Physics prospects of the JUNO experiment

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For the JUNO Collaboration
JUNO is a “medium-baseline” (53km) reactor neutrino experiment located in China, under construction (data taking foreseen in 2020).

- JUNO will be the largest Liquid Scintillator detector ever built (20kt).
- Goals: Measurement of the neutrino mass hierarchy (NMH) and oscillation parameters + astroparticle and rare processes.

JUNO = Jiangmen Underground Neutrino Observatory

What is JUNO?

Yangjiang and Taishan under construction by 2020: 26.6 GW

700 m overburden

20 kt

53 km

53 km

2.5 h drive
Neutrino Mass hierarchy (NMH)

The electron antineutrino survival probability in vacuum:

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

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

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

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

\[ \Delta_{ij} = 1.27 \Delta m^2_{ij} L/E \]

Depending on the NMH, the oscillation frequency differs:

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

NH: \[ |\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}| \quad \omega P_{31} > \omega P_{32} \]

IH: \[ |\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}| \quad \omega P_{31} < \omega P_{32} \]

The L/E spectrum contains the NMH information

Key issues:
- energy resolution and energy scale
- Large statistics
JUNO Collaboration

EUROPE (30)
- Armenia (1)
  YPI Erevan
- Belgium (1)
  ULB Brussels
- Czech (1)
  Charles U.
- Finland (1)
  U. Oulu
- France (6)
  APC Paris
  CENBG France
  CPPM Marseille
  IPHC Strasbourg
  LLR Paris
  Subatech Nantes
- Germany (7)
  FZ Julich
  RWTH Aachen
  TUM Munich
  U Hamburg
  IKP FZI Jülich
  U Mainz
  U Tuebingen
- Latvia (1)
  IECS Riga
- Italy (8)
  INFN Catania
  INFN-Frascati
  INFN-Ferrara
  INFN-Milano
  INFN-Bicocca
  INFN-Padova
  INFN-Perugia
  INFN-Roma3
- Russia (3)
  JINR Dubna
  INR Moscow
  MSU Moscow
- Slovakia (1)
  Comenius U

ASIA (37)
- China (33)
  BISEE
  BNU
  CAGS
  CQU
  CIAE
  DGUT
  ECUST
  Guangxi
  HIT
  IHEP
  IMP
  CAS
  Jilin U
  Jinan U
  Nanjing U
  Nankai U

- Natl. CT U
- Natl. Taiwan U
- Natl. United U
- NCEPU
- Pekin U
- Shandong U
- Shanghai JTU
- Sichuan U
- SUT
- Natl. CT U
- SYSU
- UCAS
- USTC
- U. of S. China
- Wuhan
- Wuyi
- Xiamen U
- Xi’an JTU

AMERICA (5)
- PUCC Chile
- UTFSM Chile
- Maryland U
  (2 groups)
- UEL Brazil
- Thailand SUT
- Thailand CU
- Thailand NARIT
- Pakistan PINST

72 institutes
553 members

The 10th JUNO Collaboration Meeting
July 17-21, 2017, IHEP Beijing
Today’s presentation

- (Short introduction to) The JUNO detector
- The neutrino mass hierarchy measurement
- Other physics programs
The JUNO detector

Only the general concepts here
Next talk: Design and Status of the JUNO experiment
by Pedro Ochoa
**Detector design**

**Central detector:**
Large volume of Liquid Scintillator (LS) → for the statistics

- **Muon veto:**
  - Top Tracker (The OPERA TT is re-use as Top Tracker for JUNO)
  - Water Cherenkov Veto
  - 20kt water and 2000 20” PMTs

- **Stainless steel**
- **Acrylic sphere (35.4 m diameter)**
  Filled with 20kt LS
  18000 20” PMTs and 25000 3” PMTs (double calorimetry)
  High light coverage → for energy resol.

