The JUNO experiment

T2K-JUNO-HK group @ LLR

(M. Buizza Avanzini, O. Drapier, J. Imber, M. Gonin, Th. A. Mueller)

R. Pain Visit

LLR, 26/05/2015
Neutrino Oscillation Matrix

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= \begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \theta_{23} & \sin \theta_{23} \\
0 & -\sin \theta_{23} & \cos \theta_{23}
\end{pmatrix}
\begin{pmatrix}
\cos \theta_{13} & 0 & e^{i\delta} \cos \theta_{13} \\
0 & 1 & 0 \\
-e^{i\delta} \sin \theta_{13} & 0 & \cos \theta_{13}
\end{pmatrix}
\begin{pmatrix}
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-\sin \theta_{12} & \cos \theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

\(\theta_{\text{atm}}\) \hspace{1cm} \(\theta_{13}, \delta\) \hspace{1cm} \(\theta_{\text{sol}}\)

SuperK., K2K, Minos
\(\sin^2 \theta_{23} \ (\text{NH}) = 0.44 \ (7\%)\)
\(|\Delta m^2_{23}| = 2.43 \times 10^{-3} \text{ eV}^2 \ (3\%)\)

Double Chooz, RENO, DayaBay, T2K
\(\sin^2 \theta_{13} \ (\text{NH}) = 0.023 \ (9\%)\)

Homestake, Sage, Gallex/GNO SuperK., SNO, Borexino, Kamland
\(\sin^2 \theta_{12} = 0.308 \ (5\%)\)
\(\Delta m^2_{21} = 7.54 \times 10^{-5} \text{ eV}^2 \ (3\%)\)


\(\delta_{\text{CP}}?\)

\(\Rightarrow\) Mass hierarchy? \(\Leftarrow\)

\((\Delta m^2_{31} > 0 \text{ or } < 0)\)?
Why the MH?

Mass Hierarchy (MH)
1. helps in to define the goal of searching for $\beta\beta0\nu$
2. Is crucial factor for measuring the lepton $\delta_{CP}$
3. Is a key parameter of neutrino astronomy (supernova nucleosynthesis) and neutrino cosmology
4. …
The JUNO Experiment

- Jiangmen Underground Neutrino Observatory, a multiple-purpose neutrino experiment, approved in Feb. 2013. ~ 300 M$.

- 20 kton LS detector
- 3% energy resolution
- 700 m underground
- Rich physics possibilities
  - Reactor neutrino for Mass hierarchy and precision measurement of oscillation parameters
  - Supernovae neutrino
  - Geoneutrino
  - Solar neutrino
  - Atmospheric neutrino
  - 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, Jiang Men city, Guangdong Province

by 2020: 26.6 GW (6 YJ + 2 TS cores)
Antineutrino Detection

Anti-ν are observed via Inverse Beta Decay (IBD)

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

The energy spectrum is a convolution of flux and cross section \( (E_{\text{thr}} = 1.8 \text{ MeV}) \)

**Signal signature** is given by:

* **Prompt** photons from \( e^+ \) ionisation and annihilation \( (1-8 \text{ MeV}) \)
  \[ E_{\text{VIS}} \approx E_\nu - (M_n - M_p) + m_e \]

* **Delayed** photons from n capture on H:
  \( \Delta t \approx 200 \mu s, E=2.2 \text{MeV} \) in about 1m
MH determination with reactor anti-$\nu$ (1)

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

3 oscillation frequencies:
- Low frequency $\Delta m_{21}^2$ ($\sim 7.54 \times 10^{-5}$ eV$^2$)
- High frequencies: $\Delta m_{31}^2$ and $\Delta m_{32}^2$ ($2.43 \times 10^{-3}$ eV$^2$)
The goal is to determine the highest frequency

Shifted spectra by a phase \( \phi \), energy related

Precision energy spectrum measurement interference between the term in \( \Delta m^2_{31} \) and in \( \Delta m^2_{32} \)
MH sensitivity

