Latest Results on Reactor Antineutrino Disappearance at Daya Bay

Karsten M. Heeger
Yale University

On behalf of the Daya Bay Collaboration

Yale, September 30, 2013

Reactor Neutrinos

2012 - Measurement of θ_{13} with Reactor Neutrinos

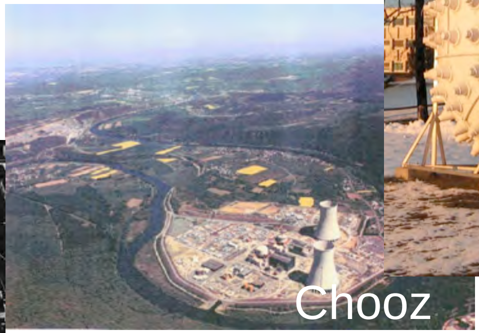
2008 - Precision measurement of Δm_{12}^2 . Evidence for oscillation

2003 - First observation of reactor antineutrino disappearance

1995 - Nobel Prize to Fred Reines at UC Irvine

1980s & 1990s - Reactor neutrino flux measurements in U.S. and Europe

1956 - First observation of (anti)neutrinos



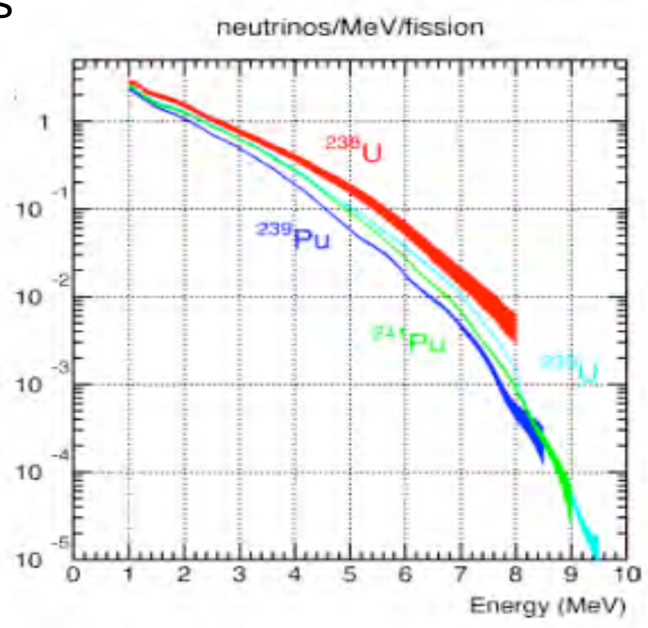
Past Reactor Experiments
Hanford
Savannah River
ILL, France
Bugey, France
Rovno, Russia
Goesgen, Switzerland
Krasnoyark, Russia
Palo Verde
Chooz, France

55 years of liquid scintillator detectors
a story of varying baselines...

Reactor Antineutrinos

Source

$\bar{\nu}_e$ from β-decays
of n-rich fission products

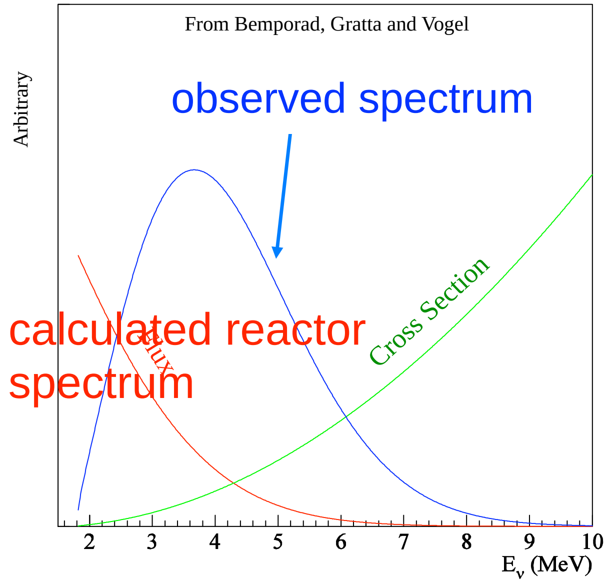


pure $\bar{\nu}_e$ source

> 99.9% of ν_e are produced by fissions in ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

Detection

inverse beta decay
$\bar{\nu}_e + p \rightarrow e^+ + n$

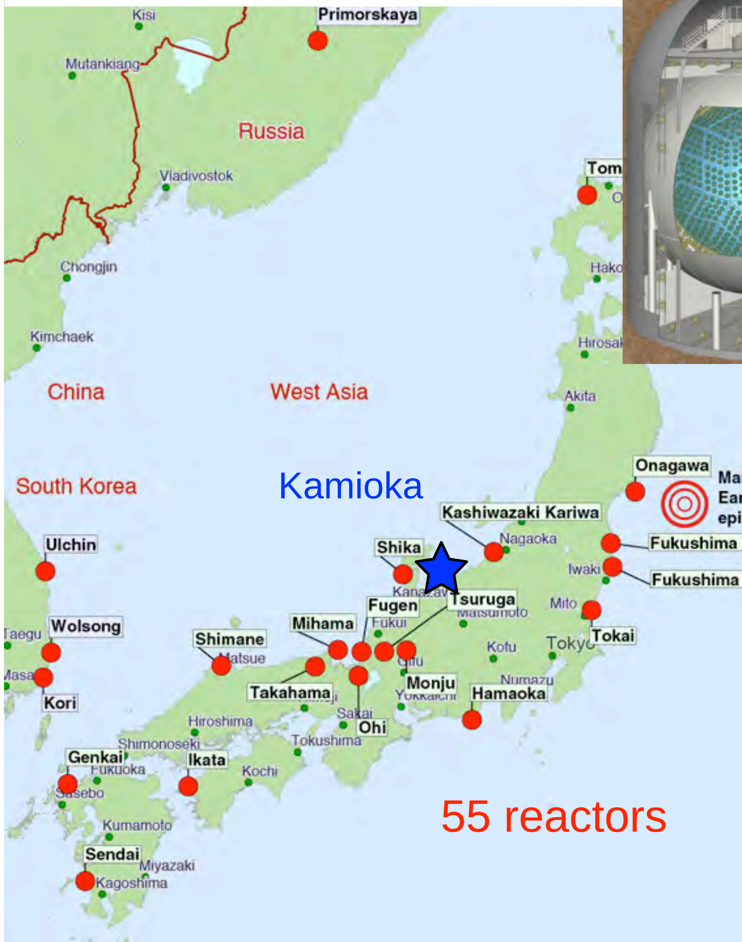


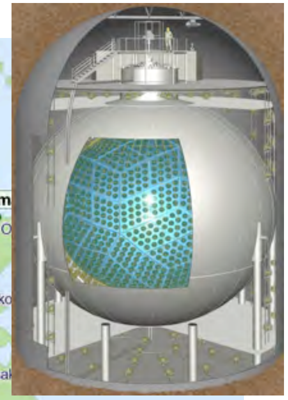
mean energy of $\bar{\nu}_e$: 3.6 MeV

only disappearance experiments possible

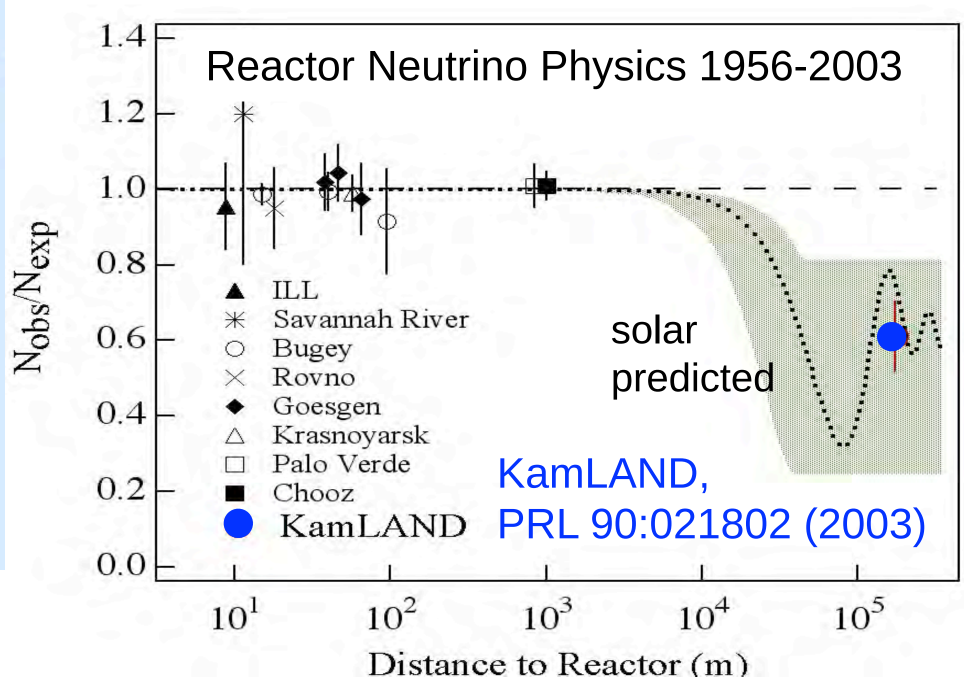
Observation of Reactor $\bar{\nu}_e$ Disappearance

KamLAND 2003





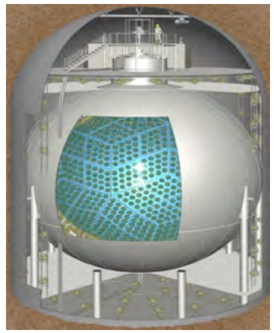
1kt liquid scintillator detector

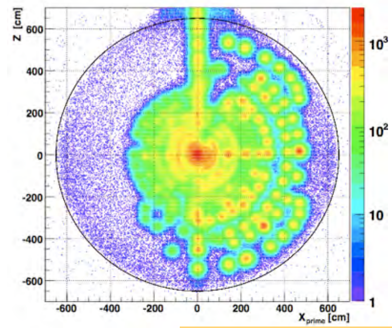


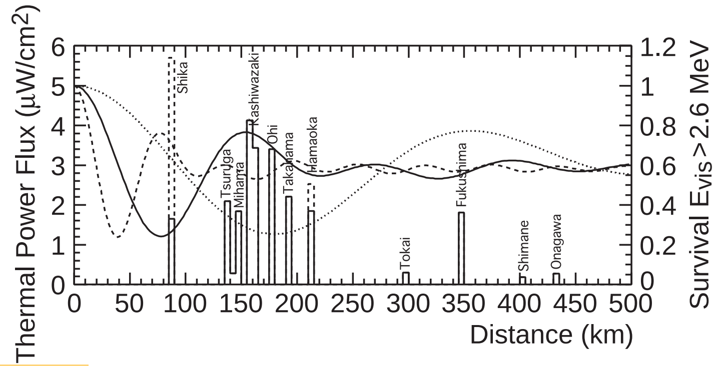
mean, flux-weighted reactor distance ~ 180km

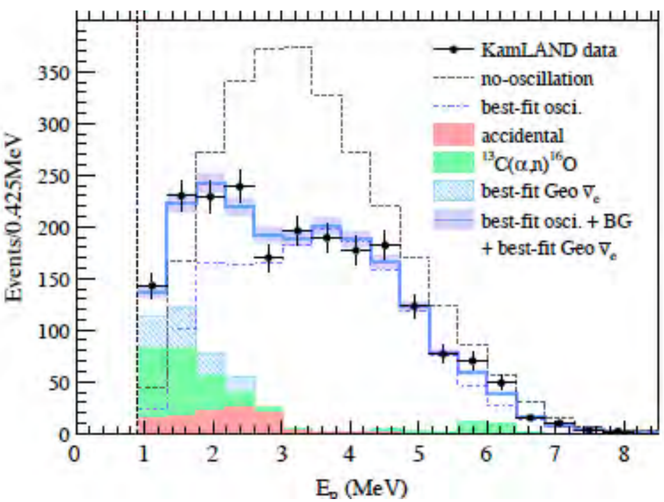
Reactor Antineutrinos at KamLAND

KamLAND 2007-2010

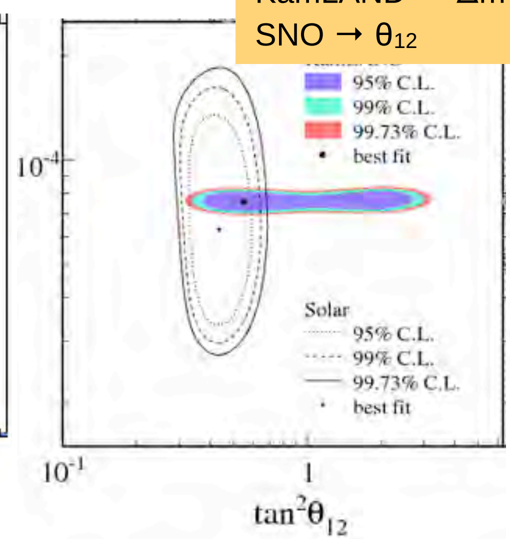




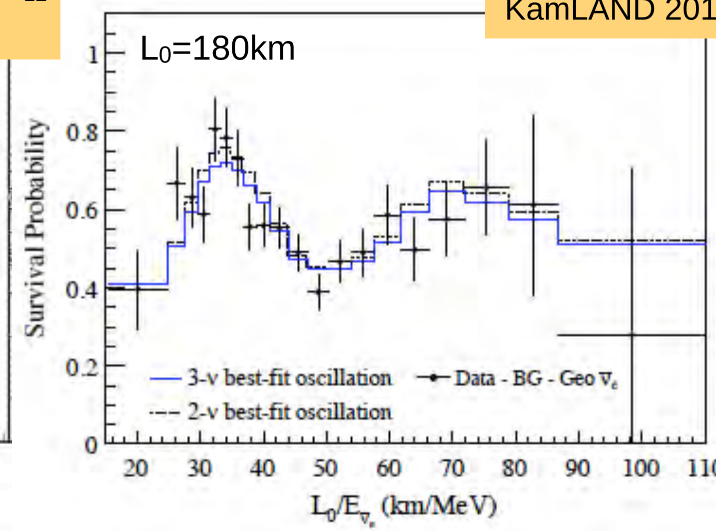




KamLAND → Δm^2_{12}
SNO → θ_{12}



KamLAND 2010



Evidence for spectral distortion

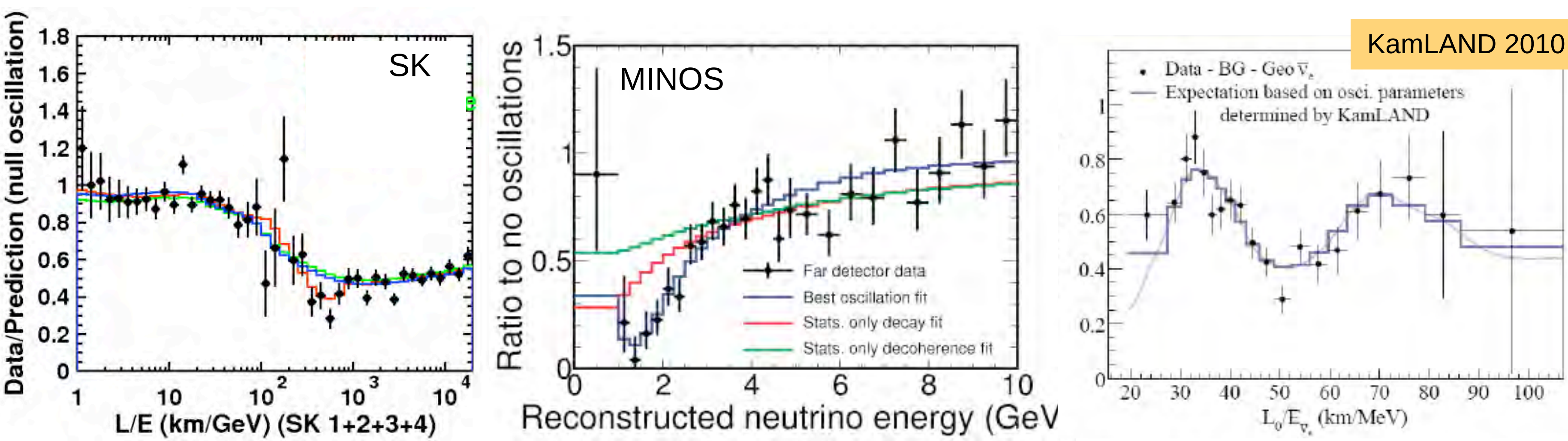
KamLAND has measured Δm_{12}^2 to ~2.8%

Direct evidence for oscillation

Neutrino Oscillation Measurements

Recent Observations

- atmospheric ν_μ and $\bar{\nu}_\mu$ disappear most likely to ν_τ (SK, MINOS)
- accelerator ν_μ and $\bar{\nu}_\mu$ disappear at L~250, 700 km (K2K, T2K, MINOS)
- some accelerator ν_μ appear as ν_μ at L~250, 700 km (T2K, MINOS)
- solar ν_e convert to ν_μ/ν_τ (Cl, Ga, SK, SNO, Borexino)
- reactor $\bar{\nu}_e$ disappear at L~200 km (KamLAND)
- reactor $\bar{\nu}_e$ disappear at L~1 km (DC, Daya Bay RENO)



Experiments have demonstrated vacuum oscillation L/E pattern

$$P_{i\to i} = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

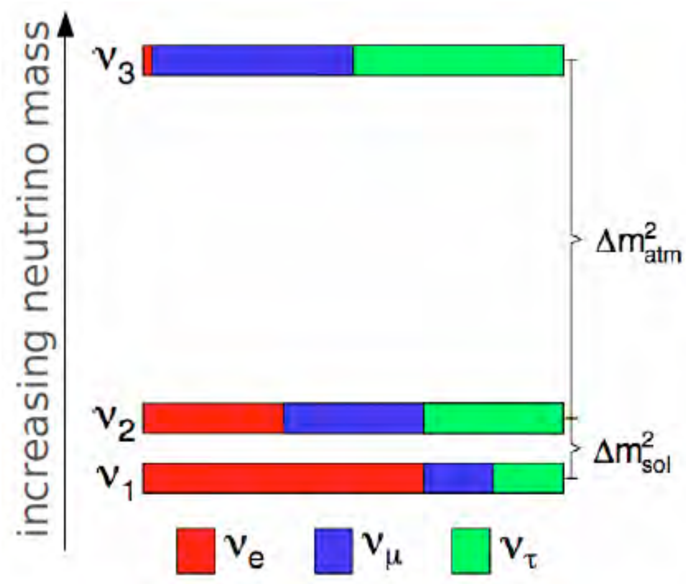
Neutrino Oscillation

Neutrino Oscillation Imply Neutrino Mass

mass eigenstates ≠ flavor eigenstates

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$$

flavor composition of neutrinos changes as they propagate



$$P(\nu_\alpha \rightarrow \nu_\beta) = |\langle\nu_\beta|\nu_\alpha(L)\rangle|^2$$

$$= \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2[1.27\Delta m^2_{ij}L/E]$$

$$+2\sum_{i>j} \Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2[2.54\Delta m^2_{ij}L/E]$$

2-neutrino case

$$P_{i\rightarrow j} = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

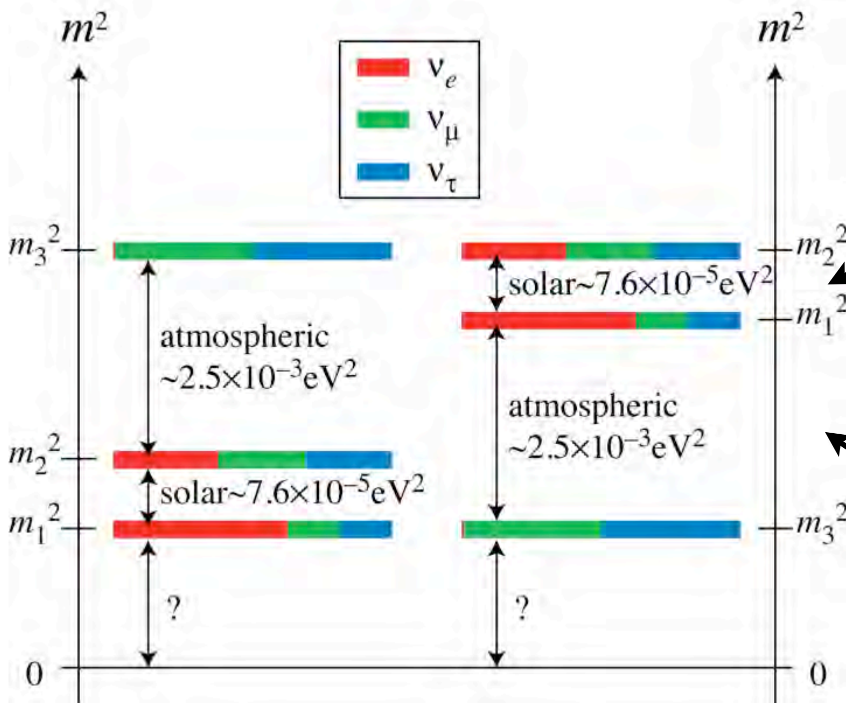
energy and baseline dependent

osc frequency depends on Δm^2

amplitude depends on θ

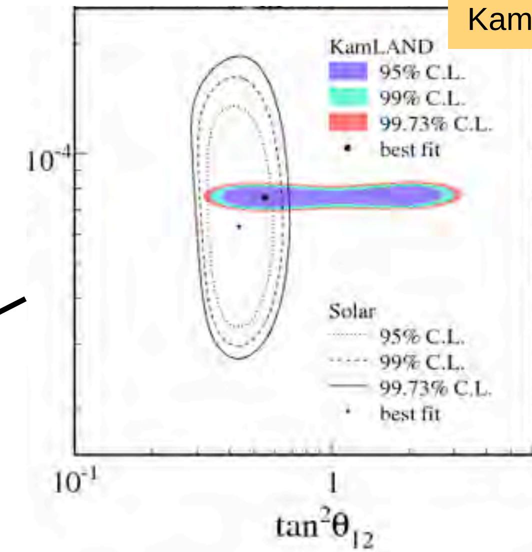
Measurement of Fundamental Parameters

Mass Splittings

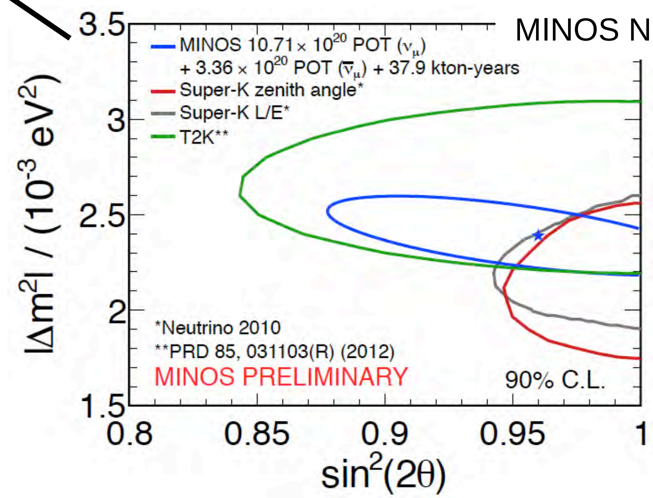


normal inverted

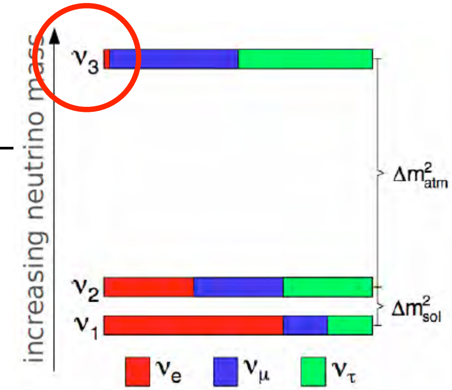
KamLAND 2010



MINOS Nu2012



Neutrino Oscillation - Before 2011



Mixing Angles

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 0.8 & 0.5 & U_{e3} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

U_{MNSP} Matrix

Maki, Nakagawa, Sakata, Pontecorvo

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}$$

atmospheric, K2K | reactor and accelerator | SNO, solar SK, KamLAND | $0\nu\beta\beta$

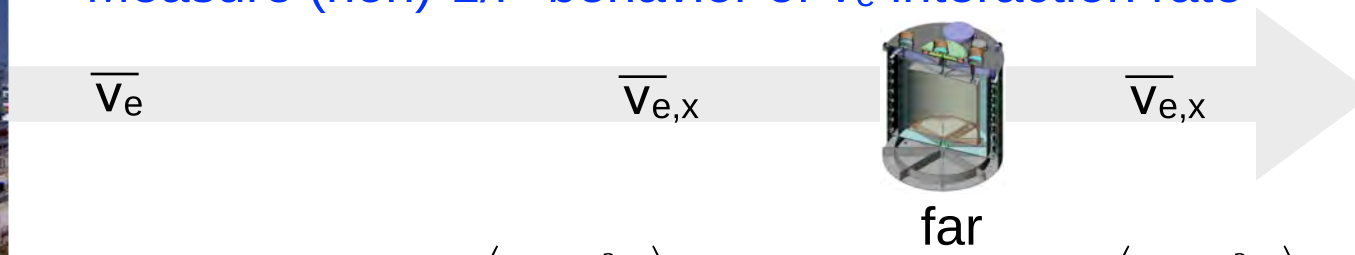
$\sin^2\theta_{23}$: $0.50^{+0.07}_{-0.06}$ — maximal?

