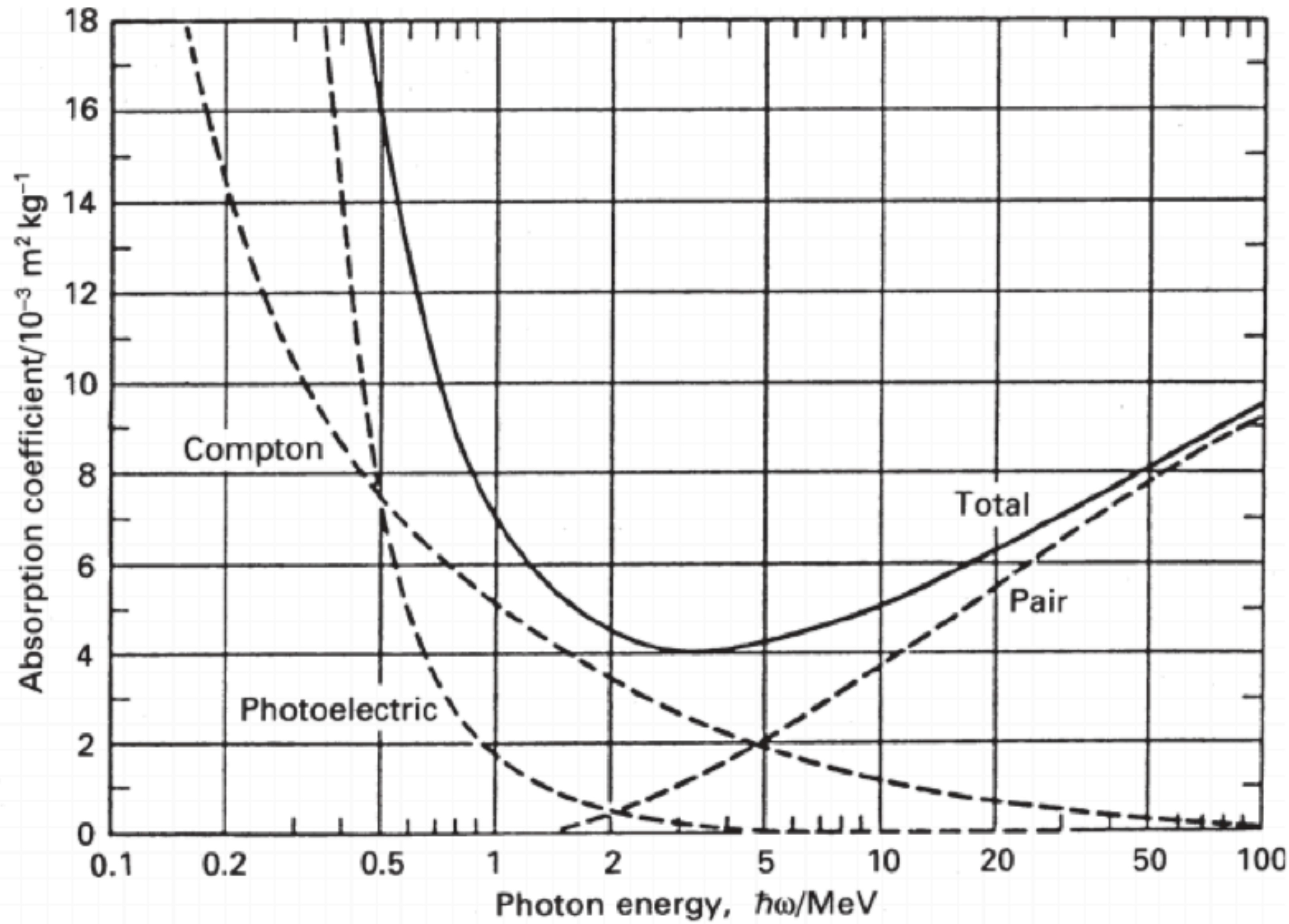
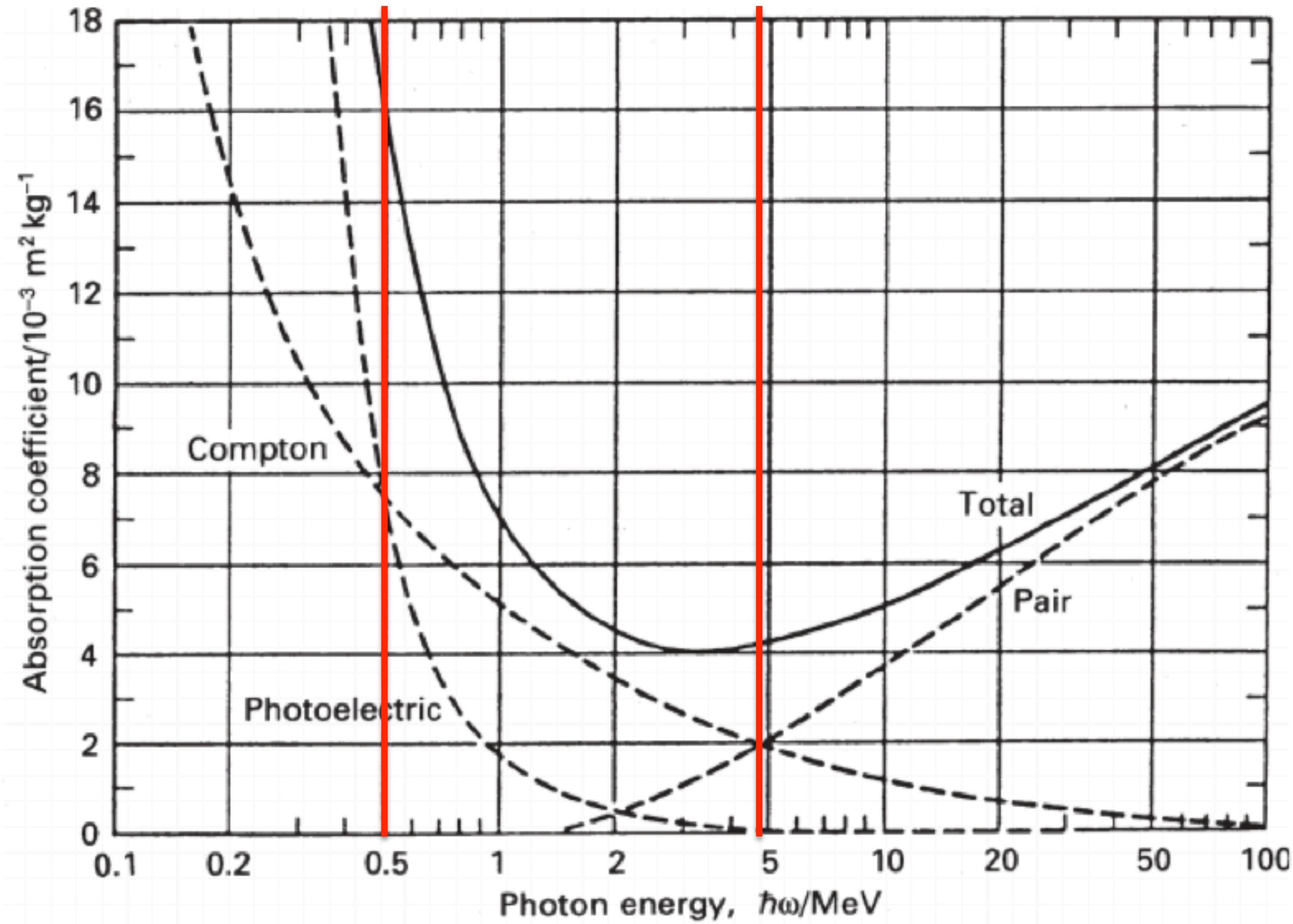
Gamma-Ray Detection, and History and Techniques of Imaging Atmospheric Cherenkov Telescopes mostly, but also with quite alot of space-based stuff, because, as it turns out, it's really cool and interesting (in my opinion).

Jamie Holder, 2015 Fermi Summer School

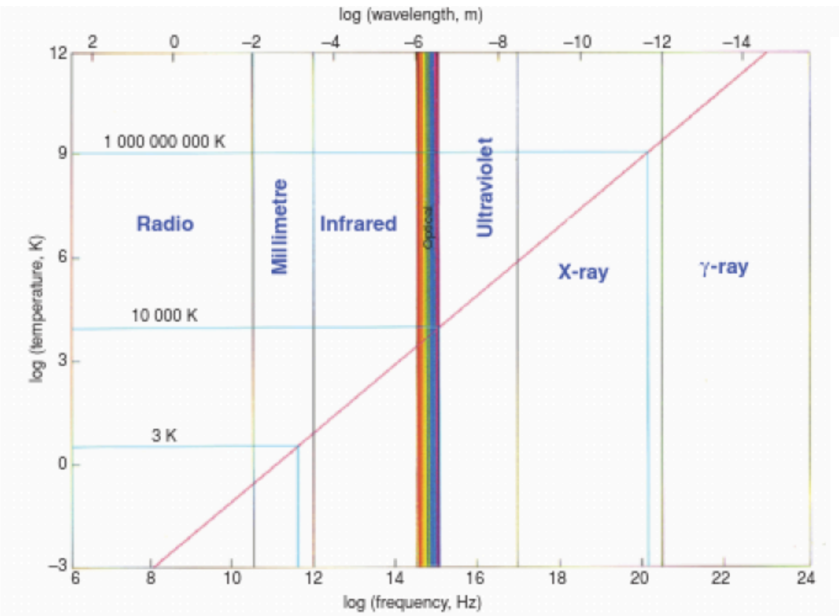
Energy loss of Photons in Matter

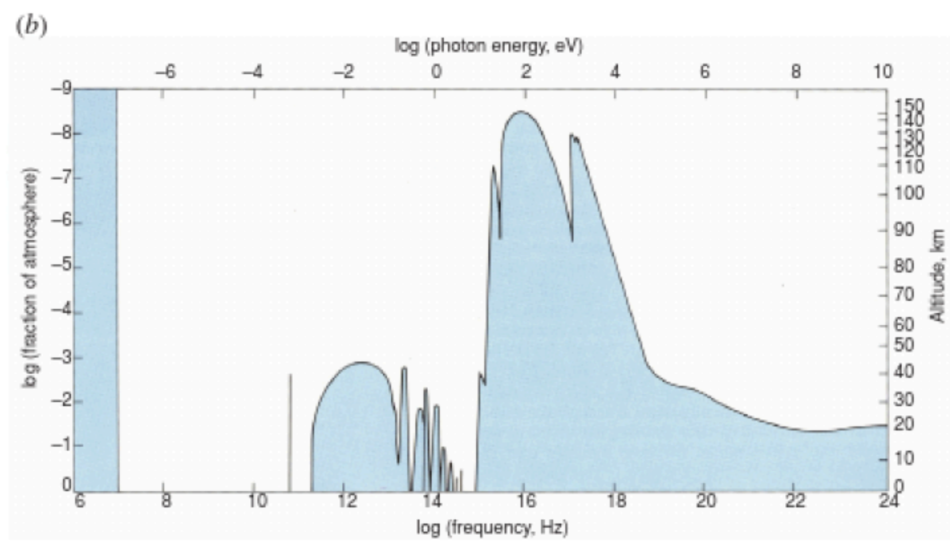


Energy loss of Photons in Matter



Astrophysical gamma-rays cannot be directly observed from the ground





particle data group

About PDG | PDG Authors | PDG Citation | Contact Us

The Review of Particle Physics

K.A. Olive *et al.* (Particle Data Group), Chin. Phys. C, **38**, 090001 (2014).

- pdgLive - Interactive Listings
- Summary Tables
- Reviews, Tables, Plots
- Particle Listings
- Search

Outline

- A bit of history…
- Gamma-ray detection in general.
- Apologies if you've heard some of it before…
- Deeper focus on how Atmospheric Cherenkov Telescopes work
- Details of the analysis methods, and how to work with IACTs (Lecture 2)

So how do we detect gamma-rays?

- Two options
  - Go into space/ upper atmosphere
  - Or use indirect detection techniques
- Balloons allow access to the upper atmosphere (26 miles/ 42km)
  - Payload size is limited
  - Lifetime is limited (and uncertain)
- Space is much better, in principle
  - Easy removal of charged particle background
  - Good detection efficiency
  - All of the gamma-ray energy can be deposited in the instrument (good energy resolution)
- But space is **expensive**
  - Effective area of a space-based detector is limited to ~1m^2
  - Most gamma-ray sources have steep power-law spectra
  - The brightest sources produce only a few photons/m^2/year at 1TeV

Hubble: $2.5B

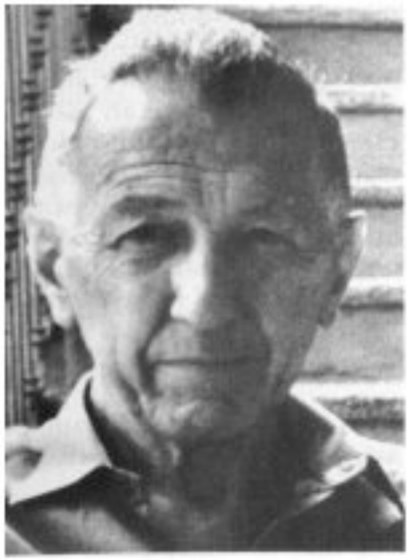
Chandra: $1.6B

James Webb: $8.8B?

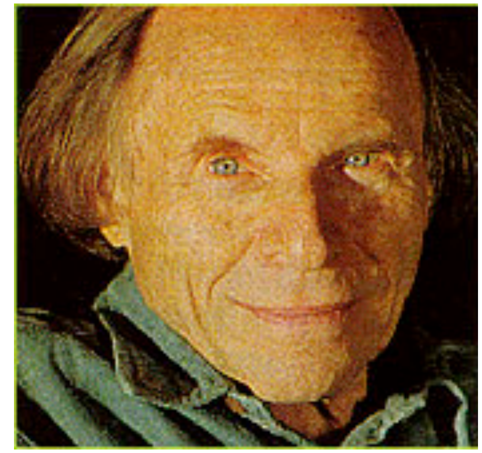
Nimitz Class: $4.5B

ALMA: $1.3B for 66

ISS: $150B



Motivations



- 1958: Philip Morrison predicts gamma-ray fluxes from various sources
- 1959: Giuseppe Cocconi predicts a flux of TeV gamma-rays from the Crab Nebula which could be detected with an array of particle detectors.
  - We now know he overestimated the true flux by a factor of x10,000!

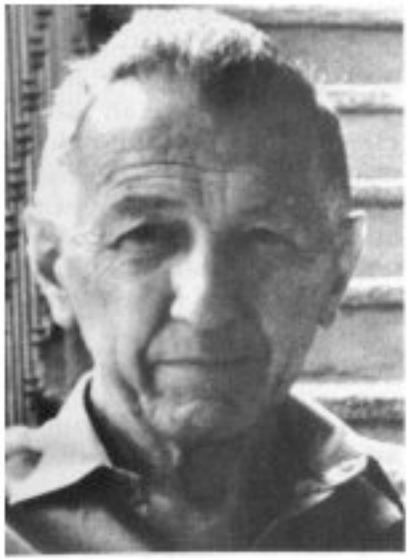
On Gamma-Ray Astronomy.

P. Morrison

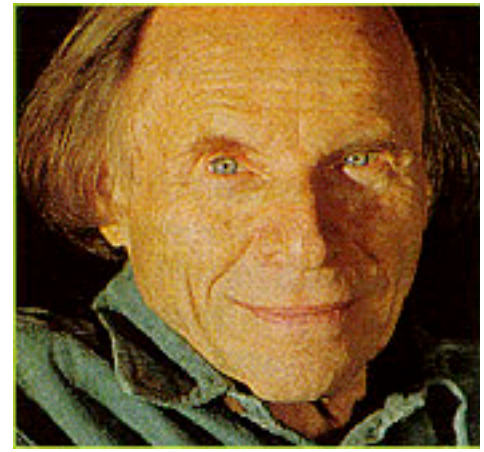
Department of Physics, Cornell University - Ithaca, N. Y.

