Neutrinos: Break the Standard Model

• Standard Model assumes
  – Massless neutrinos
  – Lepton number, \( L \), conserves:
    \[ L = L_e + L_\mu + L_\tau \]

• SNO’s results showed
  – Lepton number is still invariant
    • \( \Delta L = 0 \)
  – Lepton flavour number violated
    • \( \Delta L_\tau \neq 0 \)

• Super-K discovered
  – Neutrino oscillation
    • Neutrinos have mass
Learning More About The Neutrinos

- Neutrino mixing parameters for 3 generations
  - Mixing angles: $\theta_{12} (33.6^\circ \pm 0.8^\circ)$, $\theta_{23} (38^\circ - 52^\circ)$, $\theta_{13} (8.4^\circ \pm 0.1^\circ)$
  - Mass-squared differences: $\Delta m^2_{ij} = m_i^2 - m_j^2$ such that
    $$\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21}$$

- CP-violating phase: $\delta$

- Existence of sterile neutrinos
- Absolute mass of neutrinos
- Nature of neutrinos: Majorana or Dirac fermions

$$\nu = \overline{\nu} \quad \nu \neq \overline{\nu}$$
Neutrino Mixing
Reactor Neutrino Experiments

- Nuclear reactors are intense sources of pure low-energy electron anti-neutrinos
  - $1 \text{ GW}_{\text{el}} \Leftrightarrow 3 \text{ GW}_{\text{th}}$ produces $\sim 6 \times 10^{20} \nu_e / \text{s}$
  - $E_\nu \leq 10 \text{ MeV}$

- Detect $\bar{\nu}_e$ via inverse $\beta$-decay reaction:
  $$\nu_e + p \rightarrow e^+ + n$$

- Look for $\nu_e$ disappearance:
  $$P_{\text{ex}} \approx \sin^2 2\theta_{13} \sin^2 \left( \frac{m_3^2 L}{4E} \right) + \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left( \frac{m_2^2 L}{4E} \right)$$
Current Reactor-based $\theta_{13}$ Experiments

- Use near and far detectors to reduce correlated errors
- Stable Gd-loaded liquid scintillators to detect inverse $\beta$-decay reactions
- Catcher to improve $\gamma$-ray detection
- Water-shielded detectors with redundant cosmic-ray taggers
Mixing Parameters: $\theta_{13}$ and $|\Delta m^2_{32}|$

Daya Bay: $\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$
Ultimate precision: 0.0025

Daya Bay: $\Delta m^2_{32} = (2.47 \pm 0.07) \times 10^{-3}$ eV$^2$ (NH)
$\Delta m^2_{32} = (-2.58 \pm 0.07) \times 10^{-3}$ eV$^2$ (IH)
Ultimate precision: $0.06 \times 10^{-3}$ eV$^2$

Daya Bay and RENO will finish data taking by the end of 2020
**Tackle Mass Hierarchy With Reactors**

- Large $\theta_{13}$ enables determination of mass hierarchy with reactors [Petcov-Piai, PLB533(2002)94]
- Survival probability of $\overline{\nu_e}$ is given by:

$$P(\overline{\nu_e} \rightarrow \overline{\nu_e}) = 1 - \sin^2 2\theta_{13} \left[ \cos^2 2\theta_{12} \sin^2 \left( \frac{m_{31}^2 L}{4E} \right) + \sin^2 2\theta_{12} \sin^2 \left( \frac{m_{32}^2 L}{4E} \right) \right] \cos^4 13 \sin^2 2\theta_{12} \sin^2 \left( \frac{m_{21}^2 L}{4E} \right)$$

- Need high statistics and excellent energy measurement.

