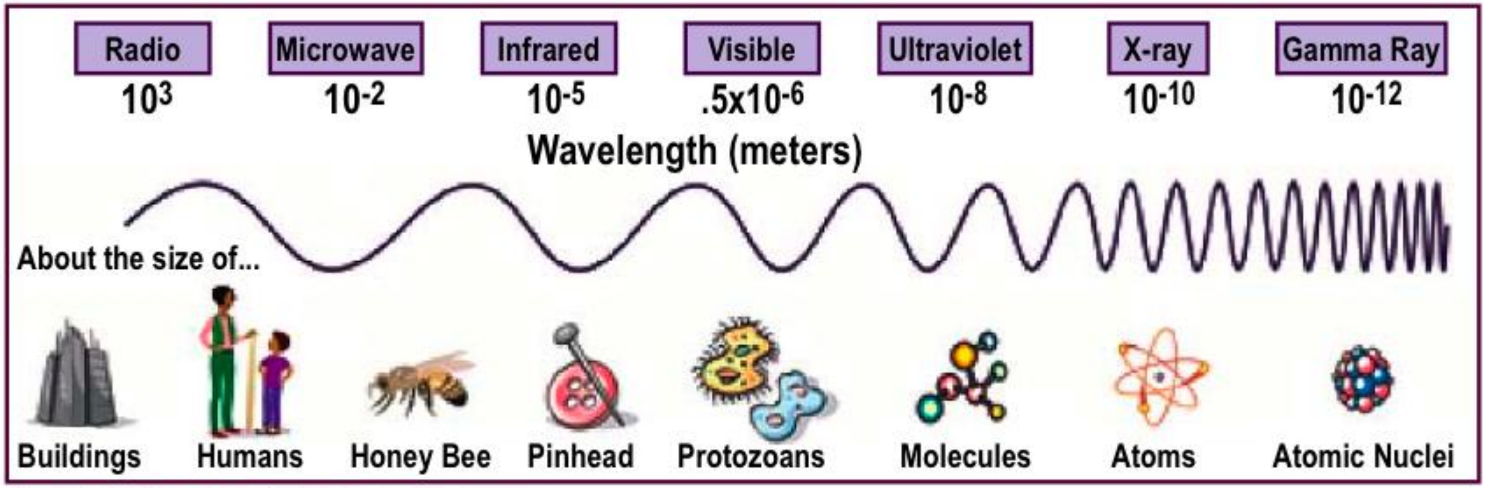
Cosmic Rays Seen in Particles and in Light

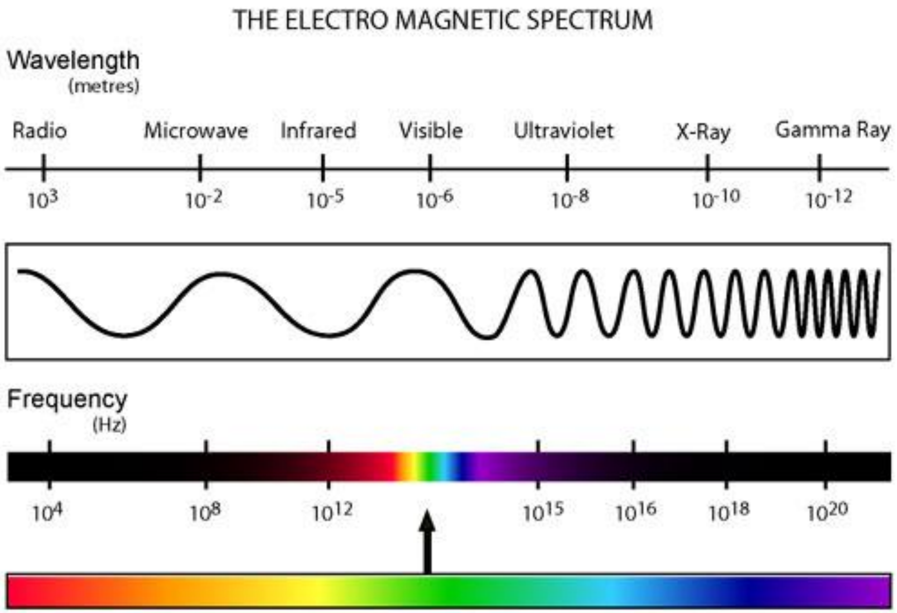
Razmik Mirzoyan

Max-Planck-Institute for Physics (Werner-Heisenberg-Institute) Munich, Germany
National Academy of Sciences of Republic of Armenia

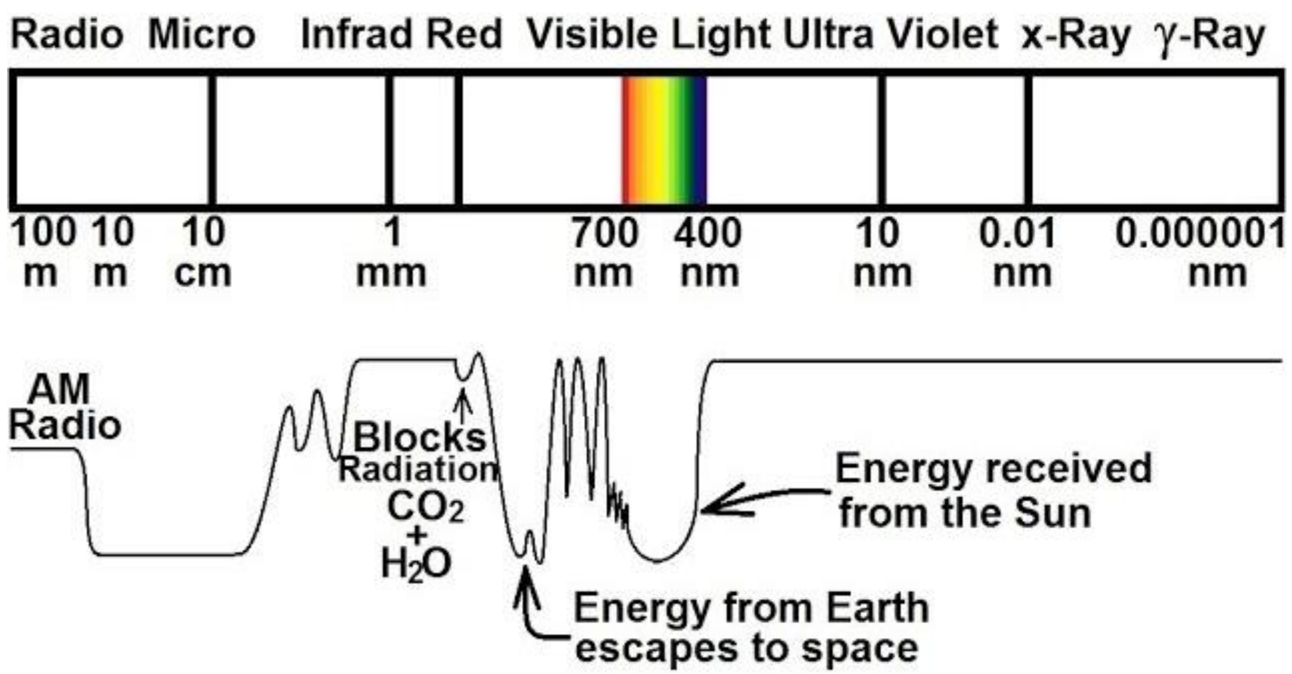
The electromagnetic spectrum

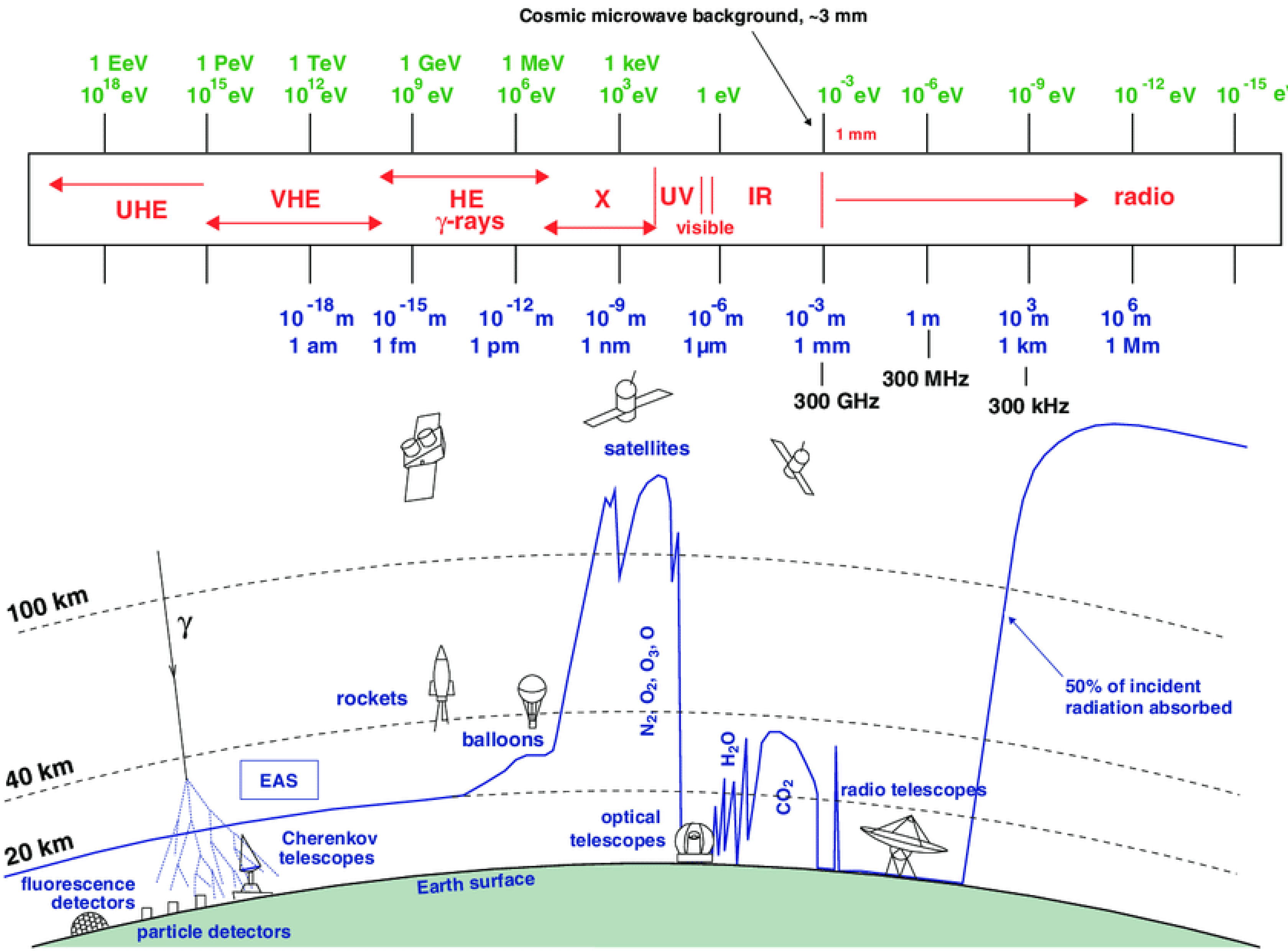


Credit: NASA / Ruth Jennings



Transparency of atmosphere to incident electromagnetic radiation

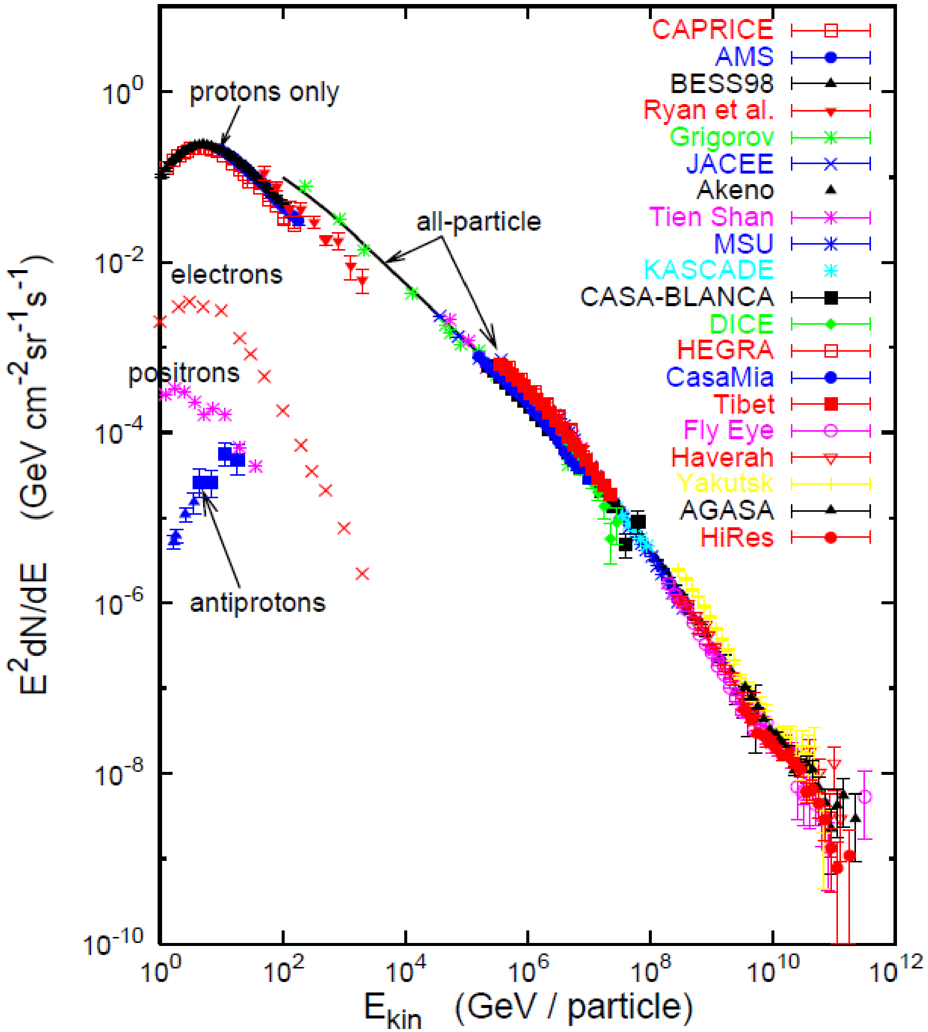




Cosmic microwave background, ~3 mm
1 EeV 10^{18} eV
1 PeV 10^{15} eV
1 TeV 10^{12} eV
1 GeV 10^{9} eV
1 MeV 10^{6} eV
1 keV 10^{3} eV
1 eV
10^{-3} eV
10^{-6} eV
10^{-9} eV
10^{-12} eV
10^{-15} eV
1 mm
UHE
VHE
HE
γ-rays
X
UV
visible
IR
radio
10^{-18} m 1 am
10^{-15} m 1 fm
10^{-12} m 1 pm
10^{-9} m 1 nm
10^{-6} m 1 µm
10^{-3} m 1 mm
1 m
10^{3} m 1 km
10^{6} m 1 Mm
300 GHz
300 MHz
300 kHz
satellites
100 km
γ
rockets
balloons
N_2, O_2, O_3, O
H_2O
CO_2
50% of incident
radiation absorbed
40 km
EAS
radio telescopes
optical
telescopes
20 km
Cherenkov
telescopes
fluorescence
detectors
Earth surface
particle detectors

