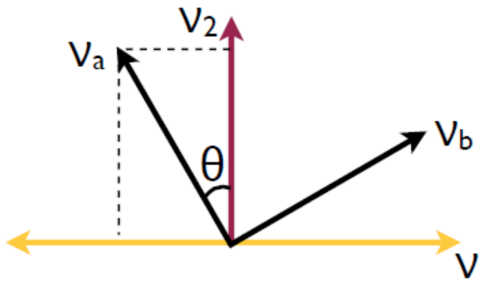
An updated measurement of electron antineutrino disappearance at Daya Bay

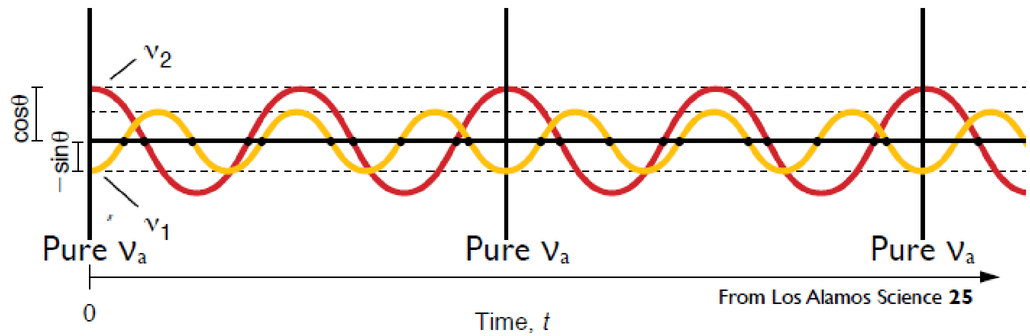
David Webber
On behalf of the Daya Bay Collaboration
July 24, 2012

Neutrino Oscillation (2-flavor)



$$\begin{pmatrix} \nu_b \\ \nu_a \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\Psi_{\nu_a}(x,t) = f(x,t) \sum_i U_{ai} e^{-i(m_i t/2E)}$$



$$P(\nu_a \rightarrow \nu_b) = \sin^2 2\theta \sin^2 \left[1.27 \Delta m^2 (eV^2) \frac{L(km)}{E_\nu(GeV)} \right]$$

Oscillation Amplitude

Oscillation Frequency

Experimental Parameter

Neutrino Oscillation (3-flavor)

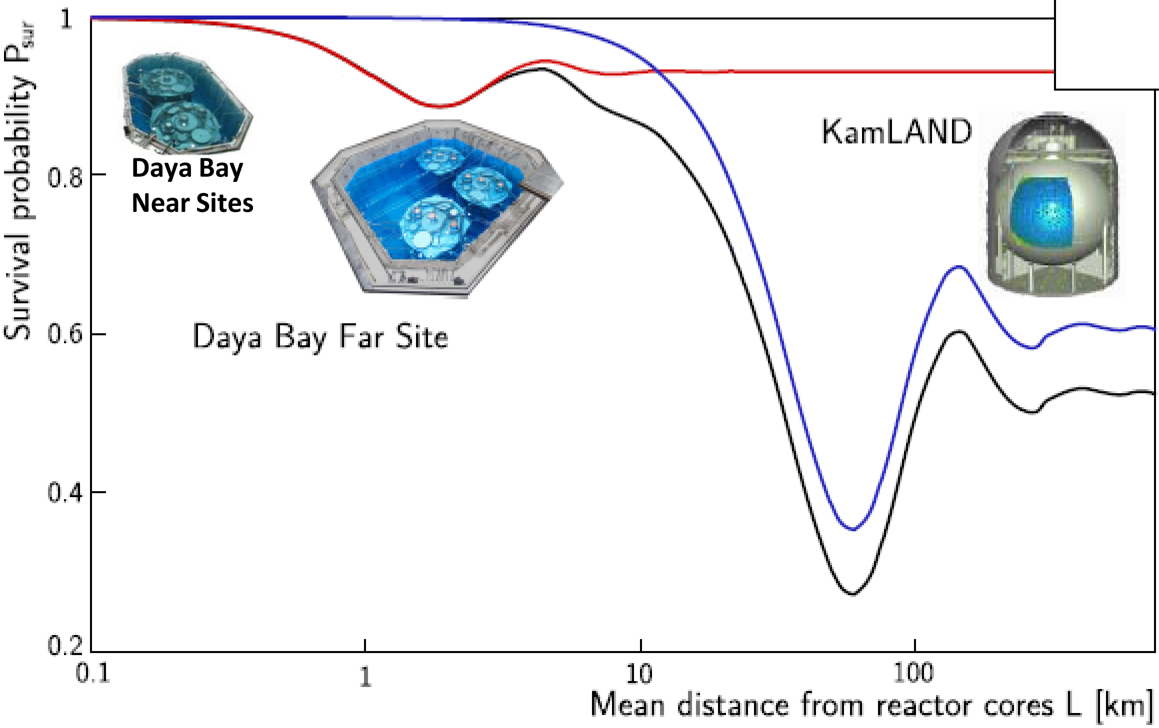
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2}\nu_1 \\ e^{i\alpha_2/2}\nu_2 \\ \nu_3 \end{pmatrix}$$

$c_{ij} = \cos(\theta_{ij})$;
$s_{ij} = \sin(\theta_{ij})$;

U_{MNSP} Matrix
Maki, Nakagawa, Sakata, Pontecorvo

$$P_{sur} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{32} \frac{L}{4E}\right) - \sin^2 2\theta_{12} \cos^4 2\theta_{13} \sin^2\left(\Delta m^2_{21} \frac{L}{4E}\right)$$

$$\Delta m^2_{32} \approx \Delta m^2_{31} \approx \Delta m^2_{atm}$$



Why measure θ_{13}?
- Least-known mixing angle
- Access to ν hierarchy
- Access to CP-violating phase δ

Near/far measurement reduces systematic uncertainties

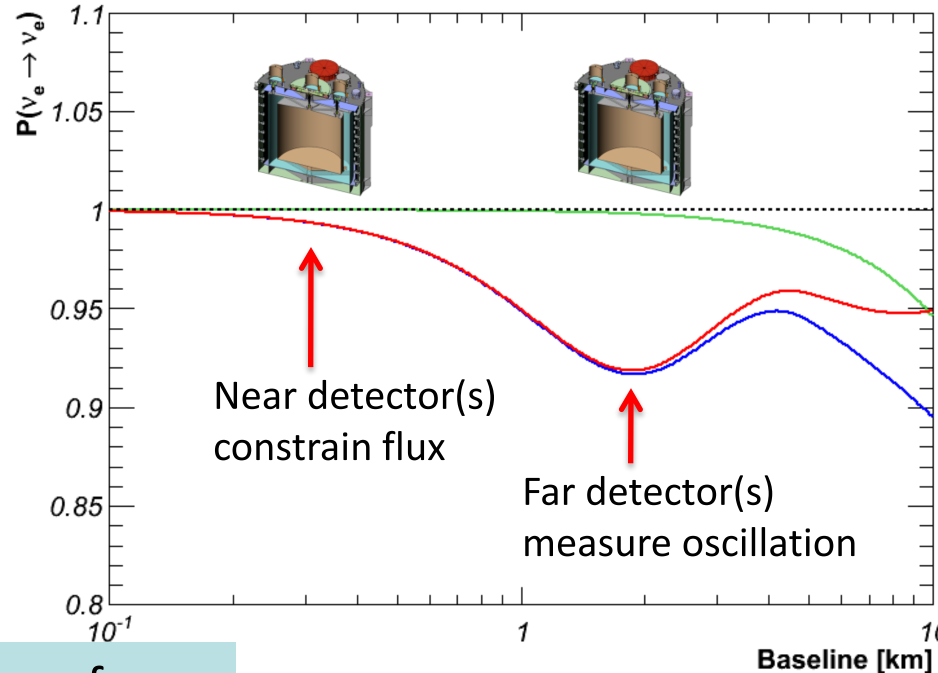
Absolute Reactor Flux:

Largest uncertainty in previous measurements

Relative Measurement:

Multiple detectors removes absolute uncertainty

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



Far/Near ν_e Ratio

Distances from reactor

Oscillation deficit

$$\frac{N_{\rm f}}{N_{\rm n}} = \left(\frac{N_{\rm p,f}}{N_{\rm p,n}}\right)\left(\frac{L_{\rm n}}{L_{\rm f}}\right)^2\left(\frac{\epsilon_{\rm f}}{\epsilon_{\rm n}}\right)\left[\frac{P_{\rm sur}(E, L_{\rm f})}{P_{\rm sur}(E, L_{\rm n})}\right]$$

Detector Target Mass

Detector efficiency

Location of Daya Bay

Daya Bay Experiment Site

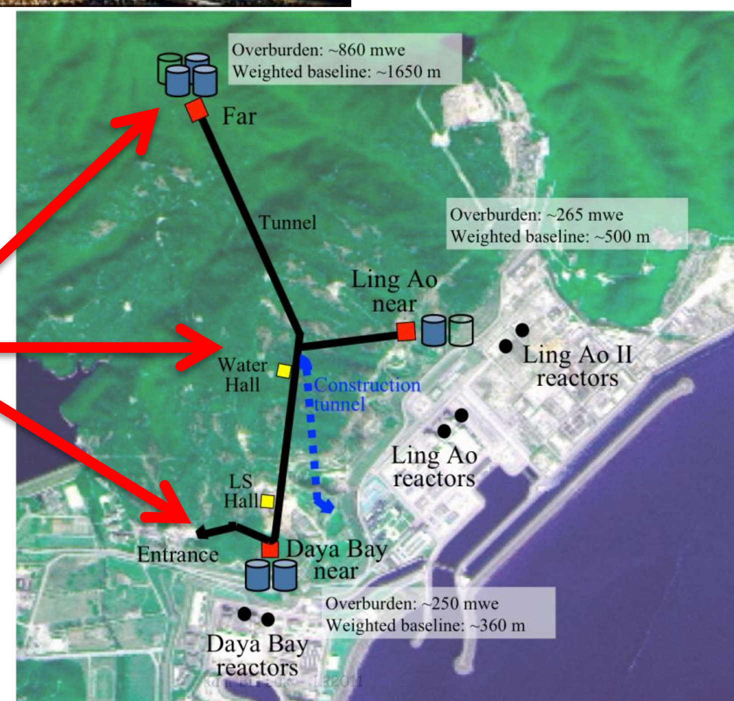
Adjacent mountains with horizontal access provide 860 (250) m.w.e cosmic shielding.

Daya Bay

Ling Ao I + II

6 commercial reactor cores with 17.4 GW_{th} total power.

6 Antineutrino Detectors (ADs) give 120 tons total target mass.

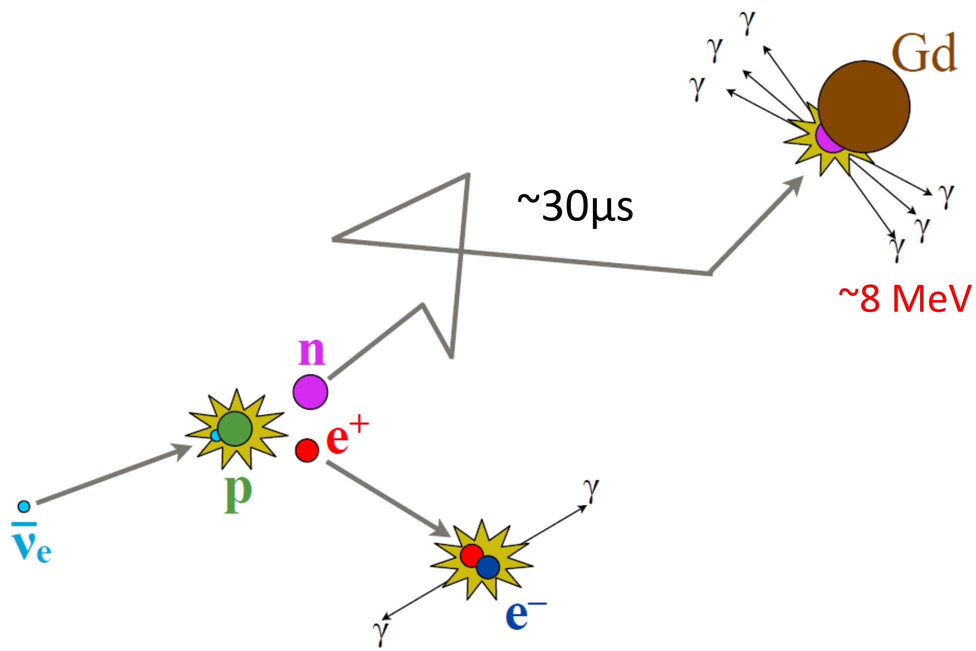


Via GPS and modern theodolites, relative detector-core positions known to 3 cm.

