Results and Prospectives of Reactor Neutrino Experiments

Liangjian Wen

The 12th particle physics phenomenology workshop (PPP12)
16-19 May, NCTU, Hsinchu, Taiwan
Outline

• Reactor Neutrinos
• Oscillation measurement: $\theta_{13}$ and $\Delta m^2_{ee}$
  – Daya Bay, Double Chooz, RENO
• Sterile Neutrino Search
• Rate and spectrum anomaly
• Future: determining Neutrino Mass Ordering
  – JUNO, RENO-50
• Summary
What we have learned?

Standard Parametrization of the PMNS Matrix

\[
V = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
e^{i\rho} & 0 & 0 \\
0 & e^{i\sigma} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

\( \theta_{23} \sim 45^\circ \)

\( |\Delta m_{32}^2| \sim 2.5 \times 10^{-3} \text{ eV}^2 \)

Atmospheric, LBL accelerator

\( \theta_{13} \sim 9^\circ \)

\( \delta \sim ? \)

Reactor, LBL accelerator

\( \theta_{12} \sim 34^\circ \)

\( |\Delta m_{21}^2| \sim 8 \times 10^{-5} \text{ eV}^2 \)

Solar, KamLAND

0ν2β, LNV?

Quarks vs. Leptons: A big puzzle of fermion flavor mixings

CKM

\[
|U| = \begin{pmatrix}
\text{yellow} & \text{green} & \cdot \\
\text{green} & \text{yellow} & \text{green} \\
\cdot & \cdot & \cdot
\end{pmatrix}
\]

Hierarchy!

PMNS

\[
|V| = \begin{pmatrix}
\text{black} & \text{blue} & \text{yellow} \\
\text{black} & \text{black} & \text{blue} \\
\text{blue} & \text{yellow} & \text{yellow}
\end{pmatrix}
\]

Approximate \( \mu-\tau \) symmetry?
Reactor Neutrinos

- Discovery of neutrino in 1956
- Early search for oscillation 70’s-80’s
- Small $\theta_{13}$ in 1990s
- Limit on neutrino magnetic moment (00’s)
- Observation of reactor $\bar{\nu}_e$ disappearance in 2003
- Discovery of non-zero $\theta_{13}$ in 2012
- Mass hierarchy and precision measurements
- Sterile neutrinos, Magnetic moment, ...
Reactor $\bar{\nu}$ Flux

- Neutrino spectra of fission isotopes, ILL

- Neutrino flux of a commercial reactor with $3 \text{ GW}_{th}$: $\sim 6 \times 10^{20} \nu/s$

- Distinguishing correlated and uncorrelated errors is important
Reactor $\bar{\nu}$ Detection

- $\nu$-e scattering
- Inverse-$\beta$ reaction (IBD)

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$E_{\bar{\nu}} \cong T_{e^+} + T_n + (M_n - M_p) + m_{e^+}$

10-40 keV  1.8 MeV: Threshold

Capture on H

Capture on Gd

0.1% Gd
A little history of $\bar{\nu}_e$ disappearance ...

Precision of early Reactor experiments (3-6%):

- Reactor power: \(\sim 1\%\)
- $\nu$ spectrum: \(\sim 0.3\%\)
- Fission rate: \(\sim 2\%\)
- Target mass: \(\sim 1-2\%\)
- Backgrounds: \(\sim 1-3\%\)
- Efficiency: \(\sim 2-3\%\)

Near-far relative measurement was proposed (Mikaelyan and Sinev, hep-ex/9908047) to reduce the uncertainties from reactor and detector.
Daya Bay, Double Chooz, RENO

Daya Bay

80t
1650 m
17.4 GW_th
40t
365 m
40t
490 m

Double Chooz

8.5 GW_th
1050 m
400 m
8t

RENO

16.8 GW_th
290 m
1380 m
16t

8t

P_sur

Daya Bay

RENO

Double Chooz

L [km]
Daya Bay: Best Site for $\theta_{13}$

- Powerful reactor complex (Top 5)
- Close to mountains $\Rightarrow$ enough shielding
- Luminosity 5-20 times of DC and RENO
- Featured design $\Rightarrow$ side-by-side calibration (2-4 ADs at each site) $\Rightarrow$ actual relative det. error 0.13% /$\sqrt{N}$,
- Discovered an unexpectedly large $\theta_{13}$ in Mar. 2012. $\Rightarrow$ precision measurement afterwards


<table>
<thead>
<tr>
<th>Designs</th>
<th>Luminosity (ton⋅GW)</th>
<th>Detector Systematics</th>
<th>Overburden (near/far, mwe)</th>
<th>Sensitivity (3y, 90% CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daya Bay</td>
<td>1400</td>
<td>0.38%/\sqrt{N}</td>
<td>250 / 860</td>
<td>$\sim$ 0.008</td>
</tr>
<tr>
<td>Double Chooz</td>
<td>70</td>
<td>0.6%</td>
<td>120 / 300</td>
<td>$\sim$ 0.03</td>
</tr>
<tr>
<td>RENO</td>
<td>260</td>
<td>0.5%</td>
<td>120 / 450</td>
<td>$\sim$ 0.02</td>
</tr>
</tbody>
</table>

