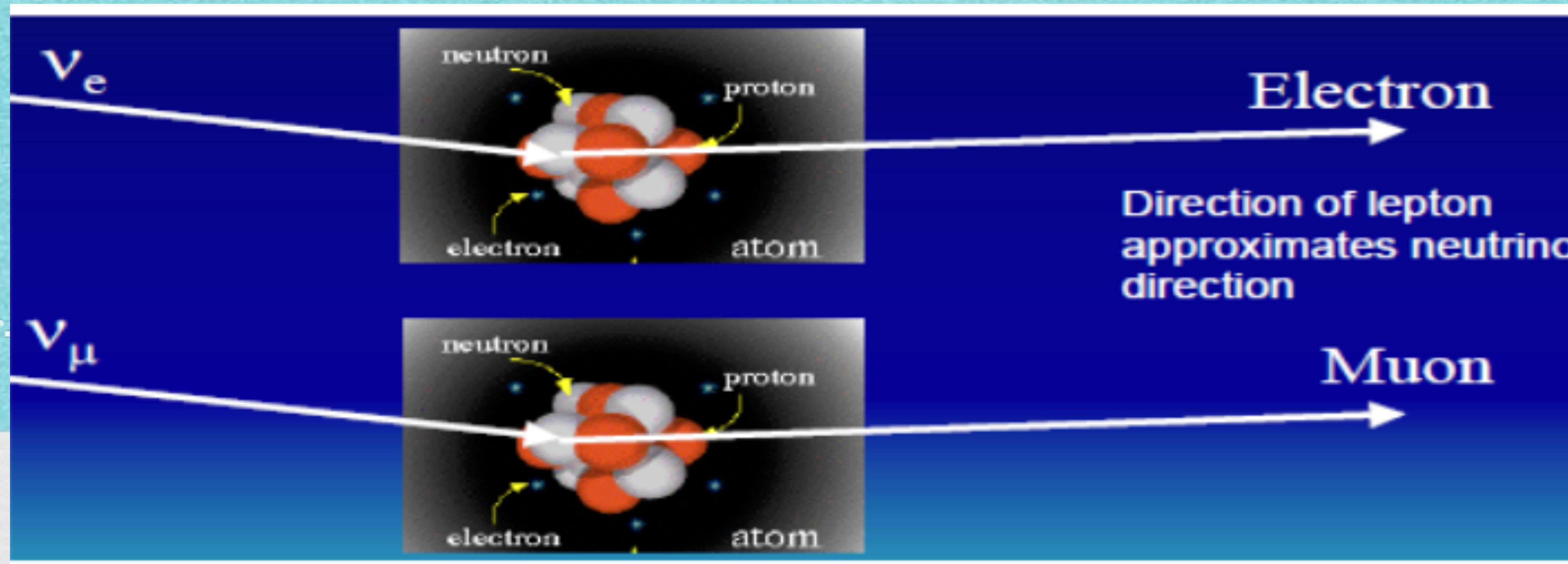


Neutrino Oscillation

Srubabati Goswami
Physical Research Laboratory

Birth of the neutrino

- The story of the neutrino started in 1930

Wolfgang Pauli

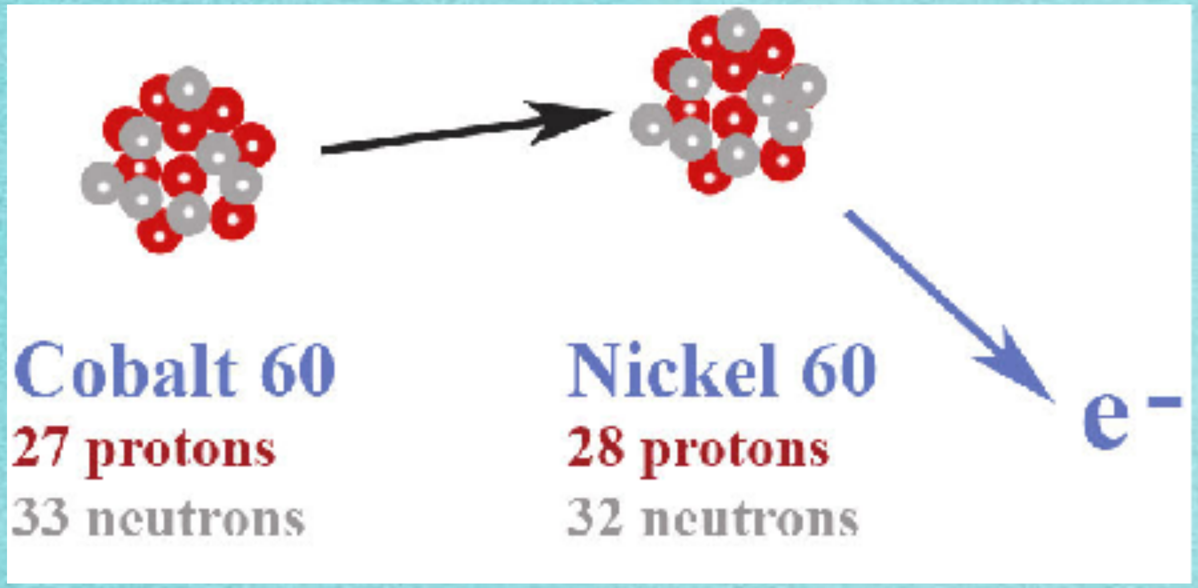
Austrian (American/Swiss) Physicist
1900-1958

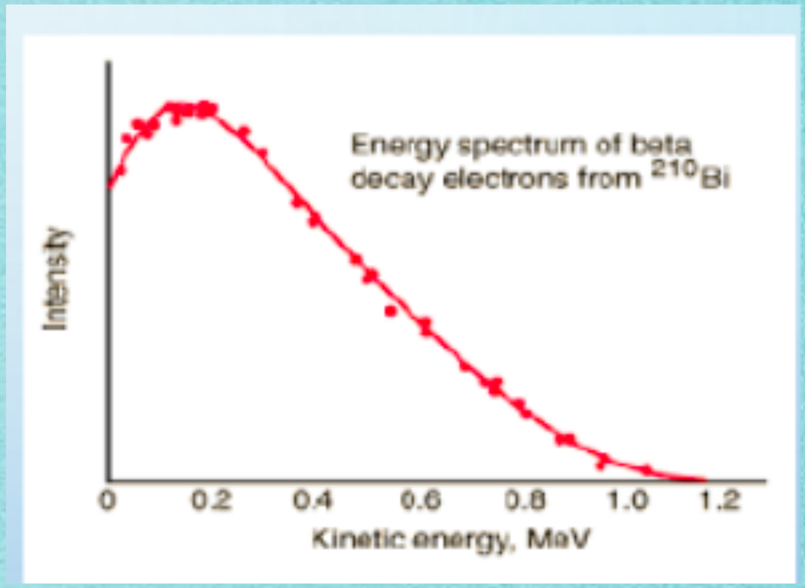
Dear Radioactive Ladies and Gentlemen,

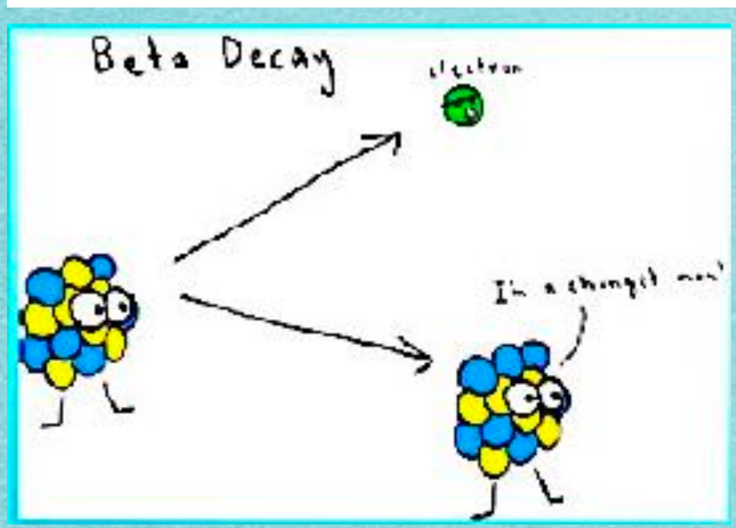
…I have hit upon a desperate remedy to save the law of conservation of energy…there could exist… electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle …

I agree that my remedy could seem incredible…
But only the one who dare can win…
…dear radioactive people, look and judge.
Your humble servant
W. Pauli

A problem encountered in beta decay







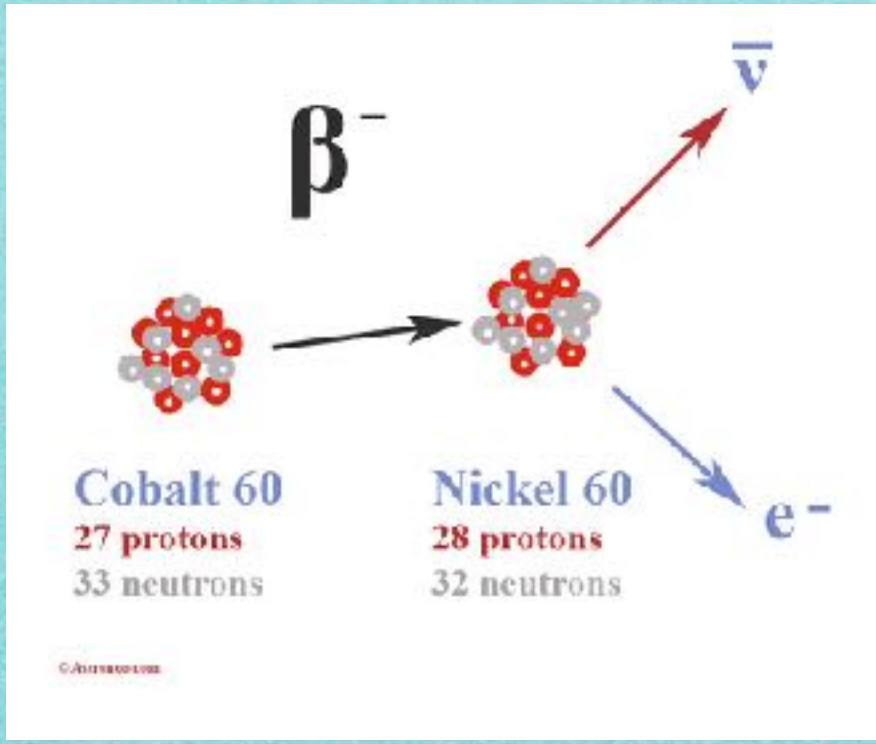
$$A \to B + C$$

$$E_A = E_B + E_C$$

What happens to conservation of energy ?

A desperate remedy

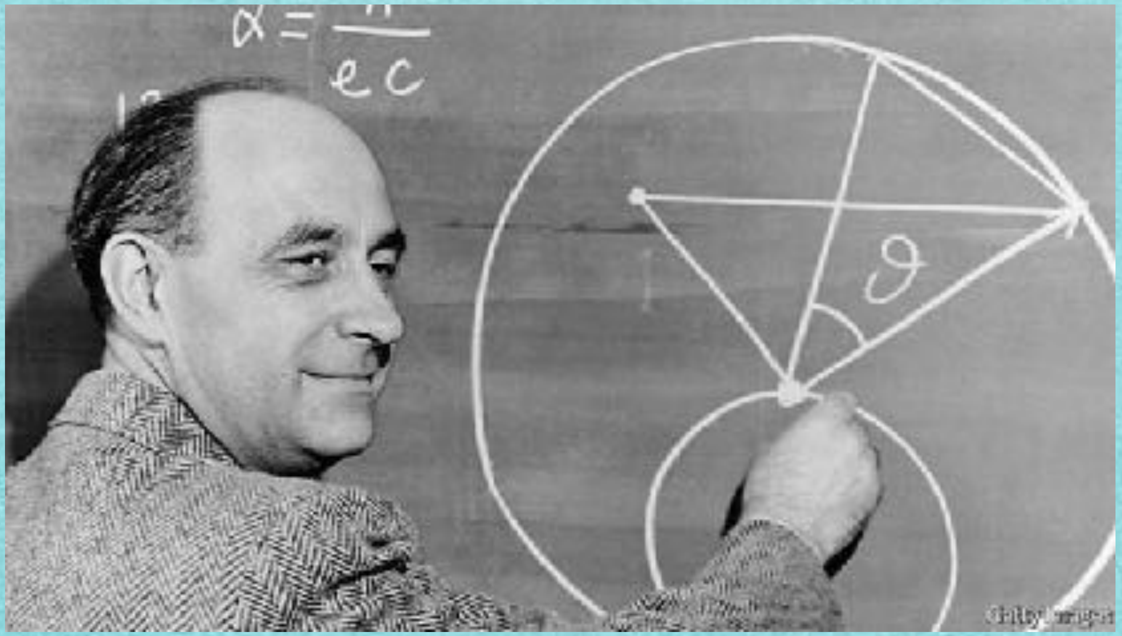
- In order to save conservation of energy Pauli proposed that there is a third particle sharing the energy



Neutrinos help in restoring the energy conservation

The little neutral one

Enrico Fermi gave the name neutrino and a theory of Beta decay



Neutrino : Little Neutral One in Italian

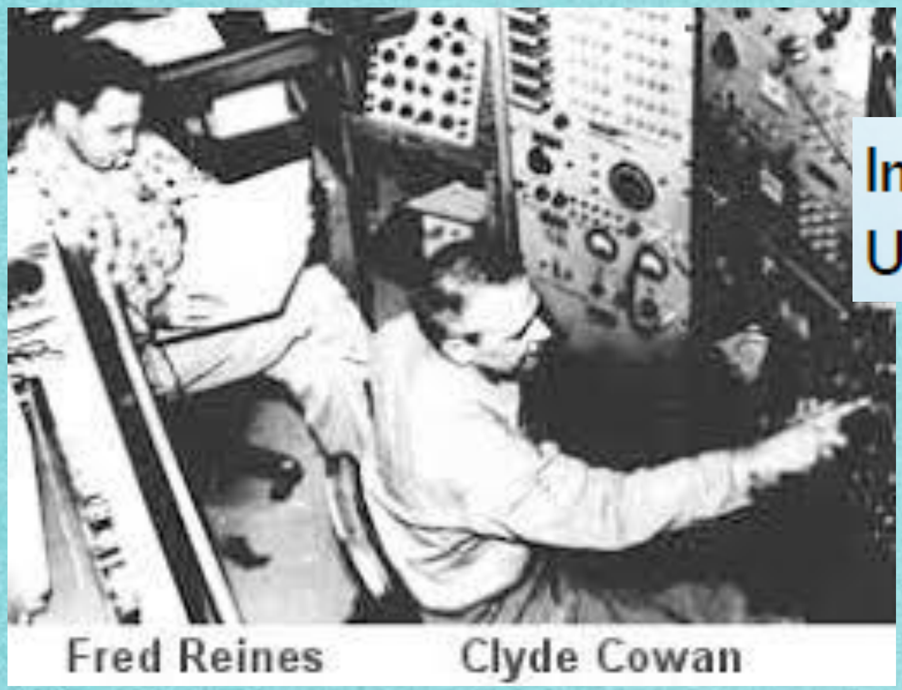
The phantom of the Opera

- Properties of neutrinos

Massless
Chargeless
Weakly interacting

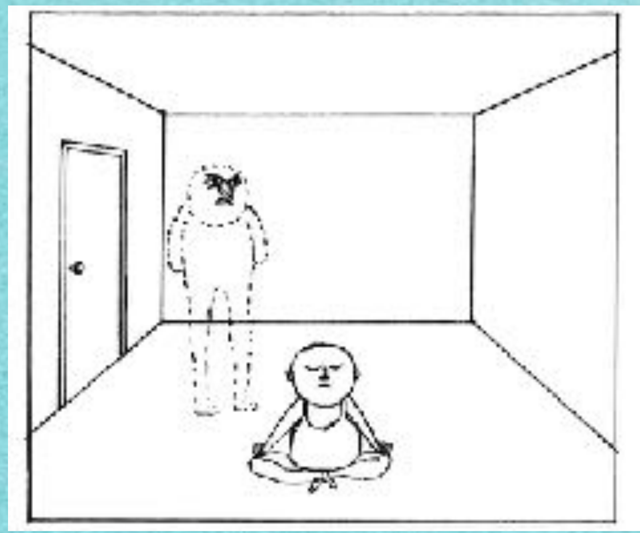
Makes it difficult to detect them

Neutrino : From poltergeist to particle

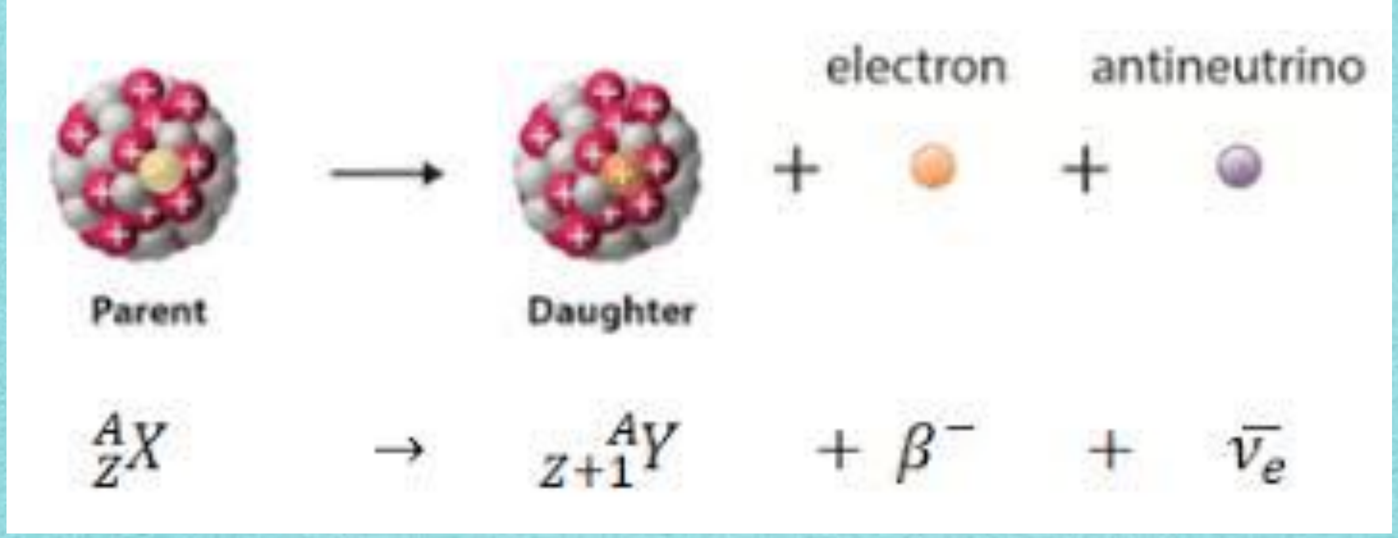


In 1956, 25 years after neutrinos were proposed
Using antineutrinos produced in nuclear reactors

