JUNO – Detector Design and Status

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The JUNO Project – An Overview

Jiangmen Underground Neutrino Observatory

Multi-purpose experiment but with a main focus: Measurement of the Neutrino Mass Ordering using reactor anti-electron neutrinos

Neutrinos from two Nuclear Power Plants
26.6 GW$_{th}$ power by 2020 (35.8 GW$_{th}$ final)

JUNO Central Detector
20 kt Liquid Scintillator Target
The JUNO Collaboration

78 members from 16 countries!  
675 collaborators

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</table>
JUNO physics prospects - neutrino mass ordering and beyond

**Solar Neutrinos**
~ 10000 / day

**Proton Decay Search**
\[ p \rightarrow K^+ + \nu \]

**Reactor Neutrinos**
~ 60 / day

**Supernova Neutrinos**
(burst)
5000 in 10 s for 10 kpc

**Diffuse Supernova Neutrinos**
~ 3 / year

**Atmospheric Neutrinos**
several / day

**Cosmic Muons**
~ 250k / day, \( <E> = 215 \) GeV

**Geo Neutrinos**
~ 1 / day

JUNO Yellow Book
arXiv:1507.05613
The Neutrino Mass Ordering

\[ \Delta m_{ij}^2 = m_i^2 - m_j^2 \]
\[ \Delta m_{21}^2 = 7.5 \times 10^{-5} \text{(eV)}^2 \quad \text{Slow Oscillation!} \]
\[ |\Delta m_{31}^2| = 2.4 \times 10^{-3} \text{(eV)}^2 \quad \text{Fast Oscillation!} \]

The sign and the absolute value of \( \Delta m_{31}^2 \) depend on the Neutrino Mass Ordering!

Solving the Mass Ordering problem is a key for other open questions in neutrino physics:

- \( 0\nu\beta\beta \) decay – Majorana or Dirac neutrinos?
- \( \delta_{\text{CP}} \) in the neutrino sector?
- Octant of \( \theta_{23} \)?
Detection of electron anti-neutrinos

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

Detection via the Inverse Beta Decay (IBD)

Golden Channel for the detection of neutrinos

- High cross section
- Two signal coincidence (\(~ 236 \mu s\))
- \( \nu \) energy can be reconstructed from \( e^+ \) signal
- Threshold of 1.8 MeV
Requirements for the JUNO Detector

Reactor baseline variation: < 0.5 km
JUNO site in Jiangmen meets this requirements!

Energy resolution: \(\sim \frac{3\%}{\sqrt{E(\text{MeV})}}\)
This is a crucial parameter!

Energy scale uncertainty:
Large uncertainties and unknown non-linearity could lead to the wrong mass ordering result!
→ Meticulous Calibration!
→ Double calorimetry (small + large PMTs)

Statistics: 100 kEvents within 6 years!
26.6 GW\(_{\text{th}}\) reactor power
20 kt detector target (\(~ 60 \text{ Evts. / Day}\))
Minimization of the vetoed volume by precise muon track reconstruction

Energy spectrum of the JUNO \(\bar{\nu}_e\) events
(Effect of the energy resolution on the expected signal)
Overall Detector Design and Veto

Central detector:
- Acrylic sphere with liquid scintillator
- 17571 large PMTs (20-inch)
- 25600 small PMTs (3-inch)
- 78% PMT coverage
- PMTs in water buffer

Water Cherenkov muon veto:
- 2400 20” PMTs
- 35 ktons ultra-pure water
- Efficiency > 95%
- Radon control $\rightarrow$ less than 0.2 Bq/m3

Compensation coils:
- Earth magnetic field <10%
- Necessary for 20” PMTs

Top tracker:
- Precision muon tracking
- 3 plastic scintillator layers
- Covering half of the top area

