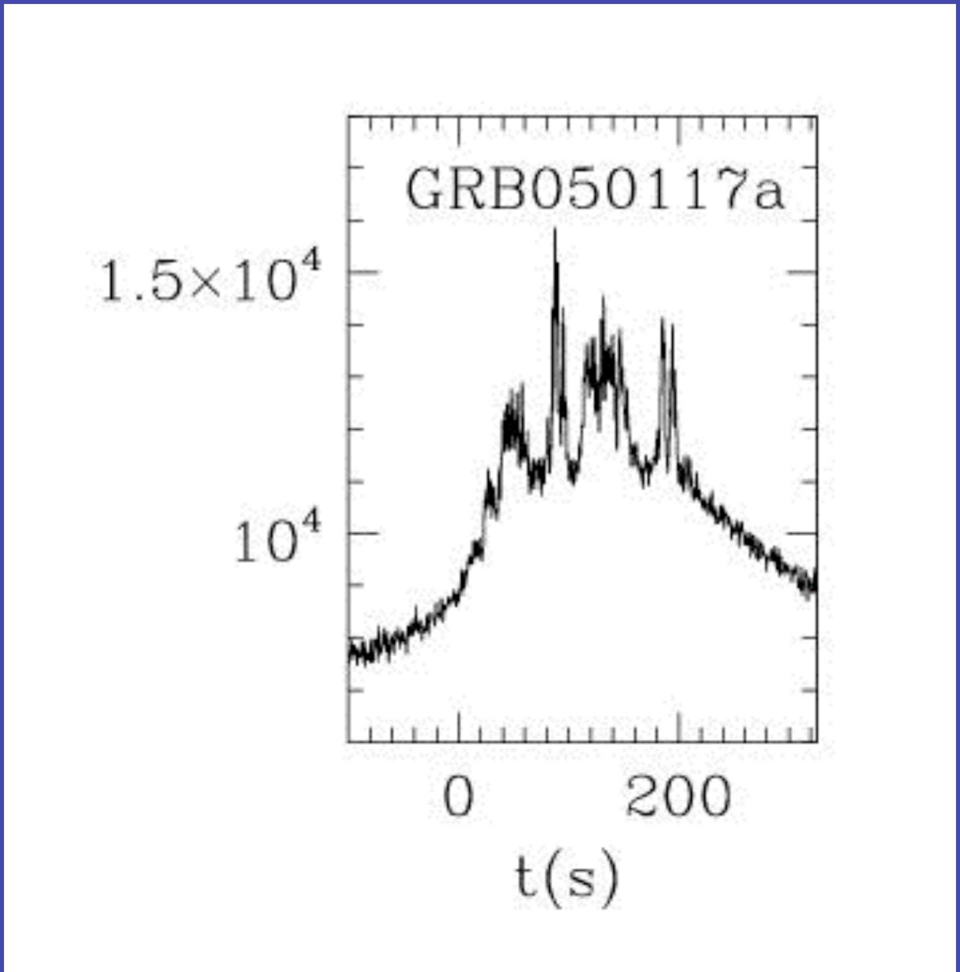
In the News...

Feb 3 2005



Birth of a Black Hole?

GRB lightcurve from the Burst Alert Telescope (BAT) on SWIFT. Also pinpointed by SWIFT's X-ray Telescope (XRT) - *first time the X-ray emission from a GRB has been detected while the GRB is in progress.*

Significance: allows a determination of distance to the burst to determine total energetics; if cosmological, helps in understanding how black holes formed in the early universe

Instrumentation

Outline:

- Properties of Radiation
- Observatories
- Issues in High Energy Radiation Detection
- X-ray instruments
  - counters
  - spatial discrimination
  - telescopes
  - imaging detectors
  - spectrometry
- Gamma ray observatories
- Cosmic Ray Observatories
- Gravitational radiation Observatories in Space
- the future

Detectable Properties of EM Radiation

EM radiation is characterized by:

- frequency (wavelength, energy)
- polarization (linear or circular)
- energy flux = $(c/4\pi)$ **E** x **B**

Radiant sources characterized by:

Luminosity: amount of EM energy emitted by a body over all directions per second (ergs/s)

Bolometric luminosity: emitted over all directions, and all wavelengths

Flux: amount of radiant energy passing through a given area in a given time (ergs/s/cm^2)

$$F = \frac{L}{4\pi r^2}$$

inverse square law for an isotropic emitter at a distance r

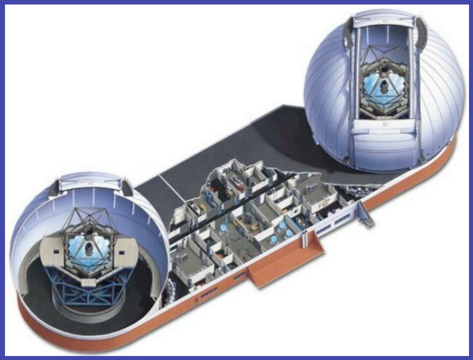
Characterization of Radiation

Observable	Physical Property	Method
Flux	Distance if luminosity is known; luminosity if distance is known	Collect and determine number of photons or source intensity through some area in a given amount of time (Photometry)
Spectral distribution (flux vs. wavelength)	Temperature of source; size if temperature and distance known	Collect & determine brightness in restricted wavelength bands (Spectrometry)
Polarization	Geometry of emitter for linear polarization; magnetic field strength and geometry if circular	Collect photons, determine orientation of net electric vector as a function of time (Polarimetry)
Spatial Distribution	gravity-dominated structure; statistical properties of sources	Collect radiation using a spatially-sensitive detector
Temporal distribution	Size of variable structure; time dilation; size and shape; source identification	Measure brightness vs. time

Generic Observatory

Consists of a Light bucket (telescope) and one or more of:

- imaging system (lenses, mirrors)
- wavelength or polarization-sensitive filter
- disperser (prism, grating)
- detector (photometer, photographic plate, charge-coupled device)



W. M. Keck Telescope

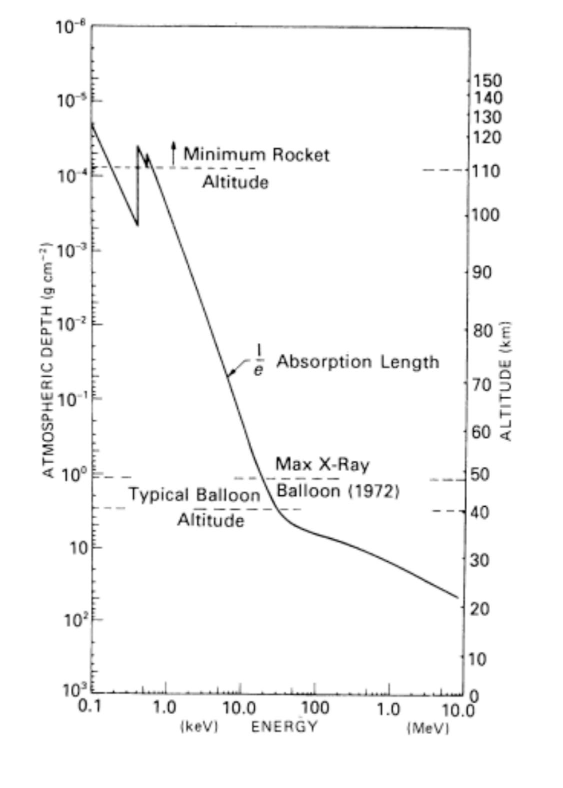
Mauna Kea, HI

Observing Environment

high energy radiation doesn't penetrate earth's atmosphere very far due to photo-electric absorption

