A Quipu on Reactor Neutrino Experiments

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http://physics.princeton.edu/~mcdonald/examples/mcdonald_silafae_181127.pdf

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Destruction of Nuclear Bombs Using

Ultra-High Energy Neutrino Beam

— dedicated to Professor Masatoshi Koshiba —

Hirotaka Sugawara* Hiroyuki Hagura† Toshiya Sanami‡

Abstract

We discuss the possibility of utilizing the ultra-high energy neutrino beam ($\simeq$ 1000 TeV) to detect and destroy the nuclear bombs wherever they are and whoever possess them.

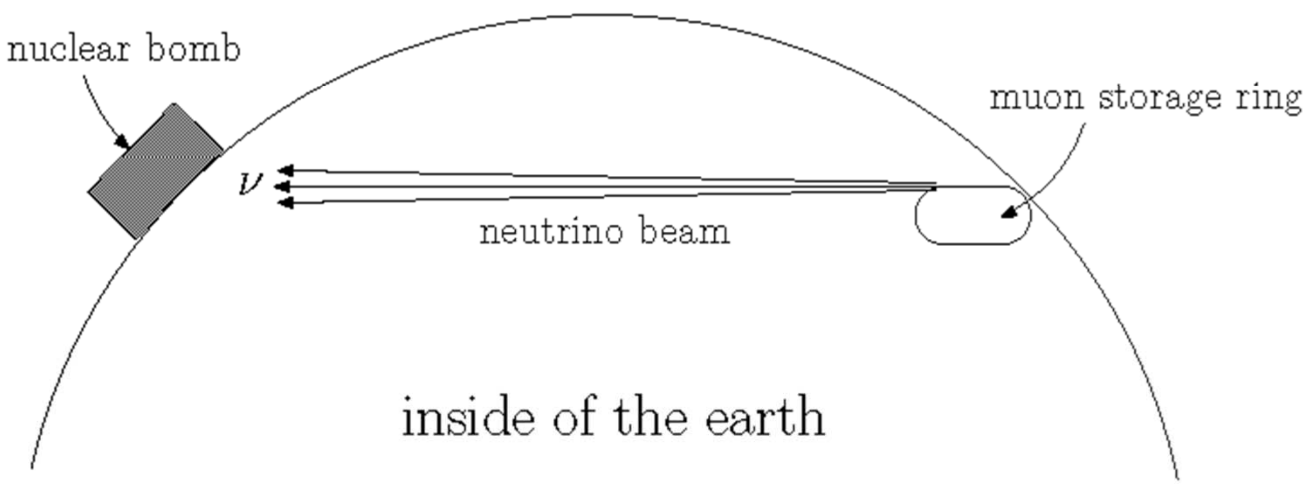


Figure 2: *Neutrino beam is aimed at the nuclear bomb that is placed on the opposite side of the earth. The beam is emitted downstream from one of the straight sections of the muon storage ring (see fig. 1), and reaches the bomb after passing through the inside of the earth.*

Beta Decay

1896: H. Becquerel discovered that uranium salts can activate photographic film through black paper, as if penetrating rays were emitted. C.R.A.S, **122**, 501 (1896)

1897: M. Curie found similar behavior for thorium, and coined the term "radioactivity." C.R.A.S, 126, 1101 (1898)

E. Branly called a "coherer" of radio waves a "radioconducteur". Éclair. Élec. **8**, 565 (1897)

1898: M. and P. Curie discovered radioactive elements polonium and radium. C.R.A.S. **127**, 1215 (1898)

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). Phil. Mag. **47**, 109 (1899)

1901: Becquerel showed that beta rays are electrons. C.R.A.S, **130**, 1583 (1900)

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

Work done as a German prisoner of war. Deutsch. Verh. Phys. Ges. **16**, 383 (1914)

Neutrinos

1930: Pauli noted that if a new particle is produced in beta decay, this would restore conservation of energy, and obey Fermi statistics if the particle has spin ½.

This was the first solution to a problem in particle physics by invention of a new particle. [Astronomy, unexplained perturbations to known planets ⇒ new planet.]

Zürich, Dec. 4, 1930

Dear Radioactive Ladies and Gentlemen,

...because of the "wrong" statistics of the N and ^{6}Li nuclei and the continuous β-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 ½ 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 β-spectrum would then become understandable by the assumption that in β-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.

J. Chadwick and D.E. Lea, *Proc. Camb. Phil. Soc.* **30**, 59 (1934)

M.E. Nahmias, *Proc. Camb. Phil. Soc.* **31**, 99 (1935)

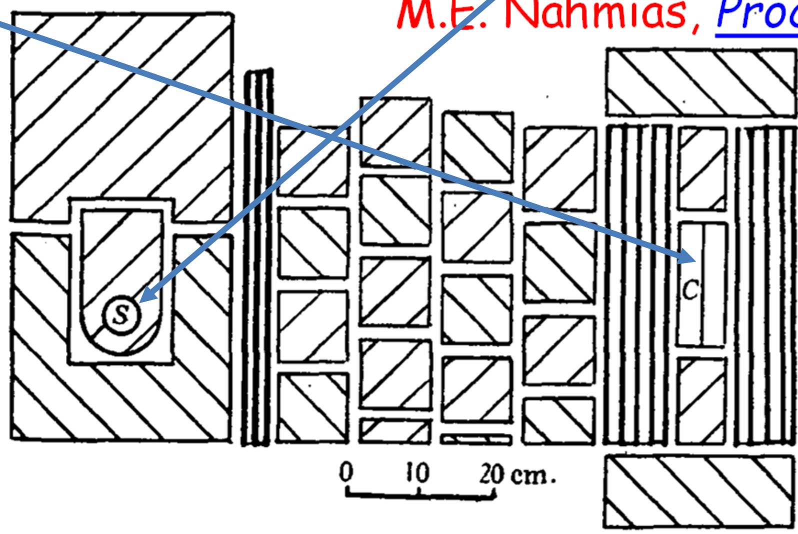


Fig. 1. First arrangement. S, source; C, counter.

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

$$\mu_\nu = \frac{3eG_F m_\nu}{8\pi^2\sqrt{2}} \approx 10^{-7}\mu_e \frac{m_\nu m_e}{m_p^2} \approx 10^{-18}\mu_e, \text{ for } m_\nu \approx 0.1\text{ eV},$$ *i.e., extremely small.*

K. Fujikawa and R.E. Schrock, *Phys. Rev. Lett.* **45**, 963 (1980)

Pontecorvo

1946: Pontecorvo suggested that neutrinos might be observed via inverse beta decay of neutrinos from the Sun, or from a "pile" = nuclear reactor. *B. Pontecorvo, Chalk River PD-205 (1946)*

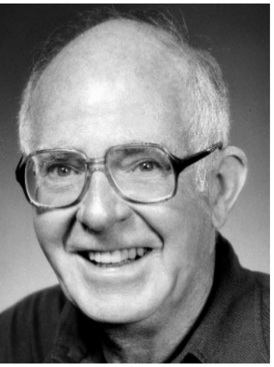
In particular, he suggested study of the chlorine reaction:

$$\nu + Cl^{37} \rightarrow Ar^{37} + e^{-}$$

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)*

Davis



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.

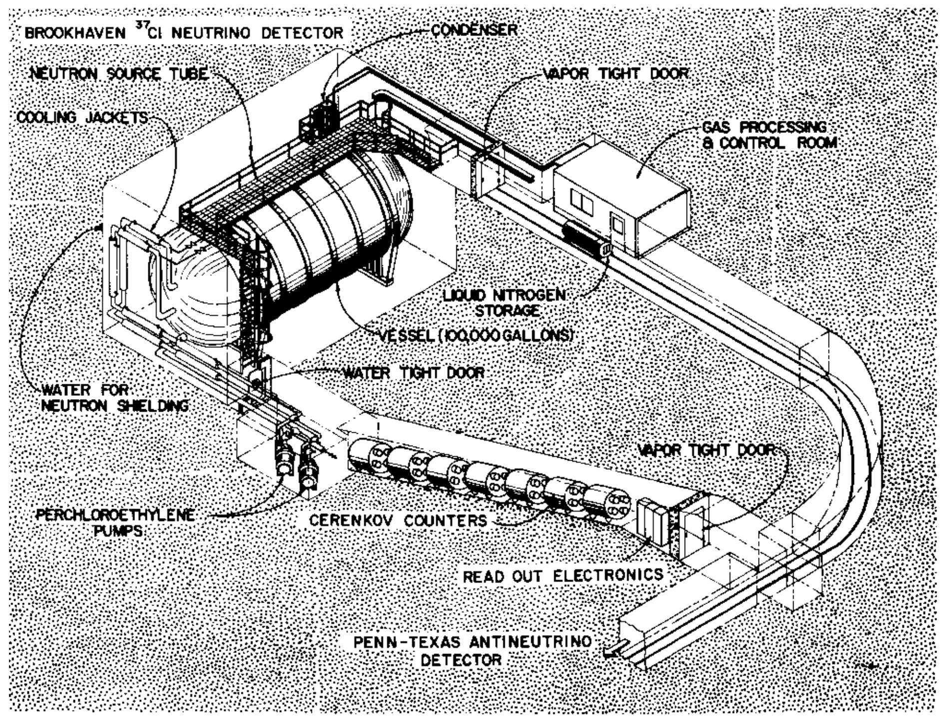
He obtained no signal, but remarked that the detector mass (4 tons) was too small for a signal to have been observed, even if the nominal antineutrinos from a reactor were actually neutrinos as per Majorana.

*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."

*Cleveland et al., Ap. J. **496**, 505 (1998)*



Cowan and Reines

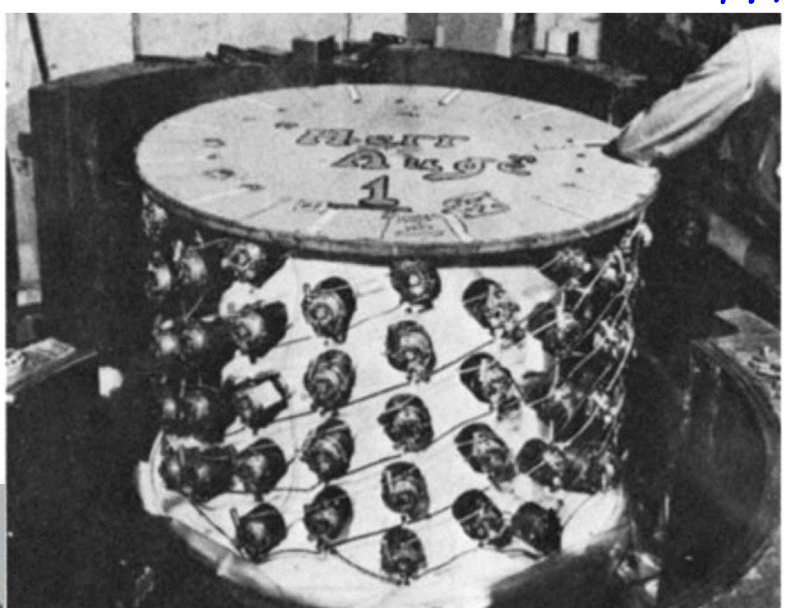
1953: Cowan and Reines noted that a better way to detect reactor antineutrinos (produced via the beta decay $\mathrm{n} \rightarrow p\, e^{-}\, \bar{\nu}_e$) is via the inverse-beta-decay process, $\bar{\nu}_e\, \mathrm{p} \rightarrow n\, e^{+}$, using a liquid-scintillator detector that first observes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

C.D. Anderson and S.H. Neddermeyer, *Phys. Rev. 50, 263 (1936)*

J.C. Street and E.C. Stevenson, *Phys. Rev.* ***52****, 1003 (1937)*

1962: Muon neutrinos observed in spark chambers.

G. Danby *et al.*, *Phys. Rev. Lett.* ***9****, 36, (1962)*

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

M.L. Perl *et al.*, *Phys. Rev. Lett.* ***35****, 1489 (1975)*

2001: Tau neutrinos observed in emulsion detectors.

4 events: K. Kodama *et al.*, *Phys. Lett. B* ***504****, 218 (2001)*

5 events: N. Agafonova *et al.*, *Phys. Rev. Lett.* ***115****, 121802 (2015)*

Measurement of the "invisible" width of the Z^0 boson at e^+e^- colliders $\Rightarrow$ No. of low-mass, Standard-Model neutrinos is 2.984 ± 0.008. *Phys. Rep.* ***427****, 257 (2006)*

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.

B. Pontecorvo, *Sov. Phys. JETP* **6**, *429 (1957)*

1962: Maki, Nakagawa and Sakata considered a triplet model for leptons, that 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, θ_{ij}, and CP-violation parameter $\delta_{\rm CP}$.

