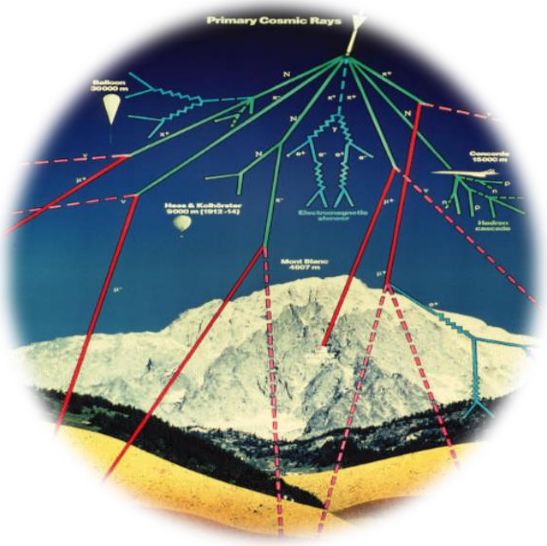
MIDDLE EAST TECHNICAL UNIVERSITY

Particle Data Analysis in High Energy Physics

Lecture 7

Cosmic Rays



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METU, Physics

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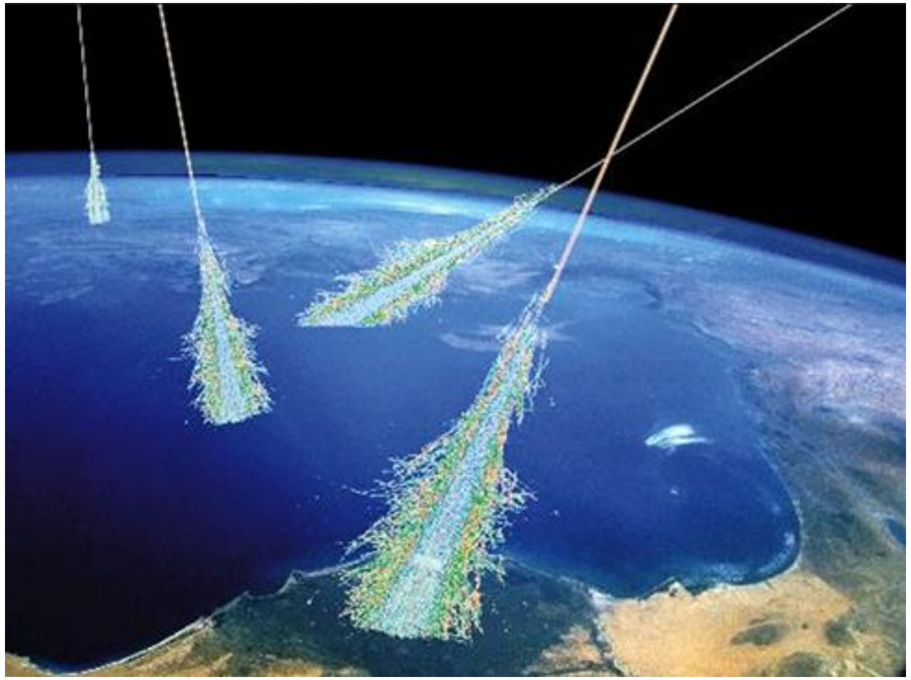
Cosmic Rays

Cosmic rays are energetic particles which do not originate from Earth.

Primary Cosmic Rays originate from energetic processes on the Stars and travel interstellar medium.

The cosmic radiation comes from Sun and outside the solar system
(such as rotating neutron stars, supernovae)

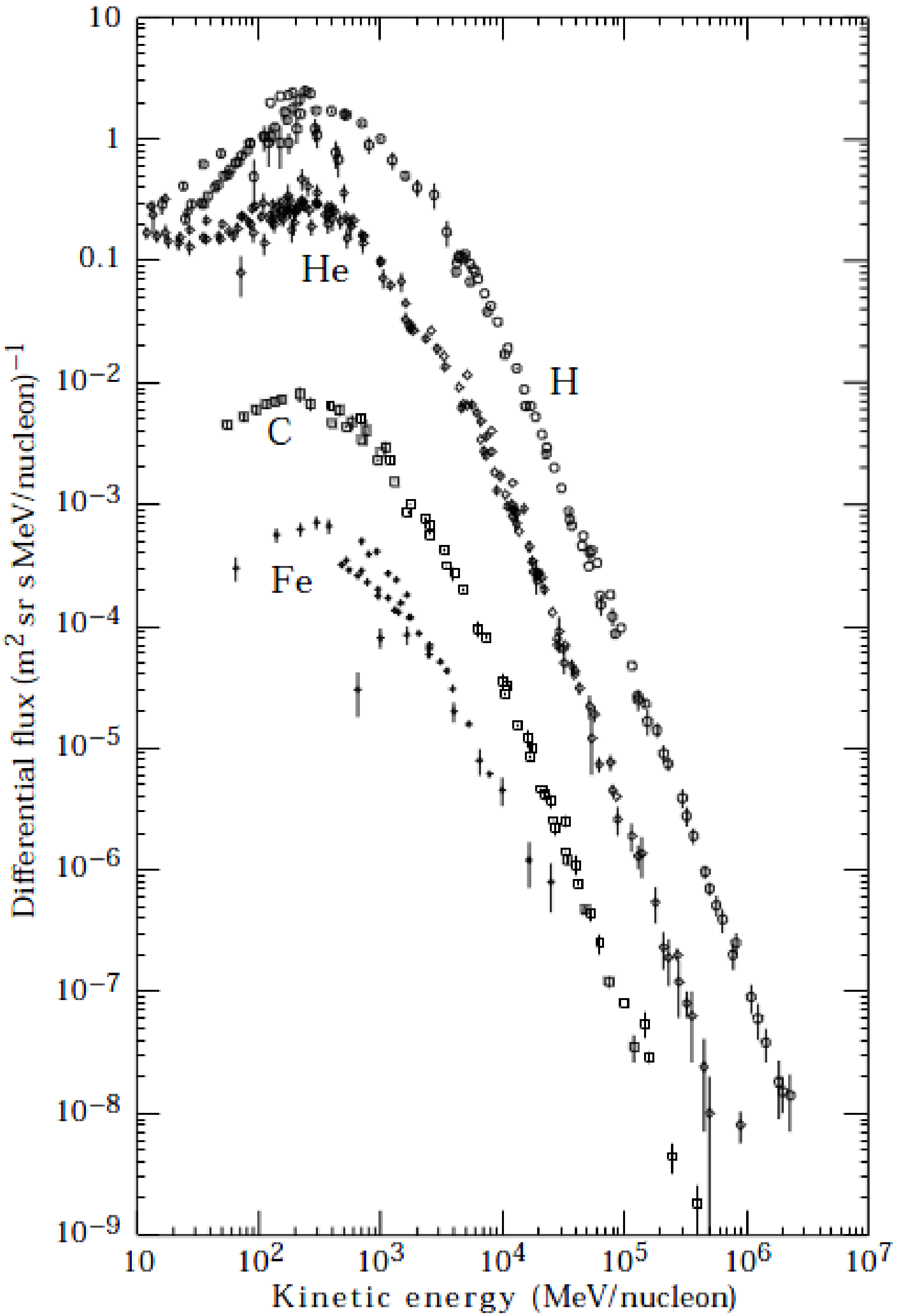
High energy primary cosmic rays collide with particles high in the atmosphere and cause jets of **secondary particles** known as air shower.