[Graph showing normal and inverted hierarchy with $L = 50$ km as an ideal example]
JUNO

- Overburden: 700 m
- Detector: 20 kt LAB-LS

53 km

- Resolve mass hierarchy at 3-4 standard deviations in six years
- < 1% precision in \(\sin^2 2\theta_{12}, \Delta m^2_{21},\) and \(\Delta m^2_{32}\)

Yangjiang NPP (under construction)
- 6 x 2.9 GW

Taishan NPP (under construction)
- 4 x 4.6 GW

Distance to Reactor (m)

N_{obs}/N_{exp}
Pinning Down $\Delta m^2_{21}$

$\Delta m^2_{21}$ measured by KamLAND using reactor $\nu_e$ disagrees with the one determined by solar-neutrino measurements by $\sim 2$ standard deviations.

$$\sin^2 \theta_{12} = 0.316^{+0.034}_{-0.026}$$
$$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18}$$
$$\sin^2 \theta_{12} = 0.310 \pm 0.014$$
$$\Delta m^2_{21} = 4.82^{+1.20}_{-0.60}$$
$$\sin^2 \theta_{12} = 0.310 \pm 0.012$$
$$\Delta m^2_{21} = 7.49^{+0.19}_{-0.17}$$

The unit of $\Delta m^2_{21}$ is $10^{-5}$ eV$^2$

M. Ikeda, Neutrino 2018
Status of JUNO

- Civil construction is ongoing
  - Verticle shaft and 40%-slope tunnel done
  - More than 54 m out of 70 m (H) of the cavern excavated.

- QE of 20” MCP-PMTs achieved >30%

- LAB-based liquid scintillator
  - Attenuation length of purified LAB measured: > 25 m.
  - R&D on reducing radio-activities (goal: $^{238}\text{U}/^{235}\text{Th} < 10^{-15}$ g/g, $^{40}\text{K} < 10^{-16}$ g/g)

- TAO
  - 2.6 t Gd-LS
  - 30 m from a core of Taishan NPP
  - Full coverage with SiPMs at -50 C
  - Energy resolution of ~1.5%/√E
  - Ready by 2020
  - Measure energy spectrum precisely

- 1:12 prototype built for testing filling/circulation/overflow procedure

- Aim for energy resolution: 3%/√E

- Begin data taking in 2021
NOvA and T2K

14-kt liquid-scintillator segmented

300-ton functionally identical Near Detector

Off-axis $\nu_\mu$ beam

- Magnetized multi-purpose near detector
- 2.5° off-axis narrow-band $\nu_\mu$ beam, 0.6 GeV peaked at first oscillation maximum

Matter effect ~10% for T2K and ~30% for NOvA, good for resolving degeneracies
IceCube-DeepCore

A giga-tonne-scale neutrino detector

IceCube Lab

IceCube Array
86 strings, 60 sensors each
5,160 optical sensors

DeepCore
6 strings optimized for low energies

Eiffel Tower
324 meters

bedrock

Each DOM is shown by a white dot
Color indicates arrival time: red first, green last
Colored spheres show sensors have detected light
Size scales with the amount of recorded light

date: November 12, 2010
duration: 3,800 nanoseconds
energy: 71.4 TeV
declination: -0.4°
right ascension: 110°
nickname: Dr. Strangepork
Update on $\theta_{23}$ & $\Delta m^2_{32}$

- **T2K**
  - has reduced uncertainties in the beam-flux and neutrino interaction model
  - error at Super-K site has gone down from $\sim$15% to $\sim$5% with improved analysis

- **NOvA** applied machine learning to improve analysis

- **IceCube-DeepCore** has used a different event selection and analysis to obtain new results, PRD 99(2019)032007

<table>
<thead>
<tr>
<th>NH</th>
<th>$\sin^2\theta_{23}$</th>
<th>$\Delta m^2_{32} \times 10^{-3}$ eV$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2K</td>
<td>$0.532^{+0.030}_{-0.037}$</td>
<td>$2.452^{+0.070}_{-0.071}$</td>
</tr>
<tr>
<td>NOvA</td>
<td>$0.58 \pm 0.03$</td>
<td>$2.51^{+0.12}_{-0.08}$</td>
</tr>
<tr>
<td>IceCube-DeepCore 2019</td>
<td>$0.58^{+0.04}_{-0.13}$</td>
<td>$2.55^{+0.12}_{-0.11}$</td>
</tr>
</tbody>
</table>

All marginally disfavor maximal mixing and Lower Octant for $\theta_{23}$
Mass Ordering and $\delta_{CP}$

