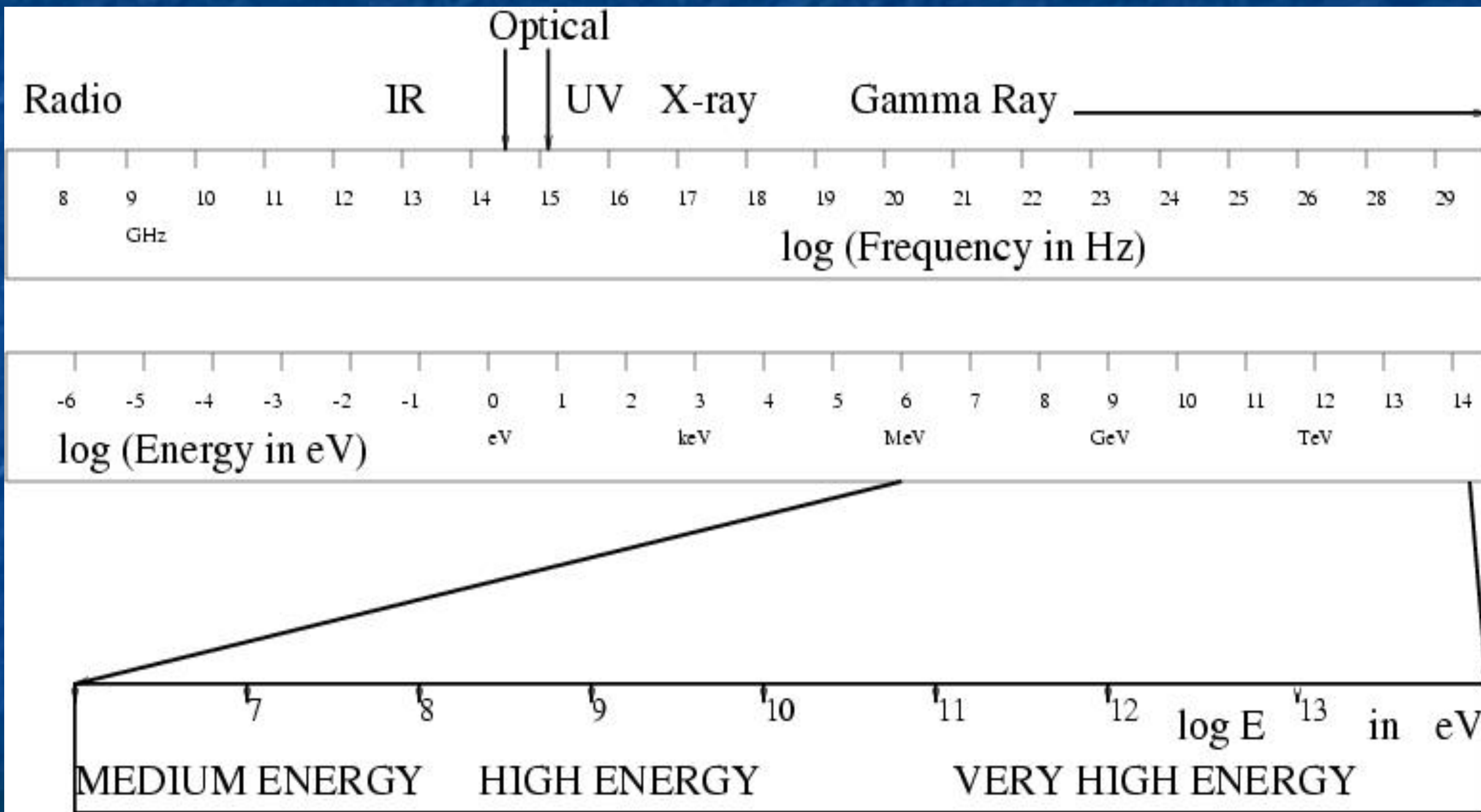
Very High Energy Gamma Ray Astronomy 101

Trevor Weekes

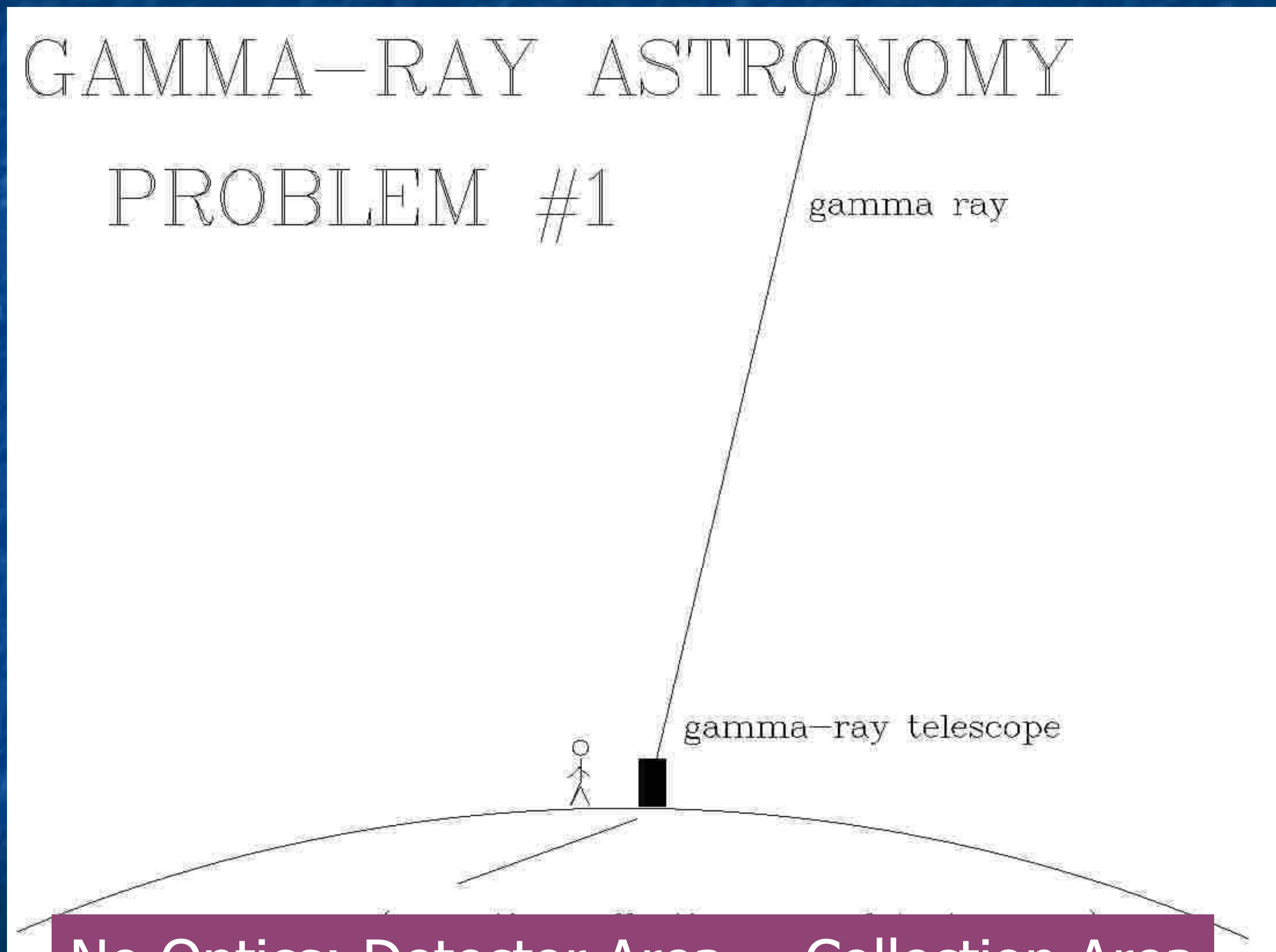
Harvard-Smithsonian Center for Astrophysics

The Electromagnetic Spectrum

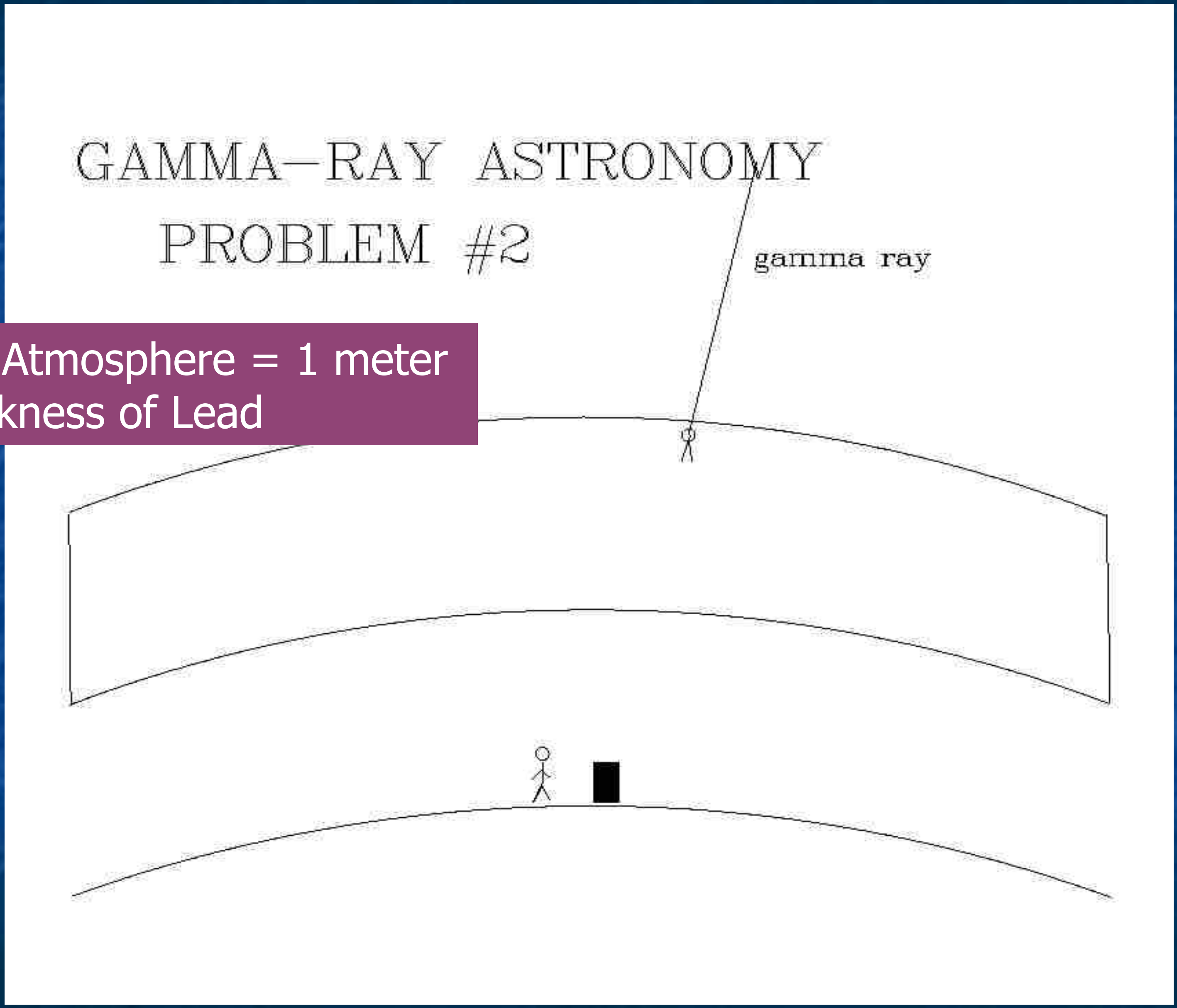


"Gamma Ray" : generic terrm that covers half the electromagnetic spectrum

Gamma-ray Astronomers Have Two Big Problems

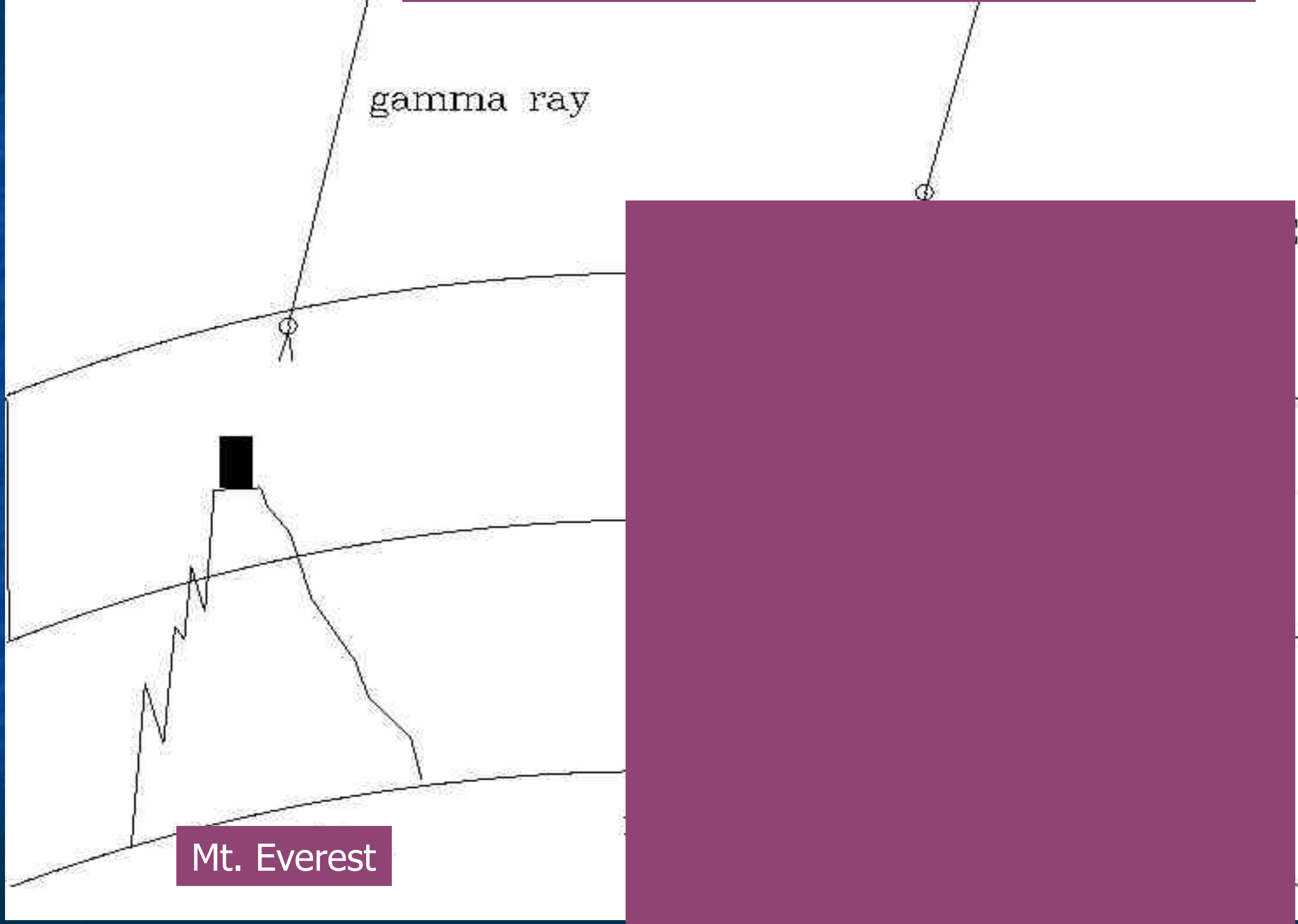


No Optics: Detector Area = Collection Area

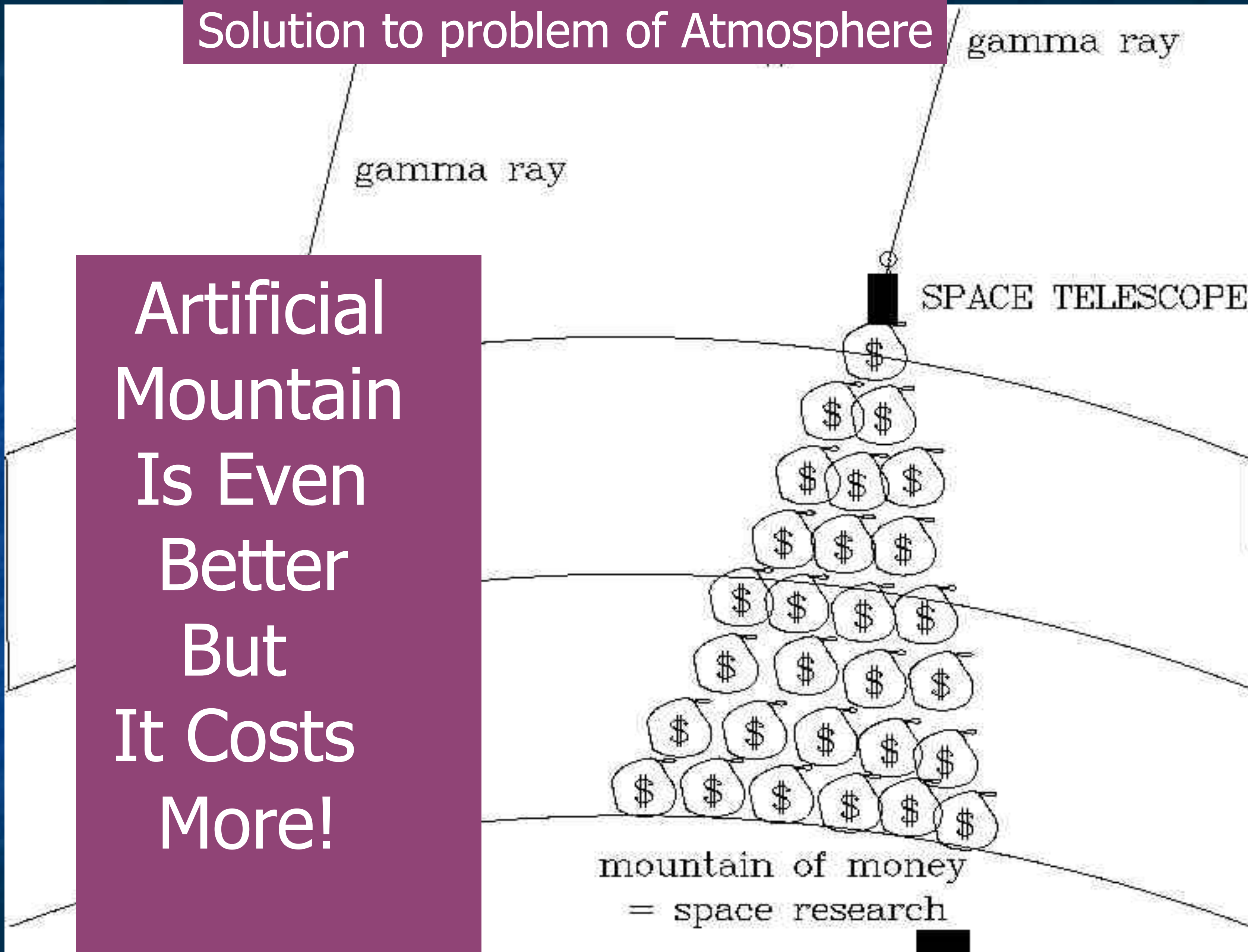


The Atmosphere = 1 meter Thickness of Lead

Solution to problem of Atmosphere



Solution to problem of Atmosphere



Artificial Mountain Is Even Better But It Costs More!