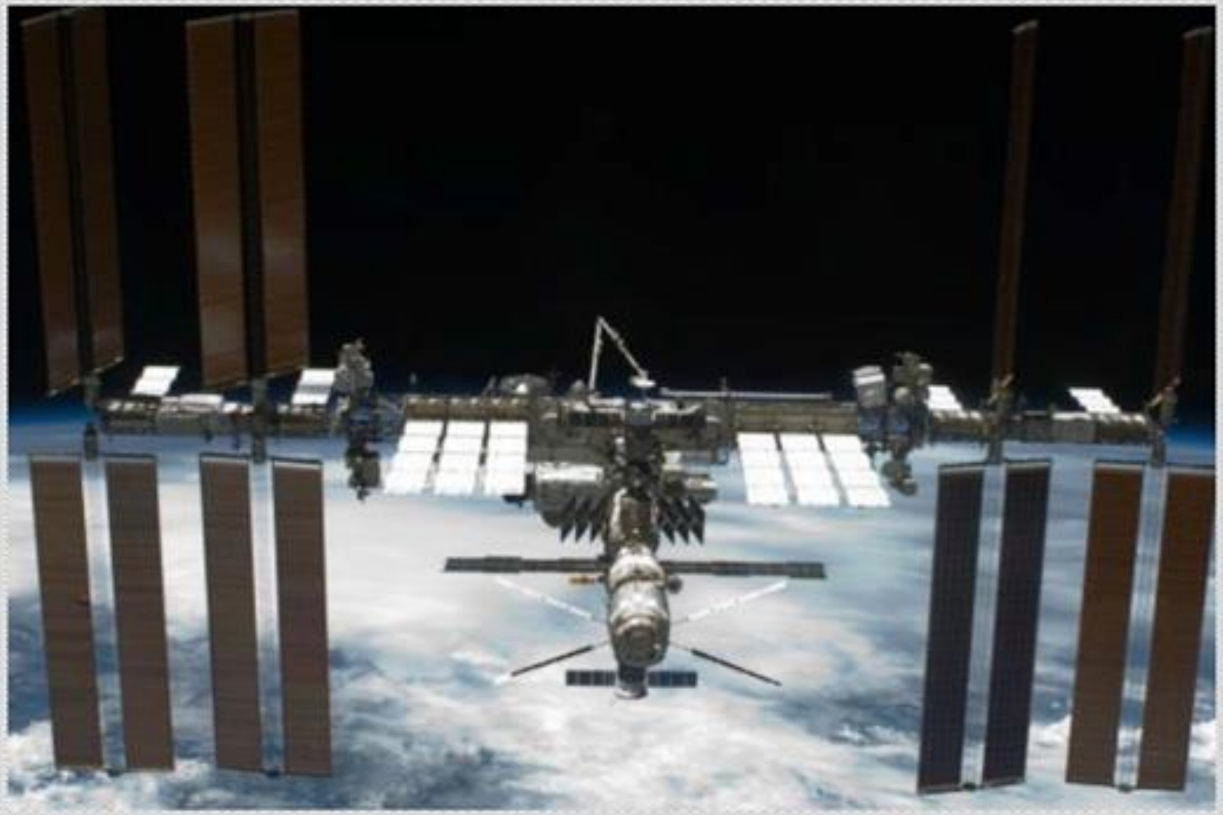
The primary cosmic radiation includes all stable charged particles and nuclei with lifetimes of order 10^6 years or longer.

- Protons (%90)
- Helium (%9)
- Electrons
- Positrons
- Antiprotons
- Lithium
- Beryllium
- Boron
- Carbon
- Oxygen
- Iron
- . . .

(Electrons through Iron and beyond: (%1))



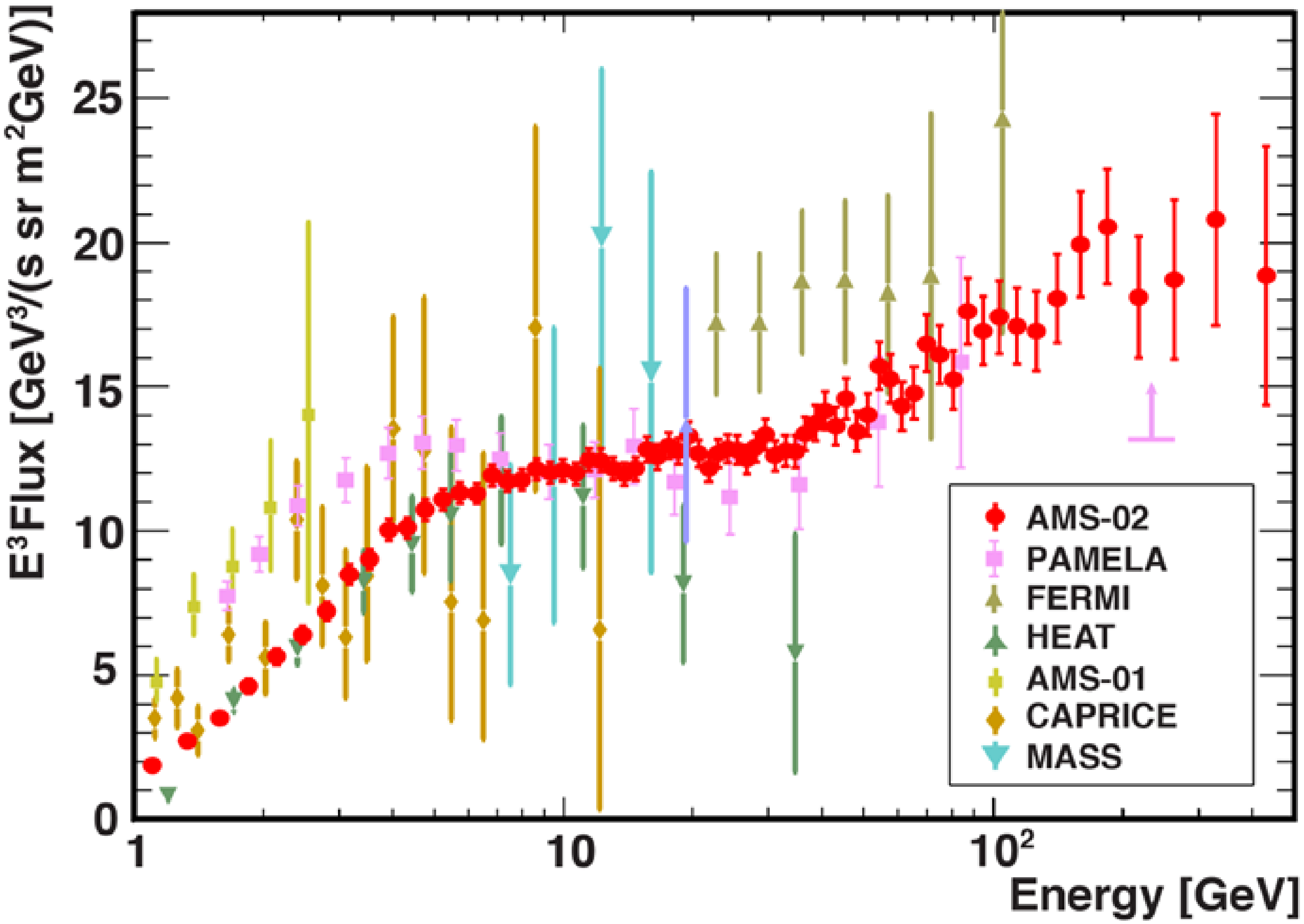
The experimental challenge



DIRECT ≠ EASY!

May 19, 2011: AMS installation completed.
In 3 years we have collected 50 billion events.
This is much more than all Cosmic Rays collected over last century.

