Cosmic Rays

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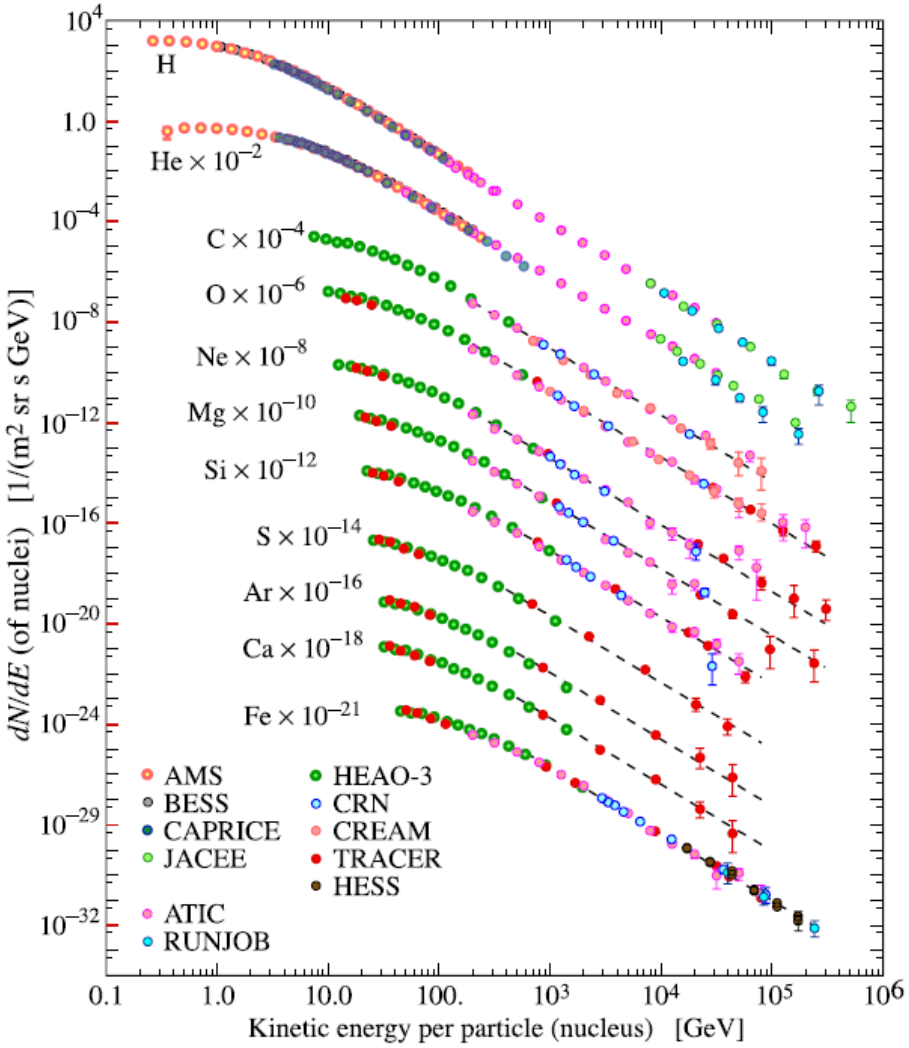
Quarknet 2012 at UCR

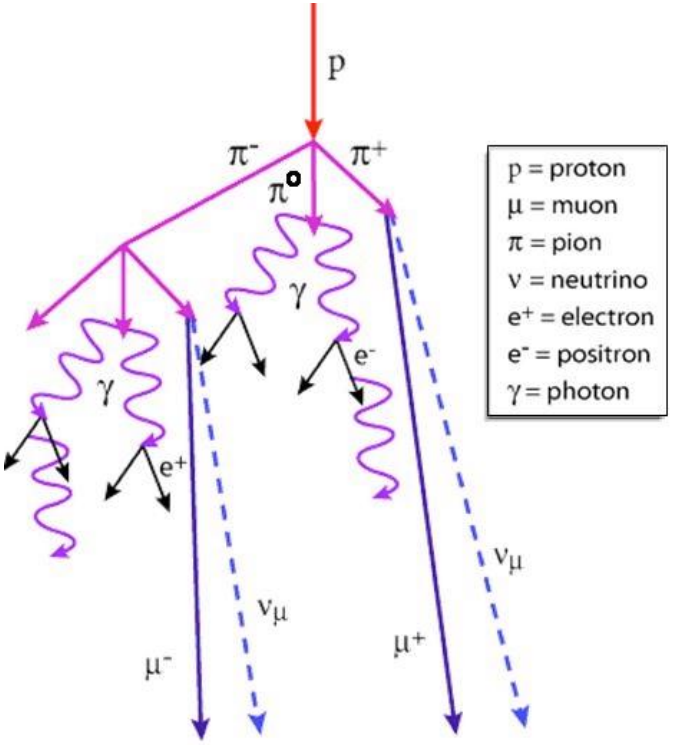
What are Cosmic Rays?

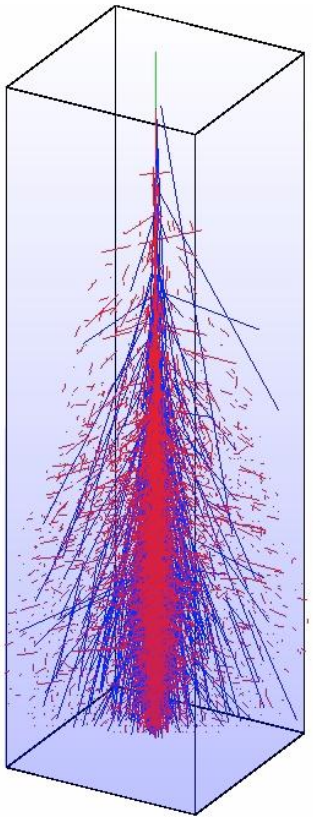
- Particles accelerated in astrophysical sources incident on Earth's atmosphere
  - Possible sources include solar activity, supernovae, rotating neutron stars, and black holes
  - Composition: primarily protons (~89%) and helium nuclei (~10%). Remainder is composed of heavier nuclei and electrons



