Neutrino Physics, Part 1

Neutrinos in the Standard Model, and Why The Standard Model is Wrong

Scott Oser

UBC

Lake Louise Winter Institute

February 2006
Outline

1. Neutrinos In The Standard Model
2. Neutrino Mixing And Oscillation
3. The Solar Neutrino Problem, With Solution
4. Atmospheric Neutrino Oscillations
5. Results from Long Baseline Neutrino Experiments
Neutrinos in the Standard Model

A neutrino is a neutral cousin of the electron and the other charged leptons.

Only weak interactions — carried by very heavy W, Z particles with short ranges.

In the Standard Model, $m_\nu \equiv 0$. (The current limit on the sum of the three masses is $\sim 0.6$ eV). Neutrinos are many orders of magnitude lighter than the other fermions.

Why are $\nu$'s so light? Why 3 kinds?

What's the relationship between leptons and quarks?
Different Kinds of Neutrinos: “Flavours”

Each charged lepton \((e, \mu, \tau)\) has its own kind of neutrino. For example, in these reactions you get:

\[
p + e^- \rightarrow \nu_e + n
\]
\[
p + \mu^- \rightarrow \nu_\mu + n
\]

Note that the number of particles of each flavour type seems to be conserved in each reaction.

Flavour is also conserved in the other direction:

\[
\nu_e + n \rightarrow p + e^-
\]
\[
\nu_\mu + n \rightarrow p + \mu^-
\]

In the Standard Model lepton flavour is rigorously conserved, but is not protected by any symmetry of the Lagrangian.
Weak interactions only couple to left-handed $\nu$'s, or right-handed $\bar{\nu}$'s
This is a pure V-A interaction (maximally parity violating). Weak current has the form:

$$j_\mu = \bar{\psi}\gamma_\mu(1 - \gamma_5)\psi$$

Right-handed $\nu$'s either don’t exist, or are sterile (don’t interact).

A plausible, but wrong, argument ...

1. Ockham’s Razor: the simplest solution is if right-handed $\nu$’s don’t exist.
2. In Standard Model, mass couples left-handed and right-handed states.
3. Therefore, to avoid right-handed states, neutrinos should have no mass.
In Standard Model, neutrinos are rather boring ... they have no mass, and only seem to be there to conserve lepton number, flavour number, and energy/momentum/spin.

In 1962, Maki, Nakagawa, and Sakata proposed, on the basis of zero experimental evidence, a new phenomenon called neutrino oscillation.

To understand what led MNS to this, let’s look at quark mixing first.
Weak Interactions with Quarks

The simple version: $W$ particle couples $u \leftrightarrow d$, $c \leftrightarrow s$, $t \leftrightarrow b$,

\[ W \uparrow \downarrow \quad u \quad d \]
\[ W \uparrow \downarrow \quad c \quad s \]
\[ W \uparrow \downarrow \quad t \quad b \]

But this can’t be complete, since we see weak decays such as:

\[ \Lambda(uds) \rightarrow p(uud) + \pi^- (d\bar{u}) \]

Somehow the strange quark in the $\Lambda$ gets turned into an up quark!
In reality, W particle couplings mix quark generations:

\[
\begin{align*}
\begin{pmatrix}
    u \\
    d'
\end{pmatrix} & \begin{pmatrix}
    c \\
    s'
\end{pmatrix} \begin{pmatrix}
    t \\
    b'
\end{pmatrix} \\
\begin{pmatrix}
    d' \\
    s' \\
    b'
\end{pmatrix} &= 
\begin{bmatrix}
    V_{ud} & V_{us} & V_{ub} \\
    V_{cd} & V_{cs} & V_{cb} \\
    V_{td} & V_{ts} & V_{tb}
\end{bmatrix} 
\begin{pmatrix}
    d \\
    s \\
    b
\end{pmatrix}
\end{align*}
\]

We say that flavour eigenstates (eg. d,s,b) are rotated with respect to weak eigenstates (d',s',b')

This allows generation-mixing decays such as \( \Lambda(uds) \rightarrow p\pi^- \)
Since $\nu$'s have only weak interactions, flavour eigenstates are defined as those states that couple to $W$.

