Air Cherenkov Methods in Cosmic Rays: A Review and Some History

A.S. Lidvansky,

Institute for Nuclear Research, Moscow

The Vavilov-Cherenkov radiation of high energy cosmic rays in air:

- Only extensive air showers (EAS) can produce sufficient signal to be observed against the night sky background
- Observations are possible only in clear moonless nights (no more than 10% of calendar time)
- There are three different lines of research in this field differing in both energy range and instrumentation

All these three lines of research were initiated by a single man!
(A.E. Chudakov)

Two outstanding “CH”s

P.A. Cherenkov (1904-1990)

A.E. Chudakov (1921-2001)

A.E. Chudakov about P.A. Cherenkov:

- "Always a modest individual, he was extremely scrupulous not to pretend to be involved in the developing applications just because of his contribution to the effect's discovery…"

A.E. Chudakov,

Pavel Alexeevich Cherenkov (Obituary), Physics Today, December 1992

- “He even may have been avoided using the Cherenkov technique in his own experiments…”

A.E. Chudakov,

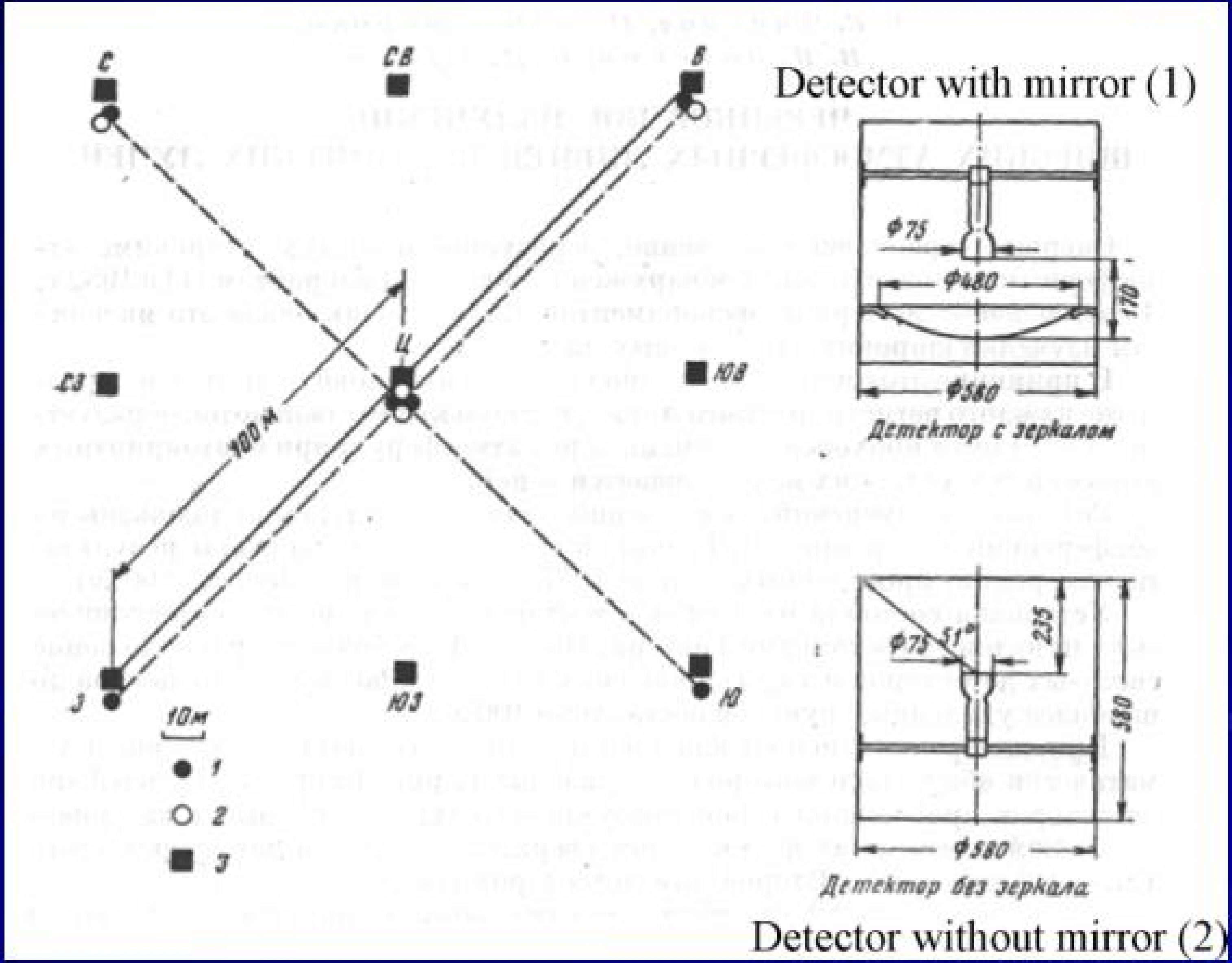
Pavel Alexeevich Cherenkov (Obituary), Physics Today, December 1992

However, in developiong the air Cherenkov technique Chudakov had some predecessors:

- P. Blackett in 1948 first discussed the possibility to detect the Cherenkov radiation of extensive air showers
- It was first detected by Galbraith and Jelly in 1952:

1. W. Galbraith and J. V. Jelley, Nature, **171**, 349 (1953).
2. J. V. Jelley and W. Galbraith, Phil. Mag., **44**, 619 (1953).

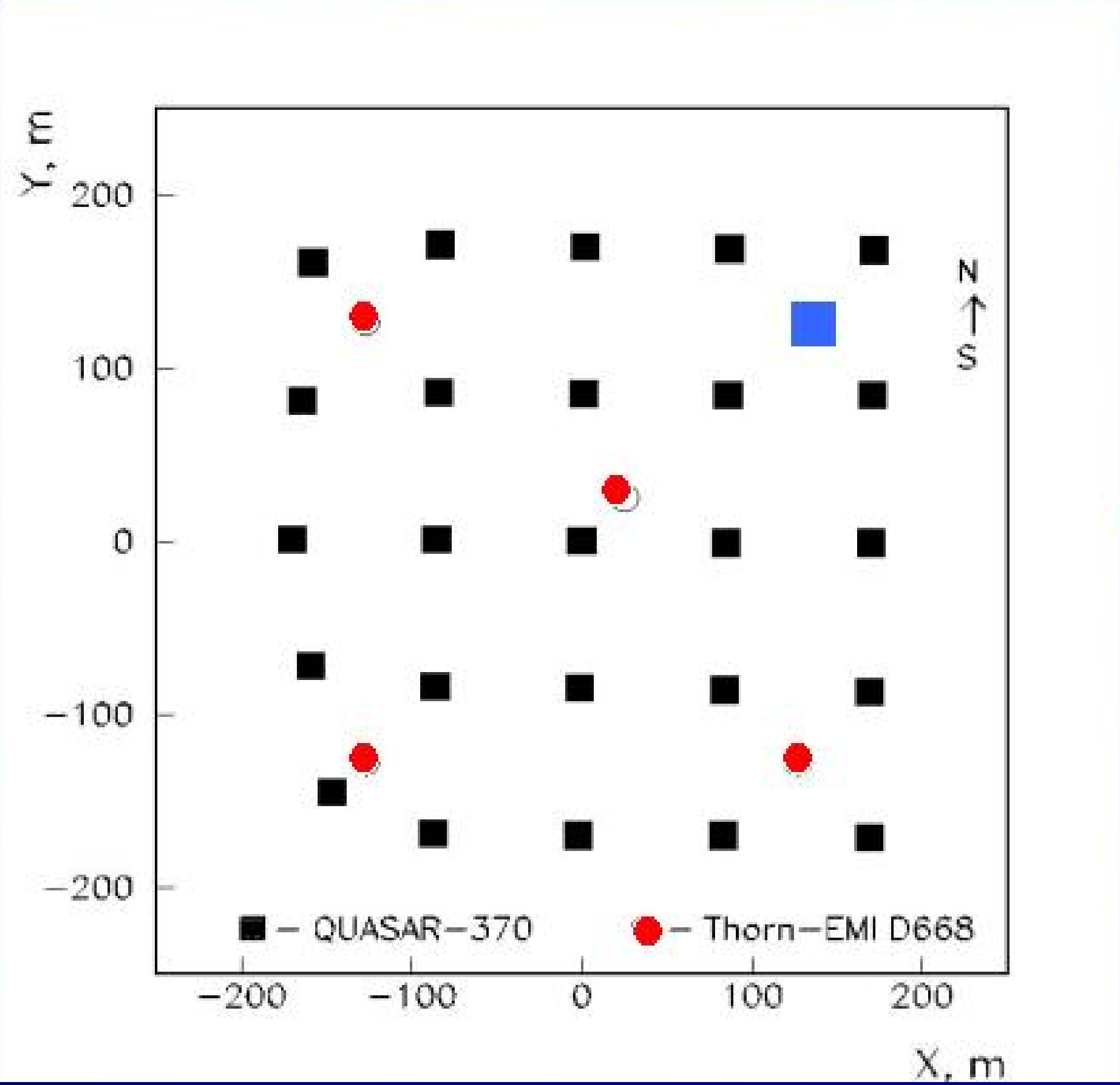
Chudakov's experimental setup in Pamirs experiments (1953-1957)



Investigations of Extensive Air Showers

- In these experiments, carried out in the Pamirs Mountains, the idea of calorimetric measurements of the cascade energy by recording its Cherenkov radiation was realized. Experimental ratio between the cascade energy and the observed number of particles was measured for the first time. The energy spectrum of primary cosmic rays was measured in a wide range.

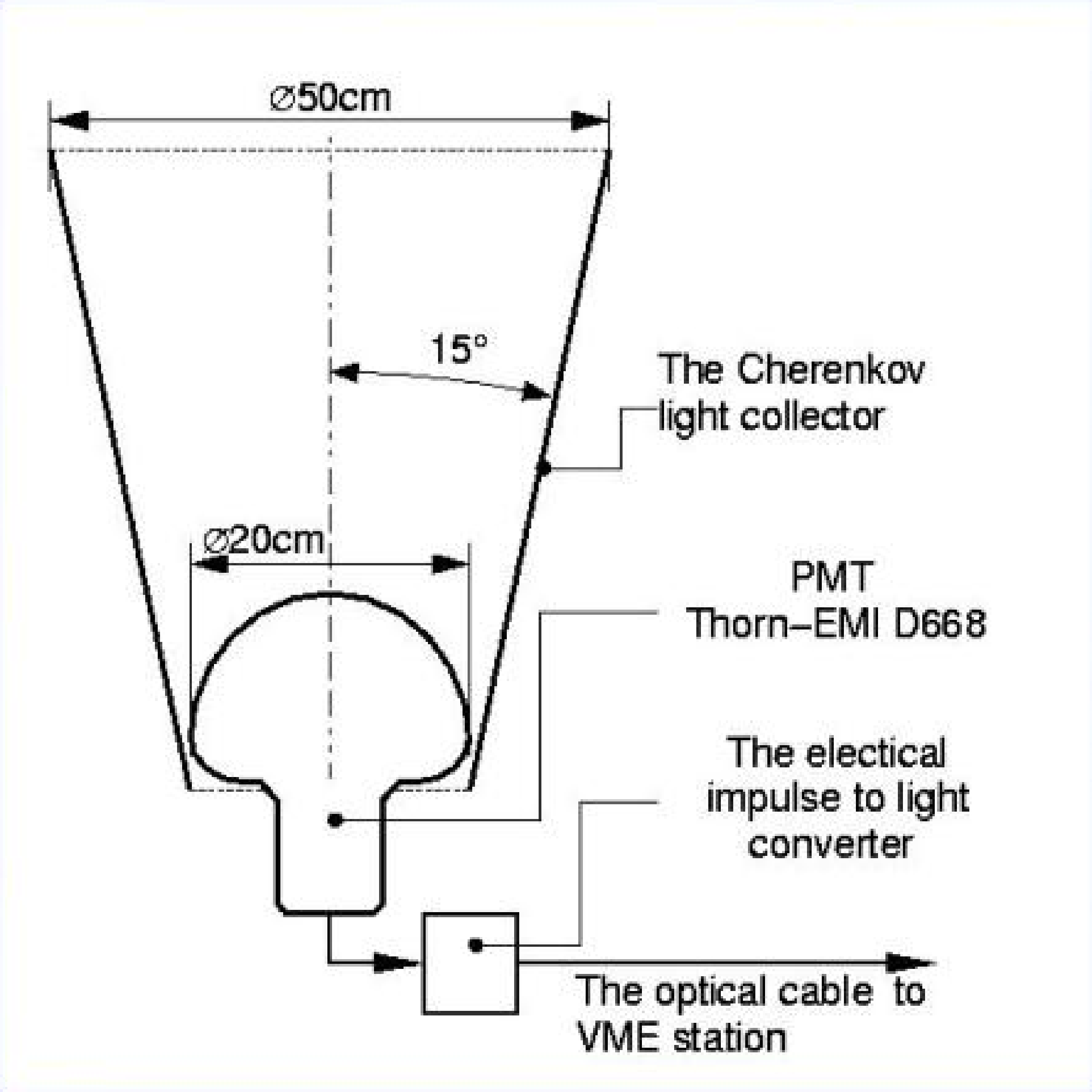
Modern Cherenkov Air Shower Array (Tunka)

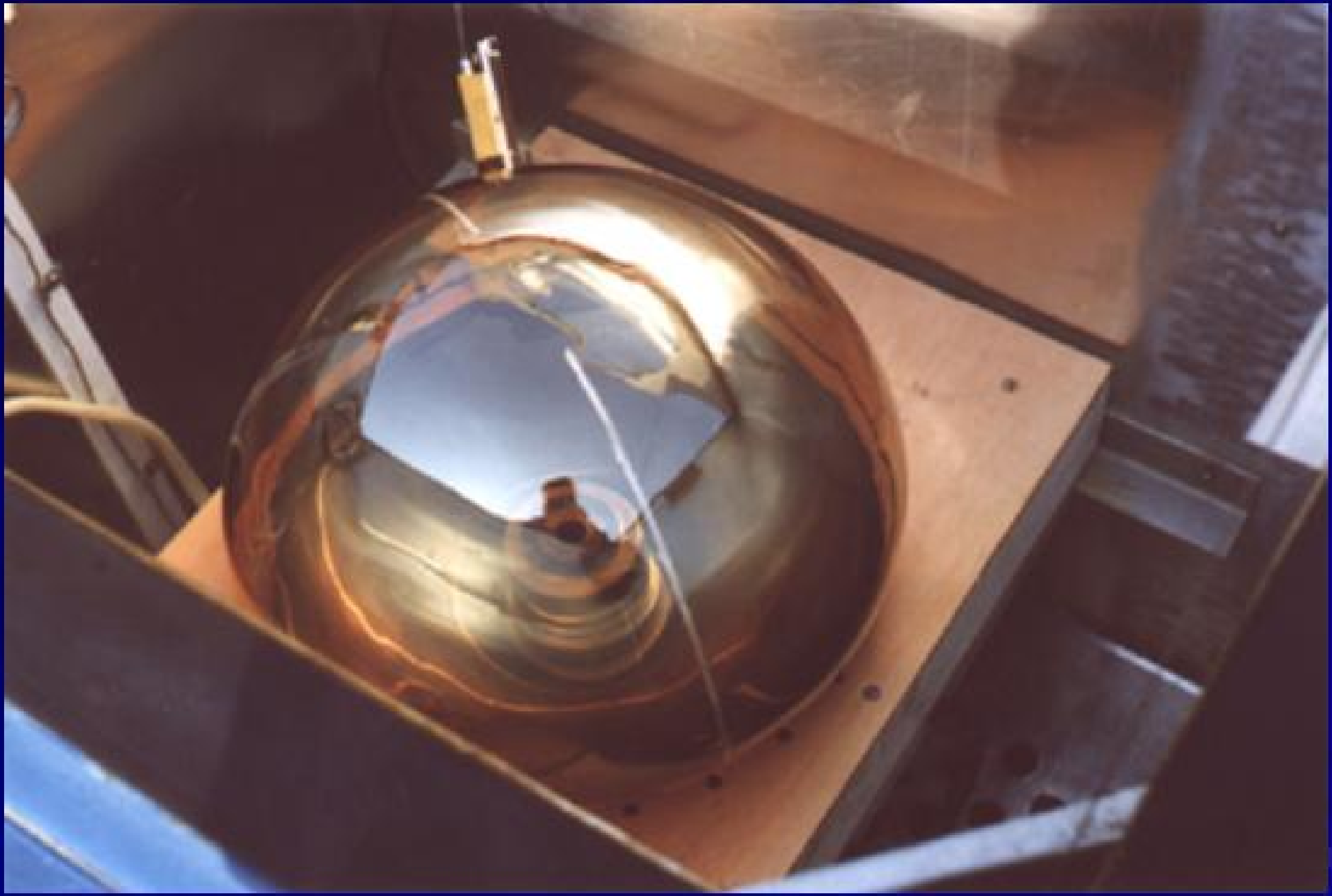


- Basic Integral Detectors
- Pulse Shape Detectors
- Remote Detector

Panorama of the Tunka array (675 m above sea level)

