Self-introduction

My name is Atsumu Suzuki (鈴木州) from Kobe University
Member of SK, HK, and T2K (Neutrino experiments)

Scuba diving
(a couple of times a year)

Tennis weekend

Skating in winter

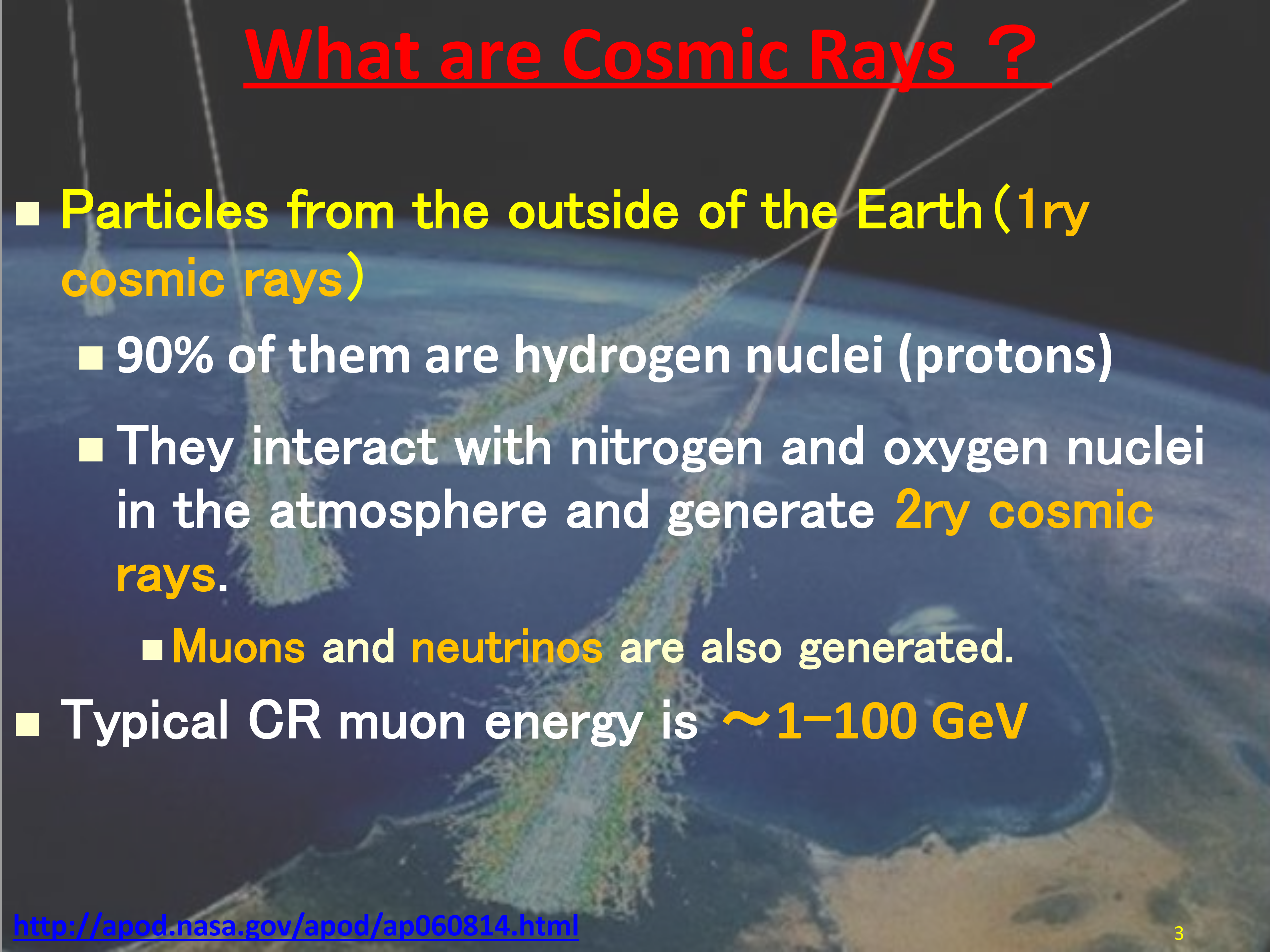
Introduction to Cosmic Ray

Atsumu Suzuki

Kobe University

http://apod.nasa.gov/apod/ap060814.html

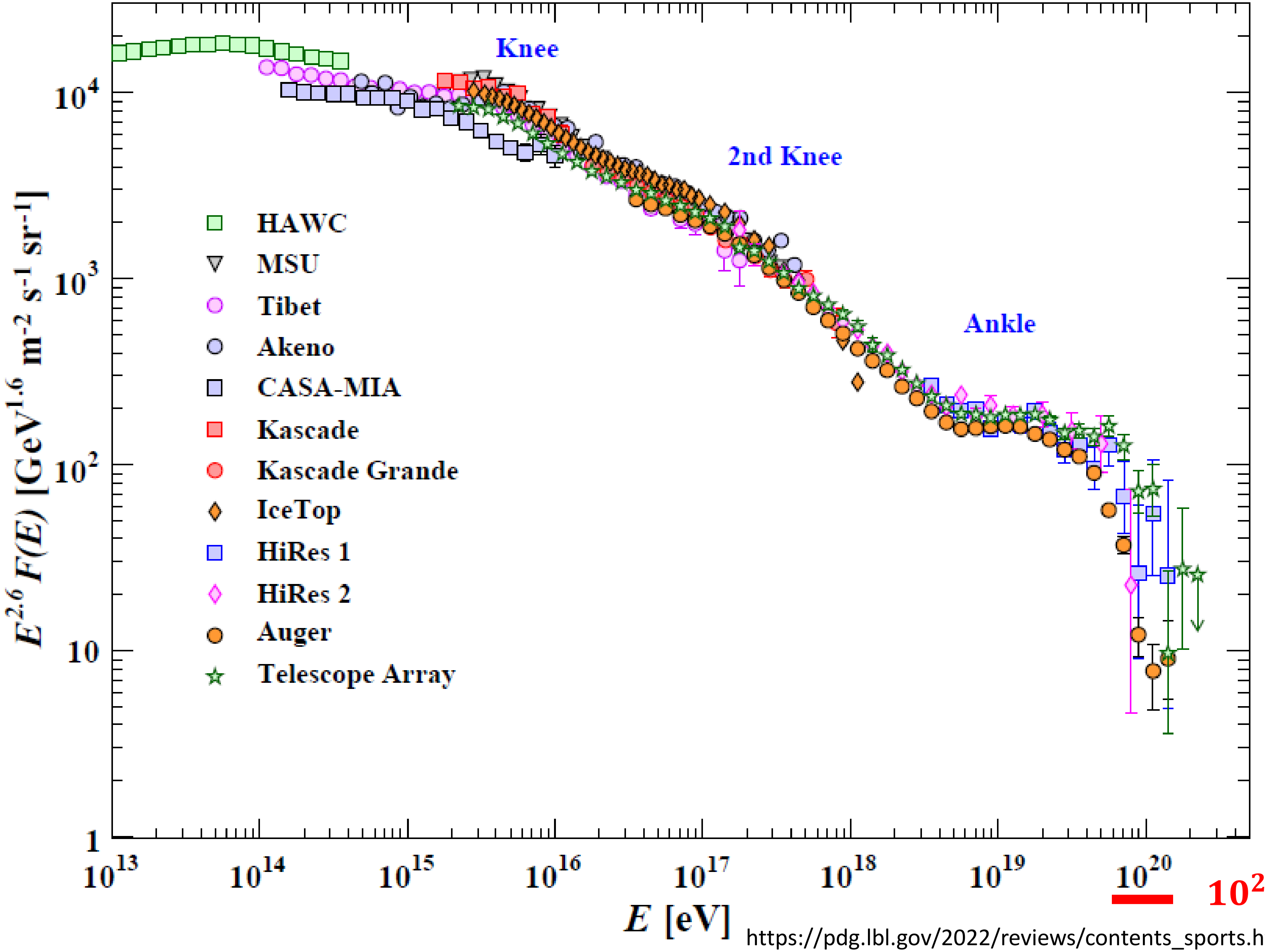
What are Cosmic Rays ？



- Particles from the outside of the Earth（1ry cosmic rays）
  - 90% of them are hydrogen nuclei (protons)
  - They interact with nitrogen and oxygen nuclei in the atmosphere and generate 2ry cosmic rays.
    - Muons and neutrinos are also generated.
- Typical CR muon energy is ～1–100 GeV

http://apod.nasa.gov/apod/ap060814.html

Cosmic Ray Spectrum



10^{20}~10^{21}

https://pdg.lbl.gov/2022/reviews/contents_sports.html

Why $10^{20}\sim10^{21}$ eV ?

High energy protons interact with Cosmic Microwave Background (CMB):

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

What is the threshold energy E_p of such a proton ?

$$\left(E_p+E_{\mathrm{CMB}}\right)^2-\left(p_p-E_{\mathrm{CMB}}\right)^2=(m_n+m_\pi)^2$$

Assuming $E_p=p_p$ because of high energy, we obtain

$$E_p=\frac{(m_n+m_\pi)^2}{4E_{\mathrm{CMB}}}$$

$E_{\mathrm{CMB}}=8.62\times10^{-5}\left[\mathrm{eV\ K^{-1}}\right]\times2.7[\mathrm{K}]=2.33\times10^{-4}[\mathrm{eV}]$,
$m_n=940\ [\mathrm{MeV}]$, and $m_\pi=140\ [\mathrm{MeV}]\rightarrow$ $E_p=1.25\times10^{21}$ eV
(consistent with measurements)

The number of UHE CR coming to the Earth is suddenly suppressed at the energy of $\sim10^{20}$ eV . ⇒
Greisen-Zatspin-Kuzmin (GZK) Cutoff

