Current status of oscillation physics, part II:

Solar neutrino experiments
Reactor neutrino experiments
Short baseline experiments

What's next for oscillation physics: $\theta_{13}$

Reactor experiments
Long baseline experiments
The Three Signals

**SOLAR NEUTRINOS**

Electron neutrinos from the Sun are *disappearing*

Distance $\sim 10^8$ km, Energy $\sim 0.1$-15 MeV

**ATMOSPHERIC NEUTRINOS**

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

Distance $\sim 10$-13000 km, Energy $\sim 0.1$-100 GeV

**ACCELERATOR NEUTRINOS**

Electron antineutrinos *appearing* in a beam of muon antineutrinos at LSND

Distance $\sim 30$ m, Energy $\sim 30$-50 MeV
Where we ended up last time: atmospheric $\nu$'s

- Super-K has clean, high statistics atmospheric $\nu_\mu$ disappearance signal; good evidence it's $\nu_\mu \rightarrow \nu_\tau$

- K2K confirmed the oscillation hypothesis with disappearance of beam neutrinos

- MINOS now has highest precision $\Delta m^2$ measurement

- Soon: CNGS experiments to explicitly see $\tau$ appearance
Next, zoom in on solar neutrinos
Solar Neutrinos: the Classic Puzzle

Electron flavor neutrinos generated in solar fusion; spectrum is well understood from weak physics
Homestake Chlorine Radiochemical Detector

\[ \nu_e + ^{37}\text{Cl} \rightarrow ^{37}\text{Ar} + e^- \]

600 tons of cleaning fluid

Threshold: 0.81 MeV

Extract atoms of Ar every few months and count decays (35 day half life): ~ 12 per month!
Shortfall: saw about 1/3 of the expected neutrinos

1 SNU = interaction/s/10^{36} atoms
Gallium radiochemical experiments

$$\nu_e + ^{71}\text{Ga} \rightarrow ^{71}\text{Ge} + e^-$$

Threshold: 0.23 MeV, 11 day half-life
Sensitive to \textit{pp} neutrinos
The SAGE Experiment

Based on liquid gallium
50 tons
1990-present

Caucasus mountains, Russia
Gallex/GNO (Gallium Neutrino Observatory) at LNGS, Italy: 1991-2006

Used gallium chloride (30 tons of Ga)
Gallium solar neutrino results

SAGE

GALLEX

Again clear shortfall: about 60% of standard solar model expectation (pp neutrinos)
Water Cherenkov Detectors
Observe elastic scattering of ~MeV solar $\nu$'s

$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$

Kamiokande-II, 1991

Point to Sun!

$E > \sim 7 \text{ MeV}$

40% of expectation
The classic puzzle, end of the 1990's

Experiments:
Cl, Ga, H₂O

have different thresholds

Energy-dependent suppression

No known solar model could explain:

is it $\nu_e \rightarrow \nu_\mu, \nu_\tau$?
The Mikheyev-Smirnov-Wolfenstein (MSW) Effect

a.k.a. "Matter Effects"

Extra forward scattering amplitude modifies the oscillation probability, which depends on:

- vacuum oscillation parameters
- matter density profile
"Classic" allowed parameters for solar neutrino oscillations

\[ \log(\Delta m^2) \]

"Small Mixing Angle"

Matter effects in Sun apply

"Vacuum" (or "Just So")

"Large Mixing Angle"

"Low"
The "Smoking Guns": oscillation signatures

- **Spectral distortion**

- **Day/night effect**: regeneration of $\nu_e$ in Earth due to matter effect enhances $\nu_e$ flux at night for some parameters

- **Seasonal variation**: variation with L for vacuum oscillation (beyond 7% expected from Earth orbit)
Super-K solar neutrino data: suppression observed

Looking for smoking guns...
Recoil energy spectrum

- SK I

Seasonal variation

- No strong effects (besides suppression) observed at Super-K

Day/night asymmetry

- SK-I
- SK-I (binned)
- SK-II

- Flux ($\times 10^6 \text{cm}^2 \text{s}^{-1}$)

- Day
- Night

⇒ constrain parameters
Large mixing favored by SK alone...
But there's another smoking gun...

