Very High Energy Gamma Ray Astronomy

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Introduction

- Very high energy (VHE) gamma rays (10 GeV to 100 TeV) offer a unique insight into some of the most extreme phenomenon of our universe.

- Detection of celestial VHE gamma rays allows the study of exotic objects like pulsars, pulsar wind nebulae, supernova remnants, micro-quasars, active galactic nuclei etc, where particles are accelerated to TeV energies and beyond.

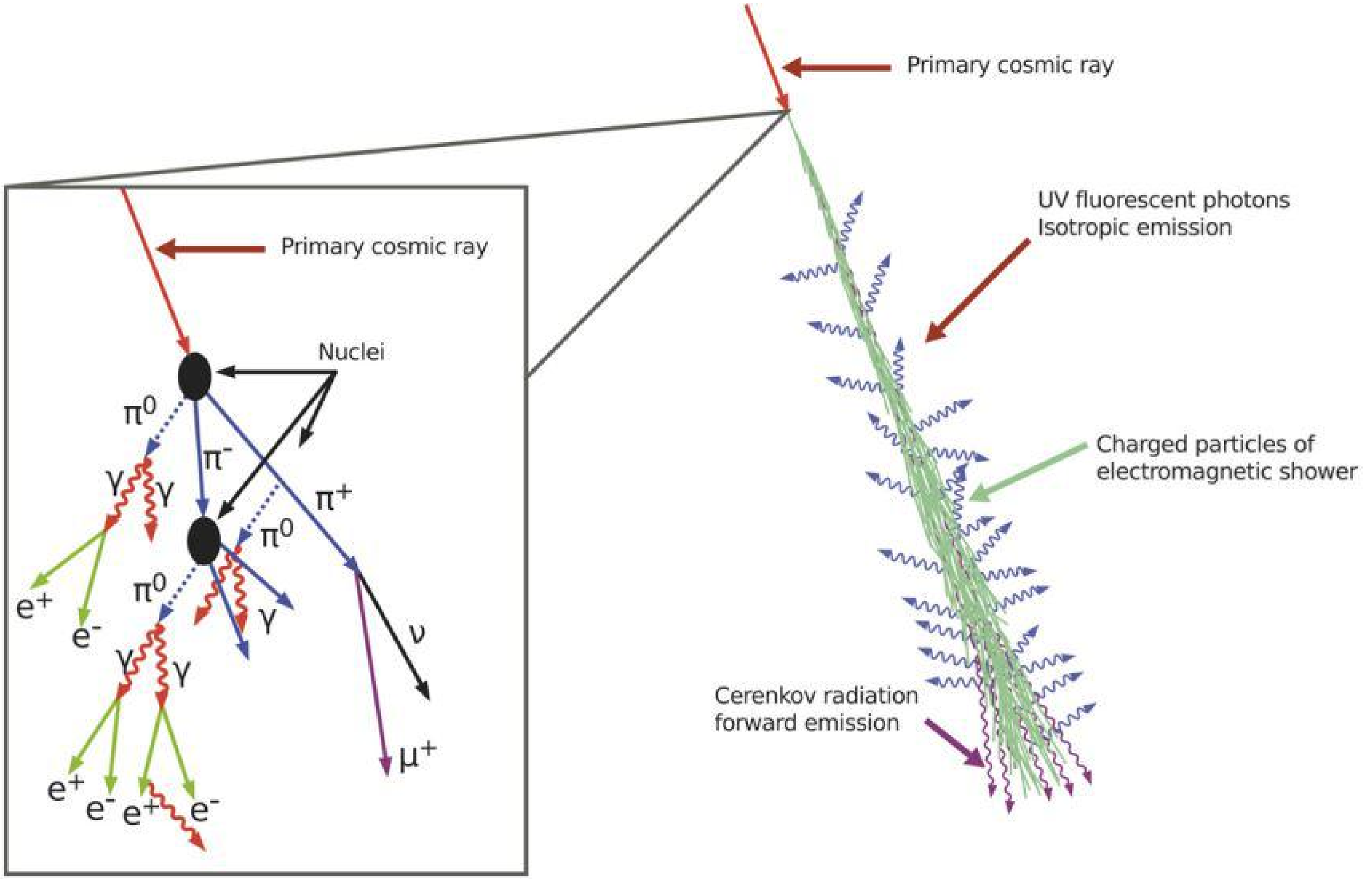
- The gamma rays trace back to cosmic accelerators which may also be responsible for the creation and acceleration of the charged cosmic rays. Thus, providing us the means to search for the origin of the high-energy cosmic rays.

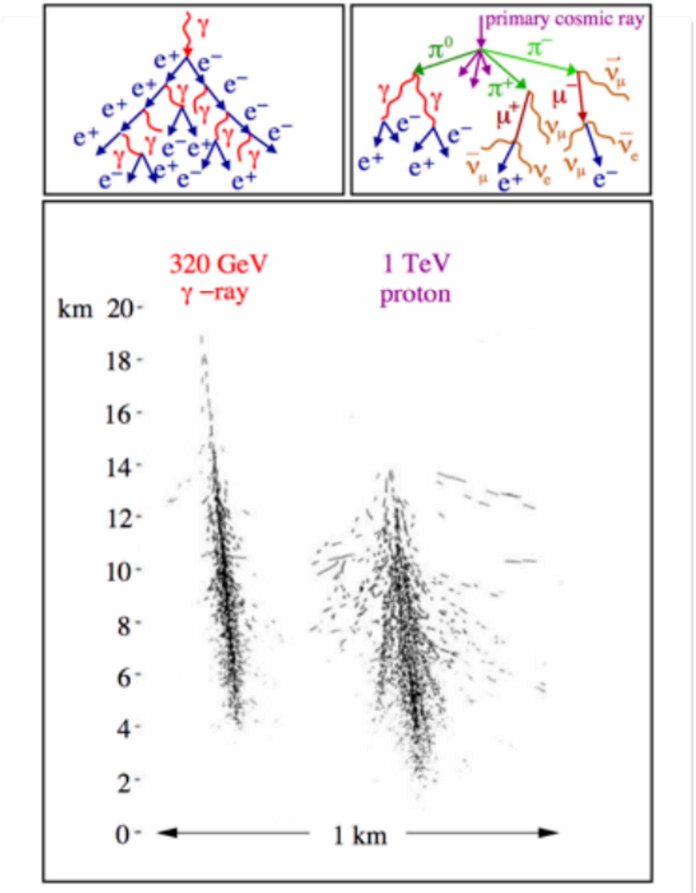
Detection and challenges

- The extremely low photon fluxes at such high energies, require detector effective area that are impractically large for current space-based instruments.
- These exceptionally energetic photons are detected on the earth by an indirect process which uses the Earth’s atmosphere as a transducer.
- They interact with the atmosphere, producing Cherenkov light flashes (lasting for few ns), detected by imaging telescopes.

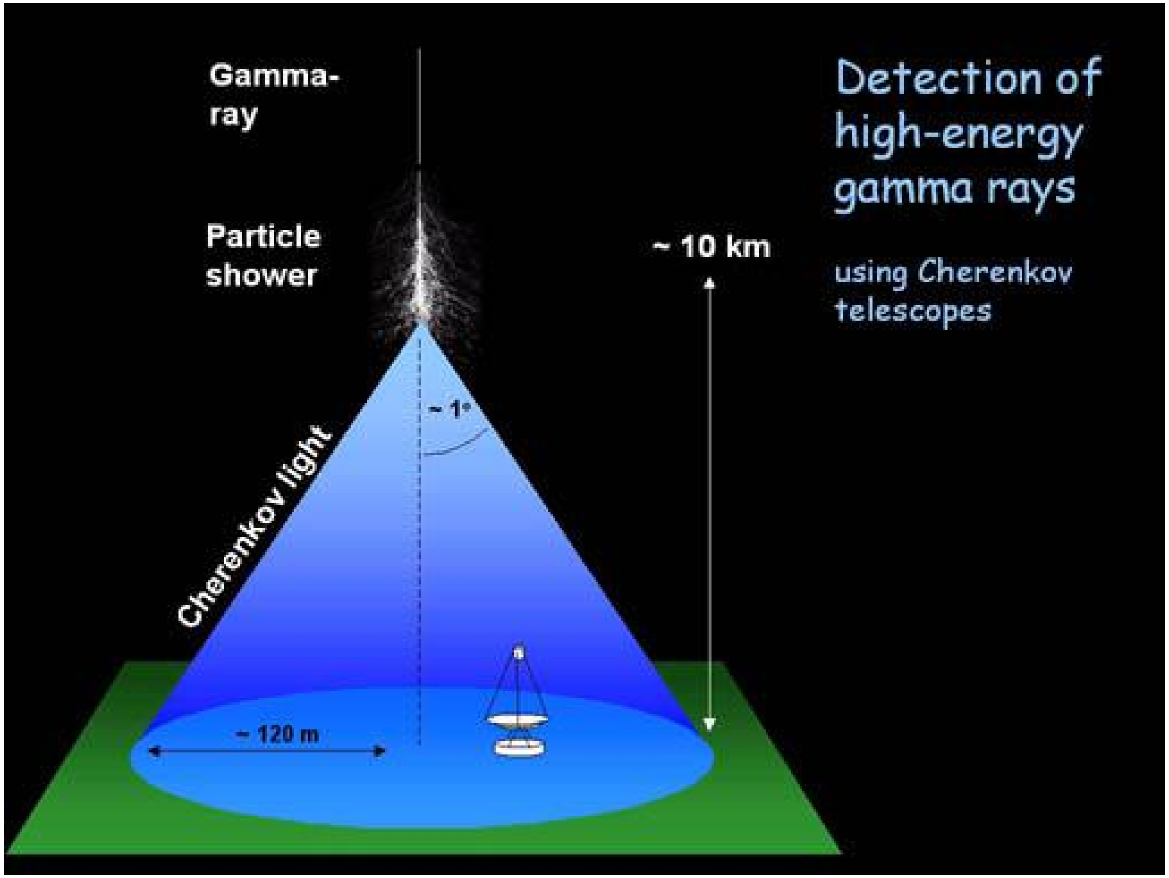
Extensive Air Shower

The different physical mechanisms that take place in gamma-ray & cosmic ray induced showers affect the characteristics of their Cherenkov images