Ingredients...
✓ 20kt valid target mass ⊕ 36GW reactor power ⊕ 6-years data
✓ 3% energy resolution ⊕ ~1% energy scale uncertainty assumed
✓ Systematics

• ~3σ → spectral measurement with no Δm² external constraint
• ~4σ → external Δm² measured to ~1% error

(νμ disappearance with ν-beam off-axis)

Δm² @~1% by T2K+NOvA combined analysis [1312.1477]
σ_E: Fundamental design parameter

- **ENERGY RESOLUTION**: 3% @ 1MeV
- **HUGE LIGHT YIELD**
  - Highest light collection 1200 p.e./MeV
  - Highest photocathode coverage (~80%)
  - High detection efficiency PMTs (DE ~ 35%)
  - Attenuation length ~ 20m
- **Detector uniform response and symmetrical** (sphere)
- **Low electronics & light noise** (radio-purity)
  - Never achieved before!

<table>
<thead>
<tr>
<th></th>
<th>KamLAND</th>
<th>Borexino</th>
<th>Daya Bay</th>
<th>JUNO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass [t]</td>
<td>~1000</td>
<td>~300</td>
<td>~170</td>
<td>20000</td>
</tr>
<tr>
<td>Energy resolution</td>
<td>6%/√E</td>
<td>5%/√E</td>
<td>7.5%/√E</td>
<td>3%/√E</td>
</tr>
<tr>
<td>Light yield [p.e./MeV]</td>
<td>250</td>
<td>500</td>
<td>200</td>
<td>1200</td>
</tr>
</tbody>
</table>
Detector Concept

Challenges:

- Engineering: mechanics, safety, lifetime, ...
- PMT: high QE, high coverage
- LS: high transparency, low background

Top muon veto: plastic scintillator strips
LS: 20 kton LAB based
LS container: acrylic or balloon?
Buffer: 6 kton mineral oil or water?
PMTs: 15000 20” PMTs for a ~80% coverage
Buffer/PMT support: Stainless steel structure or sphere?
Water Cherenkov veto: 20 kton water
PMTs: 1500 20” veto PMTs
1. Background reduction/control: Top Tracker (simulation + electronics)
2. Energy resolution optimisation: Central Detector (simulation)
Cosmogenic Background

**Cosmic $\mu$ flux @ JUNO**
- Overburden: ~700 m
- $<E_\mu>$: 214 GeV
- $\mu$ rate: 0.0031 Hz/m²
- Expected $\mu$ in the CD: 3 Hz
- Expected signal: 60-80/day

### Table of Isotopes

<table>
<thead>
<tr>
<th>Isotopes</th>
<th>$E_{max}^\beta$ (MeV)</th>
<th>$T_{1/2}$ (s)</th>
<th>Rate (per day)</th>
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<tbody>
<tr>
<td>$^{6}$He</td>
<td>3.51 ($\beta^-$)</td>
<td>0.807</td>
<td>544</td>
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<td>$^{7}$Be</td>
<td>0.861 ($\beta^-$)</td>
<td>53.24 day</td>
<td>5438</td>
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<td>$^{8}$Li</td>
<td>16.0 ($\beta^-$)</td>
<td>0.840</td>
<td>938</td>
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<tr>
<td>$^{8}$B</td>
<td>-</td>
<td>0.77</td>
<td>225</td>
</tr>
<tr>
<td>$^{9}$Li/$^3$He</td>
<td>13.6 ($\beta^-+n$)</td>
<td>0.18/0.12</td>
<td>94/11</td>
</tr>
<tr>
<td>$^9$C</td>
<td>16.0 ($\beta^+$)</td>
<td>0.13</td>
<td>30</td>
</tr>
<tr>
<td>$^{10}$Be</td>
<td>0.556 ($\beta^-$)</td>
<td>1.51e6 year</td>
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<td>19.3</td>
<td>482</td>
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<td>$^{11}$Li</td>
<td>20.6</td>
<td>0.009</td>
<td>0.06</td>
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<tr>
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<td>13.8</td>
<td>24</td>
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<tr>
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<td>0.96 ($\beta^+$)</td>
<td>1221</td>
<td>0.19 Hz</td>
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<td>11.7 ($\beta^-$)</td>
<td>0.021</td>
<td>0.45</td>
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<tr>
<td>$^{12}$B/$^{12}$N</td>
<td>16.0 ($\beta^-$)</td>
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<td>965/17</td>
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<tr>
<td>$^{13}$N</td>
<td>1.20 ($\beta^+$)</td>
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<td>19</td>
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<td>13</td>
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The JUNO cosmic muon tracker will help enormously to evaluate the contribution of the cosmogenic background to the signal.

