Neutrino Physics & Oscillations

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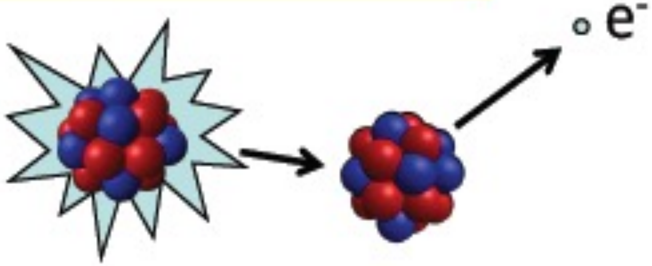
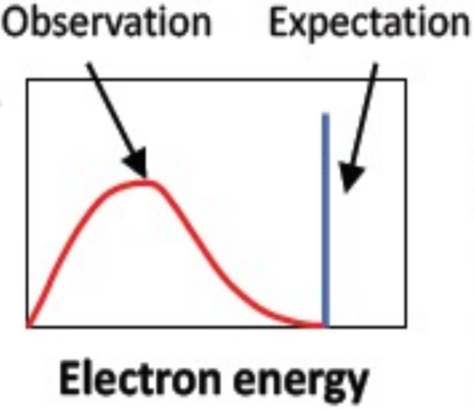
S. K. Agarwalla, IceCube Summer School, Madison, Wisconsin, USA, 5th June 2023

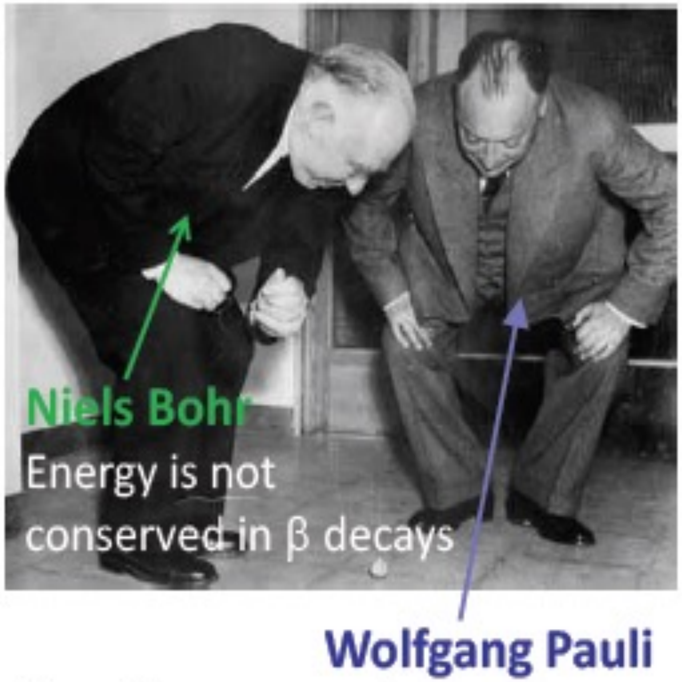
Mission Impossible: Detect Neutrinos

The problem (1914)



$n \rightarrow p + e^-$

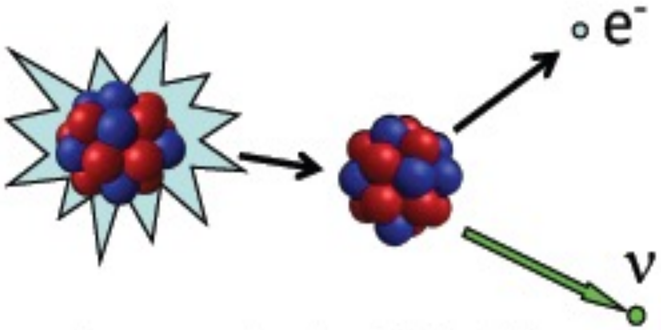




Niels Bohr
Energy is not conserved in β decays

Wolfgang Pauli

The desperate remedy (1930)



$n \rightarrow p + e^- + \nu$

There is a neutral particle able to cross all detectors without leaving any trace and carrying all the missing energy

> *«I have done a terrible thing. I have postulated a particle that cannot be detected.» (1930)*

Fortunately, Pauli was wrong, and neutrinos have been detected successfully

1934: Fermi named the new particle as 'neutrino'

Neutrinos are Omnipresent

Detected (1950s)

✓ **Nuclear Reactors**

Created & Detected (1960s)

✓ **Particle Accelerators**

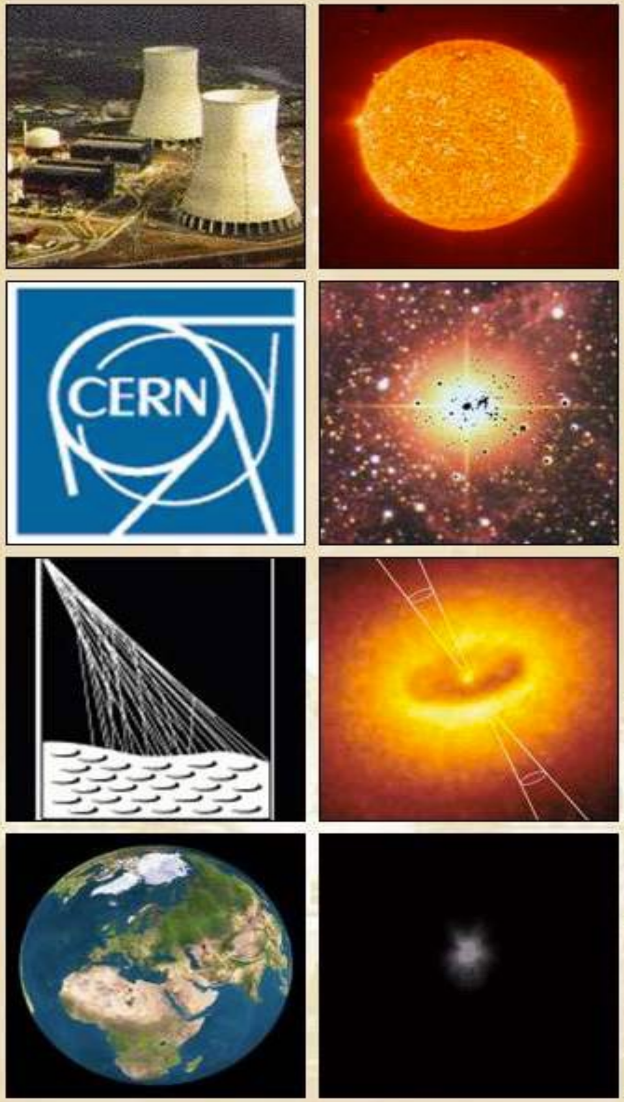
Detected (1960s)

✓ **Earth Atmosphere (Cosmic Rays)**

Detected By KamLAND in 2005

✓ **Earth Crust (Natural Radioactivity)**

Geoneutrino



Detected (1960s)

Sun ✓

Detected (1980s)

Supernovae (Stellar Collapse)

SN 1987A ✓

IceCube found in 8 years 103 contained-vertex events between 15 TeV - 2 PeV

Astrophysical Accelerators

IceCube ✓

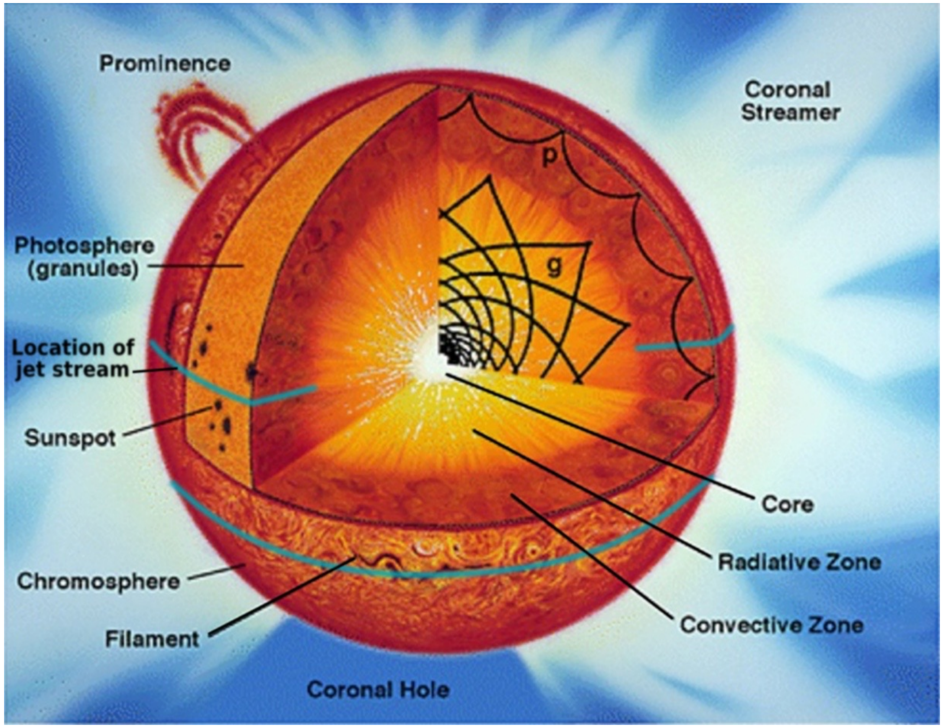
Not even close

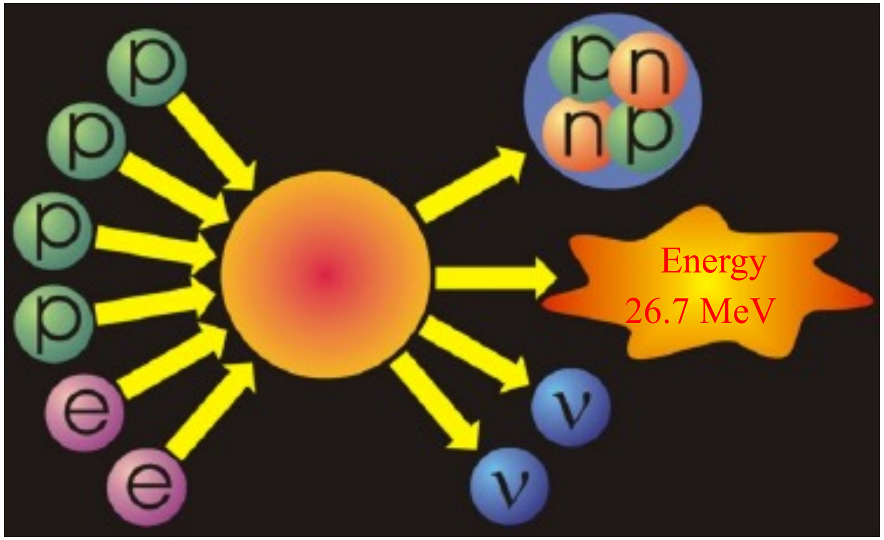
Cosmic Big Bang (Today 330 ν/cm^3)

Indirect Evidence

Extremely rich and diverse neutrino physics program

How does the Sun shine?





Solar radiation: 98% light and 2% neutrinos

At Earth 66 billion neutrinos $\text{cm}^{-2}\ \text{s}^{-1}$

- Nuclear fusion reactions: mainly

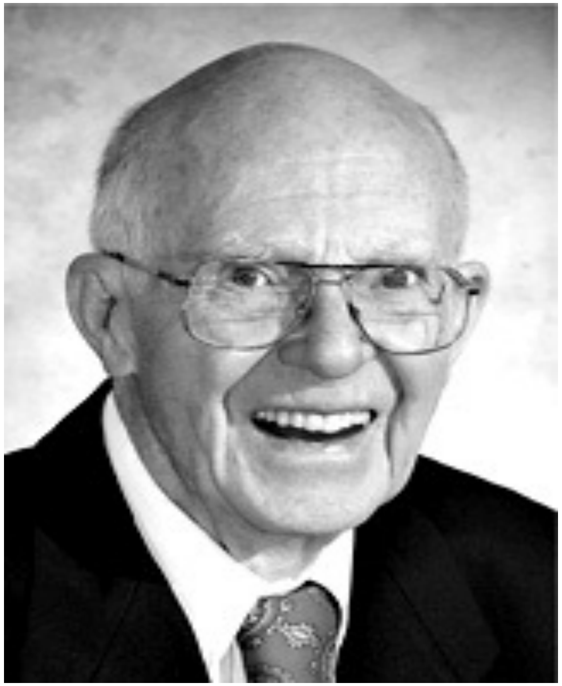
$$4\ {}^{1}_{1}\mathrm{H} + 2e^{-} \rightarrow {}^{4}_{2}\,\mathrm{He} + \mathrm{light} + 2\nu_e$$

- Neutrinos needed to conserve energy, momentum, angular momentum

Neutrinos are essential for the Sun to shine !

