Lecture Plan

Lecture #1: Neutrino Mass and Oscillations

Lecture #2: Solar Neutrinos

Lecture #3: Supernova Neutrinos
Lecture #1

- Neutrinos and why they matter
- Neutrino mass and oscillations

- Atmospheric neutrinos
- Long-baseline beam experiments

- Beyond 2-flavor: $\theta_{13}$, CP violation, hierarchy
- Next questions and generation of experiments

- Hunting down anomalies
NEUTRINOS

Quarks

\begin{align*}
&\begin{array}{ccc}
\text{u} & \text{c} & \text{t} \\
\text{d} & \text{s} & \text{b}
\end{array} \\
&\begin{array}{ccc}
\sim 3 & \sim 1200 & 174,000 \text{ MeV/c}^2 \\
\sim 6 & \sim 100 & \sim 4200 \text{ MeV/c}^2 \\
0.511 & 105.6 & 1778 \text{ MeV/c}^2
\end{array}
\end{align*}

Leptons

\begin{align*}
&\begin{array}{ccc}
\text{e} & \text{\mu} & \text{\tau} \\
\text{\nu_e} & \text{\nu_\mu} & \text{\nu_\tau}
\end{array} \\
&\begin{array}{ccc}
\sim 3 & \sim 1200 & 174,000 \text{ MeV/c}^2 \\
\sim 6 & \sim 100 & \sim 4200 \text{ MeV/c}^2 \\
0.511 & 105.6 & 1778 \text{ MeV/c}^2
\end{array}
\end{align*}

- Spin 1/2
- Zero charge
- 3 flavors (families)
- Interact only via weak interaction (& gravity)
- Tiny mass (< 1 eV)

In the Standard Model of particle physics, neutral partners to the charged leptons.
Why do neutrinos matter?

Neutrinos make up a ~few % of dark matter, but are important in understanding of history of structure formation.
And in particular: understanding of neutrino parameters may give insight into the origin of matter-antimatter asymmetry.

\[ \eta = \frac{\eta_b - \eta_{\bar{b}}}{\eta_c} \]  
\[ \approx \frac{\eta_B}{\eta_c} \sim 10^{-10} \]

CP violation is likely involved: a difference in behavior between a particle and its mirror-inverted antiparticle: observed so far in quarks but not leptons.

But knowledge of \( \nu \) properties essential for understanding!
Sources of wild neutrinos

The Big Bang

The Sun

The Atmosphere (cosmic rays)

Super novae

AGN's, GRB's

Radioactive decay in the Earth

meV eV keV MeV GeV TeV PeV EeV

J. Becker, arXiv:0710.1557
Sources of 'tame' neutrinos

- Nuclear reactors
- Proton accelerators
- Artificial radioactive sources
- Beta beams
- Stopped pion sources
- Muon storage rings

Usually (but not always) better understood...
Neutrino Interactions with Matter

Neutrinos are aloof but not completely unsociable

### Charged Current (CC)

\[ \nu_l + N \rightarrow l^\pm + N' \]

Produces lepton with flavor corresponding to neutrino flavor

(must have enough energy to make lepton)

### Neutral Current (NC)

\[ \nu_x + N' \rightarrow \nu_x + N' \]

Flavor-blind
Flavor states related to mass states by a unitary mixing matrix

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau \\
\end{pmatrix}
= 
\begin{pmatrix}
U^*_{e1} & U^*_{e2} & U^*_{e3} \\
U^*_{\mu 1} & U^*_{\mu 2} & U^*_{\mu 3} \\
U^*_{\tau 1} & U^*_{\tau 2} & U^*_{\tau 3} \\
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3 \\
\end{pmatrix}
\]

participate in weak interactions

unitary mixing matrix

eigenstates of free Hamiltonian

If mixing matrix is not diagonal, get flavor oscillations as neutrinos propagate (essentially, interference between mass states)
Simple two-flavor case

\[ |\nu_f\rangle = \cos \theta |\nu_1\rangle + \sin \theta |\nu_2\rangle \]
\[ |\nu_g\rangle = - \sin \theta |\nu_1\rangle + \cos \theta |\nu_2\rangle \]

