



Cosmic Rays

What are they?
Where do they come from?
Let's measure for ourselves!

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QuarkNet at Fermilab



Outline

- Describe Cosmic Rays - Astronomy
- What do we see on the Earth's surface?
- Cosmic Ray Muons
- QuarkNet Detector
- **Analysis – Speed of Muon**
- Use Time of Flight between detectors
- Further studies?



QuarkNet Outreach

- High Energy Physics
- CMS, ATLAS and ALICE at the LHC CERN p-p 13 TeV
- Neutrino experiments at Fermi
- Cosmic Ray Muons
- HEP detectors and techniques brought to your school (supernovae are your accelerators)
- Muons are fundamental in all of these areas



Today's Questions

What can you study with
Cosmic Rays
using QuarkNet Detectors
and
e-Lab analysis tools?



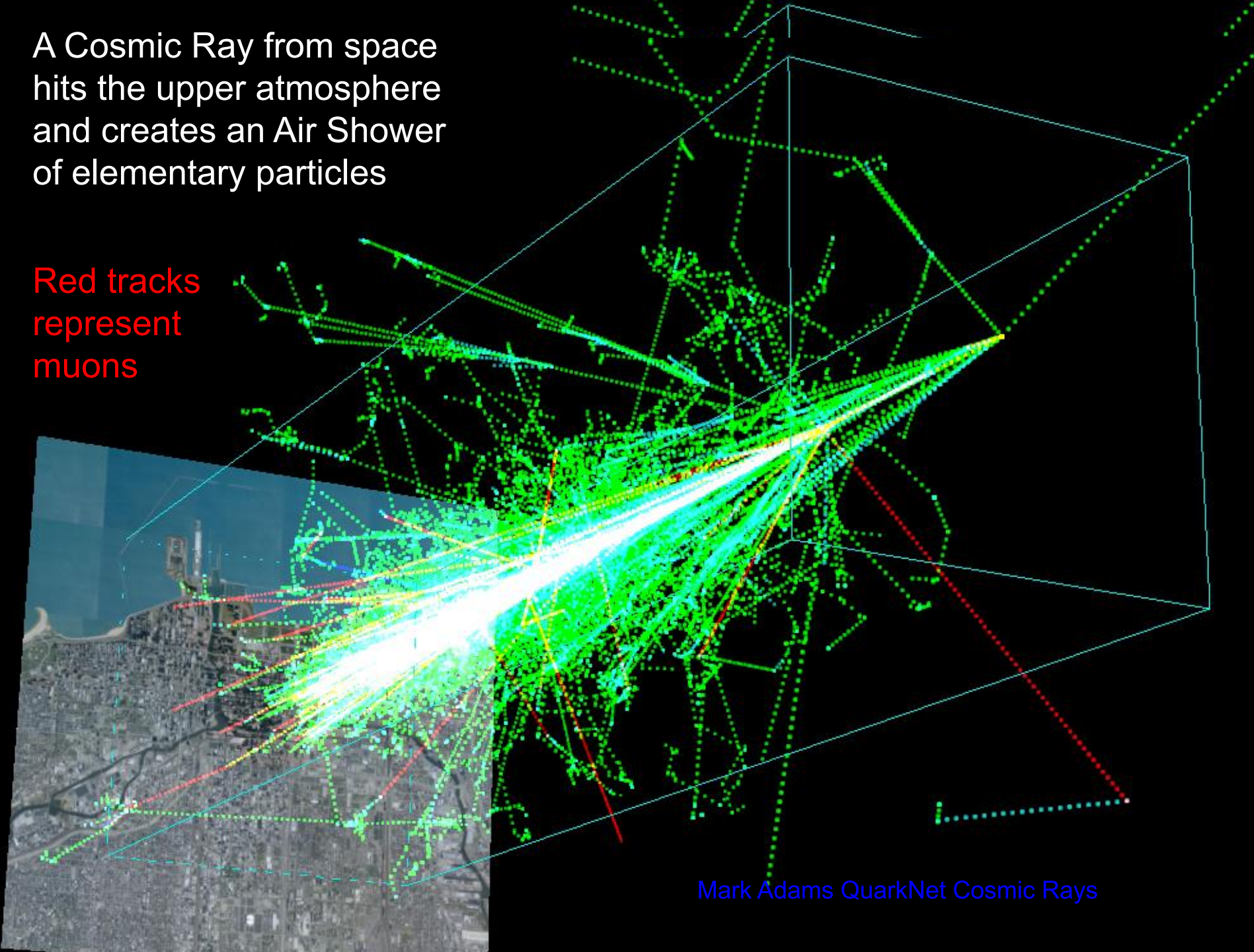
Cosmic Ray Discovery

- 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



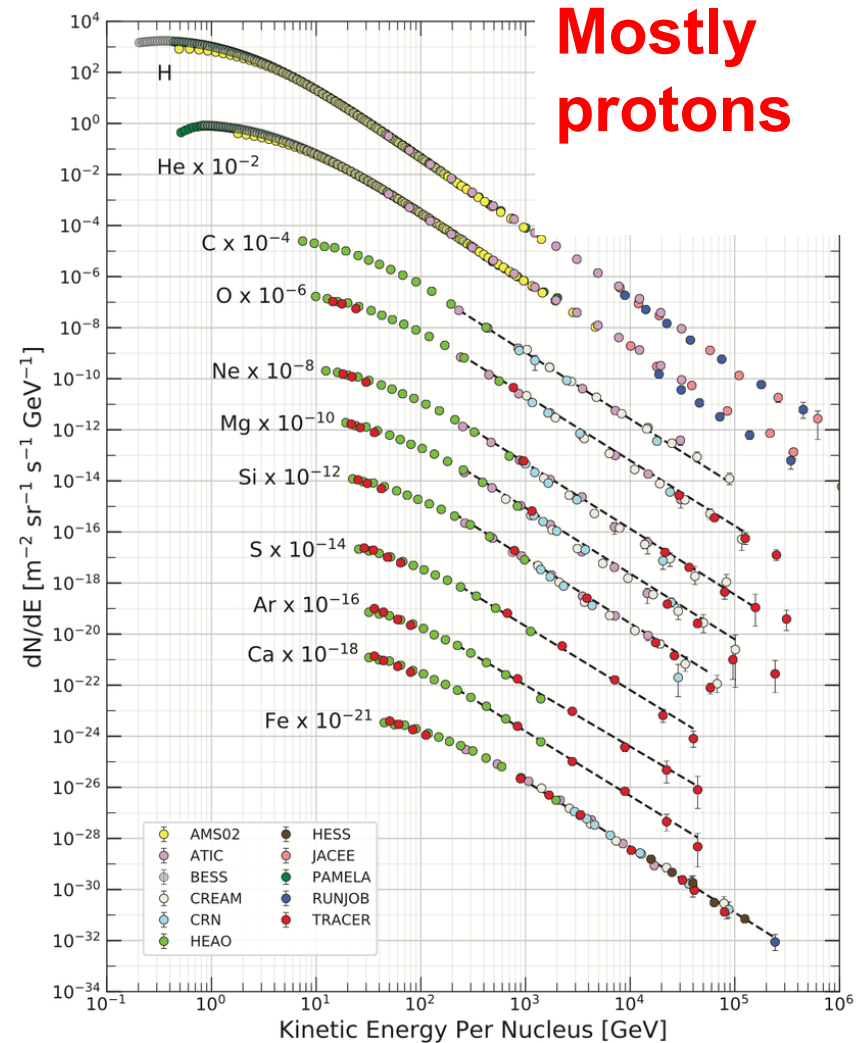
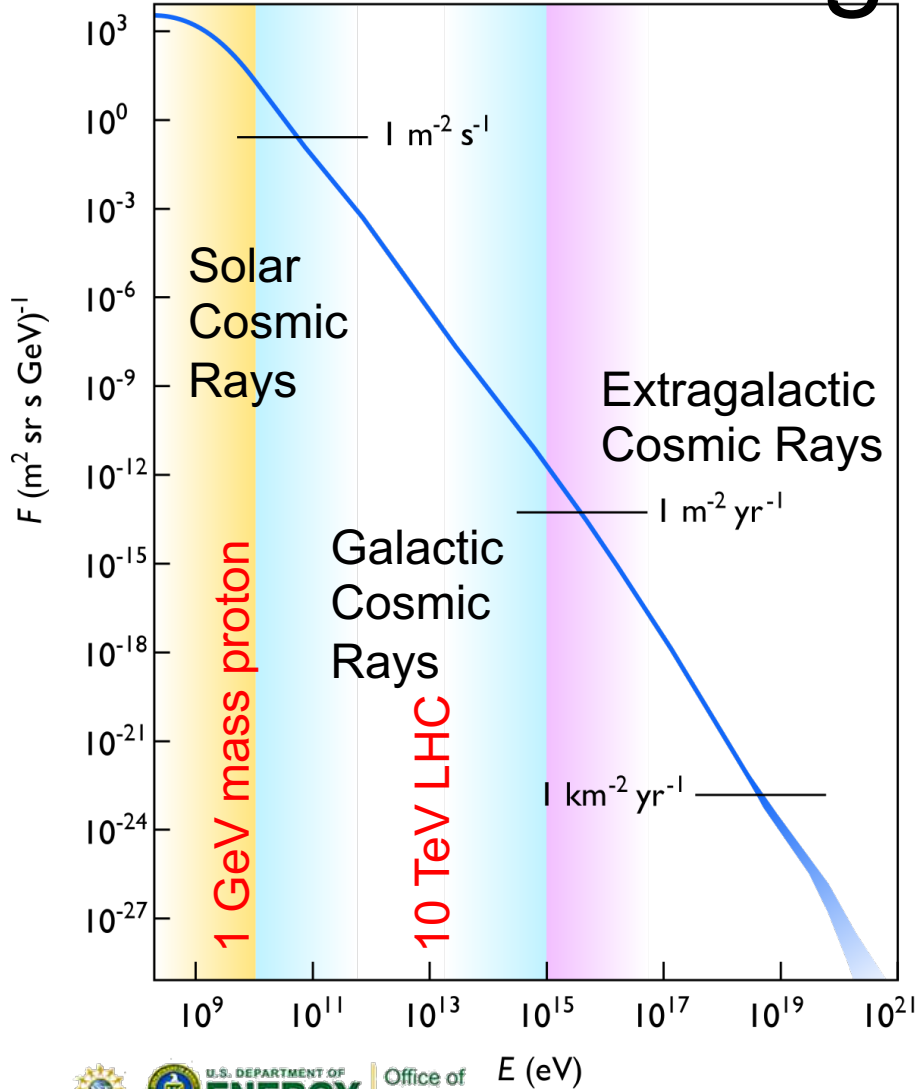
A Cosmic Ray from space hits the upper atmosphere and creates an Air Shower of elementary particles

