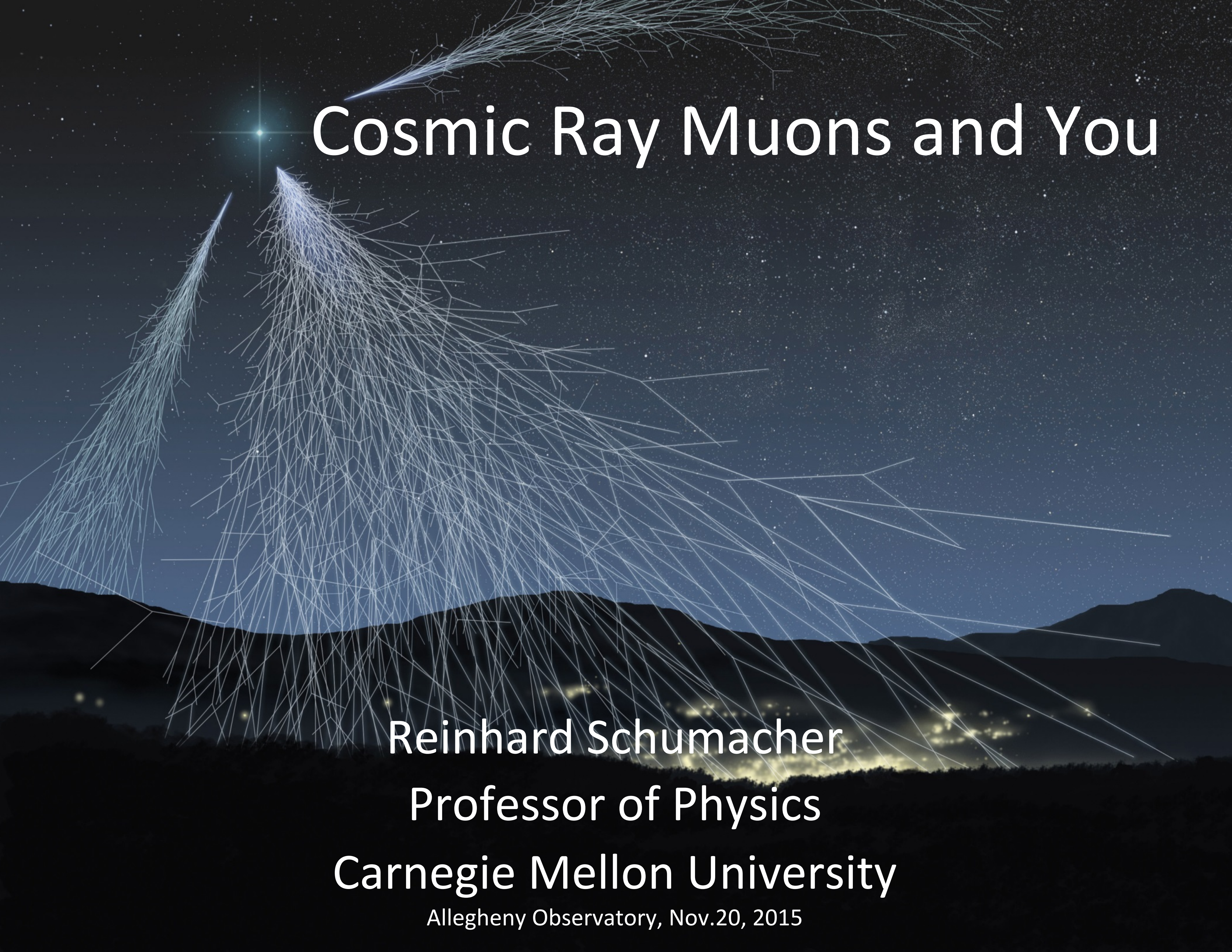


Cosmic Ray Muons and You

Reinhard Schumacher
Professor of Physics
Carnegie Mellon University

Allegheny Observatory, Nov.20, 2015

Outline

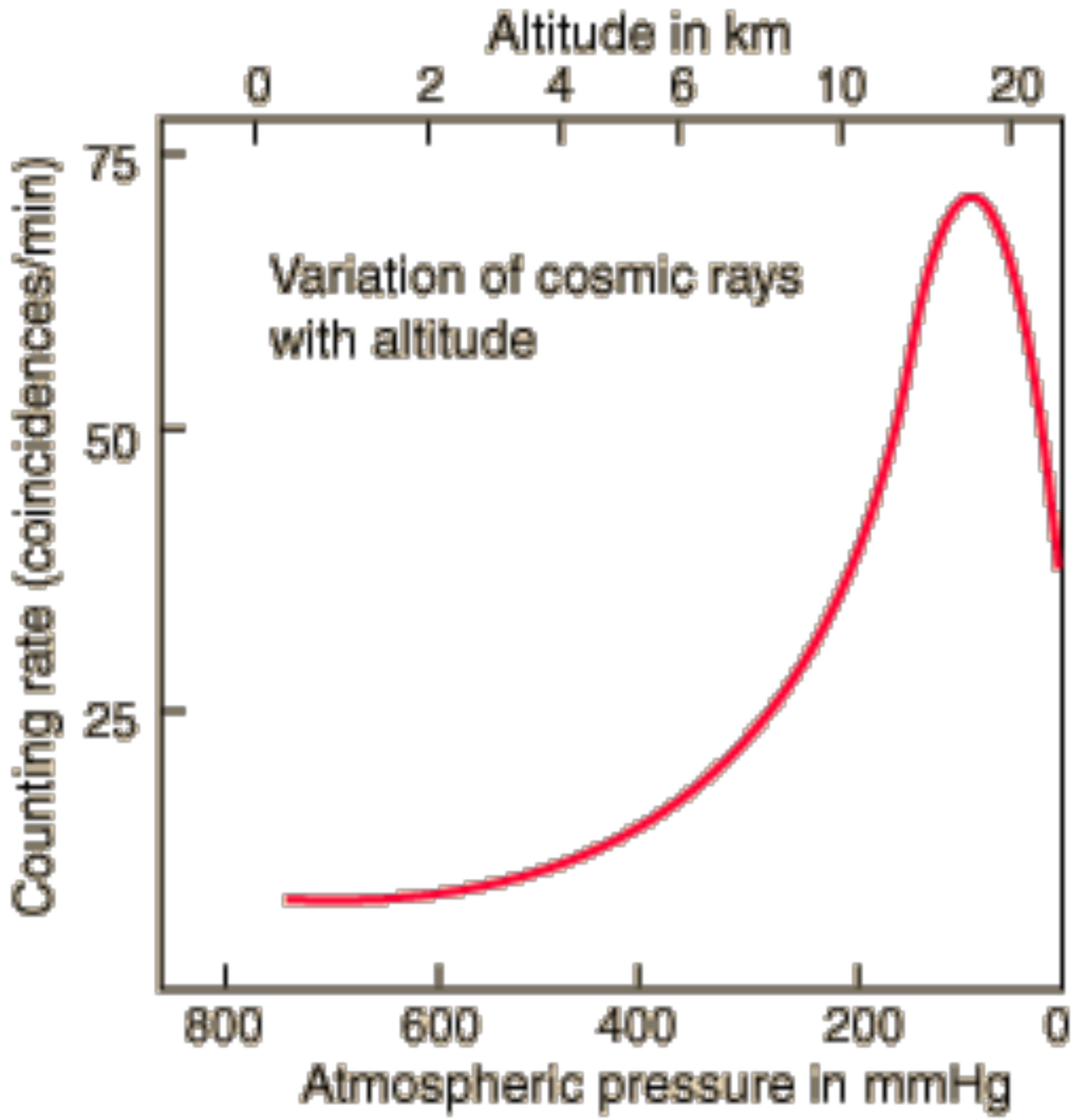
- What are Cosmic Rays?
- What are Muons?
- Radiation exposure due to cosmic rays
- Detecting Cosmic Rays and other radiation
- Cosmic ray muon intensity and the weather

BC: Johnny Hart

Viktor Hess: 1911-1913 work

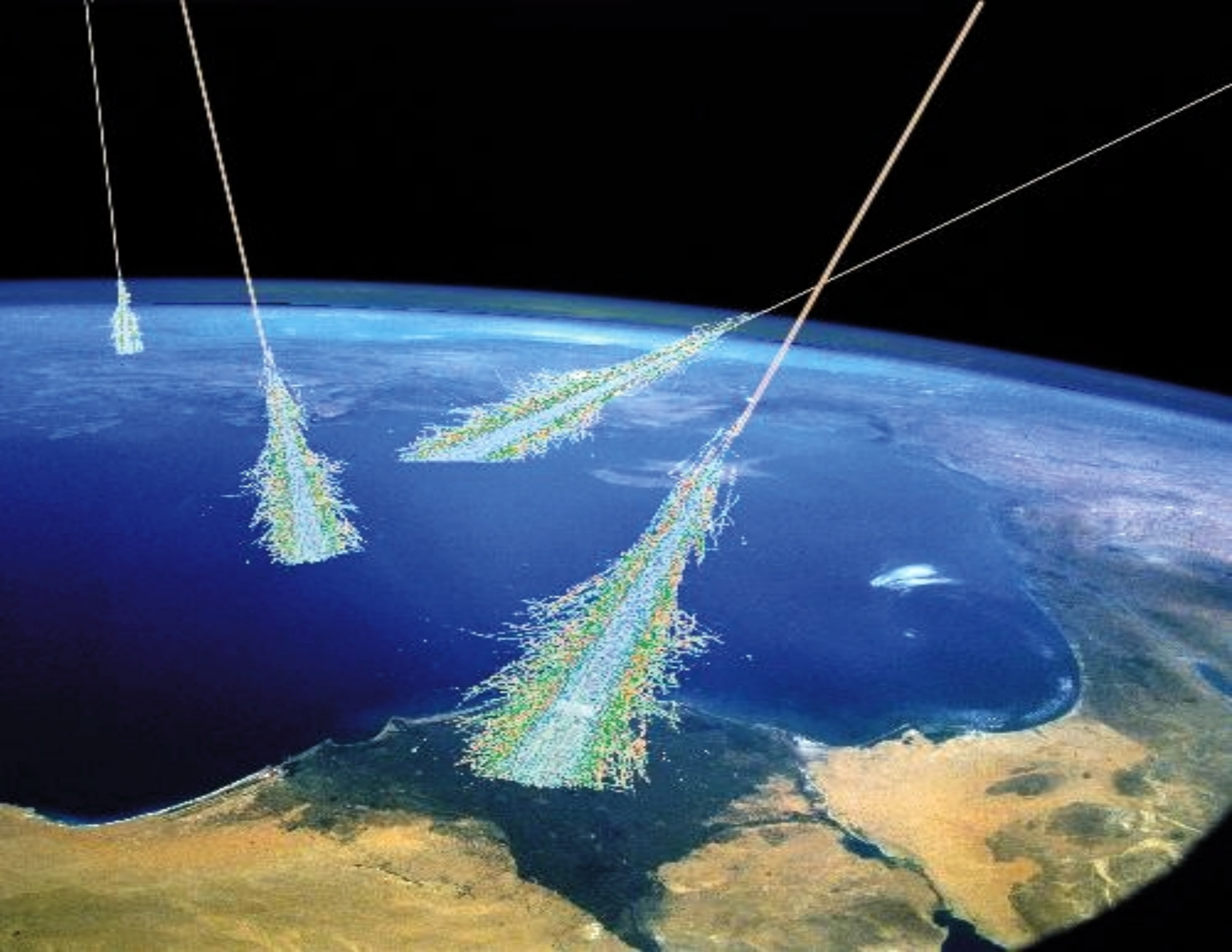
- Electroscopes…
- Natural radiation in the earth: was expect to to lessen at heights
- Eiffel Tower test : nope…
- Viktor Hess' daring balloon flights with electroscopes
  - Up to 5.3 km!
  - Intensity more than doubles
- Some radiation is of extraterrestrial origin!
- Nobel Prize 1936

