Atmospheric Neutrino Oscillation

By: Joshua Muñoz

History of the neutrino

- Problems with measured beta decay
- First predicted in 1930 by Wolfgang Pauli
  - $n^0 \rightarrow p^+ + e^- + \nu^0$

History of the neutrino (con't)

- The electron neutrino is detected in 1956 through Cowan-Reines neutrino experiment
- Using a nuclear reactor, shot neutrinos into protons, creating neutrons and positrons

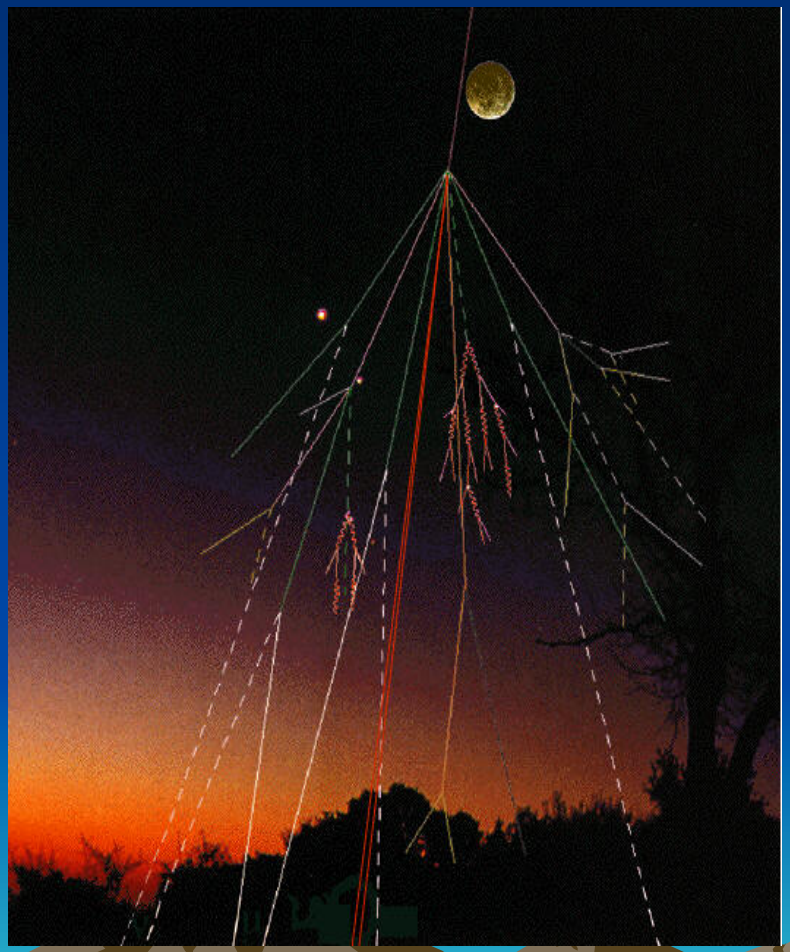
Properties of neutrinos

- Electrically neutral
- Travel close to the speed of light
- Small, but nonzero mass
- Permeate everything

Neutrino flavor

- Neutrinos come in 3 flavors: electron neutrinos, muon neutrinos, tauon neutrinos
- Each flavor is associated with the corresponding elementary particle

What is an atmospheric neutrino?

