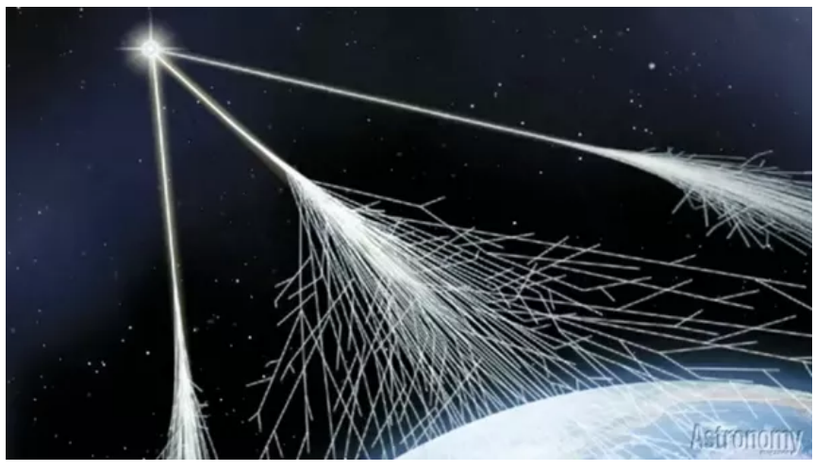
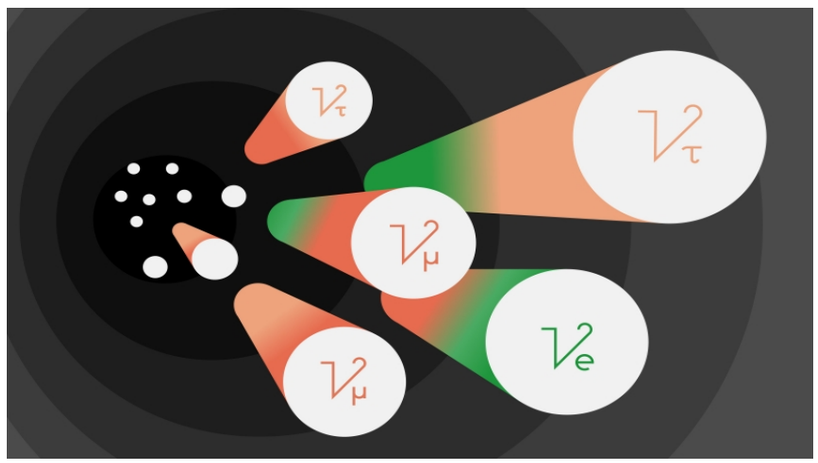
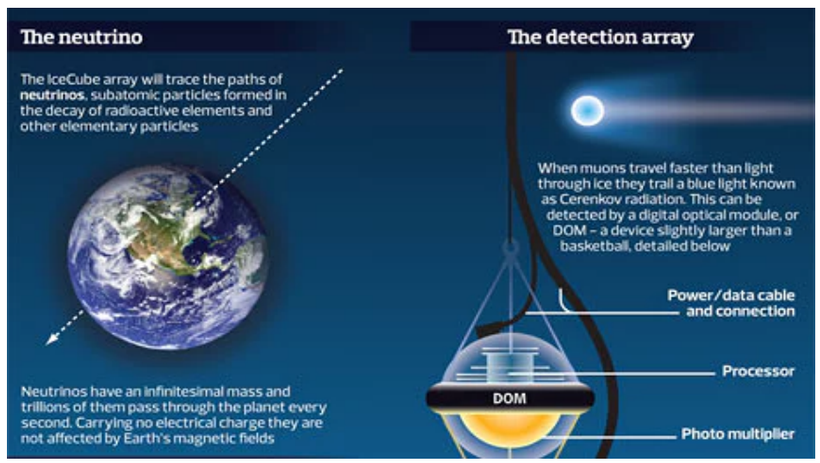
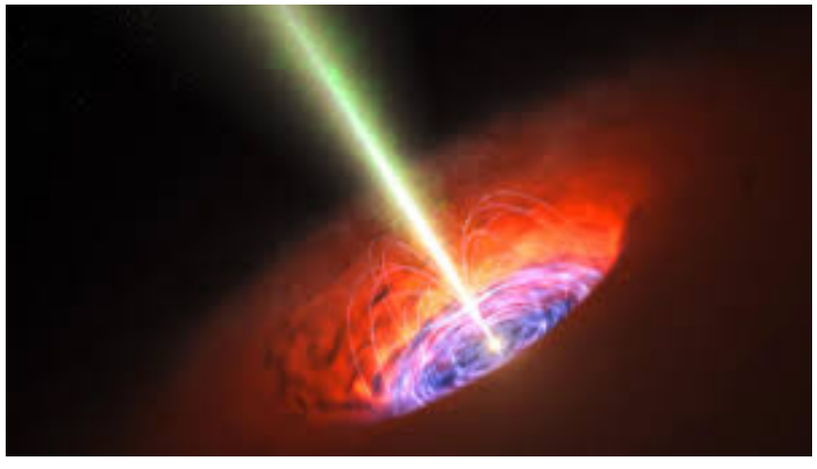
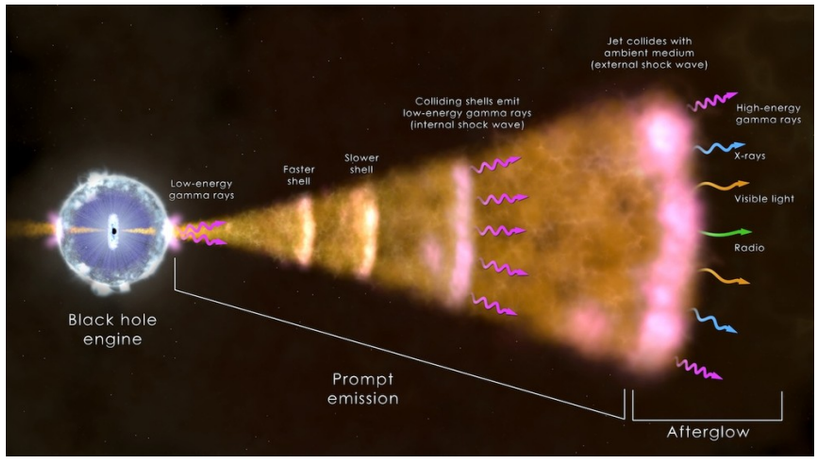
High Energy Universe
Cosmic Rays & Neutrinos & Gamma Rays

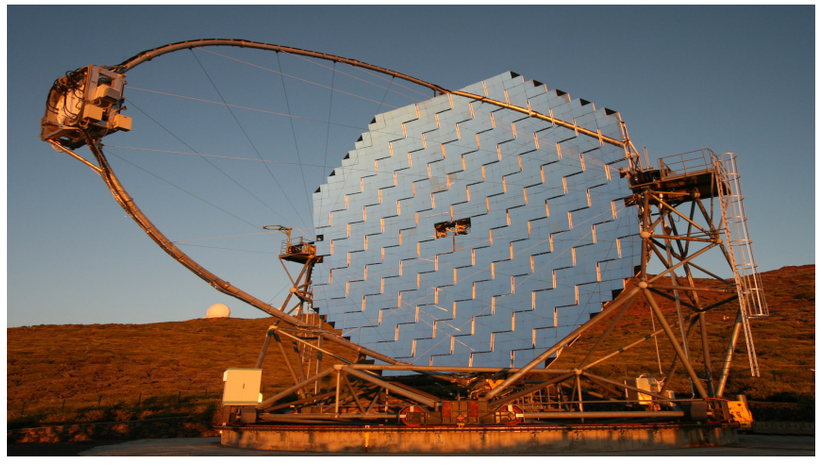












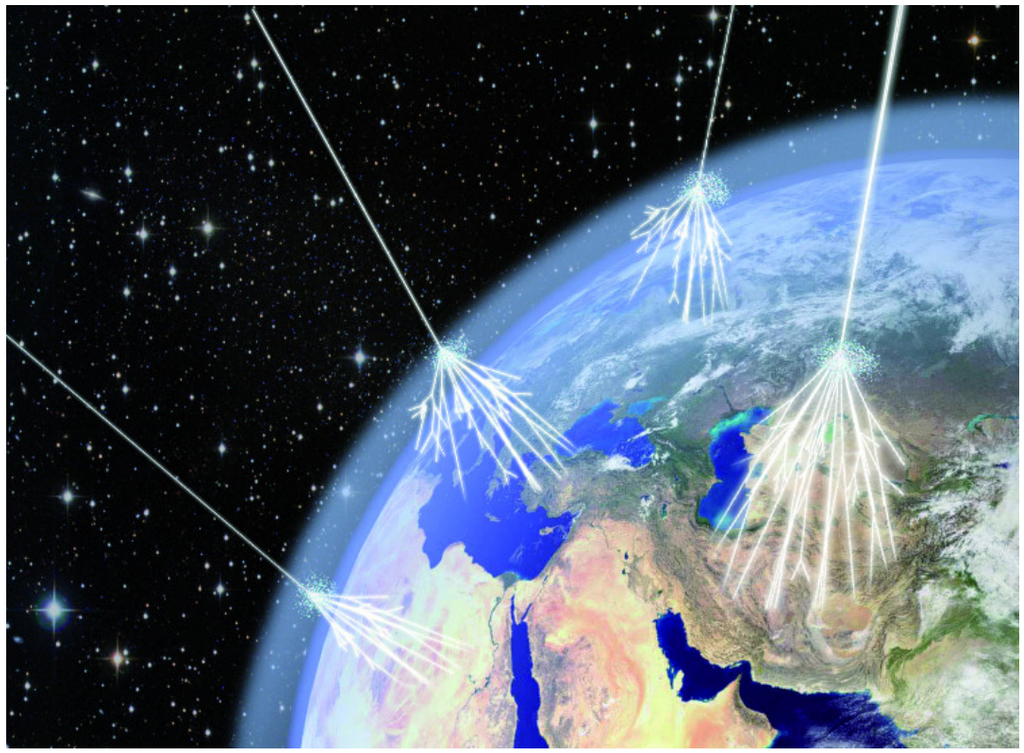
Debanjan Bose [debaice@gmail.com]

Lecture 1 [10.04.2019]