- Clyde Cowan (1919-1974)
- Fred Reines (1918 - 1998)
- Nobel Prize to F. Reines in 1995



Pauli's neutrino

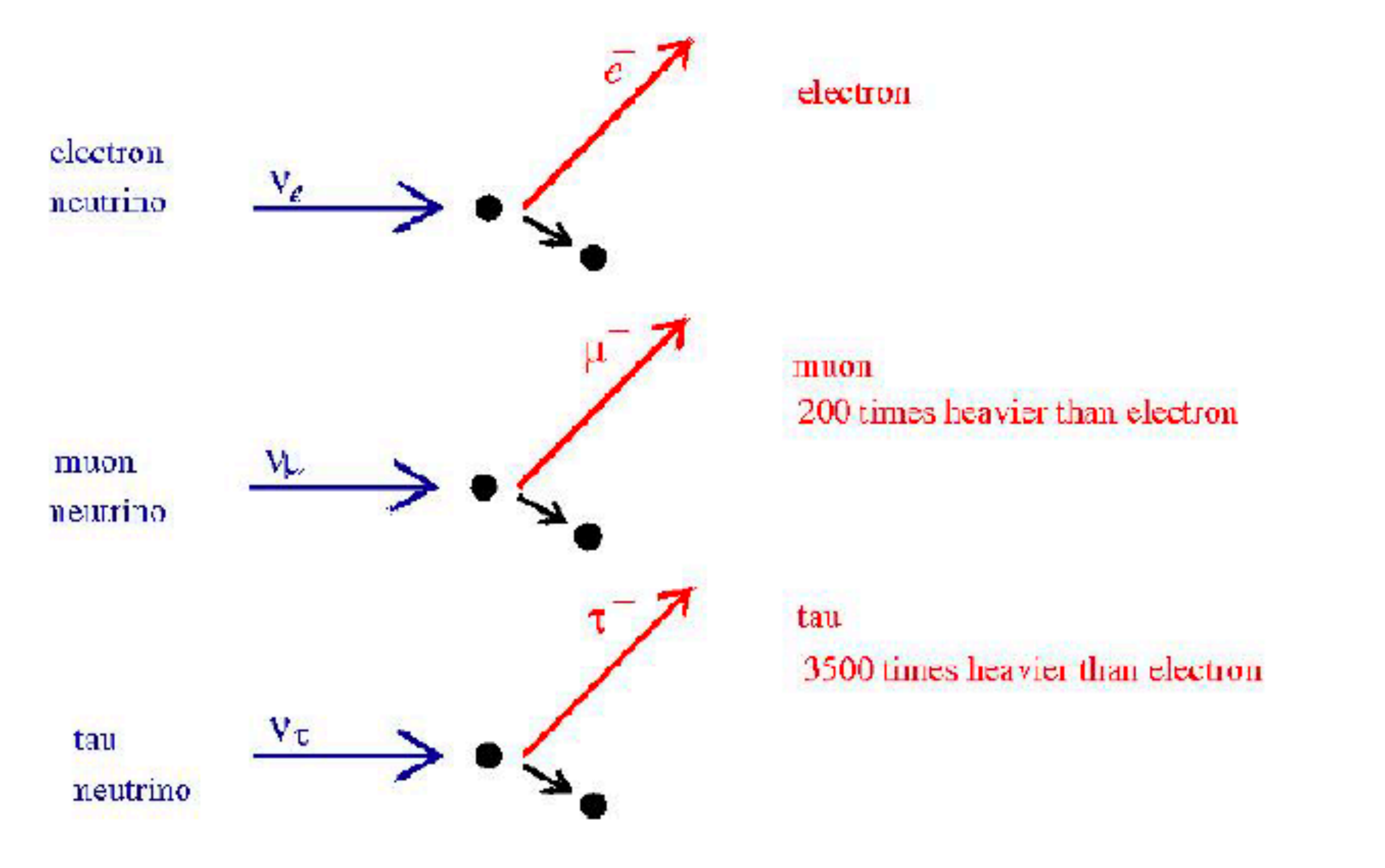


Electron type (anti) neutrino

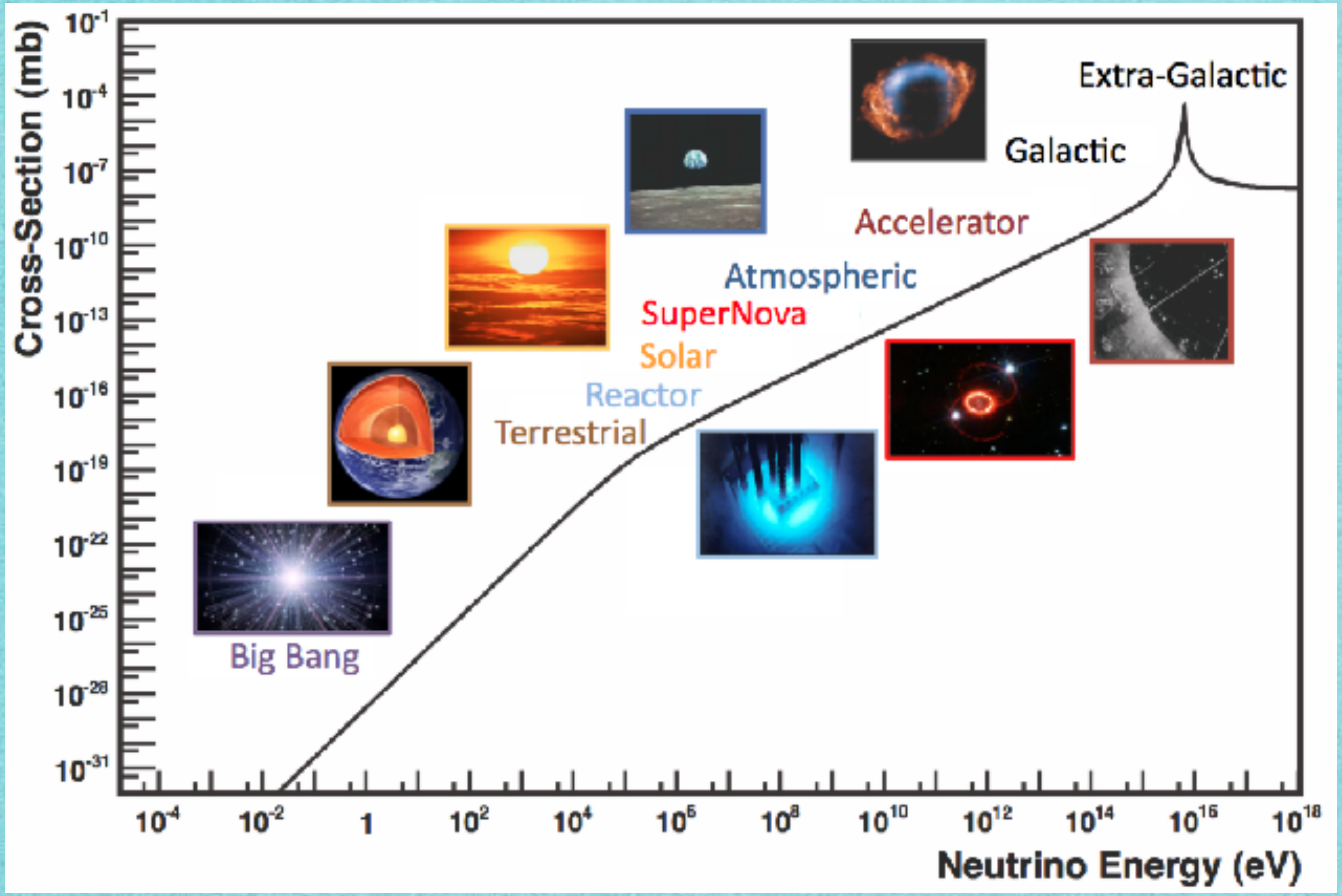
Always emitted with an accompanying electron

Two other type of neutrinos have also been discovered

Three types of neutrinos



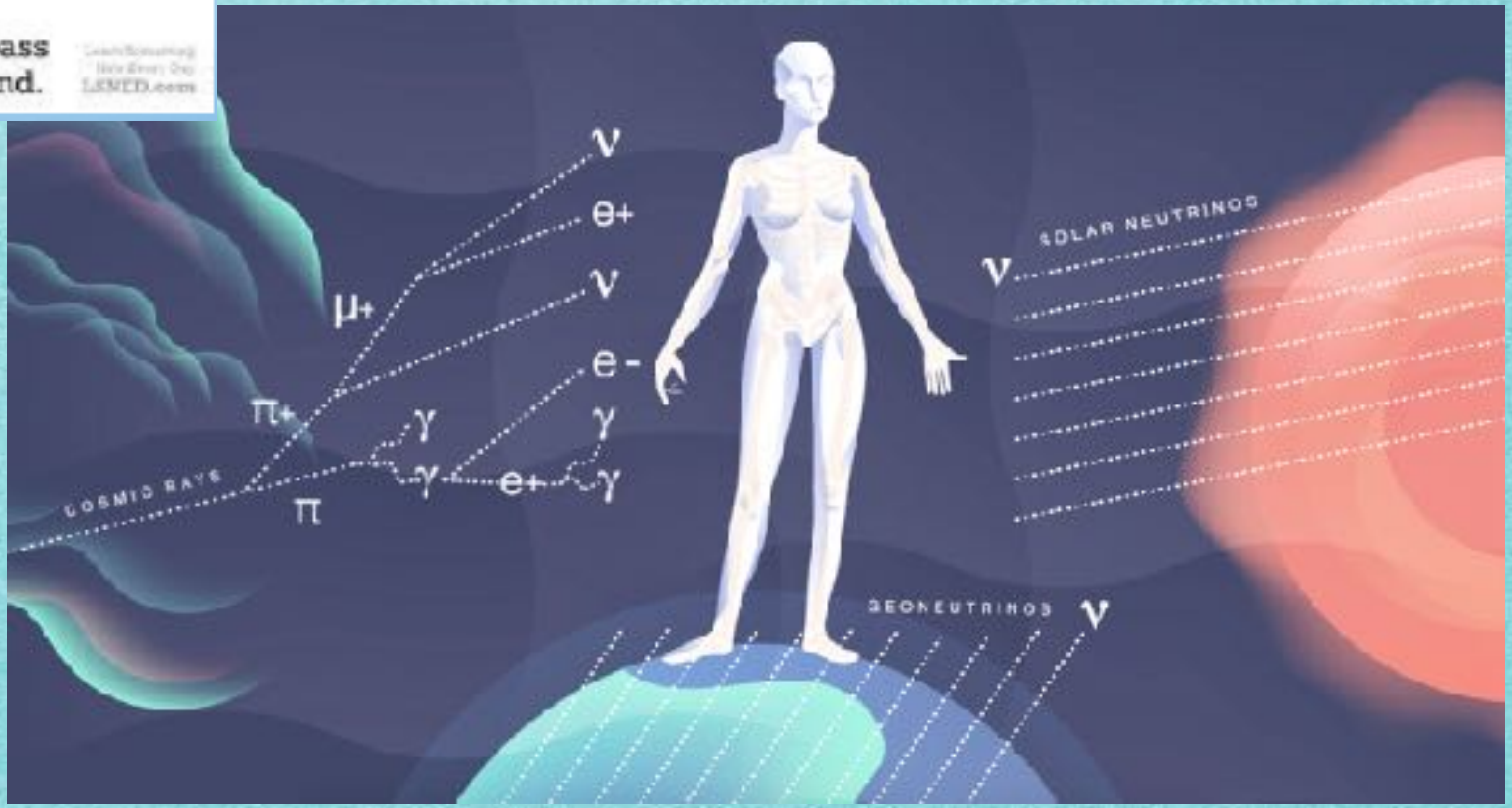
Where can they come from ?



Average kinetic energy of air molecules is 0.04 eV

Many sources, spans wide range of energy

Plenty of neutrinos



Why can't we see them ?

They interact very weakly

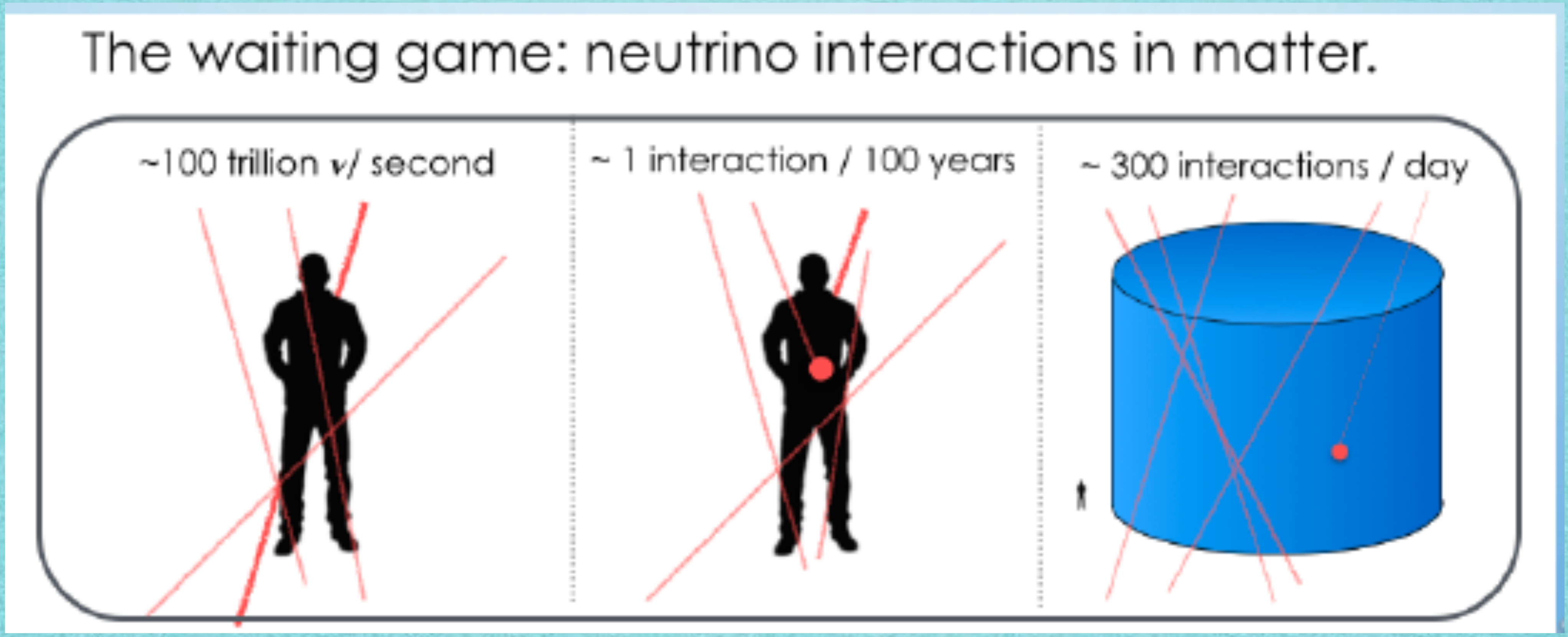
To stop a neutrino one needs lead shielding 100 light years thick (For X-rays 0.24mm)

The invisible particle

One needs special eyes => Neutrino Detectors

Detecting the Neutrinos

Huge Detectors



Need to go deep underground
Need observations over large period of time

SuperKamiokande : Worlds largest neutrino detector

Superkamiokande: 50 kiloton

50 kiloton water = 50 000 000 litres

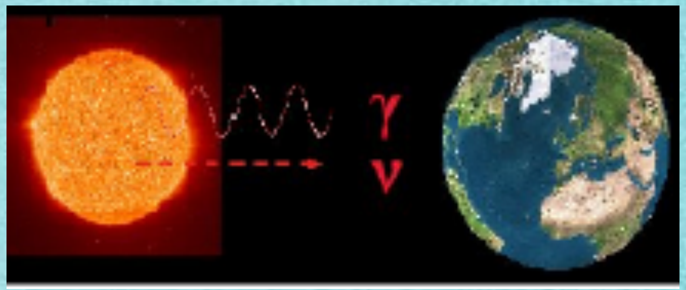
The world's largest underground detector since 1996

13000 Photomultiplier tubes

Observes about 30 neutrinos per day

Why should we try to catch them

- They are everywhere

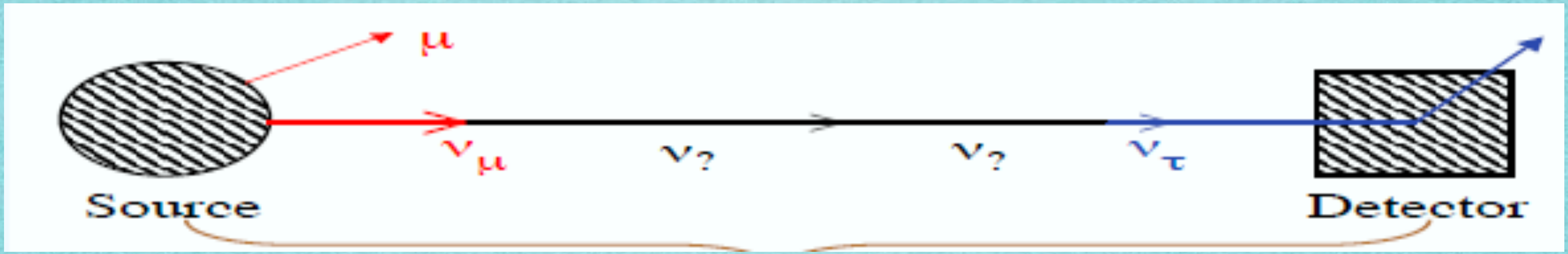


- Carry information from stars

- They pose interesting puzzles

Neutrino Oscillation

- It is found that neutrinos can change flavour after passing through a distance



- This is possible neutrinos have Mass and mixing
- The conversion probability is oscillatory-Neutrino Oscillation

