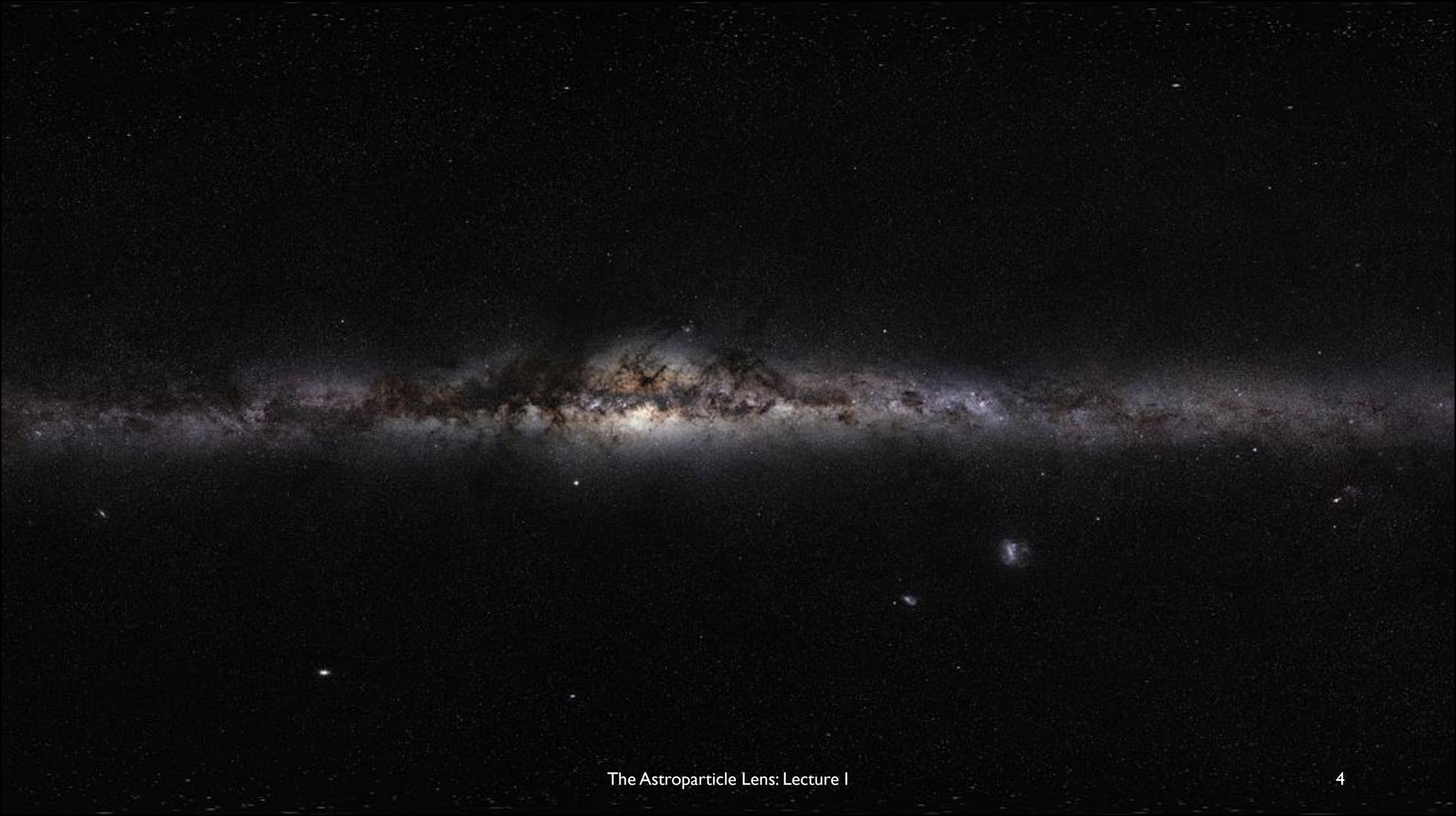


# The Astroparticles Lens: Using Particles From Space To Understand Our World

Keith McBride - Compton Lecture I







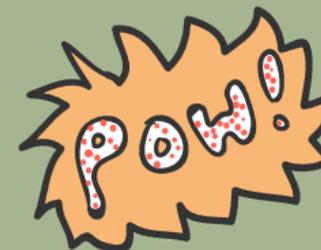
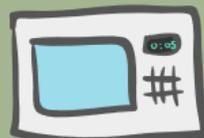
# The Electromagnetic Spectrum

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

$10^{-15}$  m  
 $\lambda \sim 1$  fm

More energy  
→

$\lambda \sim 1$  m



Radio

long wavelengths that are used for radio stations

Microwaves

Cooks snacks!

Infrared

Makes up heat

Visible Light

All the colors of the rainbow - what we see

Ultraviolet

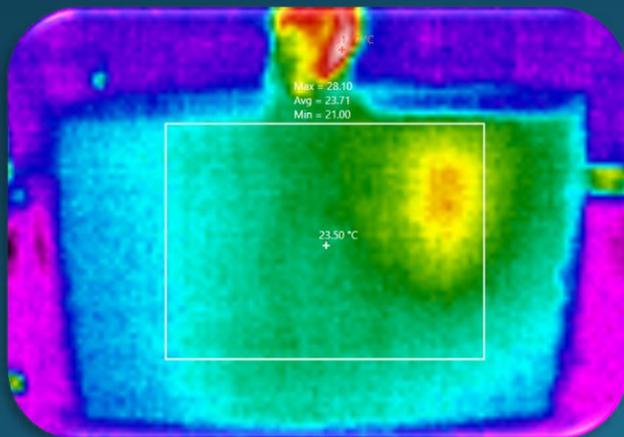
Responsible for sunburns ☹️

X-Ray

Takes pictures of your bones!

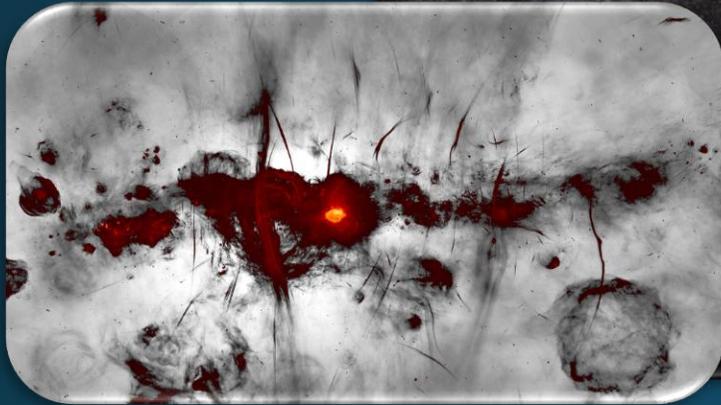
Gamma Ray

Part of many superheroes' origin stories - like the Incredible Hulk!



Optical

Radio



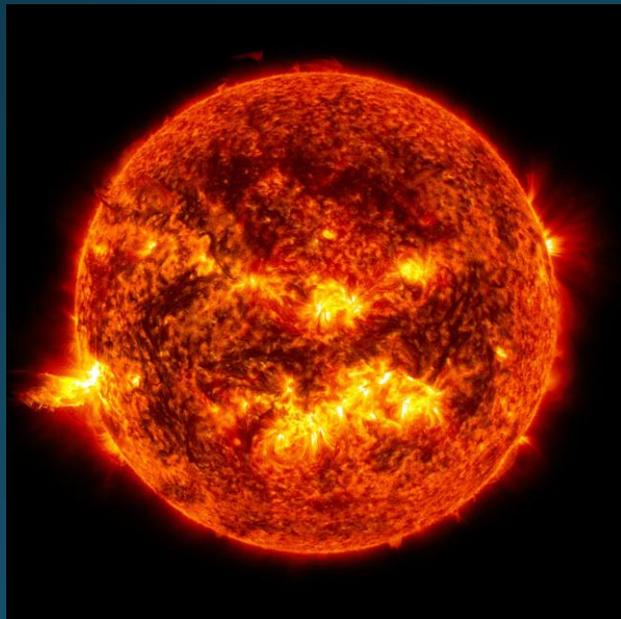
X-Ray



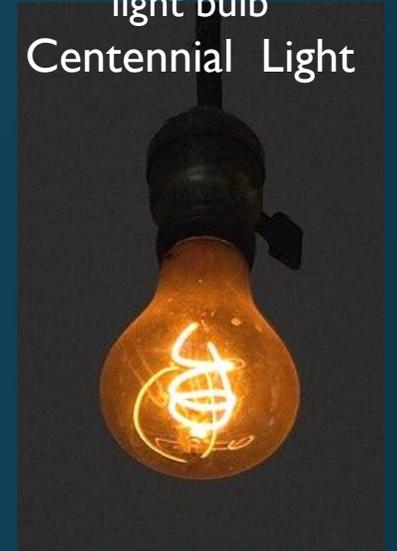
- With a different type of lens, you can:
1. See through opaque objects
  2. Observe different processes
  3. Reveal previously hidden structure

# What makes an object bright?

- Temperature and size together
- Distance: closer = brighter



Famous incandescent  
light bulb  
Centennial Light



The filament is hot!  
4000 °F (2200 °C)

Betelgeuse is 30 million  
times farther away than  
the Sun.

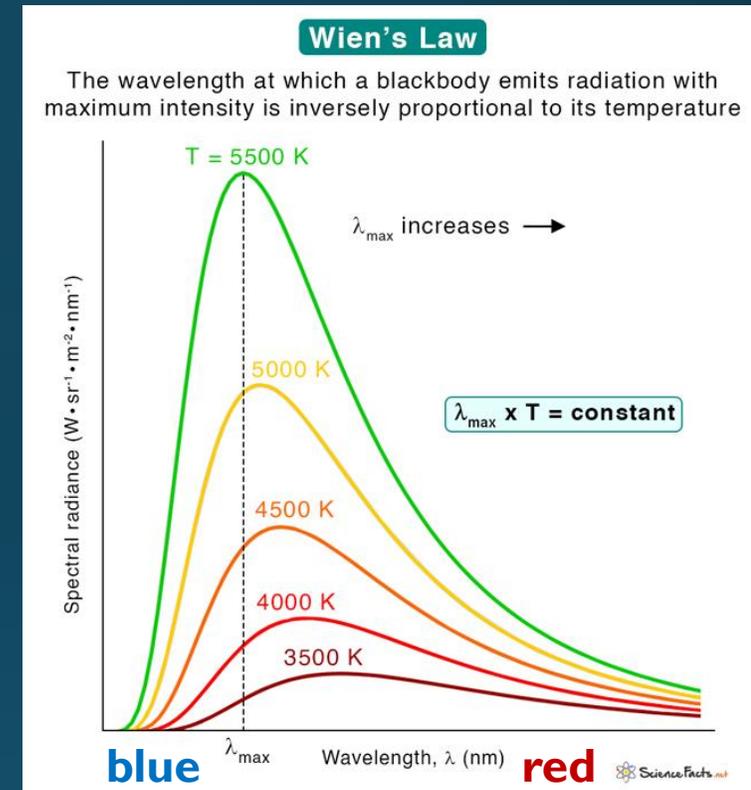
# Spectra of colors

- Many different colors are emitted for hot objects
- Learn the temperature of an object by determining its peak wavelength

“Bluer = hotter”

“hotter = smaller peak wavelength”

\*This is “thermal” emission



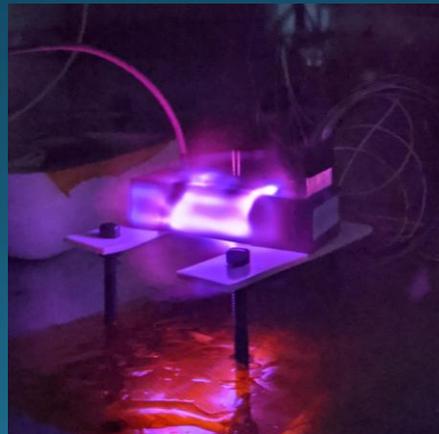
# Different types of emission

There are also non-thermal emissions

- Ionization of gas from electric fields
- Not a continuous spectra of colors!
  - See the quantized energy levels

Distance: closer = brighter

Corona  
discharge with  
High Voltage  
supply



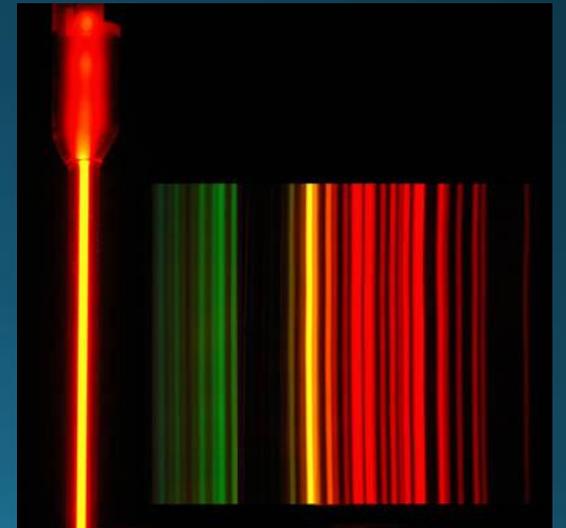
The Astroparticle Lens: Lecture I

“Neon” sign  
in Andersonville



This is probably a mixture of  
argon and mercury gas.

