Cosmic Rays

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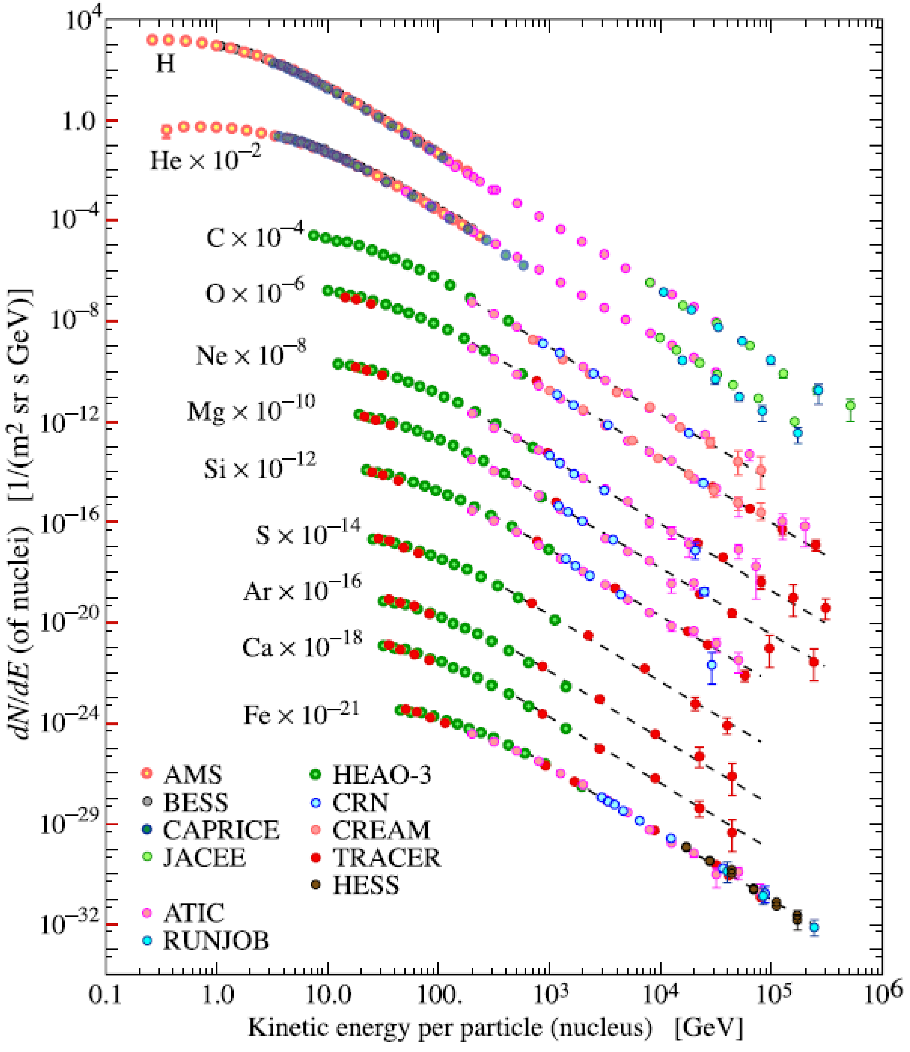
Quarknet 2009 at UCR

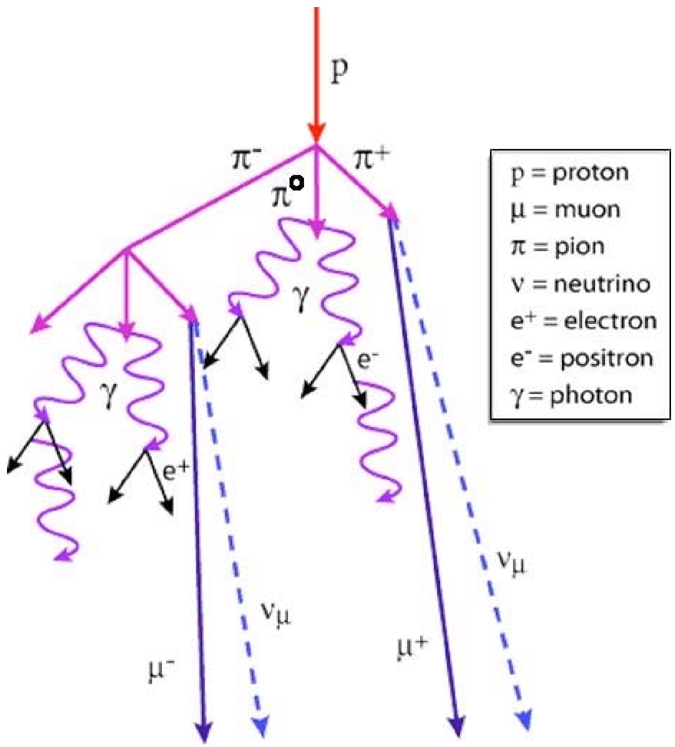
What are Cosmic Rays?