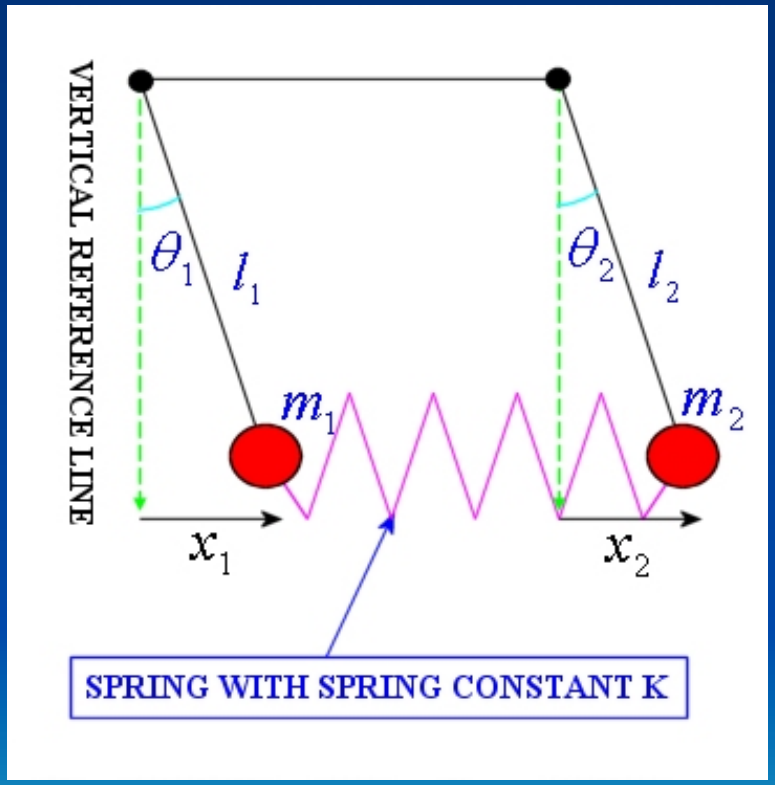


- Produced by cosmic rays striking the atmosphere
- Primarily, muon and electron neutrinos are created

What is neutrino oscillation?

- A phenomenon in which a neutrino changes from one flavor to another
- Theorized when the flux of electron neutrinos from the sun was ~1/3 of the predicted value

Neutrino oscillation (con't)



- A simple analogy is that it is like any coupled harmonic oscillator

Probability of Oscillation

- Consider the mixing matrix for two neutrinos

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

- Using the Schrödinger wave equation for two neutrinos of different mass and frequency

$$\begin{pmatrix} \nu_1(\vec{x},t) \\ \nu_2(\vec{x},t) \end{pmatrix} = e^{i\vec{p}\cdot\vec{x}} \begin{pmatrix} e^{-iE_1 t} & |\nu_1(0)\rangle \\ e^{-iE_2 t} & |\nu_2(0)\rangle \end{pmatrix}$$
$$= e^{i\vec{p}\cdot\vec{x}} \begin{pmatrix} e^{-iE_1 t} & 0 \\ 0 & e^{-iE_2 t} \end{pmatrix} \begin{pmatrix} |\nu_1(0)\rangle \\ |\nu_2(0)\rangle \end{pmatrix}$$

Probability of Oscillation (con't)

- If we combine the two equations from the first page

$$\begin{pmatrix} |\nu_\mu(\vec{x},t)\rangle \\ |\nu_\tau(\vec{x},t)\rangle \end{pmatrix} = e^{i\vec{p}\cdot\vec{x}} \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} e^{-iE_1 t} & 0 \\ 0 & e^{-iE_2 t} \end{pmatrix} \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} |\nu_\mu(0)\rangle \\ |\nu_\tau(0)\rangle \end{pmatrix}$$

- Assuming there is only one flavor of neutrino to begin with

$$\text{If } |\nu_\mu(0)\rangle = 1 \text{ and } |\nu_\tau(0)\rangle = 0:$$

$$\left| |\nu_\tau(\vec{x},t)\rangle \right|^2 = \sin^2(2\theta)\sin^2\frac{(E_2 - E_1)t}{2} \equiv P(\nu_\mu \to \nu_\tau)$$

Probability of Oscillation (con't)

