Design, status and plans of JUNO & RENO-50 as a comprehensive neutrino program

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IHEP, Beijing, China
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Chicago
Reactor Neutrinos

- Measuring $\theta_{13}$ and $\Delta m^2_{ee}$
  - Daya Bay, Double Chooz, RENO
  - Ultimate precision $\sim 3\%$
- Determining Mass Hierarchy & precision measurement of $\theta_{12}$, $\Delta m^2_{21}$ and $\Delta m^2_{31}$
  - JUNO, RENO-50
Determine MH with Reactors


\[ P_{ee}(L/E) = 1 - P_{21} - P_{31} - P_{32} \]

\[ P_{21} = \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2(\Delta_{21}) \]

\[ P_{31} = \cos^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{31}) \]

\[ P_{32} = \sin^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{32}) \]

\[ P_{ee} = 1 - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 (\Delta_{21}) \]

\[ - \sin^2 2\theta_{13} \sin^2 (|\Delta_{31}|) \]

\[ - \sin^2 \theta_{12} \sin^2 2\theta_{13} \sin^2 (\Delta_{21}) \cos (2|\Delta_{31}|) \]

\[ \pm \frac{\sin^2 \theta_{12}}{2} \sin^2 2\theta_{13} \sin (2\Delta_{21}) \sin (2|\Delta_{31}|) \]

- The big suppression is the "solar" oscillation \( \Delta m^2_{21}, \sin^2 \theta_{12} \)
- "Large" value of \( \theta_{13} \) crucial
- The NH or IH can be seen if the neutrino spectrum is as precise as 3% @ 1MeV

Also refer to arXiv1210.8141
JUNO Site

JUNO has been approved in Feb. 2013. ~ 300 M$ by China

<table>
<thead>
<tr>
<th>NPP</th>
<th>Daya Bay</th>
<th>Huizhou</th>
<th>Lufeng</th>
<th>Yangjiang</th>
<th>Taishan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Status</td>
<td>Operational</td>
<td>Planned</td>
<td>Planned</td>
<td>Under construction</td>
<td>Under construction</td>
</tr>
<tr>
<td>Power</td>
<td>17.4 GW</td>
<td>17.4 GW</td>
<td>17.4 GW</td>
<td>17.4 GW</td>
<td>18.4 GW</td>
</tr>
</tbody>
</table>

Overburden ~ 700 m

Kaiping, Jiang Men city, Guangdong Province

By 2020: 26.6 GW

Overburden ~ 700 m

2.5 h drive

Previous site candidate

53 km

53 km

53 km

53 km

Yangjiang NPP

Taishan NPP

Guangzhou

Hong Kong

Zhu Hai

Shen Zhen

macau

Kam Kraing

Near Site

Far Site

Distance to Reactor (m)
Collaboration established in July 2015
Now: 66 institutions
444 collaborators
8 observers
Rich Physics Program with Huge and precise LS Detector

- 20 kton LS detector
- 3% energy resolution
- 700 m underground
- Rich physics possibilities
  - Reactor neutrino for Mass hierarchy
  - Precision measurement of oscillation parameters
  - Supernovae neutrino
  - Geoneutrino
  - Solar neutrino
  - Atmospheric neutrino
  - Exotic searches including proton decay, dark matter

Main Challenges

- How good is the energy resolution
- How well we know the reactor spectrum
  - Model prediction (2-10%) + energy nonlinearity (1-3%) from LS and electronics/readout
  - Two approaches to mitigate the spectrum uncertainties
    - Direct measurement of the spectrum to 1% by SBL reactor exp.
    - Constraint from Daya Bay measurements, independent of models, similar LS and similar electronics → 1%

- 75% photocathode coverage
- PMT peak QE: 35%
- Attenuation length of 20 m → abs. 60 m + Rayl. scatt. 30m

<table>
<thead>
<tr>
<th></th>
<th>KamLAND</th>
<th>BOREXINO</th>
<th>JUNO</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS mass</td>
<td>1 kt</td>
<td>0.5 kt</td>
<td>20 kt</td>
</tr>
<tr>
<td>Energy Resolution</td>
<td>6% @ 1MeV</td>
<td>5% @ 1MeV</td>
<td>3% @ 1MeV</td>
</tr>
<tr>
<td>Light yield</td>
<td>250 p.e./MeV</td>
<td>511 p.e./MeV</td>
<td>1200 p.e./MeV</td>
</tr>
</tbody>
</table>
**Precision Measurements**

