Neutrino Oscillations: experimental triumphs, remaining puzzles

Giorgio Gratta
Physics Department, Stanford
What we do know:  - Status of neutrino mixing

How did we learn it:  - Solar neutrino
  - Atmospheric neutrino
  - Reactor neutrinos
  - K2K

Addressing remaining puzzles in neutrino mixing:
  - LNSD/miniBoone → see Sam Zeller
  - $\theta_{13}$ experiments
  - Hierarchy/CP violation: $\nu$-fact/\$\beta\$-beams
  - Absolute m, Majorana/Dirac $\nu$
    → see Steve Elliott

Impossible to be complete: I will just make an arbitrary
  -and hopefully interesting- selection
From LEP and SLC we know that there are 2.981±0.008 active, light ν flavors. We also know that 3 ν flavors were active in Big Bang Nucleosynthesis.

If m_ν≠0 then the 3 weak-interactions eigenstates |ν_j⟩ can be represented as superposition of mass eigenstates

|ν_j⟩ = \sum_j U_{jl} |ν_l⟩

Neutrinos are produced and detected by weak interaction but propagate in vacuum as mass eigenstates...

|ν_j⟩ ≈ \sum_l U_{lj} e^{-i(m_l^2/2E)L} |ν_l⟩ ≈ \sum_j \sum_l U_{lj} e^{-i(m_l^2/2E)L} U_{j'l}^* |ν_{j'}⟩

→ Neutrino oscillations
A possible representation of the Pontecorvo-Maki-Nakagawa-Sakata matrix

\[ U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \]

information on Neutrino \( CP \) is here factory?

\[ \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} \cos \theta_{13} & 0 & e^{-i\delta_{CP}} \sin \theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta_{CP}} \sin \theta_{13} & 0 & \cos \theta_{13} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha/2} & 0 \\ 0 & 0 & e^{-i\alpha/2-i\beta} \end{pmatrix} \]

Solar \( \nu \) KamLAND
KamLAND
Future solar \( \nu \) exp.

Chooz/Palo Verde
Off axis
Future reactors

Atmospheric \( \nu \)
K2K
Minos et al

Neutrinoless
double beta
decay

\( \theta_{12} \sim 32^\circ \)
\( \theta_{13} < 7^\circ \) @ 90\%CL
\( \theta_{23} \sim 45^\circ \)
Oscillations give the proof that neutrino masses are non-zero, but we still do not know the absolute mass scale and the hierarchy.

- From tritium endpoint (Mainz and Troitsk): $0.3\,\text{eV}$
- From $0\nu\beta\beta$: $0.3\,\text{eV}$ (if $\nu$ is Majorana)
- Solar: $2.7\times10^{-3}\,\text{eV}^2$
- Atmospheric: $8.3\times10^{-5}\,\text{eV}^2$
- From WMAP: $20\,\text{eV}$
- Time of flight from SN1987A (PDG 2002): $1\,\text{eV}$

Sign of $\Delta m^2_{13}$ (Future accelerator experiments)
$\nu_e$ are abundant by-products of nuclear fusion in the sun

$p + p \rightarrow ^2H + e^+ + \nu_e + 0.42\text{MeV}$

"pp" 99.75%

$p + e^- + p \rightarrow ^2H + \nu_e + 1.44\text{MeV}

"pep" 0.25%

$^2H + p \rightarrow ^3\text{He} + \gamma + 5.49\text{MeV}$

86%

$^3\text{He} + ^3\text{He} \rightarrow \alpha + 2p + 12.86\text{MeV}$

14%

$^3\text{He} + \alpha \rightarrow ^7\text{Be} + \gamma + 1.59\text{MeV}$

$^3\text{He} + p \rightarrow \alpha + e^+ + \nu_e$

"hep" 2.4*10^{-5}

$^7\text{Be}$ 99.89%

$^7\text{Be} + e^- \rightarrow ^7\text{Li} + \gamma + \nu_e + 0.8617\text{MeV}$

0.11%

$^7\text{Be} + p \rightarrow ^8\text{B} + \gamma + 0.14\text{MeV}$

"$^8\text{B}$" 0.11%

$^7\text{Li} + p \rightarrow \alpha + \alpha + 17.35\text{MeV}$

$^8\text{B} \rightarrow ^8\text{Be} + e^+ + \nu_e + 14.6\text{MeV}$

$^8\text{Be} \rightarrow \alpha + \alpha + 3\text{MeV}$

86% $^7\text{Be}$

2.4*10^{-5} "hep"
The detectors are located far away from the Sun

But neutrinos are produced deep inside the Sun, where most the fusion reactions take place