Cherenkov Radiation



Speed of charged particle:

$$V > V_m = c/n$$

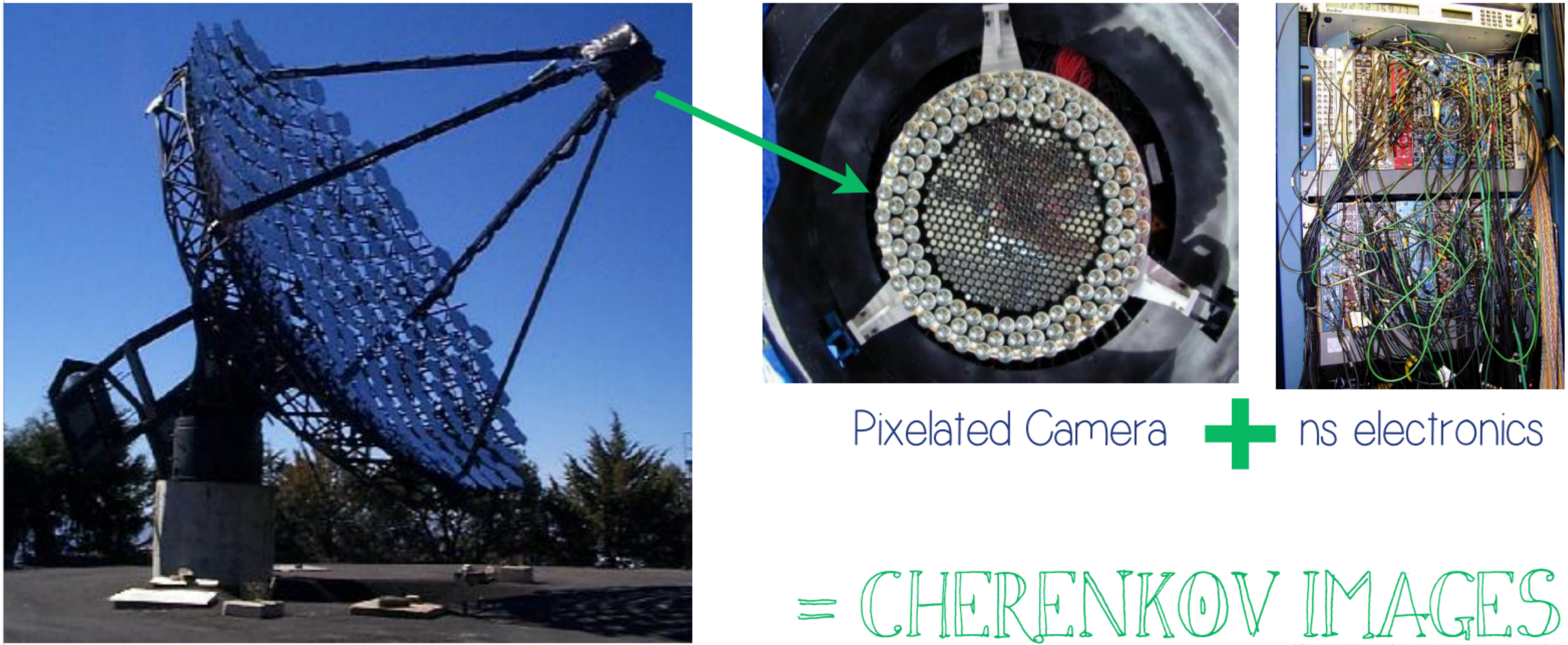
Where,

n is the refractive index of the medium

Cherenkov angle with particle trajectory,

$$\cos\delta = \frac{V_m}{V} = \frac{c}{nV} = \frac{1}{\beta n}$$

Whipple telescope (1965-2013) at ~2600m



The Whipple 10m Telescope

Pixelated Camera + ns electronics

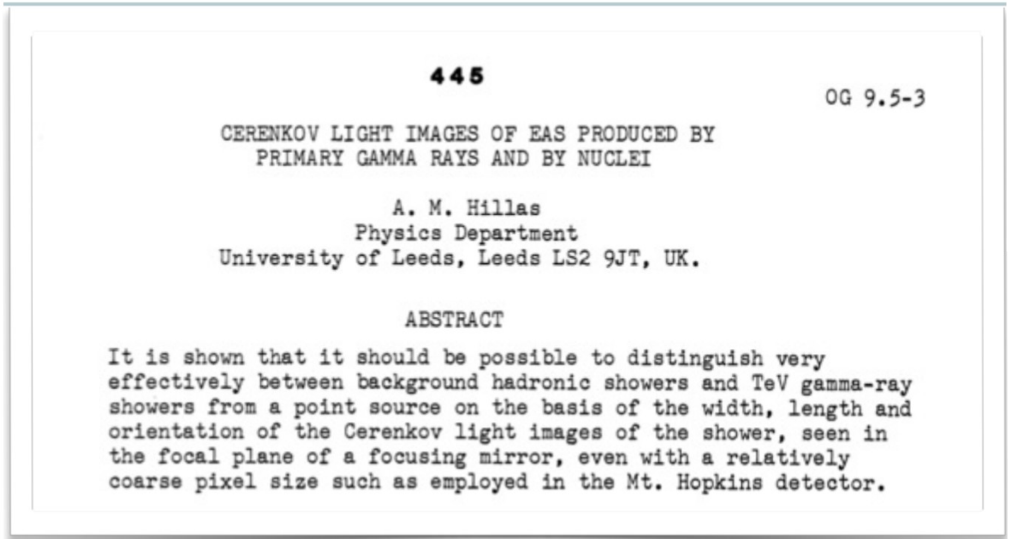
= CHERENKOV IMAGES

- The Davies-Cotton reflector held 248 hexagonal mirrors

- Total reflecting area of 75 m^2.
- 379 PMTs with a field of view of ~2.6 degrees.
- Angular resolution of 0.117 degrees.
- Operated between 300 GeV and 10 TeV.

Imaging Technique (1985)

The problem was that > 99% of the events that trigger the camera were induced by cosmic rays (background).



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CERENKOV LIGHT IMAGES OF EAS PRODUCED BY
PRIMARY GAMMA RAYS AND BY NUCLEI

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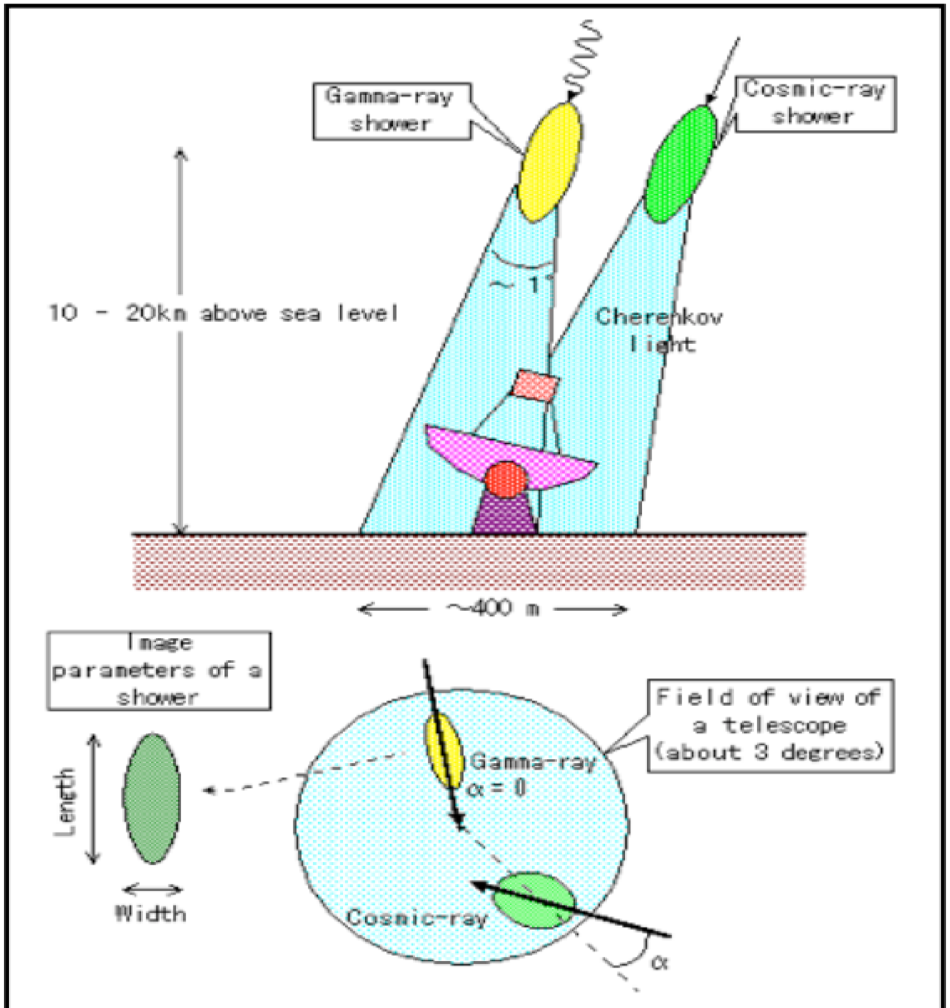
ABSTRACT

It is shown that it should be possible to distinguish very effectively between background hadronic showers and TeV gamma-ray showers from a point source on the basis of the width, length and orientation of the Cerenkov light images of the shower, seen in the focal plane of a focusing mirror, even with a relatively coarse pixel size such as employed in the Mt. Hopkins detector.