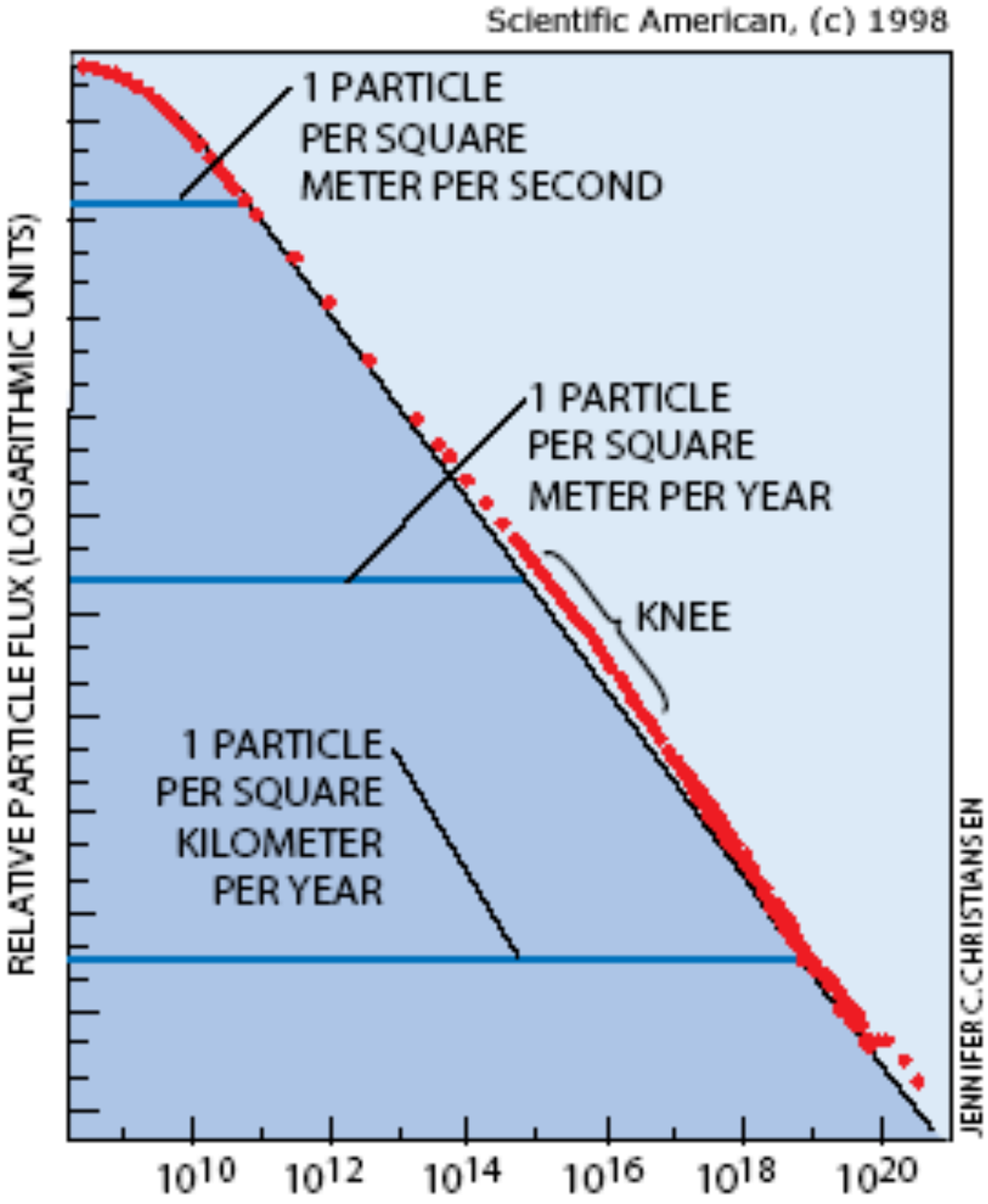
In Three Lectures I will Cover

- Cosmic Rays : Where it all started
- Motivation to study high energy Universe
- Messengers at high energy regime : Cosmic rays, Neutrinos, Gamma rays
  - Gamma-ray Astronomy from ground
  - Neutrino Astronomy from ground

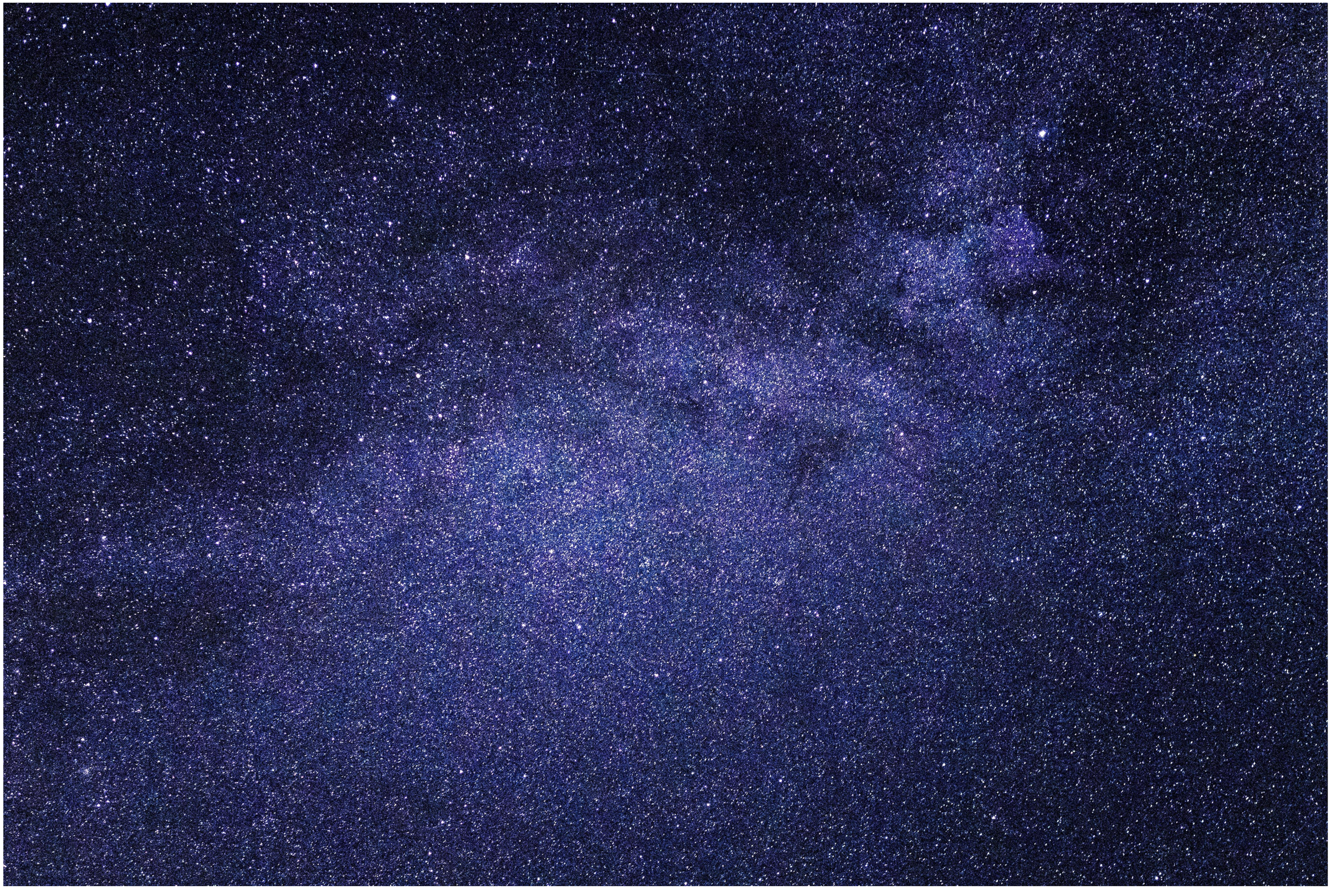
Cosmic Rays : Beginning



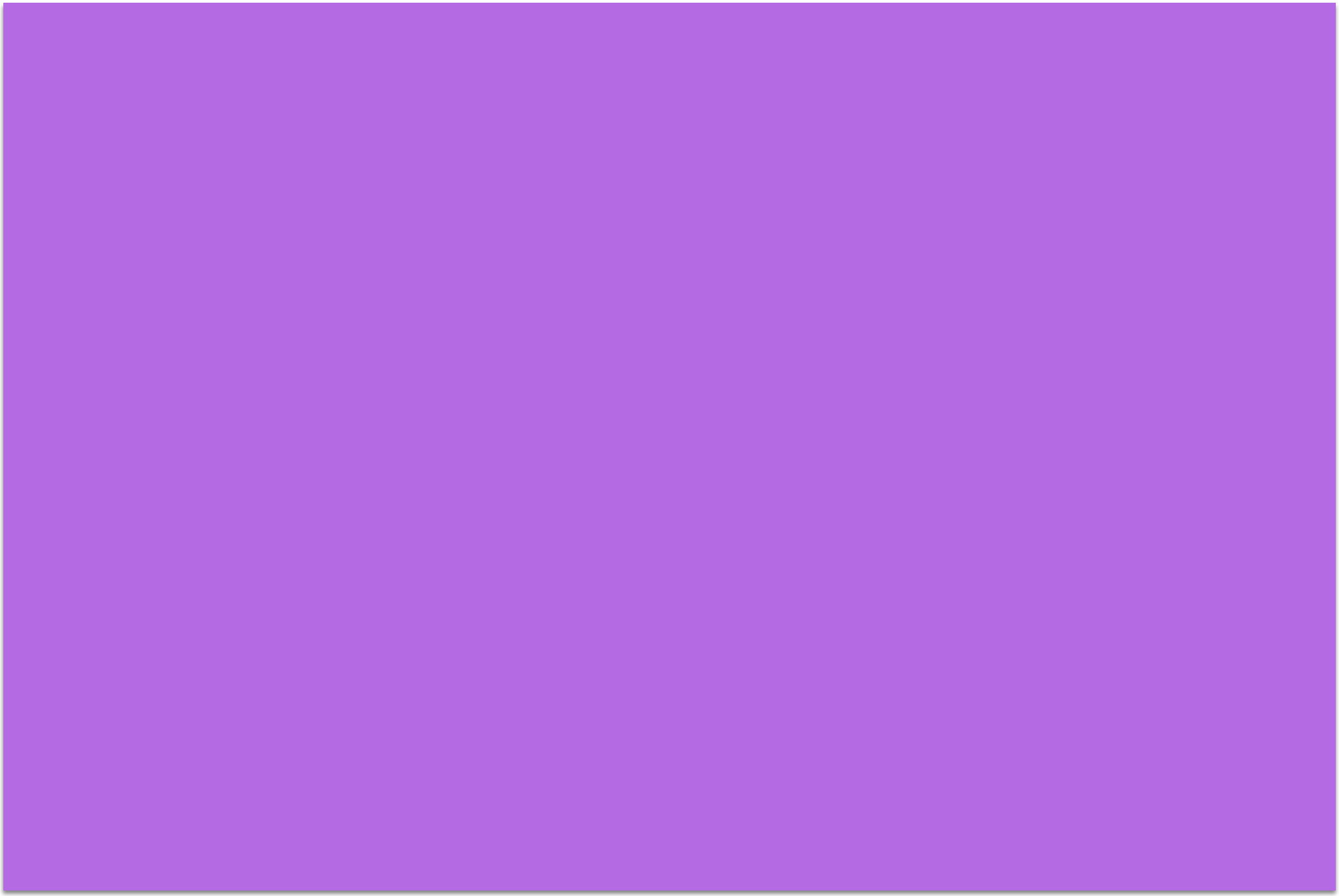
Earth is Continuosly Bombarded by
Cosmic Rays (mostly Particles)
Almost Isotropically