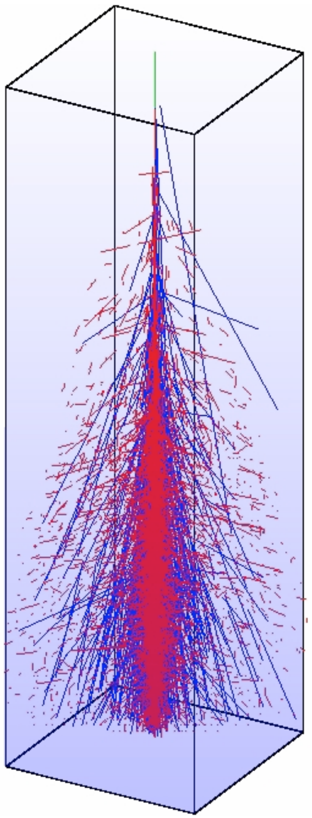
- Particles accelerated in astrophysical sources incident on Earth's atmosphere
  - Possible sources include solar activity, supernovae, rotating neutron stars, and black holes
  - Composition: primarily protons and helium nuclei. Remainder is composed of heavier nuclei and electrons



Air Shower

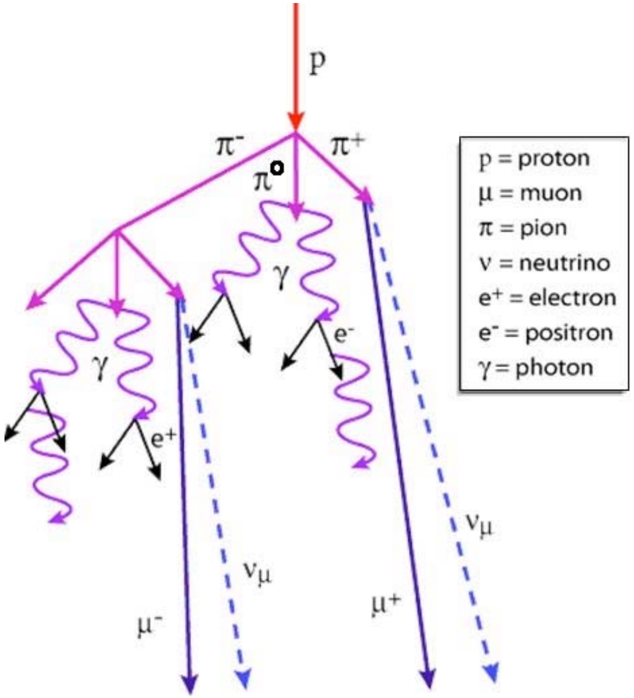
- Cosmic rays interact with Earth's atmosphere producing an air shower
  - Secondary particles are produced, primarily pions
  - The neutral pions decay to photons, which produce electrons and positrons
  - The charged pions decay to muons via the weak reactions
    $\pi^- \to \mu^- \bar{\nu}_\mu$ and $\pi^+ \to \mu^+ \nu_\mu$





Air Shower

- The pions decay before they reach sea level
- The photons, electrons, and positrons are absorbed by the atmosphere due to interactions with atomic fields
- The muons can reach sea level because
  - 1) Even though they decay, they have sufficiently long lifetime such that the more energetic muons reach sea level before decaying
  - 2) Unlike electrons (which are much lighter) they do not interact with atomic fields so easily