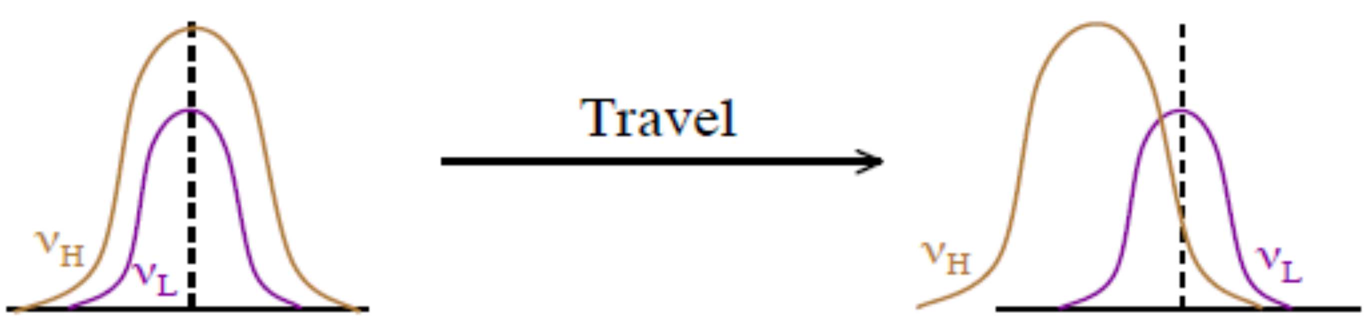
Neutrino Oscillation

- When neutrinos have mass then ν_μ, ν_τ are not particles of finite mass but are mixtures of these
- $\nu_\mu = \cos\theta\ \nu_{\text{light}} + \sin\theta\ \nu_{\text{heavy}}$
  $\nu_\tau = -\sin\theta\ \nu_{\text{light}} + \cos\theta\ \nu_{\text{heavy}}$

$\nu_{light}\ ,\ \nu_{heavy} \rightarrow \nu$'s of definite mass

$\theta \rightarrow$ mixing angle

- How does superposition of mass states evolve in vacuum ?
- As the neutrino travels with energy E its heavier part falls behind
- As a result the neutrino is not a ν_μ anymore but a mixture of ν_μ and ν_τ



At birth a ν_μ

Later

Two flavour oscillations in vacuum

- If neutrinos have mass

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

- Neutrinos acquire different phases as they propagate

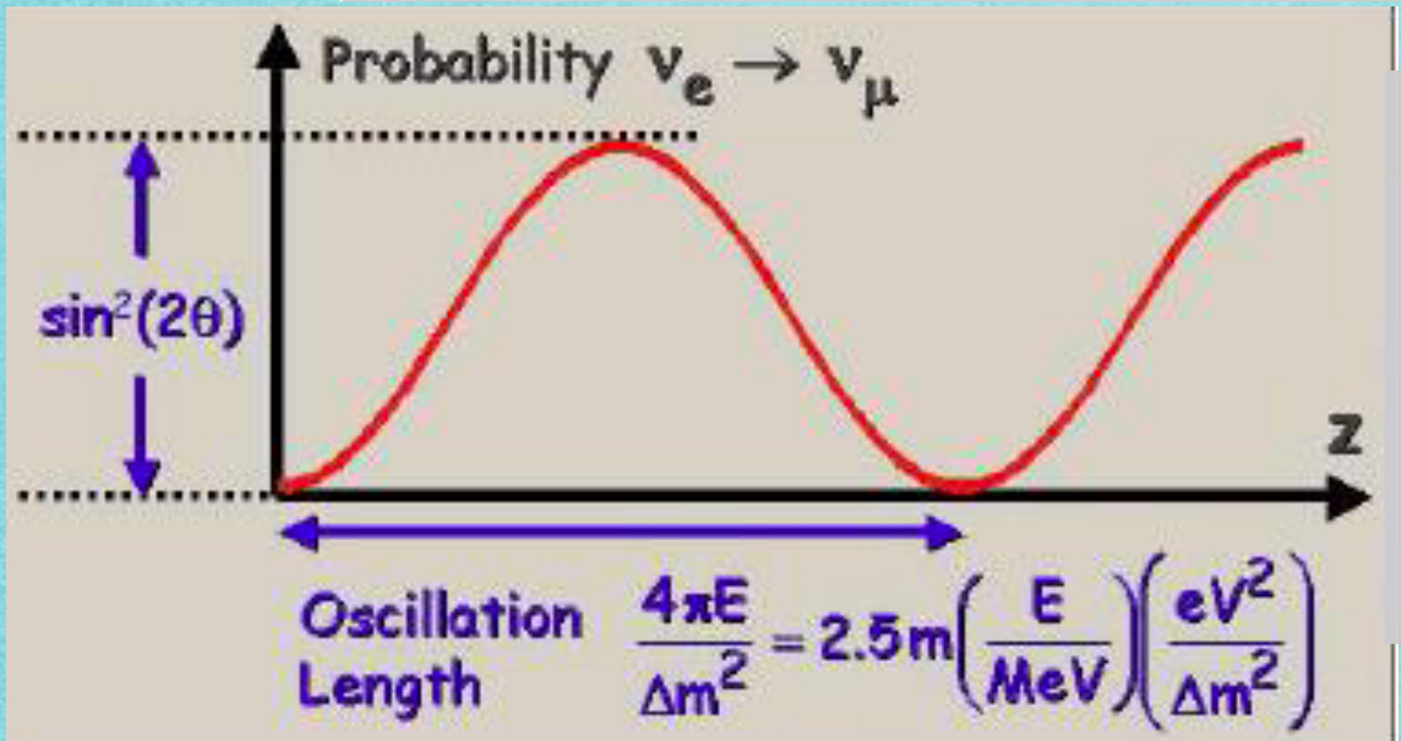
$$|\nu_j(t)\rangle = \exp(-iE_jt)|\nu_j(0)\rangle \quad E_j = p^2 + m_i^2/2p$$

- A phase difference develop between the terms since $m_1 \neq m_2$
- At some later time
  $|\nu_e(t)\rangle = \cos\theta \exp(-iE_1t)|\nu_1(0)\rangle + \sin\theta \exp(-iE_2t)|\nu_2(0)\rangle \neq |\nu_e\rangle$
- Survival Probability (in vacuum)
  $|\langle\nu_e(t)|\nu_e\rangle|^2 = P_{\nu_e\nu_e} = 1 - \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E);$
- Oscillation Probability (in vacuum)
  $P_{\nu_e\nu_\mu} = 1 - P_{\nu_e\nu_e} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$

$\Delta m^2 = m_2^2 - m_1^2$
$\theta \rightarrow$ mixing angle
L $\rightarrow$ Distance travelled (in m/Km)
$E \rightarrow \nu$ Energy (in MeV/GeV)

Two flavour neutrino oscillation

$$P_{\nu_e\nu_\mu} = \sin^2 2\theta \sin^2(\Delta m^2 L/4E) = \sin^2 2\theta \sin^2(\pi L/\lambda)$$



- Oscillation Wavelength

$\lambda = 4\pi E/\Delta m^2$

$\lambda = 2.5m(E/MeV)(eV^2/\Delta m^2)$

- $\lambda >> L, \sin^2(\pi L/\lambda) \rightarrow 0$
- $\lambda << L, \sin^2(\pi L/\lambda) \rightarrow 1/2$
- $\lambda \sim 2L, \sin^2(\pi L/\lambda) \sim 1 \rightarrow \Delta m^2 \sim E/L$

- Neutrino Oscillation requires

  Non-zero neurino mass

  Non-zero mixing angles

  Oscillation effect $\Delta m^2 \sim E/L$

Not sensitive to the absolute mass

Not sensitive to the sign of Δm^2

Neutrino Oscillation

Matter Effect

- For neutrinos passing through matter the probability changes due to interaction of the neutrinos with matter

$$P_{\nu_e\nu_\mu} = \sin^2 2\theta_m sin^2(\Delta m_m^2 L/4E)$$

$\Delta {m_m}^2 = \sqrt{A - \Delta m^2 \cos 2\theta)^2 + \sin^2 2\theta}$ Mass squared difference in matter

$\tan 2\theta_M = \frac{\Delta m_{21}^2 \sin 2\theta}{\Delta m_{21}^2 \cos 2\theta - A}$ Mixing angle in matter

$\Delta m^2 \cos 2\theta = A = 2\sqrt{2} G_F n_e,$

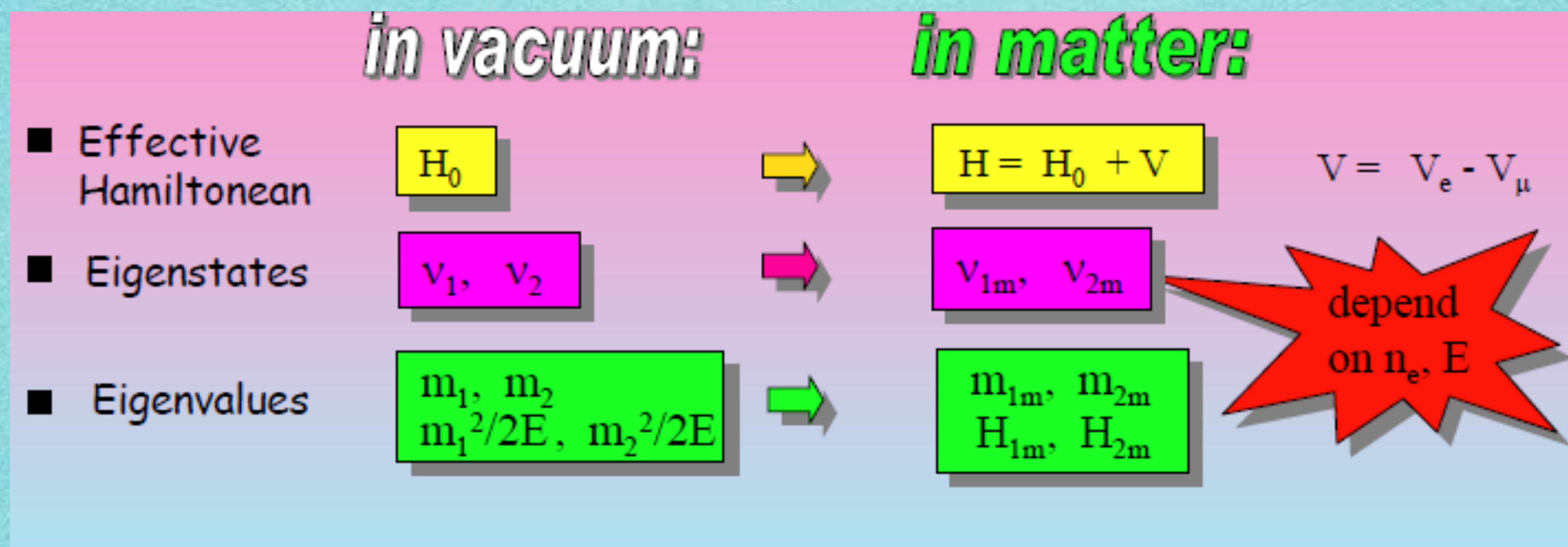
$\theta_M \to \pi/4$ MSW Resonance

Maximal mixing at resonance

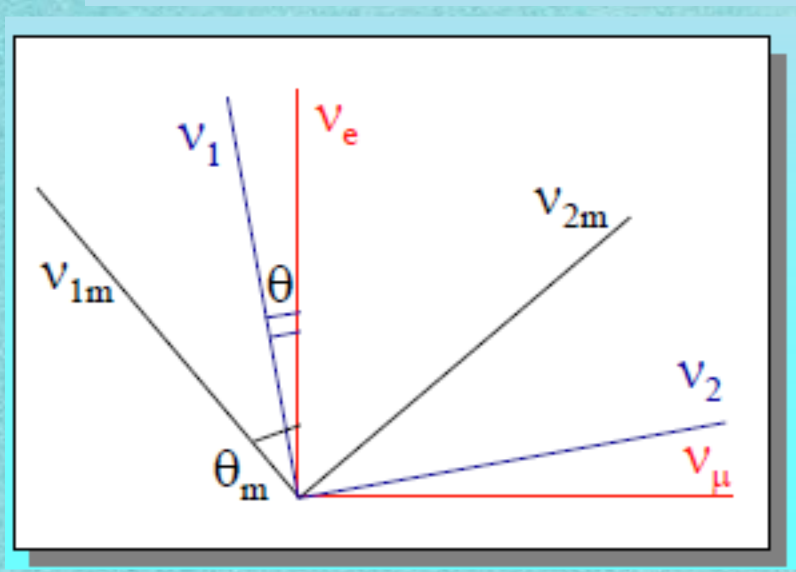
L. Wolfenstein, PRD **17**, 1978

S.P. Mikheyev, A.Yu. Smirnov, SJNP **42**, 1985

Matter Effect

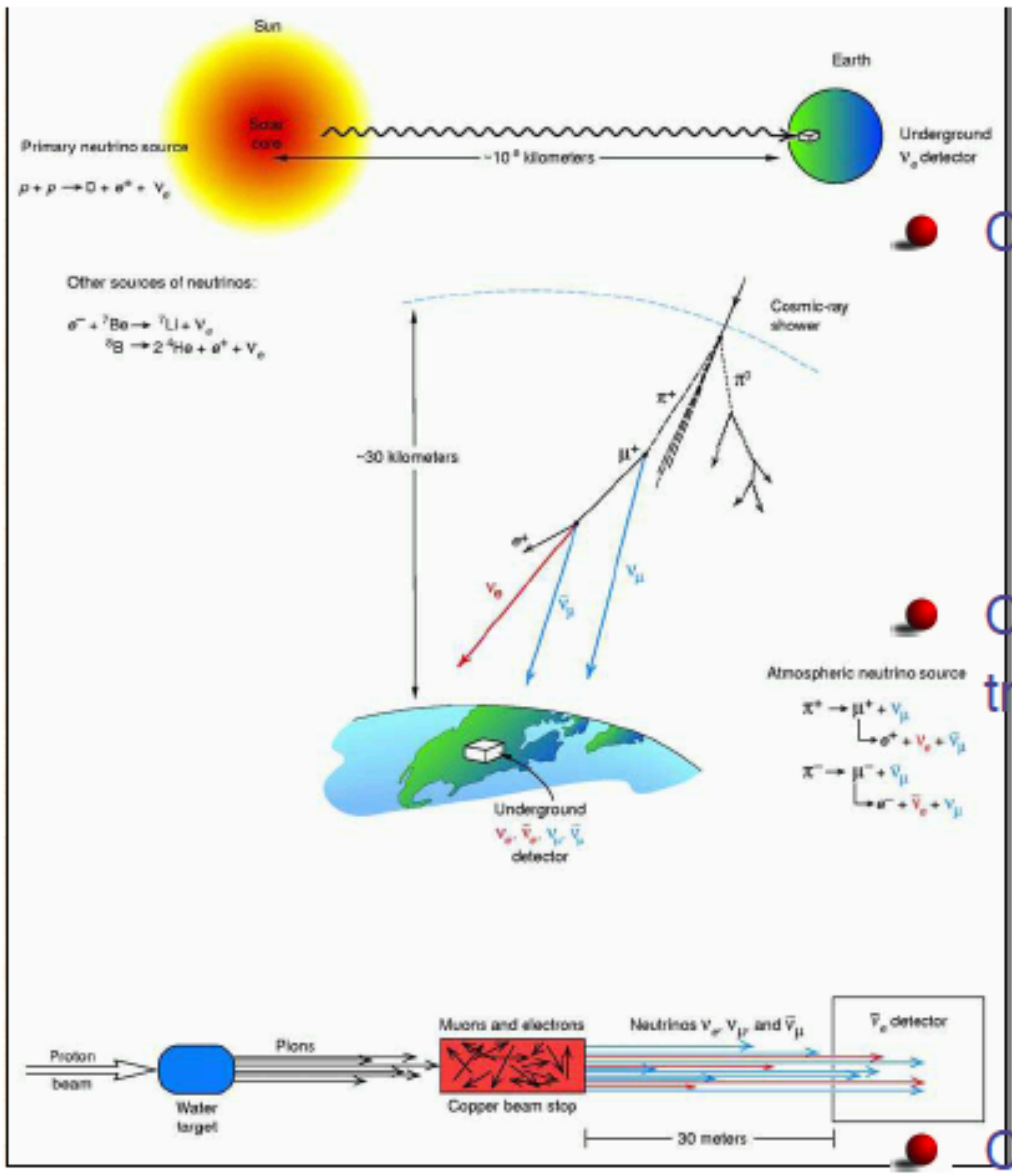


Courtsey: A. Smirnov



Mixing angle in matter defined with respect to eigenstates in matter

Evidences of Neutrino Oscillation



Solar Neutrinos

- Confirmation from reactor neutrinos

Atmospheric Neutrinos

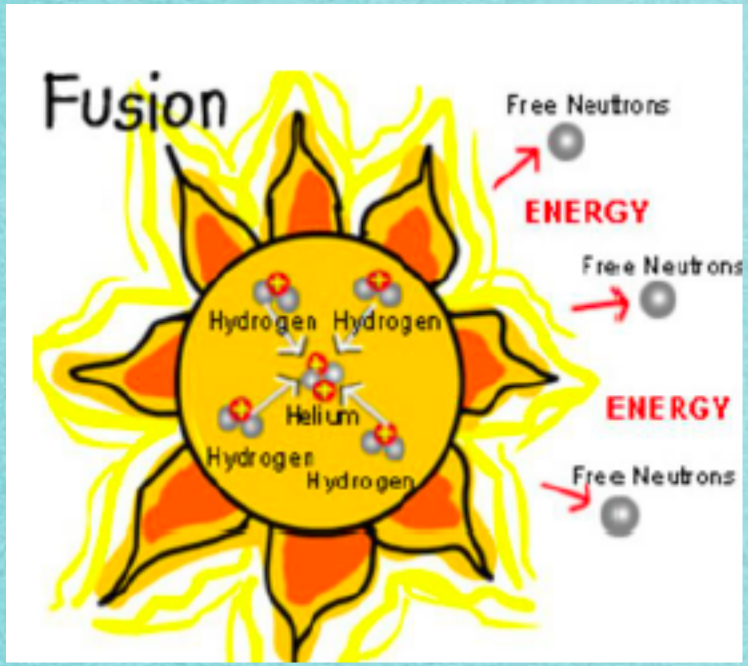
- Confirmation from accelerator neutrinos