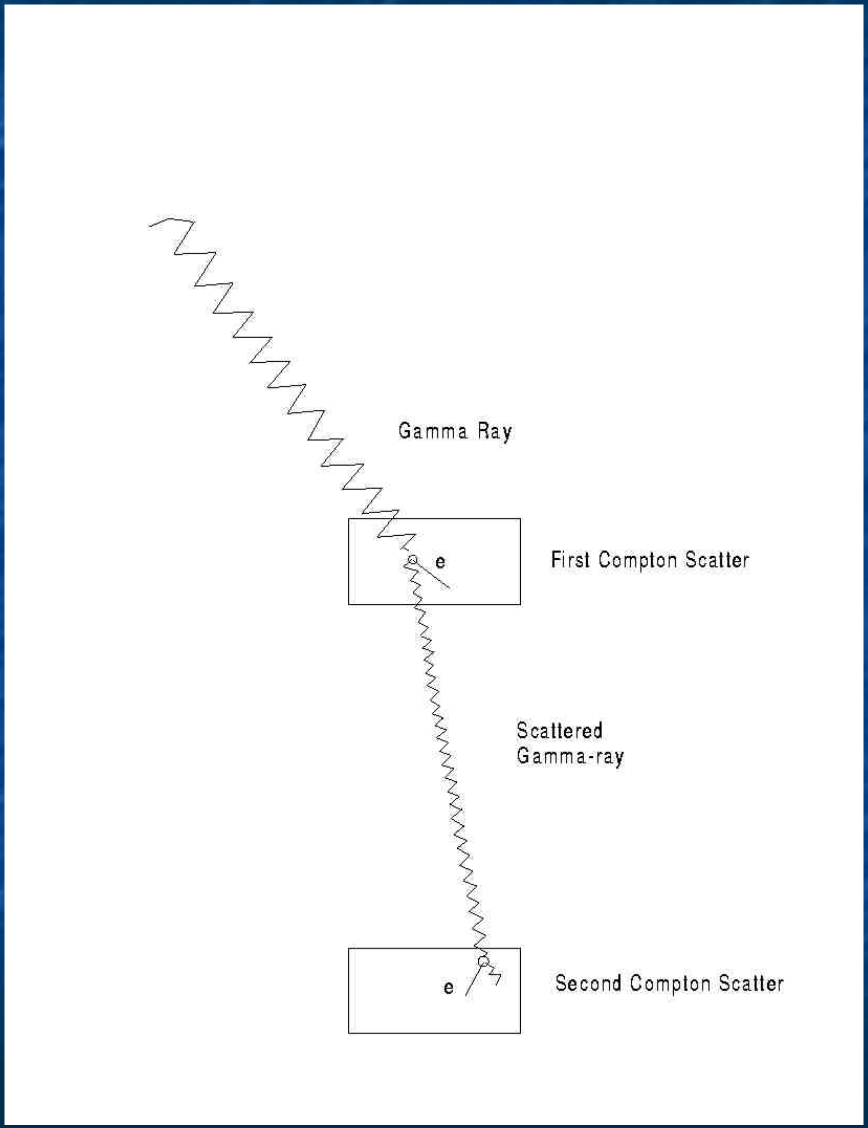
Earth's Atmosphere: Enemy of Astronomy

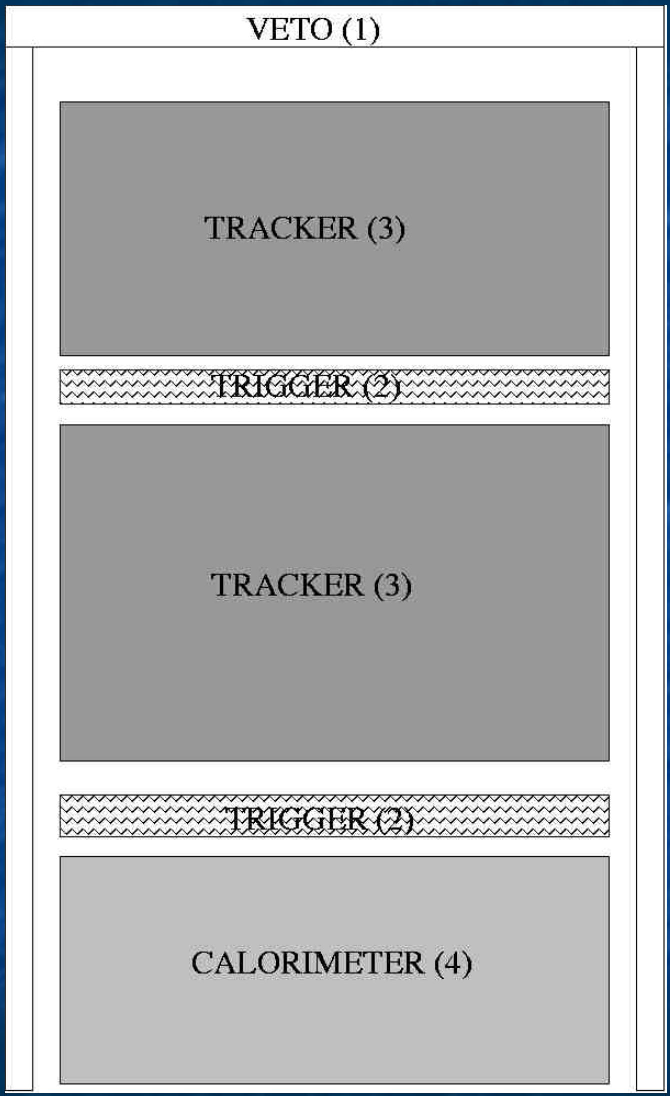
- Over most of the Electromagnetic Spectrum the Atmosphere limits observations
- Thickness ~ 1030 g cm^-2
- Equivalent to 1 m of Lead
- 28 Radiation Lengths
- No primaries > 10 eV reaching Earth's Surface
- UV, X-ray, Gamma-ray Astronomy required the development of Space Techniques
- …but not ground-based gamma-ray astronomy!

Short History of High Gamma-ray Astronomy from Space

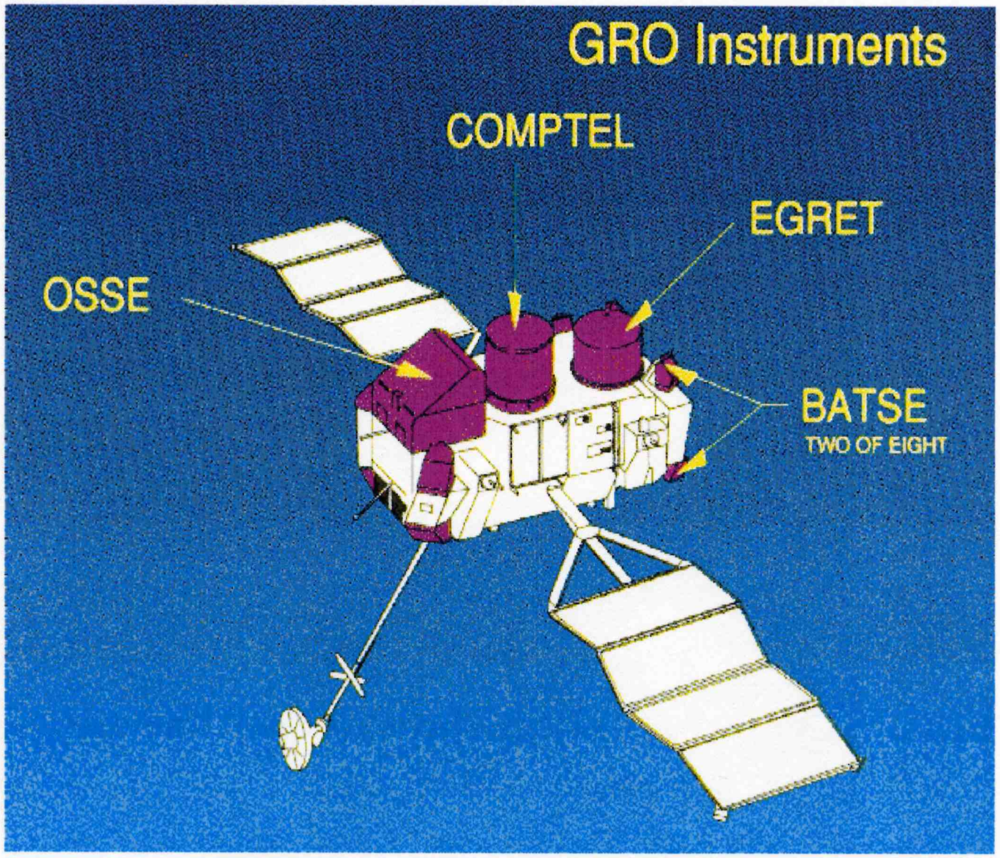
Balloon Gamma-ray Astronomy 1960-1972
Spark Chambers, Gas Cherenkov
Dark Ages . Many “sources”
Galactic Plane
Crab
Satellites:

OSO-3	1968	USA	scintillator+
SAS-2.	1973	USA	Spark Chamber
COS-B	1975-82	European	Spark Chamber
EGRET	1991-2000	Joint	Spark Chamber
AGILE	2007-	Italian	Silicon Strip
Fermi	2008-	USA+	Silicon Strip


Gamma Ray
e
First Compton Scatter
Scattered
Gamma-ray
e
Second Compton Scatter

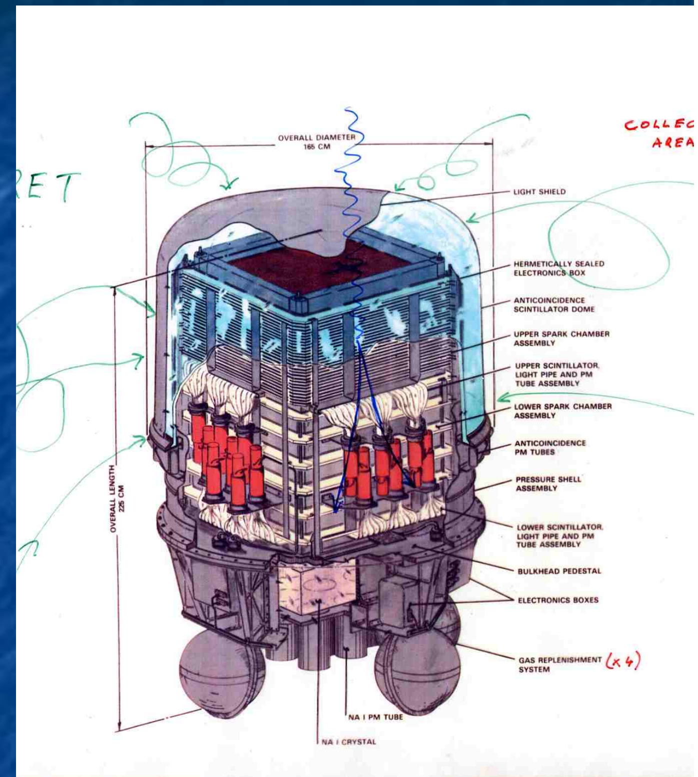

VETO (1)
TRACKER (3)
TRIGGER (2)
TRACKER (3)
TRIGGER (2)
CALORIMETER (4)

Compton Gamma Ray Observatory



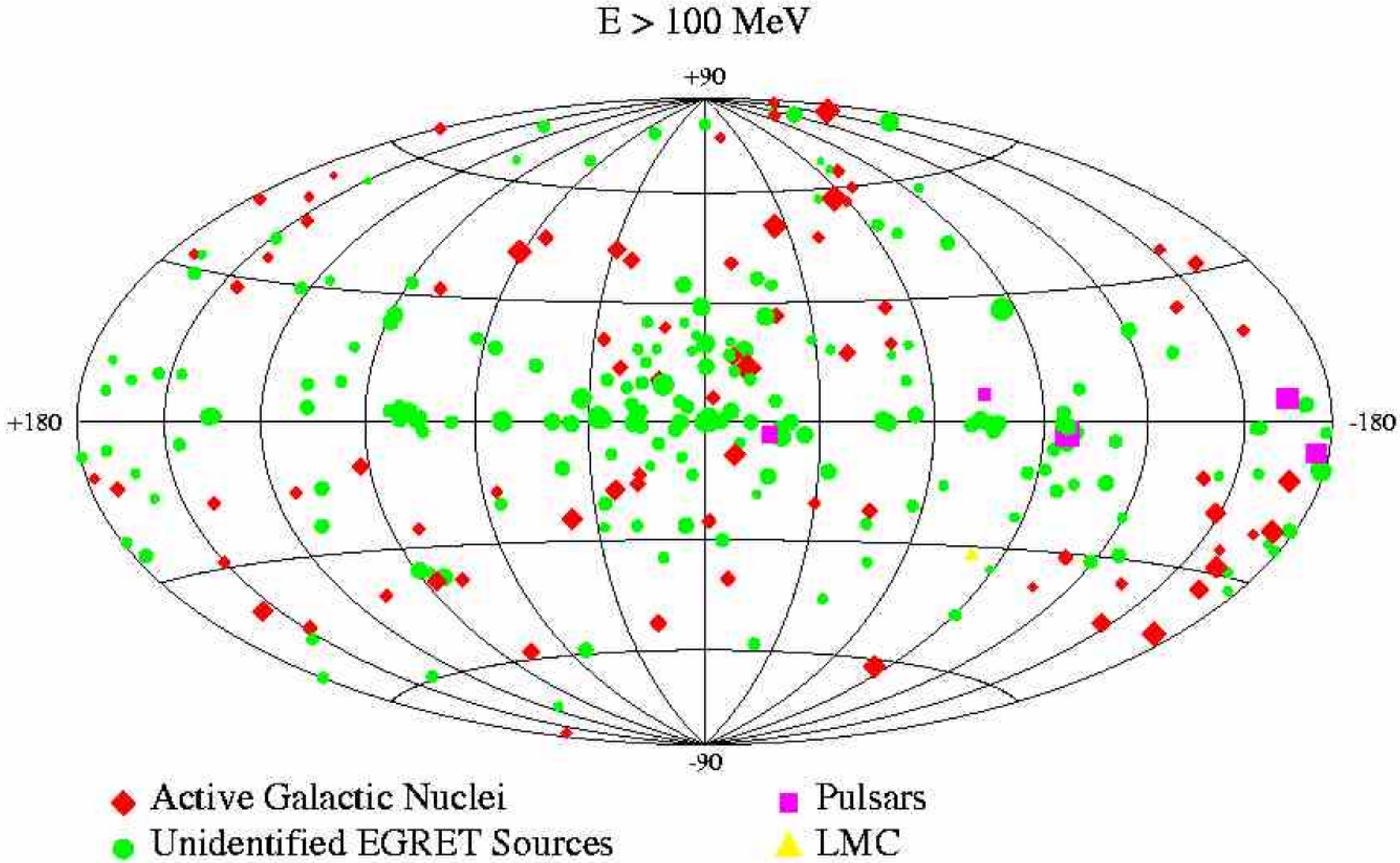
Very Successful Mission 1991-2000

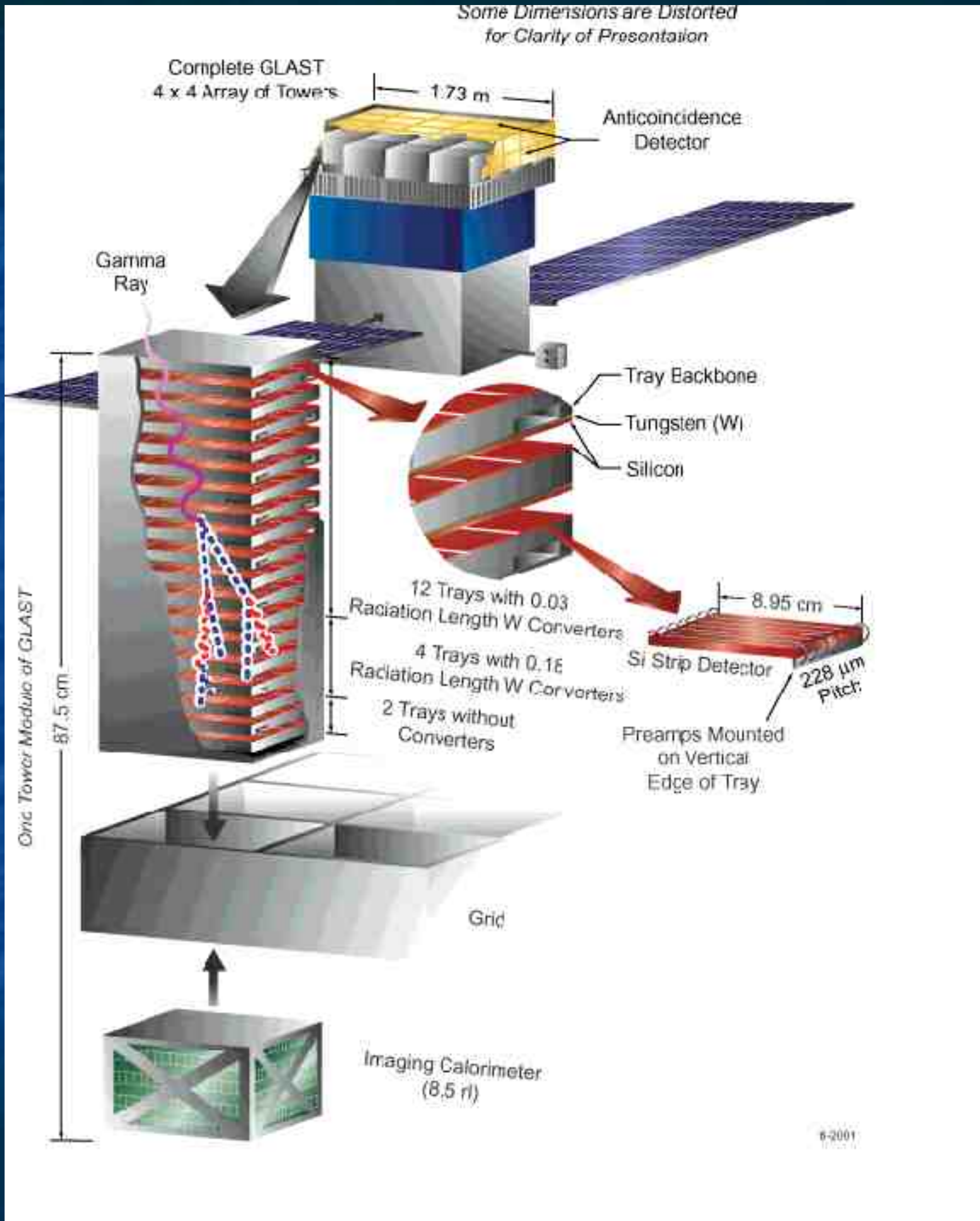
- *First Maps of Relativistic Universe*



EGRET

Third EGRET Catalog





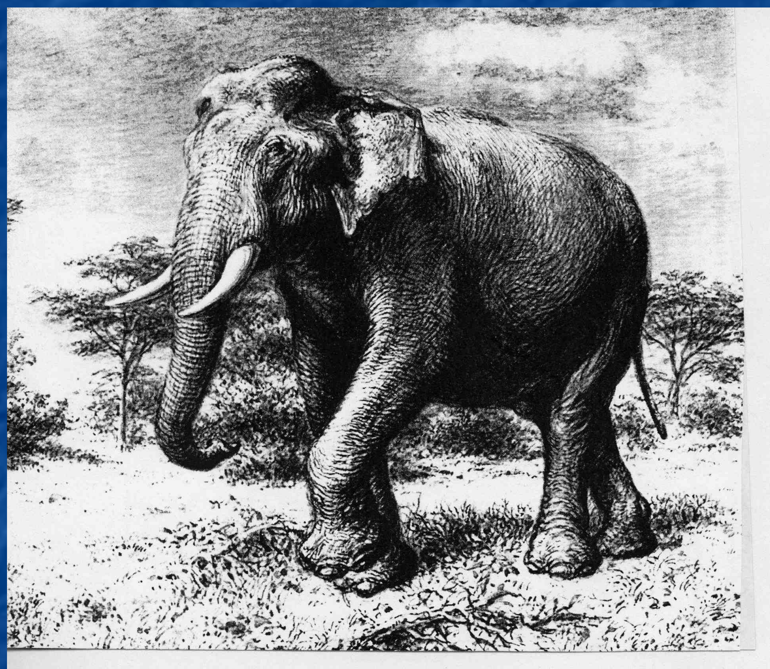
GLAST:
the Next Generation Gamma-ray Space Telescope.
2007