Pulse shape detector of Cherenkov light

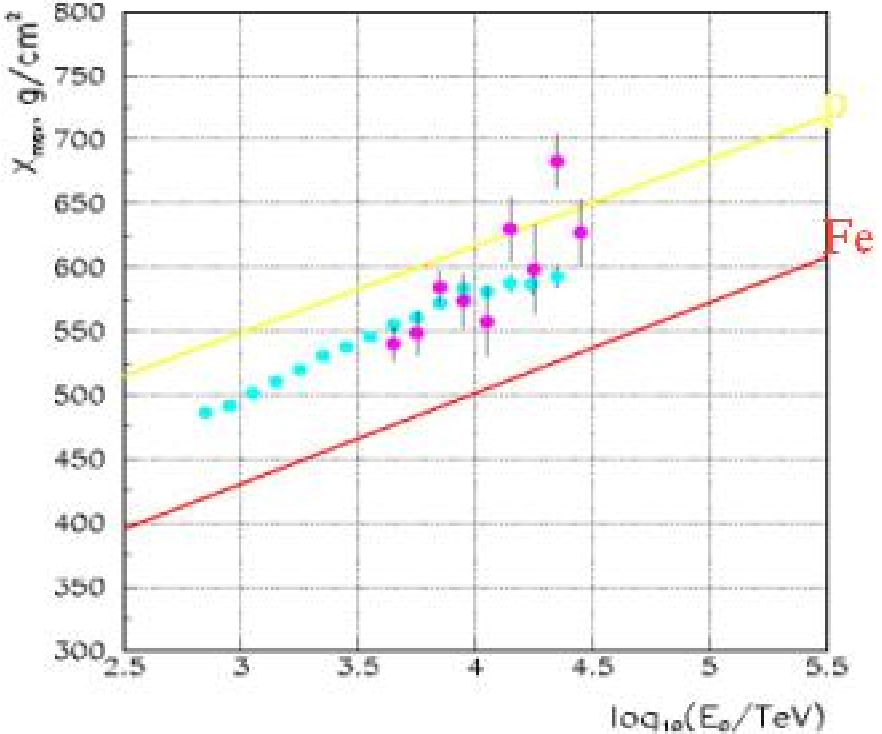




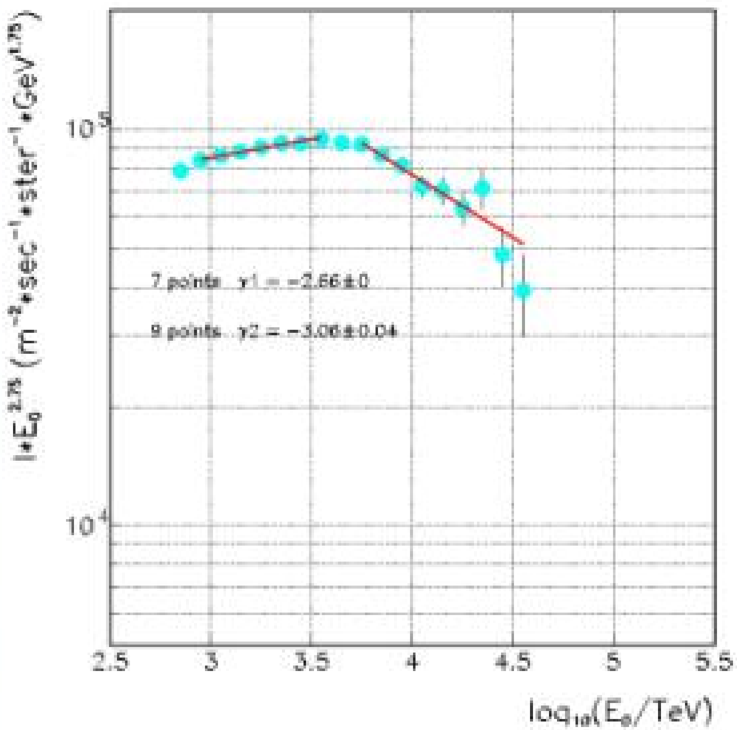
QUASAR-370 light receiver

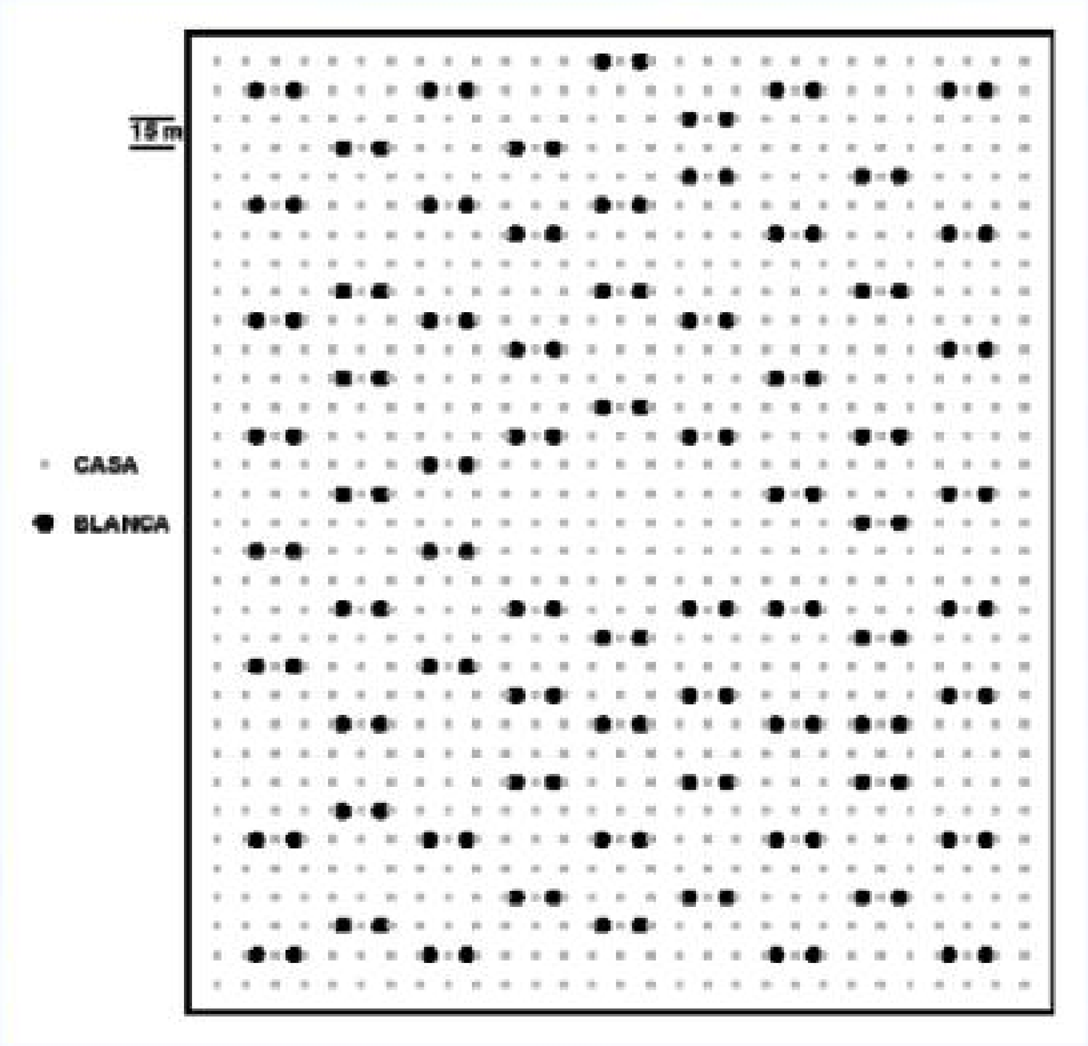
Some results of the Tunka array

Shower maximum depth



Differential energy spectrum

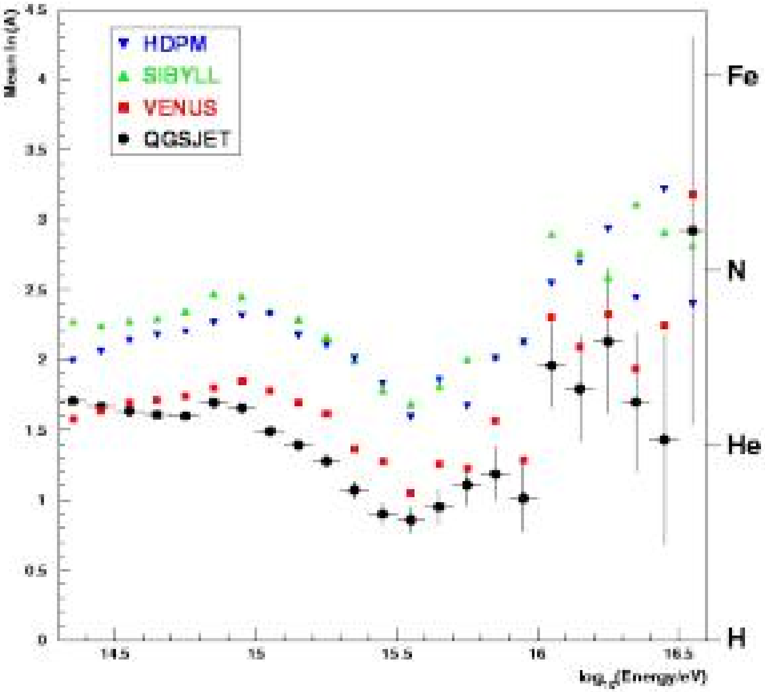


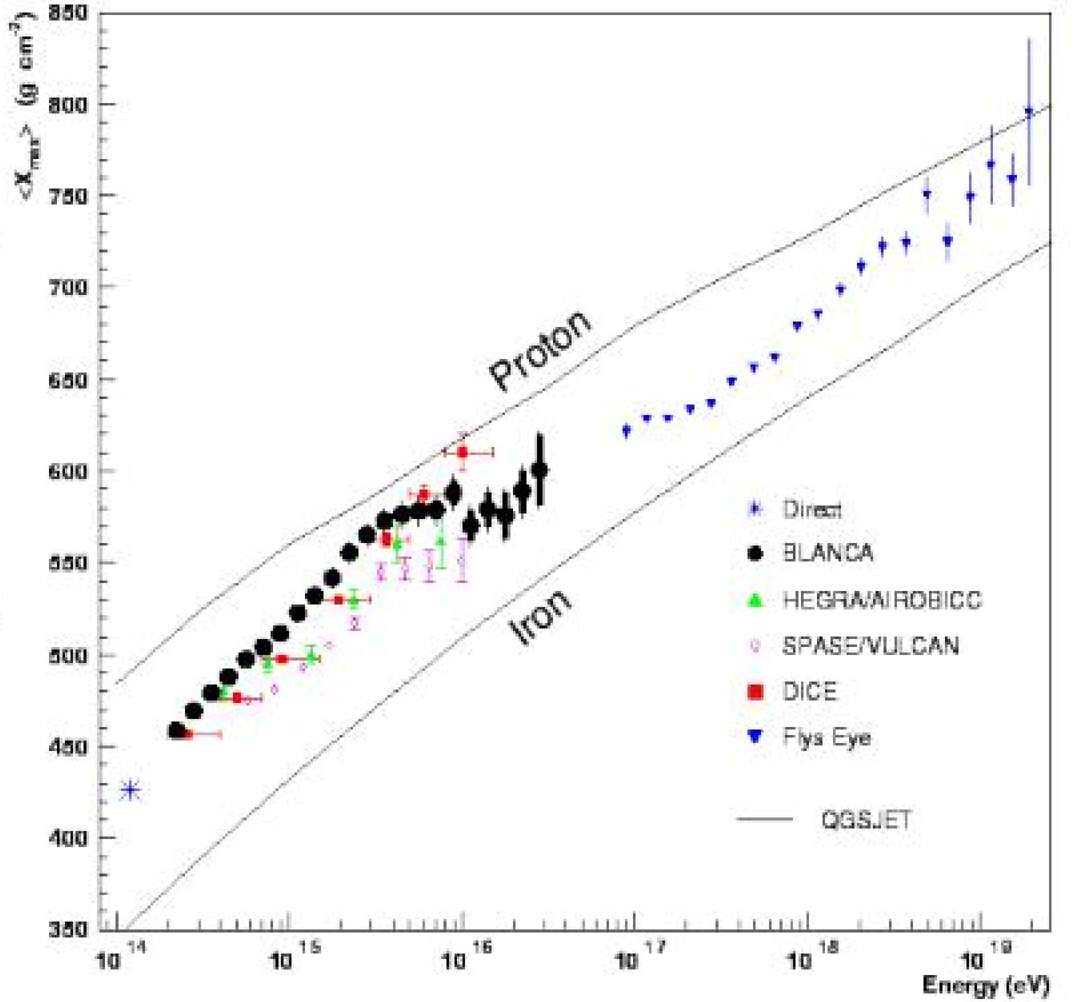


CASA-BLANCA:

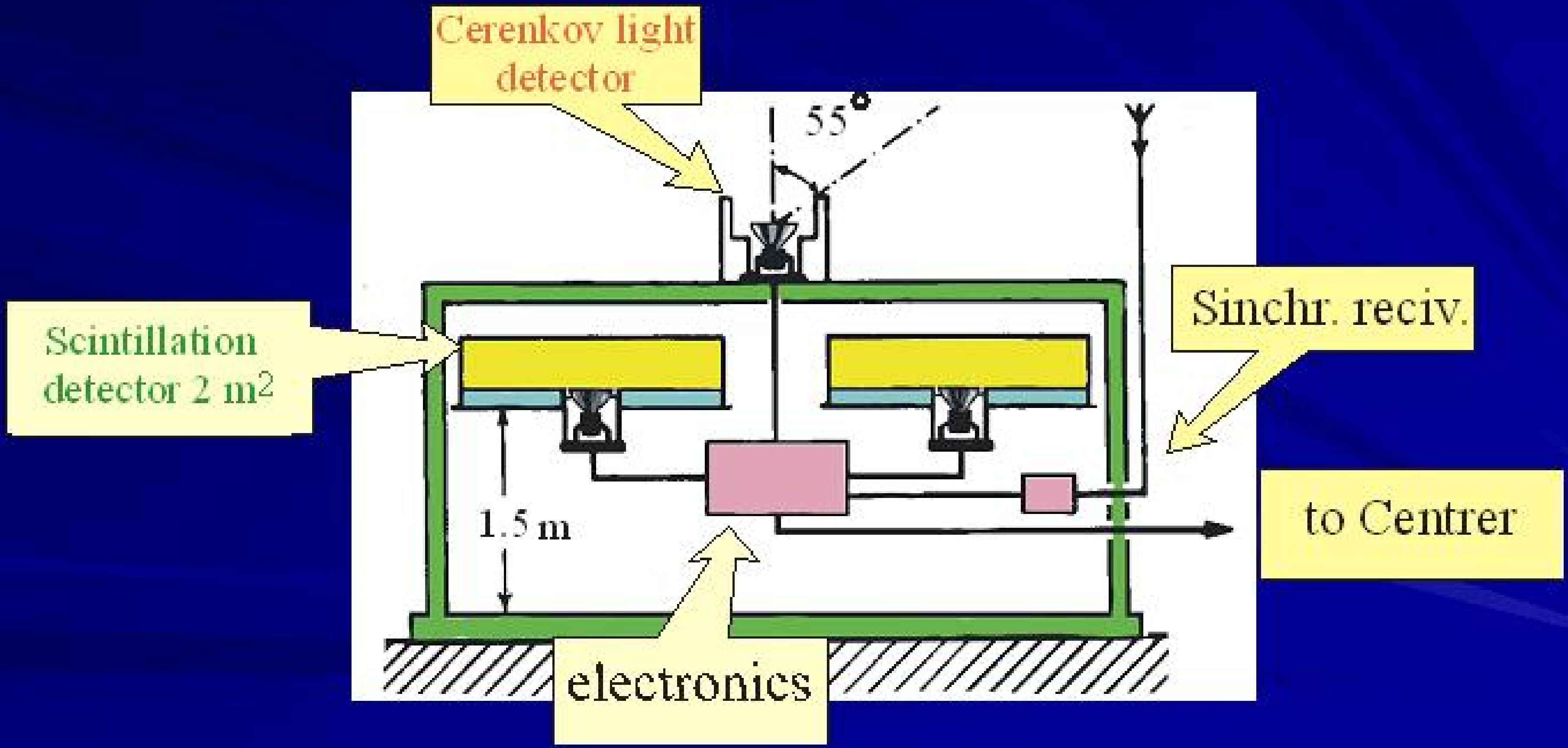
Cherenkov array BLANCA (144 detectors with an average separation of 35-40 m) and CASA air shower array (a lattice of 900 scintillation detectors with a step of 15 m).

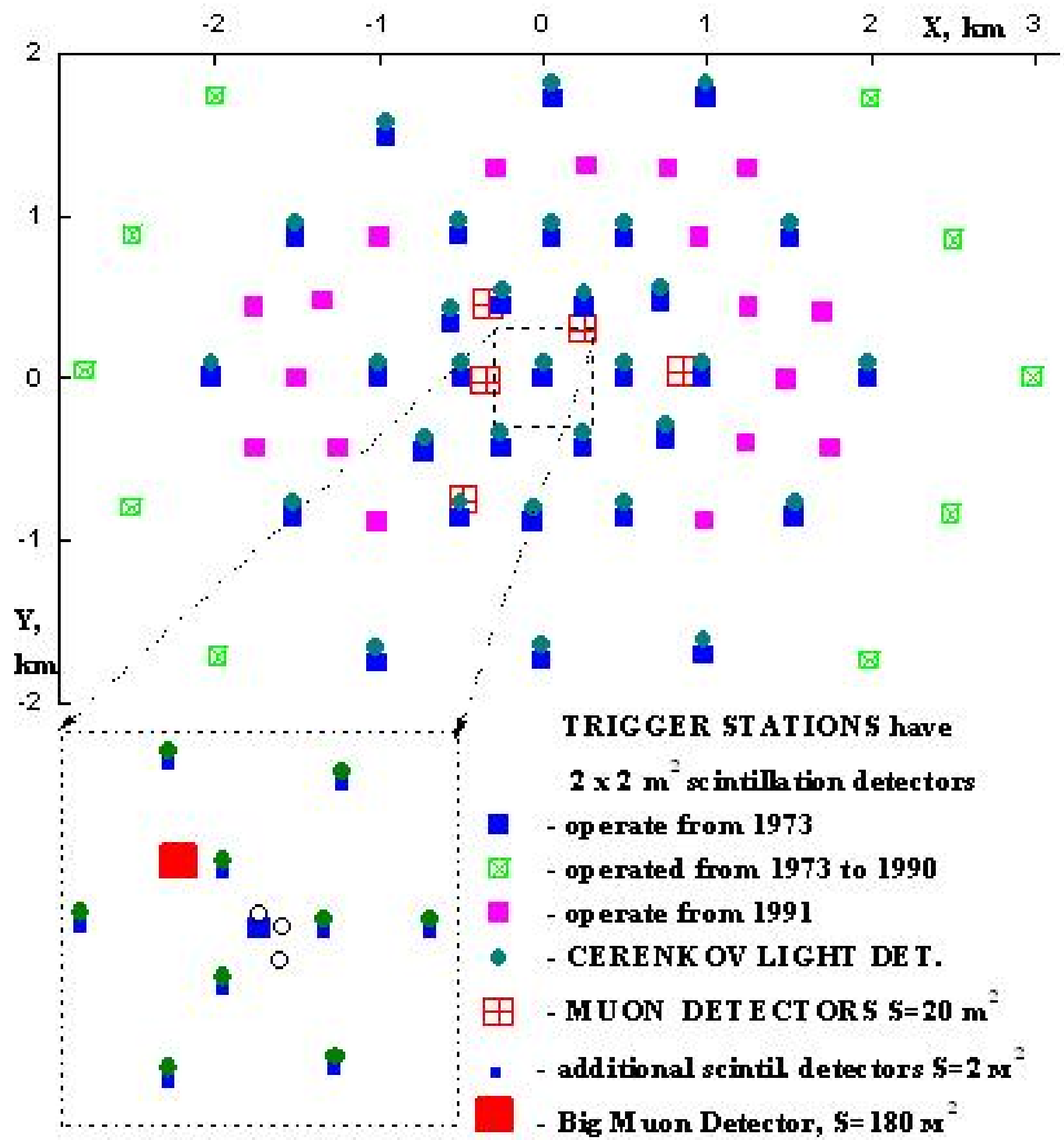
Cherenkov and fluorescence data on cosmic ray composition



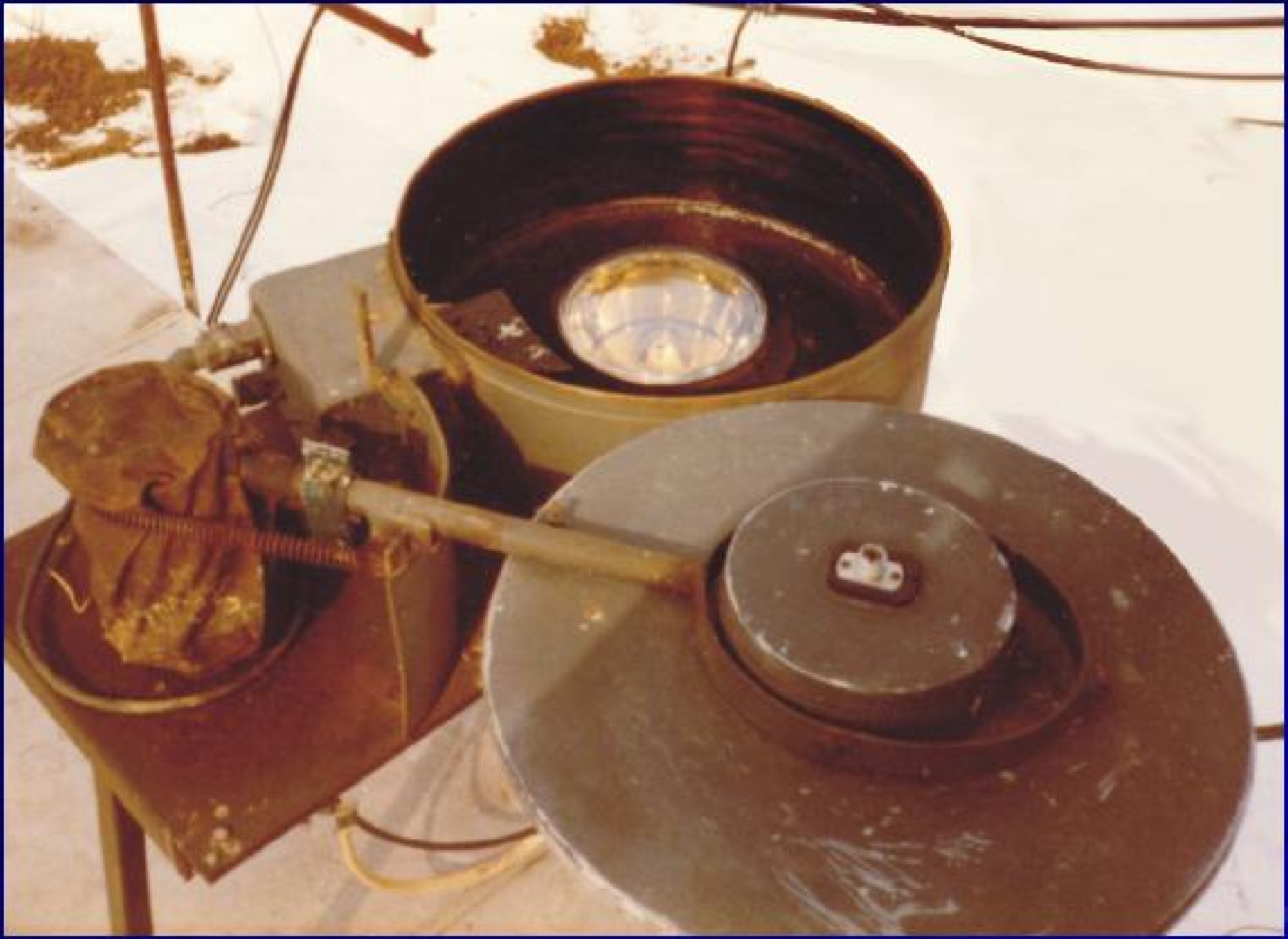


A Station of the Yakutsk EAS Array





A plan of the location of detector stations of the Yakutsk EAS Array



The Cherenkov Light Detector of Yakutsk EAS array

Estimation of shower energy E_0

The calorimetric method

The relation between parameters S300 or S600 and primary particle energy E_0 for showers close to the vertical has been determined by the calorimetric method. For the average showers with different S_{300} or S_{600} E_0 is estimated as the sum separate a components:

$$E_0 = E_i + E_{el} + E_\mu + E_{\mu i} + E_\nu + E_h$$

$E_i = k \cdot \Phi$ is the energy lost by a shower over the observation level. It is estimated by measurements of total Cerenkov light flux Φ, and

