Status and physics potential of the JUNO experiment

G. Salamanna
Roma Tre University and INFN Roma Tre
JUNO

- The Jiangmen Underground Neutrino Observatory in China
- Anti-neutrino reactor experiment
  - at a distance (~50 km) from 2 power plants
  - Facility and detector construction: 2015-20
  - expected starting date for data taking: end 2020

<table>
<thead>
<tr>
<th></th>
<th>Yangjiang</th>
<th>Taishan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp. Power(\text{Th})</td>
<td>17.4 GW</td>
<td>18.4 GW</td>
</tr>
<tr>
<td>Exp. N of cores</td>
<td>6</td>
<td>4</td>
</tr>
</tbody>
</table>

- total thermal power available by 2020: 26.6 GW
What drives the detector design?
Neutrino flavour oscillations

- We know since \( \sim 20 \) years that neutrinos oscillate.
- This can only happen if at least 2 of the 3 flavours of neutrinos have a mass.

\[
|\nu(t=0)\rangle = |\nu_\mu\rangle = U_{\mu 1} |\nu_1\rangle + U_{\mu 2} |\nu_2\rangle + U_{\mu 3} |\nu_3\rangle
\]

\[
|\nu(t>0)\rangle = U_{\mu 1} e^{-iE_1 t} |\nu_1\rangle + U_{\mu 2} e^{-iE_2 t} |\nu_2\rangle + U_{\mu 3} e^{-iE_3 t} |\nu_3\rangle \neq |\nu_\mu\rangle
\]

\[
E_k^2 = p^2 + m_k^2
\]

\[
P_{\nu_\mu \rightarrow \nu_e}(t>0) = |\langle \nu_e |\nu(t>0)\rangle|^2 \sim \sum_{k>j} \text{Re} [U_{ek} U^*_{\mu k} U^*_{ej} U_{\mu j}] \sin^2 \left( \frac{\Delta m_{kj}^2 L}{4E} \right)
\]

transition probabilities depend on \( U \) and \( \Delta m_{kj}^2 \equiv m_k^2 - m_j^2 \)

\[
\nu_e \rightarrow \nu_\mu \quad \nu_e \rightarrow \nu_\tau \quad \nu_\mu \rightarrow \nu_e \quad \nu_\mu \rightarrow \nu_\tau \\
\bar{\nu}_e \rightarrow \bar{\nu}_\mu \quad \bar{\nu}_e \rightarrow \bar{\nu}_\tau \quad \bar{\nu}_\mu \rightarrow \bar{\nu}_e \quad \bar{\nu}_\mu \rightarrow \bar{\nu}_\tau
\]
Tiny neutrino masses lead to observable macroscopic oscillation distances!

\[ \frac{L}{E} \gtrsim \begin{cases} 
10 \, \text{m/MeV} & \text{short-baseline experiments} \\
10^3 \, \text{m/MeV} & \text{long-baseline experiments} \\
10^4 \, \text{km/GeV} & \text{atmospheric neutrino experiments} \\
10^{11} \, \text{m/MeV} & \text{solar neutrino experiments}
\end{cases} \]

Neutrino oscillations are the optimal tool to reveal tiny neutrino masses!
Three-Neutrino Mixing Paradigm

Standard Parameterization of Mixing Matrix

\[
U = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix} \begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta_{13}} & 0 & c_{13}
\end{pmatrix} \begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix} \begin{pmatrix}
1 & 0 & 0 \\
0 & e^{i\lambda_{21}} & 0 \\
0 & 0 & e^{i\lambda_{31}}
\end{pmatrix}
\]

\[
= \begin{pmatrix}
c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\
-s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\
s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13}
\end{pmatrix}
\]

\[
c_{ab} \equiv \cos \vartheta_{ab} \quad s_{ab} \equiv \sin \vartheta_{ab} \quad 0 \leq \vartheta_{ab} \leq \frac{\pi}{2} \quad 0 \leq \delta_{13}, \lambda_{21}, \lambda_{31} < 2\pi
\]

OSCILLATION PARAMETERS

\{ 3 Mixing Angles: $\vartheta_{12}, \vartheta_{23}, \vartheta_{13}$ \\
1 CPV Dirac Phase: $\delta_{13}$ \\
2 independent $\Delta m^2_{kj} \equiv m_k^2 - m_j^2$: $\Delta m^2_{21}, \Delta m^2_{31}$ \}

2 CPV Majorana Phases: $\lambda_{21}, \lambda_{31} \leftrightarrow |\Delta L| = 2$ processes
## Current experimental knowledge

<table>
<thead>
<tr>
<th></th>
<th>Normal Ordering (best fit)</th>
<th>Inverted Ordering ($\Delta \chi^2 = 0.83$)</th>
<th>Any Ordering</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>bfp ±1σ</td>
<td>3σ range</td>
<td>3σ range</td>
</tr>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>0.306$^{+0.012}_{-0.012}$</td>
<td>0.271 → 0.345</td>
<td>0.271 → 0.345</td>
</tr>
<tr>
<td>$\theta_{12}/^\circ$</td>
<td>33.56$^{+0.77}_{-0.75}$</td>
<td>31.38 → 35.99</td>
<td>31.38 → 35.99</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>0.441$^{+0.027}_{-0.021}$</td>
<td>0.385 → 0.635</td>
<td>0.385 → 0.638</td>
</tr>
<tr>
<td>$\theta_{23}/^\circ$</td>
<td>41.6$^{+1.5}_{-1.2}$</td>
<td>38.4 → 52.8</td>
<td>38.4 → 53.0</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}$</td>
<td>0.02166$^{+0.00075}_{-0.00075}$</td>
<td>0.01934 → 0.02392</td>
<td>0.01934 → 0.02397</td>
</tr>
<tr>
<td>$\theta_{13}/^\circ$</td>
<td>8.46$^{+0.15}_{-0.15}$</td>
<td>7.99 → 8.90</td>
<td>7.99 → 8.91</td>
</tr>
<tr>
<td>$\delta_{CP}/^\circ$</td>
<td>261$^{+51}_{-59}$</td>
<td>0 → 360</td>
<td>0 → 360</td>
</tr>
<tr>
<td>$\frac{\Delta m_{21}^2}{10^{-5} \text{eV}^2}$</td>
<td>7.50$^{+0.19}_{-0.17}$</td>
<td>7.03 → 8.09</td>
<td>7.03 → 8.09</td>
</tr>
<tr>
<td>$\frac{\Delta m_{3\ell}^2}{10^{-3} \text{eV}^2}$</td>
<td>$+2.524^{+0.039}_{-0.040}$</td>
<td>$+2.407 \rightarrow +2.643$</td>
<td>$-2.514^{+0.038}_{-0.041}$</td>
</tr>
</tbody>
</table>