(ricevuto il 22 Dicembre 1957)

Summary. — Photons in the visible range form the basis of astronomy. They move in straight lines, which preserves source information, but they arise only very indirectly from nuclear or high-energy processes. Cosmic-ray particles, on the other hand, arise directly from high-energy processes in astronomical objects of various classes, but carry no information about source direction. Radio emissions are still more complex in origin. But γ-rays arise rather directly in nuclear or high-energy processes, and yet travel in straight lines. Processes which might give rise to continuous and discrete γ-ray spectra in astronomical objects are described, and possible source directions and intensities are estimated. Present limits were set by observations with little energy or angular discrimination; γ-ray studies made at balloon altitudes, with feasible discrimination, promise valuable information not otherwise attainable.



Motivations



SEARCHING FOR INTERSTELLAR COMMUNICATIONS

By GIUSEPPE COCCONI* and PHILIP MORR'SON†
Cornell University, Ithaca, New York

The Early Years

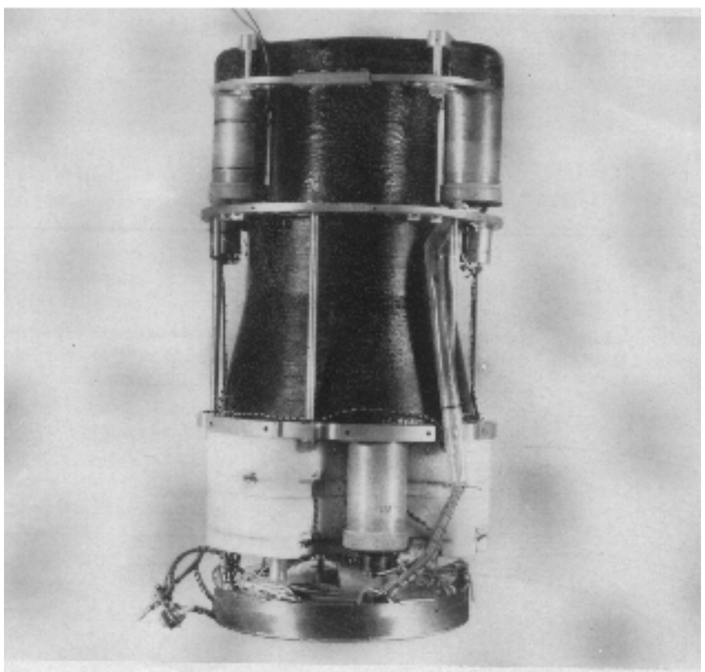
(see D. Kniffen, NASA HQ GLAST Program Scientist 1999-2005
4th Fermi Symposium)

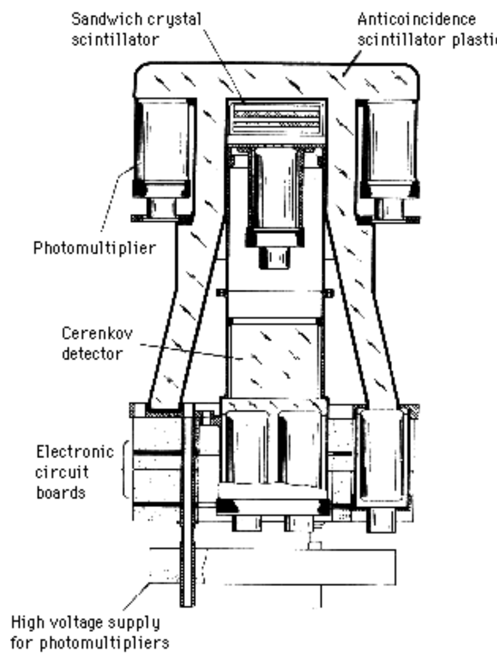
– A mixture of balloon experiments

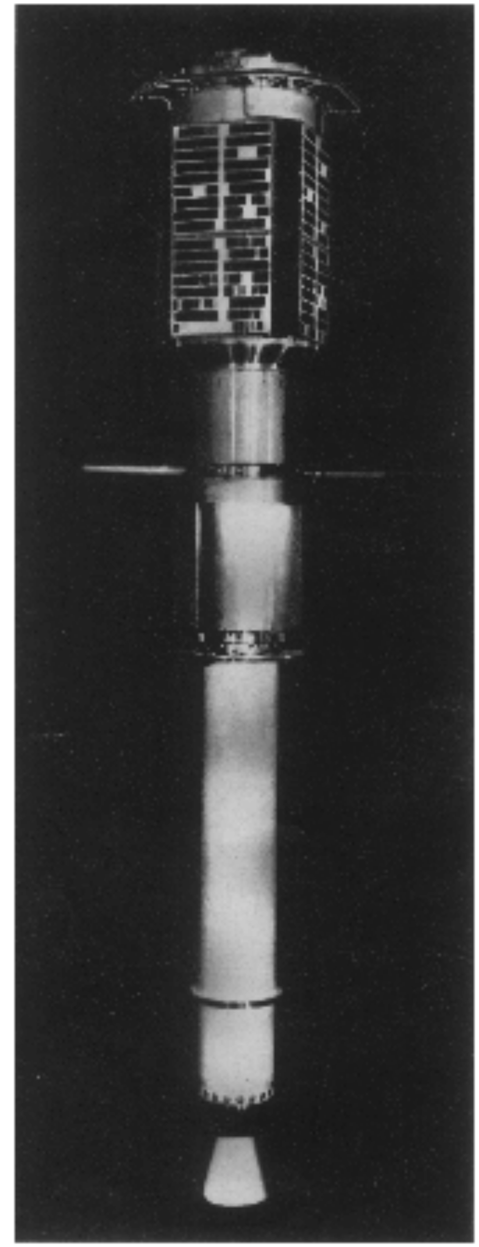
Sun Seeker

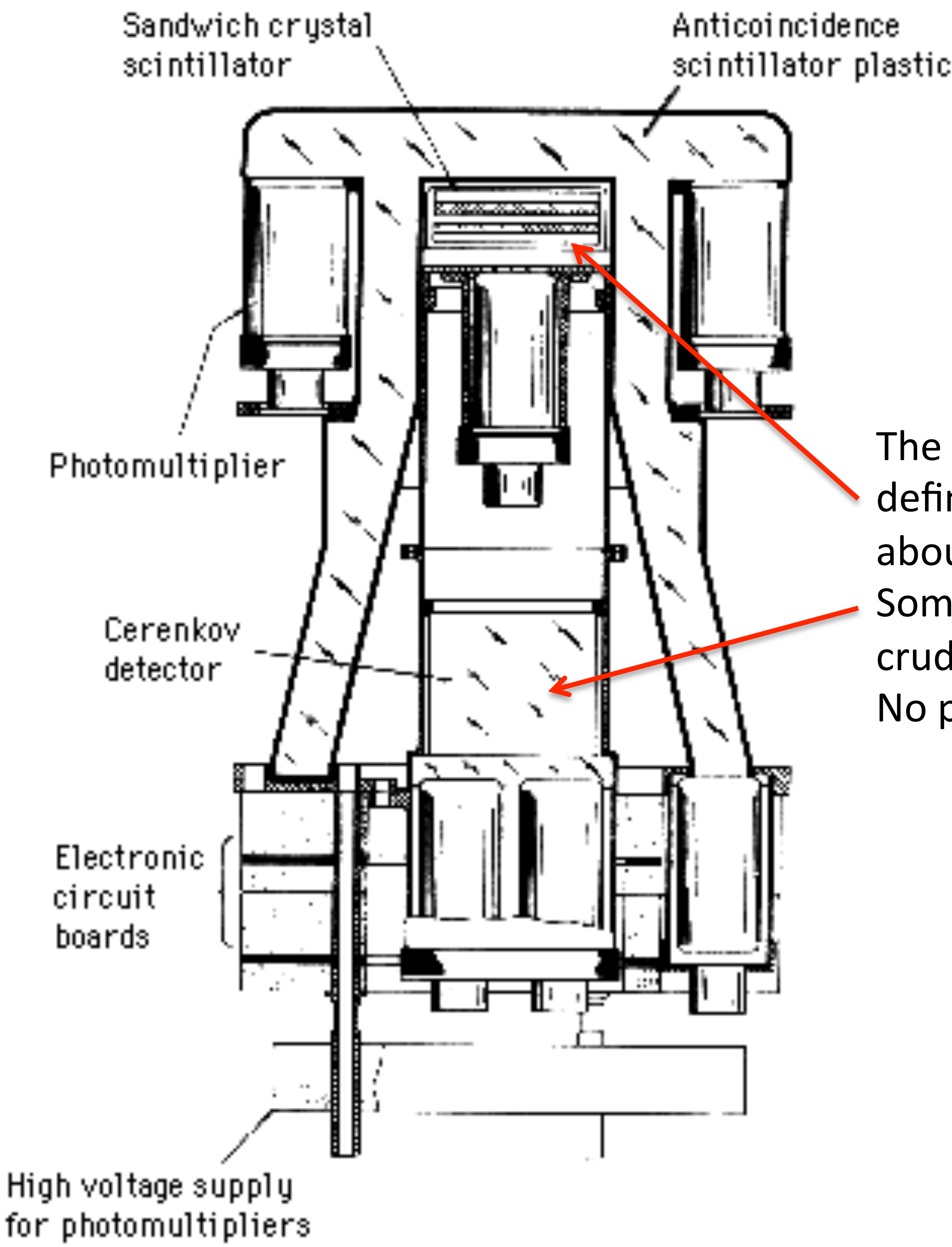
6 inch spark chamber

- And satellites
  - Explorer XI launched 27 April 1961
  - *cf* Sputnik, 4 October 1957; first US satellite (Explorer I) January 31, 1958
  - Technical problems meant only 141 hours of useful observing time from about 7 months during which the instrument operated
  - "In this data were found 22 events from gamma rays and 22,000 events due to charged cosmic rays"
  - No point sources detected - but it demonstrated that there **was** a gamma-ray flux from space







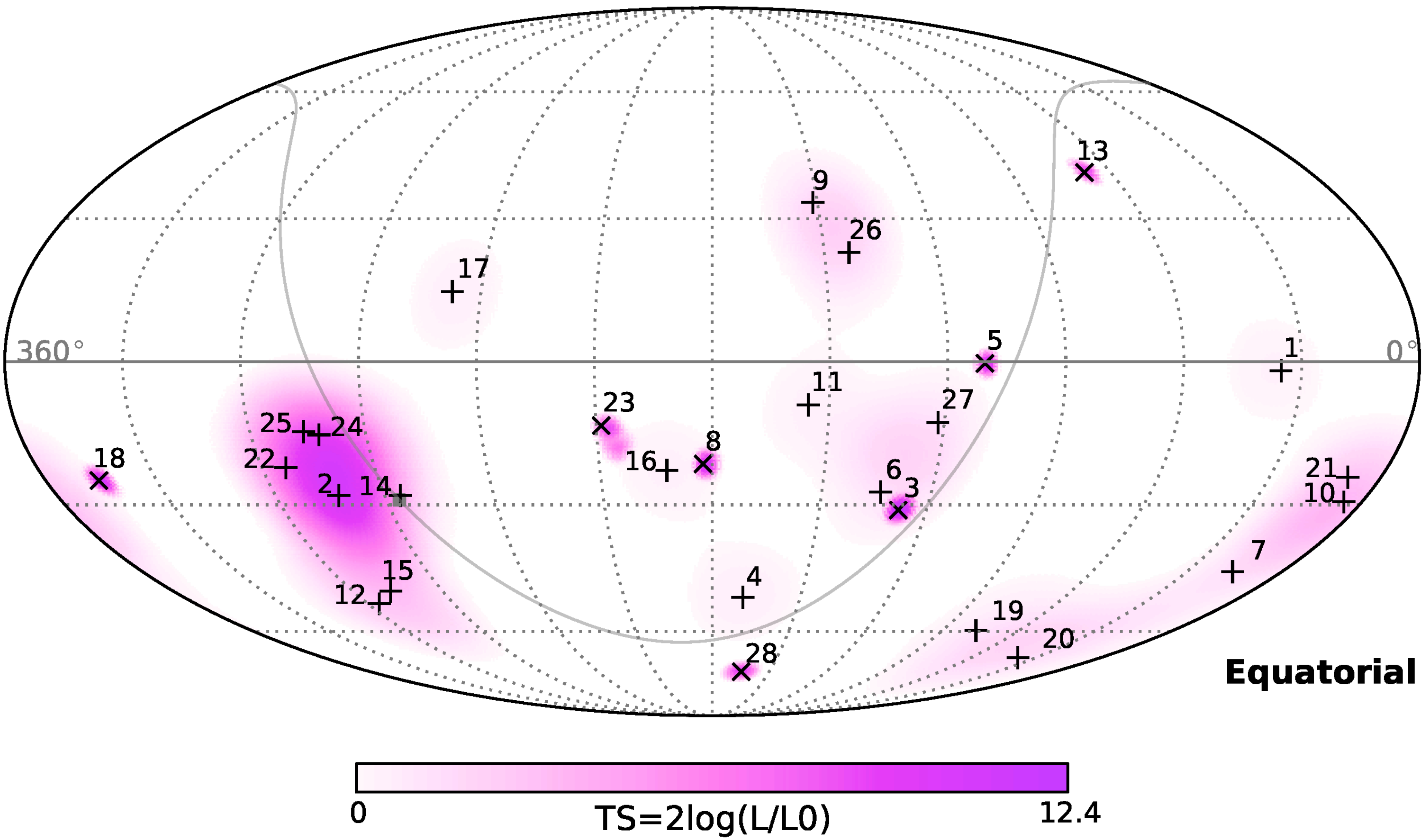


Explorer XI

The 2 detectors in coincidence serve to define the solid angle of the instrument to about 17 degrees (half-angle).

Some direction reconstruction – but very crude.

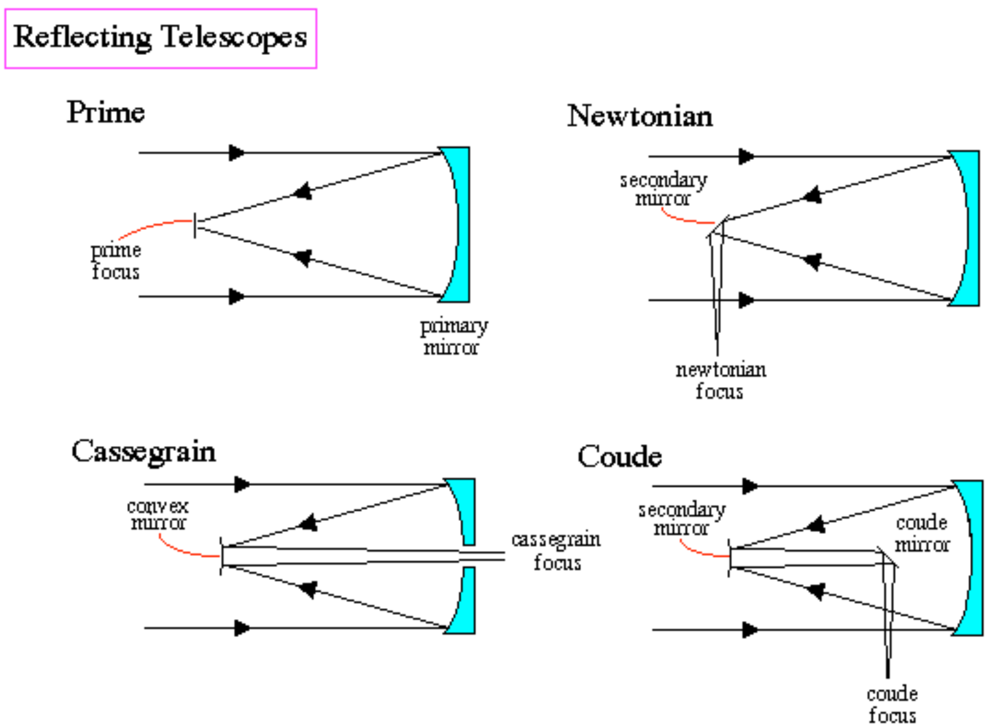
No pointing control – just set it "tumbling" *c.f.* IceCube!



360°
0°
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
Equatorial
0
TS=2log(L/L0)
12.4

Intermission: How do you make a gamma-ray telescope?