Huber et al. JHEP 0911:044, 2009
Daya Bay Experiment

Full detectors: Aug, 2012

Dec, 2012

Nov. 2011

Aug. 2011

Ling Ao site
Ling Ao-II NPP
Ling Ao NPP

Daya Bay site
Daya Bay NPP

Entrance

RPCs

Water pool

AD

AD
The Daya Bay Detectors

- Multiple AD modules at each site to check Uncorr. Syst. Err.
  - Far: 4 modules, near: 2 modules
- Multiple muon detectors to reduce veto eff. uncertainties
  - Water Cherenkov: 2 layers
  - RPC: 4 layers at the top + telescopes

Redundancy !!!
Data Periods

6-AD
2012 Summer

8-AD Data Taking

2017/02, EH1-AD1 offline

\[ \theta_{13} \text{ [PRL]} \]

\[ \theta_{13}, \Delta m^2_{ee} \text{ [PRL]} \]

\[ nH \theta_{13} \text{ [PRD(R)]} \]

sterile \( \nu \) [PRL]

reactor [PRL]

\[ \theta_{13}, \Delta m^2_{ee} \text{ [PRL]} \]

\[ nH \theta_{13} \text{ [PRD]} \]

sterile \( \nu \) [PRL, PRL]

reactor [CPC]

wave packet [EPJC*]

\[ \theta_{13} \text{ [CPC]} \]

\[ \theta_{13}, \Delta m^2_{ee} \text{ [PRL]} \]

reactor evolution [PRL*]

*submitted
Energy Calibration

Automated Calibration Units (ACU)

- 40 t MO
- 20 t LS
- 20 t Target

The relative energy scale uncertainty <0.2%

Energy Rec.
- calibration Sources
- spallation neutrons

PMT gain calibration
(dark noise, LED)

Relative Energy Scale
- $^{68}$Ge, $^{60}$Co, $^{241}$Am-$^{13}$C
- Neutrons (IBD, spallation)
- Special sources
- Natural radioactivity
Detector energy response model

- **Non-linear energy response in Liquid scintillator**
  - Quenching (known as Birks’ law) and Cerenkov (particle-, E- dep.)
  - Electronics (E- dep, modeled based on MC and single channel FADC measurement)

- **Energy model**: fit to various gamma lines and $^{12}$B beta-decay spectrum
- **Validated with**
  - $^{208}$Th, $^{212}$Bi, $^{214}$Bi beta-decay spectrum; Michel electron
  - Bench tests of Compton scattering electrons in LS

Experience on DYB energy model is valuable to JUNO (similar LS).
Signal & Backgrounds

- Accidental background
- $^9\text{Li}/^8\text{He}$
- Fast neutrons
- Am-C neutron calib. sources
- $^{13}\text{C}(\alpha,\text{n})^{16}\text{O}$
Side-By-Side Comparison

- Cross check with multiple detectors at the same site
- The relative detection efficiency uncertainty down to 0.13%, verified by comparing the rates of detectors
Precision Oscillation Measurement

\( \chi^2/NDF = 232.6/263 \)

\[ \sin^2 \theta_{13} = [8.41 \pm 0.33] \times 10^{-2} \]

NH: \( \Delta m_{32}^2 = [2.45 \pm 0.08] \times 10^{-3} \text{ eV}^2 \)

IH: \( \Delta m_{32}^2 = [-2.55 \pm 0.08] \times 10^{-3} \text{ eV}^2 \)

- Independent \( \sin^2 \theta_{13} \) meas. from nH
- run until 2020, achieve uncertainty \( \leq 3\% \)
Global Comparison

Most precise measurement
- $\sin^2 2\theta_{13}$ uncertainty: 3.9%
- $|\Delta m^2_{32}|$ uncertainty: 3.4%

Consistent results with reactor and accelerator experiments.
The n-H analysis, where the neutron captures on hydrogen, is statistically and (largely) systematically independent from the nGd one. One of the challenges: large accidental background.

Rate analysis: $\sin^2 2\theta_{13} = 0.071 \pm 0.11$, $\chi^2/\text{ndf} = 6.3/6$
Future Sensitivity

- **Daya Bay:**
  - $\Delta (\sin^2 2\theta_{13}) \sim 0.003 \rightarrow \sim 3\%$
  - $\Delta (\Delta m^2_{ee}) \sim 0.07 \rightarrow \sim 3\%$
- **RENO:** $\sim 5\%$.
- **Double Chooz:** $\sim 10\%$

**Daya Bay:** operation till 2020

**RENO:** “operation funding secured until Feb. 2019”

**Double Chooz:** “secured to Jan. 2018 (may change)”
Reactor Anomaly

- ILL spectra agree with data
- Mueller/Huber spectra higher than data
- Sterile neutrino?