⇒ Matter effects play an essential role
Several experiments detecting solar neutrinos

**Chlorine**: $^{37}\text{Cl} + \nu_e \rightarrow ^{37}\text{Ar} + e^-$  
Homestake mine (US) Taking data from 1967-2002 (!)  
The “father” of all solar neutrino experiments

**Gallium**: $^{71}\text{Ga} + \nu_e \rightarrow ^{71}\text{Ge} + e^-$  
SAGE (Baksan, Russia), Gallex and GNO (Gran Sasso, Italy)  
Lowest threshold  
Calibrated with a neutrino source

**Cerenkov**: $e^- + \nu_e \rightarrow e^- + \nu_e$  
Kamiokande and SuperKamiokande (Japan), SNO (Sudbury, Canada)  
Largest statistics  
See D. Casper’s talk

**Cerenkov: D$^\circ$ scattering**  
SNO (Sudbury, Canada)  
For the first time measure $\nu_e$ and $\nu_x$ separately  
See D. Waller’s talk
Neutrino energy spectrum includes lines and continua
Homestake Mine, Lead SD
1400 m underground

615 tons of perchloroethilene
($C_2Cl_4$)

2.2*10^{30} atoms of $^{37}Cl$
$^{36}Ar$ or $^{38}Ar$ added to the fluid as carrier gas
30 years of solar neutrinos with the Chlorine detector

![Graph showing 37Ar production rate (Atoms/day) vs. year from 1970 to 1995 with SNU on the y-axis. The graph indicates a discrepancy between observed and expected SSM results.]
Total Rates: Standard Model vs. Experiment

Prof. J.N. Bahcall
The Institute for Advanced Study
School of Natural Science
Princeton, New Jersey 08540, USA

Dear Prof. Bahcall,

Thank you very much for your letter and the abstract of the new Davis investigation the numerical results of which I did not know. It starts to be really interesting! It would be nice if all this will end with something unexpected from the point of view of particle physics. Unfortunately, it will not be easy to demonstrate this, even if nature works that way.

I will attend the Balaton meeting on neutrinos and looking forward to see you there.

Yours sincerely,

B. Pontecorvo
Ga in aqueous solution of GaCl₄. ³¹GeCl₄ is volatile and is purged/counted.

In Gallex/GNO 30.3 ton of GaCl₄, ³¹Ga is sensitive to pp neutrinos.

Ga kept liquid (>29.8°C) in aqueous solution of GaCl₄. ³¹GaCl₄ is volatile and is purged/counted.

Extraction by HCl etch and Ar purge.

28-50 ton of metallic Ga kept liquid (>29.8°C) in aqueous solution of GaCl₄. ³¹GaCl₄ is volatile and is purged/counted.
Both Ga experiments have been calibrated with a $^{51}$Cr source of about 1 MCi.
In order to better understand the situation it would be nice to also measure the total number of neutrinos from the Sun, all flavors together.