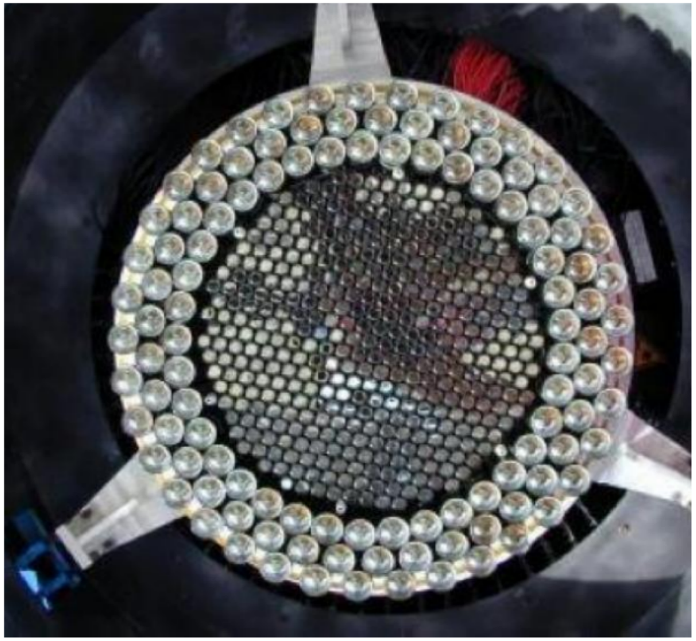


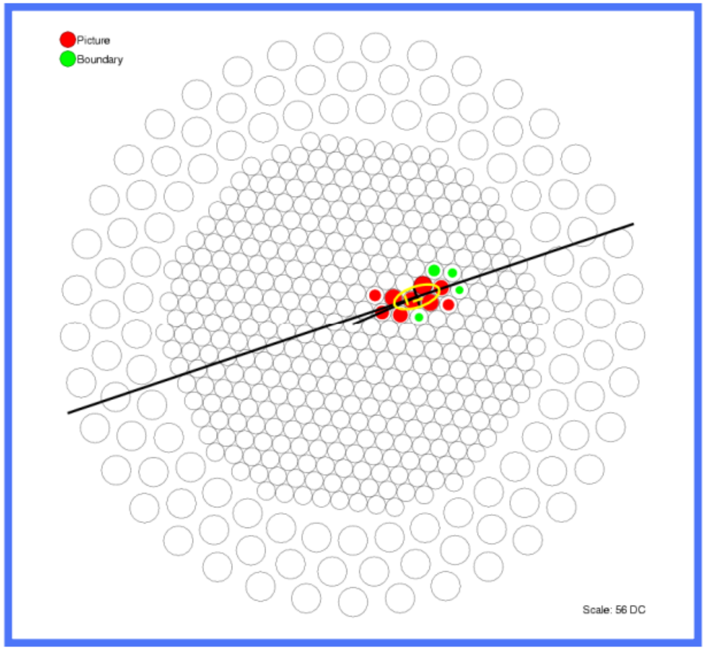
icrhp9.icrr.u-tokyo.ac.jp/method.html

The Imaging Telescope technique

- The Imaging technique was pioneered at the Whipple telescope in Arizona in ~1986.
- **Hillas Parameters:**
  - Size (or sum): Σ Pixel signal
  - Centroid: Coordinates of the centre of gravity (x,y)
  - Main Axis: Line minimising signal-weighed sums of squared pixel distance
  - Length: Signal RMS along main axis
  - Width: Signal RMS along axis perpendicular to main axis.
- The first ever TeV gamma-ray source, the **Crab Nebula** was observed in 1989.

Gamma shower image



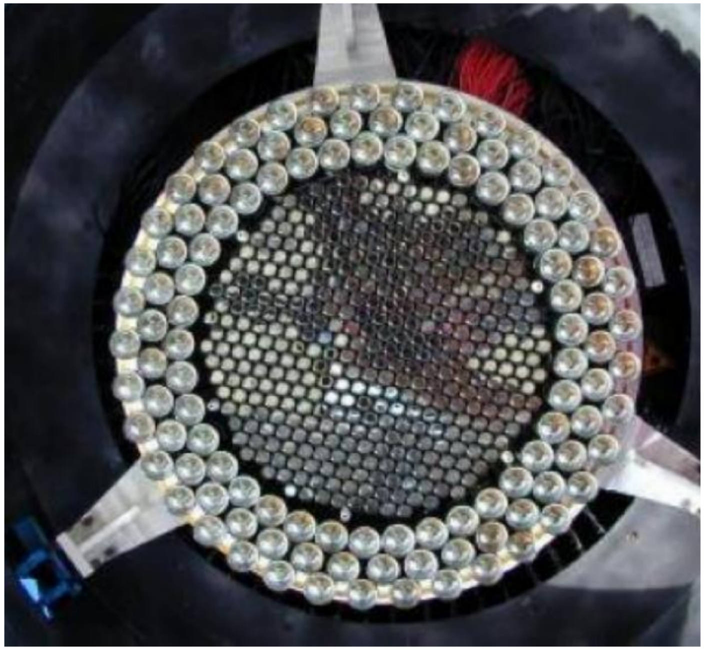


camera

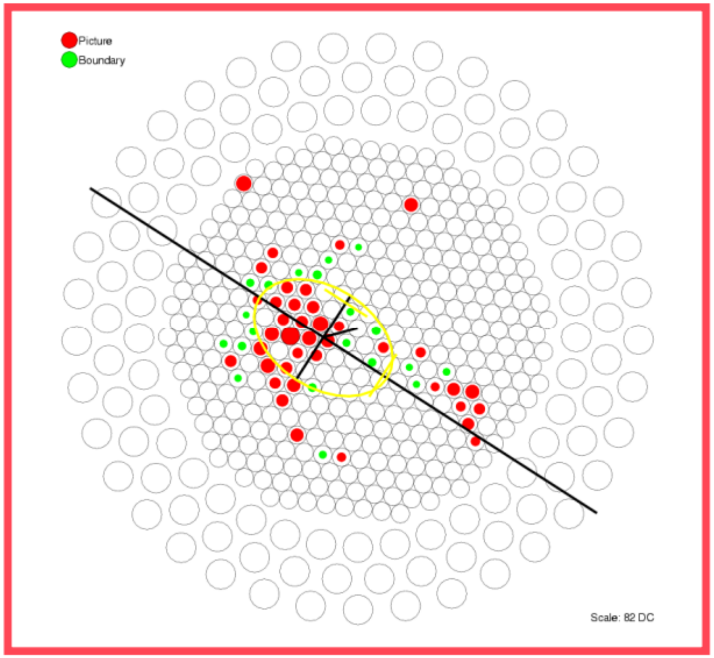
gamma ray

Image shape	elongated, quasi-elliptic shape
Image direction	point to the source (the center of field of view)

