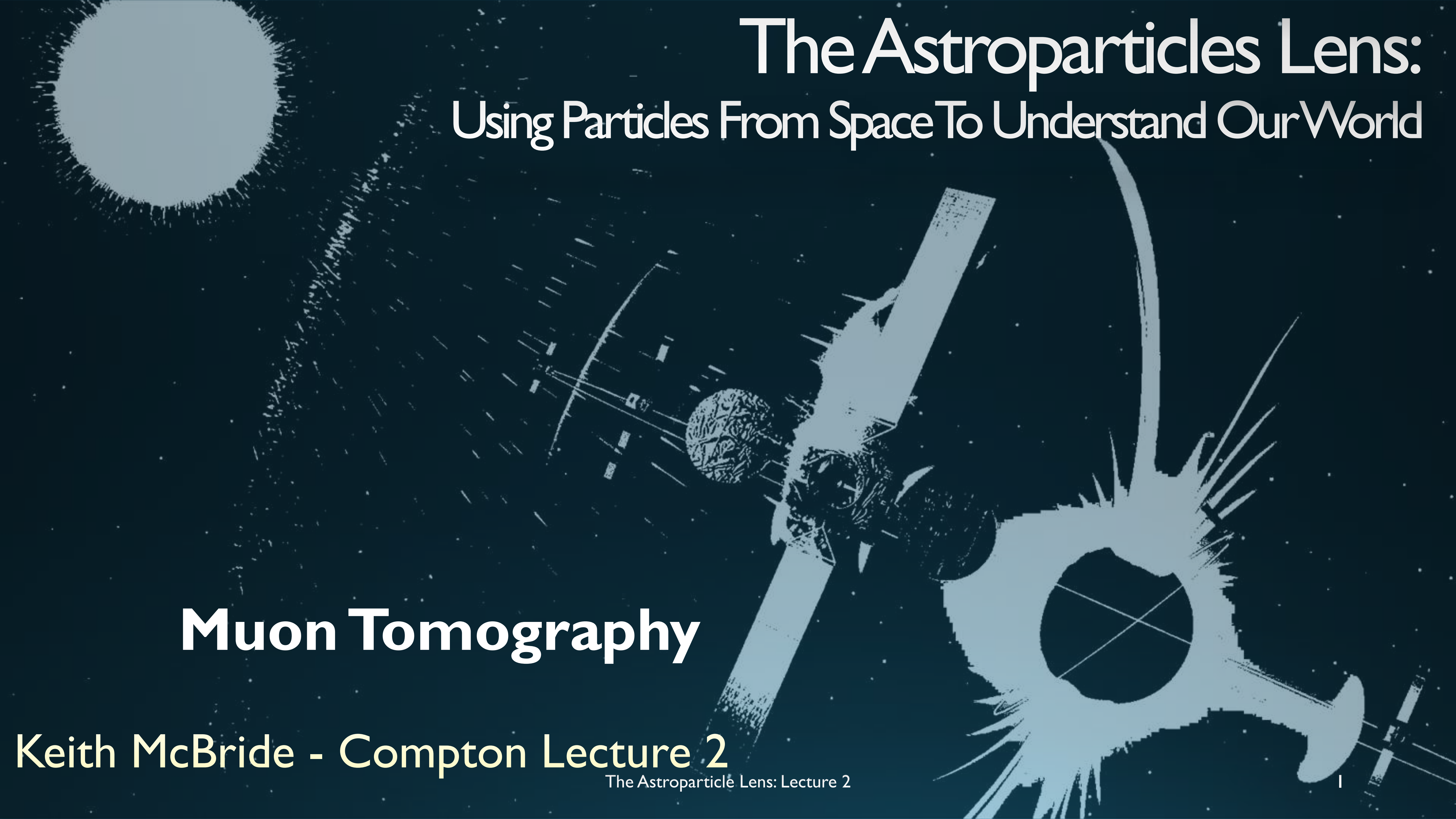
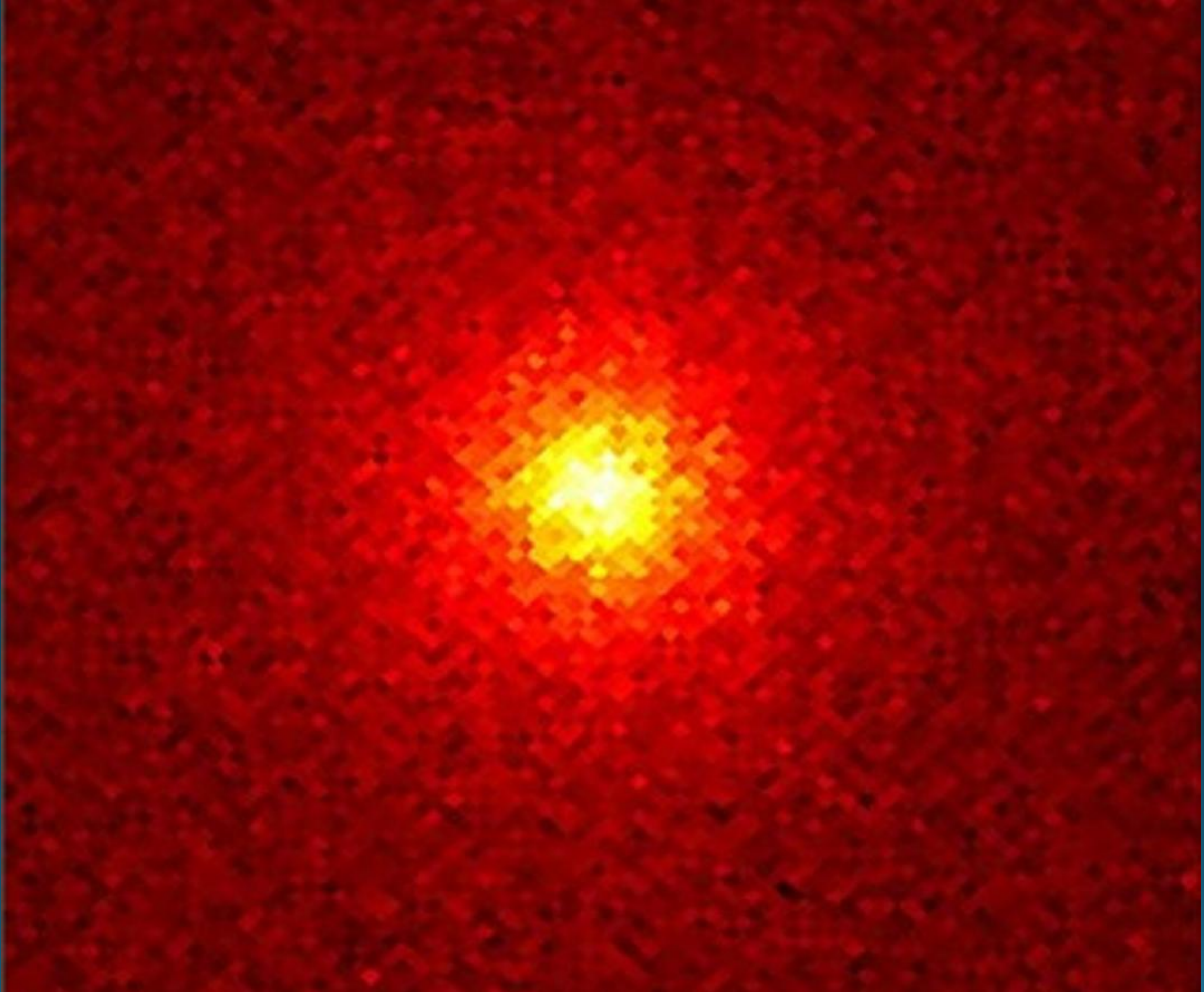


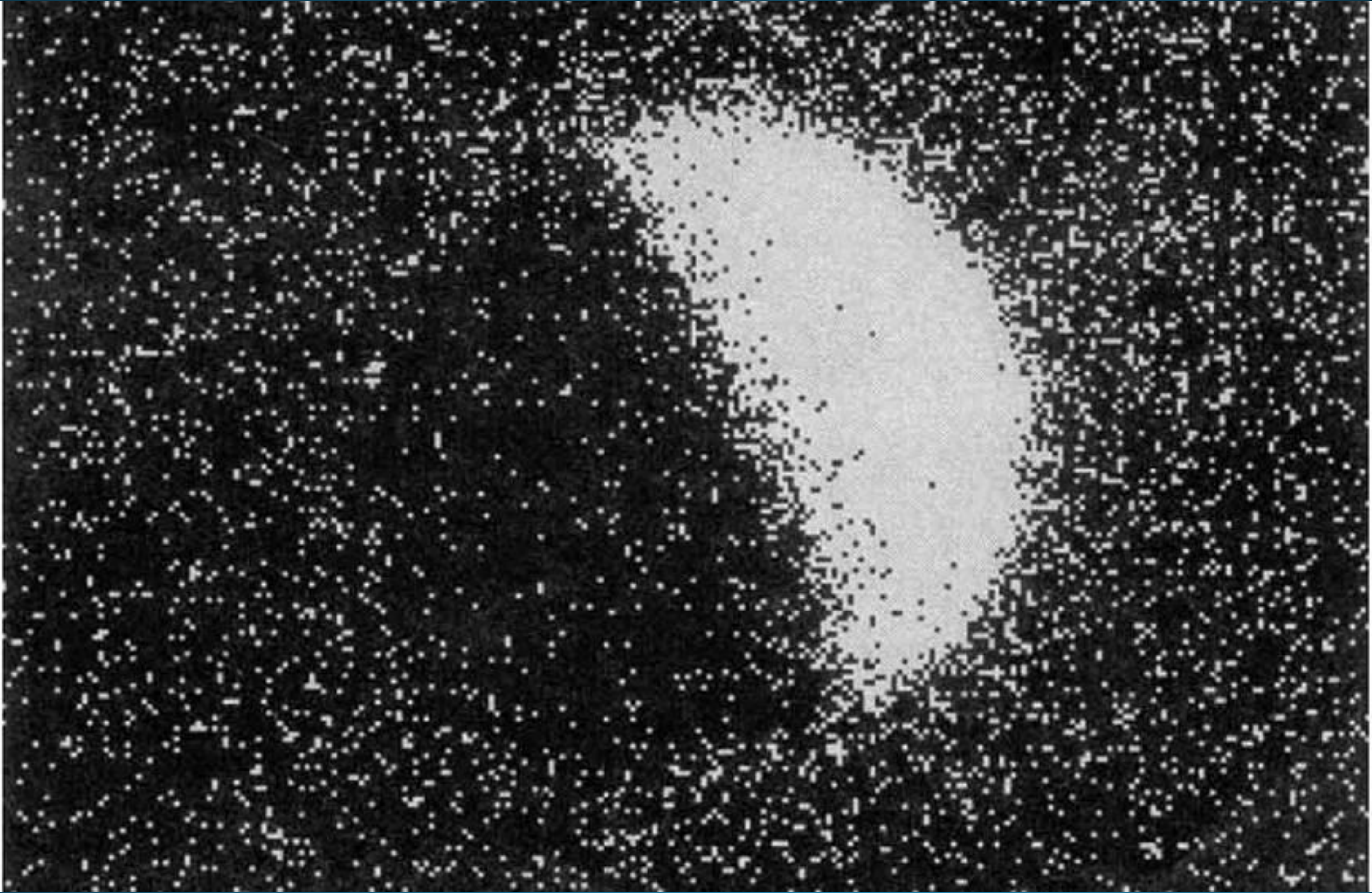
The Astroparticles Lens:

Using Particles From Space To Understand Our World

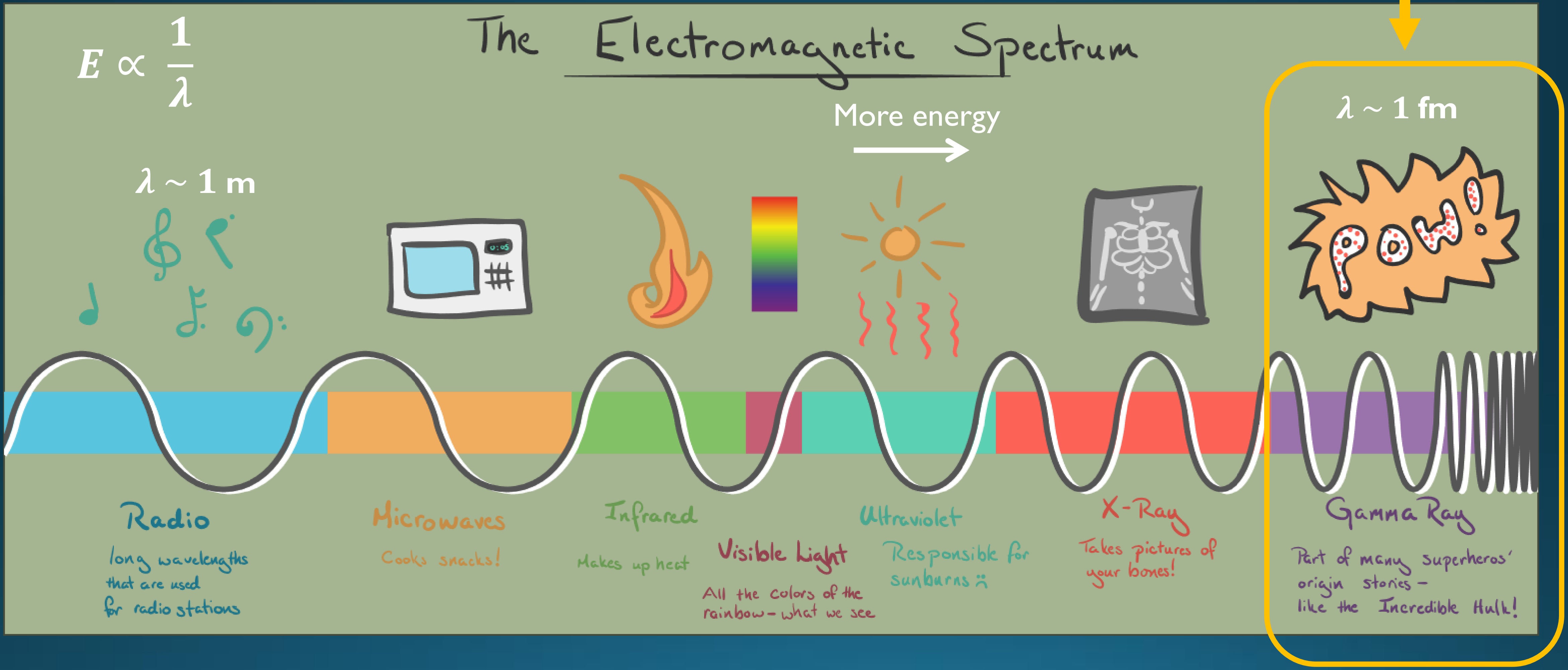
Muon Tomography

Keith McBride - Compton Lecture 2





The highest energy processes have gamma ray signatures



$$E \propto \frac{1}{\lambda}$$

$\lambda \sim 1$ m

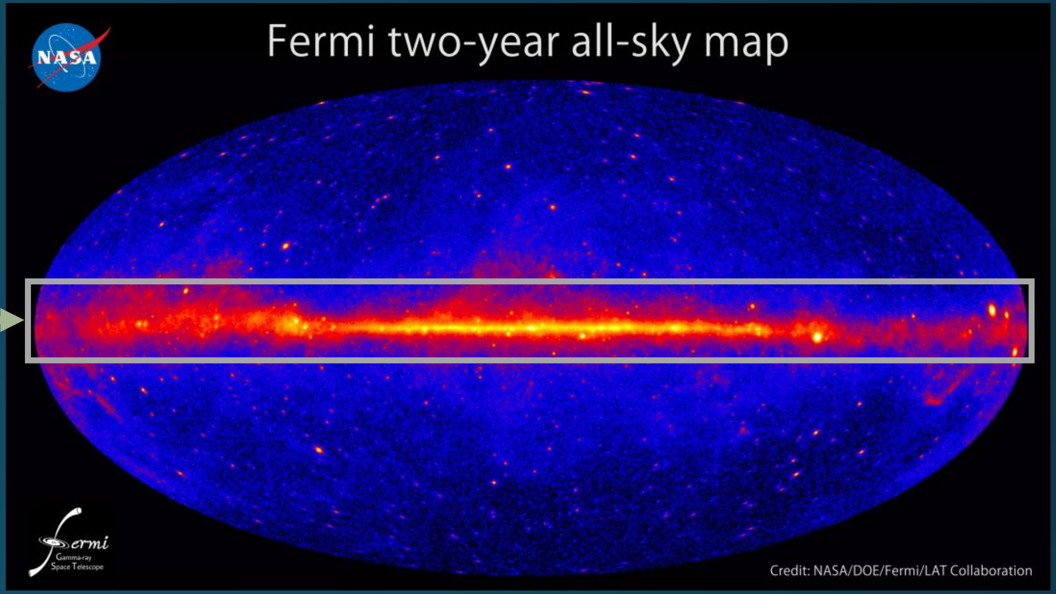
More energy

$\lambda \sim 1$ fm

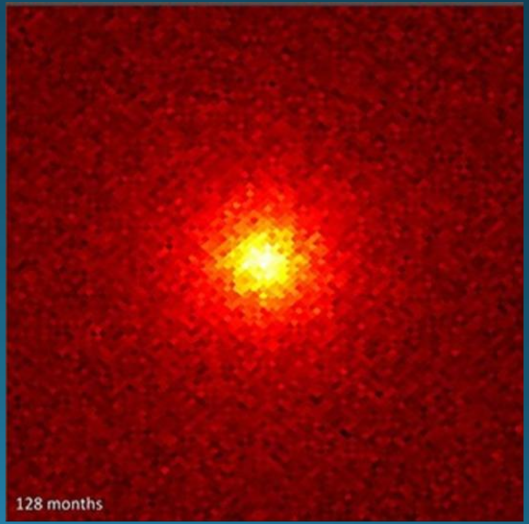
The moon in gamma rays

- Cosmic rays are high energy particles, mostly protons
- Interactions of cosmic ray protons across the universe
  - we see the milky way disk
- The cosmic ray protons also interact with the moon
  - Just like in the Milky Way disk
  - Produce gamma rays

Milky Way

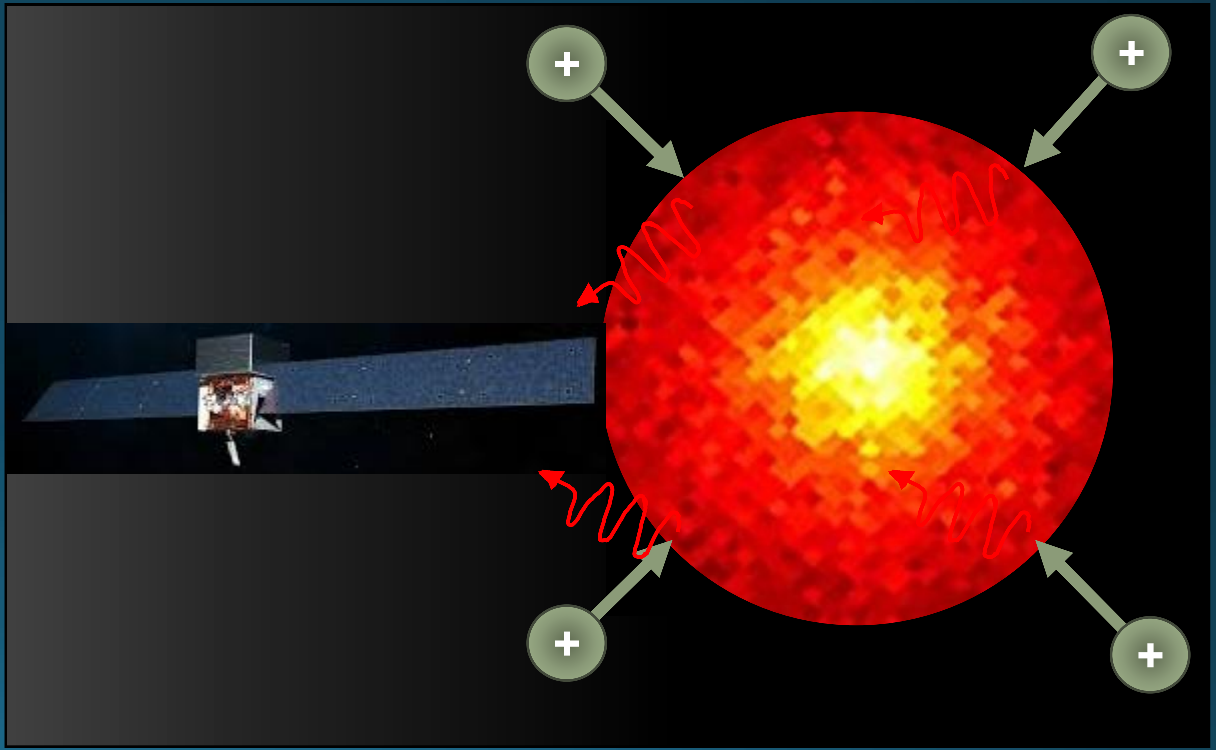


Credit: NASA/DOE/Fermi/LAT Collaboration



Why is the moon bright in gamma rays?

- In this case, the moon is bright because:
  - *Many* high-energy cosmic rays interact with its surface
    - gamma rays produced
  - AND the detector (Fermi Telescope) is able to see them essentially unimpeded
- The Moon glows in gamma rays because it exists in the sea of cosmic ray protons that covers the Milky Way.
  - And its close by

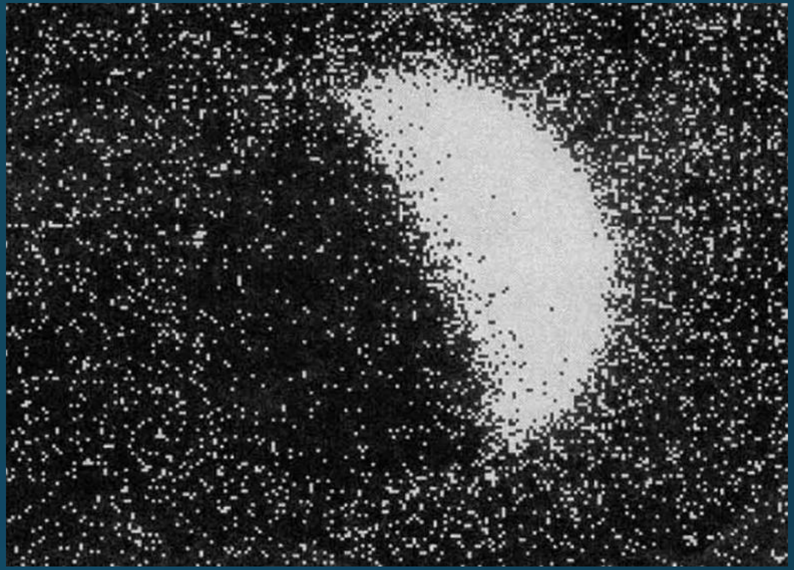


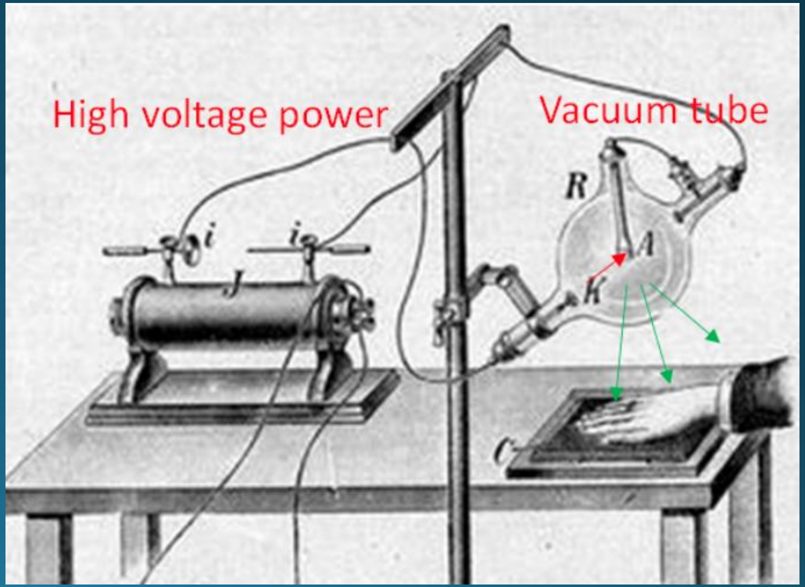
Line of Sight

- If you want to see an object, it has to be within your line of sight
  - And other objects can not absorb the light or radiation along the path to the detector (eyeball)
- Things in the way may interfere or block the radiation
  - But in X-Rays, that's what is useful!

