How Does One Obtain Spectral +Imaging Data

- 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) 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)

seehttp://pulsar.sternwarte.unierlangen.de/wilms/teach/xray1/xray10026.html for more details

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, scintillators in use today)

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

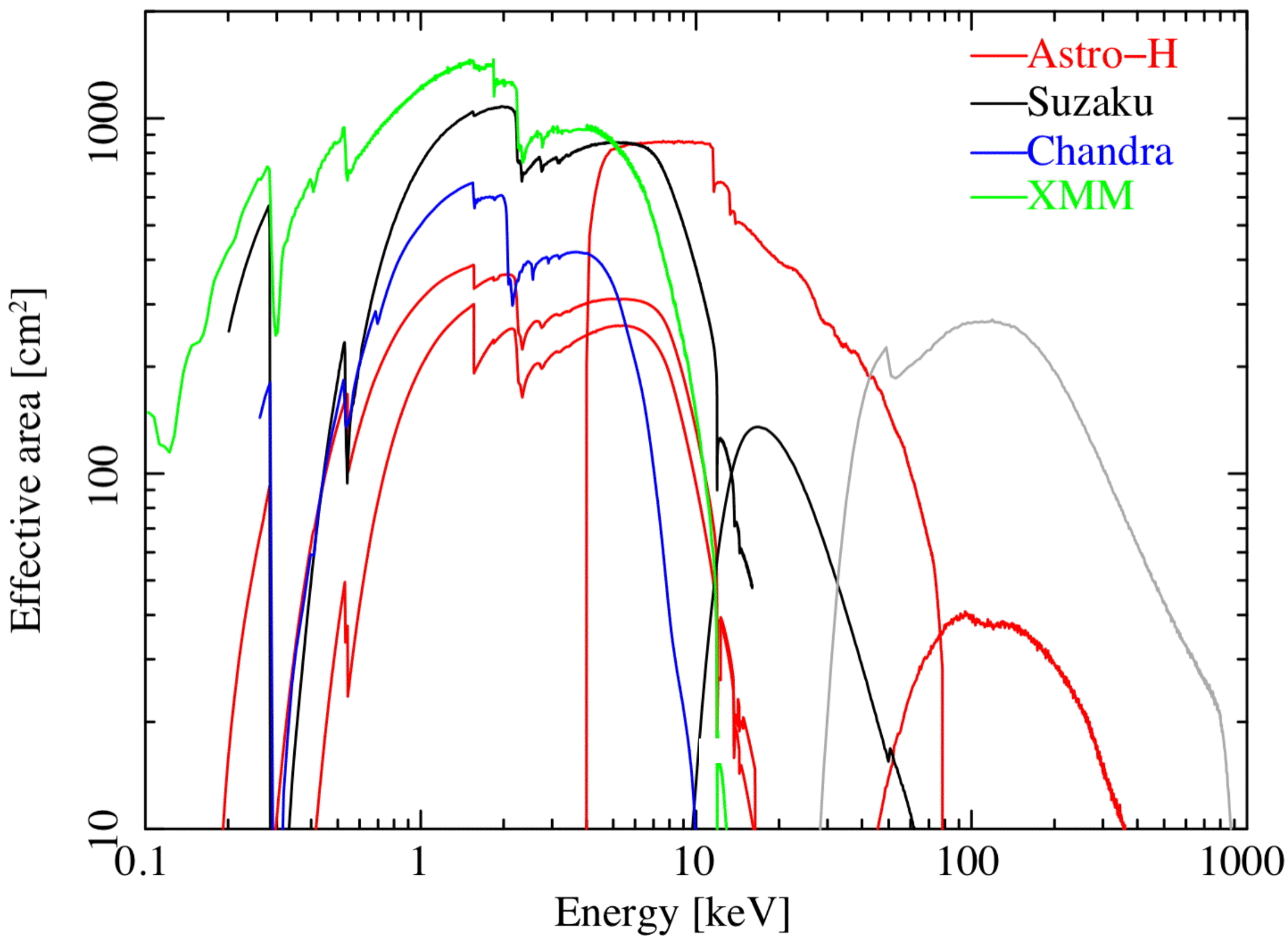
Integral **(ESA)** hard x-ray imaging and timing

Fermi (US) γ-ray (E>100 MeV) very wide field of view

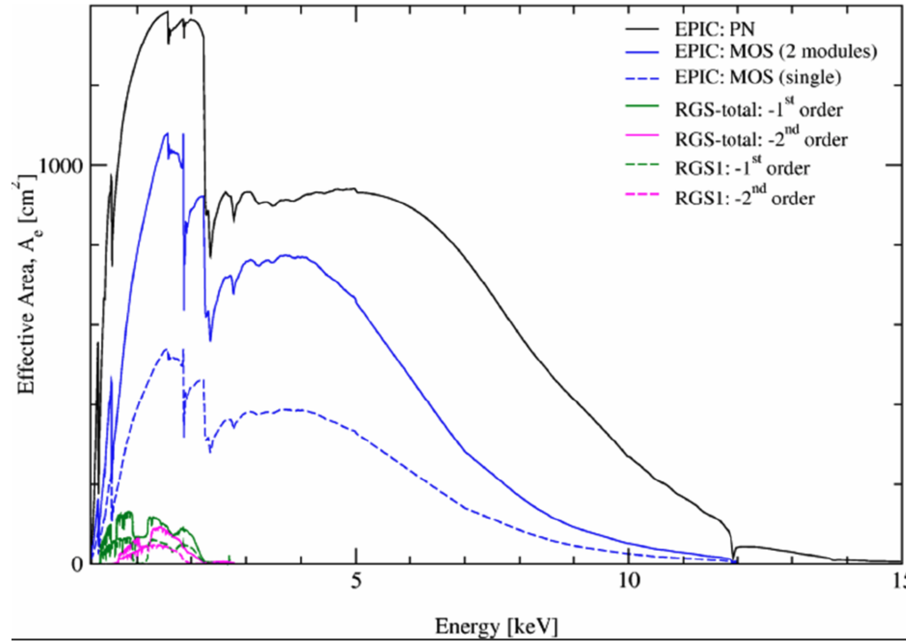
Historical X-ray Telescopes

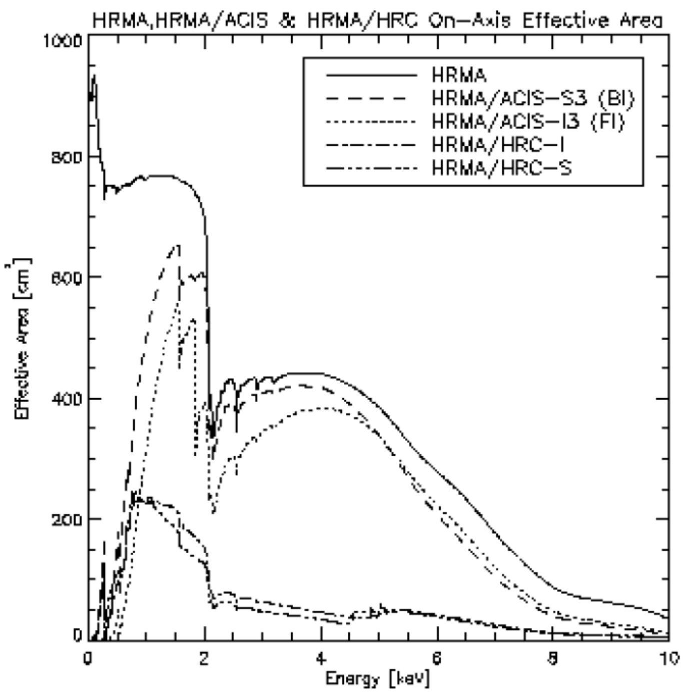
- Skylab 42 cm^2 ~2 arcsec 0.2–2 First x-ray telescope; (1975) area) solar observations
- Einstein ~200 cm^2 at 1 ~15 0.2–4.5keV First telescope observatory; Observatory discovered 7000+ sources
- ROSAT 400cm^2 at 1 keV ~5 0.1–2.4 4 Au coated Zerodur shells; (1990) discovered 150 000+ sources
- ASCA 1300 cm^2 at 1 keV, 174 0.5–10 Conical foil Al mirrors, (1993) 600 at 7 keV Au coat over lacquer, 4 separate telescopes
- BeppoSAX 330 cm^2 at 1 keV 60 0.1–10 Nickel-replicated conical (1996) optics, 30 nested shells
- Chandra 800 cm^2 at 1 keV 0.5 0.1–10 Highest resolution, 4 shells, (1999) largest mirror 1.2 m diameter transmission gratings
- XMM 4650 cm^2 at 1 keV, 14 0.1–12 Nickel replicas, (1999) 1800 at 8 keV 3 telescopes, 58 shells each, reflection gratings
- Suzaku

