Observation of Reactor Antineutrino Disappearance at RENO

Soo-Bong Kim for the RENO Collaboration

KNRC, Seoul National University

(presented at CERN on May 7, 2012)
Outline

- Introduction
- Experimental setup & detector
- Data-taking & data set
- Calibration
- Event selection
- Efficiency & Background
- Reactor antineutrino prediction
- Systematic uncertainties
- Results
- Summary
Neutrino Oscillation

PMNS Neutrino Mixing Angles and CP Violation

Reactor Antineutrino Oscillation

\[
P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{1.27 \Delta m^2_{31} L}{E_{\nu}} \right)
\]
\[ P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left( \frac{\Delta m_{31}^2 L}{4E_\nu} \right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2\left( \frac{\Delta m_{21}^2 L}{4E_\nu} \right) \]

- Clean measurement of $\theta_{13}$ with no matter effects

* Reactor

* Accelerator
  - mass hierarchy + CP violation + matter effects

- Complementarity:

Combining results from accelerator and reactor based experiments could offer the first glimpse of $\delta_{\text{CP}}$. 

Hypothetical result from reactor-based experiment

Hypothetical result from accelerator-based experiment
Efforts for Finding $\theta_{13}$

  \[ \sin^2(2\theta_{13}) < 0.12 \] at 90% C.L.

- T2K: 2.5 $\sigma$ excess (2011)
  \[ 0.03 < \sin^2(2\theta_{13}) < 0.28 \] at 90% C.L. for N.H.
  \[ 0.04 < \sin^2(2\theta_{13}) < 0.34 \] at 90% C.L. for I.H.

- MINOS: 1.7 $\sigma$ excess (2011)
  \[ 0 < \sin^2(2\theta_{13}) < 0.12 \] at 90% C.L. for N.H.
  \[ 0.04 < \sin^2(2\theta_{13}) < 0.19 \] at 90% C.L. for I.H.

- Double Chooz: 1.7 $\sigma$ measurement (2011)
  \[ \sin^2(2\theta_{13}) = 0.086 \pm 0.041\text{(stat.)} \pm 0.030\text{(syst.)} \]

- Daya Bay (Mar. 8. 2012)
  5.2 $\sigma$ observation
  \[ \sin^2(2\theta_{13}) = 0.092 \pm 0.016\text{(stat.)} \pm 0.005\text{(syst.)} \]

- RENO (Apr. 2. 2012)
  4.9 $\sigma$ observation
  \[ \sin^2(2\theta_{13}) = 0.113 \pm 0.013\text{(stat.)} \pm 0.019\text{(syst.)} \]
To be published in PRL

- Submitted on Apr. 2, and resubmitted on Apr. 6 after revision
- Accepted on Apr. 23 for publication
- Expected to appear on May 11  
  (Daya Bay PRL : April 27)

To be included in a new edition of Particle Data this year
RENO Collaboration

(12 institutions and 40 physicists)

- Chonbuk National University
- Chonnam National University
- Chung-Ang University
- Dongshin University
- Gyeongsang National University
- Kyungpook National University
- Pusan National University
- Sejong University
- Seokyeong University
- Seoul National University
- Seoyeong University
- Sungkyunkwan University

- Total cost: $10M
- Start of project: 2006
- The first experiment running with both near & far detectors from Aug. 2011
CHOOZ: $R_{osc} = 1.01 \pm 2.8\% \text{ (stat)} \pm 2.7\% \text{ (syst)}$

$\sin^2(2\theta_{13}) < 0.17 \text{ (90\% C.L.)}$

RENO: statistical error: $2.8\% \rightarrow 0.3\%$

systematic error: $2.7\% \rightarrow <0.5\%$

$\sin^2(2\theta_{13}) > 0.02 \text{ (for 90\% C.L.)}$

$\sin^2(2\theta_{13}) > 0.035 \text{ (for 3\sigma discovery potential)}$

- Larger statistics
  - More powerful reactors (multi-core)
  - Larger detection volume
  - Longer exposure