Visible-band observatories: ground-based

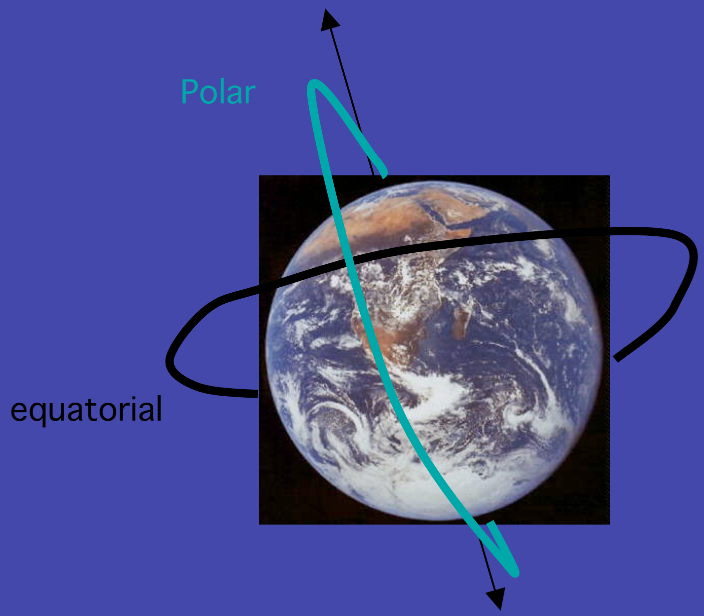
X-ray & Gamma-ray: space-based



Issue	Optical/Ground	HE/Space
Temperature fluctuation	Moderate	Extreme
Background	low (exc. IR)	high, variable (SAA)
Source targeting	varies with RA & Dec; diurnal; no CVZ	varies with source position, observatory orbit; some CVZ
Servicing	Radio Shack	NASA

see http://ads.harvard.edu/cgi-bin/bbrowse?book=hsaa&page=203

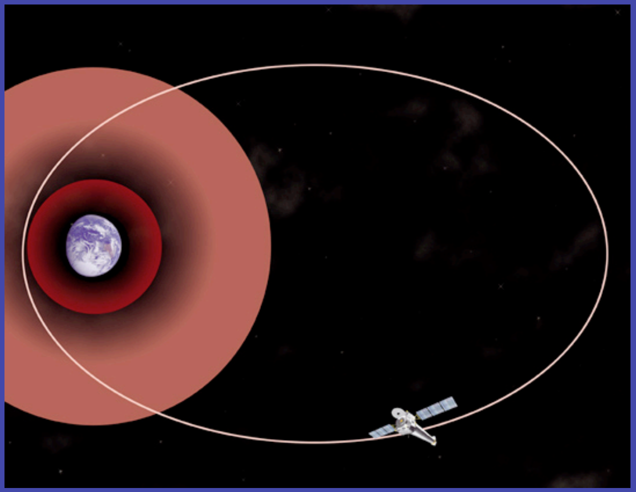
Orbits



Low Earth Orbit (LEO)

Concerns: occultation by earth, moon & sun unless CVZ
Typical period: 93 minutes
solar power + batteries

High Earth Orbit (HEO)



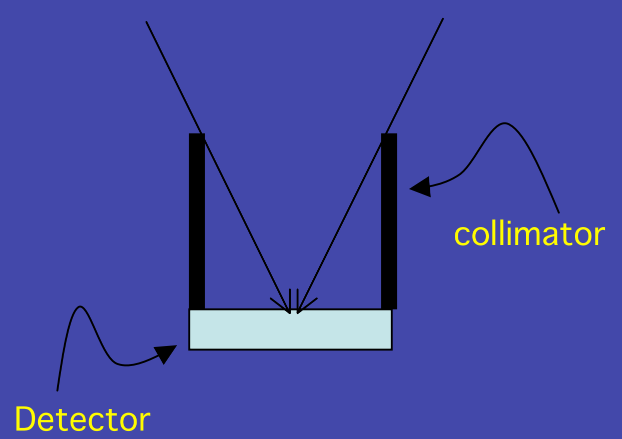
Concerns: Harsh environment
Typical Period: days
(Chandra: 64 hrs 18 min)

Restricted Fields of View

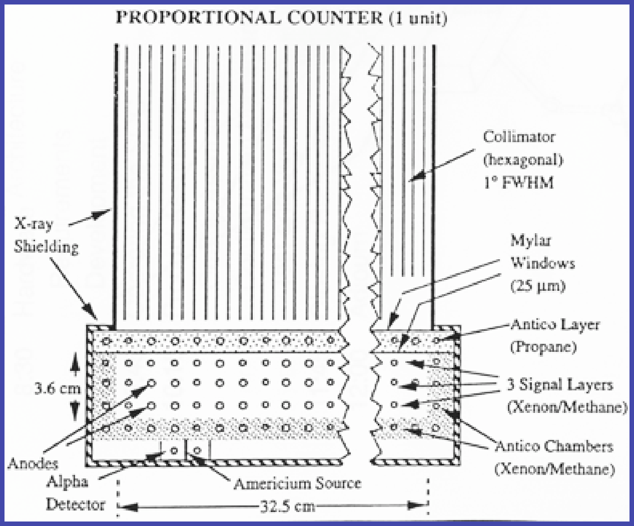
Need to resolve one source from another. How?

- If sources widely separated: collimation

Collimator: opaque structure (box) that restricts the field of view of the detector



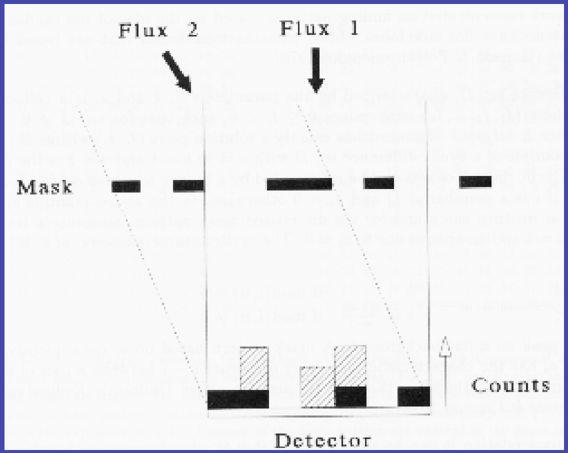
Problem: Vignetting



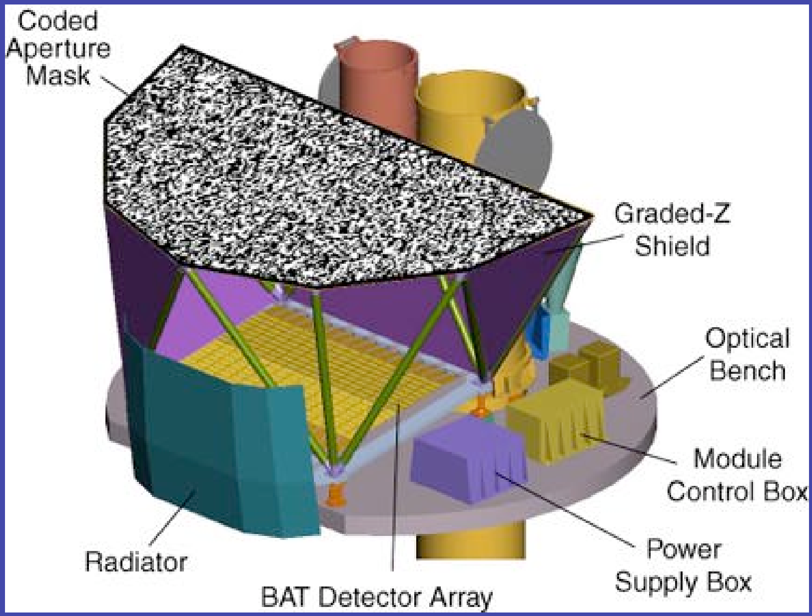
Coded Aperture Masks

see http://lheawww.gsfc.nasa.gov/docs/cai/coded_intr.html

Spatial source distributions can be reconstructed from the shadow patterns produced by an opaque “mask”.



