Neutrino and Astroparticle Physics I

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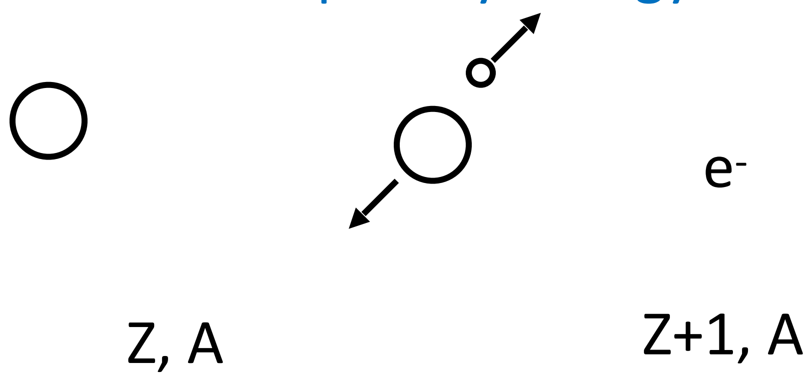
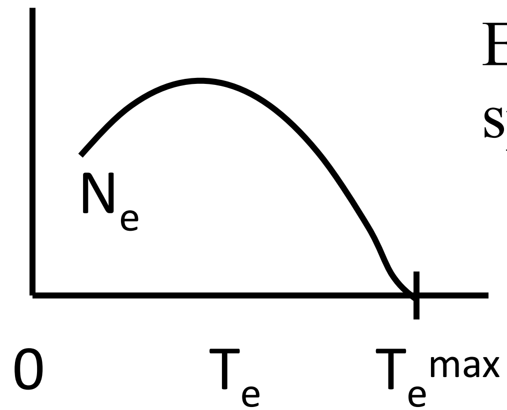
A brief history

- How was the neutrino discovered?
- Neutrino oscillations
- Solar and atmospheric neutrino oscillations and their messages to particle physicists
- The measurement of small mixing angle θ_{13}

(1). How was neutrinos discovered?

Pauli proposed the existence of neutrino to account for βdecay energy distribution.





Electron kinetic energy spectrum

$$T_e^{\max} = \left(M_{Z+1,A} - M_{Z,A}\right)c^2$$

Contradictory for 2-particle final states!

- **1931** Pauli proposed the existence of neutrino in β decay to account for energy-momentum conservation.
  (1) massless
  (2) spin 1/2
  (3) neutral
  (4) weak interacting

The Super-Kamiokande result in 1998 indicates that neutrinos are massive!

- **1956** Neutrinos detected by Cowan and Reines
  Reactor anti-neutrino is captured by proton
  with a positron produced.

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

The capture cross section is only 10^{-44} cm^2.
Huge target mass is needed.

•**1962** L. Lederman, M. Schwartz and J. Steinberger discovered the second type of neutrino, ν_μ, which is different from ν_e produced in β decay.

$$\pi^+ \rightarrow \mu^+ + \nu_\mu, \ \nu_\mu + n \rightarrow \mu^- + p$$

Indicator of neutrino species

•**2000** Direct observation of ν_τ at Fermi Lab

(2). Neutrino oscillations

Neutrinos can oscillate into one another provided that they are massive and non-degenerate in mass.

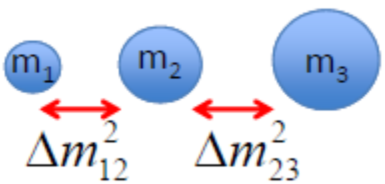
- **PMNS (Pontecorvo-Maki-Nakagawa-Sakata) matrix**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

m_2 could be heaviest

Weak eigenstates-
"flaver eigenstates"

mass eigenstates



$$U_{MNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}$$

Atmospheric — U_{23}

Reactor — U_{13}

Solar — U_{12}

Majorana Phases

U_{13} thought to be approaching I, i.e., θ_{13} is very small (prior to 2012)

$$i\frac{\partial}{\partial t}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}=\begin{pmatrix}E_1 & 0 & 0\\ 0 & E_2 & 0\\ 0 & 0 & E_3\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$$E_k=\sqrt{p^2+(m_k)^2}\cong E+\frac{(m_k)^2}{2E}$$

In flavor basis, we have

$$i\frac{\partial}{\partial t}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=U\begin{pmatrix}E_1 & 0 & 0\\ 0 & E_2 & 0\\ 0 & 0 & E_3\end{pmatrix}U^{-1}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

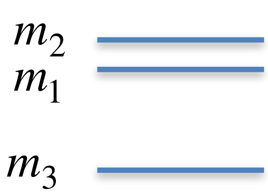
Phase redefinition results in:

$$UH_{\text{Mass}}U^{-1} \rightarrow UH_{\text{Mass}}U^{-1} - E_1 I = U(H_{\text{Mass}}U - E_1 I)U^{-1}$$

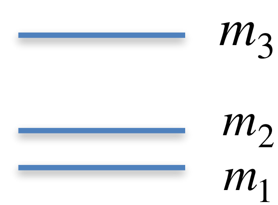
Hence

$$i\frac{\partial}{\partial t}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=U\begin{pmatrix}0 & 0 & 0\\ 0 & \frac{(m_2)^2-(m_1)^2}{2E} & 0\\ 0 & 0 & \frac{(m_3)^2-(m_1)^2}{2E}\end{pmatrix}U^{-1}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

For atmospheric neutrino oscillation, this term is not relevant. It can be put to zero



$$i\frac{\partial}{\partial t}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=U\begin{pmatrix}0 & 0 & 0\\ 0 & \frac{(m_2)^2-(m_1)^2}{2E} & 0\\ 0 & 0 & \frac{(m_3)^2-(m_1)^2}{2E}\end{pmatrix}U^{-1}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$



If we further set U_{13} in U equal to identity matrix , then

$$i\frac{\partial}{\partial t}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=U_{23}\begin{pmatrix}0 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & \frac{(m_3)^2-(m_1)^2}{2E}\end{pmatrix}\left(U_{23}\right)^{-1}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

It is clearly a 2-flavor problem

For solar neutrino oscillation, one focus on electron neutrino

$$i\frac{\partial}{\partial t}\begin{pmatrix}\nu_e\\ \nu_-\\ \nu_+\end{pmatrix}=U_{13}U_{12}\begin{pmatrix}0 & 0 & 0\\ 0 & \frac{(m_2)^2-(m_1)^2}{2E} & 0\\ 0 & 0 & \frac{(m_3)^2-(m_1)^2}{2E}\end{pmatrix}(U_{13}U_{12})^{-1}\begin{pmatrix}\nu_e\\ \nu_-\\ \nu_+\end{pmatrix}$$

$$\nu_-=\cos\theta_{23}\nu_\mu-\sin\theta_{23}\nu_\tau$$

If we further set U_{13} in U equal to identity matrix , then

$$i\frac{\partial}{\partial t}\begin{pmatrix}\nu_e\\ \nu_-\\ \nu_+\end{pmatrix}=U_{12}\begin{pmatrix}0 & 0 & 0\\ 0 & \frac{(m_2)^2-(m_1)^2}{2E} & 0\\ 0 & 0 & \frac{(m_3)^2-(m_1)^2}{2E}\end{pmatrix}(U_{12})^{-1}\begin{pmatrix}\nu_e\\ \nu_-\\ \nu_+\end{pmatrix}$$

- ν_+ decouples and it is a 2-flavor problem again
- However, the actual problem is slightly more complicated due to matter effect (see later discussions).

Taking ν_μ and ν_τ as an example：

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

ν_μ, ν_τ : weak interaction eigenstate

ν_1, ν_2 : mass eigenstate

Let ν_μ is produced in the atmosphere at t=0, then

$$\left|\nu_\mu(0)\right\rangle \equiv \left|\nu_\mu\right\rangle = \cos\theta\left|\nu_1(0)\right\rangle + \sin\theta\left|\nu_2(0)\right\rangle$$

$$\left|\nu_\tau\right\rangle = -\sin\theta\left|\nu_1(0)\right\rangle + \cos\theta\left|\nu_2(0)\right\rangle$$

At time t, each mass eigenstate picks up a phase

$$|\nu_\mu(t)\rangle = \exp(-iE_1 t/\hbar)\cos\theta|\nu_1(0)\rangle + \exp(-iE_2 t/\hbar)\sin\theta|\nu_2(0)\rangle,$$

where $E_i = \left(p^2c^2 + m_i^2c^4\right)^{1/2}$.

If $m_1 \neq m_2$, then $E_1 \neq E_2$. Therefore $|\nu_\mu(t)\rangle$ is no longer orthogonal to $|\nu_\tau\rangle$!

$$P(\nu_\mu \to \nu_\tau) = \sin^2\theta \sin^2\left(\frac{\pi x}{l}\right),$$

x is the distance traversed by the neutrino in time t, l is the oscillation length

$$l = \frac{2.5 P_\nu (\mathrm{MeV/c})}{\left(m_2^2 - m_1^2\right)\left(\mathrm{eV/c^2}\right)^2} \text{ meters}\circ$$

For $P_\nu = 1\,\mathrm{MeV/c}$, $m_2^2 - m_1^2 = 1\left(\mathrm{eV/c^2}\right)^2$, $l = 2.5\ \mathrm{m}$;

For $P_\nu = 10\,\mathrm{GeV/c}$，$m_2^2 - m_1^2 = 2.5\times10^{-3}\left(\mathrm{eV/c^2}\right)^2$, $l = 10^4\ \mathrm{km}$.

•1998 Super-Kamiokande published results on the flux of atmospheric neutrino

$$R = \left(j(\nu_\mu)/\, j(\nu_e)\right)_{\text{data}} / \left(j(\nu_\mu)/\, j(\nu_e)\right)_{\text{MC}}$$

R is significantly smaller than 1, indicating a deficit in ν_μ flux

No deficit observed for ν_e flux

The production of atmospheric neutrinos:

$$P + A \rightarrow \pi^{\pm} + X$$

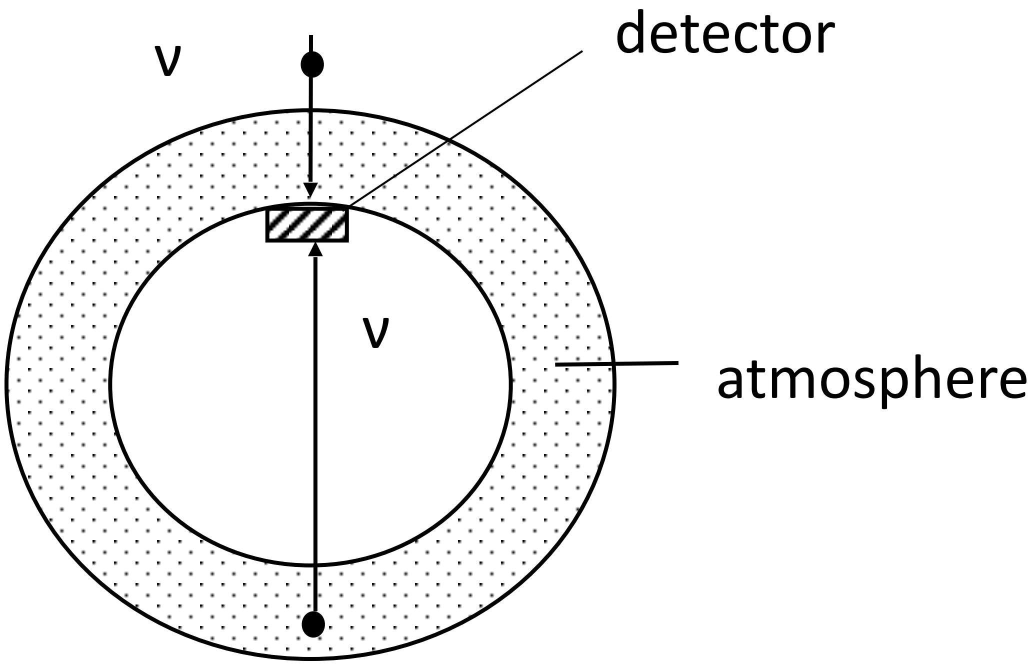
$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}, \mu^{+} \rightarrow \overline{\nu}_{\mu} + e^{+} + \nu_{e}$$

$$\pi^{-} \rightarrow \mu^{-+} + \overline{\nu}_{\mu}, \mu^{-} \rightarrow \nu_{\mu} + e^{-} + \overline{\nu}_{e}$$

- There are also neutrinos from kaon decays.

