How Does One Obtain Spectral Information

- 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)

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)

•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.]

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_

Proportional Counters Imaging or Otherwise (Rosat, RXTE)

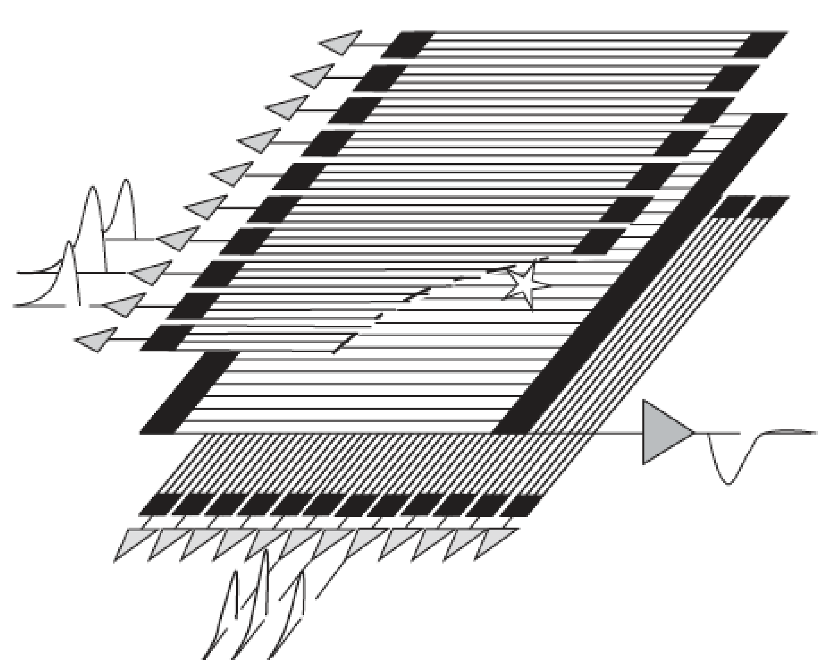
- X-ray proportional counters consist of a windowed gas cell, subdivided into a number of low- and high-electric field regions by some arrangement of electrodes.
- The signals induced on these electrodes by the motions of electrons and ions in the counting gas mixture contain information on the energies, 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