Detection of Cosmic Neutrinos

The Nobel Prize in Physics 2002



Raymod Davis Jr.

Masatoshi Koshiba

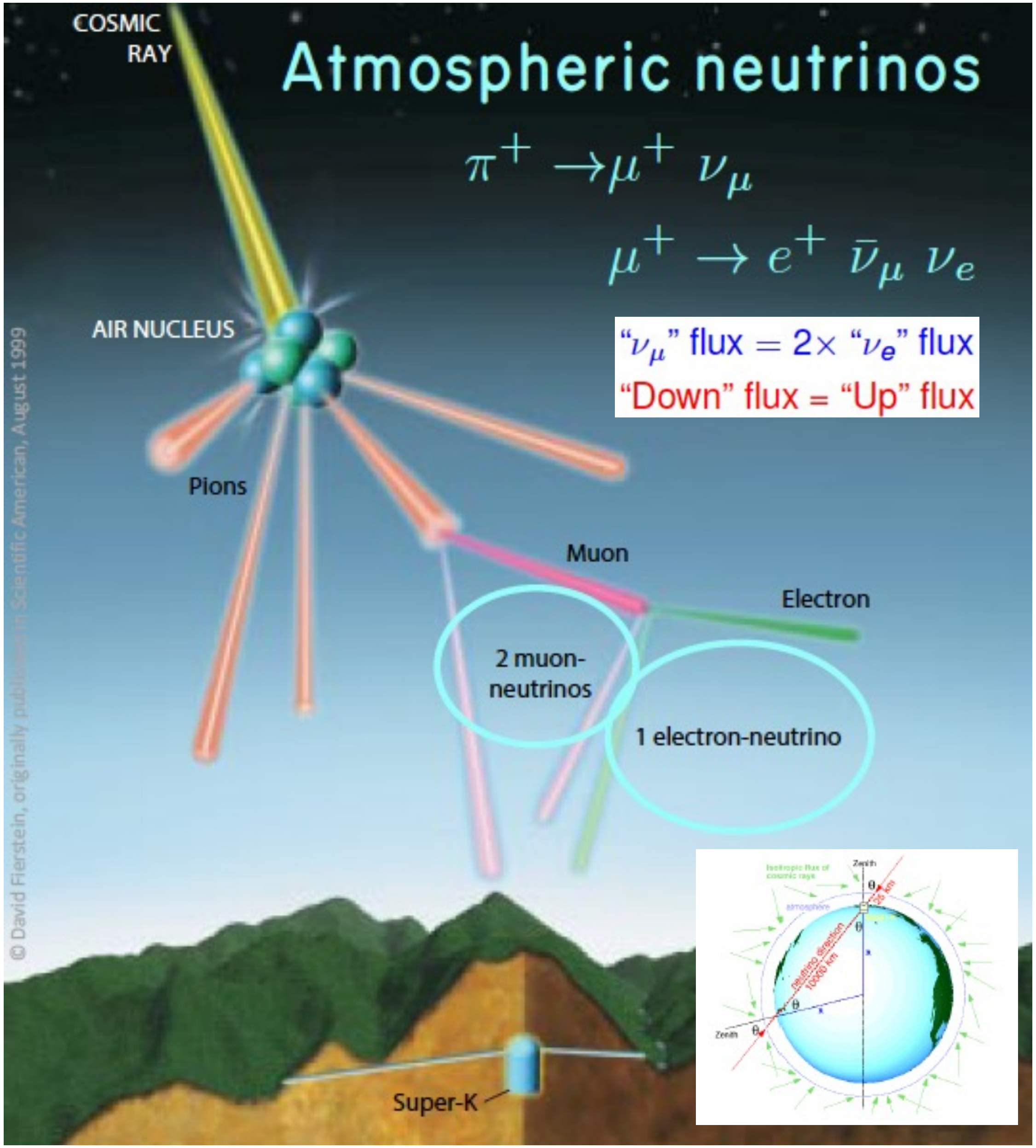
Detected Solar Neutrinos

Detected Supernova Neutrinos

Detection of Cosmic Neutrinos ➔ A New Window on the Universe

Era of Neutrino Astronomy began

Atmospheric Neutrinos



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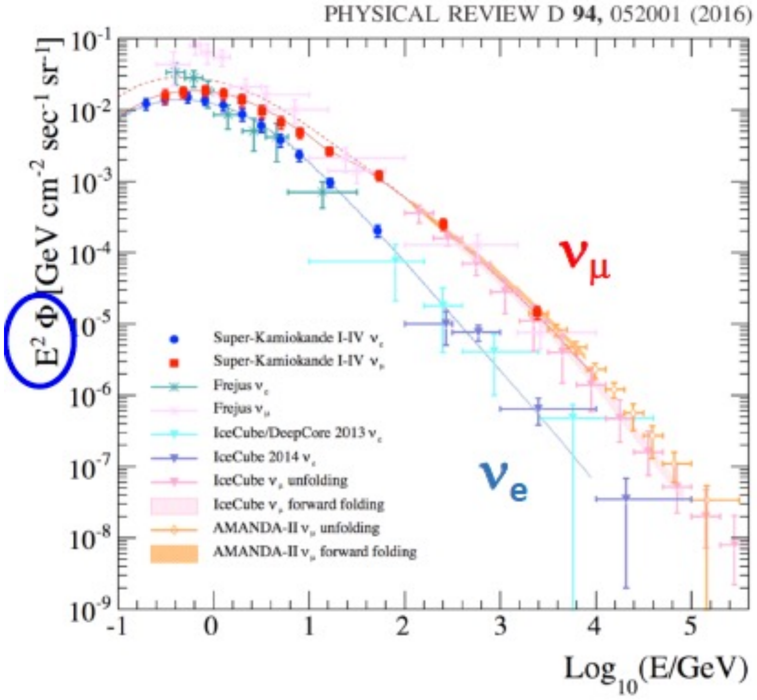
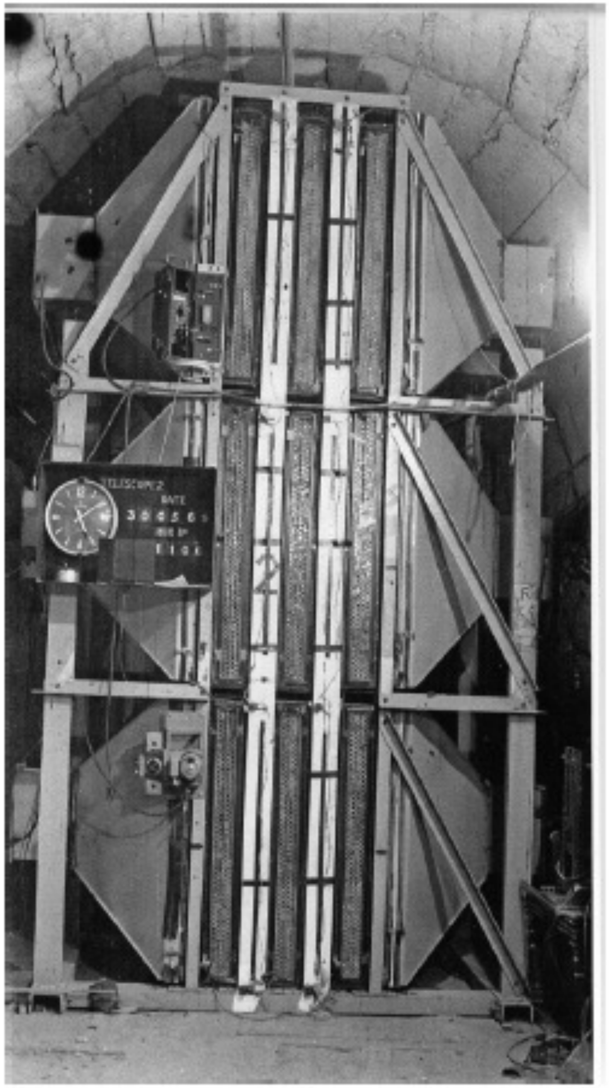


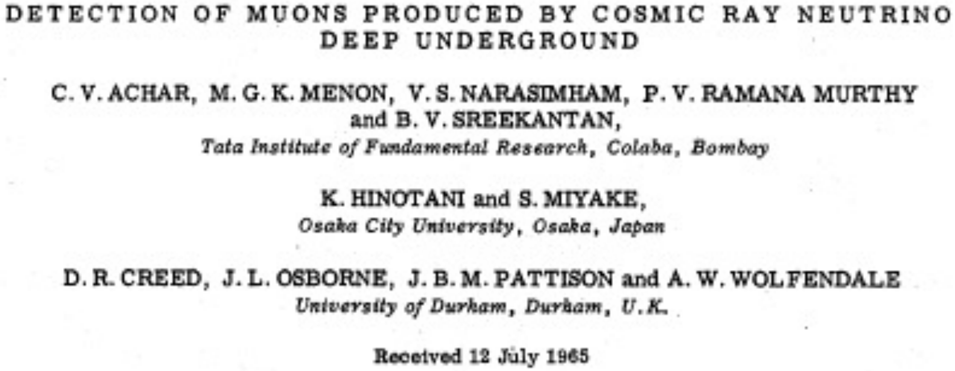
PHYSICAL REVIEW D **94**, 052001 (2016)

- **Almost isotropic flux**
  up-down symmetric
- **Known flavor composition**
  (ν_e, ν_μ, and their antiparticles)
- **Wide range of energies**
  (GeV to PeV)
- **Steeply falling power-law spectrum**

Detection of Atmospheric Neutrinos



Detector in
Kolar Gold Fields



DETECTION OF MUONS PRODUCED BY COSMIC RAY NEUTRINO DEEP UNDERGROUND

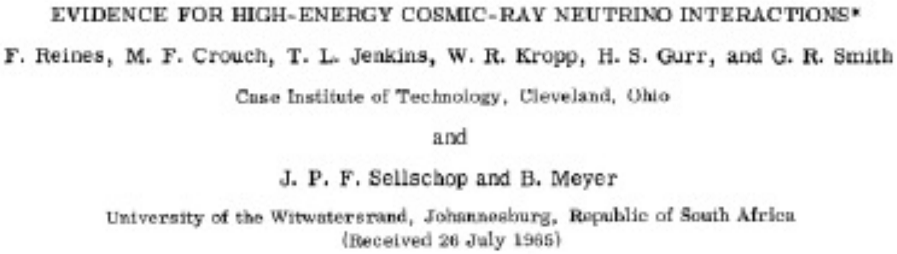
C. V. ACHAR, M. G. K. MENON, V. S. NARASIMHAM, P. V. RAMANA MURTHY
and B. V. SREEKANTAN,
Tata Institute of Fundamental Research, Colaba, Bombay

K. HINOTANI and S. MIYAKE,
Osaka City University, Osaka, Japan

D. R. CREED, J. L. OSBORNE, J. B. M. PATTISON and A. W. WOLFENDALE
University of Durham, Durham, U.K.

Received 12 July 1965

Physics Letters 18, (1965) 196
(15th Aug 1965)



EVIDENCE FOR HIGH-ENERGY COSMIC-RAY NEUTRINO INTERACTIONS*

F. Reines, M. F. Crouch, T. L. Jenkins, W. R. Kropp, H. S. Gurr, and G. R. Smith

Case Institute of Technology, Cleveland, Ohio

and

J. P. F. Sellschop and B. Meyer

University of the Witwatersrand, Johannesburg, Republic of South Africa
(Received 26 July 1965)

PRL 15, (1965) 429
(30th Aug 1965)

Few Unique Features of Neutrinos

- **After photon, neutrino is the second-most abundant particles in the universe**

Cosmic microwave background: 400 photons / cm^3 (Temperature: ~ 2.7 K)

mean energy $E_\gamma = k_B T = 2.3\times10^{-4}$ eV

Cosmic neutrino background: 330 neutrinos / cm^3 (Temperature: ~ 1.95 K)

(These are known as relic neutrinos: very low in energy: ~ 0.0002 eV)

(Even empty space between galaxies is full of neutrinos)

About 100 trillion neutrinos pass through our body every second

Hundred trillion = 100 000 000 000 000

- **The Sun produces ~ 10^{38} neutrinos per second**

But most of the neutrinos are relics of the Big Bang (~ 10^{10} years old)

