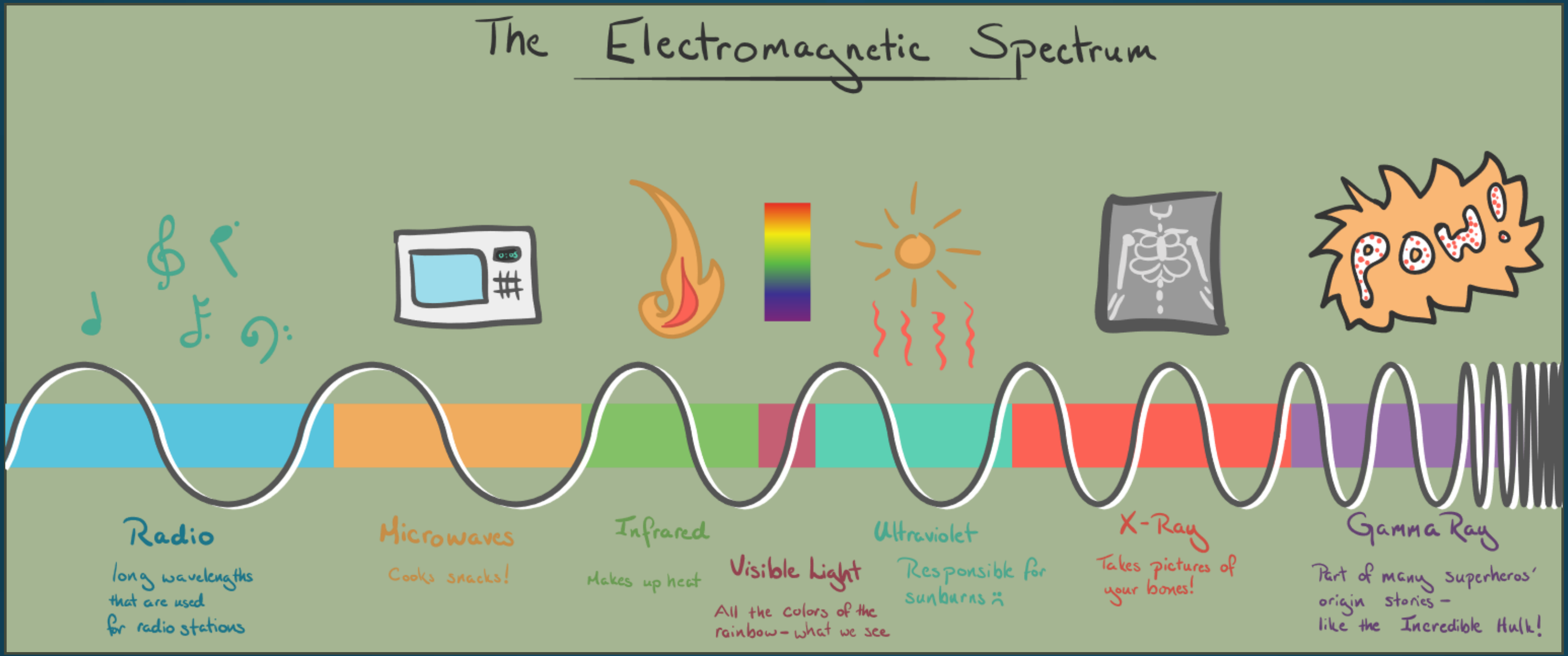
The Astroparticles Lens:

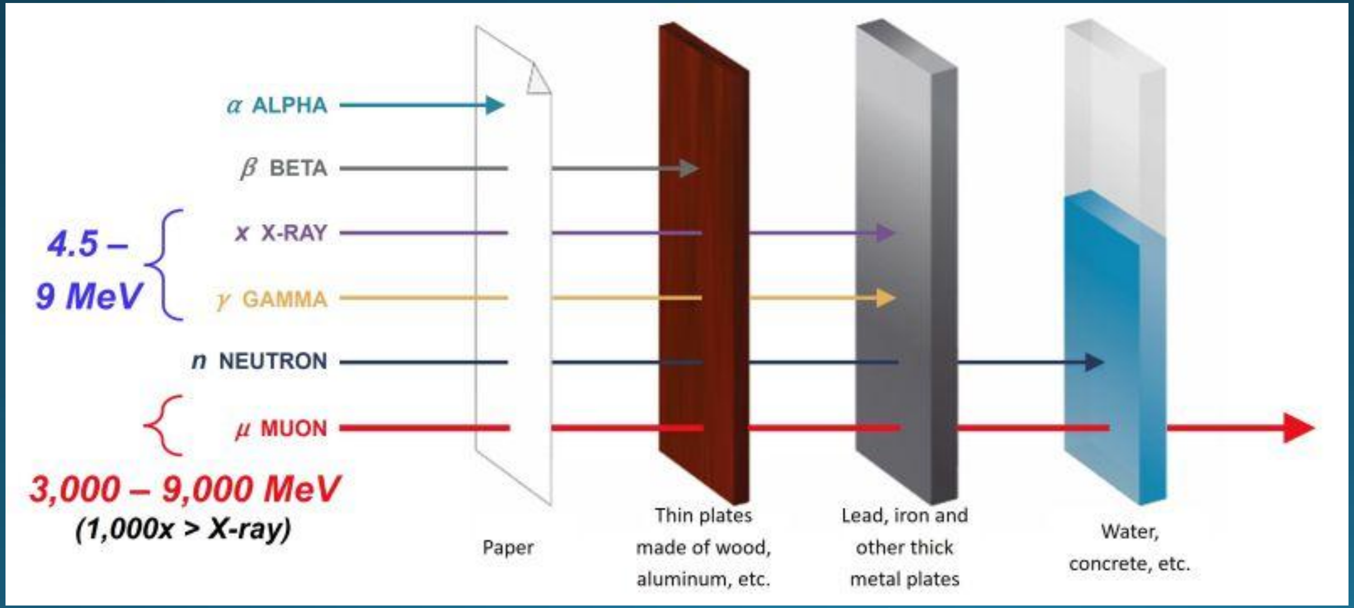
Using Particles From Space To Understand Our World

Cosmic Ray Air Showers and the Birth of Lightning

Keith McBride-Compton Lecture 4

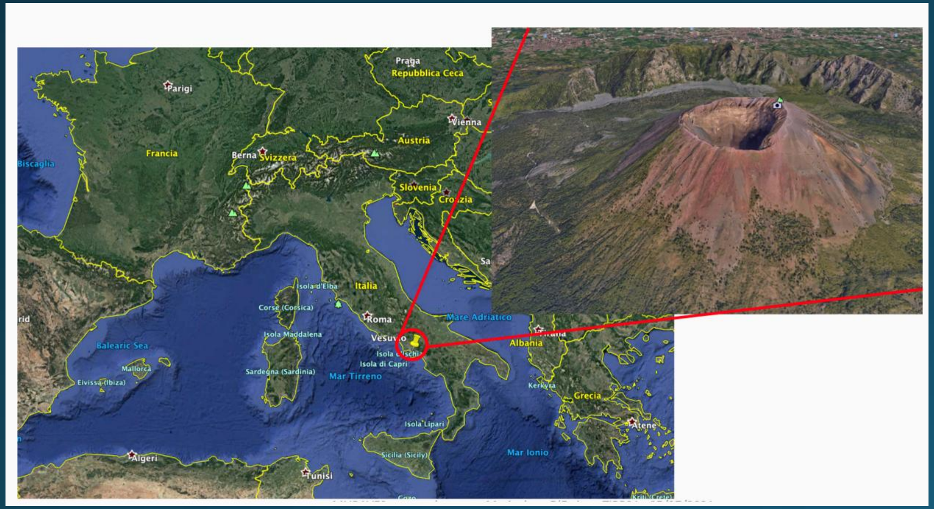
Radiation

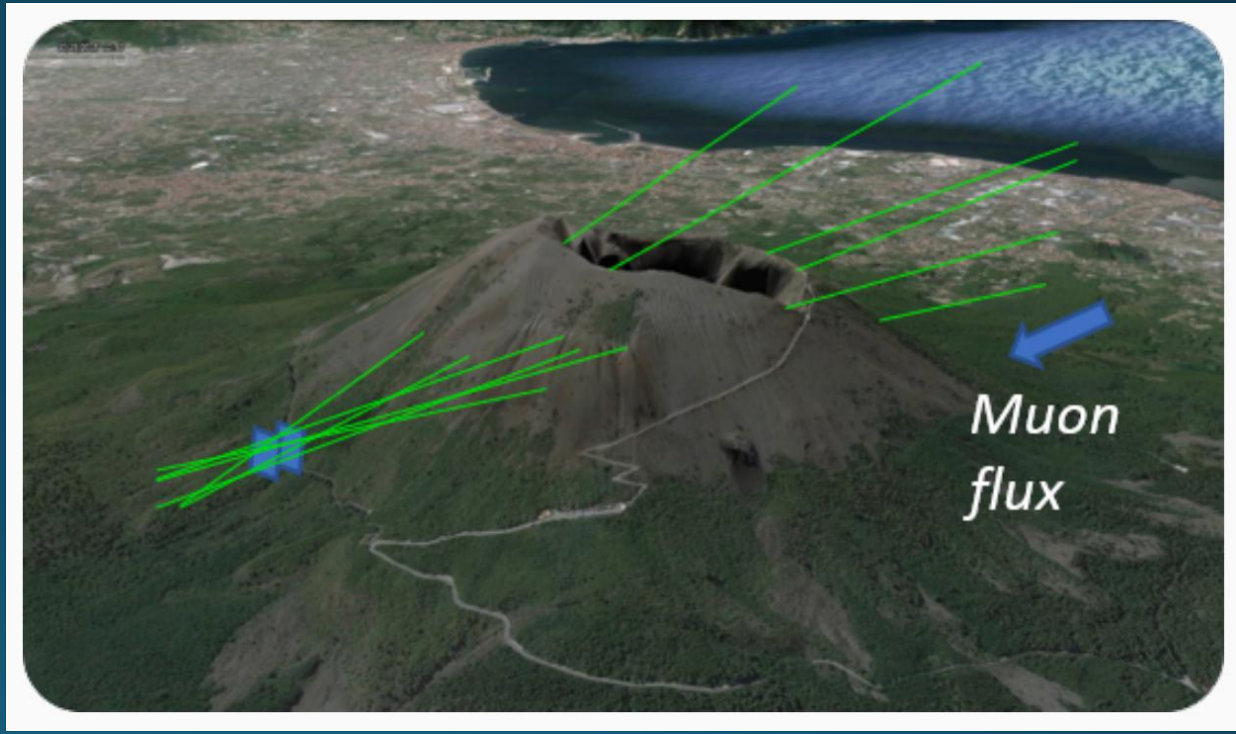

The Electromagnetic Spectrum
POW!
Radio
long wavelengths that are used for radio stations
Microwaves
Cooks snacks!
Infrared
Makes up heat
Visible Light
All the colors of the rainbow - what we see
Ultraviolet
Responsible for sunburns
X-Ray
Takes pictures of your bones!
Gamma Ray
Part of many superheros' origin stories - like the Incredible Hulk!


α ALPHA
β BETA
x X-RAY
γ GAMMA
n NEUTRON
μ MUON
4.5 – 9 MeV
3,000 – 9,000 MeV
(1,000x > X-ray)
Paper
Thin plates made of wood, aluminum, etc.
Lead, iron and other thick metal plates
Water, concrete, etc.

We can use cosmic rays muons to see through volcanoes

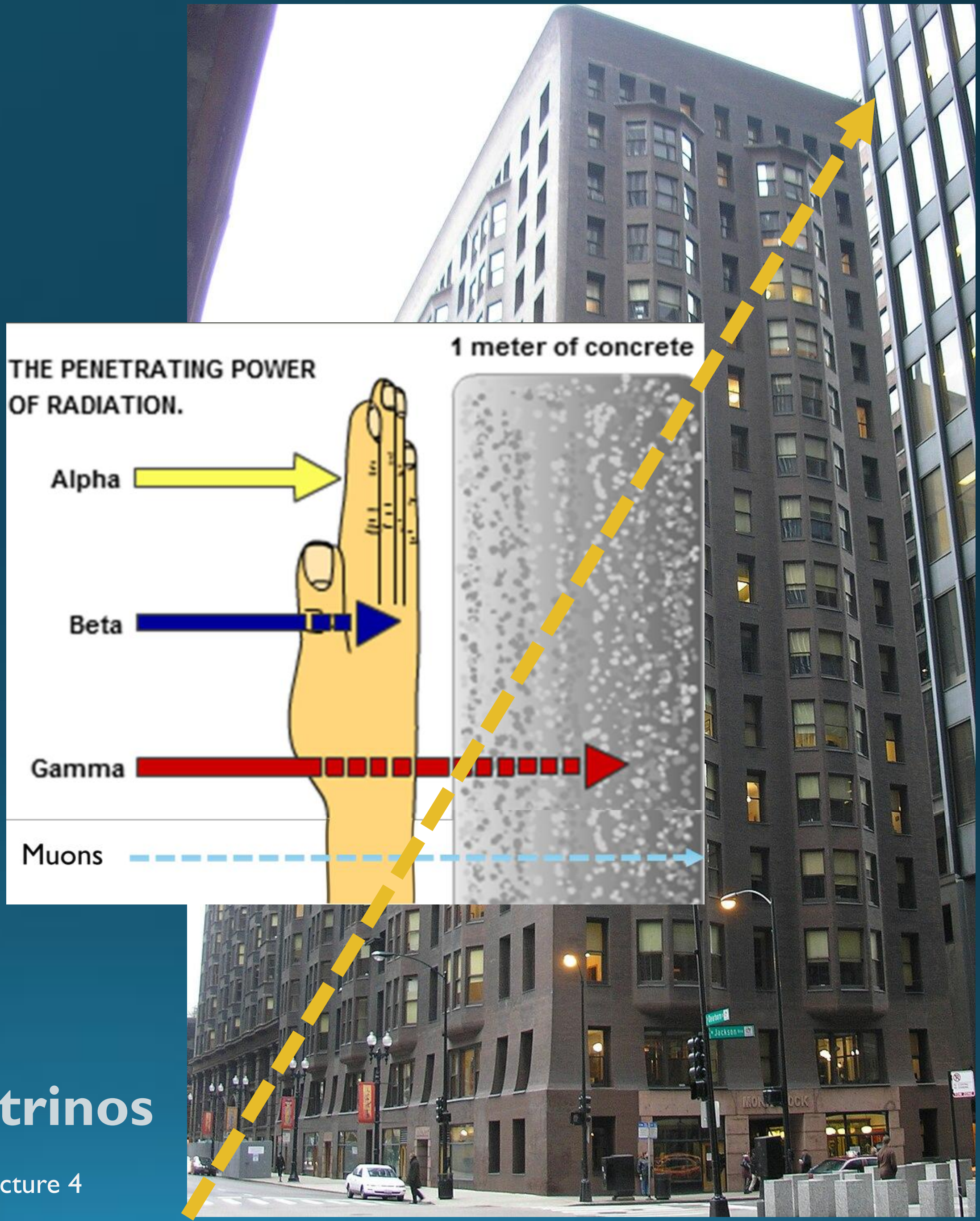
Mu-Ray project





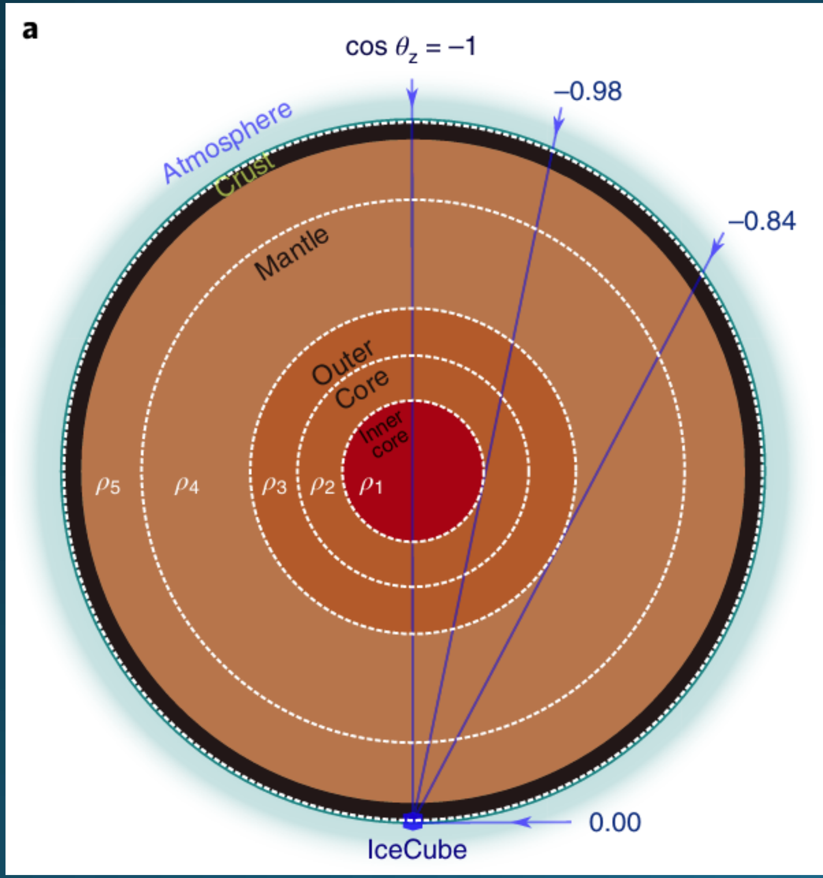
Even more penetrating particles

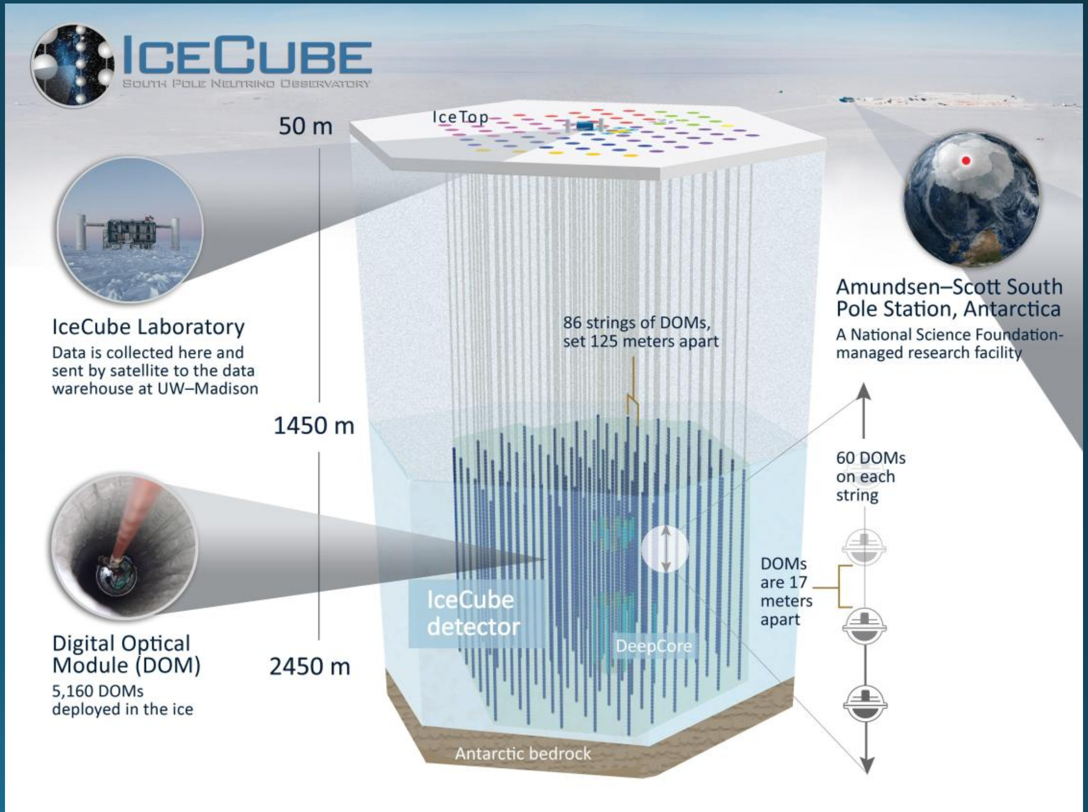
- Get rid of the electromagnetic force from the muon
  - Just have the weak force left!
- Neutrinos go through kilometers of rock
  - This is why it's called the weak force
- Need large detectors to measure their rare interactions

