Neutrino Oscillation

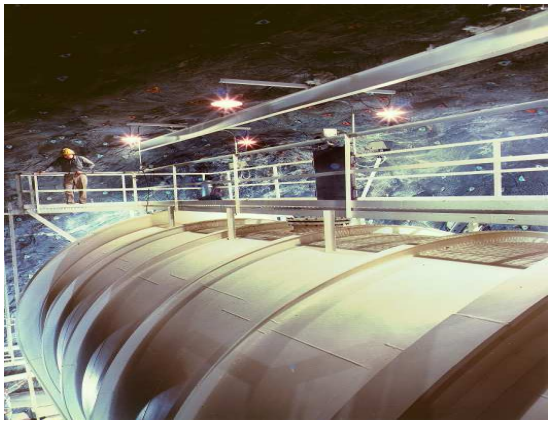
Matthew Posik
Temple University

Neutrino Oscillation

- What is neutrino oscillation
- Evidence for neutrino oscillation
- Future experiments

Solar Neutrino Problem

- Raymond Davis, Jr's Homestake Experiment (late 1960's): collect and count neutrinos emitted from the sun
- Used a tank of 100,000 gallons of chlorine rich liquid, which upon neutrino collision emitted a radio active argon isotope
- Detected only 1/3 of the predicted (John Bahcall) neutrino flux!
- Results later verified by several independent experiments (Kamiokande, Gallex, ect)



http://www.bnl.gov/bnlweb/raydavis/research.htm

Enter Bruno Pontecorvo

- Pontecorvo developed idea of neutrino oscillations (~1960)
- Neutrino oscillations due to mismatch in flavor and mass eigenstates

$$|\nu_\alpha> = \sum_i U_{\alpha i}{}^* |\nu_i> \quad (1)$$

$$|\nu_i> = \sum_\alpha U_{\alpha i} |\nu_\alpha> \quad (2)$$

Where for three neutrinos $\alpha = e, \mu, \tau$ are definite flavor and i = 1,2,3 are definite masses.

$\mathrm{U}_{\alpha i}$ is the Maki-Nakagawa-Sakata (MNS) matrix. For three neutrino flavors

$$\mathrm{U} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{12} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{\frac{i\alpha_1}{2}} & 0 & 0 \\ 0 & e^{\frac{i\alpha_2}{2}} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Flavor Change Probability

- Consider how a neutrino born according to eq. (1) evolves in time.
- Apply Schrödinger's equation:

$$|\nu_i(\tau_i)>= e^{-im_i\tau_i}|\nu_i(0)> \quad \text{(mass frame)}$$

- In lab frame, and treating the neutrino highly relativistic, the phase factor becomes:

$$\mathrm{e}^{-i(m_i\tau_i)} = e^{-i(E_it-p_iL)} \approxeq e^{-i(\frac{{m_i}^2}{2p})L}$$

$$|\nu_\alpha(L)>\approxeq \sum_i {U_{\alpha i}}^* e^{-i(\frac{{m_i}^2}{2p})L}|\nu_i> \qquad (3)$$

- Inverting (1) and putting it into (3) :

$$|\nu_\alpha(L)>\approxeq \sum_\beta[\sum_i {U_{\alpha i}}^* e^{-i(\frac{{m_i}^2}{2p})L}U_{\beta i}]|\nu_\beta> \qquad (4)$$

Flavor Change Probability

- So the probability of a flavor change:

$$\mathrm{P}(\nu_\alpha \to \nu_\beta) = |<\nu_\beta|\nu_\alpha>|^2$$

$$= \delta_{\alpha\beta} - 4\sum_{(i>j)} \Re(U_{\alpha i}{}^* U_{\beta i} U_{\alpha j} U_{\beta j}{}^*) sin^2(\frac{\Delta m_{ij}{}^2 L}{4E})$$

$$+ 2\sum_{(i>j)} \Im((U_{\alpha i}{}^* U_{\beta i} U_{\alpha j} U_{\beta j}{}^*) sin^2(\frac{\Delta m_{ij}{}^2 L}{2E}) \ ; \ \Delta m_{ij}{}^2 = m_i{}^2 - m_j{}^2 \qquad (5)$$

