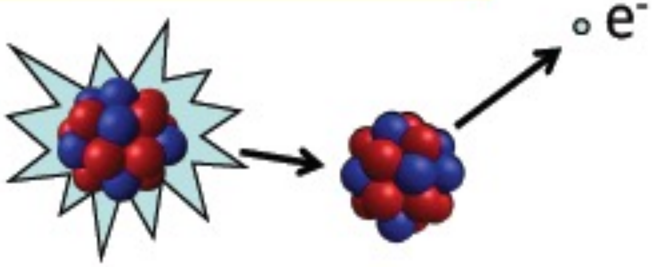
Neutrino Phenomenology

Sanjib Kumar Agarwalla
sanjib@iopb.res.in

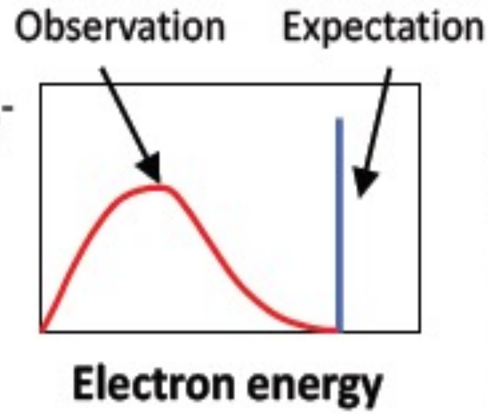
Institute of Physics, Bhubaneswar, India

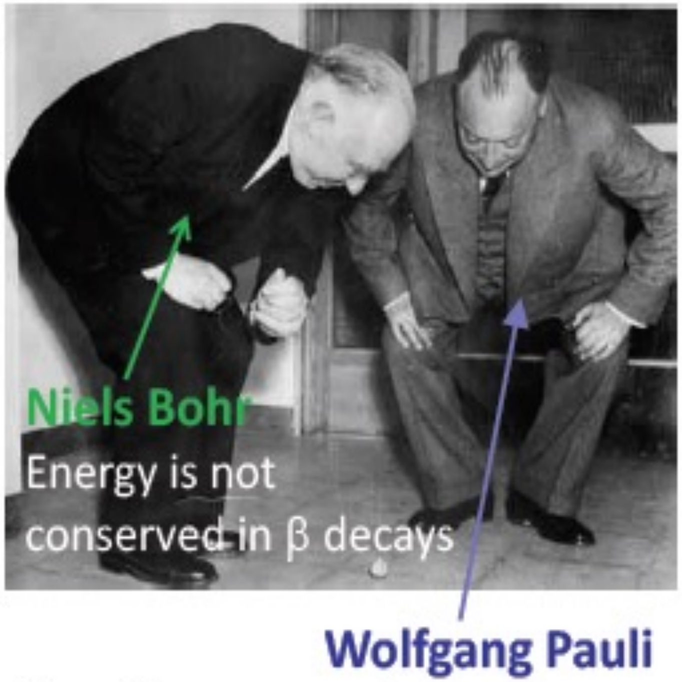
Mission Impossible: Detect Neutrinos

The problem (1914)

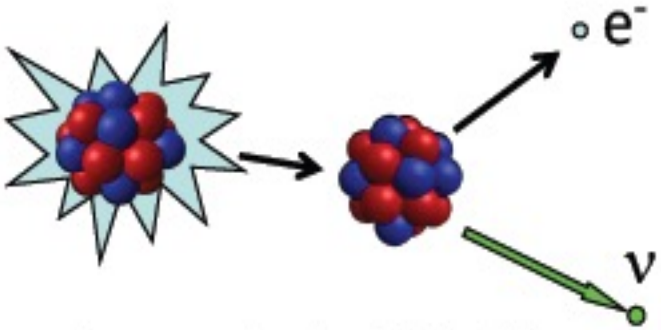


$n \rightarrow p + e^-$





The desperate remedy (1930)



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

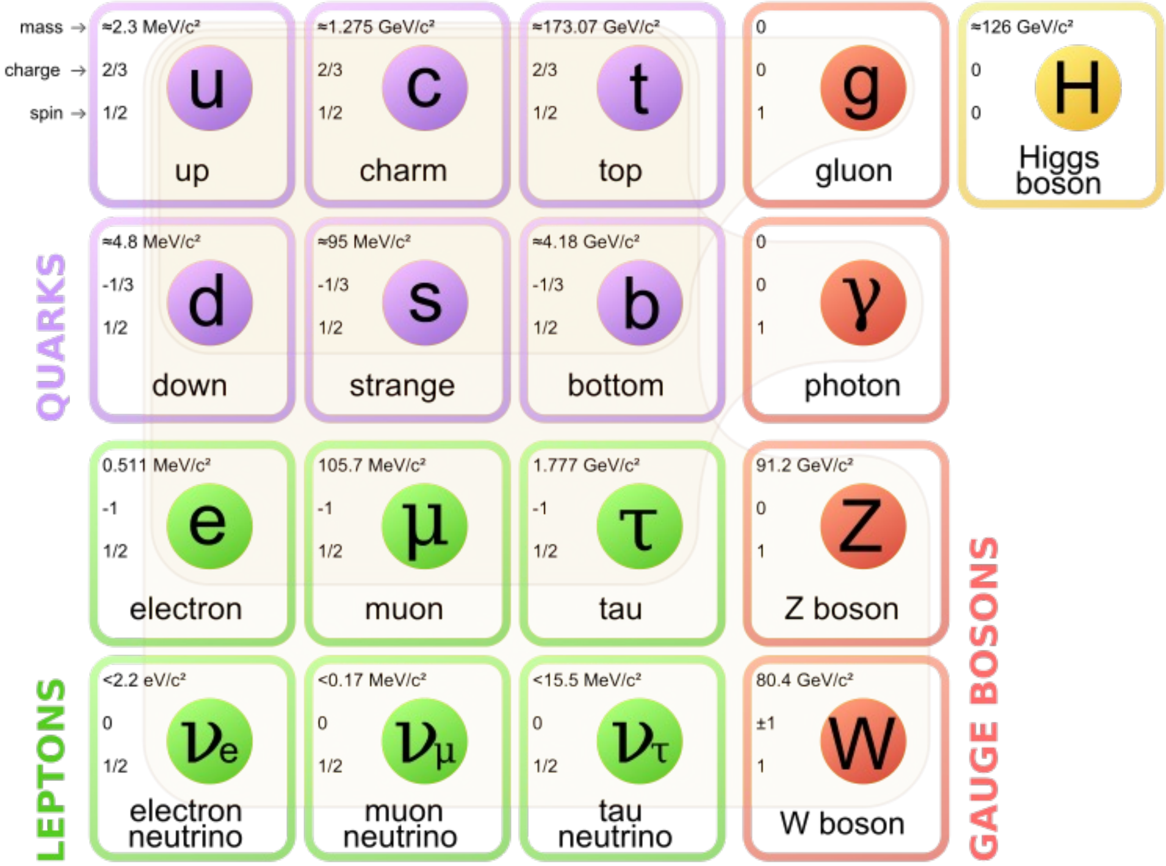
There is a neutral particle able to cross all detectors without leaving any trace and carrying all the missing energy

> *«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 in the Standard Model of Particle Physics

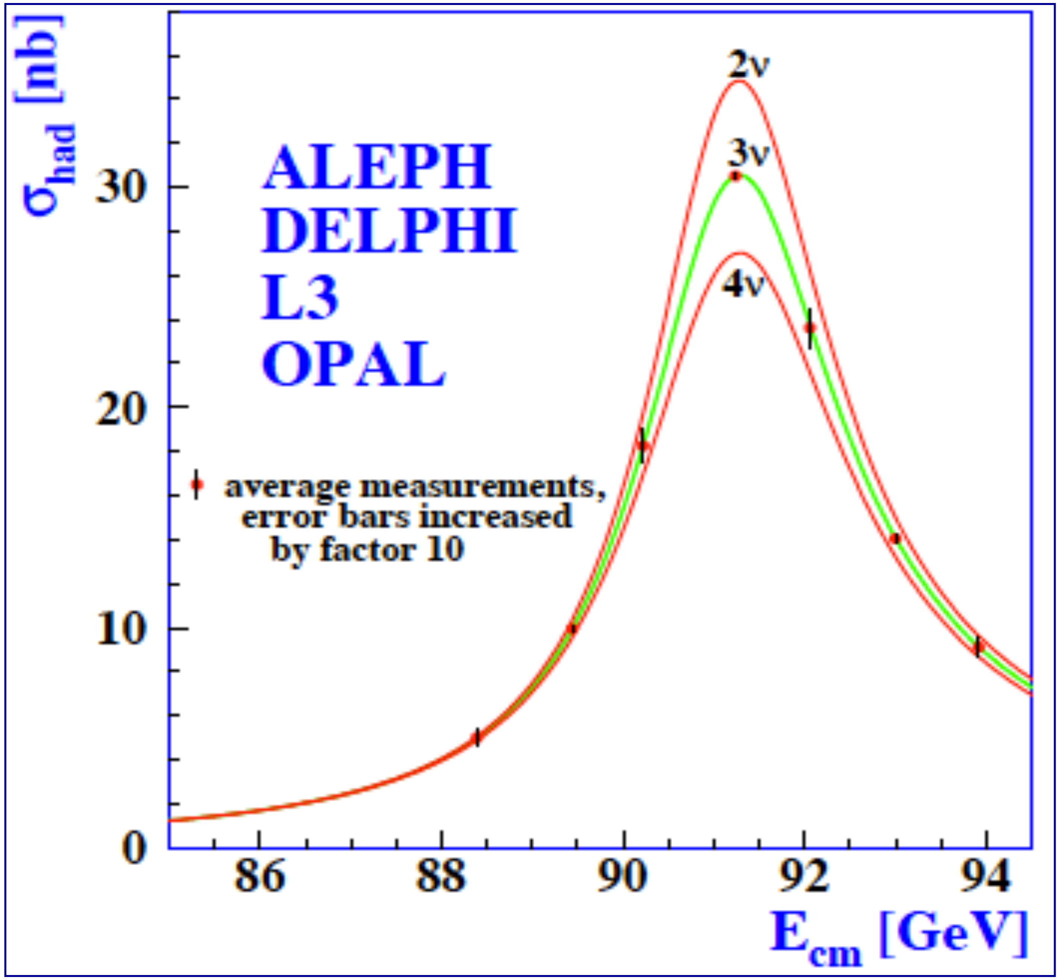


See lectures by Nhung Dao in this school

- **After photon, second most abundant particle**
- **Three active neutrinos:** ν_e , ν_μ , ν_τ
- **Zero charge (neutral)**
- **Spin 1/2**
- **Only couple to weak force**

  A lightyear of lead would stop only about half of the neutrinos coming from Sun
- **Almost massless: at least a million times lighter than electron**

Why 3 Weak Flavor States?



Precision data on the Z-decay width at the e^+e^- collider at LEP

$$e^+e^- \to Z \xrightarrow{\text{invisible}} \sum_{a=\text{active}} \nu_a \bar{\nu}_a$$

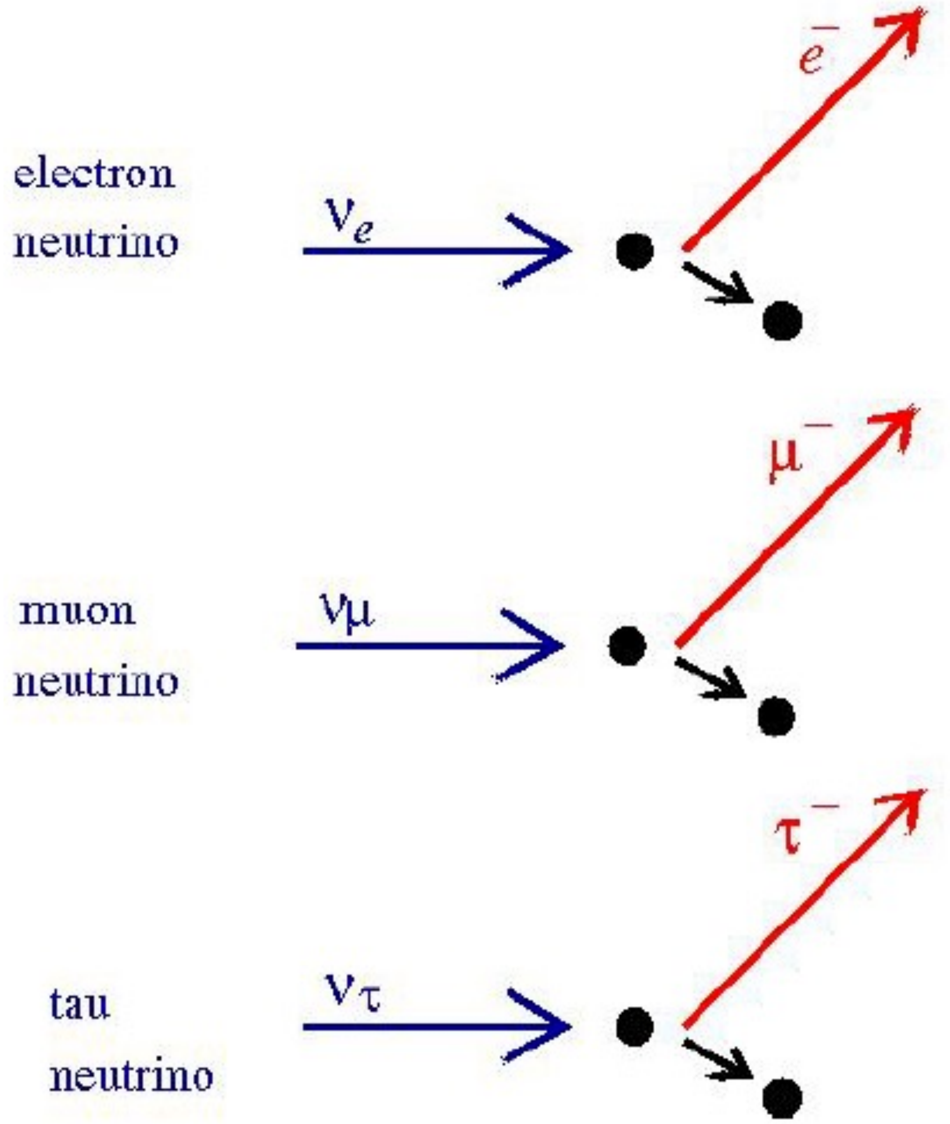
$$N_{\nu_{\text{active}}} = 2.9840 \pm 0.0082$$

[LEP, Phys. Rept. 427 (2006) 257, hep-ex/0509008]

3 light active flavor neutrinos

$\nu_e \;\; \nu_\mu \;\; \nu_\tau$

Three kinds (flavors) of neutrinos: ν_e ν_μ ν_τ



electron

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

muon

200 times heavier than electron

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

tau

3500 times heavier than electron

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

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

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:

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

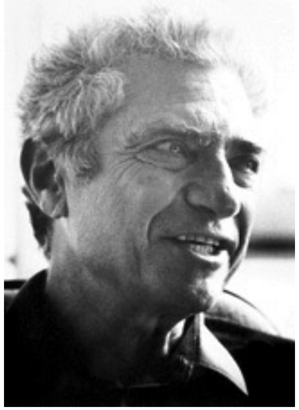
$$\nu_{(\mu)} + N \rightarrow N' + \mu^-$$

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

Nobel Prize in 1988

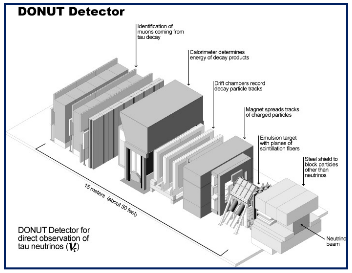

Leon M. Lederman


Melvin Schwartz


Jack Steinberger

- **Tau neutrino ν_τ : 2000**

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



Neutrinos are Omnipresent

Detected (1950s)

✓ **Nuclear Reactors**

Detected (1960s)

Sun ✓

Created & Detected (1960s)

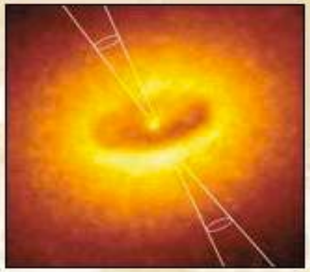
✓ **Particle Accelerators**

Detected (1980s)

Supernovae (Stellar Collapse)
SN 1987A ✓

Detected (1960s)

✓ **Earth Atmosphere (Cosmic Rays)**



First detection in 2013

IceCube found in 10 years 164 high-energy starting events w/ energies > 60 TeV

Astrophysical Accelerators **IceCube** ✓

Detected By KamLAND in 2005

✓ **Geoneutrino** **Earth Crust (Natural Radioactivity)**

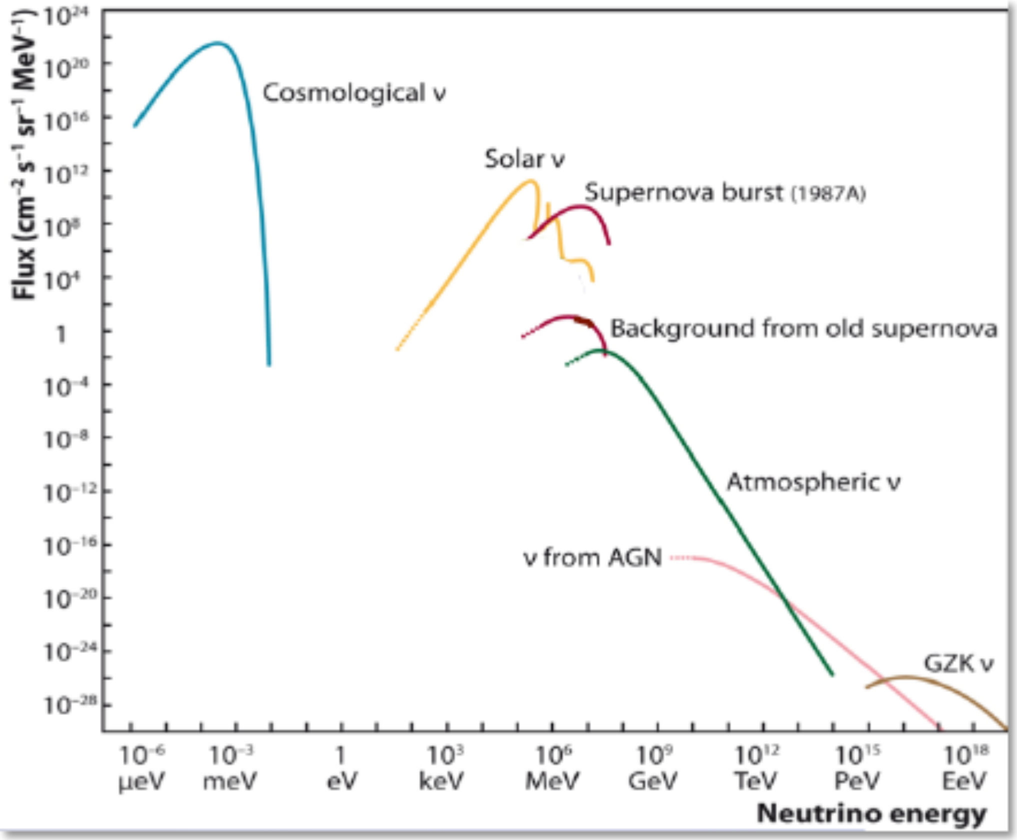
Not even close

Cosmic Big Bang (Today 330 ν/cm^3)
Indirect Evidence

Extremely rich and diverse neutrino physics program

Neutrinos From the Heavens

- neutrinos are unique messengers …



- they are not deflected by interstellar magnetic fields

  → *point back to their source*

- they rarely interact with matter

  → *arrive directly from regions where light cannot come*

- ν's carry information about the workings of the highest energy and most distant phenomenon in the univere

- "neutrino astronomy"

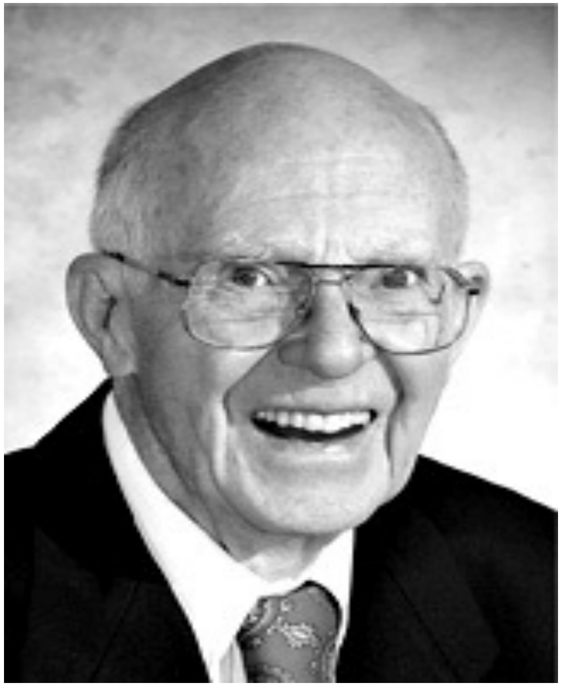
neutrinos from stars

$\underbrace{\text{supernova, solar,}}$ *atmospheric, and cosmic neutrinos*

The Greisen-Zatsepin-Kuzmin (GZK) limit: theoretical upper limit on the energy of protons traveling from other galaxies through the intergalactic medium to our galaxy

Detection of Low-Energy Cosmic Neutrinos

The Nobel Prize in Physics 2002



Raymod Davis Jr.

Detected Solar Neutrinos

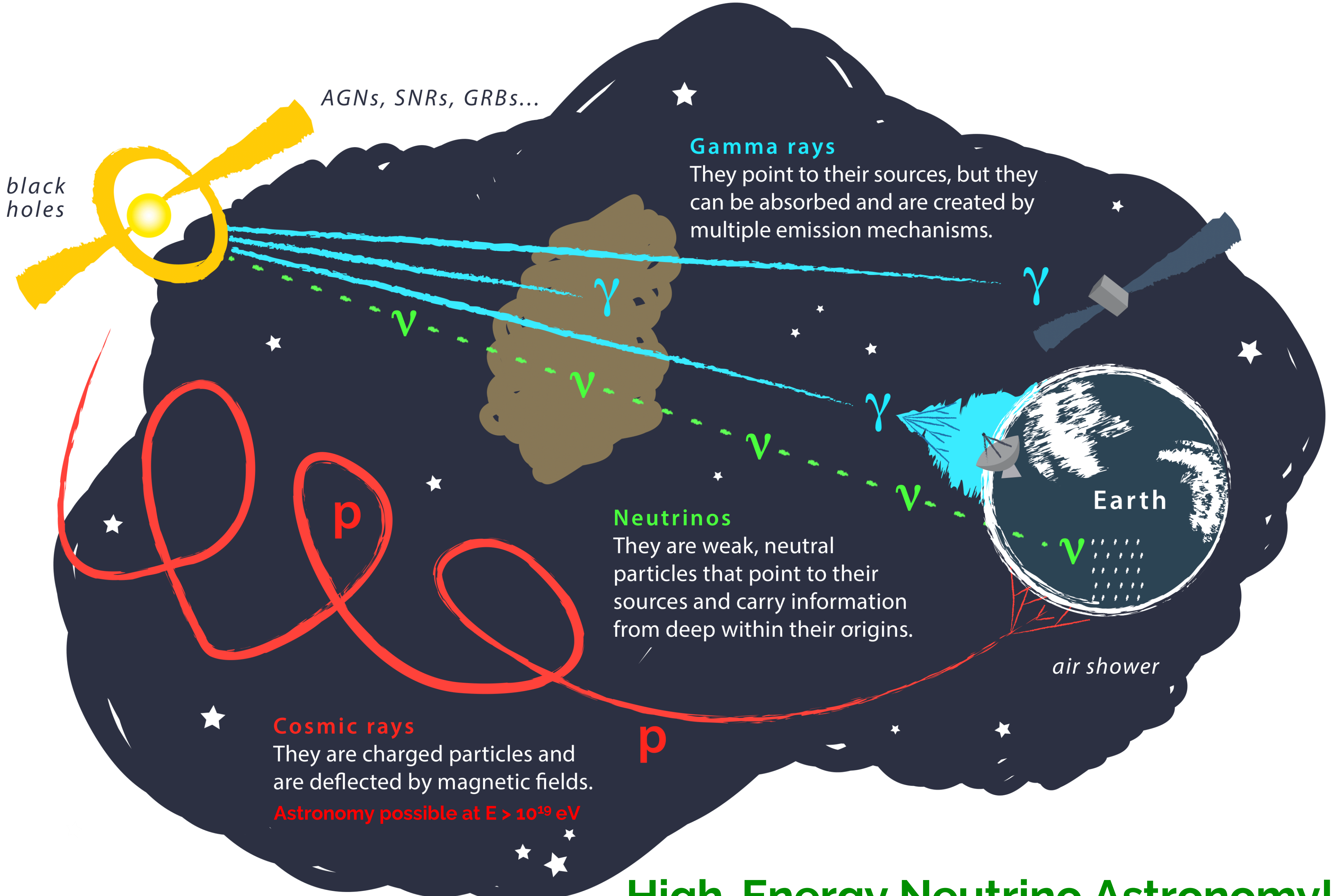
Masatoshi Koshiba

Detected Supernova Neutrinos

Detection of Cosmic Neutrinos ➔ A New Window on the Universe

Era of Low-Energy Neutrino Astronomy began!

Detection of High-Energy Cosmic Neutrinos



Gamma rays
They point to their sources, but they can be absorbed and are created by multiple emission mechanisms.

Neutrinos
They are weak, neutral particles that point to their sources and carry information from deep within their origins.

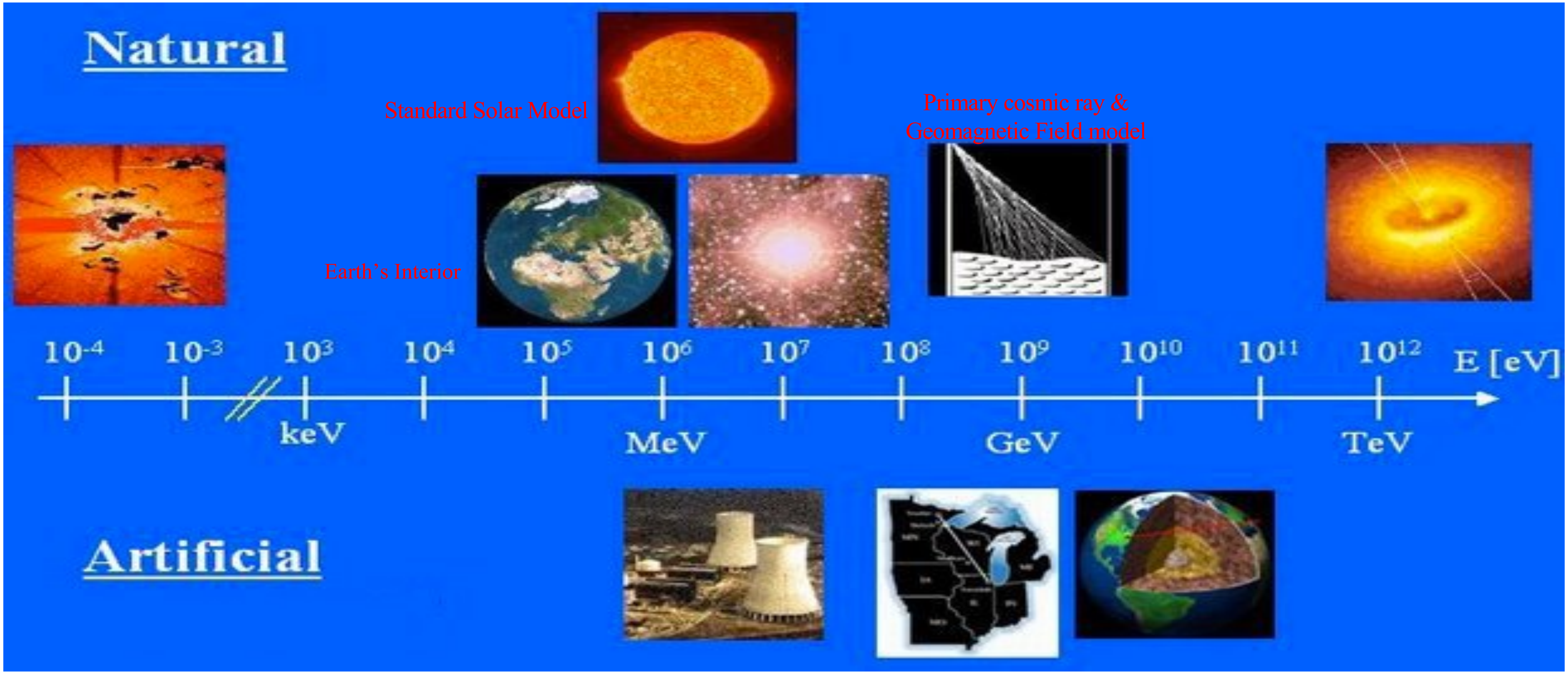
Cosmic rays
They are charged particles and are deflected by magnetic fields.
Astronomy possible at E > 10^{19} eV

High-Energy Neutrino Astronomy!

See lectures by Alba Domi in this school

Neutrinos: Exceptional Probe for Environments

Neutrino Observation: Go Beyond optical and radio observation

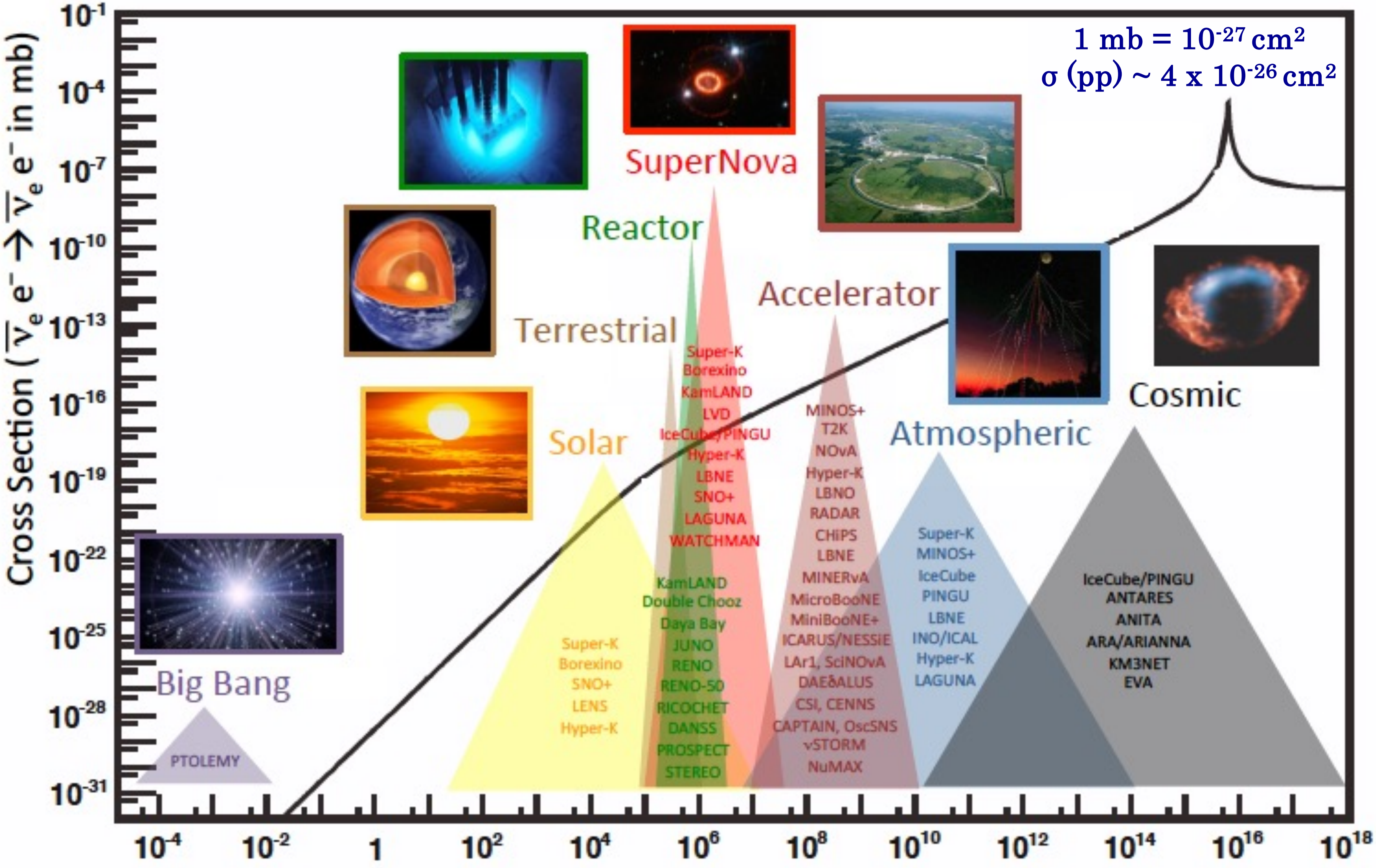


Detect neutrinos from the Sun, Supernovae, AGN, GRBs: Era of Neutrino Astronomy

ν detection involves several methods on surface, underground, under the sea, or in the ice

ν detector masses range from few kgs to megatons, with volumes from few m^3 to km^3

Neutrinos are ubiquitous: Friends across 23 orders of magnitude



1 mb = 10^{-27} cm^2
σ (pp) ~ 4 x 10^{-26} cm^2

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

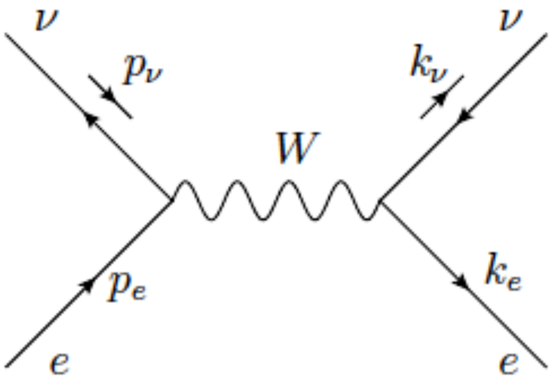
σ(1 MeV) ~ 10^{-43} cm^2, σ(1 GeV) ~ 10^{-40} cm^2

Neutrino Energy (eV)

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

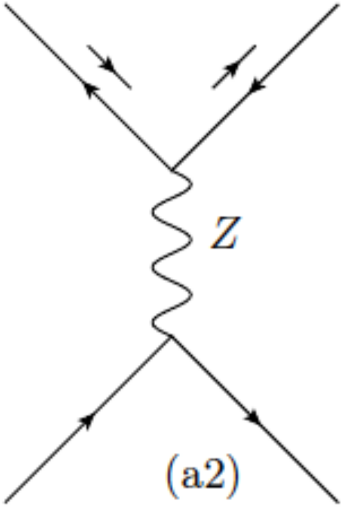
Neutrino – Electron Scattering

See lectures by Nhung Dao and Ngoc Tran in this school



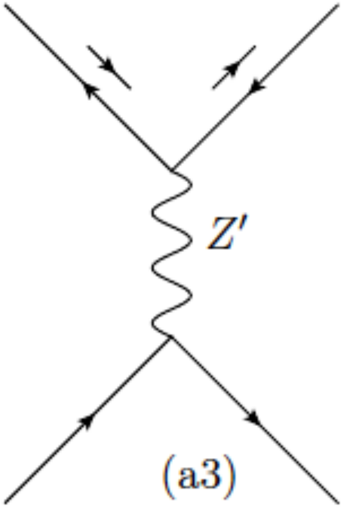
(a1)