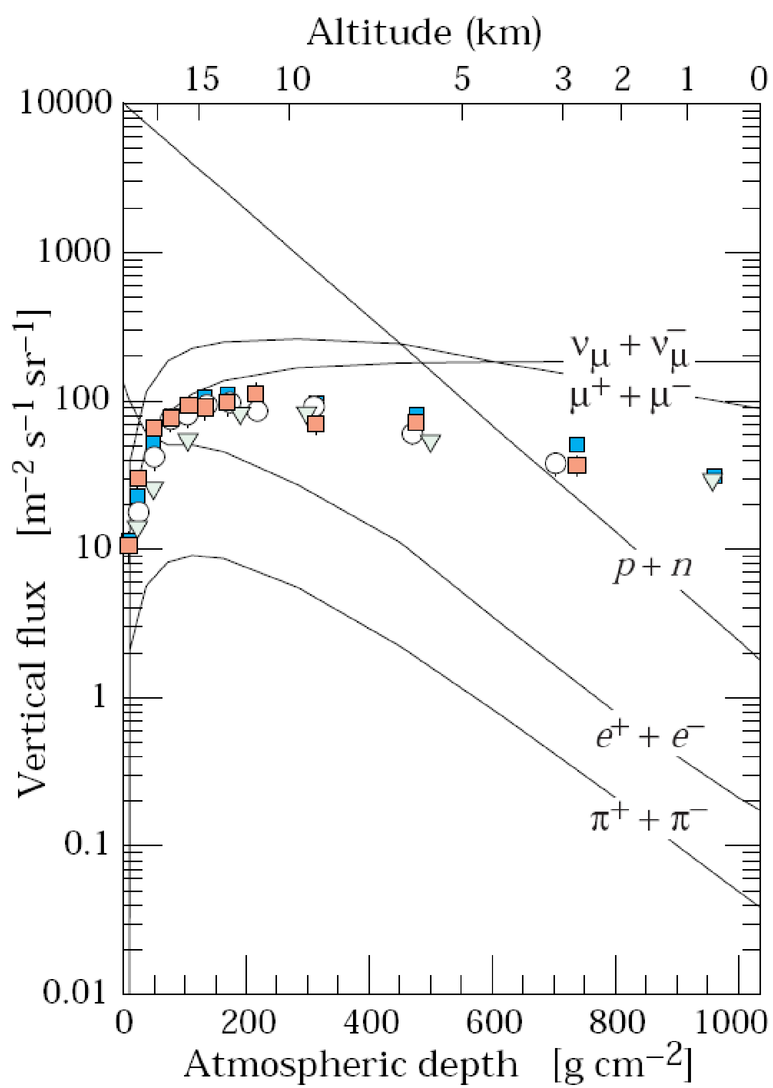


- The neutrinos interact only weakly, so they easily reach sea level (and continue straight through the Earth!)

Particle Fluxes

- At sea level (altitude 0) the muon and neutrino flux dominates

- Approximately one cosmic ray muon passes through your thumbnail every minute!



Note: points show measurements of negative muons with E_μ > 1 GeV

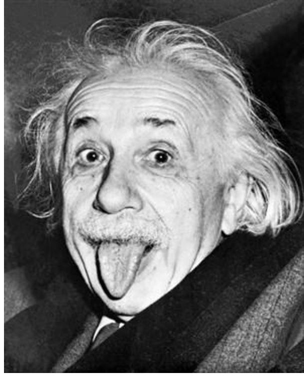
Muon Decay

- Muons decay $(\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu)$ with a mean lifetime of 2.2 μs
  - (mean lifetime = time for an assembly of decaying particles to be reduced by a factor of e)
- If a muon is created in the upper atmosphere (e.g. at h = 10 km) does it make it to sea level?
- We would expect that even if the muons are traveling at close to the speed of light, the average distance they would travel before decaying is

$$d = c\tau = (8\times 10^8 \text{ m/s})(2.2\times 10^{-6} \text{ s}) = 660 \text{ m}$$

- i.e. they would not make it to sea level

Special Relativity



- Wrong!

- According to special relativity, from our point of view time passes more slowly in a system that is in motion relative to us

- Thus, the moving muon "clock" ticks more slowly. This effect is called *time dilation* and is described by the simple formula

$$t' = \gamma t \qquad \text{where } \gamma = \frac{1}{\sqrt{1 - v^2 / c^2}}$$

- Thus, the faster moving muons (e.g. those with speed v=0.998c) will travel on average