Collecting Area of X-ray Spectrometers



XMM mirror + detectors





Effective area = (collecting area) x (mirror reflectivity) x (detector efficiency) for Chandra mirrors plus detectors

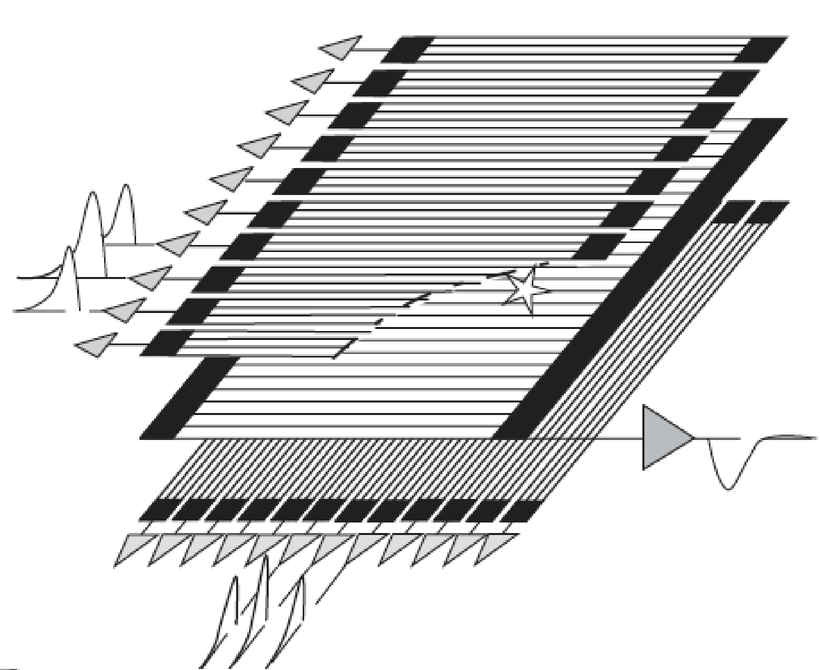
(linear plot)

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 by the motions of electrons and ions in the counting gas mixture contain information on the energies, arrival times, and interaction positions of the photons transmitted by the window.
- 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 limited by the anode-cathode spacing and the positive ion mobility. These physical factors limit the resolution to the microsecond level.

Nobel Prize - Charpak 1992



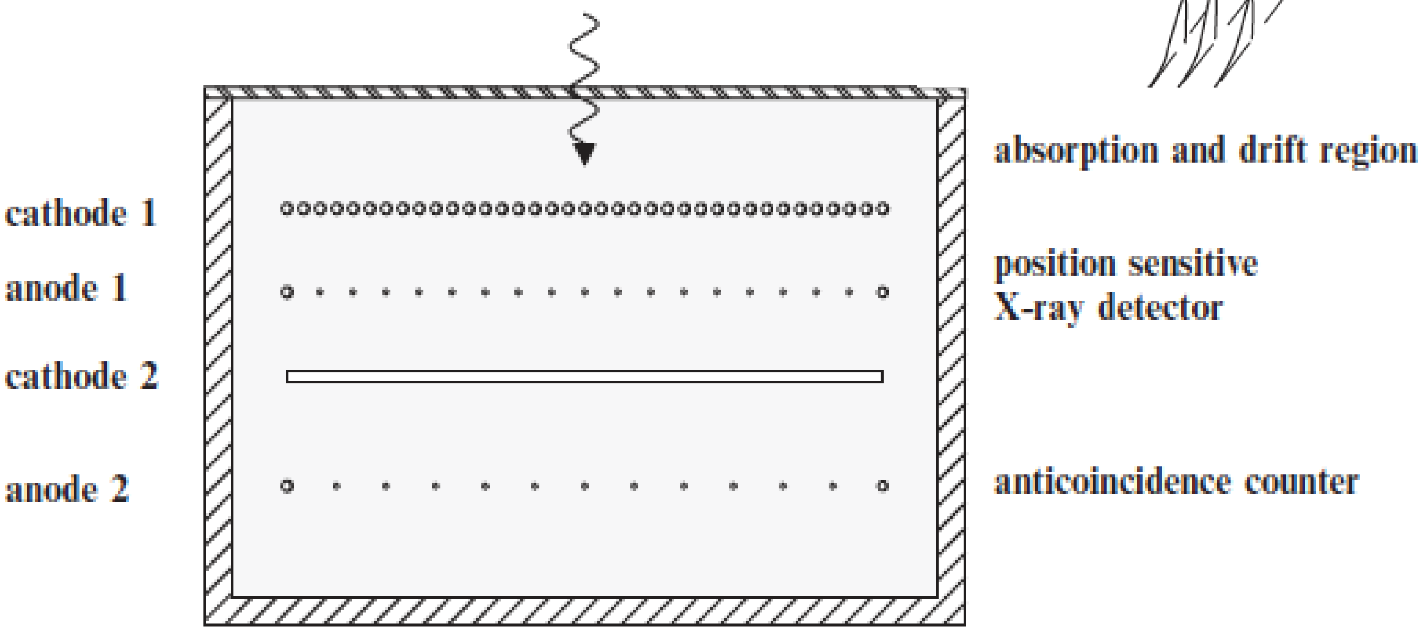


Fig. 4.1 Multiwire proportional counter for X-ray astronomy

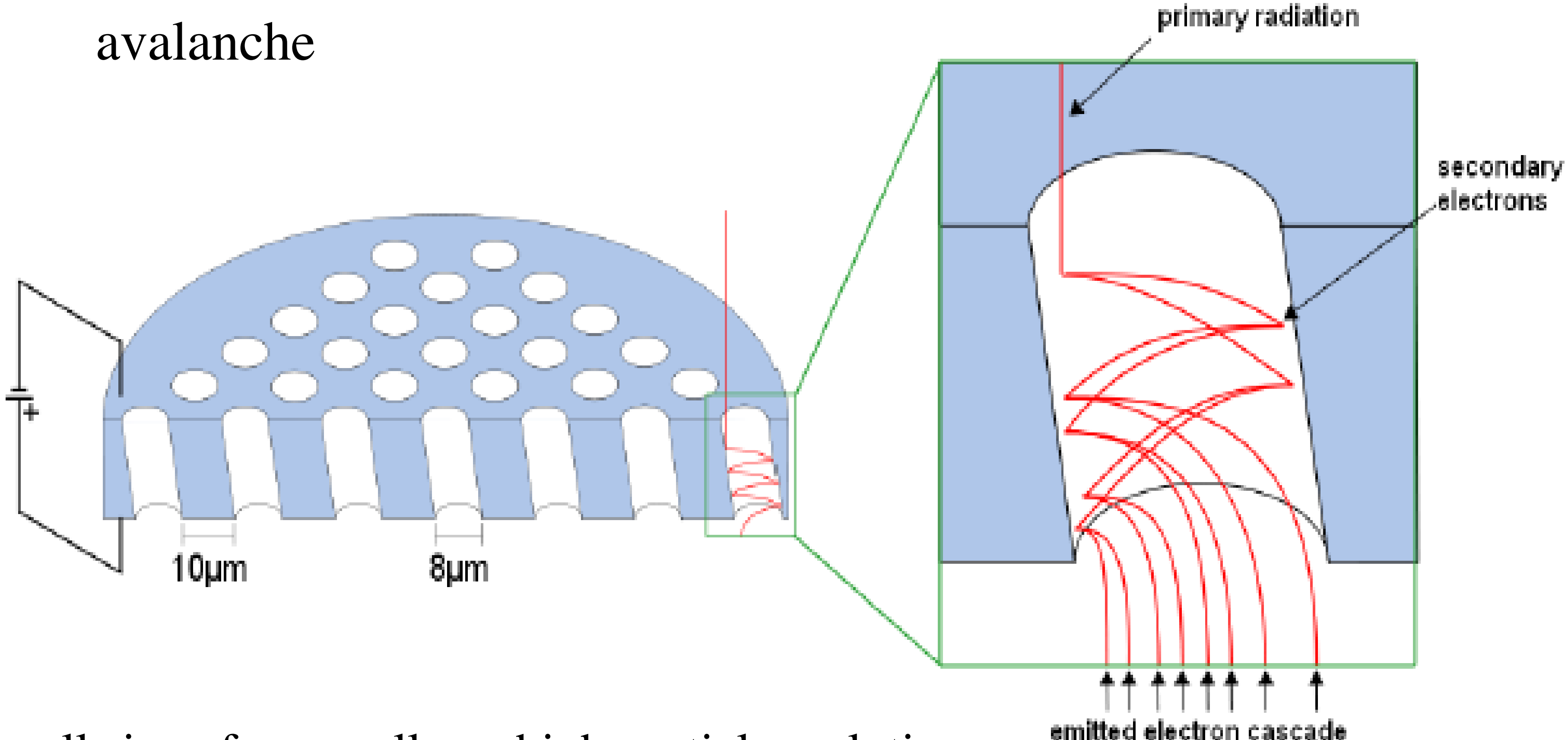
Microchannel plate (MCP)

