# Neutrino Fits

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# Summary : SM + ν mass

M. Ishitsuka + T. Iwashita + S. Hatakeyama + J. Wilson

**+ ALL other oscillation neutrino data BUT LSND**

**3 σ ranges:**

$$|U_{\alpha i}| = \begin{pmatrix} |U_{e1}| & |U_{e2}| & |U_{e3}| \\ |U_{\mu 1}| & |U_{\mu 2}| & |U_{\mu 3}| \\ |U_{\tau 1}| & |U_{\tau 2}| & |U_{\tau 3}| \end{pmatrix} = \begin{pmatrix} 0.78-0.88 & 0.47-0.62 & 0.00-0.23 \\ 0.18-0.55 & 0.40-0.73 & 0.57-0.82 \\ 0.19-0.55 & 0.41-0.75 & 0.55-0.82 \end{pmatrix}$$

$$5.2 \le \frac{\Delta \mathrm{m}^2}{10^{-5}\,\mathrm{eV}^2} \le 9.8$$

$$1.4 \le \frac{\Delta \mathrm{M}^2}{10^{-3}\,\mathrm{eV}^2} \le 3.4$$

# Summary : beyond standard

M. Ishitsuka + T. iwashita + S. Hatakeyama + J. Wilson

+ ALL other oscillation neutrino data

?

# Why a combined analysis ?

- Framework to test different scenarios on equal footing
- Correlations, Subleading effects, Consistency
- Determine ranges of parameters involved :
  - Differences of squared masses : differences of phases
  - Leptonic mixing angles : weak and free fields not aligned
- Determine physics involved,e.g., A. Mirizzi, A.M.Rotunno
- Pool analysis : identifying systematics Fogli et al 2002

# 3 ν : Parameter Space

$$U_{\alpha i} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{+i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\Delta m^2 \geq 0$$

$$\Delta M^2 \geq 0$$

$$0 \leq \theta_{ij} \leq \frac{\pi}{2}$$

$$0 \leq \delta \leq \pi$$

# 3 ν

$\Delta m^2 \quad (\Delta m^2_{sol})$

$\Delta M^2 \quad (\Delta M^2_{atm})$

**interference**

$$\frac{\Delta m^2}{E} \sim L$$

**refraction index**

$$\frac{\Delta m^2}{E} \sim G_F N_e$$

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

**Searched by :**

- $c_{23}$: **Atmospheric**, **K2K**
- $c_{13}$: **CHOOZ**, **Palo Verde**
- $c_{12}$: **Solar**, **KamLAND**

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**Searched by :**

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**K2K**

**CHOOZ**
**Palo Verde**

**Solar**
**KamLAND**

# 3 ν

**If** $\Delta m^2 << \Delta M^2$

**Solar** $P_{3\nu}(\nu_e \to \nu_e) = P(\Delta m^2, \theta_{12}, \theta_{13})$

$$P_{3\nu}(\nu_e \to \nu_e) = \cos^4\theta_{13} P_{2\nu}(\nu_e \to \nu_e) + \sin^4\theta_{13}$$

**Atmospheric** $P_{3\nu}(\nu_{\alpha=e,\mu} \to \nu_{\beta=e,\mu}) = P(\Delta M^2, \theta_{23}, \theta_{13})$

$$P_{3\nu}(\nu_e \to \nu_\mu) = \sin^2 2\theta_{13,m} \sin^2\theta_{23} \sin^2(\Delta M^2 L / 4E)$$

**Reactor** $P_{3\nu}(\bar{\nu}_e \to \bar{\nu}_e) = P(\Delta M^2, \Delta m^2, \theta_{12}, \theta_{13})$

**Two scales**


Gonzalez-Garcia, Maltoni, hep-ph/0202218

Fogli, Lisi, Palazzo, PRD65, 2002

Gonzalez-Garcia, Maltoni, P-G, Valle, PRD63, 2001

Bilenky, Nicolo, Petcov, PLB538, 2002

Mocioiu, Shrock, JHEP0111, 2001

# 3 ν : results

$3\sigma$ (b.f.)

$$5.2 \le \frac{\Delta m^2}{10^{-5}\,\mathrm{eV}^2} \le 9.8 \quad (7.1)$$

$$1.4 \le \frac{\Delta M^2}{10^{-3}\,\mathrm{eV}^2} \le 3.4 \quad (2.4)$$

$$0.29 \le \tan^2\theta_{12} \le 0.64 \quad (0.42)$$

$$0.49 \le \tan^2\theta_{23} \le 2.2 \quad (1.0)$$

$$\sin^2\theta_{13} \le 0.054 \quad (0.008)$$

# 3 ν : results

Gonzalez-Garcia, PG (2003), see also Maltoni et al (2003), Fogli et al (2003)

$$|U_{\alpha i}| = \begin{pmatrix} |U_{e1}| & |U_{e2}| & |U_{e3}| \\ |U_{\mu 1}| & |U_{\mu 2}| & |U_{\mu 3}| \\ |U_{\tau 1}| & |U_{\tau 2}| & |U_{\tau 3}| \end{pmatrix} = \begin{pmatrix} 0.78-0.88 & 0.47-0.62 & 0.00-0.23 \\ 0.18-0.55 & 0.40-0.73 & 0.57-0.82 \\ 0.19-0.55 & 0.41-0.75 & 0.55-0.82 \end{pmatrix}$$

