Neutrino Oscillation Phenomenology

Review of the ISAPP summer school - Valencia, 2008

Thomas Mueller

October 15, 2008

Oscillations in vacuum

- The oscillation probability in vacuum is given by:

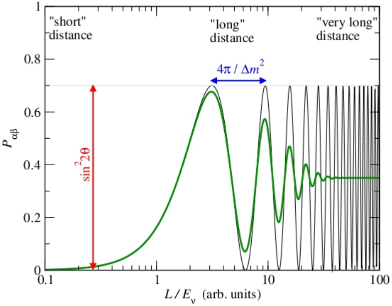
$$P_{\nu_\alpha \to \nu_\beta}(L,E) = \sum_{kj} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} \exp(-i \frac{\Delta m^2_{kj} L}{2E})$$

- $\Delta m^2_{kj} \equiv m^2_k - m^2_j$
  $\longrightarrow$ oscillations are sensitive only to mass-squared differences (not to absolute mass!)

- To observe oscillations one needs:
  1. non-trivial mixing $U_{\alpha i}$
  2. non-zero mass-squared differences Δm^2_{kj}
  3. a suitable value for L/E

Phases of neutrino oscillations

1. "short" distance $\Leftrightarrow$ $\Phi \ll 1$:
   - no oscillation can develop
   - $P_{\nu_\alpha \to \nu_\beta} = \delta_{\alpha\beta}$ because of $\sum_j U_{\alpha j} U^*_{\beta j} = \delta_{\alpha\beta}$



2. "long" distance $\Leftrightarrow$ $\Phi \gtrsim \pi/2$:
   - oscillations are observable

3. "very long" distance $\Leftrightarrow$ $\Phi \gg 2\pi$:
   - oscillations are averaged out (independant of L and E)

3-flavour oscillation parameters

$$\underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\Delta m^2_{31}} \begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\Delta m^2_{21}}$$

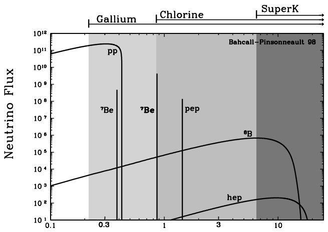
LBL + atmospheric — Chooz — Solar + KamLAND

- 3-flavour effects are suppressed because:
  1. $\theta_{13} \ll 1$
  2. $\Delta m^2_{21} \ll \Delta m^2_{31}$

$\Rightarrow$ Dominant oscillations are well described by 2-flavour oscillations

Solar neutrino experiments

- Homestake, Kamiokande, GALLEX/GNO, SAGE, Super-K, SNO, Borexino
- Thermonuclear fusion reactions in the solar core $\Rightarrow$ source of ν_e

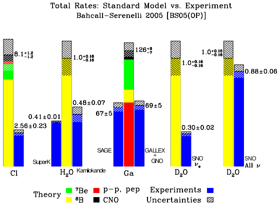


Solar neutrino energy spectrum

- Accessible oscillation parameters $\rightarrow \theta_{12}, \Delta m^2_{21}$

The solar problem and its solution

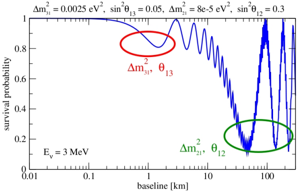
- Evidence for an oscillation $\nu_e \longrightarrow \nu_{\mu,\tau}$



- LMA + MSW:
  1. $\tan^2\theta_{12} = 0.45^{+0.09}_{-0.07}$ (SNO)
  2. $\Delta m^2_{21}\cos 2\theta_{12} = 2EV \Rightarrow \Delta m^2_{21} > 0$

Reactor neutrino experiments

- Bugey, Palo Verde, CHOOZ, KamLAND
- Nuclear fission in reactor cores $\Rightarrow$ source of $\bar{\nu}_e$
- Only disappearance experiment because of E $\approx$ 4 MeV

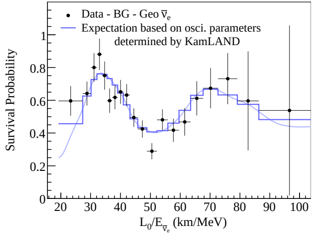


- Accessible oscillation parameters $\rightarrow$ θ_{13}, Δm^2_{31} or θ_{12}, Δm^2_{21} depending on the baseline