Detection Method

Inverse β-decay (IBD):

$$\bar{\nu}_e + p \rightarrow e^+ + n$$
$$\downarrow$$
$$n + {}^{x}Gd \rightarrow {}^{x+1}Gd + \gamma$$



Prompt positron:

Carries antineutrino energy

$E_{e+} \approx E_\nu - 0.8$ MeV

Delayed neutron capture:

Efficiently tags antineutrino signal

Prompt + Delayed coincidence provides distinctive signature

Antineutrino Detectors

6 'functionally identical' detectors:
Reduce systematic uncertainties

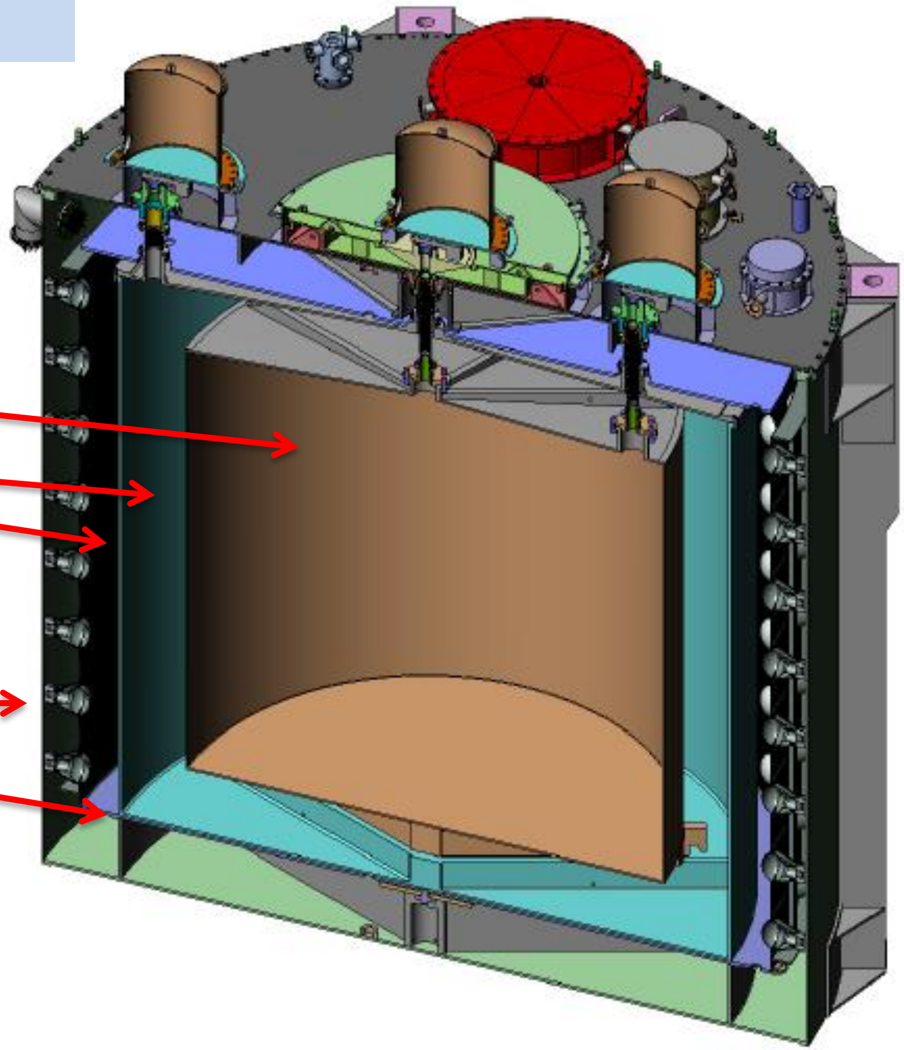
$$\frac{N_{\rm f}}{N_{\rm n}} = \left(\frac{N_{\rm p,f}}{N_{\rm p,n}}\right)\left(\frac{L_{\rm n}}{L_{\rm f}}\right)^2\left(\frac{\epsilon_{\rm f}}{\epsilon_{\rm n}}\right)\left[\frac{P_{\rm sur}(E,L_{\rm f})}{P_{\rm sur}(E,L_{\rm n})}\right]$$

3 nested cylinders:

Inner: 20 tons Gd-doped LS (d=3.1m)
Mid: 20 tons LS (d=4m)
Outer: 40 tons mineral oil buffer (d=5m)

Each detector:

192 8-inch Photomultipliers
Reflectors at top/bottom of cylinder
Provides (7.5 / √E + 0.9)% energy resolution



Interior of Antineutrino Detector

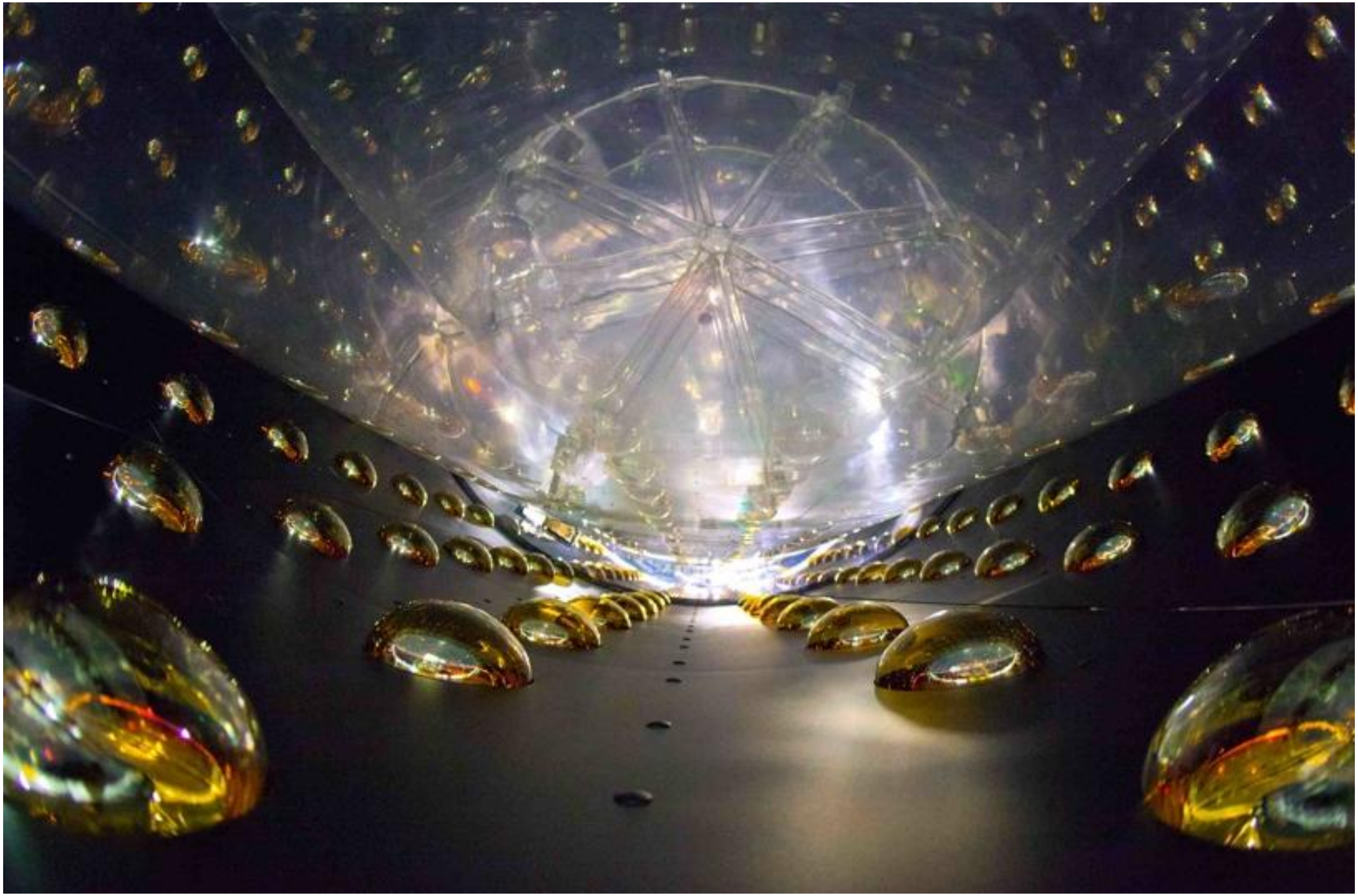


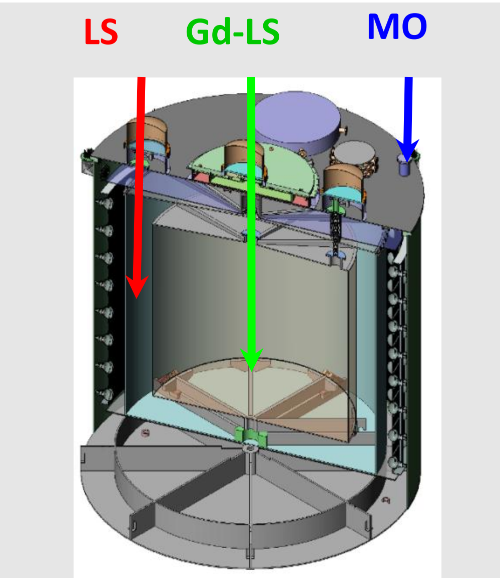
Photo by Rot Kaltschmidt

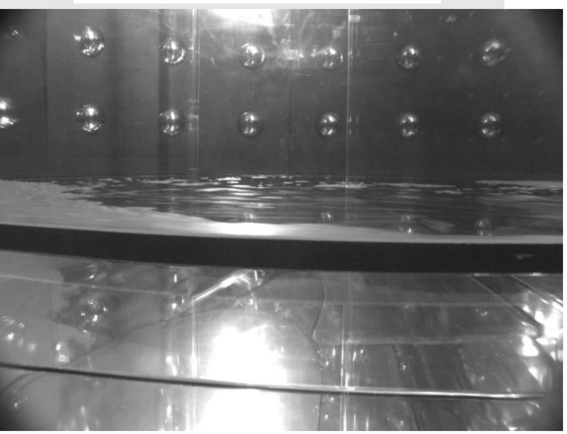
Antineutrino detectors are transported from surface assembly building to underground filling hall

Antineutrino detectors are transported from surface assembly building to underground filling hall