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

\[
P_{ee}(L/E) = 1 - P_{21} - P_{31} - P_{32}
\]

\[
P_{21} = \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2(\Delta_{21})
\]

\[
P_{31} = \cos^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{31})
\]

\[
P_{32} = \sin^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{32})
\]

\[
\Delta m_{ee}^2 = \cos^2\theta_{12} \Delta m_{31}^2 + \sin^2\theta_{12} \Delta m_{32}^2
\]

---

<table>
<thead>
<tr>
<th>Statistics</th>
<th>Systematics considering: BG+1% b2b+1% Scale +1% EnonL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>0.54%</td>
</tr>
<tr>
<td>$\Delta m_{21}^2$</td>
<td>0.24%</td>
</tr>
<tr>
<td>$\Delta m_{ee}^2$</td>
<td>0.27%</td>
</tr>
</tbody>
</table>
Supernova Detection

Three phases of supernova, Fischer et al. (Basel group), A&A 517:A80, 2010 [arxiv:0908.1871]

<table>
<thead>
<tr>
<th>Channel</th>
<th>Type</th>
<th>12 MeV</th>
<th>14 MeV</th>
<th>16 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{\nu}_e + p \rightarrow e^+ + n$</td>
<td>CC</td>
<td>$4.3 \times 10^3$</td>
<td>$5.0 \times 10^3$</td>
<td>$5.7 \times 10^3$</td>
</tr>
<tr>
<td>$\nu + p \rightarrow \nu + p$</td>
<td>NC</td>
<td>$0.6 \times 10^3$</td>
<td>$1.2 \times 10^3$</td>
<td>$2.0 \times 10^3$</td>
</tr>
<tr>
<td>$\nu + e \rightarrow \nu + e$</td>
<td>ES</td>
<td>$3.6 \times 10^2$</td>
<td>$3.6 \times 10^2$</td>
<td>$3.6 \times 10^2$</td>
</tr>
<tr>
<td>$\nu + {^{12}}C \rightarrow \nu + {^{12}}C^*$</td>
<td>NC</td>
<td>$1.7 \times 10^2$</td>
<td>$3.2 \times 10^2$</td>
<td>$5.2 \times 10^2$</td>
</tr>
<tr>
<td>$\nu_e + {^{12}}C \rightarrow e^- + {^{12}}N$</td>
<td>CC</td>
<td>$0.5 \times 10^2$</td>
<td>$0.9 \times 10^2$</td>
<td>$1.6 \times 10^2$</td>
</tr>
<tr>
<td>$\bar{\nu}_e + {^{12}}C \rightarrow e^+ + {^{12}}B$</td>
<td>CC</td>
<td>$0.6 \times 10^2$</td>
<td>$1.1 \times 10^2$</td>
<td>$1.6 \times 10^2$</td>
</tr>
</tbody>
</table>

Table. JUNO can detect the quantity of neutrino from a galactic SN @ 10 kpc. Special trigger and buffer memory are designed.

The neutrino event spectra with respect to the visible energy $E_d$ in the JUNO detector for a SN at 10 kpc

Roughly: one time / 22 years in our galaxy, SN 1987a, Kamiokande II, $\sim 10 \nu$

JUNO can do
- Big quantity with distinguished different $\nu$ flavors
- Reconstruct $\nu$ energies and luminosities
- Almost background free due to time information
- Study the explosion mechanism
- Together with gravitational wave / optical observation
Geoneutrino detection

- Geoneutrino: antineutrino from the decay of $^{238}\text{U}$, $^{232}\text{Th}$, $^{40}\text{K}$ in the Earth, occupying 99% radiogenic heat in the earth. Nature. 310 (5974): 191–198
  
- Results from Kamland:
  - PRD 88 (2013) 033001
  - 2002-2012 data: geoneu.
  - 116±27

- Results from Borexino:
  - PLB 722 (2013) 295
  - 2007-2012 data: geoneu.
  - 14.3±4.4

- JUNO’s unprecedented size and sensitivity allows for the recording of $\sim 400$ geoneutrinos per year. 6 months JUNO would match the present world sample of recorded geoneutrinos in the world.
  
