The Design of JUNO and Its Current Status

Wei Wang / 王為, Sun Yat-sen University
AAP 2018, LLNL, Oct 10, 2018

• A Brief Introduction to JUNO
• The Design of the JUNO Detector System
• Current status of JUNO
• Summary
MEASUREMENTS OF $\theta_{13}$

Double Chooz
TnC MD (n-H $\rightarrow$ n-C $\rightarrow$ n-Gd)

Daya Bay
PRD 95, 072006 (2017) n-Gd
PRD 93, 072011 (2016) n-H

RENO
PRL 116, 211801 (2016) n-Gd

T2K
PRD 96, 092006 (2017)

$\Delta m_{32}^2 > 0$
$\Delta m_{32}^2 < 0$

Total Uncertainty
Statistical Uncertainty

$\sin^2(2\theta_{13}) = 0.105 \pm 0.014$

$\sin^2(2\theta_{13}) = 0.084 \pm 0.003$
$\sin^2(2\theta_{13}) = 0.071 \pm 0.011$

Marginalisation ($\delta_{CP}, \theta_{23}$)

$0.05$ $0.1$ $0.15$

$\sin^2(2\theta_{13})$

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**Known $\theta_{13}$ Enables Neutrino Mass Hierarchy at Reactors**

- How to resolve neutrino mass hierarchy using reactor neutrinos
  - KamLAND (long-baseline) measures the solar sector parameters
  - Short-baseline reactor neutrino experiments designed to utilize the oscillation of atmospheric scale
  ✓ Both scales can be studied by observing the spectrum of reactor neutrino flux

\[
P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21} - \sin^2 2\theta_{13} \left( \cos^2 \theta_{12} \sin^2 \Delta_{31} + \sin^2 \theta_{12} \sin^2 \Delta_{32} \right)
\]

✓ Mass hierarchy is reflected in the spectrum
✓ Signal independent of the unknown CP phase

\[
\propto \sin^2 2\theta_{13}
\]

Realization & Plausibility: L. Zhan et al, PRD.78.111103; J. Learned et al PRD.78.071302
JUNO Found a Sweet Spot

Best baseline is ~60km
(OR at the solar oscillation maximum)
Collaboration established on July 2014
Now 77 institutions ~600 collaborators

JUNO Collaboration

Yale now an Observer


Armenia: Yerevan Physics Institute

Belgium: Université libre de Bruxelles

Brazil: PUC, UEL

Chile: PCUC, UTFSM

China: BISEE, Beijing Normal U., CAGS, ChongQing University, CIAE, DGUT, CUG, Guangxi U., Harbin Institute of Technology, GG, GGCAS, HEP, Beijing Normal U., UCAS, USTC, Wu Yi U., Xi'an JT U., Xiamen University, Zhengzhou U.

Czech: Charles U.

Finland: University of Oulu

France: APC Paris, CENBG, CPPM Marseille, IPHC Strasbourg, Subatech Nantes


Italy: INFN Catania, INFN di Frascati, INFN-Ferrara, INFN-Milano, INFN-Milano Bicocca, INFN-Padova, INFN-Perugia, INFN-Roma 3, LECS

Latvia: IECS

Pakistan: PINSTECH (PAEC)

Russia: INR Moscow, JINR

Slovakia: FMPICU

Taiwan: National Chiao-Tung U.

Thailand: NARIT, PPRLCU, SUT

USA: UMD1, UMD2, UCI
Challenges in Resolving MH using Reactors

- Energy resolution: $\sim 3\%/\sqrt{E}$
- Energy scale uncertainty: $<1\%$
- Statistics (the more the better)
- Reactor distribution: $<\sim 0.5\text{km}$
JUNO Detector System

- **Center Detector**
  - Acrylic sphere containing Liquid Scintillator (LS)
  - PMT in water (18k 20” + 25k 3”)
  - 20 kt LS + 78% photocathode coverage

- **Veto Detector (μ tagger)**
  - Water Cherenkov detector
  - Top tracker
  - For μ tagging and track reconstruction

- **Earth magnetic field compensation coils**

- **Calibration System**
  - 4 complimentary sub-systems

- **Electronics:**
  - 1 GHz, 14 bit, 1~4000p.e. dynamic range

Collect as many p.e. as possible
**Calibration System based on the Daya Bay experiences**

- **Automatic Calibration Unit (ACU)**
- **Guide Tube Calibration System (GTCS)**
- **Cable Loop System (CLS)**
- **Remotely Operated under-liquid-scintillator Vehicles (ROV)**

