How Does One Obtain The Data -Instruments and Telescopes

- What we observe depends on the instruments that one observes with !
- In x and γ-ray spectroscopy we have 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 high quantum efficiency is a major goal

γ-ray spectroscopy is dominated by continuum processes (lines are rare-nuclear lines) 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

I will focus on x-ray spectrometers of 'recent' vintage-

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)

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: σ^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)

e.g at 6.4 keV theoretical is 120 eV

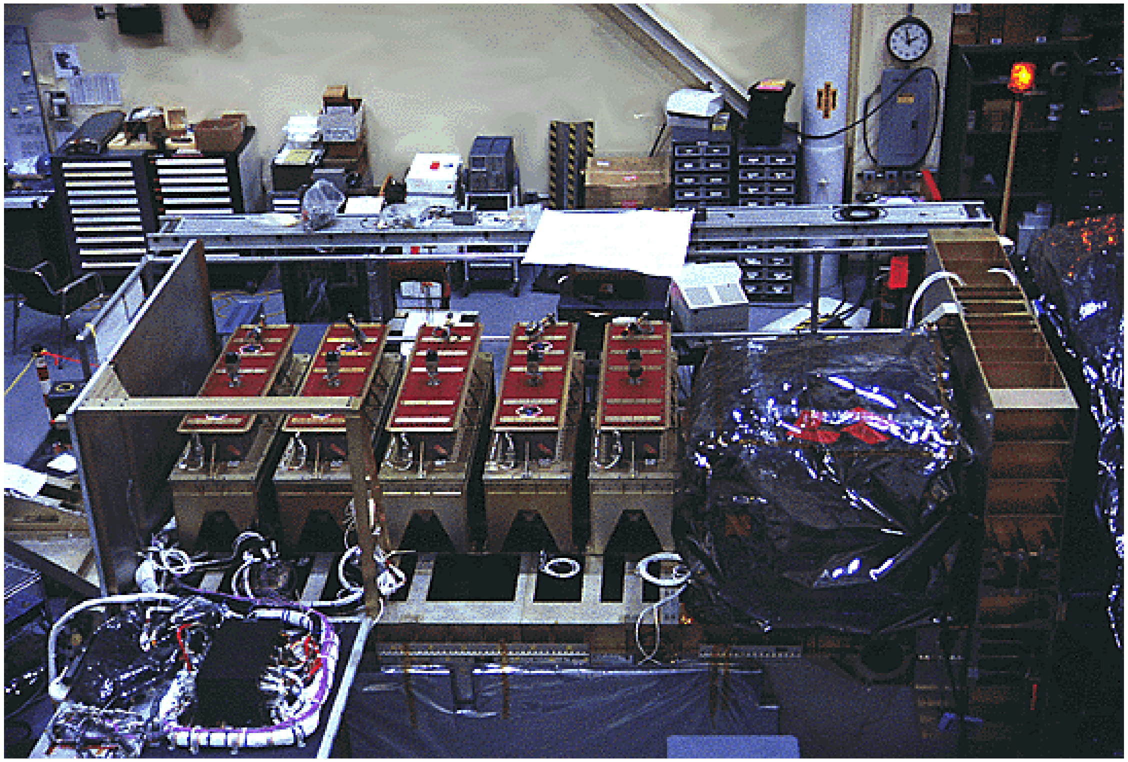
•Resolution ΔE, or resolving power $E/\Delta E$, function of E

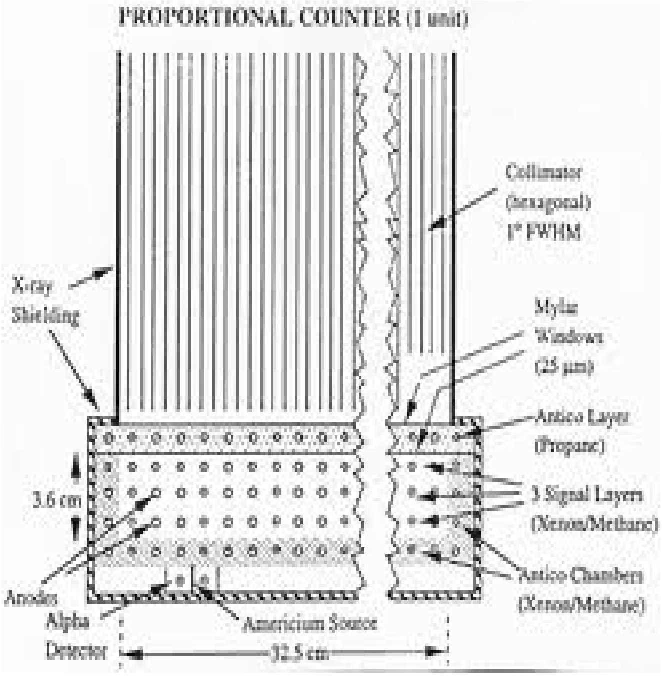
this is different to the case for absorption of visible / UV wavelengths which produce only one photoelectron per detected (i.e. absorbed) photon and so there is no relation between total charge and energy of the photons

Lots of 'Historical' Detectors

- 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, proportional counters, scintillators in use today)





RXTE proportional counters during assembly

Proportional Counters Imaging or Otherwise (Rosat, RXTE)

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

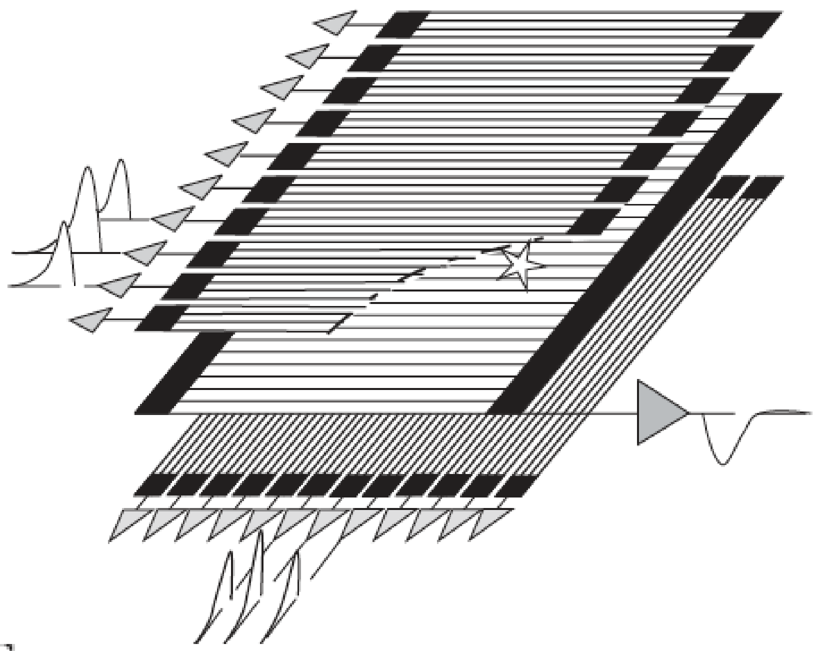
Photons deposit their energy within a short distance , so that only one cell is activated. A charged particle ionizes the gas through collisions, leaving a trail of ionized particles through more than one cell.

The intrinsic timing resolution is limited by the anode-cathode spacing and the positive ion mobility. These physical factors limit the resolution to the microsecond level.

Advantages- fast, high QE, large area, bandpass adjustable used from 0.1-90 keV, can be imaging, can be low background

Disadvantages- low spectral resolution $E/\Delta E \sim 16\%$-messy gas systems

Nobel Prize - Charpak 1992



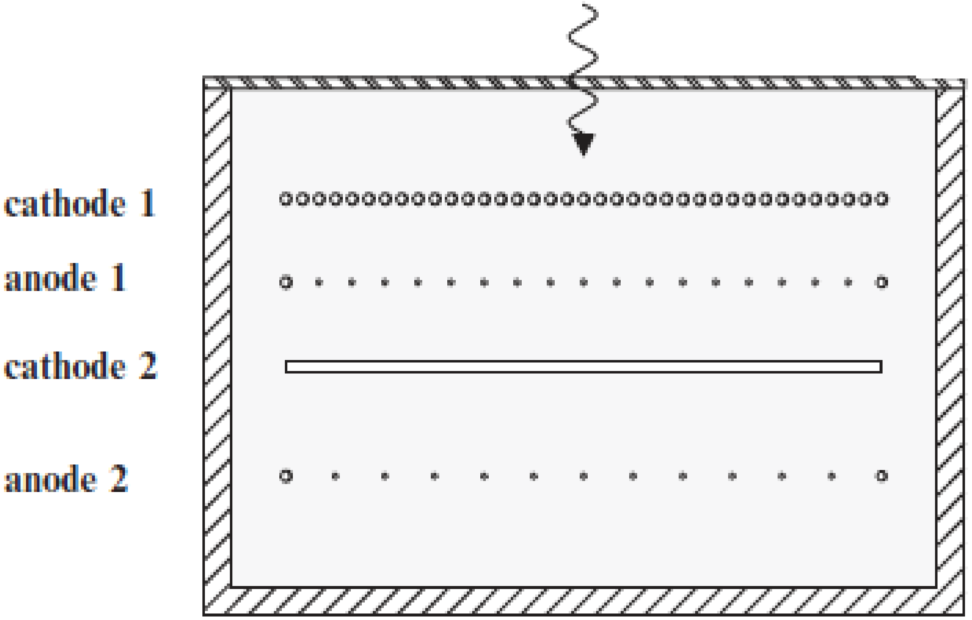


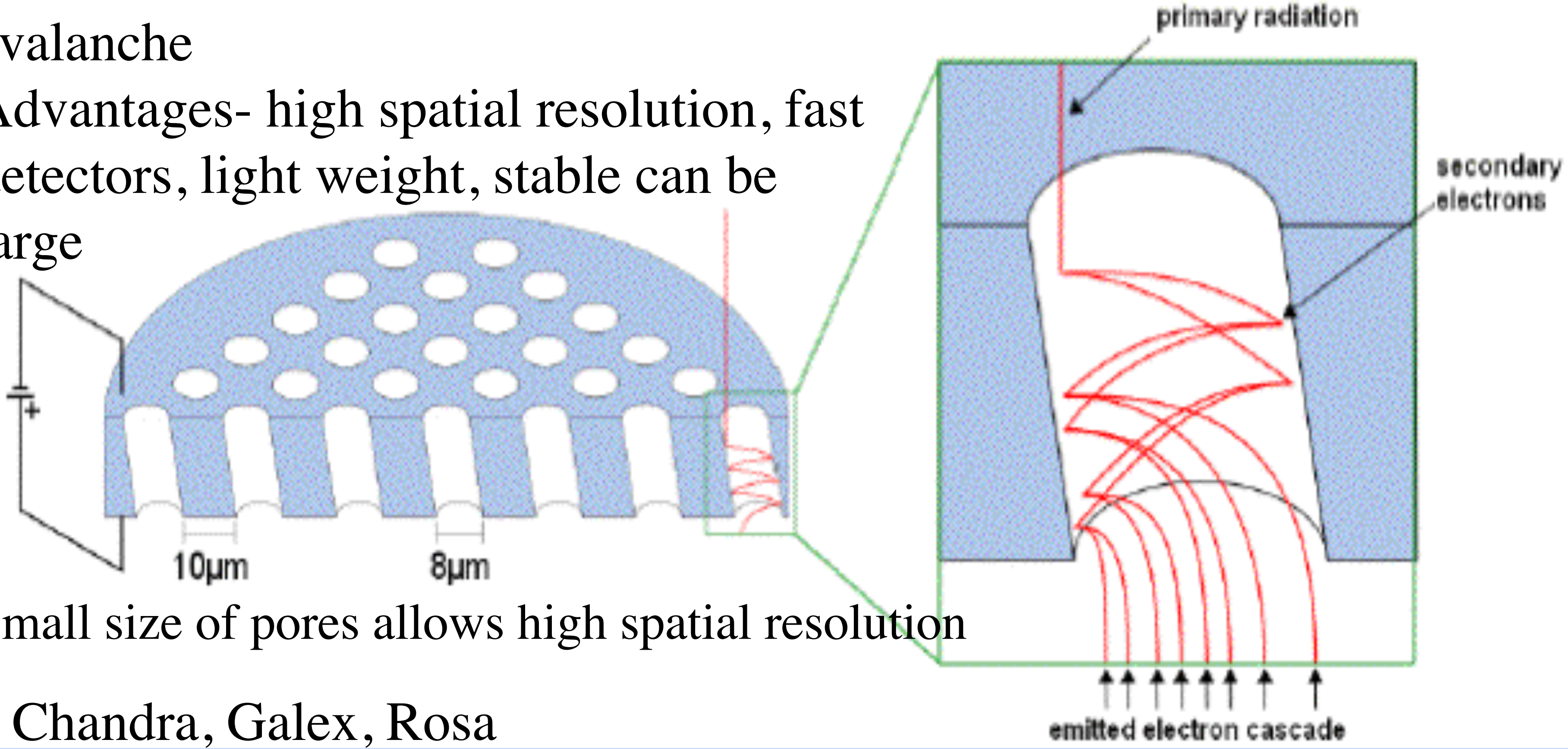
Fig. 4.1 Multiwire proportional counter for X-ray astronomy

Microchannel plate (MCP)

Electron avalanche is excited
at the semiconducter walls

Disadvantages
High background, poor energy resolution, low QE, can be quite fussy to make work well

Need read out device to detect electron avalanche
Advantages- high spatial resolution, fast detectors, light weight, stable can be large



Small size of pores allows high spatial resolution

Chandra, Galex, Rosa

X-ray CCD

2009 Nobel Prize in Physics

- x-ray is absorbed in silicon of the CCD, resulting in the production of 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 whilst 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.

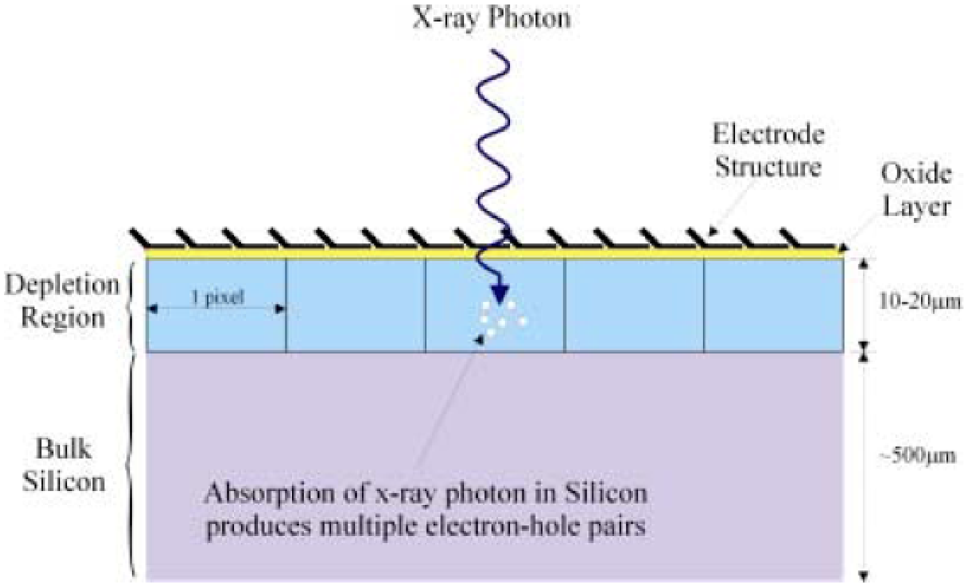


Figure 3: Schematic illustration of the direct detection of an X-ray photon.

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

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.