- Smaller experimental errors
  - Identical multi detectors

- Lower background
  - Improved detector design
  - Increased overburden

$\text{G. Fogli et al. (2009)}$
RENO Experimental Setup

Near Detector

Far Detector

290m

1380m
## Contribution of Reactor to Neutrino Flux at Near & Far Detectors

<table>
<thead>
<tr>
<th>Reactor #</th>
<th>Far ( % )</th>
<th>Near ( % )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13.73</td>
<td>6.78</td>
</tr>
<tr>
<td>2</td>
<td>15.74</td>
<td>14.93</td>
</tr>
<tr>
<td>3</td>
<td>18.09</td>
<td>34.19</td>
</tr>
<tr>
<td>4</td>
<td>18.56</td>
<td>27.01</td>
</tr>
<tr>
<td>5</td>
<td>17.80</td>
<td>11.50</td>
</tr>
<tr>
<td>6</td>
<td>16.08</td>
<td>5.58</td>
</tr>
</tbody>
</table>

- Accurate measurement of baseline distances to a precision of 10 cm using GPS and total station
- Accurate determination of reduction in the reactor neutrino fluxes after a baseline distance, much better than 0.1%
- 354 ID +67 OD 10” PMTs
- Target : 16.5 ton Gd-LS,  \( R=1.4m, H=3.2m \)
- Gamma Catcher : 30 ton LS,  \( R=2.0m, H=4.4m \)
- Buffer : 65 ton mineral oil,  \( R=2.7m, H=5.8m \)
- Veto : 350 ton water,  \( R=4.2m, H=8.8m \)
Summary of Detector Construction

- 2006. 03 : Start of the RENO project
- 2008. 06 ~ 2009. 03 : Civil construction including tunnel excavation
- 2008. 12 ~ 2009. 11 : Detector structure & buffer steel tanks completed
- 2010. 06 : Acrylic containers installed
- 2010. 06 ~ 2010. 12 : PMT test & installation
- 2011. 01 : Detector closing/ Electronics hut & control room built
- 2011. 02 : Installation of DAQ electronics and HV & cabling
- 2011. 03 ~ 06 : Dry run & DAQ debugging
- 2011. 05 ~ 07 : Liquid scintillator production & filling
- 2011. 07 : Detector operation & commissioning
- 2011. 08 : Start data-taking
PMT Mounting (2010. 8~10)
Detector Closing (2011. 1)

Near : Jan. 21, 2011
Far : Jan. 24, 2011
Detection of Reactor Antineutrinos

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

(prompt signal)

\[ \sim 180 \, \mu s \]

\[ + p \rightarrow D + \gamma (2.2 \, \text{MeV}) \]

(delayed signal)

\[ \sim 28 \, \mu s \]

\[ + \text{Gd} \rightarrow \text{Gd} + \gamma's (8 \, \text{MeV}) \]

- Neutrino energy measurement

\[ E_{\bar{\nu}} \equiv T_{e^+} + T_n + (M_n - M_p) + m_{e^+} \]

- Linear Alkyl Benzene (LAB)

\[ C_{n}H_{2n+1}-C_{6}H_{6} \quad (n=10-14) \]

\[ C_{12}H_{25} \]

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

(prompt signal)

\[ 30 \, \mu s \]

\[ \sum E_{\gamma} \sim 8\text{MeV} \]

From Bemporad, Gratta and Vogel

.Observable $\bar{\nu}$ Spectrum

Flux

Cross Section

Arbitrary
**Gd Loaded Liquid Scintillator**

## Recipe of Liquid Scintillator

<table>
<thead>
<tr>
<th>Aromatic Solvent &amp; Flour</th>
<th>WLS</th>
<th>Gd–compound</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAB</td>
<td>PPO + Bis-MSB</td>
<td>0.1% Gd+(TMHA)$_3$ (\text{trimethylhexanoic acid})</td>
</tr>
</tbody>
</table>

* Stable light yield over the time period: \(~250\ \text{pe/MeV}\)*

* Measured cosmic induced neutron’s Gd capture time

**C$_{n}$H$_{2n+1}$-C$_6$H$_5\ (n=10\sim14)$**

**Linear Alkyl Benzene (LAB)**

**Carboxylic acids**

**Gd$_2$O$_3$**

**GdCBX**
Liquid(Gd-LS/LS/MO/Water) Production & Filling (May-July 2011)

Gd Loaded Liquid Scintillator

Gd-LS filling for Target

Water filling for Veto

LS filling for Gamma Catcher
1D/3D Calibration System

- Calibration system to deploy radioactive sources in 1D & 3D directions
- Radioactive sources: $^{137}\text{Cs}, ^{68}\text{Ge}, ^{60}\text{Co}, ^{252}\text{Cf}$
- Laser injectors
Data Acquisition System