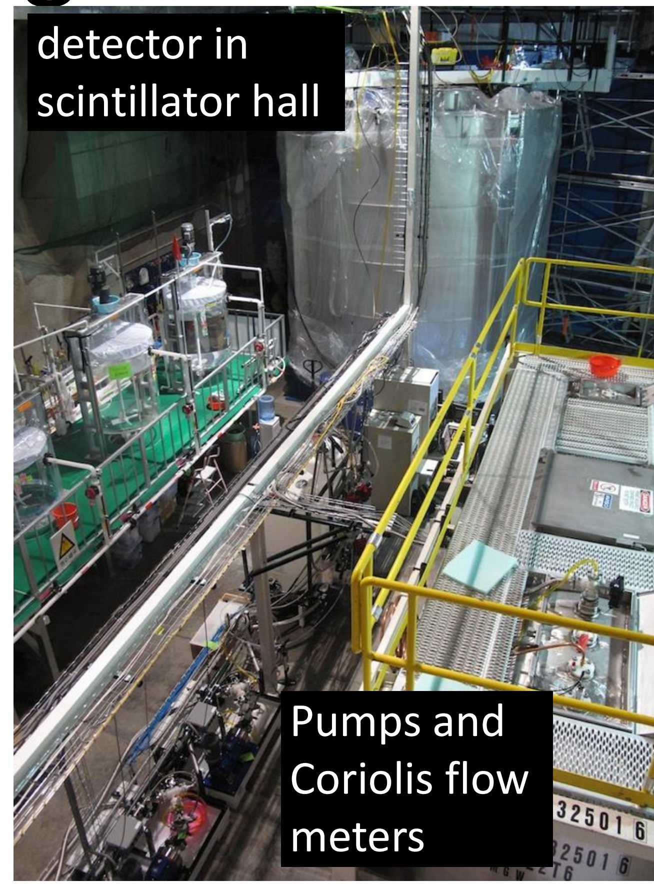
Liquid Scintillator Hall

Detector Filling





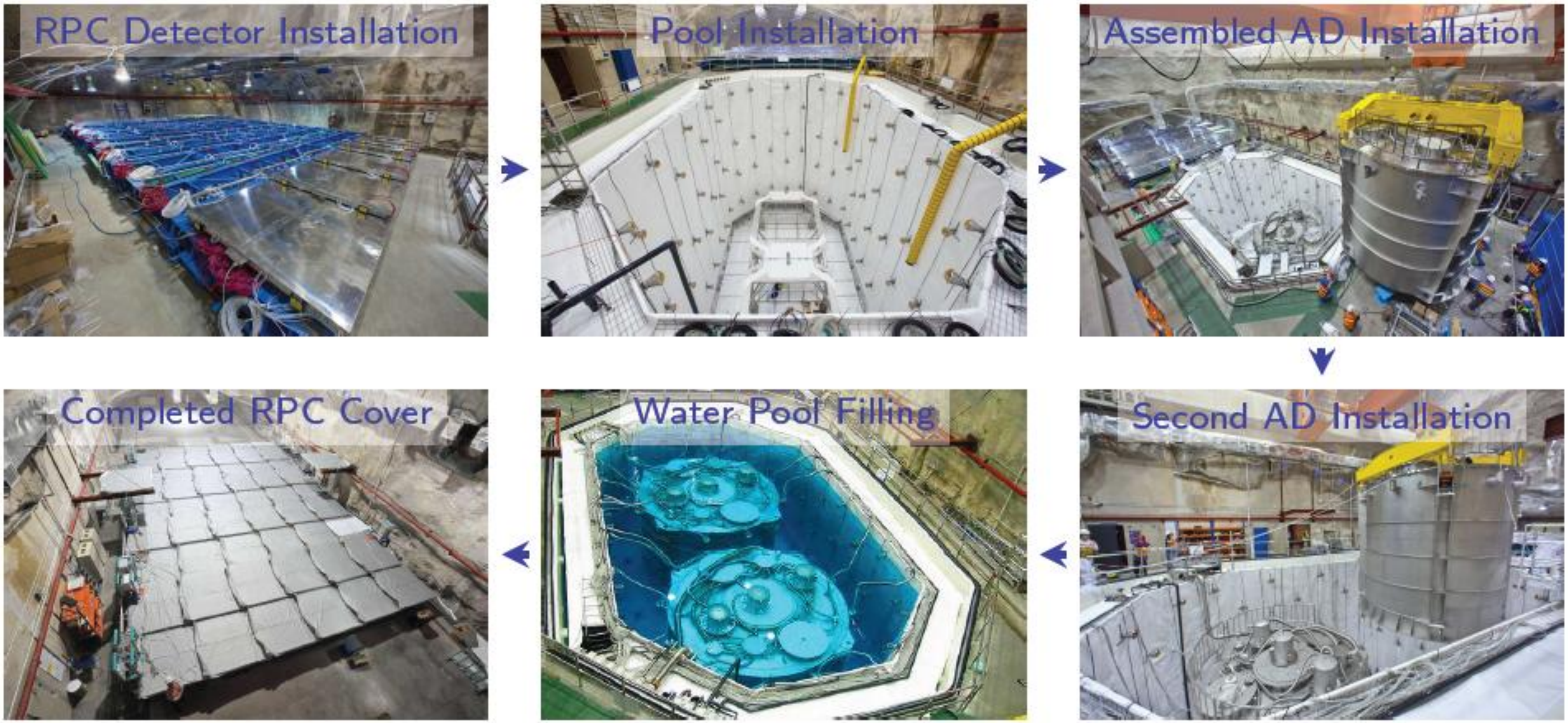
Detectors are filled from same reservoirs *"in-pairs"* within < 2 weeks.



3 fluids filled simultaneously, with heights matched to minimize stress on acrylic vessels

- **Gadolinium-doped Liquid Scintillator (GdLS)**
- **Liquid Scintillator (LS)**
- **Mineral Oil (MO)**

Hall 1 installation

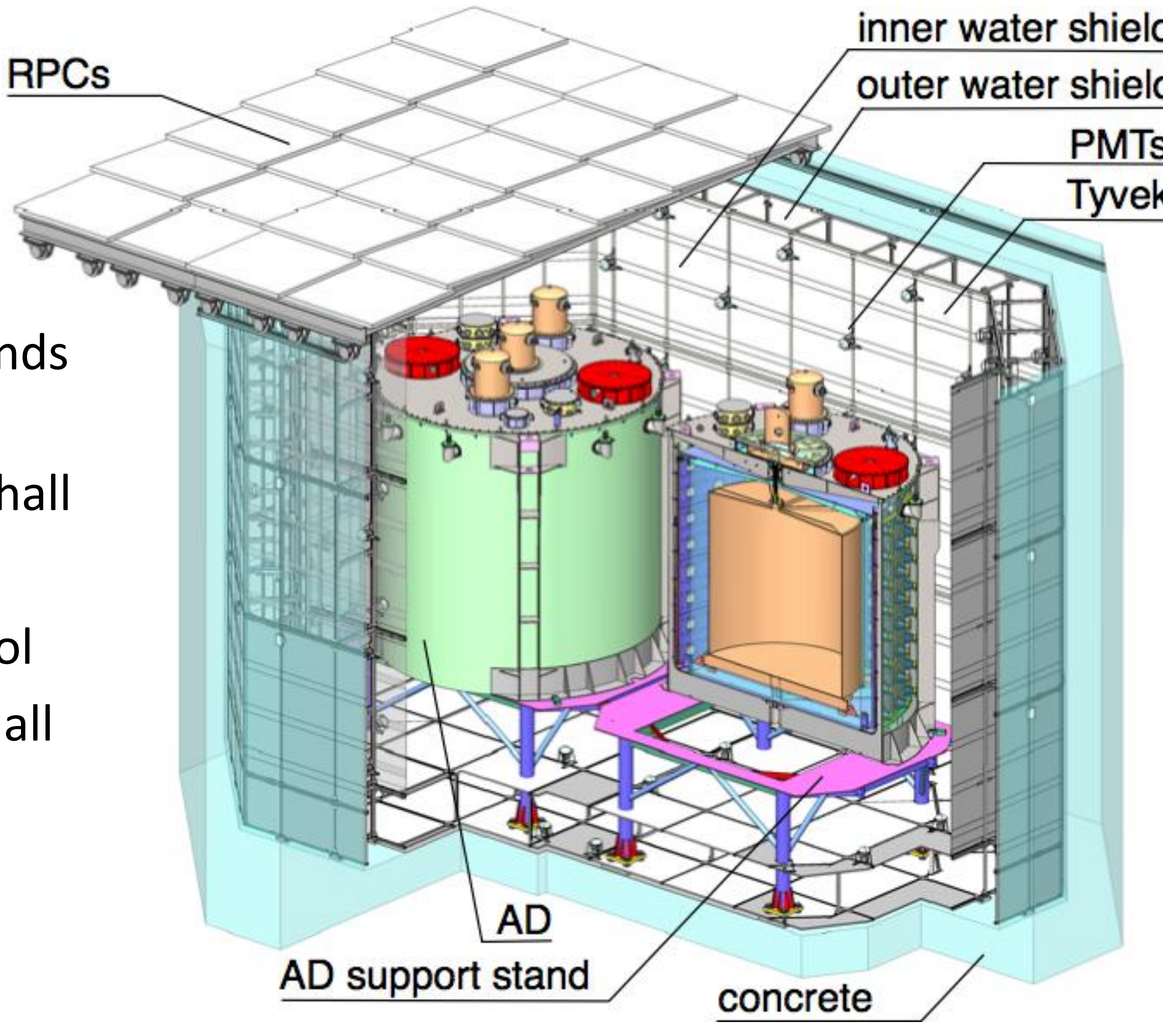


Hall 1 data taking began Aug. 15, 2011

Muon Tagging System

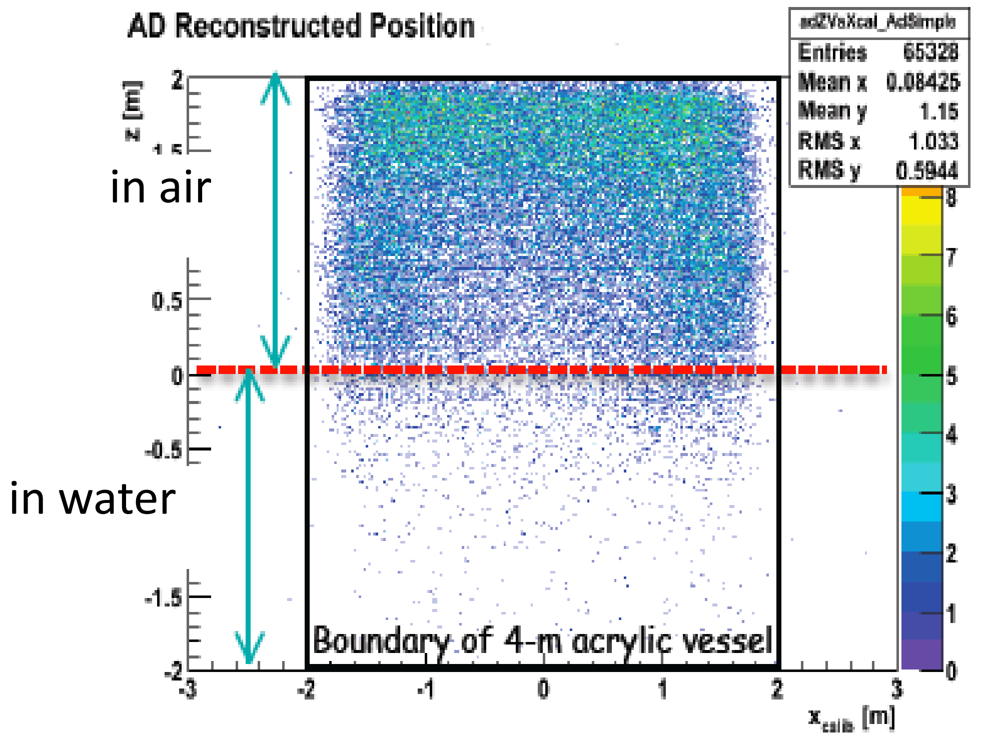
Dual tagging systems: 2.5 meter thick two-section water shield and RPCs