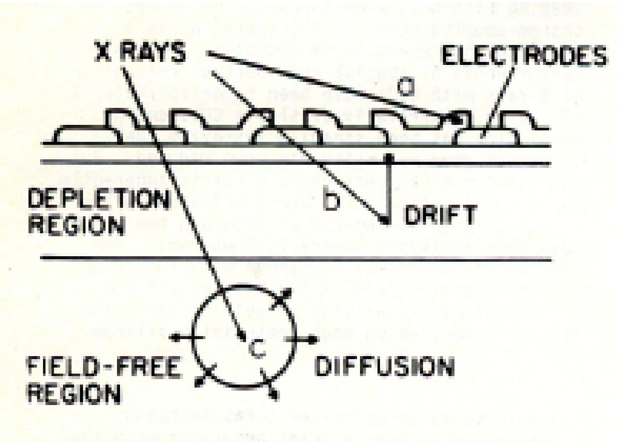
Quantum efficiency is set by physics

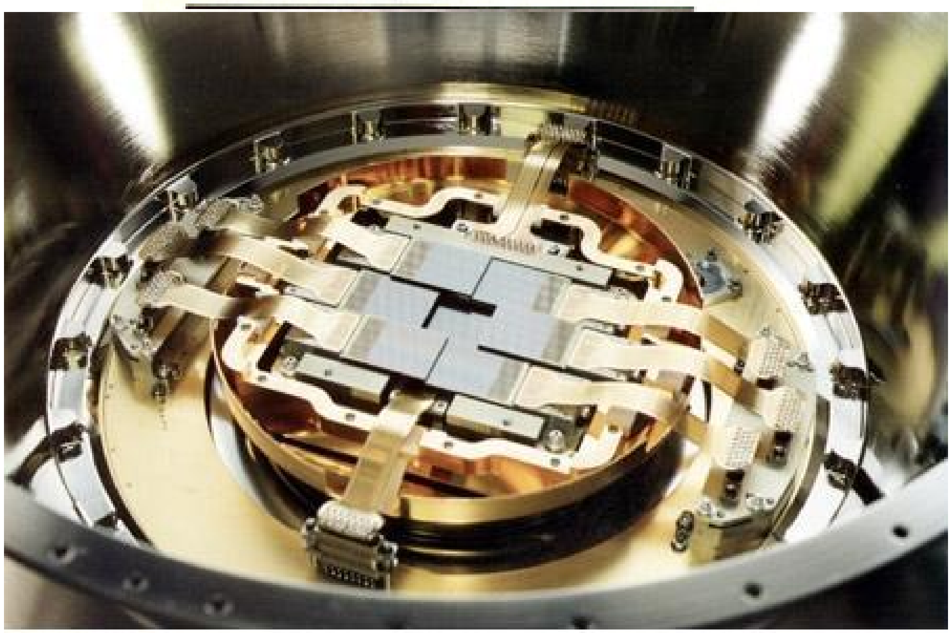
'dead' layer controls low E efficiency

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)





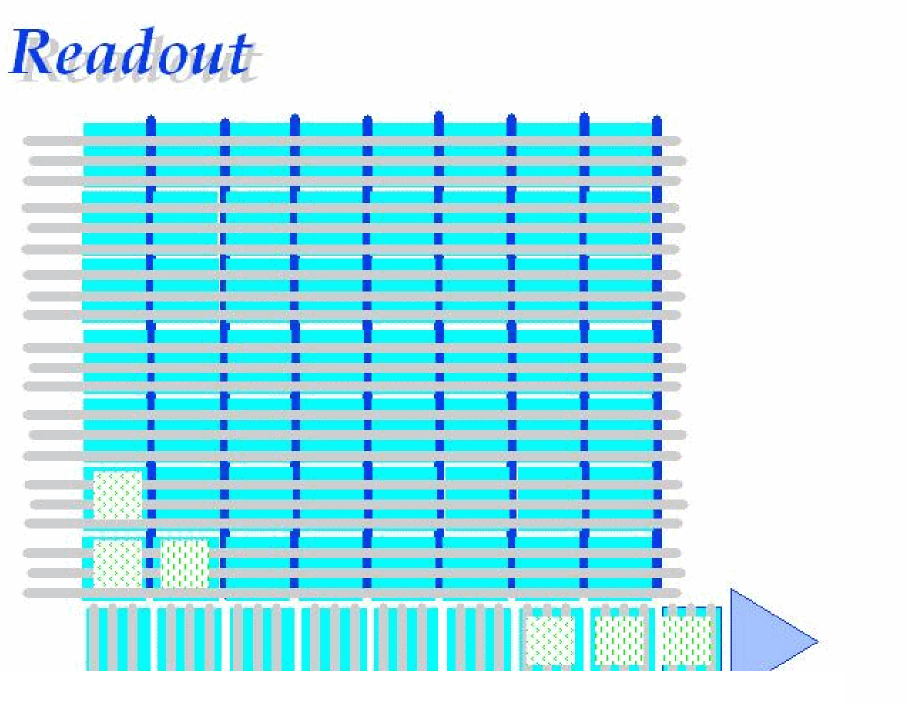
EPIC-MOS CCDs

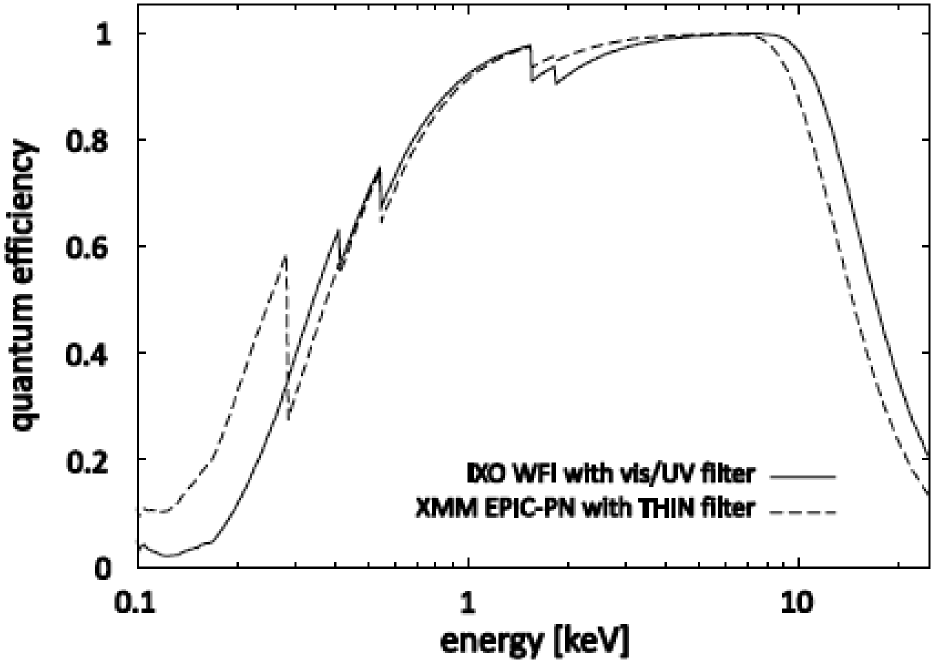
Image courtesy of Leicester University, University of Birmingham, CEA Service d'Astrophysique Saclay

European Space Agency

CCDs

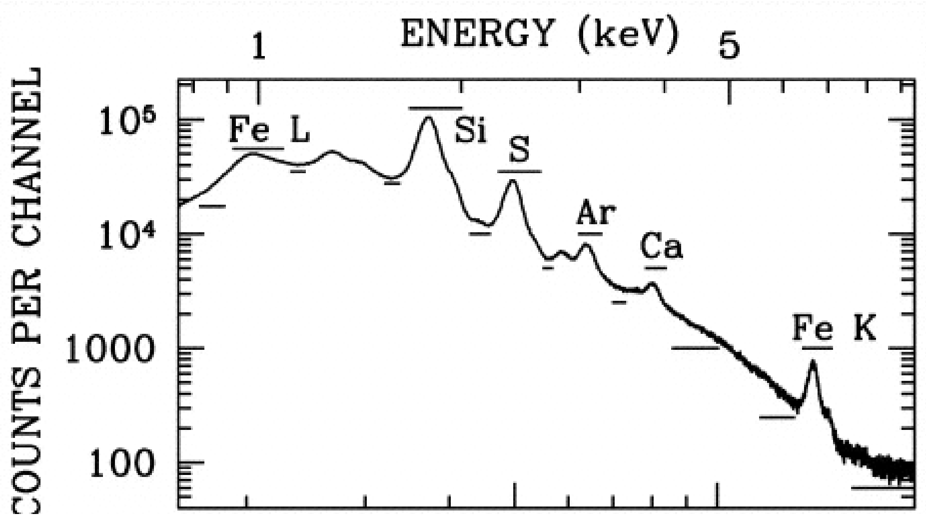
- X-ray CCD is fundamentally different from optical devices-
- Each photon generates charge (typically 1 e- per 3.3 ev of energy) Charge is 'read out' by shifting it from pixel to pixel until it reaches the readout register.
- Goal is to measure the amount of charge ~energy of incoming photon
- Which 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
- http://www.astro.ufl.edu/~oliver/ast3722/lectures/BasicCCDs

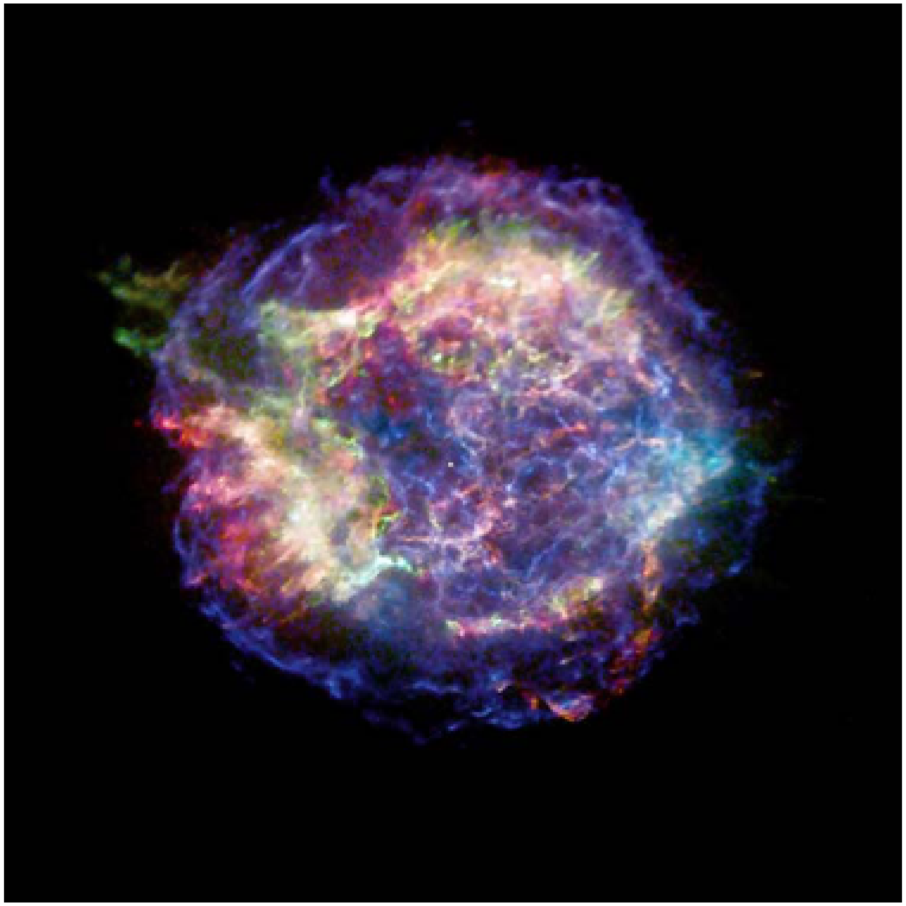




What Sort of Results from CCDs

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

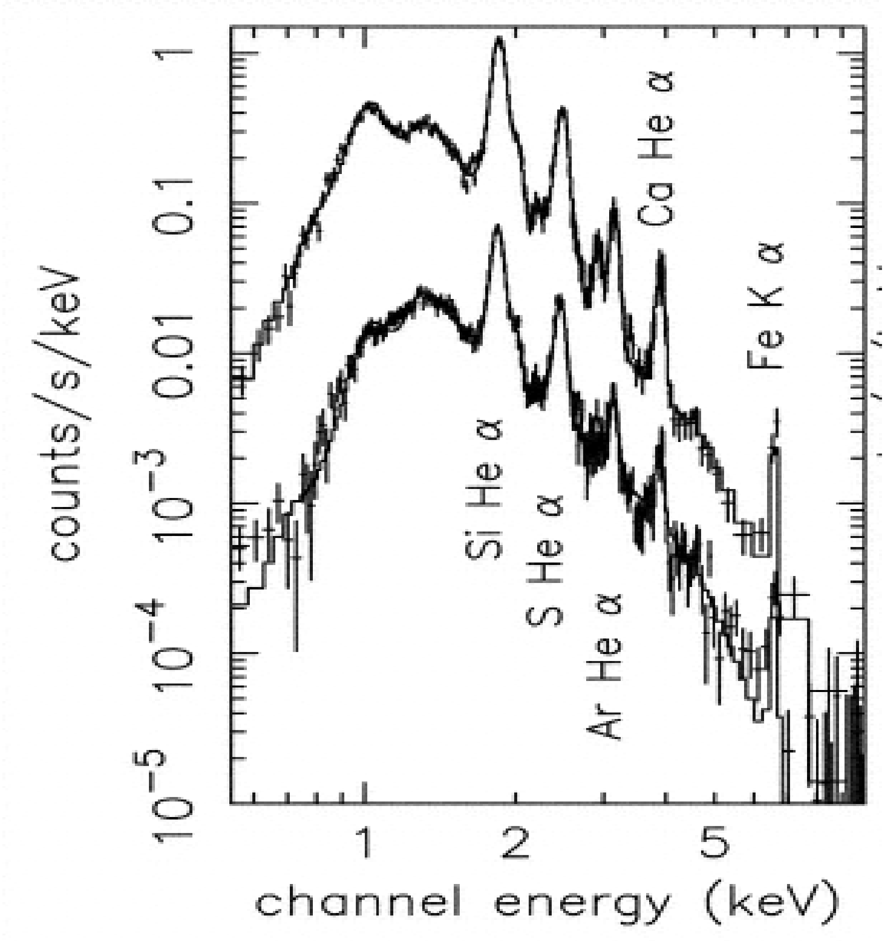


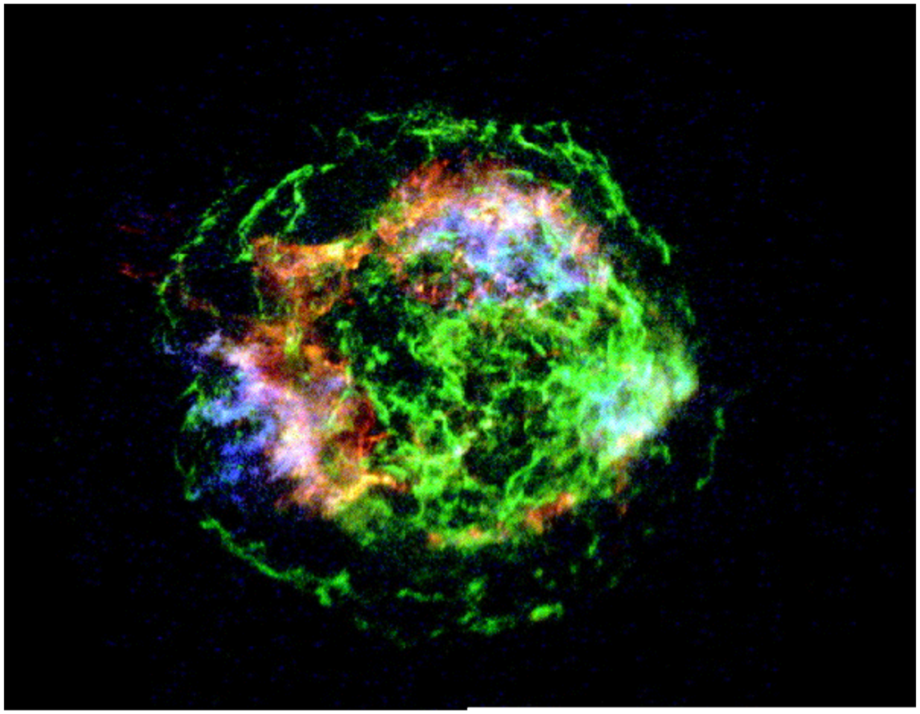


Credit: NASA/CXC/SAO/D.Patnaude et al.