- **Magnetic Field Compensating Coil**

**Electronics**

**Calibration**
4-complementary calibration systems (1D, 2D, and 3D)
Neutrino detection

Neutrinos are observed via Inverse Beta Decay (IBD):

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]
\[ \tau \simeq 200 \mu s \]
\[ n + p \rightarrow d + \gamma \]

\[ E_{\bar{\nu}_e} \simeq E_{e^+} + E_n + (M_n - M_p) + m_{e^+} \]

- Prompt photons from \( e^+ \) ionisation and annihilation (1-8 MeV).
- Delayed photons from \( n \) capture on Hydrogen (2.2 MeV).
- Time (\( \Delta t \sim 200 \mu s \)) and spatial correlation.

\[ \rightarrow E : (2 \text{ to } 8) \text{ MeV} \]

The signal signature is given by:

- Very clean signature
## Detector performance goals

<table>
<thead>
<tr>
<th></th>
<th>Daya Bay</th>
<th>BOREXINO</th>
<th>KamLAND</th>
<th>RENO-50</th>
<th>JUNO</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Target Mass</strong></td>
<td>20t</td>
<td>~300t</td>
<td>~1kt</td>
<td>~18kt</td>
<td>~20kt</td>
</tr>
<tr>
<td><strong>PE Collection</strong></td>
<td>~160 PE/MeV</td>
<td>~500 PE/MeV</td>
<td>~250 PE/MeV</td>
<td>&gt;1000 PE/MeV</td>
<td>~1200 PE/MeV</td>
</tr>
<tr>
<td><strong>Photocathode Coverage</strong></td>
<td>~12%</td>
<td>~34%</td>
<td>~34%</td>
<td>~67%</td>
<td>~80%</td>
</tr>
<tr>
<td><strong>Energy Resolution</strong></td>
<td>~7.5%/√E</td>
<td>~5%/√E</td>
<td>~6%/√E</td>
<td>3%/√E</td>
<td>3%/√E</td>
</tr>
<tr>
<td><strong>Energy Calibration</strong></td>
<td>~1.5%</td>
<td>~1%</td>
<td>~2%</td>
<td>?</td>
<td>&lt;1%</td>
</tr>
</tbody>
</table>

→ An unprecedented LS detector!
The physics program

Selection cuts and background

Main backgrounds for the reactor neutrino oscillation analysis:
- **Cosmogenic bg**: in the LS, cosmic µ can interact with $^{12}\text{C} \rightarrow$ radioactive isotopes as Lithium ($^9\text{Li}$), Helium ($^8\text{He}$). Can decay via (beta, neutron) $\rightarrow$ mimic antineutrino signal
- **Accidental bg**: mainly three types of random coincidence: (radioactivity, radioactivity), (radioactivity, cosmogenic isotope) and (radioactivity, spallation neutrons)

Expected rate of events per day:

<table>
<thead>
<tr>
<th>Selection</th>
<th>IBD efficiency</th>
<th>IBD</th>
<th>Geo-vs</th>
<th>Accidental</th>
<th>$^9\text{Li}/^8\text{He}$</th>
<th>Fast n</th>
<th>$(\alpha,n)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>-</td>
<td>83</td>
<td>1.5</td>
<td>$\sim 5.7 \times 10^4$</td>
<td>84</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Fiducial volume</td>
<td>91.8%</td>
<td>76</td>
<td>1.4</td>
<td>410</td>
<td>77</td>
<td>0.1</td>
<td>0.05</td>
</tr>
<tr>
<td>Energy cut</td>
<td>97.8%</td>
<td>73</td>
<td>1.3</td>
<td></td>
<td>71</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time cut</td>
<td>99.1%</td>
<td>60</td>
<td>1.1</td>
<td>1.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertex cut</td>
<td>98.7%</td>
<td>60</td>
<td>1.1</td>
<td>0.9</td>
<td>1.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Muon veto</td>
<td>83%</td>
<td>60</td>
<td>1.1</td>
<td>3.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combined</td>
<td>73%</td>
<td>60</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For 36 GW thermal power, L= 53 km, And with a 20-kton LS detector

