Reactor Neutrino Experiments

KT McDonald  
*Princeton U.*  
(November 27, 2018)  

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Beta Decay

1896: H. Becquerel discovered that uranium salts can activate photographic film through black paper, as if penetrating rays are emitted.

1897: M. Curie found similar behavior for thorium, and coined the term “radioactivity.”

1898: M. and P. Curie discovered radioactive elements polonium and radium.

1899: E. Rutherford showed that radioactive materials have an exponential decay, and that there are 2 types of radioactivity, alpha (not very penetrating) and beta (more penetrating).

1901: Becquerel showed that beta rays are electrons.

1914: J. Chadwick gave first clear evidence that the energy spectrum of electrons in beta decay is continuous, which implies apparent energy nonconservation.
Neutrinos

1930: Pauli notes that if a new particle is produced in beta decay, this would restore conservation of energy, also Fermi statistics if the particle has spin $\frac{1}{2}$. This is the first solution to a problem in particle physics by invention of a new particle.

Zürich, Dec. 4, 1930

Dear Radioactive Ladies and Gentlemen,

...because of the “wrong” statistics of the N and $^6$Li nuclei and the continuous $\beta$-spectrum, I have hit upon a desperate remedy to save the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin $\frac{1}{2}$ and obey the exclusion principle ..... The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous $\beta$-spectrum would then become understandable by the assumption that in $\beta$-decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and electron is constant.

....... For the moment, however, I do not dare to publish anything on this idea ...... So, dear Radioactives, examine and judge it. Unfortunately I cannot appear in Tübingen personally, since I am indispensable here in Zürich because of a ball on the night of 6/7 December. ....

W. Pauli
First Attempts to Detect a Neutrino

Bethe and Peierls argued that a spin-1/2 neutrino might have a magnetic moment, which would cause a small amount of ionization in matter by a penetrating neutrino.

H. Bethe and R. Peierls, Nature, 133, 532 (1934)

Two experiments were performed in 1934 using radium sources and cloud chambers to detect this effect, with negative results.


In the Standard Model, the magnetic moment of a neutrino is proportional to its mass,

\[ \mu_v = \frac{3eG_F m_v}{8\pi^2\sqrt{2}} \approx 10^{-7} \mu_e \frac{m_v m_e}{m_p^2} \approx 10^{-18} \mu_e, \text{ for } m_v \approx 0.1 \text{ eV, i.e., extremely small.} \]

1946: Pontecorvo suggested that neutrinos might be observed via inverse beta decay of neutrinos from the Sun, or from a “pile” = nuclear reactor. 

In particular, he suggested study of the chlorine reaction:

\[ v + Cl^{37} \rightarrow Ar^{37} + e^- \]

Note that Pontecorvo proposed to search for neutrinos at a nuclear reactor, although reactors (unlike the Sun) produce antineutrinos!

He was inspired by Majorana’s comment that neutrinos might be their own antiparticles.

E. Majorana, Nuovo Cimento 14, 171 (1937)
1955: Following a suggestion of Pontecorvo, Davis searched for the reaction
\[ \nu + Cl^{37} \rightarrow Ar^{37} + e^- \]
with a detector placed near a nuclear reactor.

He obtained no signal, but remarked that the detector mass (4 tons) was too small for a signal to have been observed, even if the nominal antineutrinos from a reactor were actually neutrinos as per Majorana.

*R. Davis Jr, Phys. Rev. 97, 766 (1955)*

This version of Davis’ experiment has never been repeated.

Davis switched his efforts to the detection of solar neutrinos, deep underground and far from any nuclear reactor, with now-famous results: the solar-neutrino “deficit.”

1953: Cowan and Reines noted that a better way to detect reactor antineutrinos (produced via the beta decay $n \rightarrow p e^- \bar{\nu}_e$) is via the inverse-beta-decay process, $\bar{\nu}_e p \rightarrow n e^+$, using a liquid-scintillator detector that first observes the positron, and then the delayed capture of the thermalized neutron on a nucleus, with subsequent emission of $\gamma$-rays.

