Status and Prospects of the JUNO Experiment

Matthias Raphael Stock
on behalf of the JUNO Collaboration

The 17th International Workshop on Tau Lepton Physics (TAU2023), Louisville, 12/07/2023

Technical University of Munich
TUM School of Natural Sciences
Physics Department
Jiangmen Underground Neutrino Observatory

- Multi-purpose experiment currently under construction in South China
- Main goal is the determination of the neutrino mass ordering at 3σ after 6 years data taking by measuring the oscillated electron antineutrino energy spectrum from nuclear reactors.
Civil construction finished in December 2021

- 564 m vertical tunnel
- 700 m depth, 1,800 meter water equivalent

Photo taken in February 2023
Overview of the JUNO Detector

Central Detector
- 20,000 tons of liquid scintillator (LS) in 35.4 m in diameter acrylic sphere, largest in the world
- Unprecedented energy resolution of 3 % at 1 MeV:
  - High light yield of LS: ~10,000 photons per MeV expected
  - High transparency of LS: ~20 m attenuation length at 430 nm
  - High photocoverage of ~78 %: 17,612 large PMTs (20-inch) and 25,600 small PMTs (3-inch)

Water Cherenkov Detector
- 35,000 tons of ultra-pure water in cylinder of 43.5 m in diameter and 44 m in height
- 2,400 large PMTs (20-inch)
- Veto and shielding surrounding radioactivity

Top Tracker
- Combined with CD or WCD, well reconstructed muon sample with >99 % purity → used to calibrate & tune algorithms to improve reconstruction algorithms for CD and WCD of atmospheric muons & veto affected regions

700 m depth to detector center
1,800 meter water equivalent
0.004 Hz/m² muon flux
JUNO is a multi-purpose observatory with a broad physics program.

- **Reactor neutrinos**: ~ 45 IBDs per day
- **Geoneutrinos**: few IBDs per day
- **Atmospheric neutrinos**: several per day
- **Solar neutrinos**:
  - $^8$B ~ 50 per day
  - $^7$Be ~ $10^4$ per day
  - CNO ~ $10^3$ per day
- **Supernova neutrinos**:
  - ~ $10^4$ for CCSN at 10 kpc
- **Diffuse supernova neutrinos**: ~ 2 to 4 IBDs per year

Energy (MeV): 0.1, 1, 10, $10^2$, $10^3$, $10^4$
# List of Members of the JUNO Collaboration

<table>
<thead>
<tr>
<th>Country</th>
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+ Observers: University of Liverpool

74 institutes in 17 countries/regions
~700 collaborators
Jan 2022
Stainless Steel Supporting Structure fully assembled (sub-cm precision)

May 2022
Lifting platform

Aug 2022
Acrylic vessel bonding from top to bottom, transparency > 96% in pure water
Acrylic sphere installed down to equator

inner diameter is \((35.40 \pm 0.04) \text{ mm}\)

thickness is \((124 \pm 4) \text{ mm}\)

radiopurity of \(\frac{^{238}\text{U}}{^{282}\text{Th}}/\frac{^{40}\text{K}}{\text{ppt}} < 1 \text{ ppt}\)

Ongoing PMT installation of CD and WCD
Large Photomultiplier Tubes

Performance testing of more than 20,000 PMTs concerning gain-voltage dependency, dark count rate, peak-to-valley, timing characteristics, pre-/afterpulses…

- 5,000 x 20-inch dynode PMTs from Hamamatsu, Japan
- 12,612 x 20-inch Micro-channel plate (MCP) PMTs for CD and 2,400 MCP-PMTs for WCD from North Night Vision Technology (NNVT), China


- Transit time spread (TTS)
  - Micro-channel plate $\langle \sigma_{TTS} \rangle = 7 \text{ ns}$
  - Dynode $\langle \sigma_{TTS} \rangle = 1.3 \text{ ns}$

- Photo detection efficiency (PDE)
  - Micro-channel plate $\langle \text{PDE} \rangle = 30.1 \%$
  - Dynode $\langle \text{PDE} \rangle = 28.5 \%$
  - All $\langle \text{PDE} \rangle = 29.6 \%$