Primary cosmic-ray flux

Chemical composition

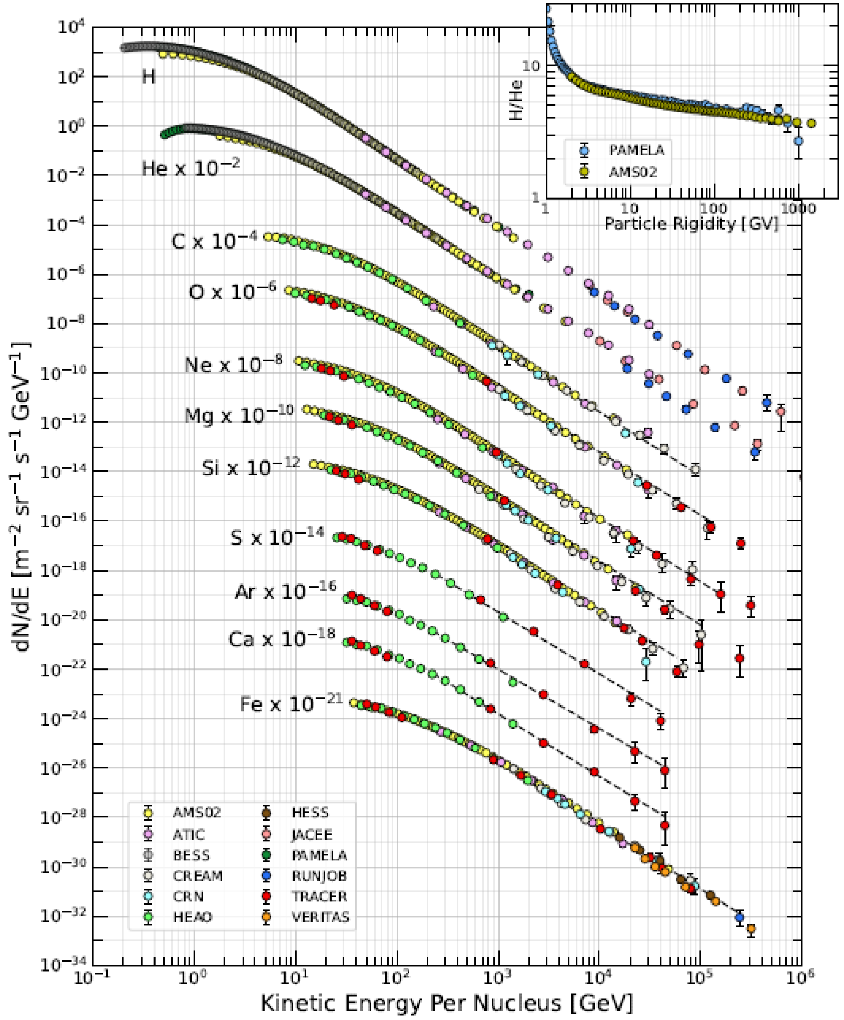
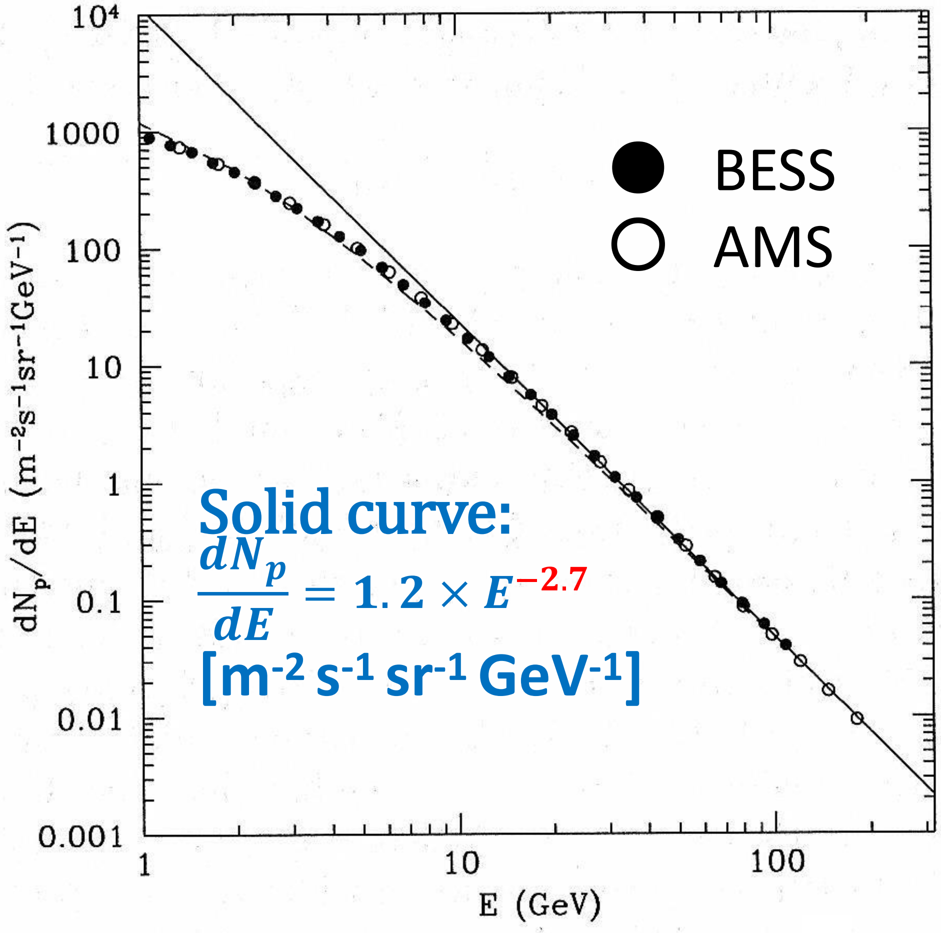


Figure 30.1: Fluxes of nuclei of the primary cosmic radiation in particles per energy-per-nucleus are plotted vs energy-per-nucleus using data from Refs. [1–15] The inset shows the H/He ratio as a function of rigidity [1,3].

1ry CR proton energy distribution



Solid curve:

$$\frac{dN_p}{dE} = 1.2 \times E^{-2.7}$$

[m^{-2} s^{-1} sr^{-1} GeV^{-1}]

https://pdg.lbl.gov/2022/reviews/contents_sports.html

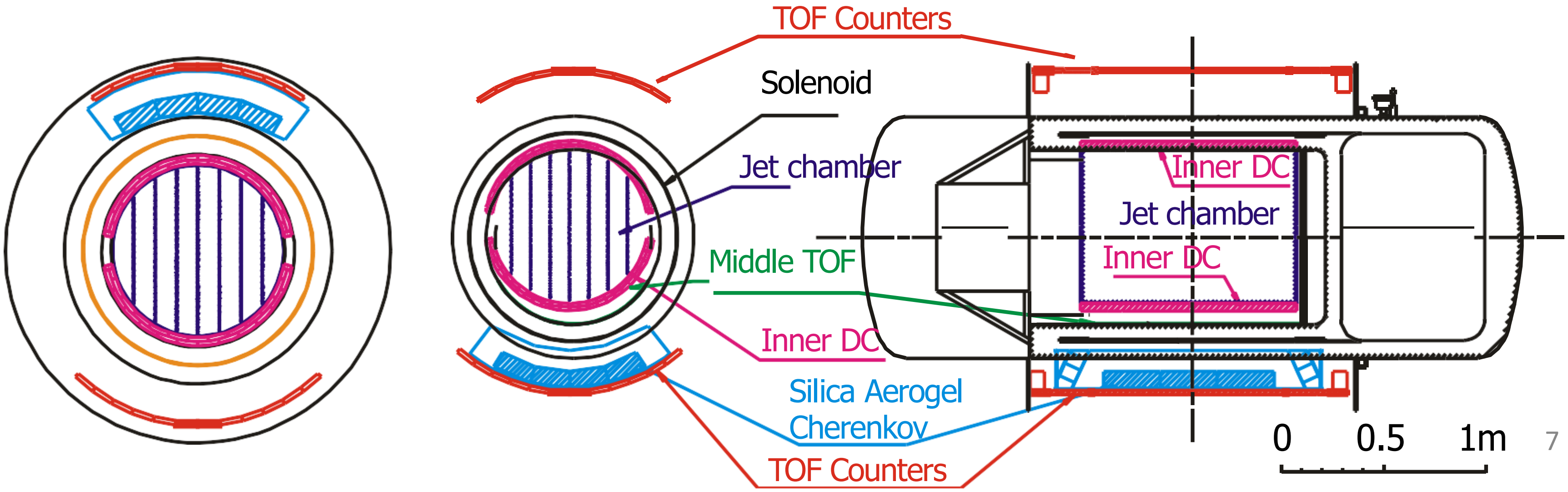
Balloon-borne Experiment with a Superconducting Spectrometer (BESS)

BESS-2000

- Collaboration between Japan and US(KEK, Univ.of Tokyo,Kobe Univ.,JAXA,NASA, and Univ.of Maryland)
- Purposes

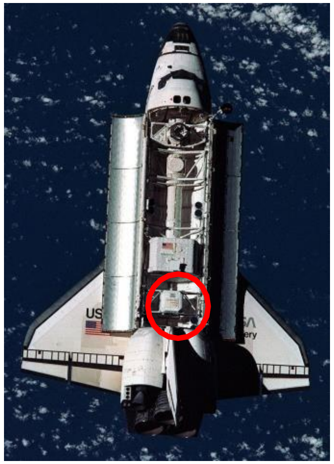
1. Precision measurement of low energy 1ry CR **antiprotons**
2. Search for CR antimatter (anti He nucleus)
3. Precision measurement of 1ry CR proton and helium energy spectrums etc.