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

J.H. Christenson *et al.*, *Phys. Rev. Lett.* **13**, *138 (1964)*]

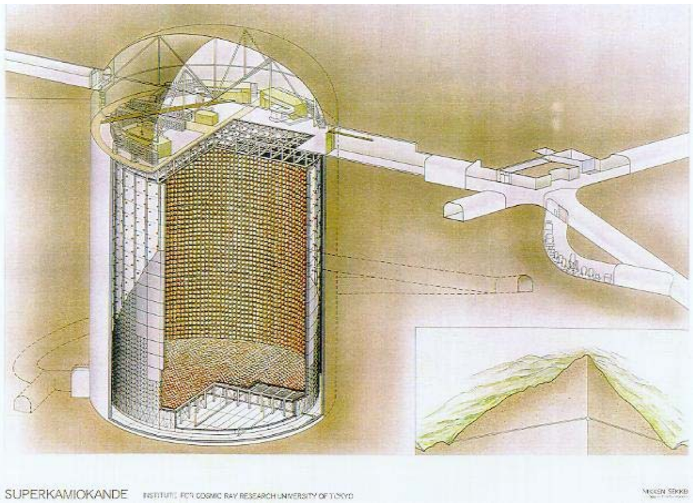
Initial searches for neutrino oscillations at a nuclear reactor used only a single detector, at a single distance from the reactor, hoping to find a signal for (electron) antineutrinos smaller than that expected for the case of no oscillations.

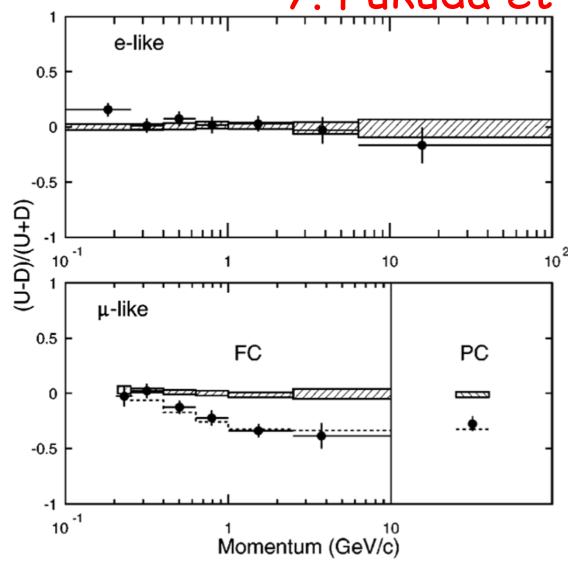
Perhaps not surprisingly, results from these experiments were negative.

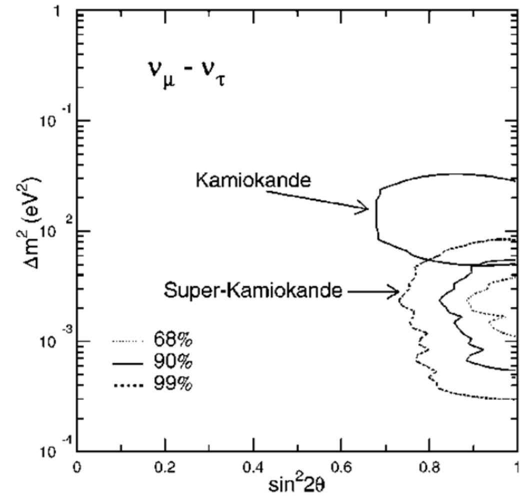
[See also slides 18 and 31-32.]

Atmospheric and Solar Neutrino Oscillations

1998: Following hints of atmospheric neutrino oscillations in the Kamiokande expt, the Super-Kamiokande water-Ĉerenkov detector showed a clear difference in the energy dependence of 0.2-20 GeV electron and muon neutrinos produced in the upper atmosphere. Y. Fukuda *et al.*, *Phys. Rev. Lett.* ***81***, *1562 (1998)*

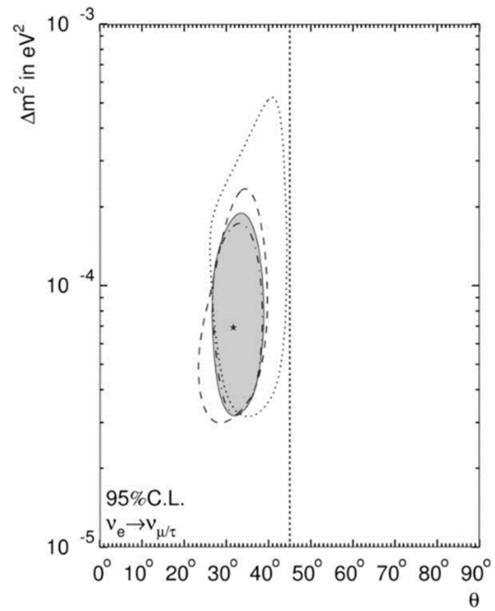






$$\left|\Delta m_{32}^2\right| = 2 \pm 1 \times 10^{-3}\,\mathrm{eV}^2, \quad \sin 2\theta_{23}^2 \approx 0.9.$$

2002: By study of 5-20 MeV electron neutrinos, Super-K determined parameters of solar-neutrino mixing. Y. Fukuda *et al.*, *Phys. Lett. B* ***539***, *179 (2002)*



$$\Delta m_{21}^2 = m_2^2 - m_1^2 = 7 \pm 2 \times 10^{-5}\,\mathrm{eV}^2, \quad \theta_{12} = 33^\circ \pm 7^\circ.$$

$$m_2 > m_1 \ \text{by definition.}$$

Do Neutrino Oscillations Conserve Energy?

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,

$$|\nu_e\rangle\, |X\rangle = a_1 |\nu_1\, |X_1\rangle + a_2 |\nu_2\rangle\, |X_2\rangle + a_3 |\nu_3\rangle\, |X_3\rangle.$$

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

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

http://physics.princeton.edu/~mcdonald/examples/neutrino_osc.pdf

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 ν_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, $A \to A' \, e \, \nu_e$, the interaction of A' and e with nearby atoms does not "measure" their energies precisely. Rather, the entanglement of the ν_e with A' and e becomes transferred to neighboring 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.

X.-S. Ma et al., Quantum erasure with causally disconnected choice, Proc. Nat. Acad. Sci. ***110****, 1221 (2013)*

What is Decoherence of Neutrino Oscillations?

Since the different ν_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 ~ 15^{th} oscillation?

NO -- if the detector is "good enough"!

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 ν_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 different ν_i can have very different velocities, and the quantum description of this is that the ν_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.

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,

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

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

Physical neutrinos are not plane-wave states as above, but are wave packets with a spread of energies ΔE_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

$$\Delta x \approx \frac{\hbar c}{\Delta E} = |\mathrm{v}_1 - \mathrm{v}_2| t_{\mathrm{coh}} = \left|\frac{c^2 P_1}{E_1} - \frac{c^2 P_2}{E_2}\right| t_{\mathrm{coh}} \approx \left|m_1^2 - m_2^2\right| \frac{c^5 t_{\mathrm{coh}}}{2E^2},$$

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

$$\boxed{L_{\mathrm{coh}} \equiv c t_{\mathrm{coh}} \approx \frac{2E^2 \hbar c}{\Delta E\, \Delta m_{12}^2 c^4}.}$$

*C. Giunti, C.W. Kim and U.W. Lee, Phys. Lett. B **421**, 237 (1998)*

*T. Ohlsson, Phys. Lett. B **502**, 158 (2001)*

*M. Beuthe, Phys. Rev. D **66**, 013003 (2002)*

Oscillation Length

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

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

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

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

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

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

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

$$\boxed{L_{\text{osc}}\equiv\frac{4E\hbar c}{\Delta m_{12}^2c^4},}$$

$$\boxed{L_{\text{coh}}\approx\frac{E}{2\Delta E}L_{\text{osc}}\approx\frac{E}{\sqrt{2\pi}\sigma_E}L_{\text{osc}}.}$$

Number of Oscillations in the β-Decay Energy Spectrum

$$P_{a\to a}(x, E=\bar{E}+\Delta E) \approx 1-\sin^2 2\theta_{12}\sin^2\frac{x}{L_{\rm osc}} = 1-\sin^2 2\theta_{12}\sin^2\frac{\Delta m_{12}^2 c^4 x}{4E\hbar c}$$

$$= 1-\sin^2 2\theta_{12}\sin^2\frac{\Delta m_{12}^2 c^4 x}{4\bar{E}\hbar c(1+\Delta E/\bar{E})} \approx 1-\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m_{12}^2 c^4 x}{4\bar{E}\hbar c}-\frac{\Delta m_{12}^2 c^4 x}{4\bar{E}^2\hbar c}\Delta E\right),$$

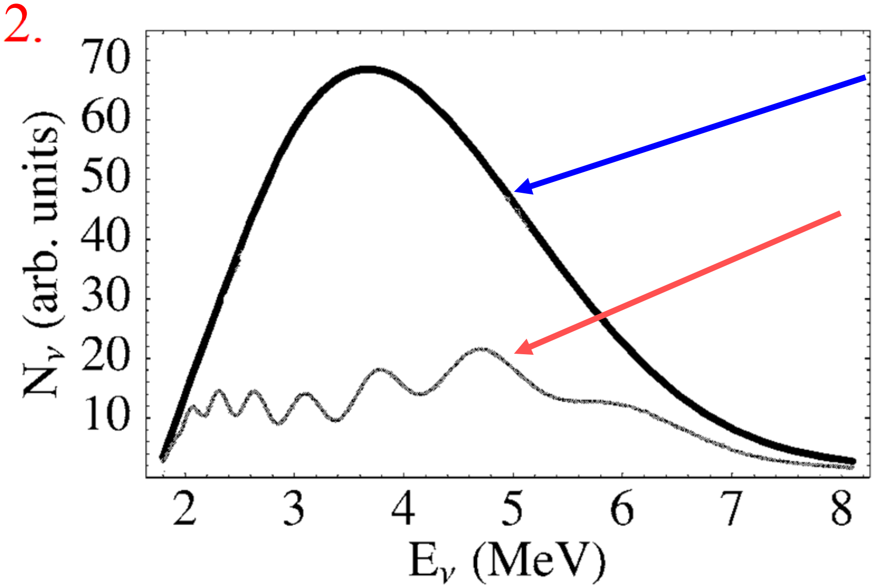
The spatial period of neutrino oscillations at fixed x is $\lambda_x = \pi L_{\rm osc}$.

The period of oscillations in the neutrino-energy spectrum from β-decay at fixed x is

$$\lambda_E \approx \frac{4\pi\bar{E}^2\hbar c}{\Delta m_{12}^2 c^4 x} = \frac{\pi\bar{L}_{\rm osc}\bar{E}}{x} = \frac{\bar{\lambda}_x\bar{E}}{x} \equiv \frac{\bar{E}}{N_{{\rm osc},x}},$$

where $\bar{E}$ is the average neutrino energy.

Thus, at distance $x = N_{{\rm osc},x}\bar{\lambda}_x$, the number of oscillations in the energy spectrum, of width $\approx \bar{E}$, is $n_E \approx N_{{\rm osc},x}/2$.



If no oscillation.

If $\sin^2 2\theta_{13} = 0.05$.

$L = 20$ km $\approx 12 L_{{\rm osc},13}$

S.R Petcov and M Piai, *Phys. Lett. B* **533**, 94 (2002)

(Non)Decoherence in a Reactor-Neutrino Experiment

In neutrino experiments, the detector energy resolution determines σ_E in the expression for the coherence length $L_{\rm coh}$.

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 $x = N\,\bar{L}_{\rm osc}$ from a nuclear reactor that produces neutrinos of average energy $\bar{E}$. Then, the neutrino-energy spectrum would show $n_E \approx N/2$ oscillations.

To resolve these oscillations, we need detector energy resolution $\sigma_E \le \bar{E}/4n_E$.

And, in this case the coherence length is $\bar{L}_{\rm coh} \approx \dfrac{\bar{E}}{2\sigma_E}\bar{L}_{\rm osc} \approx 2n_E\,\bar{L}_{\rm osc} = x.$

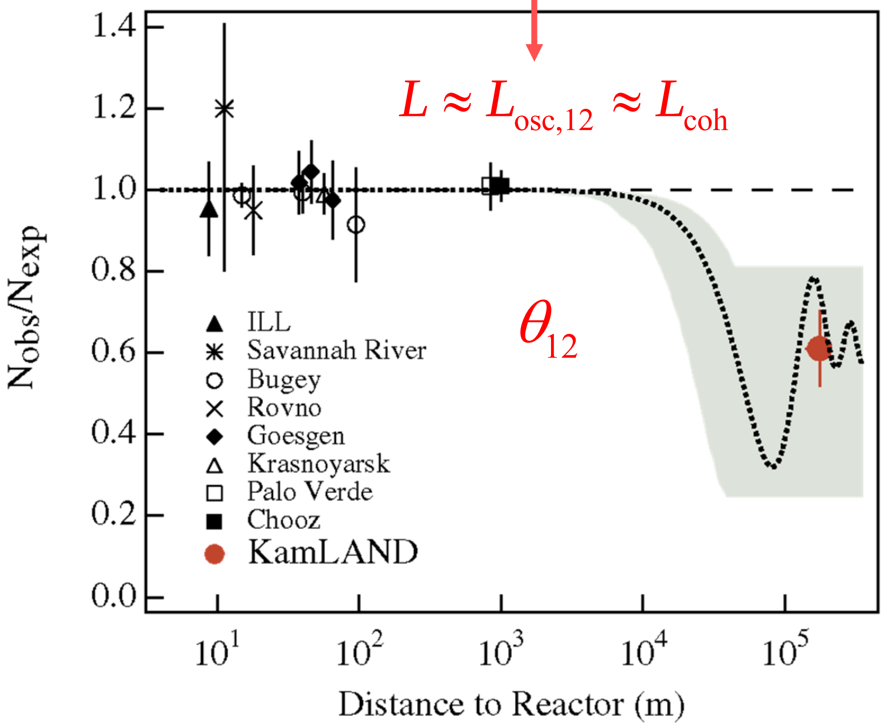
Thus, if the detector energy resolution is good enough to resolve the energy oscillations, then the coherence length is automatically long enough to avoid "decoherence."