Table 3.1. Comparison of EGRET and GLAST. (Fermi)

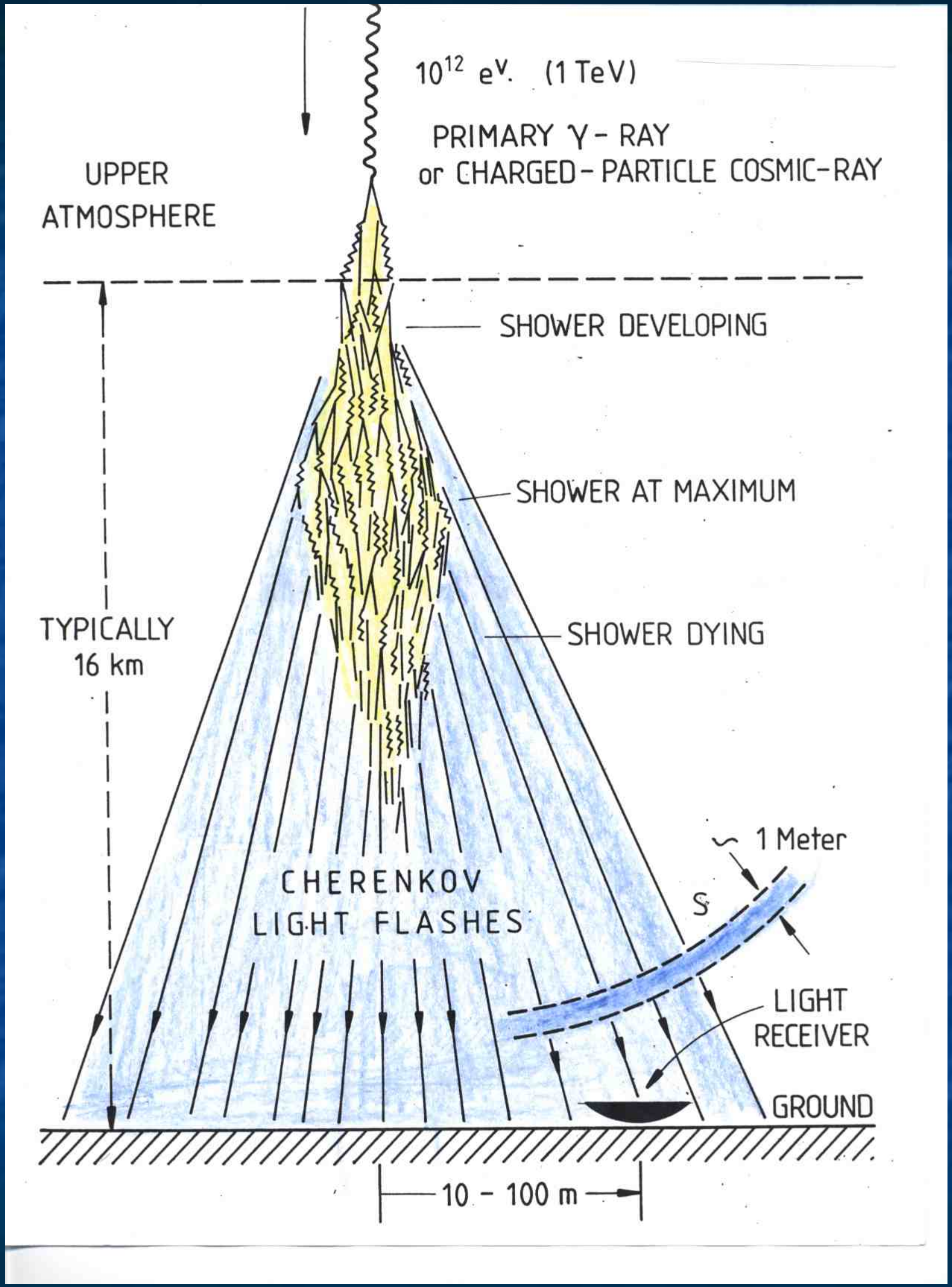
Parameter	Units	EGRET (achieved)	GLAST (desired)
Energy range	MeV	20–30 000	20–300 000
Effective area	cm^2	1500	>8000
Field of view	sr	0.5	>2
Angular resolution	(100 MeV) degrees	5.8	3.5
	(>10 GeV) degrees		<0.15
Energy resolution	%	10	10
Source sensitivity	(>100 MeV)	10^{-7}	
	$cm^{-2}\ s^{-1}$	1	0.06

Why study TeV Gamma rays?

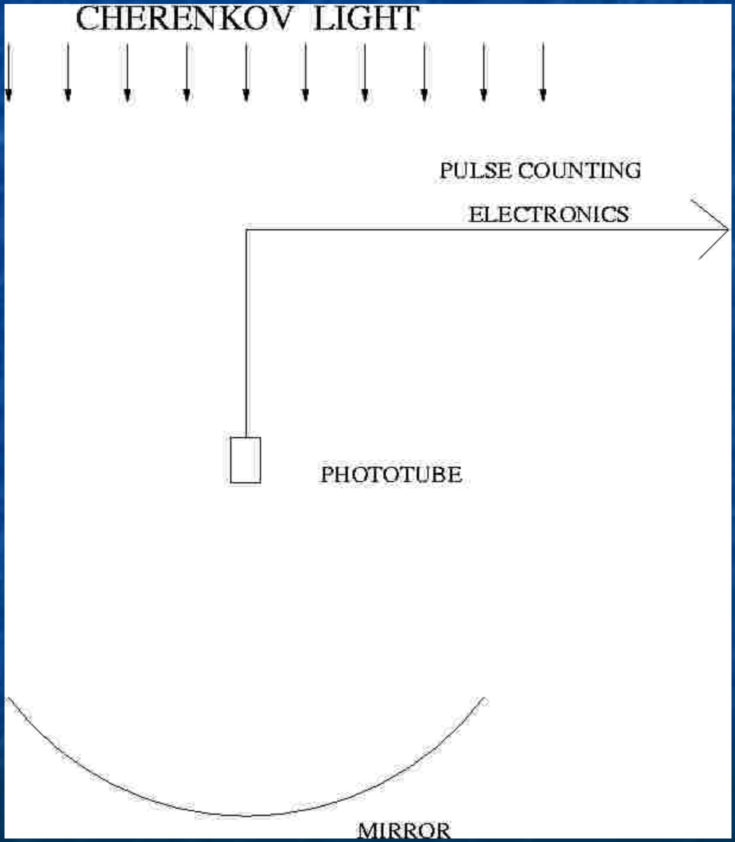
Why do we study elephants when birds are easier to find and more plentiful?



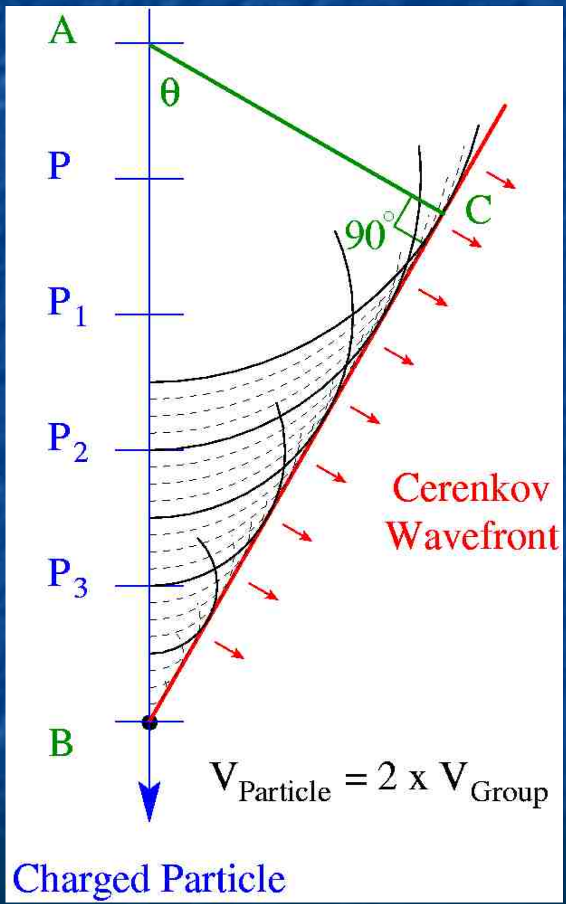
TeV gamma-rays, like elephants, are bigger, more difficult to produce, and stretch the the production models to their limits!

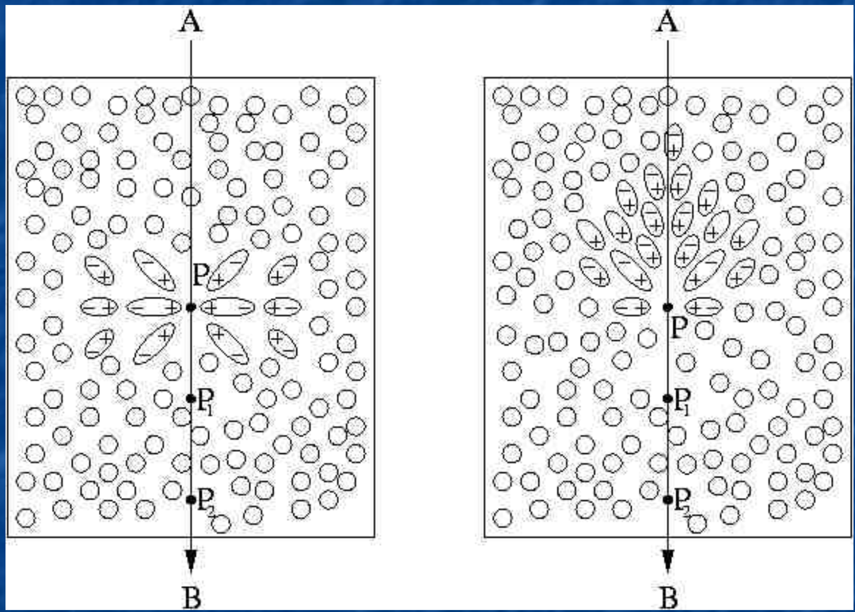


Simple Technique, Simple Detectors, Small Budgets



Cherenkov Radiation





The medium is the radiator, not the particle!

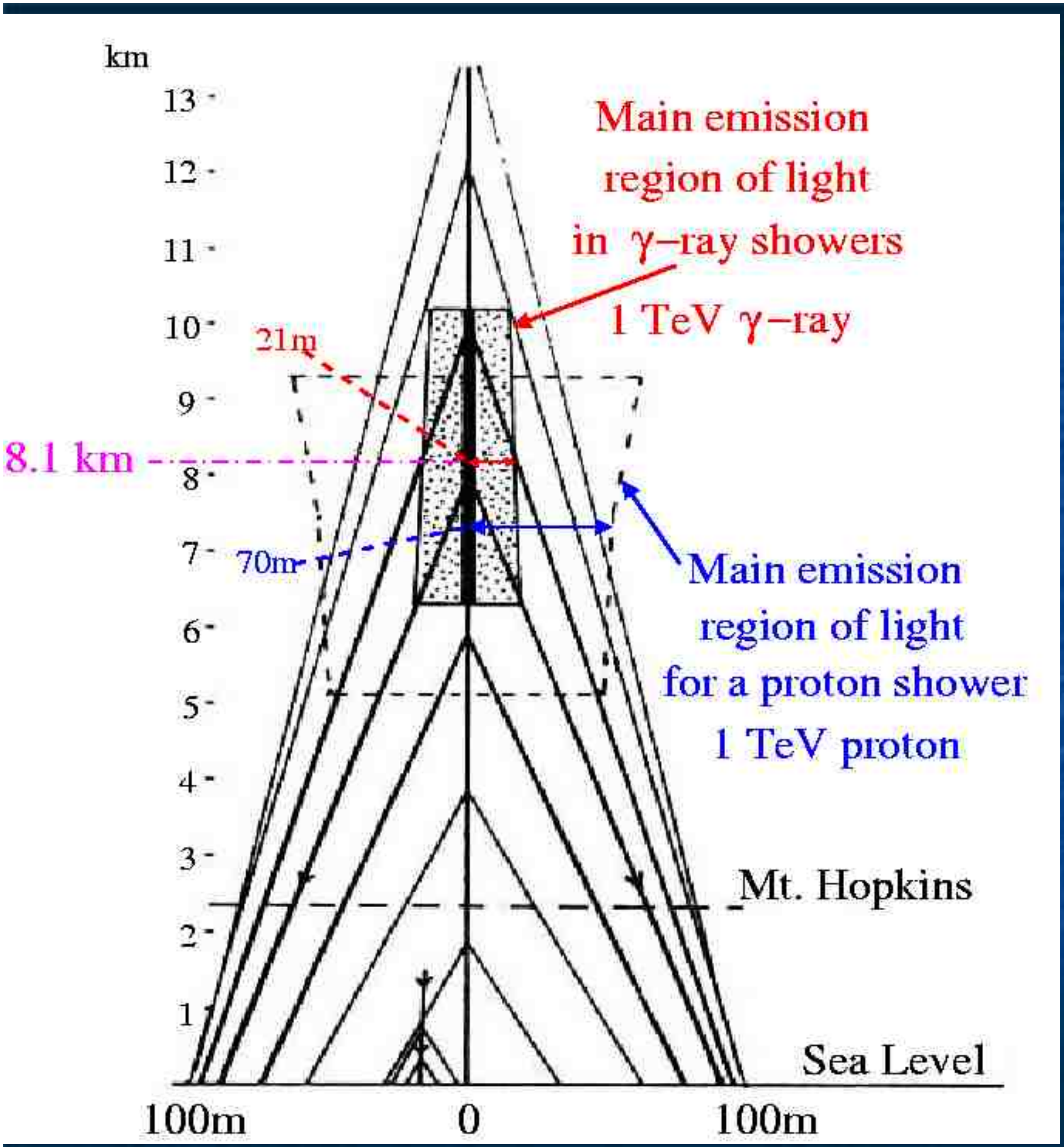
Earth's Atmosphere: Friend of VHE Astronomy

- The Atmosphere makes VHE observations possible
- Essential ingredient of detection technique
- Free and limitless; nothing to replenish!
- The Poor Man's detection medium
- But……
- No control over temperature, pressure and humidity
- No control over transmission
- Source of variable background light: air glow, lightning, meteor burnup
- Must be carefully monitored

Cherenkov Light Shower from a Gamma-ray Cascade

- First Interaction typically at elevation of 20 km
- Electromagnetic Cascade starting with electron pair;
- Opening angle ~ mc^2/E
- Cherenkov light from relativistic electrons > 21 MeV
- Typical 1 TeV shower (Hillas 1993):
- Physics well understood; detailed Monte Carlo calculations

- Three parts:
- 1. Above 10 km; Cher. Angle ~ 0.8 deg.; 25% of light generated (direction)
- 2. Intermediate 10 – 6 km; Shower Maximum: cylinder of length 4km, radius 21 m; 50% of light (energy)
- 3. Below 6 km; local particles; 25%; confusing with large fluctuations
- Detector Level: disk of light with diameter 120 m, 1 m (2-3 ns) thick
- Note: from 100 GeV primary, typical photon density in blue light is about 5 photons/m^2 out to 120 m from axis; detectable with collector of aperture a few m^2 and fast PMT



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m axis; detectable with collector of aperture a few m^2 and fast PMT

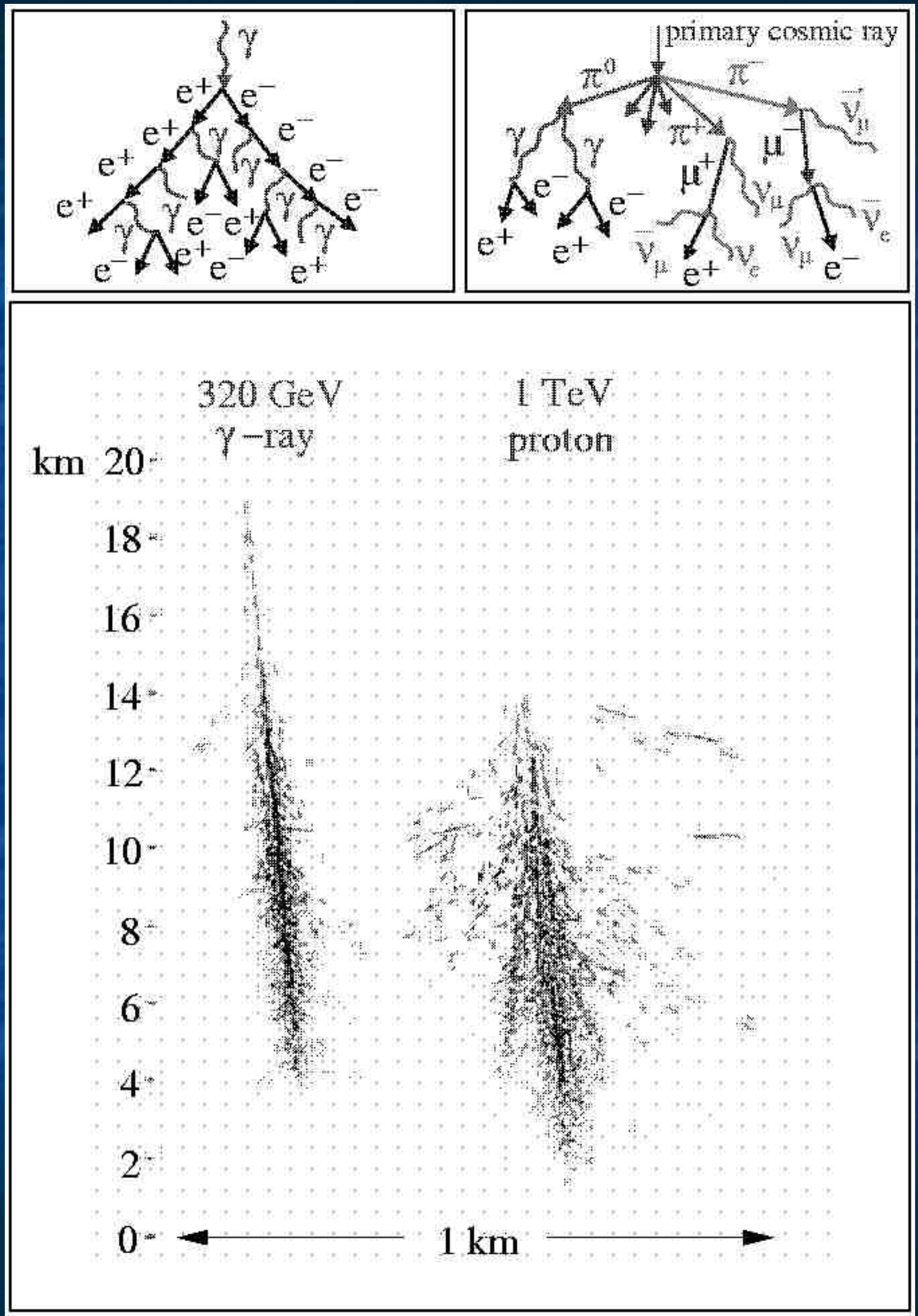
Gamma-ray Shower Characteristics as a Function of Energy

Table 2.1. Gamma-ray shower parameters as a function of energy [11].

