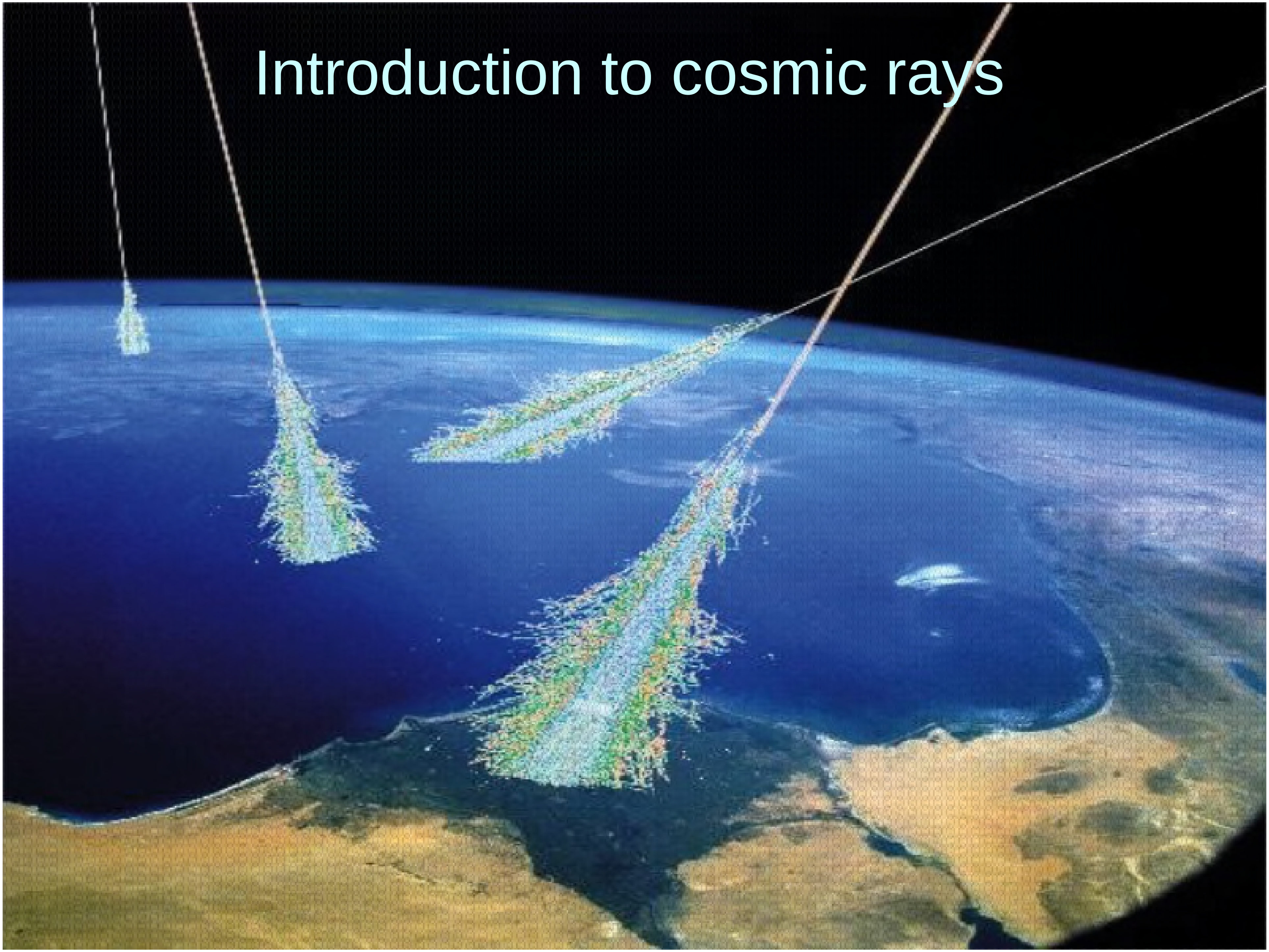
Introduction to cosmic rays



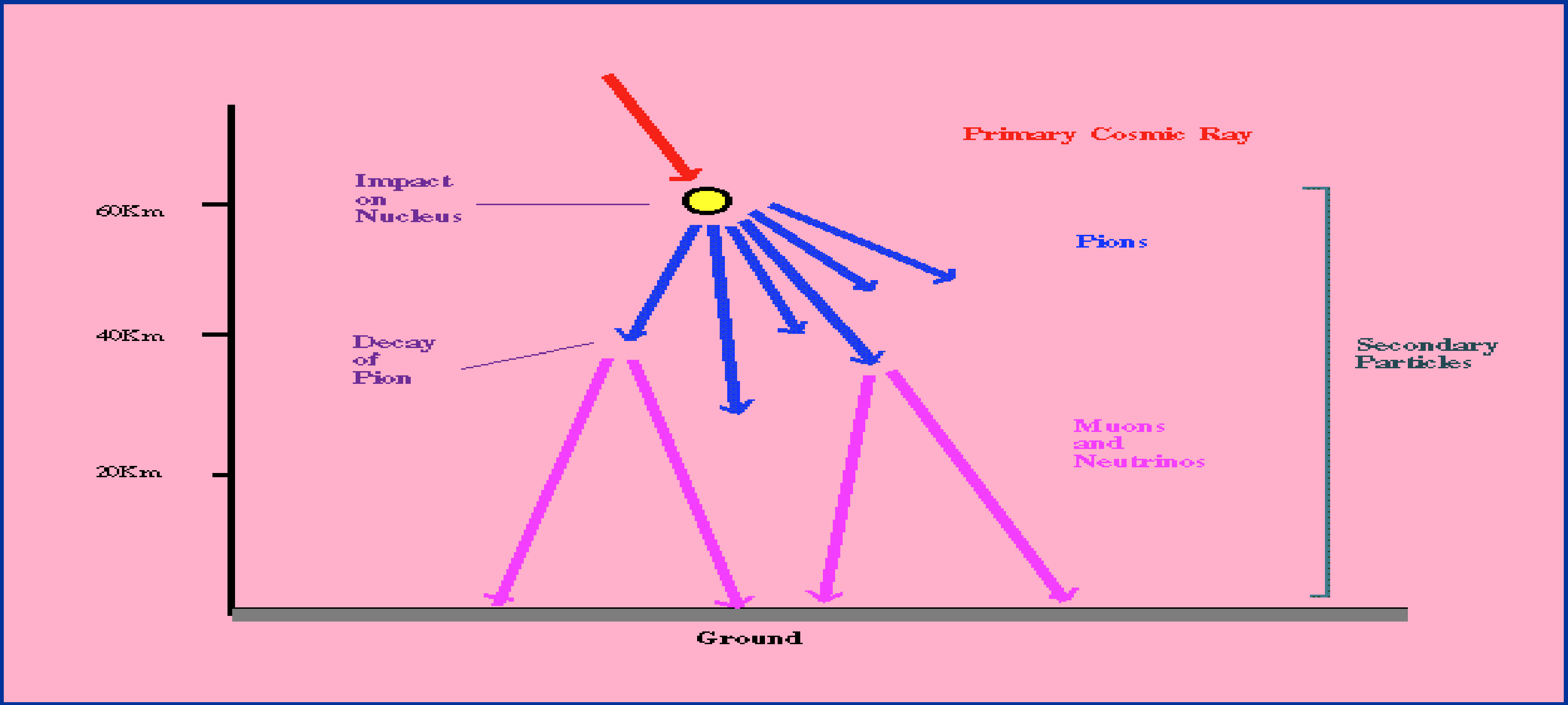
COSMIC RAYS:

Messages from exploding stars and even more powerful objects

- What are cosmic rays?
- How were they discovered?
- How do we detect them?
- What can we learn from them?
- Where do they come from?

Cosmic rays

- Discovered by Victor Hess (1912)
- Observations on mountains and in balloon: intensity of cosmic radiation increases with height above surface of Earth – must come from “outer space”
- Much of cosmic radiation from sun (rather low energy protons)
- Very high energy radiation from outside solar system, but probably from within galaxy



Role in Physics and Astrophysics

- Part of the rise of "modern" physics: early radiation detectors (ionization chambers, electroscopes) showed a dark current in the absence of sources.
- Until 1952, cosmic ray research = experimental particle physics
  - discoveries: muon, pion, and other particles
  - Energy of highest energy cosmic rays (> 10^{20} eV) >> energy available with accelerators
- extraterrestrial nature of cosmic rays confronted astronomers, but challenge could not be faced until mid 20th century.
- Today, cosmic rays are an important part of research of solar system and galactic astrophysics, including the ISM

History of CR's: 1785-1902

- 1785 Charles Coulomb
  - Discovered that charged body in the air becomes discharged “there are ions in the atmosphere”
- 1902 Rutherford, McLennan, Burton
  - Discovered that penetrating radiation passes through the atmosphere

Victor Hess' Balloon ride 1912

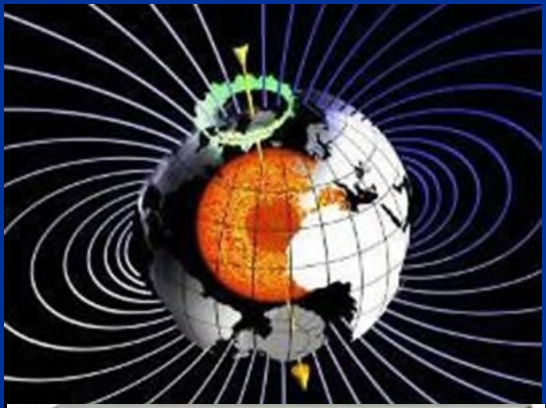
History of Cosmic Rays: Hess

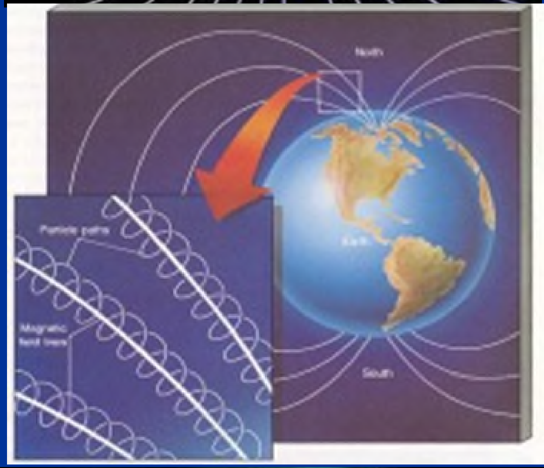
- 1912 Victor Hess
  - Investigated sources of radiation – took balloon up to 5000 meters
  - Found radiation increased after 2500 meters
  - Hess & Kohlhörster (by 1914): balloon flights to 9 km
  - Studies of the variation with height, latitude & longitude confirmed the particle nature of cosmic rays (name by Millikan) originating above the Earth's atmosphere.
  - radiation is coming from space ... "cosmic radiation"
  - Nobel Prize in 1936

- Hess after his flight, which he took without breathing apparatus in very cold and thin air!

History of Cosmic Rays: 1932- 1947

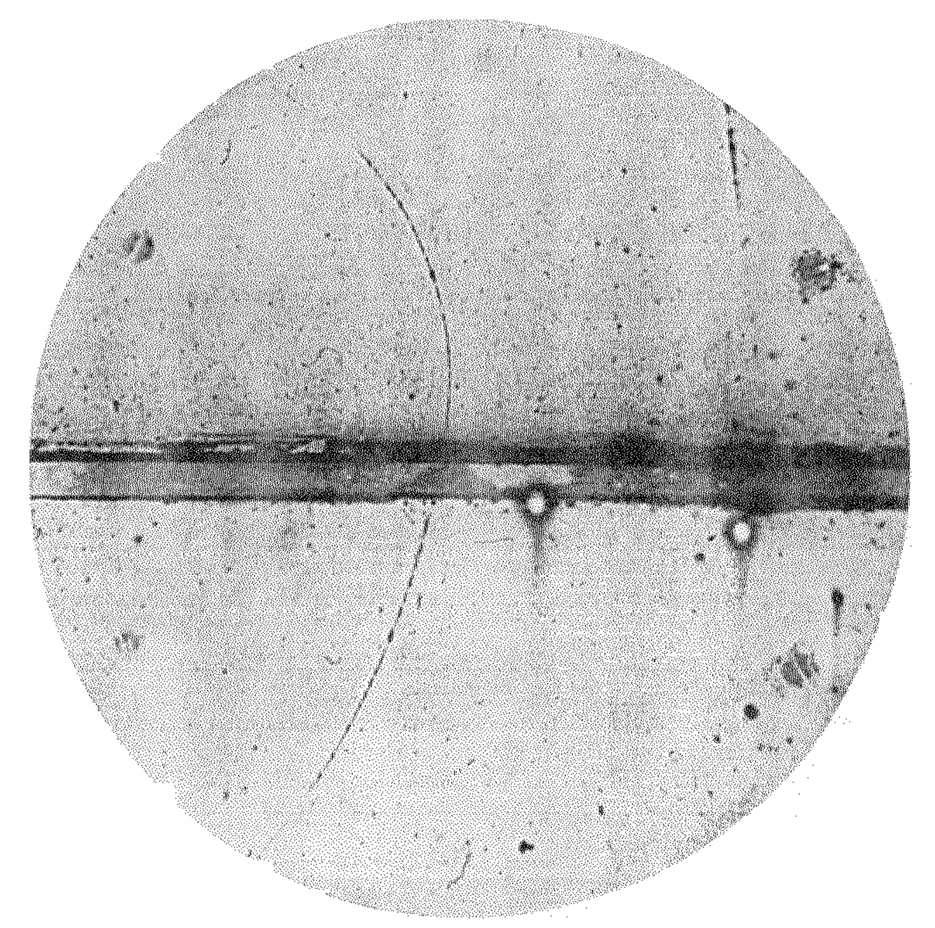
- 1932 discovery of positron
- 1933 Arthur Compton
  - Radiation intensity depends on magnetic latitude
- 1937 Street and Stevenson, Anderson and Neddermeyer
  - Discovery of the muon particle in cosmic rays (207 x heavier than an electron)
- 1938: extensive air showers (Auger)
- 1946 Kaons (“V particles”)
- 1947 pion (Lattes, Occhialini and Powell)



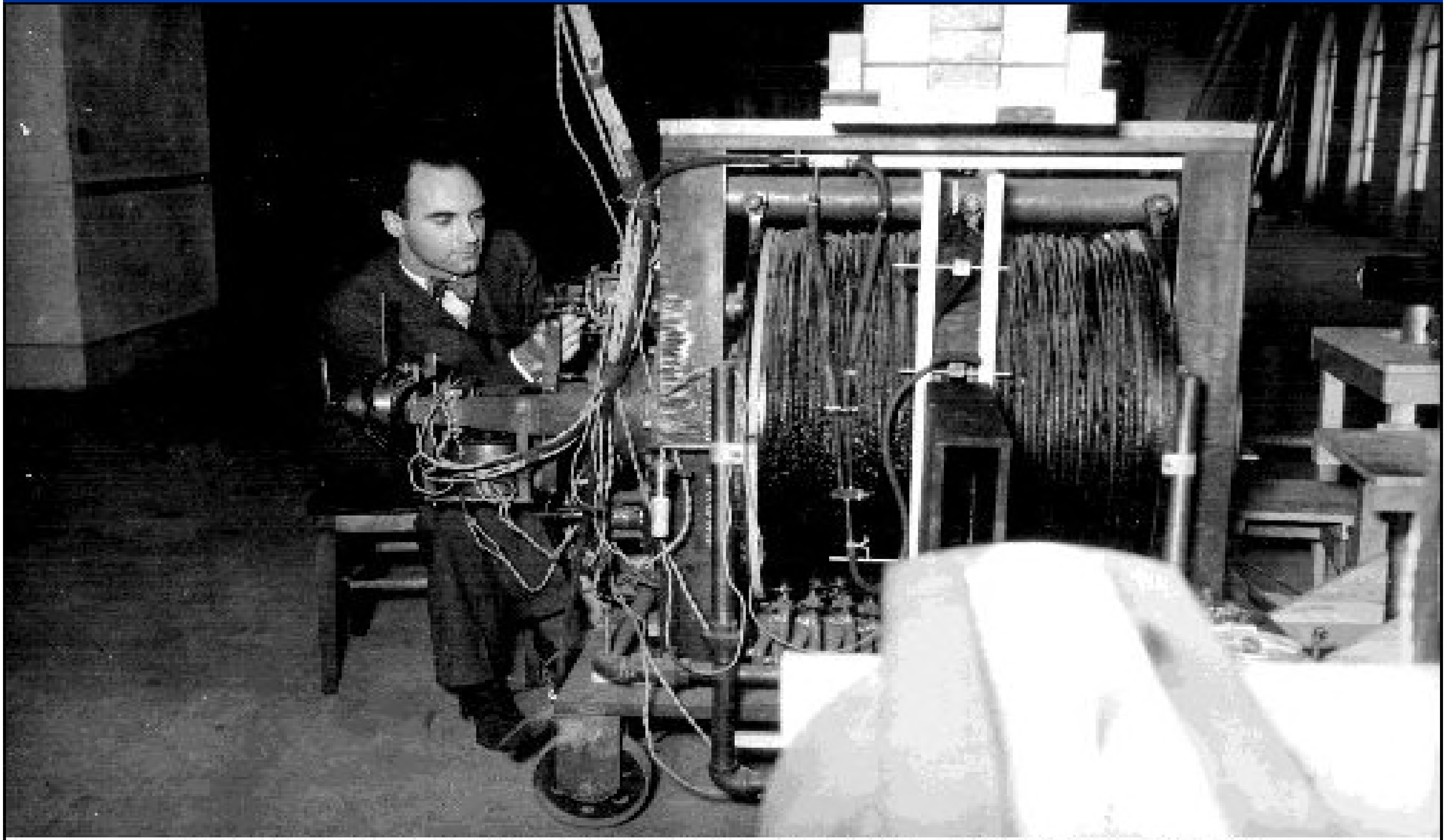


Positron

- Positron (anti-electron)
  - Predicted by Dirac (1928) -- needed for relativistic quantum mechanics
  - existence of antiparticles doubled the number of known particles!!!
  - Positron track going through lead
    - Photographed by Carl Anderson (Aug. 2, 1932)
    - Particle moving upward, as determined by increase in curvature top half of the it passed
    - and curving to the left, meaning its charge is