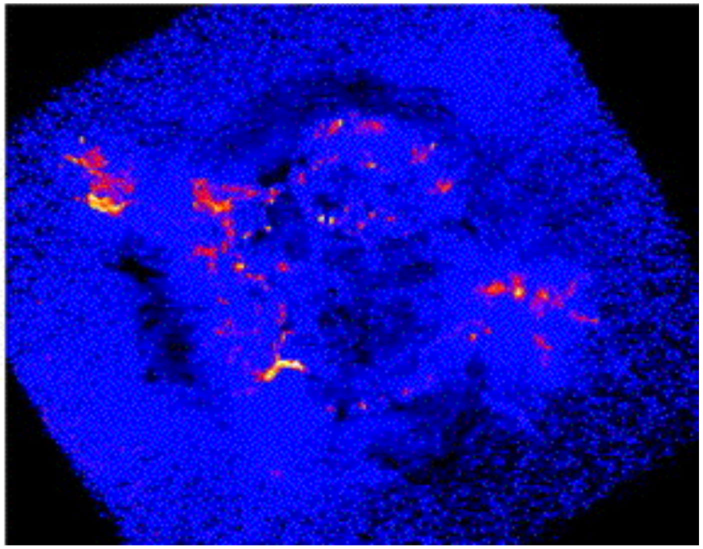
An Elemental Map of Cas-A- Exploded in ~1670 But not seen

- Red=He-like Si, blue=Fe complex
- Bottom right- ratio of Si to





Spectrum of 2 regions in SNR

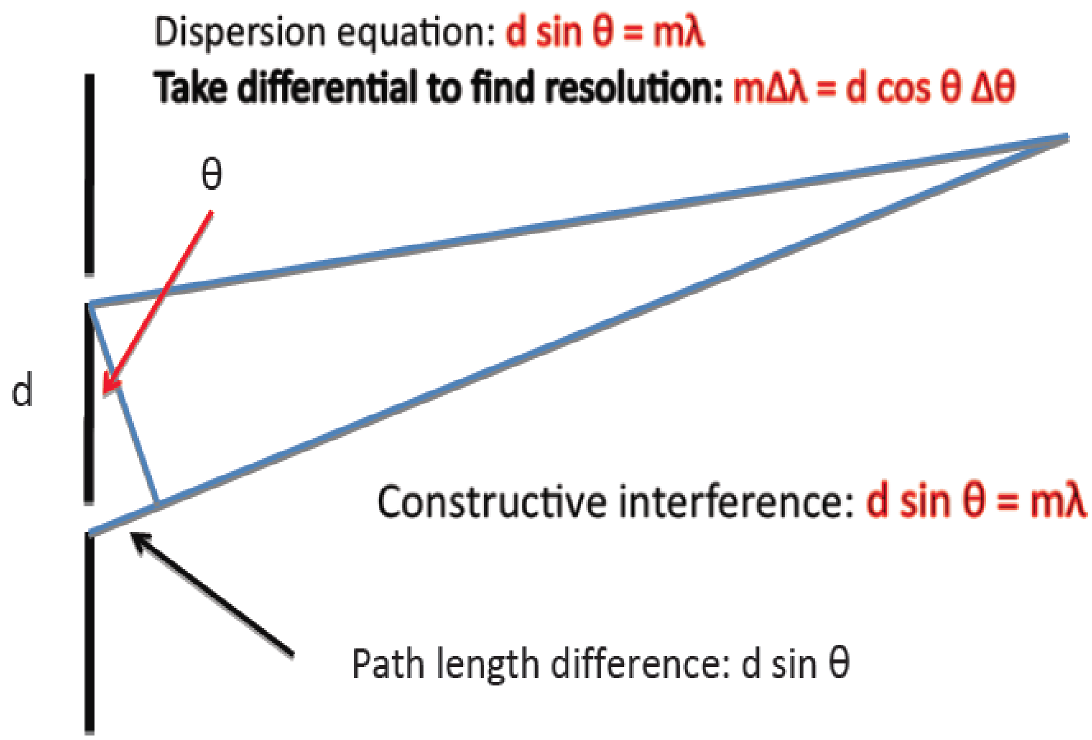


Diffractive Spectrometers- Gratings

- 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 ~1-20A 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 along seve
cleverly chosen paths; no limit to resolution (no 'natural scale', lik

Example: two slits:



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

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

Constructive interference: $d \sin \theta = m\lambda$

Path length difference: $d \sin \theta$

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

'constant $\Delta\lambda$ devices'

Spectrometer Complementarity
Cross-over Occurs in X-ray Band

Non-Dispersive E = hν

Energy Standard (courtesy of nature)

IP, band gap, phonon energy…

$\delta E \sim$ eV (10 → 0.01)

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 ($\sim 10^{2\text{-}3}$ Å)

$\delta x * \theta \sim$ 0.1-0.01 Å

Instruments

- Bragg spectrometers
- Transmission Gratings
- Reflection Gratings

Properties

$\Delta\lambda \sim$fixed

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

Canizares 2007

Chandra Gratings

Paerels and Kahn ARAA 41,291 2003

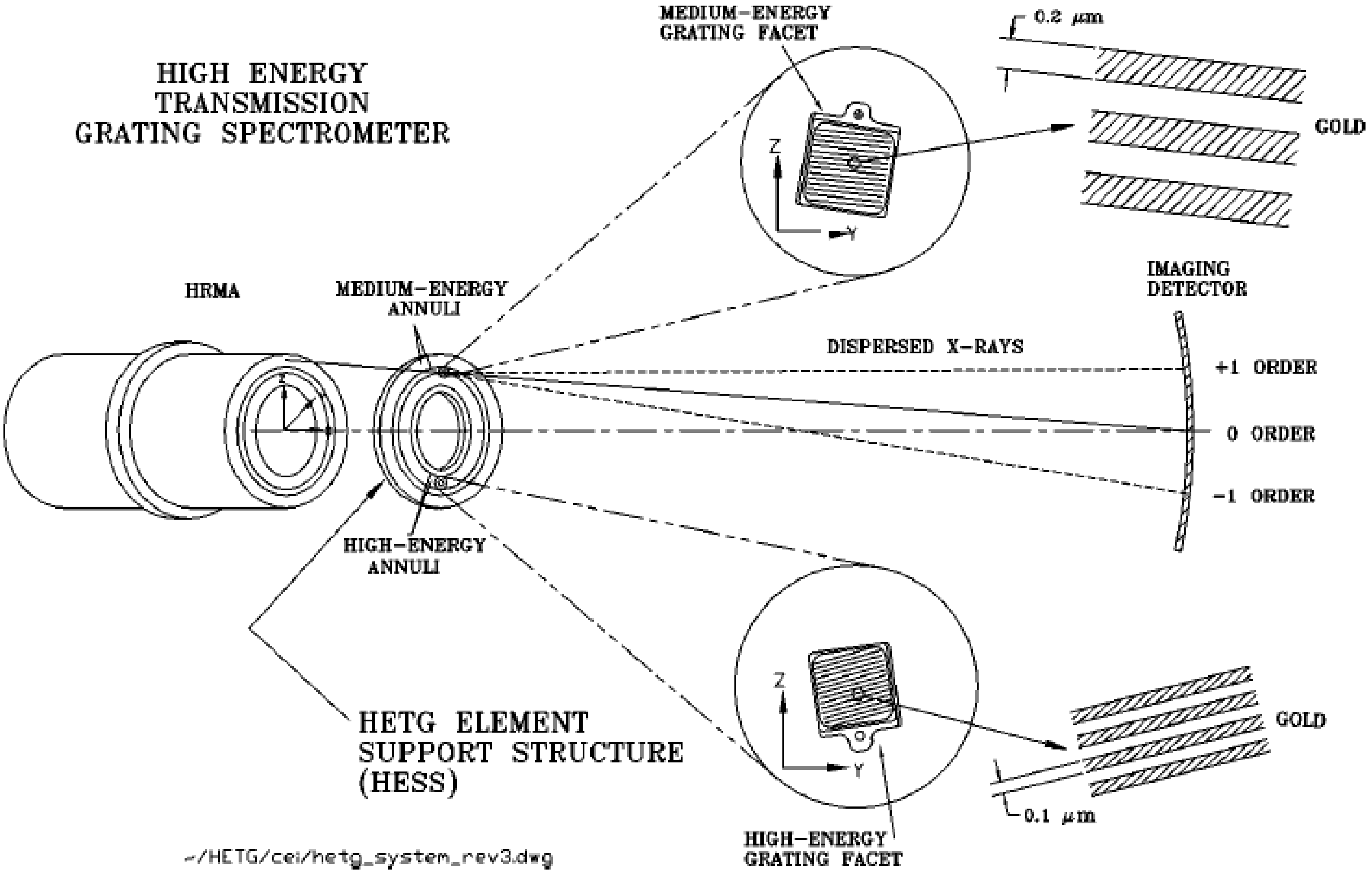
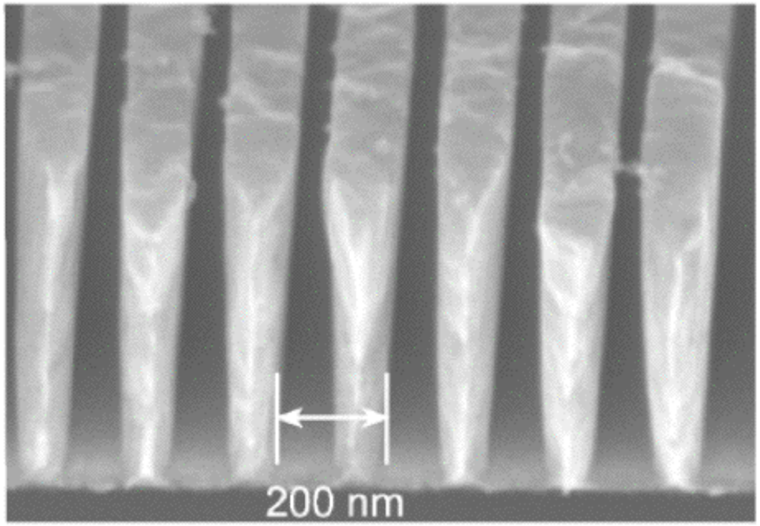
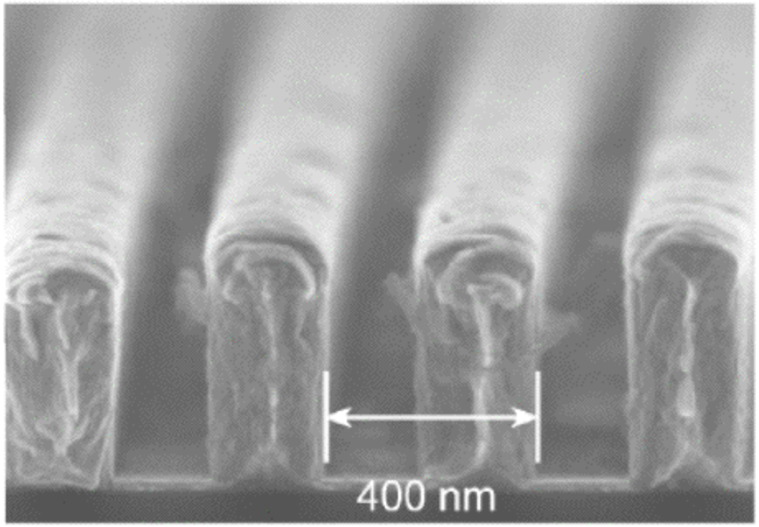


Figure 1 Geometry of the transmission grating spectrometers on *Chandra*. This

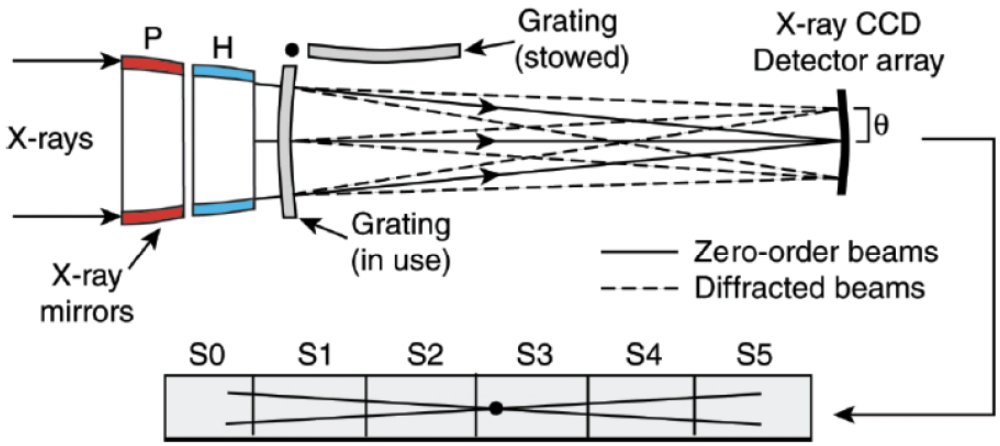
1. *Chandra* HETGS



(a) High Energy Grating (HEG).



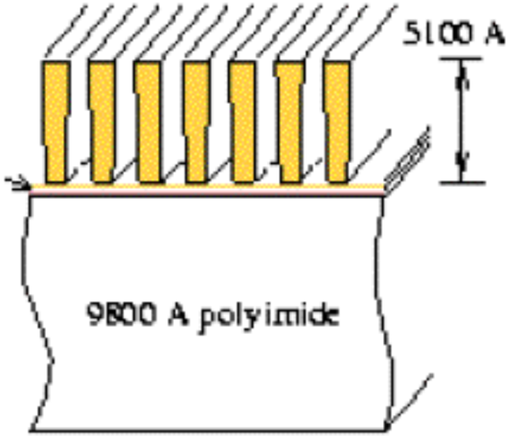
b) Medium Energy Grating (MEG).