- Complementary for covering entire energy range of reactor neutrinos and full-volume position coverage inside JUNO central detector.
<table>
<thead>
<tr>
<th></th>
<th>KamLAND</th>
<th>BOREXINO</th>
<th>Daya Bay</th>
<th>PROSPECT</th>
<th>JUNO</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Target Mass</strong></td>
<td>~1kt</td>
<td>~300t</td>
<td>20t</td>
<td>~4t</td>
<td>~20kt</td>
</tr>
<tr>
<td><strong>Photocathode Coverage</strong></td>
<td>~34%</td>
<td>~34%</td>
<td>~12% (Effective)</td>
<td>ESR + PMTs</td>
<td>~80%</td>
</tr>
<tr>
<td><strong>PE Collection</strong></td>
<td>~250 PE/MeV</td>
<td>~500 PE/MeV</td>
<td>~160 PE/MeV</td>
<td>~850 PE/MeV</td>
<td>~1200 PE/MeV</td>
</tr>
<tr>
<td><strong>Energy Resolution</strong></td>
<td>~6%/√E</td>
<td>~5%/√E</td>
<td>~7.5%/√E</td>
<td>~4.5%/√E</td>
<td>3%/√E</td>
</tr>
<tr>
<td><strong>Energy Calibration</strong></td>
<td>~2%</td>
<td>~1%</td>
<td>1.5%→ 0.5%</td>
<td>?</td>
<td>&lt;1%</td>
</tr>
</tbody>
</table>

Quite a challenging detector for JUNO!
Packing PMTs as Tight as Possible

1. Supper layer arrangement method 77.8%

2. Spherical triangle method 72%

3. Volleyball arrangement method 75.96%

4. Football arrangement method 74.08%

20” PMT (~18K)
MCP-PMT (~13K)
Hamamatsu HQE (5K)

3”sPMT (~25K)
HZC XP72B22 (Photonis)

- 1. Insulated trestle table
- 2. Anode
- 3. MCP dodule
- 4. Bracket of the cables
- 5. Transmission Photocathode
- 6. Glass shell
- 7. Reflection Photocathode
- 8. Glass joint

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Double Calorimetry Design

- 25k 3-inch PMTs, working in photon-counting mode for $E \in (1, 10)$ MeV, greatly improves the dynamic range to 4000 p.e.
  - ~60% have been delivered and tested from HZC
- Energy resolution ~17%@1 MeV: independent <1% solar mixings
- Time resolution (FWHM) ~3.5 ns: essential for muon recon
- Data acquisition without dead time: essential for SNv’s
Testing Every Single PMT with Great Care

Integration tests and training (?) of all electronics components/电子学整合测试

Acceptance (Commercial Electronics)

Potting/Characterization (JUNO Electronics)

Curing

Water testing?
Testing Every Single PMT with Great Care

**Fetching PMTs**

**Container Testing**

**Visual Inspection**

**Scanning Station Testing**
JUNO 20in PMT Performance

- >10k PMT have been delivered
- More than half have been tested
- Two independent testing systems

Test Results from first few thousands

<table>
<thead>
<tr>
<th>Type</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>NNVT</td>
<td>27.5%±1.0%</td>
</tr>
<tr>
<td>Hamamatsu</td>
<td>28.3%±1.0%</td>
</tr>
</tbody>
</table>
The New MCP-PMTs Performance

**Good news this past Summer:**

**New NNVT MCP-PMTs:** ~10% increasing on detection efficiency (PDE)

- **PDE ~30%**
  - Vendor data from NNVT

- **JUNO ~100 tubes sampled ~32%**
  - Preliminary
Central Detector Status: a prototype has been set up
JUNO is More Than Neutrino Mass Hierarchy

- Large mass (20 kt)
- Good $E$ resolution (3%)
- Rich physics potentials

1. Supernova $\nu$
   - 5-7k in 10s for 10kpc
2. Solar $\nu$
   - (10s-1000s)/day
3. Atmospheric $\nu$
   - Several/day
4. Cosmic muons
   - $\sim 250k$/day
   - 0.003 Hz/m$^2$
   - 215 GeV
   - 10% multiple-muon
5. Reactor $\nu$
   - 60/day
   - Bkg: 3.8/day
6. Geo-neutrinos
   - 1.1/day
7. 20k ton
   - LS
8. 36 GW, 53 km
Motivation of the JUNO Near Detector

- Danielson, Hayes and Garvey, *Reactor Neutrino Spectral Distortions Play Little Role in Mass Hierarchy Experiments*, arxiv.1808.03276:

**Current measurements**

| Stat. | Core dist. | DYB and HZ | Shape | B/S (stat.) | B/S (shape) | $|\Delta m_{\mu\mu}^2|$ |
|-------|------------|------------|-------|-------------|-------------|----------------|
| Size  | 52.5 km    | Table 2    | Table 2% | 1%          | 6.3%        | 0.4%          | 1%           |
| $\Delta \chi^2_{\text{MH}}$ | +16 | -3 | -1.7 | -1 | -0.6 | -0.1 | +(4 - 12) |

arXiv:1710.00092

arXiv:1407.1821
A Conceptual Design as of Summer 2018

- Gd-LS in diameter of 1.8m
  - Surface 10.2 m²; V = 3.05 m³, or 2.63 ton; 1 ton fiducial volume w/ a 25cm cut
  - ~30 m from the core, Event rate 30 times of JUNO
  - Resolution better than 1.7%