The SNO detector:
1 kton of heavy water
Neutrino interactions in $D_2O$

**Charged Current (CC):**
\[ \nu_e + d \rightarrow p + p + e^- \]
Electron neutrinos only

**Elastic Scattering (ES):**
\[ \nu_x + e^- \rightarrow \nu_x + e^- \]
\[ 0.154 \cdot \sigma(\nu_e) = \sigma(\nu_\mu) = \sigma(\nu_\tau) \]
this is all SuperK sees

**Neutral Current (NC):**
\[ \nu_x + d \rightarrow p + n + \nu_x \]
Same for all neutrino flavors!
Remarkably the SNO measurement gives $\Phi_{NC} > \Phi_{CC}$

$$\phi_{CC}^{SNO} = 1.76^{+0.06}_{-0.05} \text{(stat)}^{+0.09}_{-0.09} \text{(syst)},$$
$$\phi_{ES}^{SNO} = 2.39^{+0.24}_{-0.23} \text{(stat)}^{+0.12}_{-0.12} \text{(syst)},$$
$$\phi_{NC}^{SNO} = 5.09^{+0.44}_{-0.43} \text{(stat)}^{+0.46}_{-0.43} \text{(syst)}.$$  


*For up-to-date results see Waller's talk*

So $\nu_e$ are missing, but the total number of neutrinos is right!
Clearly all this smells of flavor mixing…

Global fit to all solar neutrino expts eliminates most of the solutions except for the MSW-LMA solution.

(The solar neutrino anomaly is a sort of neutrino-birefringence of dense matter occurring because neutrinos have finite masses -- see Boris Kayser' talk)
All of this is very interesting...

...but wouldn't it be great if we could reproduce it with artificial means?
Nuclear reactors are very intense sources of $\bar{\nu}_e$ deriving from beta-decay of the neutron-rich fission fragments.

Look for a deficit of $\bar{\nu}_e$ and spectral distortions at a distance $L$. 
Example: $^{235}\text{U}$ fission

$^{235}\text{U} + n \rightarrow X_1 + X_2 + 2n$

stable nuclei with $A$
most likely from fission

$^{94}\text{Zr}$ $^{140}\text{Ce}$

together these have
98 protons and
136 neutrons

so, on average 6 n have to
decay to 6 p to reach stable matter
Power/commercial reactors are generally used since only requirement is to have large power

\[ 200\text{MeV} / \text{fission} \]
\[ 6\bar{\nu}_e / \text{fission} \]

A typical large power reactor produces \(3\ \text{GW}_{\text{thermal}}\) and \(6 \cdot 10^{20}\) antineutrinos/s

the Chooz plant in France
>99.9% of $\bar{\nu}$ are produced by fissions in $^{235}\text{U}$, $^{238}\text{U}$, $^{239}\text{Pu}$, $^{241}\text{Pu}$

contribution $<10^{-3}$ not taken into account for neutrino flux calculations
A specific signature is provided by the inverse-β reaction

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

$$\tau \approx 200 \mu s$$

$$p + n \rightarrow d + \gamma (2.2 \text{ MeV})$$

Event tagging by coincidence in time, space and energy of the neutron capture

$$E_{\nu} \text{ measurement}$$

$$E_{\bar{\nu}} \cong T_{e^+} + T_n + (M_n - M_p) + m_{e^+}$$

Threshold: $$E_{\bar{\nu}} > 1.8 \text{ MeV}$$

→ only ~1.5 antineutrinos/fission can be detected
The $\bar{\nu}_e$ energy spectrum

Reactor $\nu_e$ spectrum (a.u.)

Observed spectrum (a.u.)

$\nu_e + p \rightarrow n + e^+$ cross section ($10^{-43}$ cm$^2$)

$E_{\nu}$ (MeV)
An experiment relevant for solar $\nu$ will have $\sim 100$ km baseline and hence will need a huge detector and a "huge source"
~1 km high
Mt Ikenoyama
Many reactors contribute to the antineutrino flux at KamLAND