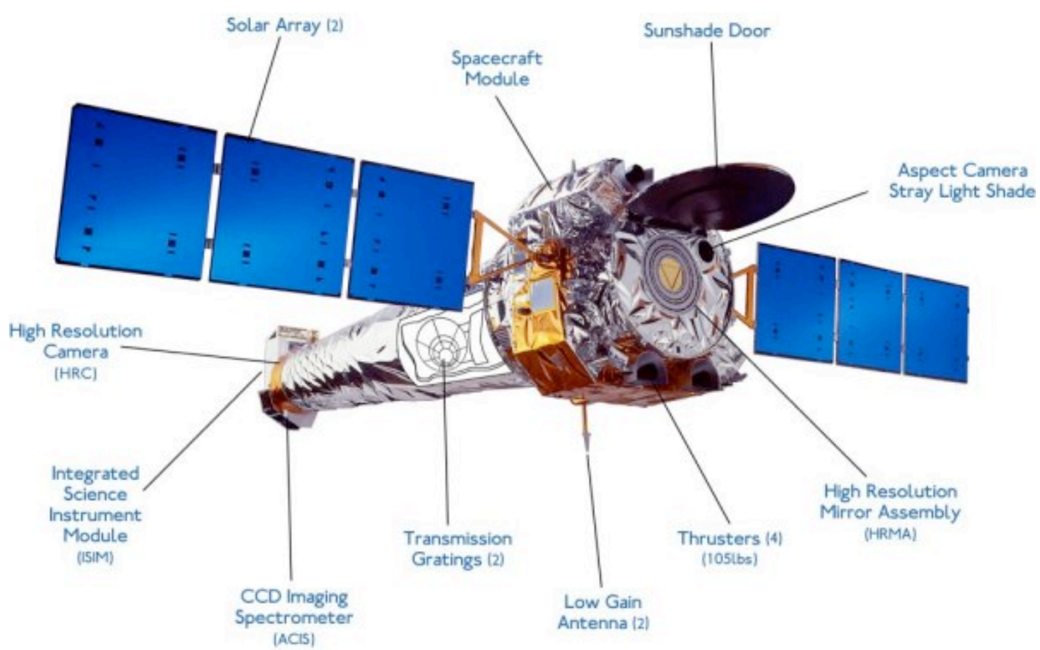
- There are two big differences between a **telescope** and a **detector**
  - A *detector* just collects photons – the dimensions of the photon detector are the same as the detector size (the *aperture*).
  - A *telescope* can concentrate the photons (the photon detector can be much smaller than the aperture), and also make an image.
  - E.g. Optical telescopes focus light using mirrors (reflecting) or lenses (refracting) – a solar panel just collects photons



Neither the LAT, nor IACTs, are telescopes, in the traditional sense…

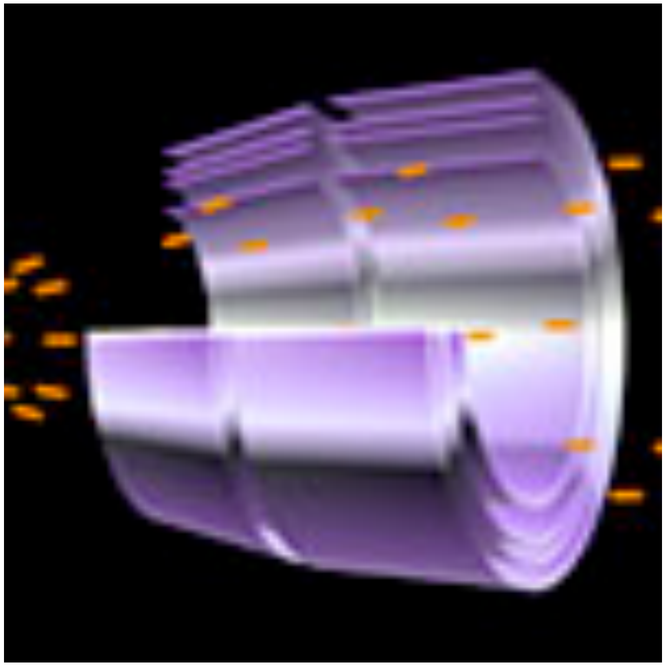
So how do you make a gamma-ray telescope?

- At higher energies, conventional mirrors transmit or absorb photons – they don't reflect.
- X-ray satellites solve this using Wolter grazing incidence optical techniques to deflect the photons
- E.g. Chandra X-ray Observatory

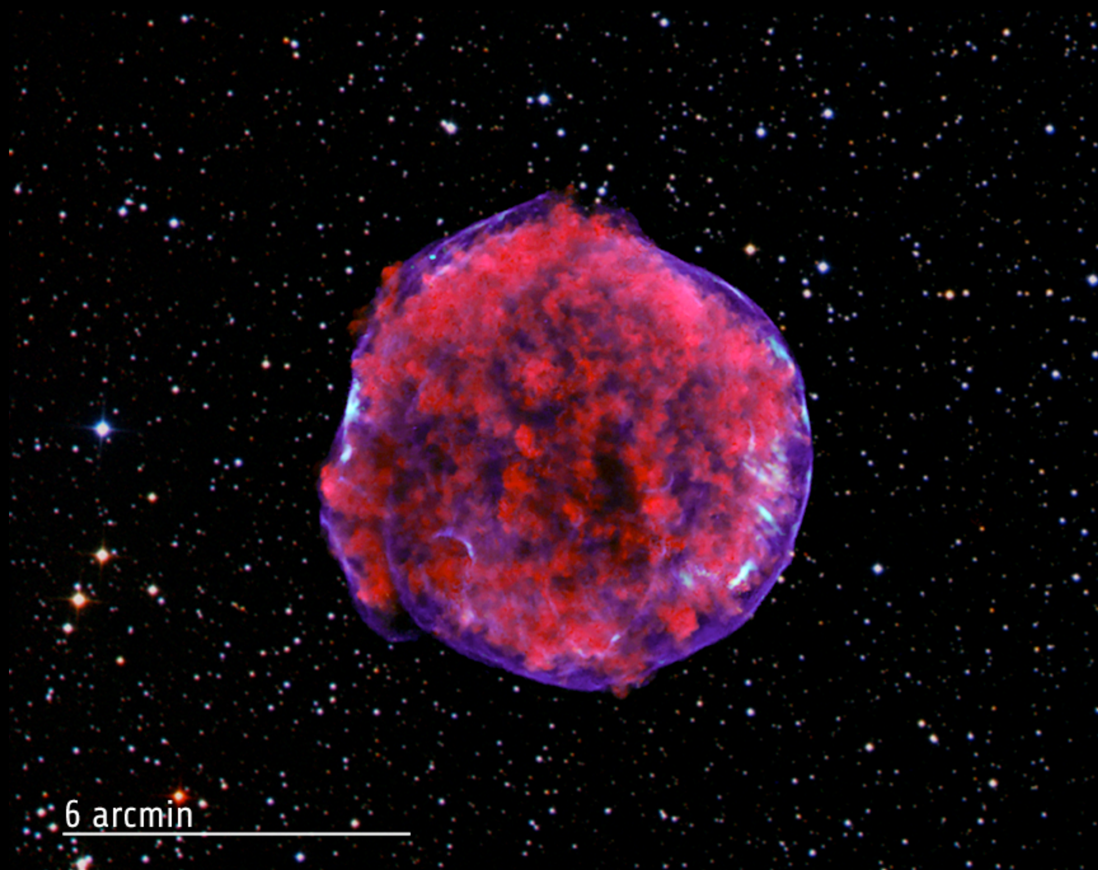


How do you make a gamma-ray telescope?

- At higher energies, conventional mirrors transmit or absorb photons – they don't reflect.
- X-ray satellites solve this using Wolter grazing incidence optical techniques to deflect the photons
- E.g. Chandra X-ray Observatory

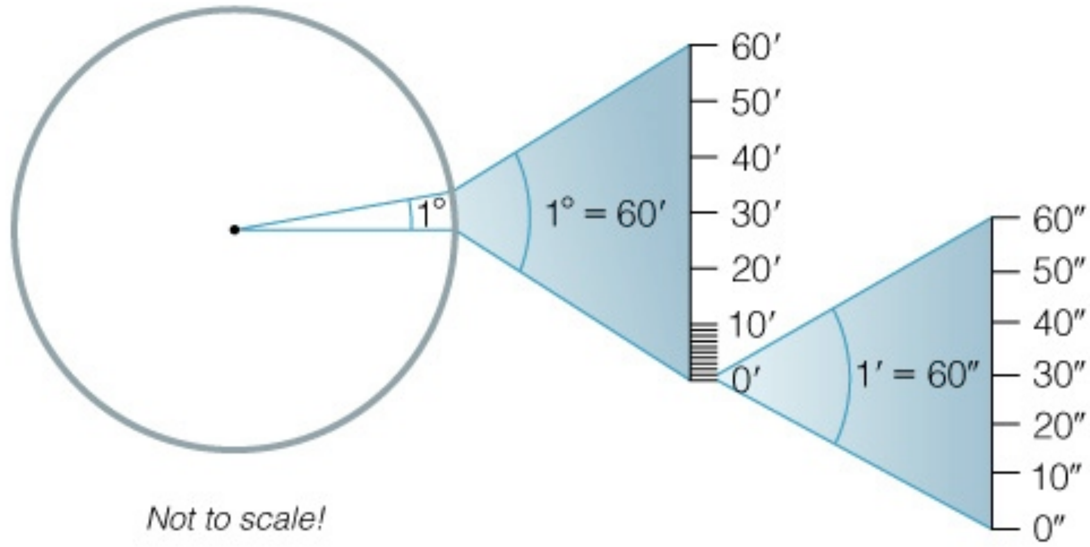


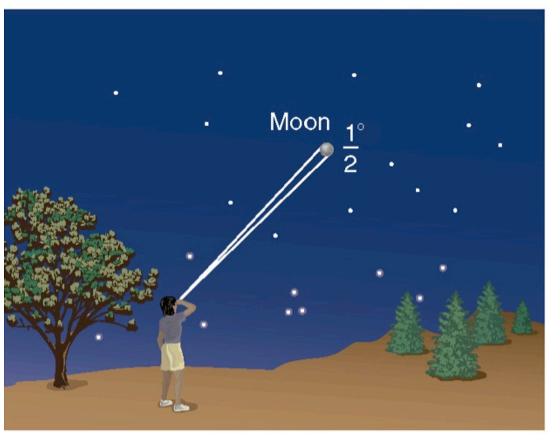
- Chandra specifications
  - Iridium coated mirrors
  - 0.1-10 keV
  - 0.5° field of view
- Spatial resolution < 1 arcsec

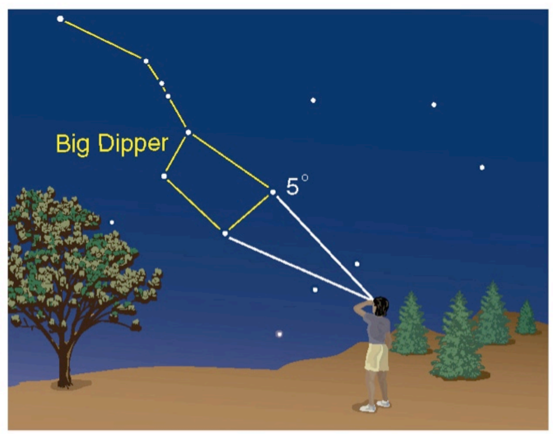


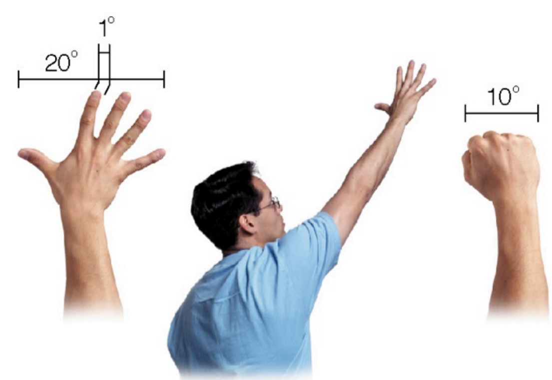
Aside…

- Full circle = 360º
- 1º = 60′ (arcminutes)
- 1′ = 60″ (arcseconds)





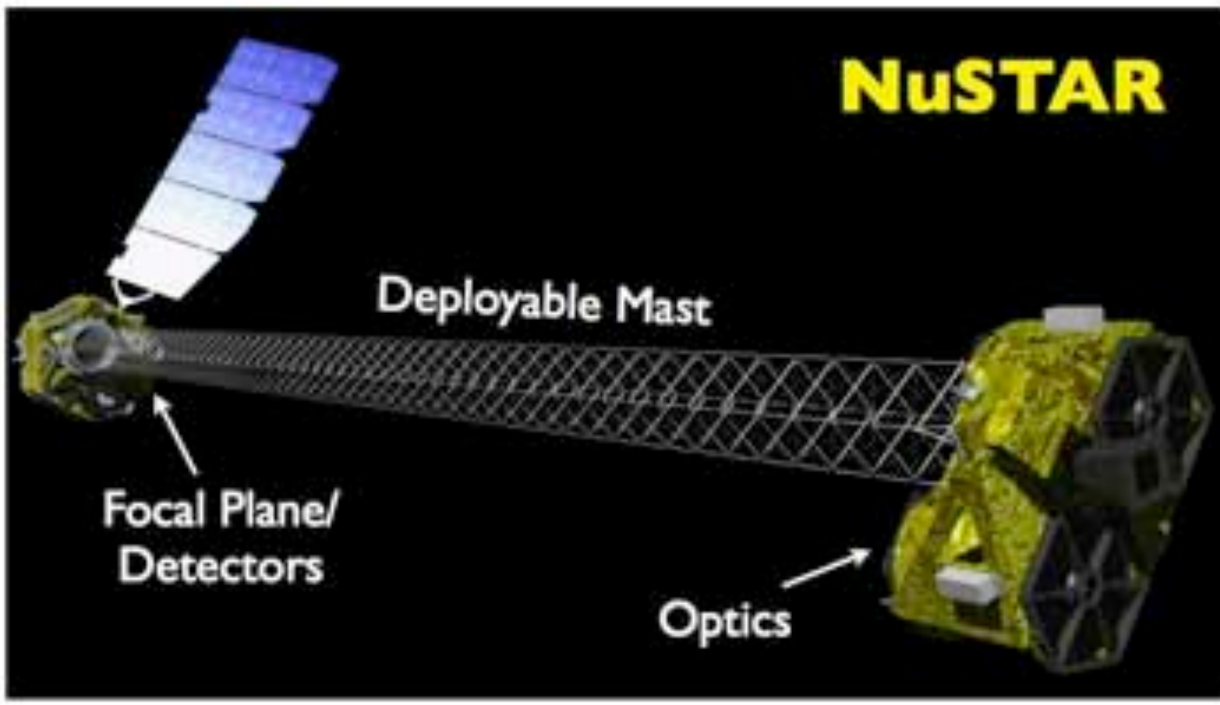




Stretch out your arm
as shown here.