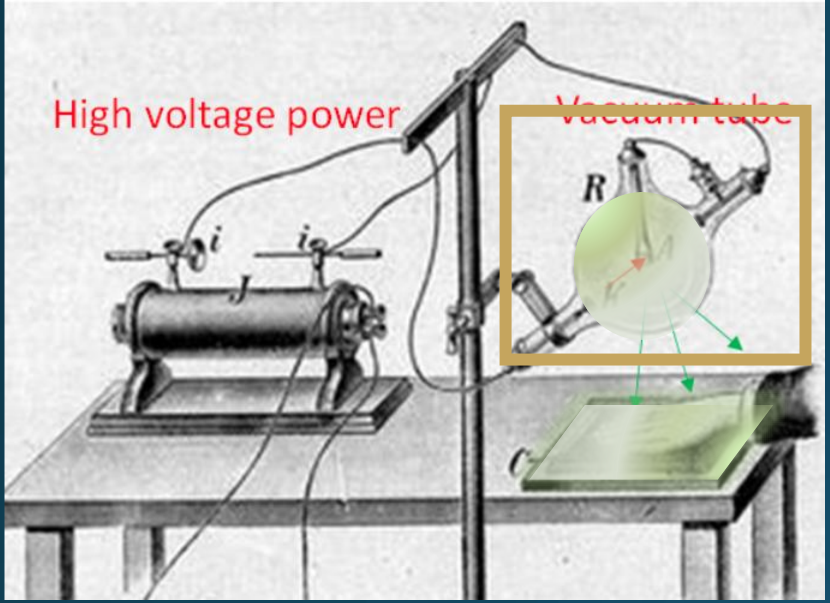
X-Rays

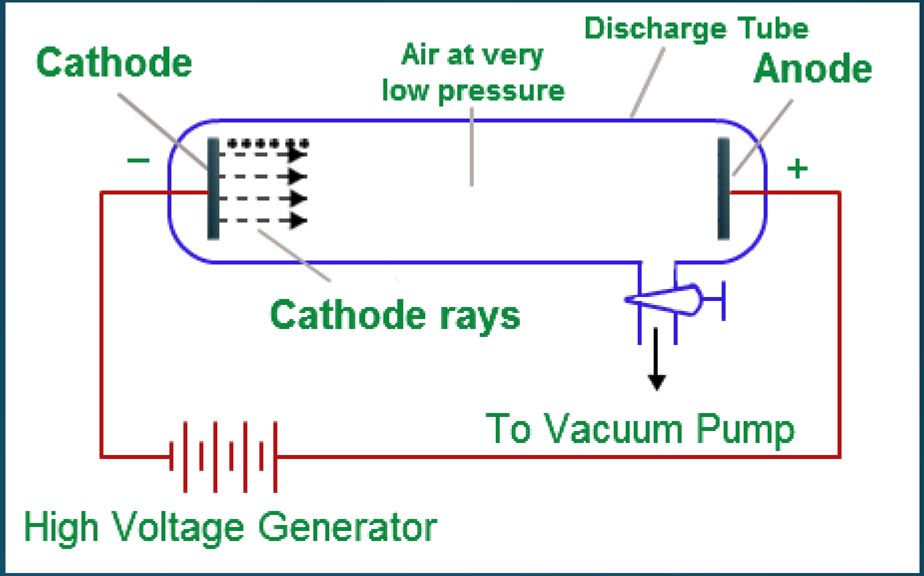
- The moon doesn’t glow in X-Rays
  - Just the sun side
- But, we see its shadow because it blocks the X-Rays from the rest of the universe
  - “background X-Rays”
- X-Rays are absorbed - radiography





Crookes tube - Multiple Rays





1. Cathode rays accelerated in Crookes tube

2. The glass glows green?

3. Lets put a bunch of paper around the tube to see it better

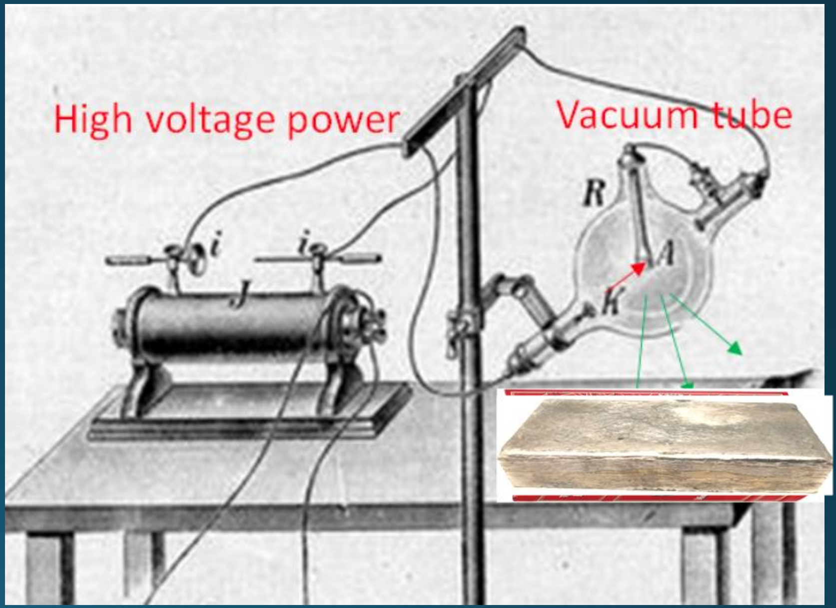
But the barium platinocyanide screen was glowing green too?

This was the first-ever Nobel Prize in Physics in 1901

Purely accidental discovery!

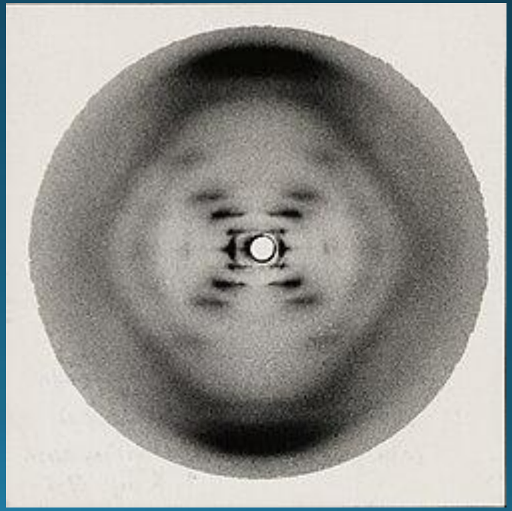
Roentgen was systematic

- Place a bunch of different materials in between the crookes tube and the film/screen
- Figured out that some materials are better at stopping these mysterious rays
- Thin lead is better than lots of paper
  - Dense = dark
- Groundbreaking discovery
  - Cathode rays contained in glass
  - Visible light stopped by cardboard
  - Inspired Henri Becquerel to investigate, discovering radioactivity In 1896



Quite interesting history of X-Rays

- It was quickly determined that X-Rays were neutral particles
  - Becquerel thought his radioactivity measurements were these fancy new x-rays!
- But it hadn't been understood that these could even be EM radiation/light
- Some workers died experimenting with X-Rays
- This changed in1912
  - Max von Laue Nobel Prize in 1914
    - X-Ray crystallography
  - And much later in 1950s

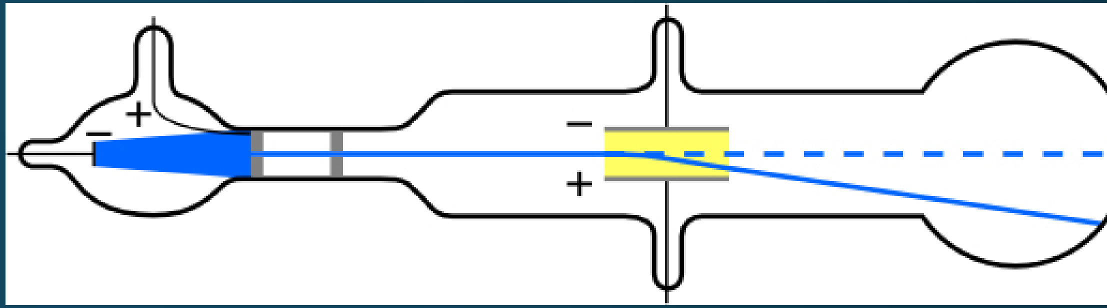


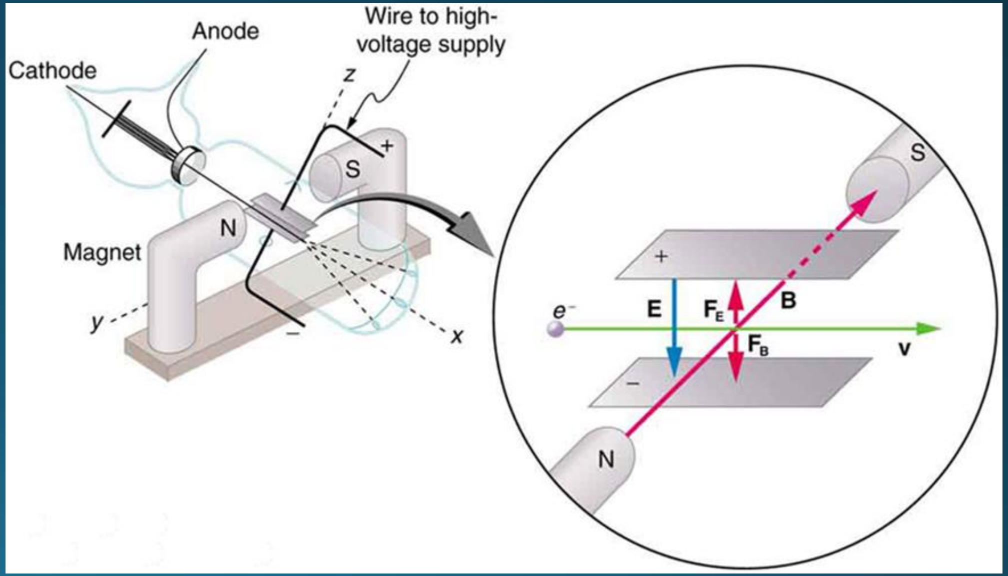
Discovery of
double helix
structure in
DNA
Photo 51

small wavelength = high energy
1nm ->1240eV X-Rays

The Cathode Rays

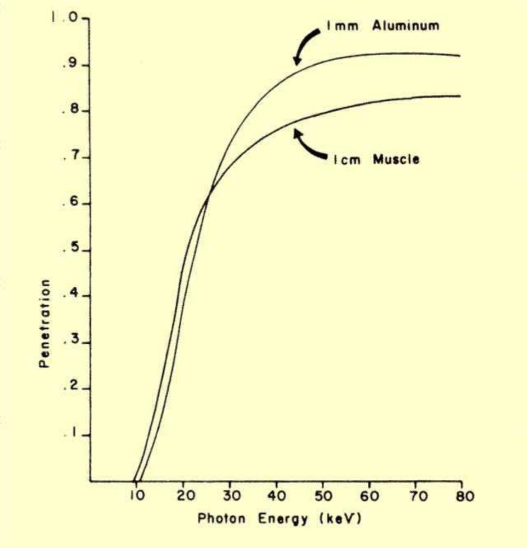
- J.J. Thompson bent the cathode rays in fields
  - calculated the charge to mass ratio
    - e/m
  - Used both electric and magnetic fields
- Improvements to Crookes tube to measure the cathode rays
- Discovery of electrons
  - Fundamental particle
  - 1906 Nobel Prize

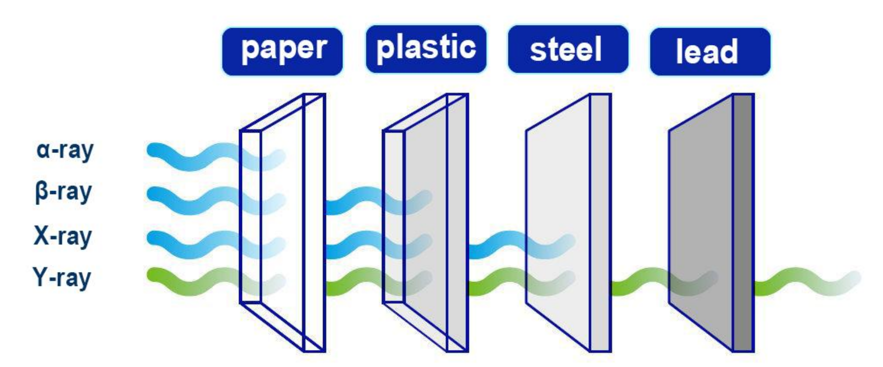




But how do we get X-Rays out of electrons in Crookes Tubes?

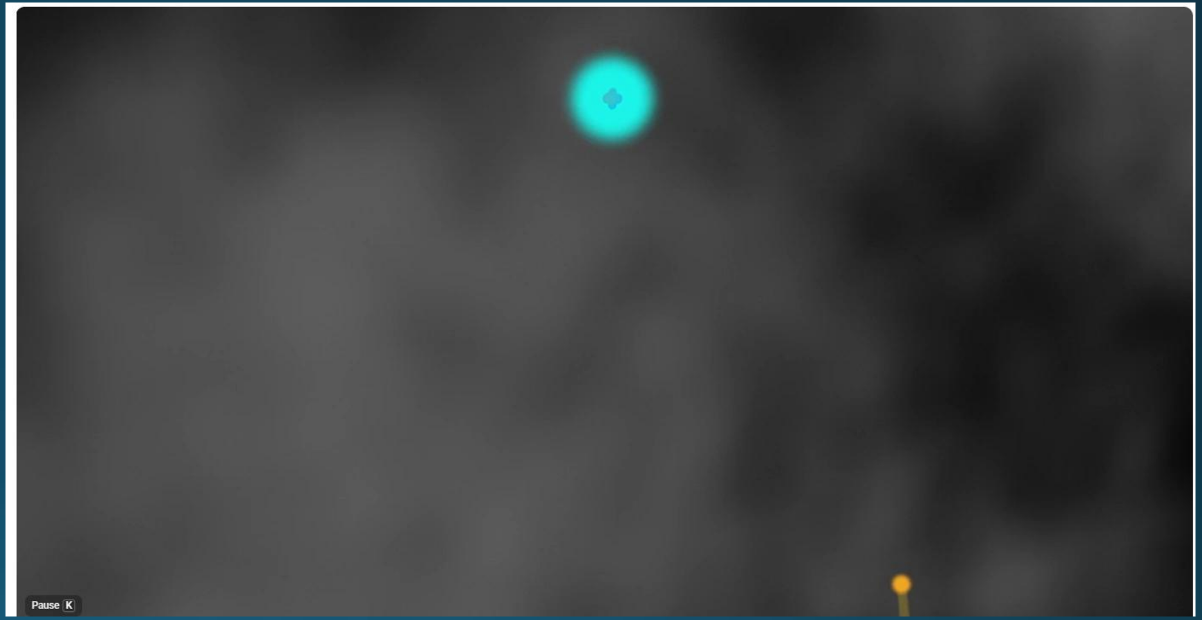
- Thompson, Roentgen, and others changed the materials inside the Crookes tube
- They measured the X-Rays going through different amounts of materials
- Different energies-wavelength as we know now
  - more penetrating = higher energy
- Rutherford classified all these radiation types by penetrating power





The problem became, why electrons produce the X-Ray radiation

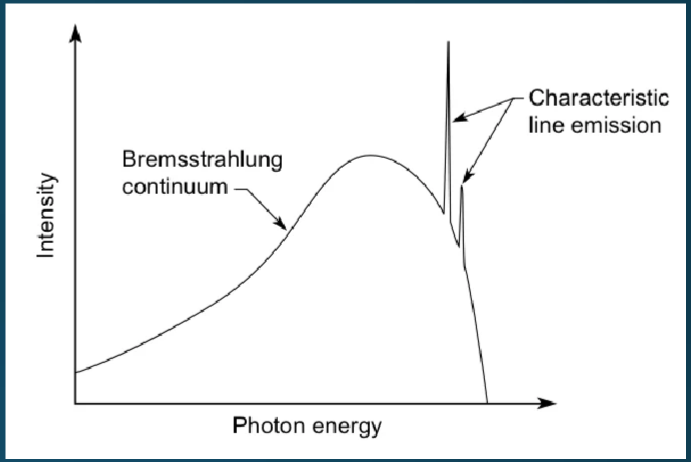
- Arnold Sommerfeld (~1909)
  - why does it depend on the material?
  - Because the atoms are causing the electrons to brake!
- Bremsstrahlung = Braking radiation
- The theory worked sort of well
  - Spectrum of X-Rays were observed
  - The amount of X-Rays is inverse to the mass squared of the charged particle: $\frac{1}{m^2}$

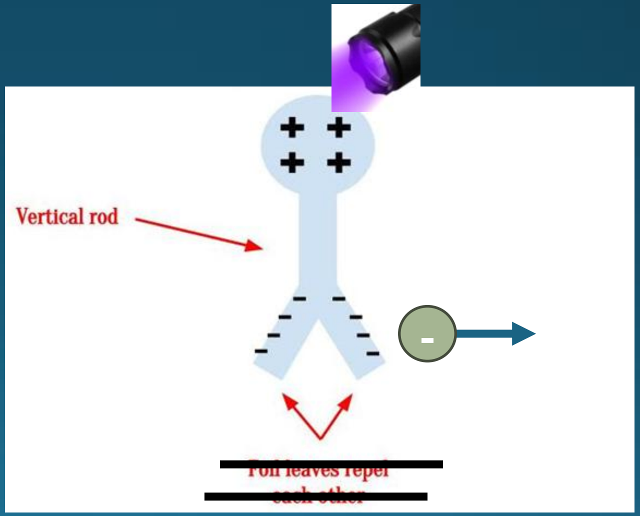


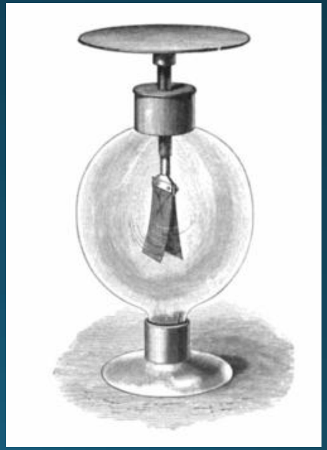
Deceleration is just a special kind of acceleration, so when a charge slows down, it shines.

The problem with this theory

- Experiment showed weird feature- high energy cutoff
  - It should go smoothly to the highest energies
  - And some spikes at some energies
- At the same time, electroscopes were being investigated
  - Hallwachs (1890s) found that ultraviolet light incident at the top plate would make the gold leaves fall
  - Electrons were being kicked out

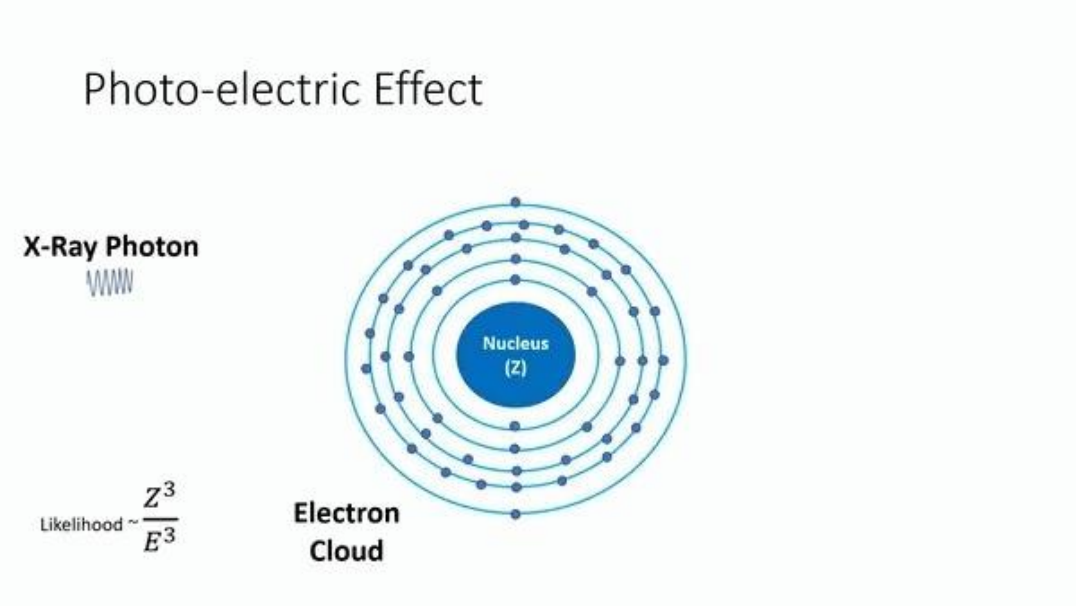


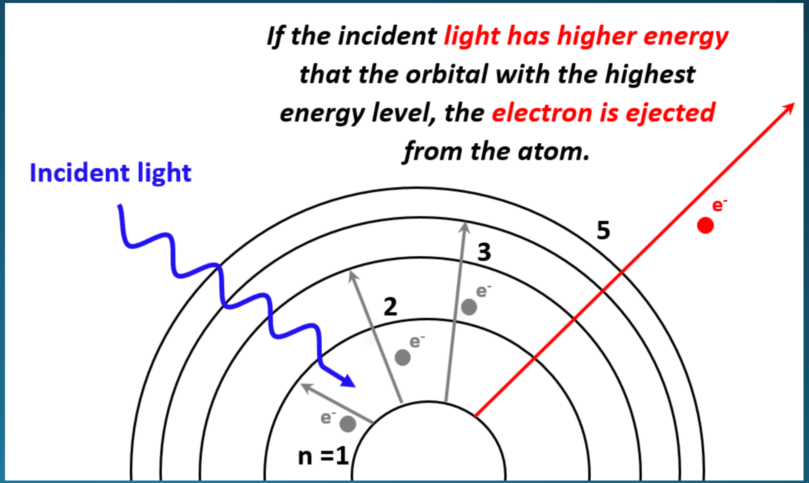




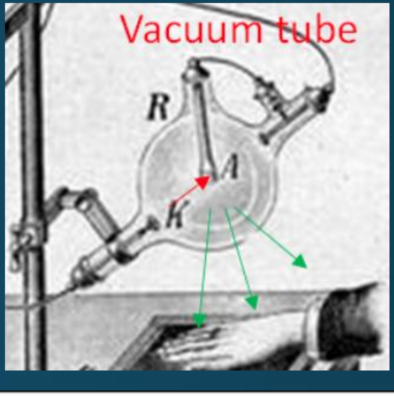
Photoelectric effect

- Completely reimagined light/EM radiation and the
  - As particles or photons
  - And the photon energy determined the electron energy
- Einstein proposed the theory for quantized light to explain photoelectric effect (1905)
- Revolution in our understanding
  - The electrons in atoms are in energy levels
  - The electrons in Crookes tube are free electrons




If the incident light has higher energy that the orbital with the highest energy level, the electron is ejected from the atom.