$\overline{\nu}_e + e^- \to \overline{\nu}_e + e^-$



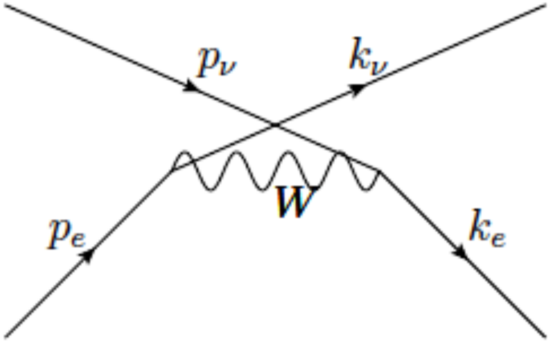
(a2)

$\overline{\nu}_\alpha + e^- \to \overline{\nu}_\alpha + e^-$



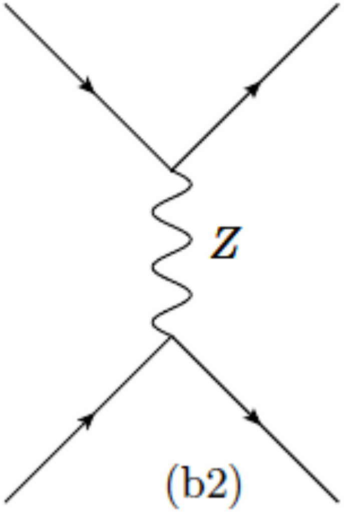
(a3)

$\overline{\nu}_\alpha + e^- \to \overline{\nu}_\alpha + e^-$



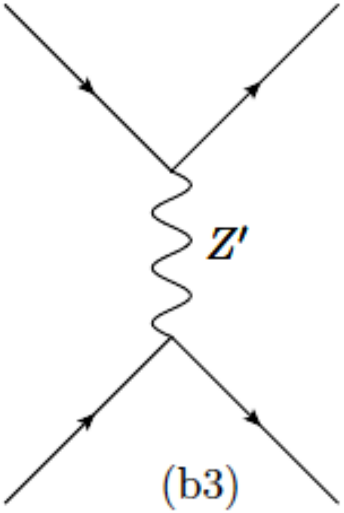
(b1)

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



(b2)

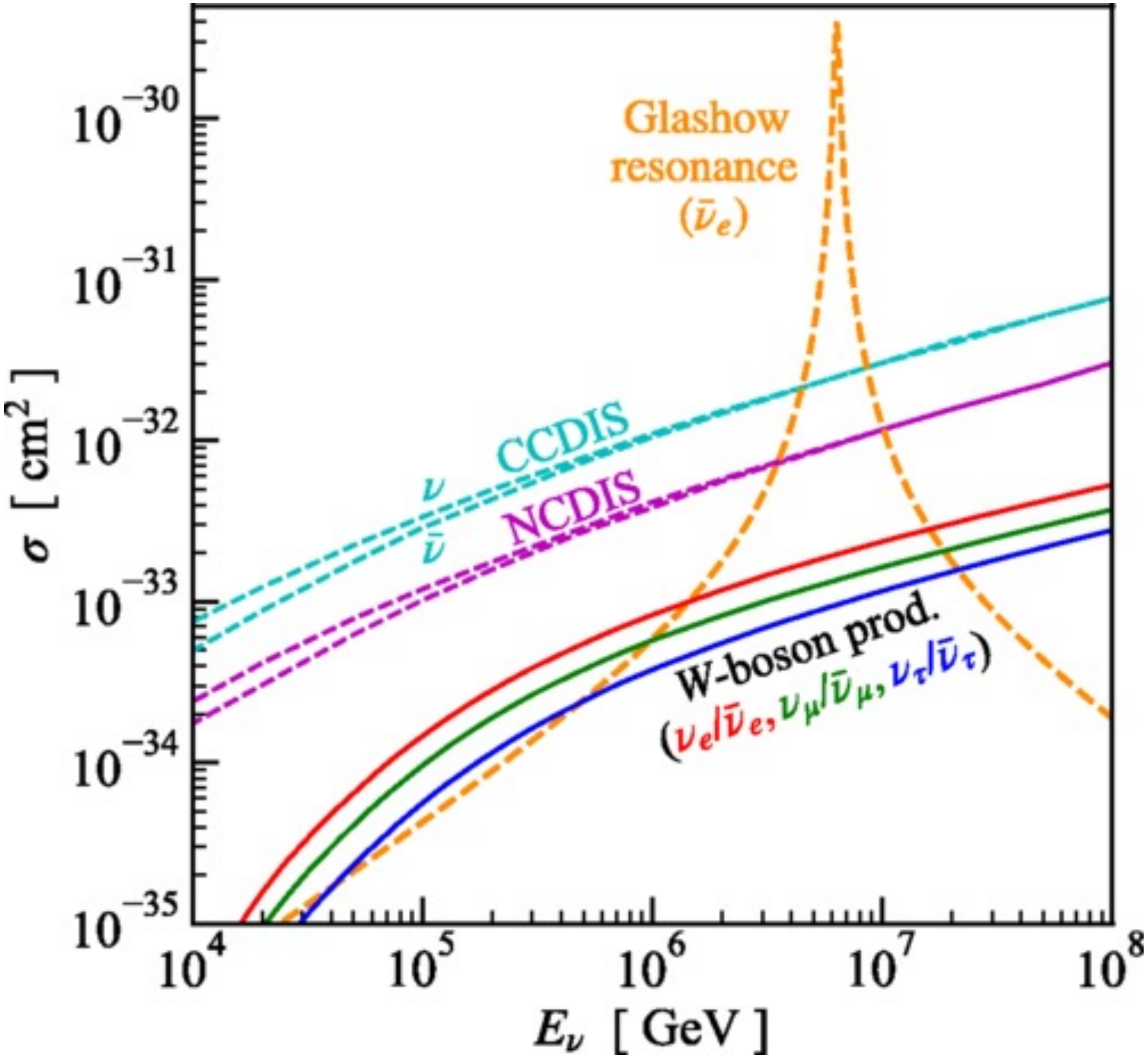
$\nu_\alpha + e^- \to \nu_\alpha + e^-$



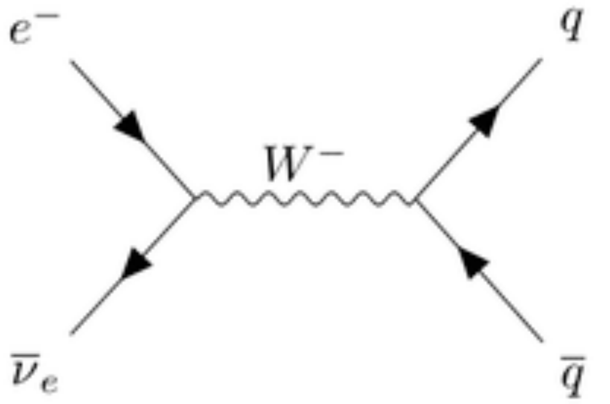
(b3)

$\nu_\alpha + e^- \to \nu_\alpha + e^-$

Glashow Resonance



Cross sections between neutrinos and ^{16}O for W-boson production, compared to those for charged-current (CC) and neutral current (NC) deep inelastic scattering (DIS), and the predicted Glashow resonance
Phys. Rev. D 101, 036010 (2020)

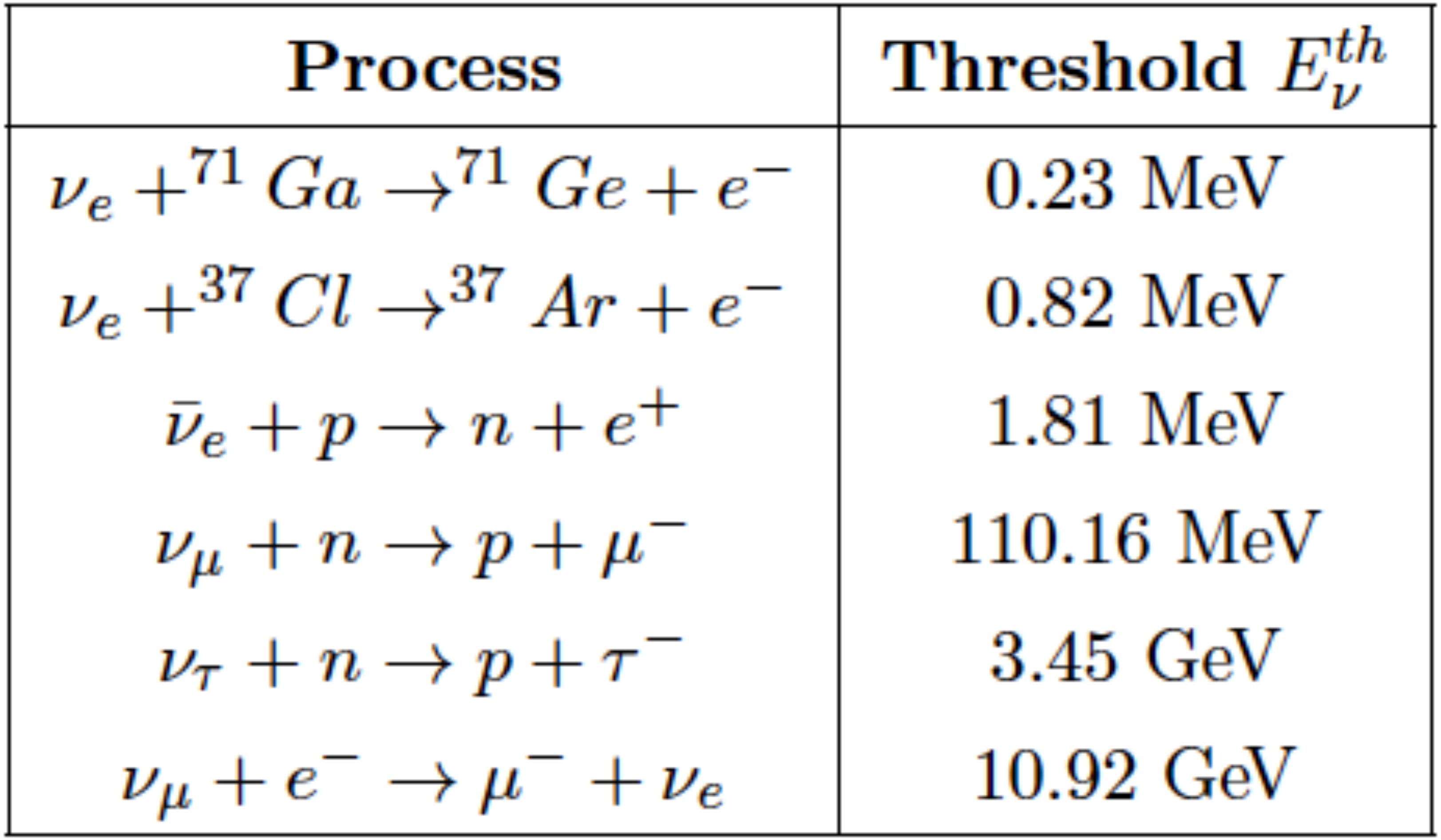


Feynman diagram of the Glashow resonance

The Glashow resonance, put forward by Sheldon L. Glashow in 1959, is the resonant formation of the W boson in electron antineutrino and electron scattering process. The threshold energy needed for neutrino for this process is 6.3 PeV when the electron is at rest in the lab frame. This process is being used to detect and study the high energy cosmic neutrinos in the IceCube experiment.

2021: Detection of a particle shower at the Glashow resonance with IceCube
Nature 591, 220-224 (2021)

Homework Problem

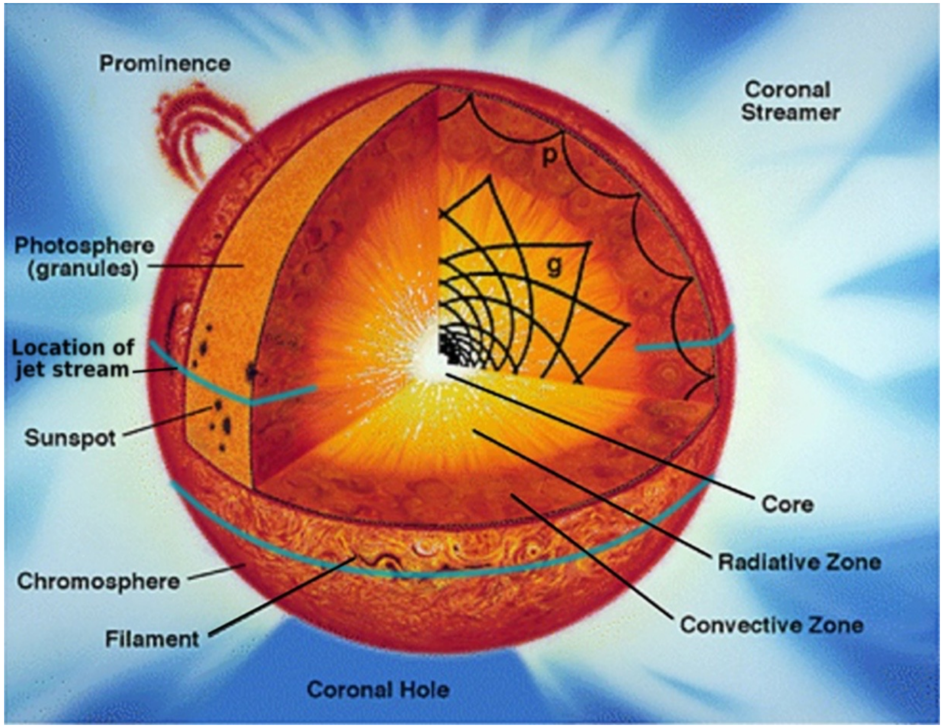


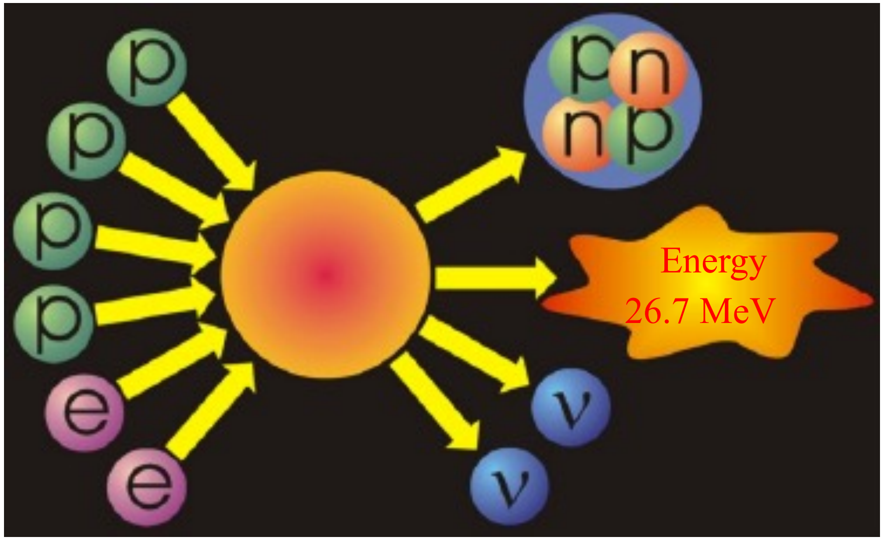
Process	Threshold E_ν^{th}
$\nu_e +^{71} Ga \rightarrow^{71} Ge + e^-$	0.23 MeV
$\nu_e +^{37} Cl \rightarrow^{37} Ar + e^-$	0.82 MeV
$\bar{\nu}_e + p \rightarrow n + e^+$	1.81 MeV
$\nu_\mu + n \rightarrow p + \mu^-$	110.16 MeV
$\nu_\tau + n \rightarrow p + \tau^-$	3.45 GeV
$\nu_\mu + e^- \rightarrow \mu^- + \nu_e$	10.92 GeV

Derive the threshold (minimum) neutrino energy required for the above processes. Answers are given in the second column!

Any Questions?

How does the Sun shine?





Solar radiation: 98% light and 2% neutrinos

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

- Nuclear fusion reactions: mainly

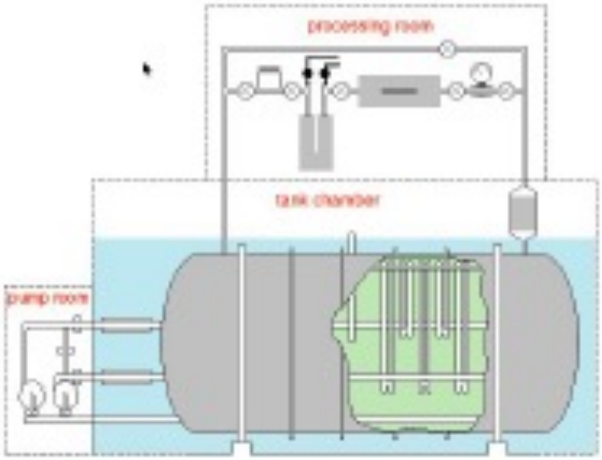
$$4\,{}^{1}_{1}\mathrm{H} + 2e^{-} \rightarrow {}^{4}_{2}\mathrm{He} + \mathrm{light} + 2\nu_e$$

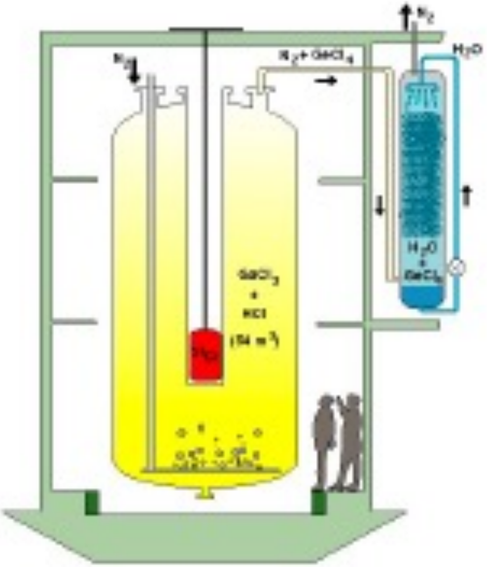
- Neutrinos needed to conserve energy, momentum, angular momentum

Neutrinos are essential for the Sun to shine !

Detecting Neutrinos from the Sun

- The Sun produces ν_e
- These ν_e can be detected at Earth: difficult, but possible





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

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

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

The Solar Neutrino Anomaly

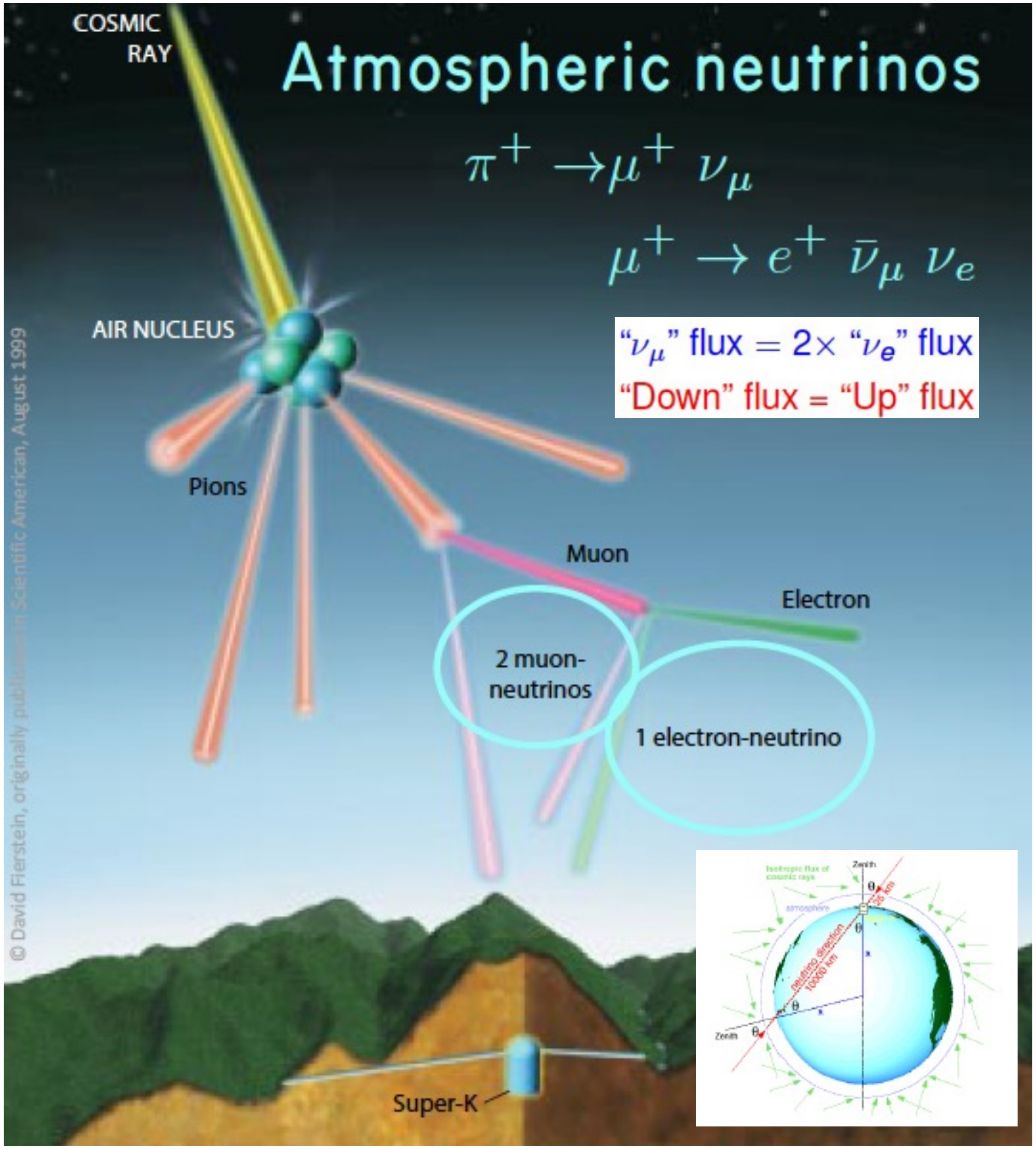
Puzzle:

- Only about 30%–50% of neutrinos from the Sun found
- Different experiments give different neutrino loss...
  (They look at different energy ranges, of course..)
- SuperKamiokande shows similar neutrino loss at all energies

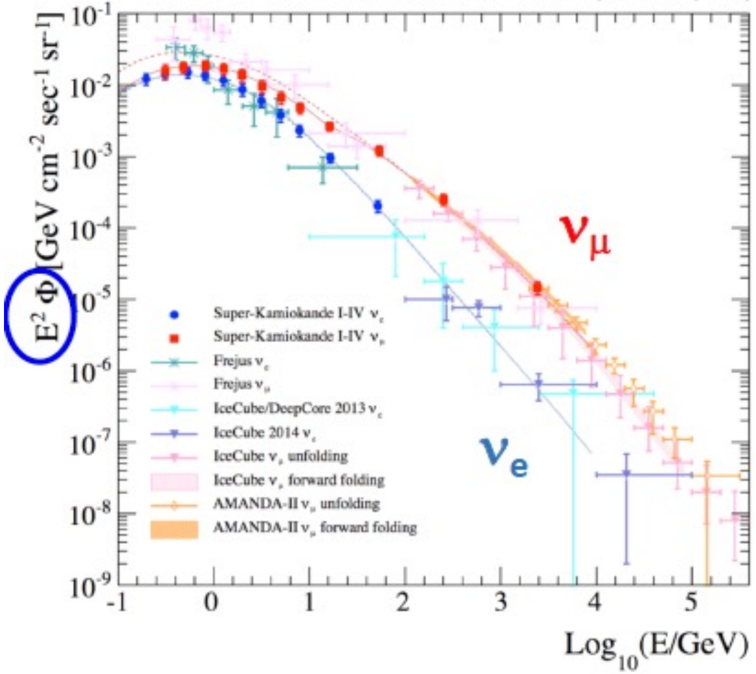
Possible Reasons:

- The astrophysicists cannot calculate accurately
- The experimentalists cannot measure accurately
- Neutrinos behave differently from what everyone thought

Atmospheric Neutrinos

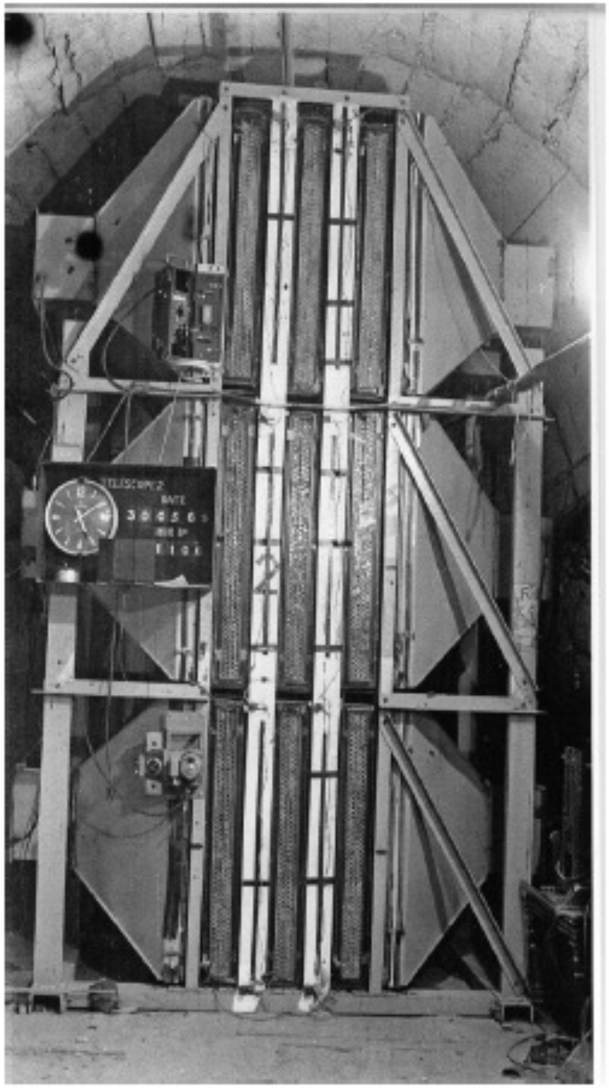


PHYSICAL REVIEW D 94, 052001 (2016)



- 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

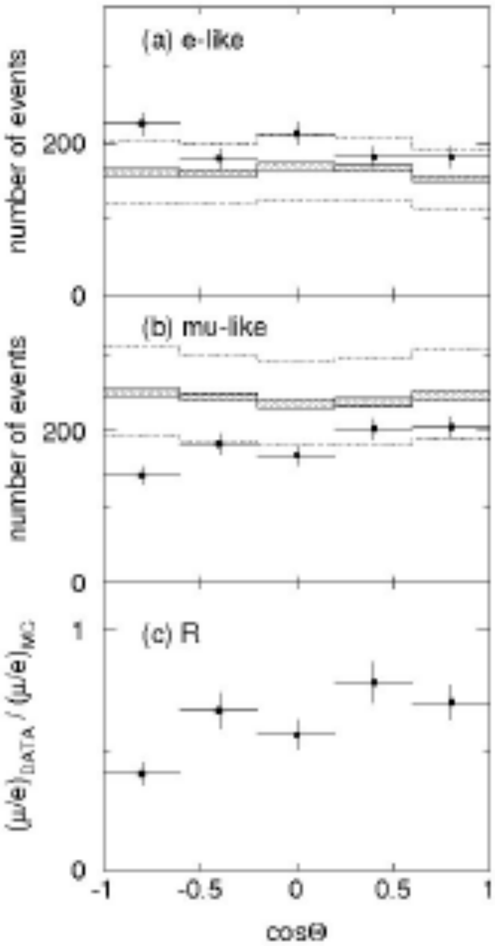
University of the Witwatersrand, Johannesburg, Republic of South Africa
(Received 26 July 1965)

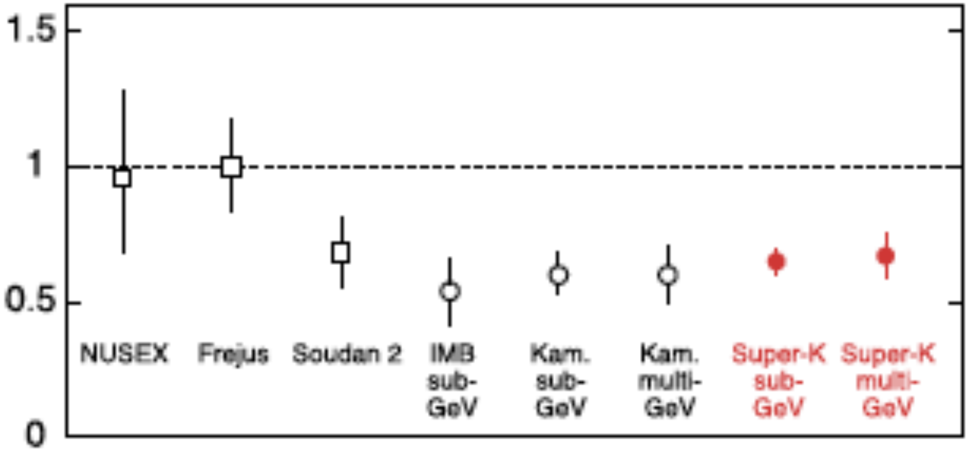
PRL 15, (1965) 429
(30th Aug 1965)

Atmospheric Neutrino Anomaly

Super-Kamiokande

Double ratio:





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

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

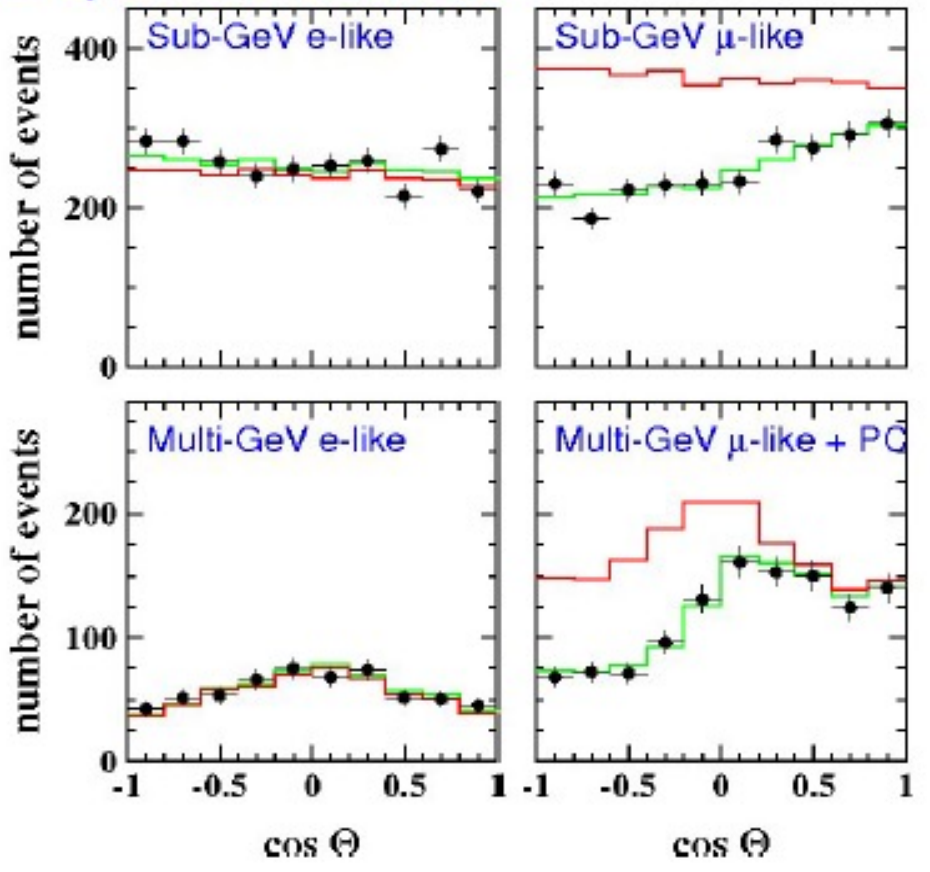
Year 1988:

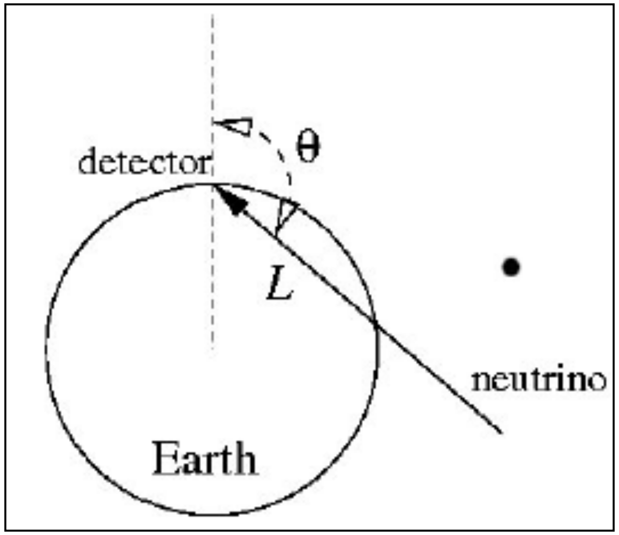
First results from Kamiokande on atmospheric neutrino anomaly

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

Golden Age of Neutrino Physics (1998 – 2024 & Beyond)

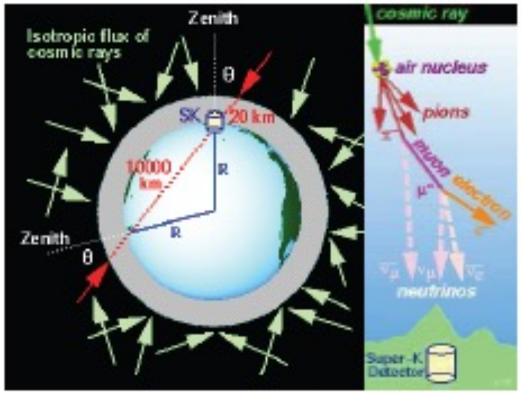
sun

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 ($\nu_\mu, \bar{\nu}_\mu$)

→

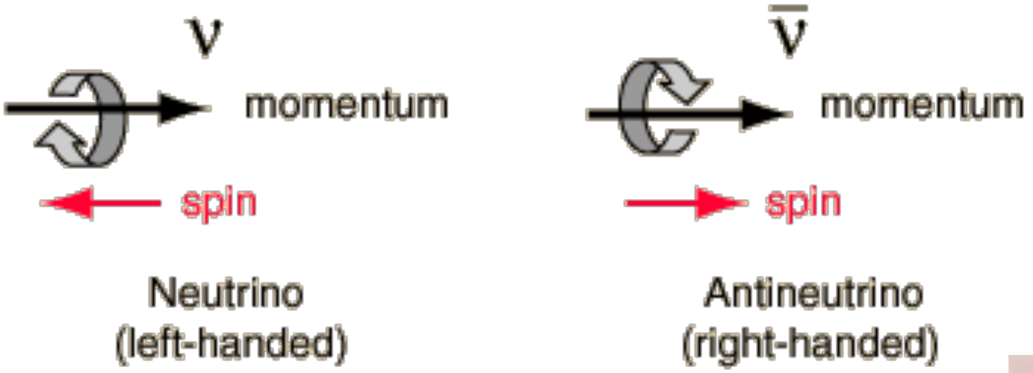
Data from various neutrino sources and vastly different energy and distance scales

↓

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

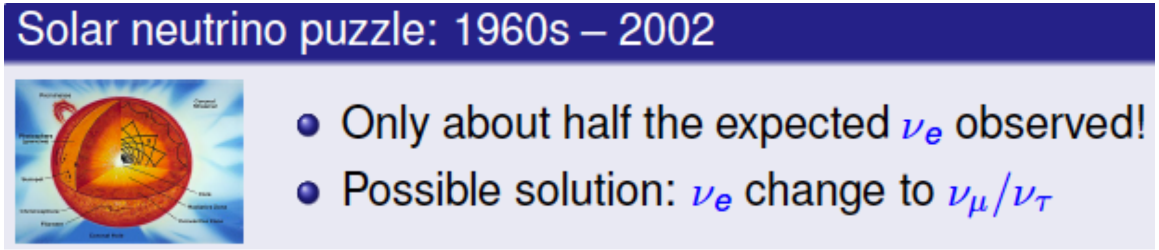
- Over the past decade, marvelous data from world class neutrino experiments firmly established that they change flavor after propagating a finite distance
- Neutrino flavor change (oscillation) demands non-zero mass and mixing