$\sin^2\theta_{13}$: small? zero?

$\sin^2\theta_{12}$: $0.318^{+0.019}_{-0.016}$ — large, but not maximal!

Reactor Neutrino Oscillation Experiments

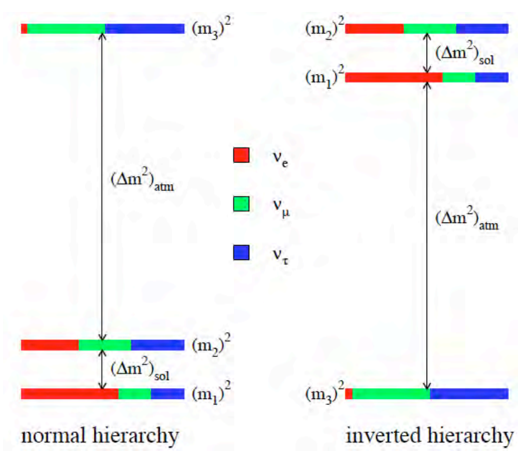
Measure (non)-$1/r^2$ behavior of $\bar{\nu}_e$ interaction rate



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

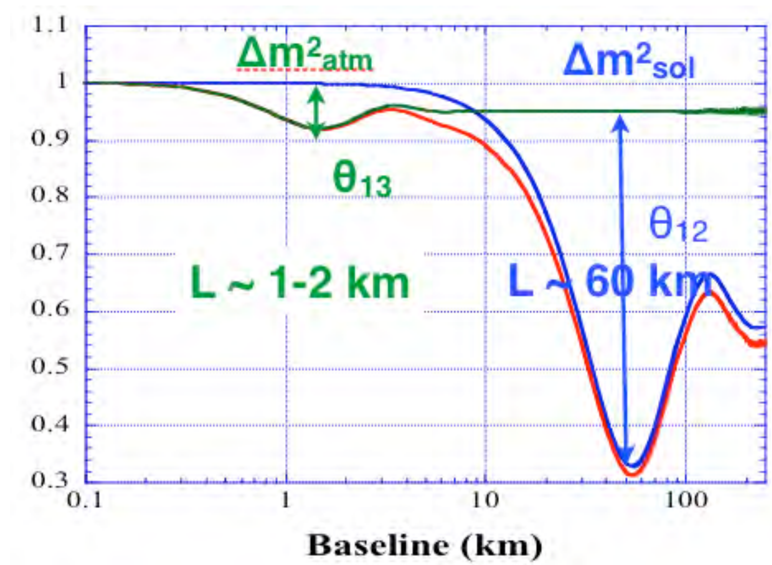
for 3 active ν, two different oscillation length scales: Δm^2_{12}, Δm^2_{23}

$L/E \rightarrow \Delta m^2$ amplitude of oscillation $\rightarrow \theta$



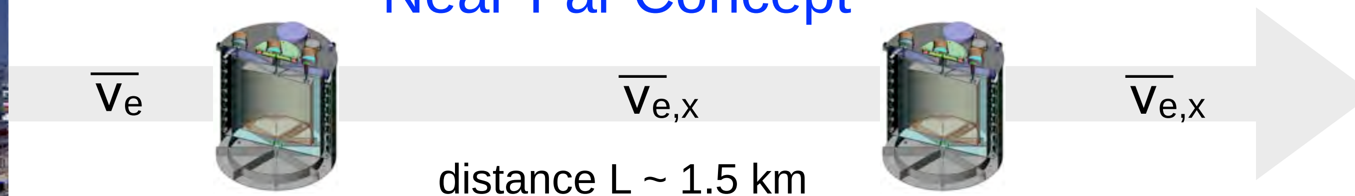
$\Delta m^2_{12} \sim 7.6 \times 10^{-5}\ eV^2$

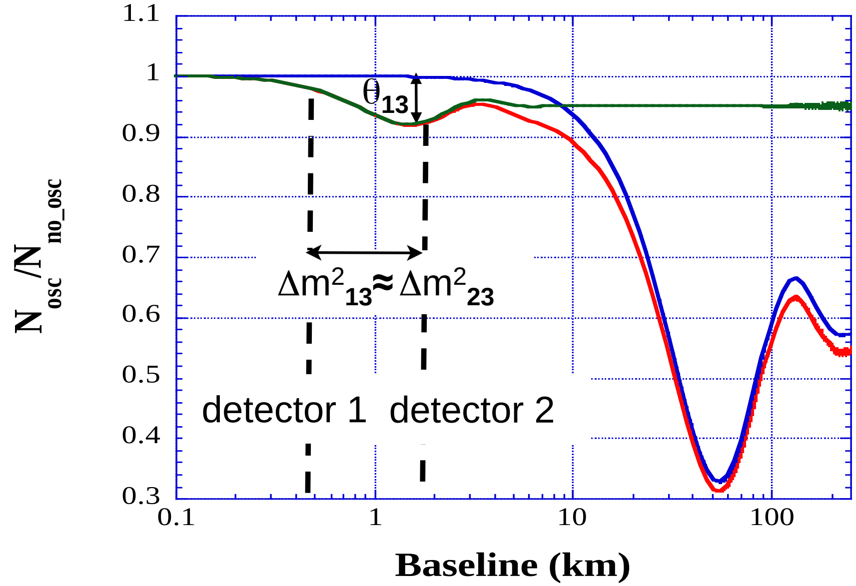
$\Delta m^2_{23} \sim 2.4 \times 10^{-3}\ eV^2$



Measuring θ_{13} with Reactor Experiments

Near-Far Concept





Absolute Reactor Flux
Largest uncertainty in previous measurements

Relative Measurement
Removes absolute uncertainties!

First proposed by L. A. Mikaelyan and V.V. Sinev, Phys. Atomic Nucl. 63 1002 (2000)

$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left[\frac{P_{sur}(E,L_f)}{P_{sur}(E,L_n)}\right]$$

far/near $\overline{\nu}_e$ ratio | target mass | distances | efficiency | oscillation deficit

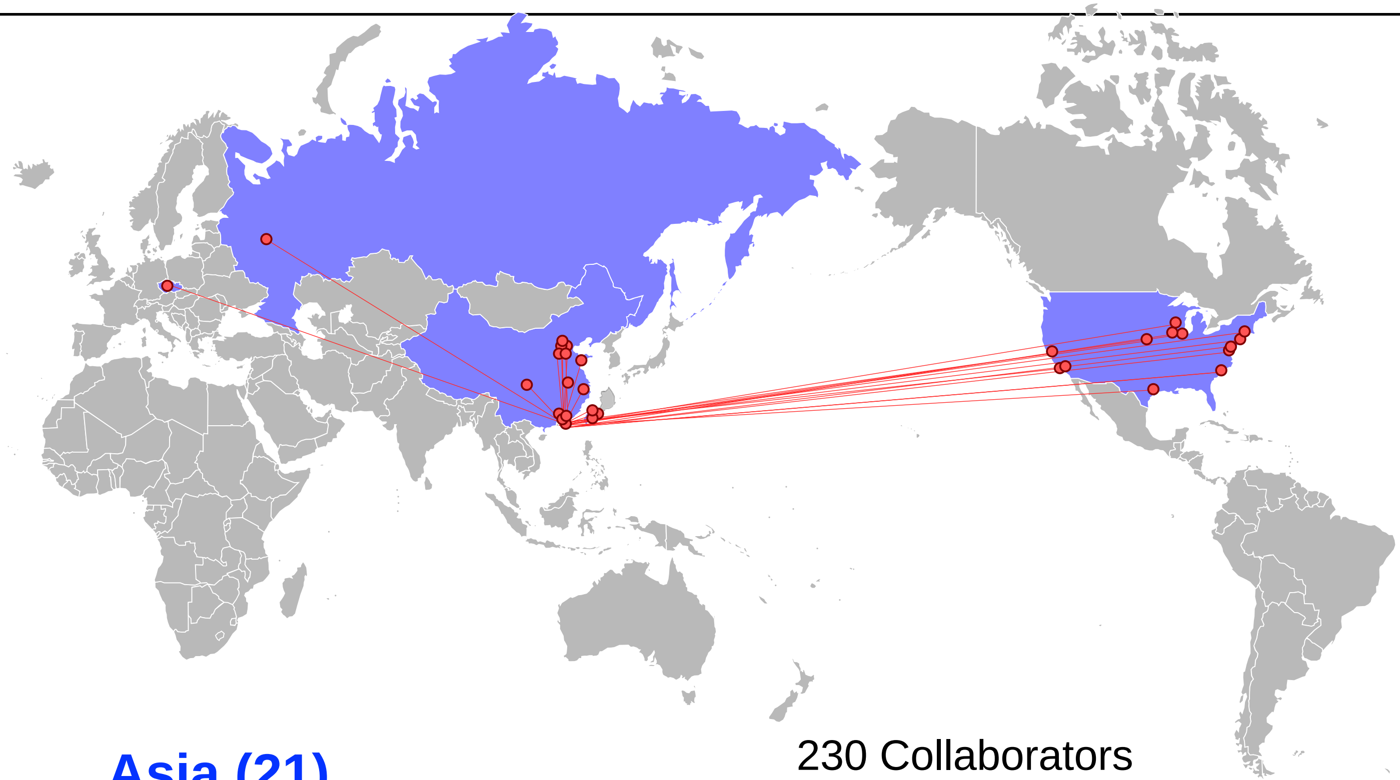
Daya Bay Nuclear Power Plant

A Powerful Neutrino Source

- Among the top 5 most powerful reactor complexes in the world, producing 17.4 GW_{th} (6 x 2.95 GW_{th})
- All 6 reactors are in commercial operation
- Adjacent to mountains; convenient to construct tunnels and underground labs with sufficient overburden to suppress cosmic rays

Reactors produce ~2×10^{20} antineutrinos/sec/GW

An International Effort



230 Collaborators
from 40 Institutions

Asia (21)

Beijing Normal Univ., CGNPG, CIAE, Dongguan Polytechnic, ECUST, IHEP, Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Xian Jiaotong Univ., Zhongshan Univ., Chinese Univ. of Hong Kong, Univ. of Hong Kong, National Chiao Tung Univ., National Taiwan Univ., National United Univ.

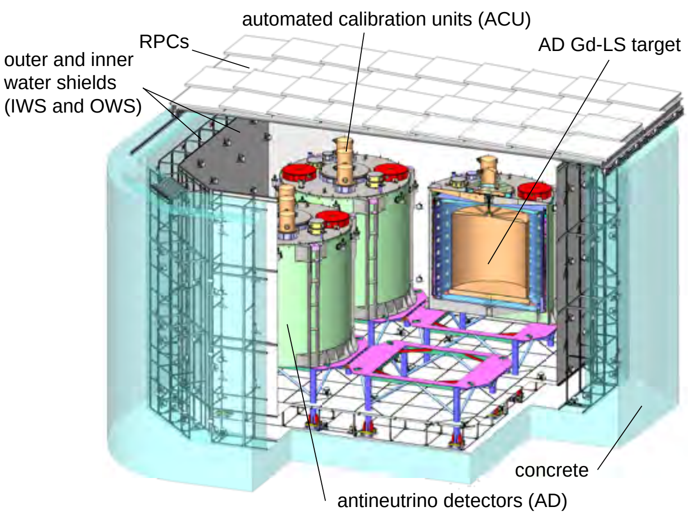
Europe (2)

Charles University, JINR Dubna

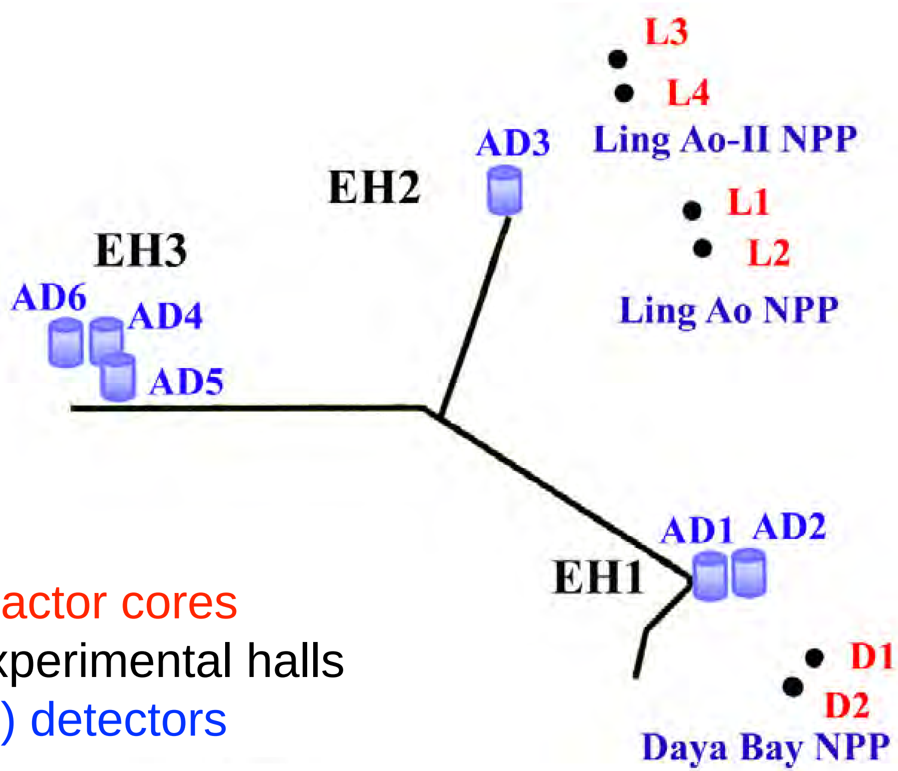
North America (17)

Brookhaven Natl Lab, CalTech, Illinois Institute of Technology, Iowa State, Lawrence Berkeley Natl Lab, Princeton, Rensselaer Polytechnic, Siena College, UC Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, UIUC, Univ. of Wisconsin, Virginia Tech, William & Mary, Yale

Daya Bay Experiment Layout



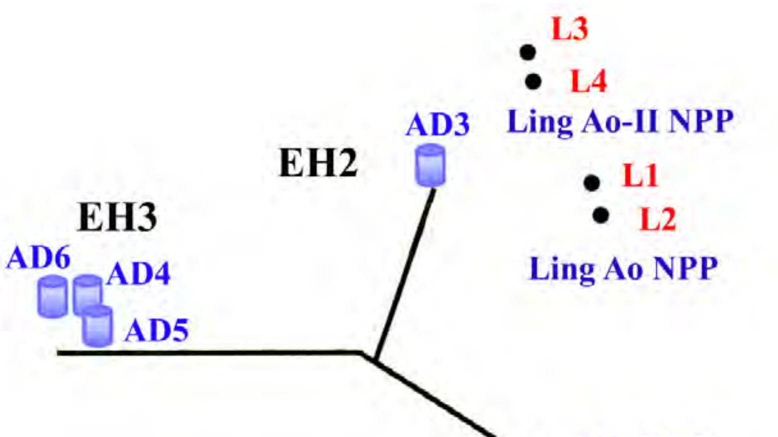
	Overburden	R_μ	E_μ	D1,2	L1,2	L3,4
EH1	250	1.27	57	364	857	1307
EH2	265	0.95	58	1348	480	528
EH3	860	0.056	137	1912	1540	1548

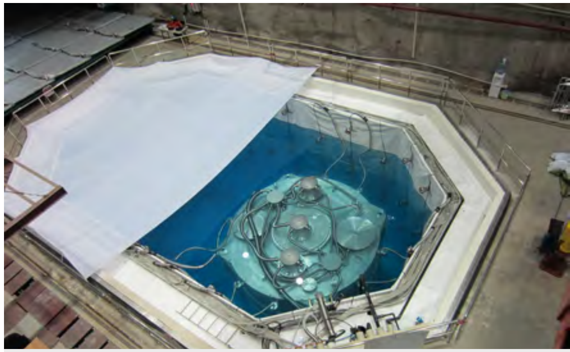


6 reactor cores
3 experimental halls
6 (8) detectors

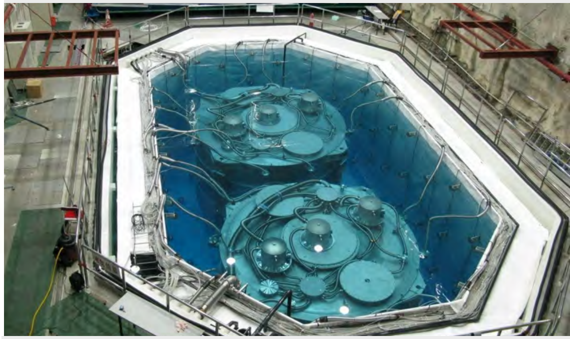
Daya Bay Experiment Layout

Hall 3: began 3 AD operation on Dec. 24, 2011





Hall 2: began 1 AD operation on Nov. 5, 2011

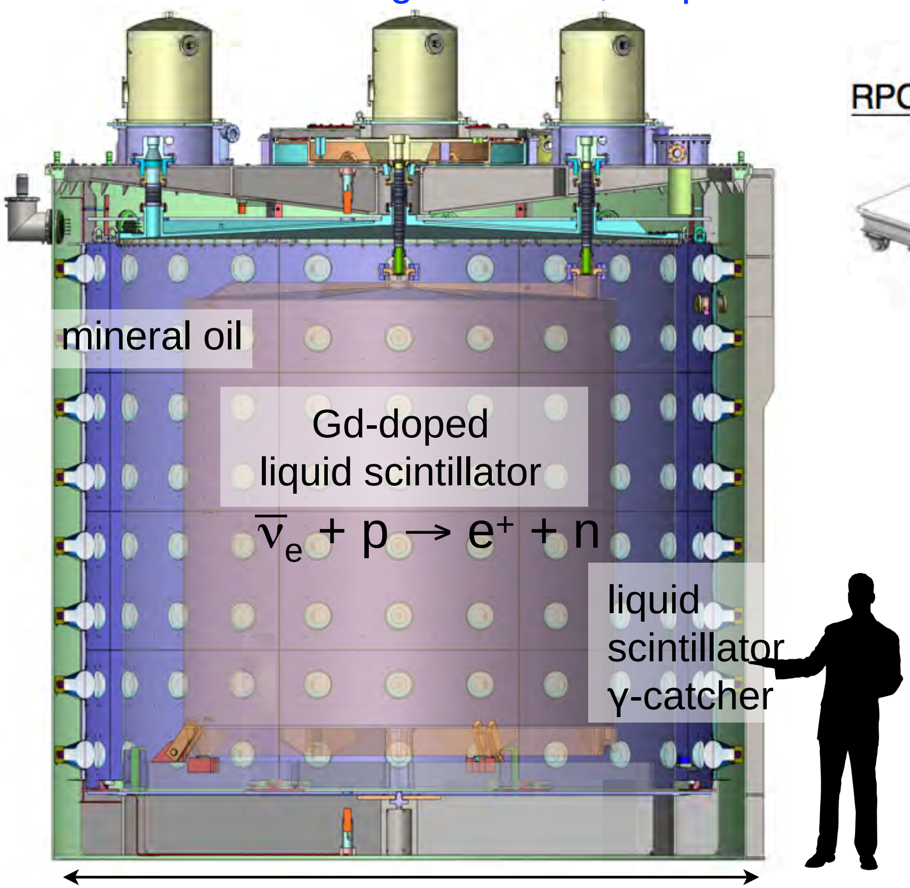


Hall 1: began 2 AD operation on Sep. 23, 2011

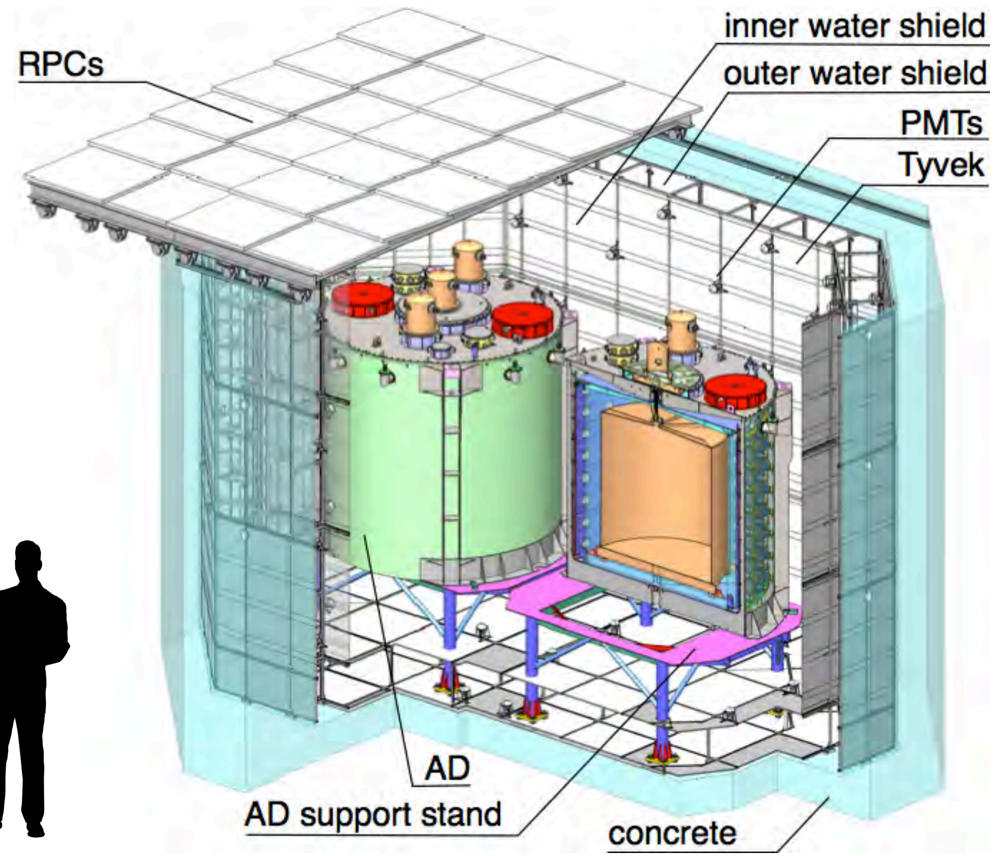
Daya Bay Detectors

6 "functionally identical" detectors
Gd-LS defines target volume, no position cut