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Daya Bay</th>
<th>Borexino</th>
<th>KamLAND</th>
<th>JUNO</th>
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<tbody>
<tr>
<td>LS Target Mass [t]</td>
<td>8 x 20</td>
<td>~ 300</td>
<td>~ 1000</td>
<td>20000</td>
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<tr>
<td>Collected p.e./MeV</td>
<td>~ 160</td>
<td>~ 500</td>
<td>~ 250</td>
<td>~1200</td>
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<tr>
<td>Energy resolution @ 1 MeV</td>
<td>~ 8.5 %</td>
<td>~ 5 %</td>
<td>~ 6%</td>
<td>~ 3%</td>
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Large PMT Array

- 15000 MCP-PMTs from NNVT (Northern Night Vision Technology)
- 5000 dynode PMTs from Hamamatsu (R12860 HQE)
- 17571 PMTs will read out the scintillation light of the Central Detector
- All PMTs delivered to the JUNO site!
- PMT testing:
  - Acceptance tests finished
  - Tests with final electronics ongoing

<table>
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<tr>
<th>Specifications</th>
<th>Unit</th>
<th>MCP-PMT (NNVT)</th>
<th>R12860 Hamamatsu HQE</th>
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<tbody>
<tr>
<td>Det. Efficiency (QE*CE)</td>
<td>%</td>
<td>26.9% (new Type: 30.1%)</td>
<td>28.1%</td>
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<tr>
<td>Peak to Valley of SPE</td>
<td></td>
<td>3.5, (&gt;2.8)</td>
<td>3, (&gt;2.5)</td>
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<tr>
<td>TTS on the top point</td>
<td>ns</td>
<td>12, (&lt;15)</td>
<td>2.7, (&lt;3.5)</td>
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<tr>
<td>Rise time / Fall Time</td>
<td>ns</td>
<td>RT<del>2, FT</del>12</td>
<td>RT<del>5, FT</del>9</td>
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<tr>
<td>Anode Dark Count</td>
<td>kHz</td>
<td>20, (&lt;30)</td>
<td>10, (&lt;50)</td>
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<tr>
<td>After Pulse Rate</td>
<td>%</td>
<td>1, (&lt;2)</td>
<td>10, (&lt;15)</td>
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<tr>
<td>Radioactivity (glass)</td>
<td>ppb</td>
<td>$^{238}$U: 50, $^{232}$Th: 50, $^{40}$K: 20</td>
<td>$^{238}$U: 400, $^{232}$Th: 400, $^{40}$K: 40</td>
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</tbody>
</table>
PMT Testing Containers (all PMTs):

- Capacity: 36 (-5) PMTs per Container
- Relative PDE Measurement
  - 1 fixed & 4 rotating reference PMTs
- Four containers
- Magnetic shielding: 10% EMF
- Climate control systems
- Two light sources:
  - stabilized LED
  - Picosecond-Laser
- Averaged PDE: 28.7%, (28.1% for dynode PMTs, 28.9% for MCP-PMTs)

Scanning Station (5-10% of PMTs):

- Provide non-uniformity measurement of PMT parameters
- Study dependence of PMT performance on magnetic field
- Provide a tool for precise PMT studies and cross calibration

Two testing containers in Zhongshan (Pan-Asia).

PMT test box with PMT holder

Light sources used in the testing containers

PMT in the scanning station

PDE differences (photocathode)
Double calorimetry

“Always” in photon counting mode

Less non-linearity: calibration of large PMT array

Better dynamic range for high energy signals

Higher granularity of the CD

25600 PMTs in the Central Detector
  • 2.5% coverage
  • Provided by HZC Photonics (Hainan, PR China)

Can effectively help in:
  • Muon tracking (+ shower muon calorimetry)
  • Supernova readout
  • Solar oscillation parameter measurement

Small PMT Array

JUNO custom design: XP72B22
QE 24%, Peak / Valley 3.0, TTS 2-5 ns

Arrangement of large and small PMTs

∼ 200 boxes × 128 PMTs

Under water box provides supply for 128 PMTs (Prototype already built and successfully tested!)
Liquid scintillator purification pilot plants (in Daya Bay)