Three-flavor oscillation parameters from our fit to global data as of August 2016. The normalization of reactor fluxes is left free and data from short-baseline reactor experiments are included. The numbers in the 1st (2nd) column are obtained assuming NO (IO), i.e., relative to the respective local minimum, whereas in the 3rd column we minimize also with respect to the ordering. Note that $\Delta m_{3\ell}^2 = \Delta m_{31}^2 > 0$ for NO and $\Delta m_{3\ell}^2 = \Delta m_{32}^2 < 0$ for IO.
Let's focus on the mass ordering
The ordering of the masses of neutrinos is important per se and entangled with several other aspects e.g.

- their Dirac vs Majorana nature
- absolute masses and effect on early universe
Survival probability after mixing

\[ P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E_\nu} - \left( \frac{\Delta m^2_{21} L}{4E_\nu} \right)^2 \cos^4 \theta_{13} \sin^2 2\theta_{12} \]

3 flavour effect
• no degeneracies
• no correlations
• no matter effects

$E=4\text{MeV}$ → 1km 180km
Survival probability after mixing

\[ P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E_{\nu}} - \left(\frac{\Delta m^2_{31} L}{4E_{\nu}}\right)^2 \cos^4 \theta_{13} \sin^2 2\theta_{12} \]

3 flavour effect
- no degeneracies
- no correlations
- no matter effects

\( E=4\text{MeV} \rightarrow 1\text{km} \quad 180\text{km} \)

Standard 3ν oscillations

SBL \quad MBL \quad LBL
$\bar{\nu}_e$ production at reactors

typically about $10^{20}/s \ \bar{\nu}_e$ emitted
The upward shift in the total flux introduces tension with short baseline reactor neutrino experiments, which is called Reactor Neutrino Anomaly [48]. The reactor antineutrinos are generally detected via the inverse beta decay (IBD) reaction $\bar{\nu}_e + p \rightarrow n + e^+$. The reaction cross section $\sigma(E_{\bar{\nu}_e})$ is calculated to the order of $1/M$ in Ref. [167].

The observable reactor neutrino spectrum is the multiplication of the neutrino flux per fission and the cross section, which is shown in Fig. 13-1 for the four isotopes.

### Figure 13-1: Neutrino yield per fission, the interaction cross section of the inverse beta decay, and the observable spectra of the listed isotopes.

- **13.1.3 Reactor Power and Fuel Evolution**

Fission rates of isotopes (at nominal power) as a function of time, as well as the fuel composition, can be obtained via core simulation. Since the fission rates are correlated with the reactor power, normally we use fission fraction in the core simulation, which is the ratio of the fission rate of an isotope over the total fission rate. Fresh fuel contains only uranium. The plutonium isotopes are gradually generated via the neutron capture of $^{238}\text{U}$ and the subsequent evolution. Generally a PWR core refuels every 12-18 months, and replaces 1/4 to 1/3 fuel assemblies each time. To describe the fuel evolution as a function of time, burnup of the fuel is defined as

$$B(t) = \frac{W \cdot D}{M_{\text{init-}\text{U}}}$$

(13.1)

where $W$ is the fission power of the fuel, $D$ is the fissioning days, and $M_{\text{init-}\text{U}}$ is the initial mass of the uranium. The unit of the burnup is $\text{MW} \cdot \text{d/ton}$. Since a fuel assembly will stay in the core for 3-4 refueling cycles, and fuel assemblies have different burnup, a more convenient variable "cycle burnup" is defined to describe the aging of a reactor core within a refueling cycle. The cycle burnup has the same expression as Eq. (13.1), but with $W$ being the total nuclear power of the reactor core, $D$ being the fissioning days since the beginning of the refueling cycle, and $M_{\text{init-}\text{U}}$ being the total initial uranium mass in the reactor core. Cycle burnup can be calculated by using the daily thermal power which are obtained by the power monitoring system.

The most accurate thermal power measurement is the Secondary Heat Balance method. Detailed description of this measurement can be found, for example, in Ref. [450]. It is an offline method.
**Event Signature and Backgrounds**

**Signature:**
\[ \bar{\nu}_e + p \rightarrow e^+ + n \]
- **Prompt:** \( e^+ \), 1-10 MeV,
- **Delayed:** \( n \), 2.2 MeV@H, 8 MeV @ Gd

**Backgrounds**
- **Uncorrelated:** random coincidence of \( \gamma \gamma, \gamma n \) or \( nn \)
  - \( \gamma \) from U/Th/K/Rn/Co... in LS, SS, PMT, Rock, ...
  - \( n \) from \( \alpha-n, \mu\)-capture, \( \mu\)-spallation in LS, water & rock
- **Correlated:**
  - Fast neutrons: \( n \) scattering - \( n \) capture
  - \( ^{8}\text{He} / ^{9}\text{Li} \): \( \beta \) decay -\( n \) capture
  - Am-C source: \( \gamma \) rays - \( n \) capture
  - \( \alpha-n: {^{13}\text{C}(\alpha,n)^{16}\text{O}} \)

Example from Daya Bay
MH from reactors

\[ P_{ee} = 1 - \cos^4 \theta_{13} \sin^2 2 \theta_{12} \sin^2 (\Delta_{21}) \]
\[ - \sin^2 2 \theta_{13} \sin^2 (|\Delta_{31}|) \]
\[ - \sin^2 \theta_{12} \sin^2 2 \theta_{13} \sin^2 (\Delta_{21}) \cos (2|\Delta_{31}|) \pm \frac{\sin^2 \theta_{12}}{2} \sin^2 2 \theta_{13} \sin (2 \Delta_{21}) \sin (2|\Delta_{31}|) \]