Neon spectra  
Photons

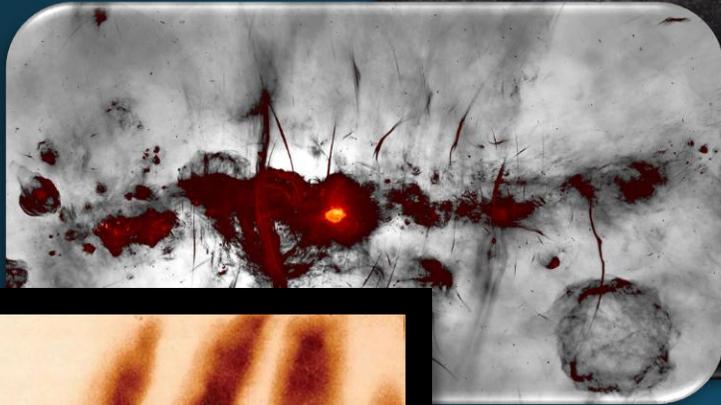


Optical

Gas in the center  
is Millions of  
degrees

Radio

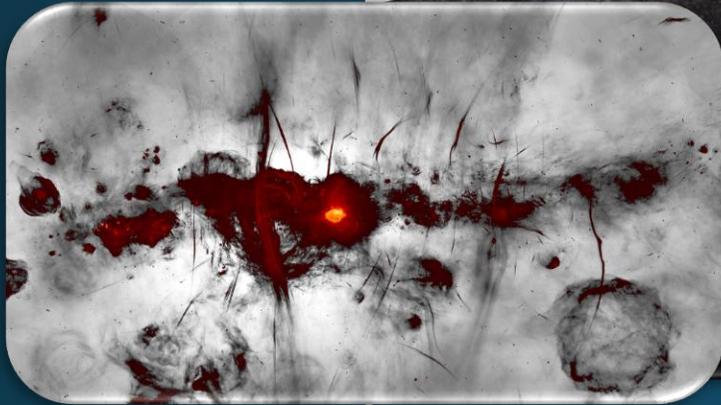
X-Ray



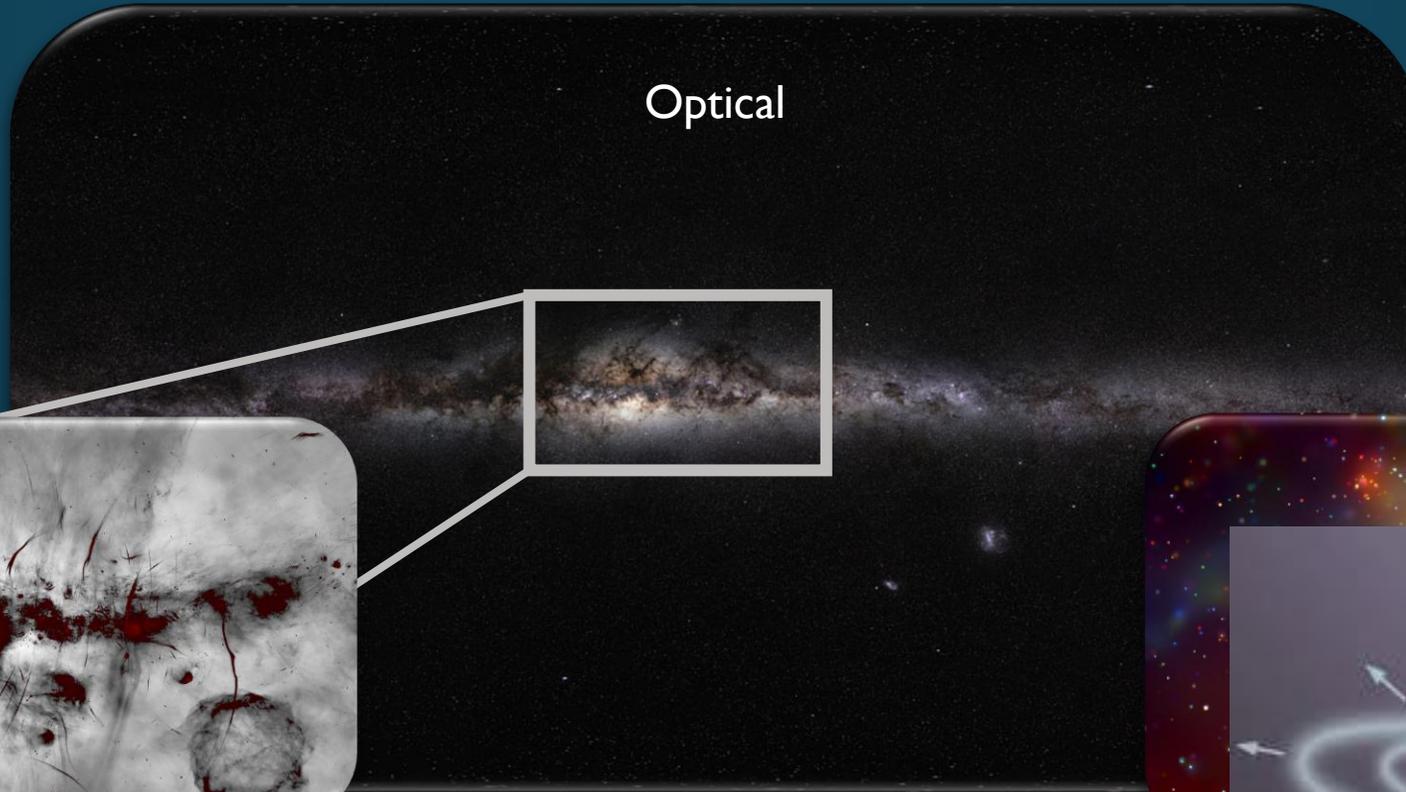
- With a different type of lens, you can:
1. See through opaque objects
  2. Observe different processes
  3. Reveal previously hidden structure

Particles like electrons interacting with magnetic fields!

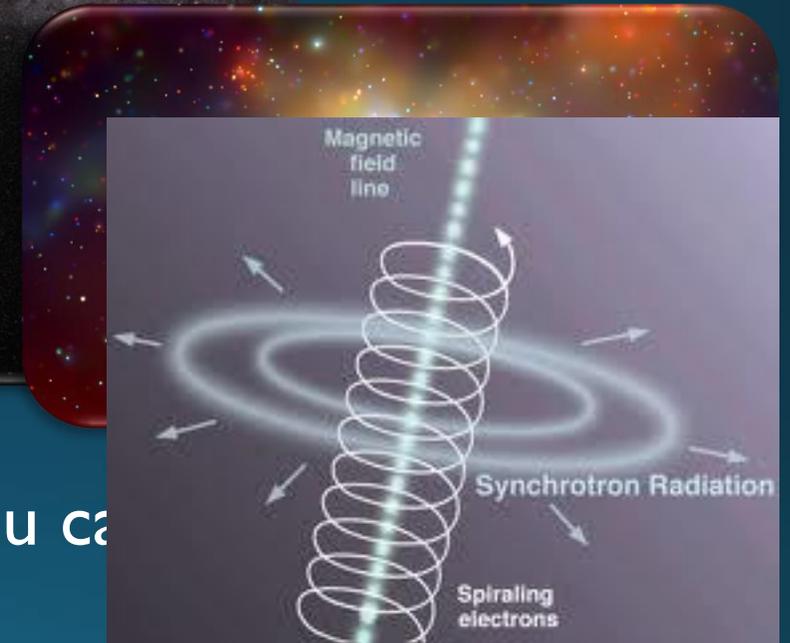
Radio



Optical



X-Ray



- With a different type of lens, you can
1. See through opaque objects
  2. Observe different processes
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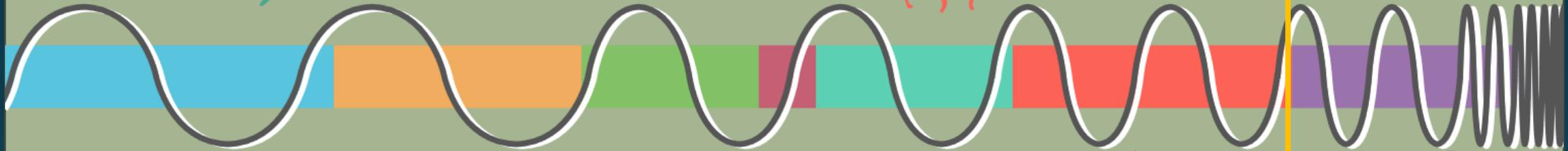
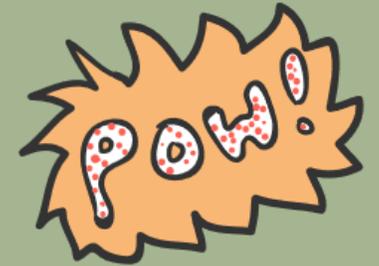
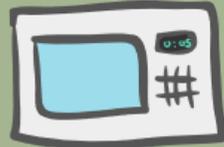
The highest energy processes have gamma ray signatures



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

# The Electromagnetic Spectrum

$\lambda \sim 1 \text{ m}$



Radio

long wavelengths that are used for radio stations

Microwaves

Cooks snacks!

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Makes up heat

Visible Light

All the colors of the rainbow - what we see

Ultraviolet

Responsible for sunburns ☹️

X-Ray

Takes pictures of your bones!

Gamma Ray

Part of many superheroes' origin stories - like the Incredible Hulk!

# The High Energy Universe

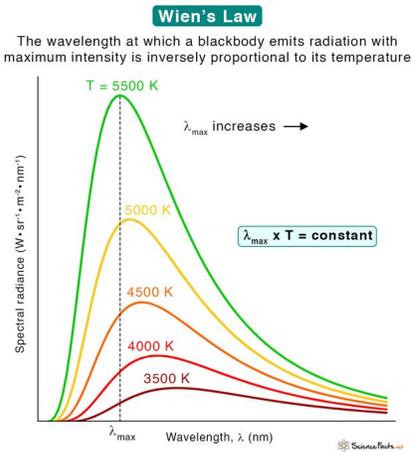
1. Is the Milky Way so hot that it glows in gamma rays?

## Fermi two-year all-sky map

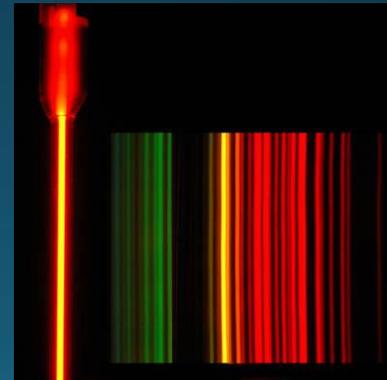


Milky Way

2. Is it gas that is emitting these gamma rays?

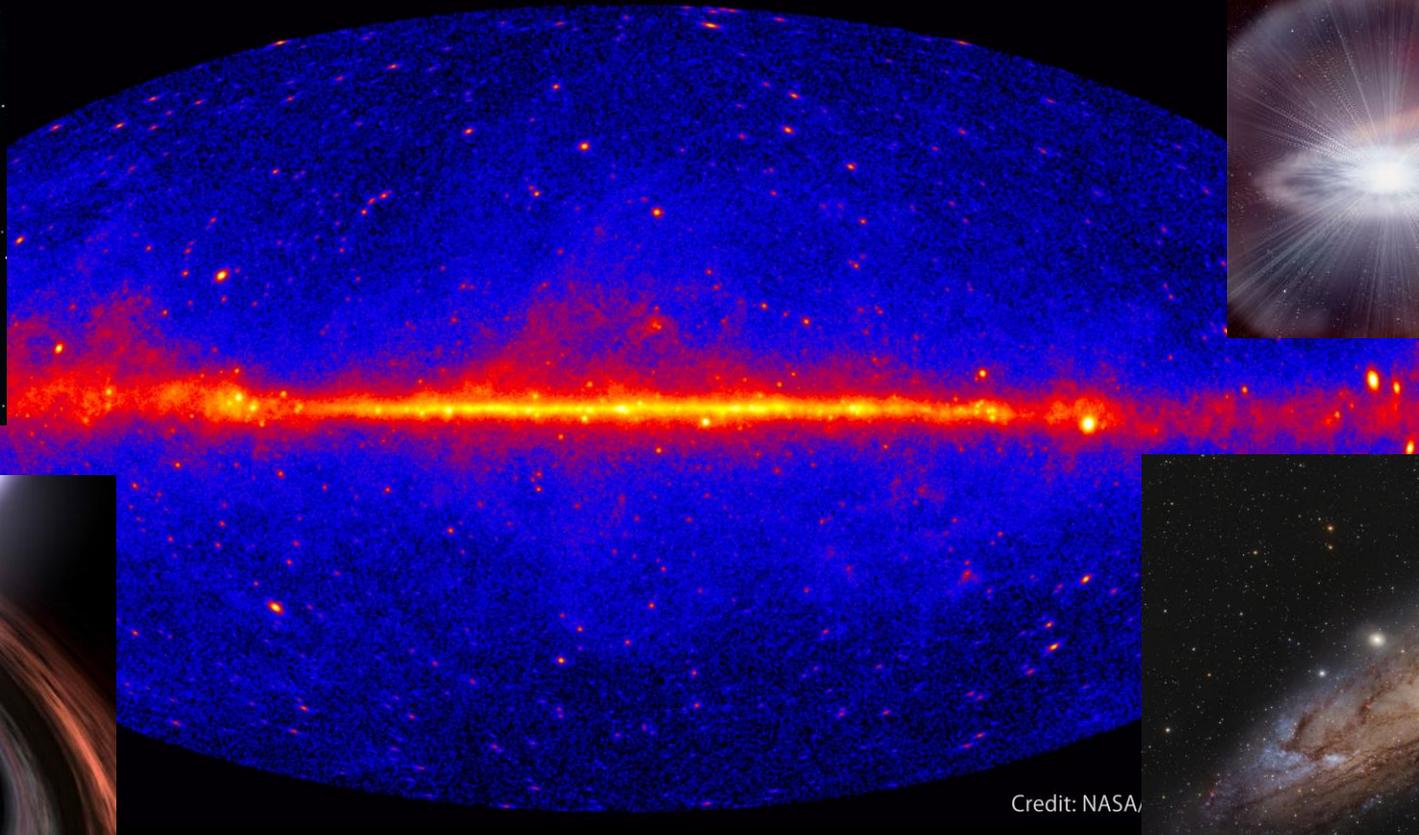
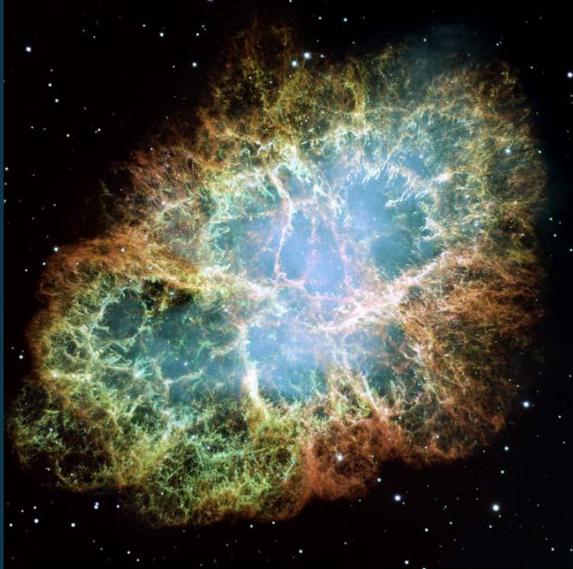


Credit: NASA/DOE/Fermi/LAT Collaboration

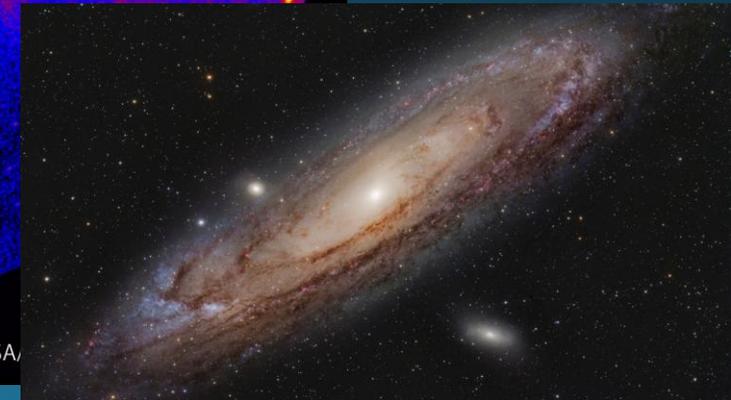


# The High-Energy Universe - Sources

Fermi two-year all-sky map



Credit: NASA



# Gamma Rays

- Discovery of gamma rays in 1900
  - Paul Villard using radium salts
- At the time, radiation was named based on the penetration depth
  - They measure the amount of radiation from decaying materials through different objects