Propagate a distance \( L \):

\[ |\nu_i(t)\rangle = e^{-iE_i t} |\nu_i(0)\rangle \sim e^{-im_i^2 L/2p} |\nu_i(0)\rangle \]

Probability of detecting flavor \( g \) at \( L \):

\[ P(\nu_f \rightarrow \nu_g) = \sin^2 2\theta \sin^2 \left( \frac{1.27\Delta m^2 L}{E} \right) \]

Parameters of nature to measure: \( \theta, \Delta m^2 = m_1^2 - m_2^2 \)
If flavor oscillations are observed, then there must be at least one non-zero mass state

\[ \Delta m^2 = m_1^2 - m_2^2 \]

*Note: oscillation depends on mass differences, not absolute masses
In 2-flavor approximation:

\[ P(\nu_f \rightarrow \nu_g) = \sin^2 2\theta \sin^2 \left( \frac{1.27 \Delta m^2 L}{E} \right) \]

\[ \Delta m^2, \sin^2 2\theta \]

are the parameters of nature;

L, E depend on the experimental setup
The Experimental Game

- Start with some neutrinos (wild or tame)
- Measure (or calculate) flavor composition and energy spectrum
- Let them propagate
- Measure flavor and energies again

Have the flavors and energies changed? If so, does the change follow

\[ P(\nu_f \rightarrow \nu_g) = \sin^2 2\theta \sin^2 \left( \frac{1.27\Delta m^2 L}{E} \right) \]?

**Disappearance:** \( \nu \)'s oscillate into 'invisible' flavor

- e.g. \( \nu_e \rightarrow \nu_\mu \) at \( \sim \text{MeV} \) energies

**Appearance:** directly see new flavor

- e.g. \( \nu_\mu \rightarrow \nu_\tau \) at \( \sim \text{GeV} \) energies
Neutrino oscillation parameter space

\[ P(\nu_f \rightarrow \nu_g) = \sin^2 2\theta \sin^2 \left( \sqrt{\frac{1.27\Delta m^2 L}{E}} \right) \]

wavelength = \( \pi E/(1.27\Delta m^2) \)

allowed region

change L/E

need experimental statistics
But we have *three* flavors: oscillation probability can be computed straightforwardly

\[ |\nu_f\rangle = \sum_{i=1}^{N} U_{fi}^* |\nu_i\rangle \]

\[ P(\nu_f \rightarrow \nu_g) = \delta_{fg} - 4 \sum_{j>i} \text{Re}(U_{fi}^* U_{gi} U_{fj} U_{gj}^*) \sin^2(1.27 \Delta m^2_{ij} L/E) \]

\[ \pm 2 \sum_{j>i} \text{Im}(U_{fi}^* U_{gi} U_{fj} U_{gj}^*) \sin^2(2.54 \Delta m^2_{ij} L/E) \]

\[ \Delta m^2_{ij} \equiv m^2_i - m^2_j \quad (\text{L in km, E in GeV, m in eV}) \]

oscillatory behavior in L and E

\[ |\Delta m^2_{23}| >> |\Delta m^2_{12}| \rightarrow \text{two frequency scales} \]

For appropriate L/E (and U_{ij}), oscillations “decouple”, and probability can be described the two-flavor expression

\[ P(\nu_f \rightarrow \nu_g) = \sin^2 2\theta \sin^2 \left( \frac{1.27 \Delta m^2 L}{E} \right) \]
We now have strong evidence for flavor oscillations: In each case, first measurement with ‘wild’ $\nu$’s was confirmed and improved with ‘tame’ ones.