Positron Flux Data with AMS



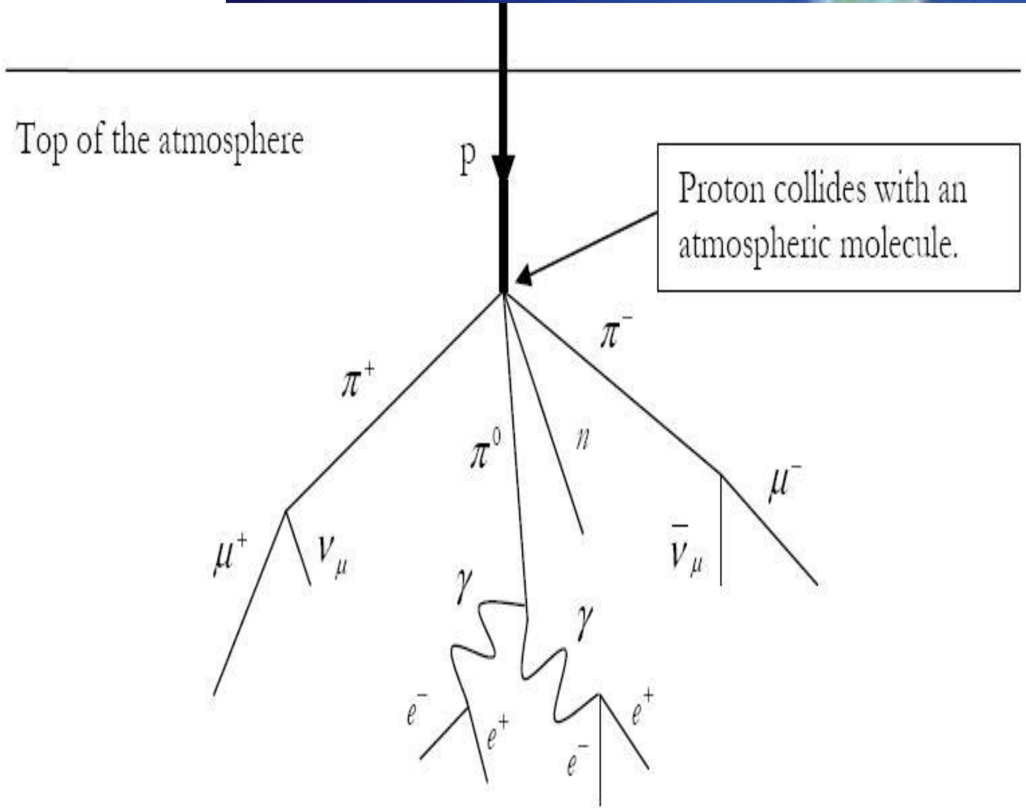
Cosmic Rays in Atmosphere

When primary cosmic rays hit Earth's atmosphere at around 30,000 m above the surface, the impacts cause nuclear reactions which produce pions, kaons and other unstable mesons called air shower.

$$p + O^{16} \longrightarrow n + \pi$$

$$n + N^{14} \longrightarrow p + C^{14}$$

This is important for radio carbon dating



Atmospheric Muons

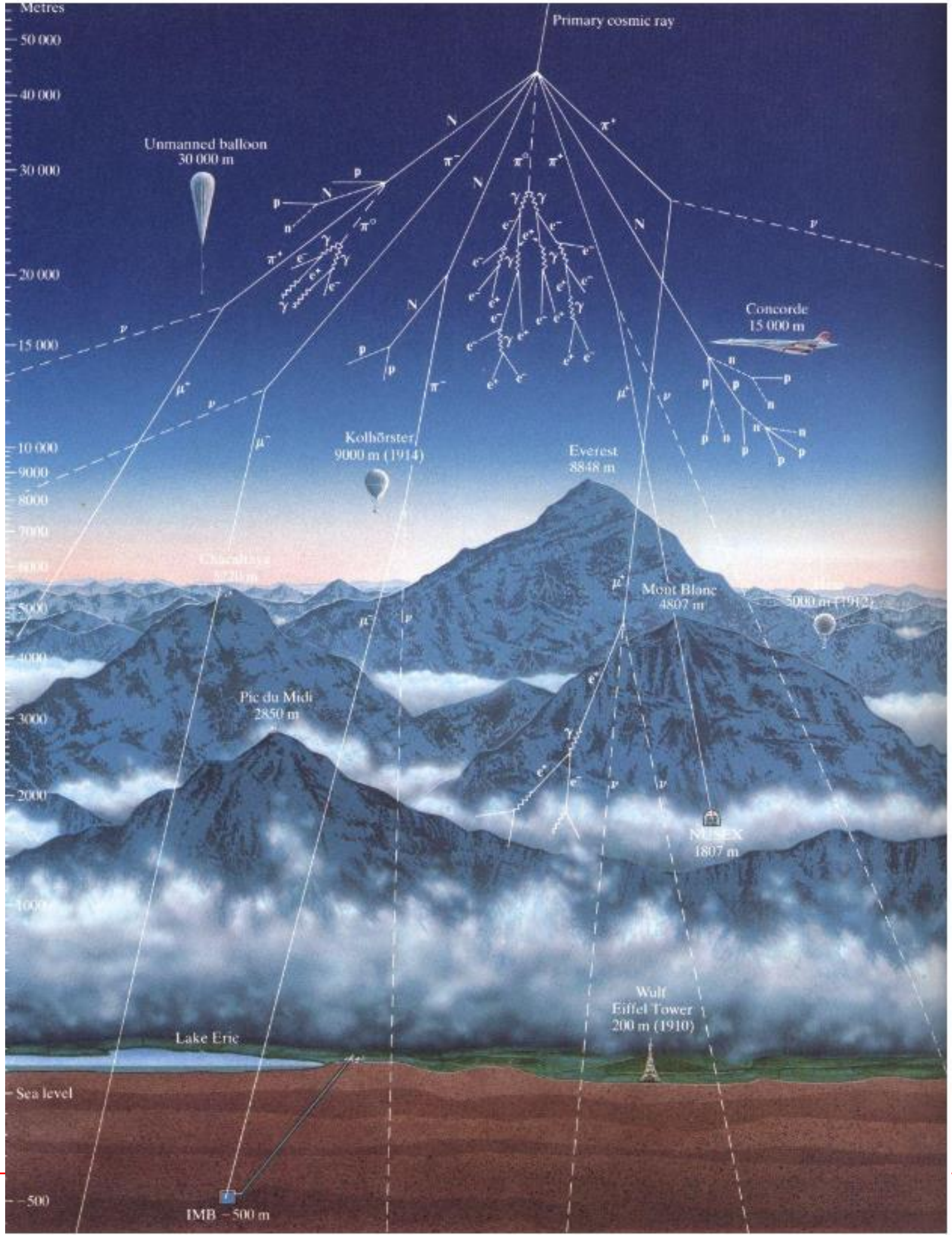
- The newly produced (many) charged pions, quickly decay into muons.

$$\pi^+ \rightarrow \mu^+ + \upsilon_\mu$$

$$\pi^- \rightarrow \mu^- + \bar{\upsilon}_\mu$$

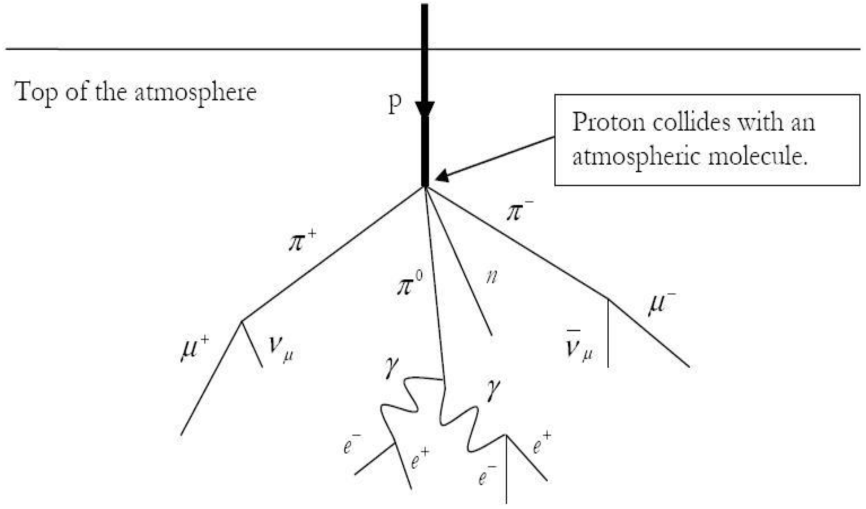
and neutral pions decay mostly to two photons