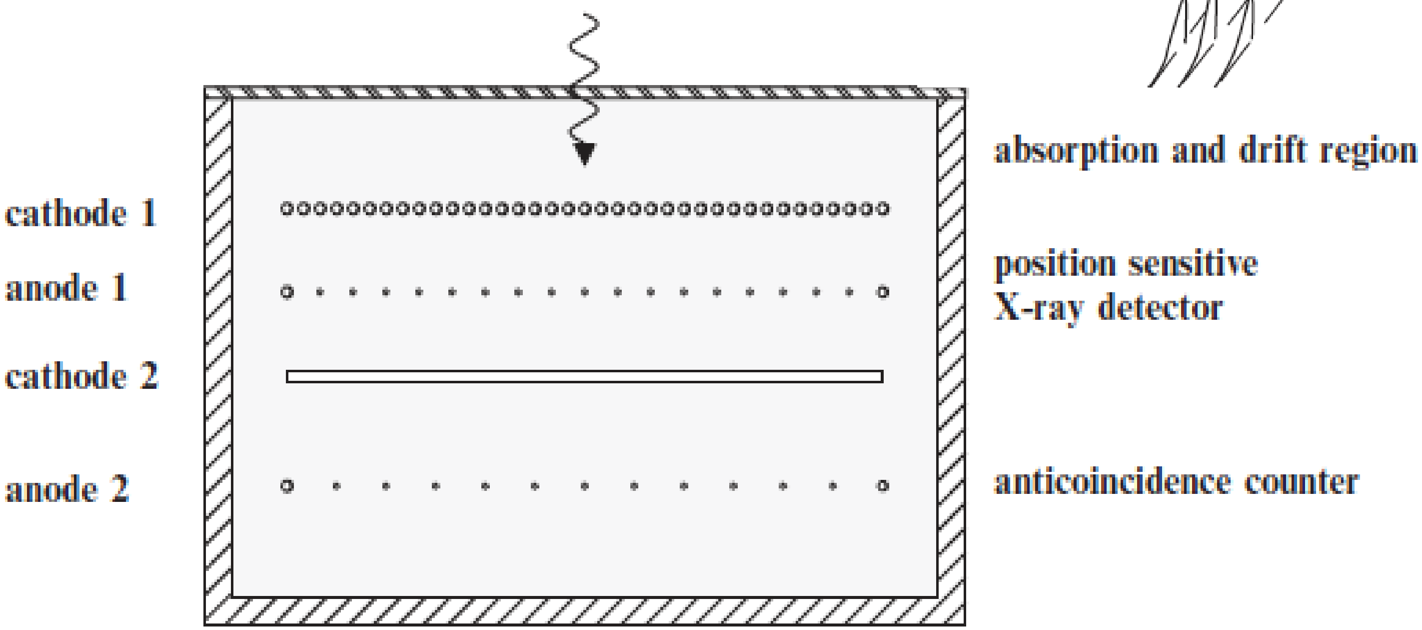


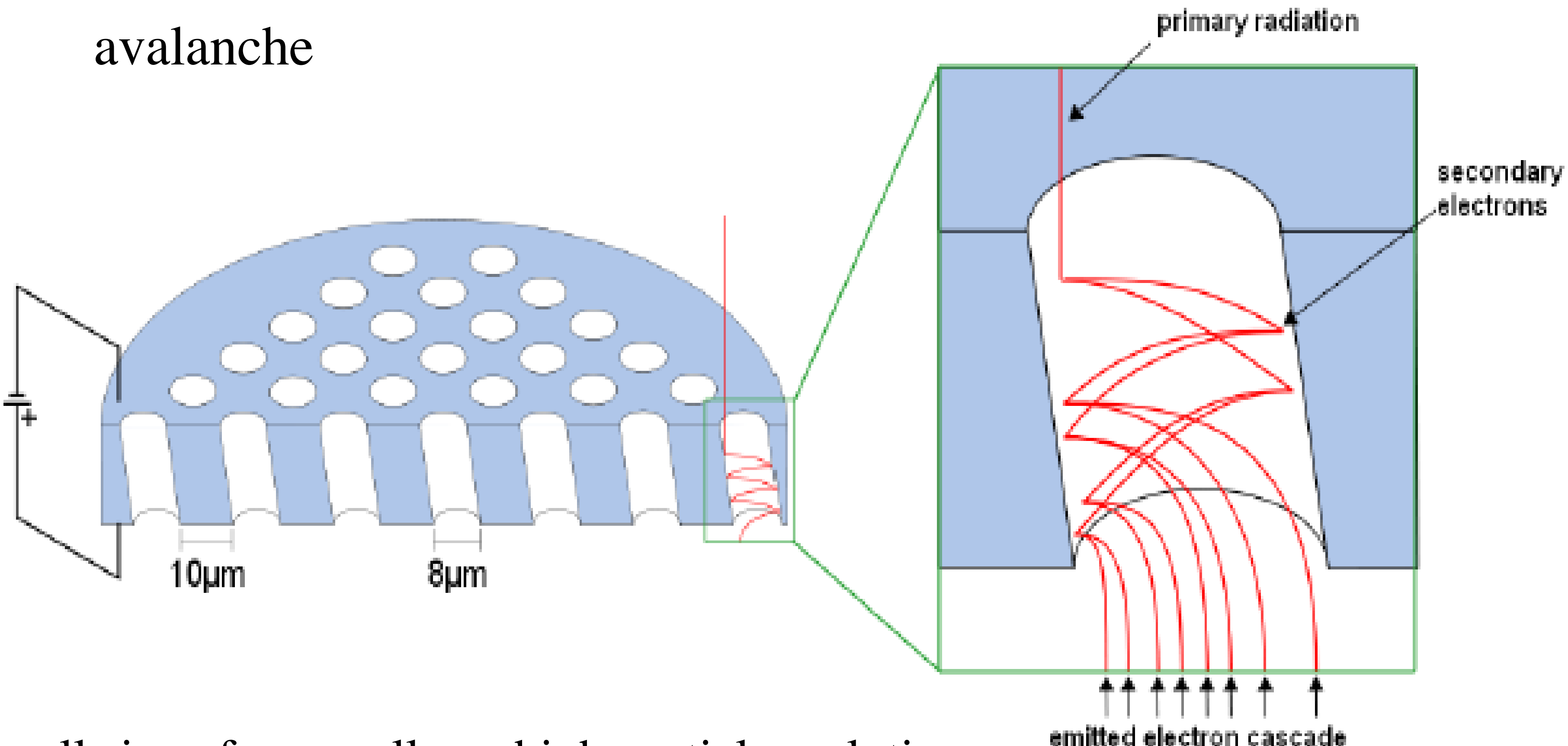
Fig. 4.1 Multiwire proportional counter for X-ray astronomy

Microchannel plate (MCP)

Electron avalanche is excited at the semiconducter walls

Emitted charge is proportional to deposited energy

Read out device to detect electron avalanche



Small size of pores allows high spatial resolution

X-ray CCD

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

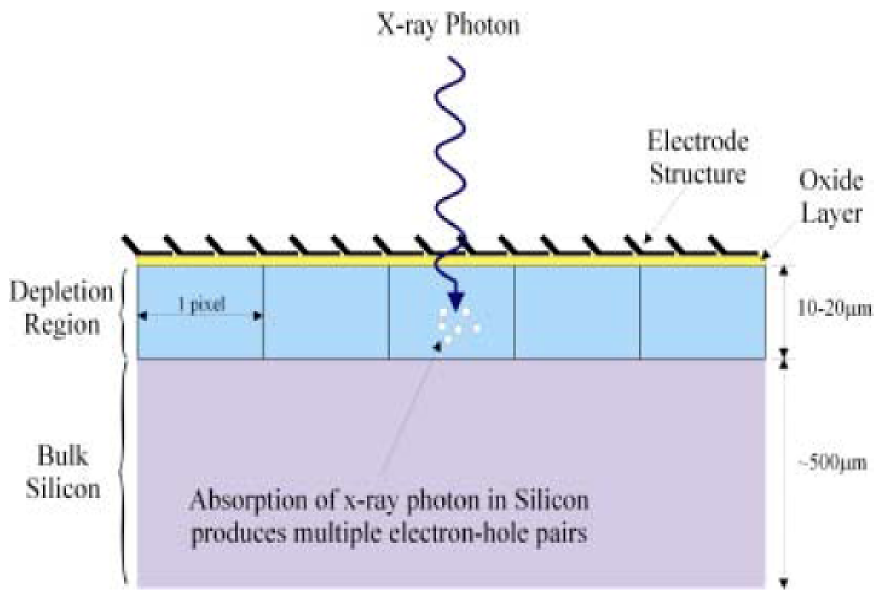


Figure 3: Schematic illustration of the direct detection of an X-ray photon.

2009 Nobel Prize in Physics

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

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.