Purification of LAB in 4 Steps:

- **Al₂O₃ filtration column**: improvement of optical properties
- **Distillation**: removal of heavy metals, improvement of transparency
- **Water Extraction**: removal of radio isotopes from uranium and thorium chain and furthermore of ^{40}K (underground)
- **Steam / Nitrogen Stripping**: removal of gaseous impurities like Ar, Kr, and Rn (underground)

Optical Requirements:

- Light output: \( \sim 10,000 \) Photons / MeV \( \rightarrow \sim 1200 \) p.e. / MeV
- Attenuation length: > 20 m @ 430 nm

Required Radiopurity:

- **Reactor neutrinos**: ^{238}U / ^{232}Th < 10^{-15} g/g, ^{40}K < 10^{-16} g/g
- **Solar neutrinos**: ^{238}U / ^{232}Th < 10^{-17} g/g, ^{40}K < 10^{-18} g/g, ^{14}C < 10^{-18} g/g

**Pilot plants** for all purification steps with a capacity of \( \sim 100 \) l/h were installed in Daya Bay in 2017.

Extensive testing with one of the Daya Bay (DYB) antineutrino detectors (AD1) in 2017-2019!

Publication:
Liquid scintillator purification pilot plants (in Daya Bay)

Optical properties:
During extensive calibrations the recipe of the LS was refined.
Light Yields above 10,000 Photons / MeV were achieved.
Excellent stability of the light yield in the detector was observed during 14 month of measurement.
Preliminary JUNO mixture: LAB + 2.5 g/l PPO + 3mg/l bisMSB
Attenuation length of LAB improved by the purification from ~ 14 m to ~ 28 m @ 430 nm

Radiopurity:
The concentrations of $^{238}$U / $^{232}$Th were determined with the 24 t DYB AD1 exploiting the fast Bi/Po-coincidences of the decay chains.
Results: (Test in 2017)

$$C(^{238}\text{U}) = (7.52 \pm 1.41\text{(sys.)} \pm 0.37\text{(stat.)}) \times 10^{-15}\text{g/g}$$

$$C(^{232}\text{Th}) = (3.24 \pm 1.00\text{(stat.)} \pm 0.66\text{(sys.)}) \times 10^{-15}\text{g/g}$$
Liquid Scintillator purity monitor

Idea:

Detect radioactive contaminated scintillator after purification but before filling it into the acrylic vessel!

Exploit fast coincidences in the $^{238}$U and $^{232}$Th chains!

18 t LS volume ($\varnothing = 3$ m, $H = 3$ m)

Instrumentation:

~68x 20” PMTs for the scintillator
~12x 20” PMTs for the muon veto

Expected Sensitivity (Simulation):

JUNO IBD limit within a few hours
JUNO solar limit possible
Overview of JUNO’s Calibration Systems (including laser calibration system)

ACU (Automatic Calibration Unit)

ROV (Remotely Operated Vehicle)

Guide Tube System

Cable Loop System

Calibration Systems

JUNO TAO - Taishan Antineutrino Observatory

Measure reactor anti-neutrino spectrum with high resolution

- provide model-independent reference for JUNO
- benchmark to test nuclear databases
- provides increased reliability in measured isotopic antineutrino yields
- improve nuclear physics knowledge of neutron-rich isotopes
- shed light on reactor spectrum anomaly (5 MeV bump)
- searching for light sterile neutrinos with a mass ~1 eV
- ~36 x JUNO statistics

TAO Design Features:

- 2.6 ton Gd-LS as target material (1 ton fiducial mass)
- Detector placed at 30 m distance from a 4.6 GWth reactor core
- 10 m² SiPM, with 50% PDE, Coverage: > 95%
- SiPMs and LS cooled down to -50 °C (-60 °C)

Expected Performance:

- ~ 4500 p.e. / MeV collected charge
- Energy Resolution: ~ 1.7% @ 1 MeV, < 1.0% above 3 MeV

Planned to be online when JUNO starts the data taking!
Schedule & Milestones

2014
- Int. Collaboration established!

