Gamma astronomy with ground based air Cherenkov telescopes and other ground based detectors

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Lecture for Physics 801, March 2006

Lecture 1:

- Showers
- Characteristics of Cherenkov radiation
- Atmospheric optics, transmittance, lnight sky background
- Signal to noise analysis
- Physics backgrounds, event rates

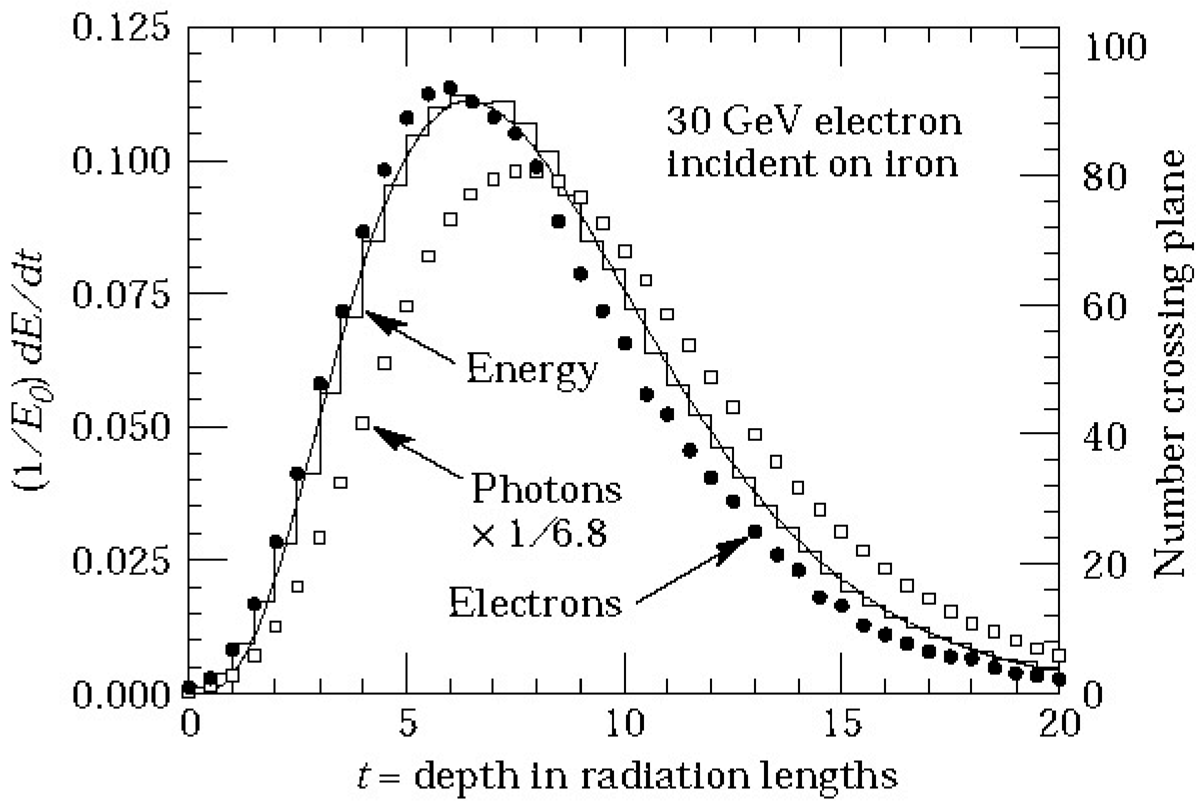
Lecture 2:

- Background rejection by image analysis
- Stereoscopic analysis principle
- Historic development
- Ground based Imaging air Cherenkov Telescopes
  - Third generation instruments
  - New developments
- Other techniques (wide angle):
  - Milagro,
  - AIROBICC,
  - IceCube

Brief review on showers

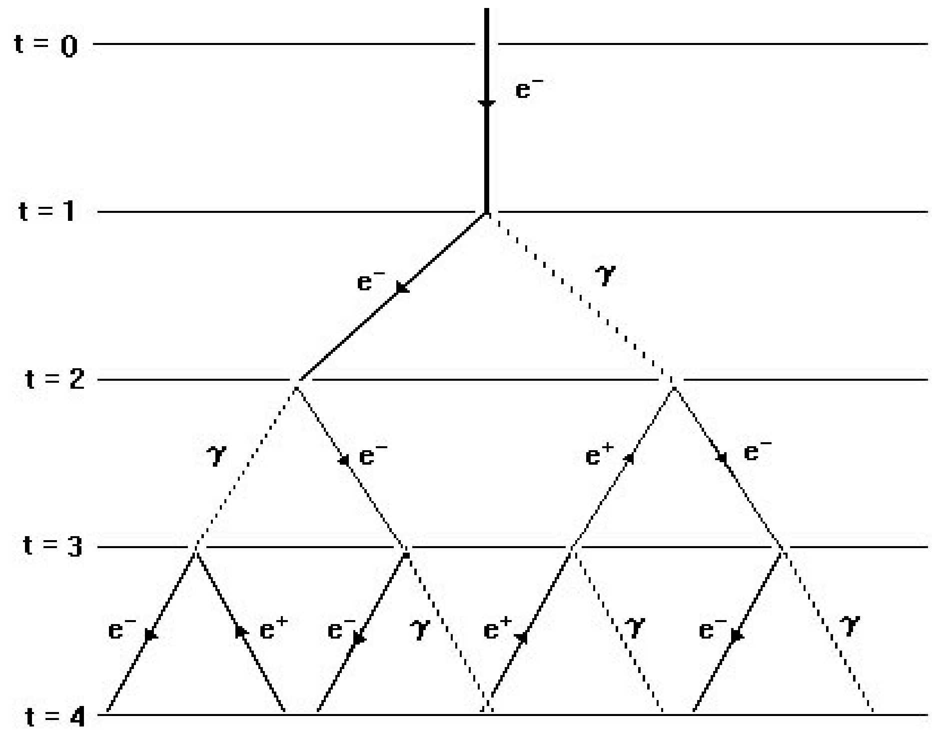
Gamma and hadron showers in the atmosphere

Electromagnetic cascades
“Showers”

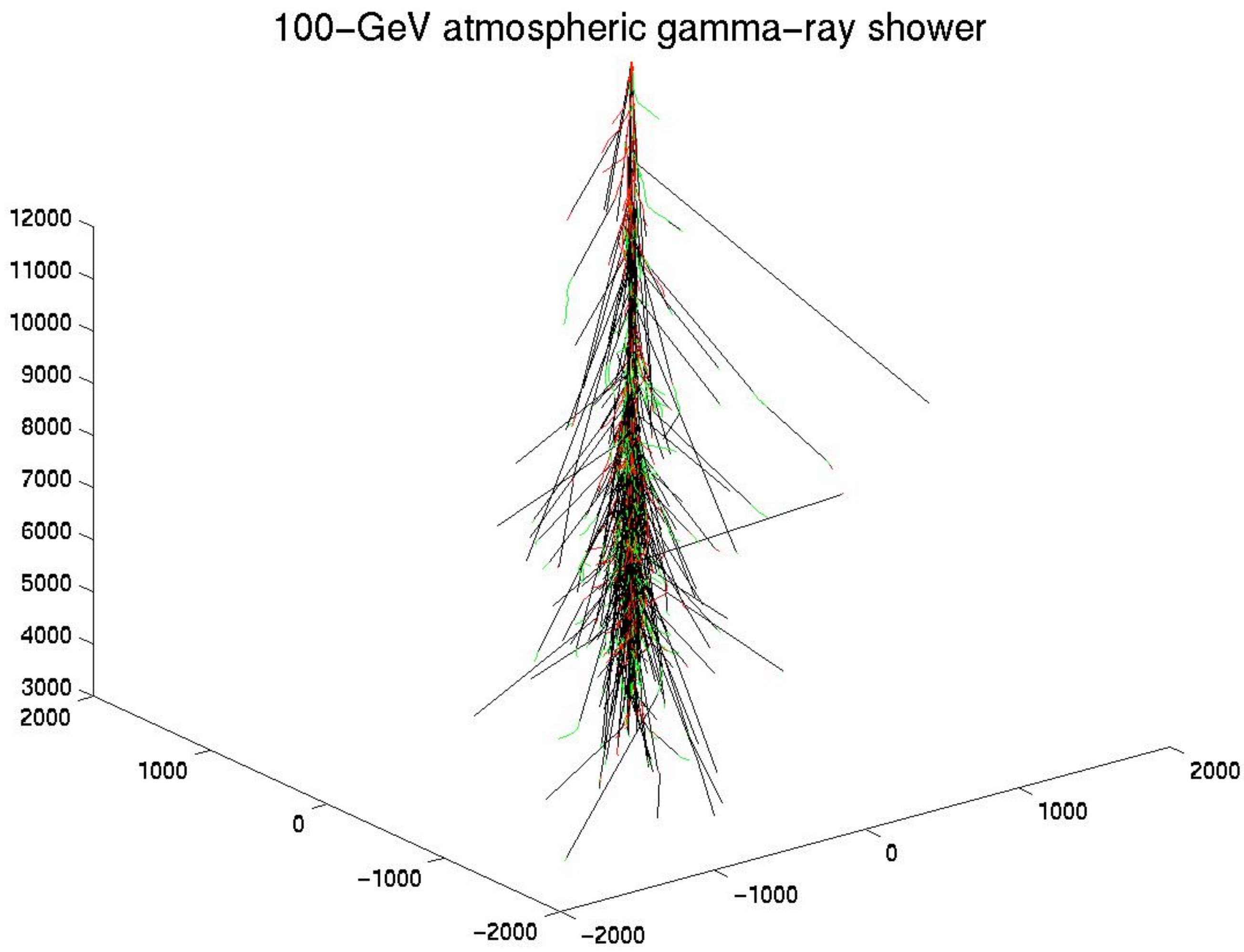


Toy model

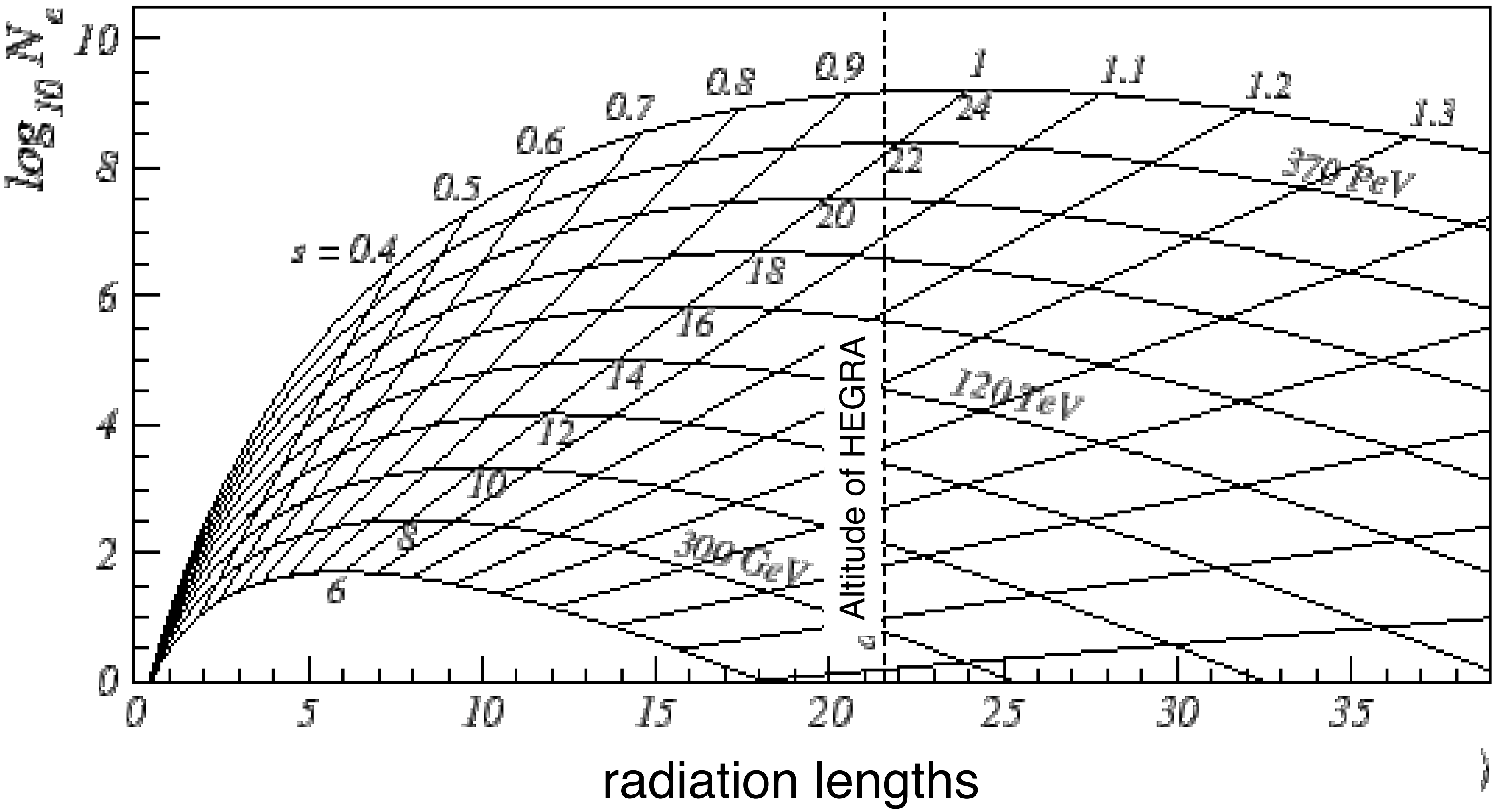
- The Cherenkov light production scales with the integrated track length of charged particles.
- Most of the light is generated by the low energy electrons at the end of the shower development.
- The Cherenkov threshold matters because a lot of light is produced in the last generation.



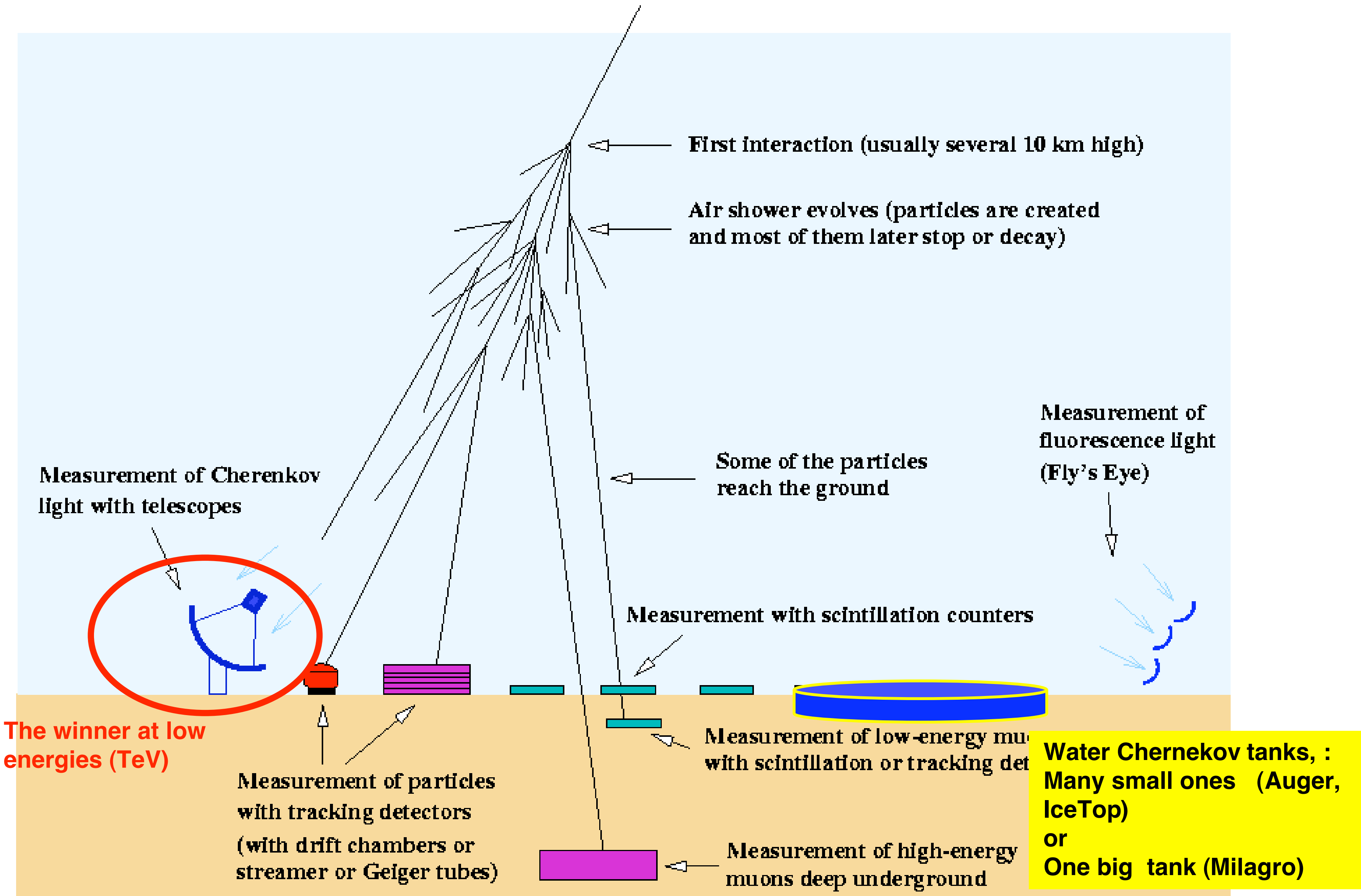
Monte-Carlo simulation of a 100 GeV gamma ray shower in the atmosphere



Electromagnetic showers
-longitudinal profile

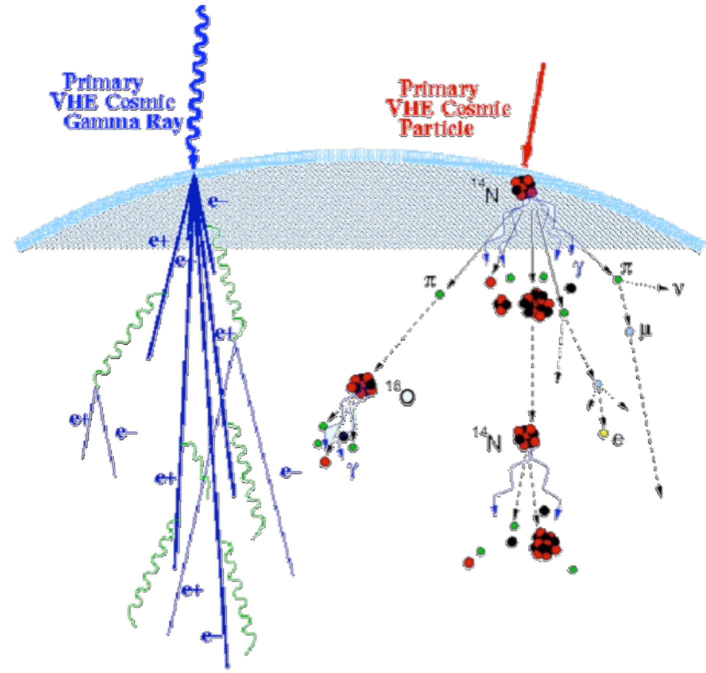


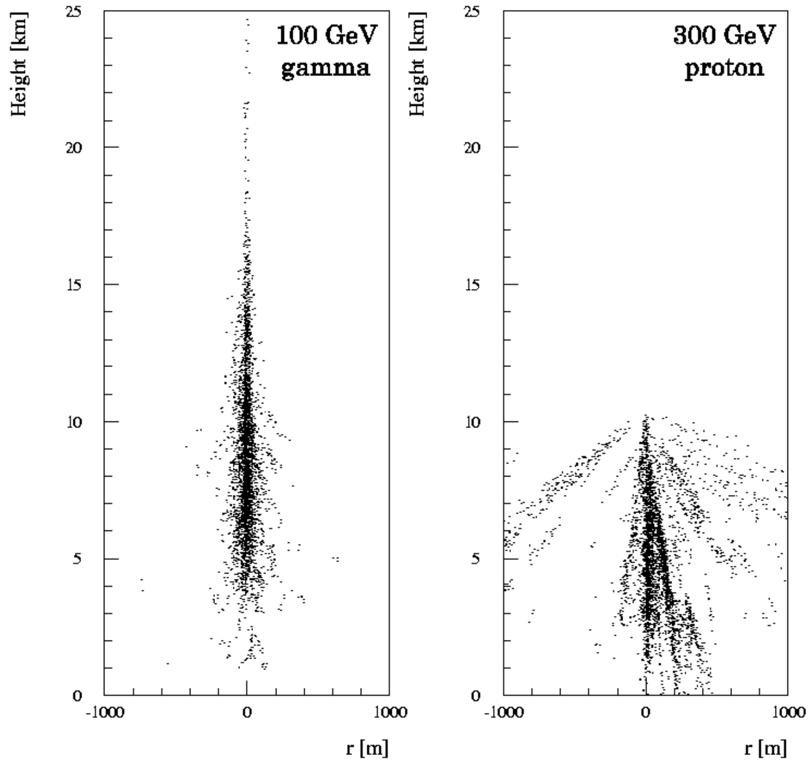
Measuring cosmic-ray and gamma-ray air showers



Hadronic and e.m. showers

- Electromagnetic showers develop more regularly, with less fluctuations.
- In the 300 GeV shower one can see jets of secondaries.
- At higher energies they are more strongly forward boosted.
- The difference in structure can be used for particle identification.





Gamma Ray Astronomy

Energy Range	Nomenclature	Detection Technique
10MeV-30GeV	high(HE)	satellite based detectors
30GeV-30TeV	very high(VHE)	ground based atmospheric Cherenkov detectors
30TeV and above	ultra high (UHE) and extremely high (EHE)	ground based air-shower particle detectors and ground based air-fluorescence detectors

Cherenkov radiation

Some important properties of
Cherenkov radiation
in general and
in air showers specifically

Cherenkov - basic formulas

- The Cherenkov angle can be used to measure beta (momentum). Ring imaging detectors in lab experiments.
- Cherenkov condition: $\beta > 1/n$ ---> $\theta > 0$
- The energy threshold (Lorentz factor) is determined by the refractive index.
- The number of photons scales with lambda^{-2}: Cherenkov light is blue in typical media such as water and air.
- The number of photons scales with $\sin^2\theta$

$$\cos\theta = \frac{1}{n\beta}$$

$$\gamma > \frac{1}{\sqrt{1-n^{-2}}}$$

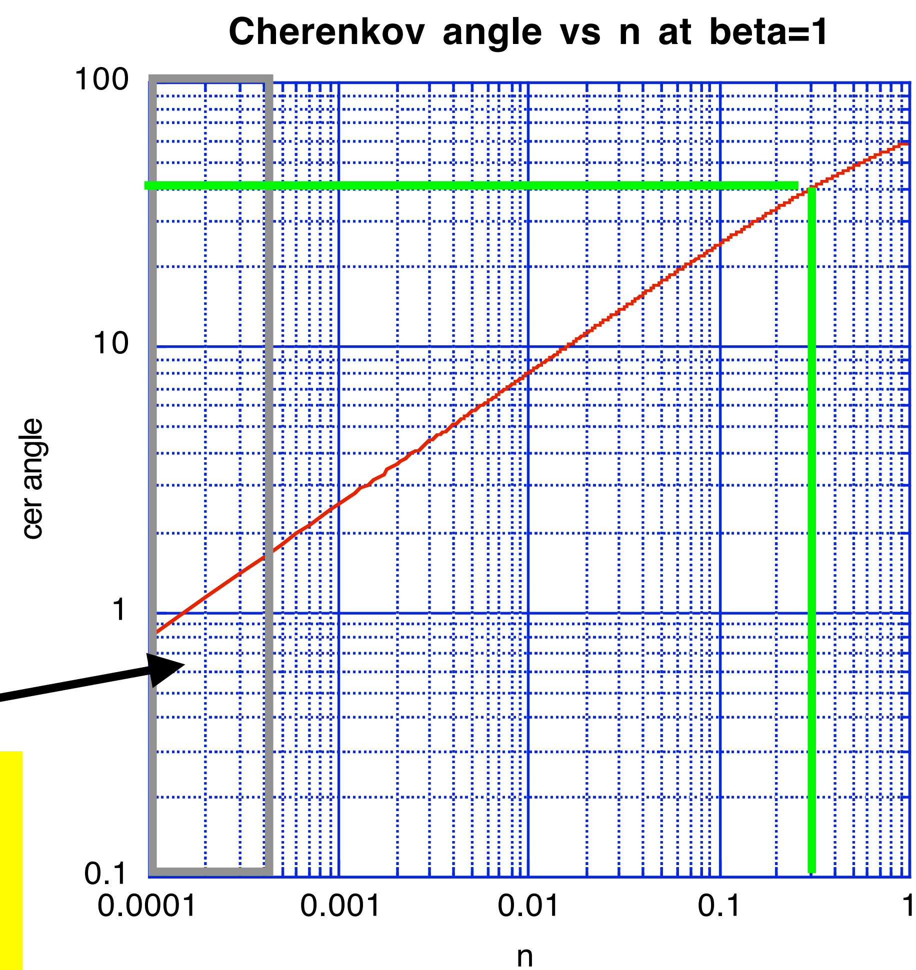
$$\frac{dN}{dx} = 2\pi\alpha z^2 \int \left(1 - \frac{1}{n^2\beta^2}\right) \frac{d\lambda}{\lambda^2}$$

$$\frac{dN}{dx} = 2\pi\alpha z^2 \int \sin^2\theta \frac{d\lambda}{\lambda^2}$$

Cherenkov angle at β=1

- The Cherenkov angle increases with the refractive index (more specifically with n-1, will revisit this later.)