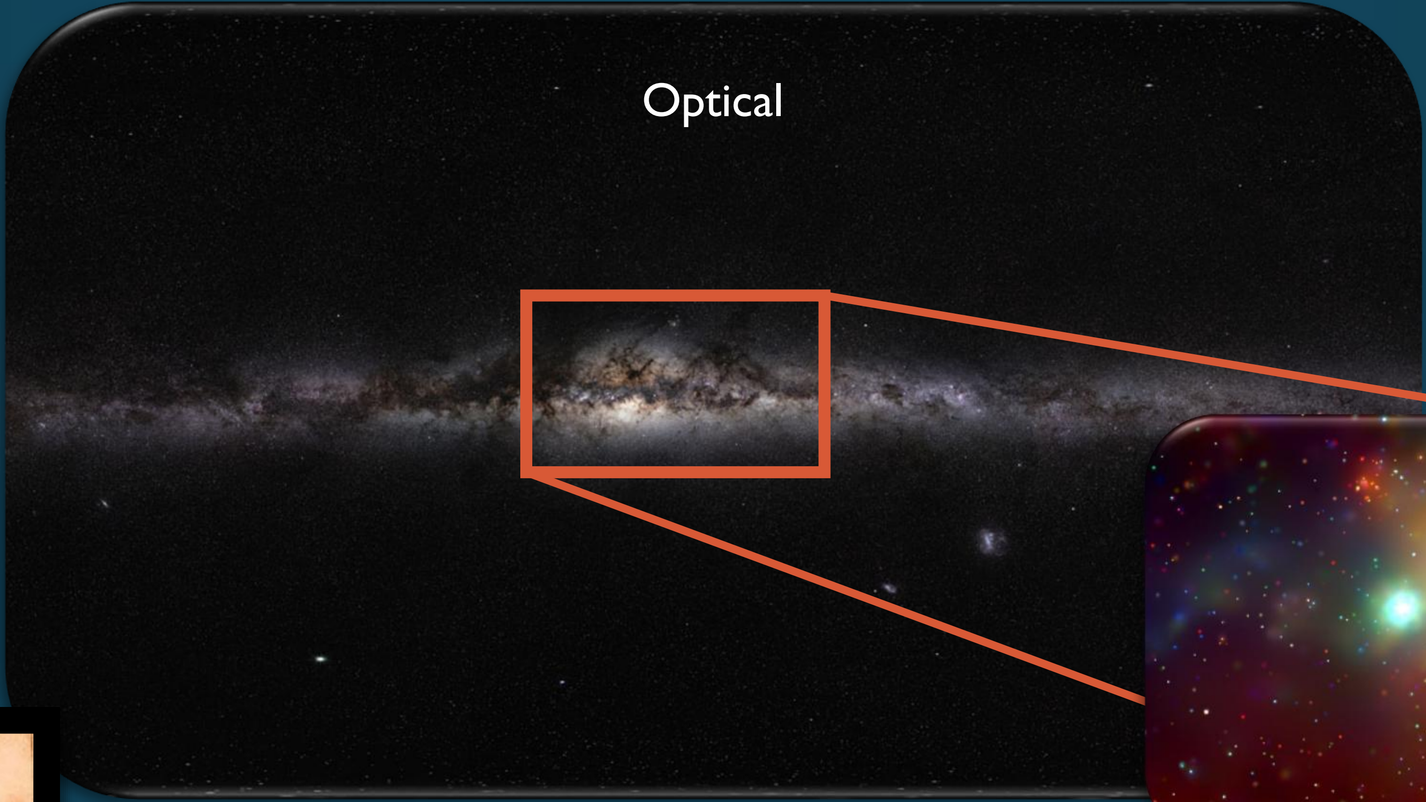


Neutrinos

We can use cosmic rays neutrinos to see through the Earth







Gas in the center is Millions of degrees!

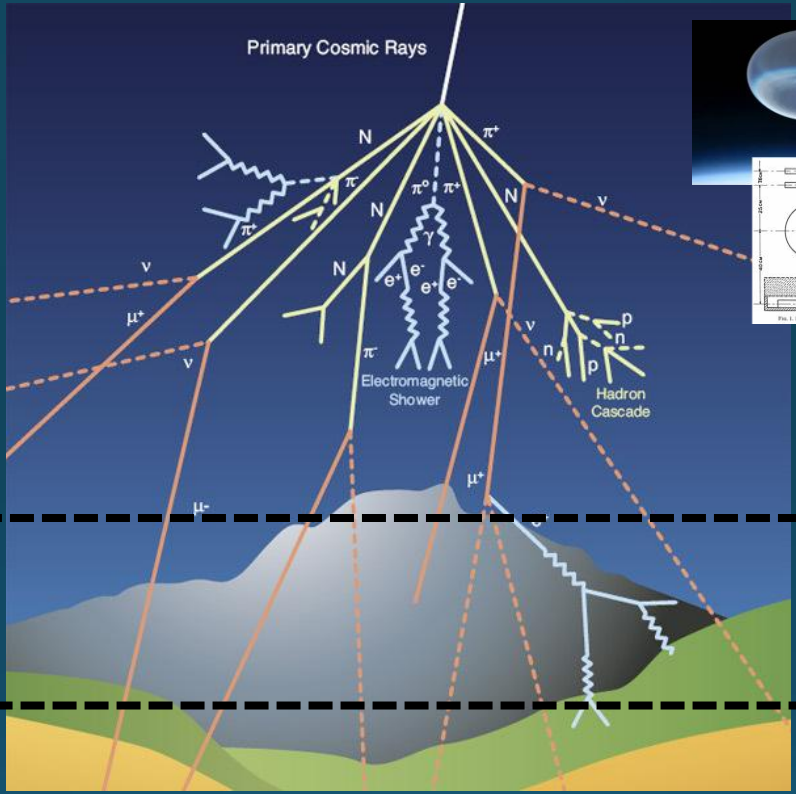
X-Ray

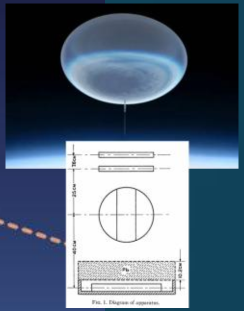
With a different type of lens, you can:

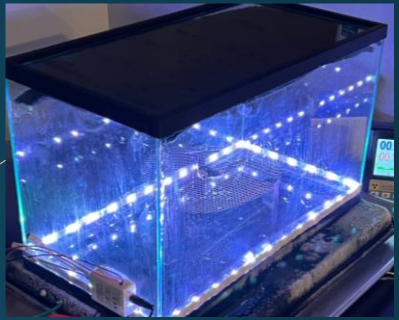
1. See through opaque objects

Cosmic ray muon lens
Cosmic ray neutrino lens

We get these particles (cosmic ray muons and neutrinos) from showers







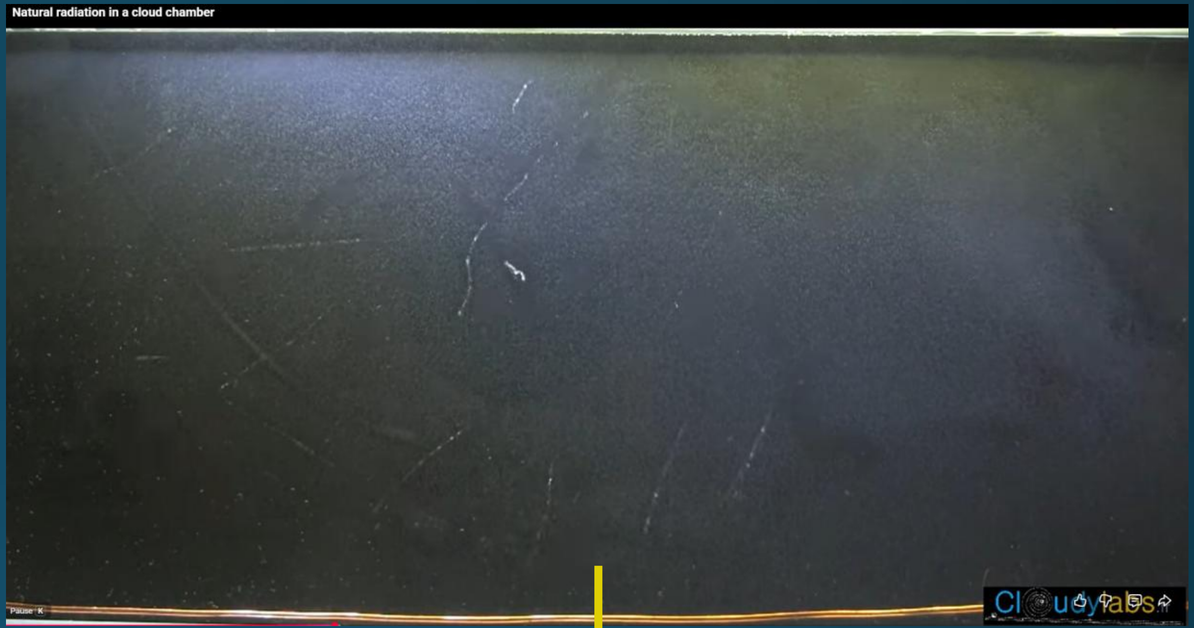
1. Cosmic ray particles from across the universe
2. With enough energy to break apart nucleus of the atoms in air molecules

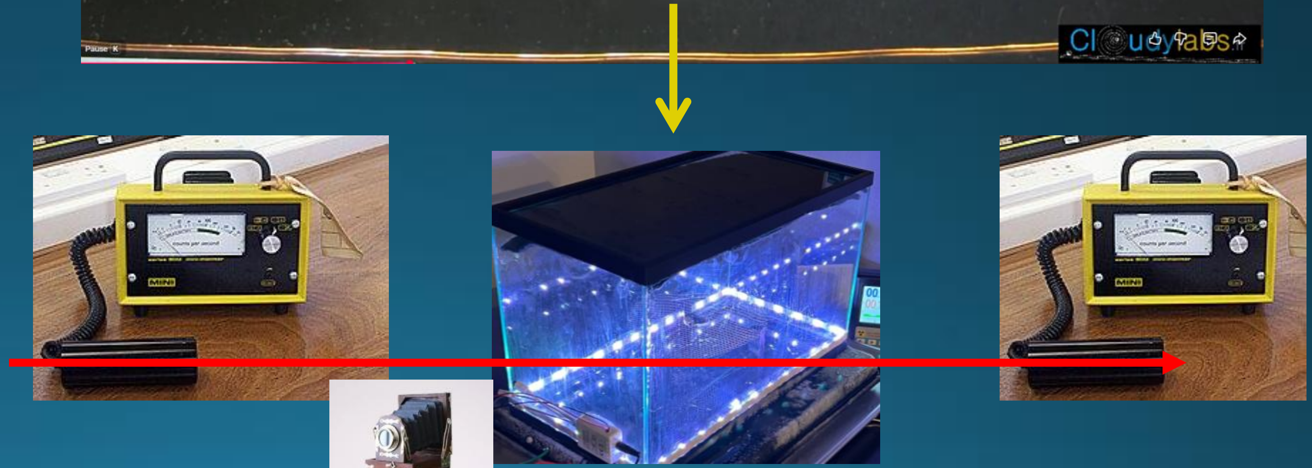
3. Higher energy particles at higher altitudes (ascend in balloons)

Cloud chambers and counters

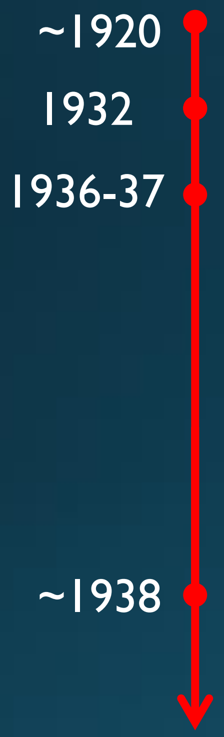
~1930's

- 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!





Cosmic ray showers in the 1930s



- The cloud chamber showed us:
  - Electron "showers"
  - Muons are particles that go through more material without creating showers
- Bhaba and Heitler:
  - Developed new theory of cascades
    - Electrons Bremsstrahlung
    - Gamma rays pair produce

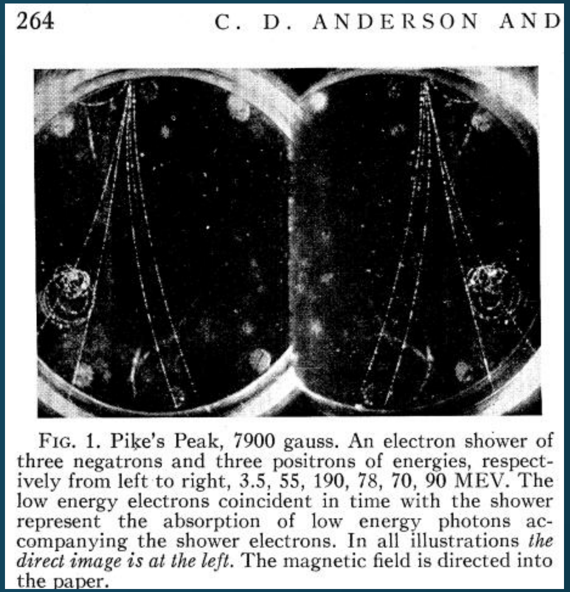

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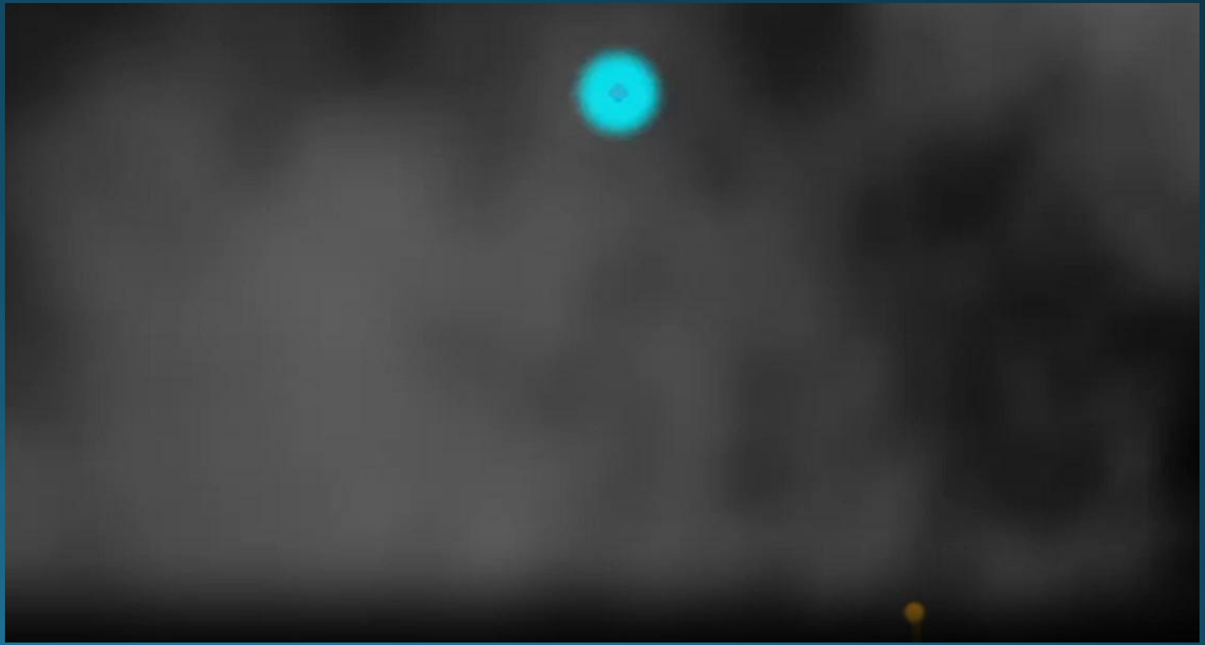
FIG. 1. Pike's Peak, 7900 gauss. An electron shower of three negatrons and three positrons of energies, respectively from left to right, 3.5, 55, 190, 78, 70, 90 MEV. The low energy electrons coincident in time with the shower represent the absorption of low energy photons accompanying the shower electrons.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



Showers of electrons

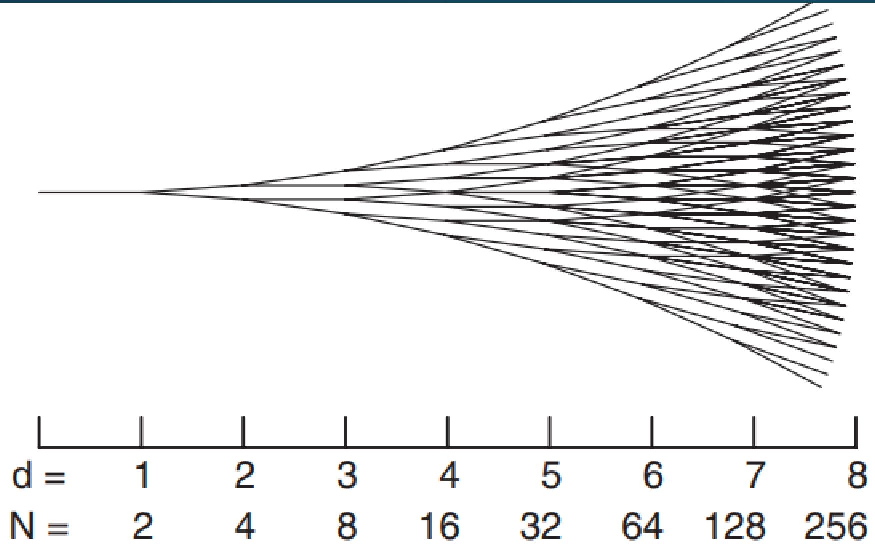


FIG. 2. Heitler's schematic evolution of an electromagnetic cascade. At each stage of the cascade the number of particle is multiplied by two, through either pair creation or single photon bremsstrahlung. The evolution stops when individual particle energy fall below the critical energy, about 80 MeV in air.