Applying the different selection cuts:
Fiducial volume, energy cut, time cut, vertex cut, muon veto

Signal rate: 60 events/day
Background rate: 3.8 events/day

(About 6% of background)
Expected antineutrino signal spectrum
For the signal and the 5 kinds of backgrounds

Nominal luminosity for six years of data taking (20 kt LS, and 36 GW reactor power)
→ a total of 100k IBD events
Assuming an energy resolution of 3%/\sqrt{E}
Neutrino oscillation parameters

- NMH: For $\sigma(E) = 3\%$ at 1 MeV $\rightarrow 3\sigma$ sensibility ($\Delta \chi^2 = 9$) for 100 000 events (20Kt x 36 GW x 6 years of data taking)

- Three oscillation parameters: $\Delta m^2_{12}$, $|\Delta m^2_{ee}|$, and $\sin^2 2\theta_{12}$ can be measured with precision better than 1%
  $\rightarrow$ Probing the unitarity of $U_{PMNS}$ to $\sim$1% level
Neutrino oscillations - In the 3-flavour framework: 6 independent parameters

Current best estimation:

[F. Capozzi et al., arXiv: 1703.04471]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Uncertainty (1σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>0.297</td>
<td>5%</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}$</td>
<td>0.0214</td>
<td>0.0218</td>
</tr>
<tr>
<td>$\theta_{23}$</td>
<td>~45°</td>
<td>octant is unknown</td>
</tr>
<tr>
<td>$\Delta m^2_{21}$</td>
<td>$7.37 \cdot 10^{-5}$ eV$^2$</td>
<td>2.3%</td>
</tr>
<tr>
<td>$</td>
<td>\Delta m^2_{31}</td>
<td>$</td>
</tr>
<tr>
<td>$\delta_{CP}$</td>
<td>1.35</td>
<td>1.32</td>
</tr>
</tbody>
</table>

Expected JUNO precision:

- < 1% 
- < 1% 
- sign
JUNO Physics goals

**JUNO sensitivity**

- Solar Mixing Angle
  - $\sin^2(\theta_{12})$: 0.54%
- Solar Mass Splitting
  - $\Delta m^2_{21}$: 0.24%
- Atmospheric Mass Splitting
  - $\Delta m^2_{ee}$: 0.27%

**NuFit 3.0 (2016)**

- **Solar Mixing Angle**
- **Solar Mass Splitting**
  - NO
  - IO
- **Atmospheric Mass Splitting**

[15]

JUNO Physics goals

But also:

- **TERRESTRIAL AND EXTRATERRESTRIAL NEUTRINO SOURCES:**
  - Neutrino from supernova burst
  - Diffused supernova neutrino background (1-4 events/year)
  - Solar neutrinos
  - Atmospheric neutrinos
  - Geo-neutrinos

- **EXOTIC PHYSICS:**
  - Exotic searches as proton decay \((p \rightarrow K^+ + \bar{v})\)
  - Sterile neutrinos: using an artificial source close to or inside the LS
  - Indirect dark matter search
  - ...


- The galactic core-collapse SN rate is one every few decades → not to be missed
  - The \( \nu \) burst occurs several hours before the explosion and optical outburst → alert
- Large amount of neutrino events:
  - \( \sim 10^4 \) for a burst@ 10 kpc
- Short time: \( \sim 10 \) seconds
- DAQ system adapted to detect SN
- Separate detection of \( \nu_e, \bar{\nu}_e \) and \( (\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau) \)