**NOvA**
- NOvA prefers NH at 1.8$\sigma$

**T2K**
- ruled out $\delta_{CP} = 0$ or $\pi$ (CP conserves) by $>2\sigma$.
- in favour of NH (89%) vs IH (11%)

**T2K+Super-K**
- best-fit $\delta_{CP} = 4.88_{-1.48}^{+0.81}$ radians
Prospects of NOvA and T2K

- NOvA
  - improve calibration with a test-beam program and better understanding of detector response
  - upgrade to high-power target in 2019, and PIP-II with beam power > 0.9 MW

- T2K
  - upgrade near detector by replacing PI0 and Barrel ECals to TPCs and Super-FGD
  - increase beam power from 0.5 MW to 1.3 MW
  - load Super-K detector with Gd to tag neutrino interactions

- NOvA and T2K
  - will continue to run till 2024
  - by then, may find CP violation and resolve mass hierarchy at 3σ
Future: DUNE and Hyper-K

DUNE
- Active mass: 17 kt × 4
- Liquid–Ar TPCs
- Mass effect of DUNE: ~45%

Hyper-K
- f. v. = 260 kt
- Mass effect of T2HK: ~10%

• Both experiments
  - are multi-purpose
    - accelerator neutrino
    - atmospheric neutrino
    - solar neutrino
    - supernova neutrino
    - nucleon decay
  - plan to start around 2026
State-of-the-art Instrumentation

ProtoDUNE-SP (2018)

New 50cm PMT
- 2 efficiency
- 2 timing resolution
- 2 pressure tolerance

760 ton ProtoDUNE-SP

dE/dx of 1-GeV beam

Hyper-K

Hyper-K PMT

Super-K PMT

A.K. Ichikawa
DUNE and T2HK: Sensitivity in CP Violation

**DUNE**

CP Violation

![DUNE Sensitivity Diagram](image1)

- Normal Ordering
- Sin$^2\theta_{13} = 0.085 \pm 0.003$
- $\theta_{23}$: NuFit 2016 (90% C.L. range)
- Sin$^2\theta_{23} = 0.441 \pm 0.042$

**T2HK**

sin$\delta_{\text{CP}} = 0$ exclusion

![T2HK Sensitivity Diagram](image2)

- Normal mass hierarchy
  - Sin$^2\theta_{13} = 0.1$
  - Sin$^2\theta_{23} = 0.5$

Width of band indicates variation in possible central values of $\theta_{23}$
Sterile Neutrinos
Existence of Light Sterile Neutrinos?

- Experimental hints:

  - LSND/MiniBooNE Anomaly
  - Reactor Antineutrino Anomaly
Addressing Reactor Antineutrino Anomaly

- Very short-baseline reactor neutrino experiments & proposals to look for $\bar{\nu}_e$ disappearance

<table>
<thead>
<tr>
<th>Project</th>
<th>Gd</th>
<th>$^6$Li</th>
<th>Segmented</th>
<th>Move</th>
<th>Det.</th>
<th>Dist. (m)</th>
<th>Power (MW)</th>
<th>Mass (ton)</th>
<th>Depth (m)</th>
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<td>30-2800</td>
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<td>6-12</td>
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<td>1</td>
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<td>~15</td>
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<td>Stéréo</td>
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<td>8.8-11.2</td>
<td>57</td>
<td>1.75</td>
<td>18</td>
</tr>
</tbody>
</table>

M. Pallavicini

- Challenge: beat down background from reactor & cosmic ray
Empty-Handed First Results

- **NEOS**: PRL118(17)121802
- **STEREO**: PRL121(18)161801
- **DANSS**: PLB787(18)56
- **PROSPECT**: PRL121(18)251802
Maltoni at Neutrino 2018: ‘Sterile neutrino models fail to simultaneously account for $\nu_e$-to-$\nu_e$ data, the $\nu_\mu$-to-$\nu_e$ data, and the $\nu_\mu$-to-$\nu_\mu$ data. This conclusion is robust.’
Short-Baseline Neutrino (SBN) Program

- All three detectors are liquid-argon TPCs
  - ICARUS will start data taking towards the end of 2019
  - Build a DUNE-style detector: SBND will see beam in 2020
Sensitivities of the SBN Program

- Appearance and disappearance measurements with the same detectors
- SBN has the potential to cover the entire range of interest

\[ \nu_e \text{ appearance} \]

\[ \nu_\mu \text{ disappearance} \]