- Sinusoidal dependence on L/E and mass difference
- Neutrino oscillation introduces neutrino mass

Flavor Change Probability

- If CPT invariance holds

$$\mathrm{P}(\overline{\nu_\alpha} \to \overline{\nu_\beta}) = P(\nu_\beta \to \nu_\alpha)$$

- Then

$$\mathrm{P}(\overline{\nu_\alpha} \to \overline{\nu_\beta}; U) = P(\nu_\beta \to \nu_\alpha; U^*)$$

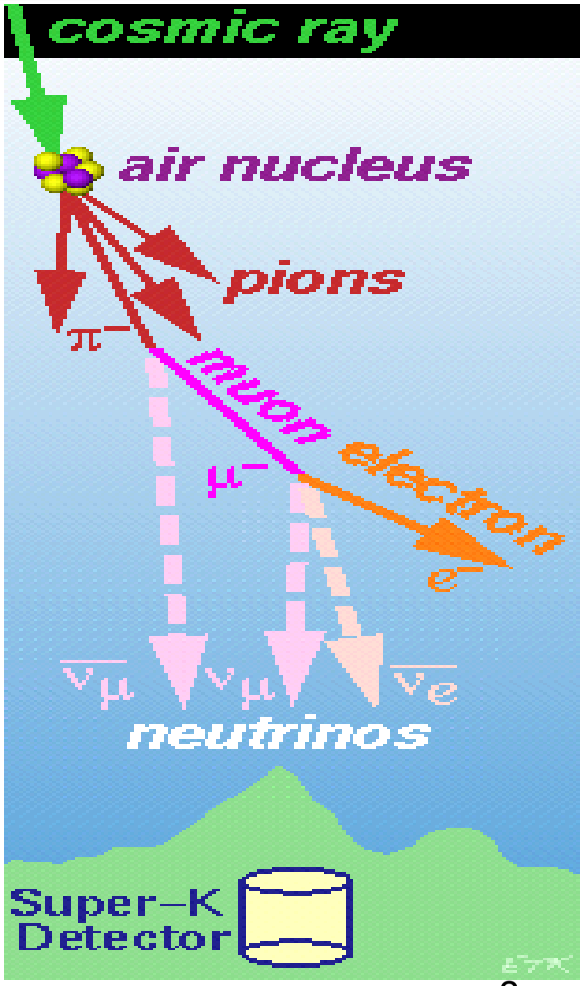
- If U is not real, then the probabilities of the neutrino and anti-neutrino can differ. This can be seen in the last term of eq. (5).

- If such a probability difference is seen, and CPT invariance holds, then CP would be violated.

Atmospheric Neutrino Oscillation (Super-Kamiokande)

- Located in Mozumi mines in Japan
- Measure muon neutrino disappearance as a function of L/E and constrain the mixing angle.
- Survival Probability:

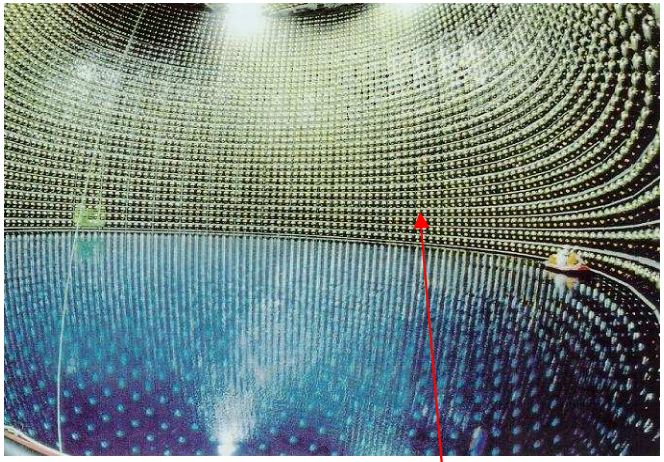
$$\mathrm{P}(\nu_\mu \to \nu_\mu) = 1 - sin^2 2\theta sin^2(\frac{1.27\Delta m^2(eV^2)L(km)}{E(GeV)})$$