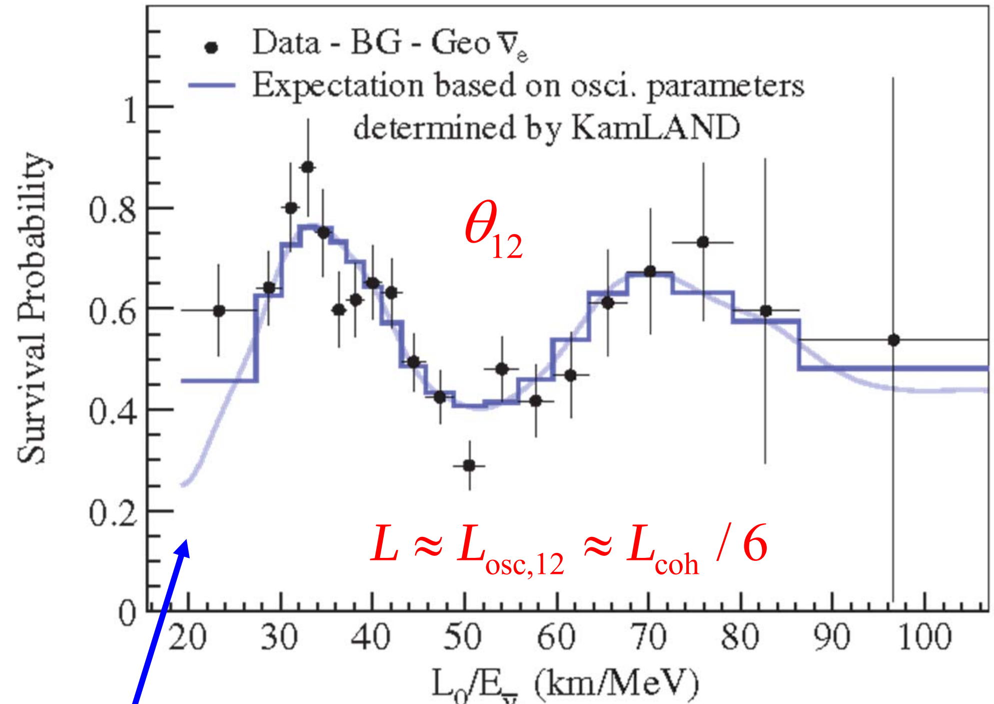
Moral: Decoherence is unimportant in a "good enough" neutrino experiment.

http://physics.princeton.edu/~mcdonald/dayabay/decoherence.pdf

Example: The KamLAND Reactor Neutrino Experiment

In their initial oscillation analysis, the KamLAND experiment ignored the neutrino energy, so that $E/\sigma_E \approx 1$, and they could only see an average effect of the first oscillation in $P_{e\to e}(x)$. *K. Eguchi et al., Phys. Rev. Lett.* ***90**, 021902 (2003)*





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

S. Abe et al., Phys. Rev. Lett. ***100**, 221803 (2008)*

Effect of Source Size

Neutrinos from sources at different distances are not coherent with one another, when source size ≥ oscillation length (as for solar neutrinos and supernovae).

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

$$P_{e\to e}(x) \approx 1 - \sin^2 2\theta_{12} \sin^2 \frac{x}{L_{\rm osc}} \to 1 - \frac{1}{2}\sin^2 2\theta_{12}.$$

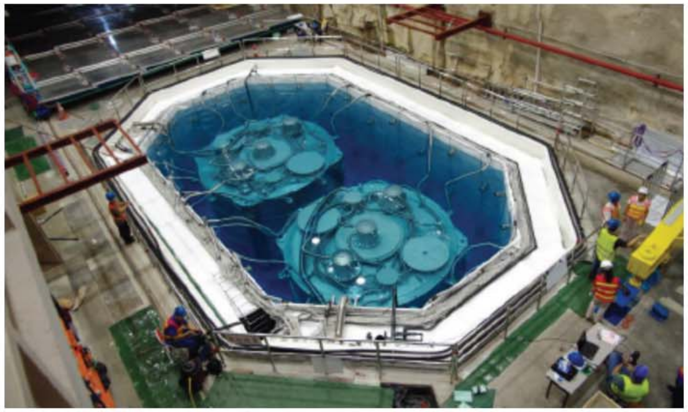
This is not strictly an effect of decoherence, in that neutrinos produced in different primary interactions do not interfere with one another.

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

B.T. Cleveland et al., Ap. J. ***496****, 505 (1998)*

J.N. Bahcall, M.H. Pinsonneault and S. Basu, Ap. J. ***555****, 990 (2001)*

Extracts from



Results - Daya Bay, RENO, and Double Chooz

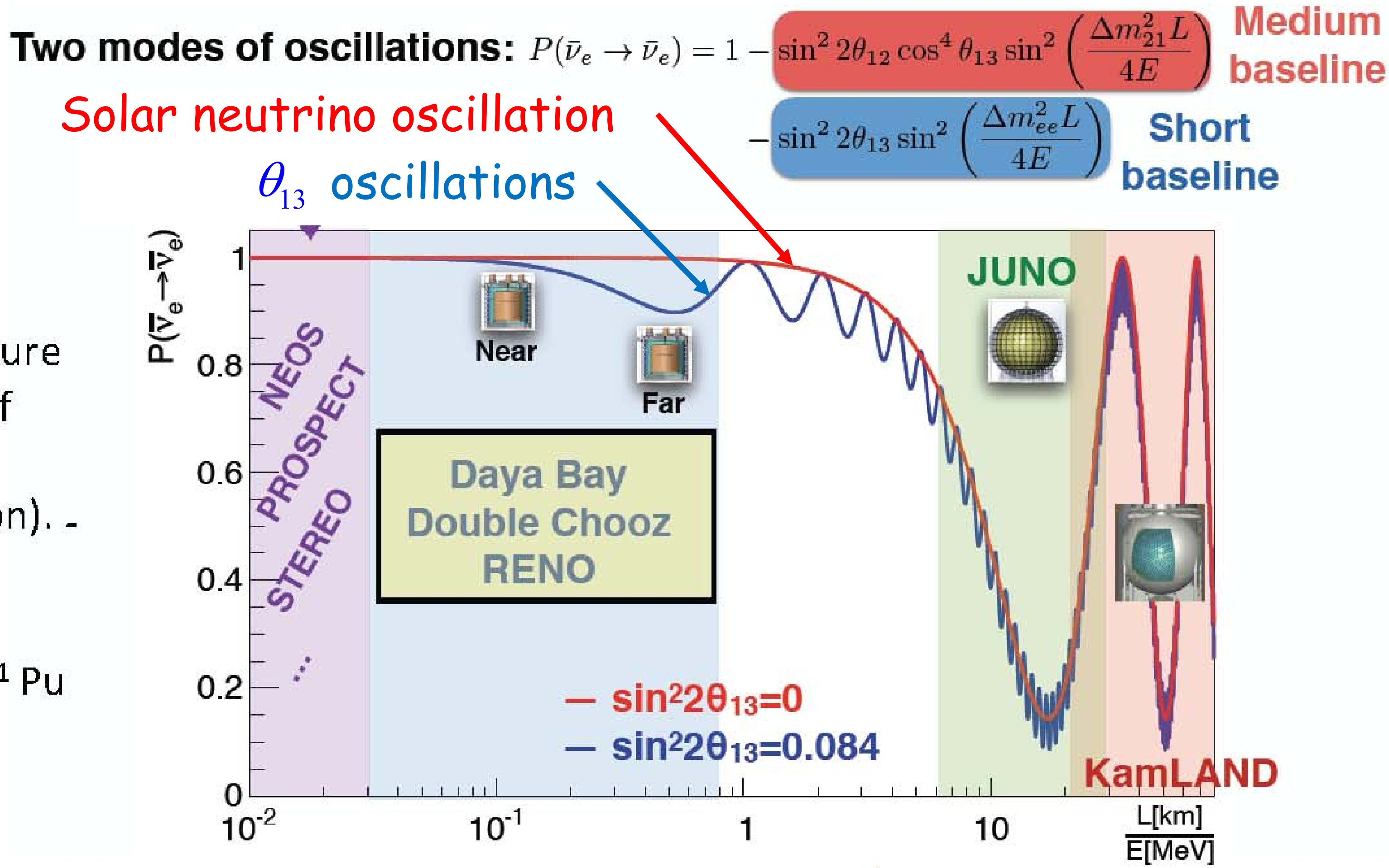
Henry Band

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



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

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

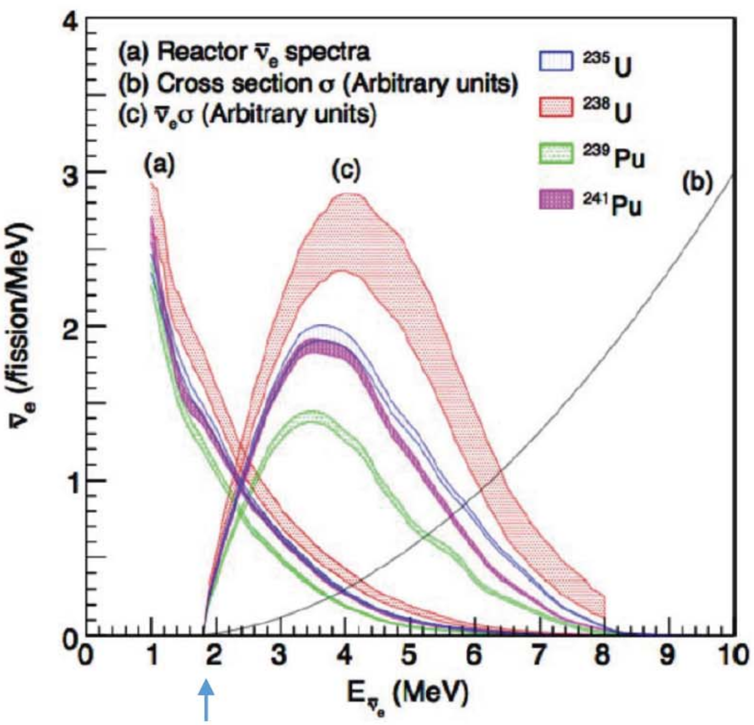
$\bar{\nu}_e$ + p → e^+ + n (prompt signal)

$E_e \sim E_\nu$ - 0.8 MeV

~30μs (0.1% Gd)

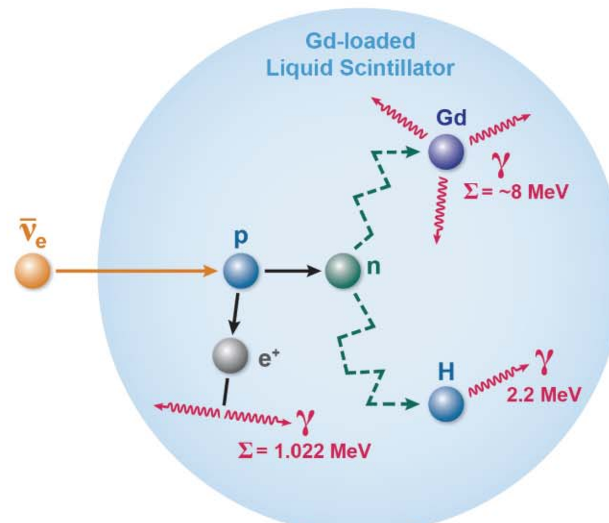
→ + p → D + γ (2.2 MeV) (delayed signal) ~15%

→ + Gd → Gd* → Gd + γ's (8 MeV) (delayed signal) ~85%



1.8 MeV

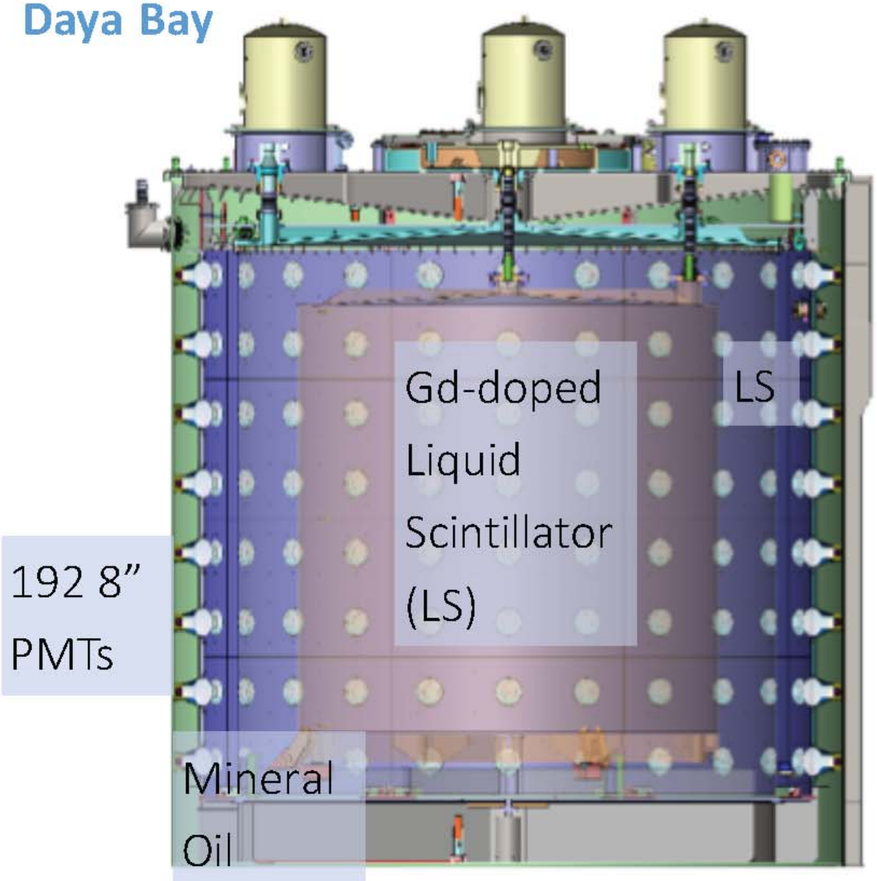
- Powerful background rejection
- Positron preserves most information about antineutrino energy