Dual tagging systems: 2.5 meter water shield and RPCs



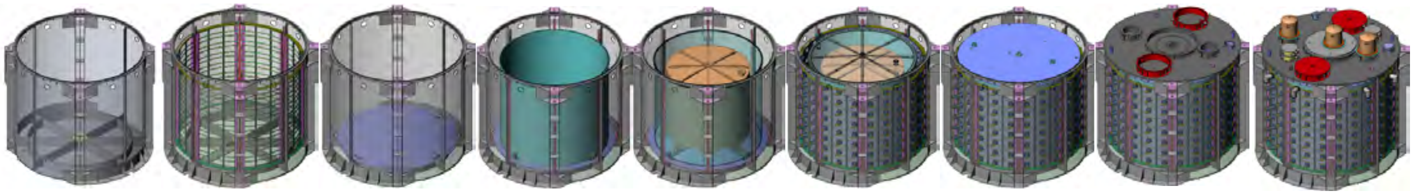
target mass: 20 ton per AD
photosensors: 192 8"-PMTs
energy resolution: $(7.5 / \sqrt{E} + 0.9)\%$

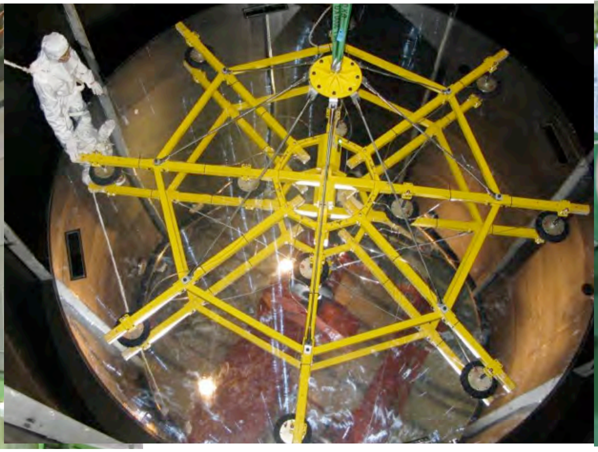


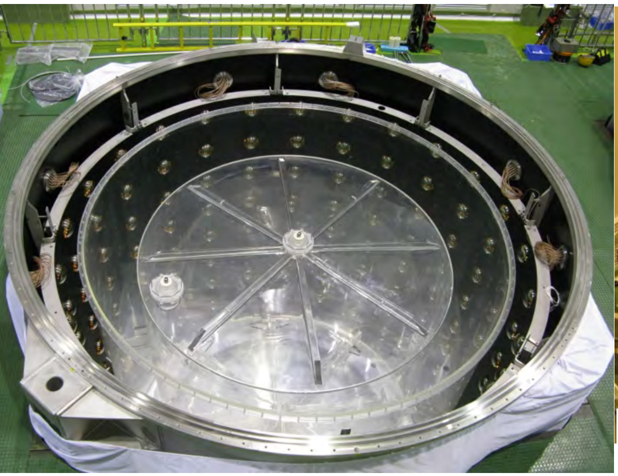
Two-zone ultrapure water Cherenkov detector

multiple detectors allow comparison and cross-checks

Antineutrino Detector Assembly



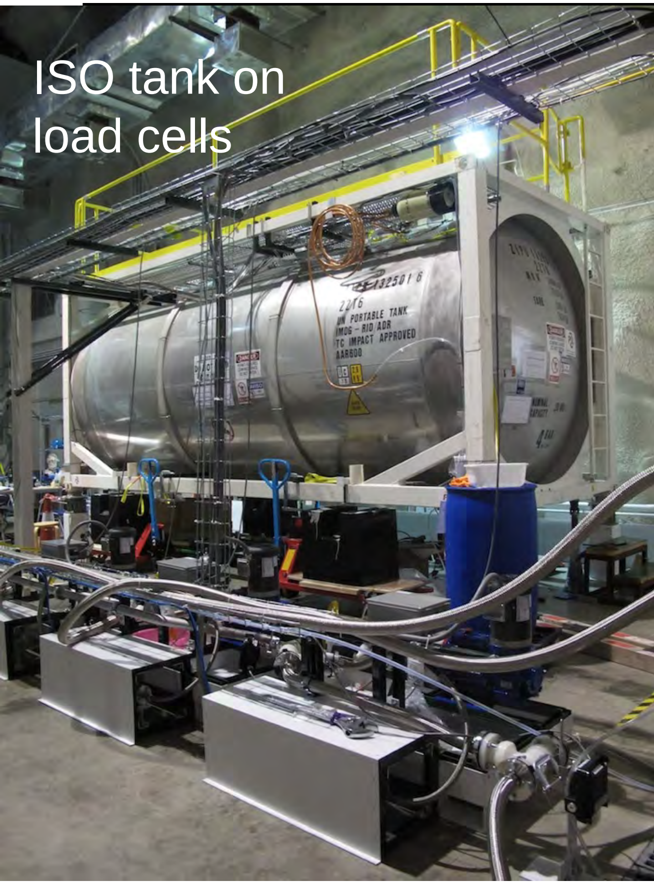


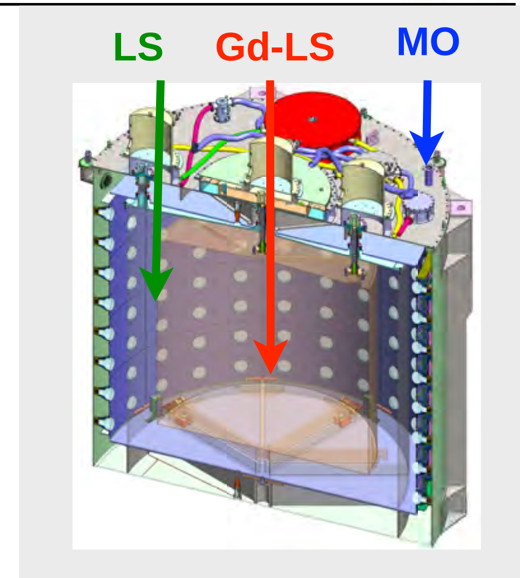


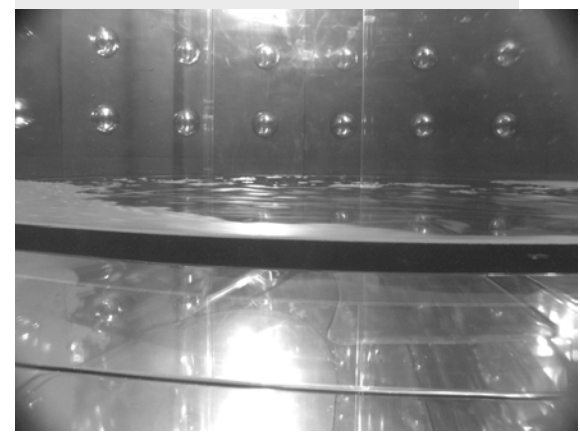
detector assembly in pairs

Liquid Scintillator Hall

Detector Filling and Target Mass Measurement







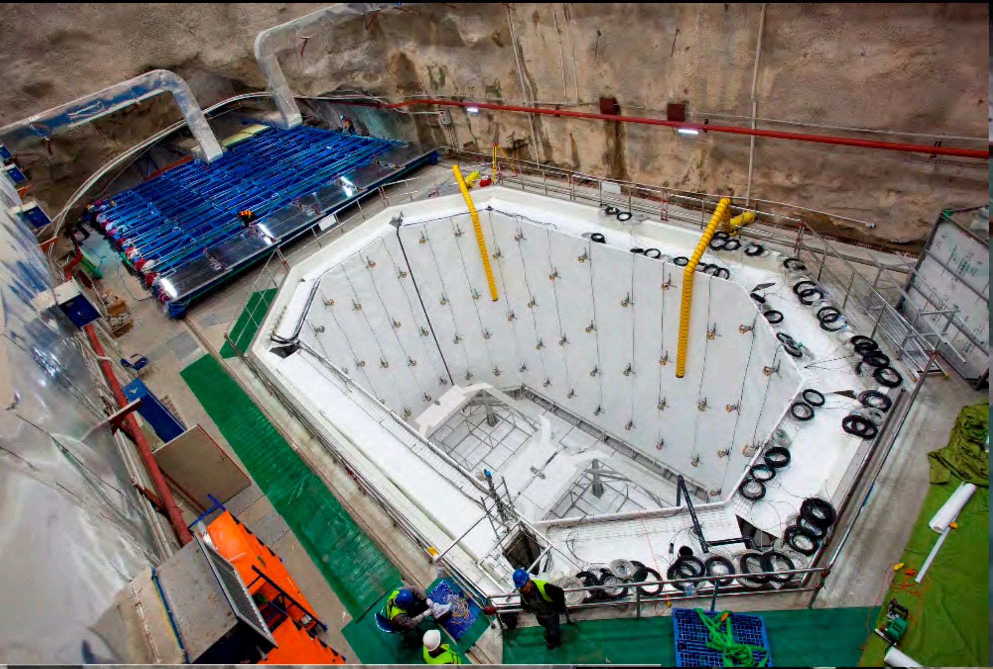
Quantity	Relative	Absolute
protons/kg	neg.	0.47%
Density (kg/L)	neg.	neg.
Total mass	0.015%	0.015%
Overflow tank geometry	0.0066%	0.0066%
Overflow sensor calibration	0.0043%	0.0043%
Bellows Capacity	0.0025%	0.0025%
Target mass	0.017%	0.017%
Target protons	0.017%	0.47%

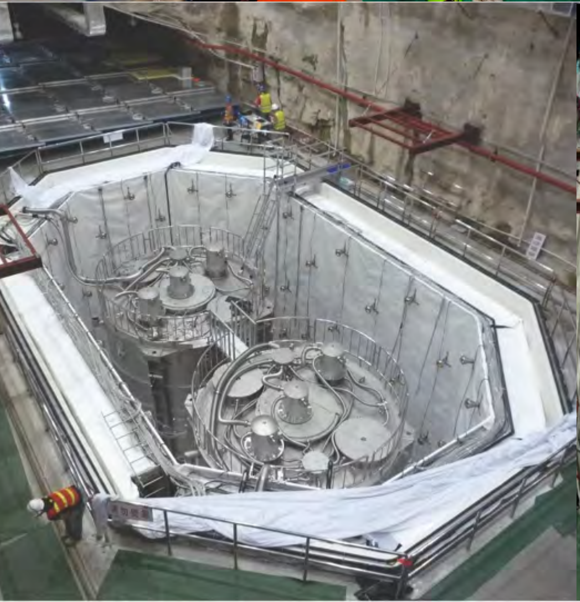
Target mass determination error
± 3kg out of 20,000

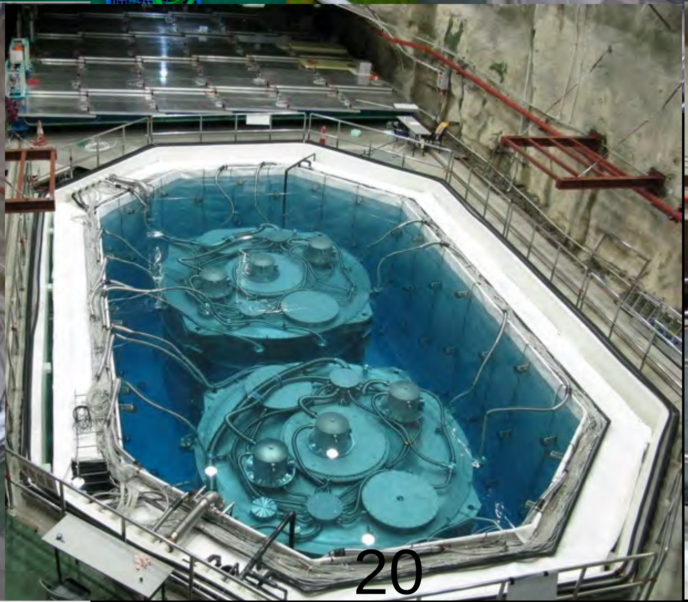
<0.03% during data taking period

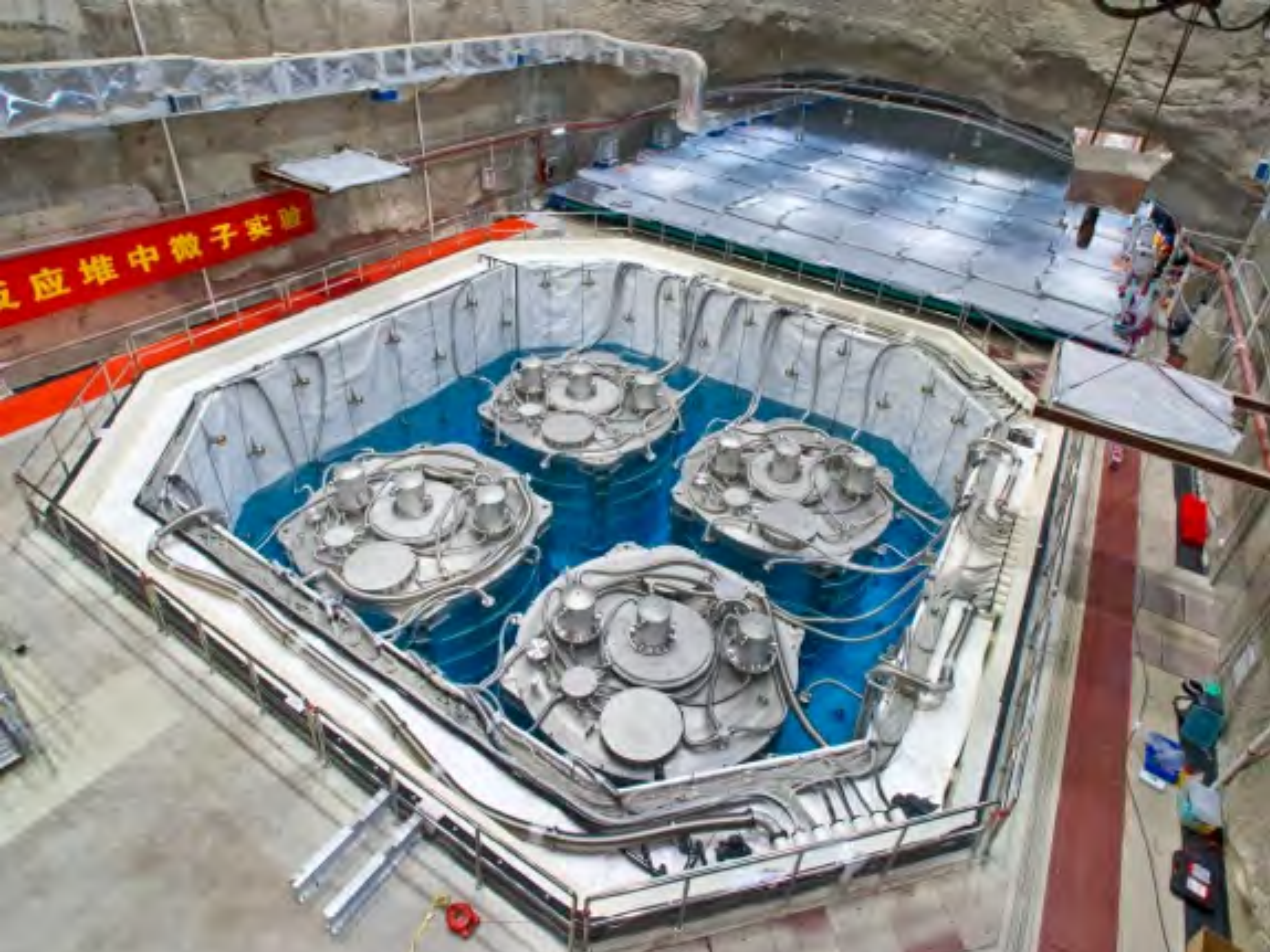
Detectors are filled from same reservoirs *"in-pairs"* within < 2 weeks.

Antineutrino Detector Installation - Near Hall



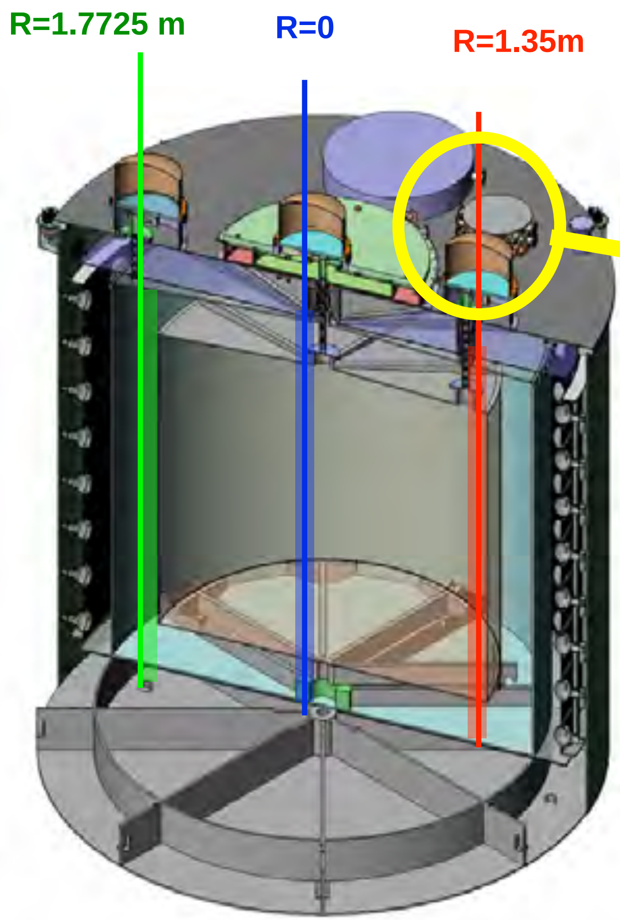




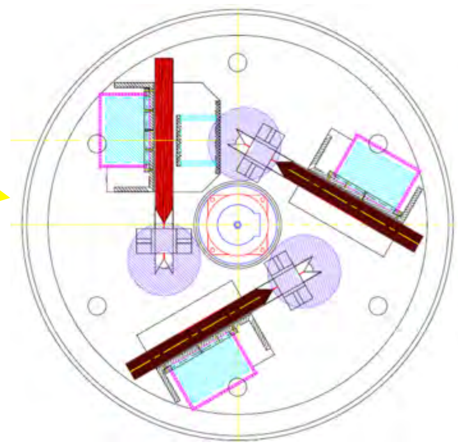

反应堆中微子实验

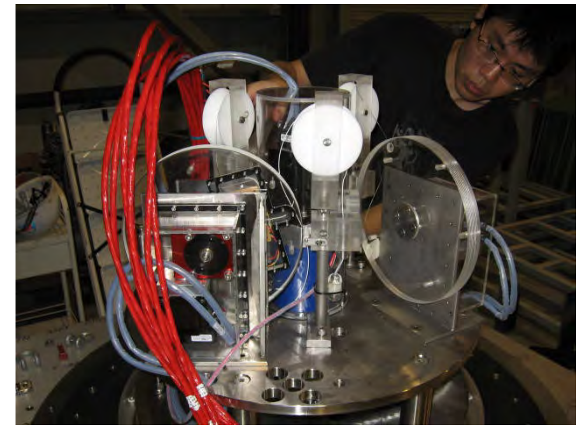
Automated Calibration System

3 Automatic calibration ‘robots’ (ACUs) on each detector



Top view





3 sources in each robot, including:

- 10 Hz ^{68}Ge (0 KE e^+ = 2×0.511 MeV γ’s)
- 0.75 Hz ^{241}Am-^{13}C neutron source (3.5 MeV n without γ)
  \+ 100 Hz ^{60}Co gamma source (1.173+1.332 MeV γ)
- LED diffuser ball (500 Hz) for time calibration

Temporary special calibration sources:

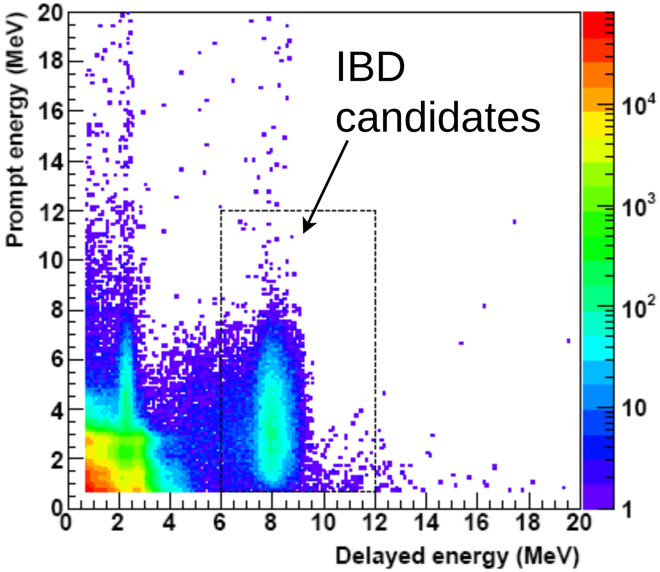
γ: ^{137}Cs (0.662 MeV), ^{54}Mn (0.835 MeV), ^{40}K (1.461 MeV)

n: ^{241}Am-^{9}Be, ^{239}Pu-^{13}C

Three axes: center, edge of target, middle of gamma catcher

Antineutrino Candidates (Inverse Beta Decay)

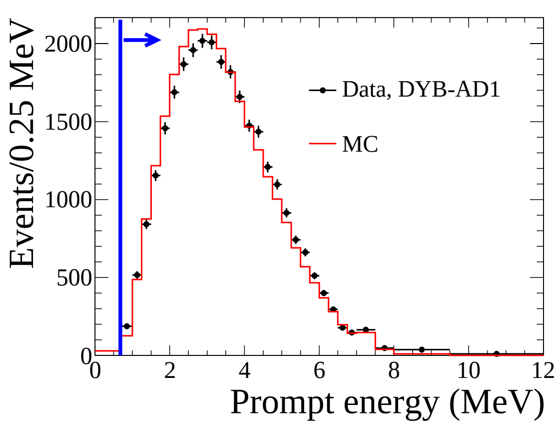
Prompt + Delayed Selection



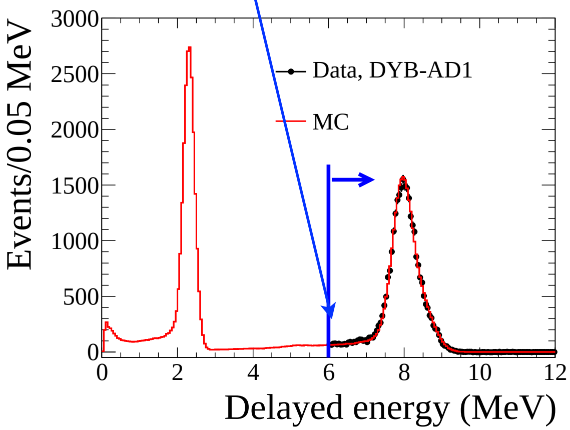
$$\overline{\nu}_e + p \rightarrow e^+ + n$$

Uncertainty in relative E_d efficiency (0.12%) between detectors is largest systematic.