- 24 channel PMT input to ADC/TDC
- 0.1pC, 0.52nsec resolution
- ~2500pC/ch large dynamic range
- No dead time (w/o hardware trigger)
- Fast data transfer via Ethernet R/W
Data-Taking & Data Set

- Data taking began on Aug. 1, 2011 with both near and far detectors.
- Data-taking efficiency > 90%.
- Trigger rate at the threshold energy of 0.5~0.6 MeV: 80 Hz
- Data-taking period: 228 days Aug. 11, 2011 ~ Mar. 25, 2012

A candidate for a neutron capture by Gd

Event rate before reduction

Data-taking efficiency

Graph showing data-taking efficiency over time (2/Aug/2011 to 20/Mar/2012) with a peak around 0.973118.
RENO’s Status & Plan

- RENO was the first reactor neutrino experiments to search for $\theta_{13}$ with both near & far detectors running, from the early August 2011.

- RENO started to see a signal of reactor neutrino disappearance from the late 2011.

- According to reported schedules of the other experiments, RENO was thought to present a result first soon. We planned to publish our first results in April without a hurry and to present them in the Neutrino 2012.

- But …..
PMT Threshold & Gain Matching

- PMT gain: set 1.0x10^7 using a Cs source at center
- Gain variation among PMTs: 3% for both detectors.

PMT threshold: determined by a single photoelectron response using a Cs source at the center
Energy Calibration

**Energy Distribution(Cs)**

- Cs 137 (662 keV)
- Near Detector
- Far Detector

**Energy Distribution(Ge)**

- Ge 68 (1,022 keV)

**Energy Distribution(Co)**

- Co 60 (2,506 keV)

**Energy Distribution(Cf)**

- Cf 252 (2.2/7.8 MeV)
Energy Scale Calibration

Near Detector

\[ \delta E = \frac{5.9\%}{\sqrt{E(\text{MeV})}} + 1.1\% \]

- ~ 250 pe/MeV (sources at center)
- Identical energy response (< 0.1%) of ND & FD
- Slight non-linearity observed

Far Detector
Detector Stability & Identity

- Cosmic muon induced neutron’s capture by H

- Near Detector
- Far Detector
IBD Event Signature and Backgrounds

**IBD Event Signature**

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

- **Prompt signal (e+)**: 1 MeV 2\(\gamma\)'s + e\(^+\) kinetic energy \((E = 1\sim10\, \text{MeV})\)
- **Delayed signal (n)**: 8 MeV \(\gamma\)'s from neutron's capture by Gd
  \(~\sim28\, \mu\text{s} \, (0.1\% \text{ Gd}) \text{ in LS}~\)

**Backgrounds**

- Random coincidence between prompt and delayed signals \((\text{uncorrelated})\)
- \(^9\text{Li}/^8\text{He} \, \beta\hspace{0.1em}-\hspace{0.1em}n \text{ followers produced by cosmic muon spallation}\)
- Fast neutrons produced by muons, from surrounding rocks and inside detector
  \((n \text{ scattering} : \text{prompt}, \quad n \text{ capture} : \text{delayed})\)
IBD Event Selection

- Reject flashers and external gamma rays: $Q_{\text{max}}/Q_{\text{tot}} < 0.03$

- Muon veto cuts: reject events after the following muons
  
  (1) 1 ms after an ID muon with $E > 70$ MeV, or with $20 < E < 70$ MeV and OD NHIT > 50

  (2) 10 ms after an ID muon with $E > 1.5$ GeV

- Coincidence between prompt and delayed signals in 100 μs
  
  - $E_{\text{prompt}} : 0.7 \sim 12.0$ MeV, $E_{\text{delayed}} : 6.0 \sim 12.0$ MeV
  