\[ P(\nu_f \rightarrow \nu_g) = \sin^2 2\theta \sin^2 \left( \frac{1.27 \Delta m^2 L}{E} \right) \]

**SOLAR NEUTRINOS**
Electron neutrinos from the Sun are *disappearing*...

\[ \nu_e \rightarrow \nu_\mu, \nu_\tau \]
\[ \bar{\nu}_e \rightarrow \nu_x \]

... now confirmed by a reactor experiment

Described by $\theta_{12}, \Delta m^2_{12}$

**ATMOSPHERIC NEUTRINOS**
Muon neutrinos created in cosmic ray showers are *disappearing* on their way through the Earth

\[ \nu_\mu \rightarrow \nu_\tau \]

...now confirmed by beam experiments

Described by $\theta_{23}, \Delta m^2_{23}$
In fifteen years, parameters have been shrunk down many orders of magnitude!

Solar/reactor neutrinos are described by $\theta_{12}$, $\Delta m_{12}^2$.

Atmospheric/beam neutrinos are described by $\theta_{23}$, $\Delta m_{23}^2$.

There is a zoom-in area indicated for further investigation.
Atmospheric Neutrinos

Absolute flux known to ~15%, but *flavor ratio* known to ~5%

By geometry, expect flux with *up-down symmetry* above ~1 GeV (no geomagnetic effects)

E ~ 0.1-100 GeV
L ~ 10-13000 km
Detecting Neutrinos with Cherenkov Light

Charged particles produced in neutrino interactions emit Cherenkov radiation if $\beta > 1/n$

### Thresholds (MeV)

<table>
<thead>
<tr>
<th>Particle</th>
<th>Threshold</th>
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<tr>
<td>$e$</td>
<td>0.73</td>
</tr>
<tr>
<td>$\mu$</td>
<td>150</td>
</tr>
<tr>
<td>$\pi$</td>
<td>200</td>
</tr>
<tr>
<td>$p$</td>
<td>1350</td>
</tr>
</tbody>
</table>

### Angle:

$$\cos \theta_C = \frac{1}{\beta n}$$

$\theta_C = 42^0$ for relativistic particle in water

No. of photons $\propto$ energy loss
Water Cherenkov $\nu$ Detectors

Phosphors
- Photons
- Photoelectrons
- PMT pulses
- Digitize charge, time
- Reconstruct energy, direction, vertex
Super-Kamiokande

Super-Kamiokande is a Water Cherenkov detector in Mozumi, Japan. It is 1 km underground to keep away from cosmic rays.

Outer detector: 1889 outward-looking PMTs

Inner detector: 11,146 inward-looking PMTs

32 kton of ultrapure water
Atmospheric $\nu$'s Experimental Strategy:

High energy interactions of $\nu$'s with nucleons

\[ \nu_e + n \rightarrow e^- + p \]
\[ \bar{\nu}_e + p \rightarrow e^+ + n \]
\[ \nu_\mu + n \rightarrow \mu^- + p \]
\[ \bar{\nu}_\mu + p \rightarrow \mu^+ + n \]

CC quasi-elastic ("single ring")
Get different patterns in Cherenkov light for e and μ (sim. for other detector types)

From Cherenkov cone get angle, infer pathlength
Zenith angle distribution

1489 days of SK data

Deficit of $\nu_\mu$ from below (long pathlength)

Up-going

Down-going

e-like

$\mu$-like
Allowed Parameters

Disappearance consistent with $\nu_\mu \rightarrow \nu_\tau$

$\Delta m^2_{23}, \theta_{23}$

$\Delta \chi^2 (\text{decoherence}) = 4.8\sigma$

$\Delta \chi^2 (\text{decay}) = 5.3\sigma$

Parameters describing disappearance inside this region at 90% C. L.
Next: INDEPENDENT TEST of atmospheric neutrino oscillations using a well-understood $\nu$ beam