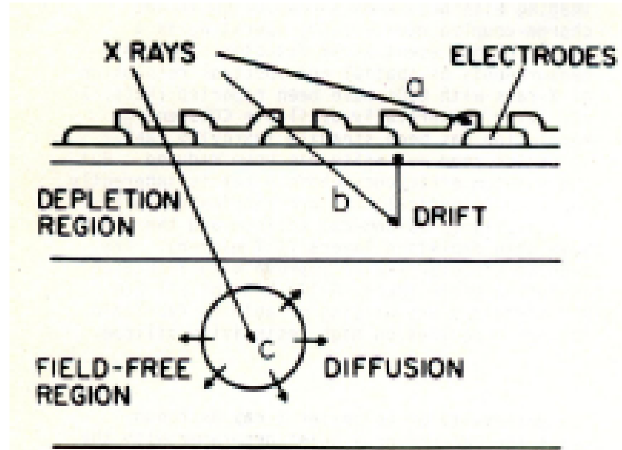
Quantum efficiency is set by physic:s

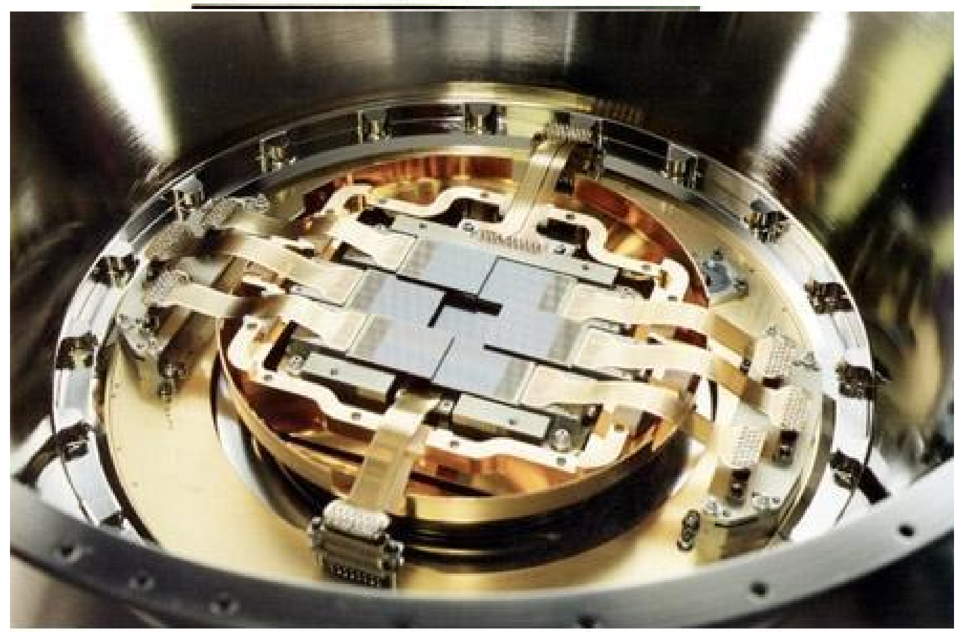
'dead' layer controls low E efficiency

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)





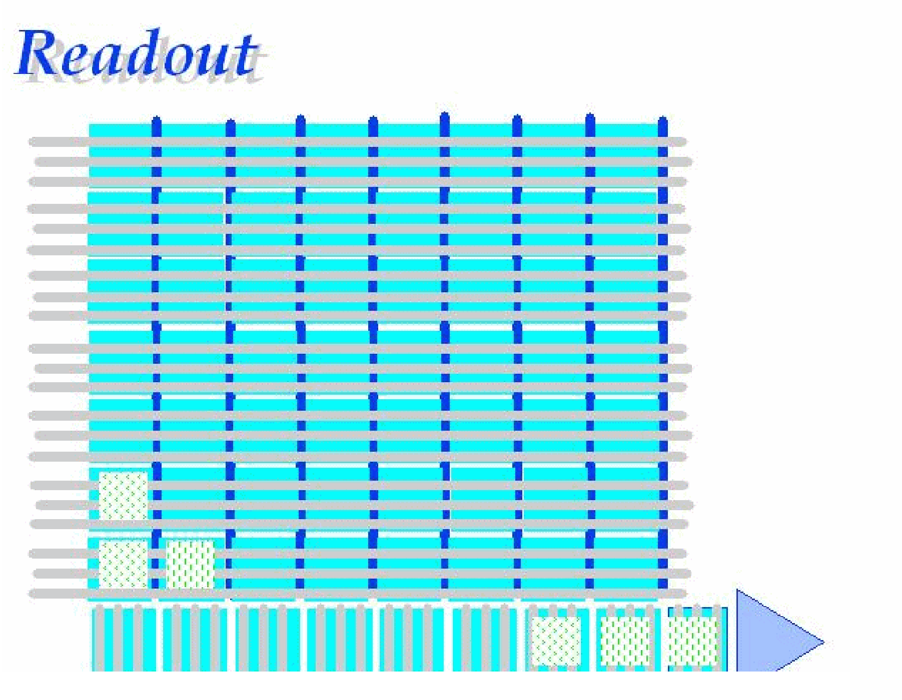
EPIC-MOS CCDs

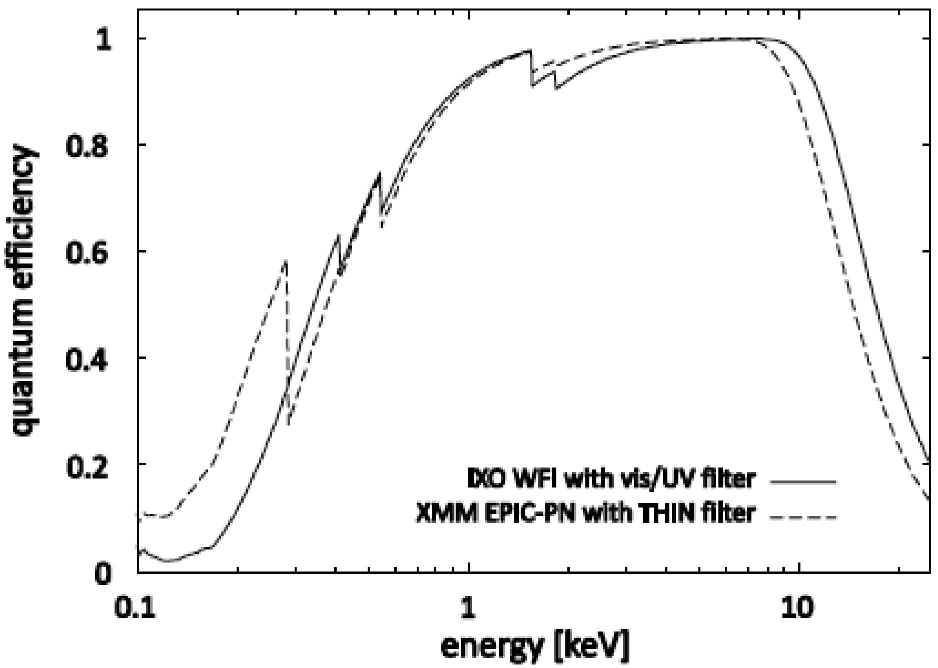
Image courtesy of Leicester University, University of Birmingham, CEA Service d'Astrophysique Saclay