- The measured ν_{μ} is less than expected, implying possible oscillations of ν_{μ} to other flavors.

Super-Kamiokande studied the correlation of ν_μ flux with the zenith angle of incident neutrinos



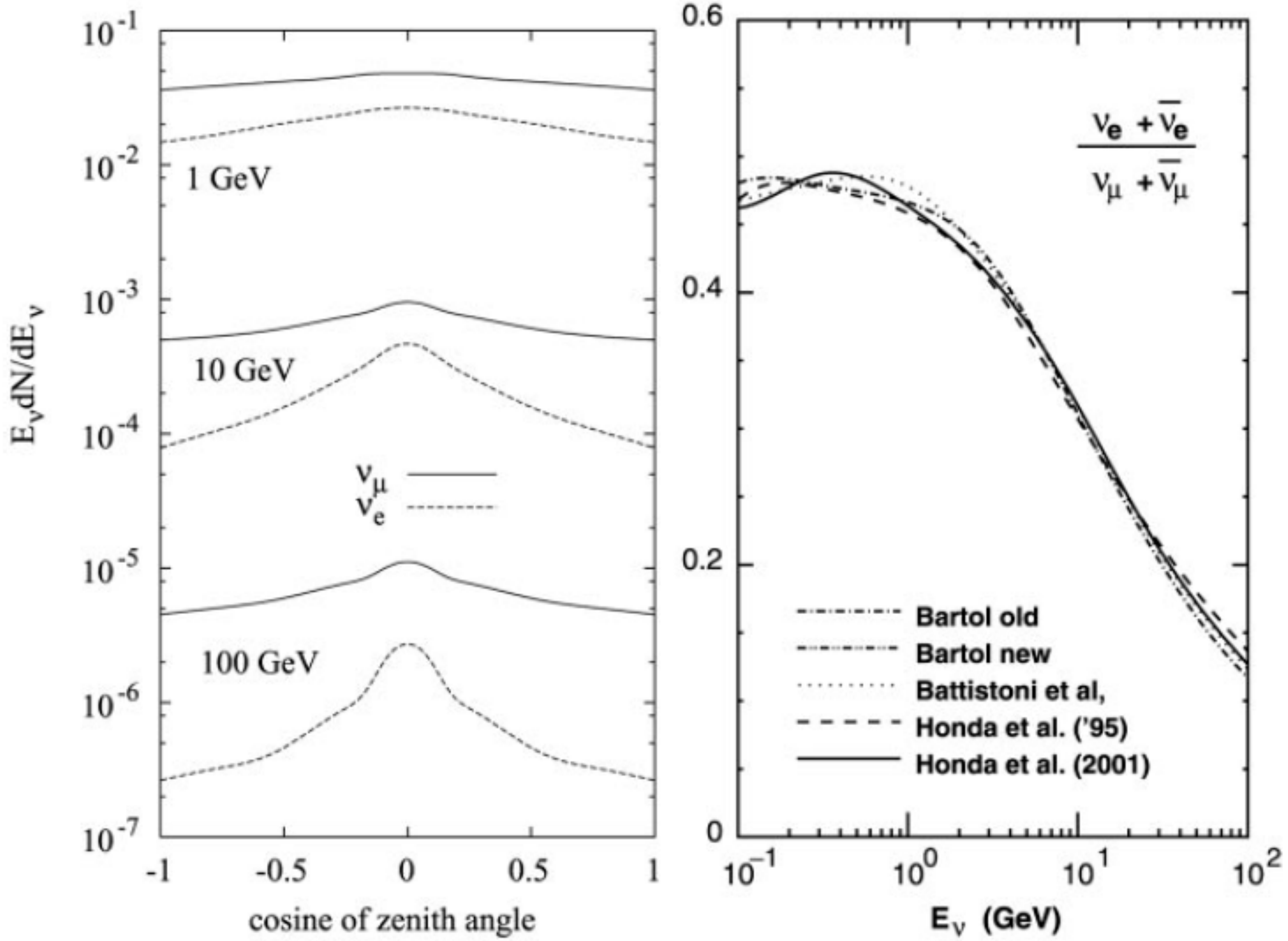
The neutrino oscillation hypothesis was verified in this way

Flux of atmospheric neutrinos

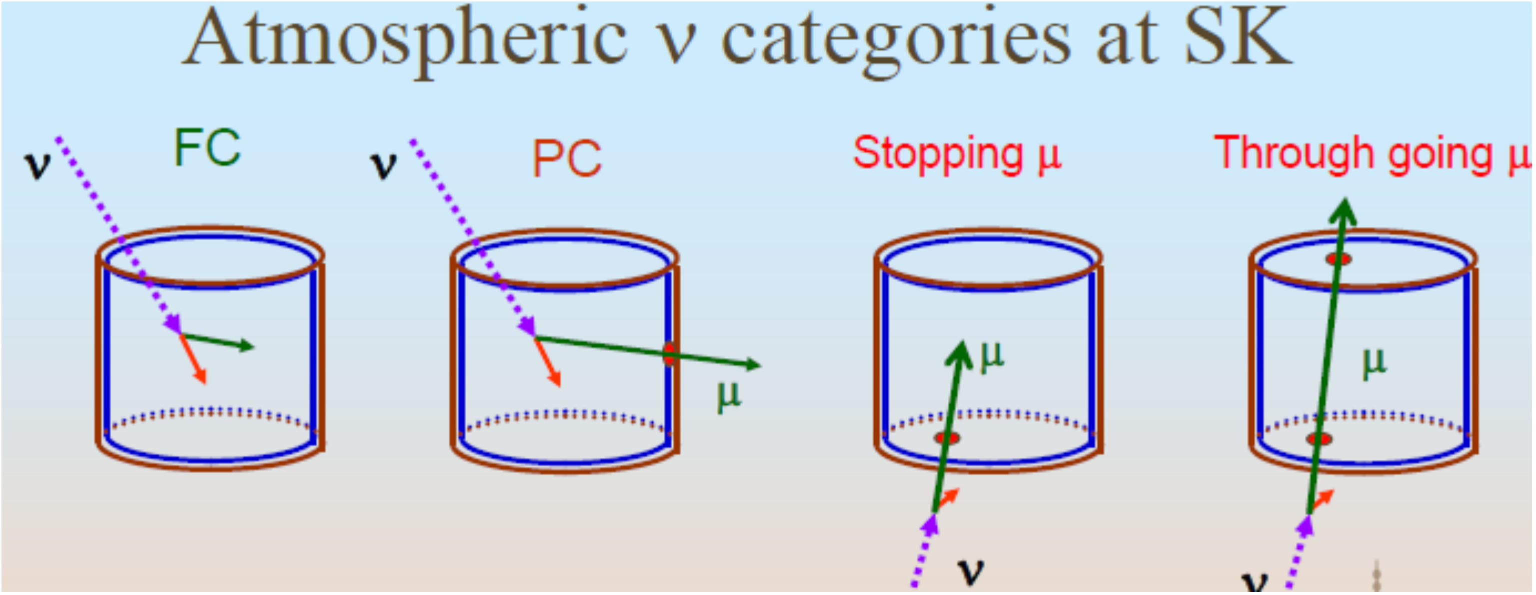
$$\phi_A(E_N) = K \times (E_N + b\exp[-c\sqrt{E_N}])^{-\alpha},$$

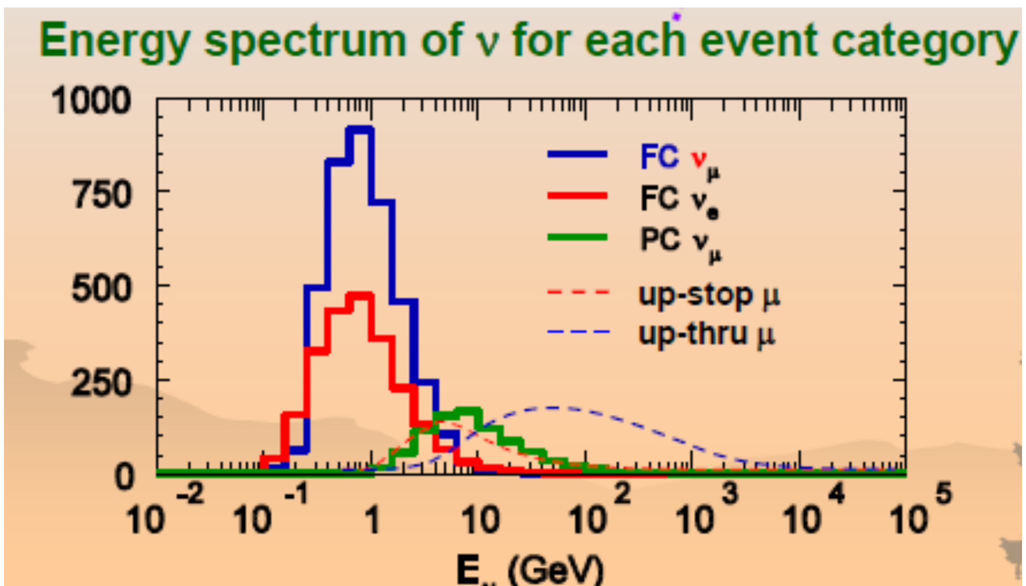
Parameter/component	α	K	b	c
Hydrogen ($A = 1$) ($\leq 10^2$ GeV)	2.74	14900	2.15	0.21
Hydrogen ($A = 1$) ($> 10^2$ GeV)	2.71	14900	2.15	0.21
He ($A = 4$)	2.64	600	1.25	0.14
CNO ($A = 14$)	2.60	33.2	0.97	0.01
MgSi ($A = 25$)	2.79	34.2	2.14	0.01
Iron ($A = 56$)	2.68	4.45	3.07	0.41

Parameterization of cosmic ray flux



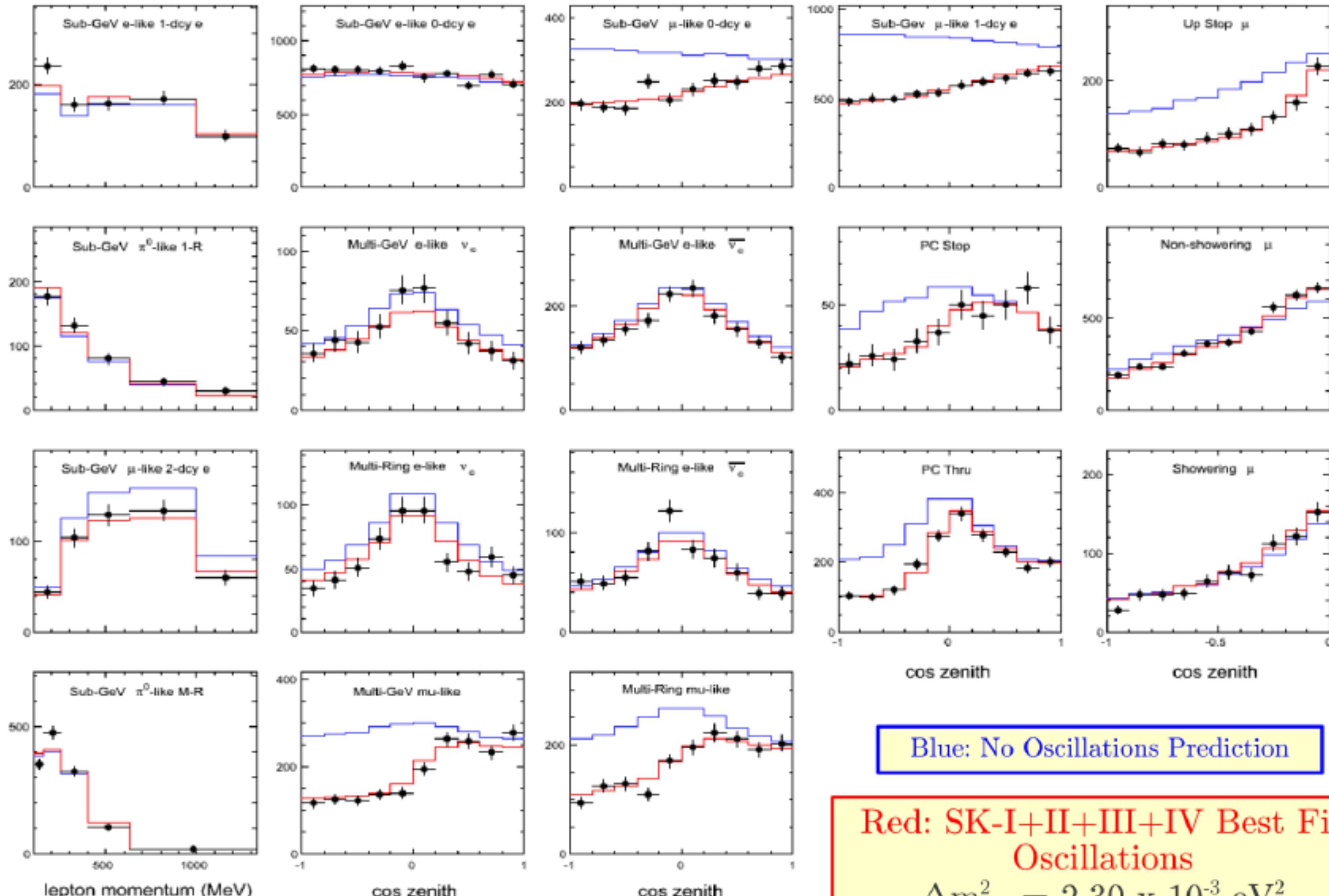
T. K. Gaisser and M. Honda, 2002





Y. Itoh
Neutrino 2012

2-flavor analysis update (SK1-4)