  - coincidence: $2 \mu s < \Delta t_{e+n} < 100 \mu s$

- Multiplicity cut: reject pairs if there is a trigger in the preceding 100 ms window
Random Coincidence Backgrounds

Calculation of accidental coincidence

\[ N_{\text{accidental}} = N_{\text{delayed}} \times \left(1 - \exp\left[-R_{\text{prompt}}(\text{Hz}) \times \Delta T(s)\right]\right) \pm \frac{N_{\text{accidental}}}{\sqrt{N_{\text{delayed}}}} \]

- \( \Delta T = 100 \mu s \) time window
- Near detector:
  \( R_{\text{prompt}} = 8.8 \text{ Hz}, \ N_{\text{delay}} = 4884/\text{day} \) → \( BG_{\text{near accidental}} = 4.30 \pm 0.06/ \text{day} \)
- Far detector:
  \( R_{\text{prompt}} = 10.6 \text{ Hz}, \ N_{\text{delay}} = 643/\text{day} \) → \( BG_{\text{far accidental}} = 0.68 \pm 0.03/ \text{day} \)
9\textsuperscript{Li}/8\textsuperscript{He} $\beta$-n Backgrounds

- Find prompt-delay pairs after muons, and obtain their time interval distribution with respect to the preceding muon.

- Near detector:
  \[BG^{\text{near}}_{\text{Li} / \text{He}} = 12.45 \pm 5.93 \text{ / day}\]

- Far detector:
  \[BG^{\text{far}}_{\text{Li} / \text{He}} = 2.59 \pm 0.75 \text{ / day}\]
$^9\text{Li}/^8\text{He} \beta$-n Backgrounds

- $^9\text{Li}$ production at near detector
- $^9\text{Li}$ production at far detector
Fast Neutron Backgrounds

- Obtain a flat spectrum of fast neutron’s scattering with proton, above that of the prompt signal.

- Near detector:
  \[ BG_{\text{near neutron}} = 5.00 \pm 0.13 \text{ / day} \]

- Far detector:
  \[ BG_{\text{far neutron}} = 0.97 \pm 0.06 \text{ / day} \]
Spectra & Capture Time of Delayed Signals

- Observed spectra of IBD delayed signals

Near Detector
\[ \tau = 27.8 \pm 0.2 \, \mu\text{sec} \]

Far Detector
\[ \tau = 27.6 \pm 0.4 \, \mu\text{sec} \]
## Summary of Final Data Sample

<table>
<thead>
<tr>
<th>Detector</th>
<th>Near</th>
<th>Far</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selected events</td>
<td>154088</td>
<td>17102</td>
</tr>
<tr>
<td>Total background rate (per day)</td>
<td>21.75±5.93</td>
<td>4.24±0.75</td>
</tr>
<tr>
<td>IBD rate after background</td>
<td>779.05±6.26</td>
<td>72.78±0.95</td>
</tr>
<tr>
<td>subtraction (per day)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DAQ Live time (days)</td>
<td>192.42</td>
<td>222.06</td>
</tr>
<tr>
<td>Detection efficiency (ε)</td>
<td>0.647±0.014</td>
<td>0.745±0.014</td>
</tr>
<tr>
<td>Accidental rate (per day)</td>
<td>4.30±0.06</td>
<td>0.68±0.03</td>
</tr>
<tr>
<td>$^6$Li/$^8$He rate (per day)</td>
<td>12.45±5.93</td>
<td>2.59±0.75</td>
</tr>
<tr>
<td>Fast neutron rate (per day)</td>
<td>5.00±0.13</td>
<td>0.97±0.06</td>
</tr>
</tbody>
</table>
Measured Spectra of IBD Prompt Signal

Near Detector
154088 (BG: 2.7%)

Far Detector
17102 (BG: 5.5%)
**Expected Reactor Antineutrino Fluxes**

- **Reactor neutrino flux**

\[
\Phi(E_\nu) = \frac{P_{th}}{\sum_{isotopes} f_i \cdot \phi_i(E_\nu)} \sum_{i} f_i \cdot E_i
\]

- \( P_{th} \): Reactor thermal power provided by the YG nuclear power plant
- \( f_i \): Fission fraction of each isotope determined by reactor core simulation of Westinghouse ANC
- \( \phi_i(E_\nu) \): Neutrino spectrum of each fission isotope
  [* P. Huber, Phys. Rev. C84, 024617 (2011)
- \( E_i \): Energy released per fission

