Daya Bay 実験における反電子ニュートリノ消失の観測

中島　康博

Lawrence Berkeley National Laboratory

Kyoto University
April 27, 2012

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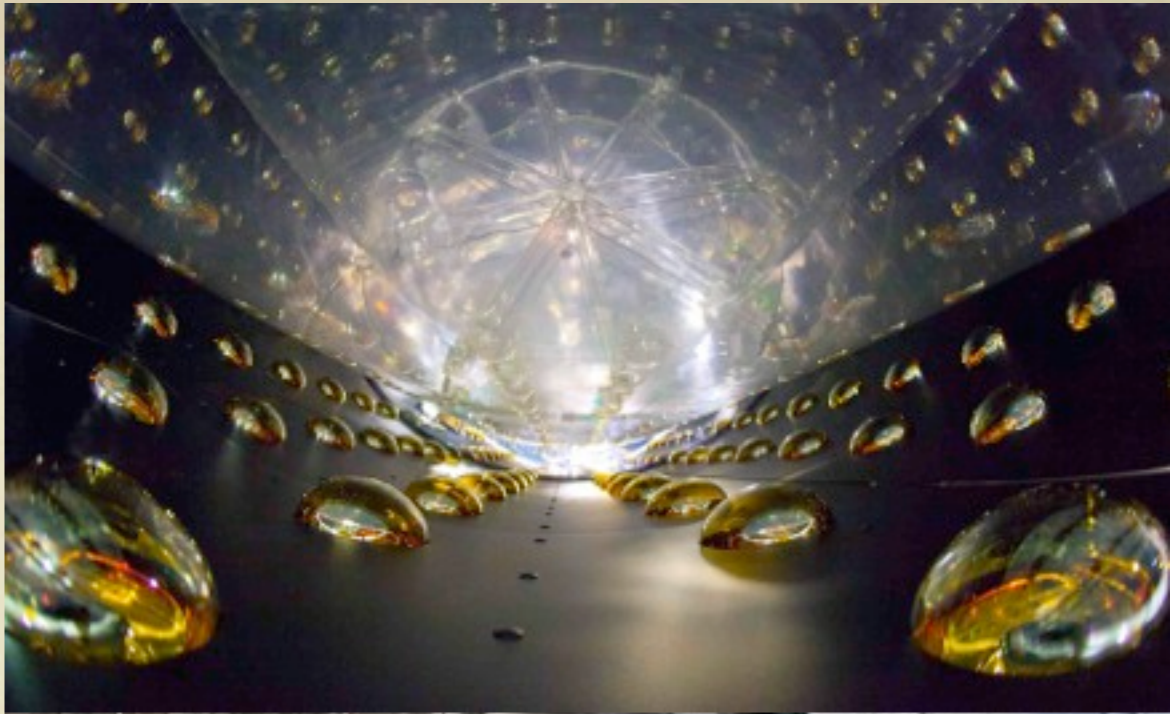
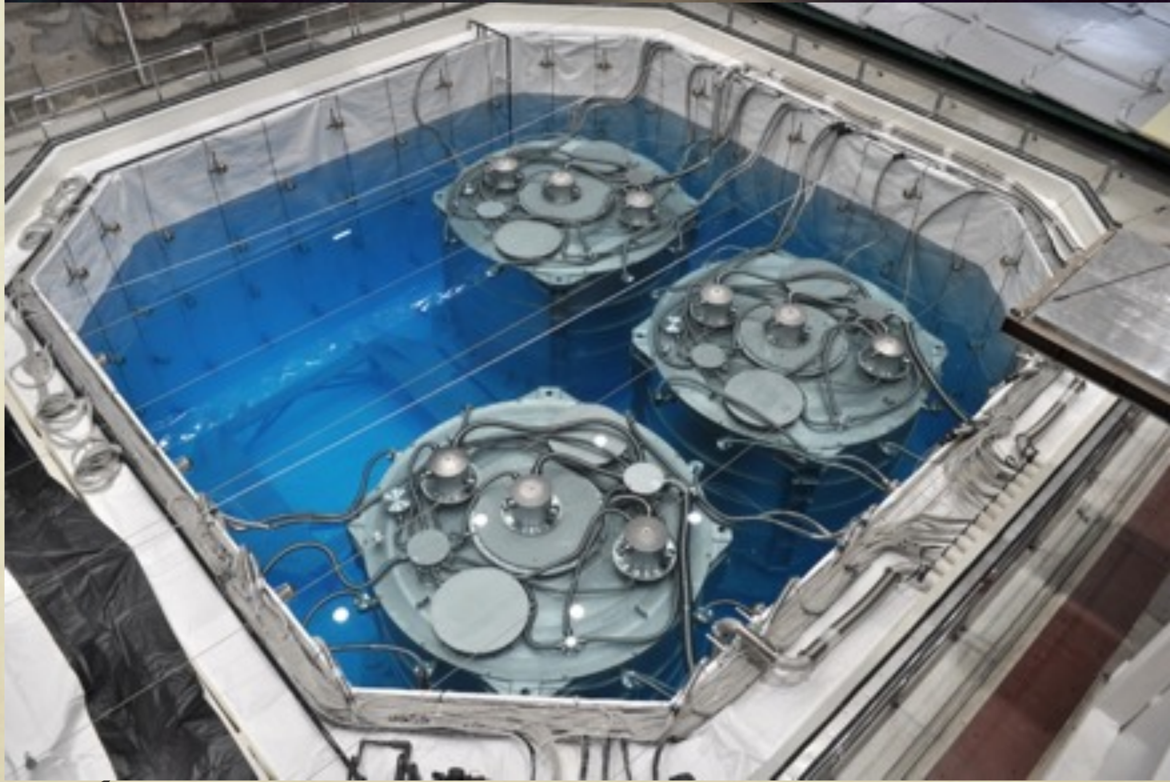