The baseline of the JUNO Top Tracker is the OPERA Target Tracker (TT)

**Muon Top Tracker using Opera**

Multianode PMT

One strip view

One Opera xy wall
Three considered geometries with
3 layers v1
3 layers v2
4 layers

Geometries (1)

3 walls
Vertical space between walls = 3 m (2 x 1.5 m)
Water tank
Central detector
62 walls

4 walls
Vertical space between walls = 3 m (3 x 1 m)
2 layers above chimney
4 layers each
58 walls

3 walls configuration 2
Vertical space between walls = 3 m (2 x 1.5 m)
2 layers above chimney
3 layers each

Side view of conf 3walls v2

Z [m]

X [m]
Study on the Rock Radioactivity

Abundances measured on a rock sample from the JUNO site:

<table>
<thead>
<tr>
<th>Element</th>
<th>Abundance</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{232}$Th</td>
<td>$\sim 105$ Bq/kg</td>
<td>$1.11 \times 10^9$ Hz</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>$\sim 110$ Bq/kg</td>
<td>$1.17 \times 10^9$ Hz</td>
</tr>
<tr>
<td>$^{40}$K</td>
<td>$\sim 1340$ Bq/kg</td>
<td>$1.42 \times 10^{10}$ Hz</td>
</tr>
</tbody>
</table>

Fake muons estimation for different configurations and thresholds:

<table>
<thead>
<tr>
<th>Config.</th>
<th>N xy coinc.</th>
<th>0.33p.e. OR</th>
<th>1 p.e. OR</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 layers</td>
<td>2</td>
<td>$1.6E6 \ (\mu: 2.72)$</td>
<td>$3.6E5 \ (\mu: 2.72)$</td>
</tr>
<tr>
<td>3 layers</td>
<td>3</td>
<td>$21.1 \ (\mu: 2.3)$</td>
<td>$2.2 \ (\mu: 2.22)$</td>
</tr>
<tr>
<td>4 layers</td>
<td>2</td>
<td>$4.6E5 \ (\mu: 2.02)$</td>
<td>$1.0E5 \ (\mu: 2.01)$</td>
</tr>
<tr>
<td>4 layers</td>
<td>3</td>
<td>$15.0 \ (\mu: 1.85)$</td>
<td>$1.4\mu \ (\mu: 1.83)$</td>
</tr>
</tbody>
</table>
Read out and Trigger

<table>
<thead>
<tr>
<th>RATES (Hz/PMT)</th>
<th>0.33 pe : L or R</th>
<th>1 pe : L or R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plane 1</td>
<td>~ 53k</td>
<td>~ 36k</td>
</tr>
<tr>
<td>Plane 0</td>
<td>~ 48k</td>
<td>~ 33k</td>
</tr>
</tbody>
</table>