Energy, E_γ	X_{max} (g cm^{-2})	h_{max} (km)	N_{max}	N_{sl}	N_{mt}	ρ_{sl} (photon m^{-2})	ρ_{mt} (photon m^{-2})
10 GeV	175	12.8	1.6×10^1	4×10^{-4}	2×10^{-2}	2.7×10^{-1}	3.6×10^{-1}
100 GeV	261	10.3	1.3×10^2	4.0×10^{-2}	1.4×10^0	4.6×10^0	7.6×10^0
1 TeV	346	8.4	1.1×10^3	3×10^0	6.0×10^1	7.4×10^1	1.3×10^2
10 TeV	431	6.8	1.0×10^4	1.3×10^2	1.7×10^3	1.1×10^3	1.7×10^3
100 TeV	517	5.5	9.3×10^4	4.5×10^3	3.6×10^4	1.6×10^4	1.9×10^4
1 PeV	602	4.4	8.6×10^5	1.15×10^5	5.7×10^5	1.9×10^5	1.9×10^5

The Cherenkov Light Shower from a Hadron-initiated Cascade

- Penetrates further into atmosphere; radiation length typically 80 g-cm^-2
- Hadronic Cascade starting with pion production
- Opening angle ~ mc^2/E; more diffuse
- Penetrating Particles, mostly muons, reach ground level
- Fluctuations are greater
- Cherenkov light from relativistic electrons (> 21 MeV) and muons (>8 GeV)
- For same primary energy, Cherenkov light production from hadron shower is a factor of 2-3 times less efficient than from gamma-ray shower
- Hadrons are 1,000 to 10,000 times more numerous than fluxes of gamma rays from typical VHE source
- Light from a single local muon, remnant of low energy hadron interaction, is an important source of background for VHE gamma-ray telescope
- Hadrons are charged and hence arrival directions are rendered isotropic at these energies by interstellar magnetic fields
- VHE telescopes can be used to study Hadron (cosmic ray) background: composition and spectrum



Physics of Gamma-ray and Hadron Shower

Fundamental difference in Opening Angle in Electromagnetic and Hadronic interactions

The Cherenkov Light Shower from an Electron-initiated Cascade

- Cosmic Electrons are less than 1% of Hadronic Background
- Spectrum steepens above 1 TeV
- Important background ~ 300 GeV
- Isotropic to first order
- Not possible (yet!) to distinguish gamma-ray cascade from electron cascade ; angular resolution important

Signal-to-Noise for Cherenkov Detectors

2.4.1.1 Signal

If the integration time of the photomultiplier pulse counting system, τ, is greater than the duration of the Cherenkov light flash (typically 3–5 ns), then the light signal (in photoelectrons) detected is given by

$$S = \int_{\lambda_2}^{\lambda_1} C(\lambda)\eta(\lambda)A\,\mathrm{d}\lambda$$

where $C(\lambda)$ is the Cherenkov photon flux within the wavelength sensitivity bounds of the PMT, λ_1 and λ_2, and $\eta(\lambda)$ is the response curve of the PMT.

$$C(\lambda) = kE(\lambda)T(\lambda)$$

where $E(\lambda)$ is the shower Cherenkov emission spectrum ($\propto 1/\lambda^2$), $T(\lambda)$ is the atmospheric transmission (figure 2.5) and k is a constant which depends on the number of particles in the shower, and the geometry of the emitting particles and detector.

2.4.1.2 *Background*

The Cherenkov light pulse must be detected above the fluctuations in the night-sky background in the time interval, τ.

The sky noise B is given by

$$B = \int_{\lambda_2}^{\lambda_1} B(\lambda)\eta(\lambda)\tau A\Omega \, d\lambda.$$

Hence the signal-to-noise ratio is essentially

$$S/N = S/B^{0.5} = \int_{\lambda_2}^{\lambda_1} C(\lambda)[\eta(\lambda)A/\Omega B(\lambda)\tau]^{1/2} \, d\lambda.$$

The smallest detectable light pulse is inversely proportional to S/N; the minimum detectable gamma ray then has an energy threshold, E_T given by

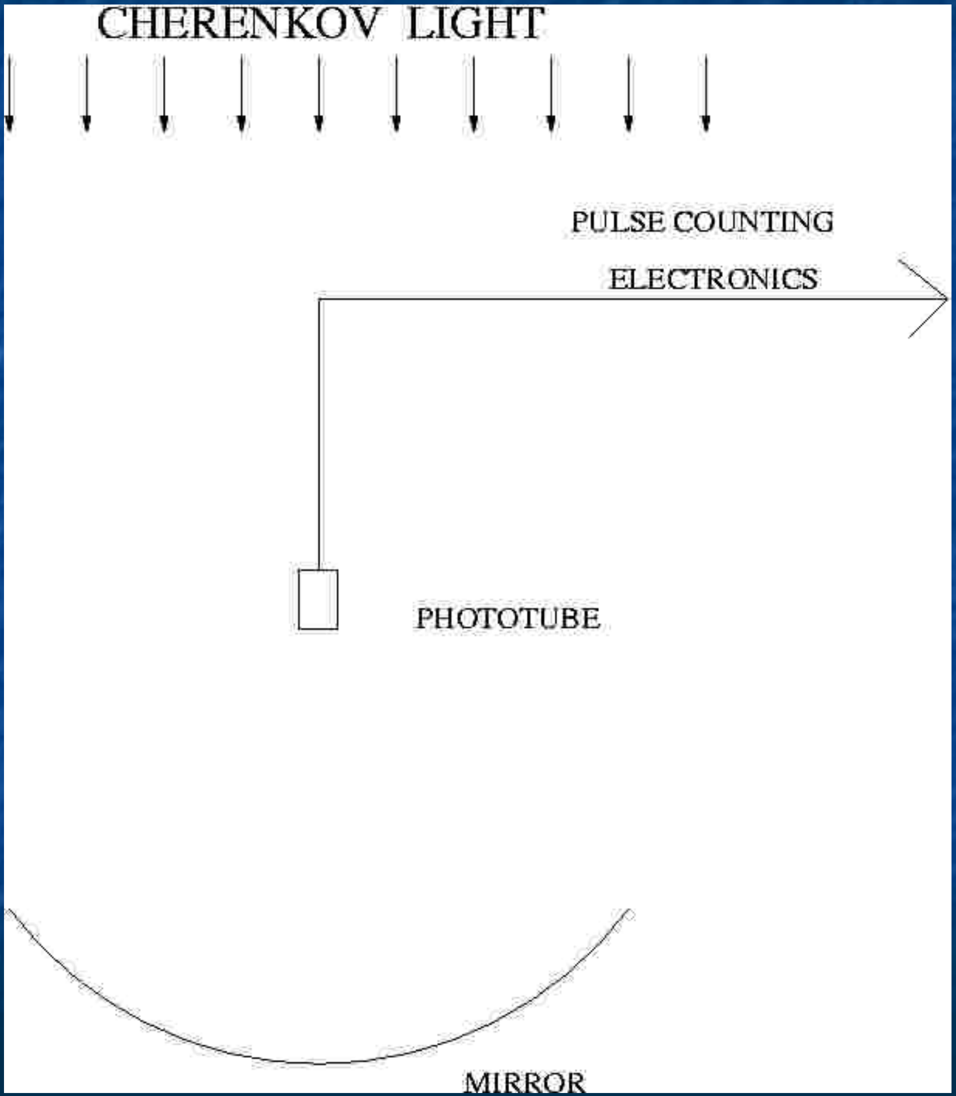
$$E_T \propto 1/C(\lambda)[B(\lambda)\Omega\tau/\eta(\lambda)A]^{1/2}.$$

For the signal to be identified as coming from other than an extreme fluctuation in the ambient light background, it must be ~5–7 times N, depending on the configuration of the detector electronics.

Atmospheric Cherenkov Detectors

Inherently Simple and Economical

- Light Collectors
- Light Detectors: PMTs
- Electronics: FADC
- Dark Site, High Elevations
- Clear Skies



Detection Elements

- PMT’s
- Electronics
  - Bias curve
  - Coupling
  - Pedestal
  - CFD’s
  - QADC and FADC
- Optics
- Wavelength dependence

Gamma-ray Signal-to-Noise for Source Detection.

2.5.2 Flux sensitivity

Ground-based gamma-ray telescopes operate in a domain where their flux sensitivity is dominated by an unavoidable background of cosmic ray events. The cosmic ray background has a power-law spectrum:

$$F_{cr}(> E) \propto E^{-a}.$$

In the range of interest, $a = 1.7$. Similarly, the gamma-ray source energy distribution can be assumed to have the form:

$$F_\gamma(> E_\gamma) \propto E_\gamma^{-a_\gamma}.$$

a_γ can have values from 1 to 3 and is generally assumed to increase with energy, i.e. the spectrum steepens.

If S equals the number of gamma rays detected from a given source in a time, t, and A_γ is the collection area for gamma-ray detection, then $S = F_\gamma(E) A_\gamma t$. The telescope will register a background, B, given by

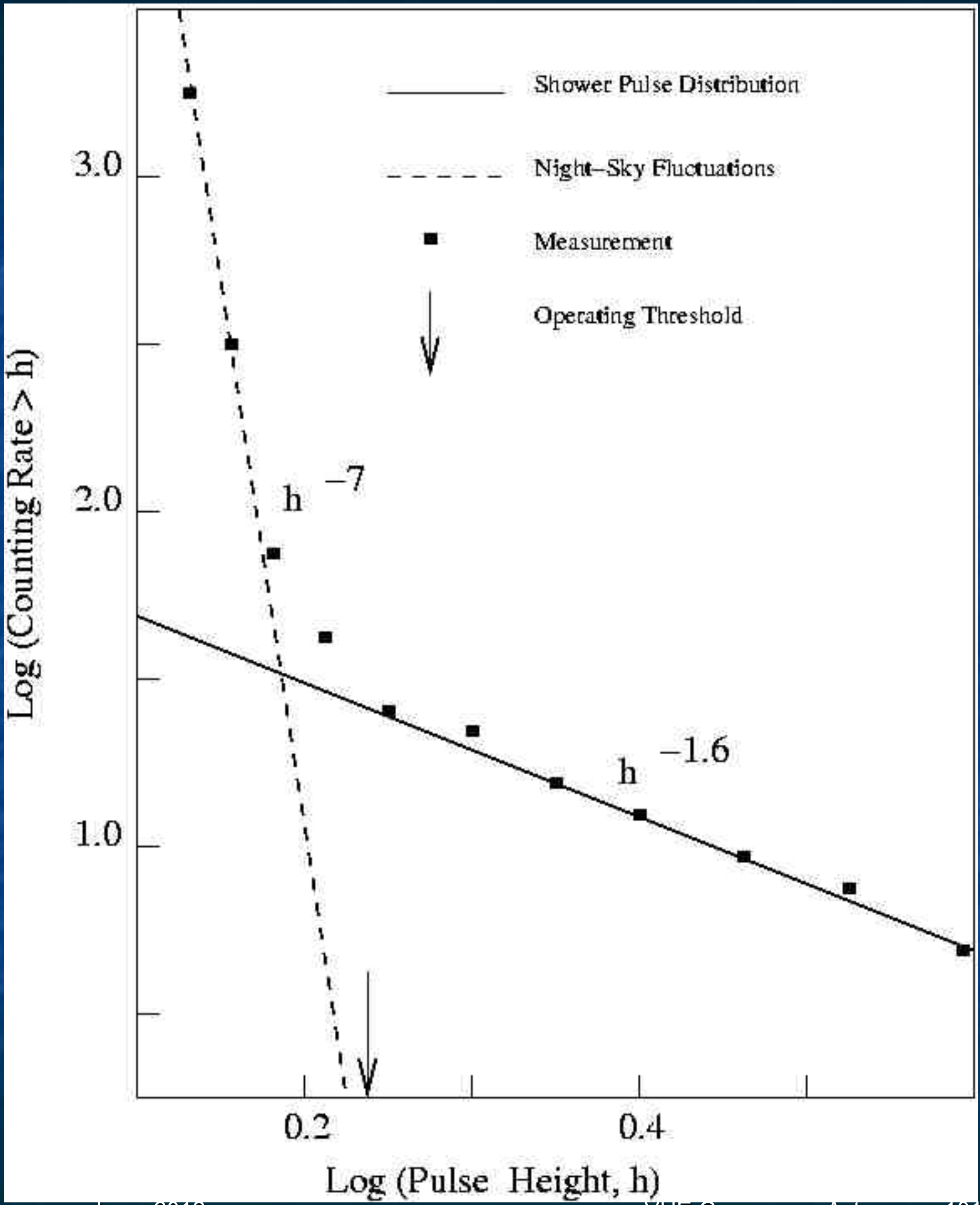
$$B = F_{cr} A_{cr}(E) \Omega t$$

where $A_{cr}(E)$ is the collection area for the detection of cosmic rays of energy E.

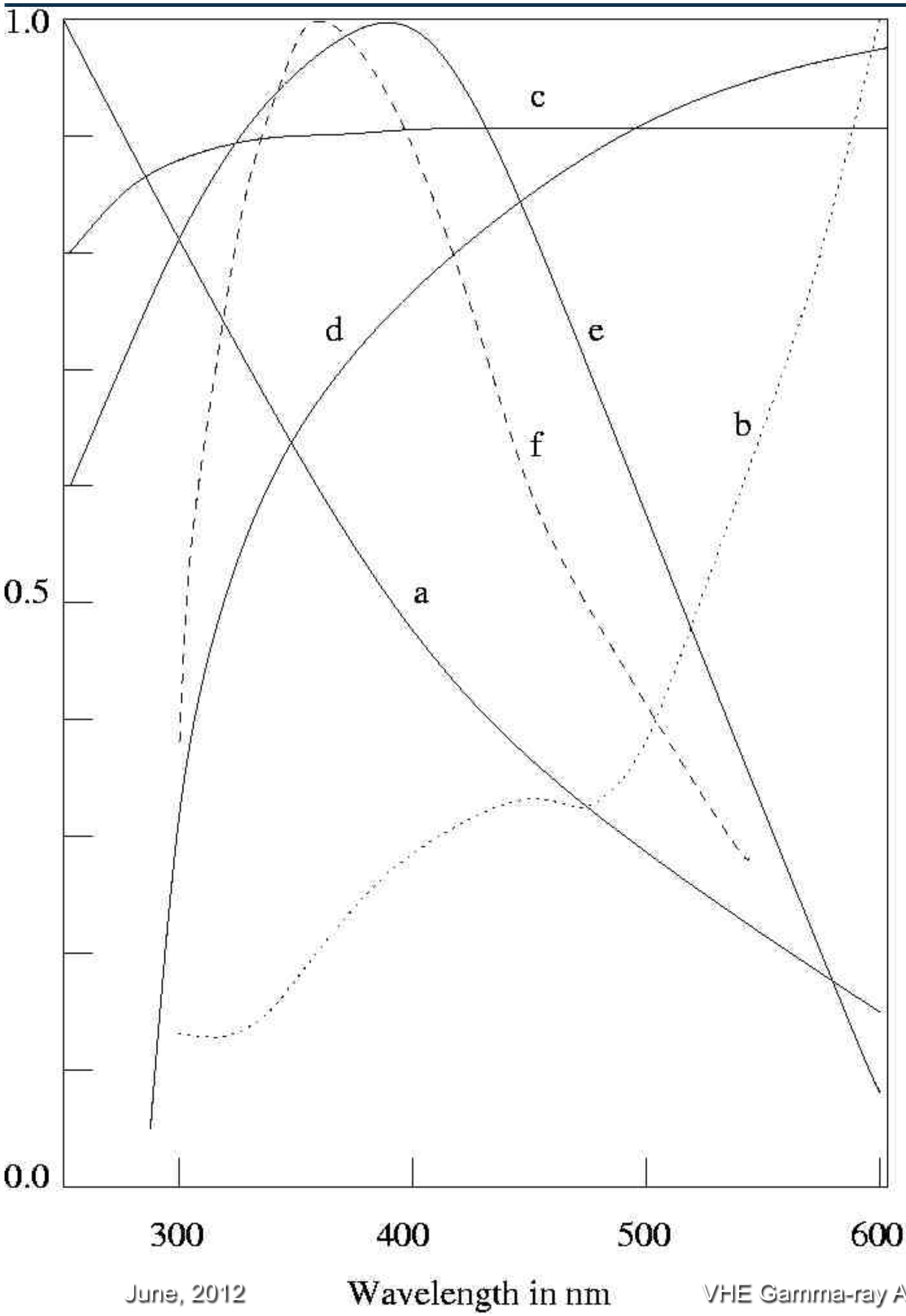
Then the standard deviation,

$$\sigma \propto S/B^{1/2} \propto E^{1.7/2 - a_\gamma} [A_\gamma / A_{cr}]^{1/2} t^{1/2}.$$

The minimum number of standard deviations, σ, for a reliable source detection is generally taken as five.



Noise Spectrum (night-sky noise and cosmic ray)



Cherenkov Detection Considerations as a Function of Wavelength:

a: Cherenkov light spectrum
b: Night-sky Background Light
c: Mirror Reflectivity
d: Atmospheric Transmission
e: Bi-Alkali Photocathode
f: Product of a,c,d and e.