Cosmic ray rate (intensity) vs. altitude



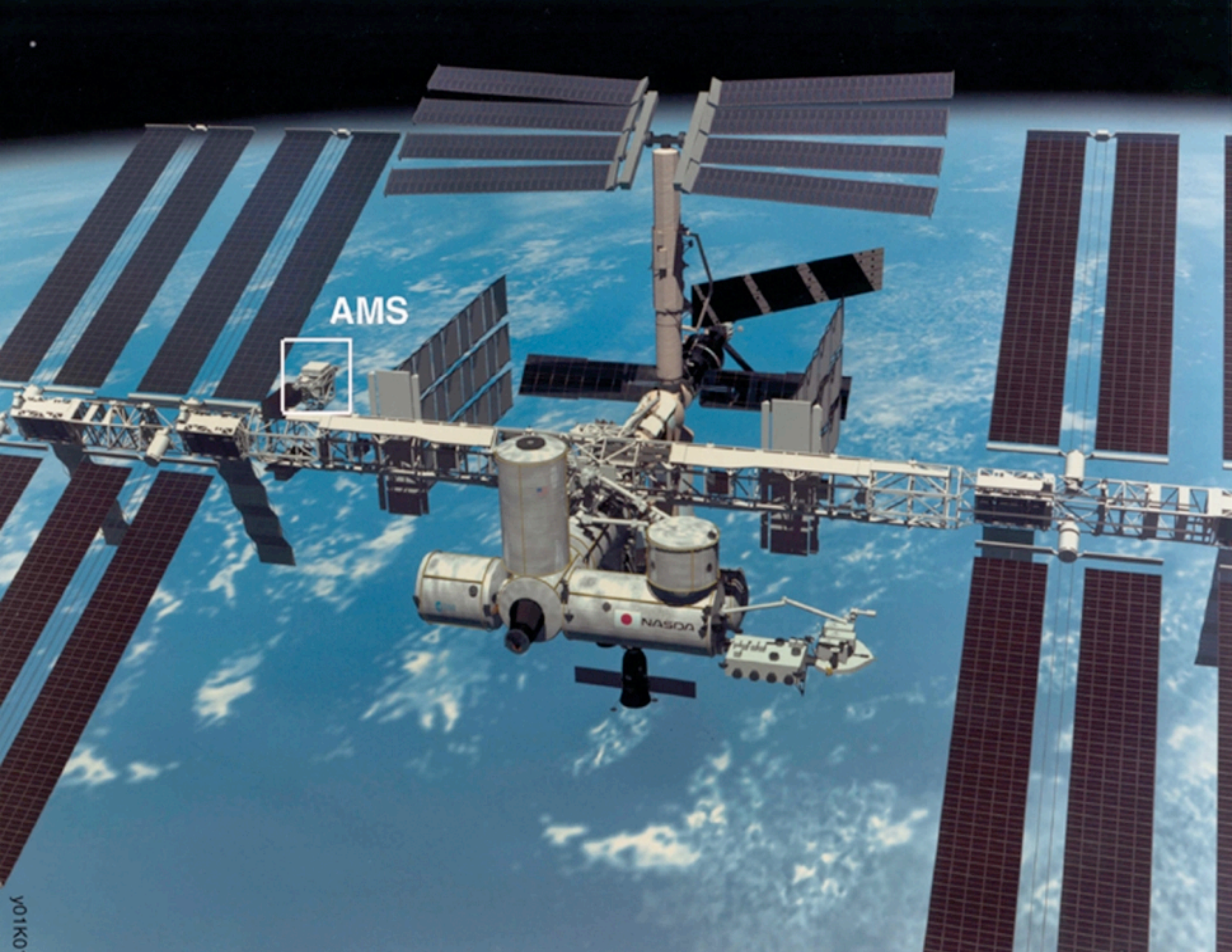
Yes, but what is this radiation?

- At the top of the atmosphere:
  - Protons
  - Anti-particles
  - AMS / Space Station
- In between
  - Particle “showers”
- At ground level
  - Muons ← our main topic!
  - Neutrons



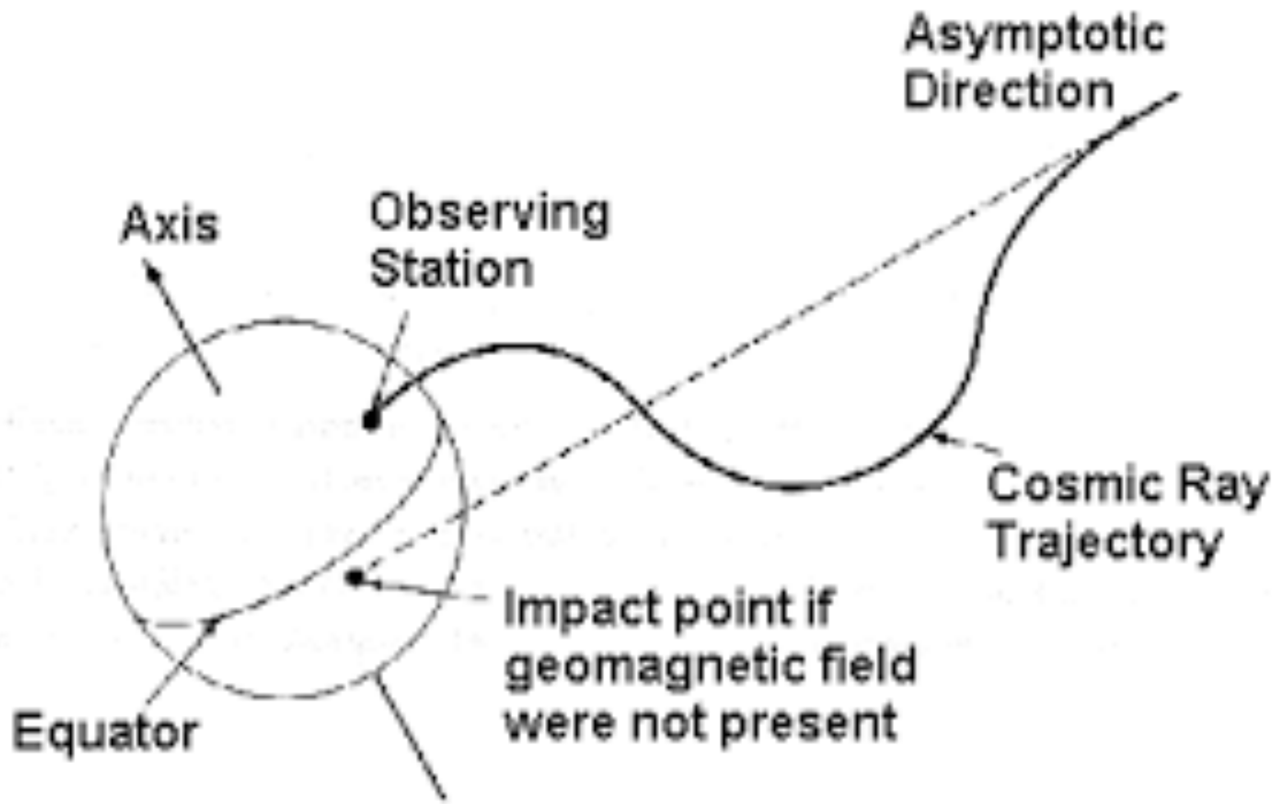
"Primary" Cosmic Rays

- Mostly Protons: stable, live forever
- Bits of lots of other stuff: electrons, helium nuclei… iron nuclei, anti-particles…
- Alpha Magnetic Spectrometer (AMS-02) on International Space Station
  - Taking a census of everything arriving at earth