Few Unique Features of Neutrinos

- **Nature's most elusive messenger, interacts very rarely, very hard to detect**

Invisible: do not interact with light

100 billion neutrinos + the whole Earth = only one interaction

Stopping radiation with lead shielding: 50 cm for α, β, γ

Stopping neutrinos from the Sun: light years of lead

- **Arrives 'unscathed' from the farthest reaches of the Universe**

Brings information from deep within the stars (Not possible with light)

- **The lightest massive particles**

A million times lighter than the electron

No direct mass measurement yet

Close Encounter with Neutrinos

- **When we take our morning walk on the green Nature, our body receives**

  400000 billion neutrinos from the Sun

  50 billion neutrinos from the natural radioactivity of the Earth

  10 – 100 billion neutrinos from the nuclear power plants all over the world

- **We can still enjoy our walk. Typically, a neutrino must zip through**

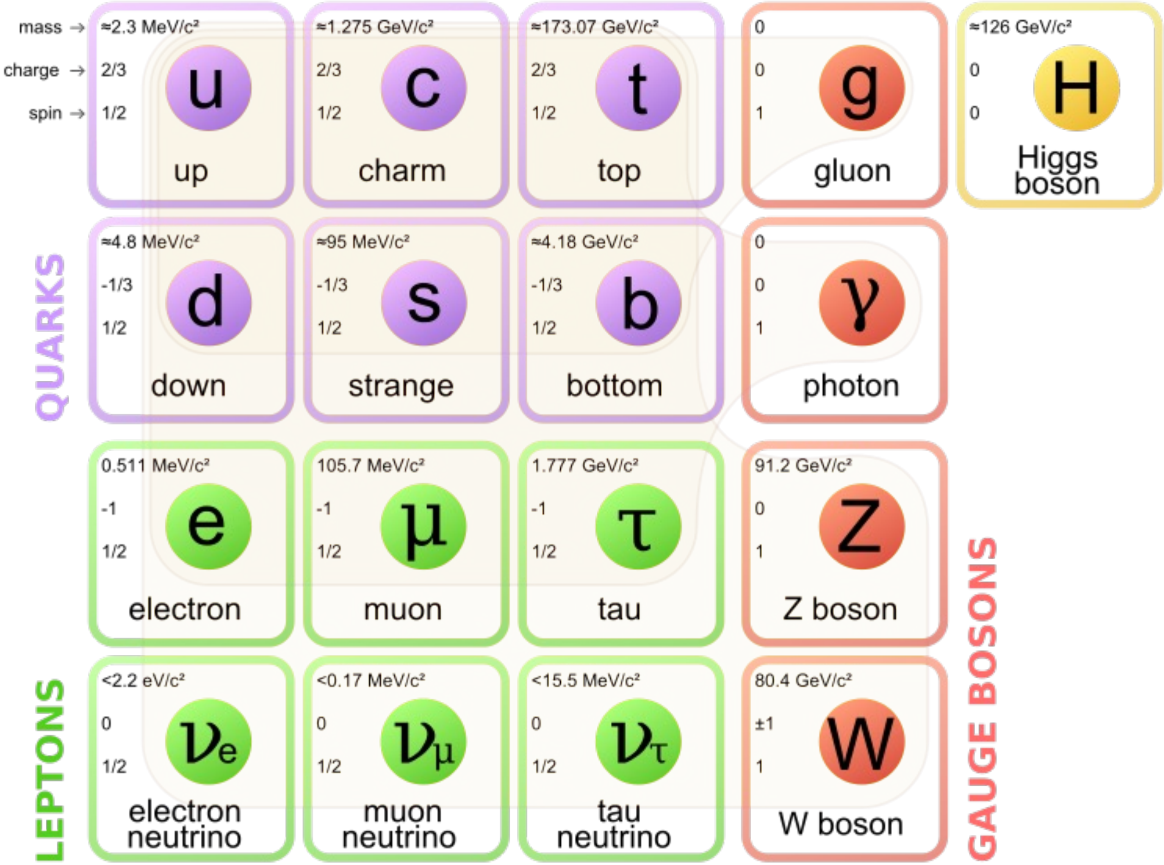
  10,000,000,000,000,000,000 people before doing anything

- **Our body contains about 20 milligrams of ^{40}K which is beta-radioactive**

  We emit about 340 million neutrinos per day, which run from our body

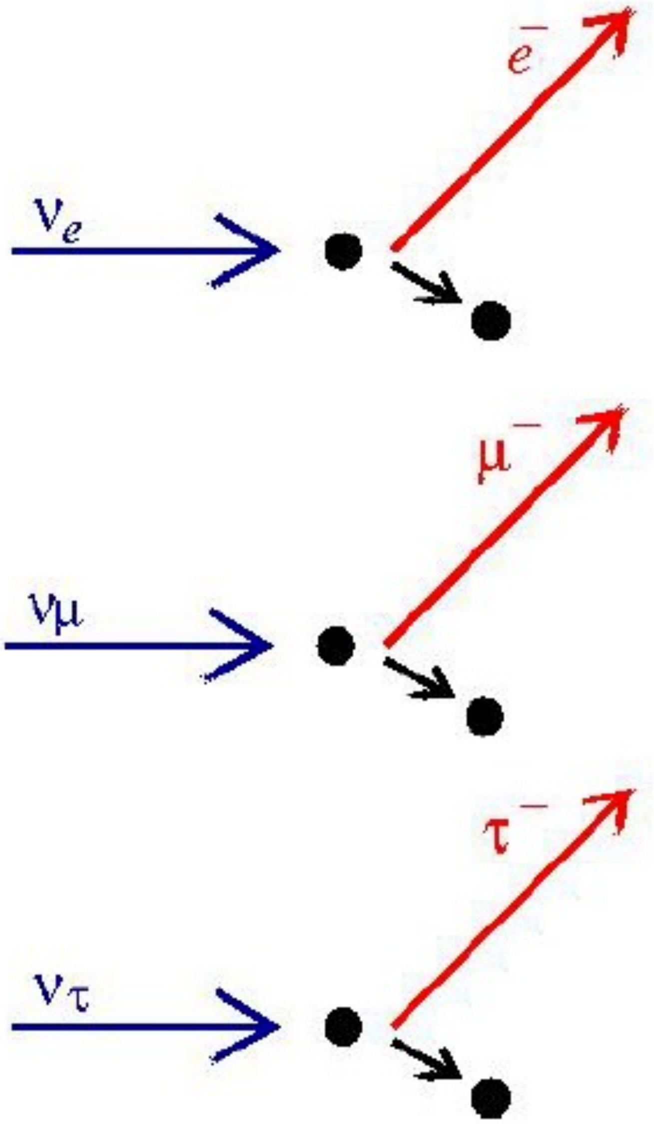
  at the speed of light until the end of the Universe

Neutrinos in the Standard Model of Particle Physics



- 3 active neutrinos:
  ν_e , ν_μ , ν_τ
- Zero charge (neutral)
- Spin 1/2
- Only couple to weak force (and gravity)
- Almost massless: at least a million times lighter than electron

Three kinds (flavors) of neutrinos: ν_e ν_μ ν_τ



electron
neutrino

electron

$m_e = 0.511$ MeV $P_{\text{thresh}} = 0.511$ MeV

muon
neutrino

muon

200 times heavier than electron

$m_\mu = 106$ MeV $P_{\text{thresh}} = 112$ MeV

tau
neutrino

tau

3500 times heavier than electron

$m_\tau = 1.78$ GeV $P_{\text{thresh}} = 3.47$ GeV

$$E_\nu > \frac{m_\tau^2 + 2m_\tau m_{\text{nucleon}}}{2m_{\text{nucleon}}} \approx 3.5 \text{ GeV}$$

Antineutrinos $\overline{\nu}_e$, $\overline{\nu}_\mu$, $\overline{\nu}_\tau$ produce positively charged particles

Discovery of Invisible Neutrinos

- **Electron neutrino ν_e : 1956**

Reactor anti-neutrinos: $\bar{\nu}_e + p \rightarrow n + e^+$

Nobel Prize to Frederick Reines in 1995

Clyde Cowan

Frederick Reines

- **Muon neutrino ν_μ : 1962**

Neutrinos from pion decay:

$$\pi^- \rightarrow \mu^- + \nu_{(\mu)}$$

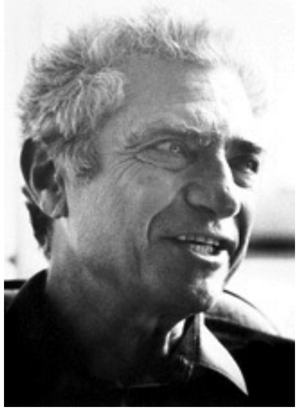
$$\nu_{(\mu)} + N \rightarrow N' + \mu^-$$

Always a muon, never an e^-/e^+

Nobel Prize in 1988

Leon M. Lederman

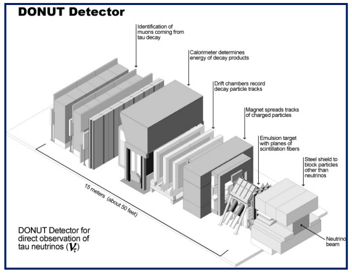
Melvin Schwartz



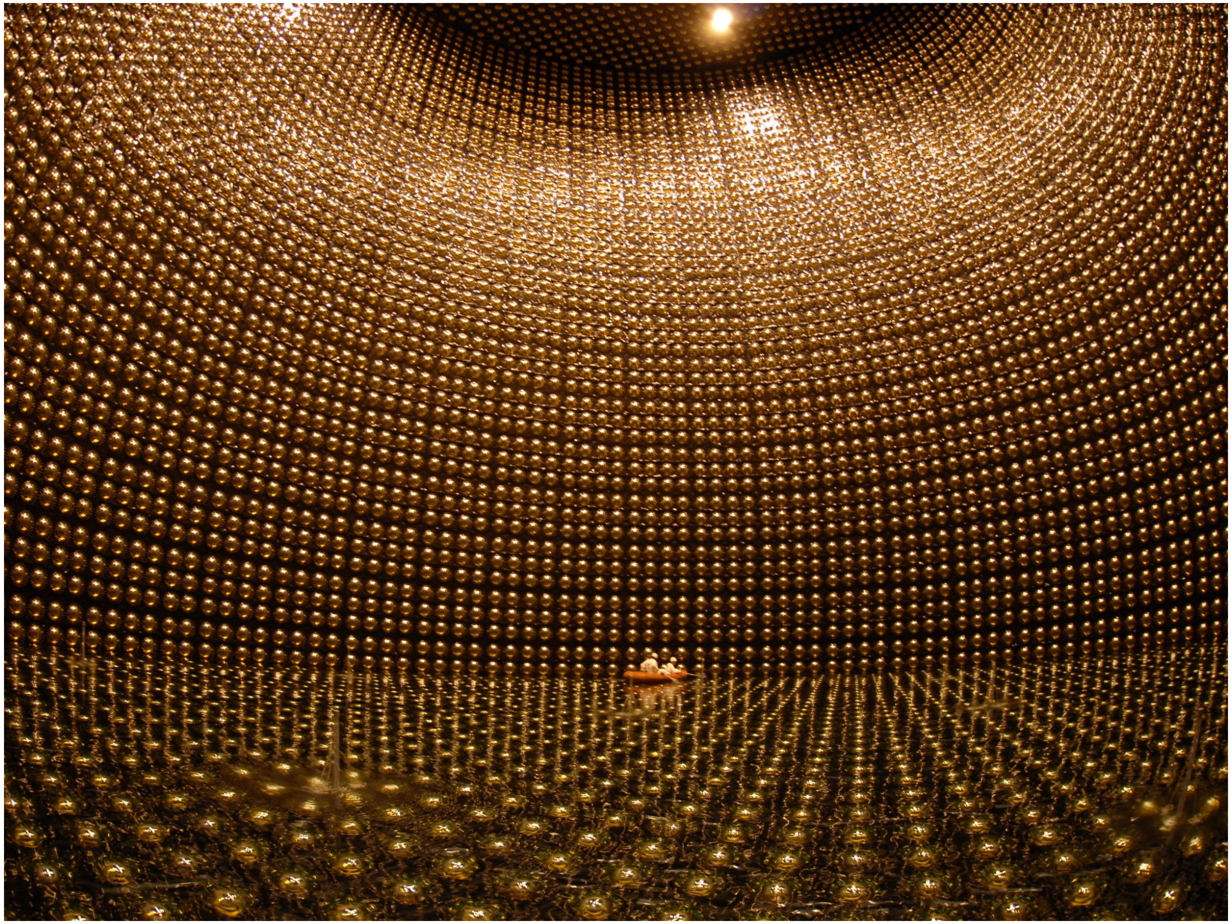
Jack Steinberger

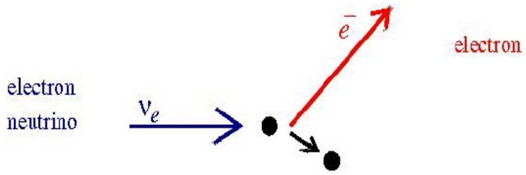
- **Tau neutrino ν_τ : 2000**

DONUT experiment at Fermilab: $\nu_\tau + N \rightarrow \tau + N'$



Neutrino Detection in Super-Kamiokande





Around 11,146 Photomultiplier tubes (PMT)