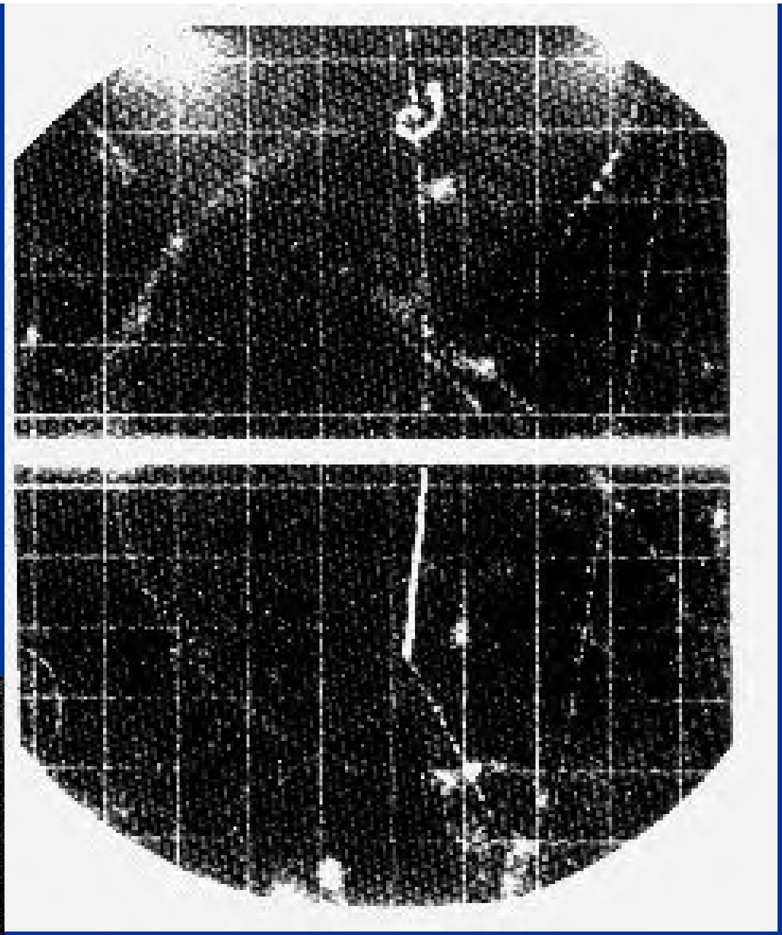


Anderson and his cloud chamber



More particles: Muon

- 1937: "mesotron" is observed in cosmic rays (J. Curry Street, Edward C. Stevenson and Carl Anderson, Seth Neddermeyer "mesotron" -- mass between that of electron and proton



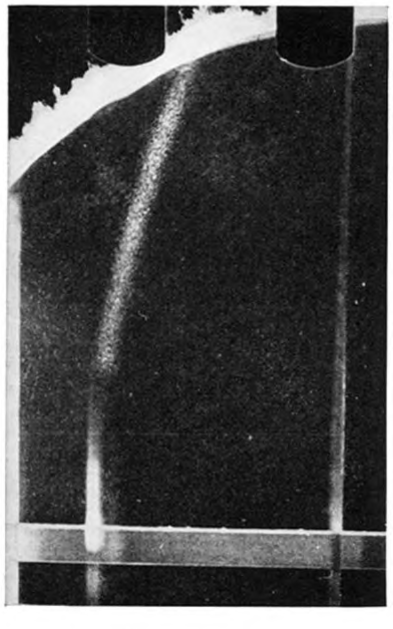
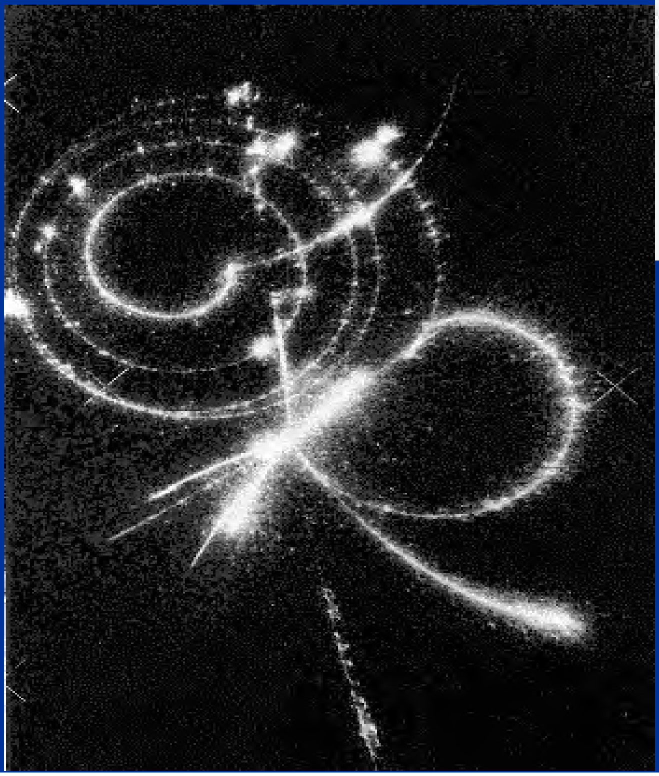


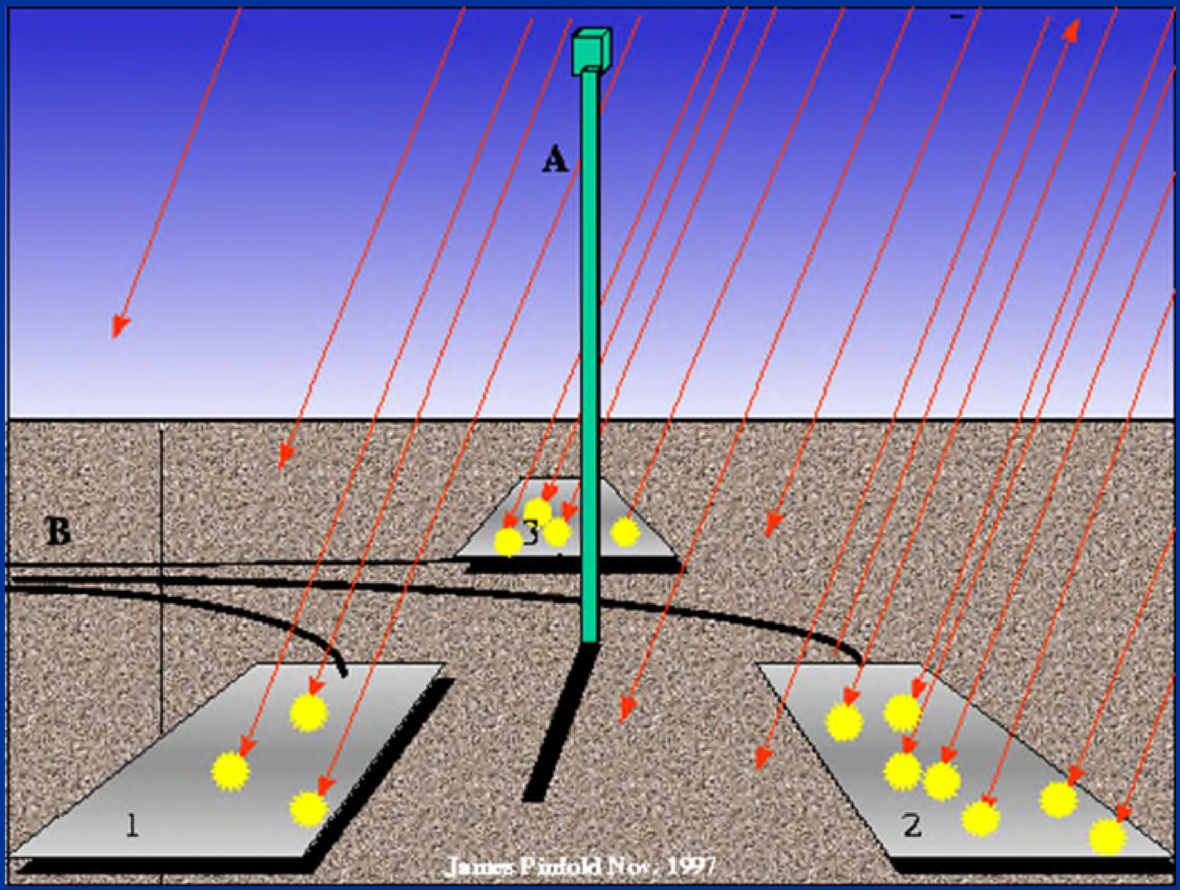
FIG. 3. Track B.



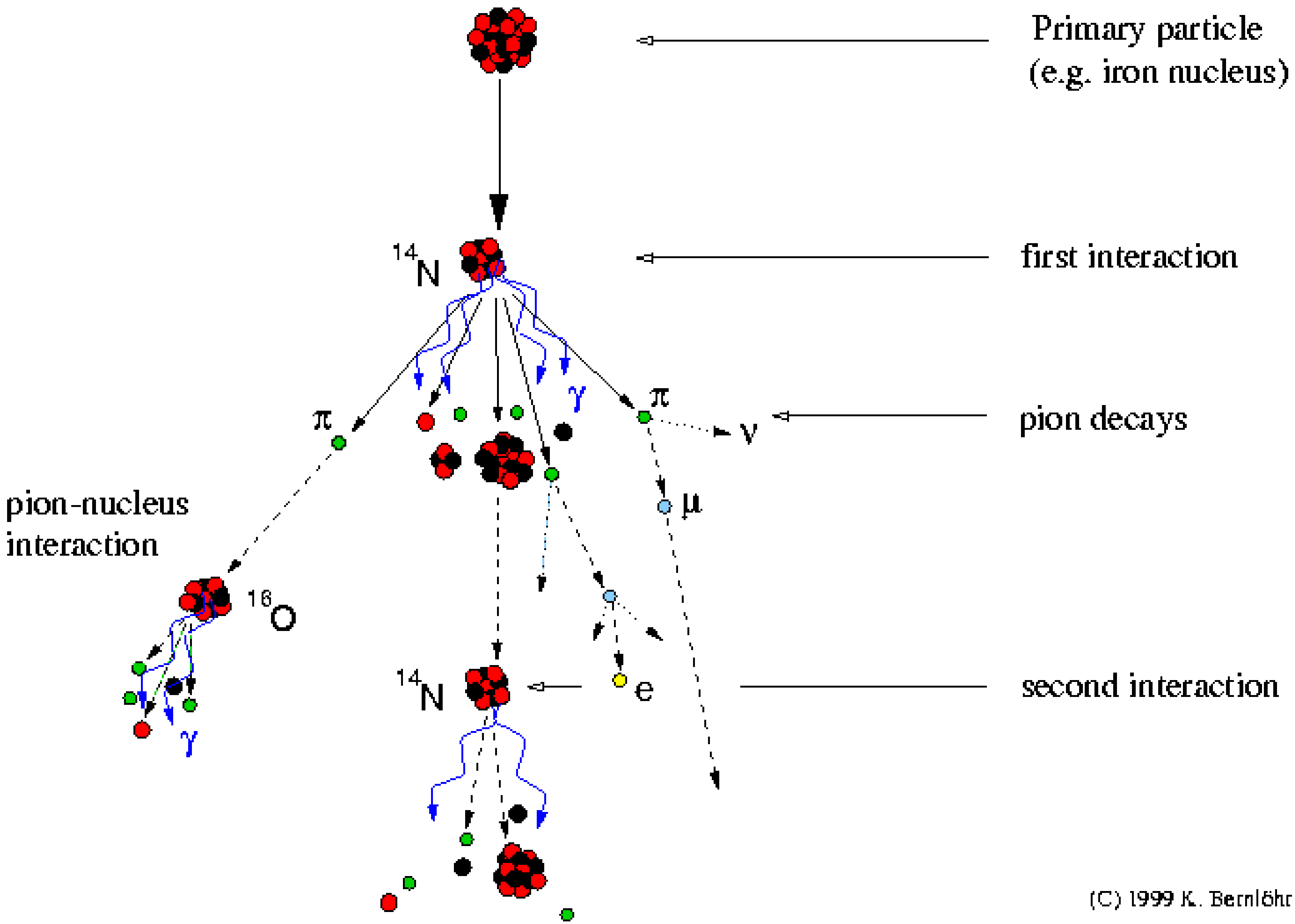
- New particle first interpreted to be the particle predicted by Yukawa as mediator of strong nuclear interaction
- However it was shown in 1941 that mesotrons didn't interact strongly with matter.

History of Cosmic Rays: 1938

- Pierre Auger and Roland Maze - “Extensive Air Showers”
  - Rays in detectors separated by 20m (later 200m) arrive simultaneously
  - “coincidence”

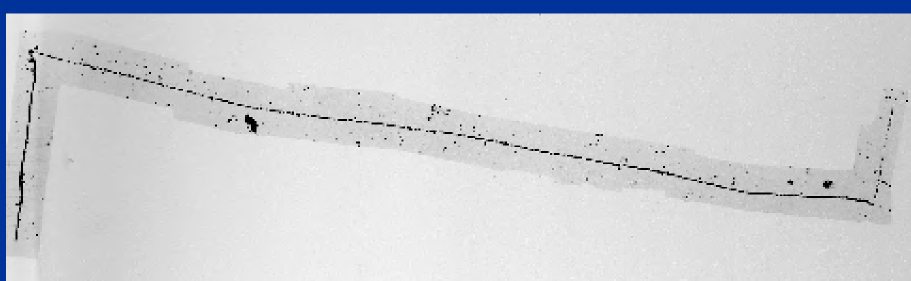


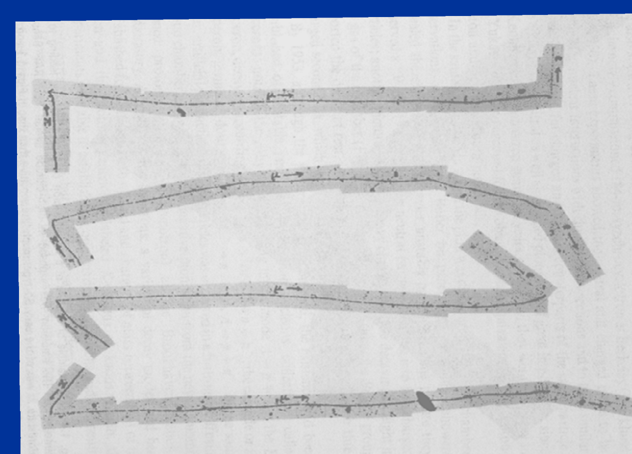
Development of cosmic-ray air showers



Discovery of pion

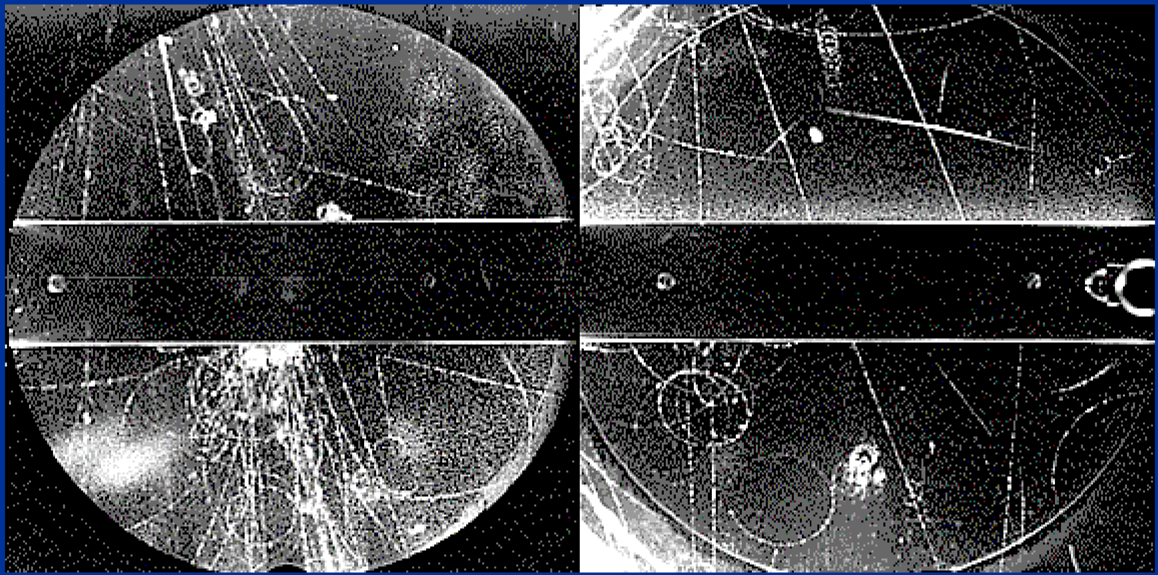
- **Lattes, Occhialini and Powell** (Bristol, 1947) (+ graduate student Hugh Muirhead): observed decay of a new particle into two particles
- decay products:
  - muon (discovered 1937),
  - the other is invisible (**Pauli's** neutrino).
- muon in turn also decays into electron and neutrino