- Nylon bag w/ acrylic support (JUNO backup option)
- 10 m² SiPM of 50% PDE, at -50
- LAB+quencher as buffer cryogenic vessel
- DYB Automatic Calibration Unit
Go 700m Underground

Slope tunnel
1340m

Vertical
shaft 581m

Underground
lab space:
~5600 m²
Civil Status as of Summer 2018
Civil Status as of Summer 2018
Experimental Hall Roof
Entering the Experimental Hall
Bottom of the Elevator Shaft
Summary

• The value of theta13 has enabled the possibility of resolving neutrino mass hierarchy in medium-baseline reactor neutrino experiments → JUNO is under construction

• JUNO has been designed to reach an unprecedented energy resolution for such a massive LS detector
  – Unique dual calorimetry
  – An extremely rich physics program, especially antineutrino related fields

• A high-resolution near detector has been proposed to measure the fine structures of the reactor neutrino flux

• JUNO is going forward smoothly and will be ready for data taking in 2021
JUNO Milestones & Schedule

2014:
- International collaboration established
- Start civil construction

2015:
- PMT production line setup
- Start CD parts production

2016:
- Start PMT testing
- TT arrived

2017:
- Start PMT production
- Start CD parts production

2018:
- PMT potting
- Starts Delivery of surface buildings
- Start production of acrylic sphere

2019-2020:
- Electronics production starts
- Civil work and lab preparation completed
- Detector constructing

2021:
- Detector ready for Data taking!

Thanks for your Attention!
The 5-Campus system of SYSU is attracting, training and keeping top-level talents for the Greater Bay Area (Guangdong - Hong Kong - Macao); SYSU in return enjoys resources and opportunities for developments and talent cultivation.
School of Physics: Facts and Vision

Currently: ~85 Faculties

ESI Top 1%; Top 10 in China

Goal: ~150 Faculties

First Class in the World

Traditionally Established
- Theoretical Physics
- Condensed Matter
- Optics

Newly Developed
- Energy Physics
- Soft Condensed Matter

New Research Platforms
- Neutron Science Center
- Ultrafast Laser Platform
- Center for Particle Physics
Surface Facilities: Look into the Near Future……
## Global Efforts Resolving ν Mass Hierarchy

<table>
<thead>
<tr>
<th>Source / Principle</th>
<th>Matter Effect</th>
<th>Interference of Solar&amp;Atm Osc. Terms</th>
<th>Collective Oscillation</th>
<th>Constraining Total Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmospheric ν</td>
<td>Super-K, Hyper-K, PINGU/IceCUBE, ICAL/INO, ORCA/KM3NeT, DUNE</td>
<td>Atm νµ + JUNO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam νµ</td>
<td>T2K, NOνA, T2HKK, DUNE</td>
<td>Beam νµ + JUNO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reactor νe</td>
<td>JUNO, JUNO+Beam νµ</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supernova Burst ν</td>
<td>Super-K, Hyper-K, PINGU/IceCUBE, ORCA/KM3NeT, DUNE, JUNO</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ν during Struc. Form.</td>
<td>Cosmological Data</td>
<td></td>
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</tbody>
</table>
Putting Everything Together (Simulation)

- Assumptions: PMT QE 35%; LS light yield 10.4k photons/MeV and $L_{\text{attn}} = 20\text{m @}430\text{nm}$; 75% coverage is reachable.
Other Physics Potential of JUNO

- Supernova neutrinos
- Diffused supernova neutrinos
- Proton decay $P \rightarrow K^+ + \bar{\nu}$
  \[ \tau > 1.9 \times 10^{34} \text{ yr} \quad (90\% \text{ C.L.}) \]
- Geoneutrinos
  - KamLAND: $30 \pm 7$ TNU
    [PRD 88 (2013) 033001]
  - BOREXINO: $38.8 \pm 12.0$ TNU
    [PLB 722 (2013) 295]
  - JUNO (preliminarily projected): $37 \pm 10\%\text{(stat)} \pm 10\%\text{(syst)}$ TNU
- Dark matter indirect searches
- Solar neutrinos: high demand on the radioactive background purity.
- Atmospheric neutrinos: could potentially aid the MH
**Precision Oscillation Parameters Warranted**

Current precision as in PDG 2018

<table>
<thead>
<tr>
<th>Parameter</th>
<th>best-fit</th>
<th>3σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m^2_{21} \left[10^{-5} \text{ eV}^2\right]$</td>
<td>7.37</td>
<td>6.93 – 7.96</td>
</tr>
<tr>
<td>$\Delta m^2_{31(23)} \left[10^{-3} \text{ eV}^2\right]$</td>
<td>2.56 (2.54)</td>
<td>2.45 – 2.69 (2.42 – 2.66)</td>
</tr>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>0.297</td>
<td>0.250 – 0.354</td>
</tr>
</tbody>
</table>

**JUNO Yellow Book: arXiv:1507.05613**

- Precision <1% measurements
- The only experiment for the solar mixing parameters in the foreseeable future