Some useful numbers:

- Water, refractive index, n=1.33
- Air, n = 1.00029;
- Ch. Angle in air:
  - 0.8 deg. at 10km;
  - 1.3 deg. at S.L.
- Threshold for Cherenkov Emission:
  - Electron > 21 MeV
  - Muon > 4 GeV
- Yield:
  - 30 photons/m
  - 10,000 photons/radiation length
- 100 GeV gamma ray: 5 photons/m^2
- Background Light from Night-Sky:
  6.4 x 10^7 photons/(s-cm^2-ster) in 300-400 nm band

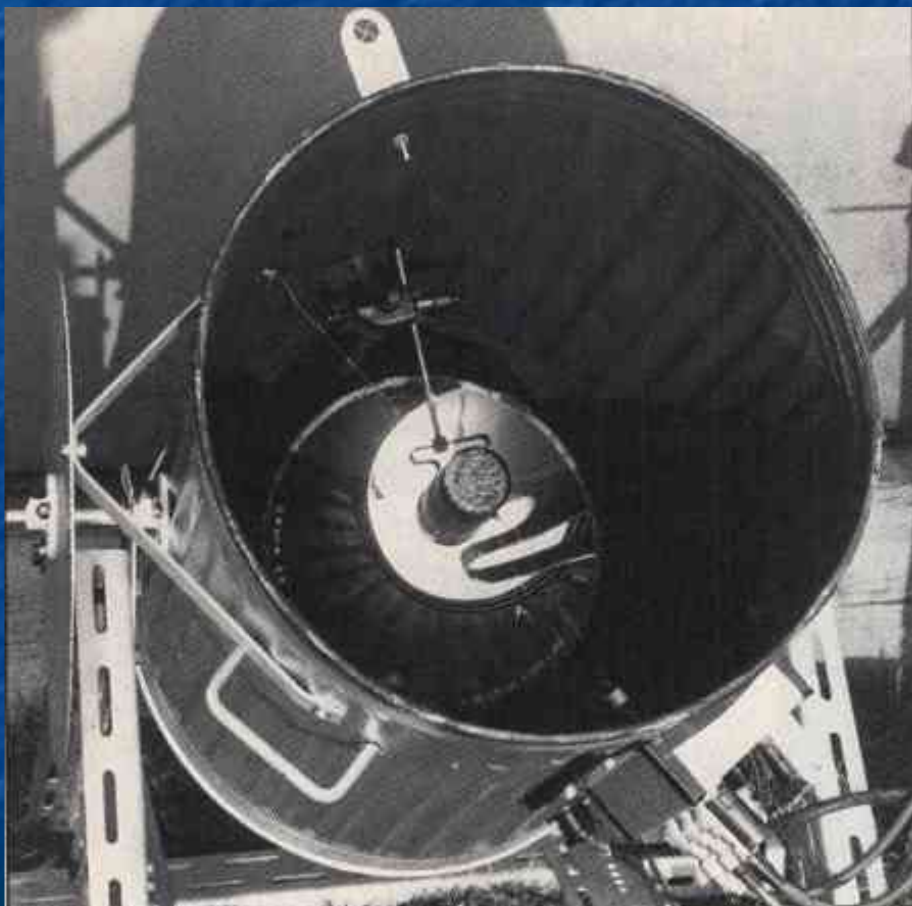
In the beginning…

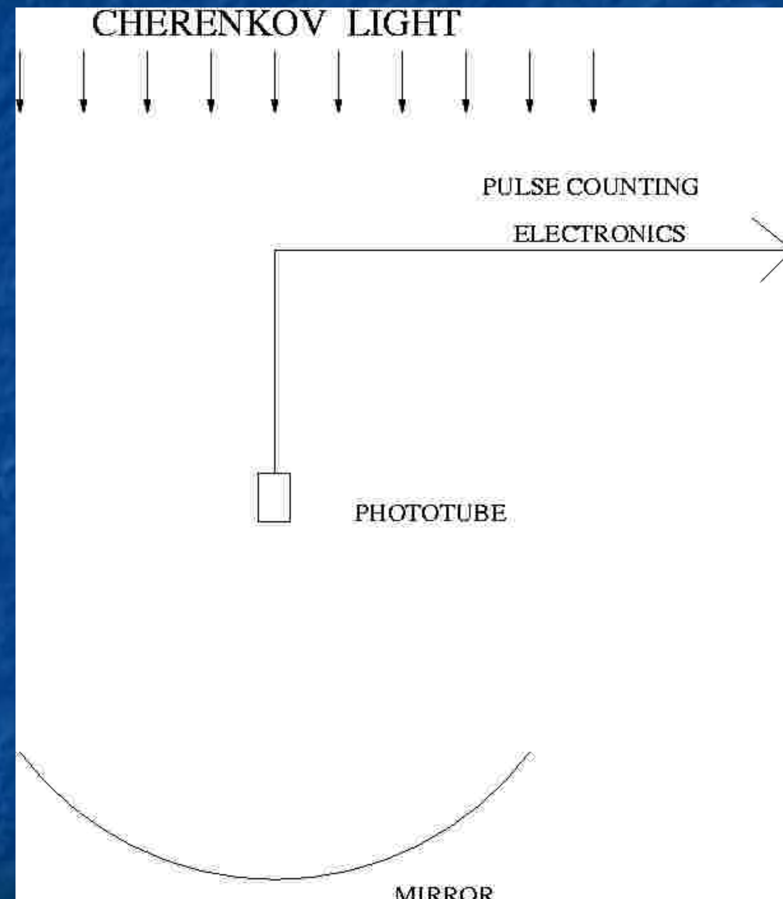
1948 P.M.S. Blackett (Nobel Laureate) points out that 1/10,000 of night-sky light should come from cosmic rays

Previously Cherenkov light only detected in solids and liquids; Jelley working on gas detector

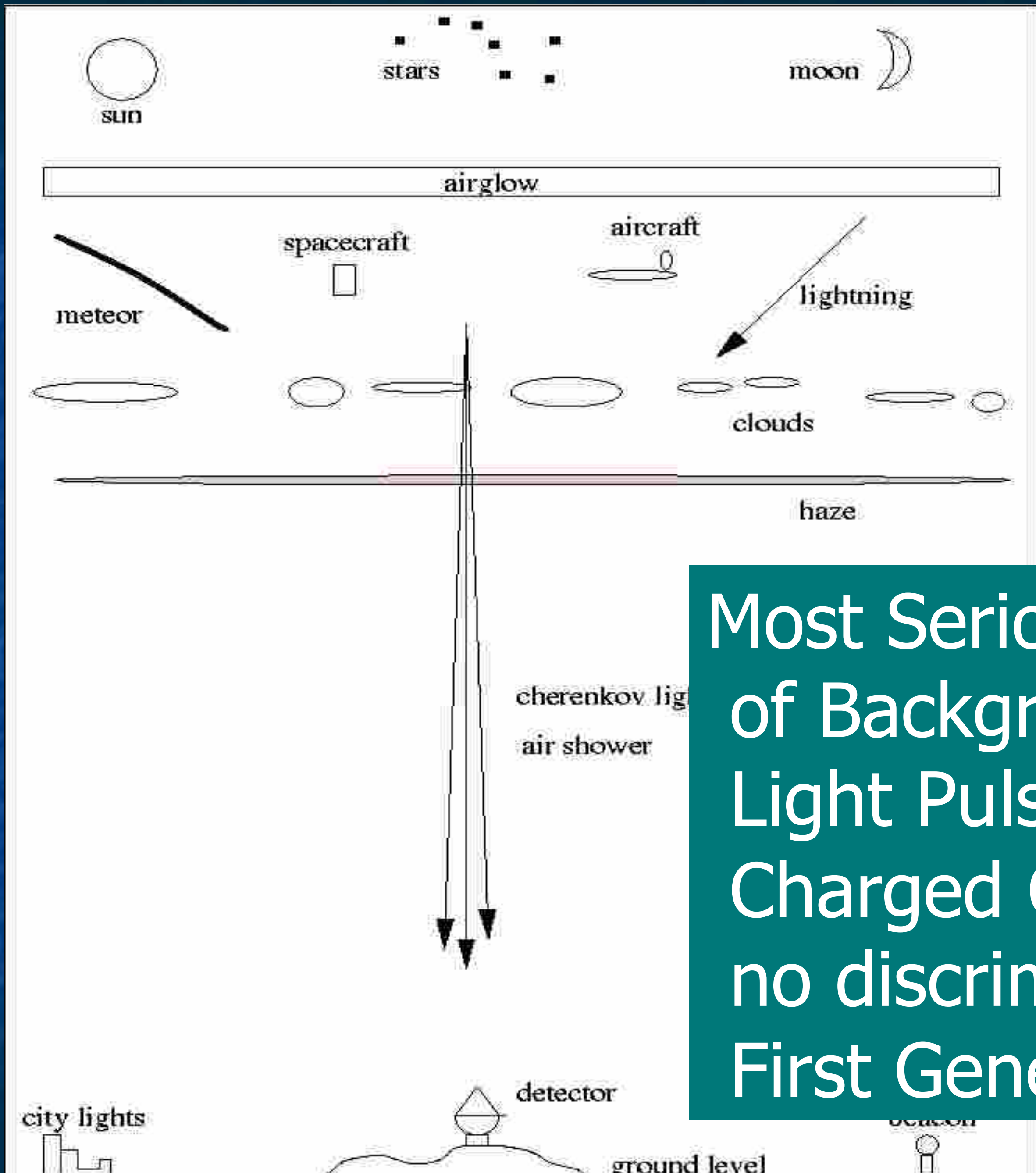
1953 Galbraith and Jelley (Atomic Energy Research Establishment, Harwell) postulate that Cherenkov light might be detectable as light pulse from air shower

Simple Optical Detector at Harwell, U.K. 1951





Experiment in a garbage can, Galbraith and Jelley, 1953



Natural and Manmade Sources of Background Light and Absorption.

Most Serious Source of Background is Light Pulses from Charged Cosmic Rays; no discrimination in First Generation Telescopes

Gamma-ray Astronomy: Motivation

Seminal paper by Phillip Morrison, 1958

Also proposed at higher energies independently by Giuseppe Cocconi, 1959

AN AIR SHOWER TELESCOPE

AND THE DETECTION OF 10^{12} eV PHOTON SOURCES

Giuseppe Cocconi *

CERN - Geneva.

1) This paper discusses the possibility of detecting high energy photons produced by discrete astronomical objects. Sources of charged particles are not considered as the smearing produced by the magnetized plasmas filling the interstellar spaces probably obliterates the original directions of movement.

2) [illegible]

The Crab Nebula: Visual magnitude of polarized light m = 9.

Magnetic field in the gas shell $H \simeq 10^{-4}$ gauss.

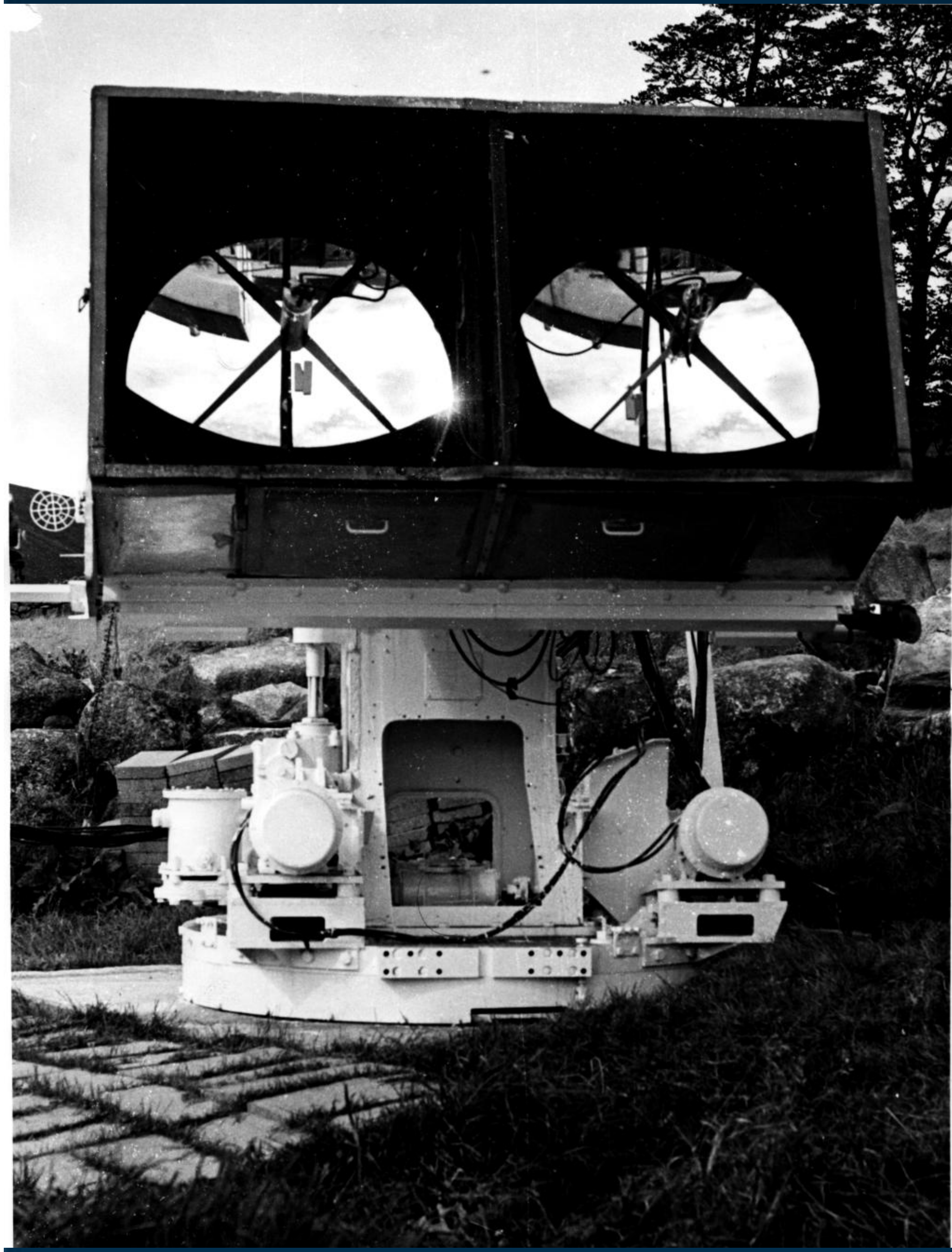
Therefore: $U_\gamma = 10^{12}\,eV$ and $R(10^{12}eV) \approx 10^{-3.2}\ m^{-2} s^{-1}$.

The signal is thus about 10^3 times larger than the background (2). Probably in the Crab Nebula the electrons are not in equilibrium with the trapped cosmic rays, and our estimate is over-optimistic. However, this source can probably be detected even if its efficiency in producing high energy photons is substantially smaller than postulated above.

M87, the Jet Nebula: m = 13.5 $H \simeq 10^{-4}$ gauss.

$R(10^{12}eV) \simeq 10^{-5} m^{-2} s^{-1}$, still well above the background (2). For this object our evaluation is probably not fundamentally wrong.

processes of quite different type are also of importance for the evolution of



First Generation Atmospheric Cherenkov Telescope

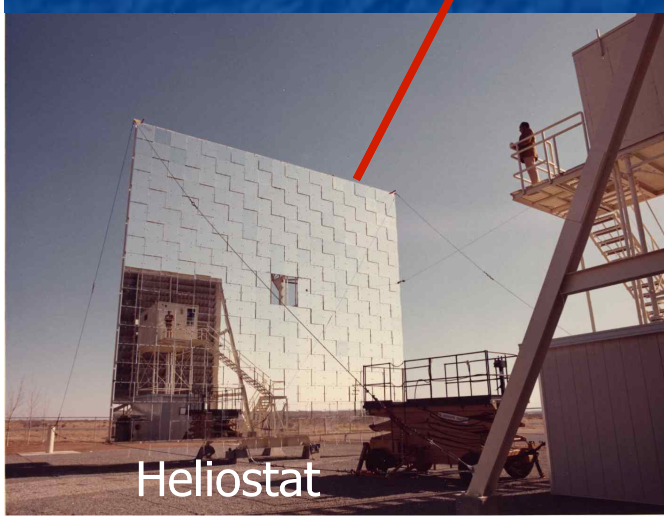
Glencullen, Ireland ~1962-66

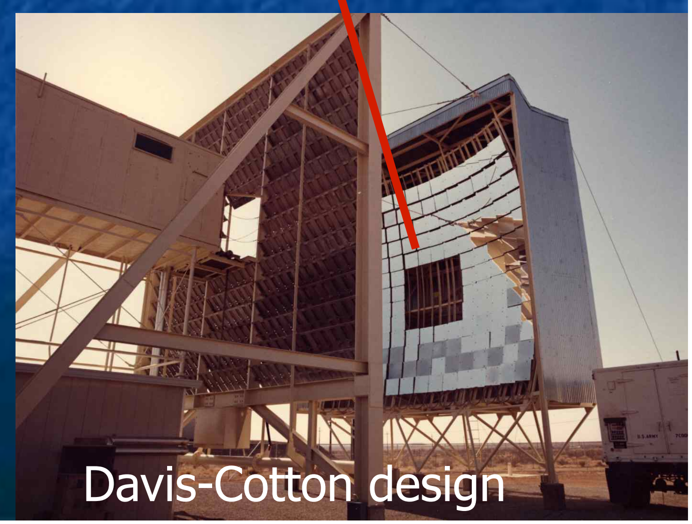
University College, Dublin group led by Neil Porter (in collaboration with J.V.Jelley)

WWII Surplus: Gunmount, searchlight mirrors

(Targets:
quasars (AGN), variable stars, Supnovae remnants, Crab)

First Smithsonian venture into VHE gamma-ray used Solar Furnace at Natick, MA ~ 1965-6.
Gamma-ray Astronomy Group led by Giovanni Fazio