- Site：Lynn Lake（Canada）, Antarctica



Alpha Magnetic Spectrometer (AMS)

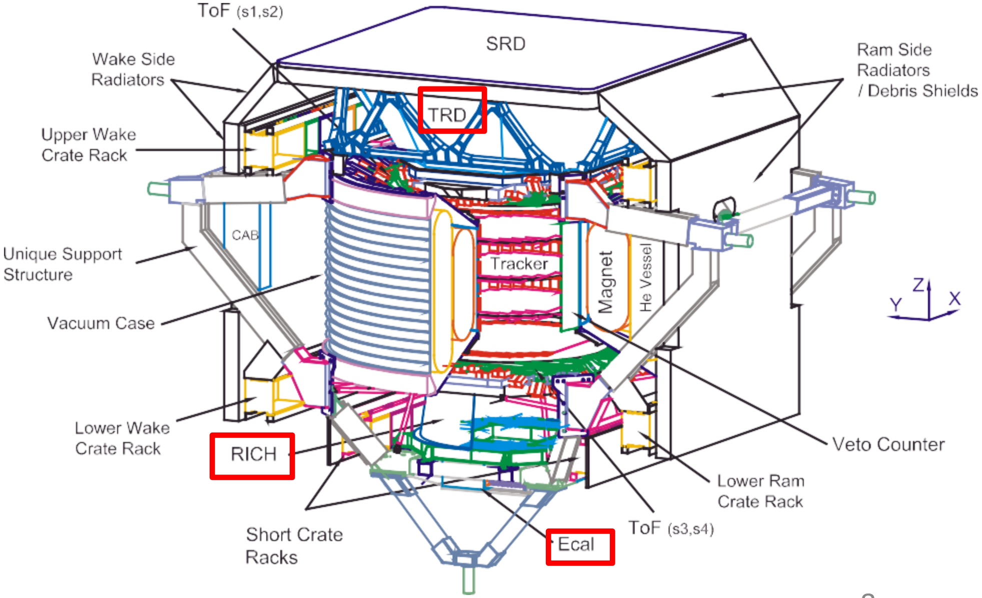
- Particle physics detector on the international space station for the cosmic ray measurement.



AMS01 on space shuttle (STS-91, June 1998).

- Large area and solid angle
- Superconducting magnet + Si detector
- Good particle identification (PID)
  - TRD (Transition Radiation Detector)
  - RICH (Ring Imaging Cherenkov detector)
  - ECAL (Electromagnetic CALorimeter)
- Total weight: 6t

AMS-02 on the space station.



Cosmic ray flux measurements

Japanese American Cooperative Emulsion Experiment (JACEE) : Direct measurements of 1ry CR components and energy spectrum in **Antarctica** Balloon-borne experiment

Russia-Nippon Joint Balloon Experiment (RUNJOB)
purpose: measuring the chemical compositions and energy spectra of the primary cosmic ray, balloon, **Russia**

HEAT (High-Energy Antimatter Telescope)
purpose: study of CR e^-e^+, isotopic composition,
balloon, New Mexico & **Lynn Lake (Canada)**

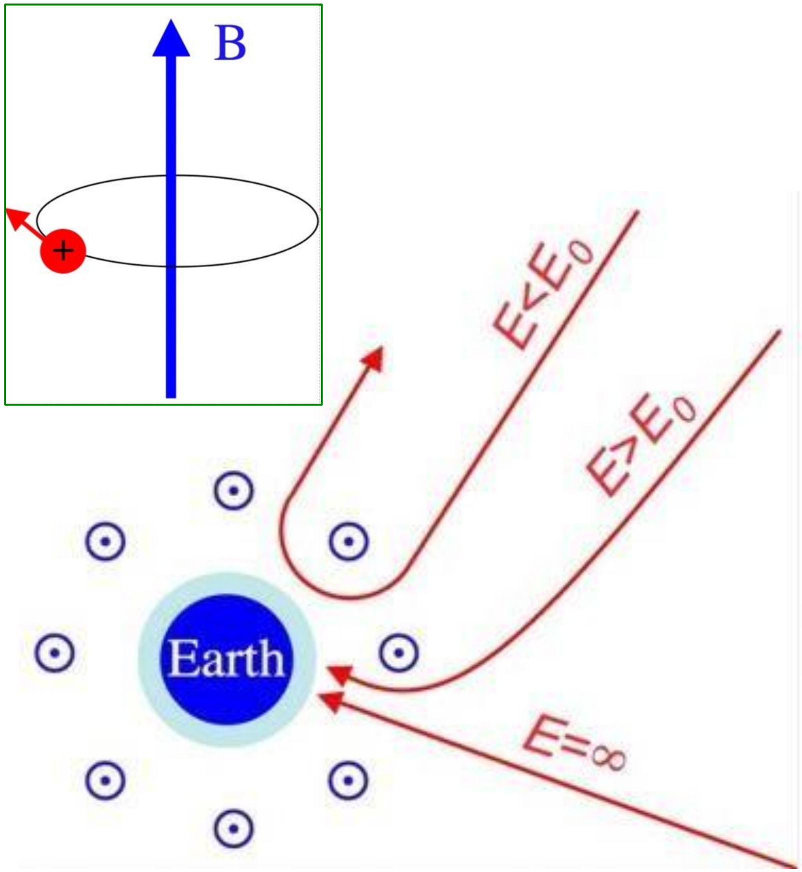
TRACER (Transition Radiation Array for Cosmic Energetic Radiation)
purpose: direct measurements of the heavier primary cosmic-ray nuclei at high energies, balloon, **Antarctica**

ATIC (Advanced Thin Ionization Calorimeter)
purpose: measuring the energy and composition of cosmic rays, balloon, **Antarctica**

CREAM (Cosmic Ray Energetics and Mass)
purpose: determining the composition of cosmic rays up to the 10^{15} eV (also known as the “ knee prospect ") in the cosmic ray spectrum, balloon, **Antarctica**

Why at high latitude ?

To lower the cut-off rigidity R_c. The rigidity $R = p/z$, where *p* is the momentum and *z* is the charge (R for a proton of $p = 1$ [GeV] is 1 [GV], and for a helium of $p = 1$ [MeV] is 0.5 [MV]).



Plan view from the north pole

Estimate $\boldsymbol{Rc}$. Magnetic field $\boldsymbol{B} \approx \mathbf{5 \times 10^{-5}}$ [T] at the altitude h ≤ ~ 1,000 km.

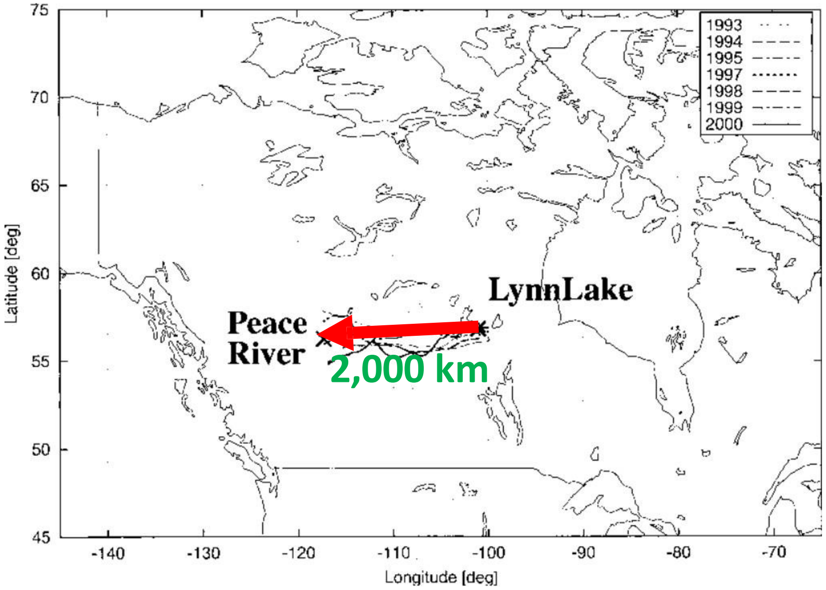
$\boldsymbol{Rc} = \mathbf{0.3}\boldsymbol{hB}$ (if *h* is in m and *B* in T, *Rc* is in GV)

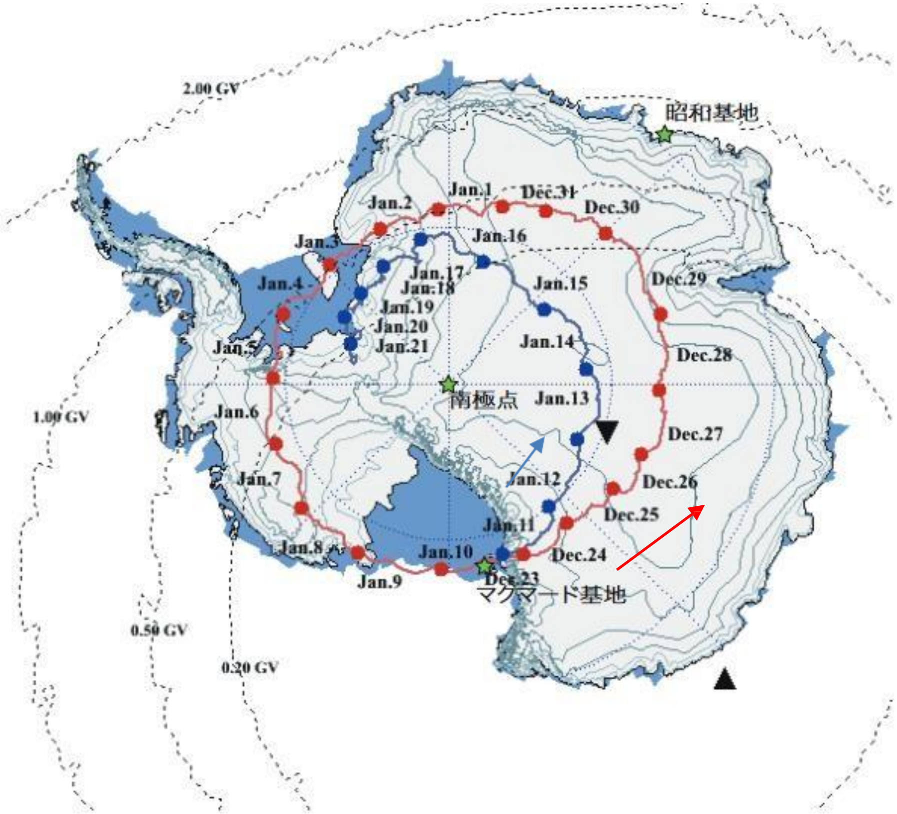
$= \mathbf{0.3 \times 10^{6} \times 5 \times 10^{-5} = 15}$ [GV]

Tokyo : $\boldsymbol{R_c} \approx$ **11 GV**

Why especially in Antarctica ?

*1ry cosmic ray measurements are mainly done by balloon.