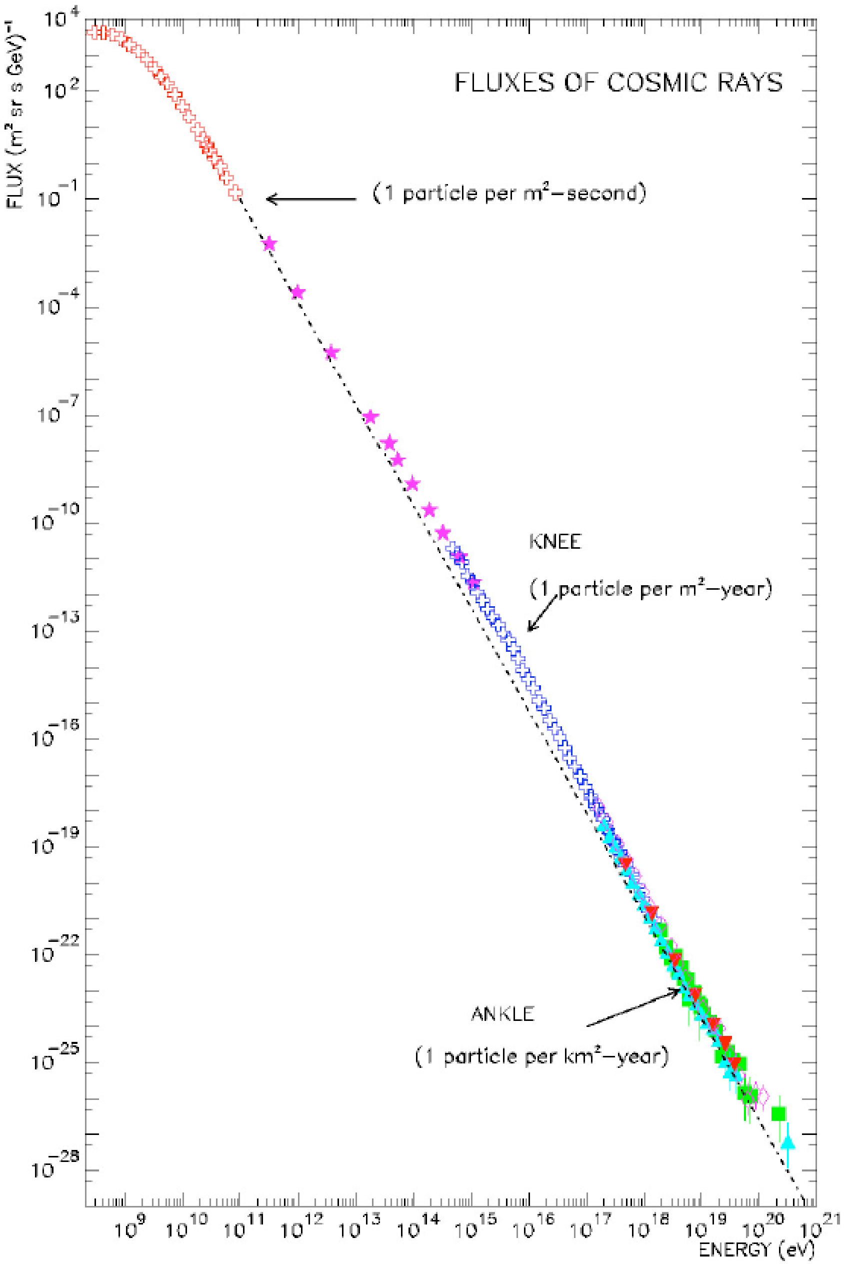
$$d' = c\tau' = \gamma c\tau = \left(\sqrt{\frac{1}{1 - 0.998^2}} \right) (660 \text{ m}) = (15.8)(660 \text{ m}) = 10.4 \text{ km}$$

- So, the faster moving muons make it to sea level!

Energy Spectrum of Cosmic Rays

- Flux follows power law
  - $E^{-2.7}$ knee
  - $E^{-3.2}$ ankle
  - $E^{-2.8}$ above ankle

- Cosmic rays can have energies above 10^{20} eV
  - Far higher than energies of beams available in modern accelerators