What if the flavour eigenstates are rotated relative to the mass eigenstates (eigenstates of Hamiltonian with well-defined mass)?

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= 
\begin{bmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{bmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]
How does superposition of mass eigenstates evolve in vacuum?

\[ |\nu_e\rangle = \cos \theta |\nu_1\rangle + \sin \theta |\nu_2\rangle \]
\[ |\nu_\mu\rangle = -\sin \theta |\nu_1\rangle + \cos \theta |\nu_2\rangle \]

Each term evolves with a phase factor of \( e^{i(px - Et)} \)

If \( m_1 \neq m_2 \), then arguments of exponential will be different! For example, if we consider \( p \) to be fixed, then

\[ E = \sqrt{p^2 + m^2} = p\sqrt{1 + m^2/p^2} \approx p + m^2/(2p) \]

As neutrino propagates, a phase difference develops between terms!

\[ |\nu(t)\rangle \propto \cos \theta |\nu_1\rangle + e^{i\phi} \sin \theta |\nu_2\rangle \]

with

\[ \phi = \left( \frac{m_1^2}{2p} - \frac{m_2^2}{2p} \right) t \]
Neutrino Oscillation

Net result: at some later time, $|\nu(t)\rangle \neq |\nu_e\rangle$.

Probability that the original $\nu_e$ is detected as a $\nu_\mu$ at some later time:

$$P(\nu_e \rightarrow \nu_\mu) = |\langle \nu_\mu | \nu(t) \rangle|^2 = \sin^2 2\theta \sin^2 \left( \frac{1.27 \Delta m^2 L}{E} \right)$$

$\theta$ = neutrino mixing angle

$\Delta m^2 = m_1^2 - m_2^2$ (in eV$^2$)

$L$ = distance $\nu$ has travelled (in km)

$E$ = neutrino energy (in GeV)

Neutrino oscillation:

- requires at least one non-zero neutrino mass
- requires non-zero mixing elements
- results from the QM of the propagation, not from an interaction
Matter Effects On Neutrino Oscillation

Surprisingly the oscillation formula can be dramatically altered in matter!

\[ i \frac{d}{dt} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2}{4E} \cos 2\theta + \sqrt{2}G_FN_e & \frac{\Delta m^2}{4E} \sin 2\theta \\ \frac{\Delta m^2}{4E} \sin 2\theta & -\frac{\Delta m^2}{4E} \cos 2\theta \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} \]

The relevant process is forward scattering, in which no momentum is exchanged. In matter, \( \nu_e \)’s have a different forward scattering amplitude than the other flavours:

\[ e^- e^- e^- e^- \]
\[ \nu_e \nu_e \nu_e \nu_e \]

AT SOLAR NEUTRINO ENERGIES:

| \( \nu_x \) | \( \nu_x \) | \( e^- \) | \( e^- \) |
| \( Z^0 \) | \( W^+ \) | \( e^- \) | \( \nu_e \) |

All neutrino flavors | Only electron neutrinos

This produces a matter-induced potential that is different for \( \nu_e \). Effectively \( \nu_e \)’s have a different “index of refraction” in matter.

The size of the potential is proportional to the electron density \( N_e \).

For solar \( \nu \)'s, matter effects are dominant.
Solar Neutrinos

The Sun is an intense source of MeV neutrinos!

\[ 4p + 2e^- \rightarrow ^4\text{He} + 2\nu_e + 26.731 \text{ MeV} \]

Shape of Spectra Determined By Nuclear Physics.

Solar Models Only Affect Normalization.
The $pp$ Chain

\[ p + p \rightarrow ^2H + e^+ + \nu_e \]  
\[ p + e^- + p \rightarrow ^2H + \nu_e \]  

\[ ^2H + p \rightarrow ^3He + \gamma \]  
\[ ^3He + ^4He \rightarrow ^7Be + \gamma \]  

\[ ^7Be + e^- \rightarrow ^7Li + \nu_e \]  
\[ ^7Li + p \rightarrow ^4He \]  

\[ ^7Be + p \rightarrow ^8B + \gamma \]  
\[ ^8B \rightarrow ^8Be^* + e^+ + \nu_e \]  
\[ ^8Be^* \rightarrow ^4He \]
The $^{37}$Cl experiment started in the 1960’s

Ray Davis and John Bahcall with the tetrachloroethylene tank.

