OBSERVATIONAL ASTRONOMY

AUTUMN 2023

Lecture 6

Vitaly Neustroev

X-ray Detectors

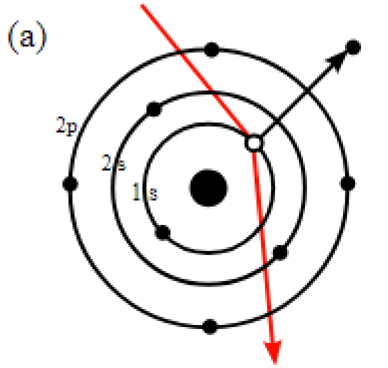
- Proportional counters
- X-ray CCDs
- Microchannel plates

X-ray detectors

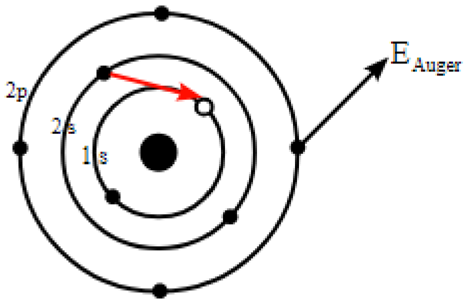
- X-ray photons are few, but are very energetic.
  X-ray detectors can measure the energy as well as
  the spatial position of X-ray photons,
  by counting the secondary photoelectrons they produce.
- X-ray detectors are chosen to have good spatial resolution
  as well as some level of intrinsic energy resolution.
  The three types in serious use today are:
  - Proportional Counters
  - CCDs
  - Microchannel Plates

Auger effect

- The principles that X-ray detectors work on are all pretty similar. The primary photon is very energetic, and produces a number of secondary electrons by the Auger effect.
- The **Auger effect** is a physical phenomenon in which the transition of an electron in an atom filling in an inner-shell vacancy causes the emission of another electron.
- The number of electrons released is proportional to the energy of the incident photon. In the gas proportional counter these electrons are produced by interaction of a photon with an atom of inert gas.



Electron collision
or ionization by an X-ray photon

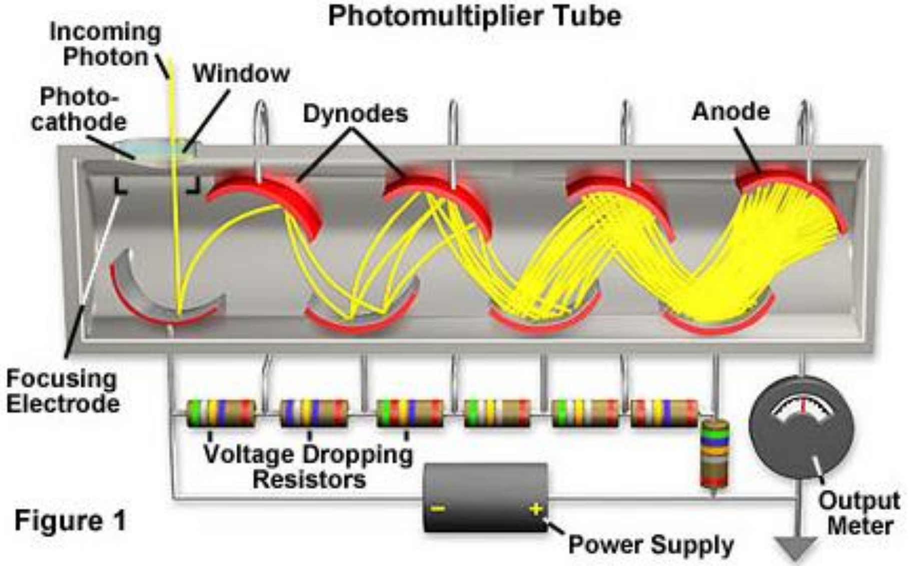


Auger electron emission

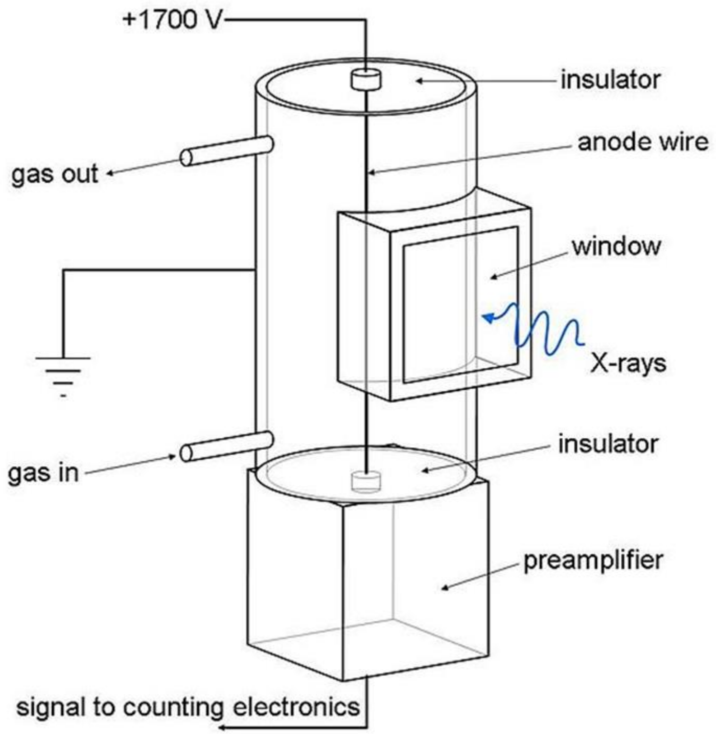
Geiger counters

- Two electrodes inside an enclosure are held at such a potential difference that a discharge in the medium filling the enclosure is on the point of occurring.
- X-ray ionizes gas. Produced electrons accelerate toward anode and cause further ionization, producing more electrons – electron avalanche.
  The amplification factor (gain) is about 10^8.
- Amplifier records a charge pulse.
- Operates in saturated regime:
  no energy resolution.