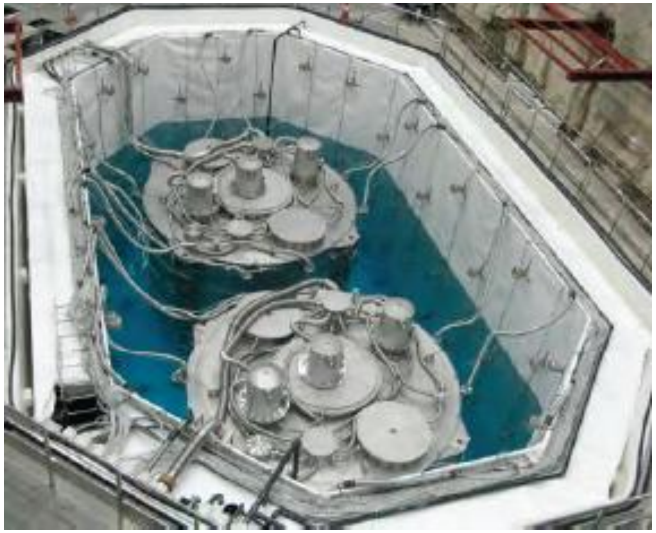
- Outer layer of water veto (on sides and bottom) is 1m thick, inner layer >1.5m. Water extends 2.5m above ADs
  - 288 8” PMTs in each near hall
  - 384 8” PMTs in Far Hall
- 4-layer RPC modules above pool
  - 54 modules in each near hall
  - 81 modules in Far Hall



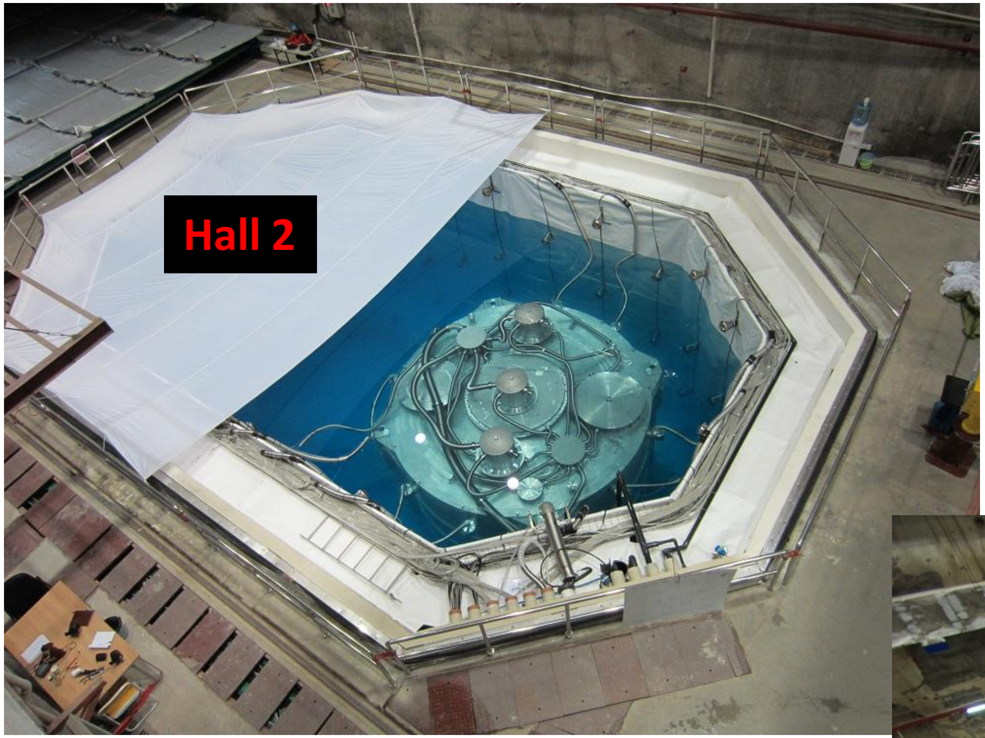
Observation of Water Shield Background Suppression

AD reconstructed events position
during the pool filling





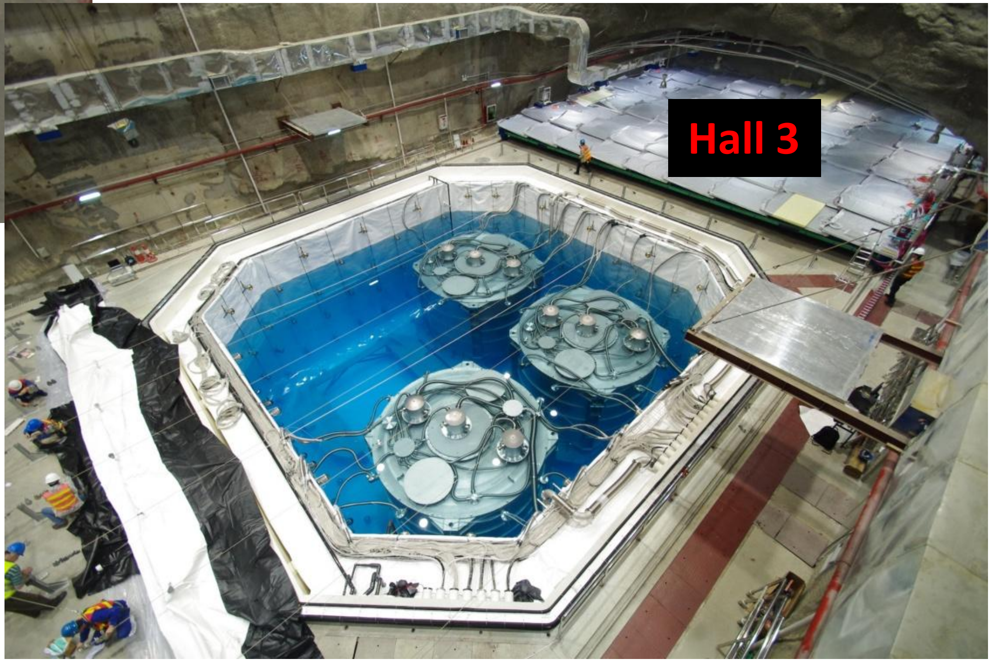
Hall 2 and Hall 3



Hall 1: Began 2 AD operation on Aug. 15, 2011

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

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

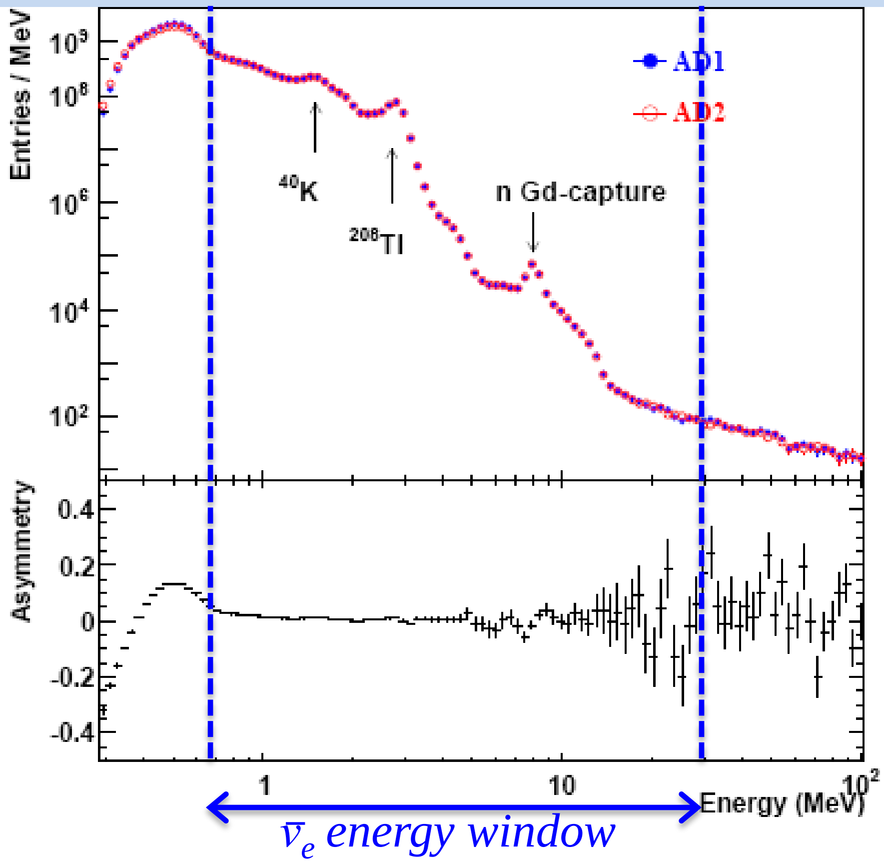


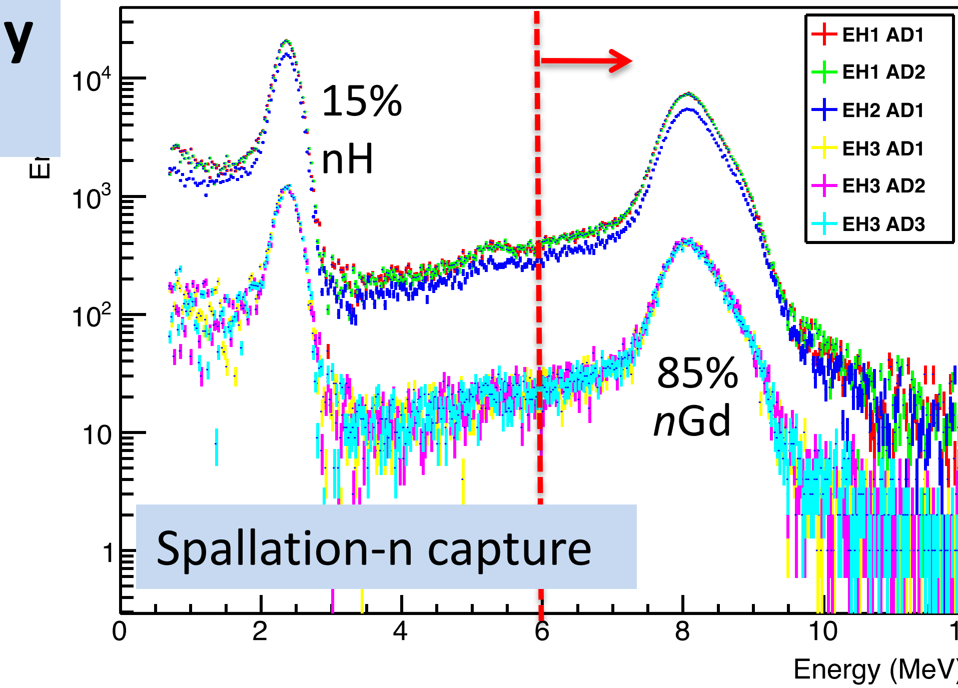
2 more ADs still in assembly; installation planned for Summer 2012

Side-by-Side Comparison

Multiple detectors allows detailed comparison and cross-checks.

Two ADs in Hall 1 have functionally identical spectra and response.

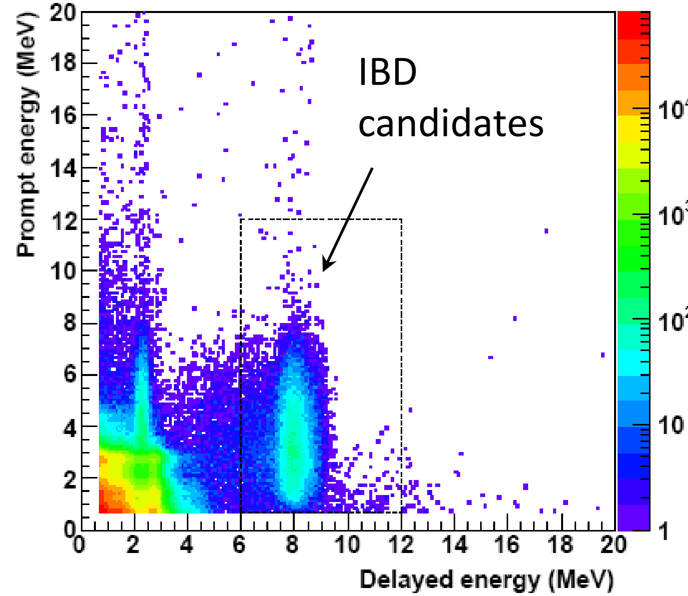




Response of all detectors to neutrons constrains largest systematic uncertainty.