- Water ≈ 41°
- Air ≈ 1.0 to 1.3°



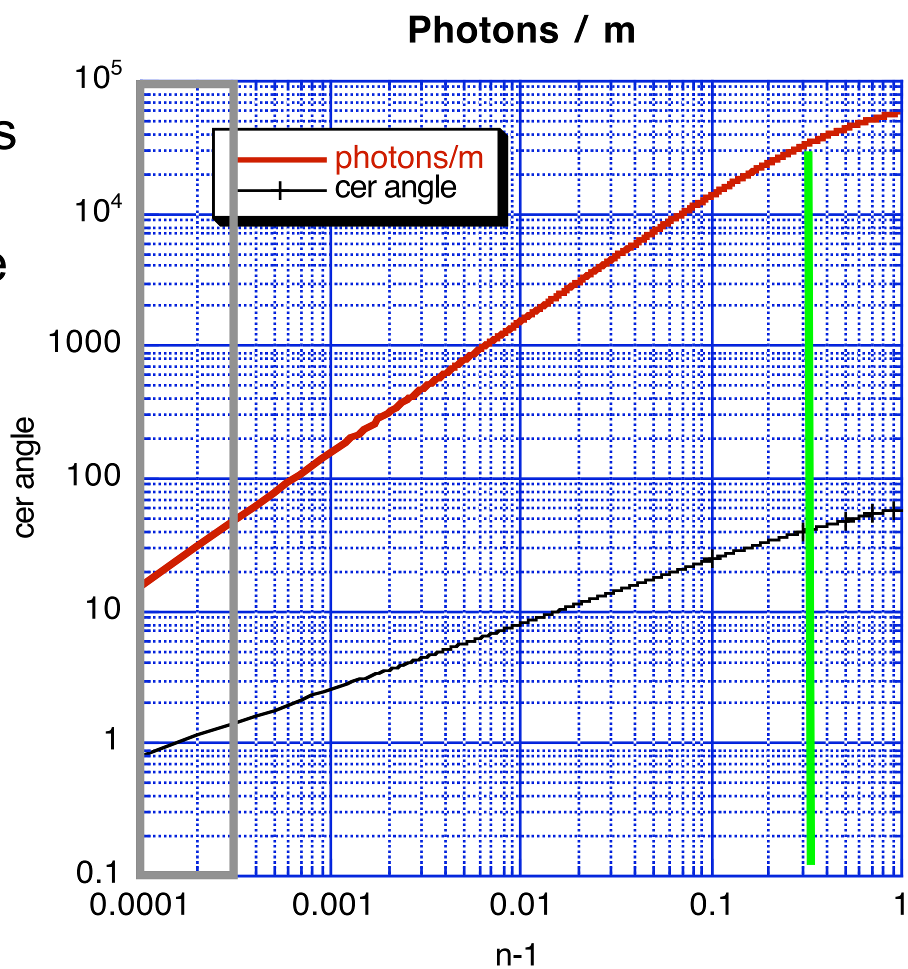
Atmosphere:
Increasing density down to sea level (n=1.0003)

→Changing Cherenkov angle
→Unique optics

Water/ice detectors
n=1.33

Cherenkov light and refractive index

- Number of Cherenkov photons for $\beta=1$ particles as function of the refractive index, or more precisely of (n-1).
- Integrated from ≈400 to 700 nm.



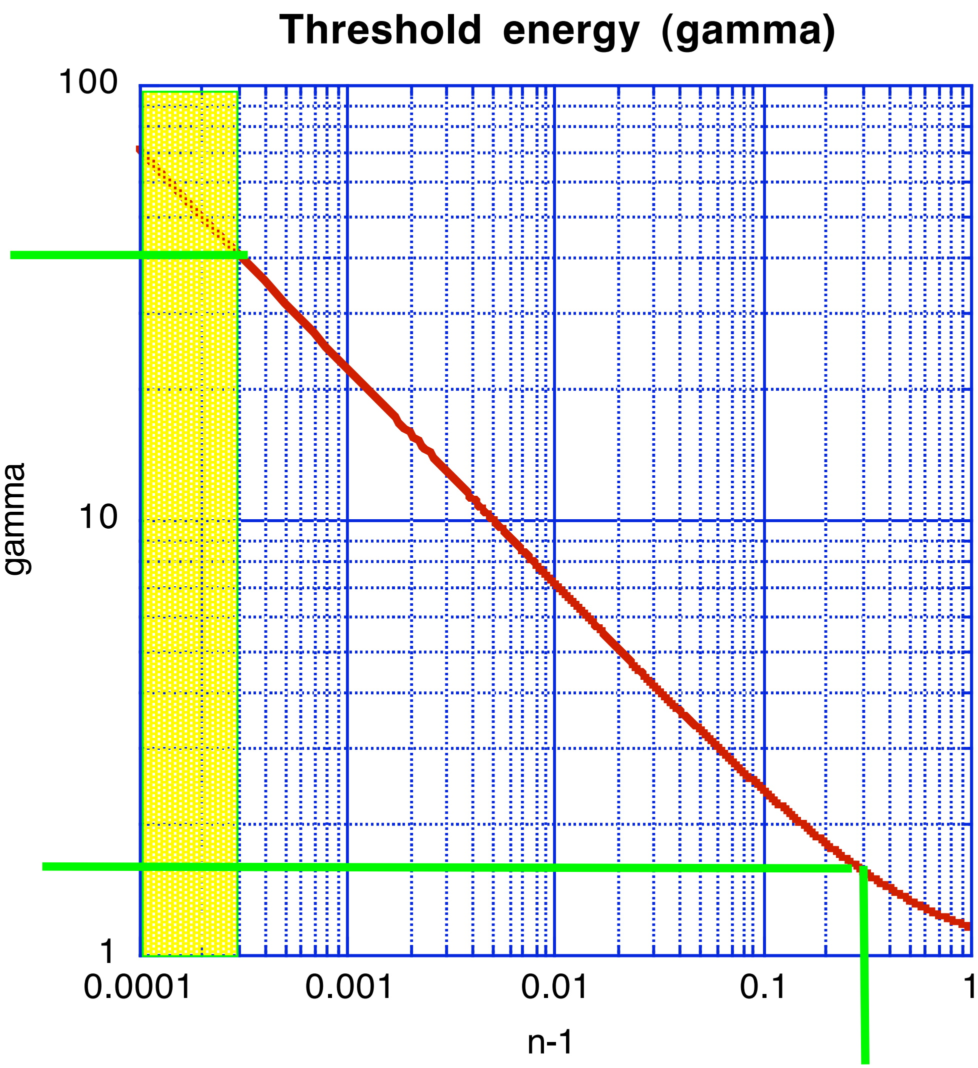
Threshold for Cherenkov radiation

- Dependence of energy threshold for Cherenkov radiation on the refactive index, if beta=1.

Lorentzfactor
- Air: 40
- Water or ice: 1.7

Threshold energy for electrons:
- Air: 20 MeV
- Water/ice: 0.7 MeV

- Implications for angular distribution of photons in air and water. More multiple scattering of low energy electrons in water.



Atmospheric optics

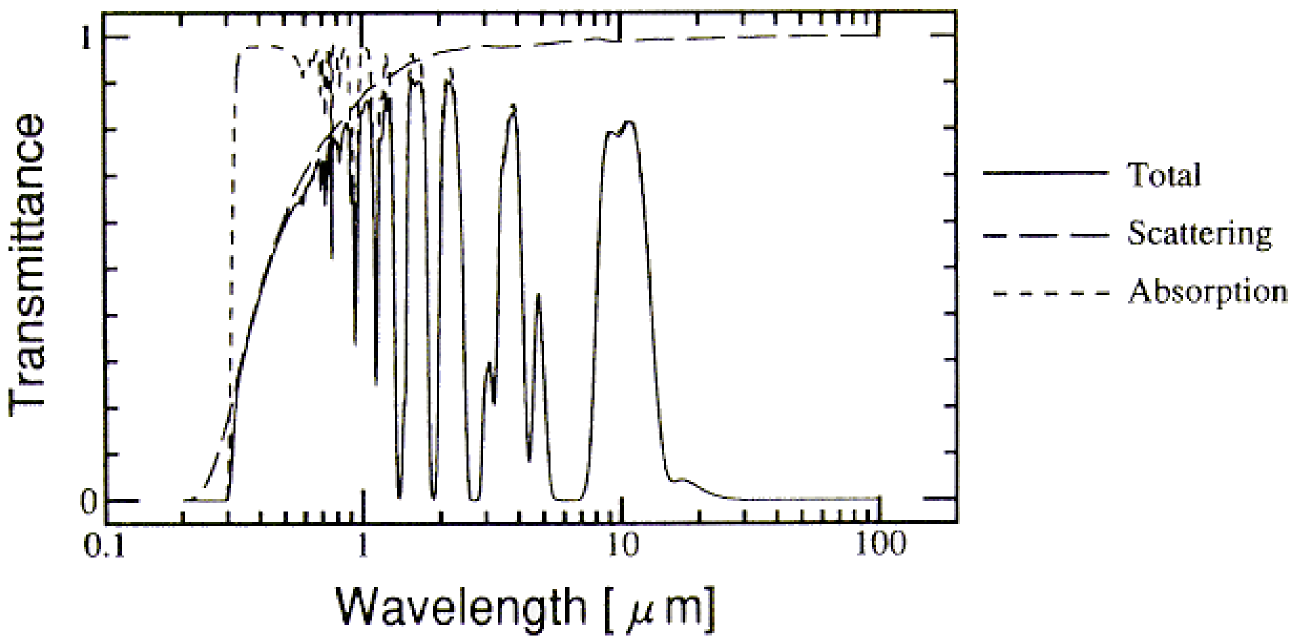
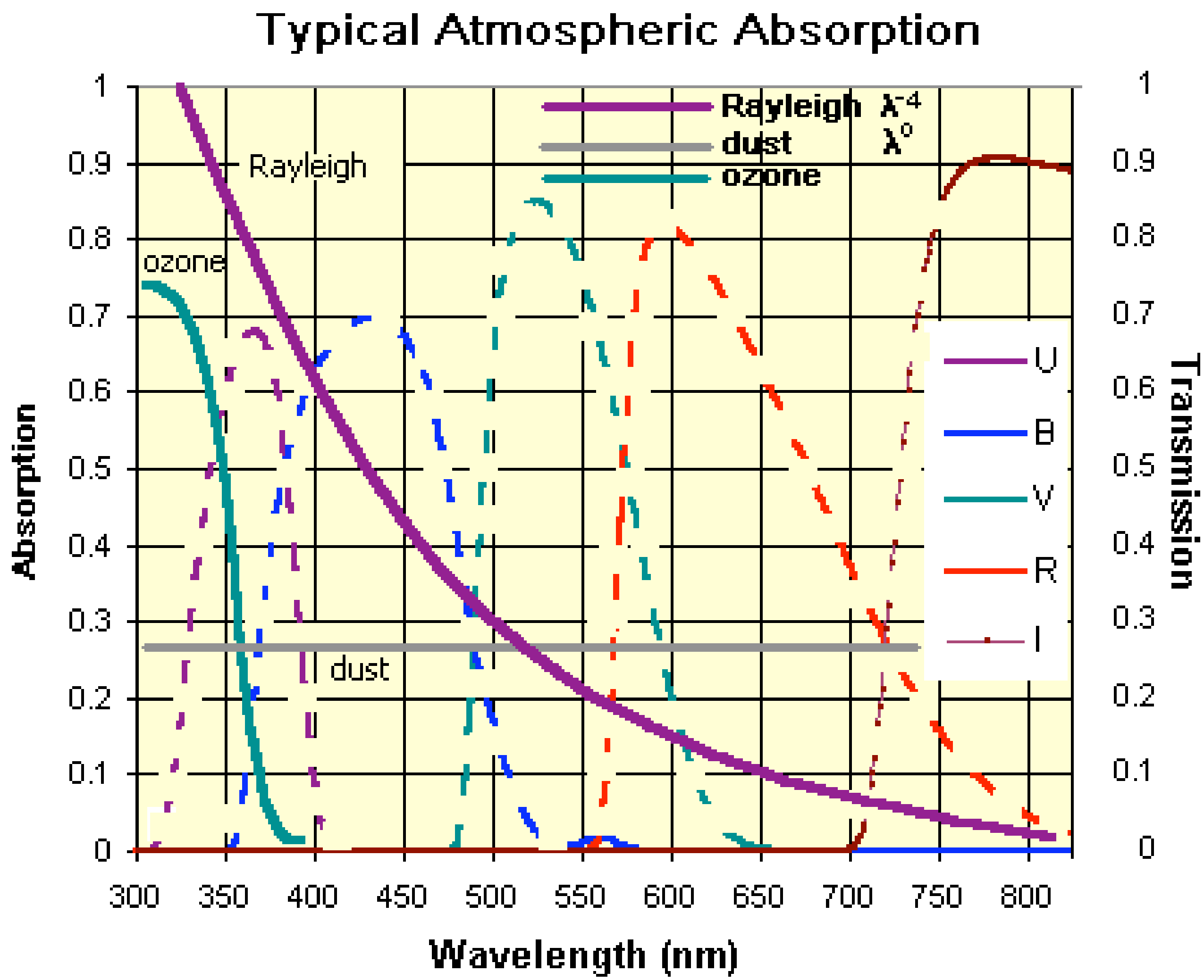


Figure 1.11.3 Atmospheric transmittance with contributions of absorption and scattering for "Clean" U.S. standard atmospheric model

Atmospheric extinction

1. Rayleigh scattering
2. Absorption by ozone, above ≈20 km
3. Aerosol , dust,…



Night Sky

- Moon
- Airglow
  - the brightest component and is caused by oxygen atoms glowing in the upper atmosphere which are excited by solar ultraviolet radiation. Airglow gets worse at solar maximum. (increases towards red)
- Zodiacal light
  - Interplanetary dust particles reflect and scatter sunlight and make up the zodiacal light and gegenschein (increases towards red)
- Star light
  - Stars mostly from Milky way
  - includes starlight is scattered by the atmosphere, just as sunlight is during the daytime. (Slightly blue)
- Aurorae borealis:
  - Cosmic ray particles from solar wind cause glow in upper atmosphere; mostly in polar regions where they spiral down the magnetic poles.

- Moonless night sky total background: $\approx 10^{12}$ photons/(m^2s sr) (± factor ≈2)

Homework problem

- Plot the photon density of a vertical muon (β = 1) versus the distance of the impact on ground level (assume mountain altitude of 2400m.)
  - You may use the barometric formula for the pressure (density) depth profile. (There is a practical formula with constants in the textbook by Gaisser.)
  - P(h) = P0 * exp (m g h / k T)

- What is the largest distance of photons from the muon at ground level?
- Make a suggestion for a detector that is sensitive to detect muons at that elevation. Imagine that all you want to measure is the muons. (Conceptual answer.)
  - Consider a night sky background of 10^12 photons/m^2/s/sr.
  - Ignore other backgrounds and absorption in the atmosphere (except for UV cutoff)

Cherenkov radiation from air showers

- Basic characteristics
- Light distribution on ground
- Dependance of light yield on
  - height of shower maximum
  - Energy
  - Primary particle
- Calorimetric function, also in atmosphere.

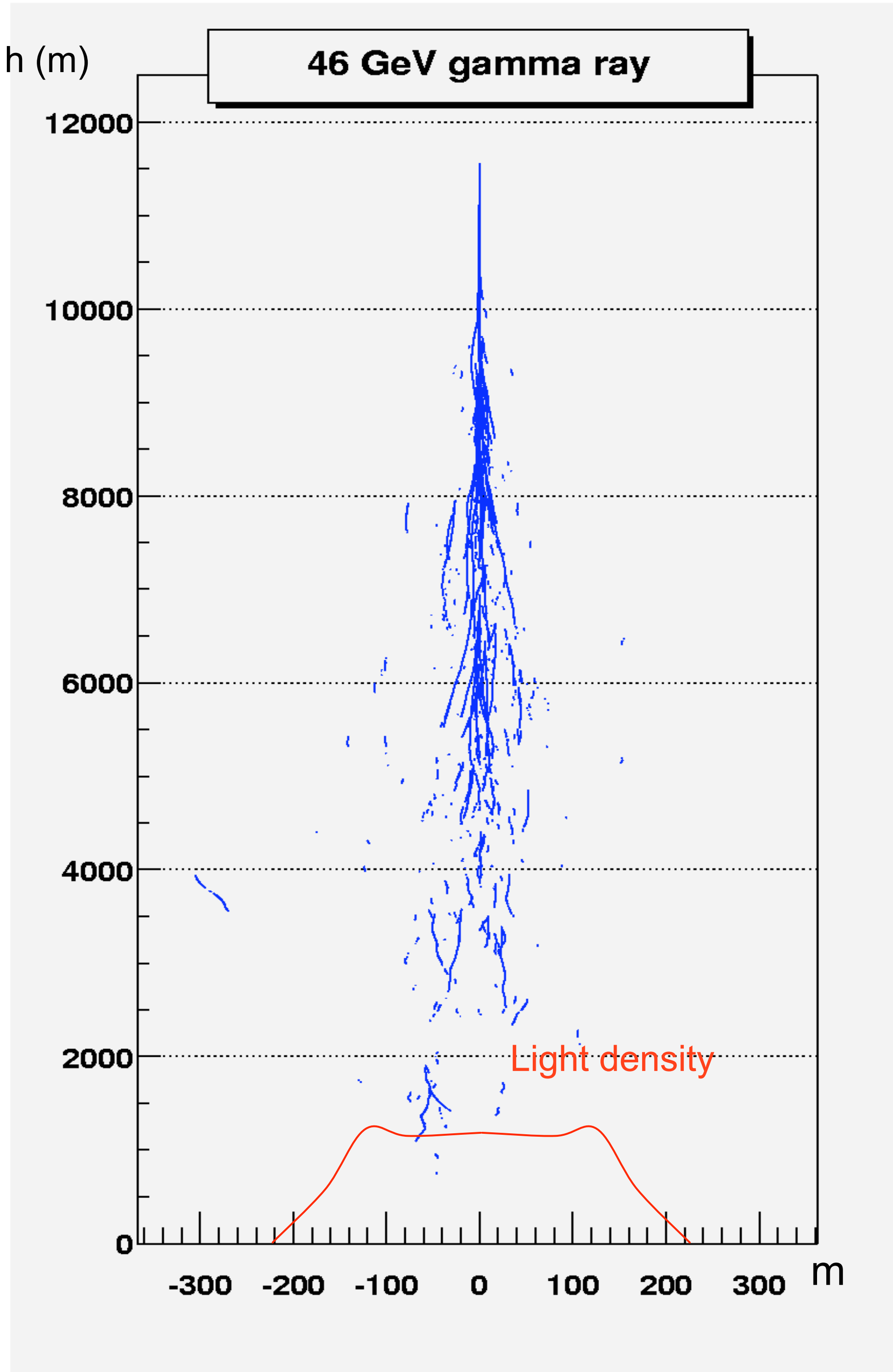
The Cherenkov Technique

Gamma rays initiate showers of charged particles ($e^{\pm}$) on entering the atmosphere

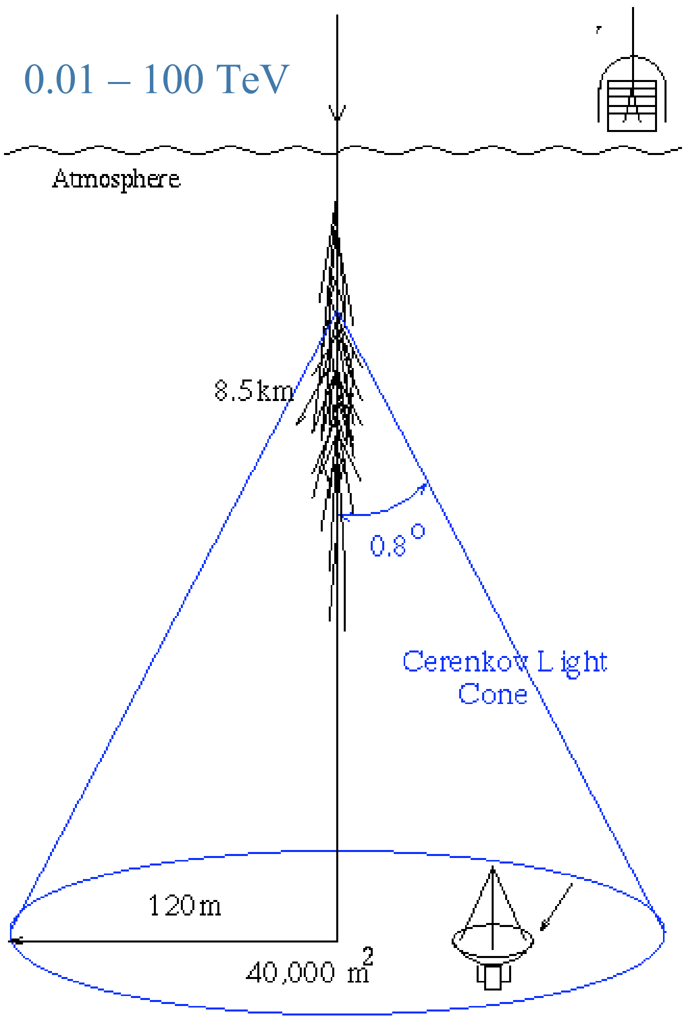
High energy $e^{\pm}$ ($v > c/n$) emit Cherenkov light which reaches ground level as a short flash (≈ 3 ns)

High background rate due to hadronic showers.

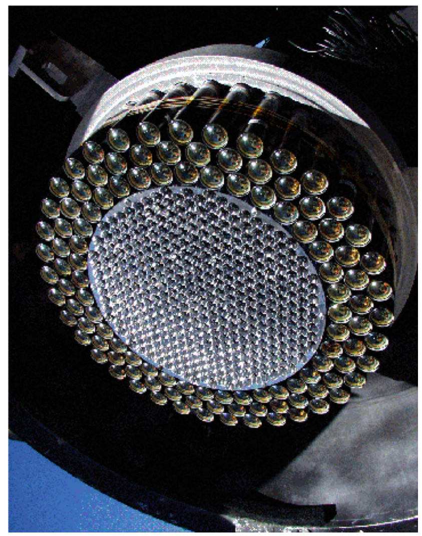
Light contamination from NSB, moon, stars.