An analogue of photomultipliers:



Proportional counters (1)



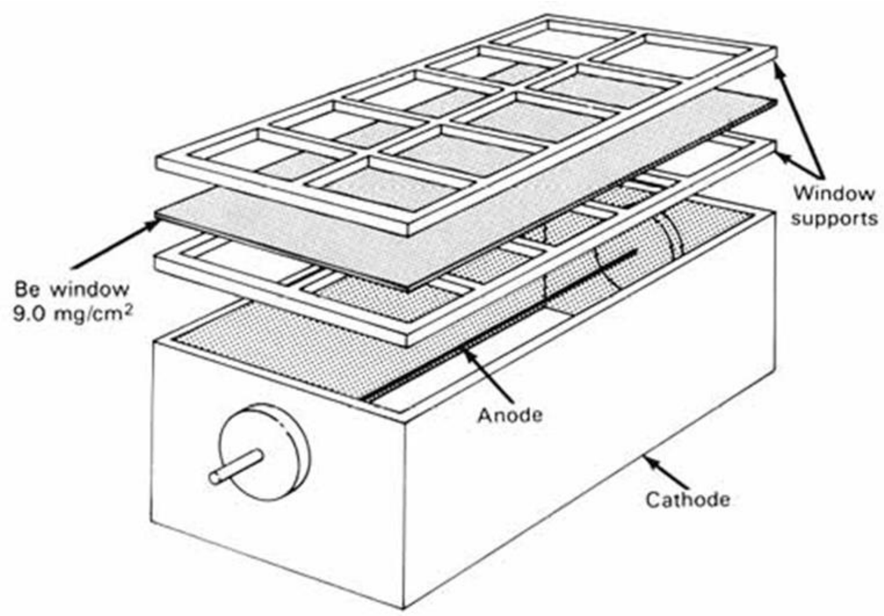
- Proportional counters are very closely related to Geiger counters but they operate at less than the trigger voltage.
- By using a lower voltage, saturation of the pulse is avoided, and its strength is then proportional to the energy of the original interaction.
- The gain is reduced to about $10^4 - 10^5$

Proportional counters (2)

- X-rays are detected through their interaction with inert gas (e.g Argon) in a windowed chamber.
- Primary photoelectron is emitted by the photoelectric effect.
- Secondary "Auger" electrons are emitted in a localized cloud.
- Mean number of electrons released is $\mathbf{N = E/w}$, where E is the energy of the X-ray photon, and w is the ionization energy of the gas (w = 26.2 eV for Argon; 21.5 eV for Xenon).
- **Disadvantage:** other forms of ionizing radiation (electrons, positrons, protons, etc.) create false signals, and so do even lower energy photons in the FUV or EUV.

Position Sensitive Proportional Counter (1)

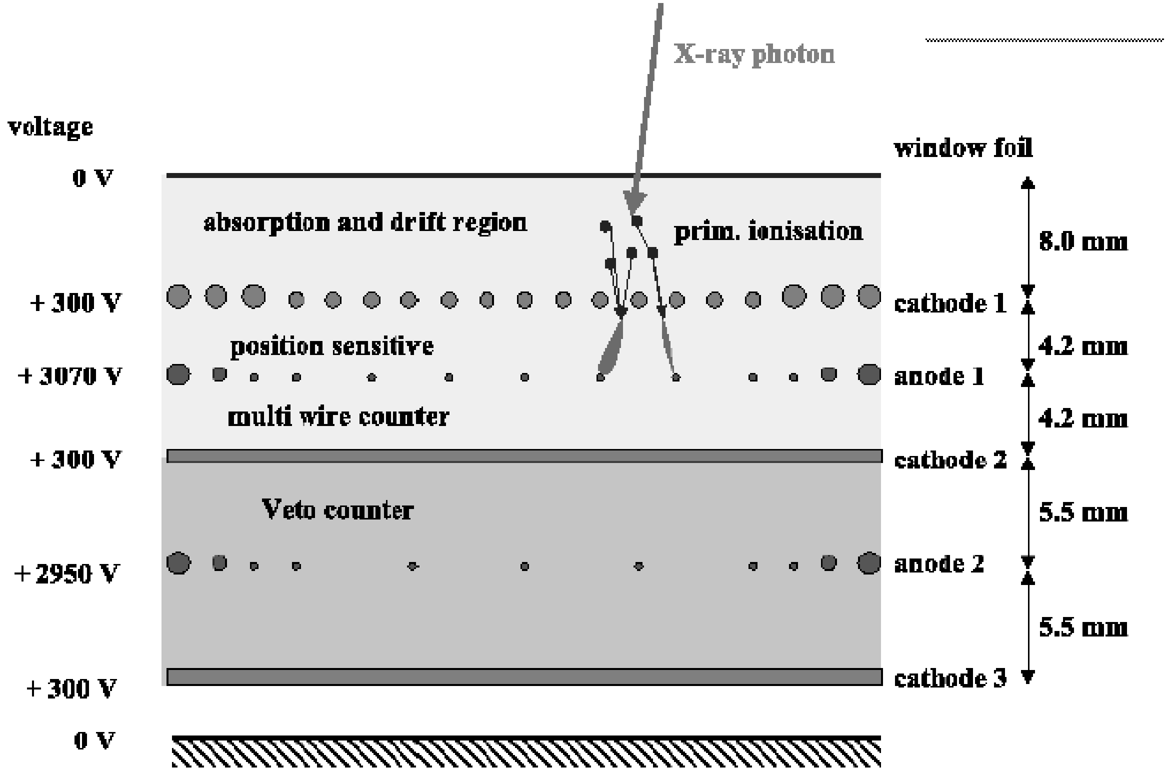
- Position information is obtained using a position sensitive (resistive) anode. The pulse is extracted from both ends of the anode, and from the size of the pulse at each end the location is determined.
- A grid of anodes provides two-dimensional imaging.
- Alternatively, the position can be measured using a pair of crossed cathode grids above and below the anode.



Large Area Proportional Counters

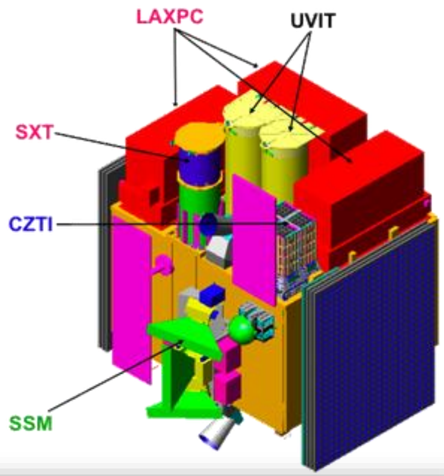
- The observation of the weak X-ray fluxes with non-imaging instruments (no telescopes, only mechanical collimators!) requires large area detectors with high background rejection capability.

The bottom chamber, the "Veto counter" is used to detect/eliminate cosmic ray events.