Red tracks represent muons



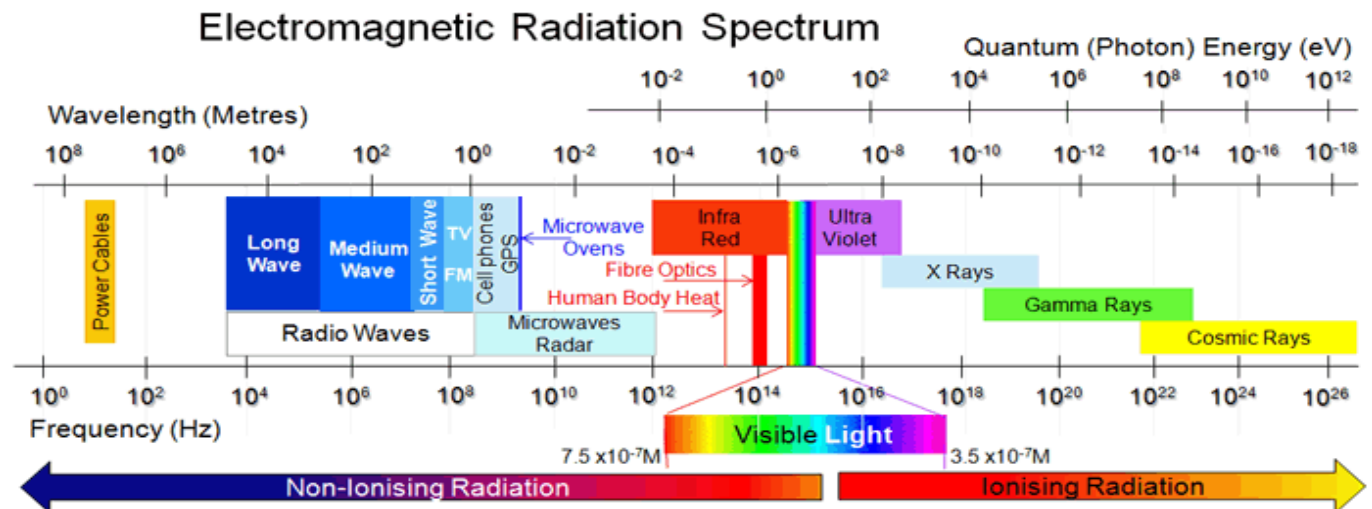


Cosmic Ray Rates Hitting the Atmosphere



How High is High Energy?

- Sun peaks with photons of energy **1 eV** -atomic energies
- **1000 eV** x-rays are from inner shell electron state
- **1,000,000 eV** nuclear energy transitions (MeV nucleus and energies in sun's core)
- **1,000,000,000 eV** gamma rays (GeV)





Energy Scales

Question – How are x-rays produced?

- A. Dental office
- B. Argonne Photon Light Source
- C. Inner shell transitions in Heavy Elements
- D. Stopping charged particles



X-rays from accelerated particles

- A. Dental office – HV accelerates electrons which hit metal plates, giving off x-ray photons
- B. Argonne Photon Light Source – Large machine accelerates electrons; magnets wiggle electron paths – Key to Covid-19 research
- C. Inner shell transitions in Heavy Elements – excited electron falls to lower inner shell state
- D. Stopping charged particles – charged particles crash into material and slow down dramatically (accelerate), radiating x-ray photons –
- E. Is why LEP(e^+e^-) didn't discover Higgs in '90s





Cosmic Ray Sources

Galactic - Supernovae



Extragalactic – Active Galaxies



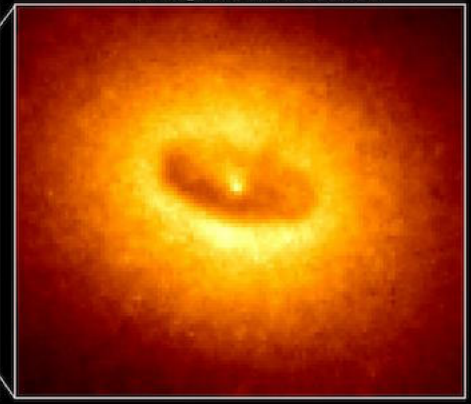
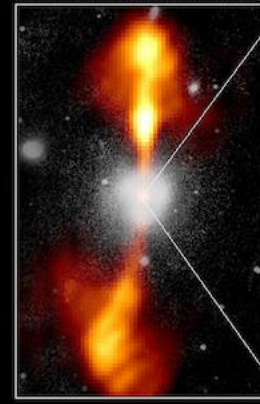
Natural very high energy accelerators

Core of Galaxy NGC 4261

Hubble Space Telescope
Wide Field / Planetary Camera

Ground-Based Optical/Radio Image

HST Image of a Gas and Dust Disk



380 Arc Seconds
88,000 LIGHTYEARS

17 Arc Seconds
400 LIGHTYEARS



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

Very poor telescope



Muons?

