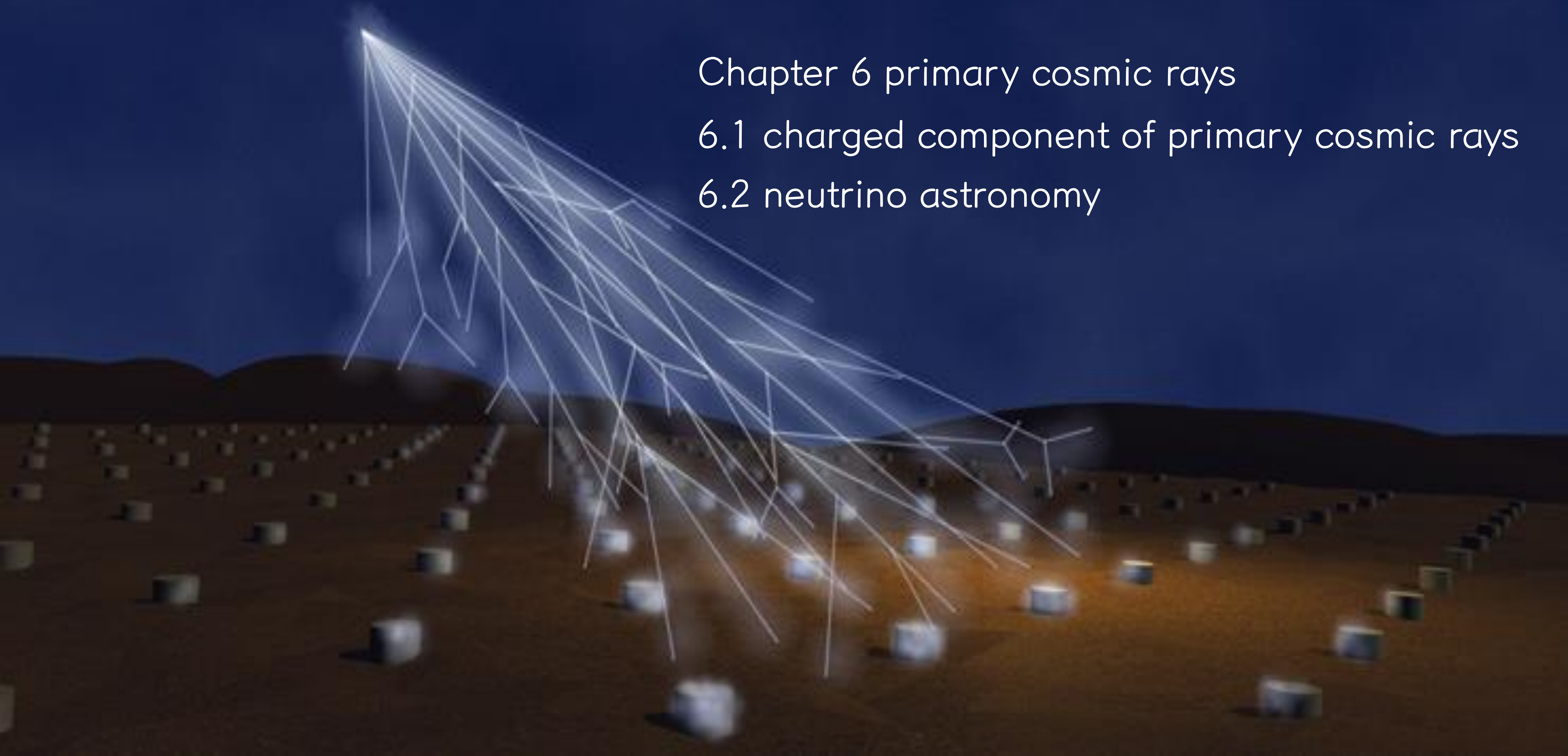
Astroparticle physics

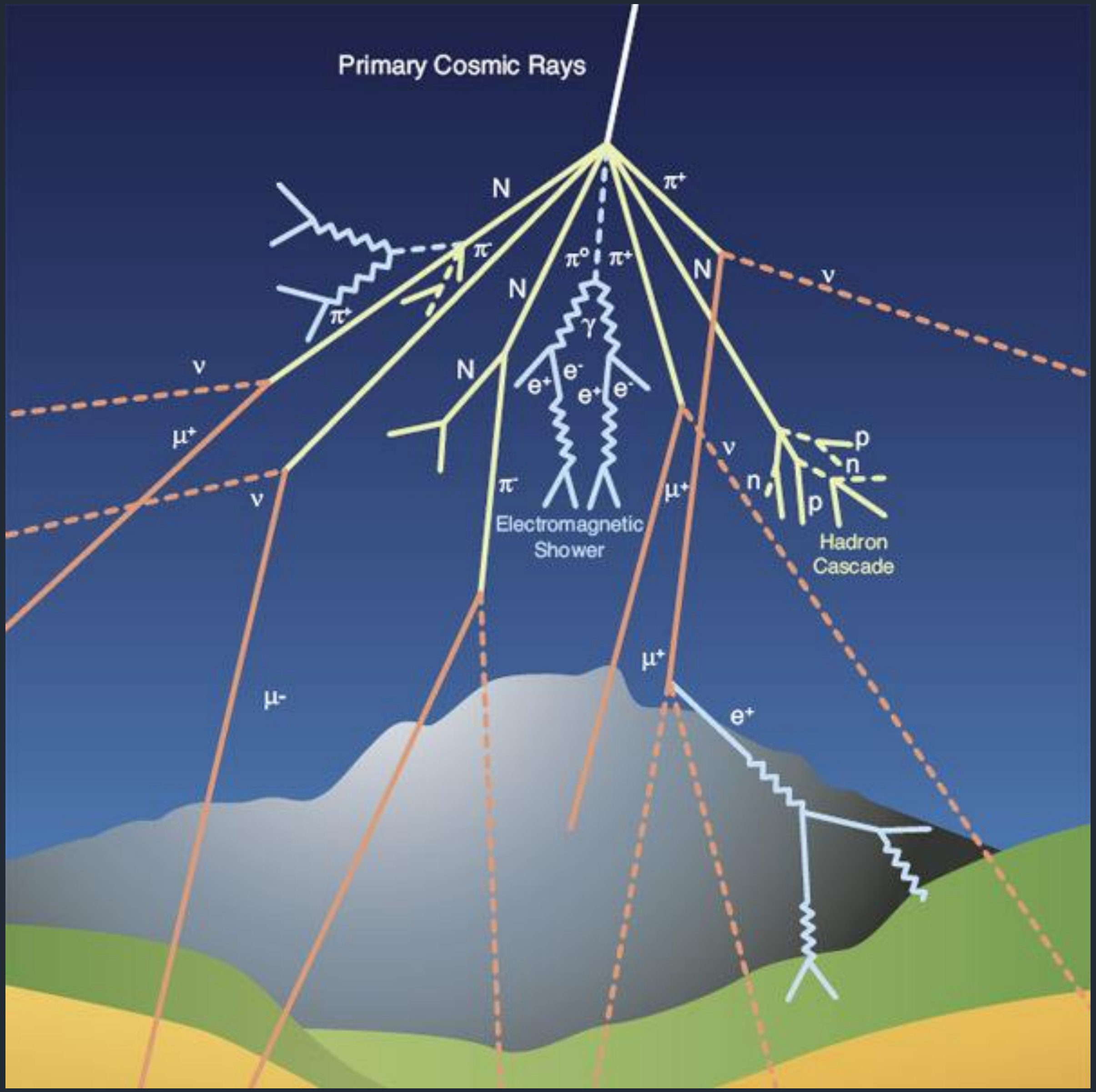
Chapter 6 primary cosmic rays

6.1 charged component of primary cosmic rays

6.2 neutrino astronomy



Introduction



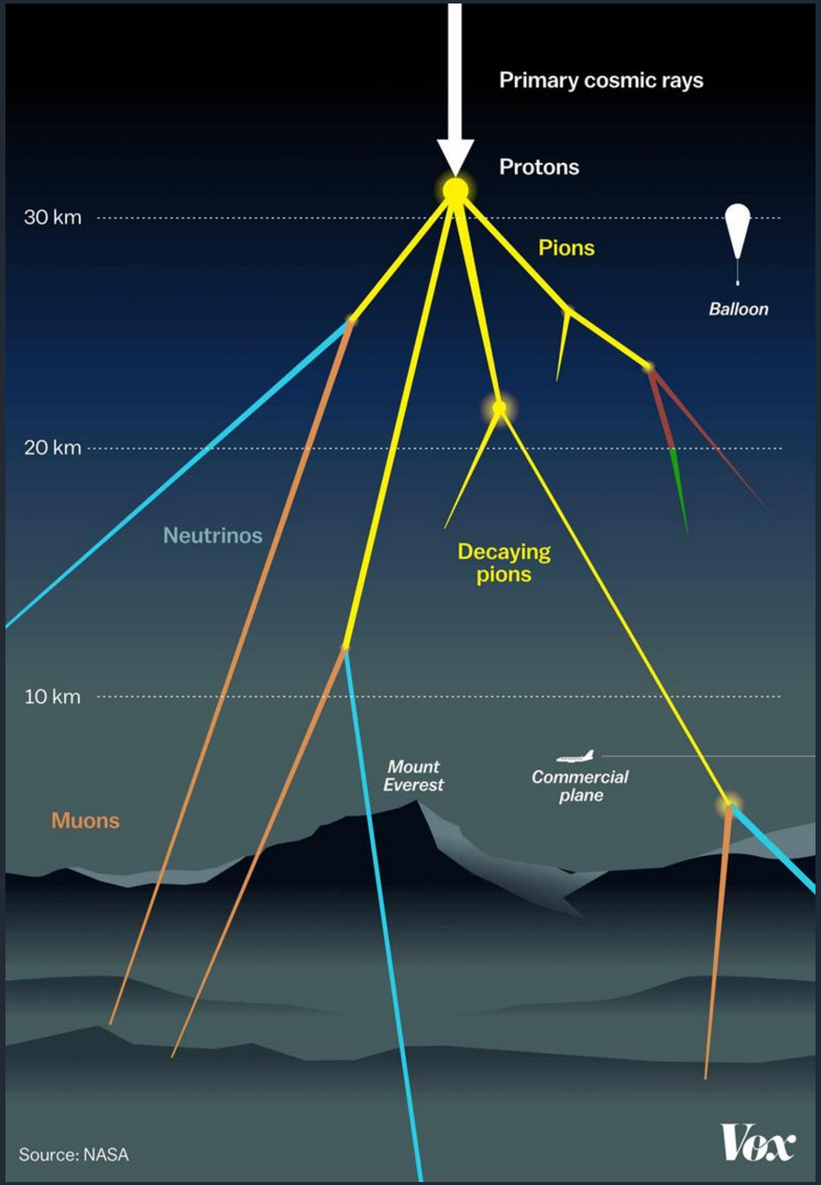
Cosmic rays

: this provide important information about high-energy processes occurring in our galaxy and beyond

What is Cosmic rays?

