VIETNAM SCHOOL ON NEUTRINOS 2022

A look at the journey of Neutrino inside the Earth

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ν_e **Mini-project group**

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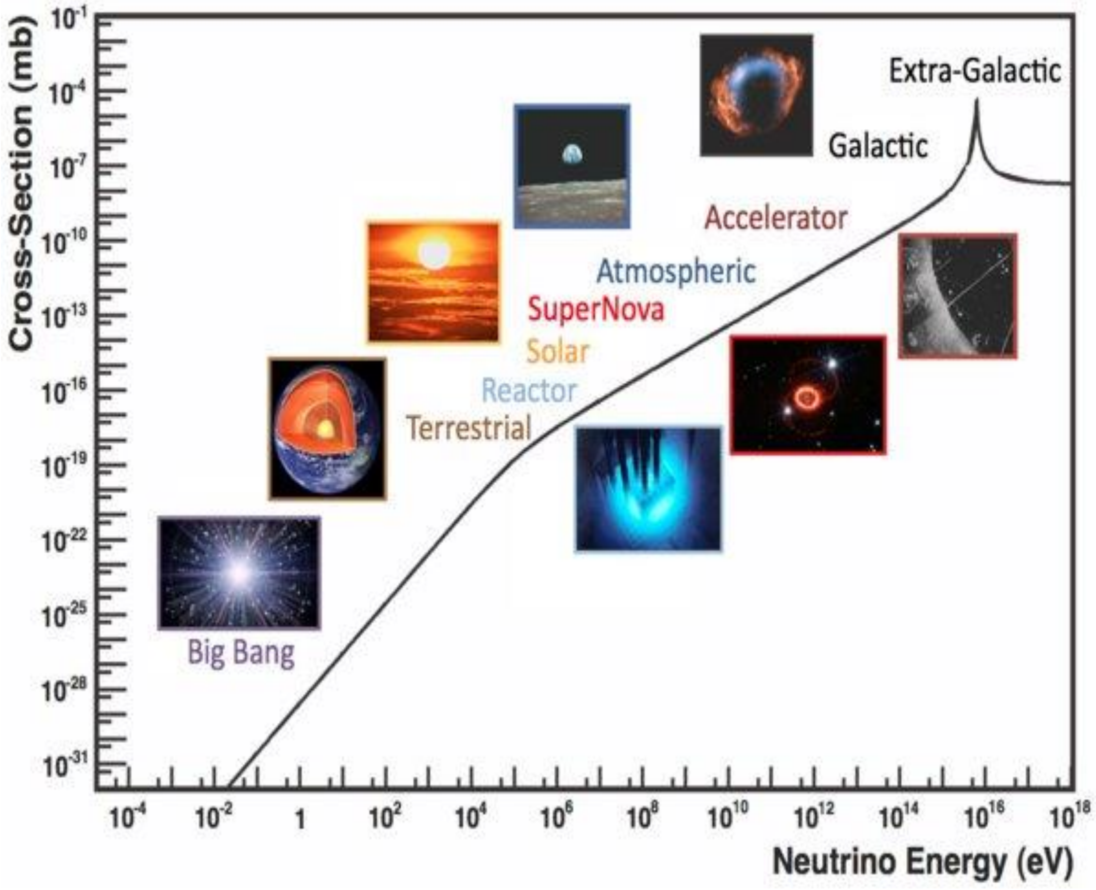
Selected topic:

Discuss the energy at which the Earth becomes opaque to neutrinos, as a function of the zenith angle, if neutrino cross sections are described by the standard model

- Research Overview
- Theoretical Basis and Result
- IceCube Experiment
- Discussion

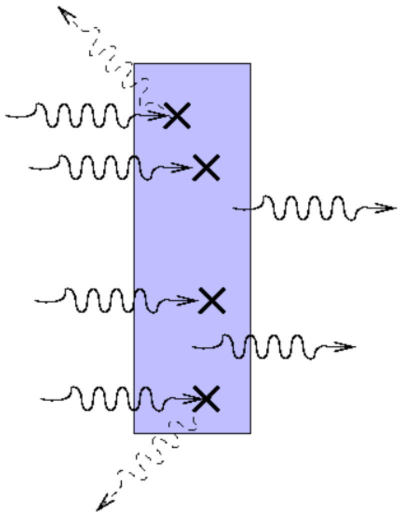
Motivation

- The charged particle trajectories are bended by magnetic fields.
- However, neutrinos are not.
- The detection of high energy cosmic neutrinos can help solve the problem of the origin of high energy cosmic rays.



The factors affect the Intensity of Neutrinos

- The greater the distance the beam travels, the more neutrinos will be removed from it.
- The greater the density of material ρ, the more neutrinos will be scattered or absorbed.
- The composition of the material.



Mathematical form:

$$dI = -\kappa \, \rho \, I \, ds$$

I: the incoming intensity of the light,
dI: the infinitesimal change in intensity,
ds: the distance it travels,
ρ: the density of the material,
κ: the **opacity** or **absorption coefficient**,

$$\frac{I}{I_0} = e^{-\kappa \rho s} = e^{-s/\ell} = e^{-\tau}$$

τ: the **optical depth** of the Earth or the ability to block the Neutrinos.