The Whipple Cherenkov telescope 10m



Imaging Camera

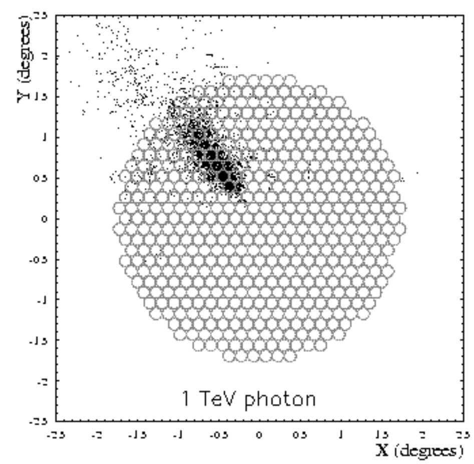


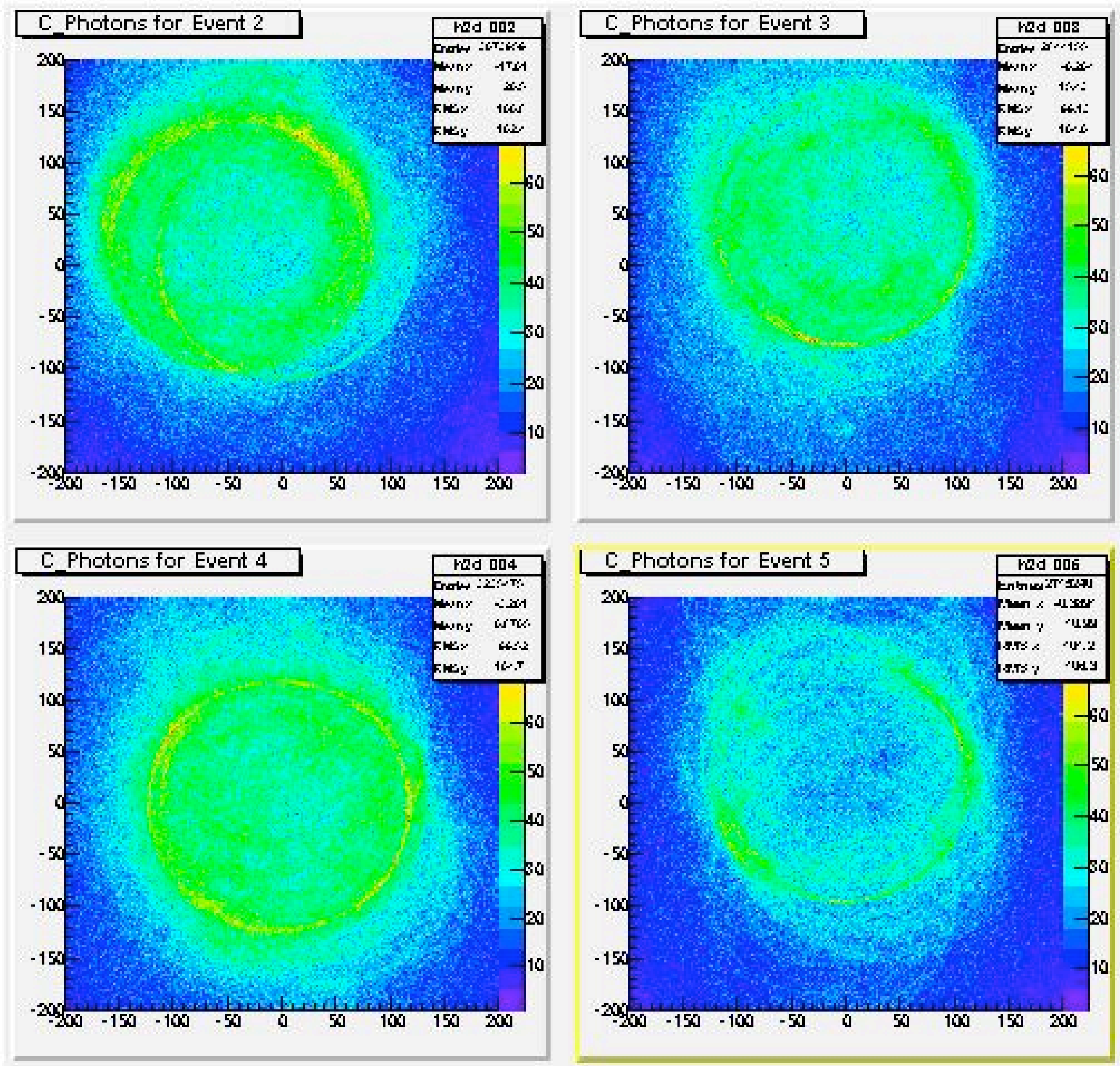
Area ~ 100,000 m^2

E ~ 0.2 – 100 TeV

$\Delta\theta/\theta$ ~ 0.2 ^{o}

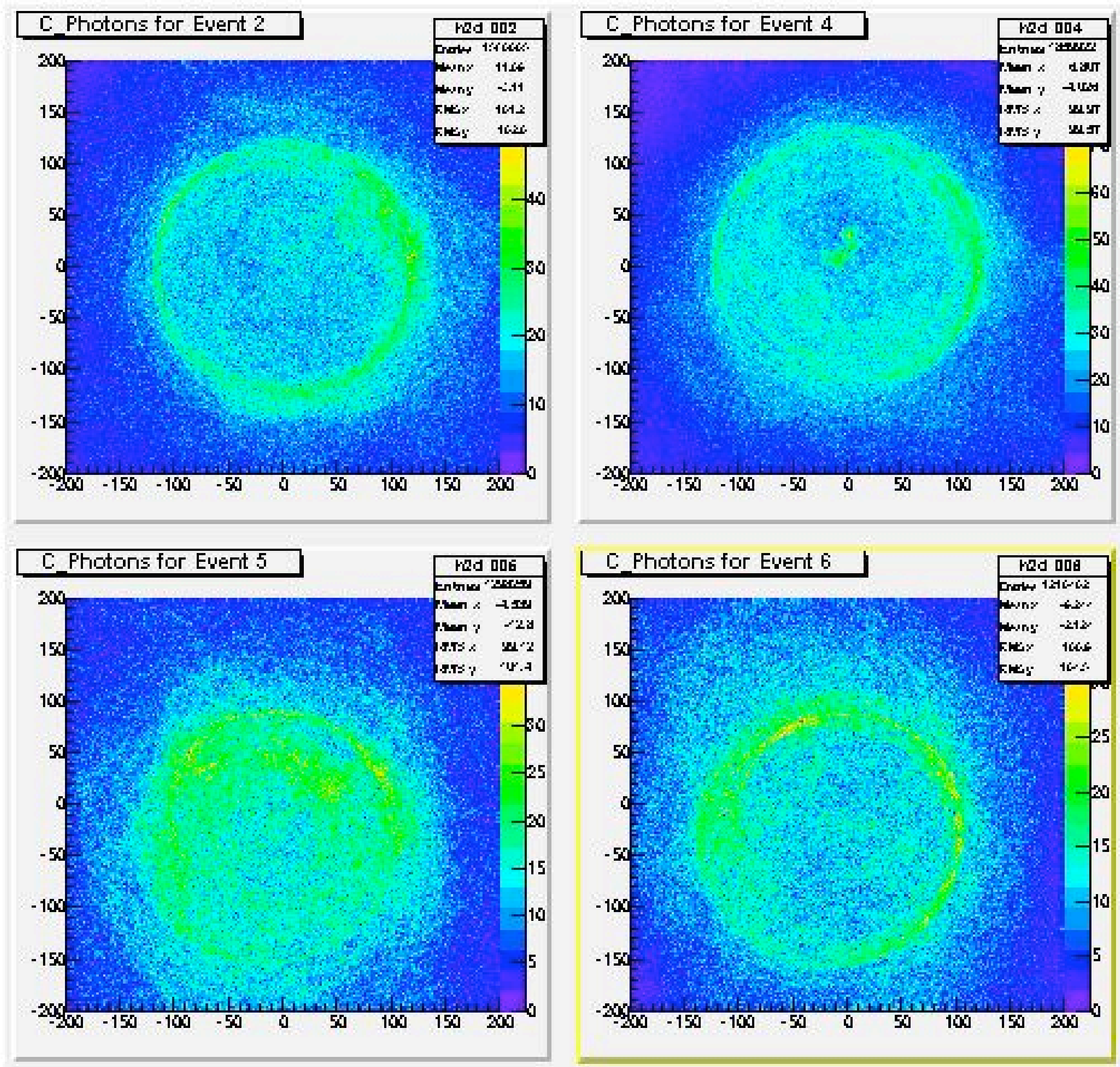
100 optical photons/m^2 TeV within a few ns



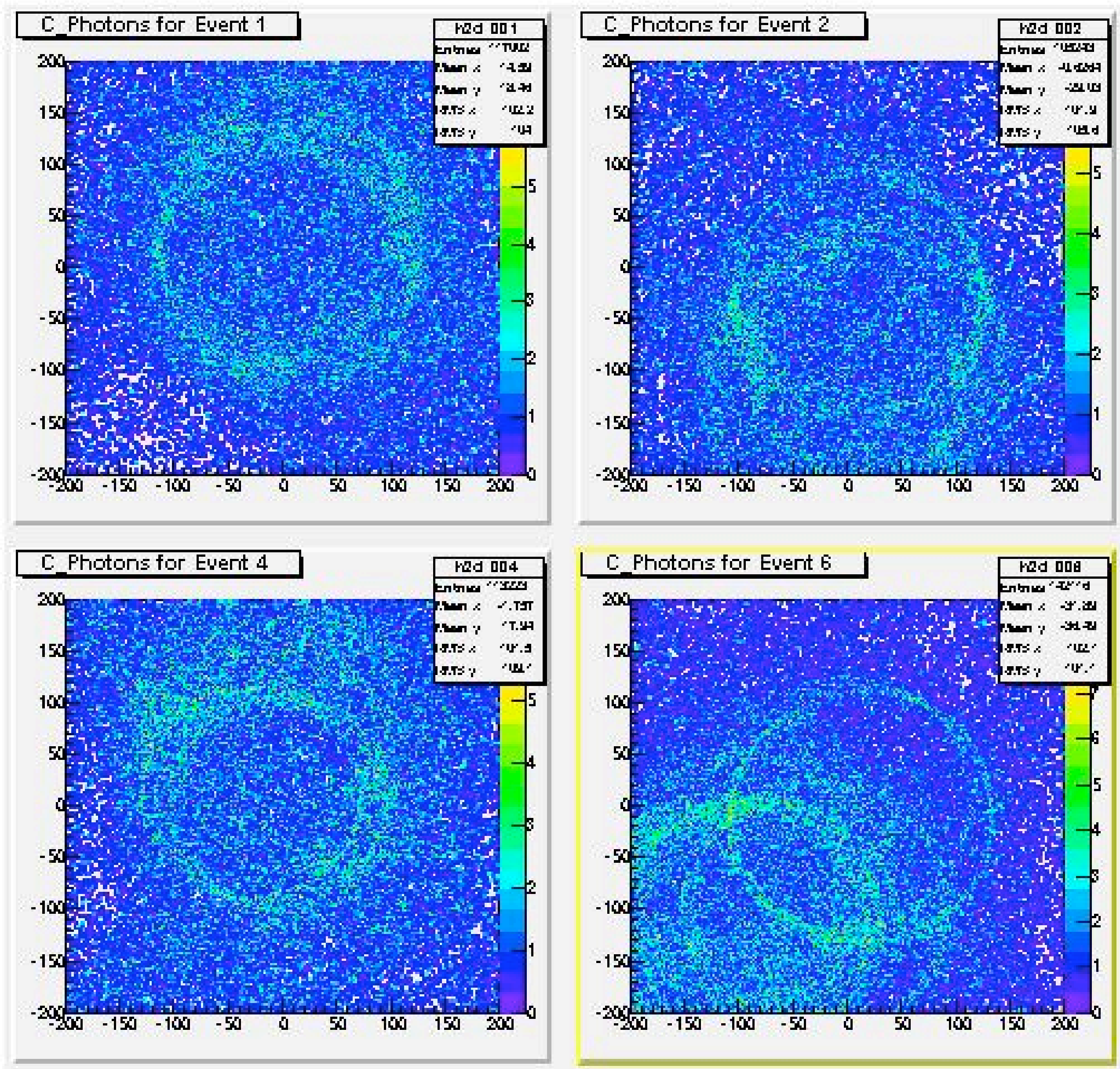


γ
shower
100 GeV

photon
density
on the
ground



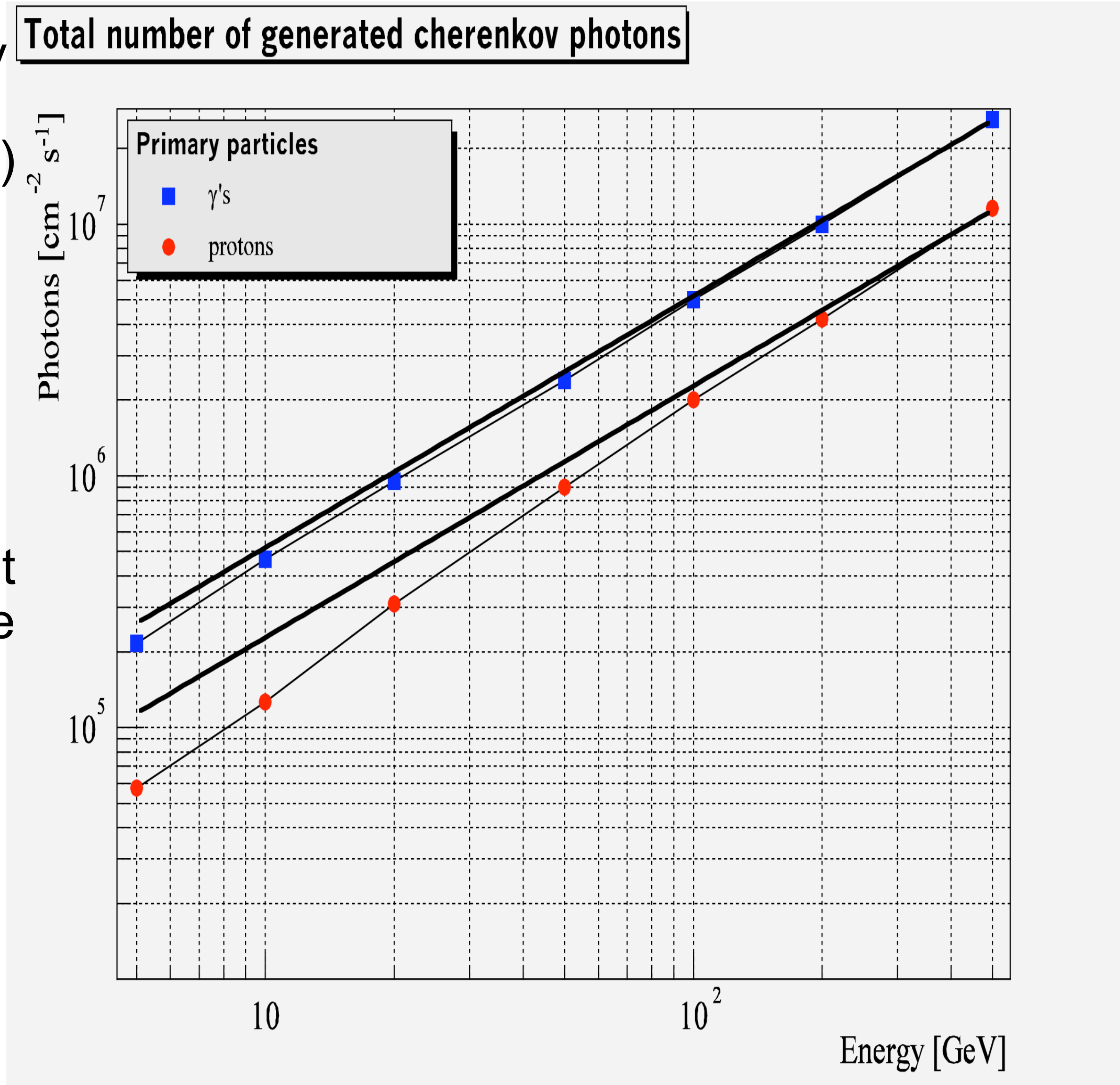
γ
shower
50 GeV



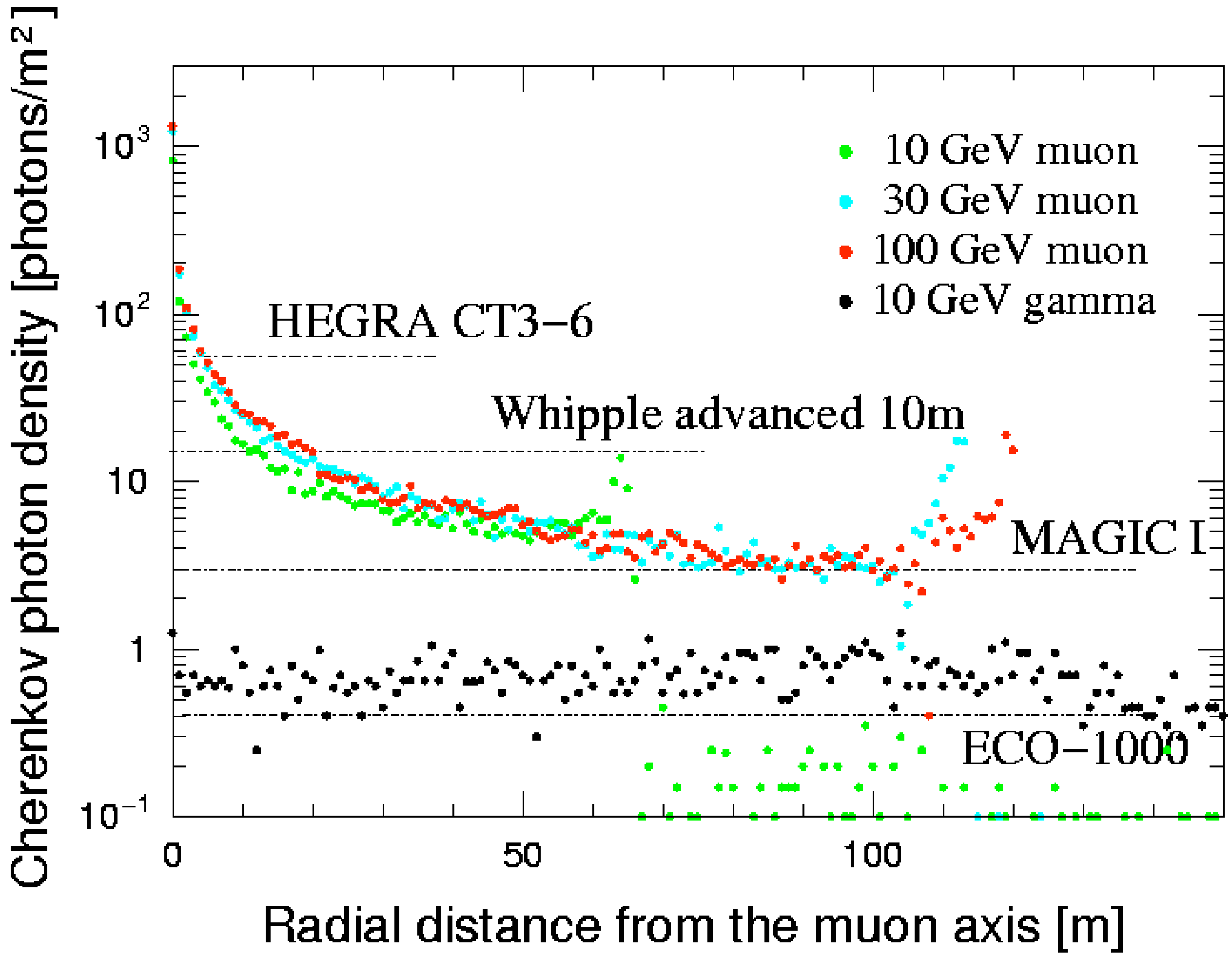
γ shower 5 GeV

Characteristics of low energy showers

- Total number of Cherenkov photons ∝ energy of primary γ. (~50000 ph/GeV)
- Decreasing number of photons for proton induced showers due to lower energy (below Cherenkov threshold) of electromagnetic component with energy. Remember the discussion on threshold.
- Higher lateral spread due to high p_t interactions reduces density.



Cherenkov photons from muons



How to detect a 100 GeV shower? Signal to noise analysis

- Night sky background: ϕ_{NSB} = 10^{12} photons/(m^2 s sr)
- Cherenkov pulse: ϕ_{Ch} = 10 photons/m^2/3ns
- Transmittance of atmosphere
- qE=quantum efficiency
- Instruments: PMT, mirrors, electronics
- Number of signal photoelectrons: ϕ_{Ch} * A * T *qE
- Number of background photoelectrons: ϕ_{NSB} * A *T*qE* $\tau * \Omega$
- Solid angle greater than shower (> 1 degree)

$$\frac{Signal}{Noise} = N_\sigma = \frac{\Phi_{ch} \cdot A \cdot T \cdot qE}{\sqrt{\Phi_{NSB} \cdot A \cdot \Omega \cdot T \cdot qE \cdot \tau}}$$

$$N_\sigma = \Phi_{ch} \sqrt{\frac{T \cdot A \cdot qE}{\Phi_{NSB} \cdot \Omega \cdot \tau}}$$

How to detect a 100 GeV shower? What detection area is needed?

- Night sky background: $\phi_{NSB} = 10^{12}$ photons/(m^2 s sr)
- Cherenkov pulse at 100 m distance: ϕ_{Ch} = 7 photons/(m^2 2ns)
- τ = 2 ns (This is the limit.)
- qE = 0.25 (not easy to change, will talk about that later)
- $N_\sigma=5\sigma$ (Not a final trigger, the noise rate at 2ns gate would be (1/2ns)*(1-0.9999997) = 150Hz. Other trigger conditions may be added at a later stage.)
- T=1 (for simplicity)
- The only free design parameters are A and Ω

$$N_\sigma = \Phi_{ch}\sqrt{\frac{T \cdot A \cdot qE}{\Phi_{NSB} \cdot \Omega \cdot \tau}}$$

$$A = \left(\frac{N_\sigma}{\Phi_{ch}}\right)^2 \frac{\Phi_{NSB} \cdot \Omega \cdot \tau}{T \cdot qE}$$

How to detect a 100 GeV shower?
Case 1: wide angle detector w. Ω= 1 sr

- What detector area is required?

$$A = \left(\frac{N_\sigma}{\Phi_{ch}}\right)^2 \frac{\Phi_{NSB} \cdot \Omega \cdot \tau}{T \cdot qE}$$

$$A = \left(\frac{5}{\Phi_{ch}}\right)^2 \cdot 10^{12} m^{-2} s^{-1} \cdot 2 \cdot 10^{-9} s \cdot /0.25 \approx 200{,}000 m^2 \cdot \Phi_{ch}$$

E.g. Φ_ch(1 GeV) = 10 photons/m^2

$$A = \left(\frac{5}{7m^{-2}}\right)^2 \cdot 10^{12} m^{-2} s^{-1} \cdot 2 \cdot 10^{-9} s \cdot /0.25 \approx 4000 m^2$$

How to detect a gamma shower?
Case 1: wide angle detector w. Ω= 1 sr

- What A is required?

$$A \approx 200{,}000 m^2 / \Phi_{Ch}^2$$

E.g. Φ_ch(100 GeV,<120m) = 7 photons/m^2

$$A = \frac{200{,}000 m^2}{\left(7\, photons \cdot E / 100 GeV\right)^2} \approx \frac{40 m^2}{\left(E / TeV\right)^2}$$

Wide angle detector with Ω= 1 sr

$$A = \frac{200{,}000m^2}{\left(7\,photons \cdot E\,/\,100GeV\right)^2} \approx \frac{40m^2}{\left(E\,/\,TeV\right)^2}$$

$$E_{threshold}\left(TeV\right) = \sqrt{\frac{40m^2}{A}}$$

The rate for noise events of such a detector would be:(1/2ns)*(1-0.9999997)=150Hz.

This is not useful, yet. We need to limit the rate of an individual pixel or sensor to such a rate to have quality event information.

The area of a 20 cm PMT with a winston cone is 0.1 m^2.

This puts our final threshold for such a detector at 20 TeV.

This is the threshold of the AIROBICC wide angle Cherenkov array.

Case 2: Reduced field of view - the Cherenkov telescope $\Omega \approx 0.001$ sr

$$N_{\sigma} = \Phi_{ch} \sqrt{\frac{T \cdot A \cdot qE}{\Phi_{NSB} \cdot \Omega \cdot \tau}}$$

$$E_{threshold}(TeV, 1msr) \approx \sqrt{\frac{1m^2}{A}}$$

From our original signal/noise analysis we know that we can compensate area by reducing solid angle.

By reducing omega by a 1000, we can reduce the threshold by sqrt(1000). This was still not enough. Let's consider the Whipple telescope.

Area = 75m^2 ,

Ω for the whole camera = 1 msr

This allowed a substantial reduction in threshold and an increase in signal/noise to enable a sophisticated image analysis.

The real breakthrough was possible by using a camera with pixels. This step enabled more sophisticated triggering, an effective reduction in solid angle by another factor of 10, and the use of image analysis for gamma/hadron separation.