Survival probability at higher orders

\[ \Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E_\nu}, \quad (\Delta m_{ij}^2 \equiv m_i^2 - m_j^2) \]

- JUNO will determine MH by reconstructing the E(\nu) spectrum and fitting it with the two signs in the survival probability at fixed L
- baseline statistical method: \( \Delta \chi^2_{min} \) of the two fits to disentangle the two mutually exclusive MH hypothesis (arXiv1210.8141)

Courtesy Y. Malyshkin
Main challenge: Energy resolution

Because fitting involves separating the red vs blue curves with data, the single most important performance aspect will be the resolution on the energy measurement.
JUNO’s MH reach

- “Success” depends on keeping linearity and uniformity of E response under control
- Not only stochastic term: it can be shown that constant term $b$ has more impact on MH sensitivity than $a$
  - non-uniformity of response in 20 KTon: challenge!

\[
\frac{\sigma E}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + b^2 + \left(\frac{c}{E}\right)^2},
\]

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal MH</td>
<td>3.4 $\sigma$</td>
<td>3.3 $\sigma$</td>
<td>1.9 $\sigma$</td>
</tr>
<tr>
<td>Inverted MH</td>
<td>3.5 $\sigma$</td>
<td>3.4 $\sigma$</td>
<td>1.9 $\sigma$</td>
</tr>
</tbody>
</table>

Table 2-3: The MH sensitivity with the JUNO nominal setup of six year running.
FIG. 12: The left (right) panel shows the median sensitivity in number of sigmas for rejecting the IO (NO) if the NO (IO) is true for different facilities as a function of the date. The width of the bands correspond to different true values of the CP phase $\delta$ for NO\text{\textit{v}}A and LBNE, different true values of $\theta_{23}$ between 40° and 50° for INO and PINGU, and energy resolution between 3\%$\sqrt{1\text{MeV}/E}$ and 3.5\%$\sqrt{1\text{MeV}/E}$ for JUNO. For the long baseline experiments, the bands with solid (dashed) contours correspond to a true value for $\theta_{23}$ of 40° (50°). In all cases, octant degeneracies are fully searched for.
“A new way to determine the neutrino mass hierarchy at reactors”

- $\Delta \chi^2$ not a priori best estimator; allows extracting from data also $\Delta m_{atm}^2$ but fit could partially cancel discrimination power of data set
- A new estimator is proposed, with a well defined pdf, which counts and compares yields (no fit) extracted from same energy spectrum
  - “success” still depends on well known $E$ response

“Proof of principle” of method with some systematic uncertainties incl’d; not final performance

- New linear estimator promising in decoupling two MH at $>5\sigma$ with 6y and $E_{\text{res}}=3\%$
- but as-is identification depends on external input of $\Delta m_{atm}^2$: will need further developments
Oscillation parameters: projections

- Reactor
- Radio and cosmology
- E scale
- E non-uniformity

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nominal</th>
<th>+ B2B (1%)</th>
<th>+ BG</th>
<th>+ EL (1%)</th>
<th>+ NL (1%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>\sin^2 \theta_{12}</td>
<td>0.54%</td>
<td>0.60%</td>
<td>0.62%</td>
<td>0.64%</td>
<td>0.67%</td>
</tr>
<tr>
<td>\Delta m^2_{21}</td>
<td>0.24%</td>
<td>0.27%</td>
<td>0.29%</td>
<td>0.44%</td>
<td>0.59%</td>
</tr>
<tr>
<td></td>
<td>\Delta m^2_{ee}</td>
<td>0.27%</td>
<td>0.31%</td>
<td>0.31%</td>
<td>0.35%</td>
</tr>
</tbody>
</table>

- <0.7% uncertainty on oscillation parameters
- Dependence of precision on energy resolution studied
- Bkgs sub-dominant in oscill. measurements (double coincidence)
From such goals descend some constraints...

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Daya Bay</th>
<th>BOREXINO</th>
<th>KamLAND</th>
<th>JUNO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target mass</td>
<td>20 ton</td>
<td>~300 ton</td>
<td>~1 kton</td>
<td>~20 kton</td>
</tr>
<tr>
<td>Optical coverage</td>
<td>~12%</td>
<td>~34%</td>
<td>~34%</td>
<td>~75%</td>
</tr>
<tr>
<td>E resolution</td>
<td>~7.5%/√E</td>
<td>~5%/√E</td>
<td>~6%/√E</td>
<td>~3%/√E</td>
</tr>
<tr>
<td>Light yield</td>
<td>~160 p.e./MeV</td>
<td>~500 p.e./MeV</td>
<td>~250 p.e./MeV</td>
<td>~1200 p.e./MeV</td>
</tr>
</tbody>
</table>
JUNO detector

~700m of stopping material above

- maximize photon statistics and minimize attenuation of IBD prompt signal
- Largest volume of liquid scintillator to date: >98% LAB (solvent, ~1200 photoelectrons/MeV) + PPO (solute) and bis-MSB (λ shifter)

Central detector
SS latticed shell
Acrylic sphere (20kL LS in it)

~17000 20” PMT
~34000 3” PMT
Connecting bars
Qty: ~600

~2000 20” VETO PMT

CD Support legs
Qty: ~100

AS: Acrylic sphere; SSLS: stainless steel latticed shell
maximize photon statistics and minimize attenuation of IBD prompt signal
- Largest volume of liquid scintillator to date: >98% LAB (solvent, ~1200 photo-electrons/MeV) + PPO (solute) and bis-MSB (λ shifter)

- Extended photo-coverage (~75%) from 17k micro-channel plate PMT (Ø=20”, QE ~ 30% at 420 nm)
  - larger collection eff and good TTS for vertex position reconstruction (bkg rejection)
  - + 25k “conventional” PMT (Ø=3”)

JUNO detector

~700m of stopping material above

- Calibration
- Top Tracker
- Central detector
  - SS latticed shell
  - Acrylic sphere (20Kt LS in it)
- ~17000 20” PMT
- ~34000 3” PMT
- Connecting bars
  - Qty: ~600
- ~2000 20” VETO PMT
- CD Support legs
  - Qty: ~100

