JUNO: Status and Prospects

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*on behalf of the JUNO collaboration
Outline

• Basics
• Physics Goals
• Detector Design & Status
• Timeline
• Summary & Conclusions
Reactor Neutrino Refresher

Nuclear reactors are a bountiful and well-understood source of electron antineutrinos.

The primary detection channel is the inverse beta decay (IBD) reaction.

Beta decay: $n \rightarrow p + e^- + \bar{\nu}_e$

IBD: $\bar{\nu}_e + p \rightarrow e^+ + n$
The Jiangmen Underground Neutrino Observatory (JUNO) is a large experiment under construction in China:

- 53 km from two major nuclear power plants (10 reactors)
- 35 m diameter sphere with 20 ktons of liquid scintillator

<table>
<thead>
<tr>
<th>LS Detectors</th>
<th>Daya Bay</th>
<th>Borexino</th>
<th>KamLAND</th>
<th>JUNO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target Mass</td>
<td>20 t x 8</td>
<td>300 t</td>
<td>1 kt</td>
<td>20 kt</td>
</tr>
</tbody>
</table>
A Multipurpose Neutrino Observatory

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

Supernova \(\nu\)'s
~10^4 in 10 s
for 10 kpc

Atmospheric \(\nu\)'s
several/day

700 m

36 GWth, 53 km

Cosmic muons
~ 250k/day

0.003 Hz/m^2, 215 GeV
10% multiple-muon

reactor \(\nu\)'s
~ 80/day

Geo-\(\nu\)'s
1-2/day

Geo-\(\nu\)'s
1-2/day
Oscillation Physics with Reactor $\bar{\nu}_e$'s

- Determination of the neutrino mass ordering (NMO)
  - Exploit interference effects in the fine structure of the oscillated spectrum
  - > 3σ sensitivity within 6 years

- Measurement of $\sin^2 2\theta_{12}$, $\Delta m^2_{21}$ and $\Delta m^2_{31}$ to better than 0.7%
  - New era of precision for model building and $U_{\text{PMNS}}$ unitarity tests (~1%)

Supernova Neutrinos

- Able to determine flavor content, energy spectrum and time evolution of SN burst neutrinos
  - $10^4$ detected events (5000 IBDs) for SN@10kpc
  - Low threshold $\sim 0.2$ MeV
  - Complementary to other detectors and with unique contributions (e.g. $\nu_x$ from $\nu$-p ES channel)

- Also sensitive to diffuse SN neutrino background (DSNB)
  - Expected detection significance of $\sim 3\sigma$ after 10 years of data
  - Provide leading constraint if DSNB is not observed

Solar and Atmospheric Neutrinos

- **Atmospheric neutrinos:**
  - Independent measurement of NMO via matter effect
  - Complementary information to that from other experiments (e.g. IceCube)
  - Also sensitive to $\theta_{23}$ (precision ~6°)

- **Solar neutrinos:**
  - Measure $^7$Be & $^8$B fluxes
  - Challenge: cosmogenic & radiogenic backgrounds
  - Planning solar phase with $10^{-17}$ g/g
  - Explore current tension in $\Delta m^2_{21}$ between solar and reactor measurements with same detector
  - Shed light on metallicity problem (low vs. high Z versions of the solar model)

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Geoneutrinos and Nucleon Decay

- 400-500 geoneutrinos per year
  - Precision of ~13% in 1 year and ~5% in 10 years
  - Local crust model under development by interdisciplinary team
- Competitive sensitivity to proton decay searches, particularly in the $p \rightarrow \bar{\nu} + K^+$ channel
  - Exploit triple coincidence enabled by liquid scintillator

Detector Concept

• Keys to fulfilling the physics goals:
  - Optimal baseline
  - High statistics
  - Superb energy resolution
  - Excellent control of energy response systematics
  - Background reduction

• How to accomplish this:

Similar concept to previous LS experiments, but much larger and more precise.
Energy resolution

- With 3% @ 1 MeV, JUNO will be the LS detector with the best energy resolution in history

- Most obvious (although not unique) requirement for achieving this resolution: seeing enough photons
  - There is no approach that can singlehandedly provide all the light needed. Have to attack the problem from different angles:

<table>
<thead>
<tr>
<th></th>
<th>KamLAND</th>
<th>JUNO</th>
<th>Relative Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total light level</td>
<td>250 p.e. / MeV</td>
<td>1200 p.e. / MeV</td>
<td>5</td>
</tr>
<tr>
<td>Photocathode coverage</td>
<td>34%</td>
<td>75%</td>
<td>~2</td>
</tr>
<tr>
<td>Light yield</td>
<td>1.5 g/l PPO</td>
<td>3-5 g/l PPO</td>
<td>~1.5</td>
</tr>
<tr>
<td>Attenuation length / φ</td>
<td>15 m / 16 m</td>
<td>20 m / 35 m</td>
<td>~0.8</td>
</tr>
<tr>
<td>PMT QE×CE</td>
<td>20%×60% ~ 12%</td>
<td>~30%</td>
<td>~2</td>
</tr>
</tbody>
</table>
Large PMT system

- JUNO will use large 20-inch PMTs as its main light-detection device

Arranged as tightly as possible, with a photocathode coverage of ~75%

2 complementary (and new!) technologies:

Microchannel plate (MCP)-PMTs
- Developed for/by JUNO
- Use of transmission + reflection cathodes to increase QE
- Good price
- Mass-produced by NNVT (China)

Dynode-PMTs
- R12860 from Hamamatsu
- New type of bialkali photocathode
- Excellent TTS (2.7 ns FWHM)

Both reach QE x CE ~ 30%!