Kaons

- First observation of Kaons:
  - Experiment by Clifford Butler and George Rochester at Manchester



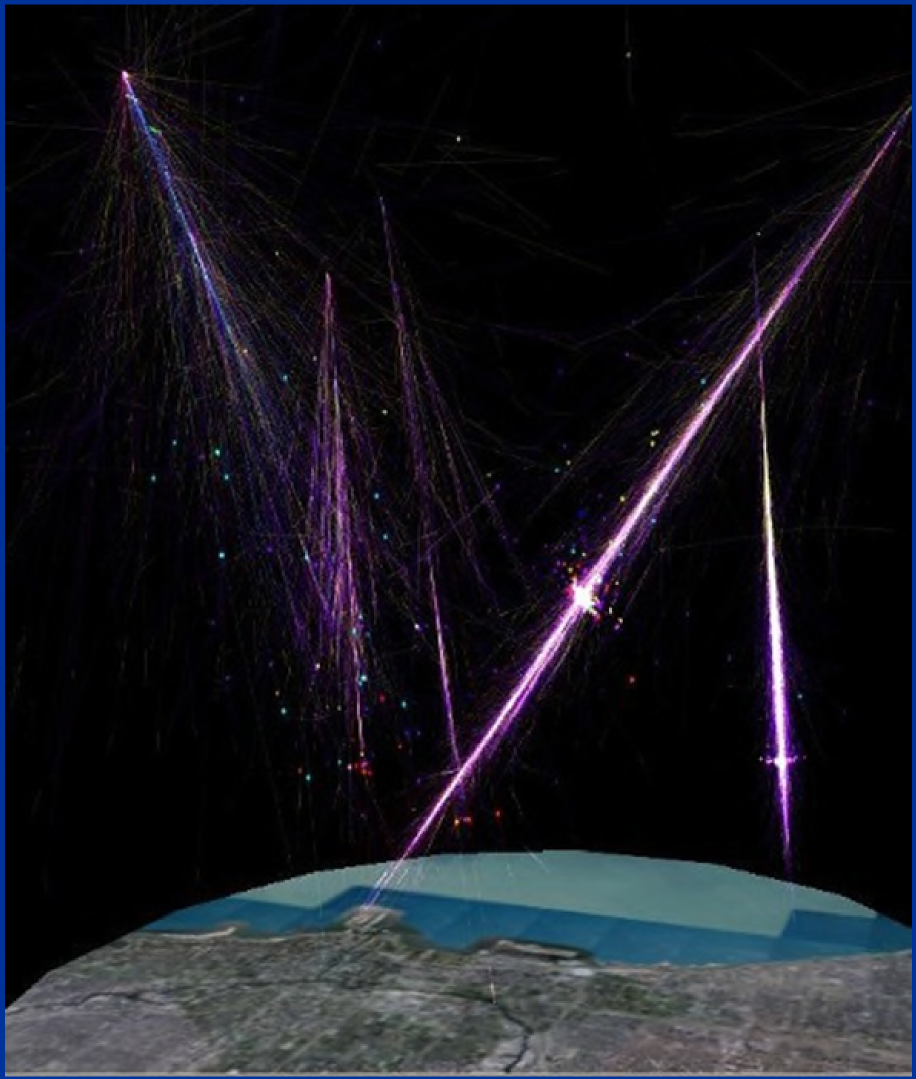
- Cloud chamber exposed to cosmic rays
- Left picture: neutral Kaon decay (1946)
- Right picture: charged Kaon decay into muon and neutrino
- Kaons first called “V” particles
- Called “strange” because they behaved differently from others

What are cosmic rays?

- Cosmic rays are high energy particles from outer space.
- About 1000 cosmic rays per second strike each square meter area of Earth's atmosphere.
- Most cosmic rays are produced in our Galaxy by supernova explosions and by objects such as neutron stars and black holes.
- Large fraction of very low energy cosmic rays produced by the Sun, with maxima during violent events called flares and coronal mass ejections (solar storms).
- About 89 % of Galactic cosmic rays are protons, 9 % are helium nuclei, and the rest are nuclei of heavier atoms.
- Extragalactic CR: origin unknown, composition unknown, but probably mostly protons

CR showers

(artist's impression)

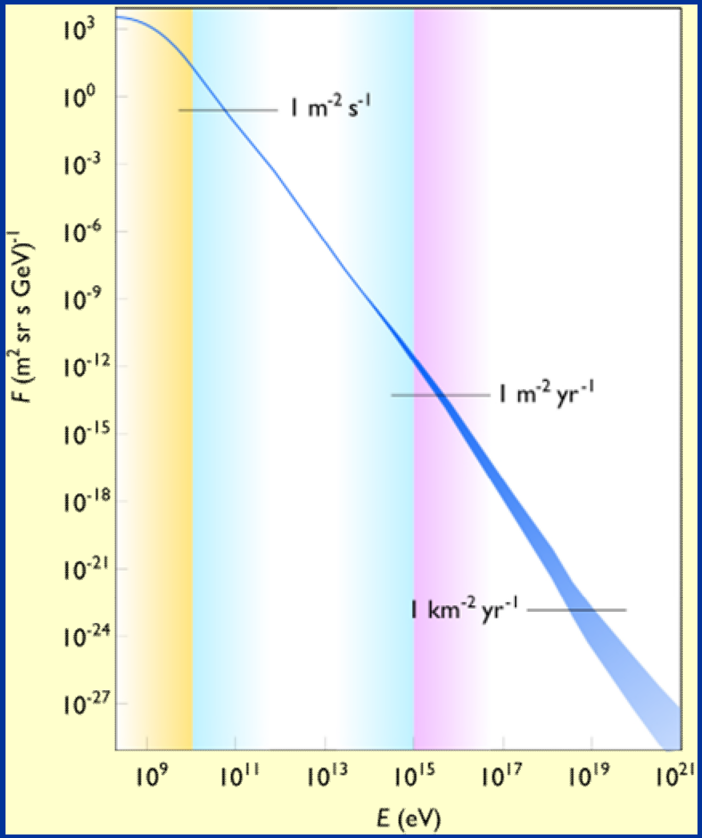


Flux vs energy

$<10^{10}$ eV: many solar

$<10^{15}$ eV: mostly galactic

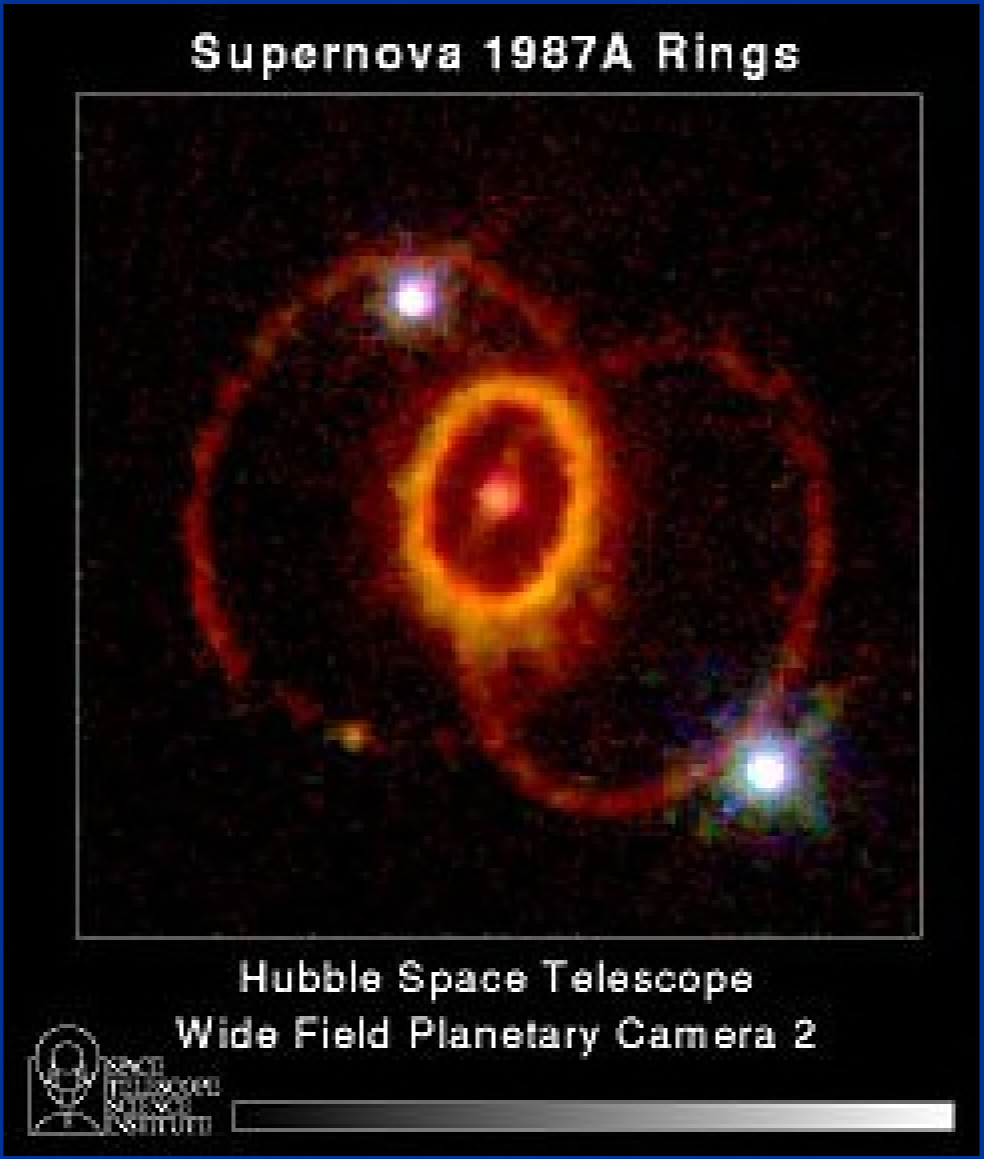
$>10^{15}$ eV: extragalactic



https://commons.wikimedia.org/wiki/File:Cosmic_ray_flux_versus_particle_energy.svg#/media/File:Cosmic_ray_flux_versus_particle_energy.svg

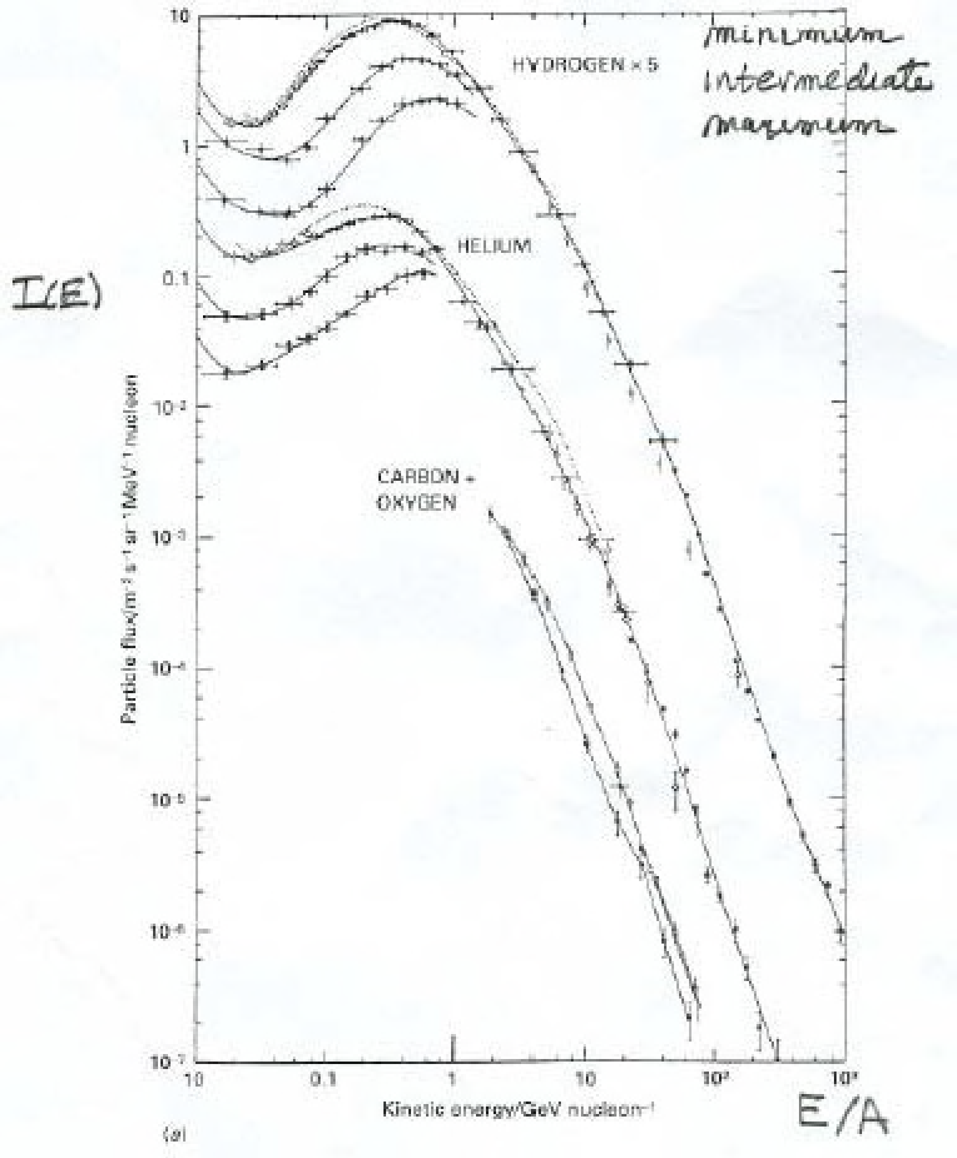
CRs from Supernovae

- Cosmic rays produced by
  - supernova explosions
  - neutron stars
  - AGNs (“active galactic nuclei”) (with black holes)
  - Quasars
  - Gamma ray bursts
  - …. ?
- Photo of the remains of Supernova 1987A:
  - taken by Hubble Space Telescope in 1994 (7 years after observation of SN explosion)