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

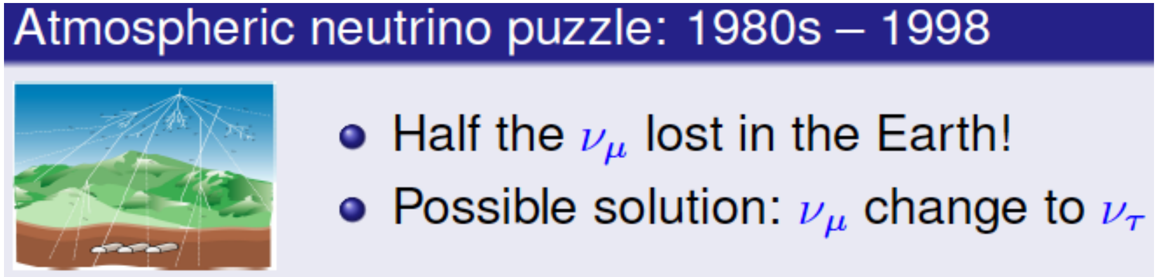
The Nobel Prize in Physics 2015



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

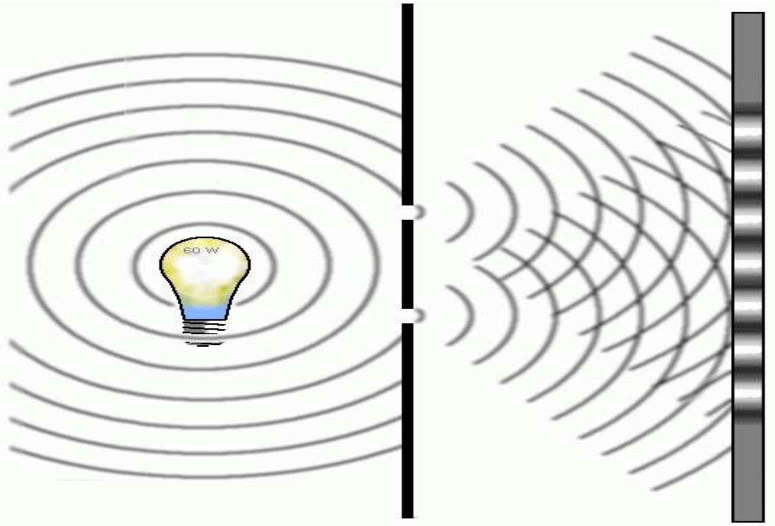
- Half the ν_μ lost in the Earth!
- Possible solution: ν_μ change to ν_τ

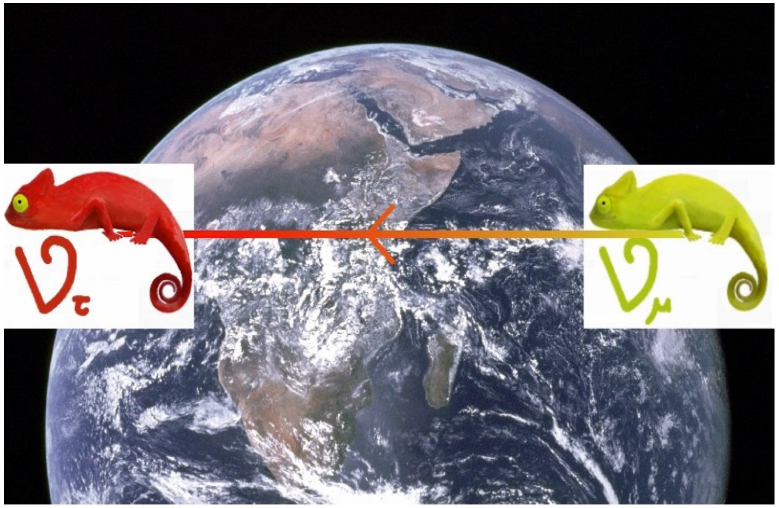
Takaaki Kajita solved this puzzle at Super-Kamiokande

Neutrinos change their flavor ➔ Neutrinos have mass

Neutrino Flavor Oscillations

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





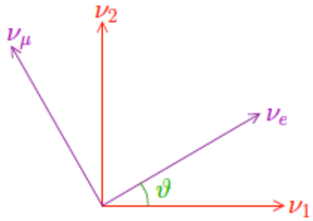
- **Neutrino oscillation: Quantum Mechanical interference phenomenon**
- **Like electrons in the double slit experiment**
- **In Neutrino Oscillation: Neutrino changes flavor as it propagates**
- **It happens if neutrinos have <u>masses</u> (non-degenerate) and they <u>mix</u> with each other**

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)

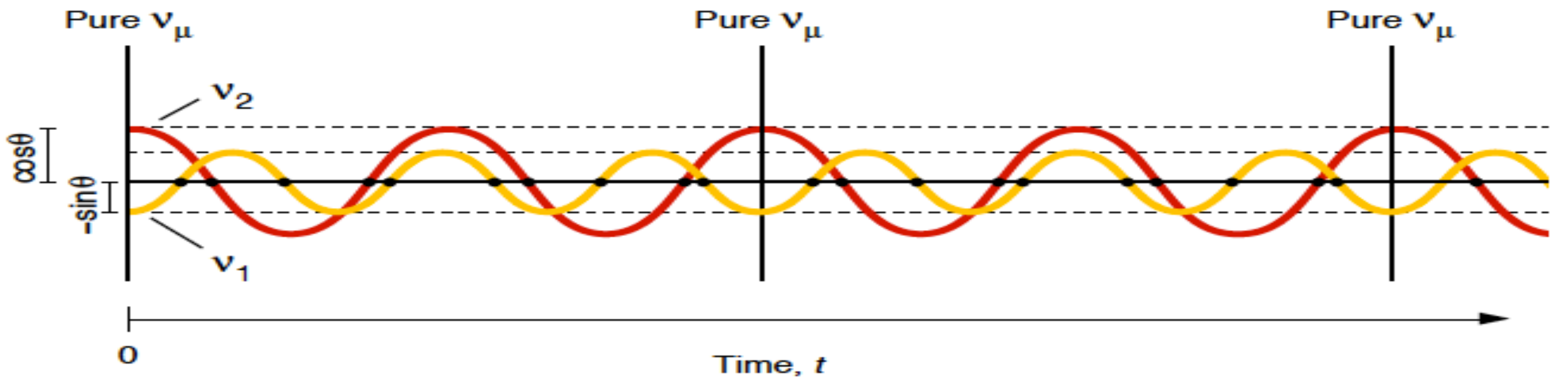
A Flavor State is a linear superposition of Mass Eigenstates

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



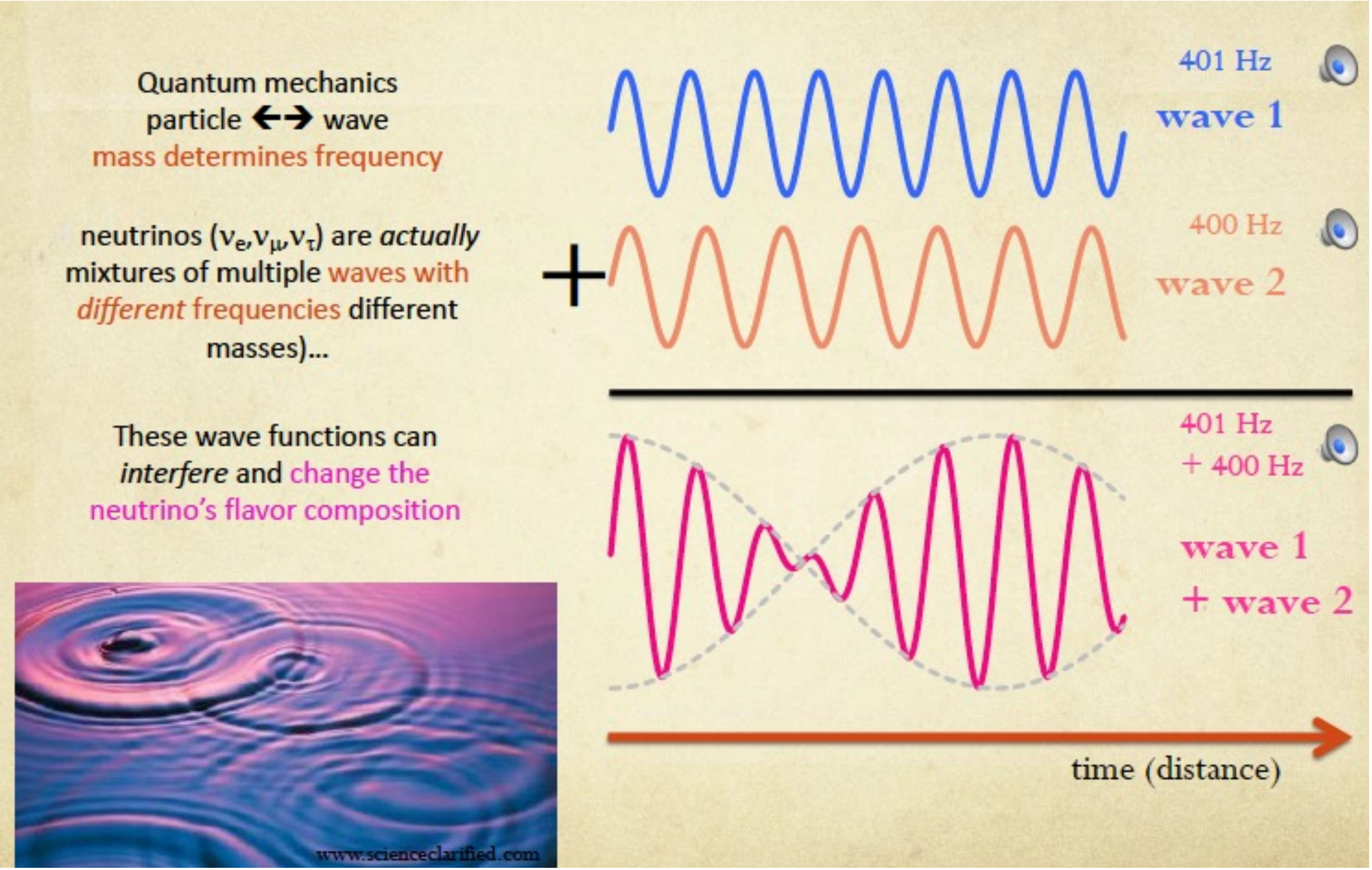
$$U = \begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix}$$

$$\boxed{\begin{aligned} |\nu_e\rangle &= \cos\vartheta\,|\nu_1\rangle + \sin\vartheta\,|\nu_2\rangle \\ |\nu_\mu\rangle &= -\sin\vartheta\,|\nu_1\rangle + \cos\vartheta\,|\nu_2\rangle \end{aligned}}$$



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

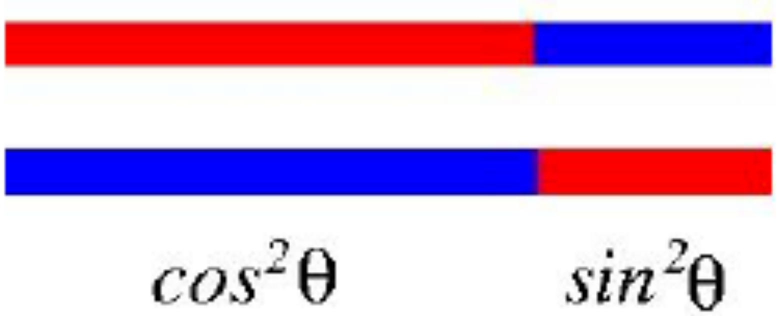
neutrinos (ν_e,ν_μ,ν_τ) are *actually* mixtures of multiple waves with *different* frequencies different masses)...

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

Neutrino Mixing

Neutrino flavours ν_e, ν_μ, ν_τ do not have fixed masses !!

For example, ν_e–ν_μ mixing:



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

$$\nu_1 = \nu_e \cos\theta + \nu_\mu \sin\theta$$

- Only ν_1 and ν_2 have fixed masses
  (*They are eigenstates of energy / eigenstates of evolution*)
- Then, if you produce ν_e, it may be observed as ν_μ !

Effective Hamiltonian for a Single Neutrino

$$H = \sqrt{p^2 + m^2} \approx p + \frac{m^2}{2p} \approx p + \frac{m^2}{2E}$$

Schrödinger's equation:

$$i\frac{d}{dt}|\nu(t)\rangle = H|\nu(t)\rangle$$

Time evolution:

$$\begin{aligned} |\nu(t)\rangle &= |\nu(0)\rangle e^{-iHt} \\ &= |\nu(0)\rangle e^{-ipt} e^{-i\frac{m^2}{2E}t} \end{aligned}$$

- Simple for a mass eigenstate with fixed momentum !

Time Evolution for a Flavor Eigenstate

- Initial flavour state $|\nu_\alpha\rangle$:

$$|\nu_\alpha\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$

- State after time t:

$$|\nu_\alpha(t)\rangle = \cos\theta|\nu_1\rangle e^{-ipt} e^{-i\frac{m_1^2}{2E}t} + \sin\theta|\nu_2\rangle e^{-ipt} e^{-i\frac{m_2^2}{2E}t}$$

- "Survival" probability of finding the flavour $|\nu_\alpha\rangle$ at time t:

$$P(\nu_\alpha \to \nu_\alpha) = |\langle\nu_\alpha|\nu_\alpha(t)\rangle|^2$$

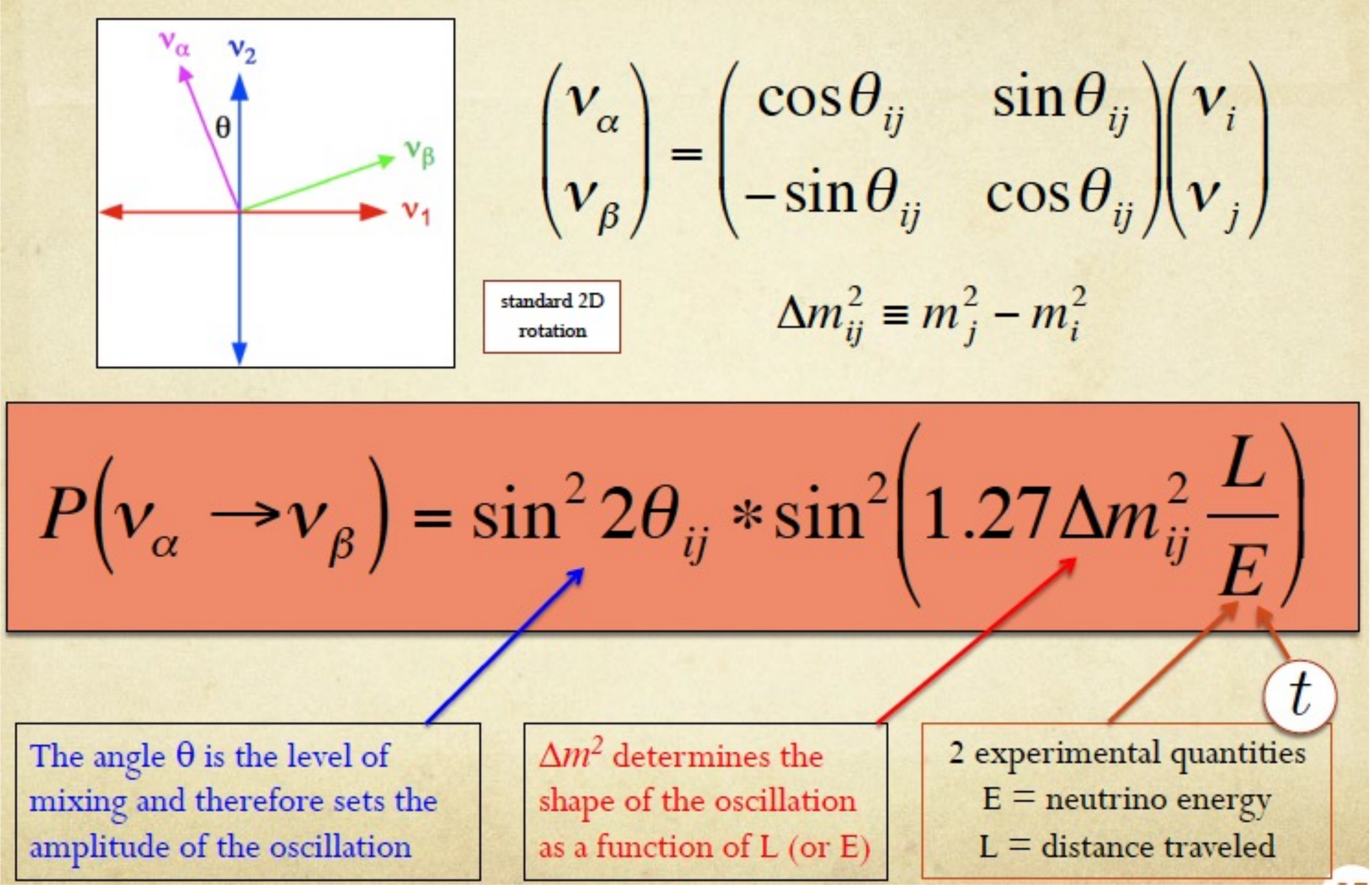
Vacuum oscillations:

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$$\Delta m^2 \equiv m_2^2 - m_1^2$$

(In Natural units, where $c = 1 = \hbar$)

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

$$\Delta m_{ij}^2 \equiv m_j^2 - m_i^2$$

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

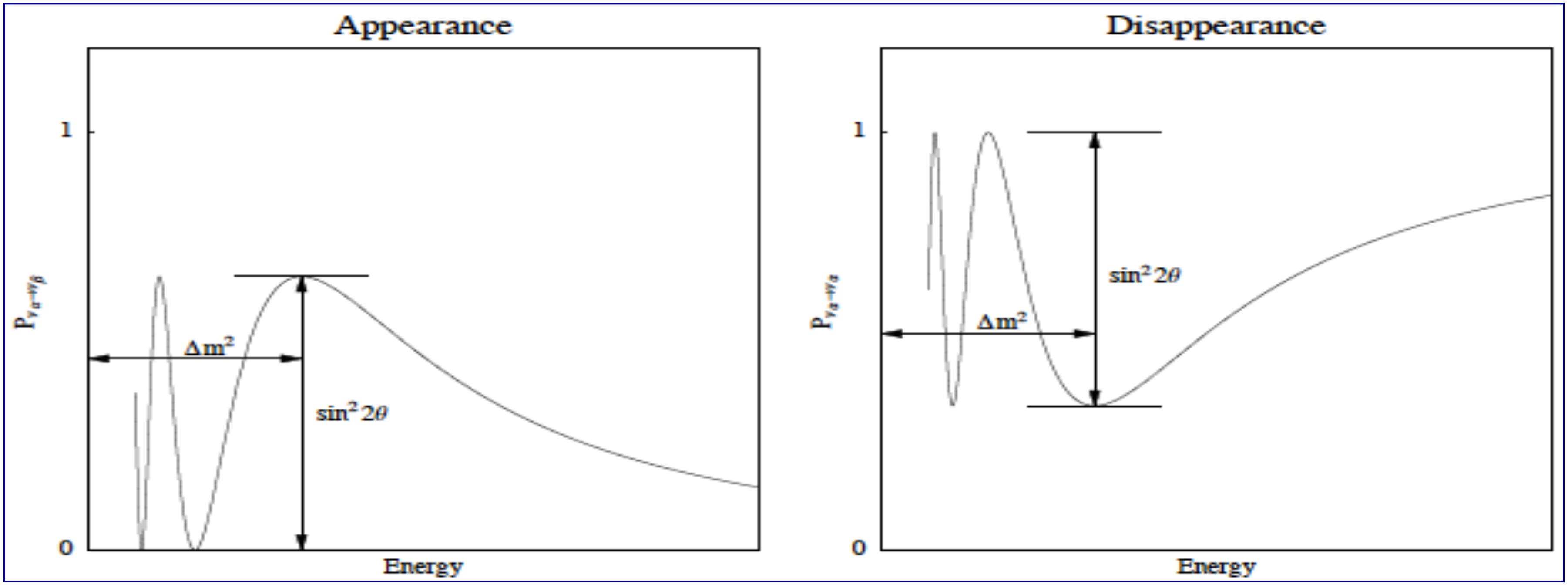
t

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

Oscillation Probabilities in 2 Flavors



$$P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\theta \ \sin^2(1.27 \Delta m^2 \frac{L}{E})$$

$$P_{\nu_\alpha \to \nu_\alpha} = 1 - \sin^2 2\theta \ \sin^2(1.27 \Delta m^2 \frac{L}{E})$$

Δm^2 is in eV^2, L is in m (km) and E in MeV (GeV)

$$\lambda = 2.47 \mathrm{km} \left(\frac{E}{\mathrm{GeV}}\right) \left(\frac{\mathrm{eV}^2}{\Delta m^2}\right) \Rightarrow \text{oscillation length}$$

Neutrino oscillations only sensitive to mass squared difference but not to the absolute neutrino mass scale

Oscillation Dip in Muon Neutrino Survival Probability

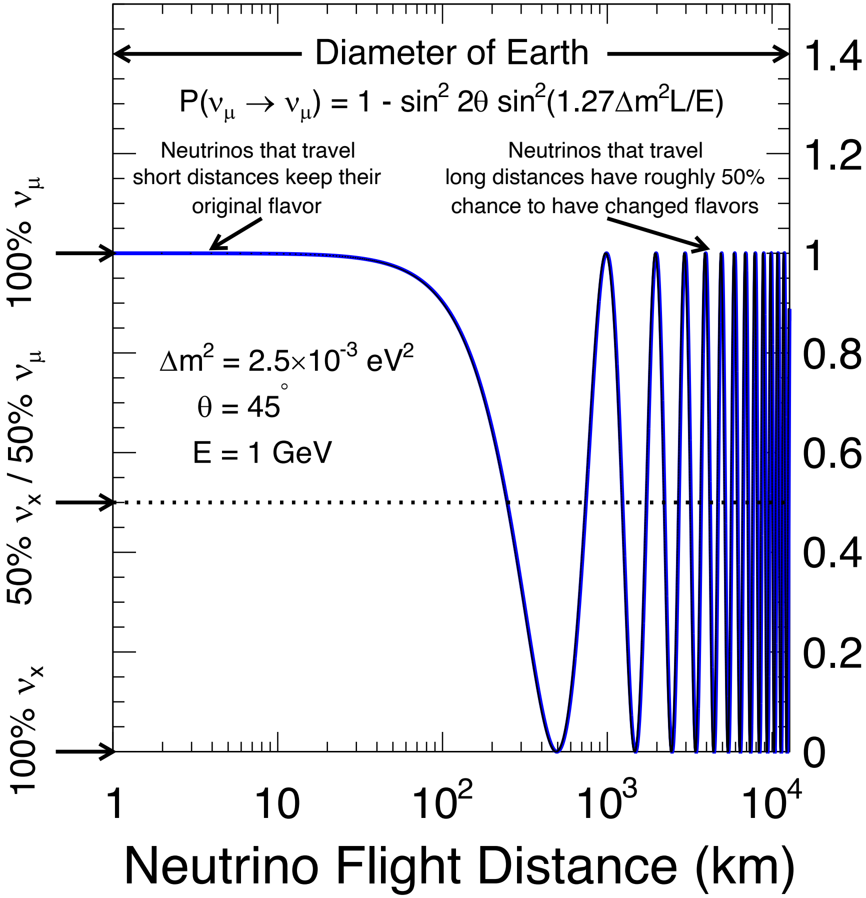
Atmospheric neutrinos have access to a wide range of baselines:

- Vertically downward-going neutrinos: 15 km
- Vertically upward-going neutrinos: 12757 km

For $E_\nu = 1$ GeV:

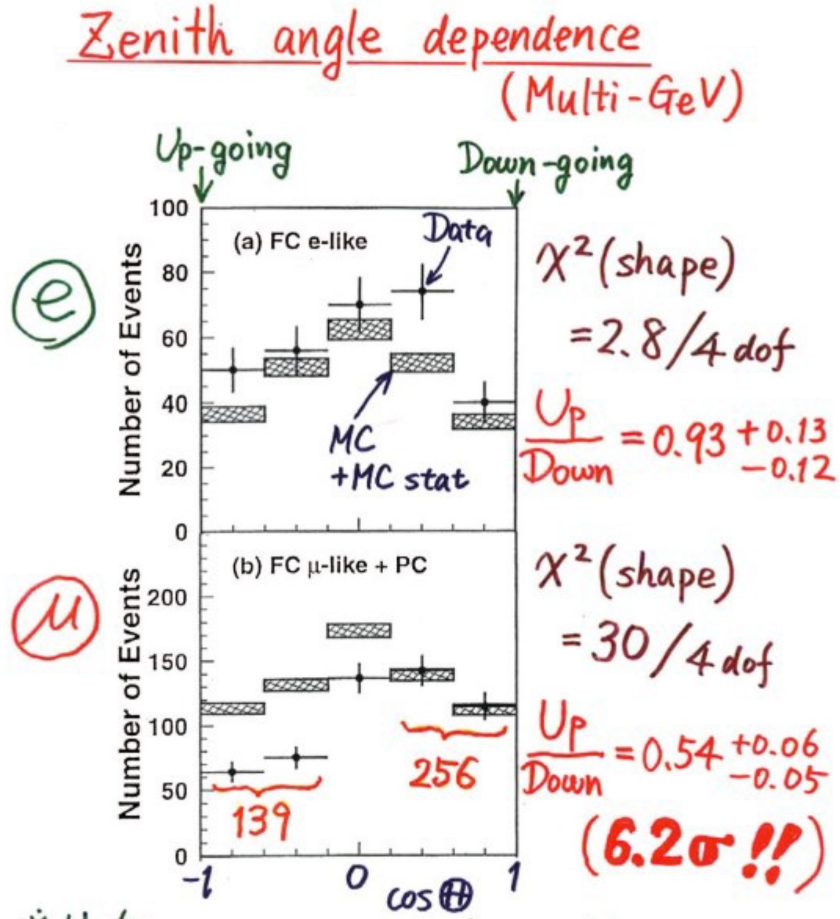
- At smaller baselines: neutrino oscillations are not developed
- At larger baselines: about 50% ν_μ have oscillated
- At certain baselines: about 100% ν_μ have oscillated

Oscillation dip feature corresponds to the case when all muon neutrinos are oscillated, i.e. $P(\nu_\mu \to \nu_\mu) = 0$.



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!



※ Up/Down syst. error for μ-like

Prediction (flux calculation …… $\lesssim 1\%$
1km rock above SK …. 1.5%) 1.8%

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

Three-Flavor Neutrino Oscillation Framework: Simple & Robust

It happens because flavor (weak) eigenstates do not coincide with mass eigenstates

$c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$

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

θ_{23} : $P(\nu_\mu \to \nu_\mu)$ by Atoms. ν and ν beam

θ_{13}: $P(\nu_e \to \nu_e)$ by Reactor ν
θ_{13} & δ: $P(\nu_\mu \to \nu_e)$ by ν beam

θ_{12} : $P(\nu_e \to \nu_e)$ by Reactor and solar ν

$L/E = 500 \text{ km/GeV}$ $\quad$ $L/E = 15,000 \text{ km/GeV}$

$\Delta m^2_{31} \sim 2.5 \times 10^{-3} \text{ eV}^2$ $\quad$ $P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta_{ij} * \sin^2\left(1.27\Delta m^2_{ij}\frac{L}{E}\right)$ $\quad$ $\Delta m^2_{21} \sim 7.6 \times 10^{-5} \text{ eV}^2$

Three mixing angles: $\theta_{23}, \theta_{13}, \theta_{12}$ and one CP-violating (Dirac) phase δ_{CP}

$$\tan^2\theta_{12} \equiv \frac{|U_{e2}|^2}{|U_{e1}|^2}; \quad \tan^2\theta_{23} \equiv \frac{|U_{\mu3}|^2}{|U_{\tau3}|^2}; \quad U_{e3} \equiv \sin\theta_{13}e^{-i\delta}$$

3 mixing angles simply related to flavor components of 3 mass eigenstates

Over a distance L, changes in the relative phases of the mass states may induce flavor change

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}[U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}]\sin^2\Delta_{ij} - 2\sum_{i>j}\mathrm{Im}[U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}]\sin 2\Delta_{ij}.$$

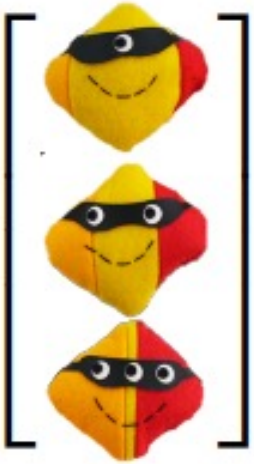
$\Delta_{ij} = \Delta m^2_{ij}L/4E_\nu$

$\Delta m^2_{ij} = m_i^2 - m_j^2$

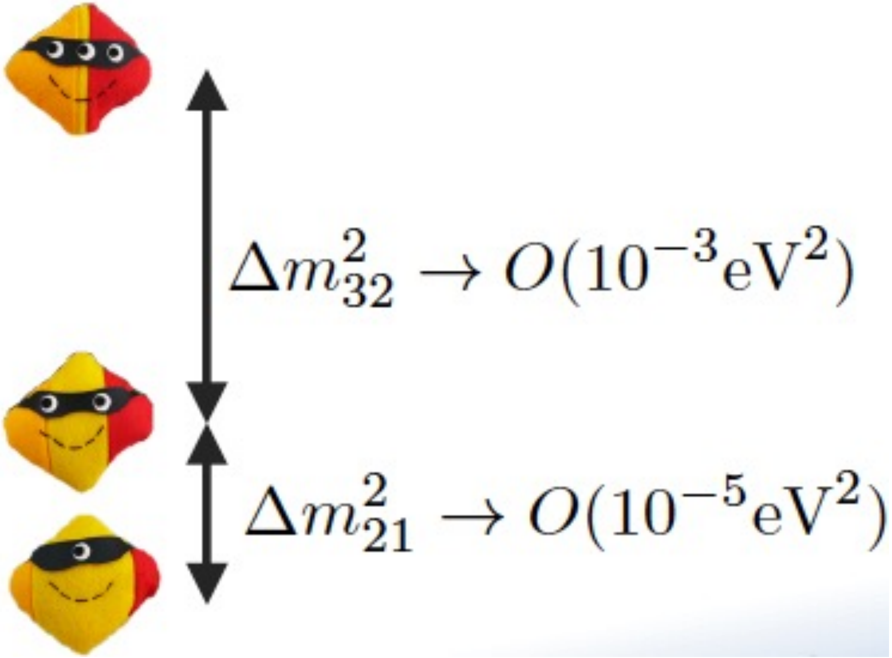
for antineutrinos replace δ_{CP} by $-\delta_{CP}$

Three-Flavor Neutrino Oscillations

$$= R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12})$$



- Oscillations among the three neutrino flavors depend on:
  - – The mixing matrix
    - $\theta_{23}, \theta_{13}, \delta_{CP}, \theta_{12}$
  - – The mass differences
    - $\Delta m^2{}_{32}, \Delta m^2{}_{21}$



$$\Delta m^2_{32} \rightarrow O(10^{-3}\mathrm{eV}^2)$$

$$\Delta m^2_{21} \rightarrow O(10^{-5}\mathrm{eV}^2)$$

Some Things We Know and Don't Know

Three neutrino mixing firmly established…

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

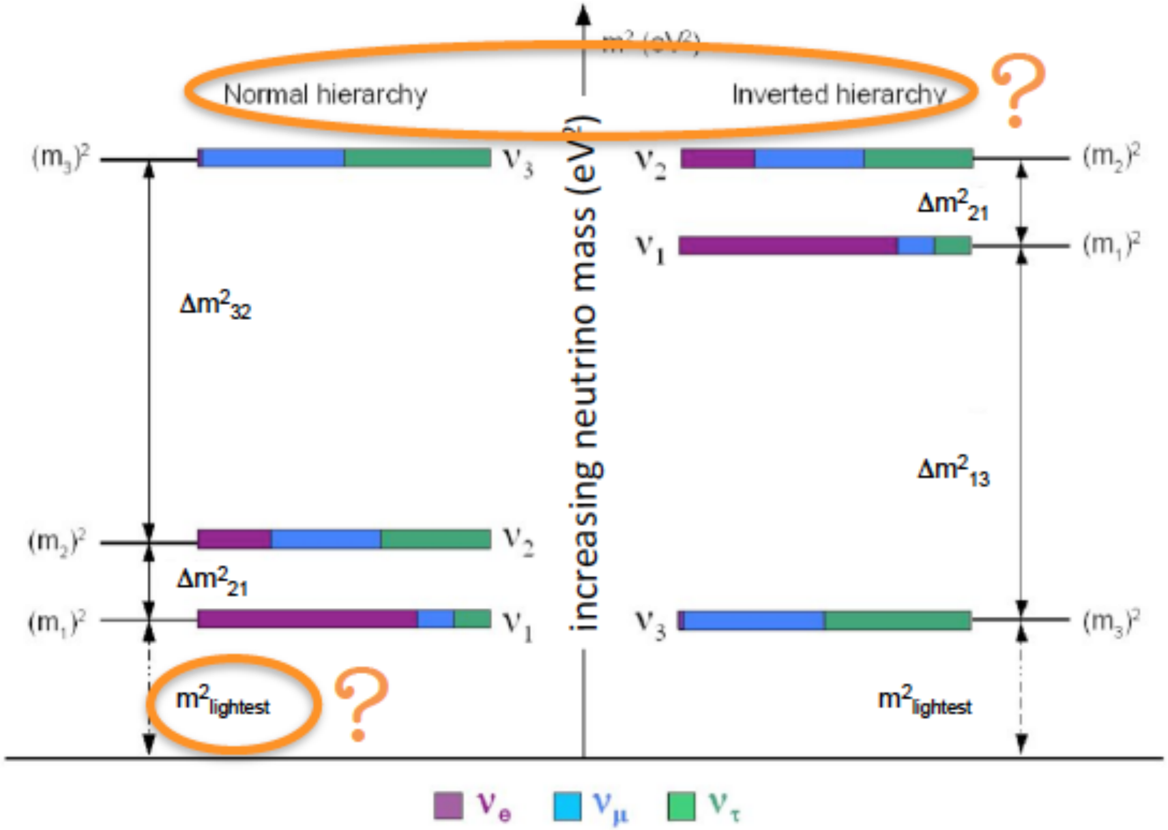
$\theta_{23} \approx 45^\circ$

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

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

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

$\delta_{CP} = \ ?$?