- **Spectral distortion**
- **Day/night effect**: regeneration of $\nu_e$ in Earth due to matter effect enhances $\nu_e$ flux at night for some parameters
- **Seasonal variation**: variation with L (beyond 7% expected from Earth orbit)

- **Neutral Current Excess**: *direct evidence* for flavor transformation

No strong effects observed at Super-K (constrain parameters)
The Sudbury Neutrino Observatory

Sudbury, Canada

1.7 kton $\text{D}_2\text{O}$

$\nu_e + d \rightarrow p + p + e^- \quad \text{CC}$

$\nu_x + d \rightarrow \nu_x + p + n \quad \text{NC}$

1 kton $\text{H}_2\text{O}$

$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^- \quad \text{Elastic scattering (CC, NC)}$

Cherenkov light from e$^-$

Neutron detection
SNO's unique feature: NC detection

\[ \nu_x + d \rightarrow \nu_x + p + n \quad \text{NC} \]

Tag NC via detection of neutron

- Phase I: capture on d (D\textsubscript{2}O)
- Phase II: capture on Cl (salt, NaCl)
- Phase III: neutron detectors (NCD)

\[ n + d \rightarrow t + \gamma + 6.25 \quad \text{MeV} \]
\[ n + ^{35}\text{Cl} \rightarrow ^{36}\text{Cl} + \gamma + 8.6 \quad \text{MeV} \]
\[ n + ^{3}\text{He} \rightarrow p + t + 0.76 \quad \text{MeV} \]
Oscillation information from SNO

\[ \nu_e + d \rightarrow p + p + e^- \quad \text{CC specifically tags } \nu_e \text{ component} \]

\[ \phi_{CC} = \phi(\nu_e) \]

\[ \nu_x + d \rightarrow \nu_x + p + n \quad \text{NC flavor-blind } \Rightarrow \text{ measure} \]

\[ \phi_{NC} = \phi(\nu_e) + \phi(\nu_{\mu,\tau}) \sim \text{total flux} \]

\[ \nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^- \quad \text{Elastic scattering (CC, NC)} \]

\[ \phi_{ES} = \phi(\nu_e) + 0.15\phi(\nu_{\mu,\tau}) \]

Also look for distortion of CC spectrum night enhancement
Phase I SNO Results, 2002

Fit data for CC, NC, ES components
Conclusion: $\nu_e$'s are oscillating into active $\nu$'s!

The solar neutrino problem solved!

$\phi_{ES} = \phi(\nu_e) + 0.15 \phi(\nu_{\mu,\tau})$

$\phi_{NC} = \phi(\nu_e) + \phi(\nu_{\mu,\tau}) \sim \text{total flux}$
Phase III with NCDs (Neutral Current Detectors)

\[ n^+ + ^3\text{He} \rightarrow p + t + 0.76 \text{ MeV} \]

SNO turned off at the end of 2006
Latest preliminary SNO results

H. Robertson, Nu2008

NC Flux (corrected to $^8$B spectrum of Winter et al.)
CC spectrum shape not constrained to $^8$B shape.

NC

$\text{D}_2\text{O} - 306 \text{ days}$

$\text{Salt} - 391 \text{ days}$

$\text{NCD} - 385 \text{ days}$

CC

$\text{D}_2\text{O Constrained} - 306 \text{ days}$

$\text{Salt} - 391 \text{ days}$

$\text{NCD} - 385 \text{ days}$

ES

$\text{SuperKÎ-} - 1496 \text{ days}$

$\text{D}_2\text{O Constrained} - 306 \text{ days}$

$\text{Salt} - 391 \text{ days}$

$\text{NCD} - 385 \text{ days}$
Preliminary SNO NCD results

Final analyses underway
Look at LMA parameter space using reactor antineutrinos.

Sum of reactor fluxes from Japan, Korea.

$E_\nu \sim \text{few MeV, } L \sim 180 \text{ km}$

Mozumi, Japan

P. Decowski, Nu2008
Inverse Beta Decay (CC)
\[ \bar{\nu}_e + p \rightarrow e^+ + n \]

Exploit delayed (~180 µs) coincidence of \( n + p \rightarrow d + \gamma \)
as tag against radiactive background

\[ E_{\text{meas}} = E_{\bar{\nu}_e} - 0.8 \text{ MeV} \]

SCINTILLATION DETECTORS

Liquid scintillator \( C_n H_{2n} \) volume surrounded by photomultipliers
- high light output
- very low energy threshold possible
- little directional capability (light is isotropic)
KamLAND: 1 kton scintillator
First KamLAND result (2003): observed suppression of reactor $\bar{\nu}_e$'s selects the LMA region
Latest KamLAND spectrum