Theoretical Basis

- Cross-section

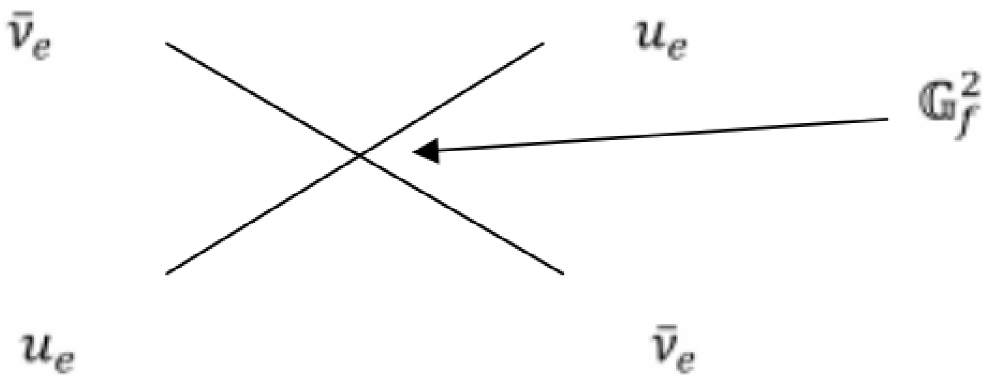
  - Fermi Theory

  - Standard Model

  - Comparison between different interactions

- Optical depth

Fermi's theory

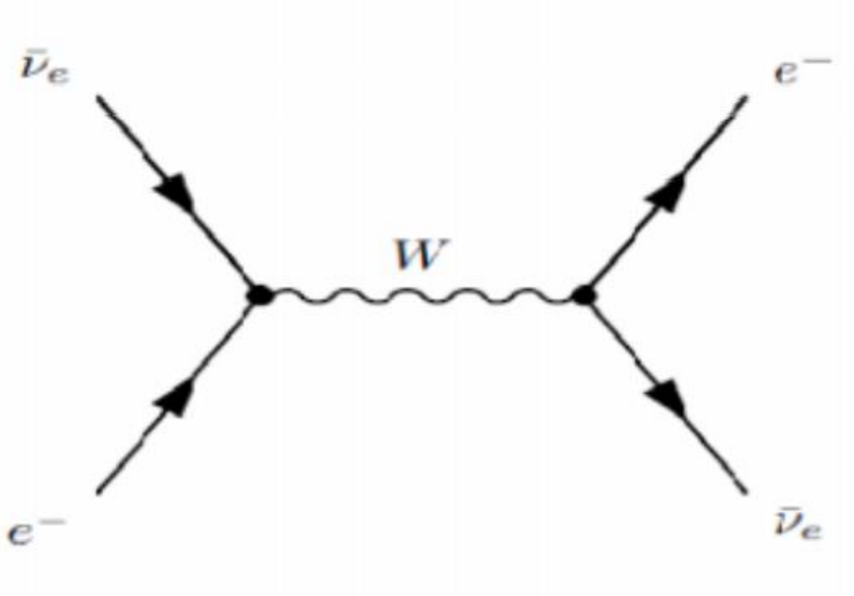


$$\sigma(\bar{\nu}_e e \rightarrow \bar{\nu}_e e) = \frac{1}{3}\frac{G_f^2}{\pi} s$$

$$s = (p_{\bar{\nu}_e} + p_e)^2 = 2E_{\bar{\nu}_e} m_e$$

- Weak interaction theory , with no bosons participating in the interaction
- Four fermions interacts directly at one point, also called as point interactions
- It's strength is expressed in terms of fermi constant G_f