Two point sources illuminate a position-sensitive detector through a mask. The detector thus records two projections of the mask pattern. The shift of each projection encodes the position of the corresponding point source in the sky; the 'strength' of each projection encodes the intensity of the point source



SWIFT Burst Alert Telescope

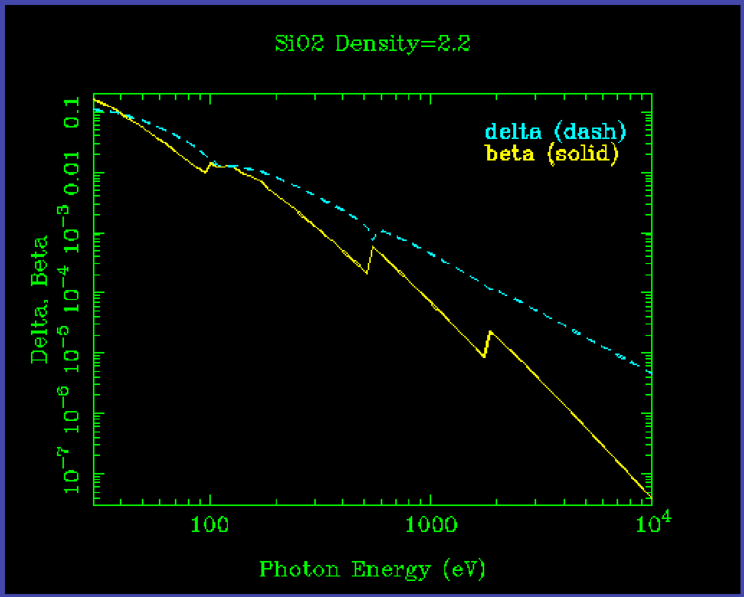
Problem: complicated source distributions difficult to reconstruct

High Energy Radiation

EM radiation in every wavelength range carries the same type of information

But, different types of EM radiation interact differently with matter

Different methods of collection, detection and analysis need to be used



Index of refraction for quartz

N=(1-delta)-i x beta

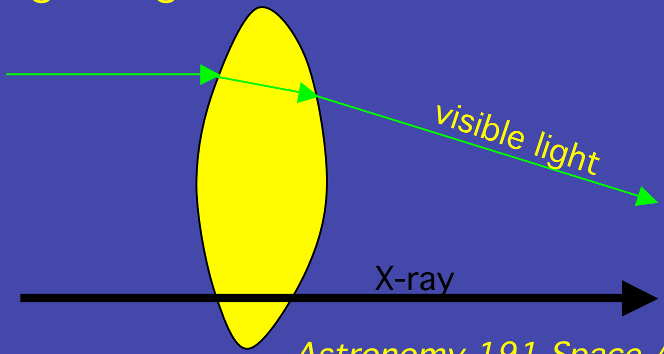
from

http://www.cxro.lbl.gov/optical_constants/getdb2.html

At 1 keV, N ≈ 1

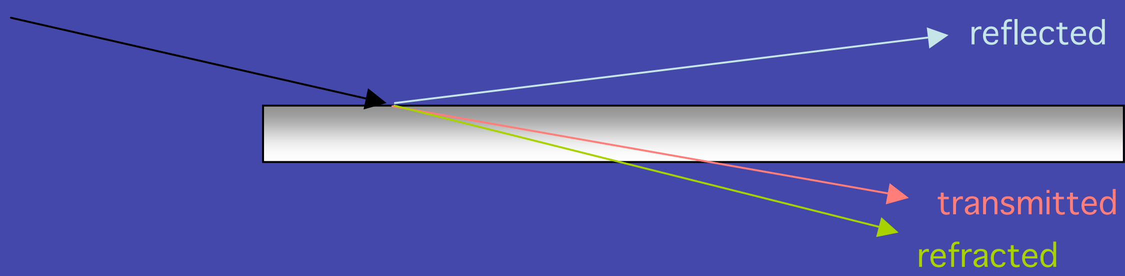
⇒for visible light, refraction/reflection at near-normal incidence

⇒ for X-rays, refraction/reflection at grazing incidence



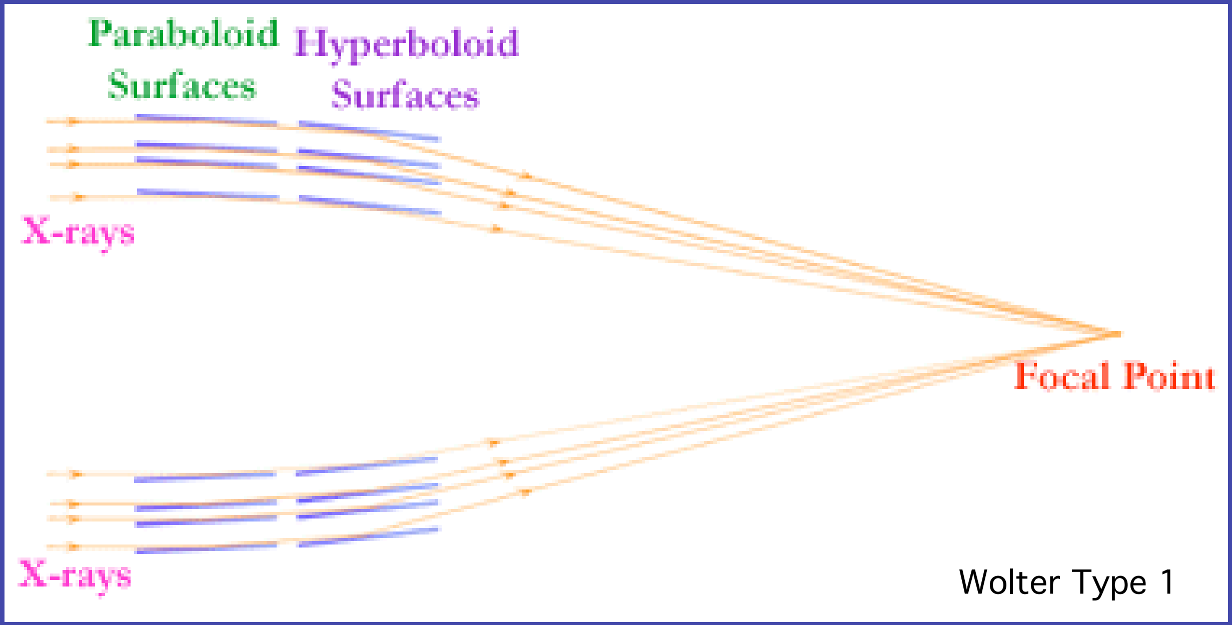
X-ray Optics

X-ray index of refraction near 1 for most substances means X-ray reflection only at near grazing angles



