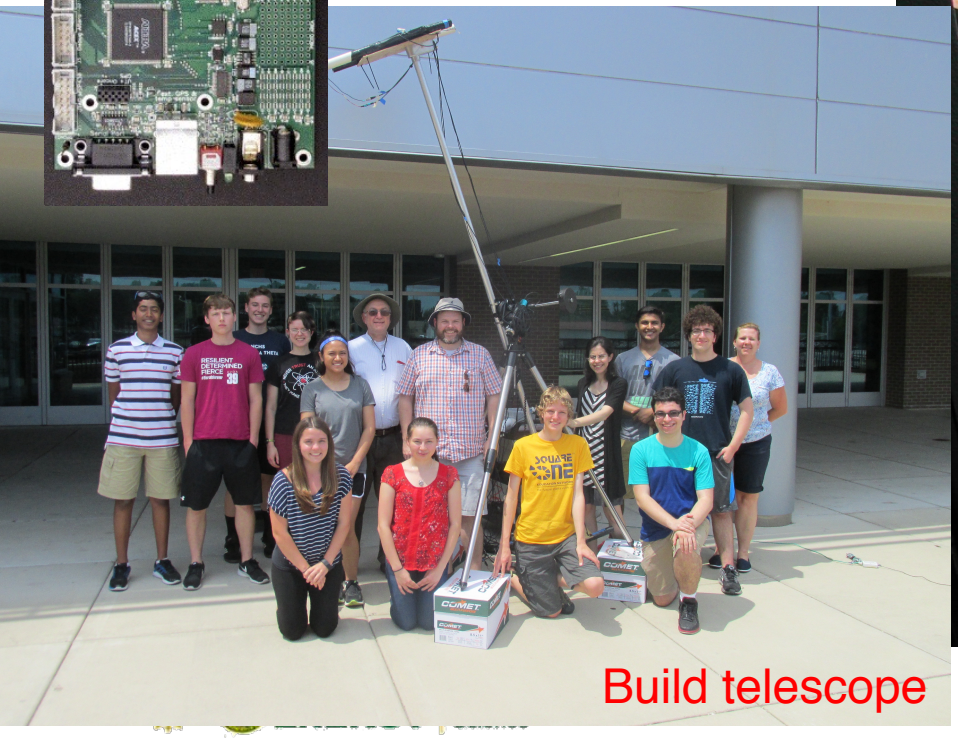
Cosmic Rays

What are they?
How do we see the invisible?

10 muons per second go through you!
You can't feel them but can detect them!

Mark Adams
QuarkNet at Fermilab

QuarkNet Detectors
High Energy Physics technology provided to high schools



Build telescope

Roof of Sears Tower

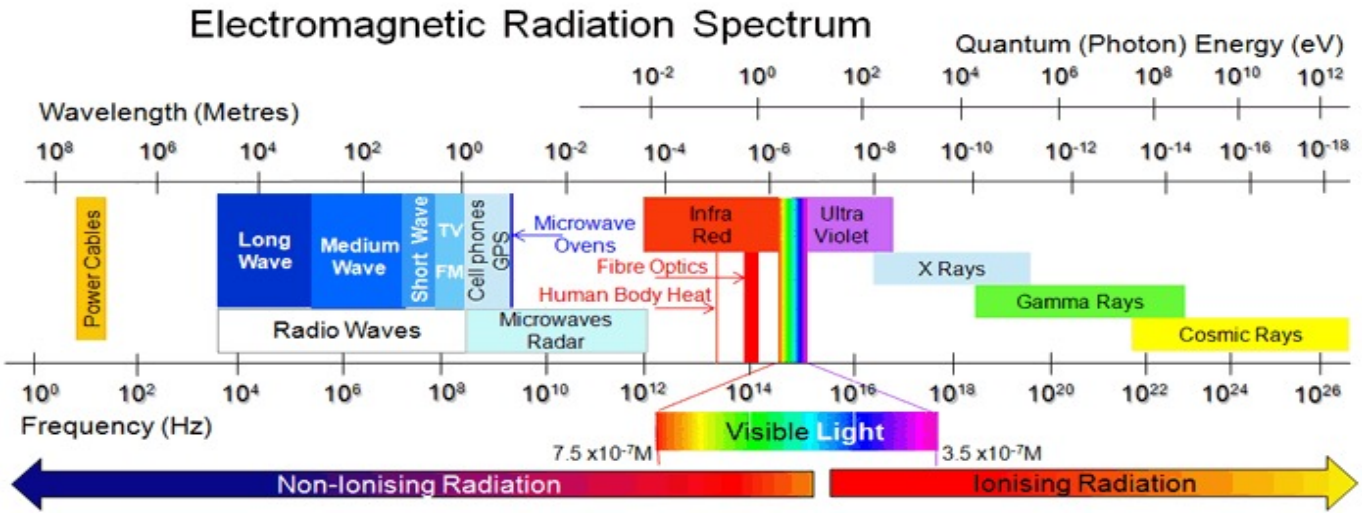
Cosmic Ray Discovery

- Cosmic Rays discovered in 1912 (Victor Hess) in balloon experiments
- Radiation higher at 5000m than at sea level – implies source hitting atmosphere
- No difference during partial eclipse – implies Sun not the source

- Really!? Cosmic rays we see on earth don’t come from the Sun?
- Why?
- They are particles with energies much higher than the energy available in the sun

How High is High Energy?