Higher energies become harder to deflect

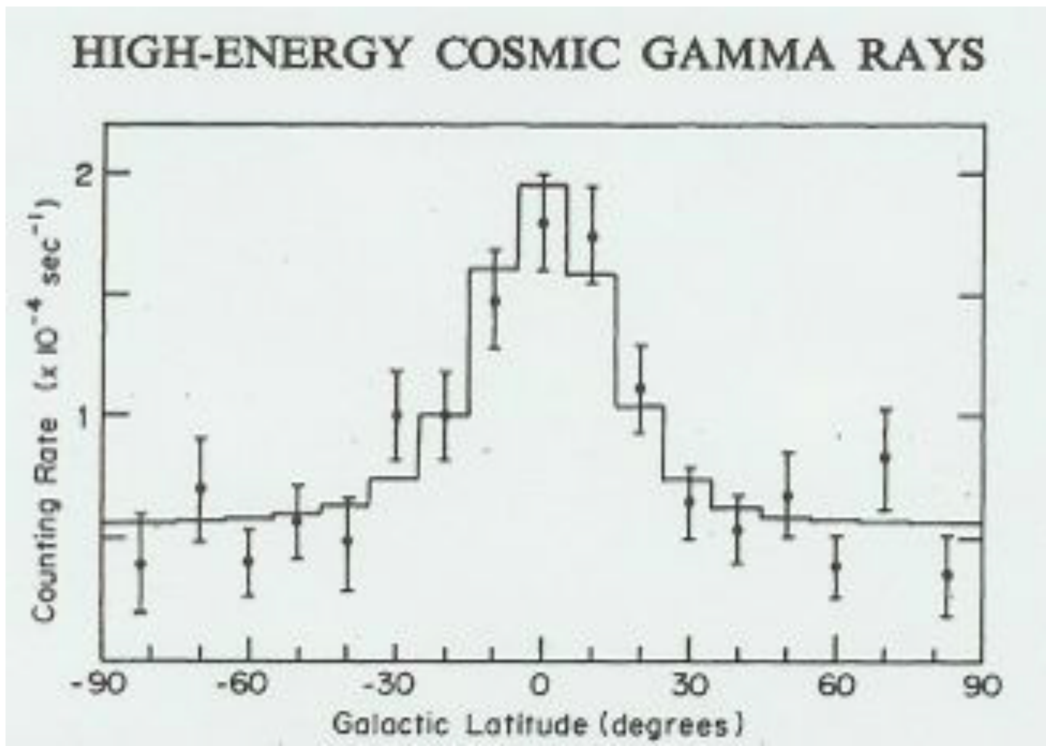
- Nustar energy range 6 - 79 keV
- 10m focal length
- Two co-aligned grazing incidence telescopes
- Launched June 2012
- But you can't do this with gamma-rays….



https://www.youtube.com/watch?feature=player_detailpage&v=2XxxEdJYF5o#t=14

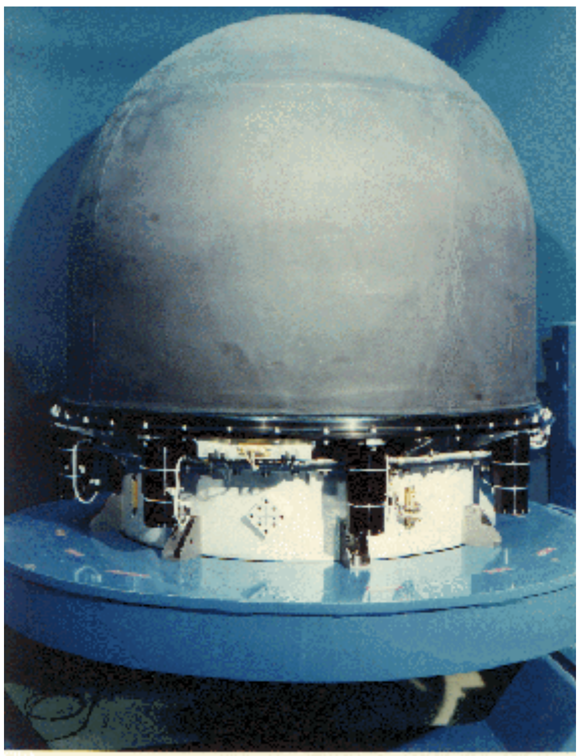
Satellites become steadily more sophisticated

– OSO 3 (March 1967) had a similar design as Explorer XI. Recorded 621 events above 50 MeV
  - detects gamma-ray emission from the Galactic plane

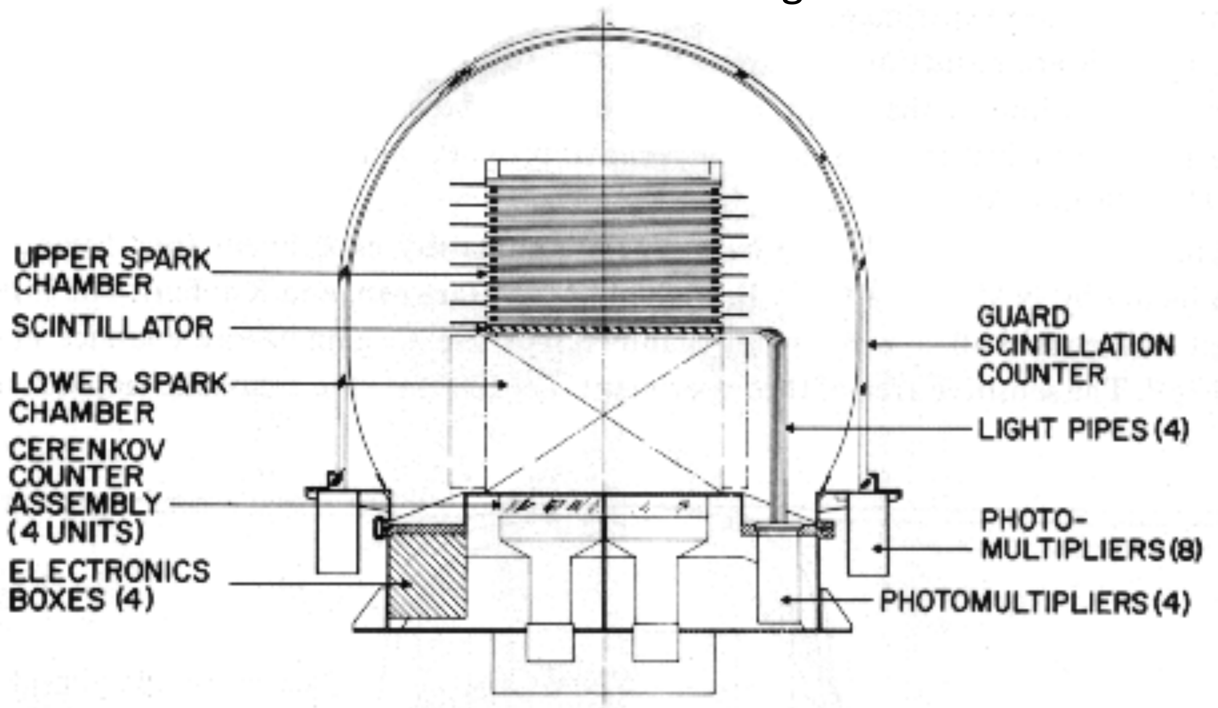


Satellites become steadily more sophisticated

- SAS 2 (November 1972) was the first satellite-borne **spark chamber**
- June 1973, a failure of the low-voltage power supply ended the collection of data.
- 20 MeV to 1 GeV, effective area of 540 cm^2
- Resolved discrete sources, correlated gamma-ray intensity with Galactic structure



A spark chamber measures arrival direction – which allows to reconstruct an image of the source



Satellites become steadily more sophisticated

- SAS 2 (November 1972) was the first satellite-borne **spark chamber**
- June 1973, a failure of the low-voltage power supply ended the collection of data.
- 20 MeV to 1 GeV, effective area of 540 cm^2
- Resolved discrete sources, correlated gamma-ray intensity with Galactic structure

D. Kniffen, 4^{th} Fermi Symposium

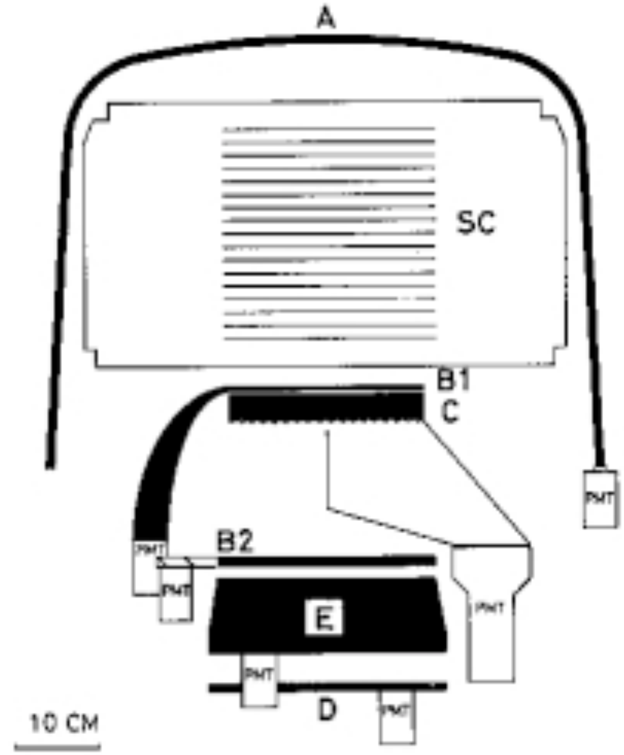
Satellites become steadily more sophisticated

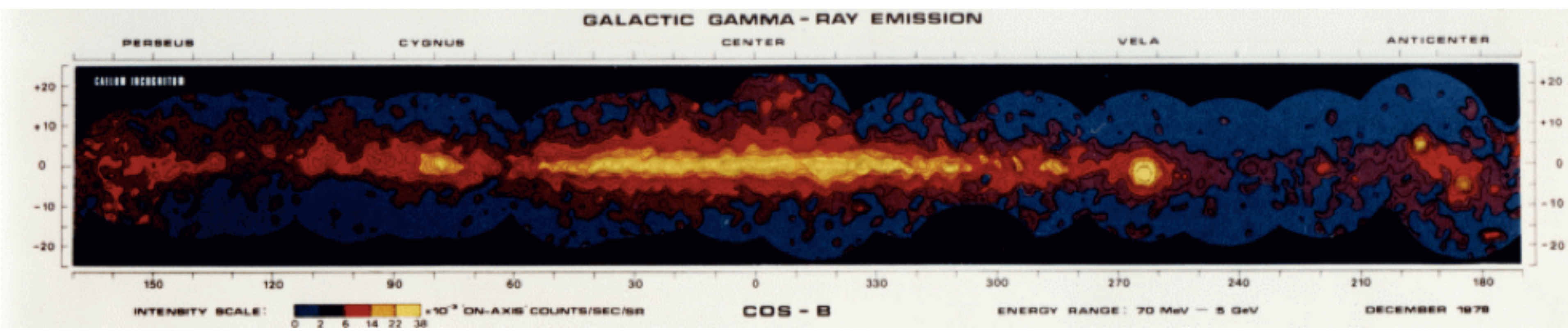
- SAS 2 (November 1972) was the first satellite-borne **spark chamber**
- June 1973, a failure of the low-voltage power supply ended the collection of data.
- 20 MeV to 1 GeV, effective area of 540 cm^2
- Resolved discrete sources, correlated gamma-ray intensity with Galactic structure

D. Kniffen, 4th Fermi Symposium

COS-B

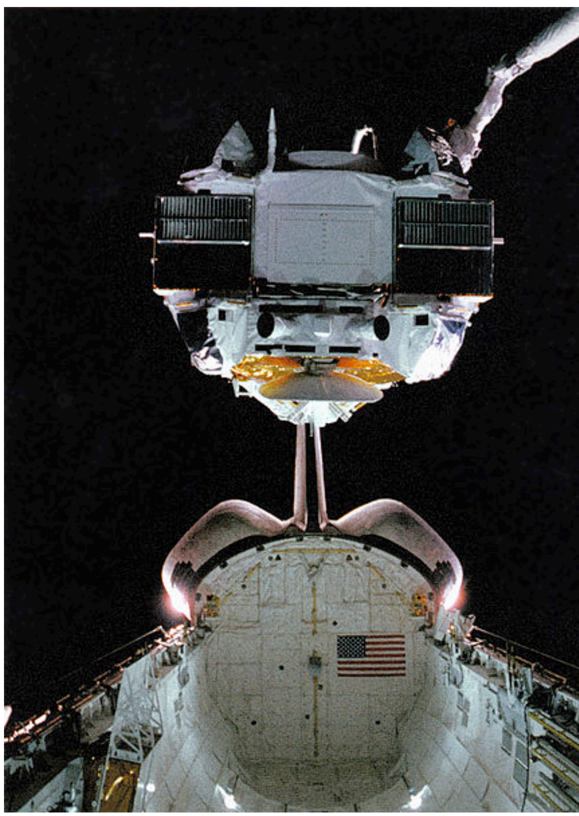
- The European version
- 1975-1982
- Mapped the Galaxy

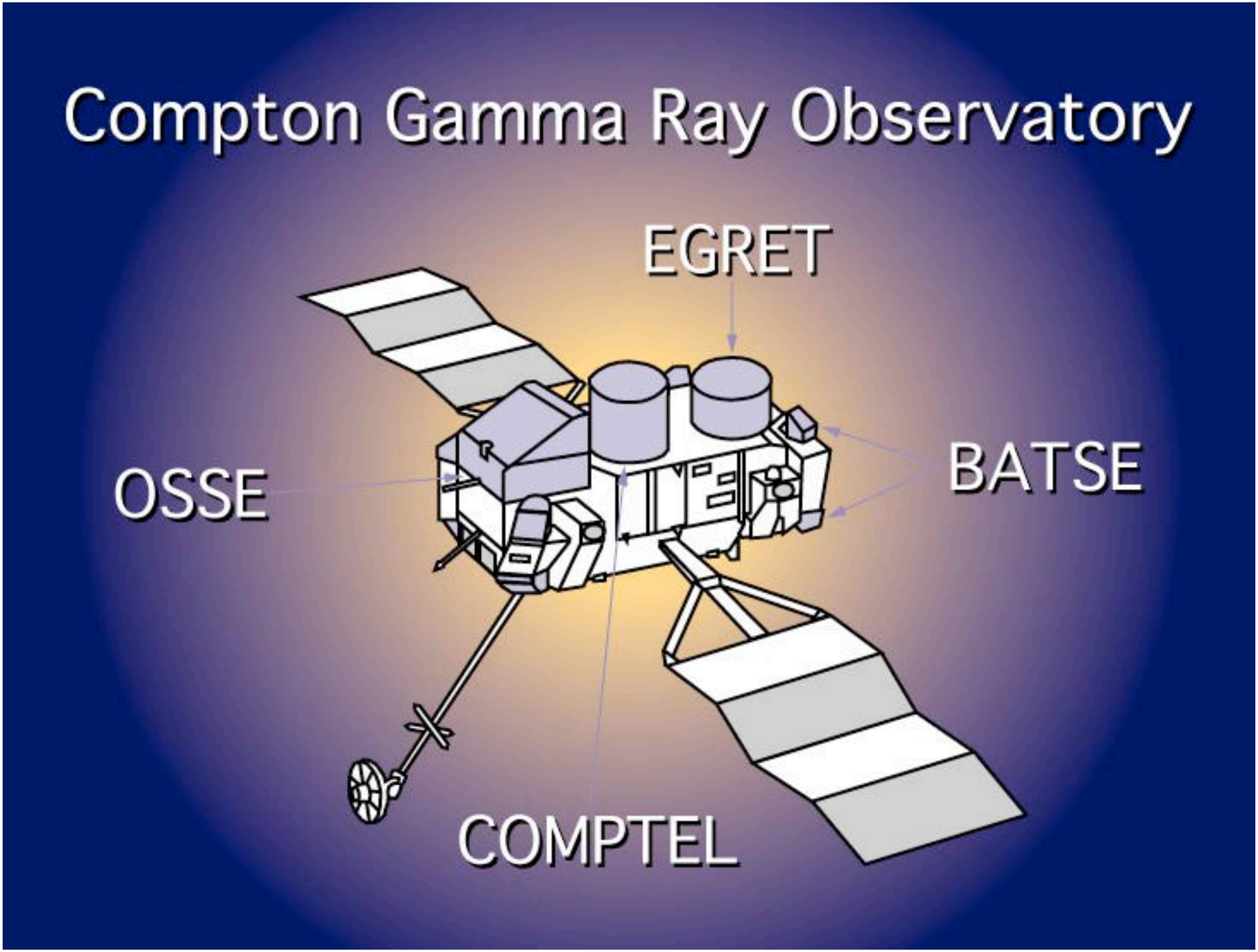




Compton Gamma-Ray Observatory

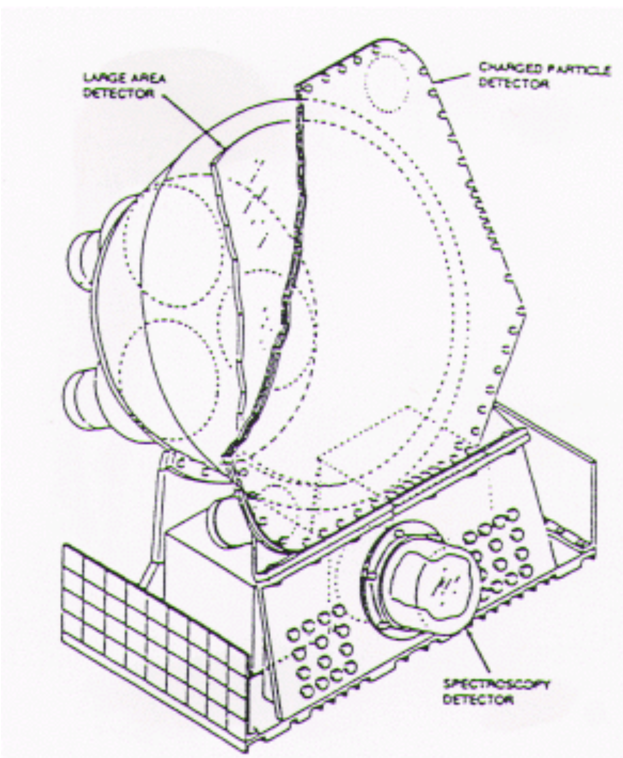
- Second of NASA's "Great Observatories" (after Hubble, before Chandra and Spitzer)
- Operated from 1991-2000
- Housed four instruments: BATSE, OSSE COMPTEL, EGRET
- Heaviest astrophysical payload ever flown at the time (17,000 Kg)
- Primary payload of Shuttle mission STS-37, deployed using the Robot arm
- High Gain antenna got stuck – had to be freed by an unscheduled spacewalk