Air Shower

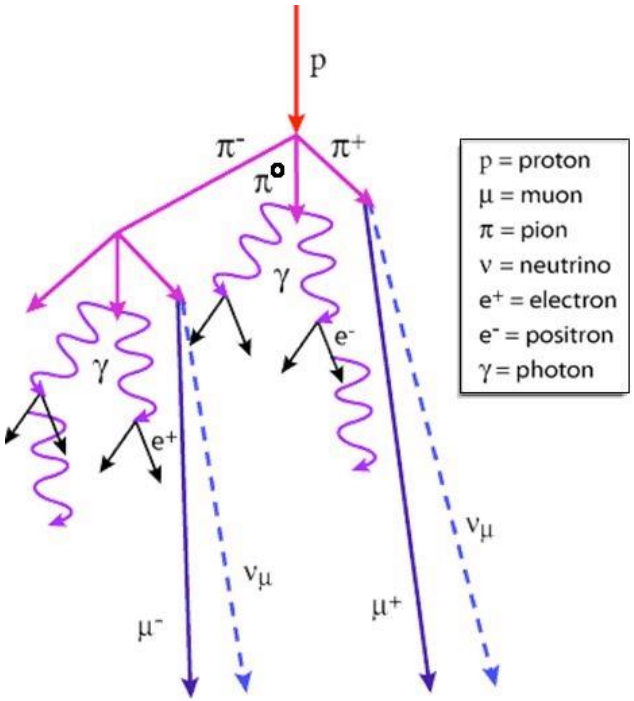
- Cosmic rays interact with Earth's atmosphere producing an air shower
  - Secondary particles are produced, primarily pions
  - The neutral pions decay to photons, which produce electrons and positrons
  - The charged pions decay to muons via the weak reactions $\pi^- \to \mu^- \bar{\nu}_\mu$ and $\pi^+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





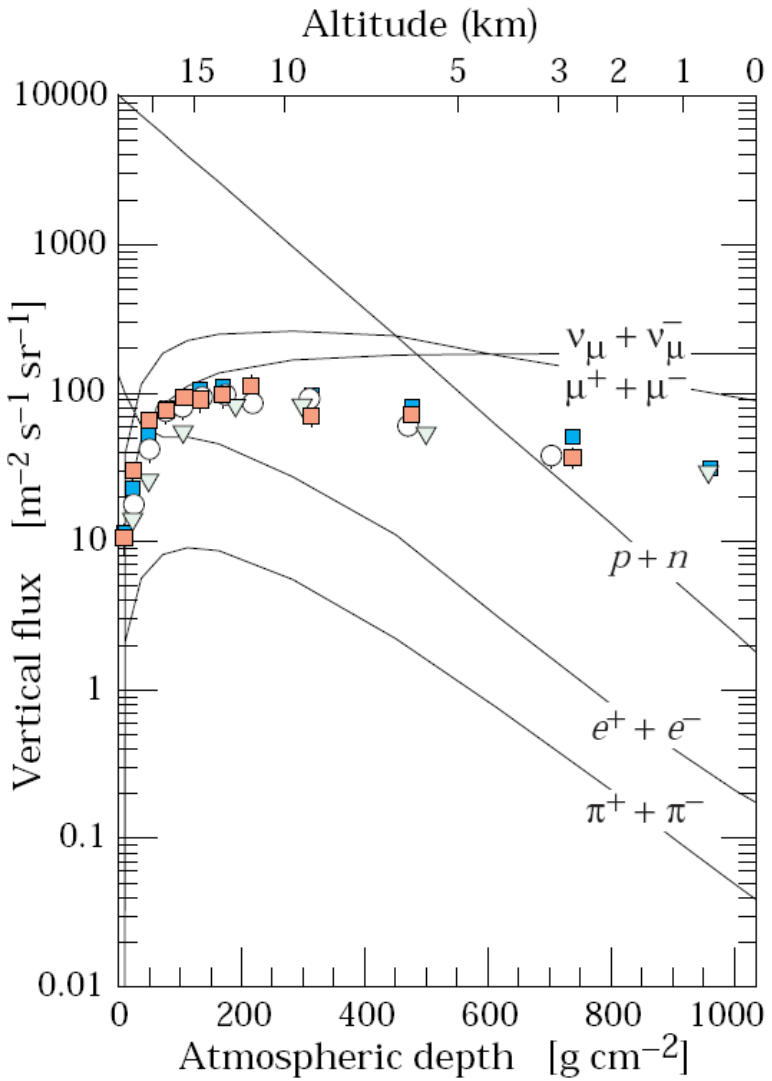
Air Shower

- 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 $E_\mu > 1$ GeV

Muon Decay

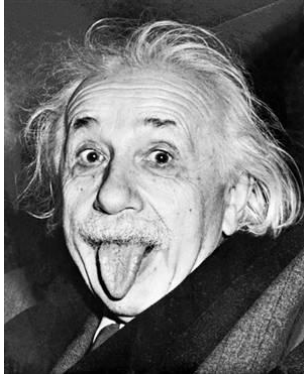
- Muons decay ($\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$) with a mean lifetime of 2.2 μs
  - (mean lifetime = time for an assembly of decaying particles to be reduced by a factor of e)
- If a muon is created in the upper atmosphere (e.g. at h = 10 km) does it make it to sea level?