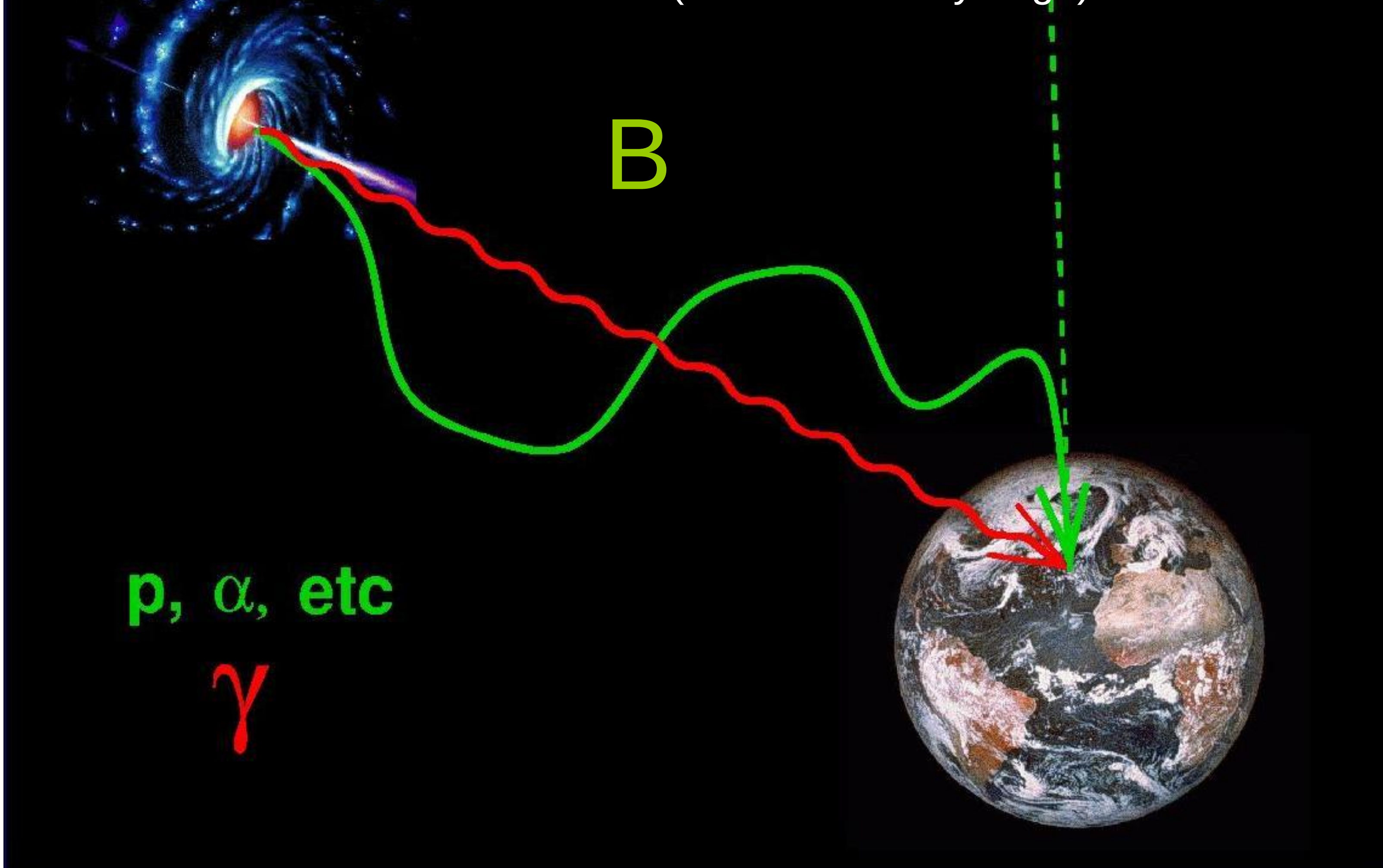
Discovery of Cosmic Rays by V. Hess in 1912

Energies and Rates of the Cosmic-Ray Particles

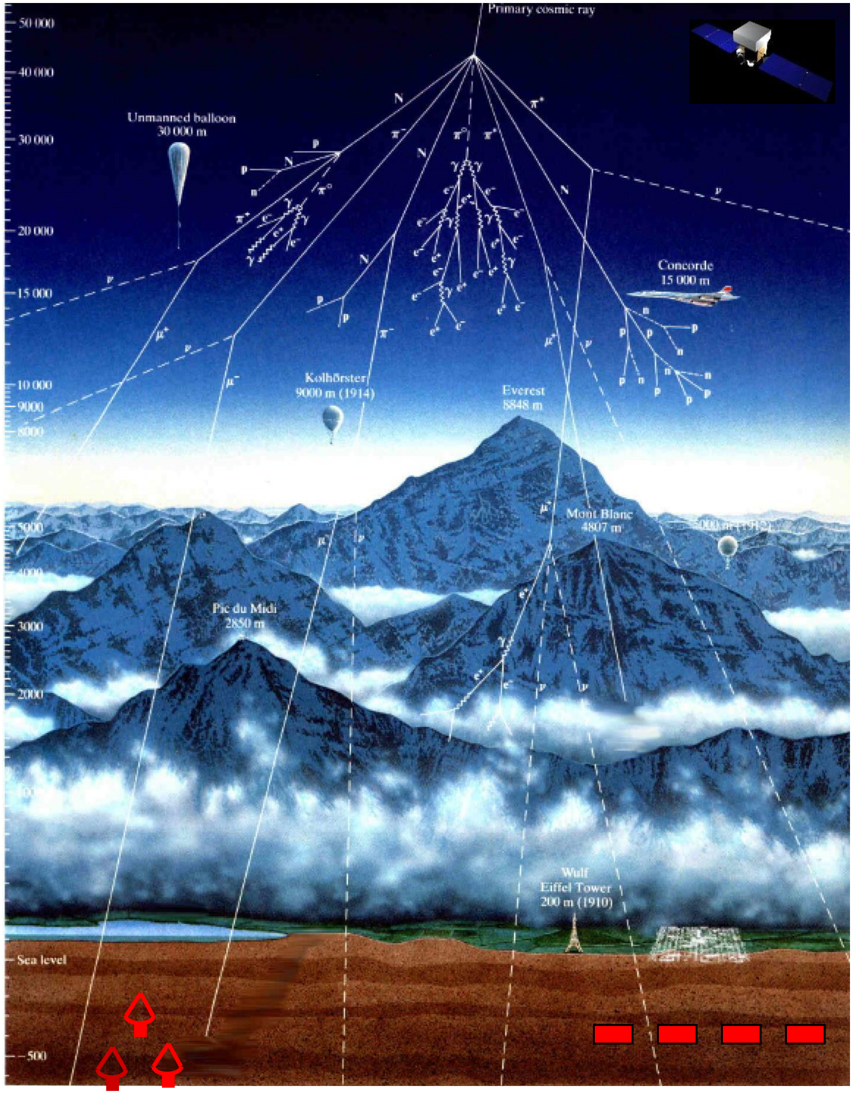


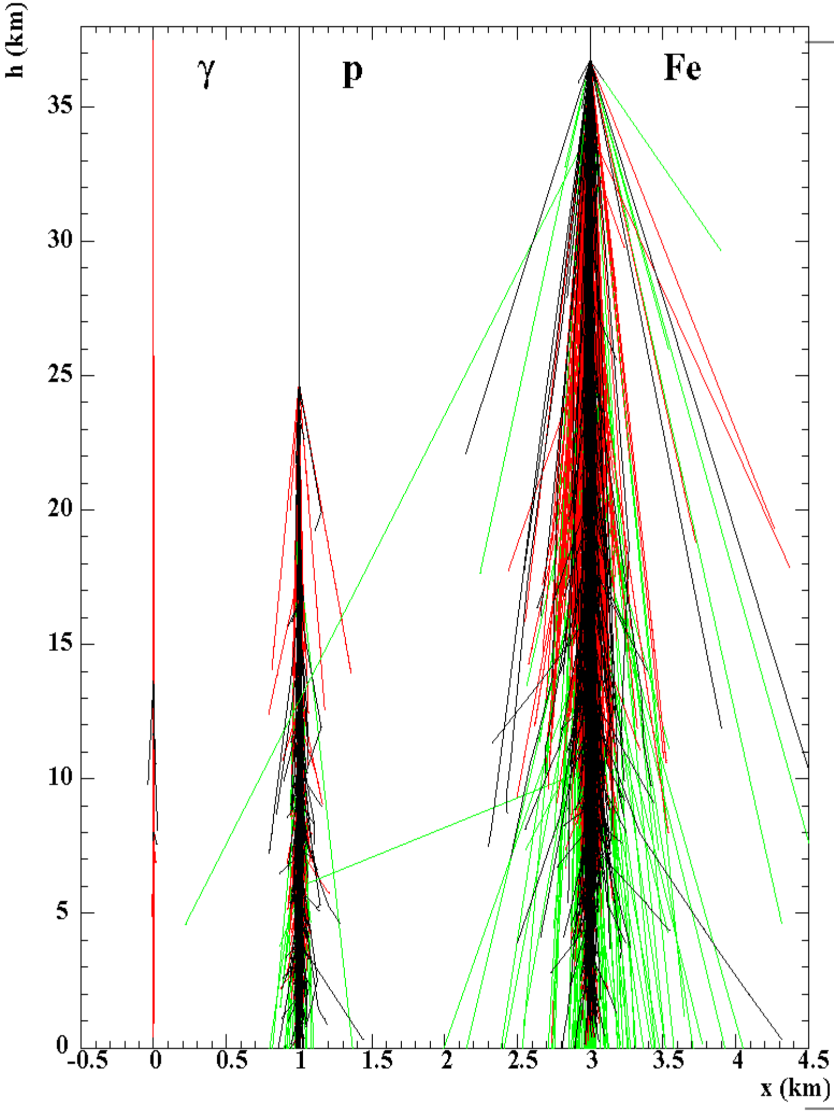
Then, why not charged CR astronomy?

Charged CR particles, deflected by magnetic fields, do not carry information on the location of the emission site (unless E is very large)



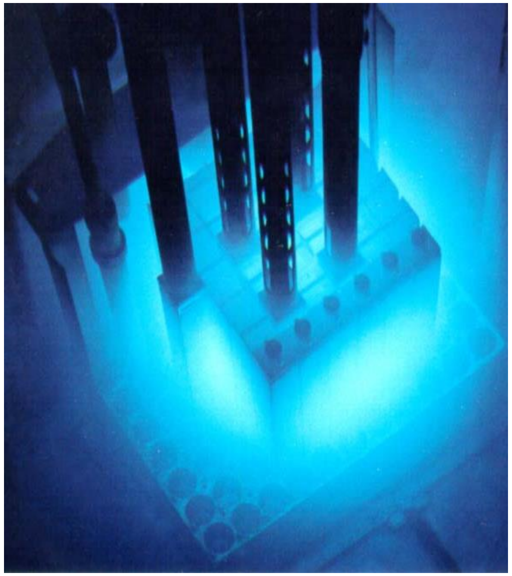
Extensive Air Showers

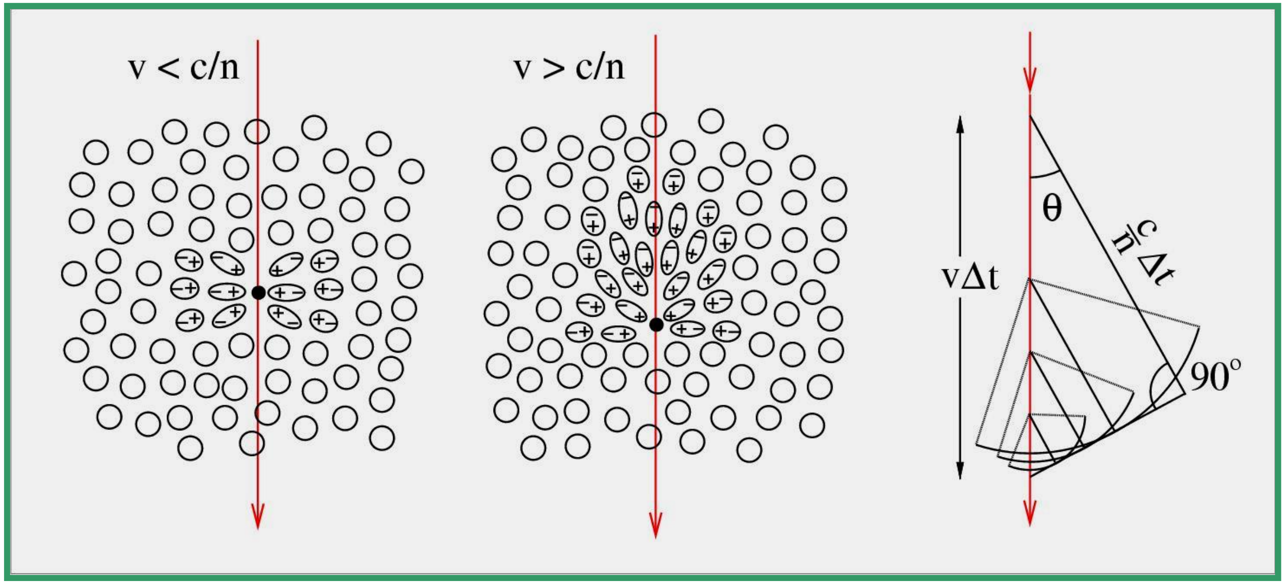




Cherenkov Radiation

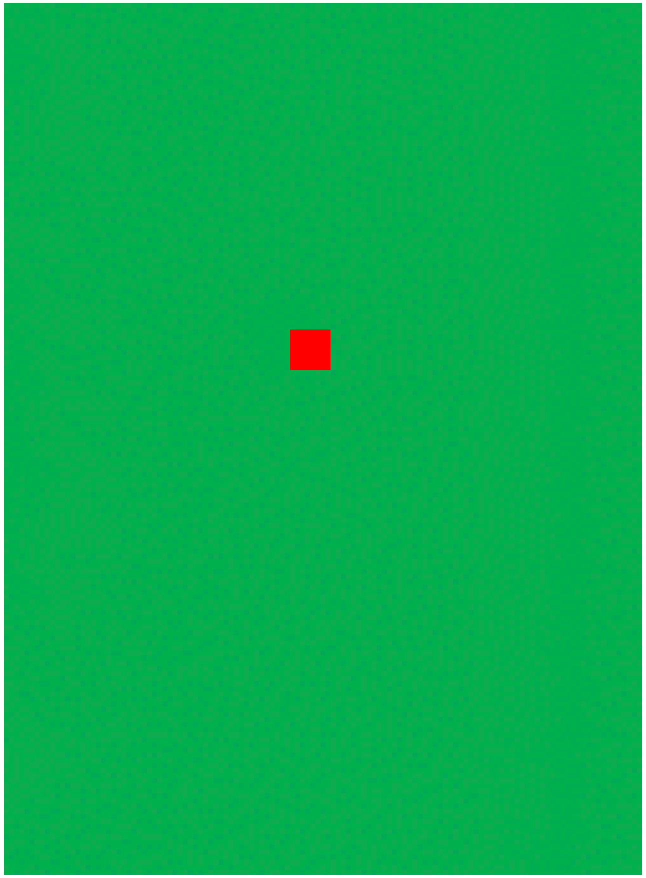
- Emitted whenever a charged particle traverses a dielectric medium at a speed larger than that of light in that medium
- The radiation results from the reorientation of electric dipoles induced by the charge in the medium. When v > c/n the contributions from different points of the trajectory arrive in phase at the observer as a narrow light pulse

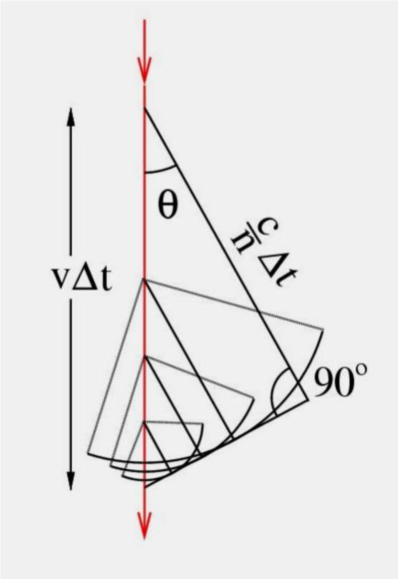




Cherenkov radiation

Analogous to “sonic boom”

