How Does One Obtain Spectral/Imaging Information

How do we measure the position, energy, and arrival time of an X-ray photon?

- 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 **as is broad bandwidth** (e.g. Fermi covers 20Mev to 300 GeV !)

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

How Does One Obtain Spectral/Imaging Information

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

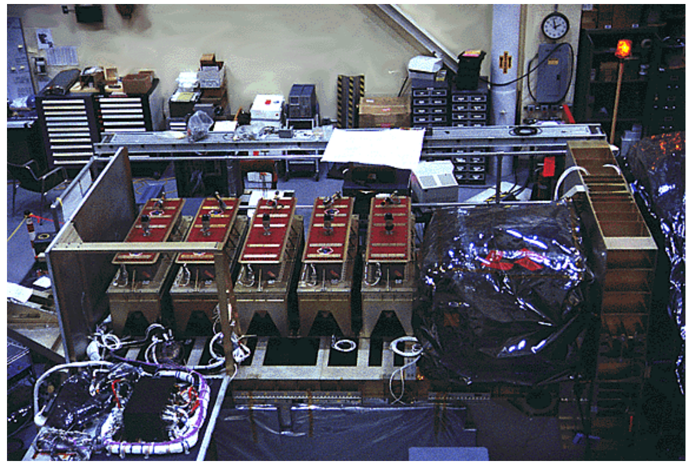
A major difference from other energy bands is that many x-ray detectors are imaging, photon counting devices
Thus one almost always get a 3d data 'cube' (e.g. every spatial element has spectral and timing data).

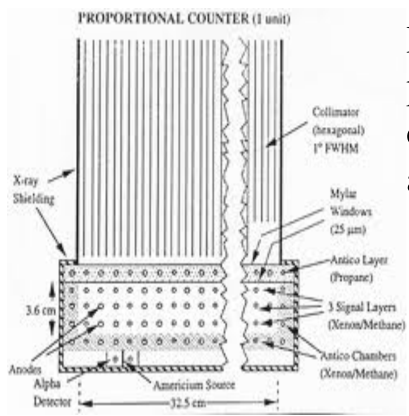
(As for any other energy band the properties of the telescopes are also very important)

Lots of 'Historical' Detectors

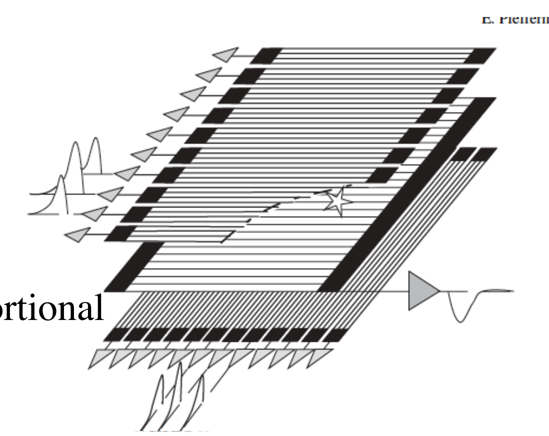
- Much of x-ray astronomy was performed with
  - Proportional counters
    - Imaging proportional counters
  - Channel plates
  - Scintillators
  - Etc. etc.

- Most of these are not anticipated for use in future missions but some (Channel plates, proportional counters, scintillators) still in use today- e.g. the recently launched (Oct 2015) Indian AstroSat





RXTE proportional counters during assembly



Gas Proportional counter
Nobel Prize - Charpak 1992

In a proportional counter the amount of charge produced by a x-ray is proportional to the energy of the x-ray

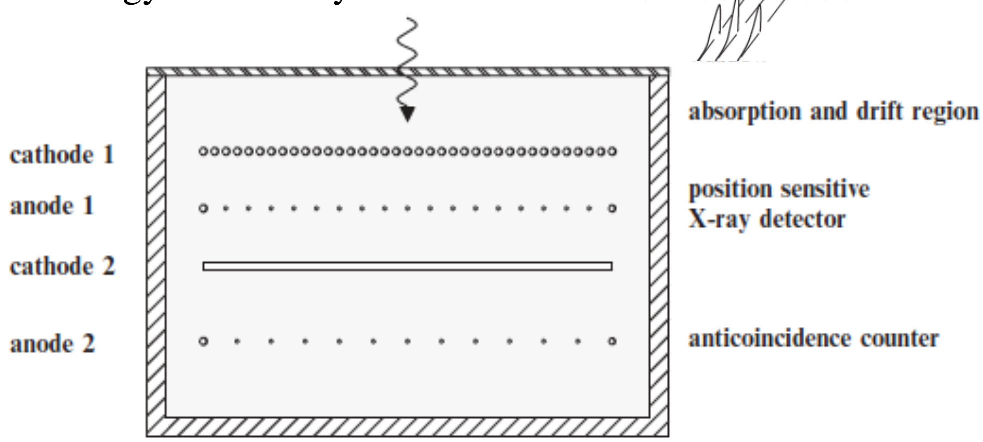


Fig. 4.1 Multiwire proportional counter for X-ray astronomy

Proportional Counters Imaging or Otherwise (Rosat, RXTE, AstroSat)

- 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.

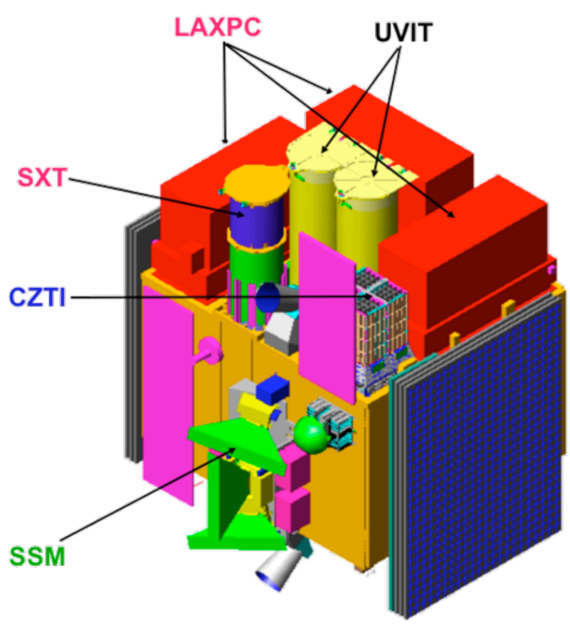
The intrinsic timing resolution ~microsecond level.

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/ΔE~16%-messy gas systems

AstroSat-http://astrosat.iucaa.in/

- Despite their being 'old' technology AstroSat (Launch Oct 2015) is flying *proportional counters* and scintillators.
- **LAXPC Instrument** X-ray timing and low-resolution spectral studies over a broad energy band (3–80 keV), Field of View of 1° × 1°)
- The effective area ~ 6000 cm^2.