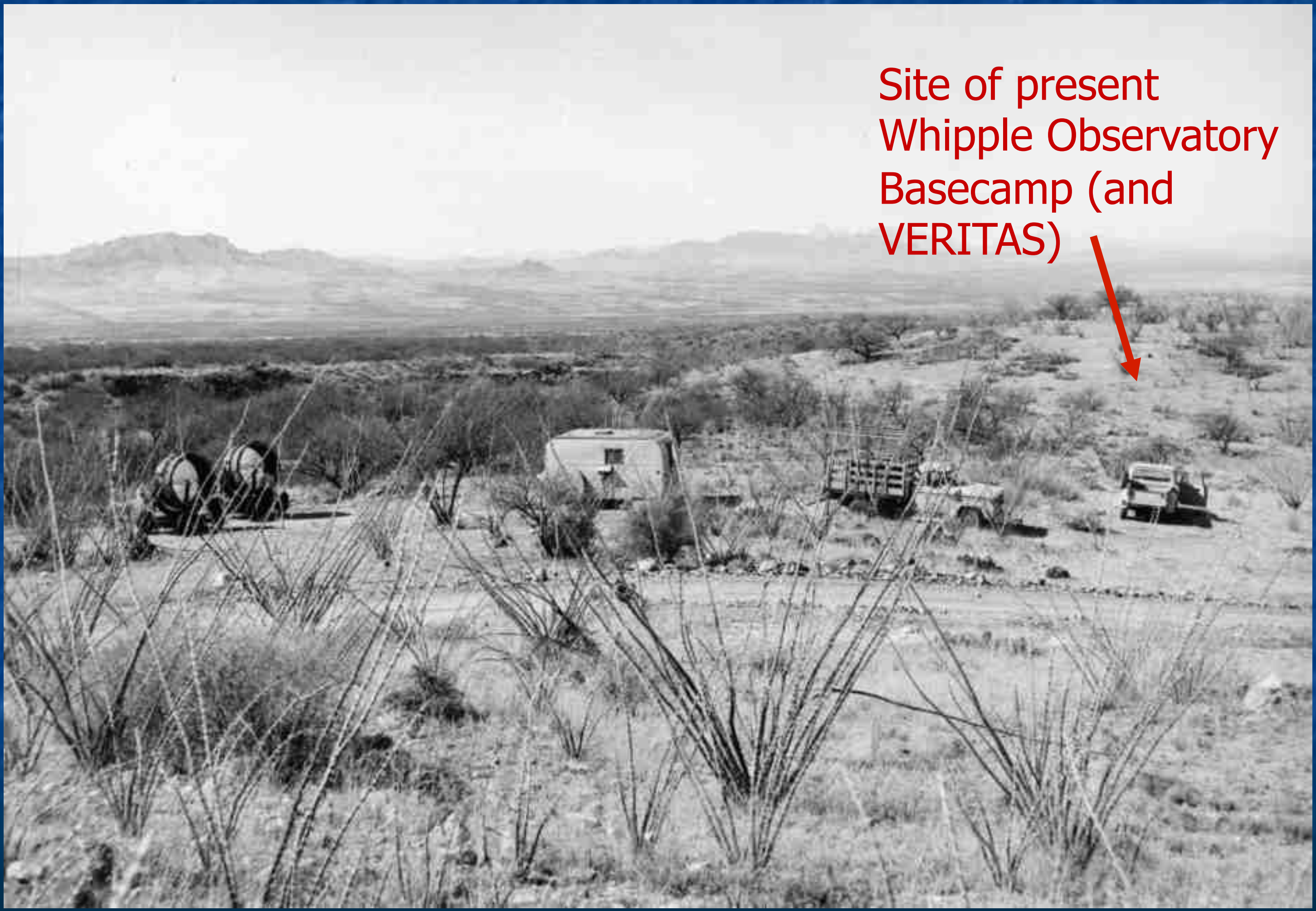


First Gamma-ray Experiment at Whipple Observatory, 1967-8

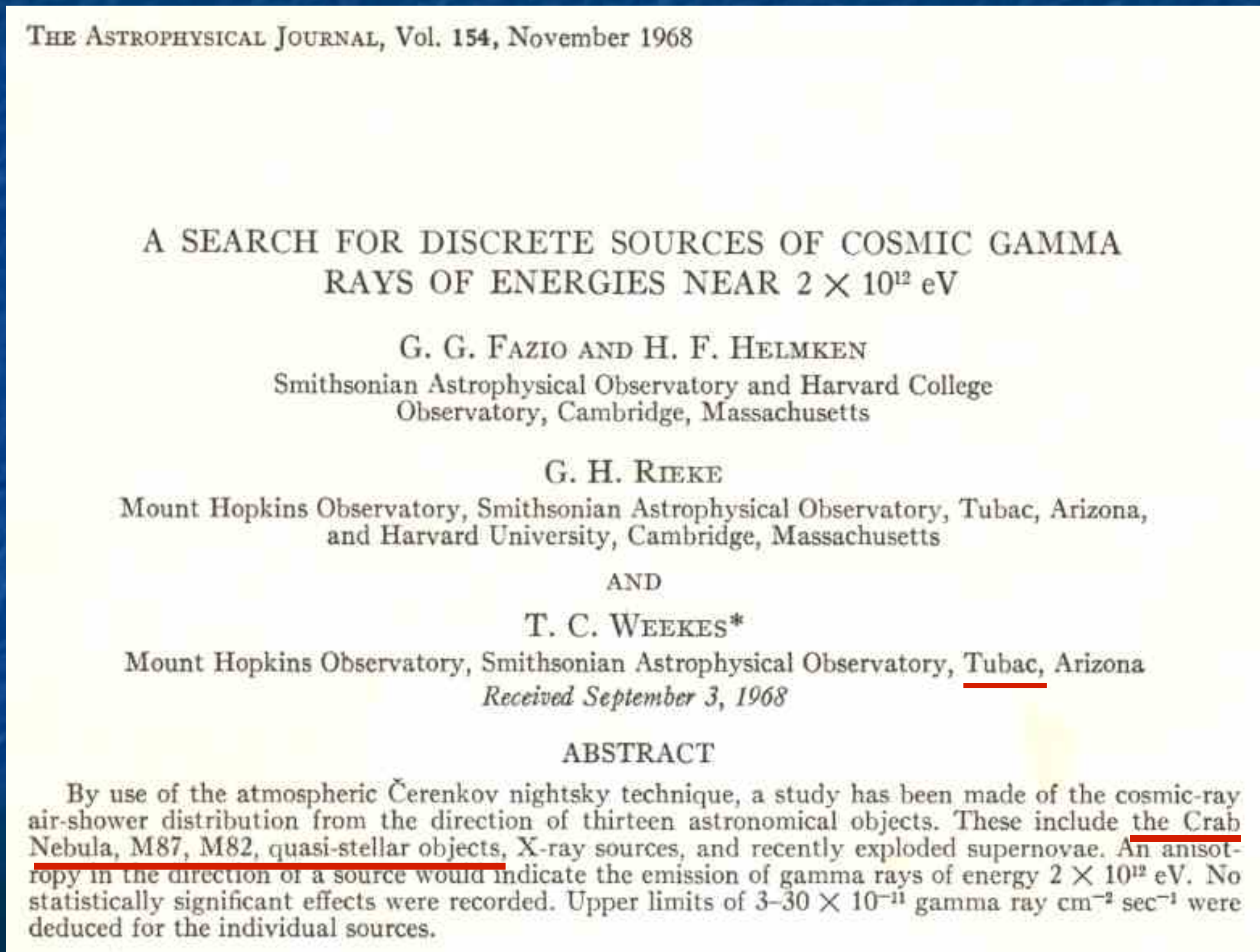
Work on the Mt. Hopkins Observatory proceeds at an astonishing pace. The laser and Baker-Nunn systems are now installed and operating and the large optical reflector is scheduled to arrive by the end of next month. In preparation for the LOR installation, Trevor Weekes (above, left) and George Rieke have conducted seeing tests with two movable searchlight reflectors. Look carefully – some outcroppings at the base of Mt. Hopkins are visible upside-down in the reflector.

Whipple Observatory, 1967-8

(wide spot on the road)



1968:Some familiar sources!


THE ASTROPHYSICAL JOURNAL, Vol. 154, November 1968

A SEARCH FOR DISCRETE SOURCES OF COSMIC GAMMA RAYS OF ENERGIES NEAR 2×10^{12} eV

G. G. FAZIO AND H. F. HELMKEN
Smithsonian Astrophysical Observatory and Harvard College Observatory, Cambridge, Massachusetts

G. H. RIEKE
Mount Hopkins Observatory, Smithsonian Astrophysical Observatory, Tubac, Arizona, and Harvard University, Cambridge, Massachusetts

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Mount Hopkins Observatory, Smithsonian Astrophysical Observatory, Tubac, Arizona
Received September 3, 1968

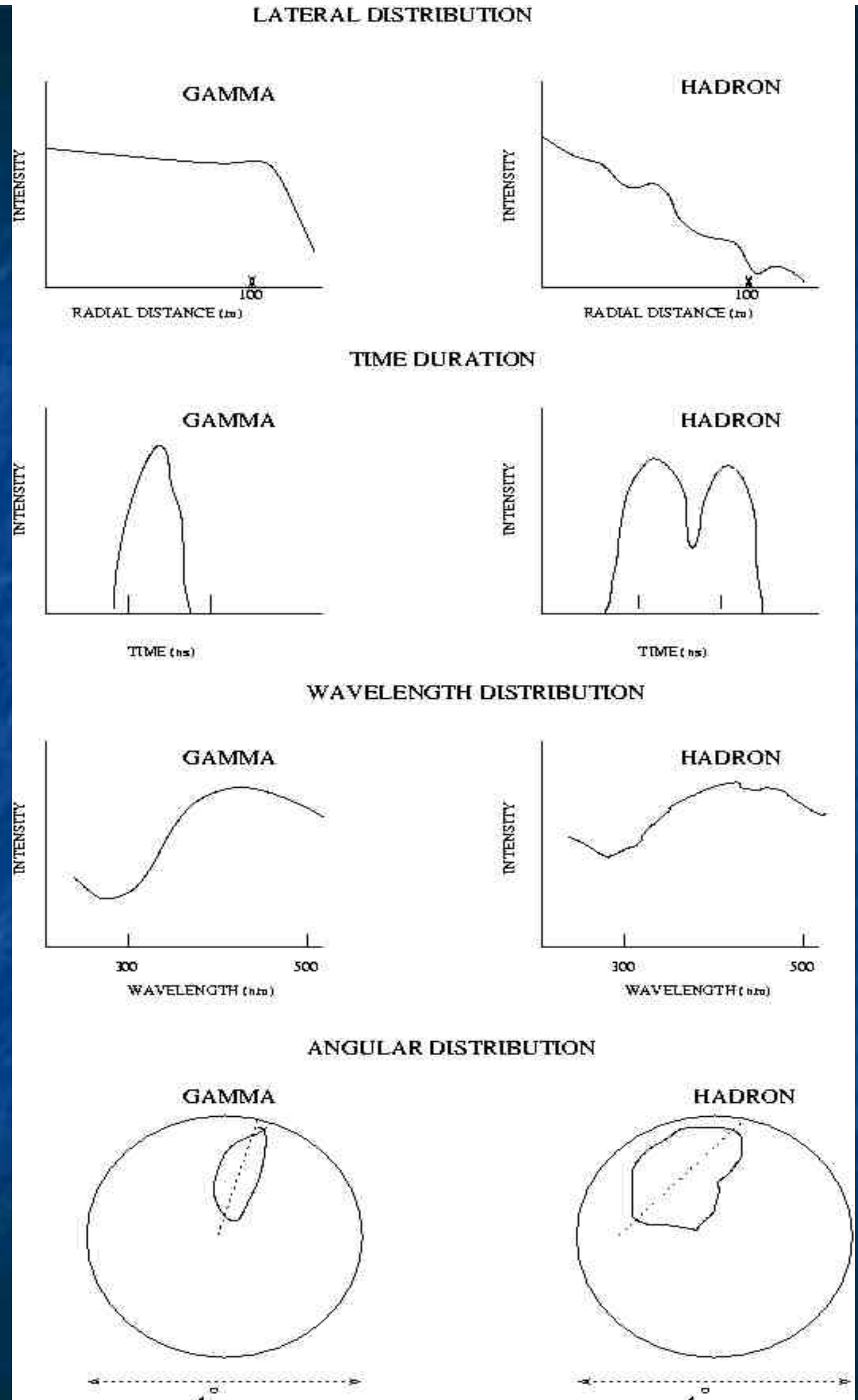
ABSTRACT

By use of the atmospheric Čerenkov nightsky technique, a study has been made of the cosmic-ray air-shower distribution from the direction of thirteen astronomical objects. These include the Crab Nebula, M87, M82, quasi-stellar objects, X-ray sources, and recently exploded supernovae. An anisotropy in the direction of a source would indicate the emission of gamma rays of energy 2×10^{12} eV. No statistically significant effects were recorded. Upper limits of $3–30 \times 10^{-11}$ gamma ray cm^{-2} sec^{-1} were deduced for the individual sources.

Discrimination of Gamma-ray Showers from Hadron Background using one or more of four differences in shower light properties.

1. Lateral distribution
2. Duration
3. UV/visible
4. Angular distribution

5. Array of detectors
6. Fast timing
7. Multiwavelength
8. Imaging



Atmospheric Cherenkov Imaging Technique, c. 1977

- Convert 10 m optical reflector into large fast camera of 10 m aperture
- Finite number of pixels
- (37 --> 370)
- Short exposures (30 nsec)

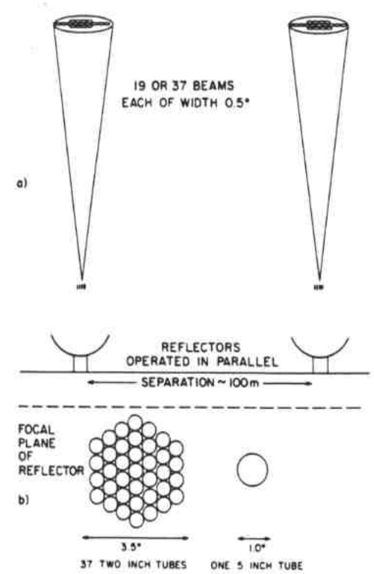


Figure 7. (a) The stereoscopic imaging system proposed in 1977. (b) The focal plane layout of pmt's is contrasted with a conventional detector.

Cherenkov Shower Imaging using Image Intensifiers (1960-65) and Stereo Detectors (1972-76)

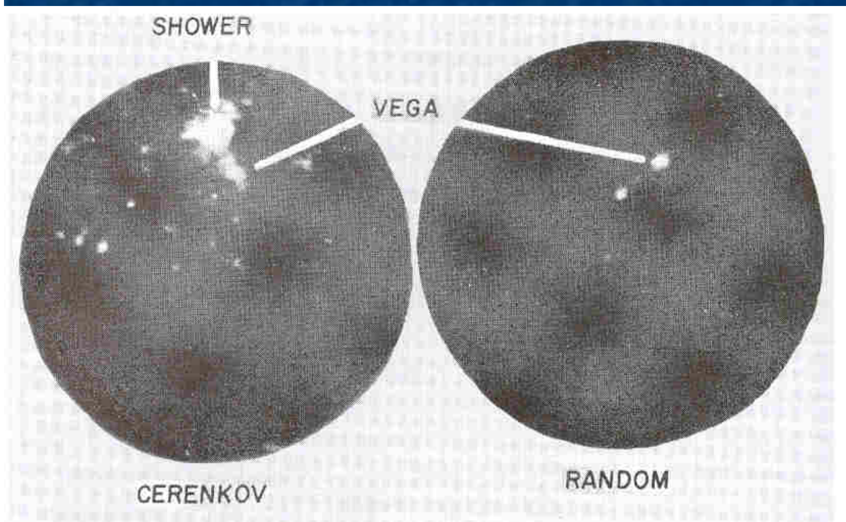
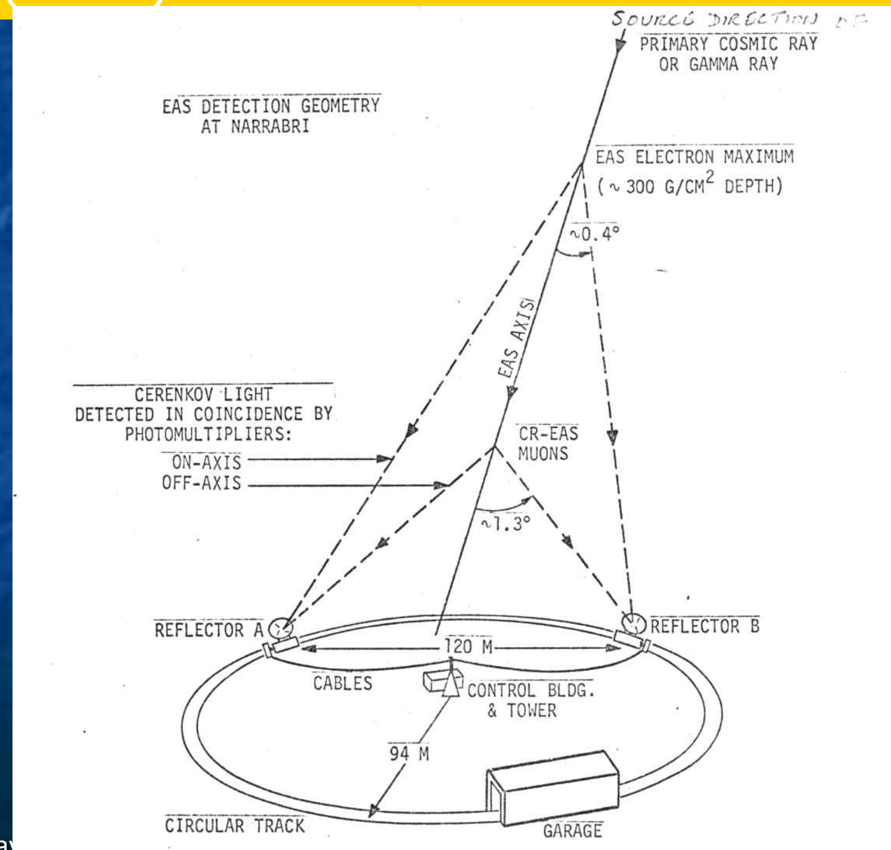
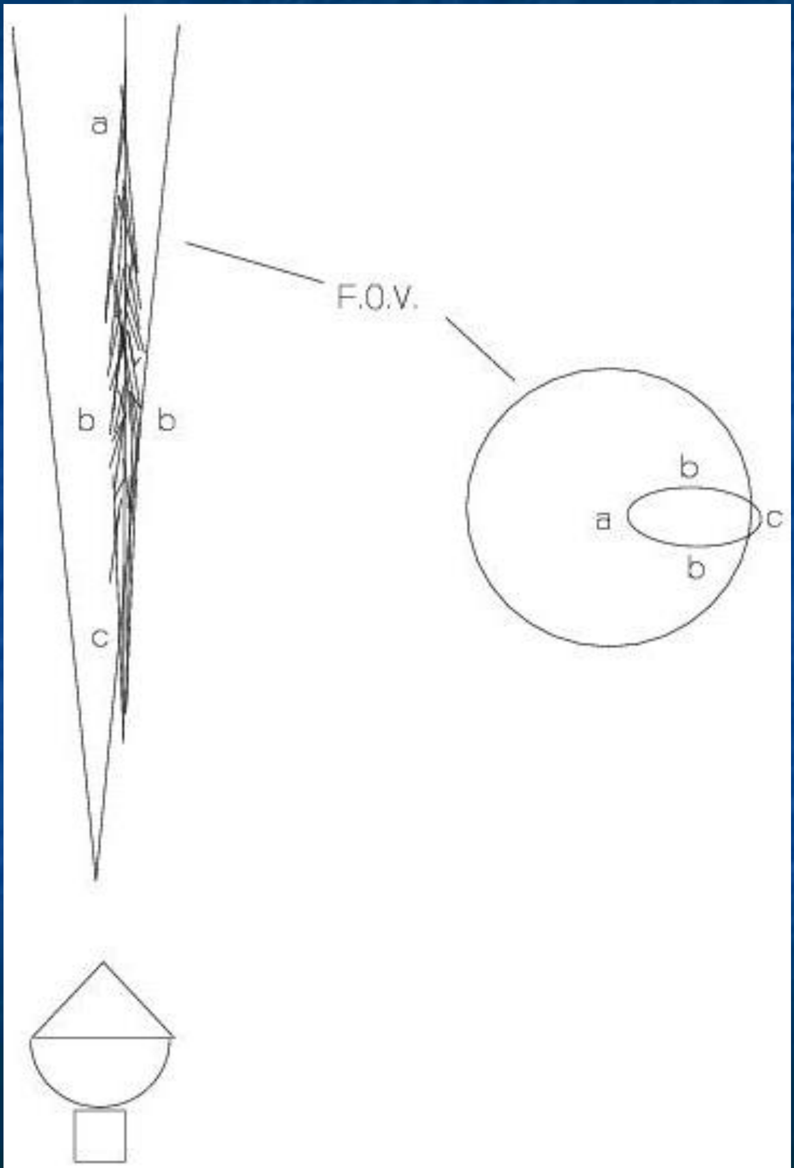