In common scientific usage, high-energy particles with intrinsic mass are known as "cosmic" rays.

What is primordial cosmic rays?

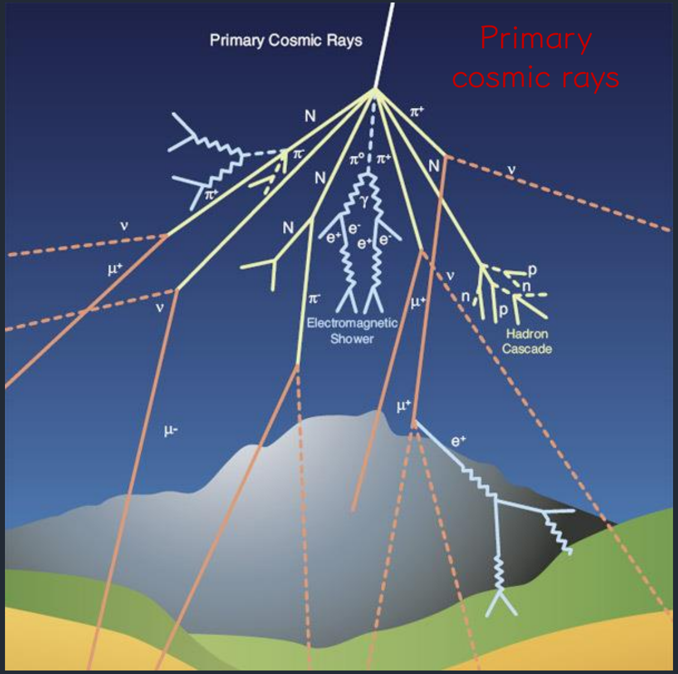


❖ The ray which is not affected by the Earth's atmosphere can be understood as a cosmic ray.

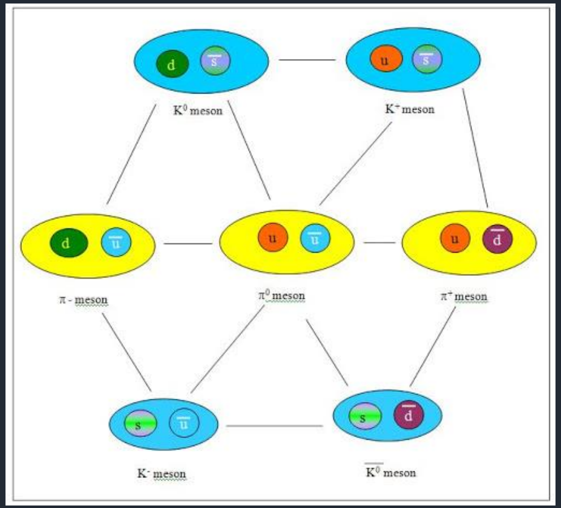
❖ because this radiation can be modified during its propagation and earth's atmosphere effects on this. (When they interact with Earth's atmosphere, they are converted to secondary particles)

primordial cosmic rays and secondary particles

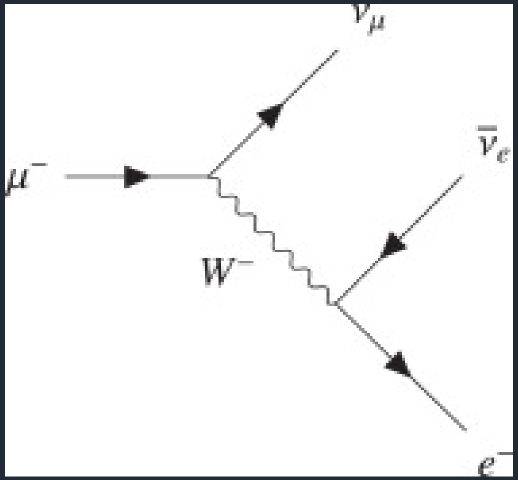
Primary cosmic rays



Secondary particles



Secondary Particles's decay

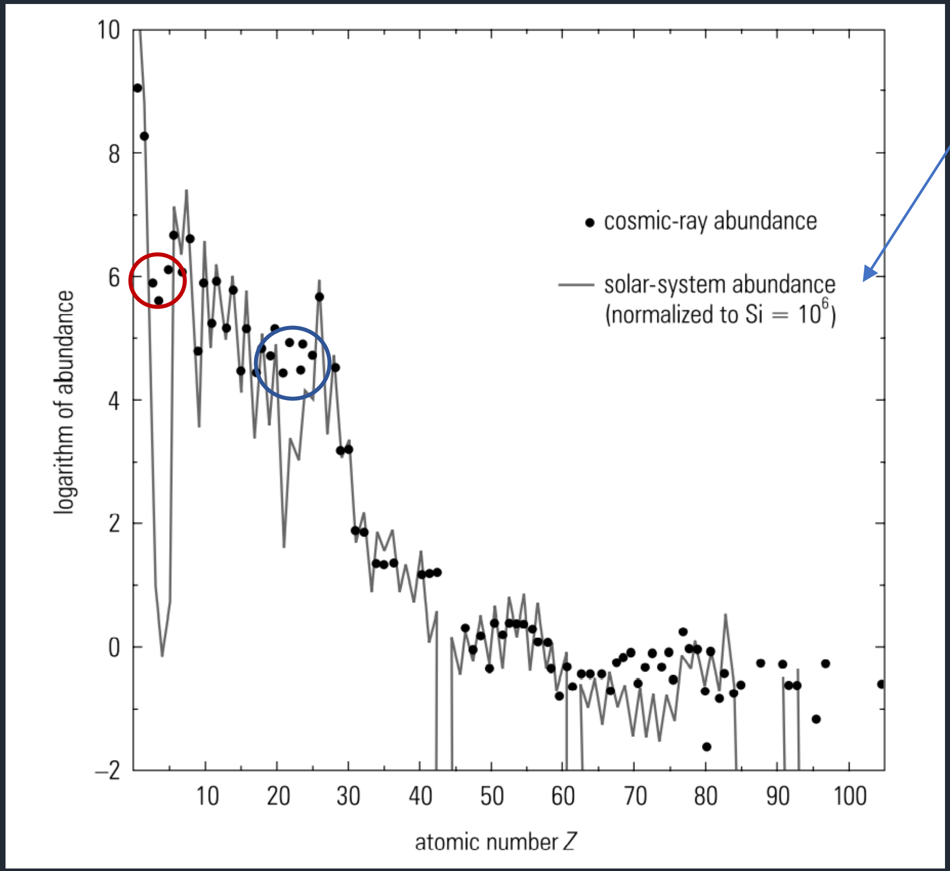


$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

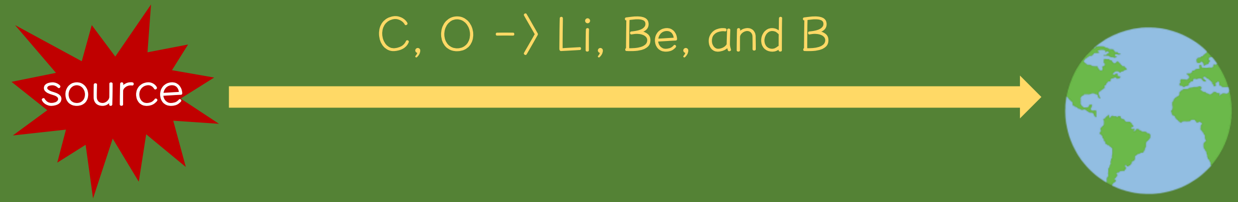
- The primary cosmic rays can produce a number of secondary particles by interactions in the sources themselves.

- These secondary particles are mostly unstable(i.e., pions and kaons) and these produce another particles in their decay

6.1 charged component of primary cosmic rays



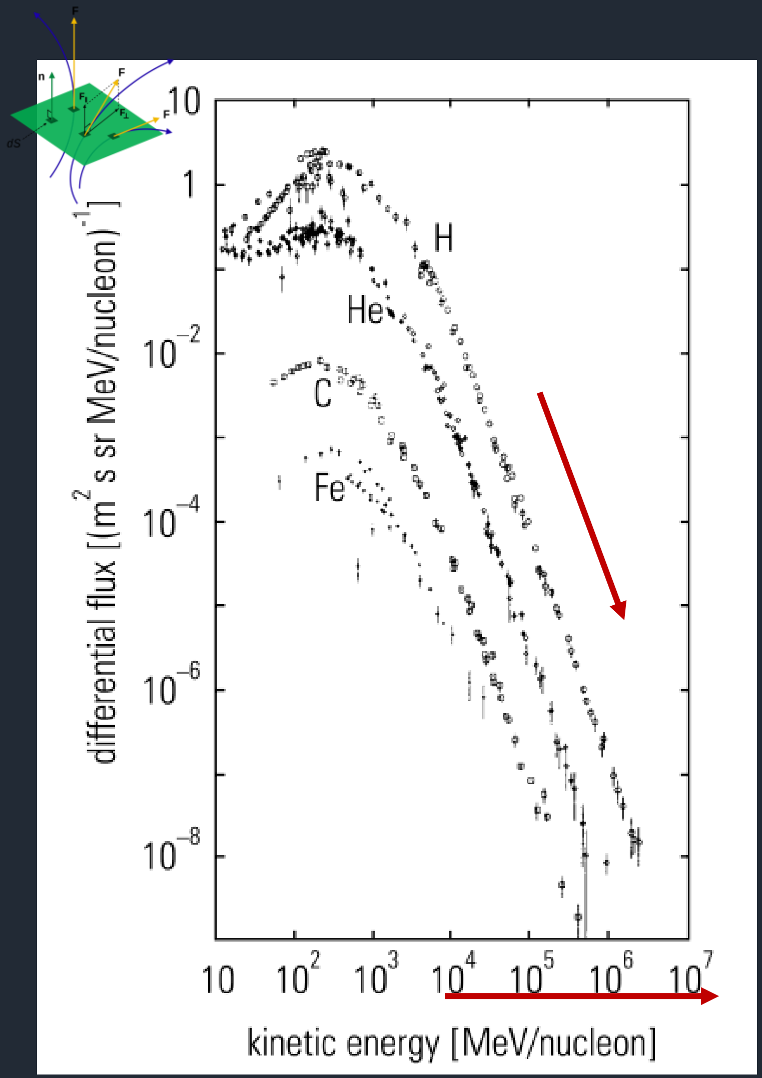
The chemical composition of the solar system