- KamLAND data
- no oscillation
- best-fit osci.
- accidental
- $^{13}\text{C}(\alpha,n)^{16}\text{O}$
- best-fit Geo $\bar{\nu}_e$
- best-fit osci. + BG
- + best-fit Geo $\bar{\nu}_e$

P. Decowski, Nu2008
KamLAND L/E Results

Oscillation pattern for a mono-energetic $\bar{\nu}_e$ at one baseline

Best-fit oscillation accounting for energy spectrum and reactor distribution

P. Decowski, Nu2008
Overall fit to the solar neutrino data

KamLAND narrows the $\Delta m^2$ range

Global fit shows that mixing is *not* maximal
Next for KamLAND: 'KamLAND low-bg'

Purify the scintillator to remove radioactive background for sensitivity to solar $\nu$ elastic scattering background.
Borexino
Gran Sasso, Italy

- 300 ton scintillator
- very low radioactivity
- <MeV threshold
New results from Borexino: $^7$Be flux, CNO/pp limits
Borexino data can constrain exotic models
Next for solar neutrinos in large detectors:

- More from Super-K and Borexino
- KamLAND low-bg
- SNO+: SNO acrylic vessel filled with scintillator
  (more tomorrow)
- LENA (Europe),
  HSD (US), ...
Ultra-low energy (sub MeV) real-time solar pp ν detectors

- can be relatively small (~10 tons) thanks to huge pp flux
- real-time energy resolution
- various materials and technologies
- must be ultra-clean to defeat radioactive background
XMASS: liquid xenon

CLEAN/DEAP: liquid neon (argon)

\[ \nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e \]

LENS: indium-loaded scintillator

\[ \nu_e + ^{115}\text{In} \rightarrow e^- + (\tau = 4.76\,\mu\text{s})2\gamma + ^{115}\text{Sn} \]
Summary of solar $\nu$'s

- Clean, high statistics signals in many detectors: entering precision measurement era
- SNO confirms oscillation to active neutrinos with NC signal
- KamLAND reactor neutrino disappearance confirms LMA
- New: Borexino sees Be-7 at low energy

- Coming up: SNO+, KamLAND-lowbg
- Frontier: realtime pp $\nu$'s XMASS, CLEAN, LENS, ...
Now zoom in on LSND parameter space

\[ \bar{\nu}_\mu \rightarrow \bar{\nu}_e \]
The LSND Experiment at Los Alamos

Liquid Scintillator Neutrino Detector

30 m baseline, 167 tons scintillator

ν beam: \( p + \text{target} \rightarrow \pi^+ \)

\( \pi^+ \) decay at rest:
\( \nu_\mu \rightarrow 20-60 \text{ MeV } \overline{\nu}_\mu \)

Look for \( \overline{\nu}_\mu \rightarrow \overline{\nu}_e \) via
\( \nu_e + p \rightarrow e^+ + n \)

\( n + p \rightarrow d + \gamma \)

tag with correlated signals

See excess of 87.9 ± 22.4 ± 6.0 beam \( \overline{\nu}_e \) events

(No longer see 20-200 MeV \( \nu_\mu \rightarrow \nu_e \) for decay in flight \( \pi^+ \))
The KARMEN experiment at RAL

Karlsruhe Rutherford
Medium Energy Neutrino Experiment

17.5 m from $\nu$ source
56 tons of scintillator

ISIS source:
stopped $\pi^+$ source
but pulsed (50 Hz) $\Rightarrow$
use time structure to:

- separate $\nu_\mu$ ($\pi$ decay) from $\nu_e$, $\bar{\nu}_\mu$ (2.2 $\mu$s $\mu$ decay)
- reduce cosmic ray bg

Karmen 2: 1997-2000
Expect: 12.3 $\pm$ 0.6 bg, see 11 candidates

NO OSCILLATION SIGNAL
LSND and KARMEN results

KARMEN rules out some of LSND's allowed region, but not all.
MiniBooNE
Booster Neutrino Experiment at Fermilab

0.8 kton of mineral oil
$E_\nu \sim 1$ GeV from 8 GeV booster
$L \sim 500$ m

Test $\nu_\mu \rightarrow \nu_e$ at same $L/E$ as LSND

$L \uparrow, E \uparrow$: different systematics

e, $\mu$, $\pi^0$ PID with scintillator, Ch. light + spectrum measurement
MiniBooNE Results: April 2007

- Some excess at low energy: currently under study for possible detector effects or backgrounds

- Interpreting as two-flavor oscillation: rules out LSND

- No evidence of energy-dependent excess of $\nu_e$!
Now running with *antineutrinos*
Possible future experiments that may help address the issue:

Experiment at the Spallation Neutron Source:
LSND-like beam with Mini-BooNE-like detector

Micro-BOONE: liquid argon TPC to study cross-sections in appropriate energy range
Summary of LSND parameter space

Gone?
Still weird stuff?