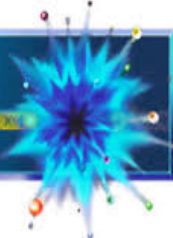
- Why haven't we discussed muons yet?
- Muons are created in the cosmic ray interactions with the atmosphere
- They have large energies (>2 GeV)



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
- Why do muons make it to ground?

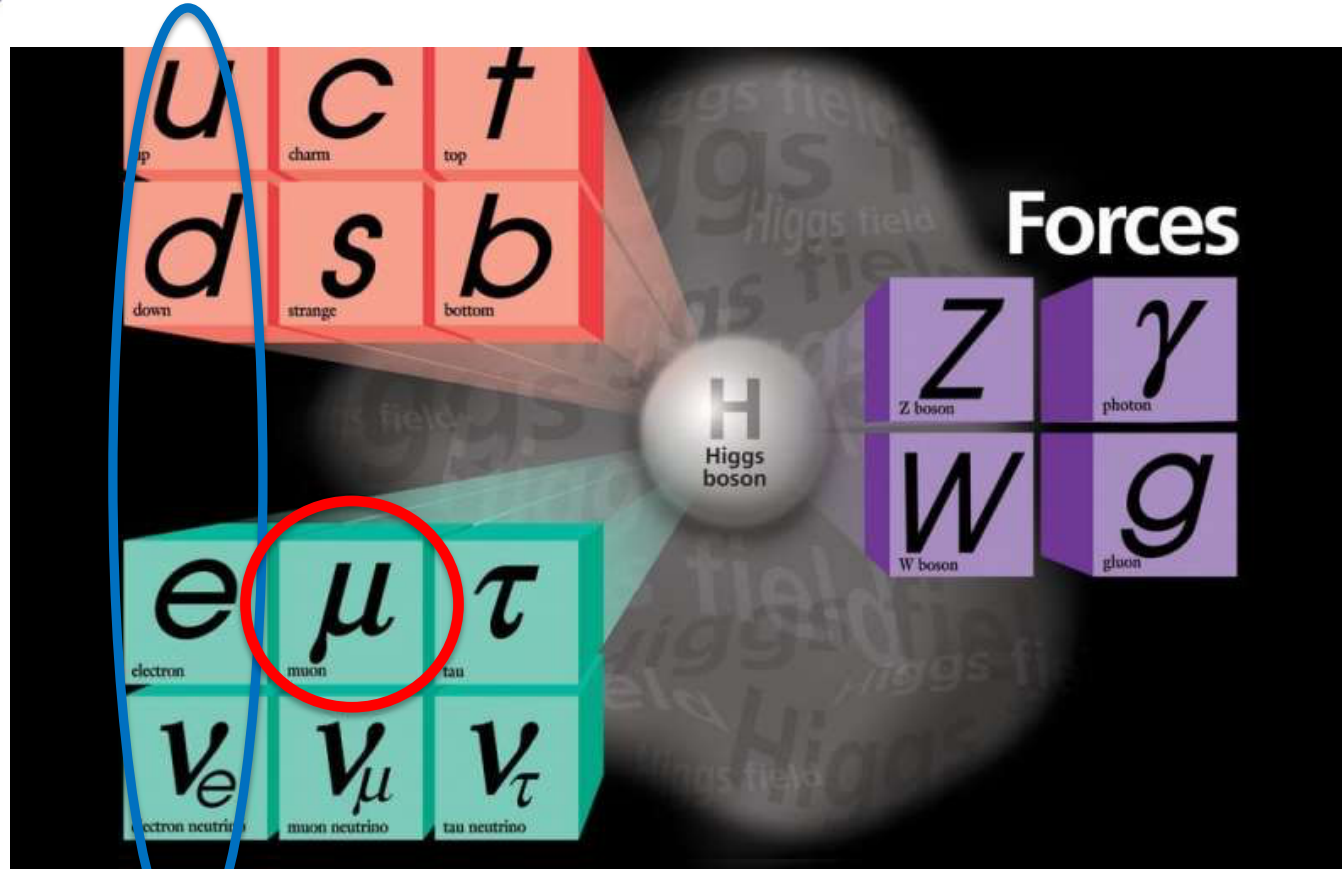
(demonstrates Einstein's Special Relativity)



The Standard Model

quarks make up protons and neutrons using Strong force

leptons don't feel the strong force



Our world

Fermions take up space

Bosons are carriers of force



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 through atmosphere gradually
 - Lives long enough to reach surface
 - Massive (unlike electron) - travels far

TRIGGER & DATA ACQUISITION

Austria, CERN, Finland, France, Greece, Hungary, Italy, Korea, Poland, Portugal, Switzerland, UK, USA

TRACKER

Austria, Belgium, CERN, Finland, France, New Zealand, Germany, Italy, Japan*, Switzerland, UK, USA

CRYSTAL ECAL

Belarus, CERN, China, Croatia, Cyprus, France, Ireland, Italy, Japan*, Portugal, Russia, Serbia, Switzerland, UK, USA

PRESHOWER

Armenia, Belarus, CERN, Greece, India, Russia, Taipei, Uzbekistan

RETURN YOKE

Barrel: Czech Rep., Estonia, Germany, Greece, Russia
Endcap: Japan*, USA, Brazil

SUPERCONDUCTING MAGNET

All countries in CMS contribute to Magnet financing in particular: Finland, France, Italy, Japan*, Korea, Switzerland, USA

FEET

Pakistan, China

FORWARD CALORIMETER

Hungary, Iran, Russia, Turkey, USA

HCAL

Barrel: Bulgaria, India, Spain*, USA
Endcap: Belarus, Bulgaria, Russia, Ukraine
HO: India

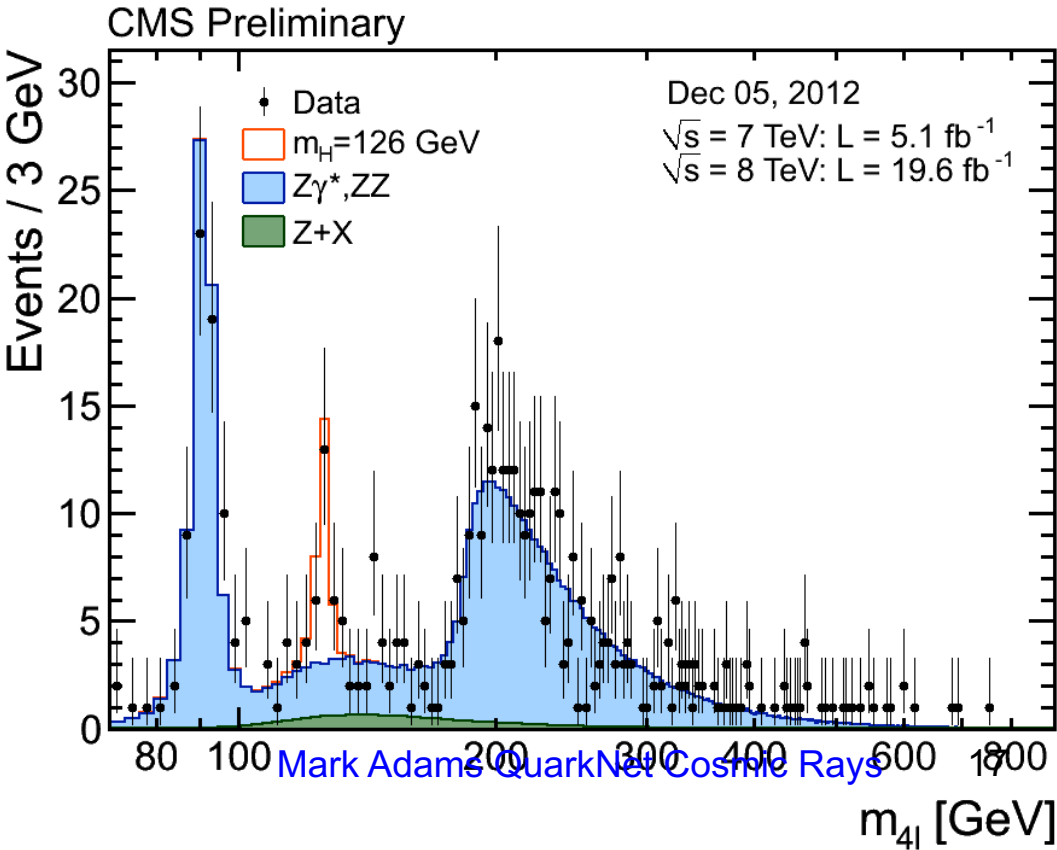
MUON CHAMBERS

Barrel: Austria, Bulgaria, CERN, China
Endcap: Ge

Total weight : 12500 T
Overall diameter : 15.0 m
Overall length : 21.5 m
Magnetic field : 4 Tesla