F. Reines and C.L. Cowan Jr, Phys. Rev. 90, 492 (1953)

They reported marginal evidence for detection of antineutrinos in 1953, and then more compelling evidence in 1956.

F. Reines and C.L. Cowan Jr, Phys. Rev. 92, 830 (1953)
C.L. Cowan Jr et al., Science 124, 103 (1956)

First large (0.3 m$^3$) liquid scintillation detector in shield. The liquid was viewed by 90 2-inch photomultiplier tubes. Before the development of this detector a 0.02 m$^3$ volume was considered large.
Three Generations of Standard-Model Leptons

1936: Muon discovered in cloud chambers.
   J.C. Street and E.C. Stevenson, Phys. Rev. 52, 1003 (1937)

1962: Muon neutrinos observed in spark chambers.

1975: Tau lepton discovered in a 4π collider detector.

2001: Tau neutrinos observed in emulsion detectors.

Pontecorvo, Maki, Nakagawa, Sakata

1957: Pontecorvo considered that lepton number might not be conserved, that neutrinos might have nonzero mass, and that they could exhibit vacuum oscillations.


1962: Maki, Nakagawa and Sakata considered a triplet model for leptons, which accommodates neutrino mixing.

Prog. Theor. Phys. 28, 870 (1962)

These suggestions have defined much of the study of neutrino interactions in last 50 years: Measurement of 3 mass differences, $\Delta m_{ij}^2 = m_i^2 - m_j^2$, 3 mixing angles, $\theta_{ij}$, and CP-violation parameter $\delta_{\text{CP}}$.

[1964: CP violation discovered in the neutral-Kaon system.


Initial searches for neutrino oscillations at a nuclear reactor used only a single detector, at a single distance from the reactor, hoping to find a signal for (electron) antineutrinos smaller than that expected for the case of no oscillations.

Perhaps not surprisingly, results from these experiments were negative.

[See slide 17.]
Atmospheric and Solar Neutrino Oscillations

1998: Following hints of atmospheric neutrino oscillations in the Kamiokande expt, the Super-Kamiokande water-Čerenkov detector showed a clear difference in the energy dependence of 0.2-20 GeV electron and muon neutrinos produced in the upper atmosphere.


\[ |\Delta m^2_{32}| = 2 \pm 1 \times 10^{-3} \text{eV}^2, \quad \sin 2\theta_{23} \approx 0.9. \]


\[ \Delta m^2_{21} = m_2^2 - m_1^2 = 7 \pm 2 \times 10^{-5} \text{eV}^2, \quad \theta_{12} = 33^\circ \pm 7^\circ. \]

\[ m_2 > m_1 \text{ by definition.} \]
If neutrinos have mass, they have a rest frame.

If a neutrino oscillates and changes its mass in this rest frame, its mass/energy is not conserved! If a moving neutrino oscillated with fixed momentum, its energy would change, or if fixed energy, its momentum would change.

Is this the way neutrino oscillations work? NO!

Neutrinos are always produced together with some other state $X$, and if the parent state has definite energy and momentum, then so does the quantum state $|\nu\rangle|X\rangle$.

If the neutrino is produced in a flavor state, it is a quantum sum of mass states, $|\nu_e\rangle = a_1 |\nu_1\rangle + a_2 |\nu_2\rangle + a_3 |\nu_3\rangle$, and the production involves an entangled state, $|\nu_e\rangle |X\rangle = a_1 |\nu_1\rangle |X_1\rangle + a_2 |\nu_2\rangle |X_2\rangle + a_3 |\nu_3\rangle |X_3\rangle$.

The sum of the energies and momenta of $\nu_i$ and $X_i$ equals the initial state energy/momentum, while the different $\nu_i$ ($X_i$) have different energies and momenta.

The coefficients $a_i$ can change with time (oscillate), but the energy of $\nu_i$ does not change with time.

Can Measurement of $X$ Suppress Neutrino Oscillations?

YES.

If $X$ is measured so well that we can distinguish the different $X_i$ from one another, then the neutrino must be observed in the corresponding state $\nu_i$.