Neutrino Mixing

- Neutrino flavor eigenstates and Mass eigenstates are mixed

Weak eigenstate (α = e, μ, τ)

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}\,|\nu_i\rangle$$

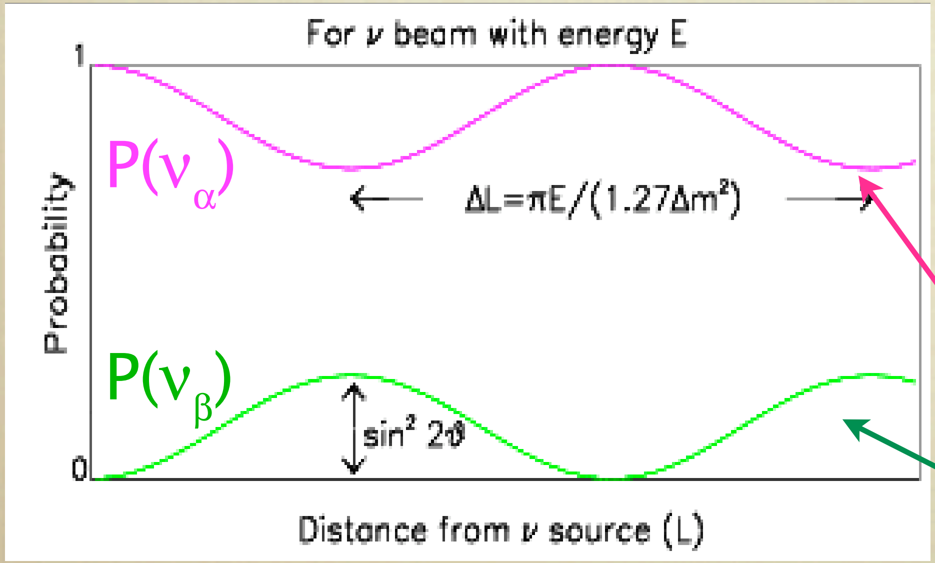
Mass eigenstate (i = 1, 2, 3)