We'll ignore it for now!
What Do We Know About the Mixing Parameters?

Two verified examples of two-flavor mixing

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

Atmospheric/beam

Solar/reactor

2 mixing angles,
2 \( \Delta m^2 \)

Allowed parameters getting squeezed down in next generation of experiments
But there's more than just squeezing down 2-flavor parameters ... 

**Beyond 2-flavor**: explore neutrino mixing in a 3-flavor context
What Do We Know About the Mixing Parameters?

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

Described by
- \(2 \Delta m^2\) ✔ ✔
- 3 mixing angles \((\theta_{23}, \theta_{12}, \theta_{13})\) ✔ ✔
- CP-violating phase \(\delta\)
What do we still *not* know?

Remaining Questions (that can be answered by oscillation experiments)

What is the mass hierarchy?

"Normal" hierarchy

\[ \Delta m^{2}_{23} \quad \text{(atm.)} \]

\[ \Delta m^{2}_{12} \quad \text{(solar)} \]

- 2 \( \Delta m \)
- 3 mixing angles \( (\theta_{23}', \theta_{12}', \theta_{13}') \)
- CP-violating phase

"Inverted" hierarchy

\[ \Delta m^{2}_{12} \]

\[ \Delta m^{2}_{23} \]

or

- maximal?

\[ \checkmark \checkmark \]

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

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

MNS mixing matrix

\[
U = \begin{pmatrix}
1 & 0 & 0 \\
0 & C_{23} & S_{23} \\
0 & -S_{23} & C_{23}
\end{pmatrix}
\begin{pmatrix}
C_{13} & 0 & S_{13} e^{-i\delta} \\
0 & 1 & 0 \\
-S_{13} e^{i\delta} & 0 & C_{13}
\end{pmatrix}
\begin{pmatrix}
C_{12} & S_{12} & 0 \\
-S_{12} & C_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

atmospheric  ???  solar
Getting at $\theta_{13}$ experimentally: look for disappearance of reactor $\bar{\nu}_e$ (few MeV, $\sim$ km)

$$1 - P(\nu_e \rightarrow \nu_e) \sim \sin^2 2\theta_{13} \sin^2 (\Delta m^2_{13} \frac{L}{4E})$$

Current best limits for $\theta_{13}$ from CHOOZ

$\bar{\nu}_e \rightarrow \nu_x$  
$\Rightarrow$ disappearance amplitude $< 5$-$10\%$

New experiments (Double CHOOZ, Daya Bay) are trying to go further
Can look for signatures of non-zero $\theta_{13}$ in SK atmospheric nus

Expect upgoing multi-GeV $\nu_e$ excess: not seen
Best knowledge so far about $\theta_{13}$:

- It's small angle, giving small modulation!

Excluded by lack of disappearance of reactor antinus

Allowed: consistent with atmospheric nus

It's small angle, giving small modulation!
Next generation of proposed experiments: improved reactor disappearance search

\[1-P(\nu_e \rightarrow \nu_e) \sim \sin^2 2\theta_{13} \sin^2 (\Delta m^2_{13} L/4E)\]

Need <1% systematics!

Cancel systematics w/ 2 detectors
New reactor experiments

Double CHOOZ, France

Daya Bay, China

RENO, South Korea
Double Chooz (France)

\[ P(v_e \rightarrow v_e) = 1 - \sin^2(2\theta_{13})\sin^2(\Delta m^2_{31}L/4E) \]

\[ P_{v_e \rightarrow v_e} \]

\[ \begin{align*}
  &10^1 &10^2 &10^3 &10^4 \\
  L [m] &\left(\langle E_{v}\rangle = 3 \text{ MeV}\right) \\
  \end{align*} \]