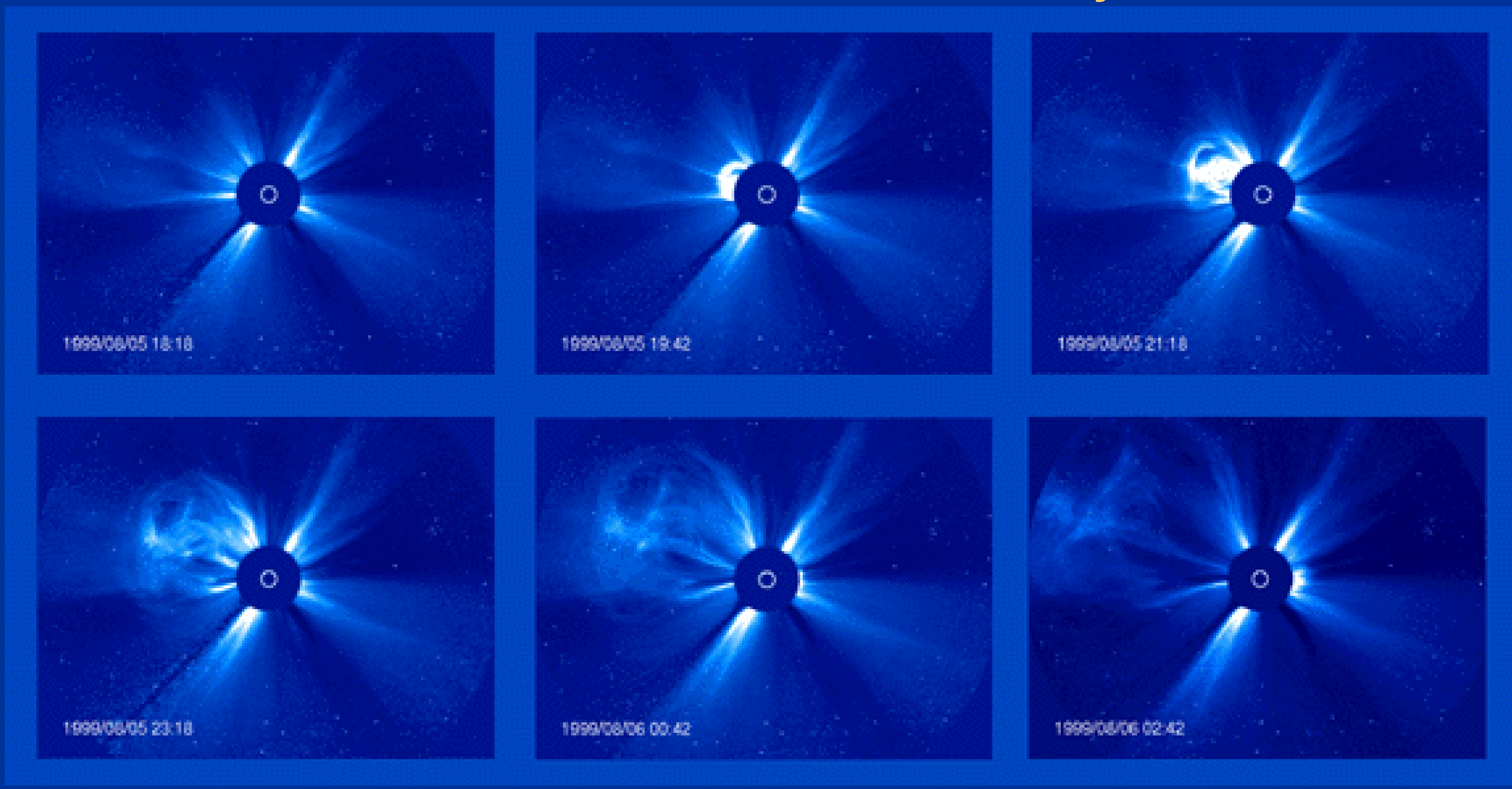
Solar contribution

- Beyond 1GeV/nucleon, I(E) decreases rapidly with E (approximate power law, $(E/GeV)^{-2.75}$
- low-energy behavior more complicated, strongly influenced by what happens in the Sun
- figure shows spectra at three levels of solar activity: Sun changes the CR intensity at low energies



CRs from Sun

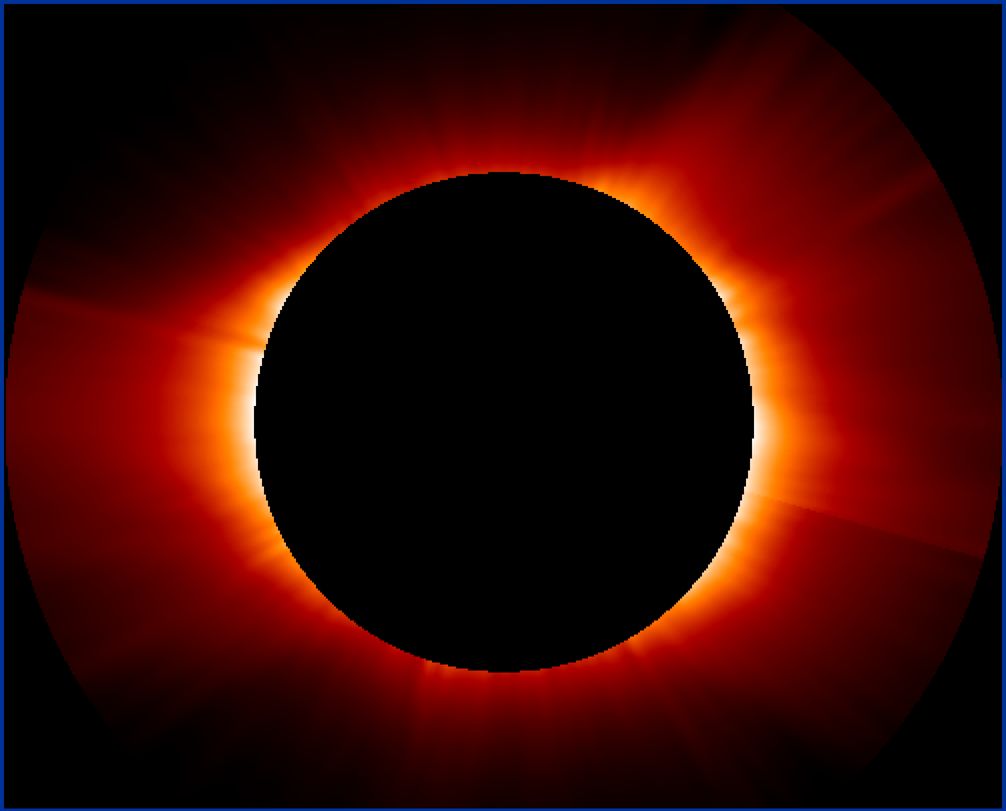
- Cosmic rays are also produced by the Sun during violent events called coronal mass ejections.



Sequence of SOHO images showing a coronal mass ejection (CME) exploding outward from the Sun (http://sohowww.nascom.nasa.gov/home.html) (ESA + NASA)

Solar Wind

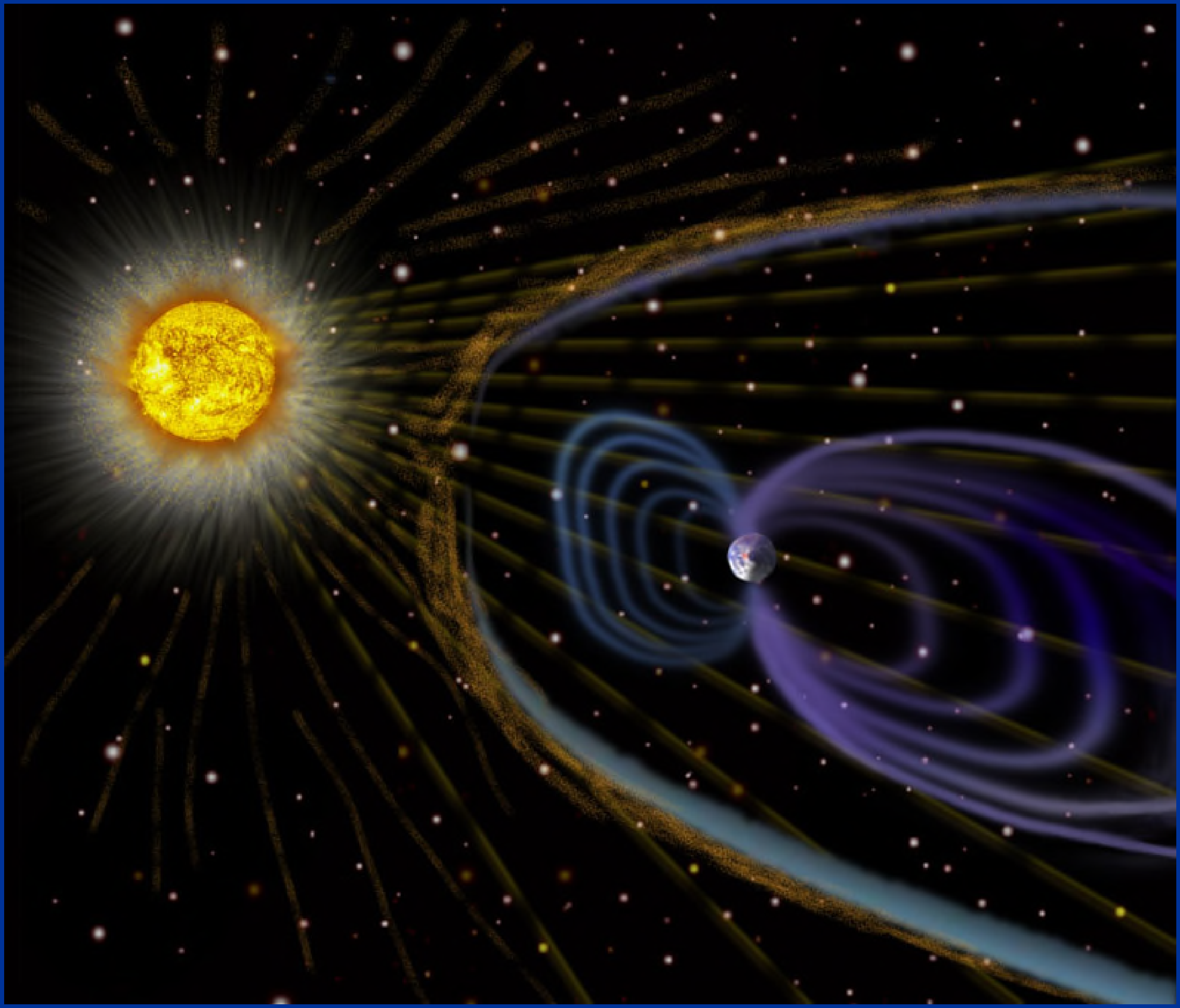
- S.W. = stream of plasma released from the upper atmosphere of the Sun.
- mostly electrons, protons and alpha particles
- Mass loss of Sun: 1 Mton/s
- energies usually between 1.5 and 10 keV.
- Speeds ≈ 400km/s
- varies in density, temperature, and speed over time and over solar longitude.
- emitted from the corona (outermost layer of Sun's atmosphere, very hot (≈ $1.5 \cdot 10^6$ K))



The Sun's corona, taken by the SOHO satellite with a special camera that blocks out light from the Sun's main disk. Courtesy of SOHO consortium. SOHO is a project of international cooperation between ESA and NASA."

Interaction of solar wind with Earth's magnetosphere

- Interaction of solar wind with Earth's magnetic field ⇒ modification of E mag field
- Particles deflected, low energy particles travel around Earth
- some trapped in Van Allen belt
- Some channeled to poles (spiral around mag field lines) ⇒ aurora



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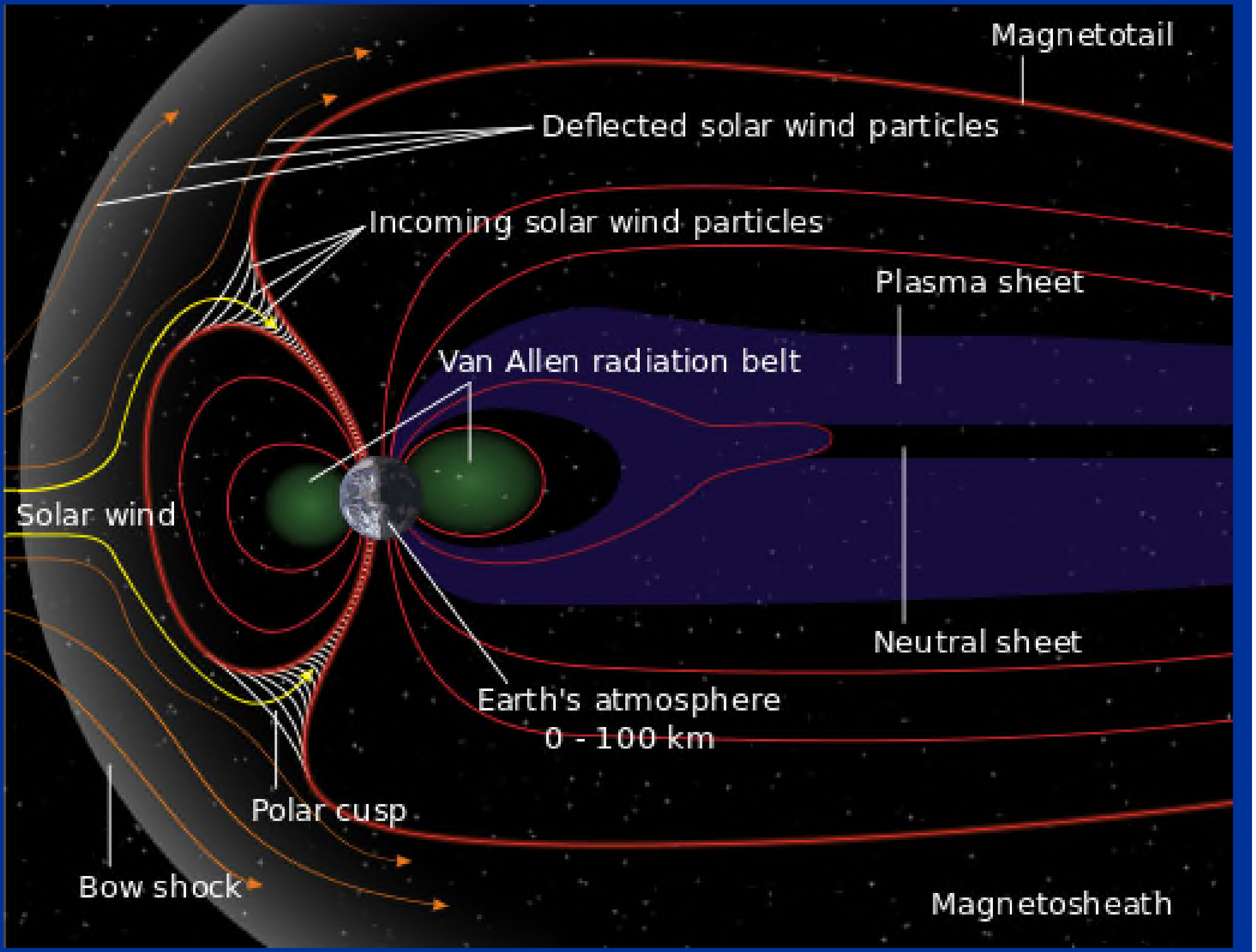


https://en.wikipedia.org/wiki/Solar_wind
http://solarscience.msfc.nasa.gov/SolarWind.shtml
http://helios.gsfc.nasa.gov/sw.html