If the neutrino is observed in a flavor state, the proportions of the 3 possible flavors are just squares of the MNS matrix elements, independent of time/distance.

However, most “observations” of state $X$ do not determine its energy so precisely that the above scenario holds.

Example: In a nuclear beta decay, $A \rightarrow A' e \nu_e$, the interaction of $A'$ and $e$ with nearby atoms does not “measure” their energies precisely. Rather, the entanglement of the $\nu_e$ with $A'$ and $e$ becomes transferred to the neighbor atoms.

Optical experiments with entangled photons illustrate how measurement of the 2nd photon of a pair can affect the quantum interference of the 1st photon.  

What is Decoherence of Neutrino Oscillations?

Since the different $\nu_i$ have different energies, they have different velocities, such that their wavepackets no longer overlap at large enough distances, and neutrino oscillation should no longer be observable.

Can this effect ruin a long-baseline neutrino experiment, particularly one like JUNO where it is proposed to observe the $\sim 15^{th}$ oscillation?

NO!

That is, when the neutrinos are observed at some large, fixed distance, and one looks for evidence of oscillations in their energy spectra, if the detector resolution is good enough to resolve the oscillations, this guarantees that the wavepackets of the different $\nu_i$ still overlap (barely).

On the other hand, if the detector energy resolution is poor, and the oscillations can’t be resolved in the energy spectrum, the quantum description of this is that the $\nu_i$ have “decohered” because their wave packets don’t overlap.

Moral: If you want to see neutrino oscillations, you have to observe them with a “good enough” detector.

Neutrinos from sources at different distances are not coherent with one another, which blurs the oscillations when source size $\geq$ oscillation length (as for solar neutrinos and supernovae).

Dirac: A photon interferes only with itself...
Coherence Length

We review the concept of coherence length by consideration of the neutrino types, 1 and 2, with masses $m_i$ and well defined energies $E_i \gg m_i$ and momenta $P_i$ in the lab frame,

$$c^2 P_i^2 = E_i^2 - m_i^2 c^4,$$

$$P_i \approx \frac{E_i}{c} \left(1 - \frac{m_i^2 c^4}{2E_i^2}\right),$$

$$\psi_i(x,t) = \psi_{i,0} e^{i (P_i x - E_i t)} \approx \psi_{i,0} e^{i E_i (x/c - t)} e^{-im_i^2 c^3 x/2E_i \hbar} \approx \psi_{i,0} e^{-im_i^2 c^3 x/2E_i \hbar} \text{ for } x \approx ct.$$  

Physical neutrinos are not plane-wave states as above, but are wave packets with a spread of energies $\Delta E_i$, with time spread $\Delta t \approx \hbar / \Delta E_i$, and spatial width $\Delta x \approx \hbar c / \Delta E_i$.

The wave packet decoheres when the packets of types 1 and 2 cease to overlap, i.e., when

$$\Delta x \approx \frac{\hbar c}{\Delta E} = \left|v_1 - v_2\right| t_{coh} = \left|\frac{c^2 P_1}{E_1} - \frac{c^2 P_2}{E_2}\right| t_{coh} \approx \left|m_1^2 - m_2^2\right| \frac{c^5 t_{coh}}{2E^2},$$

$$E \equiv \frac{E_1 + E_2}{2}, \quad \Delta m_{12}^2 \equiv \left|m_1^2 - m_2^2\right|,$$

$$L_{coh} \equiv ct_{coh} \approx \frac{2E^2 \hbar c}{\Delta E \Delta m_{12}^2 c^4}.$$  

Oscillation Length

We also remind you of the concept of oscillation length for the case of two neutrino flavors, \(a\) and \(b\).

\[
\begin{pmatrix}
\psi_a \\
\psi_b
\end{pmatrix} = 
\begin{pmatrix}
\cos \theta_{12} & \sin \theta_{12} \\
-\sin \theta_{12} & \cos \theta_{12}
\end{pmatrix}
\begin{pmatrix}
\psi_1 \\
\psi_2
\end{pmatrix},
\begin{pmatrix}
\psi_1 \\
\psi_2
\end{pmatrix} = 
\begin{pmatrix}
\cos \theta_{12} & -\sin \theta_{12} \\
\sin \theta_{12} & \cos \theta_{12}
\end{pmatrix}
\begin{pmatrix}
\psi_a \\
\psi_b
\end{pmatrix}.
\]