AS: Acrylic sphere; SSLS: stainless steel latticed shell

Pool ID: 43.5m

Pool Depth: 44m
JUNO detector

~700m of stopping material above

- Maximize photon statistics and minimize attenuation of IBD prompt signal
  - Largest volume of liquid scintillator to date: >98% LAB (solvent, ~1200 photo-electrons/MeV) + PPO (solute) and bis-MSB (λ shifter)

- Extended photo-coverage (~75%) from 17k micro-channel plate PMT (Ø=20”, QE ~ 30% at 420 nm)
  - Larger collection eff and good TTS for vertex position reconstruction (bkg rejection)
  - + 25k “conventional” PMT (Ø=3”)

- Minimize cosmic ray bkg + shield against cavern radioactivity
  - Veto activity from incoming muons and photons by surrounding water buffer (Cherenkov) and top scintillators
• Mature design
• 2016-2017 – Detector component production
• 2016-2019 – PMT production
• 2018-2019 – Detector assembly and installation
• 2020 – Filling

➡ maximize photon statistics and minimize attenuation of IBD prompt signal
• Largest volume of liquid scintillator to date: >98% LAB (solvent, ~1200 photo-electrons/MeV) + PPO (solute) and bis-MSB (\(\lambda\) shifter)

• Extended photo-coverage (~75%) from 17k micro-channel plate PMT (\(\varnothing=20''\), QE ~ 30% at 420 nm)
  • larger collection eff and good TTS for vertex position reconstruction (bkg rejection)
  • + 25k “conventional” PMT (\(\varnothing=3''\))

➡ minimize cosmic ray bkg + shield against cavern radioactivity
  • veto activity from incoming muons and photons by surrounding water buffer (Cherenkov) and top scintillators

➡ front-end electronics under water with challenging design and testing currently under-way for resilience

~700m of stopping material above
Central detector

- Acrylic Sphere and stainless steel truss immersed in water
- 265 acrylic panels of 3x8 m, with a 12 cm thickness
- Total weight: ~600 t of acrylic and ~600 t of steel
- Design and bidding completed, acrylic being produced, construction will start in 2019
20 kt liquid scintillator

- High light yield to reduce $\sigma(E)$ from statistical fluctuations: $\sim 10^4$ scintillation photons/MeV
  ➡ pure organic solvent (LAB)
    ✓ safer and cheaper than Pseudo-cumene previously largely used, but worse particle discrimination
  ➡ high fluor (PPO) concentration

- High transparency: $> 20$ m
  ➡ add wavelength shifter (bisMSB)

Liquid scintillator composition

Linear alkylbenzene (LAB) as solvent

$\lambda = 280$nm

$3$ g/L PPO

+$

$\lambda = 390$nm

$15$ mg/L bis-MSB

$\Rightarrow 430$nm, $\tau \approx 4.4$ns
Liquid scintillator: purification

- Two main constraints drive need for thorough LS purification:
  - attenuation length: > 20 m at $\lambda=430$ nm (for 3g/L PPO in LAB)
  - radio-purity: $10^{-15}$ g/g ($^{238}\text{U, }^{232}\text{Th}$) and $10^{-17}$ g/g ($^{40}\text{K}$)

4 different purification strategies developed and will be put in place:

<table>
<thead>
<tr>
<th>attenuation length</th>
<th>radio-purity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Al}_2\text{O}_3$ column plant based on the “absorption” technique to remove optical impurities in LAB</td>
<td></td>
</tr>
<tr>
<td>Distillation plant is to remove heavy metal, improve transparency</td>
<td>• Water extraction is to remove $^{238}\text{U, }^{232}\text{Th, }^{40}\text{K}$</td>
</tr>
<tr>
<td></td>
<td>• Gas Stripping plant remove the impurities : $\text{Ar, }\text{Kr and Rn}$</td>
</tr>
</tbody>
</table>
Scintillator purification: tests

- Pilot plant established in the Daya Bay LS hall and has been running in Feb-Mar
- Filled Daya Bay detector with sample LAB and purified with alumina
- Optimization of fluorescent material to get the final recipe

good a.l. attained as result of purification, after “realistic operations”

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Sampling time</th>
<th>A.L. result (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DYB AD1 LS</td>
<td>20170307 0905</td>
<td>14.6</td>
</tr>
<tr>
<td>Purified LAB before filling</td>
<td>20170306 11:05</td>
<td>25.1</td>
</tr>
<tr>
<td>5#Tank raw LAB</td>
<td>20170227 21:50</td>
<td>20.5</td>
</tr>
<tr>
<td>Filled LS (0.5g/l PPO)</td>
<td>201703122311</td>
<td>23.8</td>
</tr>
<tr>
<td>DYB AD1 Gd-LS (201703)</td>
<td>20170314-1600 取</td>
<td>8.15</td>
</tr>
<tr>
<td>DYB AD1 LS</td>
<td>20170314-2320</td>
<td>14.6</td>
</tr>
</tbody>
</table>
20” PMT: the “eyes”

- To maximize photo-coverage use large (20”) PMT
- Ordered 15k “NNVT” MCP-PMT
- + 5K Hamamatsu R12860 “conventional dynode”

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Unit</th>
<th>NNVT</th>
<th>R12860</th>
<th>Important for</th>
</tr>
</thead>
<tbody>
<tr>
<td>collection mode</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quantum efficiency (400 nm)</td>
<td>%</td>
<td>30</td>
<td>30</td>
<td>E resolution</td>
</tr>
<tr>
<td>Relative detection efficiency</td>
<td>%</td>
<td>110</td>
<td>100</td>
<td>E resolution</td>
</tr>
<tr>
<td>TTS</td>
<td>ns</td>
<td>12</td>
<td>3</td>
<td>Vertex position (against bkgs)</td>
</tr>
<tr>
<td>Anode dark current</td>
<td>KHz</td>
<td>20-30</td>
<td>10-50</td>
<td>Need for a trigger</td>
</tr>
<tr>
<td>After pulse fraction</td>
<td>%</td>
<td>3</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Glass radioactivity</td>
<td>ppb</td>
<td>$^{238}$U: 50</td>
<td>$^{232}$Th: 50</td>
<td>$^{238}$U: 400</td>
</tr>
</tbody>
</table>
20” PMT: features and QA

- About 2600 MCP and 1700 dynode produced and delivered to JUNO
- 4500 m² station operating near to JUNO site until 2020 for potting to Front-End electronics and Quality Assessment