$E_\nu \sim \text{GeV, } L \sim 100's \text{ of km for same } L/E$

$$P(\nu_f \rightarrow \nu_g) = \sin^2 2\theta \sin^2 \left( \frac{1.27 \Delta m^2 L}{E} \right)$$

LONG-BASELINE EXPERIMENTS

Compare flux, flavor and energy spectrum at near and far detectors
K2K (KEK to Kamioka) Long-Baseline Experiment

~ 1 GeV muon neutrinos

Expected suppression as a function of energy observed

\[ P(\nu_f \rightarrow \nu_g) = \sin^2 2\theta \sin^2 \left( \frac{1.27 \Delta m^2 L}{E} \right) \]

12 GeV protons on Al target + π focusing horn + decay pipe for pions
MINOS in US making precision measurements of $\nu_\mu$ disappearance

Squeezing down $\Delta m^2_{23}!$
Now entering precision measurement era for two-flavor oscillations.

Described by $\theta_{12}$, $\Delta m^2_{12}$

Atmospheric/reactor neutrinos

Described by $\theta_{23}$, $\Delta m^2_{23}$

Solar/Reactor neutrinos

Tomorrow's story
Beyond 2-flavor: explore neutrino mixing in a 3 flavor context

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau \\
\end{pmatrix}
= 
\begin{pmatrix}
U_{e1}^* & U_{e2}^* & U_{e3}^* \\
U_{\mu 1}^* & U_{\mu 2}^* & U_{\mu 3}^* \\
U_{\tau 1}^* & U_{\tau 2}^* & U_{\tau 3}^* \\
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3 \\
\end{pmatrix}
\]
Three flavor mixing

Parameterize mixing matrix $U$ as

$$ U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} $$

3 masses
$m_1, m_2, m_3$
(2 mass differences + absolute scale)

3 mixing angles
$\theta_{23}, \theta_{12}, \theta_{13}$
$\delta$

1 CP phase
$\alpha_1, \alpha_2$

$|\nu_f\rangle = \sum_{i=1}^{N} U_{fi}^* |\nu_i\rangle$

$|\Delta m_{12}^2|$, $|\Delta m_{23}^2|$, $|\Delta m_{13}^2|$

$|\Delta m_{12}^2|$, $|\Delta m_{23}^2|$

$e^{i\alpha_1/2}$, $0, 0$

$0, e^{i\alpha_2/2}, 0$

$s_{ij} \equiv \sin \theta_{ij}, c_{ij} \equiv \cos \theta_{ij}$

signs of the mass differences matter
After 15 years of oscillation measurements, remaining unknowns in the 3-flavor picture:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric/beam  

Masses

$m_1, m_2, m_3 \leftrightarrow \Delta m^2_{12}, |\Delta m^2_{23}|, \text{sign}(\Delta m^2_{23}), m_i$

Angles

(plus Majorana phases)

$\theta_{12}, \theta_{23}, \theta_{13}, \delta$

maximal?
First, $\theta_{13}$: 'the twist in the middle'

$$|\nu_f\rangle = \sum_{i=1}^{N} U_{fi}^* |\nu_i\rangle$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric  ???  solar
Strategies for determining $\theta_{13}$

**Beams**

Look for appearance of $\sim$GeV $\nu_e$ in $\nu_\mu$ beam on $\sim$300 km distance scale

- K2K, MINOS, T2K, NO$\nu$A

**Reactors**

Look for disappearance of $\sim$few MeV $\bar{\nu}_e$ on $\sim$km distance scale

- CHOOZ, Double Chooz, Daya Bay, RENO

\[
\sin^2 2\theta_{13} = 0.15 \\
\sin^2 \theta_{23} = 0.5 \\
\Delta m^2_{23} = 2.5 \times 10^{-3} \text{ eV}^2
\]
We’re closing in on the answer...