Blue: No Oscillations Prediction

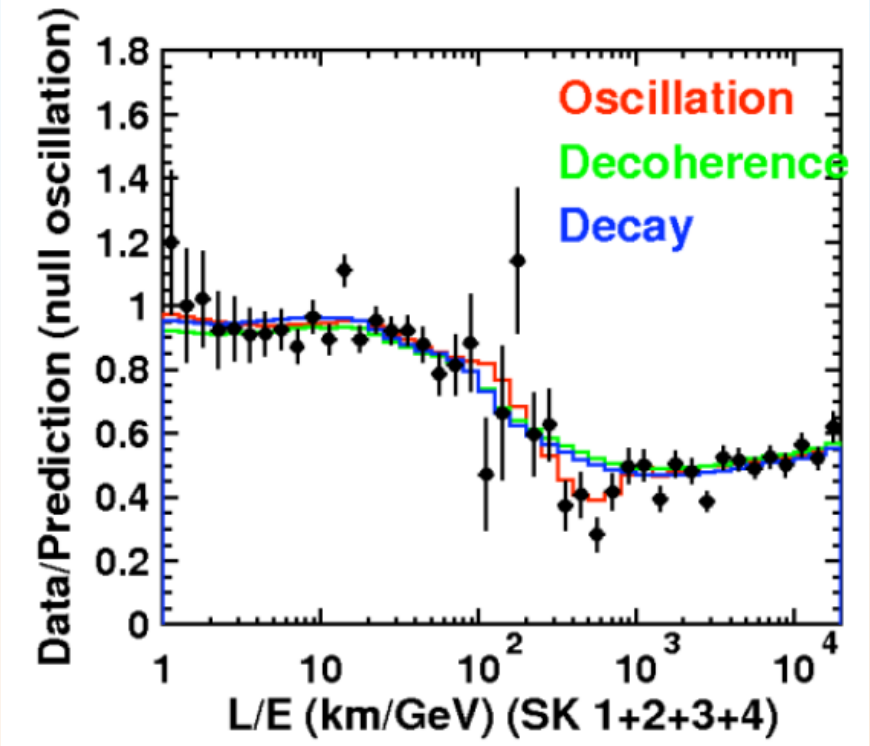
Red: SK-I+II+III+IV Best Fit Oscillations

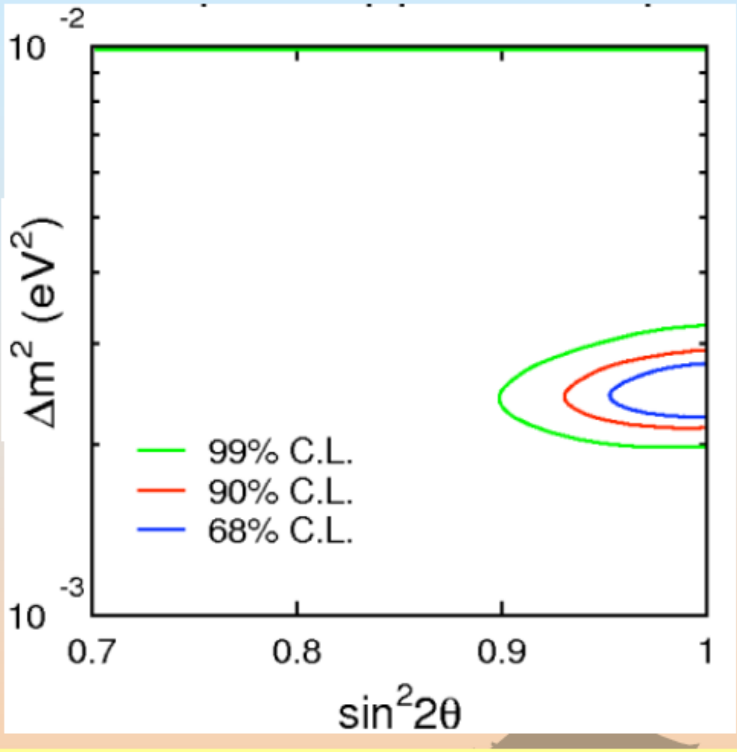
$\Delta m^2_{23} = 2.30 \times 10^{-3}\ \mathrm{eV}^2$

$\sin^2 2\theta_{23} = 0.99$

Y. Itoh
Neutrino 2012

2 flavor L/E analysis update (SK1-4)





Neutrino decay

$$\chi^2_{\min} = 187.8/169 (4.0\sigma)$$

Neutrino decoherence

$$\chi^2_{\min} = 194.8/169 (4.8\sigma)$$

⇔

2 ν oscillation result

$$\sin^2 2\theta = 1.00 (\geq 0.93 (90\% CL))$$

$$\Delta m^2 = (2.5^{+0.27}_{-0.27}) \times 10^{-3} eV^2$$

$$\chi^2_{\min} = 171.7/169$$

Y. Itoh
Neutrino 2012

Updated results at Particle Data Group 2025

Normal ordering: $\theta_{23}/\circ = 43.3^{+1.0}_{-0.9}$ $\frac{\Delta m^2_{32}}{10^{-3}\mathrm{eV}^2} = 2.438^{+0.021}_{-0.019}$

Inverted ordering: $\theta_{23}/\circ = 47.9^{+0.7}_{-0.9}$. $\frac{\Delta m^2_{32}}{10^{-3}\mathrm{eV}^2} = -2.484^{+0.020}_{-0.020}$

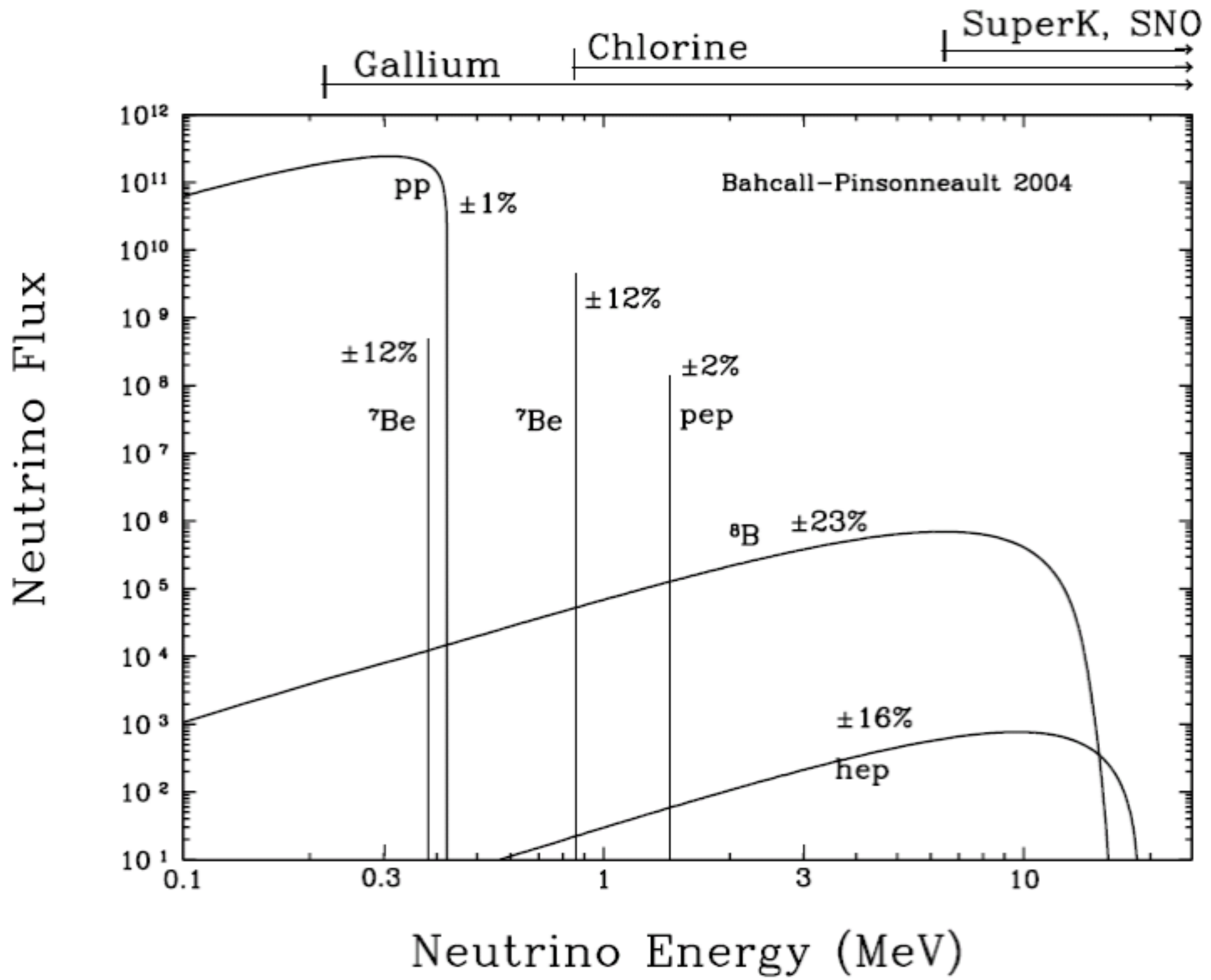
Solar Neutrinos

- Solar neutrinos are produced by nuclear fusions.
- Knowing the solar neutrino flux is crucial to understand the fusion mechanism in the Sun.
- The observed solar neutrino flux (pioneered by R. Davis) is significantly smaller than that predicted by standard solar model (J. Bahcall and his collaborators). This is now understood as due to neutrino oscillations as well.