Used on Galex, XMM optical monitor
Chandra HRI

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

Electron avalanche is excited at the semiconducter walls

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 within the 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 while the electrons are 'trapped' in the pixel until being read-out

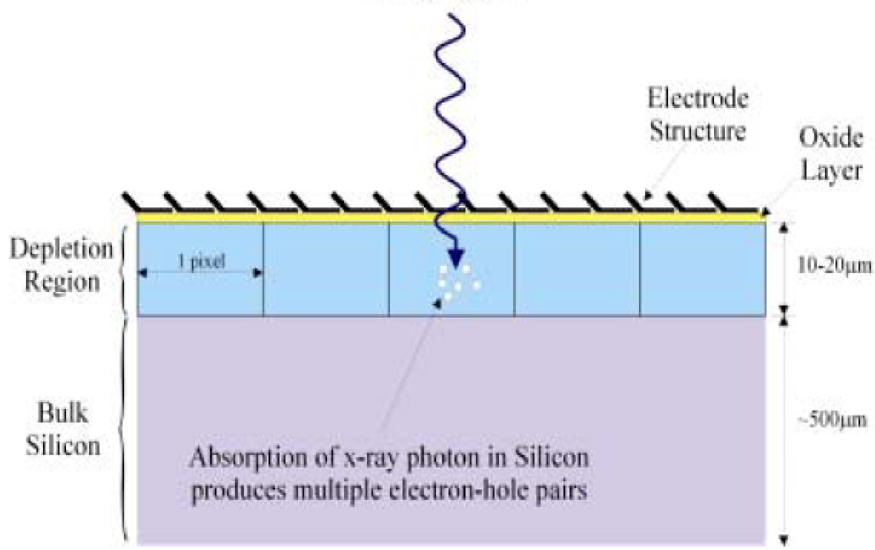


Figure 3: Schematic illustration of the direct detection of an X-ray photon.

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.

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

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<-70C) to work- other wise 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 anticiated rate to get more than one photon per pixel per readout time- other wise 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.

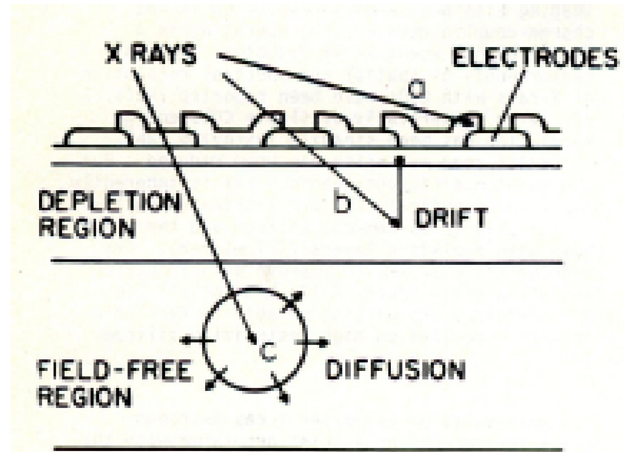
Quantum efficiency is set by physic:s

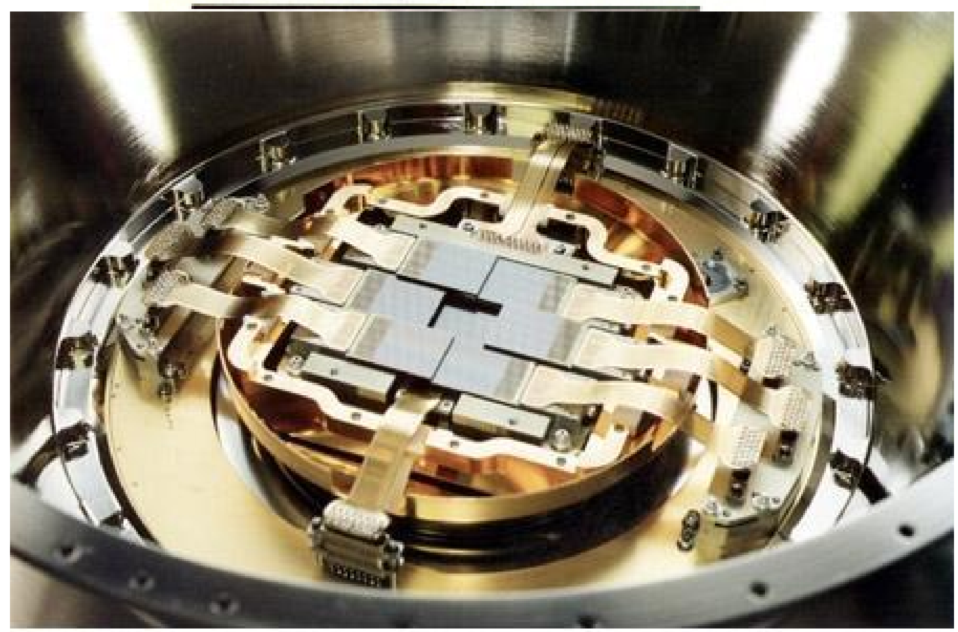
'dead' layer controls low E efficiency

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)





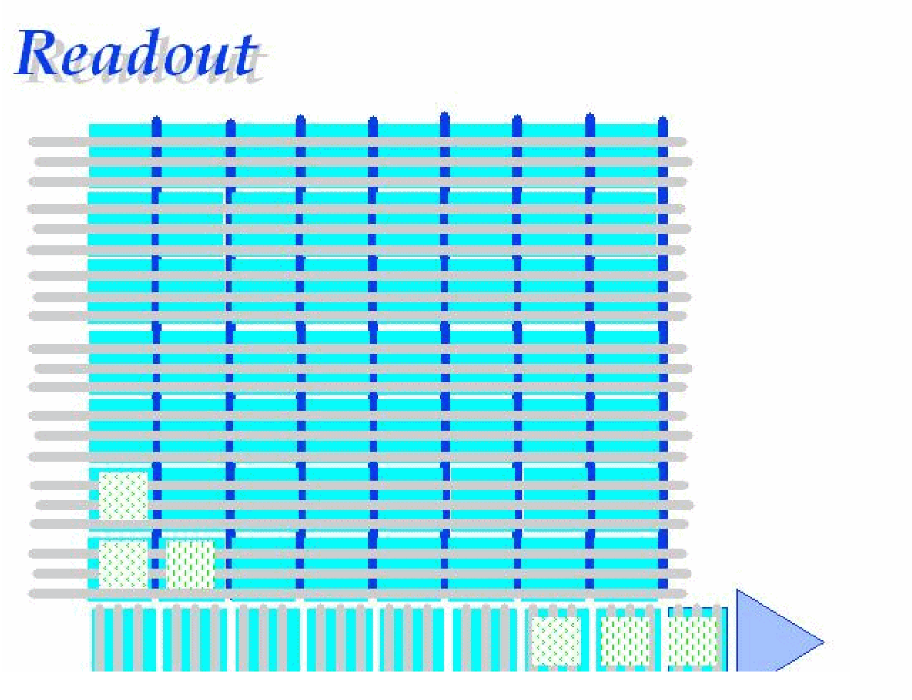
EPIC-MOS CCDs

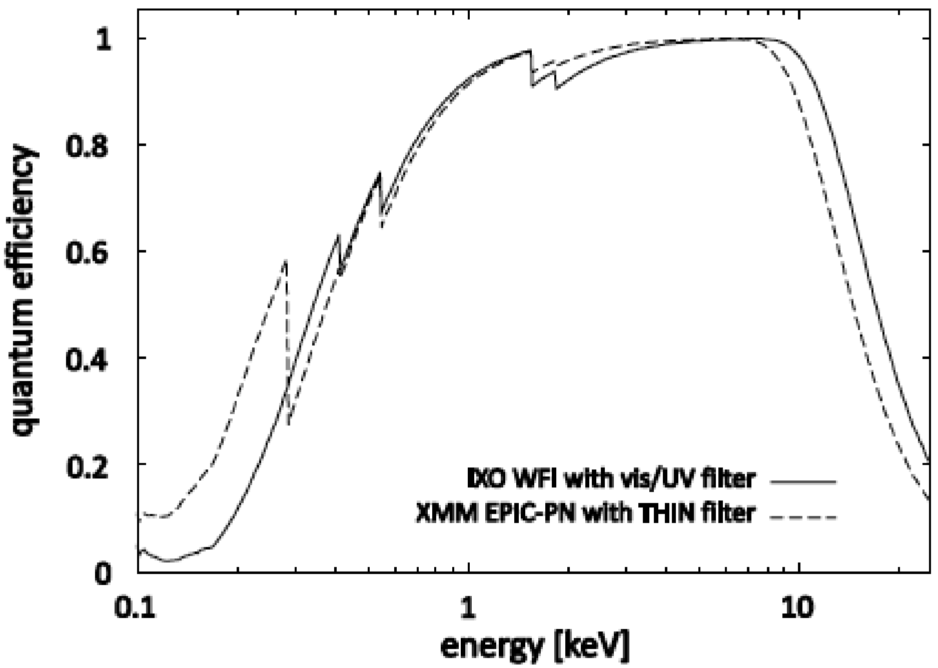
Image courtesy of Leicester University, University of Birmingham, CEA Service d'Astrophysique Saclay