100,000 gallons of cleaning fluid!

$$\nu_e + ^{37}\text{Cl} \rightarrow e^- + ^{37}\text{Ar}$$
A setback ...

Predicted rate: \(7.6^{+1.3}_{-1.1}\) SNU's

Measured rate: \(2.56 \pm 0.23\) SNU's

Most people reacted in two ways ...

- Experiment must be wrong. No one can look for 50 Ar atoms in 600 tons of cleaning fluid and expect to find them all!

- Theory must be wrong. The solar models are too complicated to take seriously. The flux changes with solar temperature by \(T^{25}\). Even a tiny mistake could change fluxes greatly!

Ray Davis checked and rechecked his experiment. John Bahcall refined astrophysical calculations. Both stuck to their guns.

Others began planning new experiments ...
Super-Kamiokande

Detector hall
Access tunnel

Control room

Inner Detector
Outer Detector

Photo multipliers

41m
39m

1,000m

Detector hall
Access tunnel
Neutrino-electron scattering

Elastic scattering of electrons by $\nu$'s

Scattered electron can move faster than light in water (since water has slowed down light).

Get *Cherenkov light*—an electromagnetic sonic boom!

- Light is blue
- Comes out in cone
- More energy $\rightarrow$ more light!
\[ \nu_x + e^- \rightarrow \nu_x + e^- \]

Rate \( \propto \phi(\nu_e) + \frac{1}{6} \phi(\nu_{\mu\tau}) \)

\[ R_{exp} = 0.465 \pm 0.005^{+0.014}_{-0.012} \times SSM \]

(hep-ex/0106064, hep-ex/0206075)
Two Classes of Experiment (so far)

- **Radiochemical**
  - $\nu_e$ interactions convert target nuclei
  - Radioactive products extracted and counted after exposure time

- **Water Cerenkov**
  - Real-time detection of scattered atomic $e^-$’s
  - Mixed CC and NC sensitivity

### Experiment, Detection Reaction, Threshold, Primary Sources

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Detection Reaction</th>
<th>Threshold</th>
<th>Primary Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homestake</td>
<td>$\nu_e + ^{37}\text{Cl} \rightarrow e^- + ^{37}\text{Ar}$</td>
<td>0.8 MeV</td>
<td>$^7\text{Be}, ^8\text{B}$</td>
</tr>
<tr>
<td>Kamiokande</td>
<td>$\nu_e, (\mu, \tau) + e \rightarrow \nu_e, (\mu, \tau) + e$</td>
<td>7.3 MeV</td>
<td>$^8\text{B}$</td>
</tr>
<tr>
<td>SAGE, GALLEX/GNO</td>
<td>$\nu_e + ^{71}\text{Ga} \rightarrow e^+ + ^{71}\text{Ge}$</td>
<td>0.23 MeV</td>
<td>$pp, ^7\text{Be}, ^8\text{B}$</td>
</tr>
<tr>
<td>Super-K</td>
<td>$\nu_e, (\mu, \tau) + e \rightarrow \nu_e, (\mu, \tau) + e$</td>
<td>5 MeV</td>
<td>$^8\text{B}$</td>
</tr>
</tbody>
</table>
The Solar Neutrino Problem

- Standard Solar Model Predictions:

- Measurements:
Sudbury Neutrino Observatory

2092 m to Surface

18 m Diameter Support Structure for 9500 PMTs, 60% coverage

1000 Tonnes D$_2$O

12 m Diameter Acrylic Vessel

1700 Tonnes Inner Shielding H$_2$O

5300 Tonnes Outer Shield H$_2$O

Urylon Liner and Radon Seal
Event Display–Neutrino Event
Solar $\nu$ Interactions in SNO

SNO measures primarily $^8$B neutrinos by three interactions:

**Charged Current:**
\[ \nu_e + d \rightarrow p + p + e^- \]

**Neutral Current:**
\[ \nu_x + d \rightarrow p + n + \nu_x \]

**Elastic Scattering:**
\[ \nu_x + e \rightarrow \nu_x + e^- \]

For the Large Mixing Angle (LMA) solution to solar neutrino problem:

\[ |U_{e2}|^2 \approx \sin^2 \theta_{12} \approx \frac{\phi_{CC}}{\phi_{NC}} \]
Three Phases of the SNO Experiment

D$_2$O Phase
(pure D$_2$O)
Nov 1999 - May 2001

$n + d \rightarrow t + \gamma$
($\sigma = 0.0005 \text{ b}$)

Detect a Compton-scattered electron from a 6.25 MeV $\gamma$

Salt Phase
(D$_2$O + 0.2% NaCl)
July 2001 - Sept 2003

$n + ^{35}\text{Cl} \rightarrow ^{36}\text{Cl} + \gamma$'s
($\sigma = 44 \text{ b}$)

Detect Compton-scattered electrons from multiple $\gamma$'s totalling 8.6 MeV

NCD Phase
(3He counters)
Dec 2004 - Dec 2006

$n + ^3\text{He} \rightarrow p + t$
($\sigma = 5330 \text{ b}$)

Detect 764 keV of ionization from the charged particles in 3He proportional counters

PRL 87, 071301 (2001)
PRL 89, 011301 (2002)
PRL 89, 011302 (2002)
PRD 70, 093014 (2004)

PRL 92, 181301 (2004)
PRL 92, 102004 (2004)
PRC 72, 055502 (2005)
PRD 72, 052010 (2005)
Signal Probability Distributions

Fit the PDFs to the data to determine fluxes. Leave out the energy PDFs to fit for the spectral shapes.
Results for the full 391-day Salt Phase

(a)

(b)

(c)
Evidence for Solar Neutrino Oscillation

Phys Rev C 72, 055502 (2005)

No evidence of spectral distortion.

\[ A_{DN} = 0.037 \pm 0.040 \]

Self-consistent picture of results from Homestake, SAGE/GALLEX/GNO, and Super-K.

SNO: Direct evidence that

\[ \phi(\nu_e) < \phi(\nu_{tot}) \]
Evidence for Reactor Neutrino Oscillations

KamLAND: Observation of reactor neutrino disappearance at $L/E$ value where solar neutrino effect occurs.
Evidence for Reactor Neutrino Oscillations

(PRL 94, 081801, 2005)
Spectral distortion seen in reactor neutrino energy spectrum

Solar data constrains $\theta_{12}$, while reactor data constrains $\Delta m^2$—extreme complementarity!
There are various ideas for precision measurement of $^7$Be and pep neutrinos by low-background scintillator detectors:

- Borexino
- KamLAND
- SNO+
- liquid noble gas detectors

Possible Motivations:

- Observe turn-up in LMA survival probability
- Constrain solar models
- Test exotic scenarios
Atmospheric Neutrinos

Incident proton strikes atmosphere, making pion

$\pi \rightarrow \mu + \nu_\mu$

$\rightarrow e + \nu_\mu + \nu_e$

Two muon neutrinos produced for each electron neutrino!

Super-Kamiokande detector
Super-Kamiokande Event Display
Super-Kamiokande Atmospheric $\nu$ Results

PRD 71, 112005 (2005)

Super-K sees suppression of $\nu_\mu$ flux at large zenith angles (distances).

$\nu_e$ flux is unaffected.

Looks to be $\nu_\mu \rightarrow \nu_\tau$ oscillations

First clear evidence for neutrino oscillations (1998)!
Neutrino Mass Hierarchy

\[ \Delta m^2 \]

\[ \Delta m^2_{\text{solar}} \}

\[ \Delta m^2_{\text{atm}} \approx 2.5 \times 10^{-3} \text{ eV}^2 \]

\[ \Delta m^2_{\text{sol}} \approx 8 \times 10^{-5} \text{ eV}^2 \]
Neutrino Mixing Matrix

Adjust $L/E$ to view oscillations at different $\Delta m^2$'s

$$U = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}$$

Atmospheric $\nu$'s:
$$\theta_{23} \approx \pi/4$$
Maximal mixing! (?)