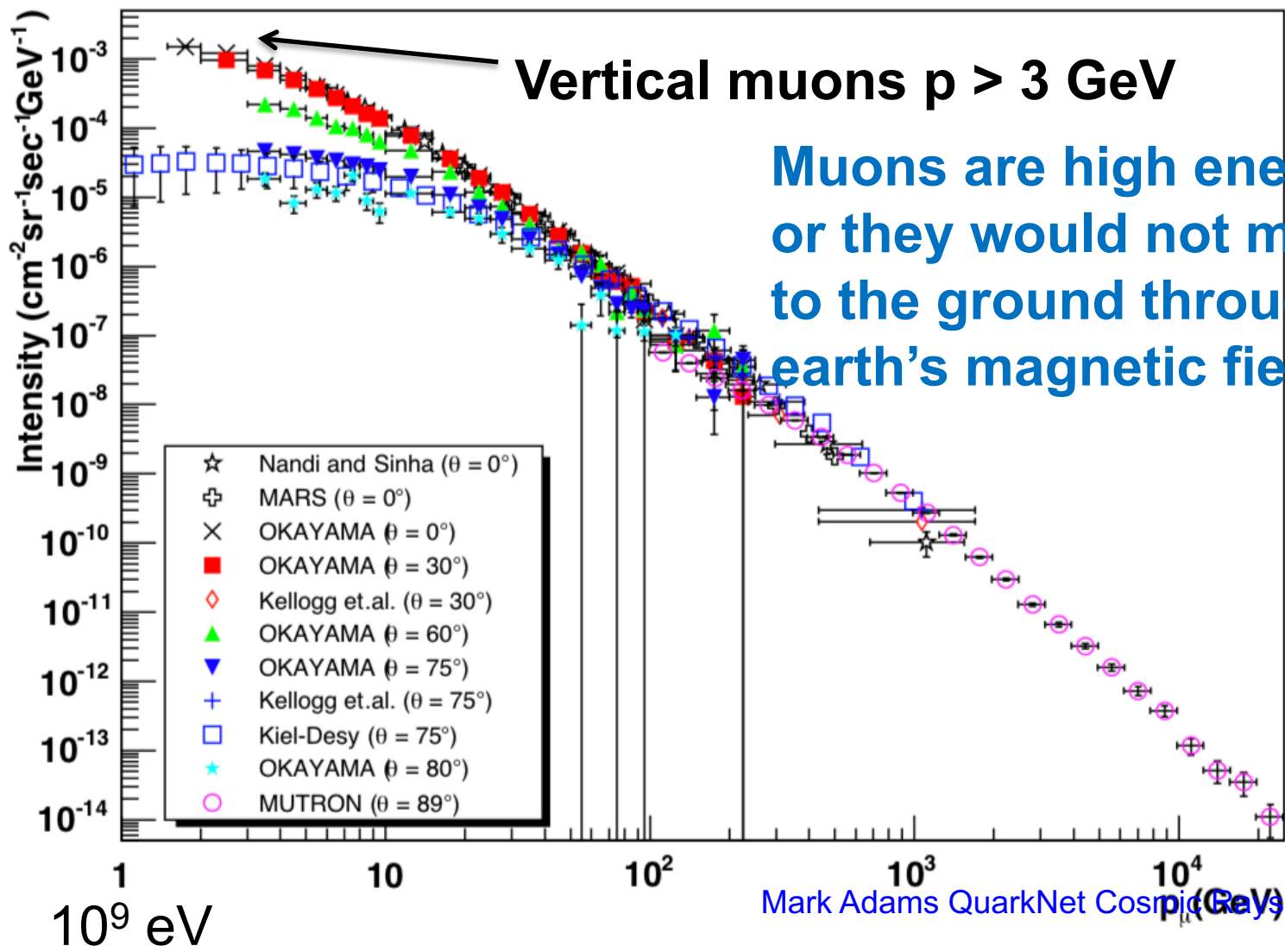
LHC experiments

Discovery of the Higgs
4 leptons – some event = $\mu \mu \mu \mu$
 μ at LHC is same as in Cosmics





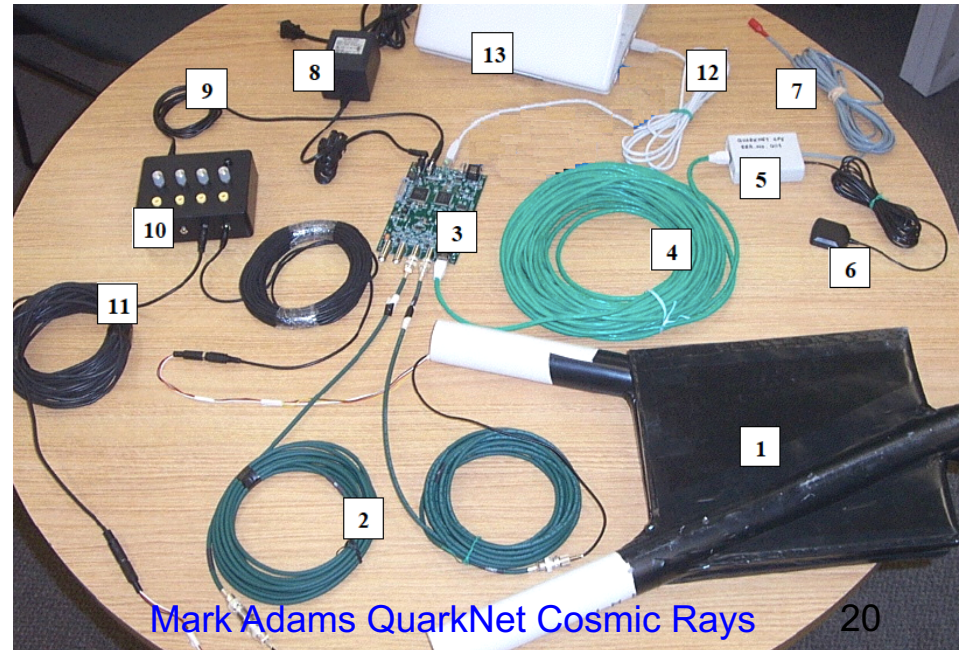
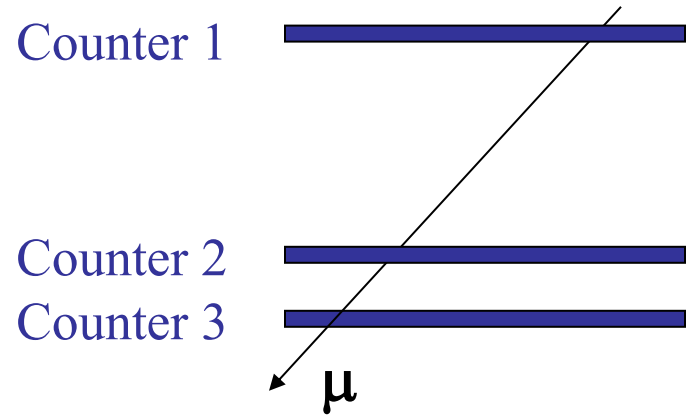
Muon momentum spectrum at surface