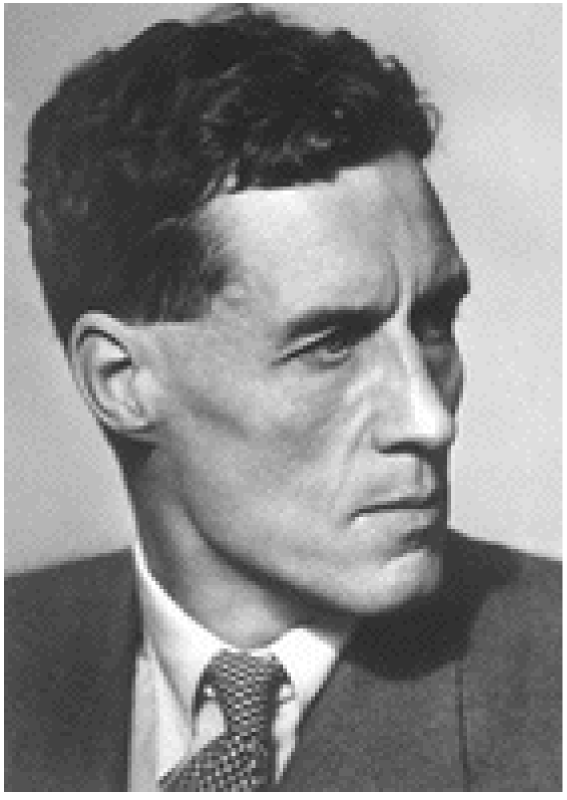




$\cos\theta = 1 / (\beta\, n)$

$\theta_{max} = \cos^{-1}(1/n)$

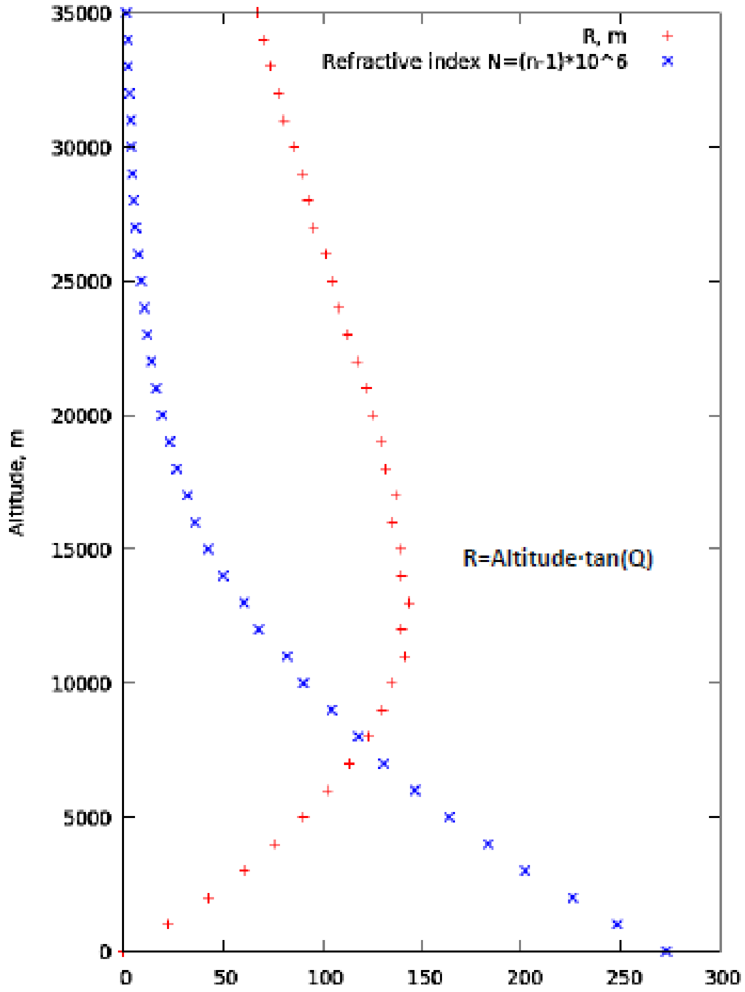
Cherenkov radiation in the atmosphere

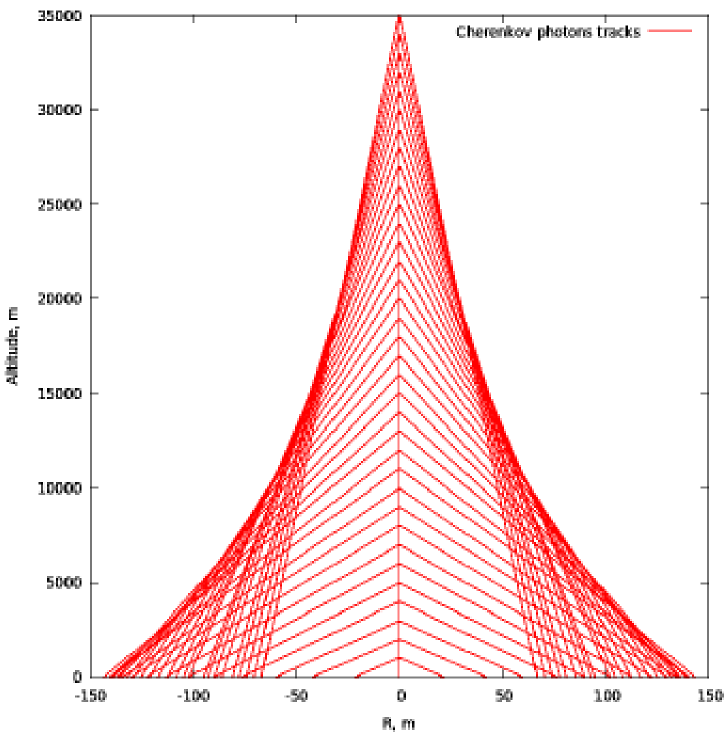


In 1948, P.M.S. Blackett suggested that secondary CR's should produce Cherenkov radiation which would account for a fraction 10^{-4} of the total night sky light

Pulses of Cherenkov light from air showers were first recorded by Galbraith and Jelley in 1953

Index of Refraction and Cherenkov Emission Angle versus Altitude



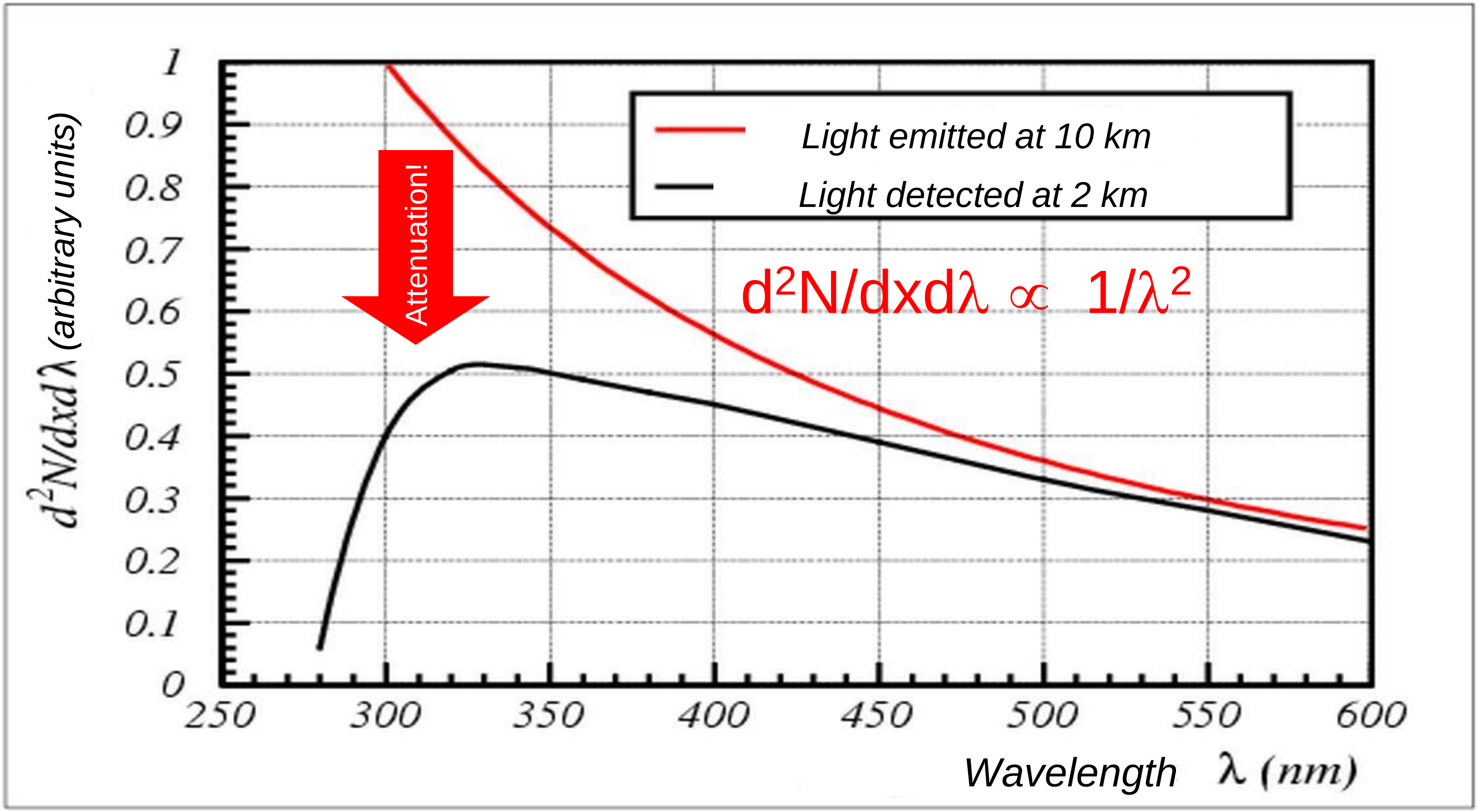


Number of emitted Cherenkov photons in the atmosphere

- A relativistic particle at a given height (slanth depth) a.s.l. will emit in the atmosphere, in the wavelength range of 300-600 nm, the following number of photons per 1m path length:

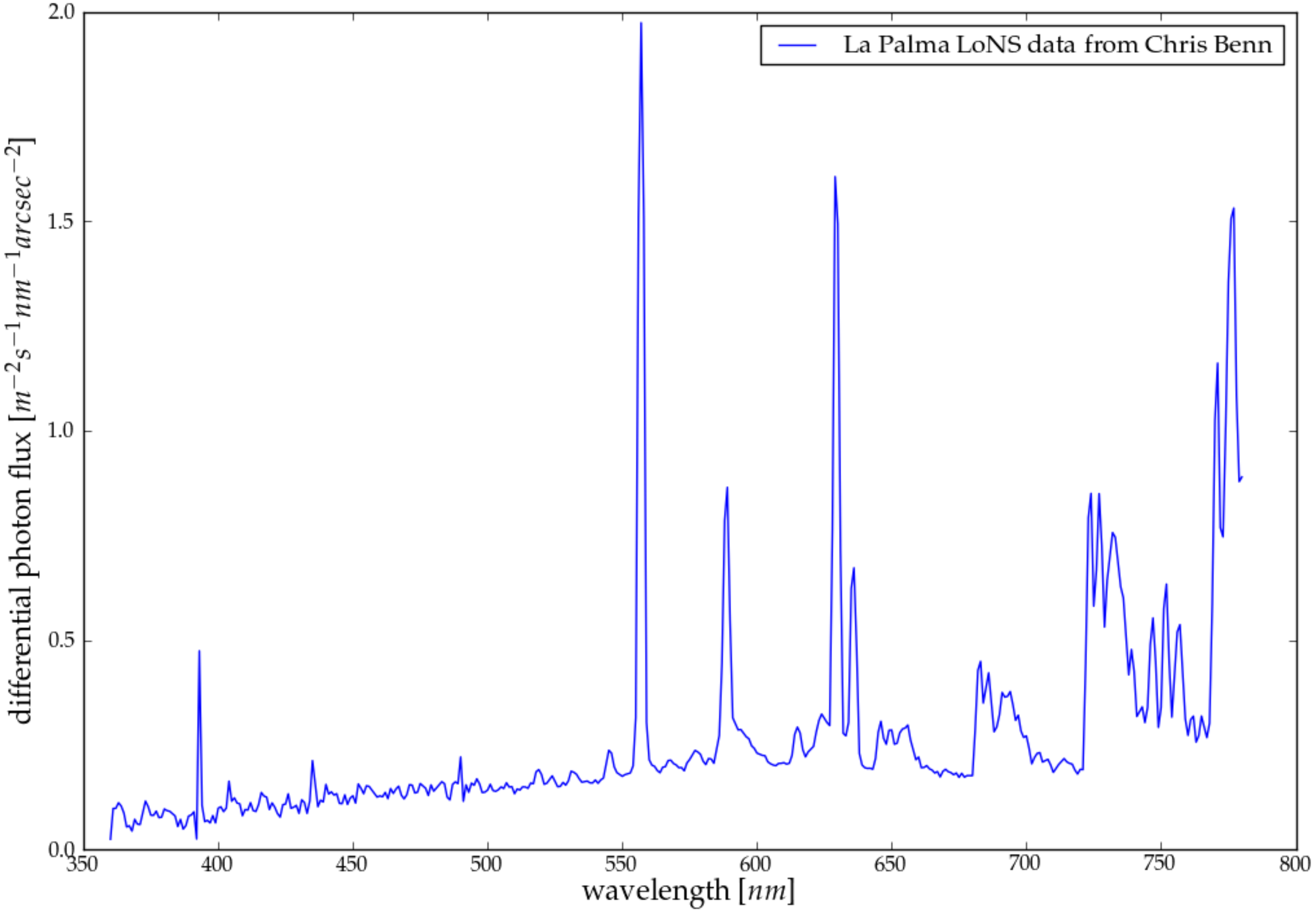
Slanth depth, g/cm^2	100	300	800	1036
Height a.s.l., km	16	10	2.2	0
Number of emitted C-photons/m	4.5	13	35	45

Spectrum of atmospheric Cherenkov light



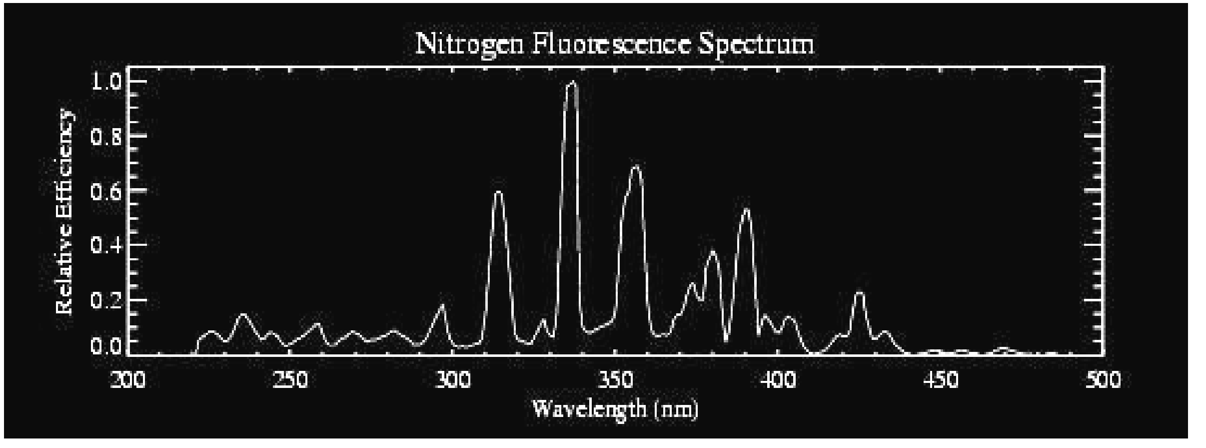
Light of Night Sky (LoNS) is a strong background emission

Integral of LoNS in 300-600nm: $2x10^{12}$ ph/m²·sr·s



More light from EAS: Air fluorescence

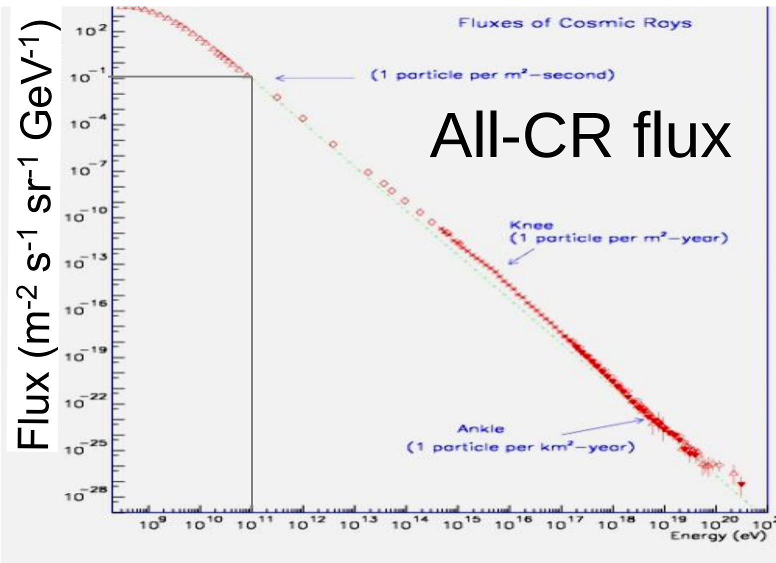
Particles of the air shower excite air molecules, which fluoresce in the UV: $N_2^* \rightarrow N_2 + h\nu$, in competition with $N_2^* + N_2 \rightarrow 2N_2$ (the excited state may also be collisionally quenched).