To form an image, need to bring reflected rays to a focal point

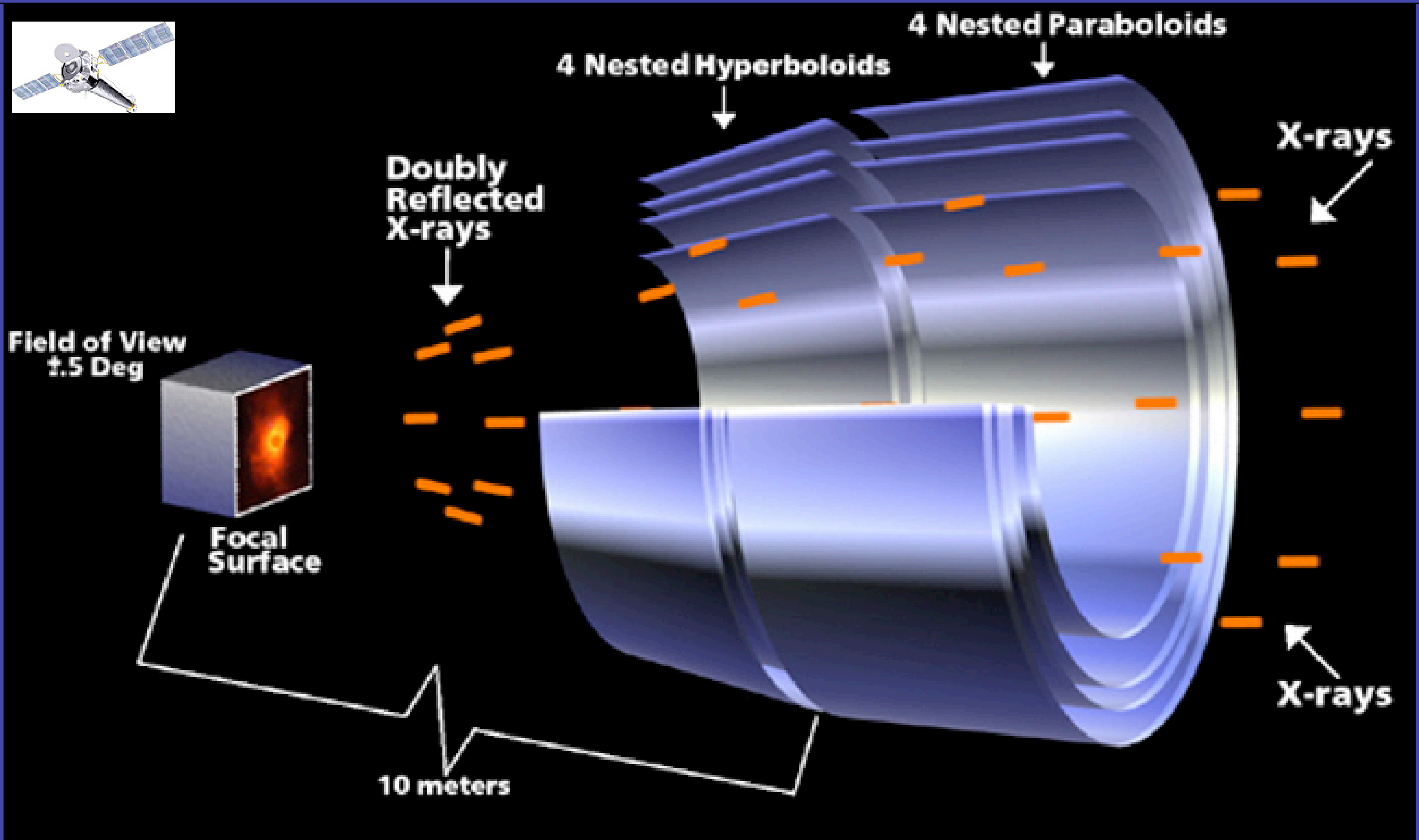
Grazing Incidence Mirrors



Nested, barrel-shaped mirrors
paraboloid shells followed by hyperboloid shells

- long focal length
- astigmatism & "chromatic" aberration

Schematic of Grazing Incidence X-ray Mirrors



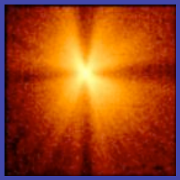
Mirror elements are 0.8 m long and from 0.6 m to 1.2 m diameter

CXC

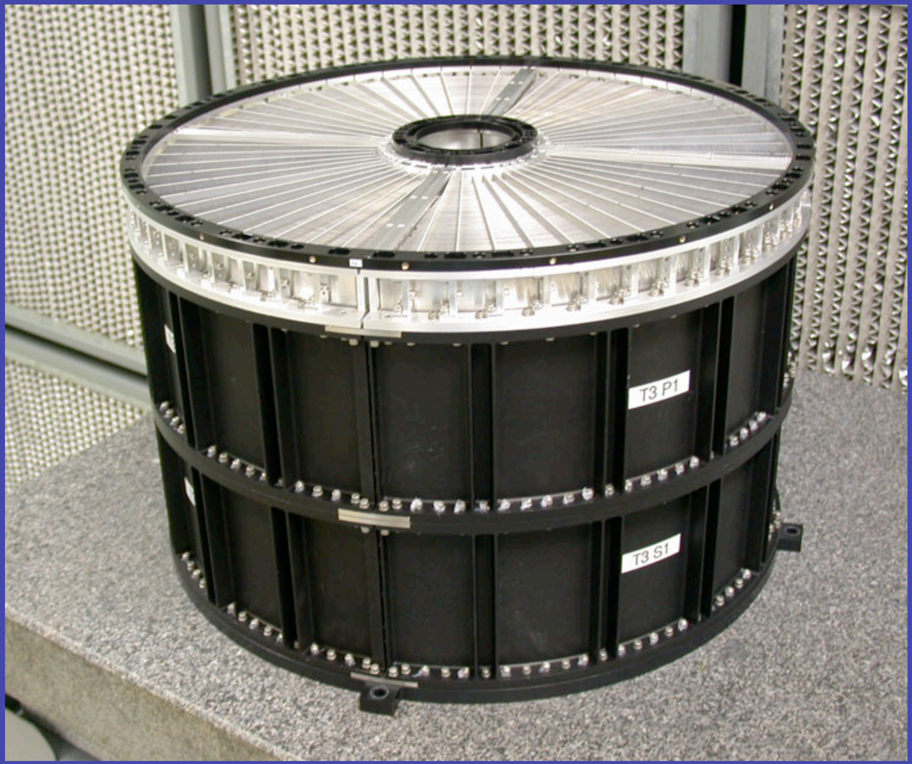
Approximate X-ray Optics

Wolter optical systems difficult to fabricate, typically heavy: expensive

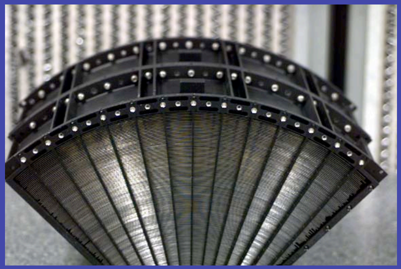
Thin-foil mirrors: use sets of nested thin gold foils in conical shells to approximate full Wolter Type-I configuration

Advantages	Disadvantages
lightweight; Many nested foils (~hundreds) provide large collecting area; broad-band energy sensitivity	imaging poor 

Example: Astro-E2 Telescope



about 180 foils are used in the telescope.
the foils are distributed in aligned concentric cones.



http://lheawww.gsfc.nasa.gov/docs/xray/astroe/MirrorLab/mir_make.html#design

Detectors I - Visible Light

Photo-sensitive material which (usually) records position, brightness (color, spectral distribution...) of incident radiation

- eye (photoabsorption via rhodopsin in rods)
- photographic emulsion (photo-chemical reactions)
- photo-multipliers (photo-electric effect in solid-state semiconductors)
- Charge-coupled devices (CCDs): arrays of tiny photomultipliers (picture elements or pixels).

  $\Rightarrow$ Benefits: high dynamic range and sensitivity; digital

  $\Rightarrow$ Disadvantages: expensive; readout time delays; saturation; bleeding

X-ray Counters

X-rays can be detected by counting individual X-ray photons through photo-ionization of a gas, photo-electric effect in a solid, scintillation in a gas or solid

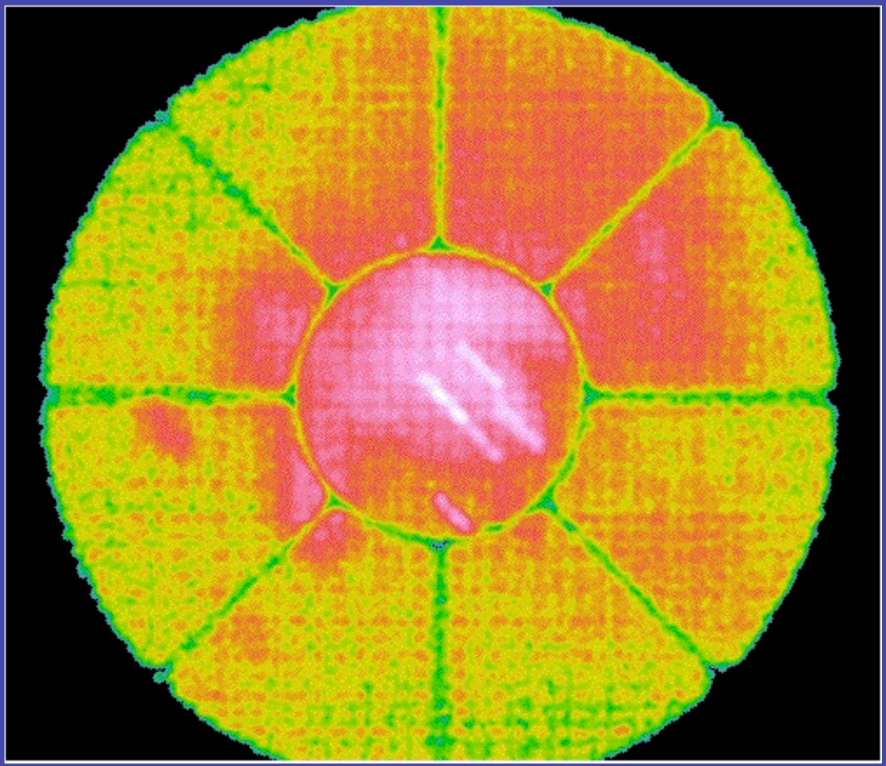
Proportional Counters: X-ray photon enters a gas-filled chamber, produces electron cloud via photo- and collisional ionization (secondary electrons) which accelerate & produce a charge on an anode grid.