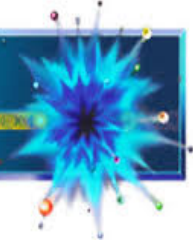




Detector QuarkNet

- Single muon passes through all detectors
- Energy > 2 GeV
- Electronics selects events with 3 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

- Rates of muons over time (day/night)
- Rates of muons versus angle
- Lifetime of muon
- Size of Cosmic Ray Air Shower
- Time Dilation
- **Speed of muons**

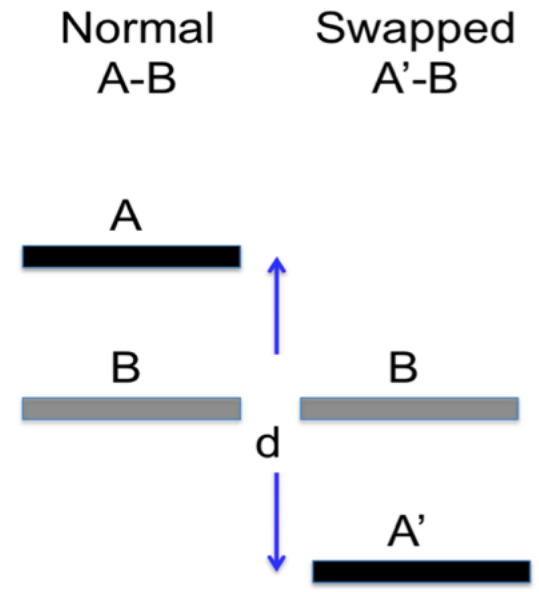
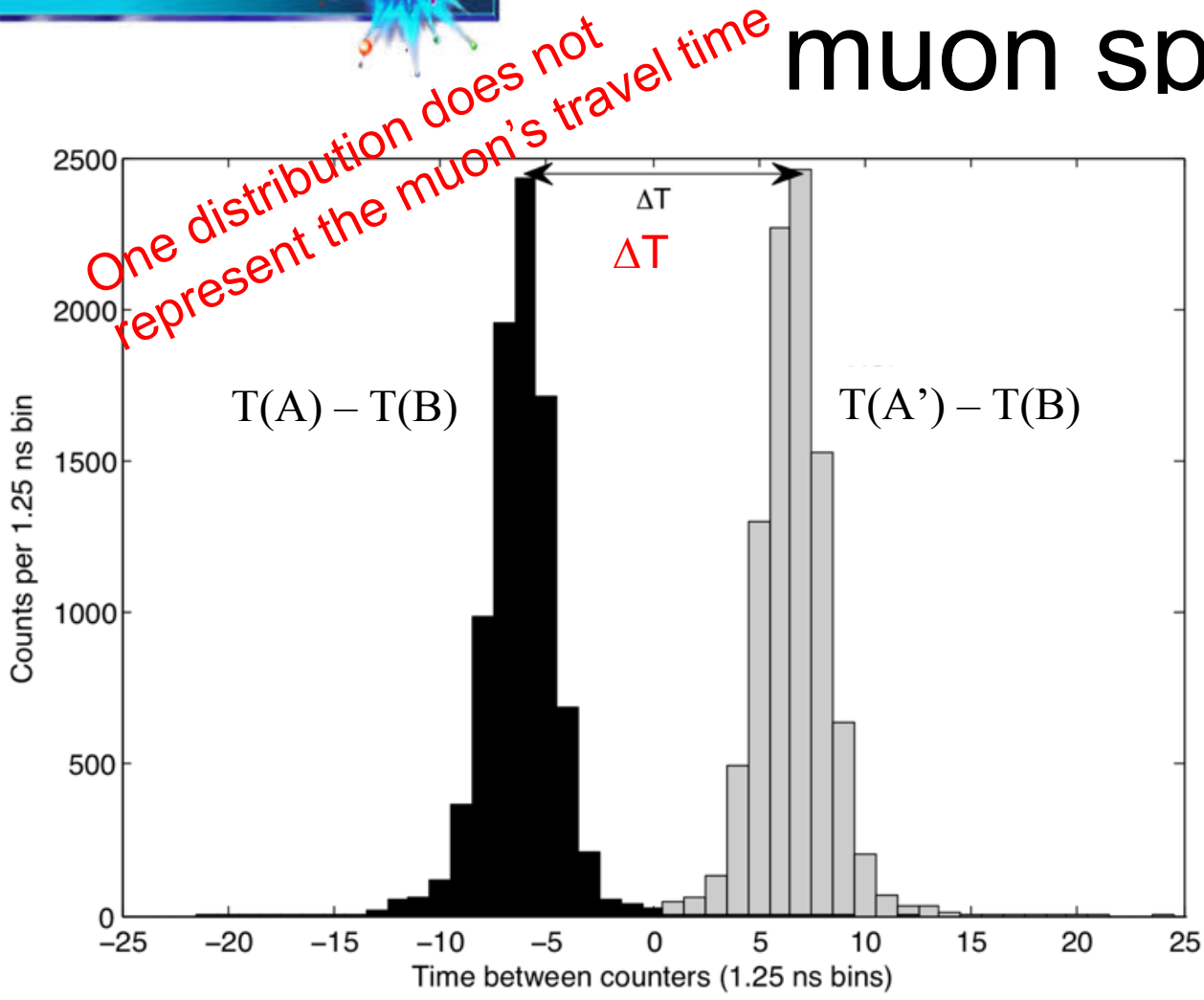


Speed of Muon

- Let's measure average speed of a collection of muons that schools have recorded with their detectors
- Ultimate speed in the universe (speed of light)
- Question to keep in mind. Why would all muons travel at the same speed?