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

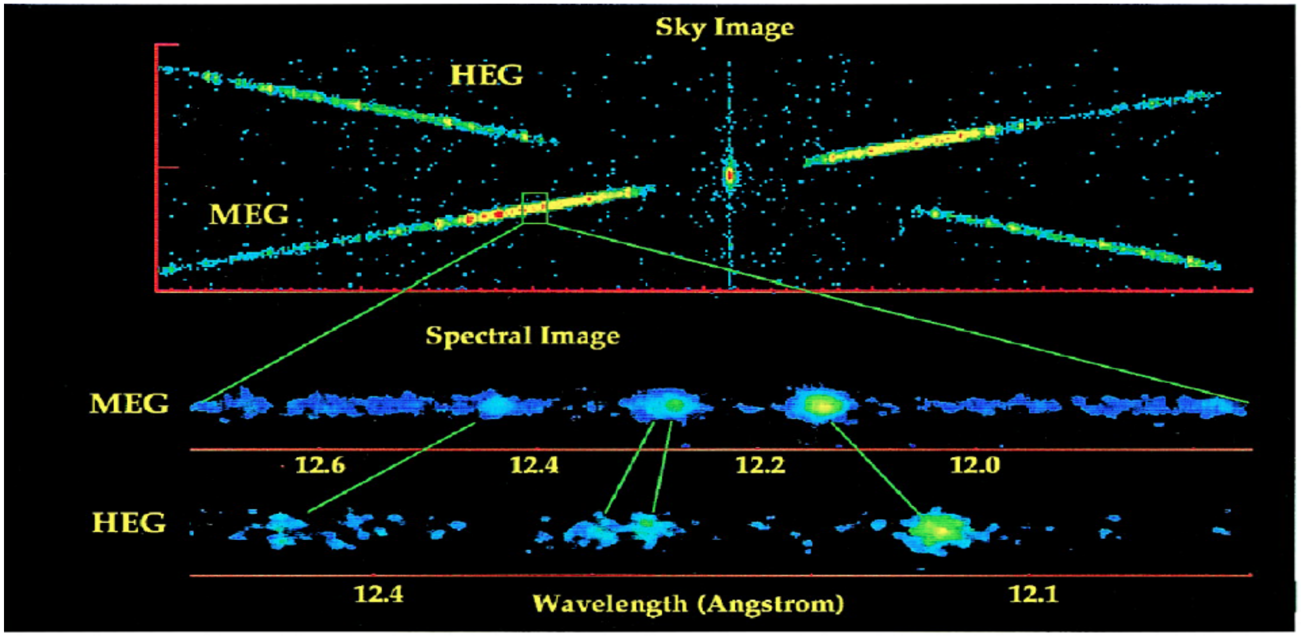
Dispersion equation: $\sin\theta = m\lambda/d$ (θ: dispersion angle, d: grating period, m: spectral order

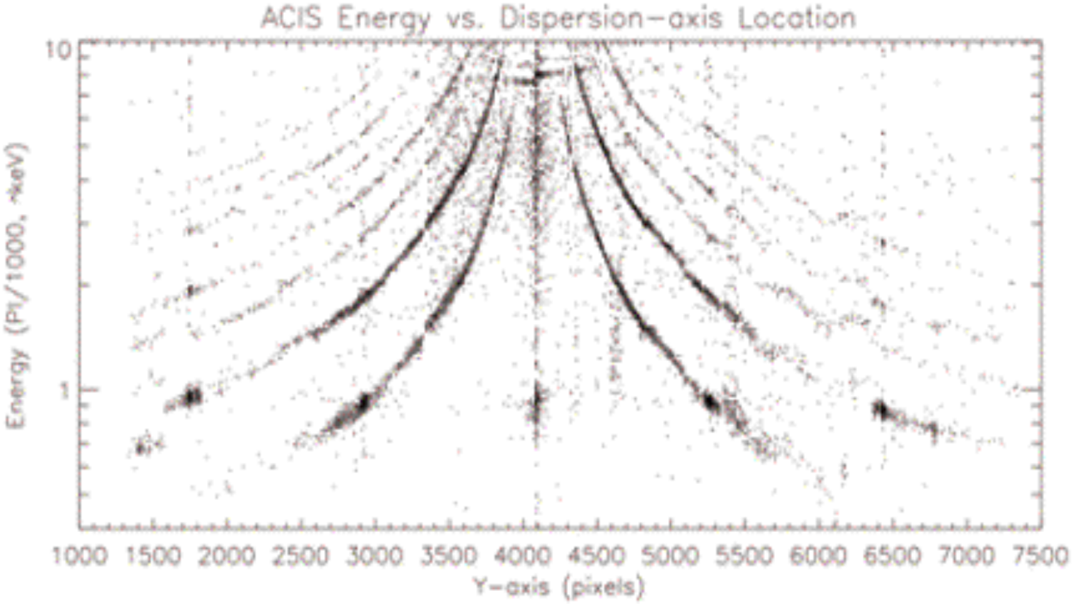
Spectral resolution: $\Delta\lambda = (d/m)\cos\theta\,\Delta\theta \cong (d/m)\Delta\theta$: dominated by telescope image ($\Delta\theta$)



Chandra LETGS uses a different technology

What the Data Look Like



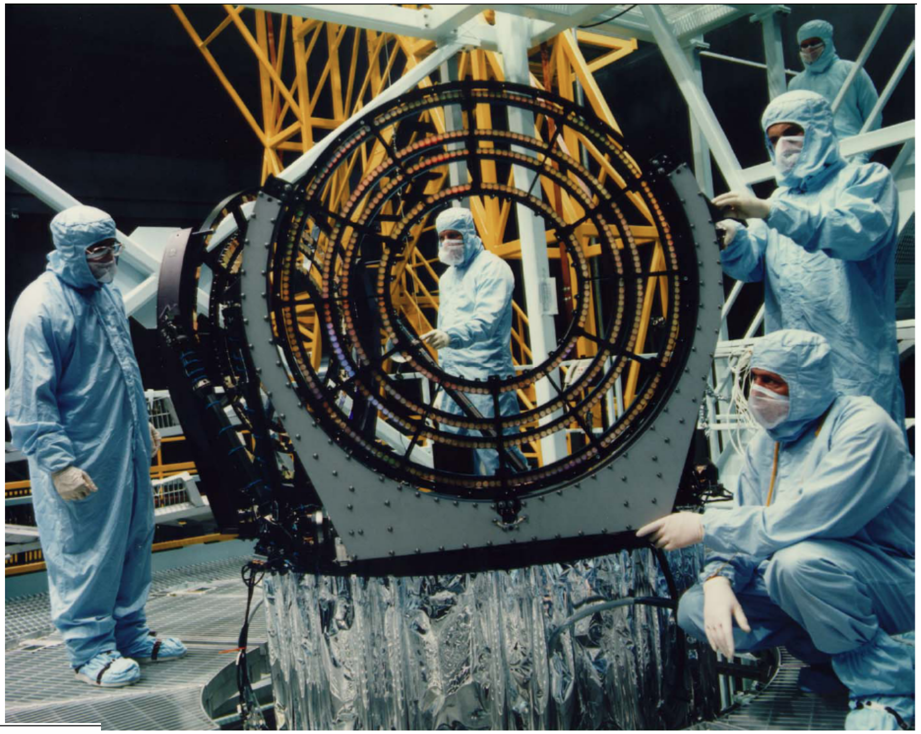


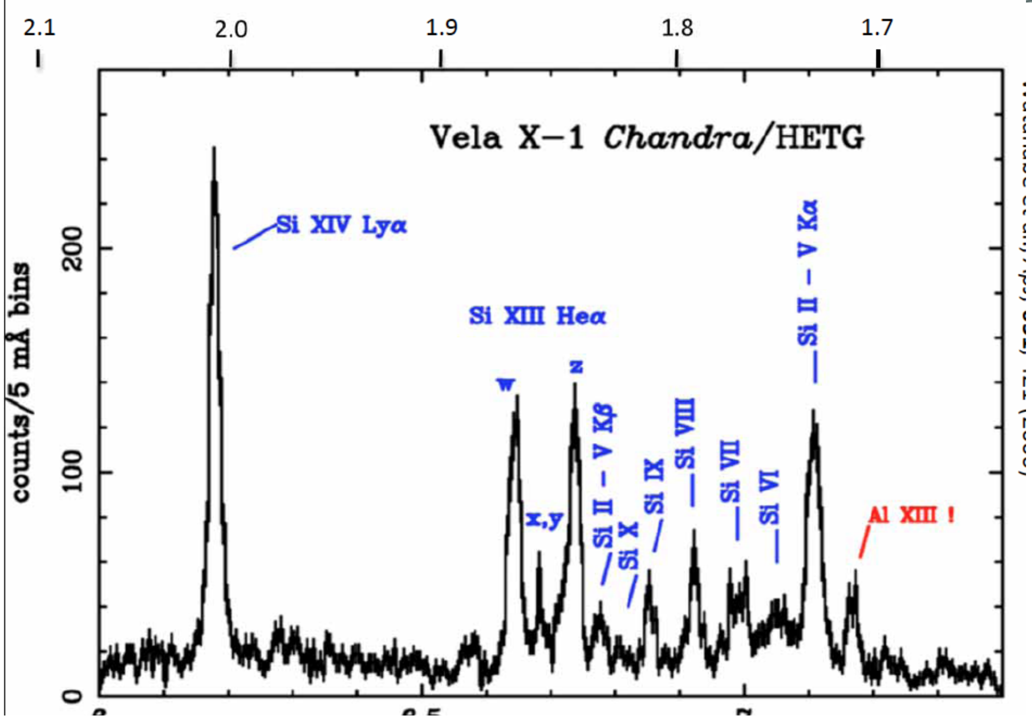
CCD/dispersion diagram
('banana')
NB: CCD energy resolution
sufficient to separate
spectral orders (m = ±1,±2, ...)

- 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

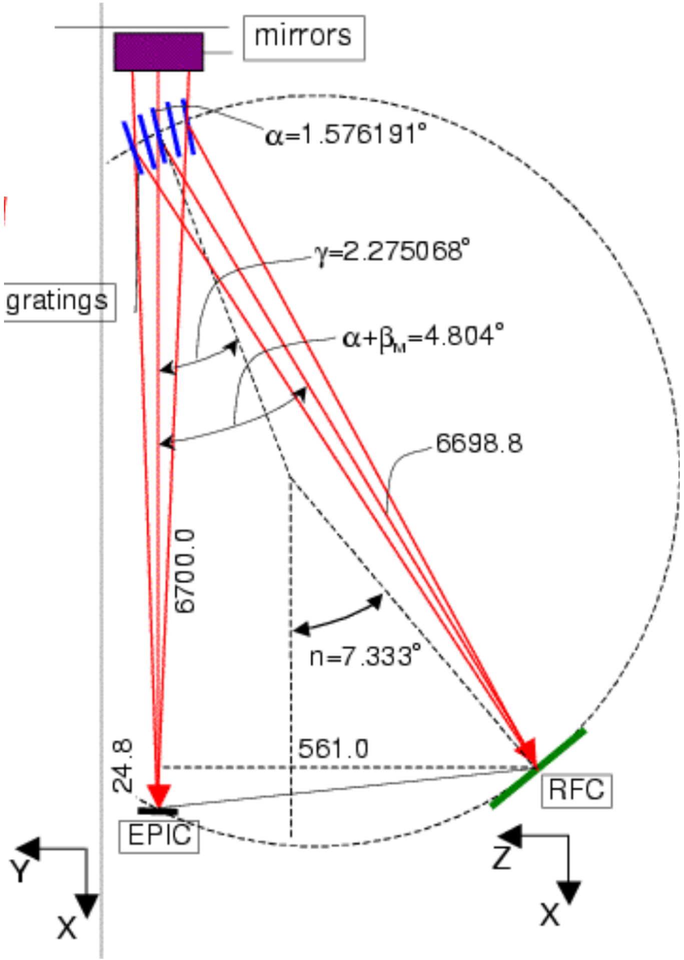




Very accurate wavelength scale: Δv/c ~ 1/10,000 !

XMM RGS

- Alternative geometry is a reflection grating
- Advantages- not free standing, easier to build(large dispersion at moderate groove density) can work on extended sources, simultaneous imaging and spectra



XMM-Newton Reflection Grating Array (RGA)

Image courtesy of Columbia University

European Space Agency

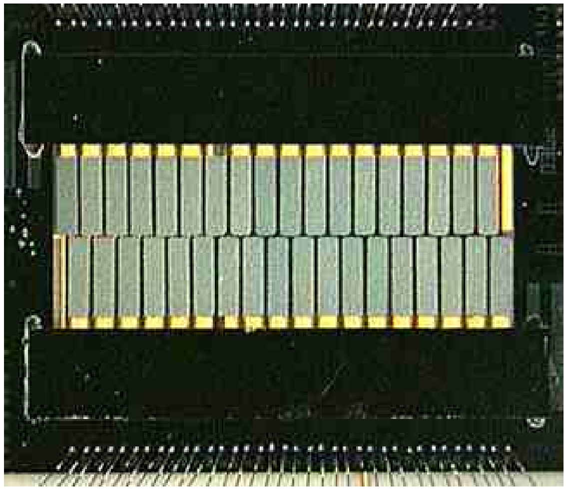
Calorimeter

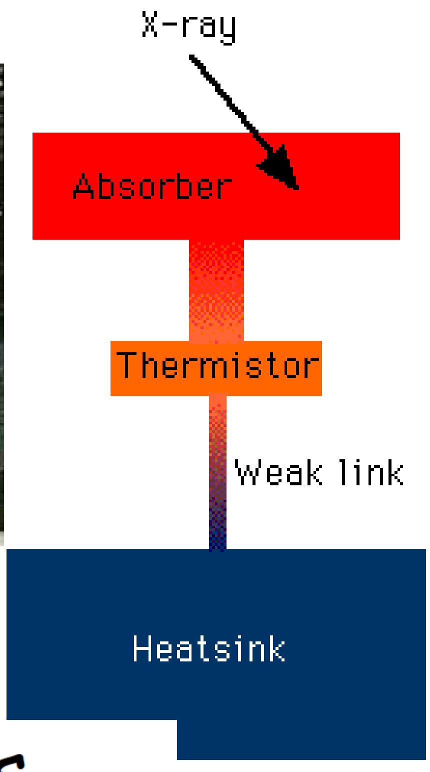
Single-photon calorimeters-Absorb a photon and measure the increase in T

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

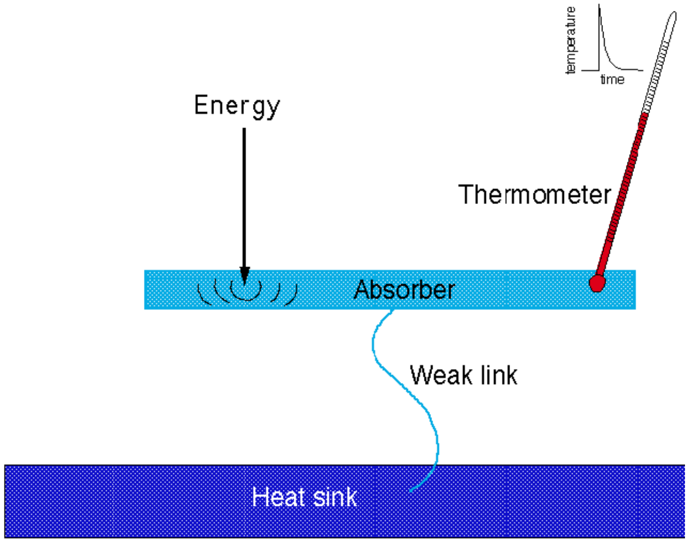
$$\Delta E \sim \sqrt{(kT_b^2 C_b)/|\alpha|}$$

- 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
- Best achieved energy resolution: 1.4eV
- Can be imaging, high quantum efficiency
- Physics Today, August 1999, pp 32-37.
- McCammon 2005 Cryogenic Particle Detection