- 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

$$d = c\tau = (3\times10^{8}\ \text{m/s})(2.2\times10^{-6}\ \text{s}) = 660\ \text{m}$$

- 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

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

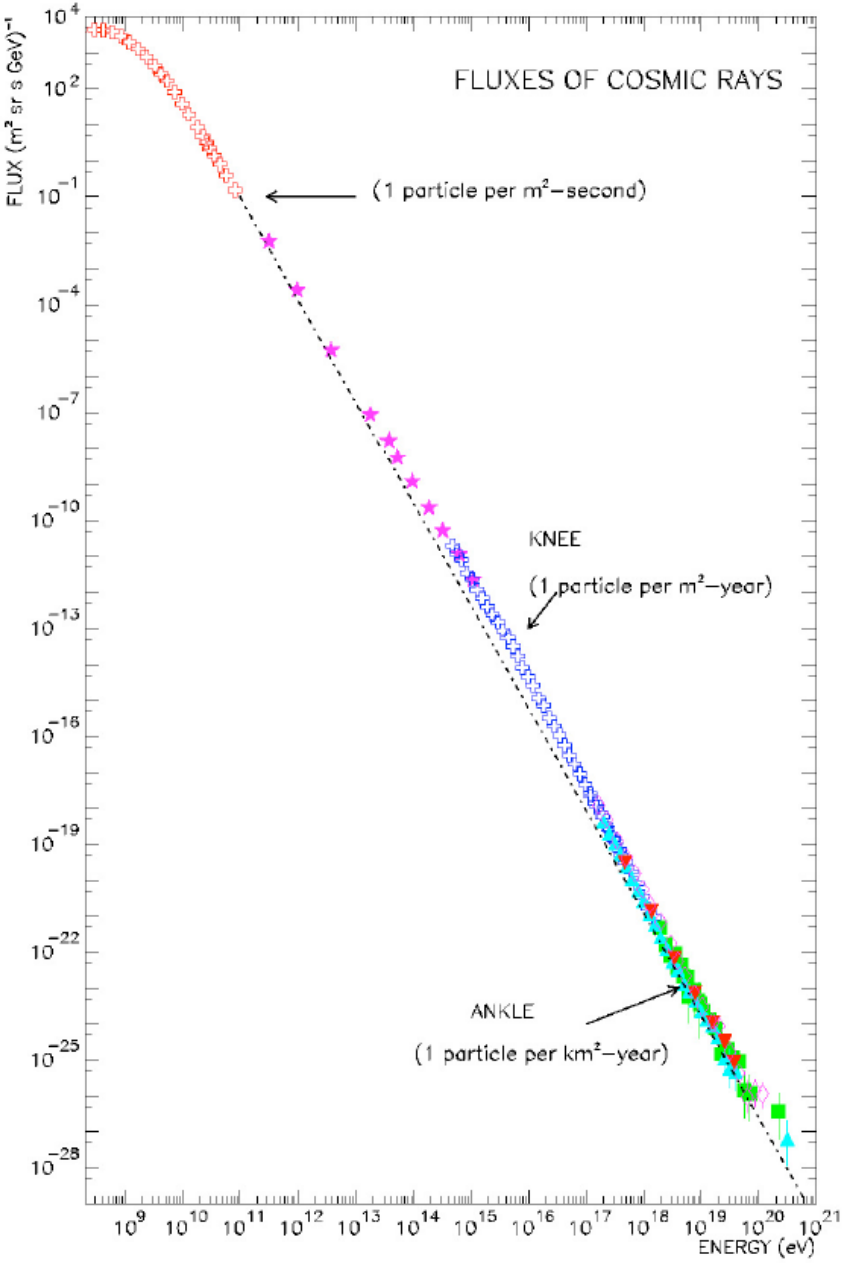
- Thus, the faster moving muons (e.g. those with speed v=0.998c) will travel on average