<table>
<thead>
<tr>
<th>Site</th>
<th>Dist (km)</th>
<th>Cores (#)</th>
<th>$P_{\text{therm}}$ (GW)</th>
<th>Flux (cm$^{-2}$ s$^{-1}$)</th>
<th>Rate noosc$^*$ ($E_{\nu}&gt;3.4\text{MeV}$)</th>
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</thead>
<tbody>
<tr>
<td>Kashiwazaki</td>
<td>160</td>
<td>7</td>
<td>24.3</td>
<td>4.1$\cdot 10^5$</td>
<td>254.0</td>
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<tr>
<td>Ohi</td>
<td>179</td>
<td>4</td>
<td>13.7</td>
<td>1.9$\cdot 10^5$</td>
<td>114.3</td>
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<tr>
<td>Takahama</td>
<td>191</td>
<td>4</td>
<td>10.2</td>
<td>1.2$\cdot 10^5$</td>
<td>74.3</td>
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<tr>
<td>Tsuruga</td>
<td>138</td>
<td>2</td>
<td>4.5</td>
<td>1.0$\cdot 10^5$</td>
<td>62.5</td>
</tr>
<tr>
<td>Hamaoka</td>
<td>214</td>
<td>4</td>
<td>10.6</td>
<td>1.0$\cdot 10^5$</td>
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<tr>
<td>Mihama</td>
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<td>3</td>
<td>4.9</td>
<td>1.0$\cdot 10^5$</td>
<td>62.0</td>
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<tr>
<td>Sika</td>
<td>88</td>
<td>1</td>
<td>1.6</td>
<td>9.0$\cdot 10^4$</td>
<td>55.2</td>
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<td>Fukushima1</td>
<td>349</td>
<td>6</td>
<td>14.2</td>
<td>5.1$\cdot 10^4$</td>
<td>31.1</td>
</tr>
<tr>
<td>Fukushima2</td>
<td>345</td>
<td>4</td>
<td>13.2</td>
<td>4.8$\cdot 10^4$</td>
<td>29.5</td>
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<tr>
<td>Tokai2</td>
<td>295</td>
<td>1</td>
<td>3.3</td>
<td>1.6$\cdot 10^4$</td>
<td>10.1</td>
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<tr>
<td>Onagawa</td>
<td>431</td>
<td>3</td>
<td>6.5</td>
<td>1.5$\cdot 10^4$</td>
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<td>Simane</td>
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<td>1.0$\cdot 10^4$</td>
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<tr>
<td>Ikata</td>
<td>561</td>
<td>3</td>
<td>6.0</td>
<td>8.3$\cdot 10^3$</td>
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<tr>
<td>Genkai</td>
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<td>10.1</td>
<td>7.8$\cdot 10^3$</td>
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<td>Sendai</td>
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<td>5.3</td>
<td>3.4$\cdot 10^3$</td>
<td>2.1</td>
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<tr>
<td>Tomari</td>
<td>783</td>
<td>2</td>
<td>3.3</td>
<td>2.3$\cdot 10^3$</td>
<td>1.4</td>
</tr>
<tr>
<td>Total Nominal</td>
<td>-</td>
<td>70</td>
<td>181.7</td>
<td>1.3$\cdot 10^6$</td>
<td>803.8</td>
</tr>
</tbody>
</table>

From electrical power
Japanese average fuel used

Detailed power and fuel composition calculation used

*From electrical power
Japanese average fuel used

Detailed power and fuel composition calculation used
The total electric power produced “as a by-product” of the νs is:

- ~60 GW or...
- ~4% of the world’s manmade power or...
- ~20% of the world’s nuclear power
A limited range of baselines contribute to the flux of reactor antineutrinos at Kamioka

Over the data period Reported here

Korean reactors $3.4 \pm 0.3\%$

Rest of the world $1.1 \pm 0.5\%$

+JP research reactors

Japanese spent fuel $0.04 \pm 0.02\%$
KamLAND: Kamioka Liquid scintillator AntiNeutrino Detector

- 1 kton liq. Scint. Detector in the Kamiokande cavern
- 1325 17" fast PMTs
- 554 20" large area PMTs
- 34% photocathode coverage
- H₂O Cerenkov veto counter
The completed detector, looking up
Scintillator is a blend of 20% pseudocumene and 80% dodecane

Different density paraffines are used to tune the density of buffer to $4 \cdot 10^{-4}$ of that of the scintillator