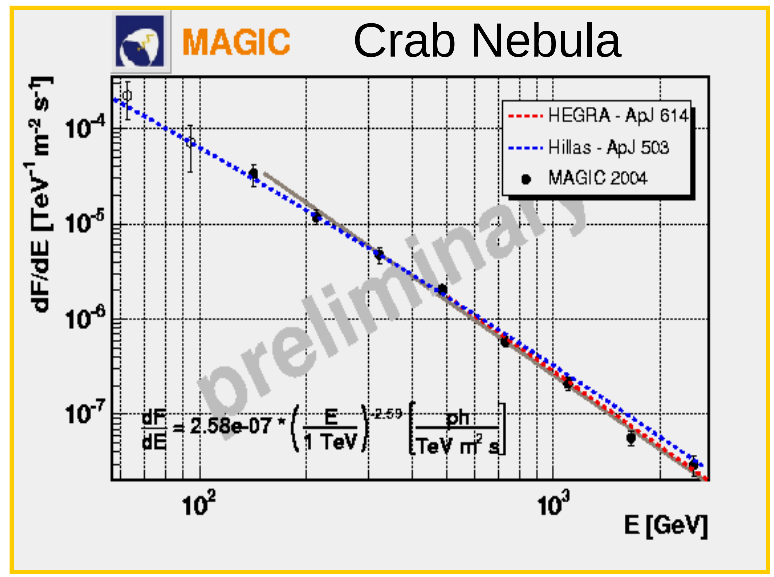


The emitted isotropic light is proportional to the number of electrons at all depths: as dE / dx per unit length goes up with higher atmospheric pressure, the efficiency of light production decreases linearly with pressure $\Rightarrow$ a fast electron produces roughly the same amount of light per unit path length at all altitudes. The downside - it is rather dim (isotropy) and is affected by atmospheric absorption.

Good news: the effects of the interaction of a VHE γ-ray in the atmosphere are spread over a large area on the ground ⇒ very large effective areas are achievable ⇒
VHE γ-ray astronomy is feasible despite the low fluxes

Drawback of ground-based γ-ray astronomy:





Charged CR showers are much more numerous than gamma showers (x 10^3 – 10^5), even for strong sources!

Air shower detection techniques

Detected shower component

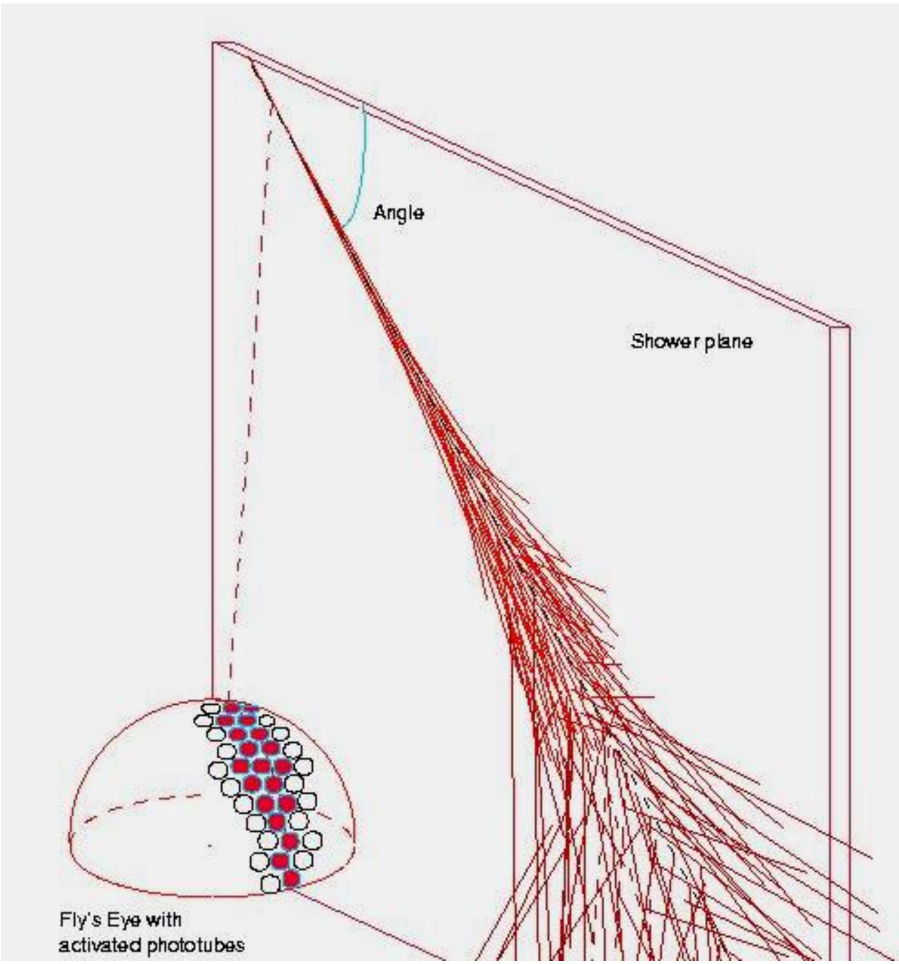
- Cherenkov light *"Atmospheric Cherenkov detectors"*
  - Imaging (IACTs)
  - Sampling
    - Narrow FOV (i.e. solar arrays)
    - Wide FOV (AIROBICC, BLANCA)
- Particles (and secondary γ's) *"Air shower detectors"*
  - Dense sampling (Milagro, HAWC, ARGO)
  - Coarse sampling (Tibet AS, HEGRA, CASA)

  LHAASO
- Fluorescence light

  i.e. Fly's eye, HiRes, AUGER

  Not used for γ-astronomy

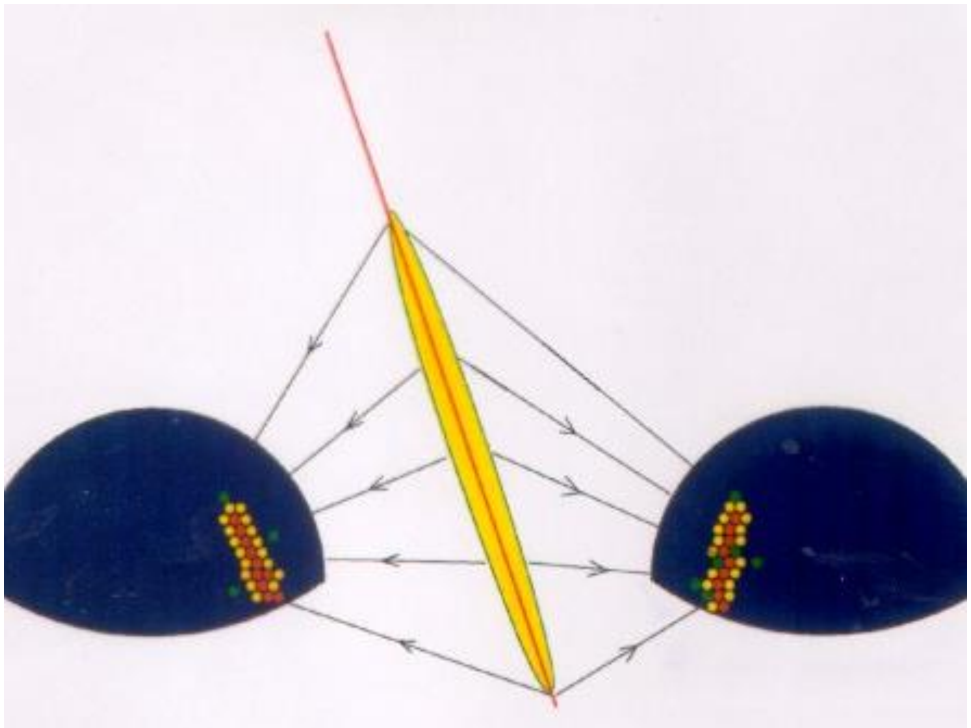
Fluorescence detectors

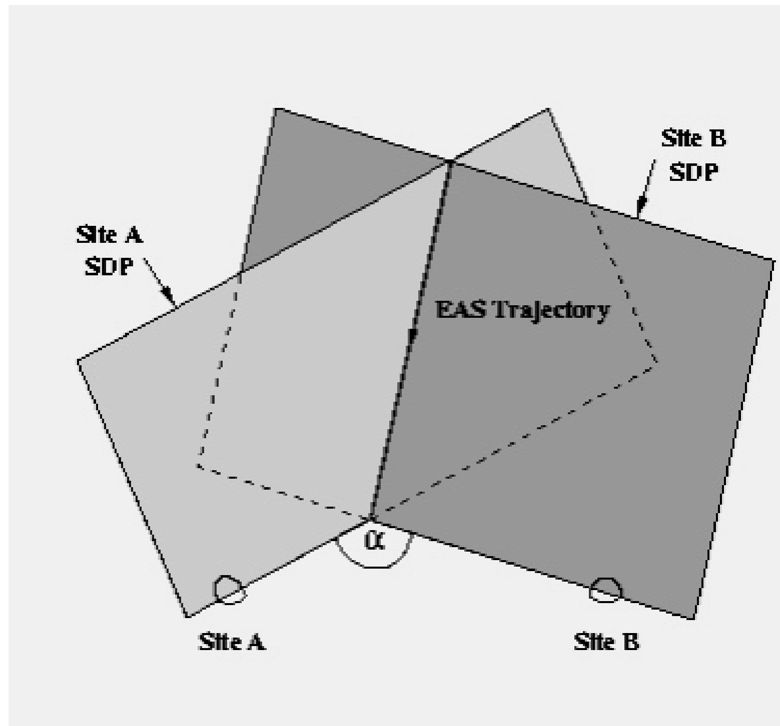


Wide field of view imaging light detector viewing the EAS “sideways” $\Rightarrow$ determination of a plane containing the shower

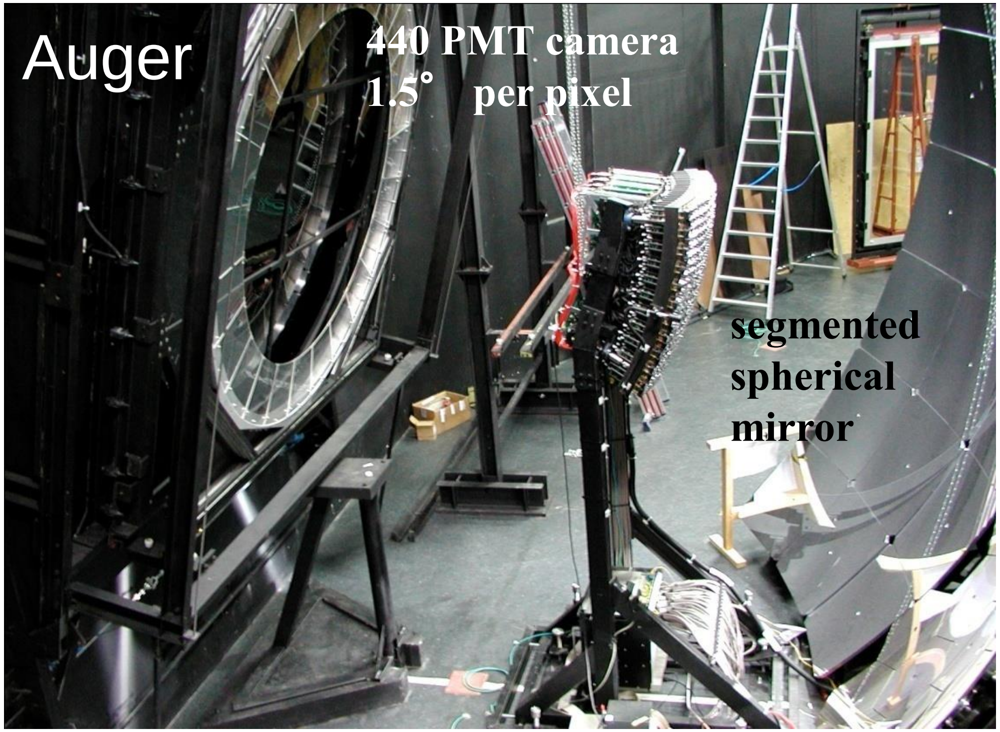
Fluorescence detectors

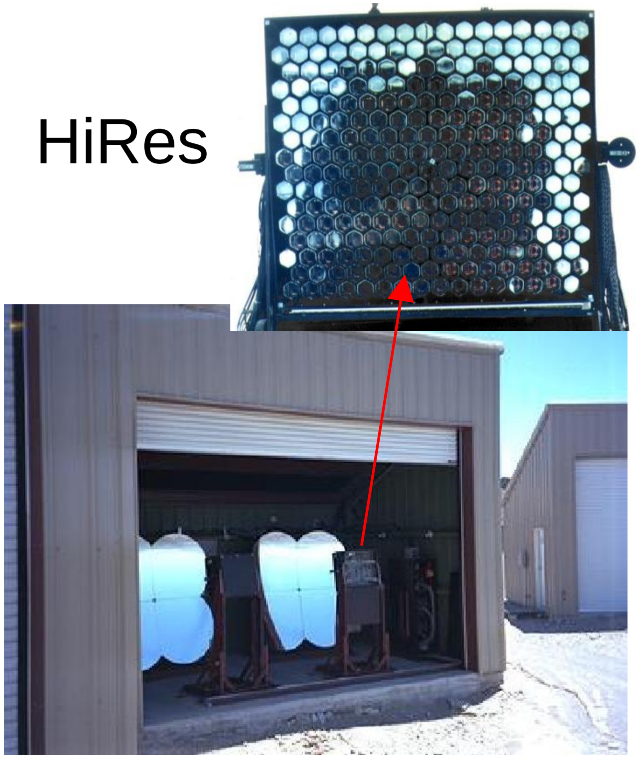
Stereo observations: better determination of shower direction and impact point