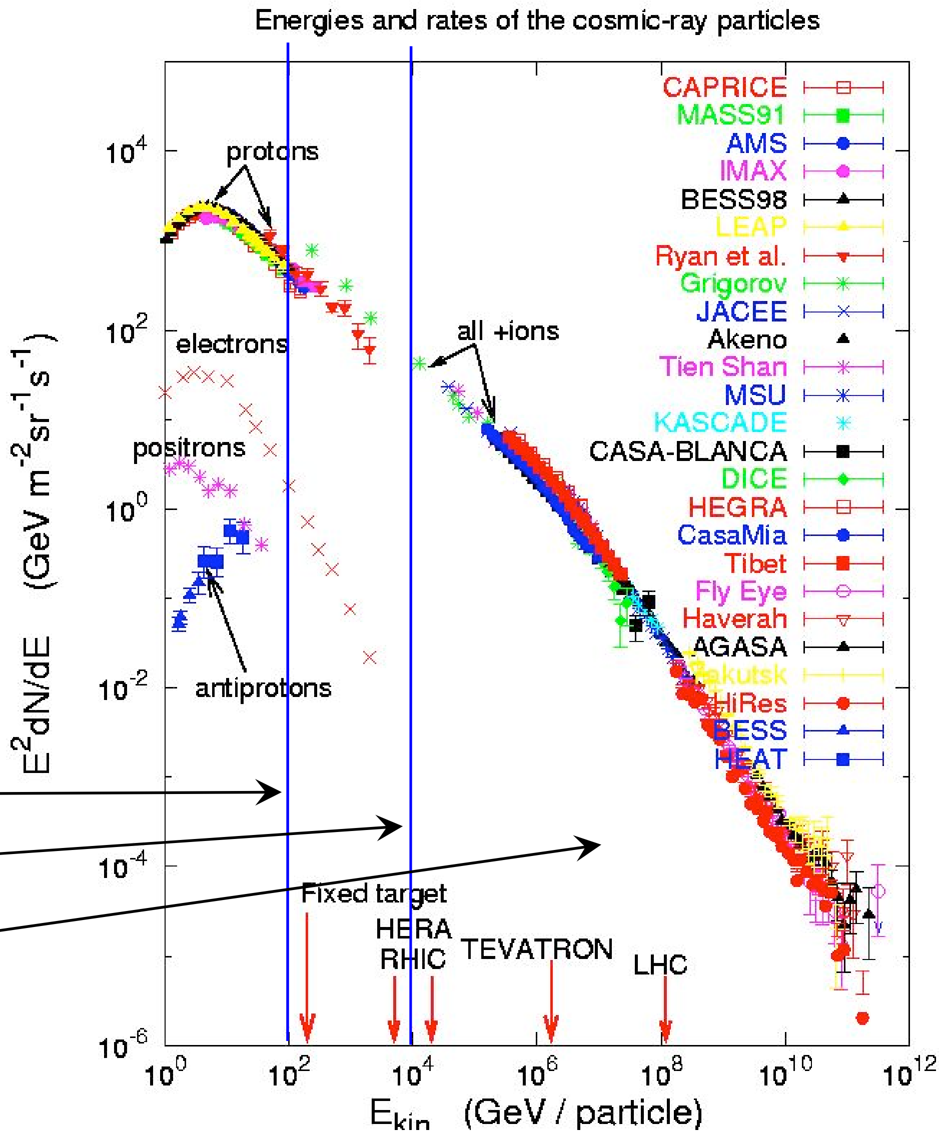
Cosmic Ray Energies

- Ultra-High Energy Cosmic Ray
  - e.g. $E_{lab} = 10^{20}$ eV
  - Equivalent to *pp* collider with CM energy of 433 TeV
- LHC at CERN
  - *pp* collider with CM energy of 14 TeV
  - Equivalent to $E_{lab} \sim 10^{17}$ eV = 10^8 GeV
- Detection via:

  Spectrometers

  Calorimeters

  Air Shower Arrays

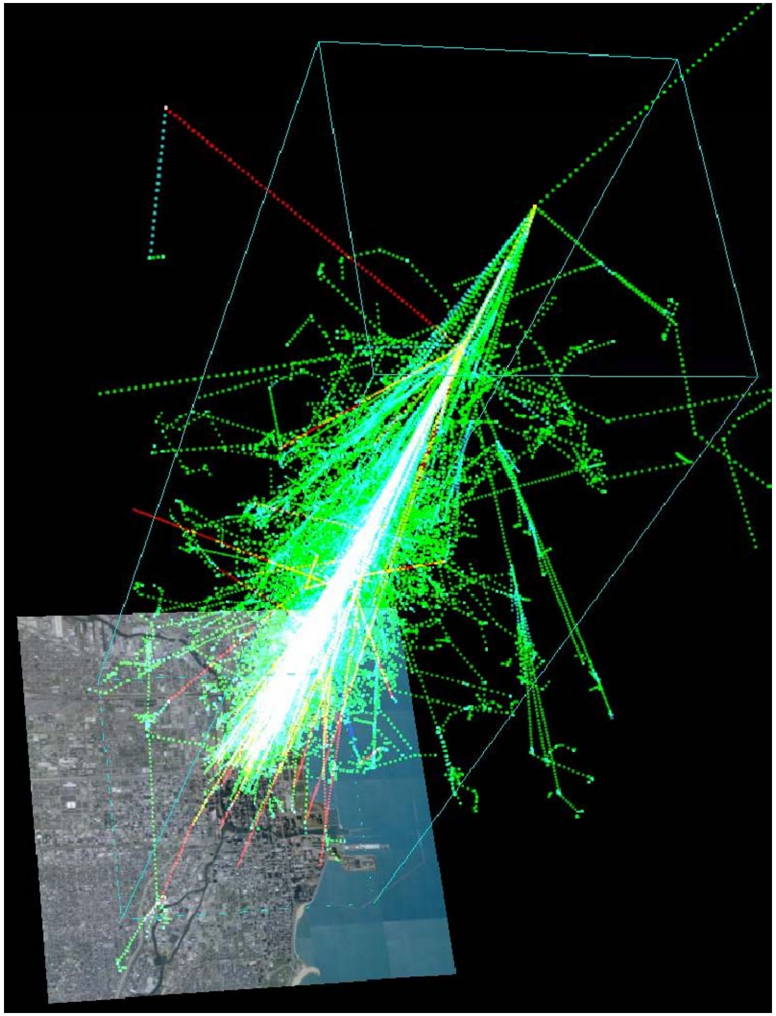


Extensive Air Shower Detectors

- Need array of detectors spread over many km

One station of the Pierre Auger extensive air shower observatory in Argentina

Simulation of 1 TeV cosmic ray shower

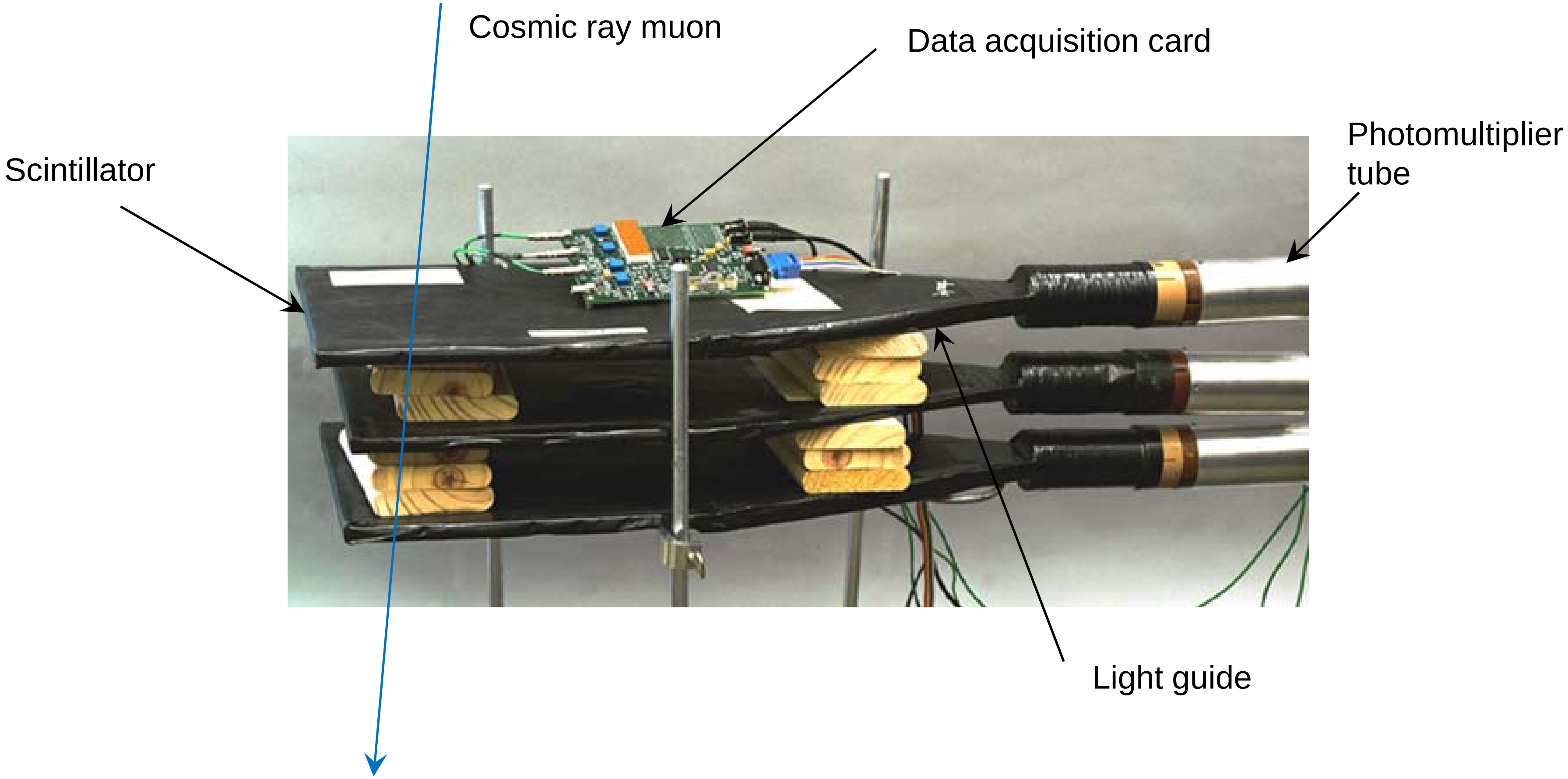


Cosmic Ray Research

- Many questions to be addressed:
  - What is the origin of cosmic rays?
  - What accelerates cosmic rays, especially at the highest energies ($\sim 10^{20}$ eV)? AGNs?
  - Are there super-GZK particles?
  - Can we point back to cosmological sources? What are the acceleration mechanisms?
  - What is responsible for the “knee” and “ankle”?
  - Where is the transition from galactic to extragalactic cosmic rays?
  - . . . Lots of good info at Pierre Auger Observatory home page