Prompt Energy Signal



Delayed Energy Signal



Antineutrino Candidates Selection

Antineutrino interactions cleanly separated from backgrounds

(1) Reject spontaneous PMT light emission ("flashers")

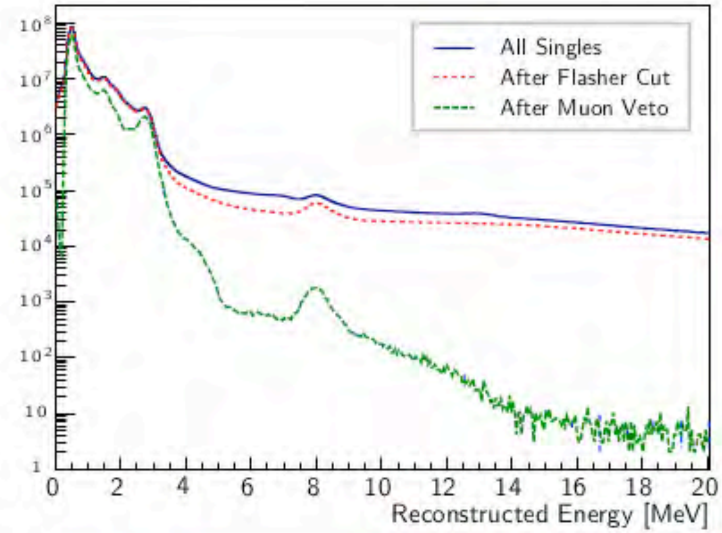
(2) Prompt positron:
0.7 MeV < Ep < 12 MeV

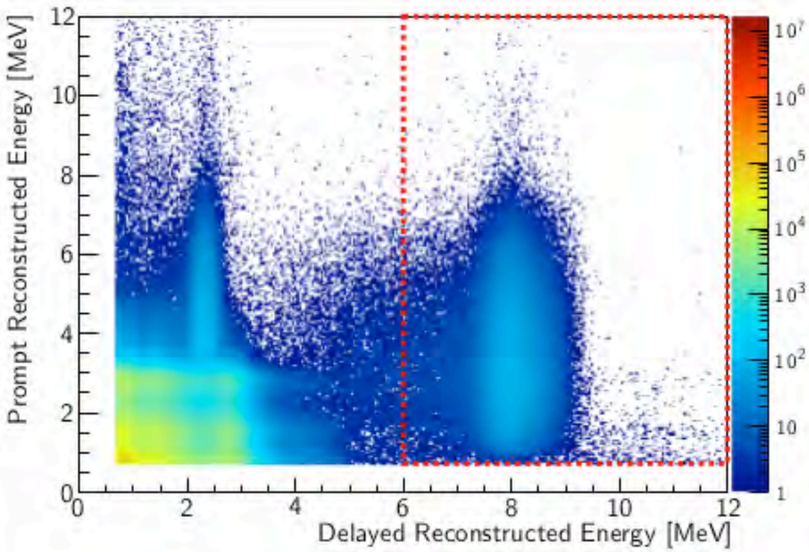
(3) Delayed neutron:
6.0 MeV < Ed < 12 MeV

(4) Neutron capture time:
1 μs < t < 200 μs

(5) Muon veto:
- Water pool muon (>12 hit PMTs): Reject [-2μs; 600μs]
- AD muon (>3000 photoelectrons): Reject [-2 μs; 1400μs]
- AD shower muon (>3×10^5 p.e.): Reject [-2 μs; 0.4s]

(6) Multiplicity:
- No additional prompt-like signal 400μs before delayed neutron
- No additional delayed-like signal 200μs after delayed neutron





Analyzed Data Sets

Two detector comparison

[1202.6181]

- 90 days of data, Daya Bay near only
- NIM A **685** (2012), 78-97

First oscillation analysis

[1203:1669]

- 55 days of data, 6 ADs near+far
- PRL **108** (2012), 171803

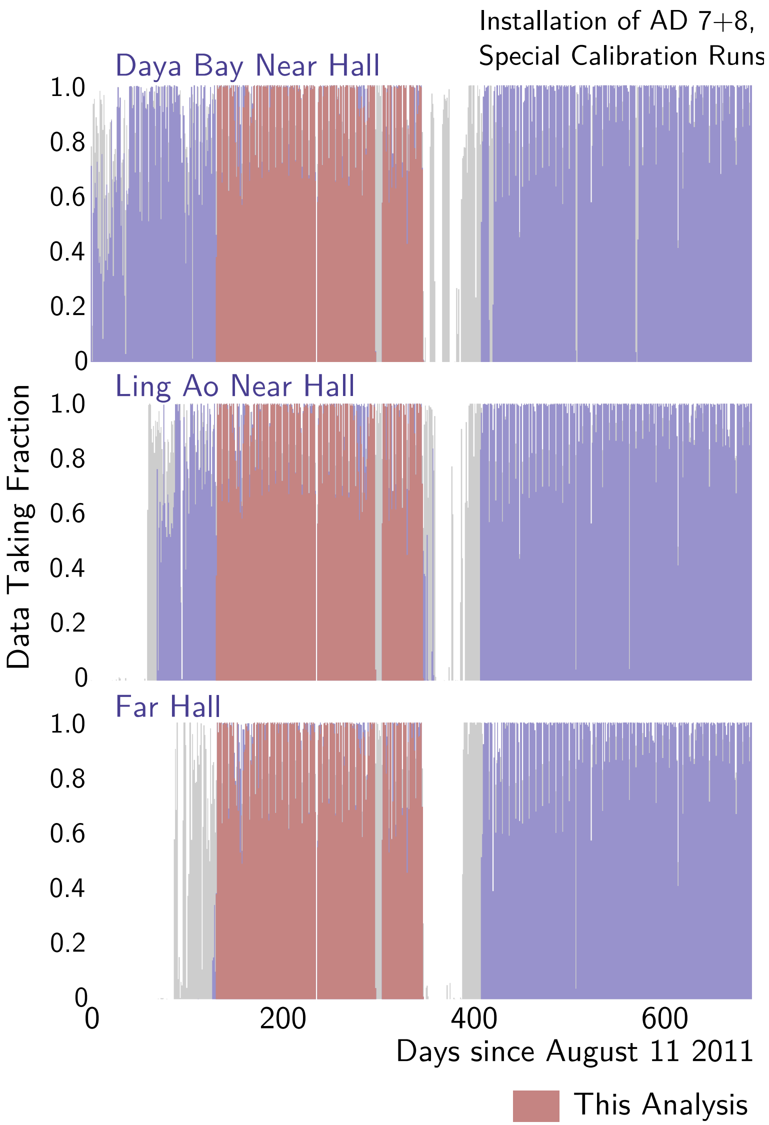
Improved oscillation analysis

[1210.6327]

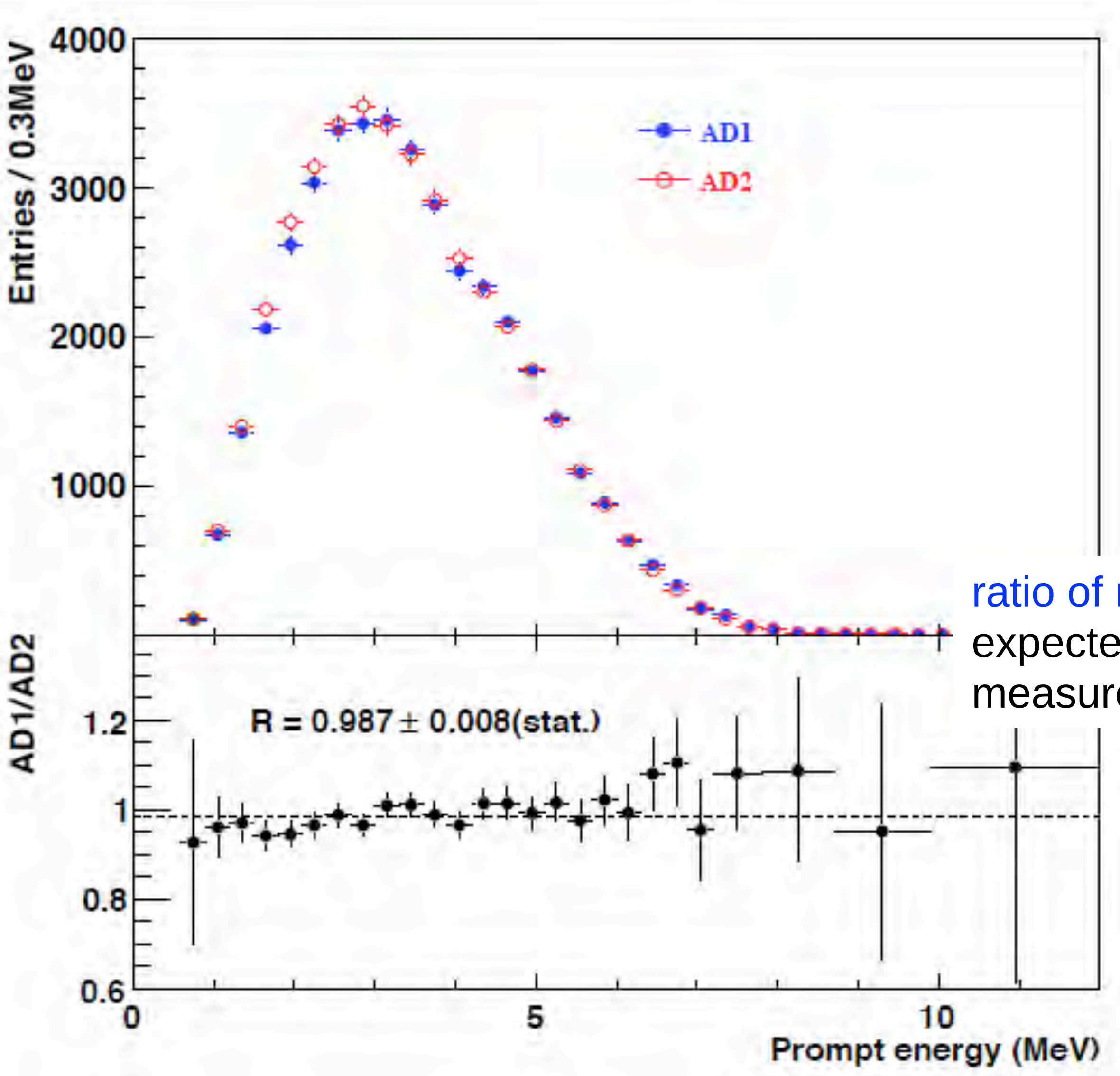
- 139 days of data, 6 ADs near+far
- CP C **37** (2013), 011001

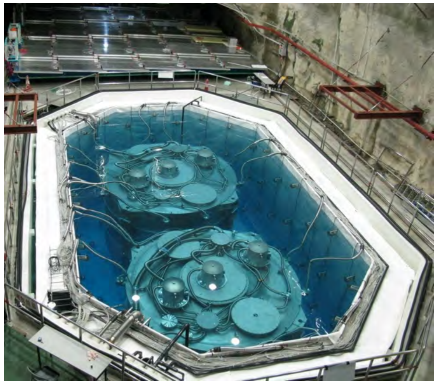
Spectral Analysis

- 217 days complete 6 AD period
- 55% more statistics than CPC result



Side-by-Side Comparison in Near Hall





Feb 2012

ratio of neutrino events in AD1 and AD2

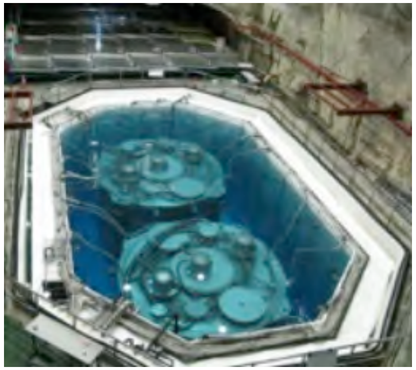
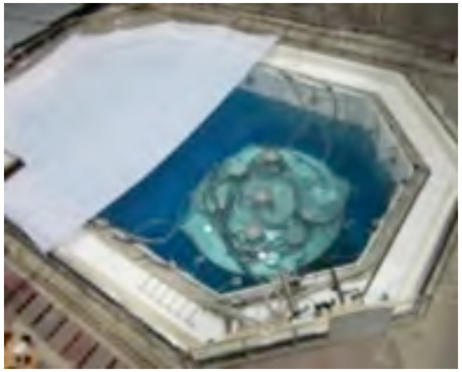
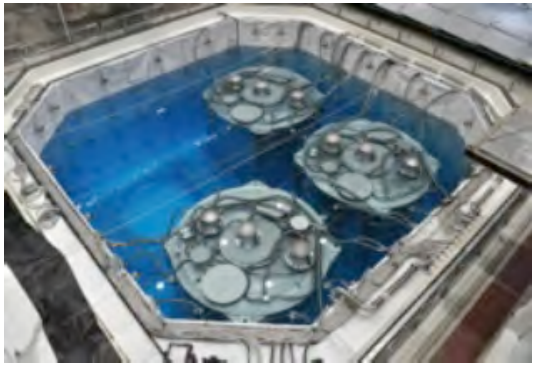
expected: 0.981

measured: 0.987± 0.008 (stat) ± 0.003

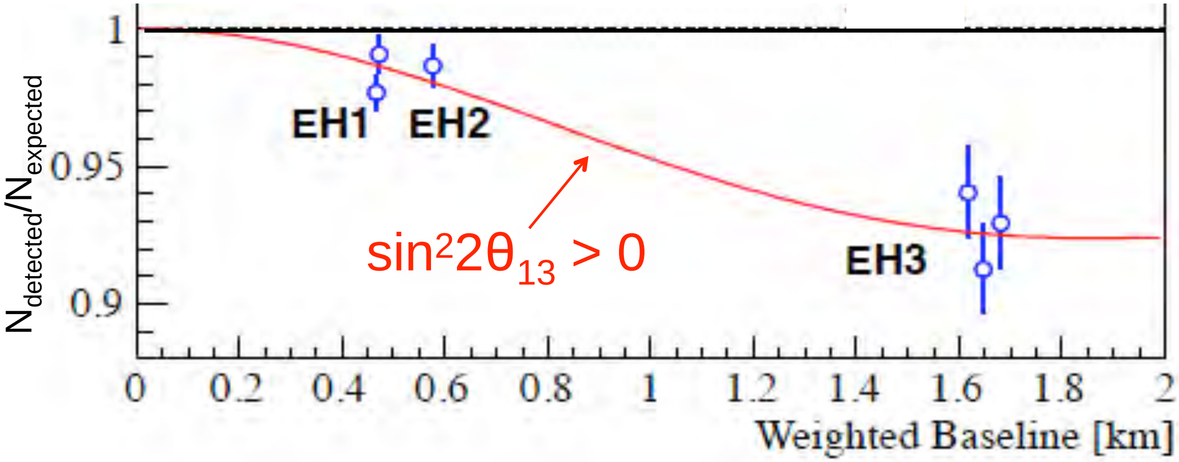
ratio is not 1 because of baseline difference

Daya Bay Collab. arXiv:1202:6181 (2012)

Daya Bay Initial Results

March 2012 Based on 55 days of data with 6 ADs, discovered disappearance of reactor $\bar{\nu}_e$ at short baseline. [PRL **108**, 171803]



June 2012 Obtained the most precise value of θ_{13}:

$\sin^2 2\theta_{13} = 0.089 \pm 0.010 \pm 0.005$ [CPC **37**, 011001]

A Top-10 Breakthrough of 2012

Science **338**, 1527

TALENs, and another genome-editing tool called meganucleases is that they must be reengineered for each new DNA target. These proteins have two parts: the DNA targeting section and the DNA-cutting section. The new technology substitutes RNA—which is simpler to make than a piece of a protein—for the DNA targeting section. It also makes use of a bacterial protein called Cas9, which is part of a natural bacterial defense system called CRISPR, to do the cutting.

Researchers have shown in a test-tube that they can combine these two RNAs into a single one that both matches the DNA target and holds Cas9 in place. Using this system, they were able to cut specific target DNA, demonstrating the potential of Cas9 to work like TALENs. Now, those researchers are trying this approach in organisms other than bacteria, and other genome engineers are quite excited about their prospects, suggesting that it may one day challenge zinc finger nucleases and TALENs as the core genome engineering technology.

CRASH PROJECT OPENS A DOOR IN NEUTRINO PHYSICS

RUNNER-UP

Sometimes it's not the result itself so much as the promise it holds that matters most. This year, physicists measured the last parameter describing how elusive particles called neutrinos morph into one another as they zip along at near–light speed. And the result suggests that in the coming decades neutrino physics will be every bit as rich as physicists had hoped—and may even help explain how the universe evolved to contain so much matter and so little antimatter.

Born in certain nuclear interactions, neutrinos come in three types or flavors that change into one another in so-called neutrino oscillations. The rates and extents to which the flavors mix depend on six parameters: the three differences between the neutrinos' masses, and three "mixing angles." In March, the 250 researchers with the Daya Bay Reactor Neutrino Experiment in China reported that last unknown parameter, the mixing angle known as θ_{13} (pronounced "theta one three"), equals 8.8°, give or take 0.8°.

The result itself is remarkable, as it's not every year that physicists measure a new fundamental parameter. The real excitement, however, stems from the result's broader implications. The measurement proves that all three mixing angles are greater than zero. That fact, in turn, implies that the oscillations of antineutrinos might differ from those of neutrinos, something that would not be possible had θ_{13} equaled zero.

That's a big deal. Such a difference would [...] analogous to the effect that created the matter-antimatter imbalance in the universe.

In fact, researchers in the United States, Japan, and Europe are engaged in experiments in which they use particle accelerators to fire neutrinos hundreds of kilometers through Earth to huge particle detectors. Current efforts seek to pin down, for example, the neutrinos emanating from the reactors at the Daya Bay Nuclear Power Plant and two neighboring plants in Shenzhen. In making a definitive measurement, they beat out teams working at reactors in France and South Korea and accelerator-based experiments in Japan and the United States.

The measurement of θ_{13} wasn't the only result in particle physics this year. Researchers working with the world's largest atom smasher, the Large Hadron Collider (LHC) in Switzerland, discovered the Higgs boson, the

That was fast! Construction of China's Daya Bay Reactor Neutrino Experiment began in 2007. With 2 months' worth of data, it scooped competitors in Japan, France, Korea, and the United States.

Spectral Information

Rate-only Analysis:

Previously reported

$$\frac{N_{far}}{N_{near}} = \frac{N_{protons,far}}{N_{protons,near}} \frac{L^2_{near}}{L^2_{far}} \frac{\epsilon_{far}}{\epsilon_{near}} \frac{\int_{E_{min}}^{E_{max}} dE\, P_{surv}(E, L_{far}; \theta_{13}, \Delta m^2_{ee})\, \sigma(E)\, \Phi(E)}{\int_{E_{min}}^{E_{max}} dE\, P_{surv}(E, L_{near}; \theta_{13}, \Delta m^2_{ee})\, \sigma(E)\, \Phi(E)}$$

Advantages: Fewer systematic uncertainties

Disadvantages: Less sensitive, Unable to constrain Δm^2_{ee}

Rate + Spectrum Analysis:

Latest result

$$\frac{\frac{dN_{far}}{dE}}{\frac{dN_{near}}{dE}} = \frac{N_{protons,far}}{N_{protons,near}} \frac{L^2_{near}}{L^2_{far}} \frac{\epsilon_{far}}{\epsilon_{near}} \frac{P_{surv}(E, L_{far}; \theta_{13}, \Delta m^2_{ee})\, \sigma(E)\, \Phi(E)}{P_{surv}(E, L_{near}; \theta_{13}, \Delta m^2_{ee})\, \sigma(E)\, \Phi(E)}$$

Advantages: Each energy bin is an independent oscillation measurement, Δm^2_{ee}

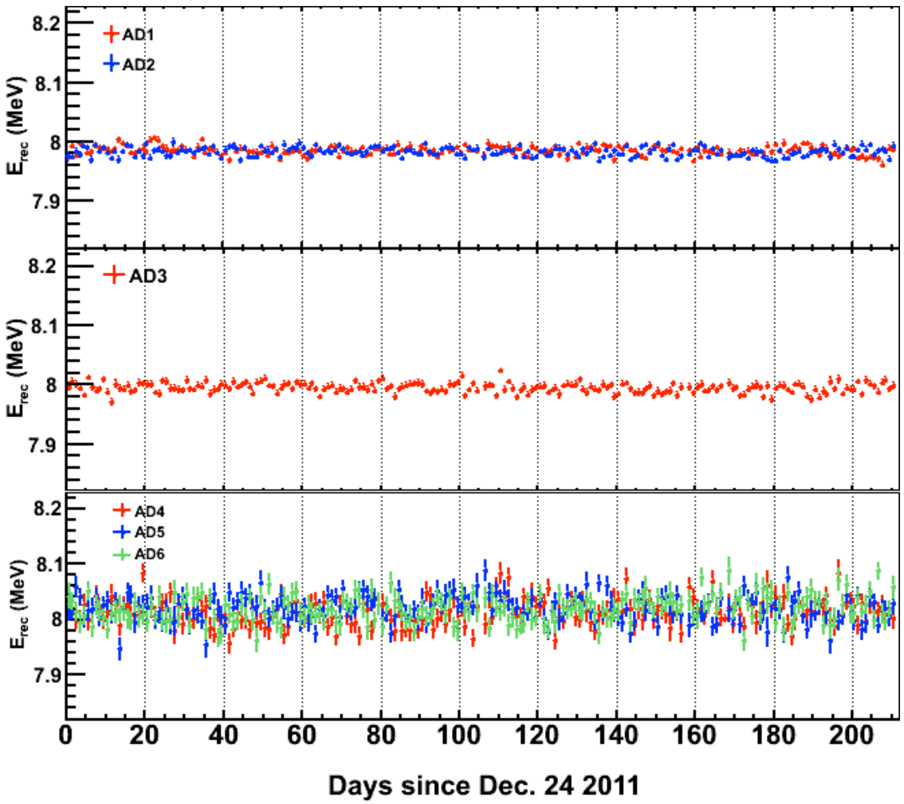
Disadvantages: Requires detailed understanding of detector energy response.

Calibration Performance

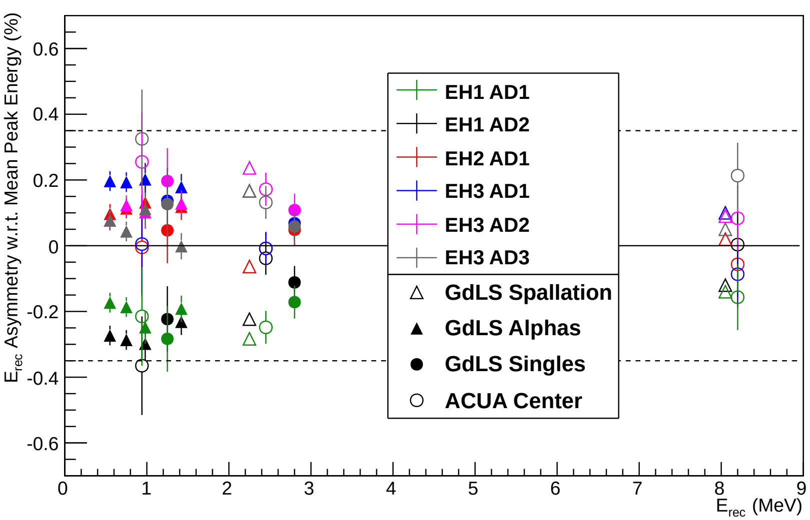
Stable and Consistent Energy Response

After calibration, achieve energy response that is **stable to ~0.1%** in all detectors, with a **total relative uncertainty of 0.35%** between detectors.