AMS
NASDA

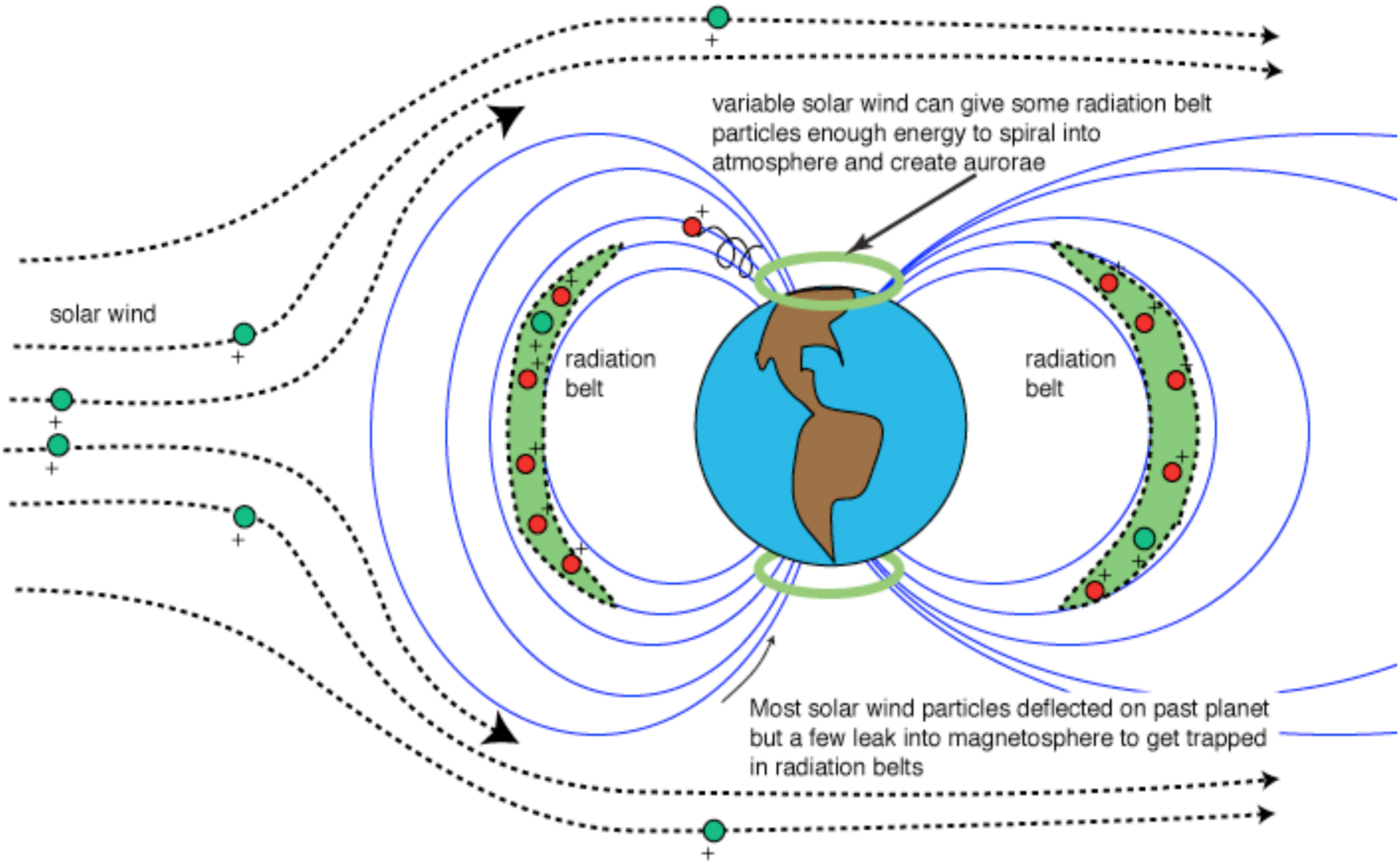

AMS
AMS

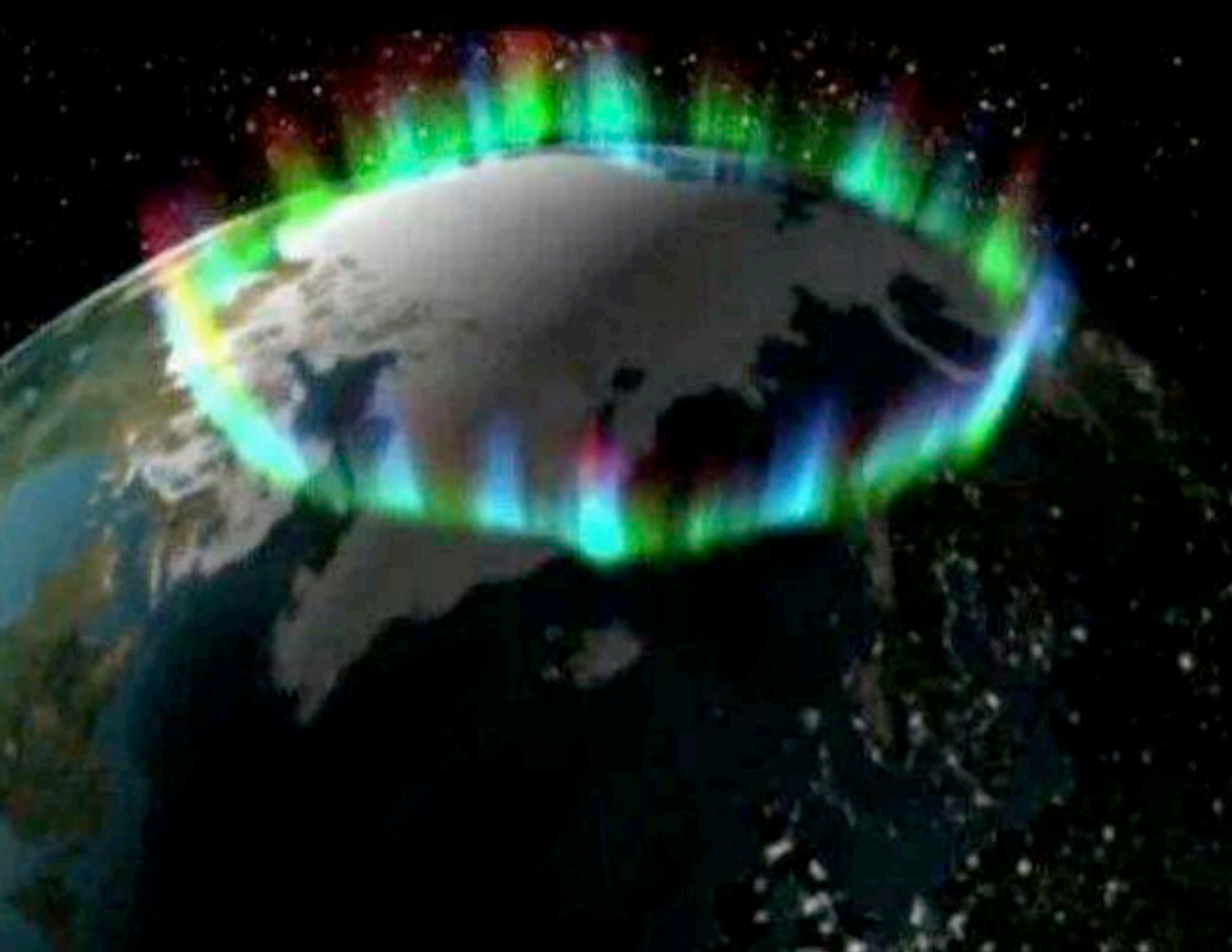
Where do cosmic rays come from?



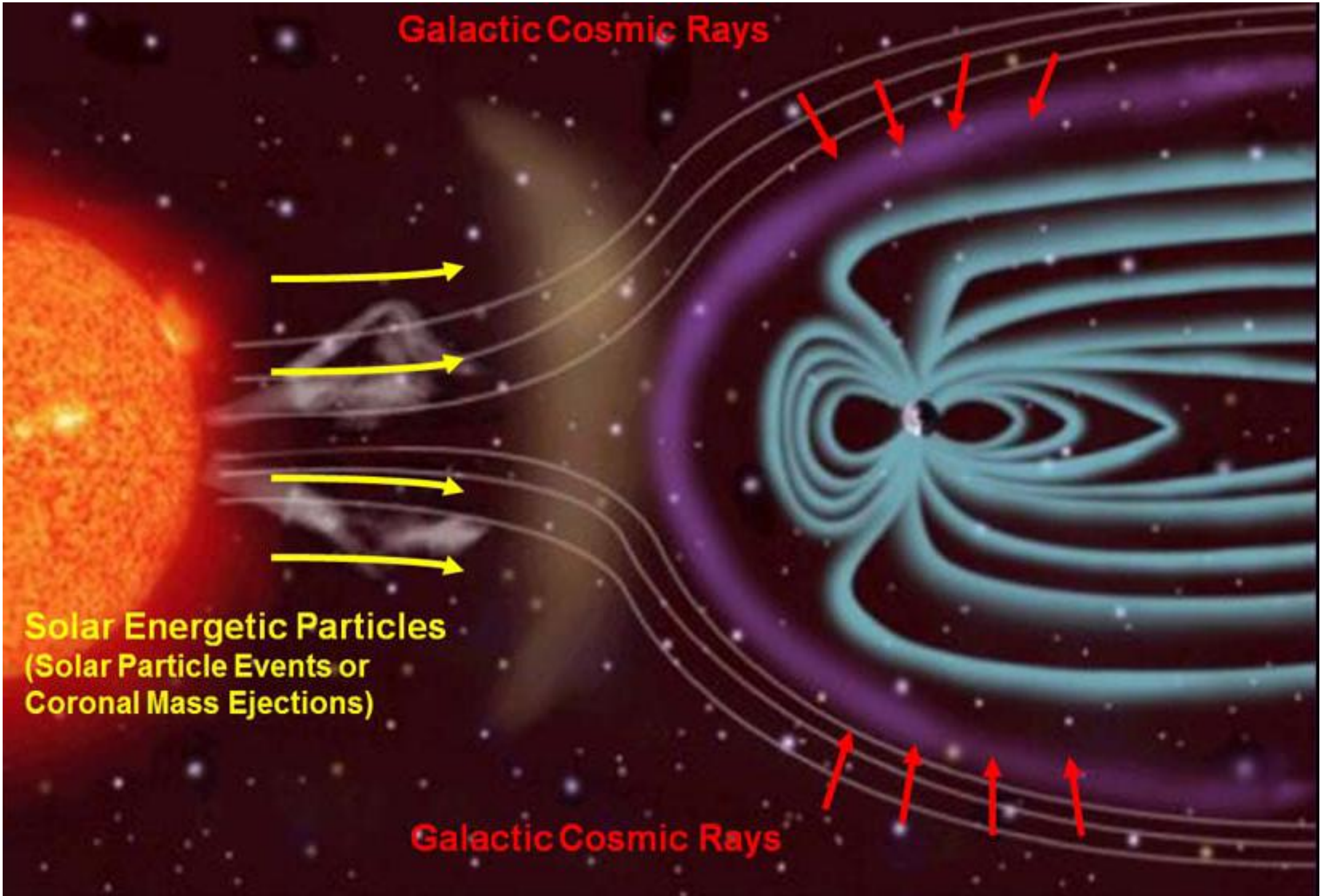
- We don't know.
- Not the sun.
- Galactic magnetic fields scramble paths
- Solar wind particles: Aurora
- Cosmic rays: ongoing mystery