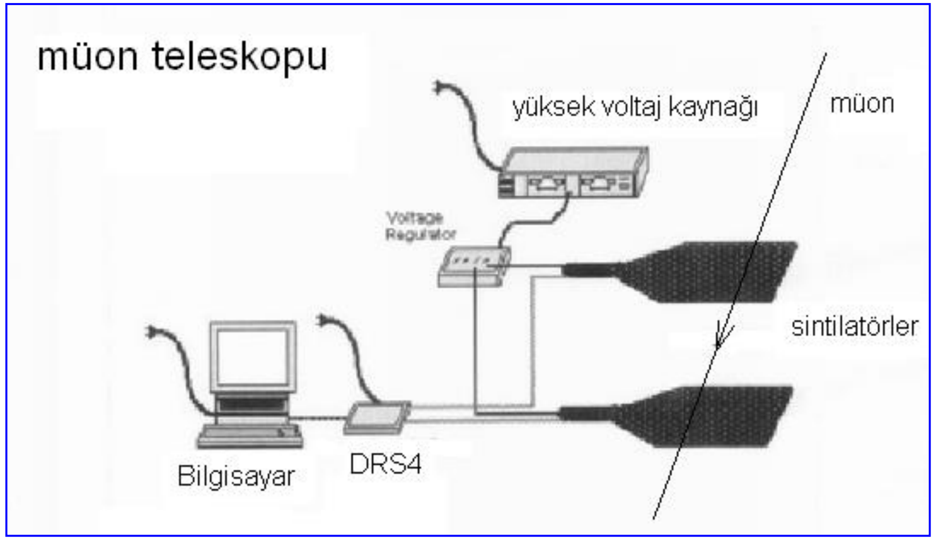
$$\pi^0 \rightarrow \gamma\,\gamma$$



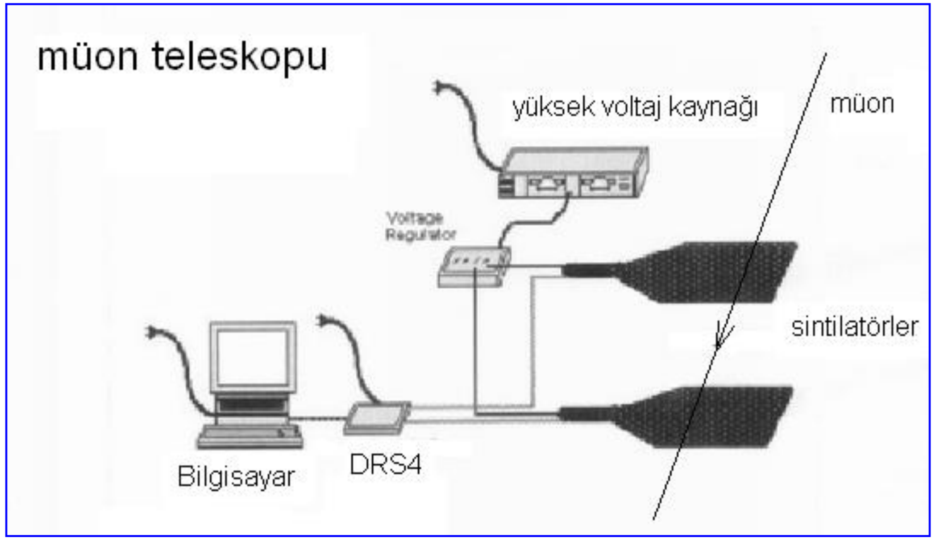
- Muons are ionizing radiation.

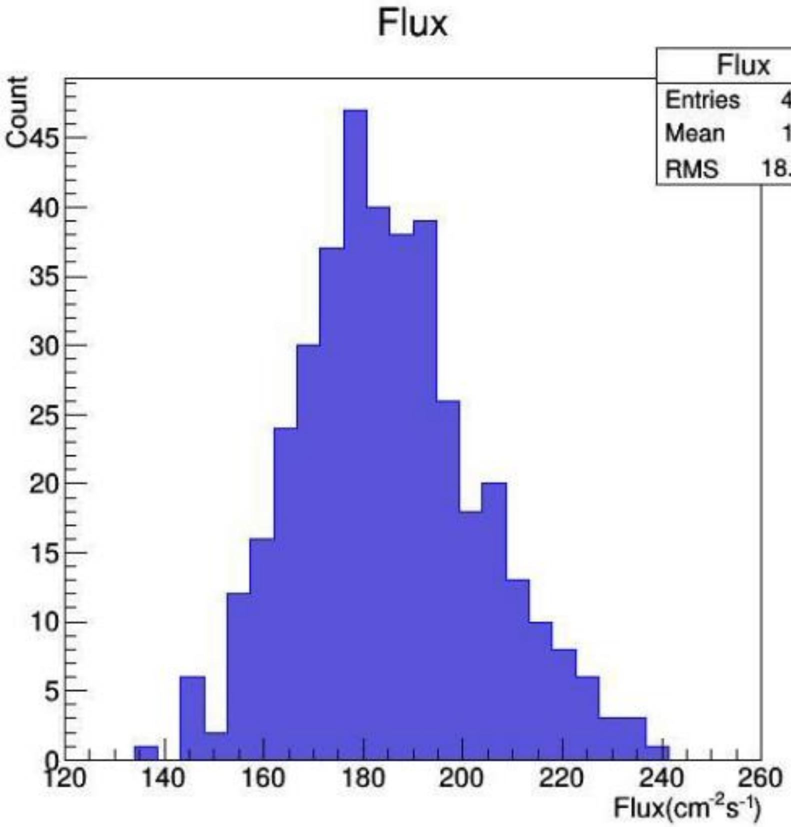
- Muons may easily be detected at sea level by many types of particle detectors such as: *Scintillation detectors*.