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

The Pontecorvo-Maki-Nakagawa-Sakata Matrix

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{pmatrix}$$

$$\boxed{\theta_{12} = 33.41^\circ{}^{+0.75^\circ}_{-0.72^\circ}} \quad \boxed{\theta_{23} = 49.1^\circ{}^{+1.0^\circ}_{-1.3^\circ}} \quad \boxed{\theta_{13} = 8.54^\circ{}^{+0.11^\circ}_{-0.12^\circ}} \quad \boxed{\delta_{\mathrm{CP}} = 197^\circ{}^{+42^\circ}_{-25^\circ}}$$

w/o Super-K atmospheric neutrino data assuming normal mass ordering

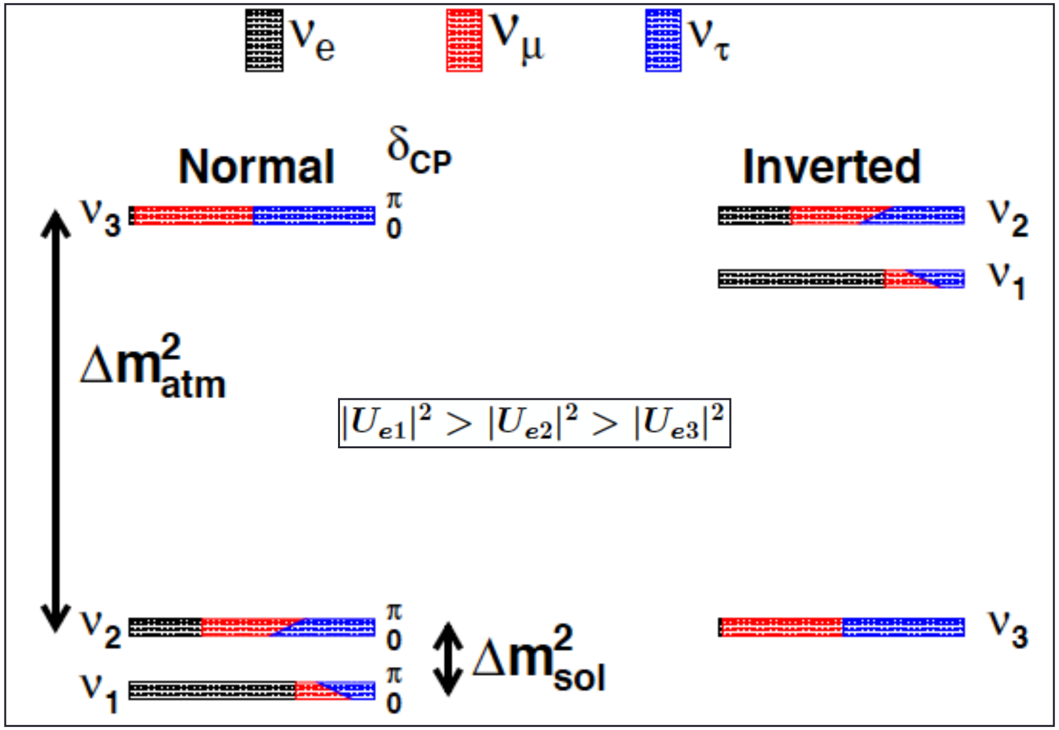
$$|U| = \begin{bmatrix} |U_{e1}| & |U_{e2}| & |U_{e3}| \\ |U_{\mu1}| & |U_{\mu2}| & |U_{\mu3}| \\ |U_{\tau1}| & |U_{\tau2}| & |U_{\tau3}| \end{bmatrix} = \begin{bmatrix} 0.803 \sim 0.845 & 0.514 \sim 0.578 & 0.142 \sim 0.155 \\ 0.233 \sim 0.505 & 0.460 \sim 0.693 & 0.630 \sim 0.779 \\ 0.262 \sim 0.525 & 0.473 \sim 0.702 & 0.610 \sim 0.762 \end{bmatrix}$$

3σ ranges (99.73% C.L.) for the magnitudes of the elements of the PMNS matrix (NuFIT.org)

- Neutrino mixings in the PMNS matrix are large as compared to the quark mixings in the CKM matrix
- In the CKM matrix, the quark mixing angles are $\theta_{12} = 13.04^\circ \pm 0.05^\circ$, $\theta_{23} = 2.38^\circ \pm 0.06^\circ$, $\theta_{13} = 0.201^\circ \pm 0.011^\circ$
- Neutrino mixings are inconsistent with TBM neutrino mixing ($\theta_{12} \approx 35.3^\circ$ $\theta_{23} \approx 45^\circ$ $\theta_{13} = 0^\circ$) at > 5σ

Neutrino Mass Ordering: Important Open Question

- The sign of Δm^2_{31} $(m^2_3 - m^2_1)$ is not known



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

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

Matter effect inside the Sun played an important role to fix the ordering between m_2 & m_1

Matter effect inside the Earth will play a crucial role to fix the ordering between m_3 & m_1

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

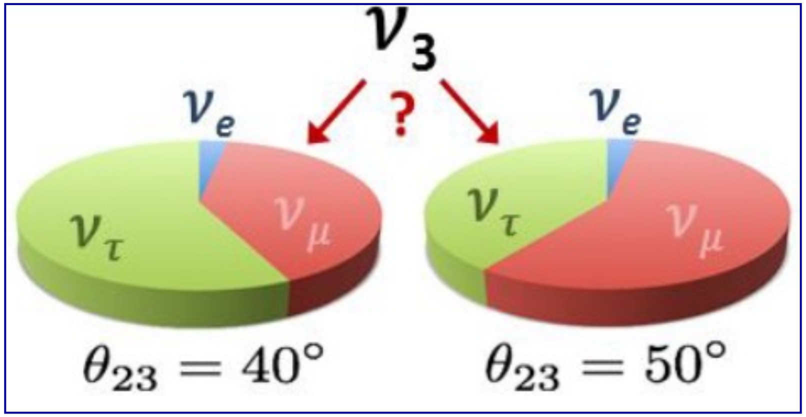
Octant of 2-3 Mixing Angle: Important Open Question

→ 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

$\nu_\mu \rightarrow \nu_e$ 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 ≠ 0° & 90° ✔
3) $\delta_{CP} \neq 0^\circ$ and 180° (Hints)

Quark Mixing vs. Neutrino Mixing

$$|V_{\rm CKM}| = \begin{pmatrix} 0.97435 \pm 0.00016 & 0.22500 \pm 0.00067 & 0.00369 \pm 0.00011 \\ 0.22486 \pm 0.00067 & 0.97349 \pm 0.00016 & 0.04182^{+0.00085}_{-0.00074} \\ 0.00857^{+0.00020}_{-0.00018} & 0.04110^{+0.00083}_{-0.00072} & 0.999118^{+0.000031}_{-0.000036} \end{pmatrix}$$

PDG 2022

$$|U|^{\text{with SK-atm}}_{3\sigma\,\text{PMNS}} = \begin{pmatrix} 0.801 \to 0.845 & 0.513 \to 0.579 & 0.144 \to 0.156 \\ 0.244 \to 0.499 & 0.505 \to 0.693 & 0.631 \to 0.768 \\ 0.272 \to 0.518 & 0.471 \to 0.669 & 0.623 \to 0.761 \end{pmatrix}$$

NuFIT 5.1 (2021)

The goal is to achieve the CKM level precision for the PMNS

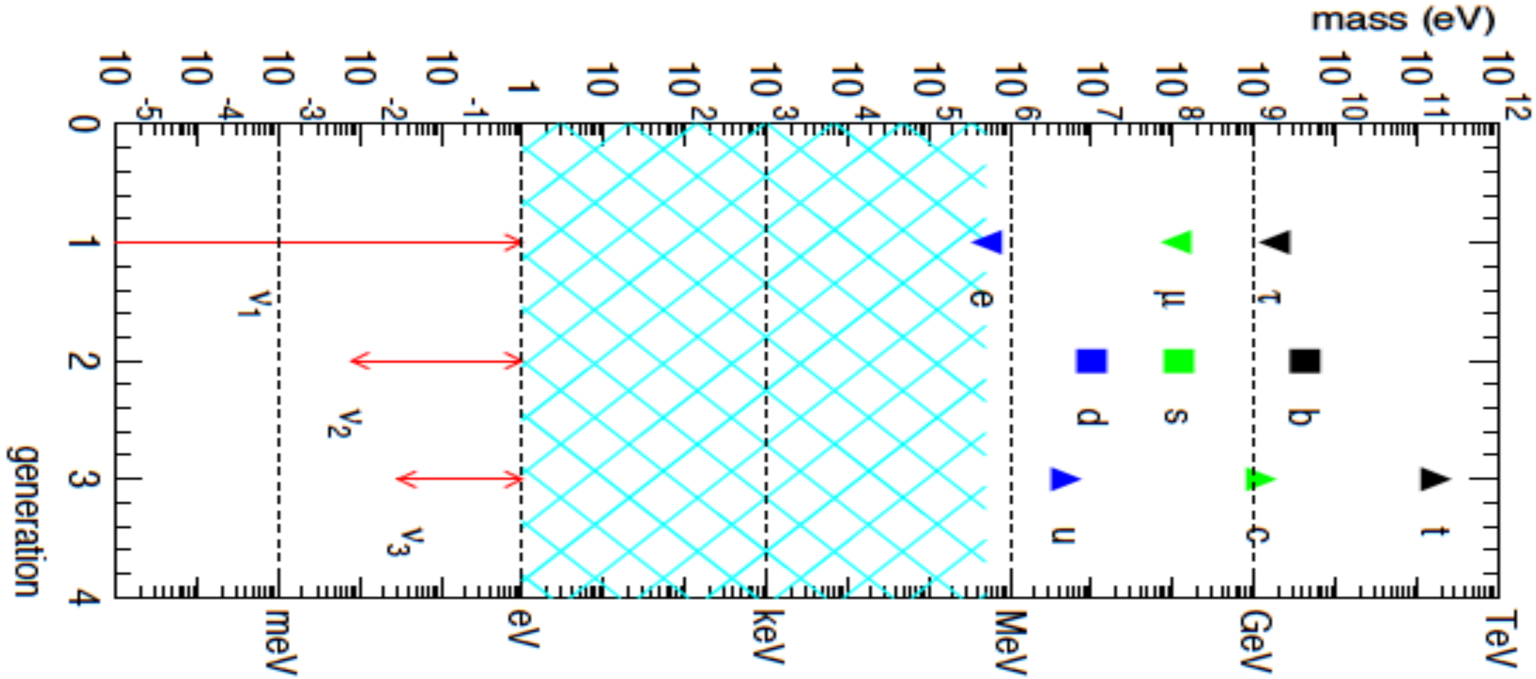
A Long Journey Ahead! But the precision is improving rapidly for PMNS

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

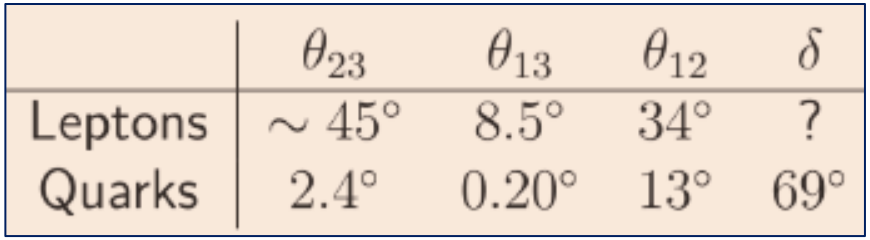
$$J_{CP} = \frac{1}{8} \cos\theta_{13}\, \sin 2\theta_{13}\, \sin 2\theta_{23}\, \sin 2\theta_{12}\, \sin\delta_{CP}$$

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

The Two Fundamental Questions



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



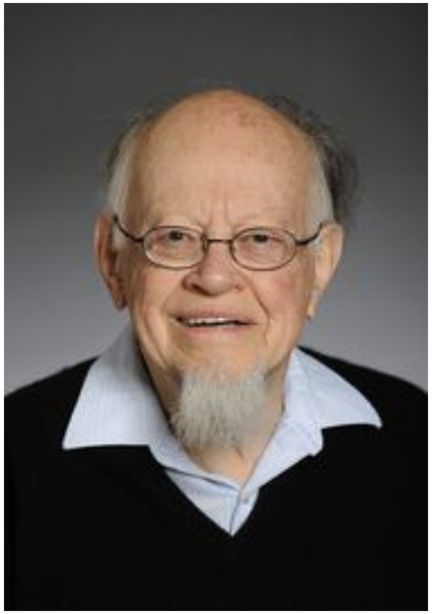
	θ_{23}	θ_{13}	θ_{12}	δ
Leptons	$\sim 45^\circ$	8.5°	34°	?
Quarks	2.4°	0.20°	13°	69°

Why are lepton mixings so different from quark mixings?

The Flavor Puzzle!

Neutrino Oscillations in Matter: MSW Effect

- **The MSW Effect (Wolfenstein, 1978; Mikheyev and Smirnov, 1985)**
- **Matter can change the pattern of neutrino oscillations significantly**
- **Resonant enhancement of oscillations and resonant flavor conversion possible**
- **Responsible for the flavor conversion of solar neutrinos (LMA MSW solution established)**

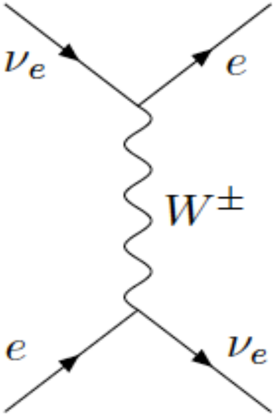


Lincoln Wolfenstein

Stanislav Mikheyev

Alexei Smirnov

Neutrino Oscillations in Matter: MSW Effect



Neutrino propagation through matter modify the oscillations significantly

Coherent forward scattering of neutrinos with matter particles

Charged current interaction of ν_e with electrons creates an extra potential for ν_e

MSW matter term: $\boxed{A = \pm 2\sqrt{2} G_F N_e E}$ or $\boxed{A(\mathrm{eV}^2) = 0.76 \times 10^{-4} \rho\ (\mathrm{g/cc}) E(\mathrm{GeV})}$

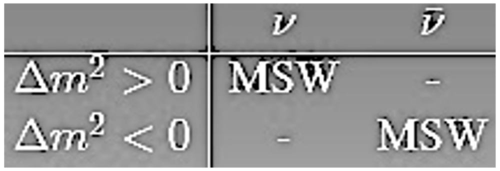
N_e = electron number density , + (-) for neutrinos (antineutrinos) , ρ = matter density in Earth

Matter term changes sign when we switch from neutrino to antineutrino

$P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \neq 0$ → **even if $\delta_{CP} = 0$, causes fake CP asymmetry**

Matter term modifies oscillation probability differently depending on the sign of Δm²

$\Delta m^2 \simeq A \quad \Leftrightarrow \quad E_{\mathrm{res}}^{\mathrm{Earth}} = 6 - 8\,\mathrm{GeV}$ → **Resonant conversion – Matter effect**



	ν	$\bar{\nu}$
$\Delta m^2 > 0$	MSW	-
$\Delta m^2 < 0$	-	MSW

→ **Resonance occurs for neutrinos (antineutrinos) if Δm² is positive (negative)**

Neutrino Oscillation Length Resonance / Parametric Resonance

- **Oscillations of atmospheric neutrinos inside Earth can feel this resonance when neutrino trajectories cross the core of Earth**

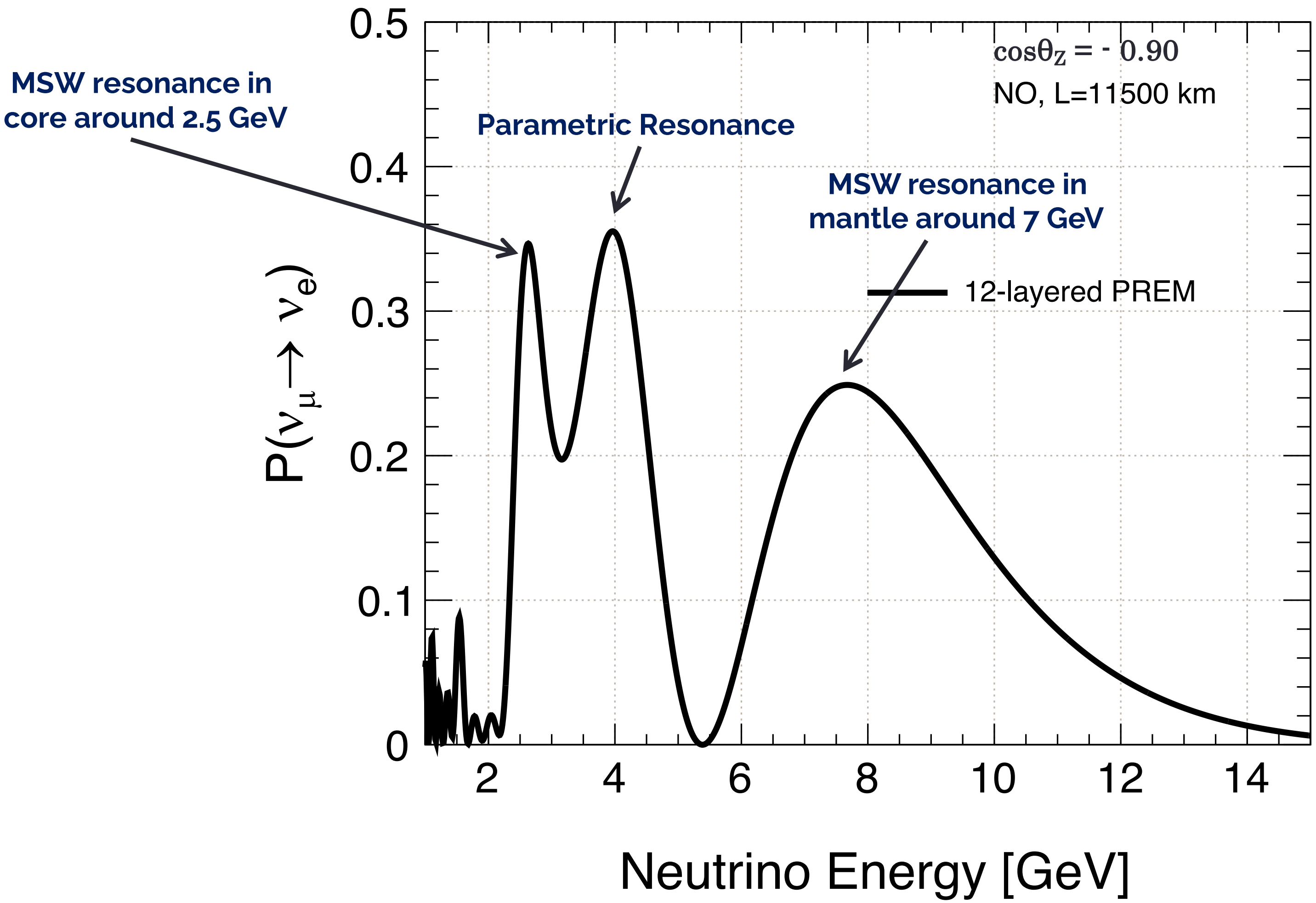
- **The probabilities of neutrino flavor transitions can be strongly enhanced if the oscillation phase undergoes certain modification in matter**

- **This can happen if the variation in the matter density along the neutrino path is correlated in a certain way with the change in the oscillation phase**

- **This amplification of the neutrino oscillation probability in matter due to specific phase relationships can get accumulated if the matter density profile along the neutrino path repeats itself (periodic)**

Petcov 1998, Liu and Smirnov 1998, Akhmedov 1998

Matter Resonances inside Earth



MSW resonance in core around 2.5 GeV

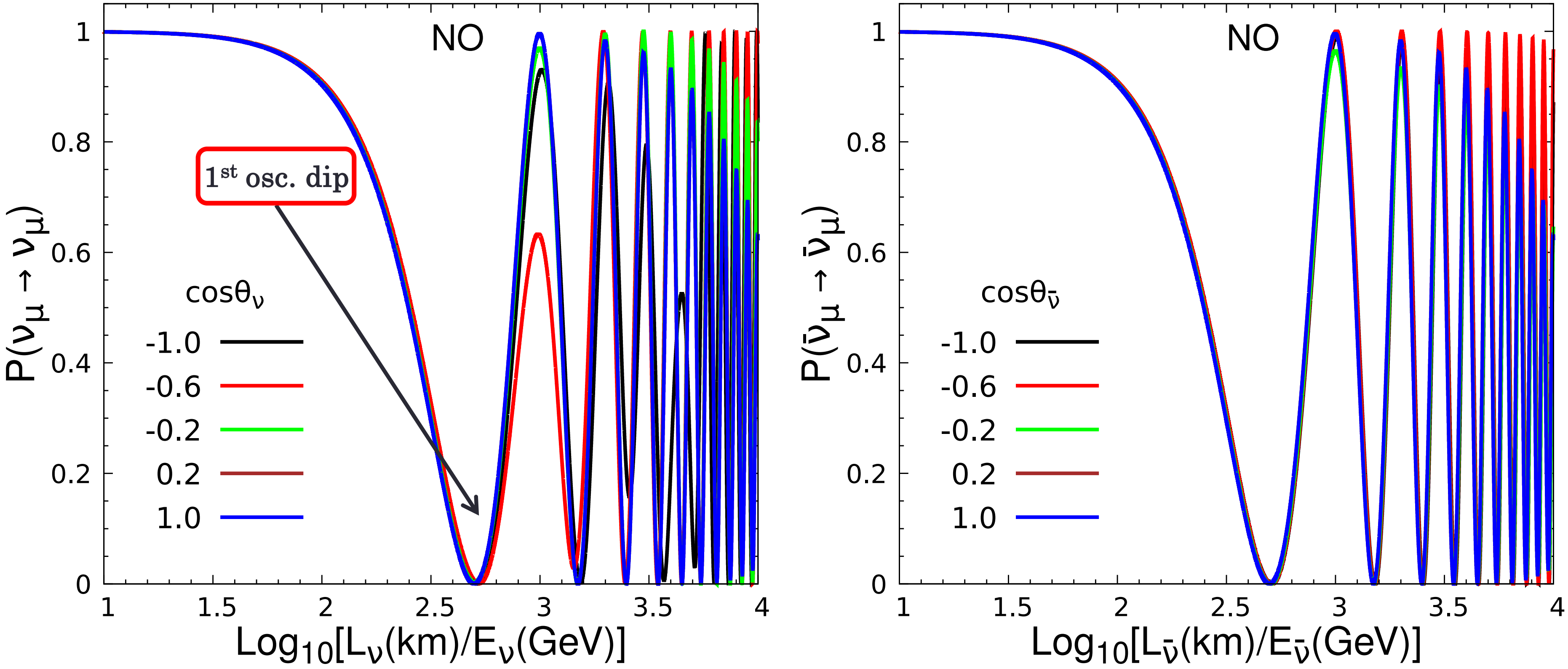
Parametric Resonance

MSW resonance in mantle around 7 GeV

$$\boxed{E_{\rm res} \equiv \frac{\Delta m^2_{31}\,\cos 2\theta_{13}}{2\sqrt{2}\,G_F\,N_e} \simeq 7\,{\rm GeV}\left(\frac{4.5\,{\rm g/cm^3}}{\rho}\right)\left(\frac{\Delta m^2_{31}}{2.4\times10^{-3}\,{\rm eV^2}}\right)\cos 2\theta_{13}}$$

Oscillation Dip in Muon Neutrino Survival Probability

Three-flavor oscillation framework in the presence of Earth's matter (PREM profile)

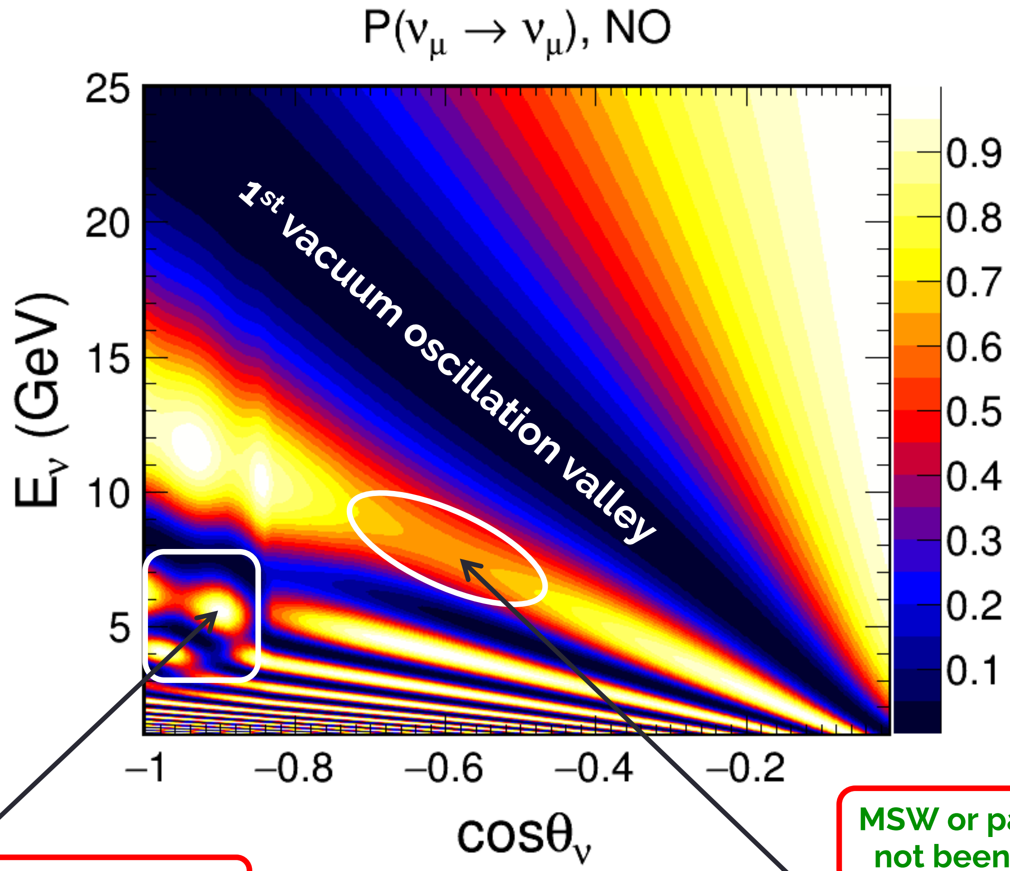


Anil Kumar, Amina Khatun, Sanjib Kumar Agarwalla, Amol Dighe, EPJC 81 (2021) 2, 190, arXiv: 2006.14529

- Oscillation dip can be observed around $\log_{10}(L_\nu/E_\nu) = 2.7$

- Matter effect in $P(\nu_\mu \rightarrow \nu_\mu)$ for the case of neutrino (due to normal mass ordering) can be observed around $\log_{10}(L_\nu/E_\nu) = 3.0$

Oscillation Valley in Muon Neutrino Survival Probability



MSW or parametric resonances have not been observed yet inside Earth!

Parametric resonance region

$\cos\theta_\nu < -0.8$
3 GeV < E_ν < 6 GeV
reducing threshold helps

MSW resonance region

$-0.8 < \cos\theta_\nu < -0.5$
6 GeV < E_ν < 10 GeV

Kumar, Khatun, Agarwalla, Dighe, EPJC 81 (2021) 2, 190

CP Violation: Necessary Requirement for Matter-Antimatter Asymmetry

Five irreducible CP-Violating Phases in the ν Standard Model

In the Quark Sector:

+ The CP-odd phase in the CKM matrix – measured to be $\gamma \simeq 70^{\circ}$
- Governs all the CP-violating phenomena observed so far

+ The strong CP-phase θ of the QCD Vacuum
- Known to be vanishingly small $< 10^{-10}$

In the Lepton Sector:

+ The Dirac CP-odd phase $\delta_{\rm CP}$ in the 3×3 unitary ν mixing matrix
- Can be measured in ν oscillation experiments (hints)

+ The Majorana neutrinos can have two more CP-violating phases
- No effect in ν oscillations, only affect LNV processes (unknown)

Remember

The CKM CP phase is not responsible for the baryon asymmetry of the Universe

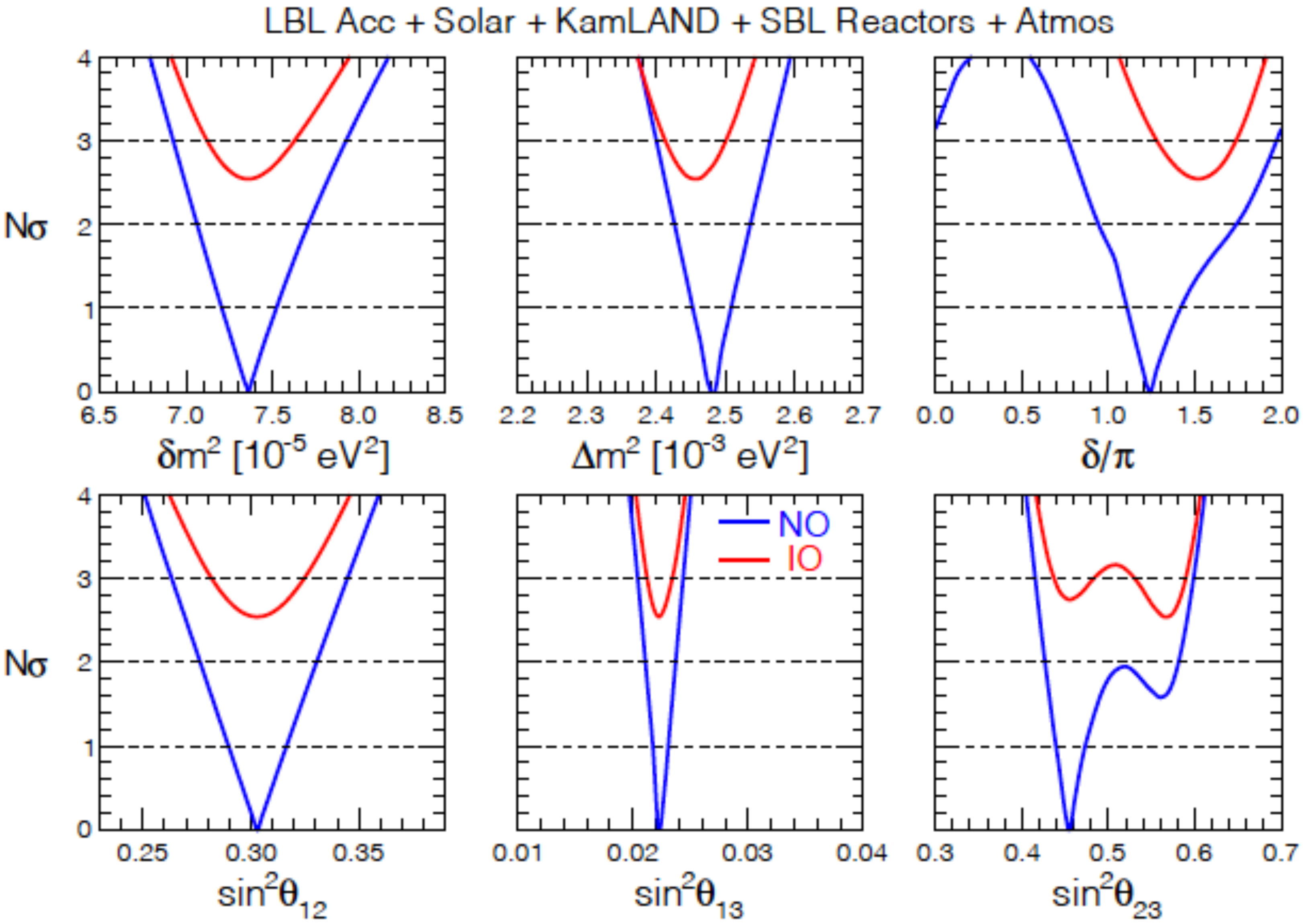
The PMNS CP phase is the only hope

The discovery of non-zero CP-violating phase δ_{CP} in neutrino oscillation experiments would be a strong indication (even if not a proof) of leptogenesis as the origin of the baryon asymmetry of the Universe

The determination of CP violation requires the full interplay of 3-flavor effects in neutrino oscillations

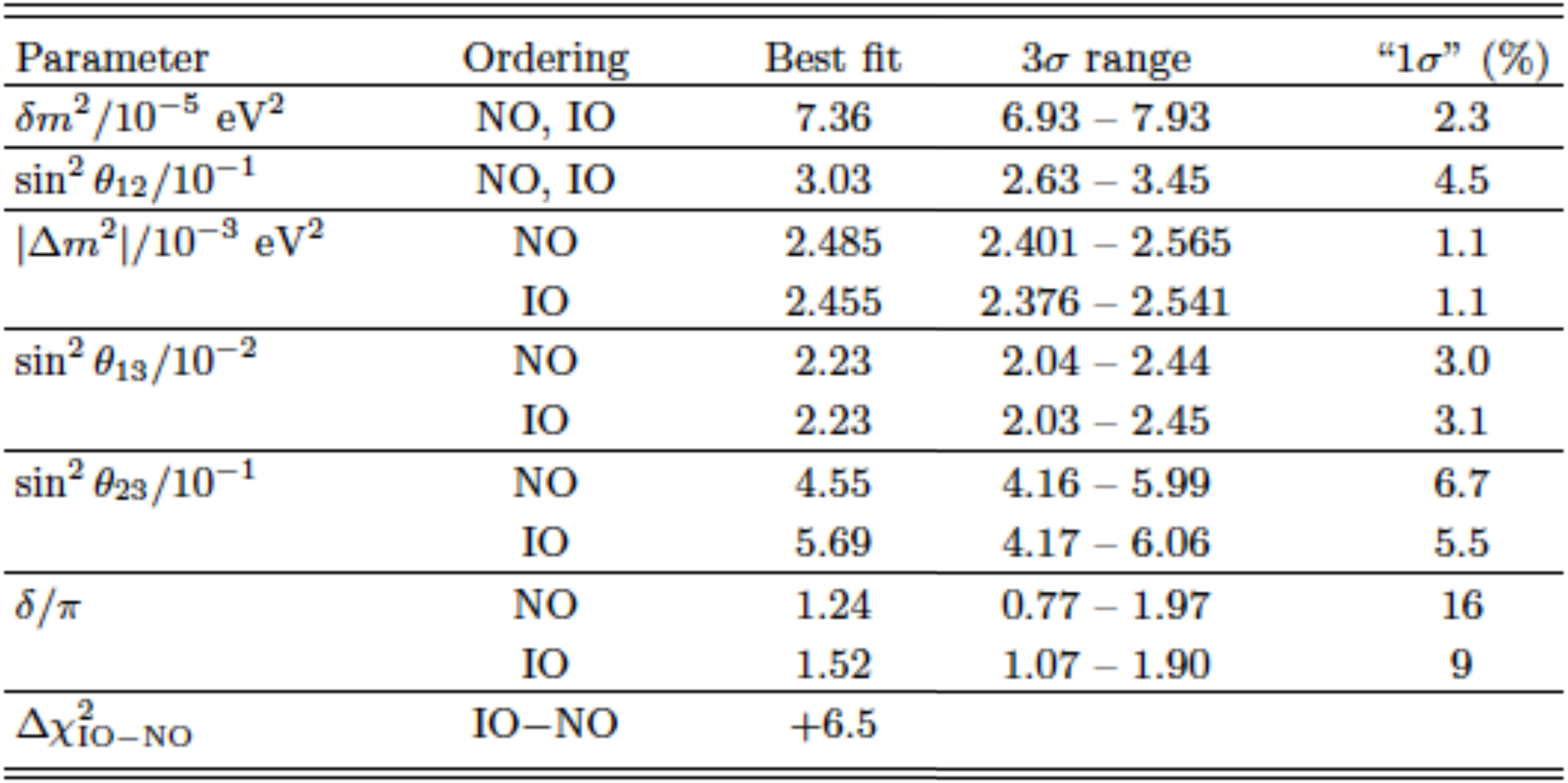
Global Fit of Neutrino Oscillation Parameters Circa 2022

Preference for Normal Mass Ordering (~ 2.5σ), θ_{23} < 45 degree and sin$\boldsymbol{\delta}$ < 0 (both at 90% C.L.)