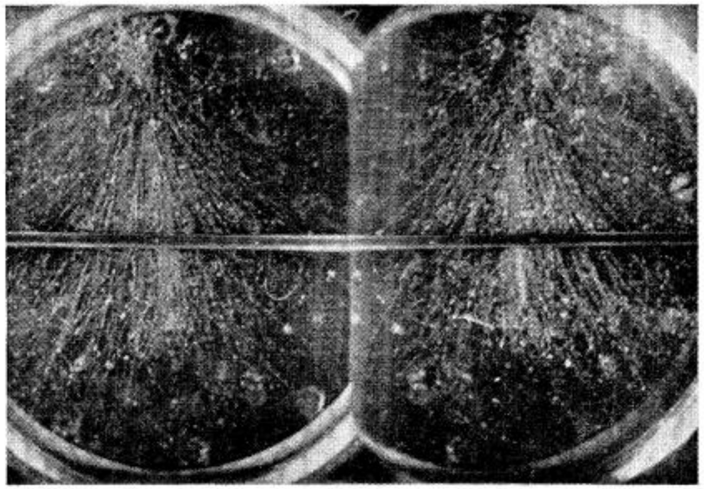
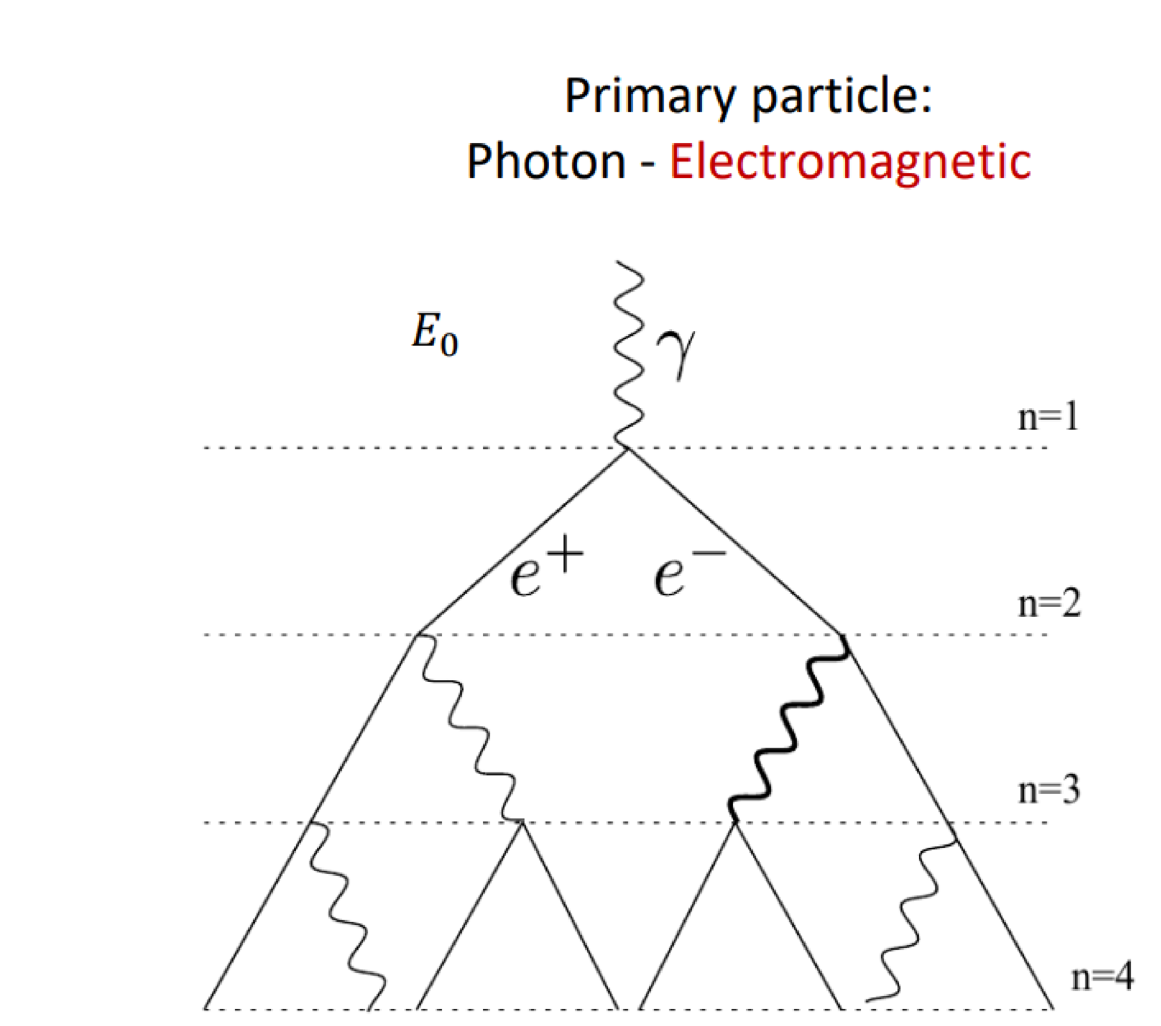


FIG. 5. Pike's Peak, 7900 gauss. A shower of a large number of electrons. The electrons in this shower were not counted, but estimates show that more than 300 are probably present. The summed energy probably exceeds 15,000 MEV.

Cascades

- A high enough energy photon i.e. gamma ray
- Pair production
- Electrons and positrons emit gamma rays from bremsstrahlung
- Those gamma rays also pair produce
  - cascade



Auger- 1938

- The coincident method was critical
- Place Geiger-Muller counters at different distances apart
- Over large distances, multiple counters fired within a small time window
  - Not one particle, but many particles coincidentally
- Deviates from the accidental rate expected

300 meters
~1,000 ft

JULY-OCTOBER, 1939 REVIEWS OF MODERN PHYSICS VOLUME 11

Extensive Cosmic-Ray Showers

PIERRE AUGER
In collaboration with
P. EHRENFEST, R. MAZE, J. DAUDIN, ROBLEY, A. FRÉON
Paris, France

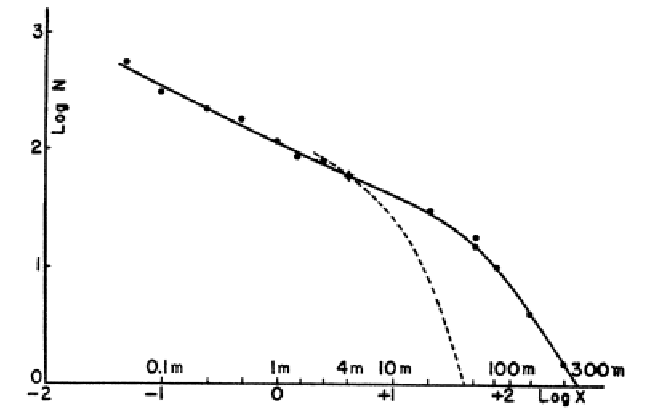


FIG. 1. Results with two parallel and horizontal counters.

Auger- The Grandes Gerbes

- "Large" detectors at high altitudes
  - 200 square cm
  - 3.5km in altitude
- The number of particles gave an estimated energy
  - Counted the number of particles
  - ~1 million particles
- 1 Peta electron volt energy
  - Neutrinos we discussed last week had about this much energy
- Before this, 10 GeV was the normal
  - 100,00 times the energy

CONCLUSION

One of the consequences of the extension of the energy spectrum of cosmic rays up to 10^{15} ev is that it is actually impossible to imagine a single process able to give to a particle such an energy. It seems much more likely that the charged particles which constitute the primary cosmic radiation acquire their energy along electric fields of a very great extension.

*Unknown what kind of particle the primary was.

Different energy scales for the cosmic rays

In 1 year:

Photon – the speed of light

1 light-year

Proton – 86% the speed of light (E = 2 GeV)

0.86 light-years

Proton – E = 1,000 GeV or 1 TeV

~1 light-year (4000km shorter)

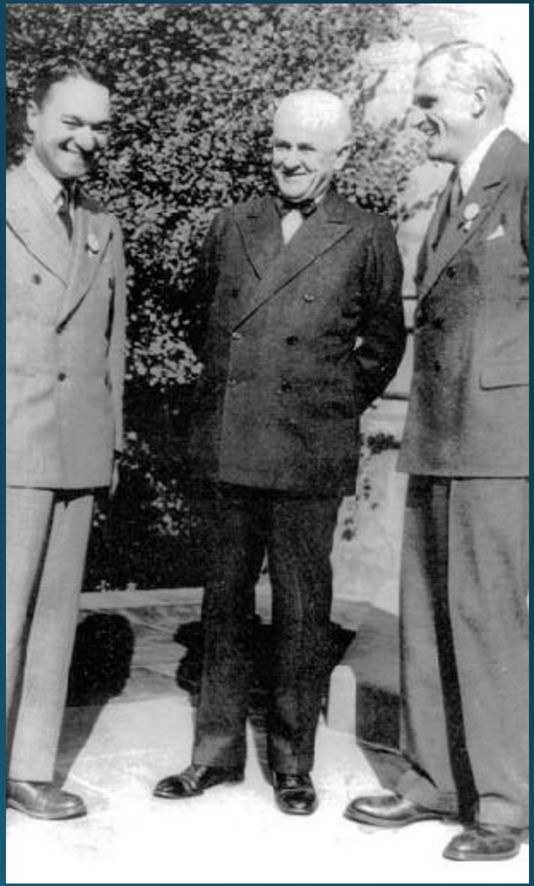
- 1 billionth of a light year shorter

Proton – E = 1,000,000 GeV or 1 PeV

~1 light-year (4 m shorter)

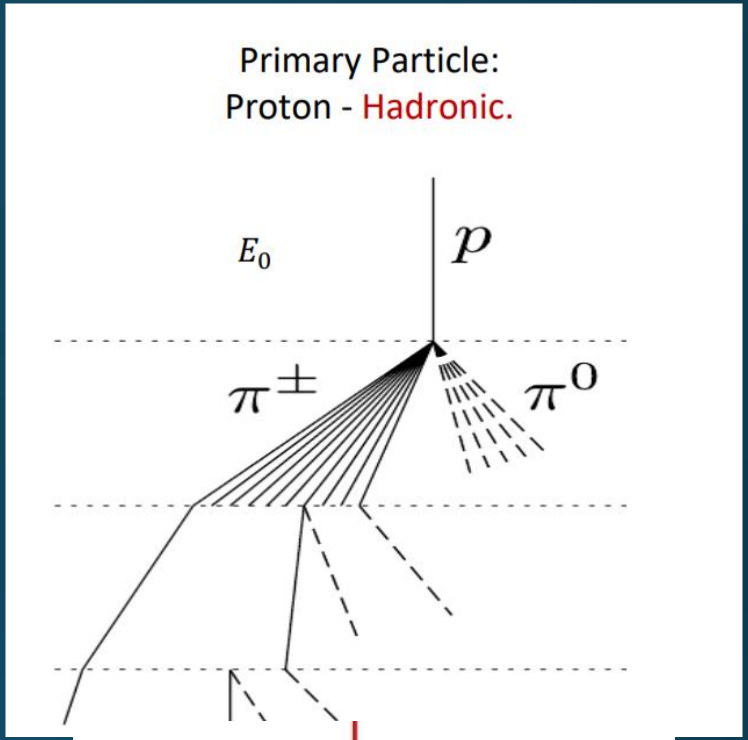
Bruno Rossi

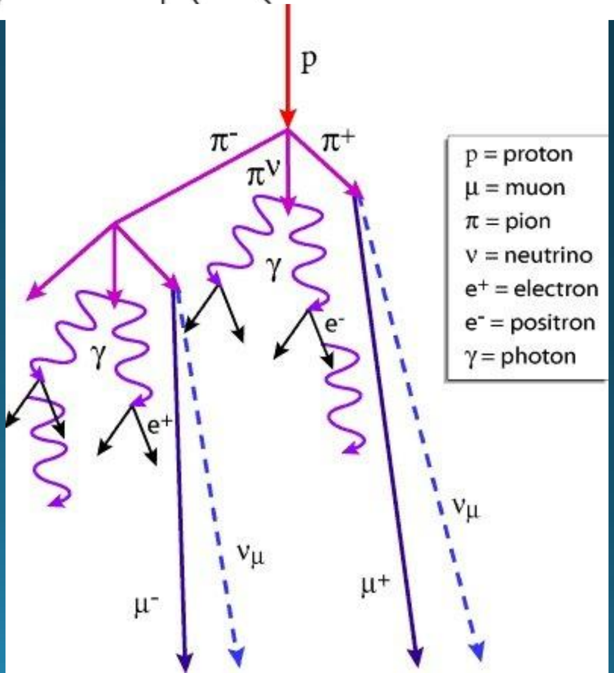
- Played a huge role in 1930s for cosmic ray experiments, including the coincidence methods
  - Invitation in 1938 from Arthur Compton to UChicago
- At a much older age, Rossi reflected on the experiments performed in the 1930's:
  - Simple experiments
  - Startling results
    - So it was hard to get them published



Cosmic ray air showers

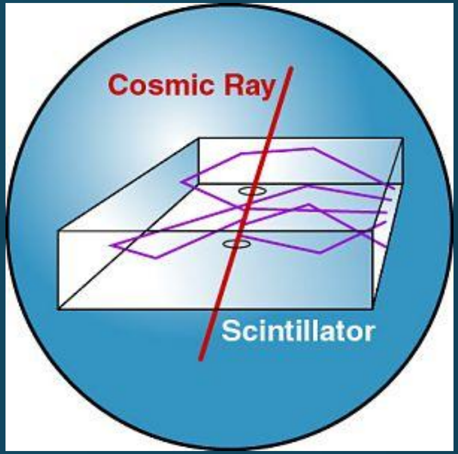
- Pions discovered
  - And Kaons
    - Strange particles
- A very high energy cosmic-ray proton interaction produces showers of particles
  - Each generation has lower energy
  - Pions
  - Muons
  - Electrons and positrons
  - Neutrinos (ignore these this lecture)

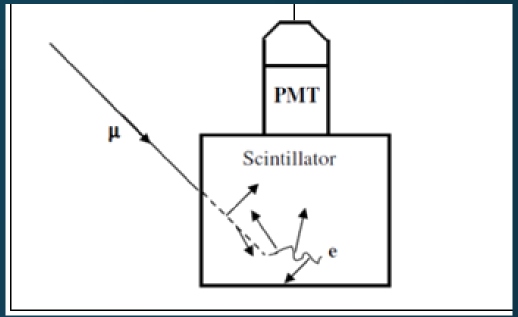


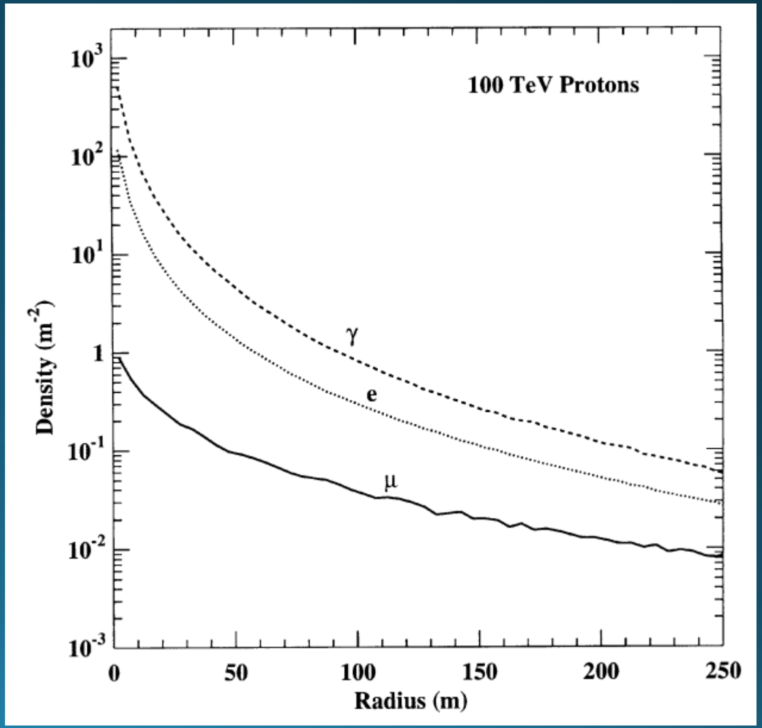


Rossi's research on showers

- Rossi developed a research program on arrays of shower detectors in 1950s
- Deployed at Oak Ridge Observatory
- 11 scintillators spread out
  - Measured cosmic rays from 10 to 1,000 PeV
  - It seemed that nature could produce energetic particles with no limit!
- Measured the density of particles directly
  - Instead of just counting the hits in tubes
  - More particles in an area, higher energy of primary particle/cosmic ray

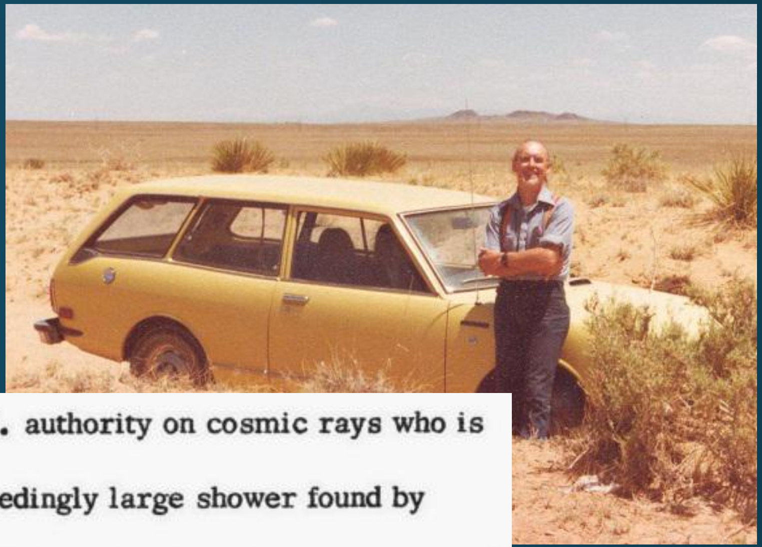




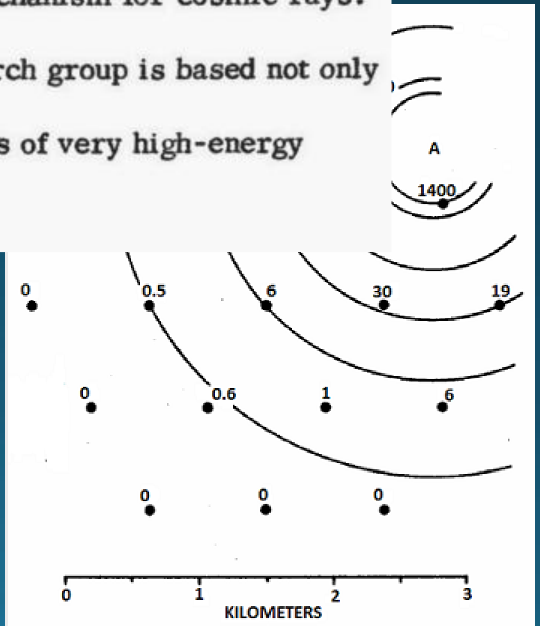


Volcano Ranch

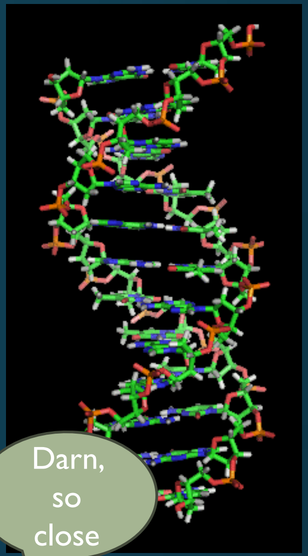
- Nearly 30 years separated Auger's measurements and Volcano Ranch
- John Linsley wa group
- Utilized the ide
    - Deployed in
- 19 detectors s ~850m spacing
    - Walk from here to the Midway skating rink
- ~8 km2 area
- Measured cosmic ray with energy 10^{20} eV



Dr. Bruno Rossi, internationally-known M.I.T. authority on cosmic rays who is vacationing in Italy, cabled this statement: "The exceedingly large shower found by Linsley and Scarsi confirms the extragalactic acceleration mechanism for cosmic rays." In offering a new explanation, the opinion of the M.I.T. research group is based not only on the super shower but also on a series of recent observations of very high-energy showers.