Effects of the Earth's Magnetic Field

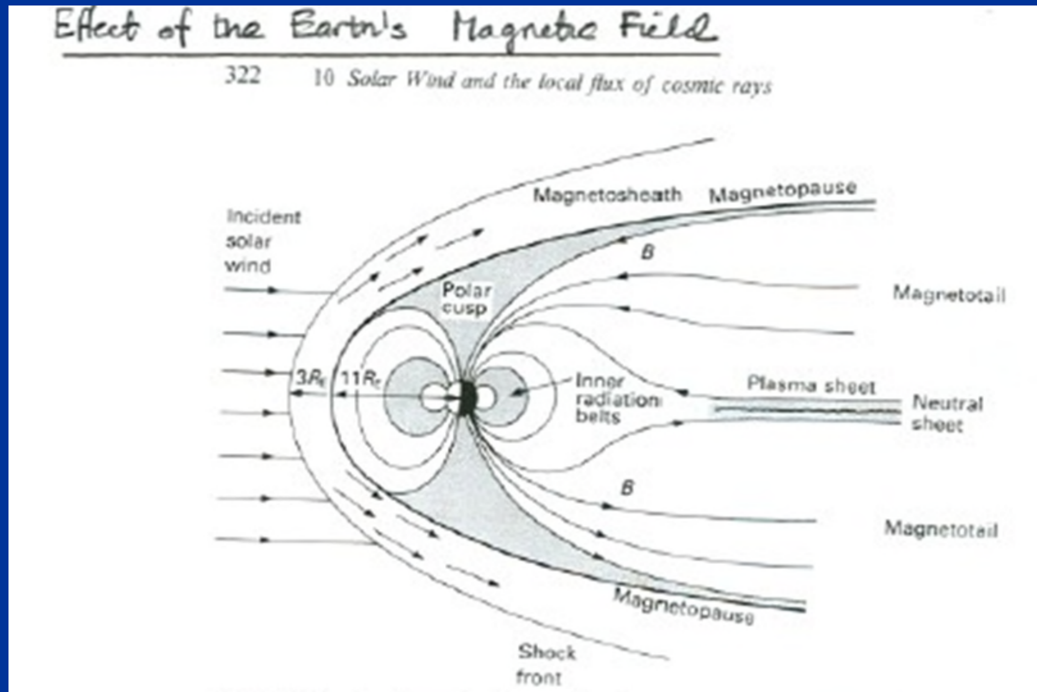
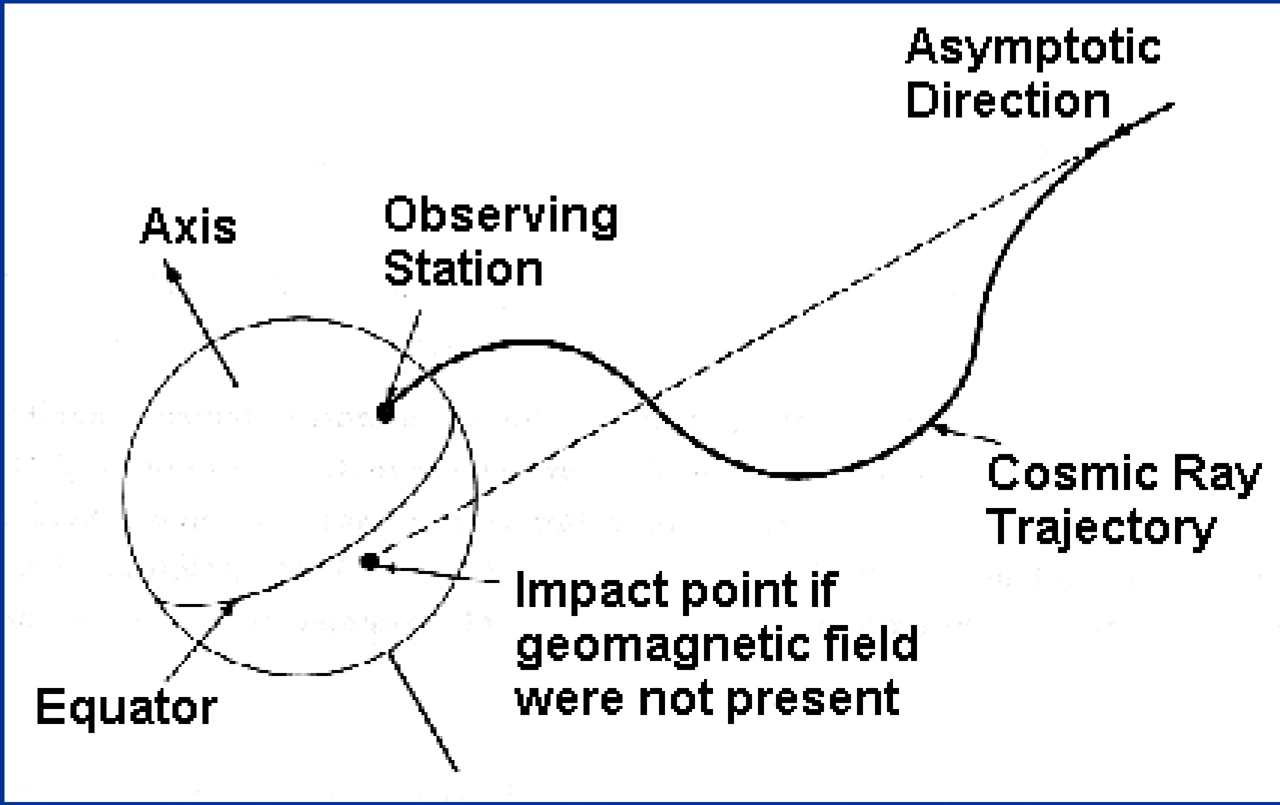


Figure 10.12. A schematic diagram showing the structure of the Earth's magnetosphere. The names of the various regions are shown.

- The effects of the Earth's magnetic field have been studied extensively for more than 100 years and are reasonably well understood. Satellite observations of CRs extend beyond this region.

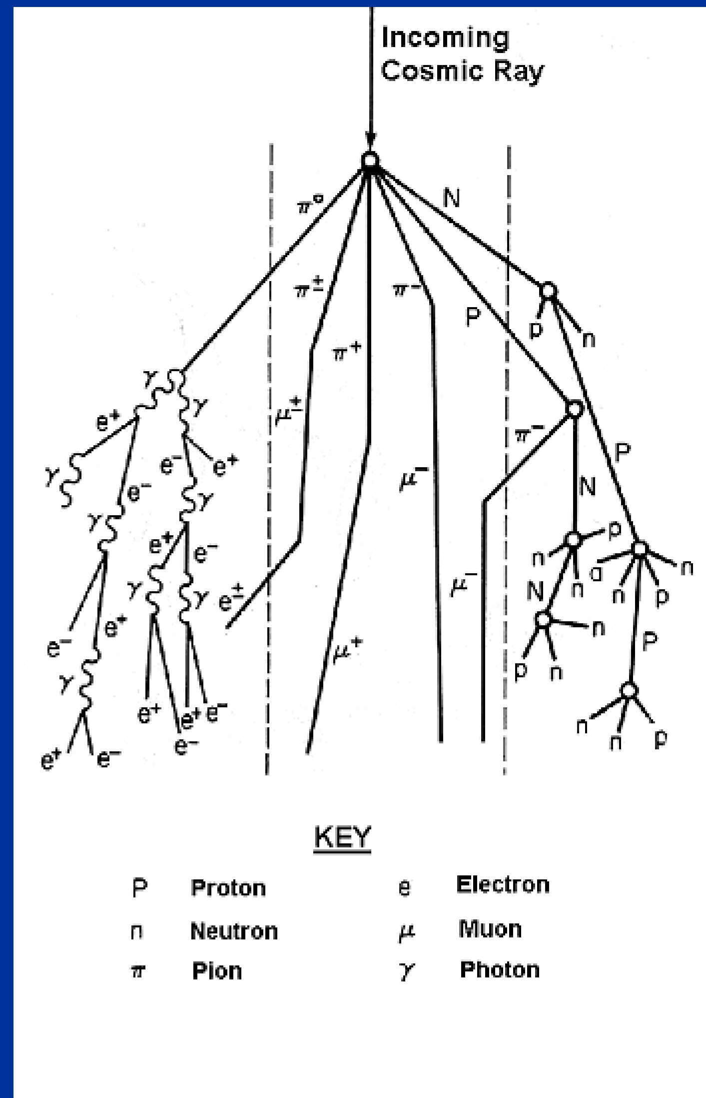
Cosmic rays and Earth

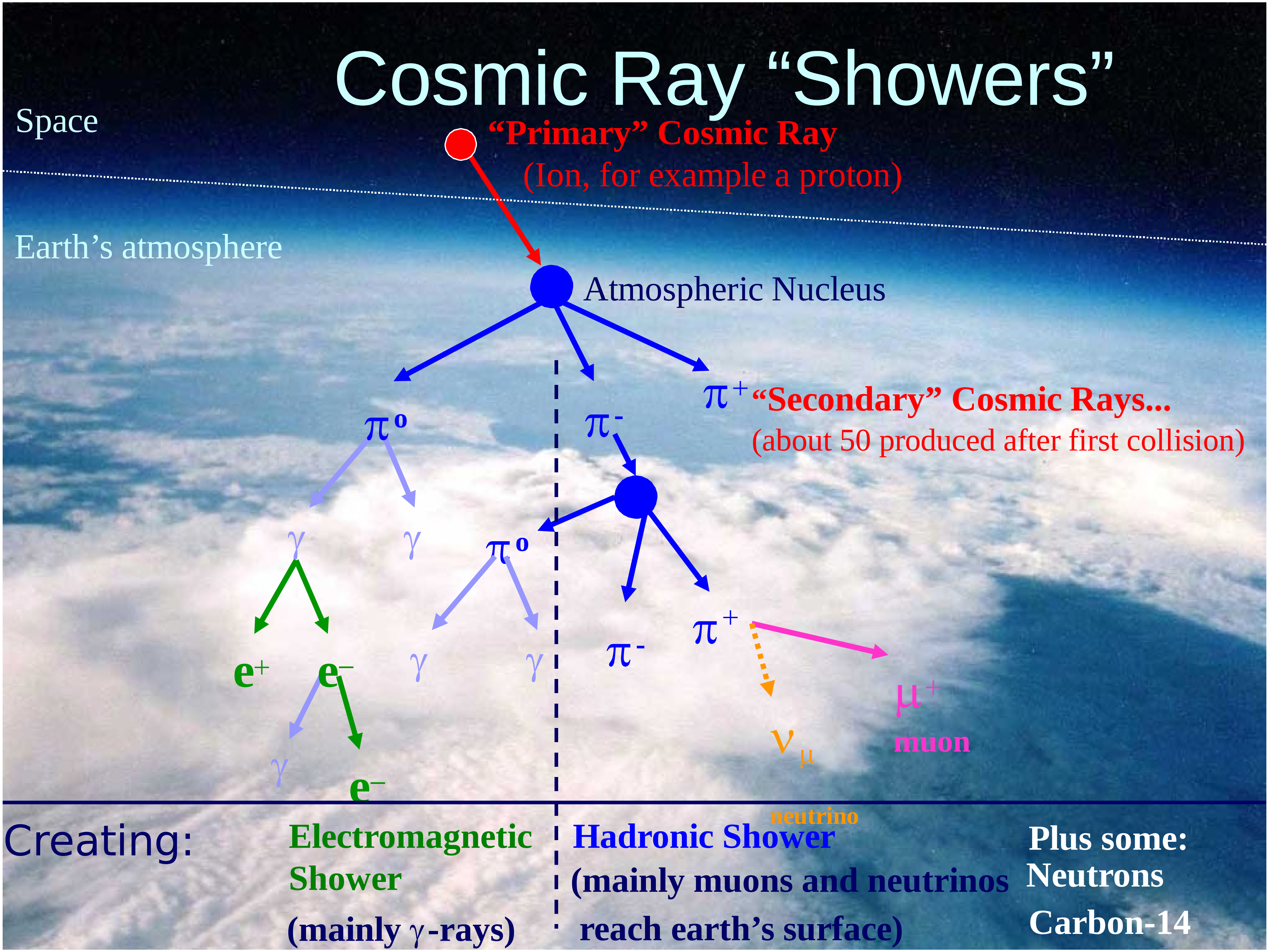


- cosmic ray approaching Earth first encounters Earth's magnetic field.
- magnetic field repels some particles altogether. Those that get through are deflected by the magnetic field.
- Computer simulations to determine how the starting direction ("asymptotic direction") is related to the impact point.

Cosmic ray showers (cascade)

- Collision of primary cosmic ray with atom in Earth's atmosphere, ⇒ produce one or more new energetic particles -- "secondary" cosmic rays
- secondary particles strike other atmospheric atoms ⇒ still more secondary cosmic rays ⇒ “atmospheric cascade”
- If energy of primary cosmic ray high enough (>500 MeV) ⇒ particles produced in cascade can reach Earth's surface




Cosmic Ray “Showers”
Space
“Primary” Cosmic Ray
(Ion, for example a proton)
Earth’s atmosphere
Atmospheric Nucleus
π+ “Secondary” Cosmic Rays...
(about 50 produced after first collision)
πo
π-
γ
γ
πo
γ
γ
e+
e–
γ
e–
π-
π+
νμ
neutrino
μ+
muon
Creating:
Electromagnetic Shower
(mainly γ-rays)
Hadronic Shower
(mainly muons and neutrinos reach earth’s surface)
Plus some:
Neutrons
Carbon-14

Energy loss in atmosphere

- Most CRs have E < 1 GeV
- particles created in showers interact primarily with atomic electrons, exciting & ionizing atoms
- For E>10 MeV, range ~ scales with energy as $E^{5/3}$
- range of a 10 MeV proton is only ~ 112cm
  (1.3 g cm^{-2})

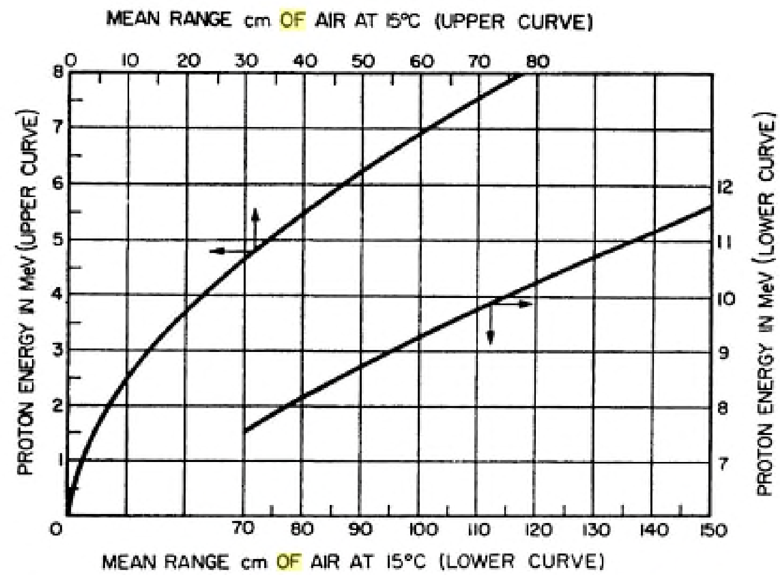


FIG. 2.1. Range–energy relation for protons in dry air at 15°C and 760 mm Hg pressure (Evans, 1955).

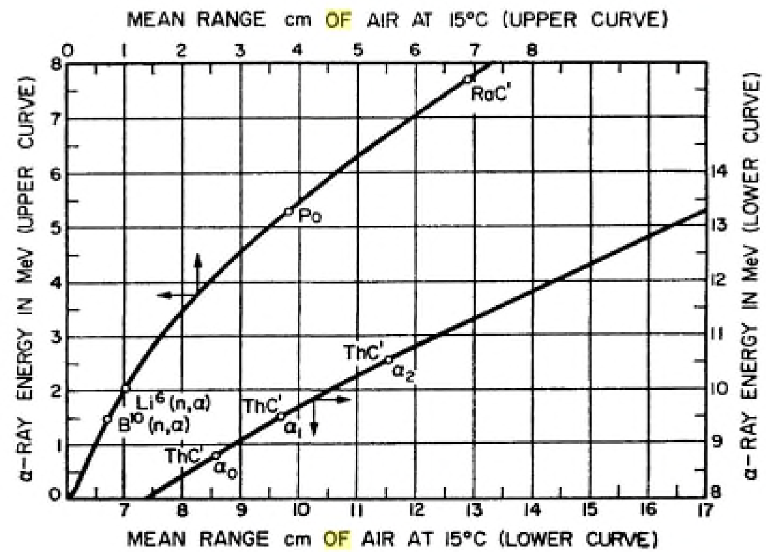
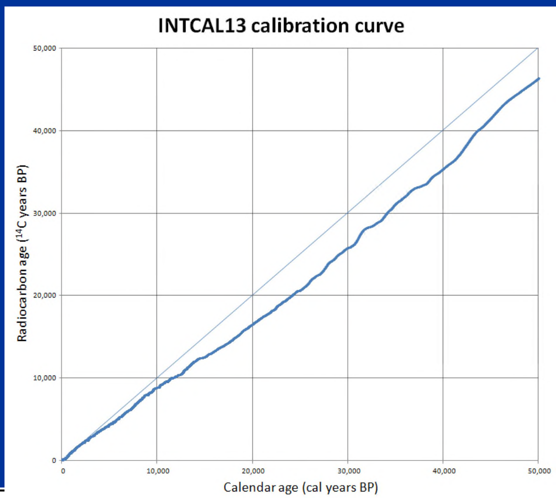
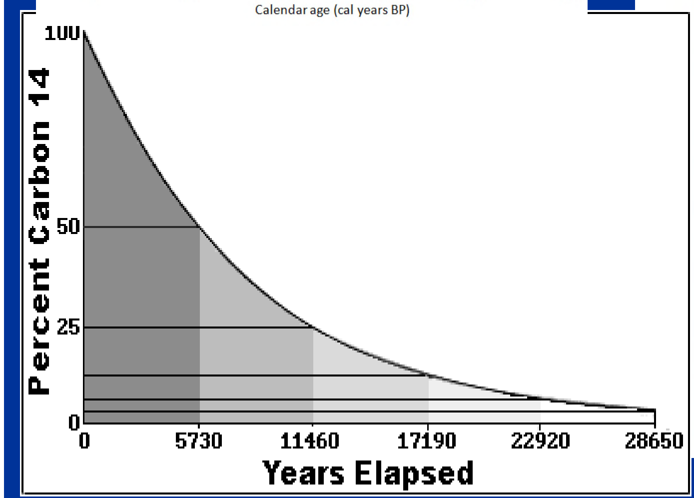