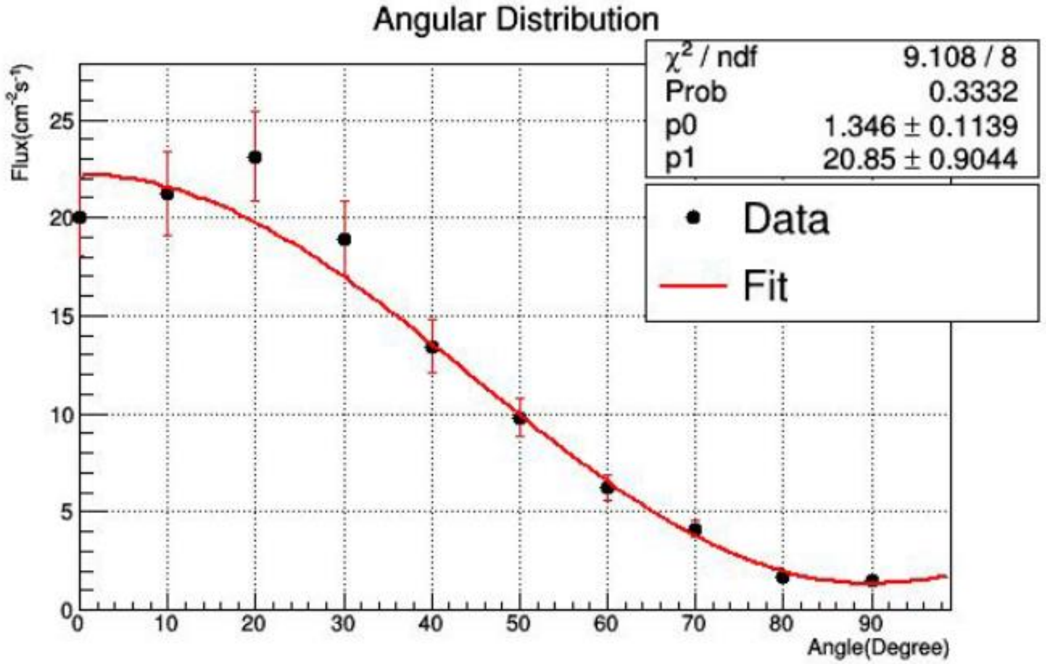


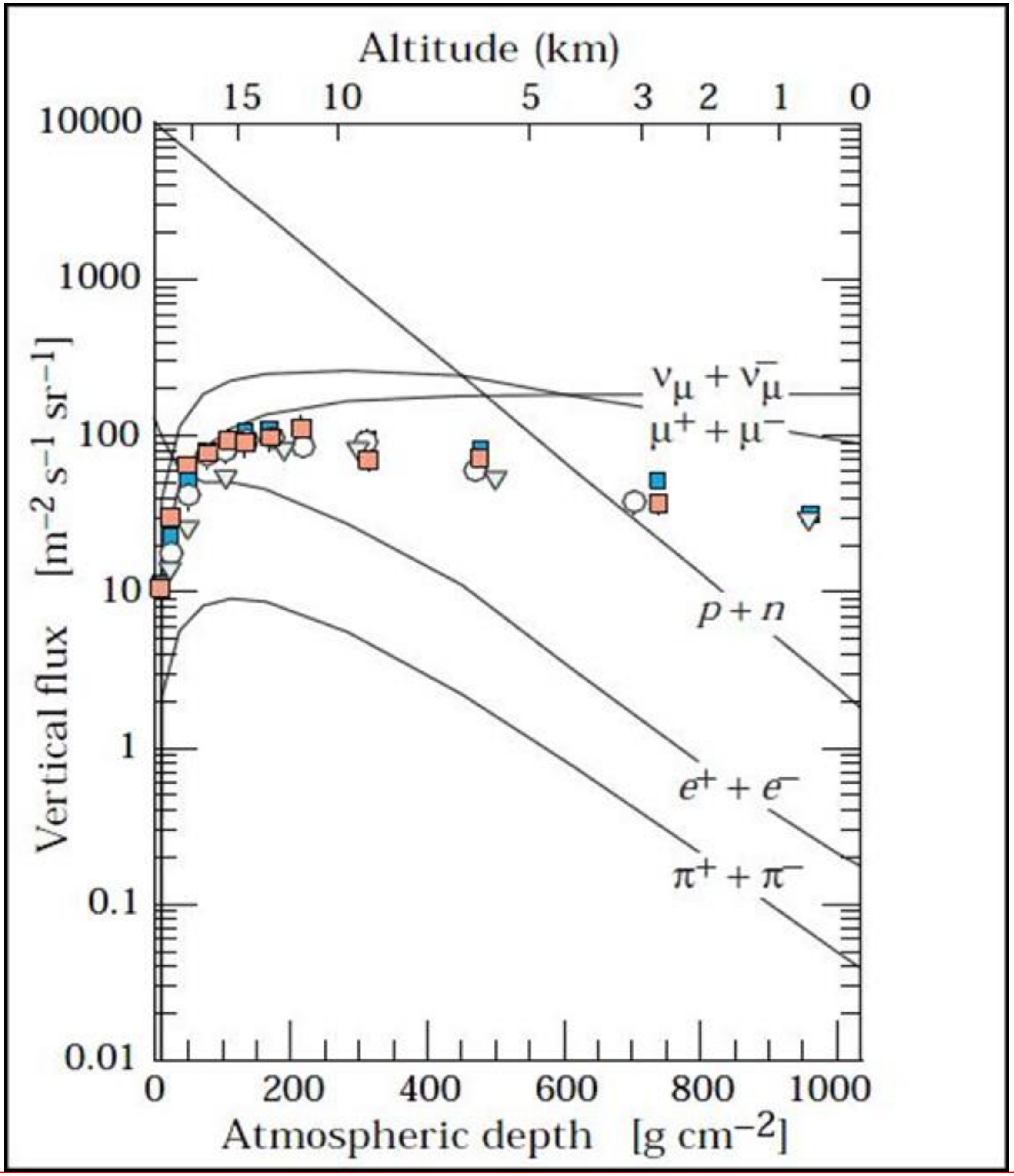


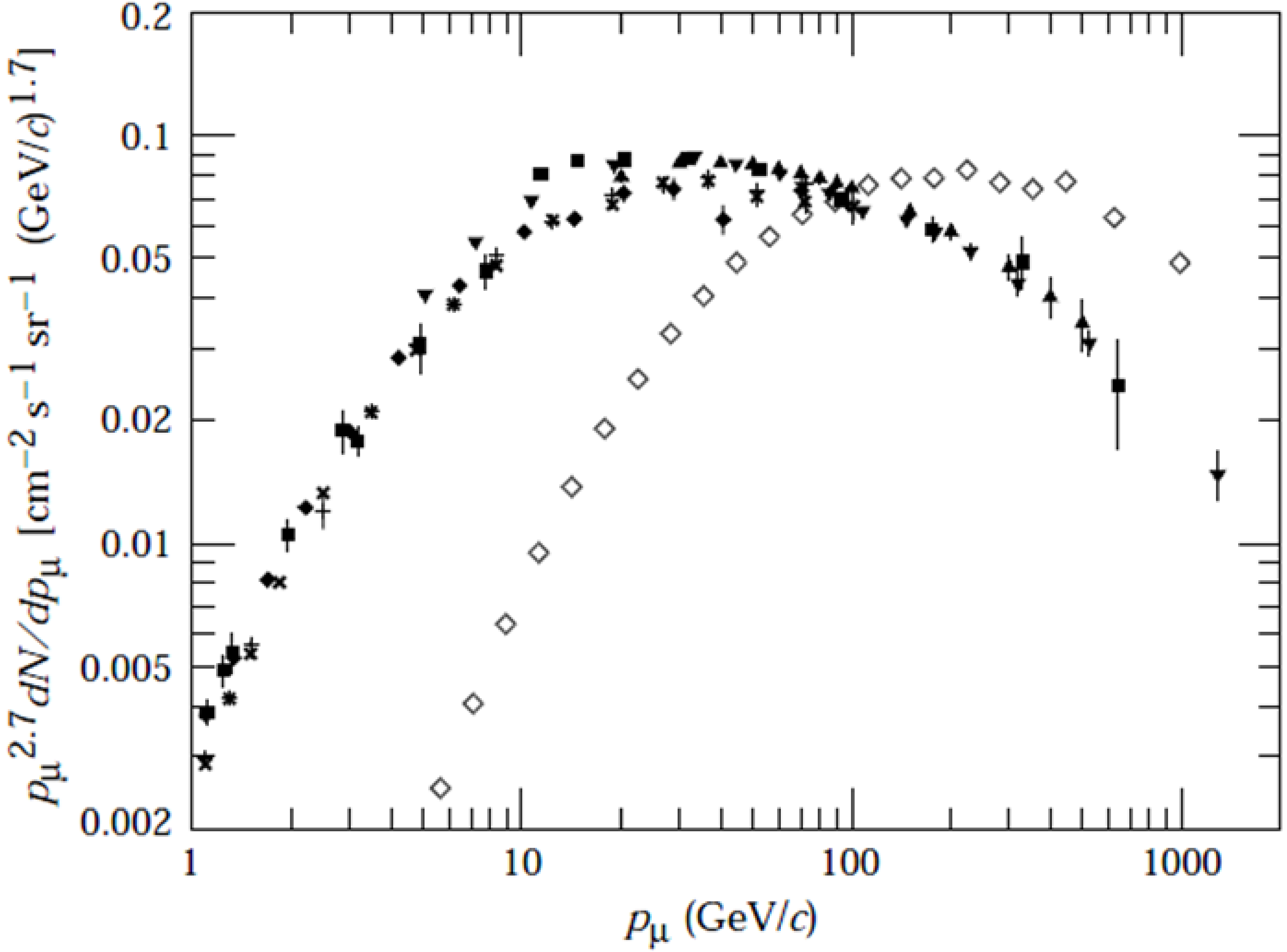
Measurements in Gaziantep





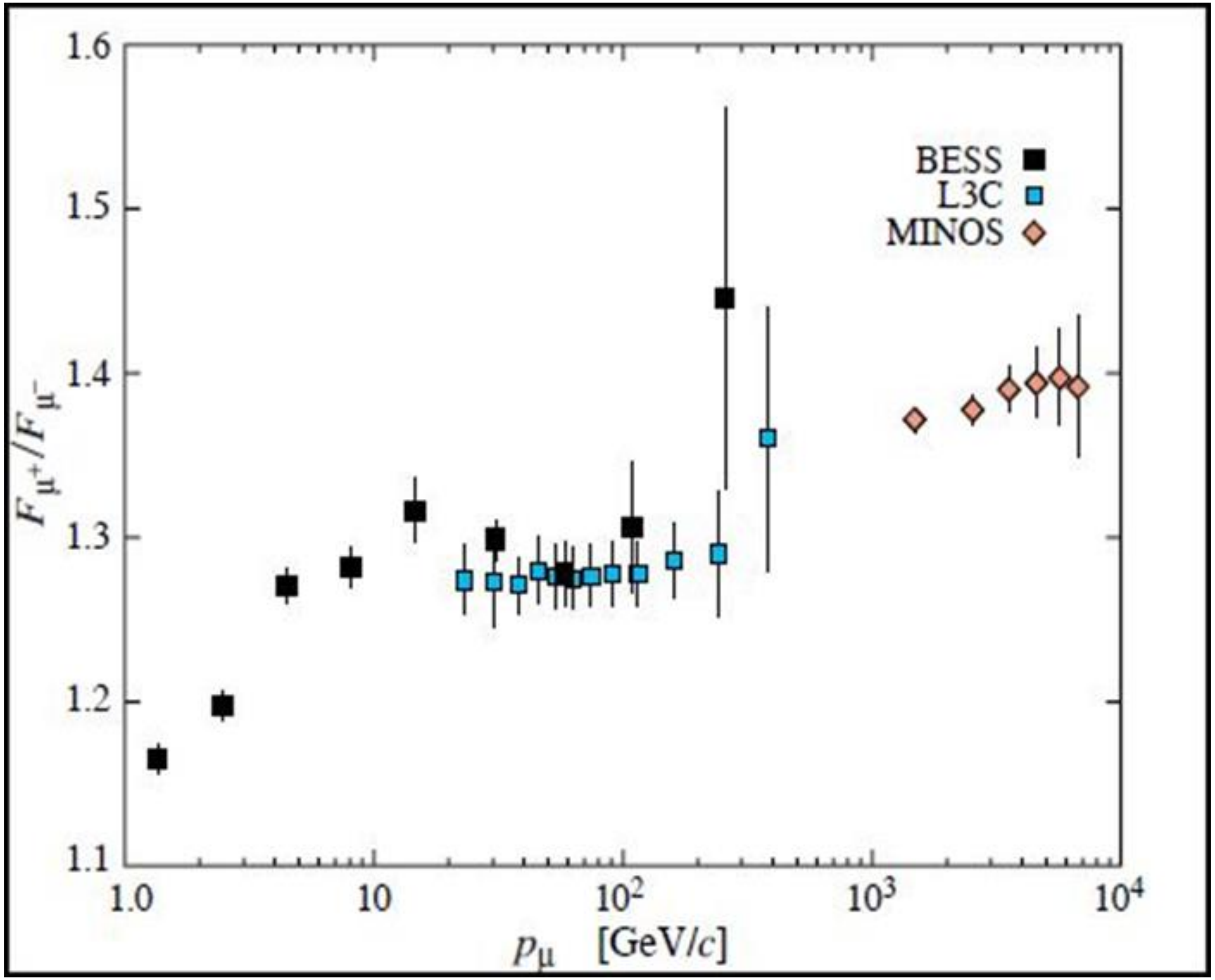



Altitude (km)
15 10 5 3 2 1 0
10000
1000
100
10
1
0.1
0.01
Vertical flux [m^{-2} s^{-1} sr^{-1}]
$\nu_\mu + \bar{\nu}_\mu$
$\mu^+ + \mu^-$
$p + n$
$e^+ + e^-$
$\pi^+ + \pi^-$
0 200 400 600 800 1000
Atmospheric depth [g cm^{-2}]