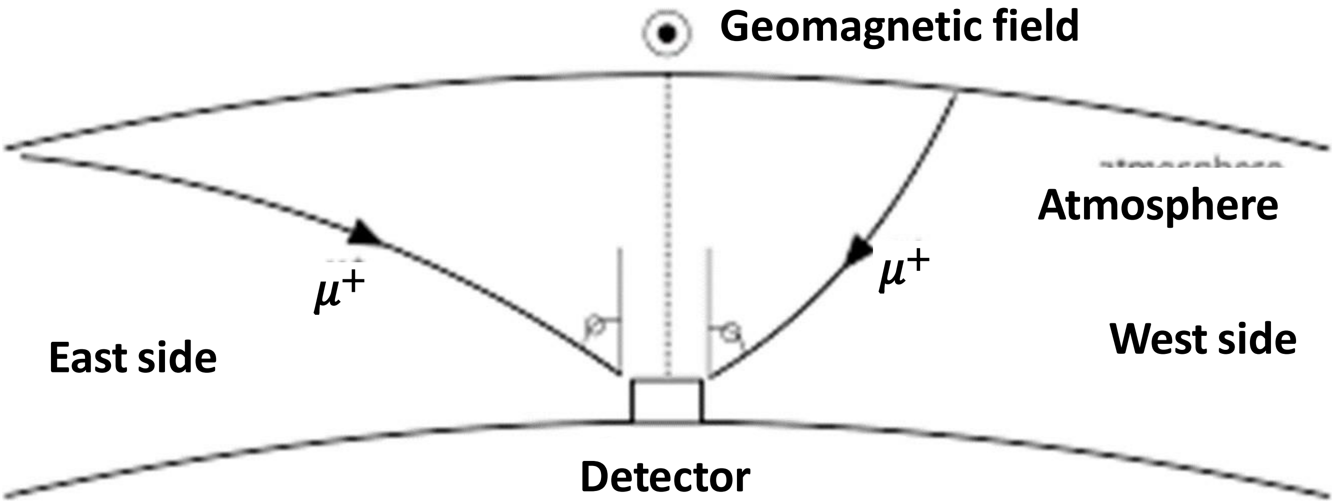
One way track
~ 20 - 30 hour flight

Circling orbit
~1 month flight

East-West effect

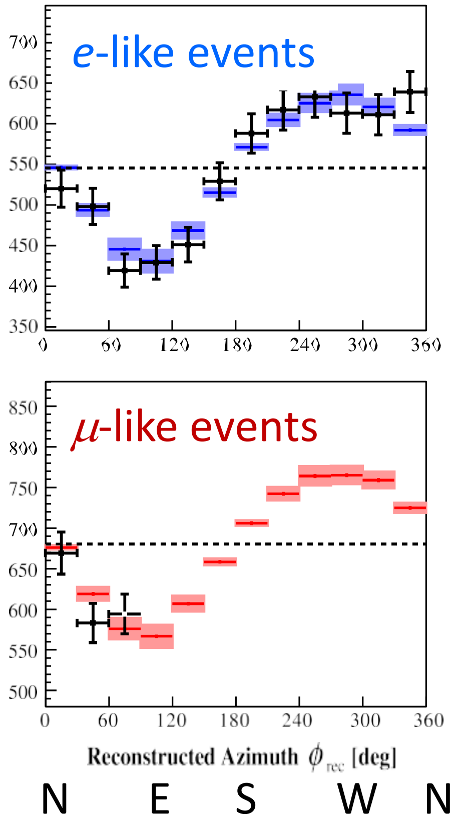
There is a difference in the number of charged cosmic rays between from east and from west.

Charged cosmic rays receive a Lorentz force from the geomagnetic field. Due to the direction of the field from the south to north, positively charged particles from the west receive the force to outside and those from the east receive the force to inside. Therefore we observe the particle from the west more than those from the east.



Result of SK

- ν's from west > ν's from east → more positively charged particles than negatively charged ones
- Agreement between the data and simulation → correctness of our understanding about atmospheric neutrinos

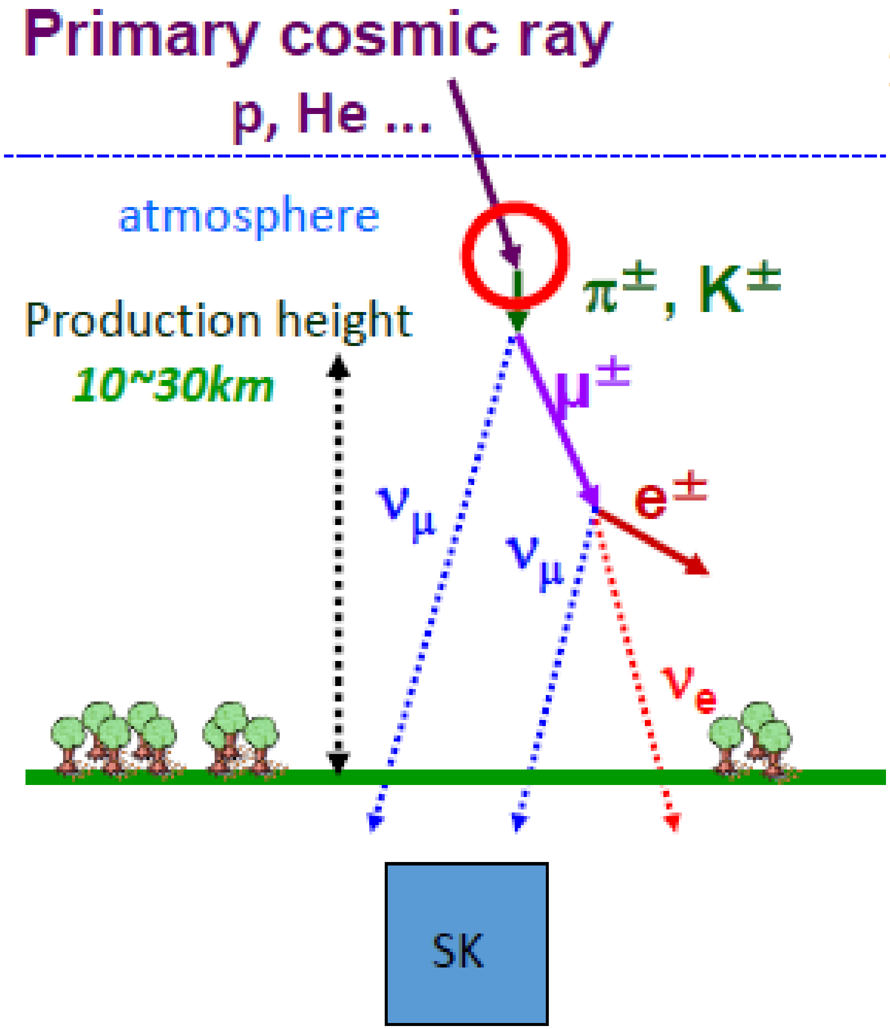


Points : data
Boxes : simulation

PhysRevD.94.052001

2ry cosmic ray generation

1ry cosmic rays interact with N, O, C, etc. in the atmosphere.



1) p + A → π / K + X

p-A cross-section (10 ~ 20GeV)
~ (40mb)$A^{2/3}$

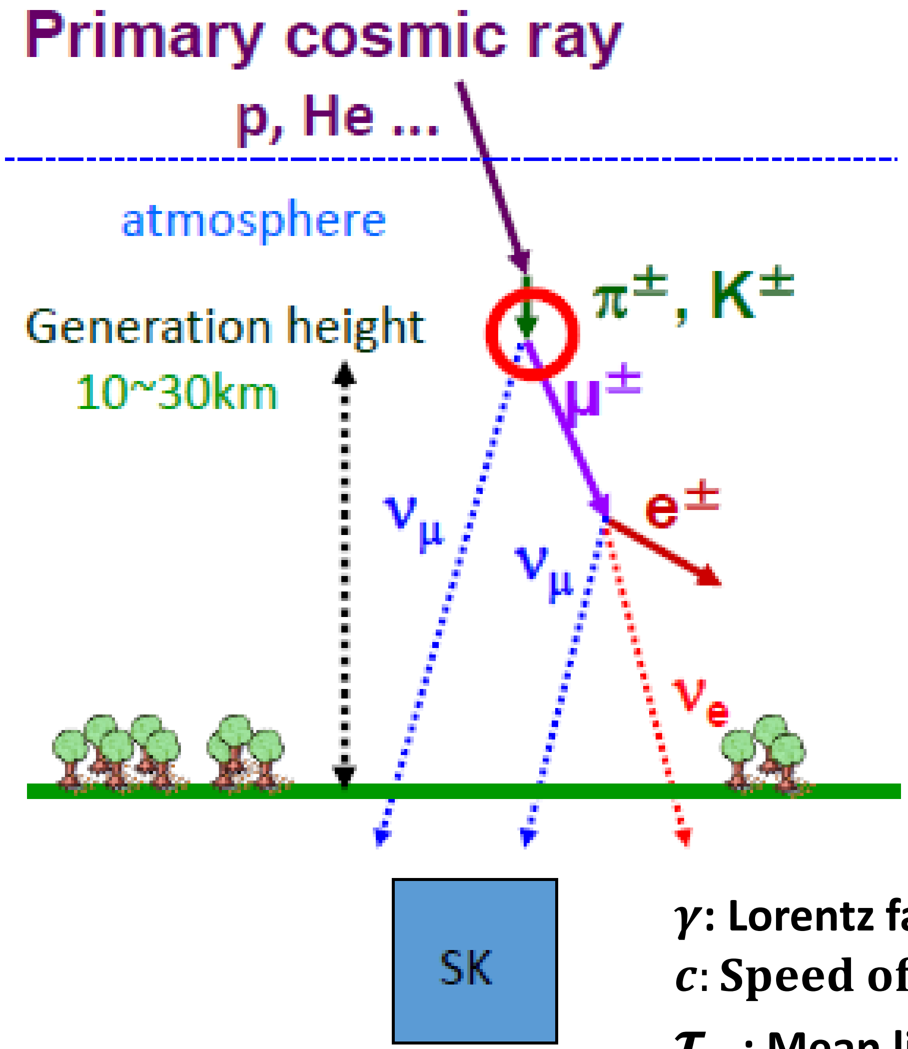
mean free path
~ $40A^{-1/3}$ g·cm^{-2}

➡ Typical altitude of
the 1st interaction
~ 15km

*** 1 b (barn) = 10^{-28} m^2**

2ry cosmic ray generation

1ry cosmic rays interact with N, O, C, etc. in the atmosphere.