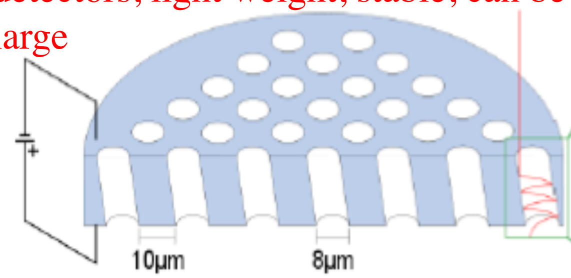
Microchannel plate (MCP)

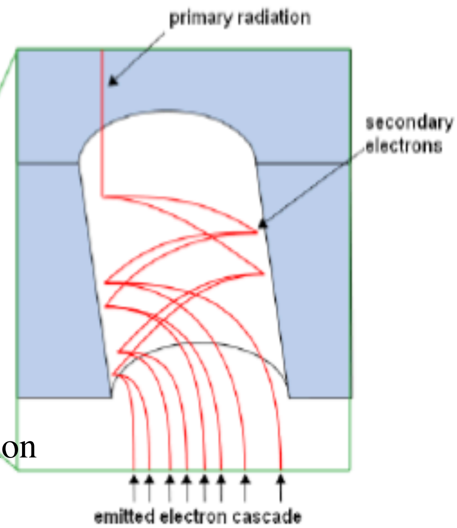
Electron avalanche is excited at the semiconducter walls

Disadvantages
High background, poor energy resolution, low QE

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, Rosat, EUVE

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
- 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.

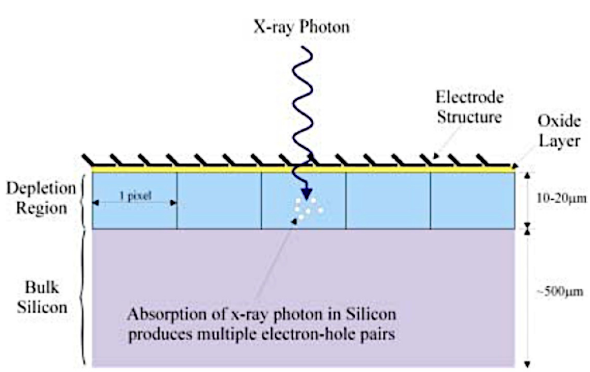
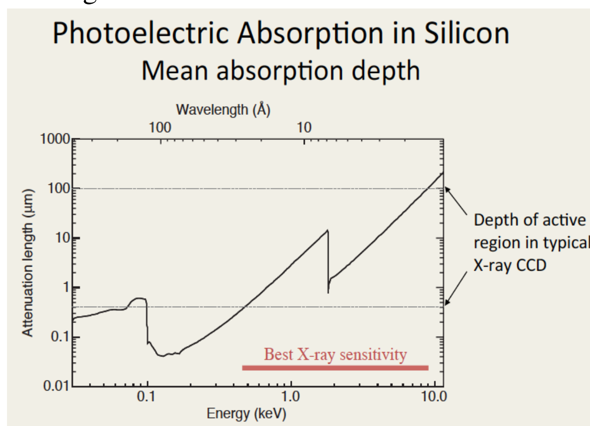


Figure 3: Schematic illustration of the direct detection of an X-ray photon.

CCDs- Basics (C. Grant 2008)

- 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 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 bandpass and efficiency are set by the absorption cross section of Silicon



X-ray CCDs-

see http://cxc.cfa.harvard.edu/xrayschool/

- 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.

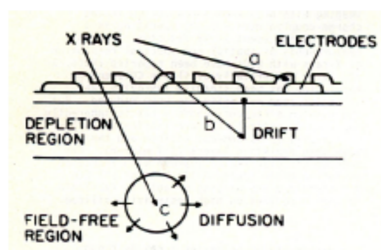
Quantum efficiency is set by physics

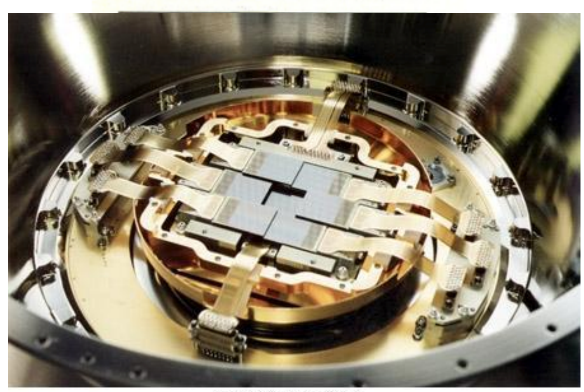
'dead' layer controls low E efficiency

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)





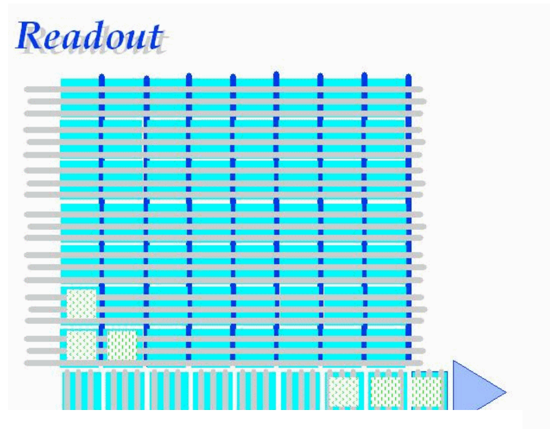
EPIC-MOS CCDs

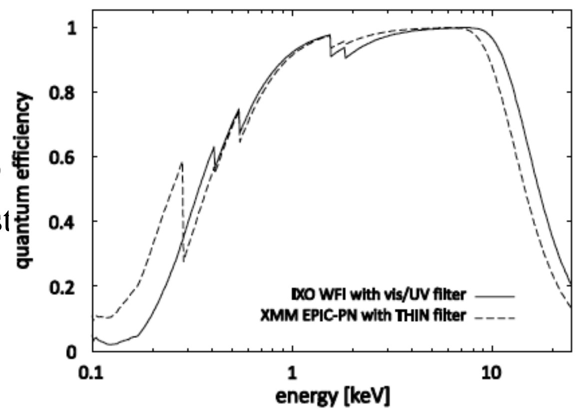
Image courtesy of Leicester University, University of Birmingham, CEA Service d'Astrophysique Saclay

European Space Agency

CCDs

- 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





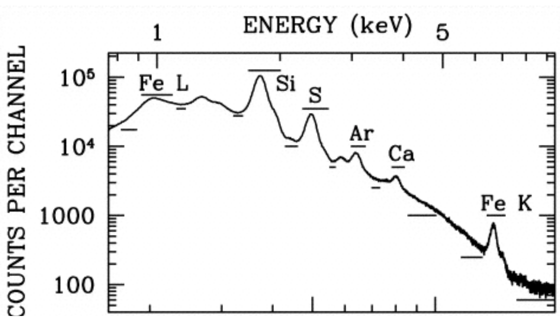
CCDs

- Advantages
  - high spatial resolution
  - reasonable energy resolution
  - good quantum efficiency
  - low background
- Disadvantages
  - need to operate at ~-90C (crud can easily accumulate)
  - subject to radiation damage
  - poor time resolution

In a CCD the amount of charge produced by a x-ray is proportional to the energy of the x-ray