Image Intensifier Pictures of Cherenkov light Image from Cosmic Ray Air Shower.
On short time-scale images are brighter than bright star (Vega).
Work by David Hill (M.I.T.) and Neil Porter (U.C.D.) in 1960



Josh Grindlay demonstrates value of stereo imaging with two-pixel system (Double Beam Technique) at Mt. Hopkins and Narrabri (1972-76)

Atmospheric Cherenkov Imaging

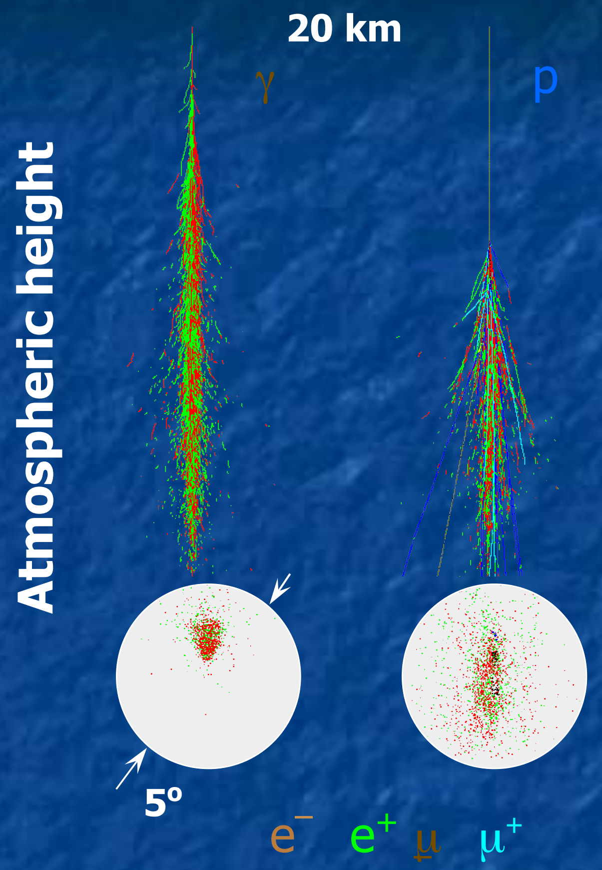


Rejection of Background because of:

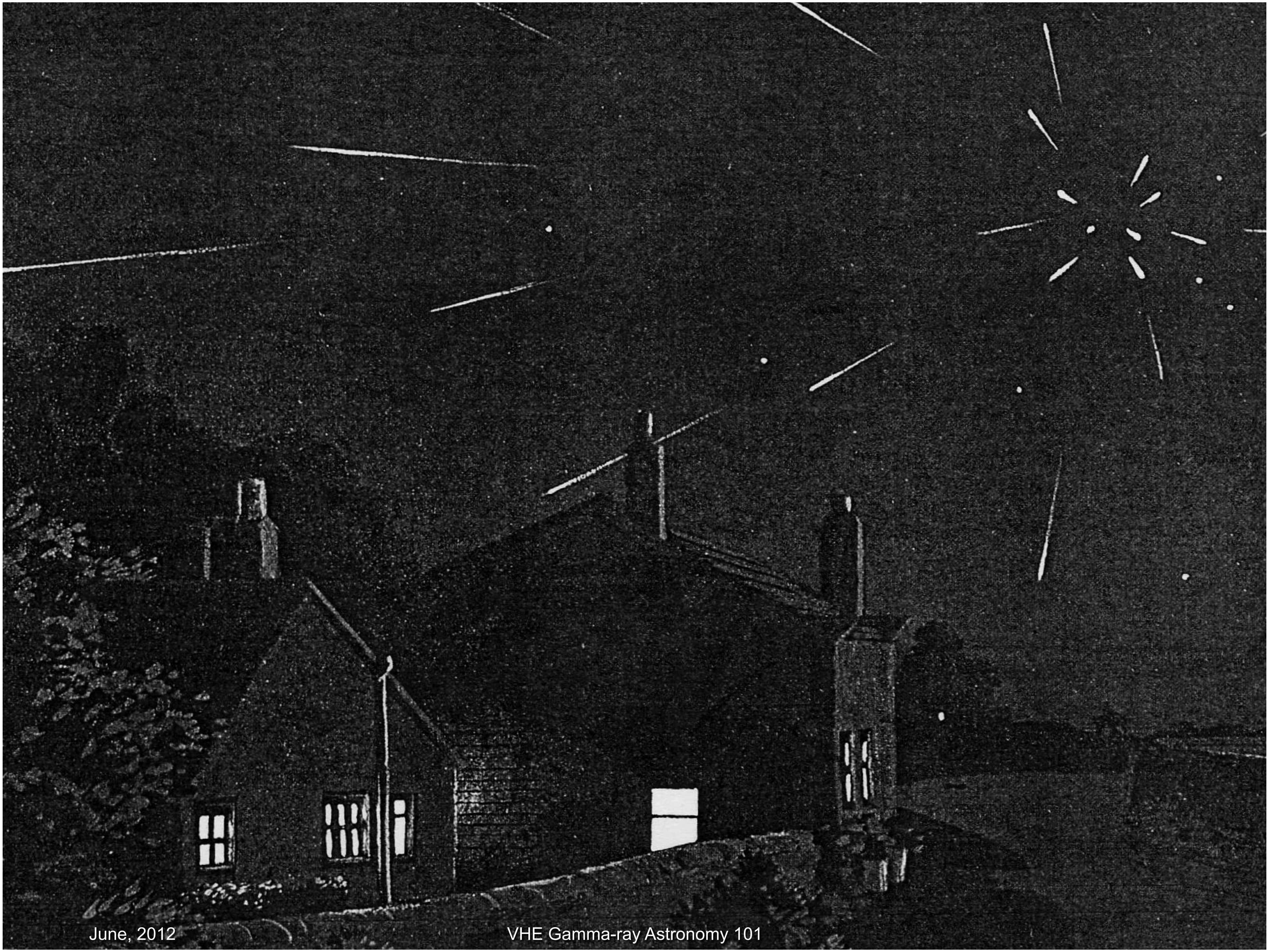
Size, shape (physics)

Orientation (geometry)

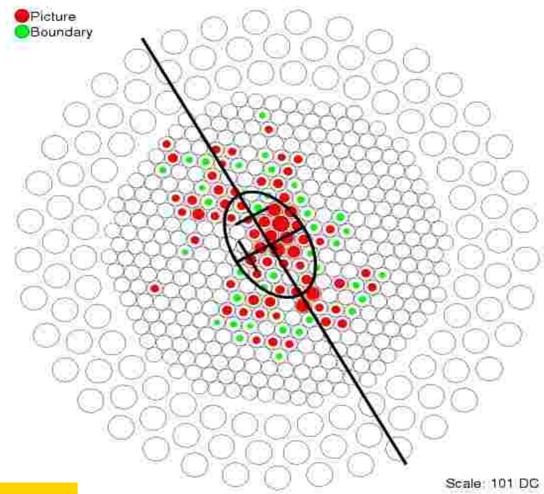
Atmospheric Cherenkov Imaging



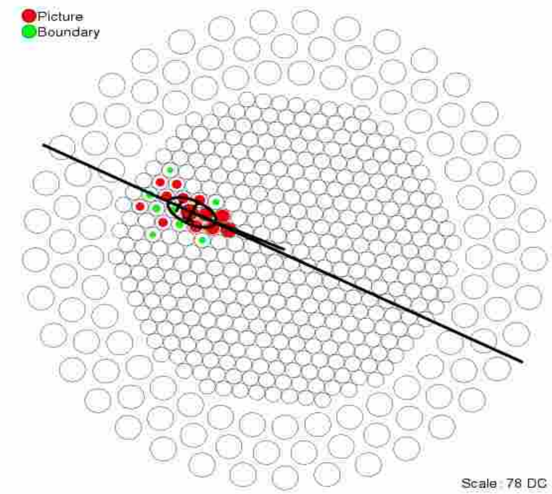
Cherenkov Imaging gives the ability to distinguish compact images of gamma-ray showers from more irregular images from hadron shower



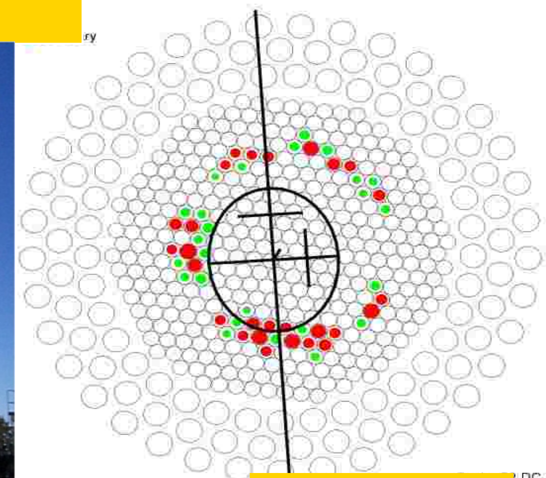
Types of images seen by atmospheric Cherenkov camera



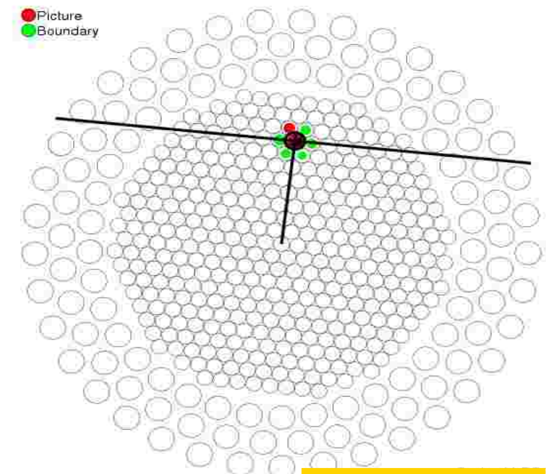
Hadron



Gamma ray

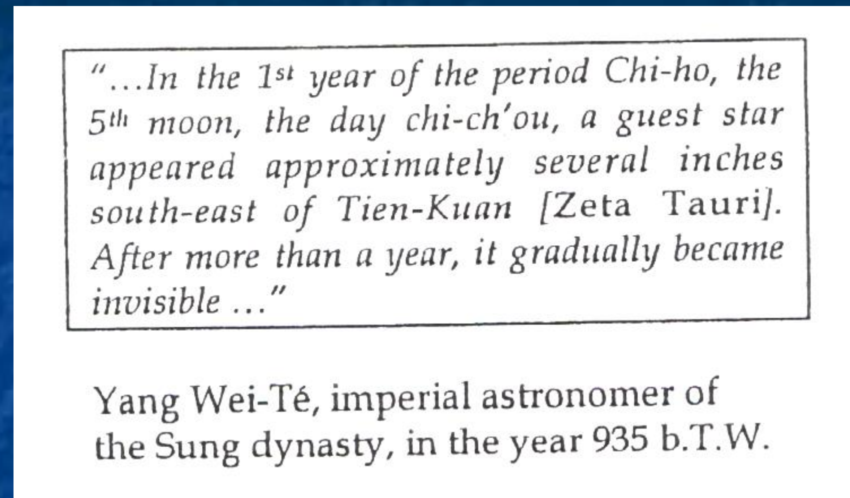


Muon Ring



Sky Noise

The First TeV Sources



"...In the 1st year of the period Chi-ho, the 5th moon, the day chi-ch'ou, a guest star appeared approximately several inches south-east of Tien-Kuan [Zeta Tauri]. After more than a year, it gradually became invisible ..."

Yang Wei-Té, imperial astronomer of the Sung dynasty, in the year 935 b.T.W.

*Imaging systems came into operation 1984 -
*First Galactic Source detected (Crab Nebula/ Whipple Observatory) 1989
*First Extragalactic Source detected (Mrk 421/ Whipple Observatory) 1992
*HEGRA array of imaging detectors 1995

A Source at last!

THE ASTROPHYSICAL JOURNAL, 342:379–395, 1989 July 1

OBSERVATION OF TeV GAMMA RAYS FROM THE CRAB NEBULA USING THE ATMOSPHERIC CERENKOV IMAGING TECHNIQUE

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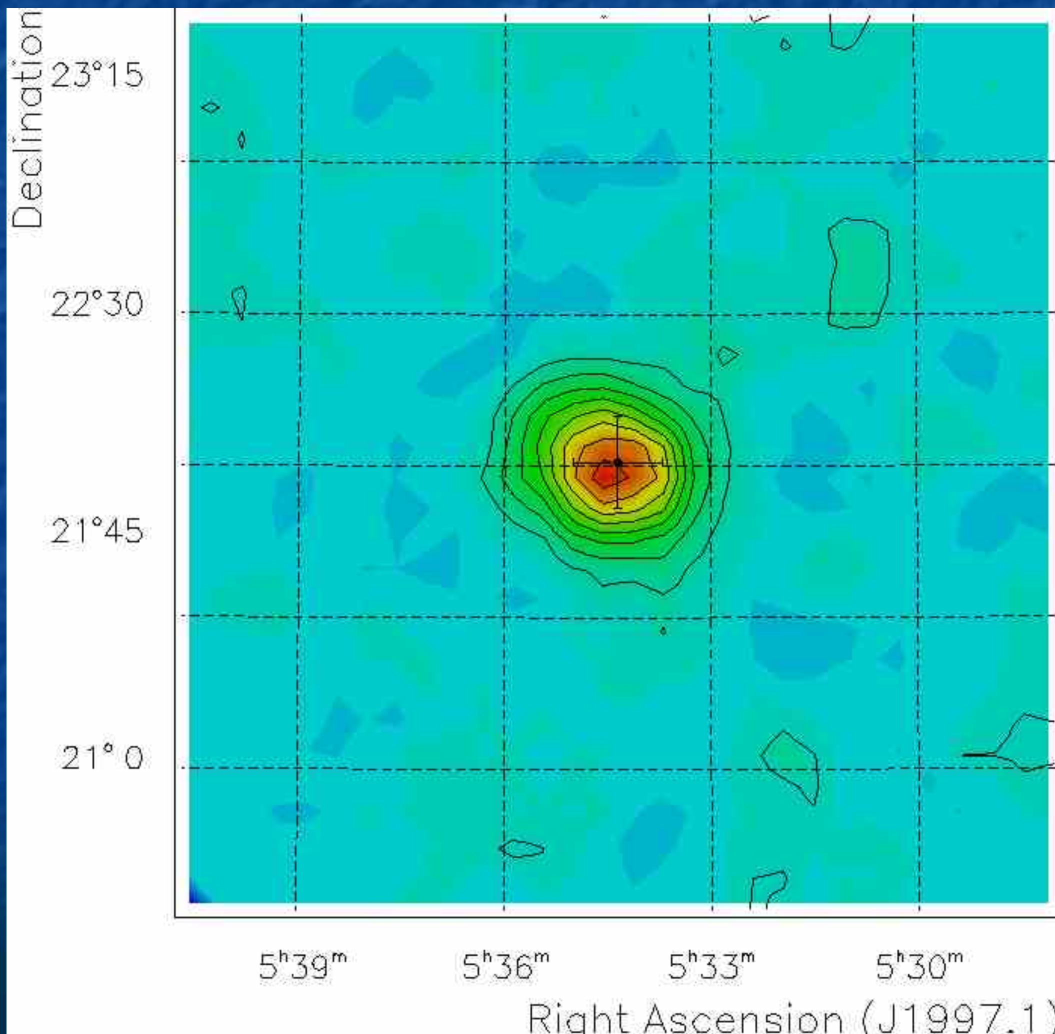
Received 1988 August 1; accepted 1988 December 9

ABSTRACT

The Whipple Observatory 10 m reflector, operating as a 37 pixel camera, has been used to observe the Crab Nebula in TeV gamma rays. By selecting gamma-ray images based on their predicted properties, more than 98% of the background is rejected; a detection is reported at the 9.0 σ level, corresponding to a flux of 1.8×10^{-11} photons cm^2 s^{-1} above 0.7 TeV (with a factor of 1.5 uncertainty in both flux and energy). Less than 25% of the observed flux is pulsed at the period of PSR 0531. There is no evidence for variability on time scales from months to years. Although continuum emission from the pulsar cannot be ruled out, it seems more likely that the observed flux comes from the hard Compton synchrotron spectrum of the nebula.