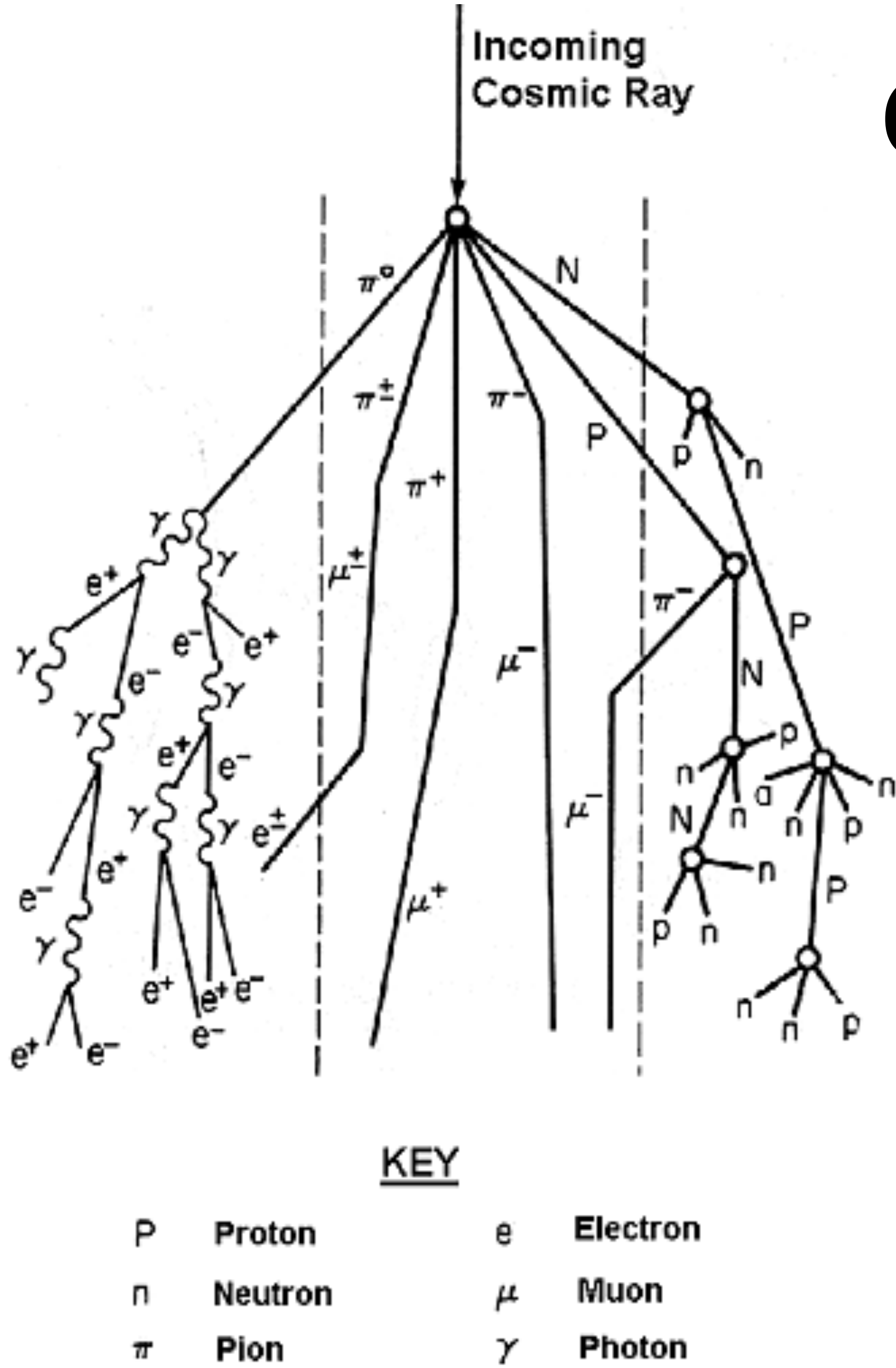
Role of the Sun in Aurorae





<u>Indirect</u> Role of the Sun on Cosmic Rays





Cosmic Ray Showers

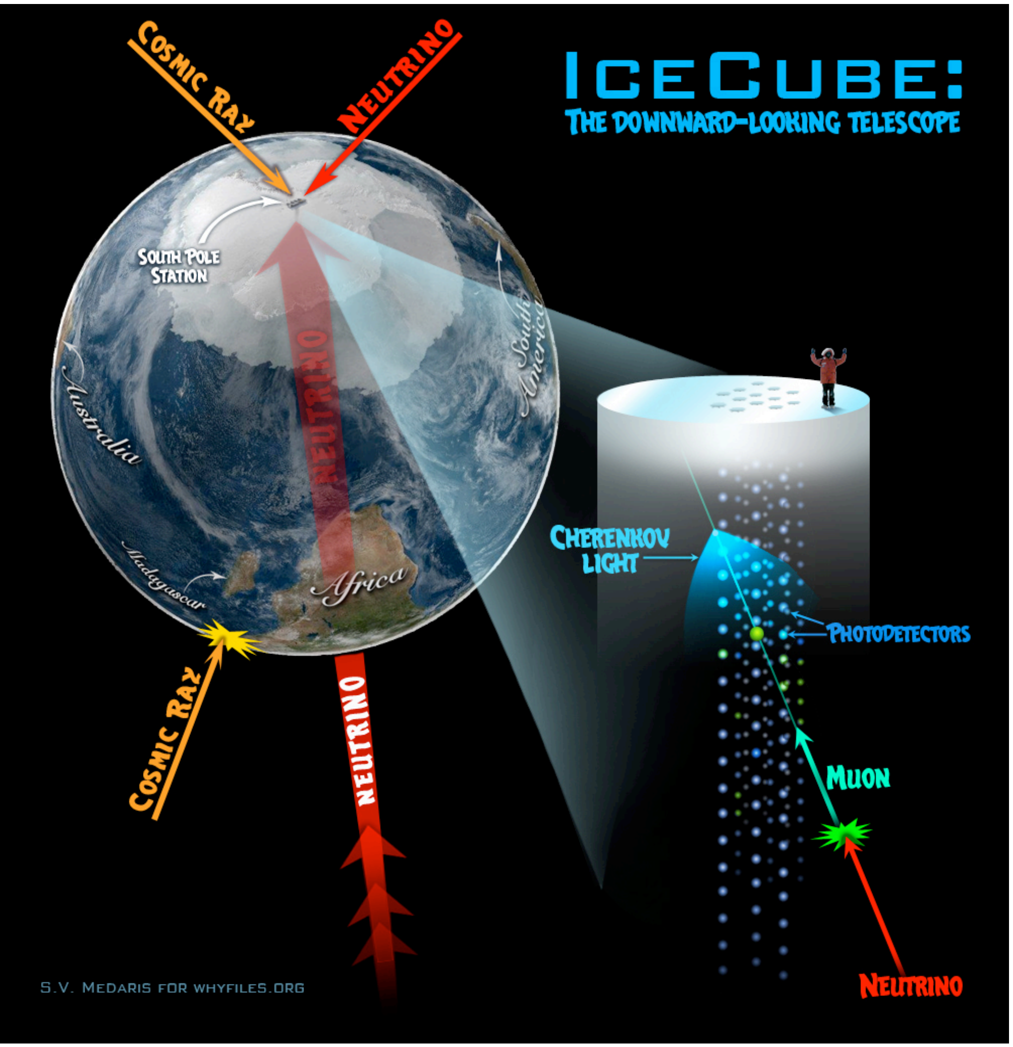
- High energy cosmic rays cause a cascade of particle production in the atmosphere
- Muons have the most bang for (energy) buck: penetrate to the surface (and below)
- Rate: 180 particles/m^2/sec

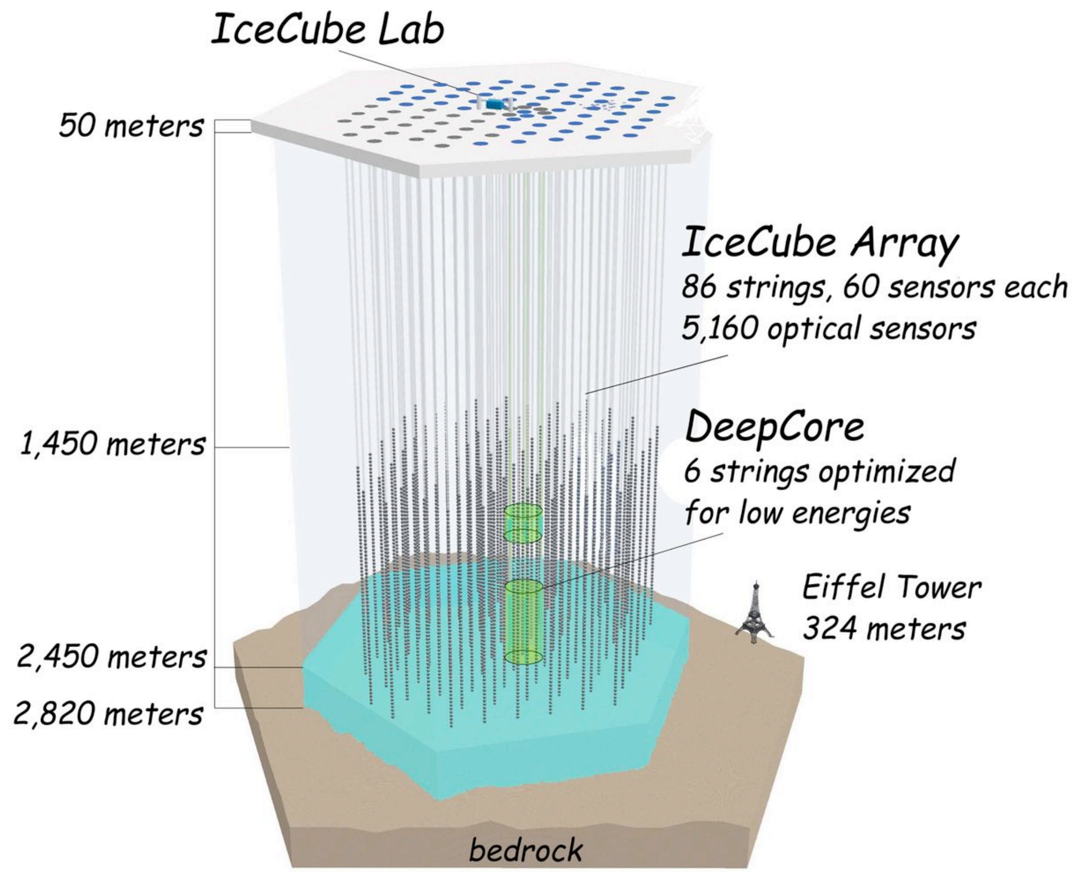
The Muon: "Who ordered that?"