Starry Sky

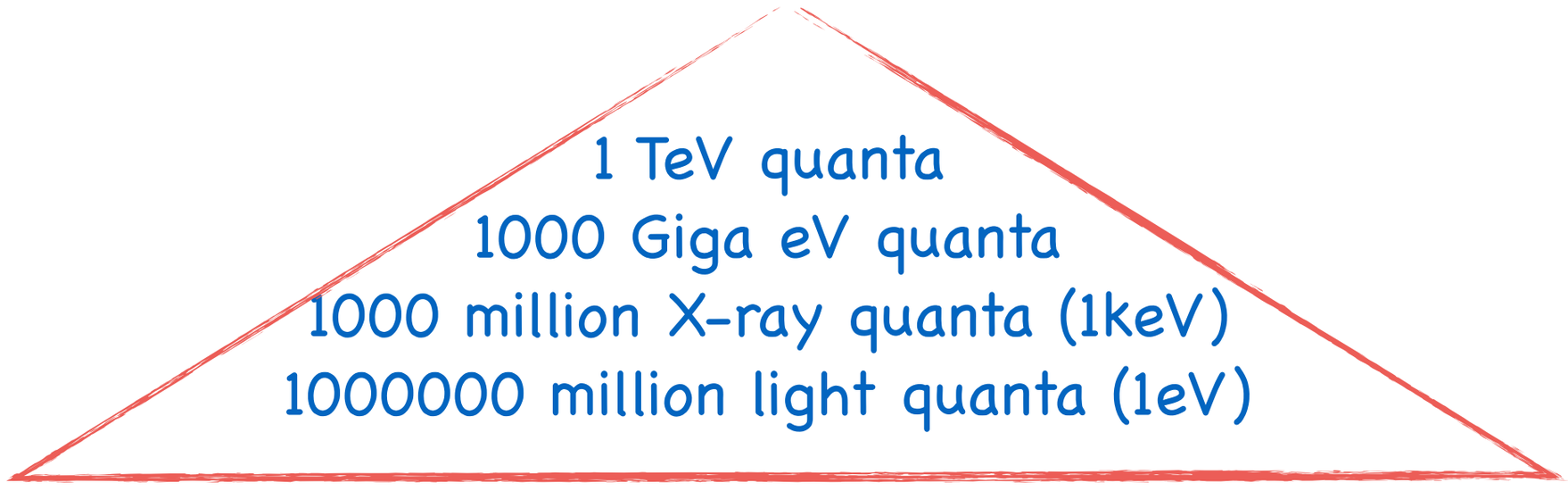


Cosmic Ray Sky



Why So few @ So High Energies

1 erg of energy approximately 10^{12} eV



1 Cosmic Ray Particle 10^{18} eV ->
Energy carried by a tennis ball moving at 100 km/h

Cosmic Rays Discovered More than 100 years Ago !

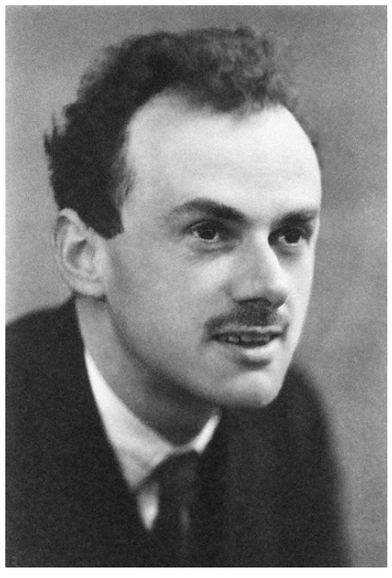
7 April 1912

- Victor Hess flew on a Ballon 18000 feet with a gold leaf electroscope
- He noticed radiation steadily increases
- He concluded they are coming from outside
- Won Nobel Prize on 1936

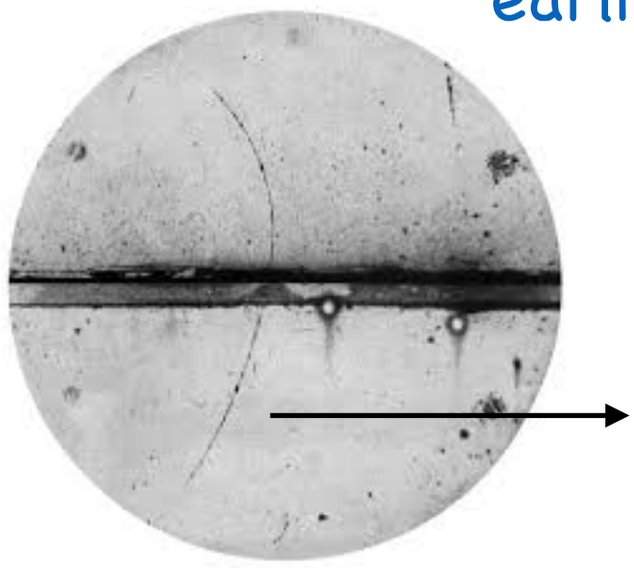
Discovery of Antimatter

Carl Anderson
Nobel prize 1936

Paul Dirac
Nobel Prize 1933



Anderson experimentally confirmed existence of antimatter (1932). Dirac earlier had predicted their existence (1928) .

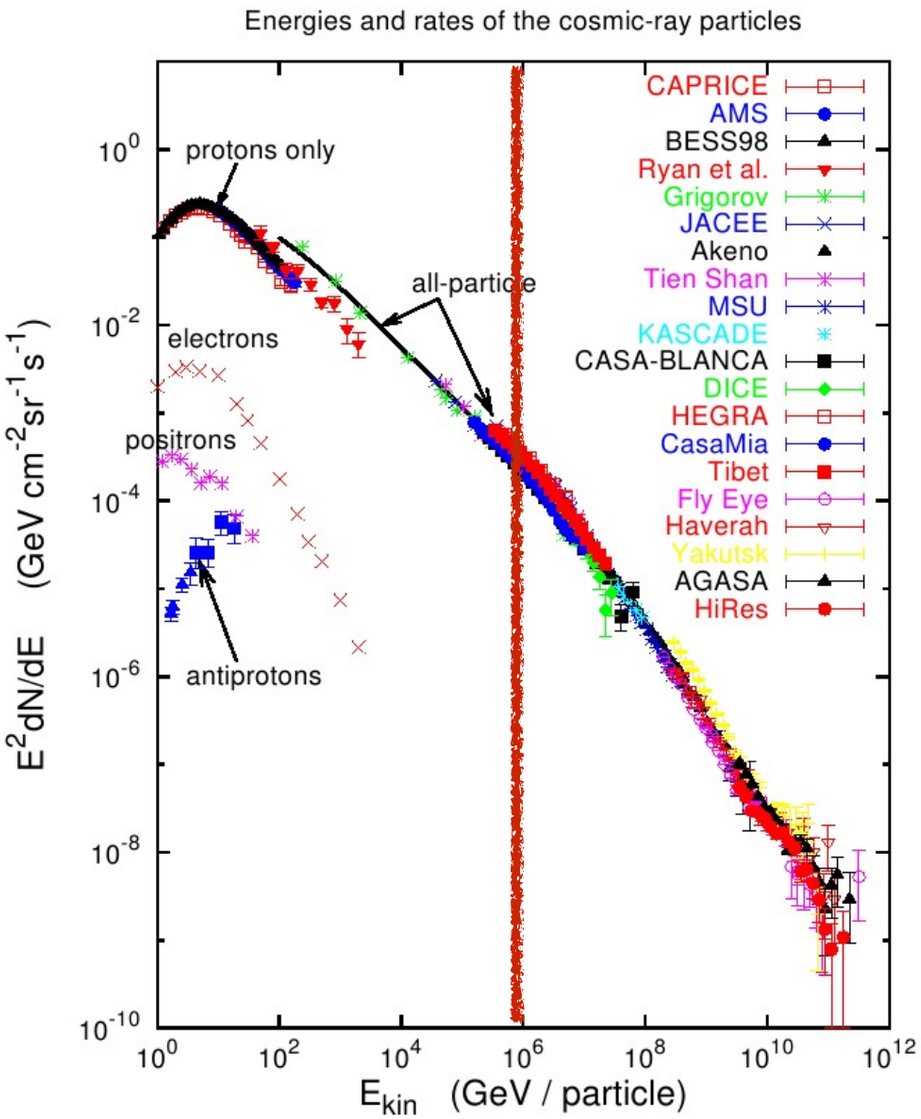


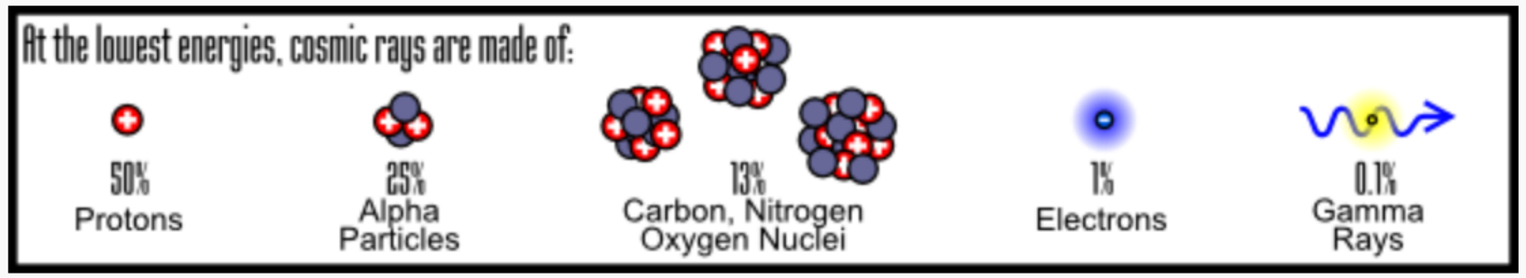
Track of Positron

Before the inventions of particle accelerators, CRs and their interactions were only source of information aboout elementary particles