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

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

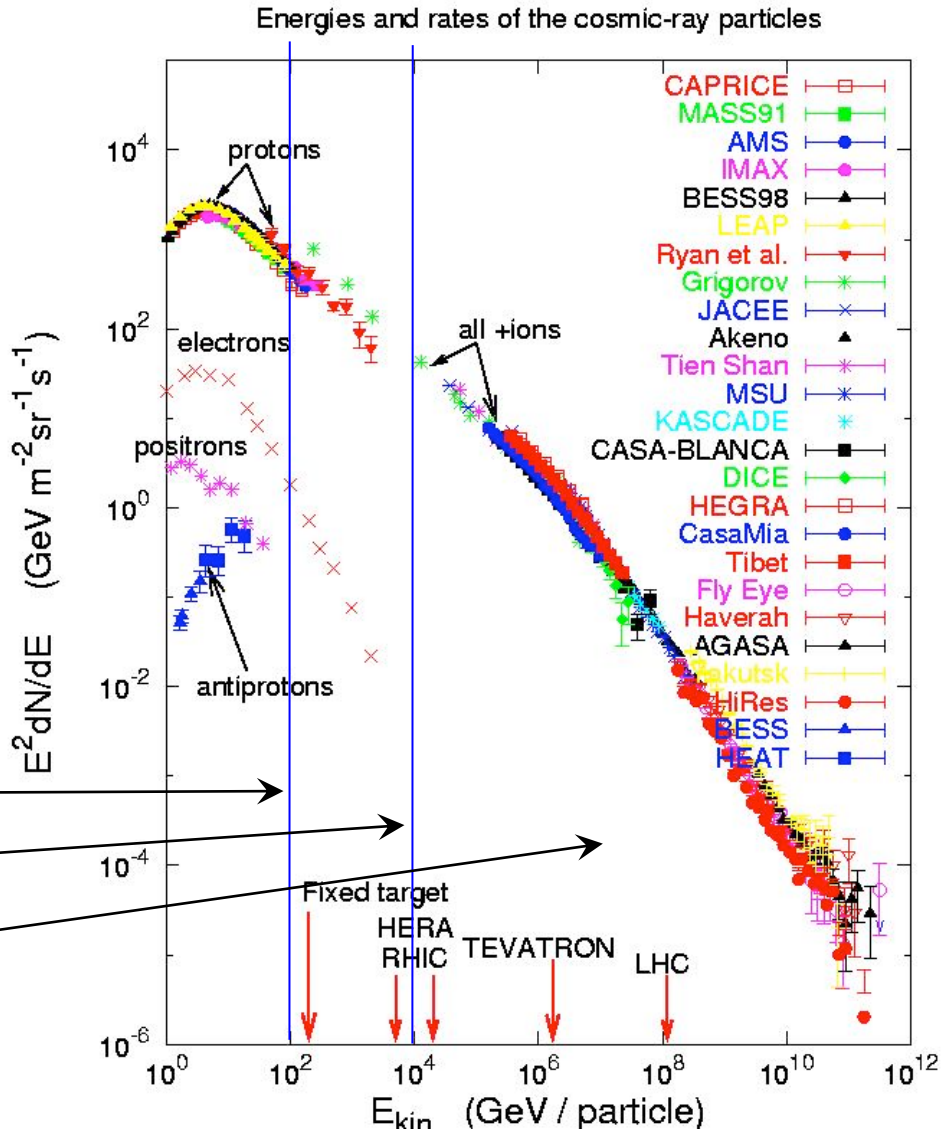
Energy Spectrum of Cosmic Rays

- Flux follows power law
  - $E^{-2.7}$ below knee
  - $E^{-3.2}$ knee to ankle
  - $E^{-2.8}$ above ankle
- Cosmic rays can have energies up to about 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 = 10^5 TeV
- Detection via:
  - Spectrometers
  - Calorimeters
  - Air Shower Arrays