Cosmic shower image



camera

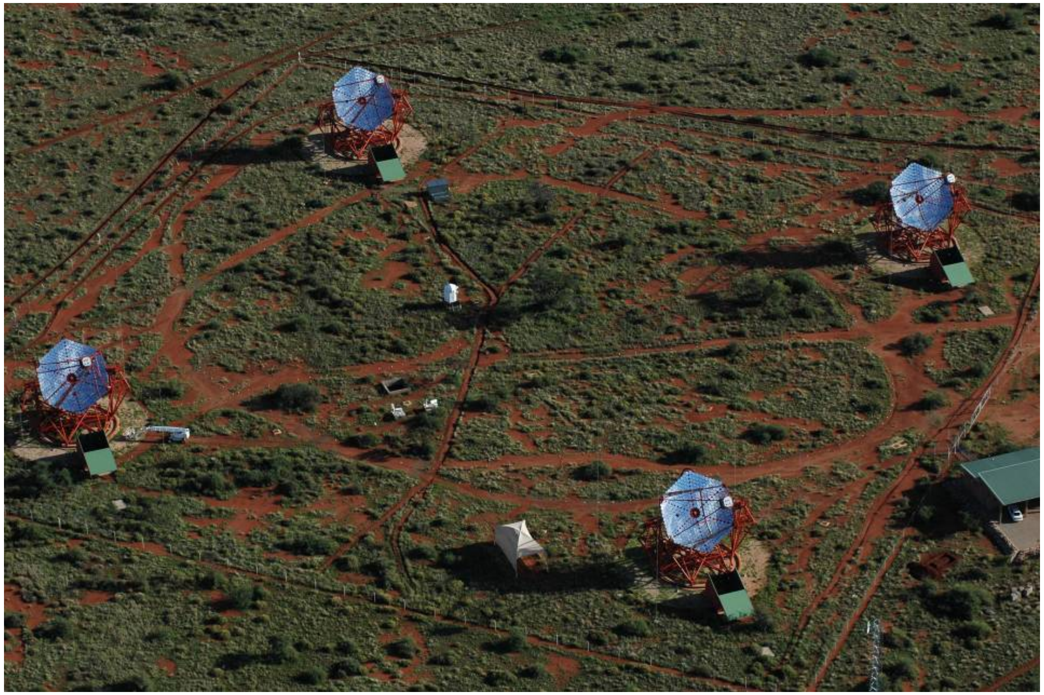


cosmic ray

Image shape	More irregular
Image Direction	Randomly oriented in focal plane

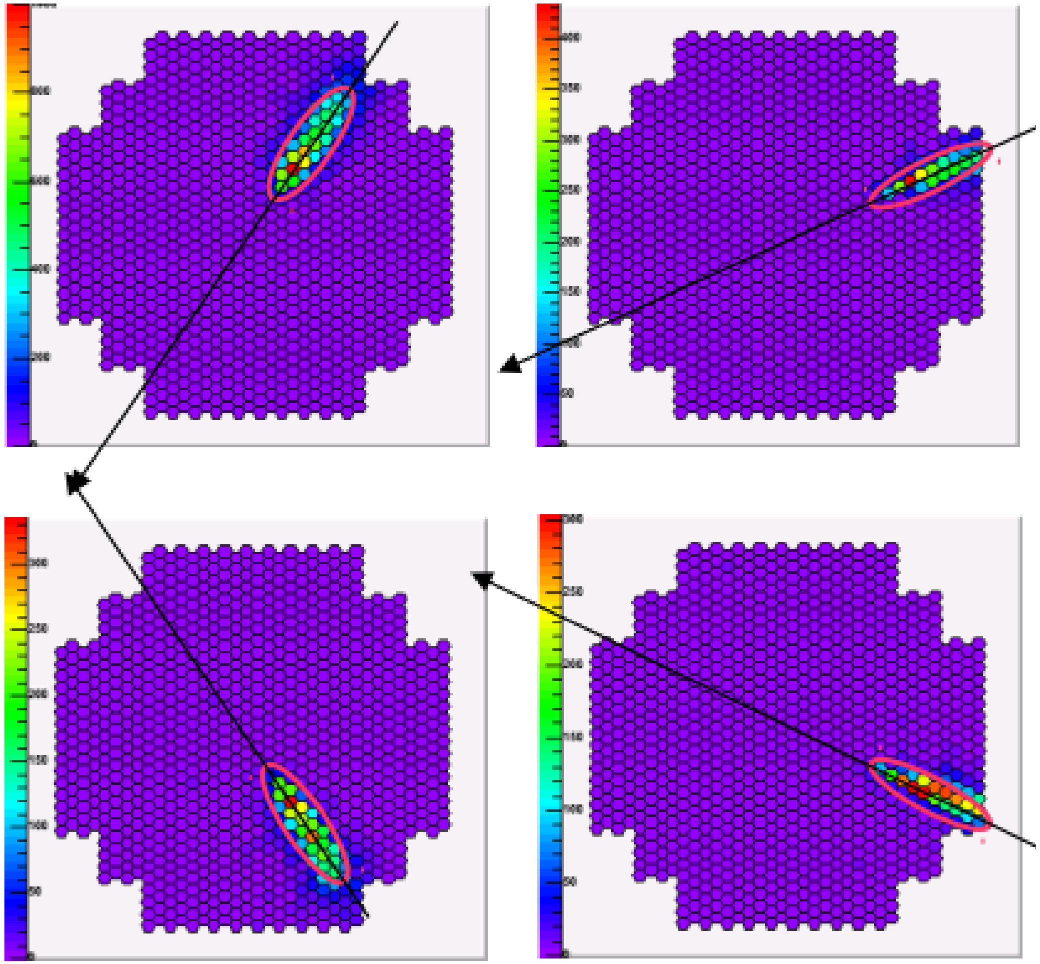
High Energy Stereoscopic System (H.E.S.S.), Namibia

- The initial four H.E.S.S. telescopes (12 m each) are arranged in form of a square with 120m side length, to provide multiple stereoscopic views of air showers.
- The total mirror area is 108 m^2 (with 380 round mirrors) per telescope. Each having camera with 960 PMTs.
- The mirrors are focused for an object distance of about 10 km, corresponding to the typical distance of an air shower from the telescopes.



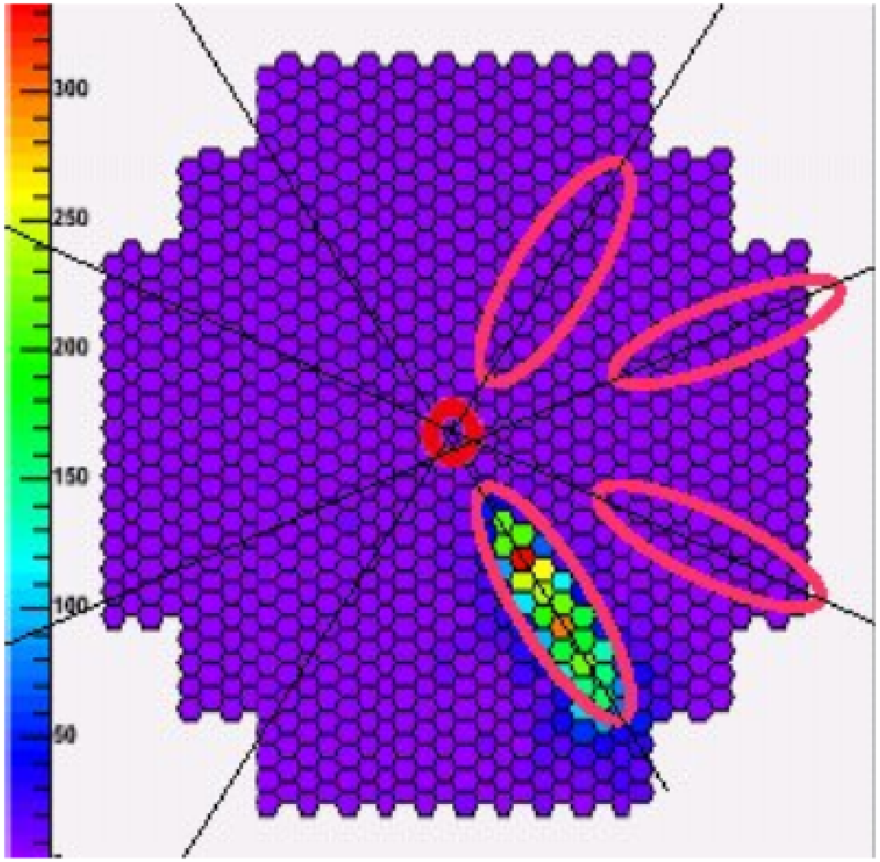
- In Phase II of the project, a single huge dish with about 600 m^2 mirror area (875 hexagonal facets) was added at the center of the array (28m).
- Better resolution with 2048 PMTs.

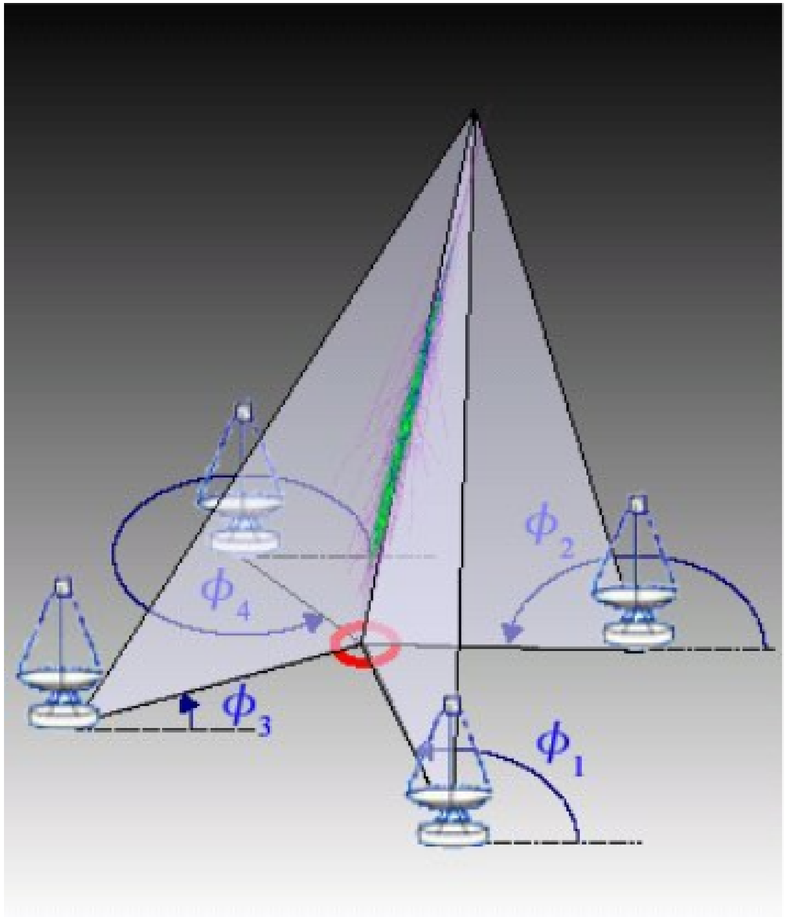
Stereoscopic measurement



- The main axis of the shower corresponds to a plane that contains the actual shower track.
- The primary particle direction corresponds to a point on this main axis.