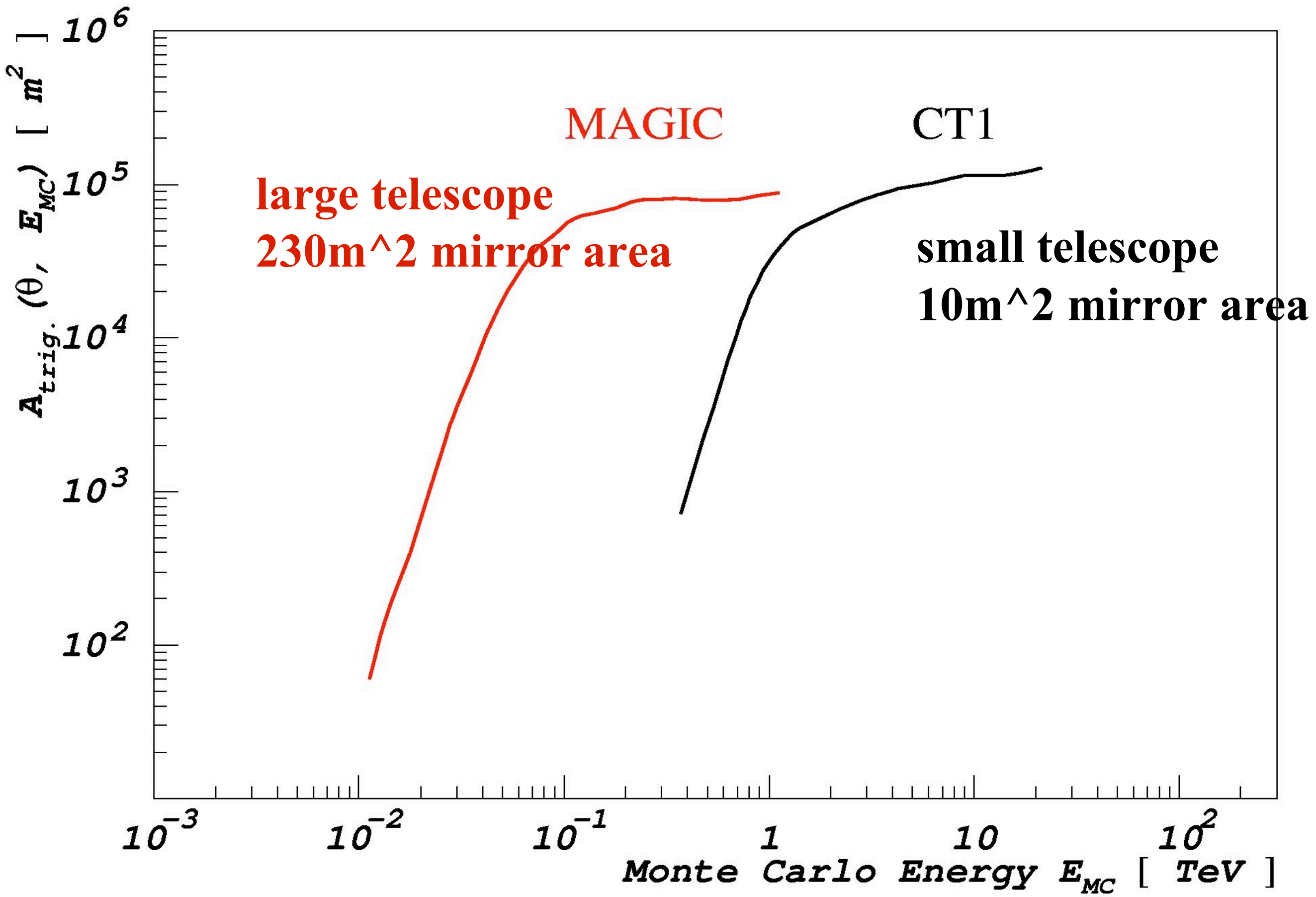
--> The IMAGING AIR CHERENKOV TELESCOPE

Caveats

- The above discussion is very simplistic and is intended to discuss the importance of important parameters.
- Realistic treatment requires a smulation to accound for
  - Lateral Cherenkov distribution
  - Triggering
  - Pixelation of camera
  - Importance and signal need for imaging technique
  - Atmospheric effects

Effective detector area (much larger than area of telescope)

- In case of MAGIC other improvements were made than just area.
- Threshold prop. 1/sqrt(A).
- Mirror quality, gate time, quantum efficiency, trigger algorithms, omega have changed, too.
- Effective area saturates at 60000m^2, not much Cherenkov light beyond 140m radius.



Physics Backgrounds

- Signal: gamma rays (em cascades)
- Backgrounds:
  - Cosmic ray showers
  - Cosmic ray primary electrons
  - Cosmic ray muons

Cosmic rays

- Diffuse flux, rate at 1 TeV: 0.27 (m^2s sr TeV)
- (change unit from GeV to TeV)

$$Rate = \int_{1}^{\infty} dN / dEdAd\Omega \cdot dE$$

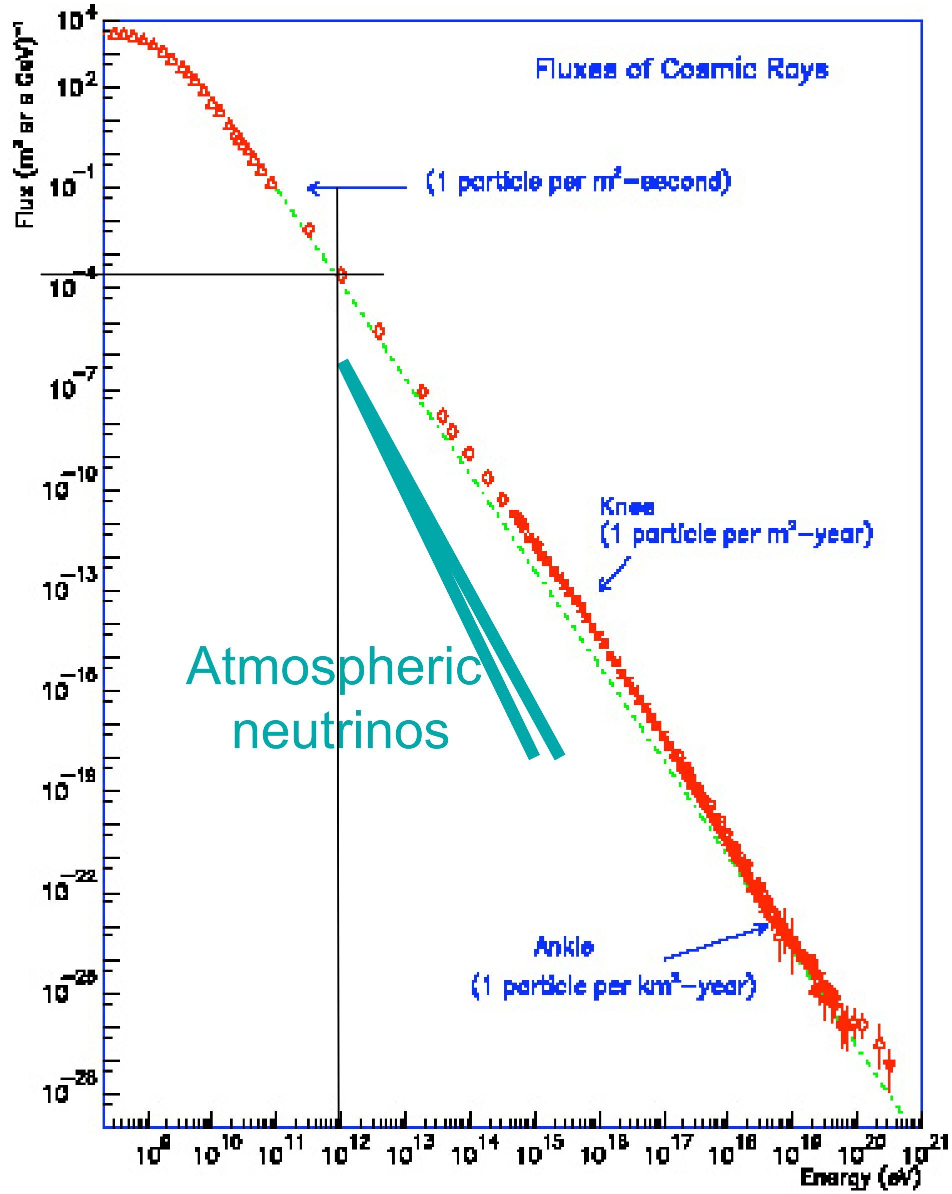
$$= 0.27 \cdot \frac{1}{m^2 s} \int_{1TeV}^{\text{inf}} E^{-2.7} dEdA$$

- Effective area TeV protons o(100,000m^2)
- FOV: o(0.005 sr)

$$Rate(E > 1TeV, 100000m^2, 5msr) =$$

$$(0.27/1.7) \cdot 10^5 / s \cdot 0.005 \approx 80Hz$$

- High background of cosmic rays in ground based cherenkov telescopes.
- Larger area, FOV results in bigger rate.
- Whipple 100 Hz, HESS 220Hz



CR trigger rates in the CT HEGRA (Simulation)

The threshold behavior is different for protons, helium and heavier nuclei.

Why?

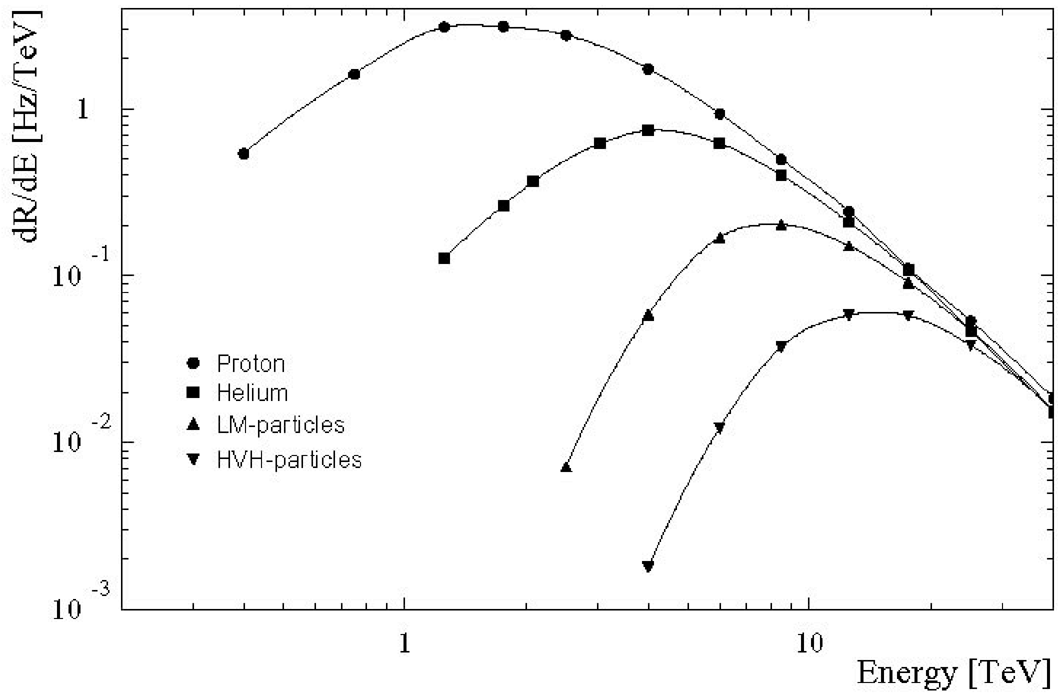


FIG. 3. Differential detection rates for different nuclei according to individual spectra following an identical power law. For a single telescope trigger a 2NN/271 > 10 ph.e. condition was applied. For the System trigger a 2/4 coincidence was required. Already on the trigger level, a clear suppression of heavier nuclei against protons can be seen. At the energy threshold for protons, this suppression amounts to at least a factor of 10.

What about CR electrons (and e+)?

- Electrons produce em. showers. Therefore they form an undistinguishable ultimate background to gammas.
- Fortunately the rate is low as the figure indicates, but it increases towards low energies.
- At 100 GeV the electron rate is ≈0.003 of the proton flux and 0.01 at 20 GeV.

24. Cosmic rays

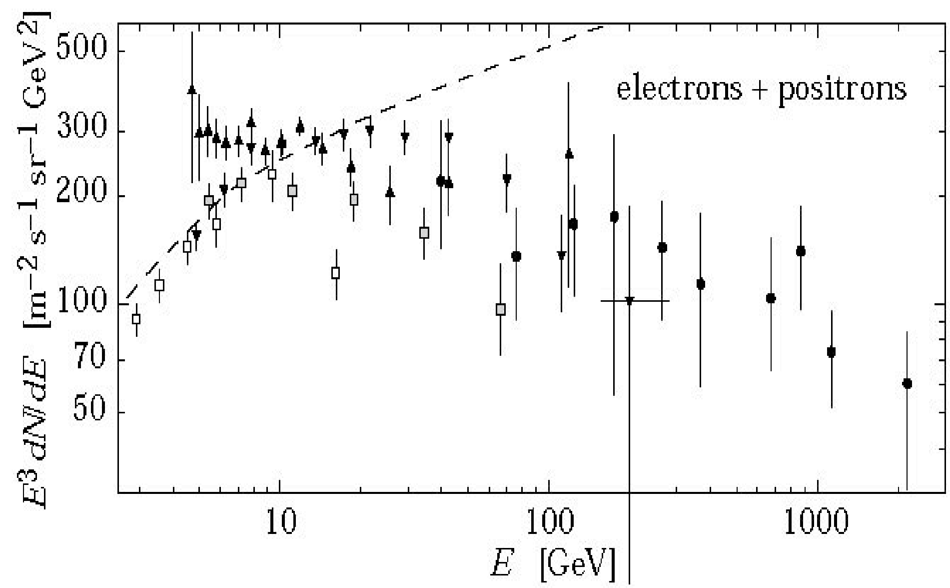
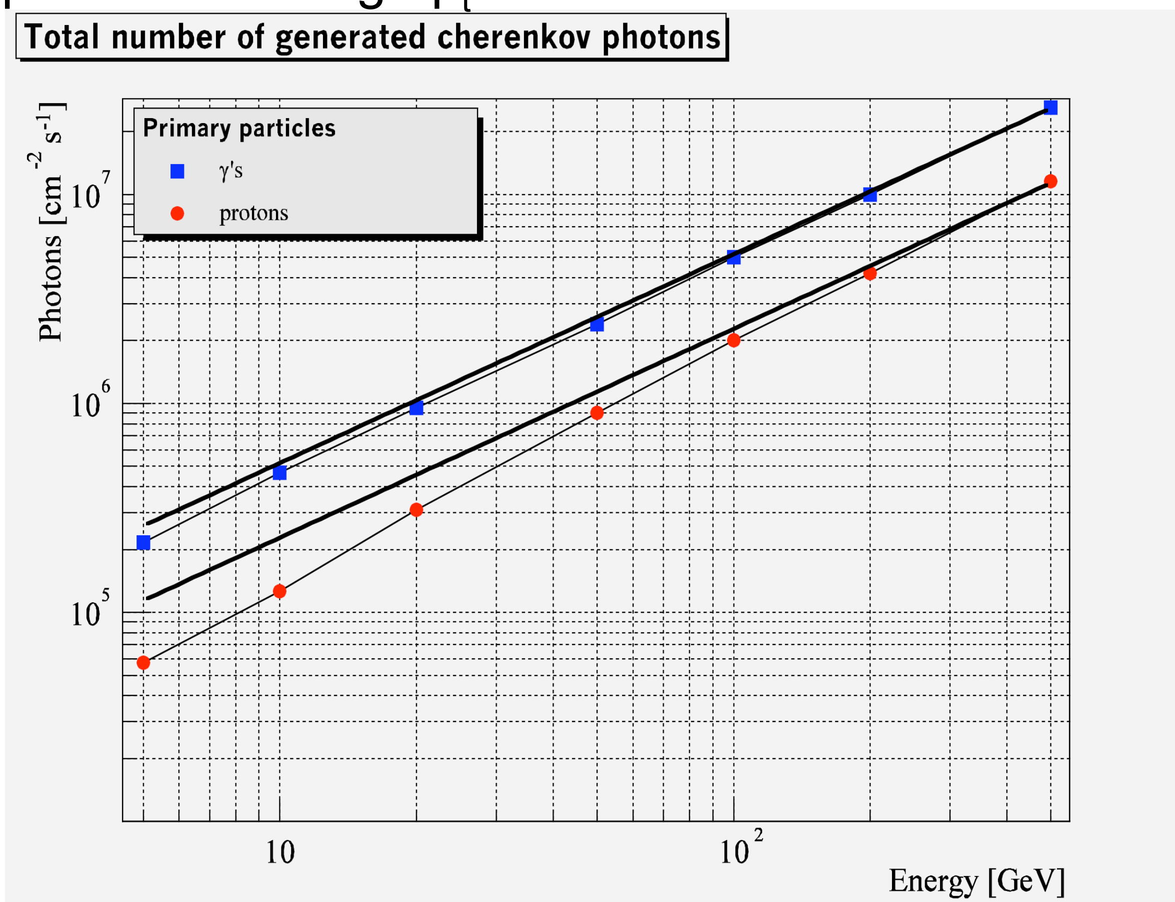


Figure 24.2: Differential spectrum of electrons plus positrons multiplied by E^3 (data summary from Ref. 9). The dashed line shows the proton spectrum multiplied by 0.01.

Characteristics of low energy showers

- Total number of Cerenkov photons scales quite well with energy for γ-ray induced showers. (~50000 ph/GeV)
- Decreasing number of photons for proton induced showers due to lower energy (below cherenkov threshold) of electromagnetic component with energy.
- Higher lateral spread due to high p_t interactions.



Simulation:
Magic,
talk from M Merck

Cosmic Rays on Earth - the muon background

Plot from PDG.

Vertical flux at mountain (Pole) altitude:
≈174 /(m^2 s sr))

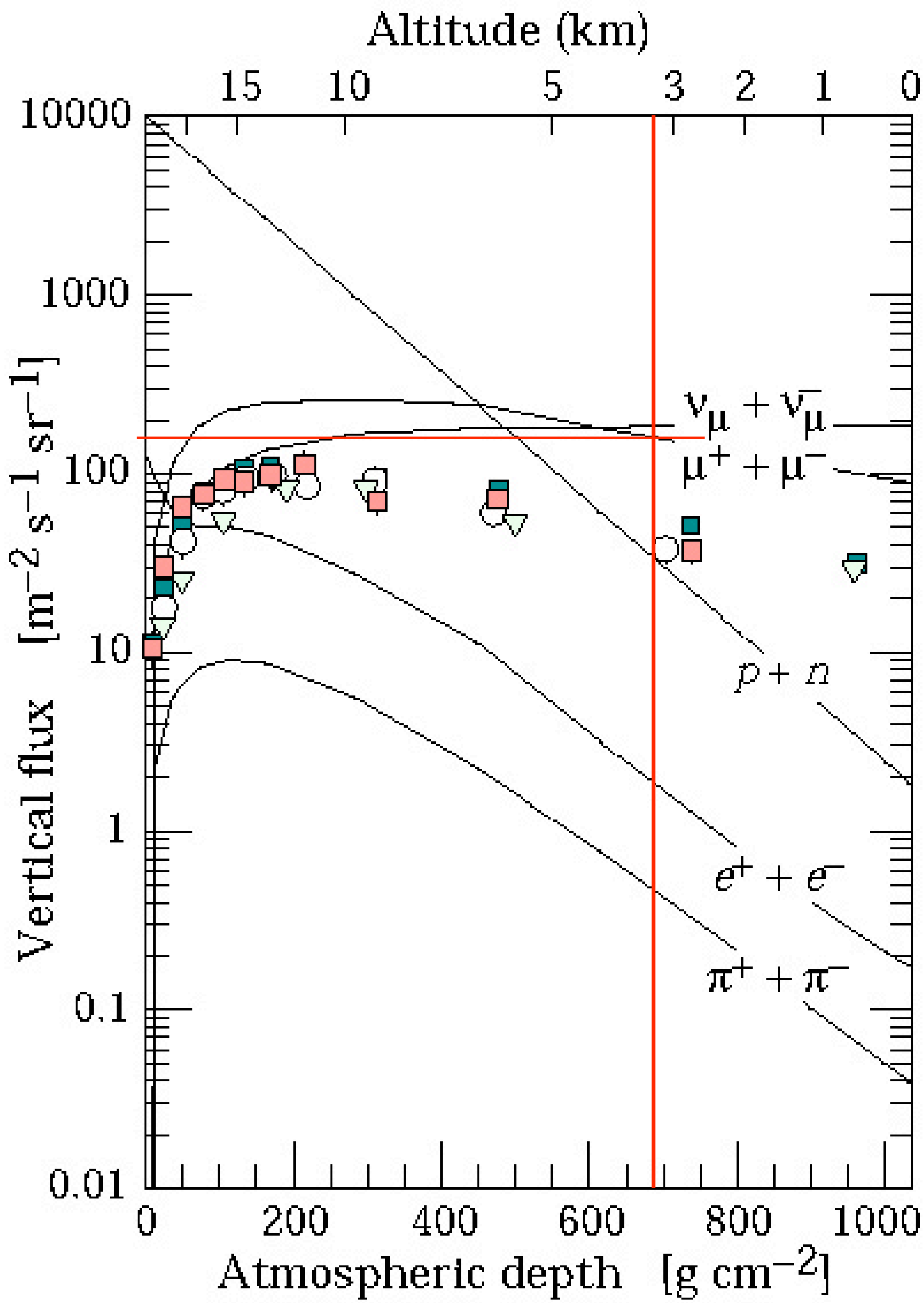
(Compare to the rate of showers with E>1TeV: ≈0.2 /m^2/s/sr.)

Mean energy: 4 GeV, but they are just single tracks.

Can the trigger a telescope? Yes.

Are they a problem? Yes, at low energies.

Solution: image analysis + stereoskopic observation



Backgrounds summary

- Cosmic ray nuclei: trigger rate of order 100 Hz (Crab nebula, extremely strong source, will trigger 0.3 Hz.)

  Rejection: Image analysis (also stereoskopic observation)

- Electrons: small effect at energies below 100 GeV

  Rejection: Impossible

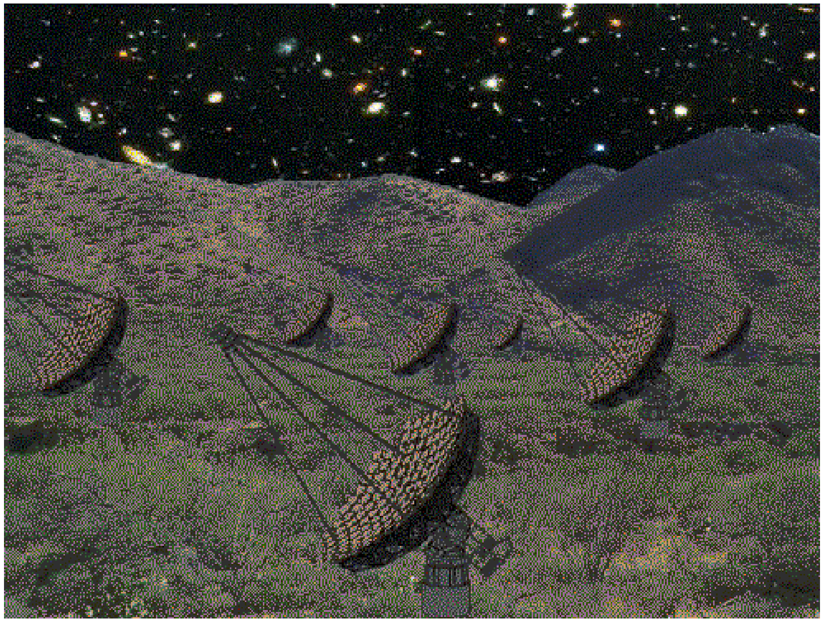
- Muons: high flux, is a tricky problem at low energies