MNS mixing matrix

- Neutrinos change their flavor as they travel (neutrino oscillation)
  - Natural interferometer to explore fundamental nature of neutrinos

Two neutrino case:

$$P(\nu_\alpha \to \nu_\beta) \;=\; |\langle \nu_\beta|\nu(t)\rangle|^2 = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2[\mathrm{eV}^2]L[\mathrm{km}]}{E[\mathrm{GeV}]}\right)$$



θ	: mixing angle
Δm^2	: mass squared difference
L [km]	: the distance traveled
E (GeV)	: the energy of neutrino

disappearance of ν_α

appearance of ν_β

Mixing Parameters

$$c_{ij} \equiv \cos\theta_{ij} \text{ and } s_{ij} \equiv \sin\theta_{ij}$$

$$U_{if} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\theta_{23} \approx 45^{o}$

Atmospheric ν

Accelerator ν

$\theta_{13} < 10^{o}$ (as of 2011)

Short-Baseline Reactor ν

Accelerator ν

$\theta_{12} \approx 35^{o}$

Solar ν

Long-Baseline Reactor ν

- θ_{13} was the only angle not firmly observed
- CP-violating phase δ is also not known.

How to Measure θ$_{13}$

- Look for ν$_e$ appearance from ν$_\mu$ beam
  - Accelerator long-baseline experiments: **T2K**, MINOS, NOvA

$$\begin{array}{rcl} P(\nu_\mu \to \nu_e) & \approx & \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 \Delta \\ & \pm & \alpha \sin 2\theta_{13} \sin \delta \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin^3 \Delta \\ & - & \alpha \sin 2\theta_{13} \cos \delta \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos \Delta \sin 2\Delta \\ & + & \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 \Delta \end{array}$$

$$\begin{array}{rcl} \alpha & \equiv & \Delta m^2_{21}/\Delta m^2_{31} \\ \Delta & = & \Delta m^2_{31} L/4E \end{array}$$

Sensitive to θ$_{13}$, δ and mass hierarchy

- Look for ν$_e$ disappearance
  - Reactor based short-baseline (~O(1) km) experiments: **Daya Bay**, RENO, Double Chooz

$$\boldsymbol{P(\nu_e \to \nu_e) \approx 1 - \sin^2 2\theta_{13} \sin^2(\Delta m^2_{31} L/4E_\nu)}$$