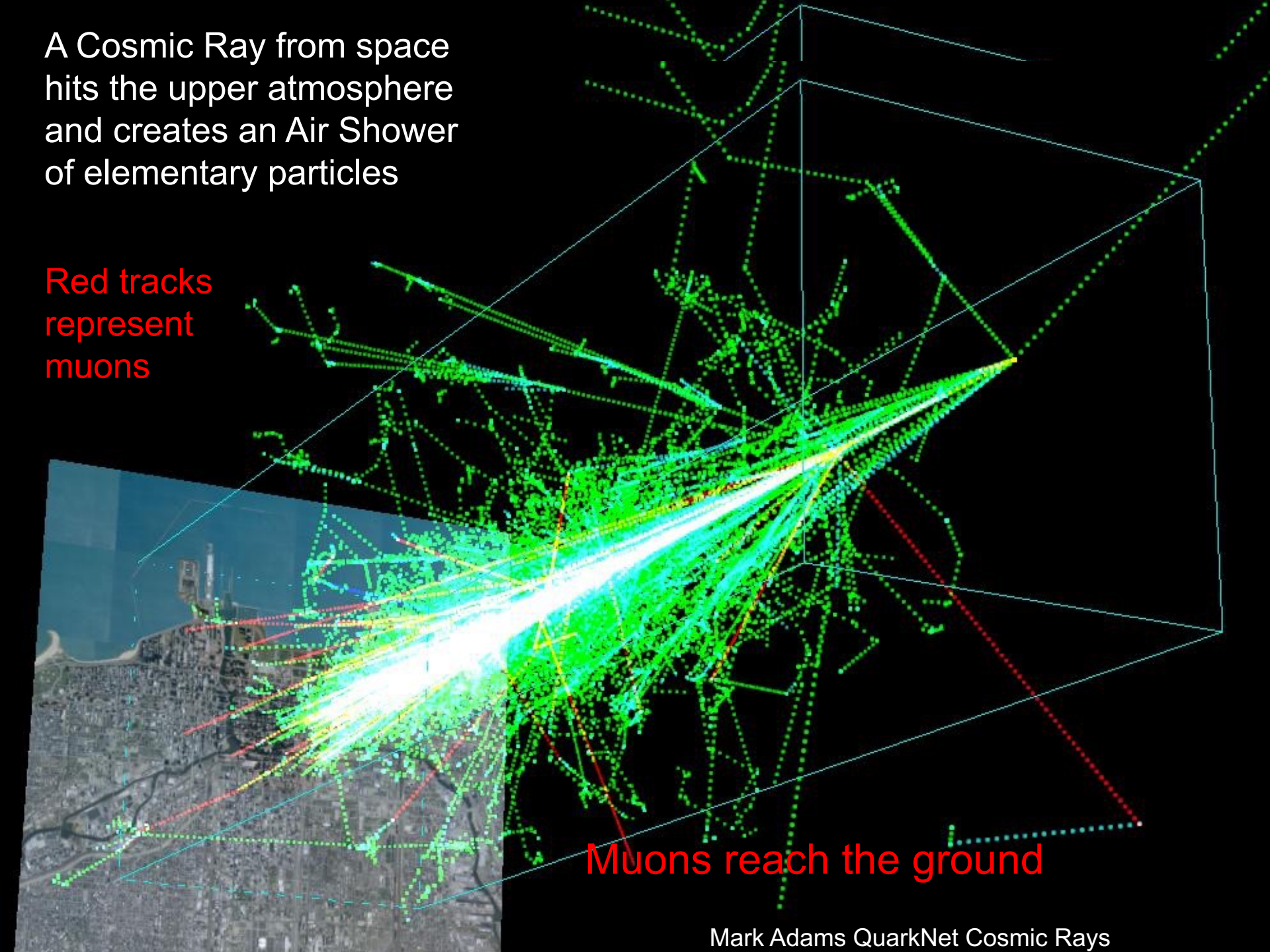
- 1 eV Sun light photons - atomic energies
- 1000 eV x-rays (keV)
- 1,000,000 eV nuclear physics in sun's core (MeV)
- 1,000,000,000 eV gamma rays (GeV)



Photons used here for energy example – but cosmic rays are charged and E > GeV

A Cosmic Ray from space hits the upper atmosphere and creates an Air Shower of elementary particles