Muon, Pion, Kaon, Lambda

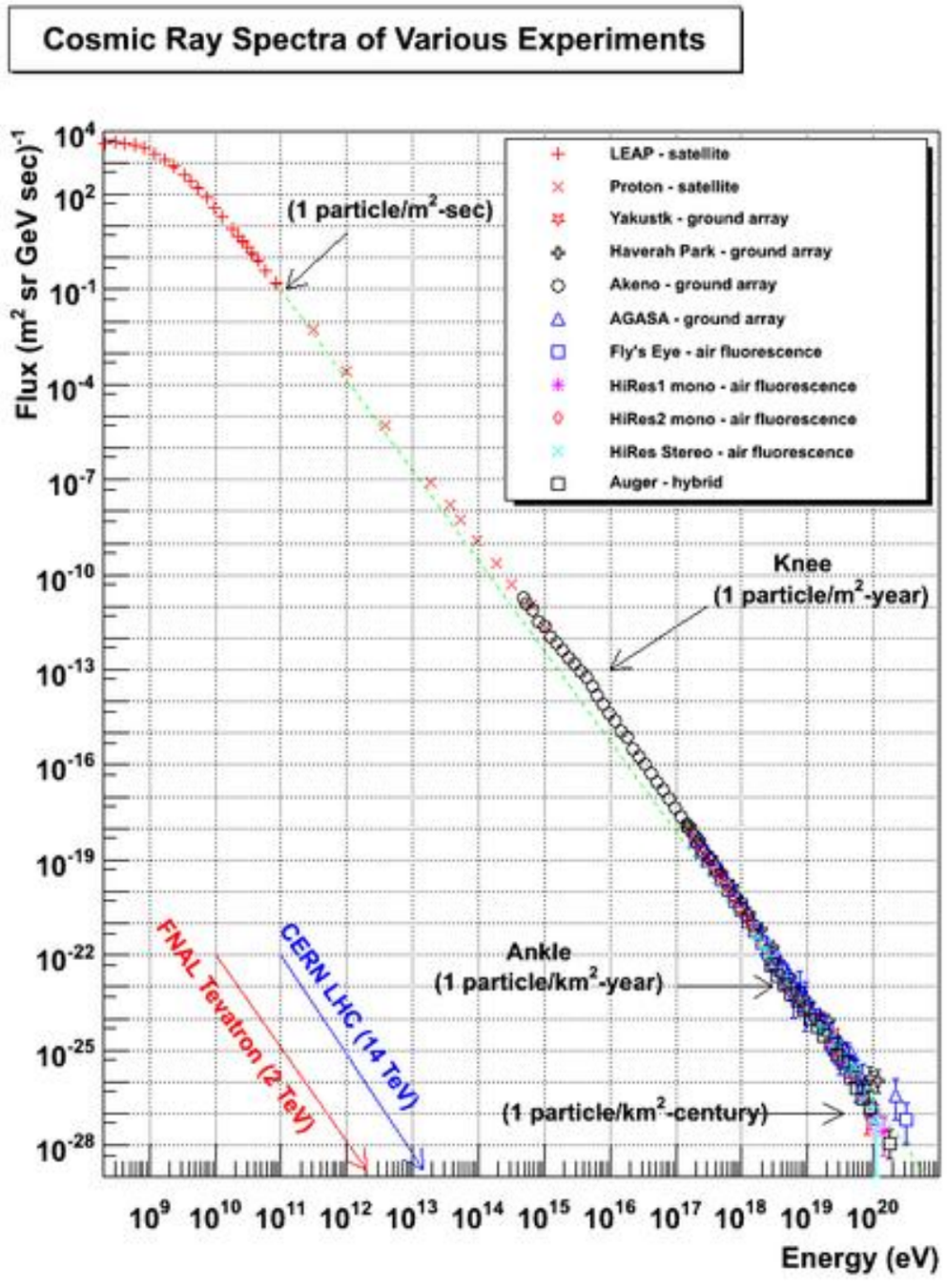
Composition of Cosmic Rays





Beyond 10^{15}eV it is not possible to measure CR spectrum directly. Measurements depends on Extensive Air Showers produced in the Atmosphere by Incident CR. Thus Composition studies has big uncertainties.

Cosmic Rays Spectrum



- 10 GeV to 1 PeV slope is -2.7 ("knee")
- 10 PeV to 1 EeV slope is -3.1 ("ankle")
- Above 10 PeV slope is -2.6

Below 10^{15} eV Galactic origin

Above Extra-Galactic

Since Most of the Cosmic Rays are Charged Particles their Origin not Known !!

Solar Wind : Low Energy Cosmic Rays

- Sun produces constant stream of particles (electrons & protons) of low energy [10 keV]
- Except a very small fraction rest are all deflected by Earth's magnetic field and absorbed in the upper atmosphere
- These particles have enough energy to ionise various gases in the upper atmosphere - Auroras

We will not discuss about Solar Wind in this Lecture Series

Study of HE Cosmic Rays : Study of Relativistic Universe

- Non-Thermal Universe
  - Thermal vs Non-thermal
- Understanding the Origin and Role of Relativistic Cosmic Particles
  - Where they are produced, How they are produced, What role they play
- Probing Extreme Environments
  - What happens close to NS/BH, Understanding relativistic jets

Acceleration Mechanism

What properties of cosmic rays must an acceleration mechanism explain :

A power law energy spectrum for particles of all types:

$$\mathrm{d}N(E) \propto E^{-x}\mathrm{d}E$$

The exponent x is usually in the range of $\sim$2.2–3.0.

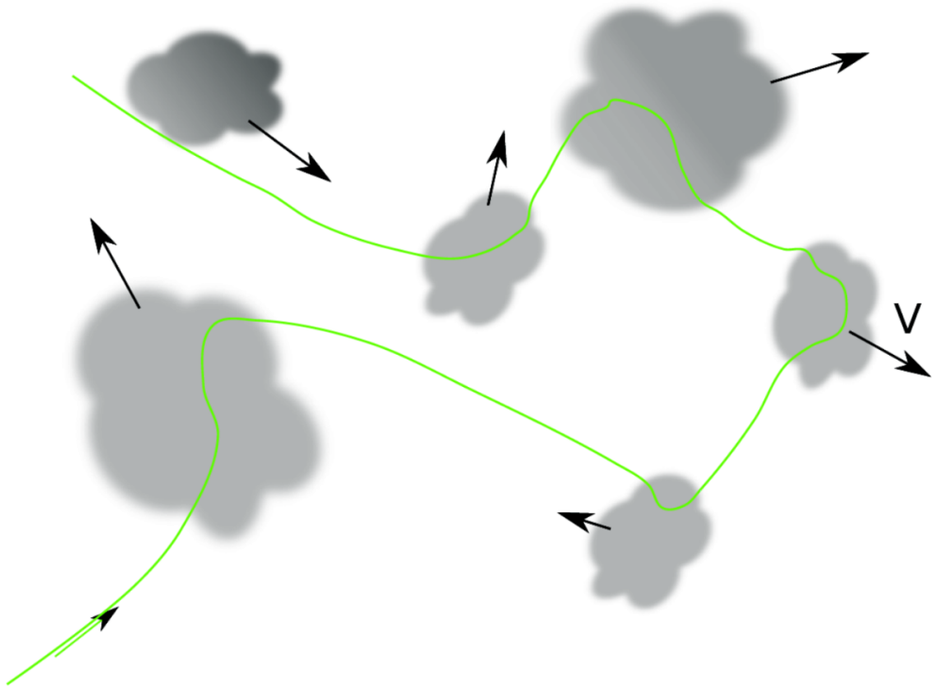
The acceleration of cosmic rays to maximum observed energies

- For galactic cosmic rays, energies up to the knee: $\sim 10^{15}$ eV
- For extragalactic cosmic rays, energies beyond the ankle: $\sim 10^{20}$ eV

Fermi Second Order Acceleration Mechanism

Fermi (1949) proposed a model for acceleration in which particles can statistically gain energy through collisions with interstellar clouds

- Original model led to second order acceleration: $\frac{\Delta \mathcal{E}}{\mathcal{E}} \propto \left(\frac{V}{c}\right)^2$
- By assuming a characteristic escape time, τ_{esc}, this results in a power law distribution of particle energies

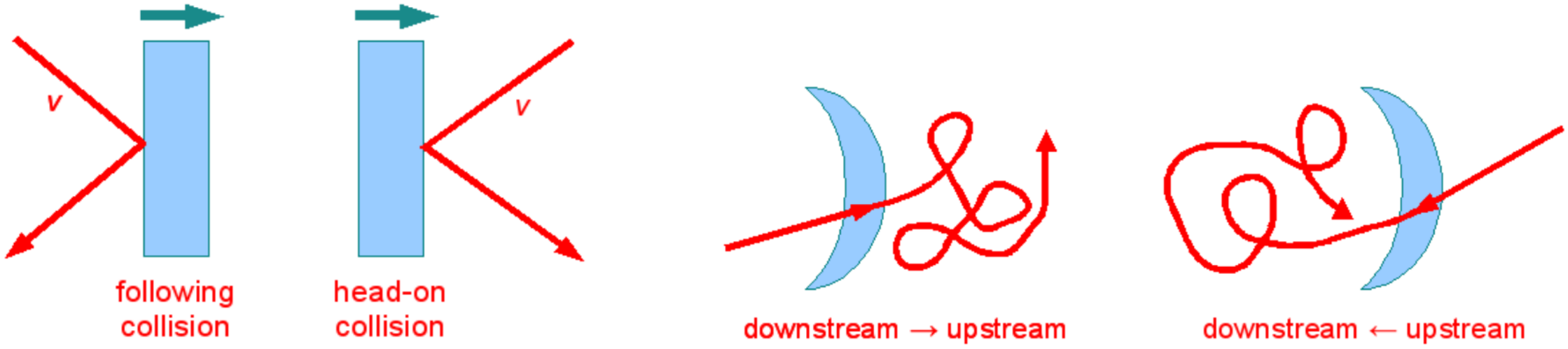


In the rest frame of the cloud, particles will be scattered elastically (only direction changes, energy constant).

In lab frame, as clouds are moving particle gains energy (from K.E. Of cloud)

Our galaxy filled with highly variable magnetic fields.

Fermi Acceleration Mechanism



(a) Second-order Fermi acceleration. **(b)** First-order Fermi acceleration.

(a)

$$\left\langle \frac{\Delta E}{E} \right\rangle = \frac{8}{3}\left(\frac{v}{c}\right)^2$$