2) Decay of π

How far can 5 GeV charged pions travel ?

$$\gamma c\tau_\pi = \frac{E_\pi}{m_\pi} c\tau_\pi = 278\ \mathrm{m} \sim 300\ \mathrm{m}$$

(3.6 g/cm^2)

*note: interaction length of $\pi \sim 160\ \mathrm{g/cm^2}$

Most pions decay

$$\pi \rightarrow \mu + \nu_\mu$$

γ: Lorentz factor

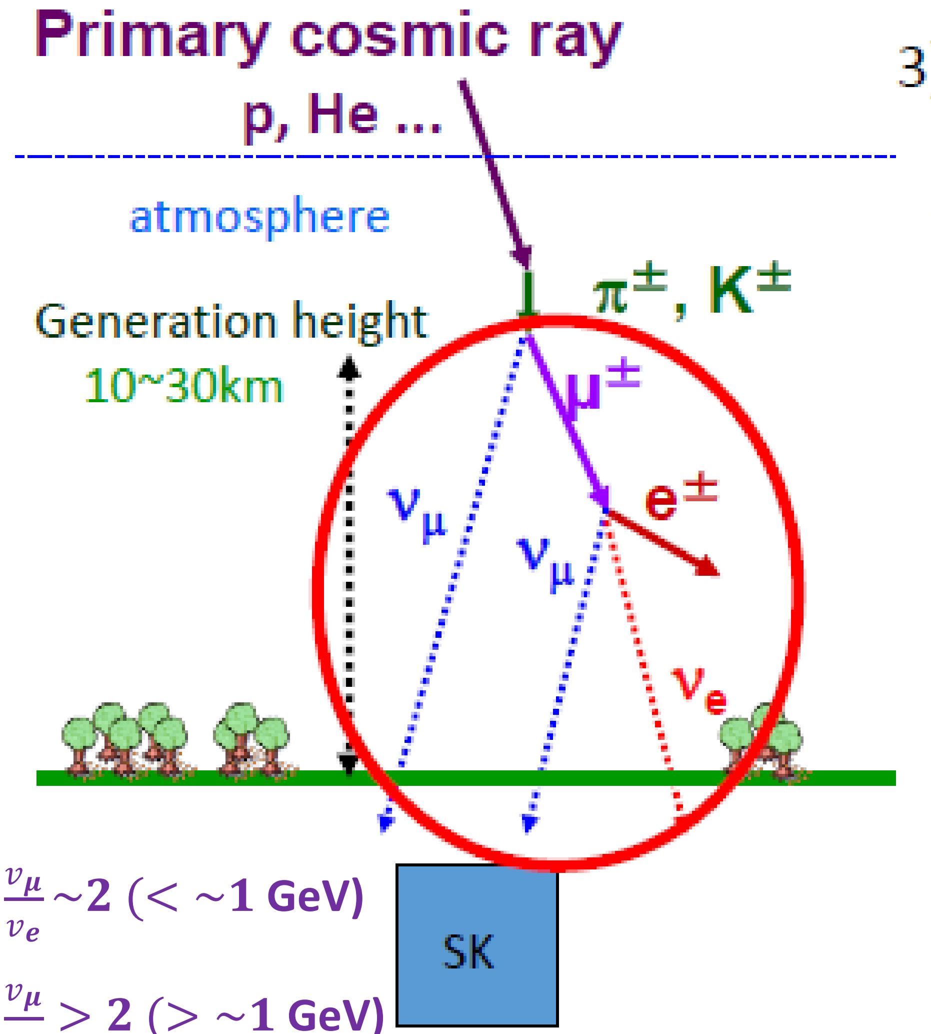
c: Speed of light, $c = 3 \times 10^8\ \mathrm{m/s}$

τ_π: Mean lifetime of muons, $\tau_\pi = 2.6 \times 10^{-8}$ sec

m_π: pion mass, $m_\pi = 140$ MeV

2ry cosmic ray generation

1ry cosmic rays interact with N, O, C, etc. in the atmosphere.



$\frac{\nu_\mu}{\nu_e} \sim 2$ (< ~1 GeV)

$\frac{\nu_\mu}{\nu_e} > 2$ (> ~1 GeV)

3) fate of μ

2.5 GeV muons

from life ~15 km

energy loss ~ 2GeV

→ decay $\mu \rightarrow e + \nu_\mu + \nu_e$

hit the ground

absorption (μ^-)

decay

Lower energy μ

Decay

Higher energy μ

Can not decay

Zenith angle and energy distributions of cosmic ray

Since the energy loss is 2 MeV/(g/cm²) for high energy charged particles, minimum energy E_{min} of the particle which can reach the surface is

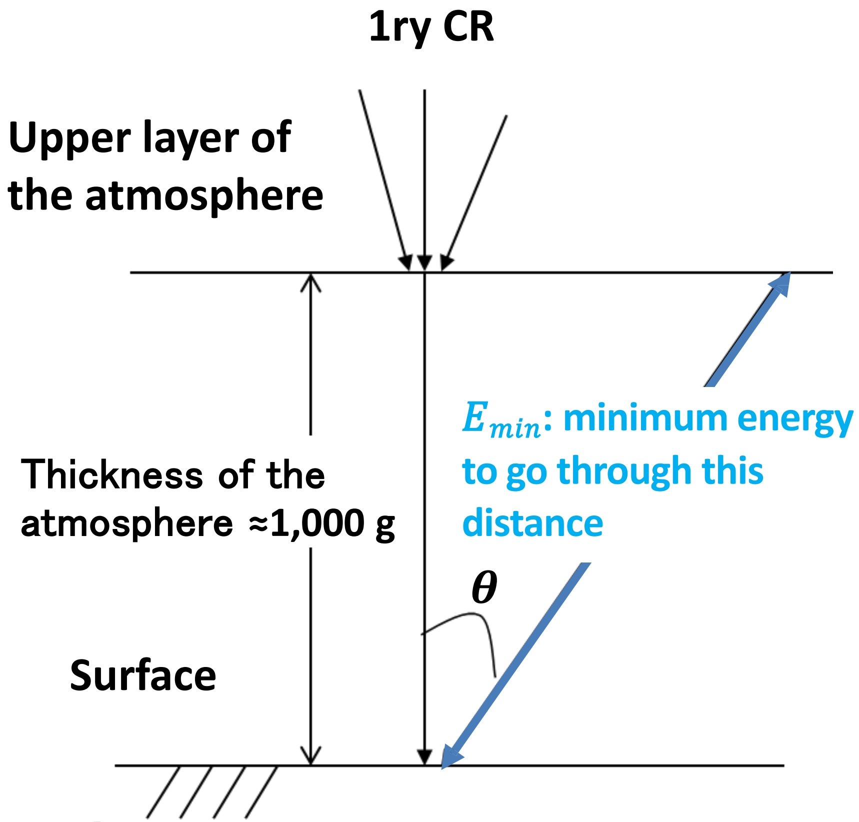
$$E_{min} = \frac{2\ [\mathrm{GeV}]}{\cos\theta}$$

Number of incident particles:

$$N(E > E_{min}) = \int_{E_{min}}^{\infty} n(E)\,dE$$

$$\propto \int_{E_{min}}^{\infty} E^{-\gamma}\,dE$$

$$= \frac{2^{1-\gamma}}{\gamma - 1}\cos^{\gamma-1}\theta$$



1ry CR

Upper layer of the atmosphere

Thickness of the atmosphere ≈1,000 g

E_{min}: minimum energy to go through this distance

θ

Surface

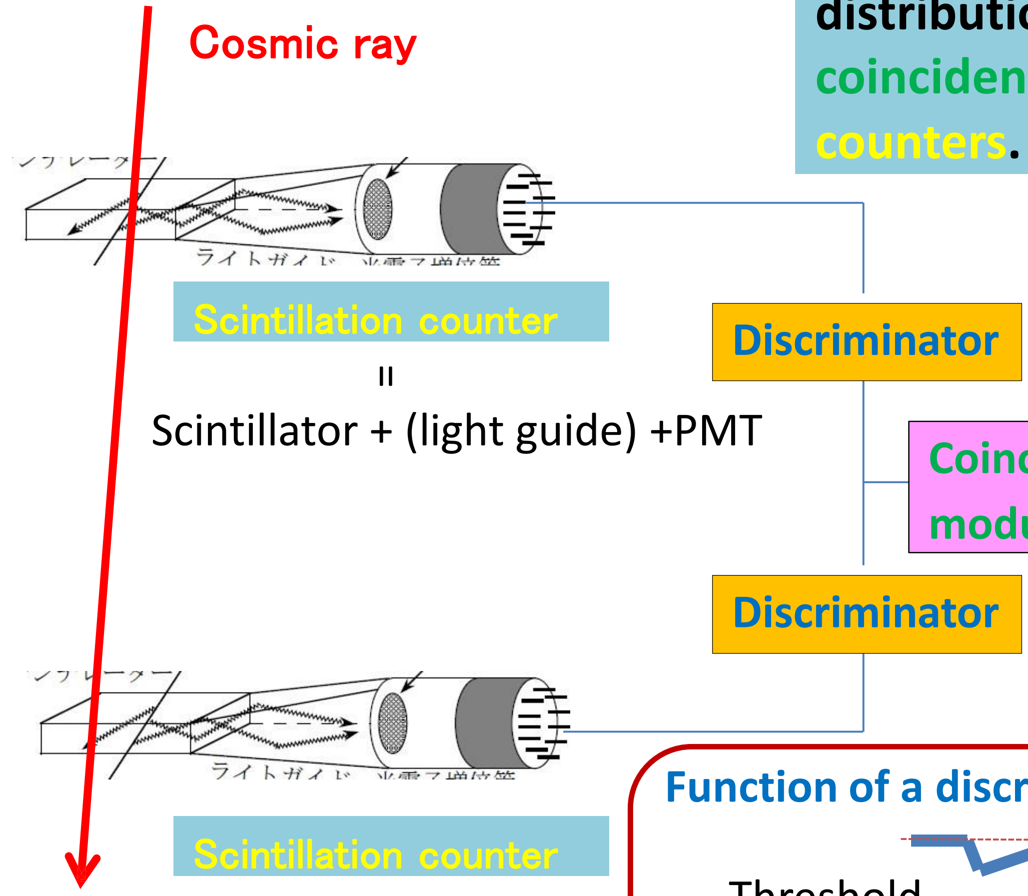
- **From many experimental measurements,**

  $\gamma - 1 \approx 2 \rightarrow\ \gamma \approx 3\ (2.7)$

Simple experiment (1)

(CR flux measurement)

Measurement of the zenith angle distribution of cosmic rays by taking a coincidence of a pair of scintillation counters.