θ_{13} = ...?
The long-baseline beam approach:

$\theta_{13}$ signature: look for small $\nu_e$ appearance in a $\nu_\mu$ beam

\[ P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left( \frac{\Delta m_{23}^2 L}{4E} \right) \]  

for $\Delta m_{23}^2 >> \Delta m_{12}^2$ and $E_\nu \sim L\Delta m_{23}^2$ (in vacuum), $\delta=0$

Hard to measure... known from the CHOOZ reactor experiment that it's a small modulation! Need good statistics, clean sample
Current Long Baseline Beam Projects

Physics goals: precision 2-3 mixing, non-zero $\theta_{13}$ search

**T2K: "Tokai to Kamioka"**

- Pre-existing detector: Super-K
- New beam from J-PARC
- 295 km baseline
- Water Cherenkov detector

**NO$\nu$A at NuMi**

- Pre-existing beam: Fermilab NuMi upgrade
- 810 km baseline
- Scintillator detector
The T2K (Tokai to Kamioka) Experiment

- second-generation long baseline experiment (following K2K, MINOS)
- high-intensity (750 kW) $2.5^\circ$ off-axis $\nu_\mu$ beam from J-PARC 295 km to Super-K, a large water Čerenkov detector
- collaboration of $\sim$500 people, $\sim$60 institutes, 12 countries
Signature of non-zero $\theta_{13}$ at far detector

$\nu_l + N \rightarrow l^\pm + N'$

select charged-current quasi-elastic events (~single ring); vertex, energy, direction from Cherenkov light

Look for electron appearance: single fuzzy rings excess on top of background, with expected spectrum
Excess of $\nu_e$-like events seen in T2K, consistent with non-zero $\theta_{13}$

28 $\nu_e$ candidate e-like rings seen, $4.64 \pm 0.52$ bg expected
T2K allowed region in $\sin^2 2\theta_{13}$ and CP $\delta$

Best fit w/ 68% C.L. error @ $\delta_{\text{CP}}=0$

normal hierarchy

$$\sin^2 2\theta_{13} = 0.150^{+0.039}_{-0.034}$$

inverted hierarchy:

$$\sin^2 2\theta_{13} = 0.182^{+0.046}_{-0.040}$$

Assuming

$|\Delta m^2_{32}|=2.4\times10^{-3}$ eV$^2$

$\sin^2 2\theta_{23}=1.0$
Side note: **MINERνA**

Detector at NuMI (Fermilab) to measure cross-sections of ~GeV neutrinos on nuclear targets (finely-segmented scintillator + em& hadronic calorimeters)

Vital to understand interactions for interpretation of long baseline oscillation experiment backgrounds & systematics!
Measuring $\theta_{13}$ with reactor experiments

$$1 - P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \sim \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{13}^2 L}{4E} \right)$$

Need <1% systematics!

Cancel systematics w/ 2 identical detectors

M. Shaevitz

RENO, South Korea  Double Chooz, France  Daya Bay, China

All taking data in 2011
Results now from all three!

Electron antineutrino deficit and spectral distortion consistent with non-zero $\theta_{13}$

... in fact now in “precision” regime
We now know that $\theta_{13}$ is large!
We need to keep testing the model!
Next on the list to go after experimentally:

mass hierarchy

(sign of $\Delta m^2_{32}$)

\[ \Delta m^2_{ij} \equiv m_i^2 - m_j^2 \]
There are many ways to measure the mass hierarchy

They are all challenging...
Four of the possible ways to get MH

- Long-baseline beams
- Atmospheric neutrinos
- Reactors
- Supernovae
Determining the MH with long-baseline beams