Electrons and X-Rays were entangled

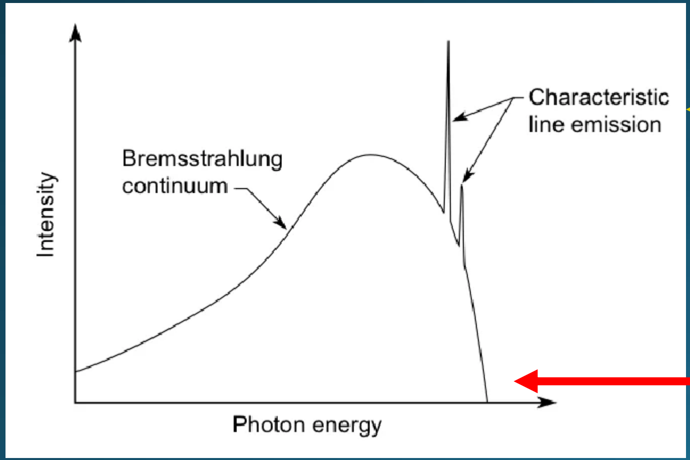


Refine the theories

Electrons in Crookes tube collide with atoms of materials

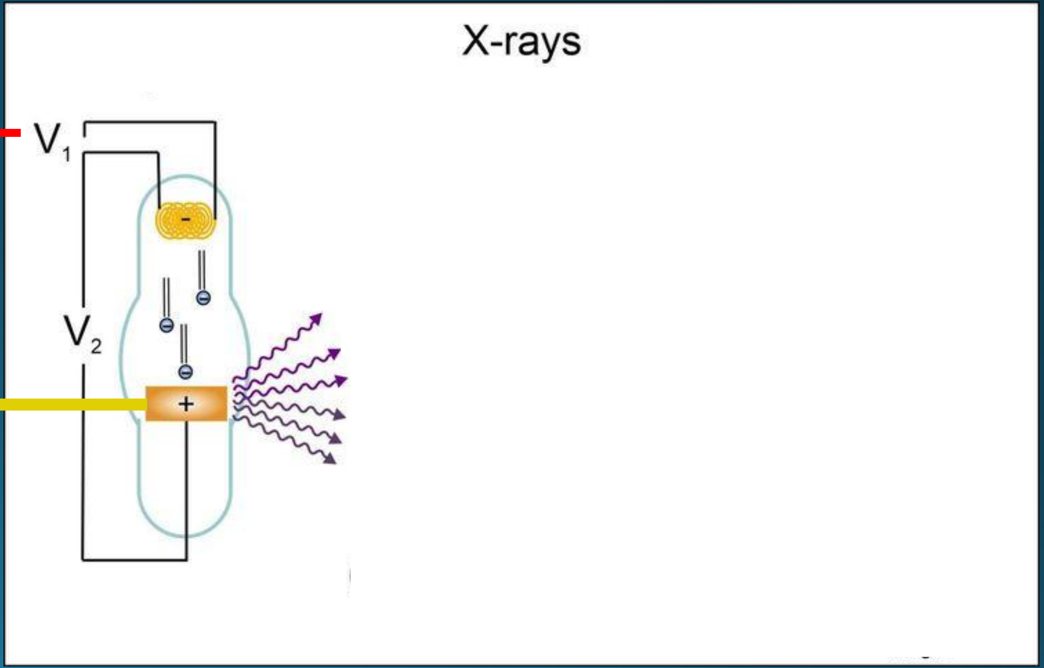
- Since the electrons in the atoms are in discrete energy levels
- emit the X-Ray photons via:
    - Bremsstrahlung
    - characteristic spikes

X-Ray spectrum



material

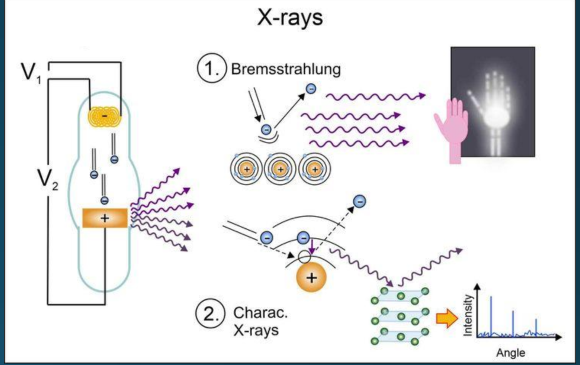
Voltage



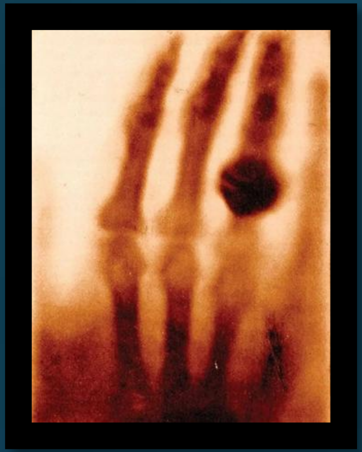
Summary of the X-Ray and electrons

Electron accelerated by voltage → Electron feels the atoms/ electrons of a material and brakes → Braking radiation (X-Rays) emitted → Cutoff of X-Rays is the energy of the electron

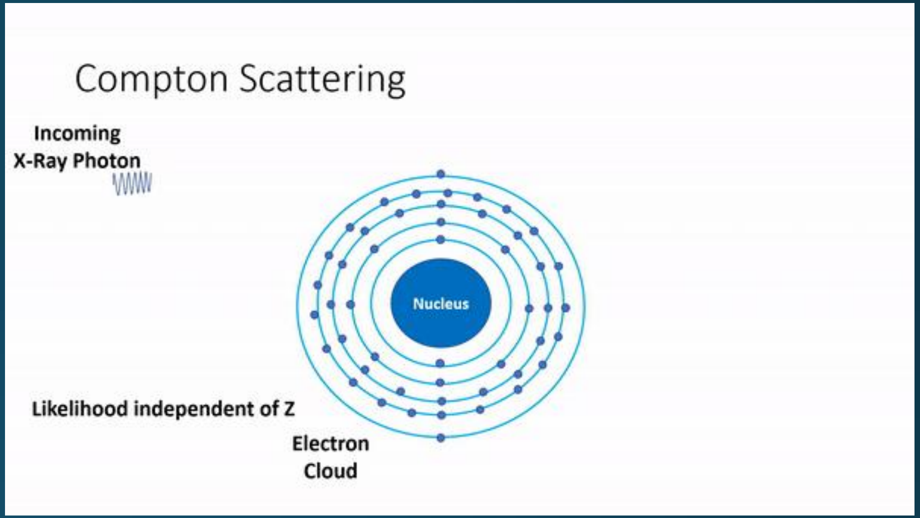
Electron accelerated by voltage → Electron kicks out an electron near the nucleus → Characteristic (X-Rays) emitted → Depends on the material



By the 1930's X-rays were a tool

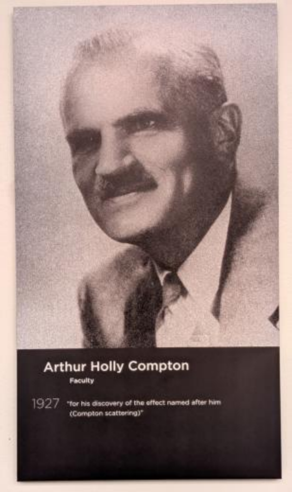


X-Rays are like billiard balls with electrons!

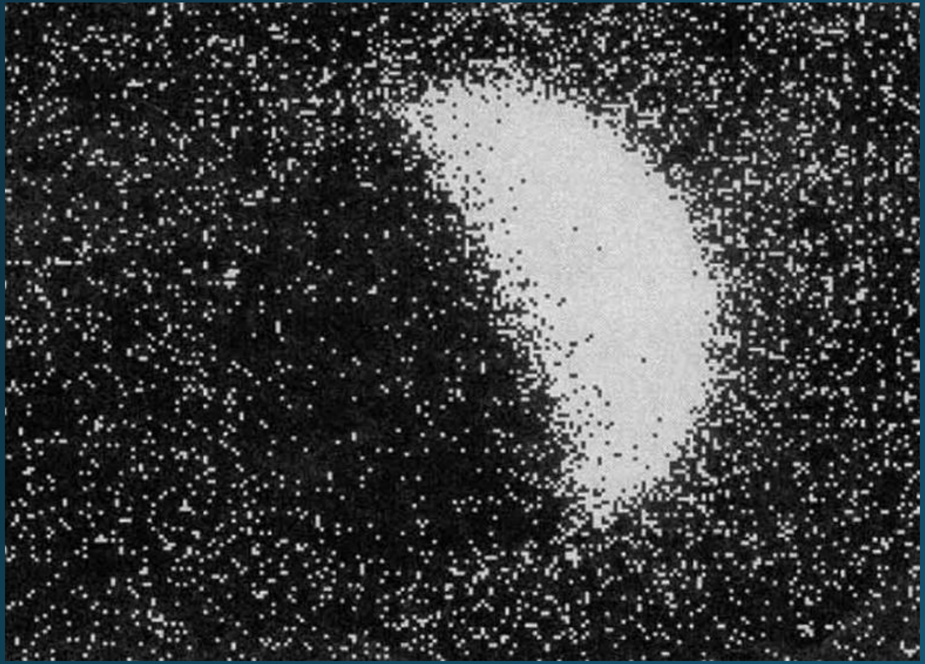


Why can't we "X-Ray" some materials?

- X-Rays in atoms interact with the electrons
  - Compton scattering
  - Photoelectric effect
    - depends on the material's nuclear charge, Z
    - The skin (Z~6)
    - The bone (Z~10)
    - The ring (Z~20)

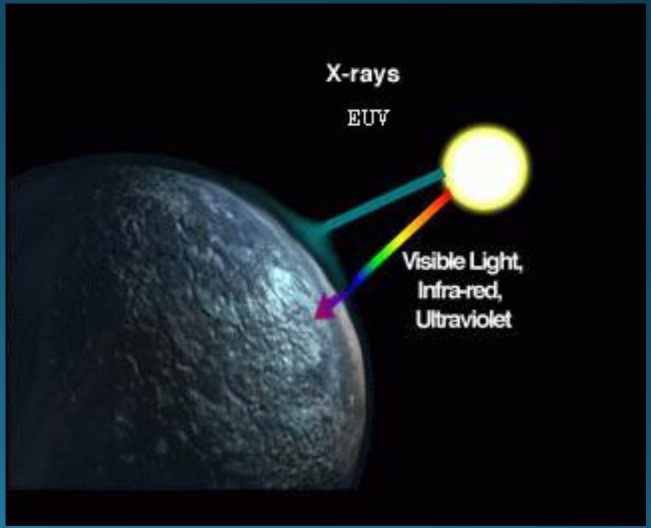


X-rays don't make it to the ground



X-Ray telescopes have to be in space

- The universe's X-rays are absorbed in the atmosphere

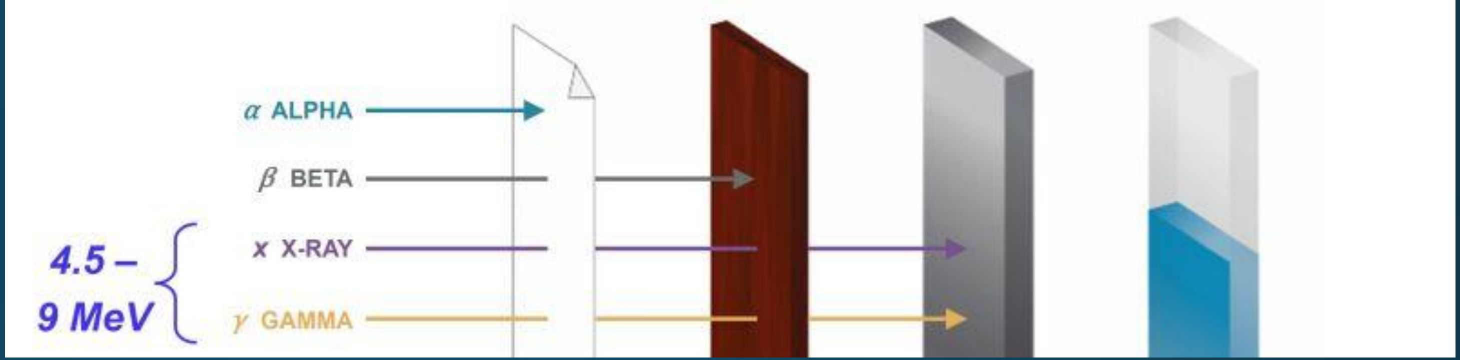


Line of sight – The atmosphere is in our way

Going into the 1930's

We can explain how matter and radiation work more or less

- X-Rays don't go through some materials
- Electrons/Beta rays go through even less
  - braking radiation -> X-Rays produced!
- But the cosmic radiation observed by Pacini and Hess was even more penetrating
  - Maybe it is just high energy electrons?



1. Matter is made up of positive protons and negative electrons
2. Charged particles radiate when going through the materials!

The debates in the 1920's and 30's

- It was very murky
  - Some identity crises!
- Compton showed cosmic rays are charged and positive!
  - Protons correctly identified
  - He and his friends went around world to measure this!
- Others validated this
  - Blackett constructed large magnets to bend the cosmic rays
  - 5 ton magnet of ~10,000 Gauss
    - 1 Tesla
    - 40,000 times stronger than the Earths field

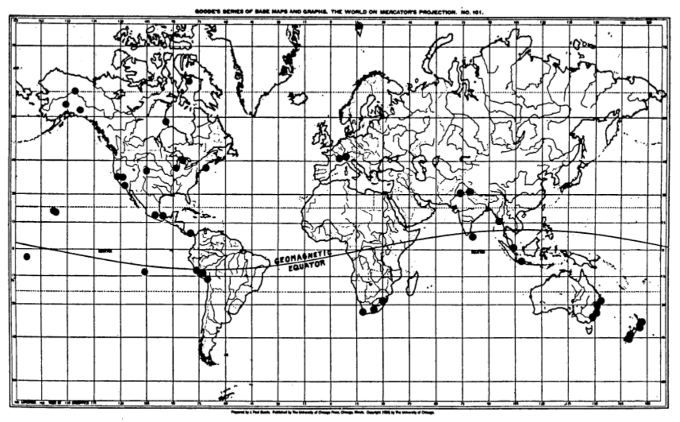
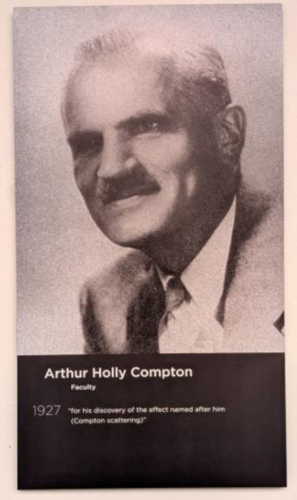
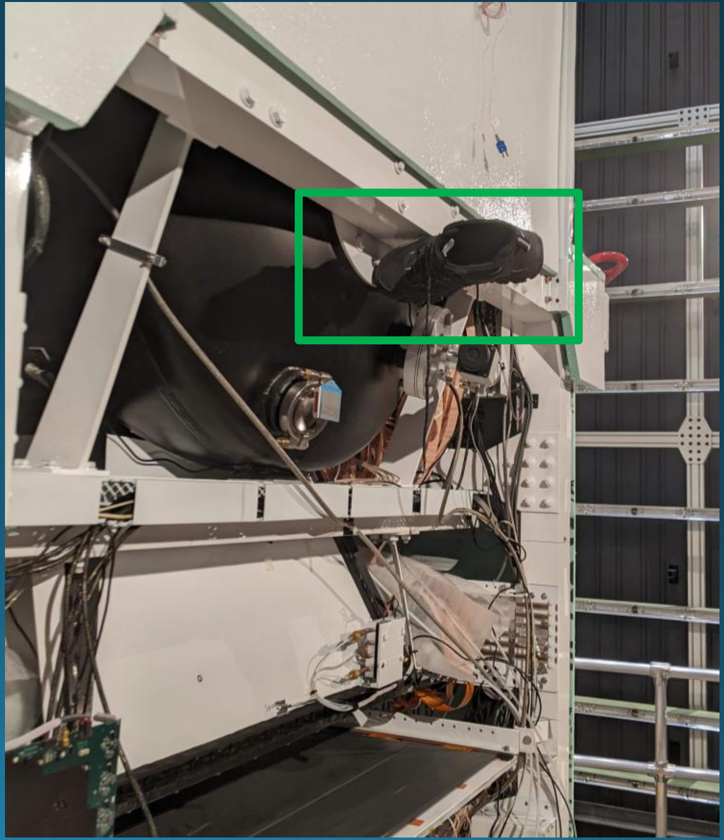


FIG. 4 Map with location of cosmic-ray measurements by Compton and his co-workers. *PR, 43* (1933), 389.

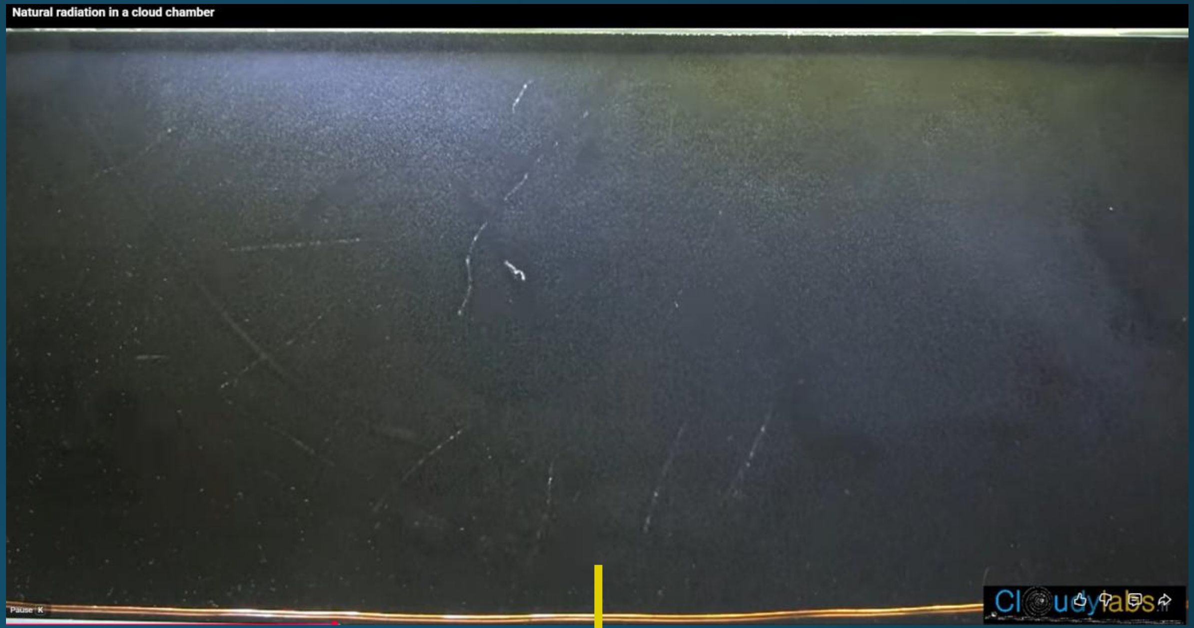


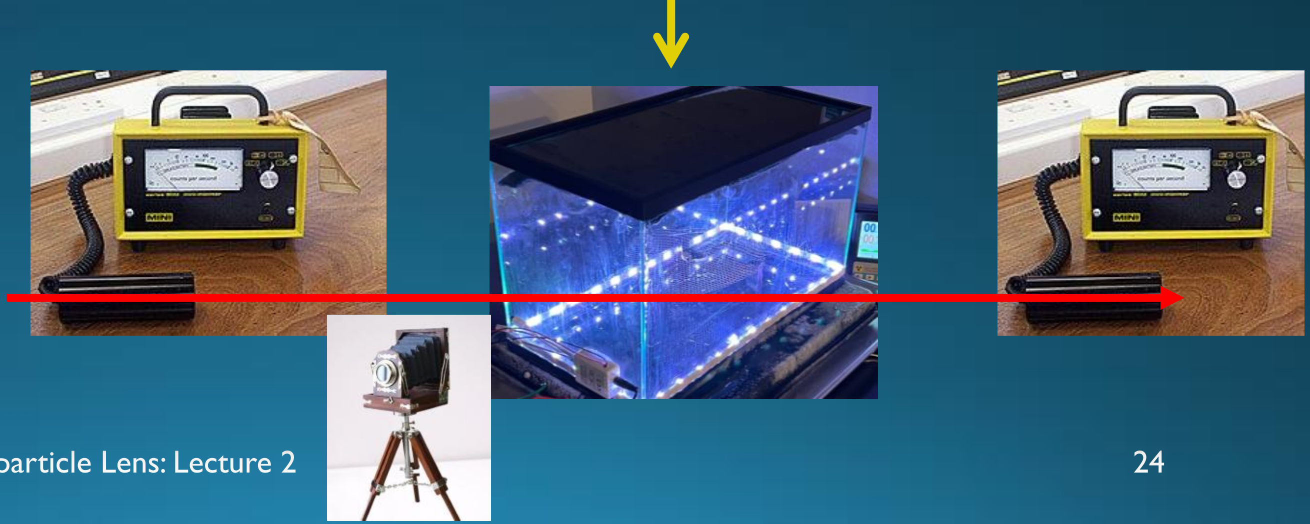


New ideas with detectors with Blackett!

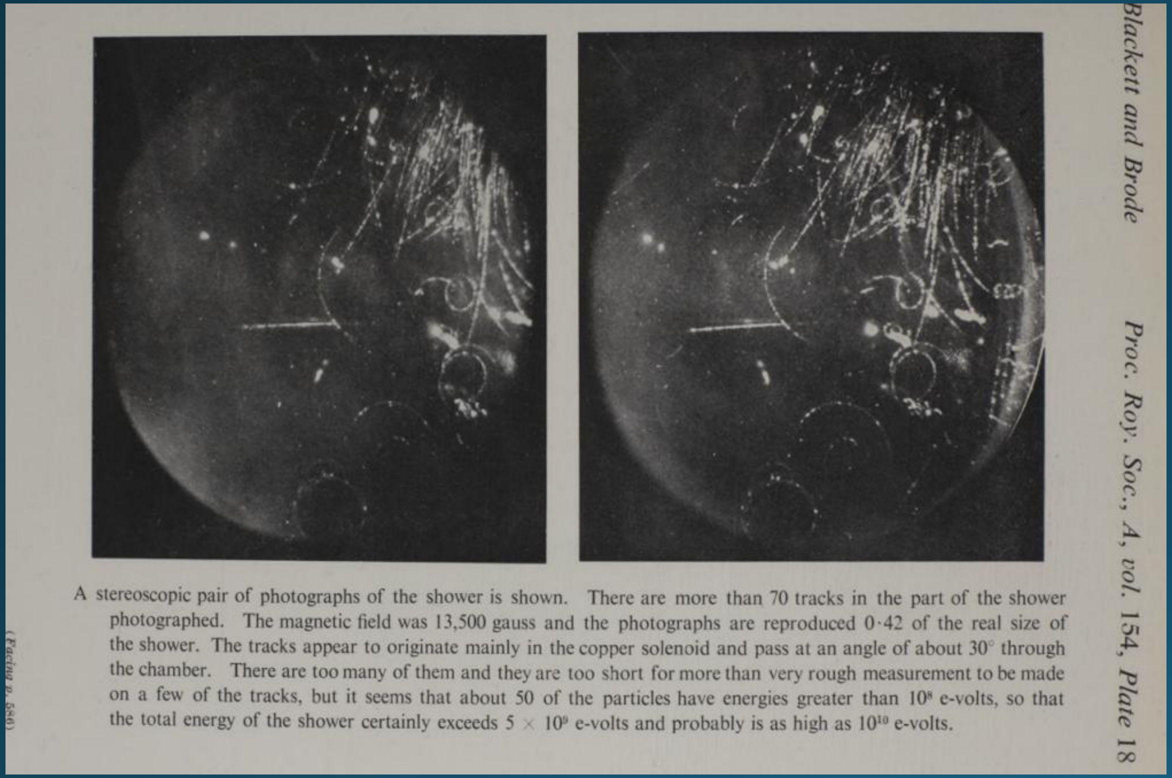
~1930's

- Cloud chamber gas was improved
- The coincidence measurements
  - Geiger-Muller counter
  - Triggering the camera to take pictures of the tracks!
- At higher altitudes to really see the cosmic rays
- Confirmation of positron mass and charge!