Alpha

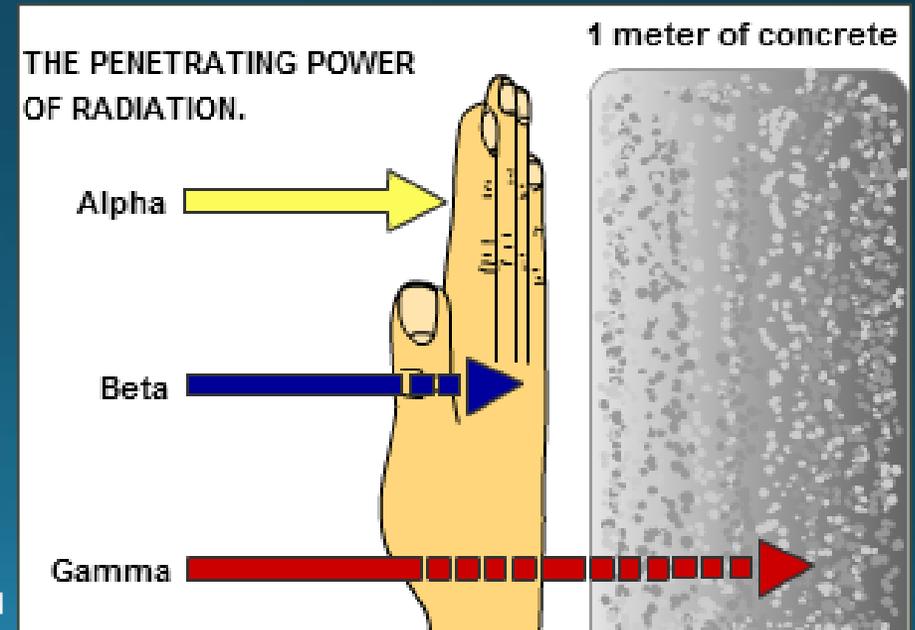
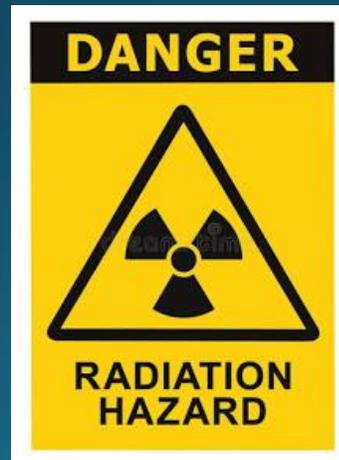
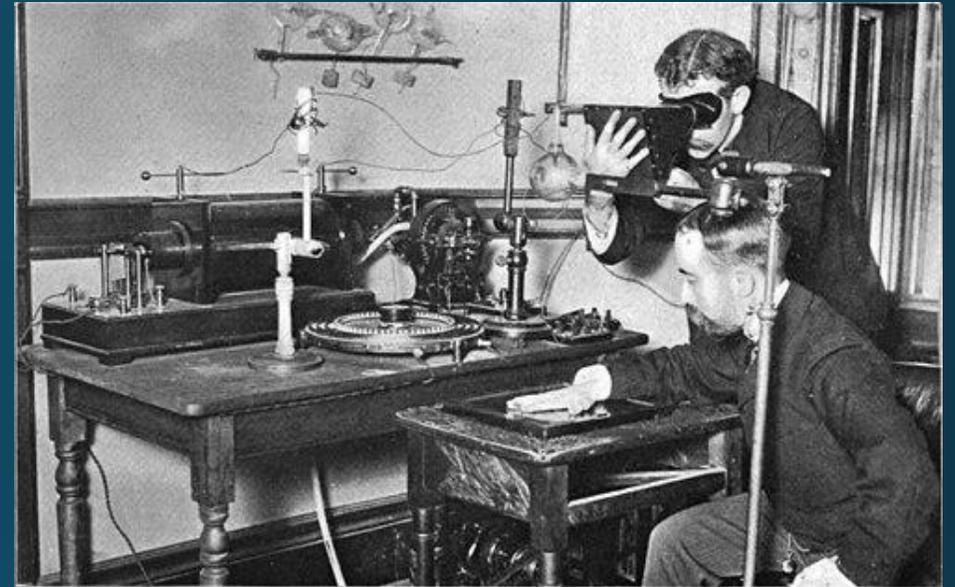
Nucleus of Helium atoms

Beta

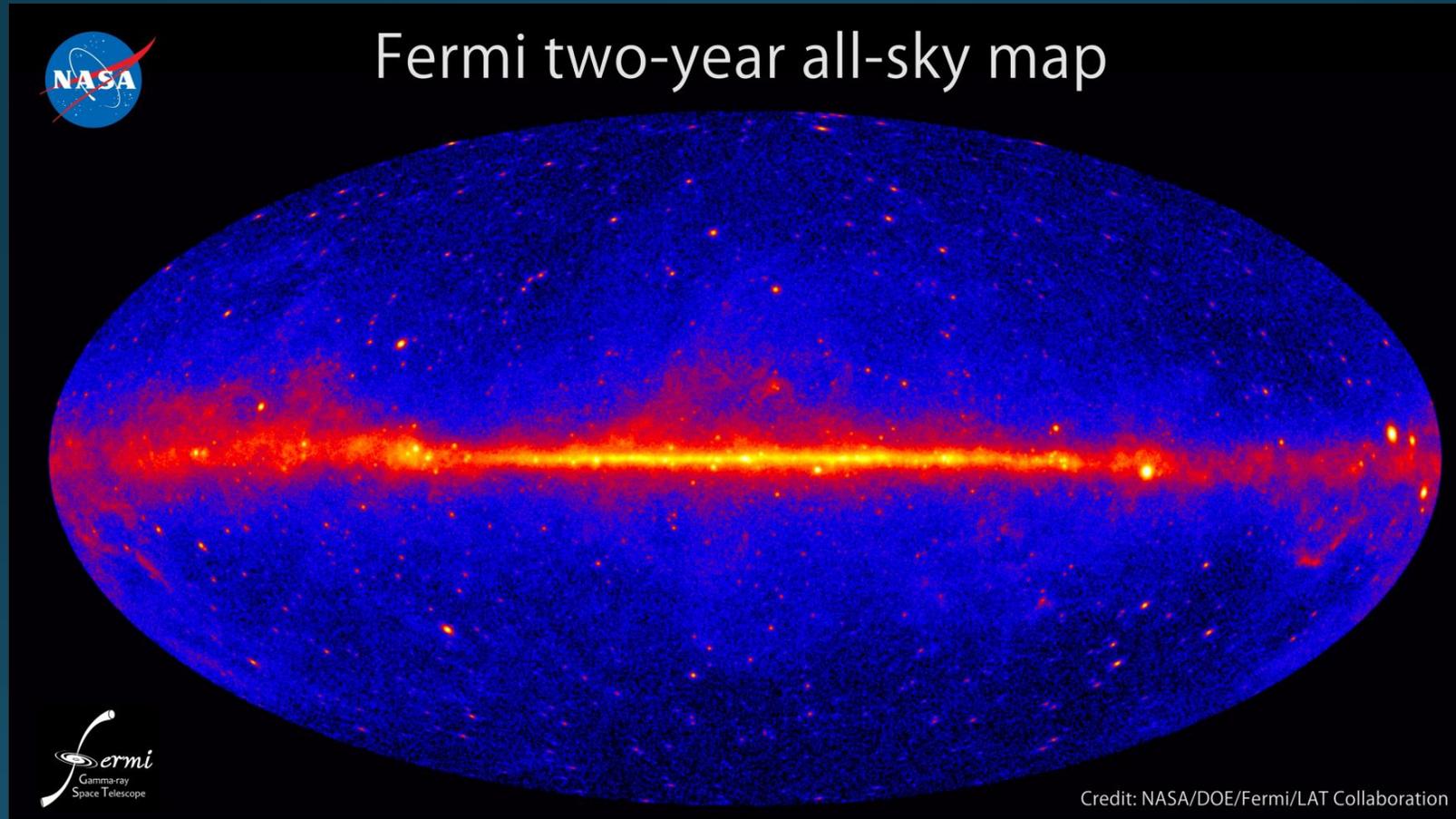
Electrons

Gamma

Photons

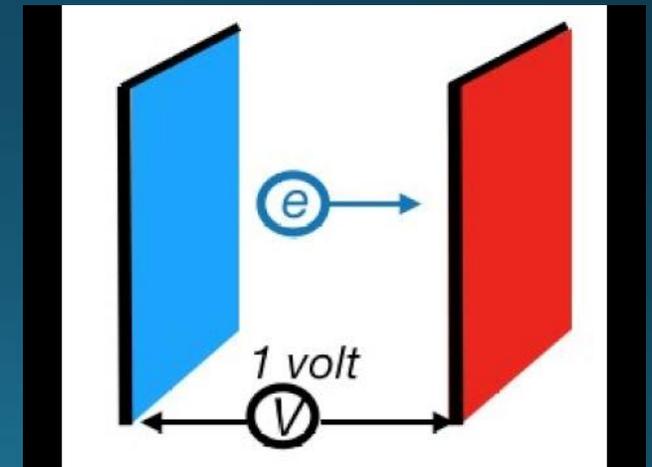
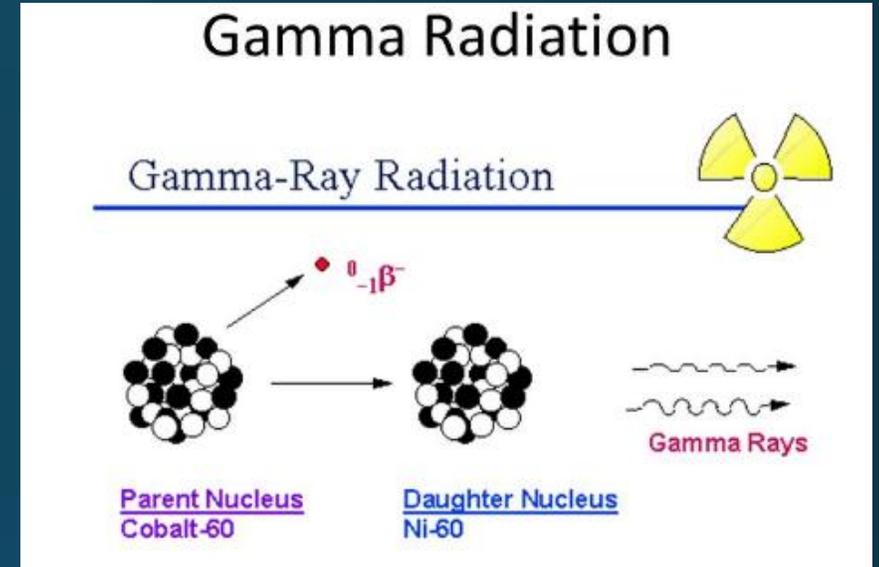
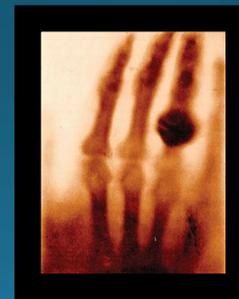


~~So gamma rays are from radioactively decaying material throughout the Universe?~~



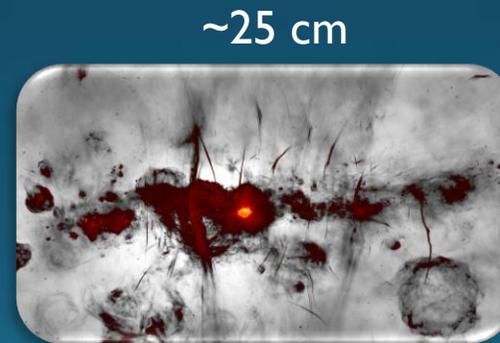
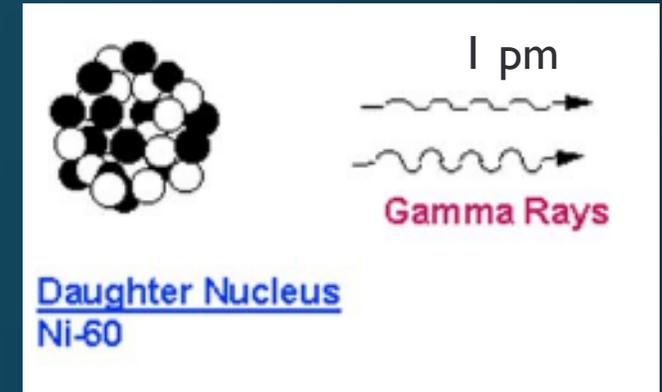
# Energy

- Unstable nuclei emit particles/energy to become more stable
- Gamma rays produced from radioactive decay of nucleus
  - example of Cobalt-60
- Nucleus is made up of nucleons
  - Protons and neutrons together in quantum states
- Photons of energy  $\sim 1$  MeV
  - Mega electron Volts
  - Equivalent of 1 Million Volts for a single electron
  - Röntgen's X-rays were  $\sim 0.04$  MeV

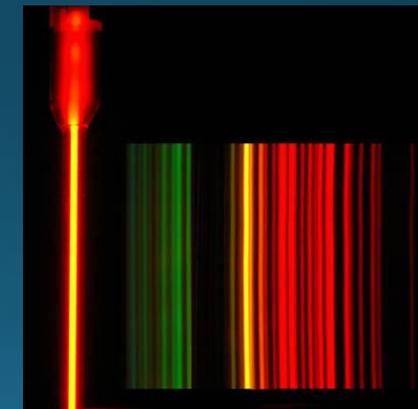


# Wavelength

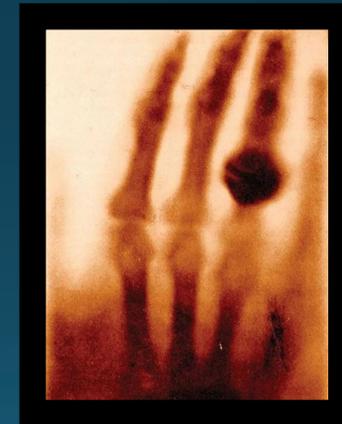
- From radioactive decay of nucleus
  - The Nickel-60 nucleus
  - 28 protons and 32 neutrons
- The gamma rays are *coherently* emitted from the nucleus when it relaxes to the ground state
- These gamma rays have wavelength  $\sim 1$  pm
  - $10^{-12}$  m
  - 1 trillionth of a meter



Radio

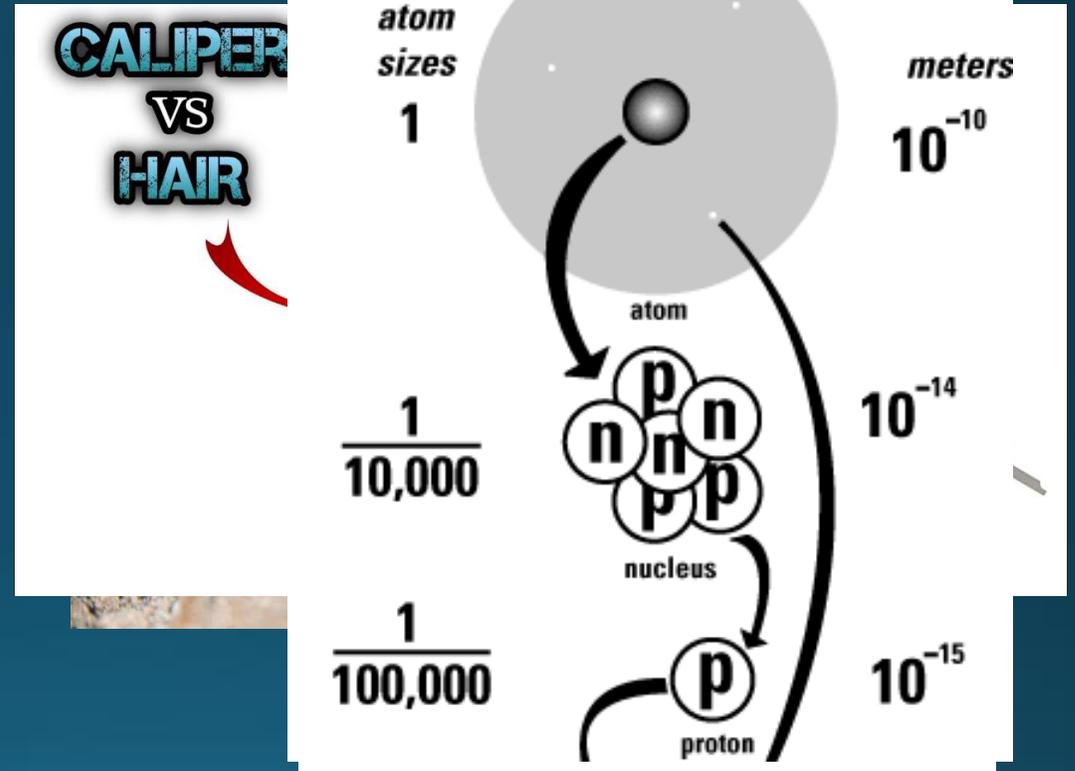
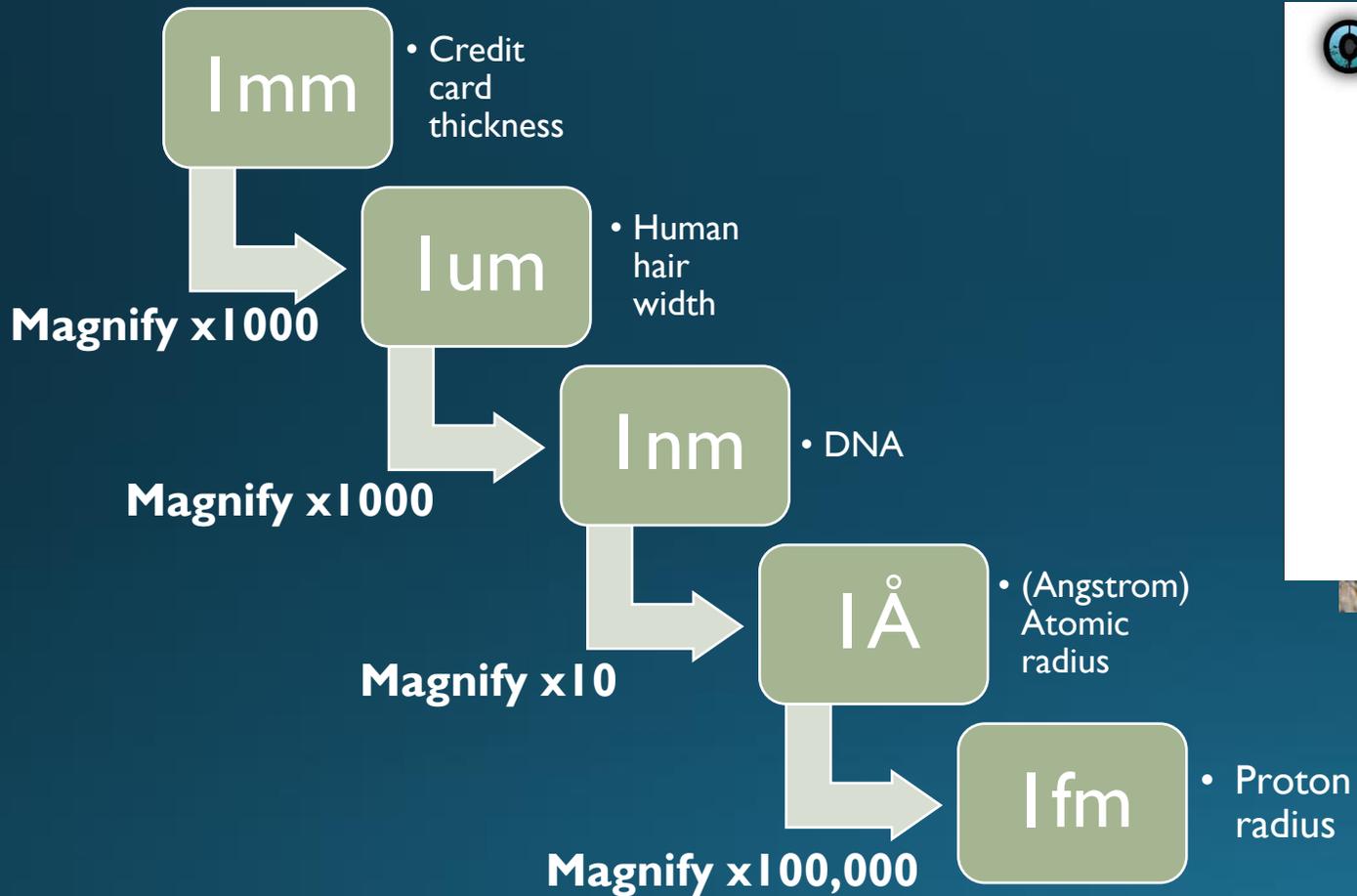