\( \Delta m^2 \) vs. \( \sin^2 2\theta_{\mu e} \)

\( \Delta m^2 \) vs. \( \sin^2 2\theta_{\mu \mu} \)

arXiv:1503.01520
Neutrinoless Double Beta Decay
Neutrinoless Double Beta Decay

- Can only happen if
  - neutrinos have mass
  - neutrinos are Majorana particles
- It is a $\Delta L = 2$ process.
- If $0\nu\beta\beta$ decay is observed:
  - it will determine the absolute neutrino mass \textit{scale}.
  - measurements in a number of different isotopes can reveal the underlying interaction dynamics.

The decay rate is given by:

$$W = \frac{2}{\hbar} |M_f(0)|^2 2 (Q_2, Z) \langle m_2 \rangle^2 \mu G_F^4 g^2 Q_5^2 \langle m_2 \rangle^2$$
## Experimental Techniques

<table>
<thead>
<tr>
<th>Source = Detector</th>
<th>Now</th>
<th>Mid-Term</th>
<th>Long-Term</th>
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<tbody>
<tr>
<td>Fluid embedded source</td>
<td>Xe-based TPC</td>
<td>EXO-200</td>
<td>nEXO</td>
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<tr>
<td></td>
<td>NEXT-10</td>
<td>NEXT-100</td>
<td>NEXT-2.0</td>
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<td></td>
<td>Liquid scintillator as a matrix</td>
<td>PandaX-III</td>
<td>PandaX-III 1t</td>
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<td>KamLAND-Zen 800</td>
<td>KamLAND2-Zen</td>
<td>SNO+ phase II</td>
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<tr>
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<td>SNO+ phase I</td>
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<table>
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<tr>
<th>High $\Delta E$ and $\varepsilon$</th>
<th>Crystal embedded source</th>
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<tbody>
<tr>
<td>Germanium diodes</td>
<td>GERDA-II</td>
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<td>LEGEND 200</td>
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<td>MJD</td>
<td>LEGEND 1000</td>
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<td>Bolometers</td>
<td>AMoRE pilot, I</td>
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<tr>
<td></td>
<td>AMoRE II</td>
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<tr>
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<td>CUORE</td>
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<td></td>
<td>CUPID</td>
</tr>
<tr>
<td></td>
<td>CUPID-0, CUPID-Mo</td>
</tr>
</tbody>
</table>
Absolute Neutrino Mass
Comparison of Experiments
Getting To The NH Region

- Need to scale the current experiments by about 1000 times
- Must suppress background at least by \((\text{mass} \times \text{time})^{-1}\)
- Need new approach
Absolute Neutrino Mass

- The energy spectrum of the electron from a beta decay is

\[
\frac{dN}{dE} = F(Z, E) p_e (E + m_e) \sqrt{(E - E_0)^2 - m^2}
\]

- Need extremely high statistics and very good energy resolution
- Current limit: \( m_\nu < 2.3 \text{ eV} \)
KATRIN

• First run in March/April 2019
• With 30 days of data, expect to reach $m_\nu < 1$ eV
Project 8

- Store tritium gas in a magnetic trap
- Decay electrons circle around the field lines at cyclotron frequency
  \[ f = \frac{f_c}{2} = \frac{eB}{2m_e + E_k} \]  with relativistic correction
- Detect cyclotron radiation, hence the energy spectrum.

- T\(_2\) run began on 8 Oct 2018
- Collected 417 events
- Spectrum consistent with expectation
- No background beyond end point
Prospects of Project 8

• Trap 10 m³ at a density of $10^{12}$ cm³ atomic T:

Limited by
• rest gas interactions
• field homogeneity
Summary

• With the discoveries of neutrino oscillation,
  – neutrinos have tiny mass
  – lepton flavour number is violated
  – there is physics beyond the Standard Model
    • how do the neutrinos get their mass?

• To guide theoretical development,
  – determine the nature of the neutrinos
    • Dirac or Majorana fermions?
  – continue to look for sterile neutrinos
  – determine the absolute mass of the neutrinos

• This is a golden era of neutrino physics

• The future of neutrino physics is bright and rewarding
  – need some innovative ideas and technologies to break new ground