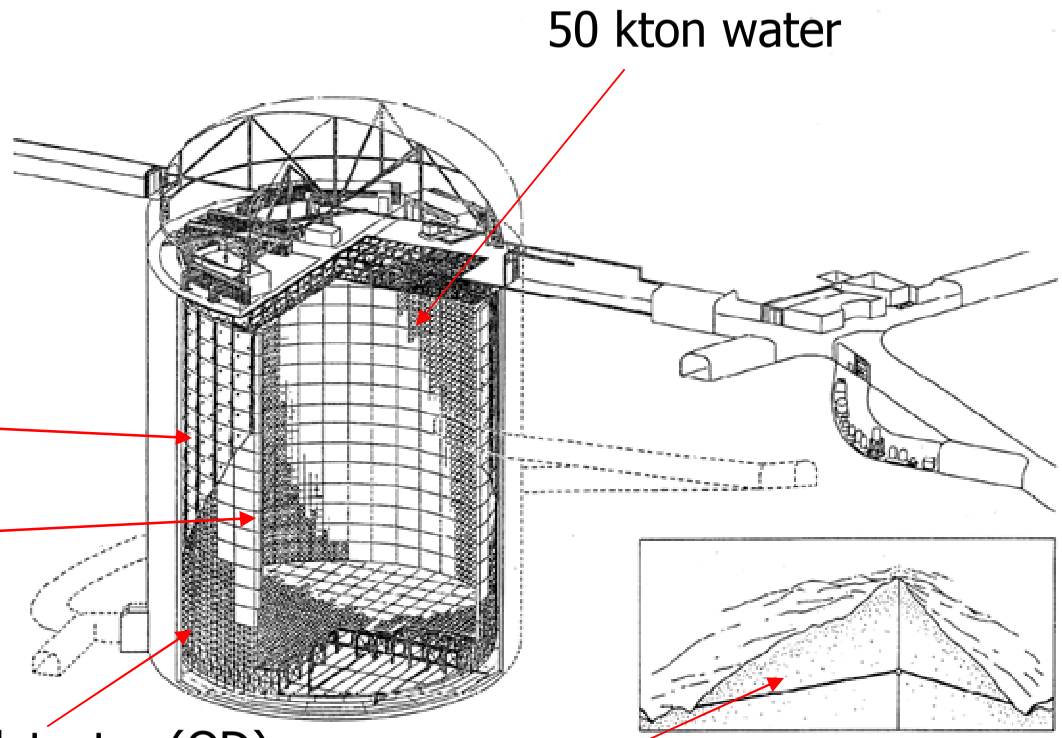


http://hep.bu.edu/~superk/atmnu/ Y. Fukuda et al. [Super-Kamiokande Collaboration], arXiv: hep-ex\0404034v1 (2004).