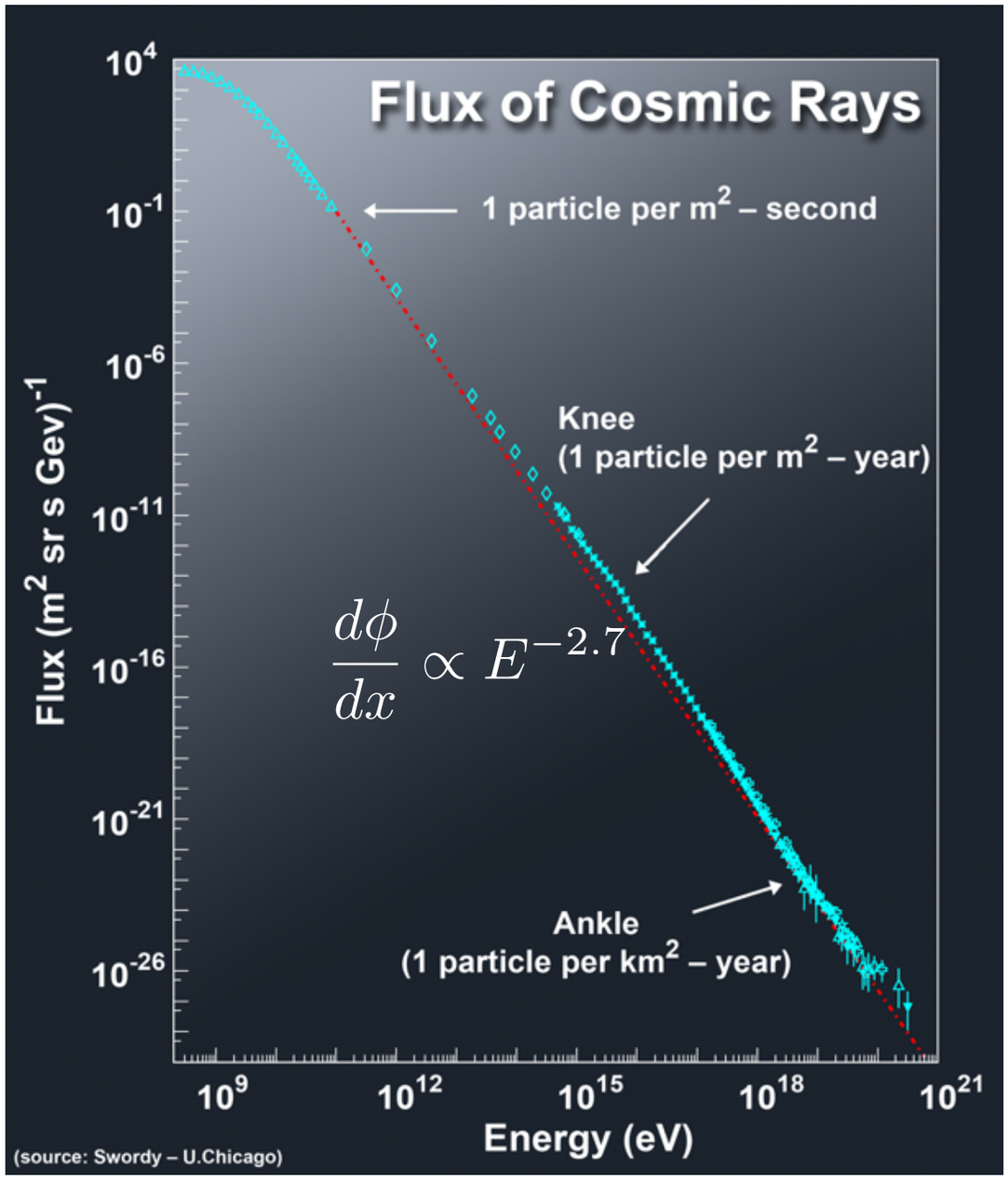
$$N\left(E\right) dE = \text{const.} \times E^{1+\frac{1}{\alpha \tau_{\text{esc}}}}\, dE$$

(b)

$$\left\langle \frac{\Delta E}{E} \right\rangle = \frac{4}{3}\left(\frac{v}{c}\right)$$

$$N\left(E\right) dE = \text{const.} \times E^{-2}\, dE$$

Cosmic Ray Propagation



Expected

$$N(E)\,dE = \text{const.} \times E^{-2}\,dE$$

CR particles produced in the Galaxy are trapped by the galactic magnetic field

$$\tau_{esc} \propto E^{-0.6}$$

Where τ_{esc} is the escape time of CR In the Galaxy

$$\frac{dN}{dE}_{obs} \propto \frac{dN}{dE}_{src} \times E^{-0.6}$$

where $\frac{dN}{dE}_{obs}$ and $\frac{dN}{dE}_{src}$ are the energy spectra of the CRs at the origin and near the earth.

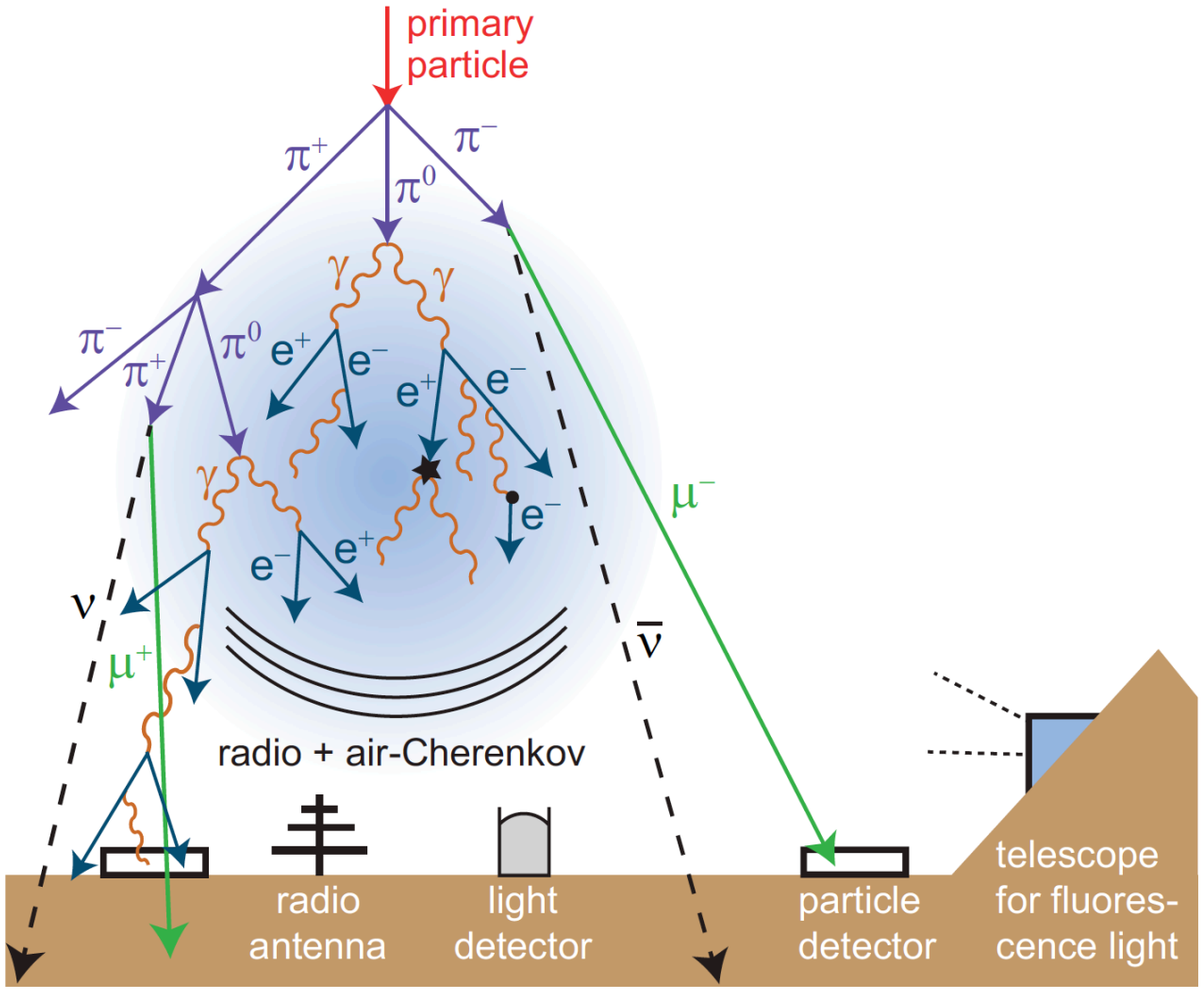
How to Detect Cosmic Rays

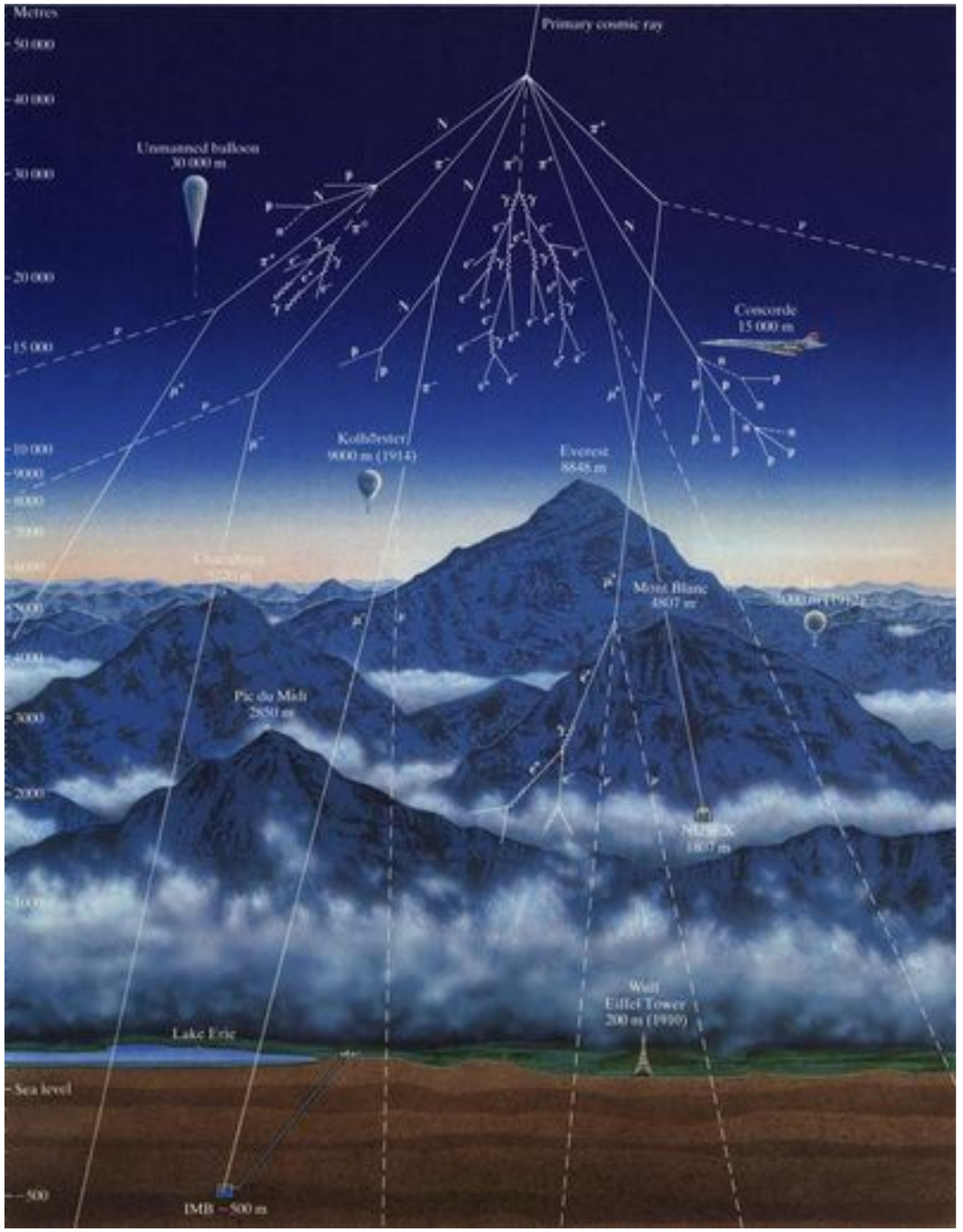
Cosmic-Ray Detection In Space & On Ground