$\Delta m^2 \approx 1 \text{ eV}^2$

G. Mention et al.
Phys. Rev. D83 (2011) 073006
Discrepancies to the Huber+Mueller model indicate:
Over estimated flux and/or underestimated flux uncertainty
Or the existence of a sterile neutrino

Consistent flux measurement with previous short baseline reactor experiments

- Daya Bay measurement of absolute Flux
  - Data/(Huber+Mueller): $0.946 \pm 0.020$
  - Data/(ILL+Vogel): $0.992 \pm 0.021$
Future Reactor Exp. for Sterile Neutrino

- Different technologies: (Gd, Li, B) (seg.)(movable)(2 det.)
- Most have sensitivity $0.02 \sim 0.03 \times \Delta m^2 \sim 1\text{eV}^2 \times 90\% \text{CL}$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Reactor Power/Fuel</th>
<th>Overburden (mwe)</th>
<th>Detection Material</th>
<th>Segmentation</th>
<th>Optical Readout</th>
<th>Particle ID Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>DANSS (Russia)</td>
<td>3000 MW LEU fuel</td>
<td>~50</td>
<td>Inhomogeneous PS &amp; Gd sheets</td>
<td>2D, ~5mm</td>
<td>WLS fibers.</td>
<td>Topology only</td>
</tr>
<tr>
<td>NEOS (South Korea)</td>
<td>2800 MW LEU fuel</td>
<td>~20</td>
<td>Homogeneous Gd-doped LS</td>
<td>none</td>
<td>Direct double ended PMT</td>
<td>recoil PSD only</td>
</tr>
<tr>
<td>nuLat (USA)</td>
<td>40 MW $^{235}$U fuel</td>
<td>few</td>
<td>Homogeneous $^6$Li doped PS</td>
<td>Quasi-3D, 5cm, 3-axis Opt. Latt</td>
<td>Direct PMT</td>
<td>Topology, recoil &amp; capture PSD</td>
</tr>
<tr>
<td>Neutrino4 (Russia)</td>
<td>100 MW $^{235}$U fuel</td>
<td>~10</td>
<td>Homogeneous Gd-doped LS</td>
<td>2D, ~10cm</td>
<td>Direct single ended PMT</td>
<td>Topology only</td>
</tr>
<tr>
<td>PROSPECT (USA)</td>
<td>85 MW $^{235}$U fuel</td>
<td>few</td>
<td>Homogeneous $^6$Li-doped LS</td>
<td>2D, 15cm</td>
<td>Direct double ended PMT</td>
<td>Topology, recoil &amp; capture PSD</td>
</tr>
<tr>
<td>SoLid (UK Fr Bel US)</td>
<td>72 MW $^{235}$U fuel</td>
<td>~10</td>
<td>Inhomogeneous $^6$LiZnS &amp; PS</td>
<td>Quasi-3D, 5cm multiplex</td>
<td>WLS fibers</td>
<td>topology, capture PSD</td>
</tr>
<tr>
<td>Chandler (USA)</td>
<td>72 MW $^{235}$U fuel</td>
<td>~10</td>
<td>Inhomogeneous $^6$LiZnS &amp; PS</td>
<td>Quasi-3D, 5cm, 2-axis Opt. Latt</td>
<td>Direct PMT/ WLS Scint.</td>
<td>topology, capture PSD</td>
</tr>
<tr>
<td>Stereo (France)</td>
<td>57 MW $^{235}$U fuel</td>
<td>~15</td>
<td>Homogeneous Gd-doped LS</td>
<td>1D, 25cm</td>
<td>Direct single ended PMT</td>
<td>recoil PSD</td>
</tr>
</tbody>
</table>

Talk by Nathaniel Bowden @NEUTRINO2016
Search for light sterile neutrinos

- **An unique opportunity for sterile neutrino searches**
  - Sterile neutrino would introduce additional oscillation mode
  - Relative meas. at multiple baselines: EH1 (~350m), EH2 (~500m), EH3 (~1600m)

- **Oscillation analysis**
  - No significant signal observed, consistent with 3-flavor neutrino oscillation.
  - Set most stringent limit at $10^{-3} \text{eV}^2 < \Delta m^2_{41} < 0.1 \text{eV}^2$

![Graph showing data and predicted uncertainty for EH2 and EH3](image.png)

PRL 113, 141802 (2014)
Parameter space allowed by LSND and MiniBooNE is excluded
5 MeV Bump on Reactor Spectrum

- Events are reactor power related & time independent
- Events are IBD-like:
  - Disfavors unexpected backgrounds
- No effect to $\theta_{13}$ if near-far meas.
- Possibly due to forbidden decays
  (PRL112: 2021501; PRL114:012502)

DC, Neutrino 2014

RENO, Neutrino 2014

Jetter, Tau2014
Reactor Antineutrino Spectrum

- Bump local significance $\sim 4.4 \sigma$
- Unfolding the reactor neutrino spectrum