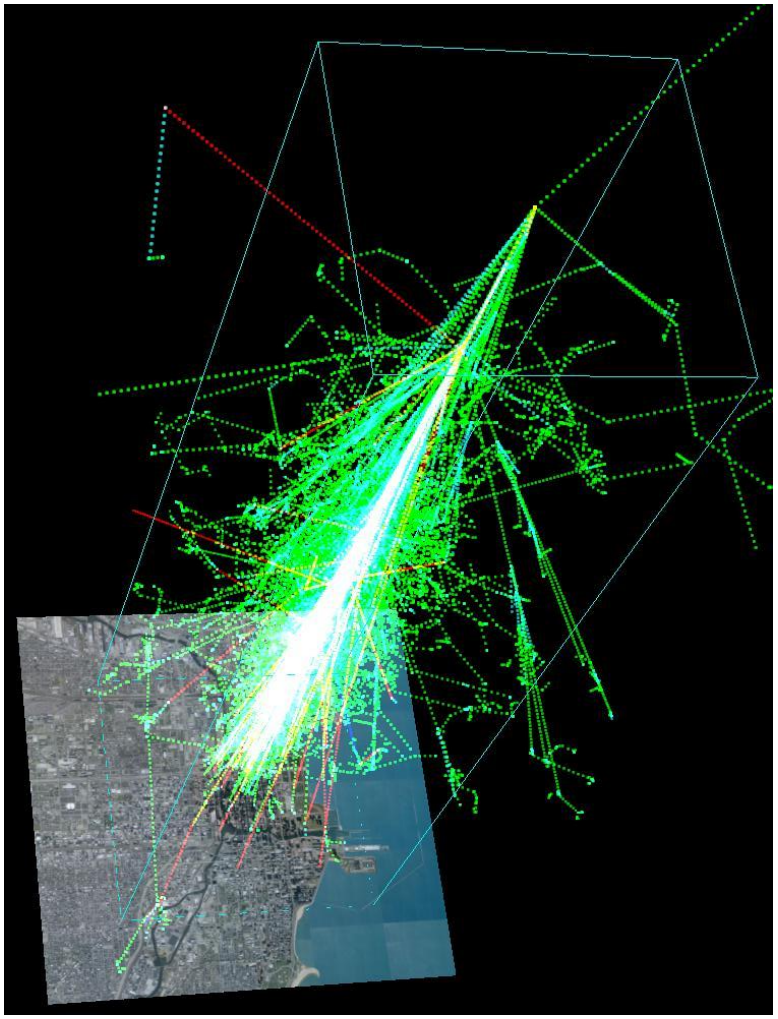


Extensive Air Shower Detectors

- 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

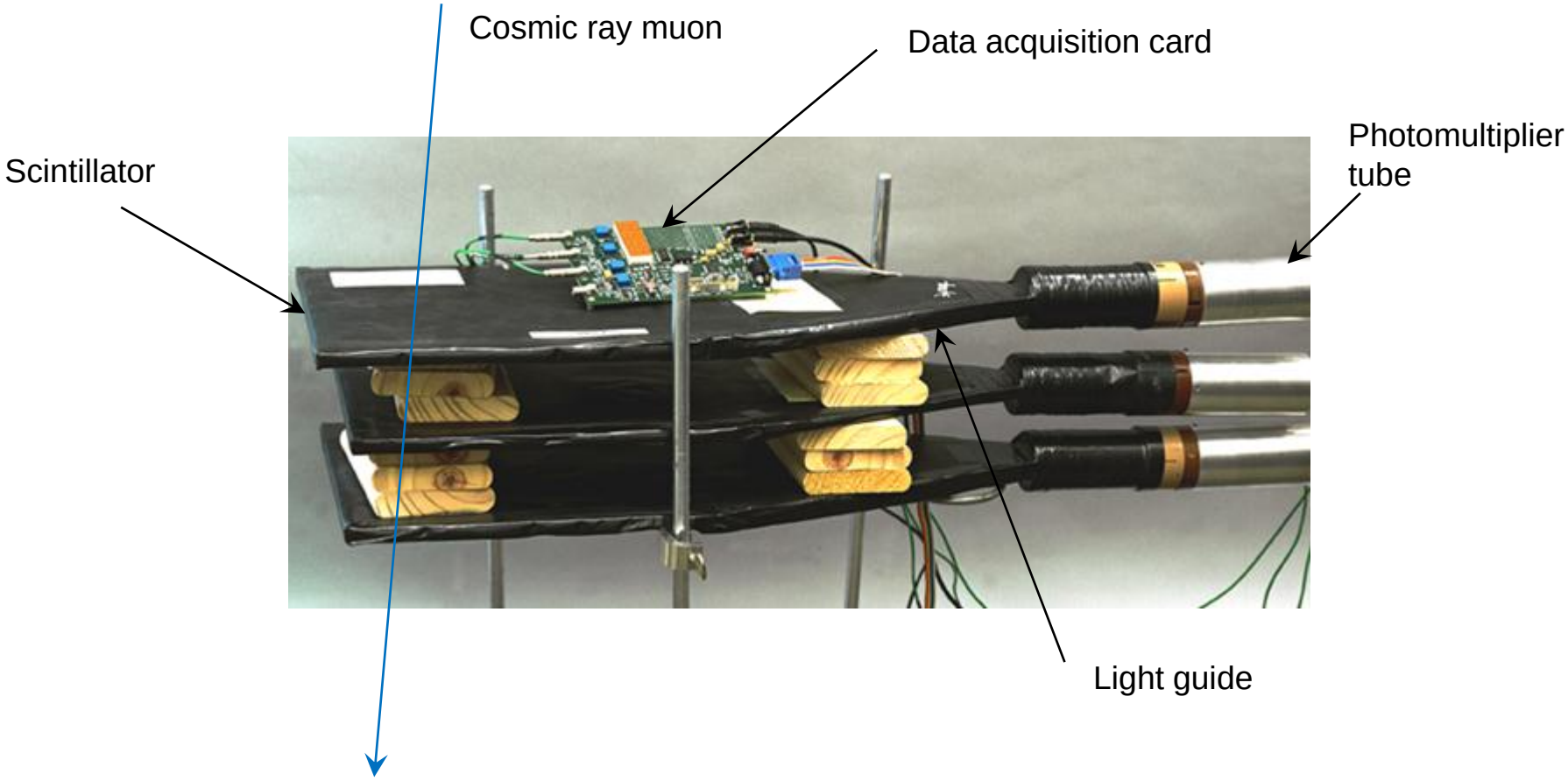


Cosmic Ray Research

- Many questions to be addressed, e.g.:
  - What is the origin of cosmic rays?
  - What accelerates cosmic rays, especially at the highest energies ($\sim 10^{19}$ eV)?
  - How do they propagate?
  - Can we point back to cosmological sources?
  - What can we learn about cosmology (large scale structure) and particle physics from cosmic rays?
  - . . . Lots of good info at Pierre Auger Observatory home page