Capozzi, Valentino, Lisi, Marrone, Melchiorri, Palazzo, arXiv:2107.00532v2 [hep-ph]

Present Status of Neutrino Oscillation Parameters Circa 2022



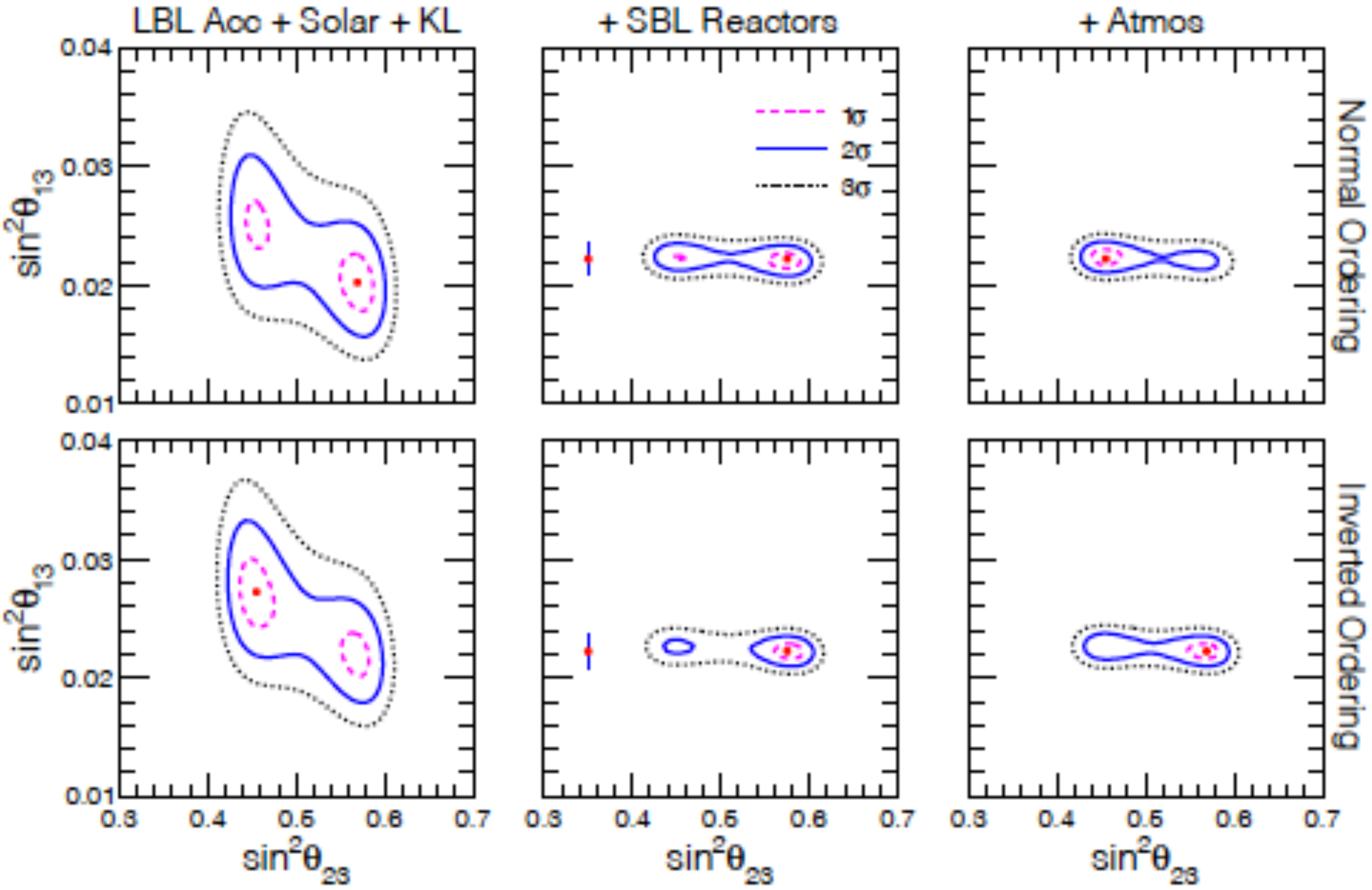
Parameter	Ordering	Best fit	3σ range	"1σ" (%)
$\delta m^2/10^{-5}$ eV^2	NO, IO	7.36	6.93 – 7.93	2.3
$\sin^2\theta_{12}/10^{-1}$	NO, IO	3.03	2.63 – 3.45	4.5
$\lvert\Delta m^2\rvert/10^{-3}$ eV^2	NO	2.485	2.401 – 2.565	1.1
	IO	2.455	2.376 – 2.541	1.1
$\sin^2\theta_{13}/10^{-2}$	NO	2.23	2.04 – 2.44	3.0
	IO	2.23	2.03 – 2.45	3.1
$\sin^2\theta_{23}/10^{-1}$	NO	4.55	4.16 – 5.99	6.7
	IO	5.69	4.17 – 6.06	5.5
δ/π	NO	1.24	0.77 – 1.97	16
	IO	1.52	1.07 – 1.90	9
$\Delta\chi^2_{\mathrm{IO-NO}}$	IO–NO	+6.5		

Capozzi, Valentino, Lisi, Marrone, Melchiorri, Palazzo, arXiv:2107.00532v1 [hep-ph]

See also, Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, arXiv:2007.14792v1 [hep-ph]

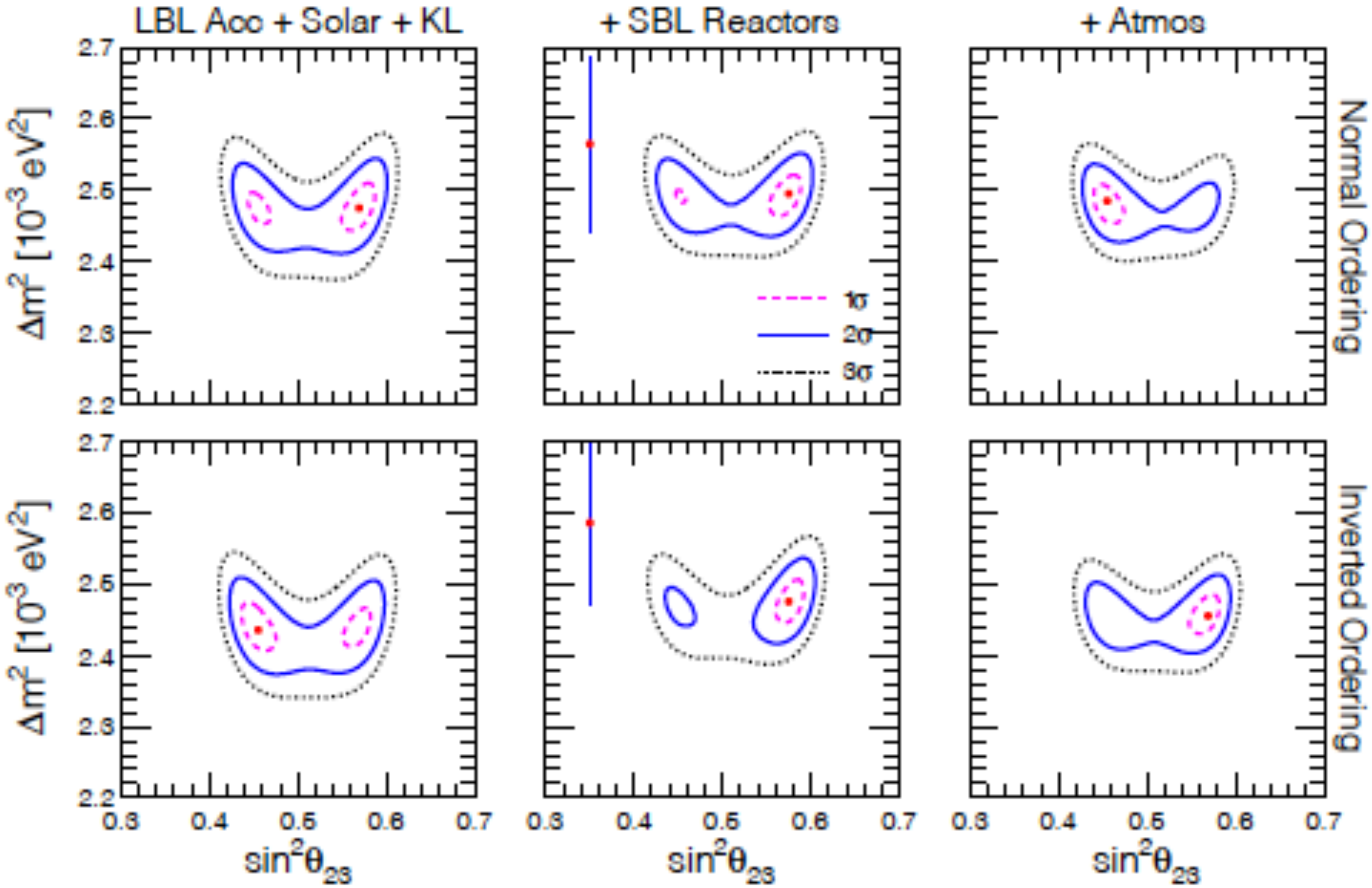
See also, de Salas, Forero, Gariazzo, Martinez-Mirave, Mena, Ternes, Tortolla, Valle, arXiv:2006.11237v2 [hep-ph]

Global Fit of Neutrino Oscillation Parameters Circa 2021



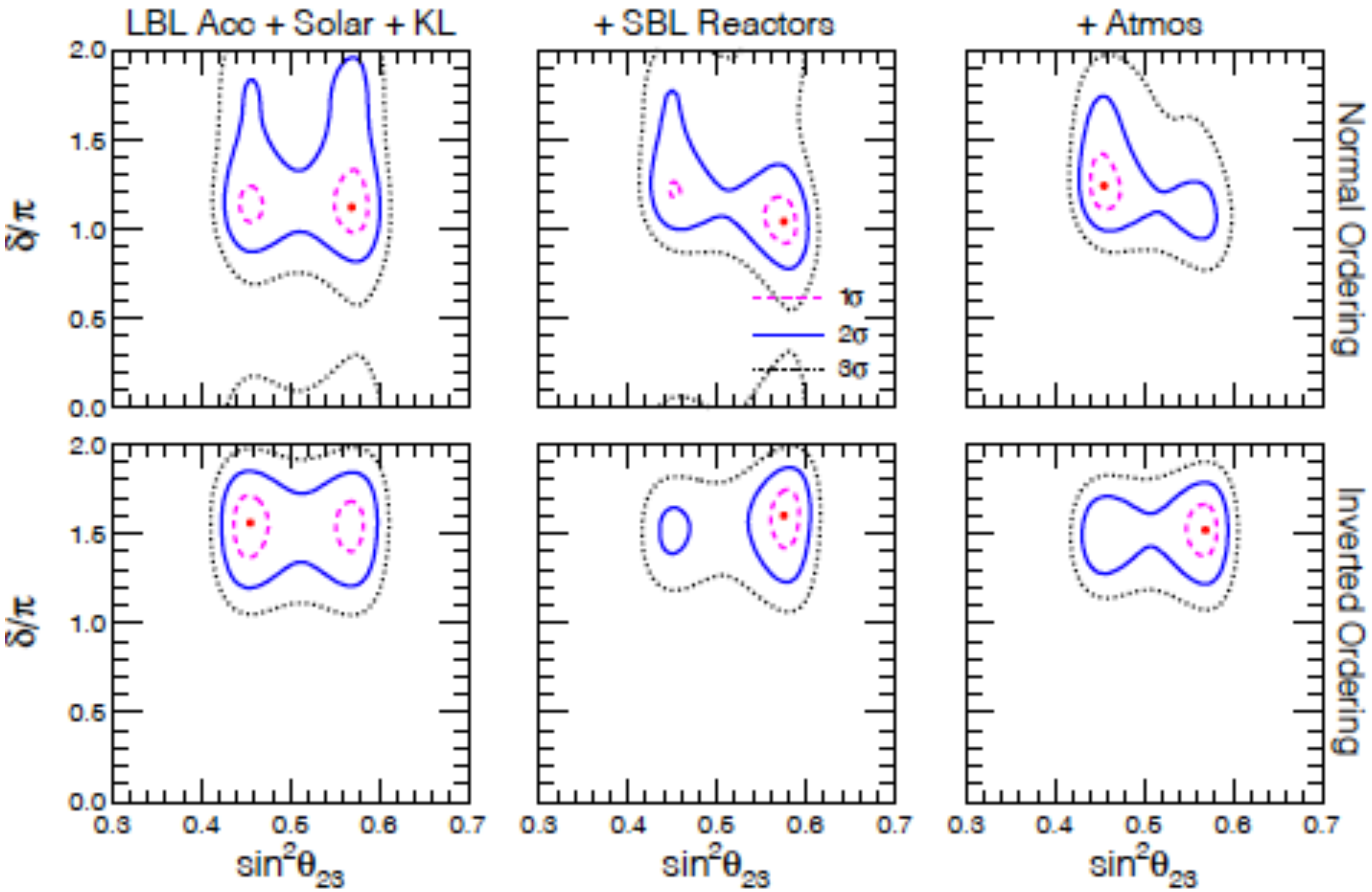
Capozzi, Valentino, Lisi, Marrone, Melchiorri, Palazzo, arXiv:2107.00532v1 [hep-ph]

Global Fit of Neutrino Oscillation Parameters Circa 2021



Capozzi, Valentino, Lisi, Marrone, Melchiorri, Palazzo, arXiv:2107.00532v1 [hep-ph]

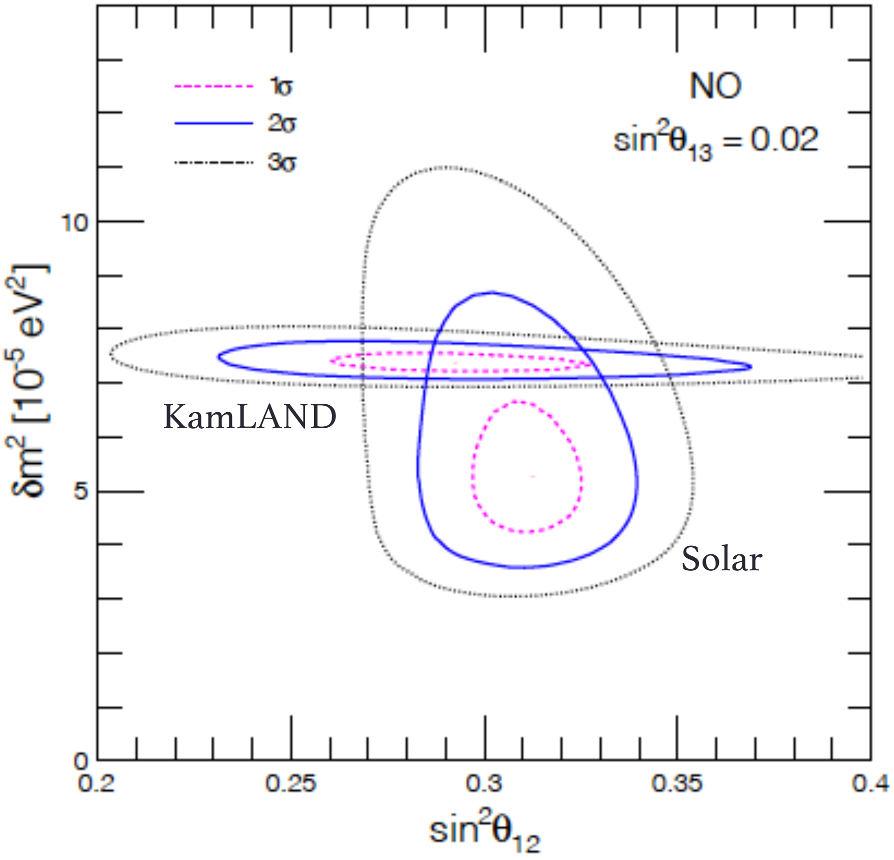
Global Fit of Neutrino Oscillation Parameters Circa 2021



Capozzi, Valentino, Lisi, Marrone, Melchiorri, Palazzo, arXiv:2107.00532v1 [hep-ph]

Tension between Solar and KamLAND data removed

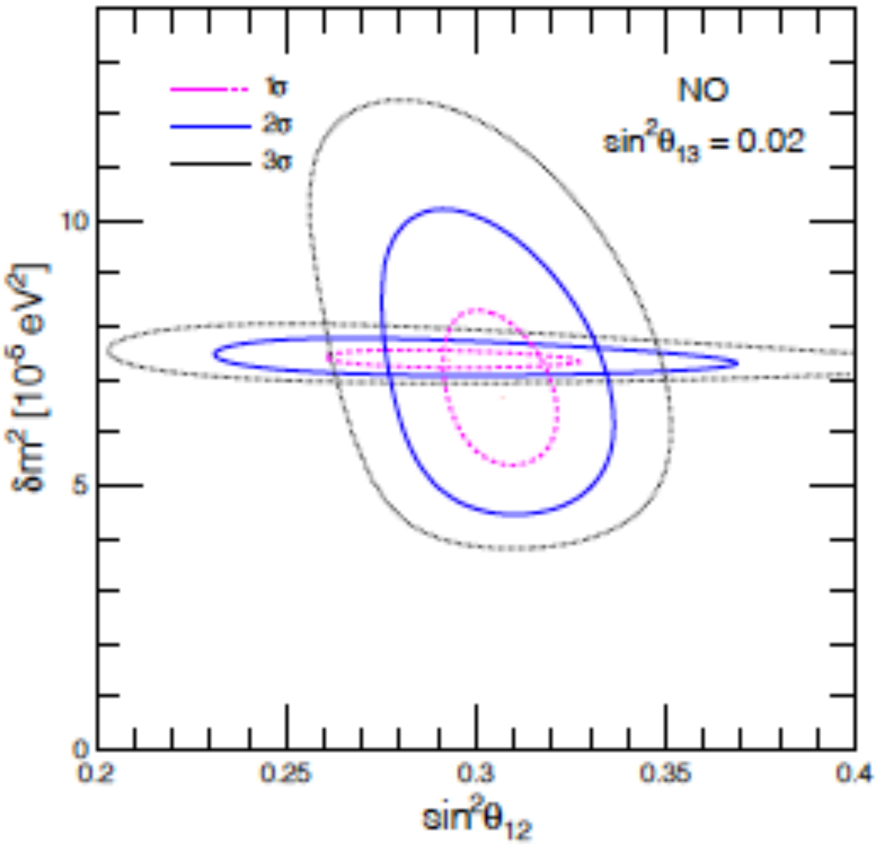
In 2018



< 2σ tension between Solar and KamLAND data

Capozzi, Lisi, Marrone, Palazzo, arXiv:1804.09678v1 [hep-ph]

In 2021

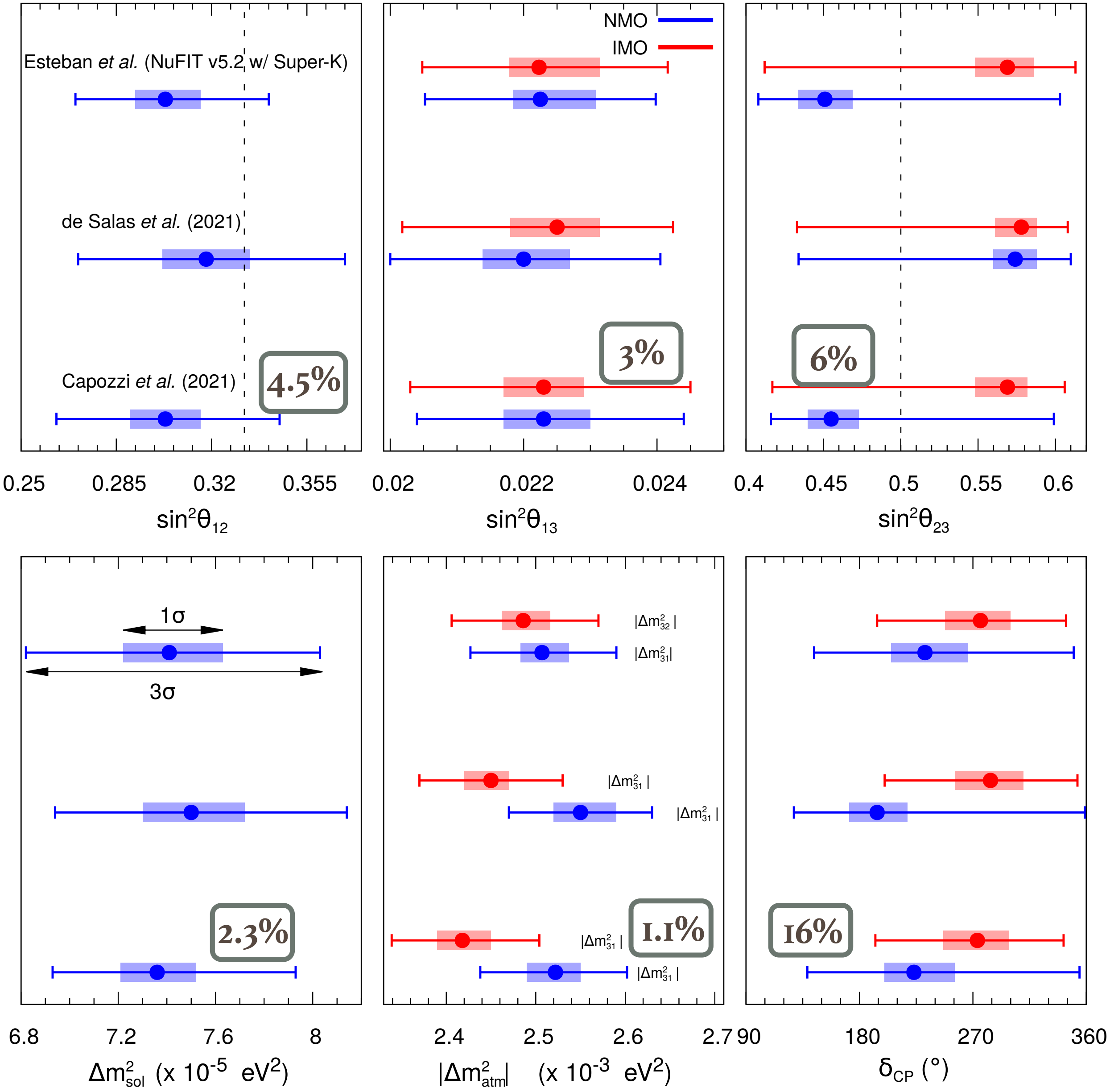


The tension is removed now!
Due to a slightly smaller day-night asymmetry in SK-IV 2970-day Solar data

Capozzi, Valentino, Lisi, Marrone, Melchiorri, Palazzo, arXiv:2107.00532v1 [hep-ph]

Remarkable Precision on Neutrino Oscillation Parameters

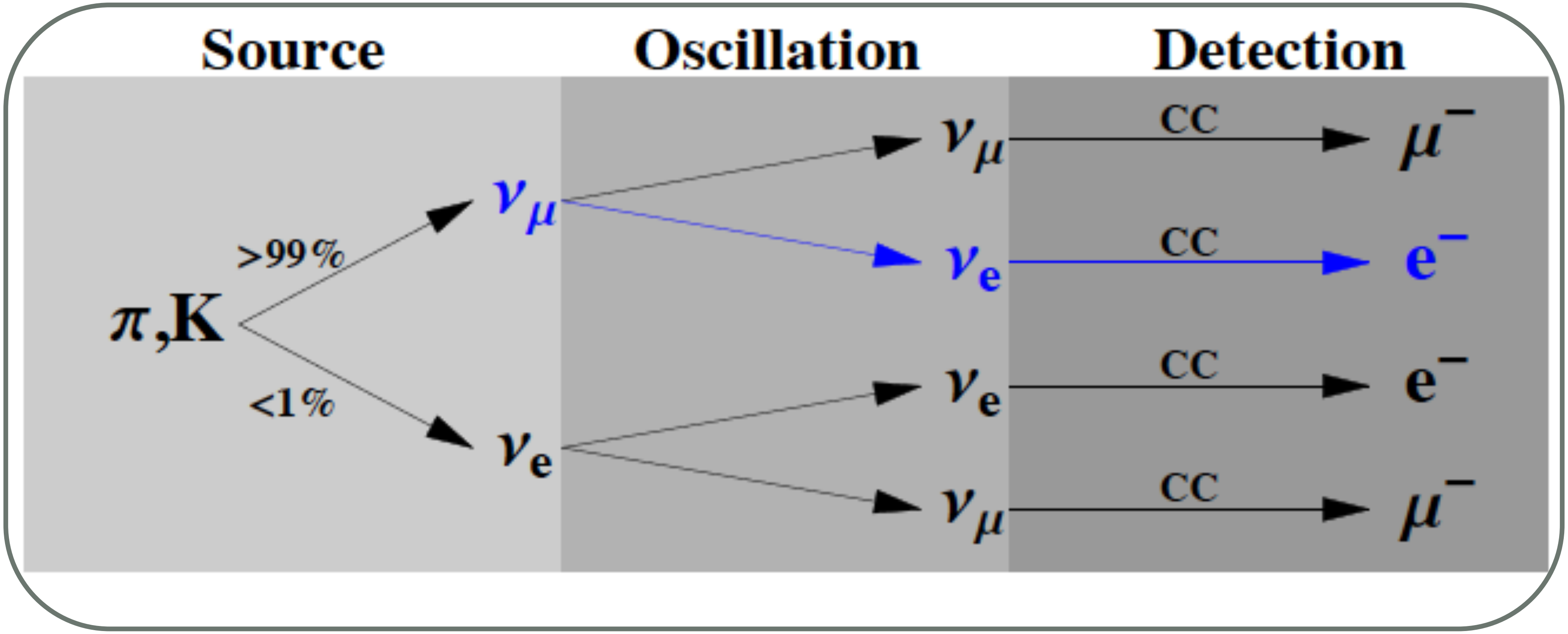
Robust three-flavor neutrino oscillation paradigm



Huge boost for the discovery of NMO, CPV, and θ_{23} Octant

Agarwalla, Kundu, Prakash, Singh, JHEP 03 (2022) 206

Superbeams



Traditional approach: Neutrino beam from pion decay

Accelerator Long-Baseline Neutrino Experiments

$\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$: Appearance Channel

$\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$: Disappearance Channel

T2K (Japan) & NOvA (USA) [running, off-axis]

FD: 295 km
1st Osc. Max. ~ 0.6 GeV

FD: 810 km
1st Osc. Max. ~ 1.6 GeV

narrow-band beam

DUNE (USA) [upcoming, on-axis]

FD: 1285 km
1st Osc. Max. ~ 2.6 GeV

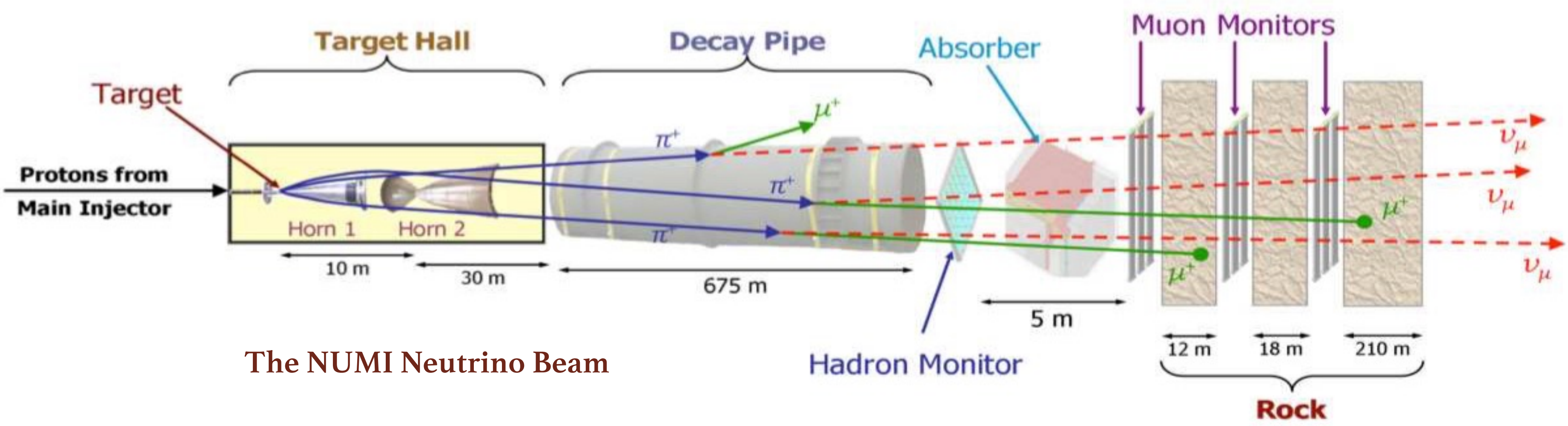
wide-band beam

T2HK (Japan) [upcoming, off-axis]

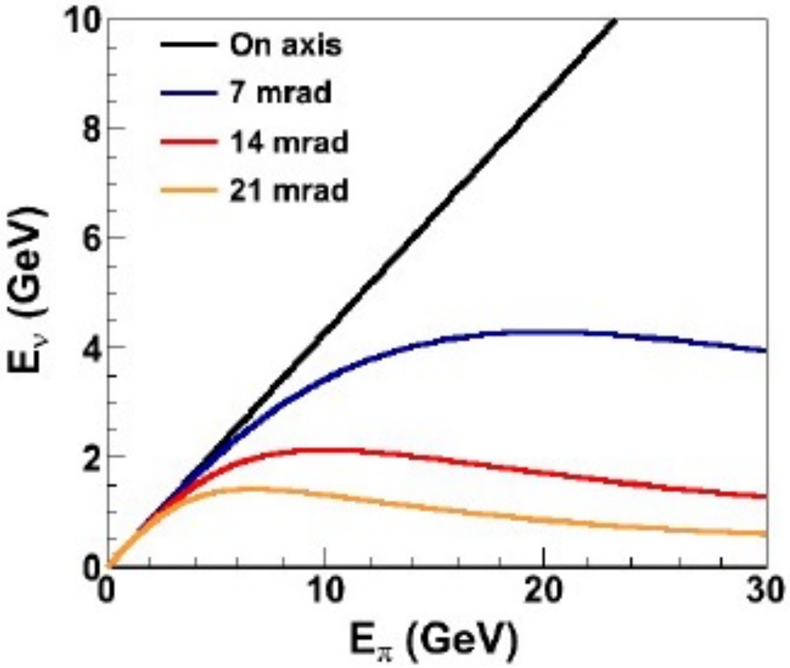
FD: 295 km
1st Osc. Max. ~ 0.6 GeV

narrow-band beam

Producing Neutrino Beam



The NUMI Neutrino Beam

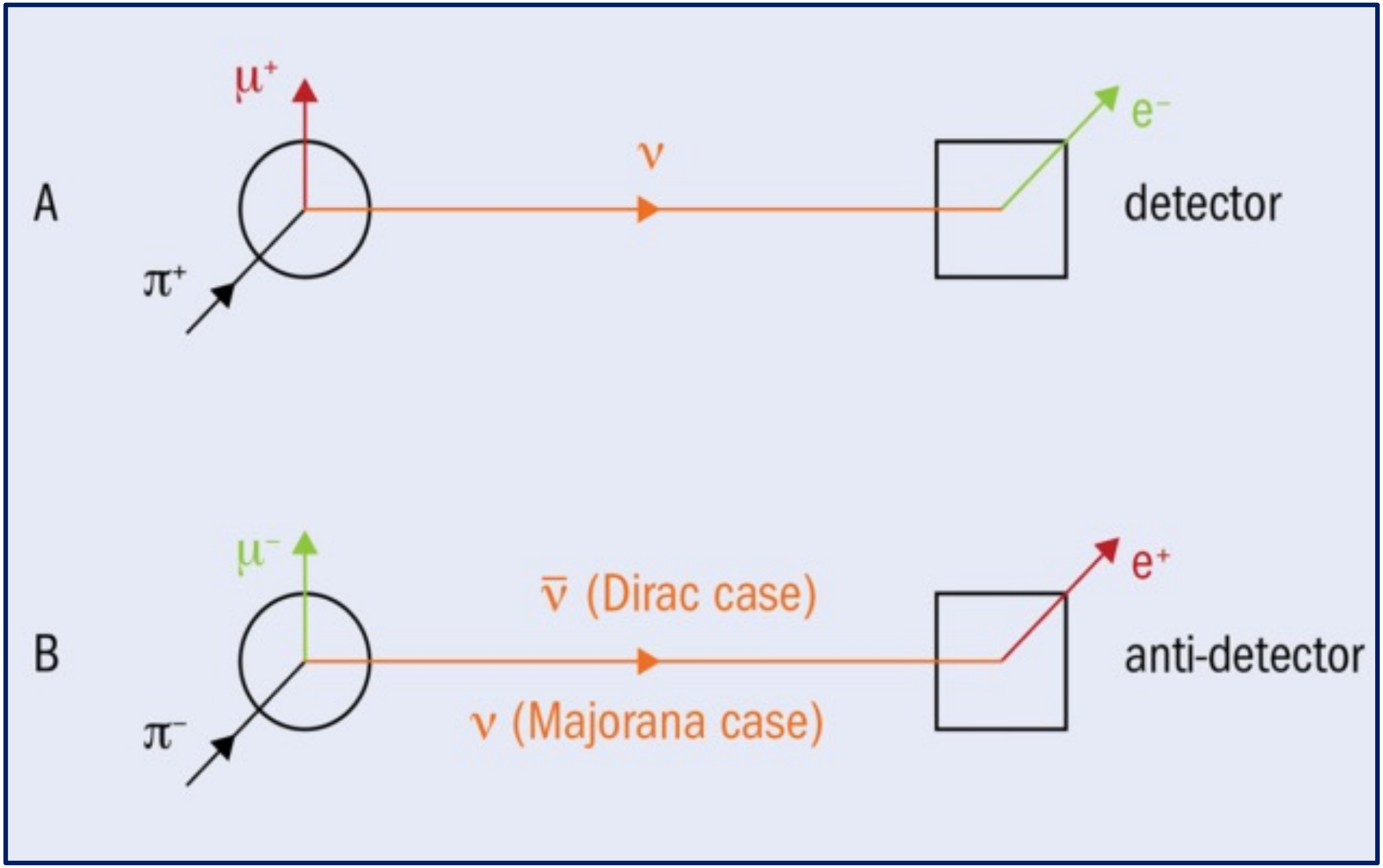


Two-body decay of pion: $\boxed{E_\nu \approx 0.43 \frac{E_\pi}{1+\gamma^2\theta_\nu^2}}$

- NOvA is 14 mrad off-axis
- Narrow-band beam peaks at 2 GeV
- Close to 1st oscillation maximum
- Reduces high-energy NC backgrounds

- T2K is at 2.5 degree (43.6 mrad) off-axis
- Narrow-band beam peaks at 0.6 GeV

The Pursuit of Leptonic CPV in LBL Experiments



The whole idea is based on comparing the rates of two CP-mirror-image processes

Above experimental approach is a perfectly valid probe of leptonic CPV regardless of whether neutrinos are Dirac or Majorana particles

Three-Flavor Effects in $\nu_\mu \to \nu_e$ Oscillation Channel

The appearance probability $(\nu_\mu \to \nu_e)$ in matter, upto second order in the small parameters $\underbrace{\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}}_{0.03}$ and $\underbrace{\sin 2\theta_{13}}_{0.3}$,

$$P_{\mu e} \simeq \underbrace{\sin^2 2\theta_{13}}_{0.09} \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2}$$

→ θ_{13} driven

$$- \underbrace{\alpha \sin 2\theta_{13}}_{0.009} \xi \sin\delta_{CP} \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})}$$

→ CP-odd

$$+ \alpha \sin 2\theta_{13}\, \xi \cos\delta_{CP} \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})}$$

→ CP-even

$$+ \underbrace{\alpha^2}_{0.0009} \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2};$$

→ Solar Term

Resolves octant

where $\Delta \equiv \Delta m^2_{31} L/(4E)$, $\xi \equiv \cos\theta_{13} \sin 2\theta_{21} \sin 2\theta_{23}$,
and $\hat{A} \equiv \pm(2\sqrt{2} G_F n_e E)/\Delta m^2_{31}$

changes sign with sgn(Δm^2_{31})
key to resolve hierarchy!

changes sign with polarity
causes fake CP asymmetry!

Cervera et al., hep-ph/0002108
Freund et al., hep-ph/0105071
Agarwalla et al., e-Print: 1302.6773 [hep-ph]

This channel suffers from: (Hierarchy – δ_{CP}) & (Octant – δ_{CP}) degeneracies. How can we break them?