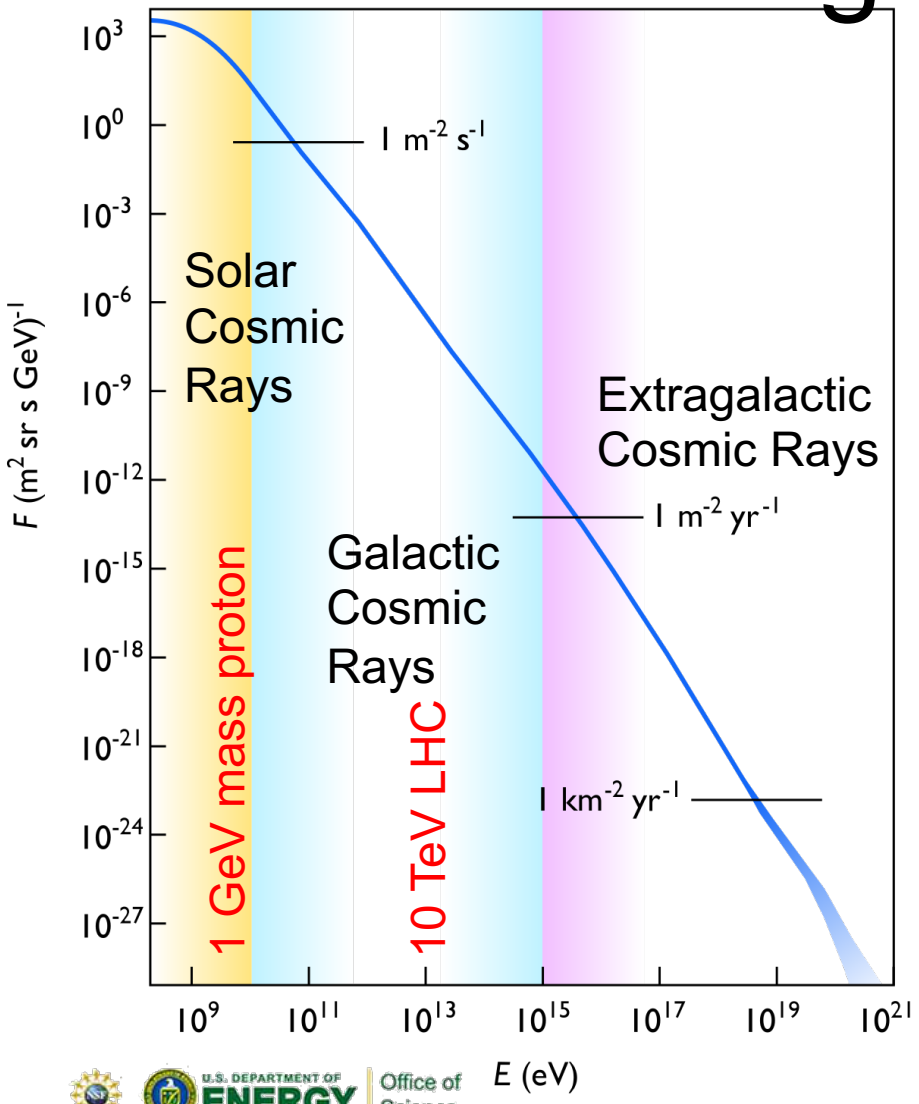
Red tracks represent muons

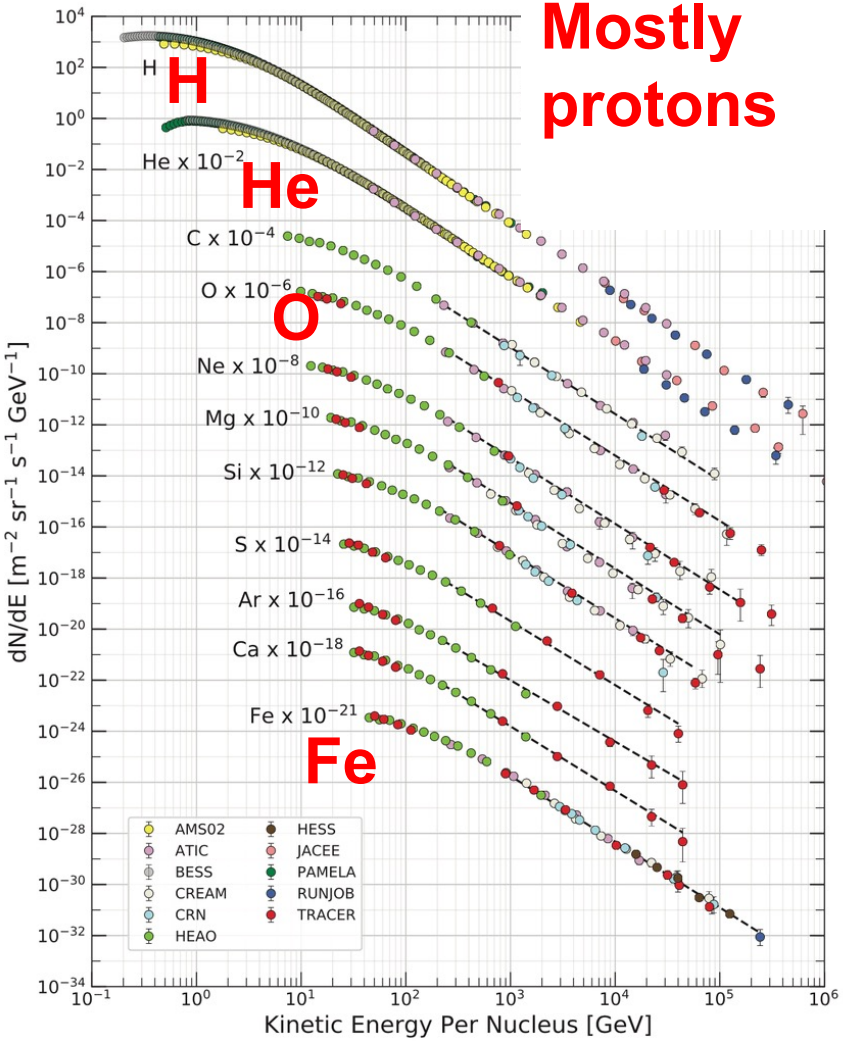


Muons reach the ground

Mark Adams QuarkNet Cosmic Rays

Cosmic Ray Rates Hitting the Atmosphere



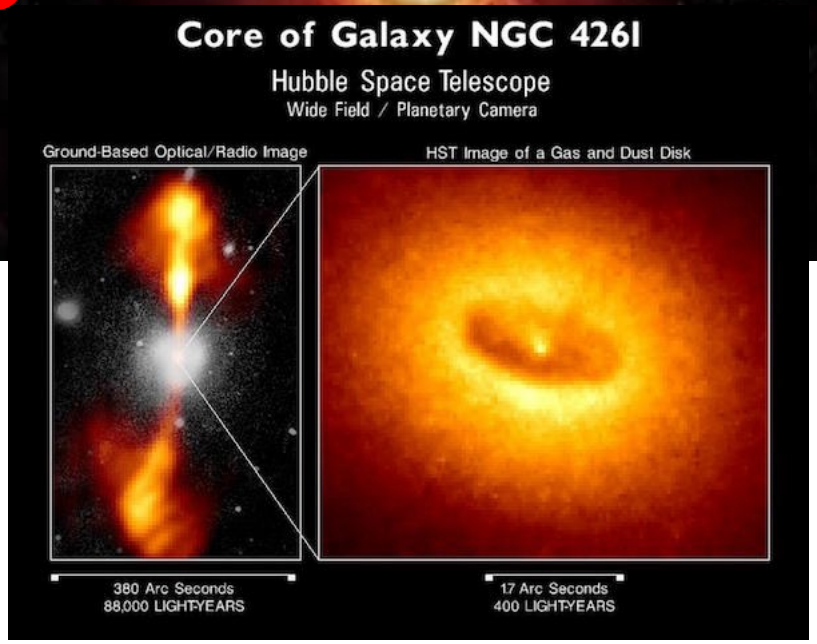


Cosmic Ray Sources

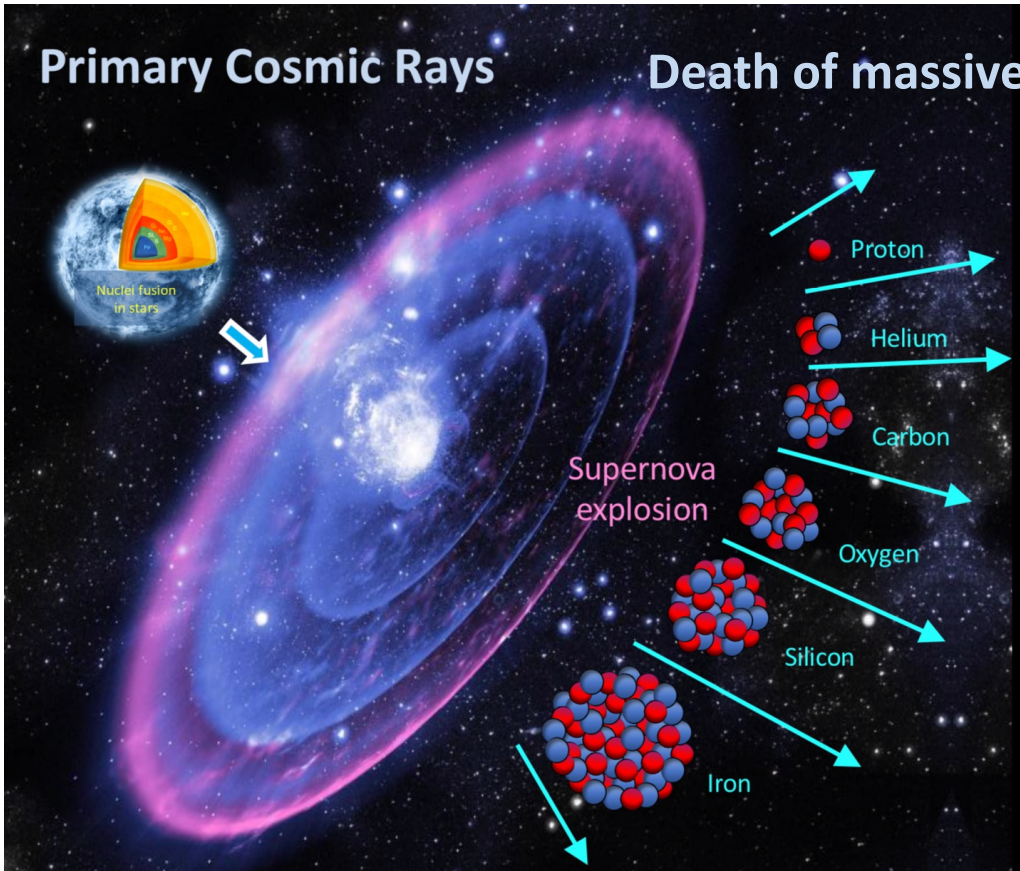
Galactic - Supernovae

Extragalactic – Active Galaxies