Standard Model

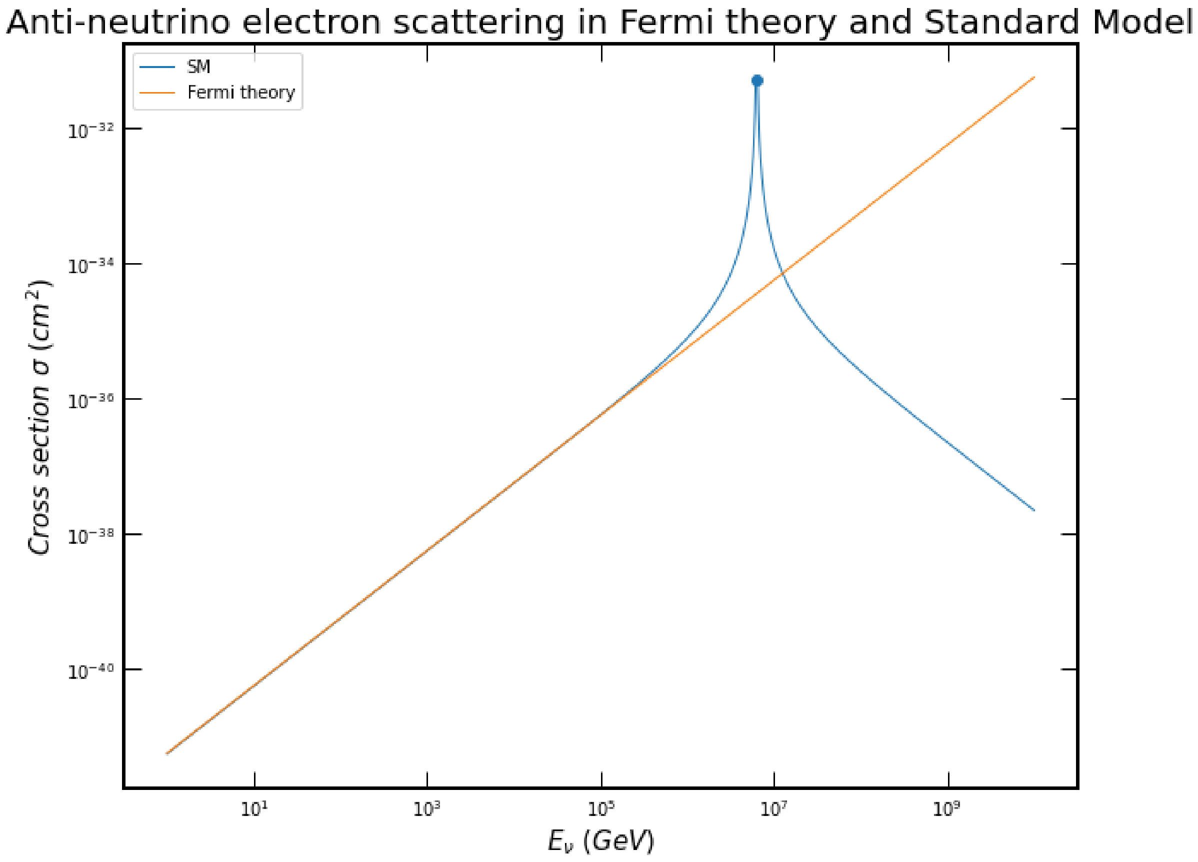


$$\sigma(\bar{\nu_e} e \rightarrow \bar{\nu_e} e) = \frac{1}{3} \frac{g^4}{32\pi^2} \frac{s}{(s - m_W^2)^2}$$

$$g^4 = 32 G_f^2 m_W^4$$

- CC interactions occur via W bosons and NC interactions occur via Z bosons
- At lower energies when $s \ll m^2_w$,the energy term can be ignored and standard model agrees with the fermi theory
- At higher energies , $s \gg m^2_w$, s term dominates

Fermi's theory vs Standard Model



- At low energy, there is no discrepancy between cross-section from Fermi theory and Standard Model.
- But for ultra-high energy (> 6.3 PeV), the Fermi theory is not good anymore.

Neutrino-nucleon interaction

- Nucleon provide much more cross-section than electron