- Very much like a "heavy electron":

  - Charged "+" or "–"
  - 206 times more massive than the electron 
  - Unstable: decays in 2.2 microseconds to an electron or positron and two neutrinos
  - A type of "ionizing radiation" because it can rip electrons off atoms

Deep Underground Muons:





-Go deep to escape cosmic ray muons
-See instead muons created by neutrinos

Human Exposure to Ionizing Radiation

Source	Place	Exposure	Units
Cosmic Rays	Sea Level	26	milli-rem / year
	Pittsburgh	30	"
	Denver	50	"
Ground		35	"
Food (^{14}C, ^{40}K)		40	"
Air (Radon)		200	"
TOTAL		~ 300	"
Workplace Limit (US)		5,000	"
Air travel / hour		0.5 / hour	milli-rem
Chest X-ray		10	"
Chest CT scan		700	"
Dental X-ray		~ 1	"
MRI scan (not ionizing!)		0	"
½ pack of cig's/day		18	"
Lethal Dose	Hiroshima, Nagasaki	450,000	mrem all at once

Does the intensity of cosmic ray muons depend on the weather?

Space conditions: magnetosphere effects

Atmospheric conditions: pressure, temperature, humidity, height…

Undergraduate Research Project

OPEN ACCESS
IOP PUBLISHING JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS

J. Phys. G: Nucl. Part. Phys. **40** (2013) 065203 (11pp) doi:10.1088/0954-3899/40/6/065203

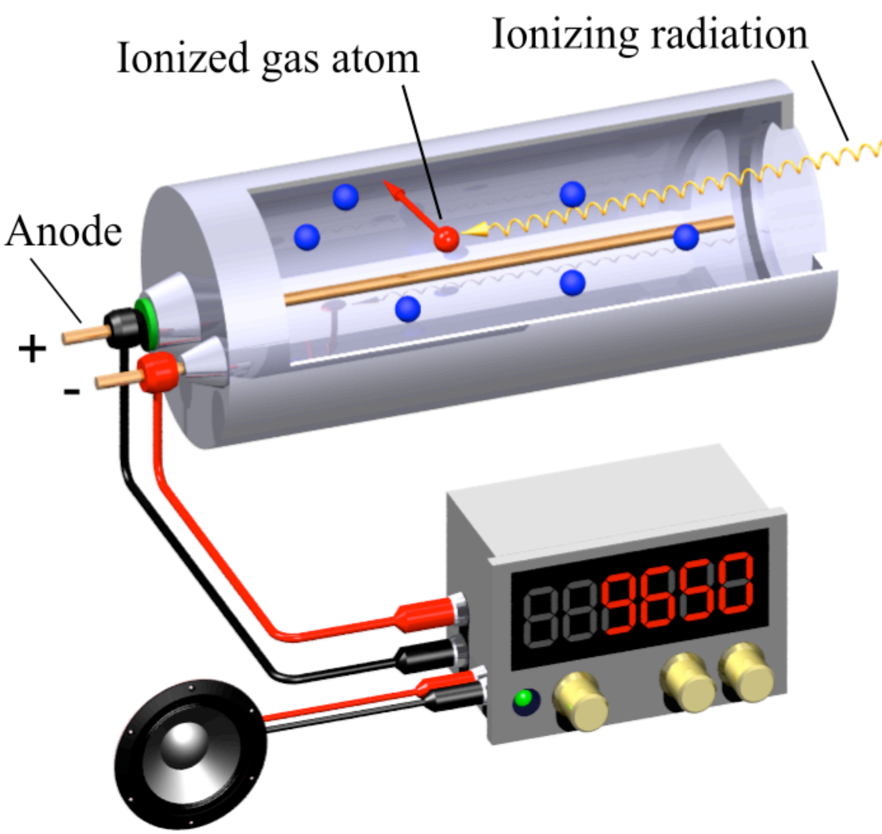
Atmospheric Dependence of the Stopping Cosmic Ray Muon Rate at Ground Level

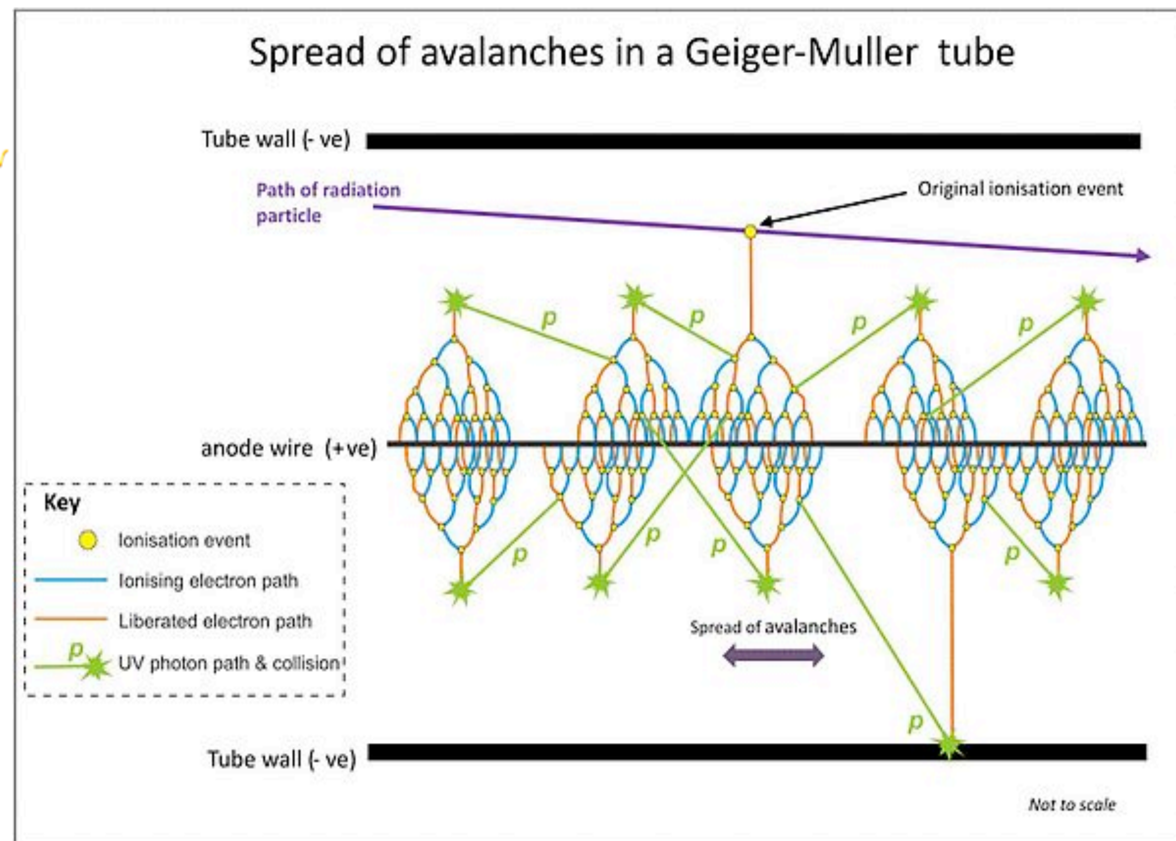
G. Bernero, J. Olitsky, and R. A. Schumacher*
Department of Physics, Carnegie Mellon University, Pittsburgh, PA 15213, USA

- What is the correlation between atmospheric conditions {Pressure, Temperature, and "Height"} with the rate of muons at ground level?