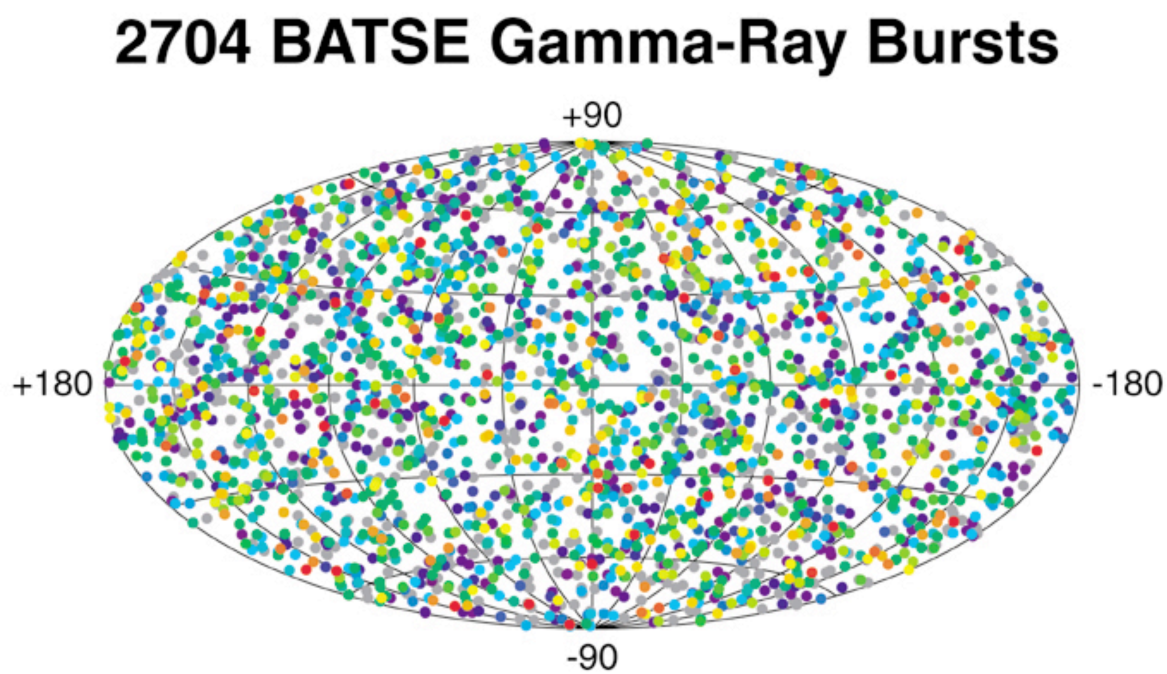



Compton Gamma Ray Observatory
EGRET
BATSE
OSSE
COMPTEL

BATSE (Burst And Transient Source Experiment)

- Eight individual scintillation detectors, one on each corner of the satellite, pointing in different directions.
- Require 2 of the 8 to see a burst at the same time
  - check within 64 ms, 256 ms, and 1024 ms windows
  - Compare count rates to determine direction (angular resolution of a few degrees)
- Sensitive from 20-600 keV (just barely gamma-rays)
- Primarily used for gamma-ray bursts – very similar to Fermi-GBM.





OSSE (Oriented Scintillation Spectrometer Experiment)

- Four movable scintillation detectors
  - Allows to measure signal and background at the same time
- Detectors are **collimated** (unlike BATSE).
  - No real imaging, but a clearly defined 4 x 11 degree field of view
- Sensitive from 0.05-10 MeV
- Used for studies of gamma-rays from radioactive decays in supernova remnants, and electron-positron annihilation near the Galactic center

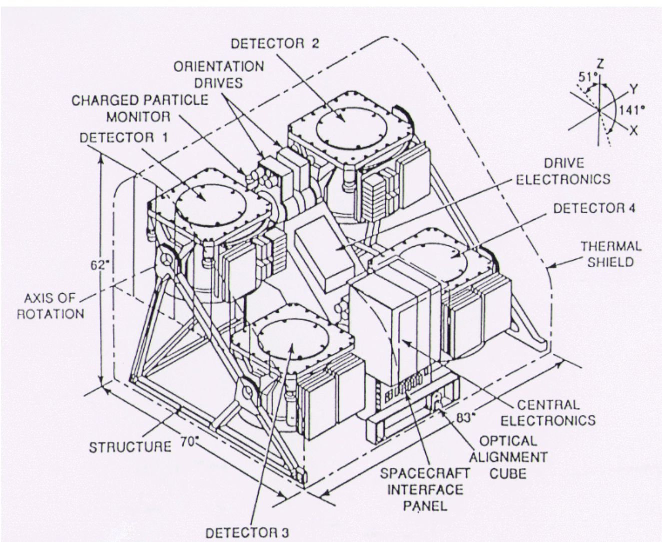
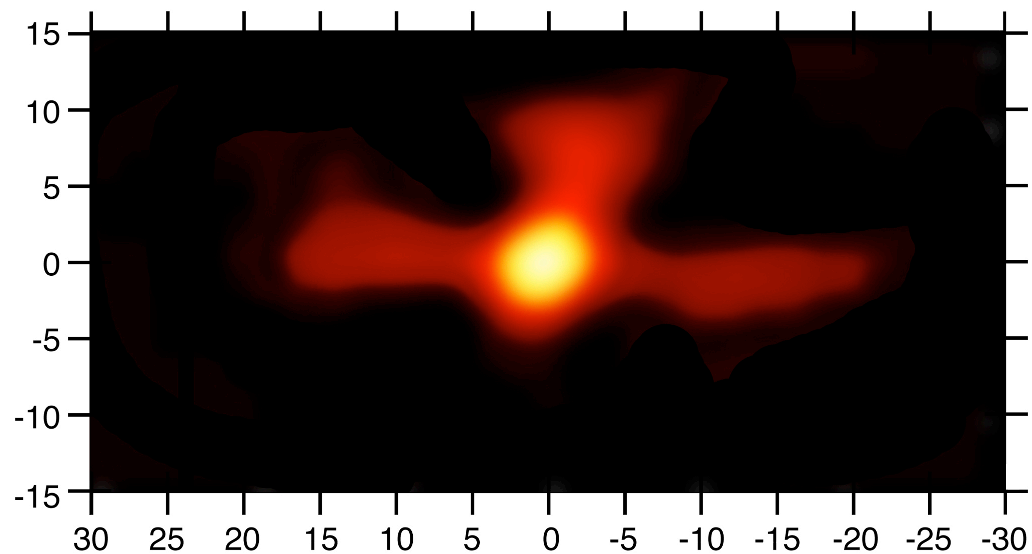
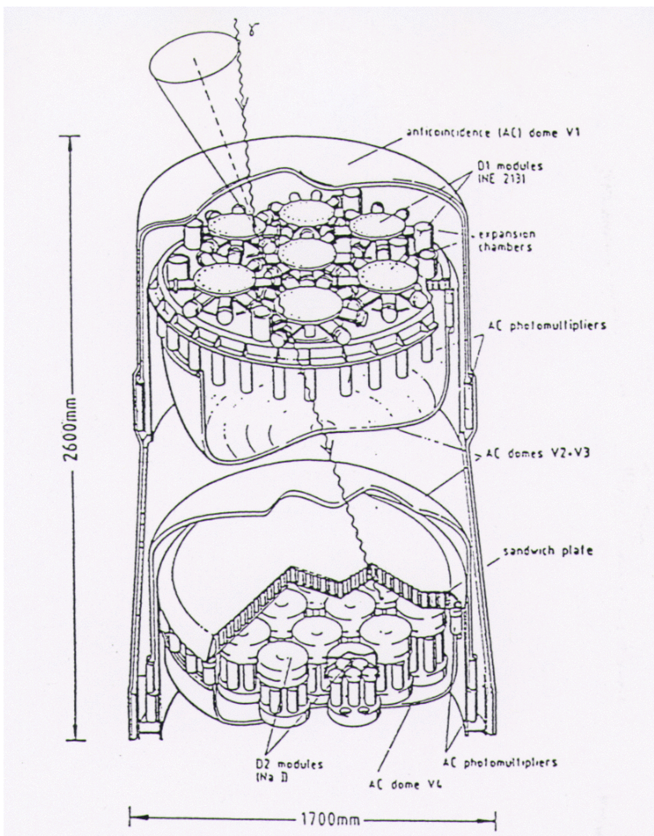


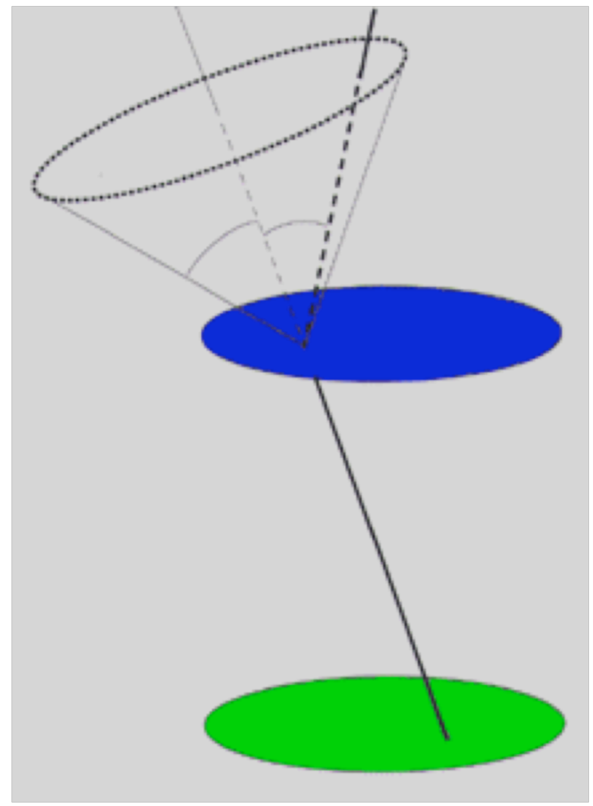
Figure II -1 The Oriented Scintillation Spectrometer Experiment (OSSE)



Comptel (Compton Telescope)

- Two detector arrays
- An incident gamma-ray is first Compton scattered in the upper detector, then totally absorbed in the lower.
- Arrival direction of each gamma-ray lies on an ‘event circle’ on the sky.
- Sensitive from 0.8-30 MeV

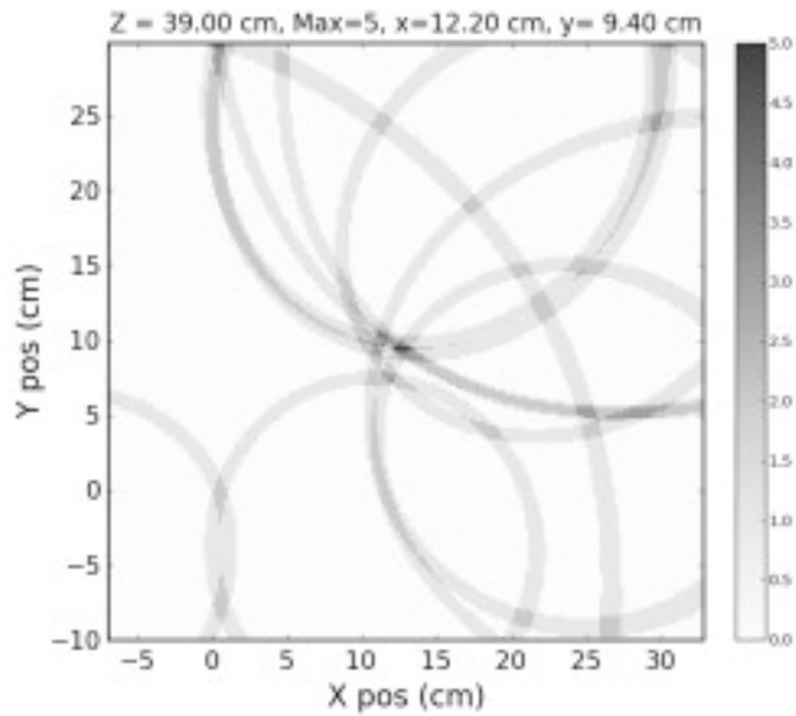




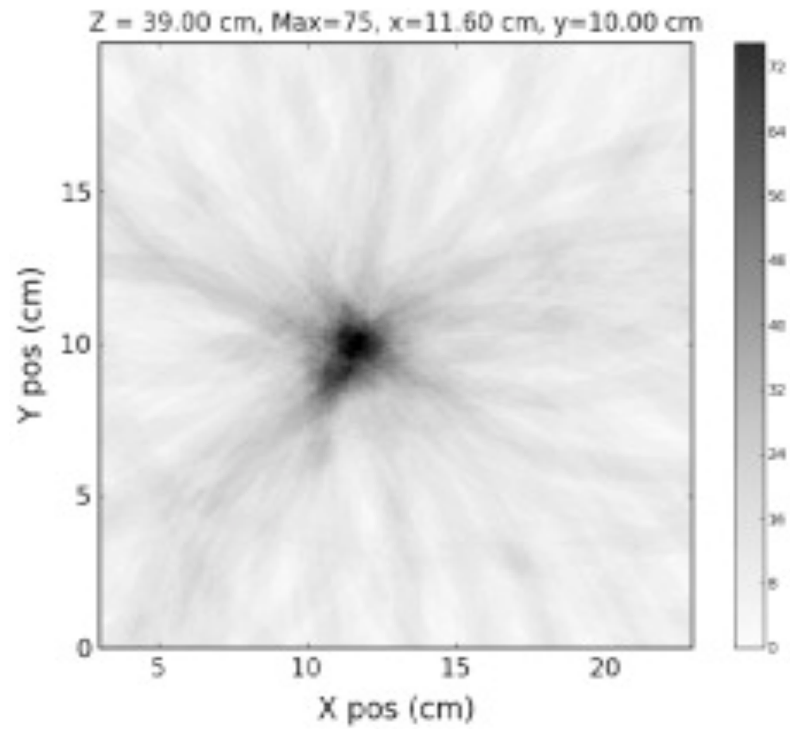
Comptel (Compton Telescope)

- Two detector arrays
- An incident gamma-ray is first Compton scattered in the upper detector, then totally absorbed in the lower.
- Arrival direction of each gamma-ray lies on an ‘event circle’ on the sky.
- Sensitive from 0.8-30 MeV