Observes about 5 -10 neutrinos per day (out of ≥ 10^{25} neutrinos passing through)

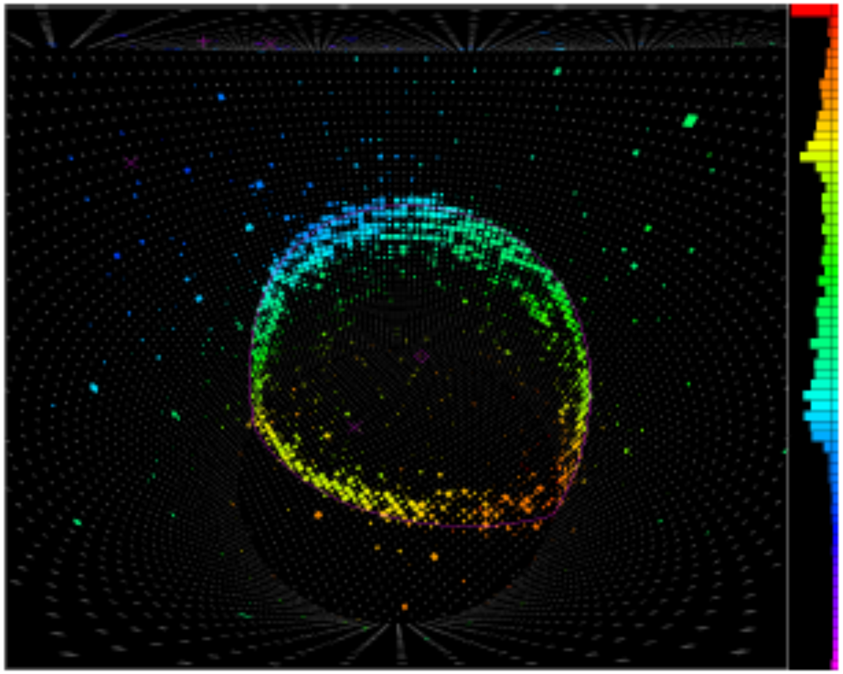
Super-Kamiokande detector in Japan is located 1,000 m (3,300 ft) underground in the Mozumi mine. It consists of a cylindrical stainless-steel tank (41.4 m tall and 39.3 m in diameter) holding 50,000,000 litres of ultra-pure water

Important message: Build very large detectors & wait for a very long time

Super-Kamiokande

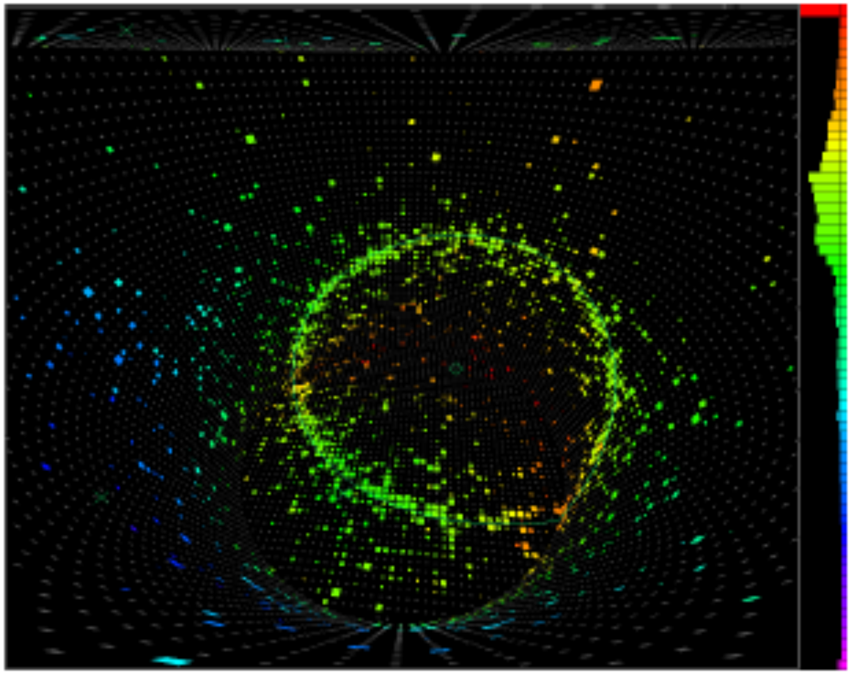
muon from ν_μ

(sharp outer edge)



electron from ν_e

(fuzzy ring)



- detector responsible for discovery of atmospheric ν oscillations (1998), being used for T2K to measure $\nu_\mu \rightarrow \nu_e$ oscillations with accelerator ν's

Golden Age of Neutrino Physics (1998 – 2022 & Beyond)

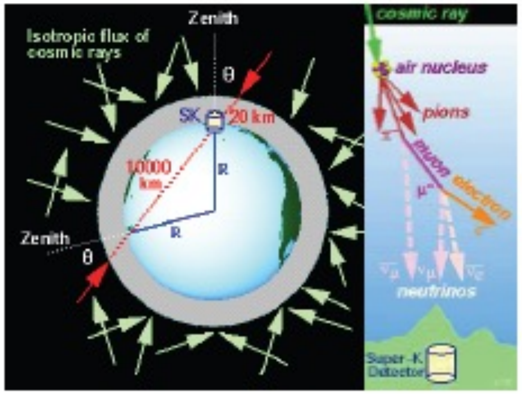
sun

Homestake,SAGE,GALLEX
SuperK, SNO, Borexino

reactors

KamLAND, CHOOZ
Double Chooz, Daya Bay, RENO

atmosphere



SuperKamiokande
IceCube, DeepCore

accelerators

K2K, MINOS, T2K
NOvA

Over the last two decades or so, marvelous data from world-class experiments

- Solar neutrinos (ν_e)
- Atmospheric neutrinos $(\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e)$
- Reactor anti-neutrinos $(\bar{\nu}_e)$
- Accelerator neutrinos $(\nu_\mu, \bar{\nu}_\mu)$

→

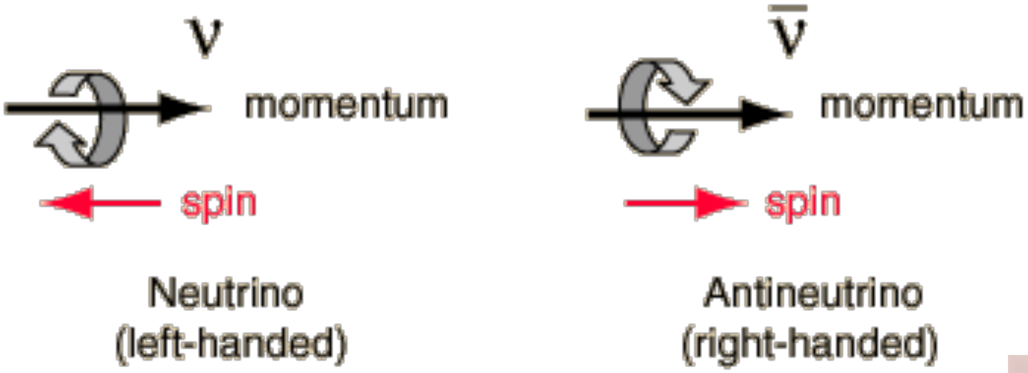
Data from various neutrino sources and vastly different energy and distance scales

↓

Neutrinos change their flavor as they move in space and time

We have just started our journey in the mysterious world of neutrinos

The Standard Model: Massless Neutrinos



Helicity is the projection of the spin onto the direction of momentum

- **Only left-handed neutrinos**
- **No right-handed neutrinos**
- **No Dirac mass term:**

$$m(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L)$$

Neutrinos are massless in the Basic SM

☐ Over the past decade, marvelous data from world class neutrino experiments firmly established that they change flavor after propagating a finite distance

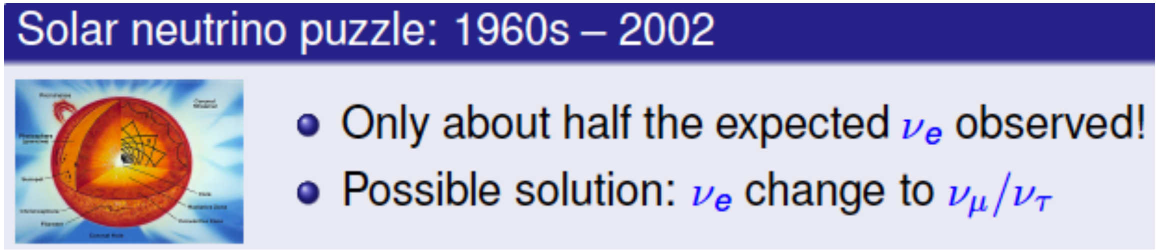
☐ Neutrino flavor change (oscillation) demands non-zero mass and mixing

Non-zero ν mass: first experimental proof for physics beyond the Standard Model

!! An extension of the Standard Model is necessary !!

Discovery of Neutrino Oscillations: Neutrinos have mass

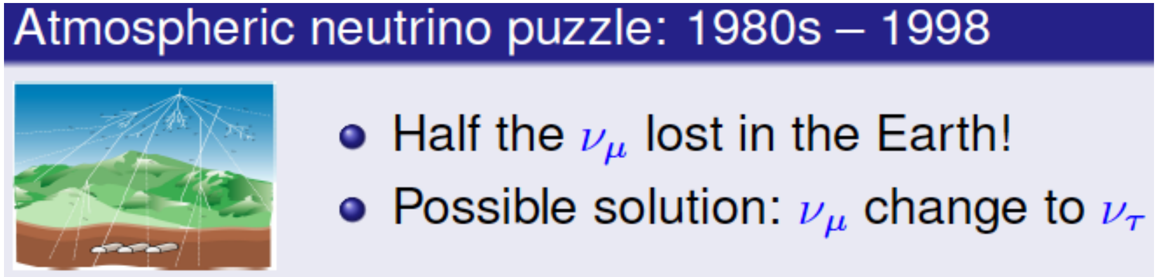
The Nobel Prize in Physics 2015



Solar neutrino puzzle: 1960s – 2002

- Only about half the expected ν_e observed!
- Possible solution: ν_e change to ν_μ/ν_τ

Arthur B. McDonald solved this puzzle at SNO



Atmospheric neutrino puzzle: 1980s – 1998

- Half the ν_μ lost in the Earth!
- Possible solution: ν_μ change to ν_τ

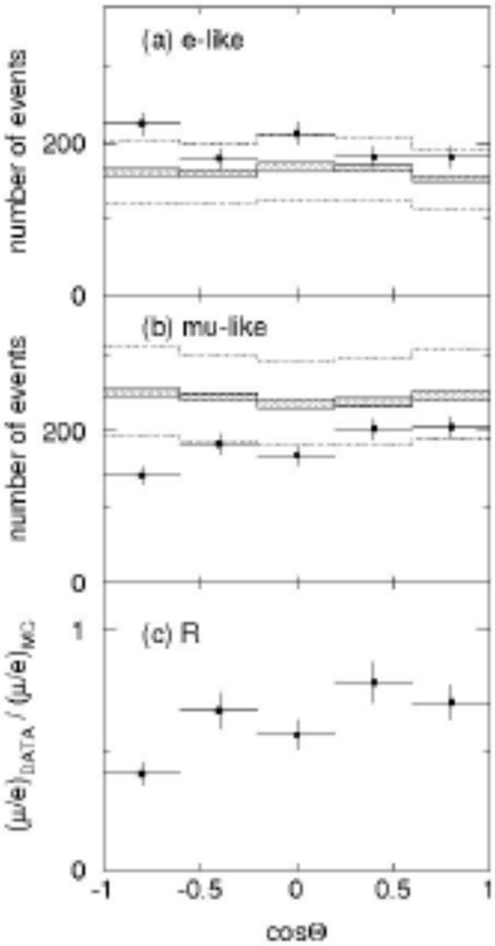
Takaaki Kajita solved this puzzle at Super-Kamiokande