  Rejection: image analysis && stereoscopic observation

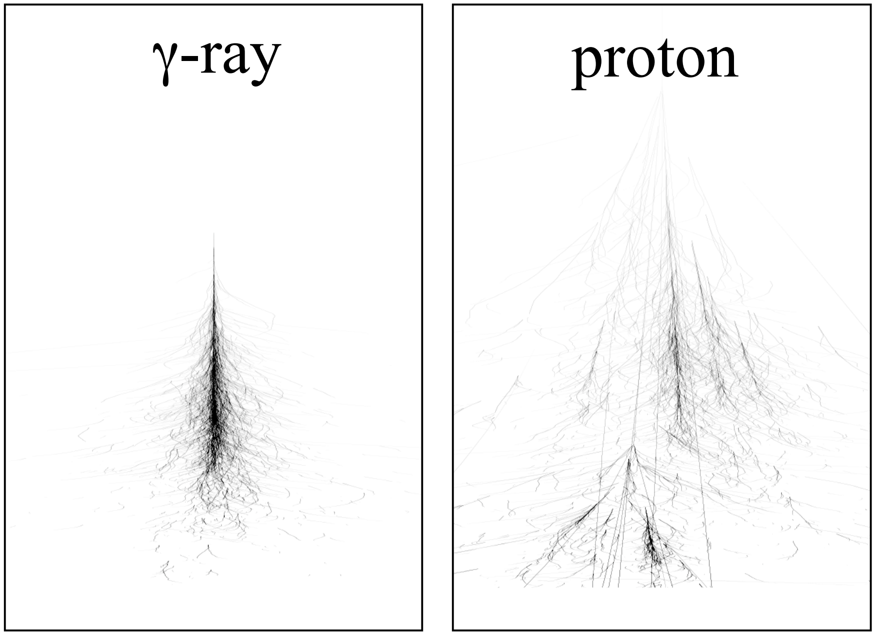
Imaging Air Cherenkov telescopes

- More details on gamma hadron separation
- Overview of telescopes

VERITAS: Next Generation Detector & Calorimeter for Gamma-Ray Astronomy



Cosmic Ray Rejection Technique

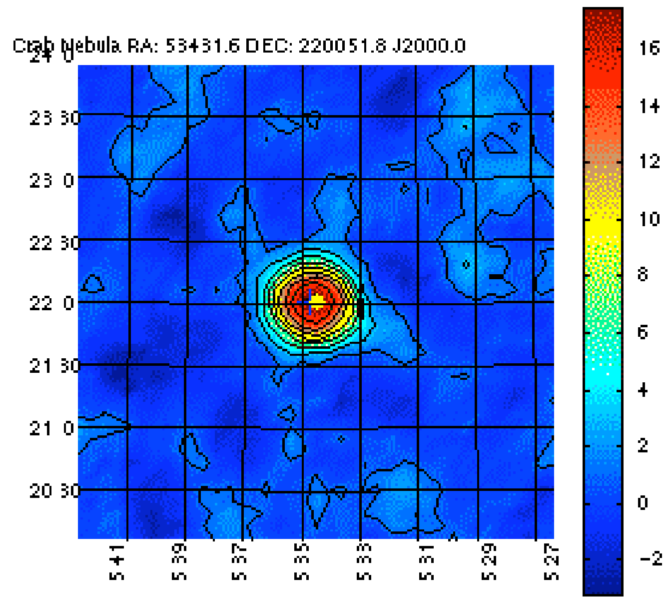


Courtesy W.Hofmann

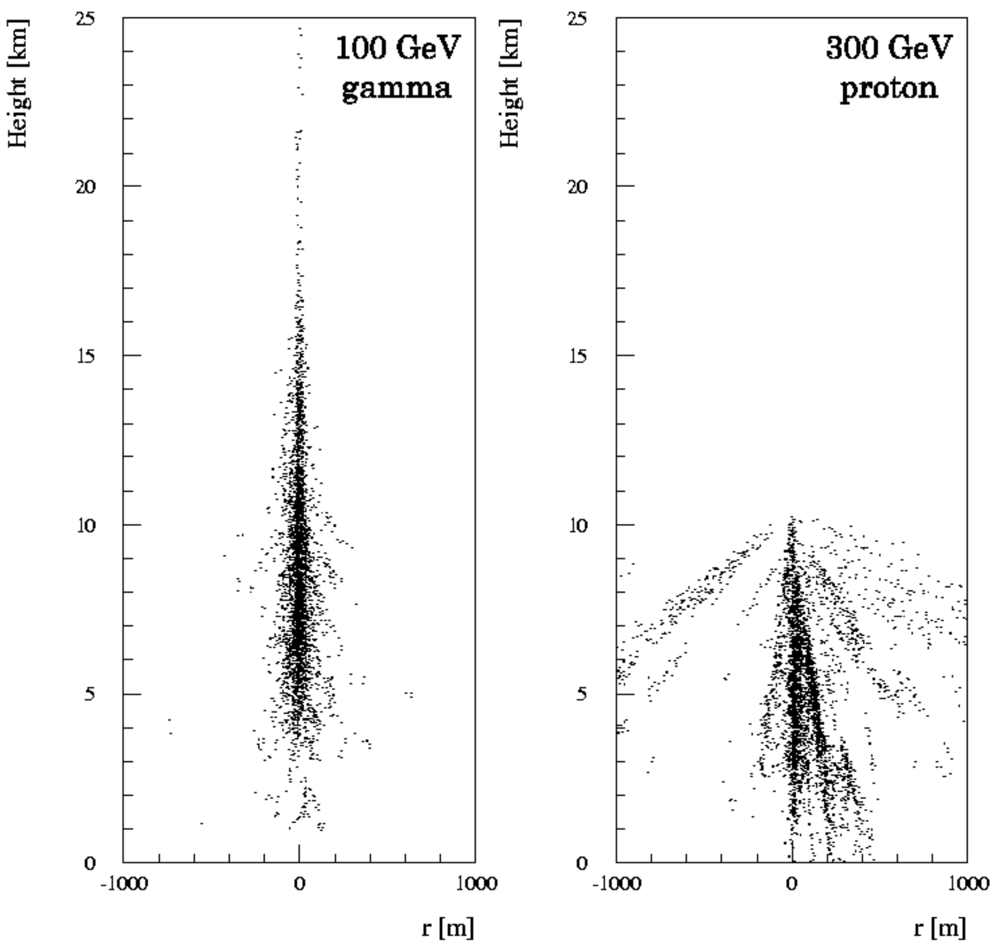
- ∀ γ-ray images:
  - narrow, short, smooth
- Hadronic images:
  - broad, long
  - local muons, patchy
- hadron rejection: 99.7% (10^{-3})

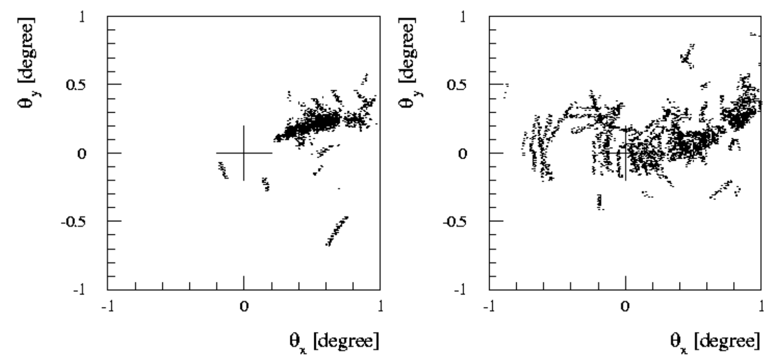
Crab Nebula

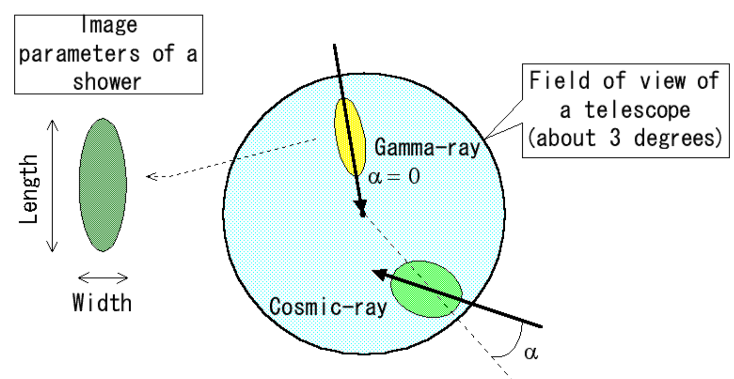
7 σ in 1hour



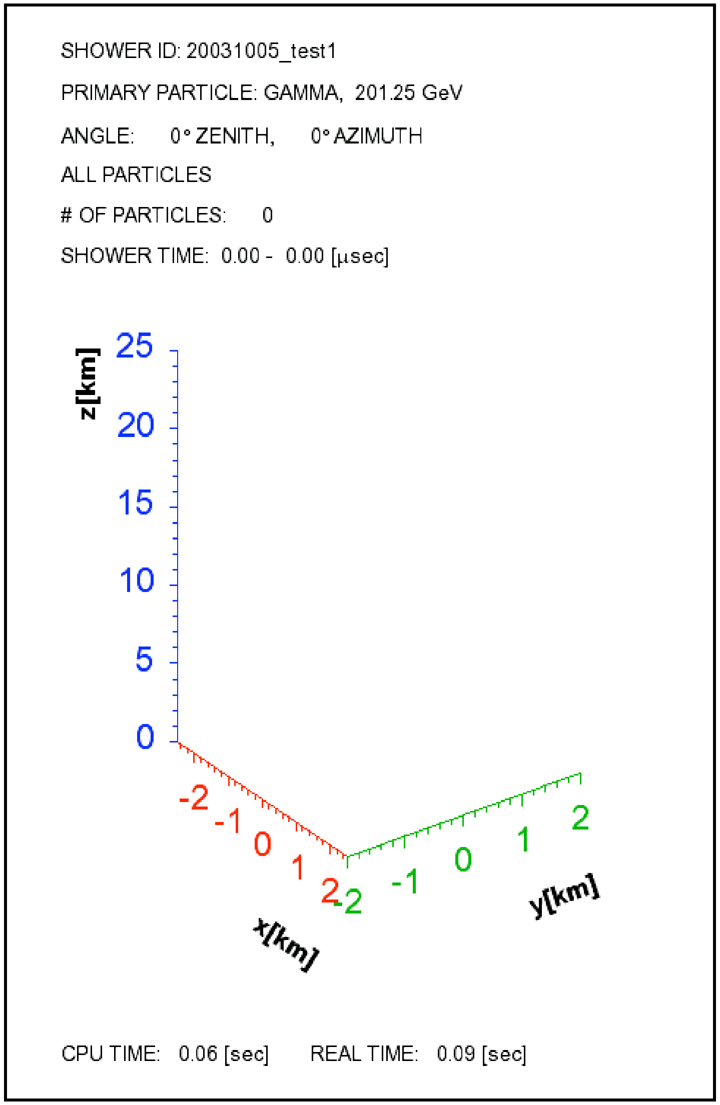
Imaging Cherenkov technique

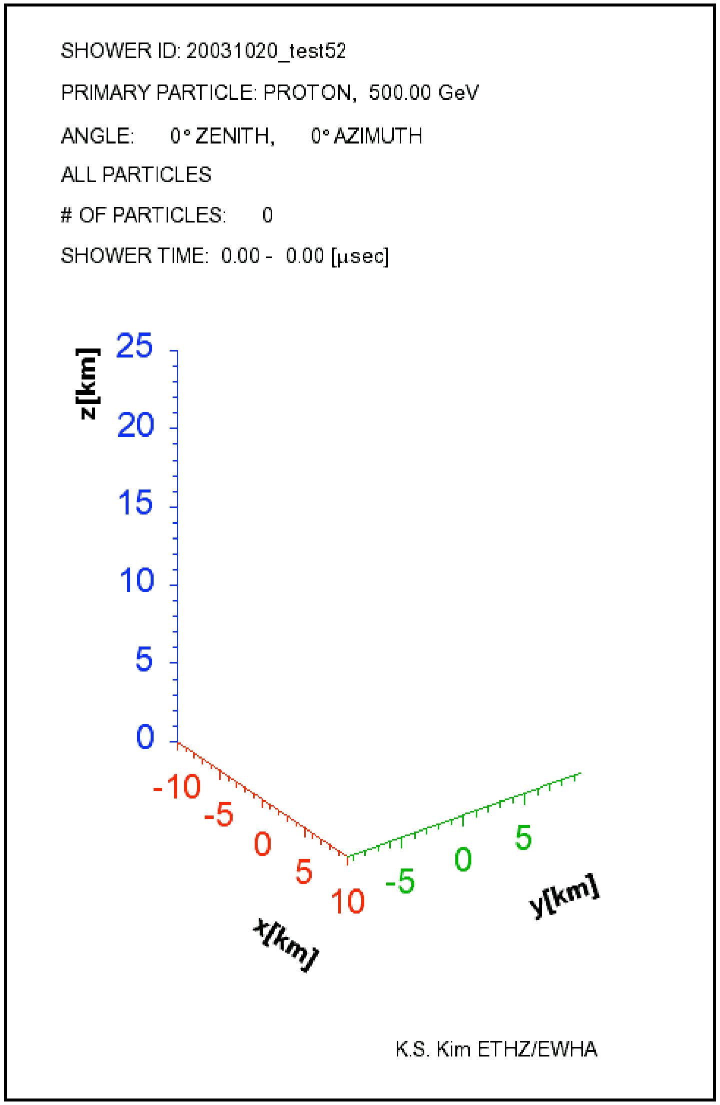




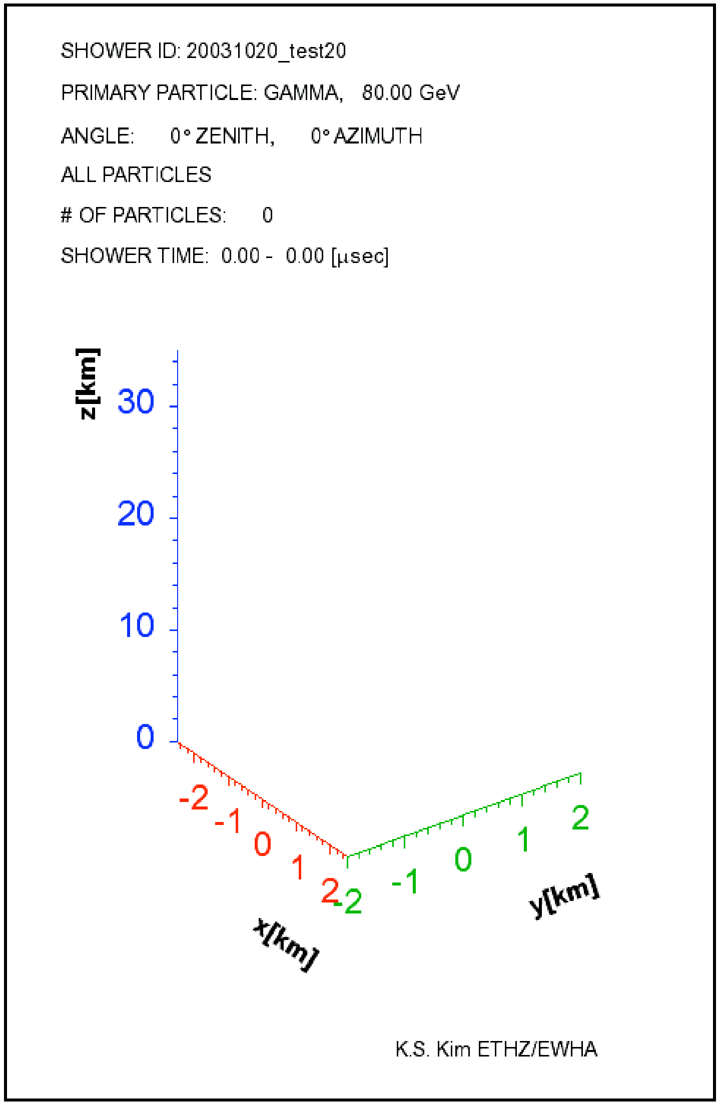


Difference between hadronic and electromagnetic cascades





Difference between hadronic and electromagnetic cascades



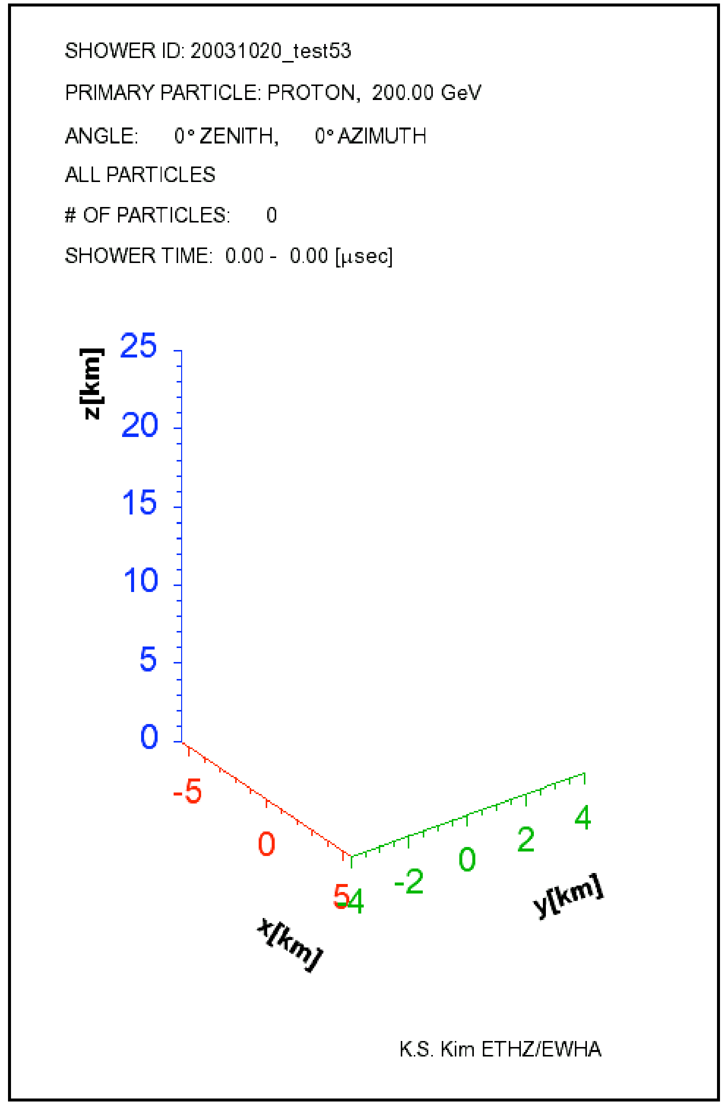
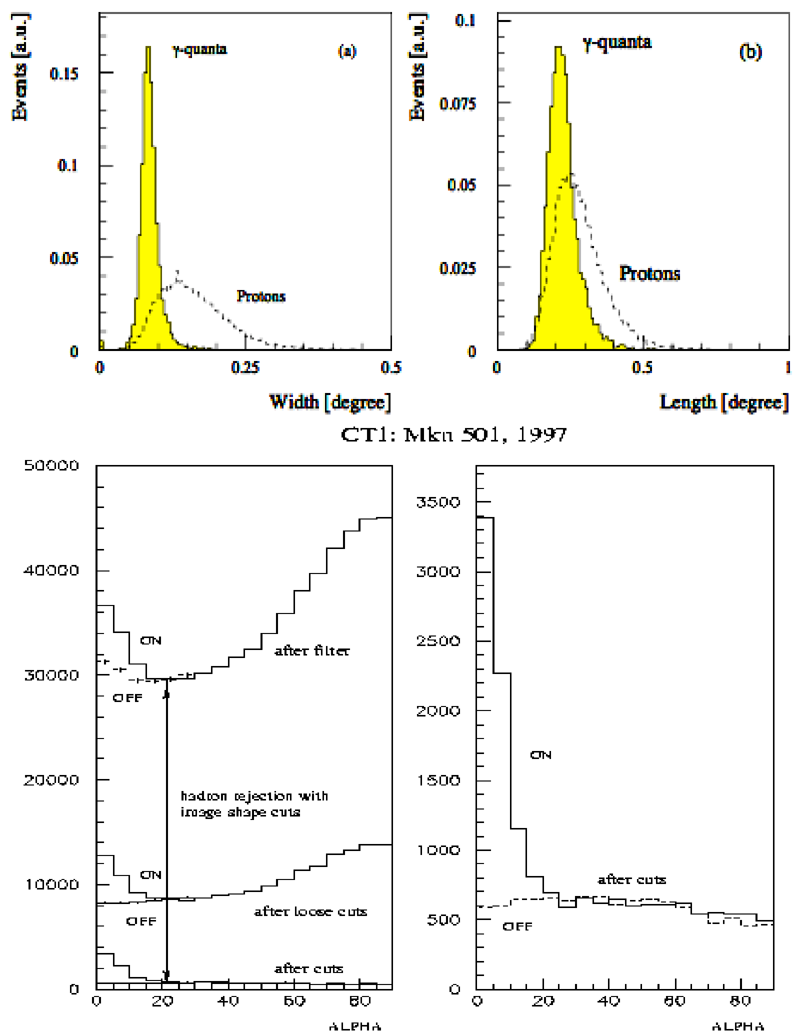
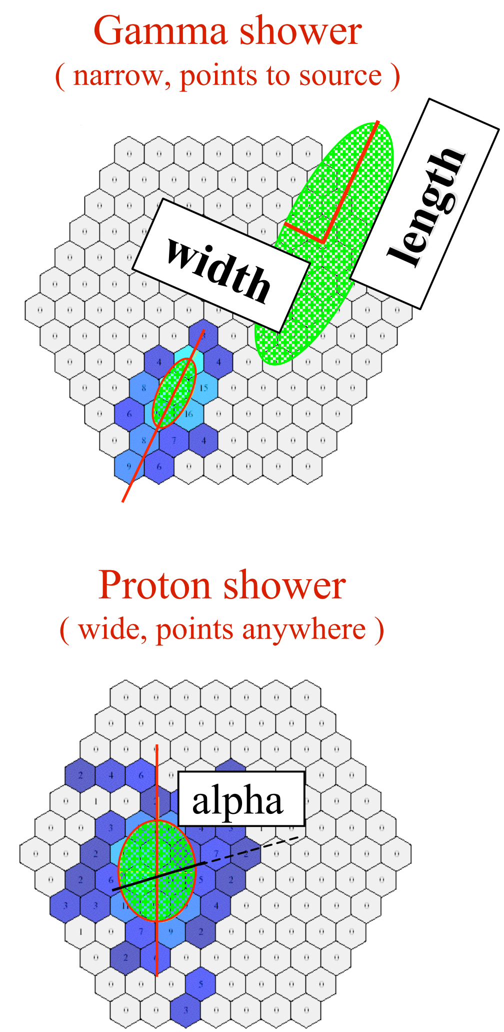


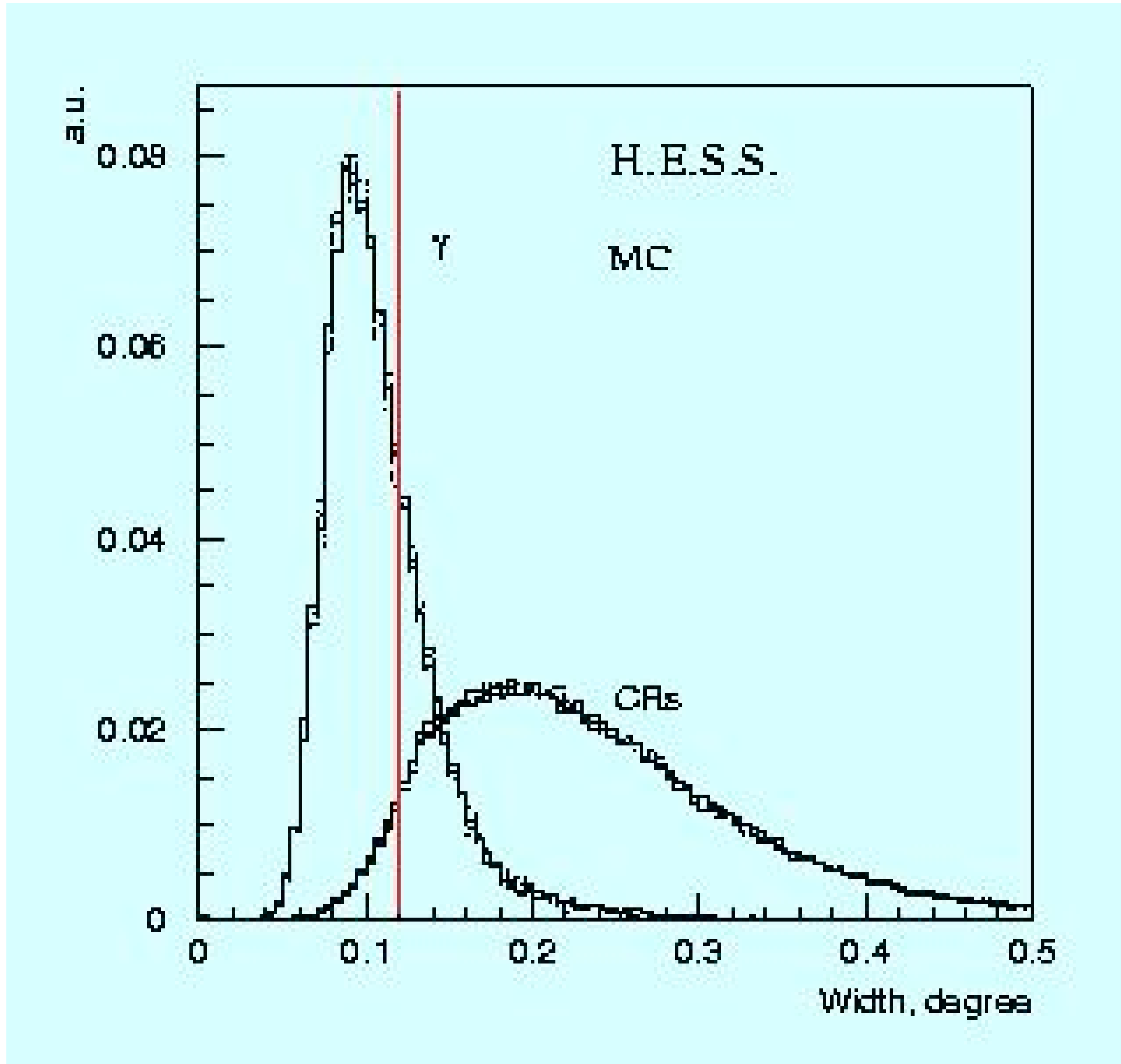
Image analysis using Hillas parameters





Result of Imaging Technique

CR rejection based on image width

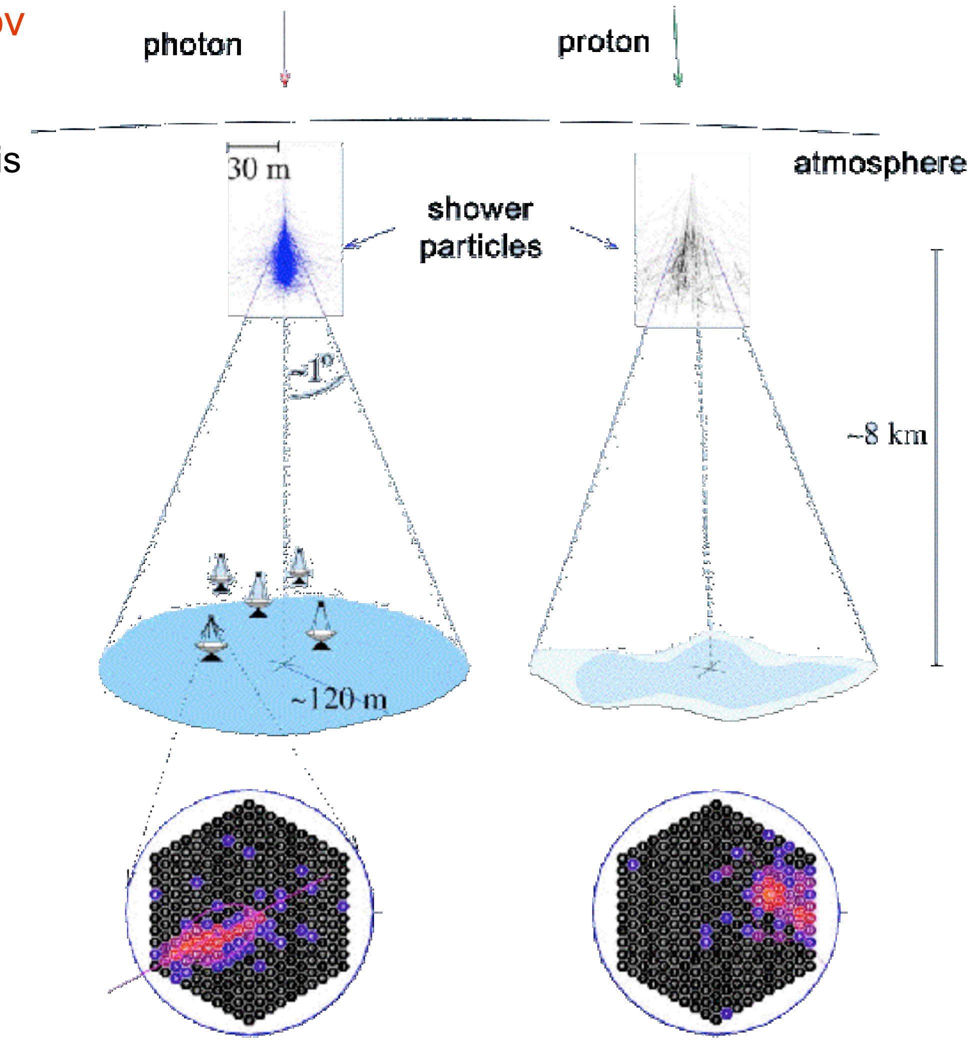


Advantage: Does not assume point source!