European Space Agency

CCDs

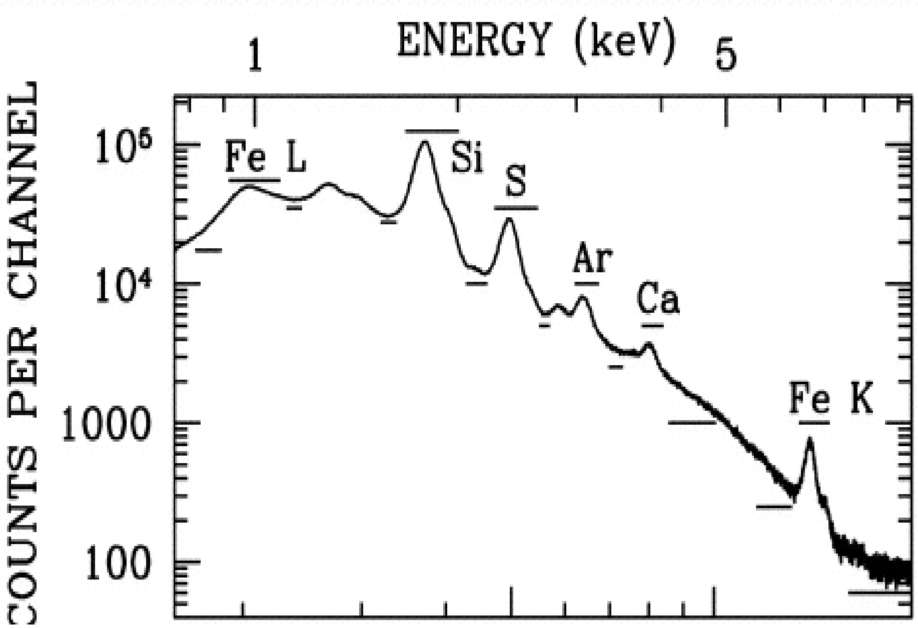
- X-ray CCD is fundamentally different from optical devices-
- Each photon generates charge (typically 1 e- per 3.3 ev of energy) Charge is 'read out' by shifting it from pixel to pixel until it reaches the readout register.
- Goal is to measure the amount of charge ~energy of incoming photon
- Which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