Suppose have pure flavor state \(a\) at the origin at \(t = 0\), \(\Rightarrow \psi_{1,0} = \cos \theta_{12}, \psi_{2,0} = \sin \theta_{12}.

\[
\psi_a (x) = \cos \theta_{12} \psi_1 (x) + \sin \theta_{12} \psi_2 (x) \approx \cos^2 \theta_{12} e^{-im_1^2 c^3 x/2E_1 h} + \sin^2 \theta_{12} e^{-im_2^2 c^3 x/2E_2 h},
\]

\[
P_{a \rightarrow a}(x, E) = |\psi_a (x)|^2 = \cos^4 \theta_{12} + \sin^4 \theta_{12} + 2 \cos^2 \theta_{12} \sin^2 \theta_{12} \left[ \frac{m_1^2}{E_1} - \frac{m_2^2}{E_2} \right] \frac{c^3 x}{2\hbar}
\]

\[
\approx \cos^4 \theta_{12} + \sin^4 \theta_{12} + 2 \cos^2 \theta_{12} \sin^2 \theta_{12} \left( 1 - 2 \sin^2 \frac{\Delta m_{12}^2 c^3 x}{4E\hbar} \right)
\]

\[
= 1 - \sin^2 2\theta_{12} \sin^2 \frac{x}{L_{osc}},
\]

The spatial period of neutrino oscillations is \(\lambda_x = \pi L_{osc}\).

The period of oscillations in the neutrino energy spectrum from \(\beta\)-decay at fixed \(x\) is \(\lambda_E \approx \frac{\pi L_{osc} \overline{E}\hbar c}{x} = \frac{\lambda_x \overline{E}\hbar c}{x} \equiv \frac{\overline{E}\hbar c}{N_{osc}},\) where \(\overline{E}\) is the average neutrino energy, etc.

Thus, at distance \(x = N_{osc} \lambda_x\), the number of oscillations in the energy spectrum is \(\approx N_{osc}\).

KT McDonald                         XII SILAFAE                       Nov 27, 2018 15
In neutrino experiments, the detector energy resolution determines $\sigma_E$ in the expression for the coherence length $L_{\text{coh}}$.

Some people have difficulty with this factoid, as they suppose that “decoherence” is something that happens before the neutrino is detected. We follow Bohr in noting that the apparatus plays a role in a quantum system. In particular, a neutrino detected with a nominal energy $E$ actually has energy in the range $\approx E \pm \sigma_E$, which affects the overlap of the wavepackets of different neutrino types when they have arrived at the detector.

Suppose the detector is at distance $x = n \overline{L}_{\text{osc}}$ from a nuclear reactor that produces neutrinos of average energy $\overline{E}$. Then, the neutrino-energy spectrum would show $\approx n$ oscillations.

To resolve these oscillations, we need detector energy resolution $\sigma_E \leq \overline{E} / n$.

And, in this case the coherence length is $L_{\text{coh}} \approx \frac{\overline{E}}{\sigma_E} \overline{L}_{\text{osc}} \approx n \overline{L}_{\text{osc}} = x$.

Thus, if the detector energy resolution is good enough to resolve the energy oscillations, then the coherence length is automatically long enough to avoid “decoherence.”

Moral: Decoherence is unimportant in a “good enough” neutrino experiment.

Example: The KamLAND Reactor Neutrino Experiment

In their initial oscillation analysis, the KamLAND experiment ignored the neutrino energy, so that \( \frac{E}{\sigma_E} \approx 1 \), and they could only see an average effect of the first oscillation in \( P_{e \rightarrow e}(x) \).


In a later analysis, the neutrino energy was used, and better evidence for neutrino oscillation was obtained.