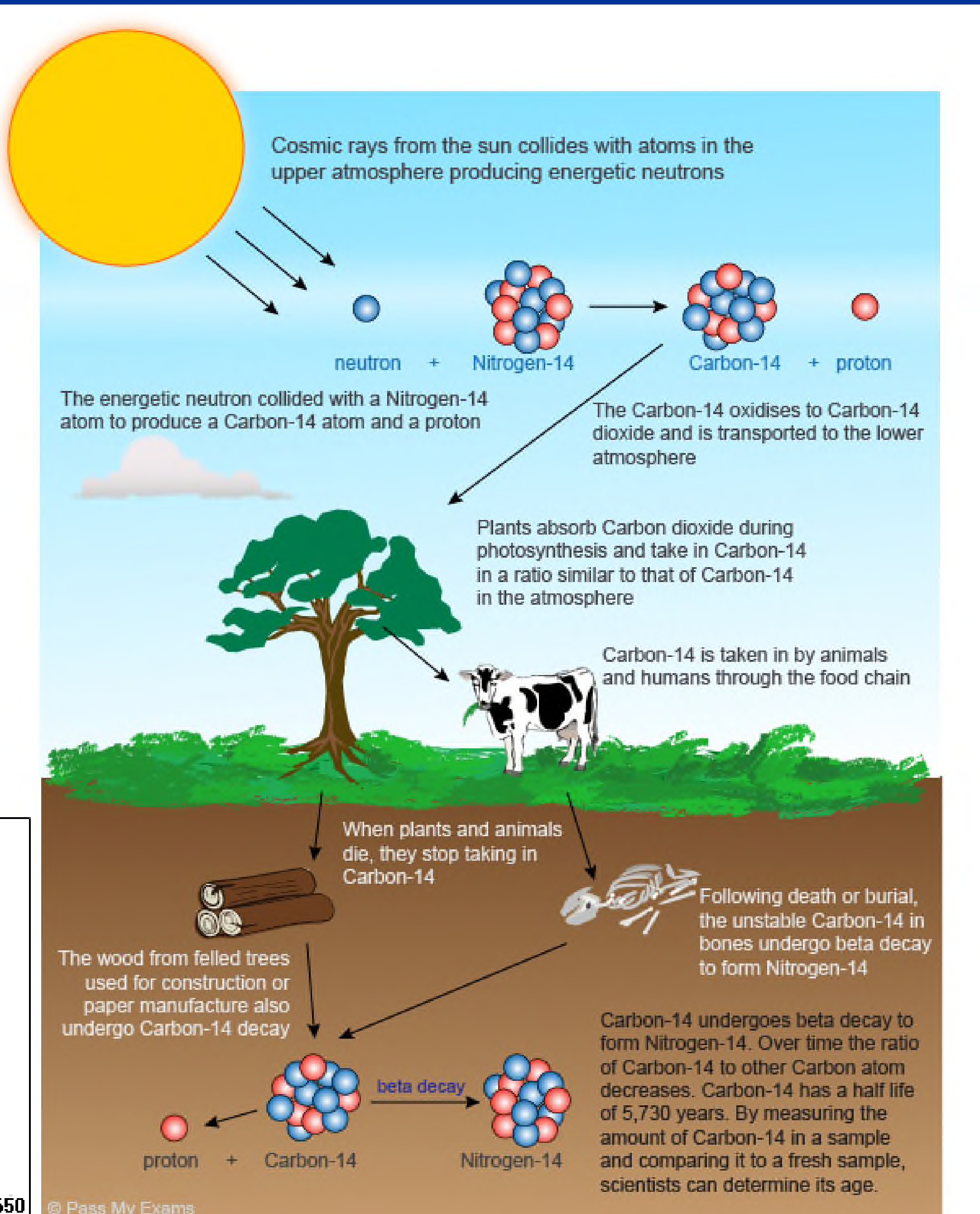
FIG. 2.2. Range–energy relation for α-particles in dry air at 15°C and 760 mm Hg pressure (Evans, 1955).

Radiocarbon dating

- Works up to 50,000 years
- Calibration and understanding time dependence of cosmic ray flux crucial

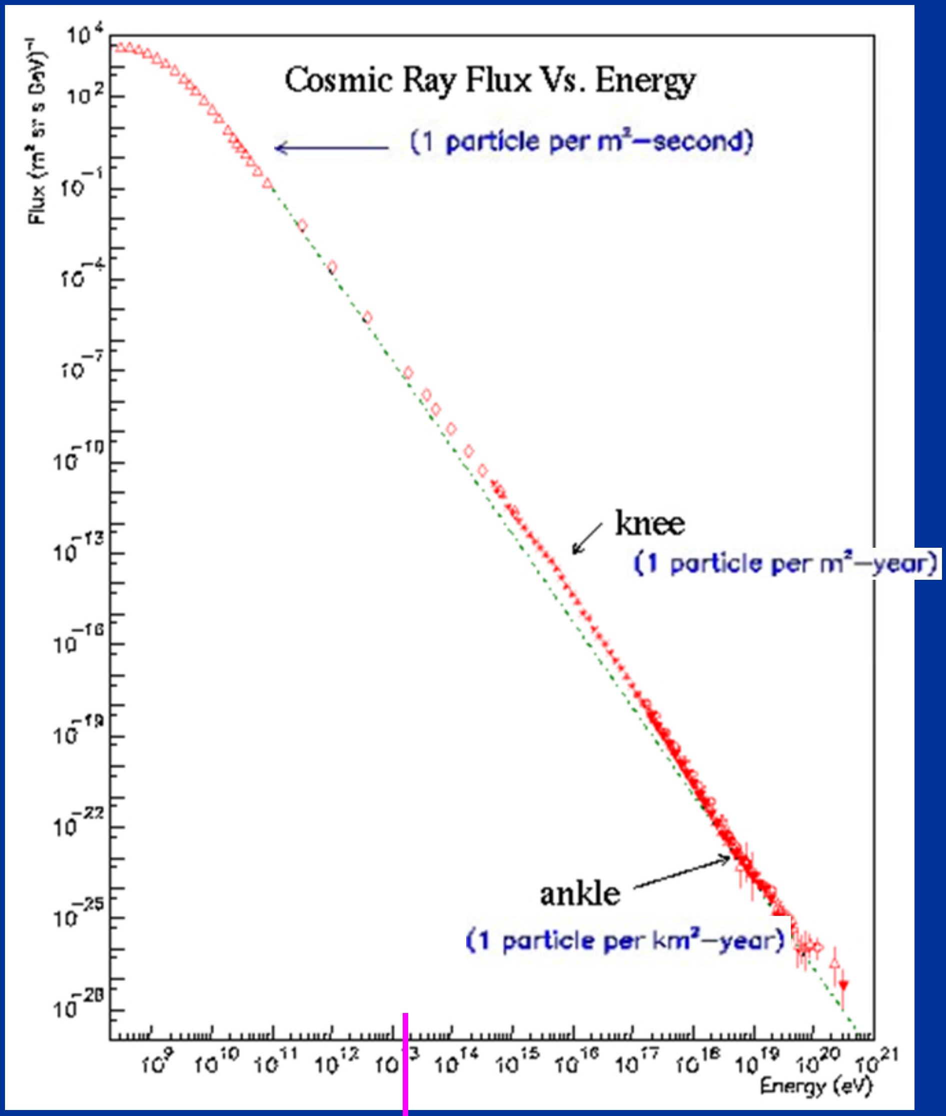






Primary Cosmic Rays

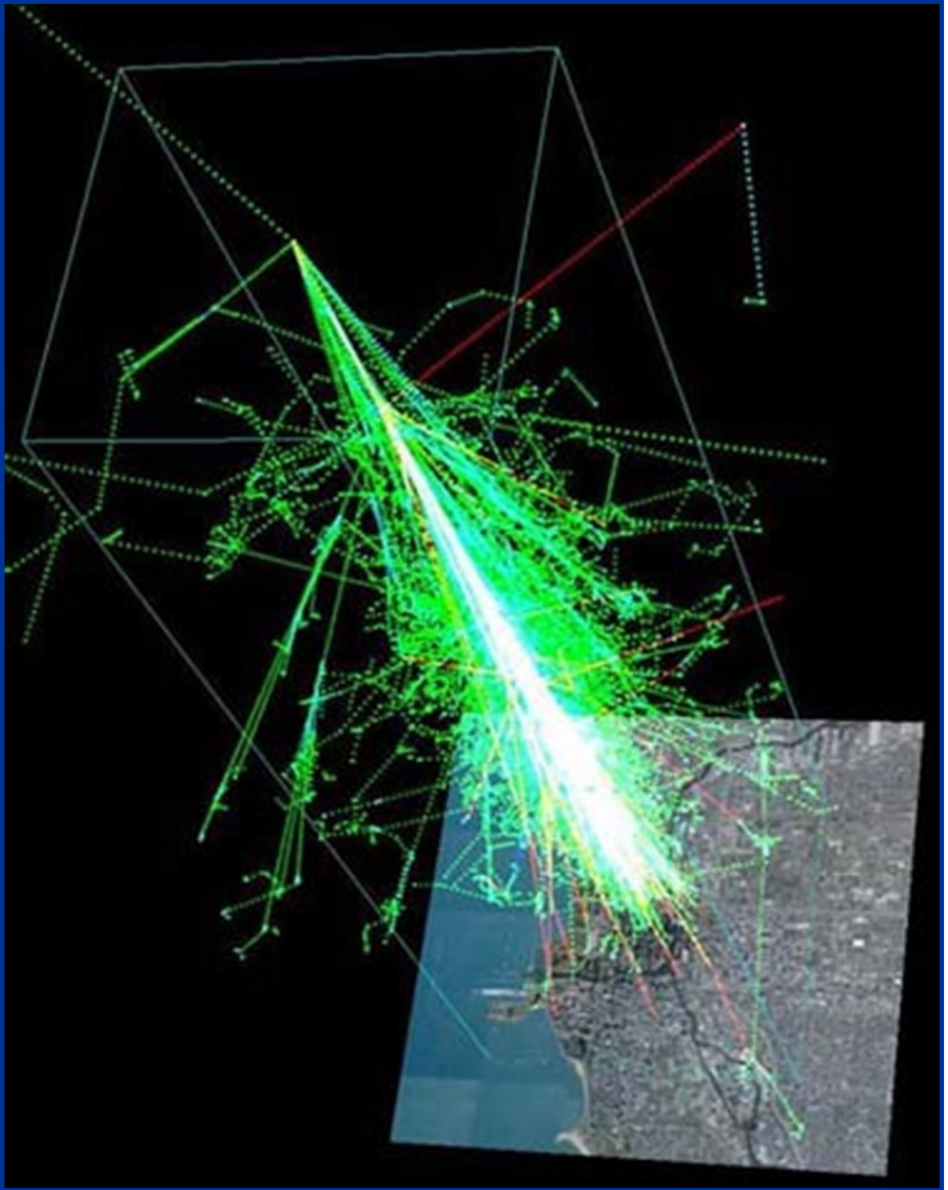
- composition:
  - Mostly H (≈89%) and He (9%) nuclei (p, α)
  - heavier elements (≈1%) (Li, Be, B..)
  - Electrons (≈1%)
- energy spectrum:
  - Peak at ≈ 0.3 GeV
  - Very steep fall-off with energy, steepening at “knee”, resume at “ankle”
  - Lower-energy CRs are common, high- energy CRs are rare
- Flux = nb/((unit area) × (unit solid angle) × (unit time))



Energy achieved by man-made accelerator

Secondary Cosmic Rays

- Shower particles:
  - Electrons, photons
  - Kaons, pions
  - muons, neutrinos
  - Can travel faster than the speed of light in air (they are still slower than the speed of light in vacuum)
  - 150 muons are striking every square meter of the Earth every second
  - Not all shower particles reach ground – some stopped in atmosphere

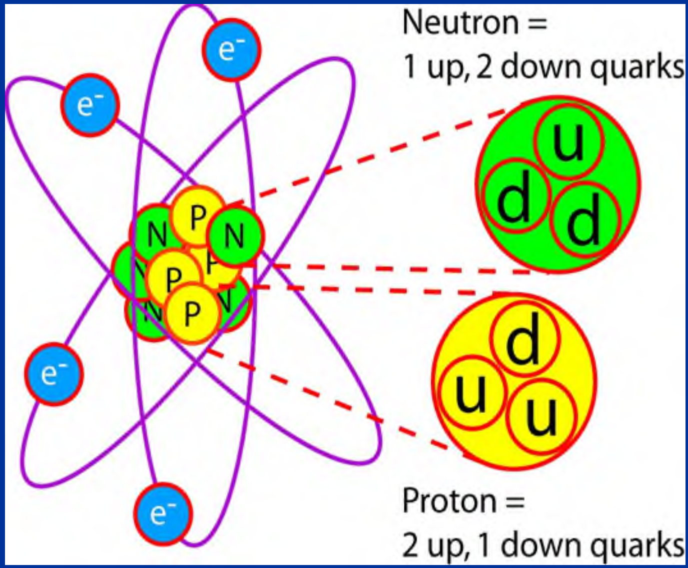


Matter in CR

- Atoms
  - made of protons, neutrons, electrons
  - Protons, neutrons made of quarks (+ gluons)
- Kaons, pions

$$\pi^+ = u\bar{d} \rightarrow \mu^+ \nu_\mu (26ns)$$
$$\pi^- = \bar{u}d \rightarrow \mu^- \bar{\nu}_\mu (26ns)$$
$$\pi^o = (u\bar{u} + d\bar{d}) \rightarrow \gamma\gamma (10^{-17} s)$$

  - made of quarks + gluons

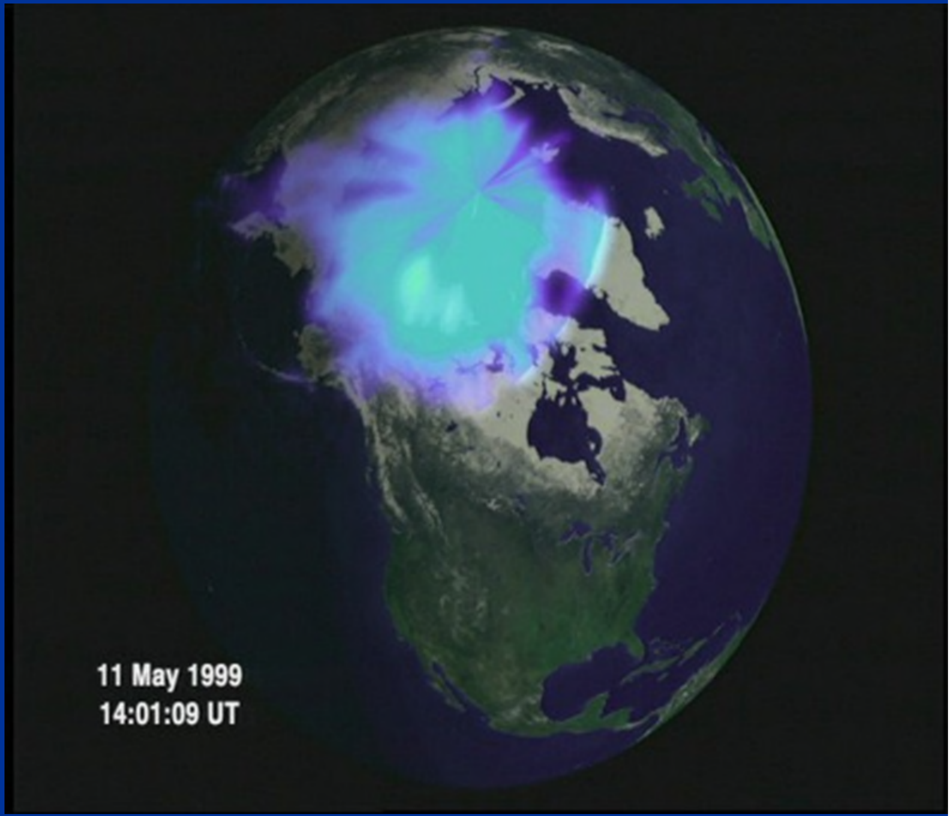


- muons, neutrinos
  - Produced when pions decay
  - Muons make up most of secondary CR that reach Earth's surface
  - Decay into electrons and neutrinos
  - Muons discovered as "penetrating component of CR"

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu (\approx 2\mu s)$$
$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu (\approx 2\mu s)$$

summary

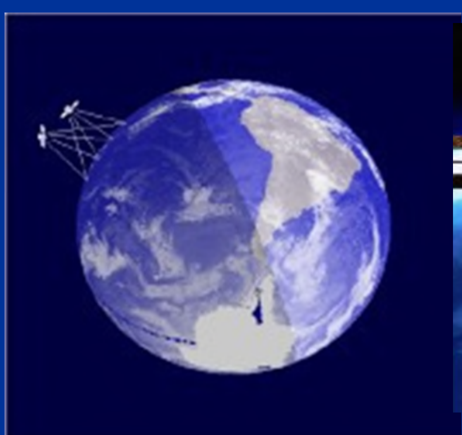
- (primary) cosmic rays are nuclei (mostly H, He, but also some heavier)
- Primary cosmic rays hit the upper atmosphere, releasing showers of secondary cosmic rays
- Even though many CRs reach the Earth's surface, CRs can be slowed and stopped by matter (Hess found more radiation at higher altitude)!
- Flux falls steeply with Energy