Gonzalez-Garcia, NOON04

$$|U_{\alpha i}| \sim \begin{pmatrix} \frac{1}{\sqrt{2}}(1+\lambda) & \frac{1}{\sqrt{2}}(1-\lambda) & \varepsilon \\ \frac{1}{2}(1-\lambda+\Delta+\varepsilon\cos\delta) & \frac{1}{2}(1+\lambda+\Delta-\varepsilon\cos\delta) & \frac{1}{\sqrt{2}}(1-\Delta) \\ \frac{1}{2}(1-\lambda-\Delta-\varepsilon\cos\delta) & \frac{1}{2}(1+\lambda-\Delta+\varepsilon\cos\delta) & \frac{1}{\sqrt{2}}(1-\Delta) \end{pmatrix}$$

$$1\sigma$$

$$\lambda = 0.23 \pm 0.02$$

$$\Delta = 0.00 \pm 0.08$$

$$\varepsilon \leq 0.02$$

$$-1 \leq \cos\delta \leq 1$$

# 3 ν : next steps

**More data in running experiments will fix plausible systematic shifts on mass scales :**
**- Solar + KamLAND : NSI effects**
**- Atmospheric and K2K : ν fluxes, cross sections**

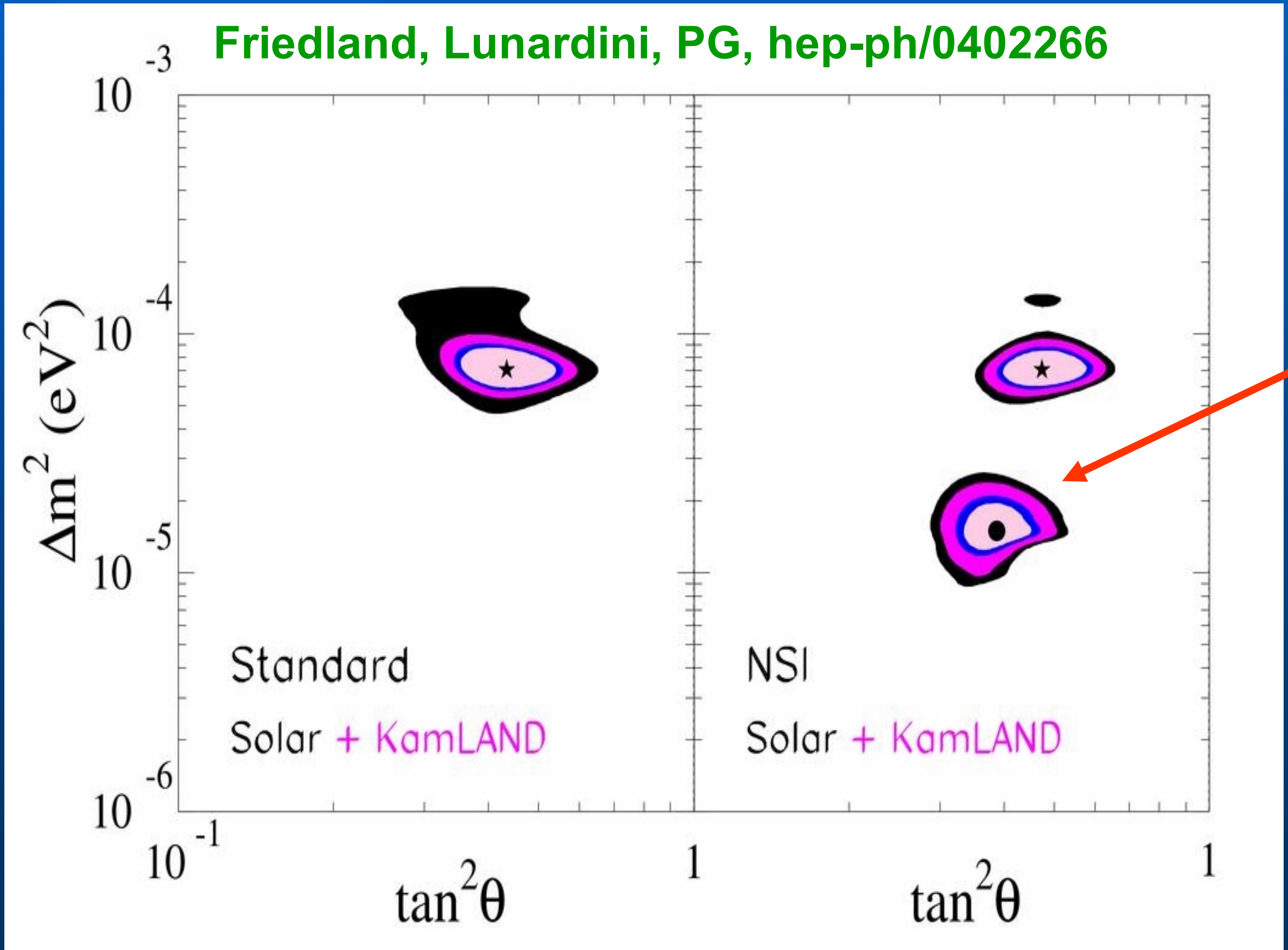
A. Cervera

**Improvements in analysis:**
**- Solar : Independ. of ν fluxes** Bahcall, PG (2003)
**- Atmospheric : Understanding uncertainties** NOON04

**Future experiments:**
**- Atmospheric scale: MINOS,ICARUS/OPERA**
**- $\theta_{13}$ determination** S. Rigolin, F. Dalnoki-Veress
**- Low energy solar neutrinos : Borexino**

# Non-standard neutrino interactions

Small flavor diagonal and flavor changing fermi interactions (~0.1$G_F$ ) with quarks → LMA with modified matter effects




**What's new :**

Lower $\Delta m^2_{21}$ region

Sensitivity in KamLAND reactor