Different energy scales for the cosmic



In 1 year:

Photon – the speed of light

1 light-year

Proton – 86% the speed of light (E = 2 GeV)

0.86 light-year

Darn, so close

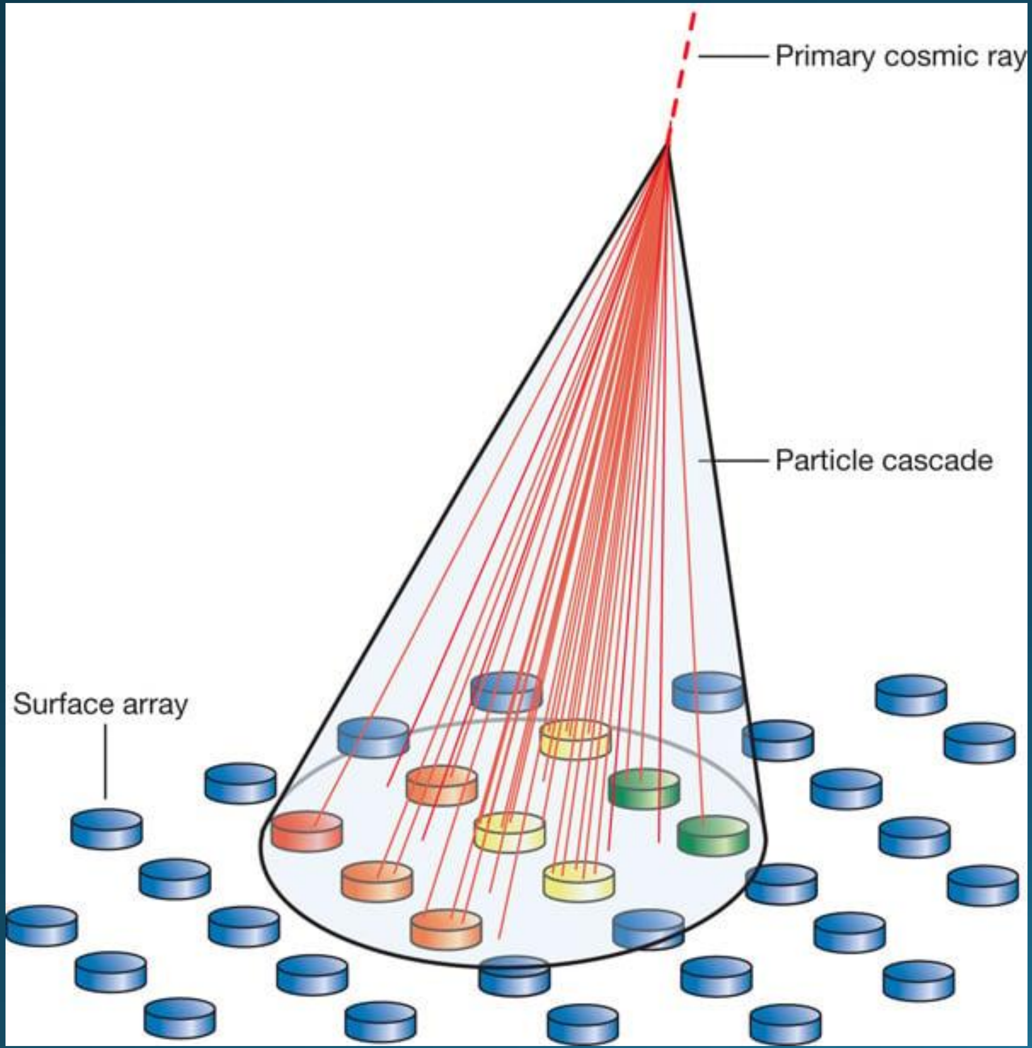
Proton – E = 1,000,000 GeV or 1 PeV

~1 light-year (4 m behind)

Proton – E = 100,000 PeV or 100 EeV

~1 light-year (40 nm behind)

Cosmic ray air showers-in summary



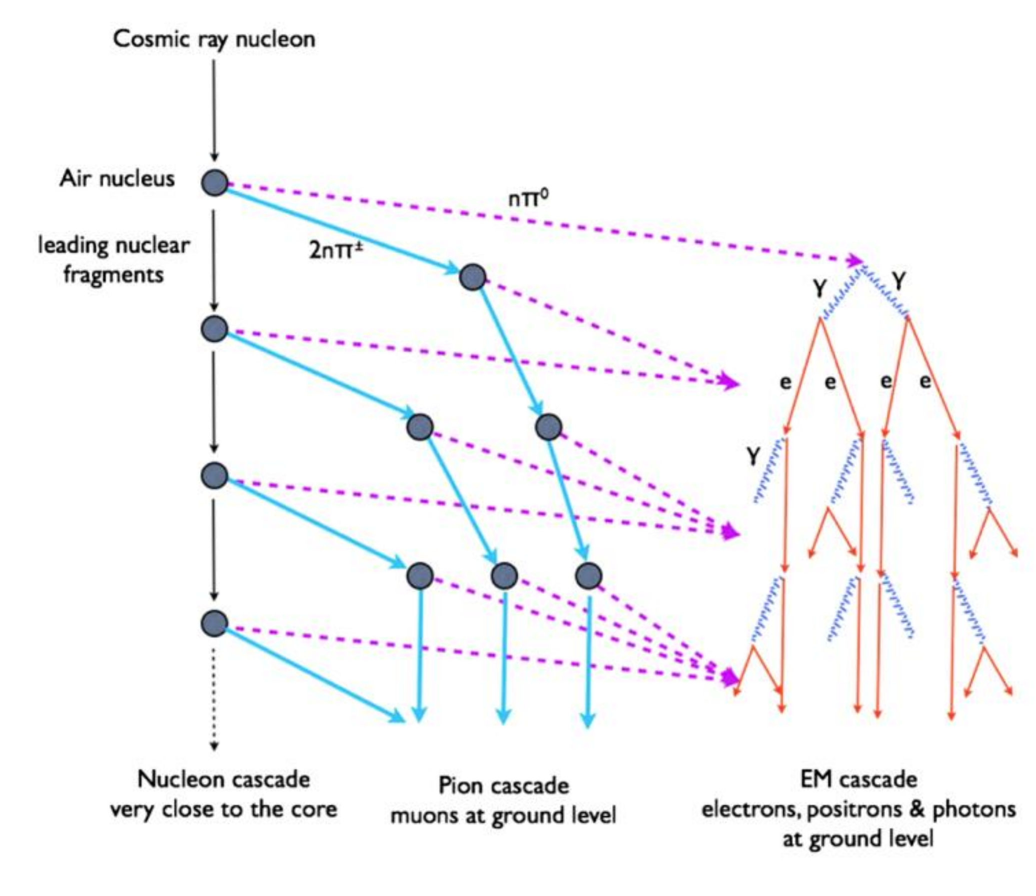
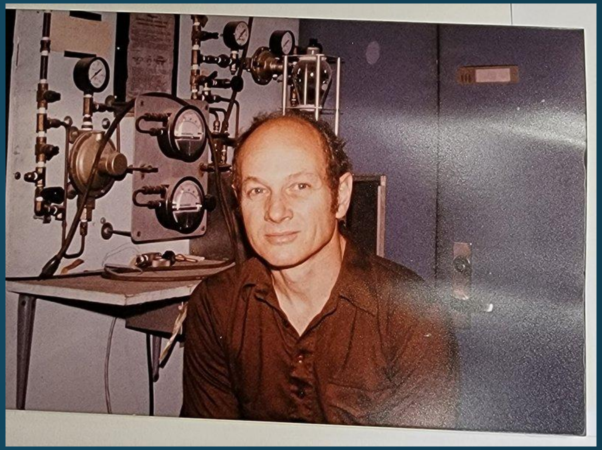
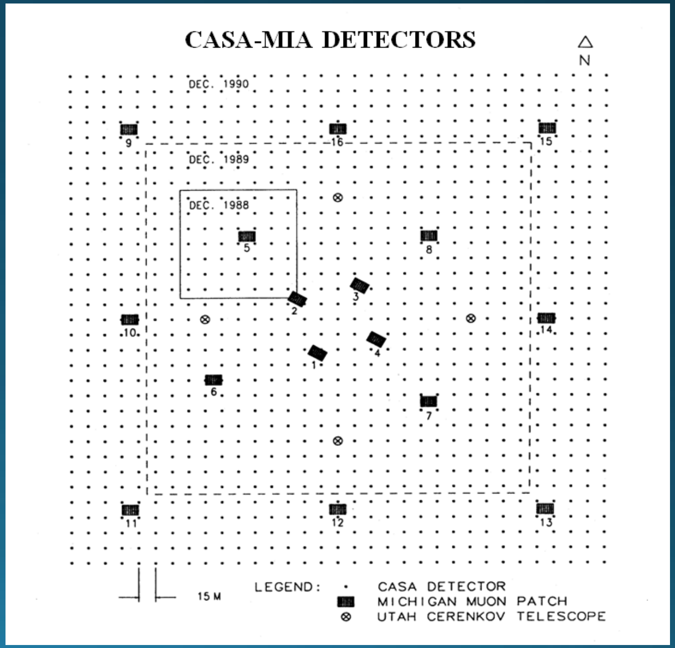


FIG. 3 (color online). Schematic evolution of an hadronic cascade. At each step roughly 1/3 of the energy is transferred from the hadronic cascade to the electromagnetic one.

CASA-Chicago Air Shower Array

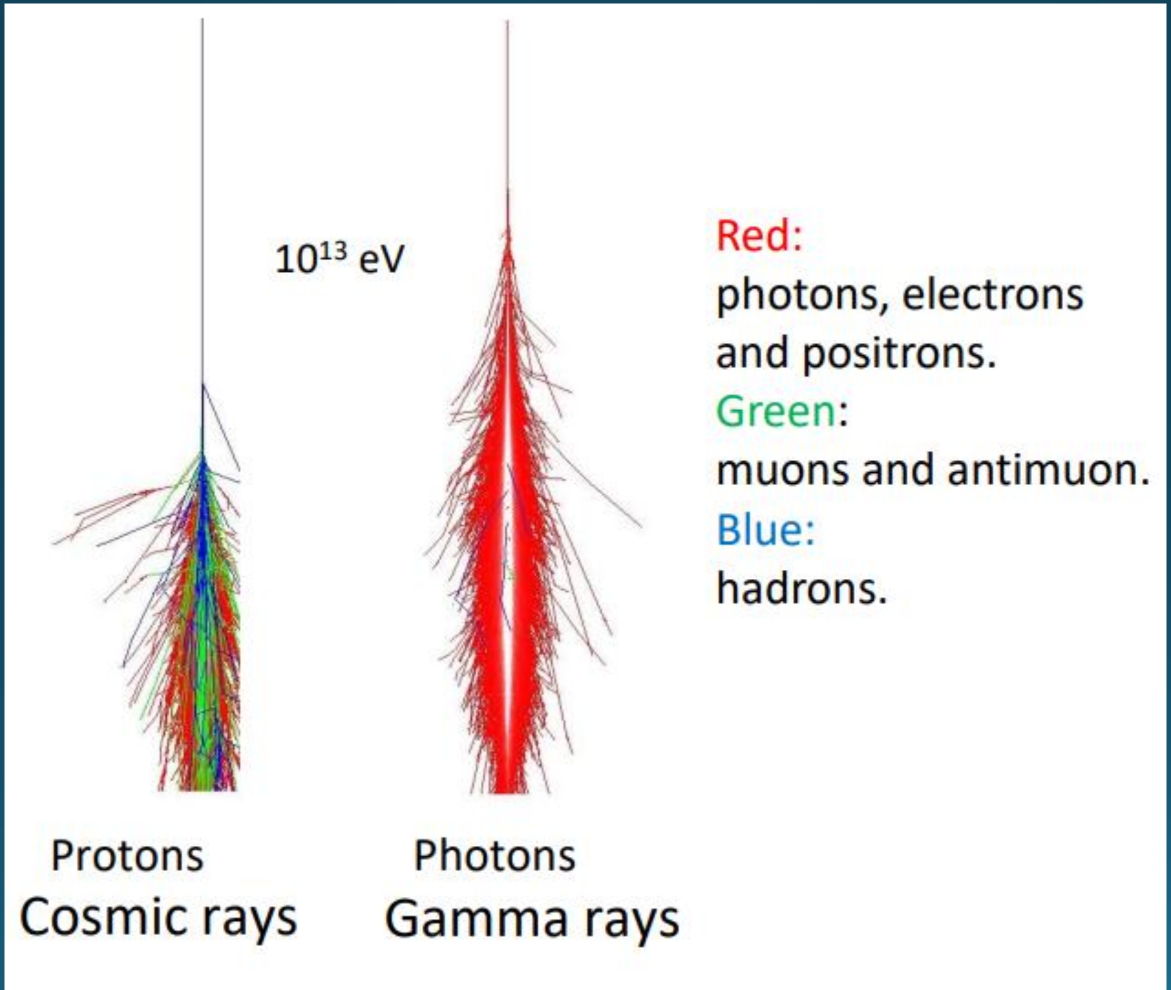


- Professor Cronin's group at UChicago
  - Nobel prize in 1980 (CP violation)
- New surface array of 1089 detectors
- With an underground array of muon detectors
  - ~3 meters below surface
  - Michigan Muon Array
- Separate gamma ray showers and cosmic ray showers
  - 100TeV to 10 PeV range
  - A lot of scientific contributions in gamma rays and cosmic rays



Cosmic ray vs Gamma ray showers

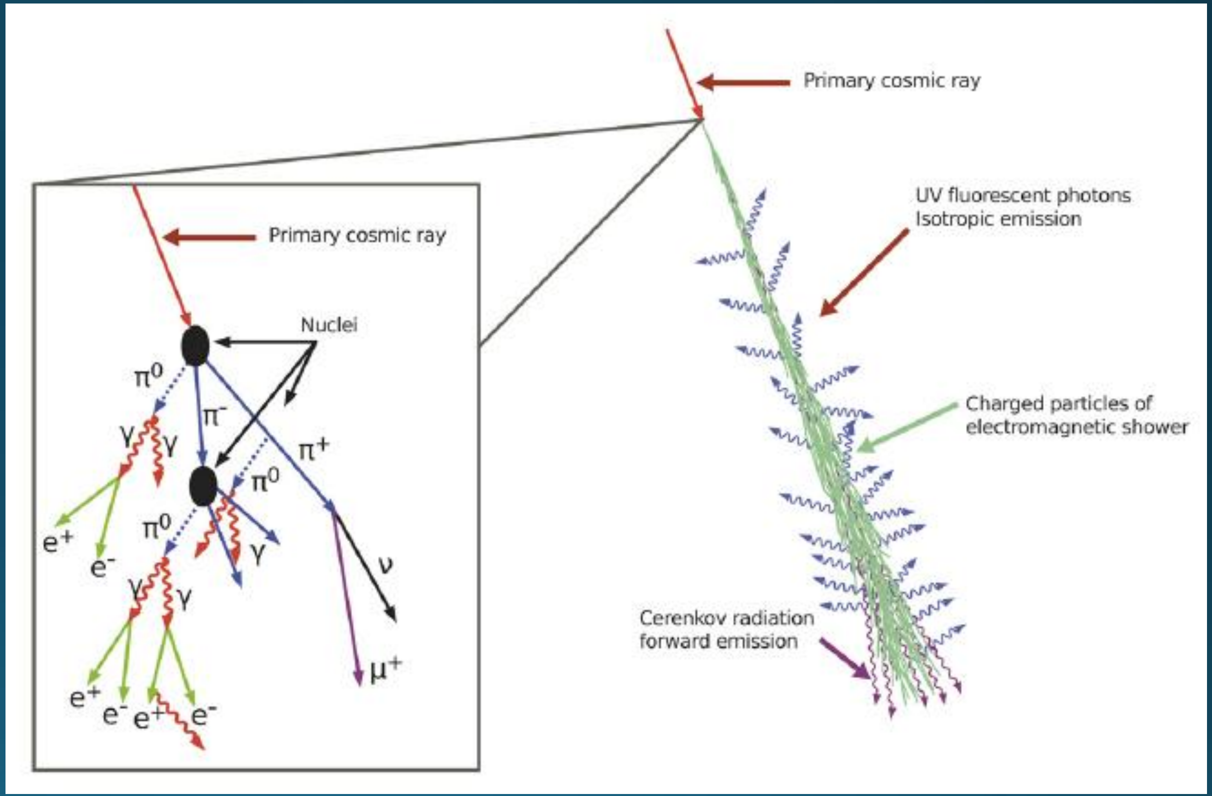
1. No pions in gamma ray showers (electromagnetic)
2. So measuring muon showers guarantees cosmic ray compared to gamma ray



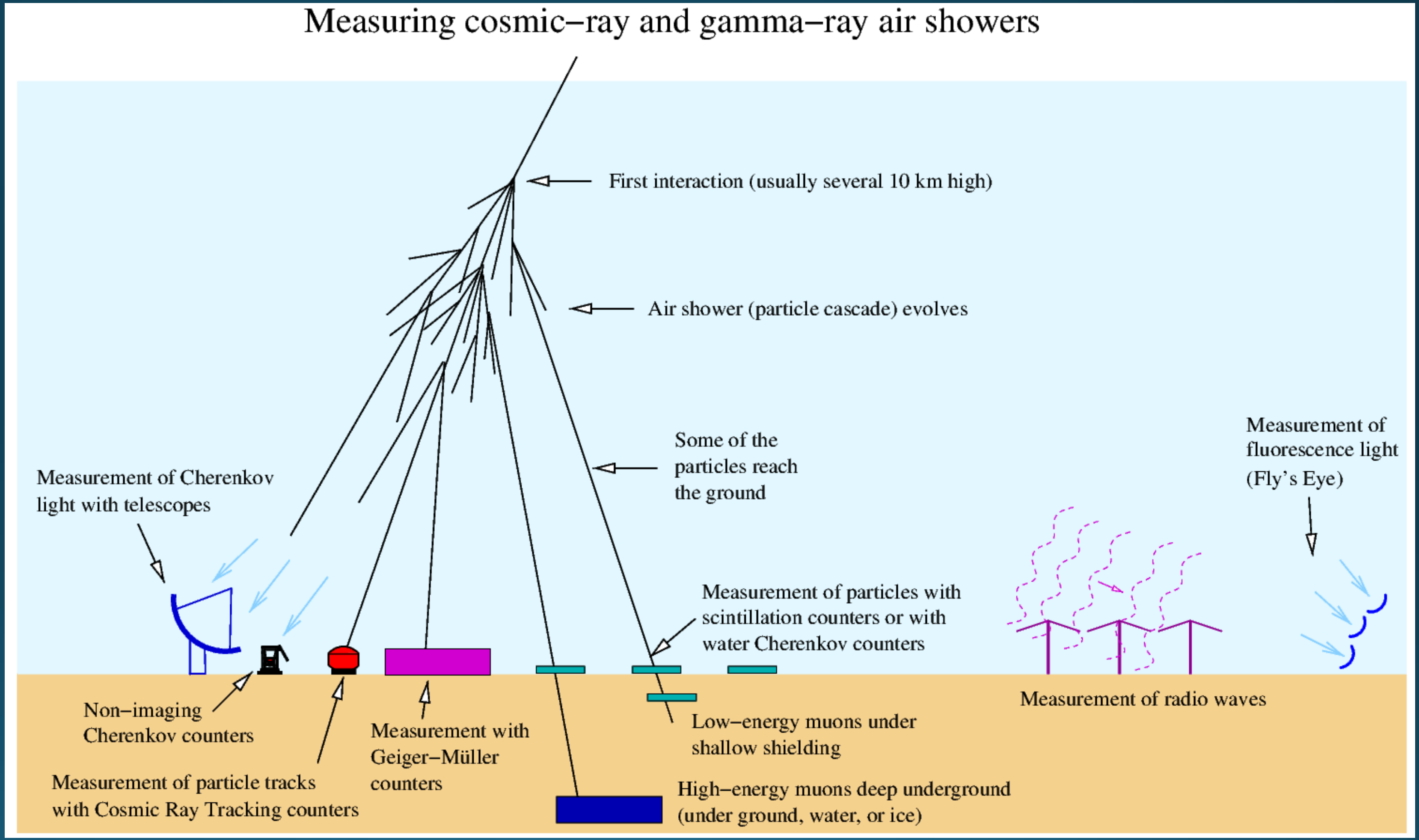

science @ NASA
Artist Rendering

The particle zoo (and detector zoo)

- Fluorescent light too
  - Fluorescent light in the atmosphere by ionizing and exciting nitrogen molecules.
- Cherenkov light
  - Charged particles in the cosmic ray shower move faster than light (since light slows down in air)

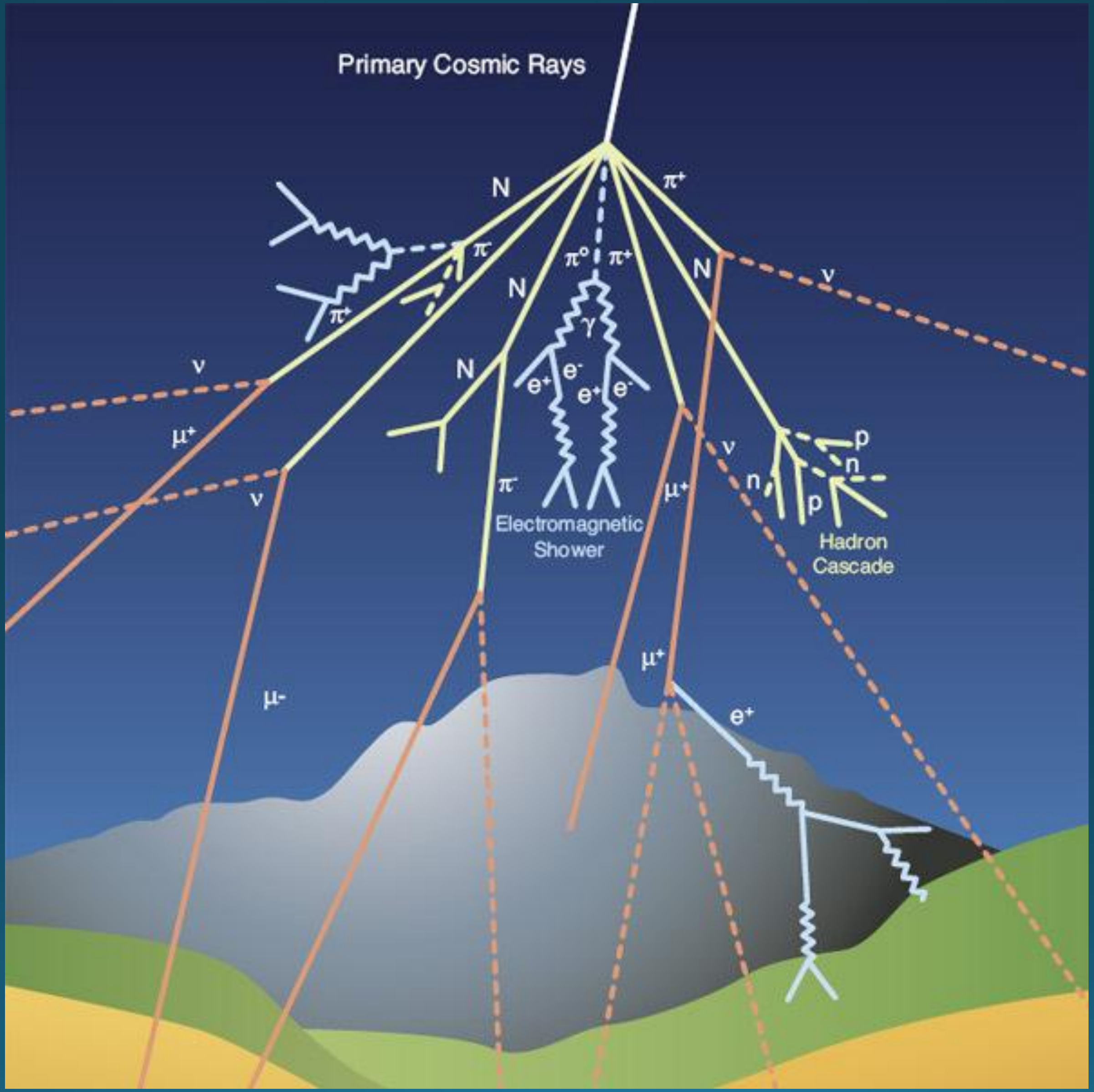


Many different detectors working simultaneously, deployed at high altitudes to measure more of the showers properties.