Spallation *n*Gd capture peak vs. time (after all calibration)



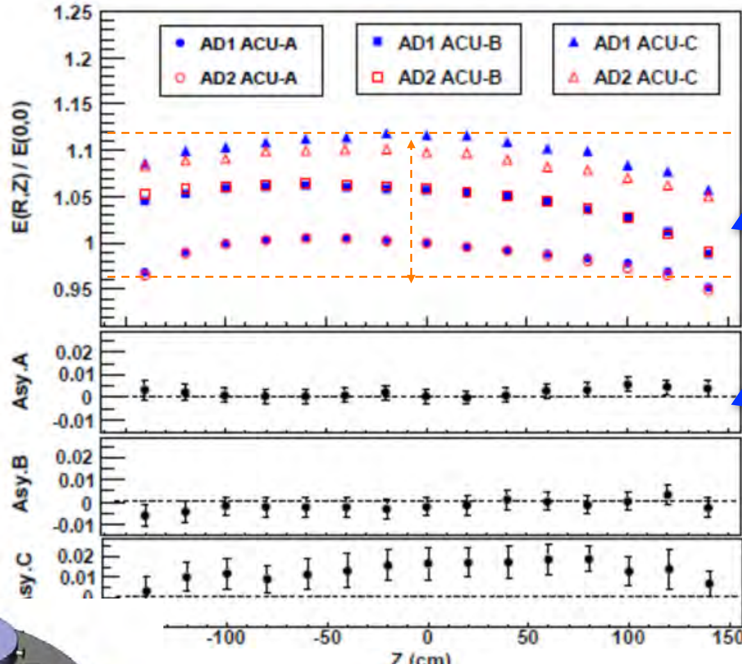
Relative energy peaks in all detectors (after calibration)



Calibration: Detector Uniformity

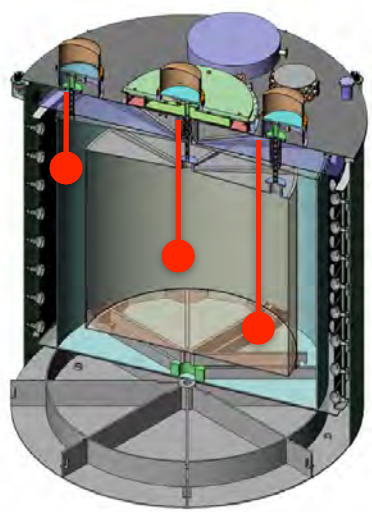
Measure uniformity with sources placed along three axes and spallation nGd events

Example: ^{60}Co



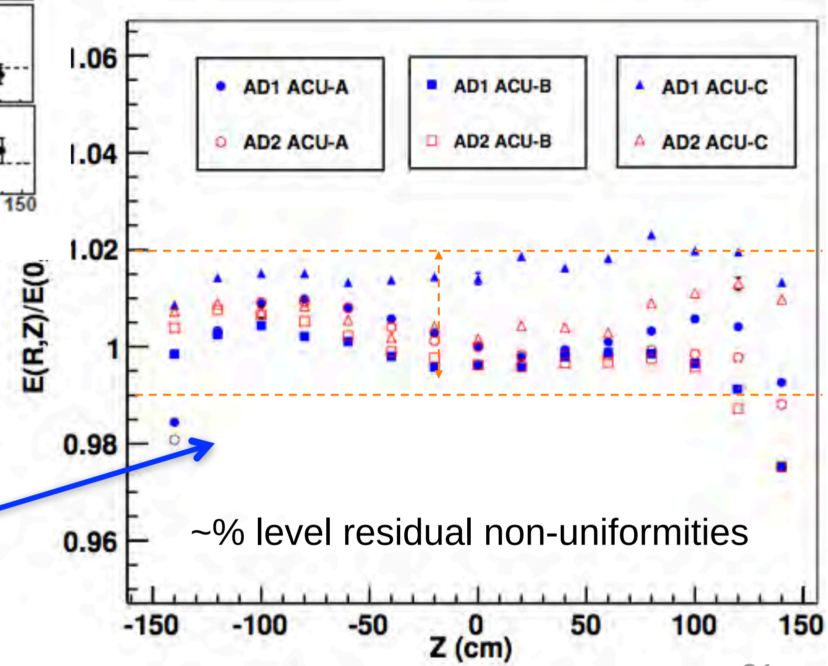
Energy response varies across detector…

…but still consistent between detectors



3 sources along 3 axes

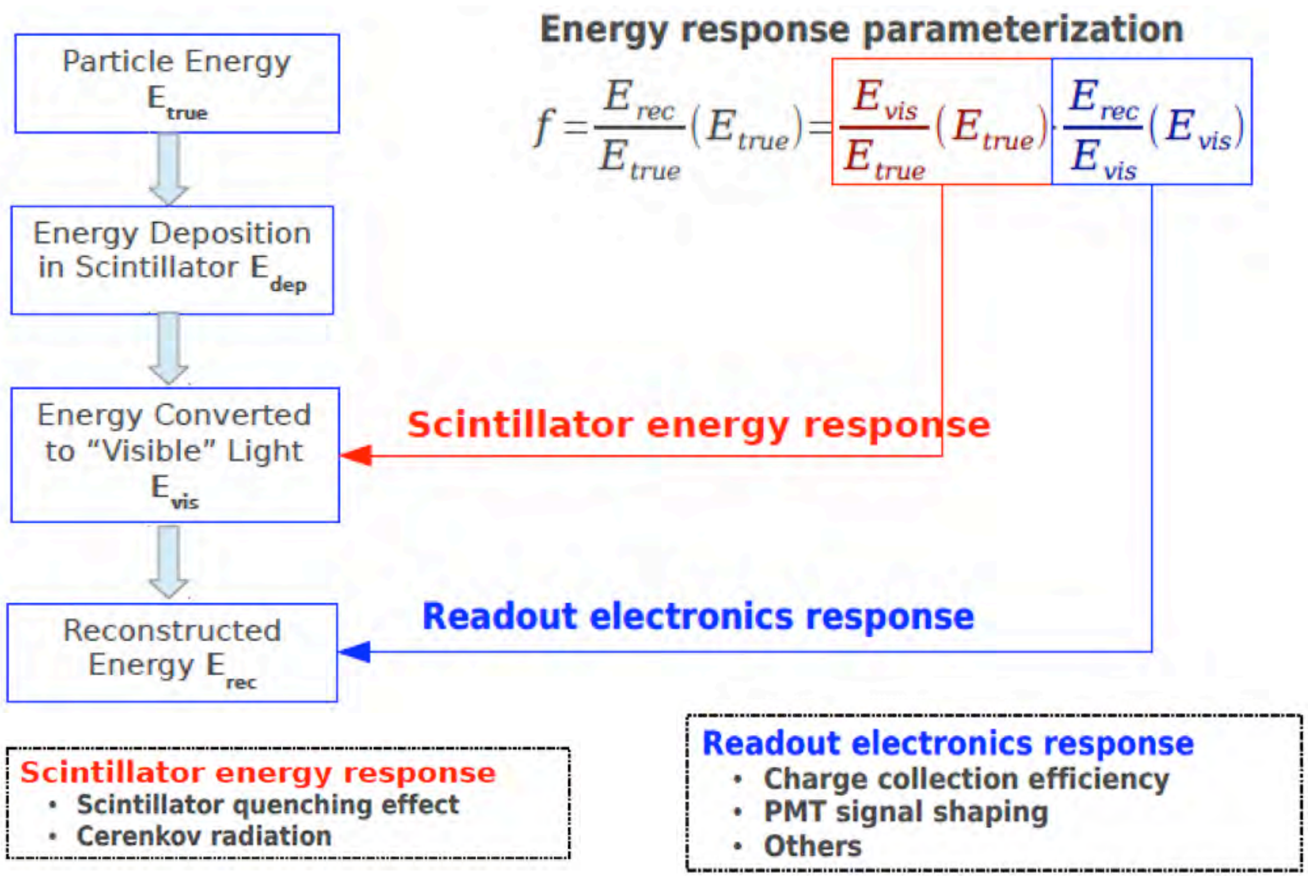
After first-order correction, energy is more uniform.



~% level residual non-uniformities

Energy Response Model

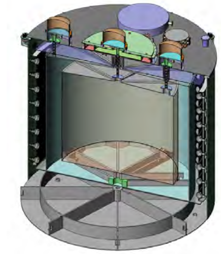
Model maps true energy E_{true} to reconstructed kinetic energy E_{rec}



- Minimal impact on oscillation measurement
- Crucial for measurement of reactor spectra

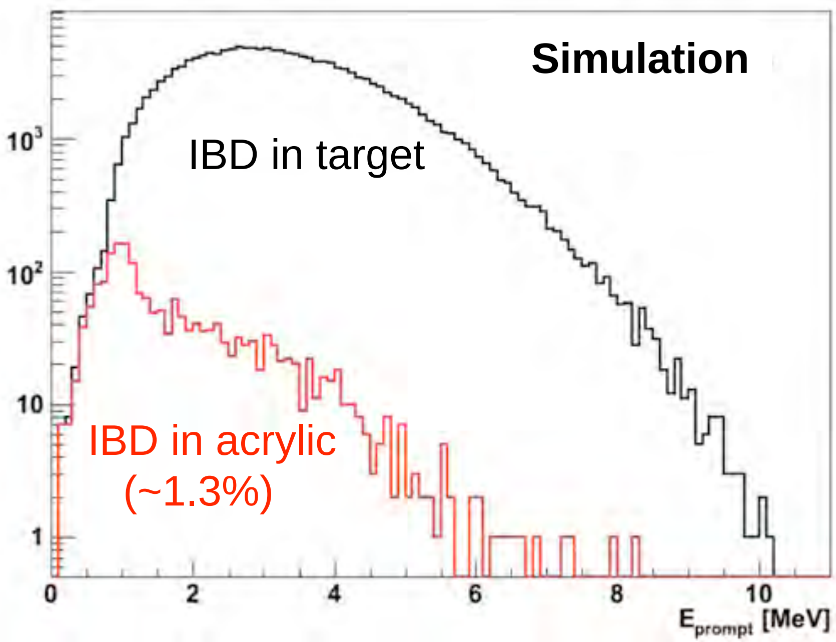
Detector Response: Acrylic Vessels

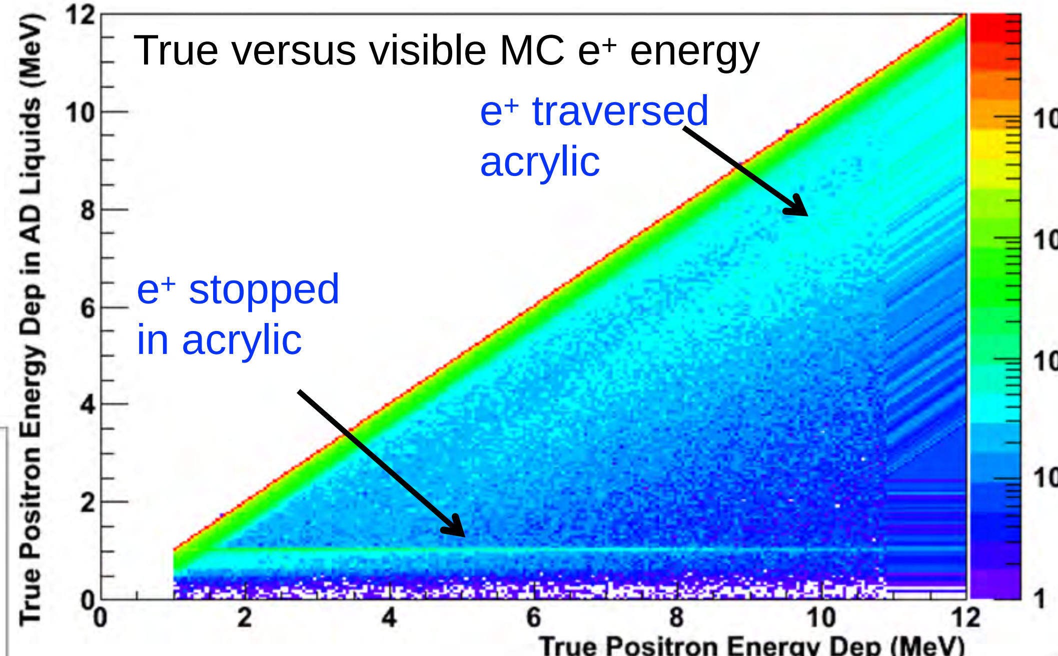
Energy loss in acrylic causes small distortion of energy spectrum



If antineutrino interacts in or near acrylic vessel, a portion of the kinetic energy of inverse beta positrons will not be detected

Annihilation gammas with longer range can also deposit energy in the vessels





Generated 2D distortion matrix from MC to correct predicted positron energy spectrum

Uncertainties from varying acrylic vessel thicknesses and MC statistics incorporated into analysis.

Scintillator Response Model

Electron response

2 parameterizations to model quenching effects and Cherenkov radiation:

1) 3-parameter purely empirical model:

$$\frac{E_{\mathrm{vis}}}{E_{\mathrm{true}}} = \frac{1 + p_3 \cdot E_{true}}{1 + p_1 \cdot e^{-p_2 \cdot E_{\mathrm{true}}}}$$

2) Semi-emp. model based on Birks' law:

$$\frac{E_{\mathrm{vis}}}{E_{\mathrm{true}}} = f_q(E_{\mathrm{true}}; k_B) + k_C \cdot f_c(E_{\mathrm{true}})$$

k_B: Birks' constant
k_C: Cherenkov contribution

Gammas + positrons

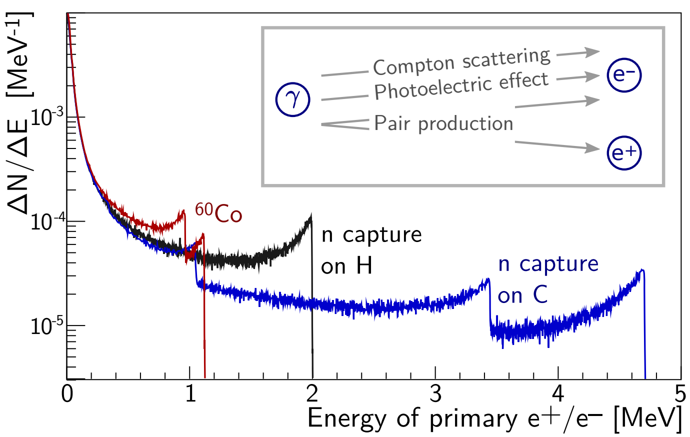
- Gammas connected to electron model through MC:

$$E_{\mathrm{vis}}^{\gamma} = \int E_{\mathrm{vis}}^{e^-}\left(E_{\mathrm{true}}^{e^-}\right) \cdot \frac{dN}{dE}\left(E_{\mathrm{true}}^{e^-}\right) dE_{\mathrm{true}}^{e^-}$$

- Positrons connected to electron model through MC:

$$E_{\mathrm{vis}}^{e^+} = E_{\mathrm{vis}}^{e^-} + 2 \cdot E_{\mathrm{vis}}^{\gamma}(0.511\,\mathrm{MeV})$$

Simulation of individual e-, e+ energies due to gamma interaction in scintillator.

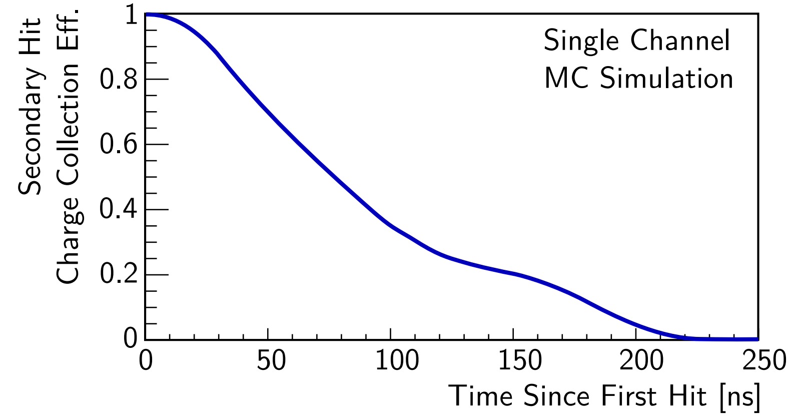


Electronics Non-Linearity Model

PMT readout electronics introduces additional biases

Electronics does not fully capture late secondary hits

- Slow scintillation component missed at high energies
- Charge collection efficiency decreases with visible light



PMT readout electronics introduces additional biases

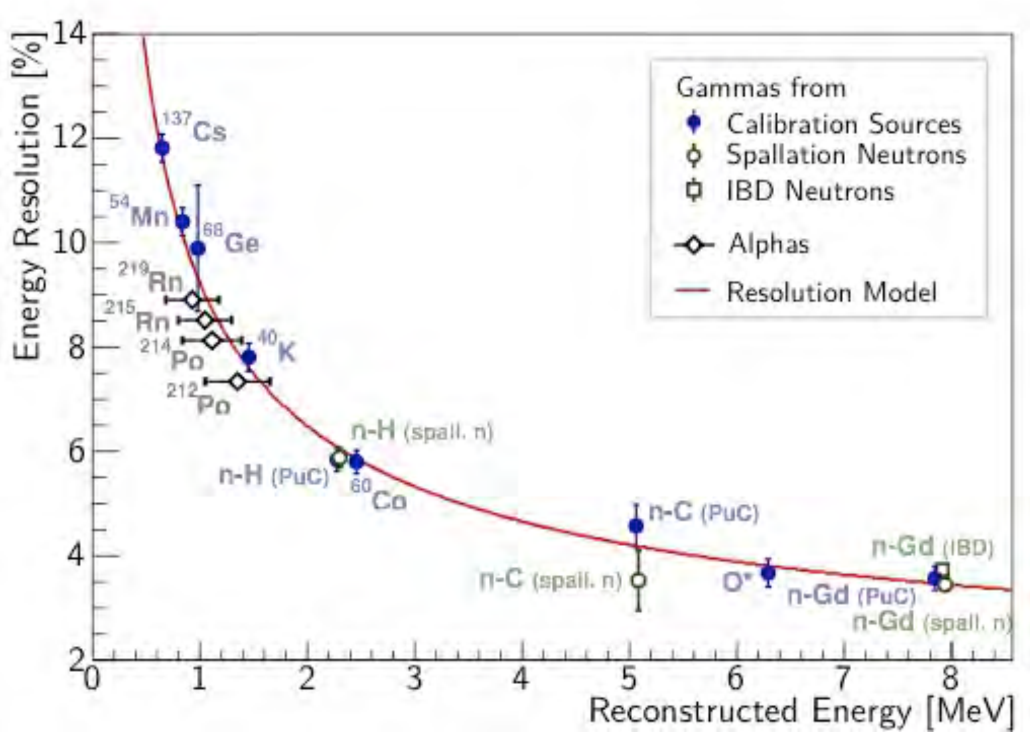
- Effective model as a function of total visible energy
- 2 empirical parameterizations: exponential and quadratic
- Total effective non-linearity f from both scintillation and electronics effects:

$$f = \frac{E_{\text{rec}}}{E_{\text{true}}} = \frac{E_{\text{rec}}}{E_{\text{vis}}} \cdot \frac{E_{\text{vis}}}{E_{\text{true}}}$$

1 Electronics non-linearity → $\frac{E_{\text{rec}}}{E_{\text{vis}}}$

2 Scintillator non-linearity → $\frac{E_{\text{vis}}}{E_{\text{true}}}$

Energy Resolution Model



Functional form:

$$\frac{\sigma_E}{E} = \sqrt{a^2 + \frac{b^2}{E} + \frac{c^2}{E^2}}$$

Contributions from:

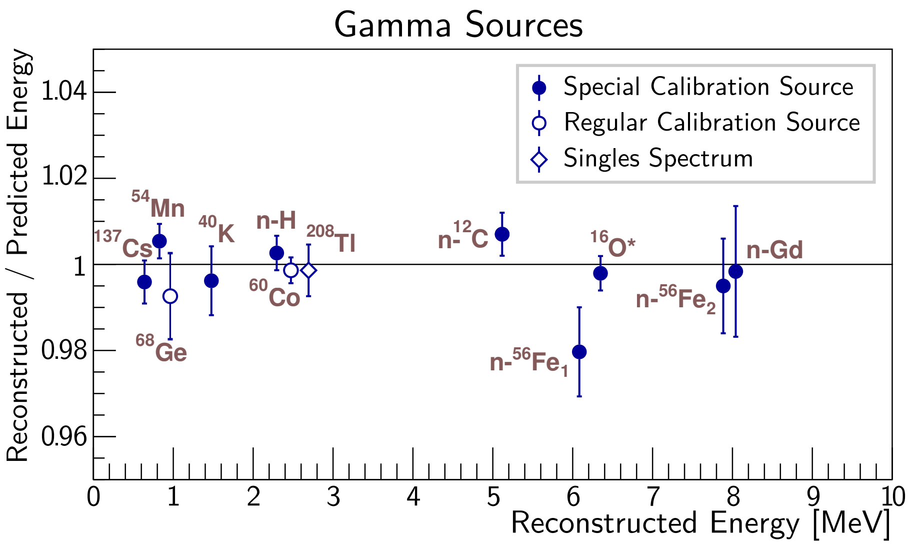
- a : Spacial/temp. resolution (∝E)
- b : Photon statistics (∝√E)
- c : Dark noise (const:)

Calibrated primarily using monoenergetic gamma sources

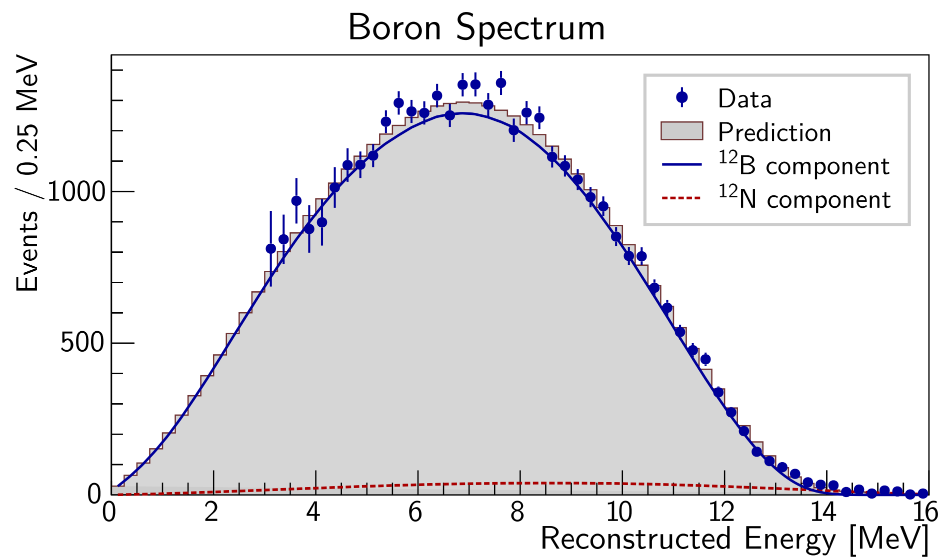
- Radioactive calibration sources placed at the detector center
- Additional data from IBD and spallation neutrons, uniformly distributed in LS
- Alpha source data used to cross-check result
  - Larger uncertainties due to different response from electronics

Constraining the Non-Linearity Parameters

Gamma Ray Energy Peaks



^{12}B Beta-Decay Spectrum



Full detector calibration data

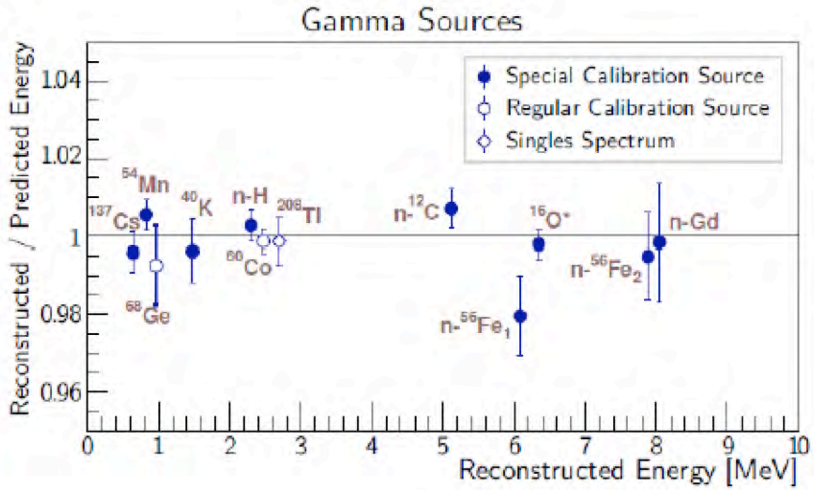
1. Monoenergetic gamma lines from various sources
   - Radioactive calibration sources, employed regularly: ^{68}Ge, ^{60}Co, ^{241}Am-^{13}C
     and during special calibration periods: ^{137}Cs, ^{54}Mn, ^{40}K, ^{241}Am-^{9}Be, Pu-^{13}C
   - Singles and correlated spectra in regular physics runs (^{40}K, ^{208}Tl, n capture on H)
2. Continuous spectrum from ^{12}B produced by muon spallation inside the scintillator