Evolution of reactor neutrino flux and spectrum

Probe the reactor anomaly

Rescaled model (equal deficit in the IBD yields from four fission isotopes)

\[ F_i(t) = \sum_{r=1}^{6} \frac{W_{th,r}(t) \bar{p}_r f_{i,r}(t)}{L_r^2 E_r(t)} \left/ \sum_{r=1}^{6} \frac{W_{th,r}(t) \bar{p}_r}{L_r^2 E_r(t)} \right. \]

\[ \sigma_f(F_{239}) = \bar{\sigma}_f + \frac{d\sigma_f}{dF_{239}}(F_{239} - \bar{F}_{239}) \]

arXiv:1704.01082
Evolution of reactor neutrino flux and spectrum

• Combined fit for major fission isotopes $^{235}\text{U}$ and $^{239}\text{Pu}$
  
• $\sigma_{235}$ is 7.8% lower than Huber-Mueller model (2.7% meas. uncertainty)

• $\sigma_{239}$ is consistent with the prediction (6% meas. uncertainty)

• 2.8$\sigma$ disfavor equal deficit (H-M model & sterile hypothesis)
Exploring $\nu$ mass ordering with Reactors

- Large $\theta_{13}$ open doors to MH
  - Exploit L/E spectrum with reactors
    - Precision energy spectrum measurement
    - Look for interference between solar- and atmospheric- oscillations
      → relative measurement

$P_{ee}(L/E) = 1 - P_{21} - P_{31} - P_{32}$

- $P_{21} = \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2(\Delta_{21})$
- $P_{31} = \cos^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{31})$
- $P_{32} = \sin^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{32})$

Independent on CP phase and $\theta_{23}$ (Acc. & Atm. do)
Energy Resolution is the key

S.T. Petcov et al., PLB533(2002)94
S.Choubey et al., PRD68(2003)113006
J. Learned et al., PRD78, 071302 (2008)
L. Zhan, Y. Wang, J. Cao, L. Wen, PRD78:111103, 2008,
PRD79:073007, 2009
J. Learned et al., arXiv:0810.2580
JUNO and RENO-50

20 kton LS Detector
~53 km from Taishan & Yangjiang reactors
~750 m rock overburden

(arXiv: 1507.05613)

18 kton LS Detector
~47 km from YG reactors
Mt. Guemseong (450 m)
~900 m.w.e. overburden
Determine NMO at JUNO

Detector size: 20kt
Energy resolution: $3\% / \sqrt{E}$
Thermal power: 36 GW
Baseline 58 km

L. Zhan, Y. Wang, J. Cao, L. Wen,

6 years, $3\sigma$
Neutrino Rates

- **Supernova ν**: ~ 5k in 10s for 10kpc
- **Atmospheric ν**: several/day
- **Solar ν**: (10s-1000s)/day
- **Reactor ν**: ~ 60/day
- **Geo-neutrinos**: 1-2/day
- **Cosmic muons**: ~ 250k/day

- **36 GW**, 53 km
- **0.003 Hz/m²**, 215 GeV
- **10% multiple-muon**

**Neutrino Rates**
Sensitivity on NMO

**JUNO** MH sensitivity with 6 years' data:

<table>
<thead>
<tr>
<th>$\sqrt{\Delta \chi^2}$</th>
<th>Relative Meas.</th>
<th>(a) Use absolute $\Delta m_{\mu\mu}^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ideal case</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>(b) Realistic case</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

(a) If accelerator experiments, e.g. NOvA, T2K, can measure $\Delta M_{\mu\mu}^2$ to ~1% level

(b) Take into account multiple reactor cores, uncertainties from energy non-linearity, etc

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**Table:**

| Ideal | Core distr. | DYB & HZ | Shape | B/S (stat.) | B/S (shape) | $|\Delta m_{\mu\mu}^2|$ |
|-------|-------------|----------|-------|-------------|-------------|------------------|
| Size  | 52.5 km     | Real     | Real  | 1%          | 6.3%        | 0.4%             |
| $\Delta \chi^2_{\text{MH}}$ | +16        | -3       | -1    | -1          | -0.6        | -0.1             |

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Y.F Li et al
PRD 88, 013008 (2013)
**Precision Measurement**

| Dominant Exps. | $\Delta m_{21}^2$ | $|\Delta m_{31}^2|$ | $\sin^2 \theta_{12}$ | $\sin^2 \theta_{13}$ | $\sin^2 \theta_{23}$ |
|---------------|-------------------|---------------------|---------------------|---------------------|---------------------|
| MINOS         | 2.6%              | 2.7%                | 4.1%                | 8.6%                | 11%                 |
| SNO           | 0.16%             | 0.24%               | 0.39%               | 0.54%               |                     |
| Daya Bay      |                   |                     |                     |                     |                     |
| SK/T2K        |                   |                     |                     |                     |                     |

**Correlation among parameters**

- $\Delta m_{21}^2$: 0.16% $\rightarrow$ 0.24%
- $\Delta m_{ee}^2$: 0.16% $\rightarrow$ 0.27%
- $\sin^2 \theta_{12}$: 0.39% $\rightarrow$ 0.54%