100 km^{-2} yr^{-1} @ 10^{18}eV

1 km^{-2} yr^{-1} @ 10^{19}eV

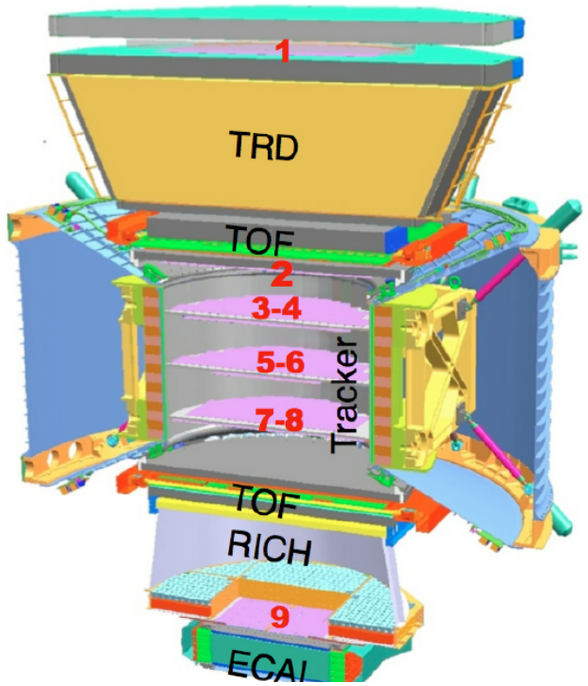
1 km^{-2} $century^{-1}$ @ 10^{20}eV





Cosmic Ray Detection in Space

Alpha Magnetic Spectrometer (AMS02)



Located at ISS

Magnet *bends in opposite directions charged particles/antiparticles*

Transition Radiation Detector (TRD) *identifies electrons and positrons among other cosmic-rays*

Time-of-Flight System (ToF) *warns the sub-detectors of incoming cosmic-rays*

Silicon Tracker (Tracker) *detects the particle charge sign, separating matter from antimatter*

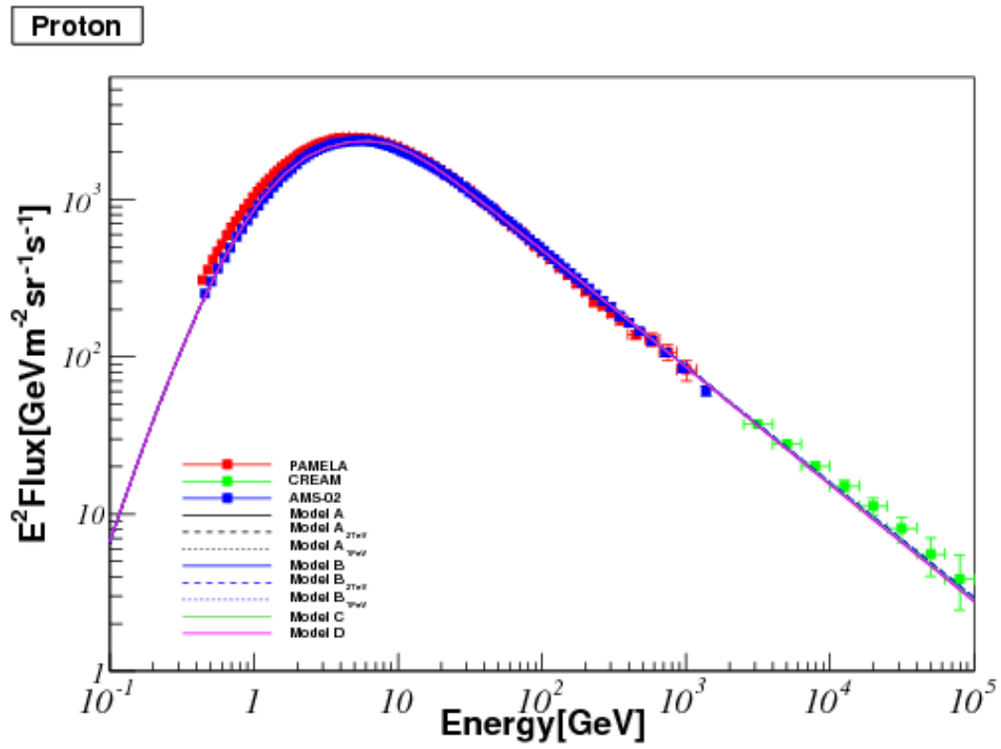
Ring-Imaging Cherenkov Detector (RICH) *measures with high precision the velocity of cosmic-rays*

Electromagnetic Calorimeter (ECAL) *measures energy of incoming electrons, positrons and γ-rays*

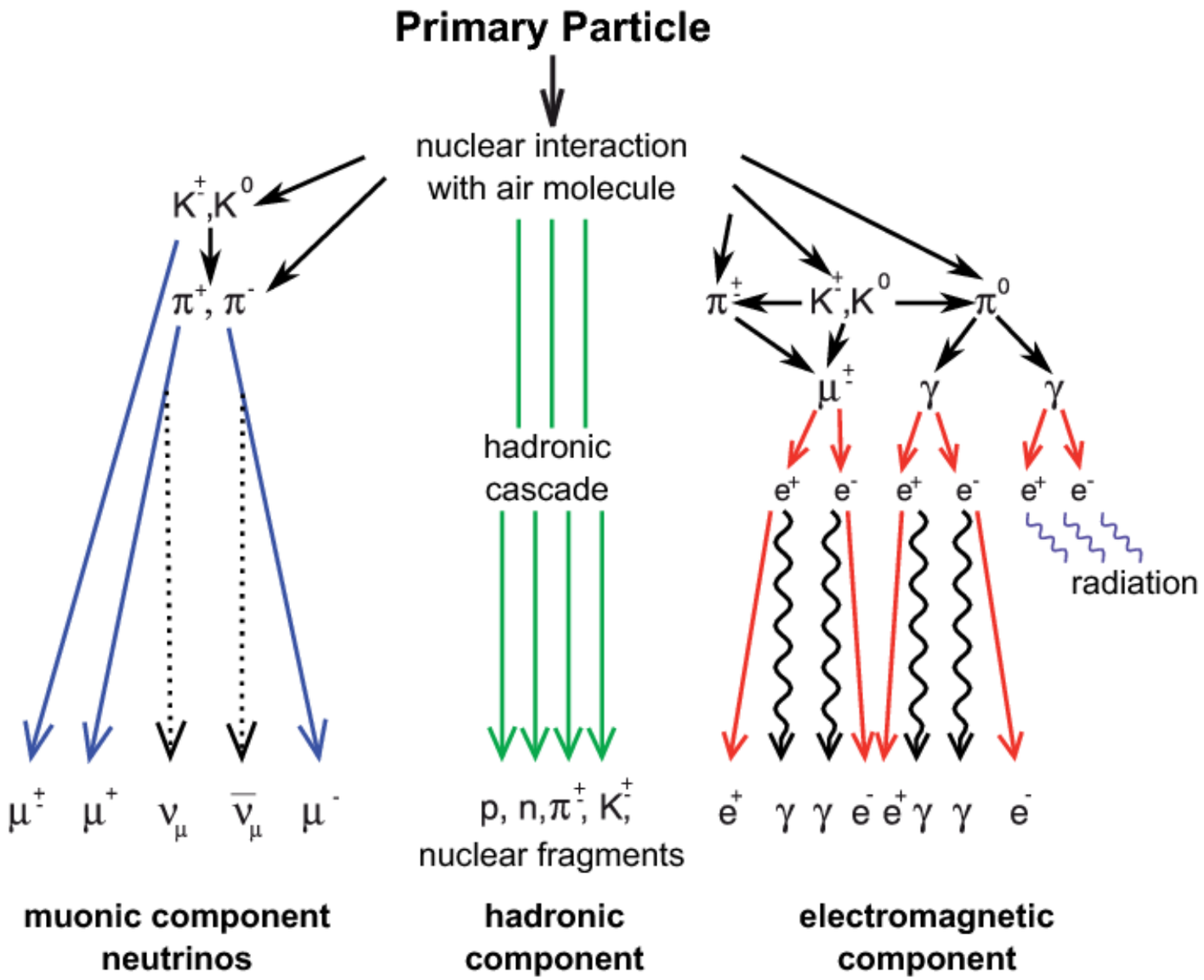
Anti-Coincidence Counter (ACC) *rejects cosmic rays traversing the magnet walls*

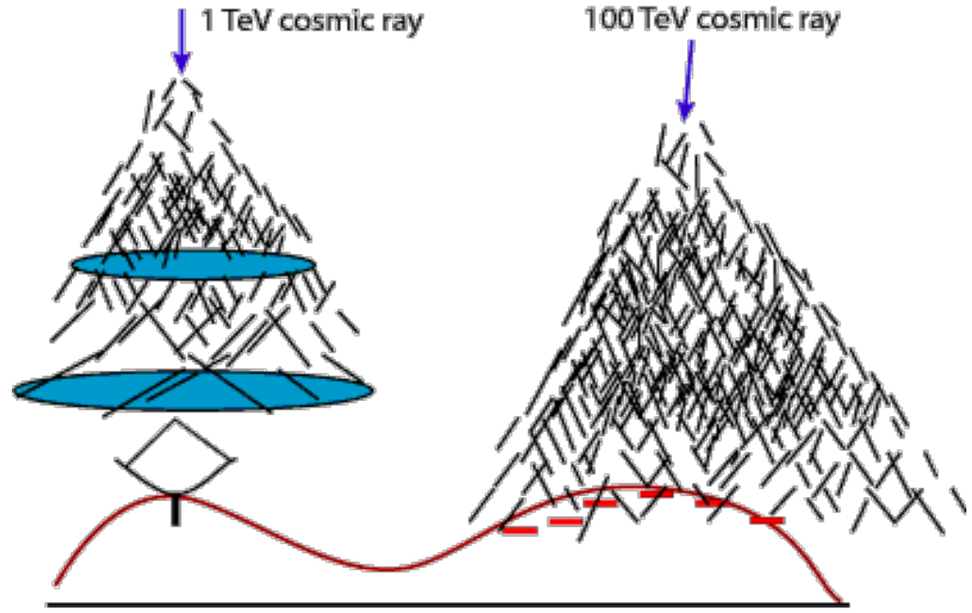
Tracker Alignment System (TAS) *checks the Tracker alignment stability*

Star Tracker and GPS *defines the position and orientation of the AMS-02 experiment*