- At high Q^2 , Deep Inelastic scattering (DIS), dominates
- We calculate the cross-section for this reaction:

$$\frac{d^2\sigma}{dxdy} = \frac{2G_F^2 M E_\nu}{\pi}\left(\frac{M_W^2}{Q^2+M_W^2}\right)^2\left[xq(x,Q^2)+x\bar{q}(x,Q^2)(1-y)^2\right]$$

- Where Q^2 is the invariant momentum transfer between the incident neutrino and outgoing lepton
- M and M_w are nucleon and intermediate boson mass and G_f is the fermi constant

The quark distribution functions are

$$q(x,Q^2) = \frac{u_v(x,Q^2)+d_v(x,Q^2)}{2} + \frac{u_s(x,Q^2)+d_s(x,Q^2)}{2} + s_s(x,Q^2)+b_s(x,Q^2)$$

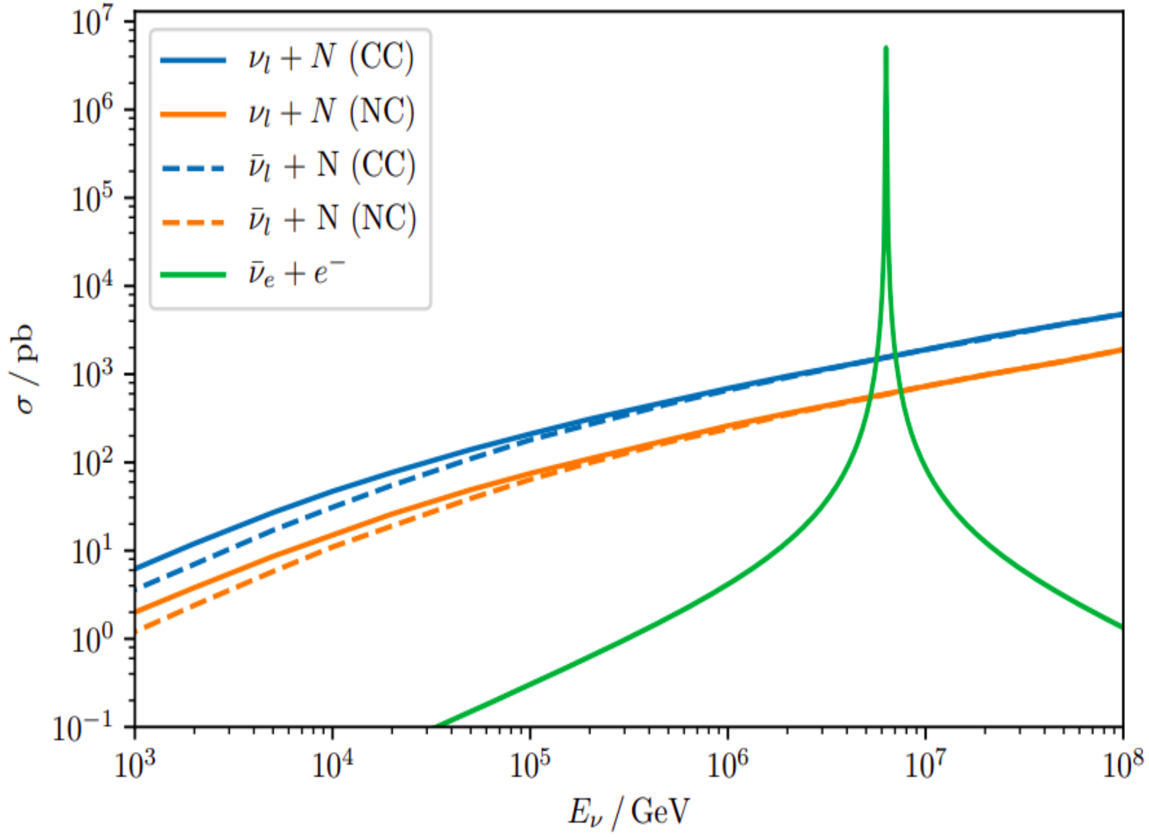
$$\bar{q}(x,Q^2) = \frac{u_s(x,Q^2)+d_s(x,Q^2)}{2} + c_s(x,Q^2)+t_s(x,Q^2),$$

according to the CTEQ4–DIS distributions.