- We assume the energies are much higher than the masses and plug back in

If $E_1, E_2 >> m_1, m_2$:

$$E_2 - E_1 = \sqrt{m_2^2 + p^2} - \sqrt{m_1^2 + p^2} \approx \frac{m_2^2 - m_1^2}{2p}$$

and

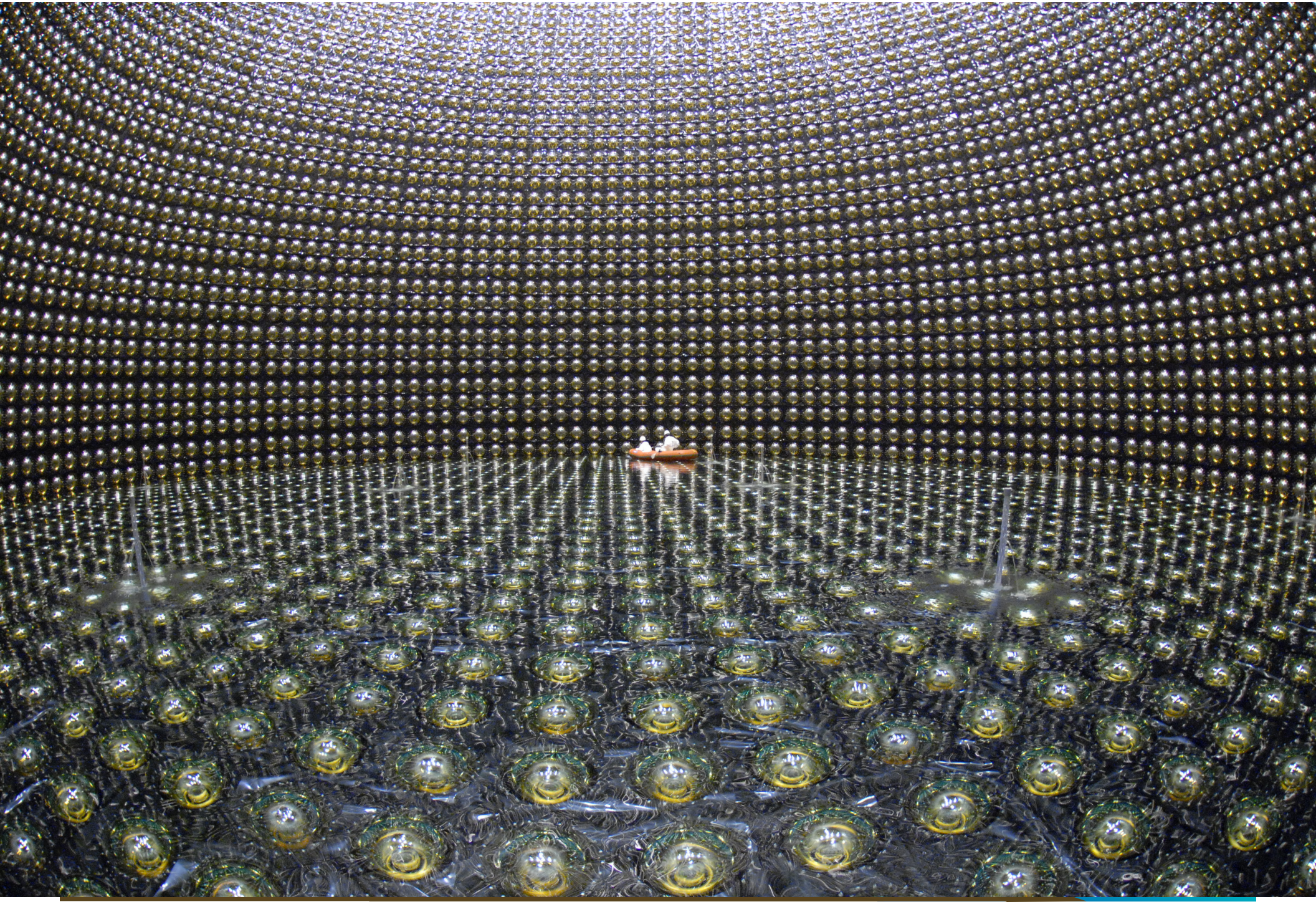
$$t \approx |\vec{x}| \equiv L,$$
$$p \approx E$$

Therefore :

$$P(\nu_\mu \to \nu_\tau) \approx \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2}{4} \frac{L}{E}\right)$$

Super Kamiokande

- Completed in 1996
- 1 km underground, 41.4 m high, 39.3 m in diameter
- Holds ~50,000 tons of ultra-pure water
- Contains 11,146 photomultiplier tubes (PMTs)