Measurements from the vendors

- MCP PMT: 2160 pieces
  - DE (QE*CE) in average: 29.1%
- Dynode PMT: 1760 pieces
  - QE in average: 30.1%

Visual inspection

Performance meas.
20” PMT: resilience/reliability

System is under-water: needs to be reliable and resilient
- Waterproof potting: multiple waterproof layers, aim at failure rate < 0.5% in first 6 years
- Shock protection: avoid propagation of waves from implosion of one PMT (from under water pressure) to neighbouring PMTs

✓ studied behaviour of various materials in 50 prototypes by performing several induced shock tests

✓ settled for acrylic + stainless steel protection covers, with 9 mm thickness optimized to balance hardness vs transparency to optical photons

Single PMT assembly

1. Top cover: 9mm acrylic
2. PMT
3. Rubber ring between cover and PMT
4. Bottom cover: 2mm stainless-steel
5. Clamps (Two half with reinforcing rib)
6. Potting structure

Naked PMT for triggering the shock wave

Implosion test
Not only statistics...

✓ 75% photo-coverage and collects ~1200 p.e./MeV
➡ but depending on event E and position, PMT could be “flooded” by p.e. and waveform saturate
→ loss of linearity
➡ and large cathode → high dark rate

➡ 2.5% photo-coverage and collects ~50 p.e./MeV
✓ but operating in photon counting mode allows for complementary, unbiased event E determination
✓ and lower dark rate

*Multi-calorimetric approach* reduces non-stochastic terms (“systematics”) in the energy resolution dependence (≤ 3% @ 1MeV in total)
* allows to extend the dynamical range in N(p.e.)
* and improve time and vertex resolution for muon reconstruction (showers saturate 20” PMT)
3" PMT: the other pair of eyes

- 26k PMT ordered from HZC-Photonics
  - custom-made: new development with improved TTS (based on KM3Net design)
- 16 PMTs read-out by a multi-channel connector on a single "underwater box" (cabling configuration matters and is being optimized)
- Bidding completed before summer, start production at beginning of 2018

<table>
<thead>
<tr>
<th>Parameters</th>
<th>HZC’s response</th>
</tr>
</thead>
<tbody>
<tr>
<td>QE×CE @ 420 nm</td>
<td>24% (&gt;22%)</td>
</tr>
<tr>
<td>TTS (FWHM) of SPE</td>
<td>&lt;5ns</td>
</tr>
<tr>
<td>P/V ratio of SPE</td>
<td>3 (&gt;2)</td>
</tr>
<tr>
<td>SPE signal width (sigma)</td>
<td>35% (&lt;45%)</td>
</tr>
<tr>
<td>Dark rate @ ¼ PE</td>
<td>1kHz (&lt;1.8kHz)</td>
</tr>
<tr>
<td>QE uniformity</td>
<td>&lt;30% in 60mm</td>
</tr>
<tr>
<td>Pre/after pulse ratio</td>
<td>&lt;5%, &lt; 15%</td>
</tr>
<tr>
<td>Nonlinearity</td>
<td>&lt;10%@1-100PE</td>
</tr>
<tr>
<td>Radioactivity</td>
<td>238U: &lt;400ppb, 232Th: &lt;400ppb, 40K: &lt;200ppb</td>
</tr>
</tbody>
</table>
3” PMT: preliminary measurements

- **Test results of XP72B22 samples**
  - QE: 23.5% - 26%; P/V: 3;
  - SPE resolution: <30%; TTS: 2-5ns

<table>
<thead>
<tr>
<th>No.</th>
<th>Resolution</th>
<th>P-V Ratio</th>
<th>Gain@1350V</th>
<th>TTS(ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>70195</td>
<td>0.231</td>
<td>4.889</td>
<td>2.5e+07</td>
<td>2.2</td>
</tr>
<tr>
<td>70197</td>
<td>0.276</td>
<td>6.818</td>
<td>2.3e+07</td>
<td>2.3</td>
</tr>
<tr>
<td>70215</td>
<td>0.245</td>
<td>2.832</td>
<td>0.4e+07</td>
<td>2.0</td>
</tr>
<tr>
<td>70218</td>
<td>0.251</td>
<td>5.239</td>
<td>1.0e+07</td>
<td>2.7</td>
</tr>
<tr>
<td>70219</td>
<td>0.279</td>
<td>4.592</td>
<td>0.6e+07</td>
<td>3.2</td>
</tr>
<tr>
<td>70222</td>
<td>0.269</td>
<td>6.657</td>
<td>1.5e+07</td>
<td>2.6</td>
</tr>
<tr>
<td>70226</td>
<td>0.239</td>
<td>7.800</td>
<td>2.3e+07</td>
<td>5.0</td>
</tr>
<tr>
<td>70236</td>
<td>0.249</td>
<td>6.440</td>
<td>2.2e+07</td>
<td>4.4</td>
</tr>
</tbody>
</table>
JUNO PMT system, overall

- optical coverage = ~78%: 18,000 20” PMTs (75%) + 25,000 3” PMTs (2.5%)

- Several geometrical arrangements probed and relative position of optical surfaces of 20” and 3” PMT optimized to maximize overall light collection, yet minimize complexity of installation
PMT readout electronics will be installed underwater, very close to PMT:

- PMT Voltage Divider and High Voltage
- Front-End electronics: analog and digital electronics

- Design advanced, prototype performances being measured
- Particular focus on reliability of UW parts
- 2 alternative HV prototypes also being tested
\[ \sigma(E): \text{calibremus, calibremus, calibremus...} \]

- Uncertainty on energy scale < 1% crucial for total \( \sigma(E)/E \sim 3\% \) at 1 MeV
- NB: uniformly in the detector
- JUNO envisaged complementary methods for E response determination across detector and for various energy loss processes

**1D**: Automatic Calibration Unit (ACU) along z axis: could reach sub-cm positioning
- **2D**: Cable Loop System (CLS) over vertical planes: test reaches 10 cm precision
- **2D**: Guide Tube Calibration System (GTCS) to probe outer CD surface: full-size tested
- **3D**: Remotely Operated under-LS Vehicle (ROV), whole detector volume scanned: first version designed and tested