- Dark count rate (DCR)
  - Micro-channel plate $\langle \text{DCR} \rangle = 15.7 \text{ kHz}$
  - Dynode $\langle \text{DCR} \rangle = 15.8 \text{ kHz}$
  - All $\langle \text{DCR} \rangle = 9.7 \text{ kHz}$

of water-proof potted PMTs

Acrylic cover
Stainless Steel cover

Clearance between PMTs: 3 mm → Assembly precision: < 1 mm

of sub-sample
Large Photomultiplier Tube Electronics Readout Scheme

Full waveform digitization
- High speed: 1 Gsample/s
- High resolution: 14 bits

Two Flash ADC converters
- Low-gain stream: from 1 PE to 100 PE with 1 PE resolution
- High-gain stream: from 100 PE to 1,000 PE with 0.1 PE resolution

For supernova burst
- All triggerless data stored using 2 GB RAM shared by 3 PMTs

Validation and integration tests of the JUNO 20-inch PMT readout electronics
NIM A 1053, 2023, 168322
Commissioning of Large PMTs and Small PMTs

- Regular light-off/light-on tests during detector assembly started
  - **Light off tests**: full data taking and processing chain with PMT HV on
  - **Light on tests**: joint elec./trigger/DAQ/DCS test with PMT HV off

- Very good electronics, shielding and grounding
  - Electronics noise of large PMTs is **2.8 ADC** counts, 4 % of SPE
    ➔ Much better than the design of 10 %
  - Electronics noise of small PMTs is **2.8 ADC** counts, ~5 % of SPE
    ➔ Much lower than the trigger threshold of 1/3 p.e.

- All tested PMTs (710 large PMTs and 3,184 small PMTs) are working well
- More tests will continue being made as installation progresses
Energy Scale Calibration

- Requirement for NMO: < 1% energy linearity and 3% effective energy resolution

- Regular calibration using radioactive sources + pulsed UV laser source by several calibration systems

- 26,500 small (3-inch) PMTs are complementary system to validate large (20-inch) PMTs calibration

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<th>Sources/Processes</th>
<th>Type</th>
<th>Radiation</th>
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<td>$^{137}$Cs</td>
<td>$\gamma$</td>
<td>0.662 MeV</td>
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<tr>
<td>$^{54}$Mn</td>
<td>$\gamma$</td>
<td>0.835 MeV</td>
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<tr>
<td>$^{60}$Co</td>
<td>$\gamma$</td>
<td>1.173 + 1.333 MeV</td>
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<td>$^{40}$K</td>
<td>$\gamma$</td>
<td>1.461 MeV</td>
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<tr>
<td>$^{68}$Ge</td>
<td>$e^+$</td>
<td>annihilation 0.511 + 0.511 MeV</td>
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<td>$^{241}$Am-Be</td>
<td>n, $\gamma$</td>
<td>neutron + 4.43 MeV ($^{12}$C*)</td>
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<td>$^{241}$Am,$^{13}$C</td>
<td>n, $\gamma$</td>
<td>neutron + 6.13 MeV ($^{16}$O*)</td>
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<td>(n,$\gamma$)p</td>
<td>$\gamma$</td>
<td>2.22 MeV</td>
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<tr>
<td>(n,$\gamma$)$^{12}$C</td>
<td>$\gamma$</td>
<td>4.94 MeV or 3.68 + 1.26 MeV</td>
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</table>
Organic Liquid Scintillator of JUNO

- Composition studied for maximal light yield in a pilot plant at Daya Bay

Solvent
LAB (linear alkylbenzene)

Fluor
2.5 g/L PPO (2,5-diphenyloxazole)

Wavelength-shifter
3 mg/L bis-MSB (1,4-bis(2-methylstyryl)benzene)
Before filling JUNO, the liquid scintillator goes through a purification chain.