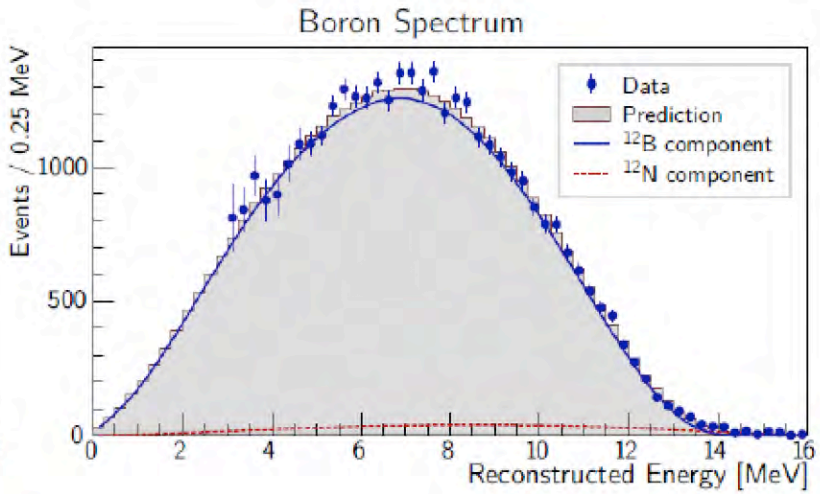
Standalone measurements

- Scintillator quenching measurements using neutron beams and Compton e^-
- Calibration of readout electronics with flash ADC

Energy Response Model

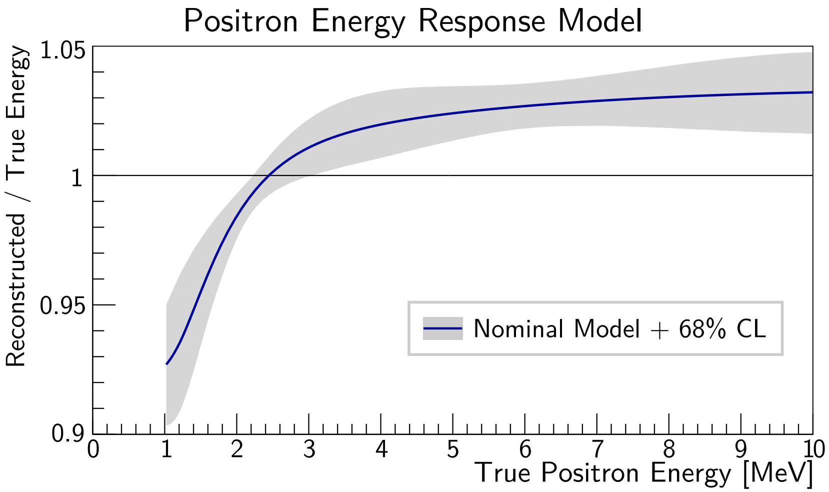
Constraints





Use calibration gamma sources and continuous ^{12}B spectrum to constrain energy model parameters

Positron Energy Response



multiple models are constructed with different data and parameter constraints

conservatively combine 5 minimal correlated energy models

Uncertainty Summary

Detector			
	Efficiency	Correlated	Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	90.9%	0.6%	0.12%
Prompt energy cut	99.88%	0.10%	0.01%
Multiplicity cut		0.02%	<0.01%
Capture time cut	98.6%	0.12%	0.01%
Gd capture ratio	83.8%	0.8%	<0.1%
Spill-in	105.0%	1.5%	0.02%
Livetime	100.0%	0.002%	<0.01%
Combined	78.8%	1.9%	0.2%

Reactor			
Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
$\overline{\nu}_e$/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%

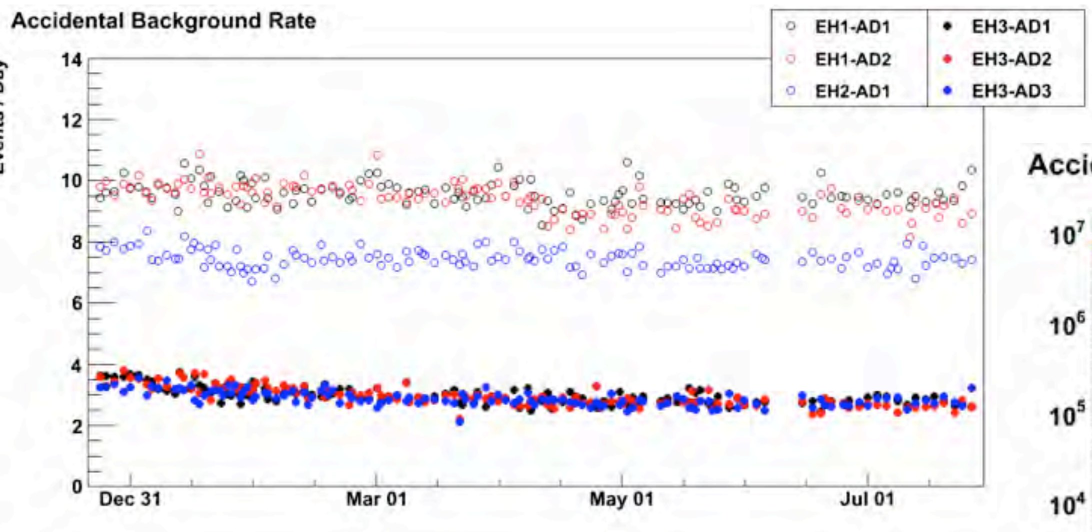
For near/far oscillation, only uncorrelated uncertainties are used.

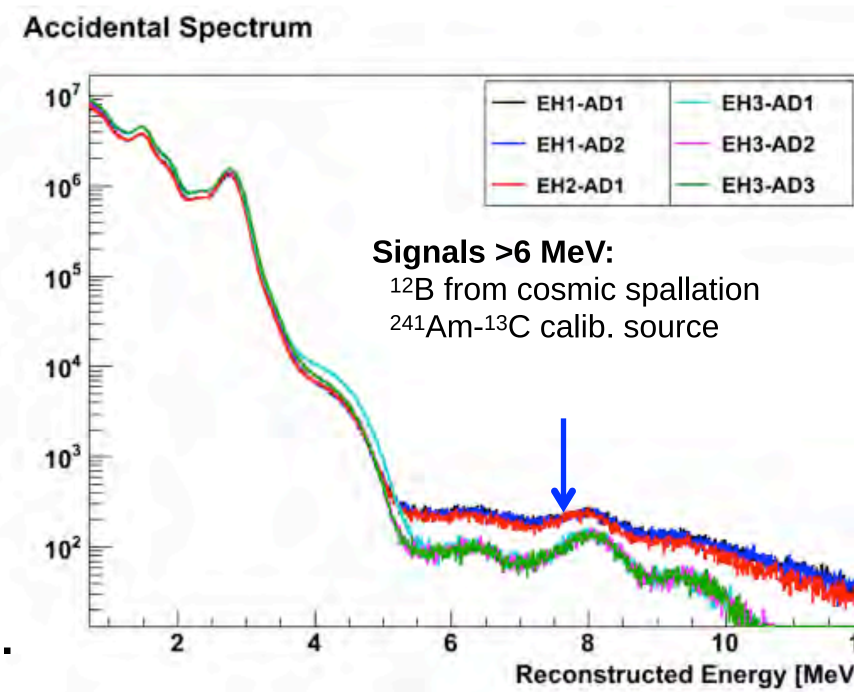
Largest systematics are smaller than far site statistics (~0.5%)

Influence of uncorrelated reactor systematics reduced by far vs. near measurement.

Accidental Background

Two uncorrelated signals can accidentally mimic an antineutrino signal.





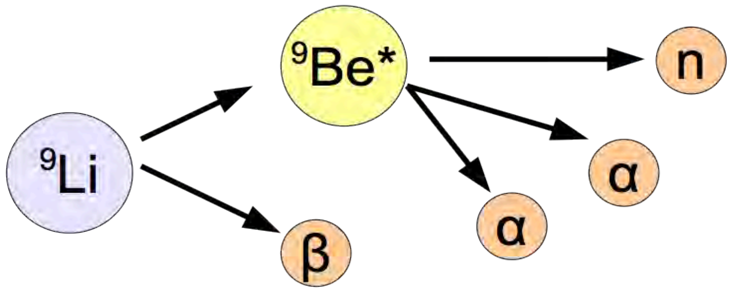
Accidental B/S is 4% (1.5%) of far (near) signal.

Accidental background be accurately modeled using uncorrelated signals in data.

➔ Negligible uncertainty in background rate or spectra.

Background: β-n decay

β-n decay:
- Prompt: β-decay
- Delayed: neutron capture

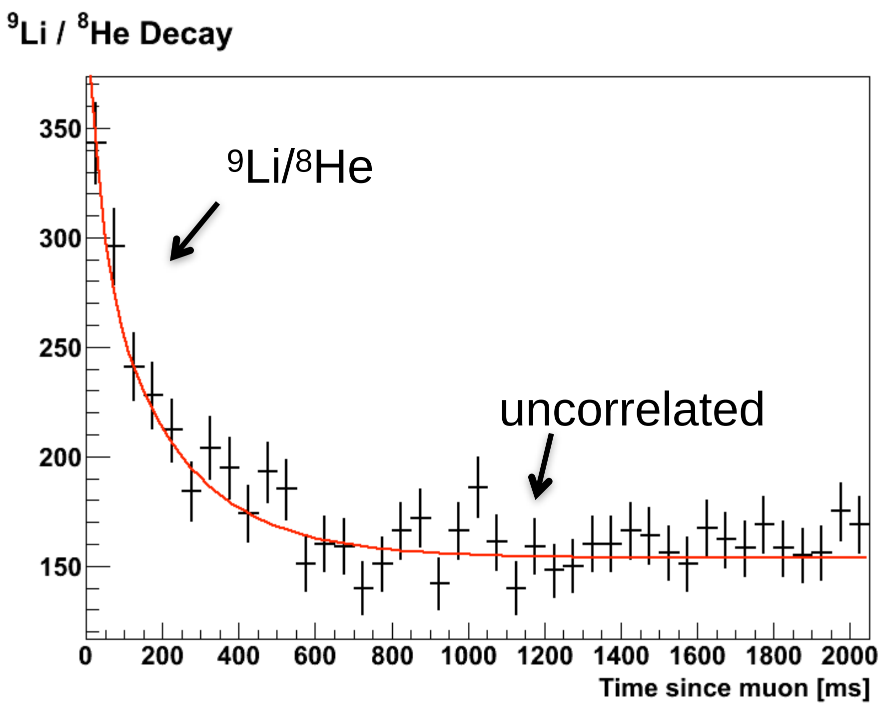


^{9}Li: $\tau_{½}$ = 178 ms, Q = 13. 6 MeV

^{8}He: $\tau_{½}$ = 119 ms, Q = 10.6 MeV

- Generated by cosmic rays
- Long-lived
- Mimic antineutrino signal

This background is directly measured by fitting the distribution of IBD candidates vs. time since last muon.

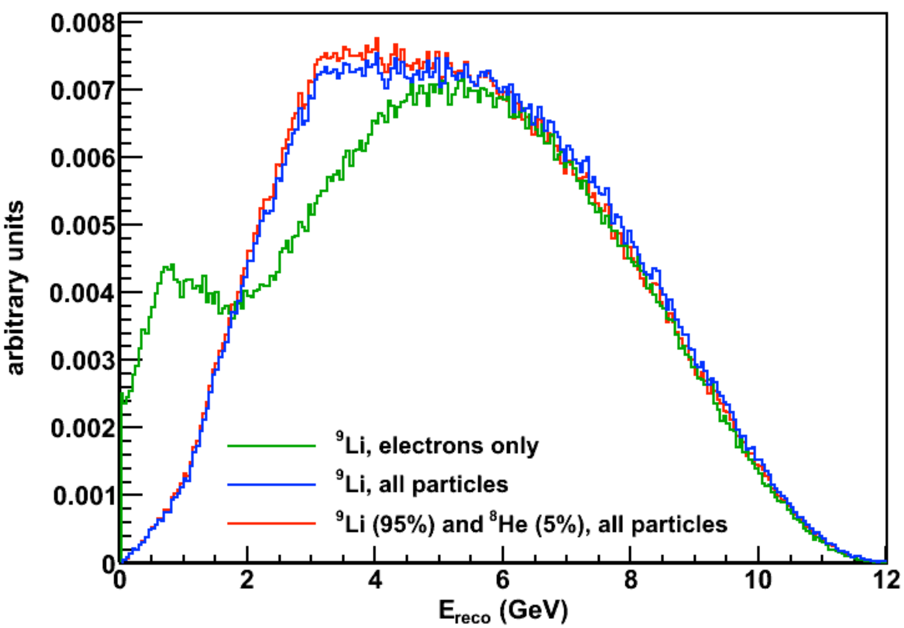


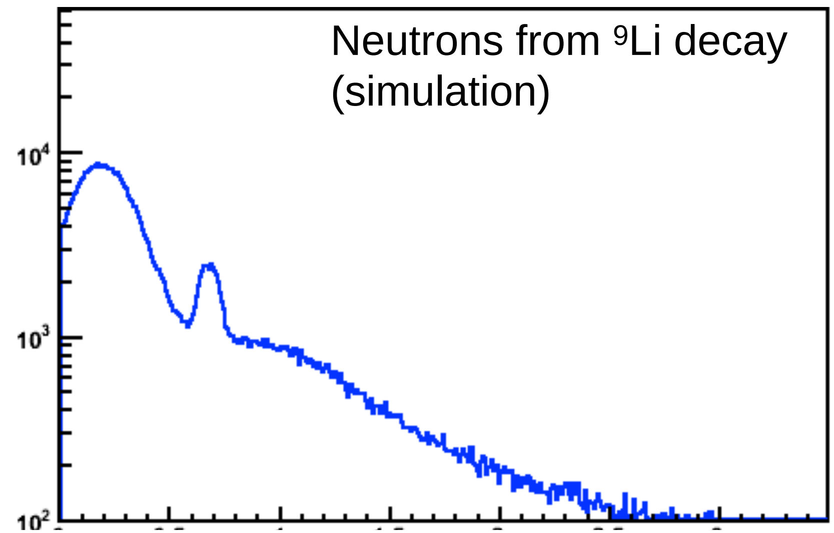
Analysis muon veto cuts control B/S to ~0.3±0.1%.

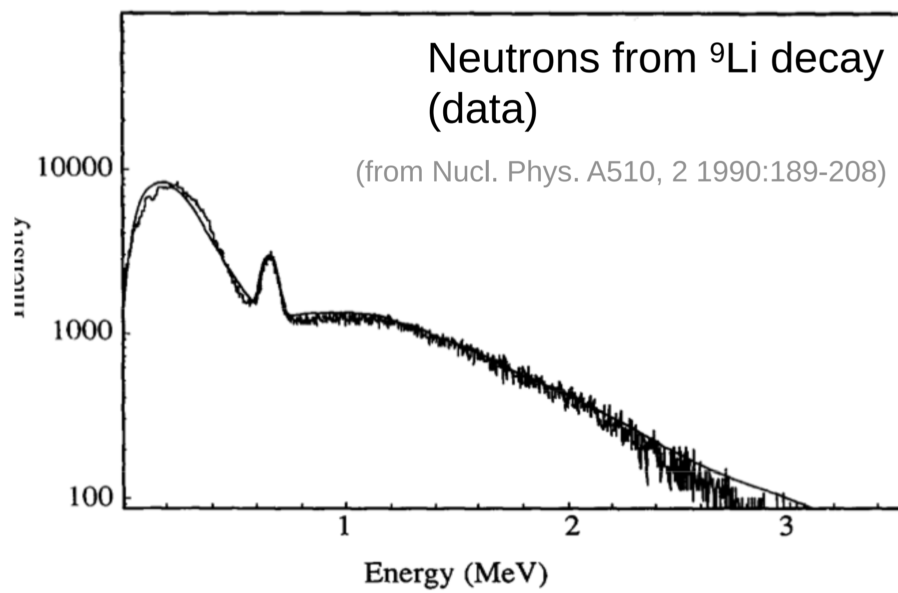
Background: β-n decay (Shape)

Shape for ^{9}Li and ^{8}He is predicted from a simulation benchmarked with external data and which accounts for all daughter particles.

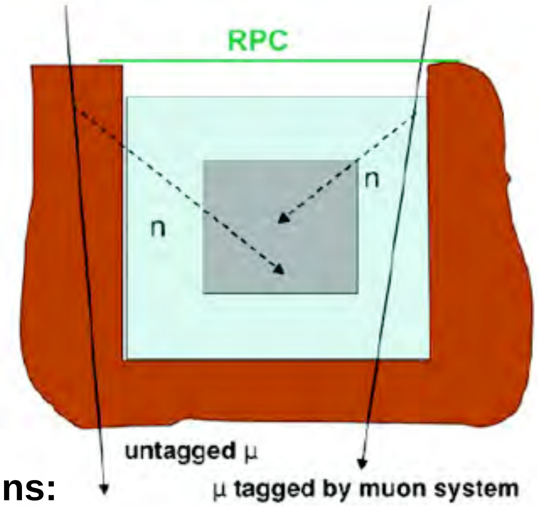
Uncertainty in shape is conservatively accounted for by varying the ^{9}Li/(^{9}Li+^{8}He) ratio, as well as the parameters of the detector response model.







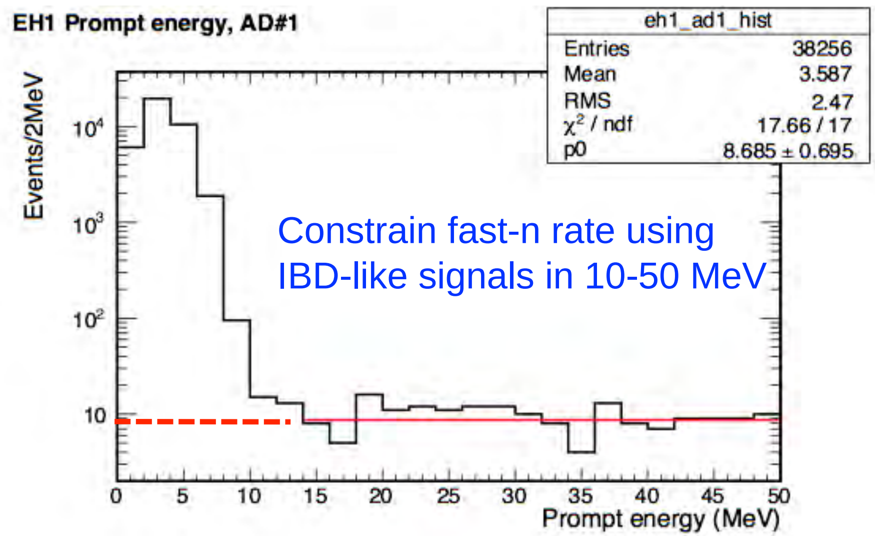
Background: Fast neutrons



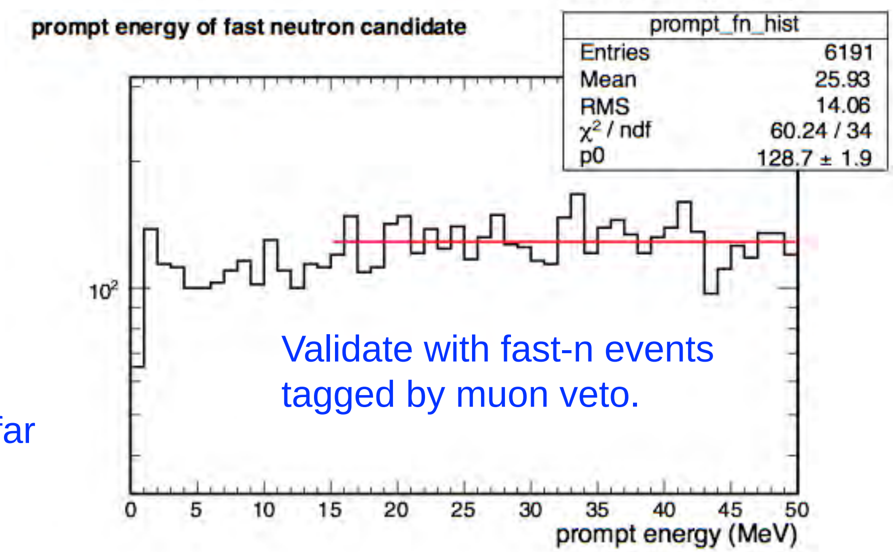
Fast Neutrons:
Energetic neutrons produced by cosmic rays (inside and outside of muon veto system)

Mimics antineutrino (IBD) signal:
- Prompt: Neutron collides/stops in target
- Delayed: Neutron captures on Gd

Analysis muon veto cuts control B/S to 0.06% (0.1%) of far (near) signal.



Constrain fast-n rate using IBD-like signals in 10-50 MeV



Validate with fast-n events tagged by muon veto.