- ✓ The larger abundance of Li, Be, and B in cosmic rays can be understood by fragmentation of heavier nuclei carbon and oxygen($Z = 8$) on their way from the source to Earth
- ✓ And this method applies to iron group($Z < 26$)

Protons are the dominant particle species(~ 85%) followed by alpha particles(~ 12%)

Energy spectra of the main components of charged primary cosmic rays



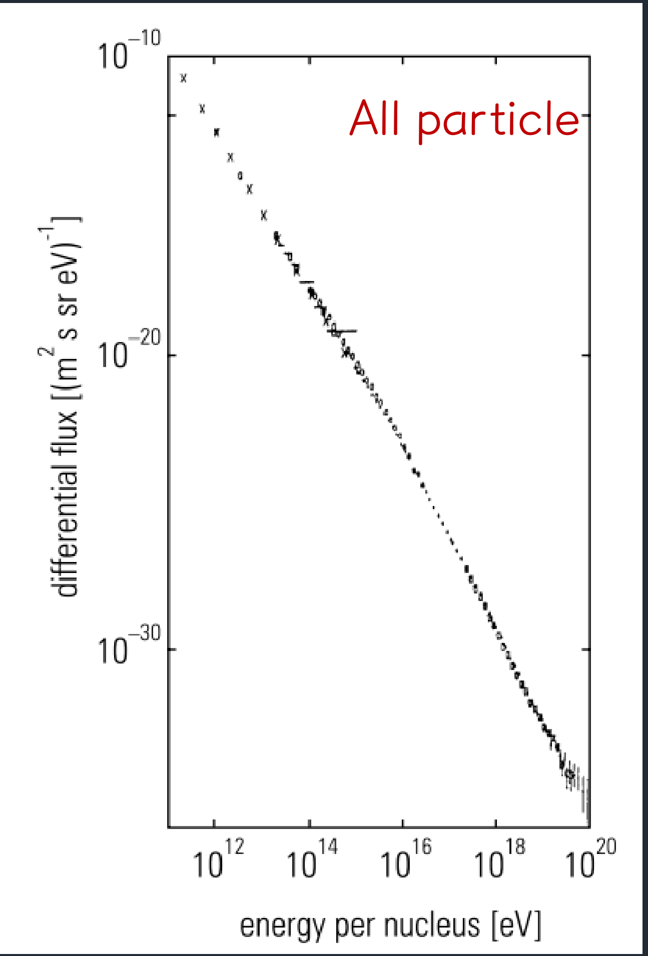
When energy is increasing, the intensity decrease.
So it is hard to measure high-energy component of cosmic rays in direct way.

We can used indirect method

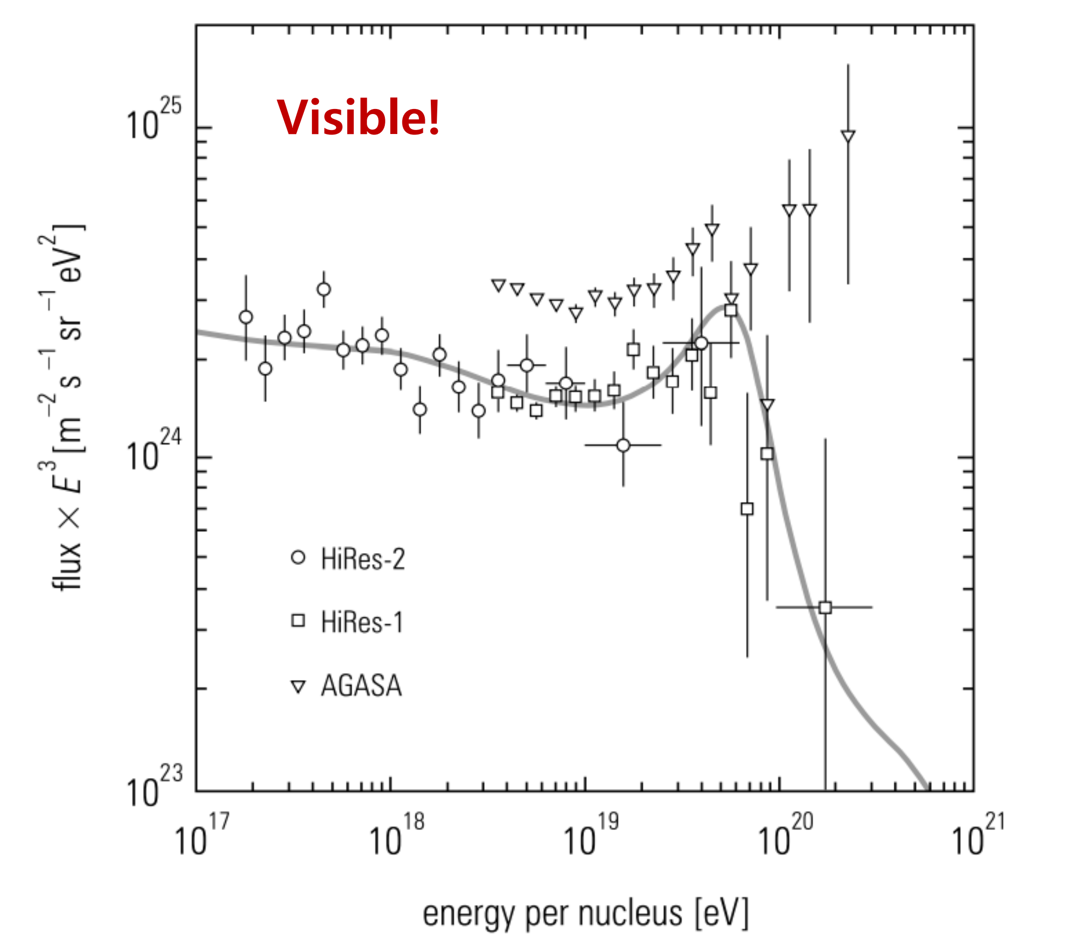
1) Atmospheric air Cherenkov technique(6.3 gamma astronomy, e.g HAWC)
2) Measurement of extensive air showers via air fluorescence
3) Particle sampling(7.4 extensive air showers)

However, by this indirect technique, it is difficult to determine the chemical composition of primary cosmic rays.

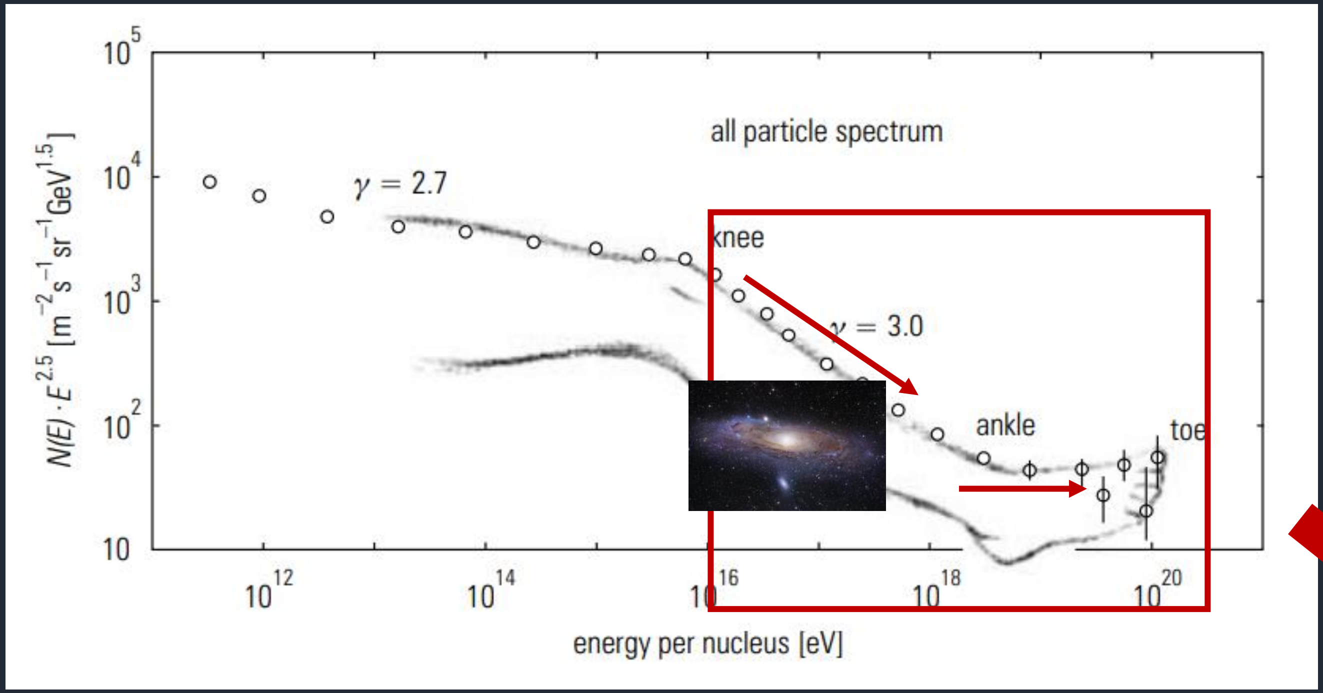
Energy spectrum of all particles of primary cosmic rays