- **Removal of heavy and high-boiling radioactive metals such as** $^{238}\text{U}$, $^{232}\text{Th}$ and $^{40}\text{K}$
- **Removal of gaseous impurities** such as $^{222}\text{Rn}$, $^{85}\text{Kr}$, $^{39}\text{Ar}$ with water steam and/or $\text{N}_2$
- **Improvement of radio-purity and optical properties** such as more transparency, less absorbance

**Aluminum (Al$_2$O$_3$) filtration plant**
- Improvement of optical properties

**Distillation Plant**
- Removal of $^{238}\text{U}$, $^{232}\text{Th}$ and $^{40}\text{K}$

**Water Extraction**
- Removal of $^{238}\text{U}$, $^{232}\text{Th}$ and $^{40}\text{K}$

**Stripping Plant**
- Removal of gaseous impurities such as $^{222}\text{Rn}$, $^{85}\text{Kr}$, $^{39}\text{Ar}$ with water steam and/or $\text{N}_2$
Radiopurity during filling of JUNO will be validated by the pre-detector OSIRIS – Online Scintillator Internal Radioactivity Investigation System.

For IBD-based physics program

\[ \leq 10^{-15} \text{ g/g} \]

For solar neutrino measurements

\[ \leq 10^{-16} \text{ g/g} \]

The design and sensitivity of JUNO’s scintillator radiopurity pre-detector OSIRIS


Potential for a precision measurement of solar pp neutrinos in the Serappis experiment


by measuring coincidence decays of

\[ ^{214}\text{Bi}-^{214}\text{Po} (\tau \sim 164 \mu s) \]

\[ ^{212}\text{Bi}-^{212}\text{Po} (\tau \sim 0.43 \mu s) \]

OSIRIS raises alert within hours if too unpure for IBD measurements.

Potential for a precision measurement of solar pp neutrinos in the Serappis experiment

JUNO-TAO - Taishan Antineutrino Observatory

Satellite detector of JUNO at ~ 44 m from Taishan reactor core 1

- High-precision measurement of the unoscillated reactor antineutrino energy spectrum, ~ 1,500 IBD events per day
- Providing model-independent reference spectrum for the determination of the neutrino mass ordering in JUNO
- Benchmark measurement to test nuclear databases

- **Energy resolution < 2 % at 1 MeV (4,500 P.E. / MeV)**
  - 2.8 ton detector using gadolinium-loaded liquid scintillator at ~ 50°C, 1.8 m in diameter acrylic sphere
  - ~ 10 m² SiPMs used to achieve ~ 100 % coverage, > 50 % photon detection efficiency → cooled down to -50°C to further lower dark noise
JUNO-TAO - Taishan Antineutrino Observatory

TAO built and tested at IHEP to be transferred to Taishan power plant

Expected performance

- Reactor antineutrino spectral shape uncertainty
- 3-years-TAO-based (arXiv:2005.08745)
- 6-years-TAO-based (arXiv:2005.08745)
- DYB-based (Phys. Rev. Lett. 123, 111801)
- JUNO Yellow Book (J. Phys. G: 43 030401)
JUNO will detect reactor electron antineutrinos via inverse beta decay (IBD)

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

- Prompt + delayed signal: large background suppression
- Reaction threshold: 1.8 MeV
- Proxy for antineutrino energy:
  \[ E_{\text{vis}}(e^+) \approx E(\bar{\nu}) - 0.8 \text{ MeV} \]
JUNO will determine the neutrino mass ordering at $3\sigma$ after 6 years data taking.

Measuring the energy spectrum in unprecedented resolution of $3\%$ at 1 MeV and $<1\%$ energy linearity

Fit spectrum with both normal ordering and inverted ordering hypotheses and compare:

$$\Delta \chi^2_{NO} = |\chi^2_{min}(NO) - \chi^2_{min}(IO)|$$
Sub-percent Precision Measurement of Neutrino Oscillation Parameters

- Simultaneous measurement of solar and atmospheric oscillation modes for the first time