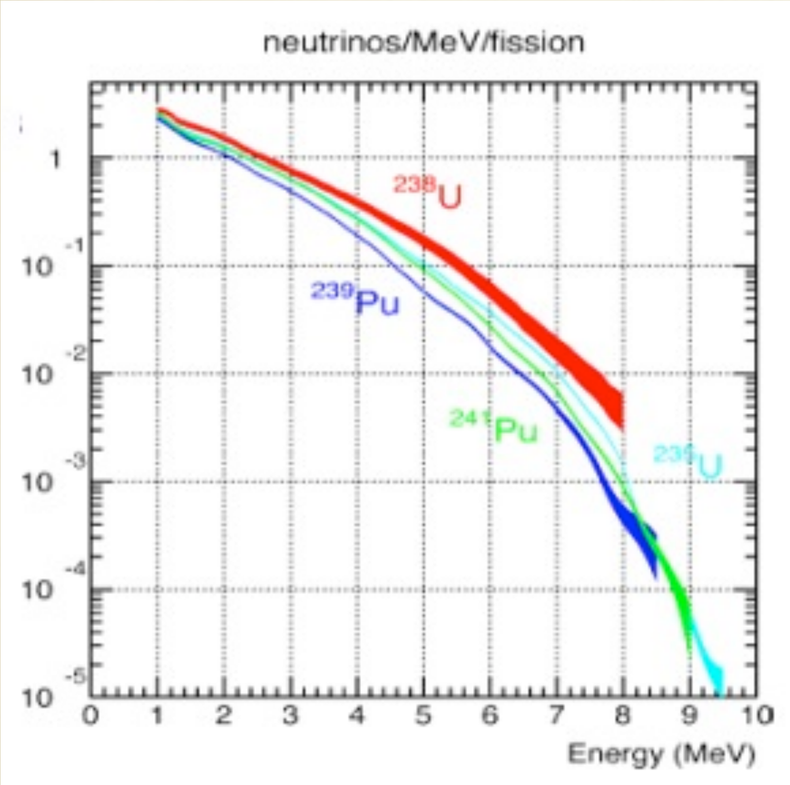
Sensitive only to θ$_{13}$

Both kinds of experiments are needed to determine CP violation and mass hierarchy