E_ν [GeV]	σ_{CC} [cm^2]	σ_{NC} [cm^2]	σ_{tot} [cm^2]
1.0×10^{1}	0.7988×10^{-37}	0.2492×10^{-37}	0.1048×10^{-36}
2.5×10^{1}	0.1932×10^{-36}	0.6033×10^{-37}	0.2535×10^{-36}
6.0×10^{1}	0.4450×10^{-36}	0.1391×10^{-36}	0.5841×10^{-36}
1.0×10^{2}	0.7221×10^{-36}	0.2261×10^{-36}	0.9482×10^{-36}
2.5×10^{2}	0.1728×10^{-35}	0.5430×10^{-36}	0.2271×10^{-35}
6.0×10^{2}	0.3964×10^{-35}	0.1255×10^{-35}	0.5219×10^{-35}
1.0×10^{3}	0.6399×10^{-35}	0.2039×10^{-35}	0.8438×10^{-35}
2.5×10^{3}	0.1472×10^{-34}	0.4781×10^{-35}	0.1950×10^{-34}
6.0×10^{3}	0.3096×10^{-34}	0.1035×10^{-34}	0.4131×10^{-34}
1.0×10^{4}	0.4617×10^{-34}	0.1575×10^{-34}	0.6192×10^{-34}
2.5×10^{4}	0.8824×10^{-34}	0.3139×10^{-34}	0.1196×10^{-33}
6.0×10^{4}	0.1514×10^{-33}	0.5615×10^{-34}	0.2076×10^{-33}
1.0×10^{5}	0.2022×10^{-33}	0.7667×10^{-34}	0.2789×10^{-33}
2.5×10^{5}	0.3255×10^{-33}	0.1280×10^{-33}	0.4535×10^{-33}
6.0×10^{5}	0.4985×10^{-33}	0.2017×10^{-33}	0.7002×10^{-33}
1.0×10^{6}	0.6342×10^{-33}	0.2600×10^{-33}	0.8942×10^{-33}
2.5×10^{6}	0.9601×10^{-33}	0.4018×10^{-33}	0.1362×10^{-32}
6.0×10^{6}	0.1412×10^{-32}	0.6001×10^{-33}	0.2012×10^{-32}
1.0×10^{7}	0.1749×10^{-32}	0.7482×10^{-33}	0.2497×10^{-32}
2.5×10^{7}	0.2554×10^{-32}	0.1104×10^{-32}	0.3658×10^{-32}
6.0×10^{7}	0.3630×10^{-32}	0.1581×10^{-32}	0.5211×10^{-32}
1.0×10^{8}	0.4436×10^{-32}	0.1939×10^{-32}	0.6375×10^{-32}
2.5×10^{8}	0.6283×10^{-32}	0.2763×10^{-32}	0.9046×10^{-32}
6.0×10^{8}	0.8699×10^{-32}	0.3837×10^{-32}	0.1254×10^{-31}
1.0×10^{9}	0.1049×10^{-31}	0.4641×10^{-32}	0.1513×10^{-31}
2.5×10^{9}	0.1466×10^{-31}	0.6490×10^{-32}	0.2115×10^{-31}
6.0×10^{9}	0.2010×10^{-31}	0.8931×10^{-32}	0.2903×10^{-31}
1.0×10^{10}	0.2379×10^{-31}	0.1066×10^{-31}	0.3445×10^{-31}
2.5×10^{10}	0.3289×10^{-31}	0.1465×10^{-31}	0.4754×10^{-31}
6.0×10^{10}	0.4427×10^{-31}	0.1995×10^{-31}	0.6422×10^{-31}
1.0×10^{11}	0.5357×10^{-31}	0.2377×10^{-31}	0.7734×10^{-31}
2.5×10^{11}	0.7320×10^{-31}	0.3247×10^{-31}	0.1057×10^{-30}
6.0×10^{11}	0.9927×10^{-31}	0.4377×10^{-31}	0.1430×10^{-30}
1.0×10^{12}	0.1179×10^{-30}	0.5196×10^{-31}	0.1699×10^{-30}

Comparison between different interactions

- The cross-section of antineutrino-electron interaction is much smaller than another kind of interactions except for the energy level around 6.3 PeV.