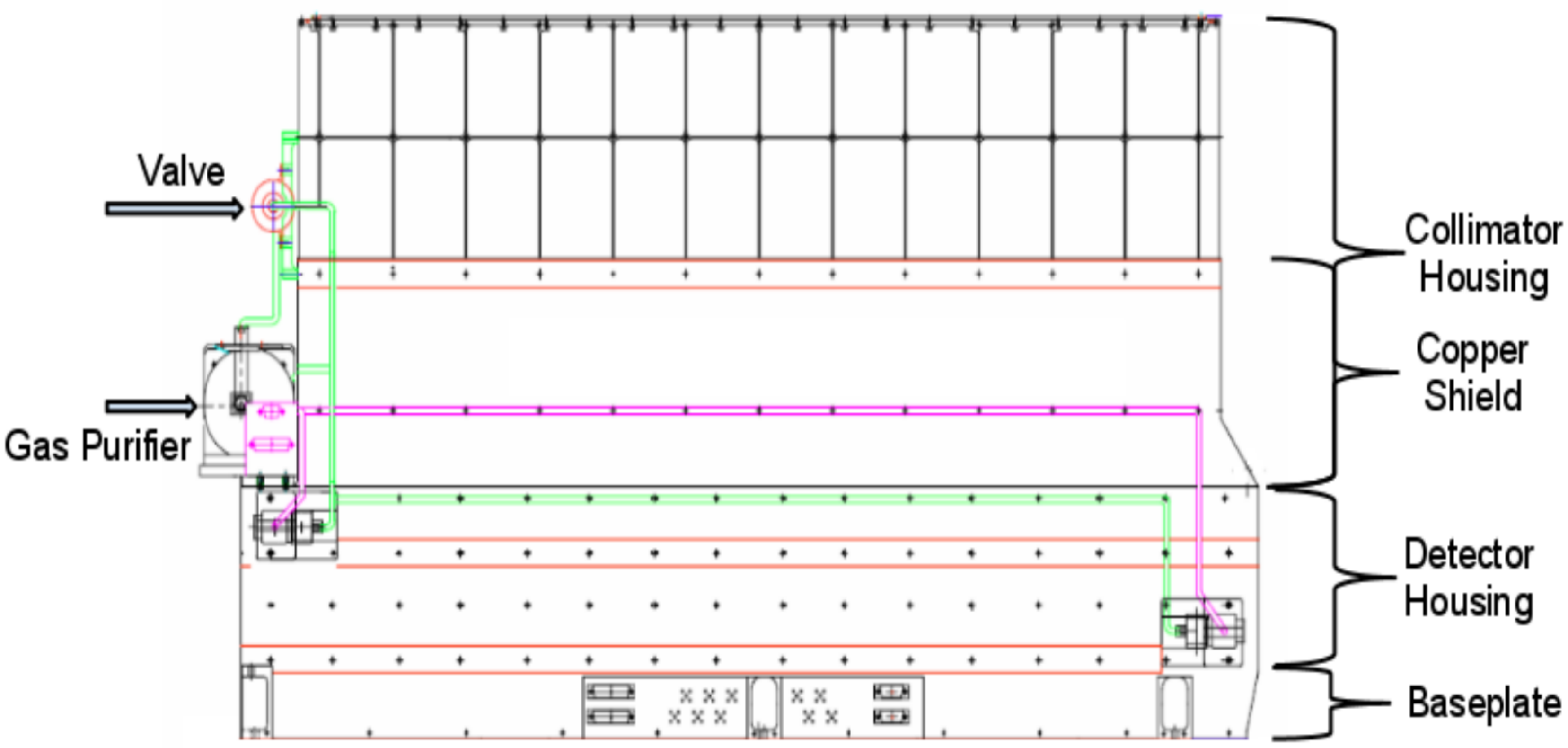


Large Area X-ray Proportional Counter (LAXPC) instrument onboard ASTROSAT

- Astrosat is India's dedicated multi-wavelength space telescope.
  It was launched on 28 September 2015.
  The scientific payload contains six instruments.
- LAXPC - a cluster of 3 co-aligned identical
  Large Area X-ray Proportional Counters (3–80 keV).



LAXPC



A Detector Size	120cm x 50cm x 70cm
X-ray detection volume	100cm x 36cm x 15cm

Proportional counters (3)

- The variation of the number *N* of electron-ion pairs created by the ionizing event is less than that estimated from Poisson statistics, because the collisions of the ionization process are **not statistically independent**.
- The Fano factor ***F*** is an empirical constant to adapt the experimental observed variance to the predicted one:

$$\sigma_N^2 = F\,N$$

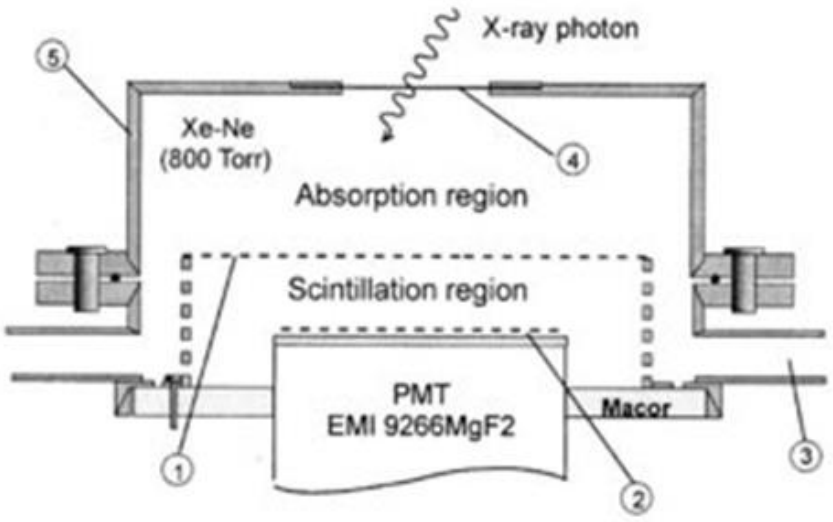
- *F* is a property of the gas, for Argon and Xenon *F* ~ 0.17.
- Energy resolution: $\frac{\sigma_E}{E} = \sqrt{\frac{w(F+b)}{E}}$,

  where *w* is the ionisation energy of the gas (~20 eV),
  b= 0.5 – 0.6 (related to the amplification of a single electron)

Proportional counters (4)

- Time resolution:
  - due to the low flux rate of most X-ray sources, each photon event can be time-tagged to high precision.
  - There is, however, a limit to your temporal resolution called "dead-time", a period when the signal from any incoming X-ray photons is essentially lost.
  - There is some time interval required for the system to return to its nominal state – such as the high voltage grid to return to normal voltage, and the ions to recombine, etc. For the typical PC this is a few of microseconds.
- **QE** approaches 100% for energies up to 50 keV

Gas Scintillation Proportional Counters (1)



The number of scintillation photons increases linearly with the number of exciting collisions of the electrons with the gas atoms.

- In conventional PCs, the charge generated by a high-energy photon is multiplied in a high electrical field.
- In gas scintillation PCs, the charge is not multiplied. However, these electrons are made to drift under an electric field and they acquire sufficient energy to excite the scintillation of the detector gas, but not to ionize it.
- Such a scintillation signal can be easily detected with a photosensor.

Gas Scintillation Proportional Counters (2)

- GSPCs reach energy resolutions of 8% at 6 keV, outperforming standard proportional counters by a factor of about 2.
- For soft X-rays below about 1 or 2 keV, GPSCs outperform any other type of large area detector, either cooled or room temperature.

X-ray CCDs (1)

- CCDs become very inefficient in the Ultraviolet, primarily because the electrodes they use become opaque to radiation.
- However, at soft X-ray wavelengths they become efficient again, especially thinned (but not so thin as optical) CCDs.
- CCDs now produce **many** electron-hole pairs per incident photon, and the number they produce depends upon the energy of the photon.
- Process is photoelectric, and is exactly the same as in a gas proportional counter.

