Outline

• Introduction to neutrinos and oscillations
• Reactor antineutrino experiments
• KamLAND
• $\theta_{13}$ experiments
• Future outlook

Thanks to: K. Heeger, W. Wang, X. Qian
Super-Kamiokande (1998)

First evidence for neutrino oscillations!
Progress Since 2000

- Sudbury Neutrino Observatory (SNO)
  → flavor change responsible for solar $\nu_e$ deficit
- KamLAND
  → observes oscillation pattern, $\delta m_{12}^2$
- K2K & MINOS
  → precise determination of $\delta m_{23}^2, \theta_{23}$
- Daya Bay (2012)
  → discovery of $\theta_{13}$
• $\bar{\nu}_e$ from n-rich fission products
• detection via inverse beta decay ($\bar{\nu}_e + p \rightarrow e^+ + n$)
• Measure flux and energy spectrum
The Reactor Neutrino Flux and Spectrum

- $^{235}\text{U}$, $^{239}\text{Pu}$, $^{241}\text{Pu}$ from $\beta$ measurements
- $^{238}\text{U}$ calculated
- Time dependence due to fuel cycle

Reactor Isotopes

- $\sim 200$ MeV per fission
- $\sim 6\ \nu_e$ per fission
- $\sim 2 \times 10^{20}\ \nu_e/GW_{th}\text{-sec}$
Detection Signal

\[ \bar{\nu} + p \rightarrow n + e^+ \]

Coincidence signal:

- **Prompt**: \( e^+ \) annihilation \( \rightarrow E_\nu = E_{\text{prompt}} + E_n + 0.8 \text{ MeV} \)
- **Delayed**: \( n+p \) 180 \( \mu s \) capture time, 2.2 MeV
  \( n+Gd \) 30 \( \mu s \) capture time, 8 MeV
The $\bar{\nu}_e$ energy spectrum

Neutrinos with $E<1.8$ MeV are not detected

$\nu_e + p \rightarrow n + e^+$ cross section ($\sim 10^{-42}$ cm$^2$)

Calculated reactor $\bar{\nu}_e$ spectrum
Figure 5: Positron spectrum measured at 45.9 m from the core of the Gösgen reactor [36]. Data points are obtained after background subtraction, errors are statistical only. The solid curve is a fit to the data assuming no oscillations. The dashed curve is derived independently by $\beta$-spectroscopy.
New Reactor Flux Analysis (2011)

$0.937 \pm 0.027$

arXiv:1101.2755
KamLAND used the entire Japanese nuclear power industry as a long-baseline neutrino source.
Energy Spectrum
KamLAND Result (2008)

Best combined fit values:

$\Delta m^2 = 7.59^{+0.21}_{-0.21} \times 10^{-5}$ eV$^2$

$\tan^2 \theta = 0.47^{+0.06}_{-0.05}$
Pontecorvo Maki – Nakagawa – Sakata Matrix

\[
U_{PMNS} = \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix} = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix} \begin{pmatrix}
c_{13} & 0 & s_{13} \cdot e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13} \cdot e^{i\delta} & 0 & c_{13}
\end{pmatrix} \begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

Gateway to CP Violation!

CP violation

SuperK atmospheric

Solar + KamLAND
CHOOZ/Palo Verde limits for $\theta_{13}$

(2001-3)

2008 MINOS result:
$|\Delta m^2_{32}| = 2.43 \pm 0.13 \times 10^{-3} eV^2$

$\sin^22\theta_{13} < 0.15$
(90% CL)
\( \bar{\nu}_e \) Survival Probability
(3 generations)

\[
P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{31}^2 L}{4 E_\nu} \right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left( \frac{\Delta m_{21}^2 L}{4 E_\nu} \right)
\]

- “Clean” measurements of \( \theta, \Delta m^2 \)
- Use 2 detector sites

Subdominant \( \theta_{13} \) Oscillation

Dominant \( \theta_{12} \) Oscillation
New Reactor $\theta_{13}$ Neutrino Experiments

- Chooz, France
- RENO, Korea
- Daya Bay, China
Two identical detectors: 10 tons each.

