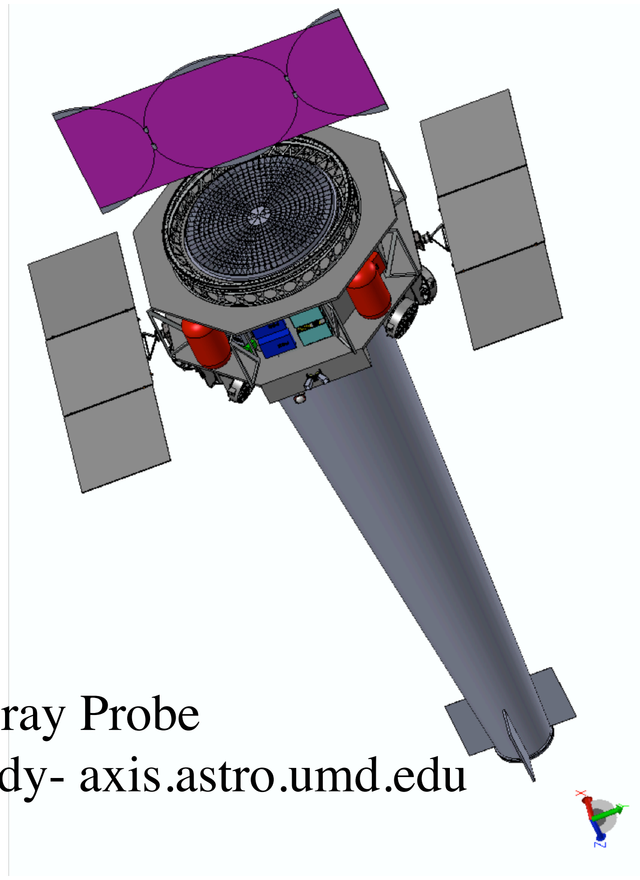

Mirror Segment


Meta-shell

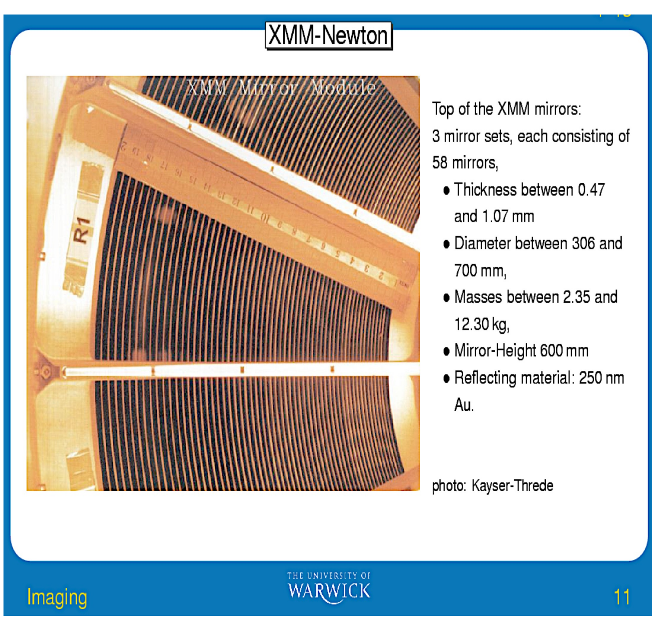

Mirror Assembly

- 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



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

Presentations

- Please read, summarize and explain
- 2017A&A...606A.122F
  Foëx, G.; Böhringer, H.; Chon, G.
  Comparison of hydrostatic and dynamical masses of distant X-ray luminous galaxy clusters

- skip section 4 "substructures"
- What did you learn about how cluster masses are determined
- what are the uncertainties
- why is this important?
- 10 min+ 5 for questions- you will be graded by your peers
- you might want to look at a theoretical article 2019MNRAS.482.3308A
  Armitage, Thomas J.; Kay, Scott T.; Barnes, David J.; Bahé, Yannick M.; Dalla Vecchia, Claudio
  The Cluster-EAGLE project: a comparison of dynamical mass estimators using simulated clusters