X-ray CCDs (2)

- X-ray causes the release of a high energy electron, which in turn releases secondary electron-hole pairs by a solid state analogue of the Auger effect.
- Number of electrons released **$N = E / w$**
- For silicon $w = 3.65$ eV
- The chip is read almost continuously, allowing reasonable time resolution (seconds).
- As some energy is transferred to the crystal lattice, there is a statistical variation in the number of electron-hole pairs produced.

- Thus, there is a solid state Fano factor, so again:

$$\sigma_N^2 = F N$$

For silicon $F \sim 0.1$

X-ray CCDs (3)

- For silicon, w is lower than for the inert gases (3.65 eV as opposed to ~20) and *F* is slightly lower (0.1 as opposed to 0.17) so CCDs have much better intrinsic energy resolution than gas proportional counters.
- Energy resolution is given by:

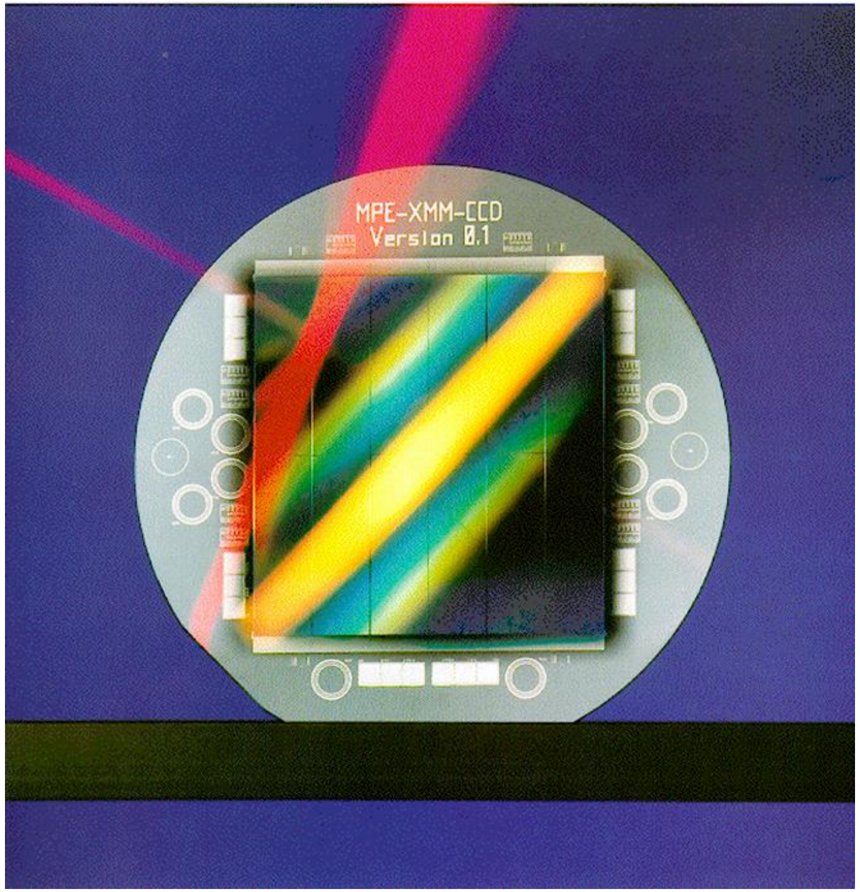
$$\frac{\sigma_E}{E} = \sqrt{\frac{wF}{E}} \quad \text{or} \quad \Delta E = 2.35\sqrt{wFE}$$

factor 2.35 is because this is expressed as a full width half maximum rather than a standard deviation (FWHM ≈ 2.35σ).

- This is why CCDs outperform gas proportional counters.

X-ray CCDs (4)

CCD array for the XMM-Newton satellite

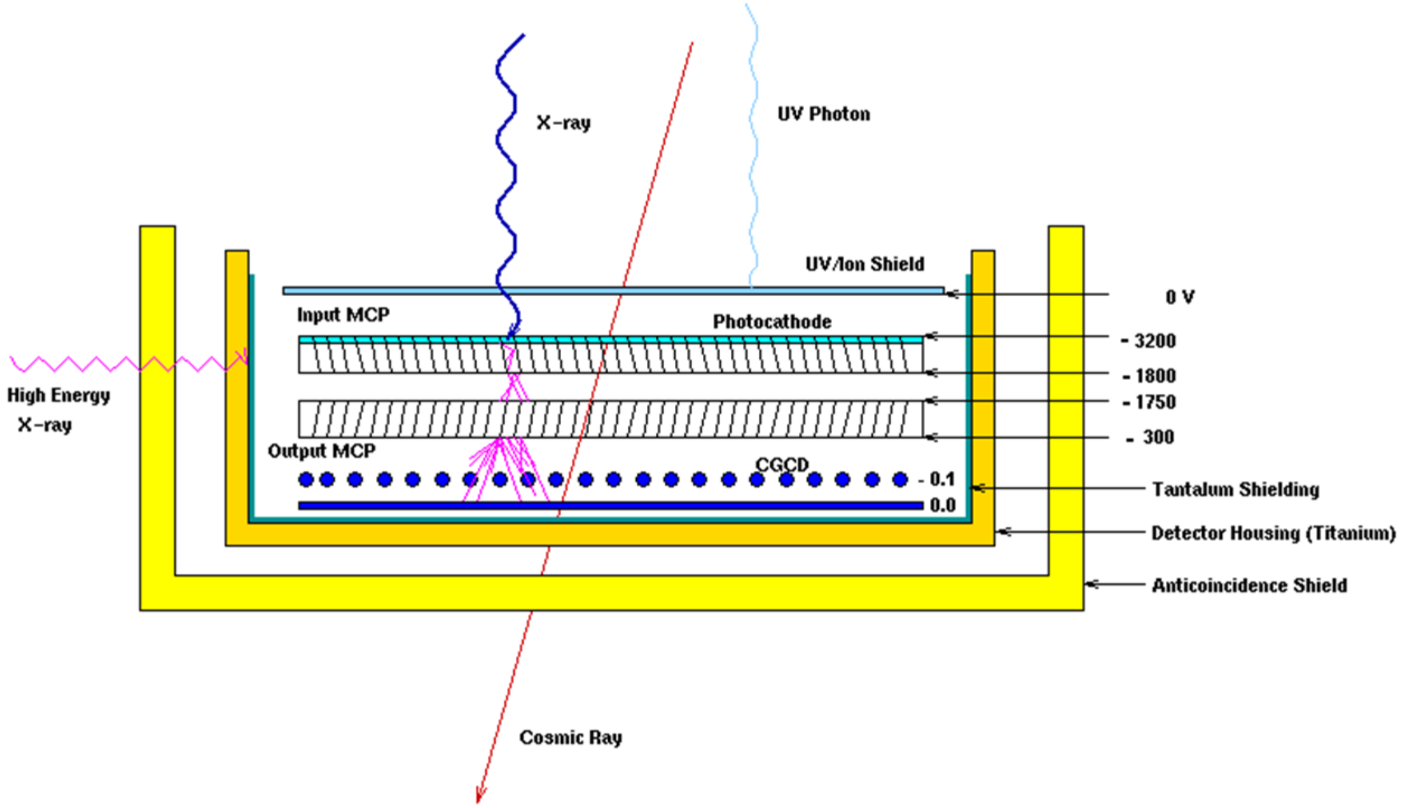


Microchannel plates (1)

- Microchannel plates work at X-ray wavelengths:
  - X-rays release photons in the lead glass channel walls directly.
  - Walls are coated with a material of high photoelectric yield, especially at energies below 1 keV.
  - At energies higher than 5 keV, X-rays can penetrate the channel walls to release photoelectrons in neighbouring channels. This degrades resolution.