European Space Agency

CCDs

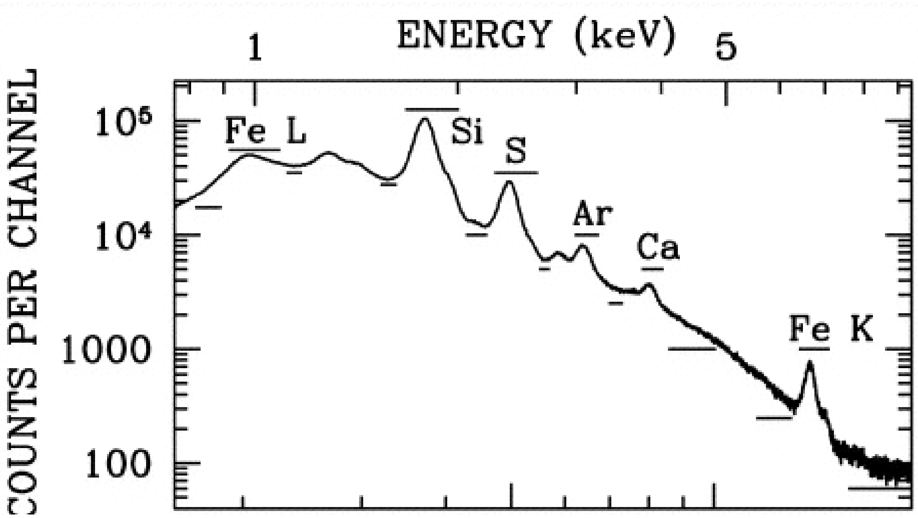
- X-ray CCD is fundamentally different from optical devices-
- Each photon generates charge (typically 1 e- per 3.3 ev of energy) Charge is 'read out' by shifting it from pixel to pixel until it reaches the readout register.
- Goal is to measure the amount of charge ~energy of incoming photon
- Which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