Signal and Background Summary

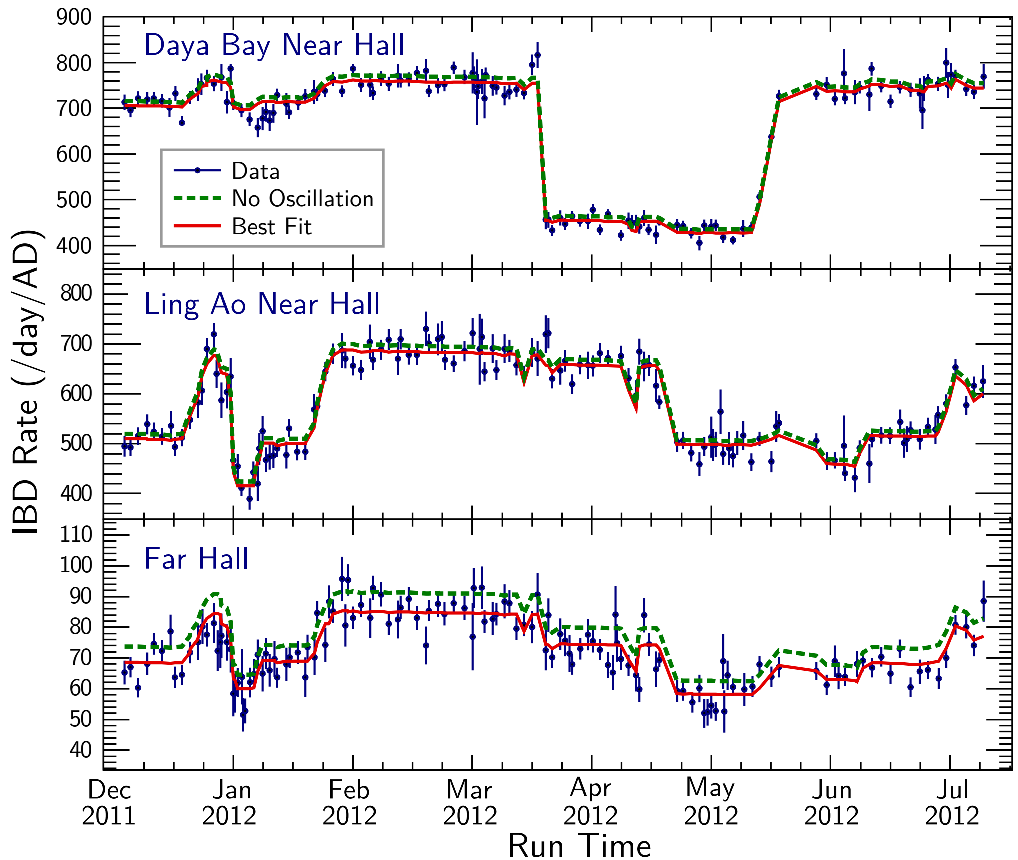
	Near Halls			Far Hall		
	AD 1	AD 2	AD 3	AD 4	AD 5	AD 6
IBD candidates	101290	102519	92912	13964	13894	13731
DAQ live time (days)	191.001		189.645	189.779		
Efficiency $\epsilon_\mu \cdot \epsilon_m$	0.7957	0.7927	0.8282	0.9577	0.9568	0.9566
Accidentals (per day)*	9.54±0.03	9.36±0.03	7.44±0.02	2.96±0.01	2.92±0.01	2.87±0.01
Fast-neutron (per day)*	0.92±0.46		0.62±0.31	0.04±0.02		
^{9}Li/^{8}He (per day)*	2.40±0.86		1.2±0.63	0.22±0.06		
Am-C corr. (per day)*	0.26±0.12					
^{13}C^{16}O backgr. (per day)*	0.08±0.04	0.07±0.04	0.05±0.03	0.04±0.02	0.04±0.02	0.04±0.02
IBD rate (per day)*	653.30±2.31	664.15±2.33	581.97±2.07	73.31±0.66	73.03±0.66	72.20± 0.66

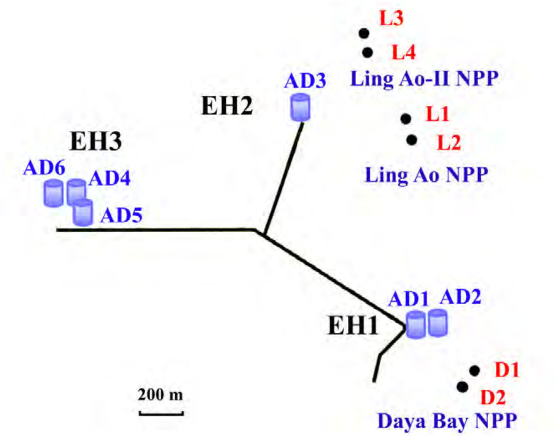
* Background and IBD rates were corrected for the efficiency of the muon veto and multiplicity cuts $\epsilon_\mu \cdot \epsilon_m$

Collected more than 300k antineutrino interactions

- Consistent rates for side-by-side detectors
- Uncertainties still dominated by statistics

Antineutrino Rate vs Time

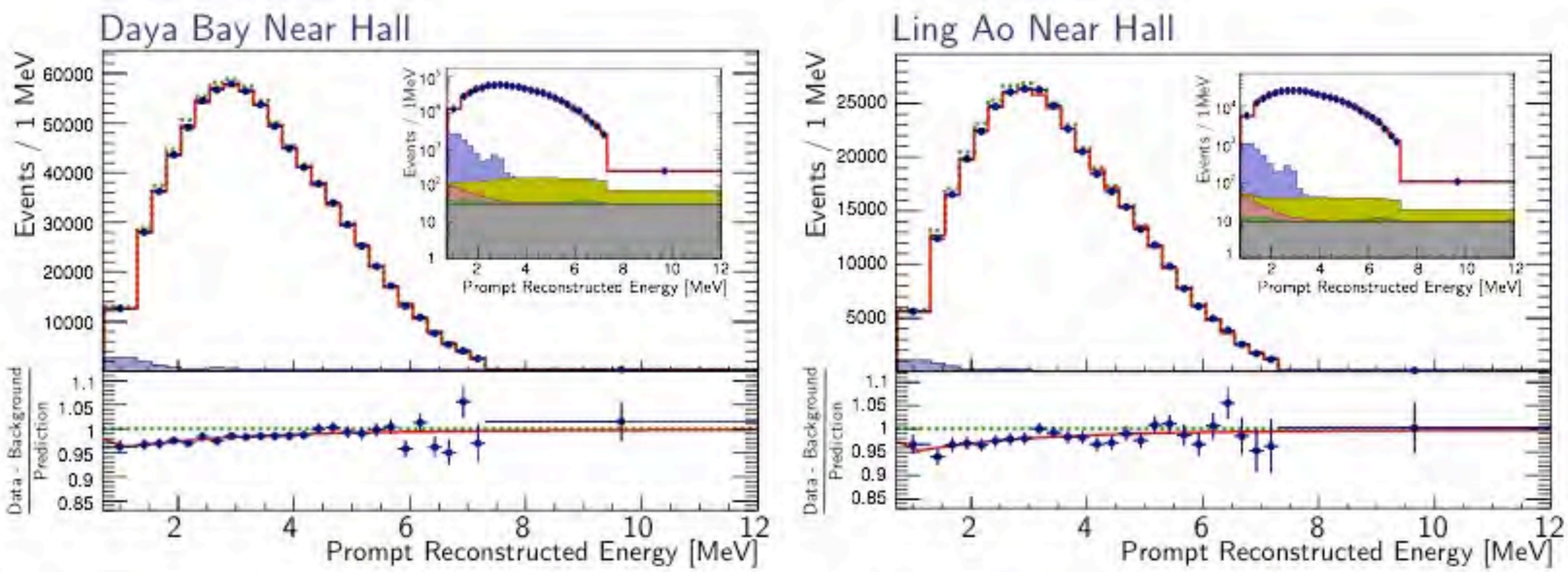


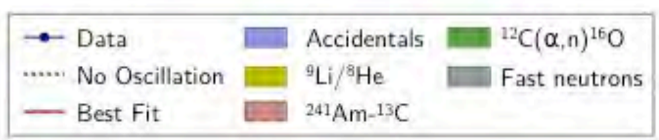


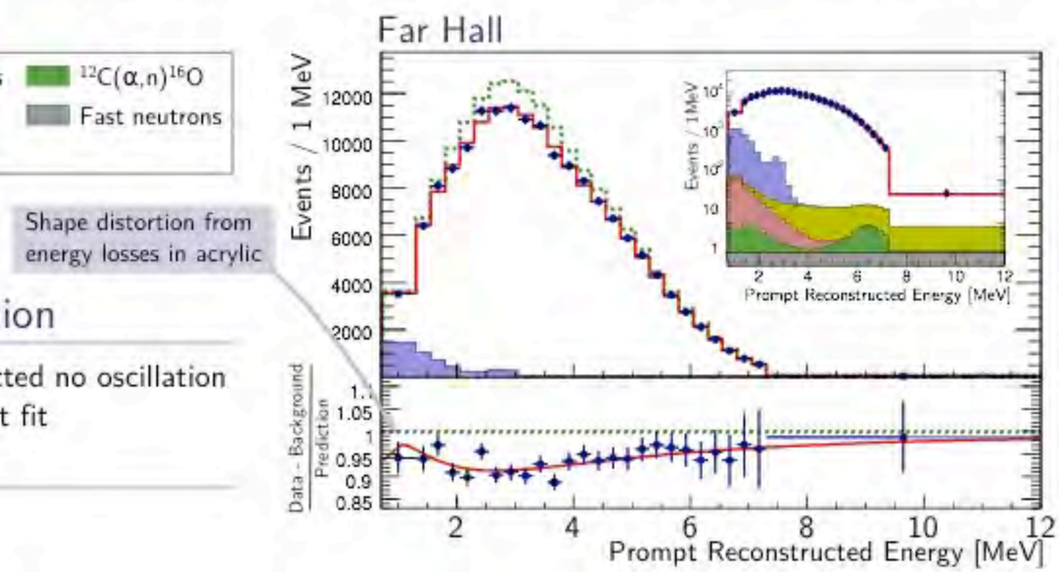
Detected rate strongly correlated with reactor flux expectations

- Predicted rate assumes no oscillation
- Absolute normalization determined by fit to data
- Normalization within a few percent of expectations

Prompt IBD Spectra





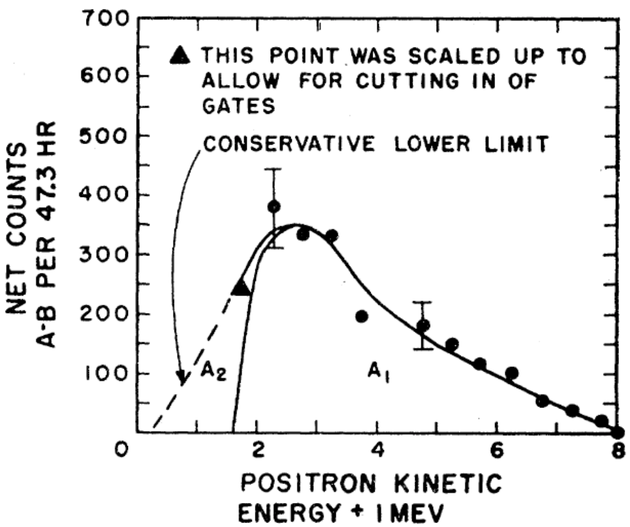


Spectral distortion consistent with oscillation

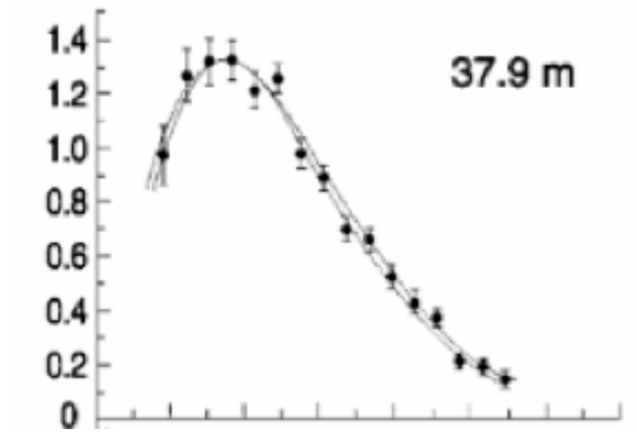
- Both background and predicted no oscillation spectrum determined by best fit
- Errors statistical only

Towards a Precision Reactor Spectrum

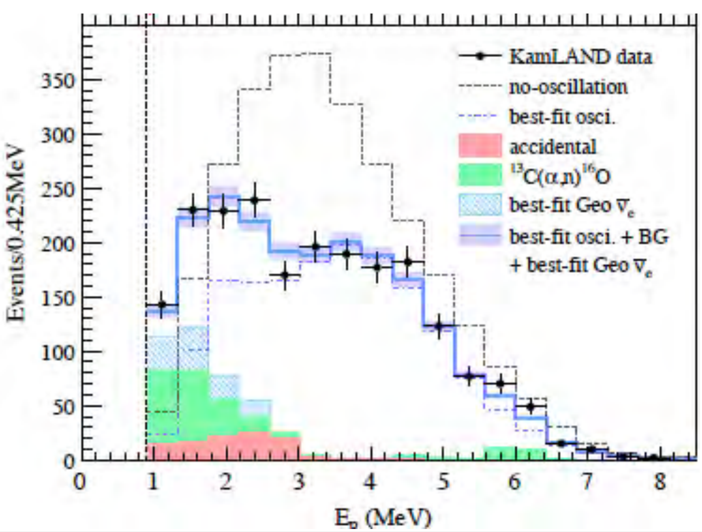
Reines 1959



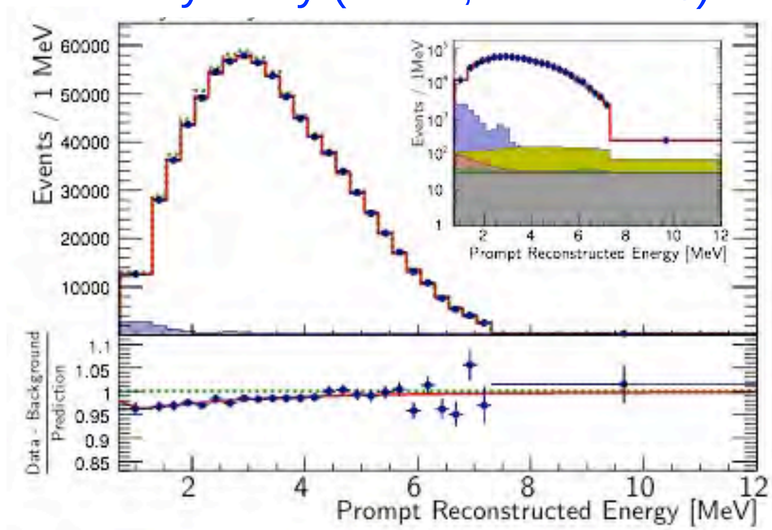
Goesgen 1986



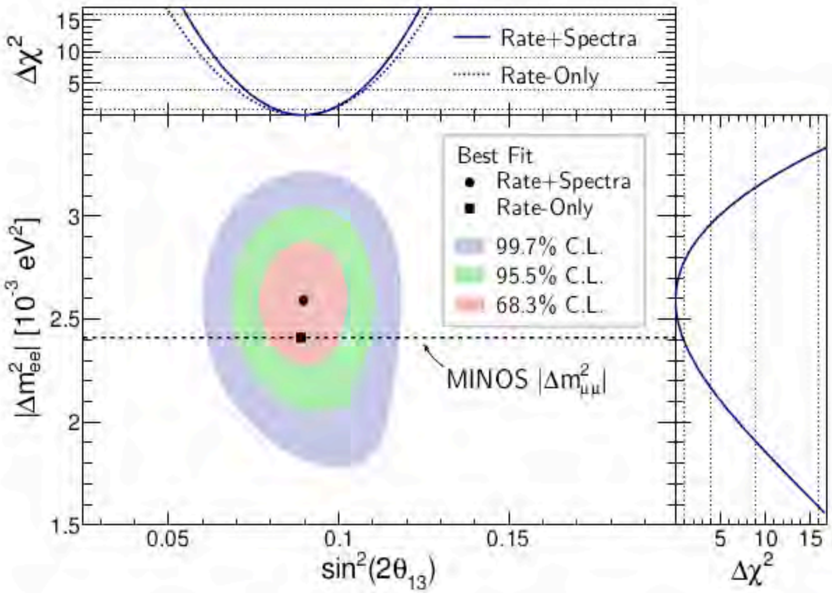
KamLAND 2010



Daya Bay (> 300,000 events)



Rate+Spectra Oscillation Analysis



$$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$$

$$|\Delta m^2_{ee}| = 2.59^{+0.19}_{-0.20} \cdot 10^{-3}\,\mathrm{eV}^2$$

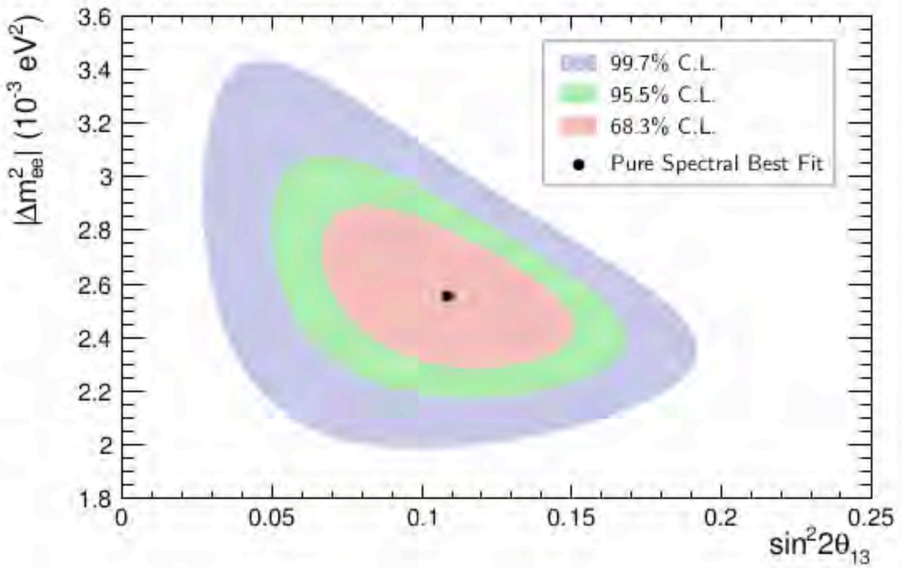
$$\chi^2/N_{\mathrm{DoF}} = 162.7/153$$

Strong confirmation of oscillation-interpretation of observed $\overline{\nu}_e$ deficit

	Normal MH Δm^2_{32} [10^{-3}eV^2]	Inverted MH Δm^2_{32} [10^{-3}eV^2]
From Daya Bay Δm^2_{ee}	$2.54^{+0.19}_{-0.20}$	$-2.64^{+0.19}_{-0.20}$
From MINOS $\Delta m^2_{\mu\mu}$	$2.37^{+0.09}_{-0.09}$	$-2.41^{+0.11}_{-0.09}$

A. Radovic, DPF2013

Pure Spectral Analysis



$$\sin^2 2\theta_{13} = 0.108 \pm 0.028$$

$$|\Delta m^2_{ee}| = 2.55^{+0.21}_{-0.18} \cdot 10^{-3} \mathrm{eV}^2$$

$$\chi^2 / N_{\mathrm{DoF}} = 161.2/148$$

θ_{13} = 0 can be excluded at > 3σ from spectral information alone

- For each AD, total event prediction fixed to observed data:

  1. θ_{13} free-floating: $\chi^2 / N_{\mathrm{DoF}} = 161.2/148$
  2. $\theta_{13} = 0$: $\chi^2 / N_{\mathrm{DoF}} = 178.5/146$

$\Rightarrow \Delta\chi^2 / N_{\mathrm{DoF}} = 17.3/2$, corresponding to $p = 1.75 \cdot 10^{-4}$

A Comment on Δm²

Short-baseline reactor experiments insensitive to neutrino mass hierarchy.

Cannot discriminate two frequencies contributing to oscillation: Δm^2_{31} , Δm^2_{32}

One effective oscillation frequency is measured:

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{ee} \frac{L}{4E}\right) - \sin^2 2\theta_{12} \cos^4 2\theta_{13} \sin^2\left(\Delta m^2_{21} \frac{L}{4E}\right)$$

$$\sin^2(\Delta m^2_{ee} \tfrac{L}{4E}) \equiv \cos^2\theta_{12} \sin^2(\Delta m^2_{31} \tfrac{L}{4E}) + \sin^2\theta_{12} \sin^2(\Delta m^2_{32} \tfrac{L}{4E})$$

Result can be easily related to actual mass splitting, based on true hierarchy:

$$|\Delta m^2_{ee}| \simeq |\Delta m^2_{32}| \pm 5.21 \times 10^{-5}\mathrm{eV}^2$$

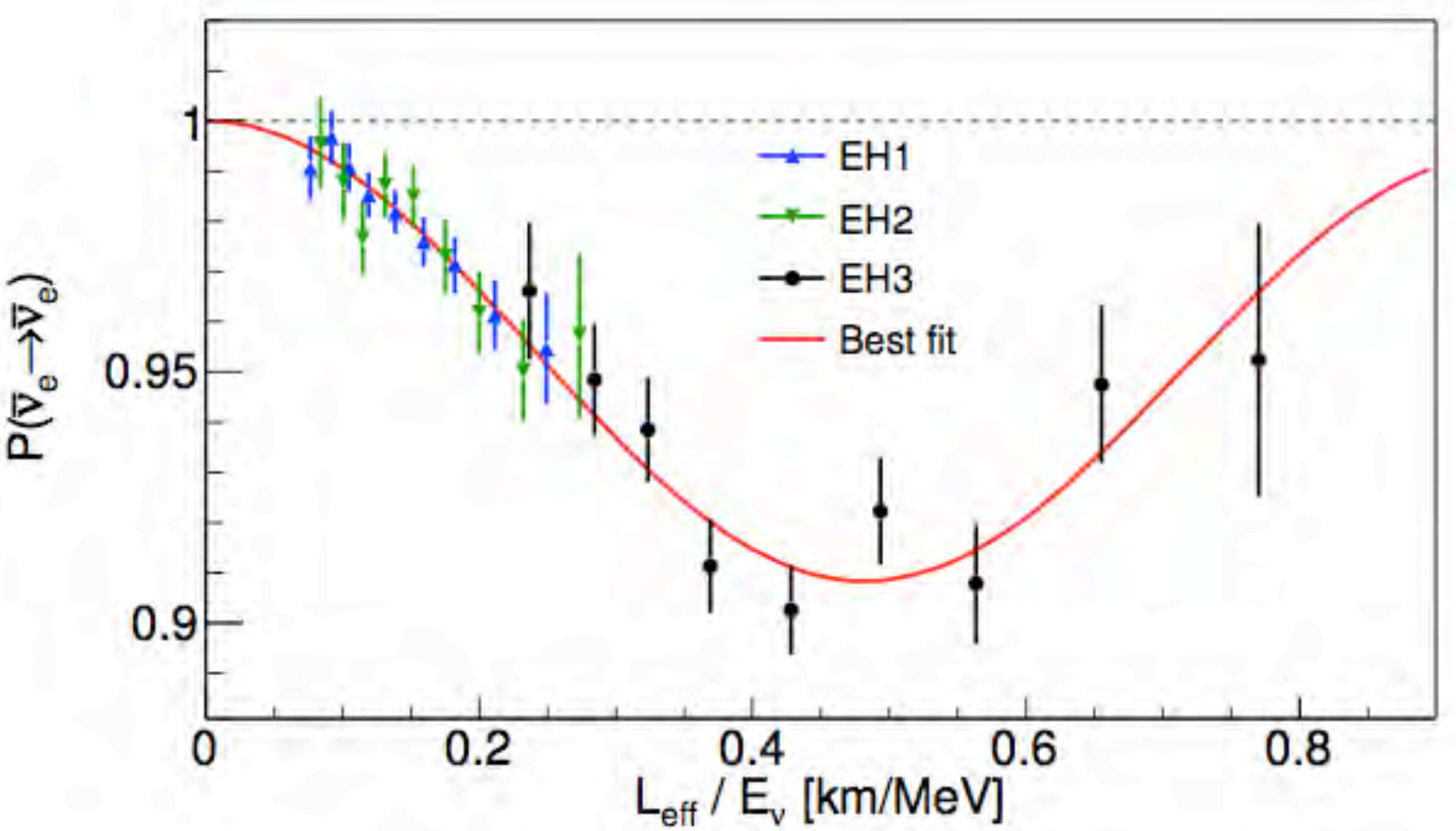
+: Normal Hierarchy

-: Inverted Hierarchy

Hierarchy discrimination requires ~2% precision on both Δm^2_{ee} and $\Delta m^2_{\mu\mu}$