Natural radiation in a cloud chamber



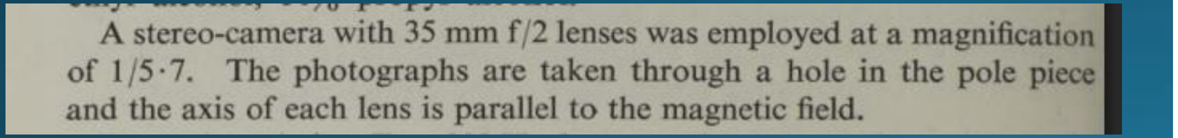
Cloud Chamber studies



Blackett and Brode Proc. Roy. Soc., A, vol. 154, Plate 18

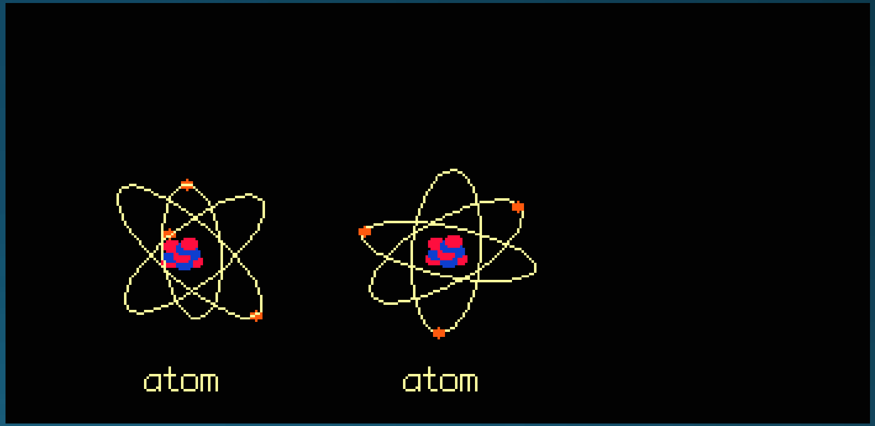
A stereoscopic pair of photographs of the shower is shown. There are more than 70 tracks in the part of the shower photographed. The magnetic field was 13,500 gauss and the photographs are reproduced 0·42 of the real size of the shower. The tracks appear to originate mainly in the copper solenoid and pass at an angle of about 30° through the chamber. There are too many of them and they are too short for more than very rough measurement to be made on a few of the tracks, but it seems that about 50 of the particles have energies greater than 10^8 e-volts, so that the total energy of the shower certainly exceeds 5×10^9 e-volts and probably is as high as 10^{10} e-volts.

(Facing p. 586)



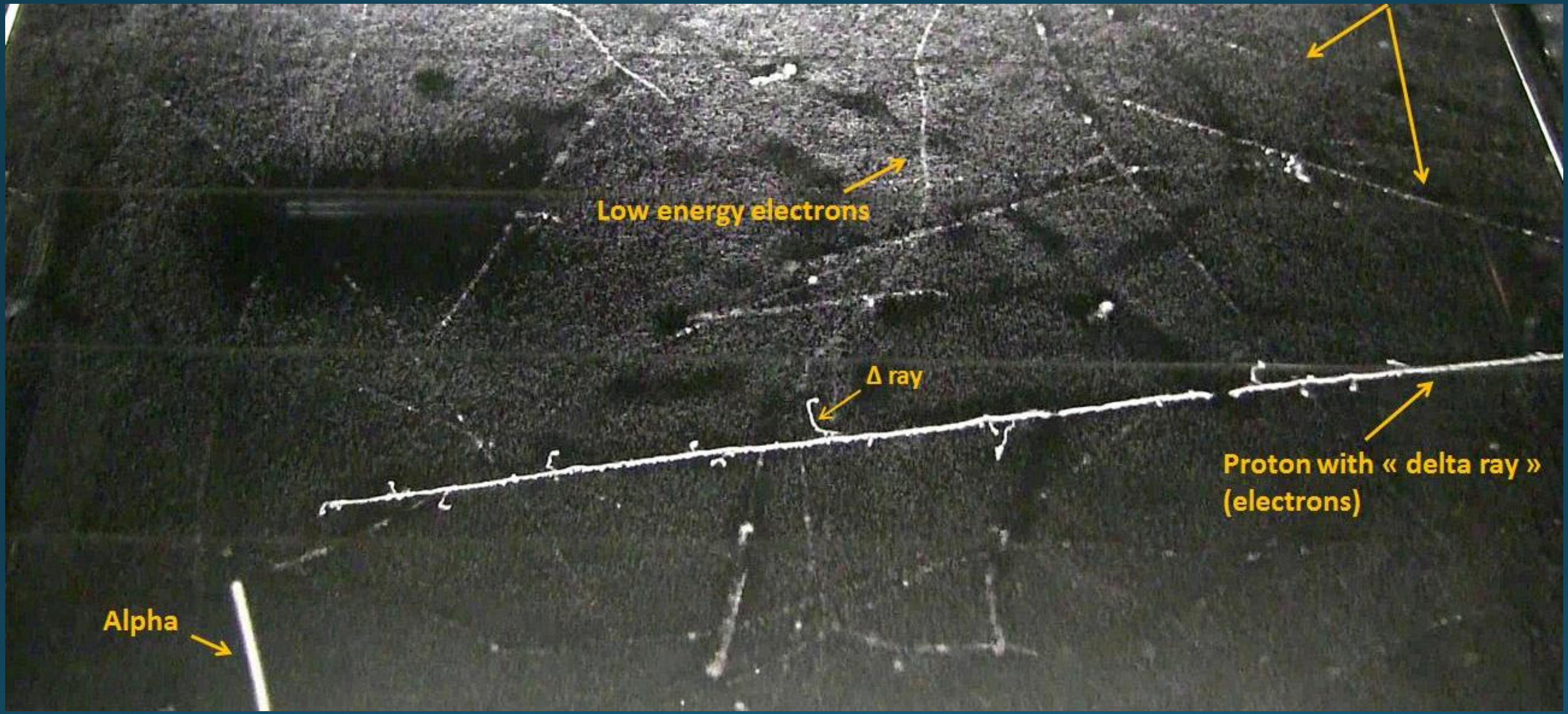
A stereo-camera with 35 mm f/2 lenses was employed at a magnification of 1/5·7. The photographs are taken through a hole in the pole piece and the axis of each lens is parallel to the magnetic field.

- It was understood charged particles would ionize the gas
  - Atoms have electrons in energy levels
- Bethe-Bloch developed the theory to explain what was being observed!



$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0} \right)^2 \cdot \left[\ln\left(\frac{2m_e c^2 \beta^2}{I \cdot (1-\beta^2)} \right) - \beta^2 \right]$$

Cloud chamber studies - tracks



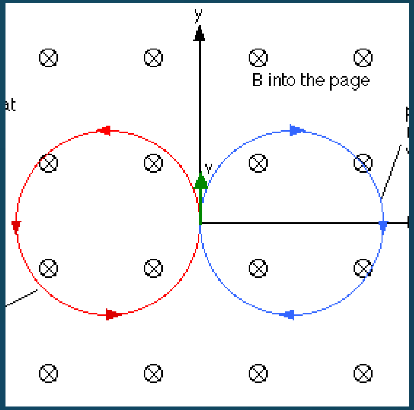
$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \cdot \left[\ln\left(\frac{2m_e c^2 \beta^2}{I \cdot (1-\beta^2)}\right) - \beta^2\right]$$

Confidently measure a particle's:

- Charge sign and momentum (Magnetic field)
- Ionization rate from thickness
- Energy from length of track

But can’t explain the cosmic radiation

- Blackett and others were counting the curved tracks
- Why is cosmic radiation even more penetrating than all other particles we know so well?
- These are new particles
  - In fact, no one really could explain it!
- I.I. Rabi heard about the new particles (which didn't seem to fit into the atomic model of the time)
  - he famously said “Who ordered all of that?”



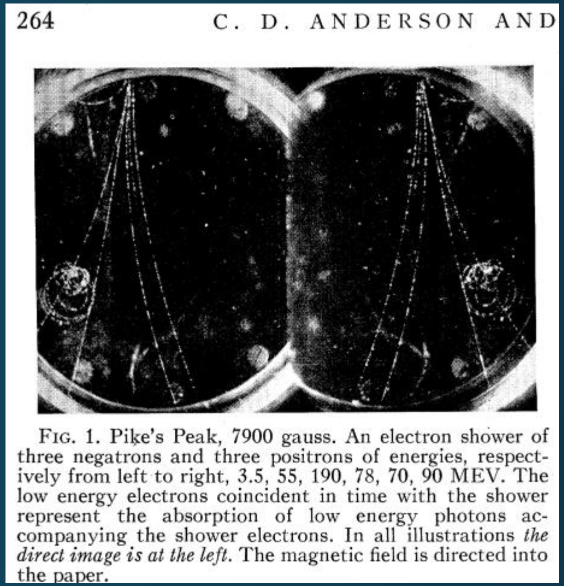

264 C. D. ANDERSON AND

FIG. 1. Pike's Peak, 7900 gauss. An electron shower of three negatrons and three positrons of energies, respectively from left to right, 3.5, 55, 190, 78, 70, 90 MEV. The low energy electrons coincident in time with the shower represent the absorption of low energy photons accompanying the shower electrons. In all illustrations *the direct image is at the left*. The magnetic field is directed into the paper.

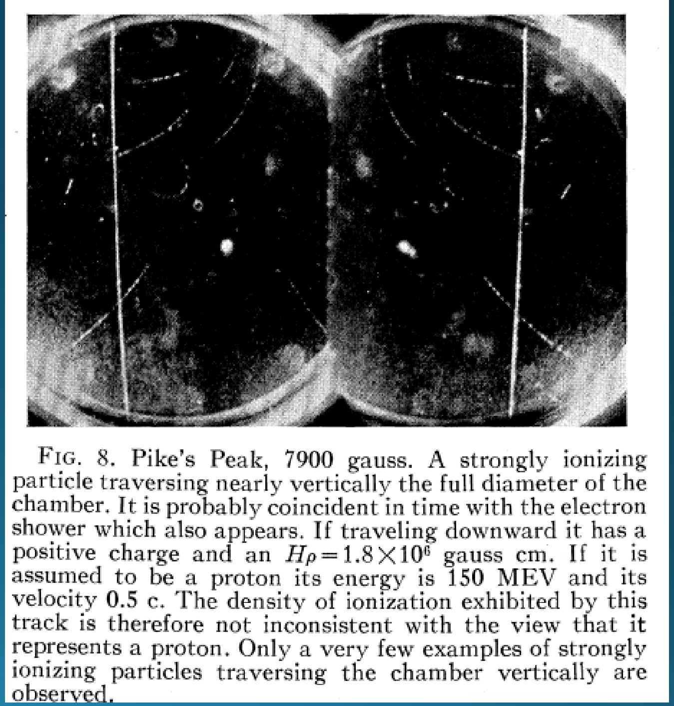


FIG. 8. Pike's Peak, 7900 gauss. A strongly ionizing particle traversing nearly vertically the full diameter of the chamber. It is probably coincident in time with the electron shower which also appears. If traveling downward it has a positive charge and an $H\rho = 1.8 \times 10^6$ gauss cm. If it is assumed to be a proton its energy is 150 MEV and its velocity 0.5 c. The density of ionization exhibited by this track is therefore not inconsistent with the view that it represents a proton. Only a very few examples of strongly ionizing particles traversing the chamber vertically are observed.

Muons and antimuons were found!

From their paper!

- Carl and Neddermeyer investigated the cosmic rays closer
  - Ionization of the gas showed not electrons and not protons
- Proposed a new particle
  - Bent like electron and positron
    - With strong magnets
- Measure the mass
  - 200 times more massive than electron/positron

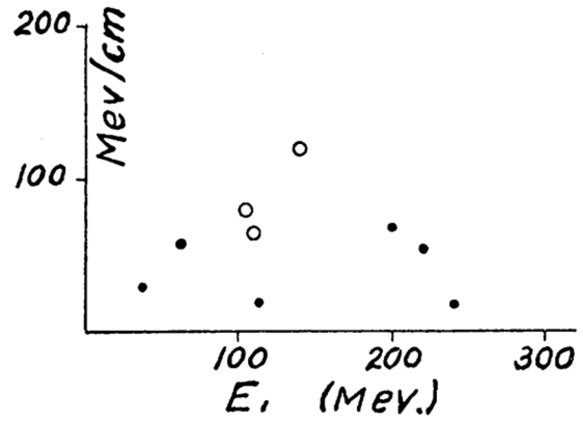
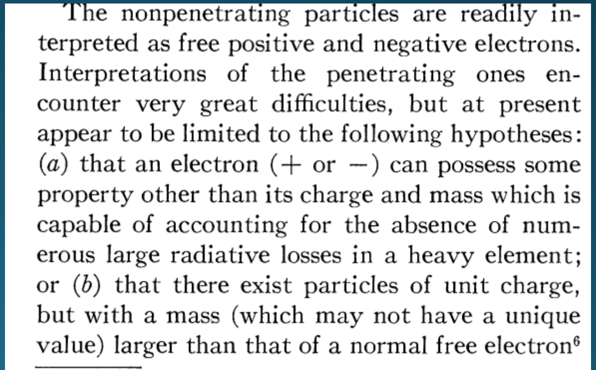
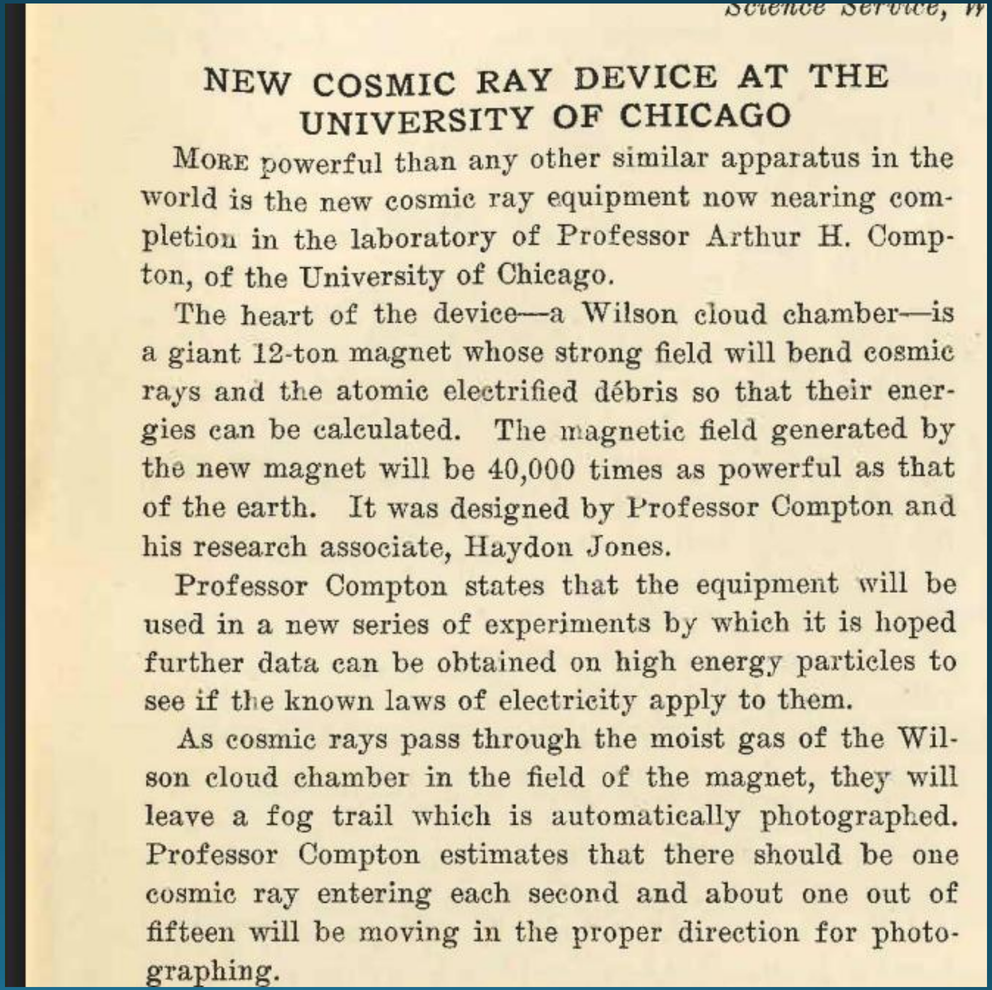


FIG. 4. Early measurements of energy loss in 0.7–1.5 cm of Pb. Dots indicate single particles; circles, shower particles.


The nonpenetrating particles are readily interpreted as free positive and negative electrons. Interpretations of the penetrating ones encounter very great difficulties, but at present appear to be limited to the following hypotheses: (*a*) that an electron (+ or −) can possess some property other than its charge and mass which is capable of accounting for the absence of numerous large radiative losses in a heavy element; or (*b*) that there exist particles of unit charge, but with a mass (which may not have a unique value) larger than that of a normal free electron[6]

Chicago was investing in this too



Science Service,

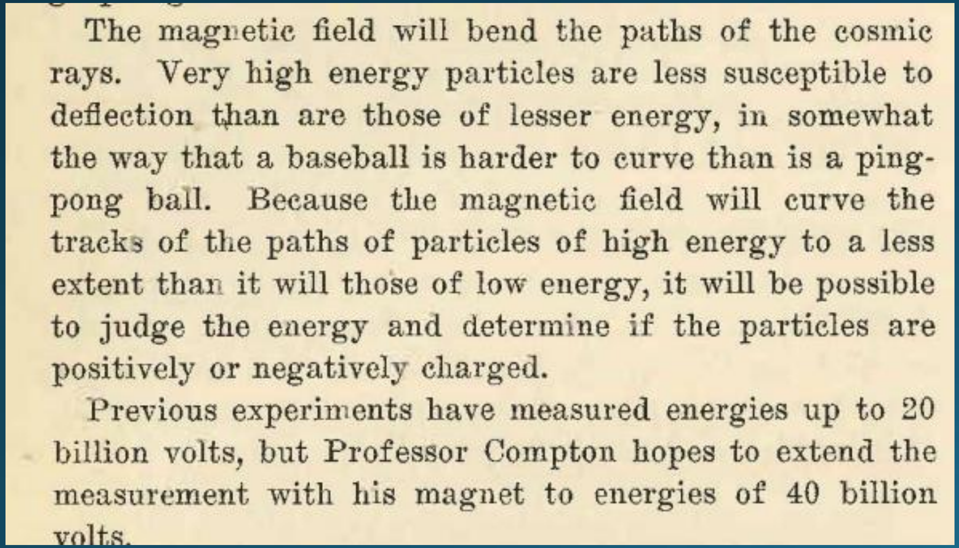
NEW COSMIC RAY DEVICE AT THE UNIVERSITY OF CHICAGO

MORE powerful than any other similar apparatus in the world is the new cosmic ray equipment now nearing completion in the laboratory of Professor Arthur H. Compton, of the University of Chicago.

The heart of the device—a Wilson cloud chamber—is a giant 12-ton magnet whose strong field will bend cosmic rays and the atomic electrified débris so that their energies can be calculated. The magnetic field generated by the new magnet will be 40,000 times as powerful as that of the earth. It was designed by Professor Compton and his research associate, Haydon Jones.

Professor Compton states that the equipment will be used in a new series of experiments by which it is hoped further data can be obtained on high energy particles to see if the known laws of electricity apply to them.

As cosmic rays pass through the moist gas of the Wilson cloud chamber in the field of the magnet, they will leave a fog trail which is automatically photographed. Professor Compton estimates that there should be one cosmic ray entering each second and about one out of fifteen will be moving in the proper direction for photographing.



The magnetic field will bend the paths of the cosmic rays. Very high energy particles are less susceptible to deflection than are those of lesser energy, in somewhat the way that a baseball is harder to curve than is a ping-pong ball. Because the magnetic field will curve the tracks of the paths of particles of high energy to a less extent than it will those of low energy, it will be possible to judge the energy and determine if the particles are positively or negatively charged.

Previous experiments have measured energies up to 20 billion volts, but Professor Compton hopes to extend the measurement with his magnet to energies of 40 billion volts.


APRIL 1, 1940 PHYSICAL REVIEW VOLUME 57

Positive Excess and Electron Component in the Cosmic-Ray Spectrum

DONALD J. HUGHES
Ryerson Physical Laboratory, University of Chicago, Chicago, Illinois

(Received January 25, 1940)

- Muons and antimuons are studied extensively
- Construction of new cosmic ray muon detector
  - Lead filtered out all the x-rays, electrons, positrons
- Positive excess confirmed
- Originally, muons were expected to be the nuclear-binding particle (the pion)

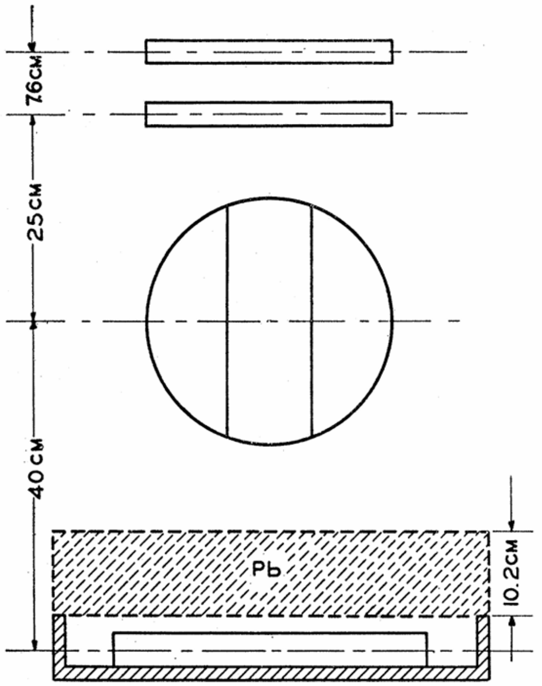


FIG. 1. Diagram of apparatus.

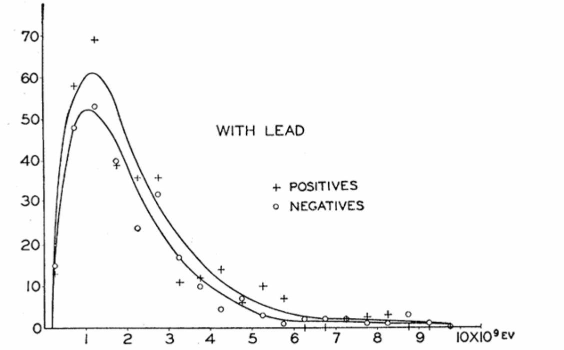


FIG. 3. Positive-negative spectra with lead absorber.

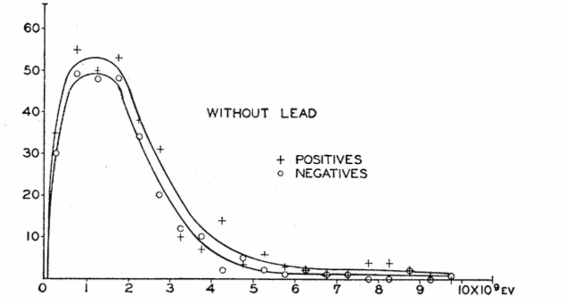
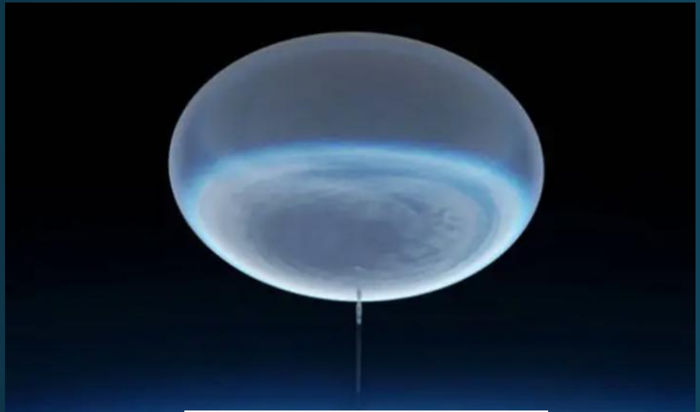


FIG. 4. Positive-negative spectra without absorber.