Natural very high energy accelerators



Source of Cosmic Rays

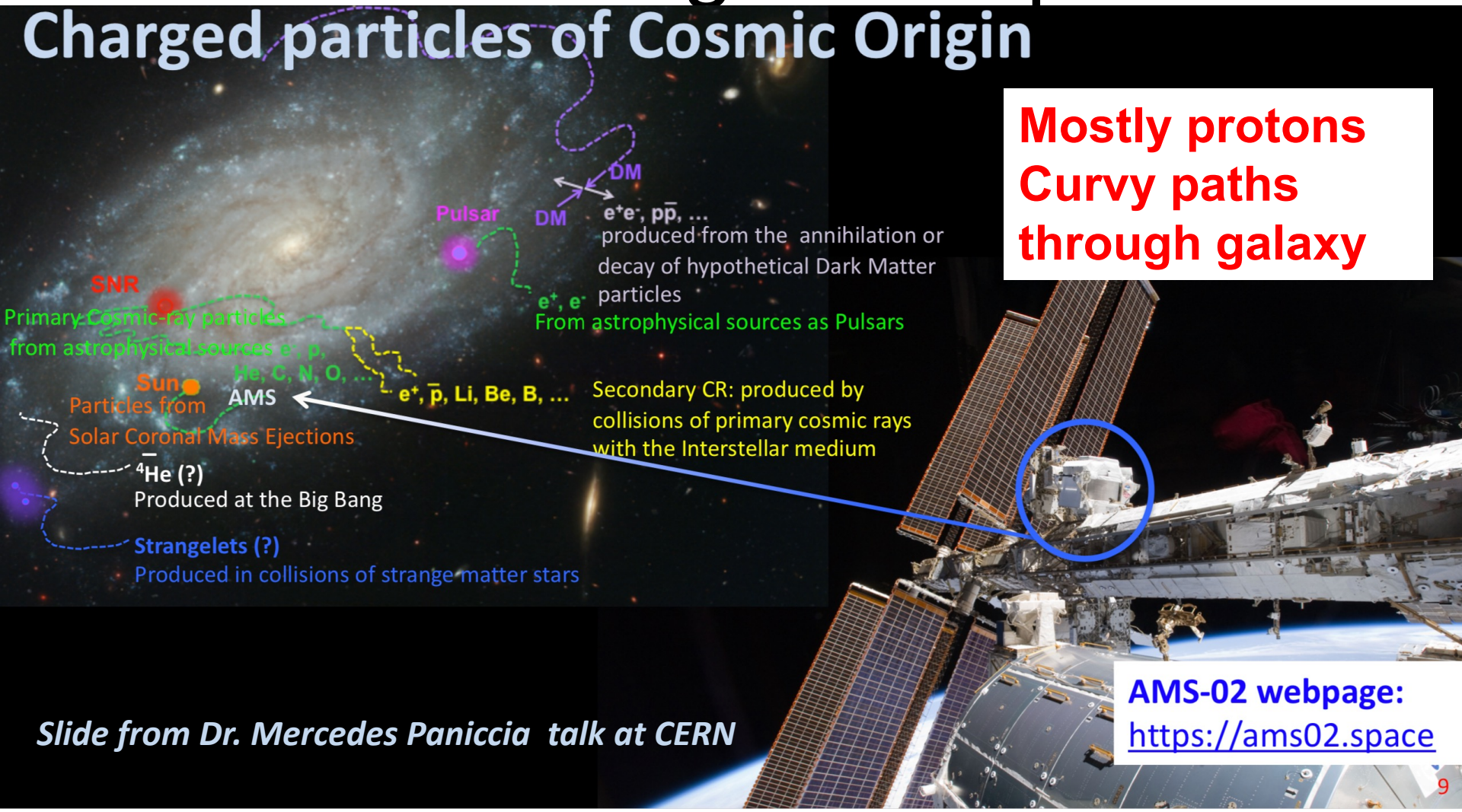


Primary elements,
protons, He, C, O, Ne, Mg, Si..., Fe nuclei
are produced
during the lifetime of stars.

They are accelerated in
supernovae explosions
and
expelled in the interstellar medium
where they propagate diffusively
through the galaxy.