L/E Oscillation

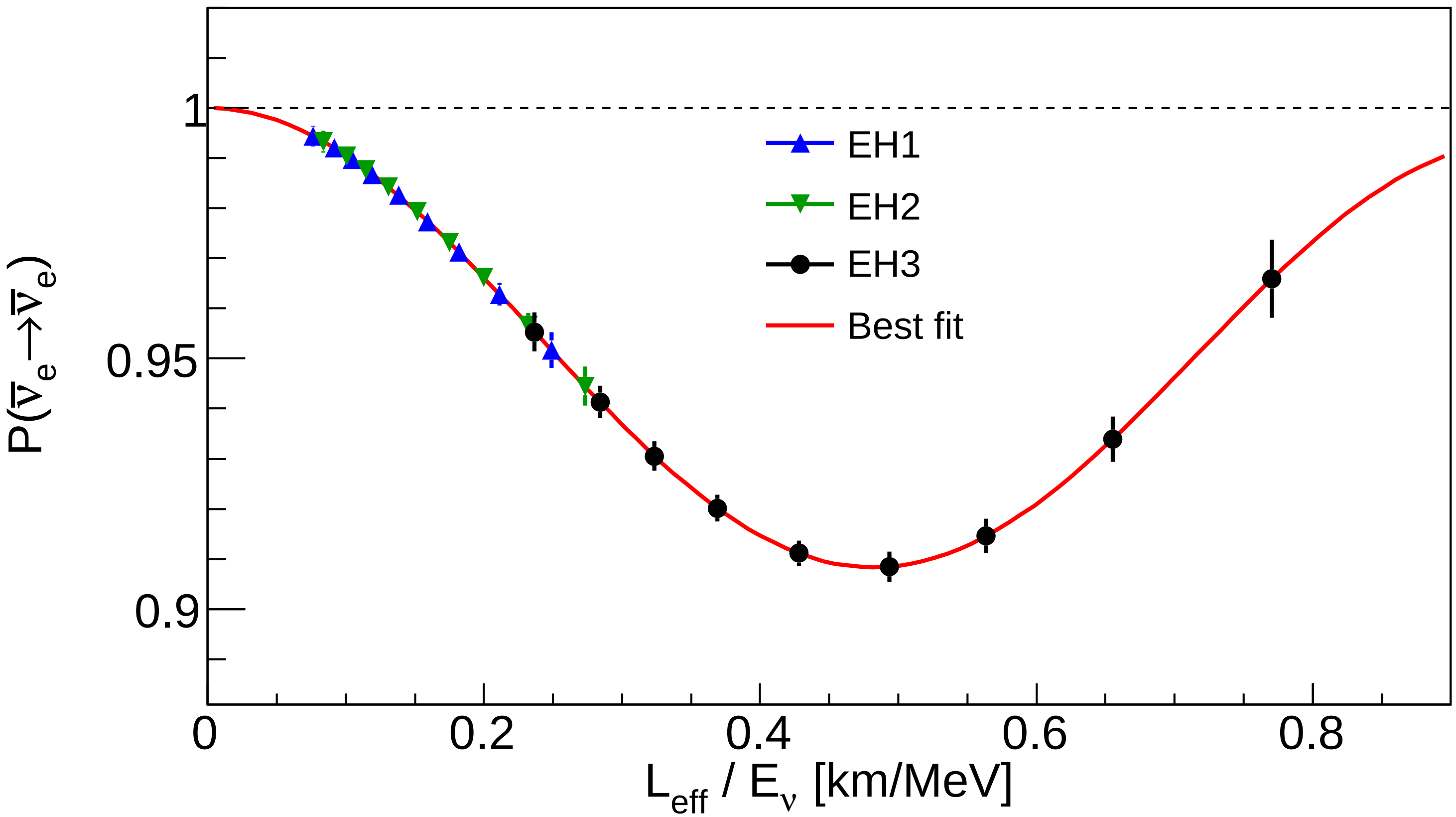
Energy and Baseline Dependence of Oscillation Effect



now

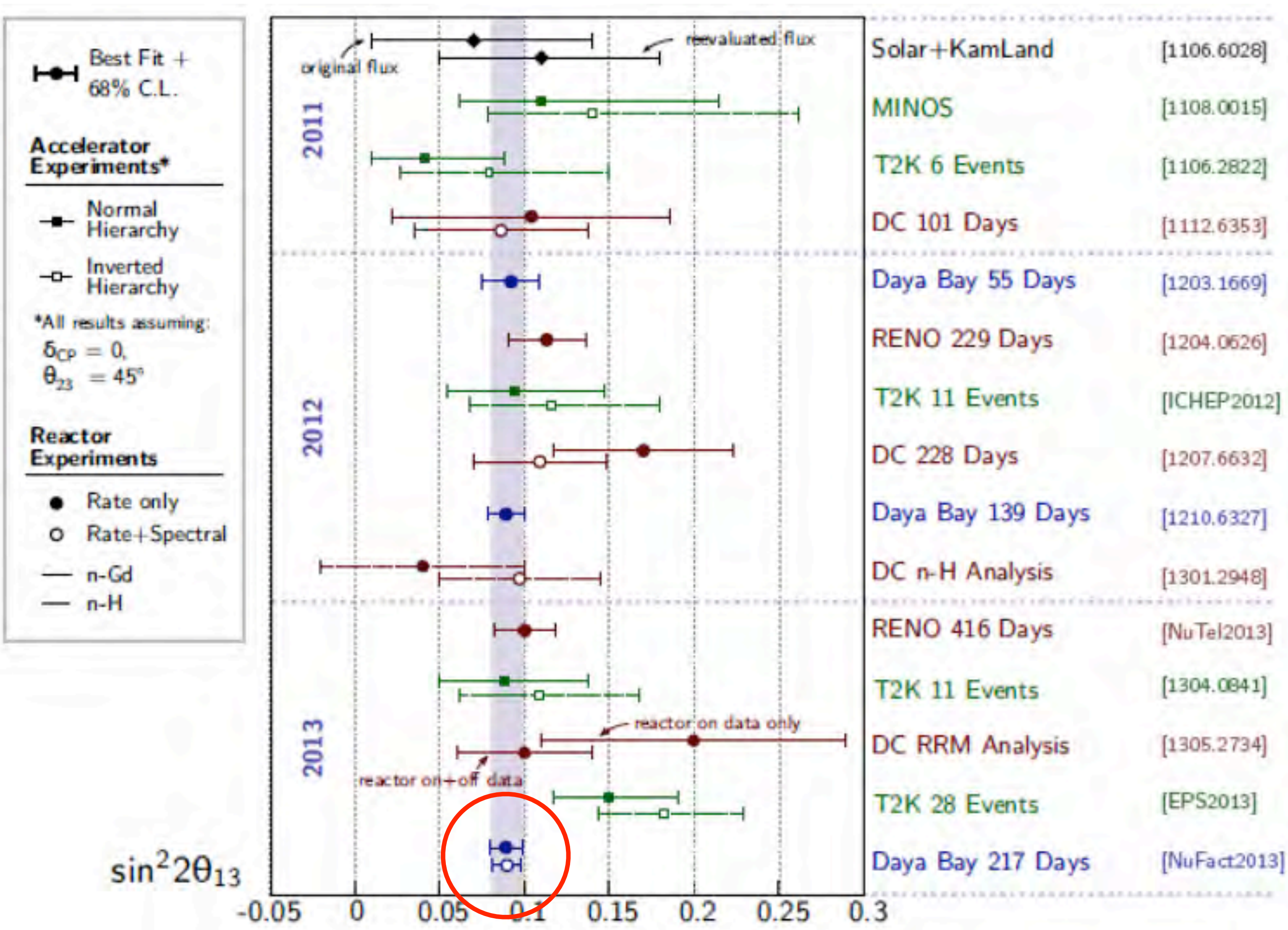
L/E Oscillation

Energy and Baseline Dependence of Oscillation Effect



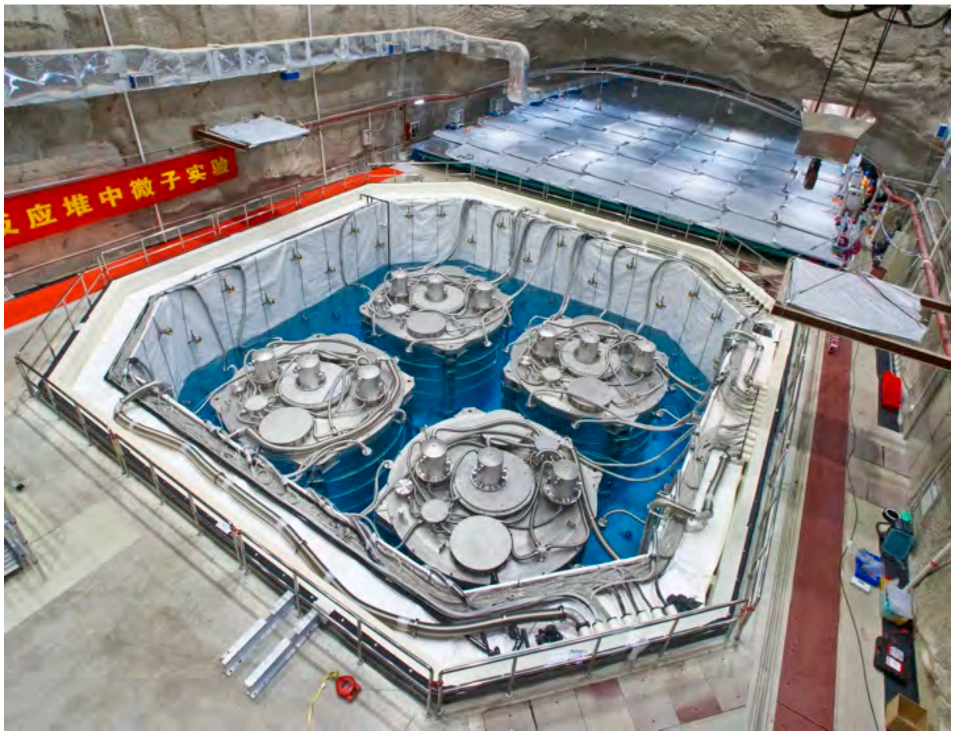
in FY17

Global Comparison of θ_{13} Measurements

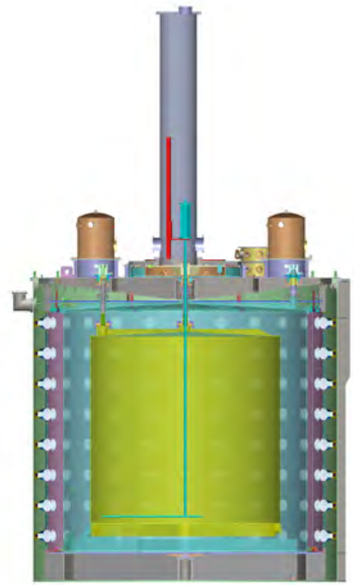


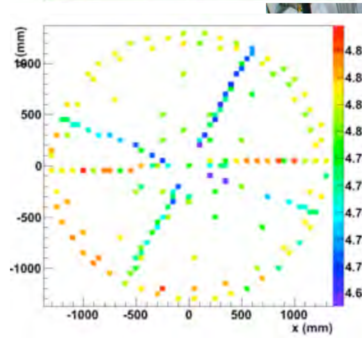
Daya Bay Fall 2012

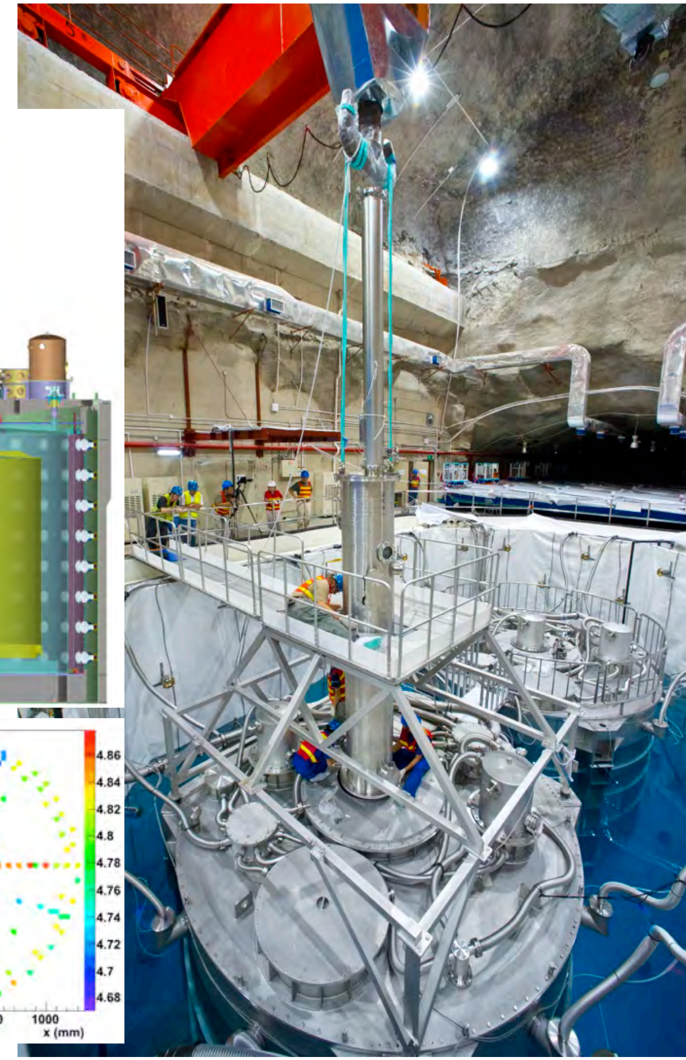
Installation of Final Antineutrino Detectors



Full Volume Calibration

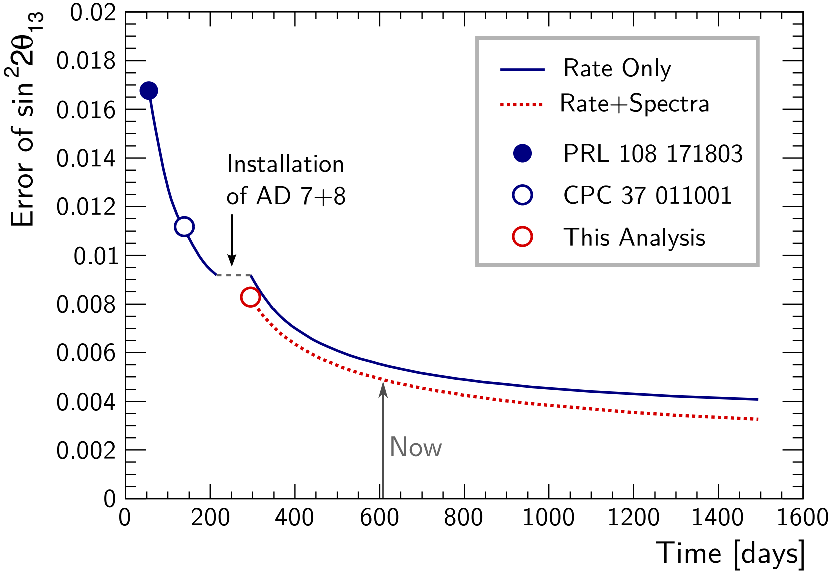


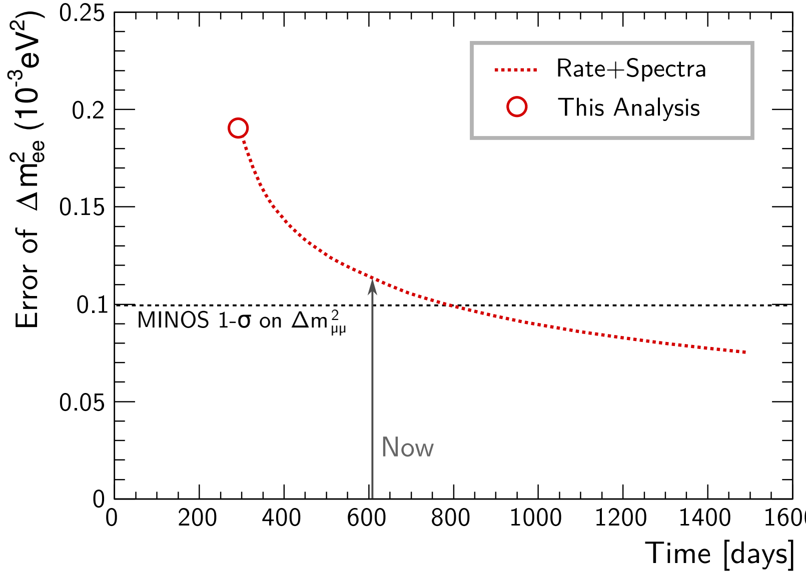




Daya Bay Future

Improved precision on oscillation parameters



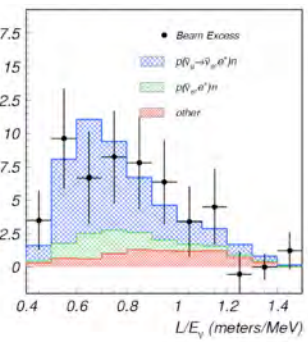


- Statistics contribute 73% (65%) to total uncertainty in $\sin^2 2\theta_{13}$ ($|\Delta m^2_{ee}|$)
- Major systematics:
  - θ_{13}: Relative + absolute energy, and relative efficiencies
  - $|\Delta m^2_{ee}|$: Relative energy model, relative efficiencies, and backgrounds
- Precision of mass splitting measurement closing in on results from μ flavor sector

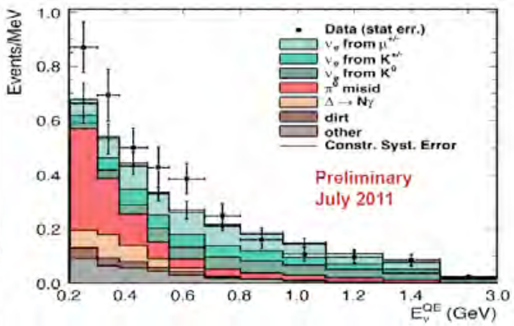
Measure absolute reactor neutrino flux and spectrum
Cosmogenic Backgrounds
Supernova Neutrinos

Neutrino Anomalies

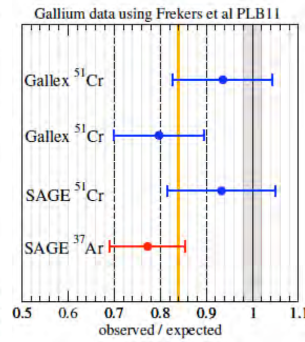
LSND



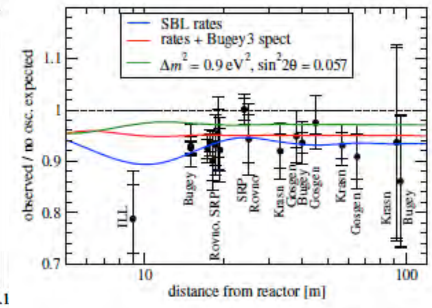
MiniBoone



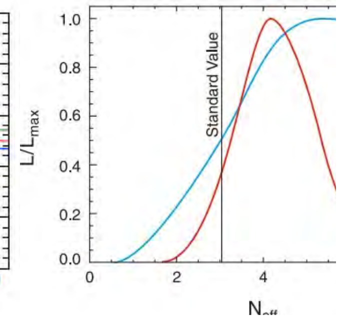
Ga Source



Reactor

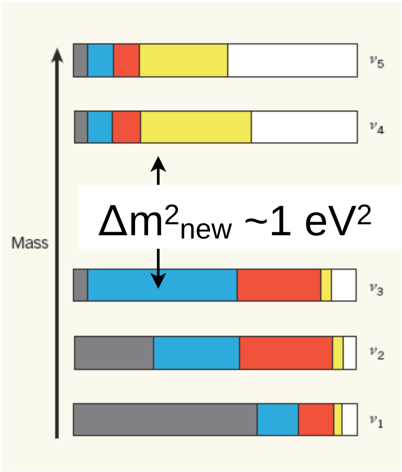


Cosmology (WMAP)



Anomalies in 3-ν interpretation of global oscillation data

LSND ($\overline{\nu}_e$ appearance)
MiniBoone (ν_e appearance)
Ga anomaly
Reactor anomaly ($\overline{\nu}_e$ disappearance)



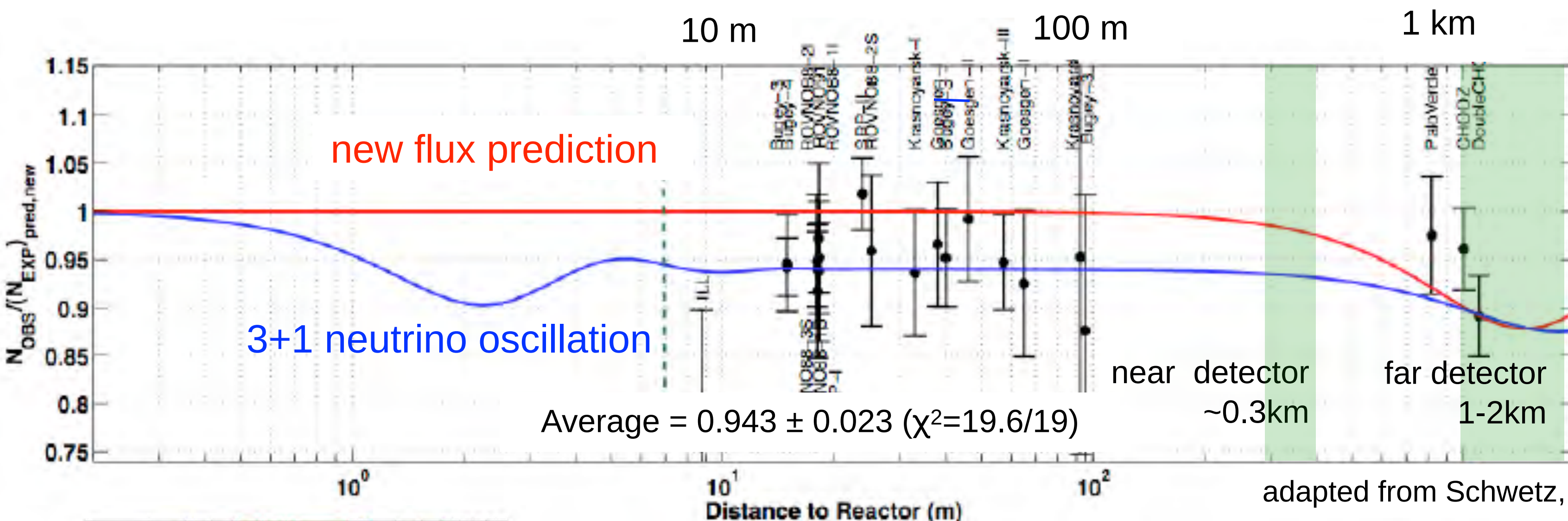
Cosmology suggests higher radiation density

$N_{eff} > 3$

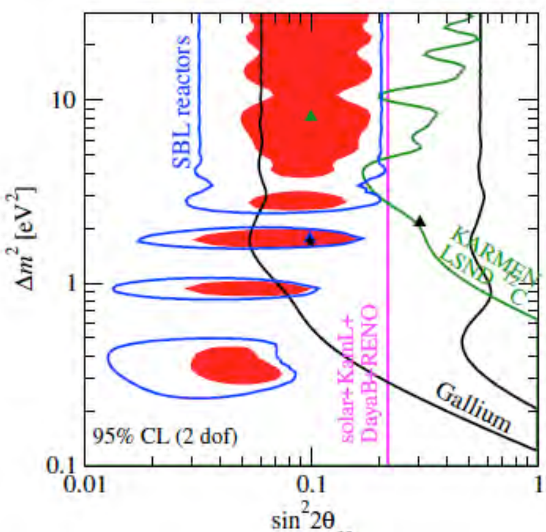
new oscillation signal requires $\Delta m^2 \sim O(1eV^2)$ and $\sin^2 2\theta > 10^{-3}$
systematics or experimental effect? ➔ need to test effects

Reactor Fluxes and "Anomaly"

Reactor θ_{13} experiments cannot directly search for short-baseline oscillations

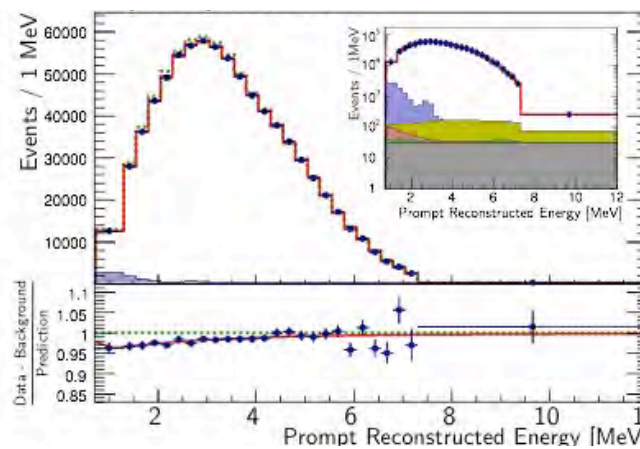


adapted from Schwetz, Neutrino2012



at ~1km reactor θ_{13} experiments probe overall suppression

Precision measurement of spectral shape can reveal new physics independent of normalization



Summary

For > 60 years reactor experiments have played an important role in neutrino physics, in both discoveries and precision measurements.

Reactors are flavor pure sources of $\overline{\nu}_e$.

Current reactor experiments **(L~1-2km)** provide precision data on $\boldsymbol{\theta_{13}}$, and **reactor antineutrino spectra**.

The Daya Bay Experiment has reported the first direct measurement of the short-distance electron antineutrino oscillation frequency:

$$|\Delta m^2_{ee}| = 2.59^{+0.19}_{-0.20} \times 10^{-3}\mathrm{eV}^2$$

The measurement has also produced the most precise estimate of the mixing angle:

$$\sin^2(2\theta_{13}) = 0.090^{+0.008}_{-0.009}$$

There is more to come... stay tuned!

End