Detectors: Geiger Counter

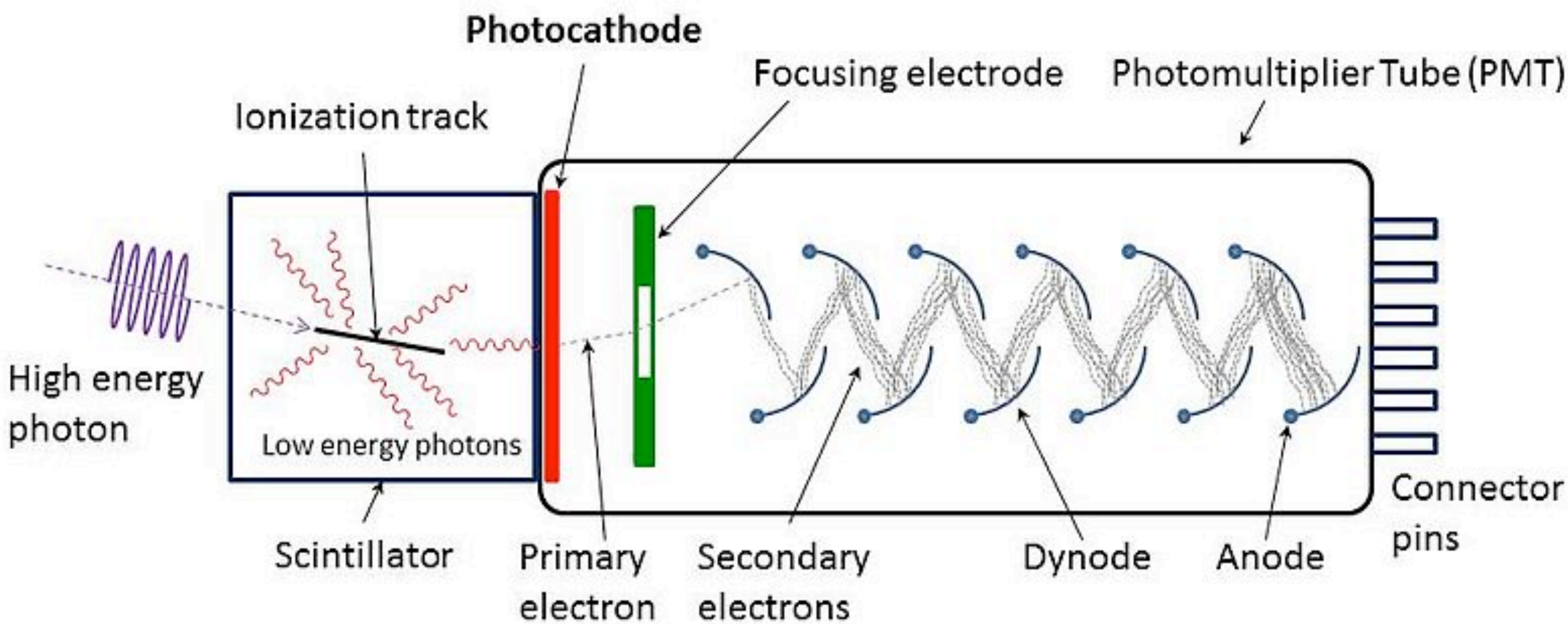
(Method 1)



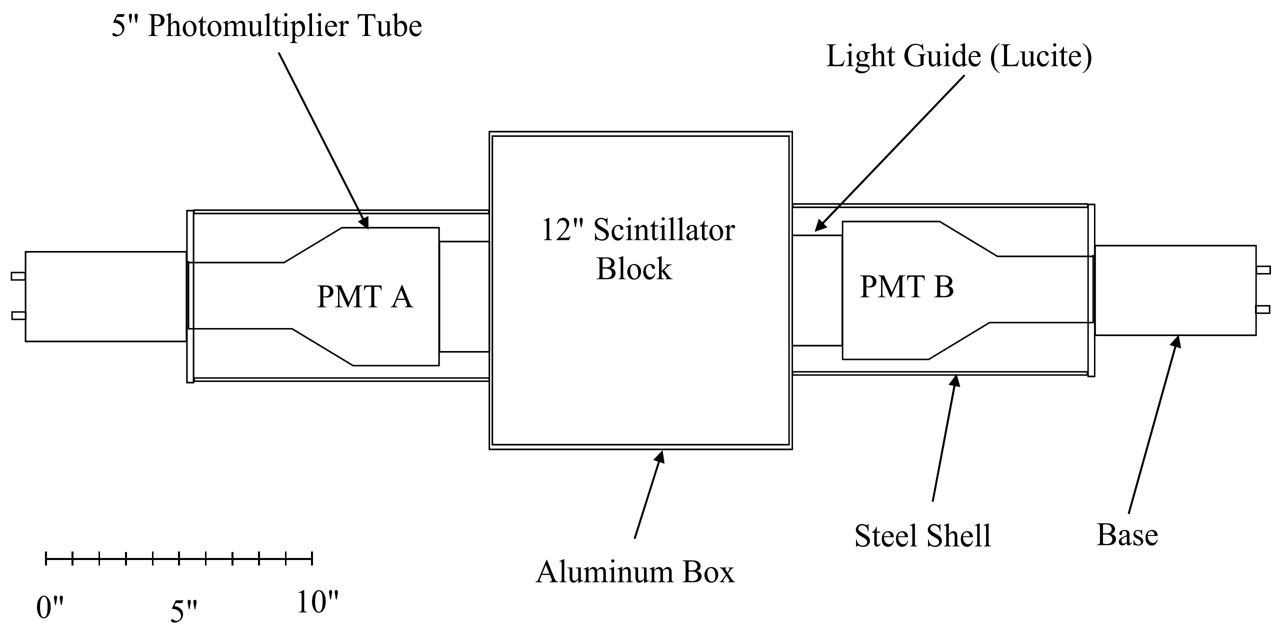


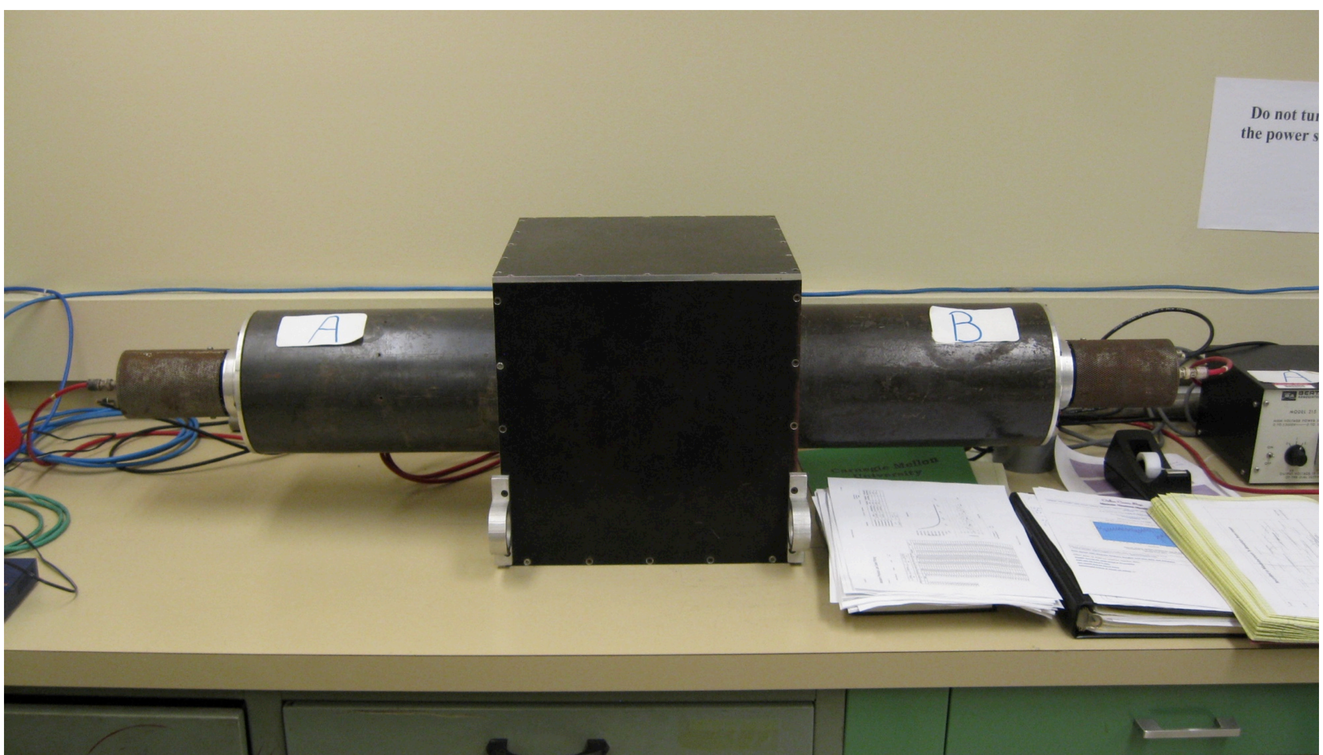
Detectors: Scintillator & Photomultiplier

(Method 2)



Experimental Setup





Experimental Setup

Weather Conditions

- Allegheny County airport aviation weather
  - Local barometric pressure (surface)
- NOAA/IGRA weather balloon data
  - Height of atmosphere at 10 kPa pressure
  - Temperature at 10 kPa pressure
- Space weather
  - We had no data source!

Muon Rate Correlations with Weather?

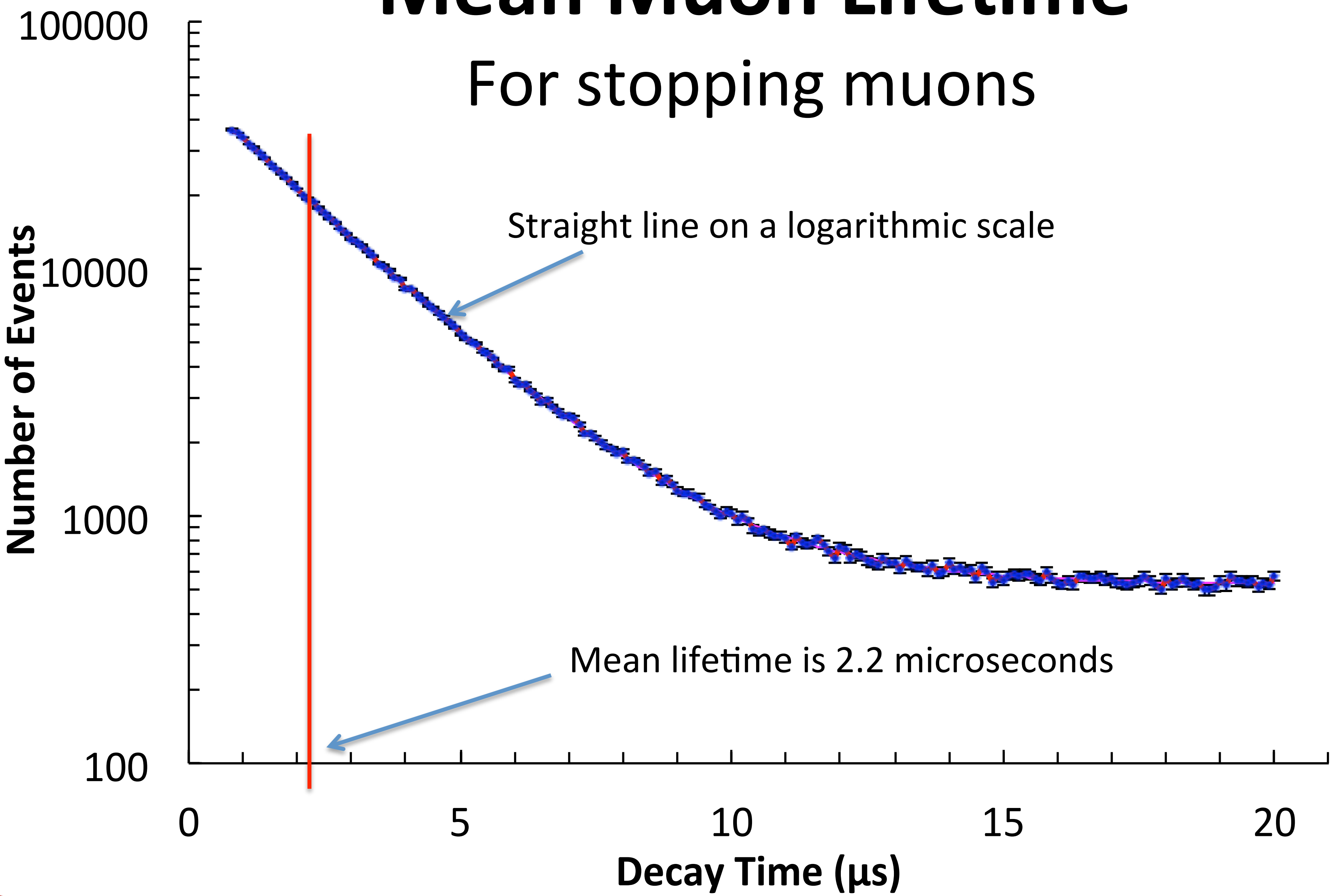
- Linear Regression Model:

$$\frac{\Phi - \langle\Phi\rangle}{\langle\Phi\rangle} = \alpha\left(\frac{P - \langle P\rangle}{\langle P\rangle}\right) + \beta\left(\frac{H - \langle H\rangle}{\langle H\rangle}\right) + \gamma\left(\frac{T - \langle T\rangle}{\langle T\rangle}\right)$$

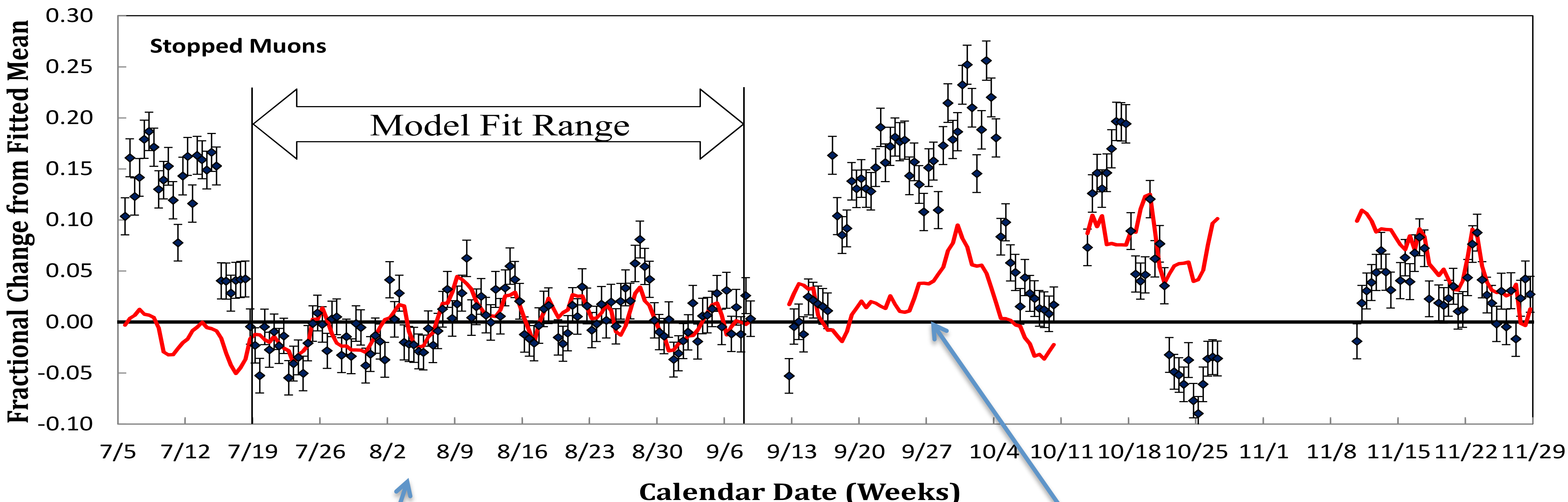
- Raw Data:
  - 5 months of averaged hourly readings of P, T, H, and Φ
    - Surface pressure (~ 101 kPa)
    - Temperature at 10 kPa pressure (~ 207 K)
    - Height of atmosphere at 10 kPa level (~ 16.6 km up)
    - Muon flux
- Two categories of muons:
  - Slow muons stop in scintillator (kinetic energy < 150 MeV)
  - Fast "in-flight" muons barrel right through the detector

Mean Muon Lifetime

For stopping muons



Raw Data: 5 months of readings

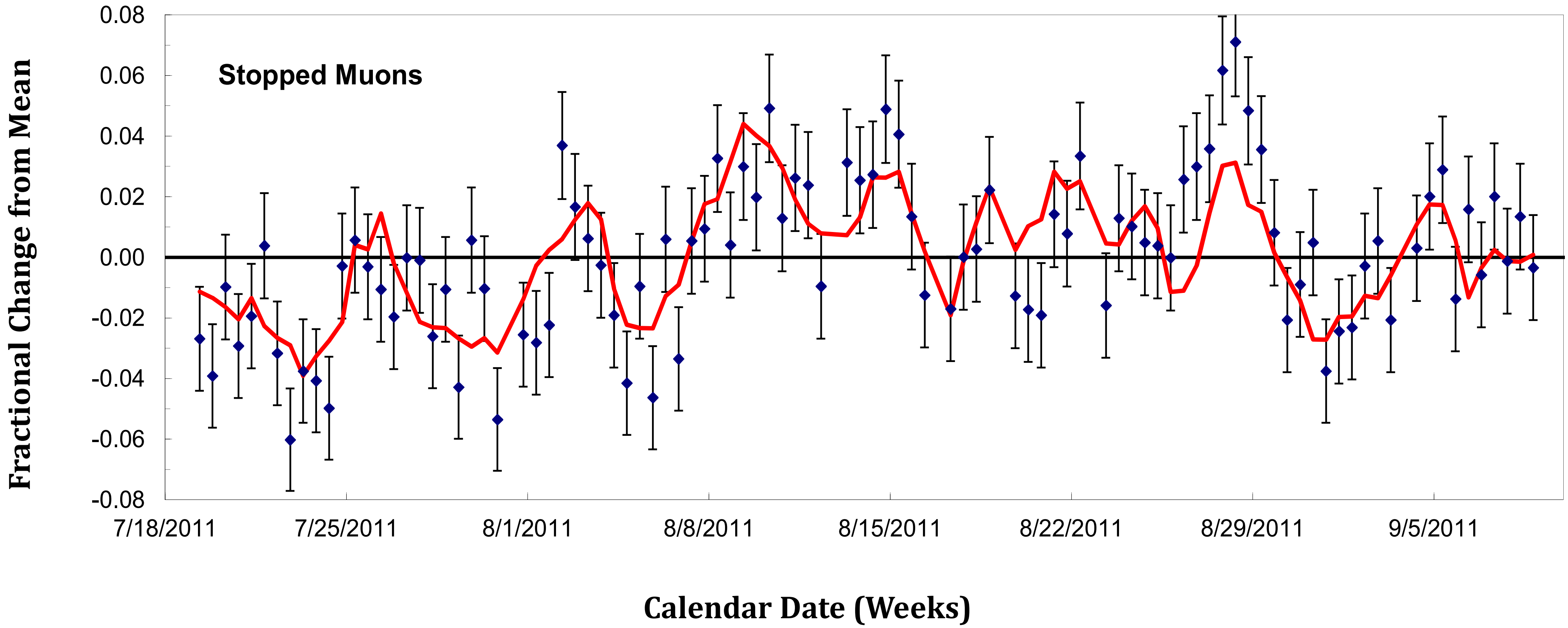


7 weeks of smooth, "clean" data

Effect of space weather: Forbush fluctuations

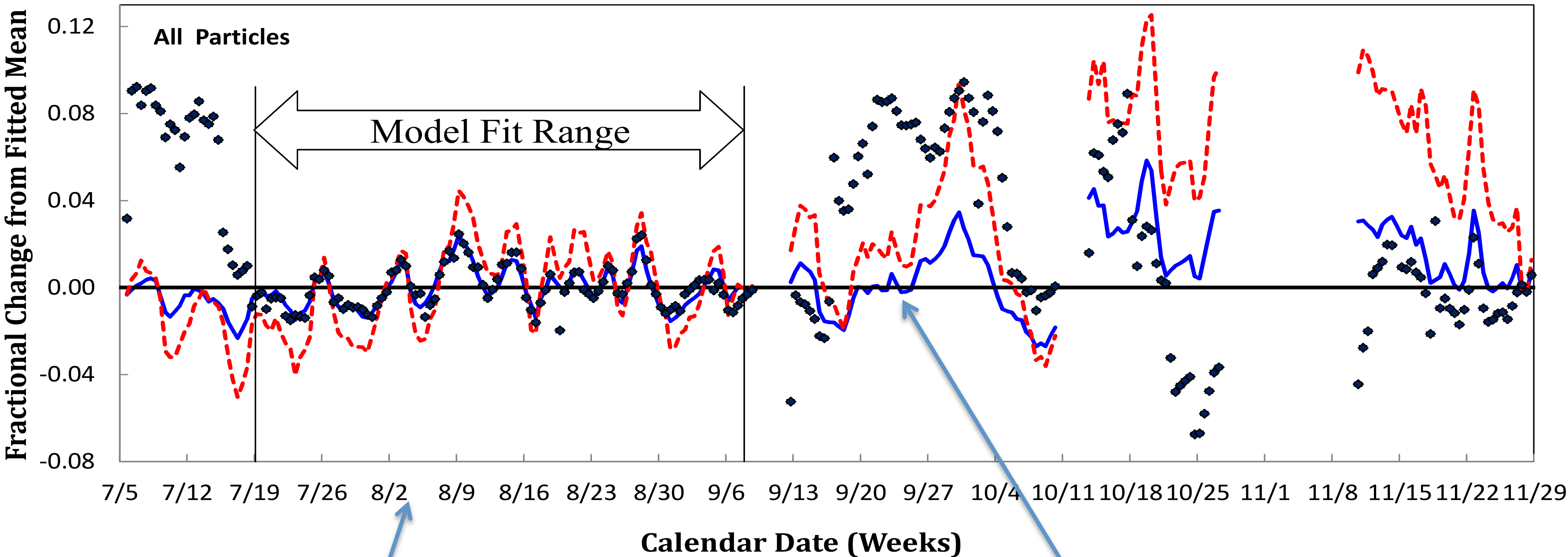
- blame the sun and Earth's magnetosphere

For stopping muons



Nice fit of model to 7 weeks of “clean” data!