Geometric reconstruction of shower direction

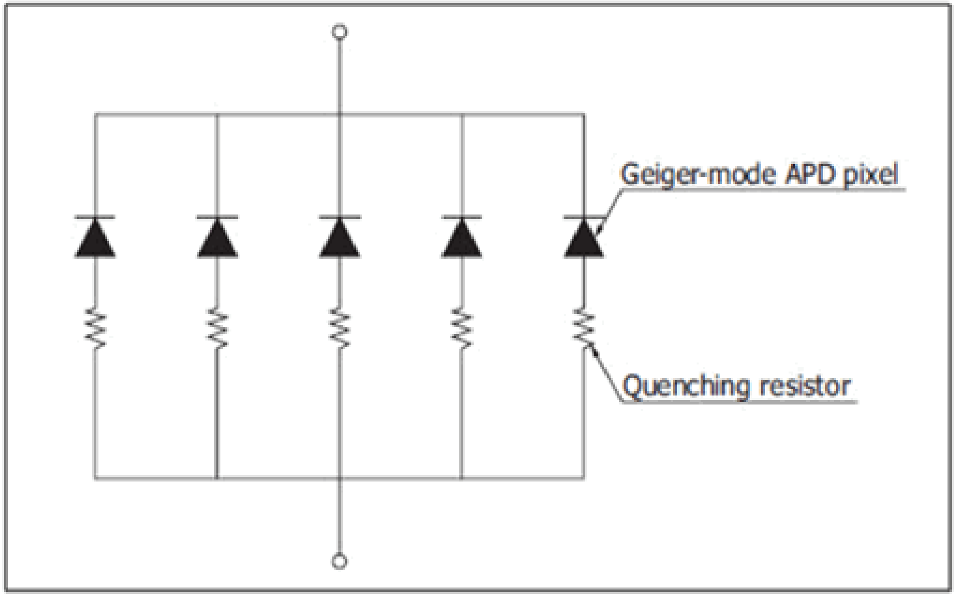




Silicon Photo Multipliers

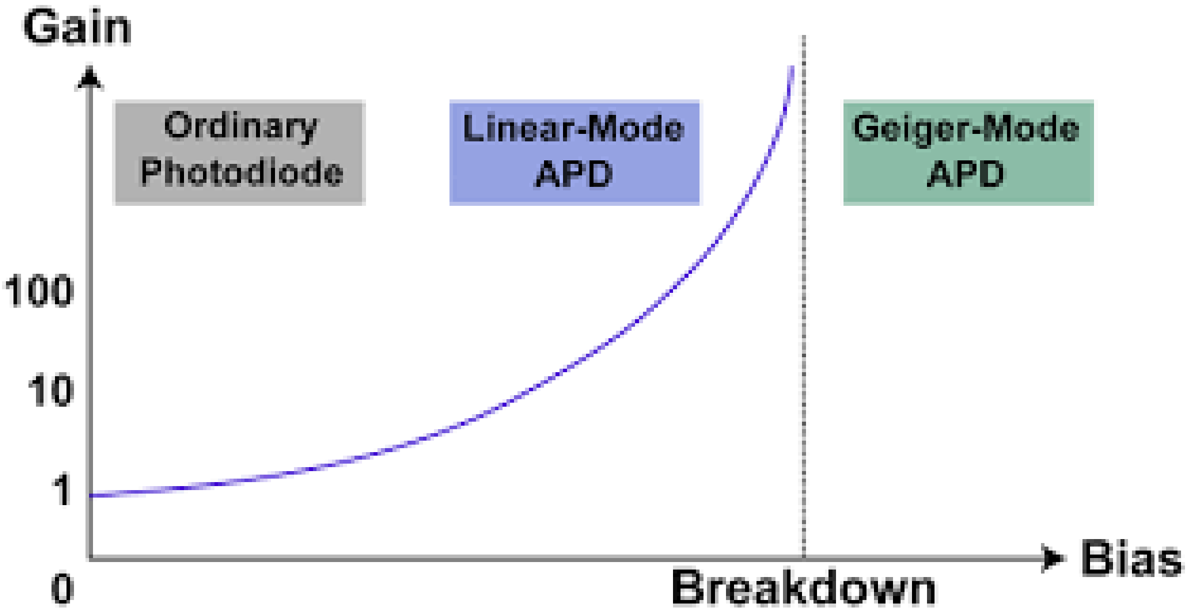
- It is a solid-state photo detector in which a photo-generated carrier can trigger an avalanche current due to the impact ionization mechanism.

- MPPC is made up of multiple such APD (avalanche photodiodes) pixels operated in Geiger mode and available in room temperature operation.



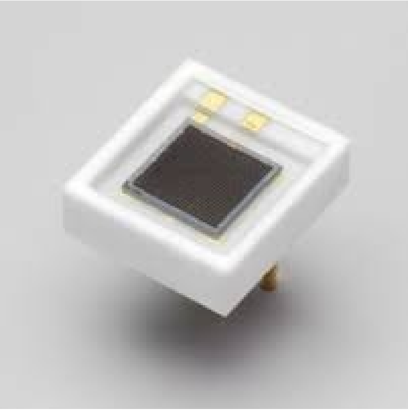
Why SiPMs

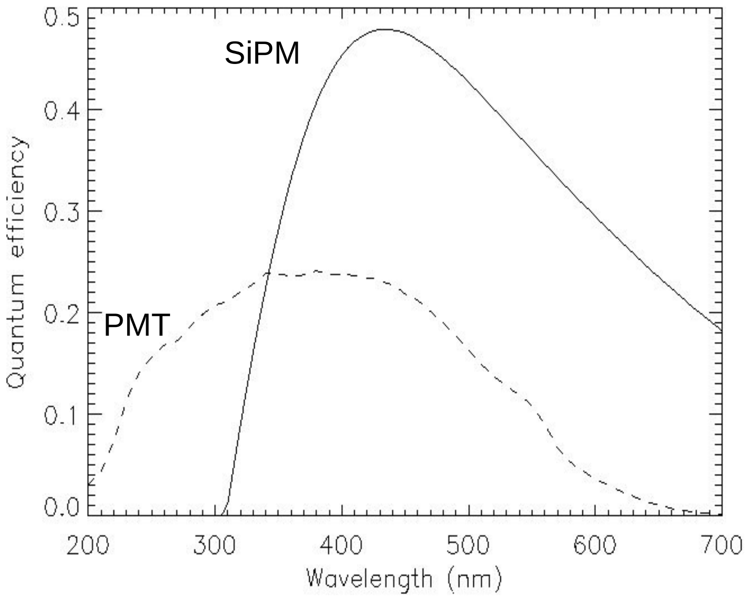
- SiPMs are specially designed to operate with a reverse bias voltage well above the breakdown voltage.
- This device is able to detect low intensity signals (**down to the single photon**) and to signal the arrival times of the photons with a jitter of a few tens of picoseconds.



PMTs Vs SiPMs

PMTs	*SiPMs*
High gain	High gain
Fast response	Fast response
Low quantum efficiency	High quantum efficiency Well resolved photoelectron spectrum
Bulky, fragile heavy	Compactness, ruggedness, light weight
High bias voltage (~KV)	Low bias voltage (~few tens of Volts)
Operation only during dark night	Operation possible even in moon light and twilight
Magnetic sensitivity	Magnetic insensitivity
	Cross talk, saturation, high dark current, temperature dependence of gain

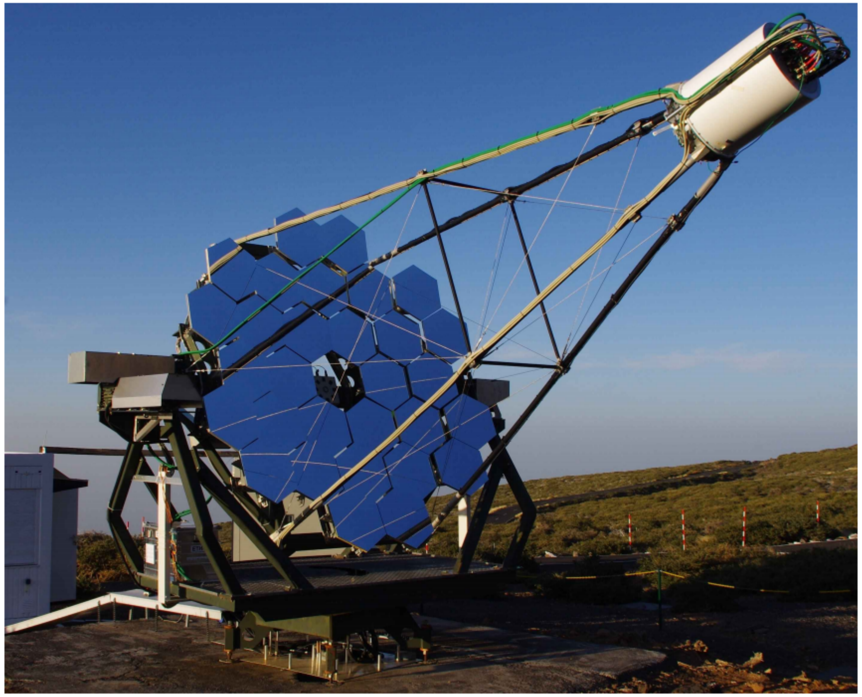




Specification of one such SiPM

MPPC :: S12572-050C	
Number of channels	1
Effective photo sensitive area	**3 X 3 mm**
Pixel pitch	50µ
Number of microcells	3600
Fill factor	61.5% (78.5% for 100µ)
Operating temperature	-10 to 40°C
Storage temperature	-20 to 70° C
Spectral response	320 to 900 nm
Peak sensitive wavelength	500 nm
Operating voltage	Breakdown voltage ± 10V

First G-APD based Cherenkov Telescope (FACT) at ~2200m.