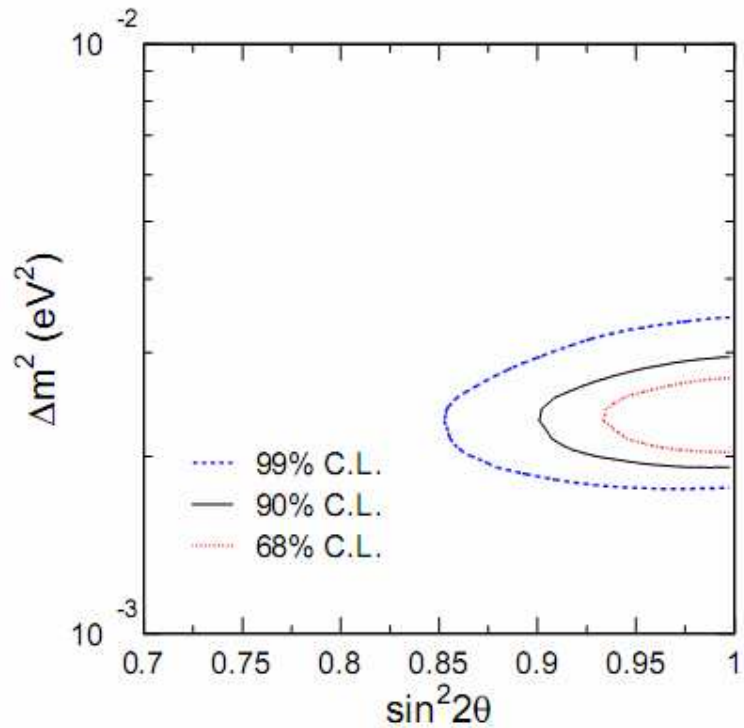
Super-Kamiokand Cherenkov Detector

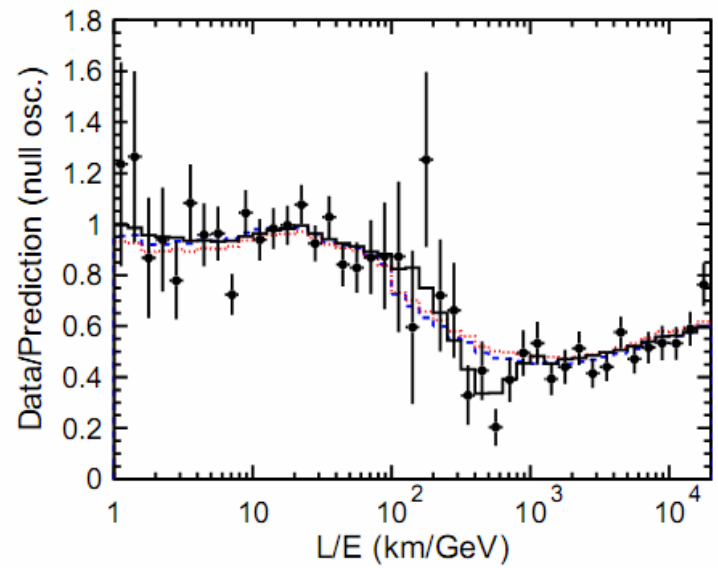
http://www-sk.icrr.u-tokyo.ac.jp/sk/index-e.html





Super- Kamiokande Results





$1.9 \text{ x } 10^{-3} eV^2 < \Delta m^2 < 3.0x10^{-3} eV^2; sin^2 2\theta > 0.90$ at 90%

Y. Fukuda et al. [Super-Kamiokande Collaboration], arXiv: hep-ex/0404034v1 (2004).

KamLAND Reactor Anti-Neutrinos

- Located in the Kamioka mines in Japan
- Determine if antineutrino disappearance is present
- Anti-neutrinos created from radioactive decays
- Electron antineutrinos are detected through inverse beta decay