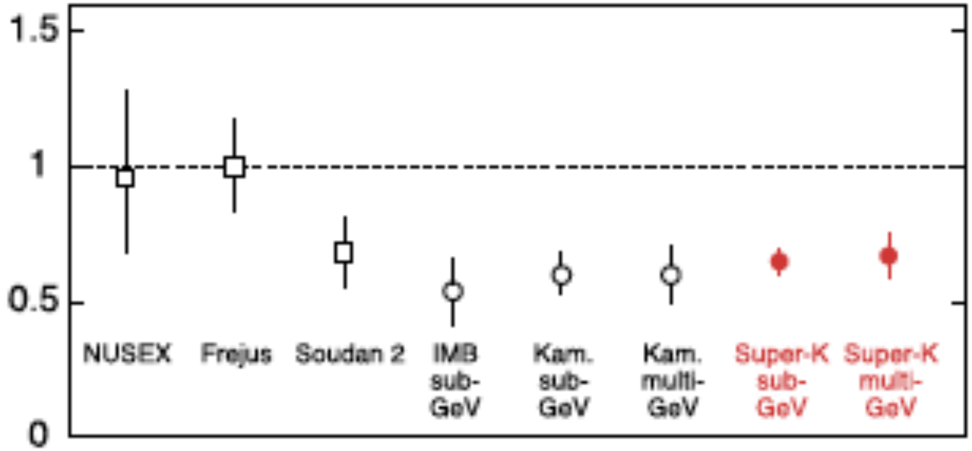
Neutrinos change their flavor ➔ Neutrinos have mass

Atmospheric Neutrino Anomaly

Super-Kamiokande

Double ratio:





$$R = \frac{(N_\mu/N_e)_{data}}{(N_\mu/N_e)_{MC}}$$

- Expected $R = 1$
- Observed $R < 1$

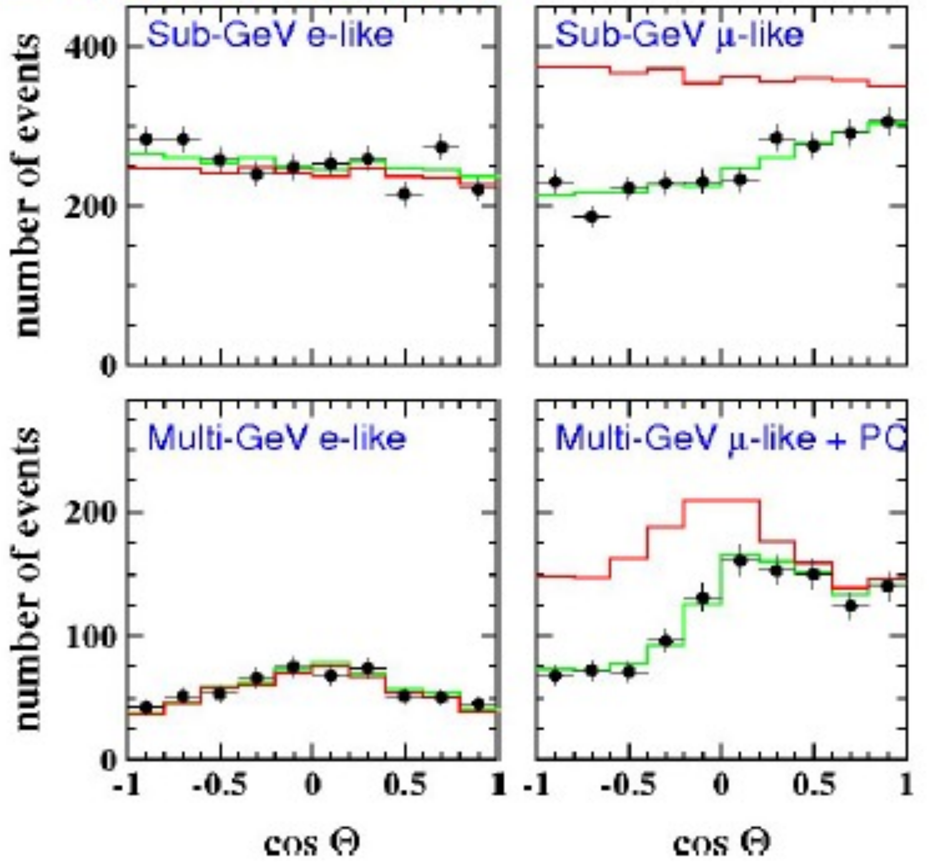
Year 1988:

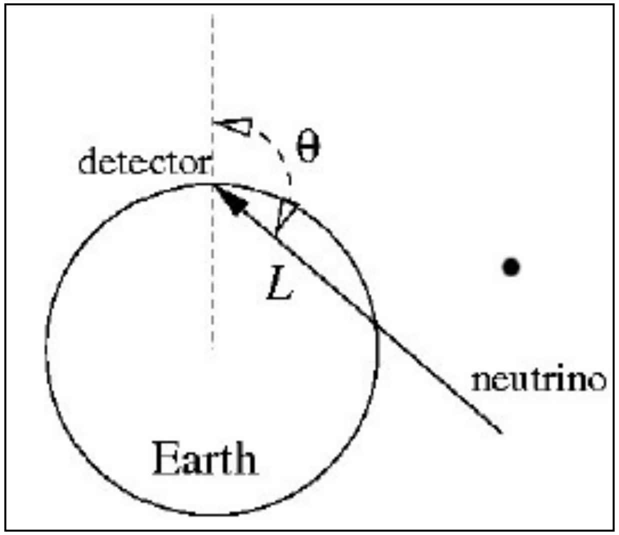
First results from Kamiokande on atmospheric neutrino anomaly

K.S. Hirata, et al., Experimental study of the atmospheric neutrino flux, Phys. Lett. B 205 (1988) 416.

Atmospheric Neutrino Anomaly

Superkamiokande:





- Electron neutrinos match predictions
- High energy ν_μ from above: match predictions
- High energy ν_μ through the earth: partially lost
- Low energy ν_μ: lost even when coming from above, loss while passing through the Earth even greater

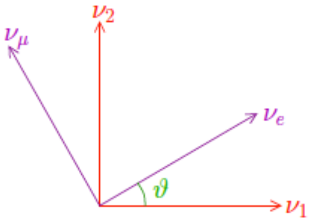
Zenith angle dependence

Neutrino Flavor Oscillations

- ➢ **Flavor States :** ν_e and ν_μ (produced in Weak Interactions)
- ➢ **Mass Eigenstates :** ν_1 and ν_2 (propagate from Source to Detector)

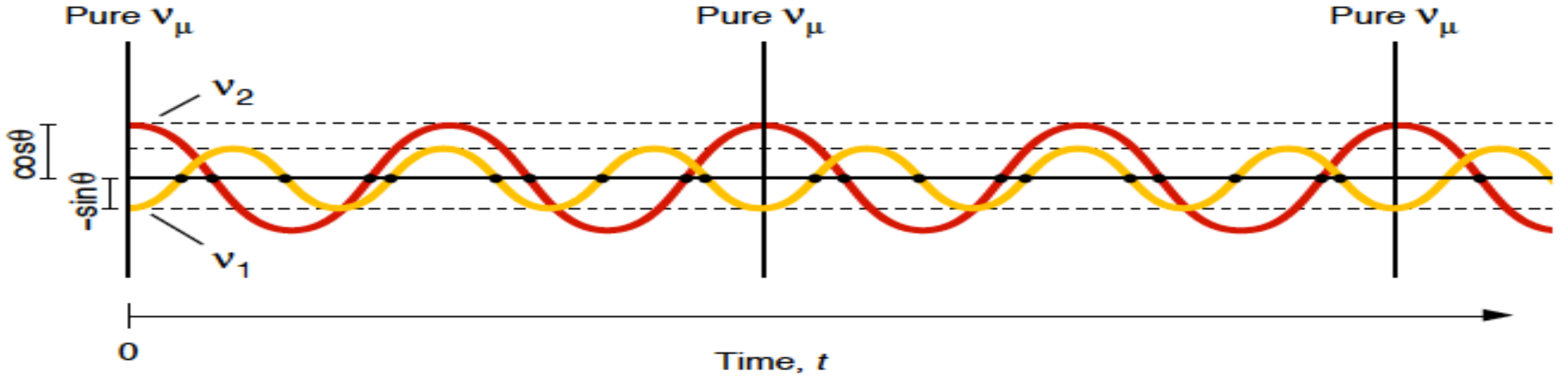
A Flavor State is a linear superposition of Mass Eigenstates

$$|\nu_\alpha\rangle = \sum_{k=1}^{2} U_{\alpha k}\,|\nu_k\rangle \qquad (\alpha = e, \mu)$$



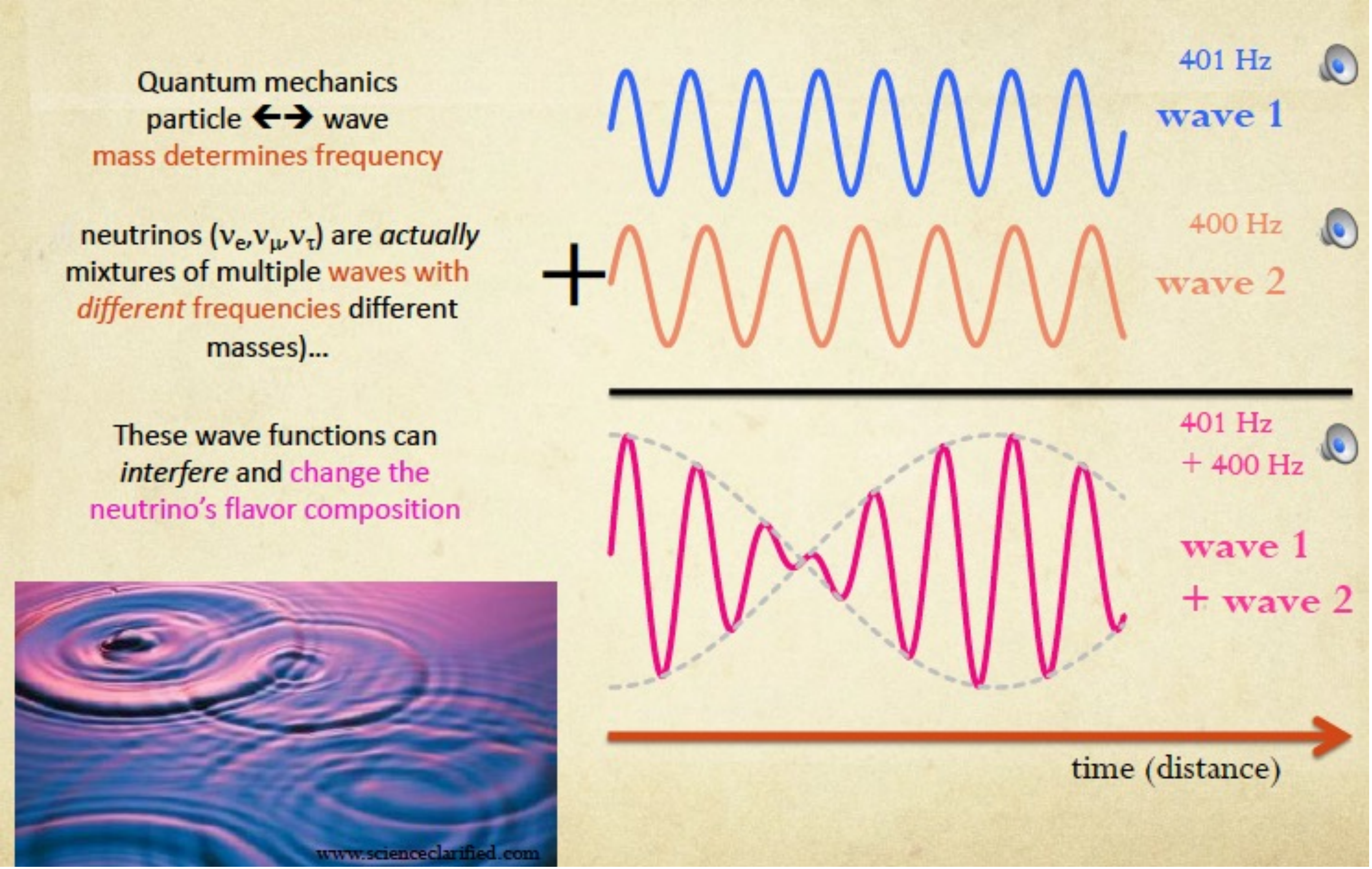
$$U = \begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix}$$

$$|\nu_e\rangle = \cos\vartheta\,|\nu_1\rangle + \sin\vartheta\,|\nu_2\rangle$$
$$|\nu_\mu\rangle = -\sin\vartheta\,|\nu_1\rangle + \cos\vartheta\,|\nu_2\rangle$$