Hess strategy :
Cameras with wide FOV,
>500 pixel cameras

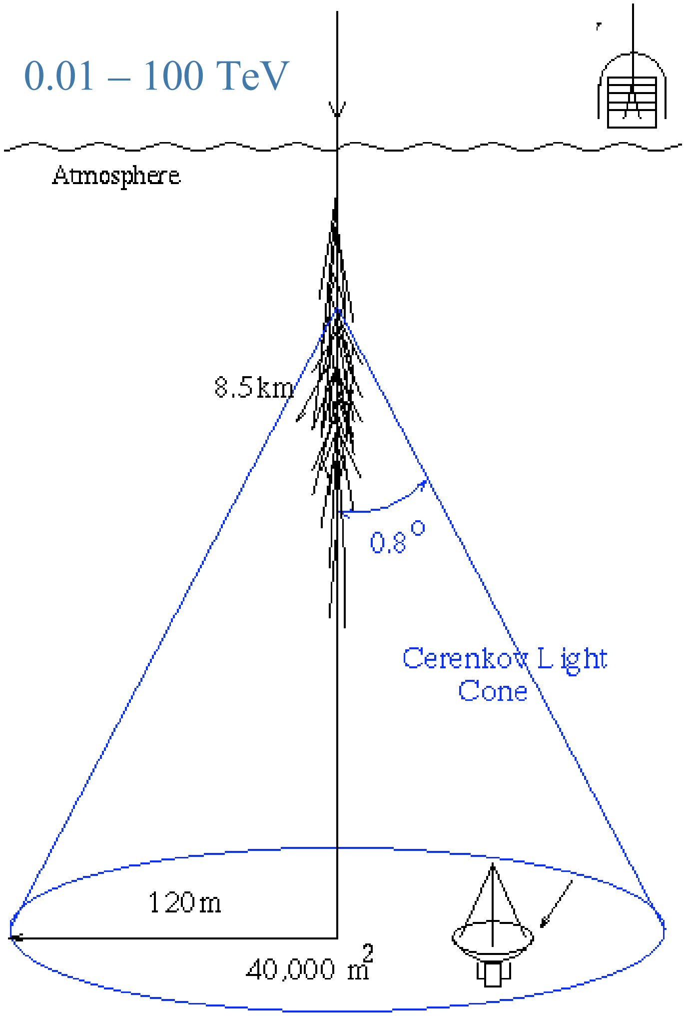
Multiple Imaging Atmospheric Cherenkov Detectors (IACTs)

- Imaging Atmospheric Cherenkov telescopes (IACTs):
  - By increasing the number of pixels in the photon detector it is possible to
    - suppress the background
    - differentiate between photon-induced showers and hadron-induced showers

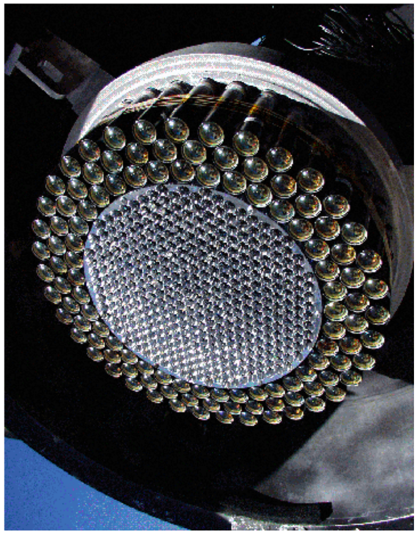


HEGRA camera images

The Whipple Cherenkov telescope 10m



Imaging Camera

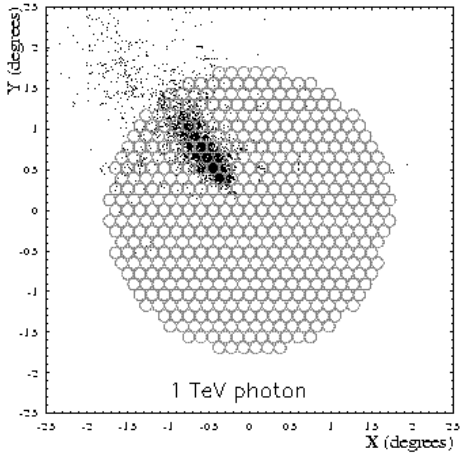


Area ~ 100,000 m^2

E ~ 0.2 – 100 TeV

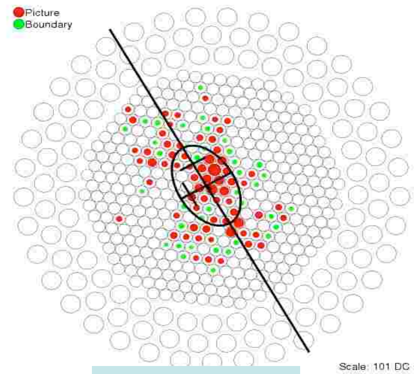
$\Delta\theta/\theta$ ~ 0.2 ^{o}

100 optical photons/m^2 TeV within a few ns

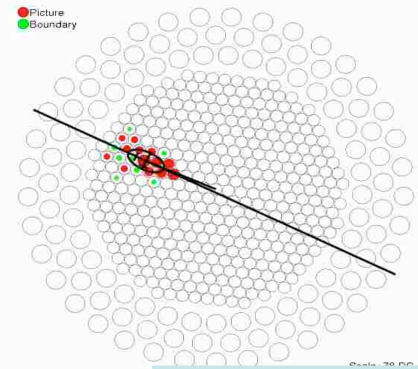


Whipple 10 m Reflector and
Camera, 1984
Prototype Imaging System

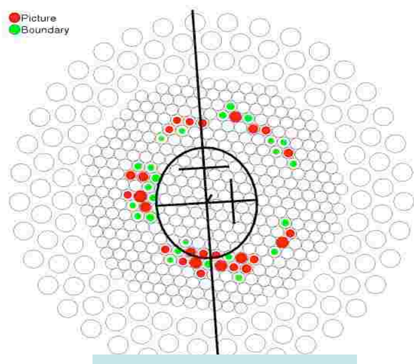
Types of images seen by atmospheric Cherenkov camera



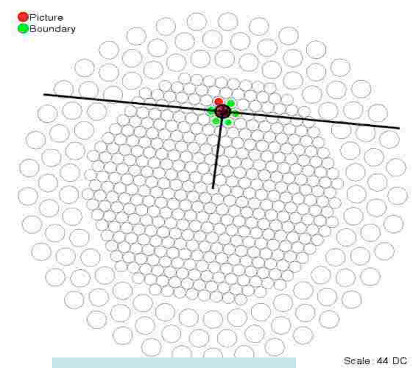
Hadron



Gamma ray

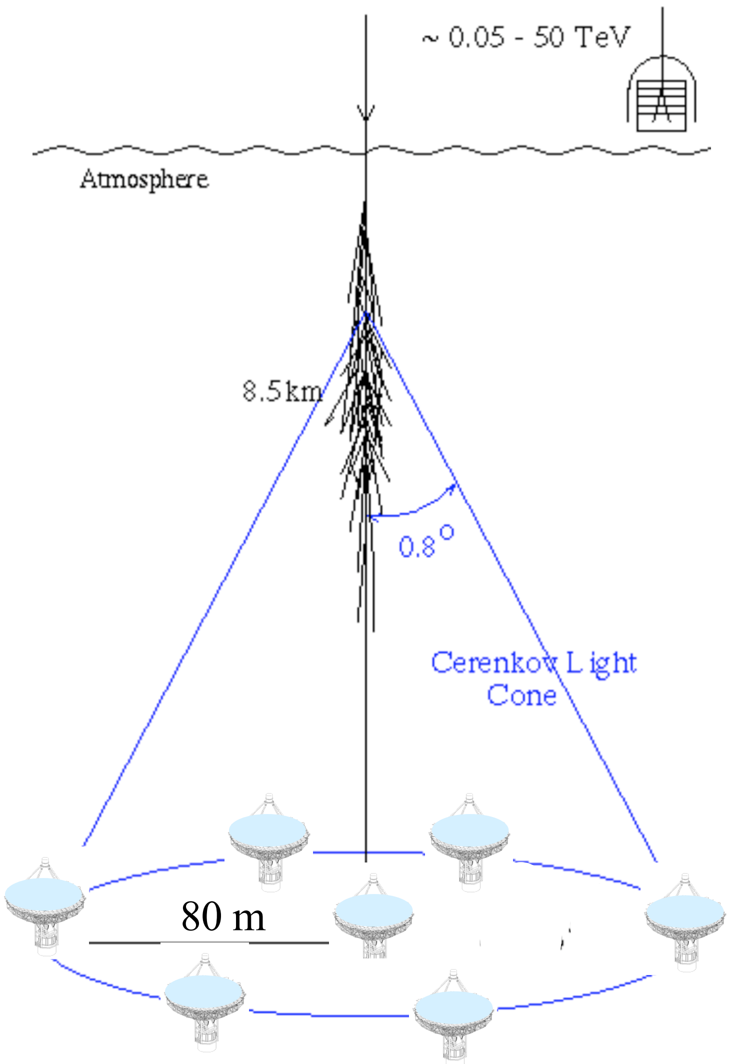


Muon Ring



Sky Noise

Improvements with VERITAS



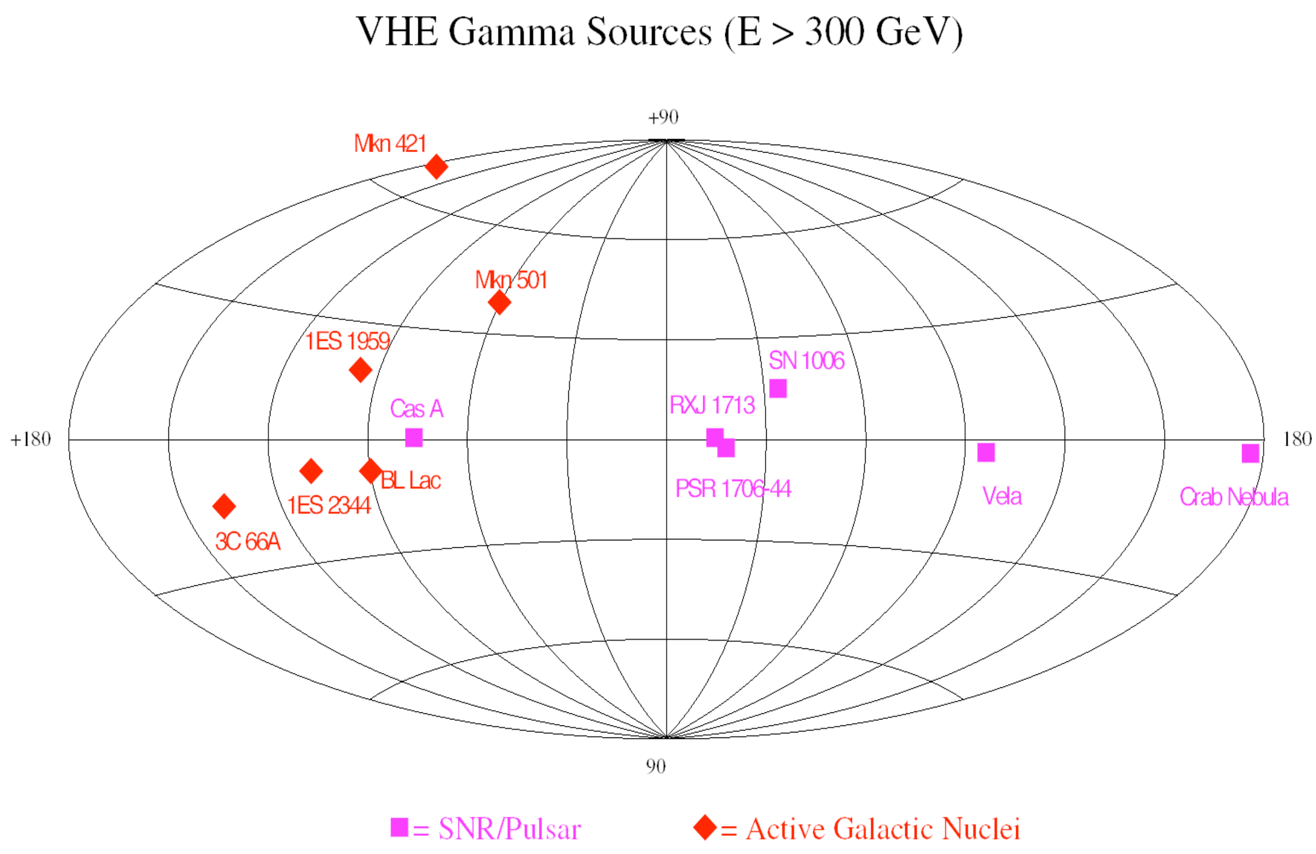
Combine stereoscopic view with improved 10m type telescope

- **improved angular resolution**
- **enhanced background suppression**
- **lower energy threshold**
- **improved energy resolution**
- **cross-calibration with GLAST**
  → **absolute energy calibration**

VERITAS

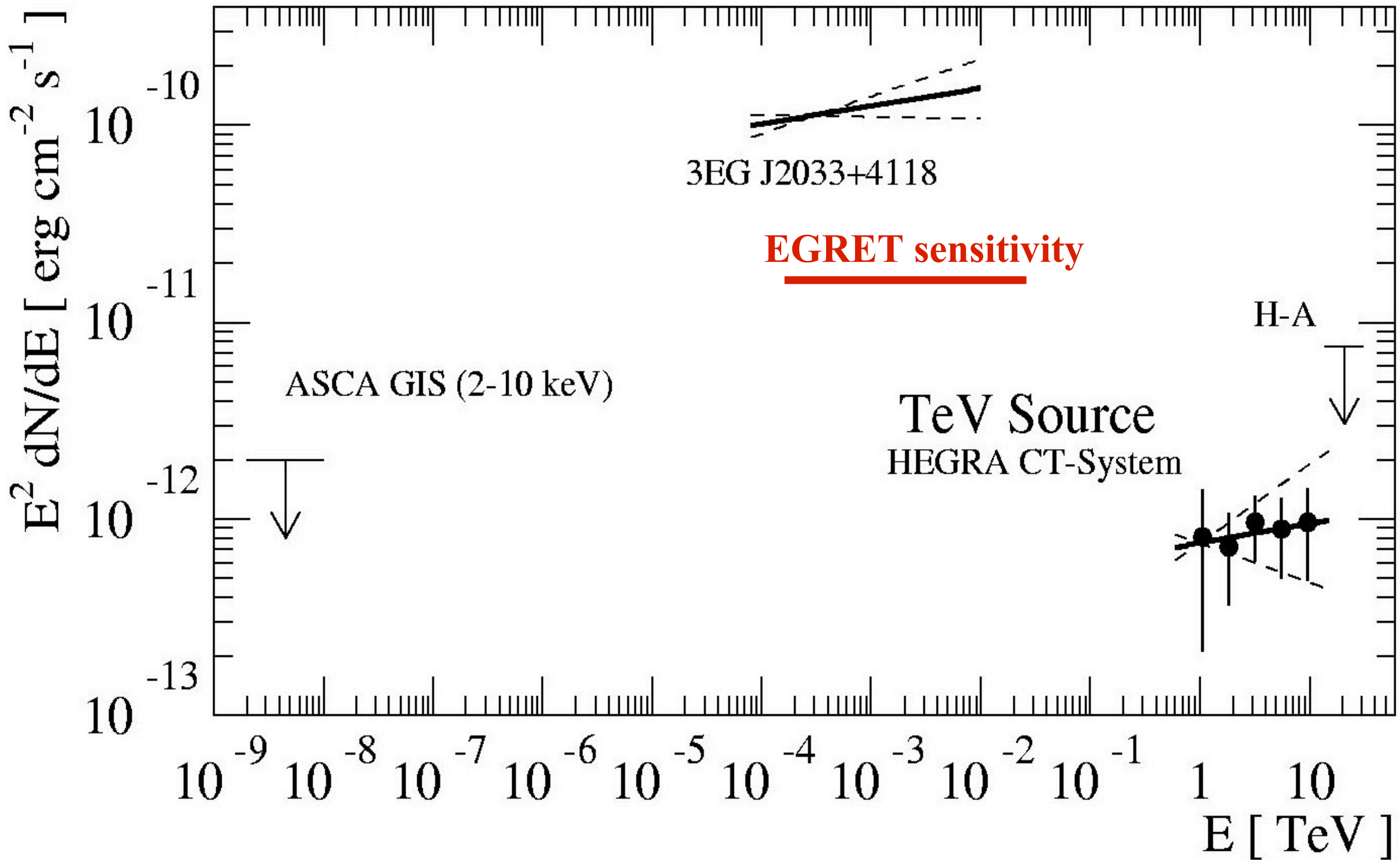
- **50 GeV – 50 TeV**
- **$\Delta\theta/\theta \sim 0.03^{o}$ @1TeV**
  $\sim 0.09^{o}$ @100GeV
- **Flux sensitivity:**
  15 mCrab @100GeV
  5 mCrab @300GeV
- **$\Delta E/E \sim 0.1$ ▯ 0.15**

Sources in the TeV γ-ray sky

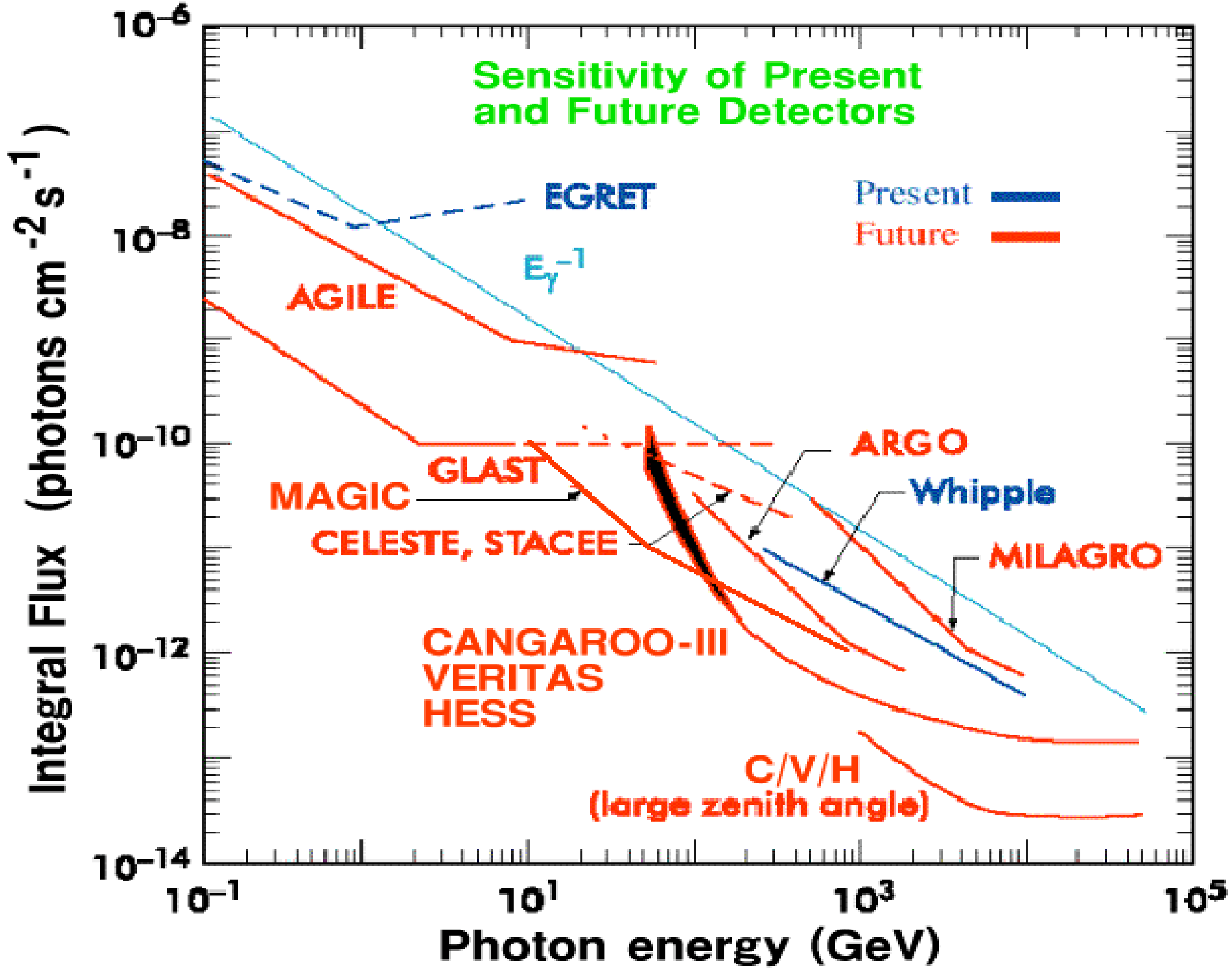


High sensitivity of Cherenkov telescopes

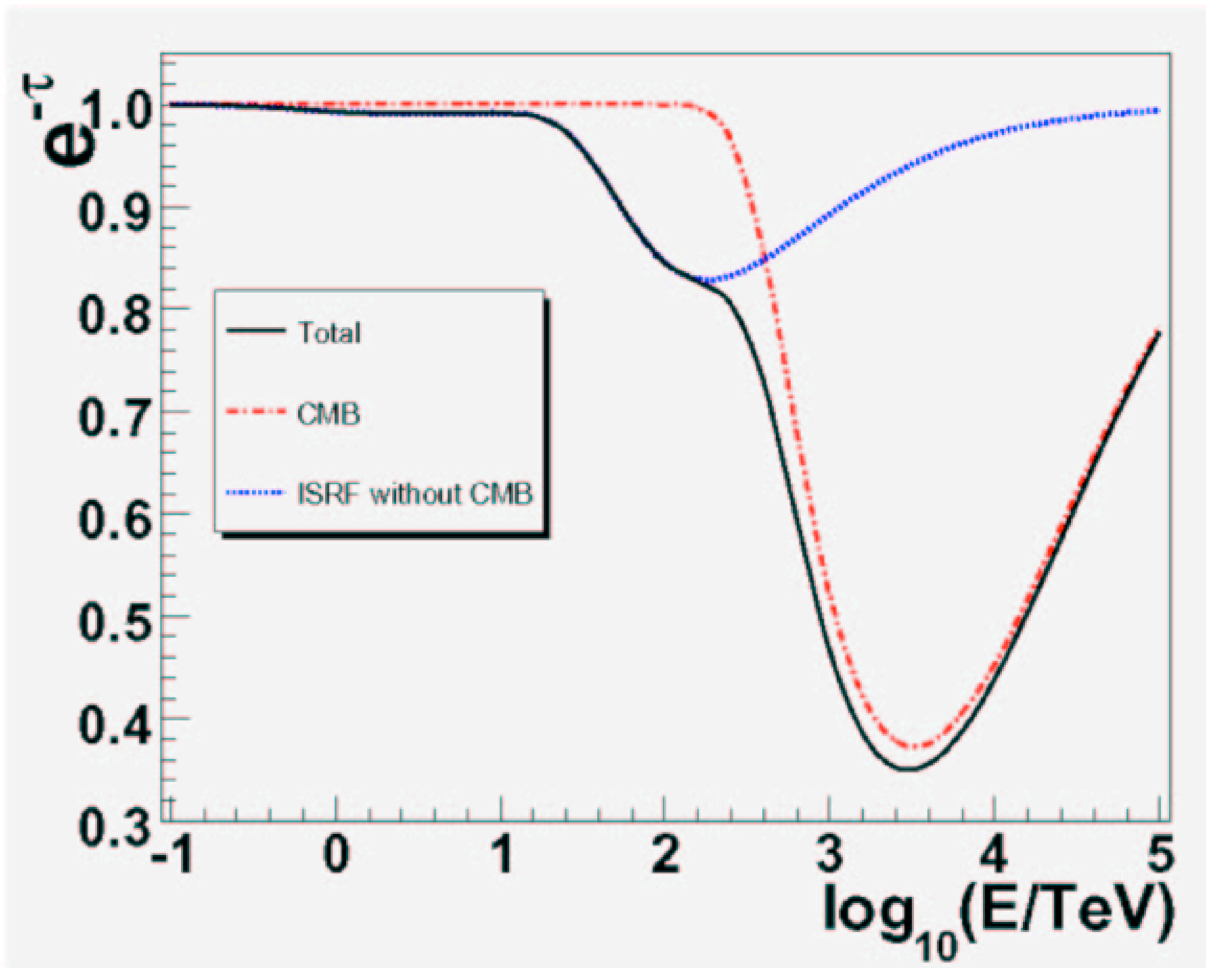
As an example we show the EGRET sensitivity compared to the measured flux of the source TeV J 2032+4131. The sensitivity of ground-based γ-ray-astronomy is a factor 10 lower then the EGRET limit (assuming a reasonable source spectrum) and may not explain the low number of detected sources.