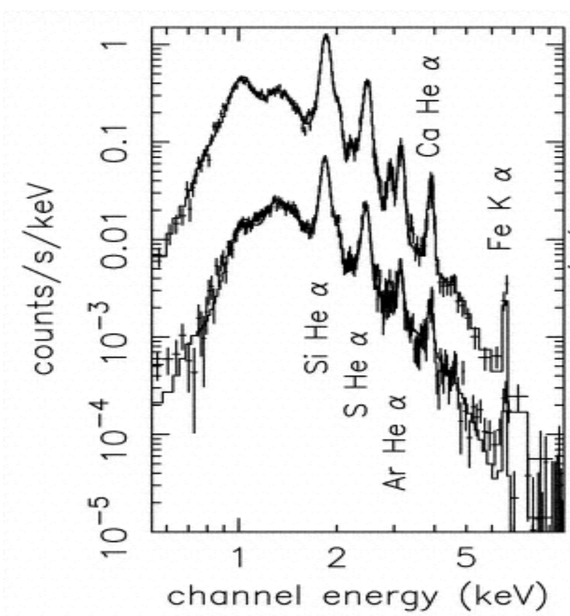
Results from CCDs

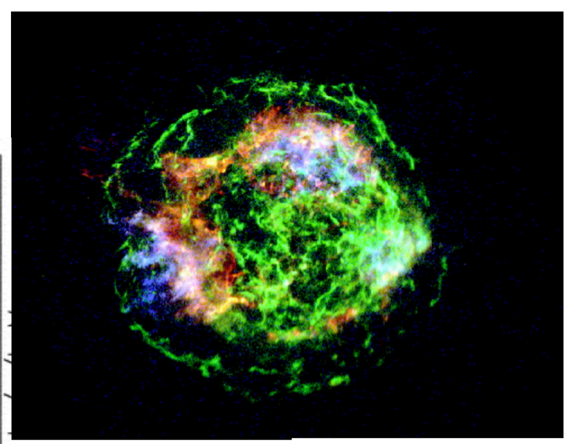
- Chandra CCD image of a supernova remnant (Cas-A)-
- The color code is energy- **blue** is high temperature gas, **green** is medium, **red** is low



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

- Red=He-like Si, blue=Fe complex



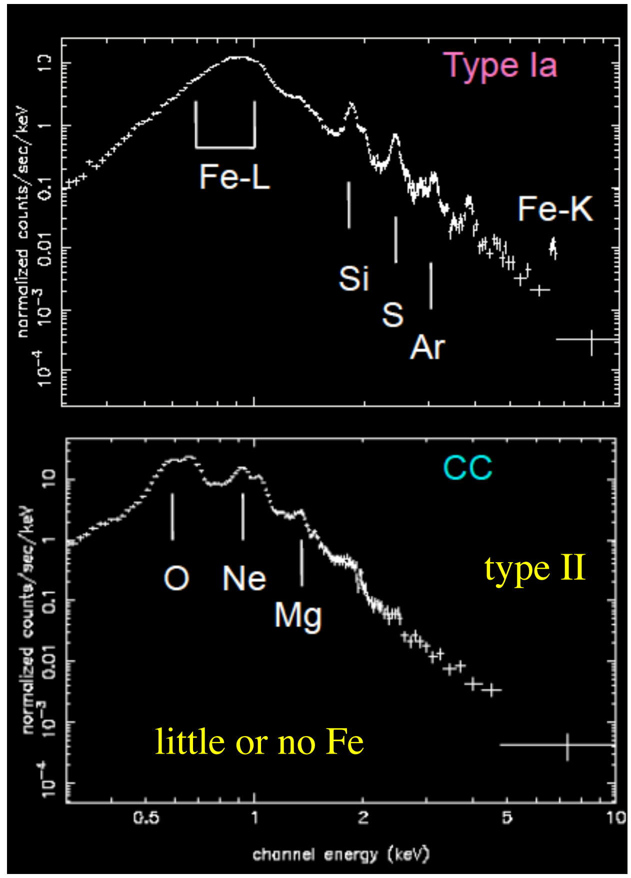


Spectrum of 2 regions in Cas-A SNR

Difference Between Type I and II Super Nova Remnants

- How to characterize the nature of a SN from x-ray CCD spectra
  - type I - a lot of Fe
  - type II- a lot of oxygen

'see' this in the x-ray spectrum



Spectrometer Complementarity
Cross-over Occurs in X-ray Band

Non-Dispersive E = hν

Energy Standard (courtesy of nature)

IP, band gap, phonon energy…

δE ~ eV (10 → 0.01)

Instruments

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

Properties

- ΔE ~ fixed
- Resolving Power = E/ΔE ~ E

Dispersive λ=c/ν=hc/E

Length Standard (courtesy of nature or engineering)

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

δx * θ ~ 0.1-0.01 Å

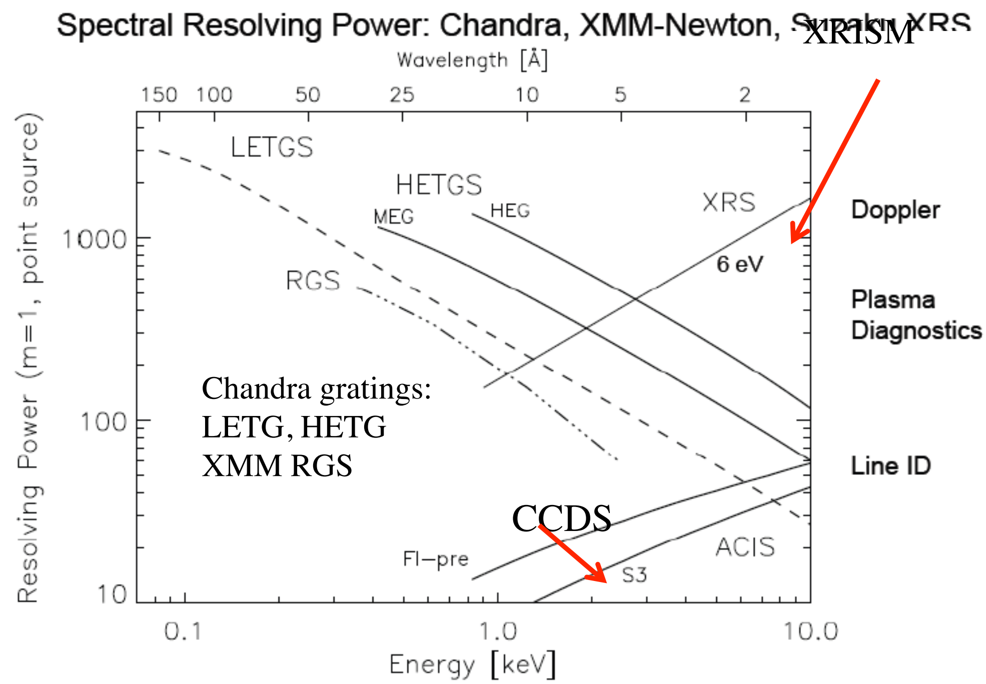
Instruments

- Bragg spectrometers
- Transmission Gratings
- Reflection Gratings

Properties

- Δλ~fixed
- Resolving Power = λ/Δλ ~1/E

Energy Resolution of Spectrometers



Spectral Resolving Power = E/ΔE = λ/Δλ

Canizares et al. 2005

Types of Detectors/ Spectrometers

- **Diffractive vs. Non-diffractive Spectrometers**
  - **Diffractive Spectrometers:** gratings, Bragg crystals
    like in optical/UV spectrometers
  - **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)