Photomultiplier Tubes

- Extremely sensitive vacuum tubes for detecting light
- Used in Super K for detecting rings of Cherenkov radiation

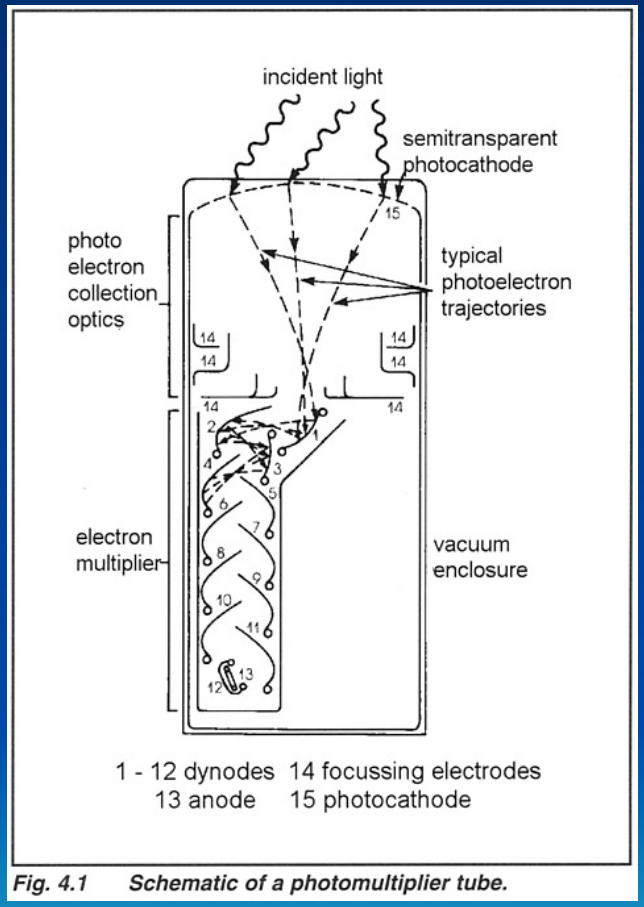


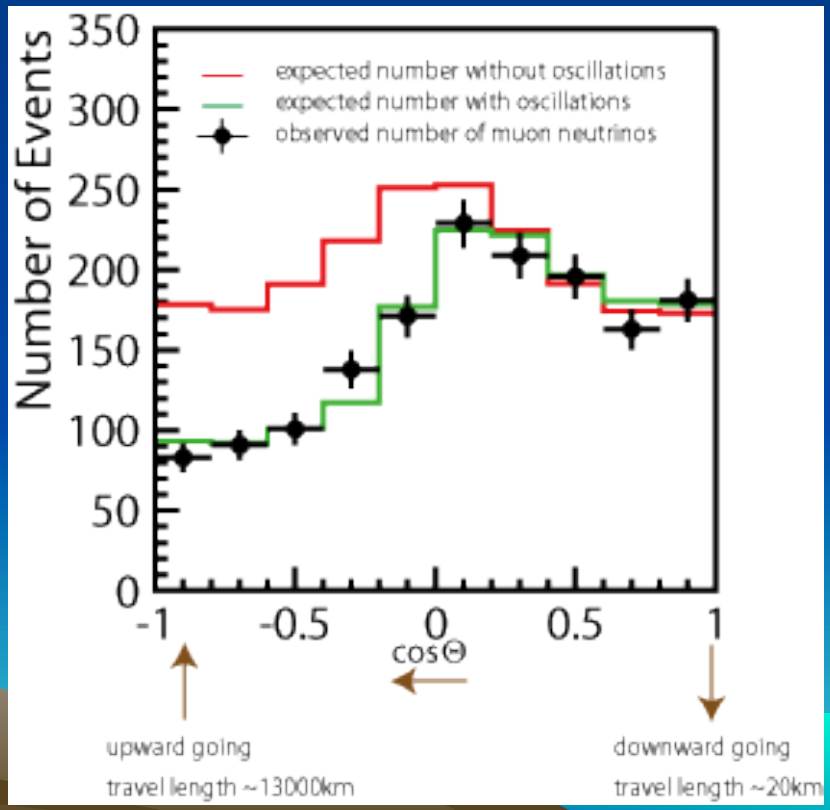
Fig. 4.1 Schematic of a photomultiplier tube.