<table>
<thead>
<tr>
<th>Isotopes</th>
<th>James</th>
<th>Kopeikin</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ^{235}\text{U} )</td>
<td>201.7±0.6</td>
<td>201.92±0.46</td>
</tr>
<tr>
<td>( ^{238}\text{U} )</td>
<td>205.0±0.9</td>
<td>205.52±0.96</td>
</tr>
<tr>
<td>( ^{239}\text{Pu} )</td>
<td>210.0±0.9</td>
<td>209.99±0.60</td>
</tr>
<tr>
<td>( ^{241}\text{Pu} )</td>
<td>212.4±1.0</td>
<td>213.60±0.65</td>
</tr>
</tbody>
</table>

![Graph showing fraction of fission rate over days](image)
Observed Daily Averaged IBD Rate

- Near Detector: R2 off
- Far Detector: R1 off
- R2 on
Reduction of Systematic Uncertainties

- Detector related:
  - “Identical” near and far detectors
  - Careful calibration

- Reactor related:
  - Relative measurements with near and far detectors

\[
\frac{N^\nu_{\text{far}}}{N^\nu_{\text{near}}} = \left(\frac{L_{\text{near}}}{L_{\text{far}}}\right)^2 \left(\frac{N^P_{\text{far}}}{N^P_{\text{near}}}\right) \left(\frac{\epsilon_{\text{far}}}{\epsilon_{\text{near}}}\right) \left[\frac{P(\bar{\nu}_e \rightarrow \bar{\nu}_e; E, L_{\text{far}})}{P(\nu_e \rightarrow \nu_e; E, L_{\text{near}})}\right]
\]

- Neutrino events
- \(1/r^2\)
- Number of protons
- Detection efficiency
- Yield of \(\sin^2(2\theta_{13})\)

- Maury Goodman’s neutrino newsletter (5/5/2012):
F. Darwin said “In Science the credit goes to the man who convinces the world, not to the man to whom the idea first occurred.”
But he wishes to give credit to Russians who first proposed a two detector neutrino reactor disappearance experiment: L. Mikaelyan & V. Sinev.
# Efficiency & Systematic Uncertainties

<table>
<thead>
<tr>
<th>Reactor</th>
<th>Uncorrelated</th>
<th>Correlated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal power</td>
<td>0.5%</td>
<td>–</td>
</tr>
<tr>
<td>Fission fraction</td>
<td>0.7%</td>
<td>–</td>
</tr>
<tr>
<td>Fission reaction cross section</td>
<td>–</td>
<td>1.9%</td>
</tr>
<tr>
<td>Reference energy spectra</td>
<td>–</td>
<td>0.5%</td>
</tr>
<tr>
<td>Energy per fission</td>
<td>–</td>
<td>0.2%</td>
</tr>
<tr>
<td>Combined</td>
<td><strong>0.9%</strong></td>
<td>2.0%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Detection</th>
<th>Uncorrelated</th>
<th>Correlated</th>
</tr>
</thead>
<tbody>
<tr>
<td>IBD cross section</td>
<td>–</td>
<td>0.2%</td>
</tr>
<tr>
<td>Target protons</td>
<td>0.1%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Prompt energy cut</td>
<td>0.01%</td>
<td>0.1%</td>
</tr>
<tr>
<td>Flasher cut</td>
<td>0.01%</td>
<td>0.1%</td>
</tr>
<tr>
<td>Gd capture ratio</td>
<td>0.1%</td>
<td>0.7%</td>
</tr>
<tr>
<td>Delayed energy cut</td>
<td>0.1%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Time coincidence cut</td>
<td>0.01%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Spill-in</td>
<td>0.03%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Muon veto cut</td>
<td>0.02%</td>
<td>0.02%</td>
</tr>
<tr>
<td>Multiplicity cut</td>
<td>0.04%</td>
<td>0.06%</td>
</tr>
<tr>
<td>Combined (total)</td>
<td><strong>0.2%</strong></td>
<td>1.5%</td>
</tr>
</tbody>
</table>
Reactor Antineutrino Disappearance

\[ R = \frac{\Phi^{Far}_{\text{observed}}}{\Phi^{Far}_{\text{expected}}} = 0.920 \pm 0.009(\text{stat.}) \pm 0.014(\text{syst.}) \]