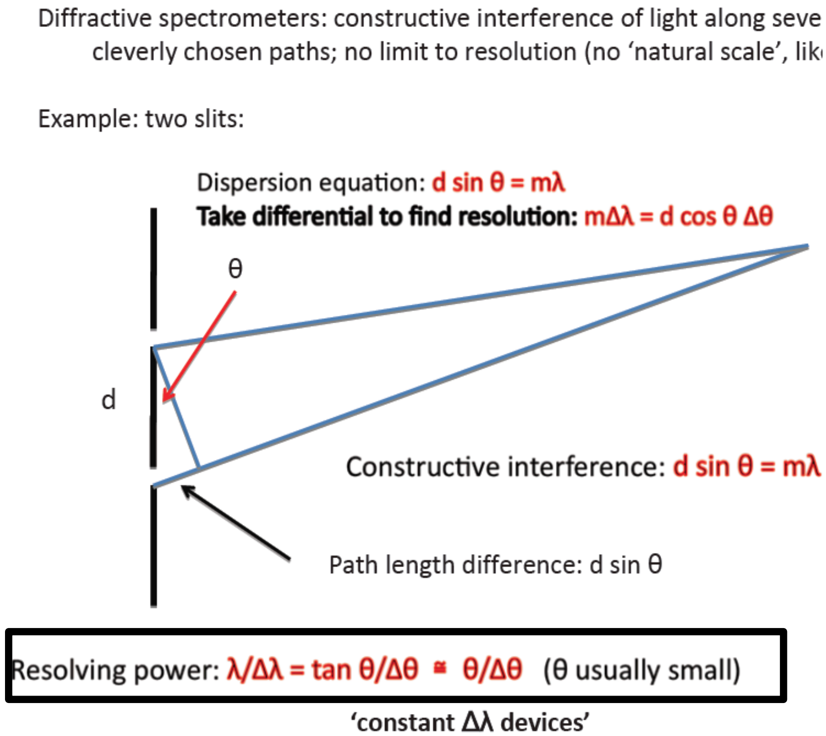
e.g. at 6.4 keV theoretical is 120 eV

•Resolution ΔE, or resolving power E/ΔE, 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

Diffractive Spectrometers- Gratings

- Just like optical light, x-rays are waves 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



Chandra Gratings

Paerels and Kahn ARAA 41,291 2003

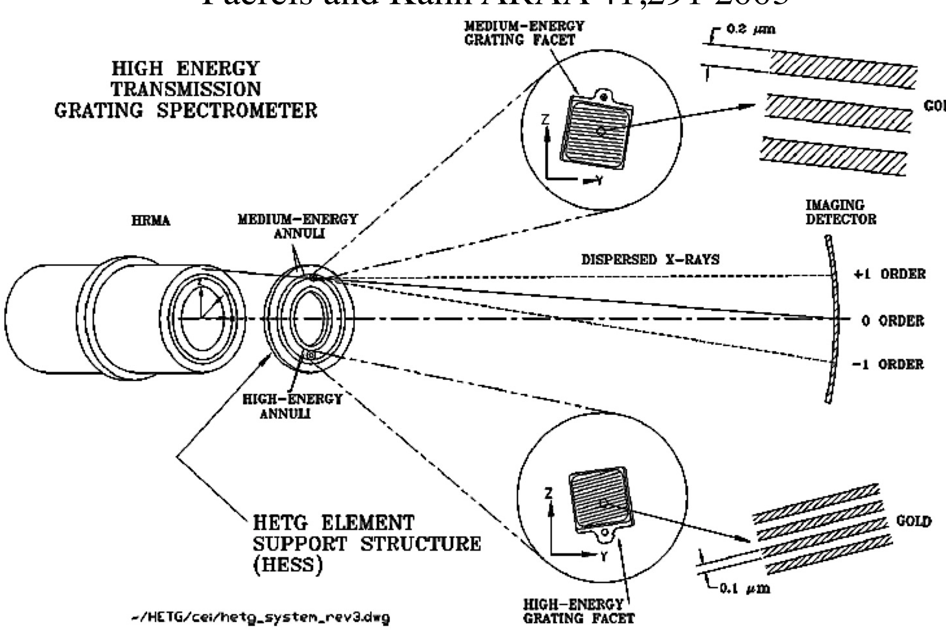
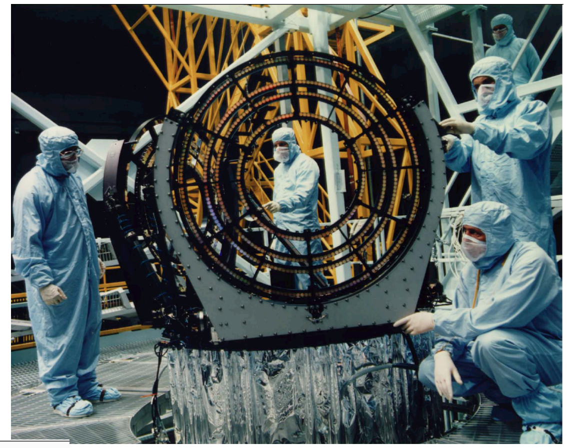
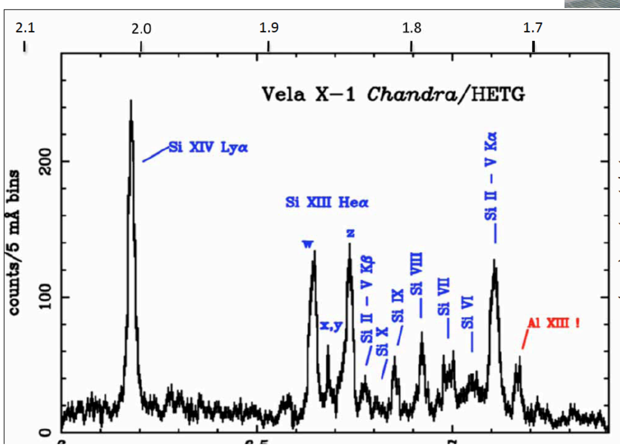


Figure 1 Geometry of the transmission grating spectrometers on *Chandra*. This

Chandra transmission gratings

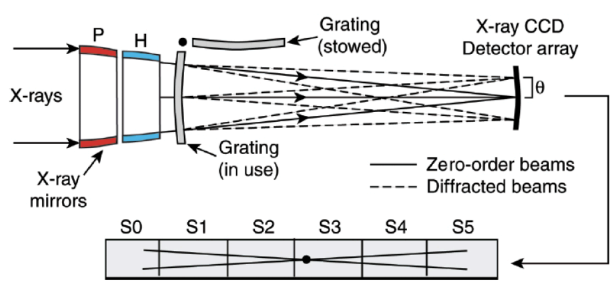
- Gratings have overlapping orders- uses energy resolution of CCD readout to separate them.
- **Chandra gratings are good for point-like and small sources**





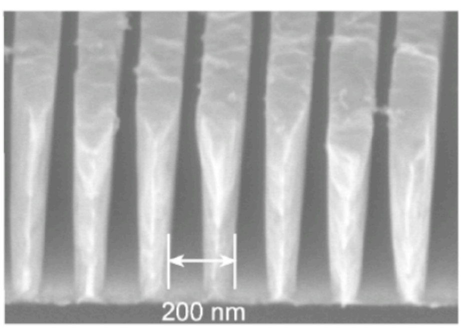
Very accurate wavelength scale:
$\Delta v/c \sim 1/10{,}000$!