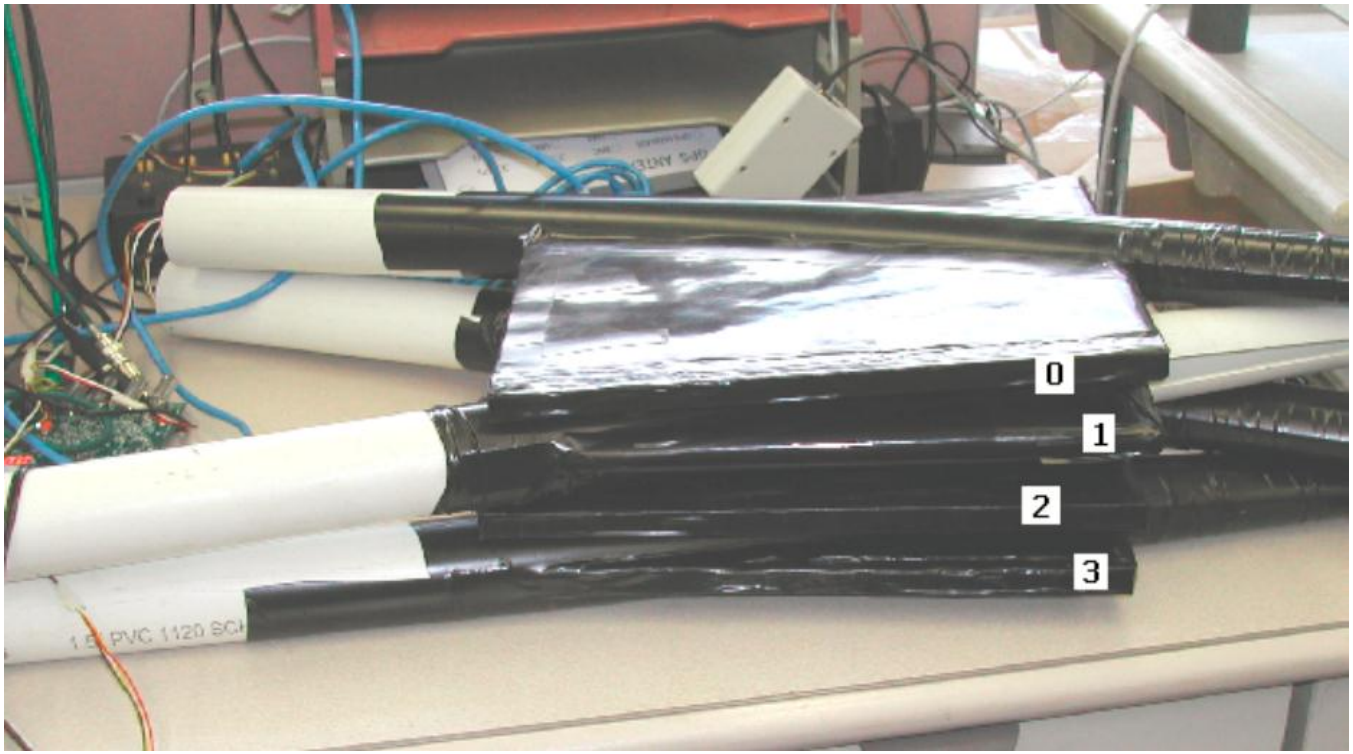
Quarknet Cosmic Ray Detector

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



Series 6000 Cosmic Ray Detector

- New design: PM tubes housed in plastic piping



Series 6000 Cosmic Ray Detector

1. Counters – Scintillators, photomultiplier tubes and PVC housing.
2. BNC signal extension cables.
3. QuarkNet DAQ data acquisition board.
4. CAT-5 network cable.
5. GPS module.
6. GPS antenna.
7. Temperature sensor.
8. 5 VDC power supply.
9. PDU power cable.
10. Power distribution unit, PDU.
11. Power extension cables for PMTs.
12. USB cable.
13. Personal Computer.

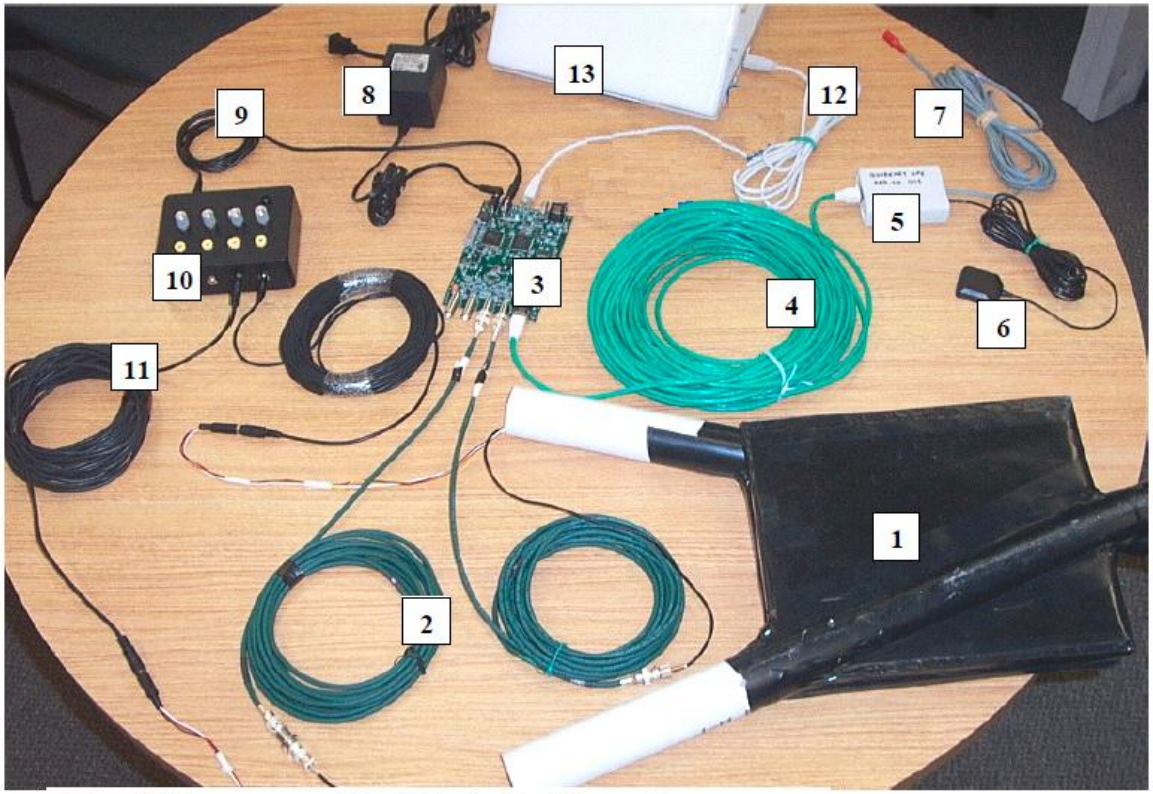
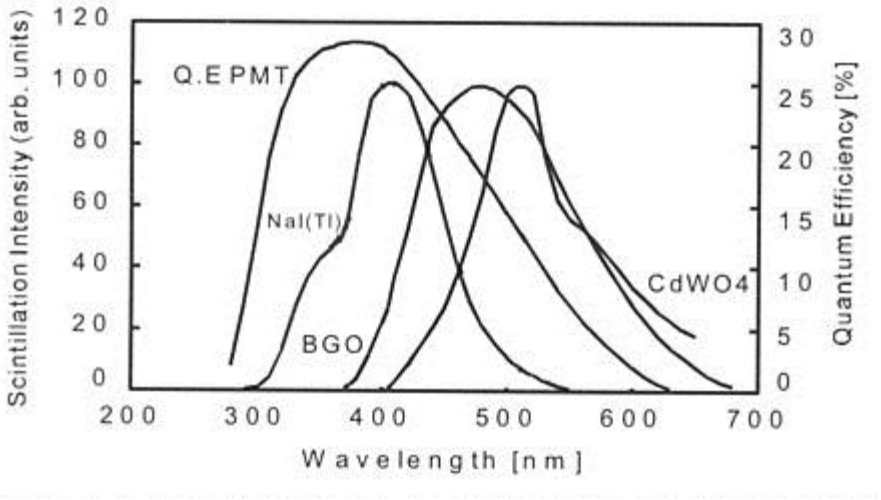
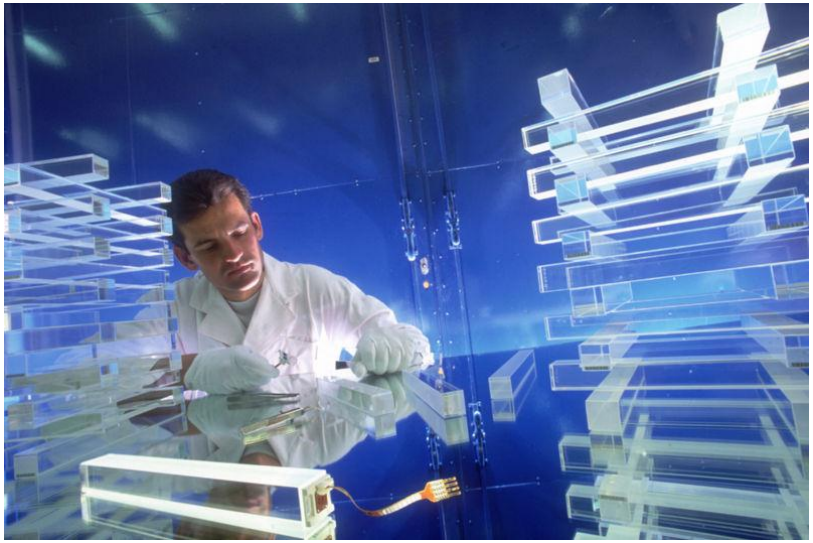