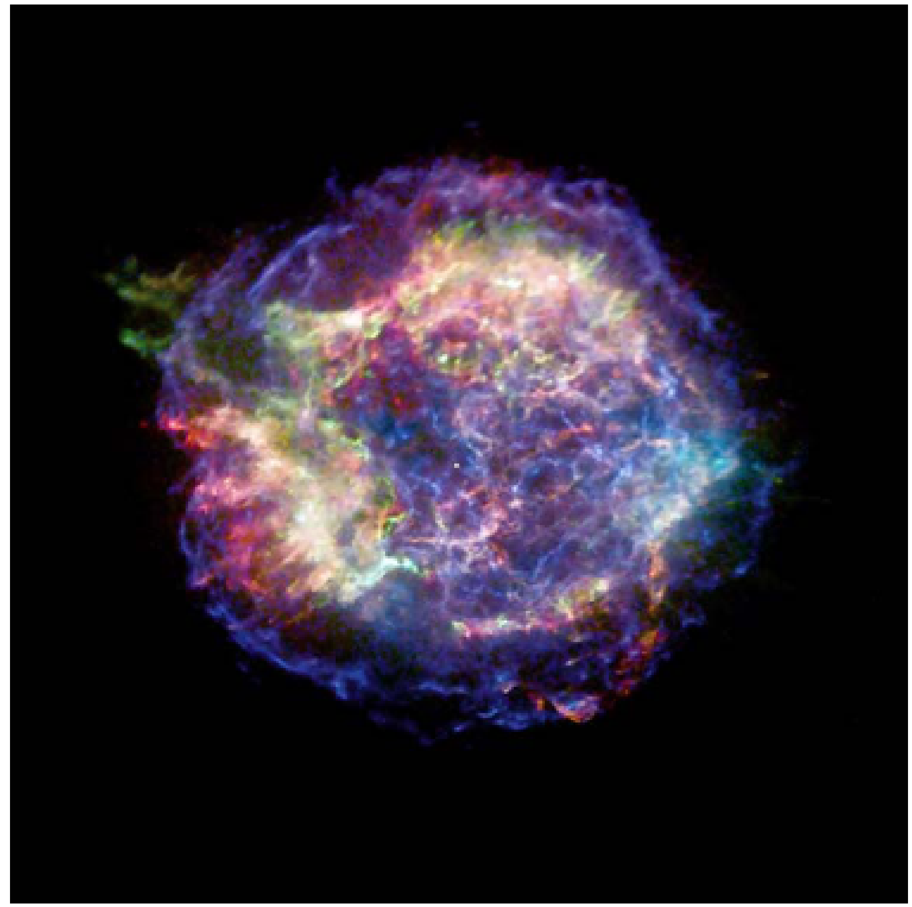




What Sort of Results from CCDs

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



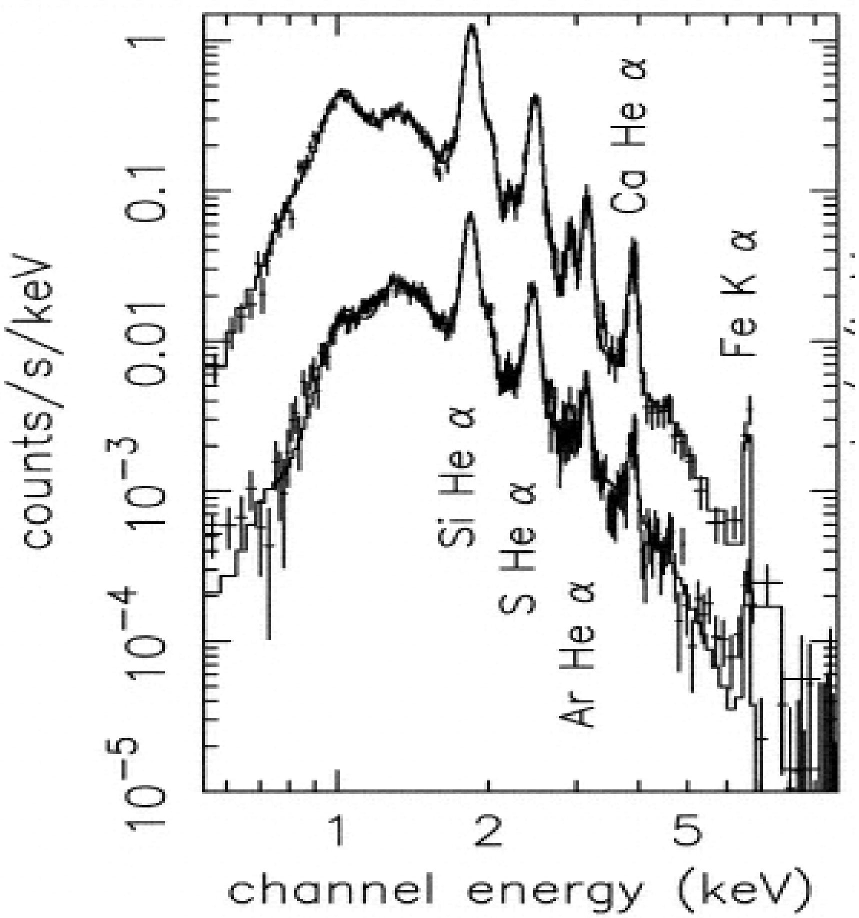


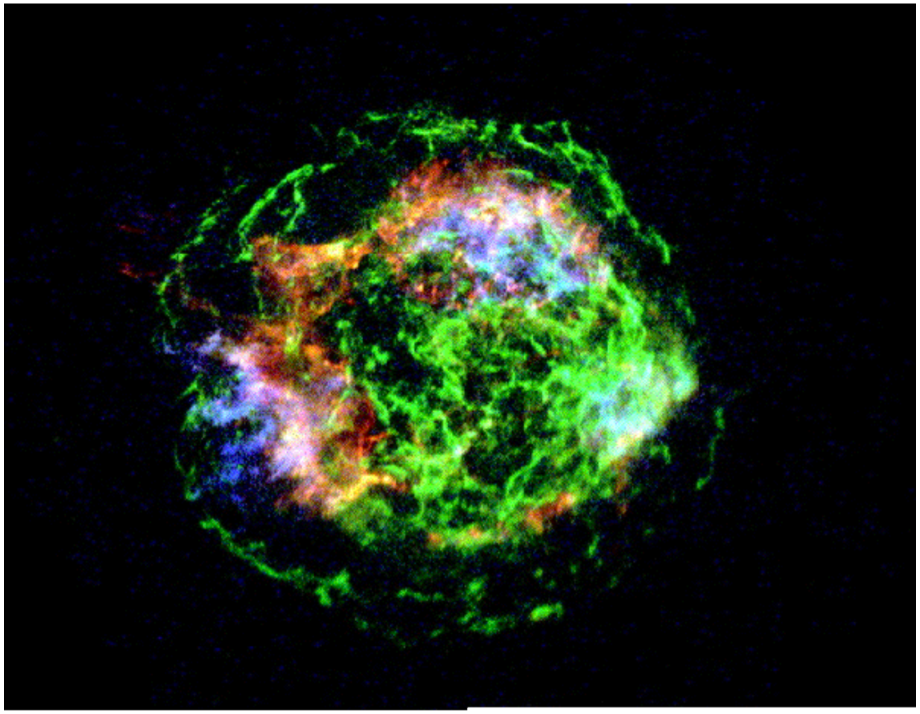
Credit: NASA/CXC/SAO/D.Patnaude et al.

Lines from abundant elements have characteristic energies

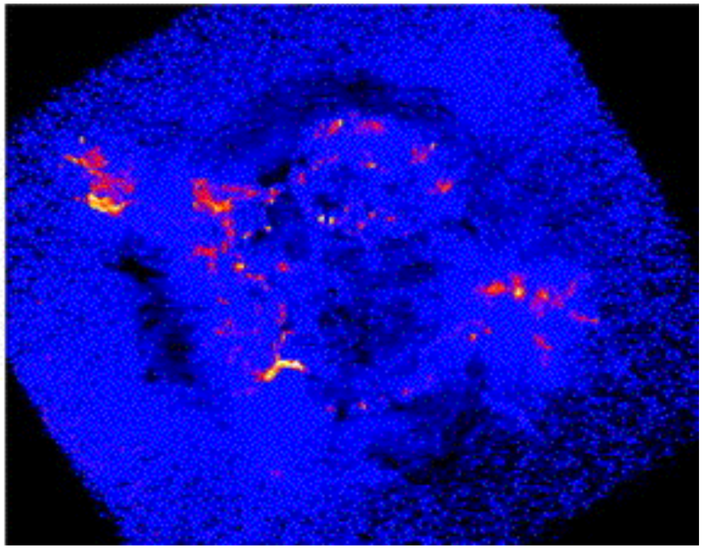
An Elemental Map of Cas-A- Exploded in ~1670 But not seen

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





Spectrum of 2 regions in SNR



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

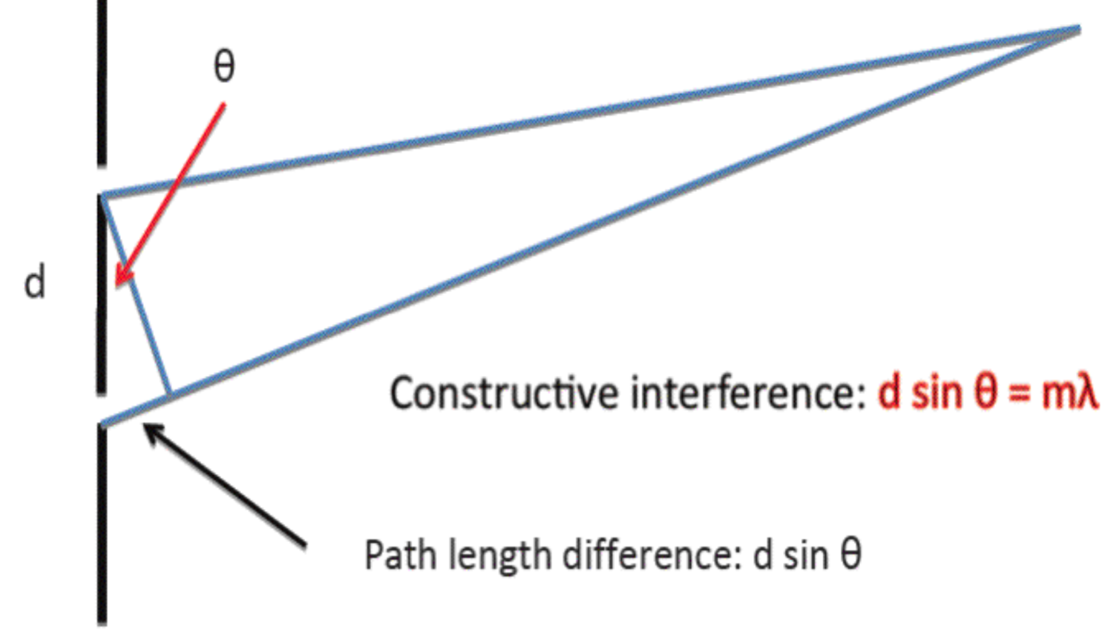
- Just like optical light, x-rays have a wave property and so can be diffracted
- The same wave equations- BUT the wavelength of x-rays is very small ~1-20Å and so there are great technical difficulties
  - Many of these have been solved and productive gratings were produced for Chandra and XMM

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 $\Delta\lambda$ 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 (~$10^{2\text{-}3}$ Å)

$\delta x * \theta \sim 0.1\text{-}0.01$ 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