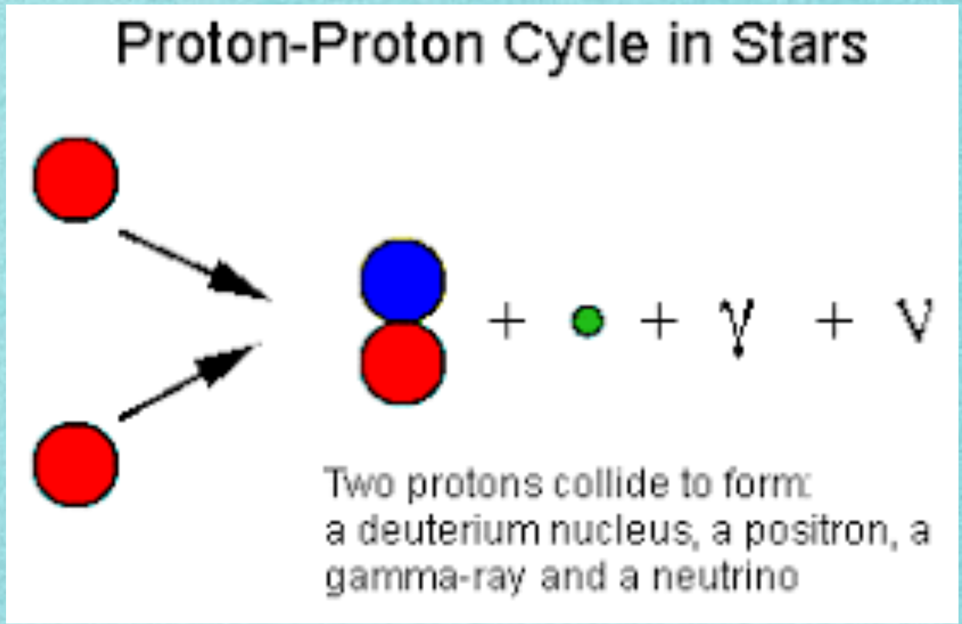
LSND Experiment

- Confirmation from MiniBoone (?)

Neutrinos from the sun

Neutrinos needed for the sun to shine



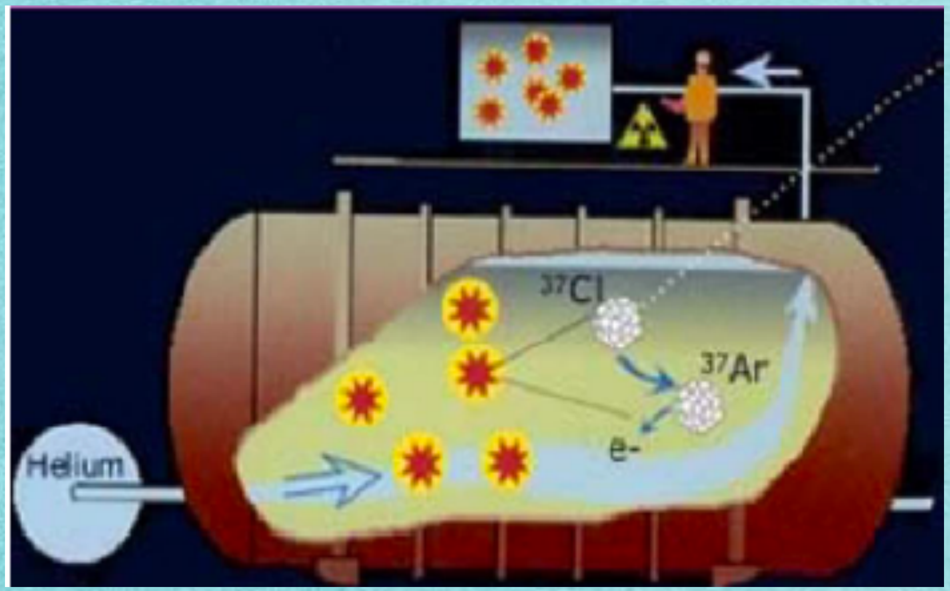


Solar fusion reactions that produce heat and light also produce neutrinos

Hans Bethe proposed to study solar neutrinos
to test the hypothesis of energy generation in Sun

First detection of solar neutrinos

$^{37}Cl + \nu_e \rightarrow ^{37}Ar + e^-$



At Homestake mine in USA

600 tons of cleaning fluid

Less than one event/day

First result in 1968

Only one-third of the predicted neutrinos were found

Where are the missing solar neutrinos ?

The Infamous "Neutrino-burglar"

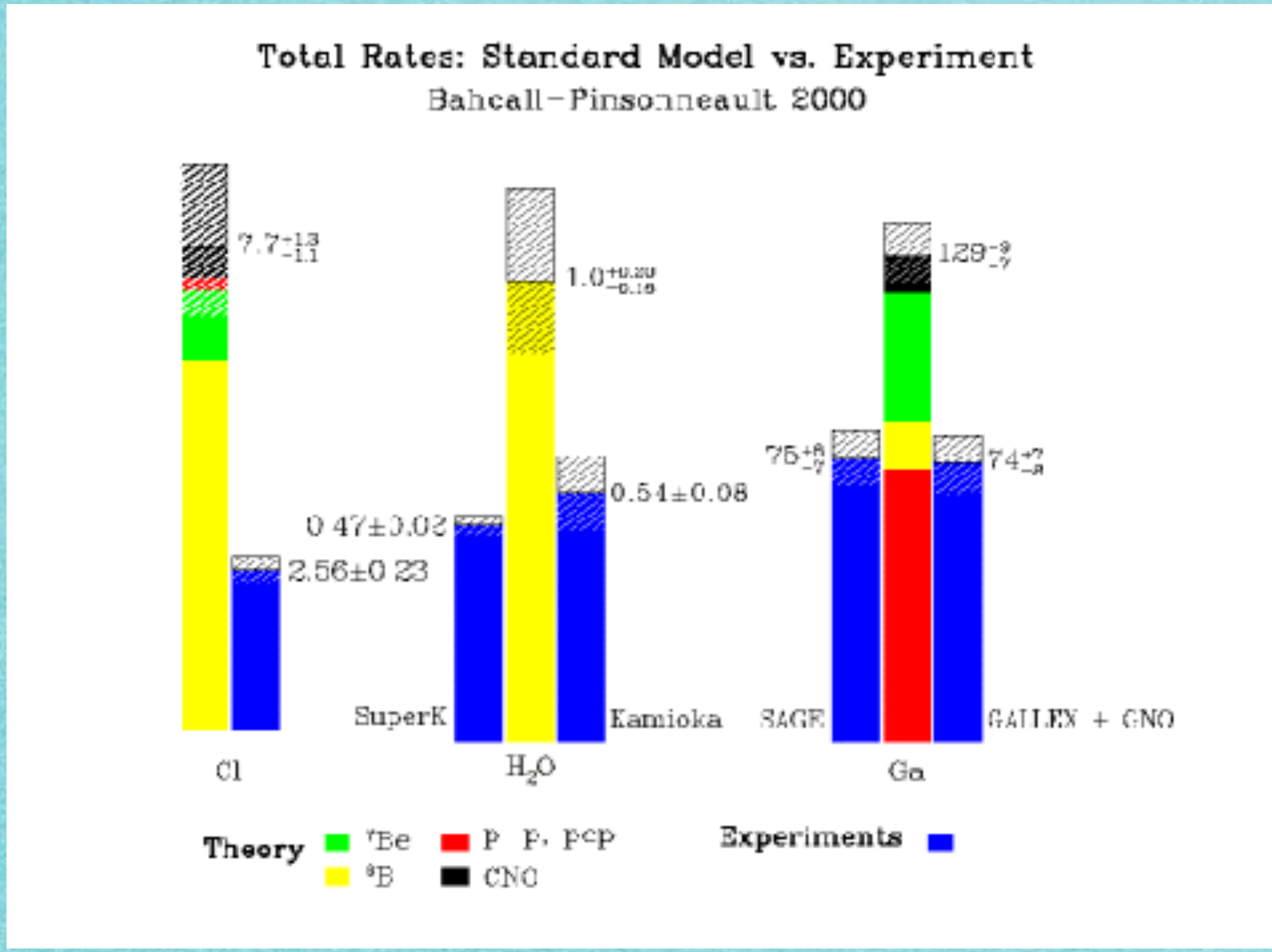
The experiment is wrong — difficult to detect a handful of Argon atoms

Solar Model calculations wrong

Solar electron neutrinos getting converted to muon or tau neutrinos

New Experiments were planned to check these results

The solar neutrino problem

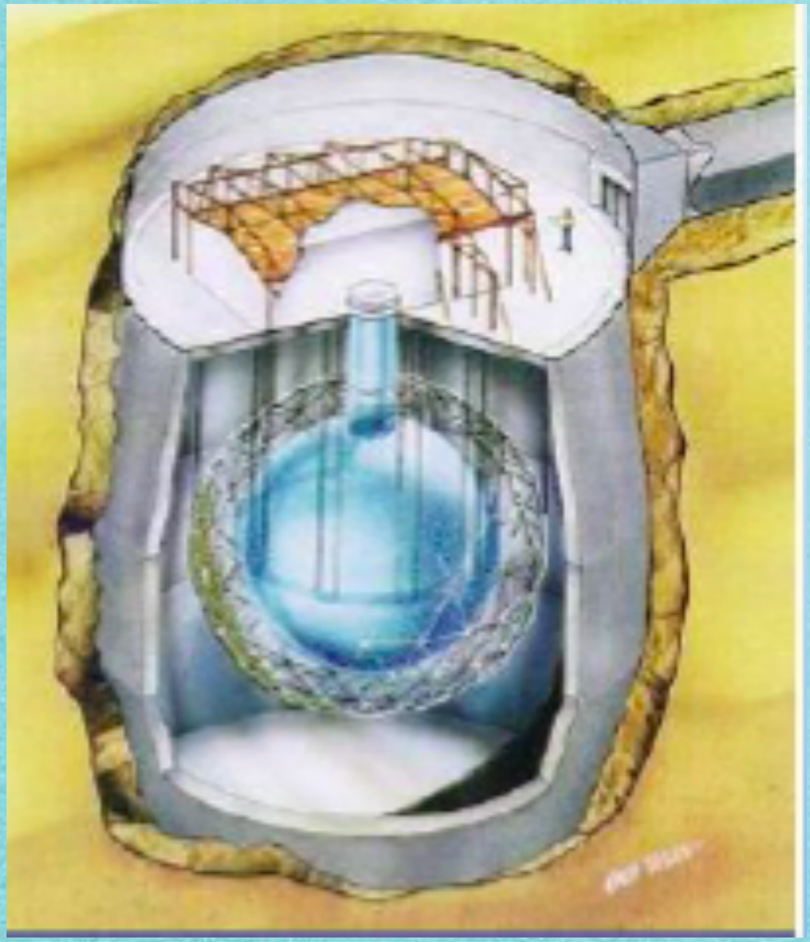


Many new experiments confirmed the shortfall

Observed flux of electron neutrinos less than theoretical predictions

- The mystery of the missing solar neutrinos
  Remained unsolved for 30 years

Sudbury Neutrino observatory



- 1000 Tonnes Heavy Water (D_2O)

Can detect separately: The electron type neutrino
All three types of neutrino

Observed: 1/3rd electron type neutrinos
2/3rd mu and tau neutrino

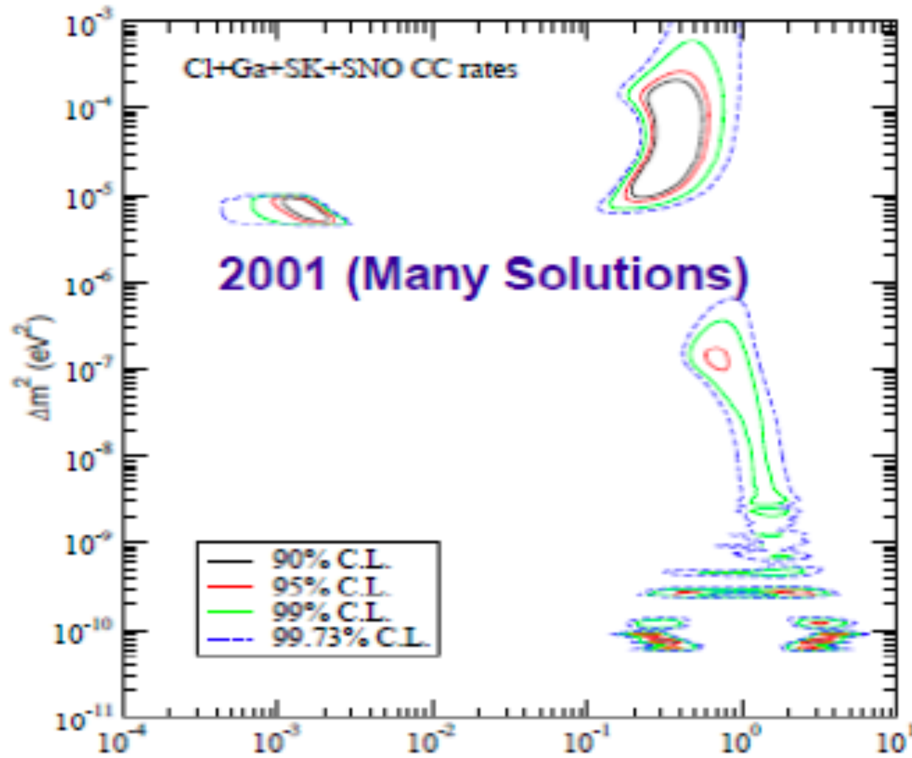
→ Solar electron neutrinos getting converted to other neutrinos

Neutrinos change themselves

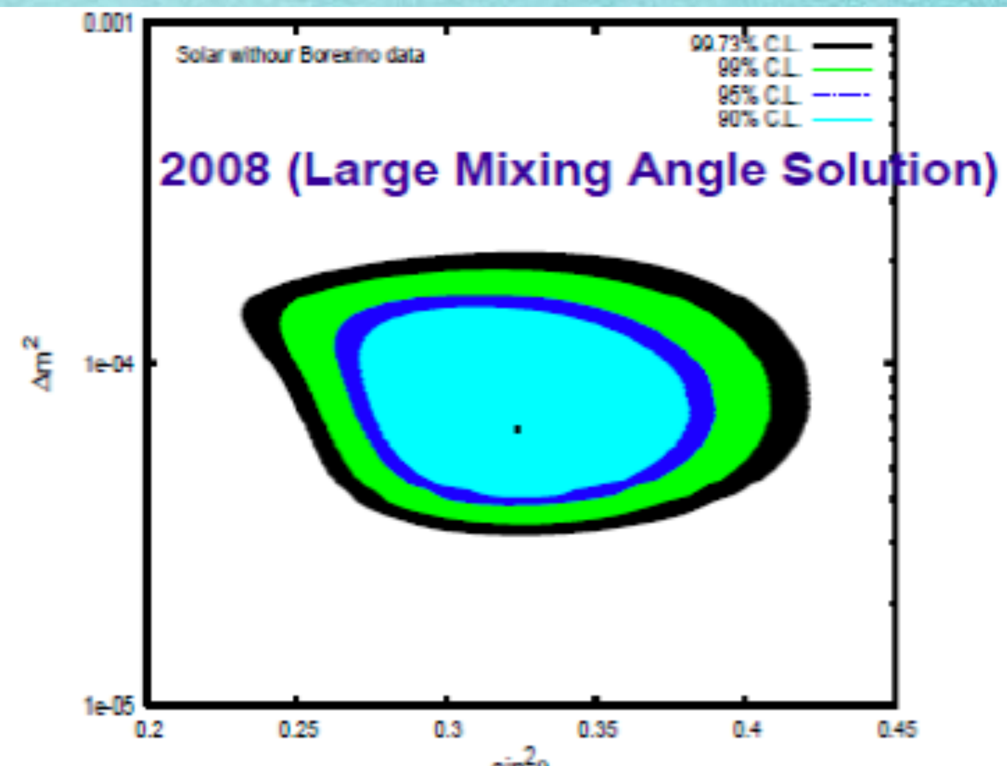
Solution to the solar neutrino problem

- **Electron neutrinos undergo MSW resonant flavour conversion in the sun**

$$\Delta m^2_{21}\cos 2\theta_{12} - 2\sqrt{2}G_F n_e E = 0$$



(Bandyopadhyay,Choubey,S.G,Kar,PLB,2001)