If the masses of these two states are different, then they will take different times to reach the same point and there will be a phase difference and hence interference

Neutrino Flavor Oscillations



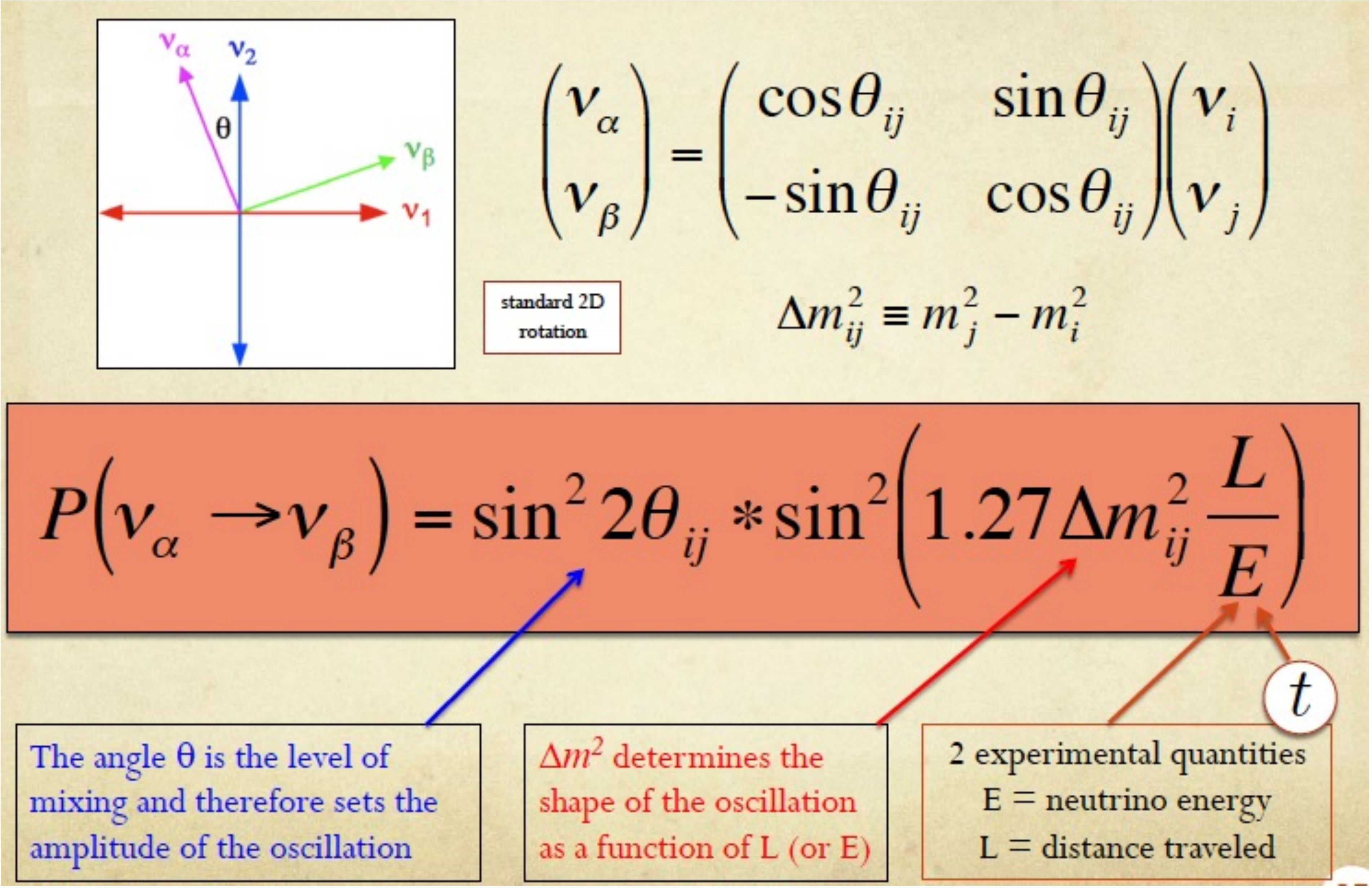
Quantum mechanics
particle ←→ wave
mass determines frequency

neutrinos (ν_e,ν_μ,ν_τ) are *actually* mixtures of multiple waves with *different* frequencies different masses)...

These wave functions can *interfere* and change the neutrino's flavor composition

www.scienceclarified.com

Two Neutrino Mixing



$$\begin{pmatrix}\nu_\alpha\\ \nu_\beta\end{pmatrix} = \begin{pmatrix}\cos\theta_{ij} & \sin\theta_{ij}\\ -\sin\theta_{ij} & \cos\theta_{ij}\end{pmatrix}\begin{pmatrix}\nu_i\\ \nu_j\end{pmatrix}$$

standard 2D rotation

$$\Delta m^2_{ij} \equiv m^2_j - m^2_i$$

$$P\left(\nu_\alpha \to \nu_\beta\right) = \sin^2 2\theta_{ij} * \sin^2\left(1.27\,\Delta m^2_{ij}\frac{L}{E}\right)$$

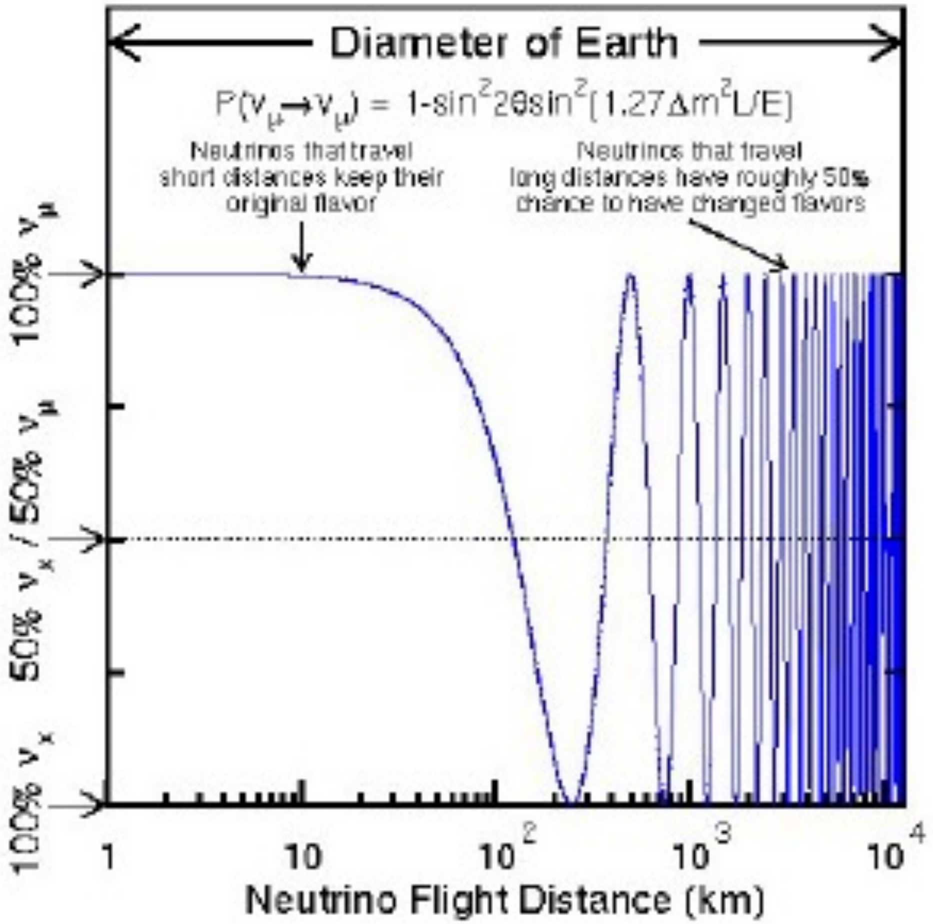
t

The angle θ is the level of mixing and therefore sets the amplitude of the oscillation

Δm^2 determines the shape of the oscillation as a function of L (or E)

2 experimental quantities
E = neutrino energy
L = distance traveled

Neutrino oscillation as a function of distance travelled



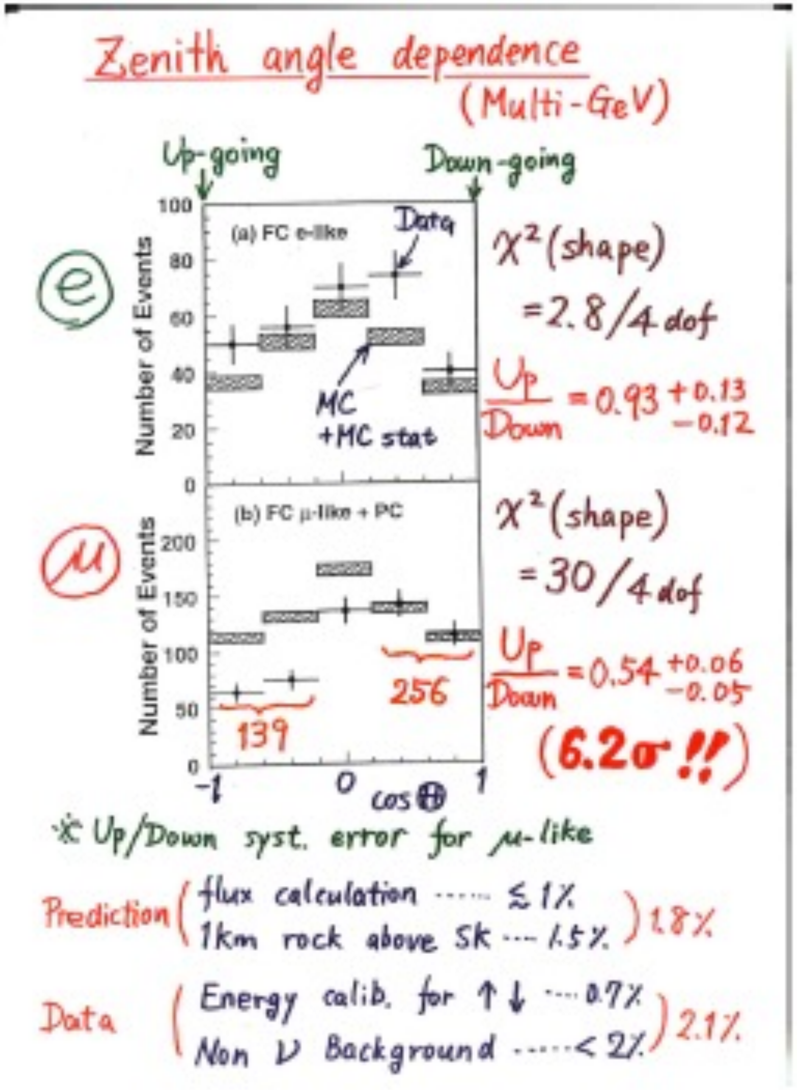
- More neutrinos 'lost" when cos(Θ) < 0

(Θ : angle made with the zenith)

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2\,(\mathrm{eV}^2)\;L\,(\mathrm{km})}{E\,(\mathrm{GeV})}\right)$$

Solution to the Atmospheric Neutrino Anomaly

- Indeed more ν_μ travelling through the Earth are lost
- The zenith angle dependence fits the form of the probability expressions exactly
- Neutrino oscillation hypothesis proved !



Zenith angle dependence
(Multi-GeV)

χ^2(shape) $= 2.8/4$ dof

$\frac{\text{Up}}{\text{Down}} = 0.93^{+0.13}_{-0.12}$

χ^2(shape) $= 30/4$ dof

$\frac{\text{Up}}{\text{Down}} = 0.54^{+0.06}_{-0.05}$

(6.2σ!!)