Timing Distributions muon speed



Speed = $\Delta z / \Delta T$

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



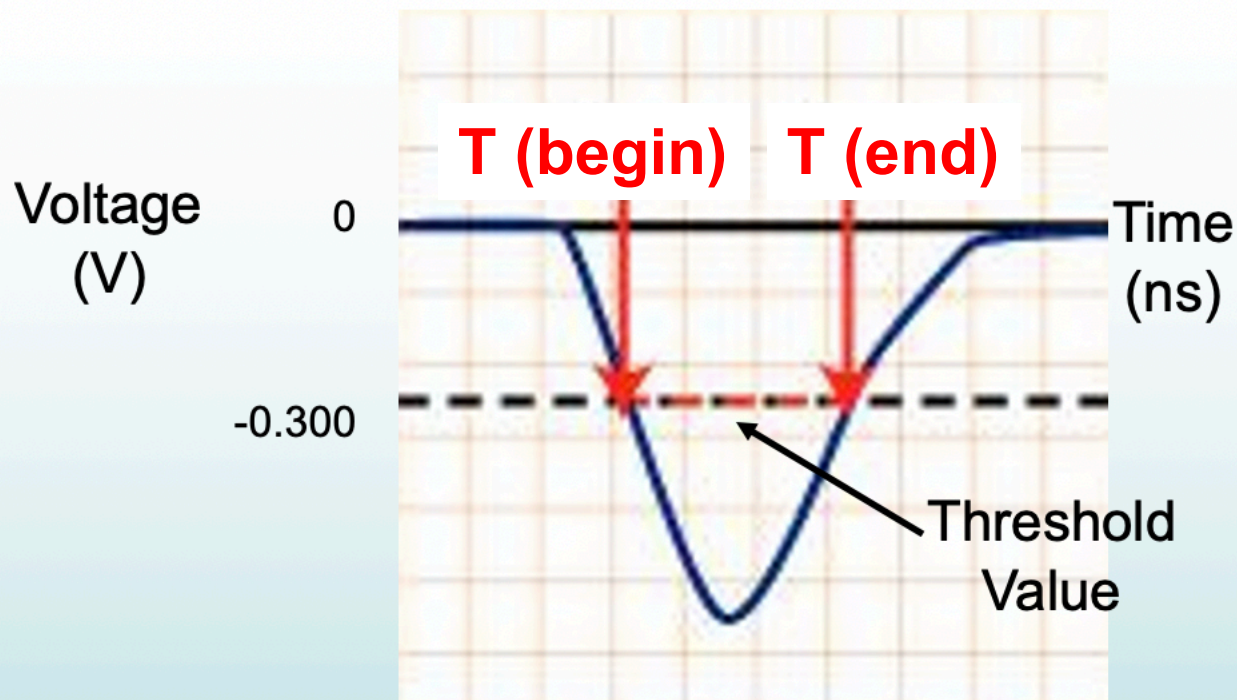
Our Muon Speed Data

- We will simplify the measurement today. Our data has had their signal cable lengths artificially adjusted in software so that $\Delta T = 0$ when the counters are next to each other (i.e. no distance between the pair for the muon to travel)
- Result is that ΔT of any pair represents the travel time for the muon



Signal vs Time

Data saved: beginning and end of pulse





QuarkNet Data Format

Time of the hit of each counter recorded to 1.25 ns precision

Interpolate between cpu ticks				Date: ddmmyy				Number of satellites			
5A49E0F4	A6 00 00 00	27 00 00 00	59289115	000002.023	010217	A 07 0	+0081	1			
5A49E0F4	00 3D 00 00	00 3C 00 00	59289115	000002.023	010217	A 07 0	+0081				
5A8F5C5C	80 00 32 00	00 00 32 00	59289115	000002.023	010217	A 07 0	+0081	2			
5A8F5C5D	00 00 00 00	00 00 00 27	59289115	000002.023	010217	A 07 0	+0081				
5A8F5C5D	00 00 00 28	00 00 00 00	59289115	000002.023	010217	A 07 0	+0081	3			
5AA6CF4C	80 00 30 00	00 00 31 00	5AA60955	000003.031	010217	A 07 0	+0081				
5AA6CF4D	00 00 00 00	00 00 00 27	5AA60955	000003.031	010217	A 07 0	+0081				
5AA6CF4D	00 00 00 29	00 00 00 00	5AA60955	000003.031	010217	A 07 0	+0081				

40ns cpu counter at trigger time

**Channel 2 LE; TE
1.25 ns Least
Counts**

**GPS 1pps latches
cpu counter**

Universa
l Time:
hhmmss

Absolute time accuracy of 100ns

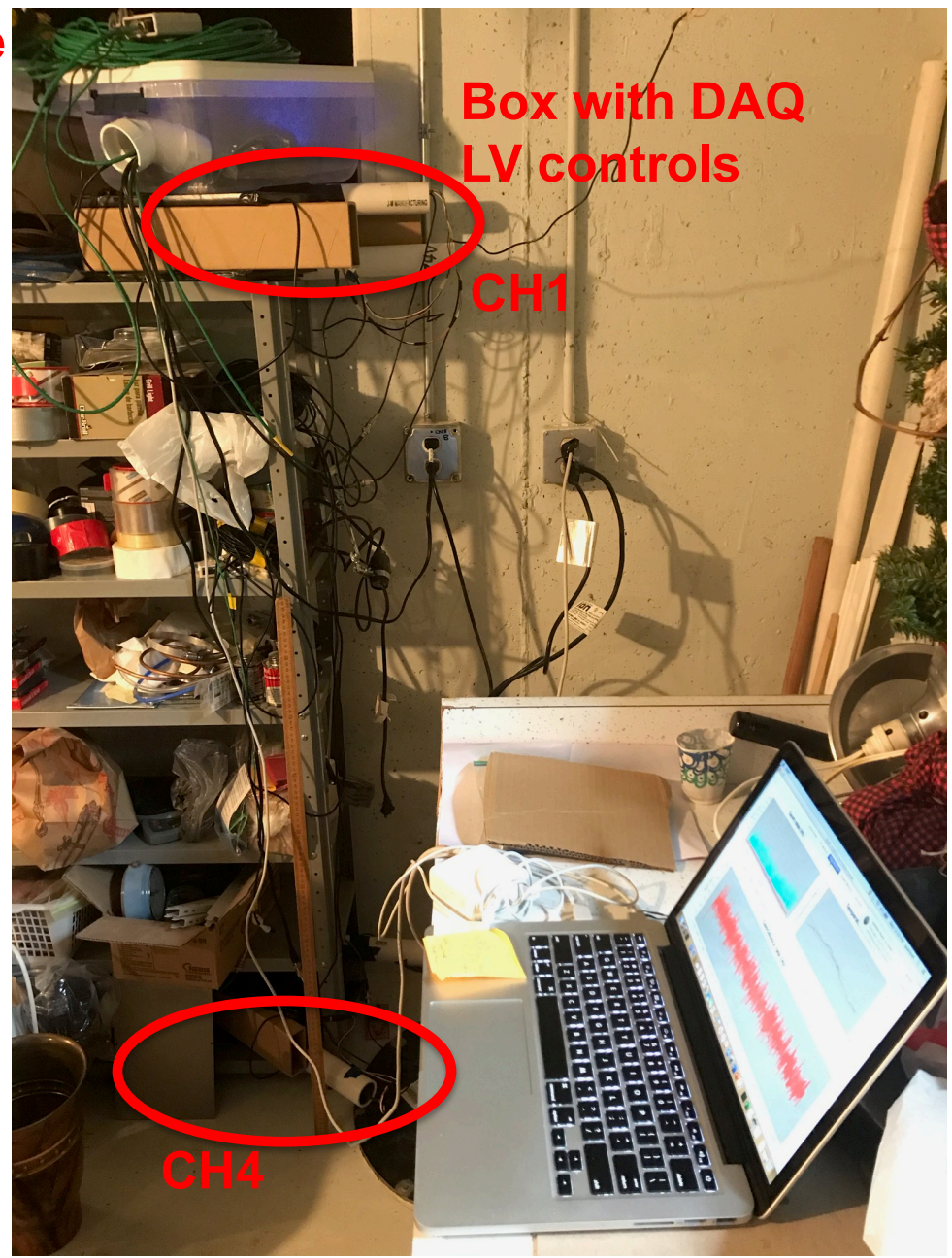
Relative time of counters in 1 DAQ to 1.25ns least count

3 triggered events! Each line represent hit information in a 10ns time slice



GPS cable

- Detector 6674 in basement
- Next to sump pump that causes lots of random noise



Box with DAQ
LV controls

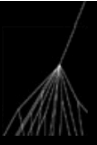
CH1

CH4



Quarknet e-Lab

i2u2.org



Cosmic Ray e-Lab

Welcome: Join an international collaboration of high school students to study cosmic rays.

**Go to i2u2.org and login in as
guest**

Click to use Flash

Log in

Username:

Password:

Login

To explore our website,
[log in as guest](#)

Need a student login?

Ask your teacher.

Need a teacher login?