**E resolution**

**Probing the unitarity of $U_{PMNS}$ to $\sim 1\%$, more precise than CKM matrix elements!**

**Current precision**

- $\sin^2 \theta_{12}$: 0.54% $\rightarrow$ 0.67%
- $\Delta m_{21}^2$: 0.24% $\rightarrow$ 0.59%
- $\Delta m_{ee}^2$: 0.27% $\rightarrow$ 0.44%

Matter Effects

\[ \tilde{H}_{\text{eff}} = \frac{1}{2E} \left[ \tilde{U} \begin{pmatrix} \tilde{m}_1^2 & 0 & 0 \\ 0 & \tilde{m}_2^2 & 0 \\ 0 & 0 & \tilde{m}_3^2 \end{pmatrix} \tilde{U}^\dagger \right] = \frac{1}{2E} \left[ U \begin{pmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_3^2 \end{pmatrix} U^\dagger - \begin{pmatrix} A & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \right] \]

\[ \sin^2 2\tilde{\theta}_{12} \approx \frac{(\alpha^2 - \beta^2) \sin^2 2\theta_{12}}{(\alpha + \beta \cos 2\theta_{12})^2} \approx \sin^2 2\theta_{12} \left( 1 - 2\frac{A}{\Delta_{21}} \cos 2\theta_{12} \right) \]

\[ \frac{A}{\Delta_{21}} \approx 1.05 \times 10^{-2} \times \frac{E}{4 \text{ MeV}} \times \frac{7.5 \times 10^{-5} \text{ eV}^2}{\Delta_{21}} \]

- With six years of running, the \( \Delta \chi^2 \) of mass ordering measurements will reduce from 10.28 (vacuum) to 9.64 (matter).
- The reduction of \( \Delta \chi^2 \) is comparable with other systematic error.
Supernova neutrinos at JUNO

Measure energy spectra & fluxes of almost all types of neutrinos

Typical galactic SN assumptions: 10 kpc galactic distance, $3 \times 10^{53}$ erg, $L_\nu$ the same for all types

<table>
<thead>
<tr>
<th>Channel</th>
<th>Type</th>
<th>Events for different $\langle E_\nu \rangle$ values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{\nu}_e + p \to e^+ + n$</td>
<td>CC</td>
<td>$4.3 \times 10^3$</td>
</tr>
<tr>
<td>$\nu + p \to \nu + p$</td>
<td>NC</td>
<td>$6.0 \times 10^2$</td>
</tr>
<tr>
<td>$\nu + e \to \nu + e$</td>
<td>ES</td>
<td>$3.6 \times 10^2$</td>
</tr>
<tr>
<td>$\nu + ^{12}C \to \nu + ^{12}C^*$</td>
<td>NC</td>
<td>$1.7 \times 10^2$</td>
</tr>
<tr>
<td>$\nu_e + ^{12}C \to e^- + ^{12}N$</td>
<td>CC</td>
<td>$4.7 \times 10^1$</td>
</tr>
<tr>
<td>$\bar{\nu}_e + ^{12}C \to e^+ + ^{12}B$</td>
<td>CC</td>
<td>$6.0 \times 10^1$</td>
</tr>
</tbody>
</table>

Correlated events. Better detection in **LS** than in **Water**


SN researches at JUNO
- NMO sensitivity
- Absolute $v$ mass
- SN direction
- flux/spectra meas. & recon.
- time evolution
- test various SN models
- ...
Supernova neutrinos

• Test average-energy hierarchy of SN $\nu$, and how total energy is partitioned among $\nu$ flavors
• $\nu$ mass: $< 0.83 \pm 0.24$ eV at 95\% CL (*JCAP 05 (2015) 044*)
• Locating the SN: $\sim 9^\circ$
Supernova neutrinos

- Reconstruct the flux & spectra of all flavor neutrinos from the observed $\nu$-$e$, $\nu$-$p$ and IBD interactions, by using the SVD-unfolding technique
- Toy MC including E-resolution, quenching, E-threshold, etc
- Verify the method with different SN models $\rightarrow$ model independent

$H. Li et al, paper to appear soon$
Supernova neutrinos

Probing neutrino mass ordering with SN vs

\[ R = \frac{\int_{E_{\nu,s}}^\infty \frac{dN}{dE} \,_{\text{NC}} \, dE}{\int_{E_{\nu,s}}^\infty \frac{dN}{dE} \,_{\text{IBD}} \, dE} \]

K-C. Lai et al,
JCAP 1607 (2016) no.07, 039
Diffuse Supernova Neutrino Background

- DSNB: Past core-collapse events
  - Cosmic star-formation rate
  - Core-collapse neutrino spectrum
  - Rate of failed SNe

10 Years’ sensitivity
Other Physics Topics

- **JUNO** will have 1-2 $\sigma$ NMO sensitivity with atmospheric neutrinos
  - Measure both lepton and hadron energy
  - Good tracking and energy resolution

- **Geo-$\nu$** measurement at JUNO
  - Huge reactor neutrino backgrounds
  - Need accurate reactor spectra
  - 20 x statistics than previous meas.