The basic strategy

Compare transition probabilities for

\[ \nu_\mu \rightarrow \nu_e \quad \text{and} \quad \bar{\nu}_\mu \rightarrow \bar{\nu}_e \]

through matter

\[
P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} = s_{23}^2 \sin^2 2\theta_{13} \left( \frac{\Delta_{13}}{\tilde{B}_\mp} \right)^2 \sin^2 \left( \frac{\tilde{B}_\mp L}{2} \right) \\
+ c_{23}^2 \sin^2 2\theta_{12} \left( \frac{\Delta_{12}}{A} \right)^2 \sin^2 \left( \frac{AL}{2} \right) \\
+ \tilde{J} \frac{\Delta_{12}}{A} \frac{\Delta_{13}}{\tilde{B}_\mp} \sin \left( \frac{AL}{2} \right) \sin \left( \frac{\tilde{B}_\mp L}{2} \right) \cos \left( \pm \delta - \frac{\Delta_{13} L}{2} \right)
\]

Change of sign for antineutrinos

\[ \tilde{J} \equiv c_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \]

\[ \theta_{13}, \Delta_{12} L, \Delta_{12}/\Delta_{13} \text{ are small} \]

Different probabilities as a function of L & E for neutrinos and antineutrinos, depending on:

- CP \( \delta \) (more later on that)

- matter density (Earth has electrons, not positrons)


\[ \Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{2E_\nu}, \quad \tilde{B}_\mp \equiv |A \mp \Delta_{13}|, \quad A = \sqrt{2}G_FN_e \]
The baseline matters:

\[ P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \text{ vs. } P(\nu_\mu \rightarrow \nu_e) \]

shown at a particular \( L/E \)
for both choices of \( \text{sign}(\Delta m^2) \)
and for full range of \( \delta_{CP} \)

\[ \Delta m^2_{32} < 0 \]
\[ \Delta m^2_{32} > 0 \]

810 km  1300 km

easier to separate MH from CP effects at long baseline

Ryan Patterson
New U.S. long-baseline experiments

NOνA
14 kt scintillator
700 kW off-axis FNAL beam
810 km baseline
operations start this year
New U.S. long-baseline experiments

**NOνA**
- 14 kt scintillator
- 700 kW off-axis FNAL beam
- 810 km baseline
- Operations start this year

**Long-Baseline Neutrino Experiment**
- 34 kton LArTPC in SD @ 4850 ft
- 1300 km baseline
- New 700 kW beam
New U.S. long-baseline experiments

**NO\text{\textsubscript{\nu}}A**
- 14 kt scintillator
- 700 kW off-axis FNAL beam
- 810 km baseline
- Operations start this year

**Long-Baseline Neutrino Experiment**
- 34 kton LArTPC in SD @ 4850 ft
- 1300 km baseline
- New 700 kW beam

Good combined reach, and improvement with more mass or beam (e.g. Project X at FNAL)

M. Diwan, Venice, Mar 2013
Atmospheric neutrinos: back into the wild

The neutrinos are free, and have a range of baselines & energies, .... but they do what they damn well please

cosmic ray (p)

resonance for neutrinos for NH and for antineutrinos for IH

Need both statistics and ability to reconstruct $\nu$ energy & direction

$$P(\nu_\mu \rightarrow \nu_e)$$
Examples: Hyper-K

- Tochibora mine, near Kamioka; (1500-1750 mwe)
- 560 ktons (25 x SK)
- LOI on arXiv:1109.3262

IceCube DeepCore/PINGU

- enormous detector volume & atmnu statistics
- sparse PMTs, so poor reconstruction
  ➔ PINGU infill for be reconstruction & lower threshold
- arXiv:1306.5846
<table>
<thead>
<tr>
<th>Experiment</th>
<th>Type</th>
<th>Location</th>
<th>Reconstruction</th>
<th>Mass (kt)</th>
<th>Notes</th>
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<td>Super-K</td>
<td>Water Cherenkov</td>
<td>Japan</td>
<td>Good</td>
<td>22.5</td>
<td>Good reconstruction, low stats</td>
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<tr>
<td>Hyper-K</td>
<td>Water Cherenkov</td>
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<td>20-100</td>
<td>Excellent reconstruction</td>
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</table>
The Reactor MH Method