Optical



X-Rays

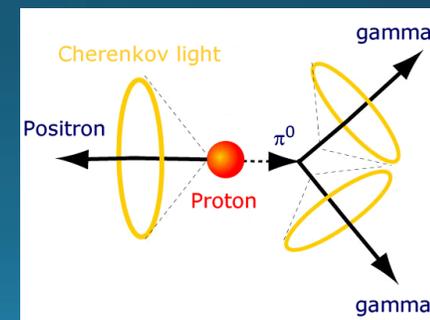
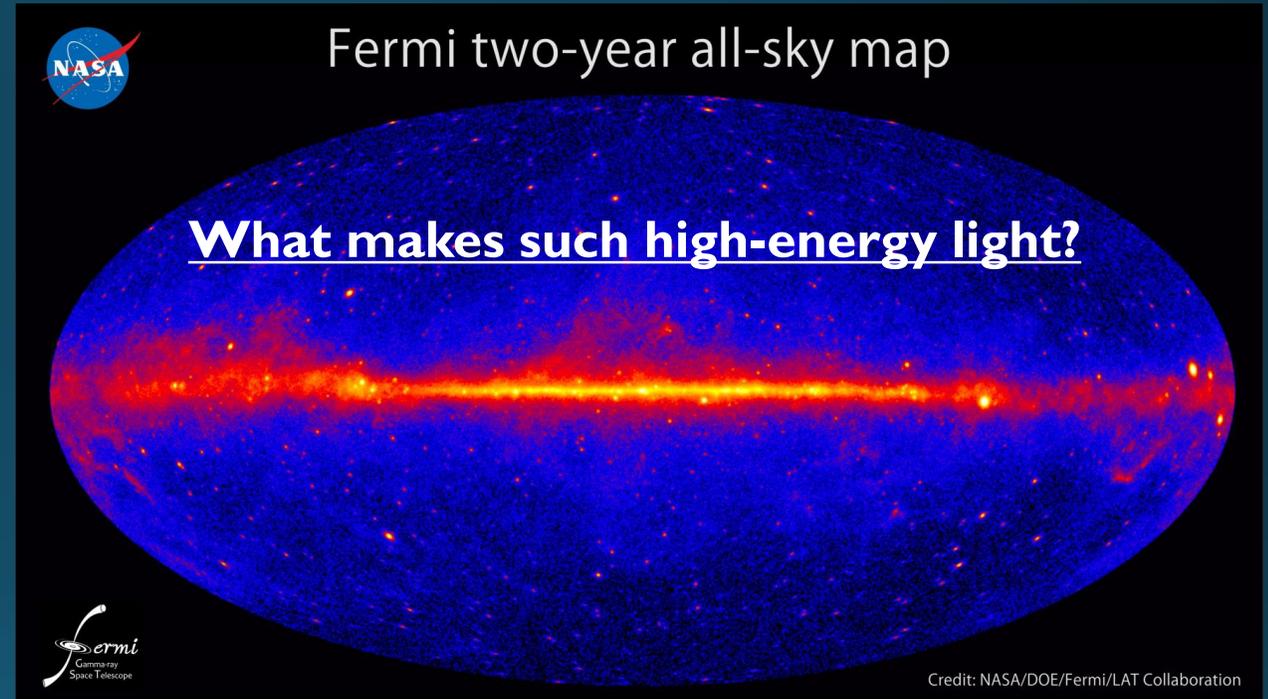
# Length Scales Overview



# High-Energy Gamma Ray Lens

- These are  $> 1 \text{ GeV}$  gamma rays
  - Giga electron Volts
  - 1000 times the energy of gamma rays from radioactive decay
- The wavelengths are  $\sim 1 \text{ fm}$ 
  - The size of the proton!
- Protons don't decay

Proton lifetime is longer than  $10^{34}$  years





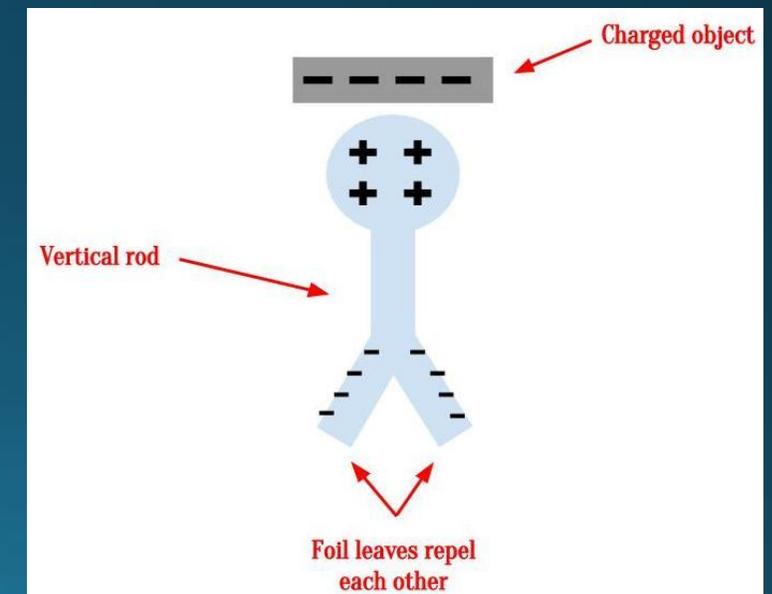


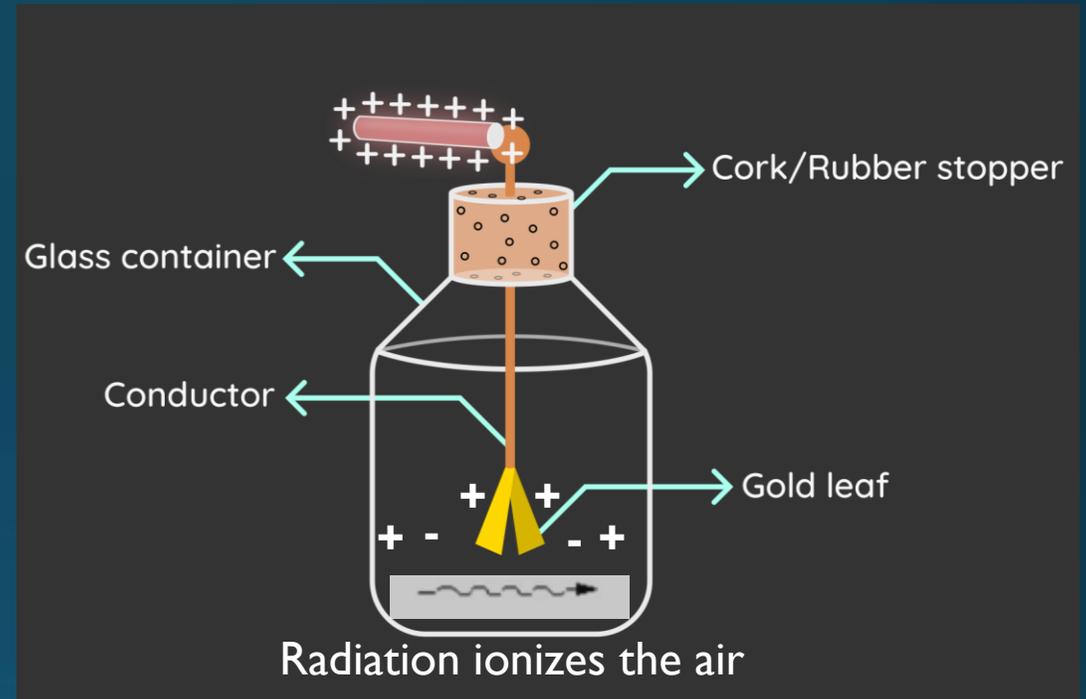
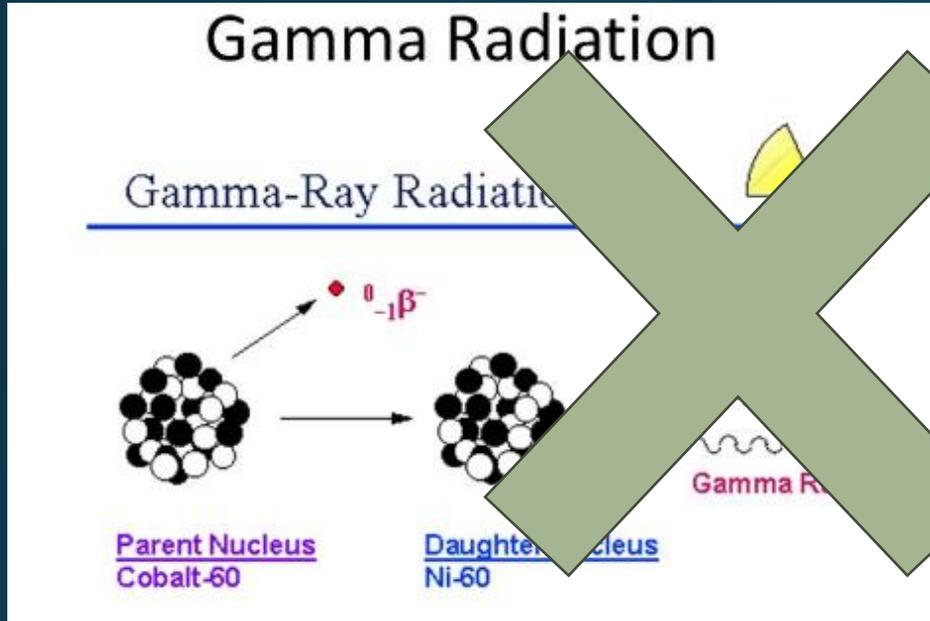
Cosmic ray protons!

What's a pion?

# Discovery of cosmic radiation

- In 1785 Coulomb showed that electroscopes discharge seemingly randomly with air.
- 50 years later, Faraday confirmed that this was a natural phenomenon and *not faulty equipment*
- 50 years after that, Crookes determined that at lower air pressures, the discharge happens *faster*
- Electroscopes were used for over 100 years





Discharge – Leaves stop repelling and fall!

But Crookes and Faraday claimed this happened without a source...

# Where is this radiation coming from?

## Team Earth

- Rutherford
- Theodor Wulf
- A.S. Eve



## Team Cosmos

- Victor Hess
- Domenico Pacini
- Robert Milikan

- Many experiments were conducted to determine where this radiation was coming from
- Eve took electroscopes over the ocean and deep in lakes
  - calibrated against local measurements at McGill University
- Away from rock and soil, there was still radiation. But maybe there is radium in the water?

Radiation was a new discovery and found to be coming from rocks naturally!

Published in 1907

[ 724 ]

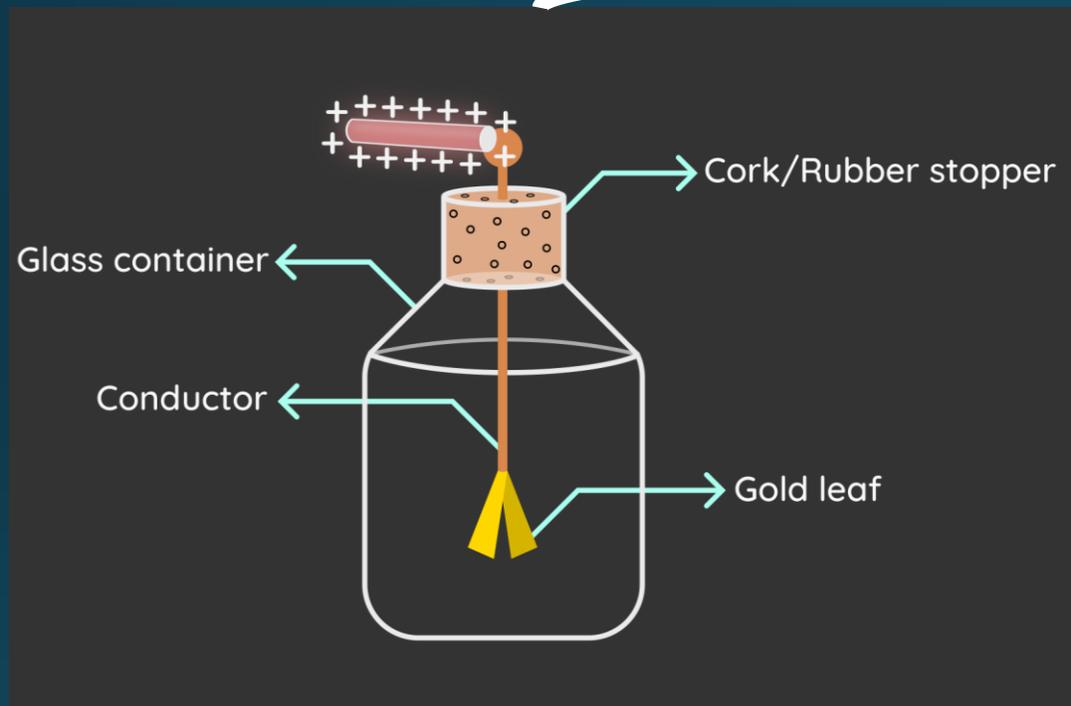
LXXII. *On the Amount of Radium Emanation in the Atmosphere near the Earth's Surface.* By A. S. EVE, M.A.\*

IT has been proved by Elster and Geitel that a negatively-charged wire, exposed for a few hours in the air, receives a radioactive deposit similar in character to the quick-changing products of radium. Radium is known to be widely dis-

an indirect method, in the following manner:—On the ground in the Campus of McGill University was placed a large zinc cylinder, of known volume, with closed ends. Along the axis was a wire, charged negatively to 10,000 volts, on which

In the autumn of 1906 Professor Rutherford found that charcoal, prepared from coconuts, entirely absorbed the radioactive emanations, provided they were passed very slowly through the charcoal. He was good enough to assign

# Domenico Pacini: Electrosopes spontaneously discharging? Put it in a copper box!



Less frequent but still discharging happens!