$k = 2.16 \cdot 10^4 / (0.37 + 1.1 \cdot (X_m / 1000))$ in the interval of waves 300-800nm In view of mean atmospheric transmittance

$E_{el} = 2.2 \cdot 10^6 \cdot N_s \cdot \lambda_N$ is the energy conveyed below the array level. It is estimated by the attenuation length λ_N of the number of charged particles N_s through the atmosphere depth

$E_\mu = \varepsilon_\mu \cdot N_\mu$ is the energy of the muon component. It is estimated by the total number of muons N_μ and average energy on one muon $\varepsilon_\mu = 10.6 \cdot 10^9$ eV

$E_{\mu i} + E_{\nu} = 0.76 \cdot E_{\mu}$ are the energy of muons losses on ionization and the neutrino

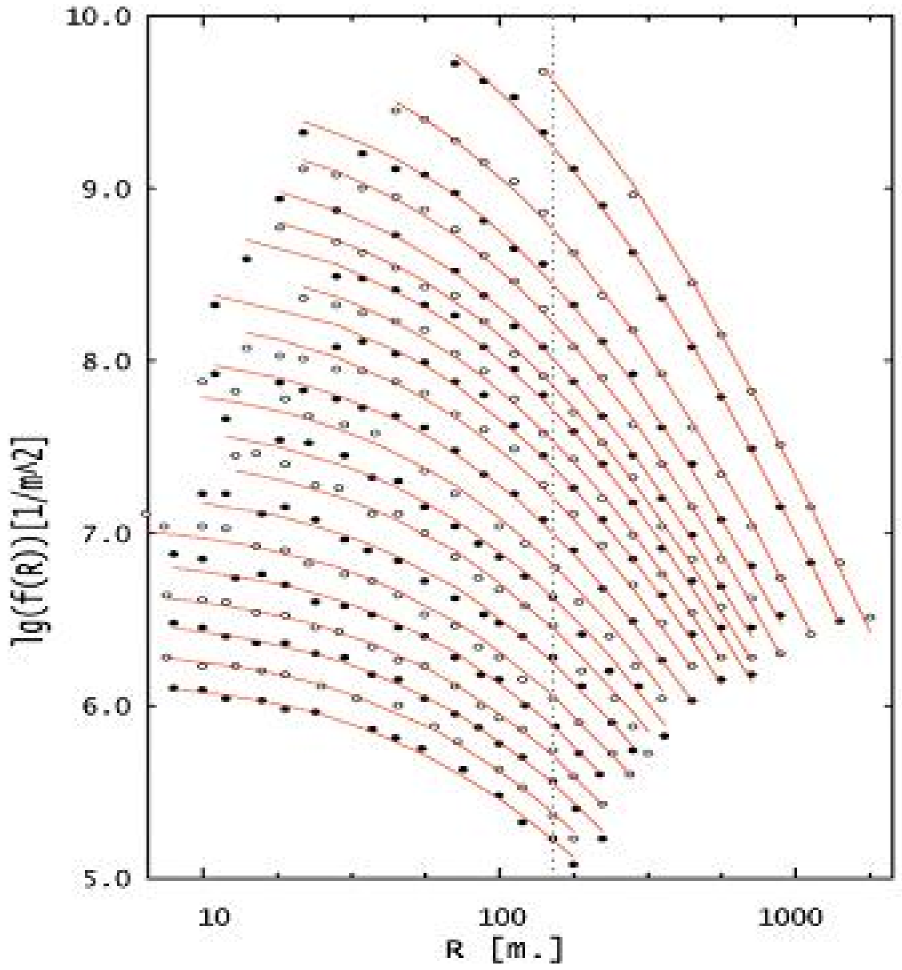
$E_h = 0.06 \cdot E_i$ is the energy on nuclear reactions in the atmosphere.

Red components are added on the basis of model calculation results.

For $E_0 \simeq 10^{19}$ eV :

$$E_i / E_0 \simeq 74\%;$$
$$E_{el} / E_0 \simeq 15\%;$$
$$E_{\mu} / E_0 \simeq 3.6\%;$$
$$(E_{\mu i} + E_{\nu} + E_h) / E_0 \simeq 7.4\%$$

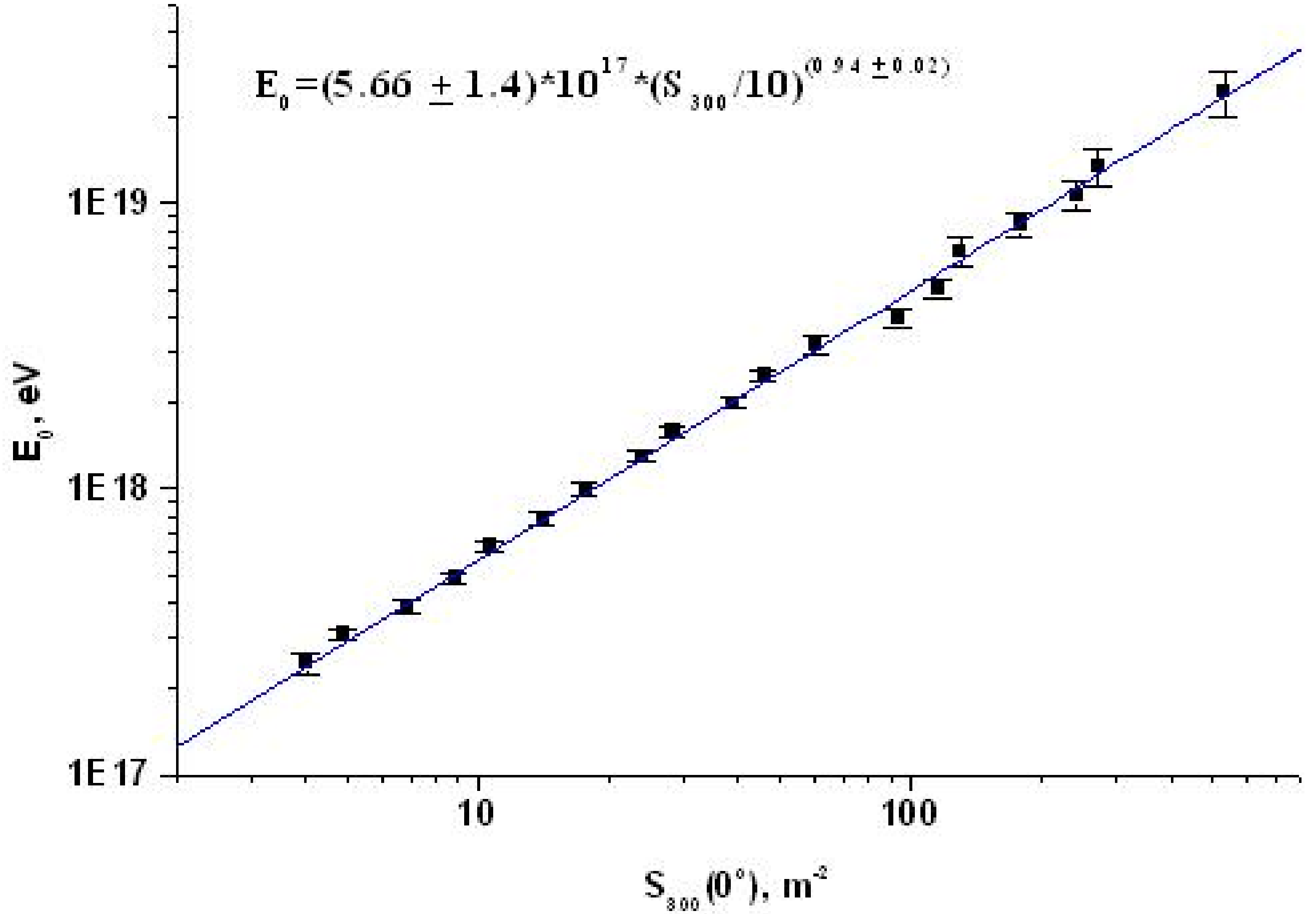
$$\Phi = \int 2\pi \boldsymbol{R} \cdot \boldsymbol{Q}(\boldsymbol{R}) \cdot \partial \boldsymbol{R}$$



Lateral distribution of EAS Cerenkov light, $\theta<30°$, $10^{15} < E_0 < 3 \cdot 10^{19}$ eV

$Q(R) = Q_{150} \cdot ((62+R)/212)^{-1} \cdot ((200+R)/(350))^{1-m}$,

$m = (1.15 \pm 0.05) + (0.30 \pm 0.06) \cdot \log(Q_{150})$



Ratio between shower energy E_0 and $S_{300}(0^o)$ determined by the calorimetric method

$$E_O = (5.66 \pm 1.4)\cdot 10^{17}\cdot (S_{300}(0^o)/10)^{0.94 \pm 0.02}$$

VHE Gamma Ray Astronomy

The gamma ray telescope constructed by Chudakov was the first instrument ever specially designed for observations of gamma rays from space. The method was suggested in a paper by **G.T. Zatsepin and A.E. Chudakov**, «On the methods of searching for local sources of high energy photons», *J. Exp. Theor. Phys.*, vol. 41 (1961), p. 655 (In Russian).

First Gamma-Ray Telescope

Katsively, Crimea

(1960-1963)

Рис. 1. Общий вид установки

One Cherenkov light receiver of the first gamma ray telescope

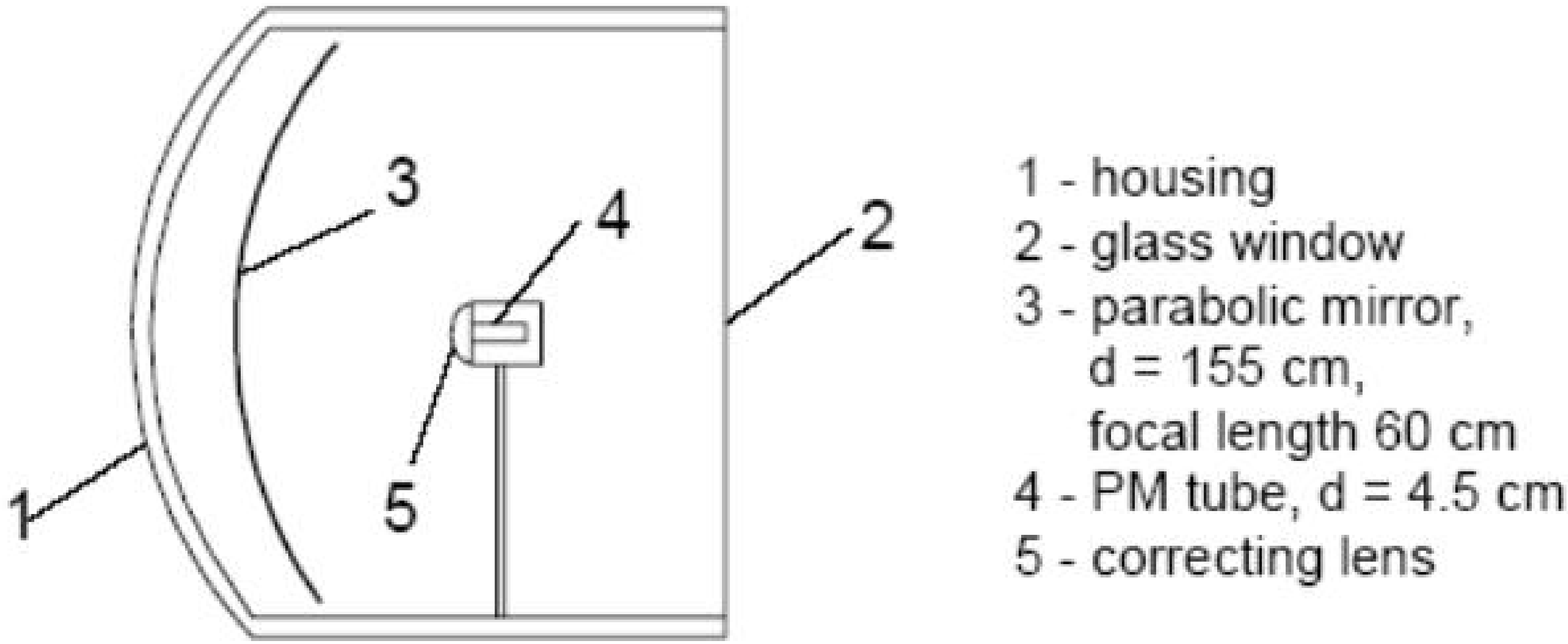
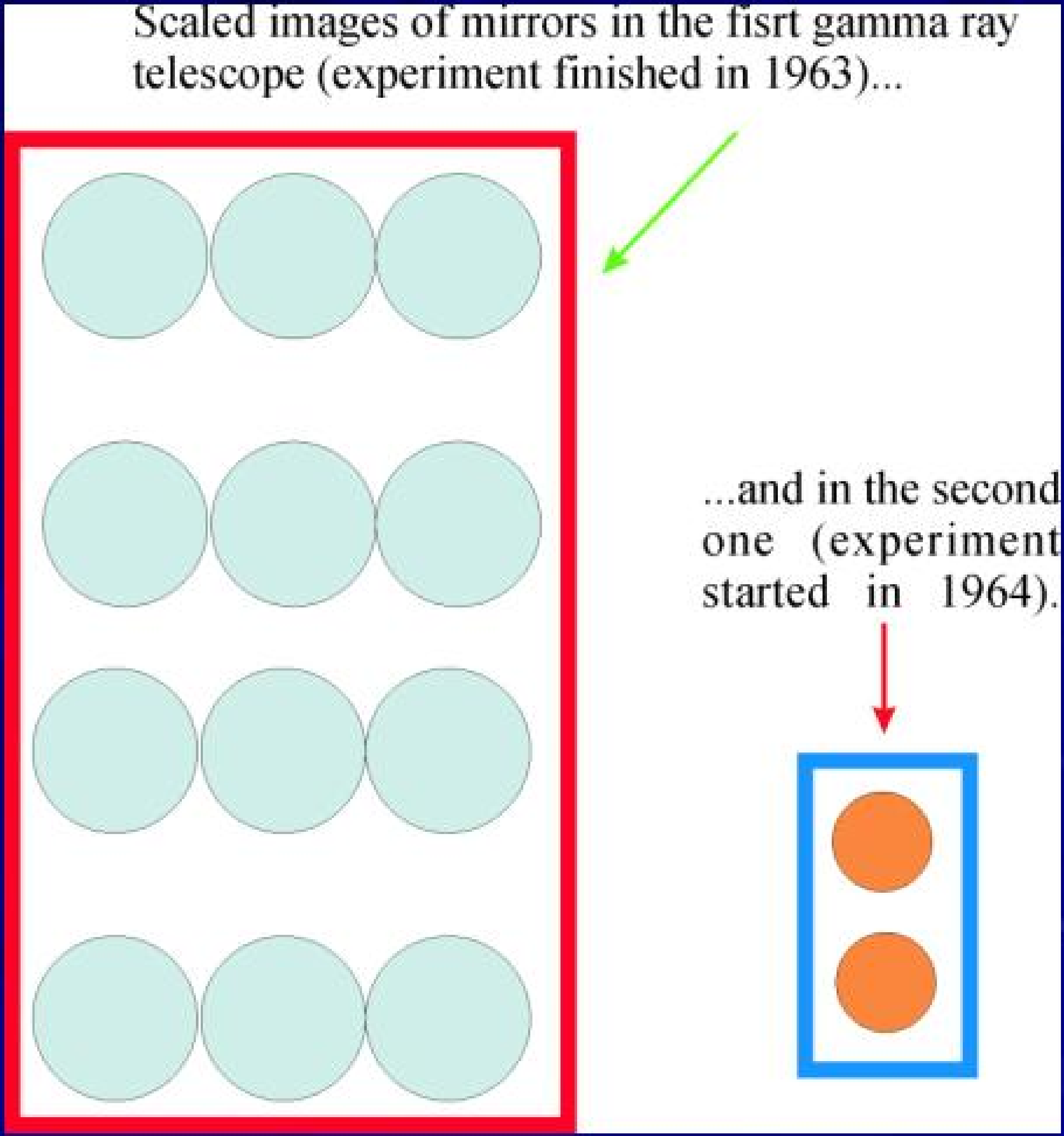


Fig. 1. The light receiver for Katsiveli experiment.

Four mirrors were installed in the season 1960, and all twelve mirrors were used in the remaining seasons 1961, 1962, and 1963.



Crab Nebula is the first detected object and the 'standard candle' of the VHE gamma ray astronomy

First Gamma-Ray Telescope

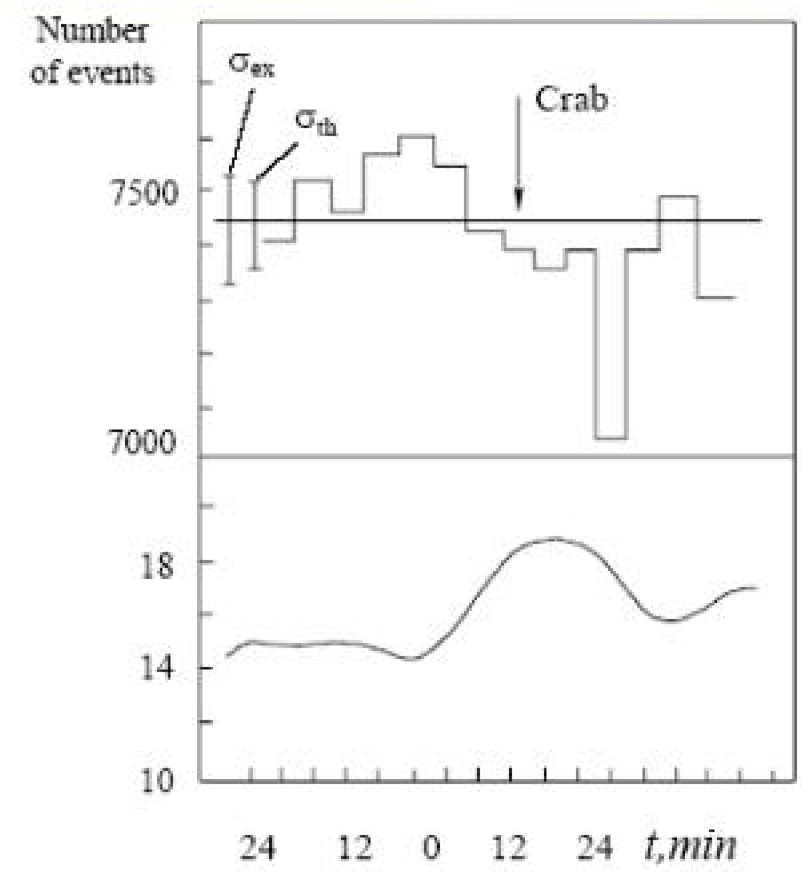


Fig. 2. The drift scan diagram for the Crab Nebula. The data of 1961. Average counting rate 143 per min. Below: total average output current of all 12 PM tubes.

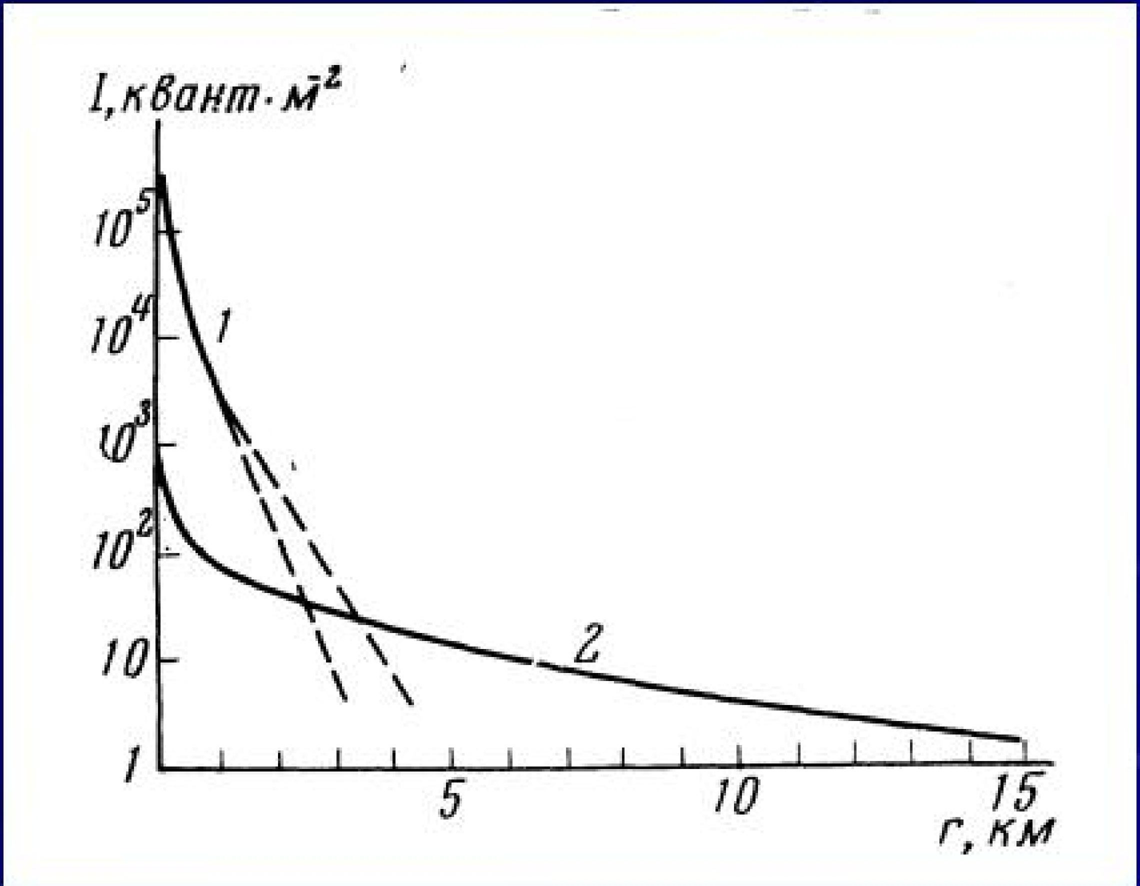
Установка в Кацивели, 1960-63 г.г.