Unitarity test of PMNS matrix possible

- \[ \Delta m_{31}^2 \times 10^{-3} \, \text{eV}^2 \]
  - Central Value: 2.5283
  - PDG2020: ±0.034 (1.3%)
  - 100 days: ±0.021 (0.8%)
  - 6 years: ±0.0047 (0.2%)
  - 20 years: ±0.0029 (0.1%)

- \[ \Delta m_{21}^2 \times 10^{-5} \, \text{eV}^2 \]
  - Central Value: 7.53
  - PDG2020: ±0.18 (2.4%)
  - 100 days: ±0.074 (1.0%)
  - 6 years: ±0.024 (0.3%)
  - 20 years: ±0.017 (0.2%)

- \[ \sin^2 \theta_{12} \]
  - Central Value: 0.307
  - PDG2020: ±0.013 (4.2%)
  - 100 days: ±0.0058 (1.9%)
  - 6 years: ±0.0016 (0.5%)
  - 20 years: ±0.0010 (0.3%)

- \[ \sin^2 \theta_{13} \]
  - Central Value: 0.0218
  - PDG2020: ±0.0007 (3.2%)
  - 100 days: ±0.010 (47.9%)
  - 6 years: ±0.0026 (12.1%)
  - 20 years: ±0.0016 (7.3%)

*Chinese Phys. C 46 123001 (2022)*
Further Physics Topics

Atmospheric neutrinos
several per day

Enhancing NMO sensitivity
> 3 σ after 6 years

JUNO sensitivity to low energy atmospheric neutrino spectra

Solar neutrinos

\[ ^8\text{B} \sim 50 \text{ per day} \]
\[ ^7\text{Be} \sim 10^4 \text{ per day} \]
\[ \text{CNO} \sim 10^3 \text{ per day} \]

JUNO sensitivity to \(^7\text{Be}\), pep, and CNO solar neutrinos
*JCAP10(2023)022 (2023)*

Feasibility and physics potential of detecting \(^8\text{B}\) solar neutrinos at JUNO
*Chinese Phys. C 45 023004 (2021)*

Supernova neutrinos

\[ \sim 10^4 \text{ for CCSN at 10 kpc} \]

Real-time Monitoring for the Next Core-Collapse Supernova in JUNO
*arXiv 2309.07109 (2023), accepted by JCAP*

Neutrino physics with JUNO

JUNO physics and detector
*Prog. in Part. and Nucl. Phys. 123 (2022) 103927*
Summary

• JUNO will be the largest liquid scintillator detector in the world with unprecedented energy resolution.
• JUNO will determine the neutrino mass ordering with 3σ after 6 years of data taking using reactor antineutrinos.
• JUNO will be an observatory for geoneutrinos, atmospheric neutrinos, solar neutrinos, supernova neutrinos, proton decay, and other exotic new physics.

<table>
<thead>
<tr>
<th>Year</th>
<th>Project approved</th>
<th>Collaboration formed</th>
<th>Civil construction</th>
<th>Start of acrylic sphere production</th>
<th>Detector construction, installation and commissioning</th>
<th>Liquid scintillator filling, detector completion and start of data taking</th>
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Thank you for your attention!
**Top Tracker (TT)**

- Constituted by decommissioned 496 OPERA modules
- Covers ~60% of the Central Detector (CD) & Water Cherenkov Detector (WCD)
- 30% of all atmospheric muons passing through the CD pass through all 3 layers of the TT
  → Veto, especially at chimney region
  → Remaining WCD and CD
- TT wall: two planes of plastic scintillator strips, one per transverse direction (63 TT walls)
- New electronics due to high rate produced by high rock radioactivity, threshold 1/3 P.E.: full detector rate ~8 MHz time coincidence in single TT wall & in 3 aligned walls of different layers → ~2 kHz compared to ~4 Hz of atmospheric muons
- Offline 3D reconstruction of muon track → few Hz
- 93% trigger efficiency & 0.2° median angular resolution (20 cm at bottom of WCD)

**The JUNO experiment Top Tracker**

*NIM A 1057, 168680* (2023)

700 m depth to detector center
1,800 meter water equivalent
15 per hour per m² muon flux