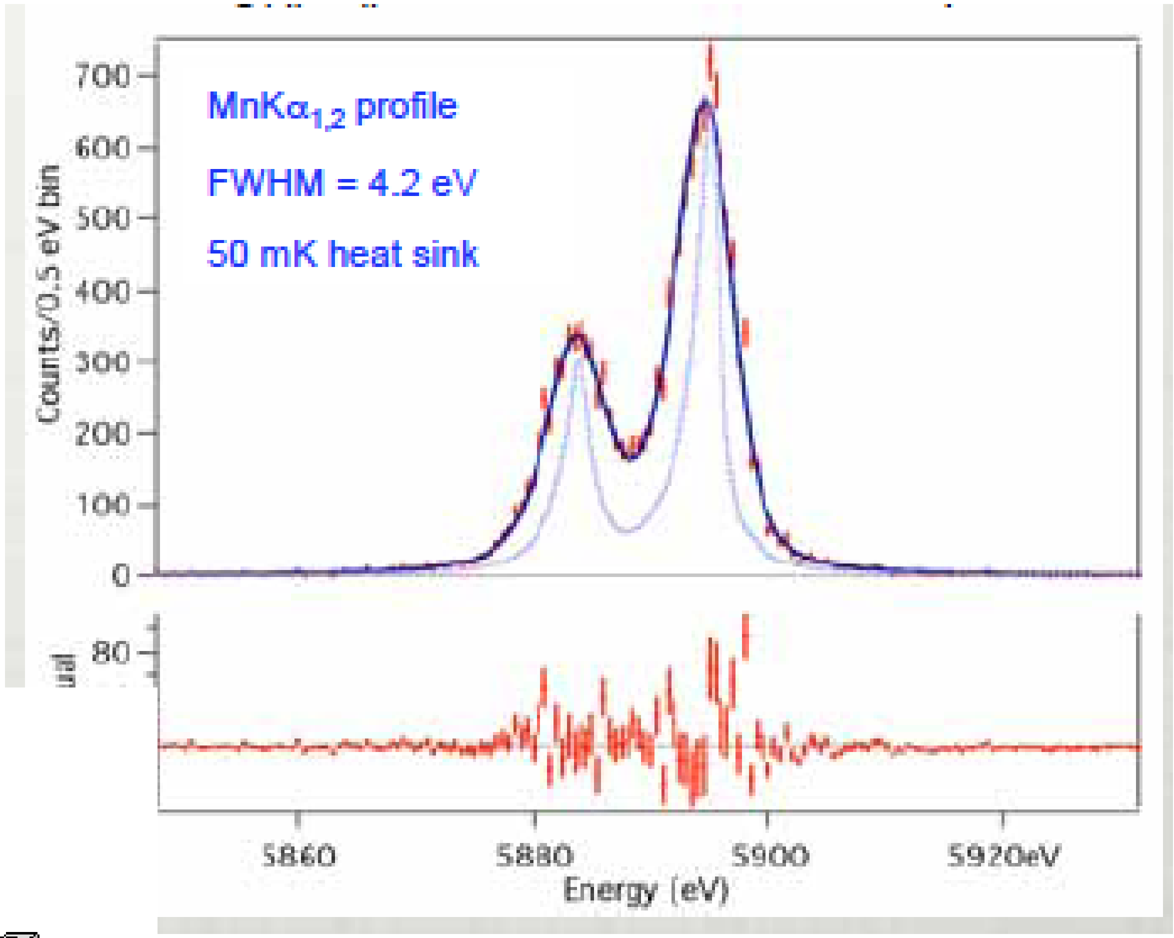


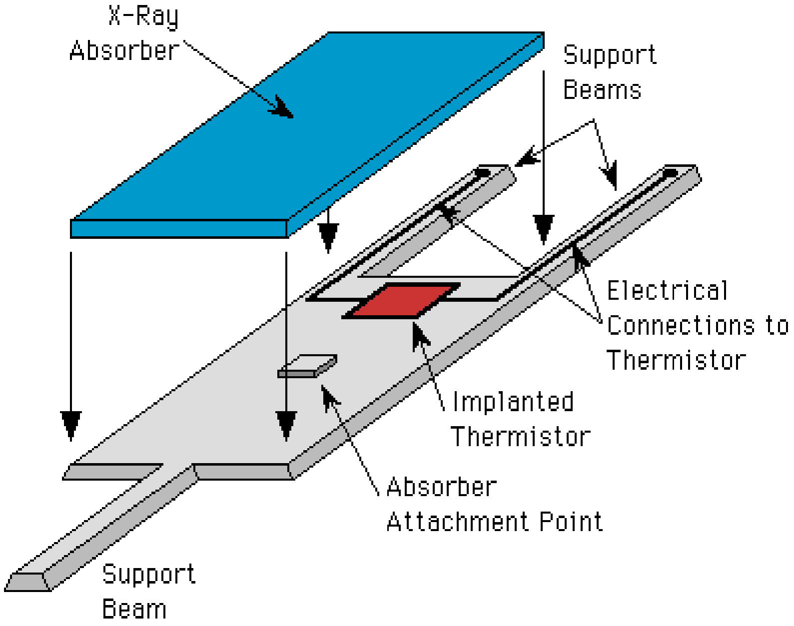
Calorimeters



Calorimeter

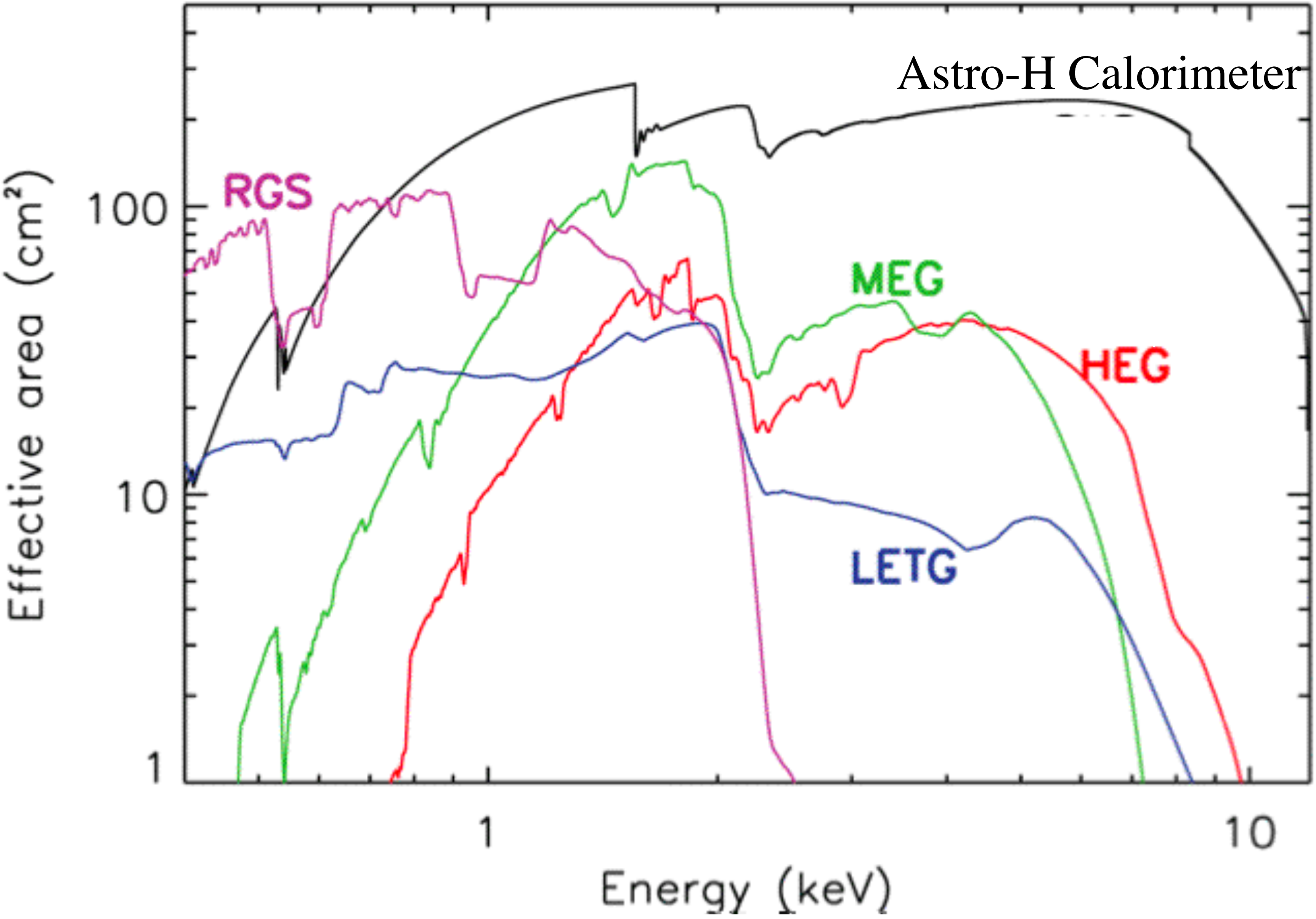
- Lots of interesting physics and engineering (how to keep a detector at 60mK for long times)





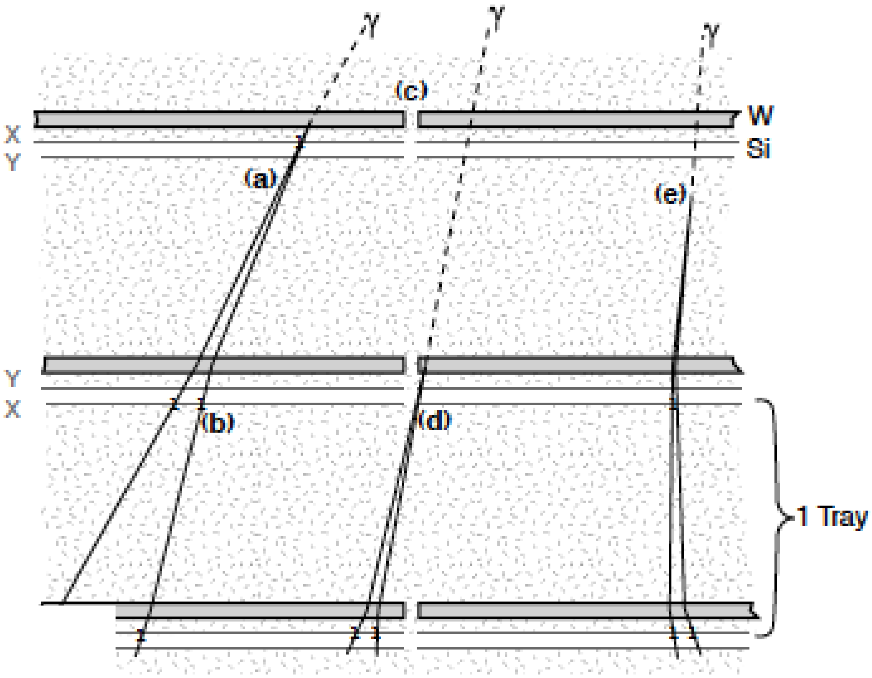
A rocket payload (Micro-X) is being built now and a μ-calorimeter for Astro-H is under development

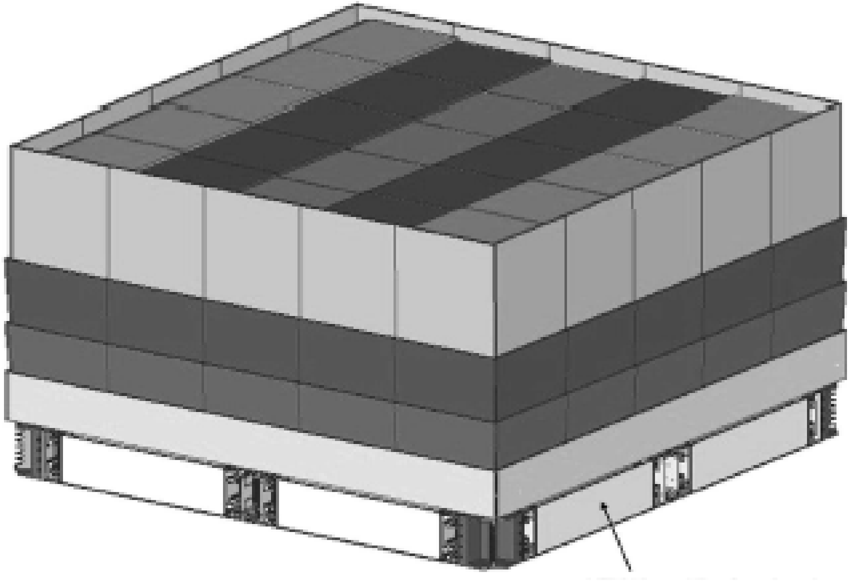
Comparison of Effective Areas of X-ray Spectrometers



γ-ray Detectors

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



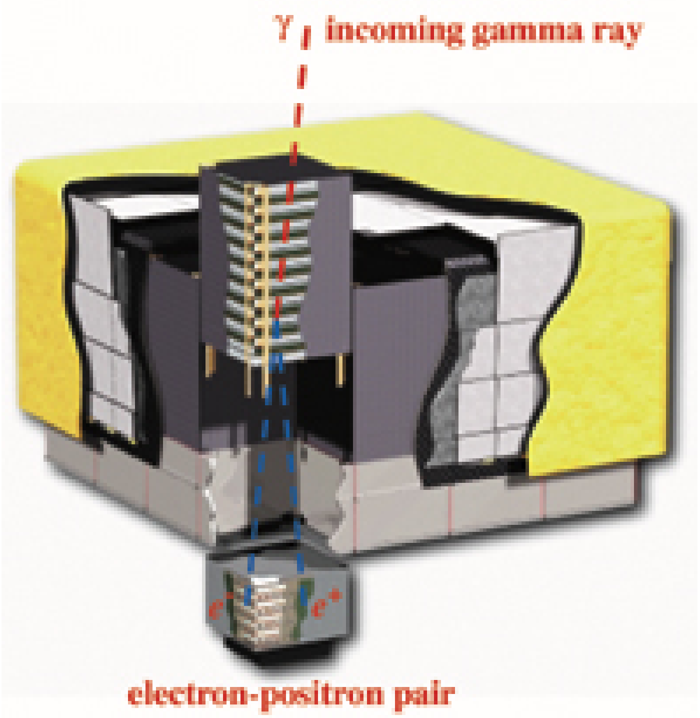


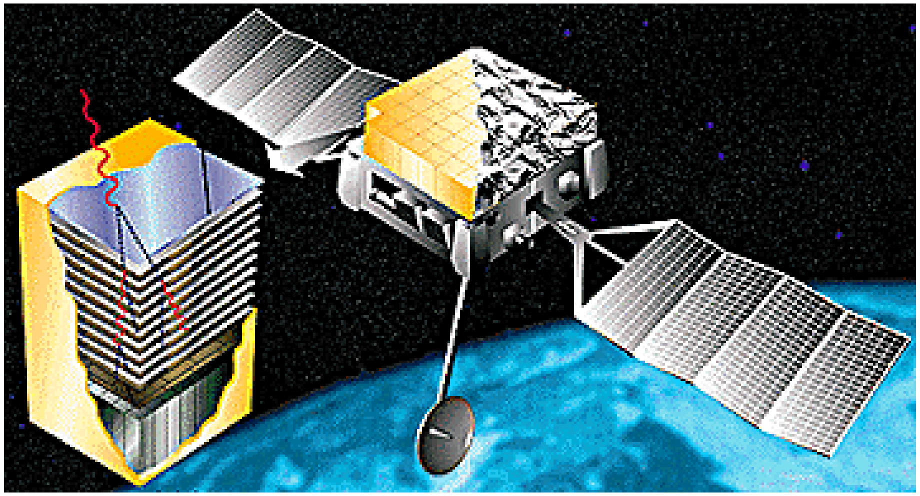
Full coverage of anti-coincidence detectors

γ-ray Detectors

Fermi energy range from 20 MeV - 300 GeV.