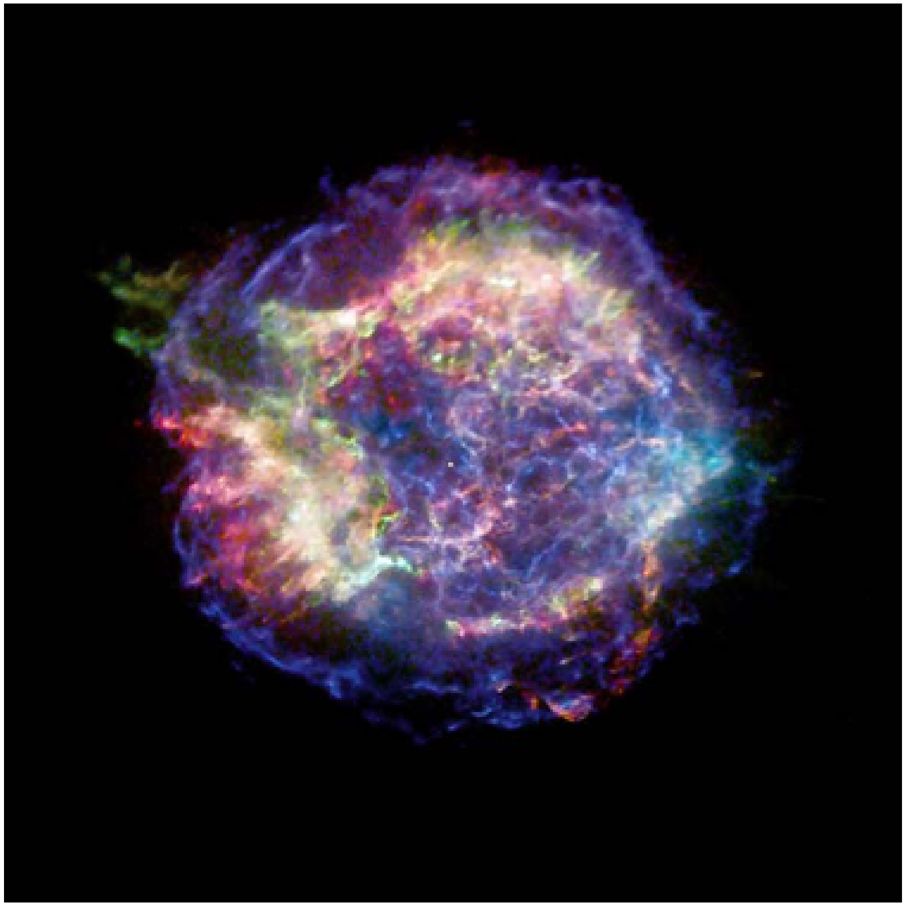




What Sort of Results from CCDs

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

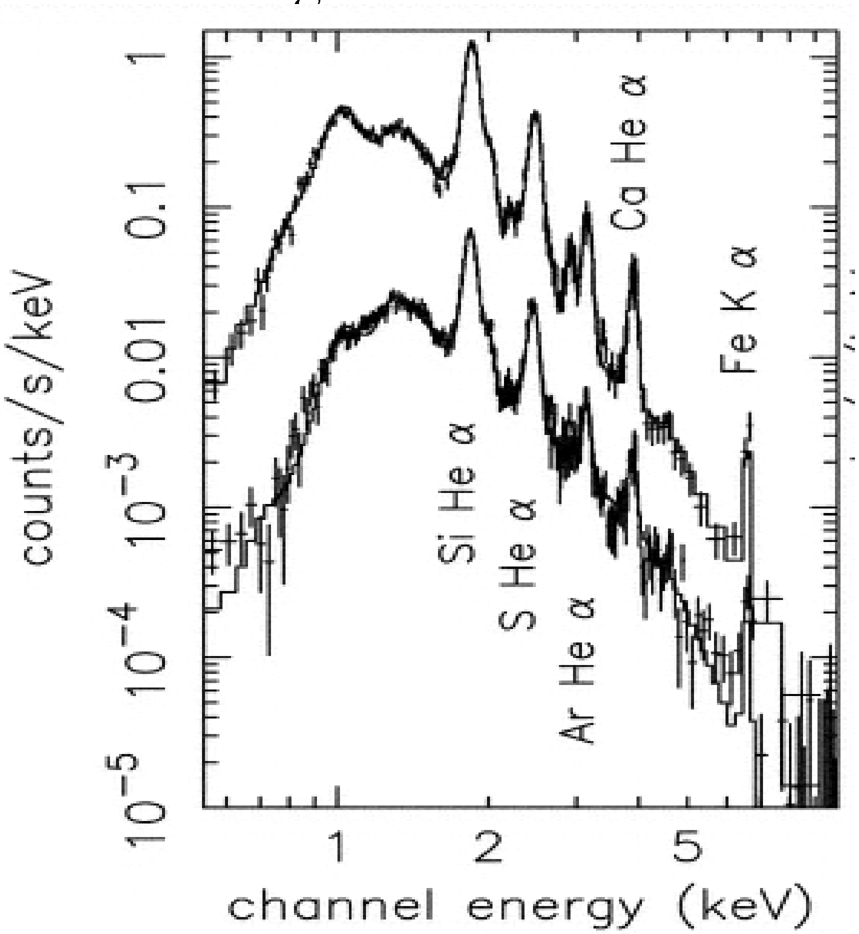


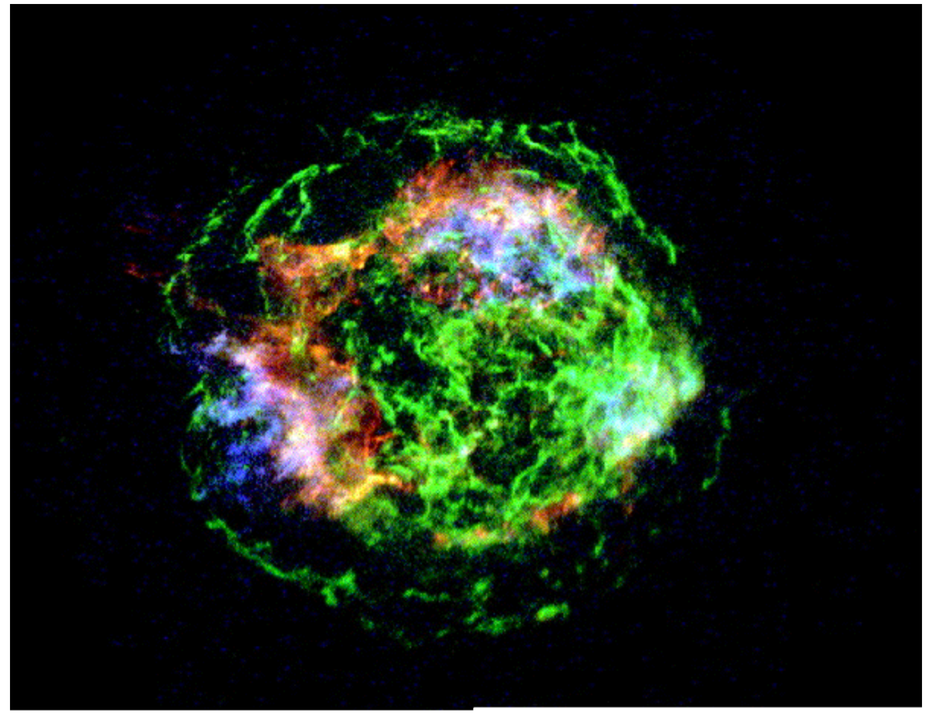


Credit: NASA/CXC/SAO/D.Patnaude et al.

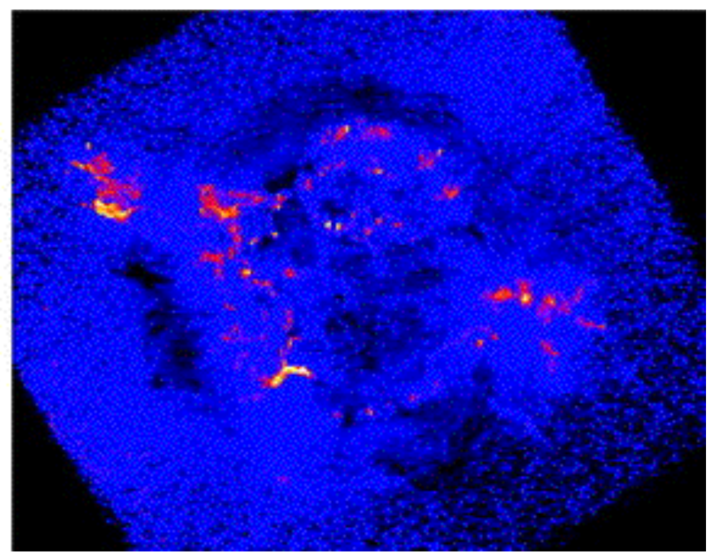
An Elemental Map of Cas-A- Exploded in ~1670 But not seen

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





Spectrum of 2 regions in SNR



Diffractive Spectrometers- Gratings

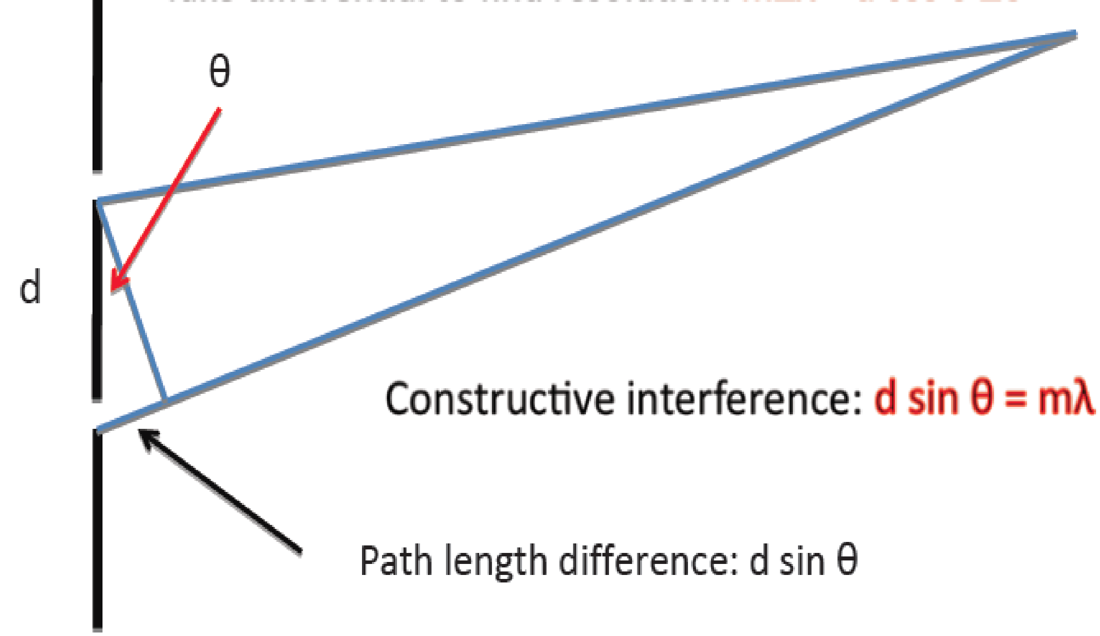
- Just like optical light, x-rays have a wave property and so can be diffracted
- The same wave equations- BUT the wavelength of x-rays is very small ~1-20A and so there are great technical difficulties
  - Many of these have been solved and productive gratings were produced for Chandra and XMM