- Combined with CD or WCD, TT provides well reconstructed muon sample with >99% purity
  → used to calibrate & tune algorithms to improve reconstruction algorithms for CD and WCD of atmospheric muons & veto affected regions
$\Delta \chi^2 = \chi^2_{\text{false}} - \chi^2_{\text{true}}$

- two independent fits for two NMO assumptions

PMNS parameters free in the fit:
$\Delta m^2_{21}, \sin^2 \theta_{12}, \Delta m^2_{31}, \sin^2 \theta_{13}$

Nuisance parameters (for JUNO and TAO):
- Normalization
- Background rates
- Energy resolution
- Detector response non-linearities
- …
Breakdown of Systematics Effects for $\Delta \chi^2$

<table>
<thead>
<tr>
<th>Uncertainties</th>
<th>$\Delta \chi^2_{\text{min}}$</th>
<th>$\Delta \chi^2_{\text{min}}$ change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistics</td>
<td>11.3</td>
<td>0.0</td>
</tr>
<tr>
<td>Stat. + Reference spectrum</td>
<td>10.7</td>
<td>-0.6</td>
</tr>
<tr>
<td>+ Nonlinearity</td>
<td>10.3</td>
<td>-0.4</td>
</tr>
<tr>
<td>+ Geoneutrinos</td>
<td>9.8</td>
<td>-0.5</td>
</tr>
<tr>
<td>+ World reactors</td>
<td>9.5</td>
<td>-0.3</td>
</tr>
<tr>
<td>+ Accidental</td>
<td>9.2</td>
<td>-0.3</td>
</tr>
<tr>
<td>+ $^9\text{Li}/^8\text{He}$</td>
<td>9.1</td>
<td>-0.1</td>
</tr>
<tr>
<td>+ Other backgrounds</td>
<td>9.0</td>
<td>-0.05</td>
</tr>
<tr>
<td>Total</td>
<td>9.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>
Geoneutrinos

- Originate from $\beta$-decays of radioactive elements in the interior of the Earth
- Only $^{238}$U and $^{232}$Th component can be detected via IBD due to the 1.8 MeV reaction threshold
- Reactor neutrinos constitute the largest background

Expected results:
JUNO will collect the largest dataset of geoneutrinos in about 1 year (1–2 events / day)

- Precision of total geoneutrino signal with Th/U mass ratio fixed to 3.9:
  $\sim$8% in 10 years
- Precision of U and Th components in 10 years:
  $^{232}$Th $\sim$35%
  $^{238}$U $\sim$30%
  $^{232}$Th+$^{238}$U $\sim$15%
  $^{232}$Th/$^{238}$U $\sim$55%
- Separation of crust and mantle signal

Existing measurements:
- Borexino: 17% [PRD 2020]
- KamLAND: 15% [GRL 2022]
Atmospheric Neutrinos

- Neutrino oscillations and NMO can be studied using atmospheric neutrinos complementary to reactor neutrinos
- > 3σ after 6 years
- Additional measurement of sin²θ_{23}

- Flavor-dependent energy spectrum can be measured in 0.1 GeV - 10 GeV energy range
Solar Neutrinos

- Nuclear fusion in Sun produces $\nu_e$
- Probe solar metallicity
- Elastic scattering detection channel: $\nu + e^- \rightarrow \nu + e^-$
- Cosmogenic background (muons) → triple-fold coincidence techniques, e.g. for $^{11}\text{C}$
- External (detector) backgrounds → fiducial volume
- Internal backgrounds (radioactivity) → pure scintillator, spectral fit

- Minimal requirement for JUNO NMO
- Best radiopurity reached by Borexino (BX)

First CNO measurement without external constraints

$^{7}\text{Be}$

$^{238}\text{U}$ and $^{232}\text{Th}$:
- Very Low
- Low
- Medium
- High

Background scenario
- BX stat.
- BX stat. + syst.
Solar Neutrinos

Elastic scattering detection channel:
\[ \nu + e^- \rightarrow \nu + e^- \]