Sensitivity of future detectors



Low energy threshold - transmission from galactic center



Development of imaging air Cherenkov technique

- Air shower arrays, mostly based on scintillators. E>100 TeV
- Initially with second hand equipment from particle physics experiments.
- More particle physics background culture and people (e.g. Lorenz @ HEGRA, Cronin w. CASA now Auger, later Hoffman w HESS)
- Recognized that threshold was too high for gamma astronomy (absorption and steep spectra).
- Abandonment of high threshold arrays. Push to lower thresholds. Wide angle sub 10 TeV detectors such as AIROBICC, Tibet, Milagro.

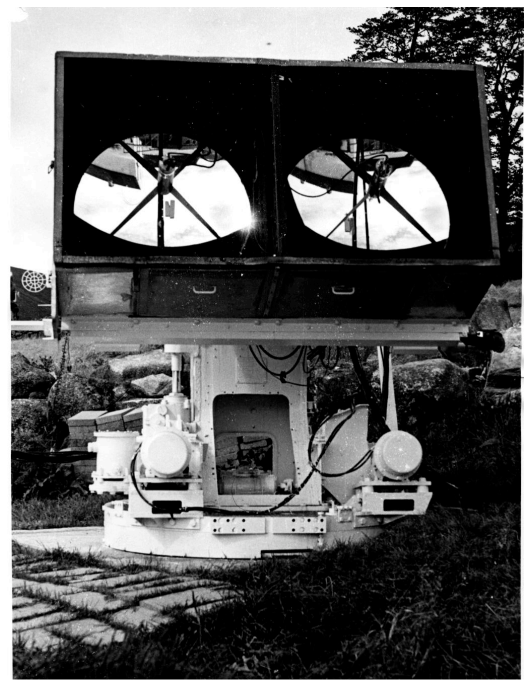
- Cherenkov telescopes with mirrors.
- Energy in the TeV regime.
- Started with PMT and mirrors to enhance signal.
- Initially very limited support by simulations.
- Development of imaging technique (theoretical understanding and simulation by M. Hillas) provided breakthrough in CR rejection.
- T. Weekes succeeds with reliable detecting Crab nebula w. Whipple.
- Detect soon more sources.

- Success of Cherenkov telescopes, better understanding of physics leads to fast development of 3rd generation Cherenkov telescopes
- Increase in mirror size, quality and camera pixels. (From ≈7 to 1000 per camera), arrays of telescopes.

Development of GeV-TeV Gamma-ray Astronomy

- First Generation Systems 1960 – 1985
  - Weak or no discrimination
  - Lebedev, Glencullen, Whipple, Narrabri, Crimea…………

Crimea 1960-64

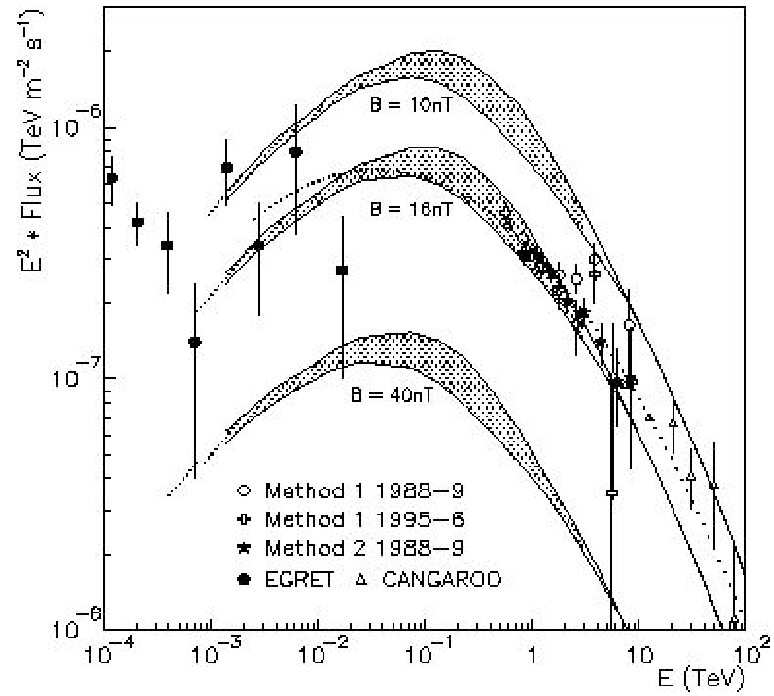


Glencullen, Ireland 1964-67

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

Whipple 10 m Telescope 1968 - First purpose-built gamma-ray telescope

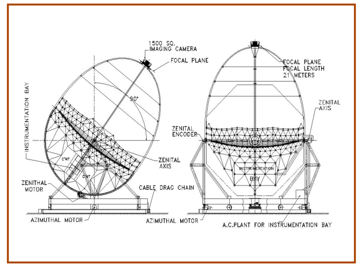
Crab Nebula: Active Source



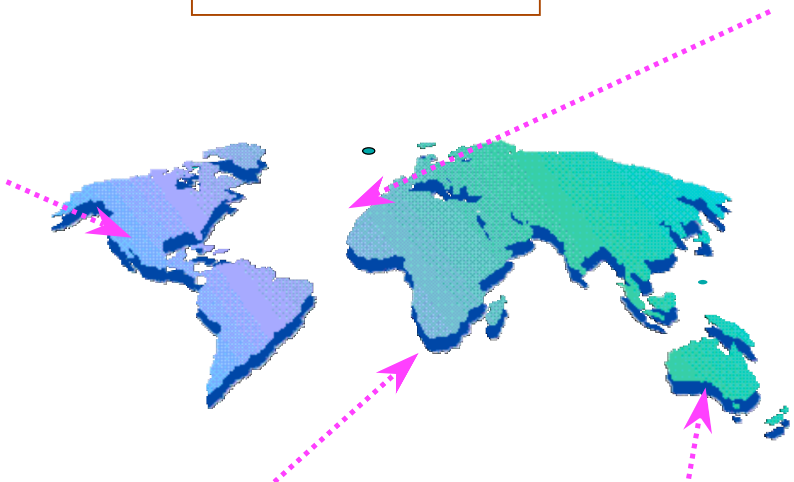
Compton Gamma-Ray Spectrum of the Crab Nebula:

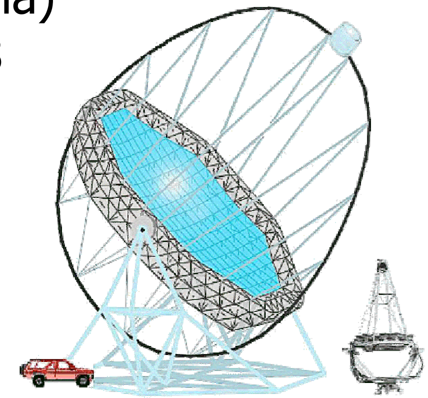
- magnetic field strength
  - 1.6 x 10^-4 gauss
- maximum electron energy
  - > 100 TeV

The Big 5 TeV ACIT Observatories



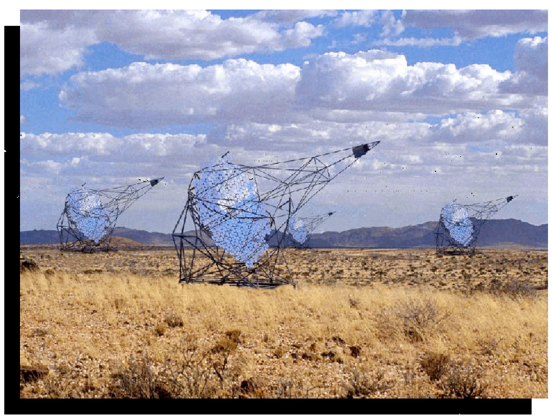
MACE (India)
2 tel. 2008



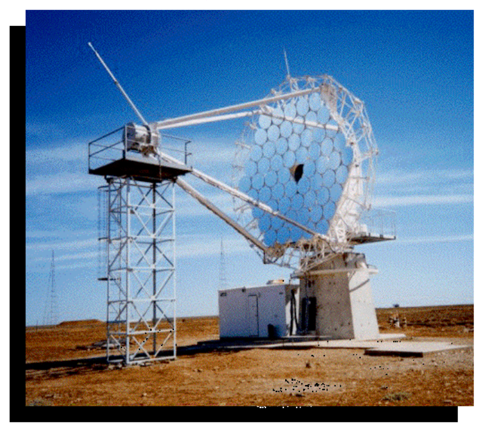


VERITAS, (Arizona)
4 tel. 2006
7 tel. 2008?

MAGIC (La Palma),
1 tel., 2004
2 tel., 2008



HESS, (Namibia) 4 tel., 2003
5 tel., 2007



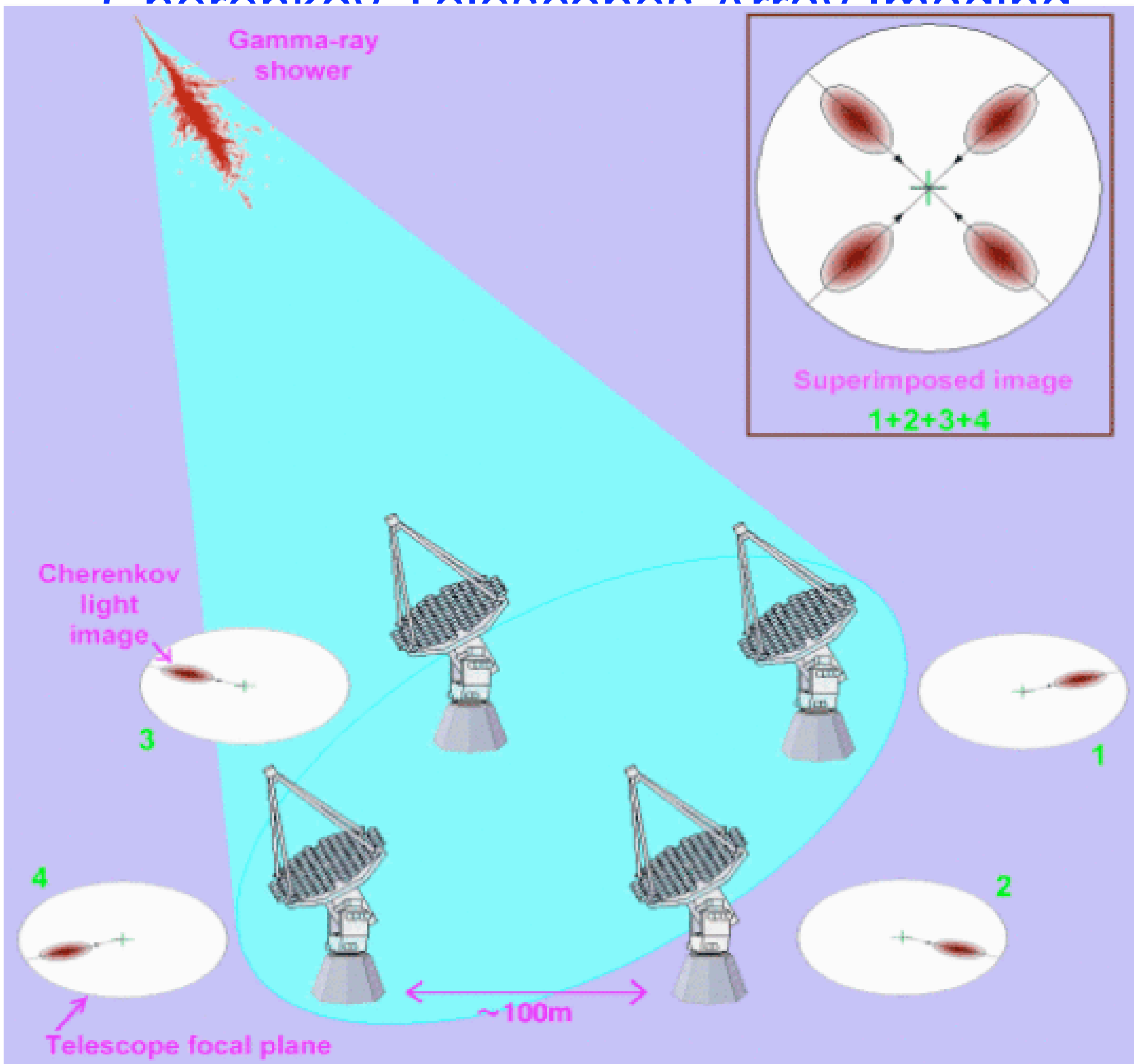
CANGAROO III, 4 tel., 2006
(Australia)

	Observatory Name	Angular Resolution (*deg.*)	γ-ray Energy Threshold (*GeV*)
Imaging Čerenkov Telescopes	Whipple	0.14 ($\in$ 68%)	500
	CAT	0.11	250
	HEGRA(CT1)	0.14 ($\in$ 68%)	1700
	CANGAROO	0.12	1000
	TACTIC	0.31	700 $\pm$ 200
	SHALON ALATOO I or II	0.4	1000*
Stereoscopic System	HEGRA	0.1	500
	SHALON ALATOO	0.1	1000*
Non-Imaging Čerenkov Telescope Arrays	THEMISTOCLE	0.63 ($\in$ 75%)	3000
	STACEE	0.25 ($\in$ 68%)	190 $\pm$ 60
	CELESTE	0.2	60 $\pm$ 20
	GRAAL	0.7 ($\in$ 63%)	250 $\pm$ 110
	PACT	$2.4'$ ($\in$ 68%)	3000*
	AIROBICC	0.29 ± 0.05 ($\in$ 68%)	30,000
EAS	MILAGRO	1.0	1000
	TIBET III	0.87 ($\in$ 50%)	3000
Proposed Imaging Arrays	VERITAS	$2.4'$($\in$ 68%)	1000*
	MAGIC	0.1, 0.2 ($\in$ 68%)	10
	HESS	0.1 ($\in$ 68%)	40
	CANGAROO III	0.1	100

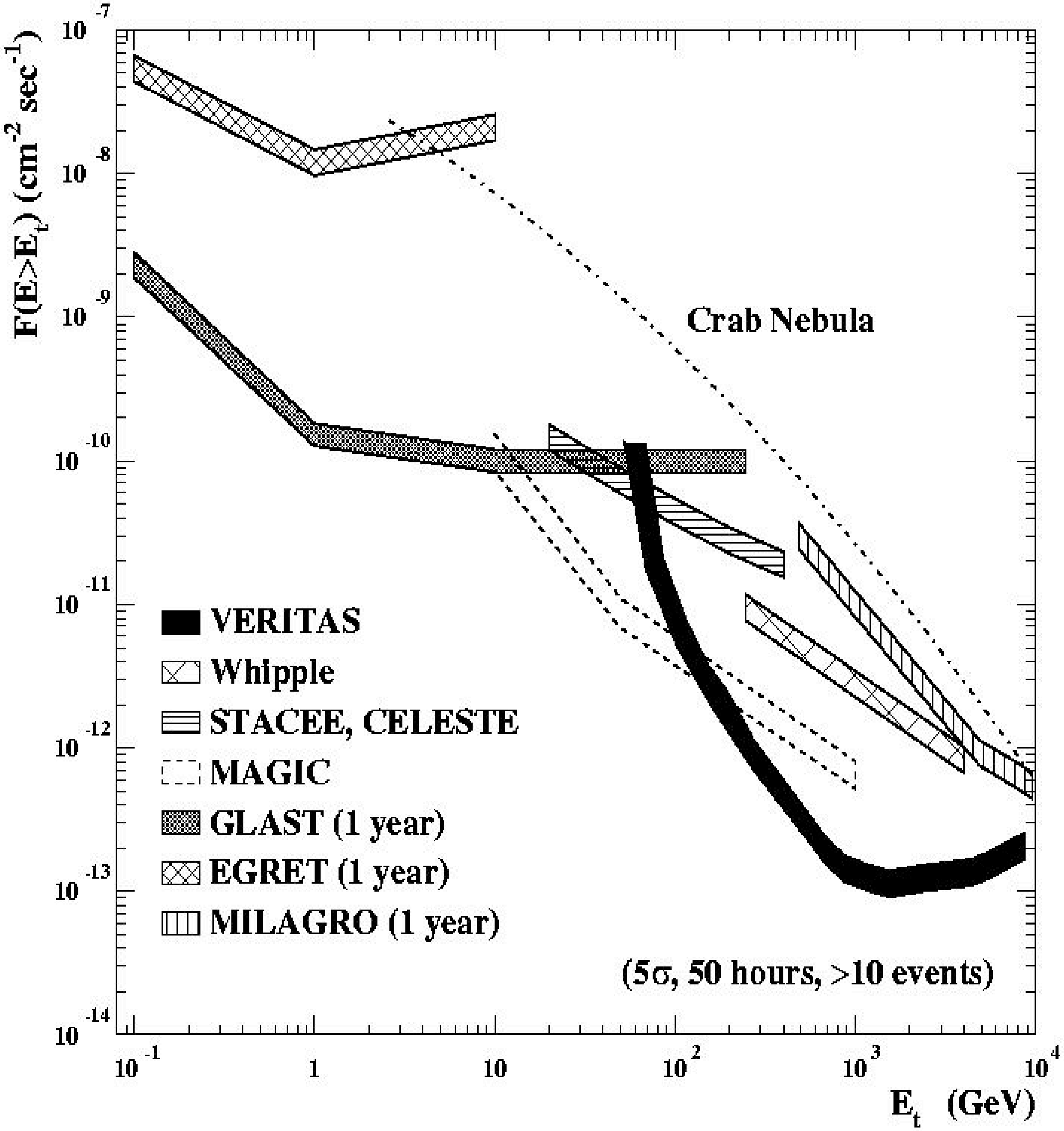
Solar array based
Light collectors,
Lack of γ/h separation

Wide FOV
Detectors, >1sr

Cherenkov Telescopes Array Imaging



Integral Flux Sensitivity



INTEGRAL SENSITIVITY:

Existing and Future Observatories

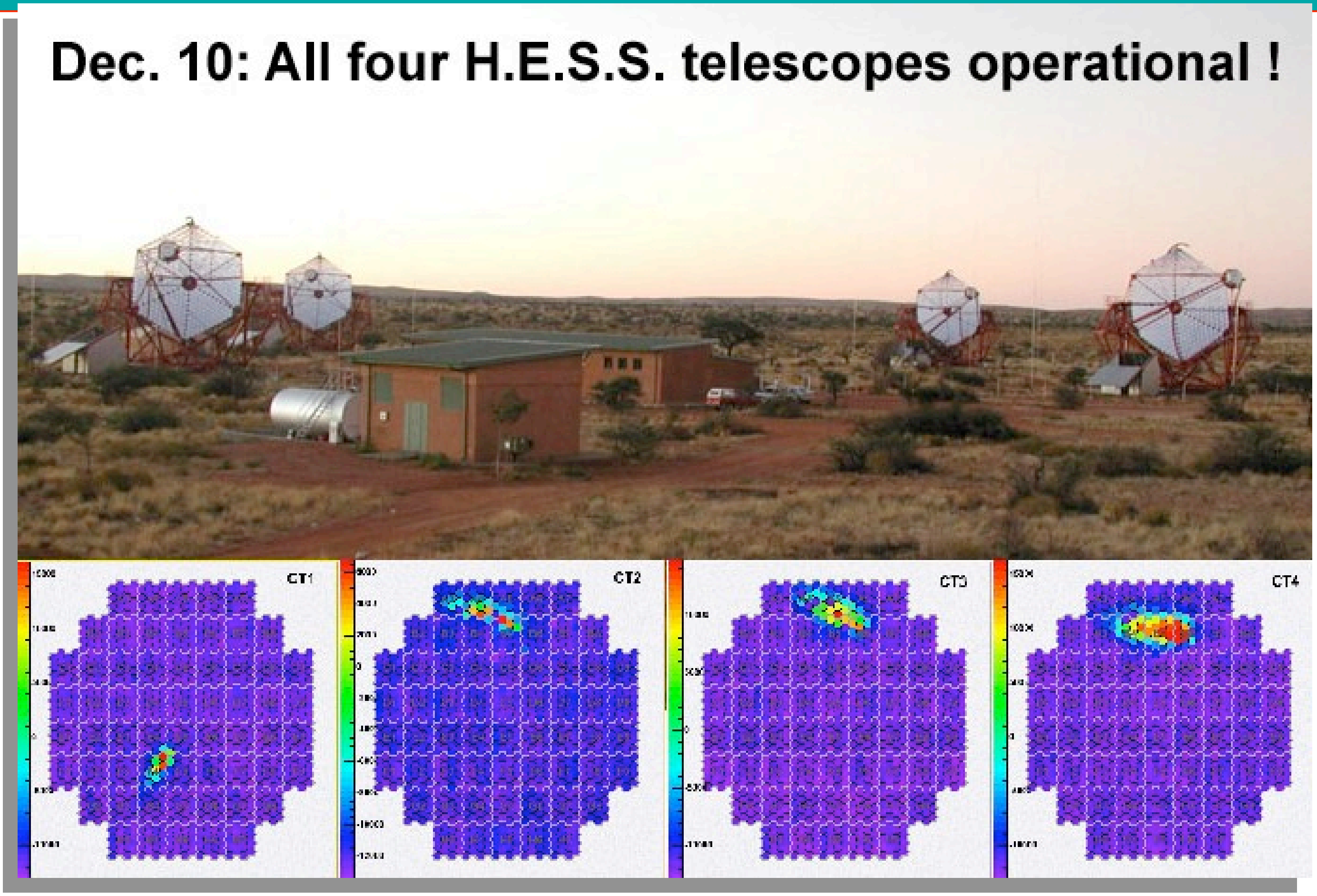
Exposure:
50 hours (pointed)
I year (all sky)

Stereoscopic IACTs

- Stereoscopic IACTs
  - By increasing the number of IACTs
    it is possible to
    - Further suppression of background
    - Shower source reconstruction is possible
    - Further reduction of treshold energy
    - Good angular resolution achieved (<0.1°)
- Pioneering work done by HEGRA (started at 1996)

HESS

European Collaboration; M.P.I (Heidelberg)
4 x 13 m Telescopes
Completed in Dec. 2003; located in NAMIBIA