Antineutrino (IBD) Selection

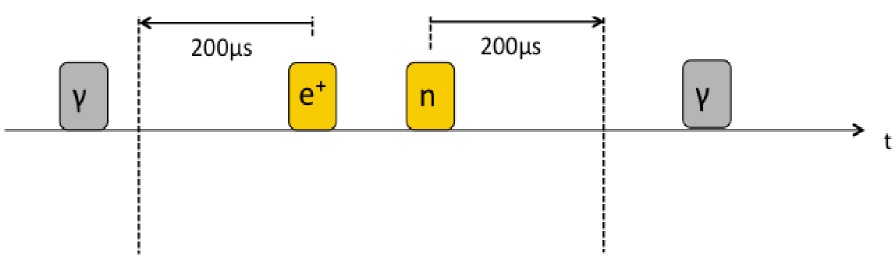
$\overline{\nu}_e + p \rightarrow e^+ + n$



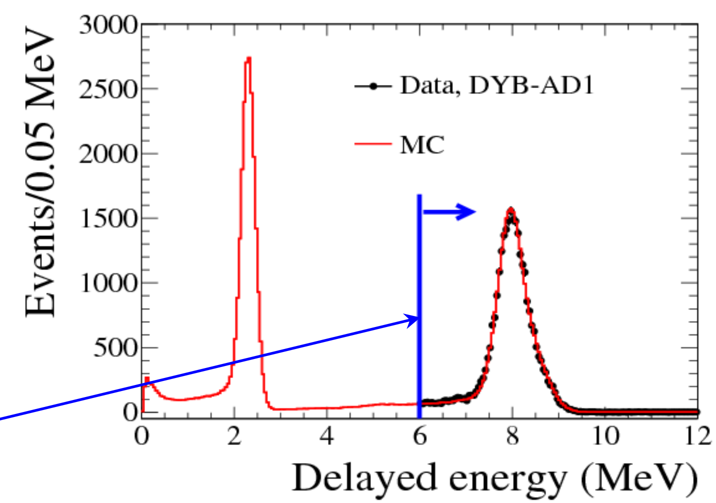
Prompt + Delayed Selection

- Reject Flashers
- Prompt Positron: 0.7 MeV < E_p < 12 MeV
- Delayed Neutron: 6.0 MeV < E_d < 12 MeV
- Capture time: 1 μs < Δt < 200 μs
- Muon Veto:
  - Pool Muon (12 PMTs): Reject 0.6 ms
  - AD Muon (>20 MeV): Reject 1 ms
  - AD Shower Muon (>2.5GeV): Reject 1 s
- Multiplicity:

No other signal > 0.7 MeV in -200 μs to 200 μs of IBD.



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

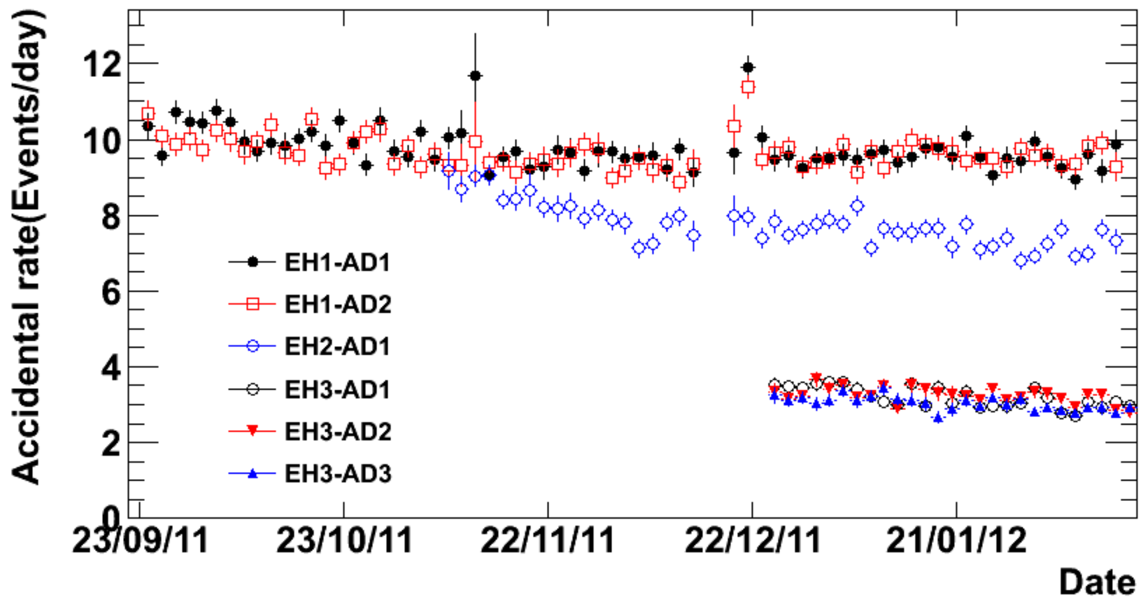


Background: Accidentals

Accidentals: Two uncorrelated events 'accidentally' passing the cuts and mimic IBD event.

Rate and spectrum can be accurately predicted from singles data.

Multiple analyses/methods estimate consistent rates.



	EH1-AD1	EH1-AD2	EH2-AD1	EH3-AD1	EH3-AD2	EH3-AD3
Accidental rate(/day)	9.73±0.10	9.61±0.10	7.55±0.05	3.05±0.04	3.04±0.04	2.93±0.03
B/S	1.4%	1.4%	1.4%	4.6%	4.8%	4.4%

Background: Fast neutrons

Correlated events mimic IBD events

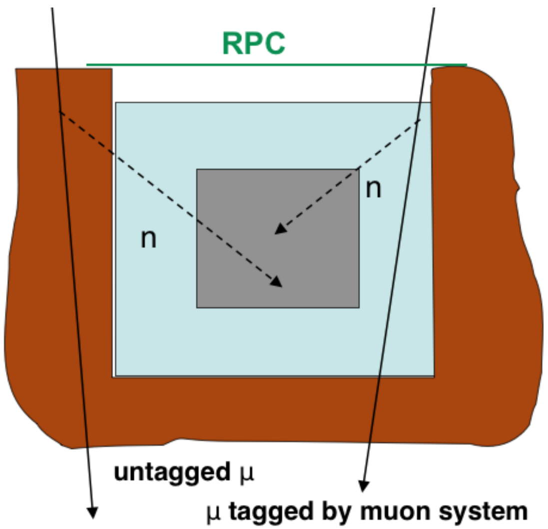
Fast Neutrons

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

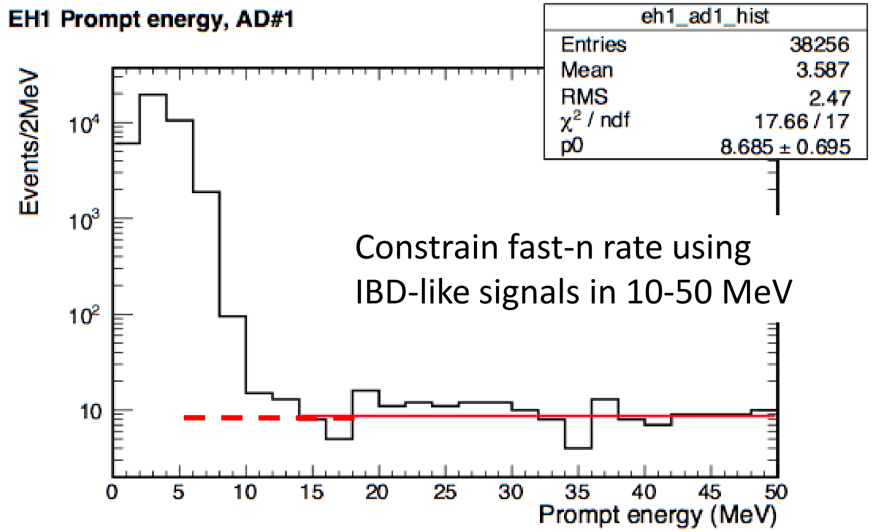
Mimics antineutrino (IBD) signal

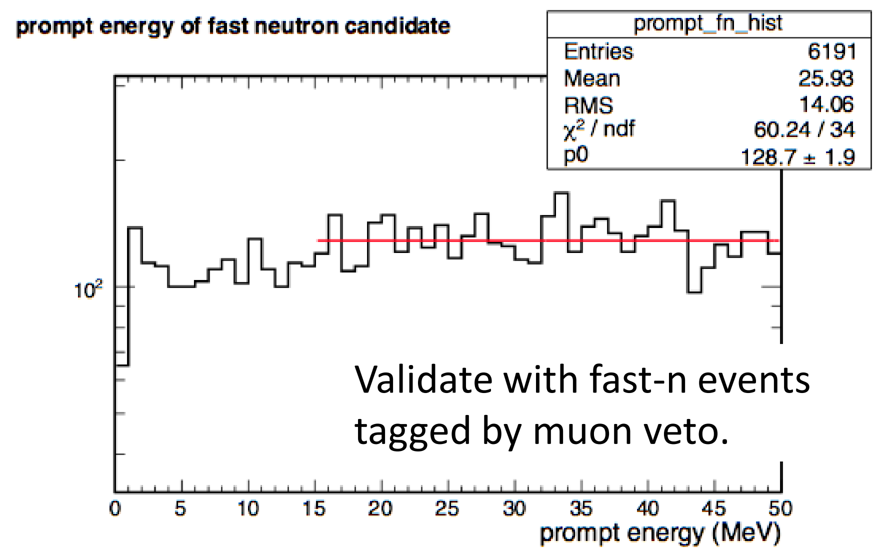
Prompt: Neutron collides/stops in target

Delayed: Neutron captures on Gd



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



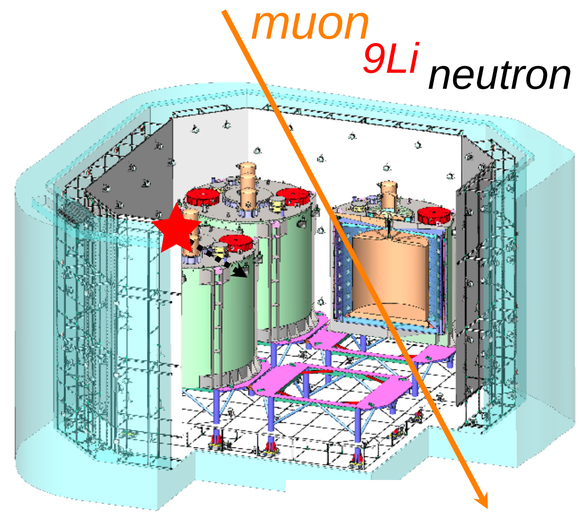


Background: Li/He decay

Correlated events mimic IBD events

- prompt: β-decay
- delayed: neutron capture

$$^{9}Li \rightarrow {}^{9}Be + e^{-} + \bar{\nu}_e$$
$$\hookrightarrow n + 2\alpha$$



Generated by cosmic rays, long-lived

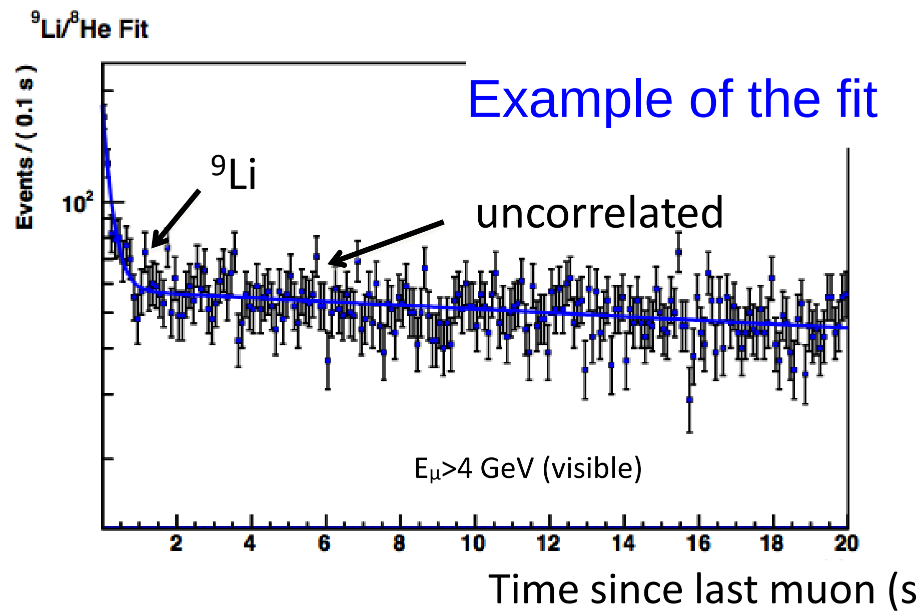
^{9}Li: $\tau_{½}$ = 178 ms, Q = 13. 6 MeV

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

^{9}Li/^{8}He, Br(n) = 48% /12%, **^{9}Li dominant**

fit with known decay times for ^{8}He/^{9}Li

Analysis muon veto cuts control B/S to ~0.3% (0.4%) of far (near) signal.