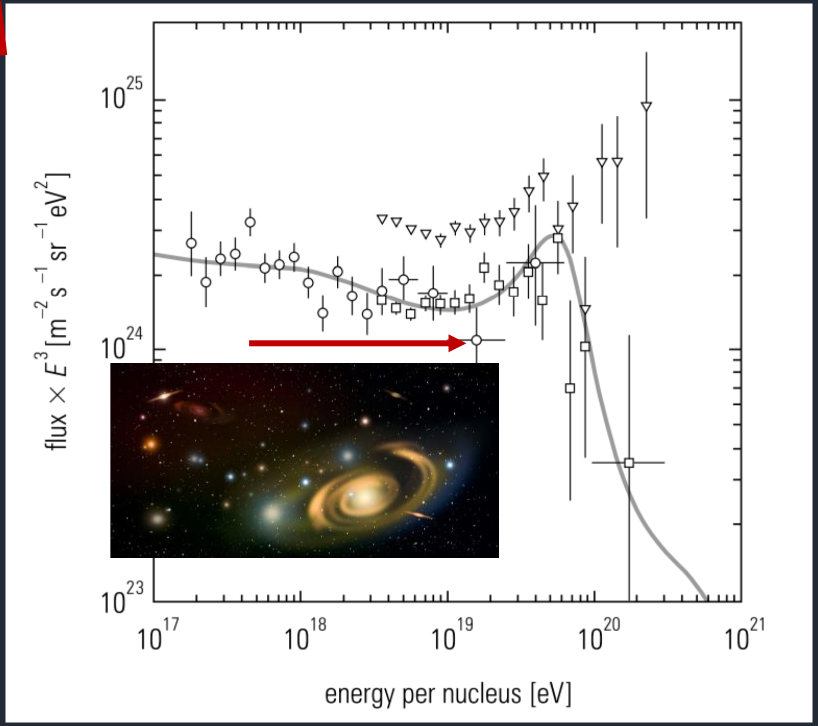


Flux x E^3



Too steep to observe in detail





- ✓ Cosmic rays above 10^15eV is believed to originated from within our galaxy.(decreasing)
- ✓ But the ankle part is often interpreted as a crossover with a galactic component from extragalactic

Why are there 'knee'?

For galactic objects, in equilibrium between the centrifugal(원심력) and Lorentz force,

Binding radius or gyroradius

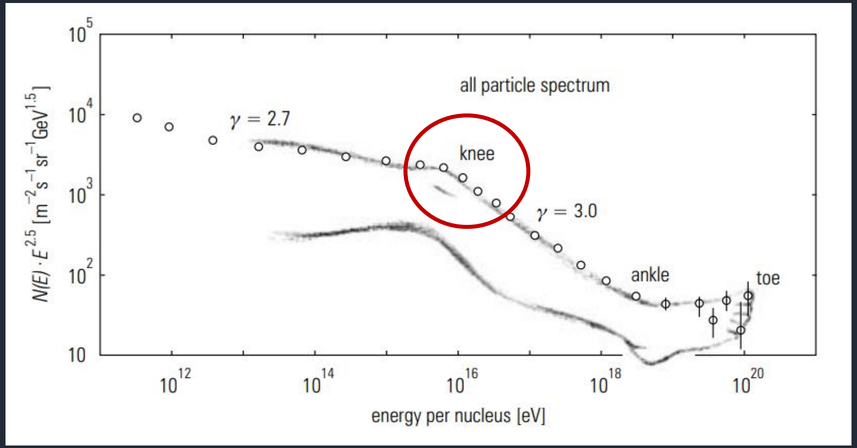
$$mv^2/\varrho = Z\,e\,v\,B \quad \Rightarrow \quad p = e\,\varrho\,B$$

The momentum of singly charged particles
(gain or lost one electron, Z = 1)

In the galaxy, for a large-area galactic magnetic field(B = 10^(-10)) and gyroradius of 5pc.
Then the momenta for particles is

$$p[\mathrm{GeV}/c] = 0.3\,B[\mathrm{T}]\,\varrho[\mathrm{m}]\,,$$

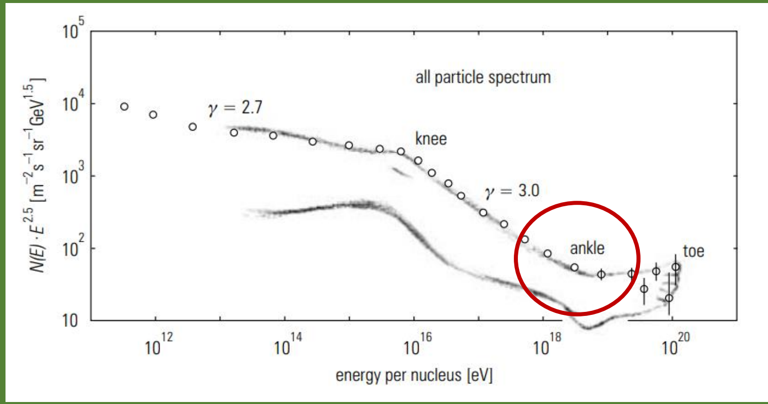
$$p_{\max} = 4.6 \times 10^6\,\mathrm{GeV}/c = 4.6 \times 10^{15}\,\mathrm{eV}/c$$



- Particles with energies exceeding 10^15eV start to leak from galaxy.
- This causes the spectrum to get steeper to higher energies

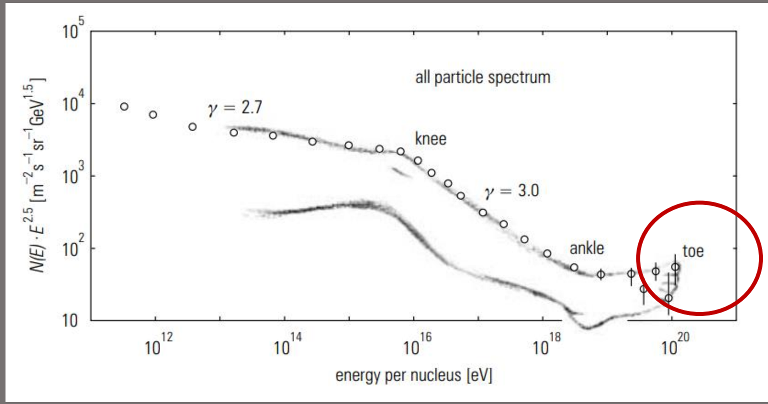
Why are there 'ankle'?

The flattening of the spectrum above 10^19eV(ankle) is generally assumed to be due to an "extragalactic component"



Why are there 'toe'?

The observation of several events in excess of 10^20eV(the toe of Primary cosmic rays) represents mystery.
Since there is no correlation of these high-energy cosmic ray events with known astronomical sources in the immediate neighnourhood or our galaxy.



Sources of cosmic rays

Even though cosmic rays have been discovered about 90 years ago, their origin is still an open question. It is generally assumed that active galactic nuclei, quasars, or supernova explosions are excellent source candidates for high-energy cosmic rays, but there is no direct evidence for this assumption.

- Photons, neutrinos : travel on straight lines in galactic and intergalactic space 〉〉 therefore pointing directly back to the sources.
- Charged particles are subject to the influence of magnetic fields. they are accelerated and lose their directional information before reaching the Earth.

Since the magnetic deflection is proportional to the charge of a particle, proton astronomy is more promising than astronomy with heavy nuclei.

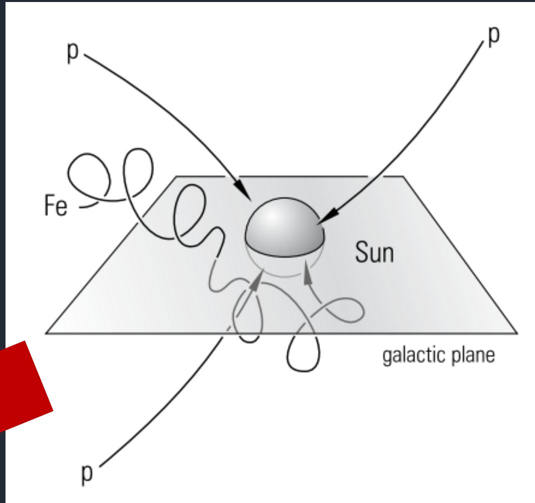
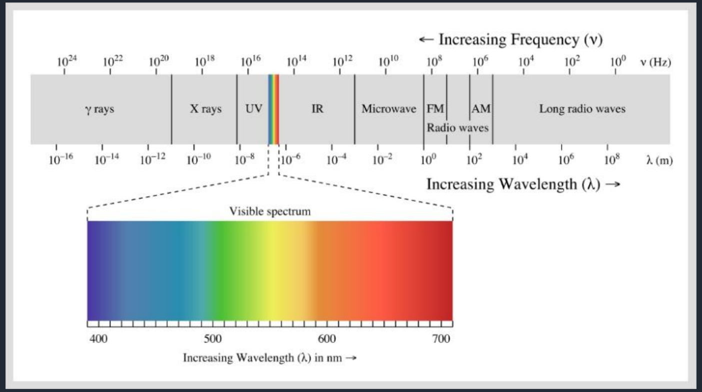


Fig. 6.7
Sketch of proton and iron-nucleus trajectories in our Milky Way at 10^{18} eV