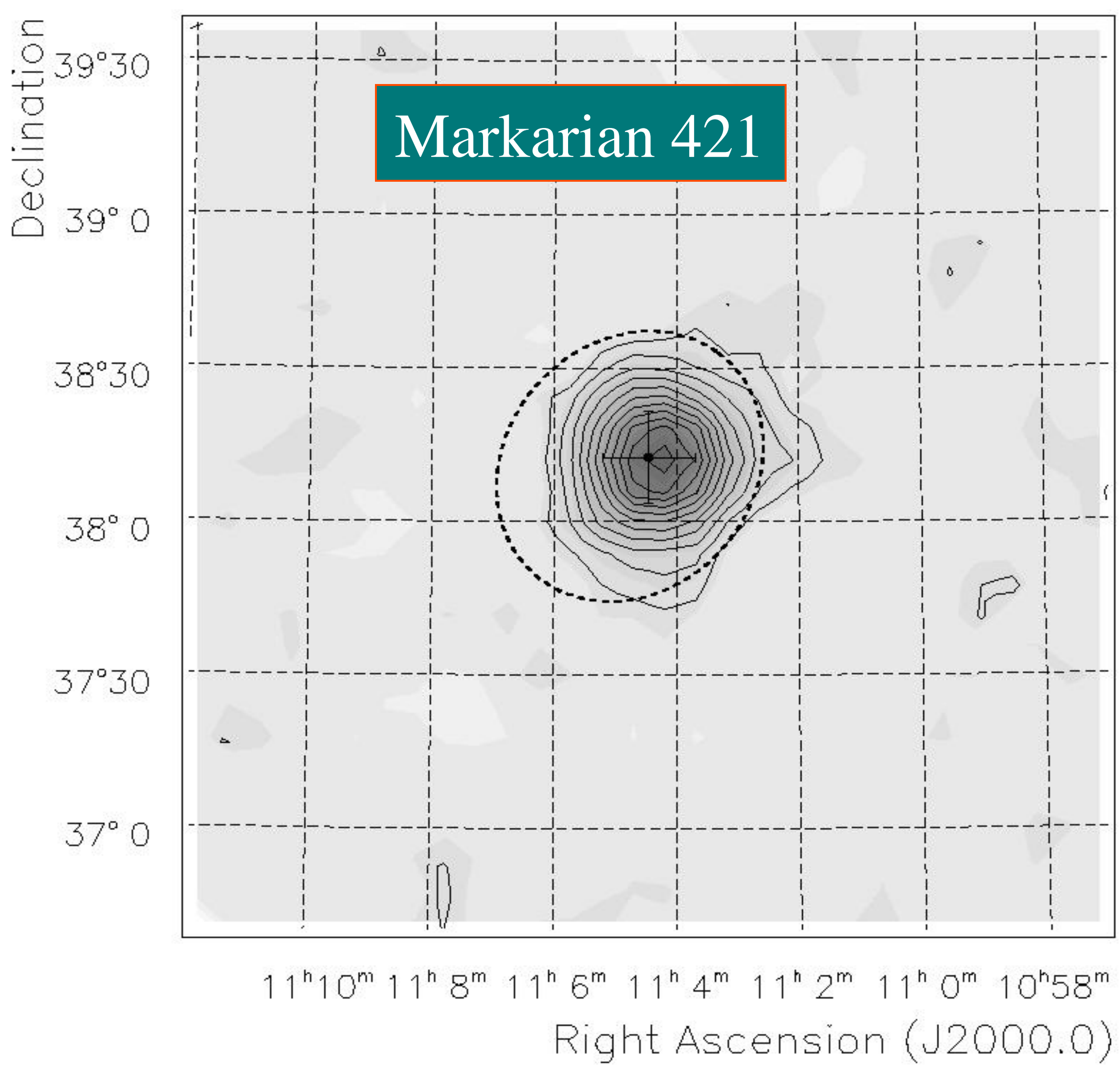
The Crab Nebula as Very High Energy Gamma Ray Source



Whipple Observatory
1986…success at last!

Supernova 1054 A.D.

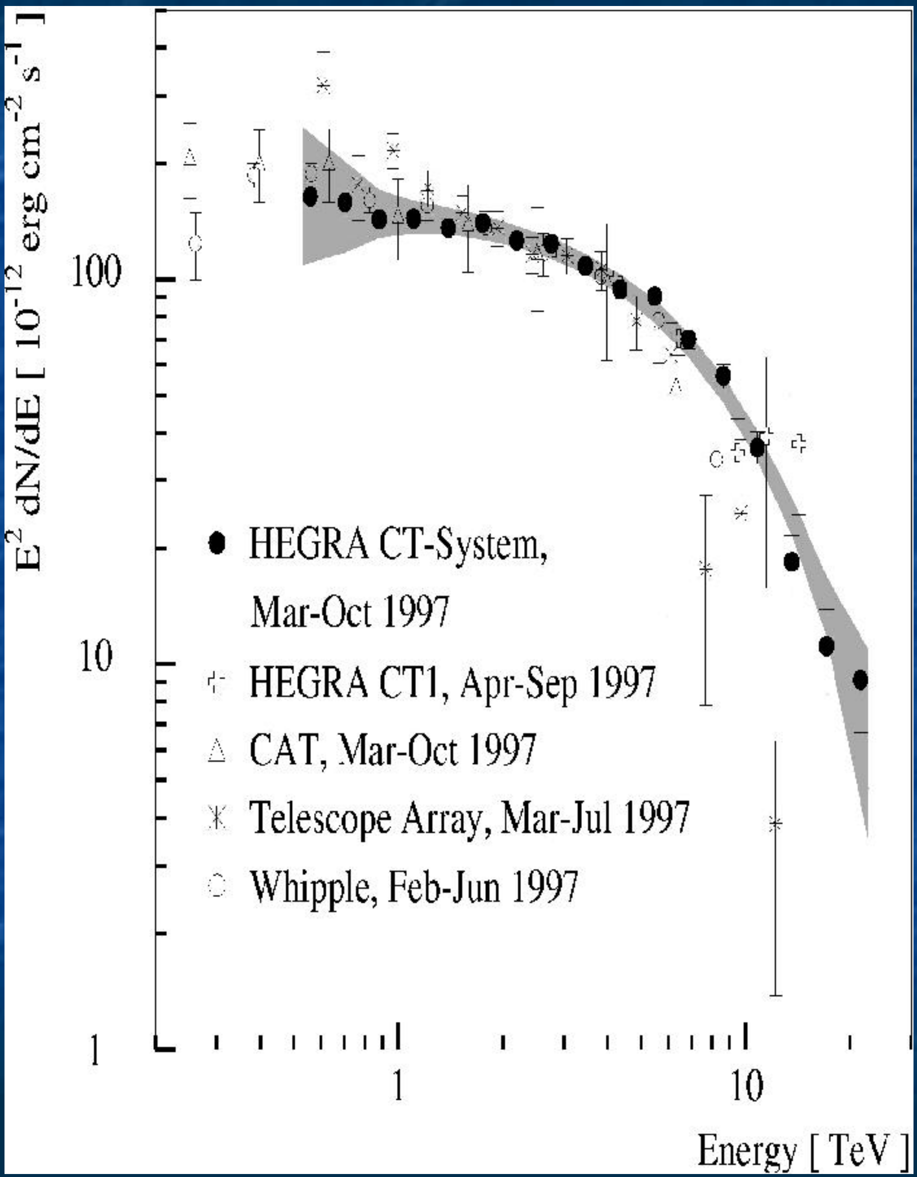
Location of TeV Gamma-ray Sources



Strong Sources can be located to a few arc-min

Cross = X-ray source
Dotted line : EGRET error circle
Contours: TeV source intensity

Spectral Measurements: Mrk 501

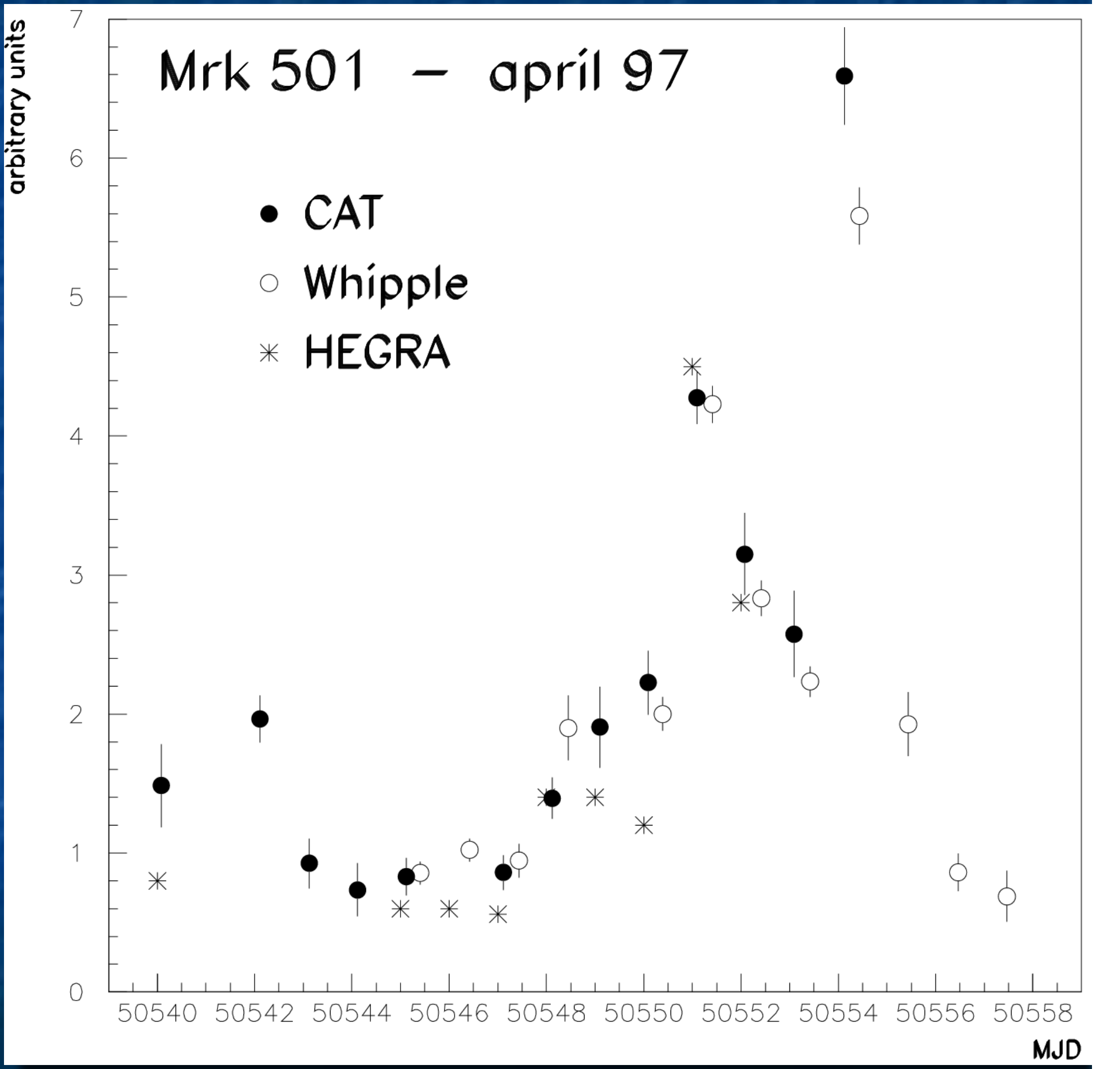


Composite spectrum of Markarian 501 showing consistency of measurements by several telescopes and detection of structure in shape of spectrum…power law plus exponential cutoff.

Aharonian et al. 1999

TeV γ-ray observations: consistency!

- High statistical significance
- Excellent agreement between ground-based experiments



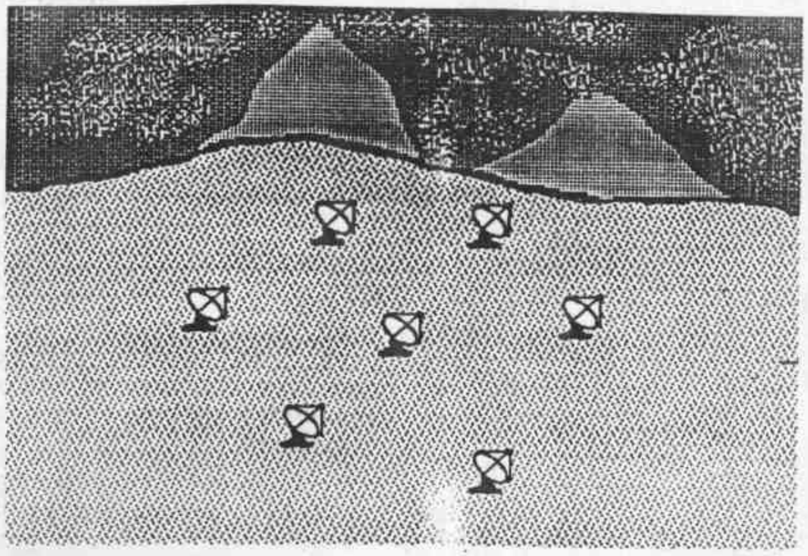
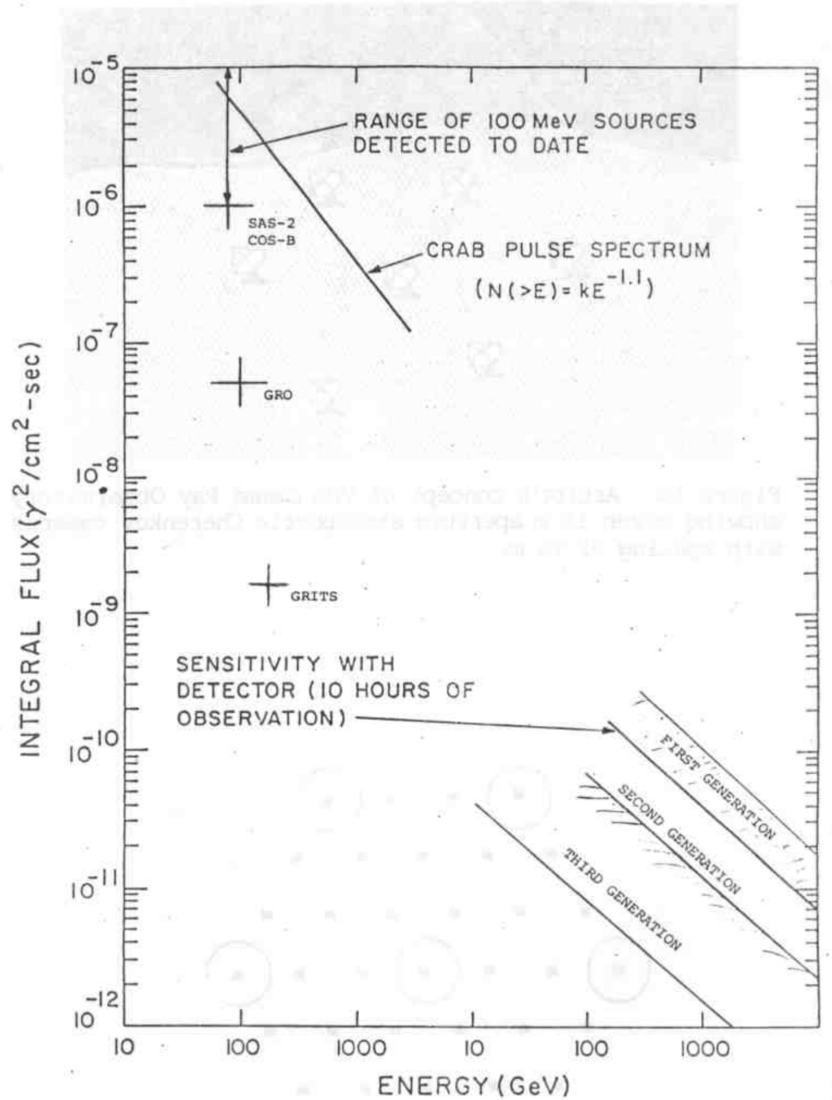


Figure 1a. Artist's concept of VHE Gamma Ray Observatory showing seven 15 m aperture atmospheric Cherenkov cameras with spacing of 75 m.

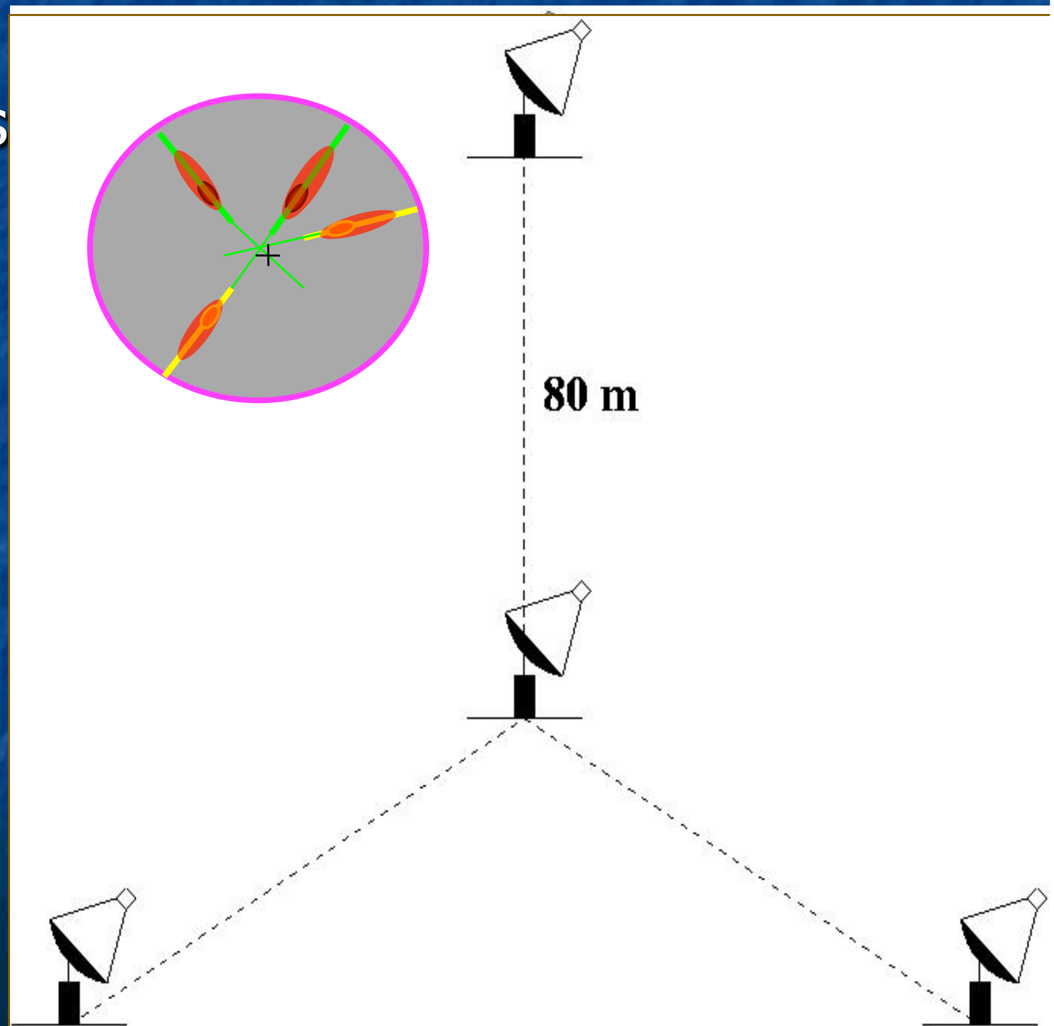


- An array of ACIT's was first proposed in 1984 (prior to the detection of the Crab Nebula).
- (NASA Workshop, Space Lab. Science, Baton Rouge, 1984)
- This is the configuration that was later adopted for VERITAS.

VERITAS Concept: 1996 →2003

VERITAS Philosophy

- Better Flux Sensitivity
- Array of "12 m" telescopes
- Imaging Cameras
- Improved Optics
- Improved Camera
- High Data Rate
- Flexible Operation
- Sub-arrays
- Reliable Operation
- New Technology where proven.



Brief History of GeV-TeV ground-based Gamma-ray Astronomy

- First Generation Systems 1960 – 1985
  - Weak or no discrimination
  - Crimea, Dublin, Whipple, Narrabri, ……….
- Second Generation Systems 1985 – 2003
  - Atmospheric Cherenkov Imaging Telescopes
- Whipple, Crimea, CAT, HEGRA, Durham, CANGAROO

……

- Third Generation Systems 2003 – 2010
  - Arrays of Large ACITs
  - MAGIC-2, HESS-5, CANGAROO-III, VERITAS-4
- Fourth Generation Systems 2014? -
  - TBD

TeV Sources

Zero

~ 10

> 100

1000?

We have come a long way! 1967 - 2007