We didn’t know yet about pions



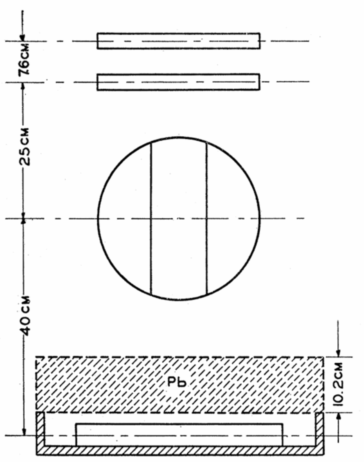
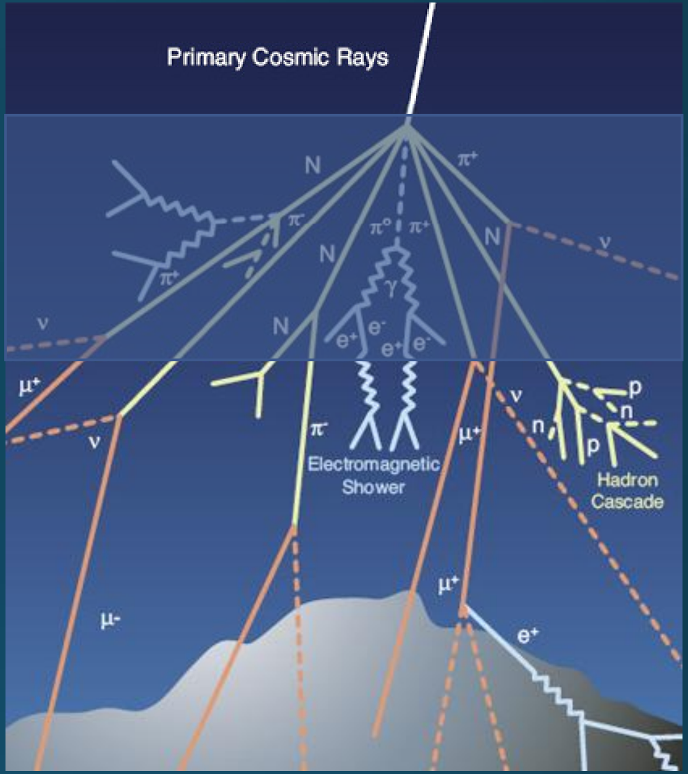
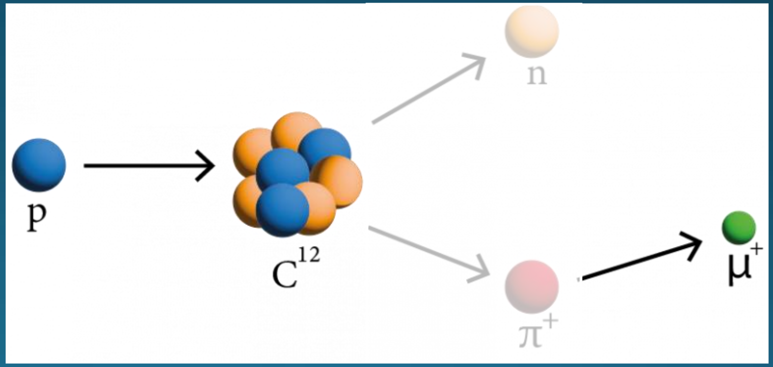


Fig. 1. Diagram of apparatus.

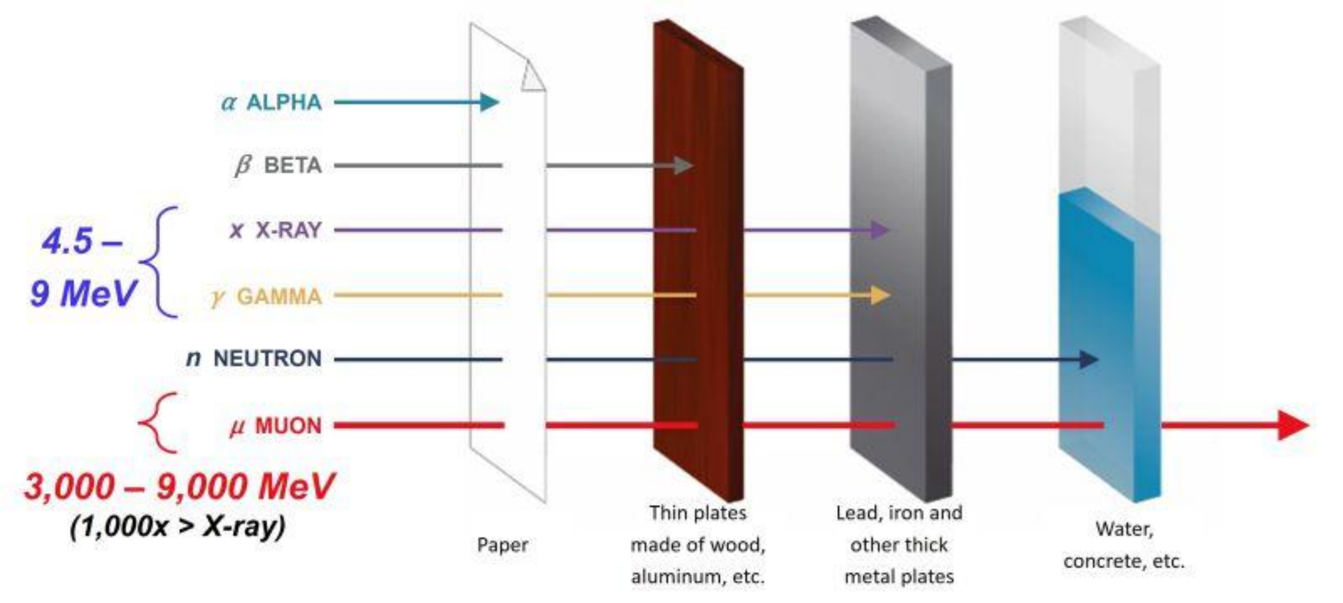


But it was clear that protons created muons



Muons are much heavier

- They don't radiate like electrons
  - Remember the amount of X-Rays is inverse to the mass squared of the charged particle: $\frac{1}{m^2}$
- They don't care about the electrons in the atoms like X-Rays
  - 1000 times more energy
  - Much higher energy than other radiation



This new particle made sense!
It was more energetic and more penetrating…
And was always around

Muons decay

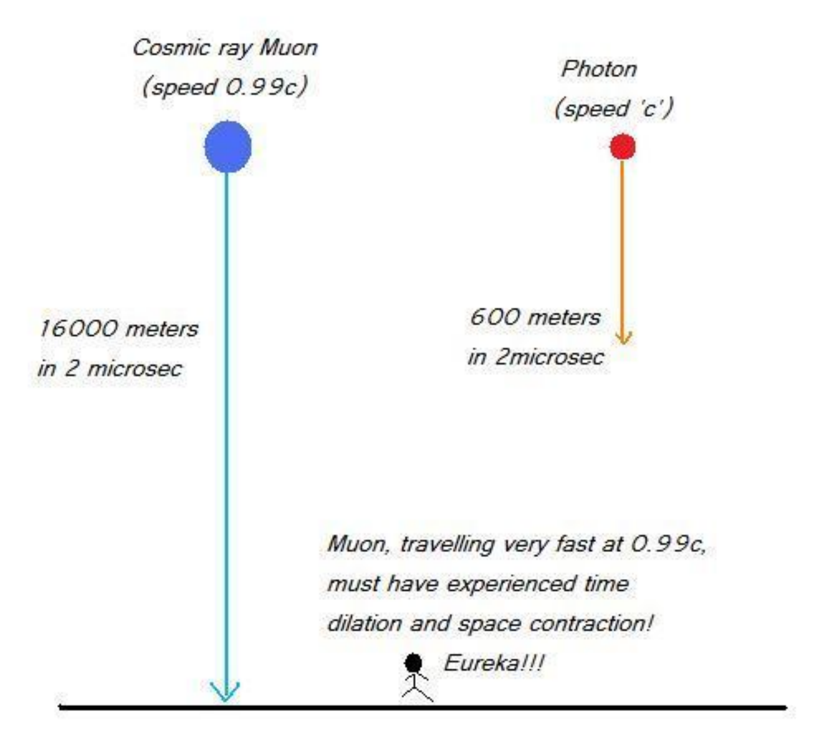
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

mass $= 207 m_e = 105.7\ \mathrm{MeV}/c^2$ of μ

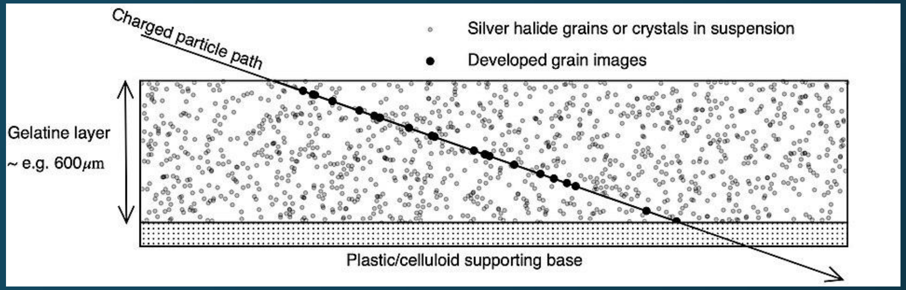
didn’t see the neutrinos

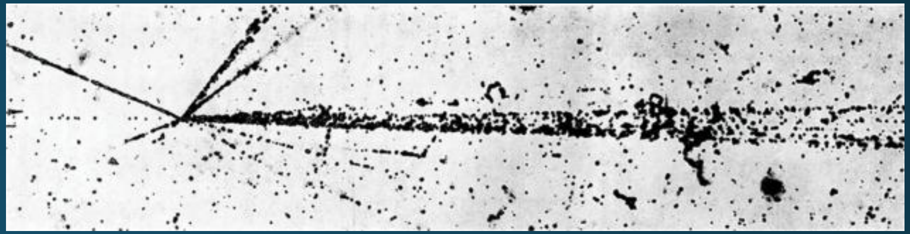
- Late 1930’s, scientists expected the muons to decay
  - Because they thought they were these fancy pion particles
- The improved cloud chambers showed “tracks with kinks”
  - And thicker tracks connected to thin tracks
- Time dilation validation
  - Bruno Rossi in 1940 at Echo Lake and Denver
  - Otherwise who could believe that guy, Albert
- Since they are so energetic, they travel far distances before decaying

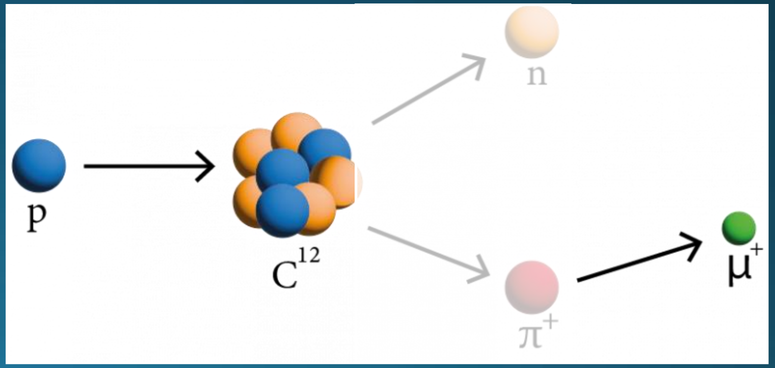


This was not the pion

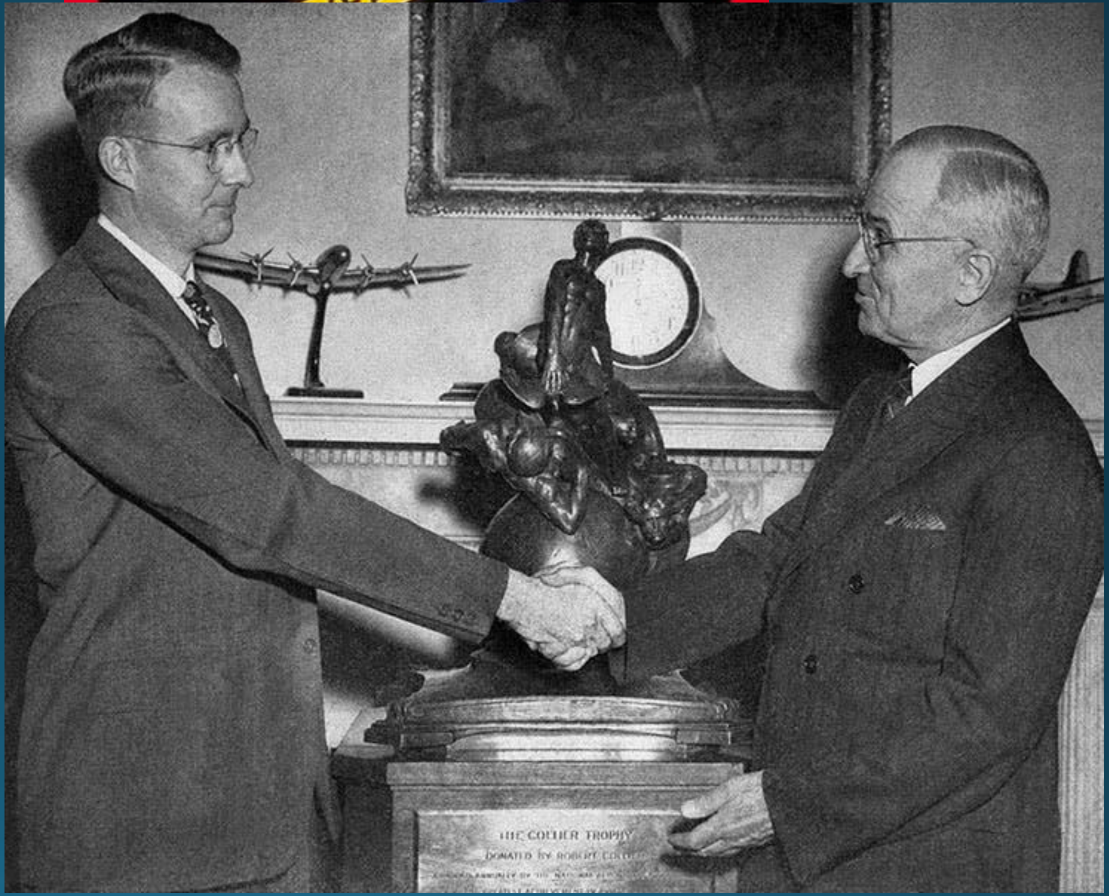
- Discovery of the pion (1947)
- We learned how to detect the pions and more particles with new detectors
  - Focused on nuclear processes
- Hydrogen Bubble Chamber
  - Luis Alvarez was instrumental
    - Muons don’t interact with the nucleus really at all, but pions and other particles do
    - Nobel prize in 1968 for his work on nuclear resonance states
  - Stories about him include radar in WWII and Manhattan project contributions







Luis Alvarez showing off bubble chamber at Berkeley



Not so long later

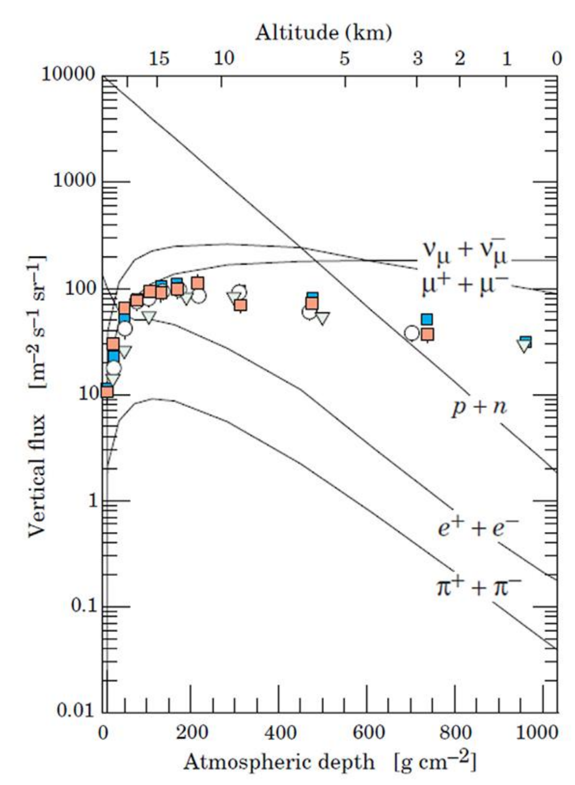
Physicist in Australia, E.P George

George detects less muons below the tunnel.
The material above his head blocked the muons.

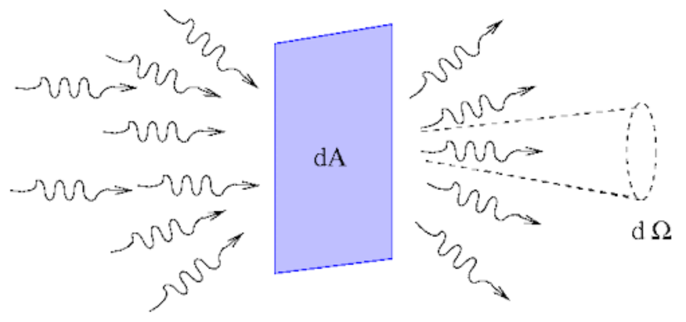
Cosmic ray muon measurements with density

Bethe-Bloch equation

$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2} \cdot \frac{n z^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0} \right)^2 \cdot \left[\ln \left(\frac{2 m_e c^2 \beta^2}{I \cdot (1-\beta^2)} \right) - \beta^2 \right]$$



1. We know how muons lose energy over distance
    1. Depending on the material
2. We know the muon flux (how many there are)
    1. Number of muons passing through an area per second

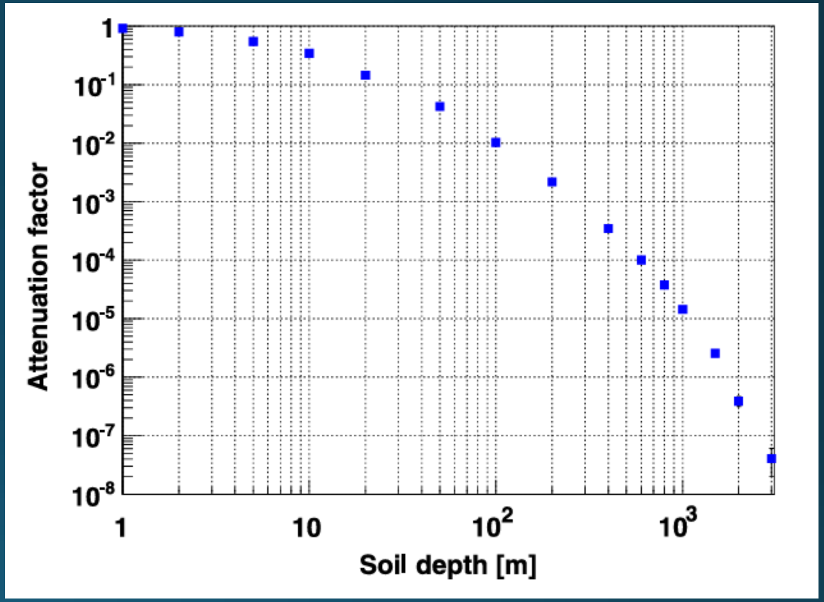


~10 muons going through each of us every second

Cosmic ray muon measurements with density

- Ratio of the number of muons detected before and after an object is opacity to the muons
- The thicker the object the less muons
  - Line of sight is blocked
- But also for the same thickness, the denser the objects the less muons

$$\int \rho(x)dx$$

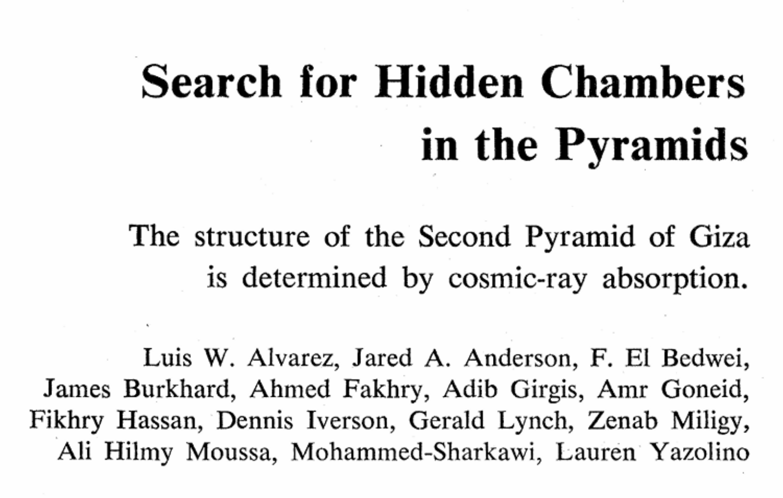


If the tunnel overburden was 100m thick, our detector only measures 1/100 muons compared to being at the surface

George's density calculation from muons was only 2% off (2.65 g/cm^3 compared to 2.68 g/cm^3

First attempt at muon tomography

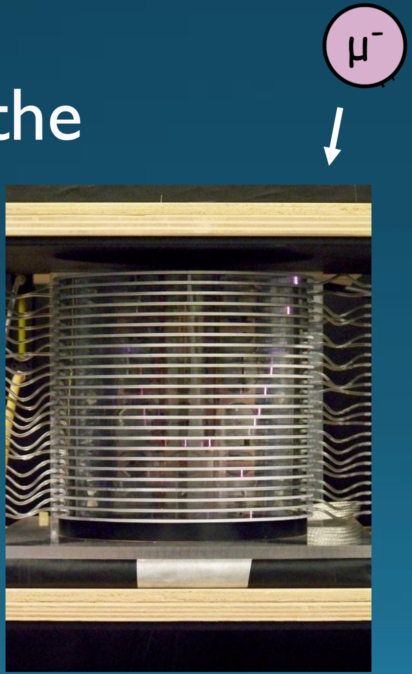
- Luis Alvarez was inspired to use muons to study the pyramids in Egypt
  - Interrupted by a war
  - Chefren pyramid in 1970
- Returned and surveyed 20% of the volume
  - Did not find “hidden” chambers
- Spark chambers used
  - To track the muons
- ~1 year of data taking

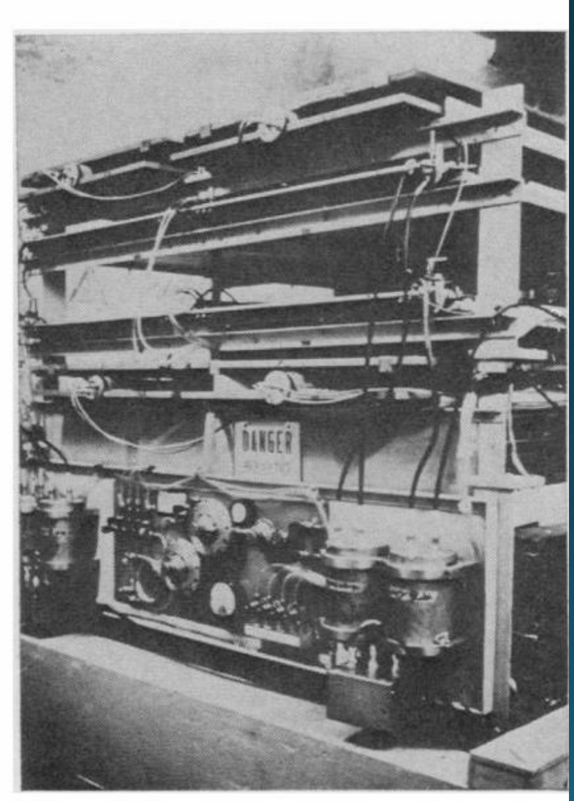


Search for Hidden Chambers in the Pyramids

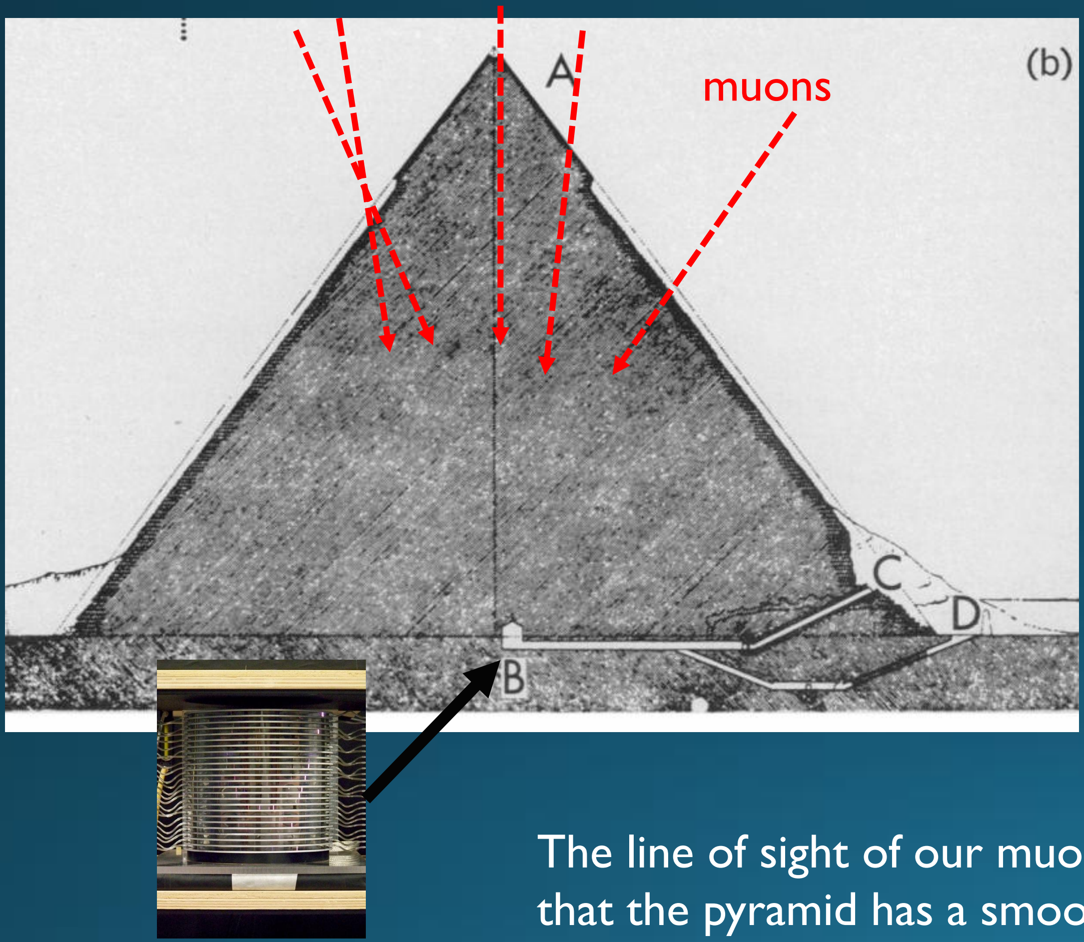
The structure of the Second Pyramid of Giza is determined by cosmic-ray absorption.