6.2 Neutrino astronomy

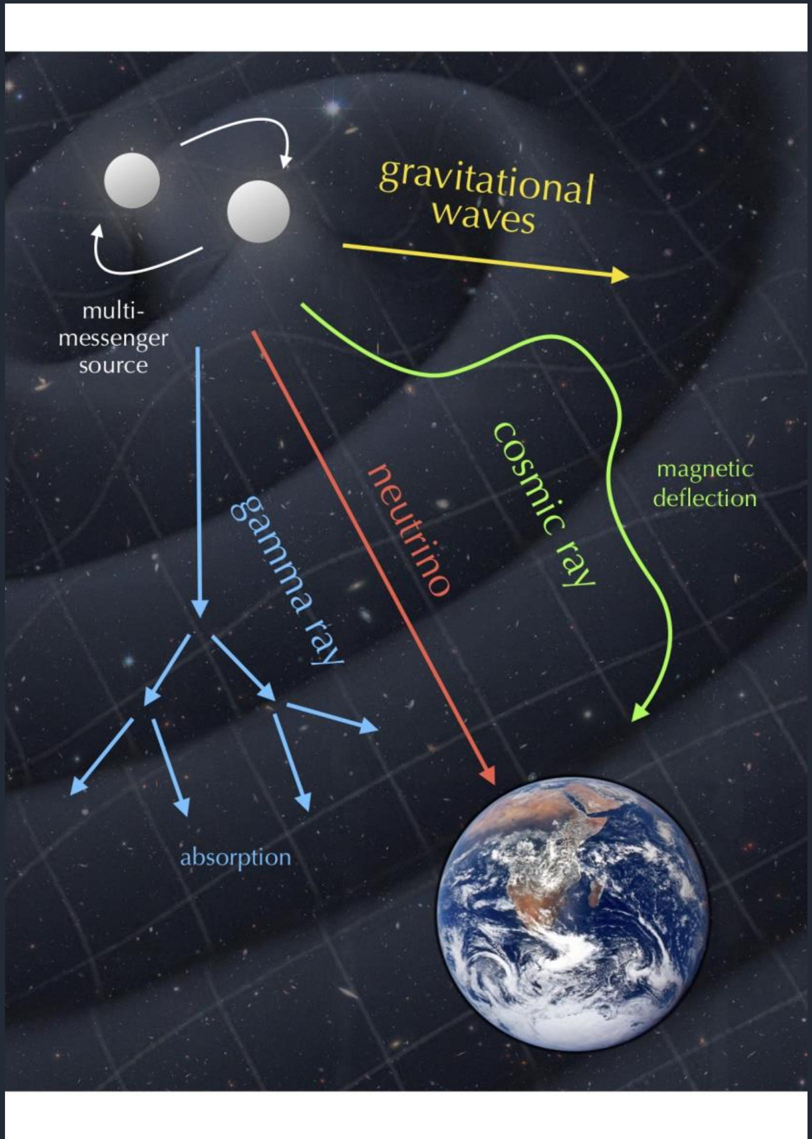
The disadvantage of classical astronomy: electromagnetic radiation is quickly absorbed in matter.



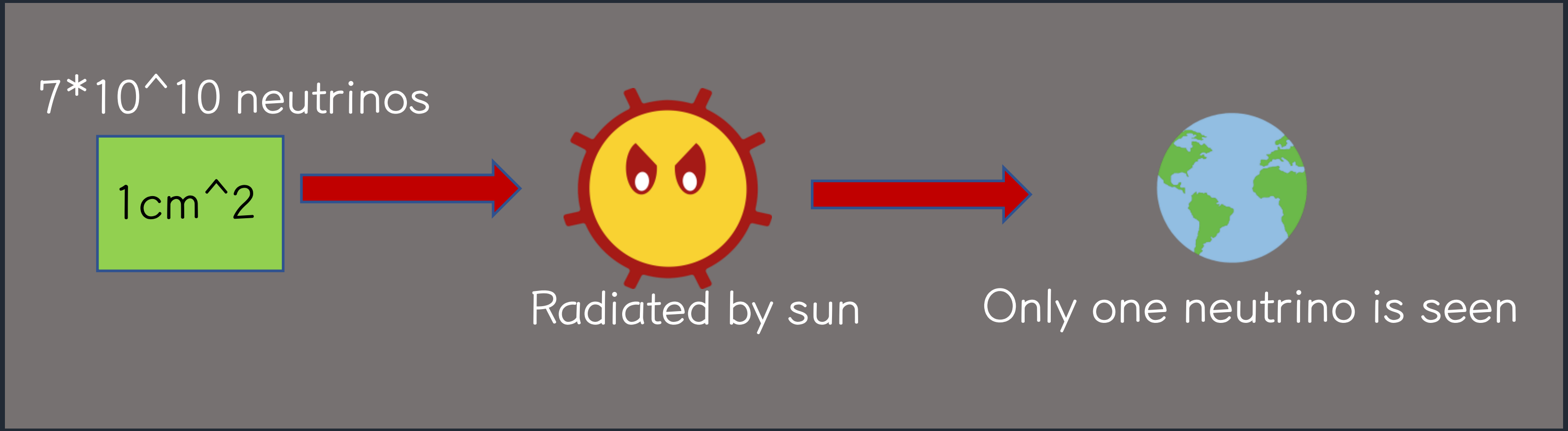
〉〉 We can't use directional information for charged particles.

These five requirements are fulfilled by neutrinos in an ideal neutrino astronomy way!

Difficulty in Neutrino astronomy

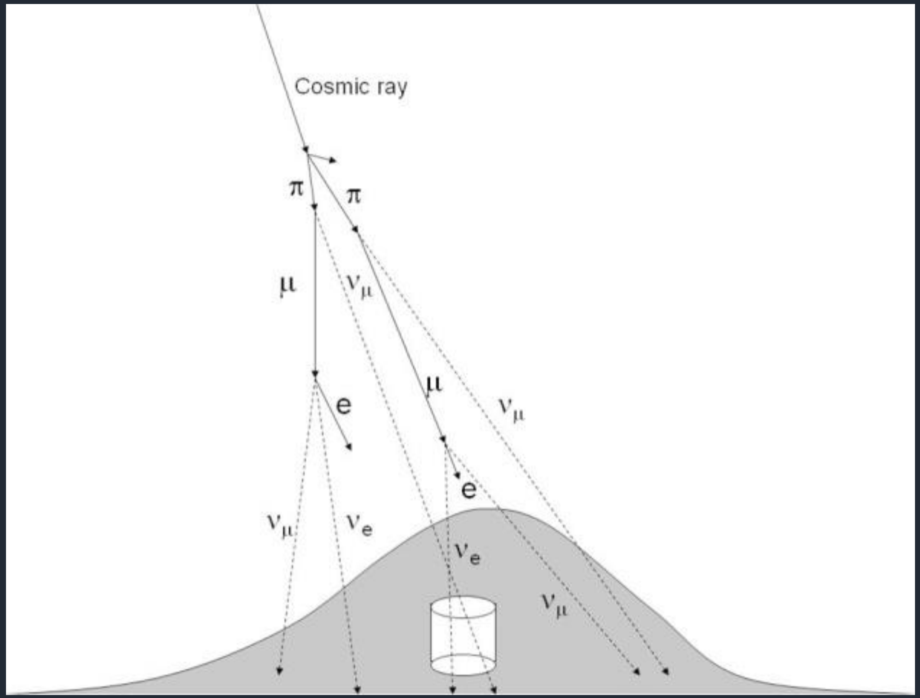


✓ since neutrinos can escape from the center of the sources,
There are huge difficulty to detect neutrinos on Earth.



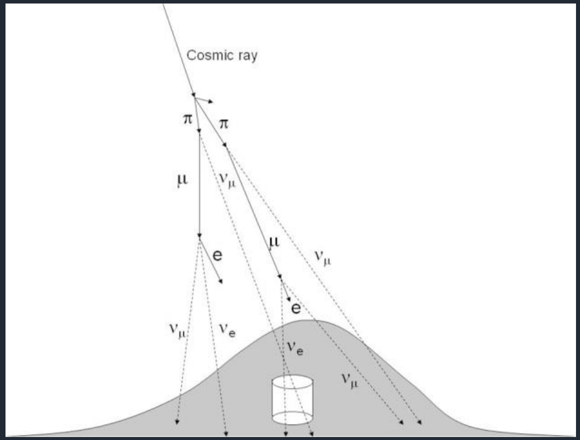
1. Atmospheric neutrinos
2. Solar neutrinos
3. Supernova neutrinos
4. High-energy galactic and extragalactic neutrinos

1. Atmospheric neutrinos



- ✓ They form when a cosmic ray crashes into Earth's atmosphere.
- ✓ When they strike an atomic nucleus in our atmosphere, there is a cascade of particles.

1. Atmospheric neutrinos



✓ They form when a cosmic ray crashes into Earth's atmosphere.

✓ When they strike an atomic nucleus in our atmosphere, there is a cascade of particles.

Primary cosmic rays → **N, O in atmosphere** → **mesons, pions(mostly)**

$$\pi^+ \to \mu^+ + \nu_\mu \ , \quad \pi^- \to \mu^- + \bar{\nu}_\mu$$

↓

muons, muons antineutrinos

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu \ , \quad \mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$

←

electron, electron antineutrino, and muon neutrino

$$\frac{N(\nu_\mu, \bar{\nu}_\mu)}{N(\nu_e, \bar{\nu}_e)} \equiv \frac{N_\mu}{N_e} \approx 2$$

Muon neutrino and electron

- ✓ We can distinguish electron from muon neutrinos.

muon

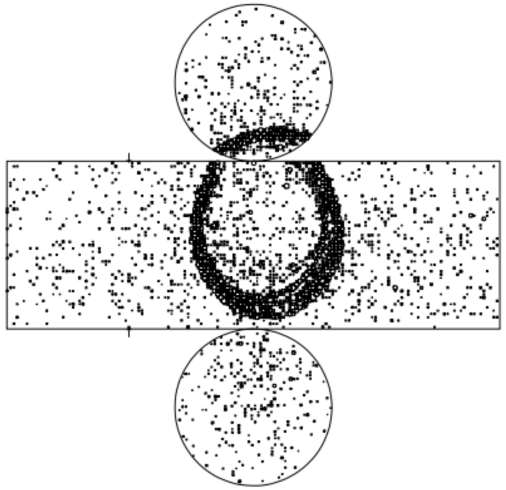


Fig. 6.10
Cherenkov pattern for an energetic muon in the Super-Kamiokande detector {9}

electron

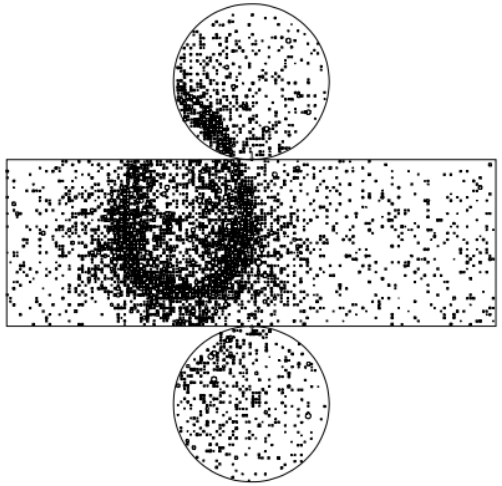


Fig. 6.9
Cherenkov pattern of an energetic electron in the Super-Kamiokande Detector {9}