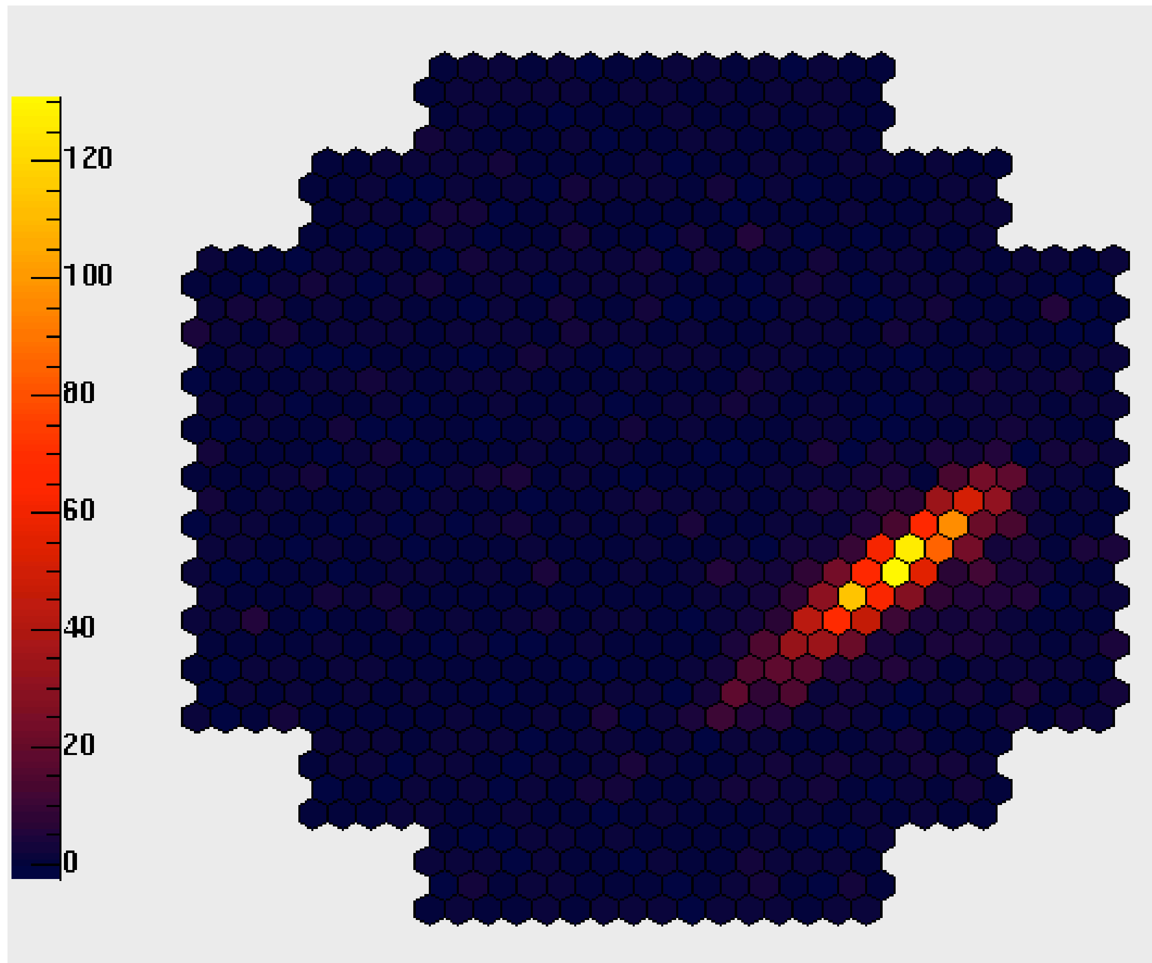
Talk by Berge

HESS - real data

- Showers
- “muon” rings

- Wide FOV: 5°
- 960 PMT, 29mm diameter form the camera

- 1 GHz Analog Ring Sampling ASICs (ARS)



CANGAROO III

- Four telescope system
  - 10m diameter
  - 100m spacing
- 427 pixel camera
  - 0.17º spacing
- Woomera, S. Australia (31ºS 138ºE 160m a.s.l.)
- 4 telescopes not yet in full operation

MAGIC

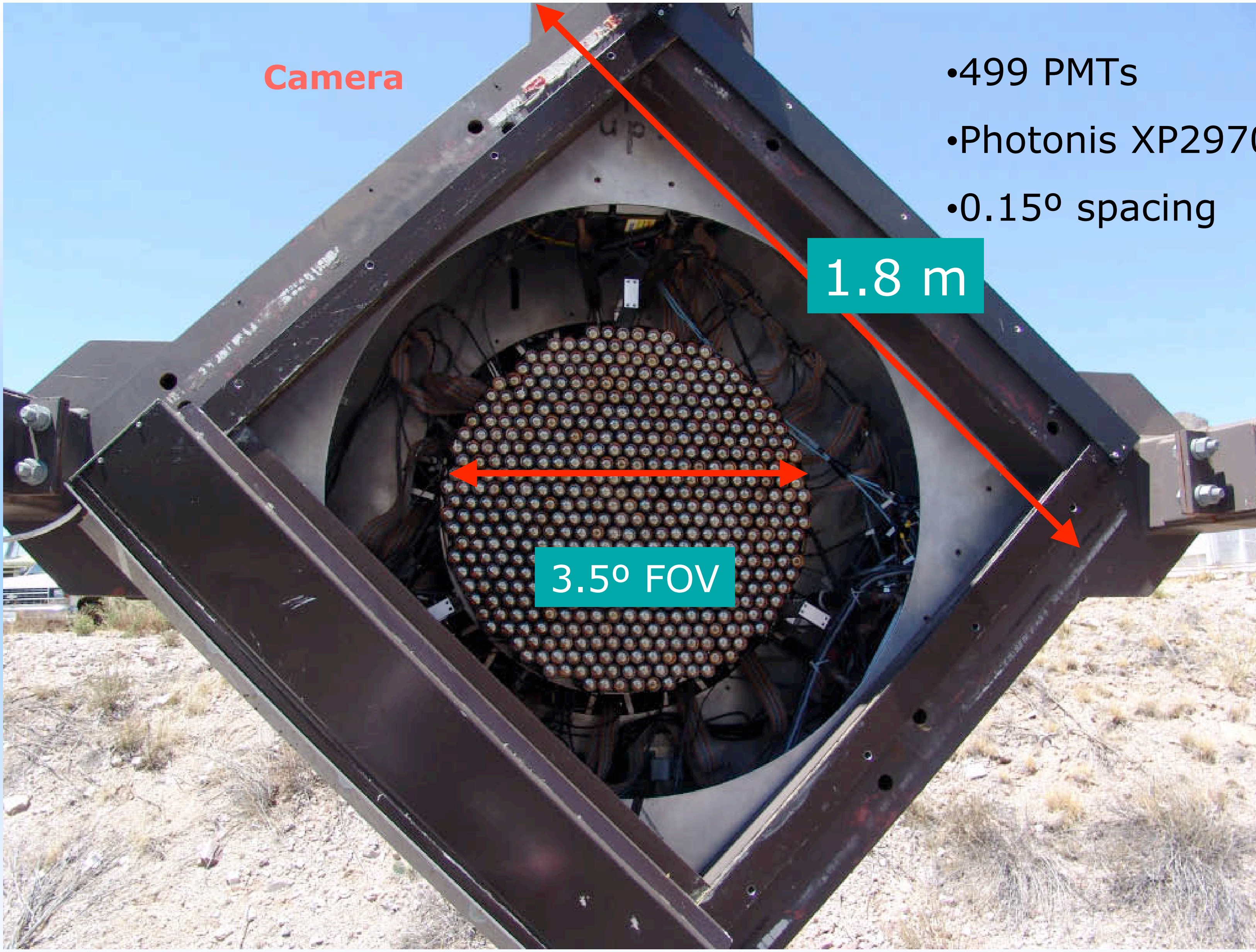
- Two large reflectors
  - Carbon fibre support frame
  - Area=239m^2
  - 577 pixel camera (397 1”, 180 1.5”)
- La Palma (28ºN 17ºW, 2300m a.s.l.
- 2nd telescope now in construction

MAGIC-II - WEBCam from this morning

MAGIC 17m -
designed to respond fast to GRB alerts

VERITAS Telescope-2

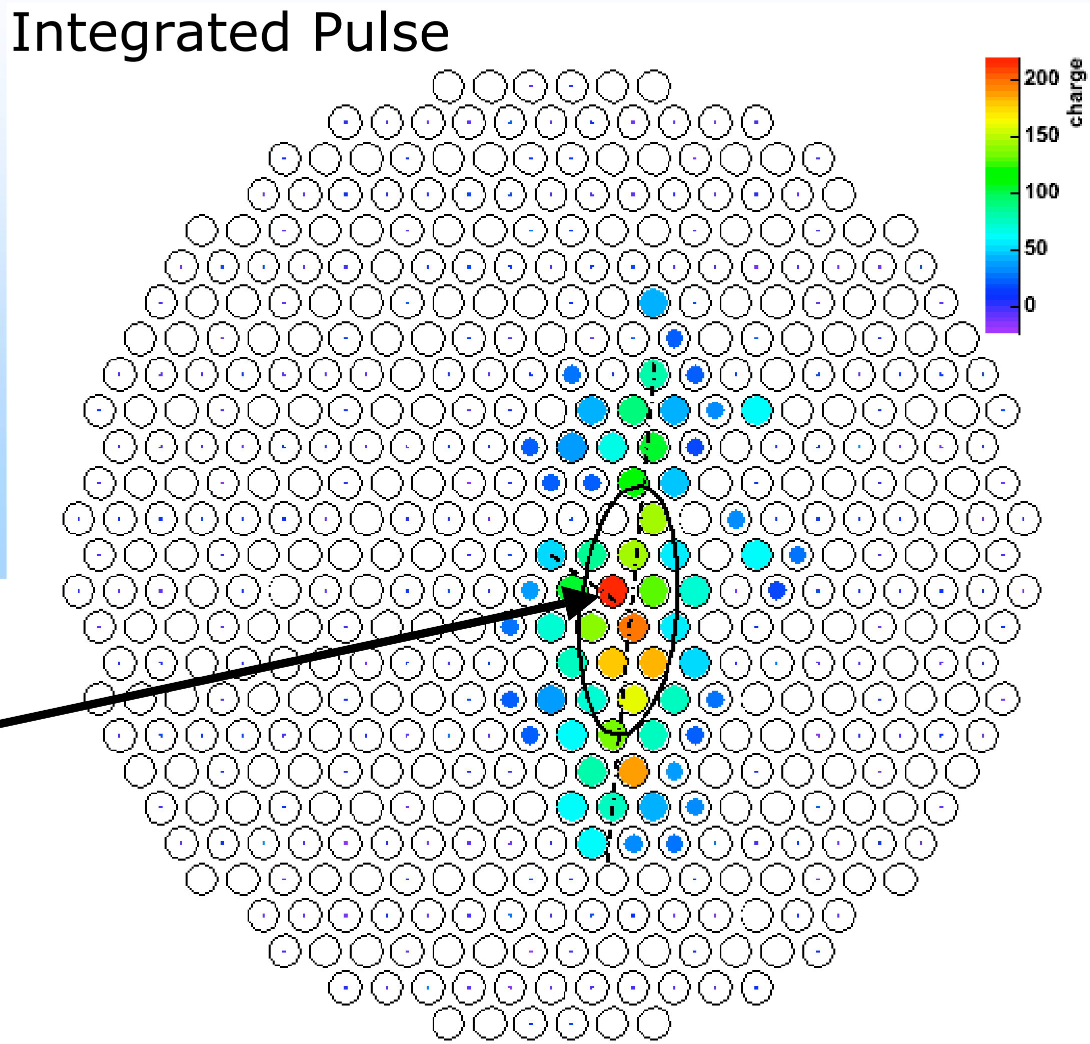
On-line December, 2005

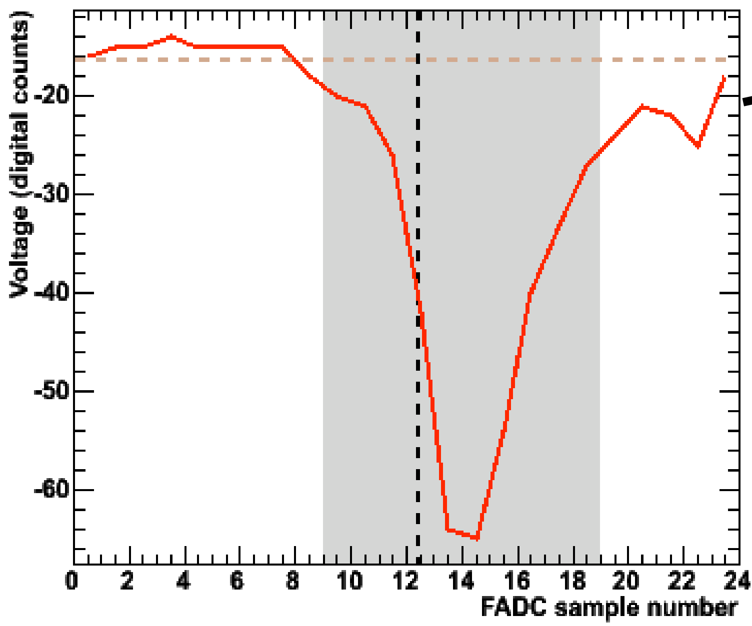


Camera
•499 PMTs
•Photonis XP2970
•0.15º spacing
1.8 m
3.5º FOV

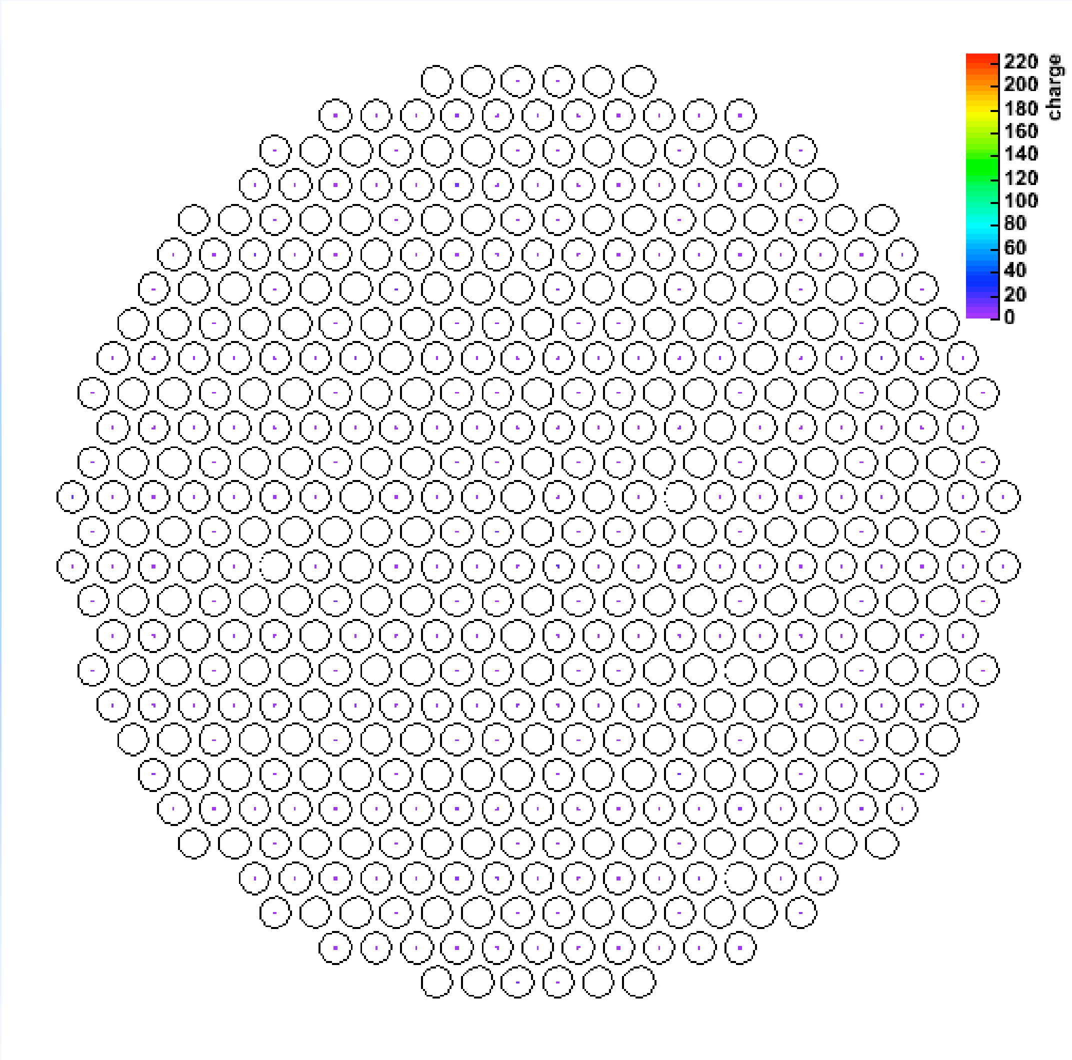
Data Acquisition

- PMT signals digitized with 500MHz sampling FADCs
- Data rates
  - 24 samples/channel
  - 13.5 kb/event
  - 10% deadtime @ 150 Hz
  - 4% with zero supression





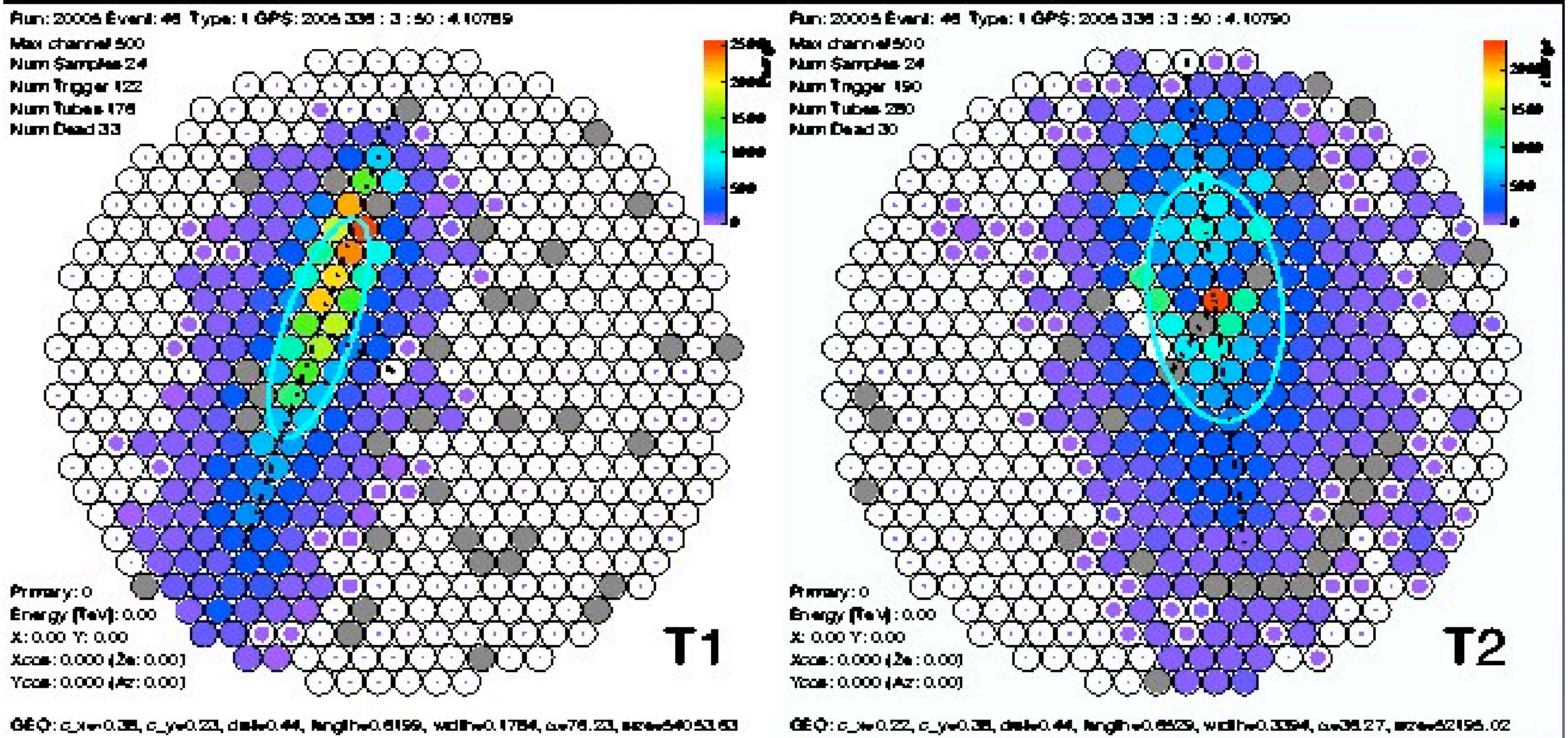
Each Image is a Movie



Poster: “Exploiting VERITAS Timing Information” Holder et al.

Stereo Events

"offline trigger"



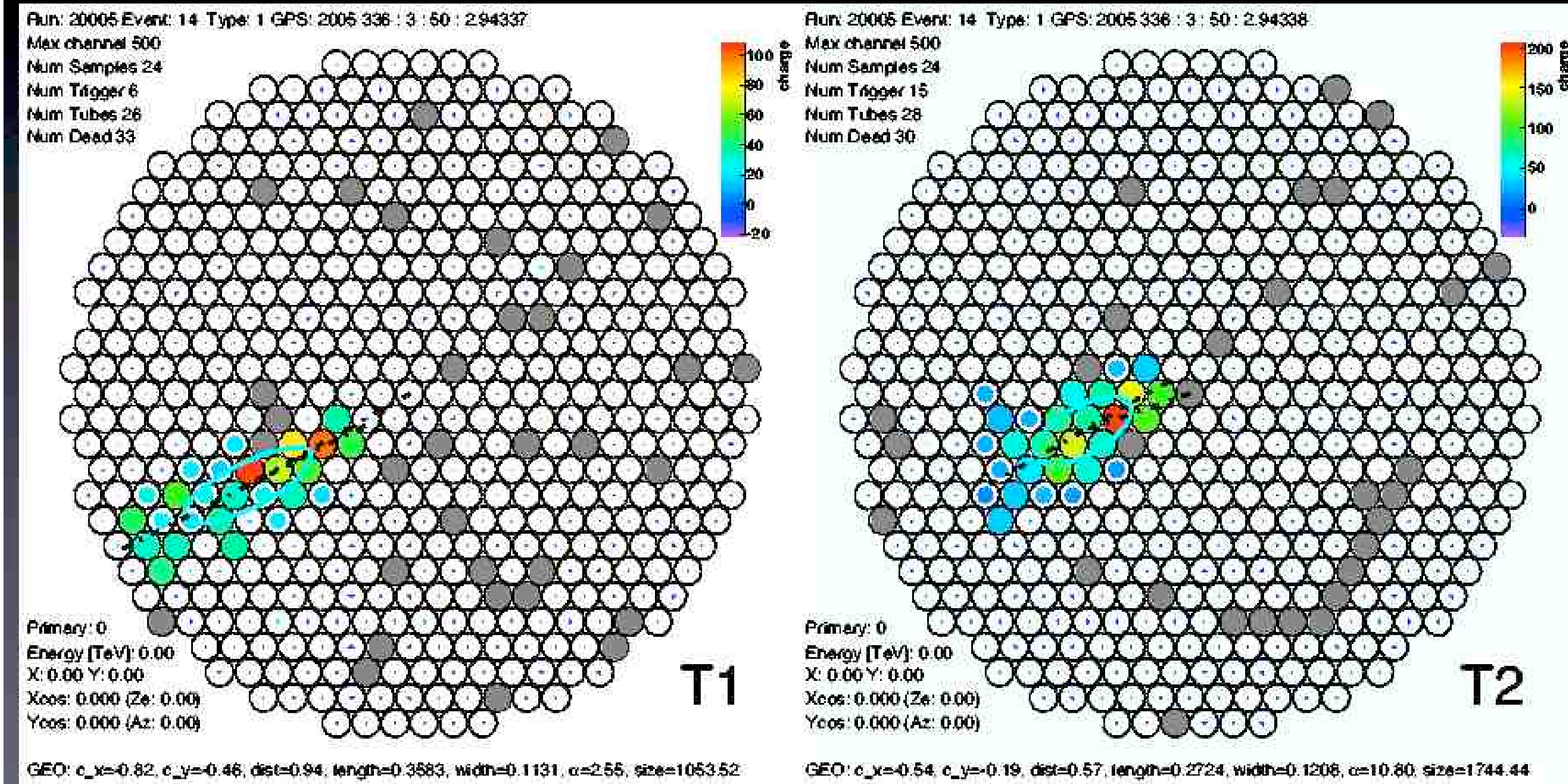
stereo run 20005 (2005/12/02)

(T1: laser run 1999, Crab run 2048)

T2: laser run 10507, Crab run 10510)

Stereo Events

"offline trigger"



stereo run 20005 (2005/12/02)

(T1: laser run 1999, Crab run 2048)

T2: laser run 10507, Crab run 10510)

Limitations and alternatives

- Telescopes have limited FOV
  - Not ideal for discovery
  - Require trigger and repositioning for GRB detection
  - On time typically 20% (moonless, clear night sky)

- Wide FOV detectors allow monitoring the sky (1 sr), but energy threshold somewhat high for extragalactic observations. Gamma/hadron rejection is poor.
  - AIROBICC (49 PMT, 0.3 deg res)
  - Tibet airshower array, 5200m elevation
  - MILAGRO 100% ontime, shower detector
  - AMANDA and IceCube - see SGR analysis

Imaging air Cherenkov telescopes

- Third generation telescopes in construction all over the world.
- Wealth of discoveries in high energy astrophysics and gamma astronomy.
- Still many new developments and new instruments to be built.
- Push for lower threshold will allow physics at high redshifts.

- *Great opportunties for postdoctoral research.*