PPO concentration is 1.52 g/l in scintillator
Autoradiography of KamLAND

238U : 214Bi → 214Po → 210Pb

$\beta+\gamma$
$E = 3.27\,\text{MeV}$
$\tau = 28.7\,\text{min.}$

$\alpha$
$E = 7.69\,\text{MeV}$
$\tau = 237\,\mu\text{s}$

In this region measure

$238U = (3.5 \pm 0.5) \times 10^{-18}\,\text{g/g}$

Top flange and chimney region
Central thermometer
Balloon
Bottom flange and plumbing
### A brief history of KamLAND

<table>
<thead>
<tr>
<th>Event</th>
<th>Dates</th>
<th>Live time (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start data taking</td>
<td>Jan 2002</td>
<td>-</td>
</tr>
<tr>
<td>Run A (data-set of 1st paper)</td>
<td>Mar 9 – Oct 6 2002</td>
<td>145.4*</td>
</tr>
<tr>
<td>Electronics upgrade &amp; 20” PMT commissioning</td>
<td>Jan/Feb 2003</td>
<td>-</td>
</tr>
<tr>
<td>Run B</td>
<td>Oct – Jan 11 2004</td>
<td>369.7</td>
</tr>
<tr>
<td>Data-set presented here†</td>
<td>Mar 9, 2002 – Jan 11, 2004</td>
<td>515.1</td>
</tr>
</tbody>
</table>

*Was 145.1 with old analysis

Vertexing is performed using timing from the 17” PMTs.
Tagged cosmogenics can be used for calibration

Fit to data shows that $^{12}\text{B} : ^{12}\text{N} \sim 100 : 1$
Energy calibration uses discrete $\gamma$ and $^{12}\text{B}/^{12}\text{N}$

Carefully include Birks law, Cherenkov and light absorption/optics to obtain constants for $\gamma$ and $e$-type depositions

$\sigma/E \sim 6.2\%$ at $1\text{MeV}$
Estimate of total volume and fiducial fraction

- flow meter meas.
- purification tank meas.
- 3,000 m$^3$ tank meas.
- spallation neutrons
  - $^{12}\text{B}/^{12}\text{N}$
Fraction of volume inside the fiducial radius verified using μ-produced $^{12}\text{B}/^{12}\text{N}$ and n (assumed uniform).
Selecting antineutrinos, $E_{\text{prompt}} > 2.6\text{MeV}$

- $R_{\text{prompt, delayed}} < 5.5\text{ m}$
- $\Delta R_{e-n} < 2\text{ m}$
- $0.5\mu s < \Delta T_{e-n} < 1\text{ ms}$
- $1.8\text{ MeV} < E_{\text{delayed}} < 2.6\text{ MeV}$
- $2.6\text{ MeV} < E_{\text{prompt}} < 8.5\text{ MeV}$

Tagging efficiency 89.8%

...In addition:
- 2s veto for showering/bad $\mu$
- 2s veto in a $R = 3\text{m}$ tube along track

Dead-time 9.7%
<table>
<thead>
<tr>
<th><strong>Systematic</strong></th>
<th>%</th>
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</thead>
<tbody>
<tr>
<td>Scintillator volume</td>
<td>2.1</td>
</tr>
<tr>
<td>Fiducial fraction</td>
<td>4.2</td>
</tr>
<tr>
<td>Energy threshold</td>
<td>2.3</td>
</tr>
<tr>
<td>Cuts efficiency</td>
<td>1.6</td>
</tr>
<tr>
<td>Live time</td>
<td>0.06</td>
</tr>
<tr>
<td>Reactor $P_{\text{thermal}}$</td>
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<tr>
<td>Fuel composition</td>
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<td>Time lag</td>
<td>0.01</td>
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<tr>
<td>Antineutrino spectrum</td>
<td>2.5</td>
</tr>
<tr>
<td>Antineutrino $\times$-section</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>6.5</td>
</tr>
</tbody>
</table>
### Results

<table>
<thead>
<tr>
<th>Observed events</th>
<th>258</th>
</tr>
</thead>
<tbody>
<tr>
<td>No osc. expected</td>
<td>365±24(syst)</td>
</tr>
<tr>
<td>Background</td>
<td>7.5±1.3</td>
</tr>
</tbody>
</table>