Muons have a well-defined range and produce a clear Cherenkov pattern with sharp edges while electrons initiate electromagnetic cascades thereby creating a fuzzy ring pattern

Muon neutrino and electron

the ratio of muons to electrons and a Monte Carlo simulation:

$$R = \frac{(N_\mu/N_e)_{\text{data}}}{(N_\mu/N_e)_{\text{Monte Carlo}}}$$

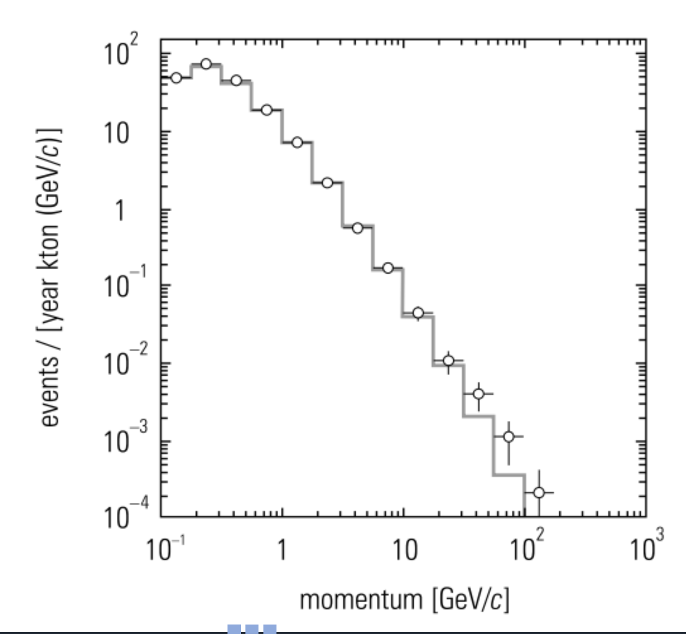
one would expect the value R = 1.

However, the experiment obtains

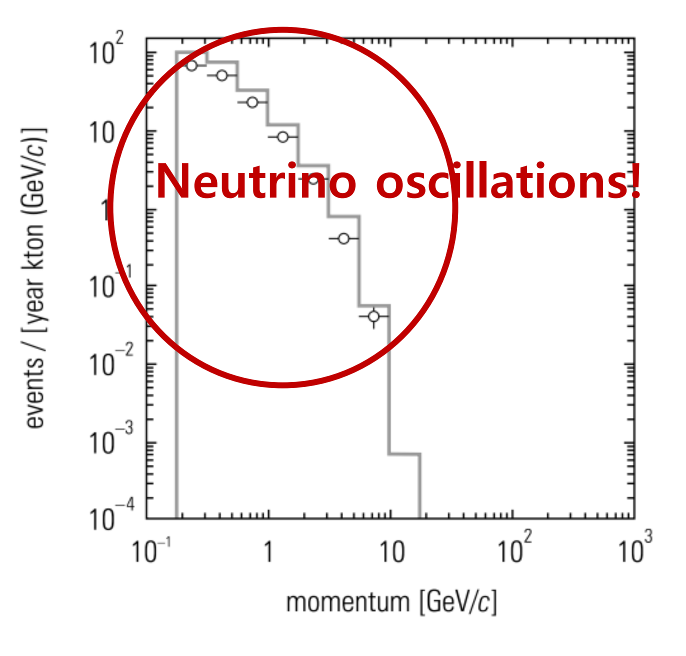
$$R = 0.69 \pm 0.06$$

which represents a clear deviation from expectation

electron-like



muon-like



Muon Neutrino could be transformed during propagation from source to the observation in detector into a different neutrino flavour

The solid line represents the Monte Carlo expectation

Neutrino oscillations

Concept:

If the muon neutrino in reality was a mixture of two different mass eigenstates $\nu 1$ and $\nu 2$, these two states would propagate at different velocities if their masses were not identical.
so mass components will get out of phase with each other.
This could possibly result in a different neutrino flavour at the detector.

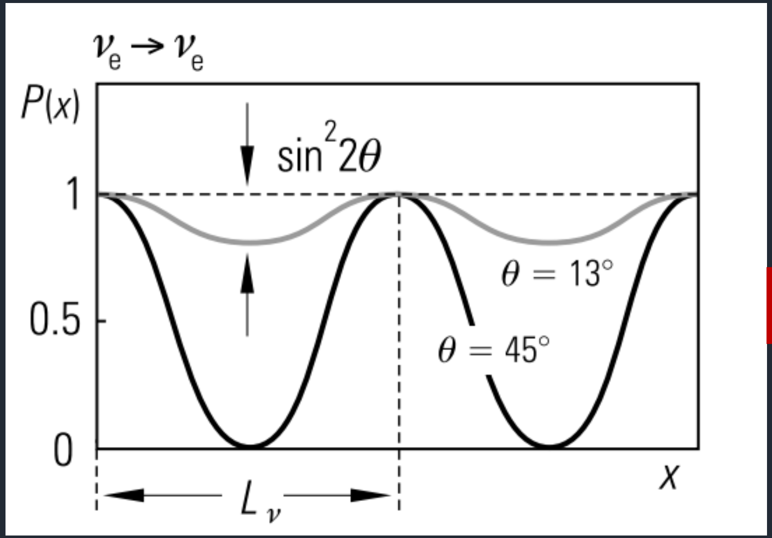
Mixture of different mass eigenstate

$$\nu_e = \nu_1 \cos\theta + \nu_2 \sin\theta \, ,$$
$$\nu_\mu = -\nu_1 \sin\theta + \nu_2 \cos\theta$$

(theta is mixing angle)

Probability of electron neutrino stays an electron neutrino

$$P_{\nu_e \to \nu_e}(x) = 1 - \sin^2 2\theta \sin^2 \left(1.27 \, \delta m^2 \frac{x}{E_\nu} \right)$$



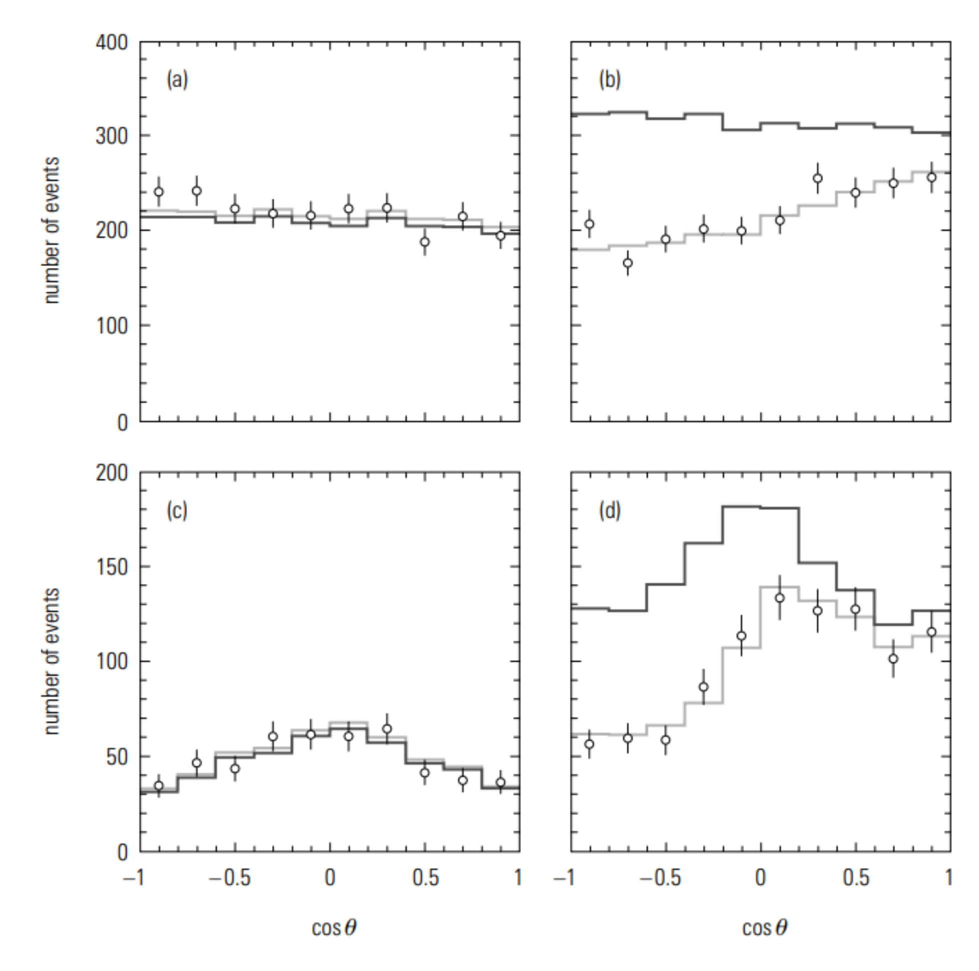
1.neutrino has a non-zero mass
2. Neutrino can be transformed to other neutrino.
3. This can explain deficit of muon neutrino(e.g., into tau neutrinos)

$$(\nu_\mu \rightarrow \nu_\tau)$$

electron muon

Sub-GeV range

multi-GeV range



Dark grey line : expectation for no oscillations
Light grey line : expectation for oscillations

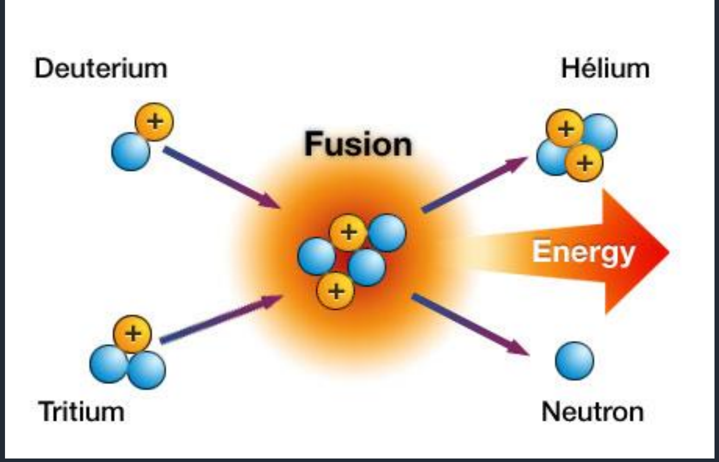
- The electron events are in perfect agreement with expectation, but the muons for no-oscillation clearly not match.