Detectors

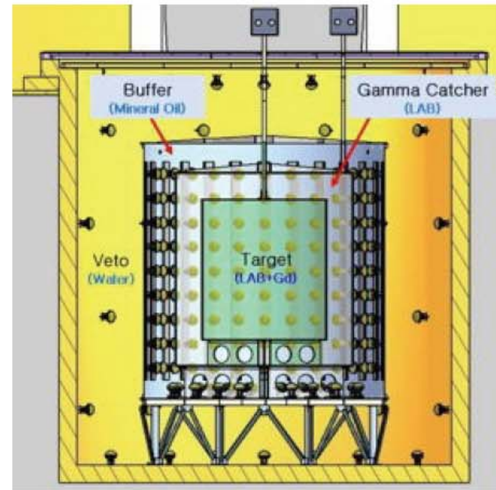
- The antineutrino detectors (ADs) are "three-zone" cylindrical modules immersed in water pools

Daya Bay

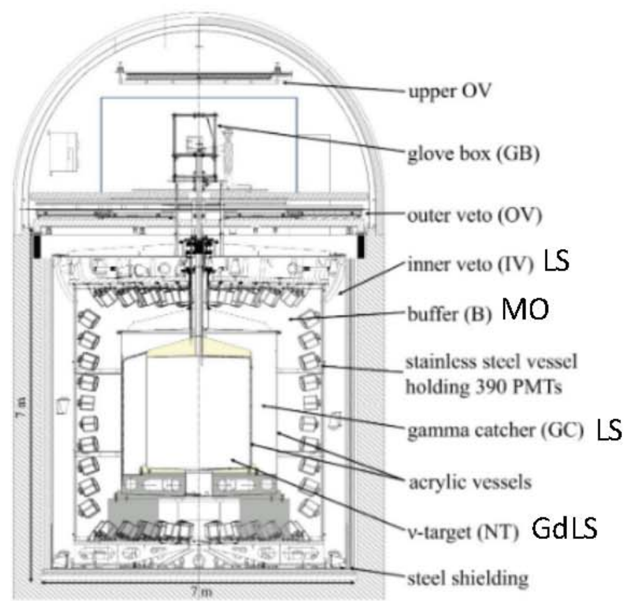


- *GdLS region defines the target mass*
- *Surrounding LS improves detection of γ-rays*
- *MO buffers outside backgrounds*
- *Water reduces backgrounds & detects muons*
- *Additional muon detection above*

RENO

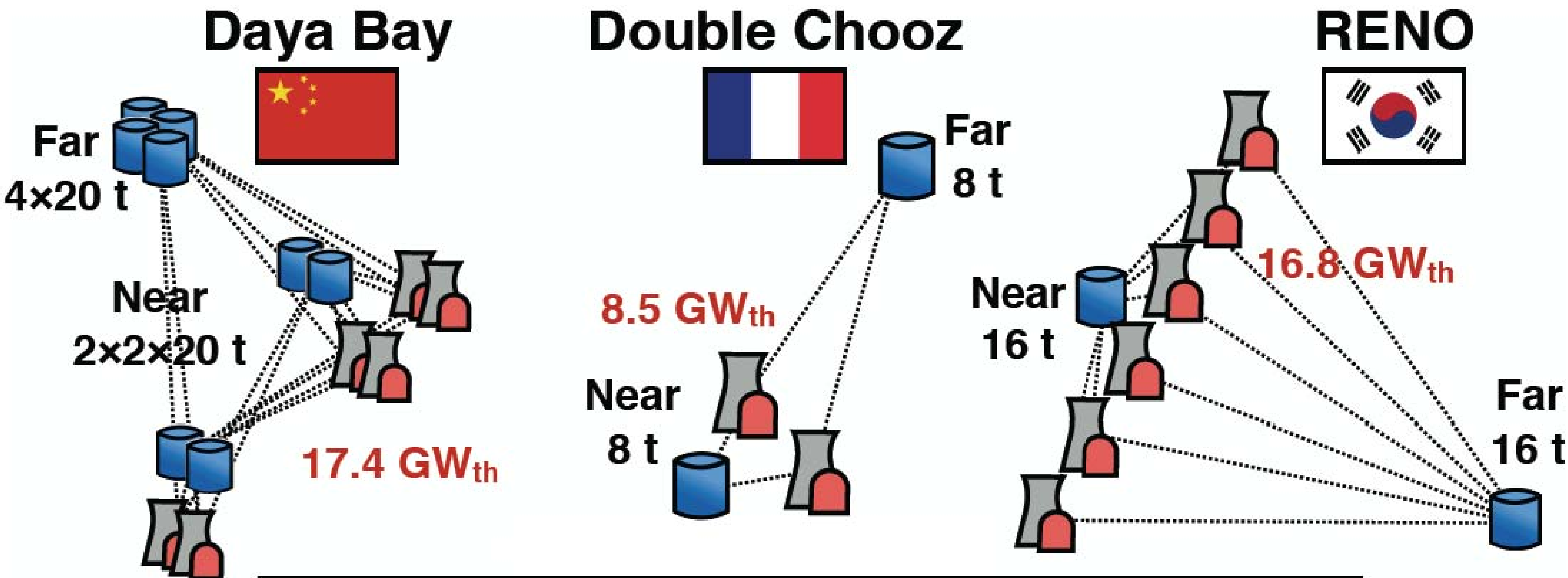


Double Chooz



Energy resolution ≅ 8.5%/√E (MeV) +1%

NIM A 811, 133 (2016)

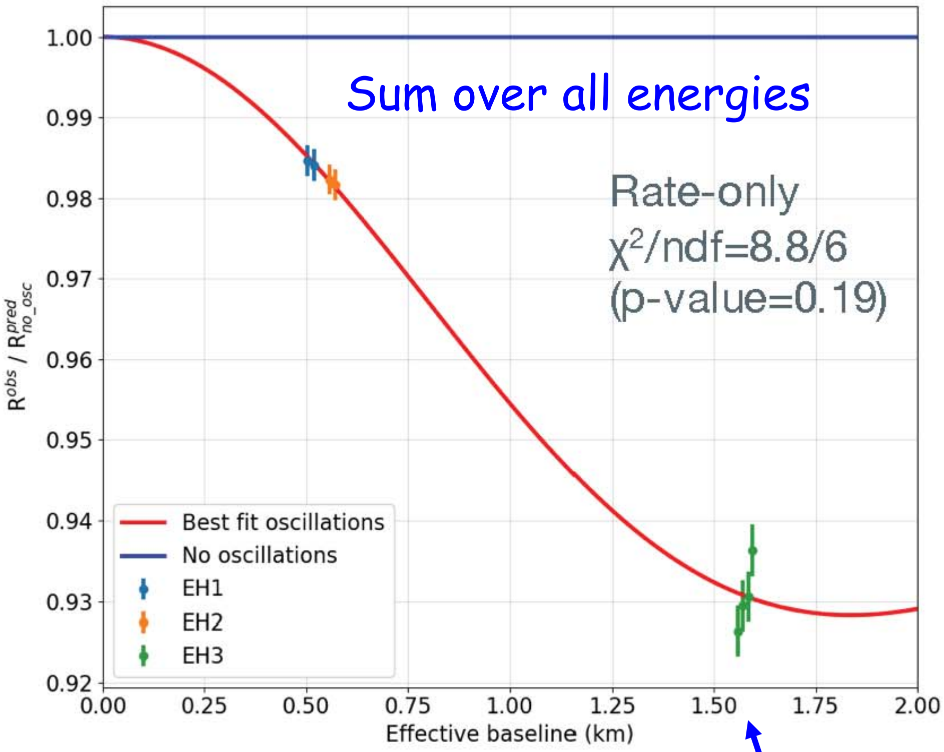


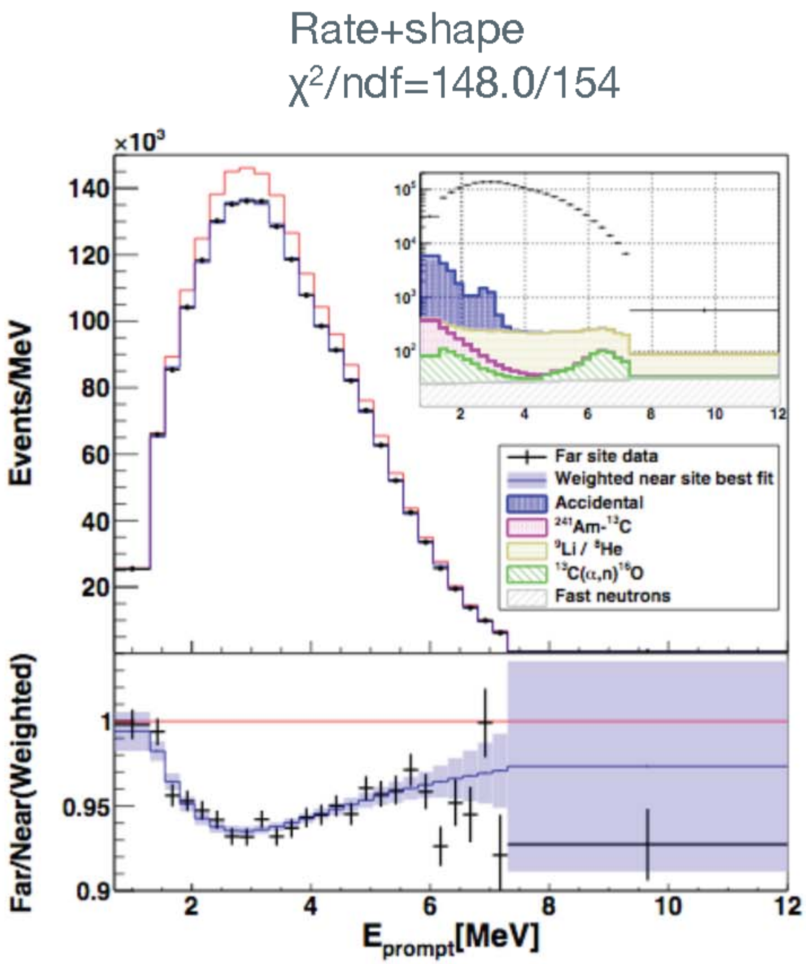
Experiment	Near/far data	Near Dector mass (ton)	Far Detector mass (ton)	Overburden near (m.w.e.)	Overburden far (m.w.e.)	Detector design	Reactor power (GWth)	Near detector baseline (km)	Far detector baseline (km)
Daya Bay	2011-2020	2*2*20	4*20	250-265	860	3 zone (GdLS, LS, MO)	6*2.9	.364-.528	1.54-1.912
Reno	2011- 2020?	16.5	16.5	120	450	3 zone (GdLS, LS, MO)	6*2.8	0.411	1.446
Double Chooz	2015-17	8.3	8.3	120	300	3 zone (GdLS, LS, MO)	2*4.25	0.415	1.05