Spectrum of muons at $\theta = 0°$ (♦ , ■ , ▾ , ▲ , ×, +)
and $\theta = 75°$ ◊

Muon charge ratio



Big-Bang

- Cosmological model to explain the universe today

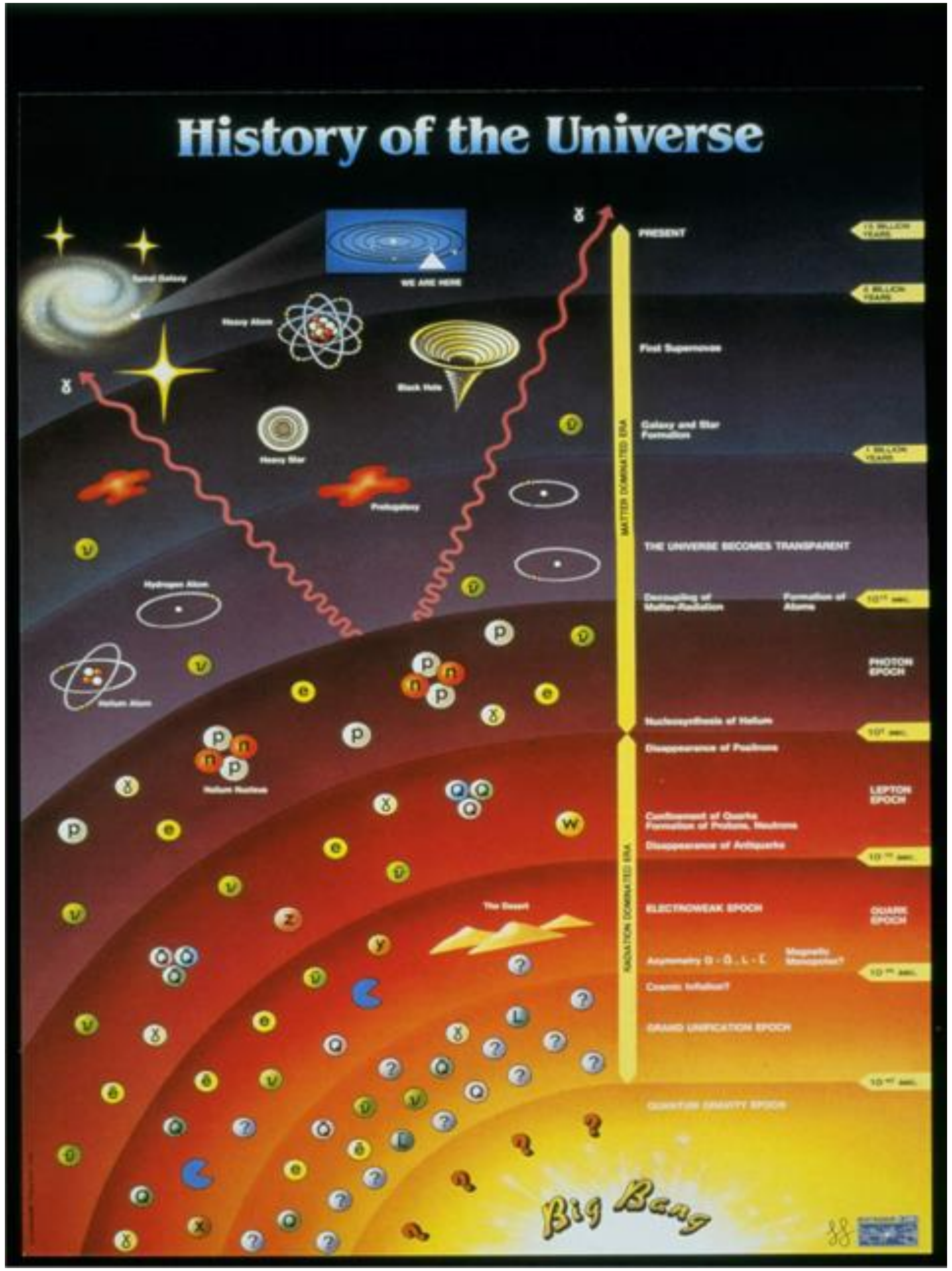
- Exapanding Universe …
  - Hubble Red shift (1924)
  - Cosmic Background (1964)
  - Temperature of the universe in Kelvin:

$$T \approx \frac{10^{10}}{\sqrt{t}}$$

t is the time in secons.

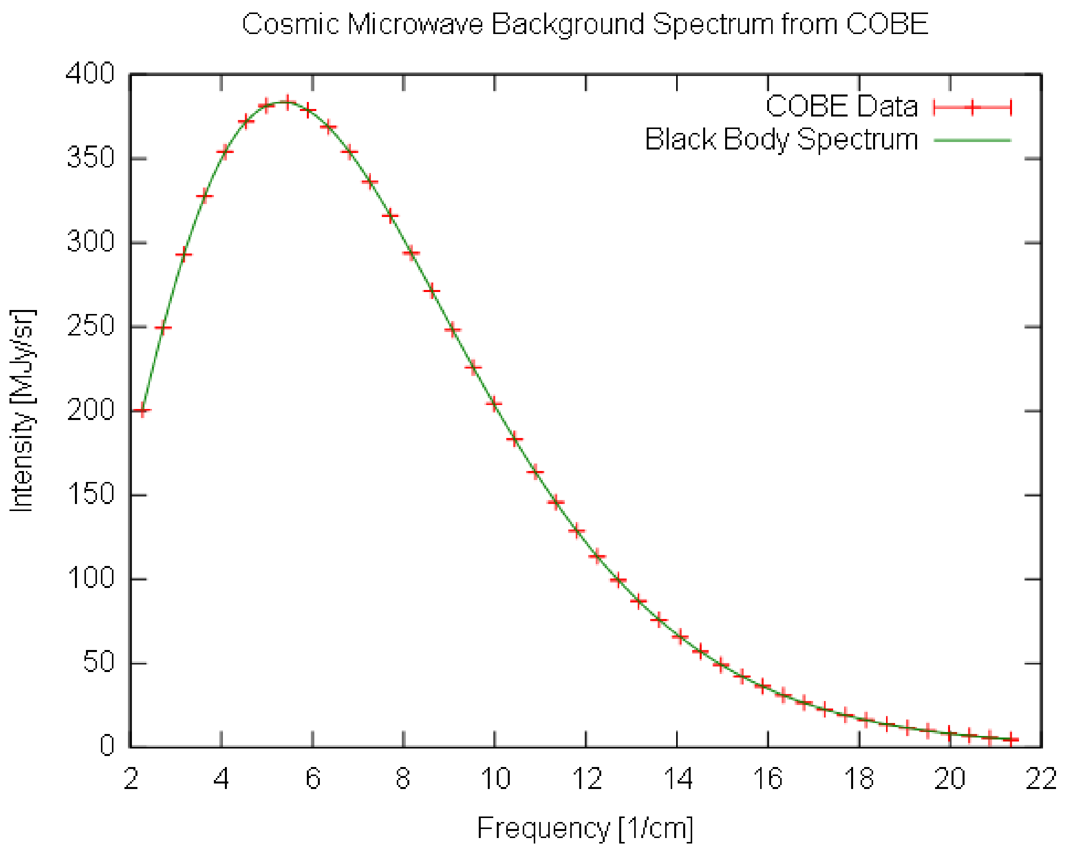
Age of the universe is: 13.798 +- 0.037 billon years.