Solar pp reaction cycle

$$4p + 2e^{-} \rightarrow {}^{4}He + 2\nu_{e} + 26.73\,\mathrm{MeV}$$

Solar neutrino spectra, taken from J. N. Bahcall's website http://www.sns.ias.edu/~jnb/SNviewgraphs/



R. Davis (2002 Nobel Prize) pioneered the solar neutrino detection

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

This experiment obtained the event rate, 2.56±0.23 SNU, while the calculated event rate is $7.7^{+1.2}_{-1.0}$ SNU

1 SNU： 10^{-36} interaction per target atom per second

Super-Kamiokande(SK) measured the solar ν flux from the decays of boron and those from other mechanisms.

$$^{8}\mathrm{B} \rightarrow {}^{8}\mathrm{Be} + e^{+} + \nu_{e}$$

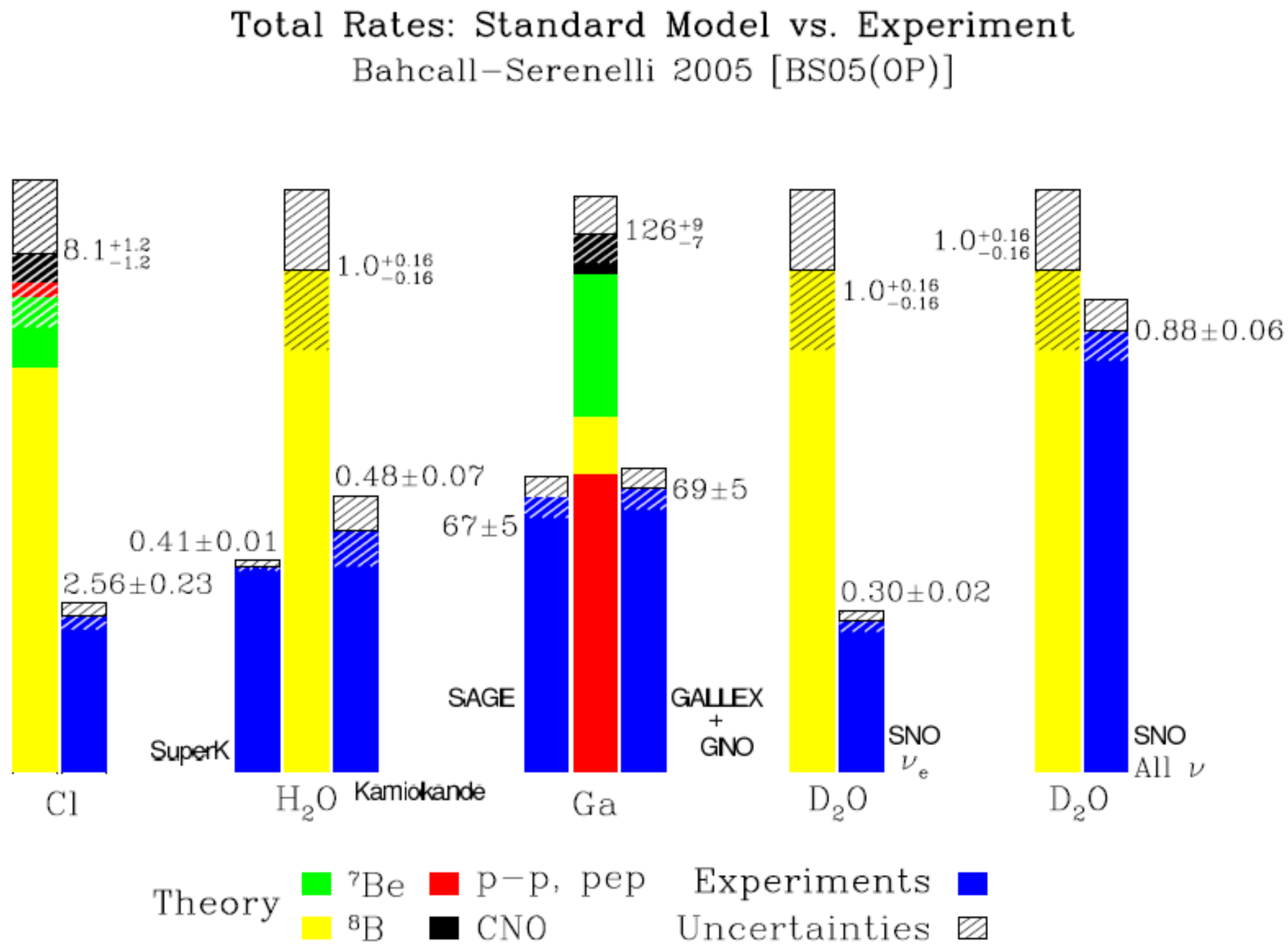
Neutrinos are detected by neutrino-electron scattering:

$$\nu_{x} + e^{-} \rightarrow \nu_{x} + e^{-}$$

Emitting Cherenkov light in water.

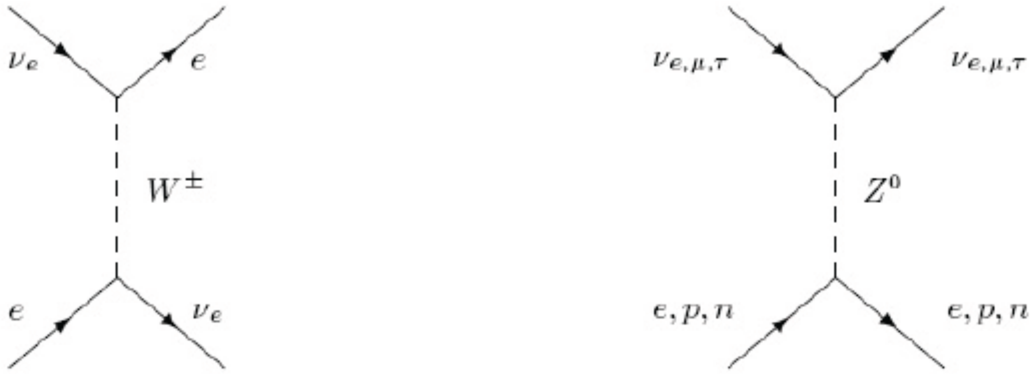
However

$$\sigma(\nu_{\mu,\tau} e) \approx 0.16\, \sigma(\nu_e e)$$

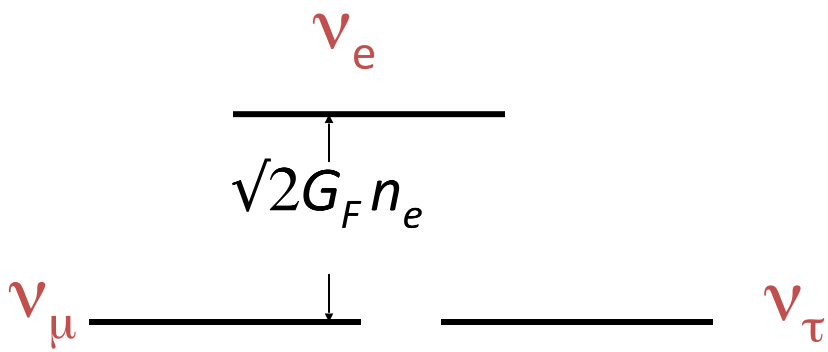


J. N. Bahcall, Solar Models and Solar Neutrinos: Current Status, Proceedings of the Nobel Symposium 2004, Enkoping, Sweden, August 19-24, 2004

Matter enhancement can occur inside the Sun. Neutrinos acquire effective potential through coherent scattering off matter inside the Sun.



ν_e is special!



Due to this shift, the mixing angle between flavor and mass eigenstates are also shifted: $\theta \longrightarrow \theta_M$. For a particular n_e, $\theta_M = \pi/4$.

MSW effect

L. Wolfenstein 1978
S. P. Mikheyev and A. Yu. Smirnov 1989

Recall

$$i\frac{\partial}{\partial t}\begin{pmatrix}\nu_e\\ \nu_-\\ \nu_+\end{pmatrix} = U_{12}\begin{pmatrix}0 & 0 & 0\\ 0 & \frac{(m_2)^2-(m_1)^2}{2E} & 0\\ 0 & 0 & \frac{(m_3)^2-(m_1)^2}{2E}\end{pmatrix}(U_{12})^{-1}\begin{pmatrix}\nu_e\\ \nu_-\\ \nu_+\end{pmatrix}$$

Adding matter effect and throwing away ν_+

$$i\frac{\partial}{\partial t}\begin{pmatrix}\nu_e\\ \nu_-\end{pmatrix} = \left[U_{12}\begin{pmatrix}0 & 0\\ 0 & \frac{(m_2)^2-(m_1)^2}{2E}\end{pmatrix}(U_{12})^{-1} + \begin{pmatrix}V & 0\\ 0 & 0\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_-\end{pmatrix}$$

with $V = \sqrt{2}G_F N_e$

$V \rightarrow -V$ for antineutrinos

$\theta_{12} \to \theta$

Diagonalizing the mass matrix again gives

$$\begin{pmatrix} \nu_e \\ \nu_- \end{pmatrix} = (U_{12})^m \begin{pmatrix} (\nu_1)^m \\ (\nu_2)^m \end{pmatrix}$$

$$\cos 2\theta_m = \frac{-A + \delta m^2 C_{2\theta}}{\sqrt{[(A - \delta m^2 C_{2\theta})^2 + (\delta m^2 S_{2\theta})^2]}}$$

$$\sin 2\theta_m = \frac{\delta m^2 S_{2\theta}}{\sqrt{[(A - \delta m^2 C_{2\theta})^2 + (\delta m^2 S_{2\theta})^2]}}$$

$A=2EV$, $\delta m^2=(m_2)^2-(m_1)^2$

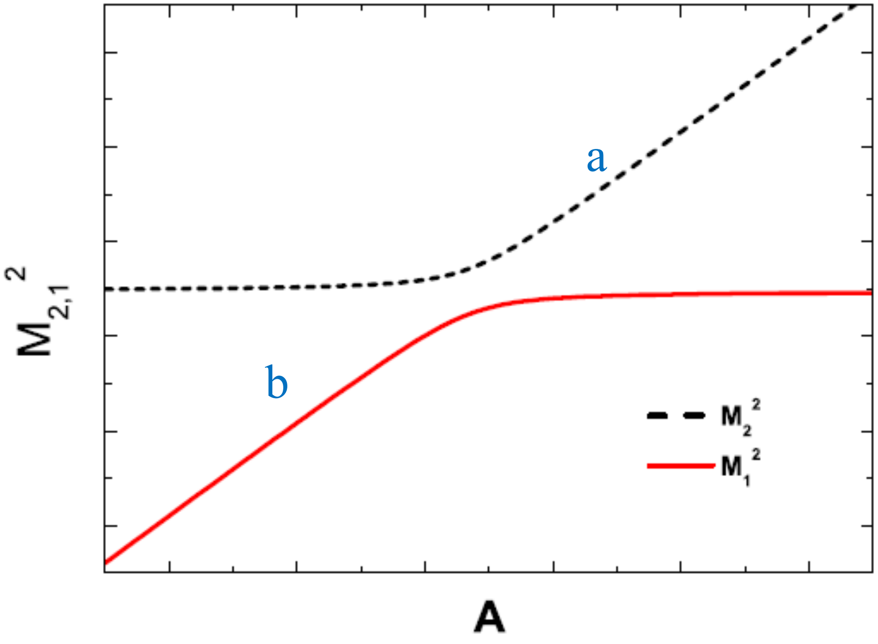
Resonance occurs at right electron density

Electron neutrino survival probability inside the Sun

$$P(\nu_e \to \nu_e) = \frac{1}{2} + (\frac{1}{2} - P_{LZ}) \cos 2\theta \cos 2\theta_m$$