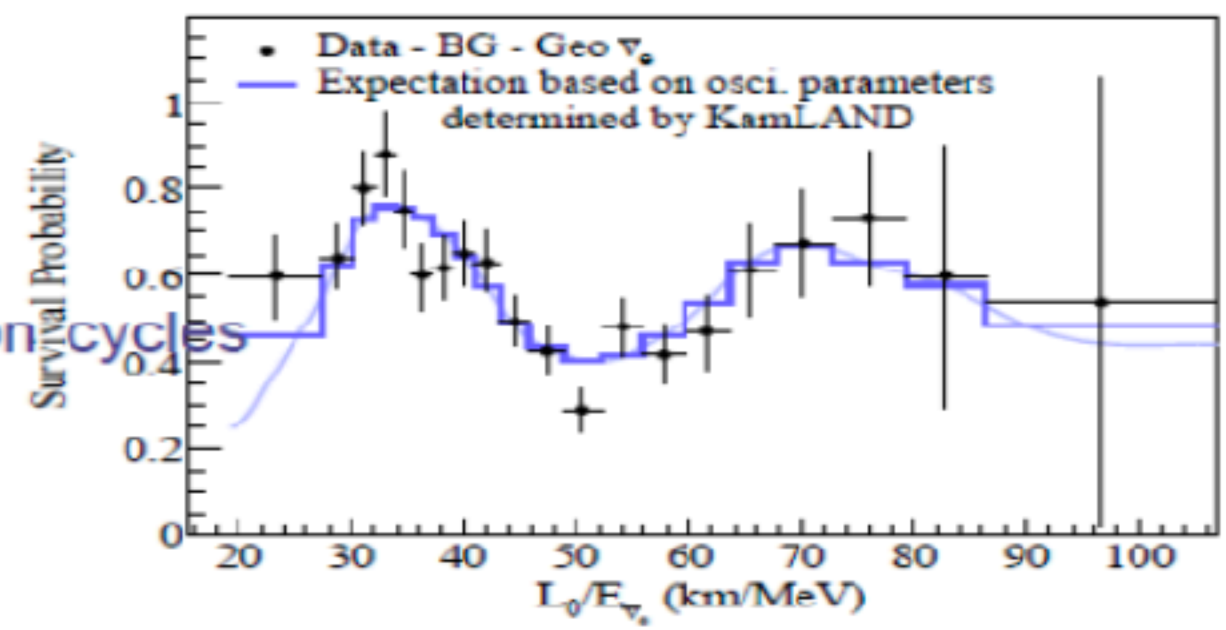
(Bandyopadhyay,Choubey,S.G,Petcov,Roy,2008)

Confirmed by the KamLAND experiment

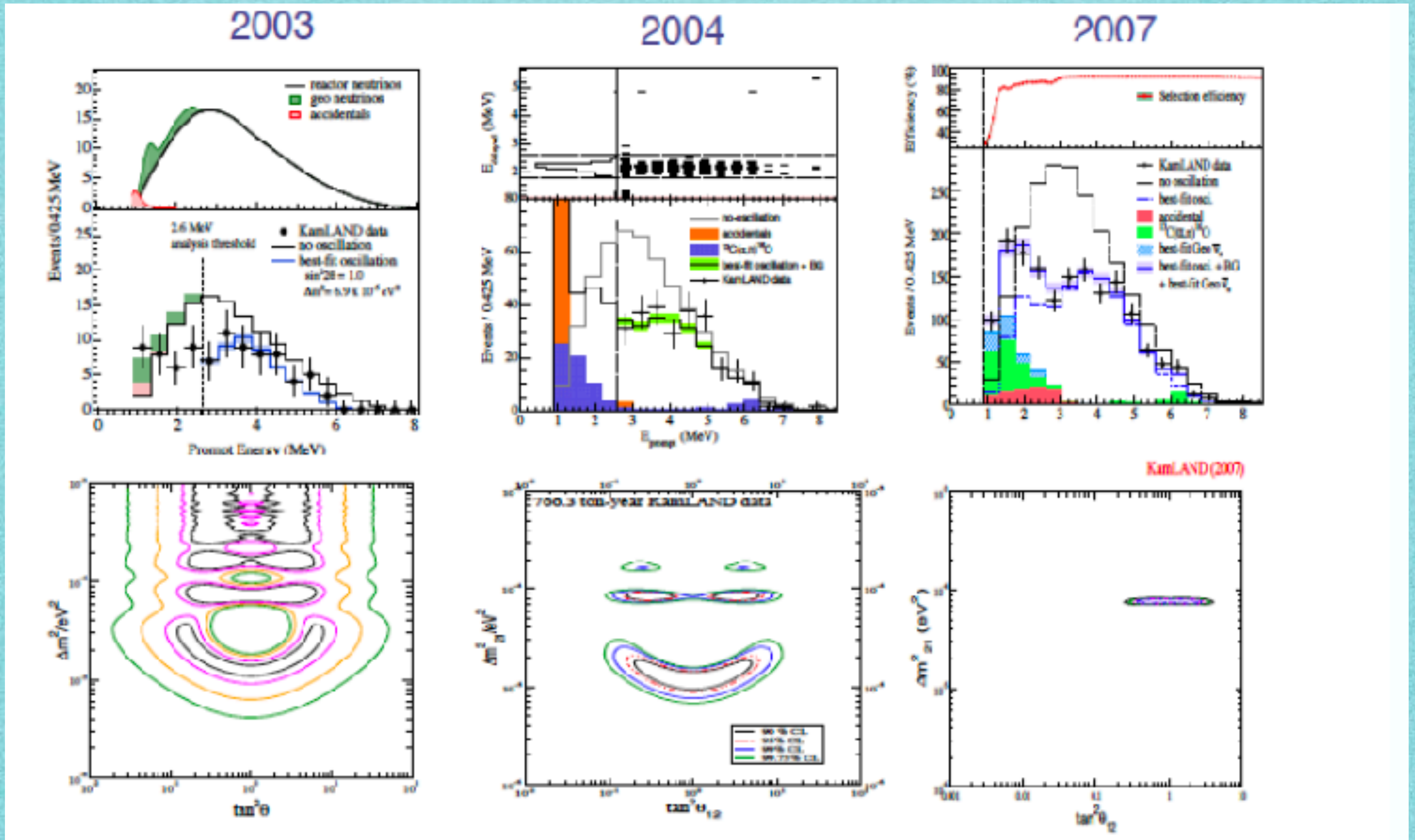
KamLAND

- 1 kton liquid scintillator neutrino detector at Kamioka, Japan
- detects antineutrinos coming from Japaneese nuclear reactors through: $\bar{\nu}_e + p \rightarrow n + e^+$
- $E_\nu \sim 3$ MeV, L $\sim 1.8 \times 10^5$ m , $\Delta m^2 \sim 1.6 \times 10^{-5}$ eV^2

- Data: 2002 - 2007
- Almost two complete oscillation cycles are observed

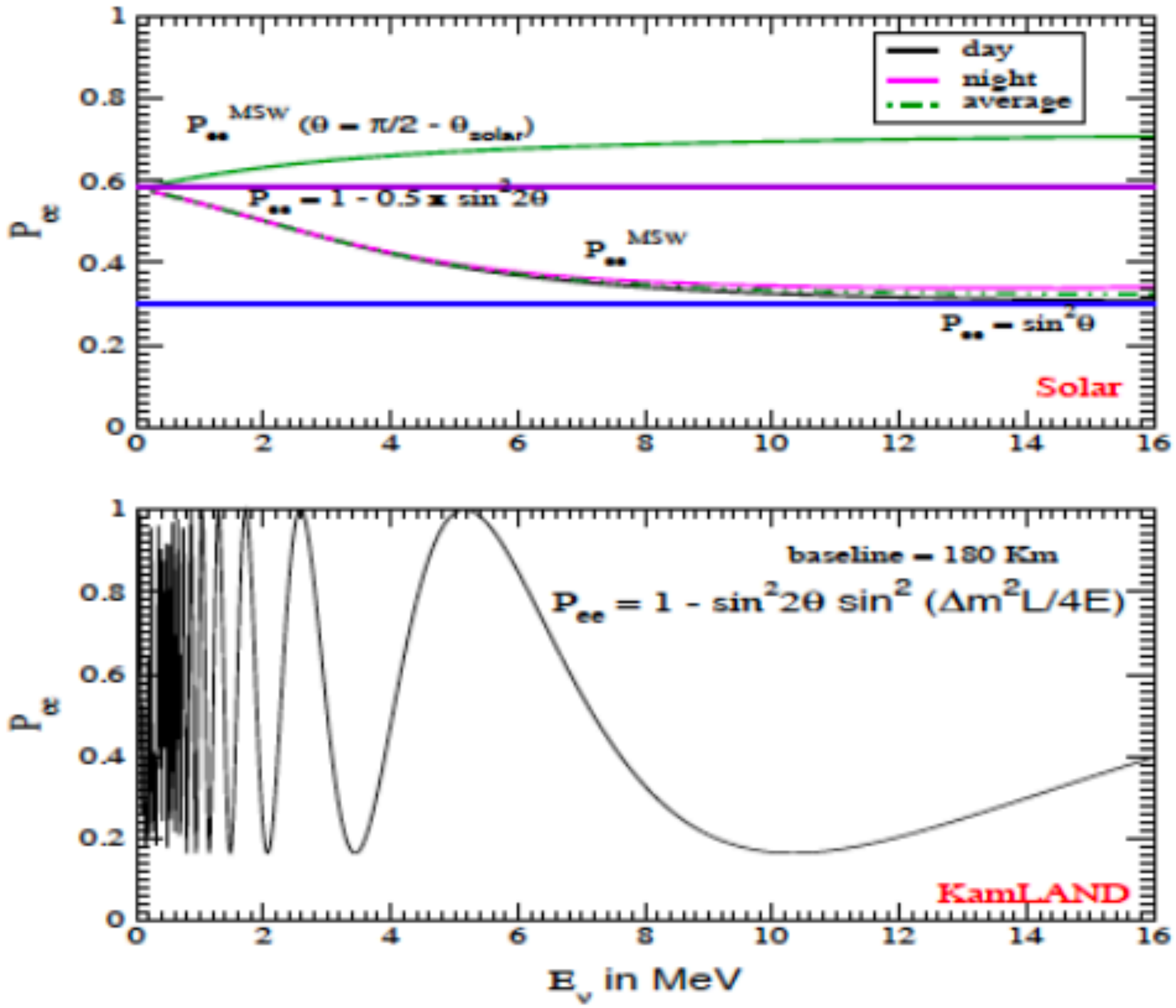


Impact of KamLAND



Bandyopadhyay,Choubey,Goswami,Petcov,Roy 2003, 2005, 2008

Probabilities



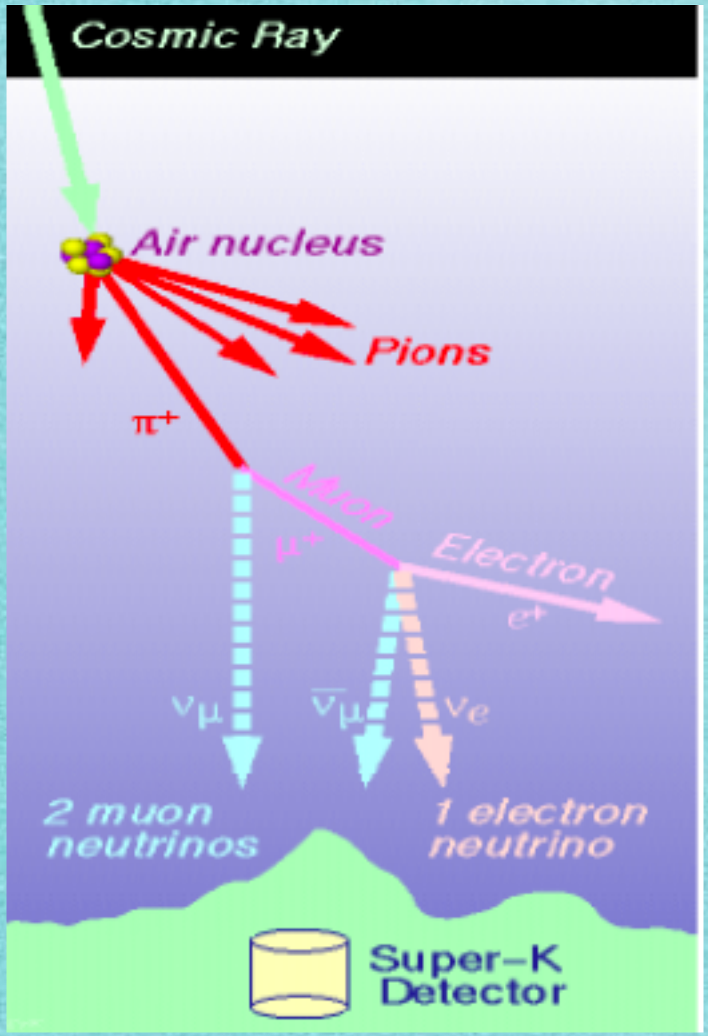
Solar Neutrinos

Δm^2_{21} effects are averaged out

KamLAND

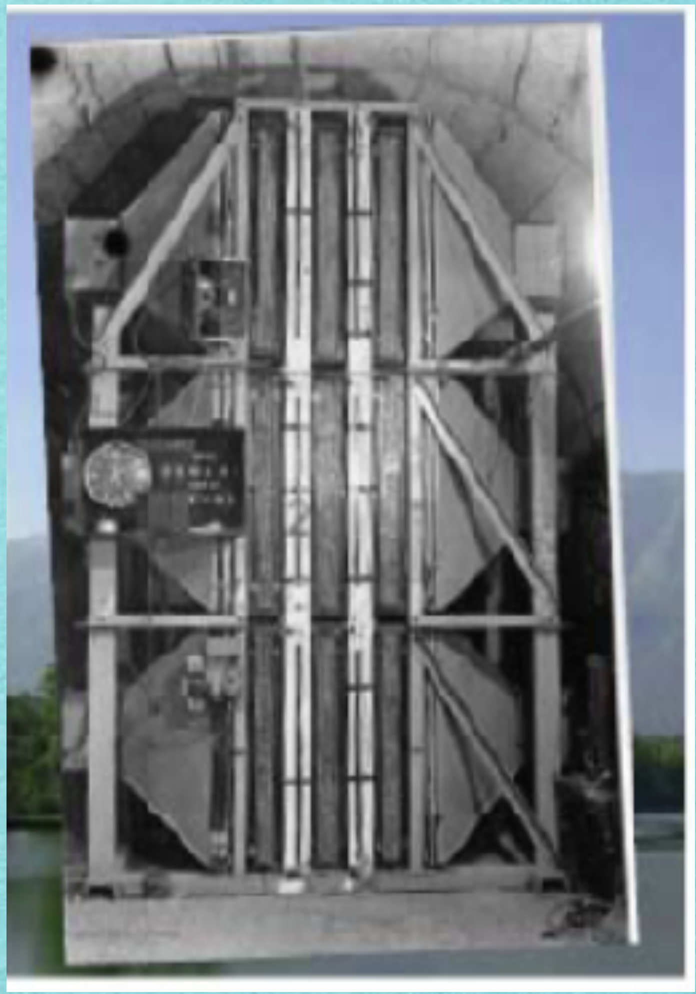
can probe the L/E dependence of the oscillations in the LMA region $\rightarrow$ unprecedented sensitivity to Δm^2

Atmospheric Neutrinos



Electron and muon type of neutrinos are produced when cosmic rays hit the air molecule

- Energy: 100 MeV - TeV
- Pathlength: 15 -13,000 km
- Provides broad L/E band



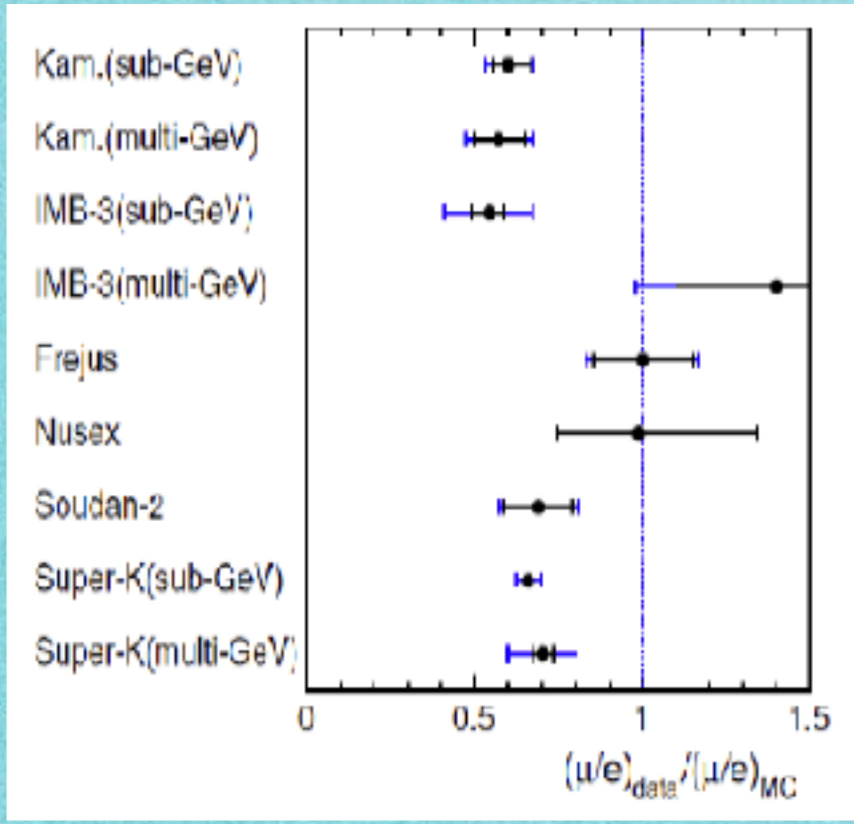
One of the first detections in Kolar Gold Mine, India in 1965

Atmospheric Neutrino Anomaly

$$\text{Cosmic Ray} + A_{air} \to \pi^+ + \ldots$$
$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$