High energy $^8$B neutrinos
- Possibility to use CC and NC interactions on $^{13}$C
- Unprecedented detection threshold at 2 MeV
- More precision: contribute to solve metallicity puzzle
- Spectral shape: study day/night asymmetry + other NSI

Feasibility and physics potential of detecting $^8$B solar neutrinos at JUNO
Chinese Phys. C 45 023004 (2021)
Core Collapse Supernova Burst Neutrinos

Inverse beta decay: $\bar{\nu}_e + p \rightarrow e^+ + n \sim 5,000$ events

Elastic neutrino-electron scattering: $\nu + e^- \rightarrow \nu + e^- \sim 300$ events

Elastic neutrino-proton scattering: $\nu + p \rightarrow \nu + p \sim 2,000$ events

CCSN flux from all neutrino flavors with high statistics $\rightarrow$ constrain CCSN physics

Multi-messenger Astronomy

- Multi-messenger (MM) trigger:
  - Lower energy threshold ($\sim O(10 \text{ keV})$)
  - Increase signal statistics
  - All triggerless data stored using 2 GB RAM shared by 3 PMTs

- JUNO as powerful neutrino telescope for transient MM observations
- Major player in the next-generation Supernova Early Warning System (SNEWS 2.0)

JUNO physics and detector

*Prog. in Part. and Nucl. Phys. 123 (2022) 103927*
Diffuse Supernova Neutrino Background

• Integrated neutrino signal from all supernovae (SNe) explosions in the Universe
• Encodes average core-collapse SN neutrino spectrum, cosmic star formation rate, fraction of failed black hole forming SNe

Before background rejection

After pulse shape discrimination and triple coincidence cut

Prospects for detecting the diffuse supernova neutrino background with JUNO

\begin{align*}
\bar{\nu}_e + p &\rightarrow e^+ + n
\end{align*}

• ~ 2 to 4 IBDs events per year
• Expected significance:
  \begin{itemize}
    \item after 3 years \(\rightarrow 3\ \sigma\) sensitivity
    \item after 10 years \(\rightarrow 5\ \sigma\) sensitivity
  \end{itemize}

• Non-observation would still improve current best limits and exclude significant region of model parameter space
Diffuse Supernova Neutrino Background

Prospects for detecting the diffuse supernova neutrino background with JUNO JCAP 10 (2022) 033 (2022)
Proton Decay

- Large number of protons in 20 kton scintillator
- SUSY-favoured decay:
  Time-correlated triple coincident signature

\[
p \rightarrow \bar{\nu} + K^+ \\
K^+ \rightarrow \nu_\mu + \mu^+ \\
\mu^+ \rightarrow \nu_e + \bar{\nu}_\mu + e^+ 
\]

- Rejecting atmospheric neutrino background

**Expected sensitivity of JUNO:**
*Chinese Phys. C 47 113002 (2023)*

- at 90% C.L. with 200 kton \(\times\) years
  in 10 years of data taking

- at 90% C.L. with 260 kton \(\times\) years

**Super-Kamiokande**
*Phys. Rev. D 90, 072005 (2014)*

- \(\Delta T_{\text{true}} = 11.6 \text{ ns} \)
- \(\Delta T_{\text{true}} = 11.6 \text{ ns} \)
- \(E_e = 119.6 \text{ MeV} \)
- \(E_\mu = 146.3 \text{ MeV} \)
- \(\chi^2/\text{ndf} = 167.0/145 \)
Sterile Neutrinos

Sensitivity at the $\Delta m^2$ region of $0.05 - 1\ eV^2$: complimentary to the longer baseline experiments
Indirect Dark Matter

• Self-annihilation of dark matter in the Milky Way
• IBD channel
• Expected limit for the range 15 - 100 MeV: $1.1 \times 10^{-25} \text{ cm}^3 \text{ s}^{-1}$ in 10 years

Detection in the IBD channel
PSD for atmo-nu rejection
15-100 MeV range

JUNO limit in 10 years
(in terms of thermally averaged self-annihilation rate)

$$\langle \sigma v \rangle = 1.1 \times 10^{-25} \text{ cm}^3 \text{ s}^{-1}$$