- Earth’s surface heat: 46 ± 3 TW, debating it is from primordial or radioactive sources.
JUNO Event Rates after selection

Supernova $\nu$
5-7k in 10s for 10kpc

Atmospheric $\nu$
several/day

Solar $\nu$
(10s-1000s)/day

Reactor $\nu$,
60/day
Bkg: 3.8/day

Cosmic muons
~ 250k/day

0.003 Hz/m$^2$
215 GeV
10% muon bundles

Geo-neutrinos
1.1/day

36 GW, 53 km

20k ton
LS

700 m
Next about JUNO Project Progress
Ground breaking in Jan. 2015
- 900 m slope tunnel excavated out of 1340 m
- 330 m vertical shaft excavated out of 611 m

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

Future Plan
- Run for 20-30 years
- Likely, double beta decay experiment in 2030
Civil Progress
Highlights: Central Detector

- March, 2014: Balloon + SS tank
- April, 2014: Acrylic module + SS tank
- May, 2014: Acrylic sphere + SS truss
- July, 2015: SS truss + Acrylic sphere
- July, 2015: Balloon + Acrylic support + SS tank

Final decision: Acrylic sphere + SS truss
Highlights: Detector Dimension

Calibration

Top Tracker

Central detector:
Acrylic sphere+
20kt Liquid Scin+
~17000 20” PMT+
~34000 3” PMT
Water Cherenkov
~2000 20” PMT

Acrylic Sphere: ID35.4m
Stainless Steel Truss: ID40.1m

D43.5m

Electronic Filling + Overflow

Filling + Overflow
Forming panel size: 3m x 8m x 120mm

Acrylic divided into 200+ panels

Prototype of spherical panel

Acrylic connection nodes

The problems of shrinkage and shape variation were resolved.
How to make the acrylic safe?

Acrylic stress is a critical issue for engineering design.

The maximum stress of acrylic is concentrated at connecting node.

How to reduce the stress on acrylic node?

a. Lower the load on connecting bar
b. Improve the design of connecting node

Worst case: running, the total vertical load is ~2600t up to ~560 connecting nodes will carry this load.

a. How to lower the max load on connecting bar?
   • Add the quantity of bar → Add light block ✗
   • Improve the load distribution on bars ✓

b. How to improve the node design
   • Optimize the structure of node
   • Two kinds of node for compressive area or tensile area

Adjust the stiffness of some connecting bars, to get a better distribution of load on whole sphere.

[Diagram showing two types of node: Type A with high tensile strength, Type B with high compressive strength]
## Highlights: 20” PMT bidding

**20-inch Hamamatus PMT**
- **Dynode**
- **Ellipsoidal Glass**

**20-inch IHEP MCP-PMT**
- **Horizontal MCPs**
- **Ellipsoidal Glass**

---

### Many prototypes of MCP-PMTs by the Chinese R&D group
- First in the world for large size MCP-PMT

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>unit</th>
<th>MCP-PMT (NNVC)</th>
<th>R12860 (Hamamatsu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detection Eff.(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, &lt;7; F</del>9, &lt;12</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>

Evaluate the impact of the PMT characteristics on the MH as well as the cost → Finished 20” PMT bidding at the end of 2015:
- **15,000 MCP-PMT (NNVVT)**
- **5,000 Dynode-PMT (Hamamatsu)**
• Put most of electronics underwater and sealed with BASE, HV together.
• Use a **CAT5+ cable** to transfer data, hit, clock, power and trigger

• Needs to consider the integration and potting structure with PMT
• Replacement under water is almost impossible, need high reliability of potting, electronics and HV
Highlights: LS Pilot plant

- Purify 20 ton LAB to test the overall design of purification system at Daya Bay. Plan to replace the target LS in one detector.

- Quantify the effectiveness of subsystems
  - Transparency: >20m A.L @430nm
  - Radio-purity: < 10^{-15} g/g (U, Th)

- Determine the choice of sub-systems
  - Al₂O₃, distillation, gas striping, water extraction
Highlights: Veto Detectors

- Cosmic muon flux
  - Overburden: ~700 m
  - Muon rate: 0.0031 Hz/m²
    - Hit on CD: ~several Hz
  - Average energy: 214 GeV
- Water Cherenkov Detector
  - > 3.9 m water shielding, Radon: <0.2 Bq/m³
  - ~2000 20” PMTs
  - 40 kton pure water, HDPE lining
  - Similar technology as Daya Bay (99.8% efficiency)
- Compensation Coil for EMF shield
- Top muon tracker
  - Decommissioned OPERA plastic scintillator
Highlights: Calibration system

Cable Loop System (CLS)

Scan the position at large

Key: automatically take source from the storage and guide it into the electronic hands.