Effect of Source Size

If the neutrino source is large compared to an oscillation length, the evidence for neutrino oscillations in a detector will be “washed out.”

\[ P_{e \to e}(x) \approx 1 - \sin^2 2\theta_{12} \sin^2 \frac{x}{L_{\text{osc}}} \rightarrow 1 - \frac{1}{2} \sin^2 2\theta_{12}. \]

This is not strictly an effect of decoherence, in that neutrinos produced in different primary interactions do not interfere with one another.

For solar-neutrino oscillations, \( \sin^2 2\theta_{12} \approx 0.86 \), \( \Rightarrow \) \( P_{e \to e}(x) \approx 0.57 \), the solar-neutrino "deficit."


Extracts from

Results - Daya Bay, RENO, and Double Chooz

Henry Band
Yale University
For the Daya Bay Collaboration

https://meetings.triumf.ca/indico/event/27/session/5/contribution/13/material/slides/0.pdf
Reactor Antineutrino oscillations

Two modes of oscillations:

\[ P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{12} \cos^2 \theta_{13} \sin^2 \left( \frac{\Delta m_{21}^2 L}{4E} \right) - \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{ee}^2 L}{4E} \right) \]

Solar neutrino oscillation

\[ \theta_{13} \] oscillations

Reactors produce pure \( \bar{\nu}_e \) from \( \beta \)-decays of neutron rich fission fragments～(6/fission).

> 99.9% of \( \bar{\nu}_e \) from \( ^{235}\text{U} \), \( ^{238}\text{U} \), \( ^{239}\text{Pu} \), \( ^{241}\text{Pu} \)

- Keys
  - Relative near/far measurements to reduce modeling systematics

- High-statistics
  - Background suppression
  - Control of systematics errors
Antineutrino Detection

- **Inverse β-decay (IBD):** coincidence of two consecutive signals
  \[ \bar{\nu}_e + p \rightarrow e^+ + n \] (prompt signal)
  \[ E_{e} \sim E_{\nu} - 0.8 \text{ MeV} \]

  \[ \sim 30 \mu s \] (0.1% Gd)

  \[ \rightarrow p \rightarrow D + \gamma \ (2.2 \text{ MeV}) \] (delayed signal) \[ \sim 15\% \]

  \[ \rightarrow Gd \rightarrow Gd^* \rightarrow Gd + \gamma's \ (8 \text{ MeV}) \] (delayed signal) \[ \sim 85\% \]

- Powerful background rejection
- Positron preserves most information about antineutrino energy
Detectors

- The antineutrino detectors (ADs) are “three-zone” cylindrical modules immersed in water pools

**GdLS region defines the target mass**
- Surrounding LS improves detection of $\gamma$-rays
- MO buffers outside backgrounds
- Water reduces backgrounds & detects muons
- Additional muon detection above

Energy resolution $\approx 8.5%/\text{VE (MeV)} + 1\%$

Double Chooz

*NIM A 811, 133 (2016)*
Daya Bay

Far
4x20 t
Near
2x2x20 t
17.4 GWth

Double Chooz

Near
8 t
Near
2x2x20 t
8.5 GWth

RENO

Far
8 t
Near
16 t
16.8 GWth

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Near/far data mass (ton)</th>
<th>Far Detector mass (ton)</th>
<th>Near Overburden m.w.e.</th>
<th>Near Overburden (GWth)</th>
<th>Near detector baseline (km)</th>
<th>Far detector baseline (km)</th>
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<td>2011-2020</td>
<td>2<em>2</em>20</td>
<td>4*20</td>
<td>250-285</td>
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<td>Reno</td>
<td>2011-2020?</td>
<td>15.5</td>
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<td>Double Chooz</td>
<td>2015-17</td>
<td>8.3</td>
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</table>
Daya Bay

- See a clear rate and shape distortion that fits well to the 3-neutrino hypothesis

\[ L \approx L_{\text{osc,13}} \approx \frac{L_{\text{coh}}}{5}. \]
Daya Bay

- Oscillation Results with 1958 Days
- Measure $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ to 3.4% and 2.8% respectively

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{1.267 \Delta m^2_{ee} L}{E} - \text{ solar term}$$