**Phase 1** (2010-12): Far Detector in existing lab.

**Phase 2** (2013): running with Near detector in new lab.
Systematic Uncertainties

- Detector: 2.1%
- Reactor: 1.8% (mostly Bugey-4)
- Background: 2.94% (mostly $^9$Li)

$\sin^22\theta_{13} = 0.086\pm0.041\text{(stat)}\pm0.030\text{(sys)}$
Daya Bay Collaboration
An International Effort

Asia (20)
IHEP, Beijing Normal Univ., Chengdu Univ. of Sci and Tech, CGNPG, CIAE, Dongguan Polytech, Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Zhongshan Univ., Univ. of Hong Kong, Chinese Univ. of Hong Kong, National Taiwan Univ., National Chiao Tung Univ., National United Univ.

North America (16)

Europe (3)
Charles Univ., Dubna, Kurchatov Inst.

~240 collaborators
Daya Bay - A Powerful Neutrino Source

- Among the top 5 most powerful reactor complexes in the world, producing 17.4 GW$_{th}$ (6 x 2.95 GW$_{th}$)
- All 6 reactors are in commercial operation
- Adjacent to mountains; convenient to construct tunnels and underground labs with sufficient overburden to suppress cosmic rays

Reactors produce $\sim 2 \times 10^{20}$ antineutrinos/sec/GW
Daya Bay Experiment Layout

6 antineutrino detectors in 3 underground experimental halls

<table>
<thead>
<tr>
<th></th>
<th>Overburden</th>
<th>$R_\mu$</th>
<th>$E_\mu$</th>
<th>D1,D2</th>
<th>L1,L2</th>
<th>L3,L4</th>
</tr>
</thead>
<tbody>
<tr>
<td>EH1</td>
<td>280</td>
<td>1.27</td>
<td>57</td>
<td>364</td>
<td>857</td>
<td>1307</td>
</tr>
<tr>
<td>EH2</td>
<td>300</td>
<td>0.95</td>
<td>58</td>
<td>1348</td>
<td>480</td>
<td>528</td>
</tr>
<tr>
<td>EH3</td>
<td>880</td>
<td>0.056</td>
<td>137</td>
<td>1912</td>
<td>1540</td>
<td>1548</td>
</tr>
</tbody>
</table>
Negligible reactor flux uncertainty (<0.02%) from precise survey.

**Detailed Survey:**
- GPS above ground
- Total Station underground
- Final precision: 28mm

**Validation:**
- Three independent calculations
- Cross-check survey
- Consistent with reactor plant and design plans
Antineutrino Detectors

6 ‘functionally identical’ detectors:
Reduce systematic uncertainties

\[ \frac{N_f}{N_n} = \left( \frac{N_{p,f}}{N_{p,n}} \right) \left( \frac{L_n}{L_f} \right)^2 \left( \frac{\epsilon_f}{\epsilon_n} \right) \left[ \frac{P_{\text{sur}}(E, L_f)}{P_{\text{sur}}(E, L_n)} \right] \]

3 nested cylinders:
Inner: 20 tons Gd-doped LS (d=3.1m)
Mid: 20 tons LS (d=4m)
Outer: 40 tons mineral oil buffer (d=5m)

Each detector:
192 8-inch Photomultipliers
Reflectors at top/bottom of cylinder
Provides \((7.5 / \sqrt{E} + 0.9)\)% energy resolution
Muon Tagging System

Dual tagging systems:
2.5 meter thick two-section water shield and RPCs

- Outer layer of water veto (on sides and bottom) is 1m thick, inner layer >1.5m. Water extends 2.5m above ADs
- 288 8" PMTs in each near hall
- 384 8" PMTs in Far Hall
- 4-layer RPC modules above pool
- 54 modules in each near hall
- 81 modules in Far Hall
- Goal efficiency: > 99.5% with uncertainty <0.25%
Detector Filling and Target Mass Measurement

ISO tank on load cells

detector in scintillator hall

coriolis flow meters

Target mass determination error ± 3kg out of 20,000

<0.03% during data taking period

Detectors are filled from same reservoirs “in-pairs” within < 2 weeks.
Antineutrino Detector Installation - Far Hall
Automated Calibration System

3 Automatic calibration units (ACUs) on each detector

3 sources for each z axis on a turntable (position accuracy < 5 mm):
- 10 Hz $^{68}$Ge (0 KE $e^+ = 2 \times 0.511$ MeV γ’s)
- 0.5 Hz $^{241}$Am-$^{13}$C neutron source (3.5 MeV n without γ) + 100 Hz $^{60}$Co gamma source (1.173+1.332 MeV γ)
- LED diffuser ball (500 Hz) for $T_0$ and gain

Three axes: center, edge of target, middle of gamma catcher
Data Period

Two Detector Comparison
- Side-by-side comparison of 2 detectors
- Demonstrated detector systematics better than requirements.
  Daya Bay Collab.