Slide from Dr. Mercedes Paniccia AMS (Alpha Magnetic Spectrometer) talk at CERN

Cosmic Rays before hitting atmosphere



Cosmic Ray Summary

Cosmic Rays are high energy nuclei (mostly proton) accelerated in some extreme condition – eventually hitting Earth's atmosphere

Galactic – Exploding massive stars

Extragalactic – Massive Black Hole accelerates particles

Weird that source of this energy is Gravity

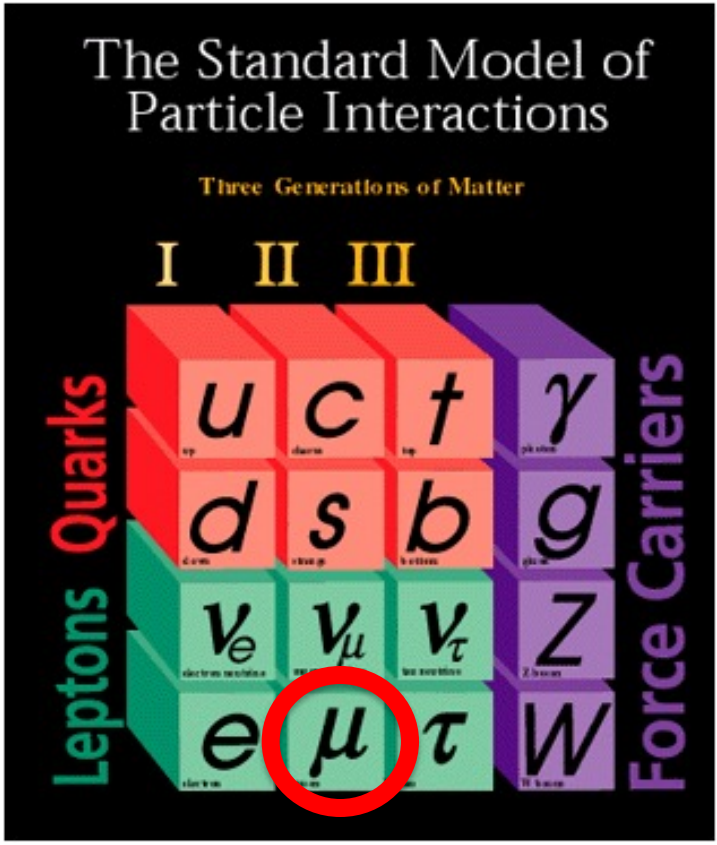
Charged – trajectory bent by magnetic fields

Can't point back to their origin

- Cosmic Ray Shower Video
- https://vms.fnal.gov/asset/detail?recid=1963802

Muons?

- Muons are created in the cosmic ray interactions with the atmosphere
- Particles that reach ground have large energies (2GeV)
- Earth's magnetic field shields us from most Cosmic Rays



Air Showers make muons

- Many particles created in collisions with atmosphere (Air Shower) ~ 15 km above surface
- Most particles interact strongly and stop
- some decay (to muons); muons live long enough to reach surface
- Muon lifetime is ~2 microseconds – at speed of light that is 600m – so, again, why do they reach the ground?
- Why do muons make it to ground?

(demonstrates Einstein's Special Relativity)

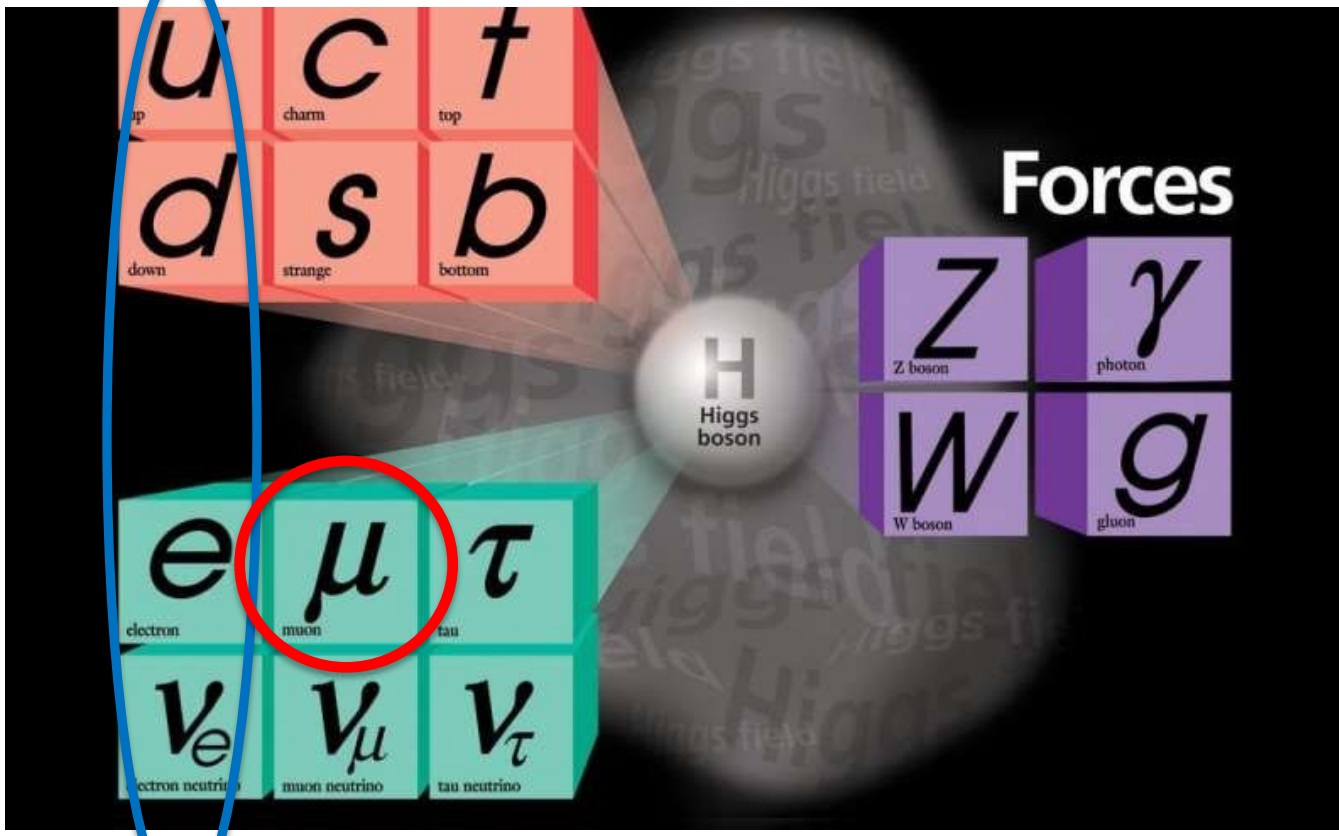
Muons at the surface

- Muons discovered (identified in air showers) in 1936 (Anderson and Neddermeyer). Rabi "Who ordered that?"
- Fundamental particle: charged, unstable lepton like a heavy (0.105 GeV) electron
- Particle sweet spot –
  - does notice nuclei (lepton); Loses energy electromagnetically through atmosphere gradually
  - **Lives long enough to reach surface**
  - Massive (unlike electron) - travels far