KamLAND: $30 \pm 7$ TNU (*PRD 88 (2013) 033001*)
Borexino: $38.8 \pm 12.2$ TNU (*PLB 722 (2013) 295*)

<table>
<thead>
<tr>
<th></th>
<th>Best fit</th>
<th>3 y</th>
<th>5 y</th>
<th>10 y</th>
</tr>
</thead>
<tbody>
<tr>
<td>U+Th fix ratio</td>
<td>0.96</td>
<td>10%</td>
<td>8%</td>
<td>6%</td>
</tr>
<tr>
<td>U (free)</td>
<td>1.03</td>
<td>19%</td>
<td>15%</td>
<td>11%</td>
</tr>
<tr>
<td>Th (free)</td>
<td>0.80</td>
<td>37%</td>
<td>30%</td>
<td>21%</td>
</tr>
</tbody>
</table>

Combined shape fit of geo-$\nu$ and reactor-$\nu$

Others (sterile neutrinos, proton decay, neutrinos from dark matter... etc)
Central detector
Water Cherenkov
Top Tracker
Calibration

Pool Depth: 44m
Pool ID: 43.5m
AS: ID35.4m
SSLS: ID40.1m

Pool Depth: 44m
AS: Acrylic sphere; SSLS: stainless steel latticed shell

Acrylic sphere:
ID: 35.4m
Thickness: 120mm

SSLS:
ID: 40.1m
OD: 41.1m

Water pool
ID: 43.5m
Height: 44m
Water Depth: 43.5m

Electronics
Filling + Overflow

JUNO Detectors

~18000 20” PMT
+~25000 3” PMT

~2000 20” PMT

Acrylic sphere:
(20Kt LS in it)

Electronics
Filling + Overflow

JUNO Detectors
R&D of 20” MCP-PMT

• **Advantages:**
  - Higher QE: transmissive photocathode at top + reflective photocathode at bottom
  - High CE: less shadowing effect
  - Easy for production: less manual operation and steps

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**Project Team**

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**MCP Principle**
MCP-PMT Performance

Quantum Efficiency (%)

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>79#</th>
<th>390</th>
<th>26.32155</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>26.18978</td>
<td></td>
<td></td>
</tr>
<tr>
<td>410</td>
<td>26.058</td>
<td></td>
<td></td>
</tr>
<tr>
<td>420</td>
<td>25.4807</td>
<td></td>
<td></td>
</tr>
<tr>
<td>430</td>
<td>24.47675</td>
<td></td>
<td></td>
</tr>
<tr>
<td>440</td>
<td>23.4516</td>
<td></td>
<td></td>
</tr>
<tr>
<td>450</td>
<td>22.37645</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Dark rate

QE & uniformity

Min: 24.5%; Max: 29%
Average: 26.5%

After pulse

$\chi^2 \text{ / ndf} = 177.5 / 137$
Prob = 0.01133
p0 = 1.771e+004
p1 = 235
p2 = 3.262
p3 = 23.95
p4 = -0.08242
p5 = 226.2
p6 = 296.4
p7 = 19.51
p8 = 41.03

Gain = 9.60e+006

$P/V = 5.010813$
# PMT Purchasing of JUNO

- **15k MCP-PMT (75%) from NNVT**
- **5k Dynode(25%) from Hamamatsu**

### Dec. 16, 2015

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>unit</th>
<th>MCP-PMT (NNVC)</th>
<th>R12860 (Hamamatsu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detection Efficiency (QE<em>CE</em>area)</td>
<td>%</td>
<td>27%, &gt; 24%</td>
<td>27%, &gt; 24%</td>
</tr>
<tr>
<td>P/V of SPE</td>
<td></td>
<td>3.5, &gt; 2.8</td>
<td>3, &gt; 2.5</td>
</tr>
<tr>
<td>TTS on the top point</td>
<td>ns</td>
<td>~12, &lt; 15</td>
<td>2.7, &lt; 3.5</td>
</tr>
<tr>
<td>Rise time/ Fall time</td>
<td>ns</td>
<td>R<del>2, F</del>12</td>
<td>R<del>5,F</del>9</td>
</tr>
<tr>
<td>Anode Dark Count</td>
<td>Hz</td>
<td>20K, &lt; 30K</td>
<td>10K, &lt; 50K</td>
</tr>
<tr>
<td>After Pulse Rate</td>
<td>%</td>
<td>1, &lt;2</td>
<td>10, &lt; 15</td>
</tr>
<tr>
<td>Radioactivity of glass</td>
<td>ppb</td>
<td>238U: 50</td>
<td>238U: 400</td>
</tr>
<tr>
<td></td>
<td></td>
<td>232Th: 50</td>
<td>232Th: 400</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40K: 20</td>
<td>40K: 40</td>
</tr>
</tbody>
</table>

**By Scaling PMT Spec for LS quantity to reach 3σ@ 6year**

**Decision based on risk, price, performance merit for physics**
Latest design of CD

- Acrylic sphere: Inner diameter 35.4m, thickness: 120mm.
- Stainless shell: Inner diameter 40.1m. Divided into 30 longitudes and 23 layers.
- Weight of acrylic sphere: ~600t.
- Weight of shell: ~590 t.
- No. of connecting bars: 590
Acrylic Sphere R&D

Acrylic nodes test:
Upto ~700 kN pulling forces when it breaks

Sphere sheet manufacturing: 3m X 8m X 0.12 m
The problems of shrinkage and shape variation were resolved.