2015
- PMT production line setup
- Start civil construction
- CD parts R&D

2016
- Start PMT production
- Start CD parts production
- PMT testing
- Top Tracker arrived!
- Daya Bay LS tests

2017
- PMT potting start
- Delivery of surface buildings
- Start production of acrylic sphere
- OSIRIS funded
- TAO working group formed

2018
- PMT testing
- Top Tracker arrived!
- Daya Bay LS tests

2019-20
- Electronics production starts
- Civil work and lab preparation
- Det. construction starts

2021-22
- Det. assembly completed
- Det. filling & commissioning
- TAO construction

Data Taking

Thank you for your attention!
Backup Slides
The Neutrino Mass Ordering

\[ P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta m^2_{21} \frac{L}{4E} - \sin^2 2\theta_{13} \left( \cos^2 \theta_{12} \sin^2 \Delta m^2_{31} \frac{L}{4E} + \sin^2 \theta_{12} \sin^2 \Delta m^2_{32} \frac{L}{4E} \right) \]

\[ \approx 1 - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta m^2_{21} \frac{L}{4E} - \sin^2 \theta_{13} \sin^2 \Delta m^2_{ee} \frac{L}{4E} \]  

\text{for } \Delta m^2_{12} \ll \Delta m^2_{32}

\( \Delta m^2_{ee} \) effective \( \nu \)-mass-squared difference (beat frequency)

With:

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

\text{NO: } |\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}| \]

\text{IO: } |\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}| \]

Different beat frequency \( \Delta m^2_{ee} \) for both orderings!
How to control the energy scale uncertainties?

How to reach <1% uncertainty on the energy scale?

Answer: Meticulous Calibration!
- Many sources over the whole energy range!
- Many positions to keep residual non-uniformity low!

Other experiments already achieved 1% accuracy:
- Daya Bay: ~0.5%, Double Chooz: 0.74%
- Borexino <1% (at low energies), KamLAND 1.4%

\[ \frac{E_{\text{rec}}}{E_{\text{true}}} \text{ for positron interactions} \]

\[ 68 \% \text{ C.L. region constrains the ratio to better than 1\%} \]
Reactor spectrum uncertainties

- Reactor spectrum might show **micro-structure**

- It might **degrade the MO sensitivity** by mimicking the periodic oscillation structures

- A known fine structure does not hurt for the Mass Ordering measurement!
  - Tested with multiple test spectra from an ab-initio calculation (PRL 114, 012502 (2015))

- An **unknown fine structure might be harmful**!
  - Current databases rely on experimental data!
  - No information beyond measured energy resolution in the databases!

Relative differences of 3 synthetic spectra to ILL-data (Huber-Mueller-model)
Sensitivity to the Neutrino Mass Hierarchy

Sensitivity with 100k Events (~ 6 years with 35.8 GWth):

- No external constraints: \( \Delta \chi^2 > 9 \)
- With 1% constraint: \( \Delta \chi^2 > 16 \)

Requirements:

- Energy resolution of < 3% at 1 MeV
- Energy scale uncertainty < 1%
- Reactor core dispersion < 0.5 km

Strong synergy with long-baseline ν program:

\[
\Delta m^2_{ee} - |\Delta m^2_{\mu\mu}| = \pm \Delta m^2_{21} \left( \cos(2\theta_{12}) - \sin(2\theta_{12}) \sin(2\theta_{13}) \tan(\theta_{12}) \cos(\delta) \right)
\]

Sign defined by the Mass Ordering

\( \Delta \chi^2 (MH) \) dependence for different input errors of \( \Delta m^2_{\mu\mu} \)