Fluorescence detectors

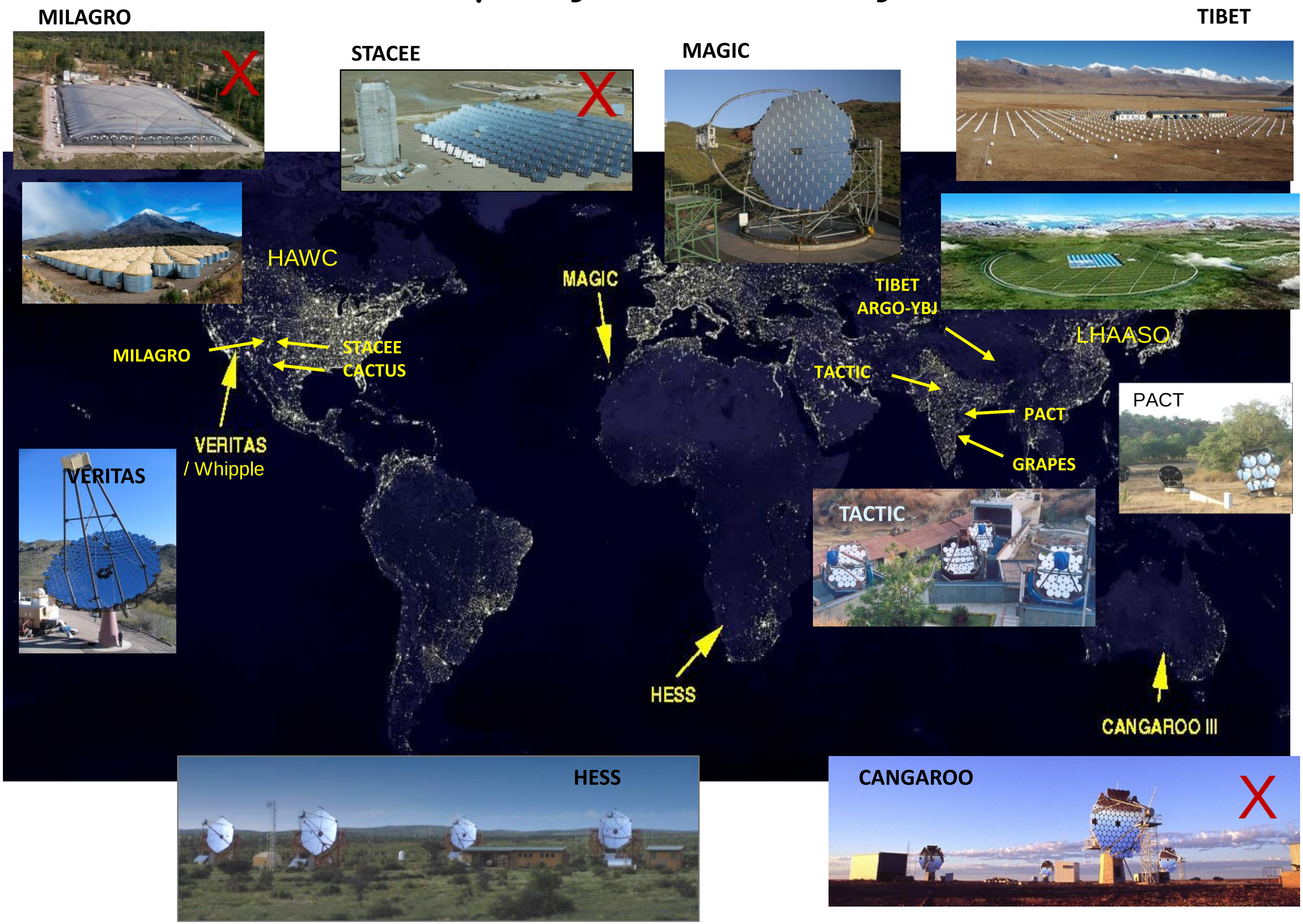




Due to the low intensity of fluorescence light, these instruments are only sensitive to showers of E > 10^{18} eV

Too high a threshold for γ-ray astronomy! (but good for CR studies)

Ground-based γ-ray astronomy in the World

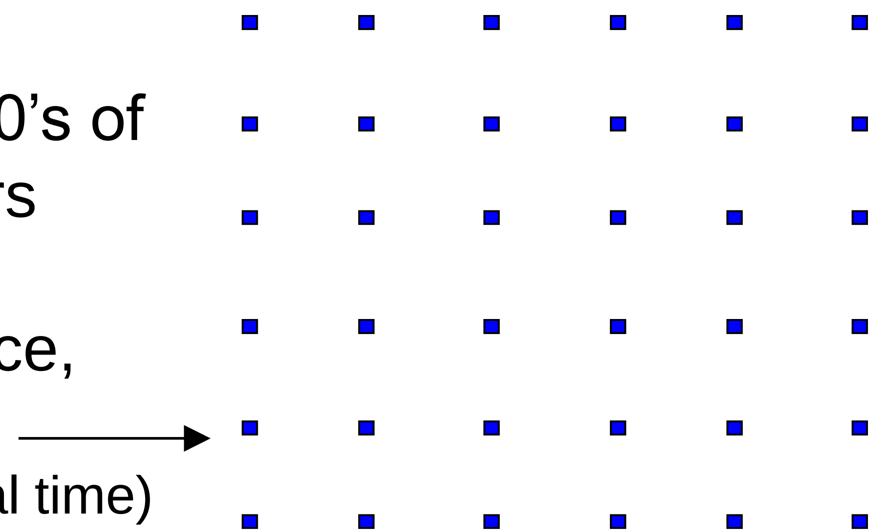


“Air Shower” detectors

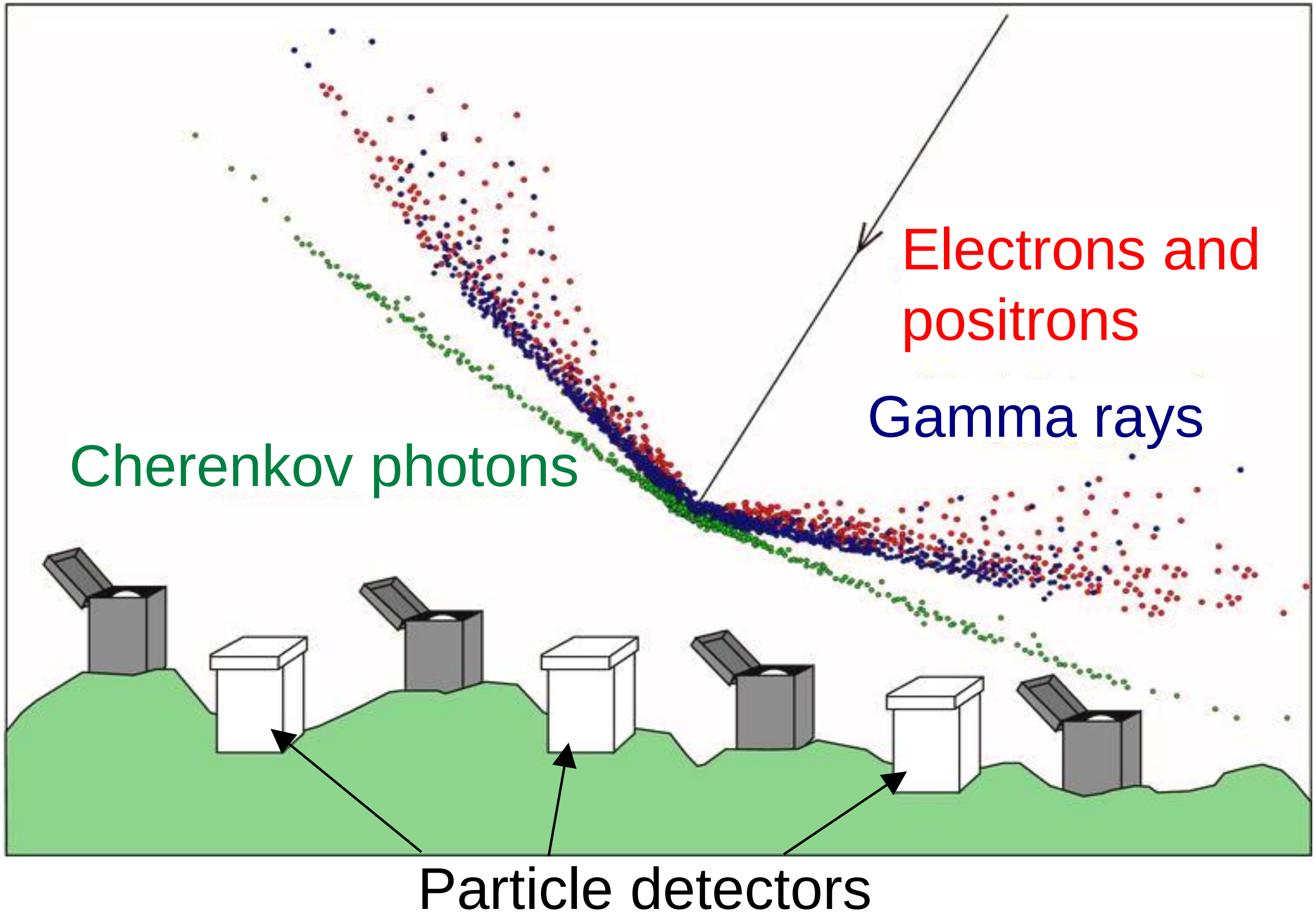
By this name we refer to instruments based on the *direct* detection of the shower secondary particles and gamma rays

By *direct* I mean that the $e^{\pm}$ and the secondary gamma rays actually enter the man-made artifacts (hence excluding atmospheric Cherenkov devices)

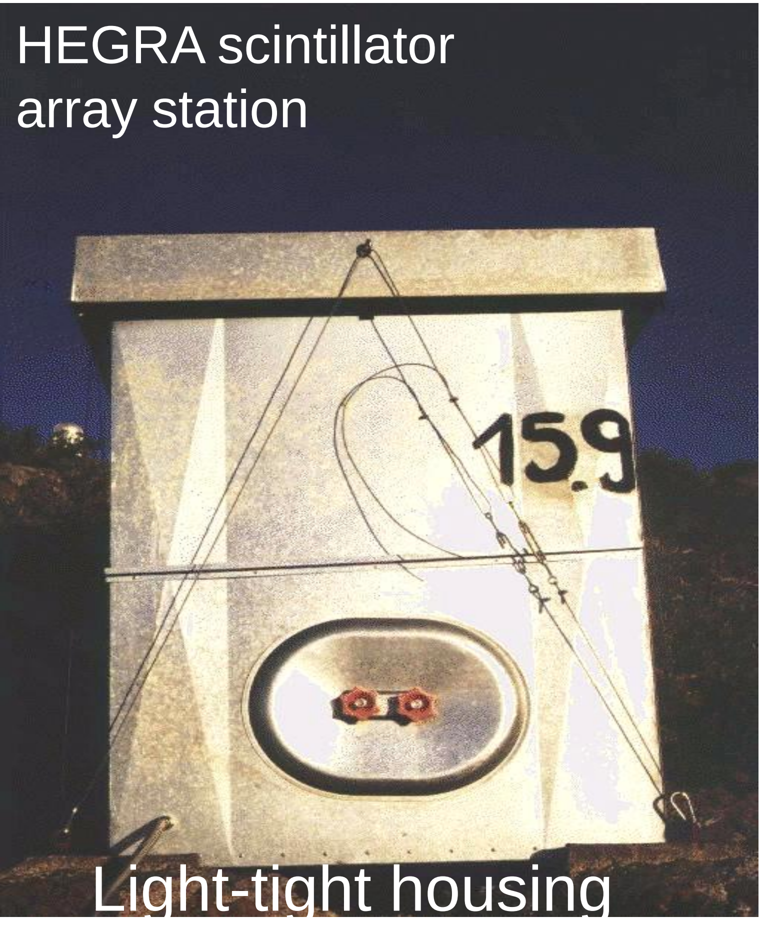
Typical air shower detector: array of ~100’s of ~1m^2 particle detectors spread over >10^4 m^2 operated in coincidence, measuring $\rho(x_i, y_i, t_i)$
(particle density and arrival time)

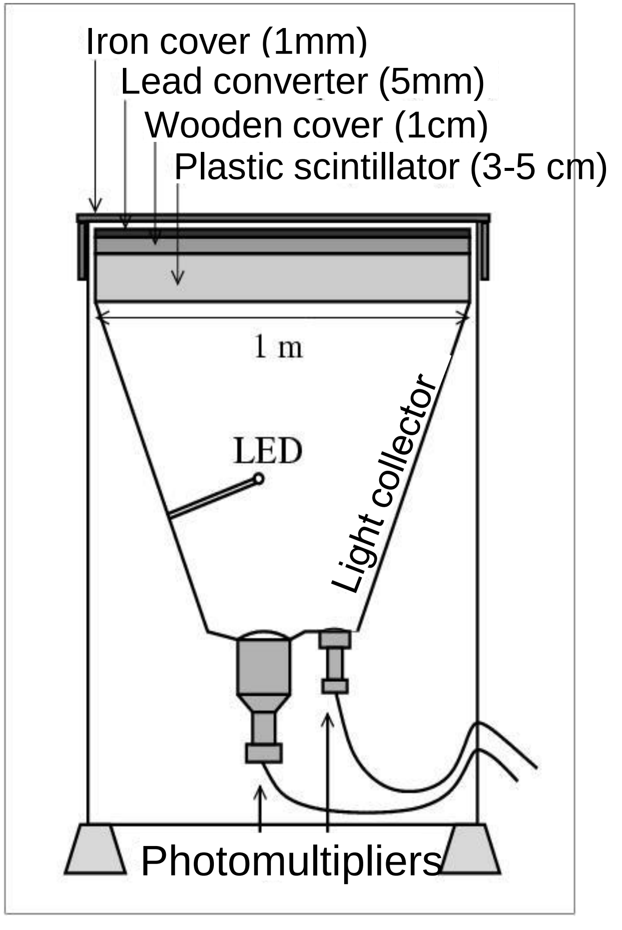


Air Shower arrays



Typical AS array detector station: Scintillator + PMT(s)





Measured light $\propto$ number of charged particles.

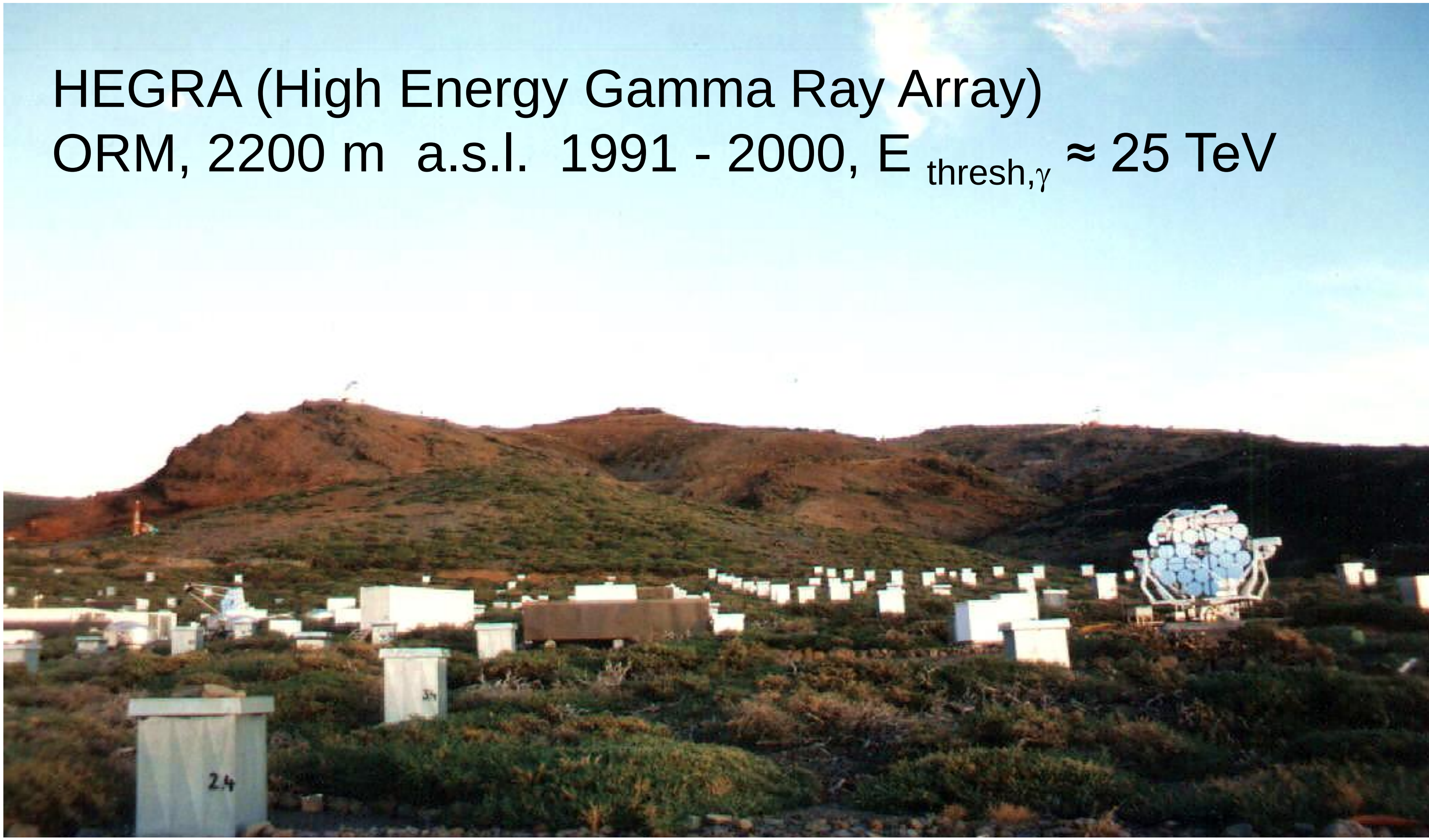
Led converter (~1 R.L.) to turn γ's into detectable $e^{\pm}$ pairs