A few events

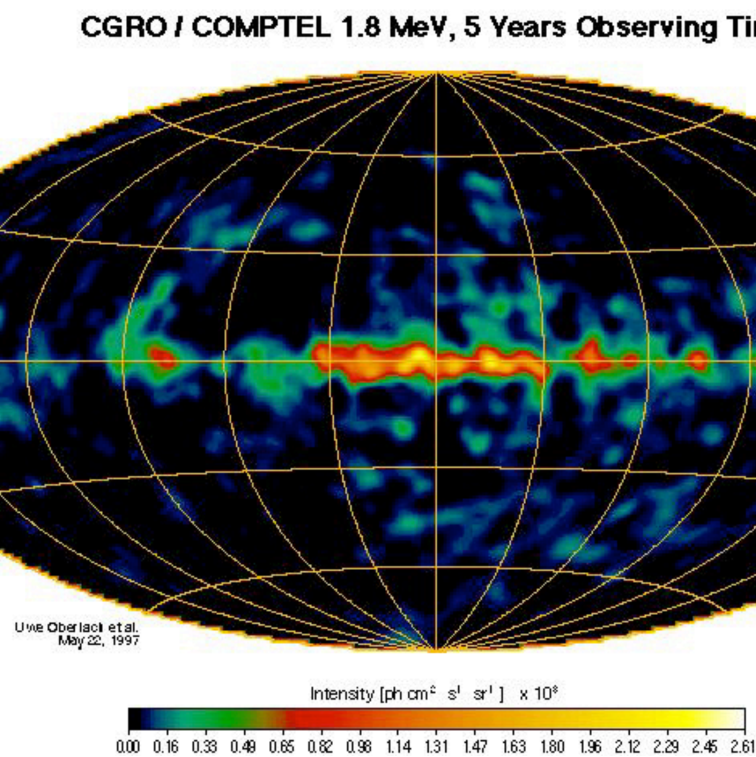


Lots of events



Comptel (Compton Telescope)

- Two detector arrays
- An incident gamma-ray is first Compton scattered in the upper detector, then totally absorbed in the lower.
- Arrival direction of each gamma-ray lies on an ‘event circle’ on the sky.
- Sensitive from 0.8-30 MeV



EGRET (Energetic Gamma-Ray Experiment Telescope)

- Gas-filled spark chamber
- Sensitive from 20 MeV - 30 GeV
- Charged particles rejected by an anticoincidence dome (**ACD**)
- Gamma-ray **converts to electron positron pair**.
  - Paths of the particles are **tracked** by the spark chamber
  - Allows to reconstruct the arrival direction
  - Energy is measured by a **calorimeter** (scintillator)

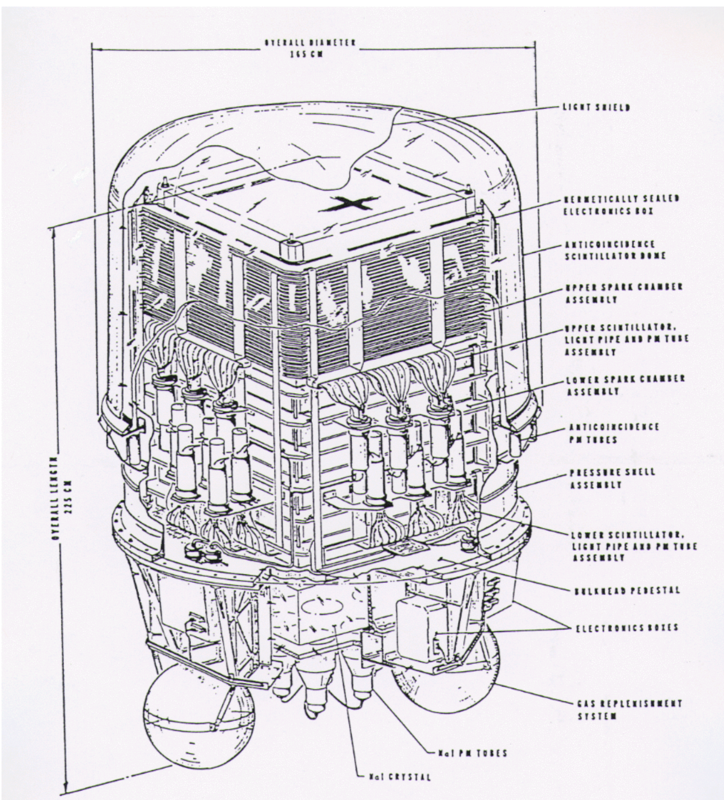
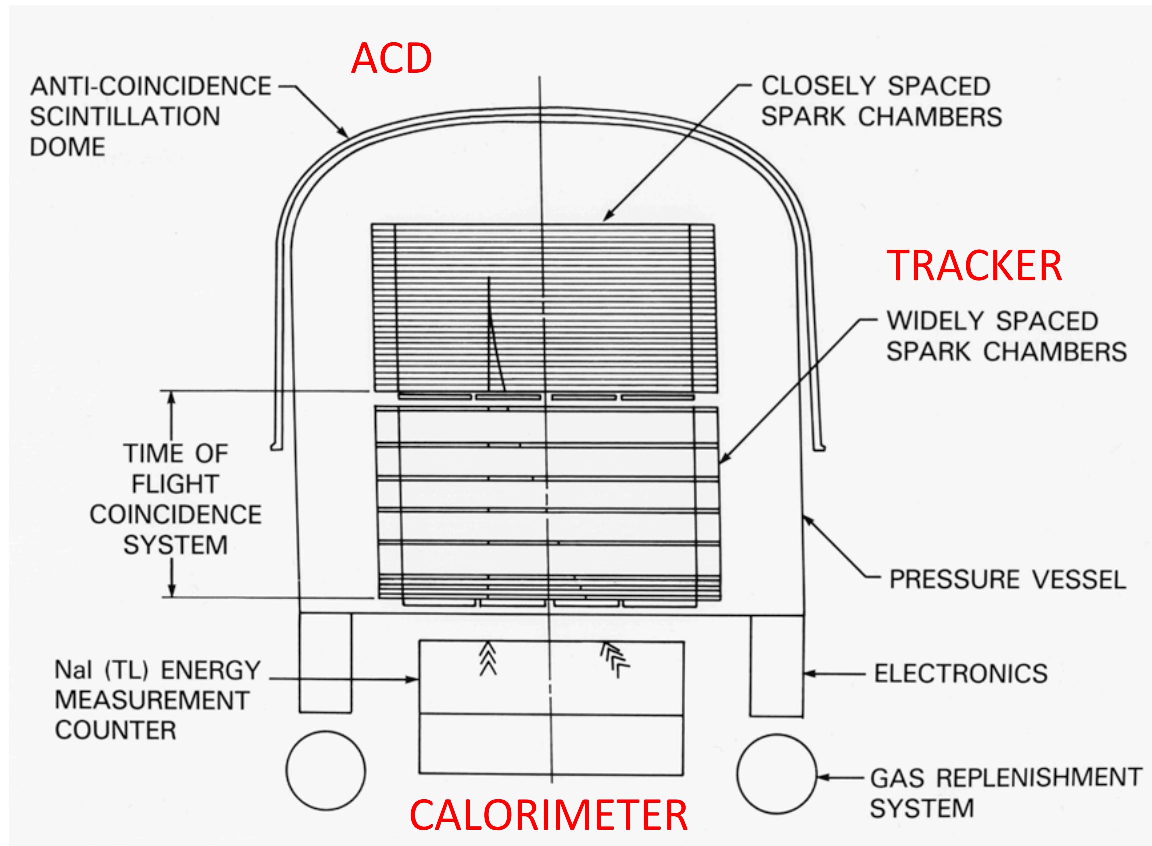
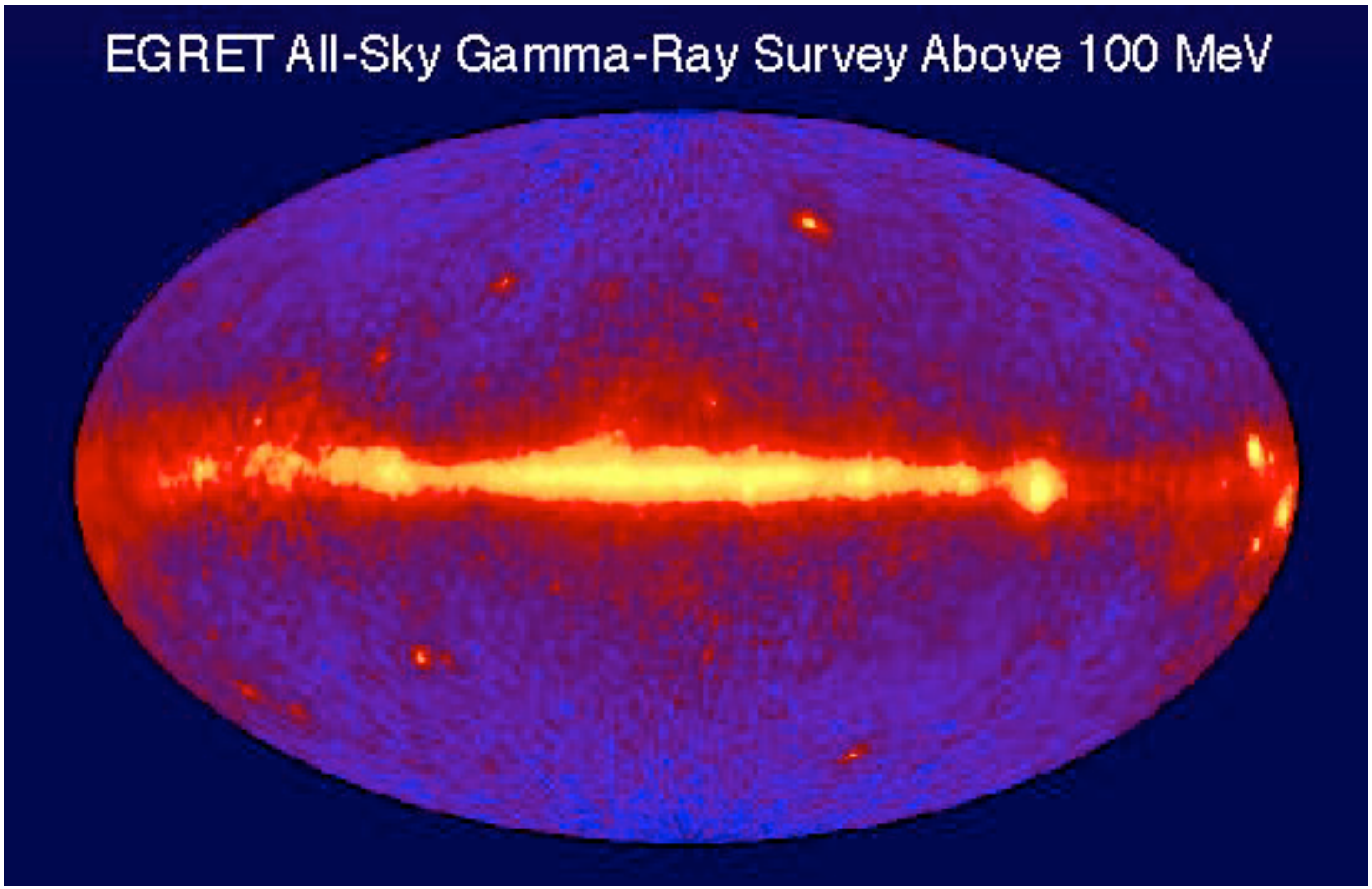


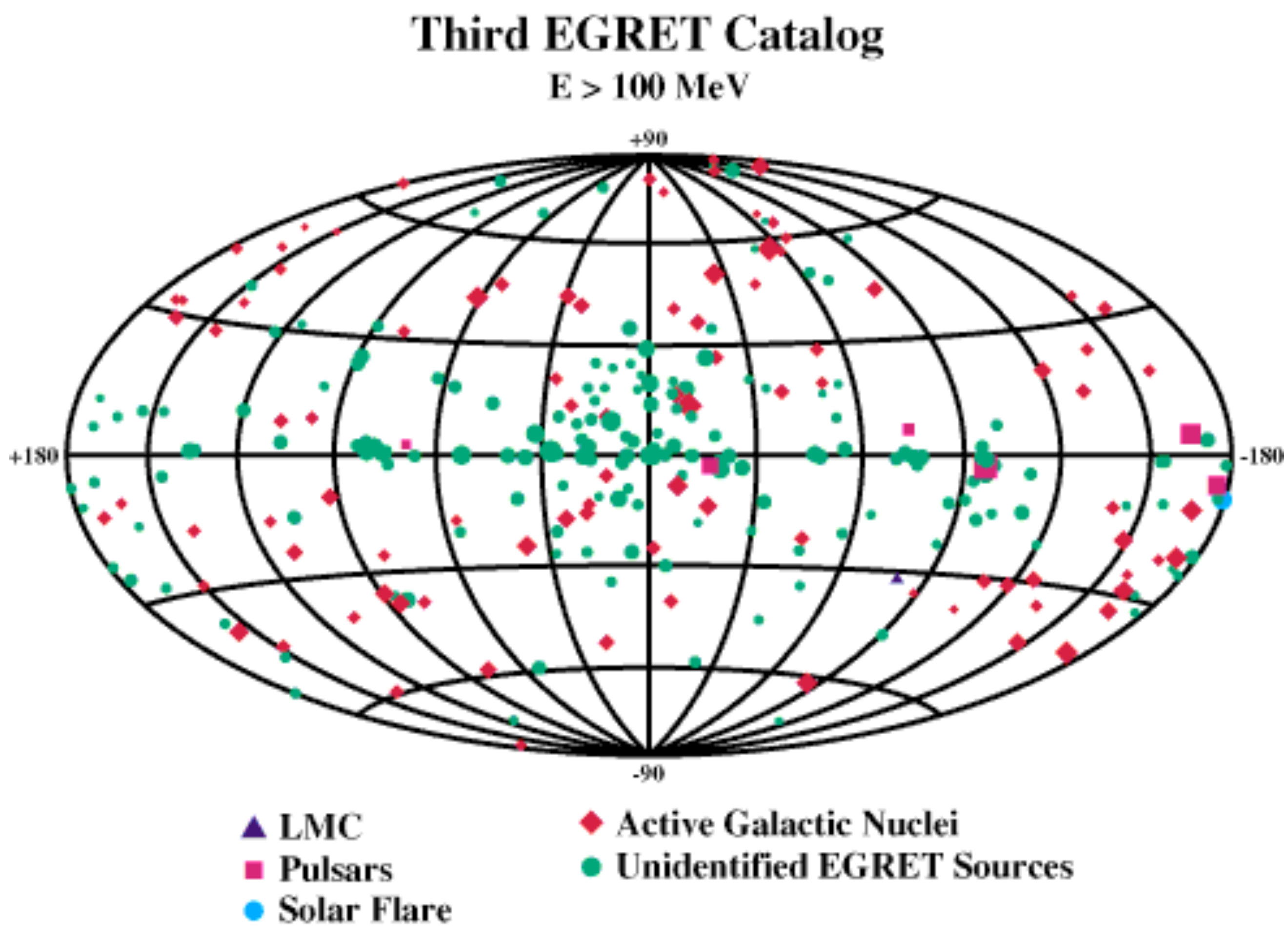
Figure IV-1. The EGRET Instrument



- Effective area ~1500 cm^2
- Field of view: 0.6 sr
- *Arrival direction accuracy* ~1-10 degree per gamma-ray
- *Source localization accuracy* ~15 arcminutes
- Sensitive from 20 MeV - 30 GeV
- Energy resolution ~10%