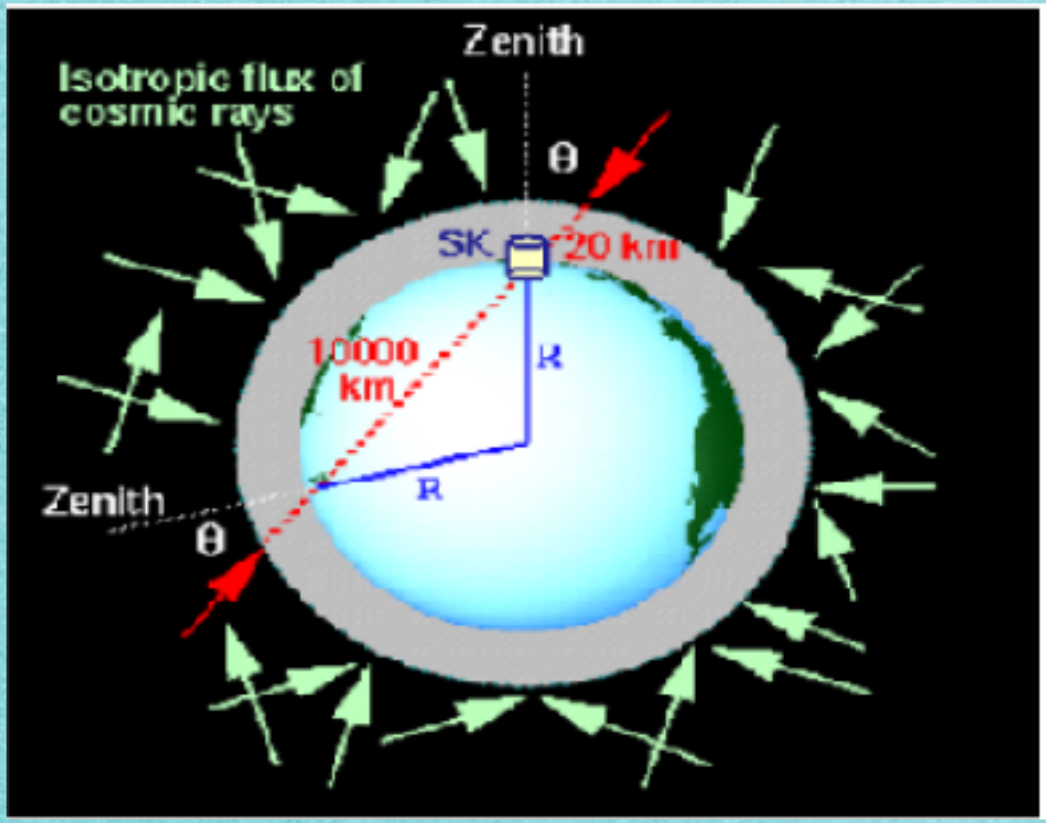
$\nu_\mu : \nu_e = 2:1$ (expected)

$\nu_\mu / \nu_e \sim 0.9 - 1$ (observed)



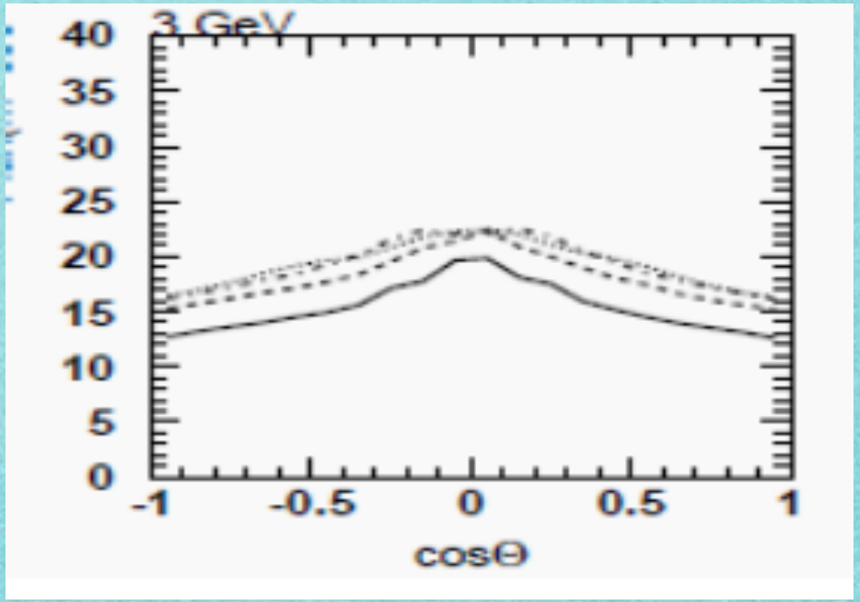
$$(\mu/e)_{data}/(\mu/e)_{MC} < 1$$

Superkamiokande



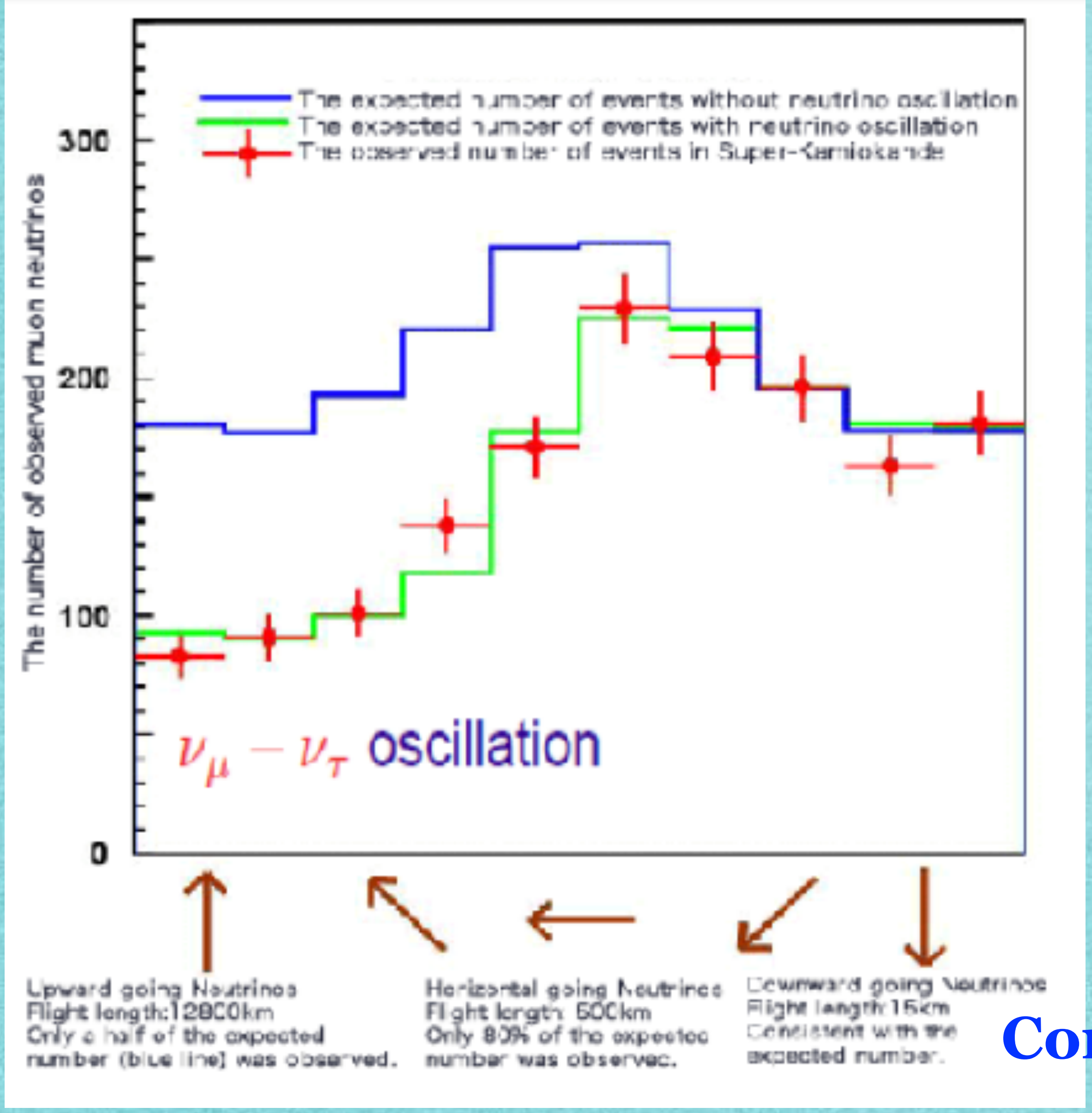
Observes atmospheric neutrinos through neutrino-nucleon interactions

Has enough statistics to study events in Zenith angle bins



- Oscillation can cause up-down assymmetry → Down going neutrinos do not oscillate
Up going neutrinos oscillate

Zenith-Angle dependence in SK data



First results were presented by T. Kajita in Neutrino 1998 conference

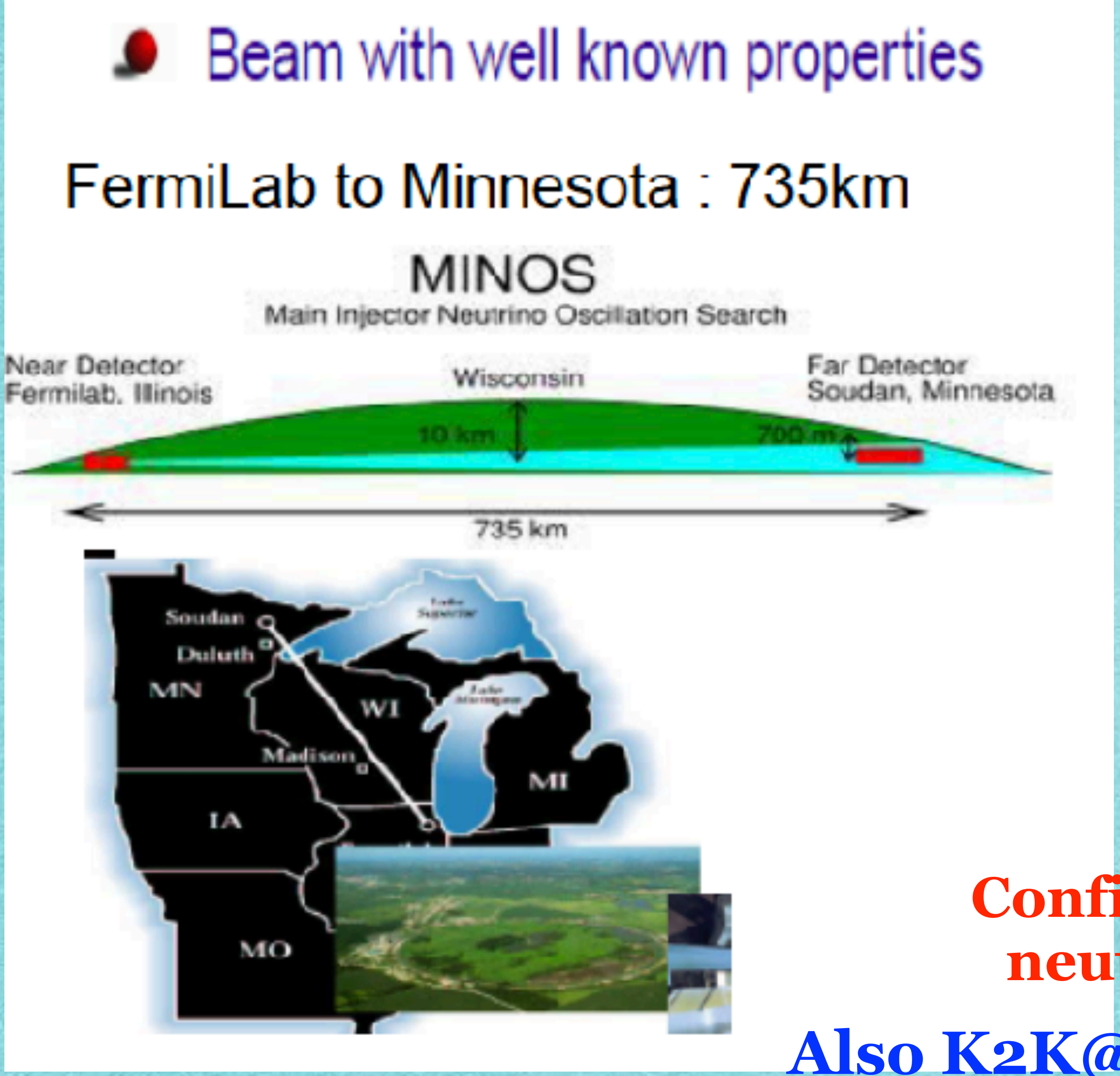
SK found evidence for up-down asymmetry in the muti-GeV muon events.

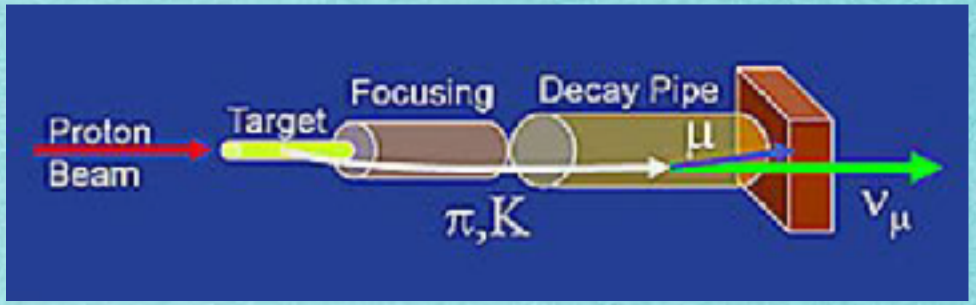
This established $\nu_\mu \rightarrow \nu_\tau$ oscillation as solution to the atmospheric anomaly

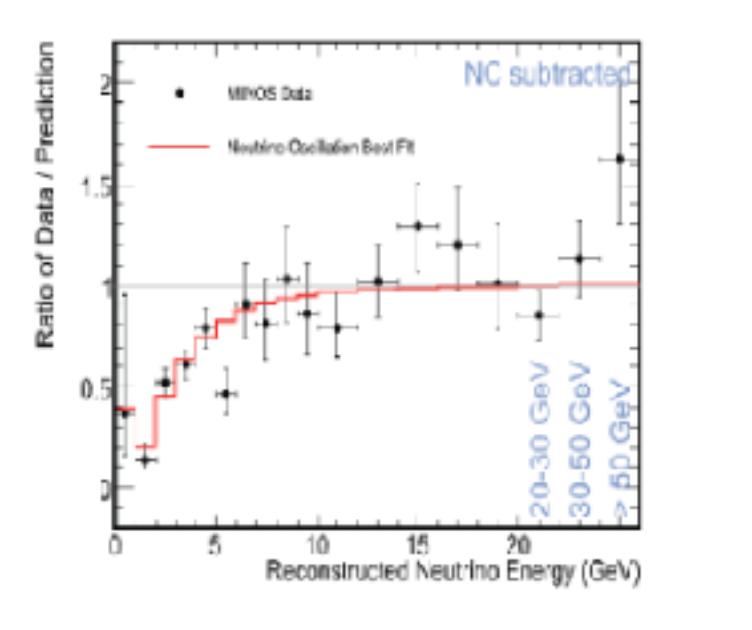
"Around the turn of the millennium, Takaki Kajita presented that neutrinos from the atmosphere switch between two identities on their way to the Super-Kamiokande detector in Japan."

Confirmed by accelerator experiments

MINOS



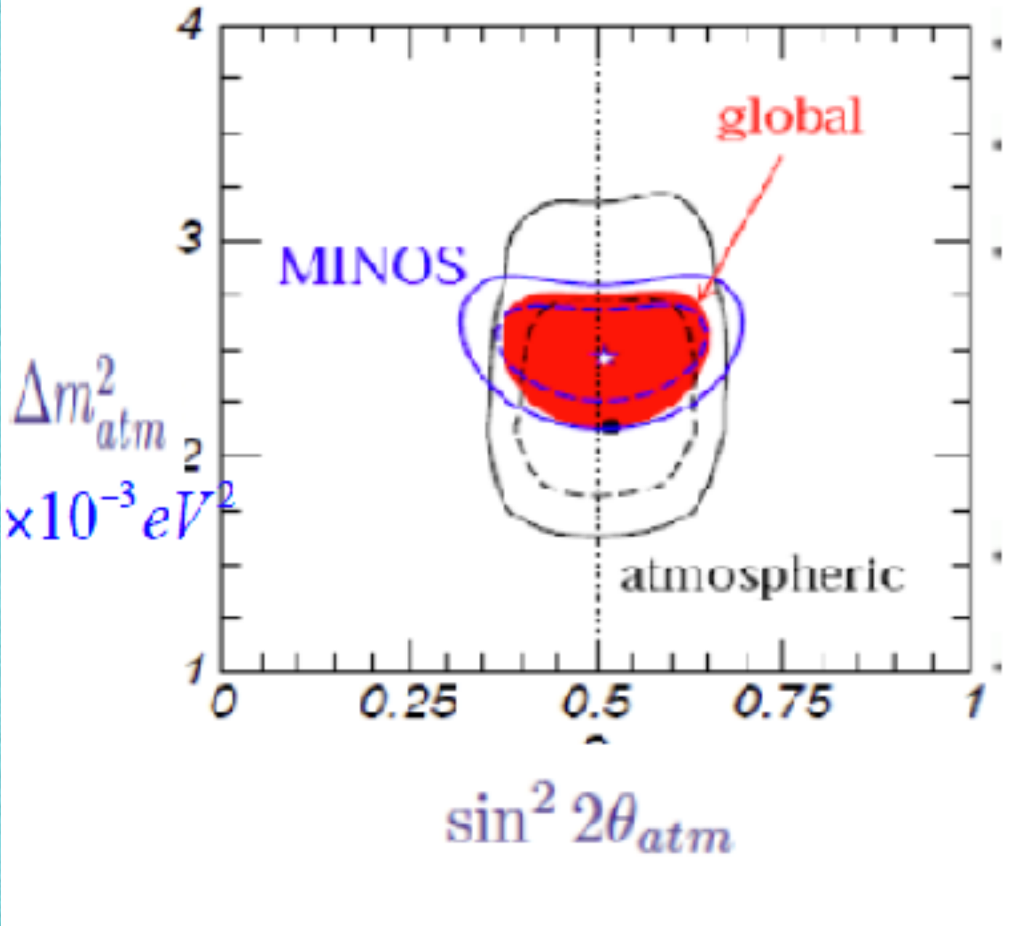




Confirmed oscillation of atmospheric neutrinos using man made sources

Also K2K@Japan, T2K@Japan, NoVA@US

Solution to the atmospheric neutrino anomaly



- Two generation $\nu_\mu - \nu_\tau$ oscillation
- Matter Effect does not play role
- Relevant probabaility

$$P_{\mu\mu} = 1 - \sin^2 2\theta_{atm} \sin^2\left(\frac{\Delta m^2_{atm} L}{4E}\right)$$

- No information on $sgn(\Delta m^2_{atm})$.