1. *Chandra* HETGS

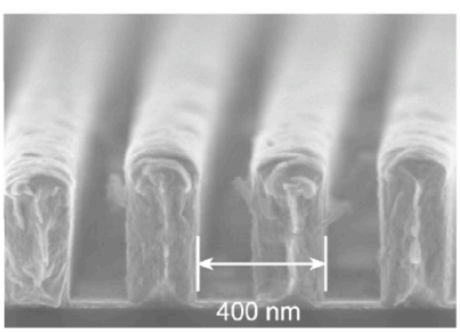


Claude Canizares et al., *Publ. Astron. Soc. Pac.*, **117**, 1144 (2005)

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 ($\Delta\theta$)

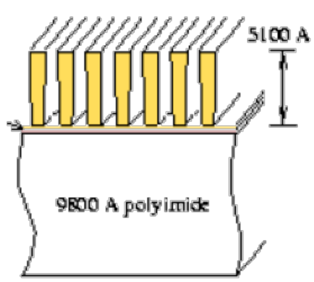


(a) High Energy Grating (HEG).

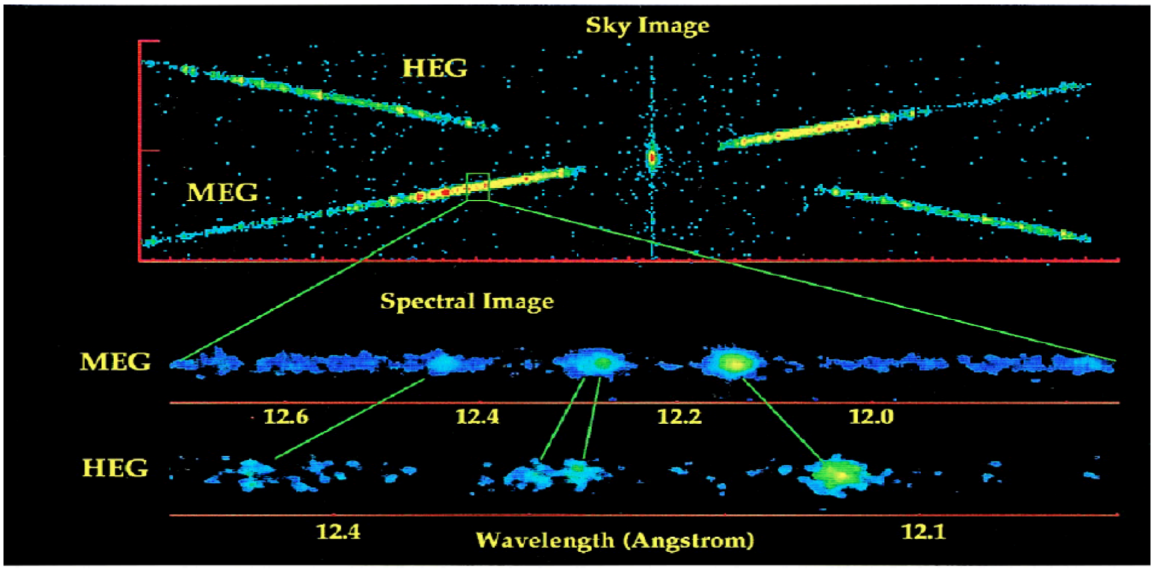


b) Medium Energy Grating (MEG).

Achieve grating period of 0.2 μm with precision of < 200 ppm across hundreds of grating facets

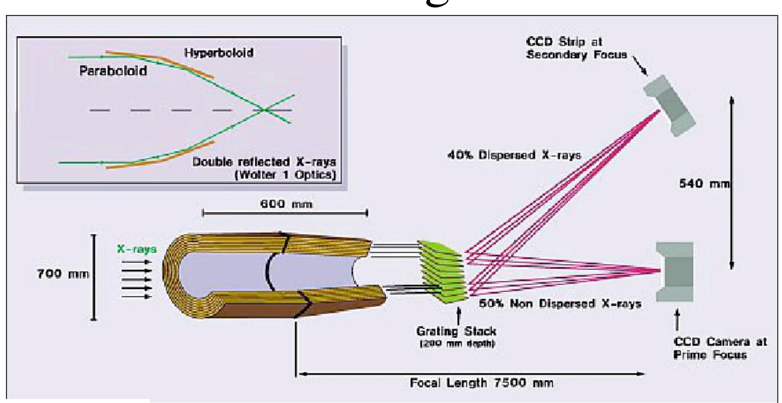


What the Data Look Like

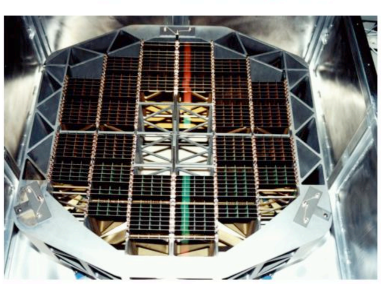


- Position and wavelength are linearly related- have overlapping orders that are separated by the energy resolution of the readout detector (a CCD)