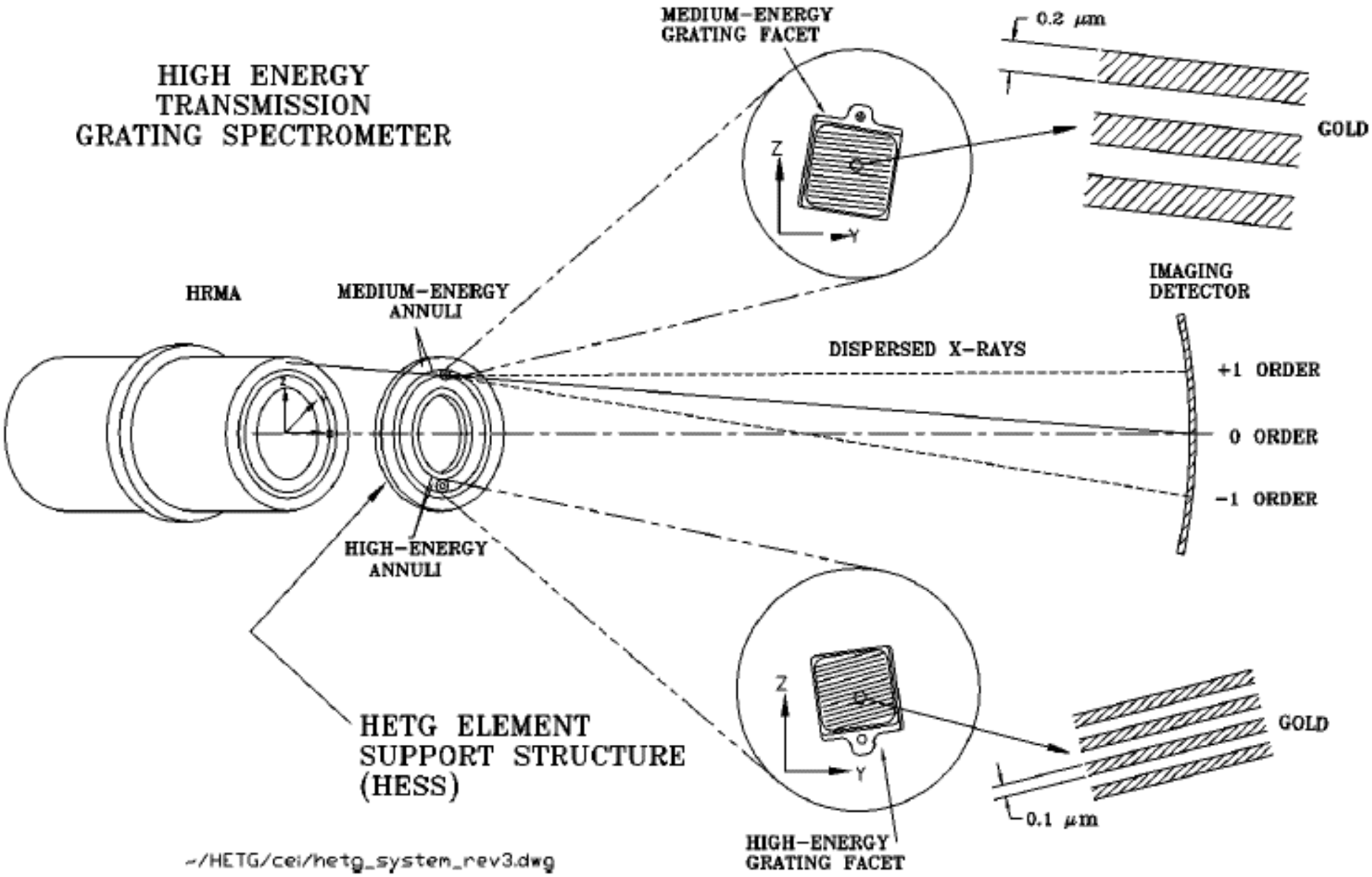
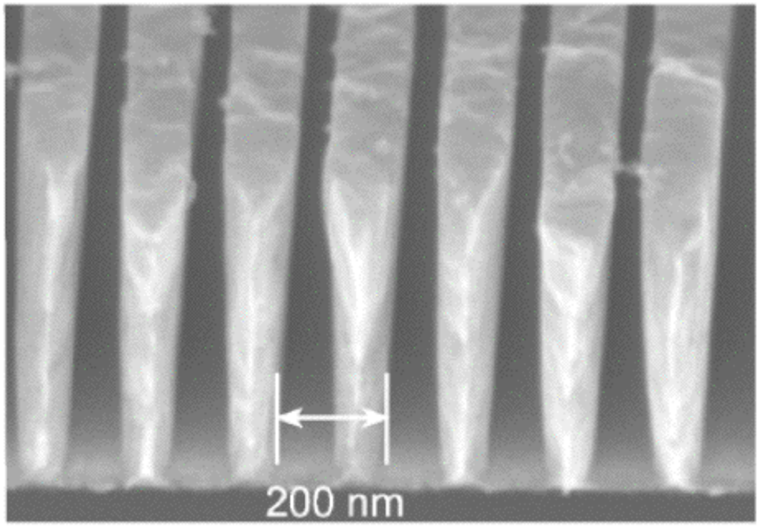
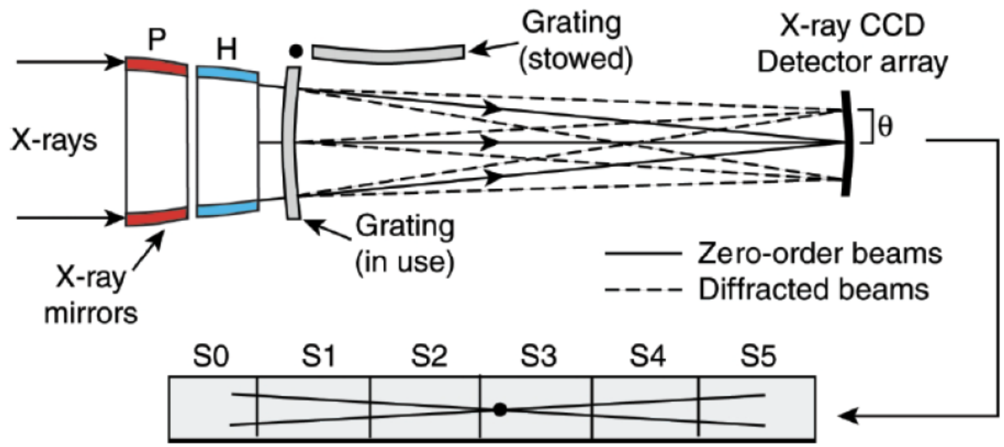


Figure 1 Geometry of the transmission grating spectrometers on *Chandra*.

1. *Chandra* HETGS



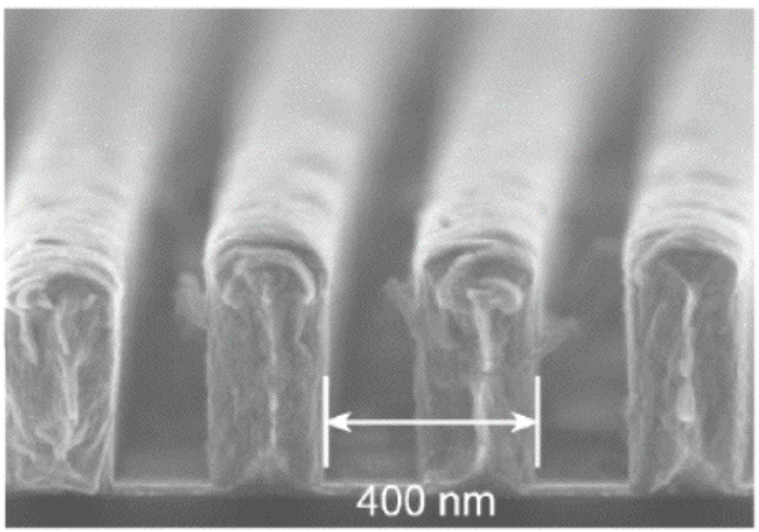
(a) High Energy Grating (HEG).



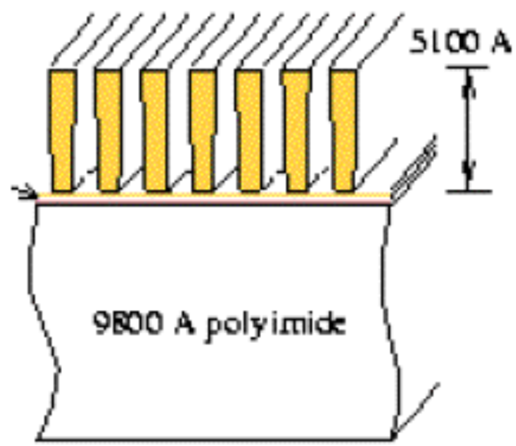
Claude Canizares et al., *Publ. Astron. Soc. Pac.*, **117**, 1144 (2005)

Dispersion equation: sin θ = mλ/d (θ: dispersion angle, d: grating period, m: spectral order

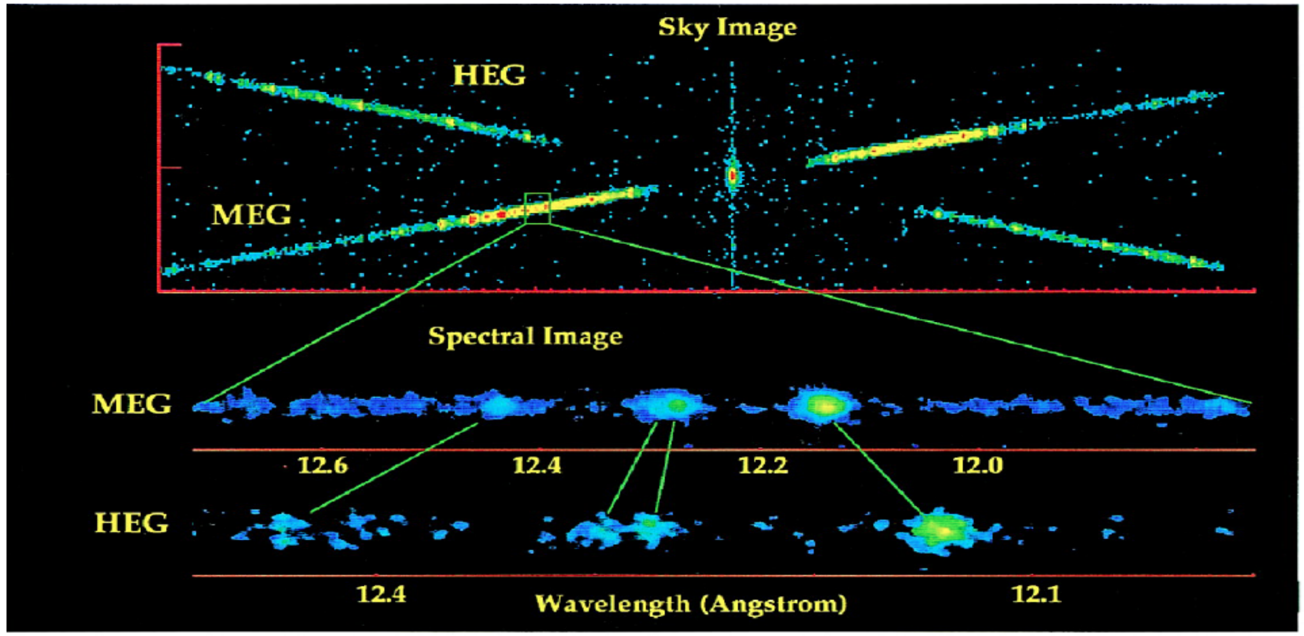
Spectral resolution: Δλ = (d/m)cos θ Δθ ≅ (d/m)Δθ: dominated by telescope image (Δθ)