Chooz and KamLAND

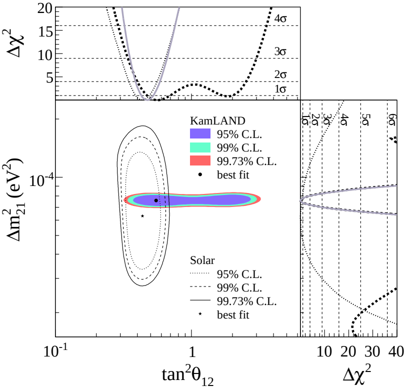
- CHOOZ: $\frac{E}{L} \approx \frac{4MeV}{1km} \approx 4 \times 10^{-3} eV^2$
  $\Rightarrow \bar{\nu}_e$ disappearence at the "atmospheric" Δm^2_{31} scale

- KamLAND: $\frac{E}{L} \approx \frac{4MeV}{175km} \approx 2 \times 10^{-5} eV^2$
  $\Rightarrow \bar{\nu}_e$ disappearence at the "solar" Δm^2_{21} scale



- $\Delta m^2_{21} = 7.59 \pm 0.21 \times 10^{-5} eV^2$

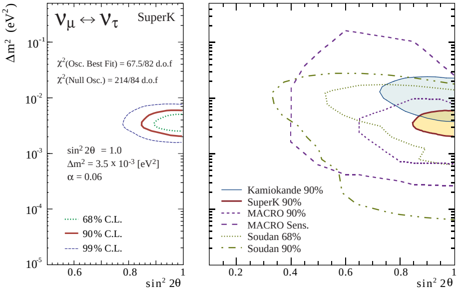
KamLAND vs solar data



$$\Delta m^2_{21} = 7.59 \pm 0.21 \times 10^{-5} eV^2 \text{ (KamLAND)}$$
$$\tan^2\theta_{12} = 0.45^{+0.09}_{-0.07} \text{ (SNO)}$$

Atmosheric neutrino experiments

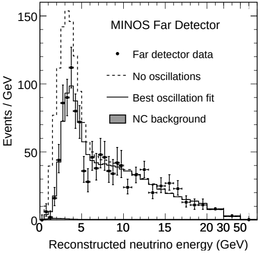
- IMB, Soudan 2, Super-K
- Hadronic showers in the earth's atmosphere $\Rightarrow \nu_{e,\mu}\ \bar{\nu}_{e,\mu}$
- Accessible oscillation parameters $\longrightarrow \theta_{23},\ \Delta m^2_{31}$



- $\sin^2 2\theta_{23} = 1.00$ (SK)

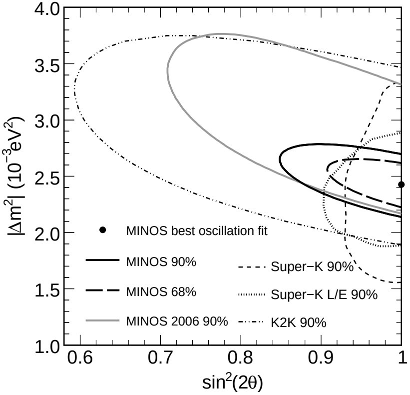
LBL neutrino experiments

- K2K, MINOS $\longrightarrow$ disappearance of accelerated ν_μ (or $\bar{\nu}_\mu$) flux
- MINOS: $\frac{E}{L} \approx \frac{3GeV}{735km} \approx 4.1 \times 10^{-3} eV^2$
- Accessible oscillation parameters $\longrightarrow \theta_{23}, \Delta m^2_{31}$



- $|\Delta m^2_{31}| = 2.43 \pm 0.13 \times 10^{-3} eV^2$ (MINOS)

Super-K + K2K + MINOS



$$|\Delta m^2_{31}| = 2.43 \pm 0.13 \times 10^{-3} eV^2 \text{ (MINOS)}$$
$$\sin^2 2\theta_{23} = 1.00 \text{ (SK)}$$

Summary

- "Known" parameters:
  1. $\Delta m^2_{21} = 7.59 \pm 0.21 \times 10^{-5} eV^2$ $\quad \sin^2\theta_{12} = 0.31^{+0.016}_{-0.023}$
  2. $|\Delta m^2_{31}| = 2.43 \pm 0.13 \times 10^{-3} eV^2$ $\quad \sin^2\theta_{23} = 0.50 \pm 0.063$

- Open questions:
  1. Sign of Δm^2_{31}?
     - Look for matter effect in $\nu_e \leftrightarrow \nu_\mu$ oscillations
     - Neutrinoless double beta decay (see Tarek's talk)
  2. Value of $\sin^2\theta_{13}$?
     - Double Chooz, Daya Bay, T2K (see Rachel's talk)
  3. Value of the phase δ?