※ Up/Down syst. error for μ-like

Prediction (flux calculation …… ≲ 1%
1km rock above SK … 1.5%) 1.8%

Data (Energy calib. for ↑↓ …… 0.7%
Non ν Background ……< 2%) 2.1%

Three Neutrino Mixing

Three neutrino mixing firmly established…

Leptonic Mixing Matrix

flavor states
participating in
standard weak
interactions

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

neutrino
mass states

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Atmospheric &
Long-baseline accelerator
neutrinos

Quasi
2-neutrino
mixing

Solar &
Long-baseline reactor
neutrinos

$$L/E = 500 \text{ km/GeV}$$

$$\Delta m^2_{31} \sim 2.5 \times 10^{-3} \text{ eV}^2$$

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta_{ij} * \sin^2\left(1.27 \Delta m^2_{ij} \frac{L}{E}\right)$$

$$L/E = 15,000 \text{ km/GeV}$$

$$\Delta m^2_{21} \sim 7.6 \times 10^{-5} \text{ eV}^2$$

Some Things We Know and Don't Know

Three neutrino mixing firmly established...

$$\theta_{12} \approx 34^\circ$$

$$\theta_{23} \approx 45^\circ$$

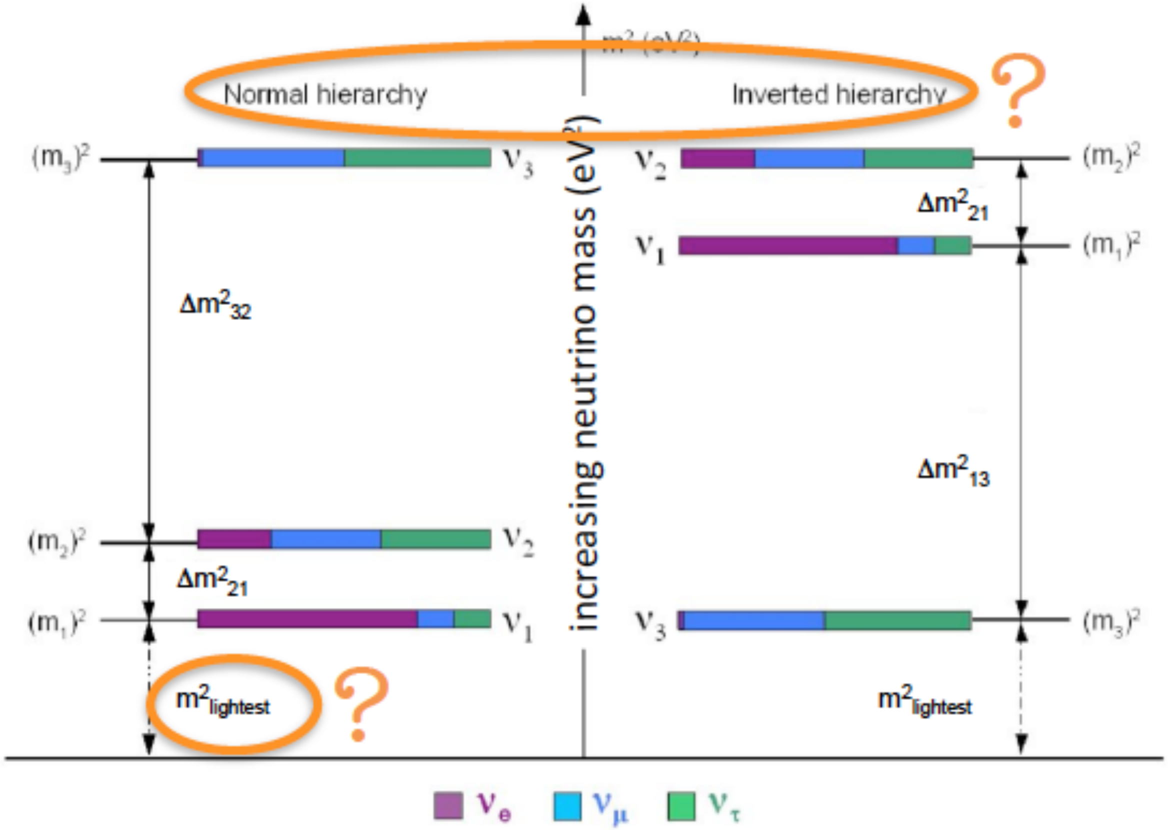
$$\theta_{13} \approx 9^\circ$$

$$\Delta m^2_{21} \approx 7.5 \times 10^{-5} eV^2$$

$$|\Delta m^2_{31}| \approx 2.4 \times 10^{-3} eV^2$$

$$\delta_{CP} = \; ?$$

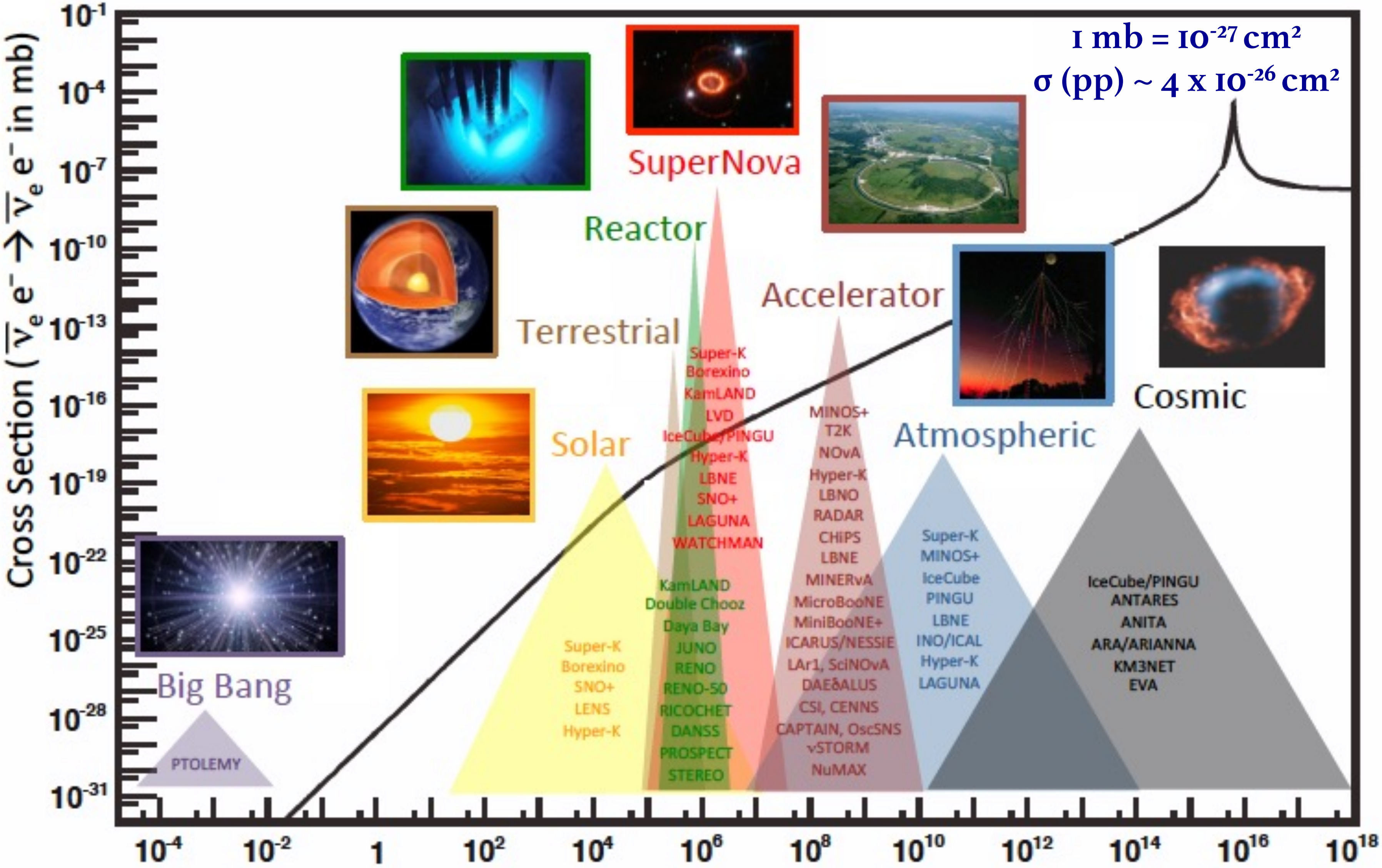
?



flavor content of the mass eigenstates determined by mixing matrix elements (mixing angles) that are measured experimentally

Extra Slides

Neutrinos are omnipresent: Friends across 23 orders of magnitude



1 mb = 10^{-27} cm^2

σ (pp) ~ 4 x 10^{-26} cm^2

$$\sigma \sim 2 m_e G_F^2 E_{\bar{\nu}} (\hbar c)^2$$

$$\sim 10^{-43} \left(\frac{E_{\bar{\nu}}}{\text{MeV}} \right) \text{cm}^2$$

σ(1 MeV) ~ 10^{-43} cm^2, σ(1 GeV) ~ 10^{-40} cm^2

J. L. Hewett et al., arXiv:1310.4340v1, Snowmass 2013 Neutrino Working Group

Neutrino Physics: An Exercise in Patience

Three most fundamental questions were being asked in the past century…

1. How tiny is the neutrino mass? (Pauli, Fermi, ’30s)

Planck + BAO + WMAP polarization data: upper limit of 0.23 eV for the sum of ν masses

Planck Collaboration, arXiv:1303.5076 [astro-ph.CO]

2. Can a neutrino turn into its own antiparticle? (Majorana, ’30s)

Hunt for ν-less Double-β decay (Z,A → Z+2, A) is still on, demands lepton number violation

Nice Review by Avignone, Elliott, Engel, Rev.Mod.Phys. 80 (2008) 481-516

3. Do different ν flavors ‘oscillate’ into one another? (Pontecorvo, Maki-Nakagawa-Sakata, ’60s)

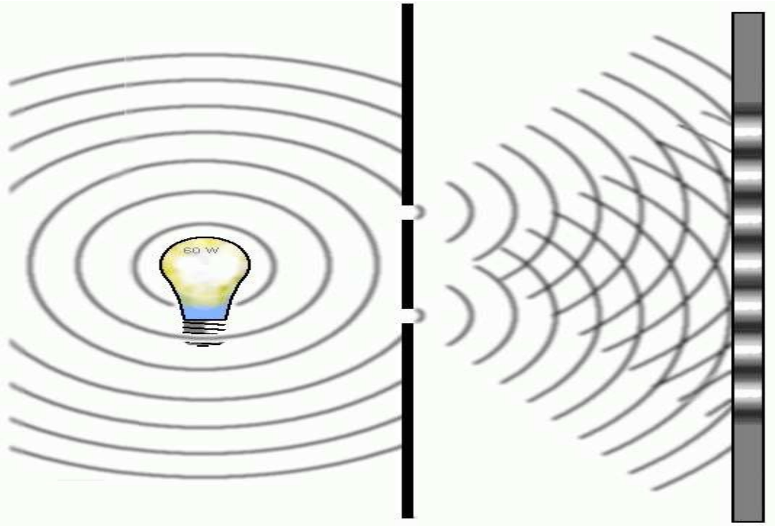
B. Pontecorvo, Sov. Phys. JETP 26, 984 (1968) [Zh. Eksp. Teor. Fiz. 53, 1717 (1967)]

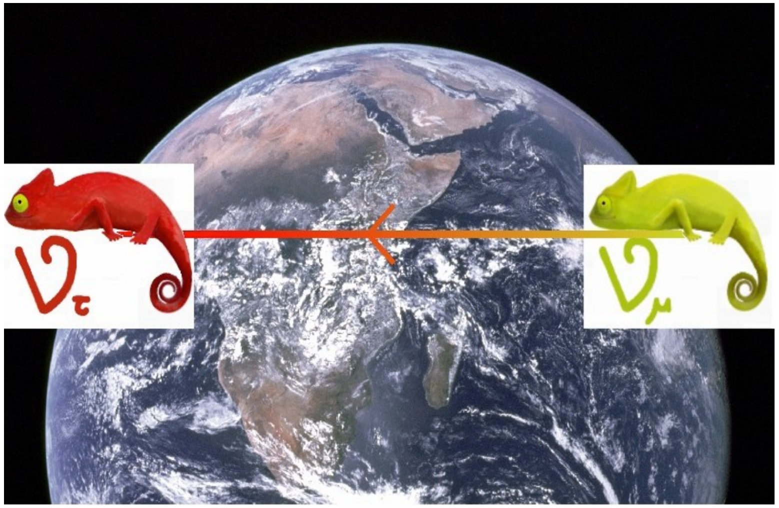
Last question positively answered only in recent years. Now an established fact that **neutrinos are massive** and leptonic flavors are not **symmetries of Nature**