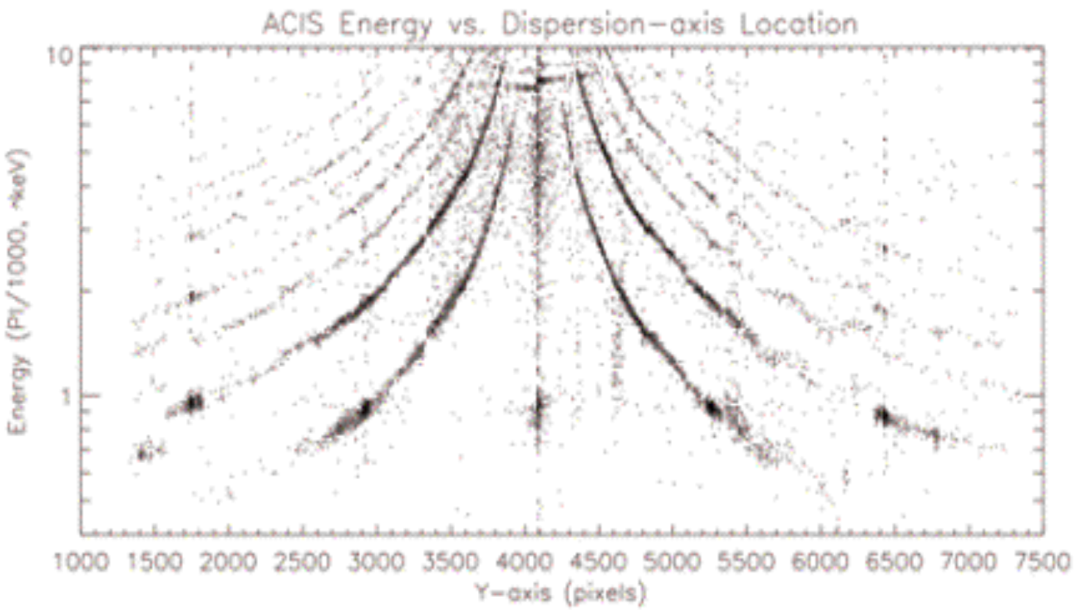


b) Medium Energy Grating (MEG).



What the Data Look Like



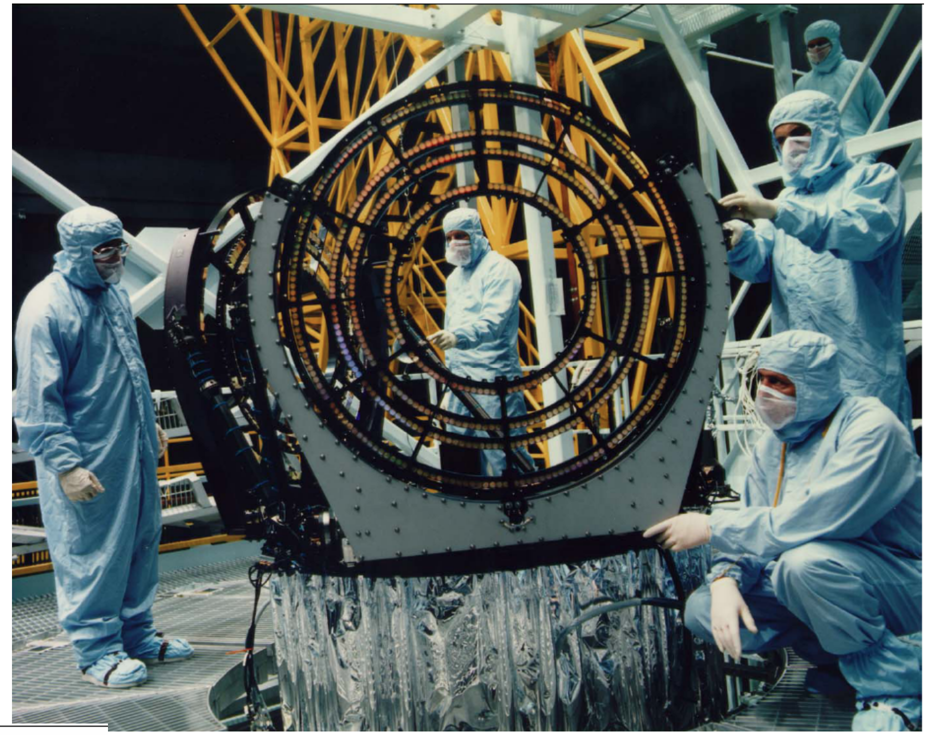


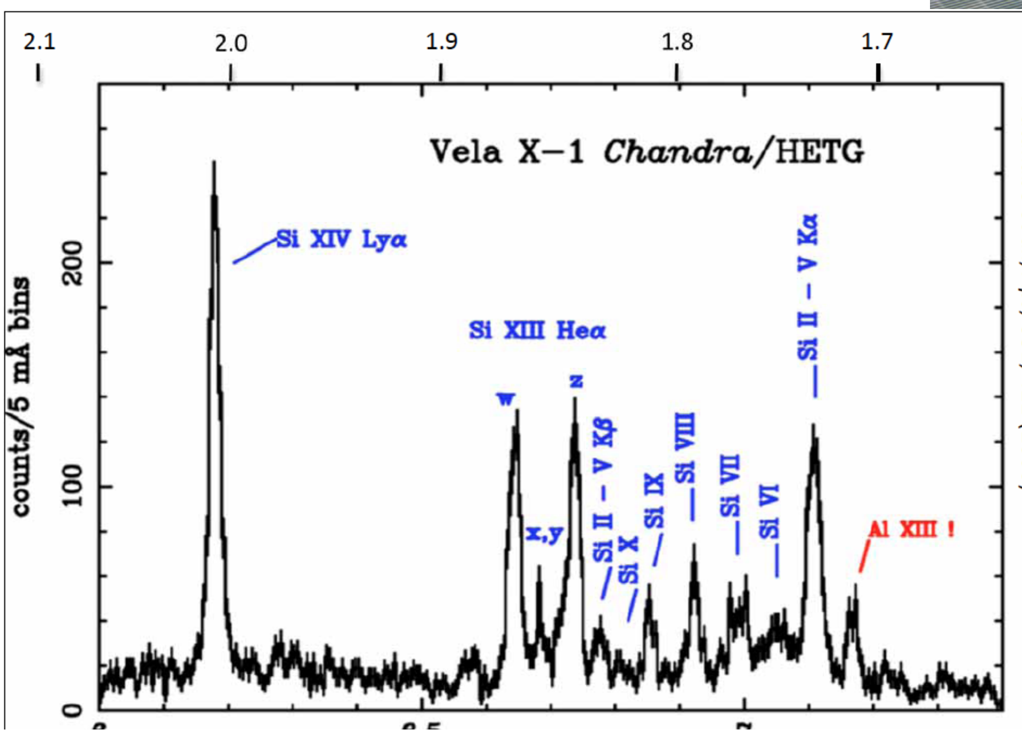
CCD/dispersion diagram ('banana')
NB: CCD energy resolution sufficient to separate spectral orders ($m = \pm1, \pm2, \ldots$)

- 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:
$\Delta v/c \sim 1/10{,}000$!