The negative result of Chudakov's experiment was important in one respect:

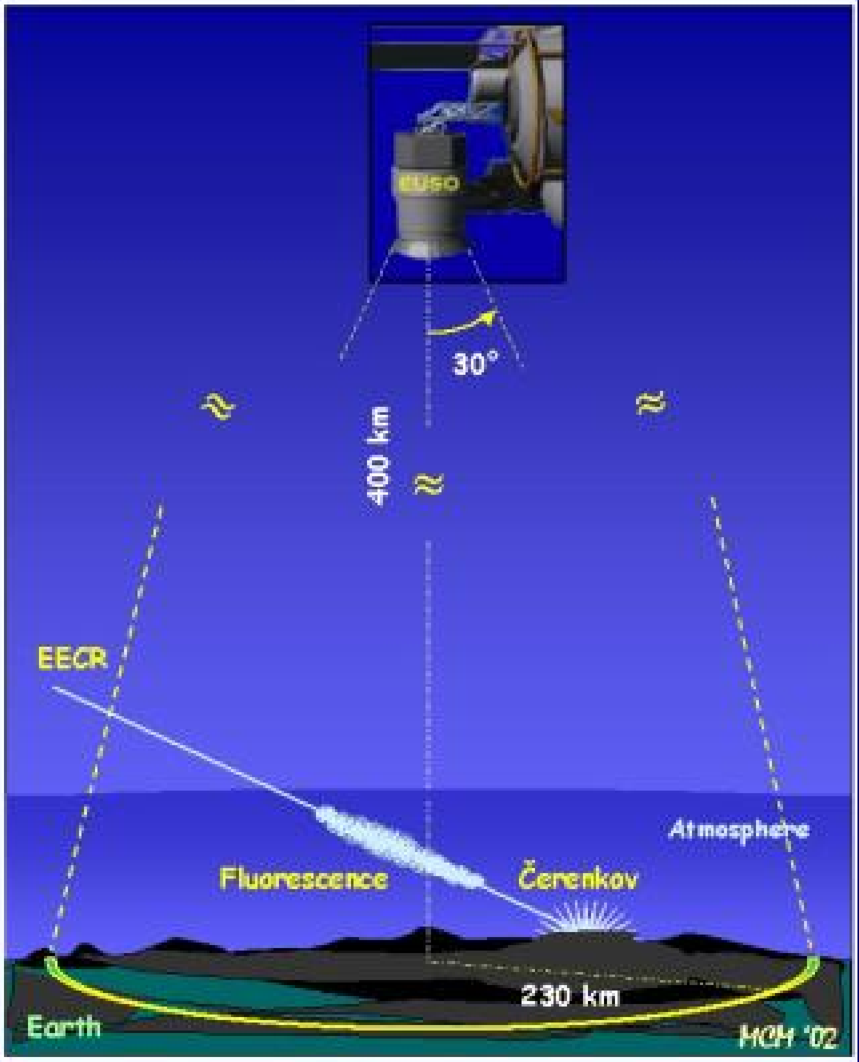
- It was generally believed at that time that the synchrotron radiation in the Crab Nebula is due to electrons of secondary origin (produced by pions generated in proton-proton collisions via $\pi \to \mu \to e$ decay).
- If so, one would expect a significant gamma ray flux from decays of neutral pions.
- **<u>The upper limit obtained by Chudakov was a proof of direct acceleration of electrons in the Crab Nebula (and other sources).</u>**

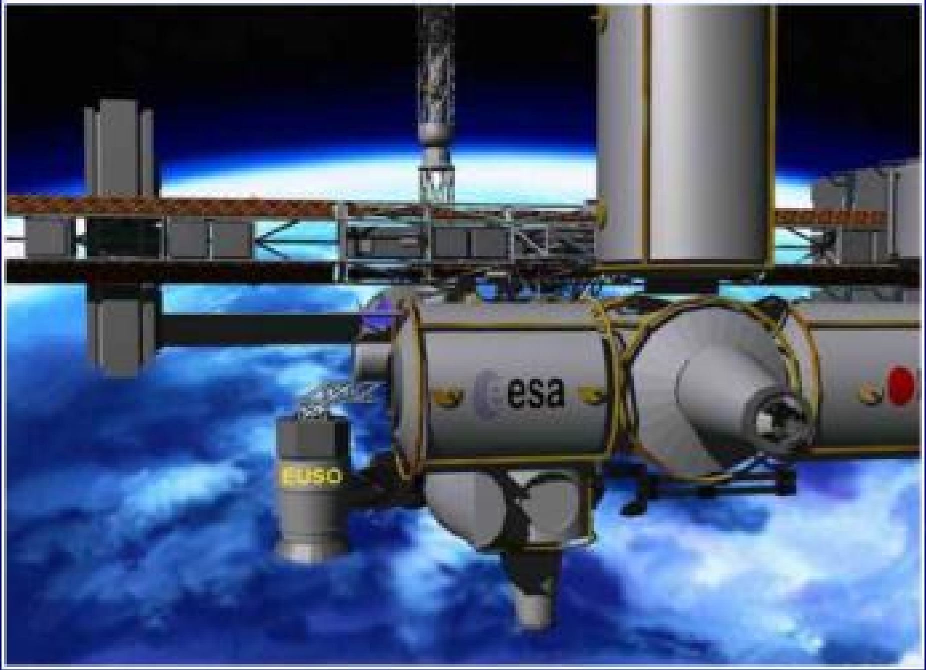
The idea of air fluoresence experiments was also put forward by A.E. Chudakov

V.A.Belyaev & A.E. Chudakov, Ionization glow of air and its possible use for air shower detection, *Bulletin of USSR Academy of Sciences, Phys. Ser.*, 1966, vol. 30, no. 10, p. 1700

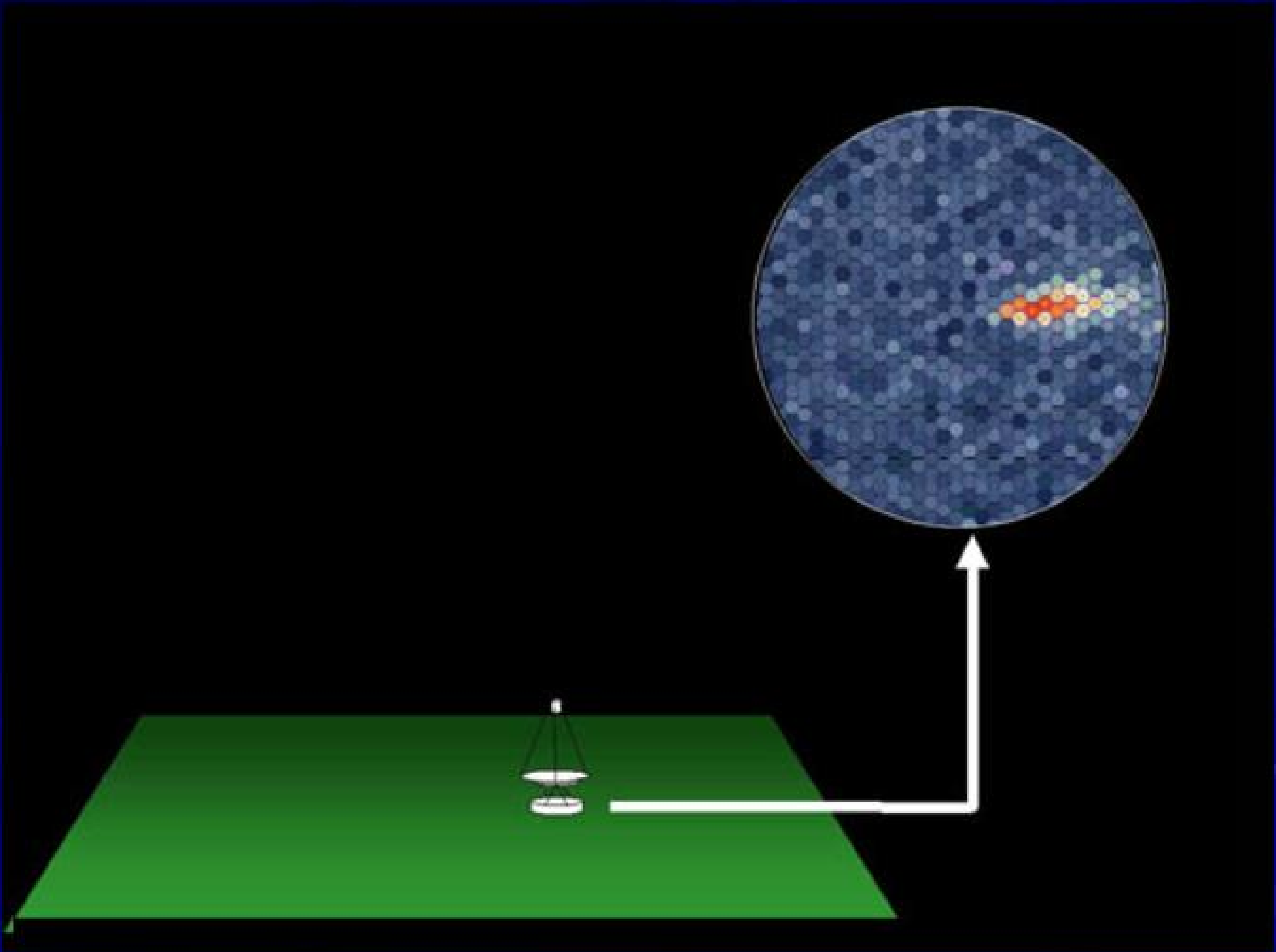


EUSO: Extreme Universe Space Observatory

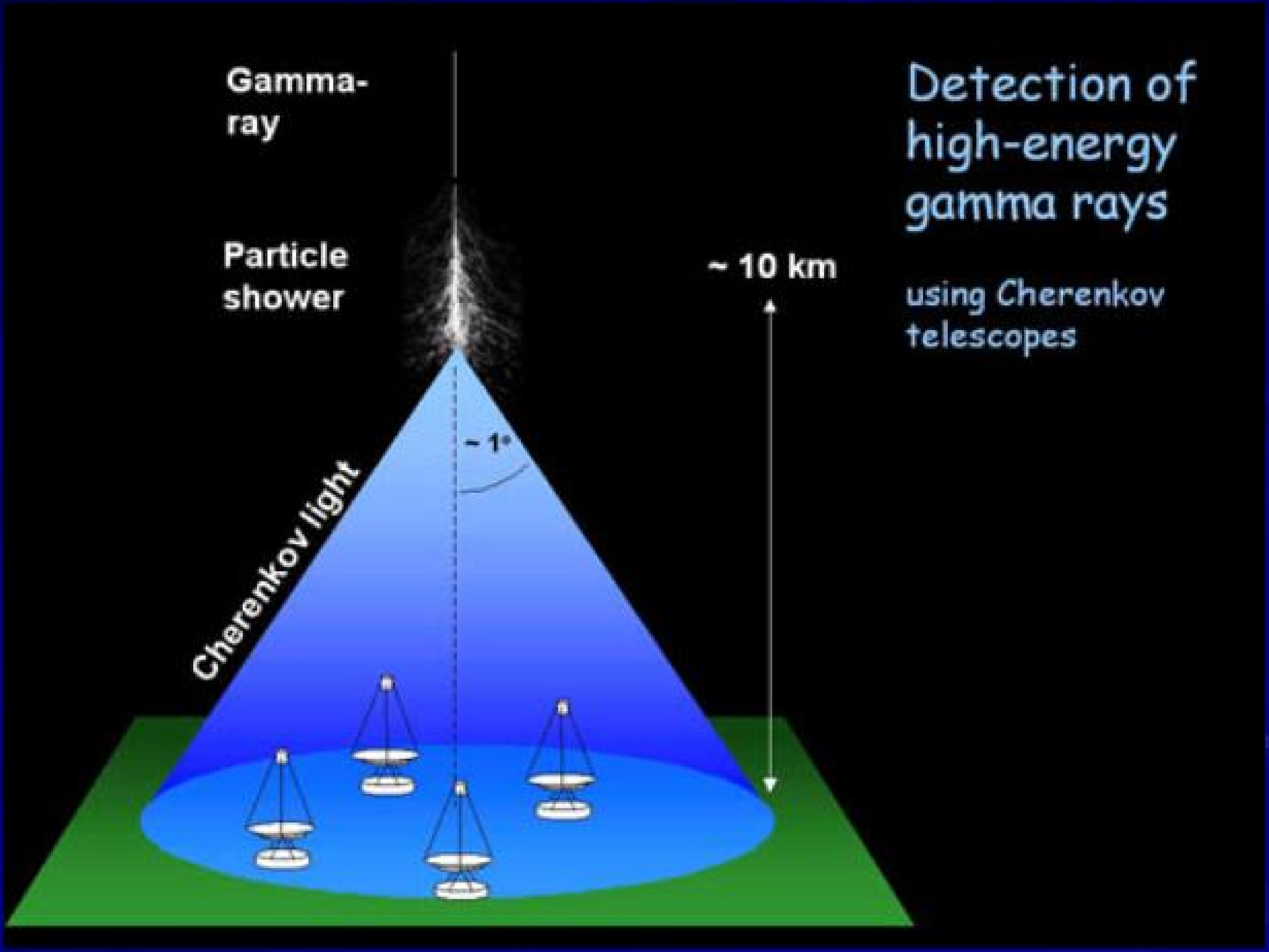




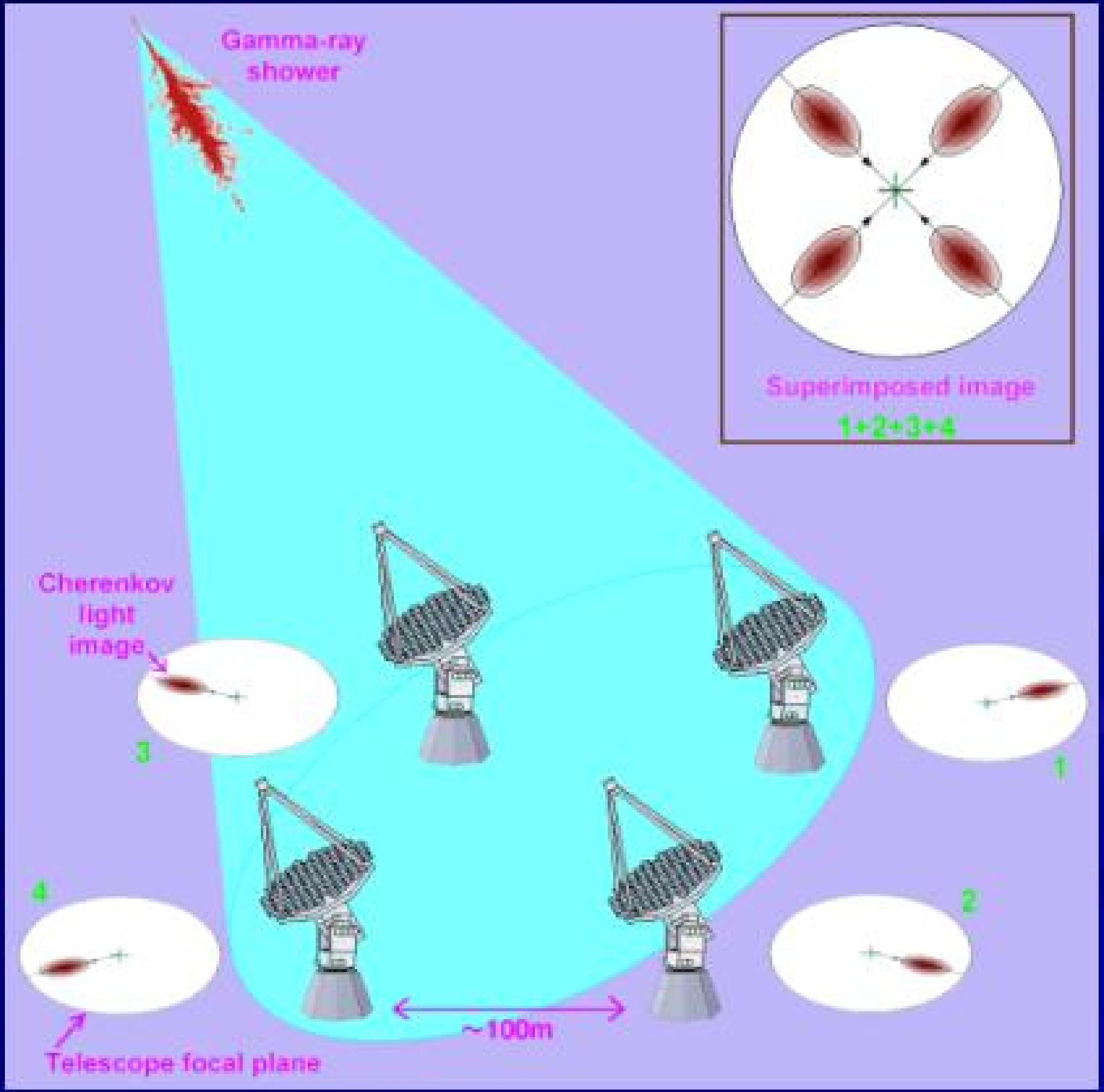
Accommodation onboard the ISS



Multiple mirror-telescopes



Stereoscopic observations in VHE astronomy



French telescope CAT (Perinei mountains)