Cosmic ray

Scintillation counter

=

Scintillator + (light guide) +PMT

Discriminator

outputs a pulse signal when an input signal is higher than the threshold (See the figure at the bottom).

Coincidence module

Scaler

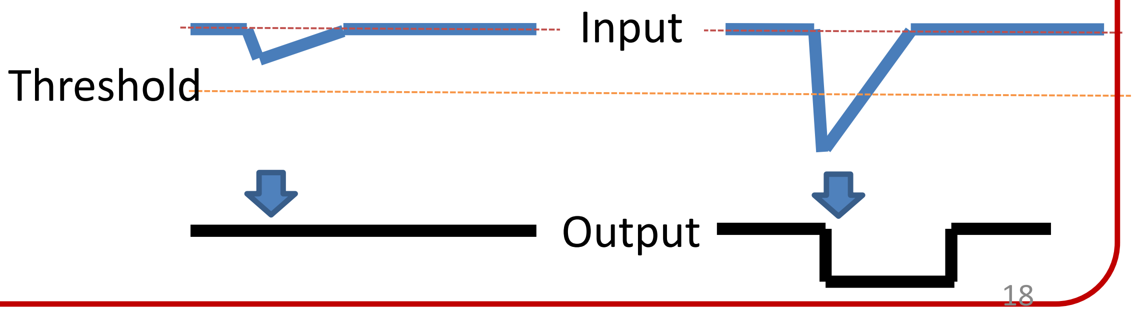
counts the number of input pulses.

Discriminator

takes a coincidence between input signals

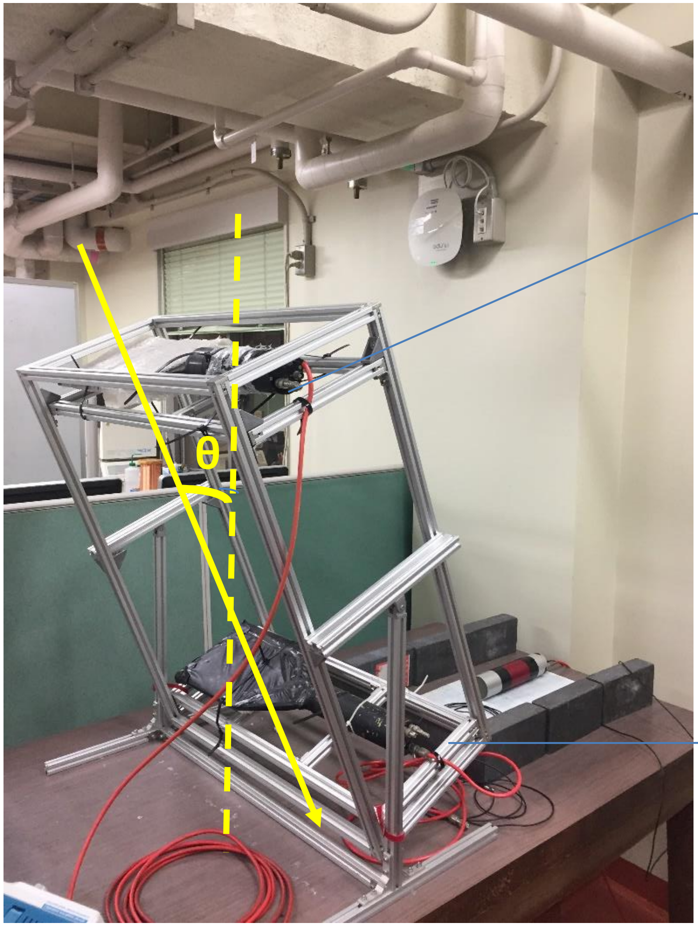
Scintillation counter

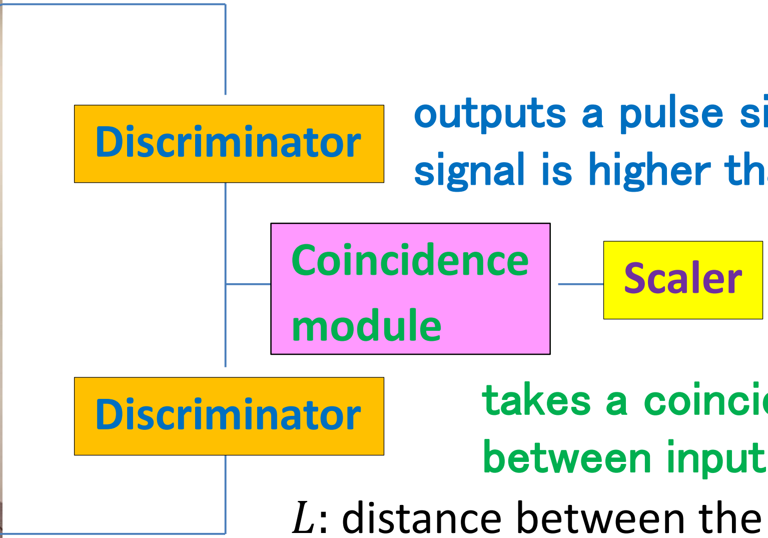
Function of a discriminator



Simple cosmic ray experiment(1)

Measurement of the zenith angle distribution of cosmic rays by taking a coincidence of a pair of scintillation counters.





Discriminator outputs a pulse signal when an input signal is higher than the threshold.

Scaler counts the number of input pulses.

Coincidence module takes a coincidence between input signals

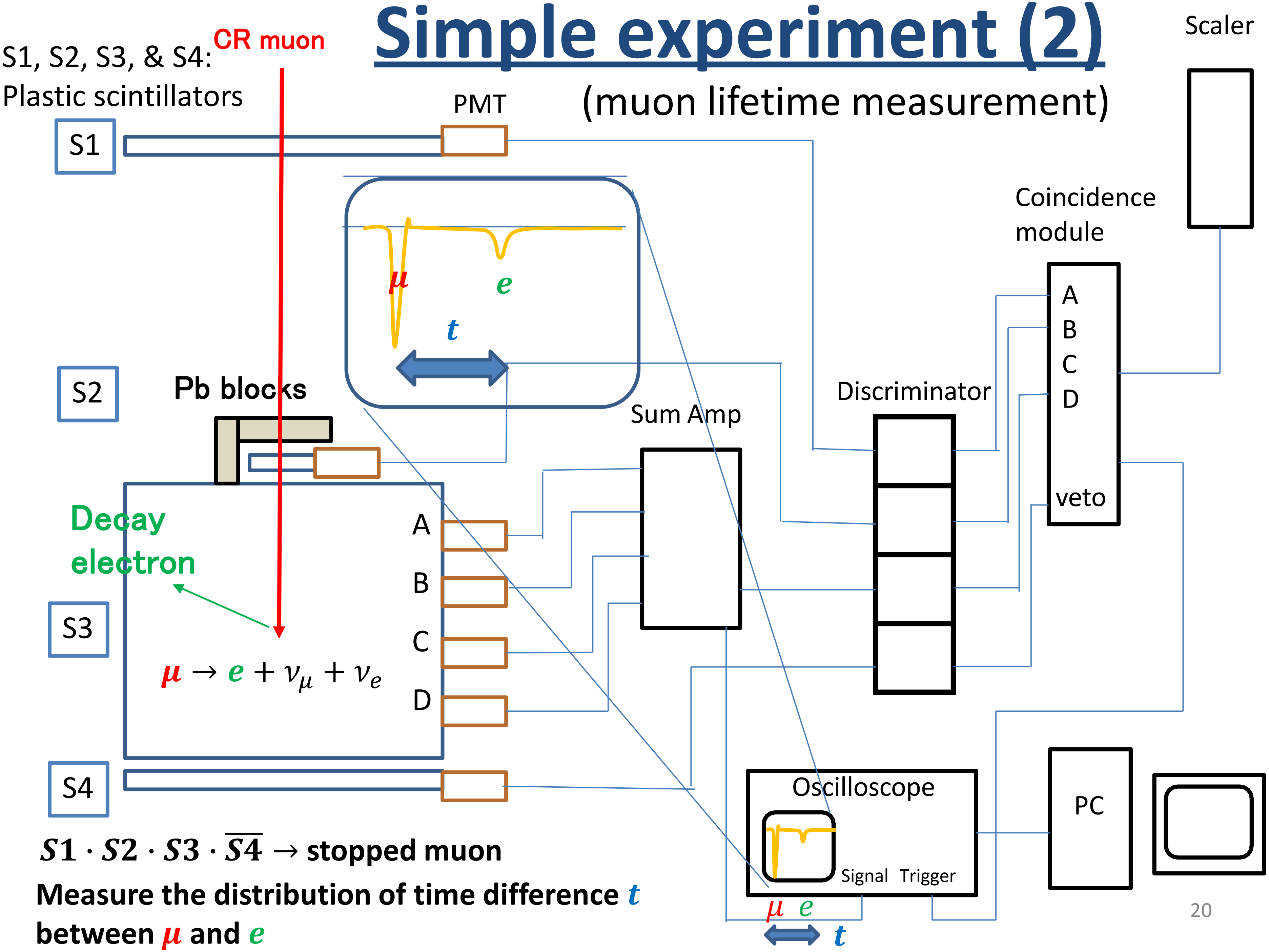
L: distance between the scintillators
S: area of the scintillator
N: number of events
T: measurement time
Ω: solid angle

Flux: $\Phi = \frac{N}{S\Omega T} \approx \frac{L^2 N}{S^2 T} \sim 100\ \mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ (typical sea-level value about vertical direction)

$\propto \cos^2\theta \rightarrow \gamma - 1 \approx 2 \rightarrow \gamma \approx 3\ (2.7)$:consistent with the measurements

Simple experiment (2)

(muon lifetime measurement)