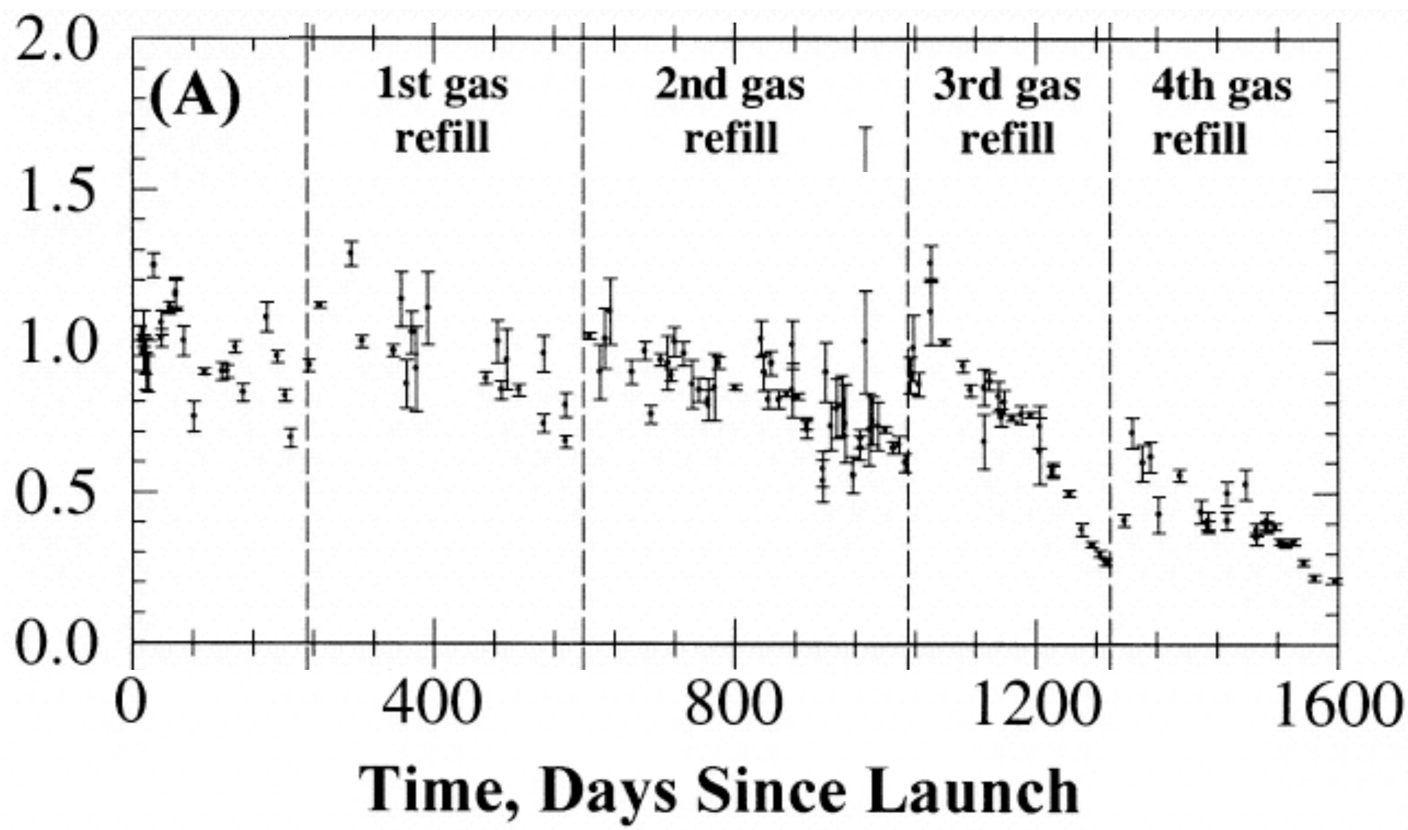


- Detected 271 sources (E > 100 MeV)
- Lots of exciting results – particularly the discovery of a large population of blazars In 2008 this was revised to 188 sources!
- '*107 former sources have not been confirmed because of the additional structure in the interstellar background*'
- Cautionary tale I: accurate modelling of the diffuse background is critical

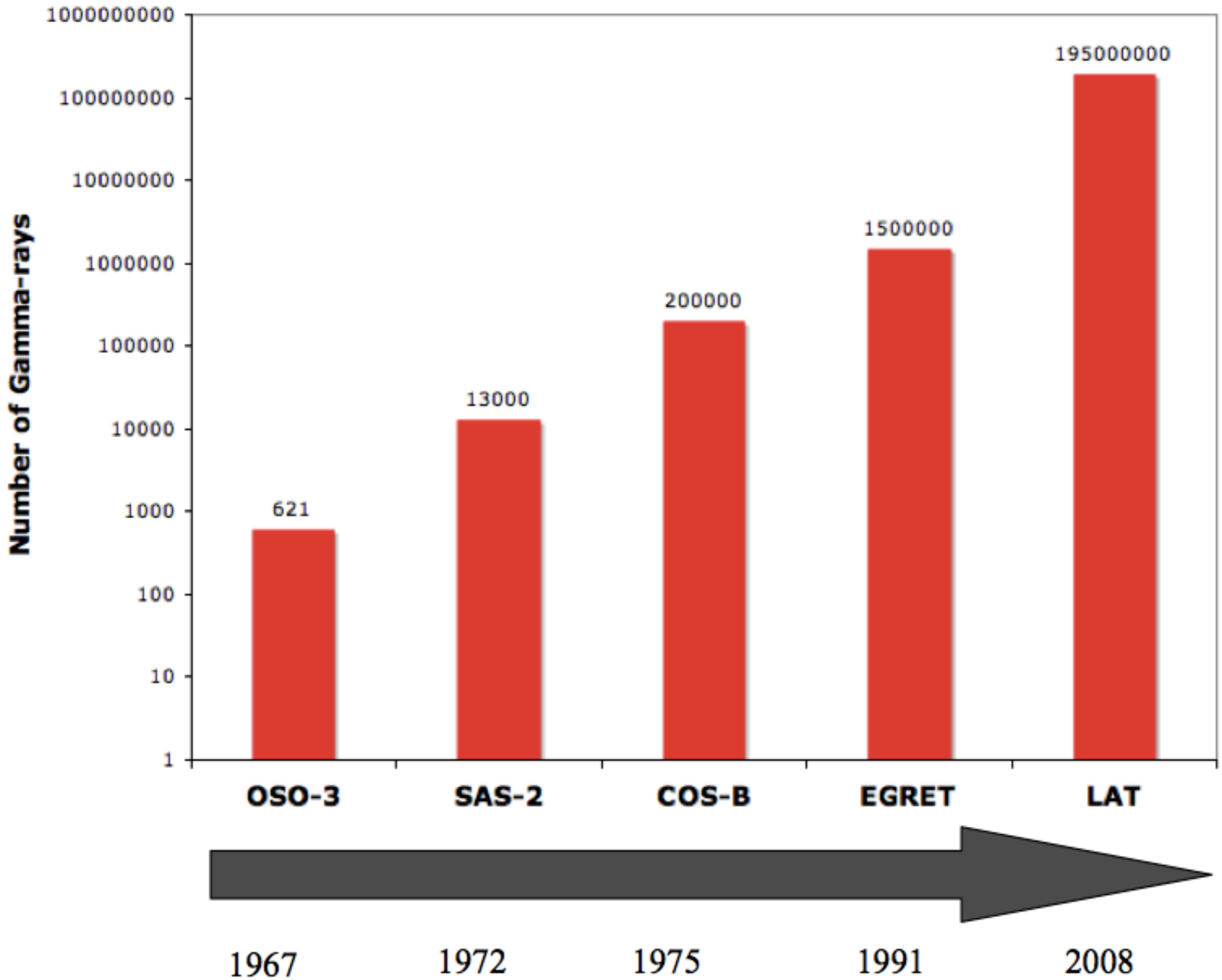


How do you improve on EGRET?

- Increase collection area (size of detector)
- Increase detection efficiency
- Increase field of view
- Improve angular resolution
- Improve energy resolution
- Increase lifetime - Remove expendables (gas)



- Fermi Gamma-ray Space Telescope (Previously GLAST)
- Launched 2008
- Two instruments (LAT & GBM)



- In 1961 Explorer XI saw 22 gamma-rays
- The LAT has now seen almost half a billion!

LAT Specifications & Performance

Quantity	LAT (Minimim Spec.)	EGRET
Energy Range	20 MeV - 300 GeV	20 MeV - 30 GeV
Peak Effective Area [1]	> 8000 cm^2	1500 cm^2
Field of View	> 2 sr	0.5 sr
Angular Resolution [2]	< 3.5° (100 MeV) < 0.15° (>10 GeV)	5.8° (100 MeV)
Energy Resolution [3]	< 10%	10%
Deadtime per Event	< 100 μs	100 ms
Source Location Determination [4]	< 0.5'	15'
Point Source Sensitivity [5]	$< 6 \times 10^{-9}\ cm^{-2}\ s^{-1}$	$\sim 10^{-7}\ cm^{-2}\ s^{-1}$

[1] After background rejection

[2] Single photon, 68% containment, on-axis

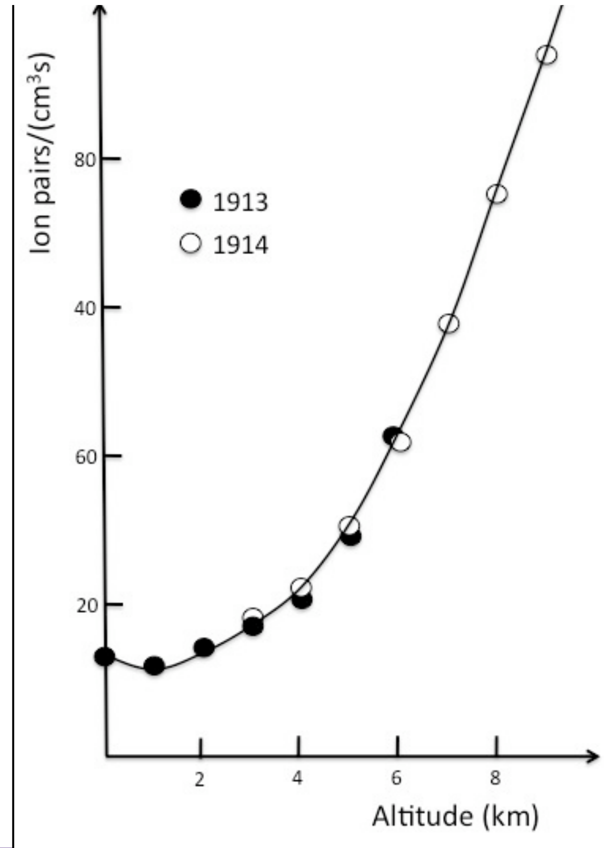
[3] 1-σ, on-axis

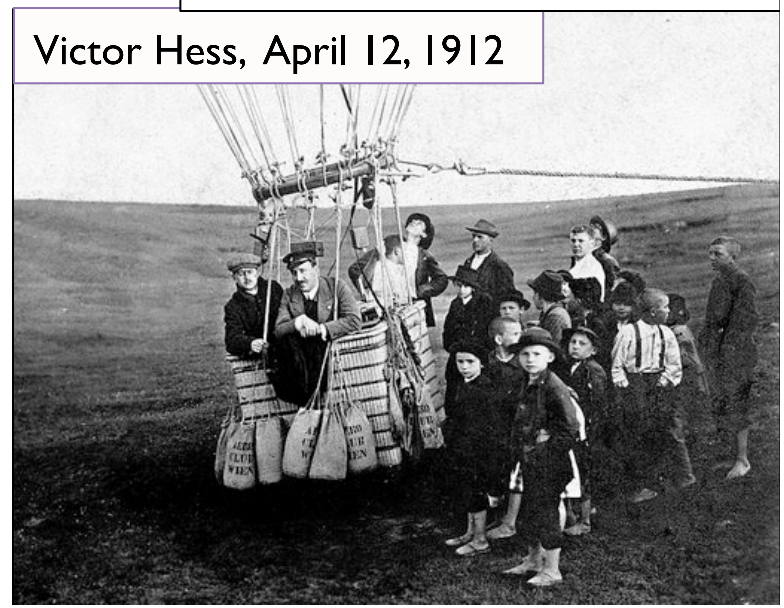
[4] 1-σ radius, flux $10^{-7}\ cm^{-2}\ s^{-1}$ (>100 MeV), high |*b*|

[5] > 100 MeV, at high |*b*|, for exposure of one-year all sky survey, photon spectral index -2

Meanwhile, back on the ground (sort of)…

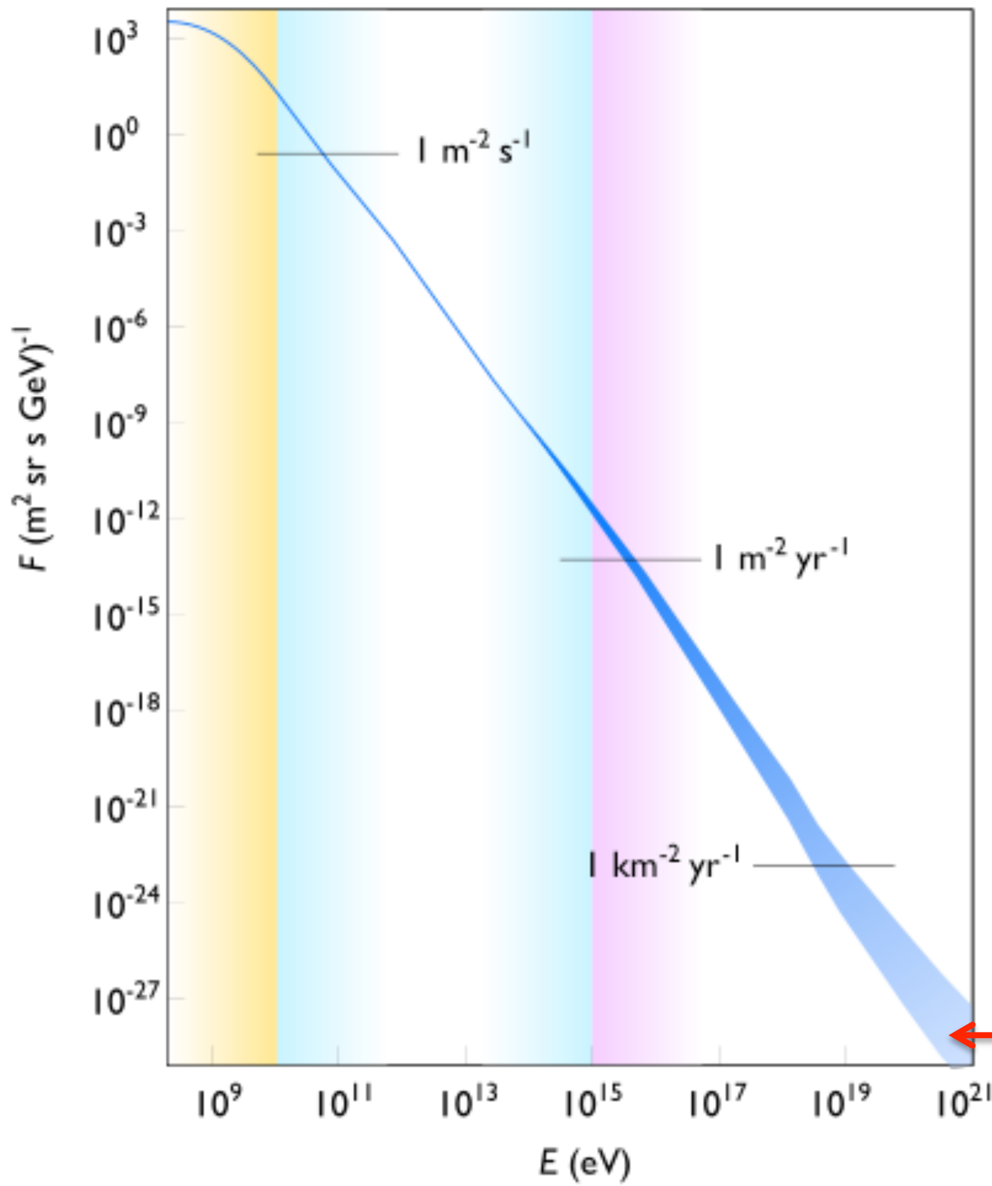
- Gamma-Ray Astrophysics is closely tied to the study of cosmic rays
  - Discovered by Victor Hess in 1912
  - Flew balloons up to 5.3 km
  - Measured the flux of ionizing radiation
  - The flux *increased* with altitude
  - The source of the radiation must be extra-terrestrial
  - Millikan later named them "cosmic rays"
  - What is their origin?