Current Long-Baseline Experiments: T2K and NOvA

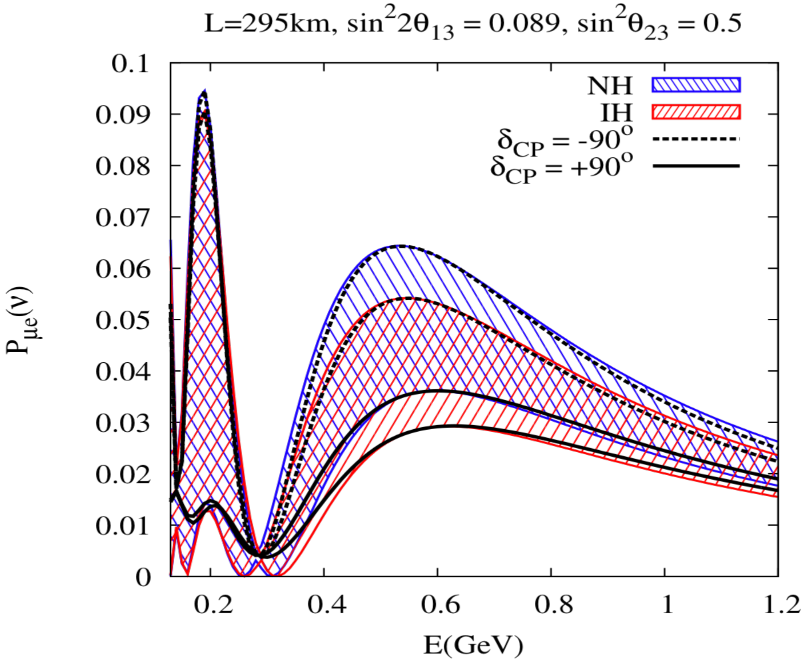
T2K & NOvA operate at different energies and baselines

Complement each other & help to remove degeneracies among various oscillation parameters

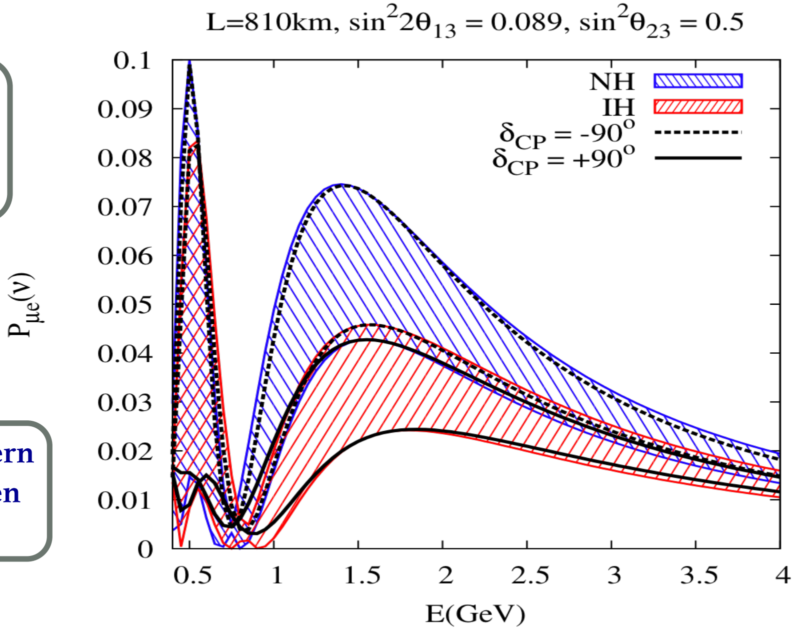
Probe multiple oscillation maxima

Compare neutrino and antineutrino oscillation probabilities

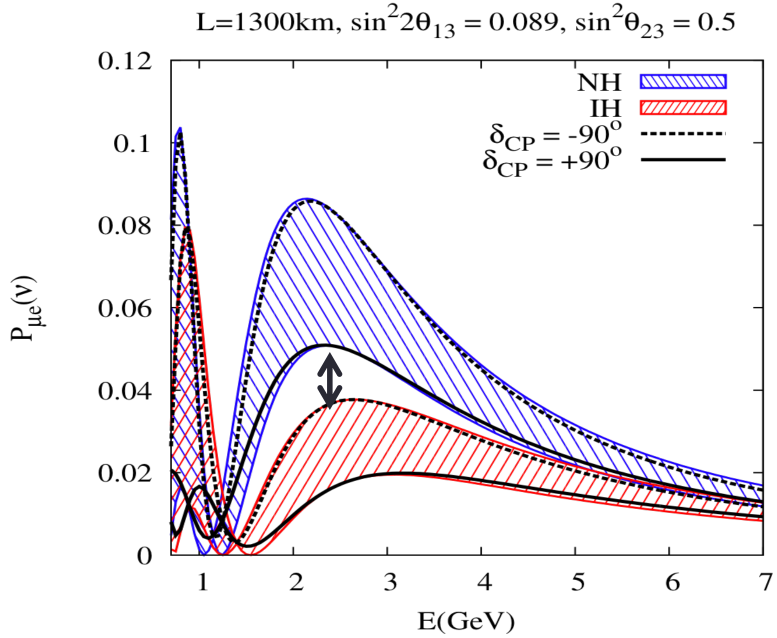
Hierarchy – δ_{CP} degeneracy in $\nu_\mu \rightarrow \nu_e$ oscillation channel


L=295km, $\sin^2 2\theta_{13} = 0.089$, $\sin^2\theta_{23} = 0.5$

For ν:
Max: NH, -90°
Min: IH, 90°

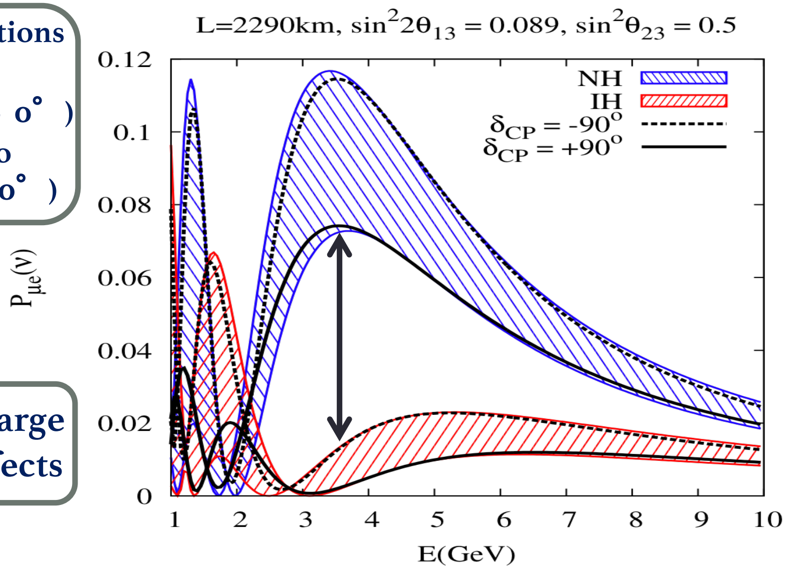

L=810km, $\sin^2 2\theta_{13} = 0.089$, $\sin^2\theta_{23} = 0.5$

Degeneracy pattern
different between
T2K & NOνA


L=1300km, $\sin^2 2\theta_{13} = 0.089$, $\sin^2\theta_{23} = 0.5$

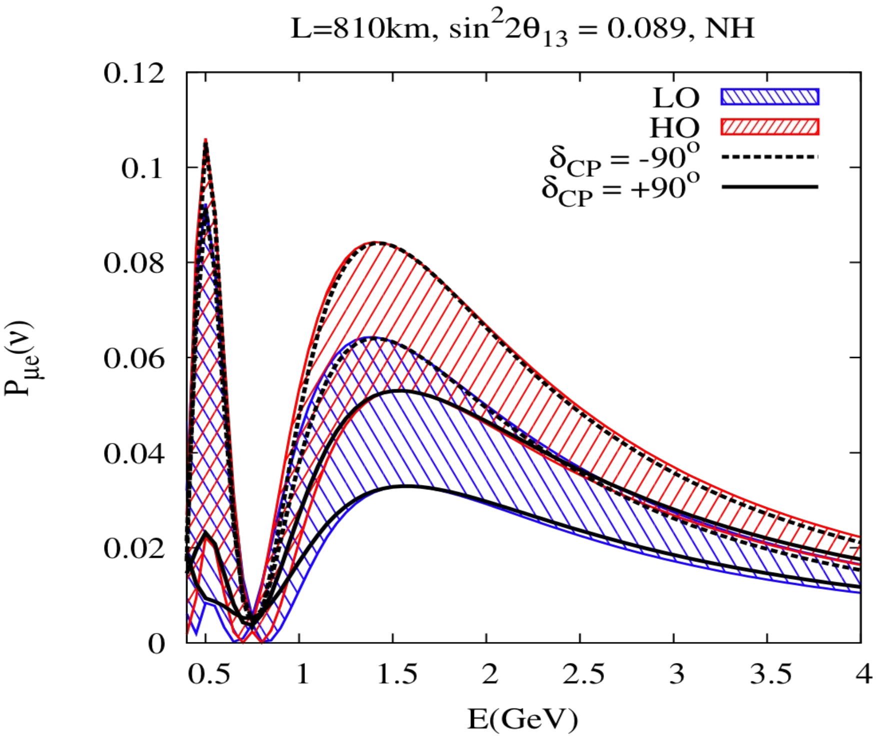
Favorable combinations
For neutrino
NH, LHP (-180° to 0°)
For antineutrino
IH, UHP (0° to 180°)

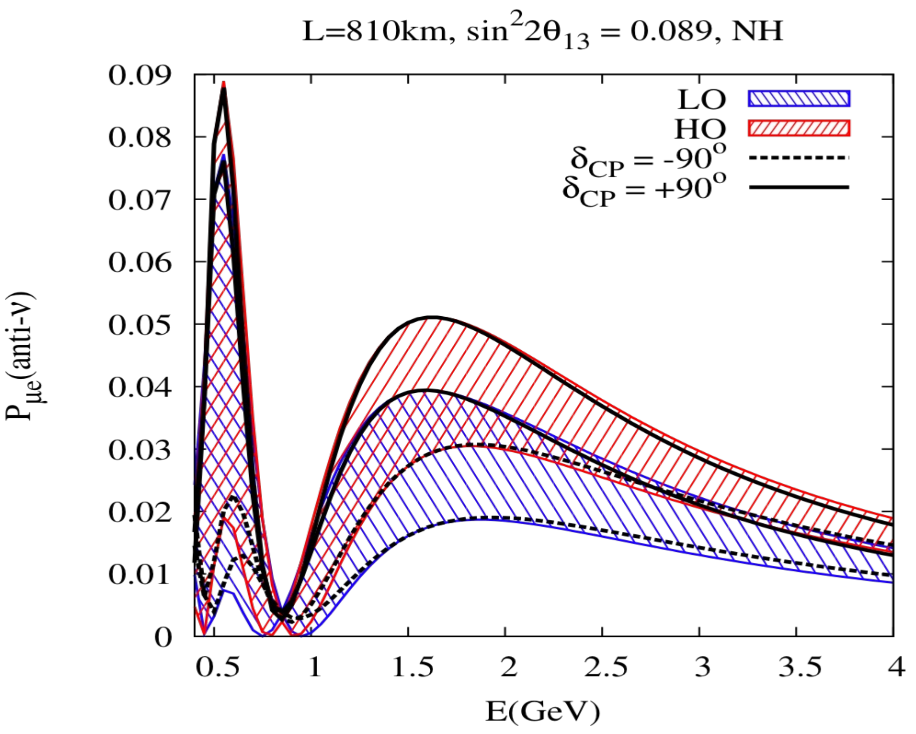
Large θ_{13} causes large
Earth matter effects


L=2290km, $\sin^2 2\theta_{13} = 0.089$, $\sin^2\theta_{23} = 0.5$

Agarwalla, Prakash, Raut, Sankar, 2012-2013

Octant – δ_{CP} degeneracy in $\nu_\mu \rightarrow \nu_e$ oscillation channel





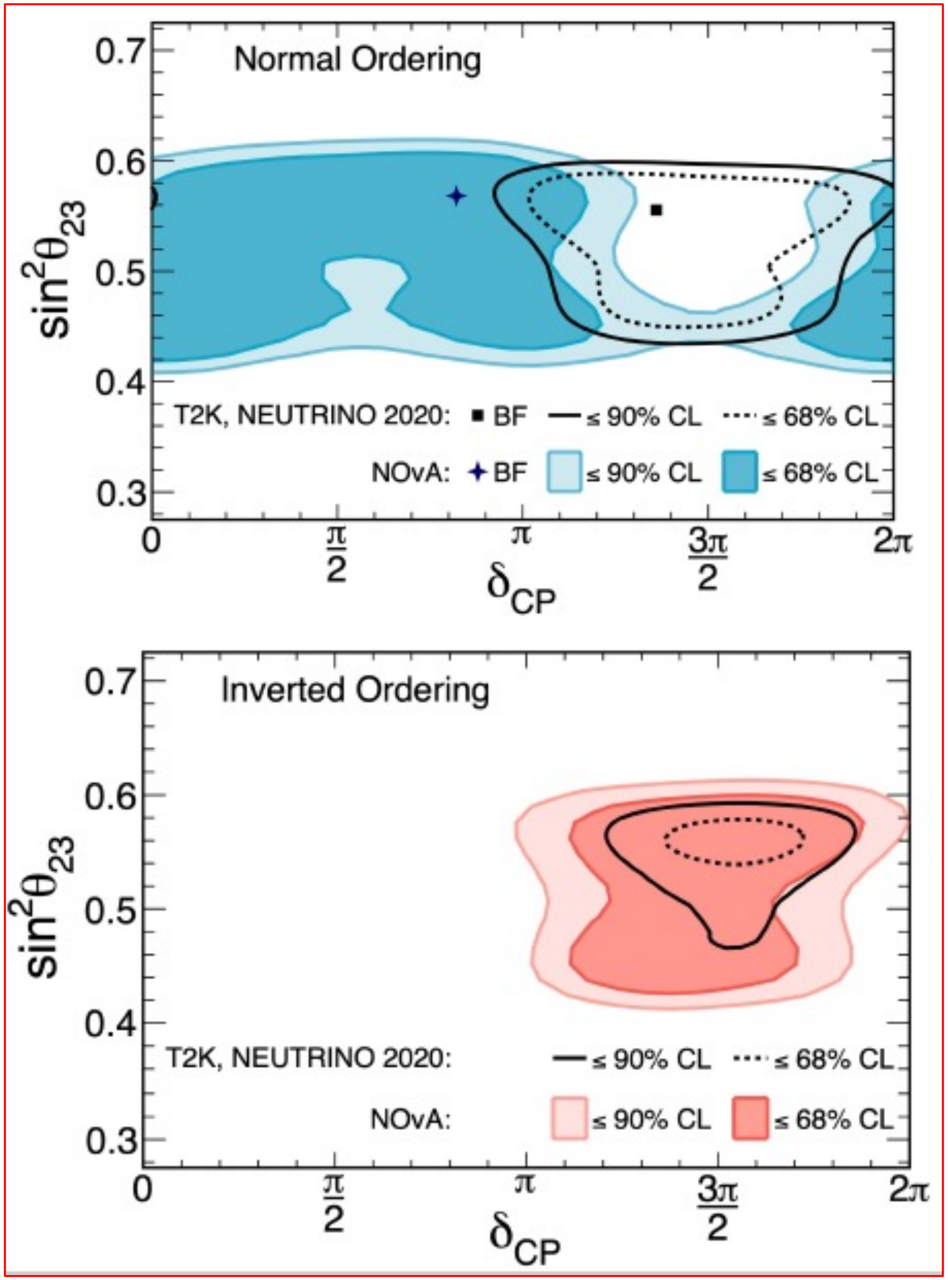
For neutrino:
Maximum: HO, -90°
Minimum: LO, 90°

For anti-neutrino:
Maximum: HO, 90°
Minimum: LO, -90°

Unfavorable CP values for neutrino are favorable for antineutrino & vice-versa

Agarwalla, Prakash, Sankar, arXiv: 1301.2574

Latest CP Measurements from T2K and NOvA



Complementarity between T2K & NOvA

Both T2K & NOvA individually show a slight preference for NMO

NMO: T2K excludes large regions of the NOvA constraints at 90% C.L., & NOvA excludes parts of T2K's 90% C.L. region

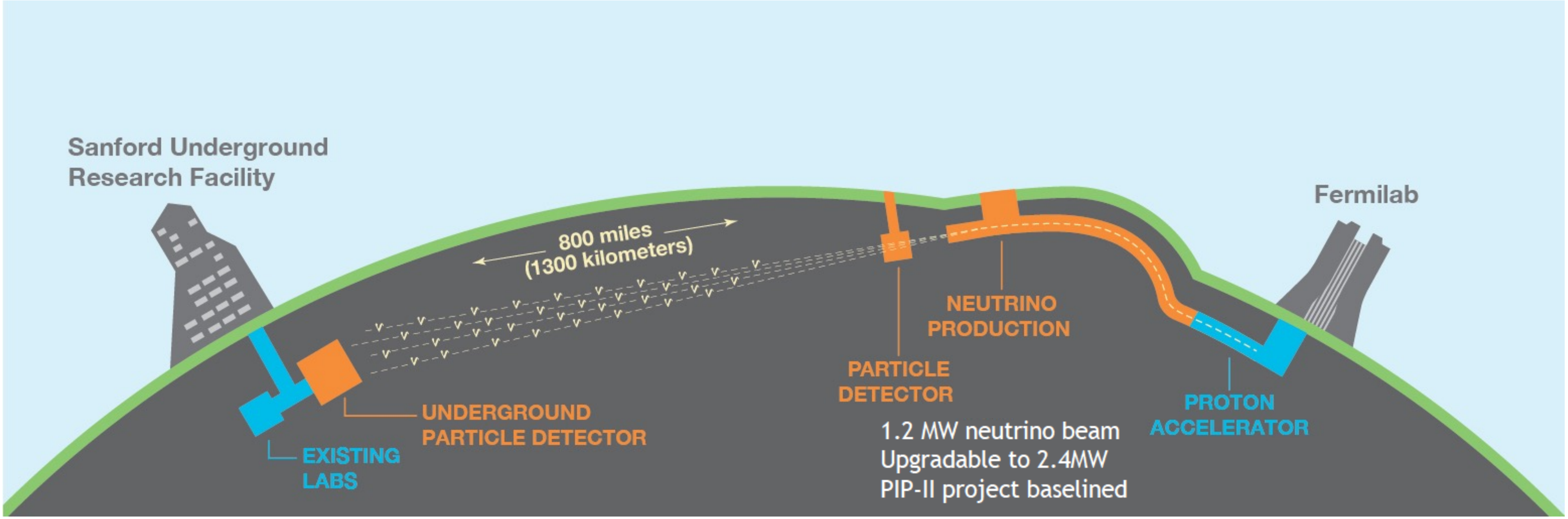
IMO: Both the experiments consistently favour the π < δ_{CP} < 2π region, with a weak preference for the upper octant

Both the experiments need more data (at present statistically limited) to have better measurements

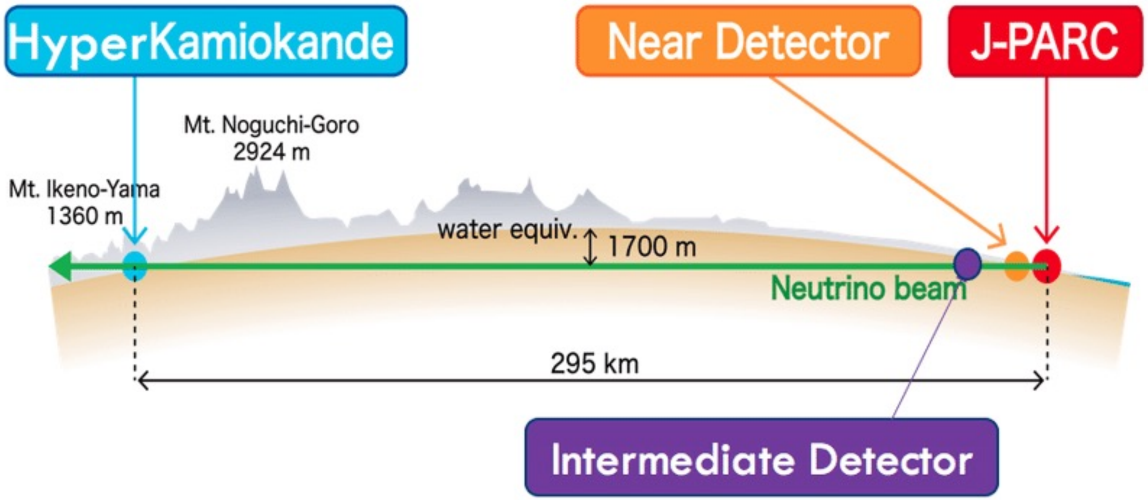
Joint oscillation analyses between T2K, Super-K, & NOvA would be very helpful

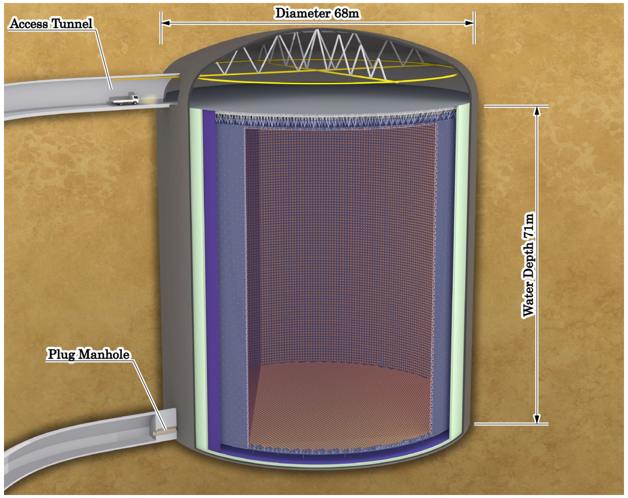
T2K: arXiv:2303.03222 [hep-ex]
NOvA: arXiv: 2108.08219 [hep-ex]

Future Long-Baseline Experiments: DUNE, T2HK, and

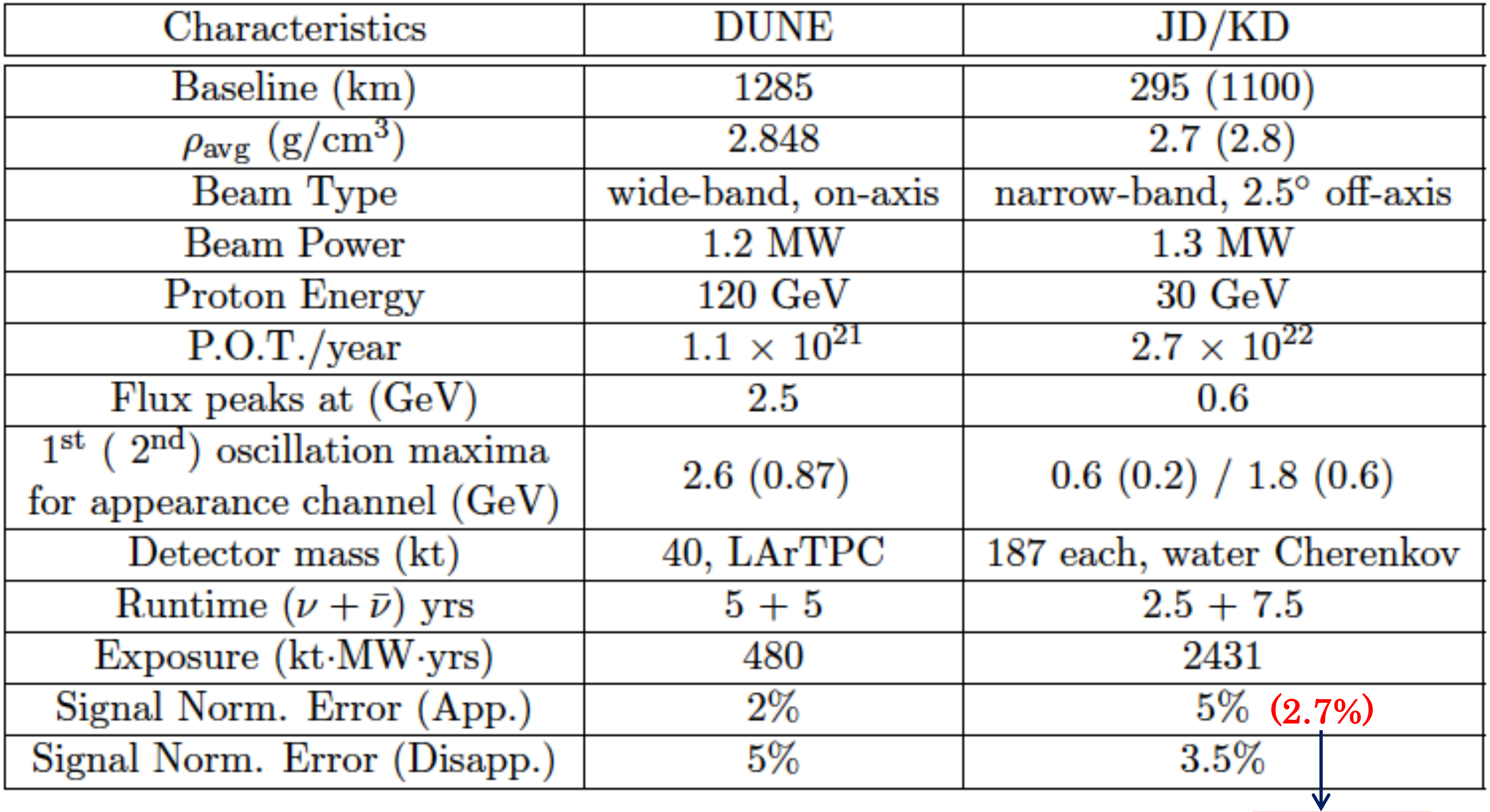


1.2 MW neutrino beam
Upgradable to 2.4MW
PIP-II project baselined





Essential Features of DUNE, T2HK (JD), and T2HKK (JD+KD)



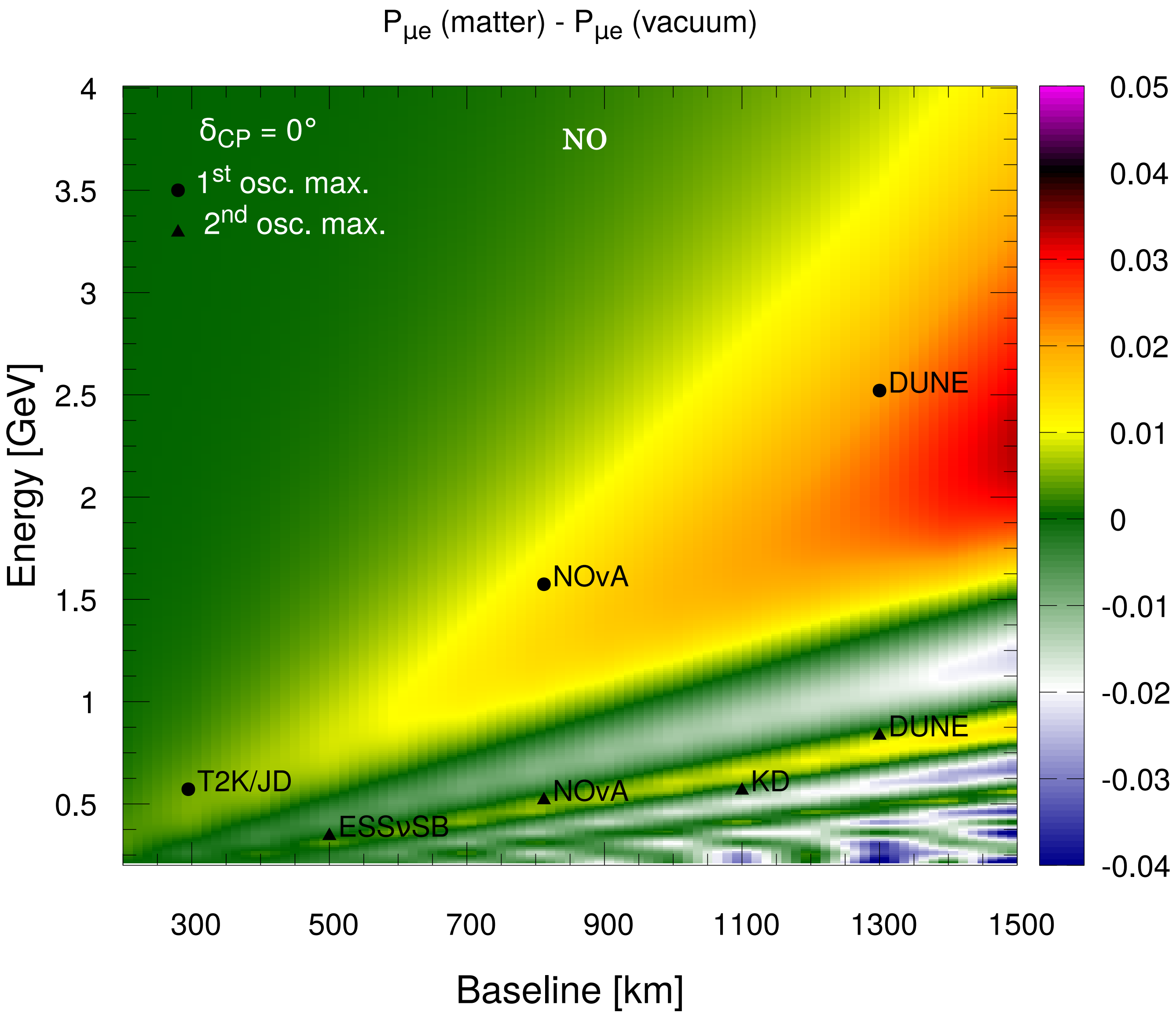
Characteristics	DUNE	JD/KD
Baseline (km)	1285	295 (1100)
ρ_{avg} (g/cm^3)	2.848	2.7 (2.8)
Beam Type	wide-band, on-axis	narrow-band, 2.5° off-axis
Beam Power	1.2 MW	1.3 MW
Proton Energy	120 GeV	30 GeV
P.O.T./year	1.1×10^{21}	2.7×10^{22}
Flux peaks at (GeV)	2.5	0.6
1st (2nd) oscillation maxima for appearance channel (GeV)	2.6 (0.87)	0.6 (0.2) / 1.8 (0.6)
Detector mass (kt)	40, LArTPC	187 each, water Cherenkov
Runtime ($\nu + \bar{\nu}$) yrs	5 + 5	2.5 + 7.5
Exposure (kt·MW·yrs)	480	2431
Signal Norm. Error (App.)	2%	5% (2.7%)
Signal Norm. Error (Disapp.)	5%	3.5%

Due to upgraded ND280 & a new Intermediate Water Cherenkov Detector (IWCD) ~ at 1 km

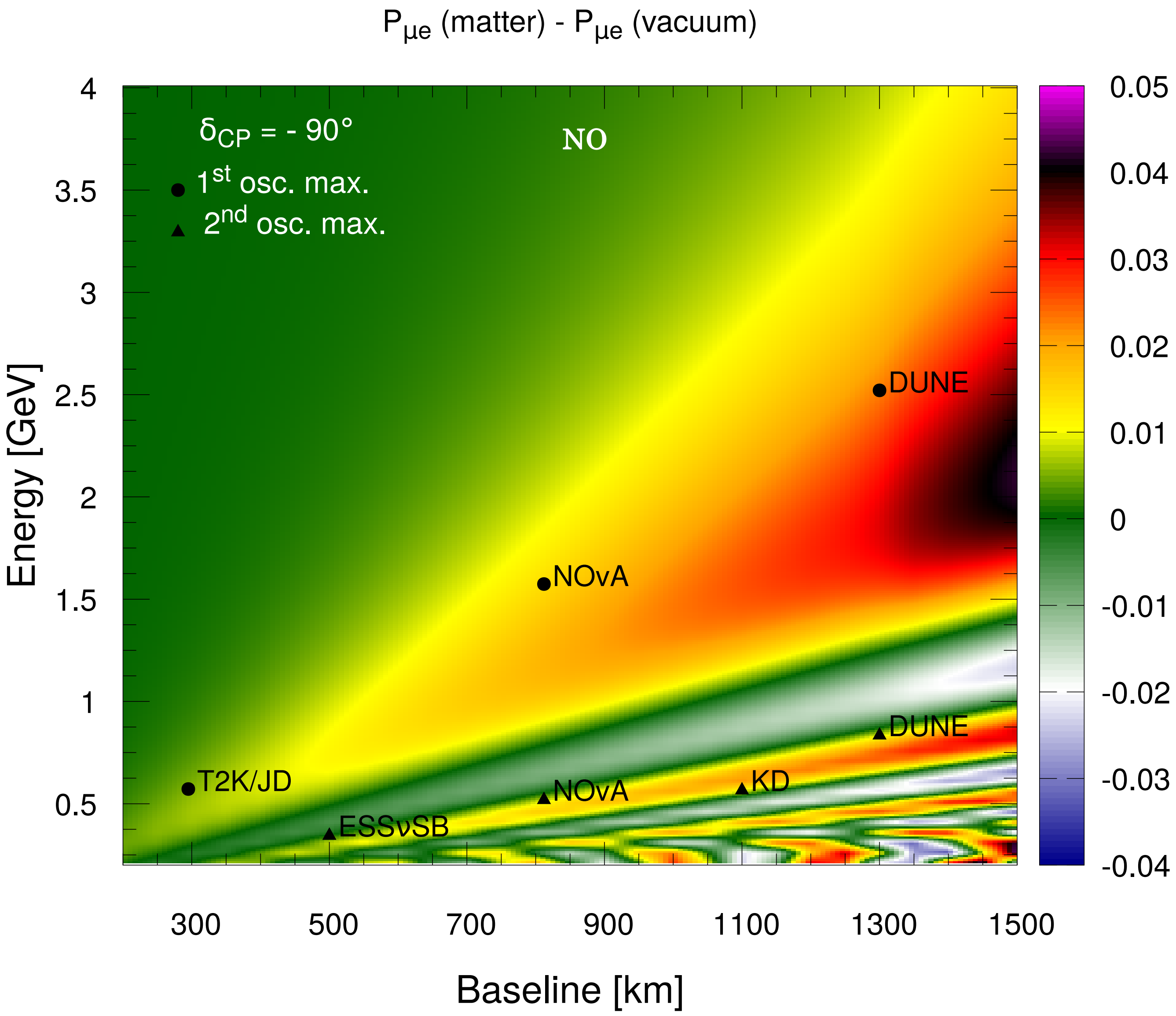
DUNE Collaboration: arXiv:2103.04797 [hep-ex]

Hyper-Kamiokande Collaboration: arXiv:1611.06118 [hep-ex]