$$T \approx 3\ \mathrm{K}$$



Cosmic Background Radiation (CBR)

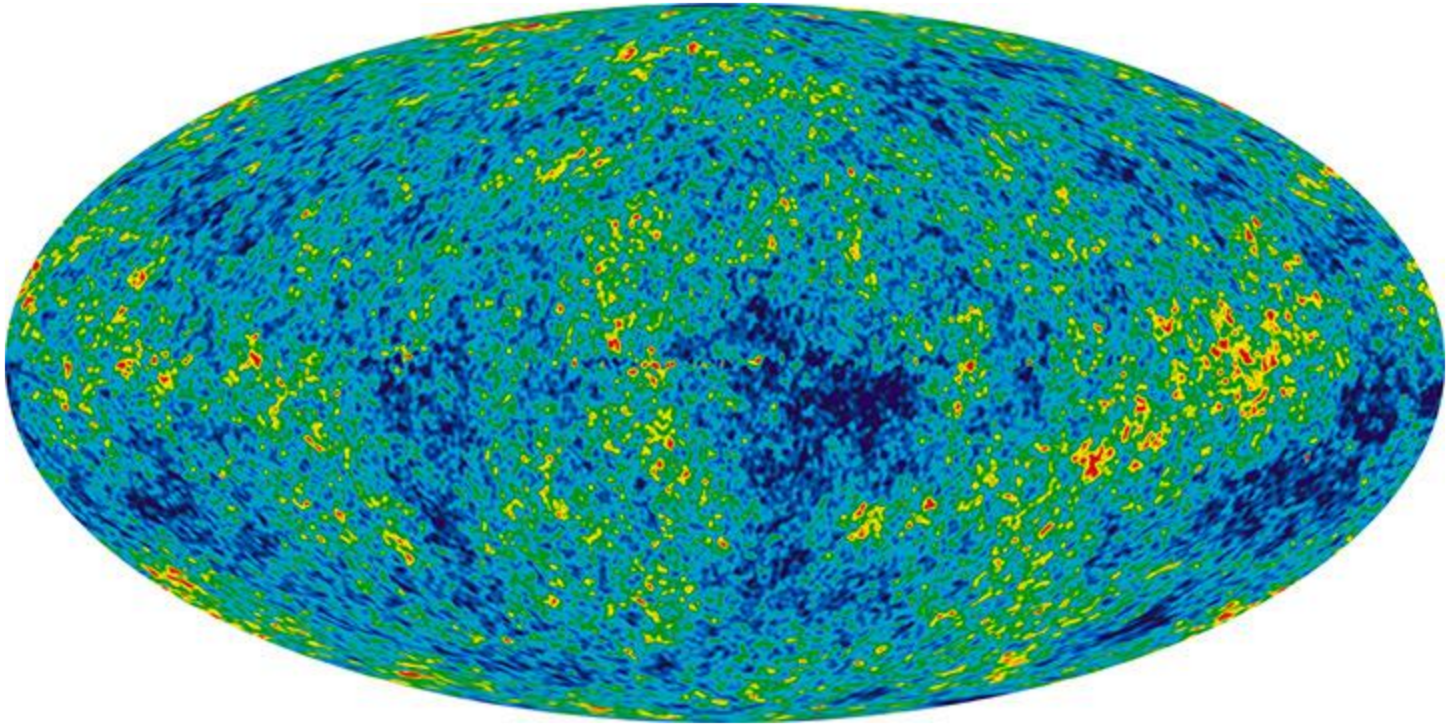
- Expanding universe cools down.
- CBR is the thermal radiation assumed to be left over from the "Big Bang" of cosmology.



With a traditional optical telescope, the space between stars and galaxies (the background) is completely dark. However, a sufficiently sensitive radio telescope shows a faint background glow, almost exactly the same in all directions.

Cosmic Background Radiation (CBR)

- WMAP data:
  The detailed, all-sky picture of the infant universe created from nine years of WMAP data. The image reveals 13.77 billion year old temperature fluctuations (shown as color differences) that correspond to the seeds that grew to become the galaxies. The signal from the our Galaxy was subtracted using the multi-frequency data. This image shows a temperature range of +- 200 microKelvin.



GZK cutoff

This cutoff is related to ultra-high energetic cosmic rays through the intergalactic space.

Consider an ultra-relativistic proton ejected from a star.
This proton may collide with a microwave from CBR and the following reaction can occur:

$$p + \gamma \rightarrow n + \pi^+$$

Energy of microvave photon: $E_\gamma = kT = 2.6 \times 10^{-10}\ \mathrm{MeV}$

Q: What is the threshold energy of proton starting this reaction?

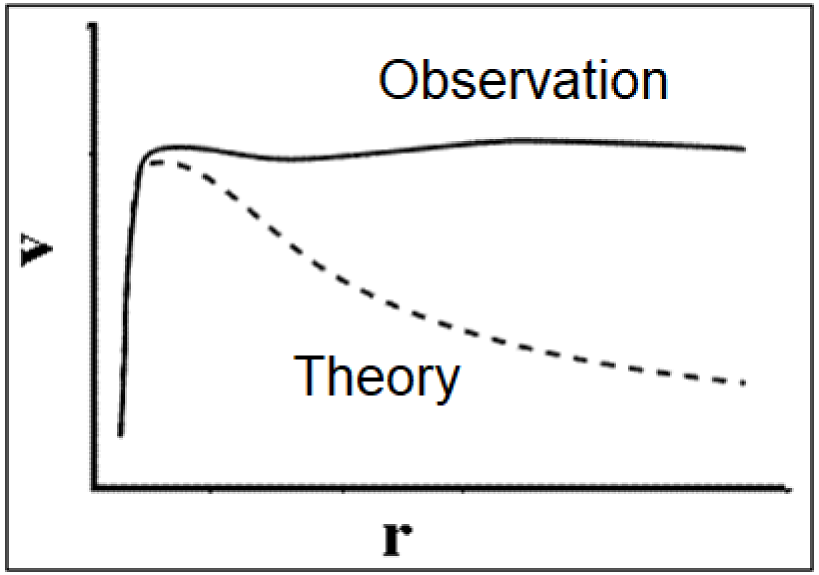
A: $$E_p = \frac{(m_n + m_\pi)^2 - (m_p)^2}{4E_\gamma} = 3 \text{ x } 10^{20}\ \mathrm{eV}$$

Above this energy no primary cosmic ray can be found!