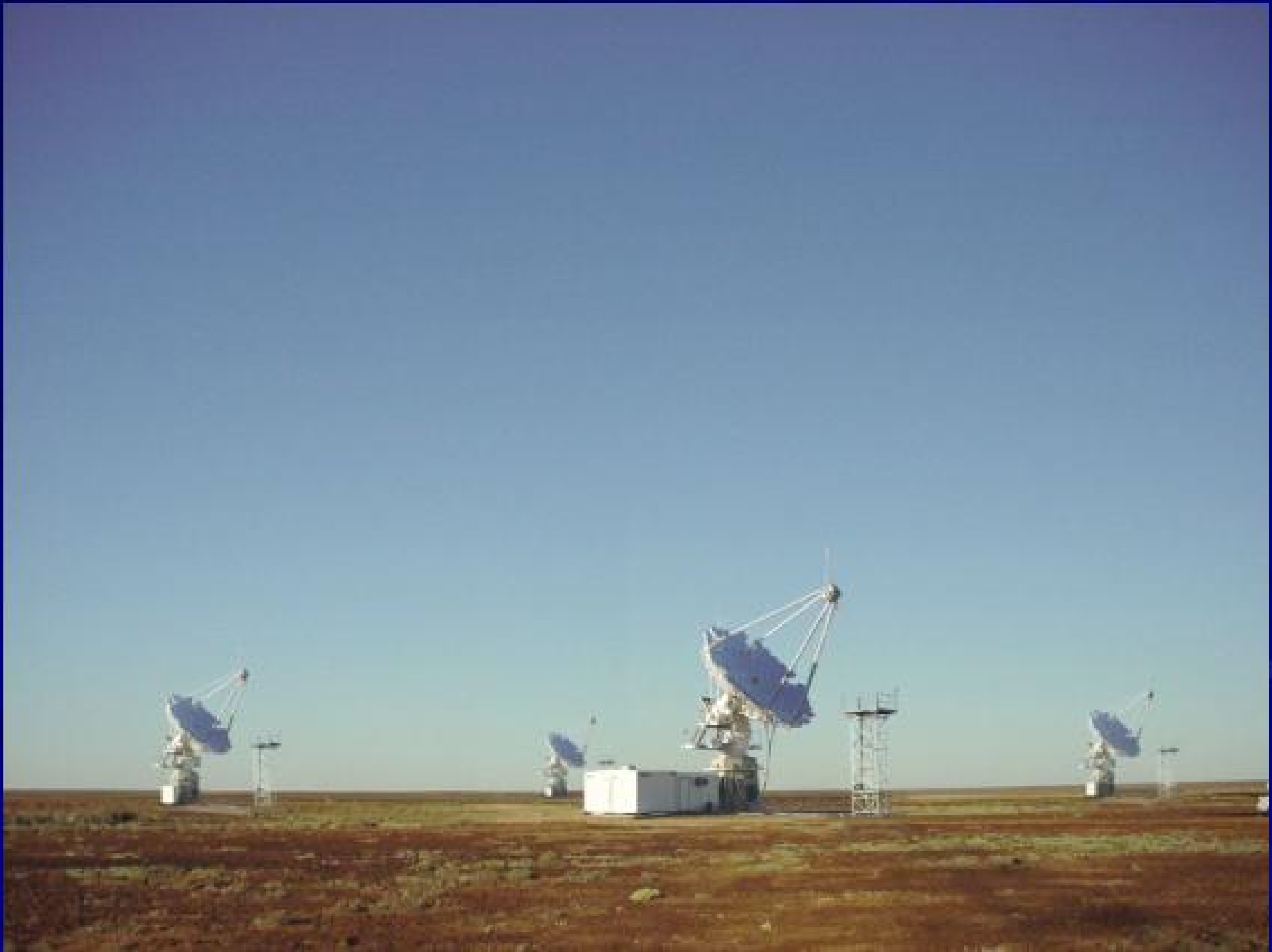
Telescope
Hegra at Canary
Islands

CT-3

CT-4

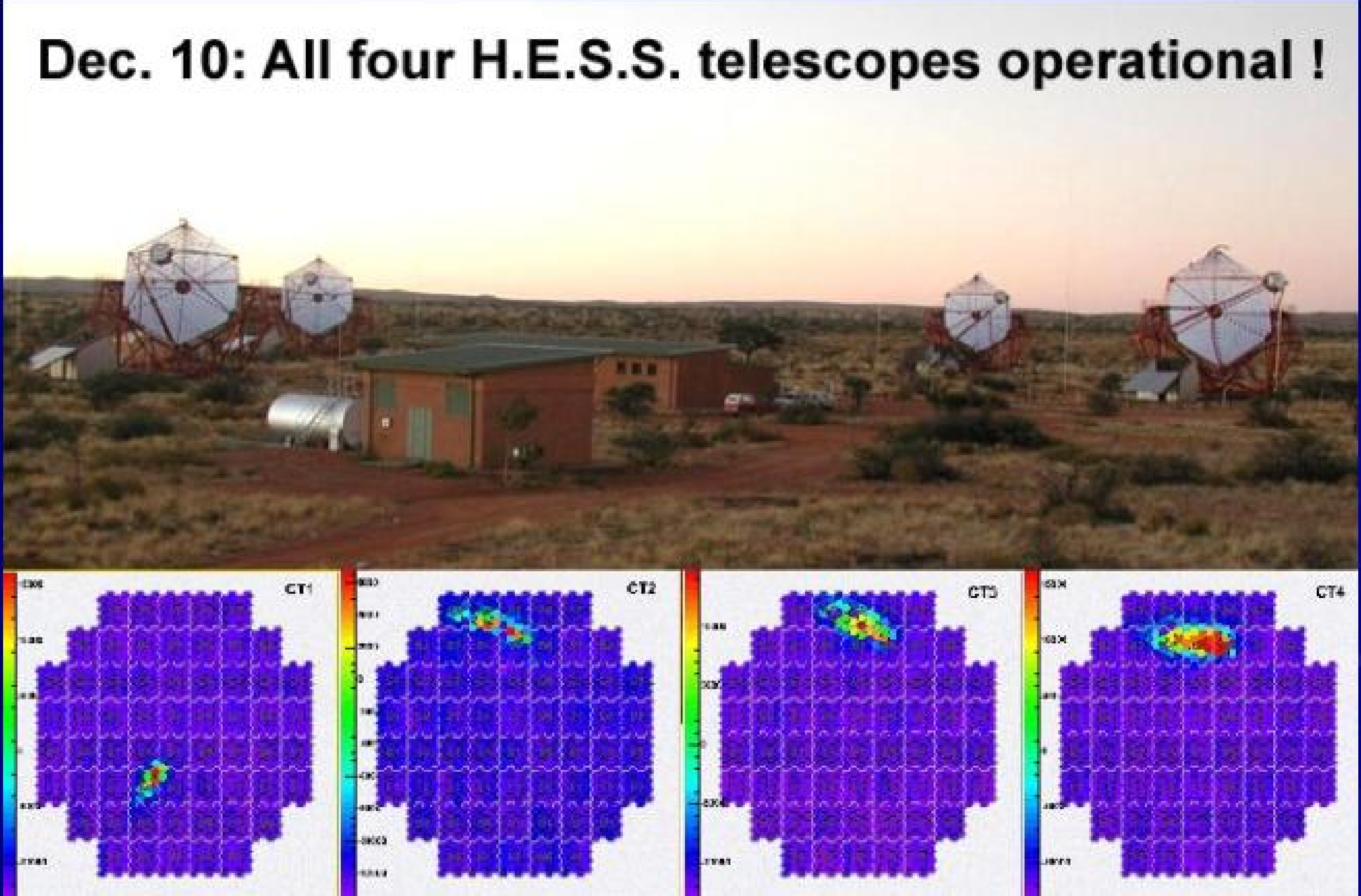
Australian-Japanese telescope Cangaroo II

Stereoscopic CANGAROO III telescope (Project)



CANGAROO III under construction (July 2003)

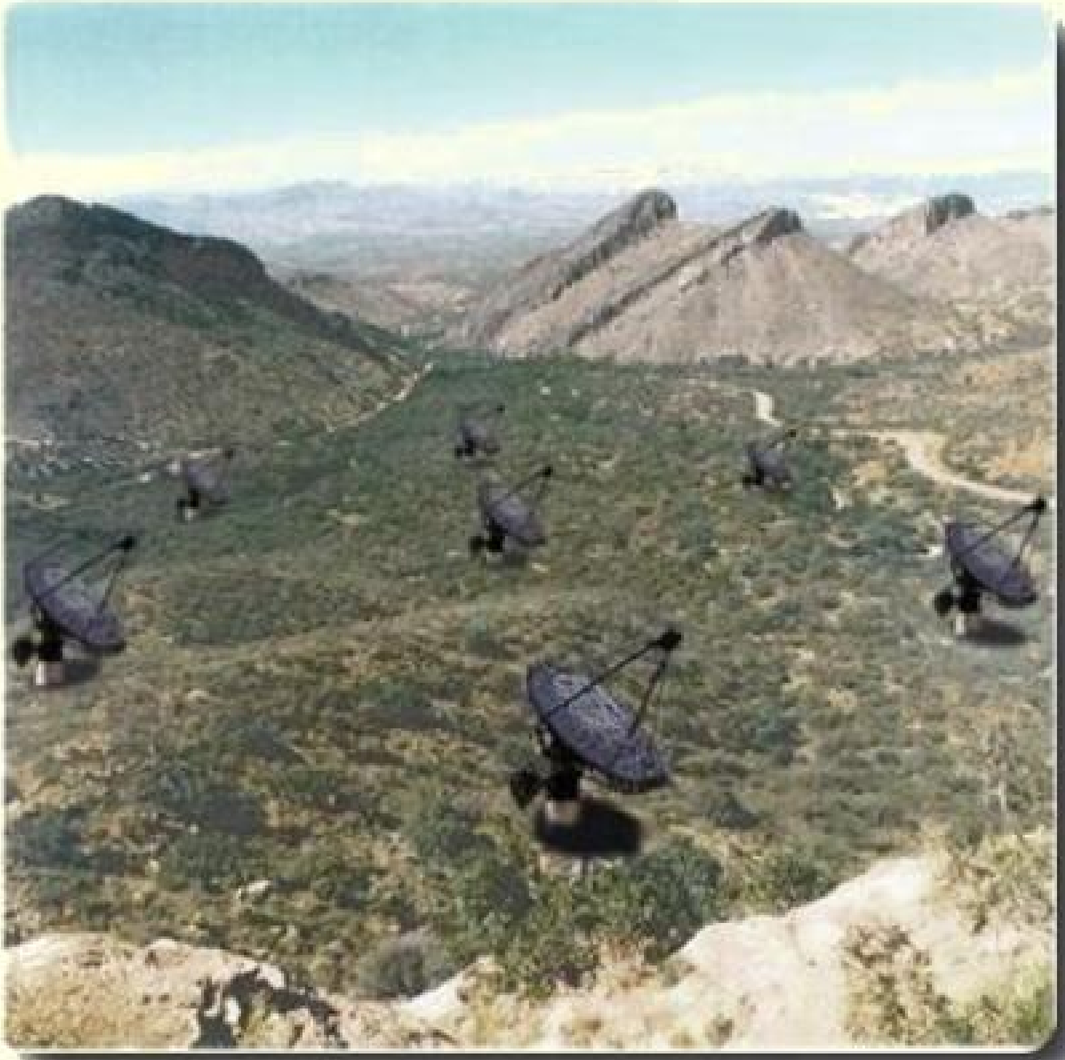
HESS (High Energy Stereoscopic System) air Cherenkov telescope in Namibia



One HESS reflector

VERITAS (Very Energetic Radiation Imaging Telescope Array System)

An array of seven 10m - 12m optical reflectors for gamma-ray astronomy in the GeV - TeV energy range

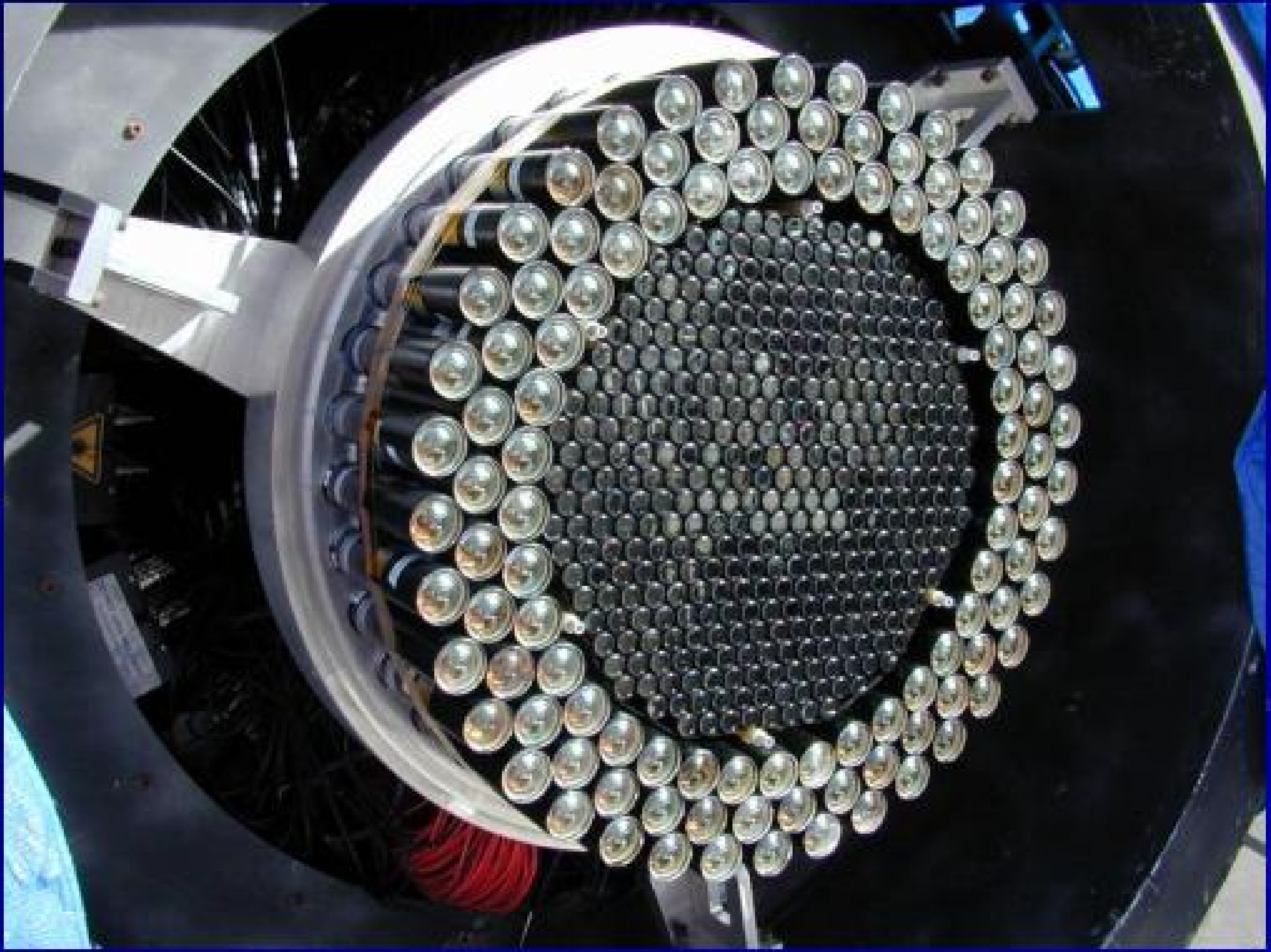


One Veritas reflector

The new array design will be based on the design of the existing 10m gamma-ray telescope of the Whipple Observatory.

PM tube camera of Veritas (499 pixels)

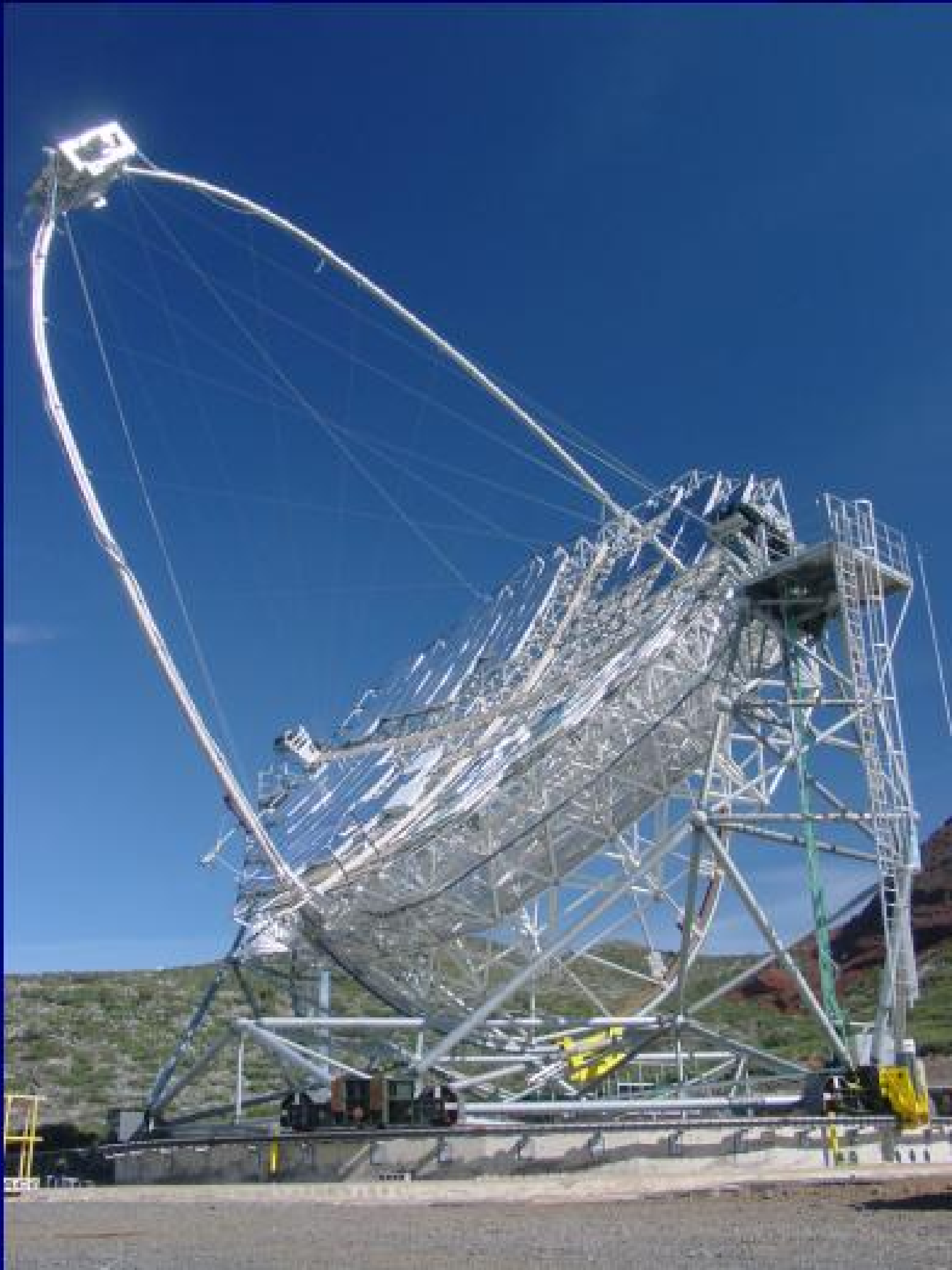
The full field of view is 3.5°.