$\Rightarrow$ Anode charge proportional to initial photon energy;

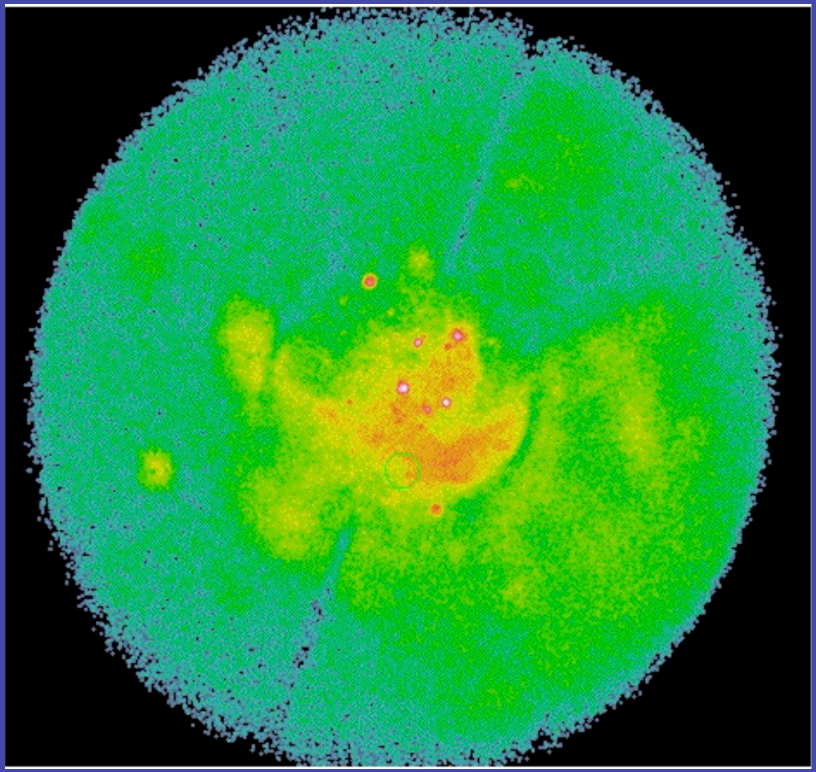
$\Rightarrow$ charge induced on perpendicular cathode grid gives photon position;

$\Rightarrow$ drift velocity sufficiently high to yield photon arrival time.

Example: ROSAT PSPC

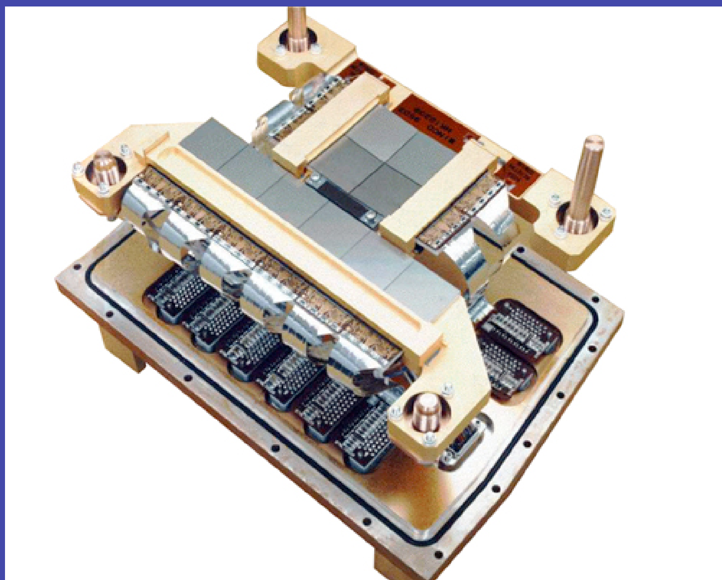


Detector Map: shows where X-rays landed relative to the detector coordinate system. Shows support structure on the PSPC window



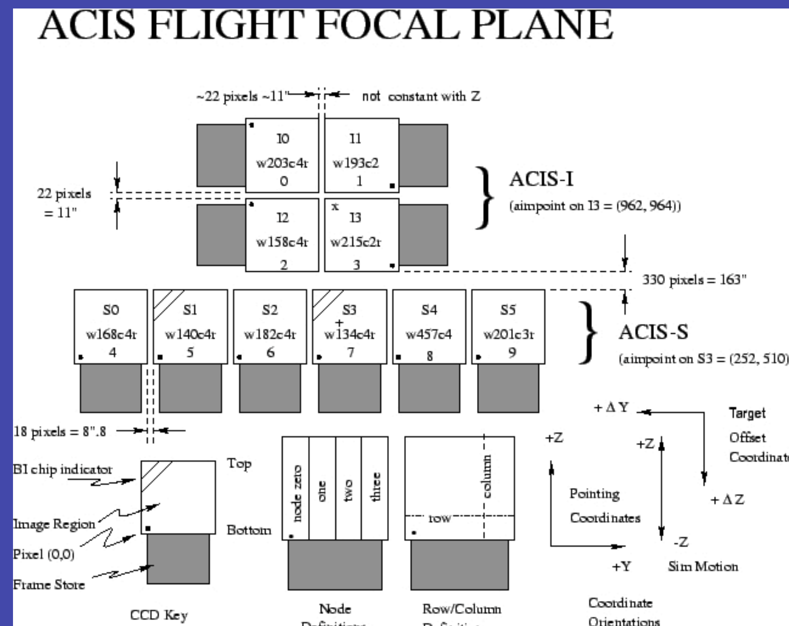
Sky Map: shows source positions in the sky (RA, Dec) coordinate system. Shows direction of the detector wobble.

Charge-Coupled Devices (CCDs)



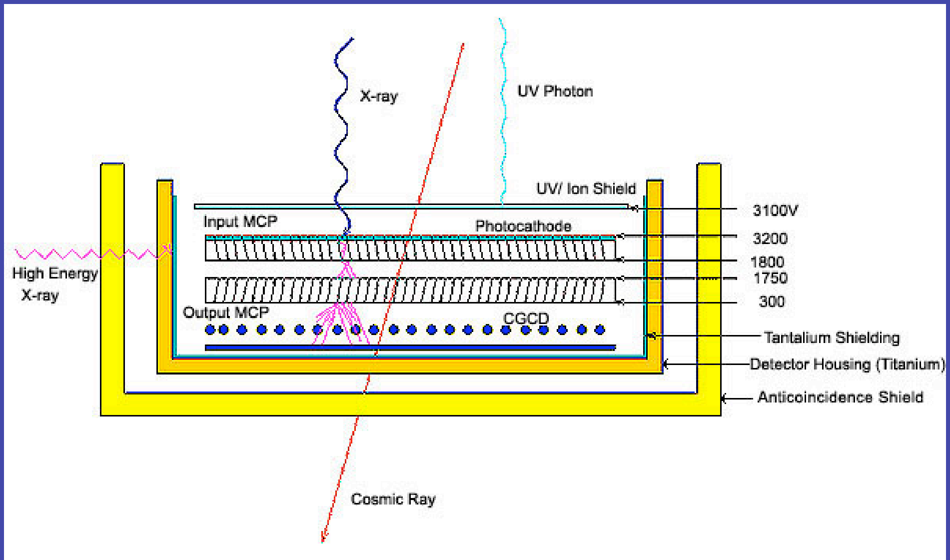
Advanced CCD Imaging Spectrometer (ACIS)

X-ray incident on a photo-active element (a pixel) produces a charge which is then collected and read out.



Provides position, time and energy of X-ray photon; but read-out delays can cause pileup.

Microchannel Plates



Chandra's High Resolution Camera:

10-cm (4-inch) square cluster of 69 million tiny lead-oxide glass tubes that are about 10 micrometers in diameter with inner photo-active coating. Photoelectrons are detected by a crossed grid of wires to determine the X-ray position to very high accuracy.