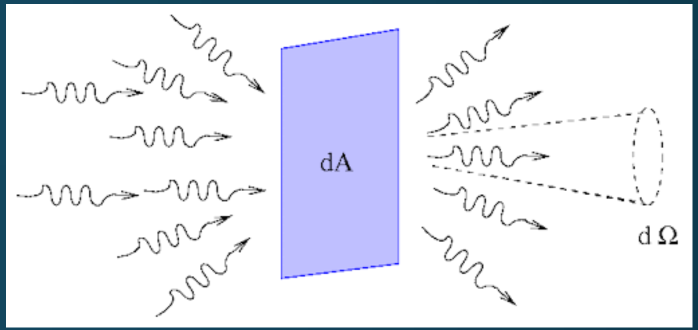
More particles at higher energy
- ➢ Fewer "total number of particles"

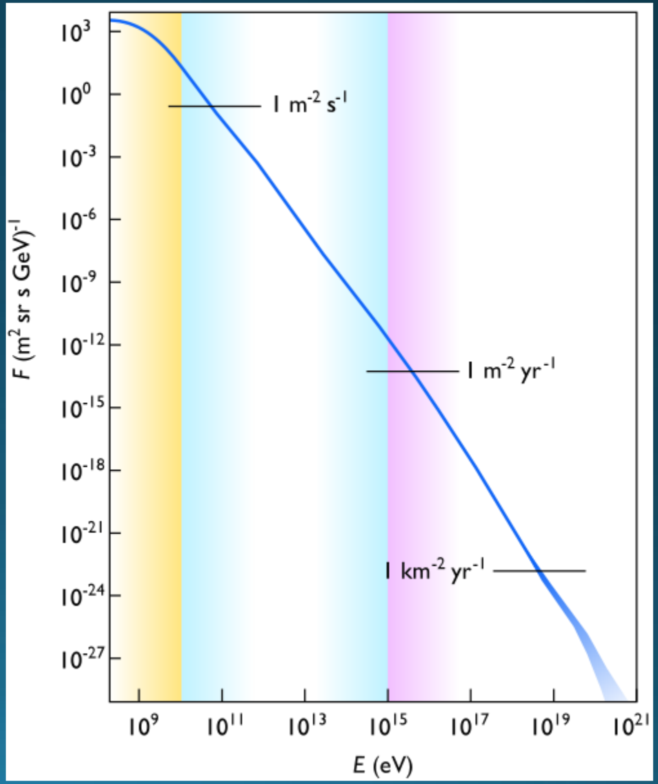
Less particles at higher energy
- ➢ lost energy through the atmosphere



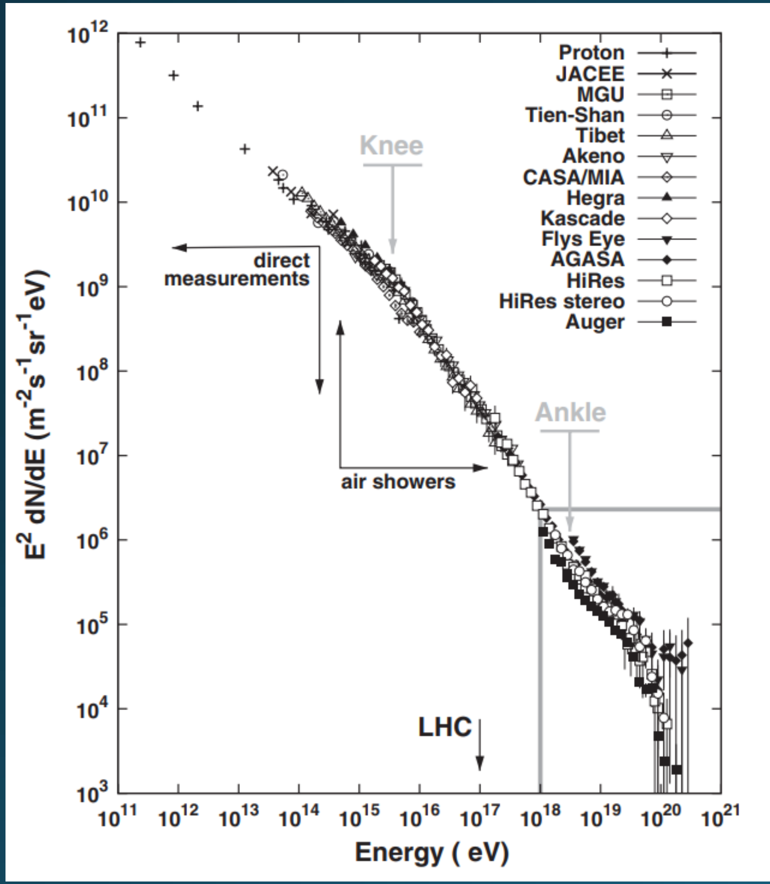
The flux of primary cosmic rays

- Cosmic rays at higher energies are rarer (i.e. less frequent)
- Measured a spectrum of cosmic rays
  - Higher energies, flux falls off (i.e. power law)
  - Hold out your hand (while in space) for 6 billion years to catch the 100 EeV cosmic ray
    - If you want 99% chance – then closer to 30 billion years
- Particles are accelerated somewhere in the universe to these extreme energies
  - Will revisit in the last lecture





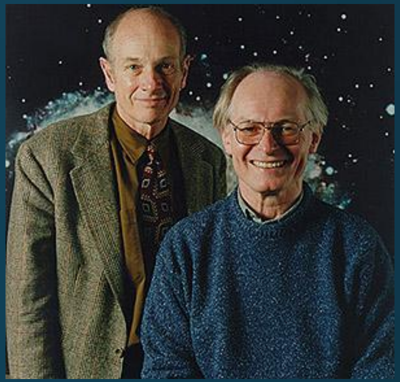
The data shows interesting features



- Somewhat good agreement between different experiments
- Different energy ranges
- "Direct" means measure the cosmic ray primary particle in the detector
- Indirect – like neutrinos – through interactions
  - Air showers

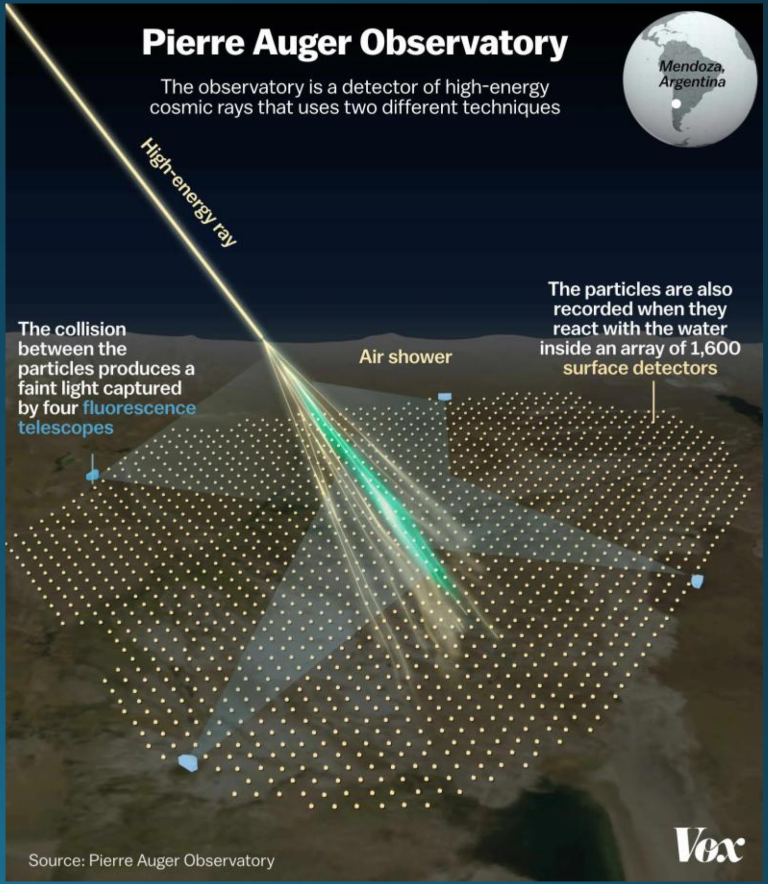
Direct cosmic ray measurements in two weeks

Pierre Auger Observatory

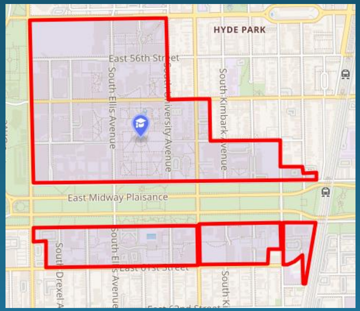


Cronin and Watson - a larger cosmic ray air shower experiment

- 1600 surface detectors
  - 100th detector in 2003
  - By 2008 all surface detectors completed
- 3,000 km^2



3,000 UChicago's



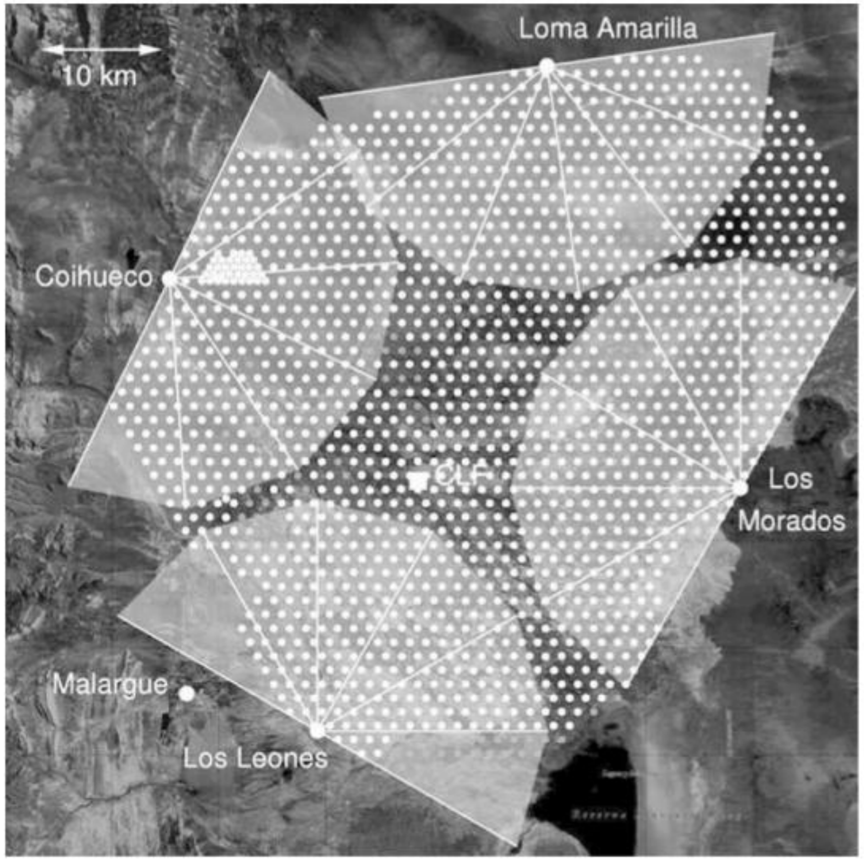


FIG. 13. The Pierre Auger observatory at the end of March 2009. Individual white dots represent Cherenkov tanks, while gray ones are unequiped positions. A denser (infill) area is visible in the upper left. Big white dots at the periphery of the array are fluorescent detector sites with the field of view of individual telescope given by the radial white line. Also shown is the Central Laser Facility (CLF) used for FD calibration and atmospheric monitoring purpose.

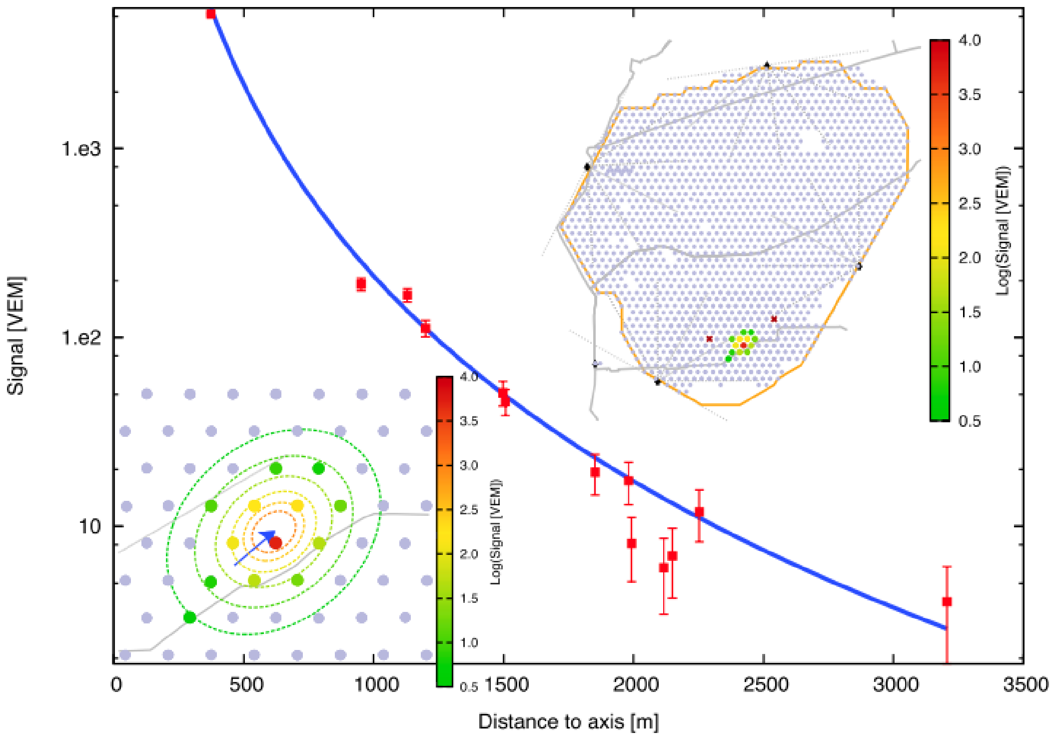


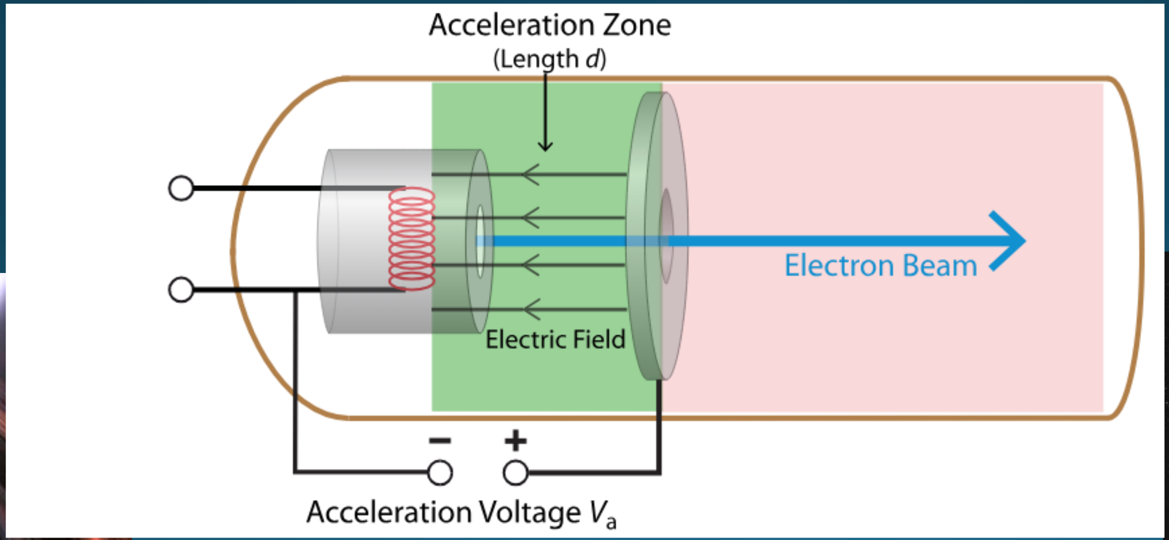
FIG. 5 (color online). Example of detection using a surface array. The upper right inset shows the whole Auger surface array and the footprint of the shower, each dot represents a detector and the spacing between them is 1.5 km. The lower inset shows details of this footprint with the estimated contours of the particle density levels. The curve represents the adjusted LDF (lateral distribution function) and the center point represents the measured densities as a function of the distance to the shower core. From the Auger Collaboration.

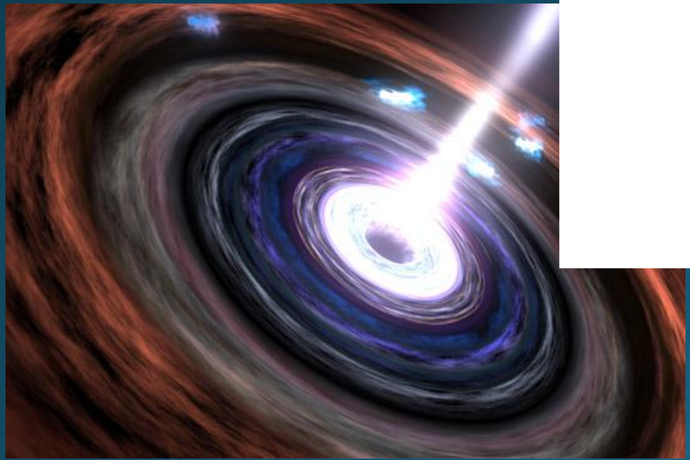
How can cosmic rays be produced at these energies?

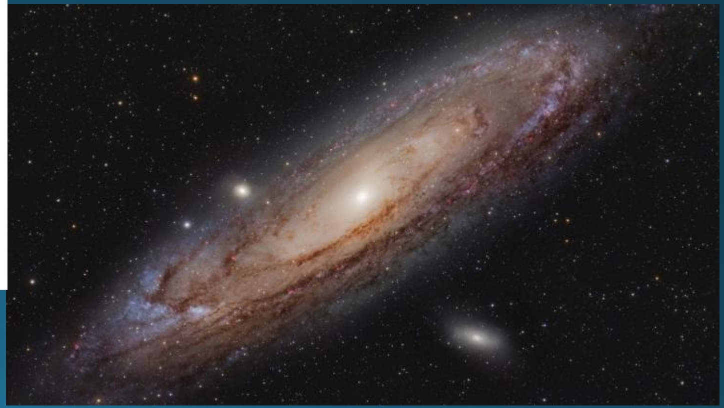
We are not sure…

We do know:

Charged particles can be accelerated by strong fields.