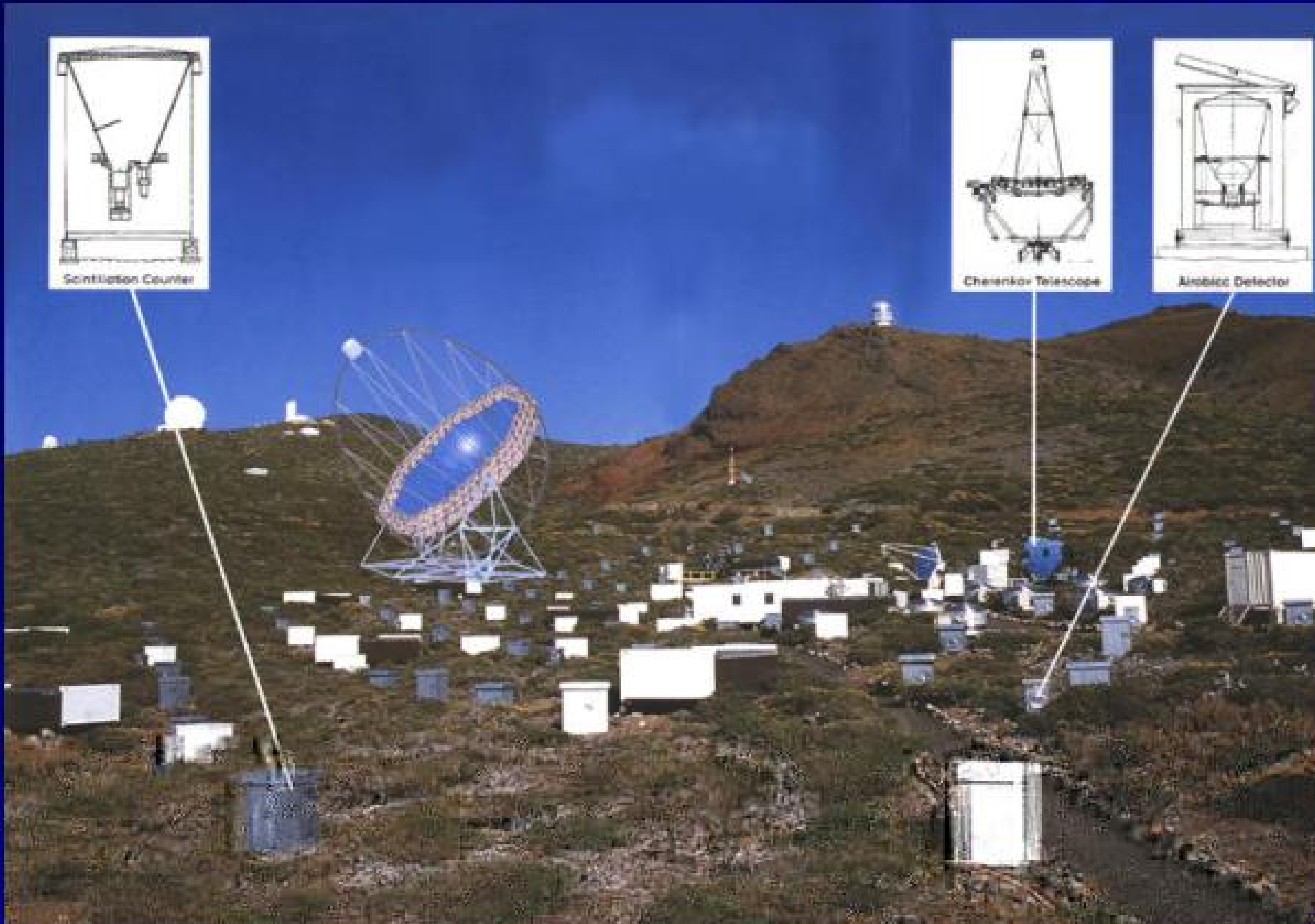
New 17 m MAGIC telescope. Plans…

... and reality

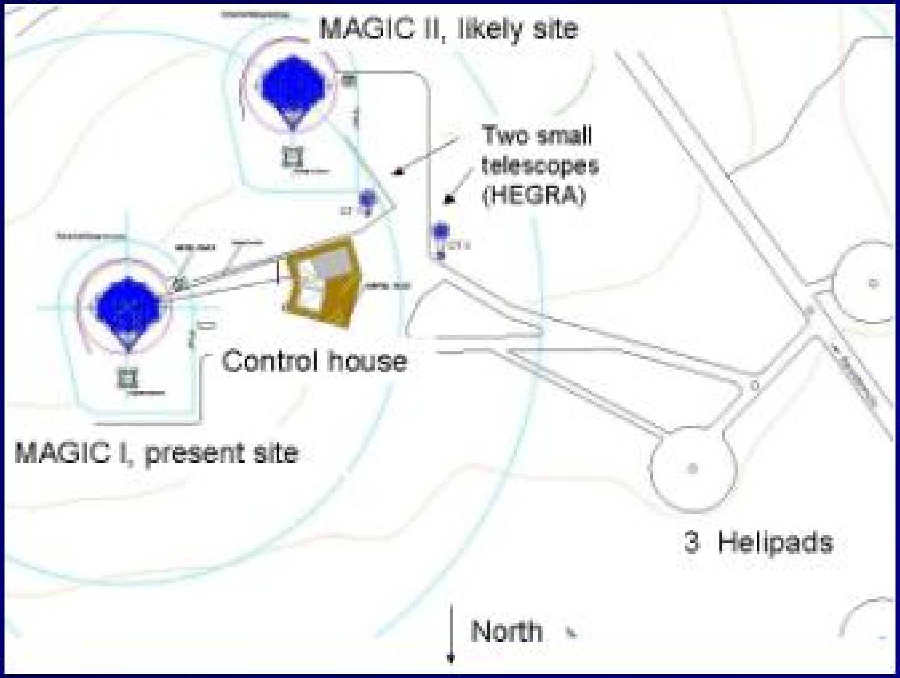
MAGIC under construction

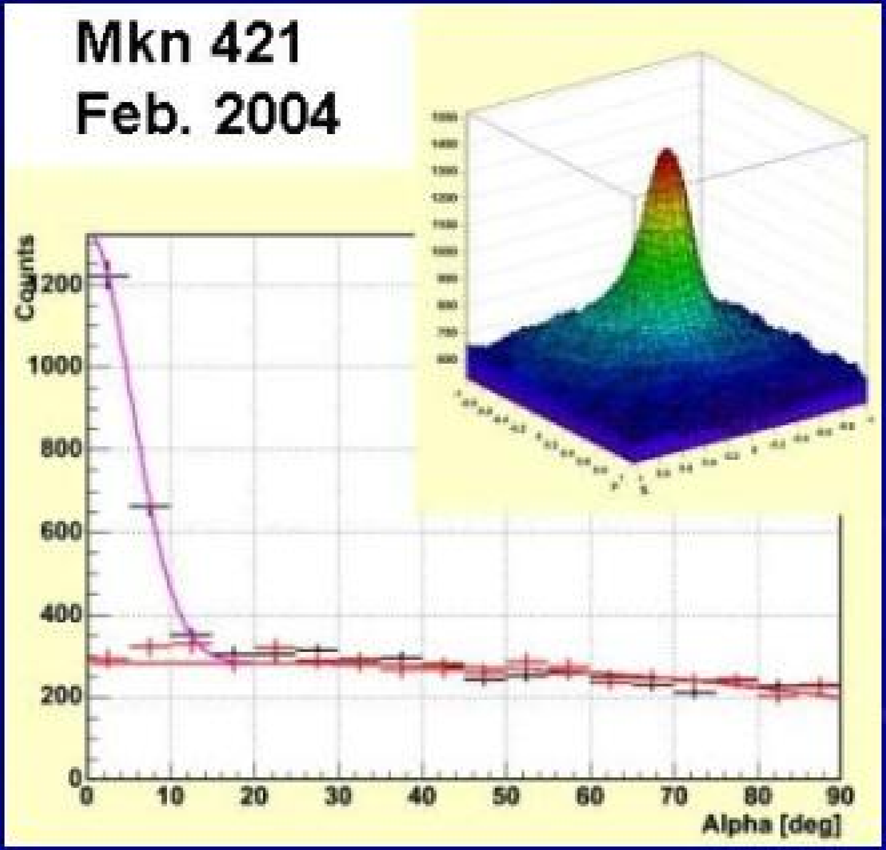


MAGIC site


Scintillation Counter
Cherenkov Telescope
Airobicc Detector

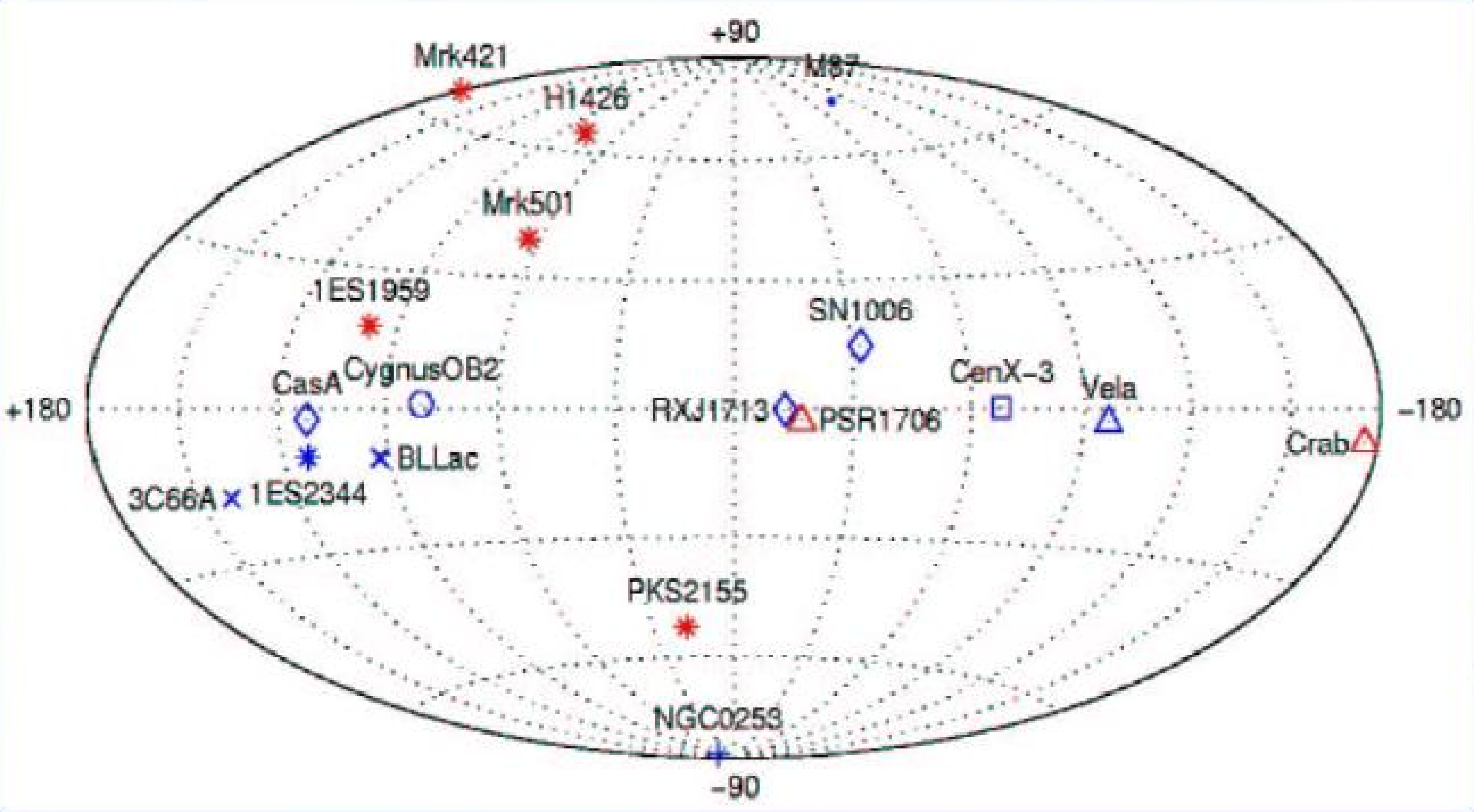
Magic I is operational, Magic II is planned





Global coverage of most powerful VHE Cherenkov telescopes

TeV Gamma Ray Sky: ~ 10 galactic and 8 extragalactic sources

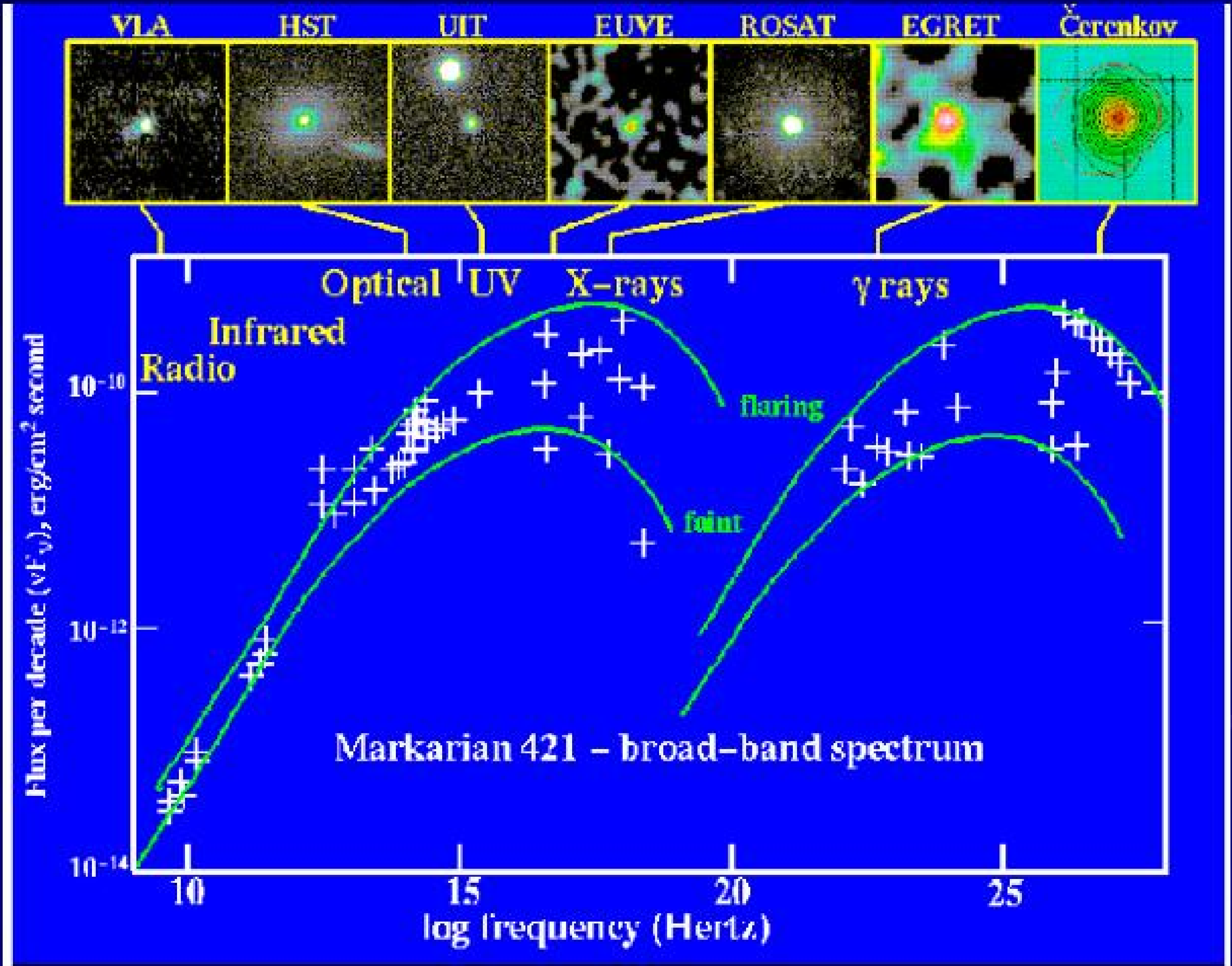


Almost all sources are identified, their number increases every year

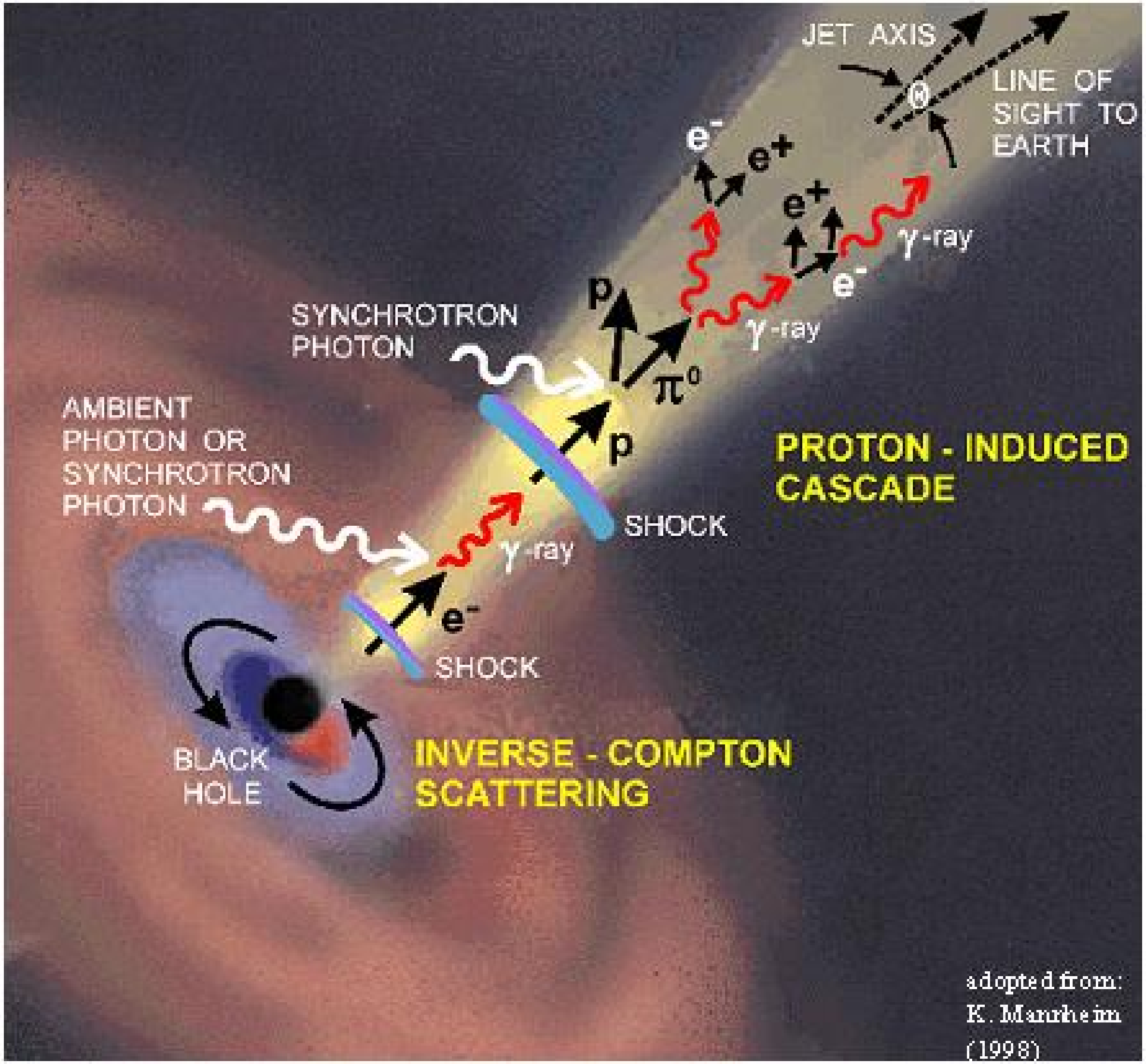
Classes of objects in TeV Catalog:

- AGN
- Radio Galaxy
- Starburst Galaxy
- Supernova Remnants
- Binary Source
- OB Association