2015 Nobel Prize in Neurino Oscillation

Three Neutrino Oscillation Parameters

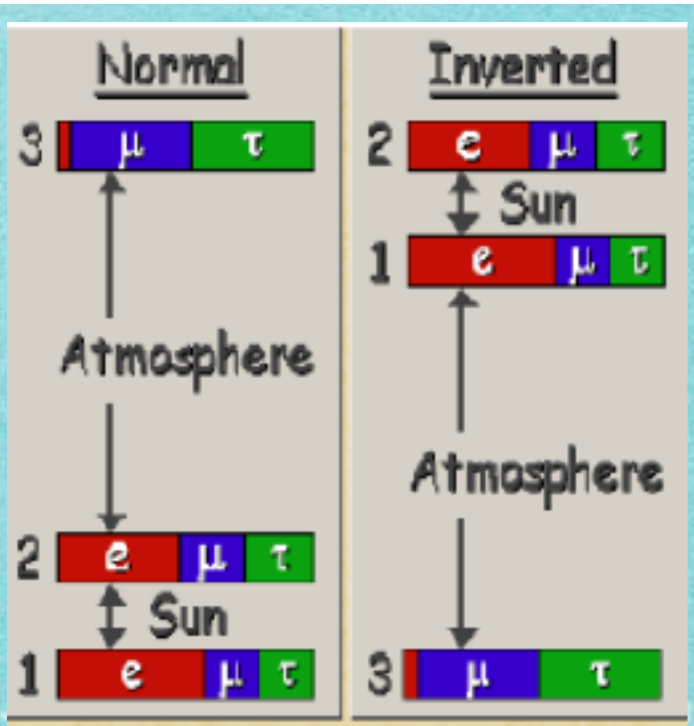
3 masses, 3 mixing angles, 1 phase

Atm +LBL | Sol+KL

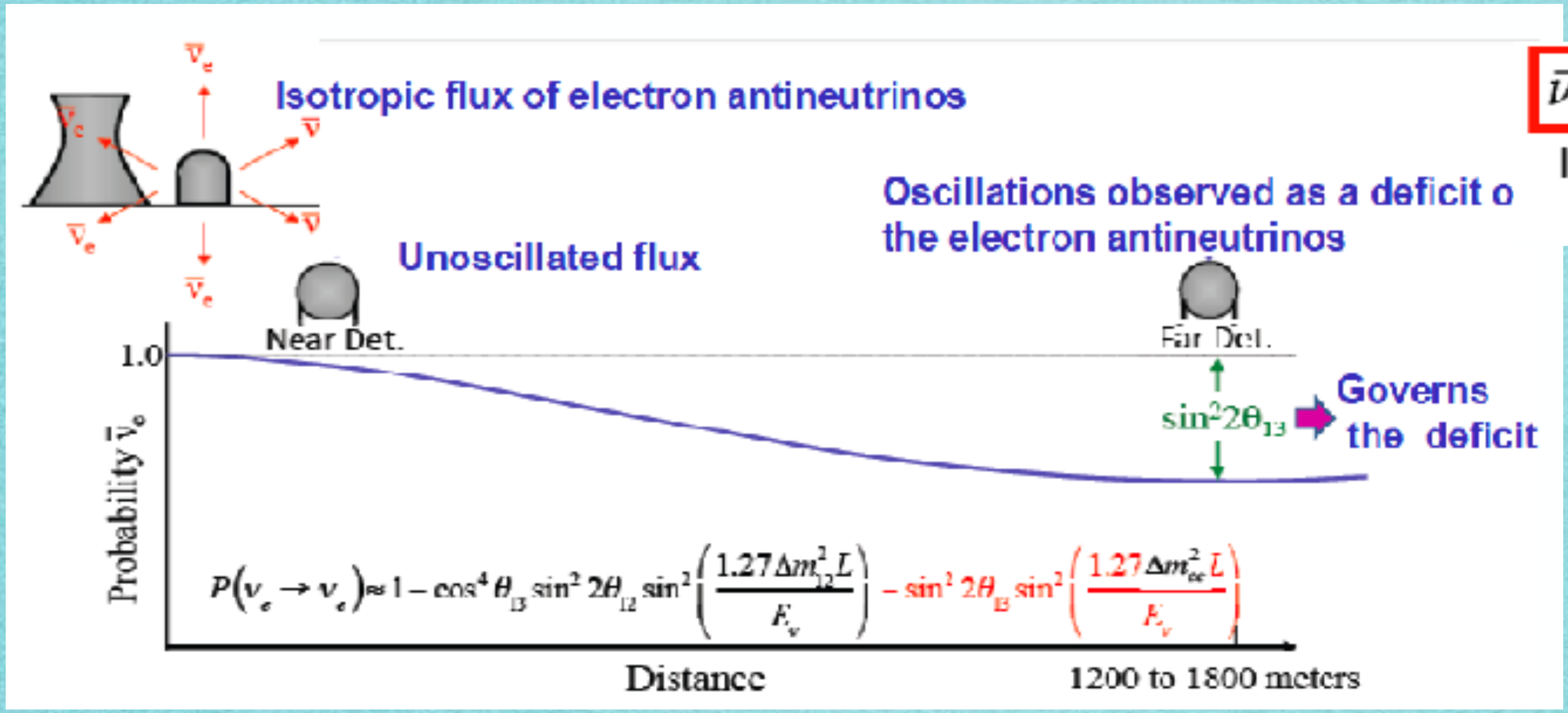
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & e^{-i\delta} s_{13} \\ & 1 & \\ -e^{i\delta} s_{13} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} &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

$c_{12} = \cos\theta_{12}$ etc., δ CP-violating phase

- Oscillation experiments – sensitive to mass squared differences
- Solar : $\Delta m^2_{21} = m^2_2 - m^2_1$, θ_{12}
- Atmospheric : $\Delta m^2_{31} = m^2_3 - m^2_1$, θ_{23}
- Reactor Neutrinos : θ_{13}



Measurement of the third mixing angle



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

Inverse Beta Decay (IBD)

Measured non-zero value of θ_{13}

Current Picture

www.nu-fit.org

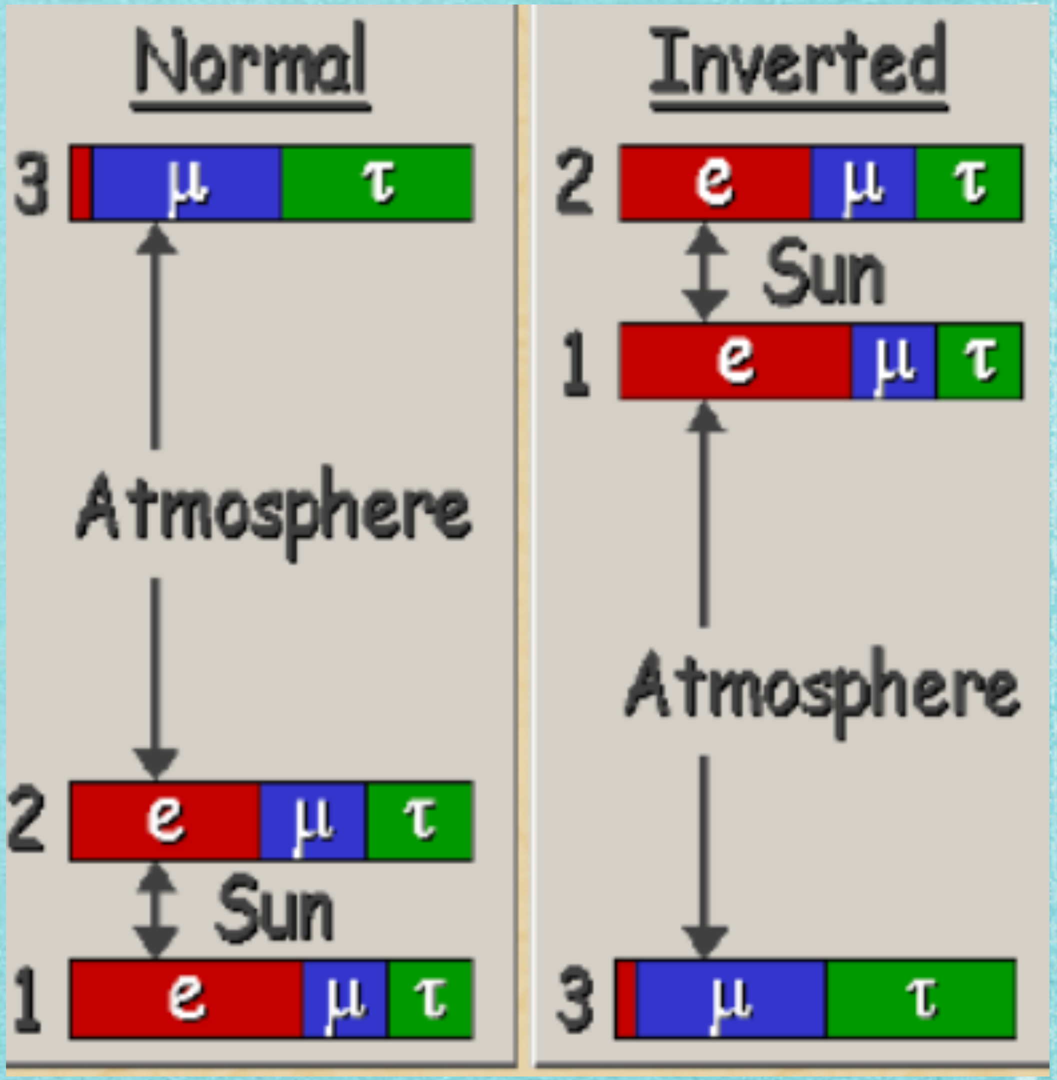
- Global oscillation of neutrino data shows some preference for normal hierarchy (NH)
- The best-fit values and 3σ ranges for NH are :

Oscillation parameter	Best-fit Value	3σ range
θ_{12}	33.82°	$31.61^\circ \to 36.27^\circ$
θ_{13}	8.61°	$8.22^\circ \to 8.99^\circ$
θ_{23}	48.3°	$40.8^\circ \to 51.3^\circ$
Δm^2_{21} ($\times 10^{-5}$eV^2)	7.39	$6.79 \to 8.01$
$\lvert\Delta m^2_{31}\rvert$ ($\times 10^{-3}$eV^2)	2.523	$2.432 \to 2.618$
δ_{CP}	222°	$141^\circ \to 370^\circ$

Global Oscillation Analysis : data from all experiments, χ^2 analysis

Outstanding issues

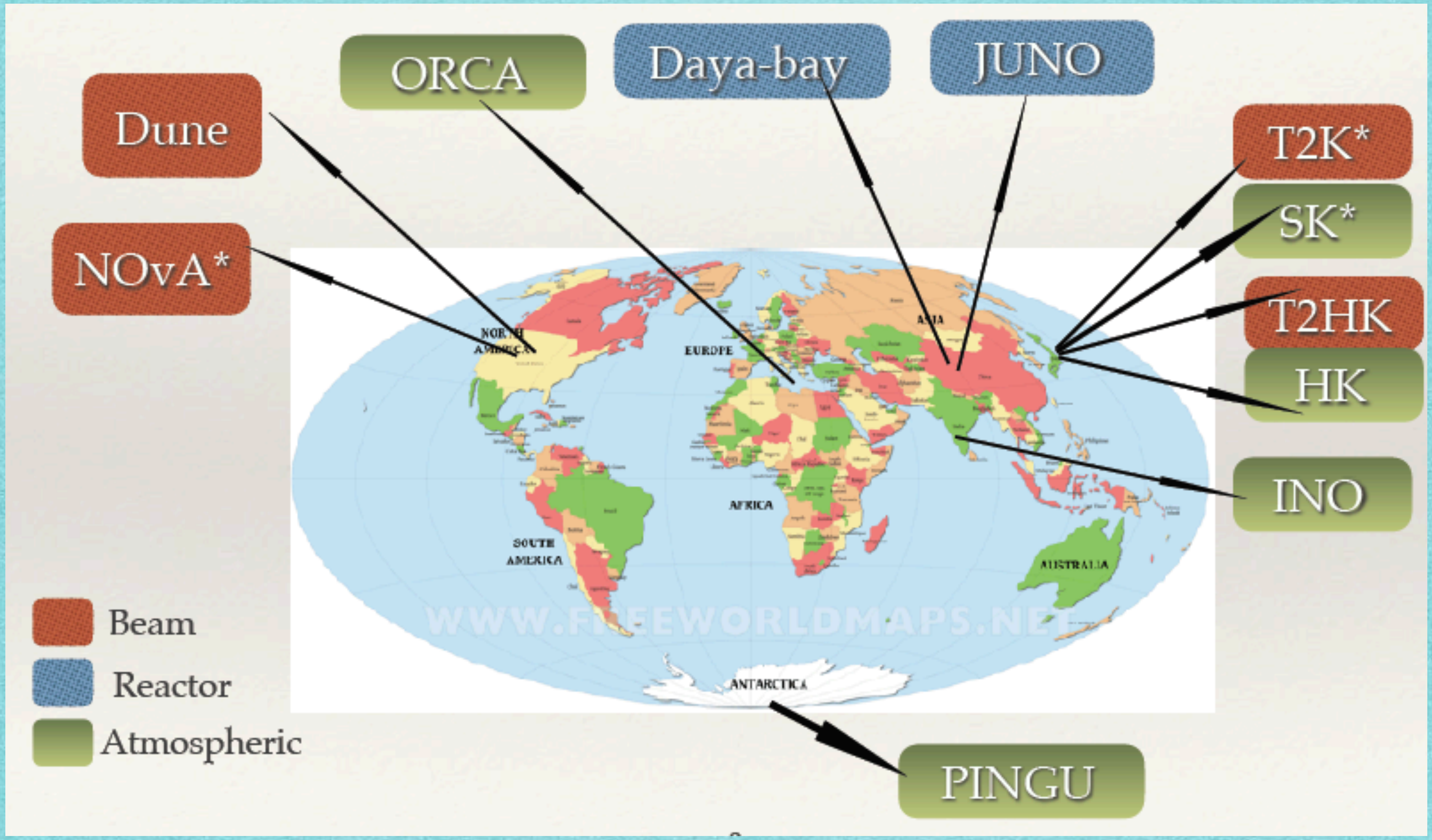
- The hierarchy of neutrino masses
- The octant of the 2-3 mixing angle
- The precise value of the CP phase



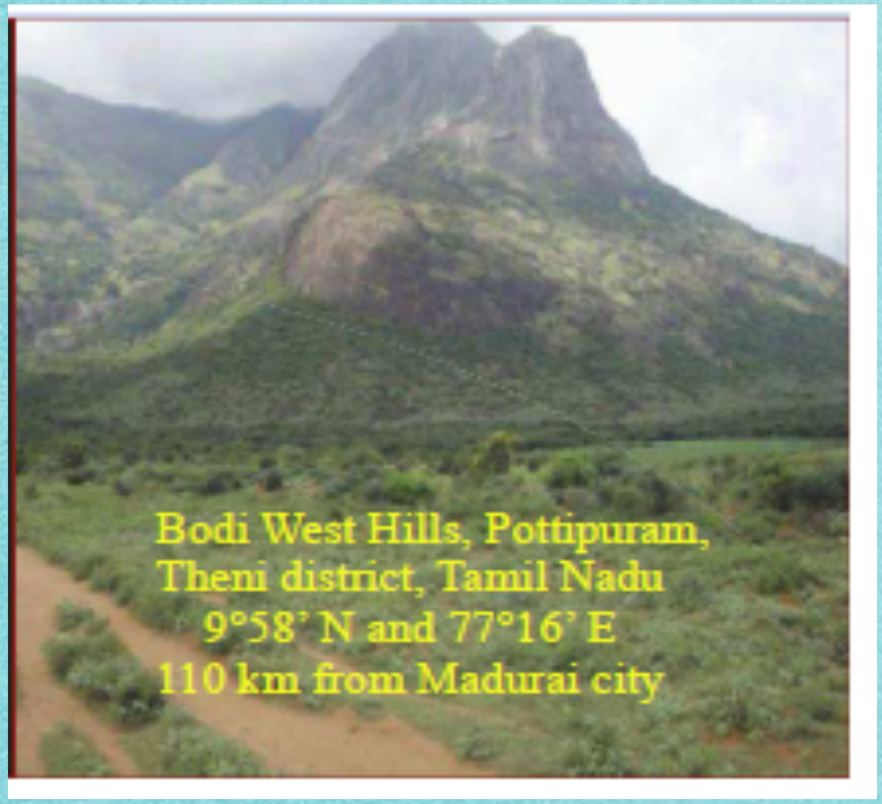
- The nature of the neutrinos
- Whether three or more neutrinos ?
- The mechanism of neutrino mass and mixing
- Whether neutrinos can explain the baryon asymmetry of the universe ?