- Operational on the canary island of La Palma.
- 30 mirrors resulting in total reflecting surface of ~9.5 m^2
- 1440 G-APDs with FoV ~4.5°

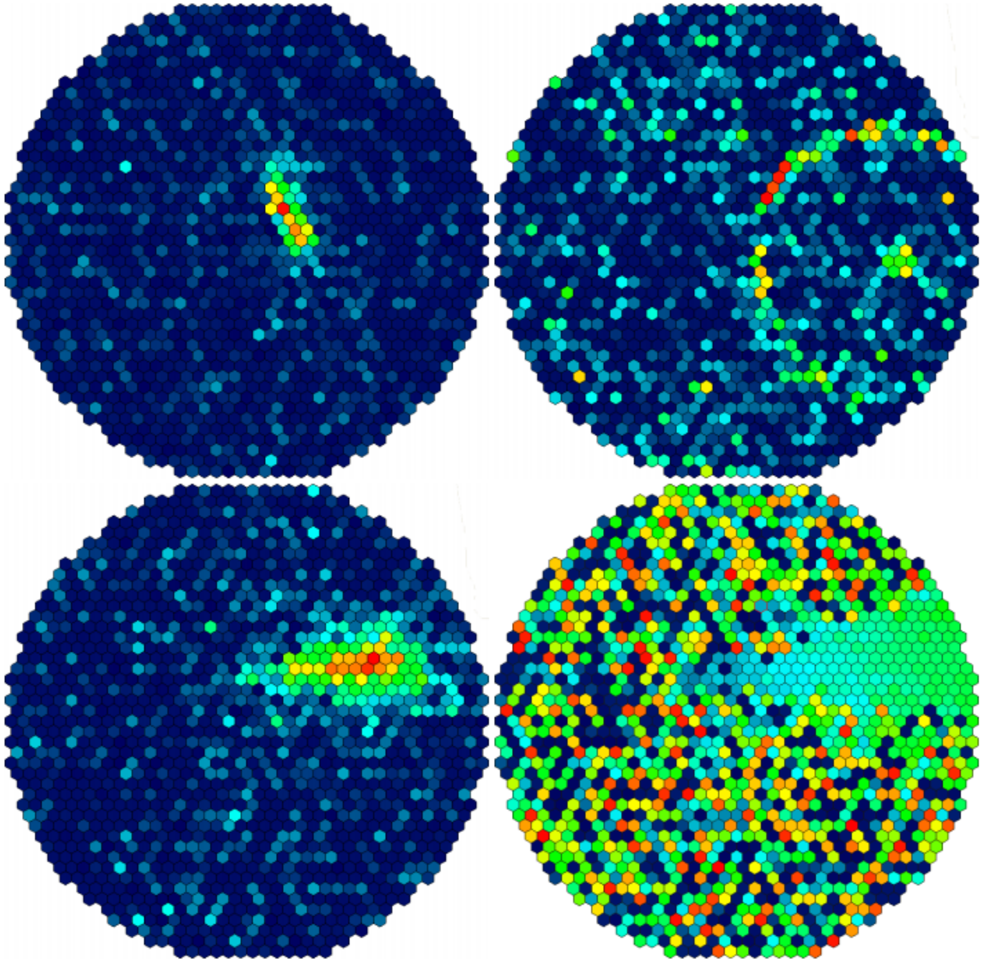


Figure 21. Examples of air shower images recorded by FACT. The two images at the top correspond to a gamma candidate and a muon event, with the color code representing the pixel amplitude. At the bottom a proton shower is shown, both in amplitude (left) and signal time (right).

Future Expectations (CTA)

- CTA will be the largest ground-based gamma-ray detection observatory in the world, with more than 100 telescopes in the northern and southern hemispheres.
- Higher sensitivity at TeV energies (x 10)
- Higher energy reach (PeV and beyond)
- Wide field of view
- Improved angular resolution
- Higher detection rates
- It will use both PMTs and G-APDs

Summary

- Gamma Ray Astronomy helps to detect VHE gamma ray sources.
- Helps to understand hadronic component in different kind of astrophysical sources.
- Can provide information regarding the origin of the high-energy cosmic rays.
- Can provide a signature in indirect detection of Dark matter.

References

- J. Knödlseder, C. R. Physique TBD (2015)
- Paredes, Josep M.; et al. (July 17, 2007)
- My Masters thesis: Estimation of Performance Parameters for Proposed G-APD based Gamma Ray Astronomy Telescope.
- Lecture 2: Gamma Ray Astrophysics, by Dmitry Semokoz, APC, Paris.
- https://fermi.gsfc.nasa.gov/science/mtgs/summerschool/2013/week1/DeirdreHoranVHEAstro.pdf
- Design and operation of FACT – the first G-APD Cherenkov telescope: H Anderhub et al 2013 JINST 8 P06008

Thank you

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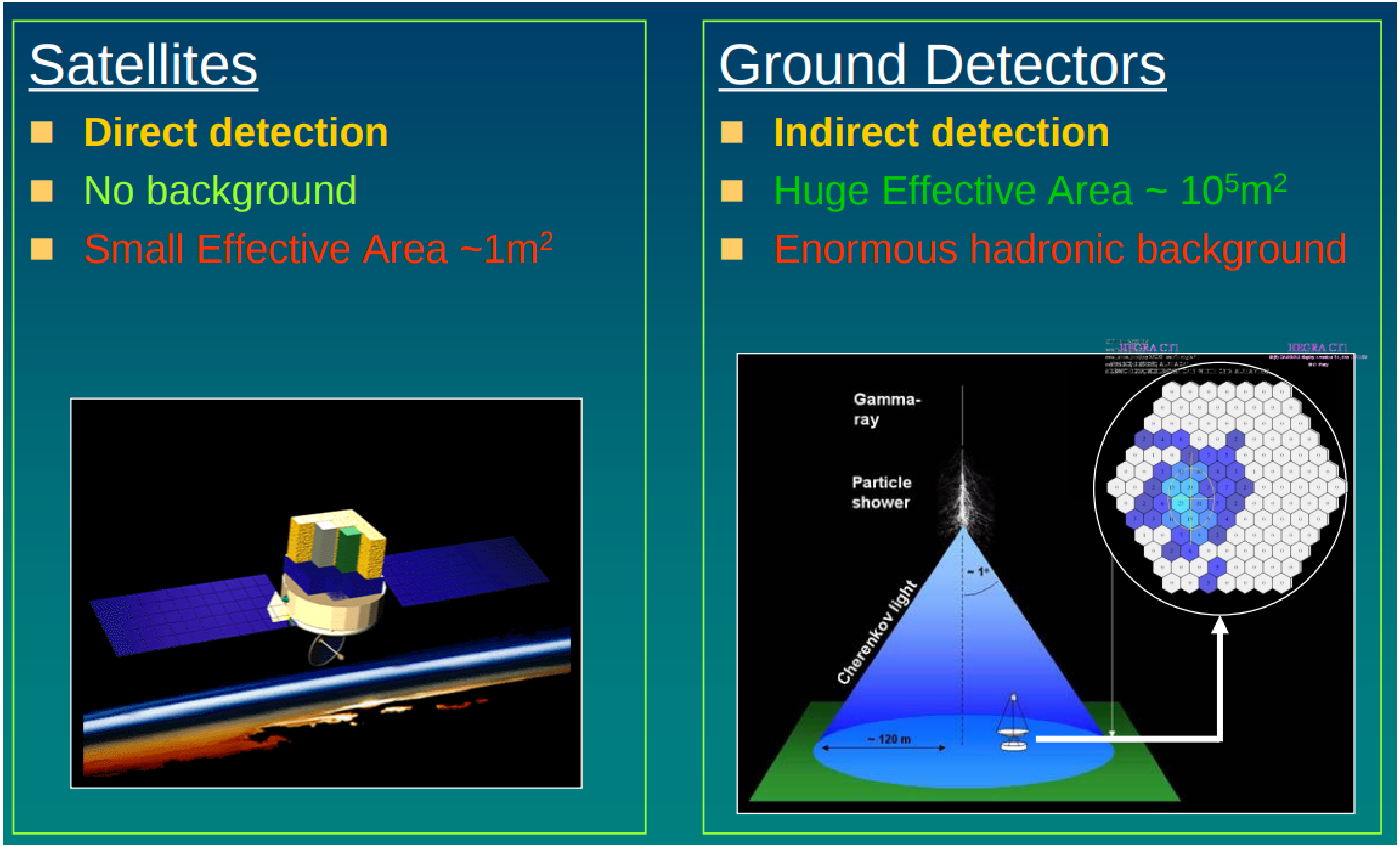
Backup