Luis W. Alvarez, Jared A. Anderson, F. El Bedwei, James Burkhard, Ahmed Fakhry, Adib Girgis, Amr Goneid, Fikhry Hassan, Dennis Iverson, Gerald Lynch, Zenab Miligy, Ali Hilmy Moussa, Mohammed-Sharkawi, Lauren Yazolino





But he did prove the idea worked well



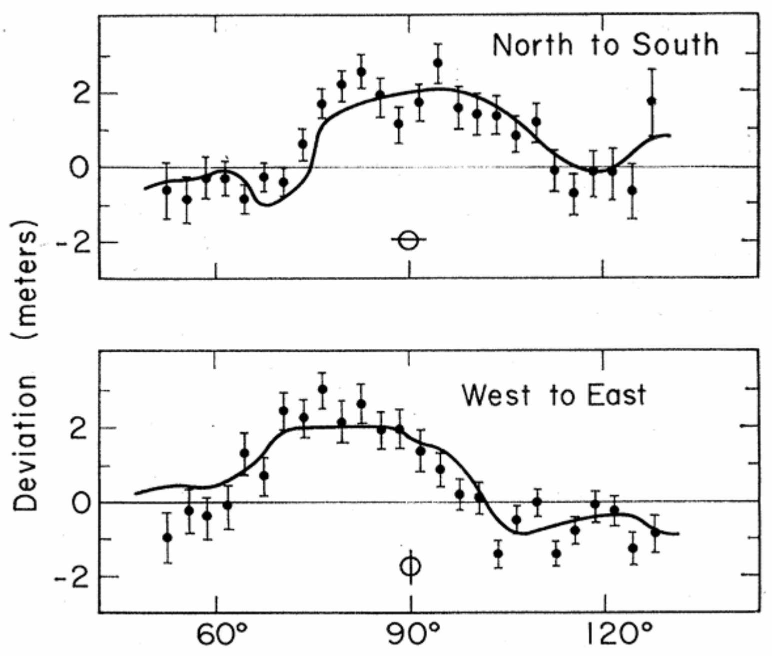
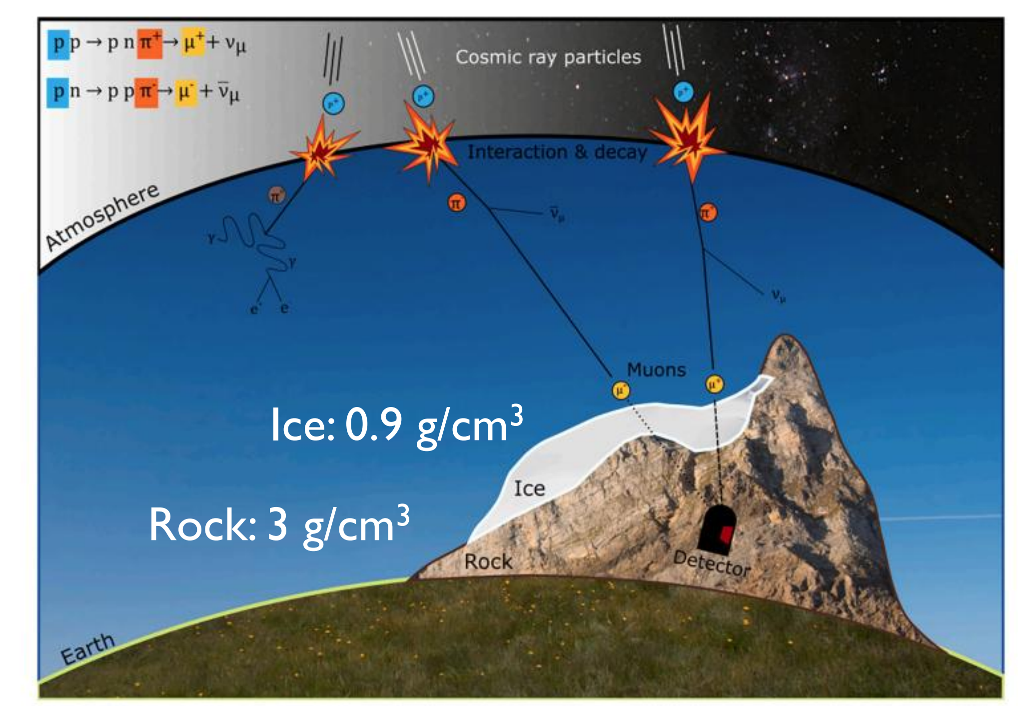


Fig. 12. This graph shows that the cap on the top of Chephren's Pyramid is observed in this experiment. The quantity plotted is the difference between the measured distance from the detector to the surface of the pyramid and the distance calculated under the assumption that the pyramid has no surface irregularities. The data points represent the distances indicated by the cosmic rays and are to be compared with the solid line, which represents the same distance measured by the aerial survey. These distances have been averaged over 24-degree-wide bands centered on the middle of the pyramid, one running north-south, the other east-west.

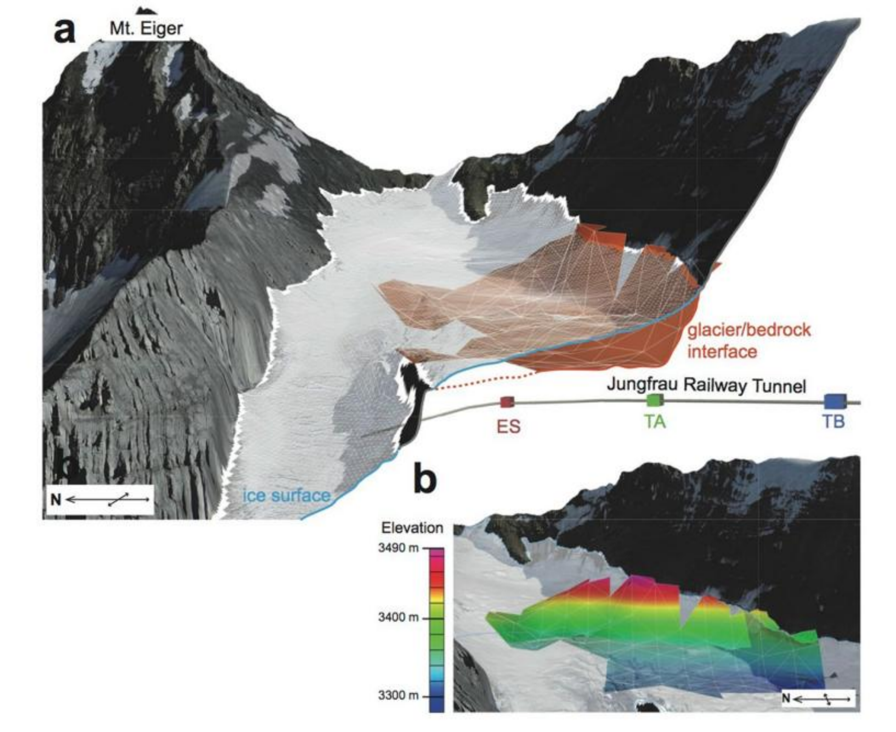
The line of sight of our muon detectors doesn't match the assumption that the pyramid has a smooth surface

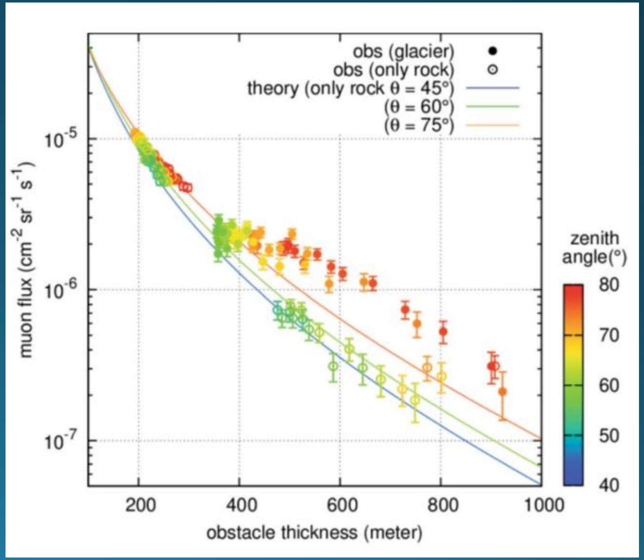
With Glaciers



Ice: 0.9 g/cm^3

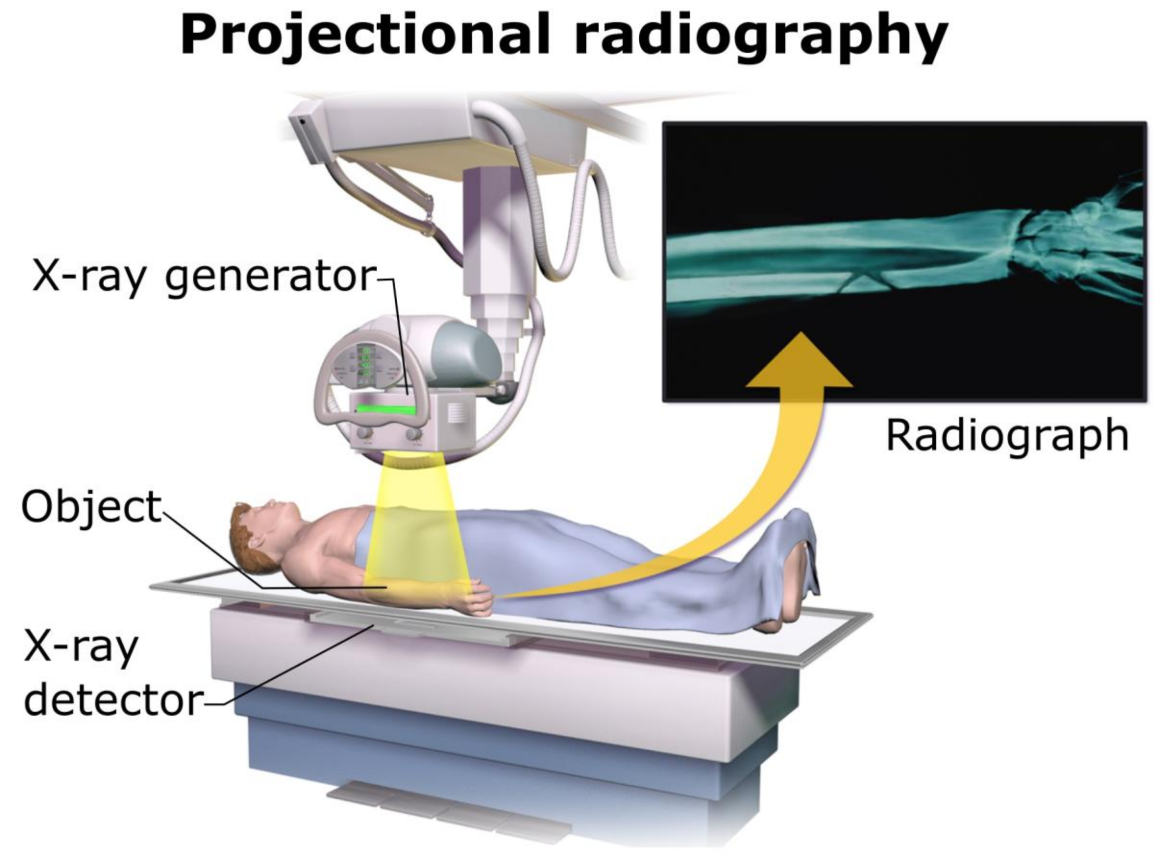
Rock: 3 g/cm^3



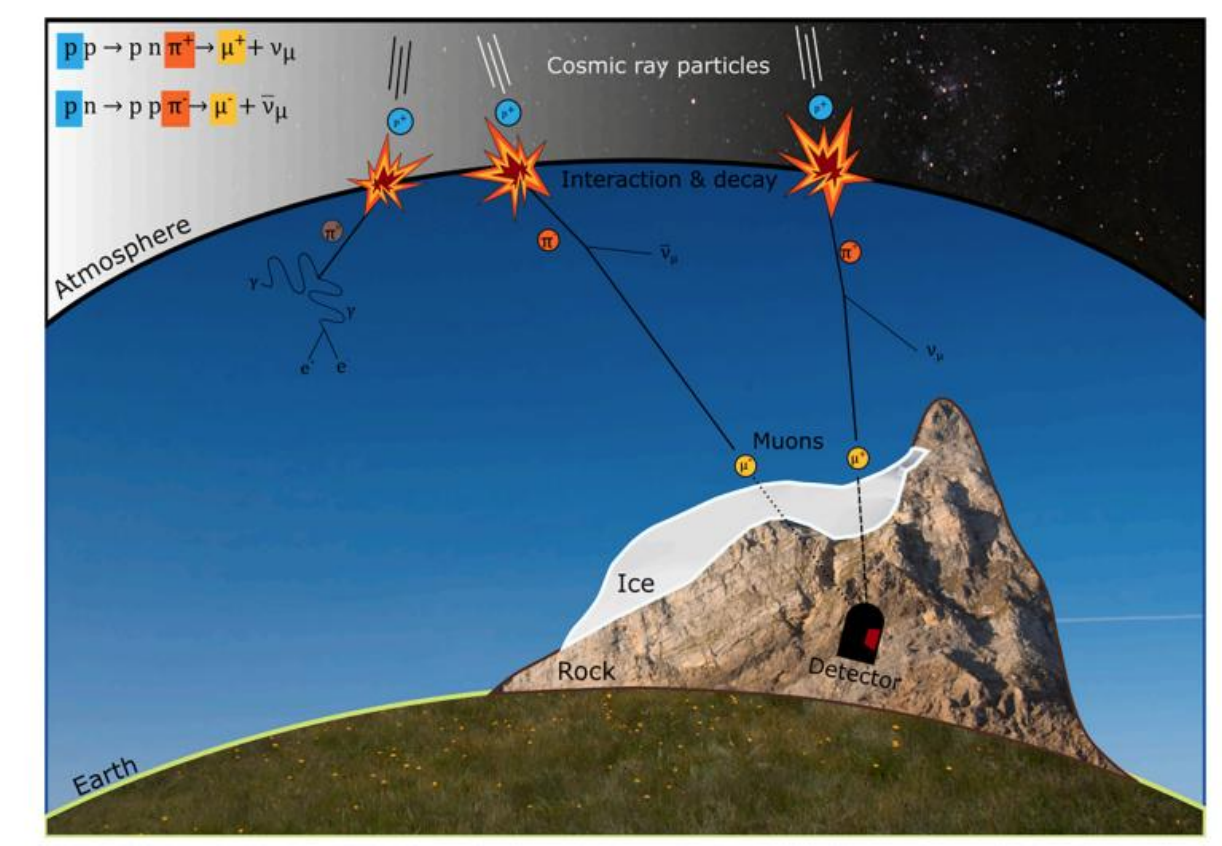


~2017, Mt. Eiger in the Swiss Alps as an example
→ Reconstruct the bedrock shape underneath the glacier

Imaging- 100 days of muon data



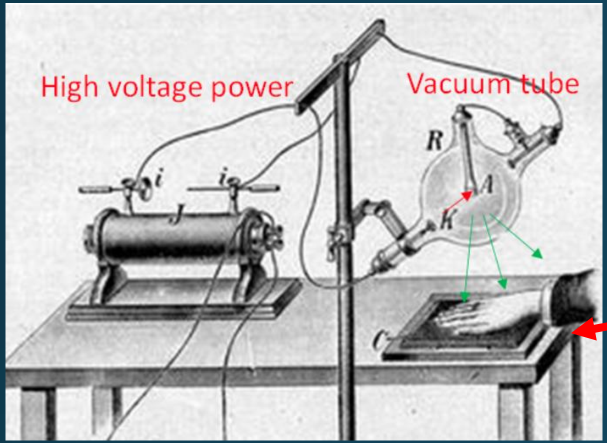
Muography

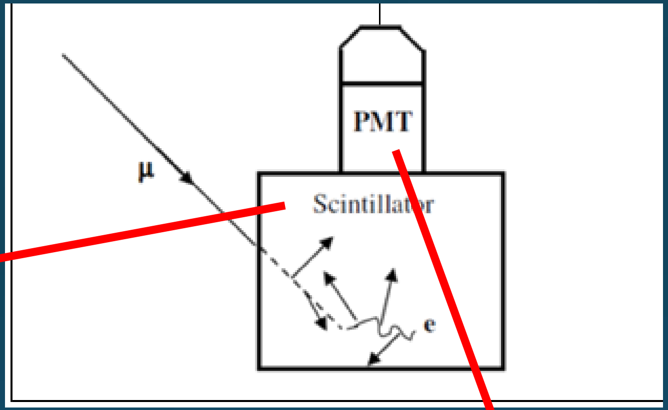


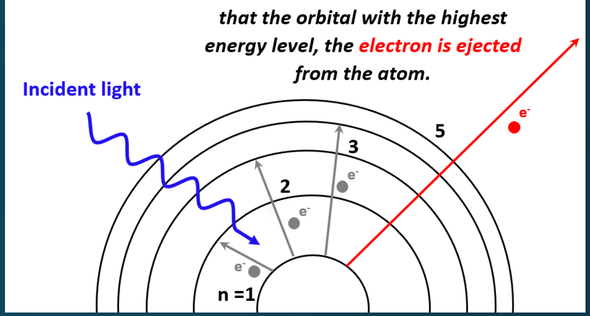
"Sit there for 100 days"

Line of sight

More sophisticated detectors



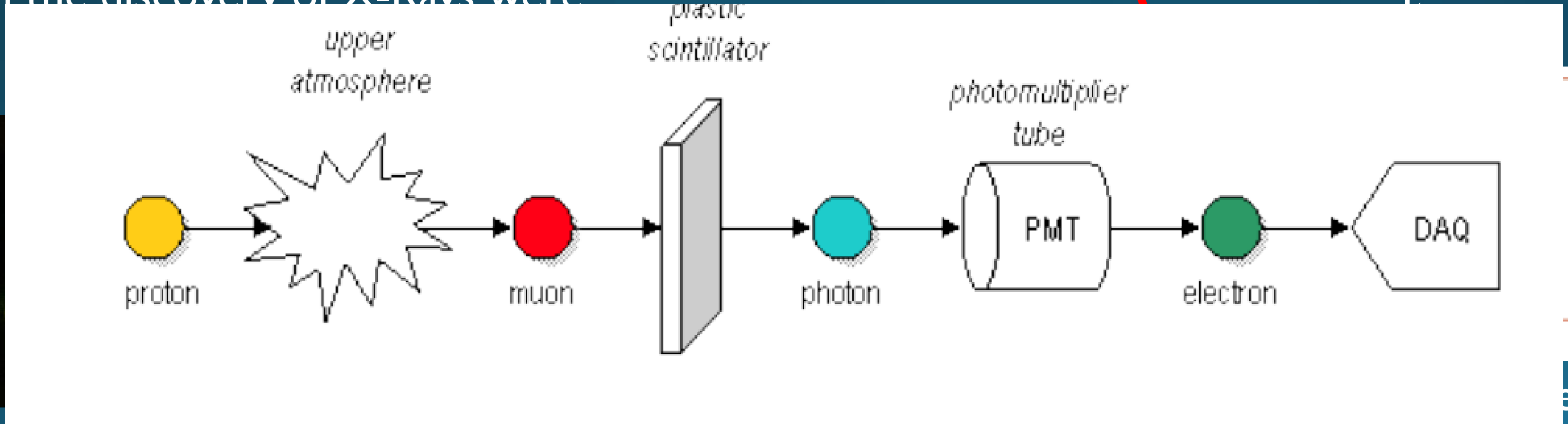


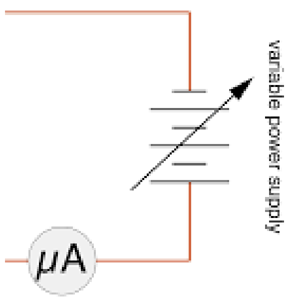

*If the incident **light has higher energy** that the orbital with the highest energy level, the **electron is ejected** from the atom.*

2. Count the light and flashes with photoelectric effect,

1. The screens that glowed green in the discovery of X-Rays were

a

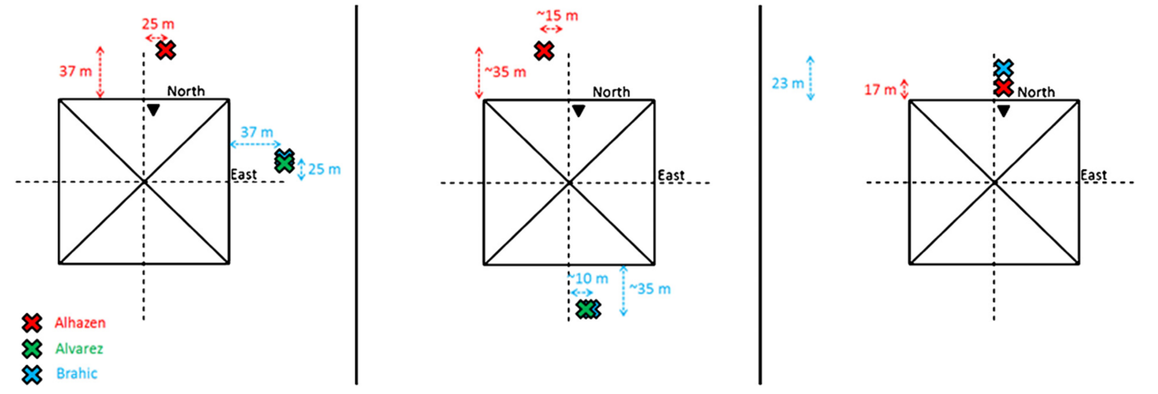


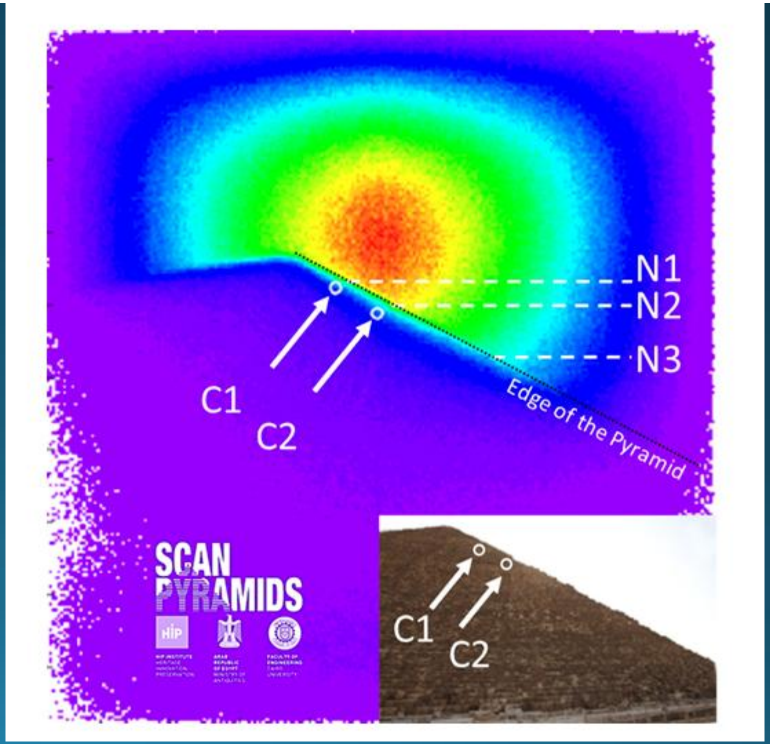


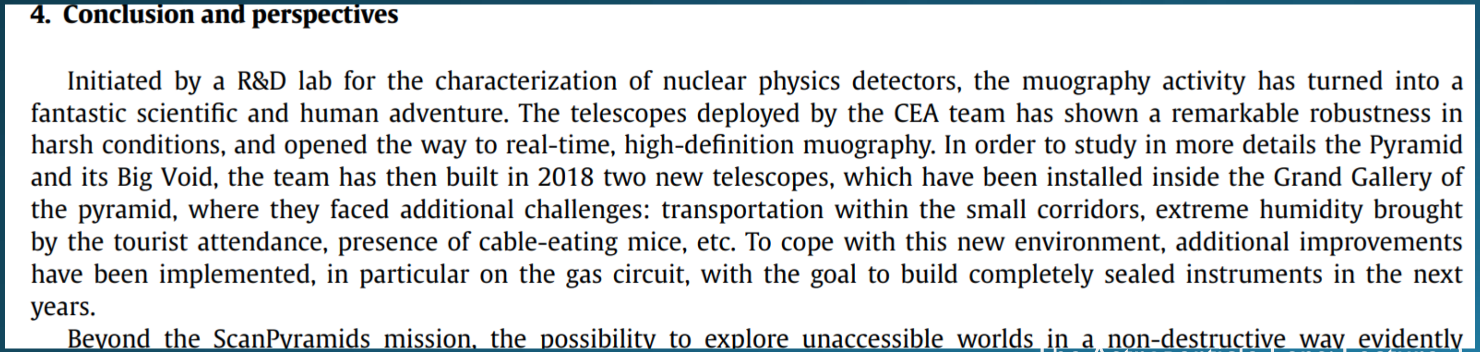
e (PMT)

New pyramid voids discovered

- More than 50 days of operation
- Multiple configurations allowed for thickness and density measurements
- International team with new detectors







4. Conclusion and perspectives

Initiated by a R&D lab for the characterization of nuclear physics detectors, the muography activity has turned into a fantastic scientific and human adventure. The telescopes deployed by the CEA team has shown a remarkable robustness in harsh conditions, and opened the way to real-time, high-definition muography. In order to study in more details the Pyramid and its Big Void, the team has then built in 2018 two new telescopes, which have been installed inside the Grand Gallery of the pyramid, where they faced additional challenges: transportation within the small corridors, extreme humidity brought by the tourist attendance, presence of cable-eating mice, etc. To cope with this new environment, additional improvements have been implemented, in particular on the gas circuit, with the goal to build completely sealed instruments in the next years.