Inconsistent with simple $1/R^2$ propagation at 99.995% CL

\[
\frac{\text{Observed-Background}}{\text{Expected}} = 0.686\pm0.044(\text{stat})\pm0.045(\text{syst})
\]

**Caveat:** this specific number does not have an absolute meaning in KamLAND, since, with oscillations, it depends on which reactors are on/off
2003 saw a substantial dip in reactor antineutrino flux
Good correlation with reactor flux

~0.03 for 3TW hypothetical Earth core reactor

(But a horizontal line still gives a decent fit with $\chi^2=5.4/4$)

Fit constrained through known background $\chi^2=2.1/4$
Energy spectrum now adds substantial information

Best fit to oscillations:
\[ \Delta m^2 = 8.3 \cdot 10^{-5} \text{ eV}^2 \]
\[ \sin^2 2\theta = 0.83 \]

Straightforward \( \chi^2 \) on the histo is 19.6/11

Using equal probability bins \( \chi^2 / \text{dof} = 18.3 / 18 \)

(goodness of fit is 42%)

A fit to a simple rescaled reactor spectrum is excluded at 99.89% CL (\( \chi^2 = 43.4 / 19 \))
Un-binned likelihood fit to 2-flavor oscillations

Δm² = 8.3 × 10⁻⁵ eV²

sin²2θ = 0.83

LMA2 excluded at 99.6% CL

"LMA0" disfavored at 94% CL

All solar ν experiments

Un-binned likelihood fit to 2-flavor oscillations
A shape-only fit gives similar results

\[ \Delta m^2 = 8.3 \cdot 10^{-5} \text{ eV}^2 \]

\[ \sin^2 2\theta = 0.98 \]
KamLAND uses a range of $L$ and it cannot assign a specific $L$ to each event. Nevertheless, the ratio of detected/expected for $L/E$ (or $1/E$) is an interesting quantity, as it decouples the oscillation pattern from the reactor energy spectrum.
More exotic, non-oscillations models for the antineutrino channel start being less favored by data.

2.6 MeV analysis threshold

Decay* excluded at 95% CL

Decoherence† excluded at 94% CL

Combined solar $\nu -$ KamLAND 2-flavor analysis

$\Delta m_{12}^2 = 8.2^{+0.6}_{-0.5} \times 10^{-5} \text{ eV}^2$

$\tan^2 \theta_{12} = 0.40^{+0.09}_{-0.07}$

Includes (small) matter effects
...it took 35 years... but we have:

1) detected neutrinos from the sun
2) found that part of the neutrino flux is missing
3) found that only $\nu_e$ are missing
4) found that matter effects in the sun (MSW effect) are responsible for the deficit
5) found that neutrinos have finite masses (required for MSW)
6) identified mixing parameters $\Delta m_{12}^2$, $\theta_{12}$
7) found that we can reproduce this effect artificially with vacuum oscillations with the same $\Delta m_{12}^2$, $\theta_{12}$
8) found that $\nu$ and anti-$\nu$ behave the same way
9) found that flavor mixing works better than other scenarios (e.g. decay)
10) found that our model for the sun (SSM) works very well
The other oscillations: Atmospheric neutrinos

Higher energy phenomenon

Measurements dominated by SuperK
SuperKamiokande: the largest “artificial” water Cerenkov detector ever built (50 kton)