Microchannel plates (2)

X-ray MCP detector flown on CHANDRA



Microchannel plates (3)

- The spatial resolution is limited to how closely the channels can be bunched together (channels can be of 12.5 microns in diameter, and are spaced at 15 micron intervals. The final resolution is limited by the channel spacing, your telescope optics, and the readout device. For Chandra , the resolution is about 0.5".
- Because these devices are operated in, or near saturation, they have insignificant energy resolution.
- The timing resolution of the devices is excellent: about 50 picoseconds (the travel time).

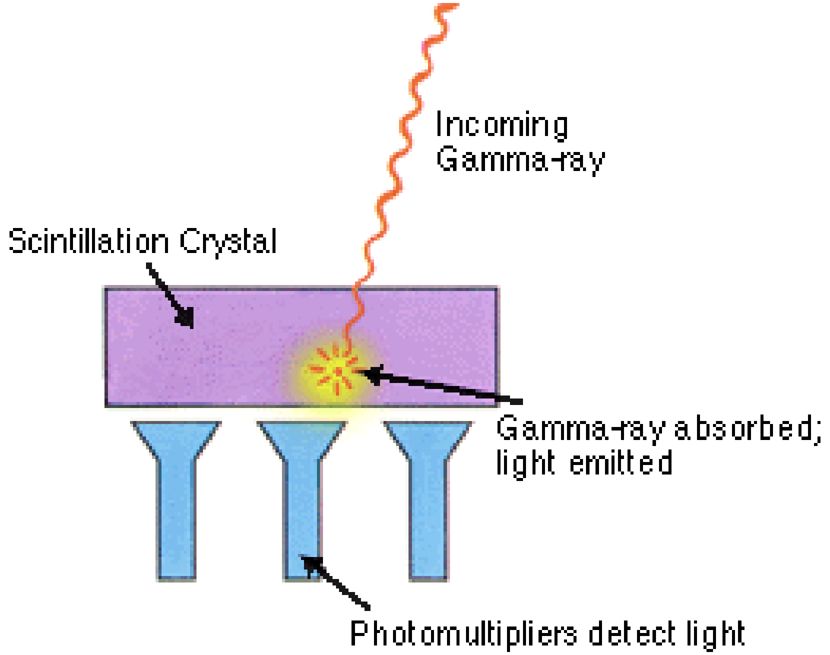
Gamma-ray Detectors

Gamma Ray Detectors

- We can’t make a reflecting surface at gamma ray wavelengths, thus the distinction between telescope and detector is not so clear:
  - Scintillation crystals
  - Solid state Cadmium Zinc Telluride detectors
  - Compton Scattering detectors
  - Pair production detectors
  - Air Čerenkov detectors

Scintillation crystals

- Crystal converts a gamma ray to a shower of lower energy photons, which are detected by a photomultiplier.



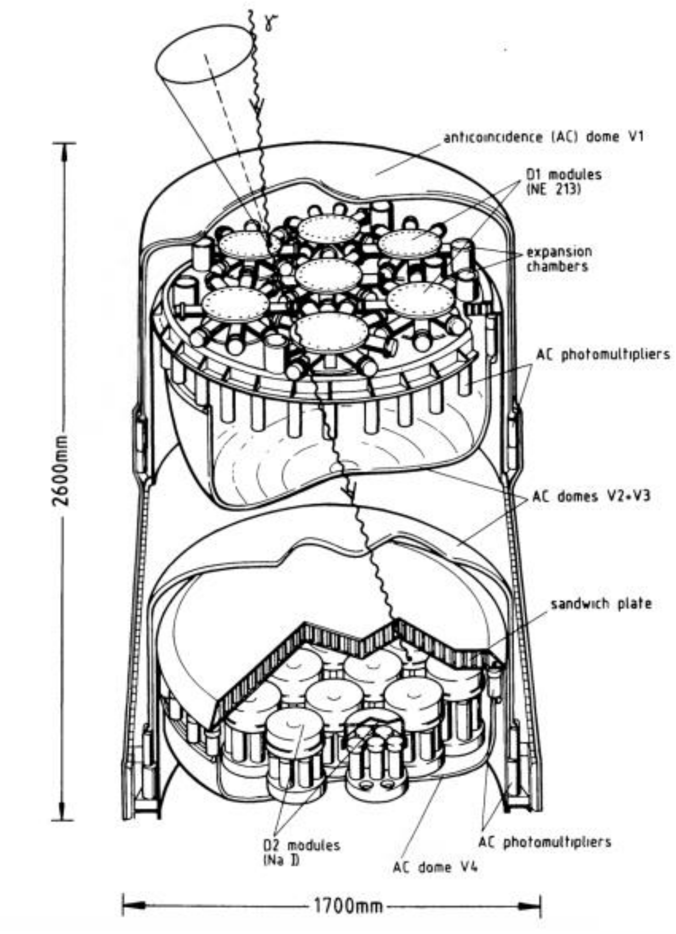
Scintillator produces very poor directional and energy resolution. **Not in use now.**

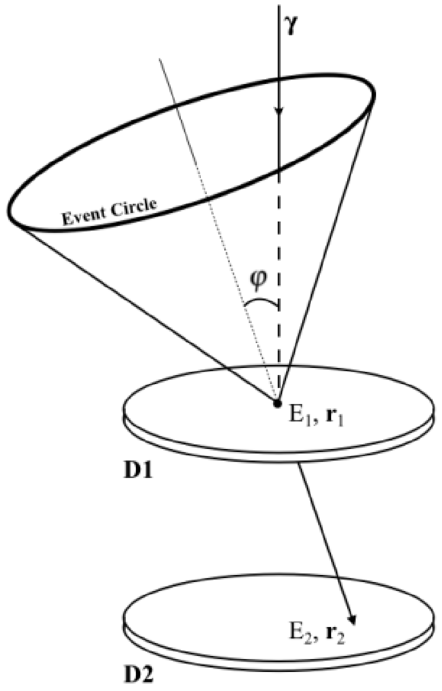
Compton Scattering Detectors (1)

We discussed them in Lecture 3 (Slides 172-173):

- Photon scatters off an electron, transferring energy to the electron.
- Detector consists of two levels. In the upper level the photon is scattered.
- Photon continues to the lower level, but electron emits a shower of photons which are measured by photomultipliers.
- Lower level is a scintillation detector, photon is absorbed again emitting a shower of low energy photons, which are measured by photomultipliers.
- From the location and energy of the two showers of photons, incoming gamma ray direction and energy can be calculated.