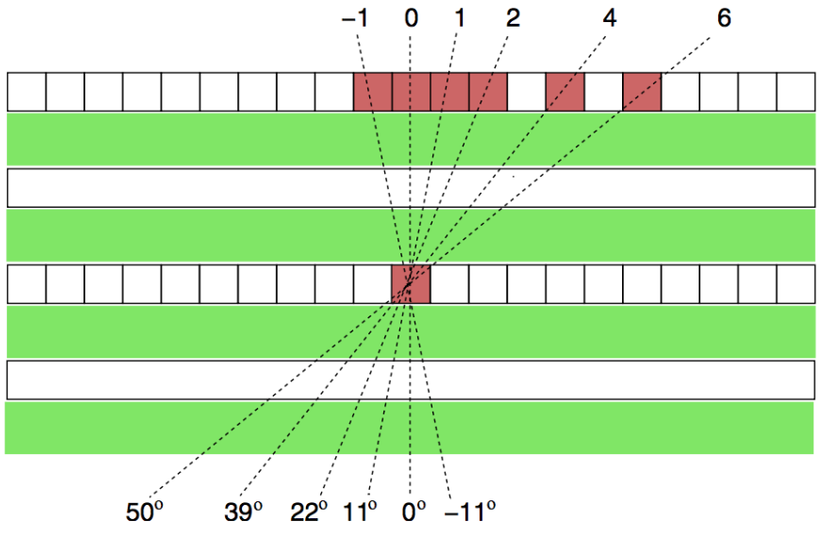


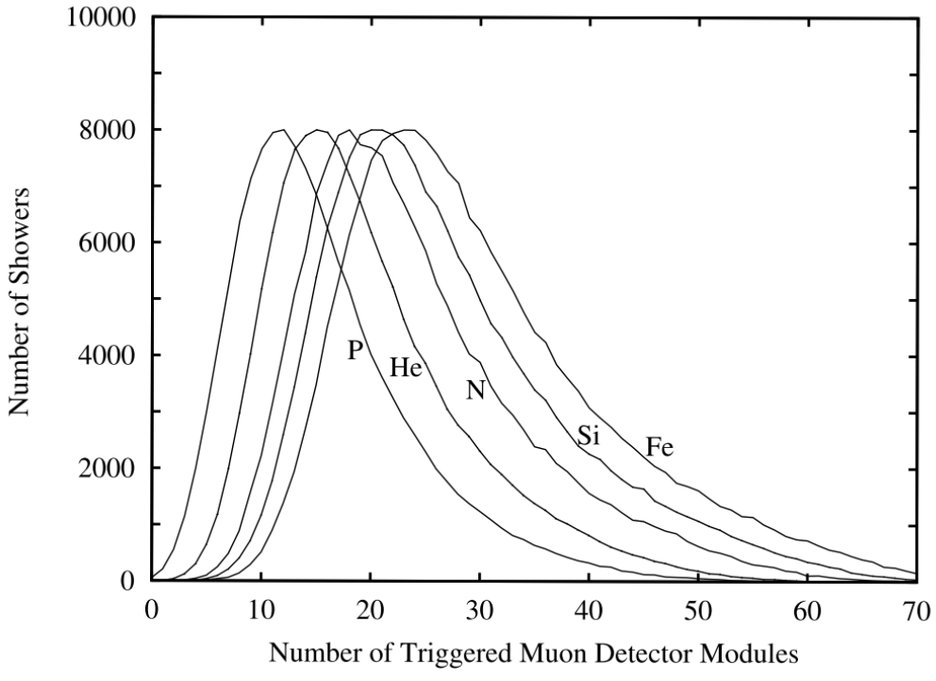
Cosmic Rays at the Earth Surface





Gamma Ray Astronomy at PeV EnergieS - 3 (GRAPES)
@ OOTY Operated by TIFR, Mumbai at altitude 2200 m





High density extensive air shower array
Studies Cosmic ray spectrum
And composition in the energy range
10^{13}eV to 10^{16}eV (around knee region)

Measurements on the distribution of the number of muons incident on the detector : muon multiplicity distribution

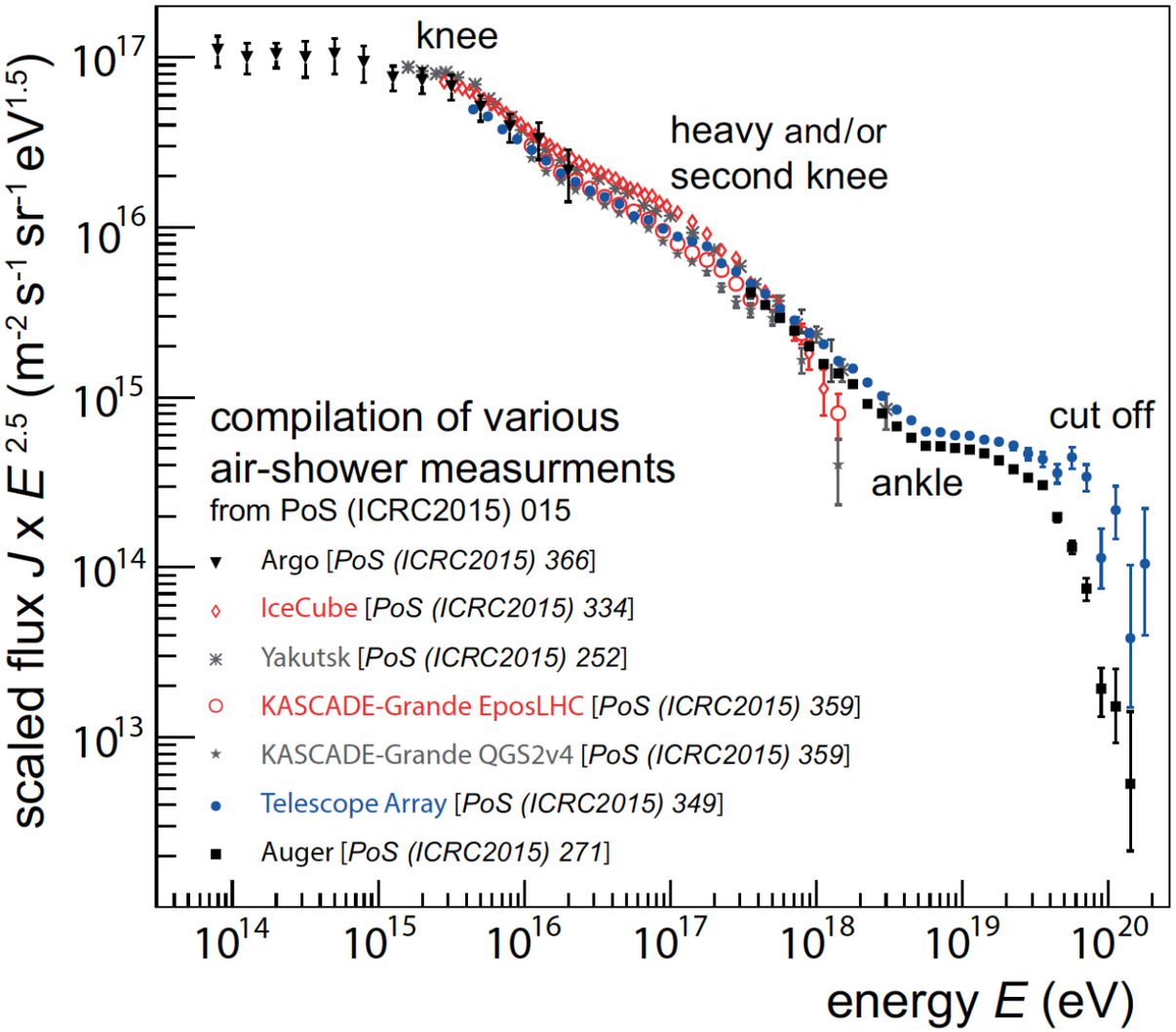
Also measures electron component

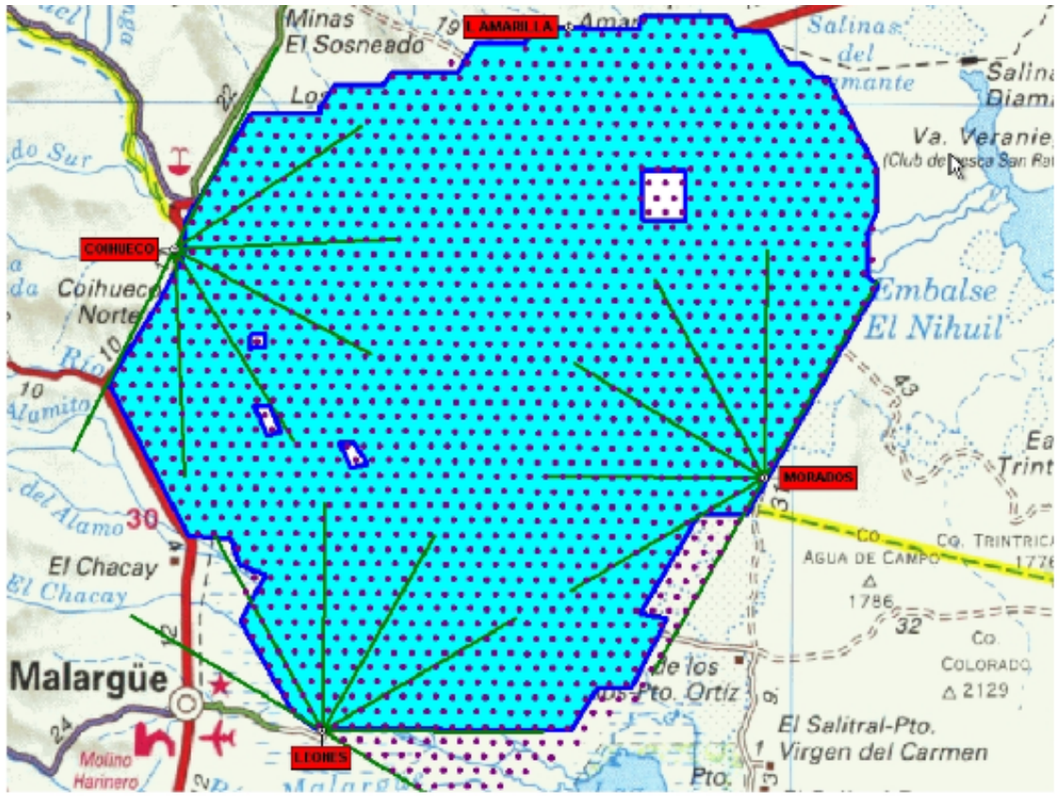
256 plastic scintillators in hexagonal pattern each 1m^2 and separaton between two scintillators 8m (for electron)

Also large area 560m^2 trackimg muon telescope (for muon)
Proportional counters

Ultra High Energy Cosmic-Rays (UHECR)

HTTPS://WWW.AUGER.ORG/





Auger EAS expt. 3000 sq. km,
@1390 m above sea,
Located in Argentina
Hexagonal Grid

At 10^{20} eV rate of cosmic Rays hit Earth's atmosphere 10/minute

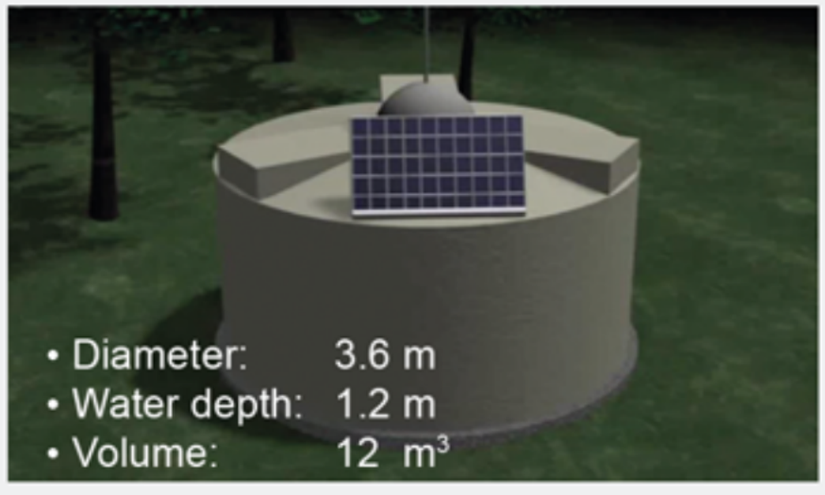
Pierre Auger Observatory Uses Hybrid Technique :
Two independent techniques to detect Cosmic Rays