$$\begin{pmatrix}
c_{13} & 0 & e^{i\delta} s_{13} \\
0 & 1 & 0 \\
-e^{-i\delta} s_{13} & 0 & c_{13}
\end{pmatrix}$$

Short baseline reactor $\nu$'s:
$$\theta_{13} < \pi/20$$
Small, quark-like mixing

$$\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}$$

Solar $\nu$'s:
$$\theta_{12} \approx \pi/6$$
Large, non-maximal mixing

Compare to identical parameterization of CKM matrix ...

$$\theta_{23} \approx \pi/76$$
$$\theta_{13} \approx \pi/870$$
$$\theta_{12} \approx \pi/14$$
Physics of Long Baseline $\nu$ Experiments

Basic idea: shoot a man-made neutrino beam through the Earth, and study neutrino oscillations in controlled way

K2K: KEK to Kamioka
T2K: J-PARC to Kamioka ($\times 50$ stats.)

Far detector: Super-K

<table>
<thead>
<tr>
<th>Measure</th>
<th>Determine</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P(\nu_\mu \rightarrow \nu_\mu)$</td>
<td>$\Delta m_{23}^2, \theta_{23}$</td>
</tr>
<tr>
<td>$P(\nu_\mu \rightarrow \nu_e)$</td>
<td>$\theta_{13}$</td>
</tr>
<tr>
<td>$P(\bar{\nu}<em>\mu \rightarrow \bar{\nu}</em>\mu)$</td>
<td>CPT</td>
</tr>
<tr>
<td>$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$</td>
<td>$\delta_{CP}, \text{sign}(\Delta m_{23}^2)$</td>
</tr>
</tbody>
</table>
K2K: KEK to Kamiokande

250 km baseline, wide-band beam

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$</td>
<td>98.2%</td>
<td>Super-K accident, reconstruction</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>1.3%</td>
<td>The first long baseline $\nu$ experiment</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$</td>
<td>0.5%</td>
<td></td>
</tr>
</tbody>
</table>

Goal: measure $\nu_\mu$ disappearance at atmospheric $\Delta m^2$
Anatomy of a Long Baseline Experiment

12 GeV protons → Al target + horns → Pion Monitor → 200 meter Decay Pipe → Muon Monitor → Near Detectors → SK

- Target: 3cm dia × 66cm long Al cylinder
- Horns: toroidal $B$ fields, pulsed at 250 kA
- 10^{11} \nu /2.2 \text{ sec}
- 10^6 \nu /2.2 \text{ sec}
- Pion monitor: gas Cherenkov detector
- Muon monitor: segmented ionization chamber + array of silicon pad detectors
Magnetic horns focus $\pi$’s, which decay in pipe to produce $\nu_\mu$. 
K2K Beam Statistics

1.1 μsec

120 nsec

\(~ 6 \times 10^{12}\) p.o.t. in 9 bunches

89.1 \times 10^{18} \text{ POT usable data}

Neutrino Energy Spectrum at KEK

On-axis beam
Relatively wide energy spectrum

Accumulated POT (10^{18})

Protons/Pulse (10^{12})
K2K Near Detectors

SCIFI/Water target

Muon Chamber

Scibar

To Super-Kamiokande

Neutrino Beam

1 kt Water Cherenkov Detector
Kiloton Water Cherenkov Detector

1 kton water Cherenkov detector normalizes beam interactions on water target.

Measure $\nu$ spectrum and backgrounds before oscillation

Used to predict event rate at Super-K

8.6 m diameter $\times$ 8.6 m high cylinder

680 Super-K PMTs with electronics—a miniature Super-K
14848 extruded scintillator strips
Read out by 1.5mm diameter WLS fibres
with multi-anode PMTs

Compare measured proton recoil
direction to quasielastic prediction to
identify or reject CCQE events
\((\nu_\mu + n \rightarrow \mu + p)\).
Analysis Flowchart

AT KEK ND:

Observed: # of $\nu$
$E_{\nu}^{rec}$ spectrum

Expectation: # of $\nu$
$E_{\nu}^{rec}$ spectrum

$\Delta m^2, \sin^2 2\Theta$

AT SK:

Observed: # of $\nu$
$p_\mu, \Theta_\mu$ distributions

Derived: $\nu$ xsec ratios
$\Phi(E_\nu)$

Neutrino Interaction MC

Beam MC
Main Interaction Types

Processes modelled with the NEUT Monte Carlo

CC Quasi-Elastic (CCQE)

- Smith & Moniz with $M_A = 1.1$ GeV

CC Resonant Single Pion (CC-1π)

- Rein & Sehgal with $M_A = 1.1$ GeV

CC Multiple Pion (DIS)

- GRV94 + JETSET with Bodek & Yang correction

CC Coherent Pion

- Rein & Sehgal with cross-section rescaling by J. Marteau

NC

+ Nuclear Effects

\[ \frac{\sigma}{E} \left(10^{-38} \text{ cm}^2/\text{GeV}\right) \]
K2K observes a deficit of forward-going $\mu$ relative to MC in all near detectors

- Seen in non-QE events

Two possible explanations:

- Suppression of CC-$1\pi$ at $q^2 < 0.1$ GeV$^2$

- Absence of CC coherent $\pi$ production

Significant nuclear effects (poorly understood).

Data favours coherent pion suppression (PRL 95, 252301 (2005)).

Oscillation analysis is insensitive to how $q^2$ deficit is modelled.
Flux measurement with the kiloton detector

The kiloton near detector, like SK, is a water Cherenkov detector. So cross-section systematics cancel in far-near ratio.

\[ N_{SK}^{exp} = N_{KT}^{obs} \cdot \left[ \frac{\int dE_\nu \Phi_{SK}(E_\nu) \sigma(E_\nu)}{\int dE_\nu \Phi_{KT}(E_\nu) \sigma(E_\nu)} \right] \frac{M_{SK}}{M_{KT}} \cdot \frac{\epsilon_{SK}}{\epsilon_{KT}} \]

[Far-near ratio (from MC) \( \approx 1 \times 10^{-6} \)]

\[ N_{SK}^{obs} = 107 \quad N_{SK}^{exp} = 150.9^{+11.5}_{-10.1} \]

Null oscillation probability: \( P = 0.0025 \ (3.02\sigma) \)

(PRL 94, 081802 (2005))
Reconstructed Neutrino Spectrum at Super-K

Reconstructed energy spectrum from 1-ring $\mu$ events

Kolgomorov-Smirnov test probability (no oscillation): 0.08%
Kolgomorov-Smirnov test probability (best-fit oscillation): 36%
Allowed K2K Mixing Parameters

Consistency with null oscillation hypothesis:

- Normalization only: 0.26%
- Spectrum only: 0.74%
- Spectrum + normalization: 0.005%

Favored mixing parameters:

\[ \Delta m^2 = 2.8 \times 10^{-3} \text{ eV}^2 \]
\[ \sin^2 2\theta = 1 \]

90% CL at \( \sin^2 2\theta = 1 \):

\[ 1.9 - 3.6 \times 10^{-3} \text{ eV}^2 \]

Null oscillation hypothesis rejected at 4.0\( \sigma \) level

(PRL 94, 081802 (2005))
The MINOS Experiment

A beam from Fermilab’s Main Injector to the Soudan mine located 720 km away
Goals of MINOS;

- precise measurement of $\Delta m^2$
- test alternatives of oscillation model (eg. neutrino decay)
Conclusions

- Neutrinos have mass and oscillate. Compelling evidence from four different kinds of experiments
  1. solar neutrinos
  2. reactor neutrinos
  3. atmospheric neutrinos
  4. long baseline neutrino beams

- Neutrino mixing opens a whole new area of lepton flavour physics. *This is new physics beyond the Standard Model, involving new fields and new fundamental constants!*

- Next time:
  1. How many neutrinos are there really?
  2. What are the theoretical implications?
  3. How do we complete our map of the neutrino mixing matrix?
  4. How might we determine the *absolute* mass of neutrinos?
  5. Are neutrinos the reason we’re all here?