Compton Scattering Detectors (2)

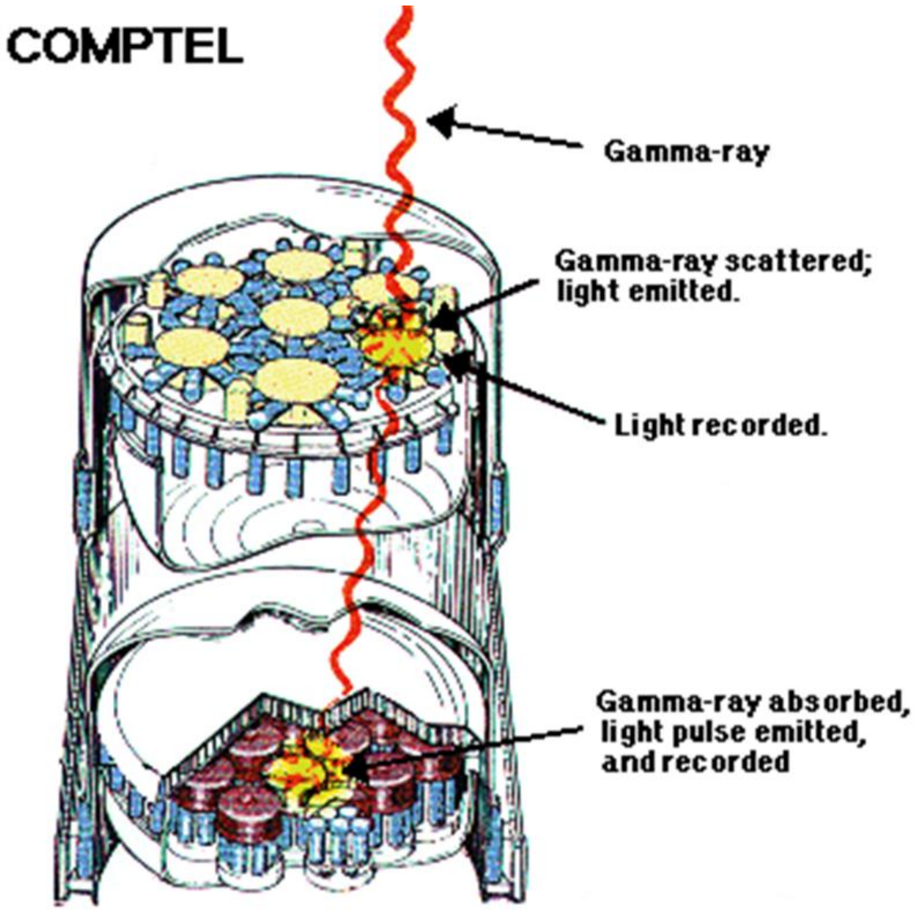




- A classic Compton telescope uses a scattering plane (D1) and an absorption plane (D2) to measure the position and energy of two interactions in a Compton event.
- From these measurements, the original photon direction can be constrained to a circle on the sky called the “event circle.”

Compton Scattering Detectors (3)

The COMPTEL detector on the CGRO



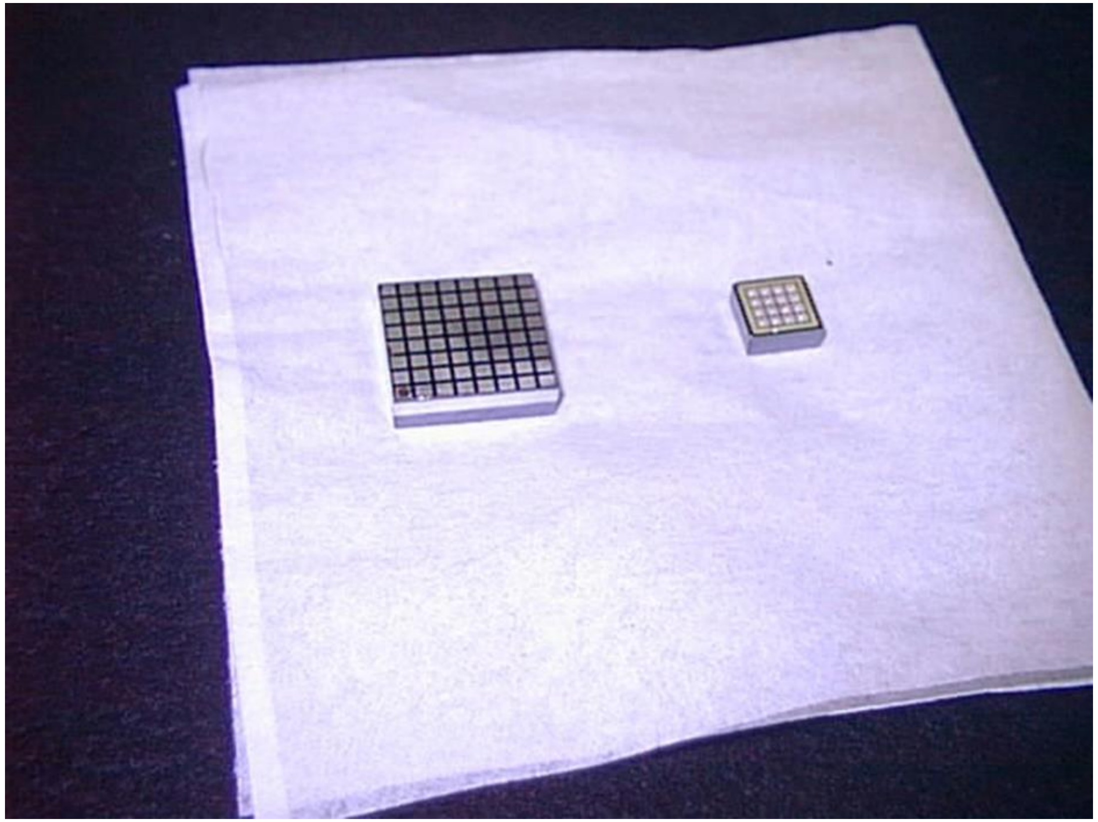
Pair production detectors

- Gamma ray with energy > 30 MeV interacts with a material to produce an electron-positron pair.
- Electron and positron are tracked by particle physics techniques (spark chamber layers).
- Energy and direction of the electron and positron give the energy and direction of the incoming Gamma ray by conservation of energy and momentum.