The Standard Model

quarks make up protons and neutrons using Strong force

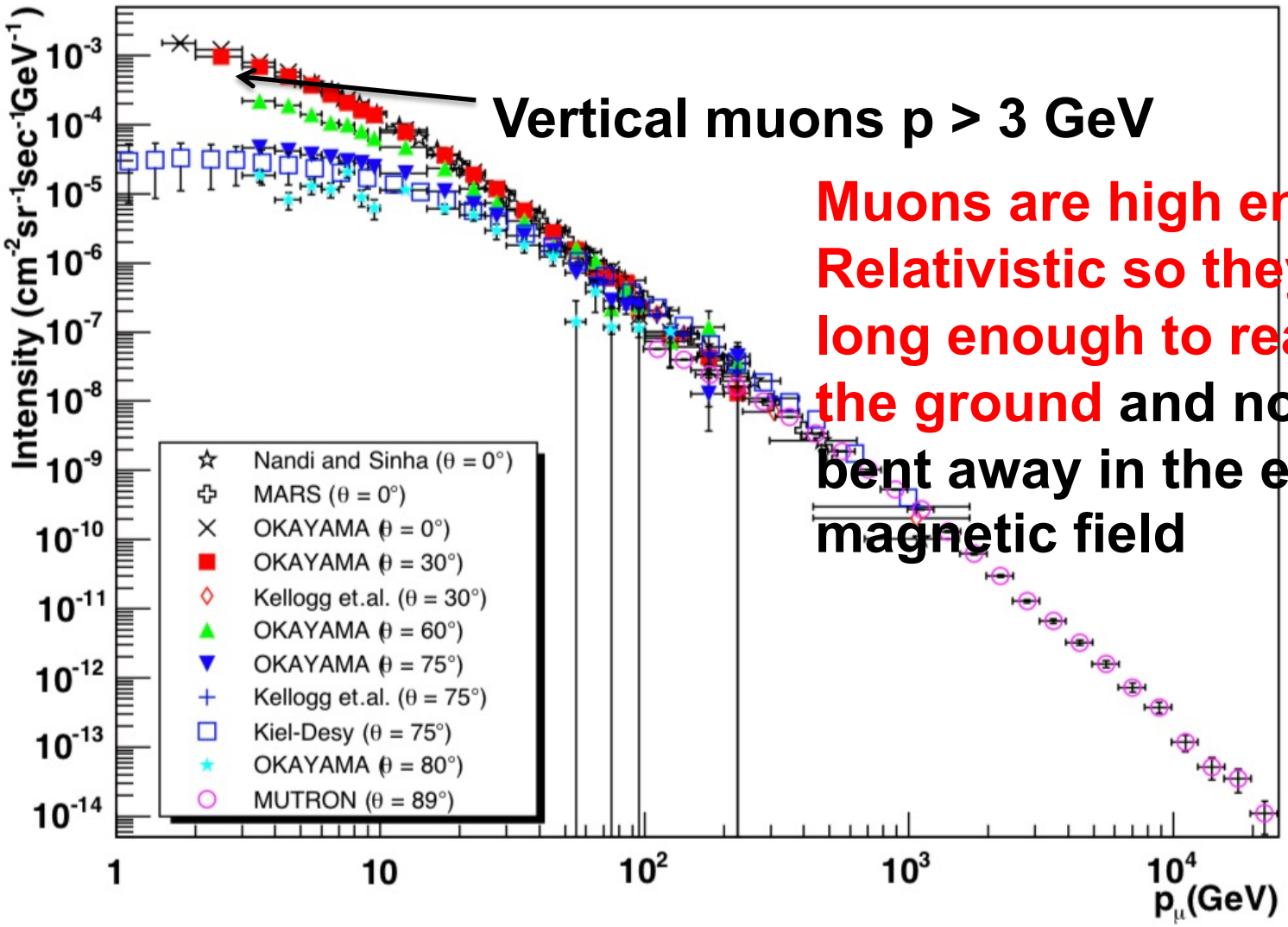
leptons don't feel the strong force



Fermions take up space

Bosons are carriers of force

Muon momentum at surface



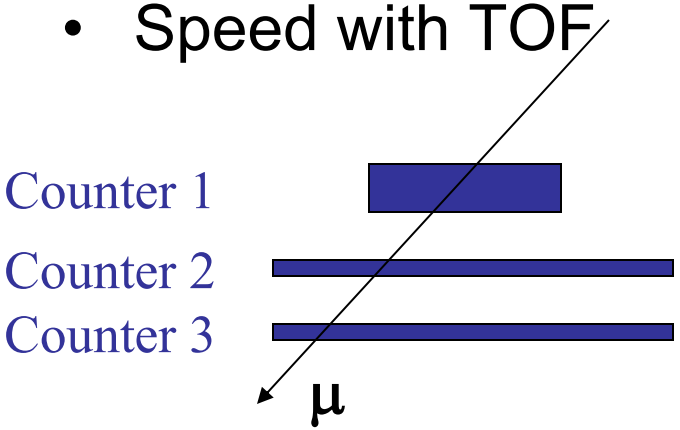
Vertical muons p > 3 GeV

Muons are high energy: Relativistic so they live long enough to reach the ground and not be bent away in the earth's magnetic field