Sensitivity in low energy solar neutrino experiments (Borexino/KamLAND sol)

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# Beyond standard

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**+ all other oscillation neutrino data**

**?**

# LSND vs KARMEN

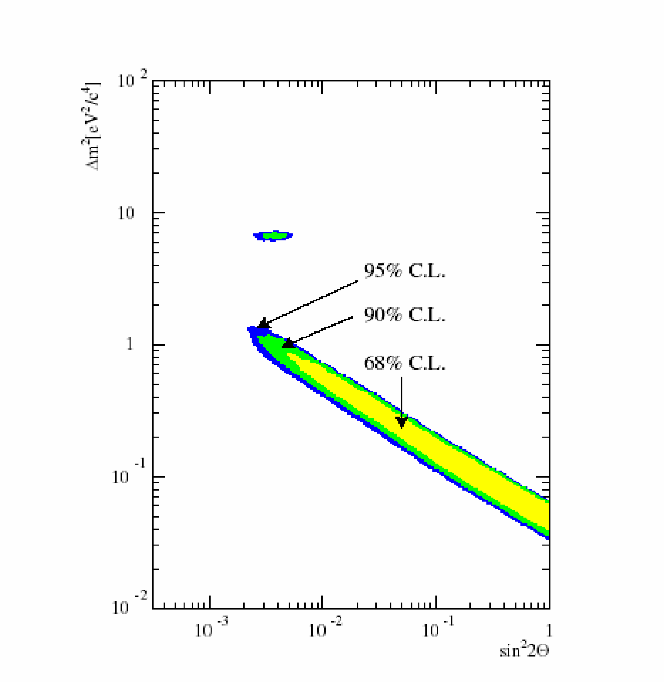
**LSND : L=30 m, 20<E<60 MeV**
**3.5 to 7 σ appearance signal depending on analysis**
**67 signal events in 1030 signal+background**

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = (2.6 \pm 0.8)\, 10^{-3}$$

**KARMEN : L=17.5 m, 20<E<60 MeV**
**15 events in 15.8 background expected**

**Not compatible at 36%CL**

**Combined LSND/KARMEN : Church et al, hep-ex/0203023**



# Beyond standard picture

* $\Delta L=2$ muon decay . Incompatible : LSND with Karmen

**Disfavoured at 3.5σ** Babu,Pakvasa, hep-ph/0204236

* + Sterile. Incompatible :
- App. in LSND with disapp. in Bugey and CDHS
- Sterile is not in solar (SNO) nor in atmospheric (SK)

**Disfavoured at 3.2(5.8)σ** Bilenki, Giunti, GG, Valle, …

* CPT violation. Incompatible : LSND with atmospheric (SK)

Baremboim et al, hep-ph/0212116

**Disfavoured at 3.4σ**

* Extra interactions. Incompatible : LSND with atm. SK

More about it tomorrow : D. Kaplan

# Concluding remarks :

Robust results (all but LSND) : improvements expected from data and analysis this year

Miniboone surprising us : J. Monroe

New ideas might be needed