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: $m\Delta\lambda = d \cos \theta \, \Delta\theta$



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

'constant Δλ devices'

Chandra Gratings

Paerels and Kahn ARAA 41,291 2003

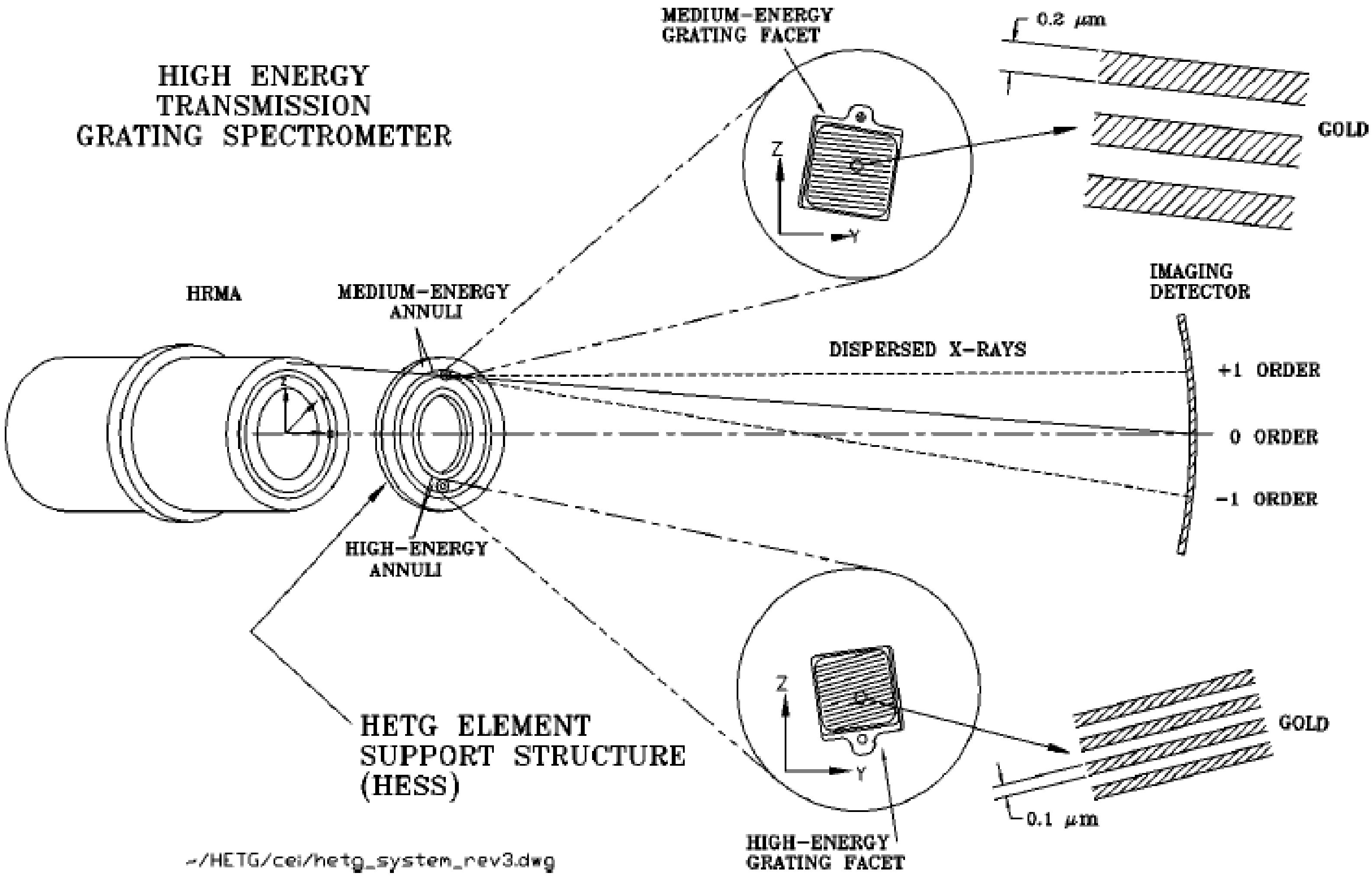
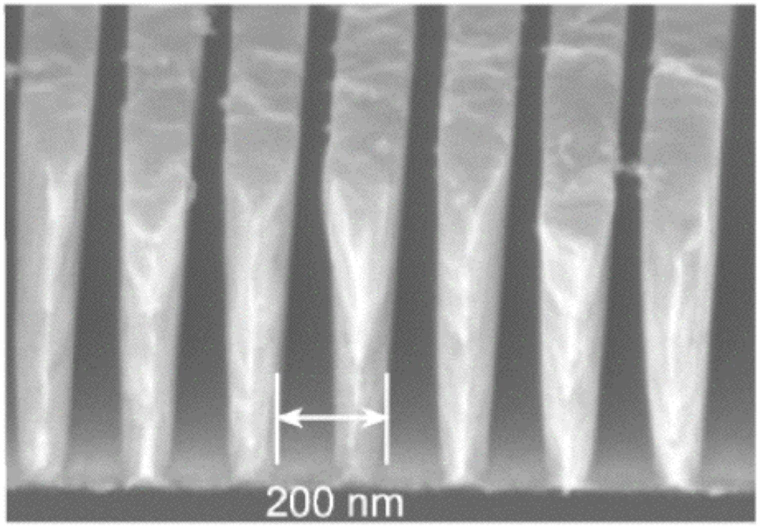
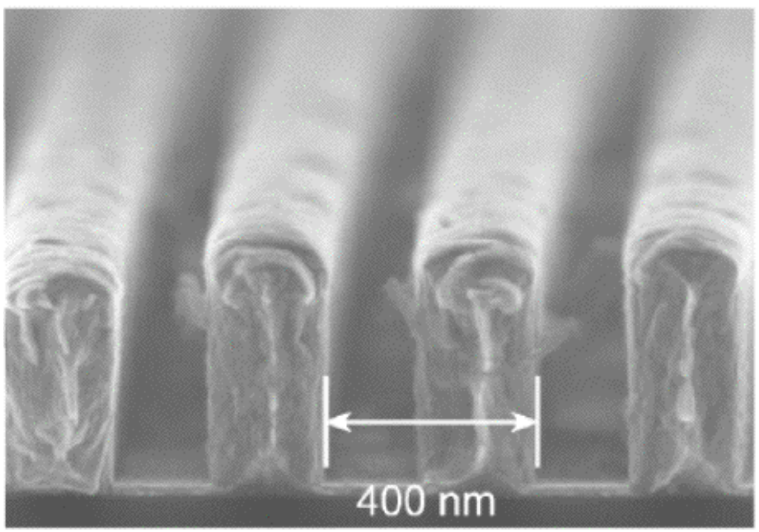