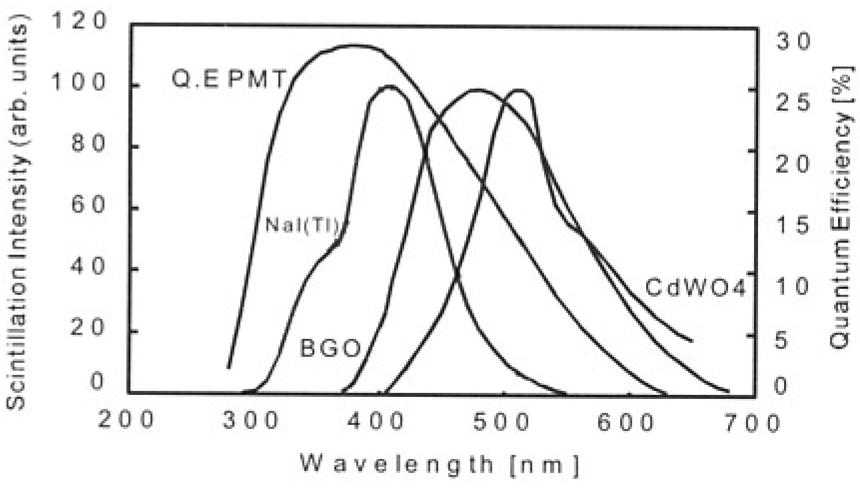
Quarknet Cosmic Ray Detector

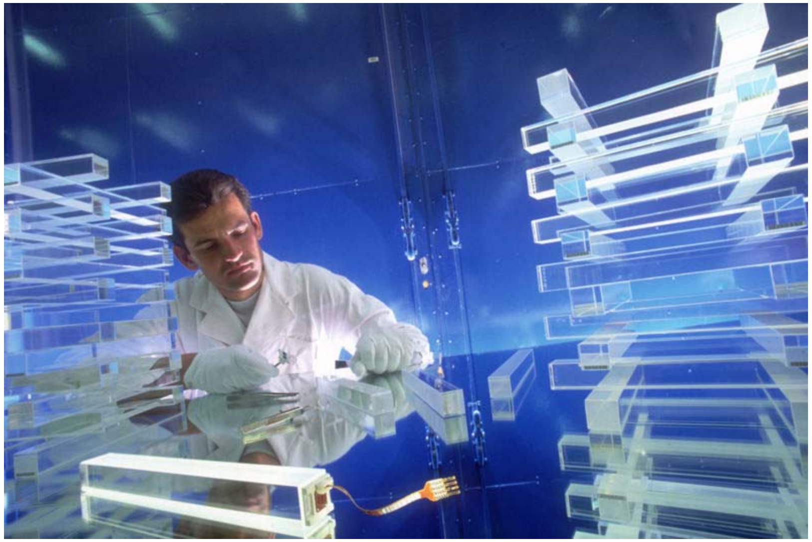
- Our Quarknet comic ray detector is a simple “benchtop” detector consisting of scintillation detectors read out using photomultiplier tubes



Scintillators

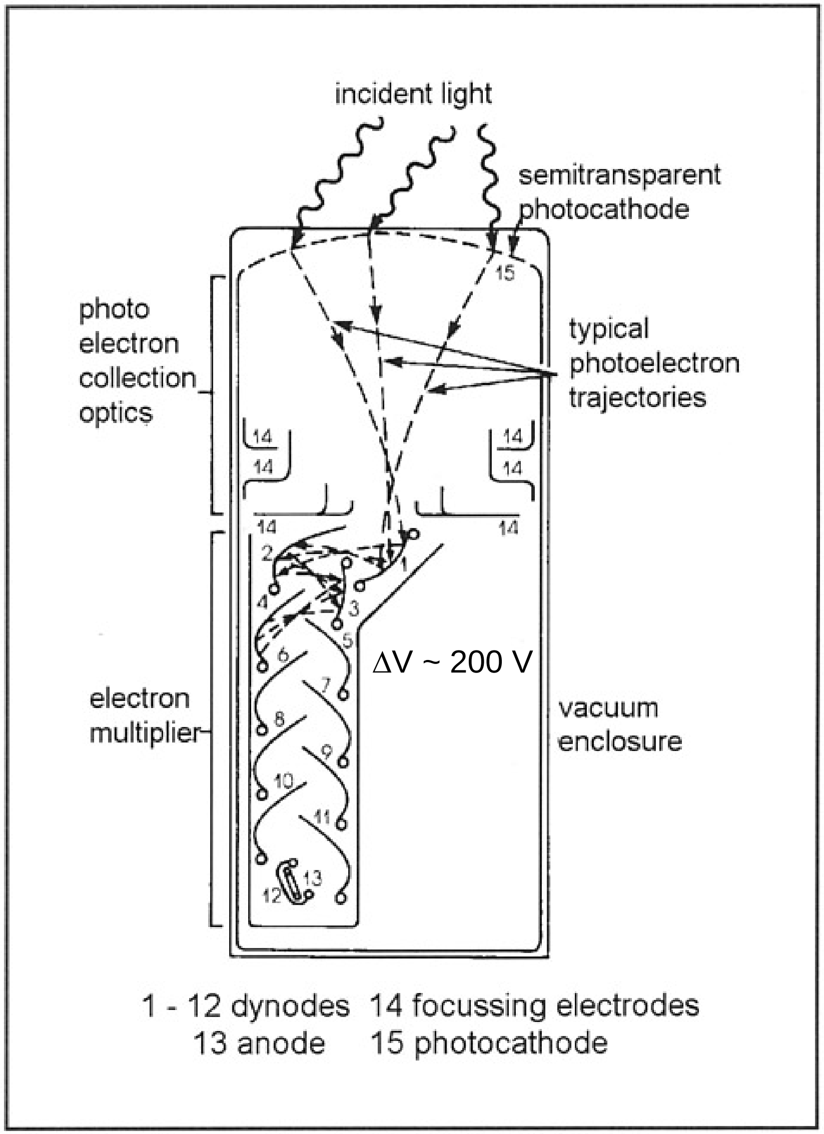
- Produce a short pulse of light in response to charged particle passing through
- Two types: inorganic and organic
- Organic scintillator (used in our detector):
  - Typically plastic doped with dye molecules
  - Mechanism is excitation of molecular levels in primary fluorescent material which decay with emission of UV light
  - Conversion to visible light achieved via fluorescent excitation of dye molecules (“wavelength shifters”)