<table>
<thead>
<tr>
<th>Channel</th>
<th>Type</th>
<th>Events for different ( (E_\nu) ) values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>12 MeV</td>
</tr>
<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 + \nu \rightarrow \nu + \nu )</td>
<td>NC</td>
<td>( 3.6 \times 10^2 )</td>
</tr>
<tr>
<td>( \nu + 12C \rightarrow \nu + 12C^* )</td>
<td>NC</td>
<td>( 1.7 \times 10^2 )</td>
</tr>
<tr>
<td>( \nu_e + 12C \rightarrow e^- + 12N )</td>
<td>CC</td>
<td>( 4.7 \times 10^1 )</td>
</tr>
<tr>
<td>( \bar{\nu}_e + 12C \rightarrow e^+ + 12B )</td>
<td>CC</td>
<td>( 6.0 \times 10^1 )</td>
</tr>
</tbody>
</table>

Physical outcomes:
- Models of SN burst - Pre-SN \( \nu \)
- SN nucleosynthesis via \( \nu_X \) spectra
- \( \nu \) mass: \( < 0.83 \pm 0.24 \) eV at 95% CL
  - [arXiv:1412.7418]
- Locating the SN: \( \sim 9^\circ \)

Three phases of neutrino emission from a core-collapse SN
Solar neutrinos

\[ \nu_{e,\mu,\tau} + e^- \rightarrow \nu_{e,\mu,\tau} + e^- \]

- Detection of solar neutrinos of all flavors through electron scattering \( \rightarrow \) single flash light in JUNO
- Low level of intrinsic background is required

The expected single spectra:

The expected rate in JUNO

- Better understanding solar model:
  - \(^7\)Be and \(^8\)B spectra
  - Metallicity (discrimination of high and low Z version of the Solar Model)

Geo-neutrinos

- Detect the earth’s emission of neutrinos (from U, Th)

**Current results:**
- KamLAND: $30 \pm 7$ TNU  
  [PRD 88 (2013) 033001]
- Borexino: $43.5 \pm 14.5$ TNU  
  [PRD 92 (2015) 031101]  
  (Statistics dominant)

**Goal:** to reach an error of 3 TNU

Terrestrial Neutrino unit = 1IBD event/year/$10^{32}$ protons (1kt LS)

- JUNO: x20 statistics
- But huge reactor neutrino bg
- Need accurate reactor spectra and accidental/Li/He bg under control

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>geo</td>
<td>408</td>
<td>406</td>
<td>$\pm 2.8 %$(rate)$\pm 1 %$(shape)</td>
</tr>
<tr>
<td>reactor</td>
<td>16100</td>
<td>3653</td>
<td>$\pm 20 %$(rate)$\pm 10 %$(shape)</td>
</tr>
<tr>
<td>$^8$Li/$^8$He</td>
<td>657</td>
<td>105</td>
<td>$\pm 100 %$(rate)$\pm 20 %$(shape)</td>
</tr>
<tr>
<td>fast n</td>
<td>36.5</td>
<td>7.7</td>
<td>$\pm 50 %$(rate)$\pm 50 %$(shape)</td>
</tr>
<tr>
<td>$\alpha$-n</td>
<td>18.2</td>
<td>12.2</td>
<td>$\pm 1 %$(rate)</td>
</tr>
</tbody>
</table>
• Neutrino sector: there are still key unknown parameters
  Key issues in our understanding of physics today

• JUNO experiment under construction - Important parameters are:
  the energy resolution/energy scale, and collecting large statistics

• JUNO will provide:
  - First measurement of NMH independent of the CP phase and matter effect
    First experiment to simultaneously observe “solar” and “atm” oscillations
    First experiment to observe more than two cycles of neutrino oscillations
  - Precise measurements of $\sin^2 2\theta_{12}, \Delta m^2_{12}, \Delta m^2_{ee}$ to < 1%
    Probing the unitarity of $U_{\text{PMNS}}$ to subpercent level
  - Several other secondary physics goals and measurements
    from terrestrial and extra-terrestrial neutrino sources
    (supernovae, solar, atmospheric, geo-neutrinos, ...), also exotic physics
    (proton decay, sterile neutrinos, ...)