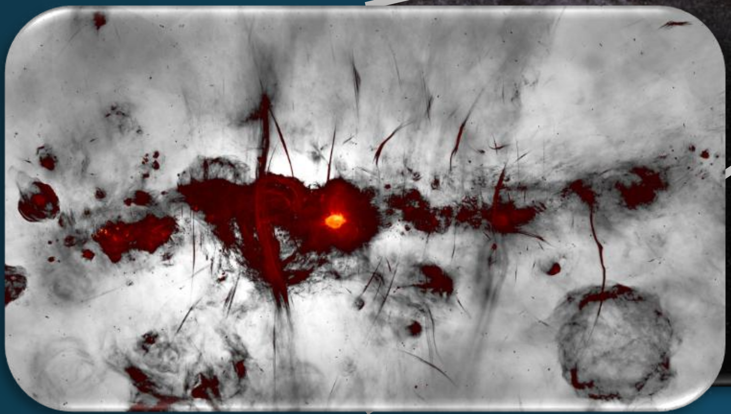


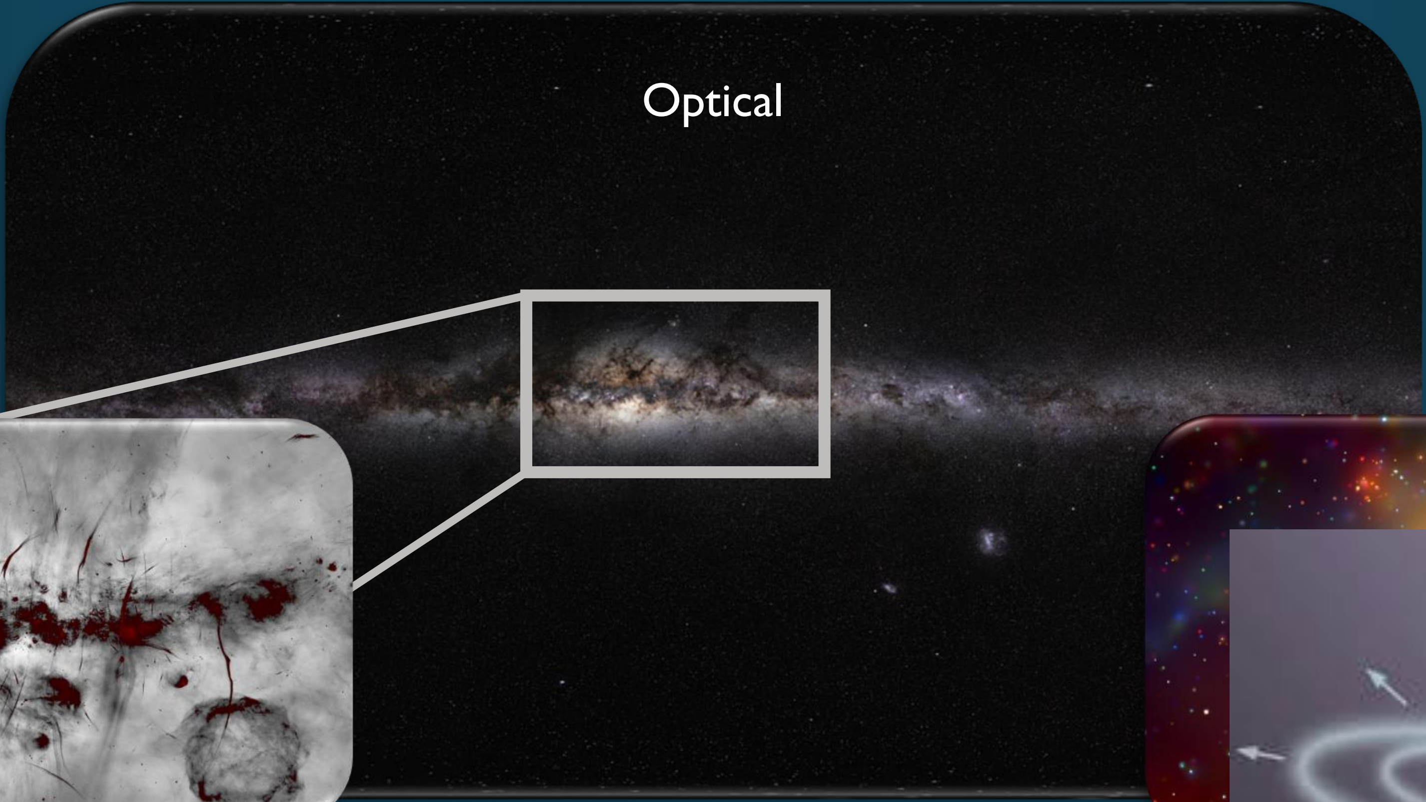




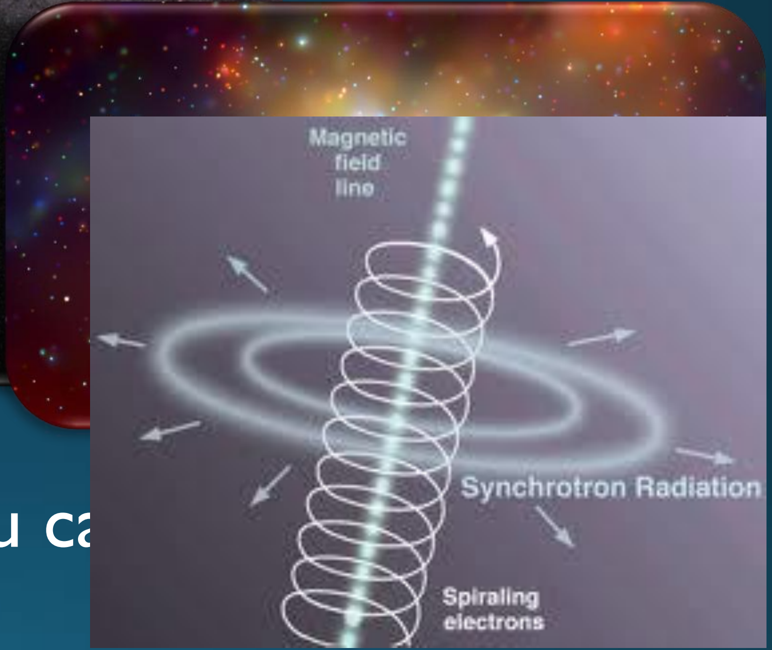
Particles like electrons interacting with magnetic fields!

Radio





X-Ray



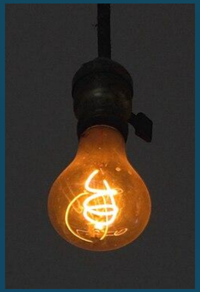
With a different type of lens, you ca

1. See through opaque objects
2. Observe different processes
3. Reveal previously hidden structure

Different types of emission

Non-thermal emissions

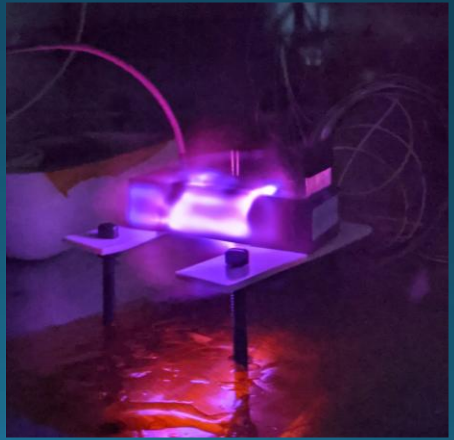
- Not because an object is hot (like incandescent light bulbs)
- Ionization of gas from electric fields
- Breakdown of air or gas because of electric fields



“Neon” sign
in Andersonville

This is probably a mixture of argon and mercury gas.

Corona discharge with High Voltage supply



Electric Fields - Arcing

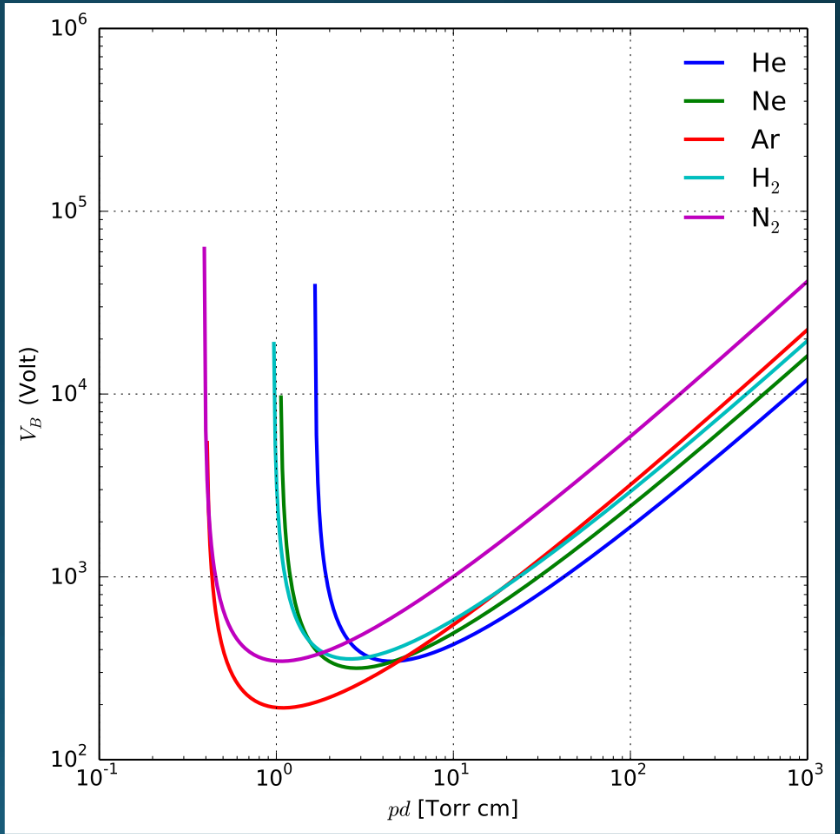
Electric breakdown of air!

3,000 kV/m

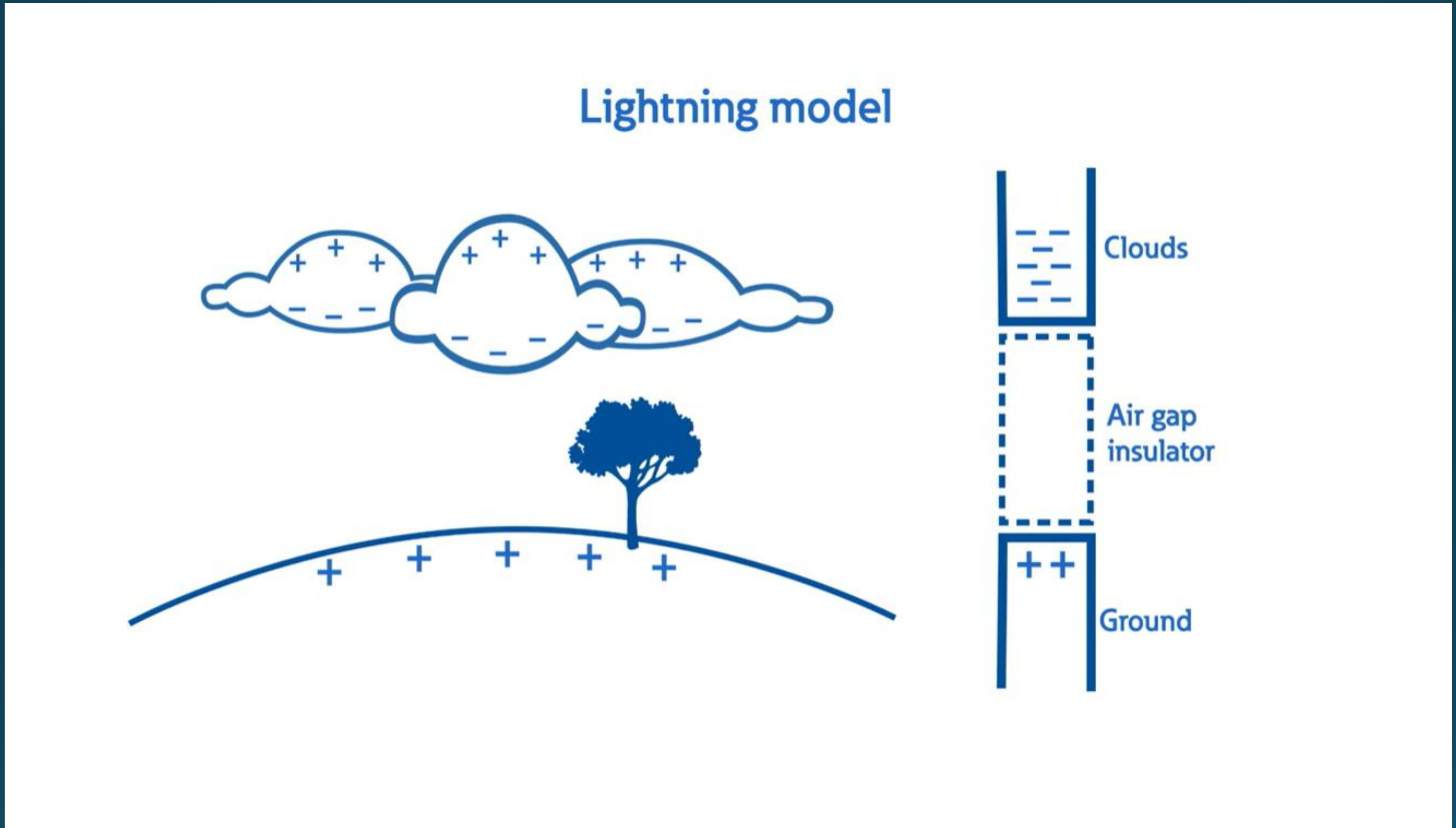
Experimentalists get to play with toys like these

Paschen's law

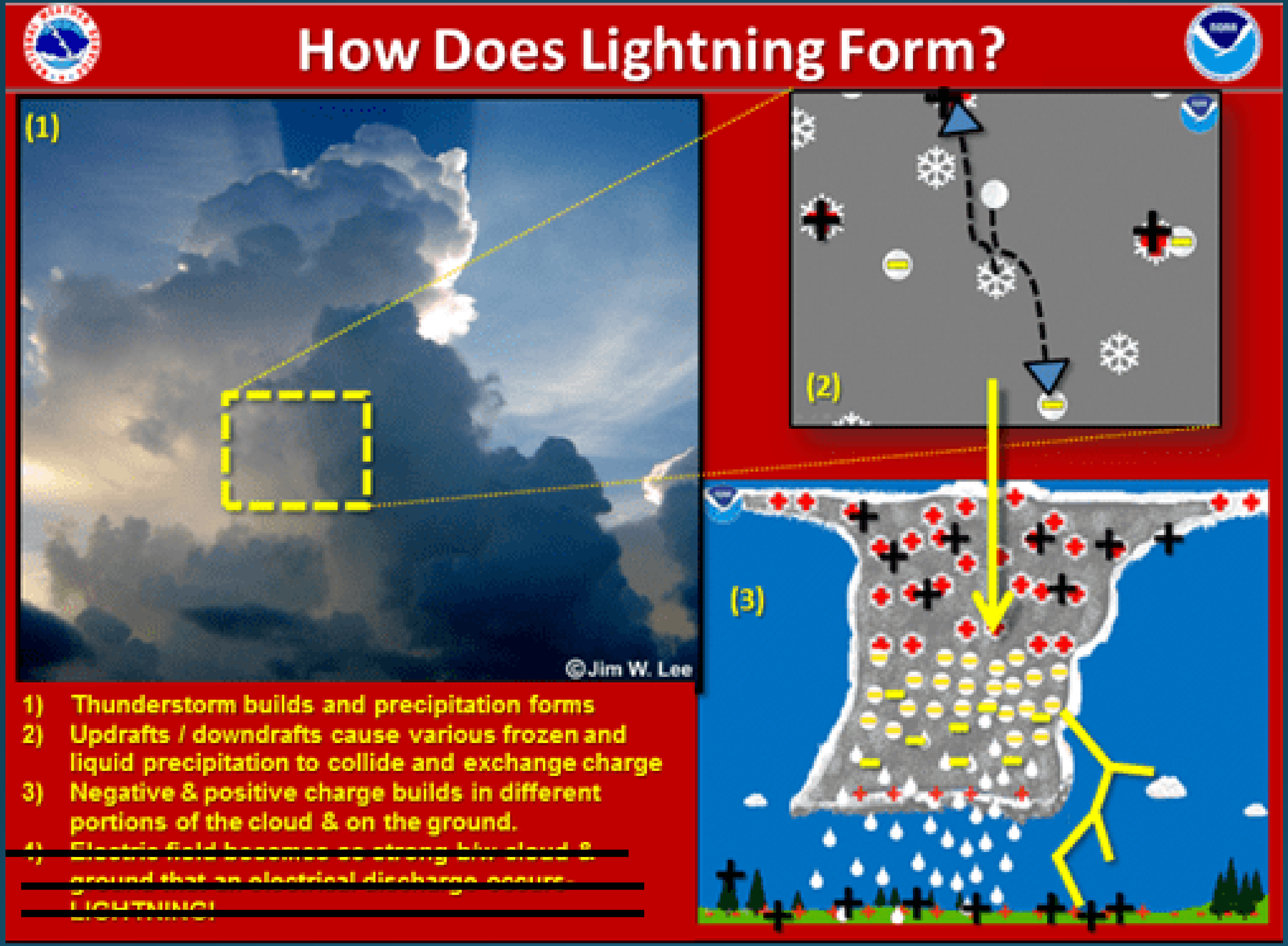
- Electric field strong enough that electrons from atoms prefer jump huge gaps!
  - The air being an insulator doesn't matter because the field is so strong
- In air (at sea level), mostly nitrogen
  - ~30,000 V for a 1 cm gap
  - Electric field of 3,000 kV/m
  - kiloVolts per meter



Just a much bigger arc?

