JUNO: A Next Generation Reactor Antineutrino Experiment

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On behalf of the JUNO proto-Collaboration
Neutrino Mass Hierarchy

- Large $\theta_{13}$ opens a door to neutrino MH and CP violating phase, as focus of next generation neutrino experiments.
- MH can be determined utilizing
  - Matter effects of accelerator (LBNE, LBNO) and atmospheric (PINGU, HK, INO) neutrinos
  - Oscillation interference effects of reactor neutrinos driven by $\Delta m^2_{32}$ and $\Delta m^2_{31}$ (JUNO, RENO-50)

Daya Bay

$\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$

$|\Delta m^2_{ee}| = 2.44^{+0.10}_{-0.11} \times 10^{-3}\text{eV}^2$

Neutrino 2014
Oscillation probability independent of CP phase

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

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

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

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

Effects of \( P_{31} \) and \( P_{32} \) interference are proportional to \( \sin^22\theta_{13} \)

\[ \Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21} \]

**NH:** \( |\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}| \)

**IH:** \( |\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}| \)

Two oscillation components

Amplitude \( P_{31} : P_{32} \sim 7 : 3 \)

Frequency

\( P_{31} > P_{32} \rightarrow \text{NH} \)

\( P_{31} < P_{32} \rightarrow \text{IH} \)

S.T. Petcov et al., PLB533(2002)94
S.Choubey et al., PRD68(2003)113006
J. Learned et al., hep-ex/0612022

Zhan, Y. Wang, J. Cao, L. Wen,
PRD78:111103, 2008
PRD79:073007, 2009
JUNO Experiment

- **Jiangmen Underground Neutrino Observatory**
- Primary goal: mass hierarchy
  - 36GW reactor power, 20 kton LS detector, 3%/√E energy resolution
- Proposed in 2008, approved in Feb. 2013

Rich physics possibilities

- **Mass hierarchy**
- Precision measurement of 3 mixing parameters
- Supernova neutrinos
- Geoneutrinos
- Sterile neutrinos
- Atmospheric neutrinos
- Exotic searches
Location of JUNO

<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, Jiangmen city, Guangdong Province

53 km

53 km

by 2020: 26.6 GW
Optimum Baseline for MH

- Optimum at the oscillation maximum of $\theta_{12}$
- Multiple reactors may cancel the oscillation structure
  - Baseline difference cannot be more than 500 m

\[ \Delta \chi^2_{\text{MH}} = \chi^2_{\text{min}}(N) - \chi^2_{\text{min}}(I) \]
Sensitivity of MH Determination

Assume NH as true MH, and fit the spectrum with false and true MH cases respectively, and we get

$$\Delta \chi^2 = \chi^2_{\text{false}} - \chi^2_{\text{true}}$$

<table>
<thead>
<tr>
<th>$\sqrt{\Delta \chi^2}$</th>
<th>Without $\Delta m^2_{uu}$ input</th>
<th>With $\Delta m^2_{uu}$ input (1%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equal baseline</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Core distribution</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

Detector size: 20kt
Energy resolution: 3%/\sqrt{E}
Thermal power: 36 GW
Running time: 6 years

Fourier transform method as cross check

Many discussions on the statistical interpretation of $\Delta \chi^2$
E.Ciuffoli et al, JHEP 1401 (2014) 095
M. Blennow et al., JHEP 1403 (2014) 028
M. Blennow et al, JHEP 1401(2014)139
Also see the next talk given by Mattias Blennow
Precision Measurement of Mixing Parameters

• Fundamental to the Standard Model and beyond
• Probing the unitarity of $U_{PMNS}$ to $\sim 1\%$ level
  – Uncertainty from other oscillation parameters and systematic errors, mainly energy scale, are included

<table>
<thead>
<tr>
<th></th>
<th>Current</th>
<th>JUNO</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m_{12}^2$</td>
<td>3%</td>
<td>0.6%</td>
</tr>
<tr>
<td>$\Delta m_{23}^2$</td>
<td>5%</td>
<td>0.6%</td>
</tr>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>6%</td>
<td>0.7%</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>10%</td>
<td>N/A</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}$</td>
<td>14% $\Rightarrow$ 4%</td>
<td>~ 15%</td>
</tr>
</tbody>
</table>

Will be more precise than CKM matrix elements!
Other Physics Potentials

• Supernova neutrinos
  – Less than 20 events observed so far
  – Estimated number of neutrino events in JUNO at distance of 10 kpc and typical SN parameters

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

Good energy resolution, all types of neutrinos

• Geoneutrinos
  – Current results: KamLAND: $30 \pm 7$ TNU (PRD 88 (2013) 033001), Borexino: $38.81 \pm 2.0$ TNU (PLB 722 (2013) 295)
  – JUNO, X10 statistics, but huge reactor antineutrino background