Near detector
Far detector

10^{21} v_e/s

Chooz Nuclear Power Station
2 cores of 4.27 GW_{th} each

Near detector
400 m

Far detector
1050 m

T. Lasserre, Nu2008
$10 \text{ m}^3 \text{ of Gd}-\text{loaded scintillator}$

$n + \text{Gd} \rightarrow \text{Gd}^* \\
\rightarrow \text{Gd} + \gamma \\
\sum E_{\gamma} \sim 8 \text{ MeV}$
Double Chooz sensitivity to $\theta_{13}$

$\Delta m^2_{\text{atm}} = 2.5 \times 10^{-3} \text{eV}^2$ (20% uncertainty)

Excluded by CHOOZ

Far detector, Both detectors (1km) alone, 1 km & 400 m

start mid-2009

T. Lasserre, Nu2008
Daya Bay, China

C. White, Nu2008

Daya Bay: Experimental Setup

Far site
Overburden: 355 m

Empty detectors: moved to underground halls via access tunnel.
Filled detectors: transported between halls via horizontal tunnels.

Ling Ao Near
Overburden: 112 m

Ling Ao II
cores

Construction
tunnel

Liquid
Scintillator
hall

Water
hall

465 m

810 m

295 m

Entrance

Daya Bay Near
Overburden: 98 m

Daya Bay
cores

Ling Ao
cores

Cont.
Daya Bay detectors (8 total)
Daya Bay sensitivity to $\theta_{13}$

Start mid-2010
One more: RENO in Korea

S. B. Kim
RENO sensitivity to $\theta_{13}$

New!! (full analysis)

90% CL

95% CL

Start ~2010
Another experimental approach:

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

\[
\nu_\mu \rightarrow \nu_{\mu,\tau} \rightarrow \nu_e
\]

For $\Delta m_{23}^2 >> \Delta m_{12}^2$ and $E_\nu \sim L \Delta m_{23}^2$ (in vacuum):

\[
P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 (\Delta m^2_{23} L/4E)
\]

small modulation $\sim 1/2$

*Hard* to measure... it's a *small* modulation!

Need good statistics, clean sample
Future Long Baseline Beam Projects 

Aim for: ~1% on 2-3 mixing, factor of ~10-20 for $\theta_{13}$ mixing

**T2K: "Tokai to Kamioka"**

Existing detector: Super-K
295 km, <1 GeV 0.75 MW beam
(30 times K2K)

Water Cherenkov detector

**NOvA at NuMi**

Existing beam: NuMi
810 km, few GeV beam
Scintillator detector

Detectors will be a few degrees off beam axis
Why are the detectors a few degrees off of the beam axis?

2-body pion decay kinematics

Off-axis, neutrino energy becomes relatively independent of $\pi$ energy
Off-Axis Neutrino Beams

Although you get some reduction in flux, get more sharply peaked neutrino energies

Good for background reduction and oscillation fits
T2K: "Tokai to Kamioka"

- Super-K III at 295 km
- J-PARC 50 GeV PS
- <1 GeV 0.75 MW \( \nu \) beam
- 2.5 deg. off axis
- will turn on 2009
Expect $\sim 1600 \nu_\mu$ events/year at SK

**Electron appearance signal in SK**

**Backgrounds**

**Intrinsic beam $\nu_e$ contamination**

**NC single pions**

$\pi^0 \rightarrow \gamma \gamma$

- asymmetric decay
- both $\gamma$ boosted forward
- one $\gamma$ near wall

$\nu_\mu$ mis-id
T2K Near Detectors

Off-axis detector complex at 280 m to characterize flux for understanding of backgrounds at Super-K
T2K sensitivity to $\theta_{13}$

$I. \text{Kato, Nu2008}$
On the US side:

NOvA

- 15 kt scintillator
- Includes NuMI upgrade from 400 to 700 kW
- 810 km baseline
Liquid scintillator in long cells + optical fiber + avalanche photodiode
NOvA sensitivity to $\theta_{13}$
### Summary of "beyond-2-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 $\nu_\mu$</td>
<td>Next generation beams (T2K, NO$\nu$A)</td>
</tr>
<tr>
<td></td>
<td>Disappearance of $\bar{\nu}_e$</td>
<td>Reactors</td>
</tr>
</tbody>
</table>

Next: what will be needed to go after mass hierarchy, CP violation
Finish the oscillation story: CP violation
mass hierarchy
farther future projects
supernova neutrinos

Kinematic neutrino mass searches
Neutrinoless double beta decay
Miscellaneous topics, as time permits