P_{LZ} is the transition probabilities between mass eigenstates

a→b



M_1, M_2 are mass eigenvalues with matter effects

SNO (Sudbury Neutrino Observatory) used 1000 tons of D_2O

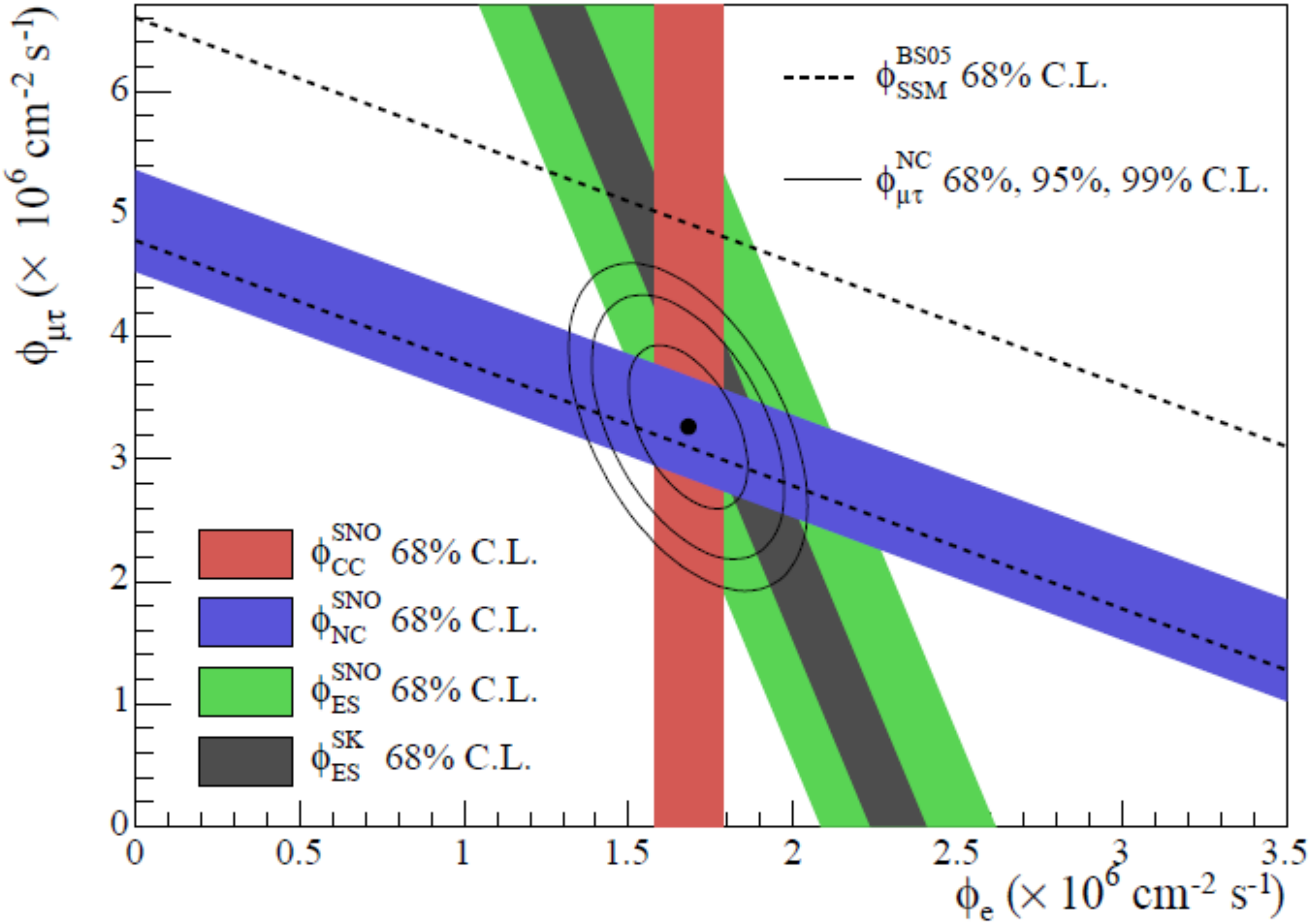
$$^{8}B \rightarrow {}^{8}Be + e^{+} + \nu_e$$

$$\nu_e + d \rightarrow e^- + p + p \qquad \text{(CC)}$$

$$\nu_x + d \rightarrow \nu_x + p + n \qquad \text{(NC)}$$

in additional to

$$\nu_x + e^- \rightarrow \nu_x + e^-$$



NC result from salt phase measurement

B. Aharmim et al., [SNO Collab.], Phys. Rev. C72, 055502 (2005).

The same set of parameters can also be measurement in reactor neutrino experiment, such as KamLAND and JUNO experiments. The details will be discussed later.

On the measurement of θ_{13}

The Daya Bay Collaboration

Europe (3) (10)

JINR, Dubna, Russia

Kurchatov Institute, Russia

Charles University, Czech Republic

North America (16)(~100)

BNL, Caltech, LBNL, Iowa State Univ., Illinois Inst. Tech., Princeton, RPI, Siena,

UC-Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, Univ. of Wisconsin-Madison, Virginia Tech., William and Mary, Univ. of Illinois-Urbana-Champaign

Asia (19) (~140)

IHEP, Beijing Normal Univ., Chengdu Univ. of Sci. and Tech., CGNPG, CIAE, Dongguan Polytech. Univ., Nanjing Univ., Nankai Univ., Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Zhongshan Univ., Univ. of Hong Kong, Chinese Univ. of Hong Kong,

National Taiwan Univ., National Chiao Tung Univ., National United Univ.

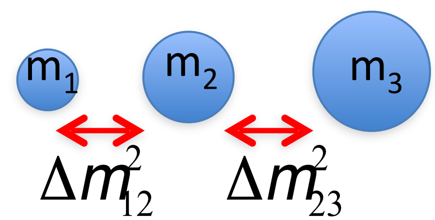
Neutrino Oscillation

- **PMNS (Pontecorvo-Maki-Nakagawa-Sakata) matrix**

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

Weak eigenstates-
”flaver eigenstates”

mass eigenstates



$$U_{MNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}$$

Atmospheric | Reactor | Solar | Majorana Phases

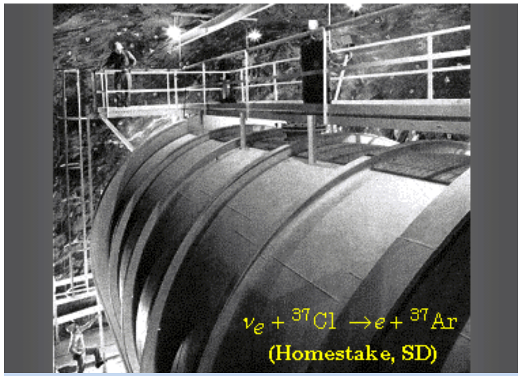
Neutrino Oscillation

- **Physical Parameters:**
  - **θ_{ij}:**
    3 mixing angles between mass/flavor eigenstates set **oscillation amplitude**
  - **Δm_{ij}^2:**
    Differences in 3 neutrino masses determine **oscillation frequency** (distance)

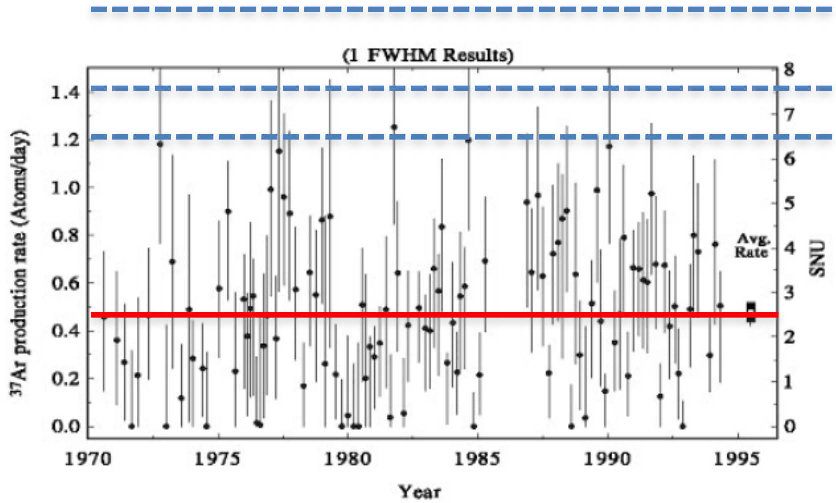
- **The survival probability of $\nu_e \rightarrow \nu_e$ is:**

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

Discoveries of Neutrino Oscillation



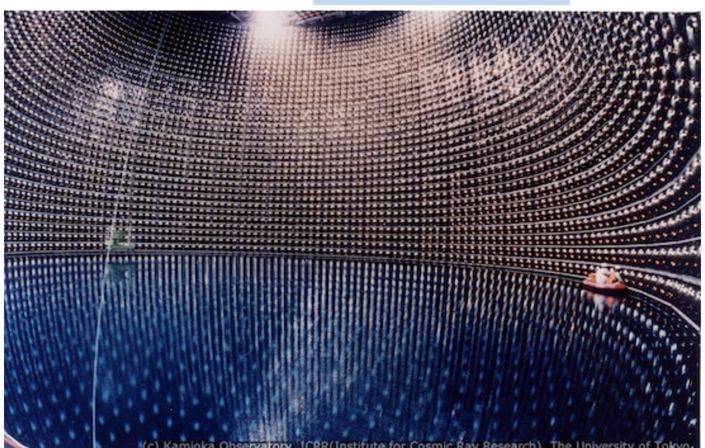
First Evidence of Oscillation:
Davis detects 1/3 expected solar neutrinos (1968)

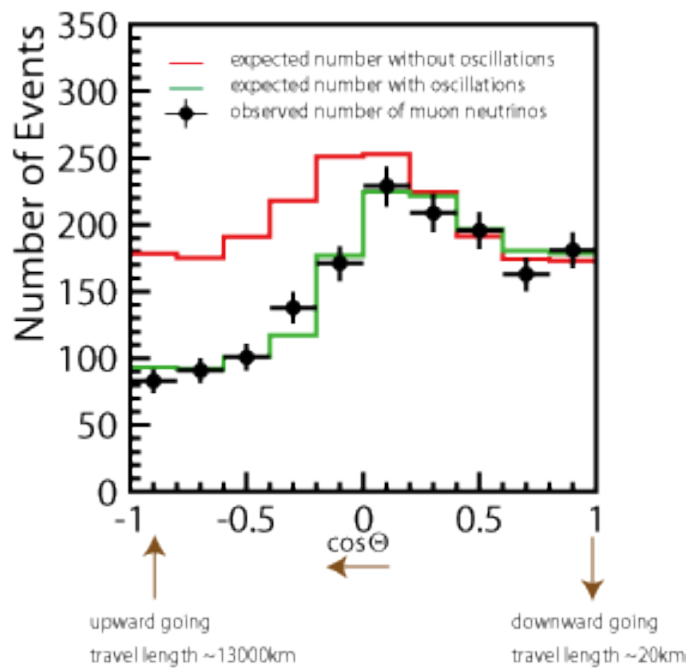


Expected rate of ν_e from the sun

θ_{12}

Supper K:



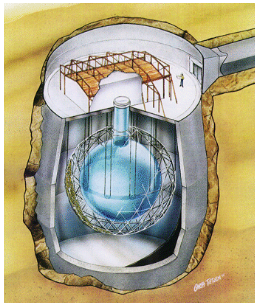


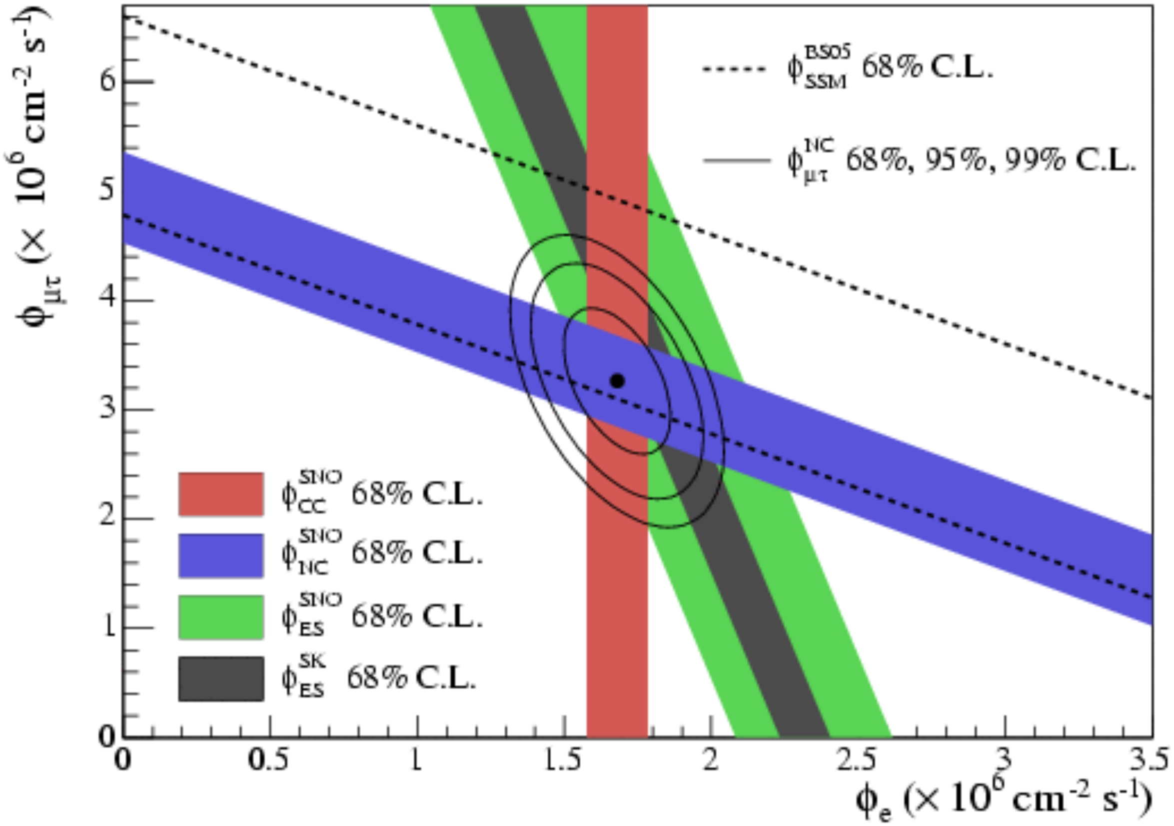
Δm_{23}^2

θ_{23}

Further Studies on Solar Neutrinos

SNO



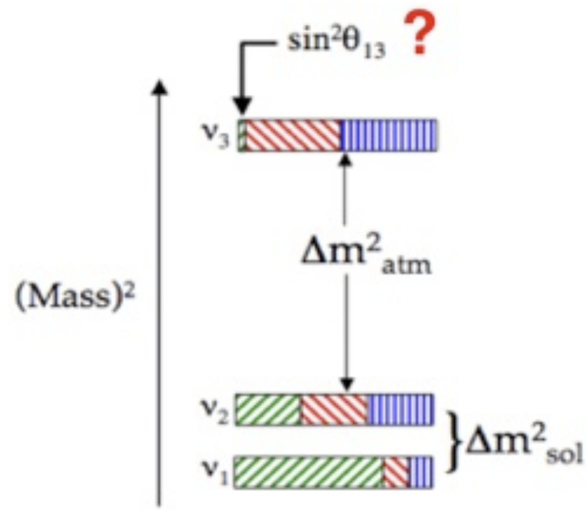


Δm_{12}^2

θ_{12}

Importance of ϑ_{13}

- It is one of the key parameters in determining the leptonic mixing matrix.
- What is the ν_3 fraction of ν_e ?