JUNO’s central detector will use 13,000 MCP-PMTs and 5,000 Dynode-PMTs
Large PMT system

- We have already received all dynode PMTs and over 10,000 MCP PMTs:
  - Have a very large storage, testing and potting facility near the JUNO site
  - Acceptance & characterization tests ongoing at full speed

- Three more containers are in Hamburg
- All of them received magnetic shielding
- Painted black inside
- Shelf system installed into next container
- HV and signal cables installed
- Industrial container mass testing system
- Photocathode uniformity scanning system

Potting lab

An industrial process!
• Using a recipe inspired from Daya Bay’s experience

Since early 2017 one of the eight Daya Bay detectors was taken down permanently and its Gd-LS replaced with JUNO LS

Invaluable experience to study different recipes and purification methods

- No doping, large fluor concentration, Al₂O₃ column purification, vacuum distillation.
Achieving a light level of 1200 p.e. / MeV is not enough. Also have to keep the systematics under control.

- Have an aggressive calibration program consisting of 4 complementary systems:
  - **1D**: Automated Calibration Unit (ACU) deploys radioactive and laser (1ns, keV-TeV range) sources along the central axis
  - **2D**: Cable Loop System (CLS) to scan vertical planes
  - **2D**: Guide Tube to scan the outer surface of the central detector (where the CLS cannot reach)
  - **3D**: Remotely Operated Vehicle (ROV) operating inside the LS to scan the full volume

Goal is to keep the energy scale uncertainty < 1%
Small PMT System

- JUNO will also have to keep the non-stochastic term of the resolution under control (≤1%)
- 25,000 3-inch PMTs will operate predominantly in photon-counting mode:
  
  Basic principle: look at the same events with two sets of “eyes” that have different systematics (e.g. nonlinearity)

- The small PMTs also bring other nice benefits to the table:
  
  - Independent physics (e.g. measurement of solar parameters)
  - Aid to position reconstruction and muon track reconstruction
  - Aid to supernova neutrino measurement
  - Others (a little extra light, larger dynamic range… etc.).
Muon Veto System

- It is also important to keep the cosmogenic backgrounds under control
- The 35 m diameter LS acrylic sphere will be immersed in a cylindrical instrumented water pool:
  - 35 kton ultrapure water with a circulation system

Double-purpose:
- Shield central detector against radioactivity from rock and neutrons from cosmic rays
- Veto cosmic-ray muons (most backgrounds are of cosmic ray origin)

Some details about the muon veto:
- About 2,000 20-inch PMTs
- Detection efficiency expected to be > 95%
Muon Veto System

• The muon veto system will also have a top tracker:
  - 3-layers of plastic scintillators
  - Reuse of OPERA’s target tracker
  - Only partial coverage

• There will also be a magnetic field (EMF) shielding system
  - Double coil system
JUNO will also deploy a satellite detector called TAO (Taishan Antineutrino Observatory)

- ~35 m from a 4.6 GW$_{th}$ reactor
- 1 ton fiducial Gd-LS volume
- SiPM and Gd-LS at -50°C
- < 2% @ 1 MeV energy resolution

Main goal: measure the reactor antineutrino spectrum with unprecedented resolution

- See fine structure due to Coulomb corrections
- Serve as benchmark for JUNO, other experiments, and nuclear databases
- Search for sterile neutrinos
- Study flux and shape change with fuel evolution & decompose isotope spectra
- Discover something?

R&D well underway and prototype under development
Civil Construction

- A new underground laboratory with a 700 m overburden and infrastructure at the surface is under construction since late 2014
- Expect to finish by summer 2020
Timeline

- Conceptual design completed. International collaboration established.
- Bidding of detector components.
- PMT mass production & testing.
- End of civil construction. Electronics mass production.
- Start of civil construction. Setup of PMT production line.
- Start PMT mass production. Electronics prototypes delivered.
- Start PMT Potting.
- PMT Installation in central detector & veto. End of detector construction.
Summary & Conclusions

• JUNO is a multipurpose neutrino observatory with a rich program in neutrino physics and astrophysics
  – Neutrino mass ordering, oscillation parameters, supernova ν’s, solar ν’s, atmospheric ν’s, geo-ν’s, proton decay, and others.

• JUNO is pushing the limits in liquid scintillator detection technology
  – New solutions in terms of PMT technology, liquid scintillator properties and detector construction
  – Developing some unique approaches to calibration and to the reduction of systematic uncertainties

• Progress is well underway, and expect to complete the construction of the detector by 2021

• Anticipate some exciting results (and maybe some surprises?)

Stay tuned!
Thank you for your attention!

The JUNO Collaboration: 77 institutions from over 15 countries