Figure 1 Geometry of the transmission grating spectrometers on *Chandra*. This

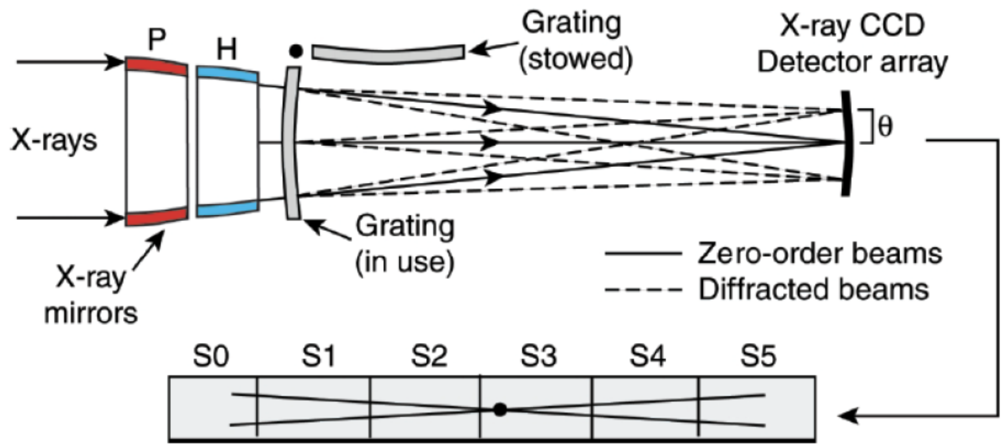
1. *Chandra* HETGS



(a) High Energy Grating (HEG).



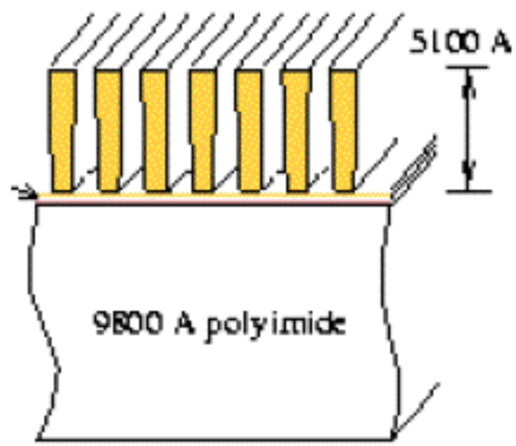
b) Medium Energy Grating (MEG).



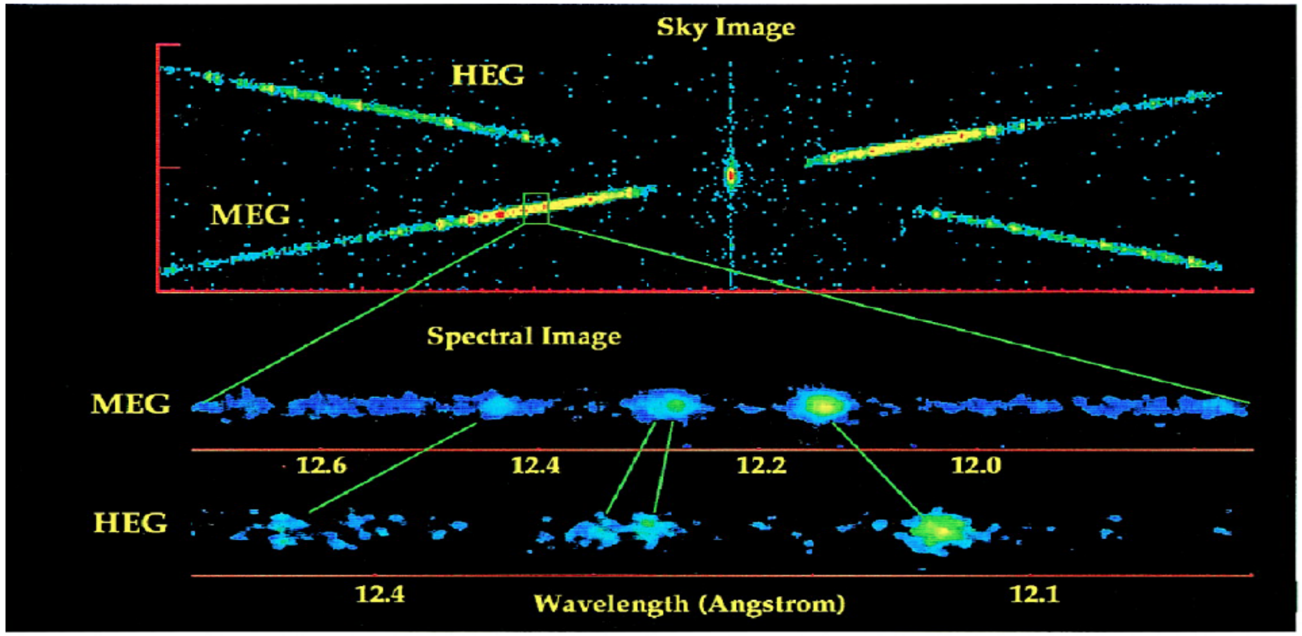
Claude Canizares et al., *Publ. Astron. Soc. Pac.*, **117**, 1144 (2005)