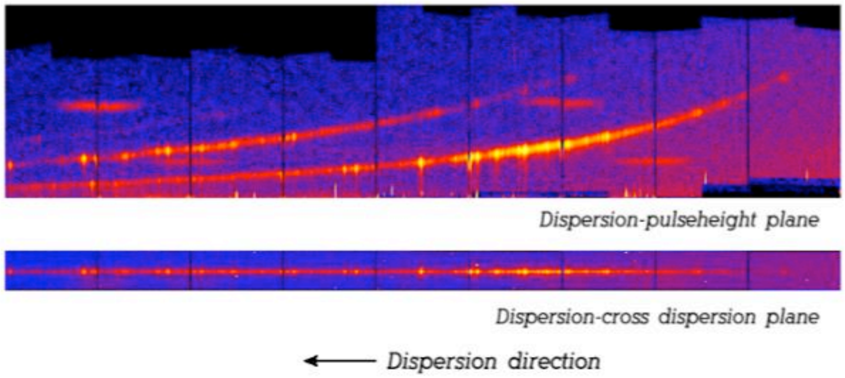
XMM Reflection Gratings



The RGS Reflection Grating Array

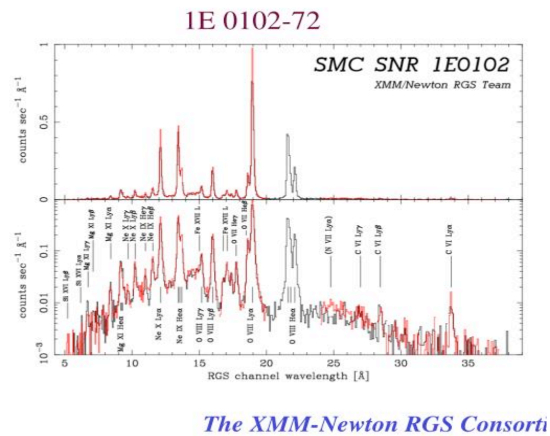


The XMM-Newton RGS Consortium



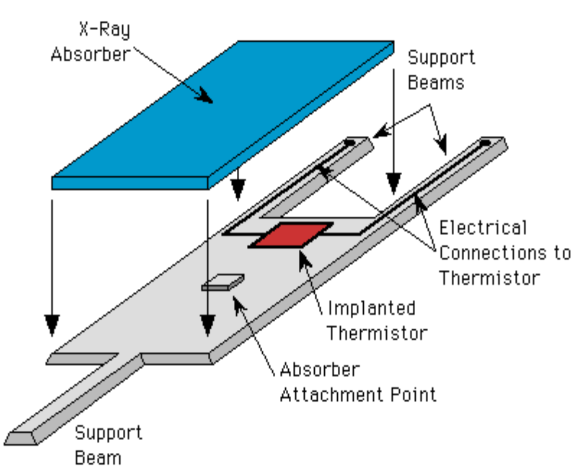
XMM RGS

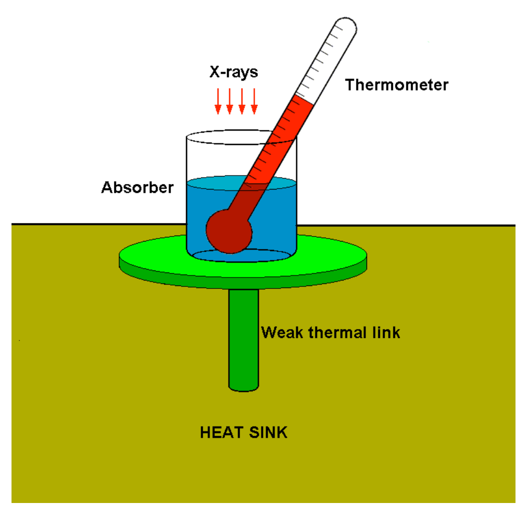
- Capella in detector units
- SNR E0102



Calorimeter

- Photon energy is thermalized, producing phonons- a thermometer then translates changes in temperature into a voltage. -see **QUANTUM CALORIMETRY** Caroline Kilbourne Stahle, Dan McCammon, and Kent D. Irwin Physics Today, August 1999, pp 32-37
- In principle very simple......

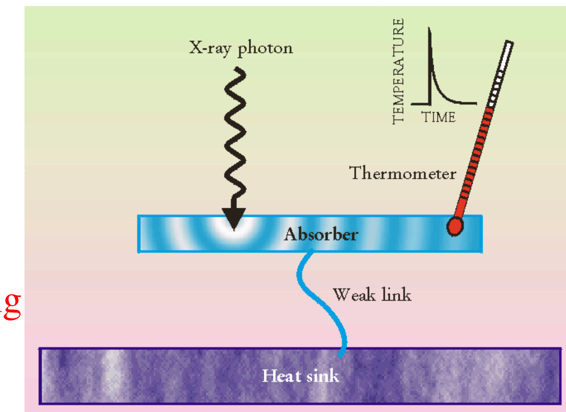




Calorimeters

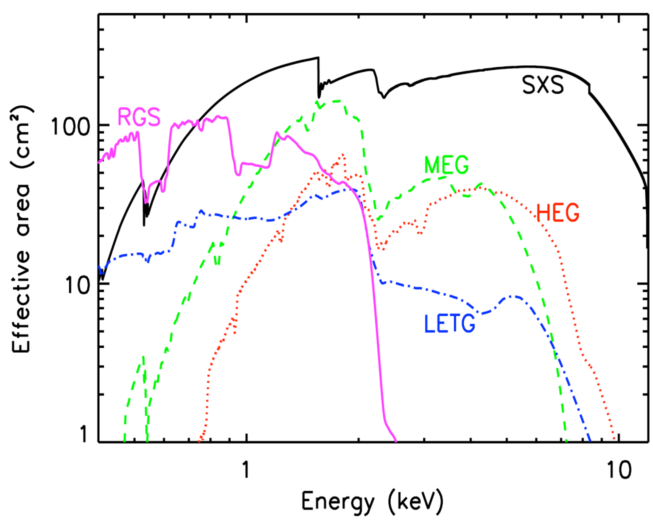
- T_{rms} fluctuations determined by phonon fluctuations
- RMS Intrinsic Energy Noise ≈ $(kT^2C)^{1/2}$
- Example: T=0.1 K, $C=10^{-13}$J/K
- **$\Delta E_{rms} \approx 1$eV**

- high efficiency
  low background
  high spectral resolution for all sources
  wide bandpass
- However, microcalorimeters are **cryogenic** experiments requiring cooling to ~60 mK



Astro-H Calorimeter (SXS)- Launched Feb 12 2016

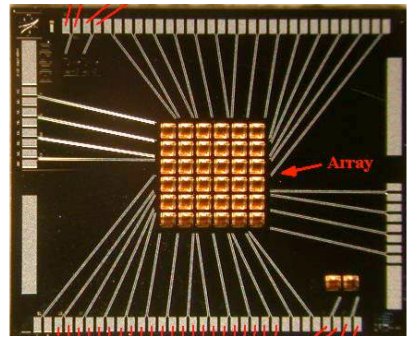
- ~100% QE over full band- low E efficiency is set by window to reject light
- Comparison of collecting area of Astro-H calorimeters (SXS) with Chandra and XMM gratings (the other high spectral resolution x-ray detectors)

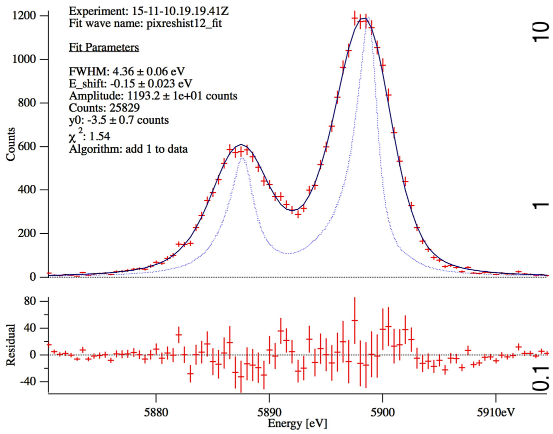


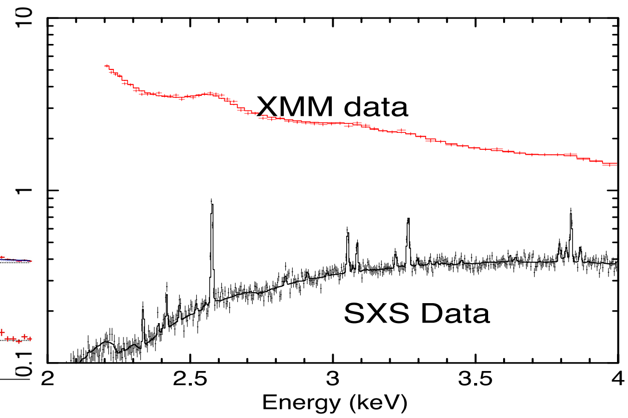
See arXiv:1412.1356, Takahashi et a

Astro-H SXS

- Actual Performance ΔE=4.36 eV, 36 pixels, FoV ~3'