# Discovery of cosmic rays – going down

- Probably the first to discover cosmic rays
- Out at sea and on land- similar rate of discharge
  - Also ruled out Halley's comet!
- Submerged in a copper box and measured radiation less often deeper into the sea



Domenico Pacini

Thanks to Dr. Yan of the University of Glasgow for pointing this out to me (through Dr. Windischhofer)!

# Discovery of cosmic rays – going up

- Victor Hess ascended in a balloon multiple times
  - Altitude 5000 meters (3 miles)
  - During a near-total solar eclipse
    - Ruled out the Sun
- Above 1500m, radiation was even more intense
  - Electroscope discharged more frequently
- Hydrogen gas used
  - Dangerous!

Victor Hess received the Nobel prize in 1936

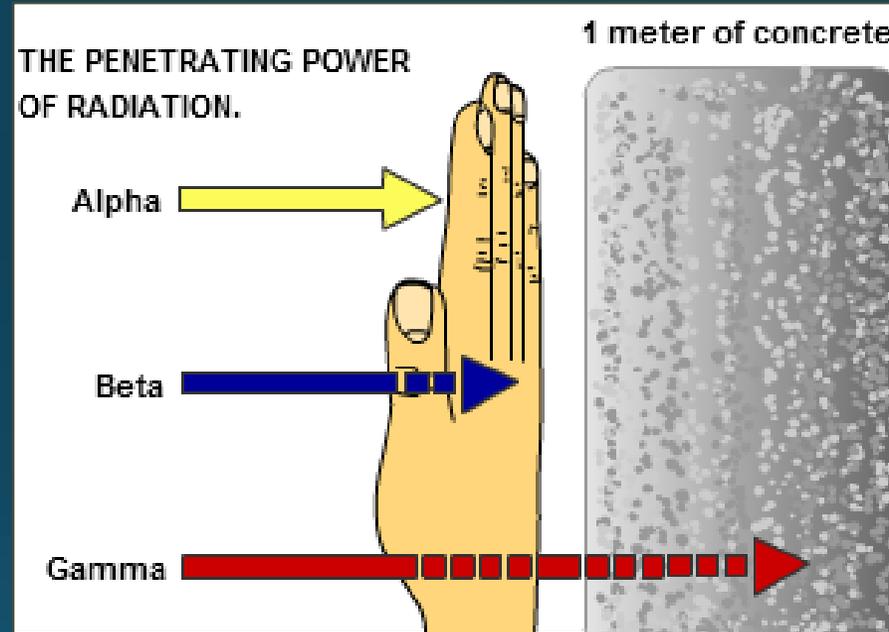
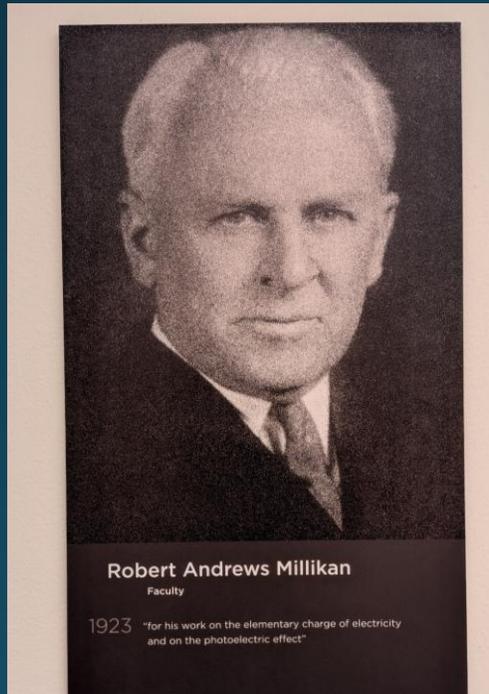
This guy is trying to observe cosmic rays



# So what is this “cosmic” radiation!?

Millikan measured the charge of the electron, awarded the Nobel Prize in 1923.

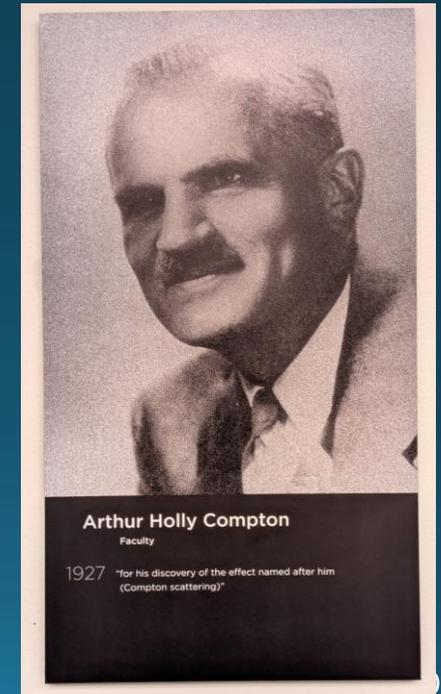
He suspected cosmic rays were Gamma rays!



← Coined the term “cosmic rays”

Compton discovered the Compton effect, awarded the Nobel Prize in 1927

He suspected cosmic rays were charged particles!



# Using the Earth's magnetic field



Collaborators measured cosmic rays with ionization chambers all around the world

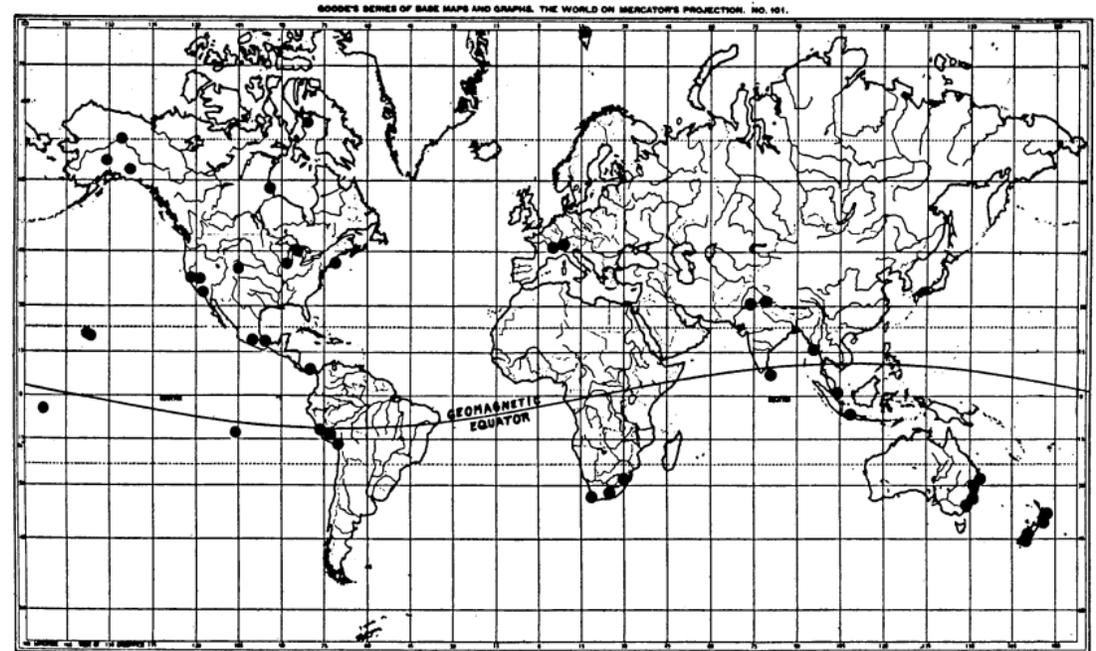


FIG. 4 Map with location of cosmic-ray measurements by Compton and his co-workers. *PR*, 43 (1933), 389.

\*This was actually a side project for Compton!

In his final report on the survey, Compton acknowledged the cooperation of more than sixty physicists of many countries and presented data obtained from 69 different stations at latitudes ranging from  $78^{\circ}\text{N}$  to  $46^{\circ}\text{S}$ , longitudes ranging from  $175^{\circ}\text{E}$  to  $173^{\circ}\text{W}$ , and elevations from sea level to more than 6000 meters (figure 4).<sup>75</sup> The final cost of the 1932 survey, excluding Compton's experiments of 1931, was \$28,840, of which \$18,000 came from Carnegie and the rest from the University of Chicago, MIT, Compton himself, and other miscellaneous sources.<sup>76</sup>

By the fall of 1932, however, the death of the two physicists was not the main subject of the news coverage of Compton's and his collaborators' exotic and eventful journeys, nor the main concern of Carnegie's officials. It was rather the rising controversy between Compton and Millikan about the nature of cosmic rays and about the meaning of their respective experimental data.

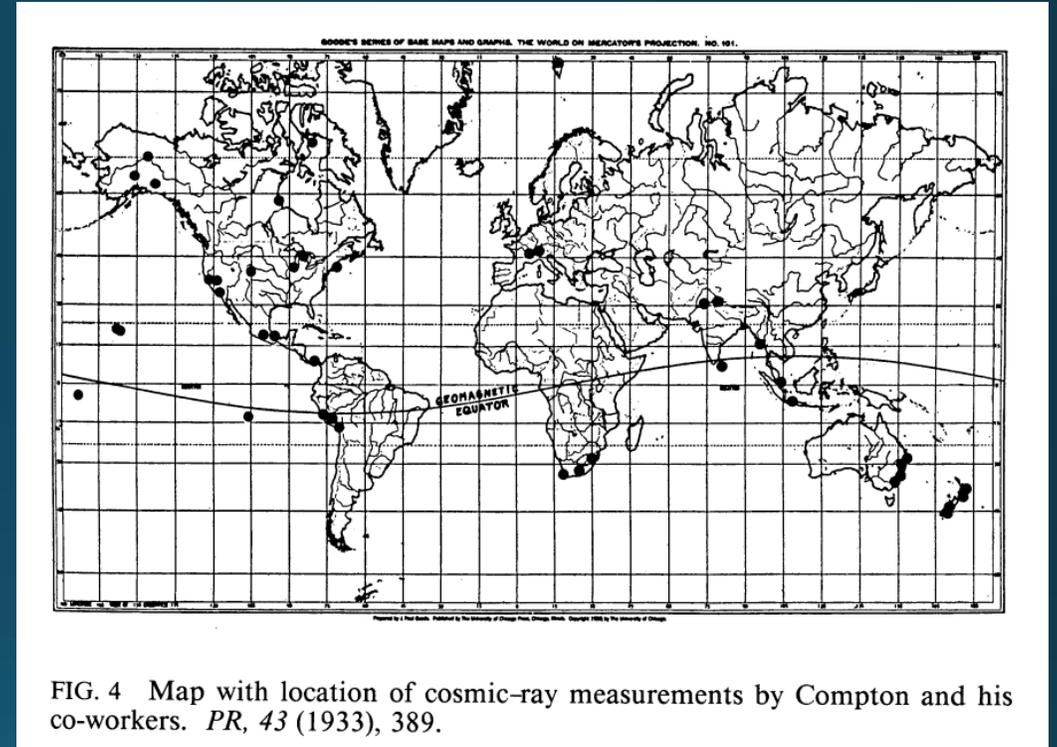
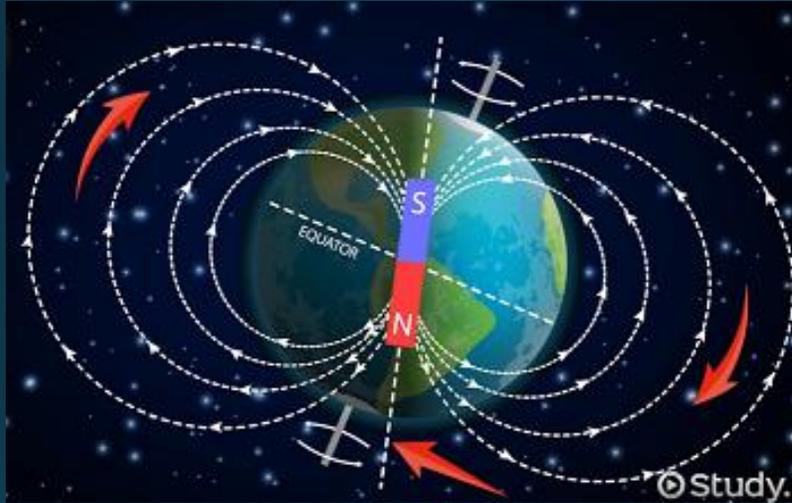
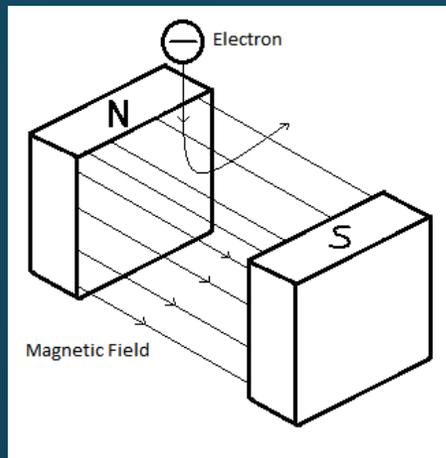
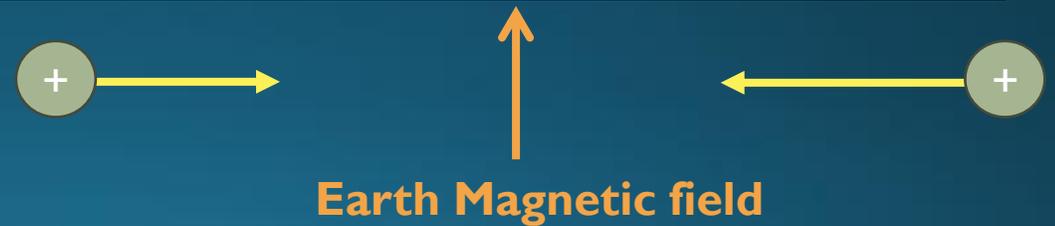


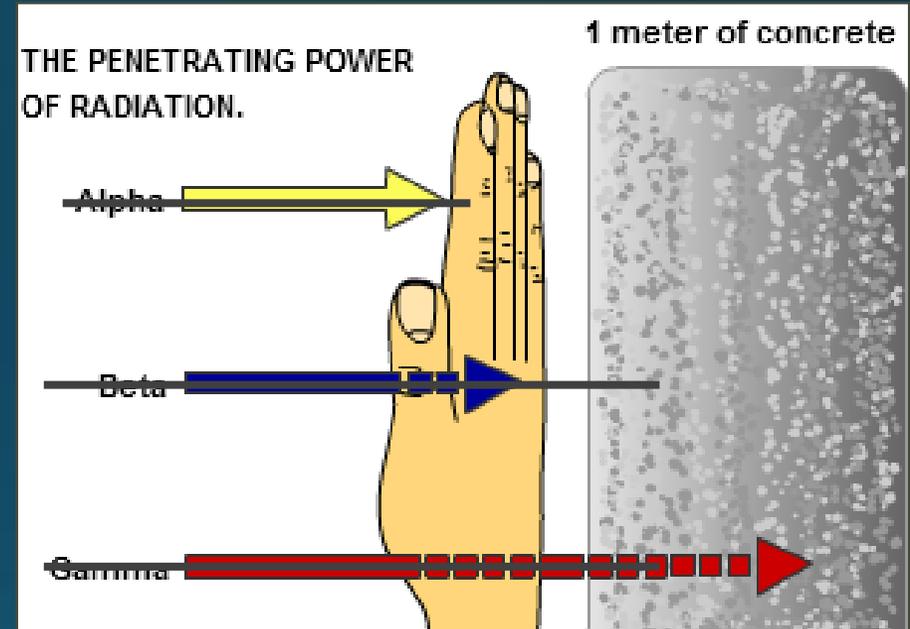
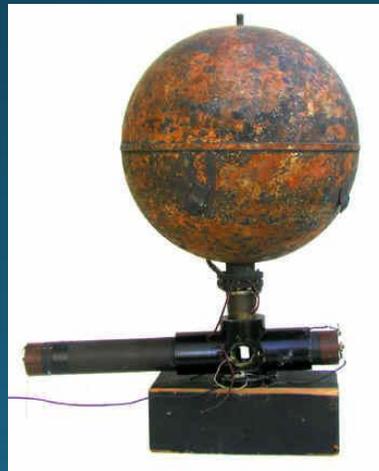
FIG. 4 Map with location of cosmic-ray measurements by Compton and his co-workers. *PR*, 43 (1933), 389.