Non Thermal

“The word non-thermal is used frequently in high energy astrophysics to describe the emission of high energy particles. I find this an unfortunate terminology, since all emission mechanisms are ‘thermal’ in some sense. The word is conventionally taken to mean ‘continuum radiation from particles, the energy spectrum of which is not Maxwellian’. In practice, continuum emission is often referred to as ‘non-thermal’ if it cannot be accounted for by the spectrum of thermal bremsstrahlung or black-body radiation”

- M. S. Longair



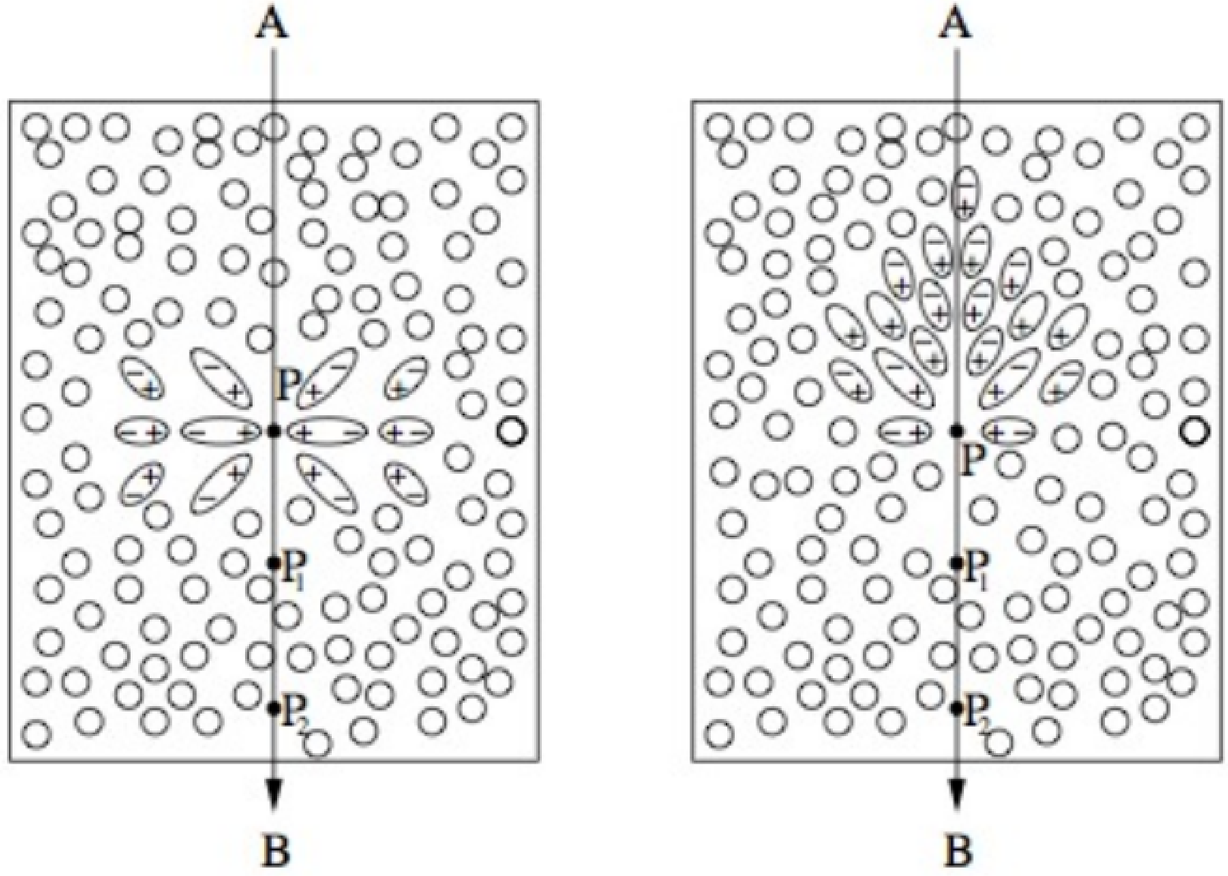
Satellites

- **Direct detection**
- No background
- Small Effective Area ~1m^2

Ground Detectors

- **Indirect detection**
- Huge Effective Area ~ $10^5 m^2$
- Enormous hadronic background