Data Set Summary

> 200k antineutrino interactions!

	AD1	AD2	AD3	AD4	AD5	AD6
Antineutrino candidates	69121	69714	66473	9788	9669	9452
DAQ live time (day)	127.5470		127.3763	126.2646		
Efficiency	0.8015	0.7986	0.8364	0.9555	0.9552	0.9547
Accidentals (/day)	9.73±0.10	9.61±0.10	7.55±0.08	3.05±0.04	3.04±0.04	2.93±0.03
Fast neutron (/day)	0.77±0.24	0.77±0.24	0.58±0.33	0.05±0.02	0.05±0.02	0.05±0.02
^{8}He/^{9}Li (/day)	2.9±1.5		2.0±1.1	0.22±0.12		
Am-C corr. (/day)	0.2±0.2					
^{13}C(α, n)^{16}O (/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
Antineutrino rate (/day)	**662.47 ±3.00**	**670.87 ±3.01**	**613.53 ±2.69**	**77.57 ±0.85**	**76.62 ±0.85**	**74.97 ±0.84**

Consistent rates for side-by-side detectors

Uncertainty currently dominated by statistics

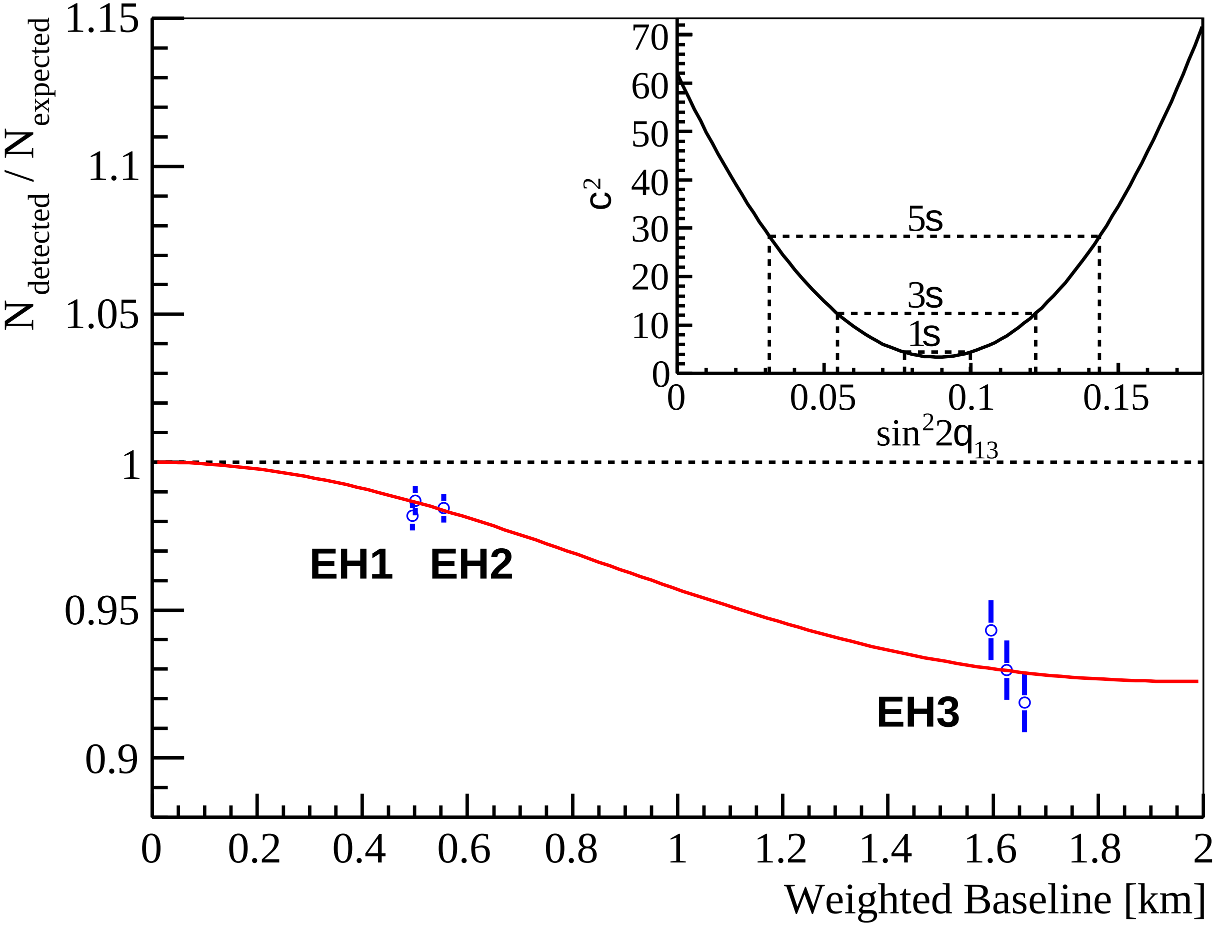
Systematic Uncertainties

	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%
IBD/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	**Combined**	**0.8%**

Rate Analysis

Estimate θ_{13} using measured rates in each detector.



Uses standard χ^2 approach.

Far vs. near relative measurement.
[Absolute rate is not constrained.]

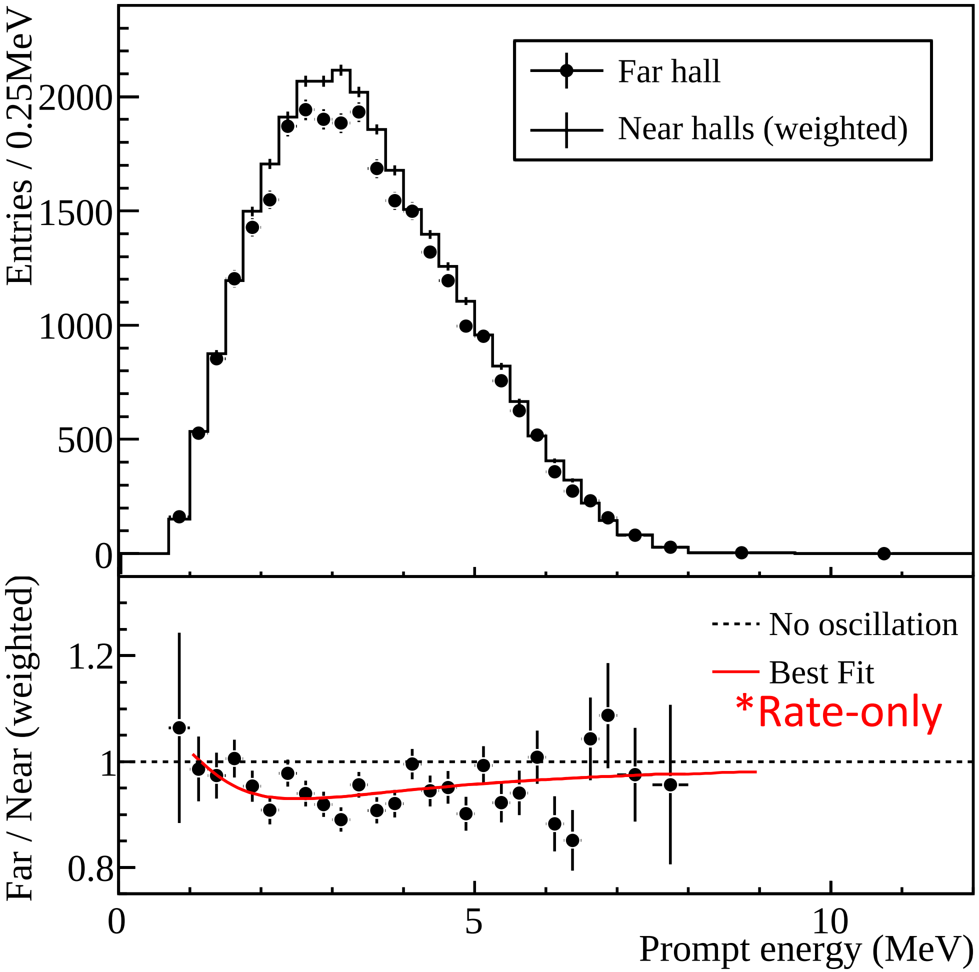
Consistent results obtained by independent analyses, different reactor flux models.

Most precise measurement of $\sin^2 2\theta_{13}$ to date.

$\sin^2 2\theta_{13} = 0.089 \pm 0.010$ (stat) ± 0.005 (syst)

Far vs. Near Comparison

Compare the far/near measured rates and spectra



$$R = \frac{Far_{measured}}{Far_{expected}} = \frac{M_4 + M_5 + M_6}{\sum_{i=4}^{6}(\alpha_i(M_1 + M_2) + \beta_i M_3)}$$

M_n are the measured rates in each detector. Weights α_i,β_i are determined from baselines and reactor fluxes.