Beyond the ScanPyramids mission, the possibility to explore unaccessible worlds in a non-destructive way evidently

Was this interesting to other scientific communities?

- At first, not really
- Conflicting accounts of whether this was an interesting discovery to Egpytologists
- Within a day or two of publicly stating that this isn't a great discovery, the tune changed

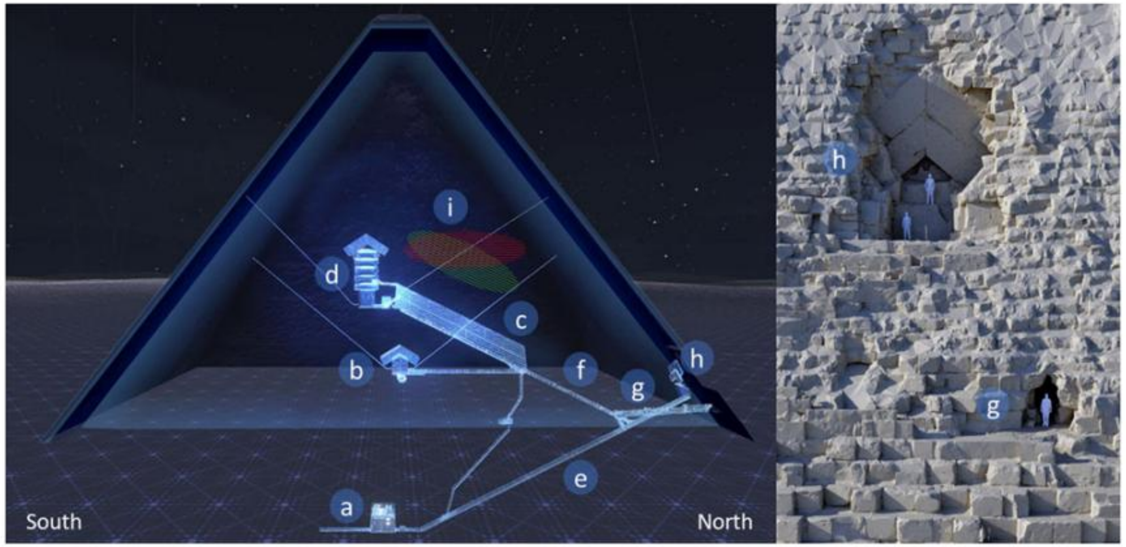
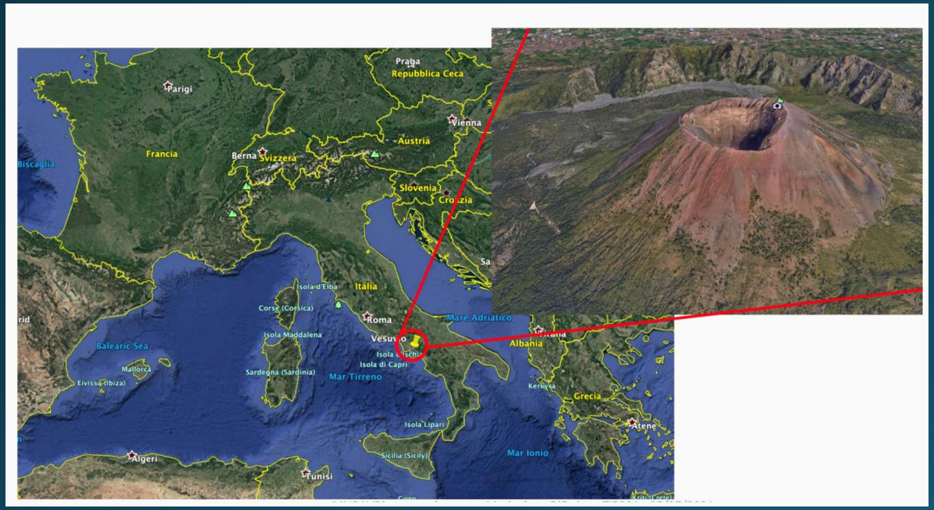
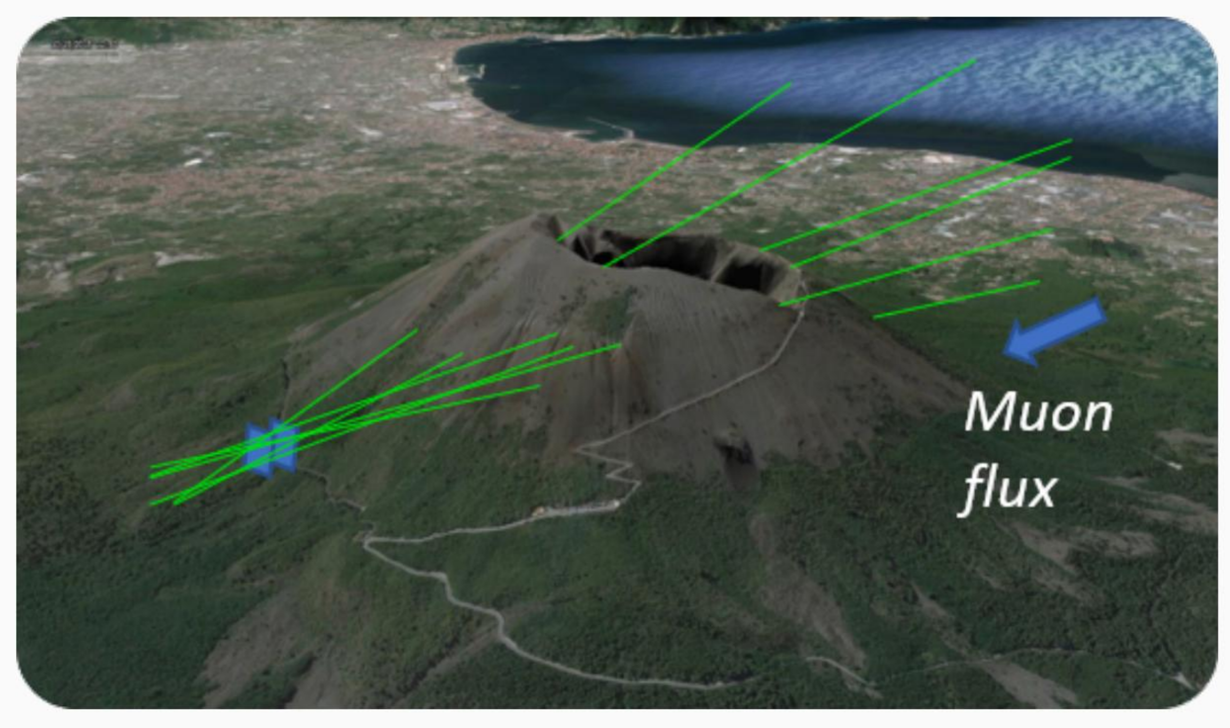


Fig. 1 | East-West cut view of the Great Pyramid and front view of the North face Chevron area. a Subterranean chamber, **b** queen's chamber, **c** grand gallery, **d** king's chamber, **e** descending corridor, **f** ascending corridor, **g** al-Ma'mun corridor, **h** north face Chevron area, **i** ScanPyramids Big Void with horizontal hypothesis (red hatching) and inclined hypothesis (green hatching) as published in November 2017[6]. All these images were obtained from a 3D modelization using dedicated laser surveys and photogrammetry data.

Volcanoes Mu-Ray project

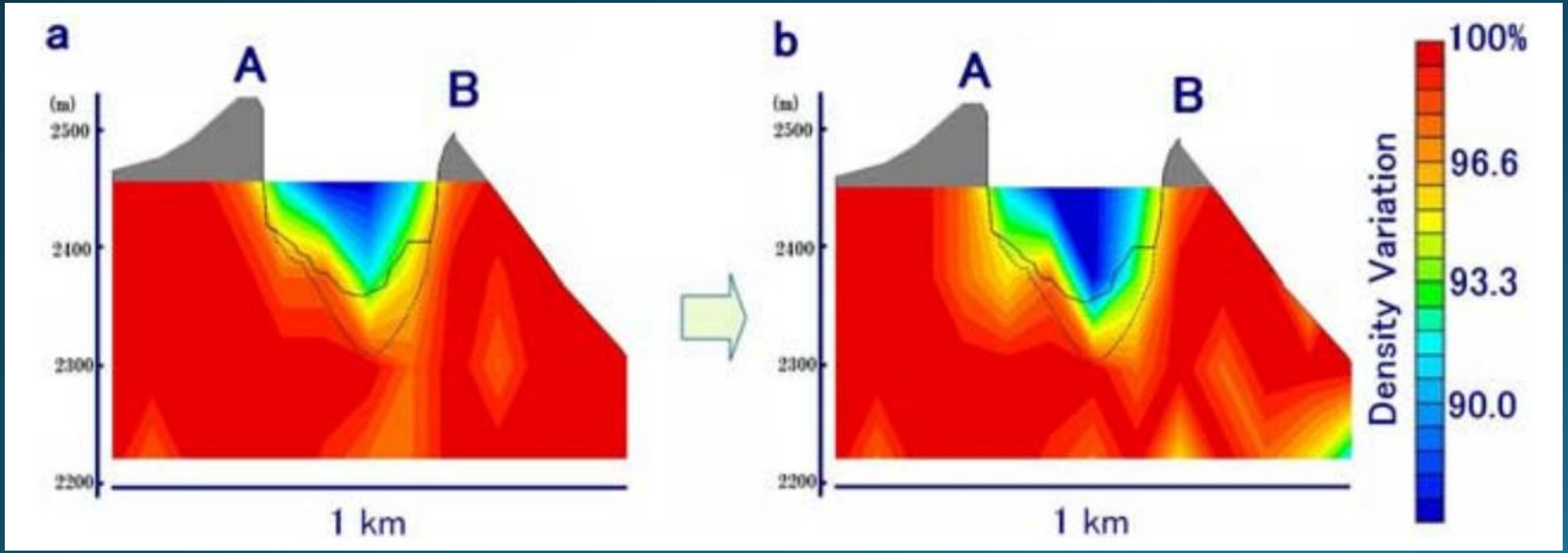




Volcano muon tomography

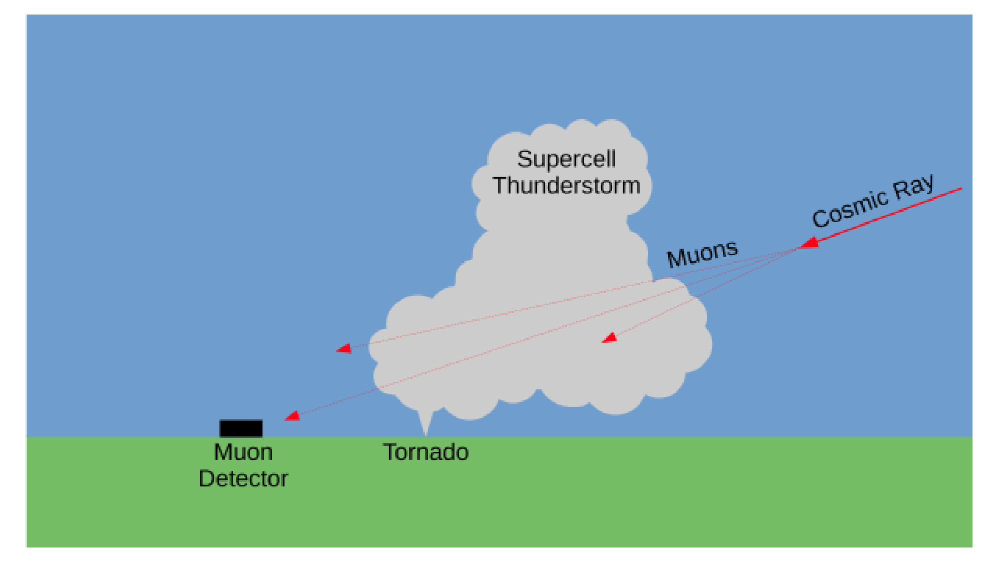
- Study in 2009 observed the mass movement inside the crater with muons
  - Compared before and after eruption
- From muon measurements estimated 60ktons
  - Volcanic ash measurements were 50ktons

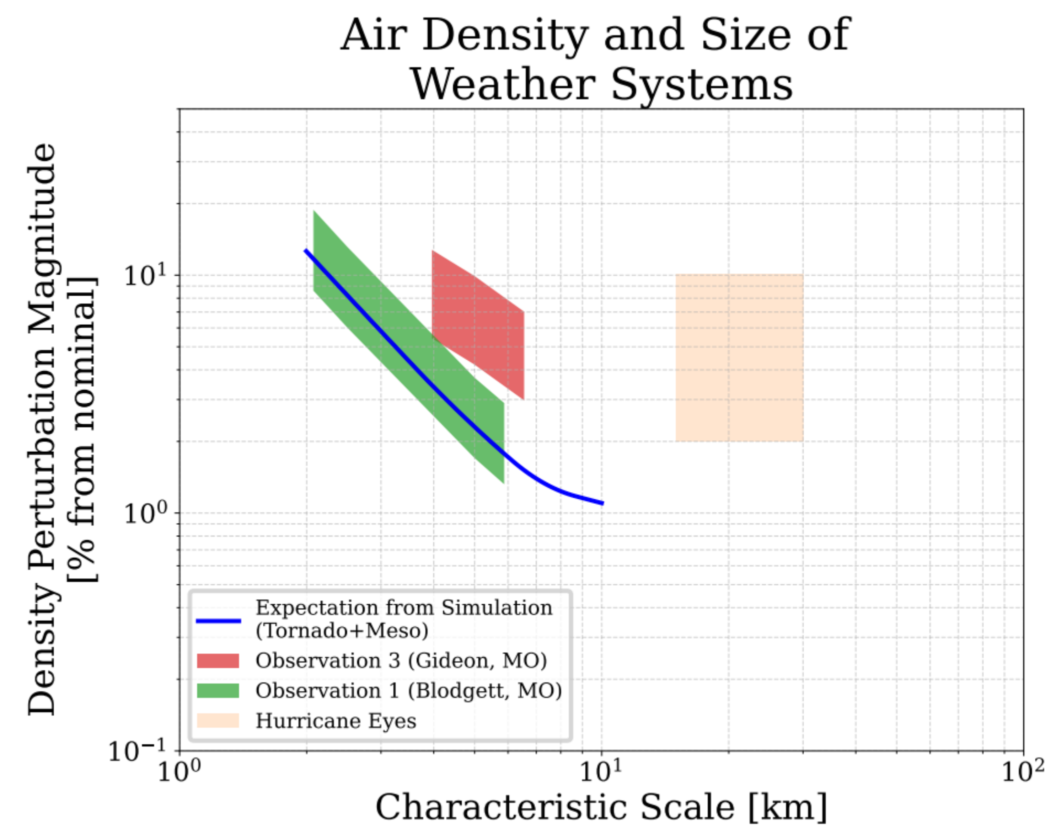
Mount Asama



Tornadoes

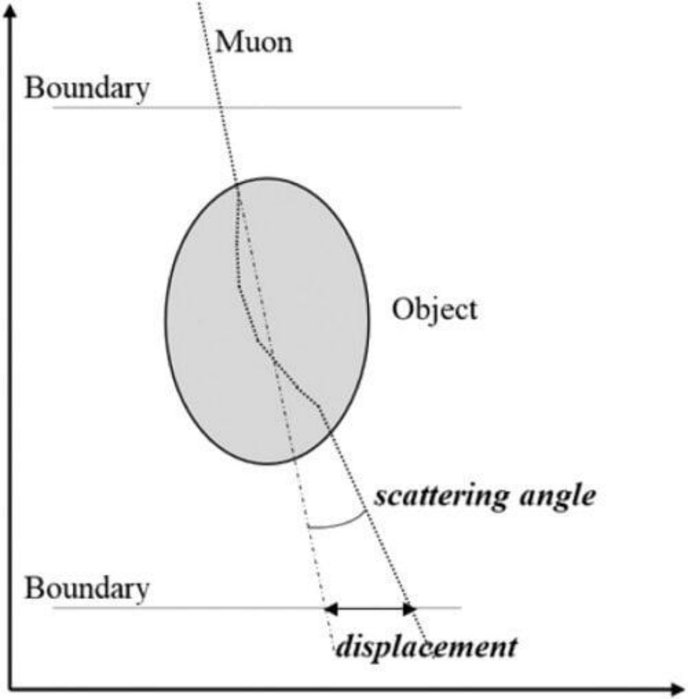
Hints that this works. Stay tuned!

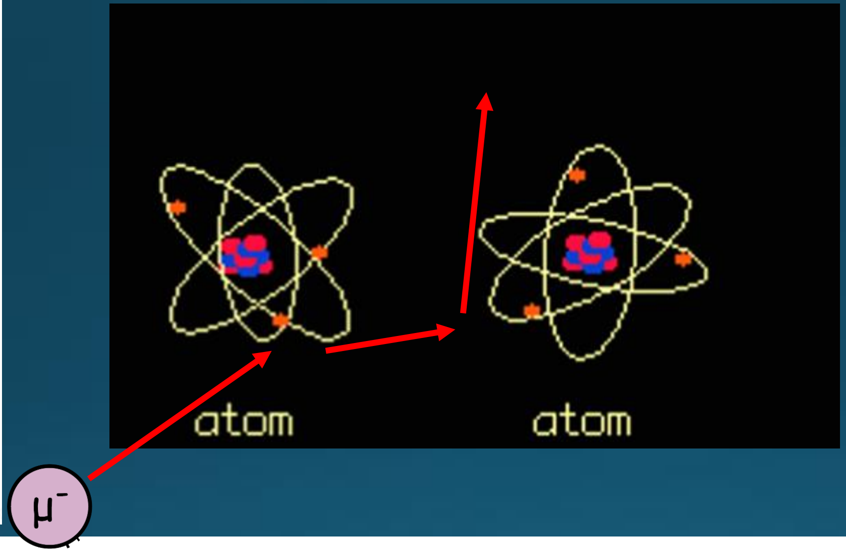


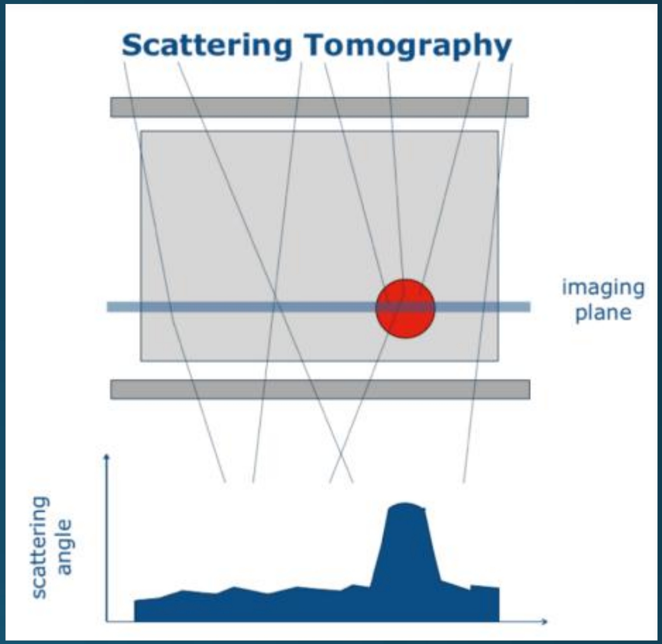


Density of air changes with pressure → Cosmic ray muon tomography

Multiple Coloumb Scattering





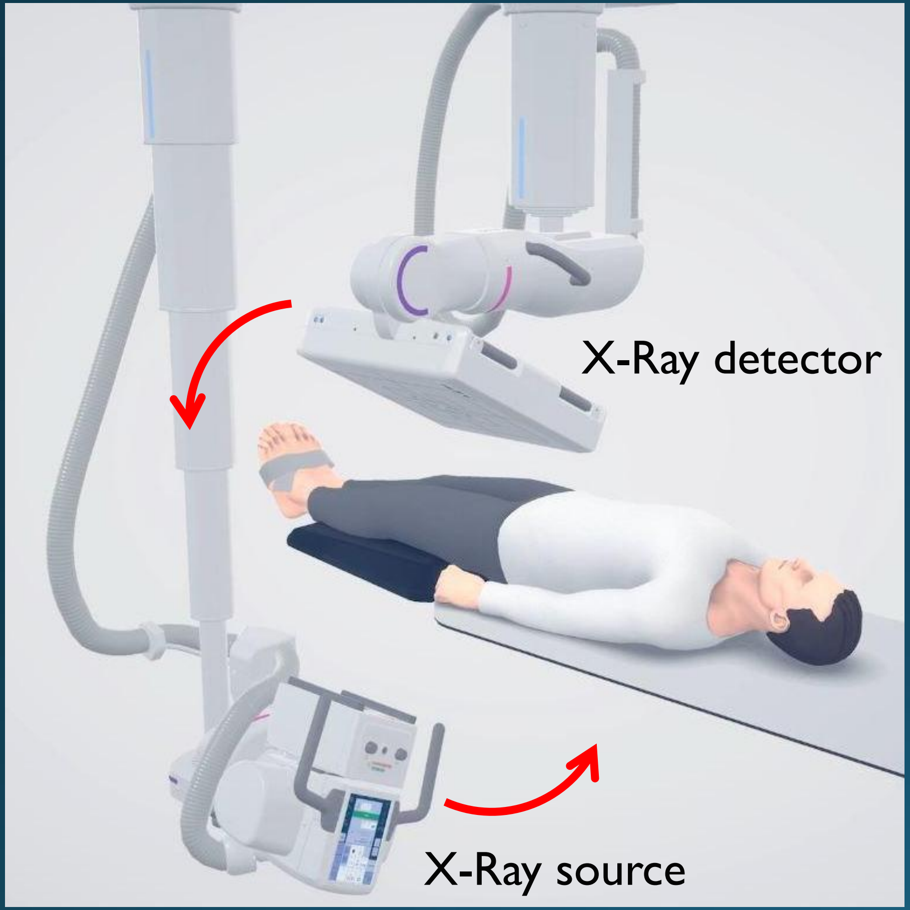


$$\theta_{MS} = \frac{13.6\ \text{MeV}}{\beta c p} Q \sqrt{\frac{x}{X_0}} \left(1 + 0.038 \ln(x/X_0)\right)$$