Air Shower arrays

Common additional component of AS arrays: muon detectors, aiming at the discrimination of hadron-initiated showers through their muon content

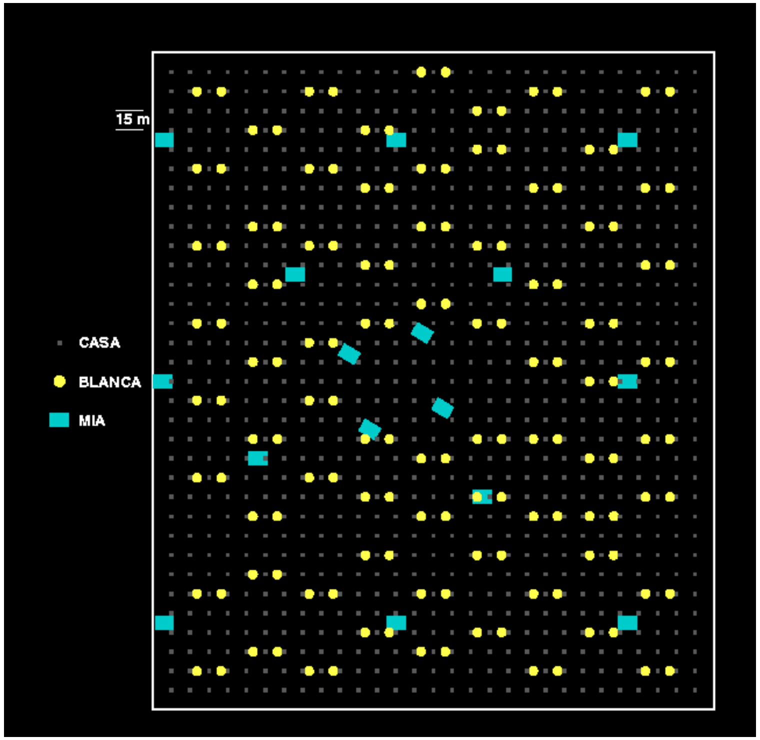
One just needs a particle detector protected from γ's and $e^{\pm}$ by a thick shield

The HEGRA scintillator array



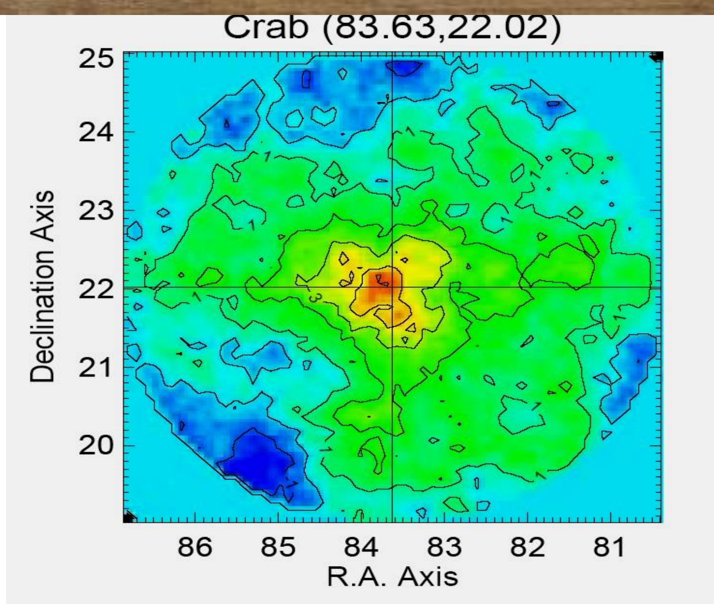
CASA-MIA

Ground array - Chicago Air Shower Array (Dugway, Utah)

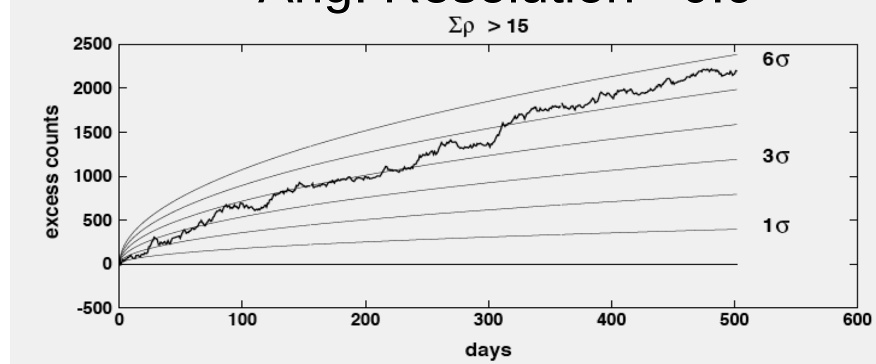


Tibet Air Shower array

4300 m a.s.l., Yangbajing



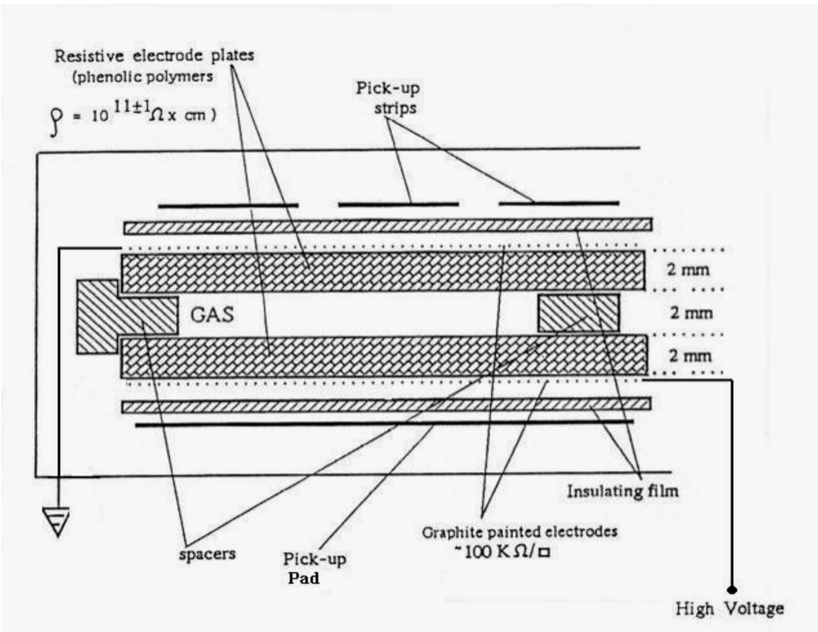
Ang. Resolution ~0.9˚



1999: Crab detection above 3 TeV (5.5 σ) in 500 days

ARGO-YBJ

Going further down in E: better coverage of the detection area

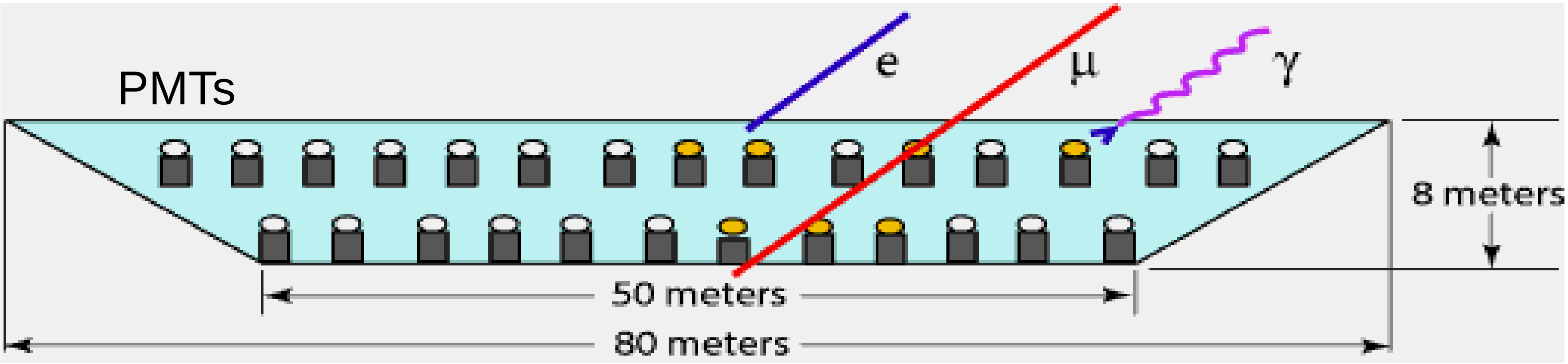


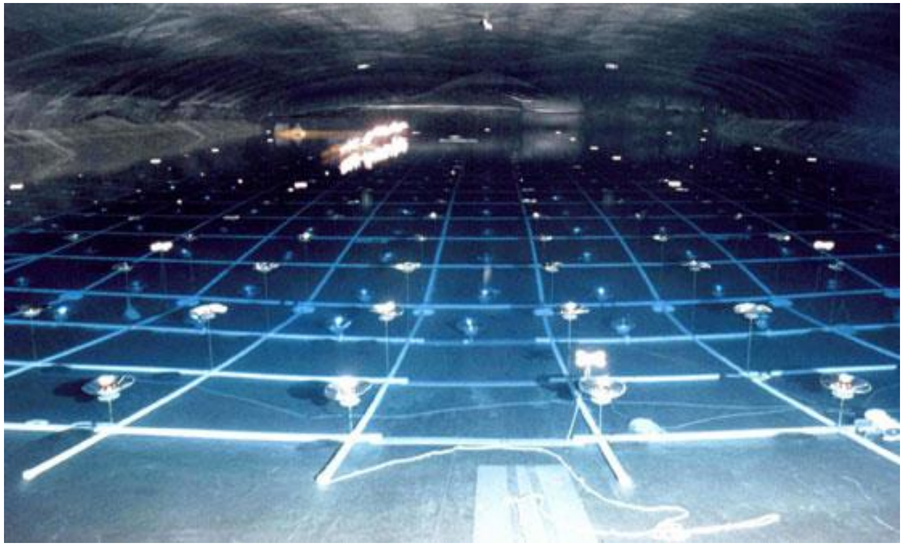
Resistive Plate Chambers (RPCs) are gaseous ionisation detectors with parallel resistive electrodes
Good time and spatial resolution

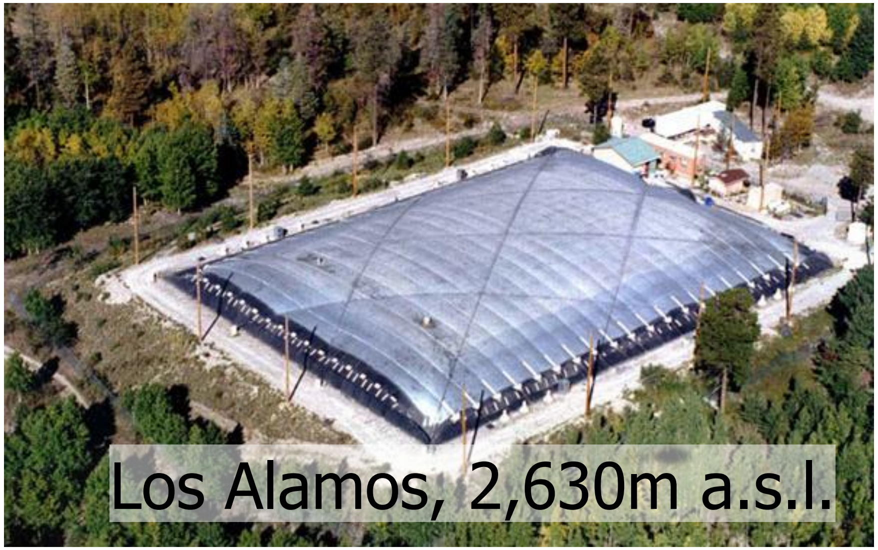
4300 m a.s.l., Yangbajing

MILAGRO (moved to → HAWC)

Achieves full coverage in a different way: Cherenkov light emission in water







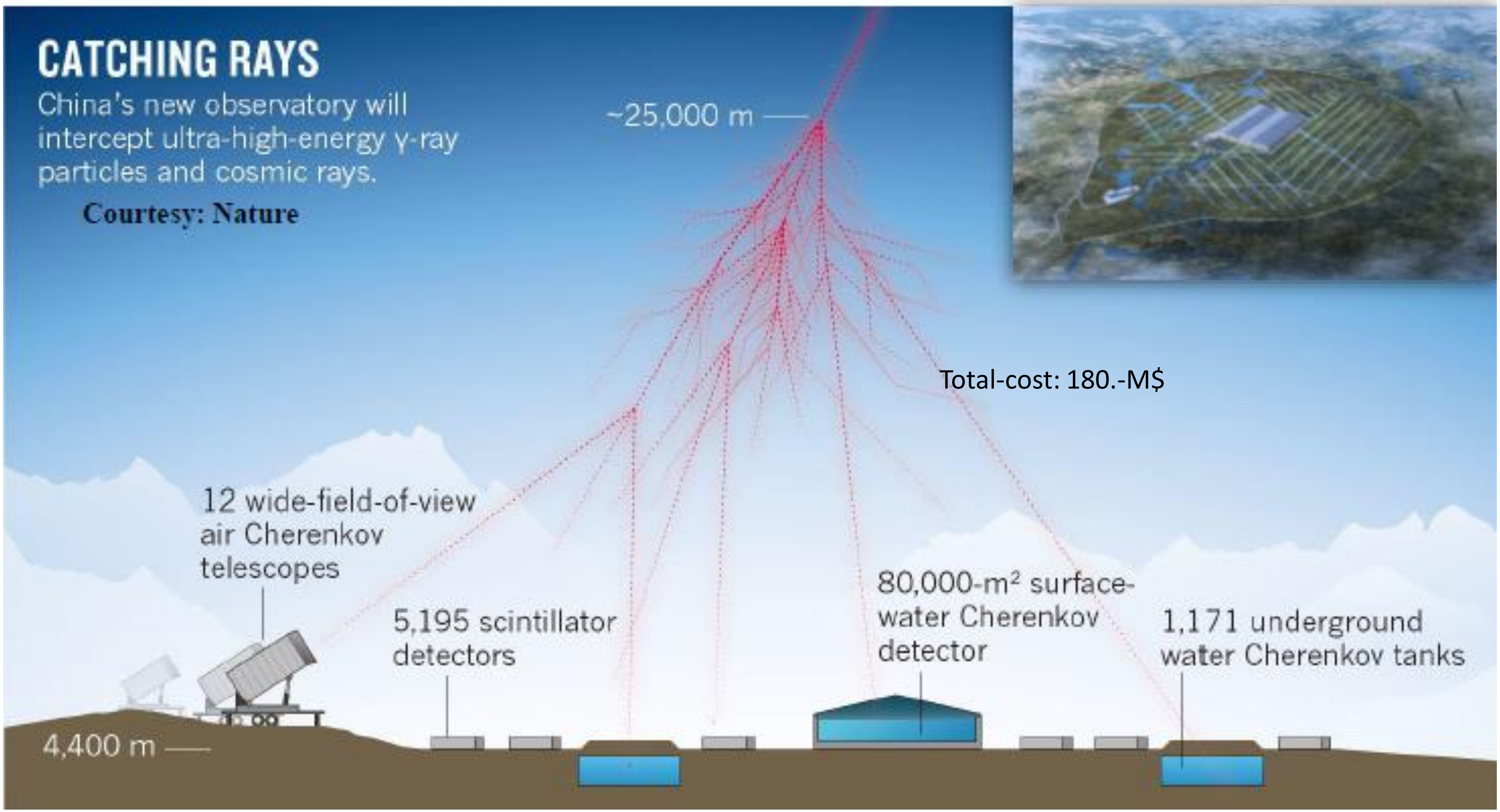
HAWC

HAWC

HAWC is located at an altitude of 4100 meters on the slope of the Volcanoes Sierra Negra and Pico de Orizaba at the border between the states of Puebla and Veracruz in Mexico.