Daya Bay

ArXiv:1809.02261

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



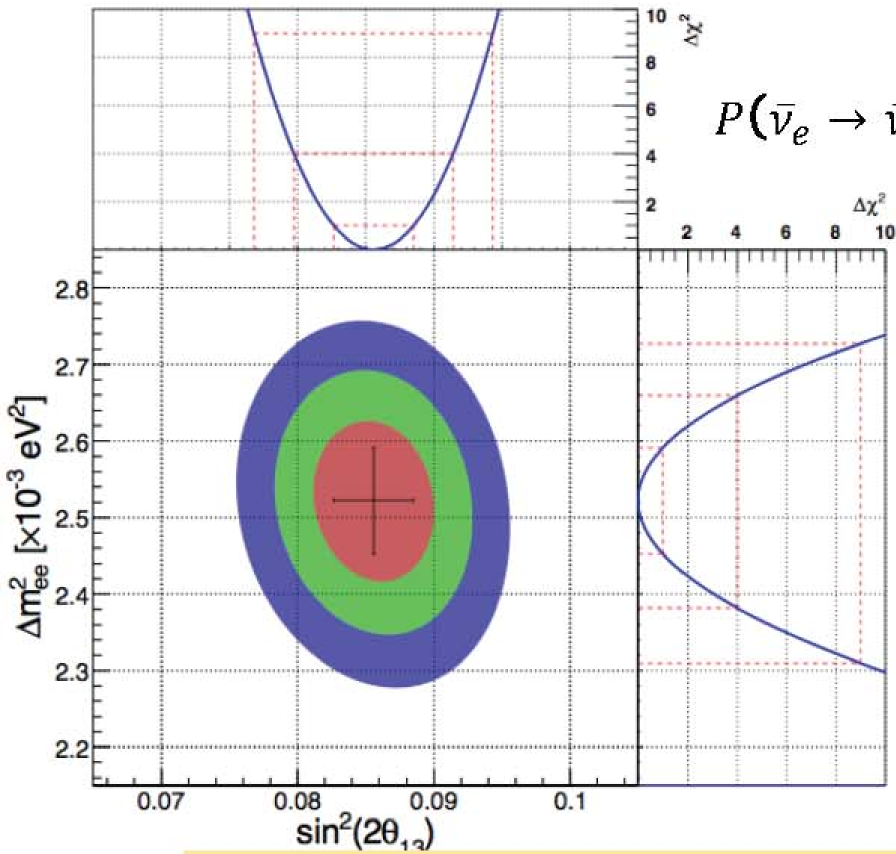


$L \approx L_{osc,13} \approx L_{coh} / 10.$

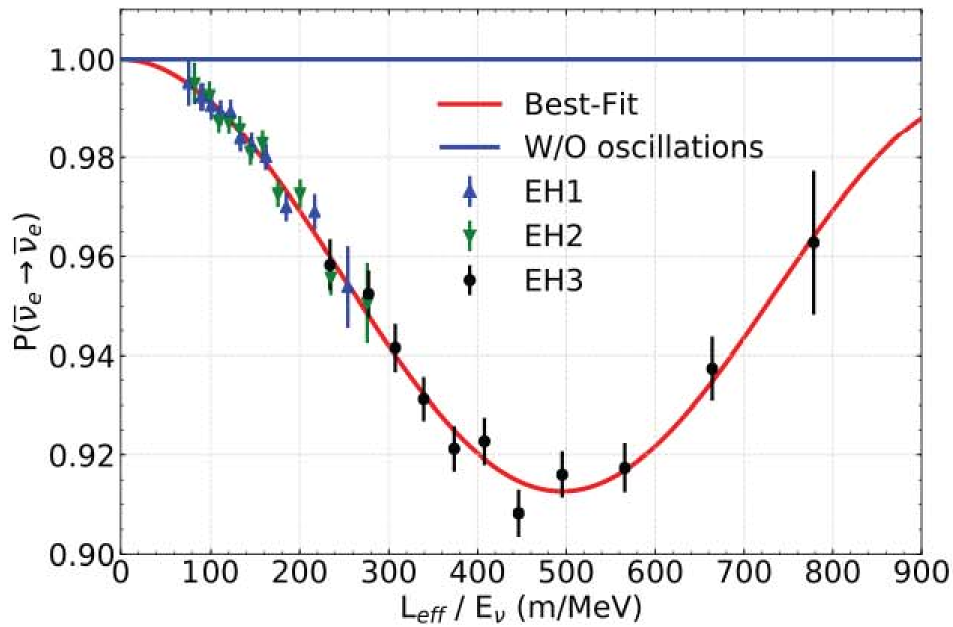
Daya Bay

ArXiv:1809.02261

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



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



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

A small variant of $|\Delta m^2_{32}|$

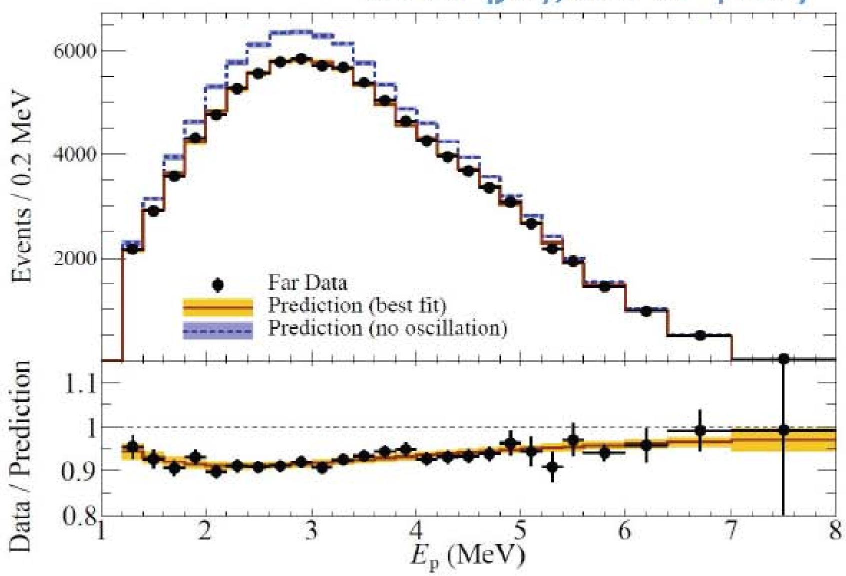
The statistical uncertainty contributes about 60% (50%) of the total θ_{13} (Δm^2_{ee}) uncertainty.

RENO & Double Chooz

RENO

ArXiv:1806.00248

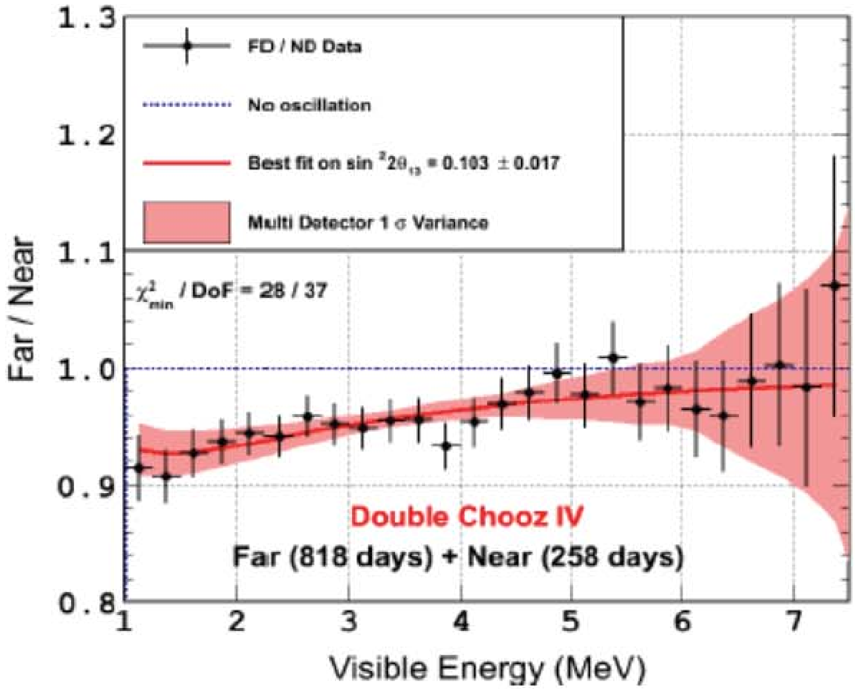
0.1 10^6 (far), 0.85 10^6 (near)



Double Chooz

Buck - Neutrino 2018

9.0 10^4 (far), 2.1 10^5 (near)



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

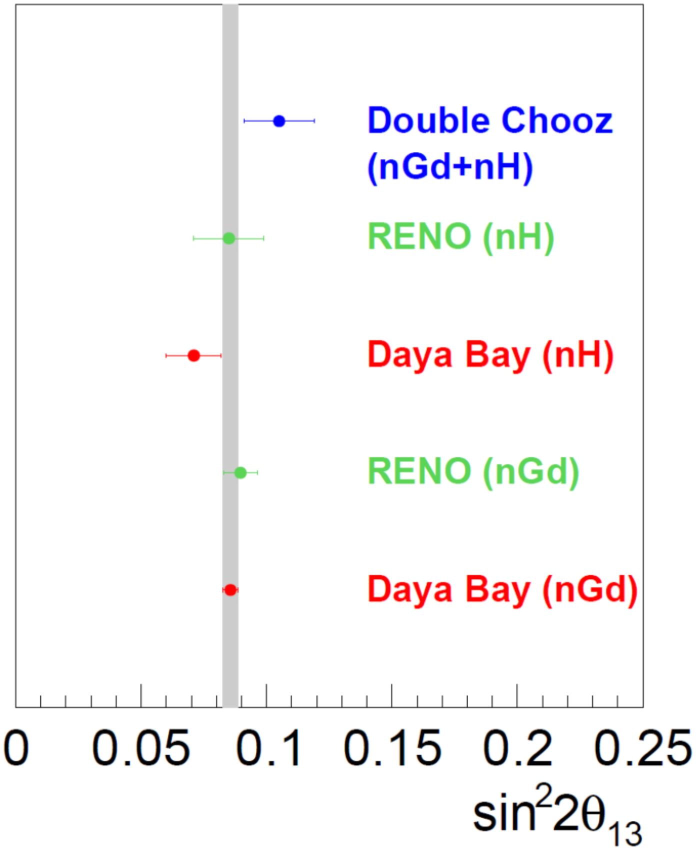
combined nGd+nC+nH

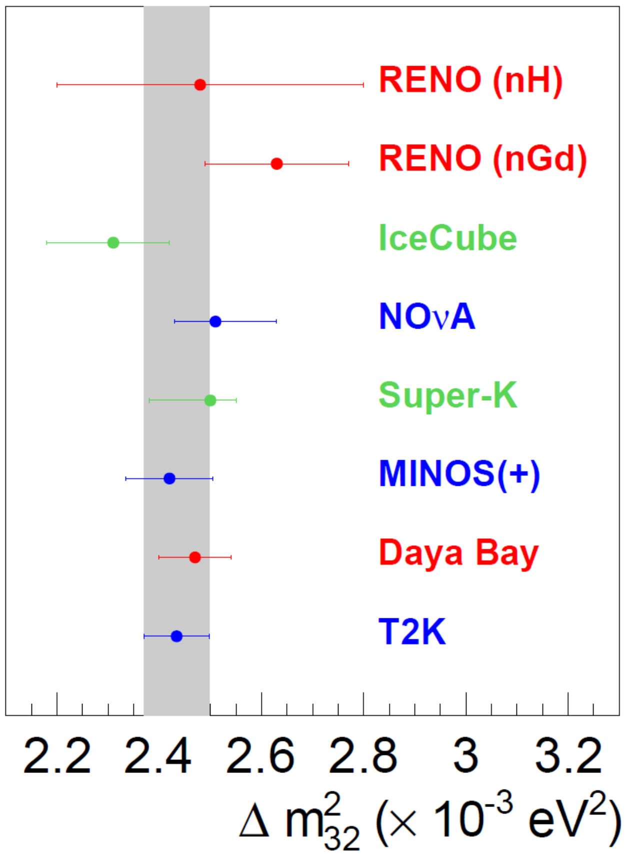
$$\sin^2 2\theta_{13} = 0.105 \pm 0.014$$

Global Comparison

results presented at
Neutrino 2018 conference

Normal Ordering Assumed

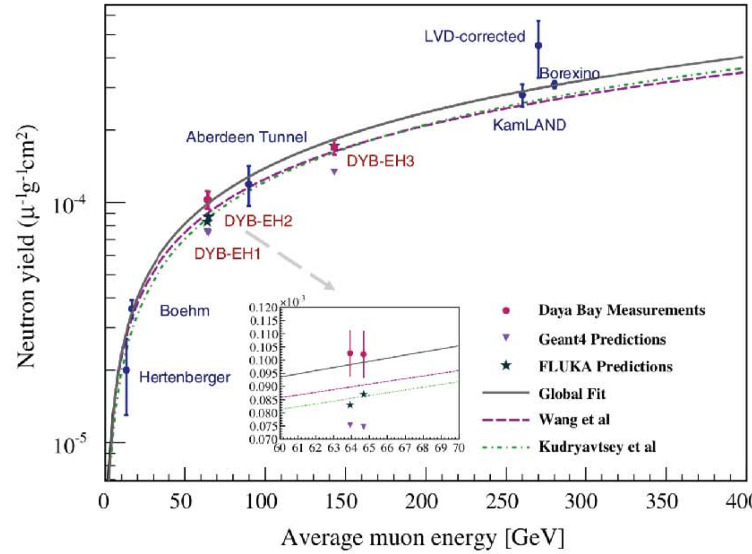


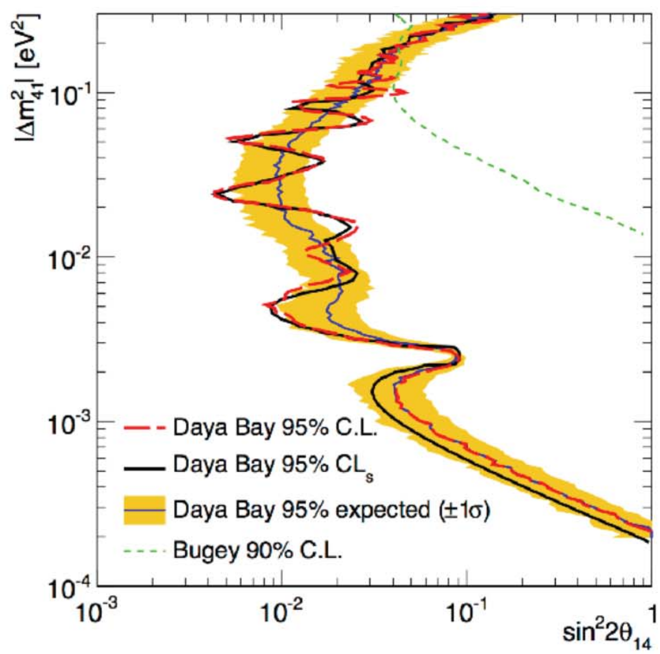


- Daya Bay – best precision of θ_{13} in the foreseeable future
- Agreement of Δm^2_{32} between accelerator & reactor experiments
- Analysis of nH events in all detectors consistent with nGd events