Photomultiplier Tube

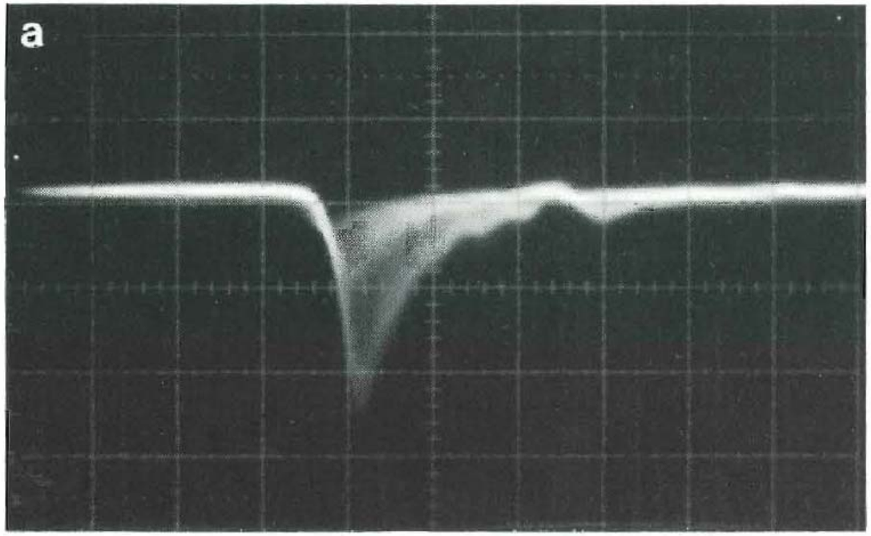
- Photon incident on photocathode
- Liberates electrons by photoelectric effect
- Electrons accelerated to 1st dynode
  - Secondary electrons emitted
- Using ~12 stages can get amplification of $\sim 10^7 – 10^8$
- Electron cascade collected at anode – induces signal
- Example: $10^8 e^- \cong 2 \times 10^{-11}$ C collected in ~5 ns
  - 50 Ω resistor to ground $\Rightarrow$ V = 200 mV pulse



Schematic of a photomultiplier tube.

Typical Signals from PM Tube

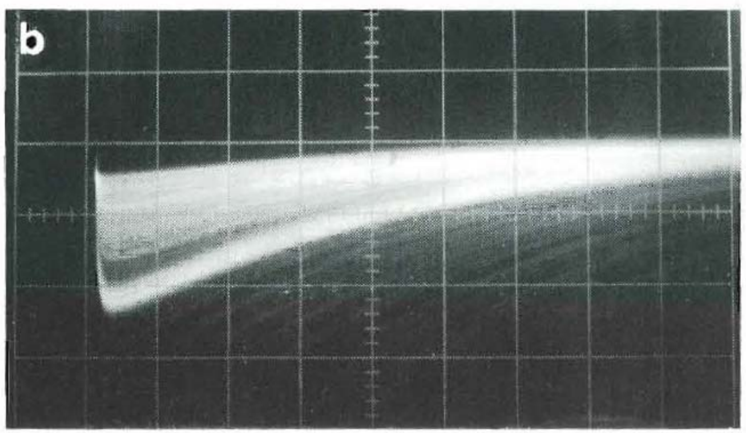
Organic Scintillator



Plastic

Vert. scale : 0.2 V/cm
Hor. scale : 10 ns/cm
Source : ^{207}Bi 10μCi

Inorganic Scintillator



NaI

Vert. scale : 0.2 V/cm
Hor. scale : 5μs/cm
Source : ^{137}Cs 10μCi

Plateau – Setting the Operating Point