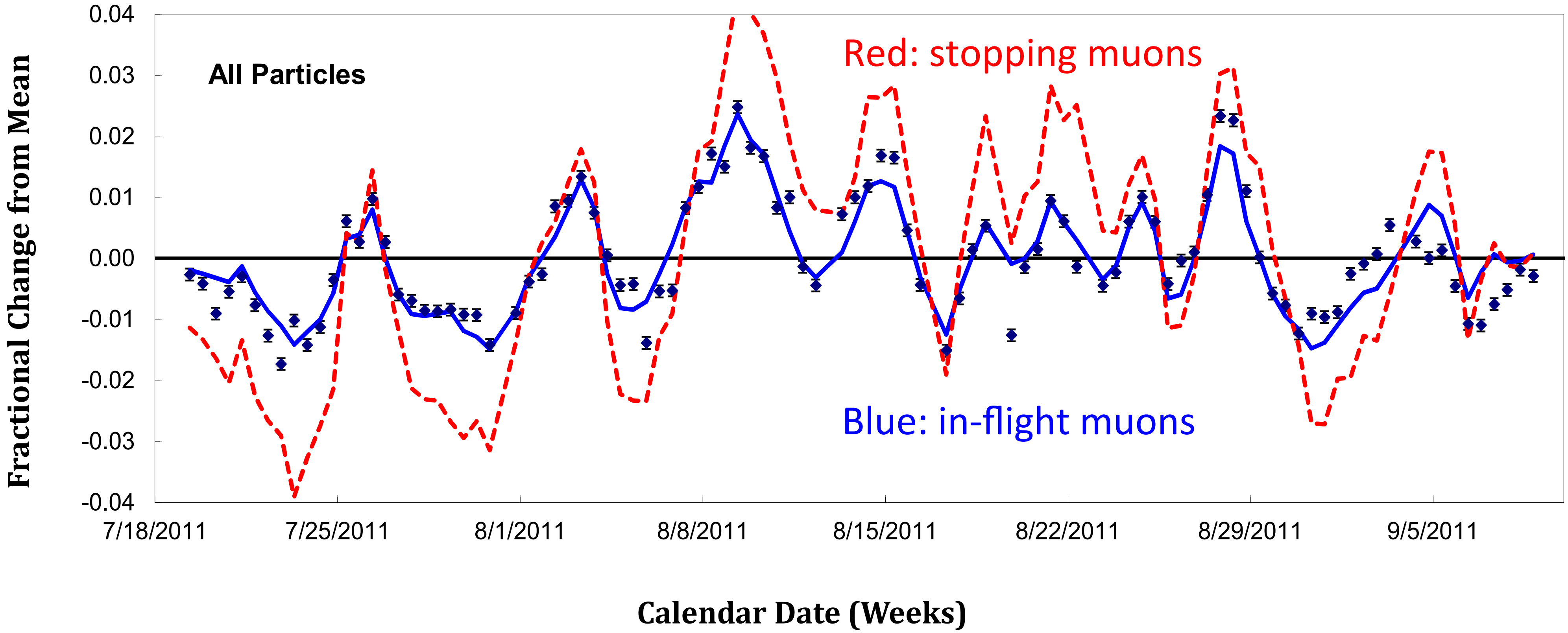
For in-flight muons



7 weeks of smooth, "clean" data

Effect of space weather:
Forbush fluctuations
- blame the sun and Earth's magnetosphere

For in-flight muons



Very good fit of model to 7 weeks of “clean” data!

Weather affects stopping muons more strongly

Experimental Results

Pressure rises → Muon rate falls

Atmosphere Expands → Muon rate falls

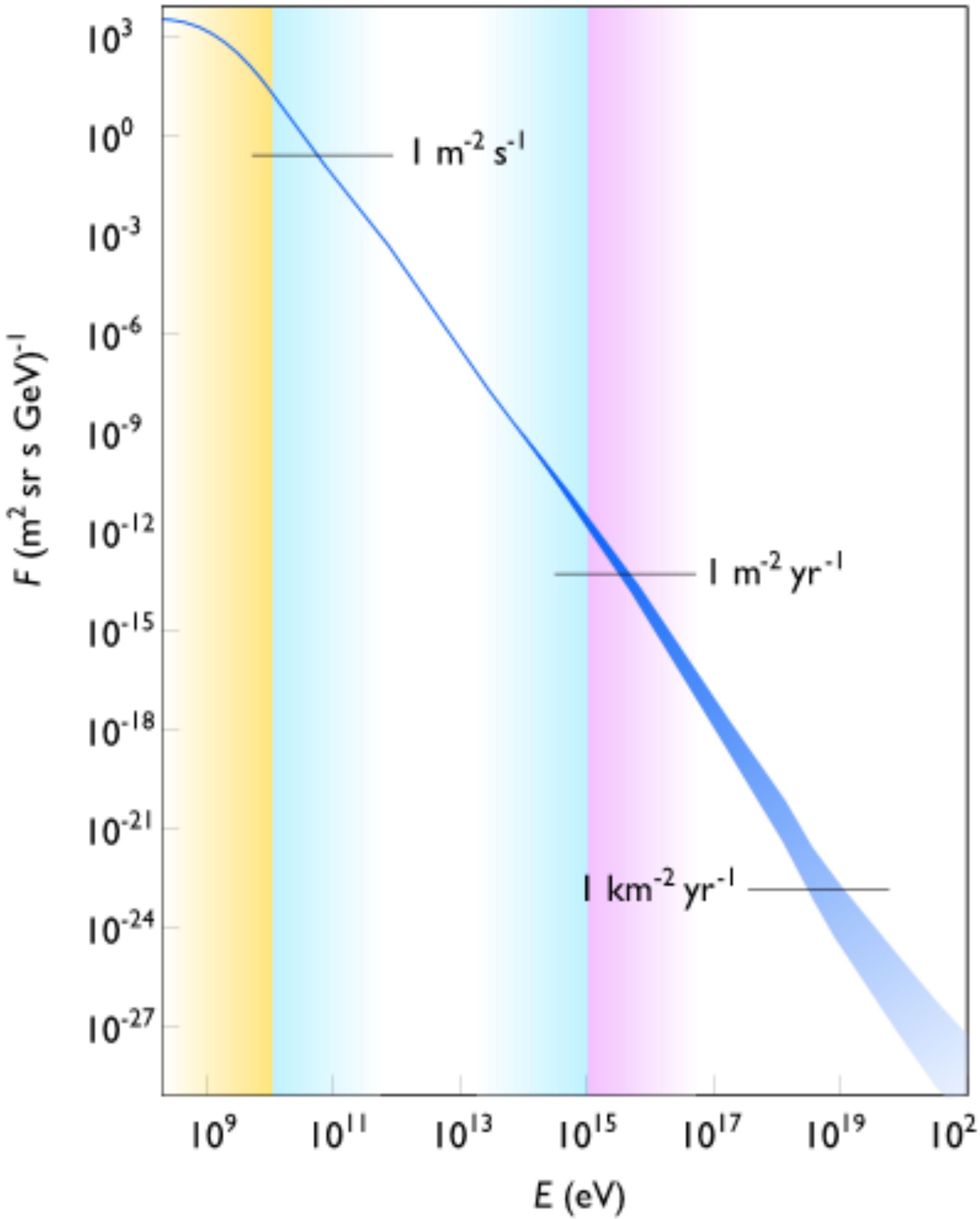
Atmosphere Warms → Muon rate rises

Parameter	Eq. 1	Stopped Muons	Total Particles
Pressure	α	-3.2 ± 0.5	-1.94 ± 0.10
Altitude	β	-2.7 ± 0.9	-0.8 ± 0.2
Temperature	γ	$+0.35 \pm 0.17$	$+0.08 \pm 0.04$
		$\chi^2_\nu = 1.07$	$\chi^2_\nu = 1.09$

Re-cap / Summary

- Cosmic rays are messengers from the galaxy and beyond… not from our sun; mostly protons
- Cosmic rays at Earth's surface are mainly muons from atmospheric "showers"
- Ionizing radiation due to cosmics: evidently we are evolved to tolerate it
- Muon intensity depends on atmospheric and space weather conditions: more-so for lowest energy muons

Supplemental Slides



F (m2 sr s GeV)-1
103
100
10-3
10-6
10-9
10-12
10-15
10-18
10-21
10-24
10-27
1 m-2 s-1
1 m-2 yr-1
1 km-2 yr-1
109
1011
1013
1015
1017
1019
1021
E (eV)

Units for Ionizing Radiation

Unit	Conversions	Quantity
bequerel	1 Bq = 1 decay / second	Activity
curie	1 Ci = 3.7×10^{10} decays/sec	
rad	100 rad = 1 Gy	Absorbed dose (energy / mass)
gray	1 Gy = 1 Joule/kg	
rem	"Röntgen equivalent in man" (1 R of X-rays ~ 1 rem in tissue)	Equivalent dose (energy / mass)
sievert	1 Sv = 100 rem	
röntgen	1 Coulomb / kg of air = 3880 R	Exposure (charge / mass)