Part of sphere are manufactured to test the techniques
Progress of LS R&D

- Test the overall design of purification system at Daya Bay. Replaced the target LS in one detector.
- Quantify the effectivities of subsystems
  - Optical: > 20m A.L @430nm
  - Radio-purity: < 10^{-15} g/g (U, Th)
- Determine the choice of sub-systems
  - Al₂O₃ column, distillation, gas striping, water extraction

Distillation and steam stripping system.
Full system tested in Daya Bay LS hall.
A new batch of purified LS was produced and filled into DYB-AD1.
LS radioactivity being evaluated with data. Further tests to optimize the LS recipe.
Calibration System

Guide Tube

Optical fiber + optical rotary joint
Manually changeable source

Neutron source
Gamma source
JUNO detector central axis

CLS
GT
JUNO Schedule

Schedule:
• Civil preparation: 2013-2014
• Civil construction: 2014-2018
• Detector component production: 2016-2017
• Detector assembly & installation: 2018-2019
• Filling & data taking: 2020-2021

Future Plan
• Run for 20-30 years
• Likely, double beta decay experiment in 2030
Exploring nature of ν’s mass

- 0νββ is currently the viable and sensitive probe to the Majorana nature of ν

Current Limit

Next generation

$T_{1/2}^{0νββ} \sim 10^{28}$ yr

Observed 0νββ?

Yes

ν is Majorana

Inverted NMO?

Yes (by other exp.)

ν is Dirac (if NOT intro. new physics)

Little hope for next generation 0νββ experiment to determine ν’s Majorana
The JUNO LS detector has good potential for DBD search

- 3%/\sqrt{E} energy resolution
- 35.4 m diameter of LS
- Clean balloon hold \text{enr}Xe gas (>80\% 136Xe) dissolved LS
- LS purity: 10^{-15} g/g (U/Th) \rightarrow 10^{-17} g/g (U/Th)
- Excellent muon track rec. \rightarrow reject cosmogenic isotopes

\textbf{Ultimate 0νββ search at JUNO}

\textbf{Expected Background:
\begin{align*}
1.34/\text{FWHM/ (ton } ^{136}\text{Xe})/\text{yr}
\end{align*}

\textbf{Possibly in 2030}
Summary

• Significant improvement on $\sin^2 \theta_{13}$ precision from the Daya Bay, Double Chooz and RENO experiments. Ultimate precision of $\sin^2 \theta_{13}$ will reach $\sim 3\%$

• Precision measurement of the absolute neutrino flux and spectrum.

• Reactor anomaly may have a definite answer before 2020.

• Future reactor neutrino experiments:
  – Mass hierarchy (3-4 $\sigma$ in 2026)
  – Precision measurement of 3/6 mixing parameters up to $< \sim 1\%$ level $\Rightarrow$ unitarity test of the mixing matrix
  – Sterile neutrinos
  – Rich physics topics with a detector like JUNO
Thanks!
Spectra of Isotopes

- **Ab initio**: Nuclear database, $\Sigma$ fragments, $\Sigma$ chains, $\Sigma$ branches $\rightarrow$ 10% uncertainty (e.g. Vogel et al., PRC24, 1543 (1981)).

- **ILL measured the $\beta$-spectra** $\rightarrow$ convert to neutrino spectra
  - **ILL spectra**: Use spectra of 30 virtual branches, fit amplitude and endpoints
  - **Mueller spectra**: 90% Ab initio, 10% fit $\rightarrow$ rate anomaly
  - **Huber spectra**: fit w/ improved nuclear effects

K. Schreckenbach et al. PLB118, 162 (1985)
A.A. Hahn et al. PLB160, 325 (1985)

Shape verified by Bugey-3 data
Normalization by Bugey-4, 1.6%
Combination Prospectives

• The 3 experiments started to discuss combination
• To the end of 2016 (by J. Zhao)
  – Daya Bay: 0.00307
  – Daya Bay + RENO: 0.00287 \(\rightarrow\) improve by 6.5%
  – Daya Bay + RENO + DC: 0.00282 \(\rightarrow\) improve by 8.2%
• Assumed uncorrelated
  – Reactor, detector, background
  – Cosmogenic bkg correlation \(\rightarrow\) worse
  – Cosmogenic bkg (50% systematic uncer.) reduction \(\rightarrow\) better
Beyond Photo-statistics

\[
\frac{\sigma_E}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + b^2 + \left(\frac{c}{E}\right)^2}
\]