$$\overline{\nu_e} + p \rightarrow e^+ + n$$

KamLAND Reactor Antineutrino Detector

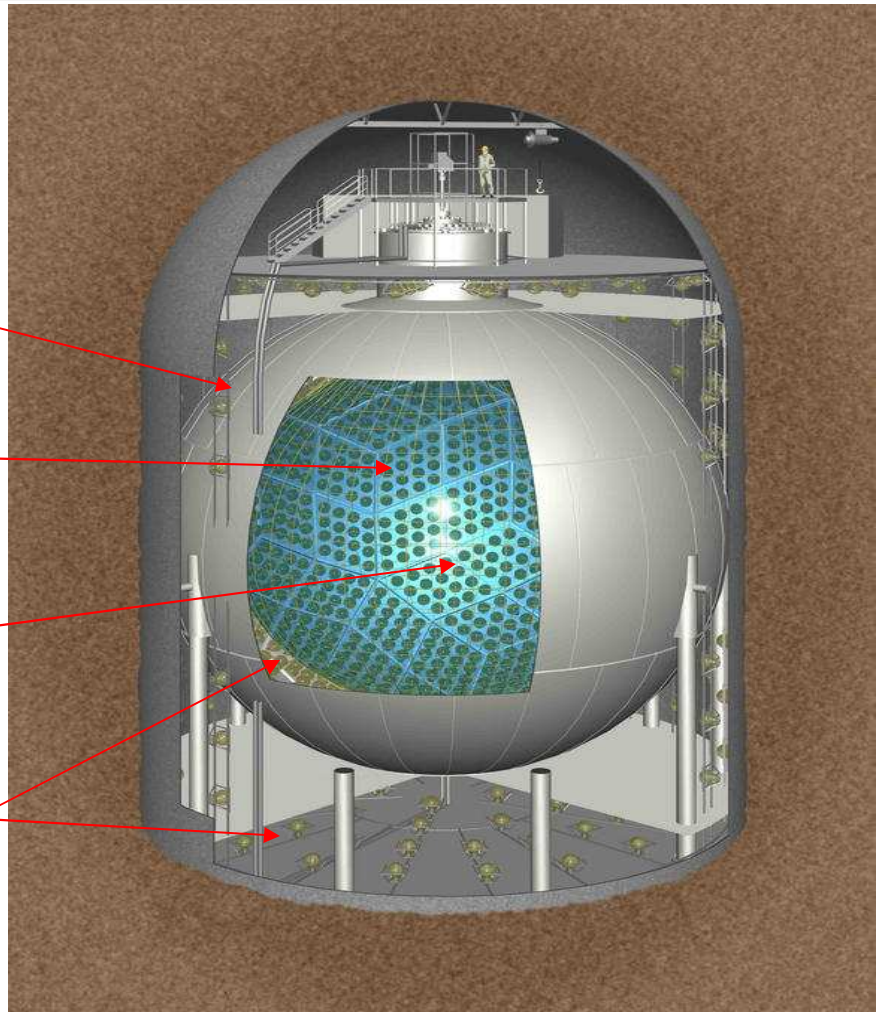
Stainless steel Vessel

13m D, nylon balloon w/pmt

1 kton liquid scintillator

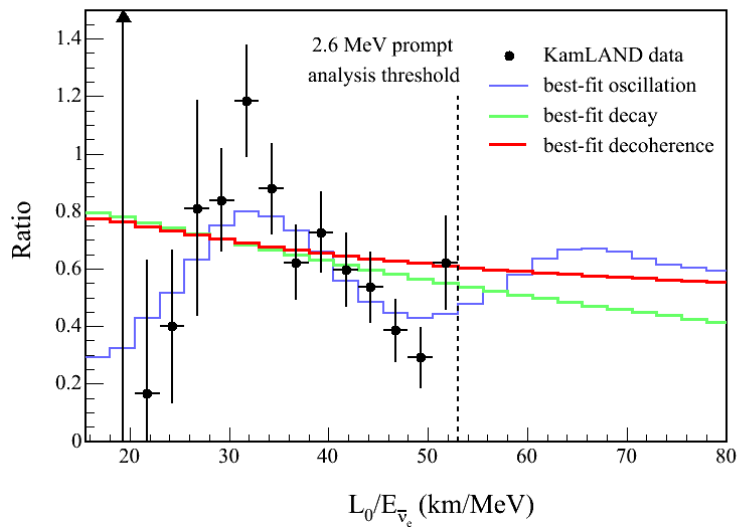
Water Cherenkov Detector

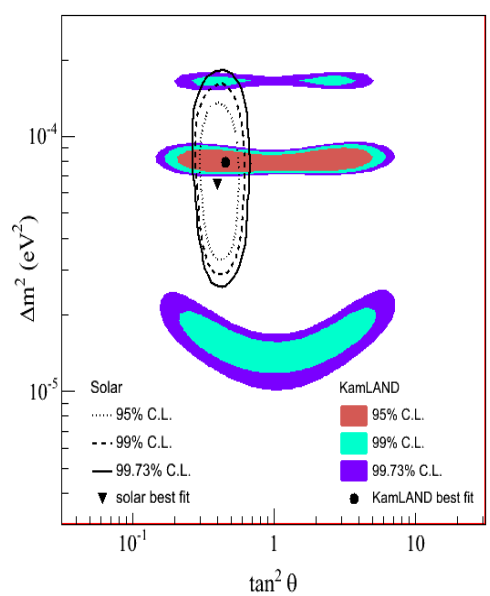
Non scintillating oil

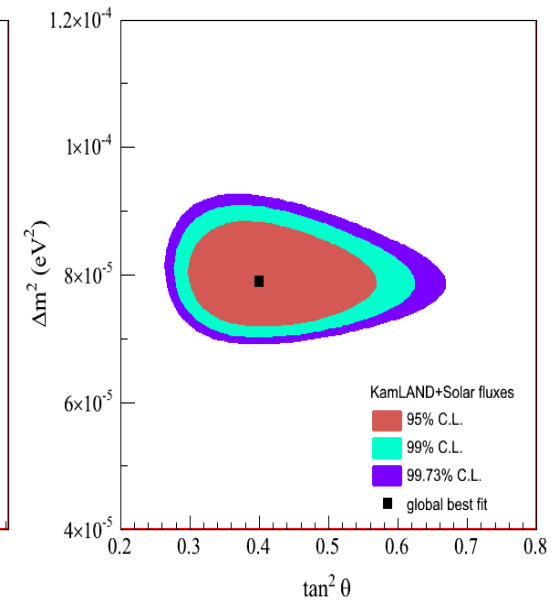


http://kamland.lbl.gov/

KamLAND Results