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



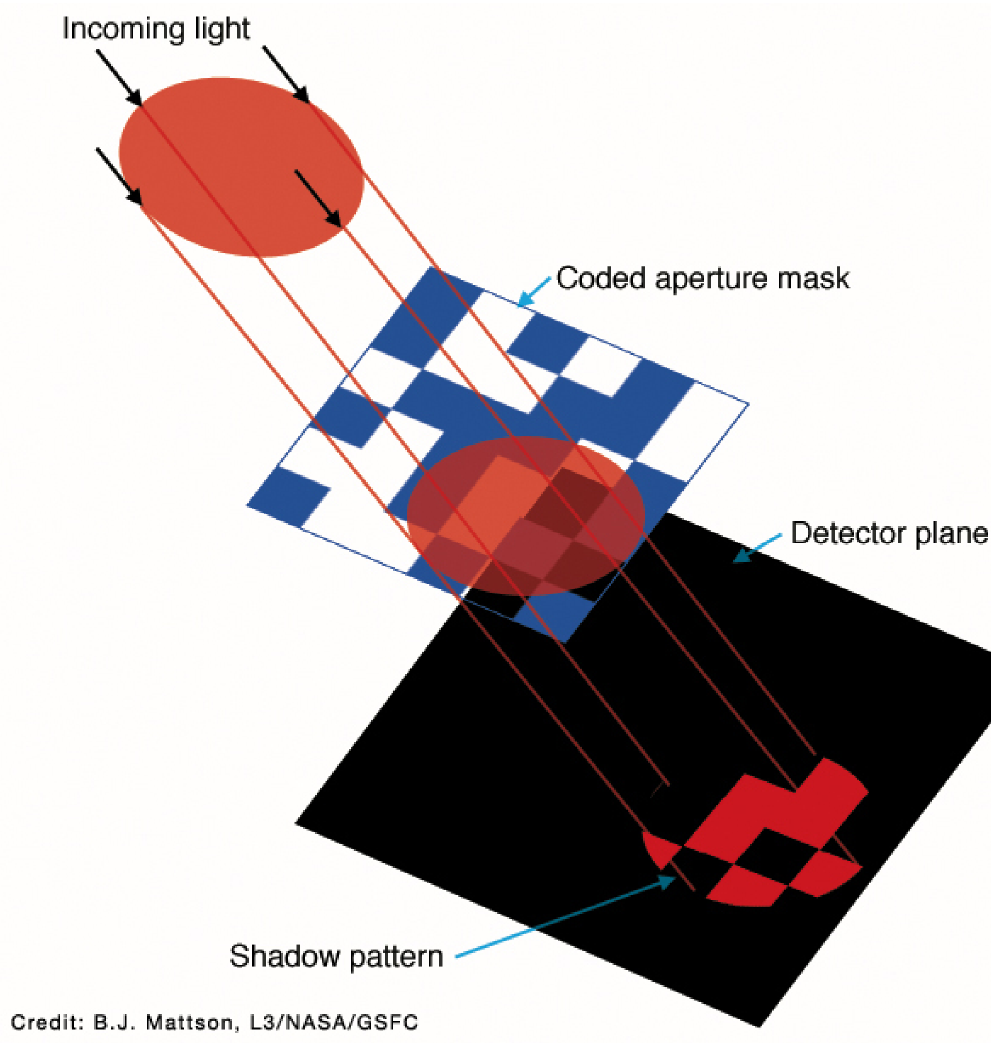


Other Detectors

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

High Energy Telescopes

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



Credit: B.J. Mattson, L3/NASA/GSFC

High Energy Telescopes

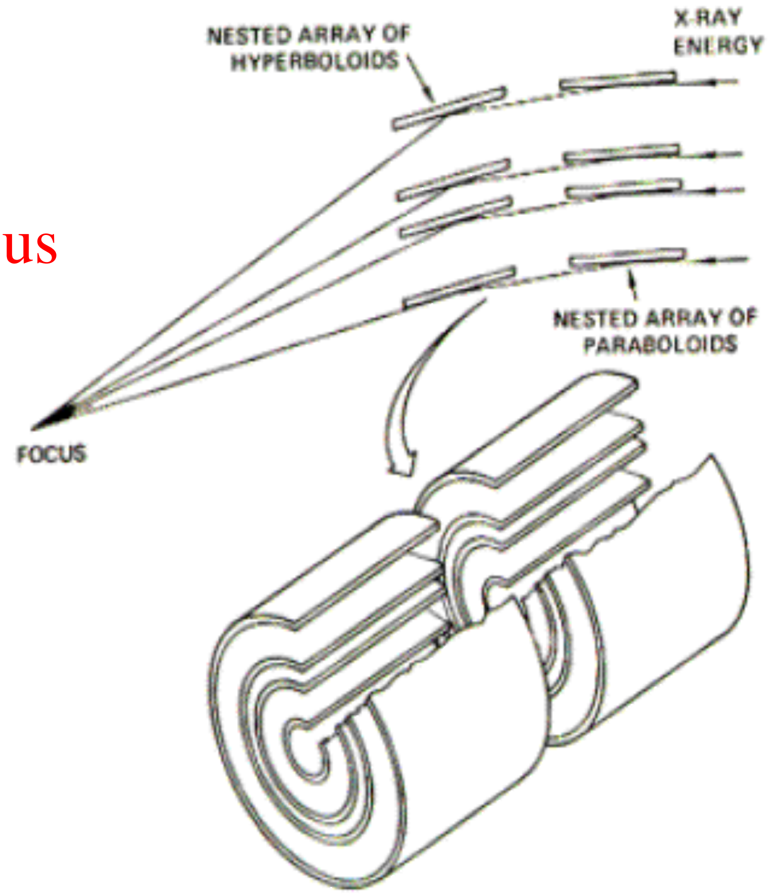
- 'true' imaging telescopes
- X-rays can be reflected at 'grazing' incidence (phenomenon of total external reflection at a surface where the index of refraction changes)

X-Ray Optics

Have to make the x-rays reflect and focus

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

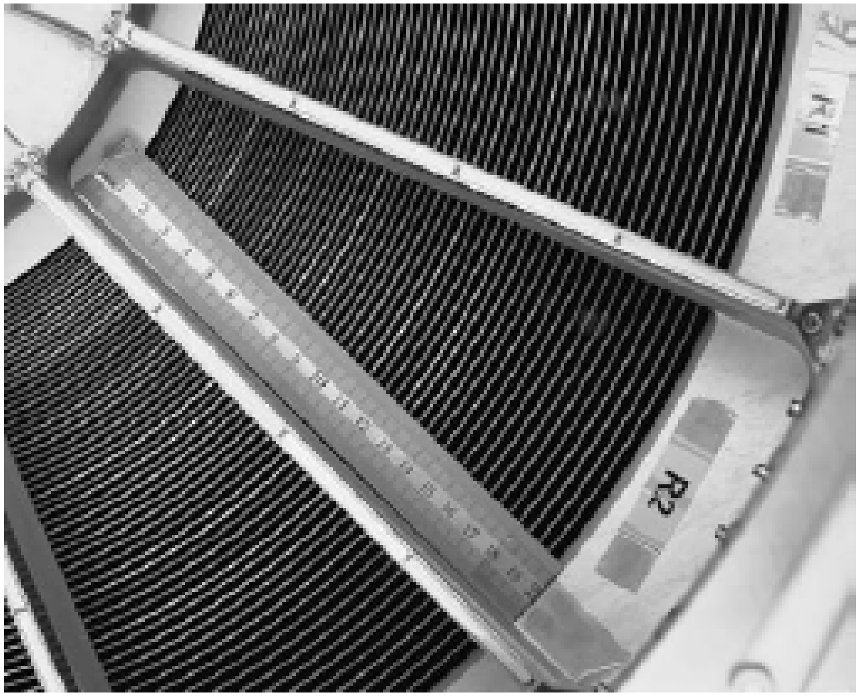
X-Ray Imaging Optics



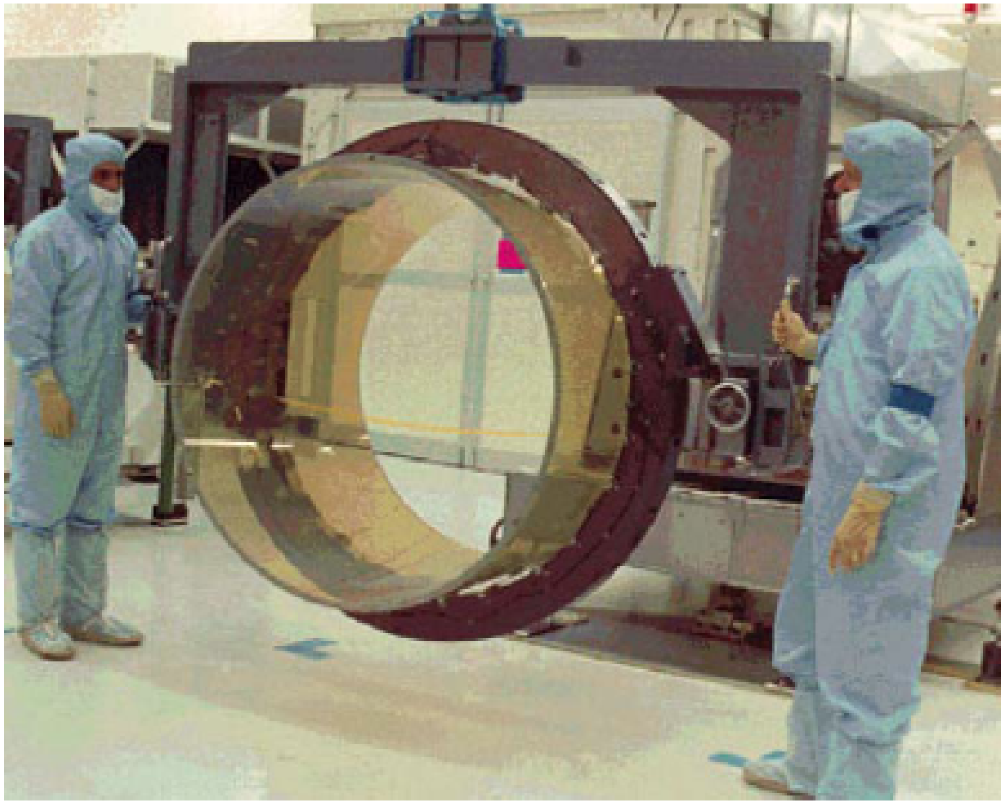
Chandra

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

Images of X-ray Optics



XMM Optics- 58 nested
Shells, 0.5mm thick



1.2m diameter, 1 m long Chandra optic

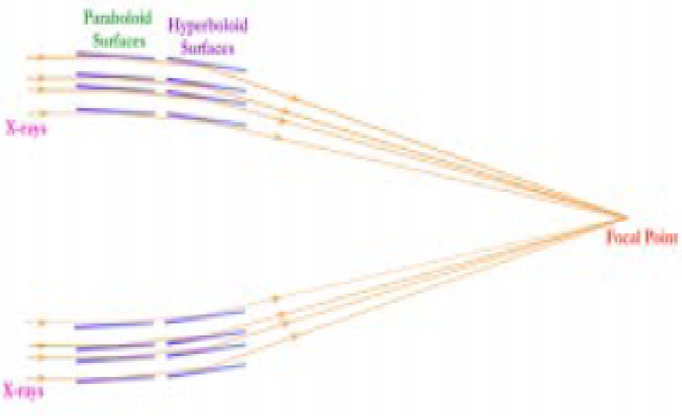
X-Ray Reflection: Zero Order Principles:

Refs:

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

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

very detailed

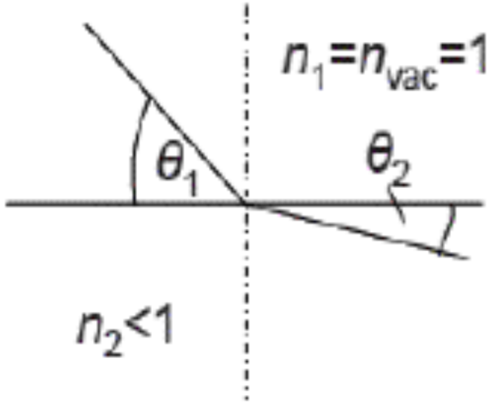


X-rays reflect at small grazing angles.

An analogy is skipping stones on water.

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

Principle of grazing incidence



Snell's law:

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

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

For X-rays the refractive index can be written as

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

δ proportional to the atomic number Z

=> n small for heavy materials

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

Grazing Incidence (Aschenbach 1984)

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

  $n_r = 1 - \delta < 1$,

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

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

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

  $\delta = (r_e/2\pi)(N_0\, \rho/A) Z \lambda^2$

- where N_0 is Avogadro's number, r_e is the classical electron radius, Z and A are the atomic number and weight, respectively, and ρ is the mass density.

- For heavy elements for which $Z/A \approx 0.5$, the incidence angle of total reflection for $\delta << 1$ can be estimated to:

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

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

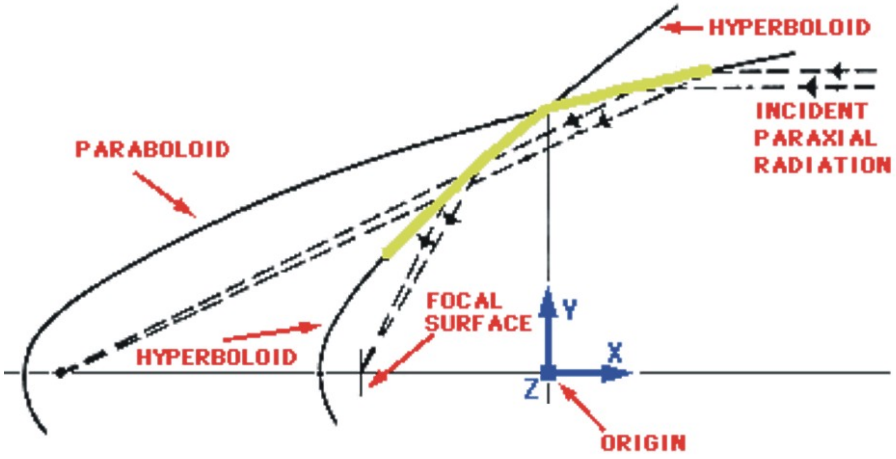
  So high density materials Au, Pt, Ir are best for reflection coatings

Wolter I mirror

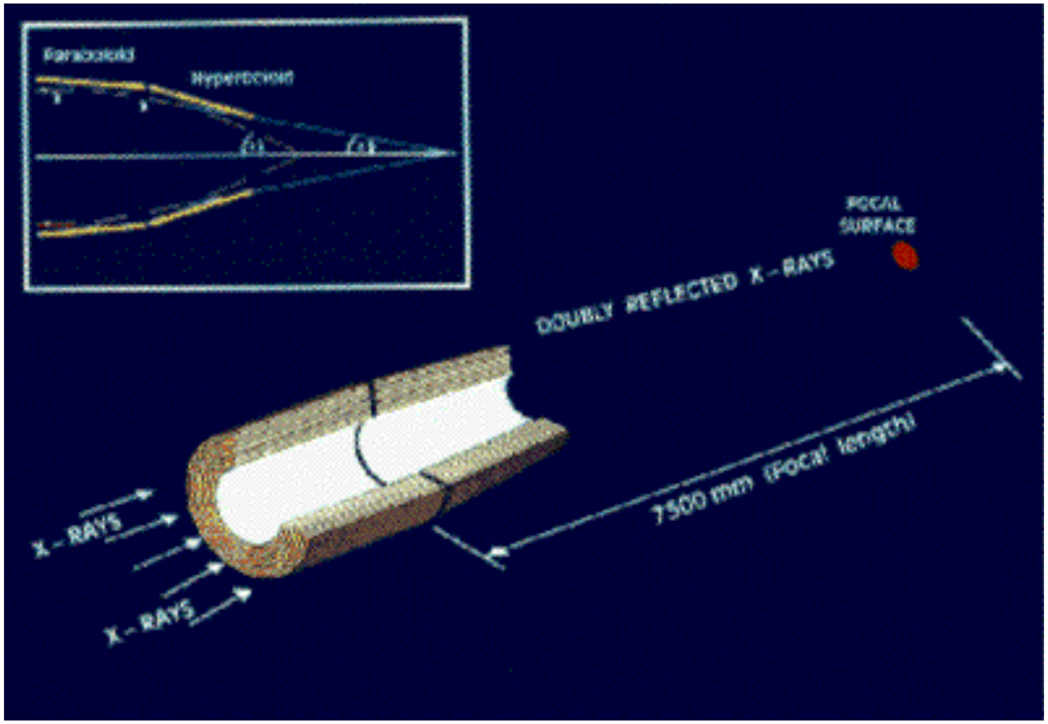
F= focal length = R / tan 4θ

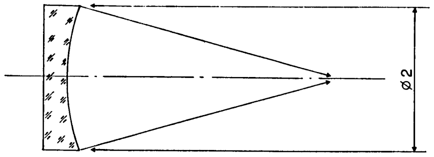
θ= *on-axis incidence angle*

R = aperture radius

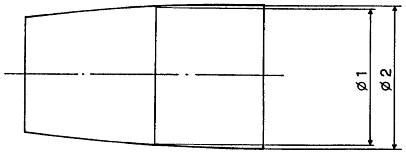


- minimum focal length for a given aperture
- it allows the nesting together of many confocal mirror shells
- Effective Area: $8 \pi F L \theta^2 \mathrm{Refl.}^2$