- **Generic form of E resolution**
  - a: stochastic term
  - b: constant term
  - c: noise term

- Data validated Full MC (DYB&DC)
- Noise term dominated by PMT dark noise
- Constant term
  - Residual non-uniformity
  - Flaws in readout electronics
  - Artifacts from resolution plotting
- No JUNO show stopper found in DYB model

Impact to MH sensitivity

Contributions to energy resolution from naked gammas

Naive JUNO projection assuming no position dependence
**Supernova Neutrinos: Elementary Particle Physics**

- **Flavor Conversion:** MSW effects in the SN envelope

**Dighe & Smirnov, hep-ph/9907423**

\[ \begin{align*}
\bar{\nu}_\tau' & \rightarrow v_{3m} \\
\bar{\nu}_\mu' & \rightarrow v_{2m} \\
\bar{\nu}_e & \rightarrow v_{1m}
\end{align*} \]

**NH**

- L - Resonance \((\Delta m^2_{21}, \theta_{12})\)
  - Res. for neutrinos
  - Always adiabatic

**IH**

- H - Resonance \((\Delta m^2_{31}, \theta_{13})\)
  - Res. for neutrinos (NH)
  - Res. for antineutrinos (IH)
**Supernova Neutrinos: Elementary Particle Physics**

### Flavor Conversion: MSW effects in the SN envelope

- **Primary fluxes (+ collective)**
  - $F_e^0$ for $\nu_e$
  - $F_{\bar{e}}^0$ for $\bar{\nu}_e$
  - $F_x^0$ for $\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$

- **Leaving the SN (+ Collective & MSW effects)**
  \[
  F_e = p F_e^0 + (1-p) F_x^0 \\
  F_{\bar{e}} = \bar{p} F_{\bar{e}}^0 + (1-\bar{p}) F_x^0 \\
  \frac{1}{4} \sum F_x = \frac{2 + p + \bar{p}}{4} F_x^0 + \frac{1-p}{4} F_e^0 + \frac{1-\bar{p}}{4} F_{\bar{e}}^0
  \]

### Survival probabilities

<table>
<thead>
<tr>
<th>Case</th>
<th>Mass ordering</th>
<th>$\sin^2(2\theta_{13})$</th>
<th>$p$ (for $\nu_e$)</th>
<th>$\bar{p}$ (for $\bar{\nu}_e$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Normal</td>
<td>$\gtrsim 10^{-3}$</td>
<td>0</td>
<td>$\cos^2(\theta_{12})$</td>
</tr>
<tr>
<td>B</td>
<td>Inverted</td>
<td></td>
<td>$\sin^2(\theta_{12})$</td>
<td>0</td>
</tr>
</tbody>
</table>
Short Baseline Exp. with Gas TPC

- Gas TPC detector at ~20 m from a reactor
  - $\nu$-e scattering
  - High energy precision ($<3%/\sqrt{E}$)
- Major motivation: high precision reactor spectrum to 1%
  - Input for JUNO. Daya Bay energy resolution 8%, JUNO 3%
- Other motivations:
  - The weak mixing angle $\theta_w$
  - Abnormal magnetic moment
  - Sterile neutrino
- Prototyping at IHEP. Prepare LOI in 2017

MUNU exp:
$\mu_\nu < 0.9 \times 10^{-10} \mu_B$
CF$_4$, $T > 700$ keV
PLB 615(2005)153
Instrumental background: PMT Flasher

Common phenomena in the past large neutrino experiments (KamLAND, Super-K, Borexino, SNO), caused by discharge on dynodes or bases. Not easy to efficiently reject at that time → Turn off the problematic PMT

A highly-efficient flasher cut developed for DYB: ~100% eff., 0.01% error
8He/9Li background

8He/9Li dominates the background uncertainty

**Classical method:** time-since-last-muon fit

**Difficulty:** large error when muon rate is high, impossible to estimate the Li9 production yield for muons that have low energy deposition

**Guess:** 8He/9Li production accompanied with neutron → reduce the rate of muon sample

**Result:** successful data-driven test and significantly reduced the error

β-n emitter: muon spallation on Carbon nuclei
Optical Model for large LS detectors

- **What’s the best LS recipe?**
  - Detector size dependent, cannot rely on lab experiment
- Predict the detector non-uniformity
- Understand non-linearity from Cerenkov

Developed a new optical model to address those issues. Key optical parameters:

- Molar attenuation coefficient of each composition
- Quantum yield of each fluor

Diagram showing the process of a photon:
- Absorbed?
  - By solvent?
    - No
    - By primary fluor (PF)?
      - No
      - By wavelength shifter (WLS)?
        - No
        - Re-emission (by PF or WLS)
  - Yes
    - Dead

Data figures and references:
- L.J Wen, Ph.D thesis