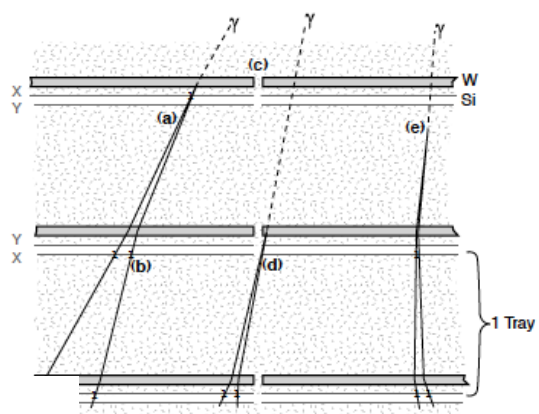


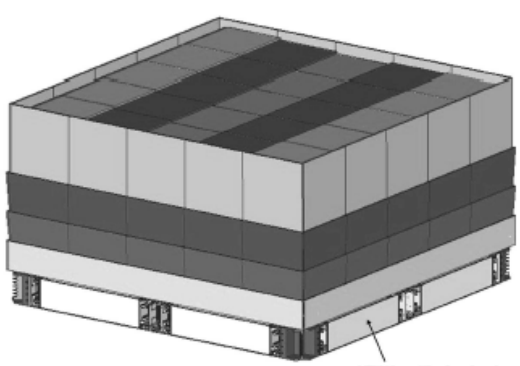




γ-ray Detectors

- **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)



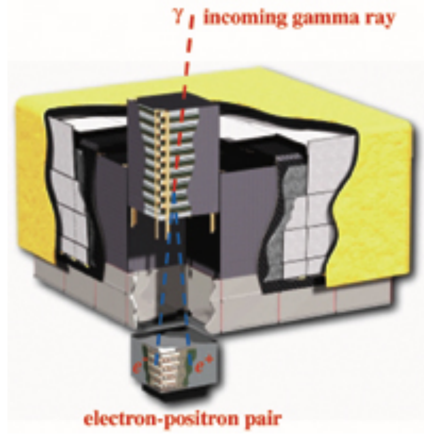


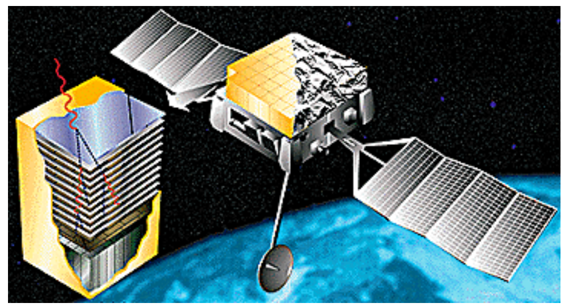
Full coverage of anti-coincidence detectors

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.

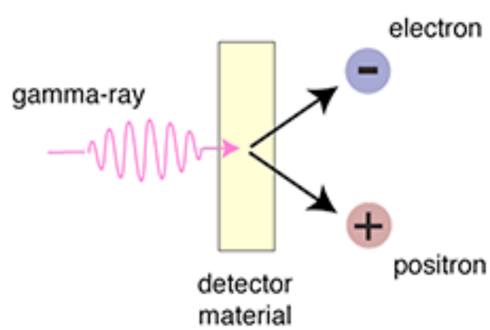




High Energy γ-Ray Detectors

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

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



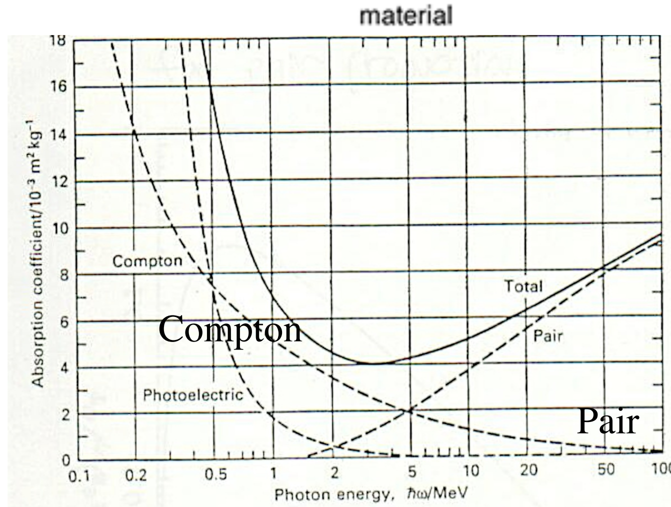


Figure 4.16. The total mass absorption coefficient for high energy photons in lead,

γ-Ray Detectors

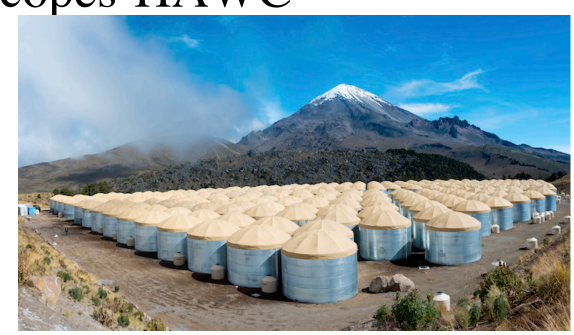
- The direction of the incoming gamma ray is determined by tracking the direction of the cascading particles back to their source

- 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.

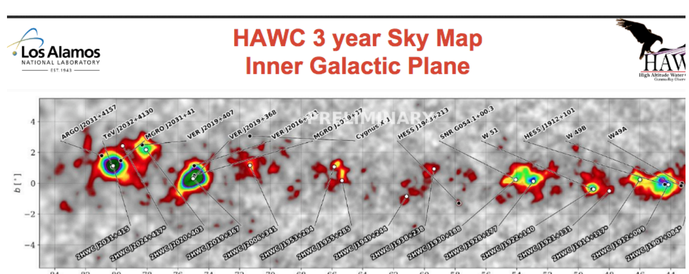
- the absorption of the pair by a calorimeter after they exit the spark chamber, determines the total energy of the γ-ray

Cerenkov Telescopes-HAWC

- HAWC detects high-energy particles striking the water in the tanks which result in Cherenkov light that is detected by the photomultiplier tubes. The high energy particles are produced by gamma-rays in the upper atmosphere.
- Very large FOV, long observing time, low sensitivity per unit time.

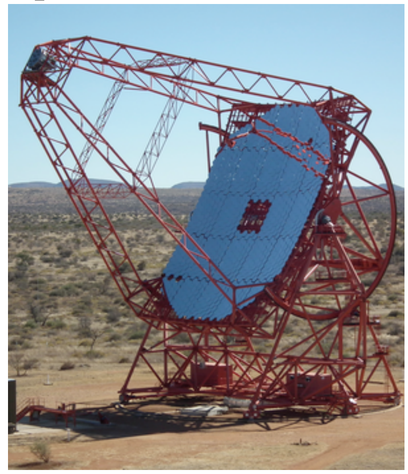


A~20000 m^2



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*
- 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