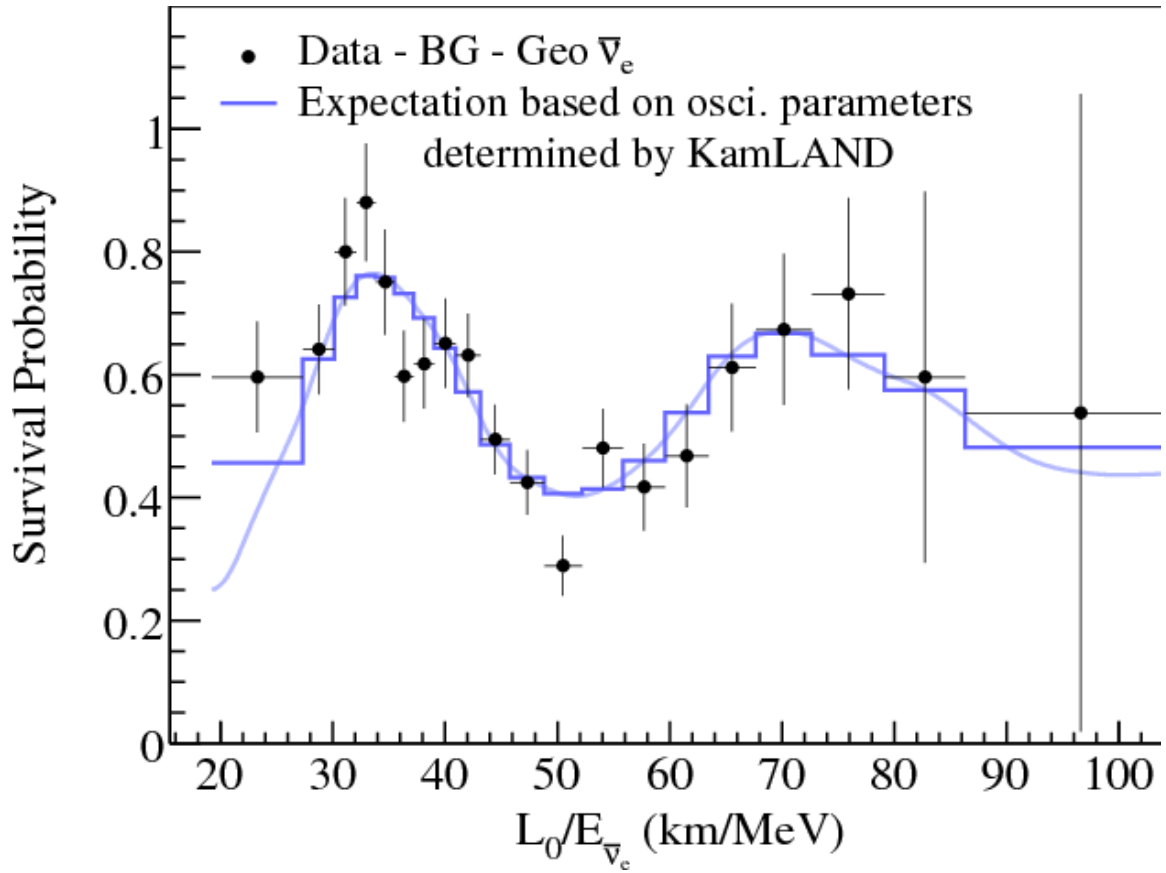




$$\Delta m^2 = 7.9^{+6.5}_{-0.5} x 10^{-5} eV^2; tan^2\theta = 0.40^{+0.10}_{-0.07}$$

T. Araki et al. Phys. Rev. Lett. **94**, 081801 (2005).

KamLAND Results (2008)



arXiv:0801.4589v2

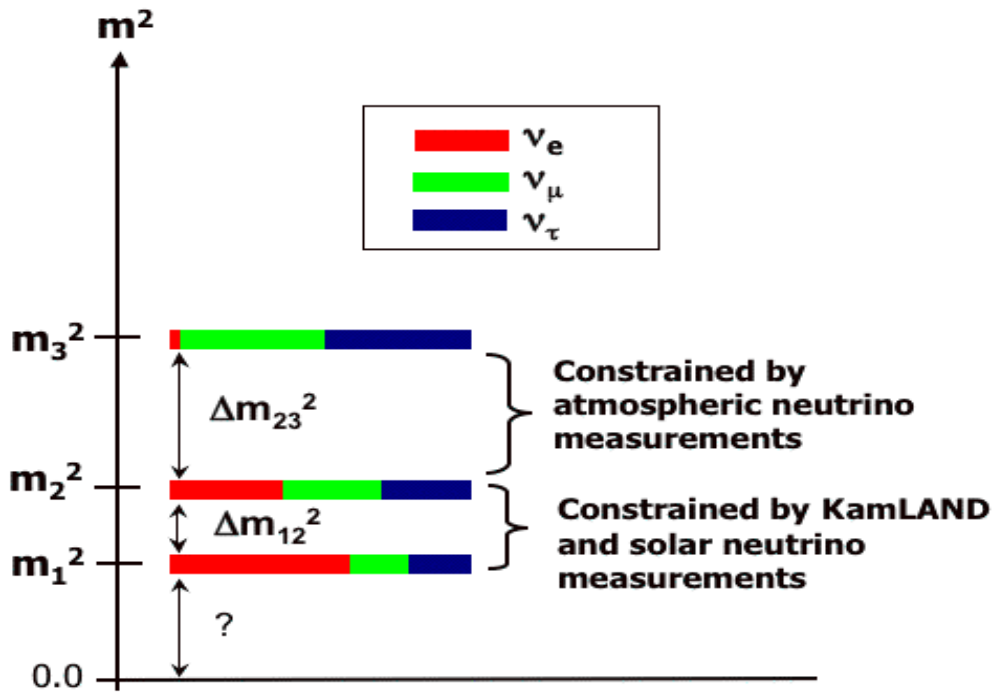
What is Next

Δm^2_{atm}	$\Delta m^2_{\odot}$	θ_{atm}	$\theta_{\odot}$	θ_{13}
$2.38^{+0.20}_{-0.16}$	$8.0^{+0.6}_{-0.4}$	45+/-7°	$33.9^o{}^{+2.4^o}_{-2.2^o}$	< 3.2^o

- More precise measure of masses and mixing angles (θ_{13})
- Determine neutrino mass spectrum
- Search for CP violation

Limit from the Solar and KamLAND Experiments, Phys. Rev. C 72, 055502 (2005); Kielczewska, Acta Phys. Pol. B 38 (2007)

Neutrino Mass Spec.



Note: Because we don't know the signs of the mass differences or the values of the masses themselves , the true spectrum may be inverted from what is shown here.

http://dnp.nscl.msu.edu/current/kamland.html