Four methods
1. ACU: center line
2. Cable loop system:
3. ROV: “submarine”
4. Surface guide tube

Remotely Operated Vehicle (ROV)

- Jet pump B
- Clamping band
- Depth sensor
- CCD camera
- Cable
- Ultrasound emitter
- PCB board
- Jet pump A
- Buoyancy adjusting device
- Leakage sensor

Guide Tube (GT)

- Regular deployment (every week)
- Deployment of radioactive and
- Scan outer surface of CD
  The radiation source is driven with rope pulled by step motors
Highlights: JUNO Prototype

- The end of 2015, finished construction/filling, start data taking
- Preliminary analysis shows:
  - all sub-system reached designed goal: detector\electronics\water system
  - PMT water potting working well
- More tests and understanding are doing...
Next about RENO-50

The contents provided by Prof. Soo-Bong Kim
Overview of RENO-50

- **RENO-50**: An underground detector consisting of 18 kton ultralow-radioactivity liquid scintillator & 15,000 20” PMTs, at 50 km away from the Hanbit(Yonggwang) nuclear power plant.

- **Goals**: Determination of neutrino mass hierarchy, high-precision measurement of $\theta_{12}$, $\Delta m^2_{21}$ and $\Delta m^2_{ee}$.
- Supernova neutrino, Geo-neutrino and solar neutrino.

- **Budget**: $100M for 6 year construction (Civil engineering: $15M, Detector: $85M)

- An R&D funding (US $2M for 3 years of 2015-2017) is given by the Samsung Science & Technology Foundation.
- Efforts on obtaining a full construction fund.

- **Schedule**: 2016 ~ 2021: Facility and detector construction
  2022 ~: Operation and experiment
Physics Potential of RENO-50

- **Determination of neutrino mass ordering**
  - $3\sigma$ sensitivity with 10 years of data

- **Precise ($\sim0.5\%$) measurement of $\theta_{12}$, $\Delta m_{21}^2$ and $\Delta m_{ee}^2$**
  - An interesting test for unitarity & essential for the future discoveries

- **Neutrino burst from a Supernova in our Galaxy**
  - ~5,600 events (@8 kpc)
  - Study the core collapsing mechanism with neutrino cooling

- **Geo-neutrinos**: ~ 1,500 geo-neutrinos for 5 years
  - Study the heat generation mechanism inside the Earth

- **Solar neutrinos**
  - MSW effect on neutrino oscillation

- **Sterile neutrino search**: reactor / radioactive sources / IsoDAR

- **Detection of J-PARC beam**: ~200 events/year
**RENO-50**

- **Near Detector**
- **Far Detector**
- **18 kton LS Detector**
- ~47 km from YG reactors
- Mt. Guemseong (450 m)
- ~900 m.w.e. overburden
RENO-50 Candidate Site

Mt. GuemSeong
Altitude : 450 m

Dongshin University
Conceptual Design of RENO-50 Detector

Water, 1000 20” PMTs

LS (18 kton)

15000 20” PMTs

RENO-50 detector (MC)
<table>
<thead>
<tr>
<th>(1) Development of DAQ electronics</th>
<th>(2) Develop techniques of LS purification</th>
<th>(3) Mechanical design of detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specification for <em>dead time free, high sensitivity and high speed signal processing</em></td>
<td>Reduction of LS radioactivity to $10^{-16}$ g/g of U and Th</td>
<td>Detailed drawing of mechanical parts in progress</td>
</tr>
<tr>
<td>Prototype boards to be tested</td>
<td>Removal of LS impurities for attenuation length of ~25 m</td>
<td>MC simulation to estimate the performance</td>
</tr>
<tr>
<td>Several methods applied for investigation and evaluation</td>
<td>Efforts on high sensitive measurement of radioactive concentration and optical parameters in LS</td>
<td></td>
</tr>
</tbody>
</table>
R&D in Progress

(4) Measurement of radioactivity for the detector materials

- Evaluate radioactive contamination of detector parts using a high purity Ge detector
- Estimate event rate contribution of those contaminations

(5) Measurement device for absolute LS attenuation length

- Developed a long pipe device with a laser source and a PMT
- Upgrade of the device in progress

- An R&D funding (US $2M for 3 years of 2015-2017) is given by the Samsung Science & Technology Foundation.
- Efforts on obtaining a full construction fund
Summary

- JUNO and RENO-50 will measure Mass hierarchy (3-4 \( \sigma \) in 2026) and 3 oscillation parameters to <1% level. And many other topics like supernova, geo-neutrino, solar neutrino, sterile neutrino, etc.