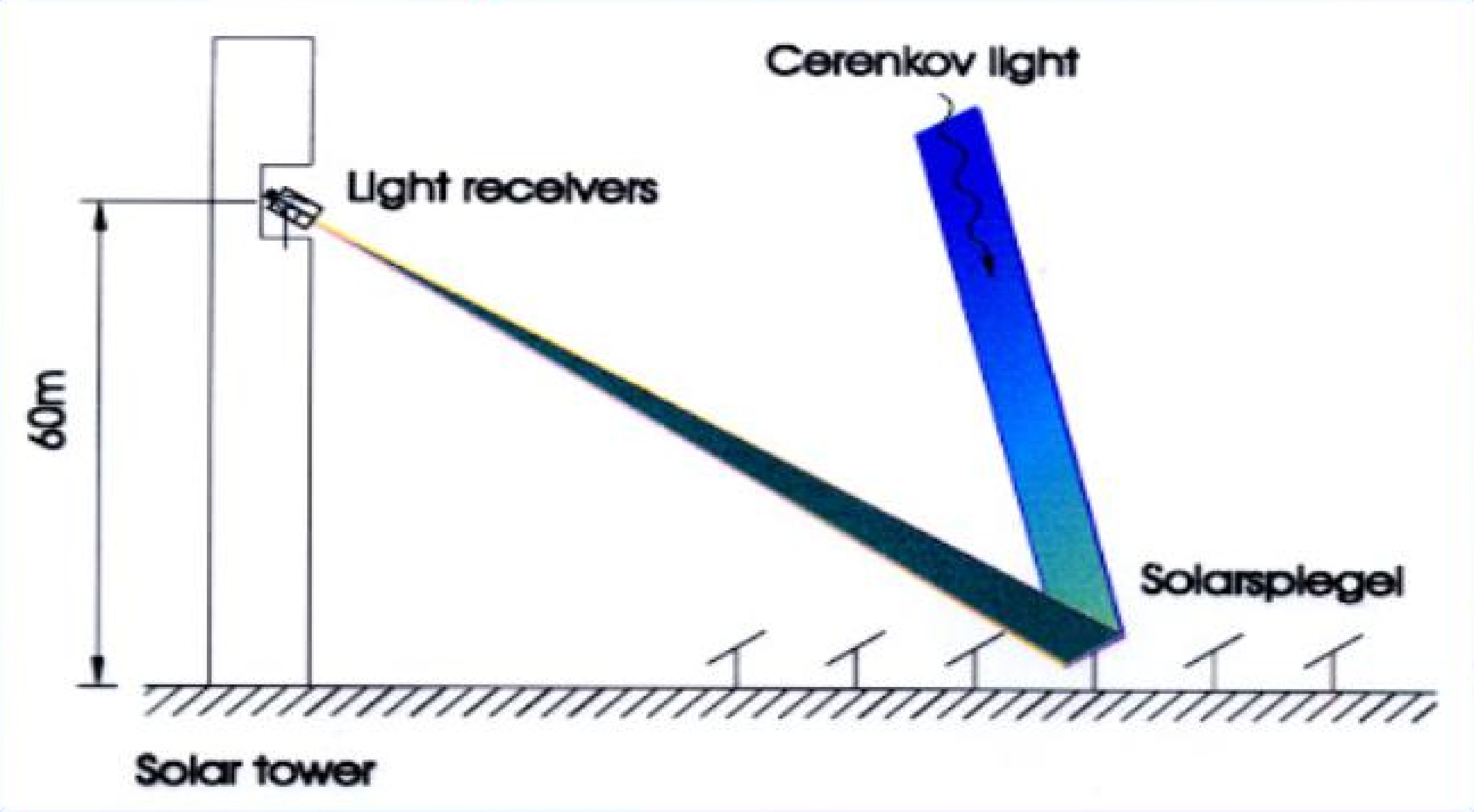
Multi-wave observations of Mrk 421



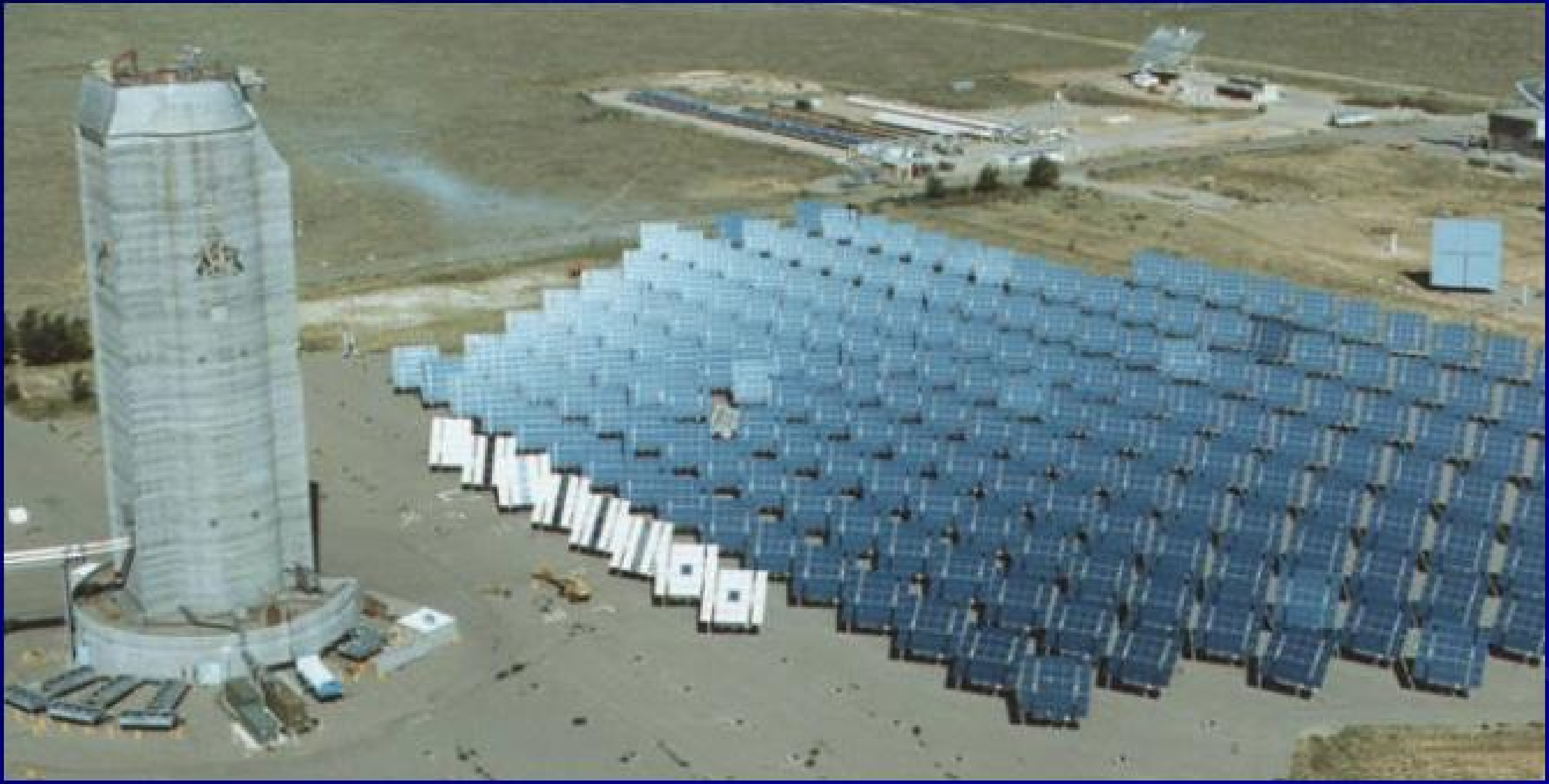
AGN jet emission



Cherenkov astronomy at solar power plants

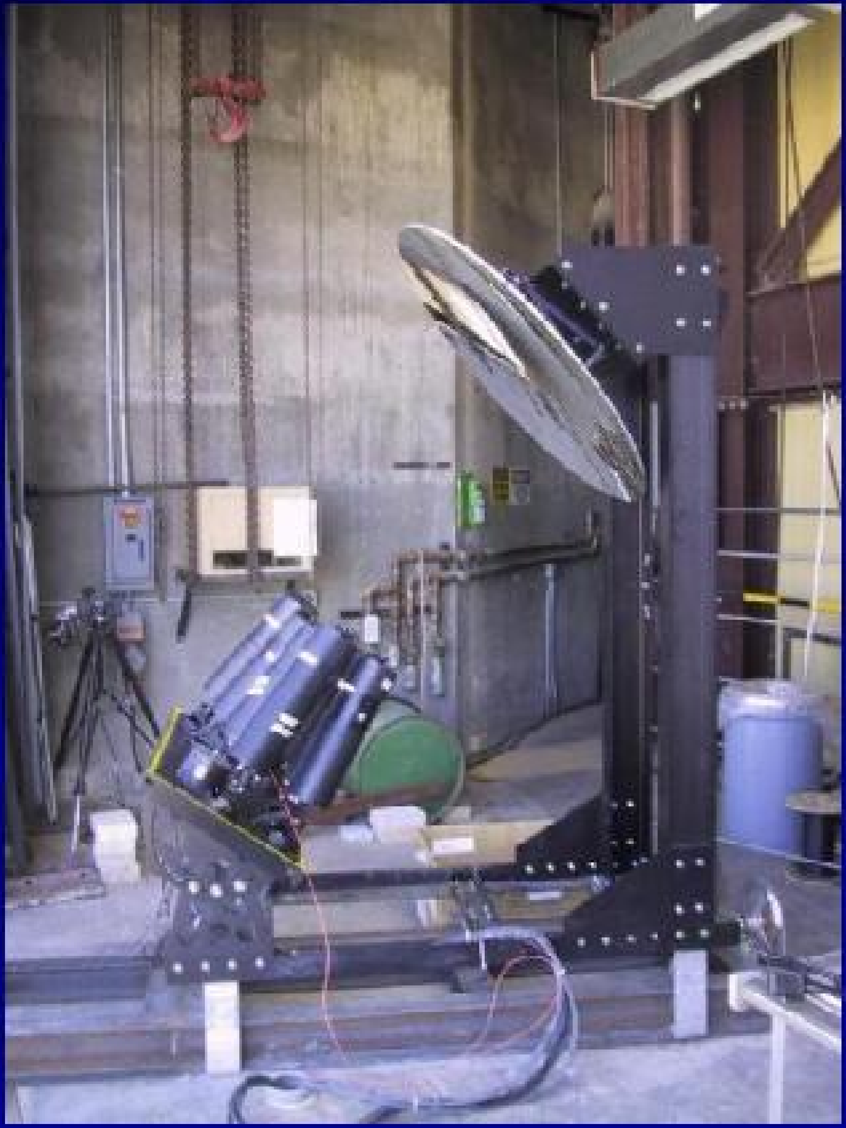


An example of solar power plant used as an air Cherenkov telescope (STACEE)

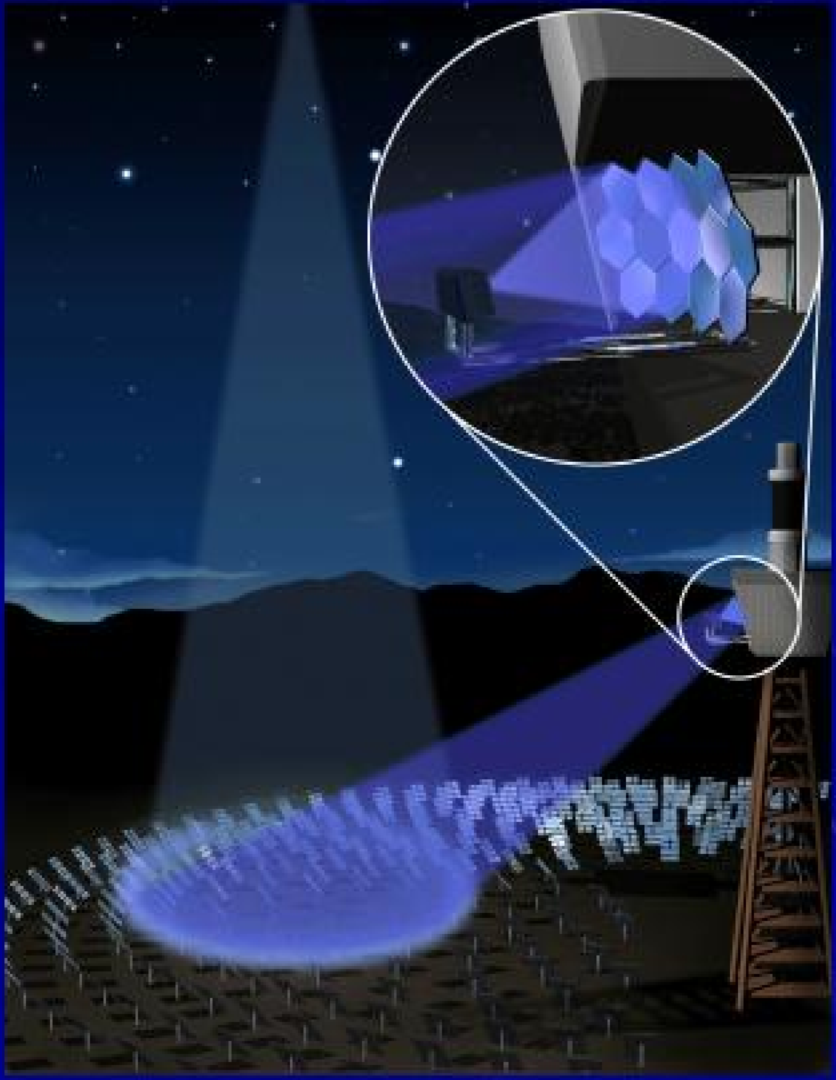


STACEE: Solar Tower Atmospheric Cherenkov Effect Experiment (New Mexico)

- Secondary mirror and detecting system

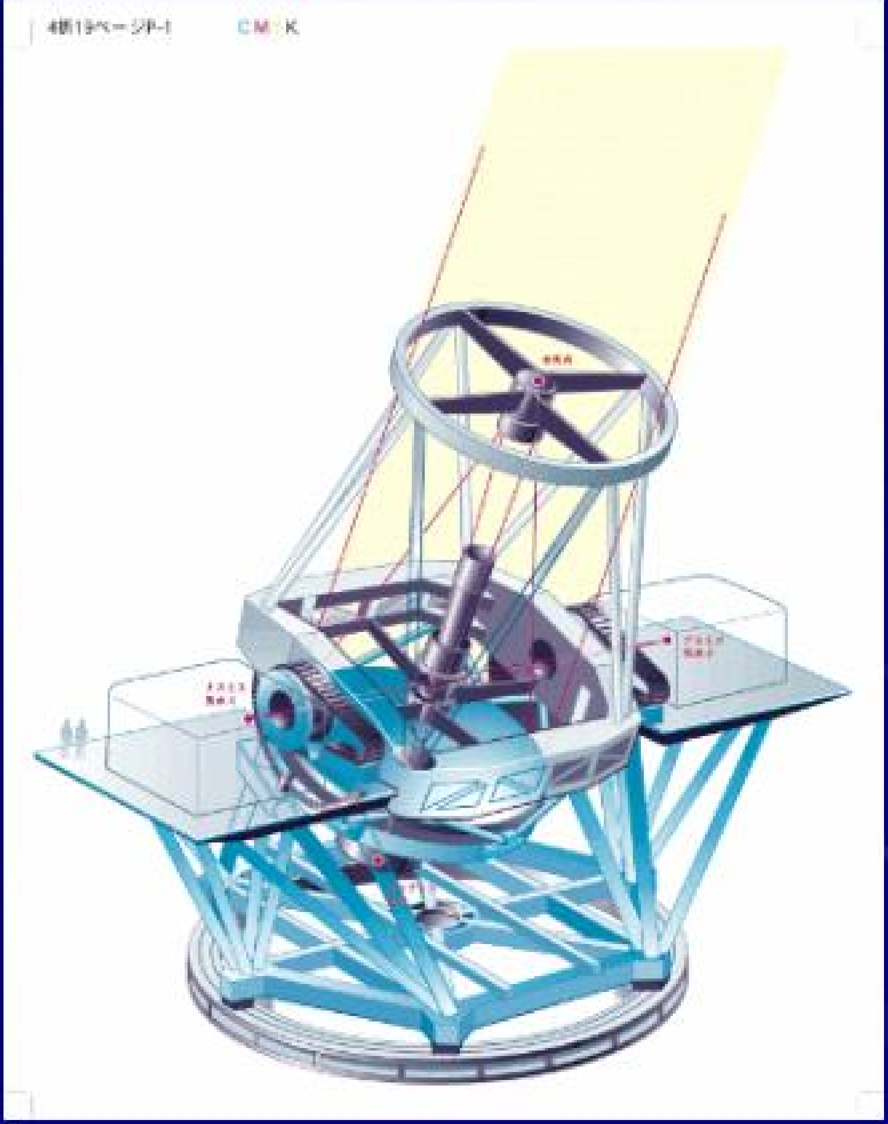


Solar II experiment (Barstow, CA)



CheSS Project: Japanese telescope SUBARU (Hawaii)

- Optical-infrared telescope with a 8.3 m mirror at 4000 m a.s.l.
- CheSS (Cherenkov light detecting System on Subaru) is aimed to detect 10 GeV gamma rays



Chudakov's suggestion of experiments with snow-reflected Cherenkov radiation:

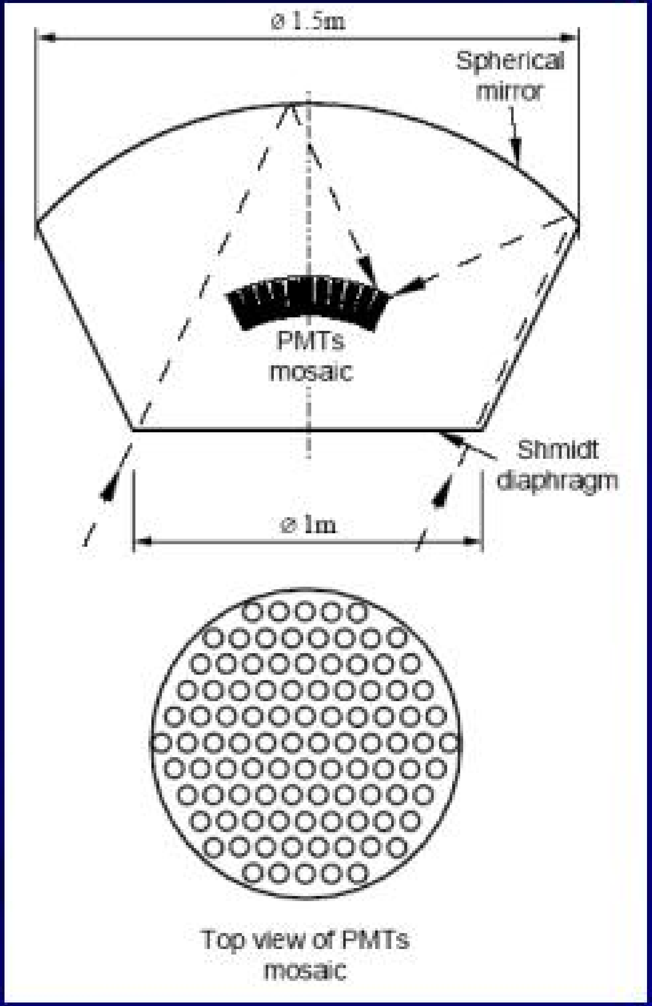
- A.E. Chudakov, A possible method to detect EAS through Cherenkov radiation reflected from snowy ground surface,

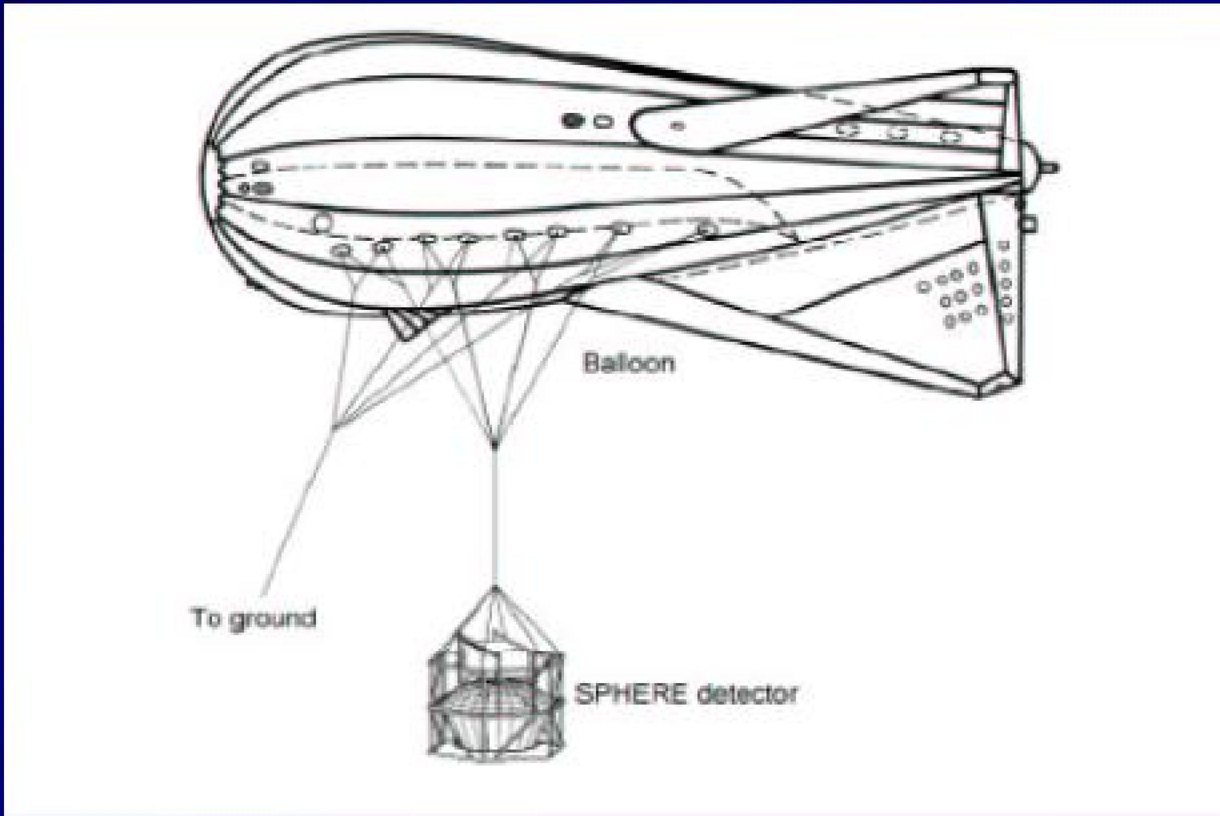
  in "*Experimental methods of studying cosmic rays of ultra-high energies*", *Proc. of All-Union Symposium, Yakutsk, 1972, p. 69.*

Original Chudakov's suggestion was never implemented

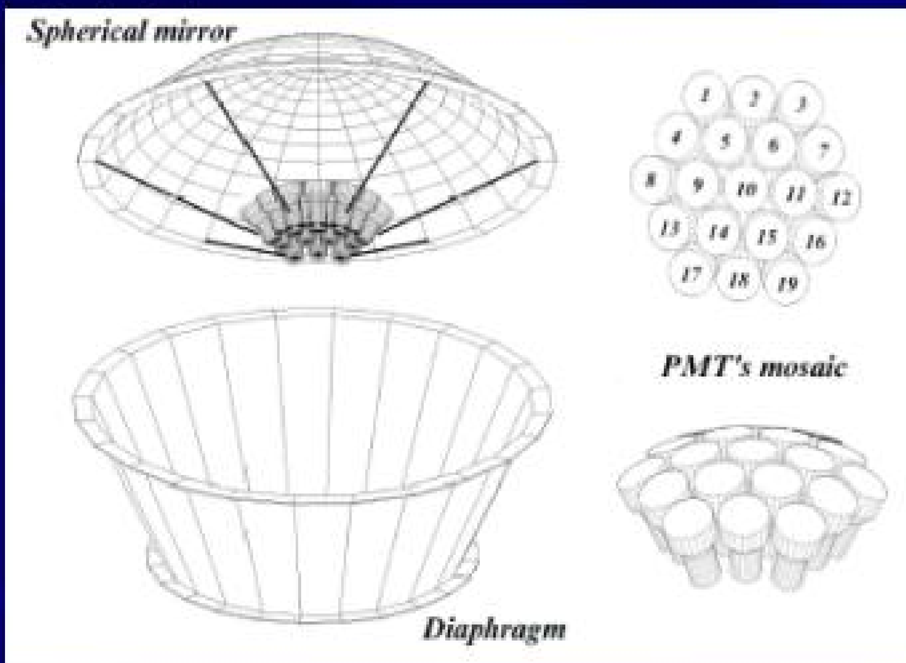
- Chudakov in his suggestion had in mind the airplane experiment during polar night
- Some attempts were made to observe reflected EAS signal in mountains
- Now the idea of a fixed balloon is realized and the project of an experiment with a high-altitude balloon is under development