- A pair production detector on the EGRET satellite:

Cadmium Zinc Telluride (CZT) detectors

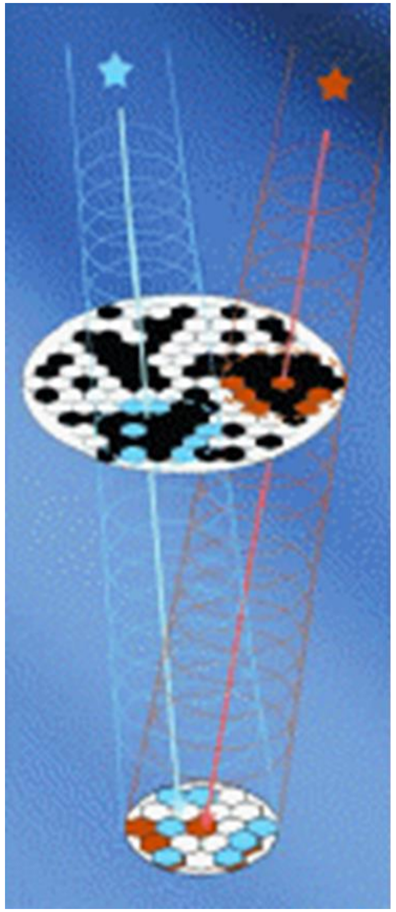
- Cadmium Zinc Telluride is a high band gap semiconductor.
- By adding pixel electrodes on one face of a wafer of CZT, a two-dimensional photoelectric solid-state detector can be made.
- These have small number of pixels, so pixels tend to be read out individually (rather than charge shuffled as in a CCD).

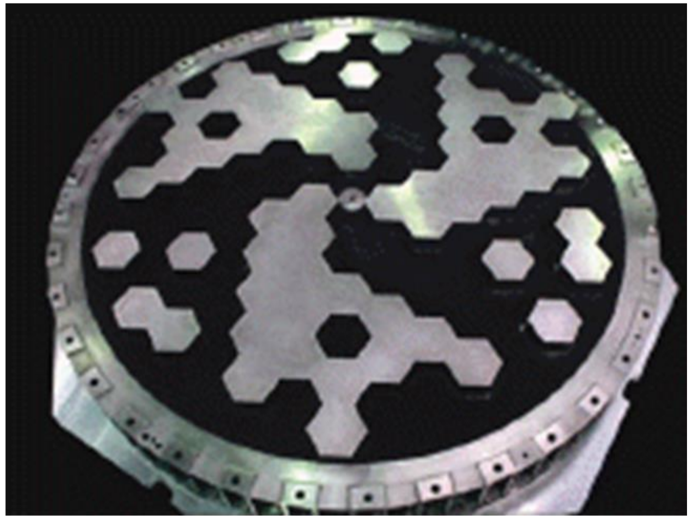


CZT crystals have a sensitivity range of 30 keV to a few MeV with a ~2% FWHM energy resolution at 662 keV.

Coded mask imaging with the CZT array

- CZT arrays are often used with coded mask imaging systems (see also Lecture 3).
- A coded mask is an array of transparent and opaque (usually lead) elements in an optimised pattern.
- It operates as an array of pinhole cameras.
- From the pattern on the CZT array you can determine the direction of the gamma ray source (there will only be one in your field of view!)

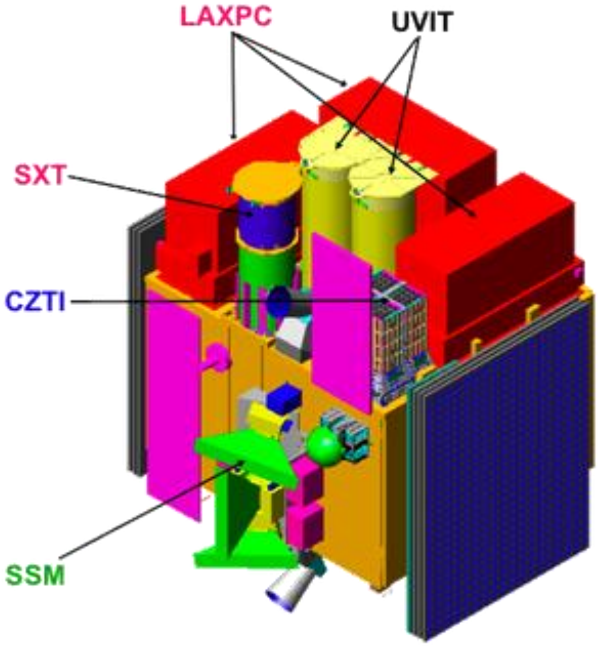


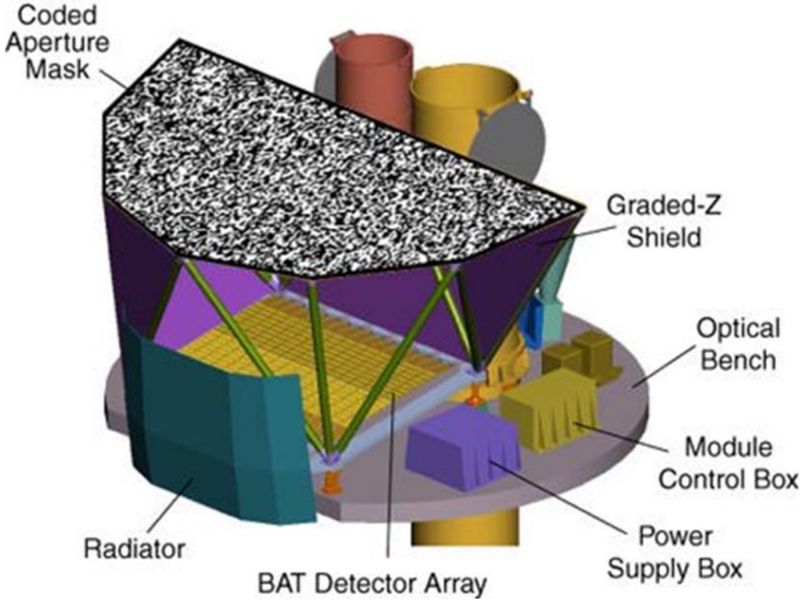


Coded mask/CZT array

Coded mask array and CZT array detector for the **SWIFT** project:
Effective area 5240 cm^2
Energy Range 15-150 keV (energy resolution ~7 keV)

AstroSat: The Cadmium Zinc Telluride Imager (CZTI) of 500 cm^2 effective area and the energy range from 10 to 150 kev.