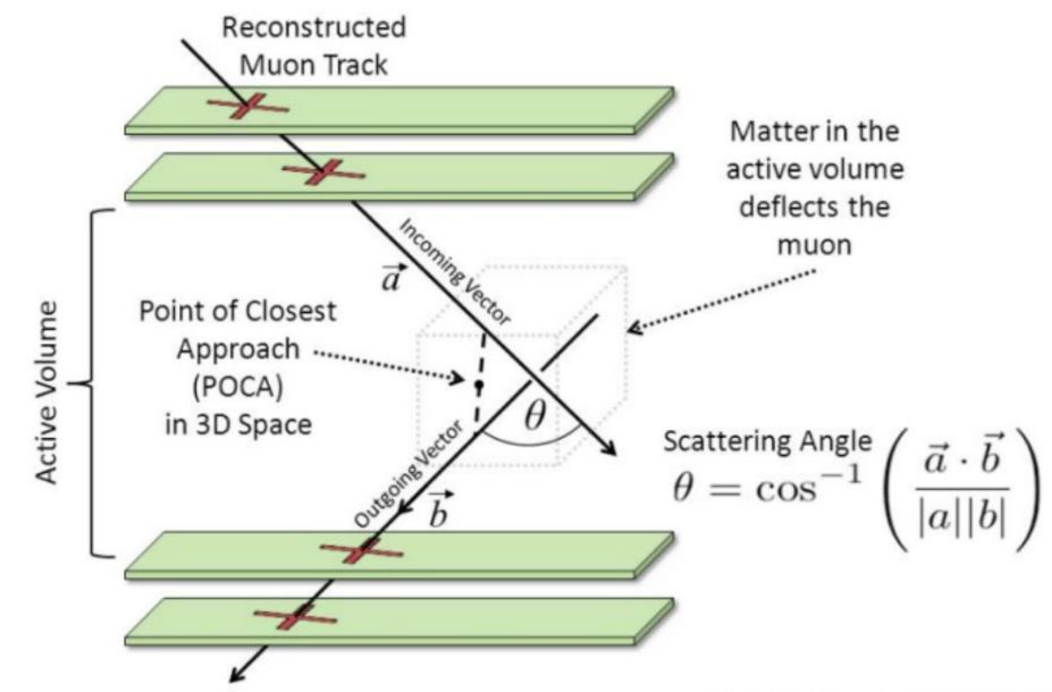
$$X_0 = \frac{716.4\,(\text{g/cm}^2)}{\rho} \frac{A}{Z(Z+1)\log(287/\sqrt{Z})}$$

either

μ^- μ^+

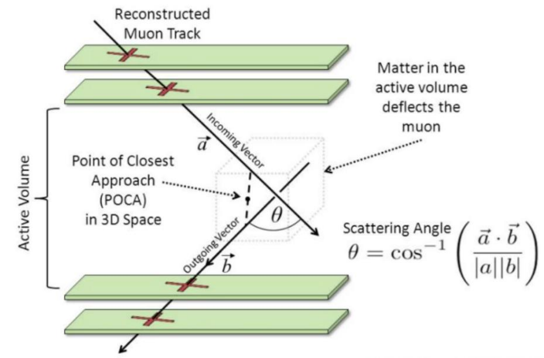


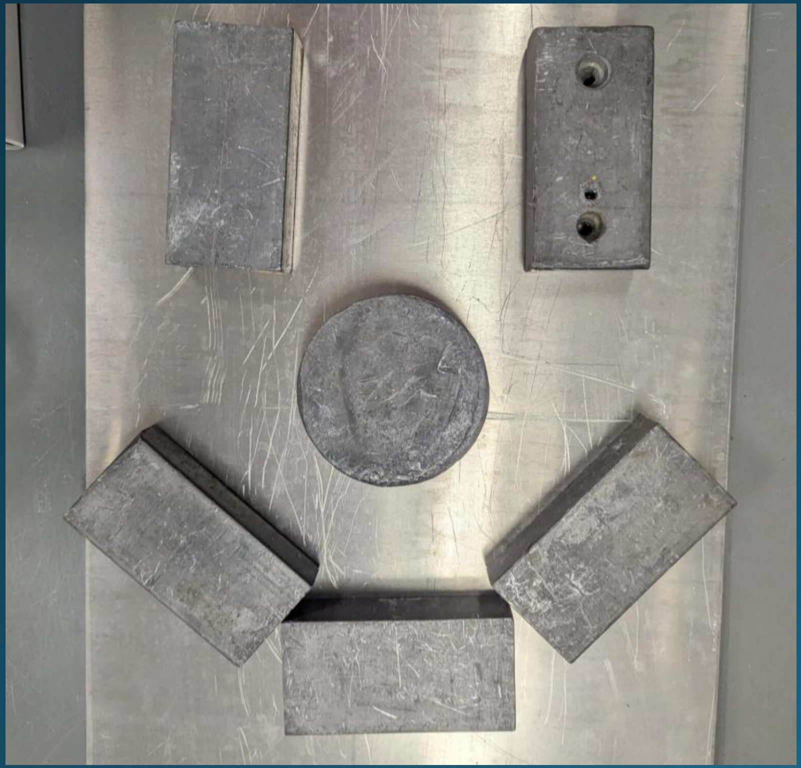
Scattering Muon tomography

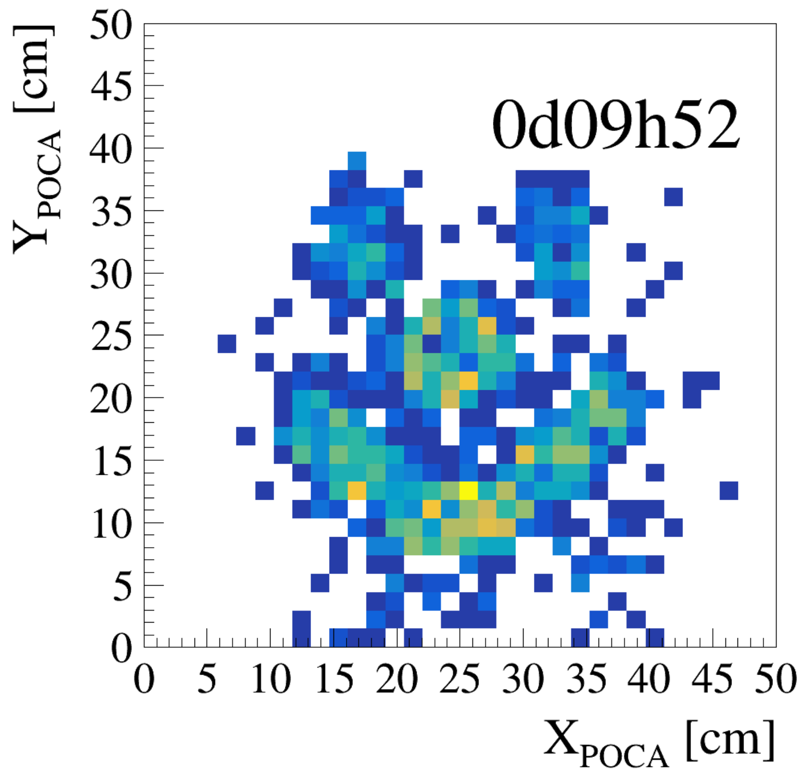


Improvements ongoing

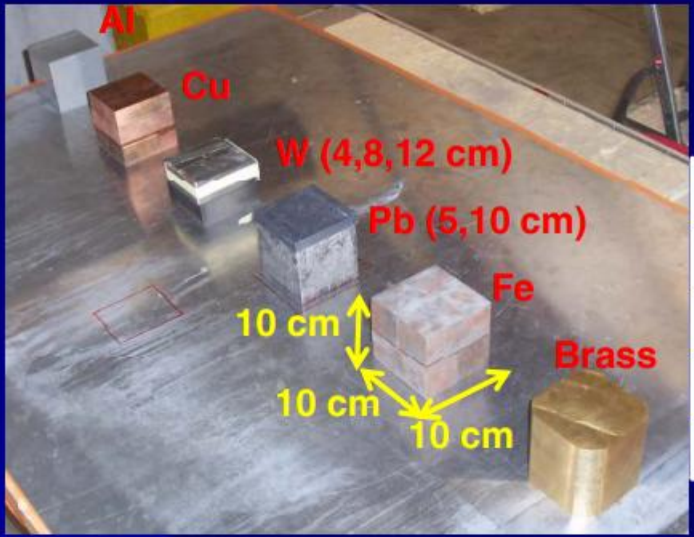
- ScanPyramid-developing new detectors with improvements



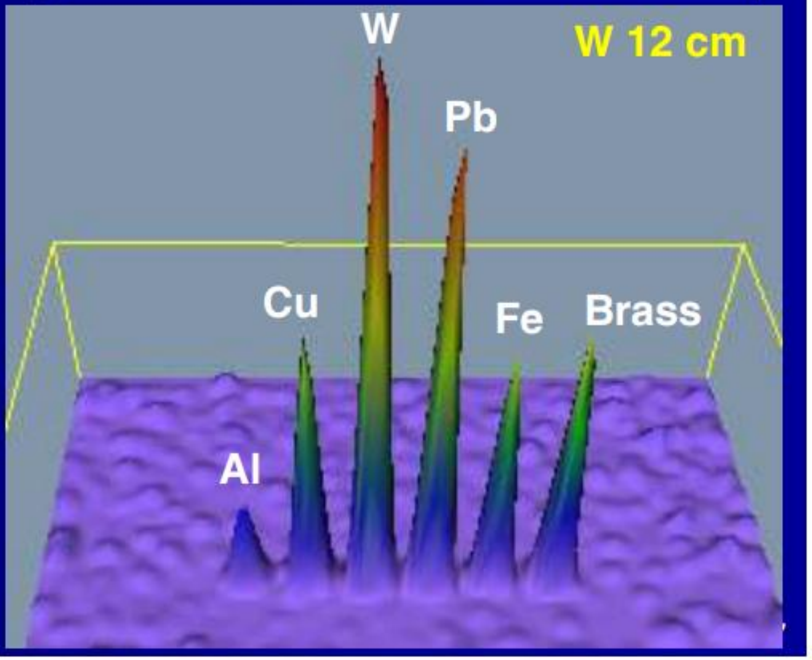




Possible to determine composition



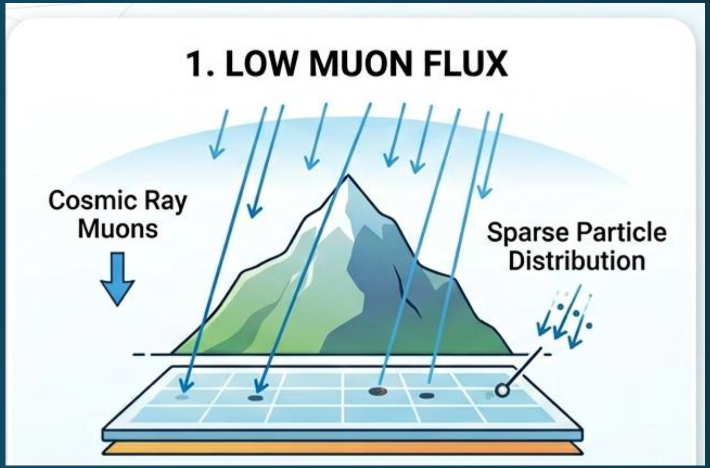
	X_0 (cm)
Al	8.9
Fe	1.76
Cu	1.43
Pb	0.56
W_s	0.37

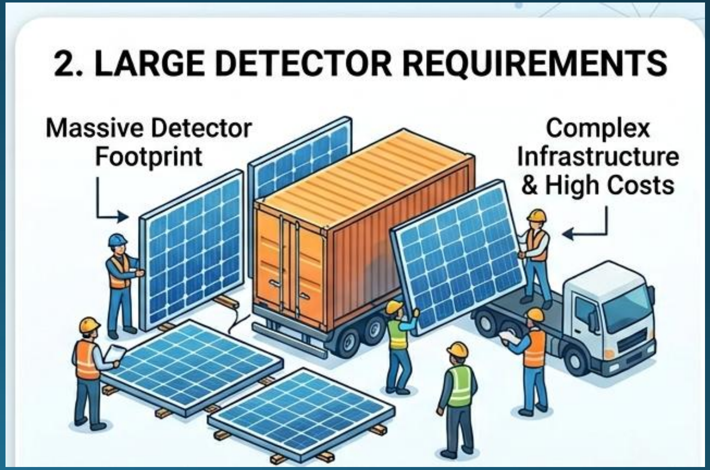


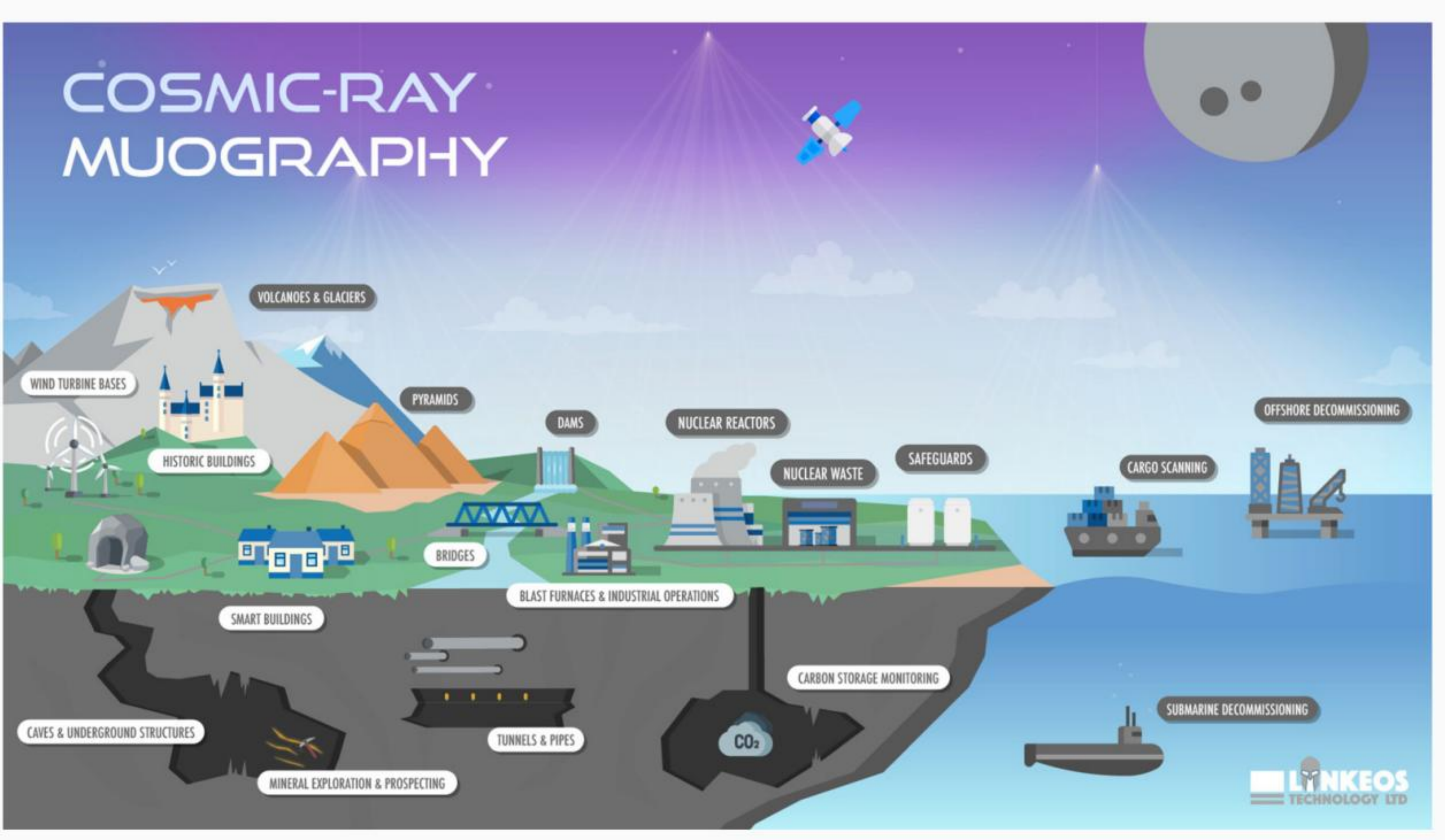
The height of the peaks is proportional to the scattering density

Muon tomography limitations

- Large detector areas
  - More directions are desired
  - Low flux of muons at the energies interested
    - Thicker – more high energy muons needed
- Detectors have good spatial resolution to record the tracks and direction
  - extract the particle direction
- Deployability
  - Compact and transportable






COSMIC-RAY
MUOGRAPHY
VOLCANOES & GLACIERS
WIND TURBINE BASES
PYRAMIDS
DAMS
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CO_2
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CAVES & UNDERGROUND STRUCTURES
TUNNELS & PIPES
MINERAL EXPLORATION & PROSPECTING
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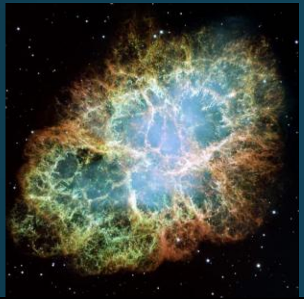
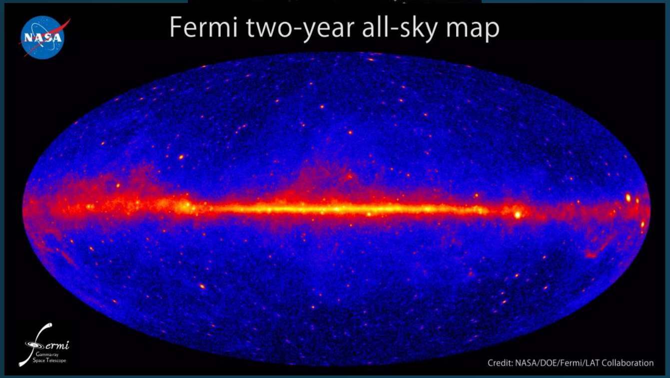
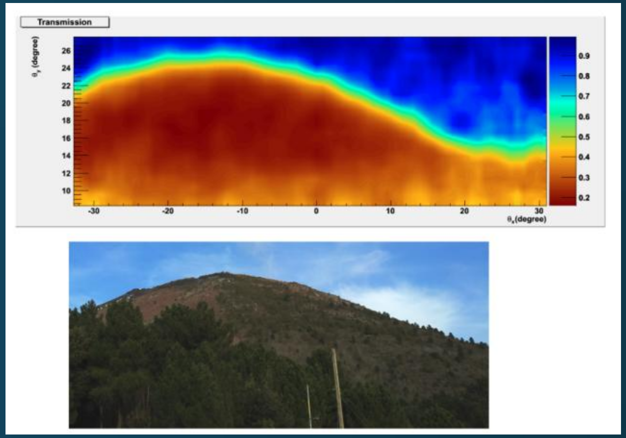
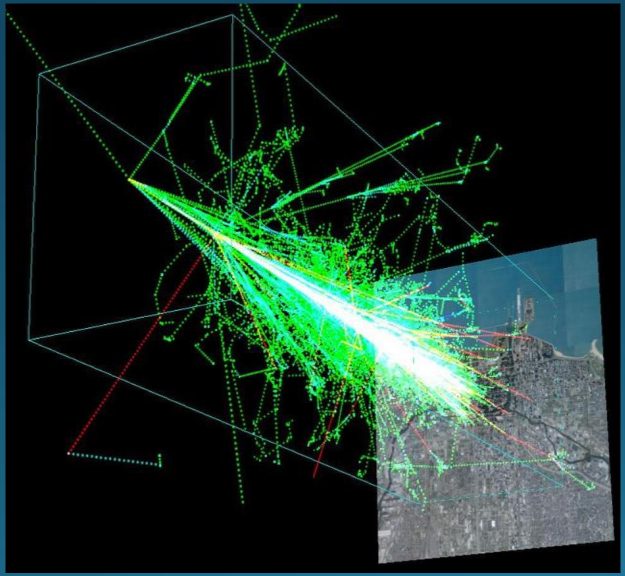


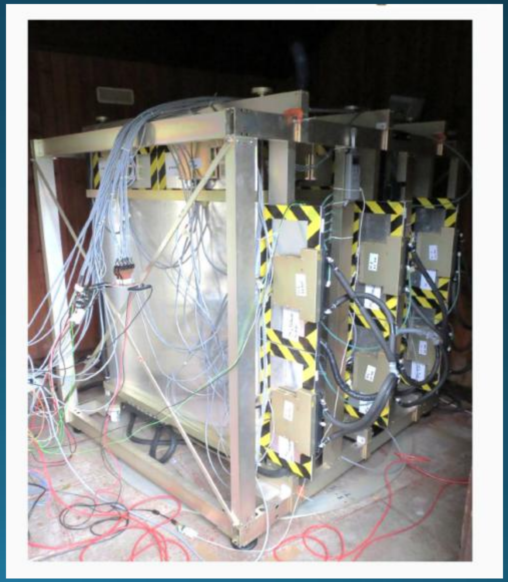


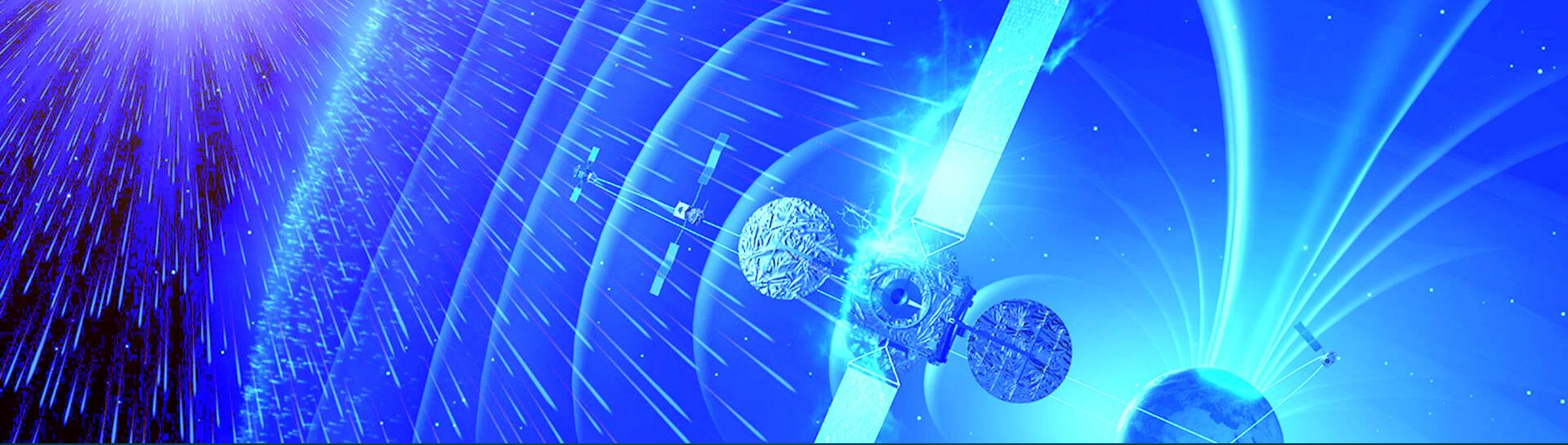
We live in a sea of cosmic rays



We just have to put on the astroparticle lens.







Thank you!