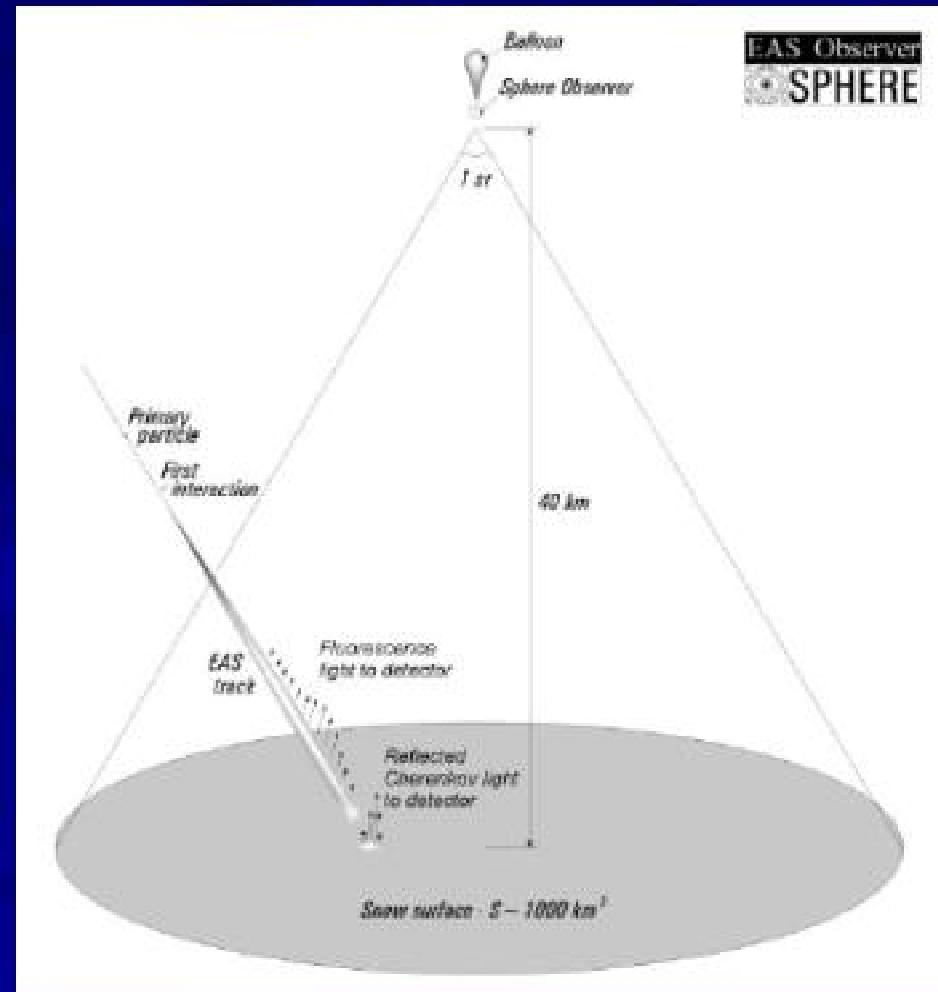
Experiment SPHERE-1 with a fixed balloon



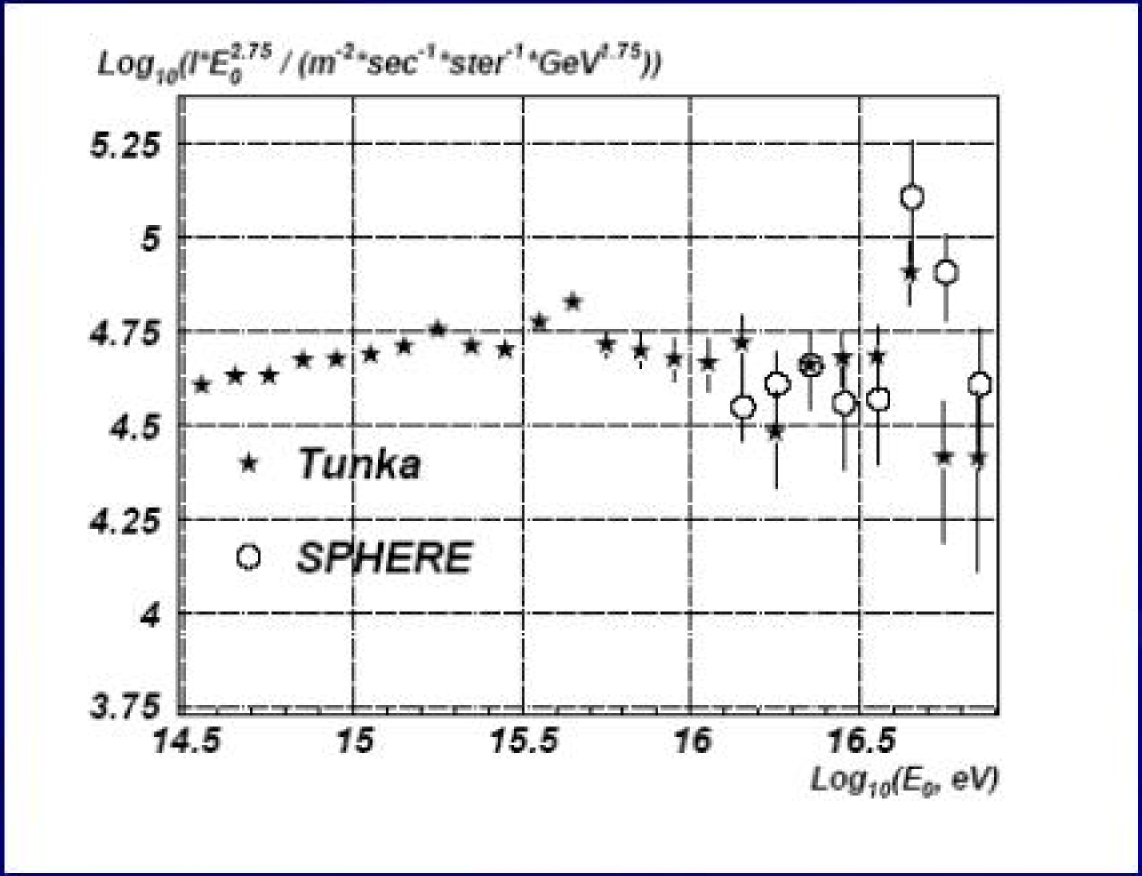


SPHERE-2 design and operation

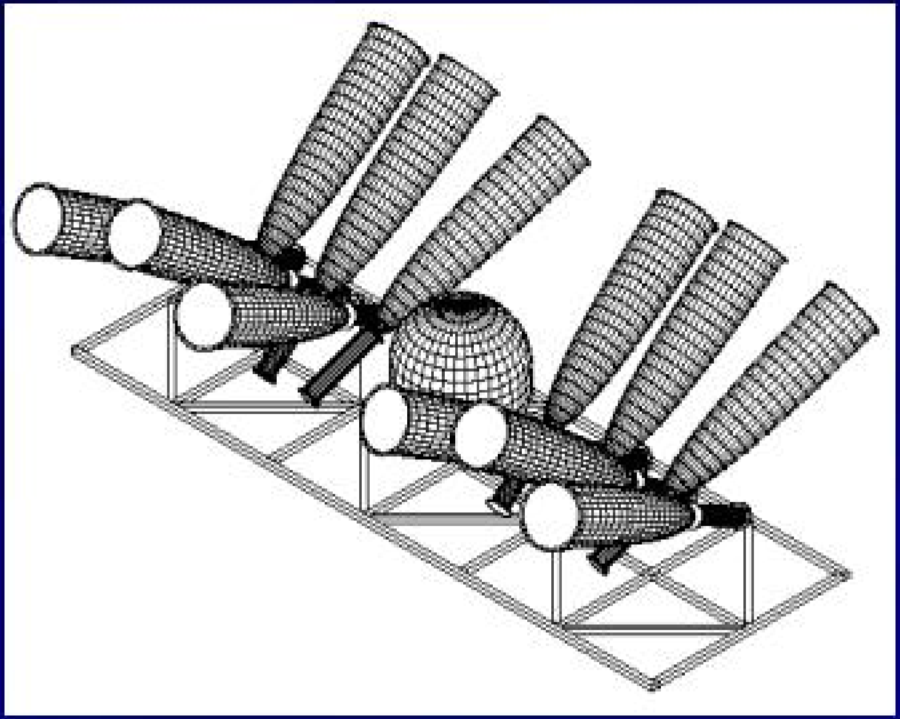


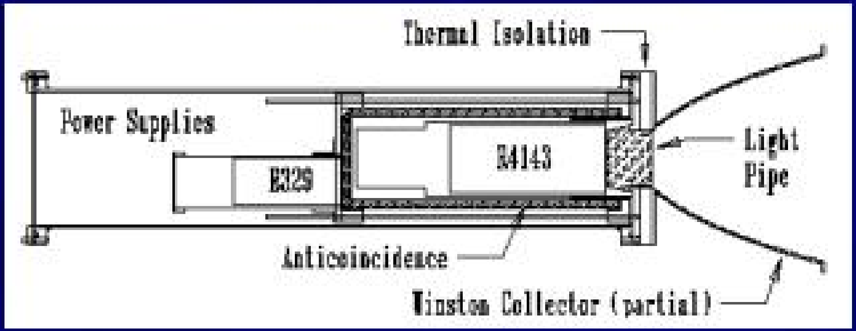


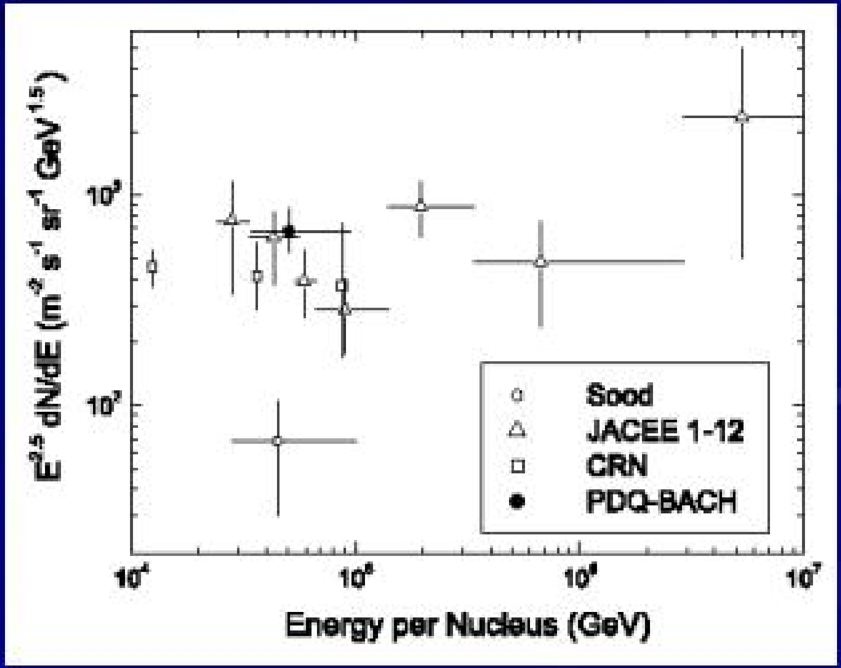
Results of the SPHERE-1 detector



BACH: Balloon Air CHerenkov experiment

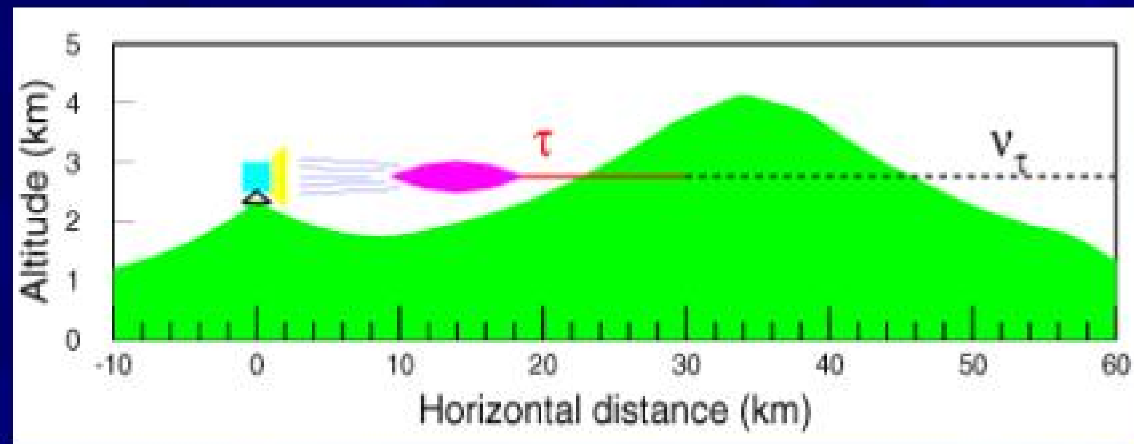






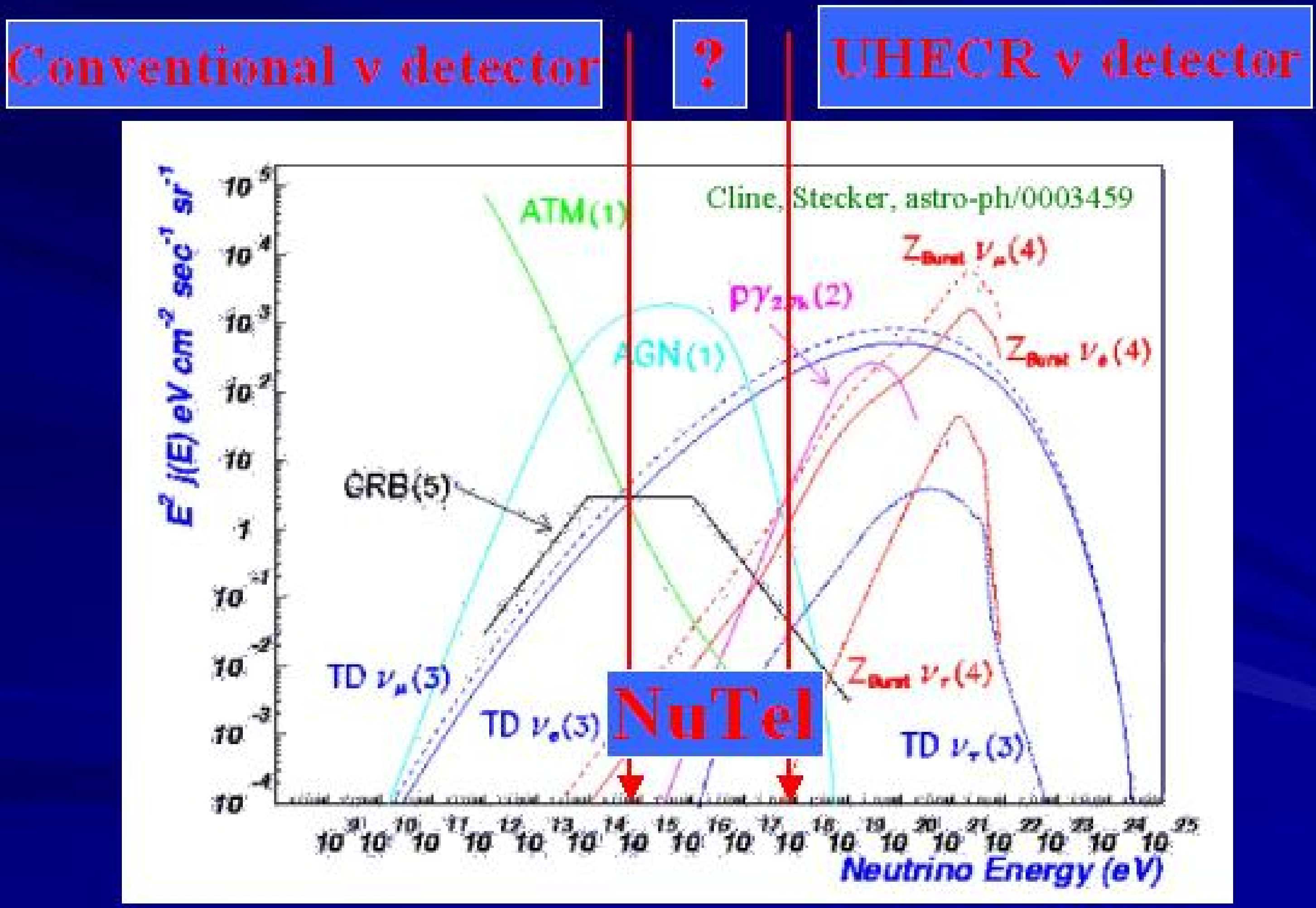
Direct measurements of the flux of iron nuclei with energy threshold of $2.2 \cdot 10^{13}$ eV

New ideas in air Cherenkov technique application: Neutrino physics and astronomy

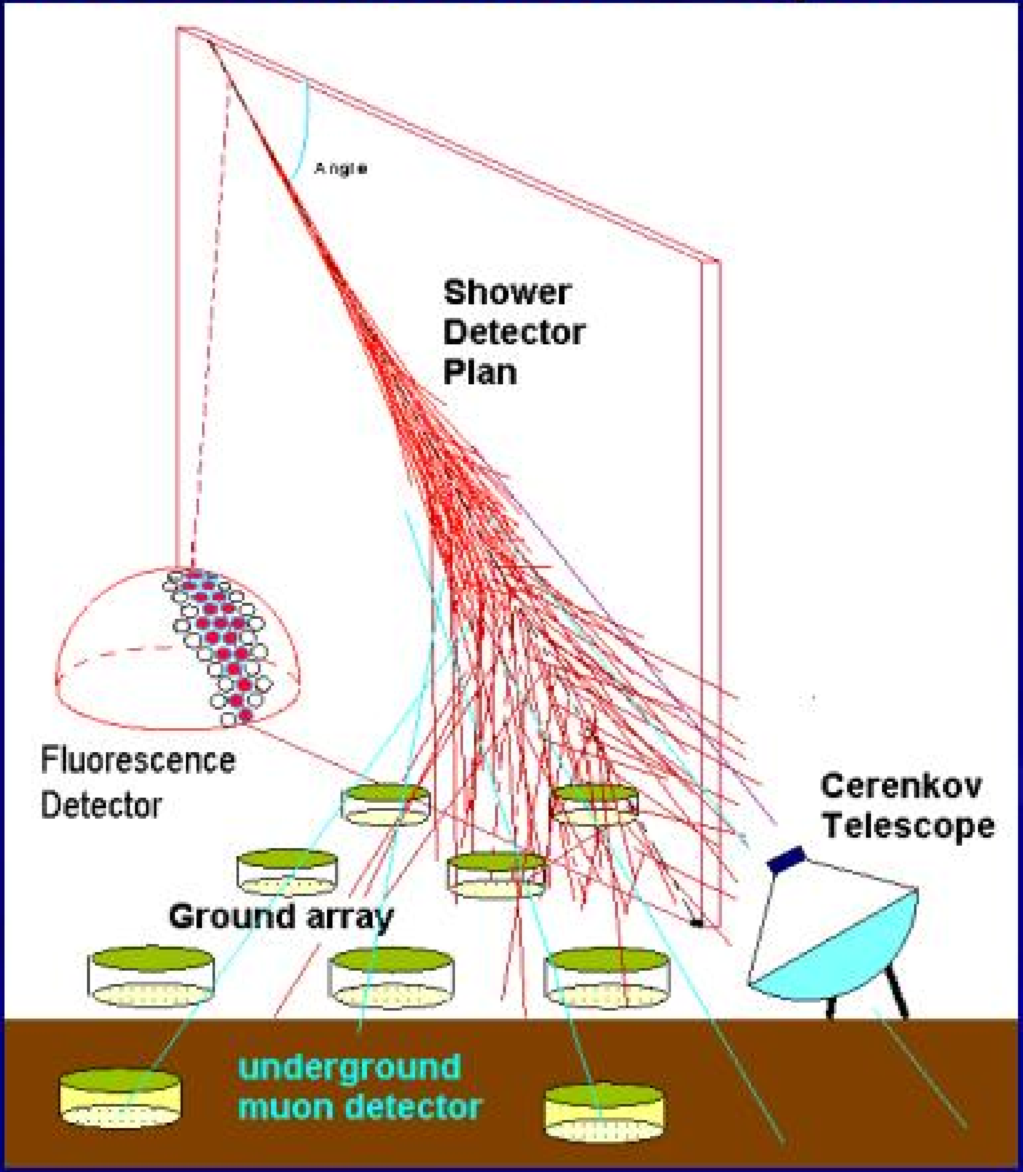


- Earth-skimming and mountain-traversing neutrinos
- NuTel collaboration prepares an experiment at Hawaii

Window of opportunity



Combination of Cherenkov and fluorescence techniques



Two outstanding "CH"s

P.A. Cherenkov (1904-1990)

A.E. Chudakov (1921-2001)

Conclusions:

- The radiation first discovered by P.A. Cherenkov serves as a basis for a variety of methods in cosmic ray studies
- Among them, air Cherenkov methods form a separate area with several lines of research
- Nearly all of the latter were first developed or suggested by A.E. Chudakov whose ideas and experimental skill laid the foundation for present-day progress