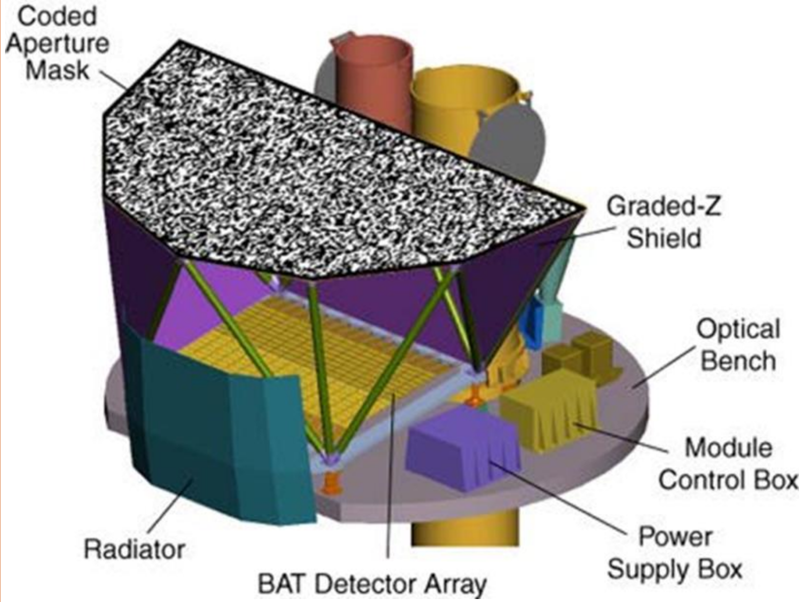


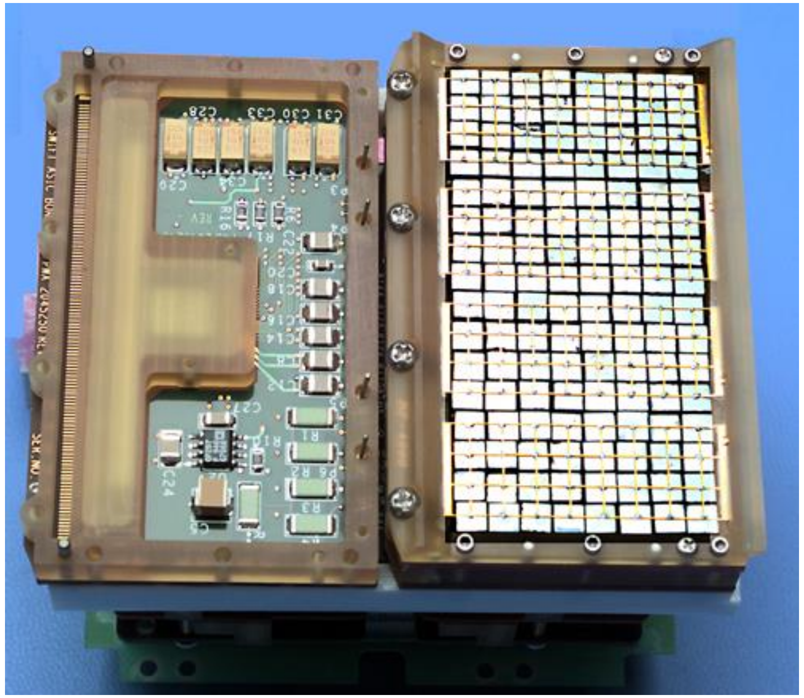
Swift's Burst Alert Telescope (BAT)

Coded mask array and CZT array detector for the **SWIFT** project: Effective area 5240 cm^2

The BAT's 32,768 pieces of 4 x 4 x 2 mm CdZnTe (CZT) form a 1.2 x 0.6 m sensitive area in the detector plane.

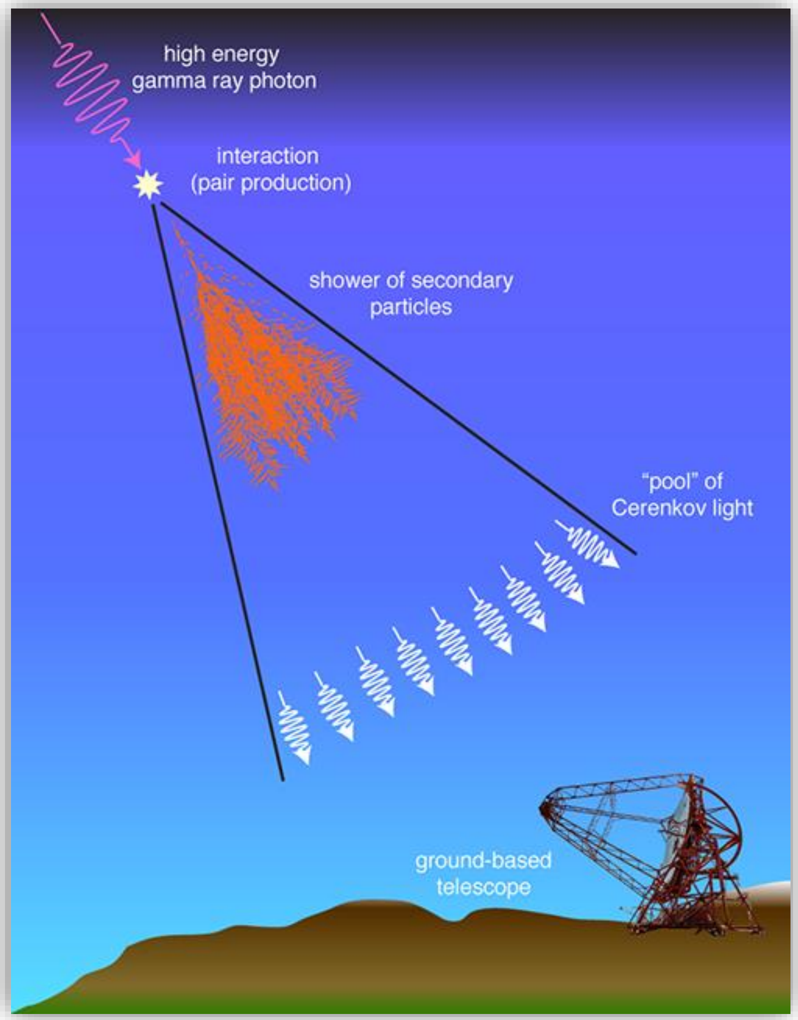
Groups of 128 detector elements are assembled into 8 x 16 arrays, each connected to 128-channel readout Application Specific Integrated Circuits (ASICs).





Čerenkov air shower telescope

- Here the atmosphere acts as a detector for very high energy gamma rays (see Lecture 3).
- Gamma rays interact in the upper atmosphere to produce secondary particles, these particles are moving at speeds greater than the speed of light in the local medium.
- Čerenkov radiation results when charged particles move at greater than the local speed of light, and because of the rapidly changing electric field cause the local medium to radiate.
- Čerenkov radiation is concentrated in a cone.



Čerenkov telescopes are large collection area telescopes with fairly crude optics. Because the shower and the consquent Čerenkov flash is spread over a wide spatial area, arrays of such telescopes are built to improve the directionality.

The Cerenkov light reflected from the mirror is detected in the focal plane by one or many photomultipliers.