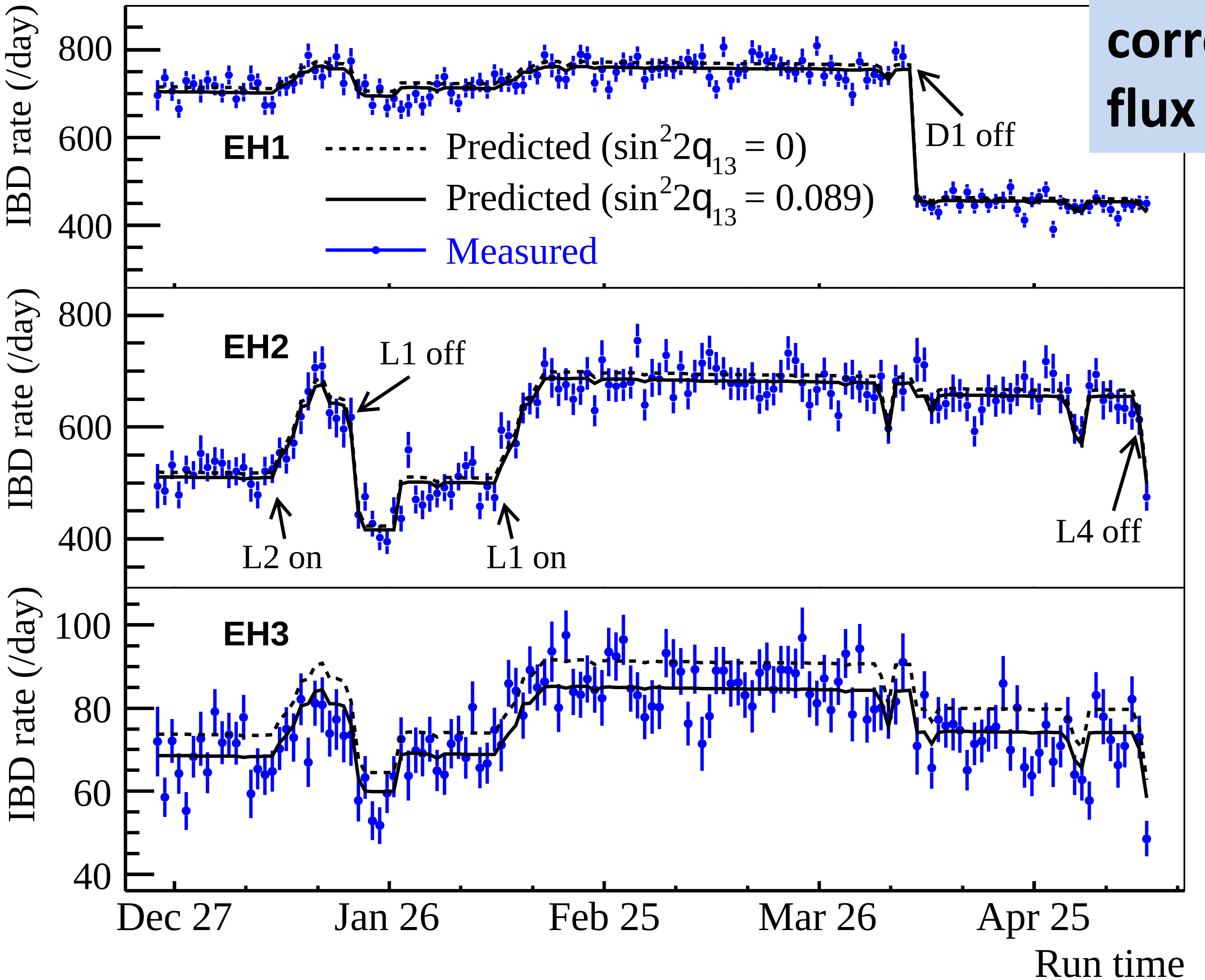
R = 0.944 ± 0.007 (stat) ± 0.003 (syst)

Clear observation of far site deficit.

Spectral distortion consistent with oscillation.*

* Caveat: Spectral systematics not fully studied; θ_{13} value from shape analysis is not recommended.

Antineutrino Rate vs. Time



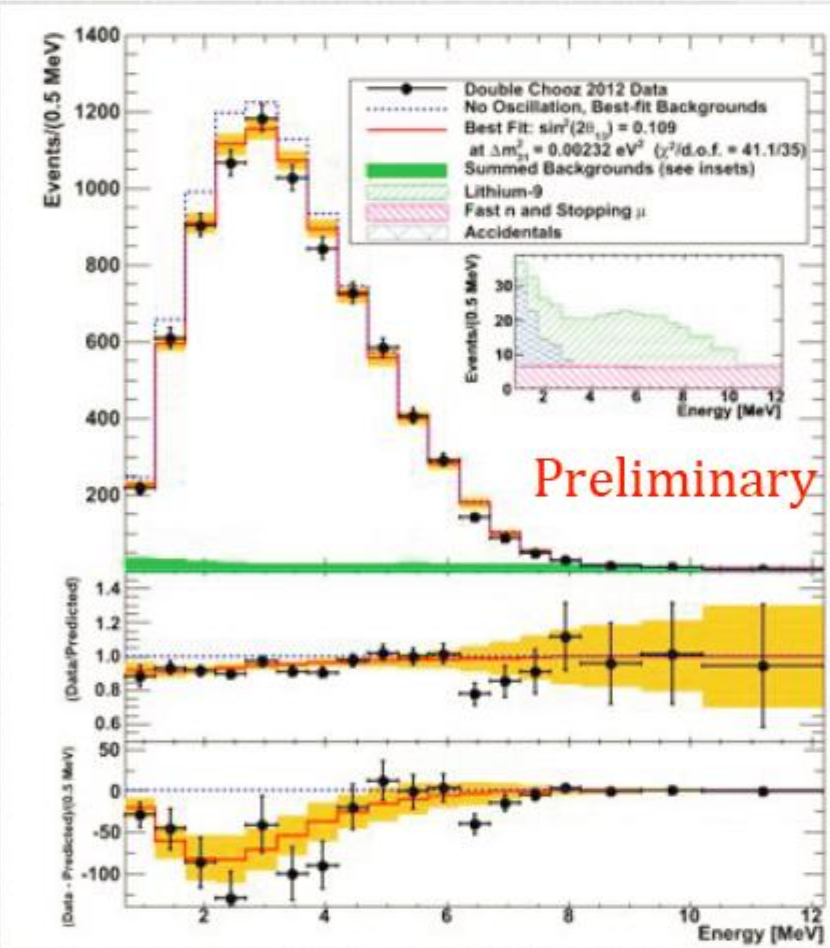
Detected rate strongly correlated with reactor flux expectations.

Predicted Rate:

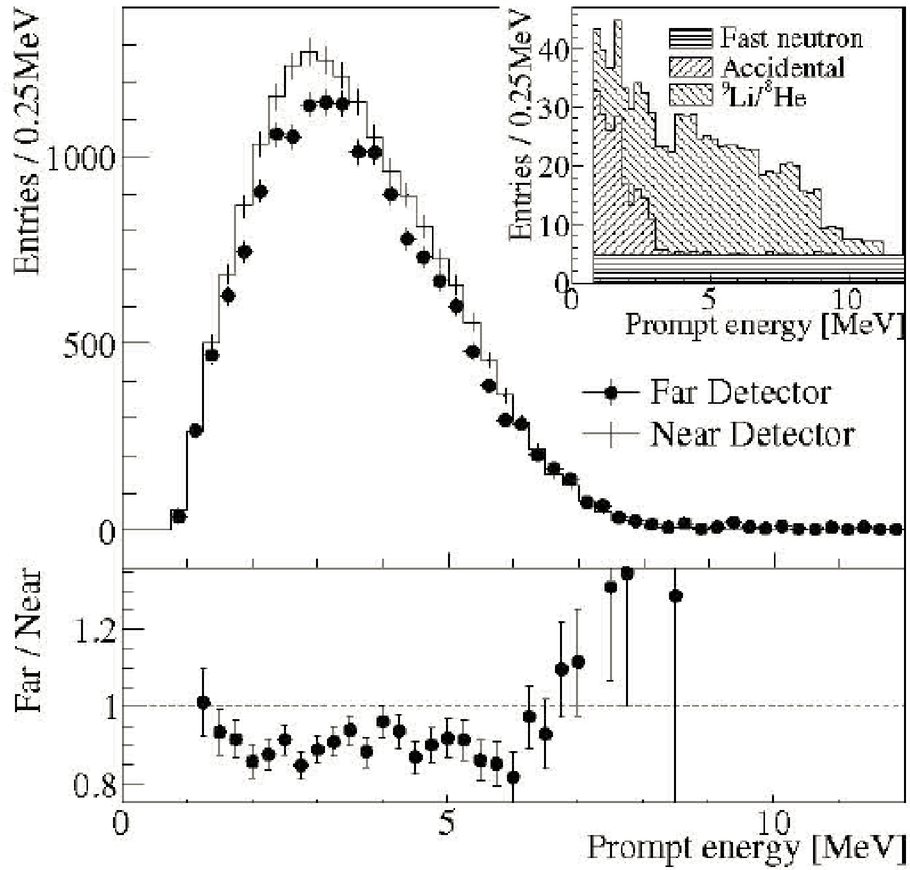
- Normalization is determined by data fit.
- Absolute normalization is within a few percent of expectations.

Other Recent θ_{13} Results

Double Chooz, Neutrino2012



RENO, Neutrino2012

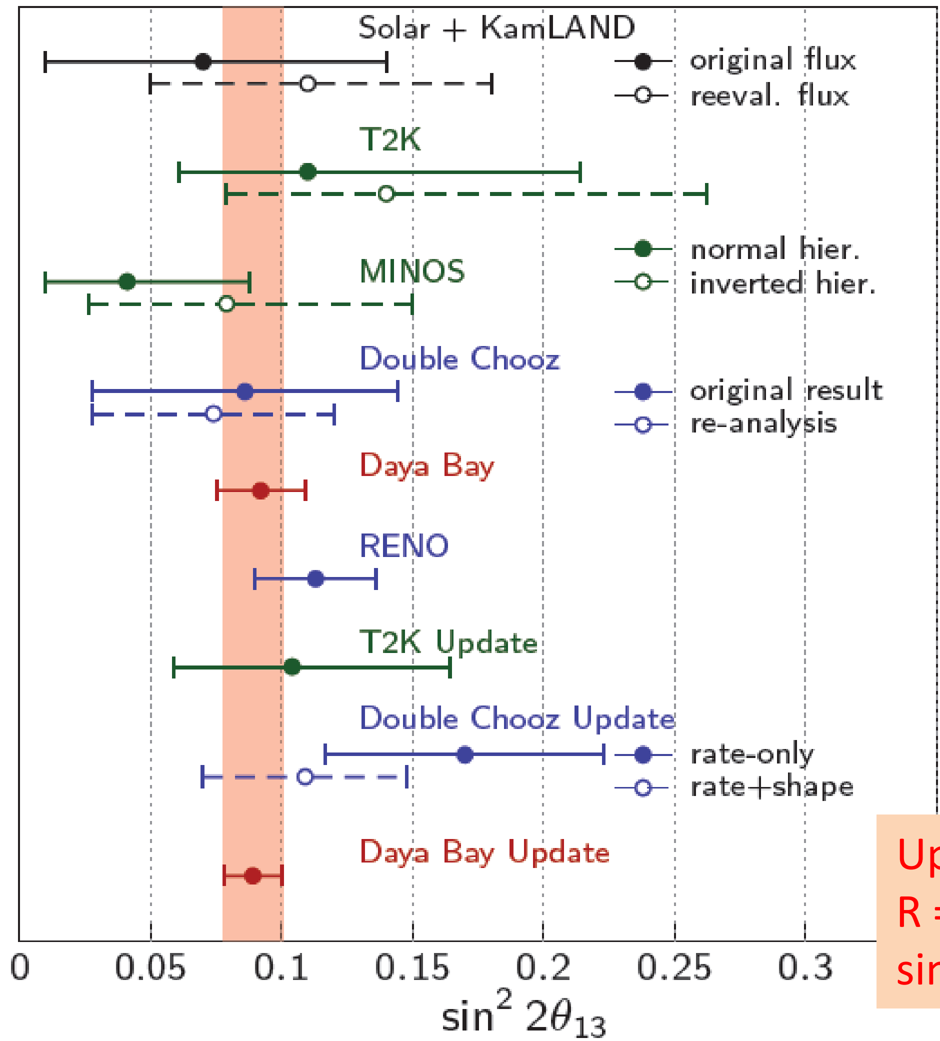


$$\sin^2 2\theta_{13} = 0.113 \pm 0.013(stat.) \pm 0.019(syst.)$$

Rate only: $\sin^2 2\theta_{13} = 0.170 \pm 0.035(\text{stat}) \pm 0.040(\text{syst})$

Rate+Shape: $\sin^2 2\theta_{13} = 0.109 \pm 0.030(\text{stat}) \pm 0.025(\text{syst})$

Comparison of θ_{13} Measurements



PRL:
R = 0.940 ± 0.011 (stat) ± 0.004 (sys)
$\sin^2 2\theta_{13}$ = 0.092 ± 0.016 (stat) ± 0.005 (sys)

Updated result:
R = 0.944 ± 0.007 (stat) ± 0.003 (syst)
$\sin^2 2\theta_{13}$ = 0.089 ± 0.010 (stat) ± 0.005 (syst)