Vacuum oscillation frequencies depend on $\Delta m^2/E_\nu$
Different MH $\Rightarrow$ slightly different frequencies at reactor energies

\[ m_3^2 \quad m_2^2 \quad m_1^2 \]
\[ m_2^2 \quad m_1^2 \]

\[ m_3^2 \]

NH: $|\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}|$
IH: $|\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}|$

Requires:
- good energy resolution (~3%)
- excellent understanding of energy scale (fraction of a percent)
Proposed reactor experiments going after MH

Daya Bay II (China)
- 20 kt detector at 55-60 km
- ~ 40 GW$_{th}$ power
- ~700 m underground
- < 3% resolution @ 1 MeV
- ~0.2% energy calibration

RENO-50 (South Korea)
- 18 kt detector at 47 km
- 16.8 GW power (Yonggwang)
- >500 m underground
- similar detector requirements
Next: CP violation

Compare transition probabilities for

\[ \nu_\mu \rightarrow \nu_e \quad \text{and} \quad \bar{\nu}_\mu \rightarrow \bar{\nu}_e \]

(matter effects understood, or absent)

\[
P_{\nu_e \nu_\mu (\bar{\nu}_e \bar{\nu}_\mu)} = s_{23}^2 \sin^2 2\theta_{13} \left( \frac{\Delta_{13}}{B_\perp} \right)^2 \sin^2 \left( \frac{B_\perp L}{2} \right) \\
+ c_{23}^2 \sin^2 2\theta_{12} \left( \frac{\Delta_{12}}{A} \right)^2 \sin^2 \left( \frac{A L}{2} \right) \\
+ \tilde{J} \frac{\Delta_{12}}{A} \frac{\Delta_{13}}{B_\perp} \sin \left( \frac{A L}{2} \right) \sin \left( \frac{B_\perp L}{2} \right) \cos \left( \pm \delta \right) \quad \frac{\Delta_{13} L}{2} \]

\[ \tilde{J} \equiv c_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \]

\[ \theta_{13}, \Delta_{12} L, \Delta_{12}/\Delta_{13} \quad \text{are small} \]

\[ \Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{2E_\nu}, \quad \tilde{B}_\perp \equiv |A \mp \Delta_{13}|, \quad A = \sqrt{2}G_F N_e \]

A. Cervera et al., Nuclear Physics B 579 (2000)
The Next Generation of CP Searches

LBNE (U.S.)
new FNAL 700 kW beam + eventual PX (1300 km)

Hyper-K (Japan)
upgraded (x50) T2K beam from J-PARC (300 km)

Farther future: new accelerator technologies: cyclotrons (DAEδALUS), neutrino factories,...
A different approach for $\nu$ CPV: DAE$\delta$ALUS

Multiple stopped-pion neutrino sources:

- $L \sim 1.5-20$ km
- $E \sim 10-50$ MeV

\[ \frac{L}{E} \sim \frac{1000 \text{ km}}{3000 \text{ MeV}} \sim \frac{10 \text{ km}}{30 \text{ MeV}} \]

20 km

\[ \bar{\nu}_\mu \rightarrow \bar{\nu}_e \]

Negligible matter effects at short baseline

Requires high PMT coverage

$\text{H}_2\text{O w/ Gd}$

scint? bg needs study

### Summary of “3-flavor” oscillation physics

<table>
<thead>
<tr>
<th>Observable</th>
<th>Signature</th>
<th>Next steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_{13}$</td>
<td>Tiny appearance of $\nu_e$ in a beam of $\nu_\mu$; disappearance of $\overline{\nu}_e$</td>
<td>New beams (T2K, NO$\nu_A$)</td>
</tr>
<tr>
<td>Mass hierarchy sign($\Delta m_{23}^2$)</td>
<td>Matter-induced $\nu/\overline{\nu}$ asymmetry, oscillation distortion</td>
<td>Superbeams, atmospheric, reactors</td>
</tr>
<tr>
<td>CPV phase $\delta$</td>
<td>$\nu/\overline{\nu}$ asymmetry</td>
<td>Superbeams, atmospheric $\nu$, cyclotrons</td>
</tr>
</tbody>
</table>

Will need multiple measurements

*Super nova*
All of this discussion is in the context of the standard 3-flavor picture and testing that paradigm....