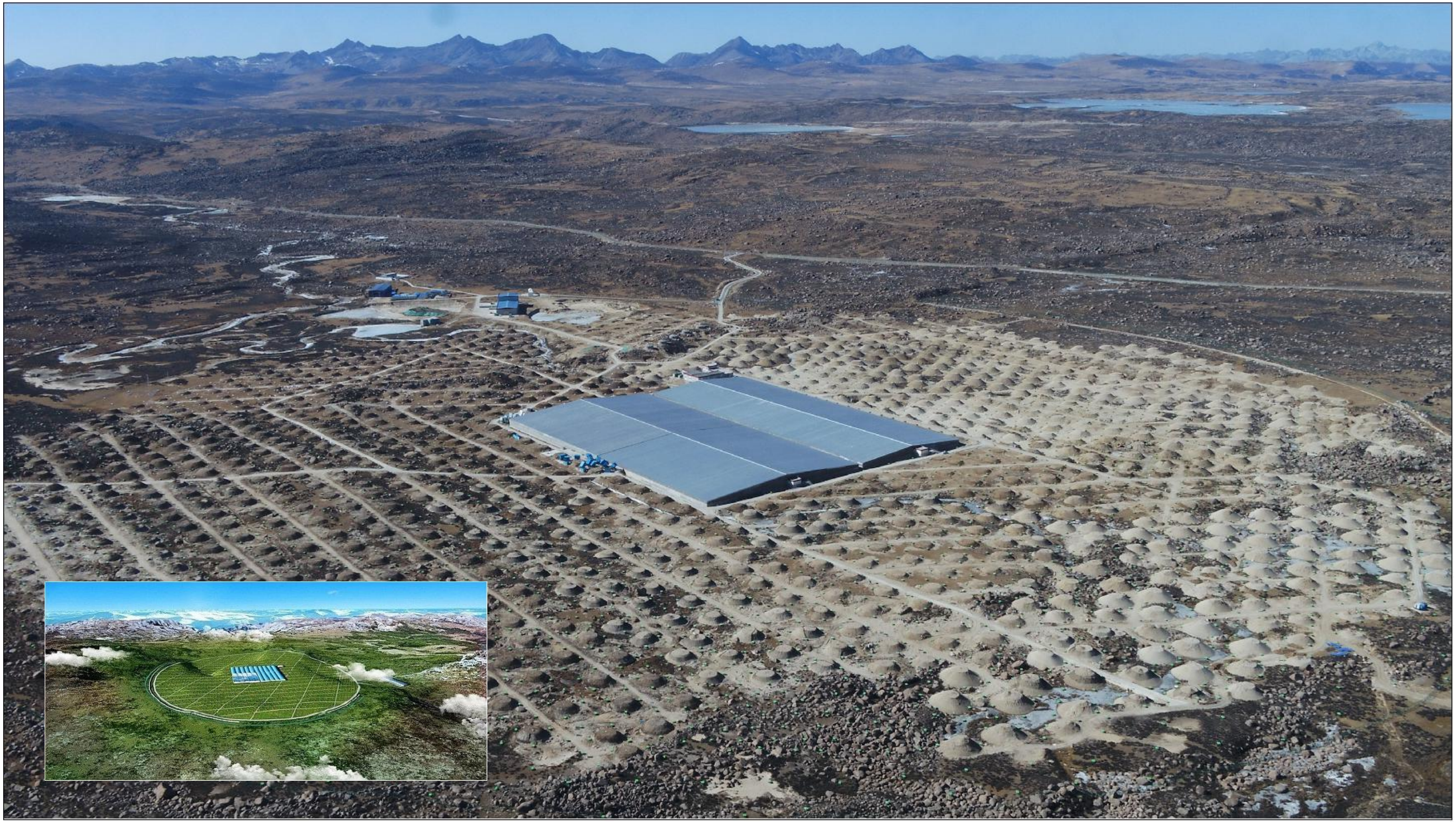
Currently all 300 Cherenkov detectors are deployed and taking data. Each Cherenkov detector consists of 180,000 liters of extra pure water stored inside an enormous tank (5 meters high and 7.3 meters in diameter) with four highly sensitive light sensors fixed to the bottom of the tank

Hybrid Detection of EASs by LHAASO



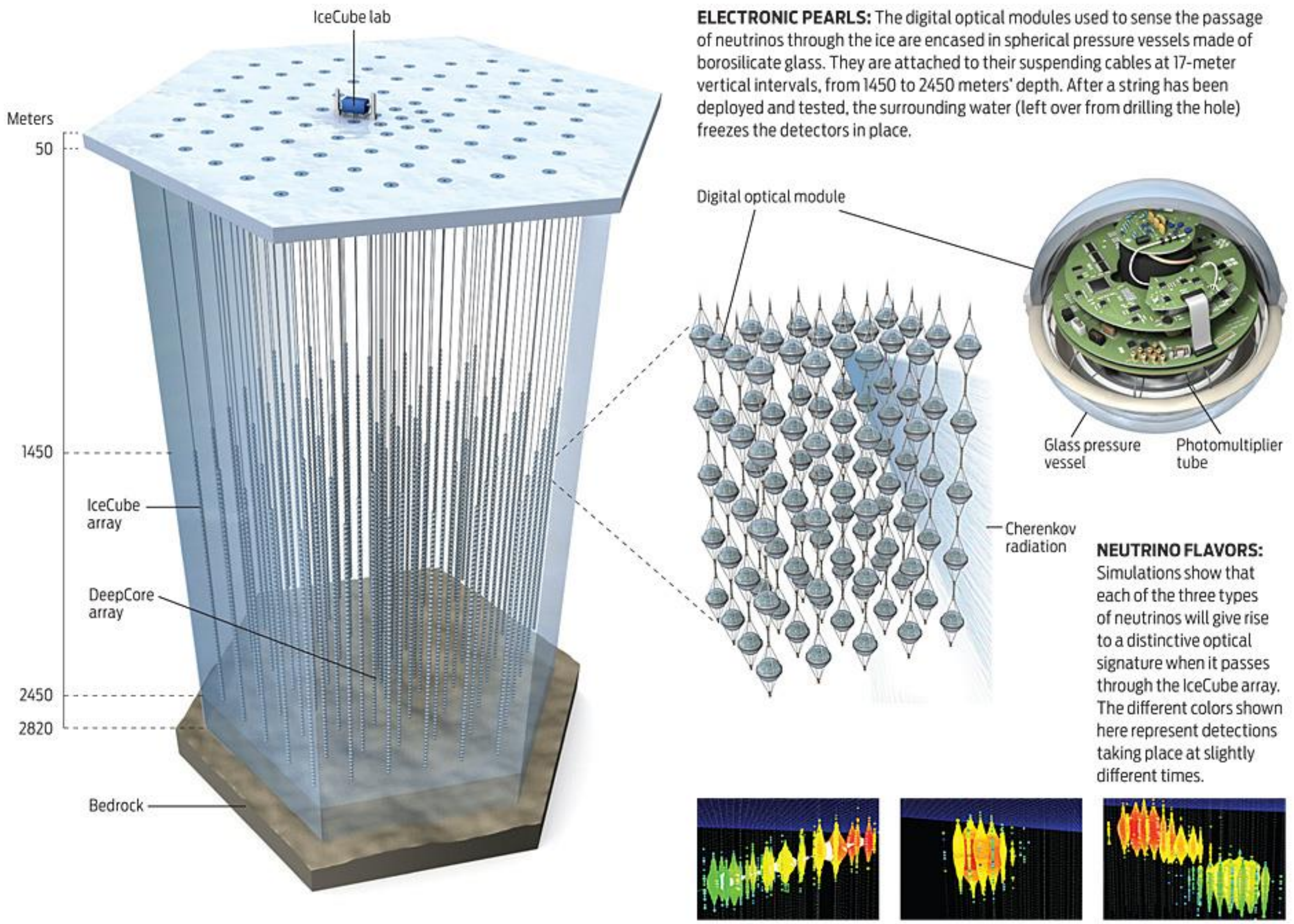
LHAASO in China

Last couple of years LHAASO discovered several tens of PeVatrons

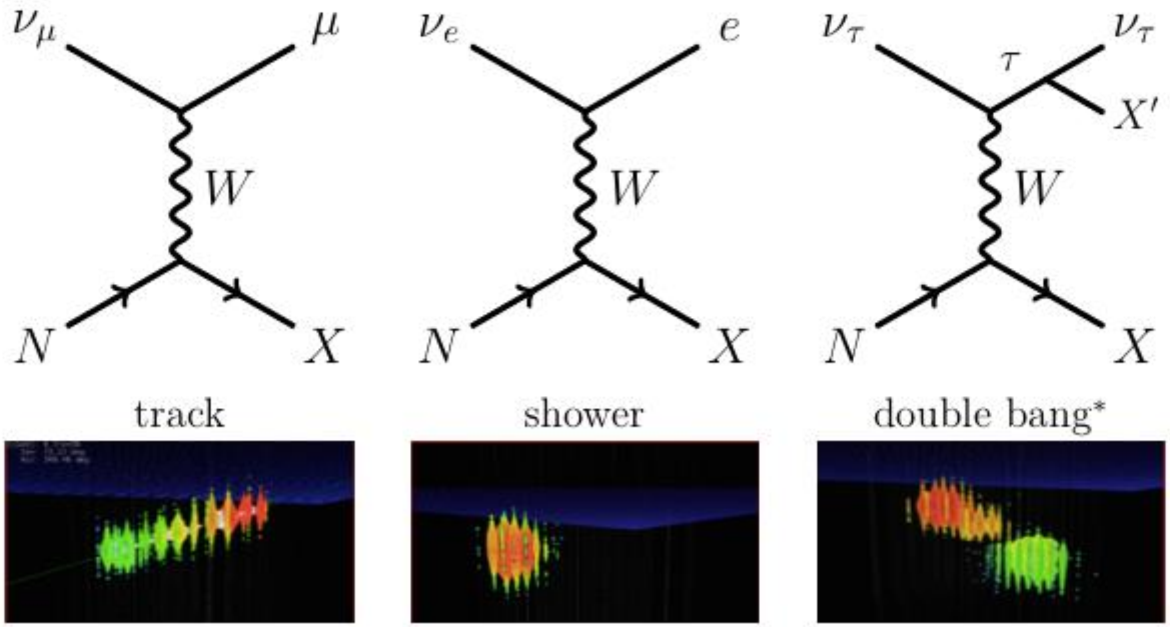


Inauguration of HAWC, Mexico, 20.03.15

IceCube detector at South Pole



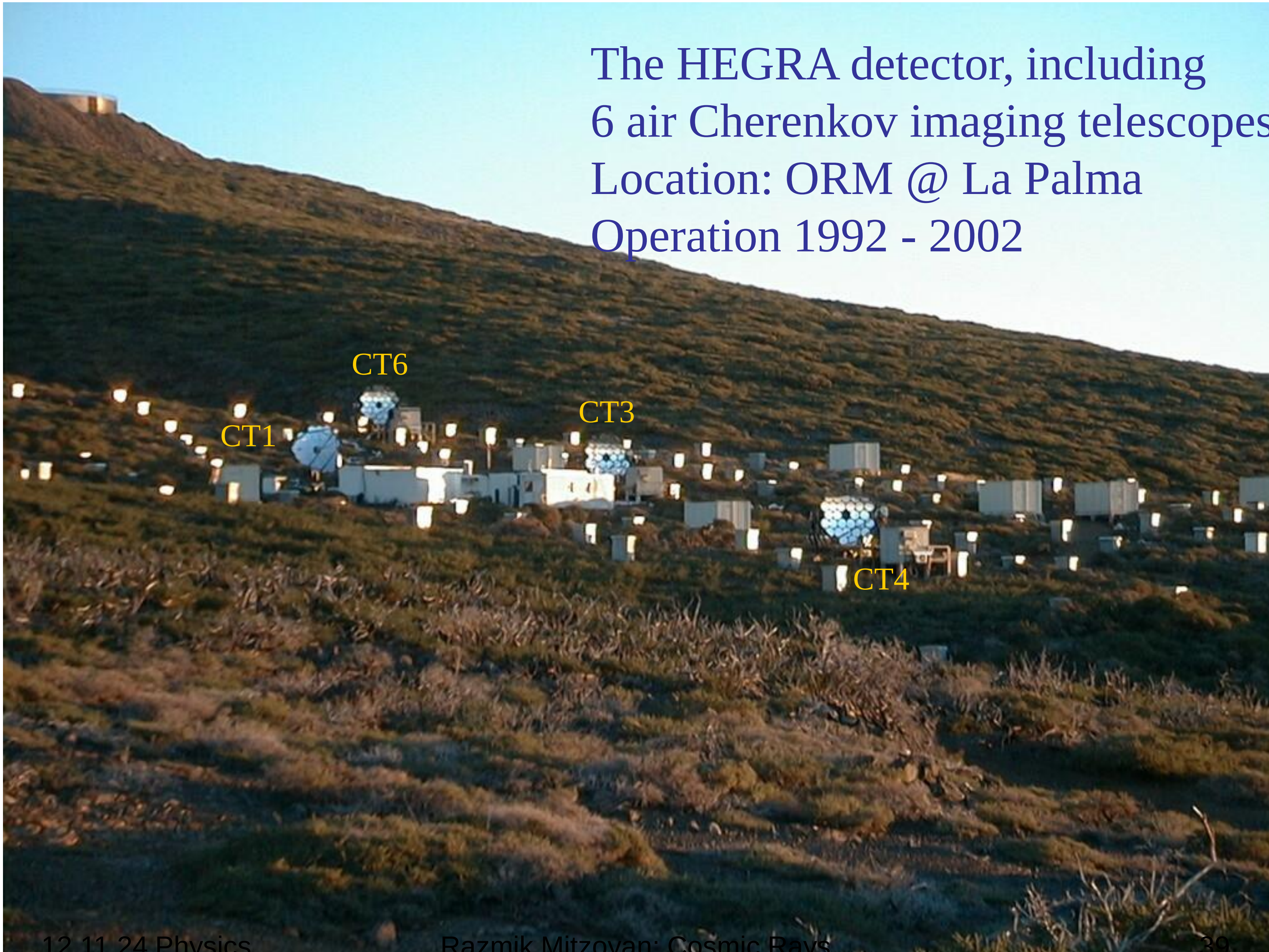
Neutrino interactions



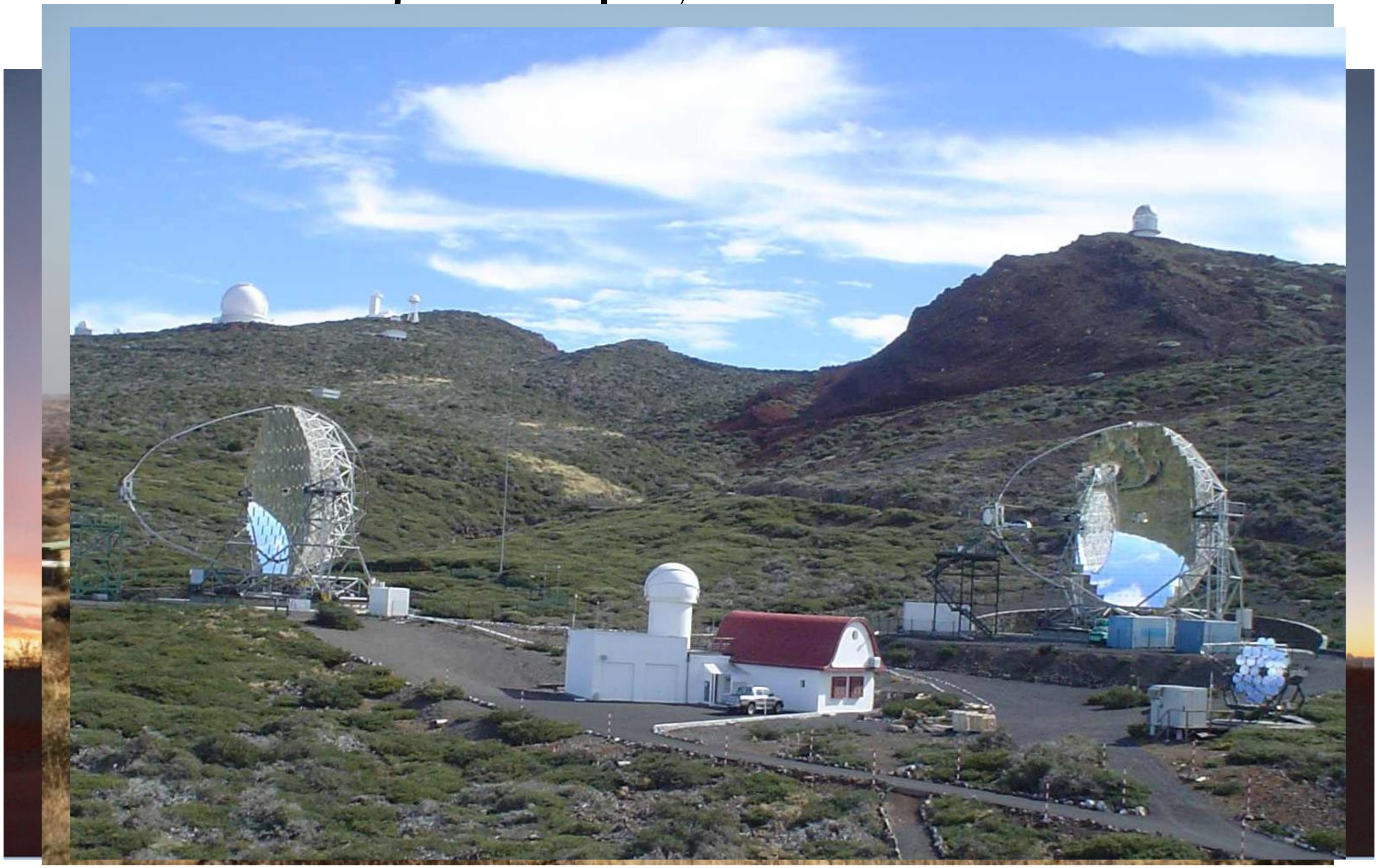
The 1st telescope (of 5 planned) we´ve built: 1989