Dark Matter

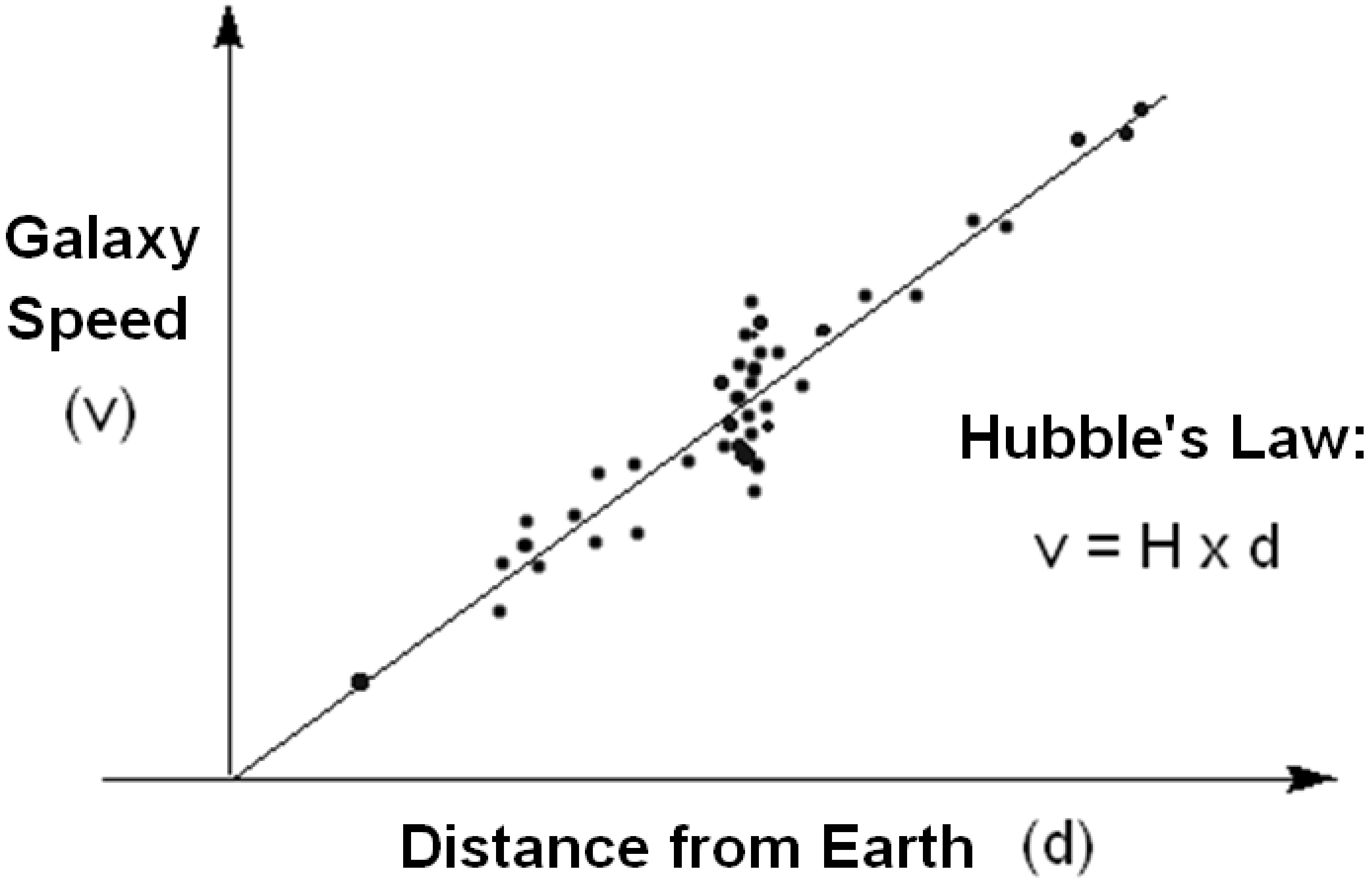
- Do not radiate and reflect electromagnetic wave
- Interacts with visible material
- Tangential speed of a star

$$\frac{mv^2}{r} = G\frac{mM}{r^2} \quad \rightarrow \quad v = (GM/r)^{1/2}$$

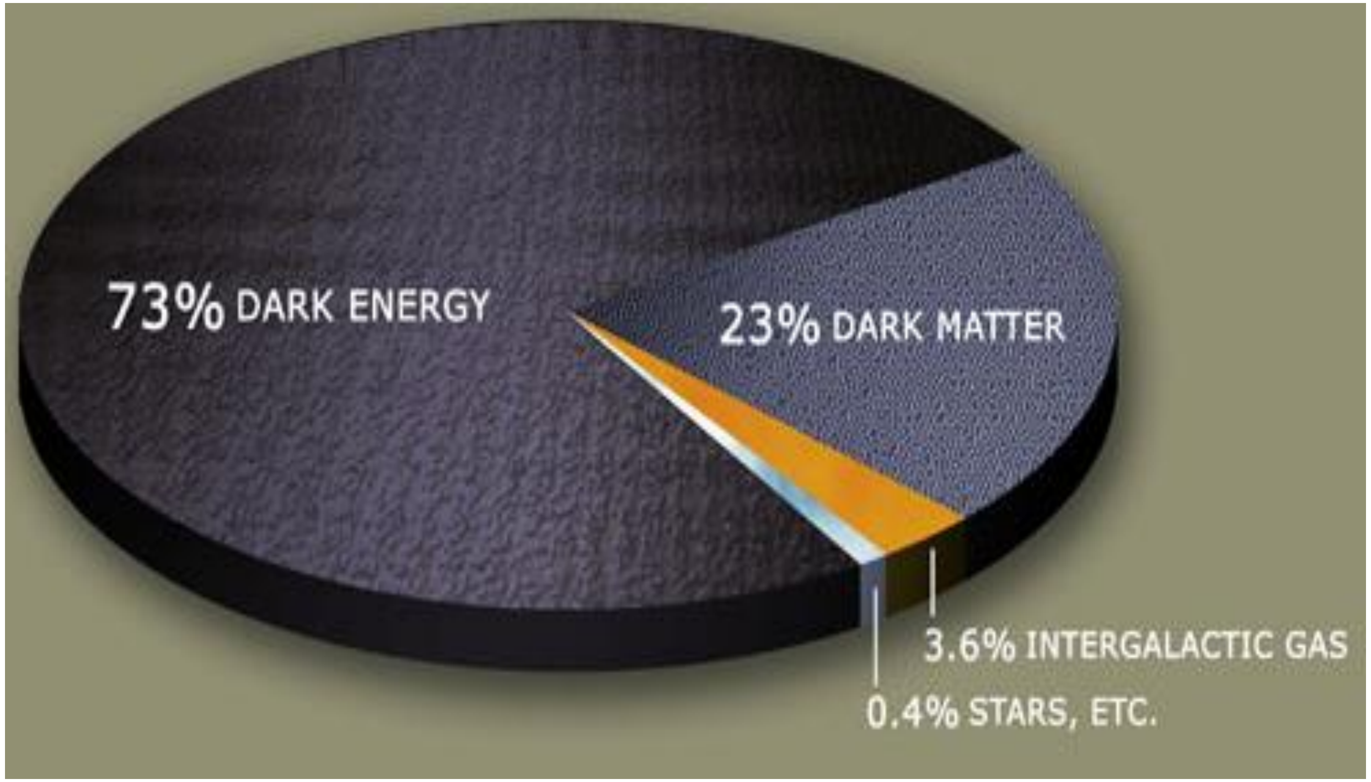


Hubble's Law

Speed of galaxies receding from the Earth is approximately proportional to their distance from the Earth.



Dark Energy



73% DARK ENERGY
23% DARK MATTER
3.6% INTERGALACTIC GAS
0.4% STARS, ETC.

Problems

1. The earth is constantly bombarded with high-energy particles coming from outer space. These particles are called the primary cosmic rays and most of them are protons. Flux of primary cosmic rays averaged over the earth surface is about $1\ cm^{-2}\ s^{-1}$ and their average kinetic energy is 3 GeV. Calculate the average power transferred (in Watts) to Earth whose radius is 6400 km.

2. Consider the head on collision of ultrarelativistic proton and cosmic microwave background photon: $p + \gamma \rightarrow n + \pi^+$

(a) Show that threshold energy of proton to start this reaction is given by:

$$E_p = \frac{(m_n + m_\pi)^2 - (m_p)^2}{4E_\gamma} = 3 \text{ x } 10^{20} \text{ eV}$$

(b) What is the maximum and minimum energy of pion in the reaction at threshold energy?

3. Figure shows energy ditribution of primary cosmic rays. Consider you have a telescope system consisting of two square detectors (each 30 cm x 30 cm) separated vertically by a distance of 20 cm.

Assuming a 90% detection efficiency for the system, calculate the expected number of protons detected per steradian during a 1-hour observation period.
A proton is detected when two detectors results in signals. Coincidence detection required (signals from both detectors).