$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$$
$$|\Delta m^2_{ee}| = (2.522 + 0.068 - 0.070) \times 10^{-3} \text{ eV}^2$$

The statistical uncertainty contributes about 60% (50%) of the total $\theta_{13}$ ($\Delta m^2_{ee}$) uncertainty.
RENO & Double Chooz

\[ \sin^2 2\theta_{13} = 0.0896 \pm 0.0068 \]
\[ |\Delta m^2_{ee}| = (2.68 \pm 0.14) \times 10^{-3} \text{ eV}^2 \]

Double Chooz  
Buck - Neutrino 2018

\[ 9.0 \times 10^4 \text{ (far), } 2.1 \times 10^5 \text{ (near)} \]

combined nGd+nC+nH
\[ \sin^2 2\theta_{13} = 0.105 \pm 0.014 \]
Global Comparison

- Daya Bay – best precision of $\theta_{13}$ in the foreseeable future
- Agreement of $\Delta m^2_{32}$ between accelerator & reactor experiments
- Analysis of nH events in all detectors consistent with nGd events
Other results

- Daya Bay
  - Search for Time-Varying Antineutrino Signal - arXiv:1809.04660
  - Seasonal Variation of the Underground Cosmic Muon Flux - JCAP 1801 no.1 (2018)
  - Independent measurement of $\theta_{13}$ via neutron capture on hydrogen Phys. Rev. D93, 072011 (2016)
Absolute reactor flux

- Updated analysis with reduced systematic errors
  - Daya Bay 1260 days
    - \( R_{\text{data/pred}} \) (Huber-Mueller) = \( 0.952 \pm 0.014 \) (exp.) \( \pm 0.023 \) (model)
    - \( \sigma_f = (5.91 \pm 0.09) \times 10^{-43} \text{cm}^2 \) fission
  - RENO 2200 days
    - \( R_{\text{data/pred}} \) (H-M) \( 0.918 \pm 0.018 \) (exp.)
    - \( \sigma_f = (5.79 \pm 0.11) \times 10^{-43} \text{cm}^2 \) fission
  - Double Chooz
    - \( R_{\text{data/pred}} \) (H-M) =
      - \( 0.945 \pm 0.008 \) (exp.)

- All 3 experiments see deviations from the expected shape in the 4-6 MeV region \( \Rightarrow \) Reactor models still not sufficiently accurate.
The Design of JUNO and Its Current Status

Wei Wang / 王為, Sun Yat-sen University
AAP 2018, LLNL, Oct 10, 2018

- A Brief Introduction to JUNO
- The Design of the JUNO Detector System
- Current status of JUNO
- Summary

Known $\theta_{13}$ Enables Neutrino Mass Hierarchy at Reactors

- How to resolve neutrino mass hierarchy using reactor neutrinos
  - KamLAND (long-baseline) measures the solar sector parameters
  - Short-baseline reactor neutrino experiments designed to utilize the oscillation of atmospheric scale
- Both scales can be studied by observing the spectrum of reactor neutrino flux


$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21}$

$- \sin^2 2\theta_{13} (\cos^2 \theta_{12} \sin^2 \Delta_{31} + \sin^2 \theta_{12} \sin^2 \Delta_{32})$

- Mass hierarchy is reflected in the spectrum
- Signal independent of the unknown CP phase

Realization & Plausibility: L. Zhan et al, PRD.78.111103; J. Learned et al PRD.78.071302
JUNO Found a Sweet Spot

JUNO Detector Site

\[ \theta_{13} \text{ oscillations} \]

Solar neutrino oscillation

Best baseline is \(~60\) km
(OR at the solar oscillation maximum)
Challenges in Resolving MH using Reactors

\[ L \approx 30L_{\text{osc,13}} \approx 2L_{\text{coh}} \]