More cosmic rays observed coming from the west direction.  
 Turns out cosmic rays were mostly positively charged particles!  
 And the Latitude effect-more cosmic rays at the poles!



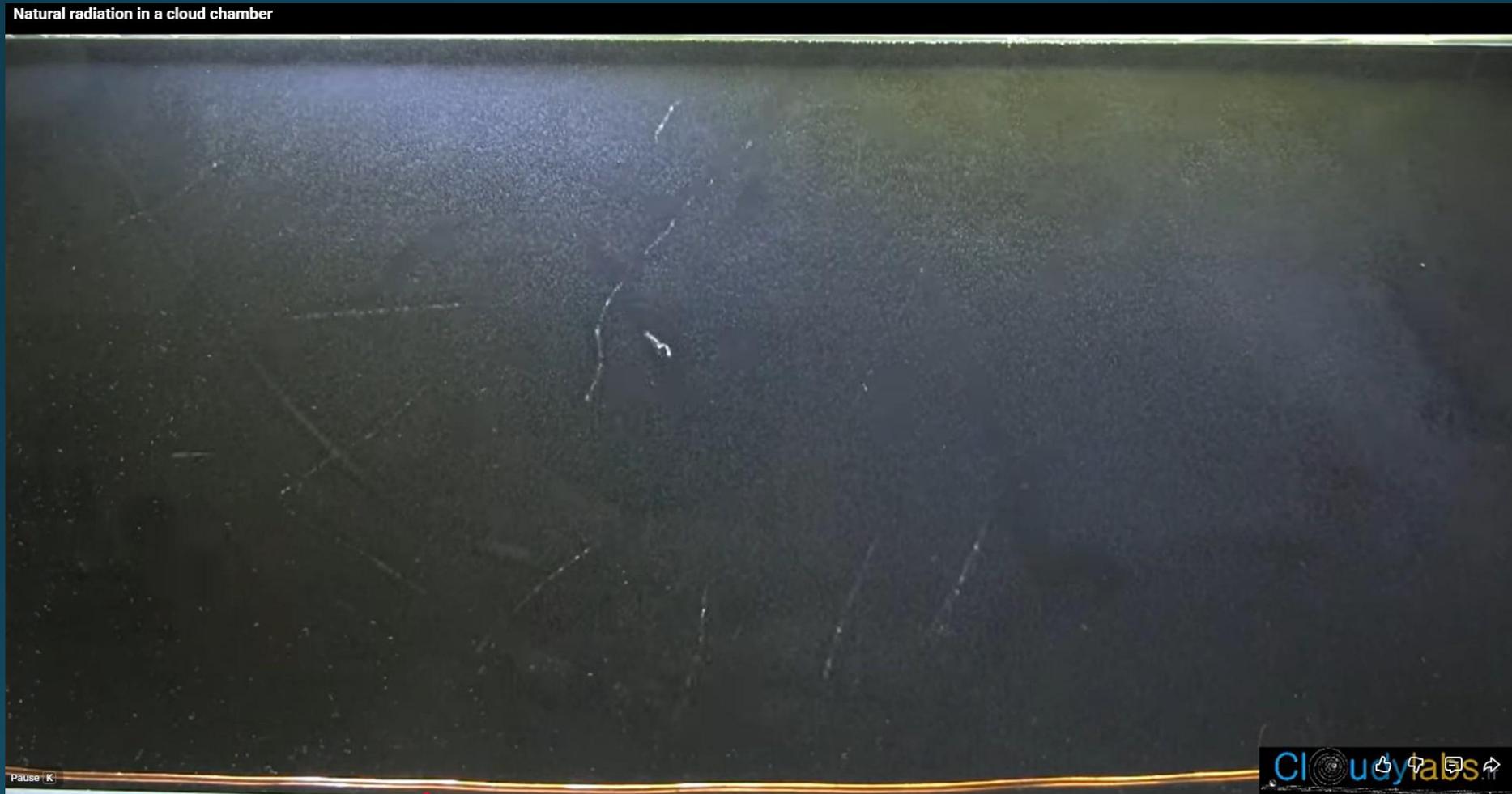
# The state of things...

- This radiation is positively charged
- But, also, more penetrating than alpha particles



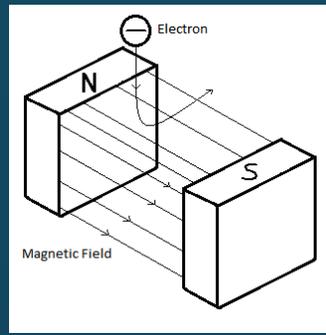
Millikan moved to Caltech and worked with Carl Anderson

Wilson invented the Cloud Chamber in 1911, awarded Nobel Prize in 1927



UChicago event South Side Science Festival

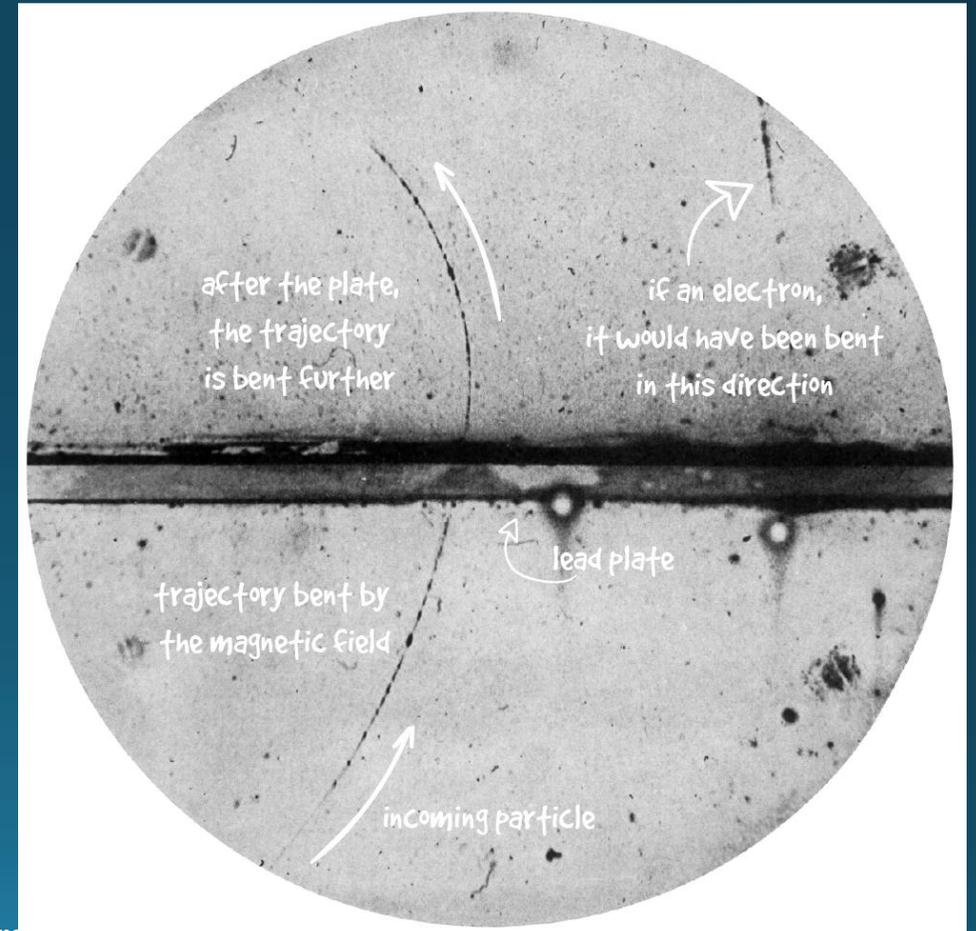
# The Positron



## THE APPARENT EXISTENCE OF EASILY DEFLECTABLE POSITIVES

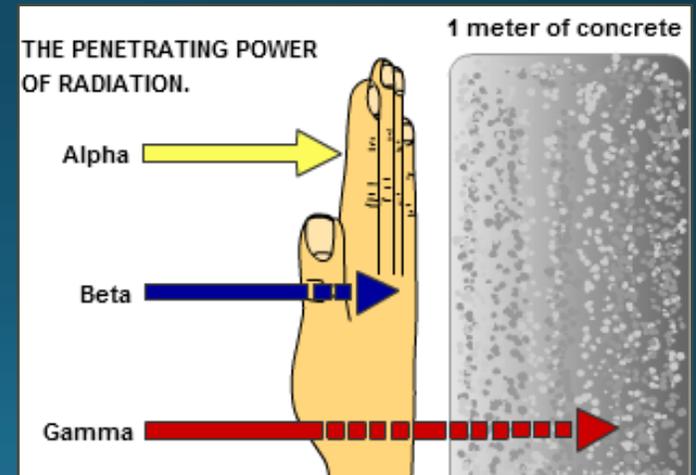
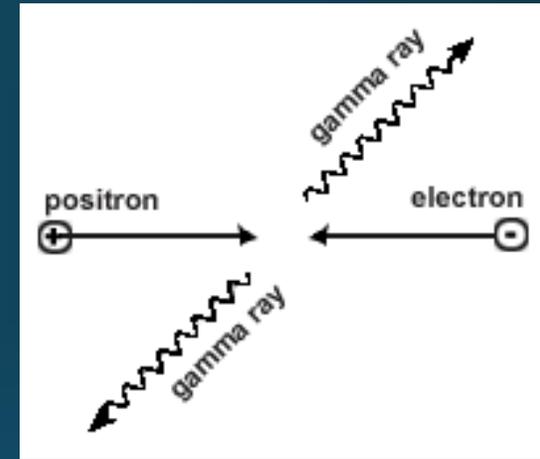
Up to the present a positive electron has always been found with an associated mass 1,850 times that associated with the negative electron. In measuring the energies of charged particles produced by cosmic rays some tracks have recently been found which seem to be produced by positive particles, but if so the masses of these particles must be small compared to the mass of the proton. The evidence for this statement is found in several photographs, three of which are discussed below.

- Carl Anderson identified positive particles that had lower mass than the proton. Awarded Nobel prize in 1936
- Dirac had proposed the existence of antiparticles of electrons



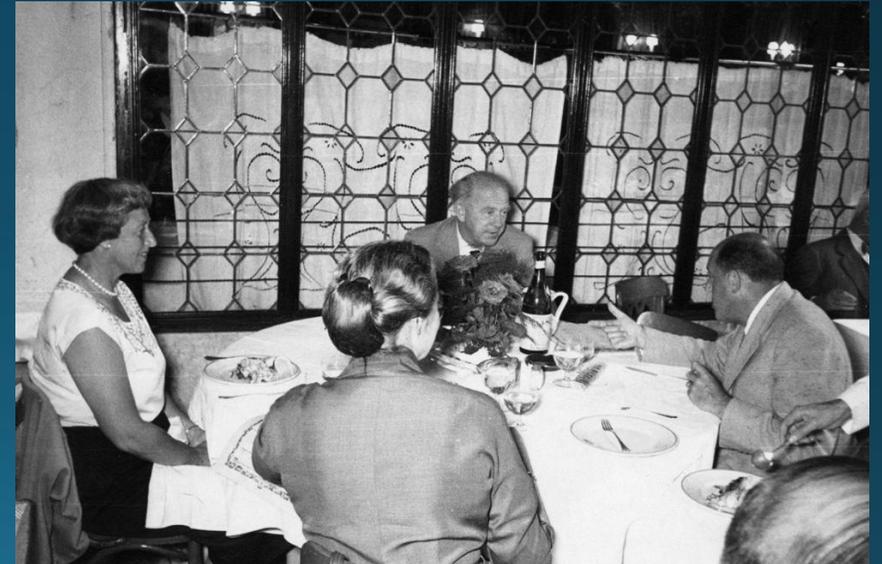
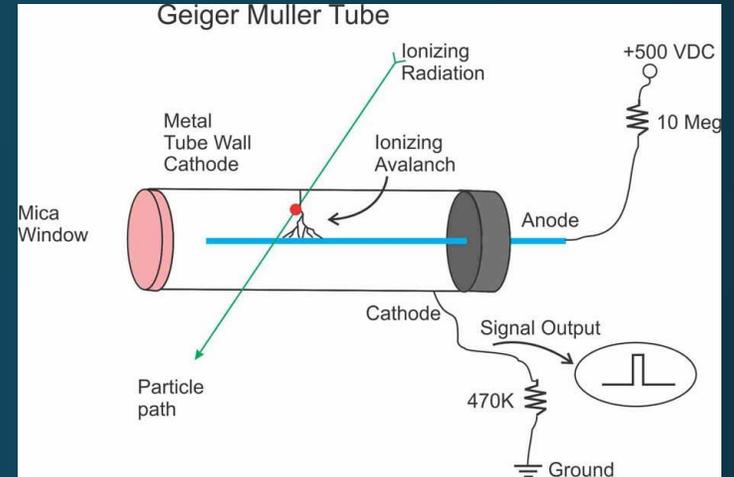
# So cosmic rays could be positrons?