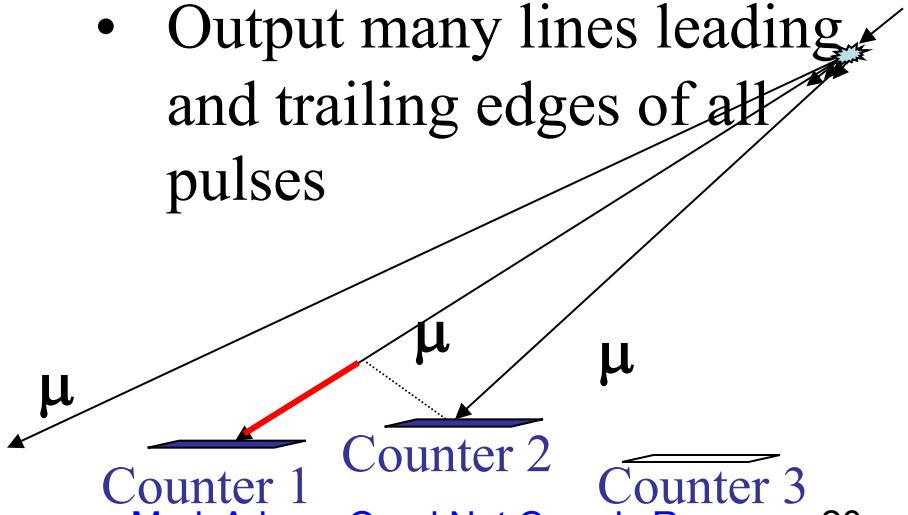
10^9 eV

Compare single and multiple muon operation

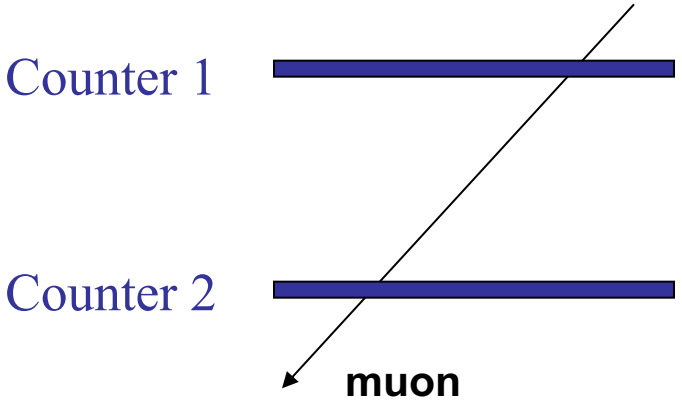
- Time Dilation; Muon Lifetime
- Single muon (plus decay)
- Energy – 1 GeV
- Trigger 3-fold vertical array
- Measure muon rates and muon decay time
- Speed with TOF



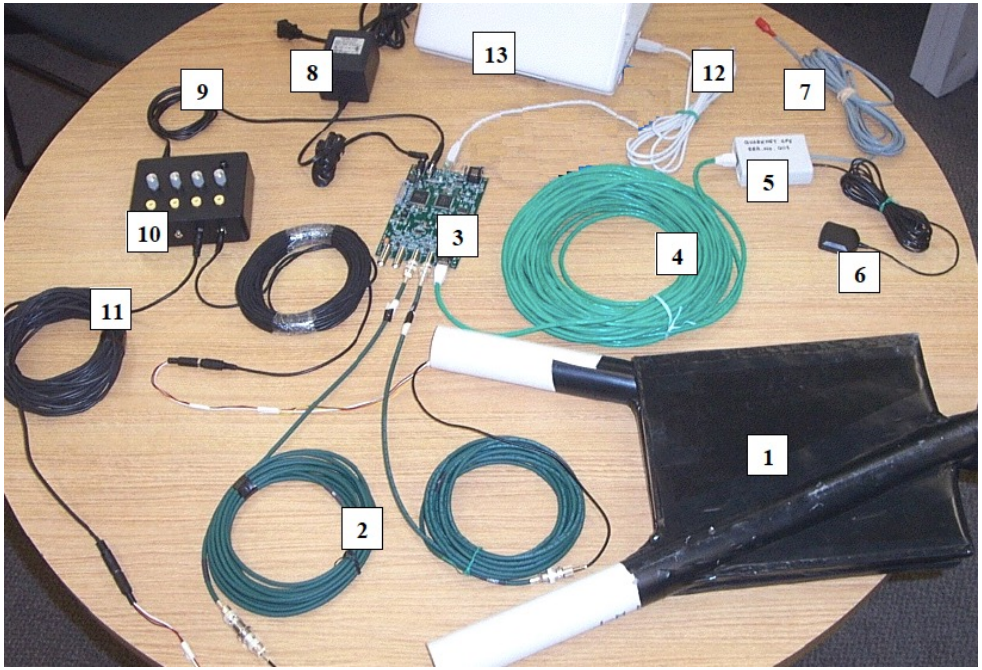
- Large Array (DAQII)
- Multiple muons - air shower
- Energy - 100 GeV
- Trigger 2 in horizontal array
- Measure rates and pattern - correlate with other arrays
- Output many lines leading and trailing edges of all pulses



QuarkNet Detector



- Single muon passes through all detectors
- Energy > 2 GeV
- Electronics selects events with 2 hit counters
- GPS gives absolute time
- A detector stack can point
- Measure Muon Speed with Time of Flight (TOF)



What can we measure?

Muons tell us about the cosmic rays, but we also can study the muons themselves

- Prove that our counters detect muons and not noise
- What direction do muons come from?
- Rates of muons versus zenith direction
- Rates of muons versus separation
- **Speed of muons**
- **Muon Lifetime**
- **Characteristics of Air Shower**
- Muon g-2; Moon Shadow; Pyramid (like your dome)