Nor Amberd cosmic ray Station, mount Aragats, 2000 m a.s.l., Armenia

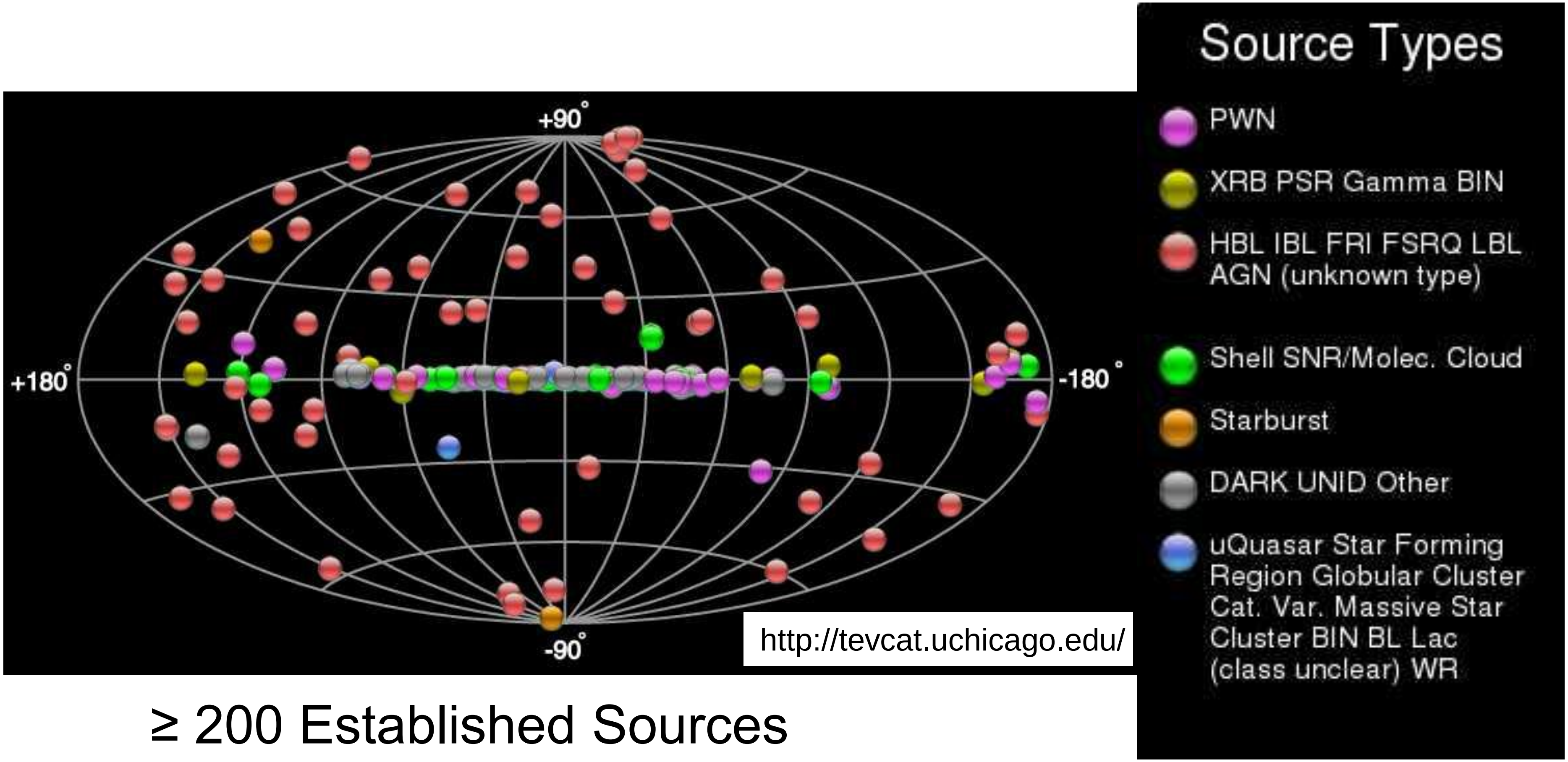
The HEGRA detector, including
6 air Cherenkov imaging telescopes
Location: ORM @ La Palma
Operation 1992 - 2002



VERITAS, H.E.S.S. & MAGIC: pushing the VHE γ-astro-physics to its limits



Today's VHE γ–ray Sources in the Sky



≥ 200 Established Sources

Outlook : the next 5-7 years

Next generation VHE γ ray Observatory: CTA

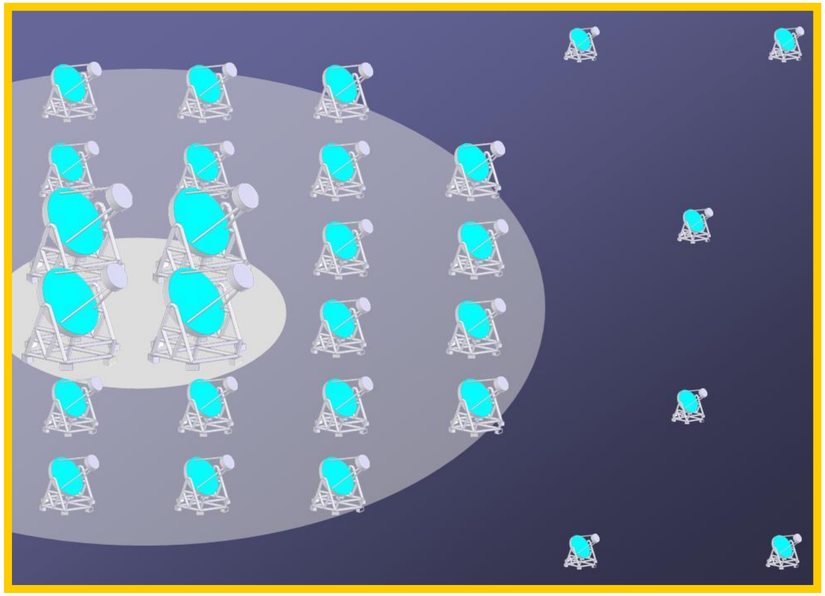
MAGIC

HESS Phase II

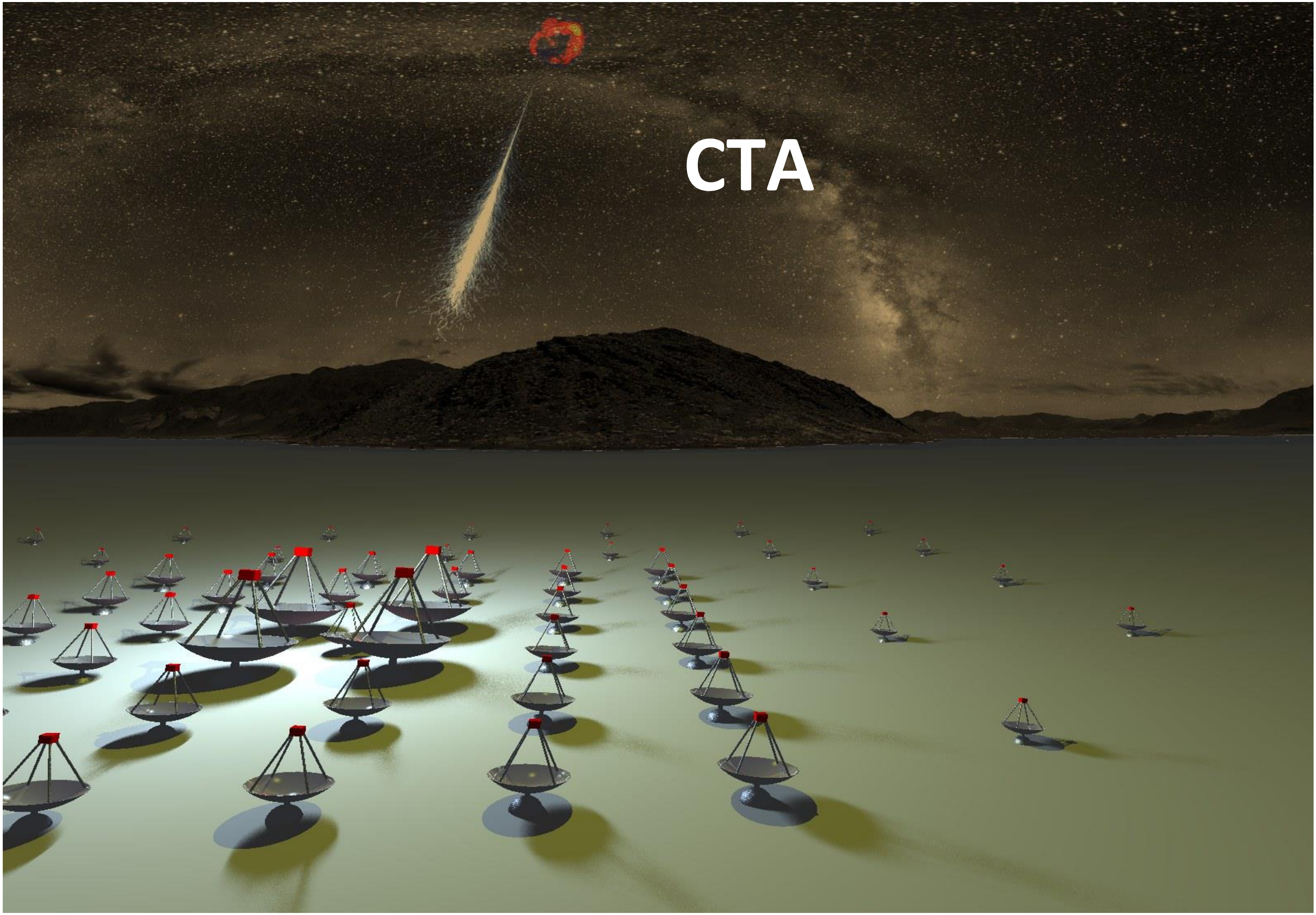
CTA

>1500 scientists
~130 institutions

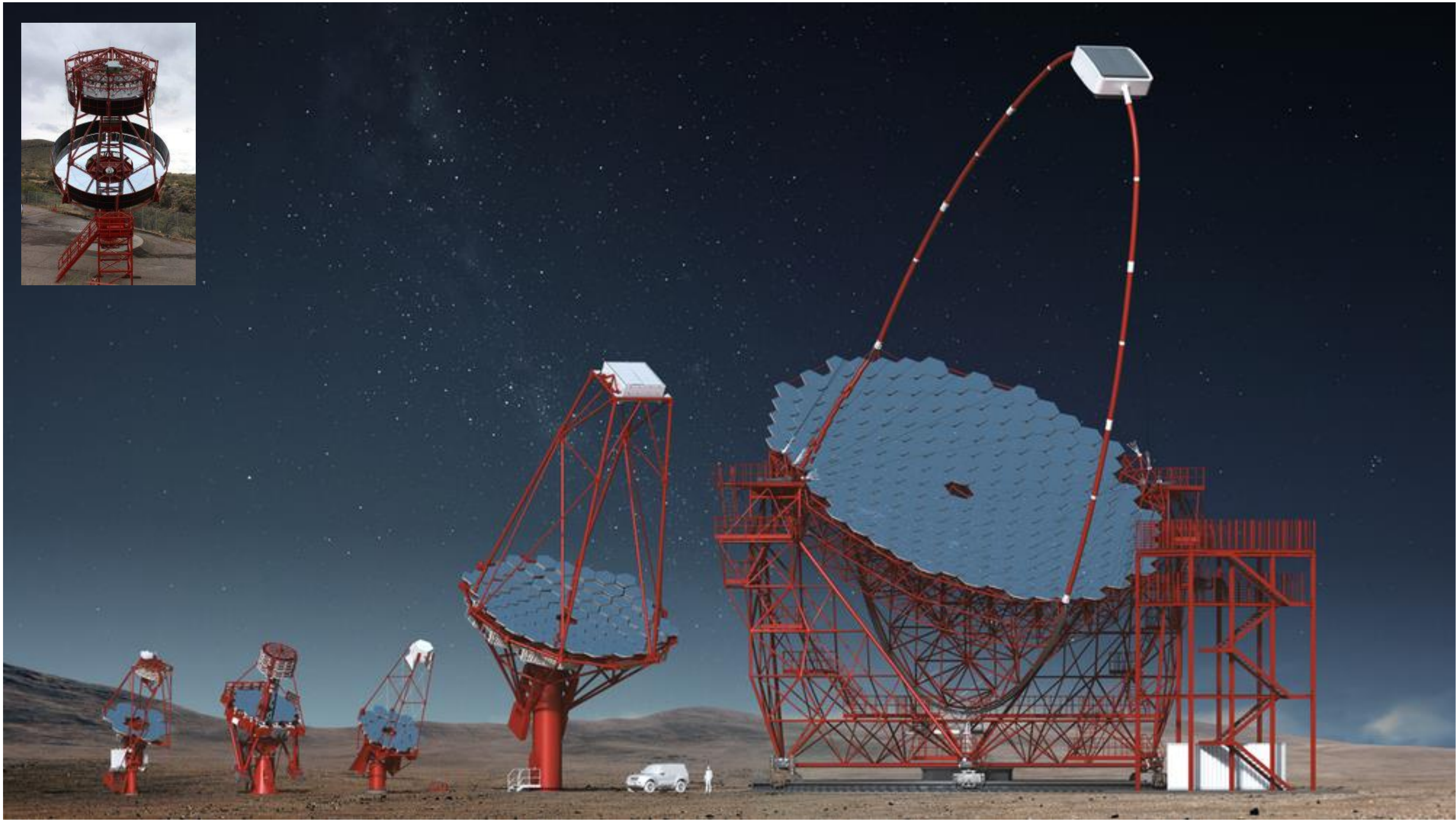
Cherenkov Telescope Array
~1000 sources will be discovered



EU, US, JAPAN, India, Brazil,…


CTA

Cherenkov Telescope Array



The 1st 23m diameter LST (between 2 MAGICs) of CTA is in the end phase of commissioning