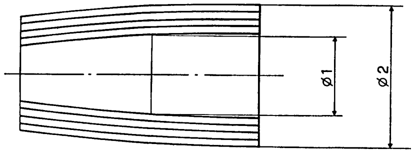




$$S_V = \frac{\pi \, ø_2^2}{4}$$

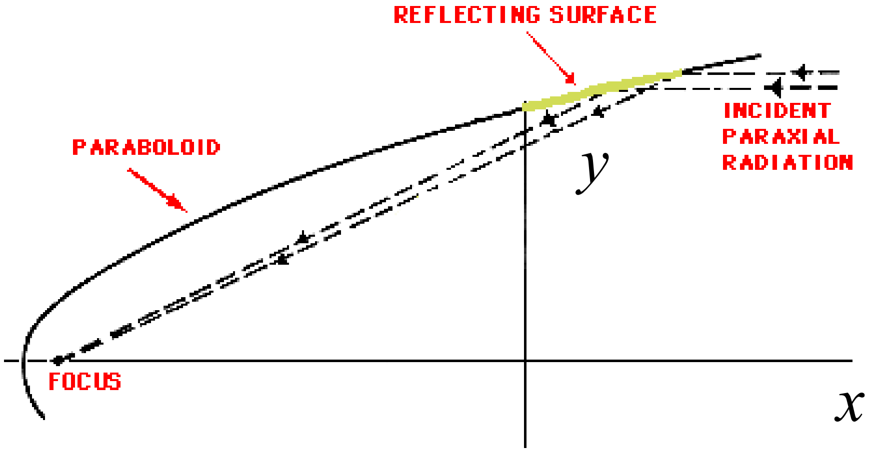


$$S_1 = \frac{\pi \, (ø_2 - ø_1)^2}{4}$$



$$S_X = \frac{\pi \, (ø_2 - ø_1)^2}{4}$$

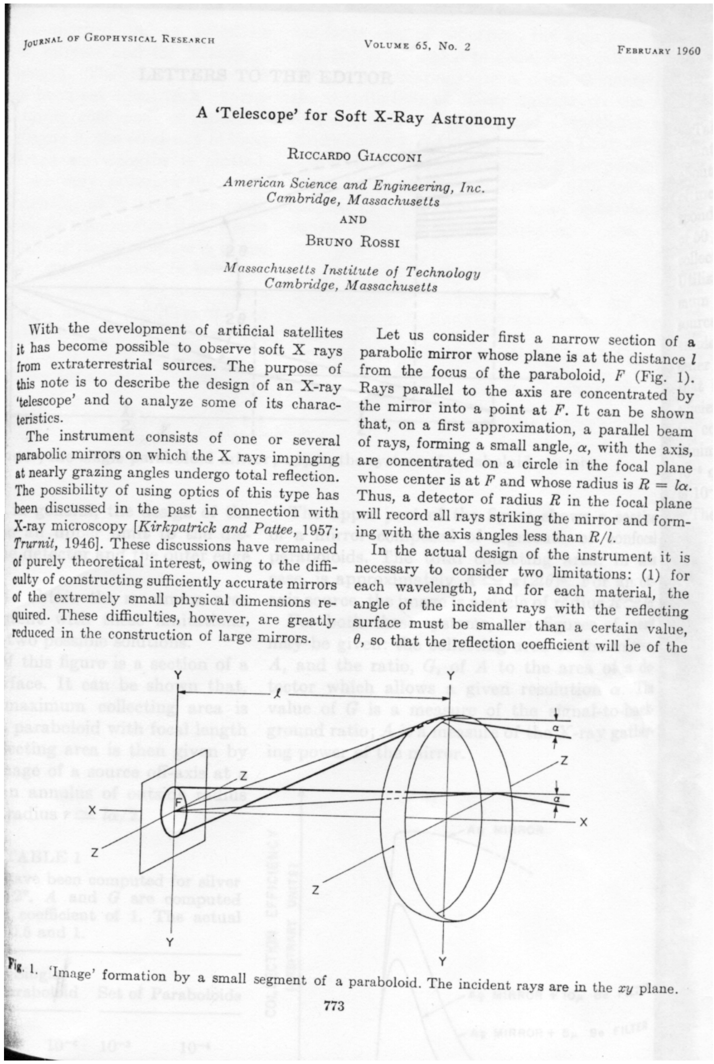
X-ray mirrors with parabolic profile



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

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

- perfect on-axis focusing
- off-axis images strongly affected by **coma**



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

A 'Telescope' for Soft X-Ray Astronomy

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American Science and Engineering, Inc.
Cambridge, Massachusetts

and

Bruno Rossi

Massachusetts Institute of Technology
Cambridge, Massachusetts

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

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

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

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

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

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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

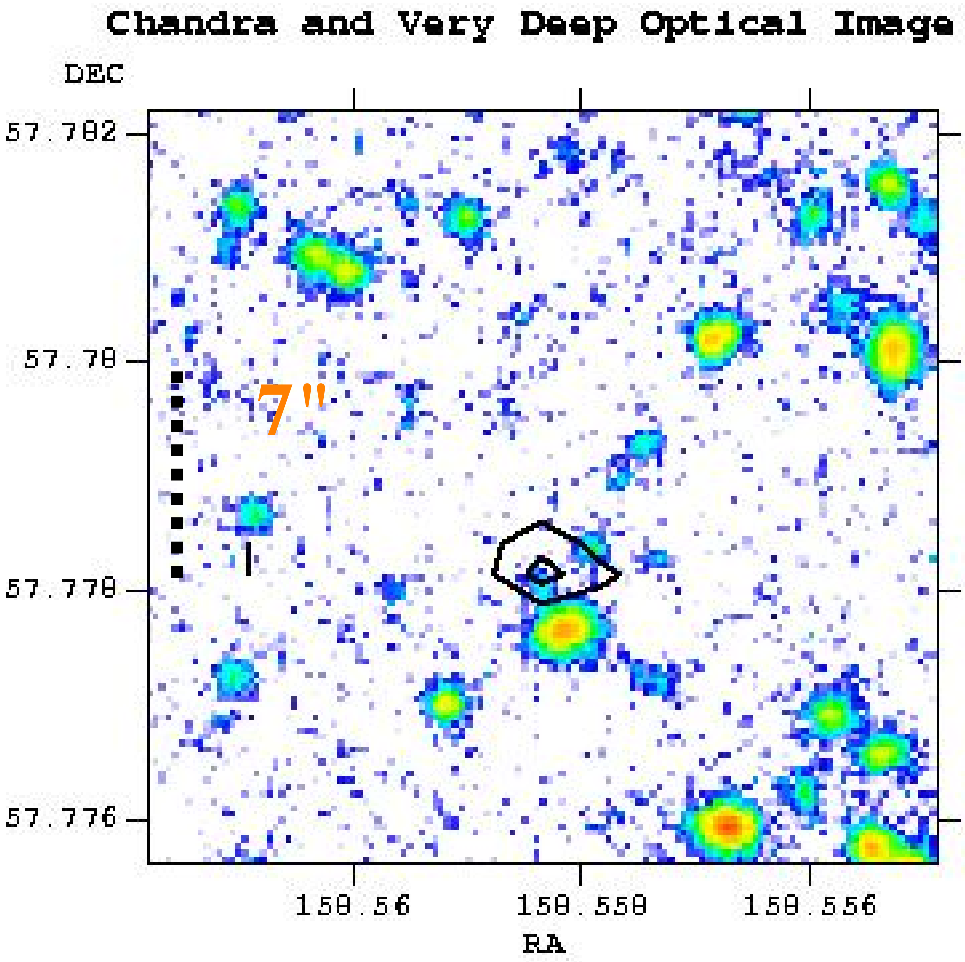
the f-number is inversely proportional to the angle of total reflection which decreases linearly with increasing photon energy- telescopes optimized for the low-energy regime (<2 keV) have lower f values (are faster- better for surface brightness)

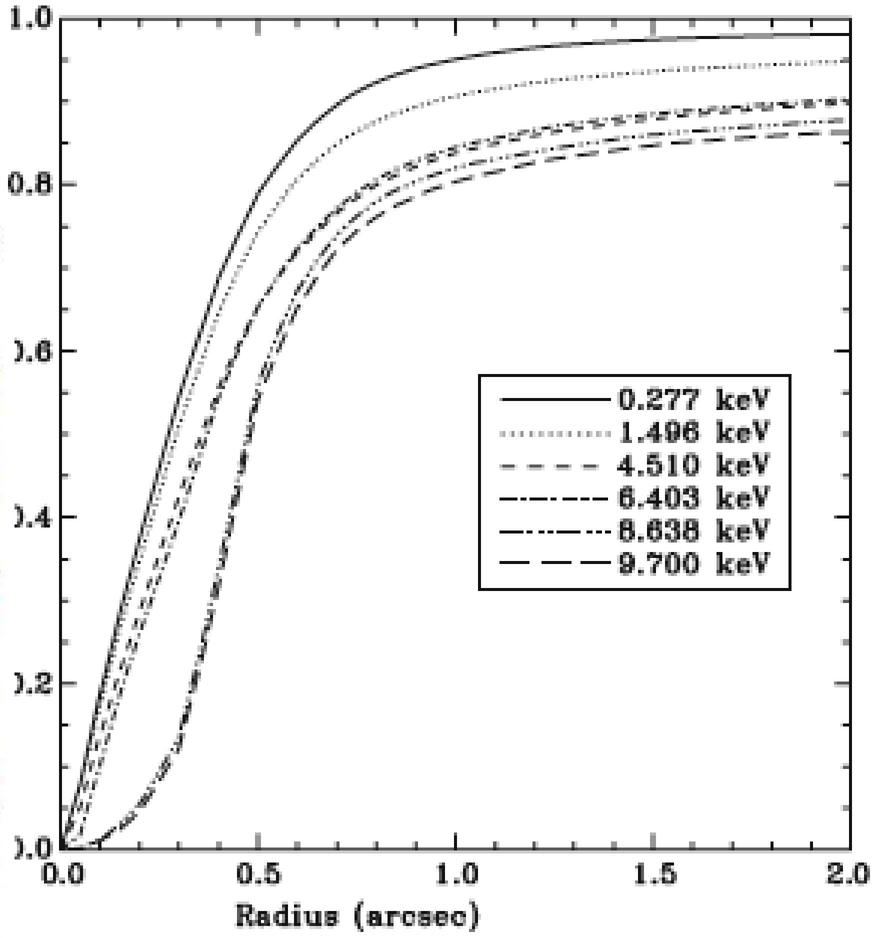
- Because of the intimate interdependence between f-number, grazing angle, telescope diameter and focal length, large diameter (collecting area) telescopes working at high energies require long focal lengths,

Rosat Telescope

Can Get Pretty Good Images

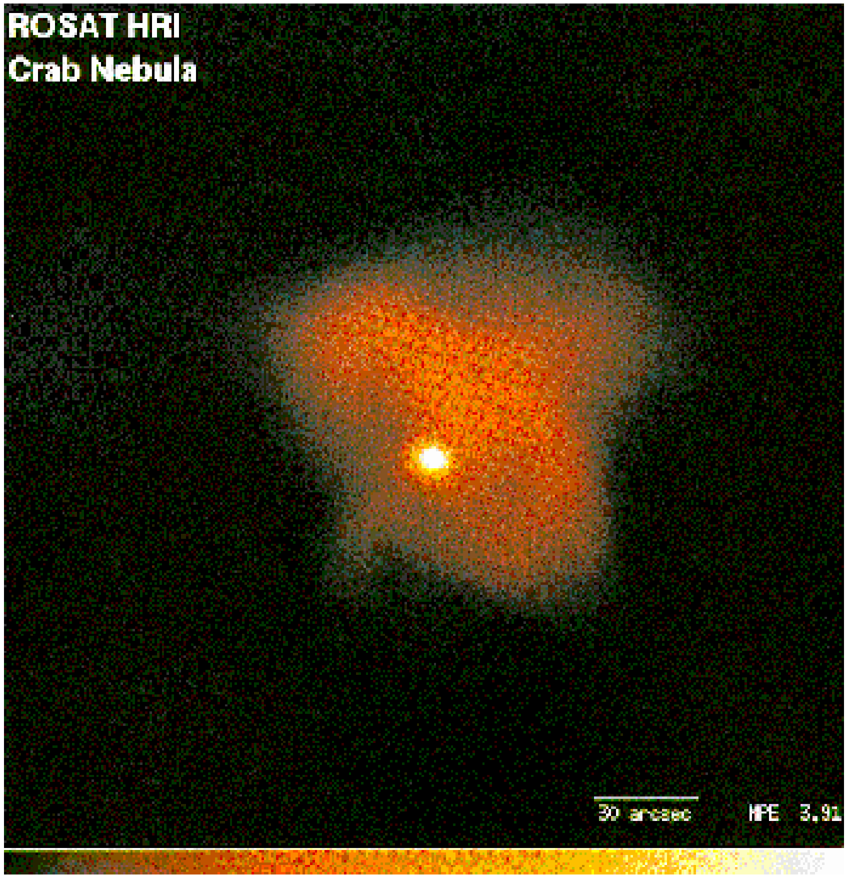
- Chandra Images are as good as the best images that can be obtained from the ground