Current Oscillation Analysis
- All 3 halls (6 ADs) operating
- DAQ uptime: >97%
  Daya Bay Collab.
- Antineutrino data: ~89%
Antineutrino (IBD) Selection

Selection of Prompt + Delayed
- Reject Flashers
- Prompt Positron: $0.7 \text{ MeV} < E_p < 12 \text{ MeV}$
- Delayed Neutron: $6.0 \text{ MeV} < E_d < 12 \text{ MeV}$
- Capture time: $1 \mu s < \Delta t < 200 \mu s$
- Muon Veto:
  - Pool Muon: Reject 0.6ms
  - AD Muon (>20 MeV): Reject 1ms
  - AD Shower Muon (>2.5GeV): Reject 1s
- Multiplicity:
  - No other signal > 0.7 MeV
  - in -200 μs to 200 μs of IBD.

Selection driven by uncertainty in relative detector efficiency

$$\frac{N_f}{N_n} = \left( \frac{N_{p,f}}{N_{p,n}} \right) \left( \frac{L_n}{L_f} \right)^2 \left( \frac{\epsilon_f}{\epsilon_n} \right) \frac{P_{\text{sur}}(E, L_f)}{P_{\text{sur}}(E, L_n)}$$

Uncertainty in relative $E_d$ efficiency (0.12%) between detectors is largest systematic.
## Data Set Summary

<table>
<thead>
<tr>
<th></th>
<th>AD1</th>
<th>AD2</th>
<th>AD3</th>
<th>AD4</th>
<th>AD5</th>
<th>AD6</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Antineutrino candidates</strong></td>
<td>28935</td>
<td>28975</td>
<td>22466</td>
<td>3528</td>
<td>3436</td>
<td>3452</td>
</tr>
<tr>
<td>DAQ live time (day)</td>
<td>49.5530</td>
<td>49.4971</td>
<td>48.9473</td>
<td></td>
<td>48.9473</td>
<td></td>
</tr>
<tr>
<td>Veto time (day)</td>
<td>8.7418</td>
<td>8.9109</td>
<td>7.0389</td>
<td>0.8785</td>
<td>0.8800</td>
<td>0.8952</td>
</tr>
<tr>
<td>Efficiency</td>
<td>0.8019</td>
<td>0.7989</td>
<td>0.8363</td>
<td>0.9547</td>
<td>0.9543</td>
<td>0.9538</td>
</tr>
<tr>
<td>Accidentalss (/day)</td>
<td>9.82±0.06</td>
<td>9.88±0.06</td>
<td>7.67±0.05</td>
<td>3.29±0.03</td>
<td>3.33±0.03</td>
<td>3.12±0.03</td>
</tr>
<tr>
<td>Fast neutron (/day)</td>
<td>0.84±0.28</td>
<td>0.84±0.28</td>
<td>0.74±0.44</td>
<td>0.04±0.04</td>
<td>0.04±0.04</td>
<td>0.04±0.04</td>
</tr>
<tr>
<td>$^8\text{He}/^9\text{Li}$ (/day)</td>
<td>3.1±1.6</td>
<td>1.8±1.1</td>
<td></td>
<td>0.16±0.11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Am-C corr. (/day)</td>
<td></td>
<td></td>
<td></td>
<td>0.2±0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{13}\text{C}(\alpha, n)^{16}\text{O}$ (/day)</td>
<td>0.04±0.02</td>
<td>0.04±0.02</td>
<td>0.035±0.02</td>
<td>0.03±0.02</td>
<td>0.03±0.02</td>
<td>0.03±0.02</td>
</tr>
<tr>
<td><strong>Antineutrino rate (/day)</strong></td>
<td>714.17±4.58</td>
<td>717.86±4.60</td>
<td>532.29±3.82</td>
<td>71.78±1.29</td>
<td>69.80±1.28</td>
<td>70.39±1.28</td>
</tr>
</tbody>
</table>
Antineutrino Rate vs. Time

Detected rate strongly correlated with reactor flux expectations.