- U_{e3} is the gateway to CP violation in neutrino sector:

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) \propto \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos\theta_{13} \sin\delta$$

Reactor Neutrino Experiment

- **Why Reactor Neutrino?**
  - Pure source
  - 6 /fission
  - 2 X 10^{20} /sec/GW_{th}
  - Clean signal
  - Free neutrinos! Large statistics

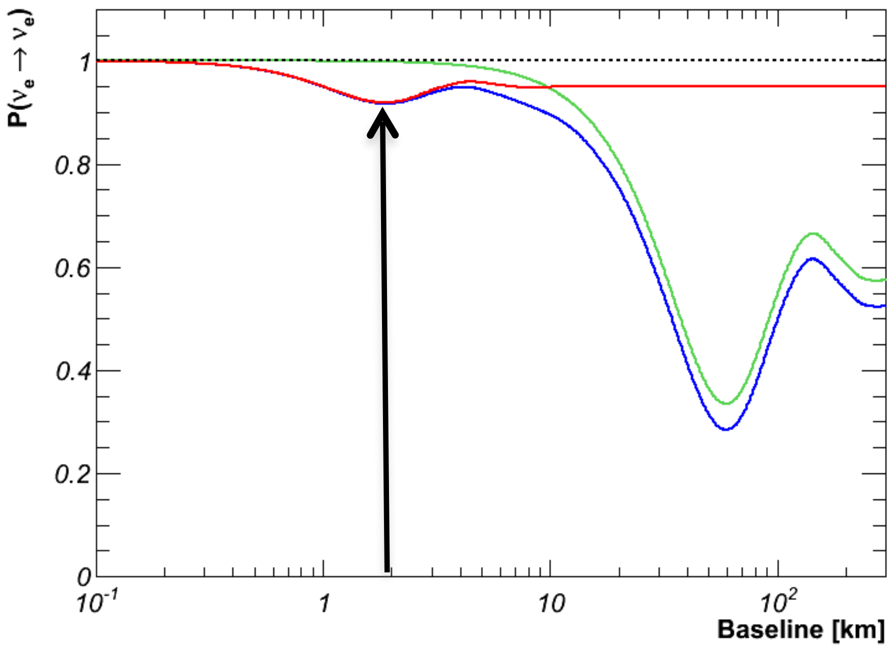
- **Why Daya Bay?**
  - 17.4 GW (thermal) reactor power adjacent to mountains.

    Reactors produce ~2×10^{20} antineutrinos / s / GW
  - Mountains shield detectors from cosmic ray backgrounds

How To Measure ϑ_{13} Better With a Reactor?

- Since reactor $\bar{\nu}_e$ are low-energy, it is a disappearance experiment:

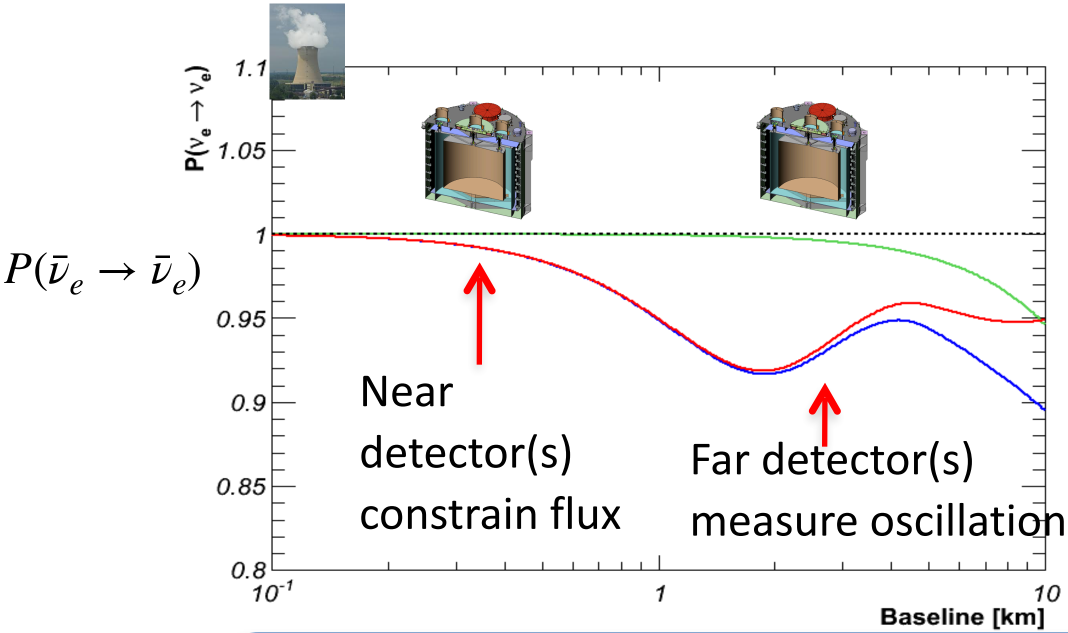
$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$



- Go deep underground to reduce cosmogenic background
- Place near detector(s) close to reactor-related systematics
- Position a far detector near the first oscillation maximum to get the highest sensitivity, and also be less affected by θ_{12}

Relative Measurement

$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\varepsilon_f}{\varepsilon_n}\right)\left[\frac{P_{sur}(E, L_f)}{P_{sur}(E, L_n)}\right]$$



N_f/N_n : far/near Ratio

N_p : Detector Target Mass

L : Distances from reactor

ε : Detector efficiency

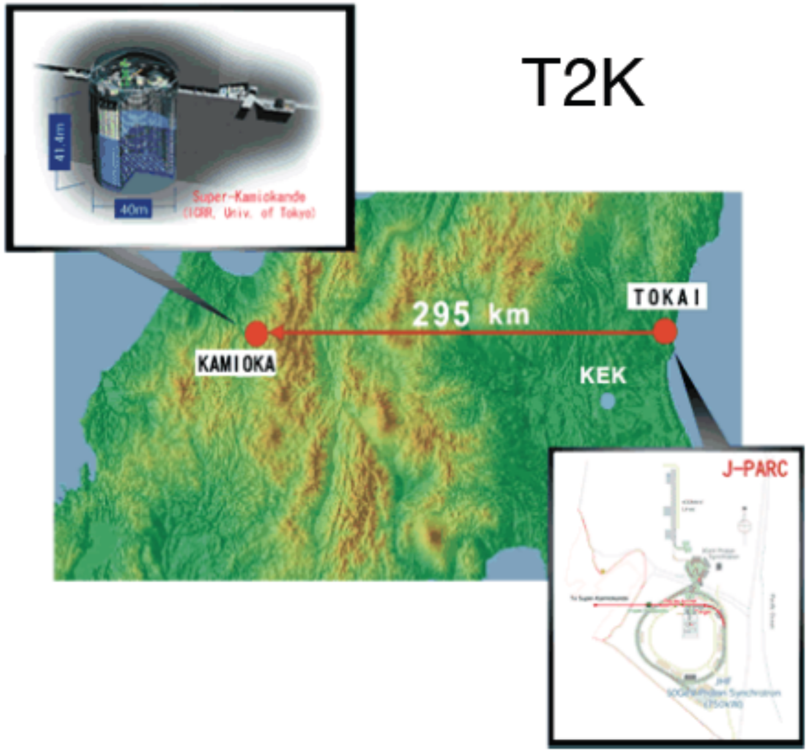
P : Oscillation deficit

- **Absolute Reactor Flux:**
  Largest uncertainty in previous measurements
- **Relative Measurement:**
  Multiple detectors removes absolute uncertainty

First proposed by L. A. Mikaelyan and V.V. Sinev, Phys. Atomic Nucl. 63 1002 (2000)

Earlier Hints of non-zero ϑ_{13}

T2K



0.03 (0.04) < $\sin^2 2\theta_{13}$ < 0.28 (0.34) at 90% C.L

Phys. Rev. Lett. 107, 041801 (2011)

Double Chooz

$\sin^2 2\theta_{13} = 0.086 \pm 0.041$ (stat) ± 0.030 (sys)

arXiv:1112.6353v1

T2K measure the appearance of electron neutrino from muon neutrino beam

Results before March 2012

Exp.	Type	Approx L/E	Reference	Result $\sin^2 2\theta_{13}$
T2K	Accelerator appearance	295 km/ 0.6GeV	PRL107: 041801	0.03 -- 0.28 90%C.L.
MINOS	Accelerator appearance	735km/3GeV	PRL107: 181802	0 -- 0.12 90%C.L.
Double Chooz	Reactor Disappearance	1.05km/ 3MeV	arXiv:1112. 6353	0.085±0.051 (1 σ)
SNO+ Kamland	Joint fit	solar parameters	PRD84: 053007	0.08 ± 0.04 (1 σ)

Accelerator results provided for normal mass hierarchy and zero CP phase.