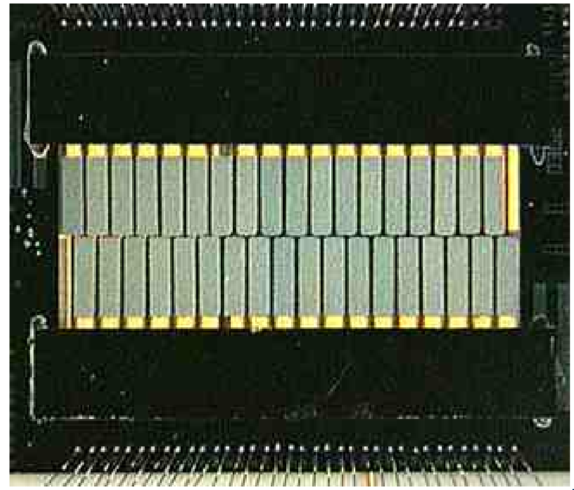
Calorimeter

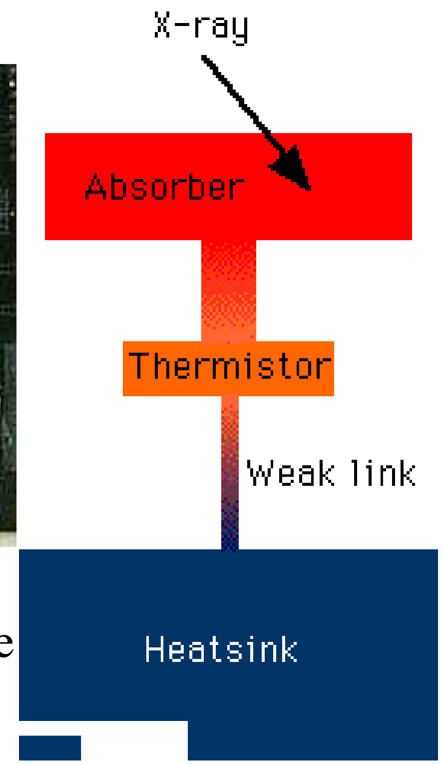
Single-photon calorimeters-Absorb a photon and measure the increase in T

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

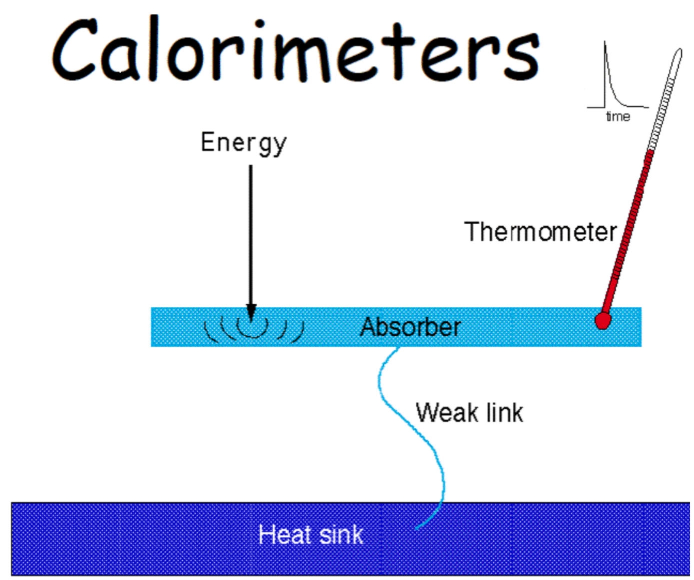
$$\Delta E \sim \sqrt{(kT_b^2 C_b)/|\alpha|}$$

- Energy sensitivity very good because are generating 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



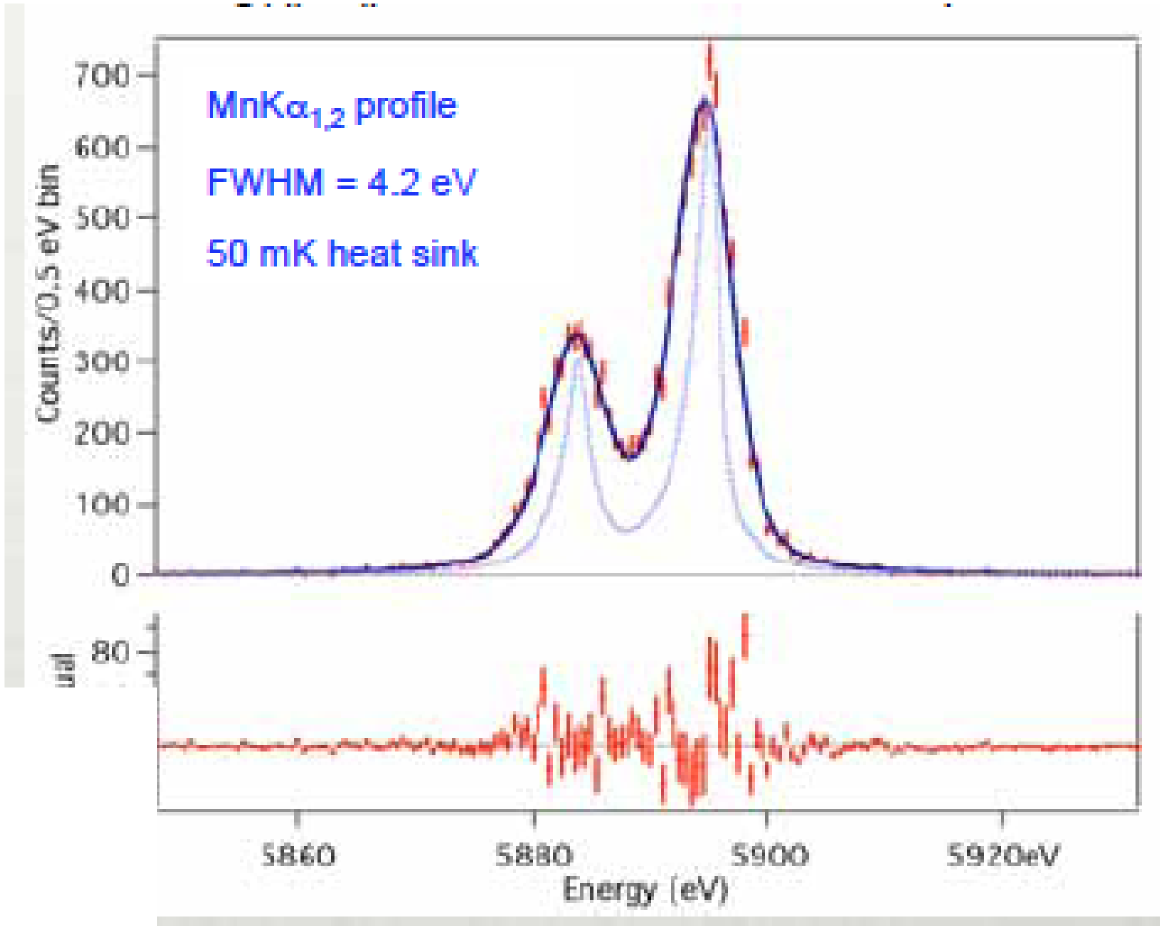


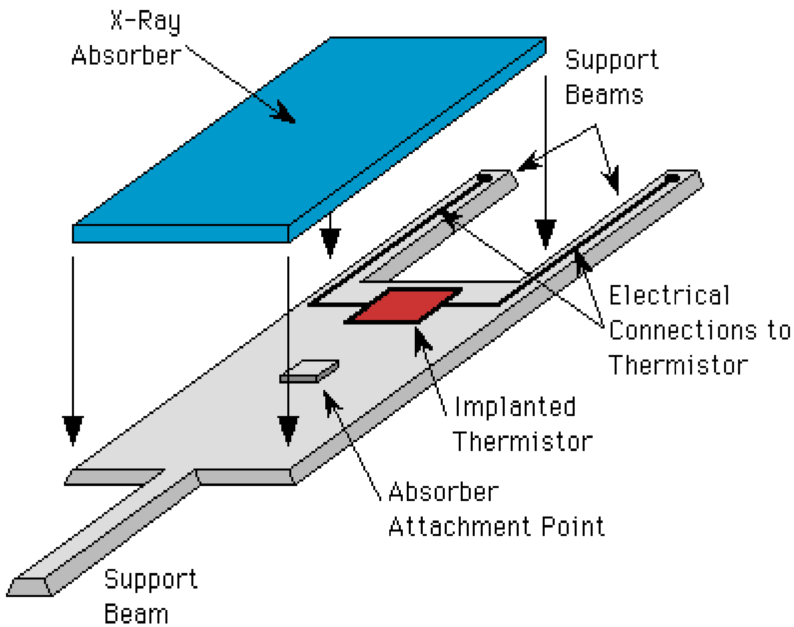
T_b=operating temperature
C_b=heat capacity



Calorimeter

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





Flying on Astro-H to be launched in early 2015 !
Flown on several rocket flights