Figure 7. The components of the 6000 series QuarkNet cosmic ray muon detector.

Scintillators

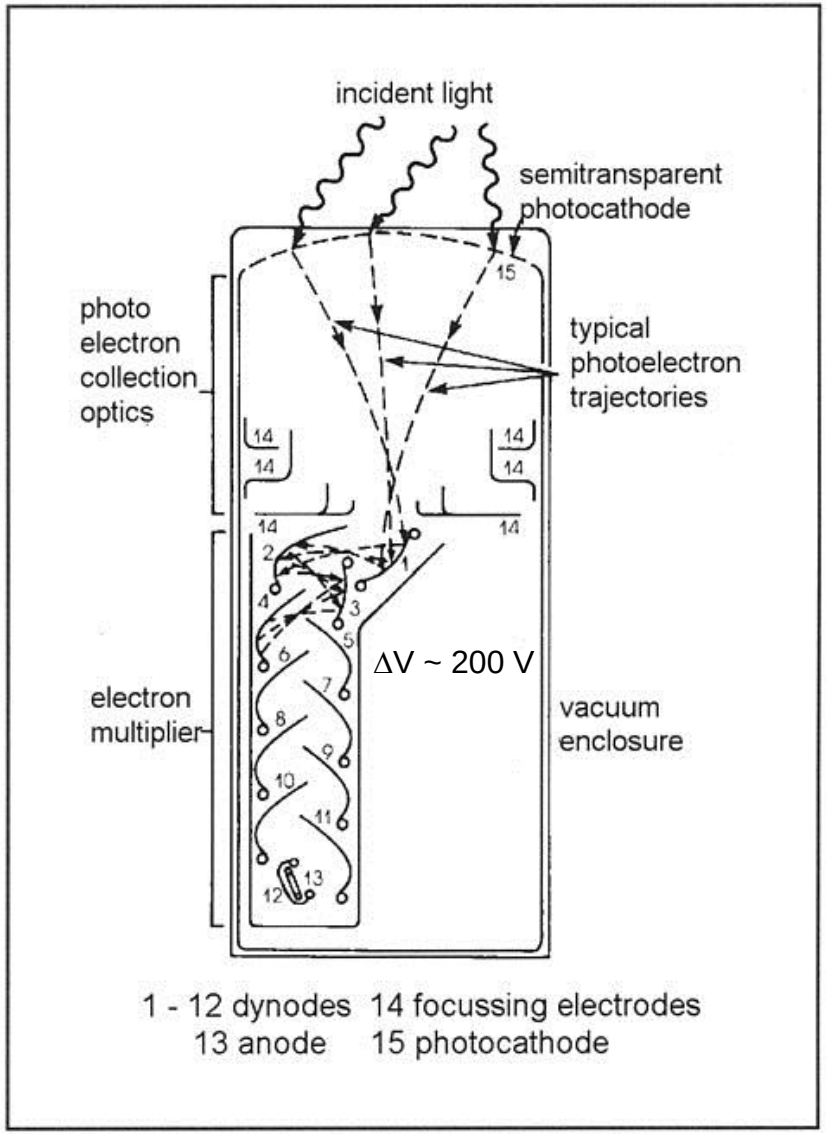
- Produce a short pulse of light in response to charged particle passing through
- Two types: inorganic and organic
- Organic scintillator (used in our detector):
  - Typically plastic doped with dye molecules
  - Mechanism is excitation of molecular levels in primary fluorescent material which decay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





Photomultiplier Tube

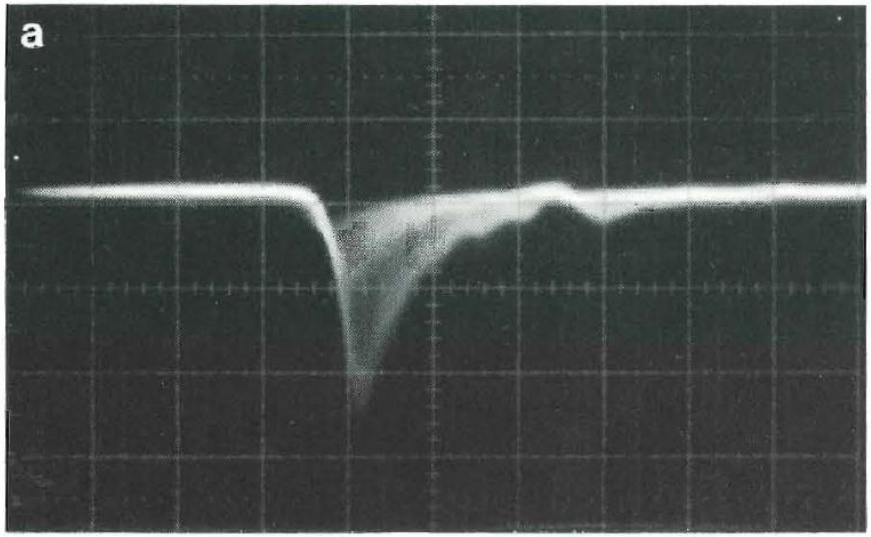
- Photon incident on photocathode
- Liberates electrons by photoelectric effect
- Electrons accelerated to 1st dynode
  - Secondary electrons emitted
- Using ~12 stages can get amplification of $\sim 10^7 - 10^8$
- Electron cascade collected at anode – induces signal
- Example: $10^8 e^- \cong 2 \times 10^{-11}$ 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