Victor Hess, April 12, 1912

Cosmic Rays After a Century of Study



Energy density: 1 eV/cm^3

Visible starlight: 0.3 eV/cm^3

B-fields: 0.25 eV/cm^3

CMB: 0.25 eV/cm^3

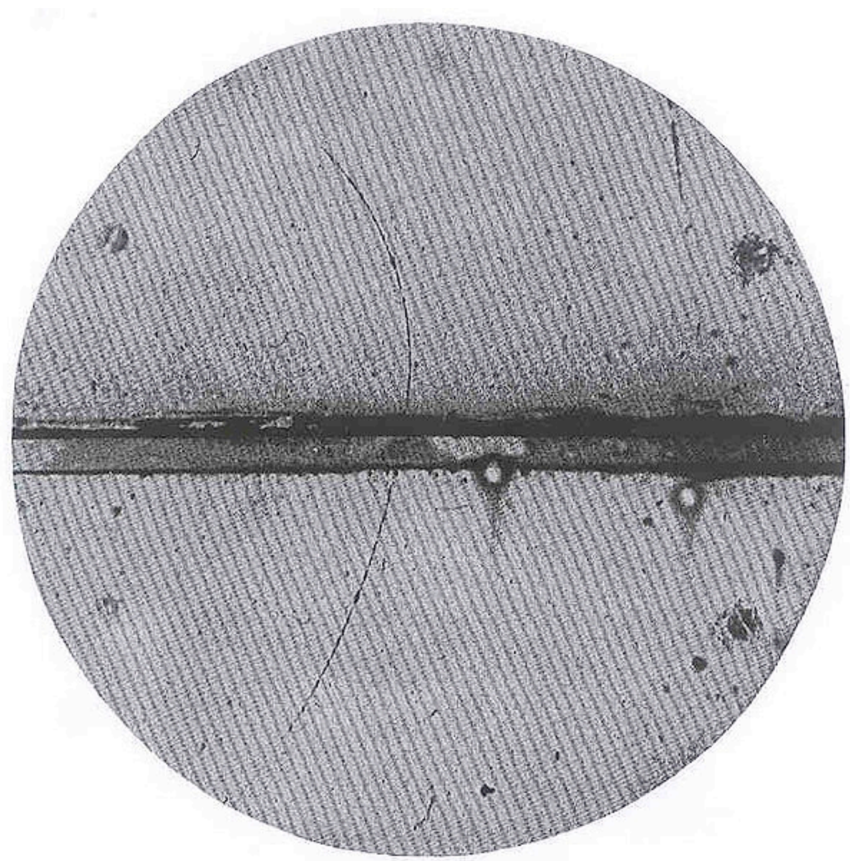
- What is their origin?

1/km^2/century

Same kinetic energy as a baseball at 60mph!

1932: The positron

- Carl Anderson used cloud chamber observations of cosmic rays to discover the positron (predicted four years earlier by Dirac)
- First antimatter particle
- He and Hess shared the 1936 Nobel Prize



THE APPARENT EXISTENCE OF EASILY DEFLECTABLE POSITIVES

UP to the present a positive electron has always been found with an associated mass 1,850 times that associated with the negative electron. In measuring the energies of charged particles produced by cosmic rays some tracks have recently been found which seem to be produced by positive particles, but if so the masses of these particles must be small compared to the mass of the proton. The evidence for this statement is found in several photographs, three of which are discussed below.

1933:Pair creation

- P.M.S. Blackett refined the technique and discovered electron-positron pair creation and annihilation.
- First direct evidence of matter – energy conversion
- Another Nobel (1948)
- Cosmic rays also led to the detection of μ's (1936), π's(1947), K, Λ, Σ, Ξ, before accelerators developed to the point where they could compete.

Some Photographs of the Tracks of Penetrating Radiation.

By P. M. S. Blackett and G. P. S. Occhialini, The Cavendish Laboratory, Cambridge University.

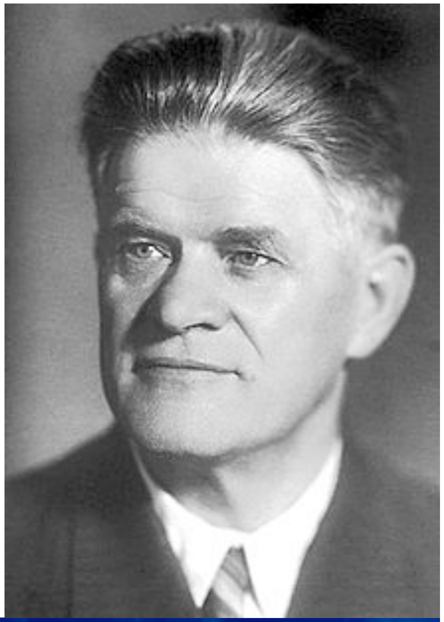
(Communicated by Lord Rutherford, O.M., F.R.S.—Received February 7, 1933.)

[Plates 21-24.]

1. *The Experimental Method.*

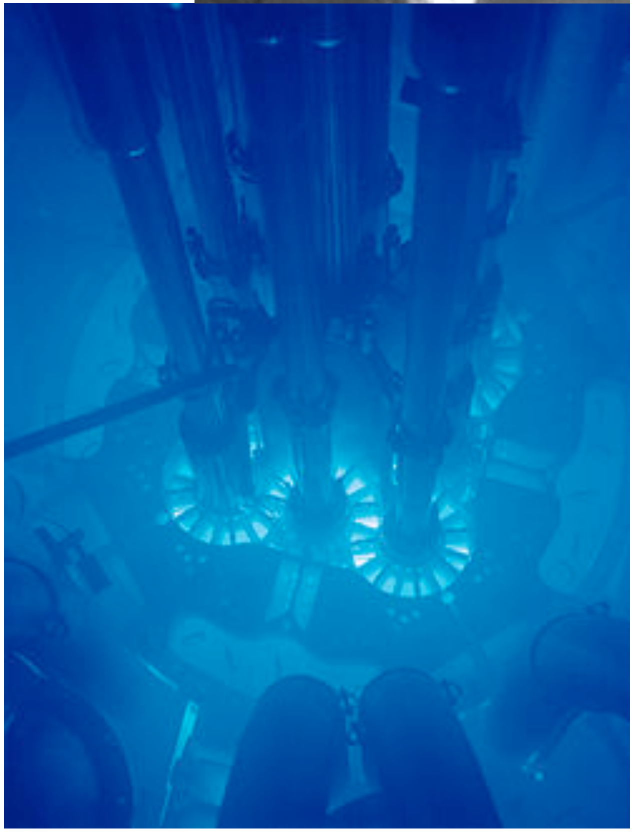
We have recently developed a method by which the high speed particles associated with penetrating radiation can be made to take their own cloud photographs.* By this means it is possible to obtain these photographs very much more speedily than by the usual method of making expansions at random.

1934: Cherenkov Radiation

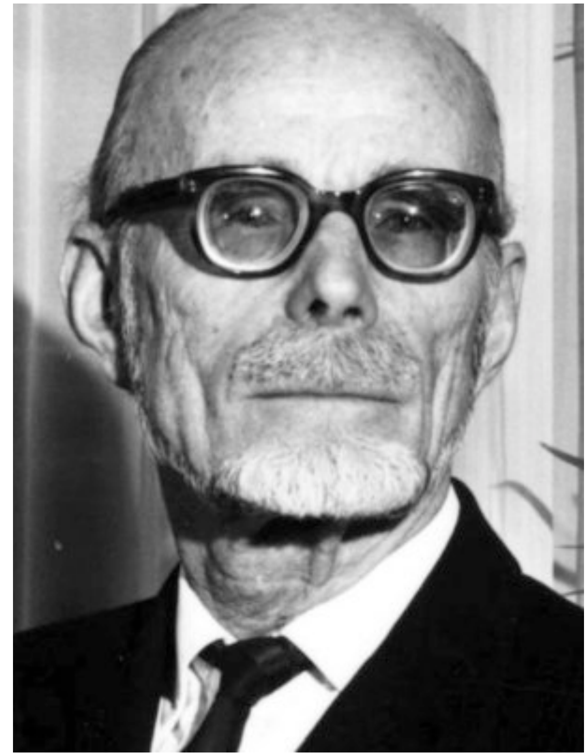


- Pavel Cherenkov studied the blue light produced by transparent substances close to radioactive sources (noted by Curie in 1910)
- Its properties matched the theory of Frank and Tamm, who explained the emission as due to charged particles moving faster than the speed of light in the substance (c/n)
- Nobel (1958)

- *"When considering the glorious development of the Cherenkov technique in experimental physics, I imagine a young and enthusiastic fellow who for several years started his working day by spending an hour in a totally dark room to prepare his eyes to observe faint light and who scrupulously repeated the observations again and again, varying the liquids and the geometries of the experiment, trying to find the clue to the nature of the puzzling radiation that now bears his name."*



1938: Air Showers



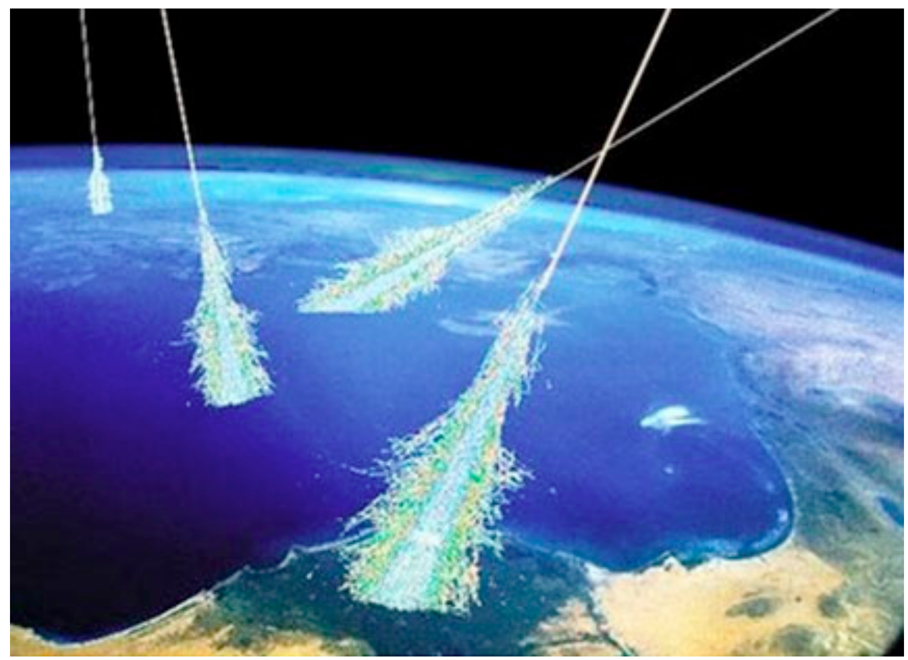
- Pierre Auger discovered that multiple cosmic rays at the ground could be coincident in time but separated by hundreds of meters
- Implies that they result from a single event
- “Particle Cascades” or “Air Showers”

Extensive Cosmic-Ray Showers

Pierre Auger
In collaboration with
P. Ehrenfest, R. Maze, J. Daudin, Robley, A. Fréon
Paris, France

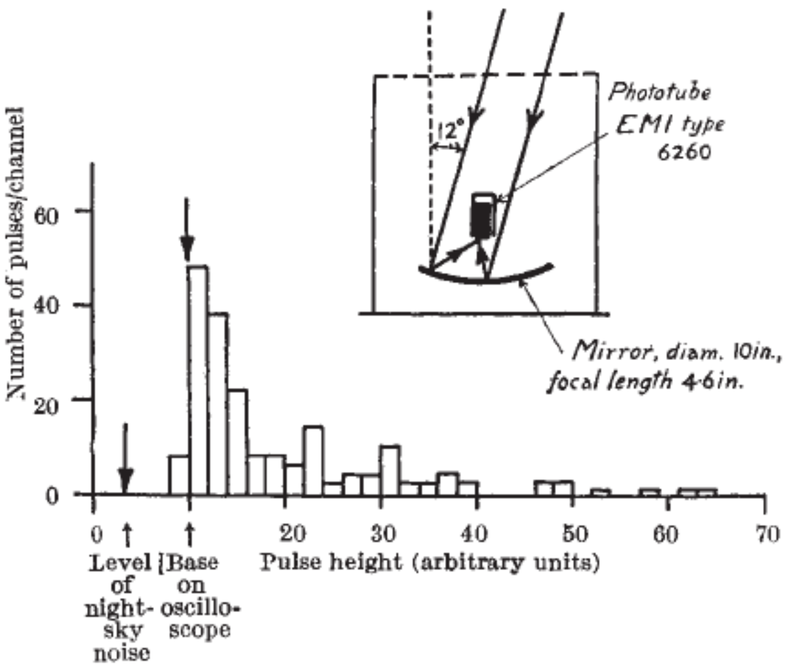
Long Distance Coincidences

If two or three counters are arranged in coincidence in free air, a small number of coincidences is observable, due to “air showers” and this number decreases quickly when the horizontal distance of the counters is increased.



1953: Cherenkov radiation from Air Showers

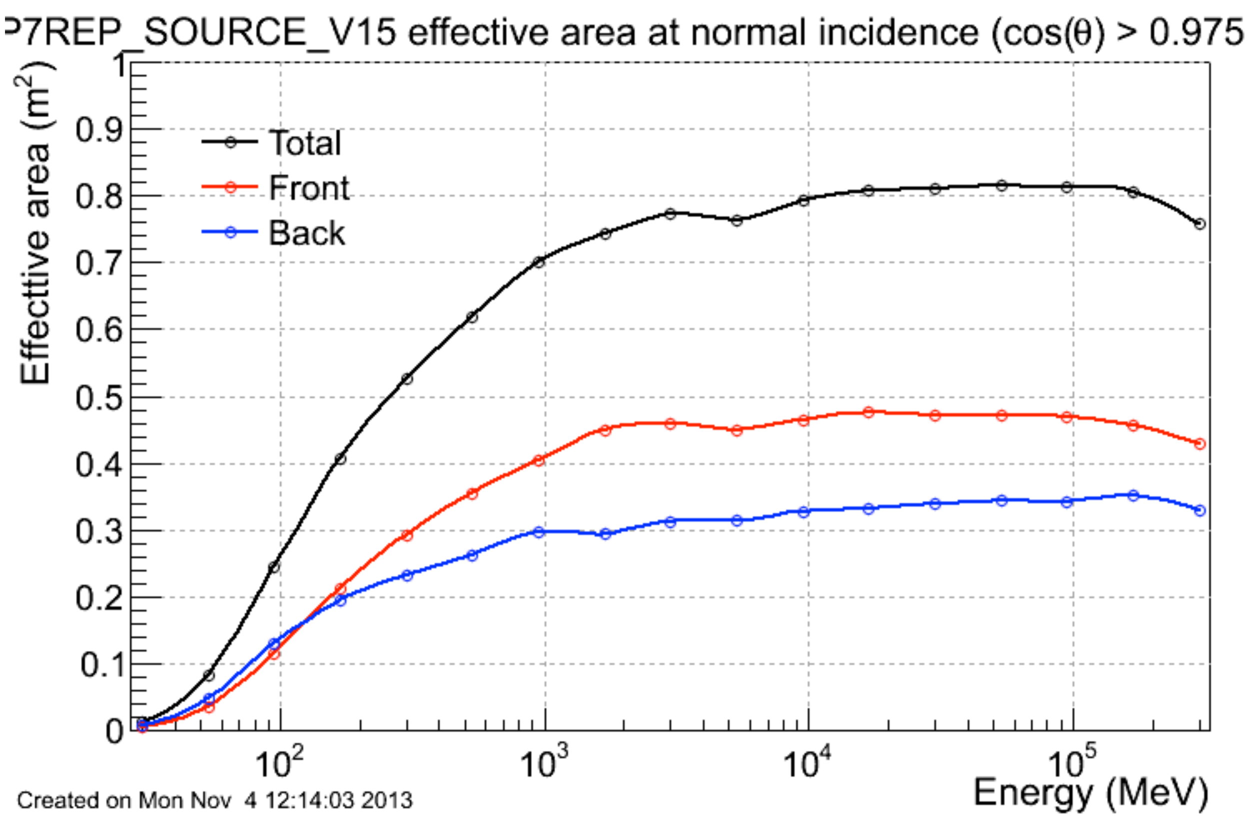
- Blackett first realized that cosmic rays would produce Cherenkov radiation in the atmosphere
- He calculated that 1/10000th of the night sky light should be due to this, but…
- *"presumably such a small intensity of light could not be detected by normal methods"*
- Inspired Jelley and Galbraith to look for Cherenkov flashes associated with Air Showers



The Jelley & Galbraith light bucket (1952)

This could be important for higher energies…

- Satellite effective area < $1m^2$
  - Effective area = trigger probability × actual area
  - Energy dependant
- e.g. Crab Nebula, Integral flux >1TeV = $6/m^2$/year
- Need to increase the effective area…



What happens when a very high energy gamma-ray enters the atmosphere?

Maybe a good point to stop…?