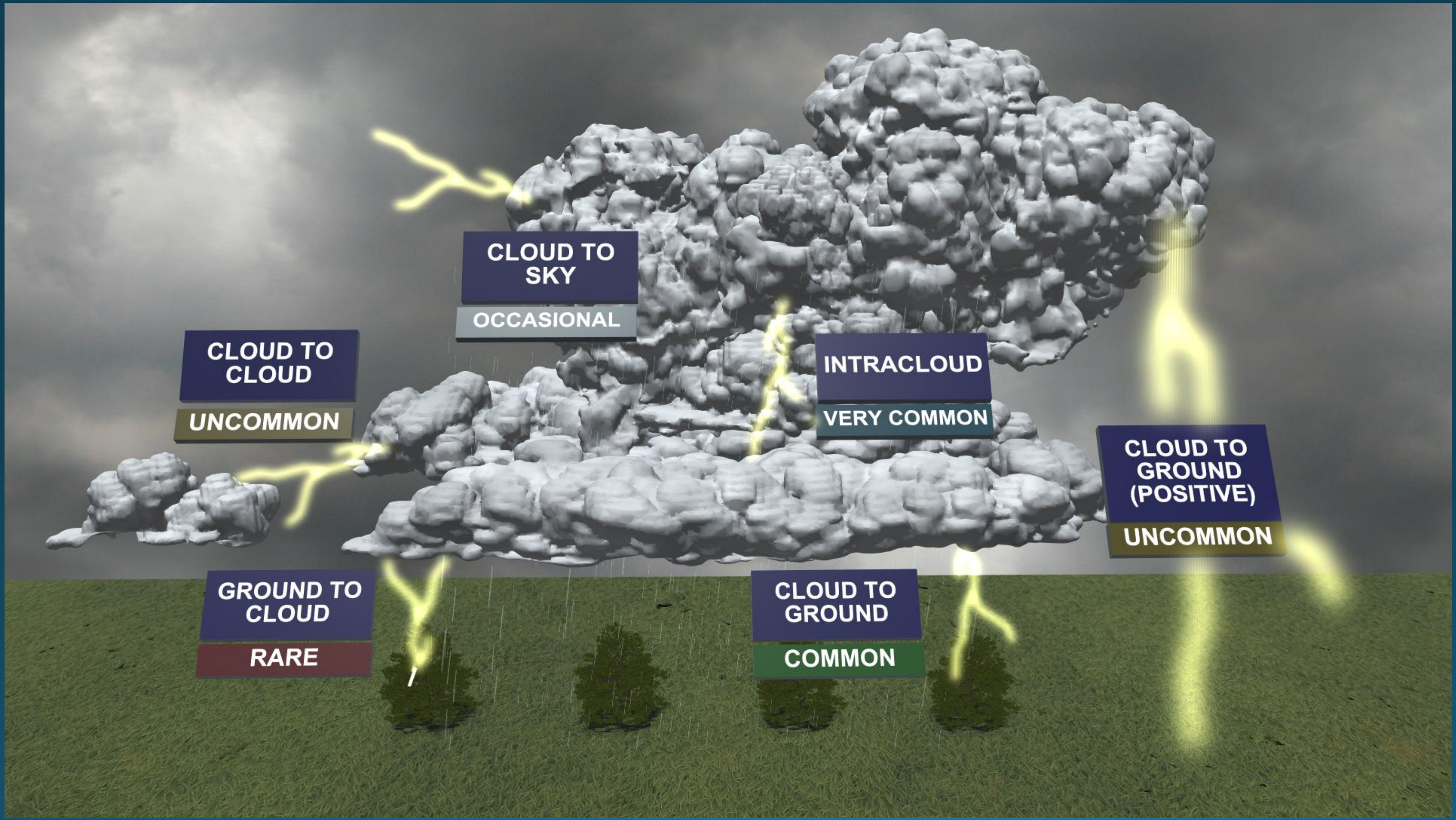


1. The electric field needed is ~1,500 kV/m
2. The air pressure is lower at high altitudes



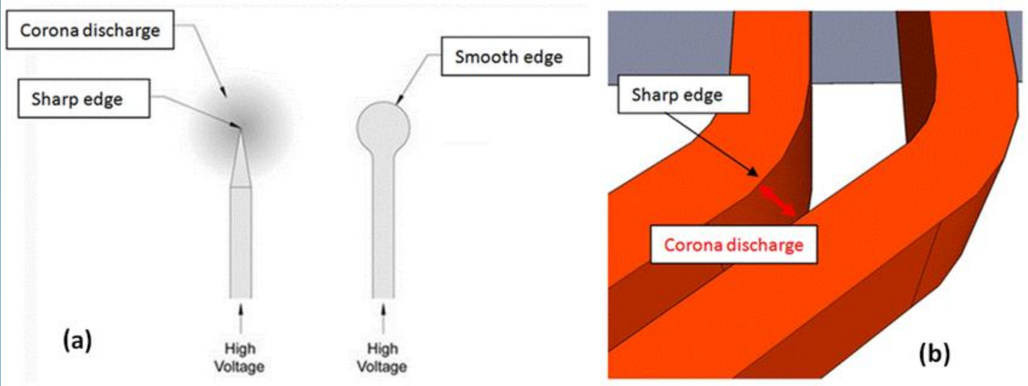
1. The electric field is created from charge exchange of ice crystals
2. ~~Electric field reaches the breakdown limit~~

Different kinds of lightning



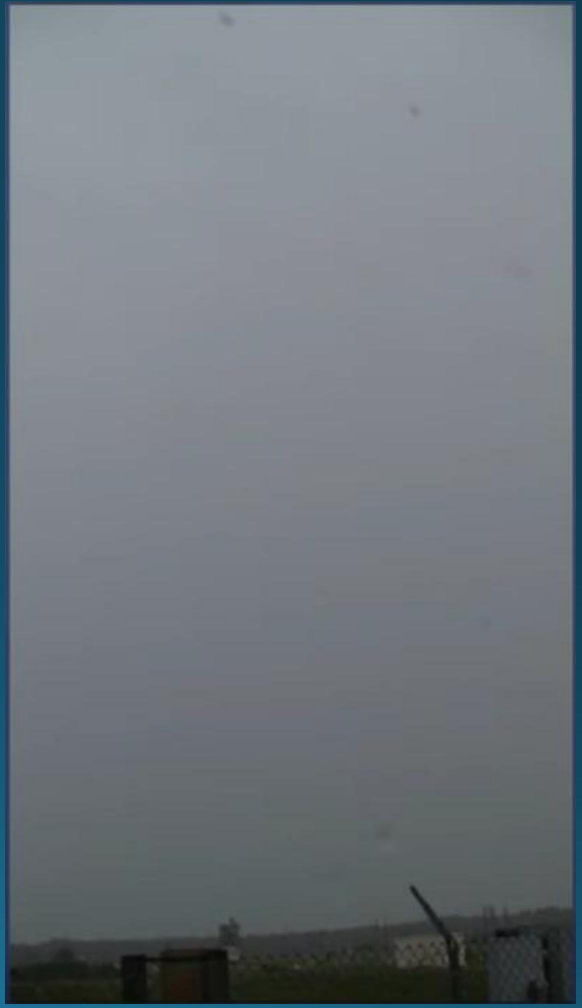
The hunt to understand lightning

- Wilson – inventor of the Cloud Chamber
  - Contributed to lightning studies in the 1920s
- Tried to measure the corona discharge
  - Sharp and smooth edges
  - Proved charges leak from the ground to the air



Launched instruments into thunderstorms

- Balloons and rockets
  - Kurt Vonnegut's brother Bernard launched balloons into thunderstorms in the 1950s
- More sophisticated, higher altitude ballooning in the 1960s and 70s
- Rockets in the 1980s
  - Wires hanging off to measure current and voltage
  - Goal to understand the Electric Field of the thunderstorm
- Still do this research today
  - Even trigger our own lightning



Breakdown of air for lightning strikes?

Its complicated… but we don't think it is just the thunderstorm

- Most instrumentation shows measurements of electric fields in thunderstorms 50-150 kV/m
  - For air at sea level like our labs: 3,000 kV/m
  - And at high altitudes would need 1,500 kV/m
    - This is at least 10 times too low!
- The measurements are robust

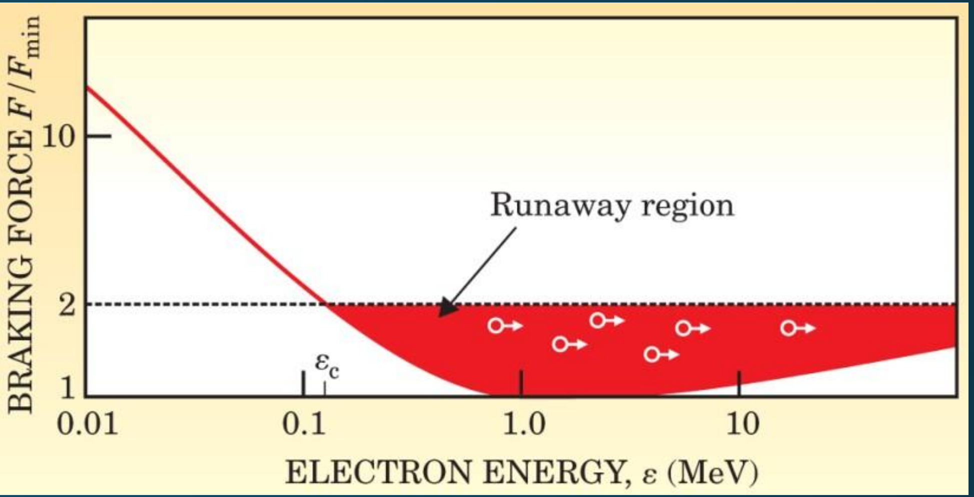
Somehow, lightning strikes without having the electric field strength we thought it needed

Relativistic Runaway Electron Avalanche

RREA

- Electric fields below the breakdown level
  - Free electrons of low kinetic energy will "feel" the material more
  - "Friction" stops them, so, no lightning
  - But fast electrons will be accelerated by the field and experience less "friction"
- Electrons that are already free with sufficient energy will "runaway" in a positive feedback loop
  - Prof. Dwyer at Florida Institute of Technology

Wilson's paper in 1925 pointed out this idea



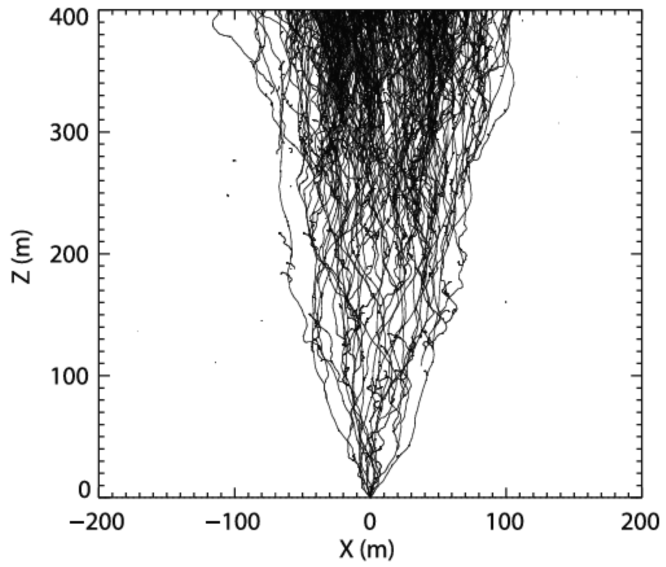
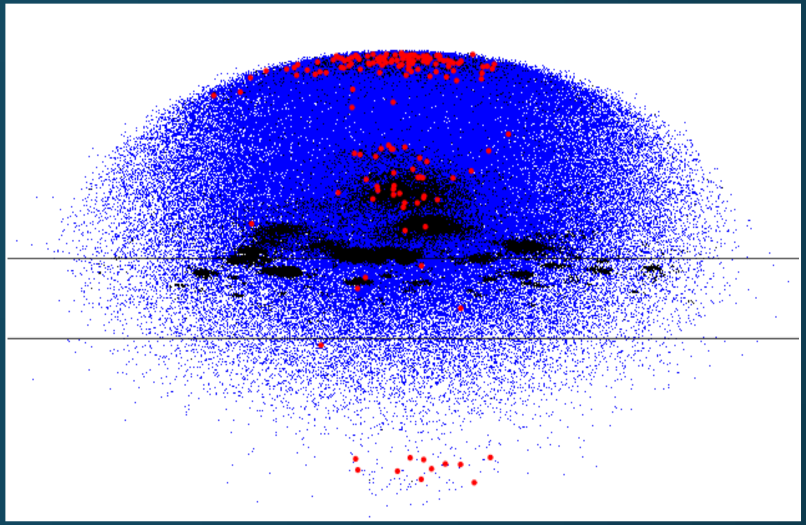
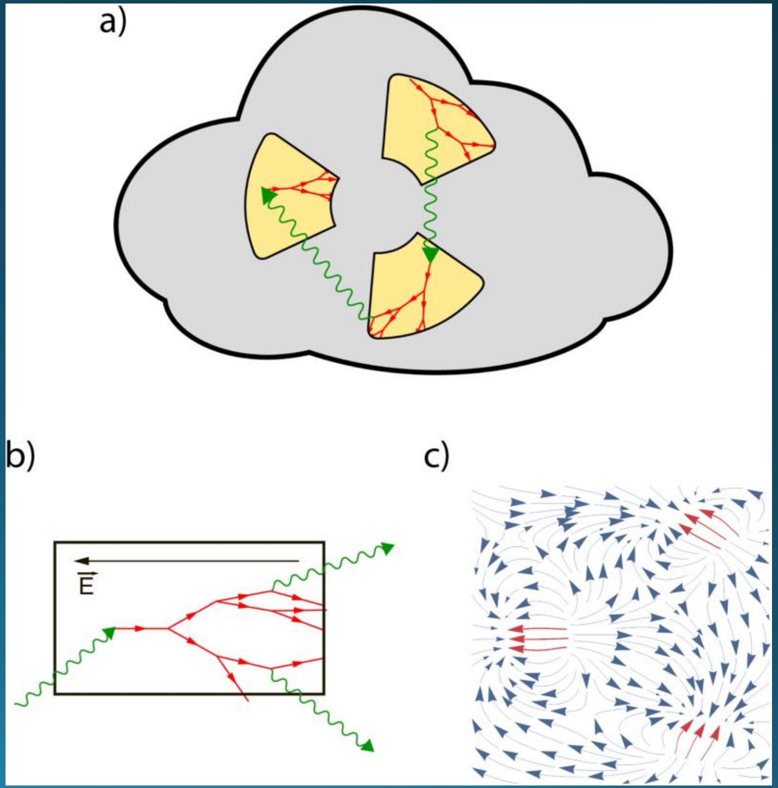


Figure 1. Monte Carlo simulation of a relativistic runaway electron avalanche in air at 1 atmosphere pressure and for a uniform, downward electric field of 350 kV/m. This ava-

Theory of RREA

- Dwyer's team launched those rockets into thunderstorms
- Gamma rays (and X-Rays) emitted
  - bremsstrahlung of electrons
    - Relativistic electrons and positrons
- Gamma rays emitted in one region result in multiplication in other regions

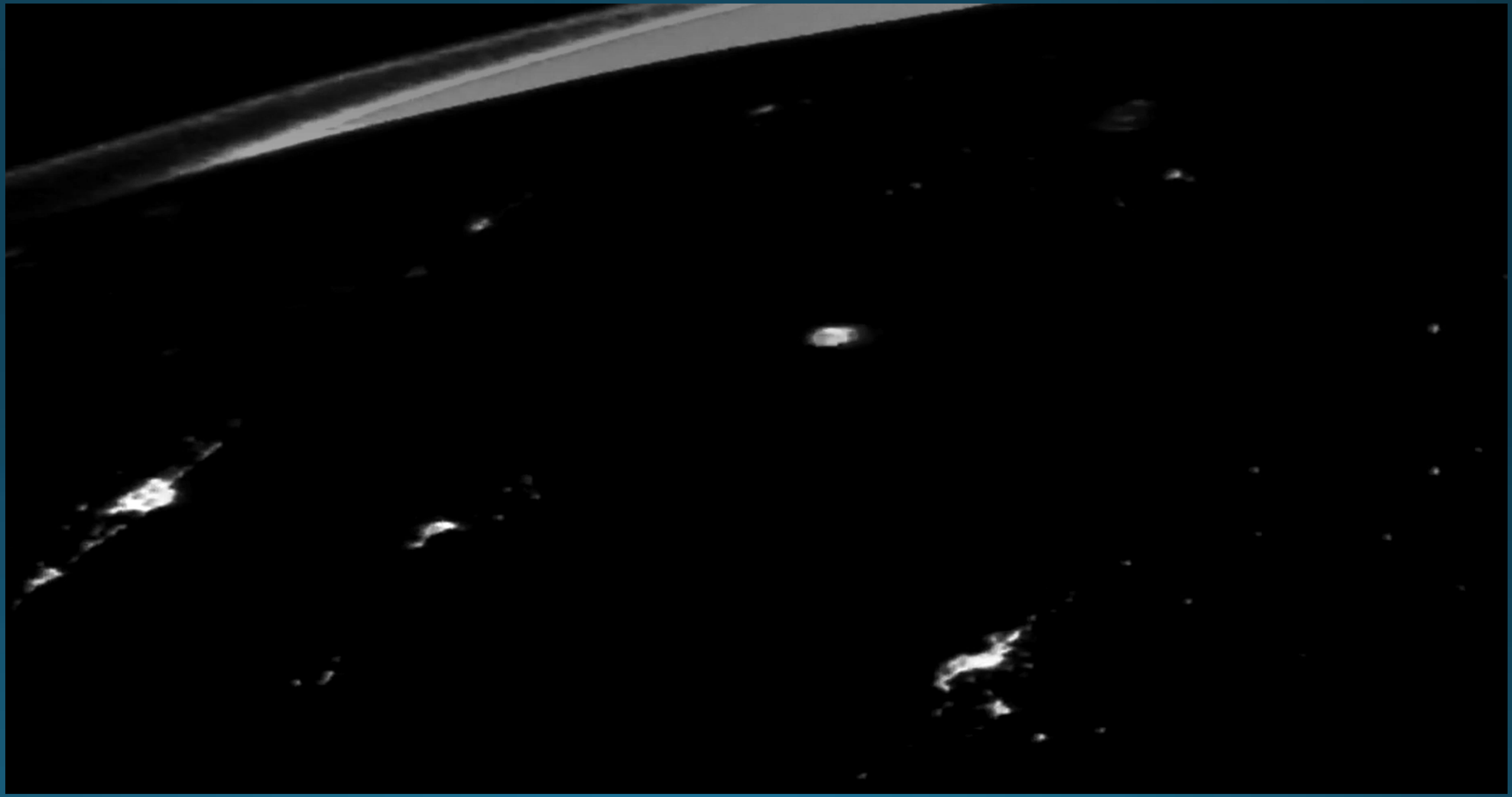




Back to Fermi Gamma ray telescope

High-energy gamma rays from thunderstorms?

- Here on Earth?
- Impossible



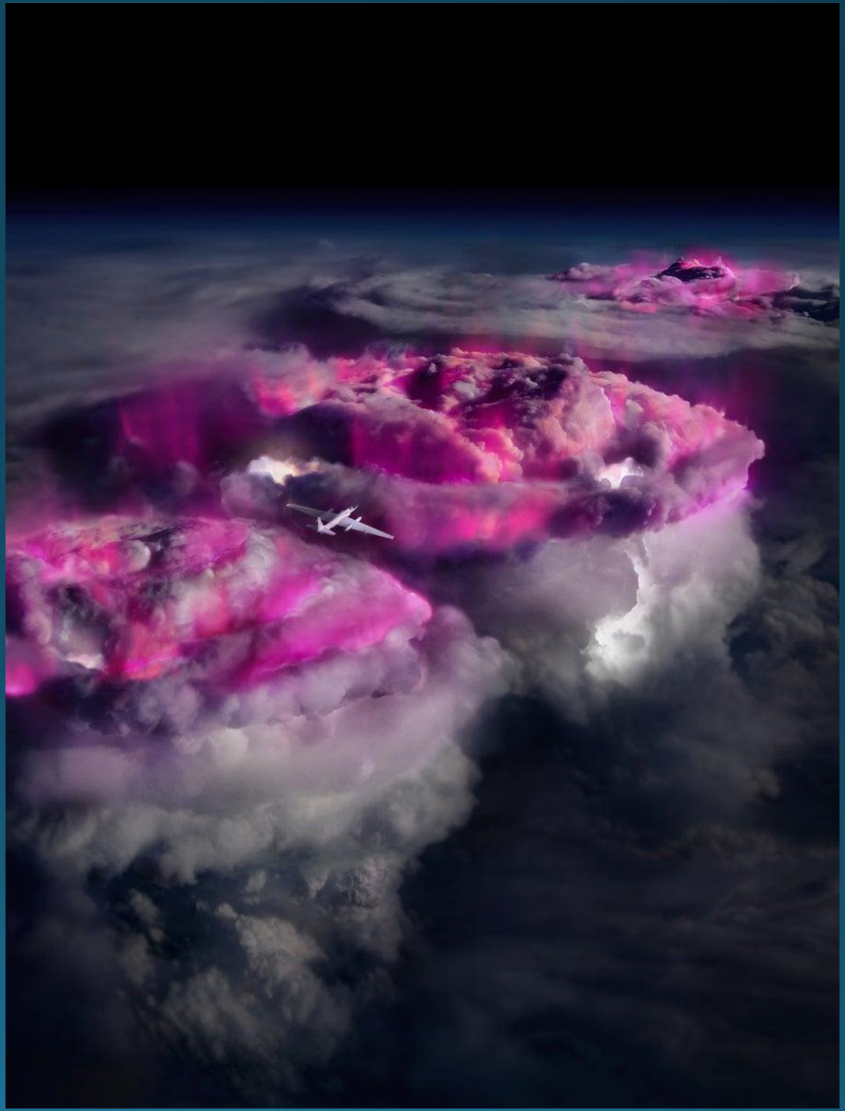
Terrestrial Gamma-Ray Flash

TGFs

- First discovered by:
  - Compton Gamma Ray Observatory (1994)

Lightning accelerates electrons to very high energies!

Flying overhead of thundercloud gamma ray flashes



- To understand these flashes, need to get closer:
- Fly-bys of modified U-2 spy planes
  - Courtesy of NASA
- Are these gamma ray flashes common?
  - Newest studies suggest the gamma rays are always there

Stay tuned for updates with this research!