→ Several key measurements,
  20 years of copious physics with reactor neutrinos and beyond

• Complementary to long baseline accelerator program
References

JUNO Timescale

- 2013: Funding approved
- 2014: Collaboration officially formed
- 2014-18: Civil construction
- 2016-19: Detector component and PMT production
- 2018-19: Detector assembly & installation
- 2020: Liquid scintillator filling
- 2020: Start of data taking

Vertical Tunnel: 611m
Finished July 2017

Slope Tunnel: 1340 m
Digging finished on June 2017

Surface Campus

Experimental hall
Overburden: 720 m
- **Central detector**: Acrylic sphere and stainless steel truss. Liquid Scintillator (LS) large volume. 
  
  -> for the statistics

Double calorimetry:

→ 18,000 large PMTs (20") → 75%
→ 25,000 small PMTs (3") → 2.5%

  High light coverage (78%)
  -> for the energy resolution

- **Muon veto**: use OPERA tracker layers. 
  
  Reject 50% of the muons
  
  Provide tagged muon sample to study muon reconstruction and bg contamination with the central detector

- **Calibration**: 4-complementary systems: Automatic calibration unit (1D- central axis scan), Cable loop system and guide tube calibration system (2D), remote operated vehicles (3D) - radiative sources (photon, positrons, neutrons)
Various projects seeking to resolve the neutrino mass hierarchy:

Two complementary methods

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Location</th>
<th>Method</th>
<th>Approved</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>PINGU</td>
<td>South pole</td>
<td>Matter effects: atmospheric ν</td>
<td></td>
<td>3...4σ in a few years</td>
</tr>
<tr>
<td>ORCA</td>
<td>Mediterranean</td>
<td>Matter effects: atmospheric ν</td>
<td></td>
<td>3...4σ in a few years</td>
</tr>
<tr>
<td>INO</td>
<td>India</td>
<td>Matter effects: atmospheric ν</td>
<td>✓</td>
<td>2σ in 10 years</td>
</tr>
<tr>
<td>NOvA</td>
<td>U.S.</td>
<td>Matter effects: ν-beam</td>
<td>✓</td>
<td>0...3σ in 6 years</td>
</tr>
<tr>
<td>Dune/LBNE</td>
<td>U.S.</td>
<td>Matter effects: ν-beam</td>
<td></td>
<td>&gt;5σ in 6 years</td>
</tr>
<tr>
<td>JUNO</td>
<td>China</td>
<td>3-flavor interference</td>
<td>✓</td>
<td>4σ in 6 years</td>
</tr>
<tr>
<td>RENO 50</td>
<td>South Korea</td>
<td>3-flavor interference</td>
<td></td>
<td>4σ in 6 years</td>
</tr>
</tbody>
</table>

Synergy with other experiments
Proton decay via $p \rightarrow \nu K$

JUNO high efficiency:
- Large mass (like SK)
- Excellent timing $\rightarrow$ K+ decay signature
- Excellent dynamic $\rightarrow$ K+ mass reconstruction
Sterile neutrinos: hypothesised gauge singlets in the SM
Do not participate to SM weak interaction but couple to active neutrinos via non-zero mixing between active and sterile flavors.

Sensibility of JUNO searches

100 kCi $^{144}$Ce source outside of the detector vessel steel (20 m) 450-day data taking time

50 kCi $^{144}$Ce source at the detector center (1-16 m) using 450-day data taking time

JUNO@IsoDAR
8 Li source
5 sigma contour
5 years data taking source at the detector center (1-16 m) using 450-day data taking time
Sterile neutrinos

Sensibility of JUNO searches with reactor antineutrinos:

Sensitivities to super light sterile neutrinos: \( \Delta m^2 \) of the order of \( 10^{-5} \text{ eV}^2 \)