Initial hints of oscillation

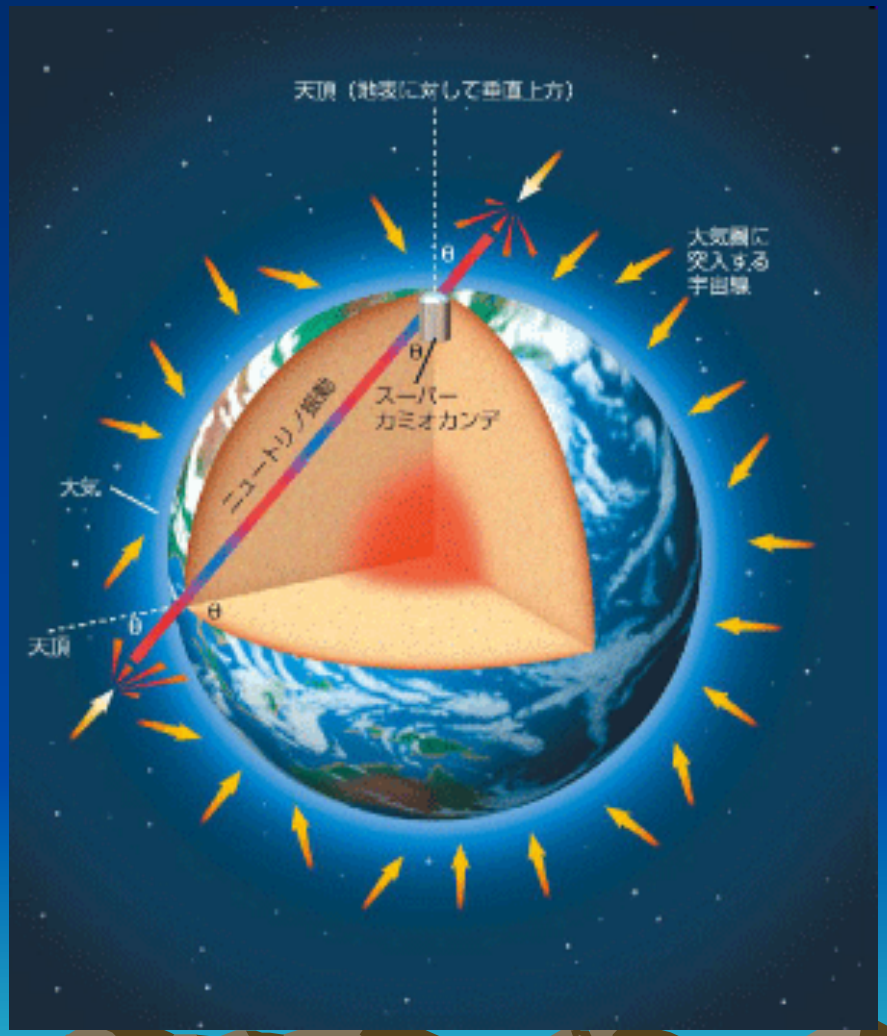
- Atmospheric neutrinos are created uniformly around the whole earth.
- The number of atmospheric muon neutrinos going “up” was less than that going “down”