- Energy resolution: \( \sim 3\%/\sqrt{E} \)
- Energy scale uncertainty: \(<1\%\)
- Statistics (the more the better)
- Reactor distribution: \(<\sim 0.5\text{km}\)

\[ Y. F. \; Li \; et \; al \]

\[ PRD88 \; (2013) \; 013008 \]

\[ 6 \; \text{years} \]

\[ L = 52 \; \text{km} \]

\[ E_{\text{res}} = 3\% \]

\[ \Delta \chi^2 \] vs \( \Delta L \) (km)

\[ 10^5 \text{Signal IBD Events} - \text{Baseline} \; 52.5 \; \text{km} - 3\% \text{Energy Resolution} \]

- Osc. Parameters

\[ \text{Capozzi} \; 1703.04471 \]

\[ \sim 3\% \; @ \; 1\text{MeV} \]
JUNO Detector System

- **Center Detector**
  - Acrylic sphere containing Liquid Scintillator (LS)
  - PMT in water (18k 20” + 25k 3”)
  - 20 kt LS + 78% photocathode coverage

- **Veto Detector (μ tagger)**
  - Water Cherenkov detector
  - Top tracker
  - For μ tagging and track reconstruction

- **Earth magnetic field compensation coils**

- **Calibration System**
  - 4 complimentary sub-systems

- **Electronics:**
  - 1 GHz, 14 bit, 1~4000 p.e. dynamic range
# The Detector Performance Goals

<table>
<thead>
<tr>
<th></th>
<th>KamLAND</th>
<th>BOREXINO</th>
<th>Daya Bay</th>
<th>PROSPECT</th>
<th>JUNO</th>
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<td><strong>Target Mass</strong></td>
<td>~1kt</td>
<td>~300t</td>
<td>20t</td>
<td>~4t</td>
<td>~20kt</td>
</tr>
<tr>
<td><strong>Photocathode Coverage</strong></td>
<td>~34%</td>
<td>~34%</td>
<td>~12% (Effective)</td>
<td>ESR + PMTs</td>
<td>~80%</td>
</tr>
<tr>
<td><strong>PE Collection</strong></td>
<td>~250 PE/MeV</td>
<td>~500 PE/MeV</td>
<td>~160 PE/MeV</td>
<td>~850 PE/MeV</td>
<td>~1200 PE/MeV</td>
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<td><strong>Energy Resolution</strong></td>
<td>~6%/√E</td>
<td>~5%/√E</td>
<td>~7.5%/√E</td>
<td>~4.5%/√E</td>
<td>3%/√E</td>
</tr>
<tr>
<td><strong>Energy Calibration</strong></td>
<td>~2%</td>
<td>~1%</td>
<td>1.5%→0.5%</td>
<td>?</td>
<td>&lt;1%</td>
</tr>
</tbody>
</table>

> Quite a challenging detector for JUNO!
Packing PMTs as Tight as Possible

Supper layer arrangement method 77.8%
Spherical triangle method 72%
Volleyball arrangement method 75.96%
Football arrangement method 74.08%

20" PMT (~18K)
MCP-PMT (~13K)
Hamamatsu HQE (5K)
3"sPMT (~25K)
HZC XP72B22 (Photonis)
JUNO is More Than Neutrino Mass Hierarchy

- Large mass (20 kt)
- Good E resolution (3%)
- Rich physics potentials

- Supernova ν
  - 5-7k in 10s for 10kpc

- Solar ν
  - (10s-1000s)/day

- Atmospheric ν
  - several/day

- Cosmic muons
  - ~ 250k/day
  - 0.003 Hz/m²
  - 215 GeV
  - 10% multiple-muon

- Reactor ν
  - 60/day
  - Bkg: 3.8/day

- 36 GW, 53 km

- 20k ton LS

- Geo-neutrinos
  - 1.1/day
Summary

• The value of theta13 has enabled the possibility of resolving neutrino mass hierarchy in medium-baseline reactor neutrino experiments → JUNO is under construction

• JUNO has been designed to reach an unprecedented energy resolution for such a massive LS detector
  – Unique dual calorimetry
  – An extremely rich physics program, especially antineutrino related fields

• A high-resolution near detector has been proposed to measure the fine structures of the reactor neutrino flux

• JUNO is going forward smoothly and will be ready for data taking in 2021