Using known radio-active sources:
- \( \gamma^{40}\text{K}, \gamma^{54}\text{Mn}, \gamma^{60}\text{Co}, \gamma^{137}\text{Cs} \)
- \( e^+^{22}\text{Na}, e^+^{68}\text{Ge} \)
- \( n^{241}\text{Am-Be}, n^{241}\text{Pu-}^{13}\text{C}, n^{241}\text{Am-}^{13}\text{C} \)
Some other **selected** topics with **JUNO**

• JUNO’s features make it an excellent detector for other physics
  • E.g. detector mass makes it a good target for a lot of physics
  • but need to control the backgrounds
Muon veto

- Unscreened muons can interact with $^{12}$C in LS and produce lighter isotopes (esp. $^9$Li and $^8$He), that mimic IBD
- TT geometrical coverage ~50%
  - veto + provide “calibration” sample to study performance of tracking algorithms
    (reject un-vetoed muons passing through central detector off-line)
- TT has been shipped to near-JUNO site for aging tests
• Even if LS is purified, surrounding environment intrinsically radioactive
• Identify “Outside-in” e and n from Cherenkov radiation in 35 kton of ultra-pure water around central sphere
• Light collected by 2k 20” PMTs
  • veto system efficiency expected to be > 95%
  • fast neutron background ~0.1/day, Rn activity < 0.2 Bq/m³
Background processes

<table>
<thead>
<tr>
<th>Selection</th>
<th>IBD efficiency</th>
<th>IBD</th>
<th>Geo-(\nu)s</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>Fiducial volume</td>
<td>91.8%</td>
<td>76</td>
<td>1.4</td>
<td>(\sim 5.7 \times 10^4)</td>
<td>84</td>
<td>77</td>
<td>0.1</td>
</tr>
<tr>
<td>Energy cut</td>
<td>97.8%</td>
<td>73</td>
<td>1.3</td>
<td>410</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>1.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertex cut</td>
<td>98.7%</td>
<td>60</td>
<td>0.9</td>
<td>3.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Muon veto</td>
<td>83%</td>
<td>60</td>
<td>0.9</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>

Expected upper limit for each material (Preliminary)

<table>
<thead>
<tr>
<th>Material</th>
<th>Mass</th>
<th>Upper limit</th>
<th>Singles(Hz)</th>
<th>All volume</th>
<th>Fiducial volume</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LS</strong></td>
<td>20kt</td>
<td>(10^{-4})ppb</td>
<td>10^{-5})ppb</td>
<td>10^{-7})ppb</td>
<td>1.4\times10^{-13})ppb</td>
</tr>
<tr>
<td><strong>Acrylic</strong></td>
<td>56lt</td>
<td>1ppt</td>
<td>1ppt</td>
<td>1ppt</td>
<td>6.92</td>
</tr>
<tr>
<td><strong>Oxygen-free copper</strong></td>
<td>10t</td>
<td>0.099ppb</td>
<td>0.1ppb</td>
<td>0.14ppt</td>
<td>1.8mBq/kg</td>
</tr>
<tr>
<td><strong>Dust</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td><strong>Pulley and Ultrasonic receiver Array</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td><strong>SS tank</strong></td>
<td>350t</td>
<td>0.097ppb</td>
<td>1.97ppb</td>
<td>0.05ppb</td>
<td>2.0mBq/kg</td>
</tr>
<tr>
<td><strong>PMT glass</strong></td>
<td>156t</td>
<td>400ppb</td>
<td>400ppb</td>
<td>400ppb</td>
<td>17.93</td>
</tr>
<tr>
<td><strong>PMT potting sealant</strong></td>
<td>6.6t</td>
<td>50ppb</td>
<td>50ppb</td>
<td>50ppb</td>
<td>1</td>
</tr>
<tr>
<td><strong>PMT protection cover</strong></td>
<td>177.5t</td>
<td>10ppt</td>
<td>10ppt</td>
<td>10ppt</td>
<td>10ppt</td>
</tr>
<tr>
<td><strong>PMT potting shell</strong></td>
<td>177.5t</td>
<td>10ppt</td>
<td>10ppt</td>
<td>10ppt</td>
<td></td>
</tr>
<tr>
<td><strong>Cable</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CUU</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Radon in water</strong></td>
<td>35kt</td>
<td>0.2Bq/m³</td>
<td></td>
<td>16</td>
<td>1.3</td>
</tr>
<tr>
<td><strong>Rock</strong></td>
<td>10ppm</td>
<td>30ppm</td>
<td>5ppm</td>
<td>7.4</td>
<td>0.984</td>
</tr>
</tbody>
</table>

➢ The most critical materials are shown with “stars” in the material column.
JUNO’s features make it an excellent detector for other physics.

- E.g. detector mass makes it a good target for a lot of physics.
- But also to much intrinsic bkg activity + it’s shallow → muons → C, Li, etc.
Supernova neutrinos

- Galactic SN at a distance of 10 kpc
- ~5000 $\nu$ events in the IBD channel, 2000 events for elastic neutrino-proton scattering, and 300 events for elastic neutrino-electron scattering in the JUNO detector
- Specialized trigger under study, to cope with concentrated spray of events with characteristic time profile
  - e.g. for Betelgeuse ($d \sim 0.2$ kpc): ~10 MHz trigger rate
Solar neutrinos: possible?

- Refined measurements of $^7\text{Be}$ and $^8\text{B}$ fluxes would constrain metallicity in Sun-like stars better.
- JUNO with large exposure ideal to enhance statistics and measure $^7\text{Be}$ “shoulder” thx to unprecedented $E_{\text{res}}$.
- Radio-purity (for $^7\text{Be}$) and event-by-event cosmogenic veto ($^8\text{B}$) capabilities main challenges that remain open.
  - also, dedicated triggers and study of $^{14}\text{C}$-$^{14}\text{C}$ overlap might be needed for low $E$.