MAROC3
Multi Anode Read Out Chip v3

Development of an online "xy trigger" ➔ rate reduction of a factor 10

1st level Trigger board

**IIPHC**
The challenge of the energy resolution

\[ \Delta m_{31}^2 (\text{IO}) \neq \Delta m_{31}^2 (\text{NO}) \implies \delta \sim 3\% \text{ (i.e. } \delta m^2 / \Delta m^2) \]

\[ \sigma_E / E = \sqrt{\left( \frac{a}{\sqrt{E}} \right)^2 + b^2 + \left( \frac{c}{E} \right)^2} \approx \sqrt{\left( \frac{a}{\sqrt{E}} \right)^2 + \left( \frac{1.6 b}{\sqrt{E}} \right)^2 + \left( \frac{c}{1.6 \sqrt{E}} \right)^2} \]

Generic form of \( \sigma_E \)
- a: statistical term
- b: constant term
- c: noise term

Requirement:
\[ \sqrt{(a)^2 + (1.6 \times b)^2 + \left( \frac{c}{1.6} \right)^2} \leq 3\% \]
The energy resolution (goal 3% @ 1MeV)

Constant term 1.6 times more important than stochastic term → systematic to be under control!

Exercise:
Extrapolation from Double Chooz

\[
\frac{\sigma}{E_{\text{vis}}} = \sqrt{\frac{a^2}{E_{\text{vis}}}} + \frac{b^2}{E_{\text{vis}}} + \frac{c^2}{E_{\text{vis}}}
\]

\(\text{JUNO}^* \) [non-stochastic terms like DC]: 3.8% @ 1MeV
\(\text{JUNO}^* \) [non-stochastic 2x DC better]: 3.2% @ 1MeV
\(\text{JUNO}^* \) [non-stochastic 6x DC better]: 2.8% @ 1MeV
\(\text{JUNO}^* \) [1.2kPE/MeV only stochastic]: 2.7% @ 1MeV

\(\text{not a fit}\)

can we reach the \(\sigma(E)/E \leq 3\% \) (total)?

we reach \(\sigma(E)/E\) (stochastic) \(\leq 3\%\)! [i.e. 1.2kPE/MeV feasible by MC]

can we reach \(\sigma(E)/E\) (non-stochastic) improve by 4x wrt today’s values?
(current detector design → good enough?)
Calorimetry regimes in JUNO

Illumination level per PMT varies by ~100x from center(⊙) to edge(⦾) Ω (solid angle) effects [20” PMT ⊕ huge Light Yield]

Energy reconstruction effects (including readout effect) → lead to large non-linearity effects

Strong dependence on the energy and on the position ➔
Non-linearity ⊕ Non uniformity

Energy via Photon Counting (PC) Estimator
Energy via Charge Integration (QI) Estimator
Multi-Calorimetry Proposal

Adding 3 inch PMTs in the space between the «large PMTS»...

Energy(PC) & Energy (Cl) are complementary...

~1.2kPE/MeV [~80% coverage]
(stochastic $\rightarrow$ $\sim 3\% /\sqrt{E}$)

~100*PE/MeV [~10% coverage]
(stochastic $\rightarrow$ $\geq 10\% /\sqrt{E}$)

~3"

Integration Window

single-PE (IBD spectrum)

Large PMTs

TRUE RECO Corrected

PRELIMINARY!!!!

Energy linearity improvement by adding small PMTs
Cosmic muons ~ 250k/day

Atmospheric $\nu$ several/day

Geo-neutrinos 1-2/day

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

Supernova $\nu$ ~ 5k in 10s for 10kpc

JUNO Physics Program

36 GW, 53 km

reactor $\nu$, ~ 60/day

20kt LS

700 m

Cosmic muons ~ 250k/day

0.003 Hz/m²

215 GeV

10% multiple-muon

Geo-neutrinos 1-2/day
Summary: JUNO @ LM

1. TT design optimisation  
   Done/ongoing
2. TT trigger design  
   Started
3. TT DAQ test setup (portable)  
   Started
4. 3” PMTs option study/optimisation  
   On going
5. Participation in the data analysis  
   Future