GRAPES-3

Gamma Ray Astronomy at PeV EnergieS

- Cosmic ray air showers
- Muon telescope
- Measured muon flux intensity changes during thunderstorms
  - Found highest potential of 1,300 MV (~ 650kV/m)
    - Higher than measurements of thunderstorm electric fields directly, but not enough for breakdown

So what actually seeds the lightning?

Lightning initiation by simultaneous effect of runaway breakdown and cosmic ray showers [1]

A.V. Gurevich [a], K.P. Zybin [a], R.A. Roussel-Dupre [b]

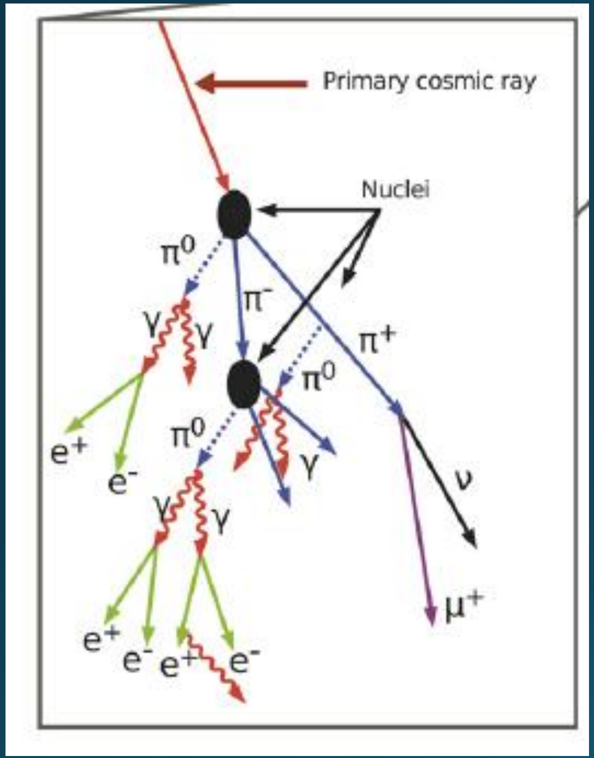
[a] *P.N. Lebedev Institute of Physics, Russian Academy of Sciences, 117924 Moscow, Russia*
[b] *Space and Science Technology Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA*

Received 8 January 1999; accepted for publication 21 January 1999
Communicated by V.M. Agranovich

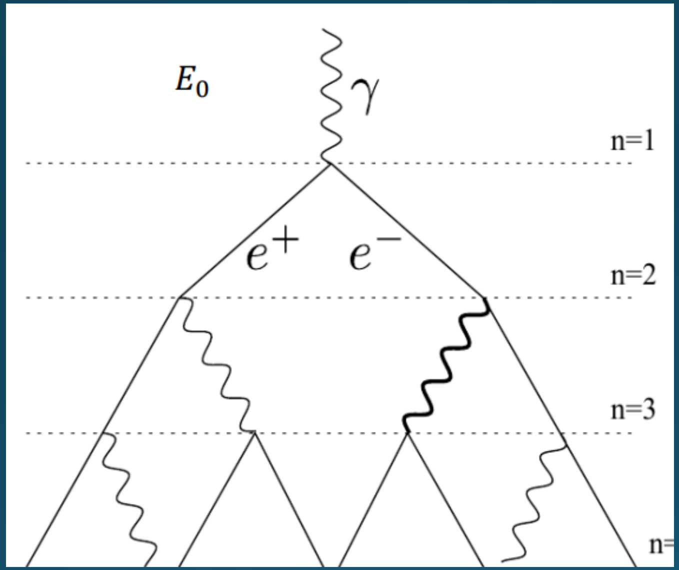
Following Wilson's [1] suggestion that thunderstorm electric field could accelerate cosmic ray secondary electrons to high energies, researches tried to observe the X-rays produced in air by high energy electrons. However, most of the early observations could not obtain a definite conformation of correlations between lightning flashes and X-rays.

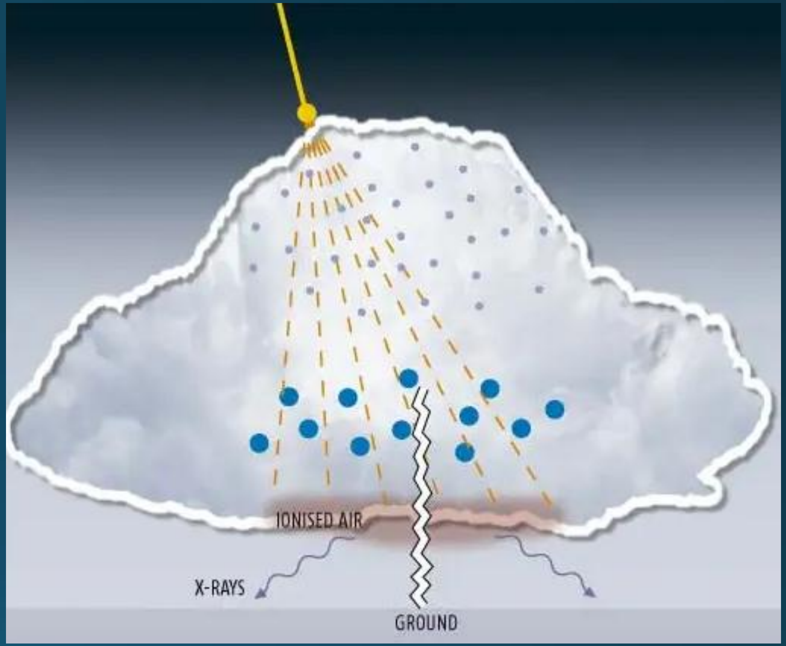
This situation changed decisively through the last few years. First of all, McCarthy and Parks [2] flew an X-ray detector on an aircraft into a thundercloud and found a significant (two to three orders of magnitude) increase in X-ray intensity. The increase lasts for about ten seconds, what means that the region of intensive X-rays has several kilometers scale. A detailed analysis

The idea of cosmic rays as the spark



Energy of primary 1 PeV = 1,000,000 GeV

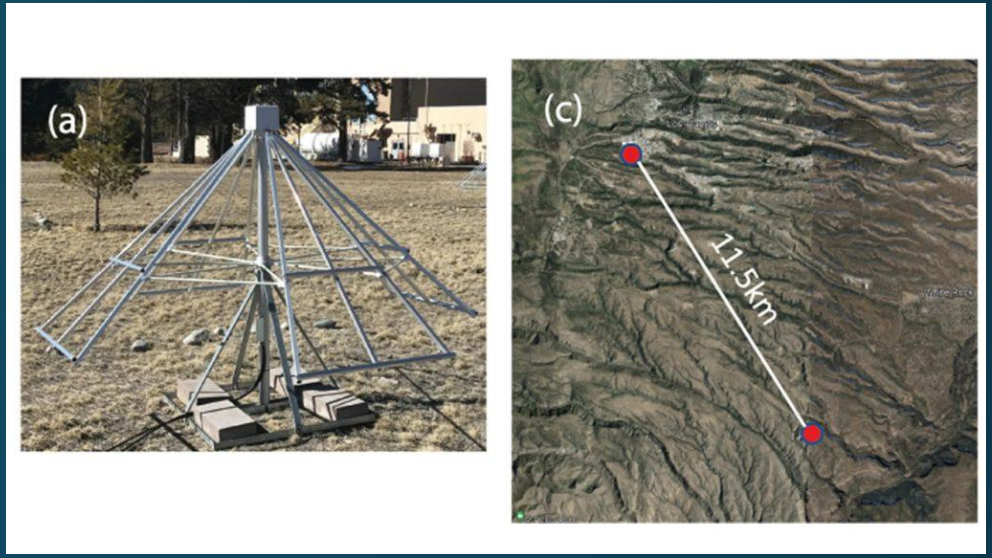


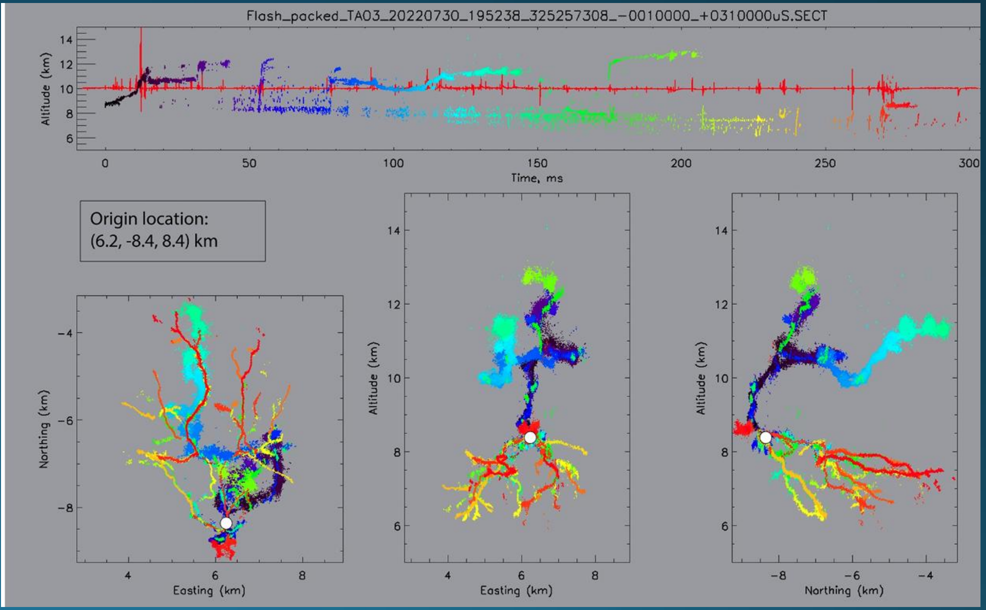


1. Each generation ~ ½ energy in each resulting particle
2. Eventually, millions of particles, each with lower energy
3. But in a thunderstorm, those particles are accelerated by electric field

Very recent result

- If I was giving this lecture series last year that would be the end of the discussion
- Los Alamos National Lab
  - Deployed two stations 11.5km apart (~7miles)
- Antenna array measuring the polarization of the radio emitted during lightning flashes
- Make a 3D map of the polarization of lightning flashes with *interferometry*
  - Discussed in later lectures



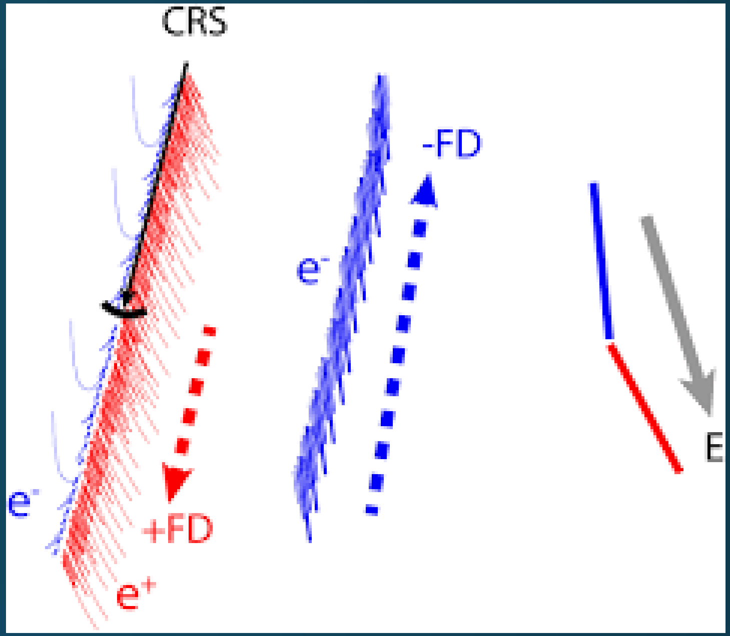


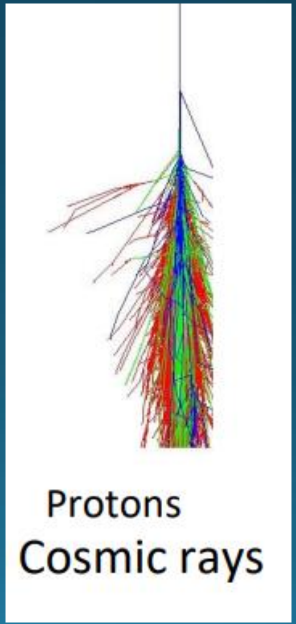
BIMAP-3D result

Broadband Interferometric Mapping and Polarization

- Always records radio measurements
  - Radio pulses occur before the flash
- "Noisy" signatures of positrons and electrons before the flash
- Those pulses have polarization that appears to align with cosmic ray air showers

*The cosmic ray showers appear to create the channel for lightning to strike





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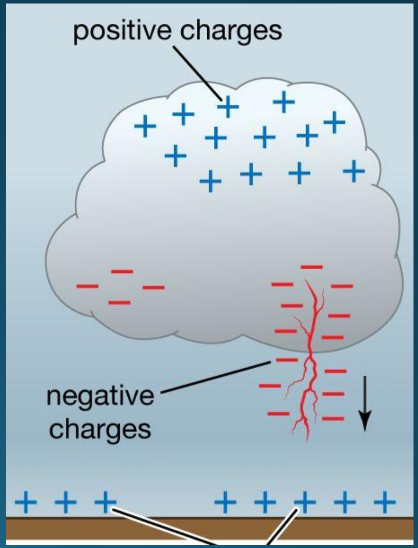
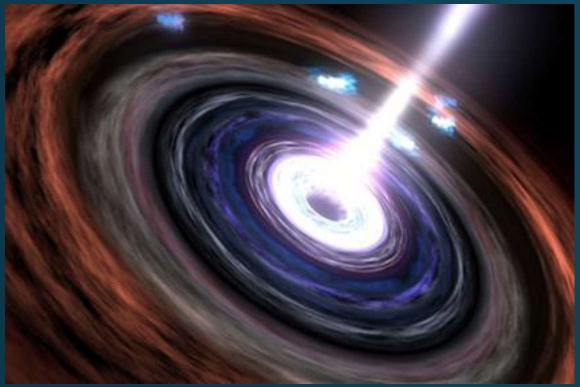
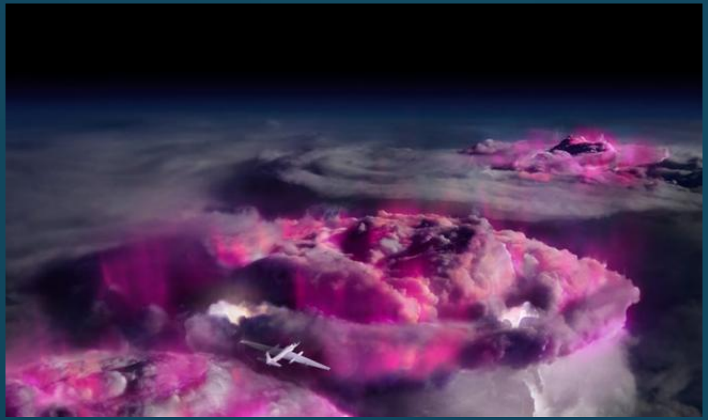
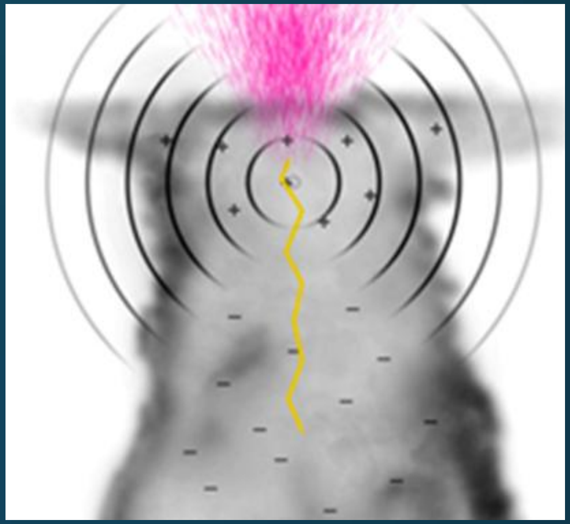
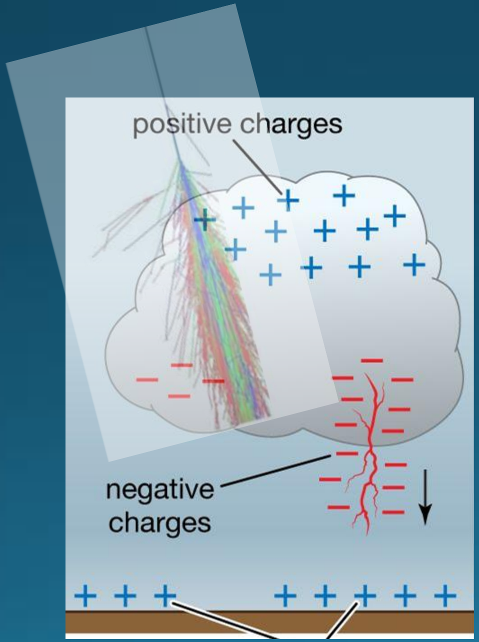


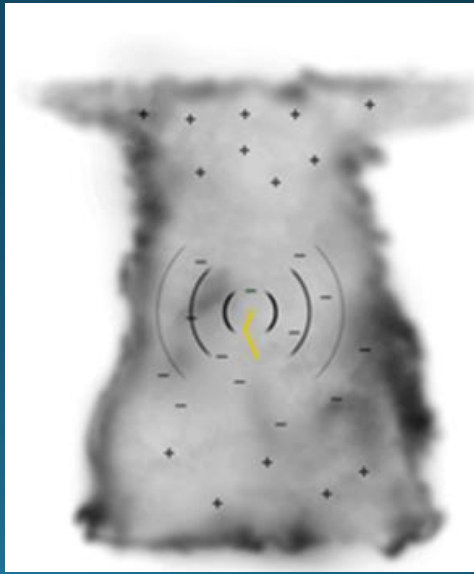


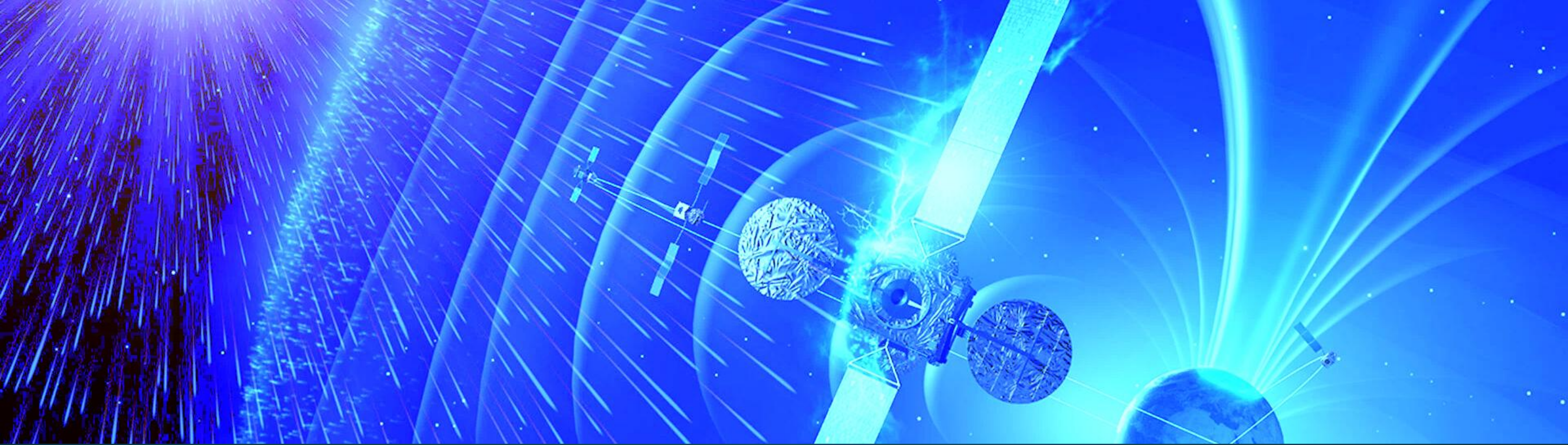




The high-energy astroparticles are there. We just have to put on the lens.







Next week: How cosmic radiation impacts the origin and survival of life

Thank you!