Assumed radio-purity: $10^{-16}$ g/g ($^{238}\text{U}$, $^{232}\text{Th}$)
Geo-neutrinos

- Geo-neutrino “observational network” now developed across world
  - current (KamLAND + Borexino) precision on geo-neutrino (U+Th) flux is ~17-25%, SNO+ will join in

- at JUNO same challenges as for solar measurements
  - reactor ν large background
  - signal can be extracted by template fit

- thanks to its mass, JUNO can reach 17% precision on the (U+Th) flux within the first year and 6% after 10 years
- U vs Th separation achievable with 11%-19% after 10 years

---

**Table 8-4:** Signal and backgrounds considered in the geoneutrino sensitivity study: the number of expected events for all components contributing to the IBD spectrum in the 0.7 - 12 MeV energy region of the prompt signal. We have assumed 80% antineutrino detection efficiency and 17.2 m radial cut (18.35 kton of liquid scintillator, 12.85 × 10^32 target protons).

<table>
<thead>
<tr>
<th>Source</th>
<th>Events/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geoneutrinos</td>
<td>408 ± 60</td>
</tr>
<tr>
<td>U chain</td>
<td>311 ± 55</td>
</tr>
<tr>
<td>Th chain</td>
<td>92 ± 37</td>
</tr>
<tr>
<td>Reactors</td>
<td>16100 ± 900</td>
</tr>
<tr>
<td>Fast neutrons</td>
<td>36.5 ± 36.5</td>
</tr>
<tr>
<td>⁹Li - ⁸He</td>
<td>657 ± 130</td>
</tr>
<tr>
<td>¹³C(α, n)¹⁶O</td>
<td>18.2 ± 9.1</td>
</tr>
<tr>
<td>Accidental coincidences</td>
<td>401 ± 4</td>
</tr>
</tbody>
</table>
Proton decay

- **JUNO complementary** to large Cherenkov detectors (e.g. SK, HK) in search for proton decays
- from H, \( p \rightarrow \nu + K^+ (\rightarrow \mu^+\nu_\mu) \) decay sub-threshold for Cherenkov light in water but \( E_{\text{kin}}(K^+) \sim 105 \text{ MeV} \) well visible as scintillation light
- Main bkg: muons from atmospheric neutrinos (but different time pattern)

*Expected background is 0.5 events in 10 years*
*Expected \( \tau > 1.9 \times 10^{34} \) yrs (Feldman-Cousins)*
*Example “observed” would be \( \tau > 6.8 \times 10^{33} \) yrs if 2 events of bkg fluctuation*
*With current projections, JUNO will be competitive (and complementary) soon after switch-on*
Schedule

2013
Complete conceptual design.
Complete civil design and bidding

2014
PMT production line manufacturing

2015
Start civil construction.
Complete prototyping (PMT & detector).
International collaboration established

2016
Start PMT production.
Start detector production or bidding

2017
Complete civil construction. Start detector construction and assembly

2018
Start LS production

2019
Complete detector assembly, installation and LS filling

2020
Start data taking
Conclusions

• With its size and unprecedented energy resolution, JUNO will have an impact on many areas of neutrino physics

• Demanding specs to meet challenging and multi-faceted physics programme (MH and beyond)

• Hope I gave you an idea of the many technical aspects considered and tests put in place to achieve best possible performance and reliability in detector and electronics design

• Now it’s the time to produce and build...
Additional material
JUNO civil construction

• 1020m slope tunnel excavated out of 1340m (few months ago)
  • initial delays on account of underground water leaks now under control
• ~580 m deep vertical shaft excavated
• Overburden to JUNO: ~700m (~1900 MWE)
Interference term

Survival probability

\[ P_{\nu_e \rightarrow \nu_e} = 1 - \sin^2 2\theta_{13} \left( \cos^2 \theta_{12} \sin^2 \Delta_{31} + \sin^2 \theta_{12} \sin^2 \Delta_{32} \right) \]
\[ \quad - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21} \]
\[ = 1 - \frac{1}{2} \sin^2 2\theta_{13} \left[ 1 - \sqrt{1 - \sin^2 2\theta_{12} \sin^2 \Delta_{21}} \cos(2|\Delta_{ee}| \pm \phi) \right] \]
\[ - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21}, \]

\[ \Delta m^2 = 4E\phi/L. \]

Can be seen as an extra effective mass-squared difference \( \Delta m^2 = f(E,L) \)

Fast oscillations with the two similar mass splittings

\[ \Delta_{ij} = \Delta m^2_{ij} L/4E, \]

\[ \Delta m^2_{ee} = \cos^2 \theta_{12} \Delta m^2_{31} + \sin^2 \theta_{12} \Delta m^2_{32}, \]

NH: +

IH: -

Effective mass-squared difference

\[ \text{NH: } 2|\Delta m^2_{ee}| + \Delta m^2_{\phi} \text{ and increases with energy} \]
\[ \text{IH: } 2|\Delta m^2_{ee}| - \Delta m^2_{\phi} \text{ and decreases with energy} \]

\( L.\text{Ludhova, ECAP Seminar} \)
Baseline optimization

Optimal baseline is at $L = 50-60$ km, at the oscillation maximum of $\Delta m^2_{12}$

Choice of the experimental site

In case of multiple reactors, minimize the spread of $L$

<table>
<thead>
<tr>
<th>Cores</th>
<th>YJ-C1</th>
<th>YJ-C2</th>
<th>YJ-C3</th>
<th>YJ-C4</th>
<th>YJ-C5</th>
<th>YJ-C6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (GW)</td>
<td>2.9</td>
<td>2.9</td>
<td>2.9</td>
<td>2.9</td>
<td>2.9</td>
<td>2.9</td>
</tr>
<tr>
<td>Baseline (km)</td>
<td>52.75</td>
<td>52.84</td>
<td>52.42</td>
<td>52.51</td>
<td>52.12</td>
<td>52.21</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cores</th>
<th>TS-C1</th>
<th>TS-C2</th>
<th>TS-C3</th>
<th>TS-C4</th>
<th>DYB</th>
<th>HZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (GW)</td>
<td>4.6</td>
<td>4.6</td>
<td>4.6</td>
<td>4.6</td>
<td>17.4</td>
<td>17.4</td>
</tr>
<tr>
<td>Baseline (km)</td>
<td>52.76</td>
<td>52.63</td>
<td>52.32</td>
<td>52.20</td>
<td>215</td>
<td>265</td>
</tr>
</tbody>
</table>
Baseline trigger

- All the PMT send out a trigger signal, synchronous with the reference clock.
- If a decision by the Global Trigger Electronics (dry), data request sent to the single PMTs. PMT reply by sending the requested waveform data, in a specific time window, through async lines.