More Work for Daya Bay

Primary Science Goals

- Definitive precision measurement of $\sin^2 2\theta_{13}$
- Measurement of Δm^2_{31}

Additional Science Goals

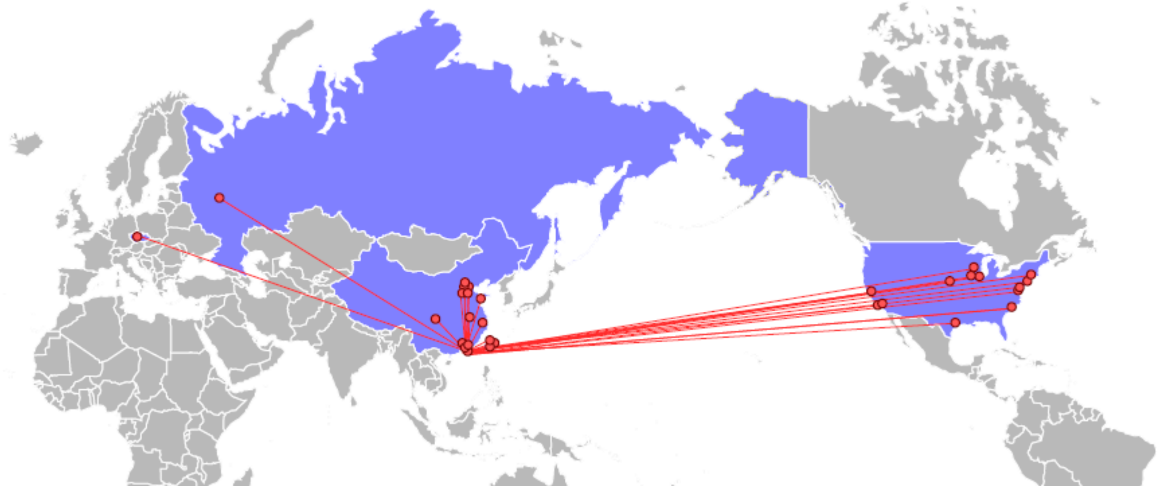
- Precise reactor flux and spectra measurements**.** Will have largest reactor antineutrino data set collected.
- Measurement of cosmogenic neutrons & isotopes over a range of muon energies and (modest) depths.
- Search for new, non-standard antineutrino interactions

Technical studies

- Demonstrate multi-year operation of "functionally identical detectors". Track performance versus time.
- Verify long term GdLS stability.

Daya Bay Collaboration

An International Effort



Asia (20)

IHEP, Beijing Normal Univ., Chengdu Univ. of Sci and Tech, CGNPG, CIAE, Dongguan Polytech, Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Zhongshan Univ., Univ. of Hong Kong, Chinese Univ. of Hong Kong, National Taiwan Univ., National Chiao Tung Univ., National United Univ.

North America (16)

Brookhaven Natl' Lab, Cal Tech, Cincinnati, Houston, Illinois Institute of Technology, Iowa State, Lawrence Berkeley Natl' Lab, Princeton, Rensselaer Polytech, UC Berkeley, UCLA, Wisconsin, William & Mary, Virginia Tech, Illinois, Siena College

Europe (2)

Charles Univ., Dubna

38 institutions
~230 collaborators

Summary

- With 2.5x more data, the Daya Bay reactor neutrino experiment measures a far/near antineutrino deficit at ~2 km:

R = 0.944 ± 0.007 (stat) ± 0.003 (syst)

[Previous value: R = 0.940 ± 0.011 (stat) ± 0.004 (syst)]

- Interpretation of disappearance as neutrino oscillation yields:

$$\sin^2 2\theta_{13} = 0.089 \pm 0.010\ (\text{stat}) \pm 0.005\ (\text{syst})$$

[Previous value: $\sin^2 2\vartheta_{13} = 0.092 \pm 0.016$ (stat) ± 0.005 (syst)]

- Installation of final pair of antineutrino detectors this year

Backup

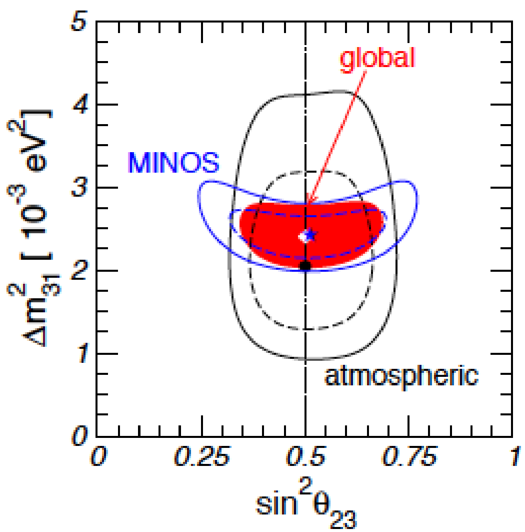
Neutrino Oscillation (3-flavor)

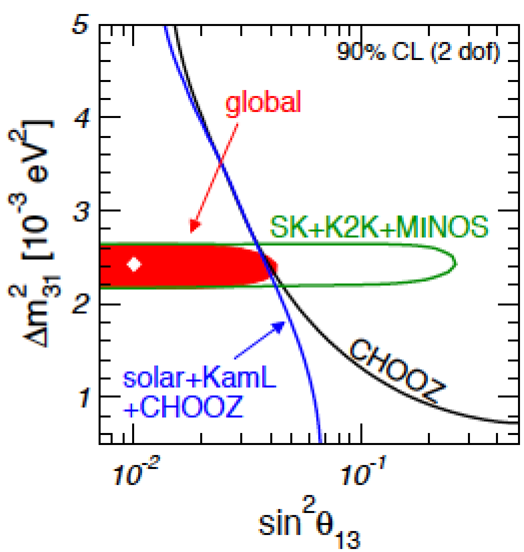
$c_{ij} = \cos(\theta_{ij})$;
$s_{ij} = \sin(\theta_{ij})$;

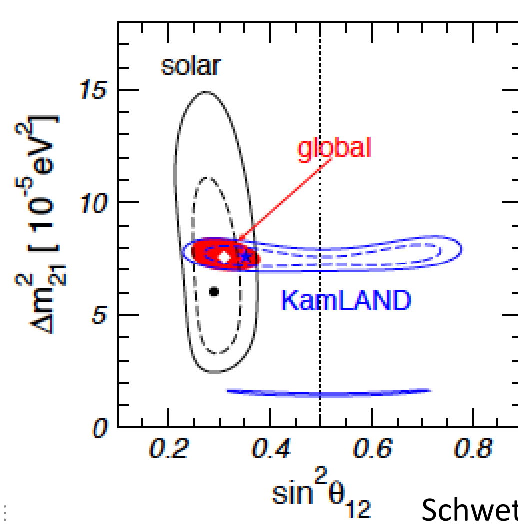
U_{MNSP} Matrix
Maki, Nakagawa, Sakata, Pontecorvo

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} e^{ia_1/2}\nu_1 \\ e^{ia_2/2}\nu_2 \\ \nu_3 \end{pmatrix}$$

atmospheric, K2K — reactor and accelerator — SNO, solar SK, KamLAND



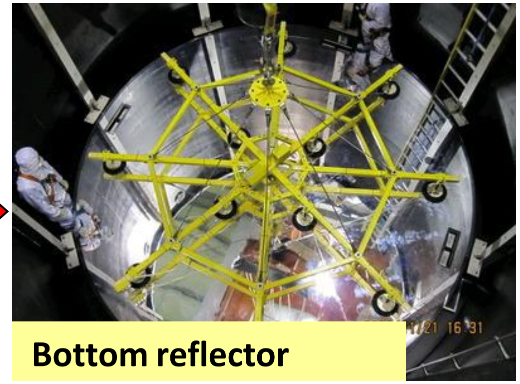


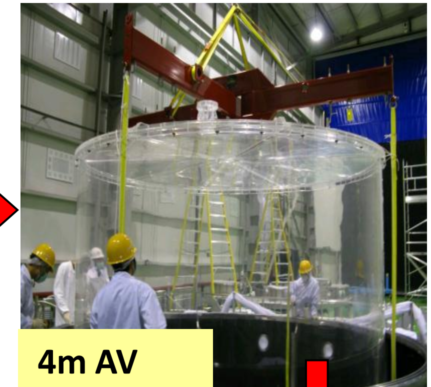


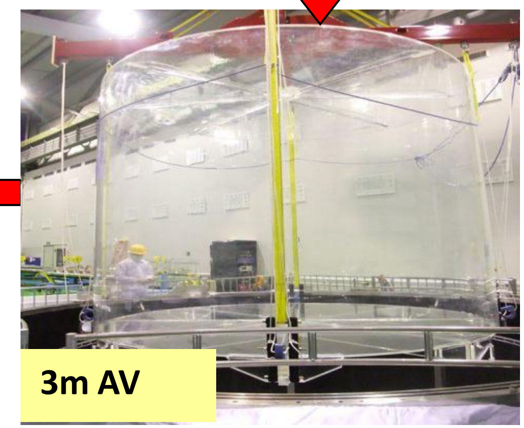
Schwetz et al
arXiv:0808.2016
updated as of 2010

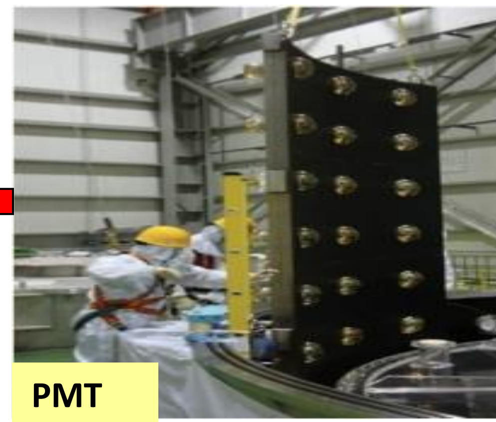
Detector Assembly

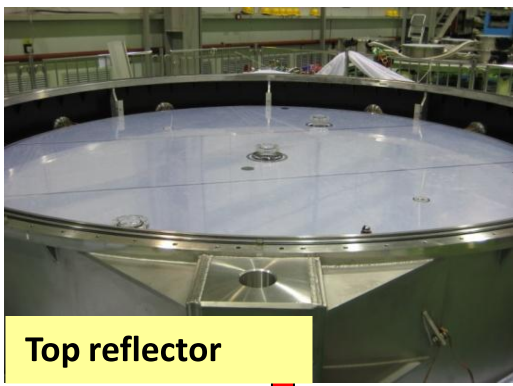

SSV

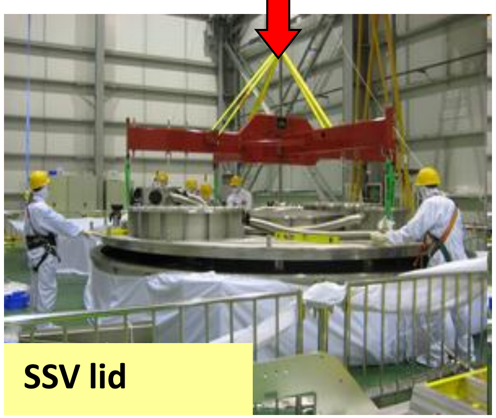

Bottom reflector


4m AV


3m AV


PMT


Top reflector


SSV lid


Leak check


ACU

Data Period

A. Two Detector Comparison: arXiv:1202:6181

- Sep. 23, 2011 – Dec. 23, 2011
- Side-by-side comparison of 2 detectors in Hall 1
- Demonstrated detector systematics better than requirements.
- Soon published in Nucl. Inst. and Meth.

B. First Oscillation Result: arXiv:1203:1669

- Dec. 24, 2011 – Feb. 17, 2012
- All 3 halls (6 ADs) operating
- First observation of ν_e disappearance
- Phys. Rev. Lett. **108**, 171803 (2012)

C. This Update:

- Dec. 24, 2011 – May 11, 2012
- More than 2.5x the previous data set