Antineutrino Detection

- **Inverse β-decay (IBD):**

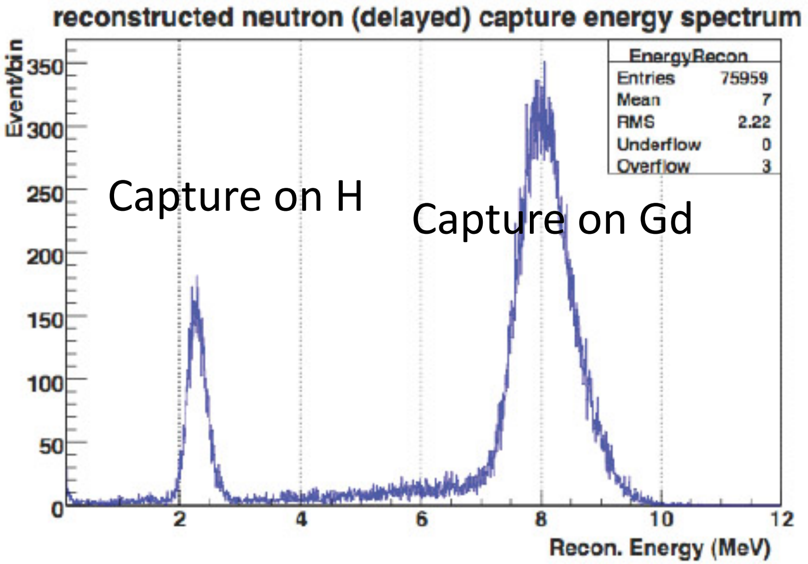
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$n + {}^{x}Gd \rightarrow {}^{x+1}Gd + \gamma$$

- **Prompt positron:**
  Carries antineutrino energy

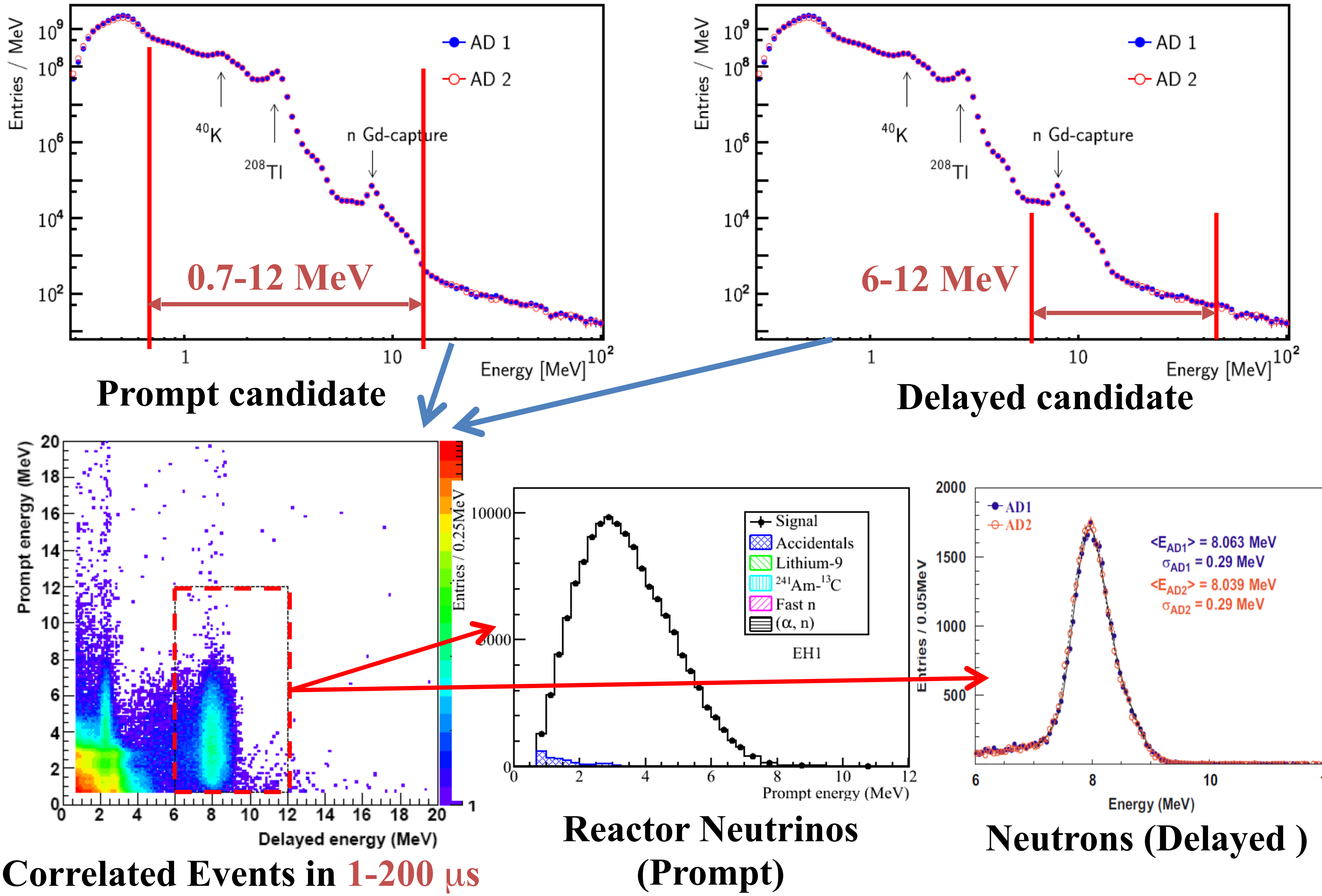
  $E_{e+} \approx E_\nu - 0.8\text{ MeV}$

- **Delayed neutron capture:**
  Efficiently tags antineutrino signal



Prompt + Delayed coincidence provides distinctive signature

Event Selection



Prompt candidate

Delayed candidate

Correlated Events in 1-200 μs

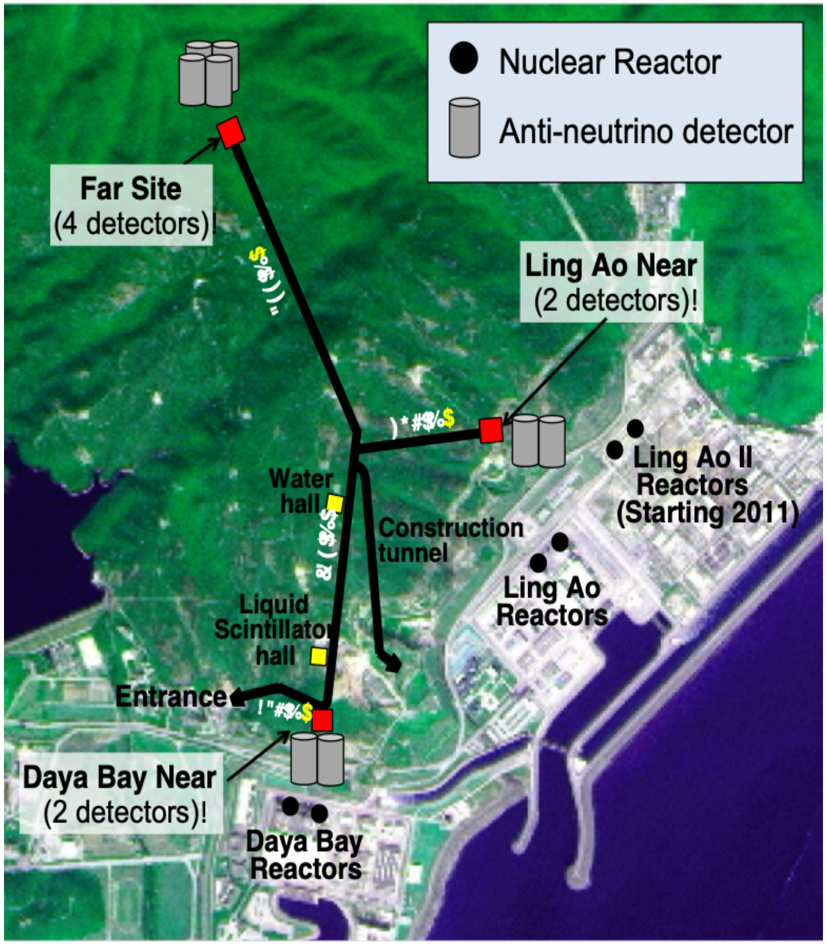
Reactor Neutrinos (Prompt)

Neutrons (Delayed)

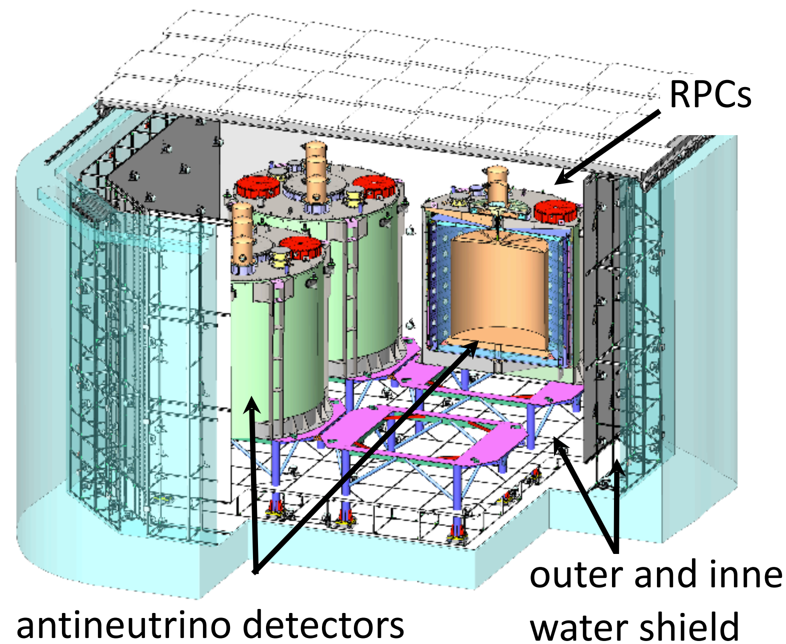
Major Backgrounds

- Cosmogenic neutron/isotopes
  - $^{8}He/^{9}Li$
  - fast neutron
- Ambient radioactivity
  - accidental coincidence

Daya Bay Layout



Daya Bay Far Hall

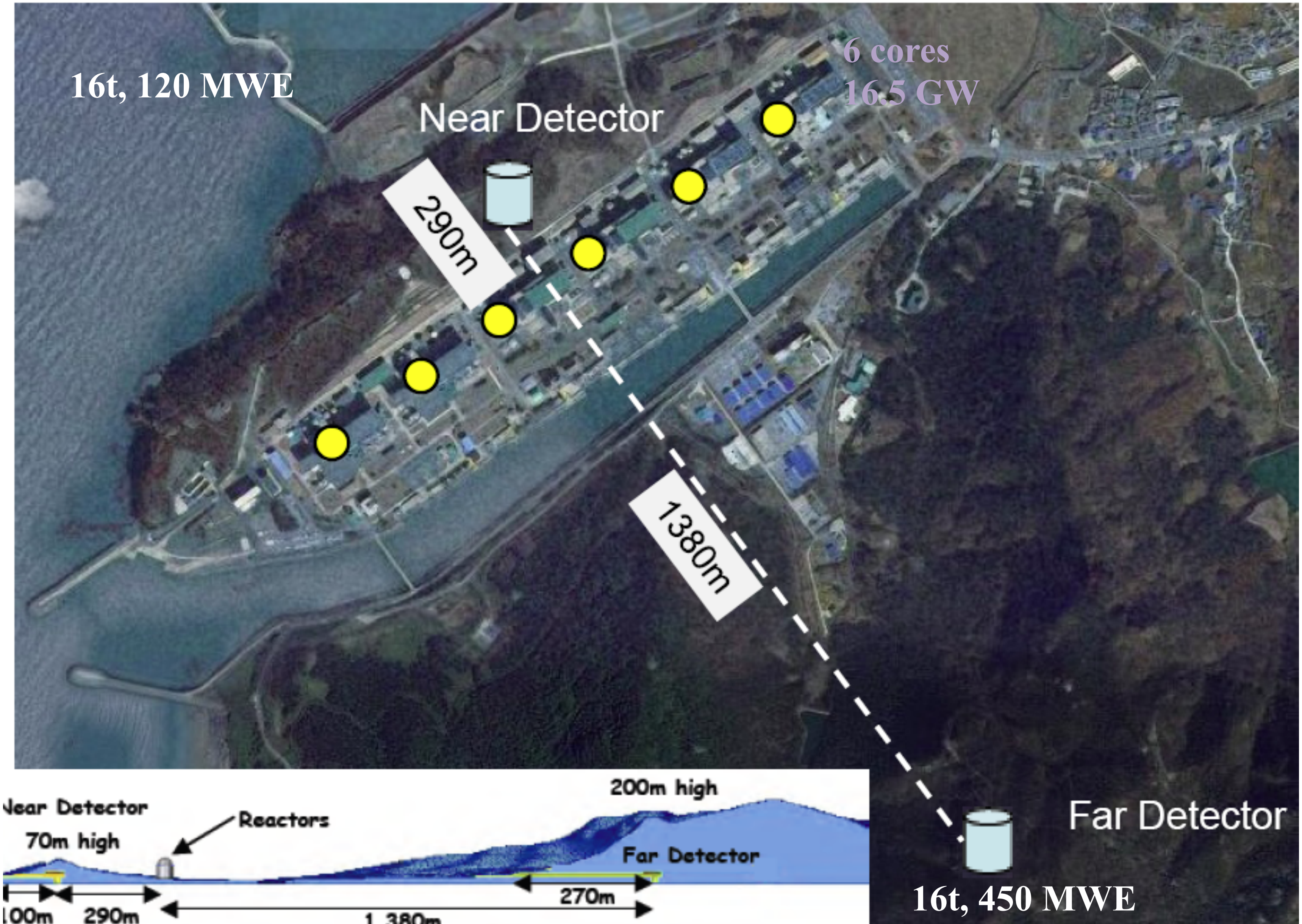


	Overburden	R_μ	E_μ	D1,D2	L1,L2	L3,L4
EH1	280	1.27	57	364	857	1307
EH2	300	0.95	58	1348	480	528
EH3	880	0.056	137	1912	1540	1548