**DAQ**
- Each 20” PMT read out one-by-one: 16 Mbit/s (with 1 kHz physics rate)
  - ~2GB/s (CDR)
- 3” PMT read out in blocks of 128 channels: ≤ 1 Mbit/s
<table>
<thead>
<tr>
<th>Isotopes</th>
<th>$Q$ (MeV)</th>
<th>$T_{1/2}$</th>
<th>Rate (per day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3\text{H}$</td>
<td>0.0186 ($\beta^-$)</td>
<td>12.31 year</td>
<td>$1.14 \times 10^4$</td>
</tr>
<tr>
<td>$^6\text{He}$</td>
<td>3.508 ($\beta^-$)</td>
<td>0.807 s</td>
<td>544</td>
</tr>
<tr>
<td>$^7\text{Be}$</td>
<td>$Q_{\text{EC}} = 0.862$ ($10.4% \gamma, E_{\gamma} = 0.478$)</td>
<td>53.22 day</td>
<td>5438</td>
</tr>
<tr>
<td>$^8\text{He}$</td>
<td>$10.66$ ($\beta^-[\gamma : 84%], 8.63$ ($\beta^-n : 16%$)</td>
<td>0.119 s</td>
<td>11</td>
</tr>
<tr>
<td>$^8\text{Li}$</td>
<td>16.0 ($\beta^-$)</td>
<td>0.839 s</td>
<td>938</td>
</tr>
<tr>
<td>$^8\text{B}$</td>
<td>16.6 ($\beta^+$)</td>
<td>0.770 s</td>
<td>225</td>
</tr>
<tr>
<td>$^9\text{Li}$</td>
<td>13.6 ($\beta^- : 49%), 11.94$ ($\beta^-n : 51%$)</td>
<td>0.178 s</td>
<td>94</td>
</tr>
<tr>
<td>$^9\text{C}$</td>
<td>15.47 ($\beta^+p : 61.6%, \beta^+\alpha : 38.4%$)</td>
<td>0.126 s</td>
<td>31</td>
</tr>
<tr>
<td>$^{10}\text{Be}$</td>
<td>0.556 ($\beta^-$)</td>
<td>1.51 e6 year</td>
<td>1419</td>
</tr>
<tr>
<td>$^{10}\text{C}$</td>
<td>2.626 ($\beta^+\gamma$)</td>
<td>19.29 s</td>
<td>482</td>
</tr>
<tr>
<td>$^{11}\text{Li}$</td>
<td>20.55 ($\beta^-n : 83%, \beta^-2n : 4.1%$)</td>
<td>0.00875 s</td>
<td>0.06</td>
</tr>
<tr>
<td>$^{11}\text{Be}$</td>
<td>11.51 ($\beta^-\gamma : 96.9%$, $2.85$ ($\beta^-\alpha : 3.1%$)</td>
<td>13.76 s</td>
<td>24</td>
</tr>
<tr>
<td>$^{11}\text{C}$</td>
<td>0.960 ($\beta^+$)</td>
<td>20.36 min</td>
<td>$1.62 \times 10^4$</td>
</tr>
<tr>
<td>$^{12}\text{Be}$</td>
<td>11.708 ($\beta^-\gamma, \beta^-n : 0.5%$)</td>
<td>0.0215 s</td>
<td>0.45</td>
</tr>
<tr>
<td>$^{12}\text{B}$</td>
<td>13.37 ($\beta^-\gamma$)</td>
<td>0.0202 s</td>
<td>966</td>
</tr>
<tr>
<td>$^{12}\text{N}$</td>
<td>16.316 ($\beta^+\gamma$)</td>
<td>0.0110 s</td>
<td>17</td>
</tr>
<tr>
<td>$^{13}\text{B}$</td>
<td>13.437 ($\beta^-\gamma$)</td>
<td>0.0174 s</td>
<td>12</td>
</tr>
<tr>
<td>$^{13}\text{N}$</td>
<td>1.198 ($\beta^+$)</td>
<td>9.965 min</td>
<td>19</td>
</tr>
<tr>
<td>$^{14}\text{B}$</td>
<td>20.644 ($\beta^-\gamma, \beta^-n : 6.1%$)</td>
<td>0.0126 s</td>
<td>0.021</td>
</tr>
<tr>
<td>$^{14}\text{C}$</td>
<td>0.156 ($\beta^-$)</td>
<td>5730 year</td>
<td>132</td>
</tr>
<tr>
<td>$^{15}\text{C}$</td>
<td>9.772 ($\beta^-$)</td>
<td>2.449 s</td>
<td>0.6</td>
</tr>
<tr>
<td>$^{16}\text{C}$</td>
<td>8.010 ($\beta^-n : 99%$)</td>
<td>0.747 s</td>
<td>0.012</td>
</tr>
<tr>
<td>$^{16}\text{N}$</td>
<td>10.42 ($\beta^-\gamma$)</td>
<td>7.130 s</td>
<td>13</td>
</tr>
<tr>
<td>$^{17}\text{N}$</td>
<td>8.680 ($\beta^-\gamma : 5%$, $4.536$ ($\beta^-n : 95%$)</td>
<td>4.173 s</td>
<td>0.42</td>
</tr>
<tr>
<td>$^{18}\text{N}$</td>
<td>13.896 ($\beta^-\gamma : 93%$, $5.851$ ($\beta^-n : 7%$)</td>
<td>0.620 s</td>
<td>0.009</td>
</tr>
</tbody>
</table>

Table 13-9: The estimated rates for cosmogenic isotopes in JUNO LS by FLUKA simulation, in which the oxygen isotopes are neglected. The decay modes and $Q$ values are from TUNL Nuclear Data Group [479].
JUNO can be a telescope

**Indirect DM search**
- discover DM or extend excluded parameter space

**Solar neutrinos**
- pp-chain measured
- CNO neutrino flux
- study solar interior

**Supernova neutrinos**
- neutrino burst established
- extract information on core-collapse and neutron star formation

**Geoneutrinos**
- now: 4σ observation
- geology: radiogenic heat, U/Th conc.

**Observation Range**
- <1 to 50 MeV

**Diffuse SN neutrinos**
- still unobserved
- discovery, z-dep. SN rate and average spectrum