Optical depth

- Optical depth (τ) is a measure of opaqueness along the path of, i.e. neutrino radiation, the degree of absorb of neutrinos passing through the medium along the way.
- Intensity falls exponentially by the optical depth: a larger optical depth means more opaque: much greater than 1 (optically thick) means neutrinos moving along this path are generally are absorbed or scattered, and much less than 1 (optically thin) means they generally get through.

$$I = I_o \exp^{-\tau}$$

$$Opaque \rightarrow \tau = 1$$

$$\tau = \frac{s}{d}$$

Formulas

$$\rho = 5.51 \times 10^{-3} kg/cm^3$$

$$m_p = m_n = 1.67 \times 10^{-27} kg$$

$$R = 6371 km$$

- General: $d\tau = \sigma_{TOT}(E_\nu) n dl$

$$\tau = \int_0^L \sigma_N(E_\nu) \frac{\rho(r)}{(m_p+m_n)/2} dl + \int_0^L Z\sigma_e(E_\nu) \frac{\rho(r)}{A(m_p+m_n)/2} dl$$

Z is the average atomic number of the Earth material

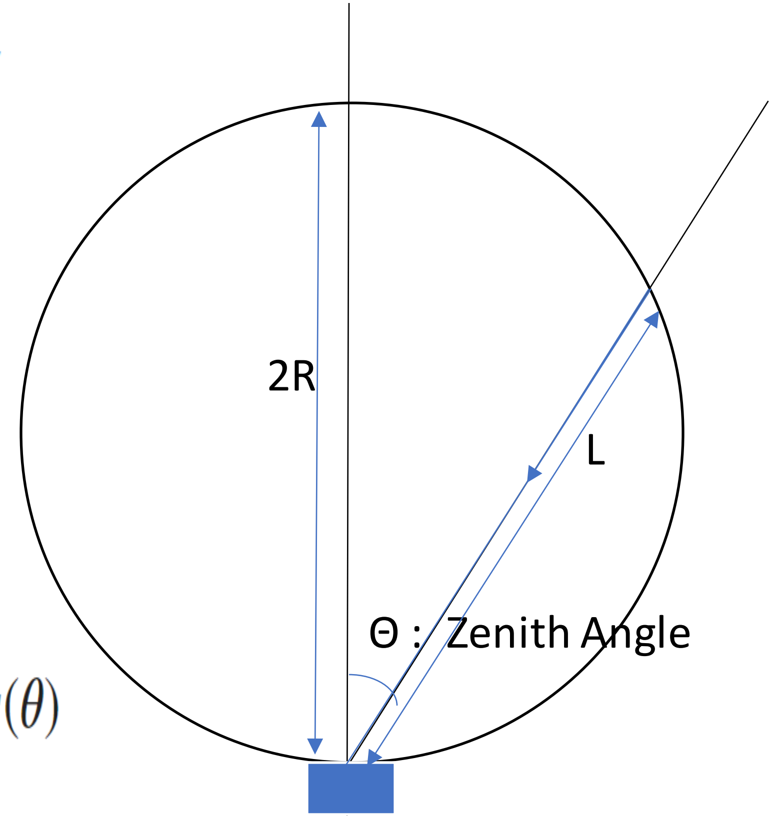
A is the average mass number

$$\frac{Z}{A} \approx 0.5$$

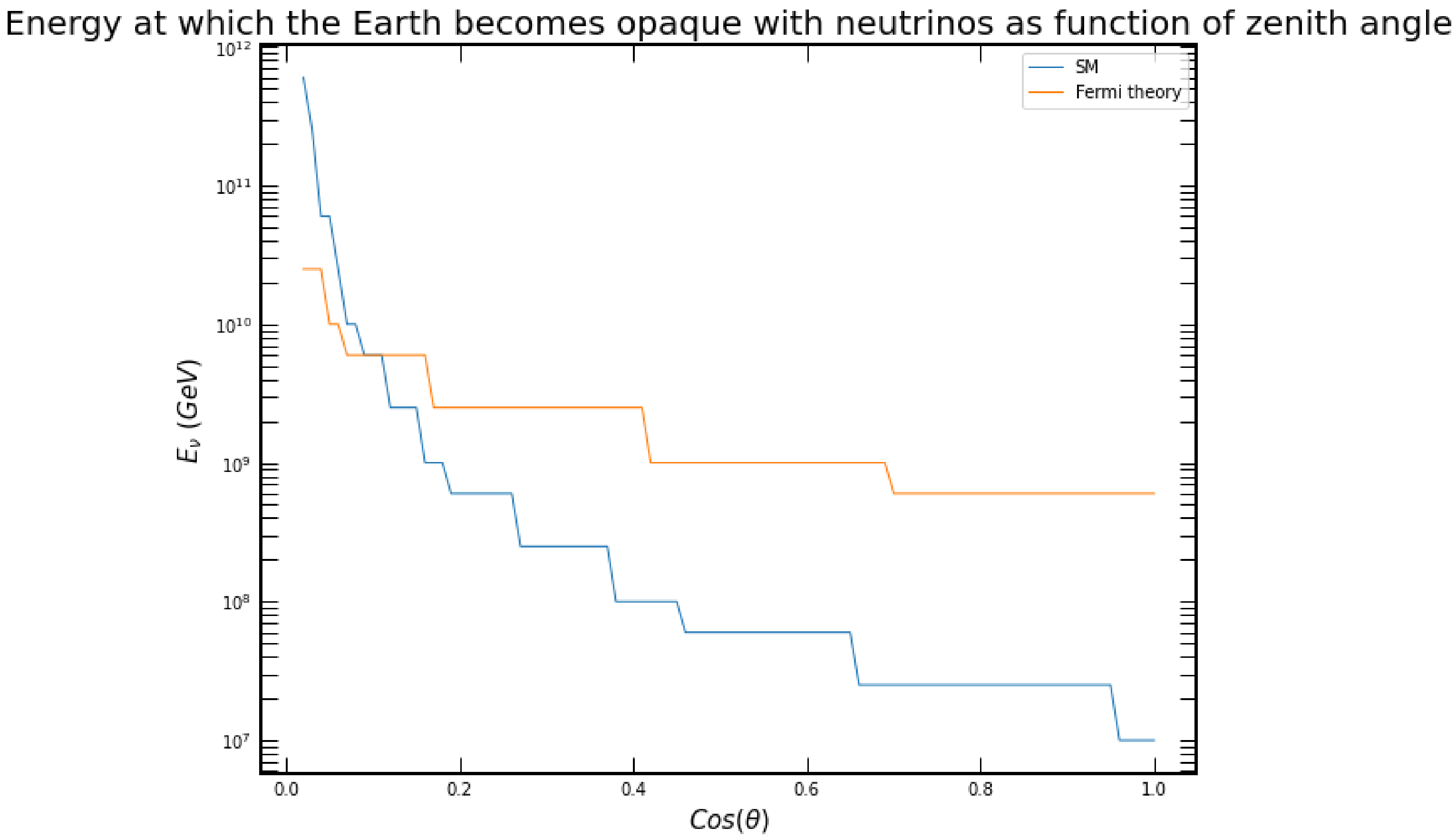
- Neglect neutrino-electron scattering:

$$\tau = \int_0^L \sigma_{TOT}(E_\nu) \frac{\rho(r)}{(m_p+m_n)/2} dl$$

$$Uniform\ Earth \rightarrow \tau = \sigma_{TOT}(E_\nu) \frac{\rho}{(m_p+m_n)/2} L = \sigma_{TOT}(E_\nu) \frac{\rho}{(m_p+m_n)/2} \times 2R\cos(\theta)$$

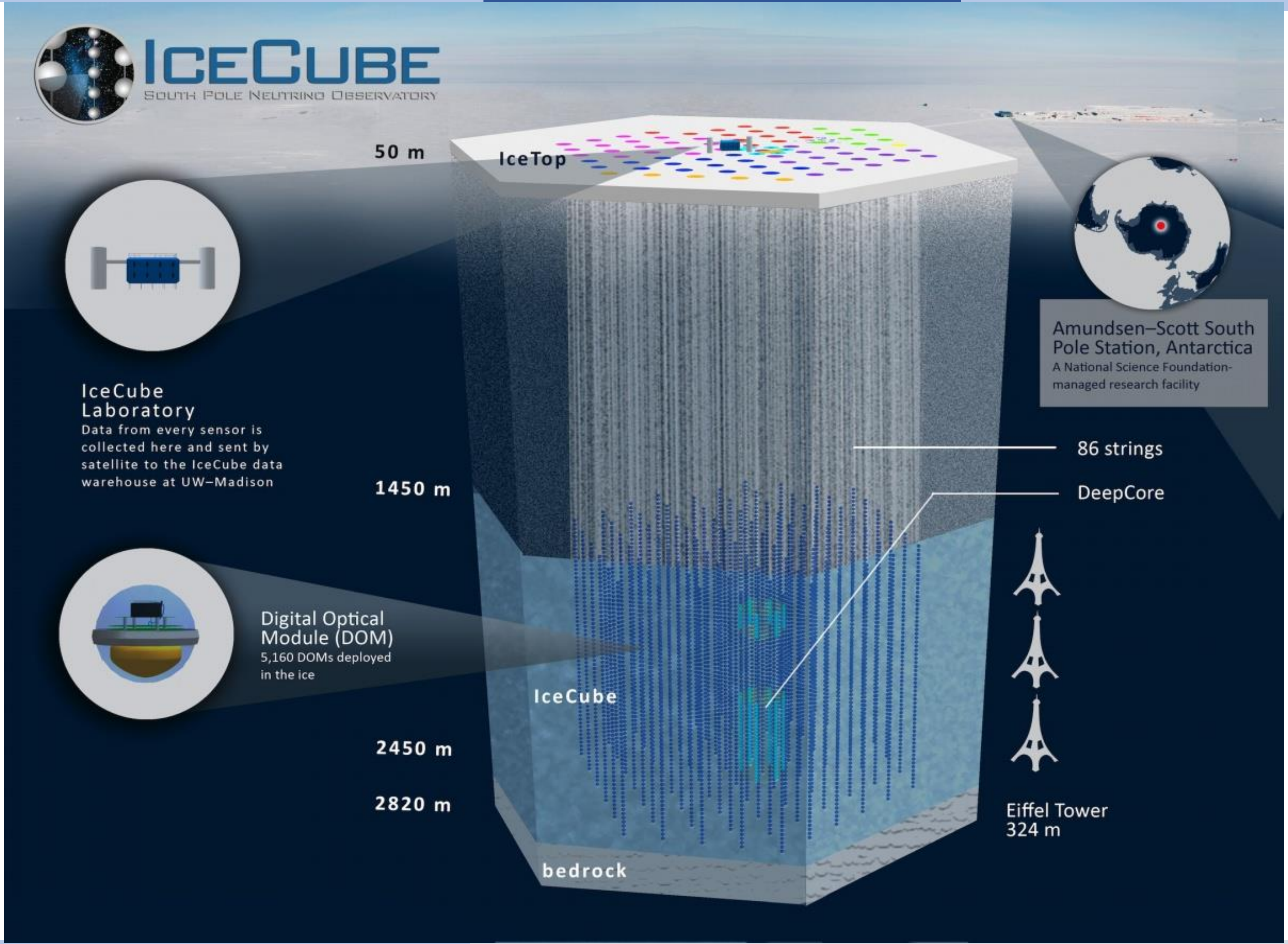


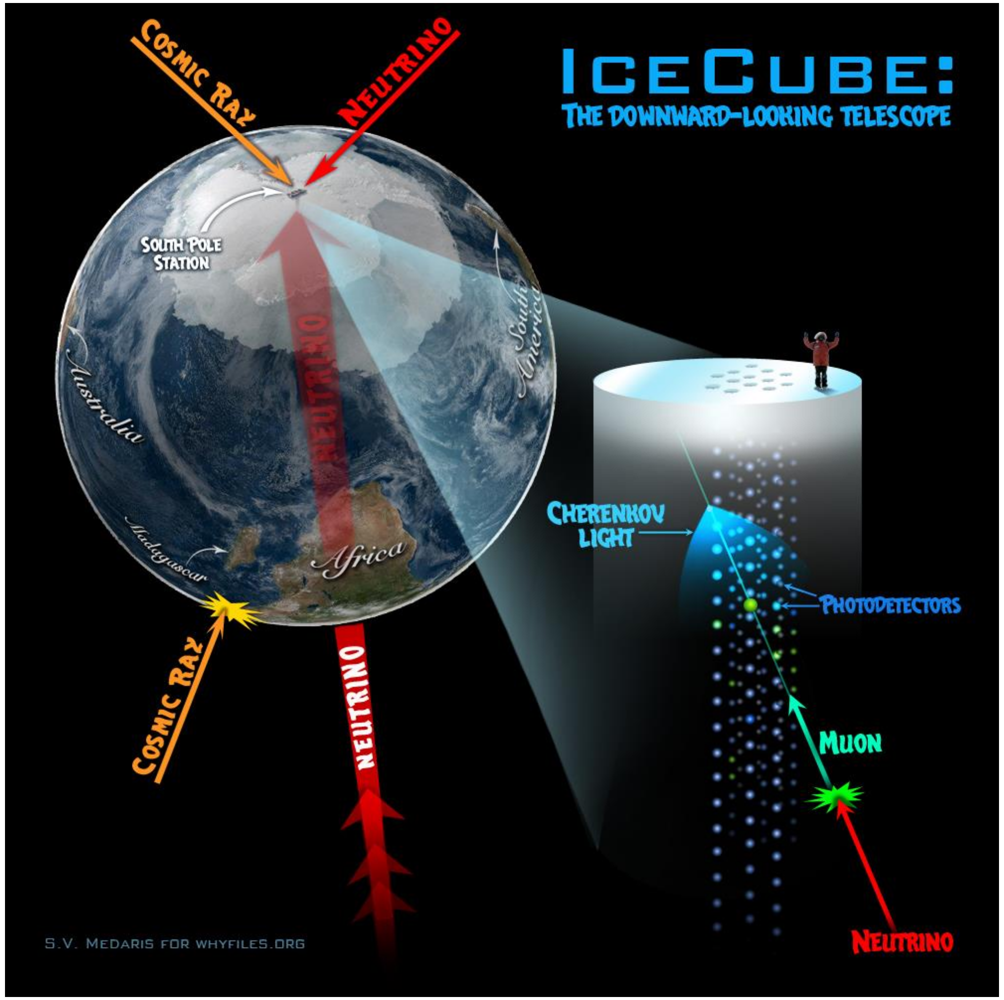
Neutrino energy (Earth becomes opaque)



- In many research, the Earth becomes completely opaque to neutrinos with PeV-scale energy.
- The Fermi Theory is not good enough to describe.
- The Earth becomes opaque with neutrinos at 1 PeV in case using Standard Model (consist with IceCube's data).