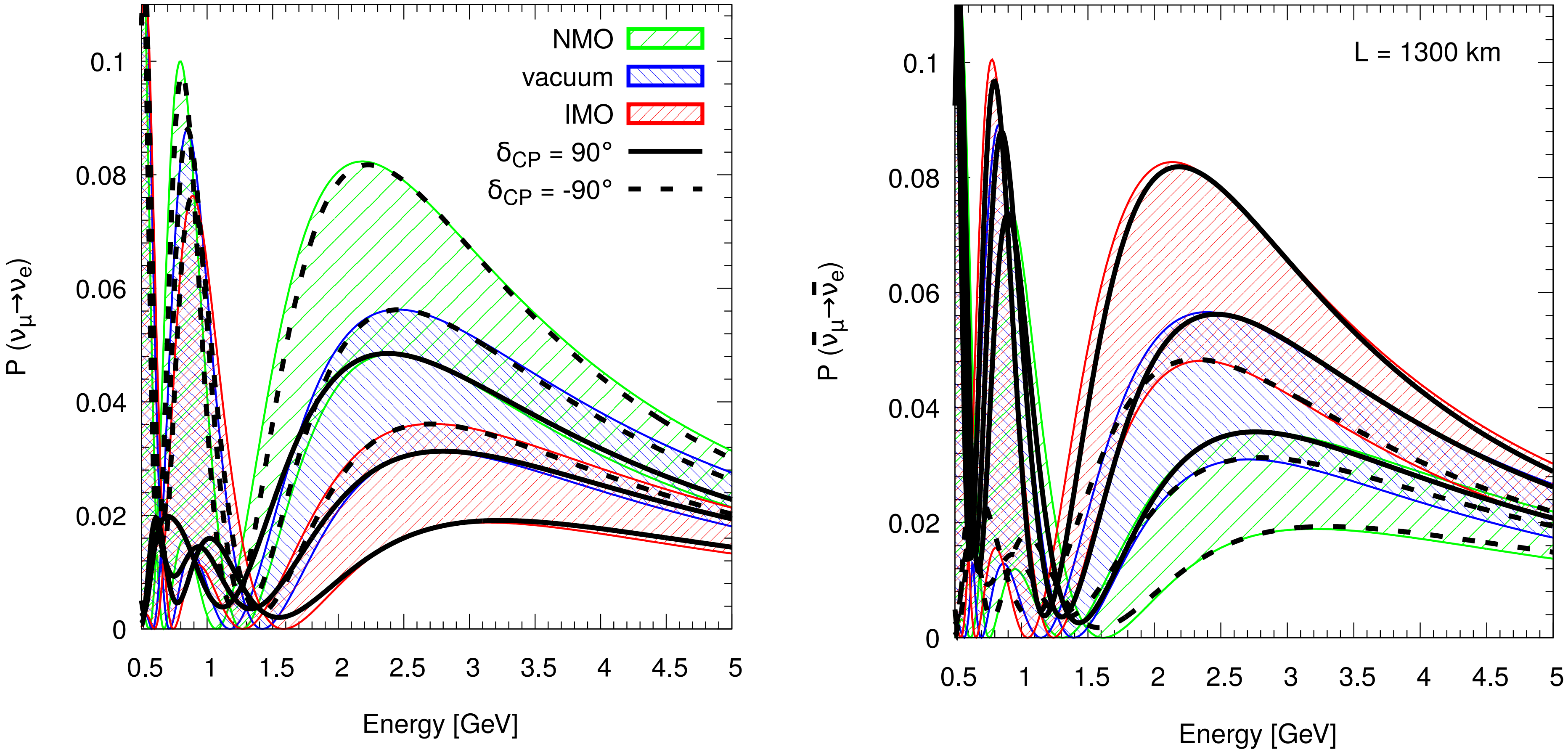
Matter Effect in Long-Baseline Experiments



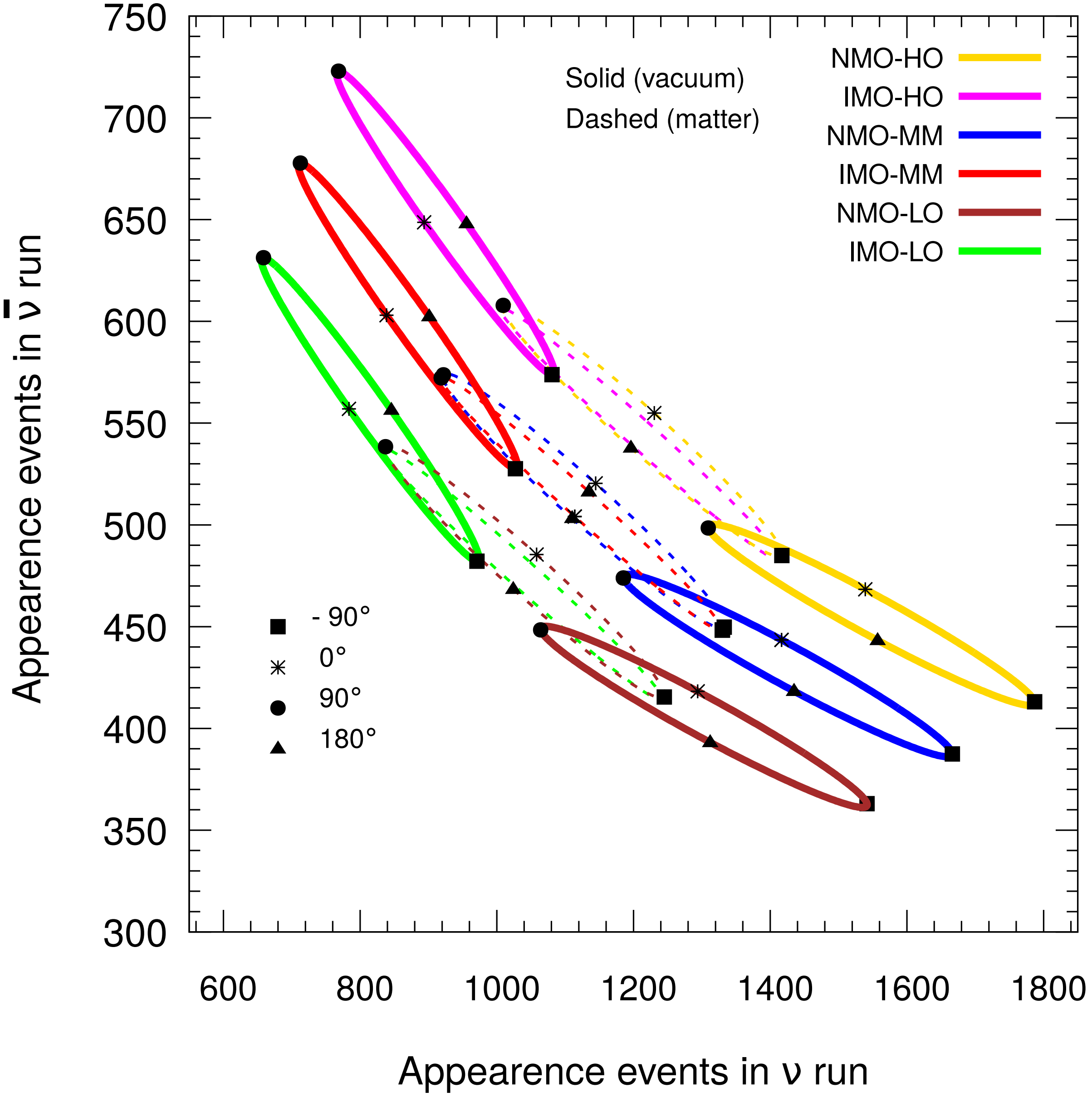
Matter Effect in Long-Baseline Experiments



Matter Effect in Long-Baseline Experiments



Matter Effect in DUNE



Extra Slides

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

Neutrino Interaction Cross Section

Elastic scattering: $\bar{\nu}e^- \rightarrow \bar{\nu}e^-$

Dimensional estimate assuming $E_{\mathrm{CM}} \gg m_e$: $\boxed{\sigma \sim G_F^2 E_{\mathrm{CM}}^x}$

(E_{CM} is the only available Lorentz-invariant scale parameter)

Dimensional analysis:

$[\mathrm{GeV}^{-2}] = [\mathrm{GeV}^{-4}][\mathrm{GeV}^x]$ ⇨ $x = 2$

$$\boxed{\sigma \sim G_F^2 E_{\mathrm{CM}}^2}$$

Energies in the CM frame (E_{CM}) and the lab frame (E_ν)

$$E_{\mathrm{CM}}^2 = (E_{\bar{\nu}} + m_e)^2 - p_{\bar{\nu}}^2 \approx 2m_e E_{\bar{\nu}}$$

Therefore, $\sigma \sim 2m_e G_F^2 E_{\bar{\nu}}$

Neutrino Interaction Cross Section

Natural units: $\sigma \sim 2m_e G_F^2 E_{\bar{\nu}}$ [unit: GeV^{-2}]

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

[Unit: GeV^{-2} × (GeV×cm)^2 = cm^2]

The cross-section has a linear energy-dependence

Numerically,

$$\begin{aligned}\sigma &\sim 2m_e G_F^2 E_{\bar{\nu}}(\hbar c)^2 = \\ &= 2 \cdot 0.5\ \mathrm{MeV} \cdot (1.166 \times 10^{-5}\ \mathrm{GeV}^{-2})^2 E_{\bar{\nu}}(0.2\ \mathrm{GeV\ fm})^2 \sim \\ &\sim 10^{-43} \left(\frac{E_{\bar{\nu}}}{\mathrm{MeV}}\right)\ \mathrm{cm}^2\end{aligned}$$

Neutrino Mean Free Path

Mean free path of a typical reactor/solar (~1 MeV) (anti)neutrino in rock:

$$\lambda = (n\sigma)^{-1} \approx \left(\frac{\rho}{2m_p}\sigma\right)^{-1} \approx \frac{2 \times 1.67 \times 10^{-24}\ \mathrm{g}}{3\ \mathrm{g/cm^3} \times 10^{-43}\ \mathrm{cm^2}} \approx$$

$$\approx\ 10^{17}\ \mathrm{m} \approx 10\ \text{light years}$$

n: density of protons [cm^{-3}].
ρ: density of matter [g cm^{-3}].
About half of the nucleons are protons.

(~ distance to α Canis Minoris)

Consider a ~1 MeV neutrino produced in the Solar core.
Probability of interaction before leaving Sun:

$$P = 1 - e^{-R_\odot/\lambda} \approx R_\odot/\lambda \sim \frac{7 \times 10^8\ \mathrm{m}}{10^{17}\ \mathrm{m}} \sim 10^{-8}$$

(average Solar density = 1.4 g/cm^3)

Take Home Message →

Low energy neutrinos are direct probes into the Sun's (and Earth's) interior
(but not into neutron stars having densities around 10^{14} g/cm^3)

Neutrino Detection

Starting point: imagine you want to build a neutrino detector

→ to measure neutrino oscillation parameters
→ or to peer deep into the Universe
→ or to look for some other exciting new physics related to neutrinos

Things to keep in mind:

a) what type of neutrino do you want to detect? ν_e , ν_μ , ν_τ or $\bar{\nu}_e$, $\bar{\nu}_\mu$, $\bar{\nu}_\tau$

b) what is the source of neutrinos? influences the energy of ν and interaction type(s)

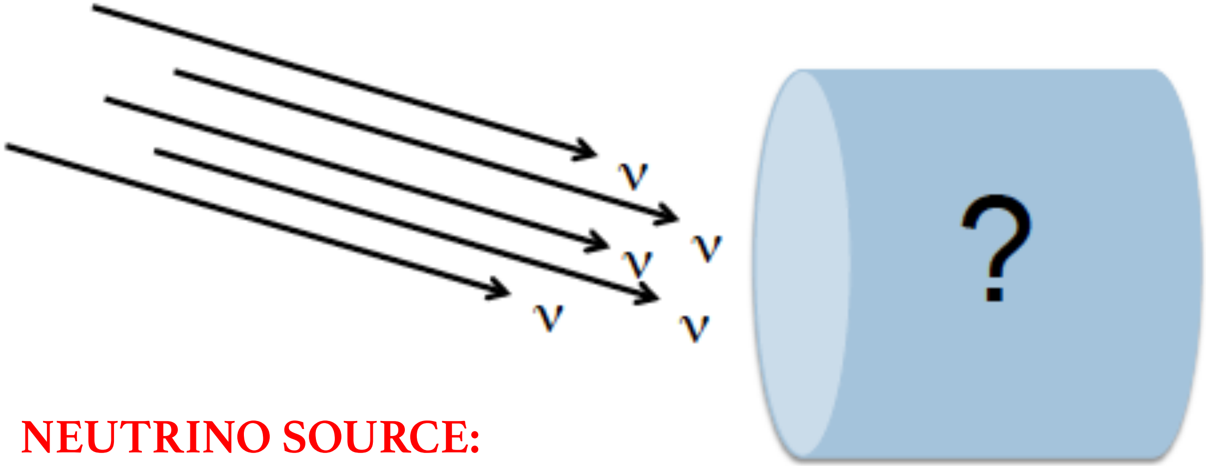
c) what do you want to measure?
– final state particles? – directional information? – energy information?

d) how many events do you need to achieve the required sensitivity?
– determines the size of the detector and what you put in

e) how much money do you have? **(most important!)**

Neutrino Detection

Let us start the game.....



NEUTRINO DETECTOR

NEUTRINO SOURCE:

Supernova, Sun, Atmosphere, Cosmic, Geo-neutrinos

Accelerator, Reactor, Radioactive Decays

QUESTIONS?

- How many neutrino interactions should I expect to see?
- How will they look like?

Neutrino Economics

$$N_\nu(E) \sim \Phi_\nu(E) \times \sigma_\nu(E) \times \text{target}$$

ν flux

(# neutrinos)

depends on your ν source

at 1 GeV $\sigma(\nu p) \sim 10^{-38}$ cm^2

compare to $\sigma(pp) \sim 10^{-26}$ cm^2

→ *ν physics is a very patient business*

ν cross section

tiny ($\sim 10^{-38}$ cm^2)

$\sigma_\nu^{tot} \sim E_\nu$

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$

tells you the probability for a ν to interact with another particle

H. Bethe and R. Peirels:

- **"there is no practically possible way of observing the neutrino"**

Neutrino Economics

$$N_\nu(E) \sim \Phi_\nu(E) \times \sigma_\nu(E) \times \text{target}$$

ν flux

(# neutrinos)

depends on your ν source

make this large!

detector

(# targets, detection ε)

make this large!

ν cross section

tiny ($\sim 10^{-38}$ cm^2)

$\sigma_\nu^{tot} \sim E_\nu$

can't do much about this unless you can increase the energy of your neutrinos

Designing a Neutrino Detector

Reactor antineutrino production rate per unit of thermal power:

$F_\nu / P_{th} \sim 10^{20}\ s^{-1}GW^{-1}$.

Power output of a typical reactor: $P_{th} \sim 1$ GW, therefore $F_\nu \sim 10^{20}\ s^{-1}$.

Let's place a detector at a distance $L = 10m$ from the reactor core.

Antineutrino flux at the detector: $d\Phi/dt = F_\nu / (4\pi L^2) \sim 10^{13}\ cm^{-2}\ s^{-1}$.

Detector active mass: $m_{det} = 100$ kg.

Rate of IBD interactions in the detector:

$F_{int} \approx (m_{det}/(2m_p))\sigma(d\Phi/dt) \approx 0.3\times10^{29}\times10^{-43}\ cm^2\times10^{13}\ cm^{-2}s^{-1} = 0.03\ s^{-1}$.

~2 interactions / minute

Most reactor antineutrinos are below IBD threshold.
Also, some protons are bound in nuclei (80% for H_2O).
The detector is not 100% efficient. Rate of detected interactions:

~ few interactions / hour

IBD Detection Principle

Inverse beta decay signature:

prompt signal from the positron annihilation +
delayed signal from the neutron capture

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$E_{threshold} = 1.8$ MeV

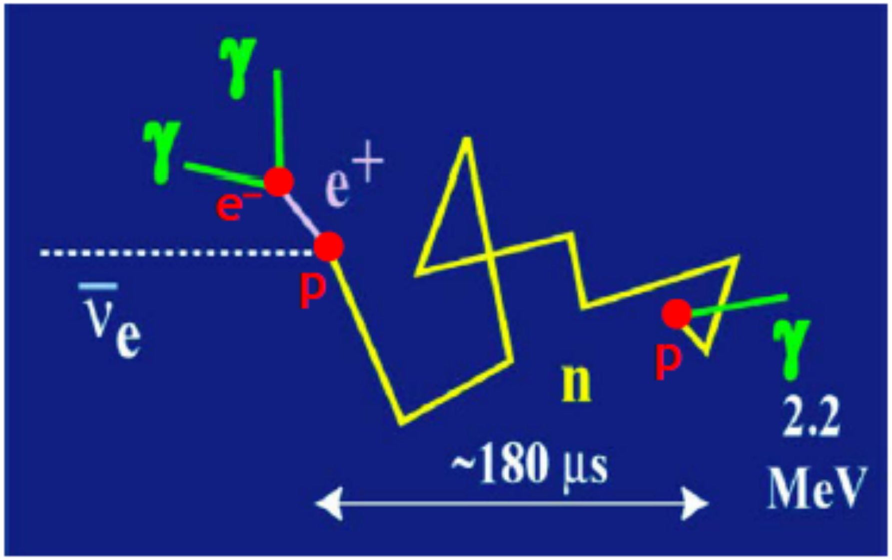
Positron detection: via annihilation

$$\boxed{e^+ + e^- \rightarrow \gamma + \gamma}$$

Neutron detection:
via thermalization & capture, e.g.

$$\boxed{n + p \rightarrow d + \gamma \ (2.2\ \mathrm{MeV})}$$

(typical capture time τ~200 μs)
(τ~10μs for Cd, Gd-doped targets)



A possible detector type: scintillation detector

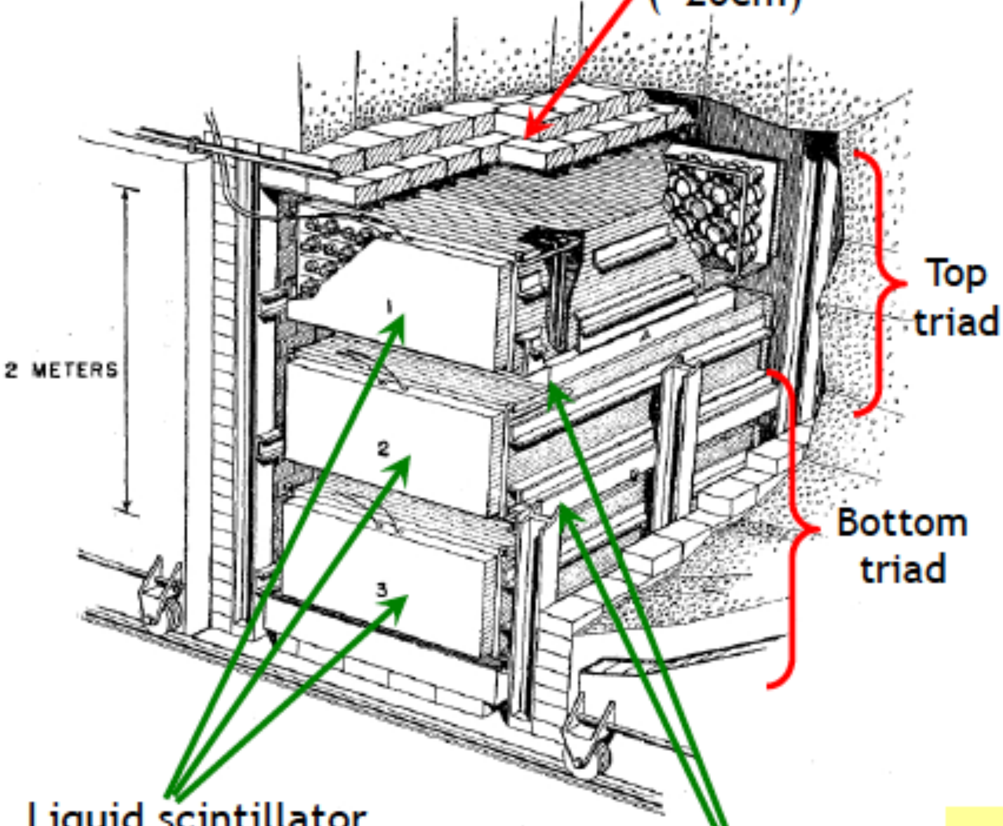
Scintillation: fast (~1ns) isotropic luminescence produced by absorption of ionising radiation

→ A real-time experiment

Cowan-Reines Experiment

(Savannah River nuclear power plant, South Carolina, US, 1955–56)

Experimental setup



Pb shielding (~20cm)

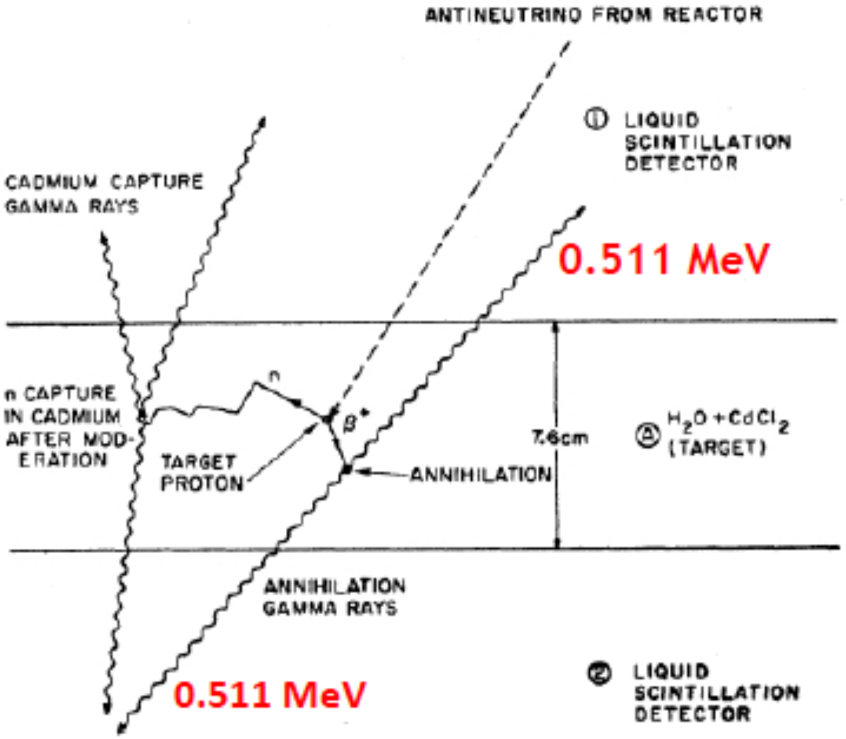
Top triad

Bottom triad

Liquid scintillator detectors (each equipped with 110 photomutipliers)

Thin H_2O+$CdCl_2$ target tanks (0.2m³ each). Cd/H atomic ratio = 1%.

Antineutrino interaction event



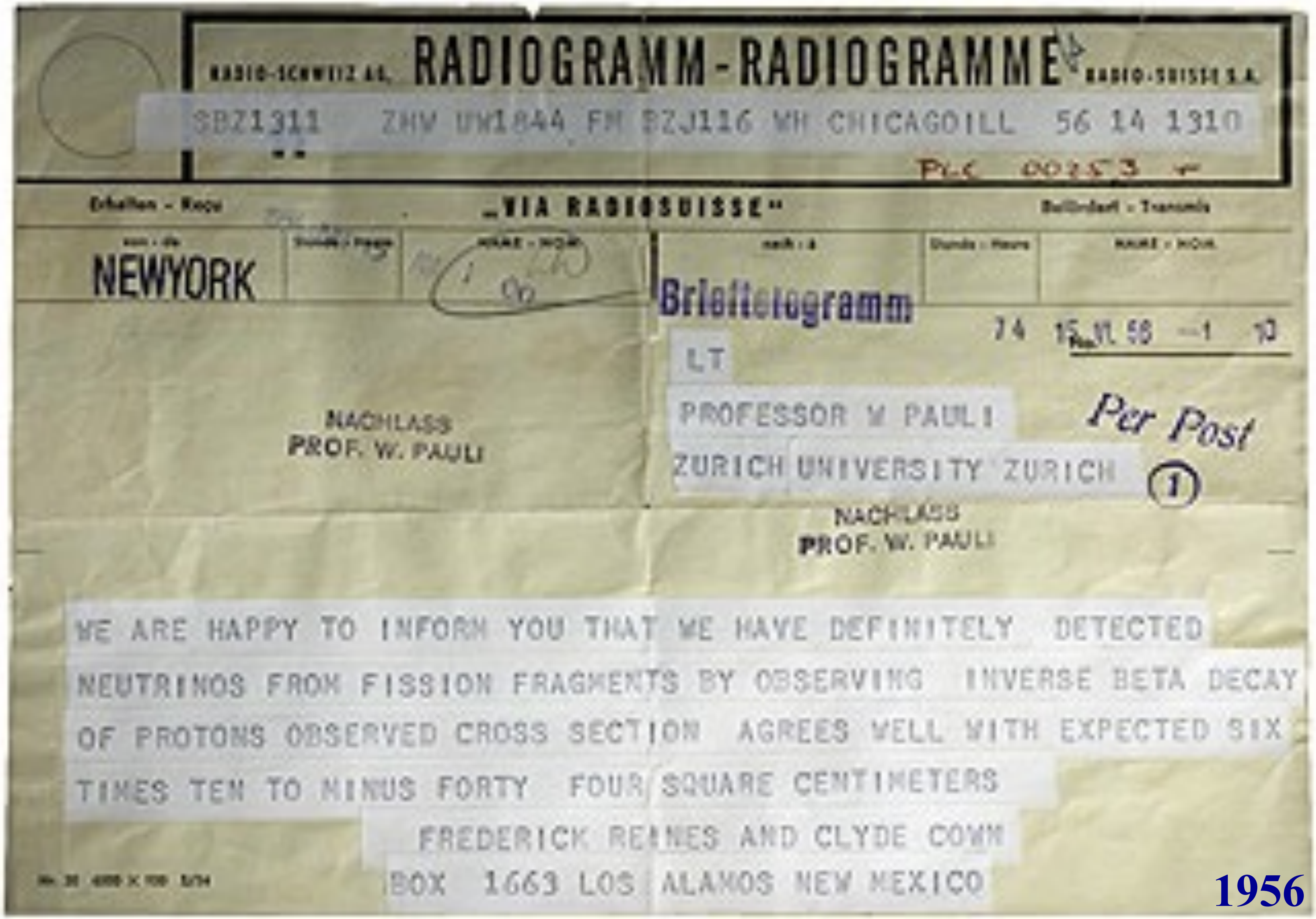
0.511 MeV

0.511 MeV

Prompt signal: 2×0.511 MeV photons.
Delayed signal: n capture on Cd, ~8 MeV.
Both signals: coincidence in two detectors.

Reines et al., Phys. Rev. 117 (1960) 159

Reines-Cowan Announcement



RADIO-SCHWEIZ AG. RADIOGRAMM - RADIOGRAMME RADIO-SUISSE S.A.

SBZ1311 ZHW UW1844 FM BZJ116 WH CHICAGOILL 56 14 1310

„VIA RADIOSUISSE"

Erhalten - Reçu

Befördert - Transmis

NEWYORK

Brieftelegramm

74 15.VI.56 -1 10

LT

PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

①

NACHLASS
PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

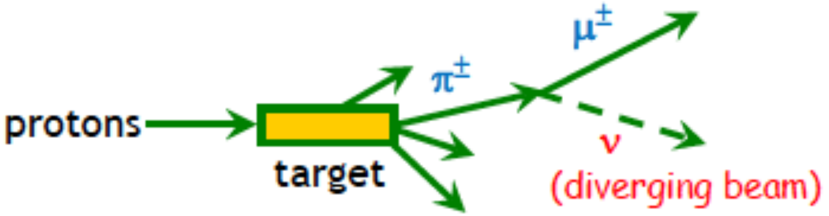
FREDERICK REINES AND CLYDE COWAN
BOX 1663 LOS ALAMOS NEW MEXICO

1956

Pauli replied: Thanks for the message.
Everything comes to him who knows how to wait.

The neutrino was discovered in 1956.
Nobel Prize awarded in 1995.

First Accelerator Neutrinos



Are the ν produced together with muons identical to the ν produced together with electrons (e.g. in a reactor)?

Neutrino interaction (IBD) cross-section:

$$\sigma(1\ \mathrm{MeV}) \sim 10^{-43}\ \mathrm{cm}^2; \quad \sigma(1\ \mathrm{GeV}) \sim 10^{-38}\ \mathrm{cm}^2$$

Accelerator-produced (GeV) ν's are
~10^5 times more likely to interact than reactor ones

Interaction probability in 2.25m thick Al block (used as the first detector):

$$P \approx \frac{\rho}{\underbrace{2m_p}_{\text{density of } \underline{\text{relevant}} \text{ nucleons}}}\sigma L \approx \frac{2.7\ (\mathrm{g}/\mathrm{cm}^3)/2}{1.66\times10^{-24}\ \mathrm{g}} \cdot 10^{-38}\ \mathrm{cm}^2 \cdot 2.25\ \mathrm{m} \approx 2\times10^{-12}$$

Production rates required for an experiment:

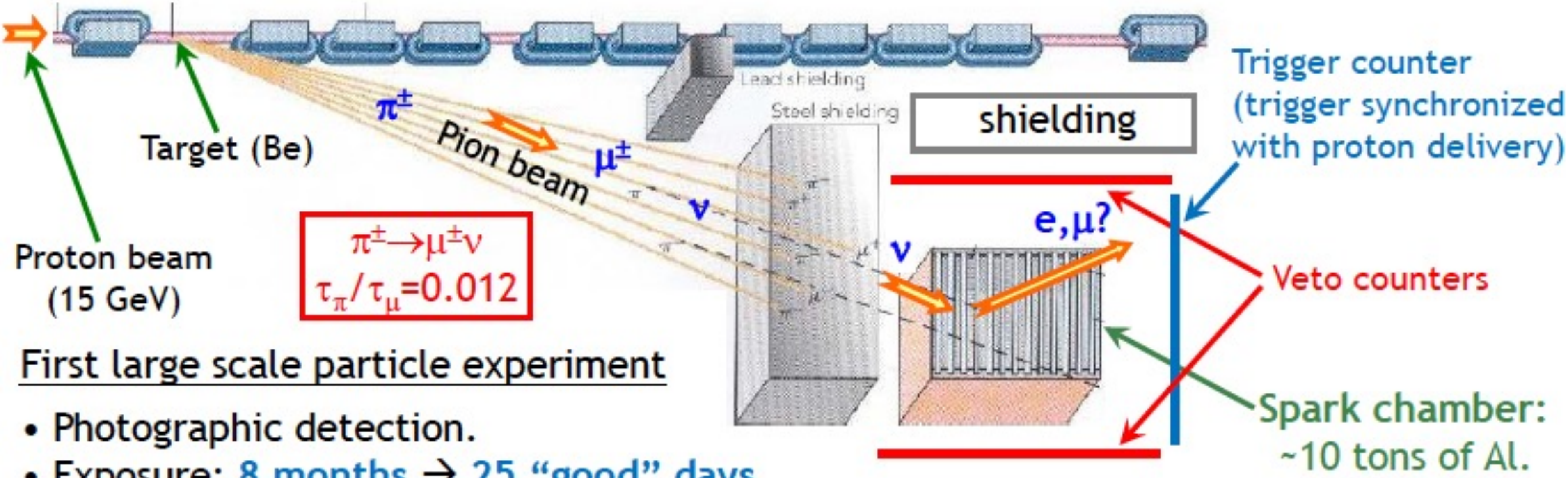
$$\nu\ \text{beam} \sim 10^{12}/\text{hour} \quad \Rightarrow \quad p\ \text{beam} \sim 10^{13}/\text{s}$$

(high intensity)

The first accelerator proton beam of such intensity became available in the Brookhaven lab (US) in the early 1960s

The Discovery of Muon Neutrino

Lederman–Schwartz–Steinberger experiment, Brookhaven, 1962



First large scale particle experiment

- Photographic detection.
- Exposure: 8 months → 25 "good" days.
- Detector "ON" for a total of 5.5 s.
- ~10^{14} neutrinos through the detector.
- ~5000 spark chamber photographs taken.

Method:

- Detect inverse beta decay in the spark chamber: e.g. $\nu n \to \ell^- p$
- Identify the lepton type (e or μ).

Results:

- ❖ 29 muon tracks identified:
  $\nu n \to \mu^- p$
- ❖ No electron tracks identified: the reaction $\nu n \to e^- p$ WAS NOT OBSERVED

ν_e and ν_μ demonstrated to be different particles: Nobel Prize 1988

The Discovery of Tau Neutrino

Secondary beam production:

$$p(800\ \mathrm{GeV}) + \underset{\text{(tungsten)}}{W} \rightarrow \ldots$$

Primary tau-neutrino source:

$$D_S^+(c\bar{s}) \rightarrow \tau^+\nu_\tau \quad \text{[BR=5.6\%]}$$

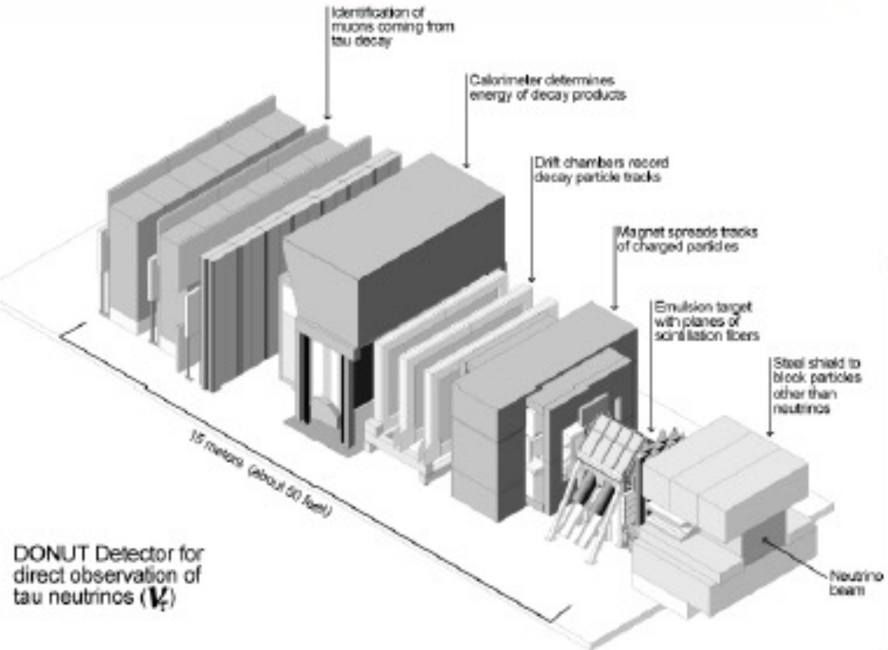
(~5% of all ν's are expected to be ν_τ)

ν_τ postulated following τ discovery in 1975; directly observed by the FNAL E872 (DONUT) experiment in 2000.