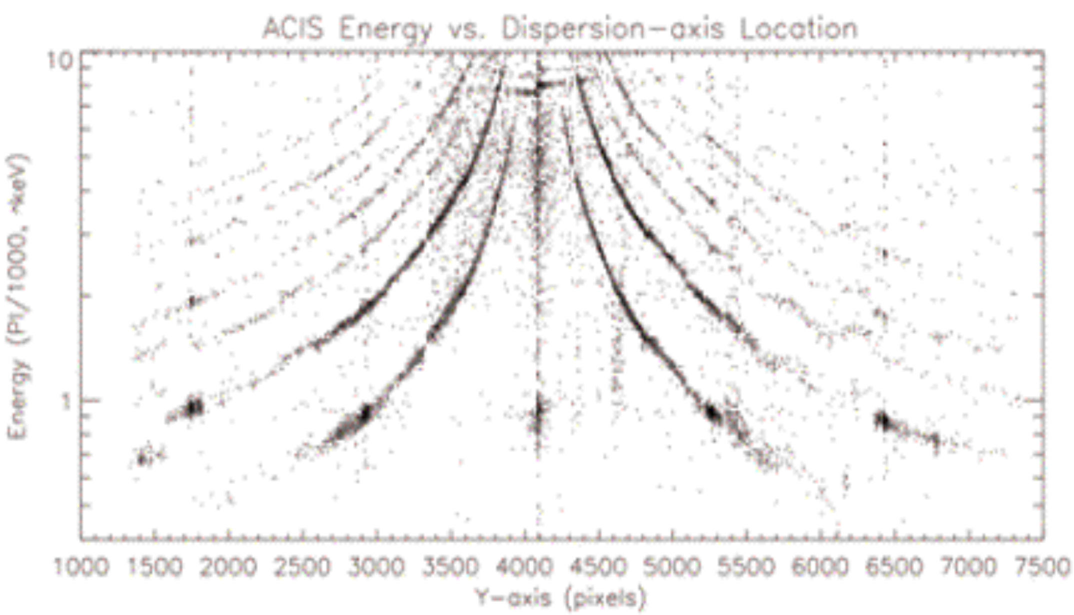
Dispersion equation: $\sin\theta = m\lambda/d$ (θ: dispersion angle, d: grating period, m: spectral order

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



What the Data Look Like



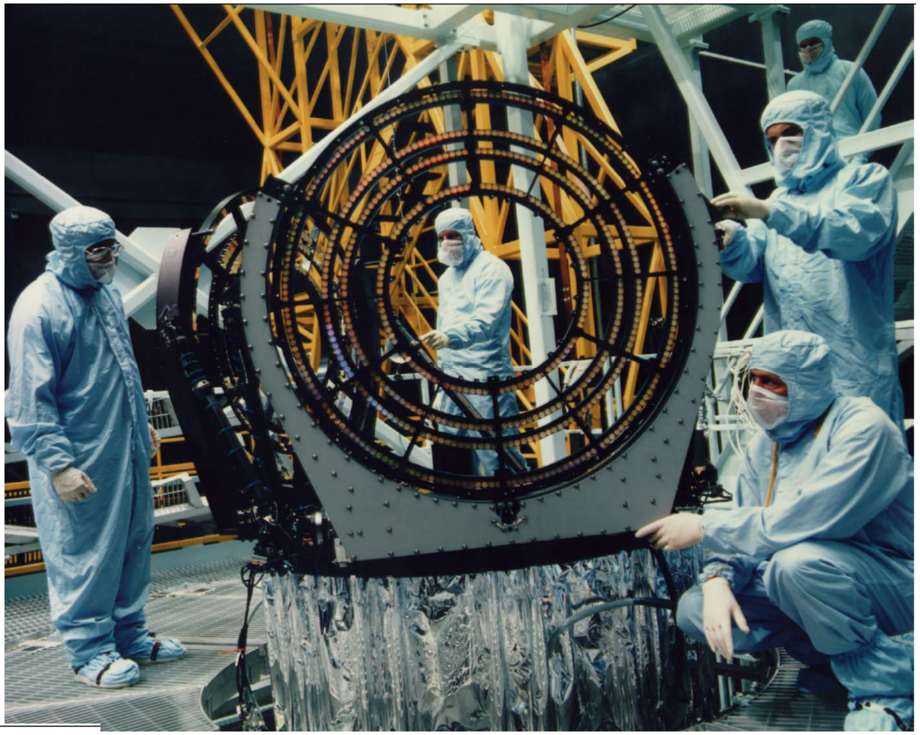


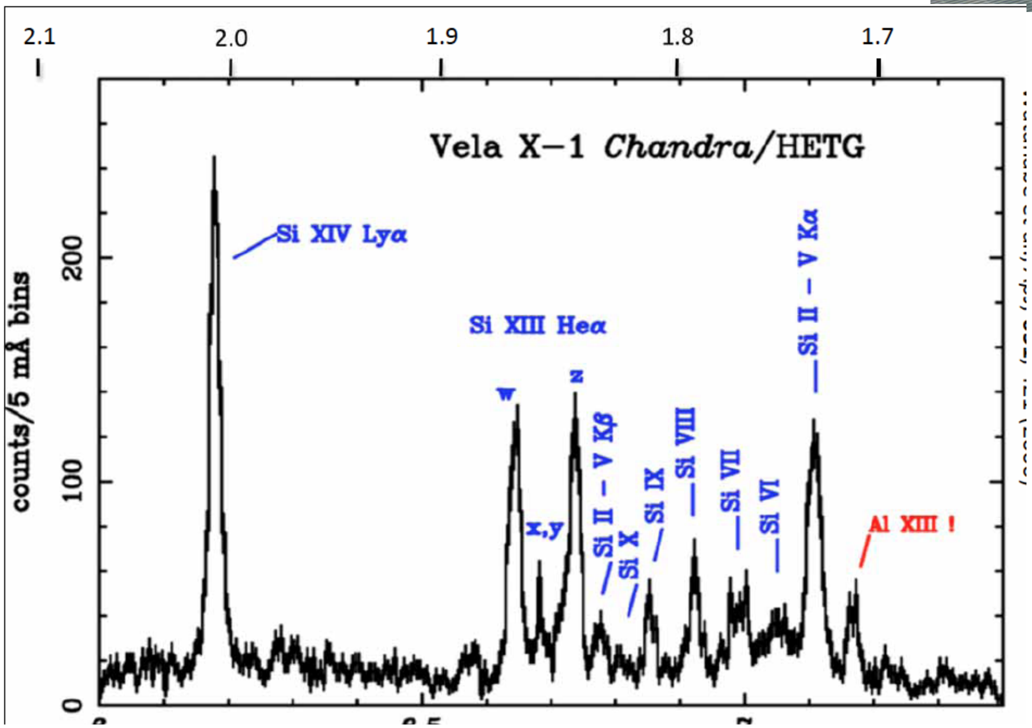
CCD/dispersion diagram ('banana')
NB: CCD energy resolution sufficient to separate spectral orders ($m = \pm1, \pm2, \ldots$)

- 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

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