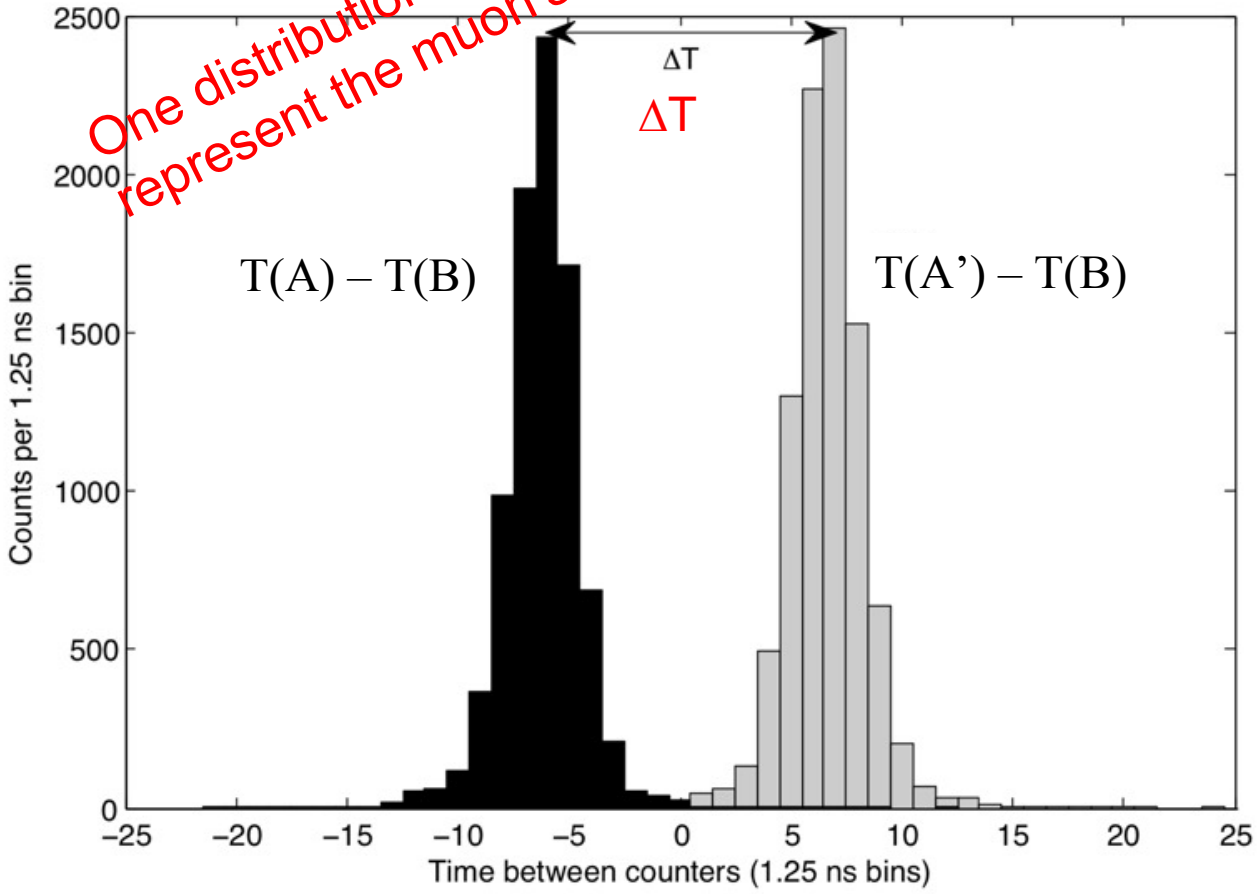
Conclusions

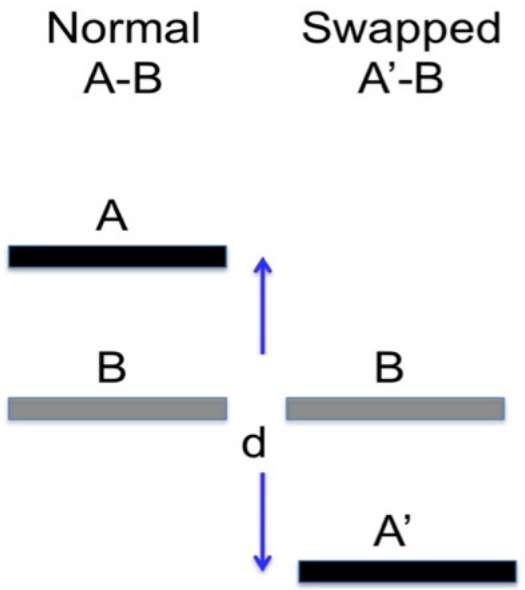
- Cosmic Rays rain down on the Earth from supernovae and Active Galaxies
- High schools use QuarkNet detectors to study cosmic rays and their resulting muons
- 100,000 files of data are available in e-Lab for all to study
- I hope you enjoy proving muons are real
- May measure maximum speed in the Universe this week

Extra Slides

Timing Distributions
muon speed

One distribution does not represent the muon's travel time





Speed = Δz/ΔT

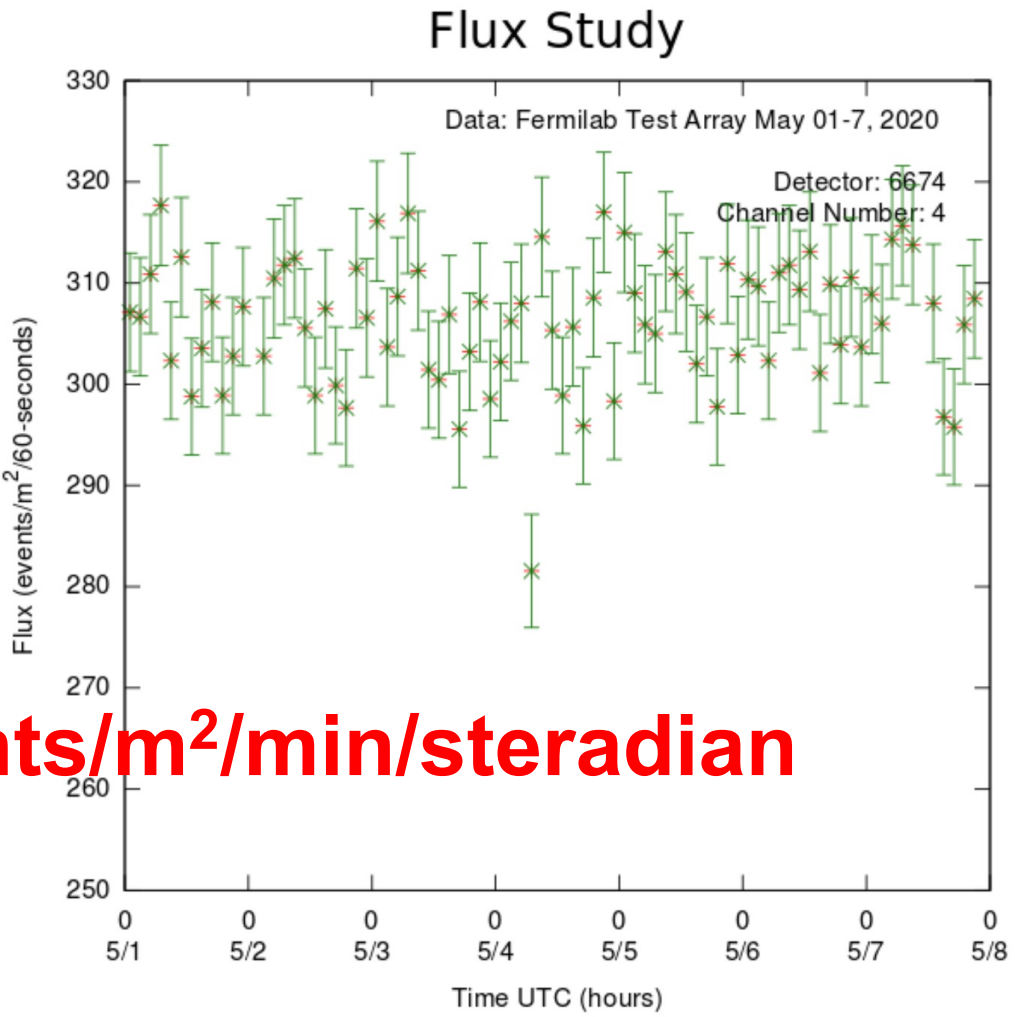
GBS HS students published a measurement of the muon's speed

Flux - Rate versus time

A week of data

Note: no big day/night effect

> Not from Sun



Number of events/m^2/min/steradian in 6-hr bins

Shower from Dense Array