• Solar neutrinos, atmosphere neutrinos, nucleon decay, sterile neutrinos

A physics book will be released by end of this year
Central Detector

- **Some basic numbers**
  - 20 kt liquid scintillator as the target
  - Signal event rate: ~60/day
  - Backgrounds with 700 m overburden:
    - Accidentals(~10%), $^{9}\text{Li}/^{8}\text{He}(<1\%),$ fast neutrons(<1%)

- **A huge detector in a water pool:**
  - Default option: acrylic tank(D~35m) + SS structure
  - Backup option: SS tank(D~38m) + acrylic structure + balloon

- **Issues:**
  - Engineering: mechanics, safety, lifetime, ...
  - Physics: cleanness, light collection, ...
  - Assembly & installation

- **Design & prototyping underway**
Muon Veto Detector

- Top tracker (Opera target tracker)
- Tracker support
- Water system
- Tyvek
- PMT support
- Water pool liner
- Earth magnetic shielding

20 kt LS

Inner tank: Φ34.5m
Outer tank: Φ37.5m
Requirements on Energy Resolution

- Energy resolution: $3\%/\sqrt{E}$ is possible
- JUNO preliminary MC, based on DYB MC (photon yield tuned to data)
  - JUNO geometry, 77% PMT coverage
  - High QE PMT: maxQE from 25% → 35%
  - LS attenuation length (1 m tube measurement @ 430nm from 15 m (= absorption 30 m + Rayleigh scattering 30 m) to 20 m (= absorption 60 m + Rayleigh scattering 30 m)
- Challenges on the performance of liquid scintillator and PMT

\[ \sigma_E = 0.18\% + \frac{2.57\%}{\sqrt{E(\text{MeV})}} \]
Liquid Scintillator

- Current Choice: LAB+PPO+BisMSB
- Requirements & works:
  - Low background: \(\rightarrow\) No Gd-loading
  - Long attenuation length: 15m \(\rightarrow\) 20m
    - Improve raw materials
    - Improve the production process
    - Purification
      - Distillation, Filtration, Water extraction, Nitrogen stripping...
  - Highest light yield: Optimization of fluor concentration
- Other works:
  - Rayleigh scattering length
  - Energy non-linearity
  - Aging
  - Engineering issues: equipment for 20kt
  - Raw material selection: BKG & purity issues

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<table>
<thead>
<tr>
<th>Linear Alky Benzene (LAB)</th>
<th>Atte. L(m) @ 430 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAW</td>
<td>14.2</td>
</tr>
<tr>
<td>Vacuum distillation</td>
<td>19.5</td>
</tr>
<tr>
<td>SiO₂ coloum</td>
<td>18.6</td>
</tr>
<tr>
<td>Al₂O₃ coloum</td>
<td>22.3</td>
</tr>
<tr>
<td>LAB from Nanjing, Raw</td>
<td>20</td>
</tr>
<tr>
<td>Al₂O₃ coloum</td>
<td>25</td>
</tr>
</tbody>
</table>

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![Graph](image-url)
High QE PMT

- Three types of high QE 20” PMTs under development:
  - New MCP-PMT: 4π collection
  - Hammamatsu R5912-100 with SBA photocathode
  - Photonics-type PMT
- MCP-PMT by Chinese industry:
  - Technical issues mostly resolved
  - Successful 8” prototypes
  - A few 20” prototypes

<table>
<thead>
<tr>
<th></th>
<th>R5912</th>
<th>R5912-100</th>
<th>MCP-PMT</th>
</tr>
</thead>
<tbody>
<tr>
<td>QE@410nm</td>
<td>25%</td>
<td>35%</td>
<td>25-30%</td>
</tr>
<tr>
<td>Rise time</td>
<td>3 ns</td>
<td>3.4 ns</td>
<td>5 ns</td>
</tr>
<tr>
<td>SPE Amp.</td>
<td>17mV</td>
<td>18mV</td>
<td>17mV</td>
</tr>
<tr>
<td>P/V of SPE</td>
<td>&gt;2.5</td>
<td>&gt;2.5</td>
<td>~2</td>
</tr>
<tr>
<td>TTS</td>
<td>5.5 ns</td>
<td>1.5 ns</td>
<td>3.5 ns</td>
</tr>
</tbody>
</table>
Current Status & Brief Schedule

- Project approved by CAS for R&D and design
- Geological survey completed
  - Granite rock, temperature ~ 31 °C, little water
- EPC contract signed:
  - Engineering design by July
  - Construction work by Nov.
- Paper work towards the construction:
  - Land, environment, safety, ...

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

• Proto-collaboration since 2013, meeting every 6 months
  – Italy, Germany, France, Russia, Czech, US, ...
  – Double Chooz, Borexino, LENA, Daya Bay, Hanohano, OPERA, ...

• Formal collaboration this summer
Backup
Comparison with Other Experiments

- JUNO is unique for measuring MH using reactor neutrinos
  - Independent of the CP phase and free from the matter effect: complementary to accelerator-based experiments
  - Competitive in time
  - Many other science goals

M. Blennow et al., JHEP 1403 (2014) 028