- JUNO construction and R&D are on schedule, aiming at data taking in 2020.
  - Many R&D accomplishments such as PMT bidding, detector design and R&D, LS pilot, Electronics, etc.

- RENO-50 has R&D funding and works for full funding, aiming at data taking in 2022.

Thank you for your attention!
<table>
<thead>
<tr>
<th>Selection</th>
<th>IBD efficiency</th>
<th>IBD</th>
<th>Geo-νs</th>
<th>Accidental</th>
<th>$^9\text{Li}/^8\text{He}$</th>
<th>Fast n</th>
<th>$(\alpha, n)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiducial volume</td>
<td>91.8%</td>
<td>83</td>
<td>1.5</td>
<td>$\sim 5.7 \times 10^4$</td>
<td>84</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Energy cut</td>
<td>97.8%</td>
<td>76</td>
<td>1.4</td>
<td>410</td>
<td>77</td>
<td>0.1</td>
<td>0.05</td>
</tr>
<tr>
<td>Time cut</td>
<td>99.1%</td>
<td>73</td>
<td>1.3</td>
<td>410</td>
<td>77</td>
<td>0.1</td>
<td>0.05</td>
</tr>
<tr>
<td>Vertex cut</td>
<td>98.7%</td>
<td>60</td>
<td>1.1</td>
<td>410</td>
<td>77</td>
<td>0.1</td>
<td>0.05</td>
</tr>
<tr>
<td>Muon veto</td>
<td>83%</td>
<td>60</td>
<td>1.1</td>
<td>0.9</td>
<td>1.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combined</td>
<td>73%</td>
<td>60</td>
<td>3.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2-1: The efficiencies of antineutrino selection cuts, signal and backgrounds rates.

<table>
<thead>
<tr>
<th>Detector material</th>
<th>$^{238}\text{U}$</th>
<th>$^{238}\text{Th}$</th>
<th>$^{40}\text{K}$</th>
<th>$^{60}\text{Co}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMT glass</td>
<td>22 ppb</td>
<td>20 ppb</td>
<td>3.54 ppb</td>
<td>-</td>
</tr>
<tr>
<td>Acrylic</td>
<td>10 ppt</td>
<td>10 ppt</td>
<td>10 ppt</td>
<td>-</td>
</tr>
<tr>
<td>Polymer film</td>
<td>2 ppt</td>
<td>4 ppt</td>
<td>1 ppt</td>
<td>-</td>
</tr>
<tr>
<td>Steel</td>
<td>0.096 ppb</td>
<td>1.975 ppb</td>
<td>0.049 ppb</td>
<td>0.002 Bq/kg</td>
</tr>
<tr>
<td>Copper</td>
<td>1.23 mBq/kg</td>
<td>0.405 mBq/kg</td>
<td>0.0377 mBq/kg</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 12-10: The estimated radioactivity of JUNO detector construction materials.

<table>
<thead>
<tr>
<th>LS</th>
<th>$^{238}\text{U}$</th>
<th>$^{238}\text{Th}$</th>
<th>$^{40}\text{K}$</th>
<th>$^{210}\text{Pb}$</th>
<th>$^{85}\text{Kr}$</th>
<th>$^{39}\text{Ar}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No distillation</td>
<td>$10^{-15}$ g/g</td>
<td>$10^{-15}$ g/g</td>
<td>$10^{-16}$ g/g</td>
<td>$1.4 \cdot 10^{-22}$ g/g</td>
<td>50 $\mu$Bq/m$^3$</td>
<td>50 $\mu$Bq/m$^3$</td>
</tr>
<tr>
<td>After distillation</td>
<td>$10^{-17}$ g/g</td>
<td>$10^{-17}$ g/g</td>
<td>$10^{-18}$ g/g</td>
<td>$10^{-24}$ g/g</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 13-11: The estimated radioactivity of JUNO LS.