Accurate timing and positions, but no energy sensitivity

Dispersive Spectrometry

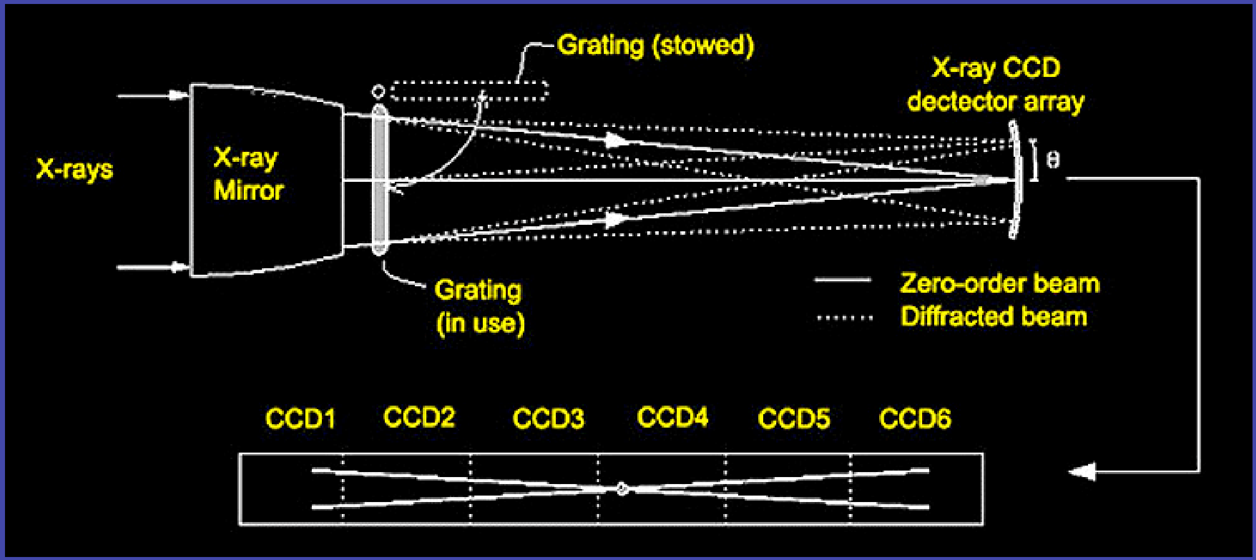
X-ray diffraction is accomplished through the use of diffraction gratings composed of high-Z regularly spaced material.
X-ray diffraction gratings produce interference maxima which obey the standard diffraction law

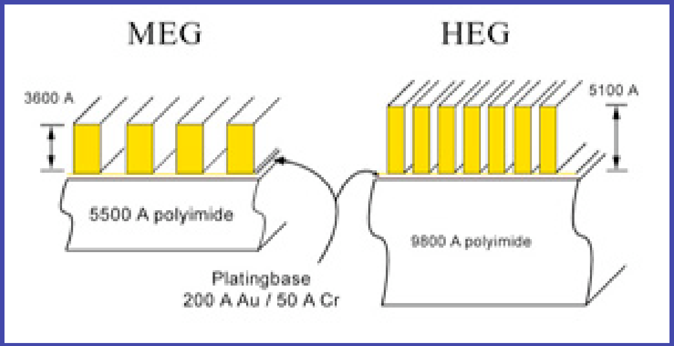
$$d \sin\theta = m\lambda$$

where *d* is the grating element spacing, θ the angular spacing of the interference maxima, and *m* the order number

Can yield resolving powers $E/\Delta E \sim 1000$

Example: Chandra's High Energy Transmission Gratings





Microcalorimeters

Microcalorimeters determine X-ray photon energy by determining the small change in temperature of material that absorbs an X-ray.

Can measure very small changes in temperature using suitable material so very high resolving powers, $E/\Delta E=2000$ or so.

Requires low temperatures and thermal stability

For example the X-ray Spectrometer (XRS) on Astro-E2 will be kept at within 0.01 mK of 65 mK.

Gamma-Ray Detectors

High energy gamma rays can't be focused or reflected.

Detected by interaction between gamma-ray photon and matter (ionization, scintillation, Compton scattering...)

Very large fields of view (nearly whole sky)

positional information by reconstructing gamma-ray tracks

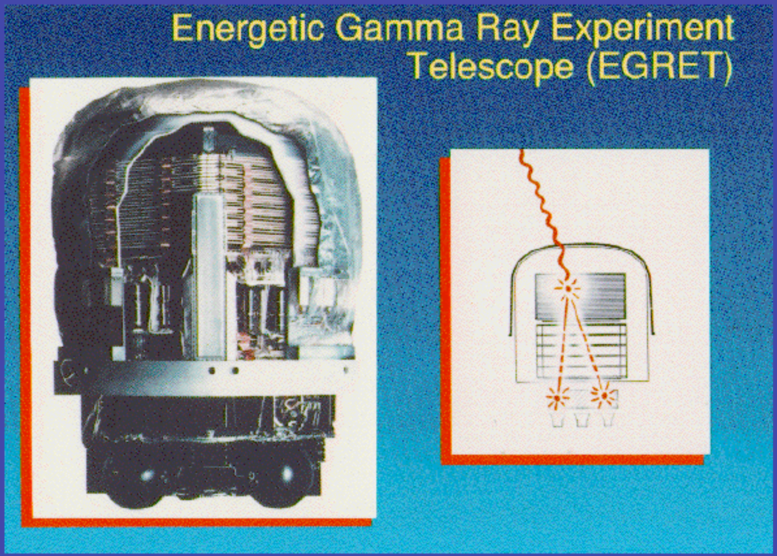
energy information

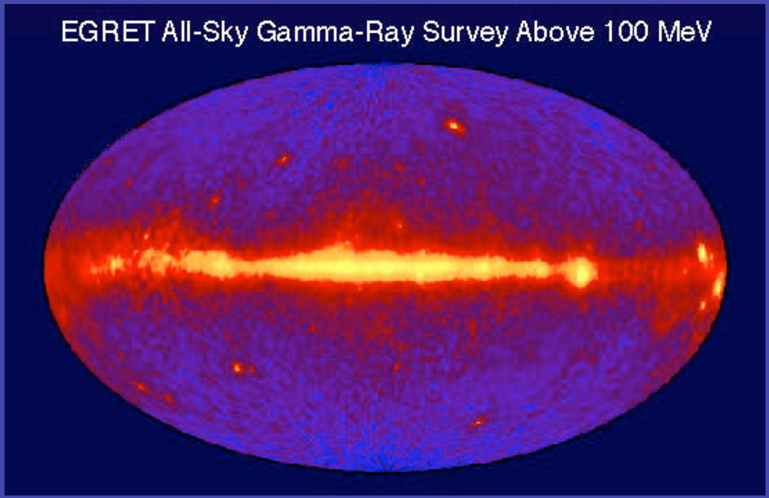
generally poor spectral and spatial resolutions

Compton Gamma-ray Observatory (CGRO): 4 instruments

- Burst and Transient Source Experiment (BATSE)
- Oriented Scintillation Spectrometer Experiment (OSSE),
- the Imaging Compton Telescope (COMPTEL), and
- the Energetic Gamma Ray Experiment Telescope (EGRET).
- launch April 5, 1991 aboard the space shuttle Atlantis.
- Deorbited(!) and re-entered the Earth's atmosphere on June 4, 2000.

CGRO-EGRET





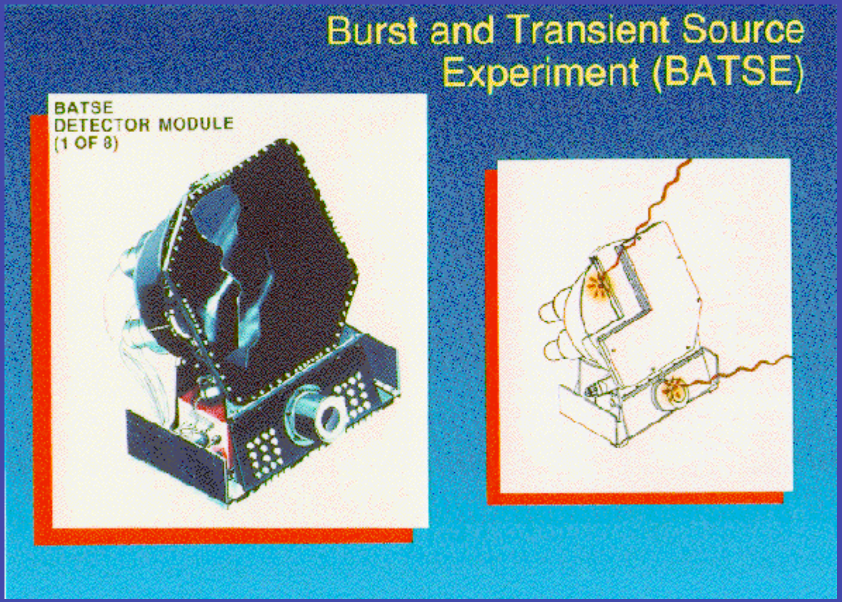
the Energetic Gamma-Ray Telescope (EGRET) produces Gamma-ray images via a high-voltage gas-filled spark chambers.