There are already some slightly uncomfortable data that don’t fit that paradigm...

Open a parenthesis:
Outstanding ‘anomalies’

**LSND @ LANL (~30 MeV, 30 m)**
- Excess of $\bar{\nu}_e$ interpreted as $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- $\Delta m^2 \approx 1 \text{ eV}^2$: inconsistent with 3 $\nu$ masses

**MiniBooNE @ FNAL (\nu,\bar{\nu} \sim 1 \text{ GeV}, 0.5 \text{ km})**
- Unexplained $>3 \, \sigma$ excess for $E < 475 \, \text{MeV}$ in neutrinos (inconsistent w/ LSND oscillation)
- No excess for $E > 475 \, \text{MeV}$ in neutrinos (inconsistent w/ LSND oscillation)
- Small excess for $E < 475 \, \text{MeV}$ in antineutrinos (~consistent with neutrinos)
- Small excess for $E > 475 \, \text{MeV}$ in antineutrinos (consistent w/ LSND)
- For $E > 200 \, \text{MeV}$, both $\nu$ and $\bar{\nu}$ consistent with LSND

Also: possible deficits of reactor $\bar{\nu}_e$ (‘reactor anomaly’) and source $\nu_e$ (‘gallium anomaly’)

Sterile neutrinos?? (i.e. no normal weak interactions)
- Some theoretical motivations for this, both from particle physics & astrophysics. Or some other new physics??
Ideas to address these anomalies...

Experiments with beams (meson decay in flight and at rest)

Experiments at reactors

Experiments with radioactive sources

Many more! see e.g. arXiv:1204.5379

Parenthesis is not closed...
Possible futures

exciting new world to explore!

anomalies confirmed

fill in the 3-flavor parameters and keep pushing on the paradigm

anomalies go away
What about the absolute neutrino mass scale?

Kinematic experiments for absolute neutrino mass
(oscillation experiments only inform on mass differences)

- Look for distortion of $\beta$-decay spectrum near endpoint

Current best limits: Mainz, Troitsk: $m_\nu < 2.2$ eV
Experimental approaches: aiming for sub-eV sensitivity

**Spectrometers**

A source is not identical to the detector. The endpoint is 18.6 keV for KATRIN, which is expected to have a sensitivity of 0.2 eV.

**Thermal calorimetry**

The endpoint is 2.5 keV for MARE. The new idea is Project-8, which uses a radioactive source (Re) to produce the endpoint (Os).

**New idea: Project-8**

Measure the energy via cyclotron frequency.
Another way of getting at absolute neutrino mass

Fits to cosmological data: CMB, large scale structure, high Z supernovae, weak lensing,...

(model-dependent)

\[ \sum m_i < \sim 0.6 \text{ eV} \]
And some giant questions I will omit...
How do we add the masses to the SM?
Are neutrinos Majorana or Dirac?

**Neutrinoless Double Beta Decay**

\[
\langle M_{\text{eff}} \rangle^2 = \left| \sum_i U_{ei}^2 M_i \right|^2
\]
Lecture #1 Summary

We now have a pretty robust, simple 3-flavor neutrino paradigm, describing most of the data.

Still a few unknown parameters in this picture, notably MH and CP $\delta$, but clear steps to take:

- MH: multiple approaches (all challenging but conceivable)
- CP $\delta$: standard LBL approach is promising

and plenty of long-term ideas....

$\Rightarrow$ need to push on the paradigm w/ precision measurements

Anomalies are still out there... they may or may not go away...