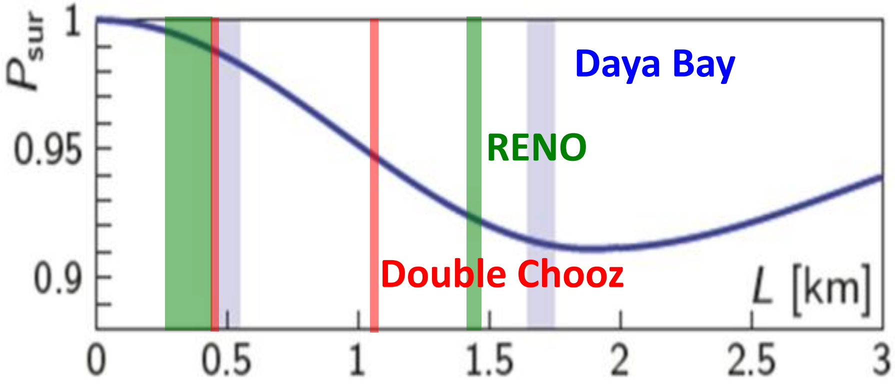
Double Chooz

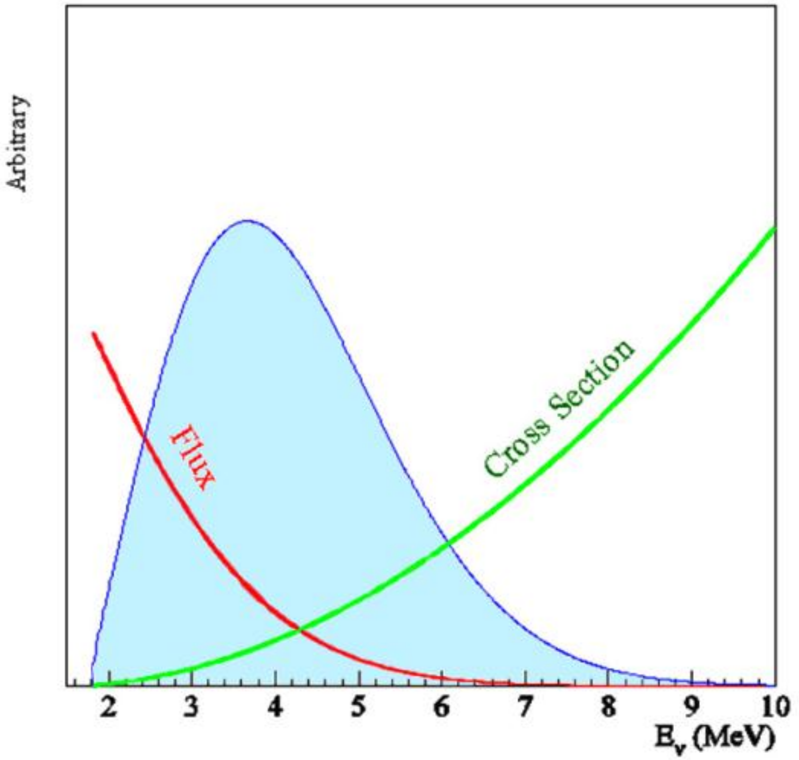
- Reactor Neutrinos -

RENO



Baseline Comparison





Detector Design

Water

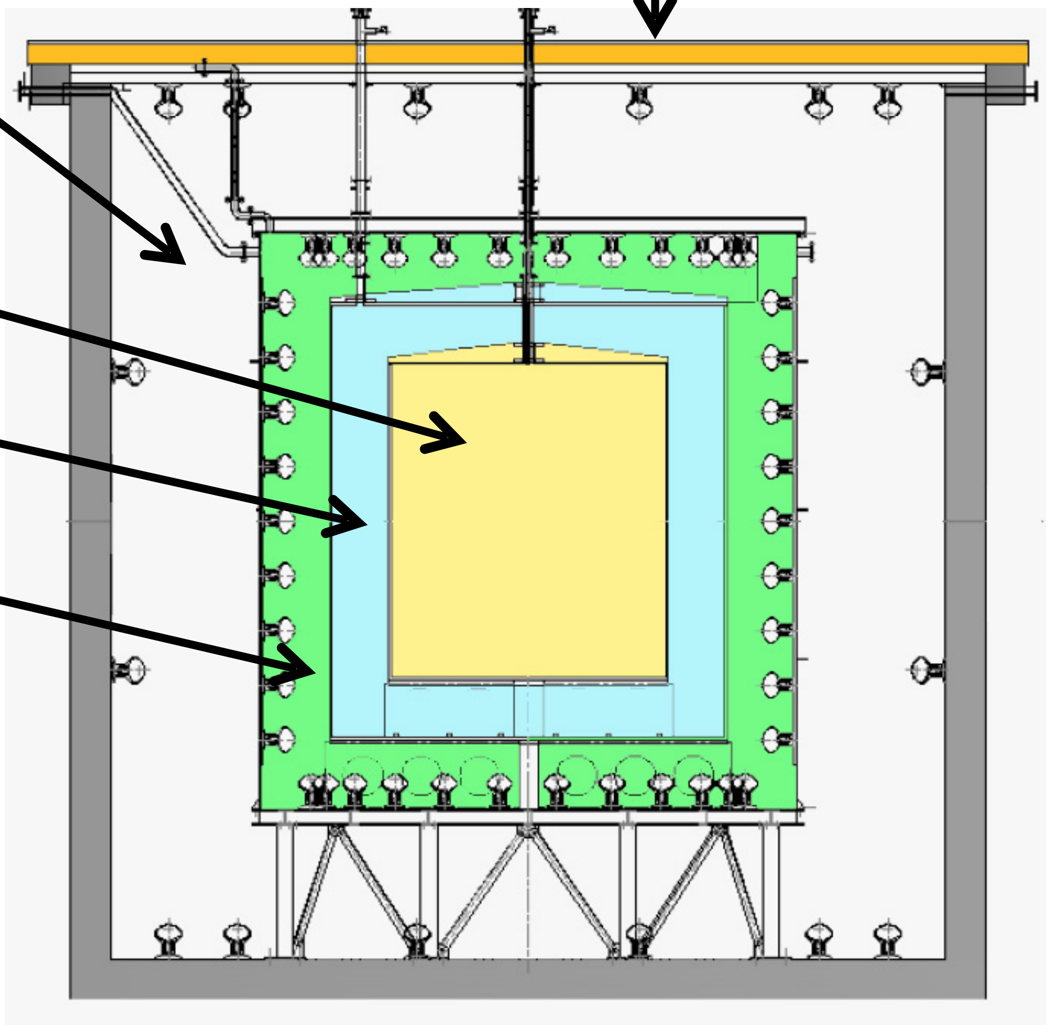
- **Shield radioactivity and cosmogenic neutron**
- **Cherekov detector for muon**

RPC or Plastic scintillator
⇨**muon veto**

Three-zone neutrino detector
⇨**Target: Gd-loaded LS**

⇨**γ-catcher: normal LS**

⇨**Buffer shielding: oil**



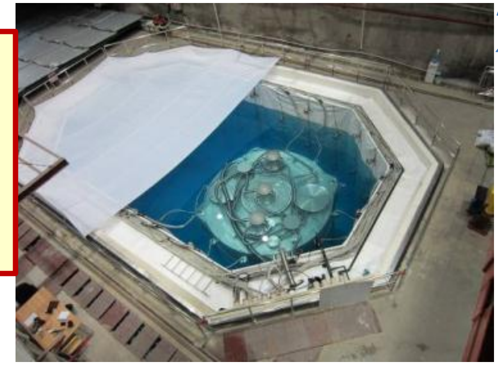
Sensitivity Comparison

Experiment	Power (GW)	Detector(t) Near/Far	Overburden (m.w.e.) Near/Far	Sensitivity (3y,90%CL)
Daya Bay	17.4	40 / 80	250 / 860	~ 0.008
Double Chooz	8.5	8 / 8	120 / 300	~ 0.03
RENO	16.5	16 / 16	120 / 450	~ 0.02

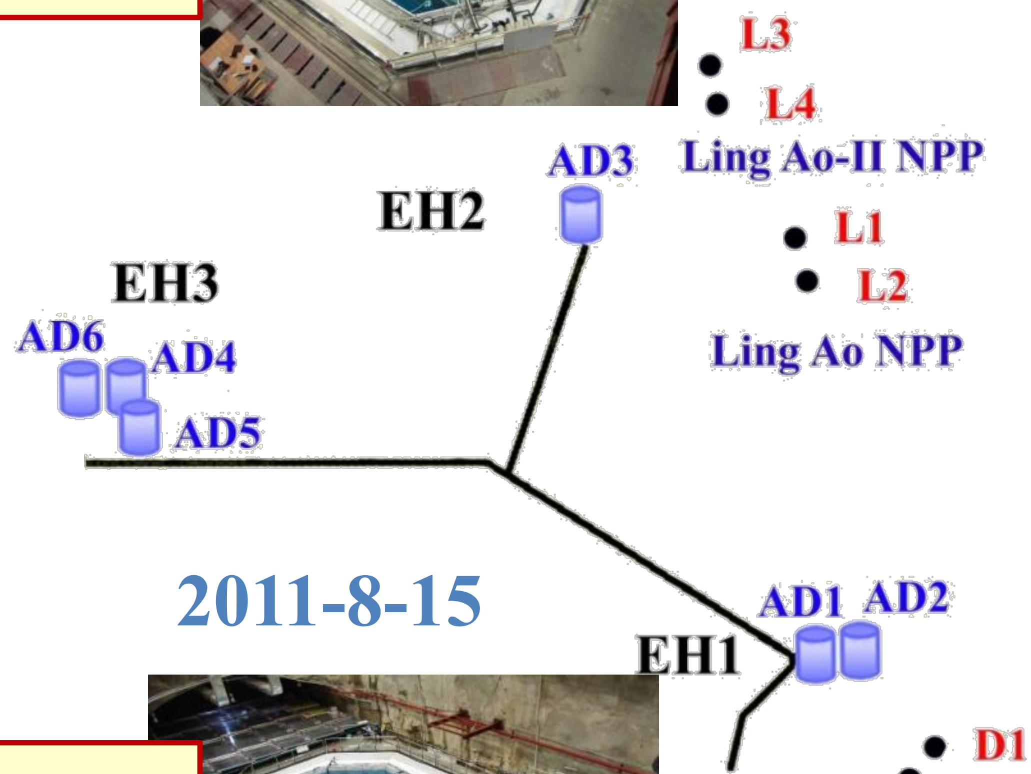
Daya Bay Results

Mar.8, 2012, with 55 day data
$\sin^2 2\theta_{13}$=0.092±0.016(stat)±0.005(syst)
5.2 σ for non-zero θ_{13}

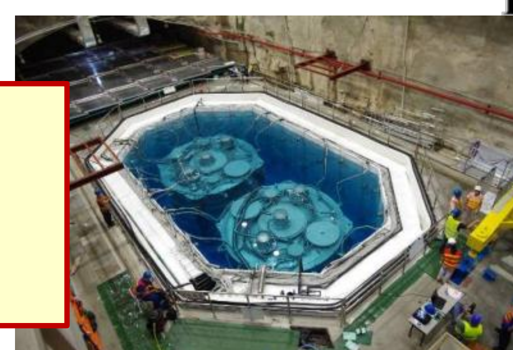
2011-11-5



2011-12-24



2011-8-15



Jun.4, 2012, with 139 day data
$\sin^2 2\theta_{13}$=0.089±0.010(stat)±0.005(syst)
7.7 σ for non-zero θ_{13}

Updated θ_{13} measurement summarized in PDG 2025

$\theta_{13}/\circ$ Normal ordering $8.56^{+0.11}_{-0.11}$

Inverted ordering $8.59^{+0.11}_{-0.11}$

Compared to the 2012 value

$\theta_{13}/\circ$ $8.68^{+0.54}_{-0.54}$