Other results

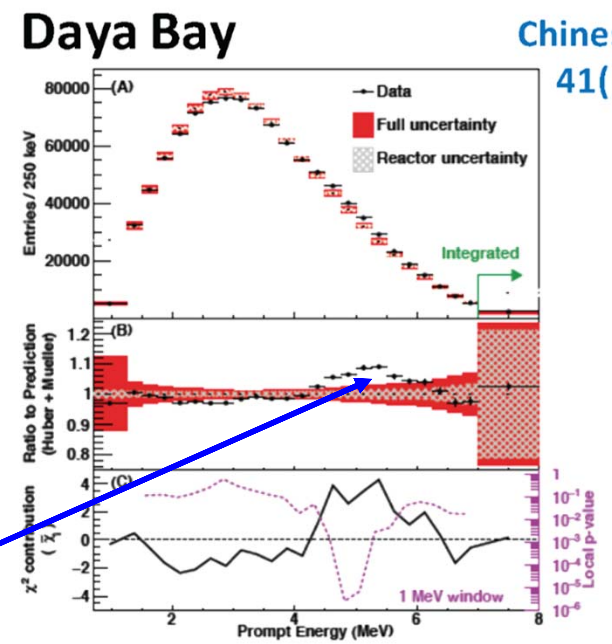
- Daya Bay
  - Search for Time-Varying Antineutrino Signal -ArXiv:1809.04660
  - Seasonal Variation of the Underground Cosmic Muon Flux - JCAP 1801 n°1 (2018)
  - Cosmogenic neutron production at Daya Bay - Phys. Rev. D97, 052009 (2018)
  - Search for neutrino decoherence Eur. Phys. J. C77, 606 (2017)
  - Improved search for a sterile neutrino (with Bugey-3 + MINOS) Phys. Rev. Lett. 117, 151801 (2016), 151802 (2016).
  - Independent measurement of θ_{13} via neutron capture on hydrogen Phys. Rev. D93, 072011 (2016)





Absolute reactor flux

- Updated analysis with reduced systematic errors
  - Daya Bay 1260 days ArXiv:1808.10836
    - $R_{\text{data/pred}}\ (\text{Huber-Mueller}) = 0.952 \pm 0.014(\text{exp.}) \pm 0.023(\text{model})$
    - $\sigma_f = (5.91 \pm 0.09) \times \frac{10^{-43}\,\text{cm}^2}{\text{fission}}$
  - RENO 2200 days Yu @ Neutrino2018
    - $R_{\text{data/pred}}\ (\text{H-M})\ 0.918 \pm 0.018(\text{exp.})$
    - $\sigma_f = (5.79 \pm 0.11) \times \frac{10^{-43}\,\text{cm}^2}{\text{fission}}$
  - Double Chooz
    - $R_{\text{data/pred}}\ (\text{H-M}) =$
    - $0.945 \pm 0.008(\text{exp.})$



Chinese Phys. C 41(1) (2017).

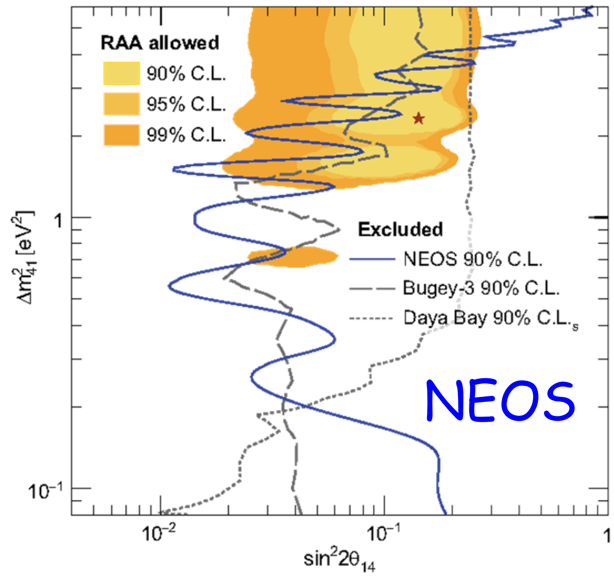
- All 3 experiments see deviations from the expected shape in the 4-6 MeV region $\Rightarrow$ Reactor models still not sufficiently accurate.

P. Huber, *Phys. Rev. C* ***84***, *024617 (2011)*

T.A. Mueller et al., *Phys. Rev. C* ***84***, *054615 (2011)*

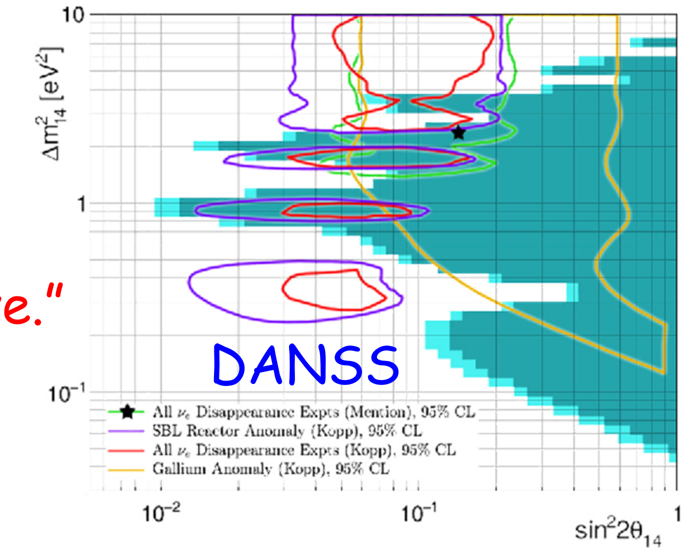
Recent, Very Short Baseline Experiments (≈ 10 m)

Inspired by the claimed "reactor anomaly", perhaps due to a 4th, light, sterile neutrino



Mention et al., Phys. Rev. D **83**, 073006 (2011)

"You can't prove a negative."

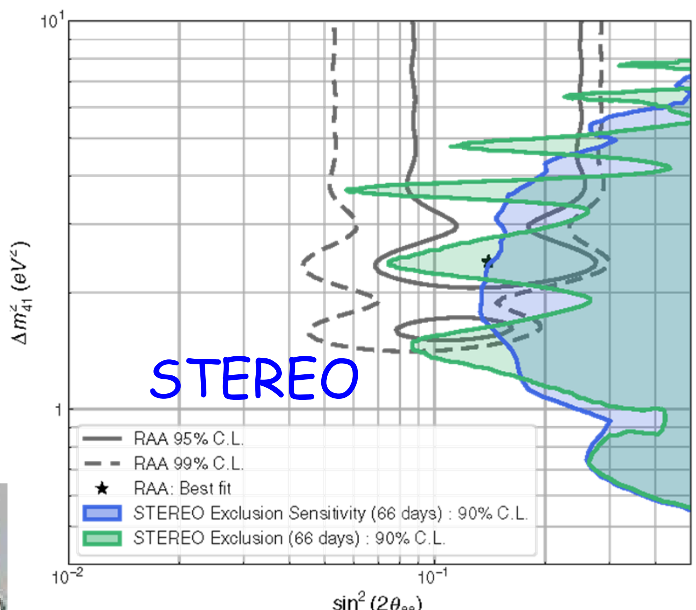


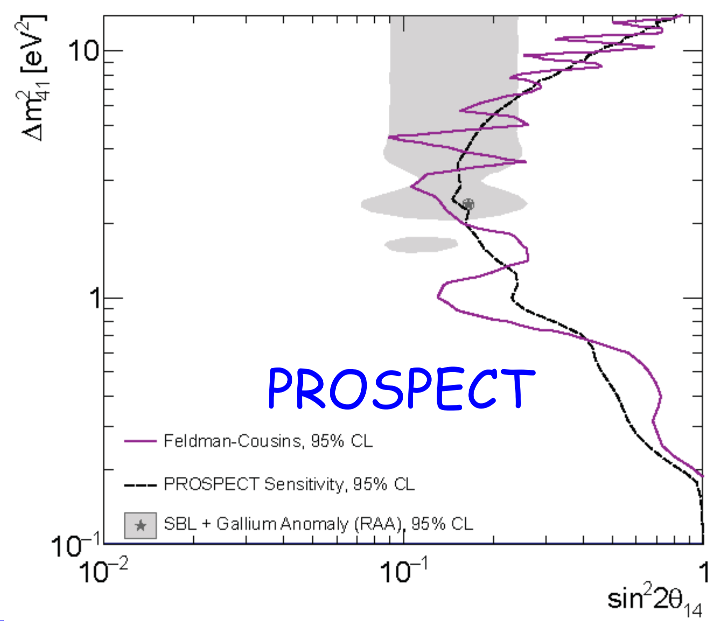
Ko et al., Phys. Rev. Lett. **118**, 121802, (2017)

Alexseev et al., Phys. Lett. B **787**, 56, (2018)

Almazán et al., Phys. Rev. Lett. **121**, 161801, (2018)

Ashenfelter et al., 1806.02784





Extracts from

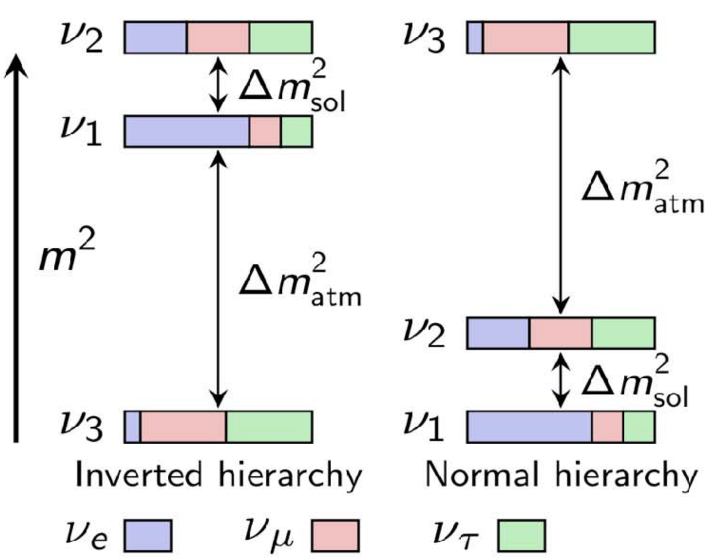
The Design of JUNO and Its Current Status

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*

https://neutrinos.llnl.gov/content/assets/docs/workshops/2018/AAP2018-JUNO-Wang.pdf

Known θ13 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

S.R Petcov and M Piai, *Phys. Lett. B* ***533***, *94 (2002)*

Sign known by definition

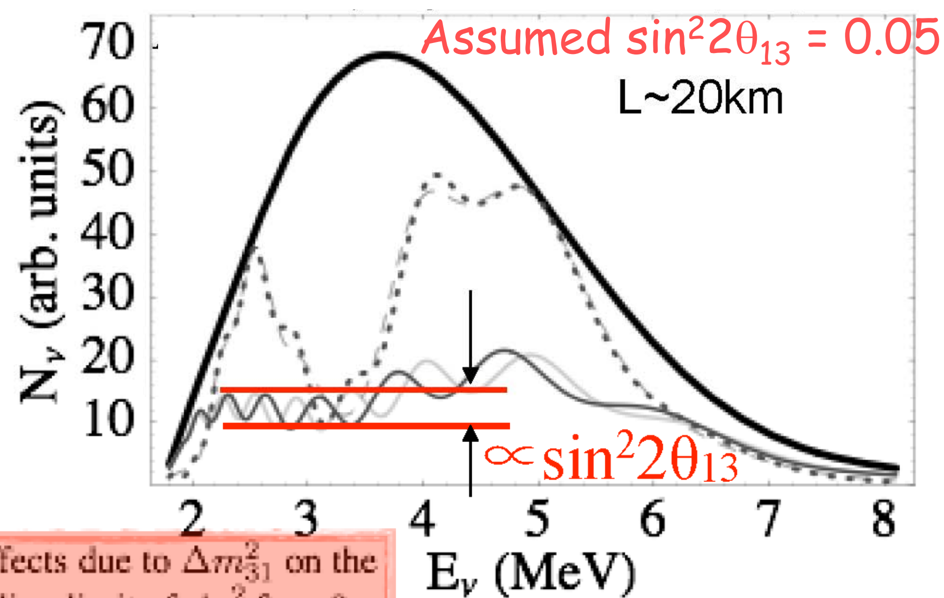
$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