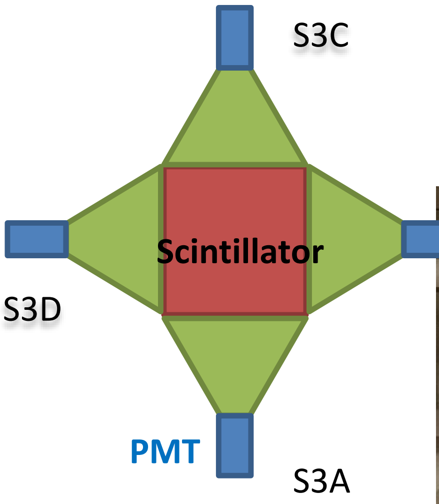
$S1 \cdot S2 \cdot S3 \cdot \overline{S4}$ → **stopped muon**

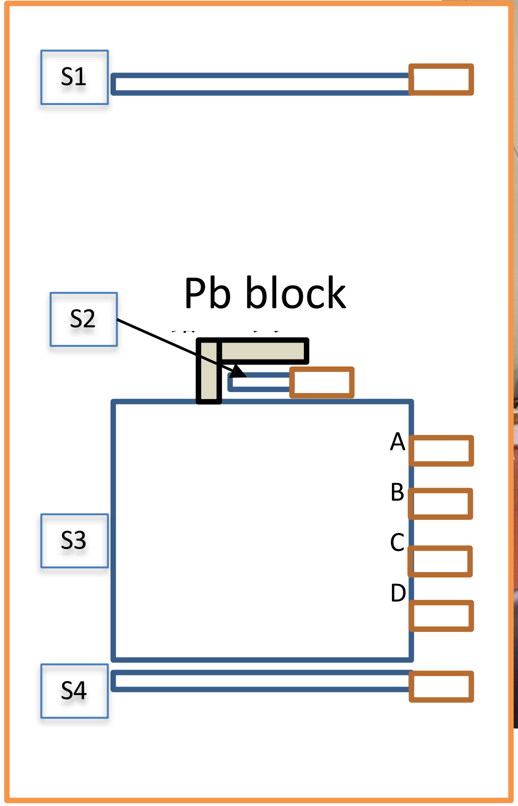
Measure the distribution of time difference t between μ and e

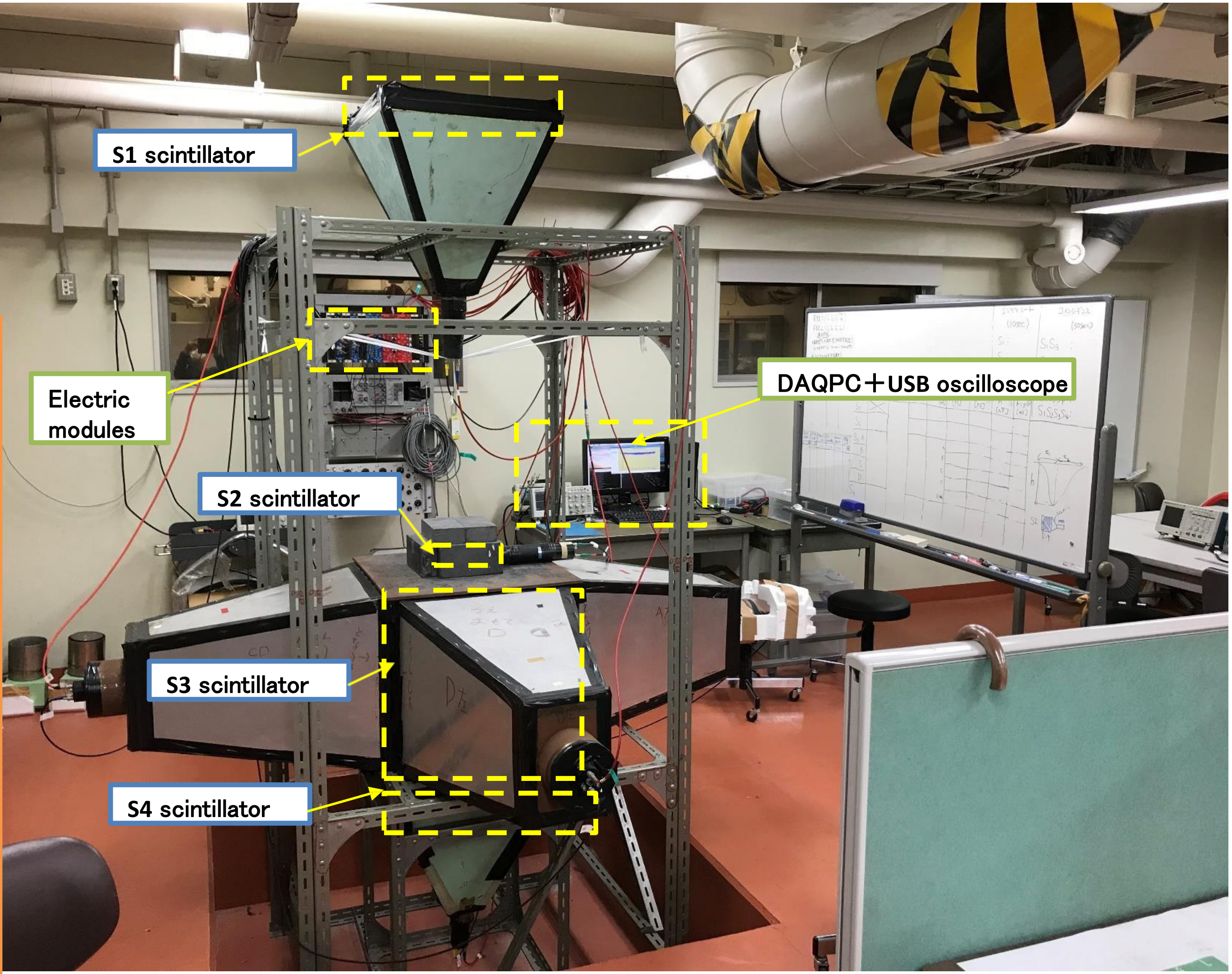
Simple experiment (2)

(muon lifetime measurement)

Plan view







S1 scintillator

Electric modules

DAQPC＋USB oscilloscope

S2 scintillator

S3 scintillator

S4 scintillator

Simple experiment (2)

Exercise (homework)

1. Particle decay follows the following formula:

$$N = N_0 e^{-t/\tau},$$

where N and N_0 are the numbers of events at time t and 0, respectively, and τ is the lifetime.

The right side table is a result of the muon decay experiment.

(a) Make a plot of the number of events as a function of the decay time. Use log scale as a vertical axis.

(b) Get the muon lifetime.

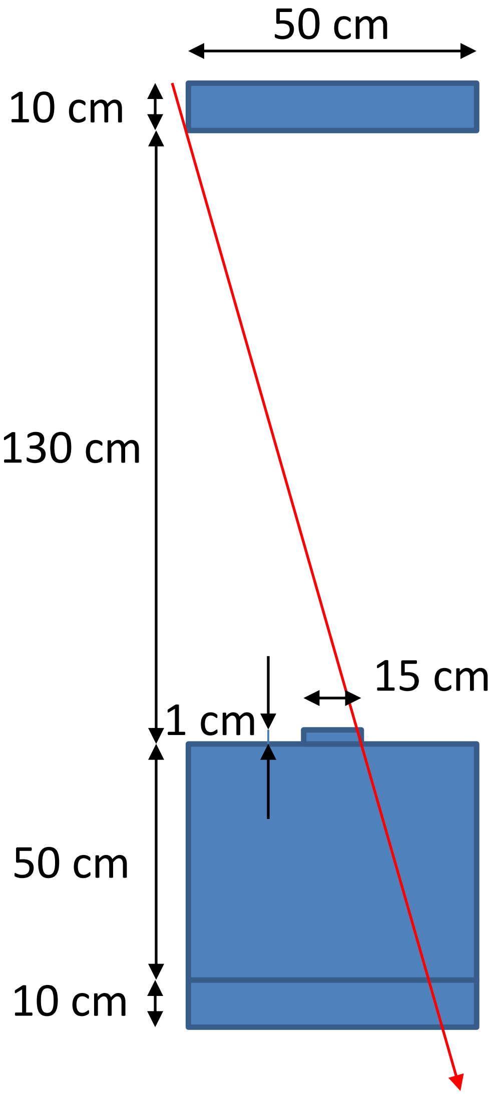
2. Some events show no 2nd signal which corresponds to decay electron. What are those events ?

* Note that the condition in the next page.

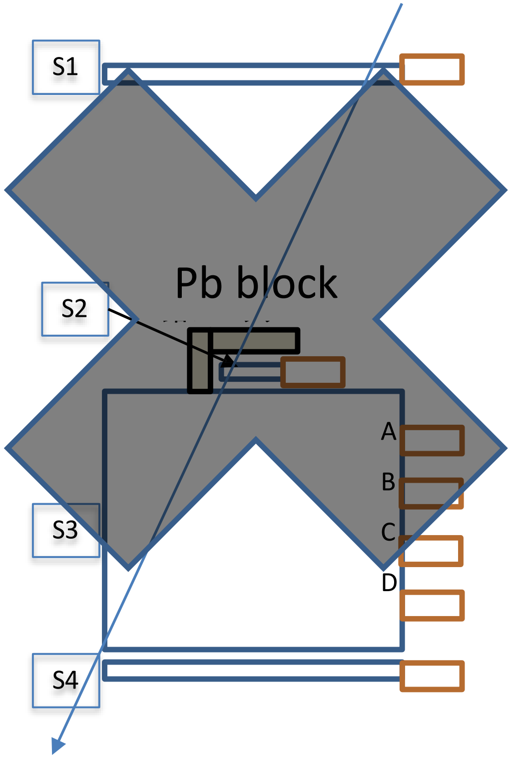
Decay time t [μ sec]	Number of events	Decay time t [μ sec]	Number of events
0.3	1501	4.7	194
0.5	1308	4.9	189
0.7	1191	5.1	155
0.9	1082	5.3	157
1.1	1024	5.5	127
1.3	886	5.7	134
1.5	823	5.9	102
1.7	775	6.1	90
1.9	700	6.3	96
2.1	610	6.5	79
2.3	544	6.7	62
2.5	547	6.9	85
2.7	497	7.1	65
2.9	463	7.3	61
3.1	422	7.5	53
3.3	380	7.7	66
3.5	340	7.9	41
3.7	291	8.1	28
3.9	276	8.3	29
4.1	283	8.5	26
4.3	245	8.7	27
4.5	204		