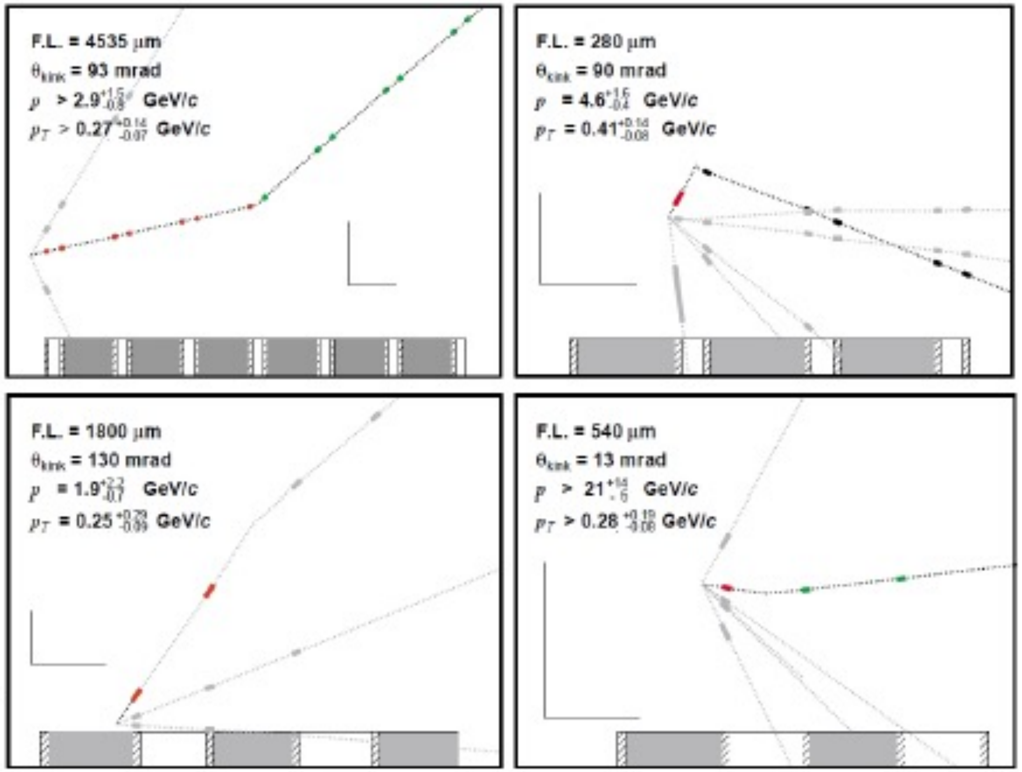
$$\nu_\tau n \rightarrow \tau^- p; \quad \tau^- \rightarrow \mu^- \nu_\tau \bar{\nu}_\mu$$

Mean τ free path: $\gamma c\tau$=2mm; decay into a single charged track: "track with a kink"

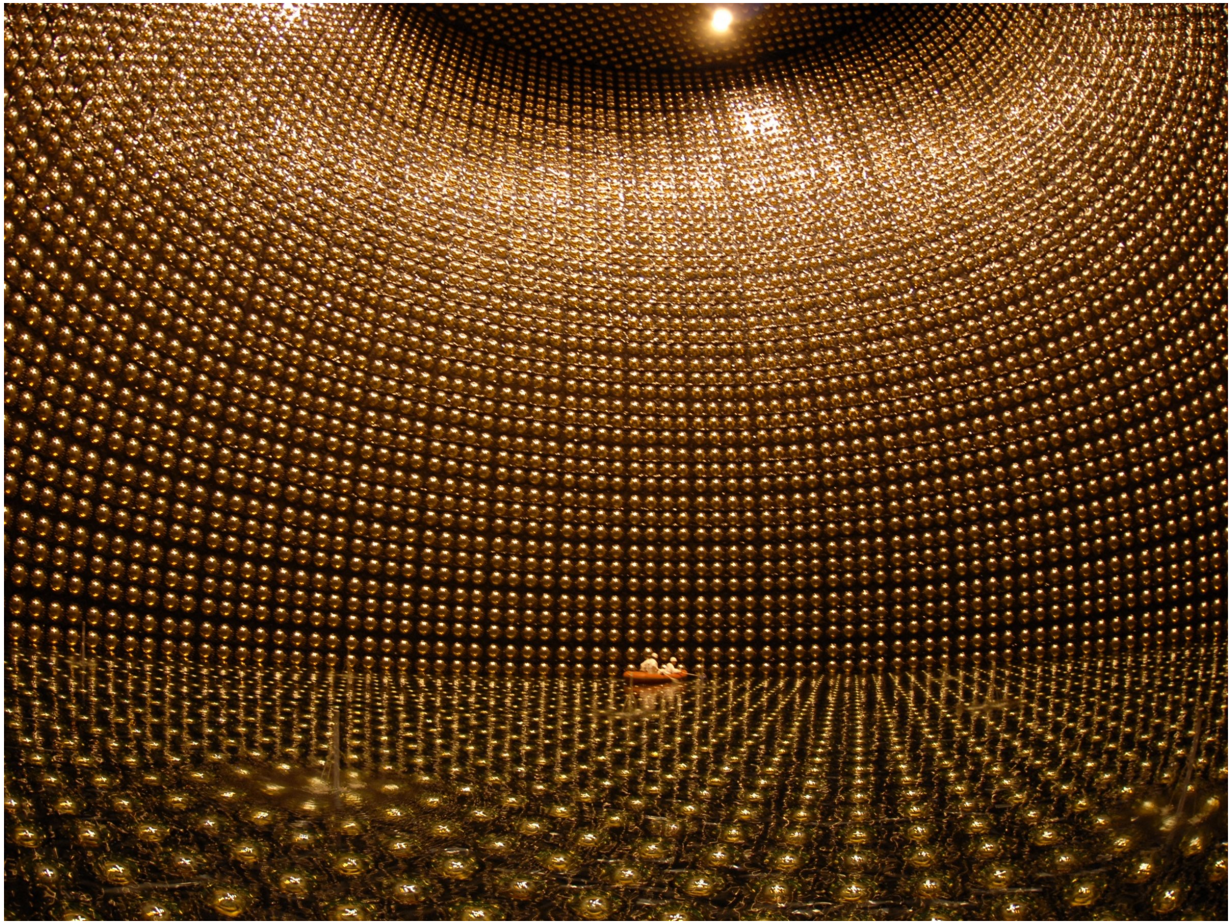
Detector type:
Pb/emulsion sandwich + spectrometer

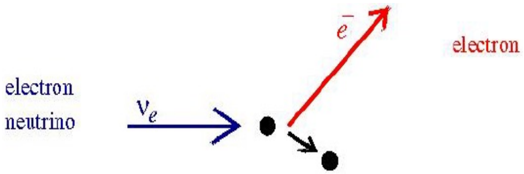


DONUT Detector for direct observation of tau neutrinos (ν_τ)



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)

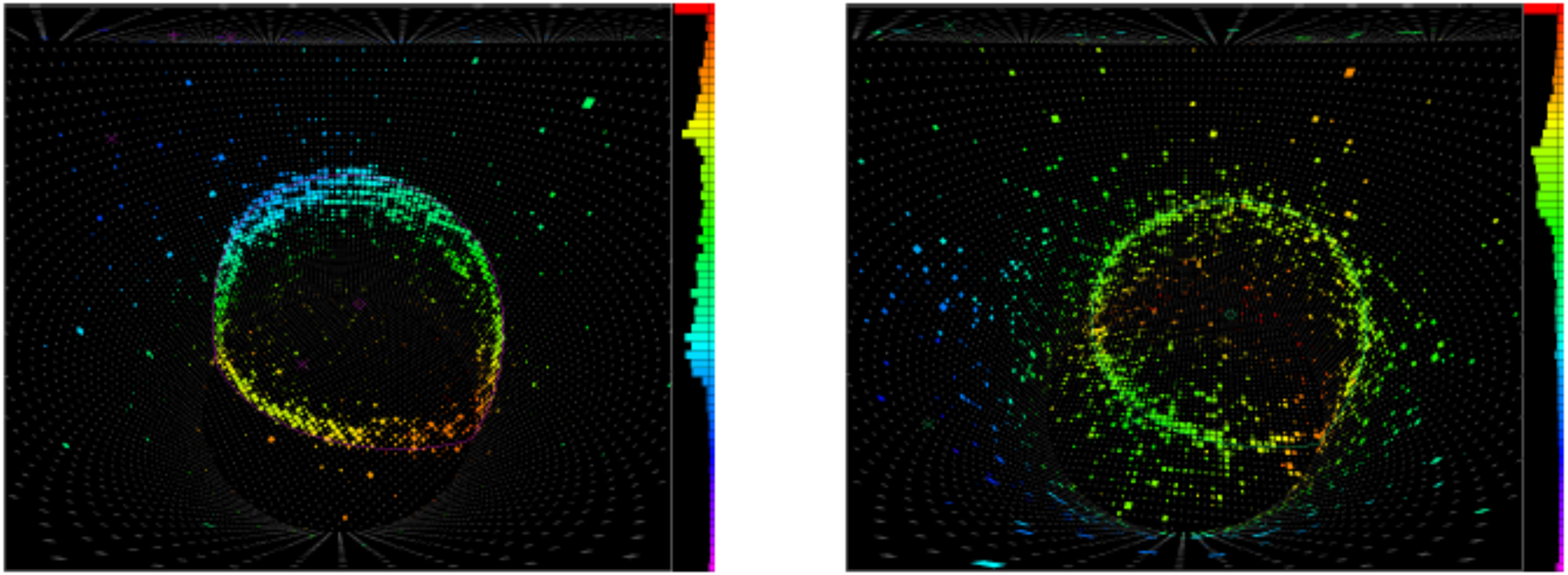
Super-Kamiokande detector in Japan is located 1,000 m (3,300 ft) underground in the Mozumi mine. It consists of a cylindrical stainless-steel tank (41.4 m tall and 39.3 m in diameter) holding 50,000,000 litres of ultra-pure water

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)



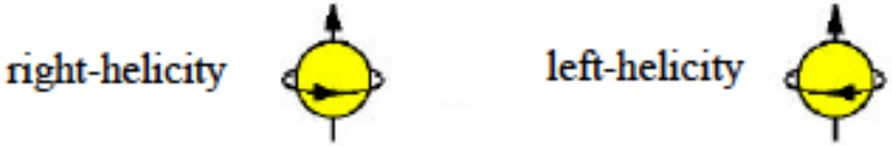
- detector responsible for discovery of atmospheric ν oscillations (1998), being used for T2K to measure $\nu_\mu \rightarrow \nu_e$ oscillations with accelerator ν's

Each dot is one phototube, and its color represents the relative amount of light it collected, in terms of the amount of electric charge produce by the phototube, during the 1.3 μs time window in which the displayed data were logged. The location and shape of the ring tell us the direction of the outgoing charged particle.

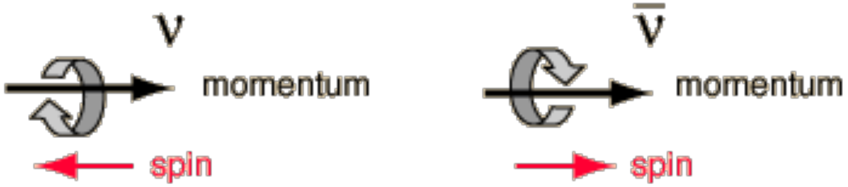
Neutrinos are Left-Handed

- Helicity is projection of spin along the particles direction
  - Frame dependent (if massive)

The operator: $\boldsymbol{\sigma} \cdot \mathbf{p}$



- Neutrinos only interact weakly with a (V-A) interaction
  - All **neutrinos** are **left-handed**
  - All **antineutrinos** are **right-handed**



Neutrino (left-handed)

Antineutrino (right-handed)

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

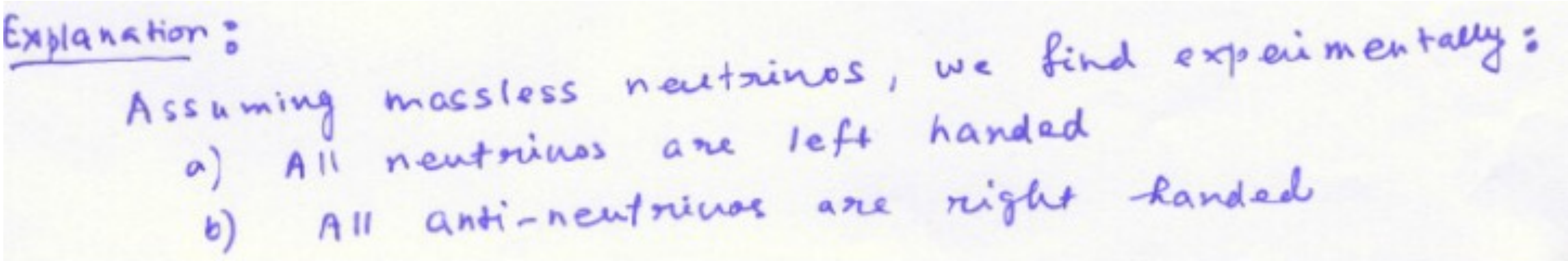
- If neutrinos have mass then left-handed neutrino is:
  - Mainly left-helicity
  - But also small right-helicity component ∝ *m/E*

- Handedness (or chirality) is Lorentz-invariant
  - Only same as helicity for massless particles.

- Only left-handed charged-leptons (e^-,μ^-,τ^-) interact weakly but mass brings in right-helicity:

$$\begin{aligned} R_{theory} &= \frac{\Gamma(\pi^\pm \to e^\pm \nu_e)}{\Gamma(\pi^\pm \to \mu^\pm \nu_\mu)} \\ &= \left(\frac{m_e}{m_\mu}\right)^2 \left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right)^2 \\ &= 1.23 \times 10^{-4} \end{aligned}$$

Neutrinos are Left Handed

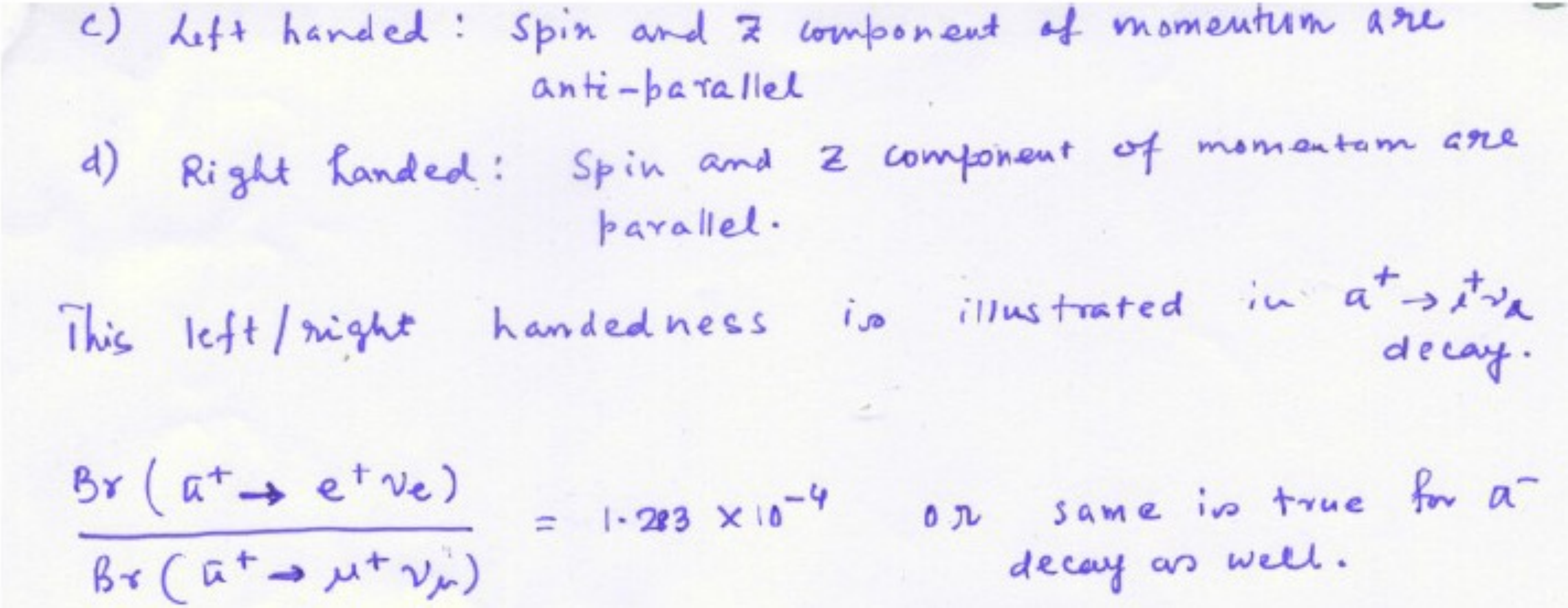


Explanation:

Assuming massless neutrinos, we find experimentally:

a) All neutrinos are left handed

b) All anti-neutrinos are right handed



c) Left handed: Spin and Z component of momentum are anti-parallel

d) Right handed: Spin and Z component of momentum are parallel.

This left/right handedness is illustrated in $\pi^+ \to \ell^+ \nu_\ell$ decay.

$$\frac{Br(\pi^+ \to e^+ \nu_e)}{Br(\pi^+ \to \mu^+ \nu_\mu)} = 1.283 \times 10^{-4}$$

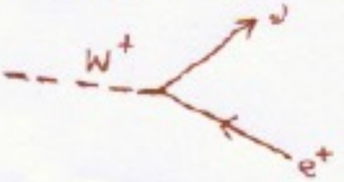
or same is true for π^- decay as well.

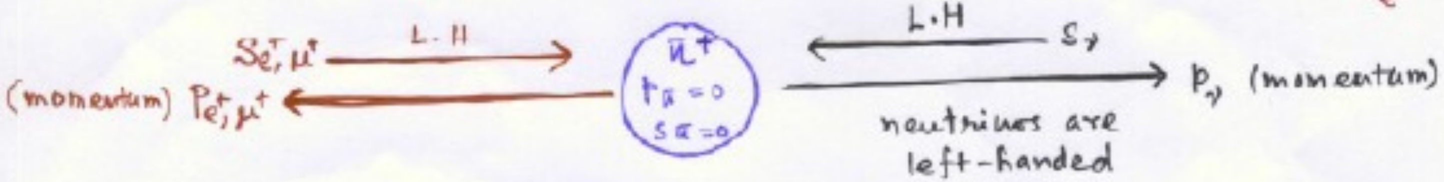
Neutrinos are Left-Handed

$$\frac{Br(\pi^+\to e^+\nu_e)}{Br(\pi^+\to\mu^+\nu_\mu)} = 1.283\times10^{-4}$$

or same is true for π^- decay as well.

If neutrinos were not left handed, the ratio would be > 1 !





neutrinos are left-handed

Angular momentum conservation forces the charged lepton (e, μ) to be in "wrong" handed state:

→ a left handed positron (e^+).

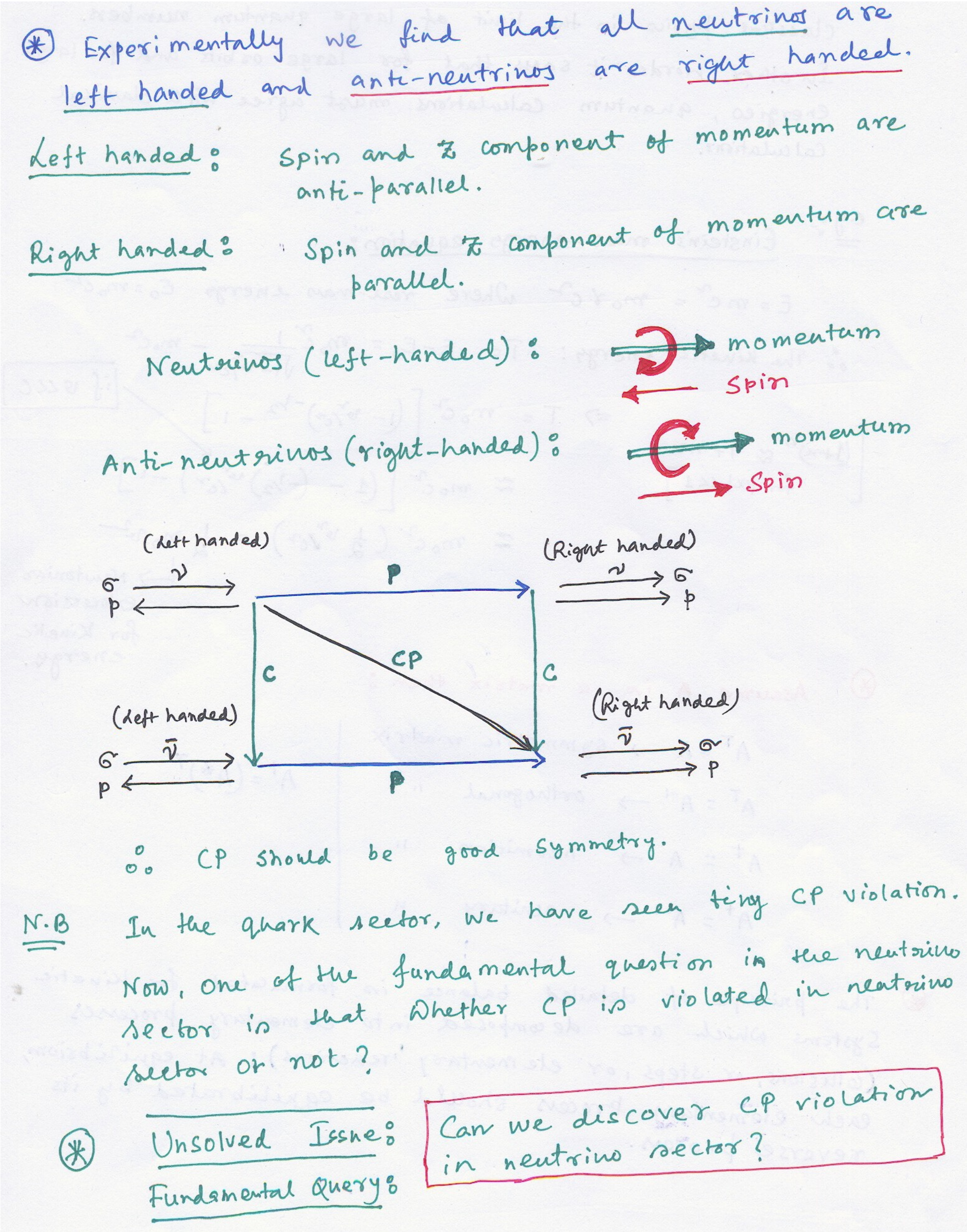
- Now the probability to be in the wrong handed state ~ m_ℓ^2

$$\frac{Br(\pi^+\to e^+\nu_e)}{Br(\pi^+\to\mu^+\nu_\mu)} = \boxed{\frac{m_e^2}{m_\mu^2}}\left[\frac{m_\pi^2-m_e^2}{m_\pi^2-m_\mu^2}\right]^2 = (1.230\pm0.004)\times10^{-4}$$

Handedness: 2×10^{-5}

Phase space ~5

C, P, CP Properties of Neutrino



⊛ Experimentally we find that all neutrinos are left handed and anti-neutrinos are right handed.

Left handed: Spin and z component of momentum are anti-parallel.

Right handed: Spin and z component of momentum are parallel.

Neutrinos (left-handed):

Anti-neutrinos (right-handed):

∴ CP should be good symmetry.

N.B In the quark sector, we have seen tiny CP violation.

Now, one of the fundamental question in the neutrino sector is that whether CP is violated in neutrino sector or not?

⊛ Unsolved Issue:
Fundamental Query:

Can we discover CP violation in neutrino sector?

Parity (P) and
Charge Conjugation (C)
are violated separately
in weak interactions.

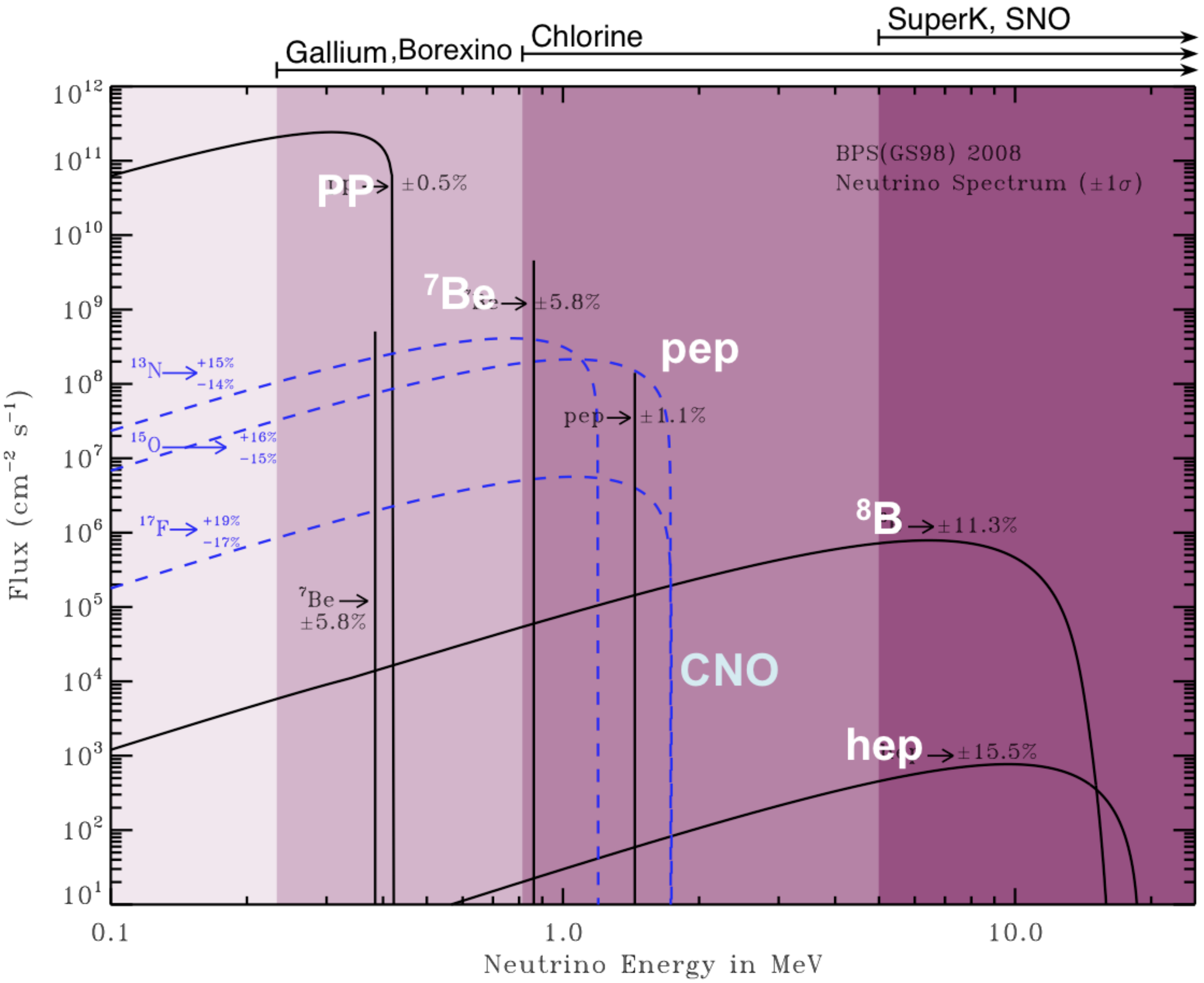
Is there CP violation
in neutrino sector?

Study of Neutrino and
Antineutrino Oscillation
probabilities separately
may provide the answer

Present and future
long-baseline neutrino
oscillation experiments are
going to shed light on this

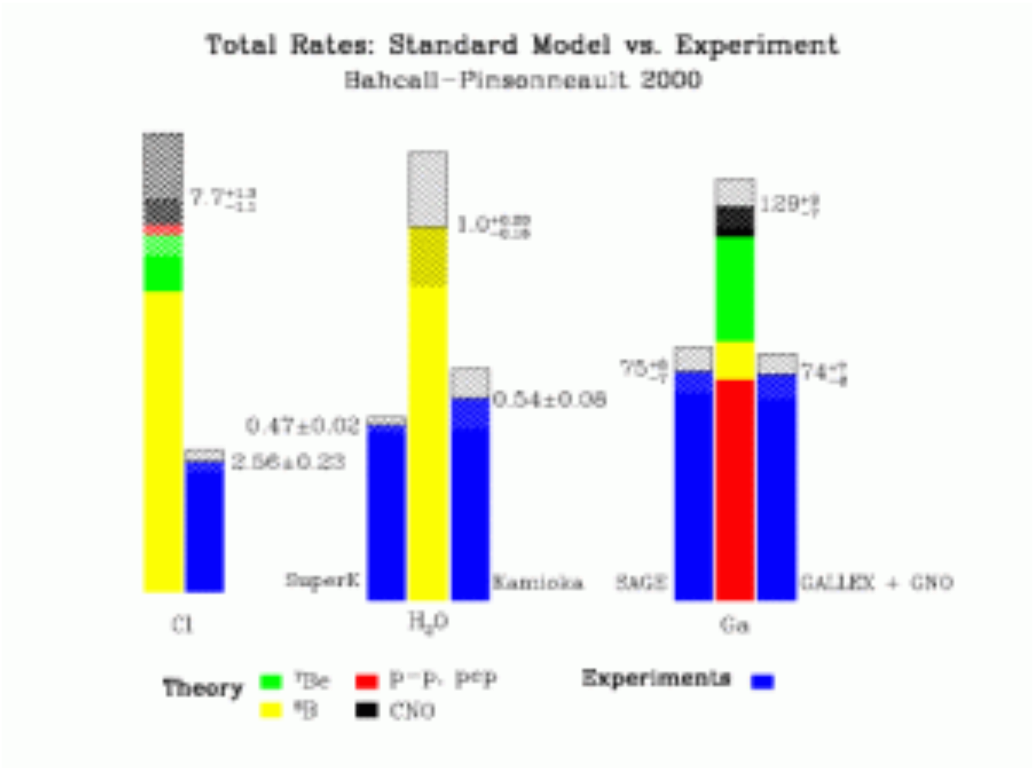
(T2K, NOvA, DUNE, T2HK)

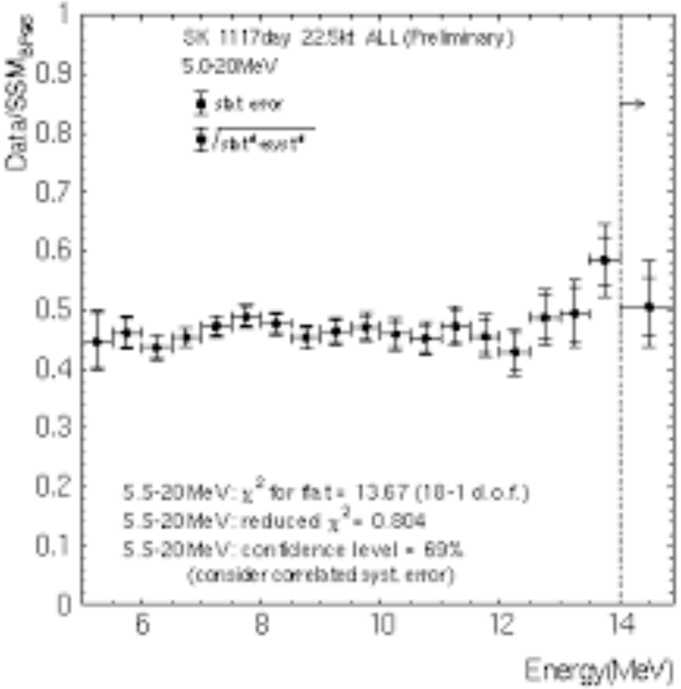
The Solar Neutrino Spectra



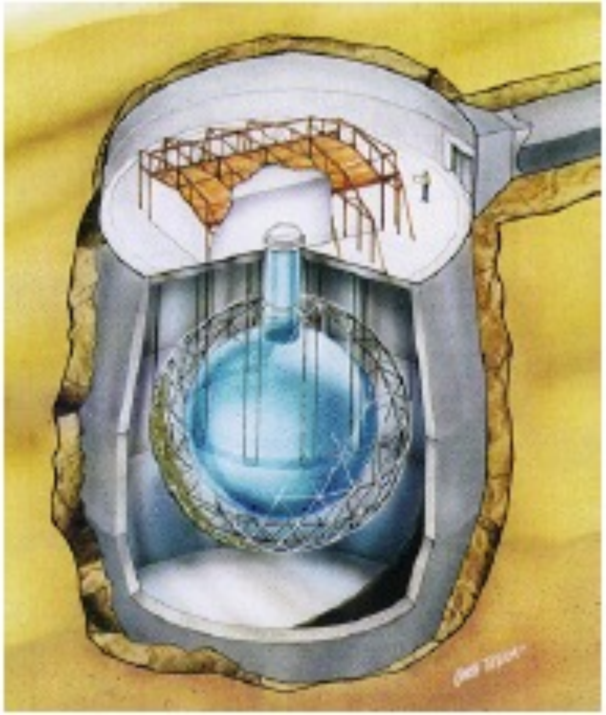
- Magnitudes of fluxes depend on details of solar interior
- Spectral shapes robustly known

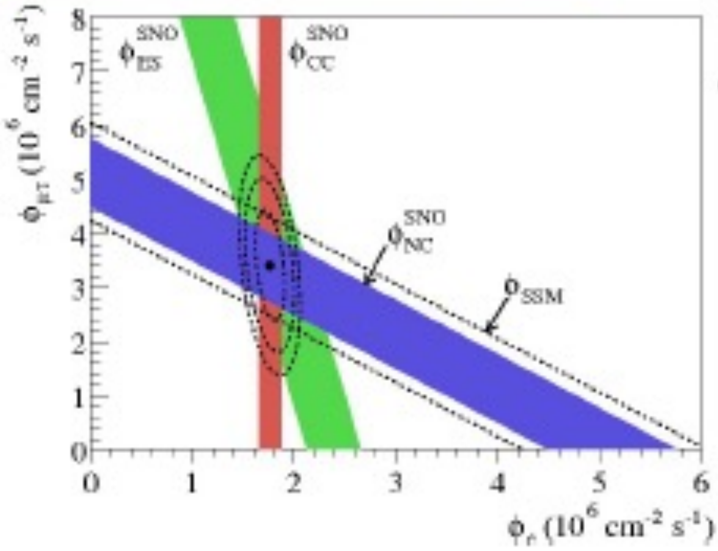
Do we really understand how the Sun shines?





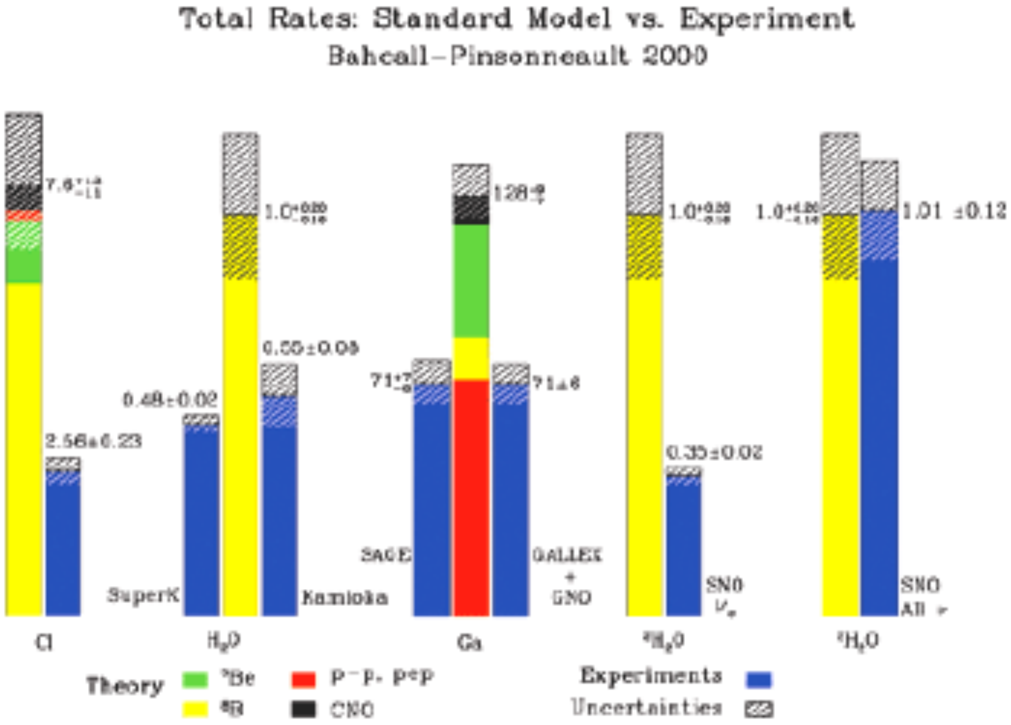
Heavy water Cherenkov experiment: SNO





- Heavy water Cherenkov
- $\nu_e\, D \to p\, p\, e^-$
  sensitive to Φ_e
- $\nu_{e,\mu,\tau}\; e^- \to \nu_{e,\mu,\tau}\; e^-$
  Sensitive to $\Phi_e + \Phi_{\mu\tau}/6$
- $\nu_{e,\mu,\tau}\; D \to n\, p\, \nu_{e,\mu,\tau}$
  sensitive to $\Phi_e + \Phi_{\mu\tau}$
- Neutral current: no effect of oscillations

Solar neutrino problem solved (2002)



- All neutrinos from the Sun are now accounted for !
- Our understanding of the Sun is vindicated...

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