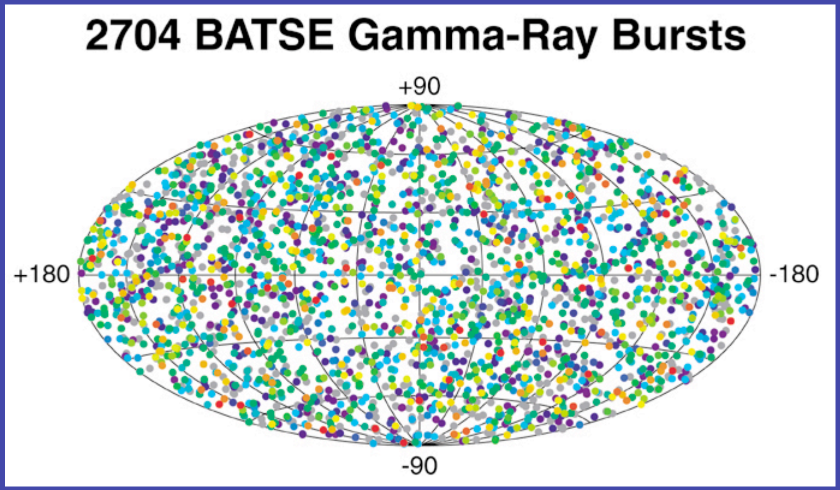
High-energy gamma rays enter the chambers and produce an electron-positron pair of particles which cause sparks.

The path of the particles is recorded allowing the determination of the direction of the original gamma ray.

The particle energies are recorded by a NaI crystal beneath the spark chambers providing a measure of the original gamma-ray energy.

CGRO-BATSE





NaI crystals produce a flash of visible light when struck by gamma rays. The flashes are recorded by light-sensitive detectors whose output signal is digitized and analyzed to determine the arrival time and energy of the gamma ray which caused the flash.

Large area detector sensitive to faint transient events

Smaller detector optimized for spectroscopic studies of bright events.

Cosmic Ray Detection

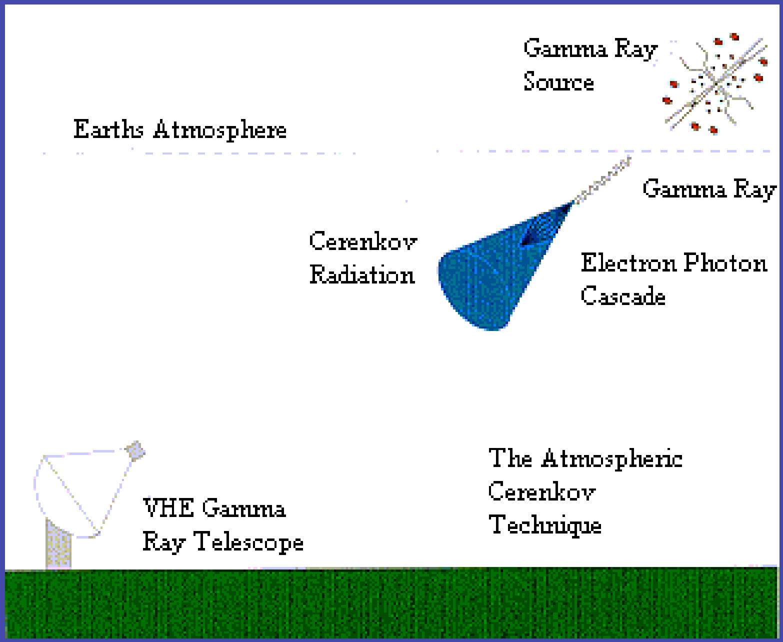
Cosmic Rays are particles (electrons & nuclei) accelerated to very high energies. Some are produced by the sun, others originate outside the solar system.

CRs can be detected by observing the effect of CRs on matter.

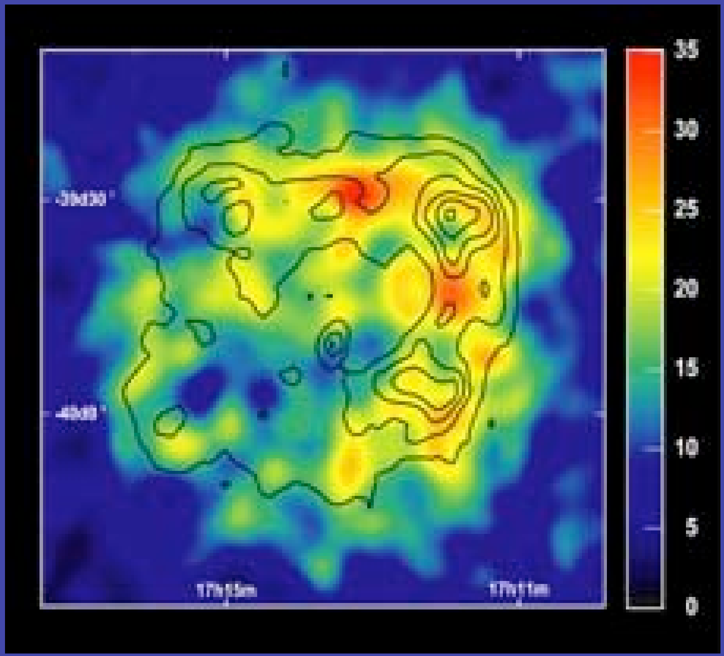
Cherenkov Telescopes use the atmosphere as an absorber of CRs

Cherenkov radiation produced when the velocity of a charged particle in a medium exceeds the speed of light in that medium ($v>c/n$). Excitation of the atoms in the medium by the particle produces a cone of bluish light.

Example: H.E.S.S.



High Energy Stereoscopic System: system of 4 atmospheric Cherenkov detectors



Cosmic Ray Image of a SNR.

Contours show X-ray emission

Neutrino Telescopes

Neutrinos are neutral subatomic particles that interact via the weak force and therefore have very low interaction cross-section

Can penetrate through enormous amounts of matter but are hard to detect.

Neutrinos can be used to determine conditions at the center of the sun and to test models of supernova explosions

Neutrino telescopes underground.

Example: Homestake Gold Mine

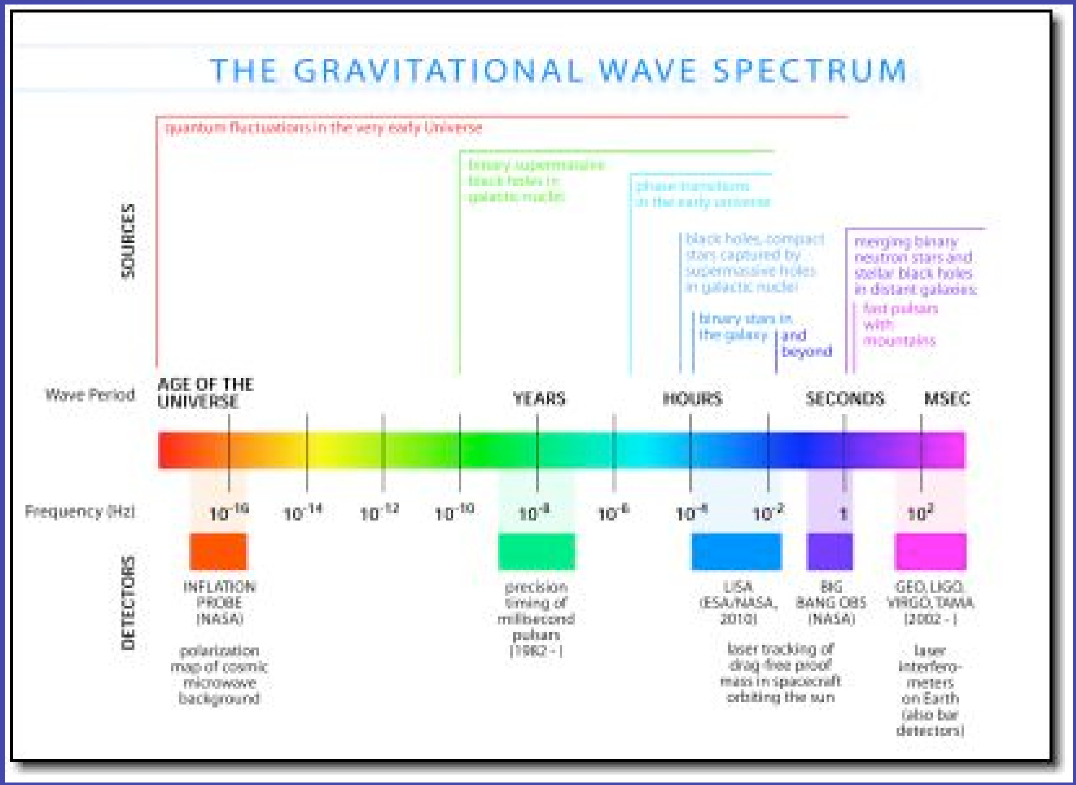
Huge underground tank of chlorine which converts to argon via neutrino interaction.