* ex. "0.3" means $0.2 \leq t < 0.4$ [μ sec]

Real Geometry of the Detector



Since S2 is small and the distance between S1 and S3 is long enough, particles which pass through S1, S2, and S3 always reach S4.
(There is no event which passes through S1, S2, and S3 but does not pass S4 like the following one:)



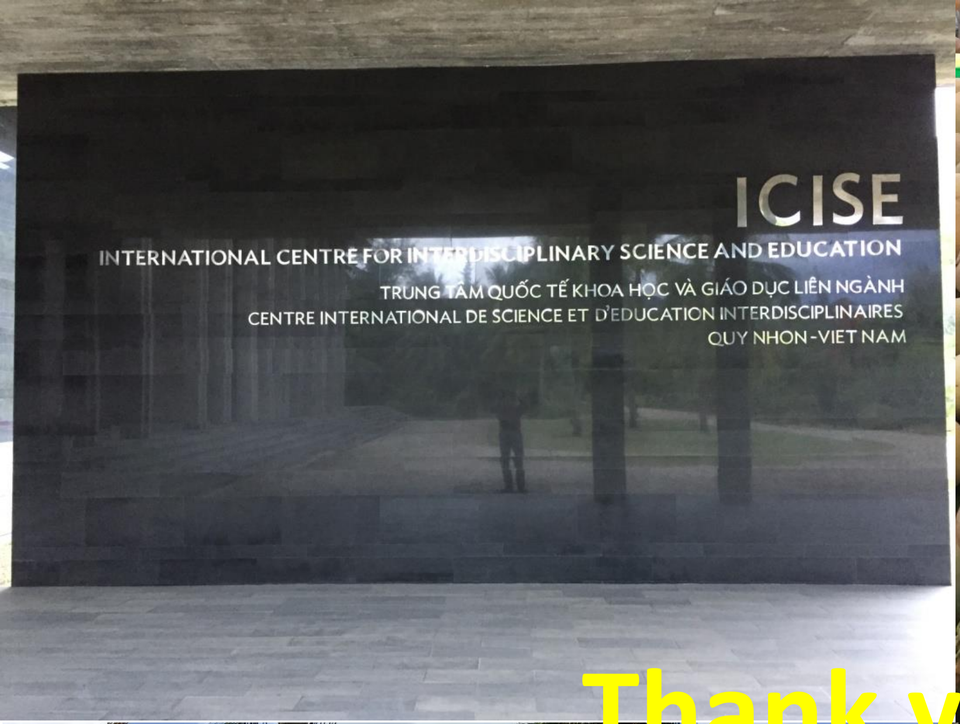
Summary

As introduction to cosmic rays :

- **What are cosmic rays ?**
- **Cosmic ray spectrum**
- **Geomagnetic effect**
- **2ry CR generation** – including atmospheric neutrinos –
- **Simple experiments** – Student experiments of Kobe Univ.

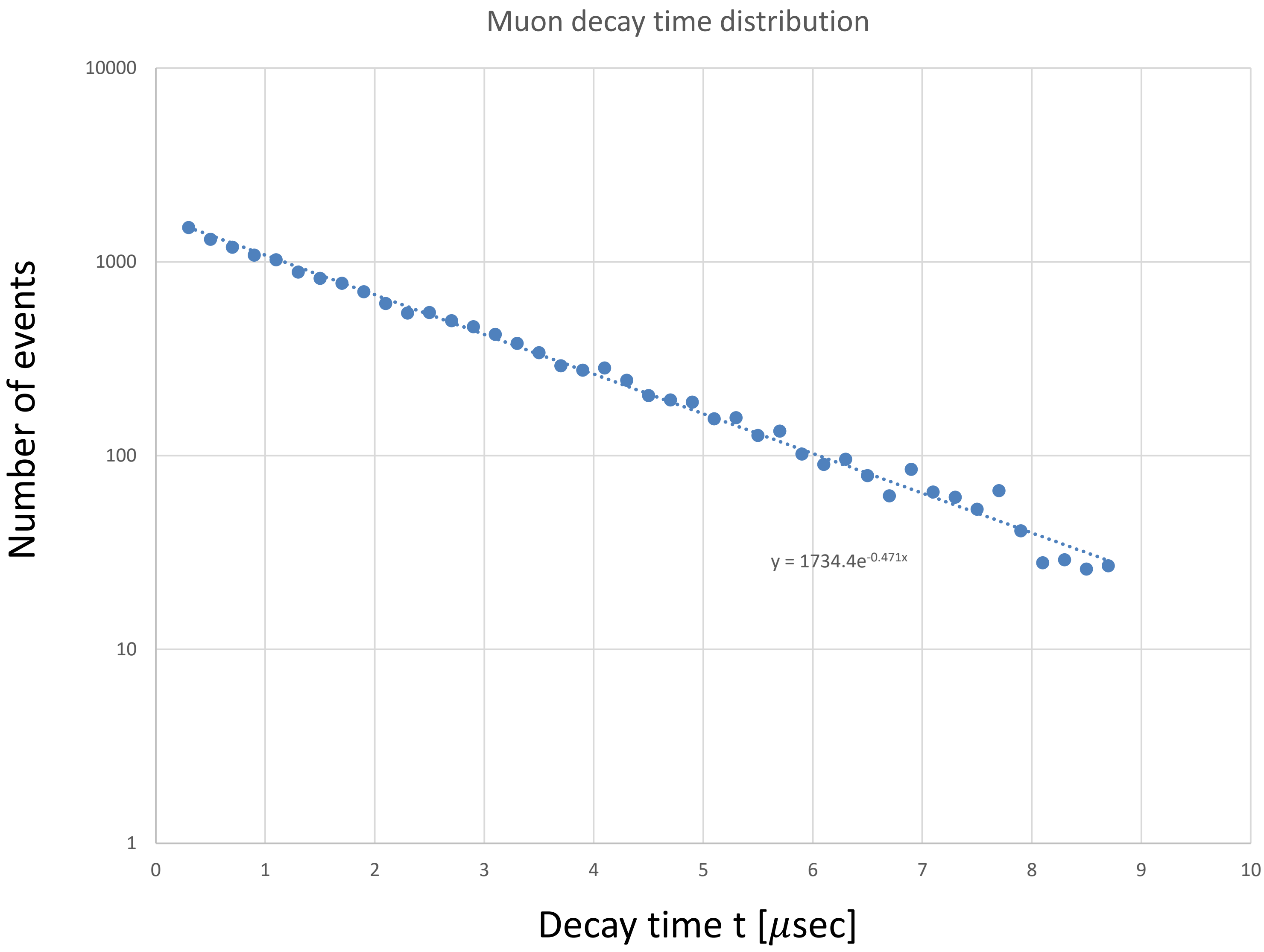
In addition to above, I gave you a homework
(I would like you to challenge !).

Thank you (^o^)



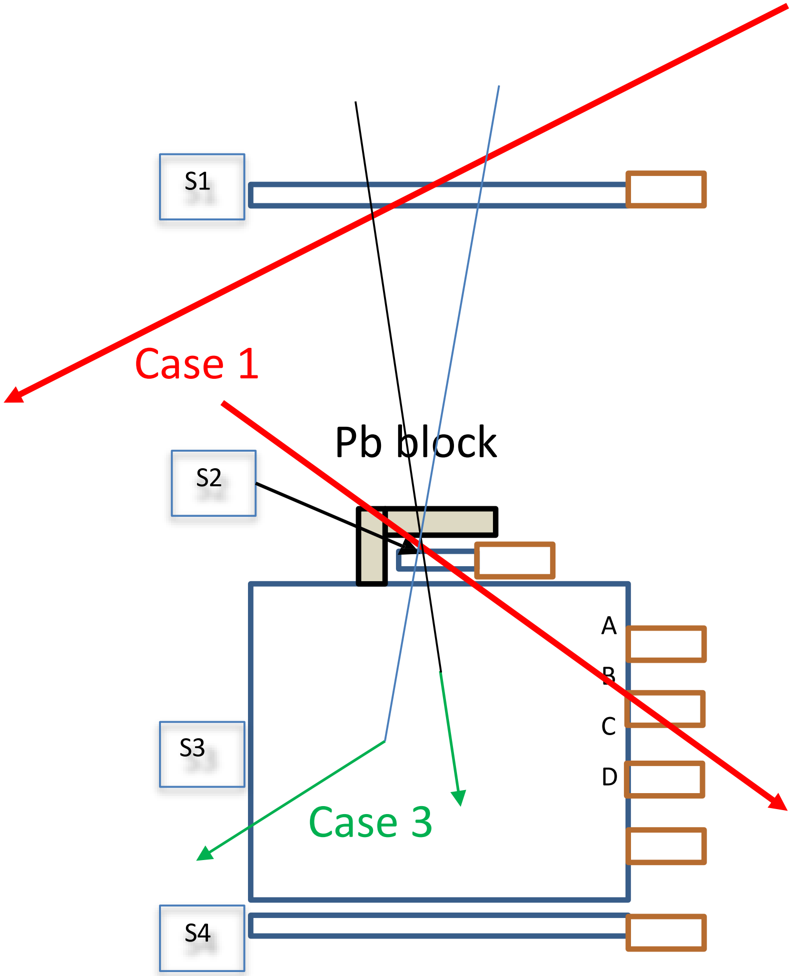
Son-san

Solution 1



Slope: 0.471 [1/μsec]= $1/\tau_\mu \rightarrow \tau_\mu = \mathbf{2.12\ \mu sec}$

Solution 2



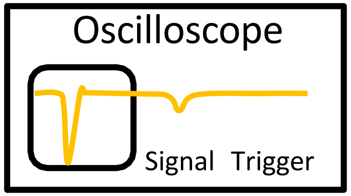
Main ones (probably)

1. Accidental coincidence of two cosmic ray muons.

2. Decay time is too short to distinguish between the muon and decay electron signals comparing to the time resolution.

3. Muon decays in flight, and decay electrons stop in S3 or escape from S3 without hitting S4.

4. Decay time is so long that the decay electron signal is out of range of the equipment:



etc.