Predicted Rate: (in figure)
- Assumes no oscillation.
- Normalization is determined by fit to data.
- Absolute normalization is within a few percent of expectations.
Prompt Positron Spectra

Near Halls

EH1

57,910 signal candidates

EH2

22,466 signal candidates

Far Hall

EH3

10,416 signal candidates

High-statistics reactor antineutrino spectra. B/S ratio is 2% (5%) at far (near) sites.
Uncertainty Summary

For near/far oscillation, only uncorrelated uncertainties are used.

Largest systematics are smaller than far site statistics (~1%).

Influence of uncorrelated reactor systematics reduced (~1/20) by far vs. near measurement.

### Detector

<table>
<thead>
<tr>
<th></th>
<th>Efficiency</th>
<th>Correlated</th>
<th>Uncorrelated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target Protons</td>
<td>99.98%</td>
<td>0.47%</td>
<td>0.03%</td>
</tr>
<tr>
<td>Flasher cut</td>
<td>99.98%</td>
<td>0.01%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Delayed energy cut</td>
<td>90.9%</td>
<td>0.6%</td>
<td>0.12%</td>
</tr>
<tr>
<td>Prompt energy cut</td>
<td>99.88%</td>
<td>0.10%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Multiplicity cut</td>
<td>0.02%</td>
<td>&lt;0.01%</td>
<td></td>
</tr>
<tr>
<td>Capture time cut</td>
<td>98.6%</td>
<td>0.12%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Gd capture ratio</td>
<td>83.8%</td>
<td>0.8%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Spill-in</td>
<td>105.0%</td>
<td>1.5%</td>
<td>0.02%</td>
</tr>
<tr>
<td>Livetime</td>
<td>100.0%</td>
<td>0.002%</td>
<td>&lt;0.01%</td>
</tr>
<tr>
<td>Combined</td>
<td>78.8%</td>
<td>1.9%</td>
<td>0.2%</td>
</tr>
</tbody>
</table>

### Reactor

<table>
<thead>
<tr>
<th></th>
<th>Correlated</th>
<th>Uncorrelated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy/fission</td>
<td>0.2%</td>
<td>Power 0.5%</td>
</tr>
<tr>
<td>$\bar{\nu}_e$/fission</td>
<td>3%</td>
<td>Fission fraction 0.6%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spent fuel 0.3%</td>
</tr>
<tr>
<td>Combined</td>
<td>3%</td>
<td>Combined 0.8%</td>
</tr>
</tbody>
</table>
Far vs. Near Comparison

Compare measured rates and spectra

$$R = \frac{\text{Far}_{\text{measured}}}{\text{Far}_{\text{expected}}} = \frac{M_4 + M_5 + M_6}{\sum_{i=4}^{6}(\alpha_i(M_1 + M_2) + \beta_i M_3)}$$

$M_n$ are the measured rates in each detector. Weights $\alpha_i, \beta_i$ are determined from baselines and reactor fluxes.

$$R = 0.940 \pm 0.011 \, (\text{stat}) \pm 0.004 \, (\text{syst})$$

Clear observation of far site deficit.

Spectral distortion consistent with oscillation.*

* Caveat: Spectral systematics not fully studied; $\theta_{13}$ value from shape analysis is not recommended.
Rate Analysis

Estimate $\theta_{13}$ using measured rates in each detector.

Uses standard $\chi^2$ approach.

Far vs. near relative measurement. [Absolute rate is not constrained.]

Consistent results obtained by independent analyses, different reactor flux models.

$$\sin^2 2\theta_{13} = 0.092 \pm 0.016 \text{ (stat)} \pm 0.005 \text{ (syst)}$$

$\sin^2 2\theta_{13} = 0$ excluded at $5.2\sigma$
• Same strategy; Similar detector design; Similar Analysis; Consistent result

\[ \sin^2 2\theta_{13} = 0.113 \pm 0.013 \text{ (stat.)} \pm 0.019 \text{ (syst.)} \]

arXiv:1204.0626v2
Summary of $\theta_{13}$ Measurements

- Solar + KamLAND
- MINOS
- T2K
- Double Chooz
- Daya Bay
- RENO

$\sin^2(2\theta_{13})$
Future
Sensitivity to $\sin^2 2\theta_{13}$
Summary

- Many exciting discoveries in neutrino oscillation physics over the last decade
- We now have determined $\theta_{13}$!
- Future experiments are being planned to study mass hierarchy, CP violation, supernova neutrinos ...

Perhaps the best is yet to come!