SK1 1996-2001
>11146 50cm PMTs
40% photocathode
22.5kton fiducial mass

2003-2005
5182 PMTs recovered
19% photocathode
K2K beam

2006-...
Original PMT coverage
T2K beam
A composite data-set

<table>
<thead>
<tr>
<th>Category</th>
<th>DATA</th>
<th>MC</th>
<th>C.C. Purity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-GeV 1-ring e-like</td>
<td>3353</td>
<td>2978.8</td>
<td>88.0%</td>
</tr>
<tr>
<td>Multi-GeV 1-ring e-like</td>
<td>746</td>
<td>680.5</td>
<td>82.6%</td>
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<tr>
<td>Sub-GeV 1-ring μ-like</td>
<td>3227</td>
<td>4212.8</td>
<td>94.5%</td>
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<tr>
<td>Sub-GeV Multiring μ-like</td>
<td>208</td>
<td>322.6</td>
<td>90.5%</td>
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<tr>
<td>Multi-GeV 1-ring μ-like</td>
<td>651</td>
<td>899.9</td>
<td>99.4%</td>
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<td>Multi-GeV Multiring μ-like</td>
<td>439</td>
<td>711.9</td>
<td>95.0%</td>
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<td>Partially Contained μ</td>
<td>647</td>
<td>1034.5</td>
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<tr>
<td>Stopping Upward μ</td>
<td>417.7</td>
<td>721.4</td>
<td>~100%</td>
</tr>
<tr>
<td>Throughgoing Upward μ</td>
<td>1841.6</td>
<td>1684.4</td>
<td>~100%</td>
</tr>
</tbody>
</table>

~14000 events total from data reduction

11530 events used (80%) in oscillation analysis

E.Kearns, Nu2004
Ratios

\[ R_{\text{sub-GeV}} = 0.658 \pm 0.016(\text{stat}) \pm 0.032(\text{sys}) \]

\[ R \equiv \frac{\langle \mu/e \rangle_{\text{DATA}}}{\langle \mu/e \rangle_{\text{M.C.}}} \]

\[ R_{\text{multi-GeV}} = 0.702^{+0.032}_{-0.036}(\text{stat}) \pm 0.099(\text{sys}) \]

\[
\left( \frac{N_{\text{UP}}}{N_{\text{DOWN}}} \right)_{\text{Multi-GeV + PC}} = 0.55^{+0.035}_{-0.033}(\text{stat}) \pm 0.005(\text{sys})
\]
Zenith Angle Distributions

E. Kearns, Nu2004
The oscillatory pattern is now also visible with atmospheric neutrinos.

And flavor oscillation is favored over other models for disappearance.

Decay rejected at 3.4σ
Decoherence rejected at 3.8σ
Parameter regions fit by different channels nicely overlap

A 3 flavor analysis favors $\nu_\mu - \nu_\tau$ oscillation as responsible for the atmospheric neutrino anomaly (more on this later...)

E. Kearns, Nu2004
Again, the quest is open to observe the oscillation phenomenon with artificial neutrinos

- 12 GeV KEK protons
- Mini-K (1kton water + other detectors) near detector (100m) $10^{11} \nu_\mu$ every 2.2s
- Super-K at 250km $10^6 \nu_\mu$ every 2.2s (detect ~1 event/2 days)
- $8.9 \cdot 10^{19}$ p.o.t. collected in ~3.5 yrs
In the 3.5 yrs of data the atm nu background in the KEK beam spill window is $10^{-2}$ events.

Although rate is low background greatly reduced by beam spill timing (0.83 ms delay, synchronized offline using GPS)
Expected no oscillation rate: $150.9^{+11.6}_{-10.0}$

- $N_{SK}^{obs} = 108$
- $N_{SK}^{exp \ (best \ fit)} = 104.8$

K2K establishes:
- $\nu_\mu$ disappearance at $2.9\sigma$ (standard physics has 0.33% CL)
- $E_\nu$ spectral distortion at $2.5\sigma$ (standard physics has 1.1% CL)

Combined we have a $3.9\sigma$ effect (standard physics has 0.011% CL)
K2K-I & K2K-II

preliminary

approximate 90% CL from global SK fit to atmospheric neutrinos
What we have discovered:

There is mixing involving $\nu_e$ with best fit at
$$\Delta m^2 = 8.3 \cdot 10^{-5} \text{ eV}^2 \quad \text{and} \quad \theta = 32^\circ \quad (\text{solar/KamLAND})$$

There is also mixing involving $\nu_\mu$ with best fit at
$$\Delta m^2 = 2.7 \cdot 10^{-3} \text{ eV}^2 \quad \text{and} \quad \theta = 45^\circ \quad (\text{atmospheric/K2K})$$

If there are only 3 neutrino families, since the two mass differences are of different order of magnitude, we expect to find a third $\Delta m^2$ similar to the larger of the two above