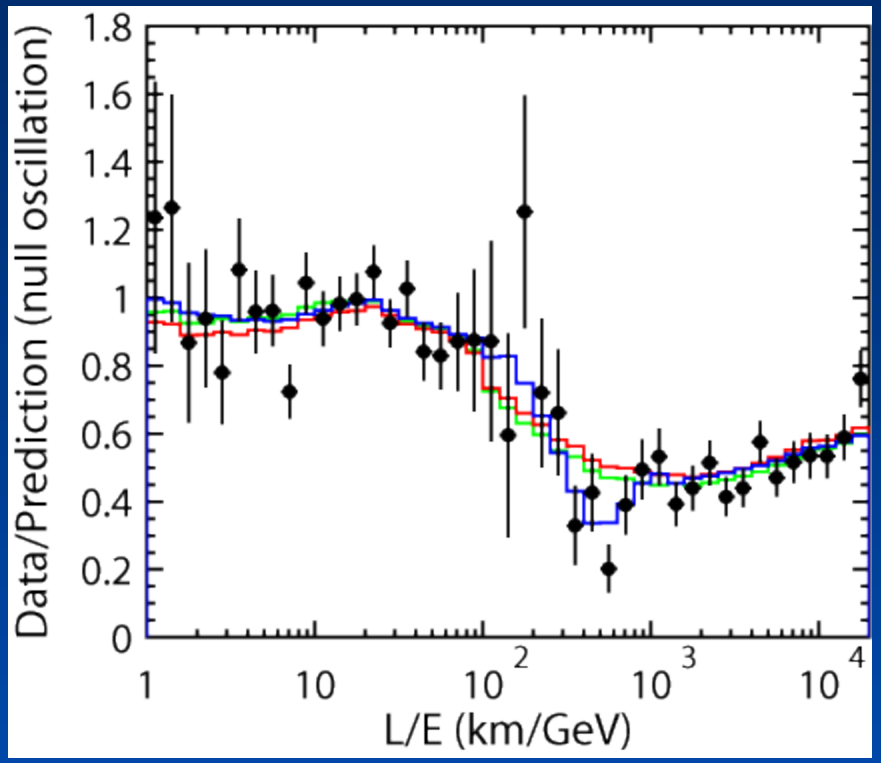
Detection of oscillation

- August 1998 article released by the Super-Kamiokande Collaboration at Tokyo University in Japan



How this is oscillation





2004 Detailed analysis of dependence of event rate and Length/Energy

Ongoing Super K Experiments

- 2004 - The observed L/E distribution constrained $\nu_\mu <-> \nu_\tau$ neutrino oscillation parameters; $1.9 \times 10^{-3} < \Delta m^2 < 3.0 \times 10^{-3} eV^2$
- 2006 – Finds a best fit tau neutrino appearance signal after 1489 days of operation

Other Experiments

- Sudbury Neutrino Observatory (SNO)
- IceCube/AMANDA
- Main Injector Neutrino Oscillation Search (MINOS)
- Irvine–Michigan–Brookhaven (IMB)

Implications

- Neutrinos have mass – not predicted through the Standard Model
  - Some theoretical solutions: unobserved right-handed neutrinos, Majorana fermions, seesaw mechanism

The Future

- Cherenkov detectors can still only calculate difference of the squares of the masses
  - New methods using nuclear beta decay (KATRIN and MARE) or neutrinoless double beta decay (GERDA, CUORE, NEMO-3)