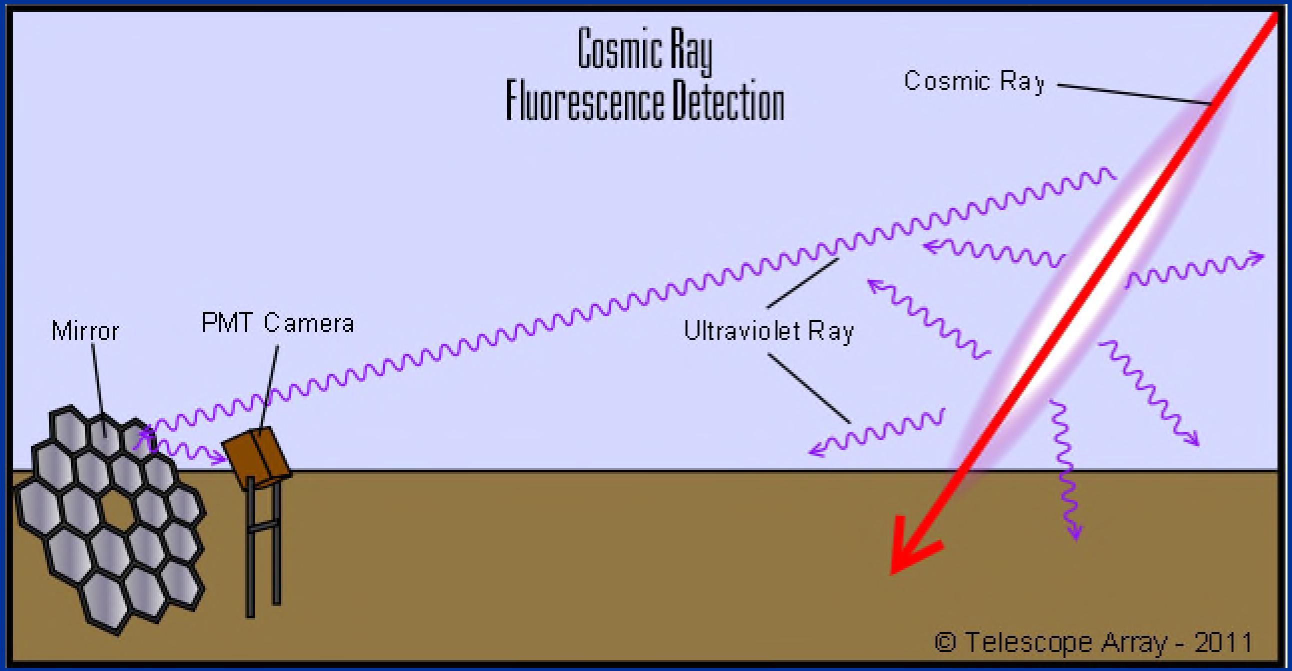
Aurora due to interaction of CR with atmosphere

How to detect cosmic rays

- observatories in space
  - Study the “primary” original cosmic ray w/o interference from the atmosphere
  - Disadvantage:
    - expensive detector
    - too small to “catch” a lot of them



- observatories on the ground
  - Good: cheaper, bigger, and detect a lot more!
  - Bad: measure cascades induced by primary $\Rightarrow$ it takes some work to figure out what the primary is like.
  - Can either detect the particles, or look for the light as those particles bounce off the air and create fluorescence



- Passage of particles through atmosphere
  - ⇒ionization and excitation of the gas molecules (mostly nitrogen).
  - some of this excitation energy is emitted in the form of visible and UV radiation
  - use mirror arrays to collect light and focus on PMTs

CR detectors: bigger is better

- They catch more cosmic rays overall
- Detect more of the ones that are rare! Ultra-high-energy cosmic rays (UHECRs) with more than 10^{18} eV are found only one per square km per century!
- Big area can detect larger shower $\Rightarrow$ from higher-energy CRs

- The West Desert provides an ideal location for fluorescence observations.
  - An altitude of ~4,500 feet where the nearest population centers are more than 30 miles away
  - Light pollution is mostly blocked by the surrounding mountains.
  - For 347 days per year, the visibility is better than 10 miles.

Particle detector arrays

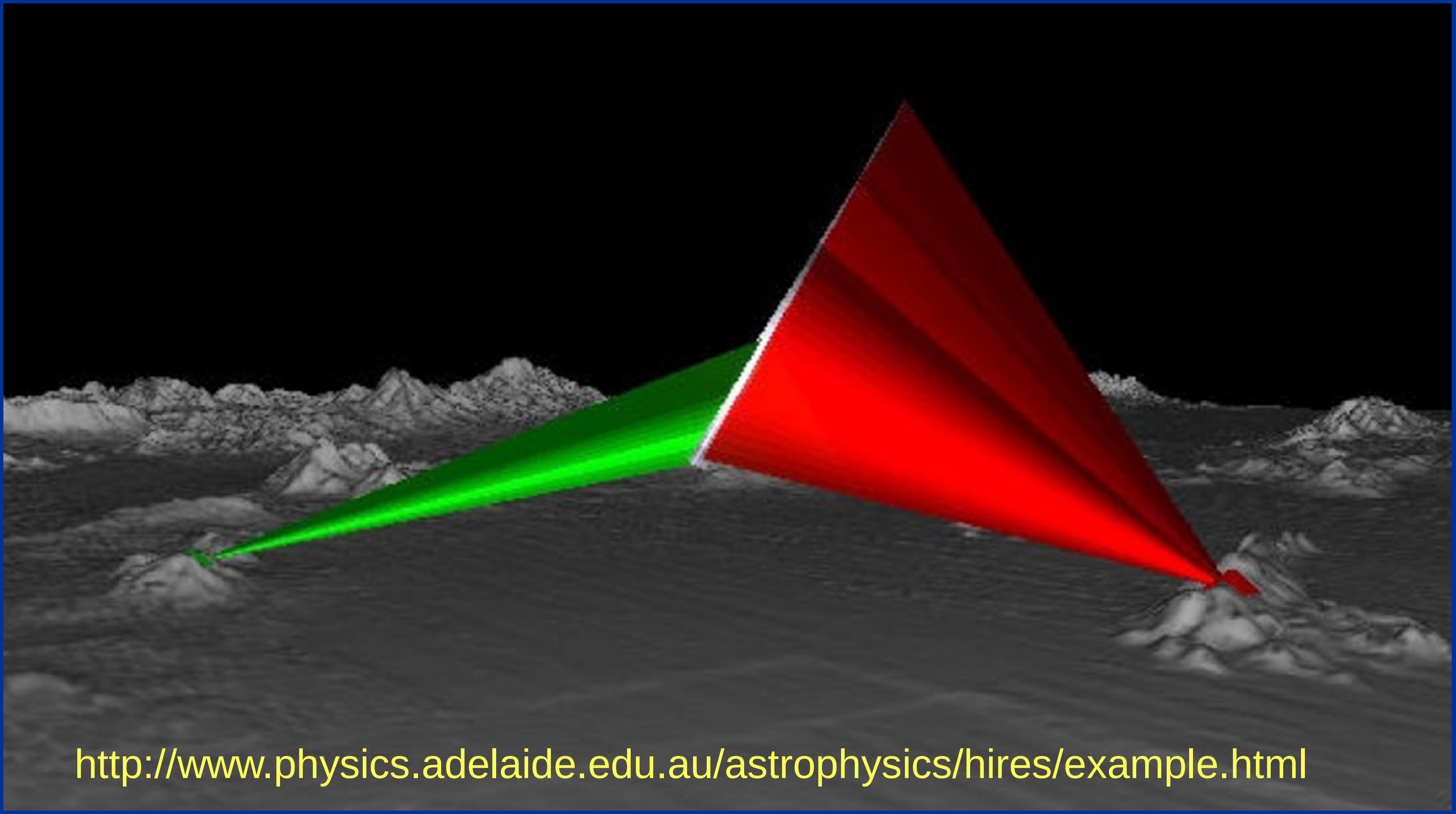
- Casa Mia, Utah (pictured below) – one of the first “big” CR detectors: 1089 detectors spaced 15 meters

Large Observatories

- STACEE: Albuquerque, New Mexico

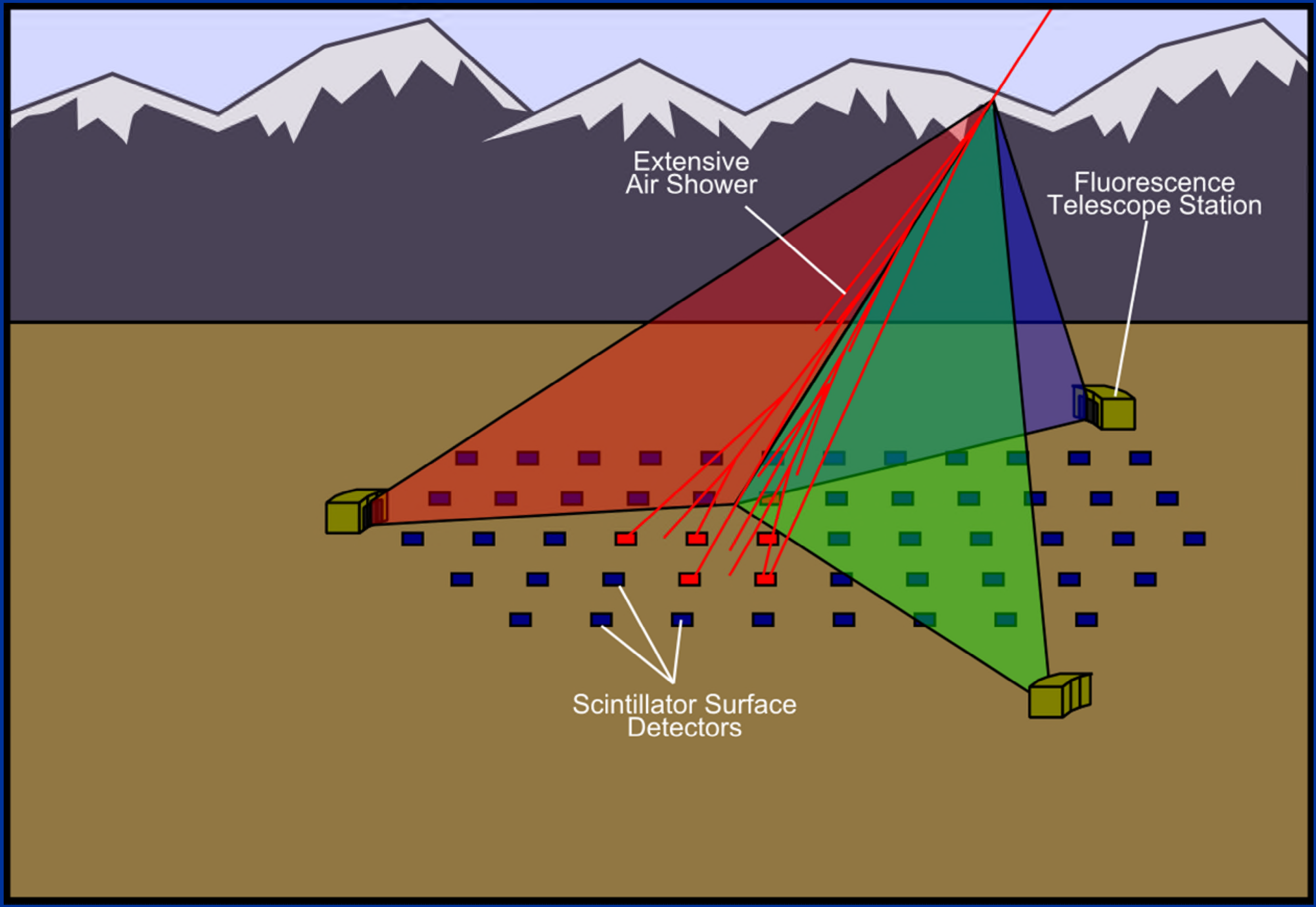
Air scintillation detector

- 1981 – 1992: Fly’s Eye, Utah
- 1999 - present: HiRes, then Telescope Array, same site
  - 2 detector systems for stereo view
  - 42 and 22 mirrors a 2m diameter
  - Each mirror reflects light into 256 photomultipliers
  - Sees showers up to 20-30 km high



http://www.physics.adelaide.edu.au/astrophysics/hires/example.html

Telescope Array



Pierre Auger Project

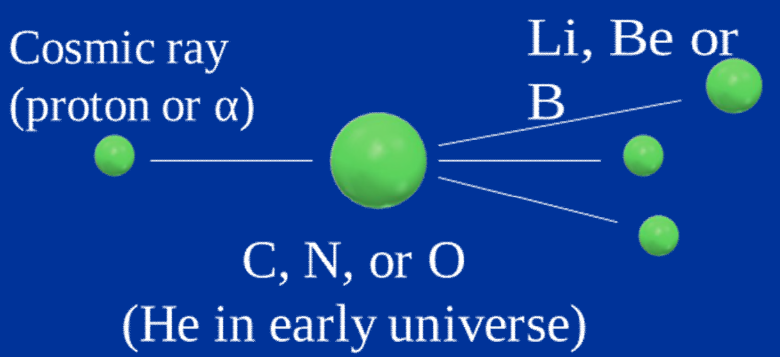
- Pierre Auger Observatory in Las Pampas around Malargue, Argentina.
- Auger North was planned for installation in Eastern Colorado (and reached the status of the Highest Priority of the European Space Agency at one point), but later cancelled.
- PAO comprises 1600 surface detectors covering an area roughly 3000 square kilometers
- observes 10^3 showers/day

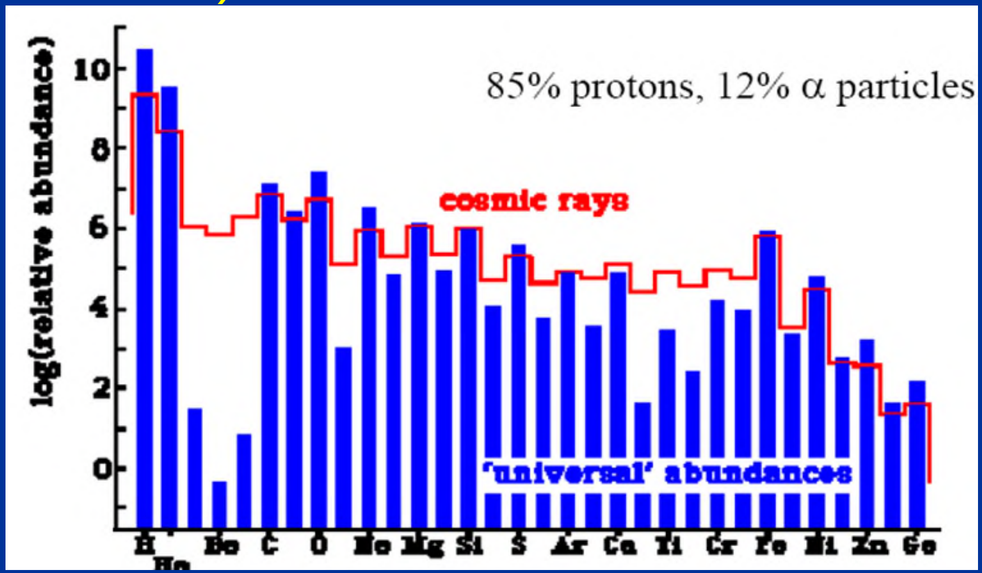
What can we learn from Cosmic Rays?