Measured flux of neutrinos from core of the sun

Ray Davis - Nobel Prize 2002

Gravitational Radiation

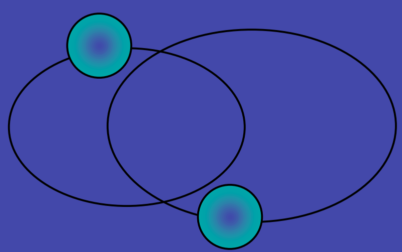
In General Relativity (and other theories of gravity) acceleration of mass produces gravity waves just like acceleration of charge produces EM waves.



Gravity waves make masses accelerate too

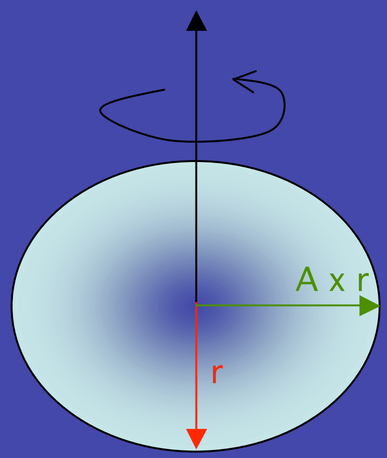
Production of Gravity Waves

Gravity waves can be produced by orbital motion or rapid rotation of massive bodies, or explosion or collapse of matter. Luminosity (in Watts) given by:



$$L_g \approx \frac{2\times 10^{-63} M^2 m^2 (1+30e^3)}{(M+m)^{2/3} P^{10/3}}$$

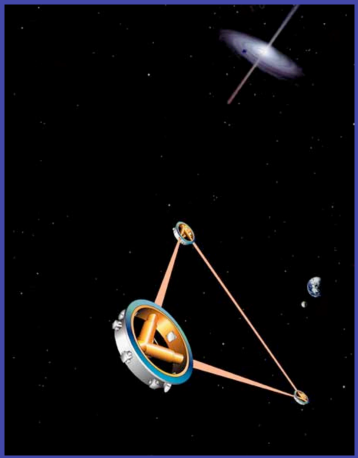
$$L_g \approx \frac{G M^2 \omega^6 r^4 (A+1)^6 (A-1)^2}{64 c^5}$$



Detection of Gravity Waves

Passage of a gravity wave causes a strain in a test mass: increase length or separation

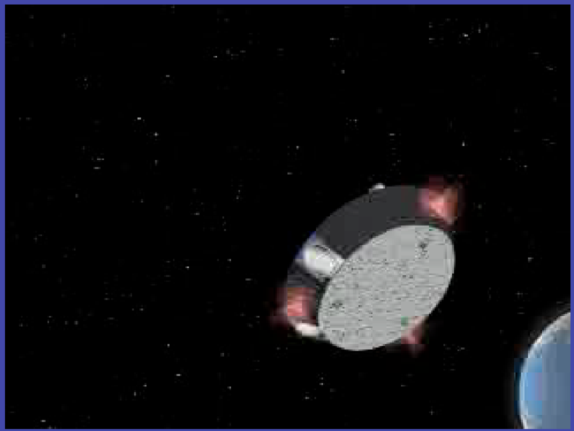
LISA: Laser Interferometer Space Antenna - 3 orbiting satellites using lasers to precisely define separation of 3 test masses. Change in separation ⇒ gravity wave (2011?)



separation: 5×10^6 km

accuracy: 10 picometers

(half a billionth of an inch)!

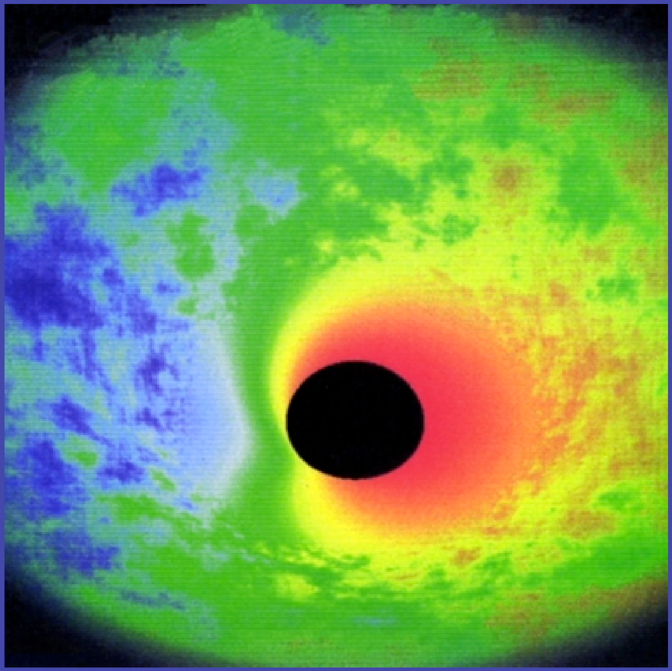


The Future

Constellation-X: complement of X-ray satellite observatories to obtain X-ray spectra of objects 100x fainter than currently feasible (2011?)

The Future

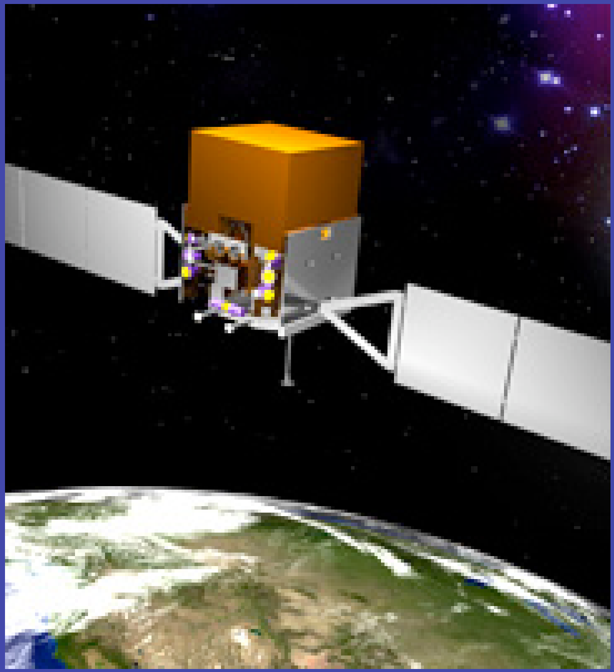
Black Hole Imager: X-ray interferometer providing 0.1 micro-arcsecond spatial resolution to probe X-ray emitting region extremely close to a black hole



The Future

GLAST: Gamma-Ray Large Area Telescope

follow-on to CGRO with better spatial resolution



- Large Area Telescope (LAT): similar to EGRET with better spatial resolution - identify
- EGRET unidentified sources
- GLAST Burst Monitor (GBM): similar to BATSE
- Launch 2007

Parting thoughts

- Although EM radiation at every wavelength has same characteristics, different energies are produced by different physical processes, interact differently with matter, and require different types of collectors.
- Space based observations carry unique risks and rewards
- Detection of gravitational radiation could open another new window on the Universe, but presents unique challenges in detection and analysis