Contact e-labs@fnal.gov



Select TOF Analysis

guest [Log out](#)

Cosmic Ray e-Lab

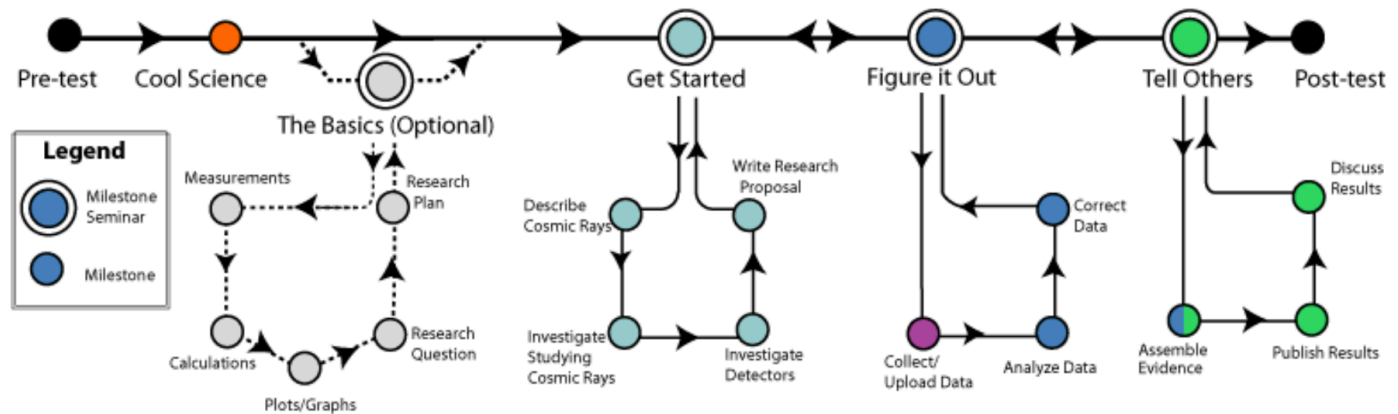
[Project Map](#) | [Library](#) | [Data](#) | [Posters](#) | [Site Map](#) | [Assessment](#)

[View Data](#) | [Performance](#) | [Flux](#) | [Shower](#) | [Lifetime](#) | [T of F](#) | [View Plots](#) | [Analyses](#)

Home: Join an international collaboration of high school students to study cosmic rays.

► [View News Alert](#)

Project Map: To navigate the Cosmic Ray e-Lab, follow the path; complete the milestones. Hover over each hot spot to preview; click to open. Along the main line are milestone seminars, opportunities to check how your work is going. Project milestones are on the four branch lines.



[Milestones \(text version\)](#)



Choose different files

- Select a file of Detector 6674 on any day in April or May.
- choose a file based on the first letter of your last name:
- Adams choose ~April 1st
- Lincoln choose April 30th
- Washington choose ~ May 28th

File Selection

Cosmic Ray e-Lab

E Log out

Project Map Library Upload **Data** Posters Site Map Assessment

View Data Performance Flux Shower Lifetime T of F View Plots Analyses

Choose data for the time of flight study.

Quick Search for E, Robert S. Peterson, Fermilab Test Array, Batavia, IL

Detector ID Search Data

Advanced Search

Please enter dates in MM/dd/yyyy format (e.g. 06/01/2020).
You may leave one or both date fields blank.

Start Date to

Search: All data Refine results with extra parameters

Stacked: Blessed:



[View and Search from detector map.](#)

* To speed up searches by default we are retrieving the last 3 months worth of data for the criteria you chose.
You can modify your date range using the Advanced Search criteria.

Results 1 - 1 of 1 for detectorid 6674 (Searched 94 files in 0.716 seconds)

▼ Fermilab Test Array

Batavia, IL

94 data files: 0 blessed, 94 stacked, 5,006,696 total events.

- ▶ March 2020, 25 files
- ▶ April 2020, 36 files
- ▼ May 2020, 33 files

Detector 6674, 33 files

Fri 01
38,050 events

Sat 02
22,184 events

Sat 02
15,890 events

Sun 03
38,485 events

Analyze

Help

[Tutorial on Time of Flight study](#)

[Step-by-step instructions](#)

FAQs

States include provinces and countries. Enter the [abbreviation](#)

Legend

- View data
- Rollover for more info
- Unstacked data
- Stacked data
- Blessed data
- Click to view blessing charts
- Rollover for more info
- Unblessed data
- Click to view blessing charts
- Rollover for more info
- Data has comments - Add more/View
- Add comments

You cannot select files with No Geo for Flux, Shower or Lifetime Studies.



TOF Control Panel

Cosmic Ray e-Lab E Log out

Project Map Library Upload **Data** Posters Site Map Assessment

Text Version Cool Science About Us

Time of Flight study

DAQ#	You're analyzing...	Chan1 events	Chan2 events	Chan3 events	Chan4 events	Raw Data
6674	Fermilab Test Array May 3, 2020 00:00:00 UTC Total (1 files 9304362 events)	1882584	1862669	1903079	3656030	View Statistics Geometry Compare files

Analyze the same files in [performance](#)

Click **Analyze** to use the default parameters. Control the analysis by expanding the options below.

▼ Analysis Controls

Location: Fermilab Test Array, Batavia, IL (6674)

Event Gate (ns): 15

Channel Coincidence: 3

Define Soft Triggers

Require Channels: 1 2 3 4

Veto Channels: 1 2 3 4

► Plot Controls

Analyze

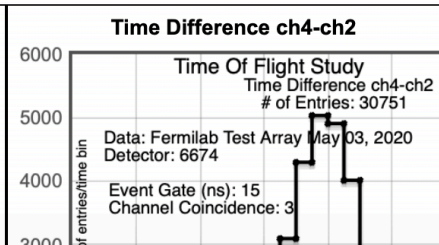
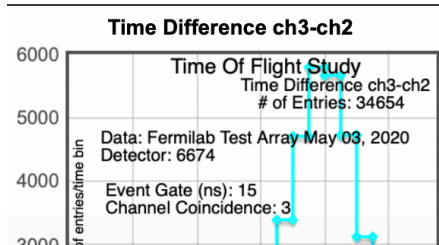
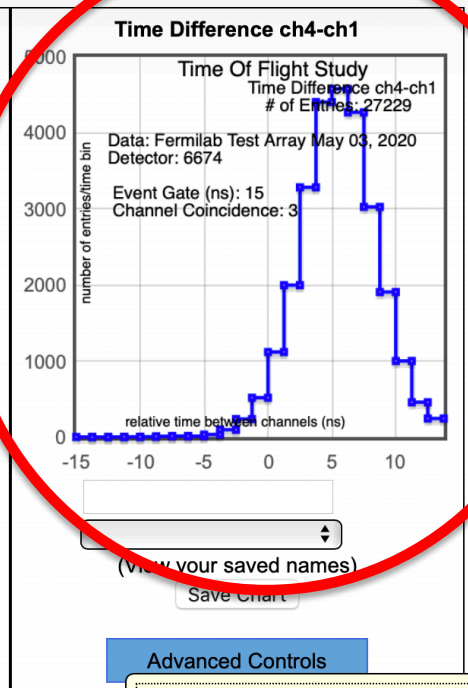
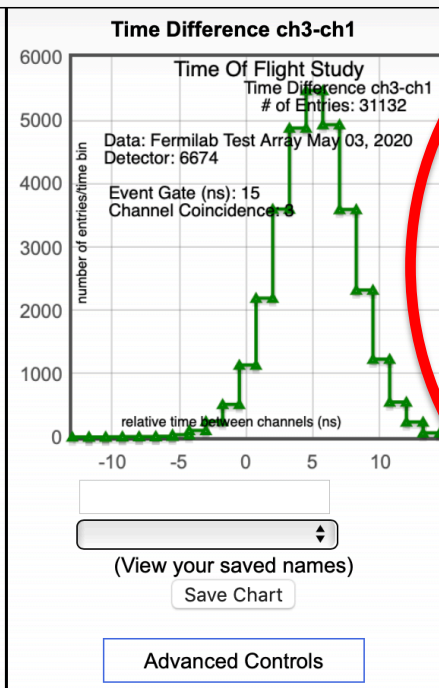
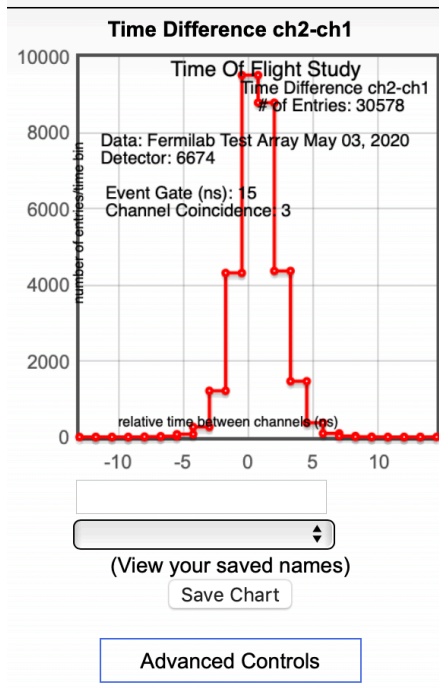
Set width of ΔT plot (ns) > 15ns