(Theta is zenith angle)

In the Standard Model of elementary particles, neutrinos have zero mass. Therefore, neutrino oscillations represent an important extension of the elementary particles physics!(and this got novel prize in 2015)

2. Solar neutrinos

The Sun is a nuclear fusion reactor



The Sun produce a pure electron – neutrino source not electron antineutrinos and or other neutrino flavours (ν_μ, ν_τ)

〈 reaction in the Sun 〉

$p + p \rightarrow d + e^+ + \nu_e$ 86% of solar neutrinos

$d + p \rightarrow {}^3\mathrm{He} + \gamma$

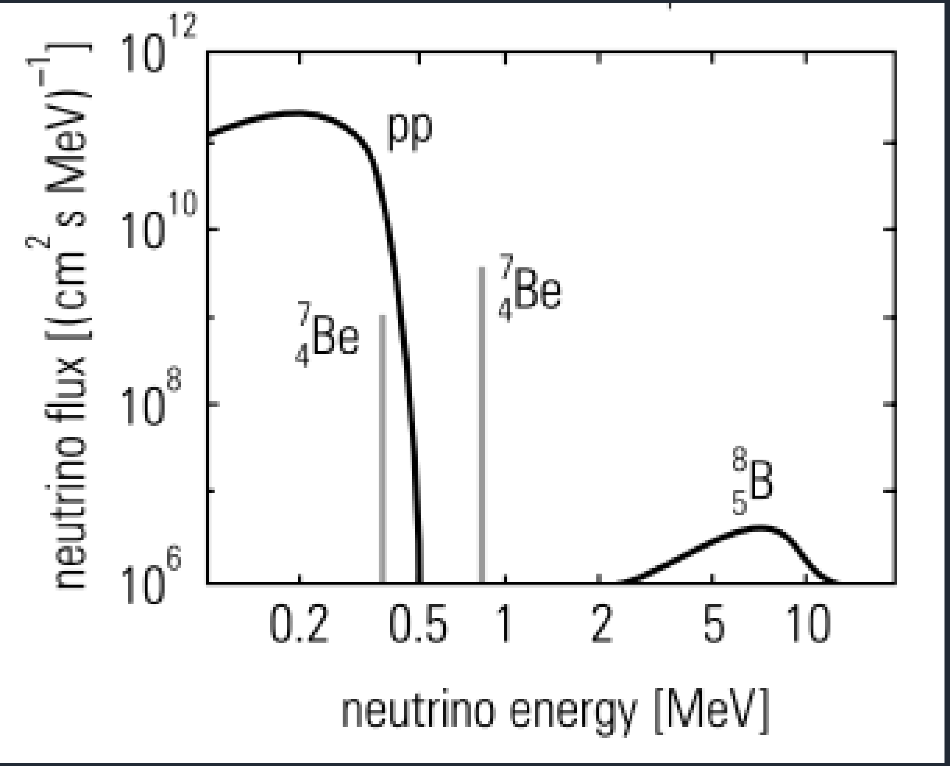
${}^3\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + 2p$

${}^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e$ 14% ne

${}^7\mathrm{Be} + p \rightarrow {}^8\mathrm{B} + \gamma$

${}^7\mathrm{Li} + p \rightarrow {}^4\mathrm{He} + {}^4\mathrm{He}$

${}^8\mathrm{B} \rightarrow {}^8\mathrm{Be} + e^+ + \nu_e$ 0.02 ne



2. Solar neutrinos's experiment : radiochemical experiment

Davis experiment(historically first experiment)

$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$$

For the 30 years of operation, davis experiment only found 27% of the standard solar model

GALLEX, SAGE

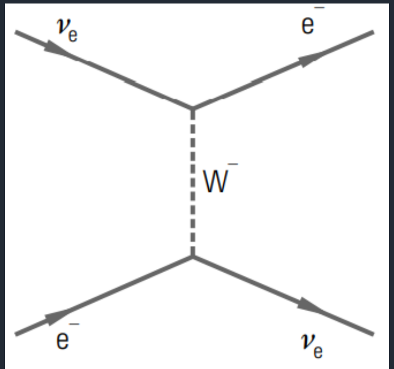
$$\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$$

they found 52% of the standard solar model

2. Solar neutrinos's experiment : water cherenkov experiment

Kamiokande and Super-Kamiokande experiment

$$\nu_e + e^- \rightarrow \nu_e + e^-$$



"Knock-on electron"

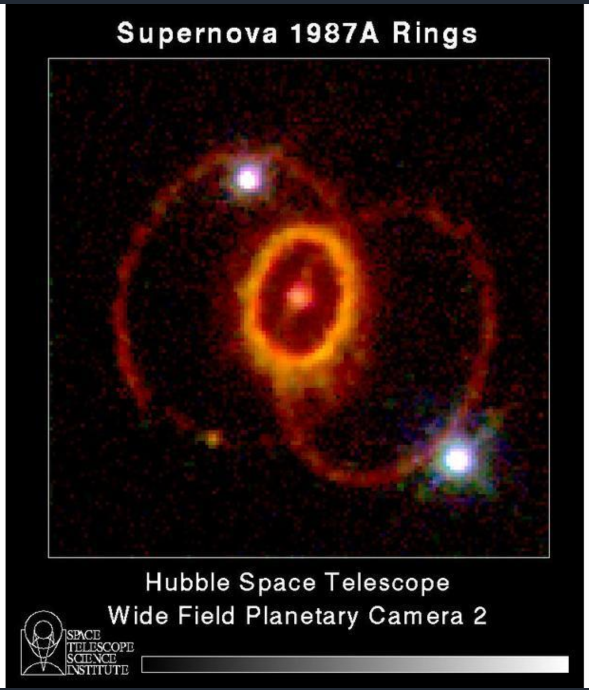
they found 40% of the standard solar model

it's extinct that we have a problem of solar neutrinos

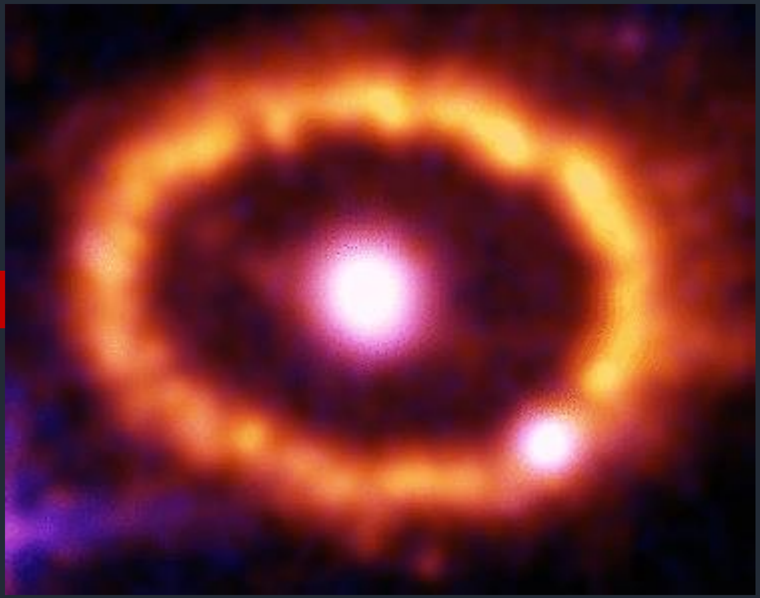
1) Doubt for correctness of the standard solar model
2) Overestimate of the reaction cross sections
3) Magnetic moment of neutrinos
4) Neutrino decay
5) Neutrino oscillations(matter oscillations)

- At the end of 2002, by the KamLAND neutrino detector,
  They found oscillation mechanism
  $(\nu_e \rightarrow \nu_\mu)$
- And all doubts about possible uncertainties of the standard solar model were removed.

3. Supernova neutrinos



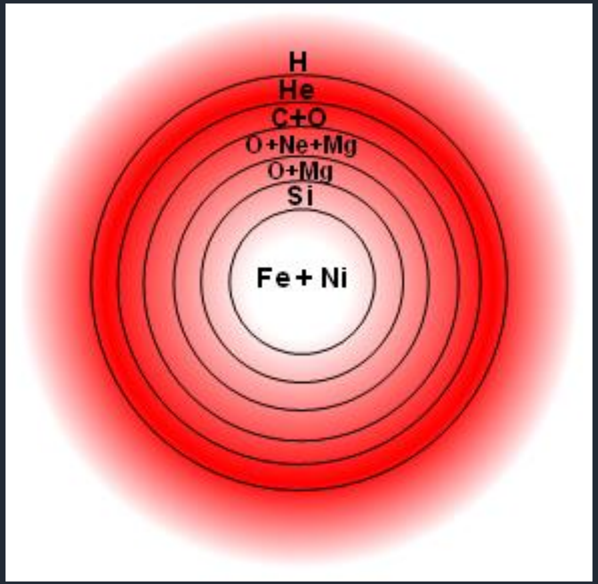
Supernova 1987A (the brightest supernova)



Sanduleak : The body before the explosion of the supernova 1987A

- ✓ During hydrogen burning Sanduleak increased its brightness reaching a luminosity 70 000 higher than the solar luminosity.
- ✓ After the hydrogen supply was exhausted, the star expanded to become a red supergiant.

3. Supernova neutrinos



When the red supergiant stop their fusion processes,
The star collapsed under its own gravity.
During this deleptonization, a neutrino burst was created.

$$e^- + p \to n + \nu_e$$

3. Supernova neutrinos

There are detector for this(kamiokande and IMB)

The energy of individual neutrinos measured in the

$$E_{\text{total}} = \sum_{i=1}^{20} \frac{E_\nu^i}{\varepsilon_1(E_\nu^i)\varepsilon_2(E_\nu^i)} 4\pi r^2 f(\nu_\alpha, \bar{\nu}_\alpha)$$

Correction factor

Probability for the interaction of a neutrino in the detector

Based on the 20 recorded neutrino events,

$$E_{\text{total}} = (6 \pm 2) \times 10^{46} \text{ Joule}$$

(The world energy consumption is 10^21 Joule per year.)