Credits

- Fukuda, Y.1 ; Hawakawa, T.1 ; Ichihara, E.1 ; Inoue, K.1 ; Ishino, H.1 ; Itow, Y.1 ; Kajita, T.1 ; Kameda, J.1 ; Kasuga, S.1 ; Kobayashi, K.1 ; Kobayashi, Y.1 ; Koshio, Y.1 ; Miura, M.1 ; Nakahata, M.1 ; Nakayama, S.1 ; Okada, A.1 ; Okumura, K.1 ; Sakurai, N.1 ; Shiozawa, M.1 ; Suzuki, Y.1 ; Takeuchi, Y.1 ; Totsuka, Y.1 ; Yamada, S.1 ; Earl, M.1 ; Habig, A.1 ; Kearns, E.1 ; Messier, M.D.1 ; Scholberg, K.1 ; Stone, J.L.1 ; Sulak, L.R.1 ; Walter, C.W.1 ; Goldhaber, M.1 ; Barszczxak, T.1 ; Casper, D.1 ; Gajewski, W.1 ; Halverson, P.G.1 ; Hsu, J.1 ; Kropp, W.R.1 ; Price, L.R.1 ; Reines, F.1 ; Smy, M.1 ; Sobel, H.W.1 ; Vagins, M.R.1 ; Ganezer, K.S.1 ; Keig, W.E.1 ; Ellsworth, R.W.1 ; Tasaka, S.1 ; Flanagan, J.W.1 ; Kibayashi, A.1 ; Learned, J.G.1 ; Matsuno, S.1 ; Stenger, V.J.1 ; Takemori, D.1 ; Ishii, T.1 ; Kanzaki, J.1 ; Kobayashi, T.1 ; Mine, S.1 ; Nakamura, K.1 ; Nishikawa, K.1 ; Oyama, Y.1 ; Sakai, A.1 ; Sakuda, M.1 ; Sasaki, O.1 ; Echigo, S.1 ; Kohama, M.1 ; Suzuki, A.T.1 ; Haines, T.J.1 ; Blaufuss, E.1 ; Kim, B.K.1 ; Sanford, R.1 ; Svoboda, R.1 ; Chen, M.L.1 ; Conner, Z.1 ; Goodman, J.A.1 ; Sullivan, G.W.1 ; Hill, J.1 ; Jung, C.K.1 ; Martens, K.1 ; Mauger, C.1 ; McGrew, C.1 ; Sharkey, E.1 ; Viren, B.1 ; Yanagisawa, C.1 ; Doki, W.1 ; Miyano, K.1 ; Okazawa, H.1 ; Saji, C.1 ; Takahata, M.1 ; Nagashima, Y.1 ; Takita, M.1 ; Yamaguchi, T.1 ; Yoshida, M.1 ; Kim, S.B.1 ; Etoh, M.1 ; Fujita, K.1 ; Hasegawa, A.1 ; Hasegawa, T.1 ; Hatakeyama, S.1 ; Iwamoto, T.1 ; Koga, M.1 ; Maruyama, T.1 ; Ogawa, H.1 ; Shirai, J.1 ; Suzuki, A.1 ; Tsushima, F.1 ; Koshiba, M.1 ; Nemoto, M.1 ; Nishijima, K.1 ; Futagami, T.1 ; Hayato, Y.1 ; Kanaya, Y.1 ; Kaneyuki, K.1 ; Watanabe, Y.1 ; Kielczewska, D.1 ; Doyle, R.A.1 ; George, J.S.1 ; Stachyra, A.L.1 ; Wai, L.L.1 ; Wilkes, R.J.1 ; Young, K.K.1 (1998). **Evidence for oscillation of atmospheric neutrinos**. *Physical Review Letters*, *81*(8), 1562-7 . Retrieved from http://www.engineeringvillage2.org.offcampus.lib.washington.edu/controller/servlet/Controller?SEARCHID=257f1b124f82f100cM32e6prod2data1&CID=quickSearchDetailedFormat&DOCINDEX=1&database=2&format=quickSearchDetailedFormat

Credits (con't)

- Higashi-Mozumi. *Super Kamiokande official Homepage.* Retrieved November 10,http://www-sk.icrr.u-tokyo.ac.jp/sk/index-e.html
- Kearns, Ed. *ATMOSPHERIC NEUTRINOS.* Retrieved November 10, http://hep.bu.edu/~superk/atmnu/
- *Read Out of Scintillation Crystals.* Retrieved November 10, http://www.scionixusa.com/pages/navbar/read_out.html
- Casper, Dave. *Super-Kamiokande at UC Irvine.* Retrieved November 10, http://www.ps.uci.edu/~superk/index.htm
- Giunti, Carlo, Laveder, Marco. *Atmospheric Neutrinos.* Retrieved November 10, http://www.nu.to.infn.it/Atmospheric_Neutrinos/index.html#hep-ex/0512036

Credits (con't)

- Neutrino. Retrieved November 10, 2009,from Wikipedia: http://en.wikipedia.org/wiki/Neutrino
- Neutrino oscillation. Retrieved November 10, 2009,from Wikipedia: http://en.wikipedia.org/wiki/Neutrino_oscillation
- Super-Kamiokande. Retrieved November 10, 2009,from Wikipedia: http://en.wikipedia.org/wiki/Super-Kamiokande