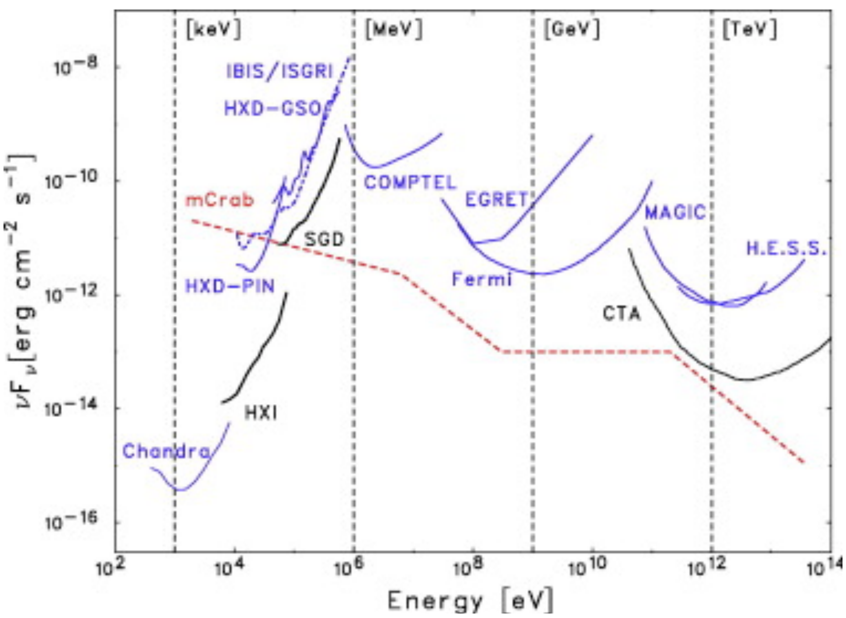
Imaging Atmospheric Cherenkov Telescopes

- 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 GeV- 30 TeV band
- detect a source with a flux of 1% of the Crab Nebula in ~20-40 hours.
- energy resolution of 15-20% angular resolution of 0.1 deg.
- field of view of 3-5 deg wide
- duty cycle is low, restricted to dark nights ~ 1200 hours of observations per year.

X-ray and Gamma-ray Sensitivity

better

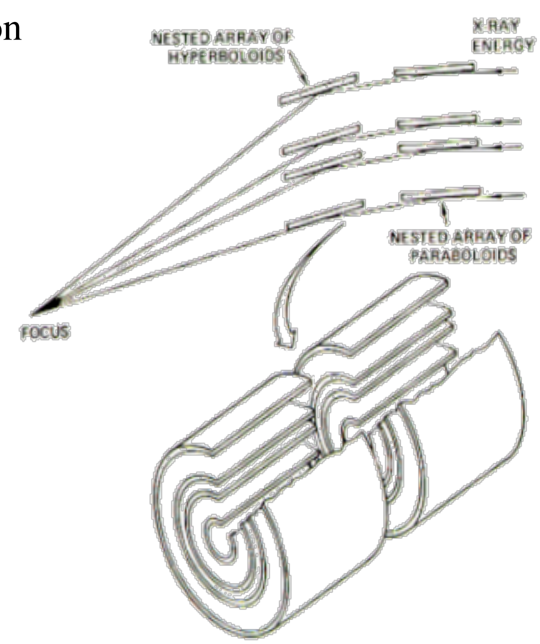


- X-ray missions ~4 orders of magnitude more sensitive than present day gamma-ray observatories for most sources.

Next Lecture- 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 Imaging Optics



X-Ray Optics

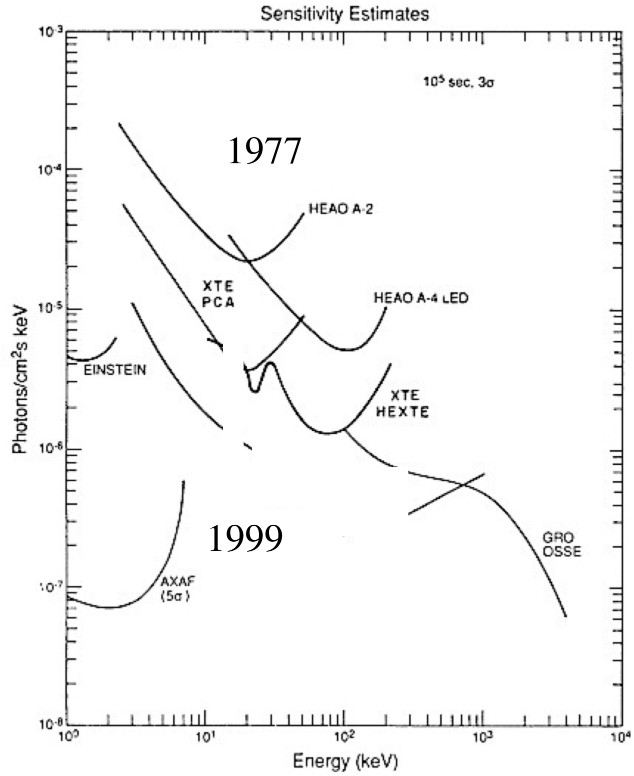
How to make the x-rays reflect and focus

- Total External Reflection
- Fresnel's Equations

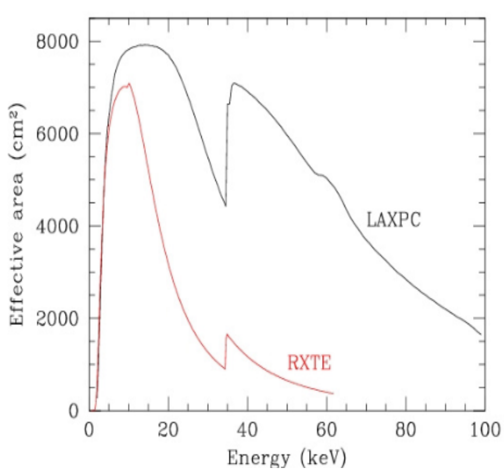
See schwartz_optics.pdf

Improvement in Sensitivity

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



AstroSat



- 12" telescope has 730cm^2
- Keck has 7.8x10^5 cm^2

TROSAT - Payload Characteristics

	UVIT	SXT	LAXPC	CZTI	S
Detector	Intensified CMOS, used in photon counting mode or integration mode	X-ray (MOS) CCD (at the focal plane)	Proportional counter	CdZnTe detector array	Pos sen propc cou
Imaging / non-imaging	imaging	imaging	non-imaging	imaging	ima
Optics	Twin Ritchey-Chretian 2 mirror system.	Conical foil (~Wolter-I) mirrors 2-m focal length	Collimator	2- D coded mask	1- D m
Bandwidth	FUV (130-180 nm), NUV (200-300 nm), VIS (320-550 nm)	0.3 - 8 keV	3 - 80 keV	10 - 100 keV	2.5 -
Geometric Area (cm2)	~1100	~ 250	10800	973	~
Effective Area (cm2)	10 - 50 (depends on filter)	128@1.5 keV 22@6 keV	8000@5-20 keV	480 (10-100 keV, normal incidence)	~11 @ ~53 @ for SS
Field of View (FWHM)	28' dia	~ 40' dia	1° x 1°	6° x 6°	10°
Energy Resolution	<1000 A (depends on filter)	~5-6%@1.5 keV ~2.5%@6keV	12%@22 keV	6% at 100 keV	25% @
Angular Resolution	1.8 arcsec (FUV, NUV) 2.2 arcsec (Vis)	~2 arcmin (HPD)	~(1-5) arcmin (in scan mode only)	8 arcmin	~12 a
Time resolution	1.7 ms	2.4 s, 278 ms	10 microsec	20 microsec	1
Typical observation time per target.	30 min	0.5 - 1 day	1 - 2 days	2 days	10
Sensitivity (Obs. Time)	Mag. 20 (5σ) 200 s (for 130-180 nm)	~15 μCrab (5σ) (10000 s)	1 milliCrab (3σ) (100 s)	0.5 milliCrab (3σ) (1000s)	~28 m (3σ)
No. of Units	2	1	3	1	
Total Mass (kg)	230	90	414	50	