During the 10 seconds lasting neutrino, burst Sanduleak radiated more energy than the rest of the universe and hundred times more than the Sun in its total lifetime of about 10 billion year

Neutrino oscillations

Concept:

If the muon neutrino in reality was a mixture of two different mass mass eigenstates eigenstates $v\,1$ and $v\,2$, these two states would propagate at different velocities if their masses were not identical and so the mass components get out of phase with each other. This could possibly result in a different neutrino flavour at the detector.

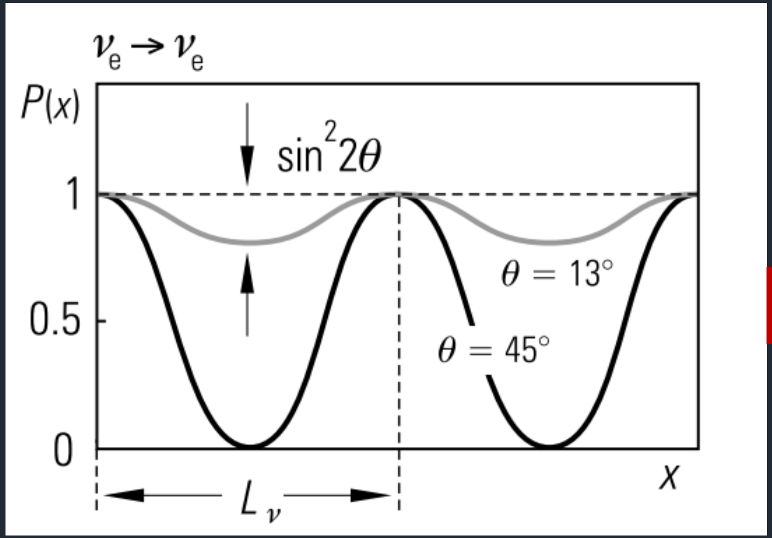
Mixture of different mass eigenstate

$$\nu_e = \nu_1 \cos\theta + \nu_2 \sin\theta \,,$$
$$\nu_\mu = -\nu_1 \sin\theta + \nu_2 \cos\theta$$

(theta is mixing angle)

Probability of electron neutrino stays an electron neutrino

$$P_{\nu_e \to \nu_e}(x) = 1 - \sin^2 2\theta \, \sin^2\left(1.27\,\delta m^2 \frac{x}{E_\nu}\right)$$



1.neutrino has a non-zero mass
2. Neutrino can be transformed to other neutrino.
3. This can explain deficit of muon neutrino(e.g., into tau neutrinos)

$$(\nu_\mu \rightarrow \nu_\tau)$$

using the result of supernova neutrinos, we can derive the neutrino mass limit

Neutrinos of nonzero mass have different velocities depending on their energy.

$$\Delta t = \frac{r}{v_1} - \frac{r}{v_2} = \frac{r}{c}\left(\frac{1}{\beta_1} - \frac{1}{\beta_2}\right) = \frac{r}{c}\,\frac{\beta_2 - \beta_1}{\beta_1\,\beta_2}$$

$$E = mc^2 = \gamma m_0 c^2 = \frac{m_0 c^2}{\sqrt{1-\beta^2}}$$

$$\beta = \left(1 - \frac{m_0^2 c^4}{E^2}\right)^{1/2} \approx 1 - \frac{1}{2}\,\frac{m_0^2 c^4}{E^2}$$

$$\Delta t \approx \frac{r}{c}\,\frac{\frac{1}{2}\frac{m_0^2 c^4}{E_1^2} - \frac{1}{2}\frac{m_0^2 c^4}{E_2^2}}{\beta_1 \beta_2} \approx \frac{1}{2} m_0^2 c^4 \frac{r}{c}\,\frac{E_2^2 - E_1^2}{E_1^2\,E_2^2}$$

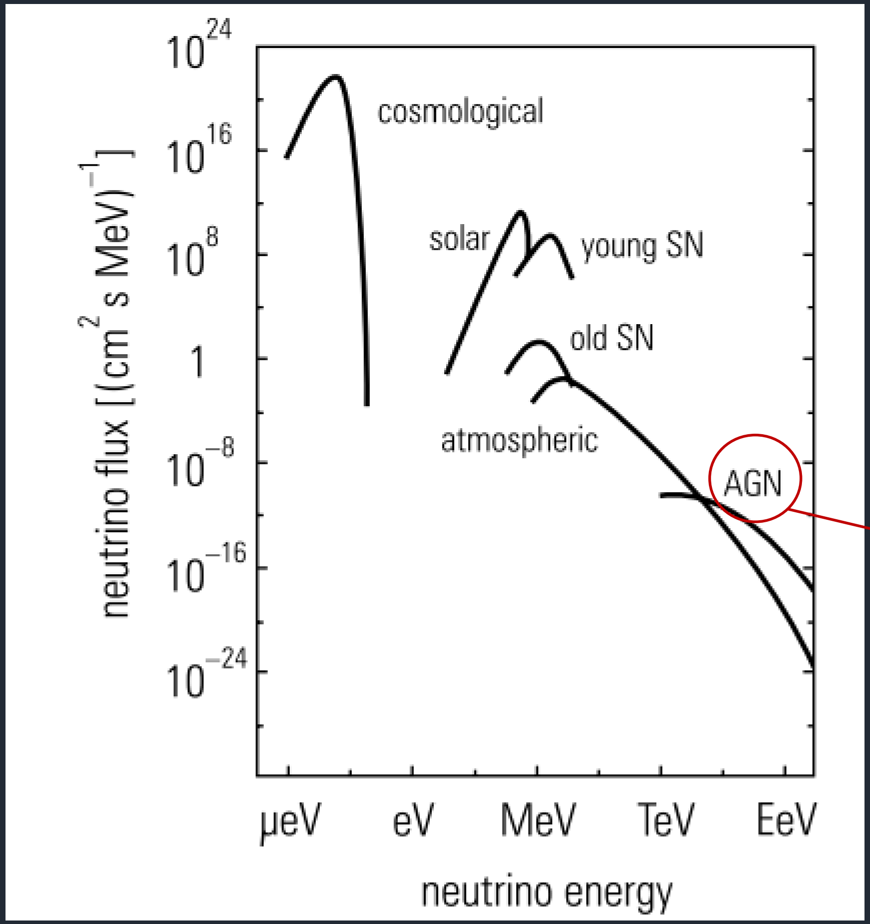
$$m_0 = \left\{\frac{2\Delta t}{r\,c^3}\,\frac{E_1^2\,E_2^2}{E_2^2 - E_1^2}\right\}^{1/2}$$

By applying the experimentally measured arrival-time differences and individual neutrino energies, we can get matter limit

$$m_{\nu_e} \leq 10\,\text{eV}$$

(This result was obtained in a measurement time of approximately 10 seconds)

4. High-Energy Galactic and Extragalactic Neutrinos



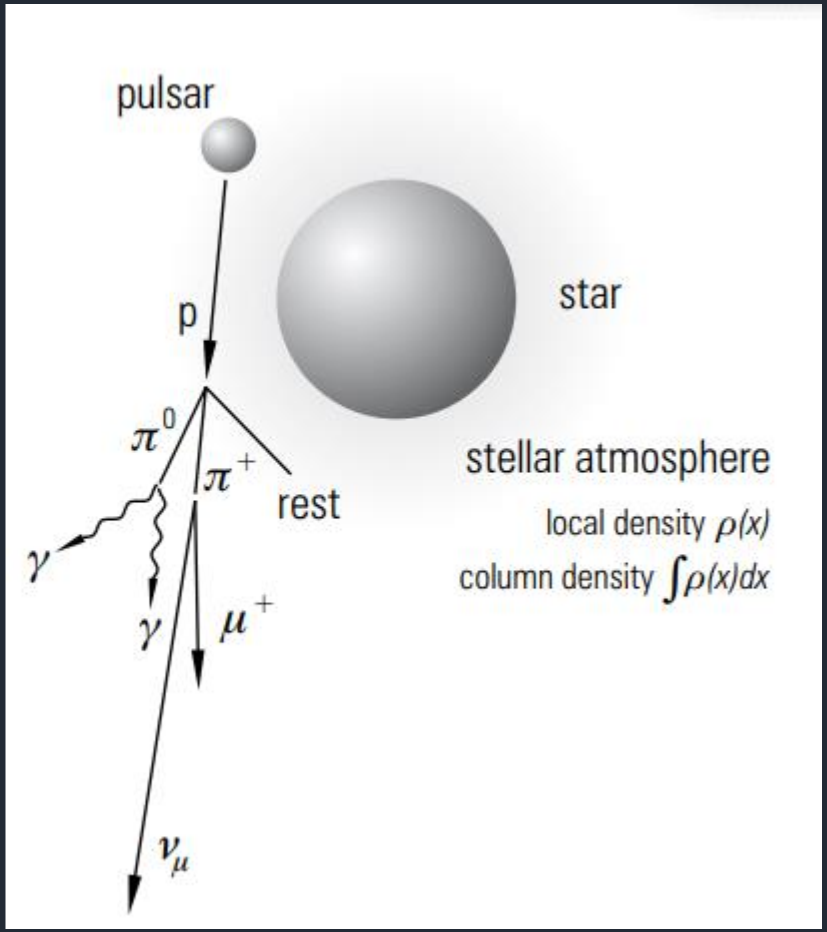
- the observation of solar ($\approx$ MeV range)
- supernova neutrinos ($\approx$ 10 MeV)
- Atmospheric neutrinos represent a background for neutrinos from astrophysical sources.
  (Their intensity is only known with an accuracy of about 30%.)

neutrinos from extragalactic sources (AGN – Active Galactic Nuclei)

4. High-Energy Galactic and Extragalactic Neutrinos

high-energy neutrinos (≥ TeV range) would directly point back to the sources of cosmic rays.
But the measurement of these neutrinos (≥ TeV range) is a big experimental challenge.

Binary system



- ✓ binaries are good candidates for the production of energetic neutrinos.
- ✓ The pulsar and the star rotate around their common center of mass
- ✓ the pulsar can manage to accelerate protons to very high energies.These accelerated protons collide with the gas of the atmosphere of the companion star and produce secondary pions
- ✓ Neutral pions decay into two energetic gamma rays
- ✓ The charged pions produce energetic neutrinos by their decay