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

Signs to be measured

✓ Mass hierarchy is reflected in the spectrum

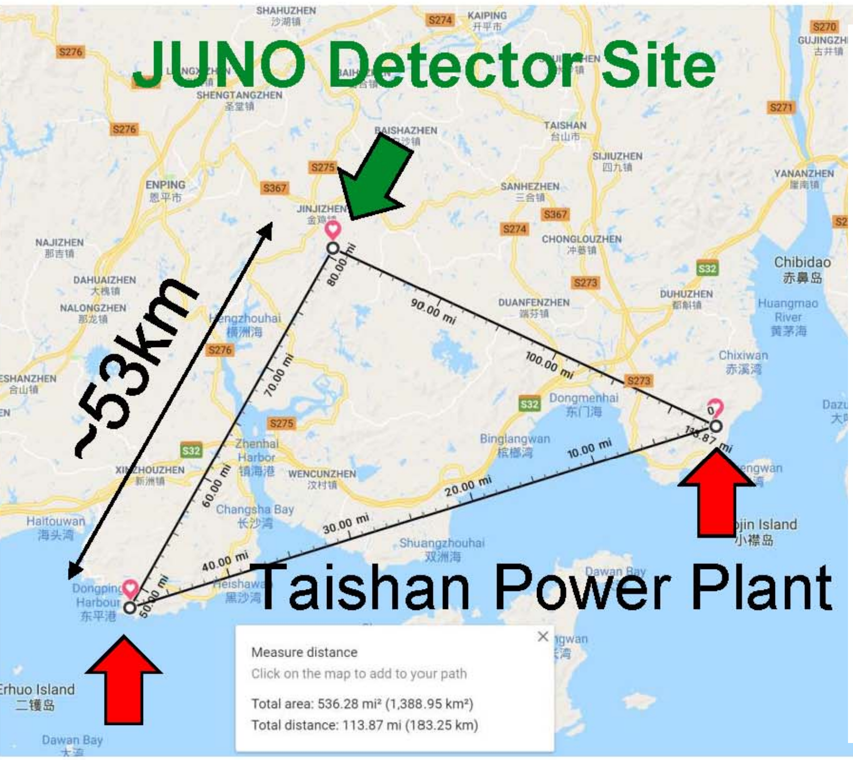
✓ Signal independent of the unknown CP phase



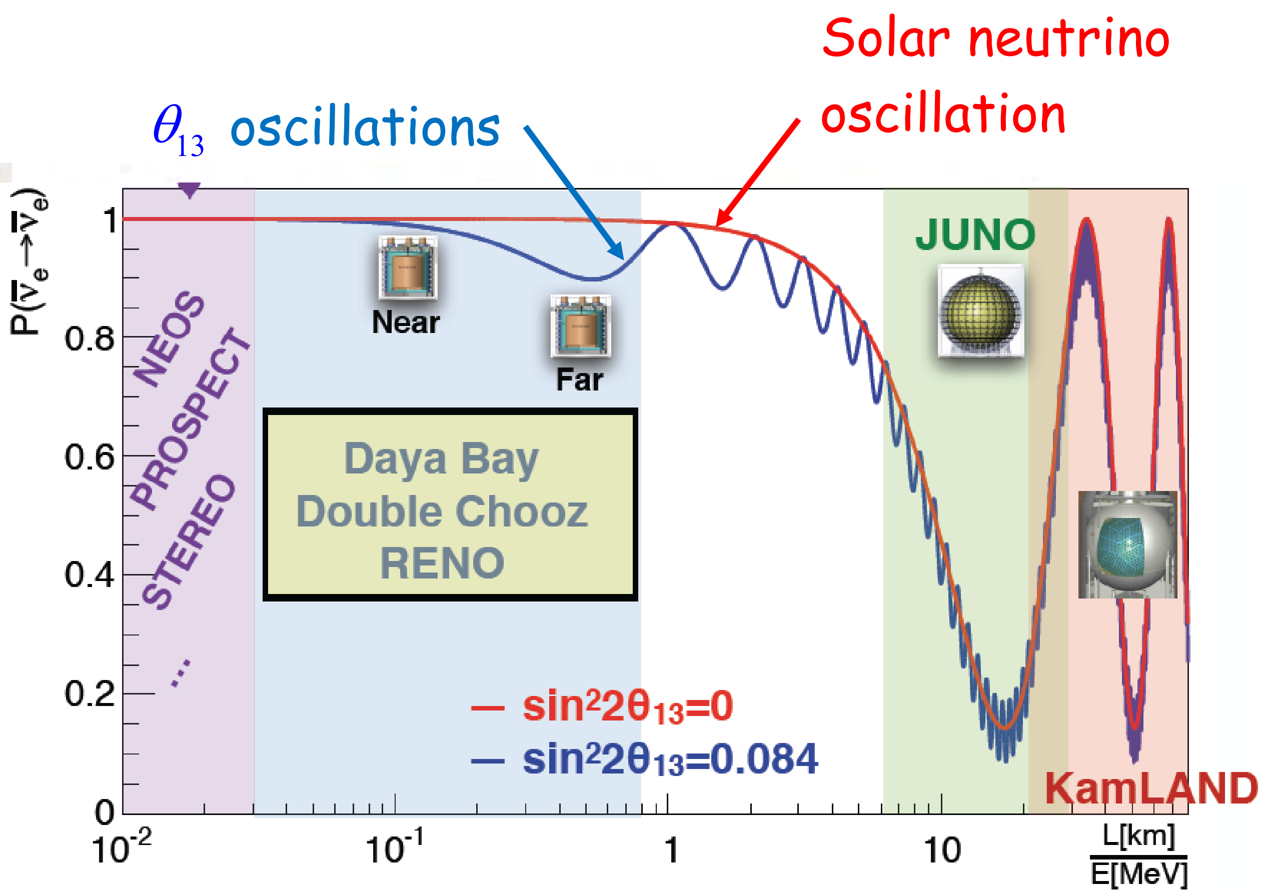
- the value of $\sin^2\theta$, which controls the magnitude of the sub-leading effects due to Δm^2_{31} on the $\Delta m^2_{\odot}$ – driven oscillations: the effect of interest vanishes in the decoupling limit of $\sin^2\theta \to 0$;

Realization&Plausibility: L. Zhan et al, PRD.78.111103; J. Learned et al PRD.78.071302

JUNO Found a Sweet Spot



Yangjiang Power Plant



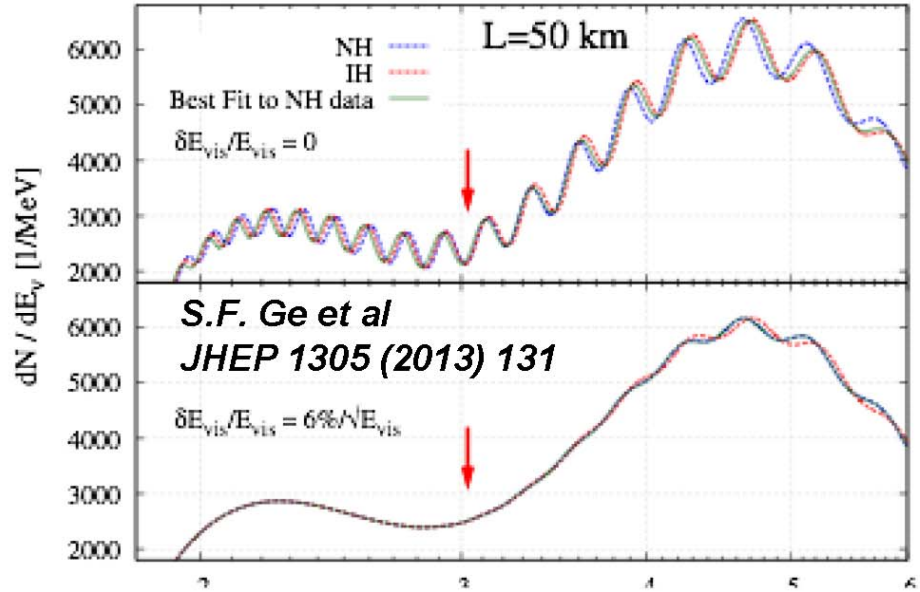
Best baseline is ~60km

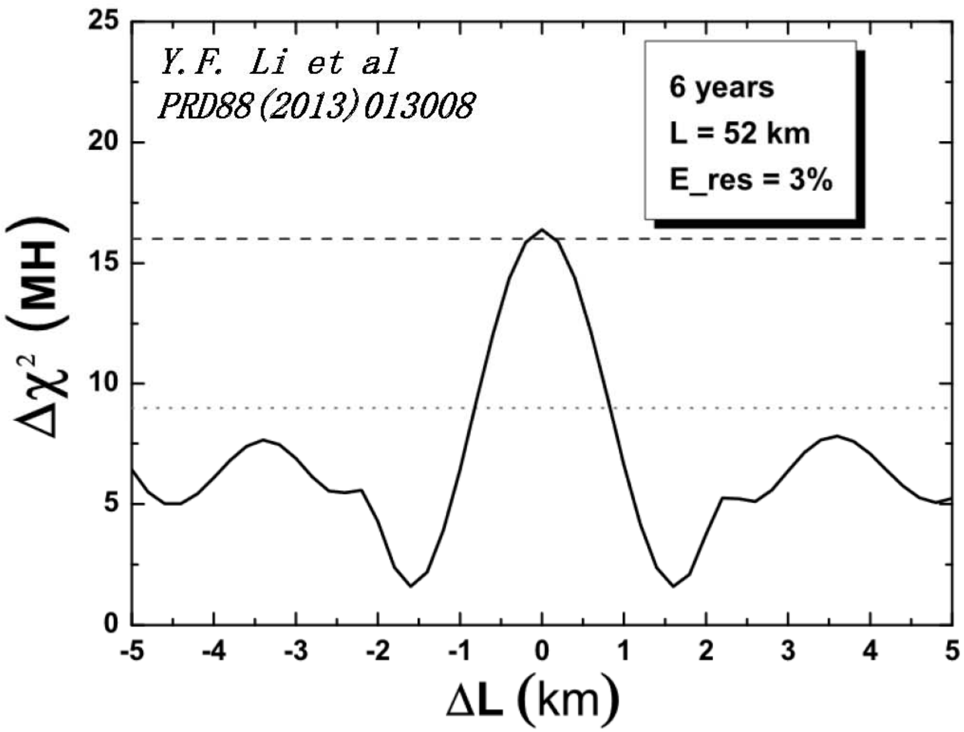
(OR at the solar oscillation maximum)

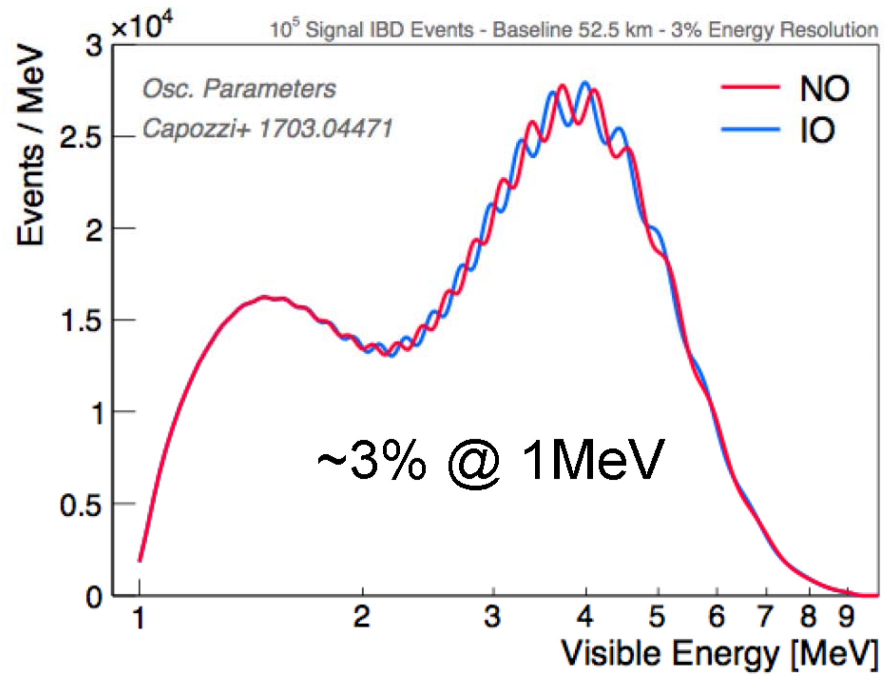
Challenges in Resolving MH using Reactors

$L \approx 30 L_{\mathrm{osc},13} \approx L_{\mathrm{coh}}$

- **Energy resolution: ~3%/sqrt(E)**
- **Energy scale uncertainty: <1%**
- Statistics (the more the better)
- Reactor distribution: <~0.5km