- A clear deficit in rate (8.0% reduction)
- Consistent with neutrino oscillation in the spectral distortion
\[ \chi^2 = \sum_{d=N,F} \left[ \frac{N^d_{\text{obs}} + b_d - (1 + a + \xi_d) \sum_{r=1}^6 (1 + f_r) N^d_{\text{exp}}}{N^d_{\text{obs}}} \right]^2 \]

\[ + \sum_{d=N,F} \left( \frac{\xi^2_d}{\sigma_d^2} + \frac{b^2_d}{\sigma_d^2} \right) + \sum_{r=1}^6 \left( \frac{f_r}{\sigma_r} \right)^2 \]
Definitive Measurement of $\theta_{13}$

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

- 4.9$\sigma$ significant signal

Near detector: 1.2% reduction

Far detector: 8.0% reduction
$\chi^2$ Distributions for Uncertainties
Future Plan for Precision Measurement of $\theta_{13}$

**RENO**

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

\[
0.113 \pm 0.023 \, (4.9 \, \sigma) \rightarrow \pm 0.01
\]

**Daya Bay**

\[
\sin^2 2\theta_{13} = 0.092 \pm 0.016 \, (\text{stat.}) \pm 0.005 \, (\text{syst.})
\]

\[
0.092 \pm 0.018 \, (5.2 \, \sigma)
\]

- Contributions of the systematic errors:
  - Background uncertainties: 0.0165
    (far: 5.5% × 17.7% = 0.97%, near: 2.7% × 27.3% = 0.74%)
  - Reactor uncertainty (0.9%): 0.0100
  - Detection efficiency uncertainty (0.2%): 0.0103
  - Absolute normalization uncertainty (2.5%): 0.0104

- Remove the backgrounds!
- Spectral shape analysis
SUMMARY

- RENO was the first experiment to take data with both near and far detectors, from August 1, 2011.

- RENO observed a clear disappearance of reactor antineutrinos.
  \[ R = 0.920 \pm 0.009 \text{(stat.)} \pm 0.014 \text{(syst.)} \]

- RENO measured the last, smallest mixing angle \( \theta_{13} \) unambiguously that was the most elusive puzzle of neutrino oscillations
  \[ \sin^2 2\theta_{13} = 0.113 \pm 0.013 \text{(stat.)} \pm 0.019 \text{(syst.)} \]

- Surprisingly large !!!
  → A plenty of tasks ahead for neutrino physicists
A surprisingly large value of $\theta_{13}$:
(Save a lot of dollars for the future neutrino experiments which may need reconsideration of their designs!!)

→ (1) Provides a complete picture of neutrino oscillations
(2) Open a bright window of understanding why there is much more matter than antimatter in the Universe today

A prospective future for neutrino physics due to a large value of $\theta_{13}$!!!

- Our measurement will strongly promote the next round of neutrino experiments to find the CP phase.
- Complimentary measurements between accelerator experiments and reactor experiments will provide significant information on the CP phase.
L~50km experiment may be a natural extension of current Reactor-$\theta_{13}$ Experiments

* $\theta_{13}$ detectors can be used as near detector
* Small background from other reactors.
RENO-50

- 5000 tons ultra-low-radioactivity Liquid Scintillation Detector
Physics with RENO-50

- Precise measurement of $\theta_{12}$
  \[
  \frac{\delta \sin^2 \theta_{12}}{\sin^2 \theta_{12}} \sim 1.0\% (1\sigma) \text{ in a year}\leftarrow \text{current accuracy : 5.4}\% 
  \]

- Determination of mass hierarchy $\Delta m^2_{13}$

- Neutrino burst from a Supernova in our Galaxy:
  ~1500 events (@8 kpc)

- Geo-neutrinos: ~300 geo-neutrinos for 5 years

- Solar neutrinos: with ultra low radioacitivity

- Reactor physics: non-proliferation

- Detection of T2K beam: ~120 events/year

- Test of non-standard physics: sterile/mass varying neutrinos