- No!
- Antimatter and matter annihilate!
  - This makes gamma rays, though!
- Positrons, like electrons, are not as penetrating as cosmic rays

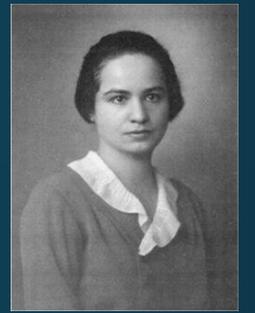


# Cosmic rays are protons

- Also known as the nucleus of Hydrogen or Hydrogen ions
- New detectors, new discoveries
  - Coincidence technique
- Marcel Schein was a part of this effort, here at Chicago, with high altitude balloons!
  - Reaching 20km! 100k feet

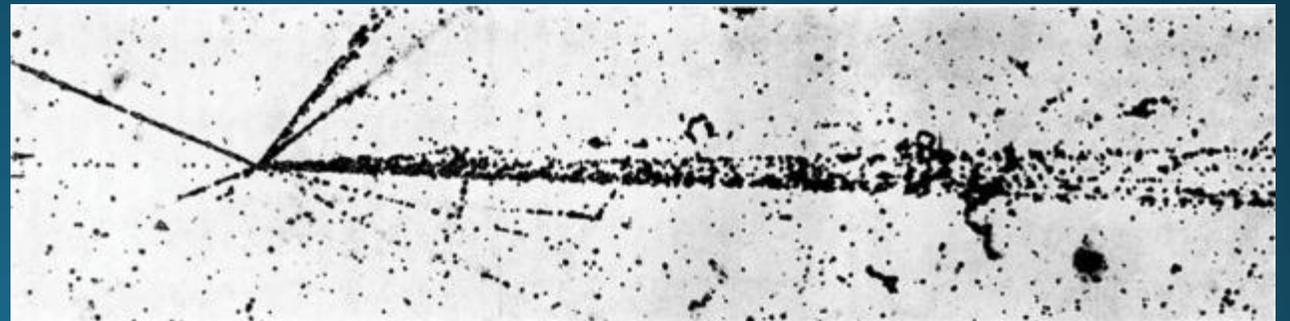
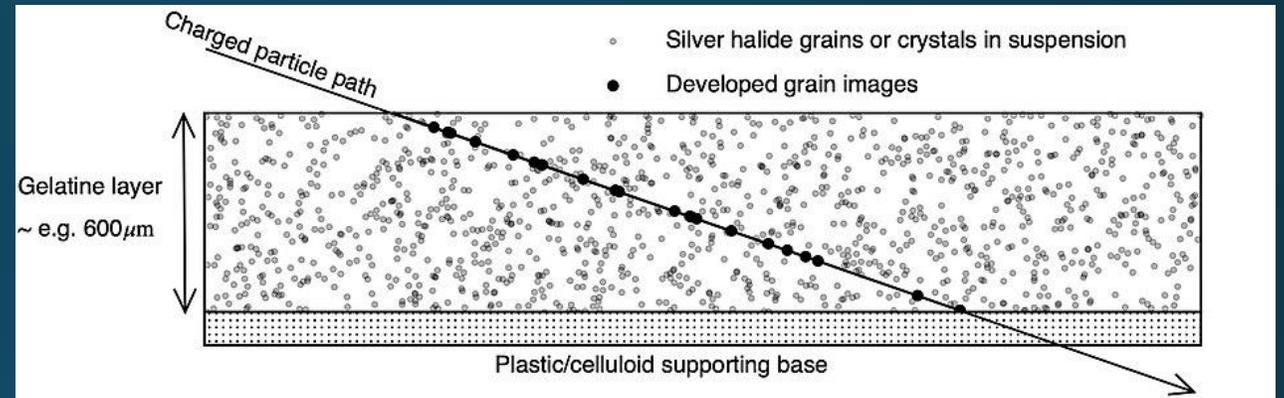


# The shower of particles – new detectors!

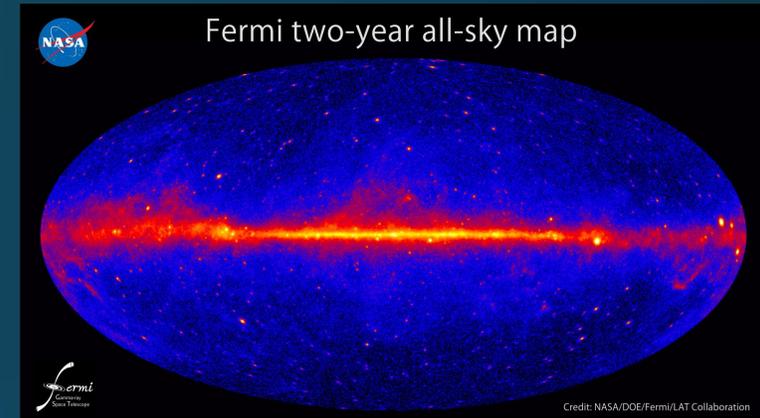
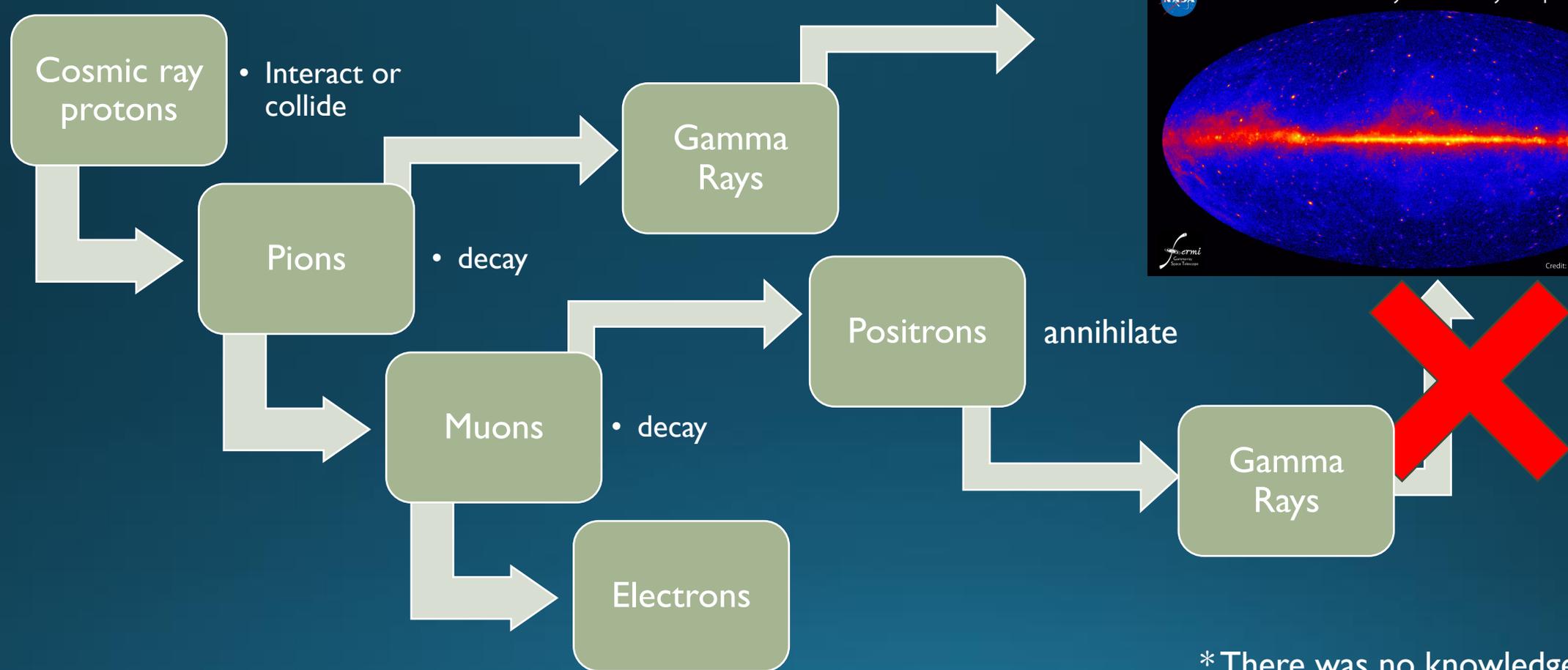


Marietta Blau

- Muons (and antimuons) discovered by Carl Anderson
  - A weird, heavier, electron-like particle
- Pions discovered
  - Bristol ballooning flights by Cecil Powell
- Direct observation of pion decay
  - Charged pions!



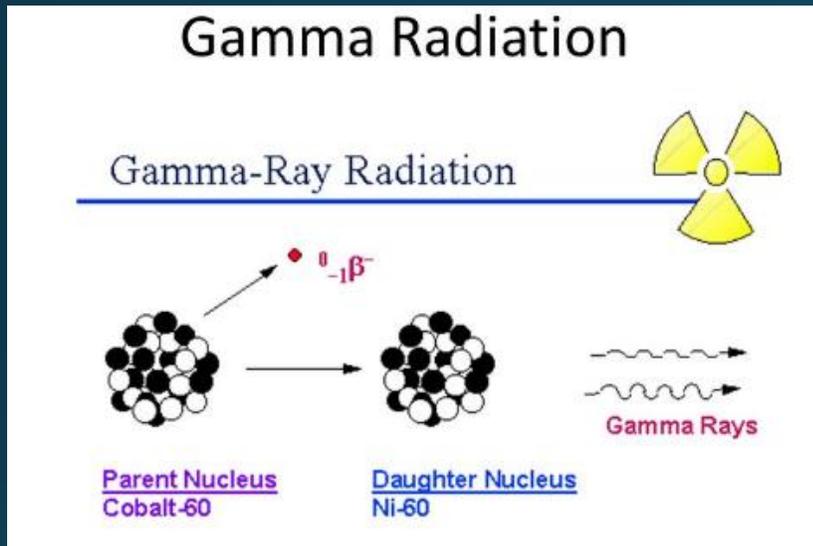
# Obtained a deeper understanding



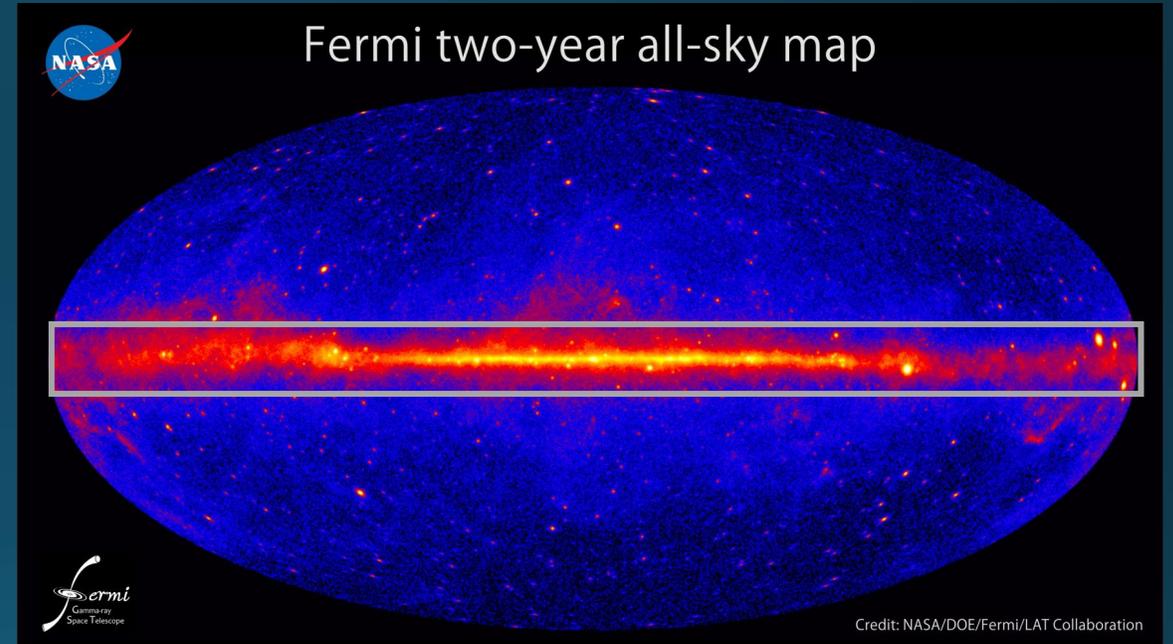
\* There was no knowledge yet of the gamma ray sky!

# The signatures of high-energy interactions

\*This is non-thermal emission



1000 light years 



1 MeV  
1 pm  
The entire nucleus

From radioactivity

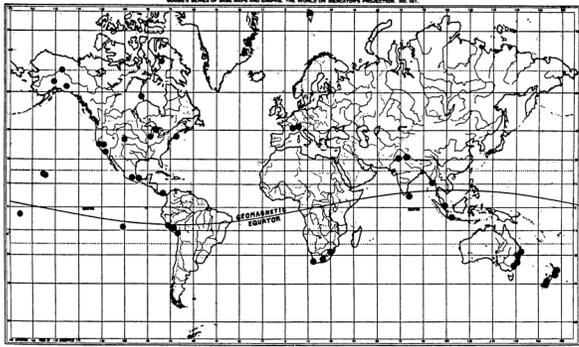
1890

To Interactions

1935

> 1 GeV  
1 fm  
The nucleons (protons and neutrons)

# Coming back to Compton's side project



The muons make it to the surface  
→ Penetrating radiation

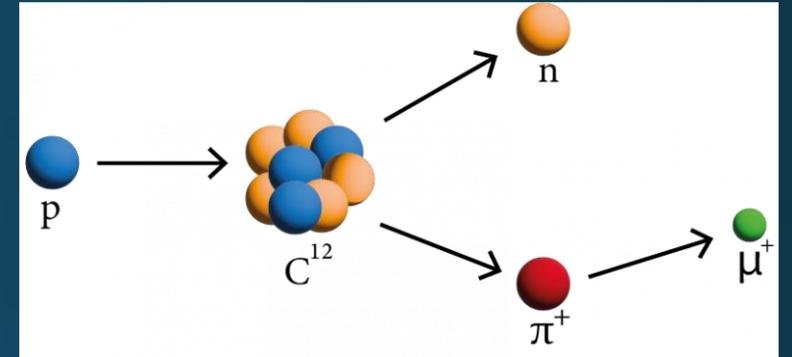


FIG. 4 Map with location of cosmic-ray measurements by Compton and his co-workers. *PR*, 43 (1933), 389.

The cosmic ray protons interact with gas in the atmosphere

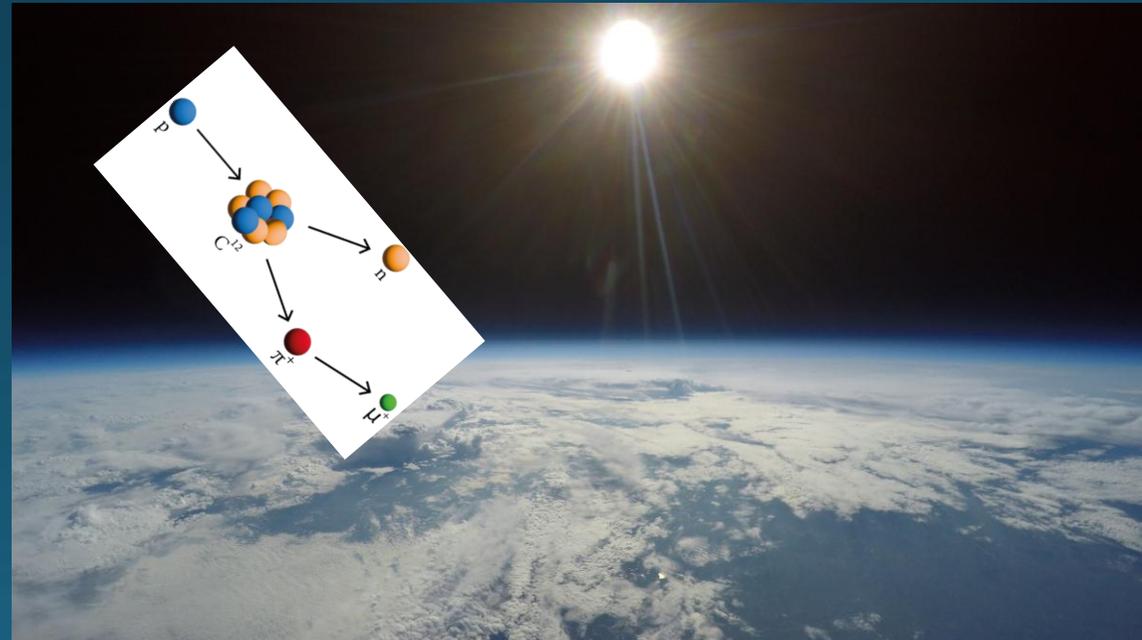
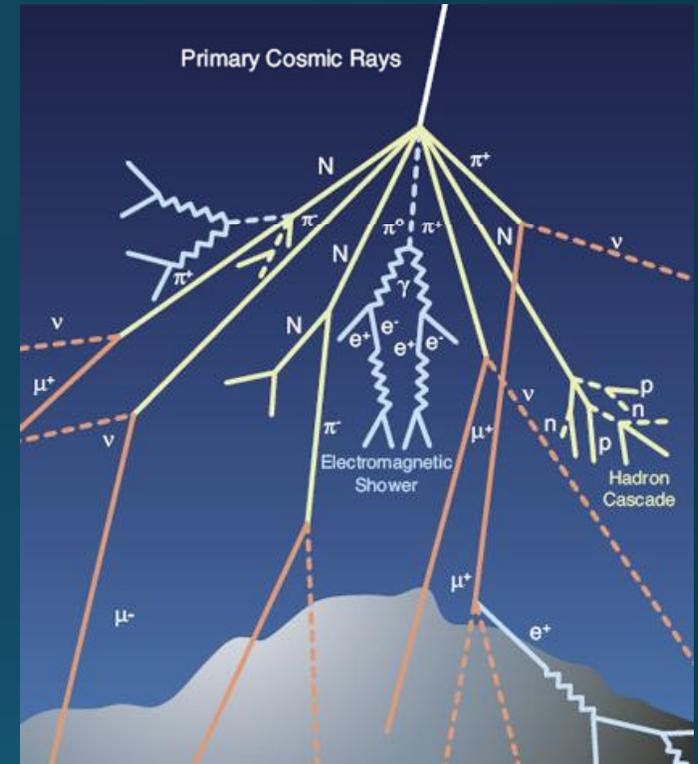