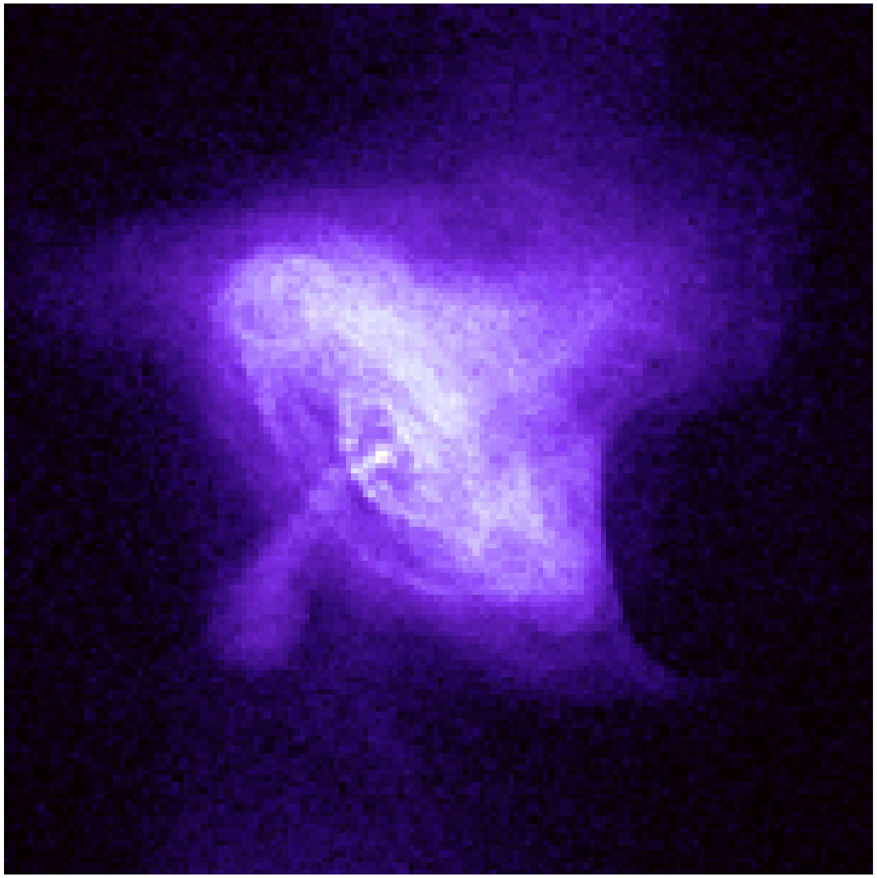


Chandra- fraction of energy inside an inscribed circle on axis

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



Rosat: HPD = 3 arcsec



Chandra: HPD = 0.5 arcsec

Mirror Collecting Area

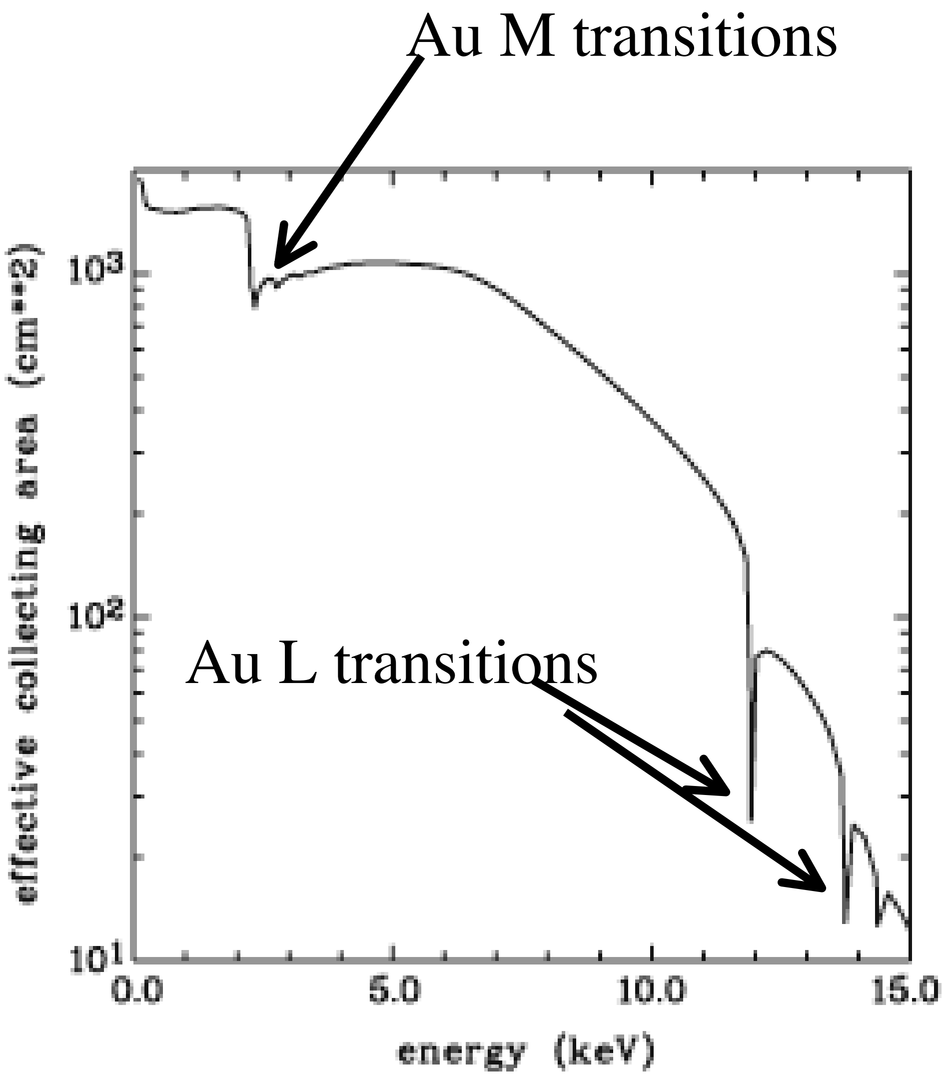
- Depends on mirror diameter, number of shells, focal length and coating of mirror (e.g. which metal coats the substrate)
- XMM mirror- the 'bumps and wiggles' are due to the atomic transitions of gold (the coating material)

- 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

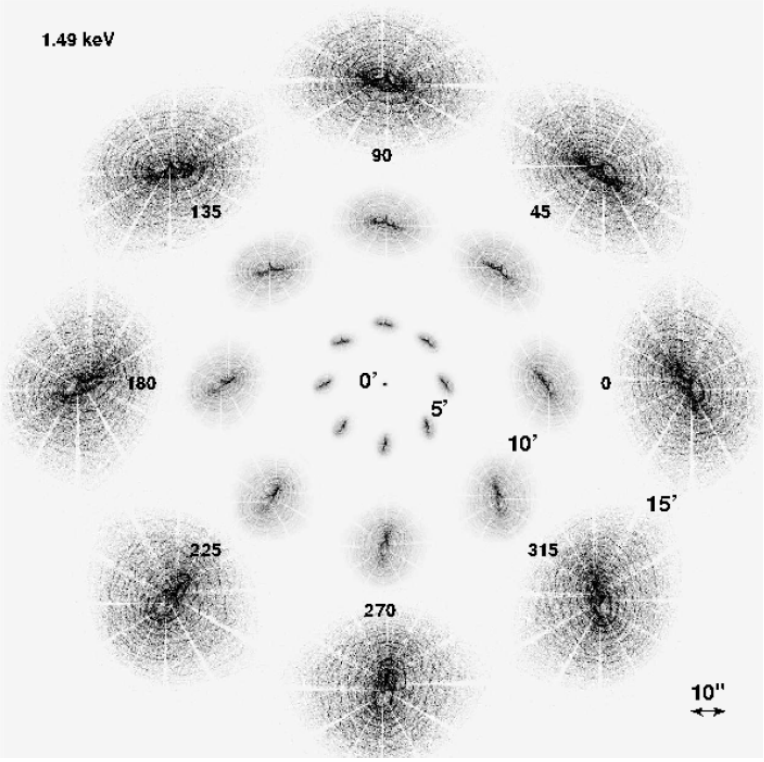

Au M transitions

Au L transitions

Some Issues

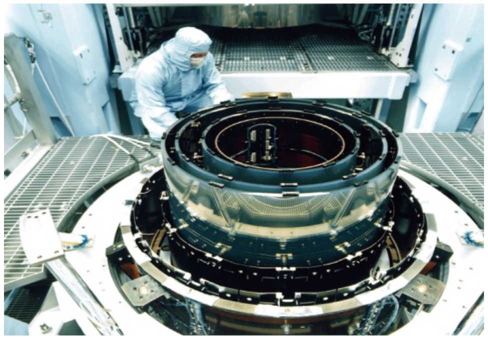
- The reflecting surfaces have to be very smooth- if they are rougher than the wavelength the photons hit 'mountains' and scatter (not reflect)
- A 'Wolter type I' optic focuses 'perfectly' at the center of the field of view- off axis the angular resolution degrades-due to coma aberration, astigmatism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



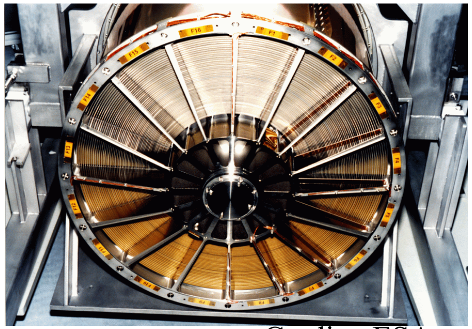
Credits: NASA

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***



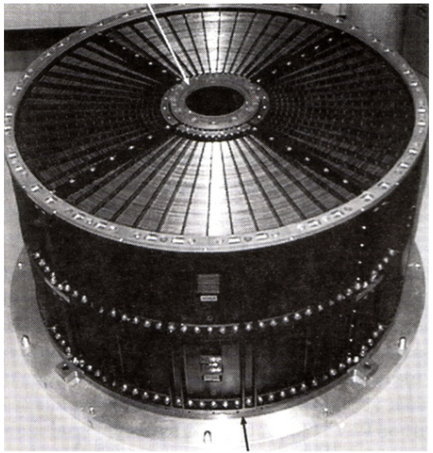
Credits: ESA

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

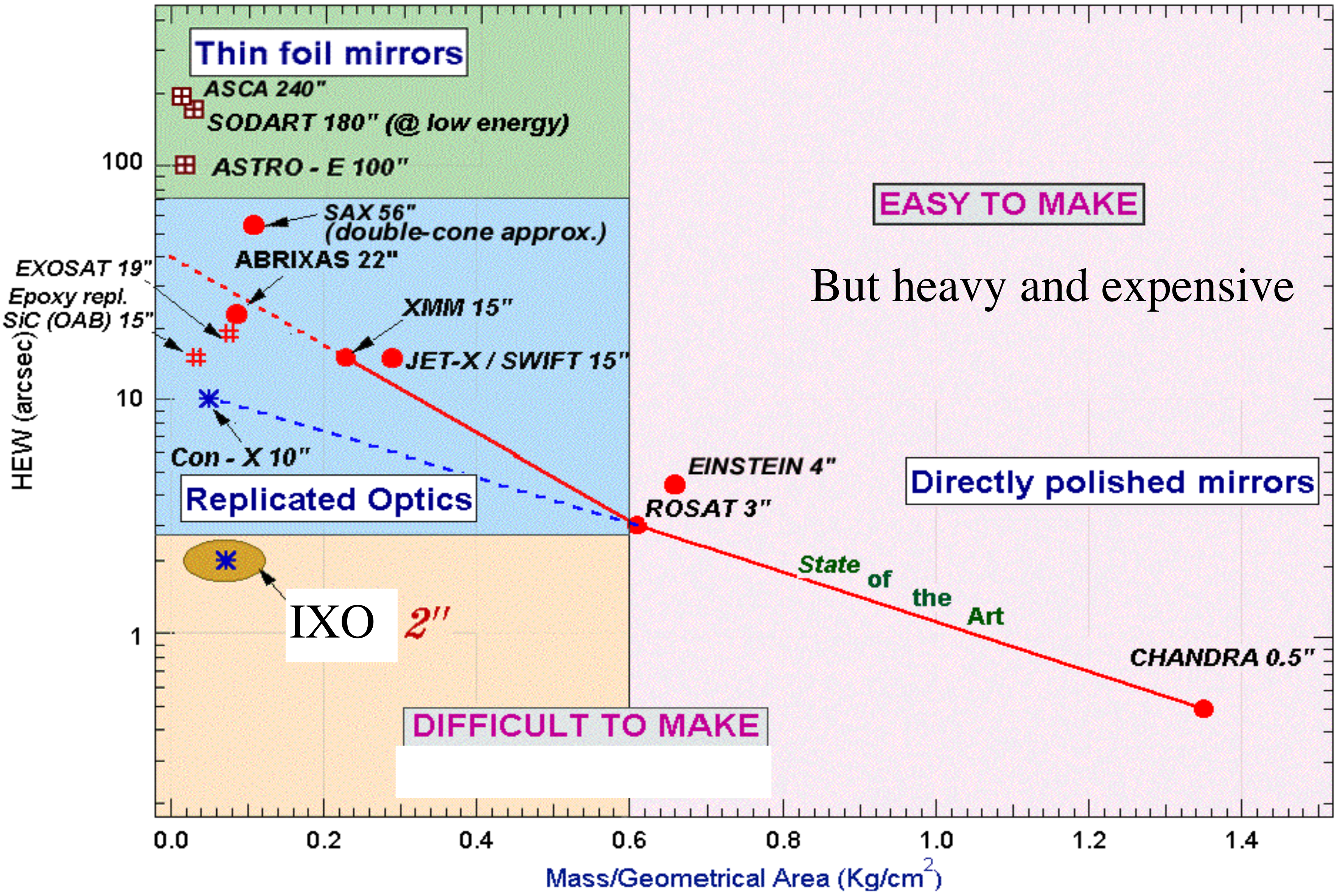
3. "Thin foil mirrors"

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)*

Present Astronomical optics technologies: HEW Vs Mass/geometrical area



But heavy and expensive

IXO 2''

X-ray optical constants

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

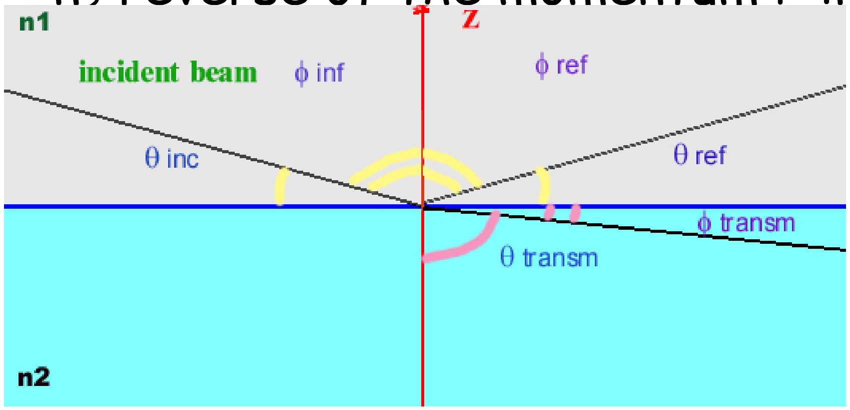
$$\boxed{\begin{array}{l}\tilde{n} = n + i\beta = 1 - \delta + i\beta \\ (\mu = 4\pi\beta/\lambda \ \ cm^{-1})\end{array}}$$

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:



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

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

⇨

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

momentum transfer

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

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

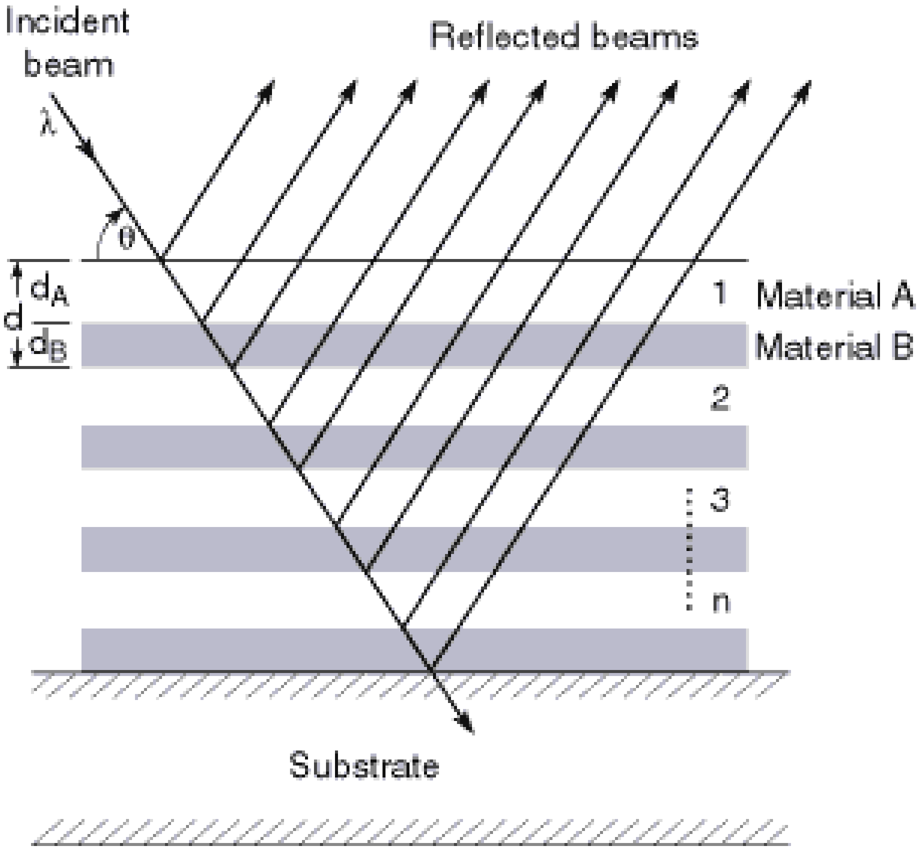
$$r_{12}^{p} = \frac{n_1 \sin\theta_2 - n_2 \sin\theta_1}{n_1 \sin\theta_2 + n_2 \sin\theta_1}$$

Multilayer Reflection- D. Schwartz

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

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

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



Now being built for NuStar and Astro-H

Bragg Reflection

$$n\lambda = 2d \sin\theta$$