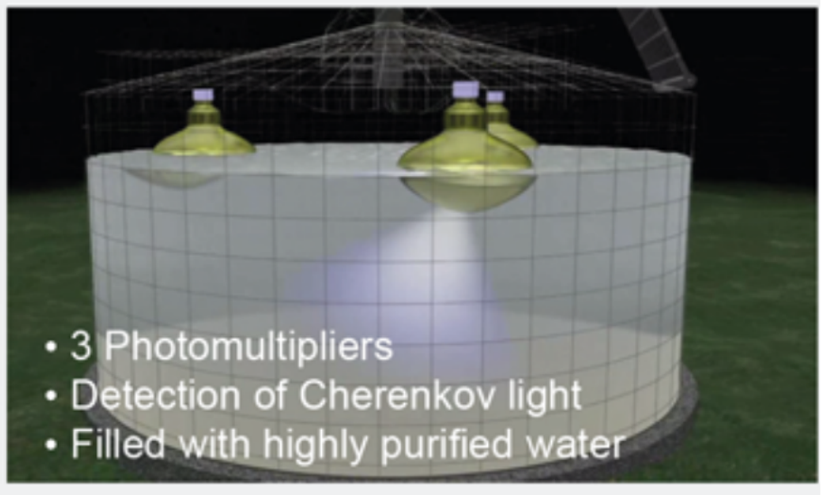
Pierre Auger Observatory

PIERRE AUGER OBSERVATORY

- Pierre Auger accidentally discovered EAS
- He found that secondary particles produced by a cosmic ray of energy 10^{15} eV will spread upto 300m in the ground
- Particles making up the showers travel through the atmosphere at the velocity of light and are confined to a relatively thin disc
- A shower produced by a cosmic ray of 10^{20} eV contains about 10^{11} particles at ground level spread out over an area of about 20 km^2

Pierre Auger Observatory
Surface Detector





1660 Water Surface Detectors : 1.5 km apart, each tank has capacity 12000 lt filled with water. Dark inside. All are equipped with antenna and GPS. Data transmitted to a central computer.

Whenever charged particles (secondaries in the EAS) pass through it produce Cherenkov Light

Detected by 3 PMTs located inside in UV-Optical band - coincidence required for an event .. 20 events/second

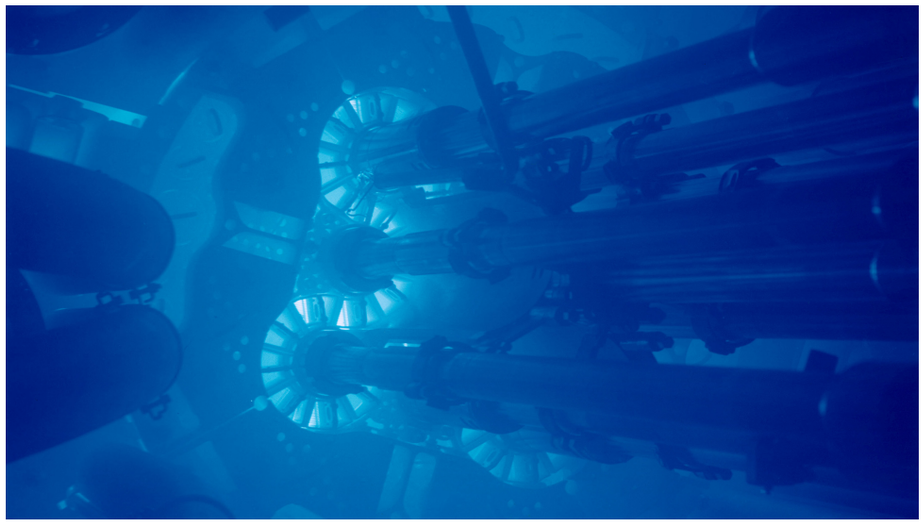
From amount of light - energy of the primary cosmic ray can be estimated

From slight differences in arrival time (detection time) at different tanks one can determine arrival direction

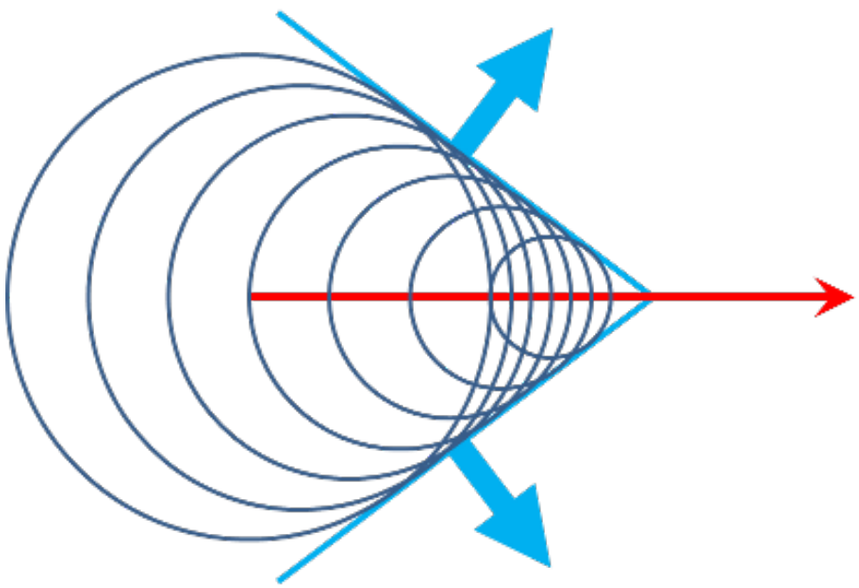
Central computer looks for clusters of detectors triggered almost simultaneously (after allowing for transit time across the array)

Cherenkov Radiation

Most Important Radiation to Detect Cosmic Messengers in High Energy Astrophysics



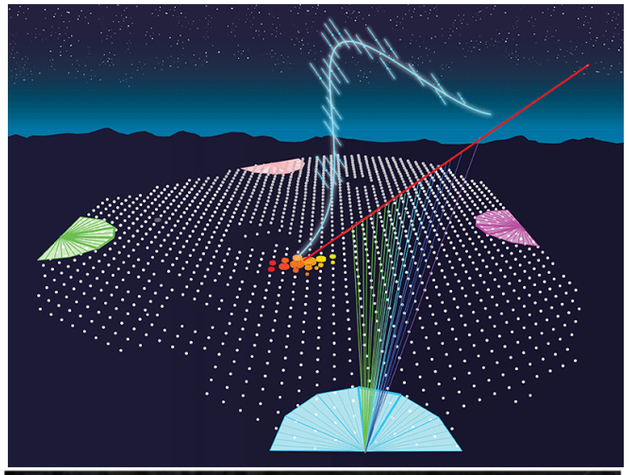
- First observed by Pavel Cherenkov in 1934
- When light travel through matter its velocity decreases : index of refraction = (speed of light in vacuum)/(speed of light in matter)

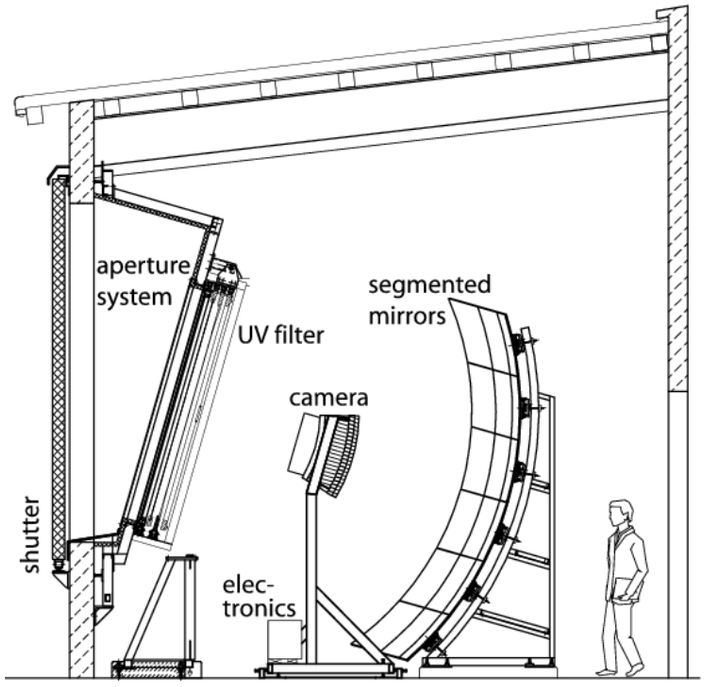


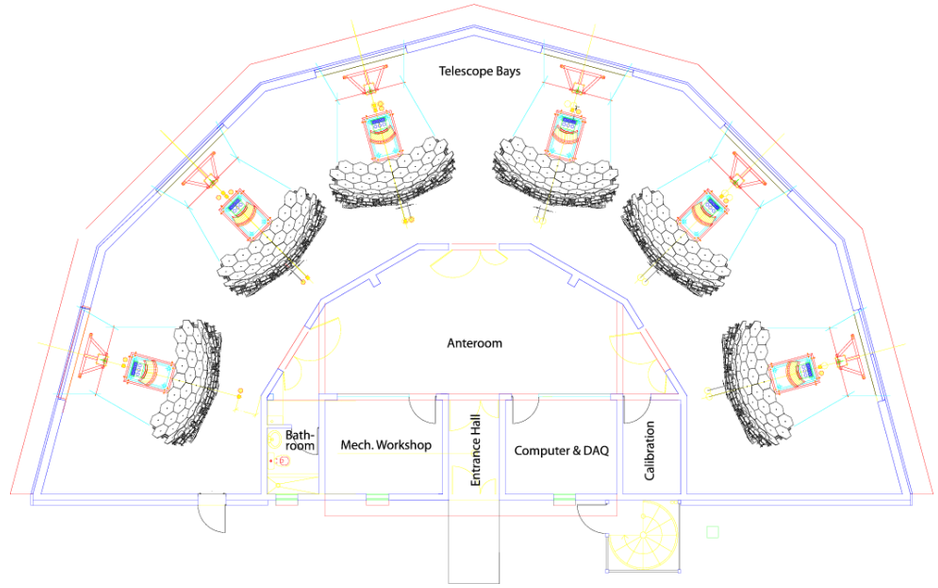
- It may happen elementary particles with speed close to c can move faster than light in the medium
- Emission is forward peak

We will return to this in more details later ..

Pierre Auger Observatory
Fluorescence Detector







Operates only in the nights

Total 4 stations. Each station has 6 telescopes. Each telescope has 440 PMTs.

Charged particles (secondaries in the EAS) interact with nitrogen in the atmosphere, causing it to emit ultraviolet light - fluorescnece

Cammeras can see air showers upto 15 kms away. Basically it studies shower Developments in the atmosphere.

Where do they come from ?

General Principle of Acceleration & Probabale Sources (Hillas Plot)

Magnetic fields themselves do not work therefore can not be directly responsible for accl. But changing magnetic field leads to inductive electric field