- Where they come from
- How they are produced
- How they are accelerated
- What elements are in the universe

Elements in the universe

- Abundance of elements:
  - Abundance of elements in CR ≠ abundance in universe
  - Elements heavier than He more frequent in CR than expected
  - Due to collisions of CR with other atoms somewhere in space
  - These collisions are a major source of lithium, beryllium and boron in the universe ("spallation reactions")





Source of cosmic rays

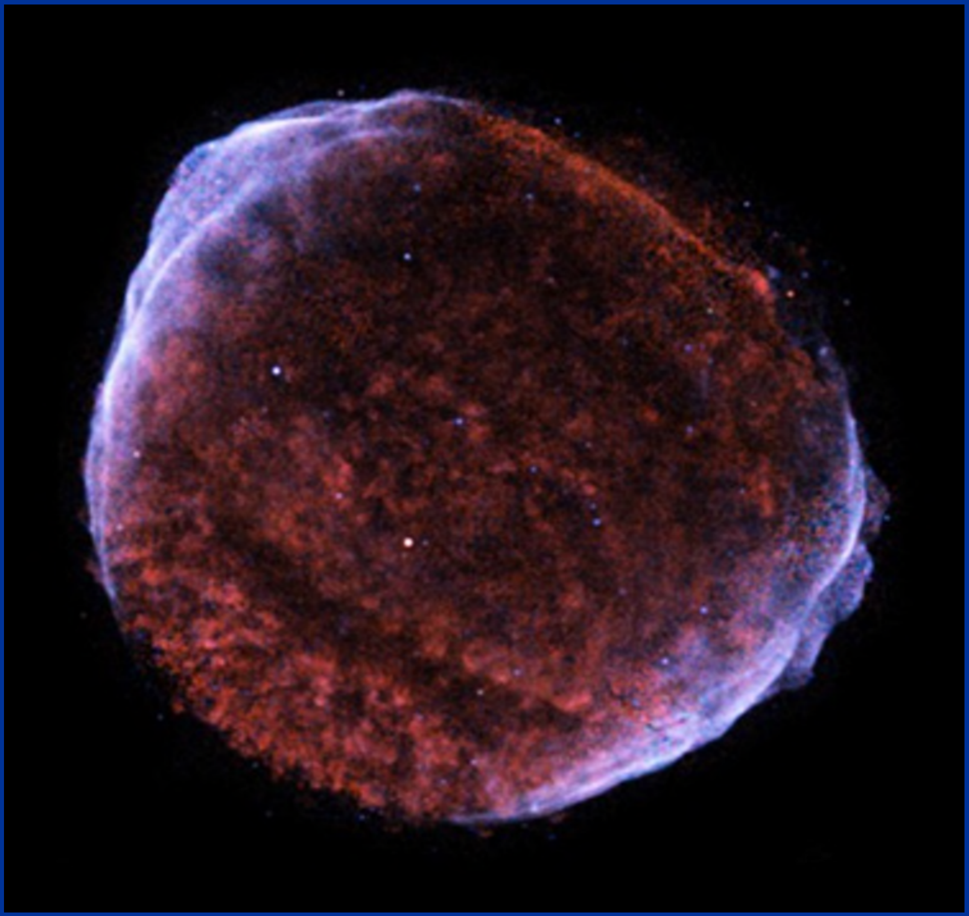
- Stars produce low-energy CRs
  - e.g., “Solar wind” - - protons, α and other particles
- Supernovae produce medium - energy CRs

But what makes “Ultra High Energy Cosmic Rays” (UHECRs), i.e. cosmic rays with $E > 10^{18}$ eV???

CR from SuperNovae

X-ray image by Chandra of Supernova 1006

- Blue: XC-rays from high energy particles
- Red: X-rays from heated gas

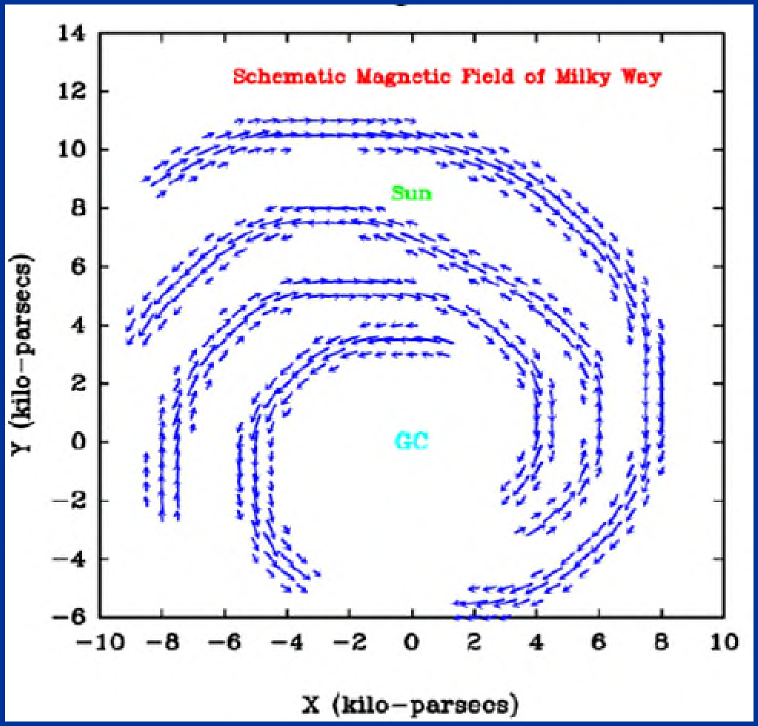


- Shockwave from the supernova hits gas surrounding the explosion, possibly accelerating CRs to 10^{15} eV. Not enough energy for UHECRs!

Sources of HE cosmic rays

- cosmic rays with $E < 10^{18}$ eV deflected in the galactic magnetic field $\Rightarrow$ sources cannot be determined
- But UHECRs (with $E > 10^{18}$ eV) much less deflected (travel straighter) $\Rightarrow$ their direction should point towards their origin

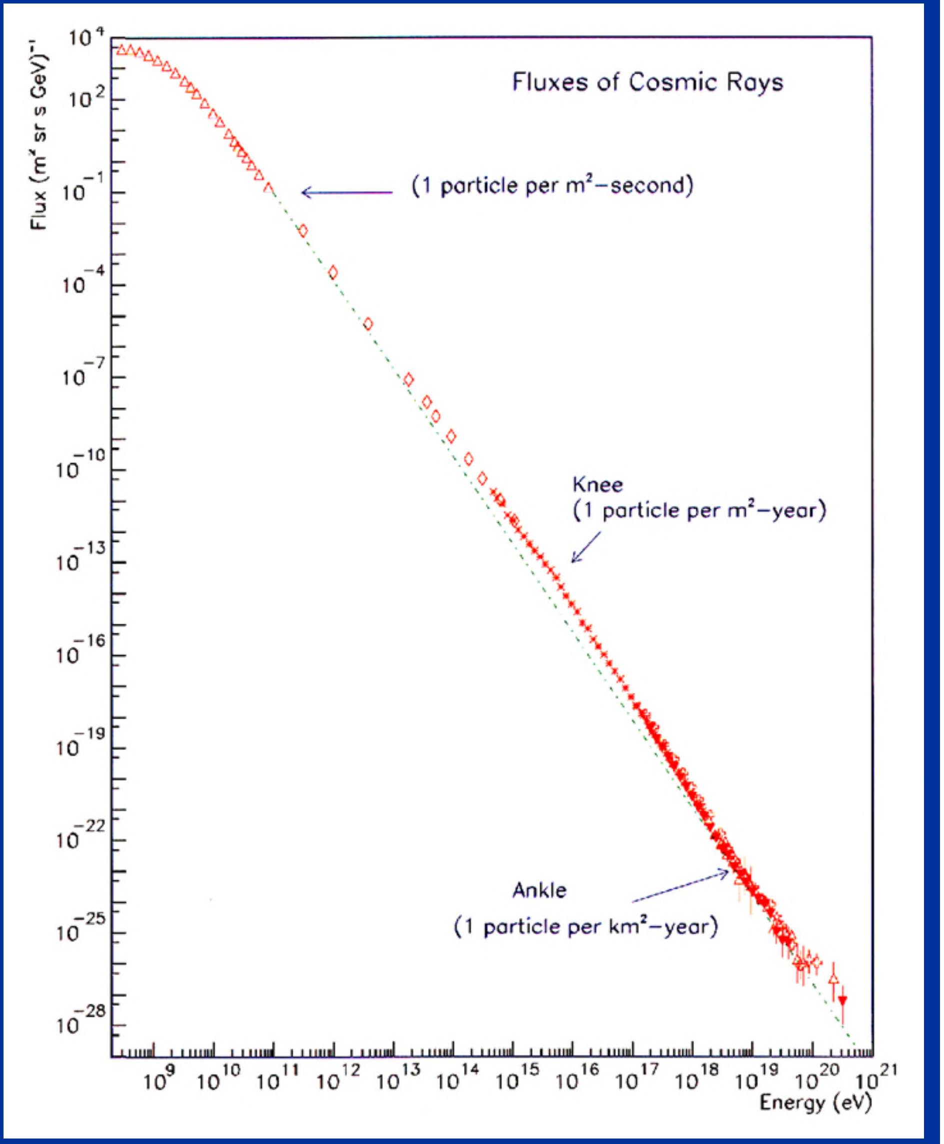
Galactic magnetic field



M83 spiral galaxy

UHECRs very rare

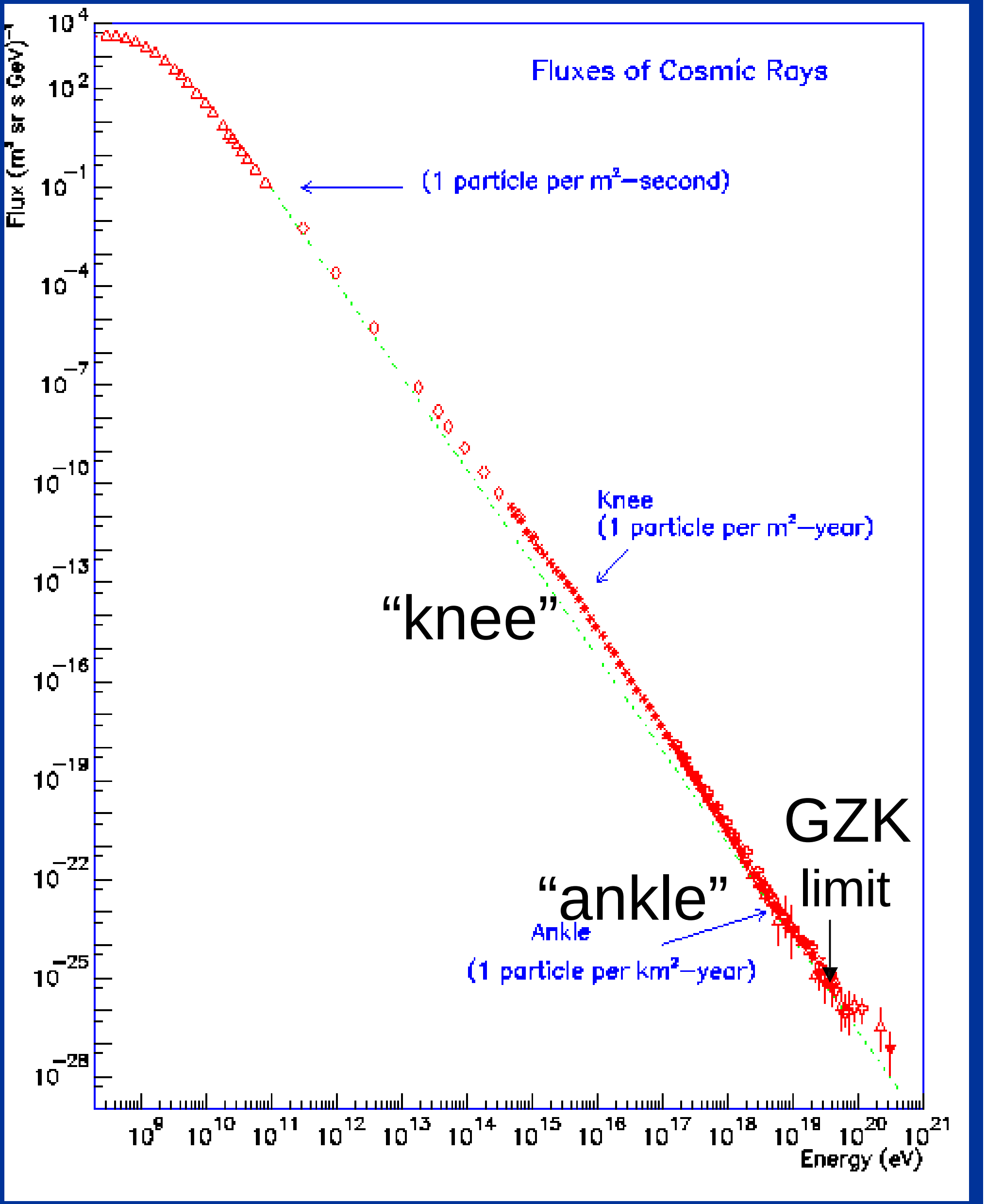
- UHECR:
  - $E>10^{18}$ eV
  - <1 per km^2 per year!
- UHECR detection:
  - very rare
  - $\Rightarrow$ need very large detectors to see them
- Telescope arrays, large collaborations



Energy range of Cosmic Ray Spectrum (10^8-10^{21} eV)

- ❑ Power law defined from 10^{10}-10^{15} eV steepens at the "knee" and recovers beyond the "ankle".
- ❑ The puzzle of ultra high-energy CRs:
  - energy too high for them to be confined by the Galactic B-field,
  - can't be produced by SNe,
  - can't come from very large distances because of interaction with CMB photons

$$I_p(E) = 1.67 \times 10^{-3} \left(\frac{E}{GeV}\right)^{-2.75} cm^{-2} s^{-1} sr^{-1} GeV^{-1}$$



Ultra High Energy Cosmic Rays: GZK cut-off

- UHECRs we have detected appear to come from all directions, $\Rightarrow$ probably come from far away (only sources nearby are galaxies in few directions)
- Problem: UHECRs should lose energy when traveling long distances (> 50Mpc)
  - Interaction with CMB $\Rightarrow$ GZK cut-off
- Another problem: have no working model of mechanism of acceleration to such

GZK cut-off

- Interaction between CR and CMB (cosmic background radiation):
  - For proton energy > $E_{GZK} = 5\times10^{19}$ eV, formation of Δ resonance becomes energetically possible

$$p+\gamma_{CMB} \rightarrow \Delta^{+} \rightarrow p+\pi^{o} \quad \text{or}$$

$$p+\gamma_{CMB} \rightarrow \Delta^{+} \rightarrow n+\pi^{+}$$

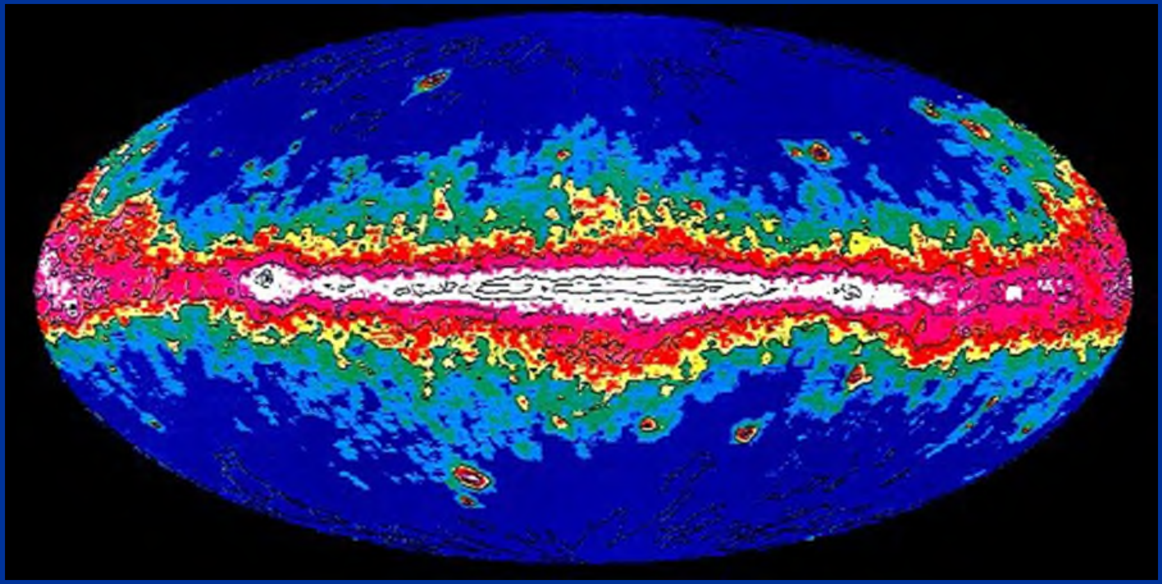
  - $\Rightarrow$ energy of primary protons drained off into pion production
  - CR proton of energy > E_{GZK} cannot travel farther than 50Mpc (= 162ly)

Sources of UHECRs

- Colliding galaxies
- Supermagnetized neutron stars
- Giant black holes spinning rapidly
- Sources of gamma ray bursts
  - Supernova or hypernova
    - Collapse into neutron star or quark star or black hole
  - Merging neutron stars
  - ???
- Something else we haven’t thought about yet?

Future of CR research

- ❑ Understand origin of UHECRs
  - Sources and production mechanisms
- ❑ Are there really EECRs (> E_{GZK})?
  (AGASA controversy)
- ❑ Space based large detectors to view atmosphere from above



A composite image showing cosmic ray distribution in the sky