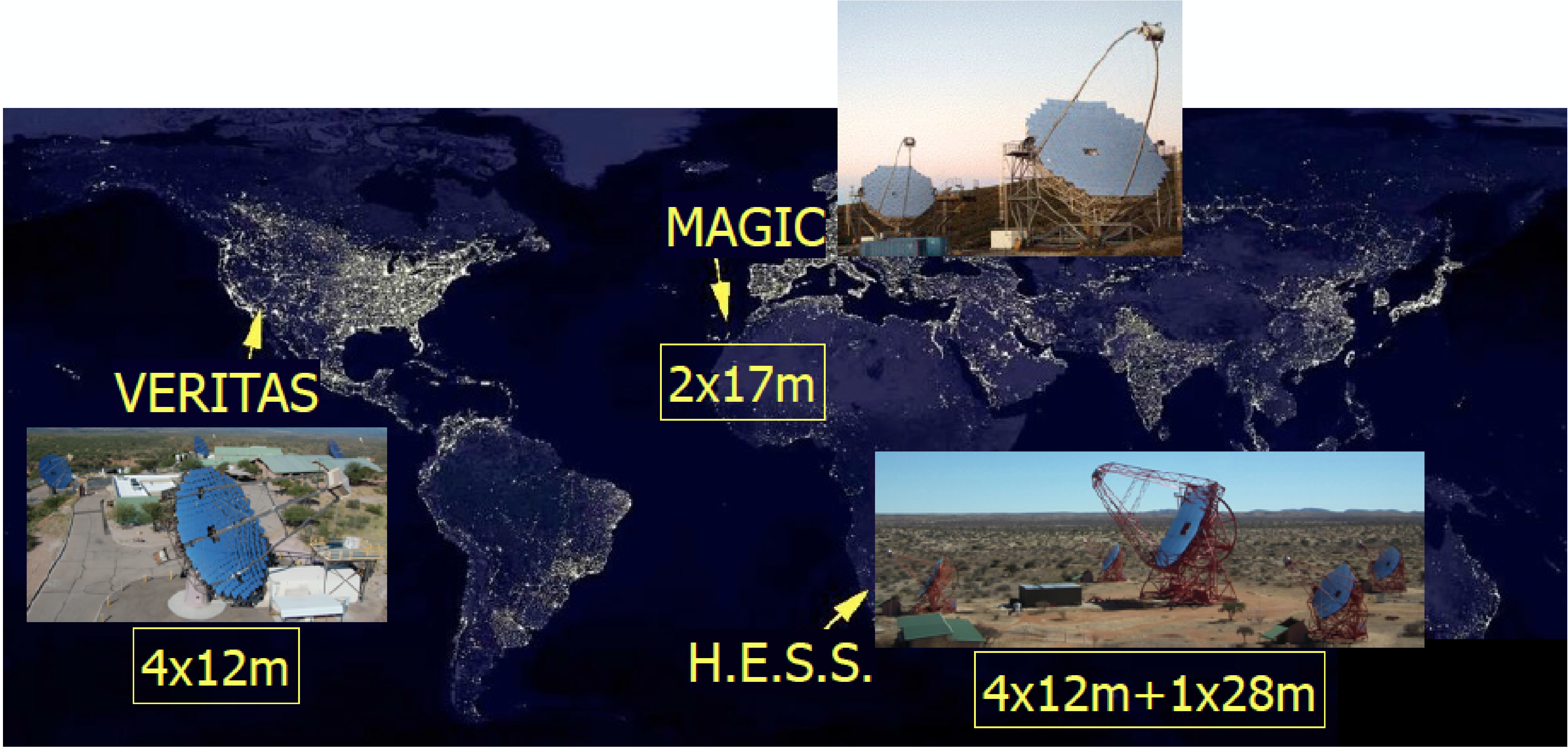
Cherenkov



e- moves relatively slowly

e- with velocity close to c

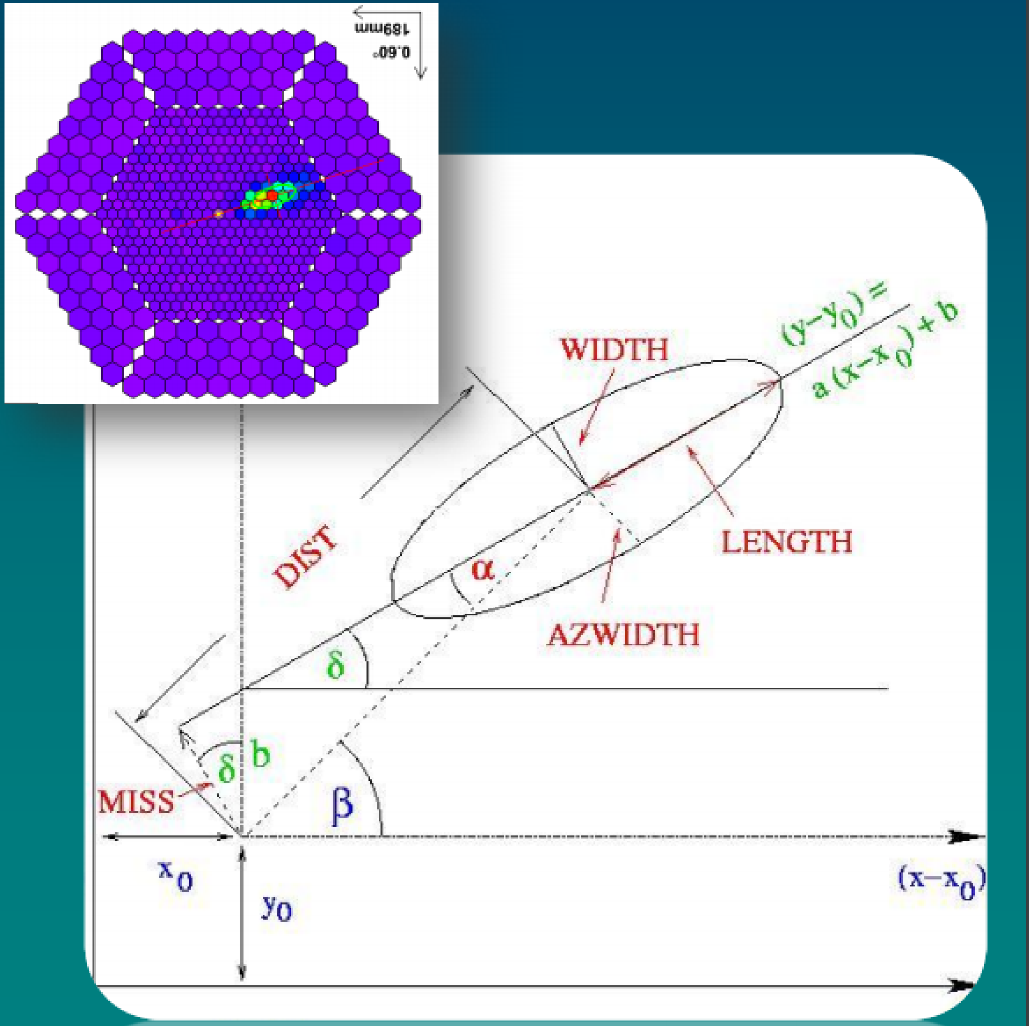
Cherenkov Telescopes



Hillas parameters

Idea: *Images of gamma showers have an oval shape. They can be described by an ellipse, defined by:*

- ***Size (or Sum):*** *Σ pixel signal*
- ***Centroid:*** *Coordinate of the center of gravity (x,y)*
- ***Main Axis (δ angle):***
  - *Line minimizing signal-weighed sum of squared pixel distance.*
  - *Angle of the 2^{nd} moment matrix diagonalization.*
- ***Length:*** *Signal RMS along main axis*
- ***Width:*** *Signal RMS perpendicular to the main axis*



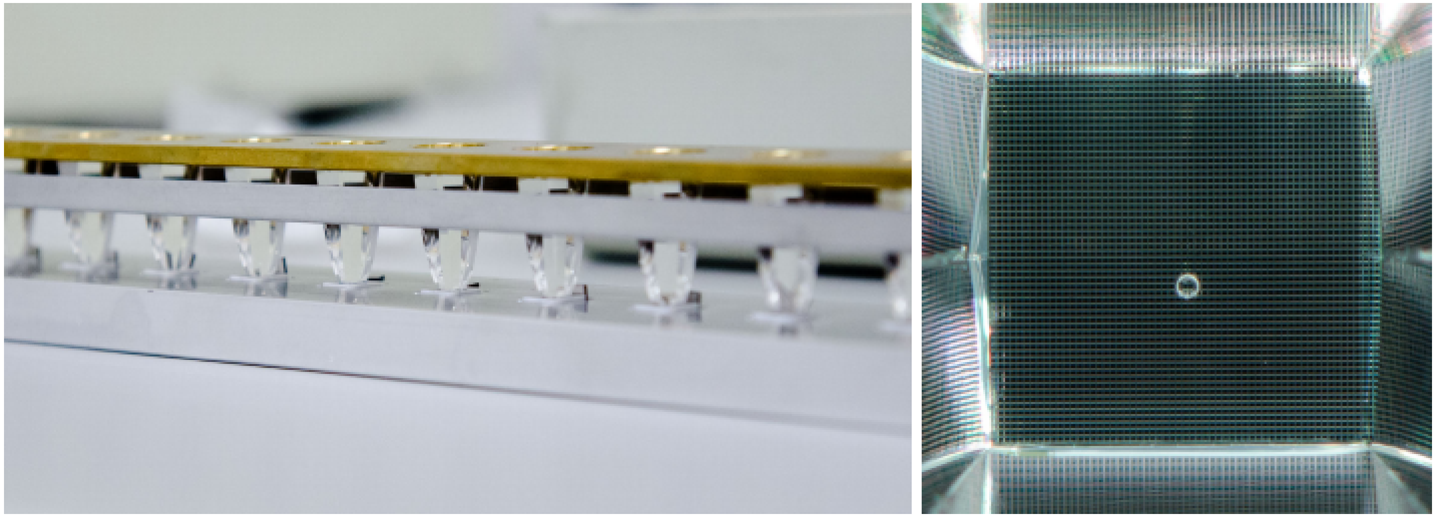


Figure 10. Left: photograph of the alignment tool to glue the light concentrators onto the G-APDs. The sensors are fixed in custom-fit sinkholes on the bottom (white ceramics packaging visible), while the concentrators are positioned with two horizontal metal bars. Right: one of the pictures taken per pixel for quality control. The 3600 G-APD cells are visible and also part of the concentrator walls. The bright spots at the borders are due to reflections. In the middle, an air bubble can be seen, affecting 16 cells. Since this is just 0.4% of the total area, this pixel was accepted. Also it should be noted that only a fraction of the photons hitting the bubble really get lost.

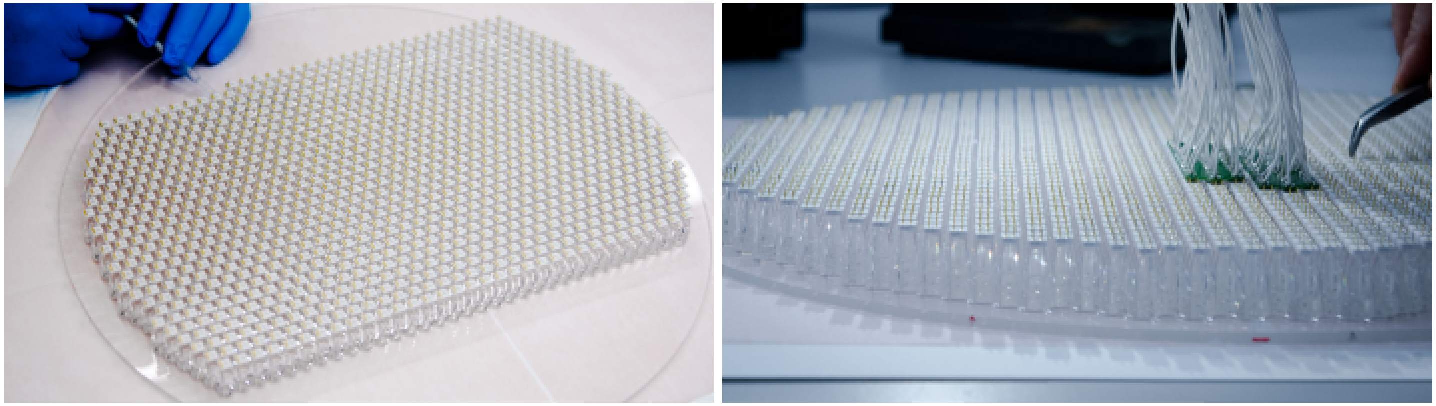


Figure 11. Photographs documenting two work steps during the assembly of the sensor compartment. Left: glueing of the pixels onto the camera window. Right: soldering of the PCBs for the signal and bias-voltage connection on the G-APD contacts (facing upwards).

G-APDs future

- Geiger-mode avalanche photodiodes (G-APD) have turned into a great option for Cherenkov telescopes, in particular also for the CTA project.

- They have kept their promise to be easy to handle and to allow for a very stable operation also during moontime conditions.

- Even though production of solid light concentrators, and their glueing process, needs further investigation to be considered for mass production, the FACT concept has turned out to be a benchmark for future Cherenkov telescopes.

- Considering the fast drop in price for solid state devices (today’s price for G-APDs is already about a factor of ten lower than when the devices for FACT were bought), the construction of the FACT camera has proven that monitoring of the brightest sources with single Cherenkov telescopes becomes affordable and that 24/7 monitoring on long-terms is possible.