After the measurement of $\boldsymbol{\theta_{13}}$, a clear first order picture of the three-flavor lepton mixing matrix has emerged, signifies a major breakthrough in ν physics

Neutrino Flavor Oscillations

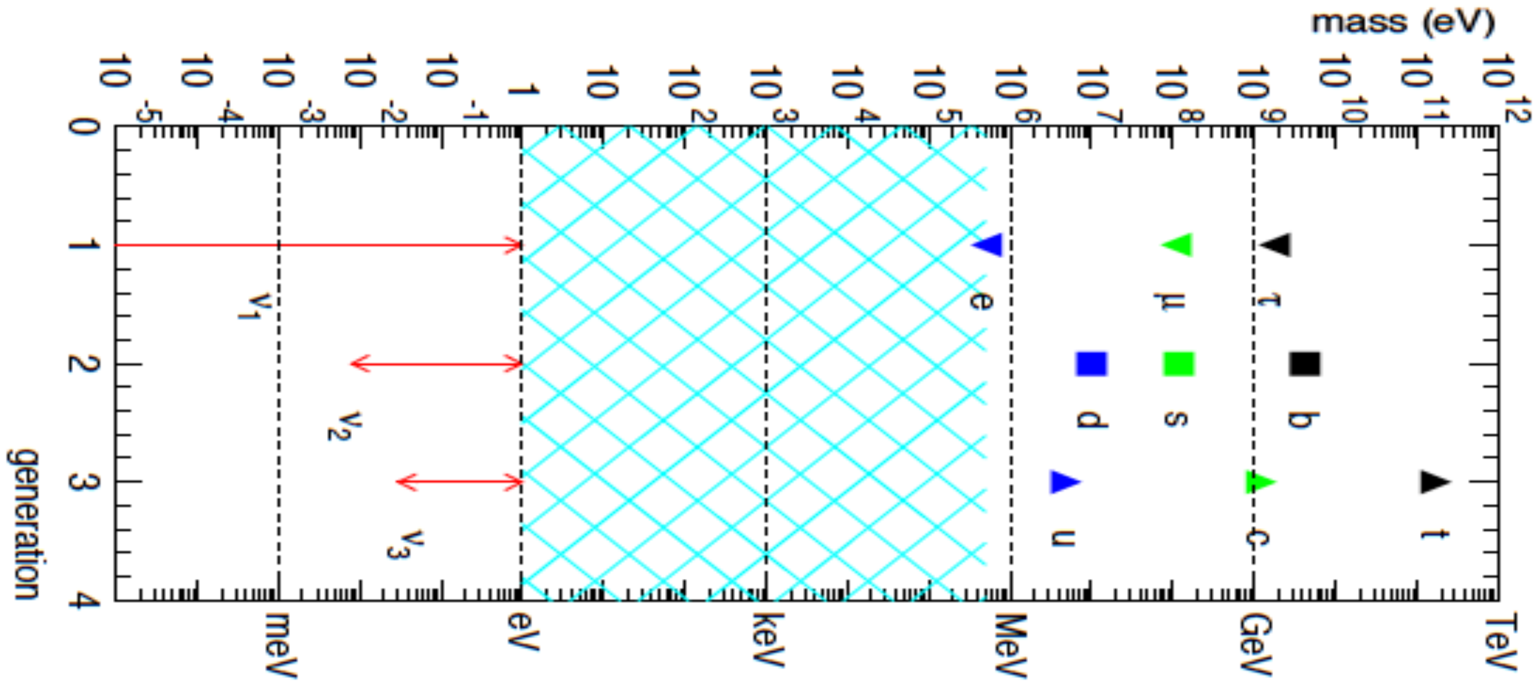
1957: Bruno Pontecorvo proposed Neutrino Oscillations in analogy with $K^0 \leftrightarrows \bar{K}^0$ oscillations (Gell-Mann and Pais, 1955)





- **Neutrino oscillation: Quantum Mechanical interference phenomenon**
- **Like electrons in the double slit experiment**
- **In Neutrino Oscillation: Neutrino changes flavor as it propagates**
- **It happens if neutrinos have masses (non-degenerate) and they mix with each other**

The Two Fundamental Questions



Why are neutrinos so light? **The origin of Neutrino Mass!**

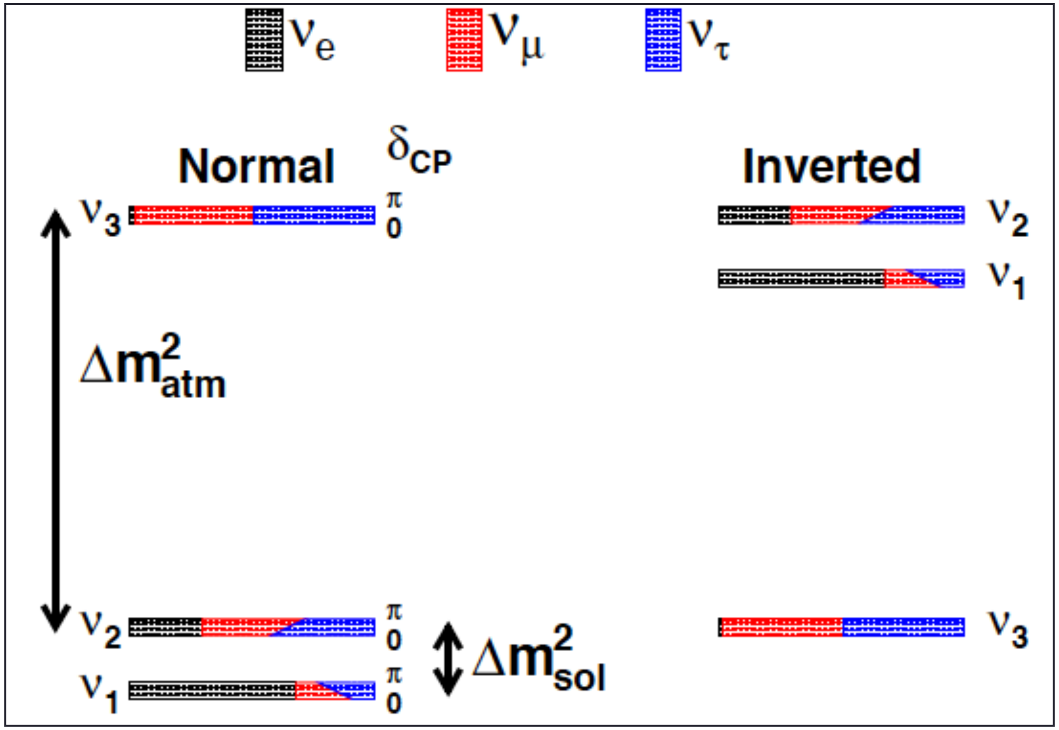
	Neutrinos (PMNS)	Quarks (CKM)
θ_{12}	35°	13°
θ_{32}	43°	2°
θ_{13}	9°	0.2°
δ	unknown	68°

Why are lepton mixings so different from quark mixings?

The Flavor Puzzle!

Neutrino Mass Ordering: Important Open Question

- The sign of Δm^2_{31} $(m_3^2 - m_1^2)$ is not known



Neutrino mass spectrum can be normal or inverted ordered

We only have a lower bound on the mass of the heaviest neutrino

$$\boxed{\sqrt{2.5\cdot 10^{-3}\mathrm{eV}^2} \sim 0.05\ \mathrm{eV}}$$

We currently do not know which neutrino is the heaviest

$$\boxed{|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2}$$

ν_e component of ν_1 > ν_e component of ν_2 > ν_e component of ν_3

Mass Ordering Discrimination : A Binary yes-or-no type question

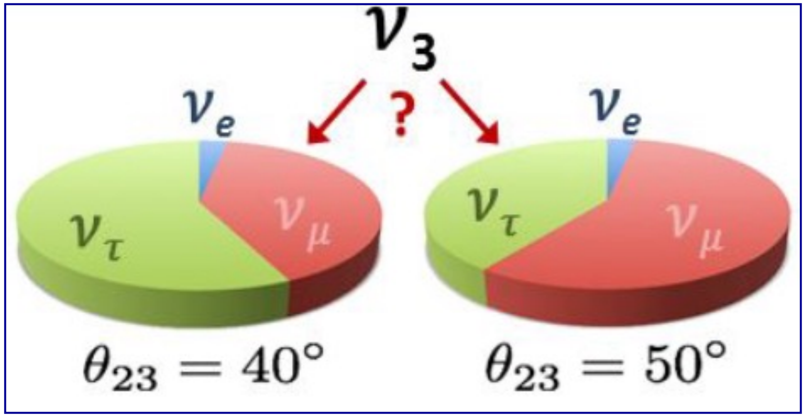
Octant of 2-3 Mixing Angle: Important Open Question

→ *In ν_μ survival probability, the dominant term is mainly sensitive to $\sin^2 2\theta_{23}$*

→ *If $\sin^2 2\theta_{23}$ differs from 1 (recent hints), we get two solutions for θ_{23}*

→ *One in lower octant (LO: $\theta_{23} < 45$ degree)*

→ *Other in higher octant (HO: $\theta_{23} > 45$ degree)*



Octant ambiguity of θ_{23}

Fogli and Lisi, hep-ph/9604415

ν_μ to ν_e oscillation channel can break this degeneracy
preferred value would depend on the choice of neutrino mass ordering

Leptonic CP-violation: Important Open Question

Is CP violated in the neutrino sector, as in the quark sector?

Mixing can cause CPV in neutrino sector, provided $\delta_{CP} \neq 0^\circ$ *and* 180°

Need to measure the CP-odd asymmetries:

$$\Delta P_{\alpha\beta} \equiv P(\nu_\alpha \to \nu_\beta;\, L) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta;\, L) \quad (\alpha \neq \beta)$$

$$\Delta P_{e\mu} = \Delta P_{\mu\tau} = \Delta P_{\tau e} = 4J_{CP} \times \left[\sin\left(\frac{\Delta m^2_{21}}{2E}L\right) + \sin\left(\frac{\Delta m^2_{32}}{2E}L\right) + \sin\left(\frac{\Delta m^2_{13}}{2E}L\right)\right]$$

Jarlskog CP-odd Invariant → $J_{CP} = \frac{1}{8}\cos\theta_{13}\,\sin 2\theta_{13}\,\sin 2\theta_{23}\,\sin 2\theta_{12}\,\sin\delta_{CP}$

Three-flavor effects are key for CPV, need to observe interference

Conditions for observing CPV:

1) *Non-degenerate masses* ✔
2) *Mixing angles* $\neq 0^\circ$ *and* 90° ✔
3) $\delta_{CP} \neq 0^\circ$ *and* 180° *(Hints)*

Quark Mixing vs. Neutrino Mixing

$$V_{\mathrm{CKM}} = \begin{pmatrix} 0.97434^{+0.00011}_{-0.00012} & 0.22506 \pm 0.00050 & 0.00357 \pm 0.00015 \\ 0.22492 \pm 0.00050 & 0.97351 \pm 0.00013 & 0.0411 \pm 0.0013 \\ 0.00875^{+0.00032}_{-0.00033} & 0.0403 \pm 0.0013 & 0.99915 \pm 0.00005 \end{pmatrix}$$

PDG

$$|U|_{3\sigma} = \begin{pmatrix} 0.799 \to 0.844 & 0.516 \to 0.582 & 0.140 \to 0.156 \\ 0.234 \to 0.502 & 0.452 \to 0.688 & 0.626 \to 0.784 \\ 0.273 \to 0.527 & 0.476 \to 0.705 & 0.604 \to 0.765 \end{pmatrix}$$

(PMNS)

NuFIT 3.1 (2017)

The goal is to achieve the CKM level precision for the PMNS
A Long Journey Ahead! But the precision is improving rapidly for PMNS

Good News: There may be large CPV in neutrino sector than quark sector

$$J_{CP} = \frac{1}{8} \cos\theta_{13}\, \sin 2\theta_{13}\, \sin 2\theta_{23}\, \sin 2\theta_{12}\, \sin\delta_{CP}$$

$J_{\mathrm{CKM}} \sim 3 \times 10^{-5}$, whereas J_{PMNS} can be as large as 3×10^{-2}