Set number of counters required Hardware required 3 – pick 3 or 4

TOF results

Time of flight study result

[View all charts combined](#)



Refit X Values: Min X: Max X: Refit X

Mean: 5.26
Std Dev: 3.00

X-axis scale: Min X: Set Max X: Set

Y-axis scale: Min Y: Set Max Y: Set



Where is position information?

3 clicks to find Geometry of the file you select

Step 1



Fermilab Test Array

Batavia, IL
94 data files: 0 blessed, 94 stacked, 5,006,696 total events.

- ▶ March 2020, 25 files
- ▶ April 2020, 36 files
- ▼ May 2020, 33 files

Detector 6674, 33 files

Fri 01
38,050 events

Sat 02
22,184 events

Sa 02
15,890 events

Sun 03
38,485 events

Step 2

6674.2020.0503.0

[Show metadata](#) | [Show Geometry](#) | [Show Blessing Charts](#) | [Download](#) | [Download Threshold File](#)

**Distance between counters 1 and 4:
1.595m - 0.085m = 1.51m**

[Geometry](#) for 6674.2020.0503.0

Step 3

Detector Geometry

If you are using EQUIP for data acquisition, you still need to enter geometry data on this page for use in the Cosmic Ray e-lab.

GPS is @ (0,0,0).

Each point (x,y,z) represents the center of a counter.

Active Channels: 1 2 3 4

Cable	Length (m)	Area(cm ²)	x:E-W(m)	y:N-S(m)	z:Up-Dn(m)
1	0.53	750.0	0	0	1.595
2	1.85	750.0	0	0	1.488
3	3.5	750.0	0	0	0.188
4	1.2	750.0	0	0	0.085

Stacked Orientation Unstacked

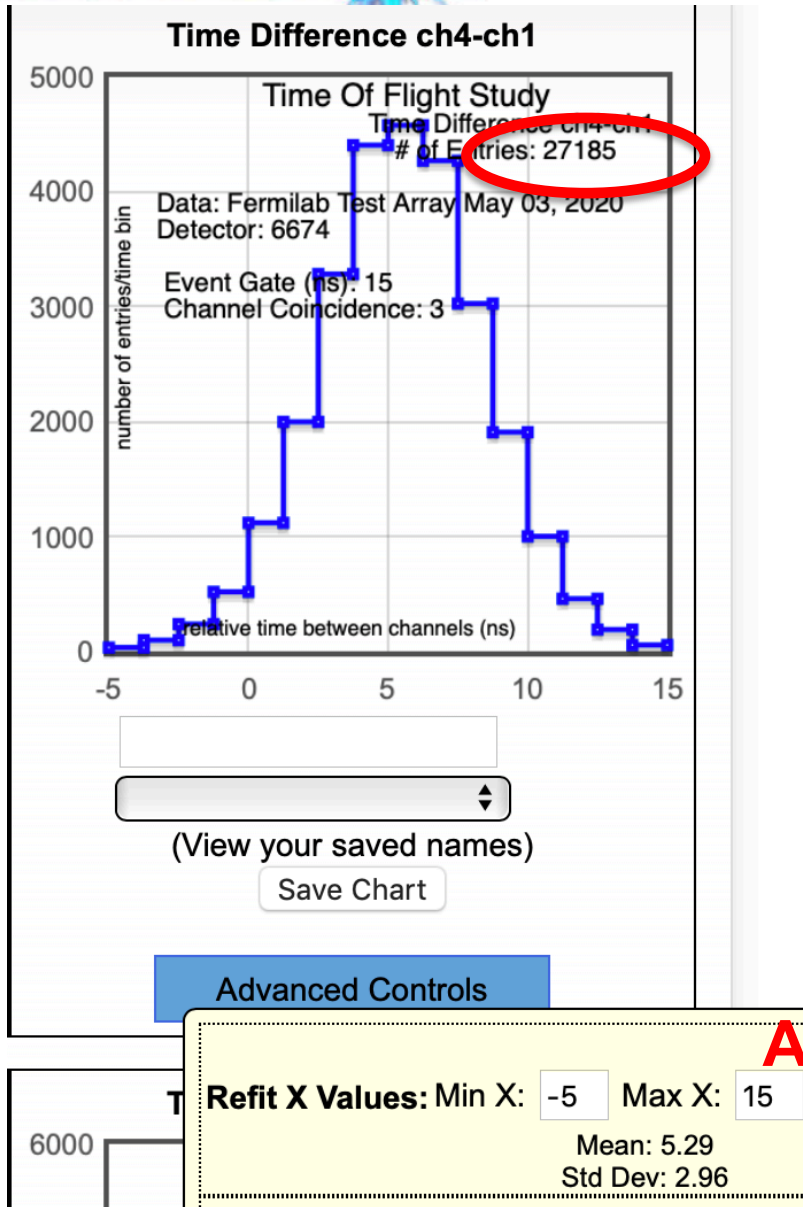
Visualize geometry

GPS Coordinates

[GPS Coordinates Tutorial](#) [Find GPS Coordinates](#)

Latitude: Longitude:

Calculate Speed



$\Delta t = 5.29$ ns with error of 2.96 ns
 Error means 68% of results fall within
 mean-error to mean+error:
Large error 2.33- \rightarrow 8.25ns

Calculate the speed:
 Speed = $\Delta z / \Delta t = 1.51\text{m} / 5.29\text{ns}$
Average muon speed = $2.85 \times 10^8\text{m/s}$

**Why is this result so close to
 accepted value of $2.95 \times 10^8\text{m/s}$?**

Error on the mean of all muons is
 much smaller (related to $1/\sqrt{N}$)

Advanced Controls will show mean



You measured maximum speed in the universe!

- Please share your results via chat.
- If we combined our analyses, the measurement would improve
- Wait! –
- **Why should all muons travel at the same speed?**
- Baseballs, cats and cars don't.



You measured maximum speed in the universe!

- Why should all muons travel at the same speed?
- Answer is due to Special Relativity - Particles can be accelerated to very high energies but their speed asymptotically approaches c :
 - Momentum = $M * v * 1/\sqrt{1-v^2/c^2}$
 - Related – faster particles go, longer they live as measured by us (time dilation)



Questions; Extra

- Can you improve the measurement?
Share ideas via chat
- Ten muons/sec go through your body, do they hurt?
- Want to do more e-Lab studies?
 - quarknet.org analysis link
<https://quarknet.org/content/resources-cosmic-ray-analyses-online>
 - Contact adams@fnal.gov



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 enjoyed your measurement of the maximum speed in the Universe
- I will stay around to answer your questions

QuarkNet



Extra Slides



Flux - Rate versus time

A week of data
Note: no big day/night effect
> Not from Sun

**Number of events/m²/min/steradian
in 6-hr bins**