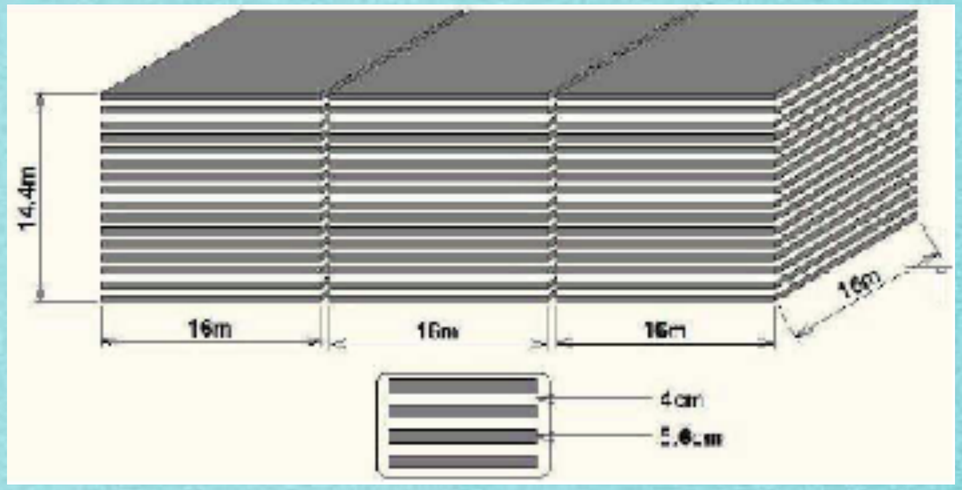
Many planned and proposed experiments

Ongoing and proposed Experiments



India-Based Neutrino Observatory





50 kton magnetized iron detector

Will observe oscillation of atmospheric neutrinos

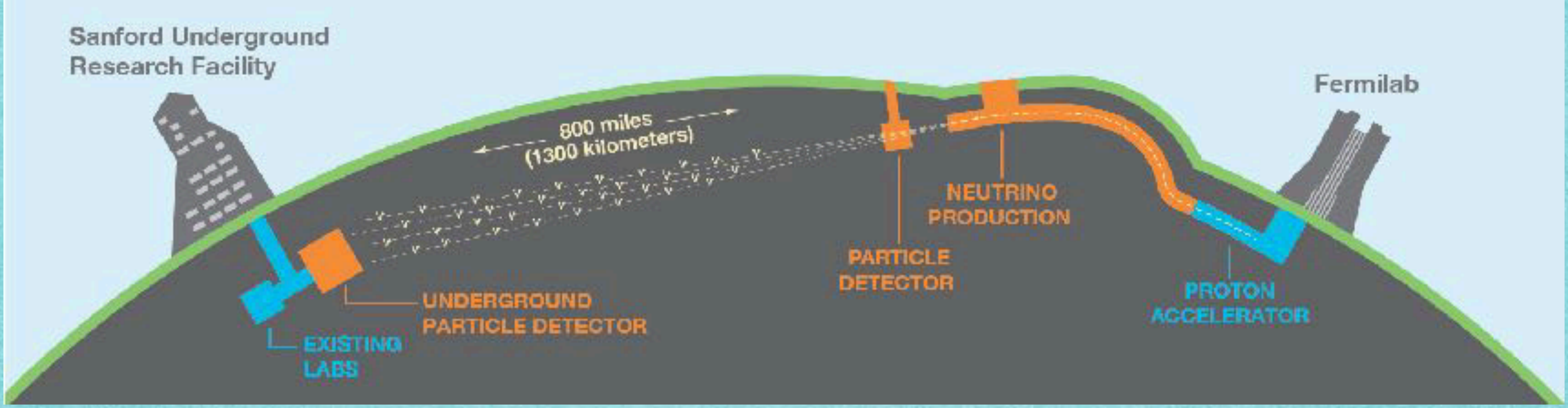
Can discover unknown neutrino properties

Simulation Framework for INO

NUANCE	**Neutrino Event Generation** $\nu_\ell + N \to \ell + X$ Generates particles that result from a random interaction of a neutrino with matter using theoretical models for both neutrino fluxes and cross-sections.	**Output:** i) Reaction Channel ii) Vertex Information iii) Energy & Momentum of all final state particles
GEANT	**Event Simulation** ℓ + X through simulated ICAL Simulate propagation of particles through the ICAL detector with RPCs and magnetic field.	**Output:** i) x, y, z, t of the particles as they propagate through the detector ii) Energy deposited iii) Momentum information
DIGITIZATION	**Event Digitization** (x,y,z,t) of final state particles including noise and detector efficiency Add detector efficiency and noise to the hits	**Output:** i) Digitised output of the previous stage (simulation)
ANALYSIS	**Event Reconstruction** (E,p) of ℓ + X (total hadrons) Fit the muon tracks using kalman filter techniques to reconstruct muon energy and momentum, use hits in hadron shower to reconstruct hadron information.	**Output:** i) Energy & Momentum of muons and hadrons, for use in physics analysis.

Deep Underground Neutrino Experiment (DINR)

@Fermilab, US



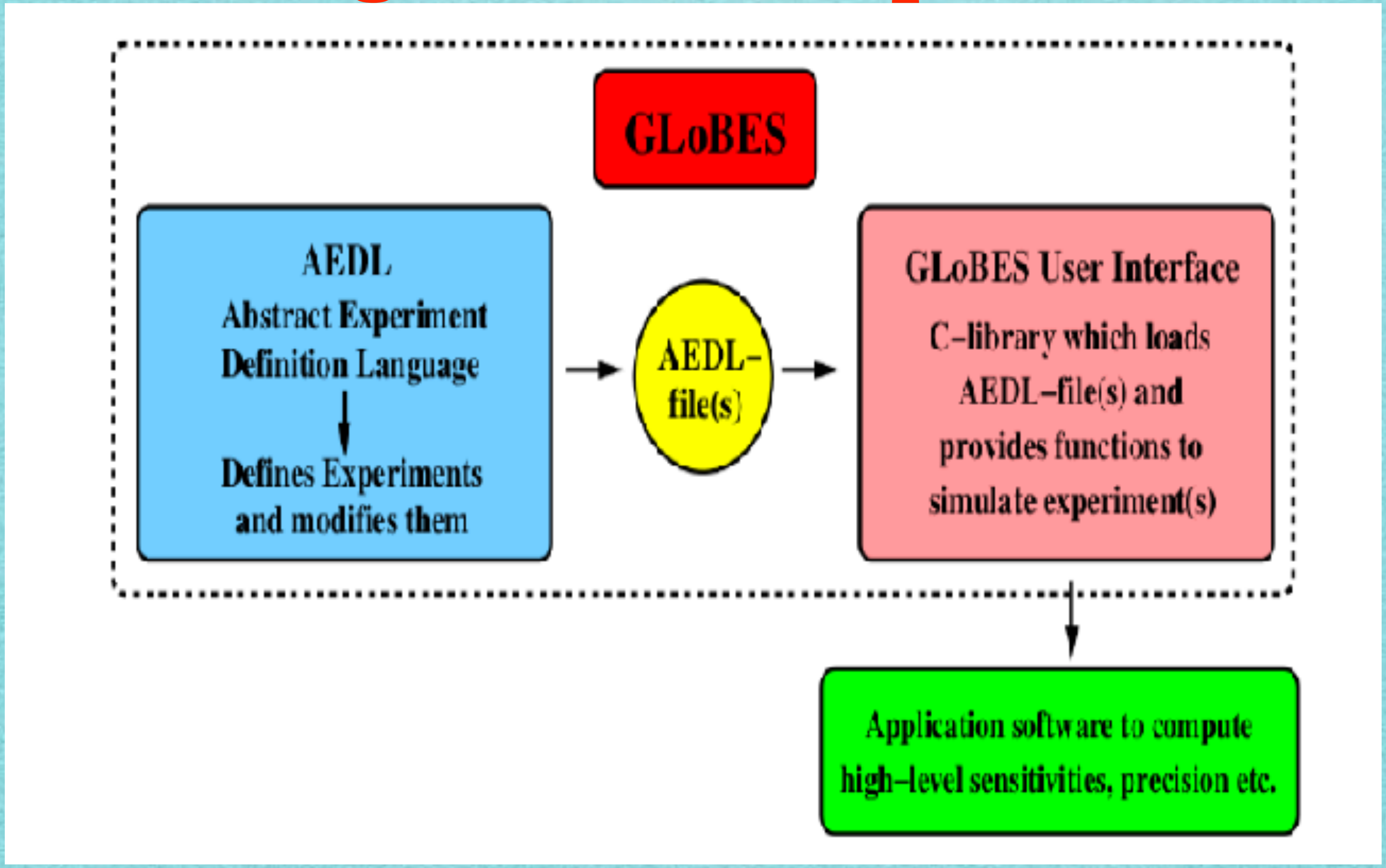
Accelerator neutrinos traveling 1300 km

Aiming for ground breaking discoveries regarding properties of neutrinos

Long-Baseline Exepriment

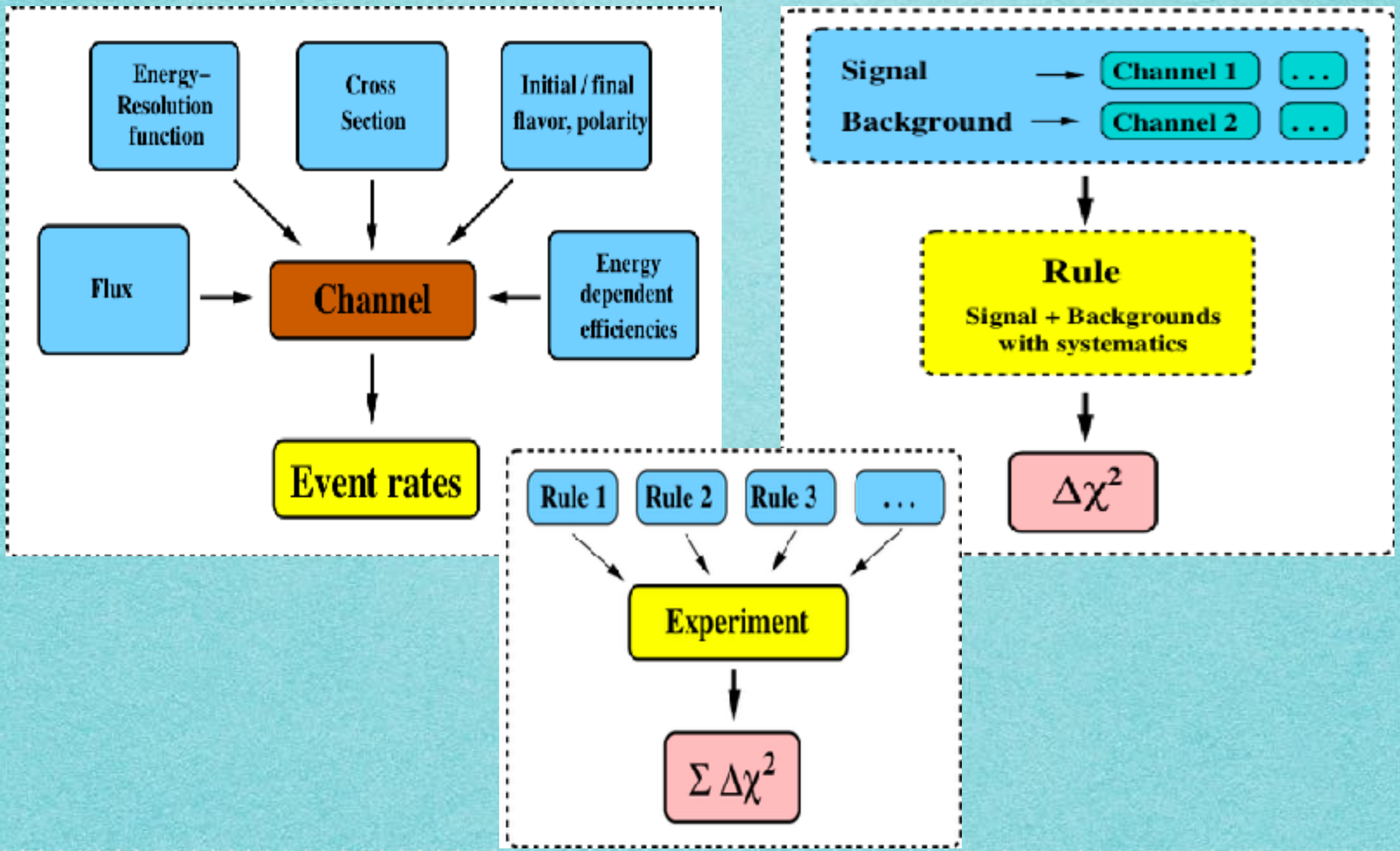
GLoBES

General Long Baseline Experiment Simulator



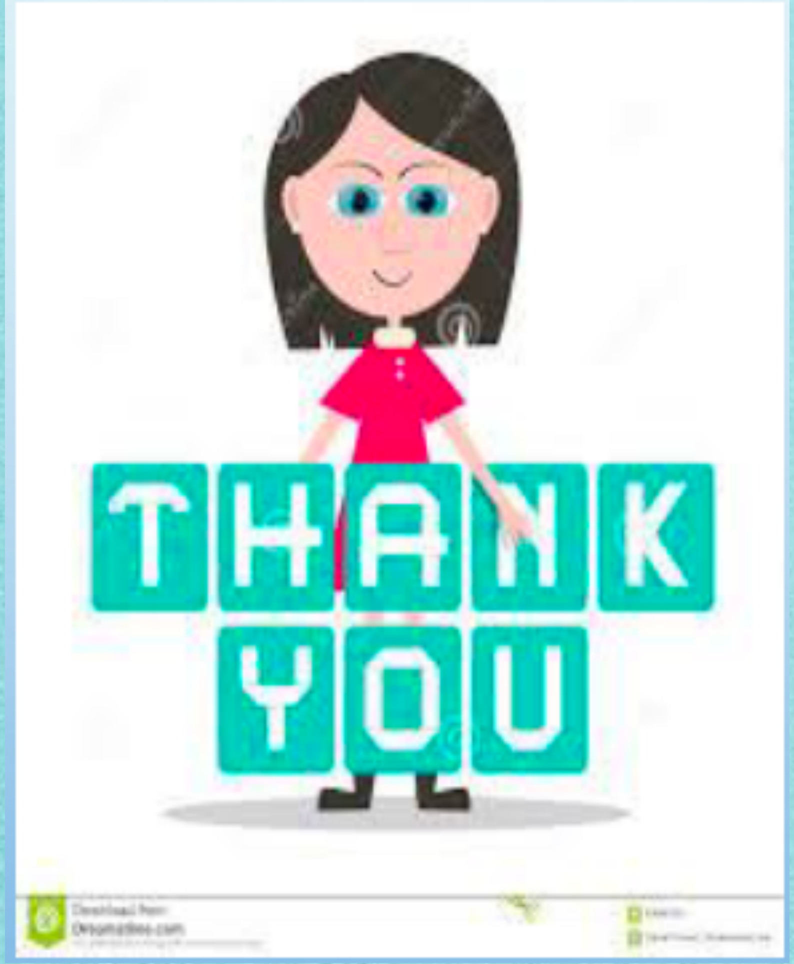
https://www.mpi-hd.mpg.de/personalhomes/globes/

GLoBES Flowchart



Summary

- Neutrinos are all around us
- They interact very weakly and one needs huge detectors to study them
- Neutrino oscillations have been observed by several experiments and provided information on neutrinos mass differences and mixing angles
- Story is not yet over, new experiments …..
- May hold the key to deeper understanding of nature



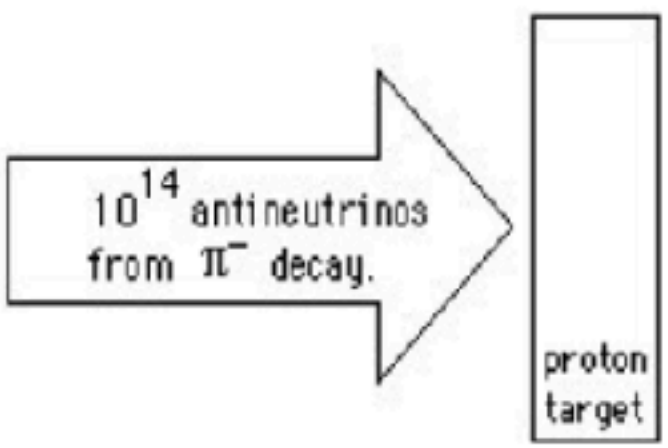
Credit: Resources from internet


BACKUP

Muon Neutrino

- In 1960 Bruno Pontecorvo suggested that the neutrinos produced in $\pi^+ \rightarrow \mu^+ + \nu$ may be different from the neutrino produced in β-decay.

- In 1962 this experiment was carried out using a beam of 15 GeV protons in the AGS accelerator in Brookhaven

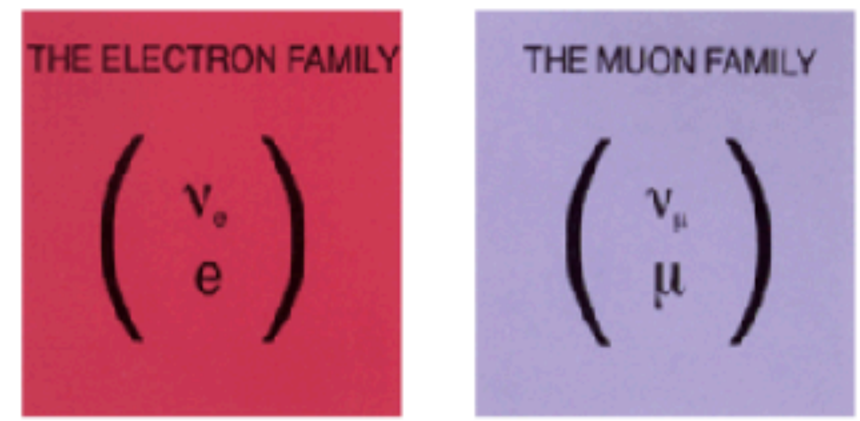


Reaction	Number observed
$\bar{\nu}_\mu + p^+ \rightarrow \mu^+ + n$	29
$\bar{\nu}_\mu + p^+ \rightarrow e^+ + n$	0

" The first high energy neutrino experiment "

1988 Nobel Prize

Nobel Prize in 1988 to Leon Lederman, Melvin Schwartz and Jack Steinberger



The known lepton families after the neutrino experiment; the electron (e) and the electron neutrino (ν_e), the muon (μ) and the muon neutrino (ν_μ).

- " for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino."
- " ...was a crucial step to the current world view of particle physics which we call Standard Model "
- **Between 1962 to 1988 "high energy neutrino beams found intensive and varied applications in particle physics experimentation "**

The Tau Neutrino

The third type of neutrino the tau neutrino was discovered in 2000 by the DONUT experiment at Fermilab (USA)

$$\nu_\tau + N \rightarrow \tau + N'$$

Three types of neutrinos have been observed