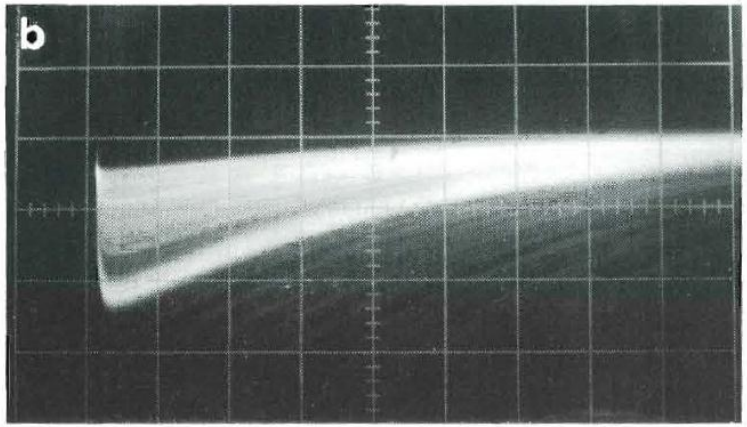
Organic Scintillator



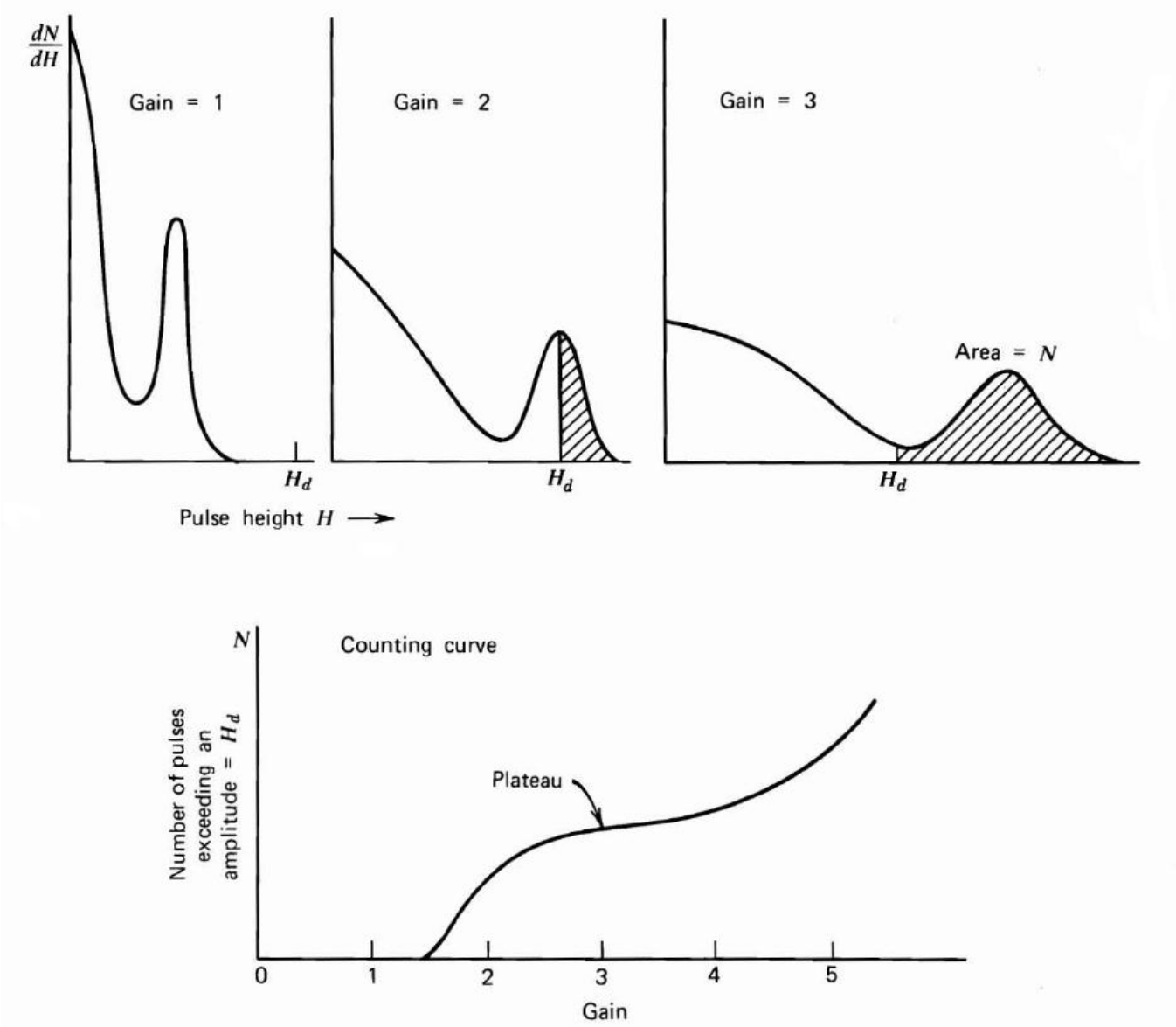
Plastic

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