Image taken from our recent flight of the HELIX payload

But they carry the directional information of the original "primary" cosmic ray

# The Atmosphere is a high-energy laboratory

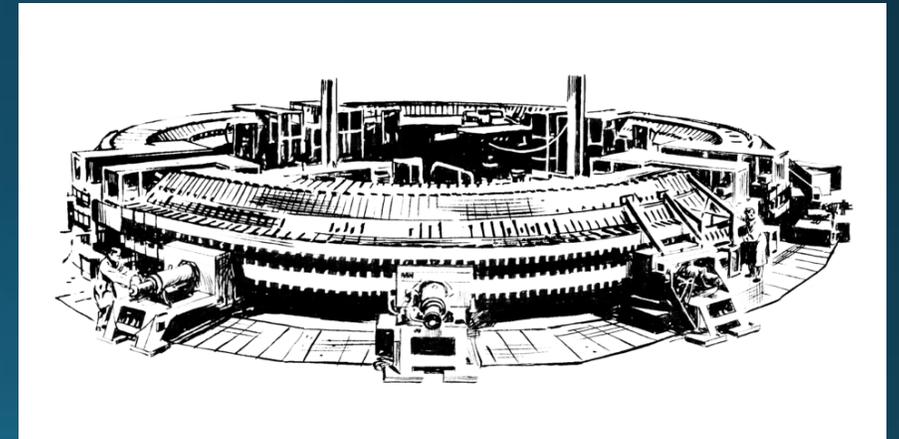
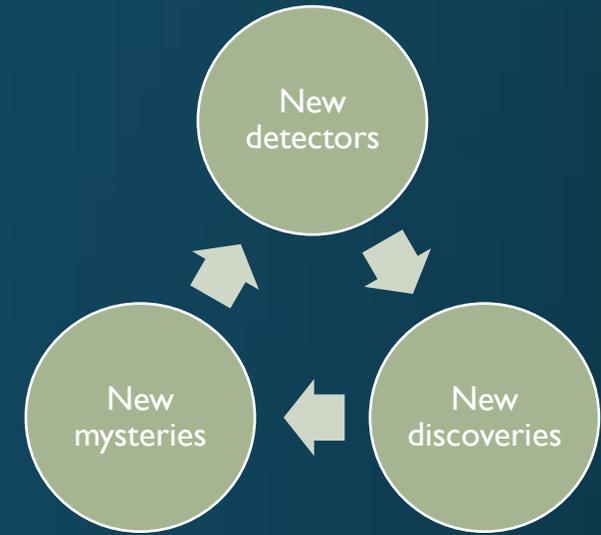
- Primary cosmic ray protons:
  - bombard the atmosphere
  - Deflect via magnetic field of the Earth
  - Give rise to many other kinds of particles
    - At lower energy
- A “zoo” of particles at sea level
  - Showers of particles



To understand cosmic rays, we need to understand particle physics

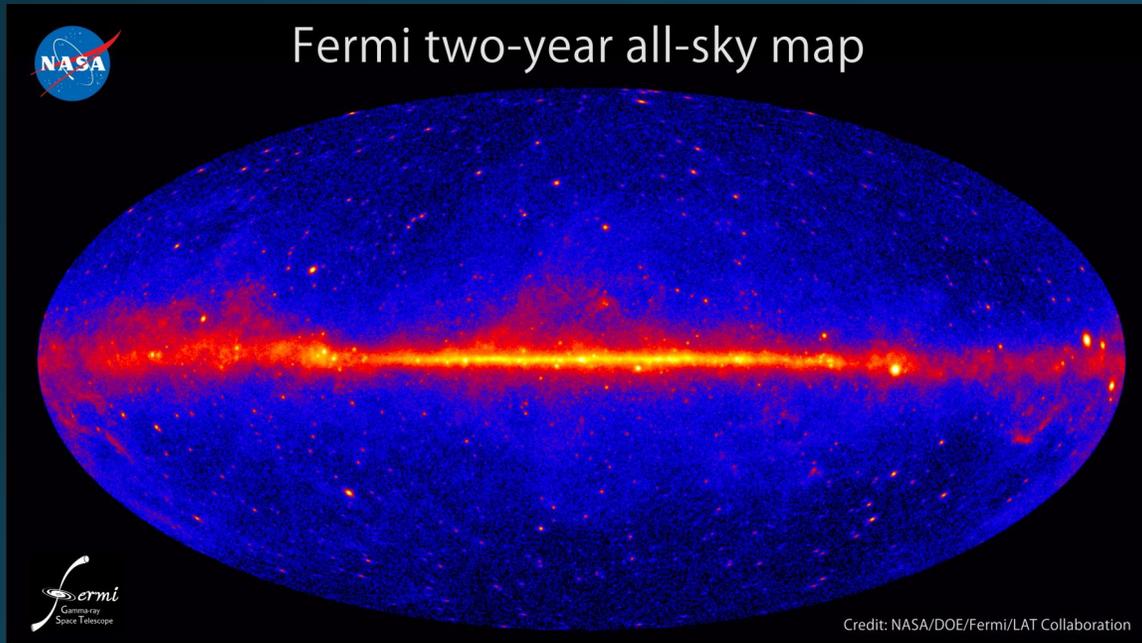
# Birth of particle physics!

- Incredible journey filled with curiosity, puzzles, drama
- Built colliders and detectors to study the high-energy particles
  - We learned to accelerate particles to higher energies than we naturally get at the surface.
  - Cosmotron-> could have been named Cosmic-ray-in-a-can
  - Also, BeV was used at one point in the US before GeV (too confusing with British “Billions”)
    - A million million



Cosmotron!

# So what really is the high-energy universe?



- A place where the nuclei of atoms are moving nearly at the speed of light!
  - 99.999 999 999 999 999 999 999 57%
- Interactions create many unstable particles all the time!
  - A sea of exotic nuclei and particles
- Light is essentially a bulldozing particle, blowing apart the nucleus of atoms it interacts with!
- The environments that produce this emission are extreme!
  - We will revisit this later

To see it we put on our high-energy particle lens

It is a violent and chaotic place...

# Cosmic Rays and Ballooning

- We still do ballooning
  - Helium gas now!
- University of Chicago has had ballooning groups since the beginning!
  - And a leader in the field!
- To learn more, we need to put detectors above the atmosphere
- But to interpret what we have measured, we need to run new controlled experiments!

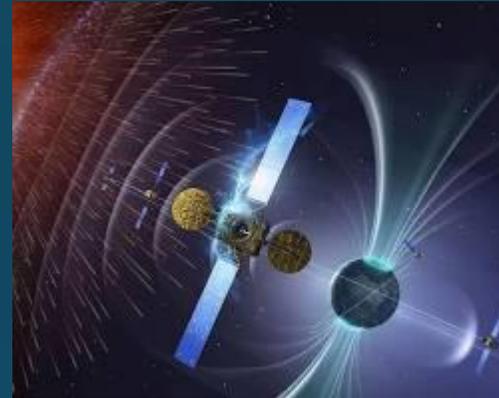


# The challenge of ballooning

- High altitude, essentially space!
- Cold and hot violent shifts
  - Electronics and detectors subjected to intense environments
- It's a dangerous place
- Not shielded from those highest of energy particles
- Recovery of instruments and data is also challenging
  - This is much easier than before!

I love it!

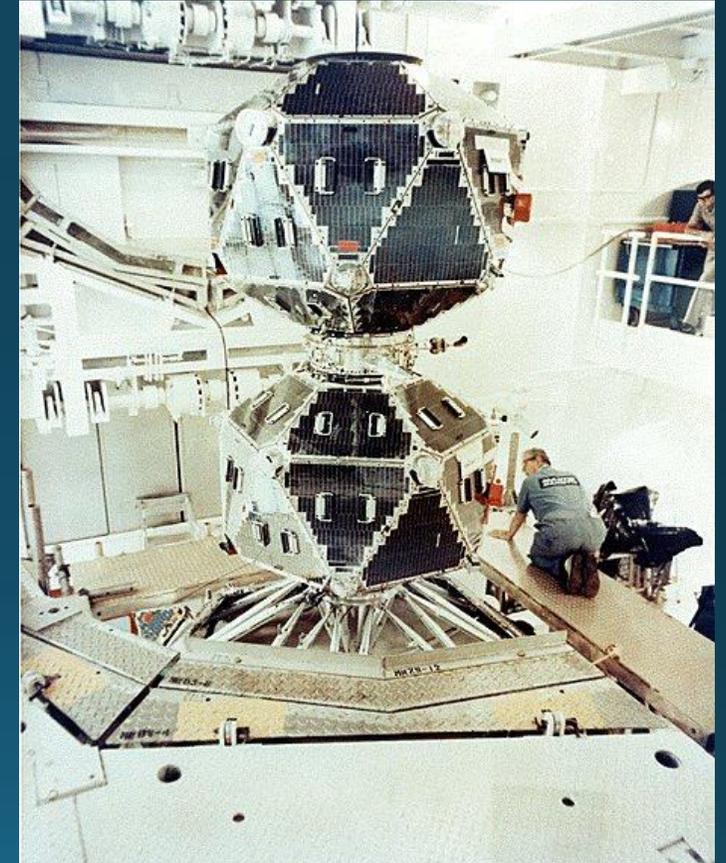
Recovery of HELIX, 2024



Recovery of PUEO, 2026

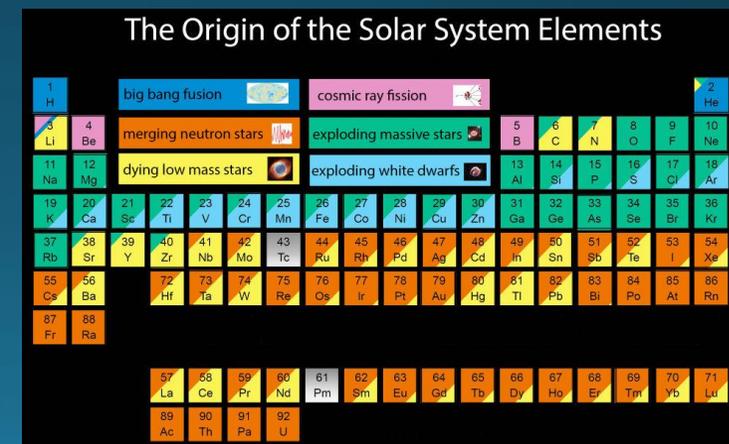
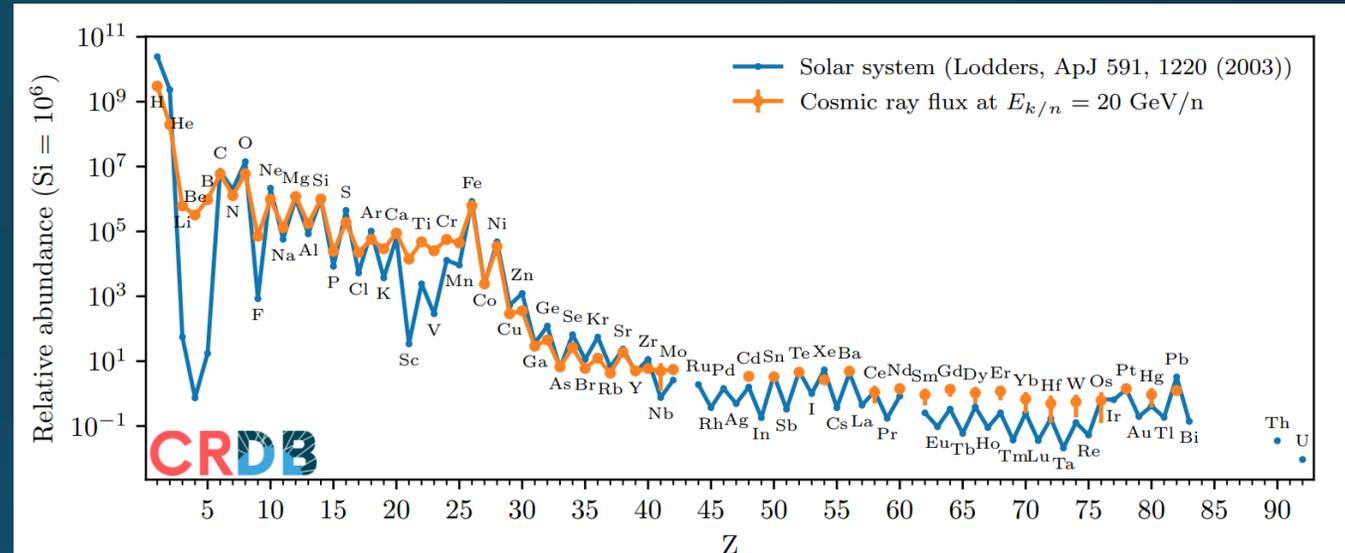
# Birth of Gamma Ray Astronomy!

- Incredible journey filled with curiosity, puzzles, drama
- Vela satellites searching for nuclear activity during the Cold War
- Discovery of Gamma Ray Bursts
  - GRBs



# We learned that cosmic rays are not just protons

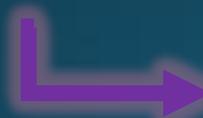
- Not just protons (Hydrogen)
- Many species of nuclei
  - Electrons removed!
- Interesting features
  - Compared to samples from meteorites
- Many balloon flights and space missions contributed to our understanding of cosmic rays

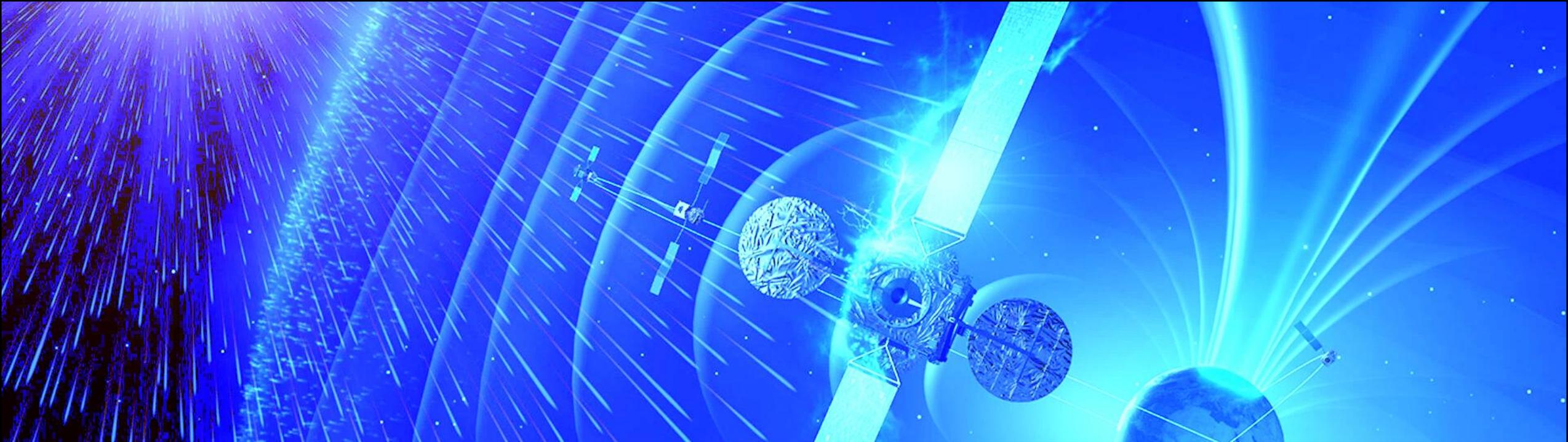


# This series will cover:

- Cosmic ray muons and how they probe dense objects
- Neutrinos and how they probe denser objects
- Cosmic ray air showers and how they may play a role in lightning
- Cosmic radiation impacting the origin and survival of life
- Cosmic ray isotopes that help us understand the Milky Way
- Cosmic rays-searching for water on the Moon (**Payton Linton**)
- The highest energy neutrinos to understand the most extreme environments



 **The astroparticles are there, just put on the lens**



# Thank you!