IceCube Experiment





- When the neutrino interacts with the Antarctic ice, it produces electrically charged
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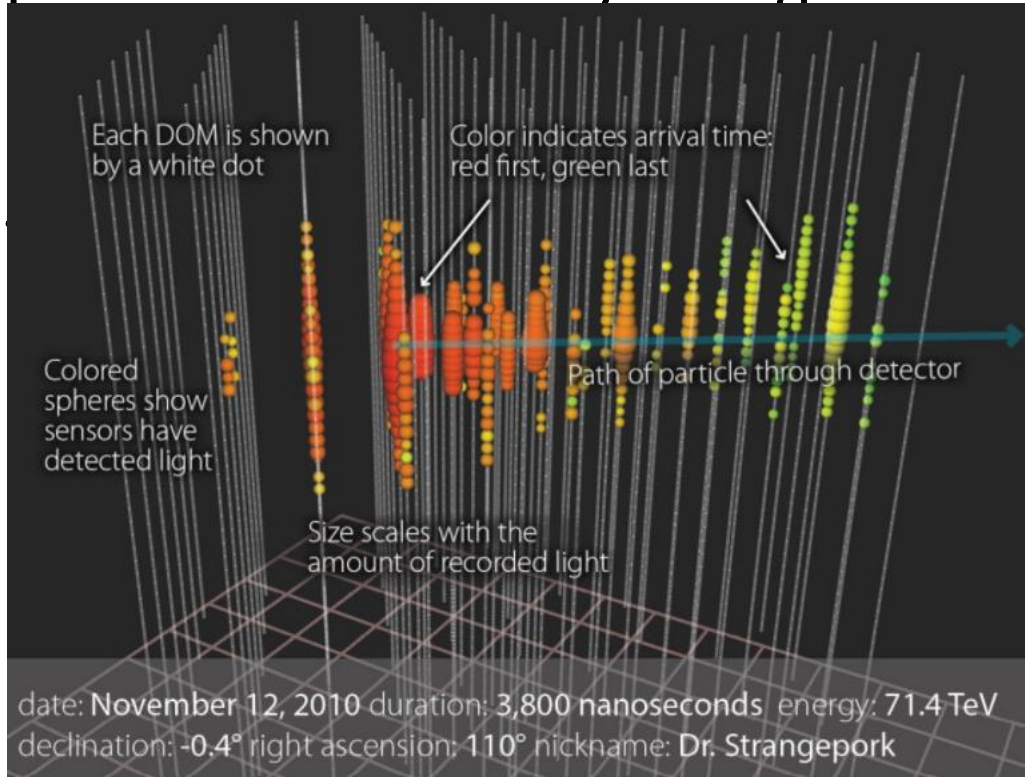
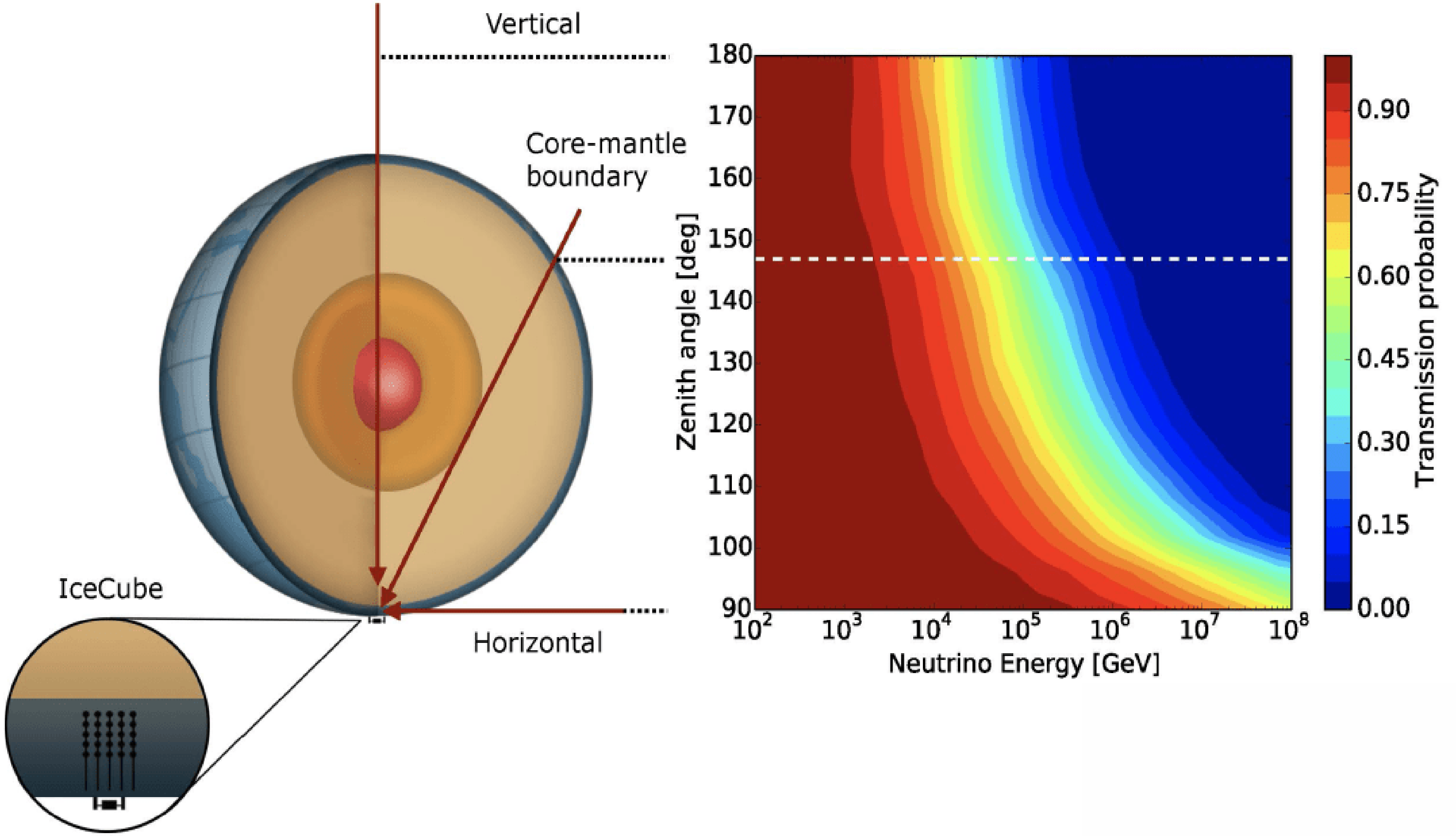


Energy spectrum with Zenith angle

- Neutrinos from the horizon have no absorption
- Neutrinos with a near vertical trajectory show the increase in absorption with energy
- The transmission probability predicted by the Standard Model for neutrinos to transit the Earth as a function of energy and zenith angle is shown



Discussion

- Density of the Earth is assumed as uniform in this project. The other assumptions can be considered to obtain the more exactly one, but the idea still the same, like PREM model, etc...
- Have not mentioned different flavors of neutrino to see the effect of antineutrino electron interaction on the measurement of the cross section and optical depth.

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Thank you for listening~