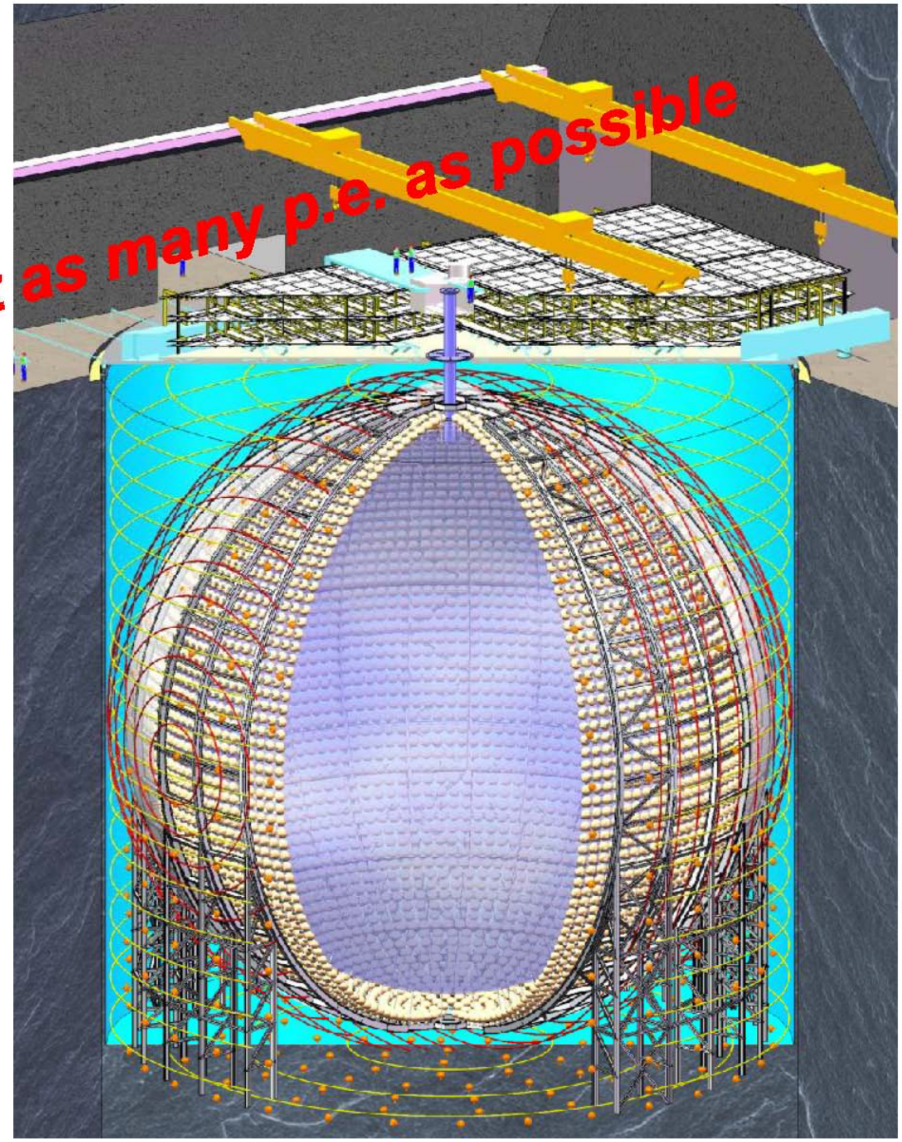






JUNO Detector System

- **Center Detector**
  - Acrylic sphere containing **L**iquid **S**cintillator(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**, 1~4000p.e.dynamic range



The Detector Performance Goals

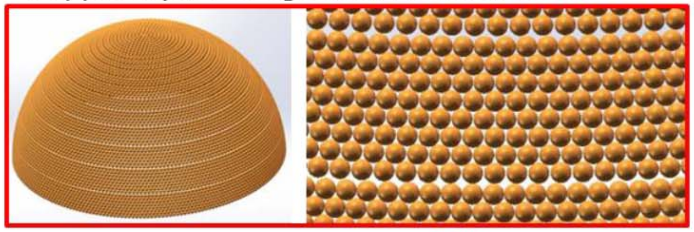
	KamLAND	BOREXINO	Daya Bay	PROSPECT	JUNO
Target Mass	**~1kt**	~300t	20t	~4t	**~20kt**
Photocathode Coverage	~34%	~34%	~12% (Effective)	ESR + PMTs	**~80%**
PE Collection	~250 PE/MeV	~500 PE/MeV	~160 PE/MeV	**~850 PE/MeV**	**~1200 PE/MeV**
Energy Resolution	~6%/√E	~5%/√E	~7.5%/√E	**~4.5%/√E**	**3%/√E**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

➡ **Quite a challenging detector for JUNO!**

Packing PMTs as Tight as Possible

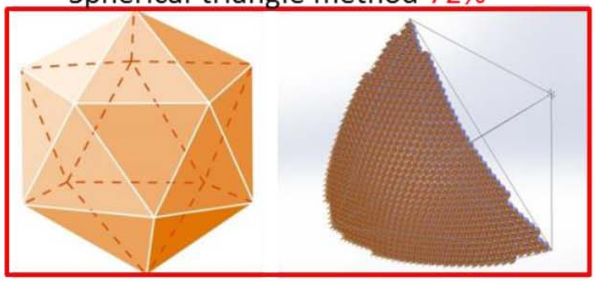
Supper layer arrangement method 77.8%

✓



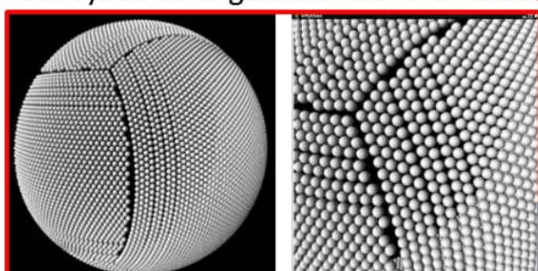
Spherical triangle method 72%

2



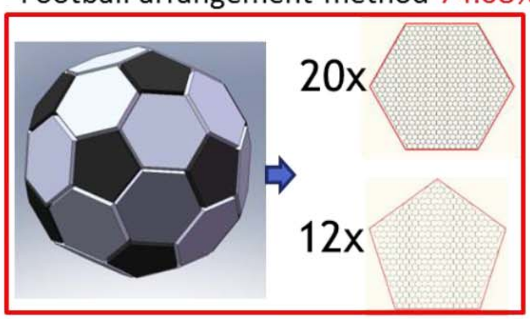
Volleyball arrangement method 75.96%

3



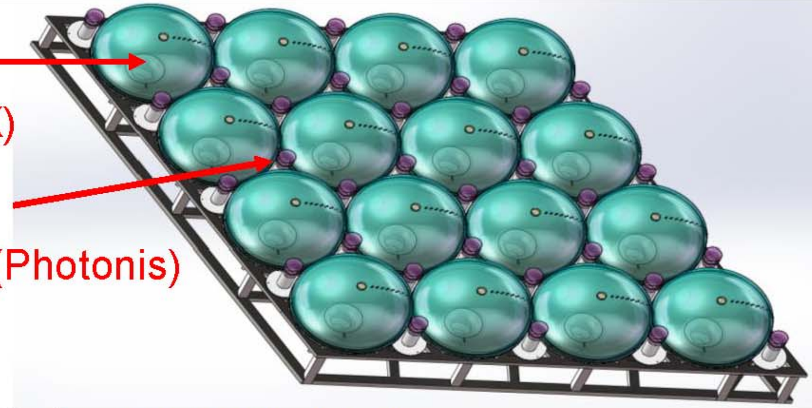
Football arrangement method 74.08%

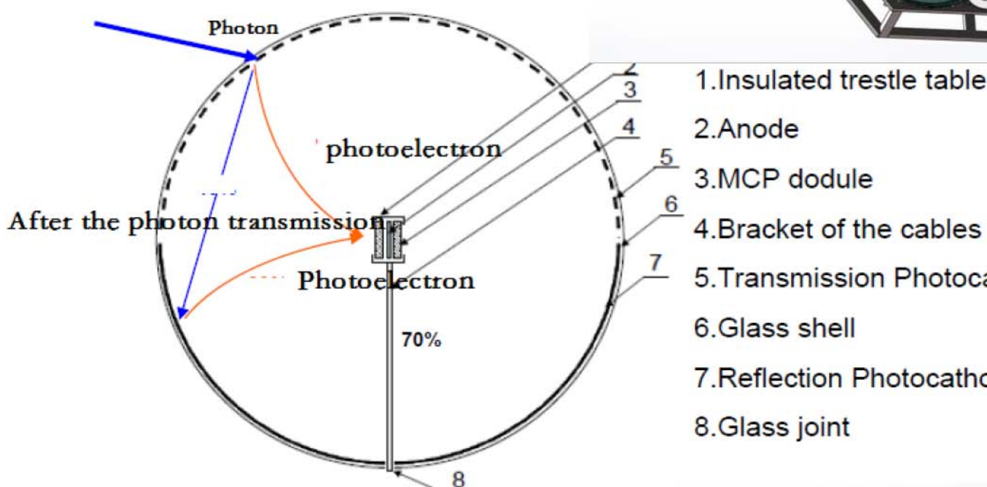
4

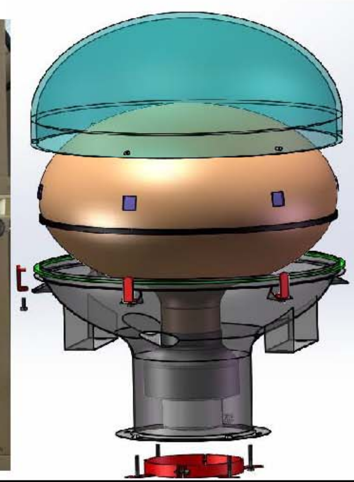


20" PMT (~18K)
MCP-PMT (~13K)
Hamamatsu HQE (5K)

3"sPMT(~25K)
HZC XP72B22 (Photonis)

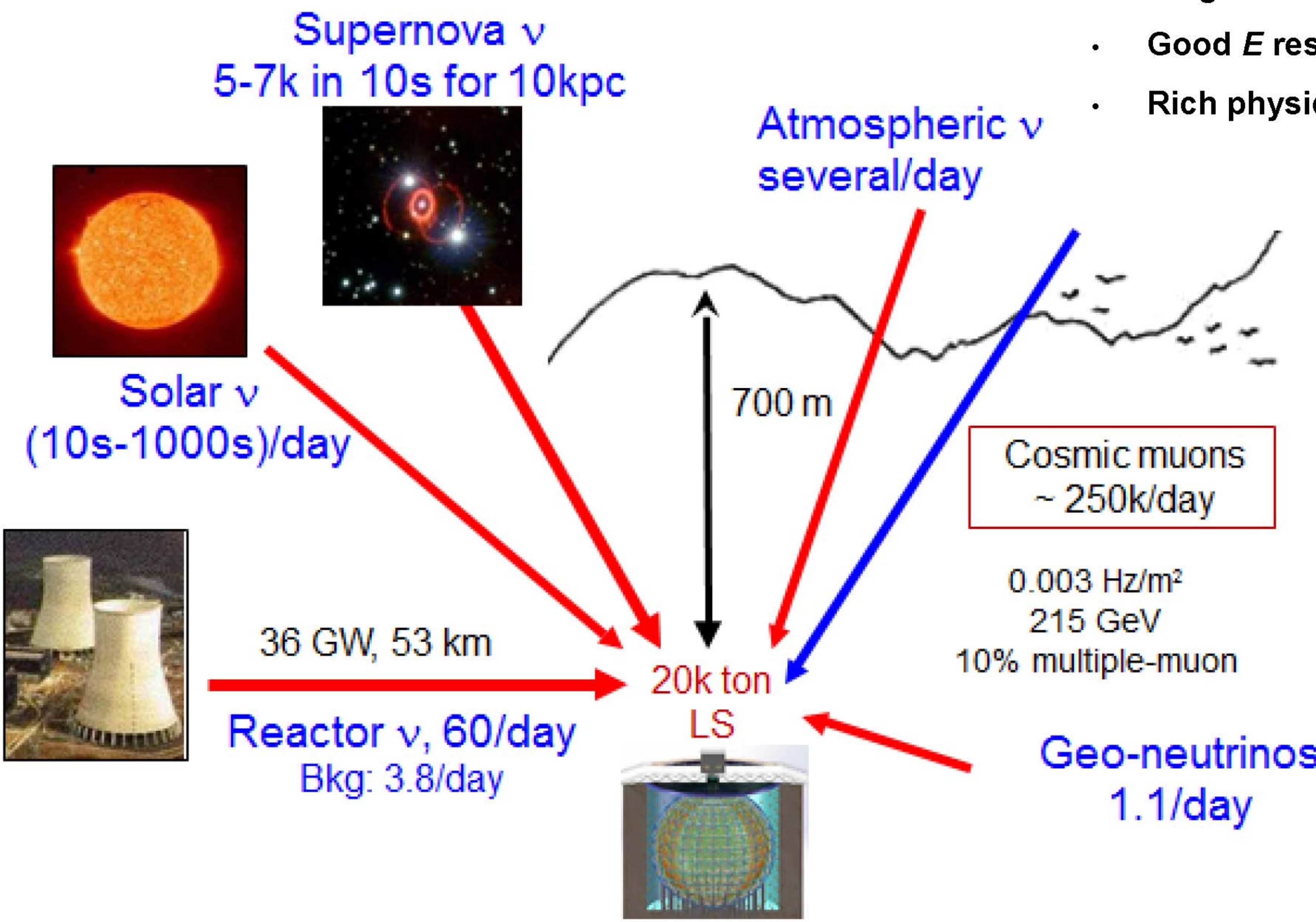






JUNO is More Than Neutrino Mass Hierarchy

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



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