Measurement of θ_{13} with reactor neutrinos

Source

$\overline{\nu}_e$ from n-rich fission products



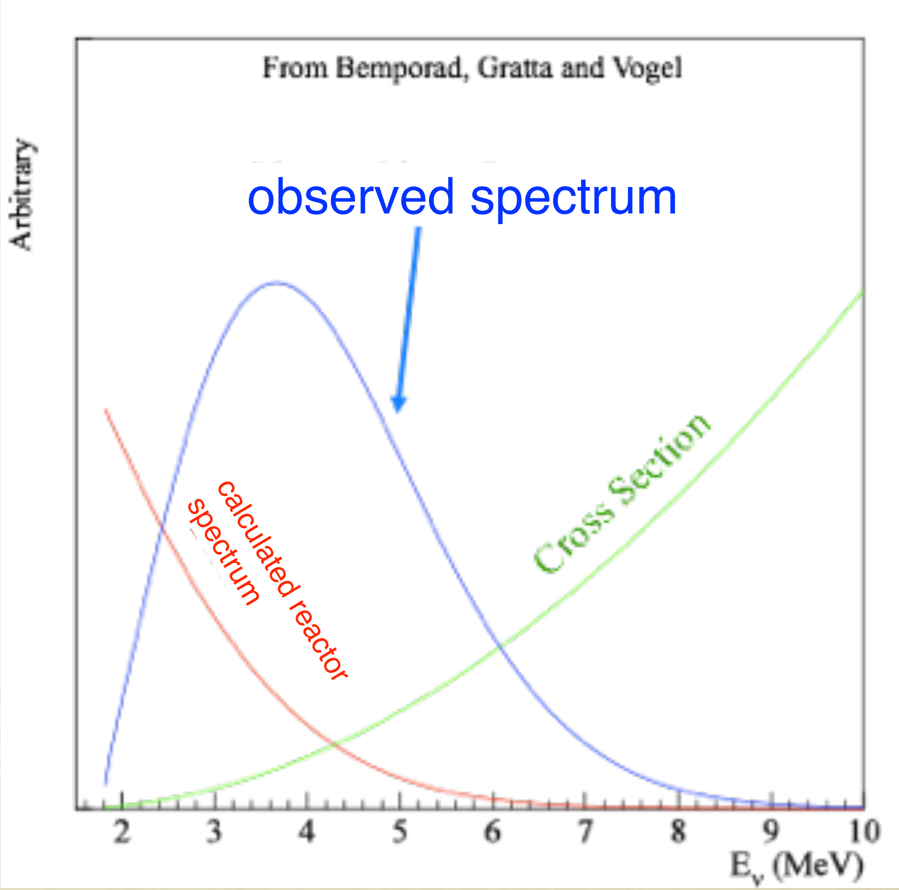
~ 200 MeV per fission

~ 6 $\overline{\nu}_e$ per fission

~ 2 x 10^{20} $\overline{\nu}_e$/GW_{th}-sec

Detection

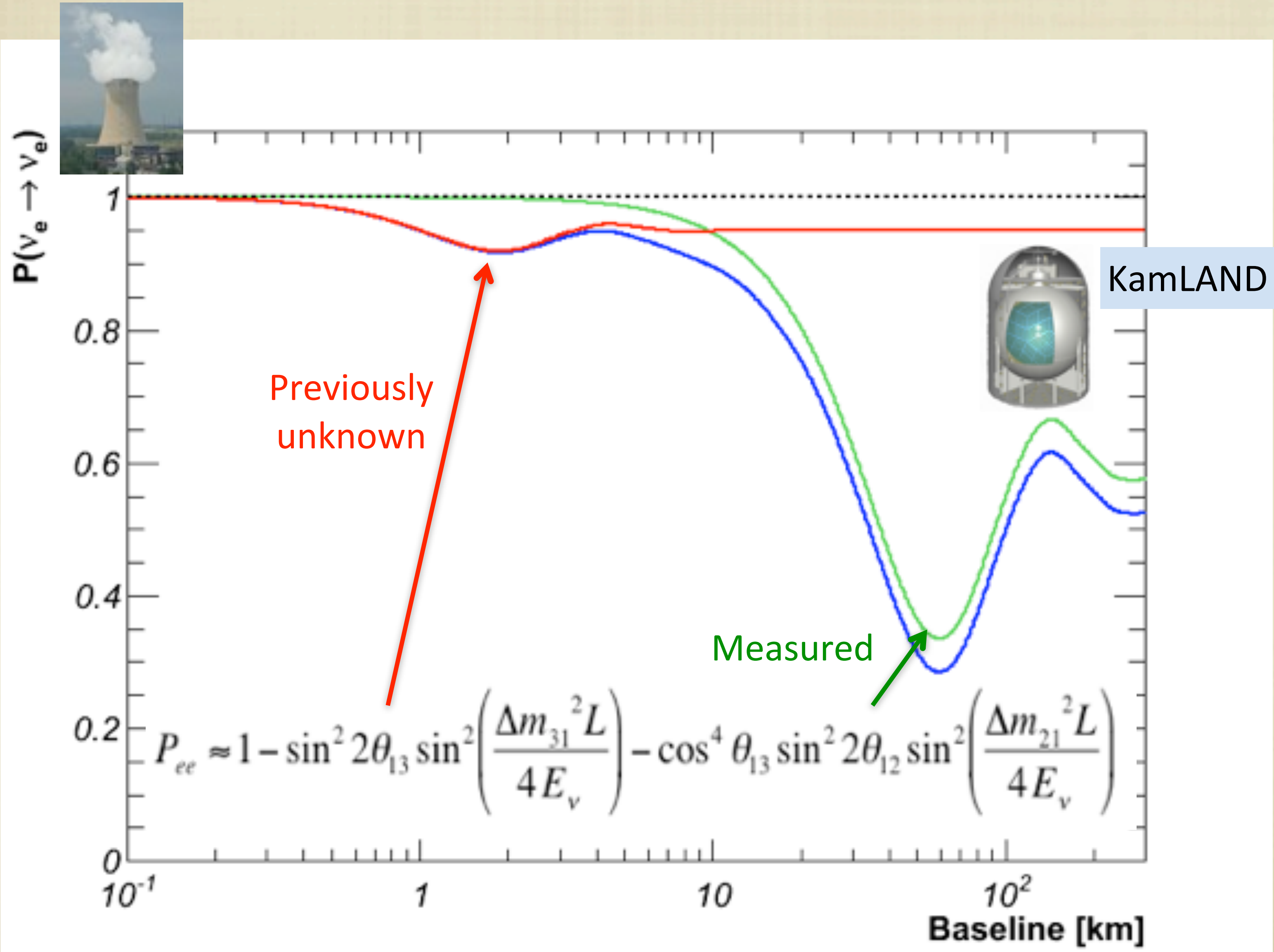
inverse beta decay $\overline{\nu}_e + p \rightarrow e^+ + n$



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

Measurement of θ_{13} with reactor neutrinos

θ_{13} revealed by a deficit of reactor antineutrinos at ~2 km.



Previously unknown

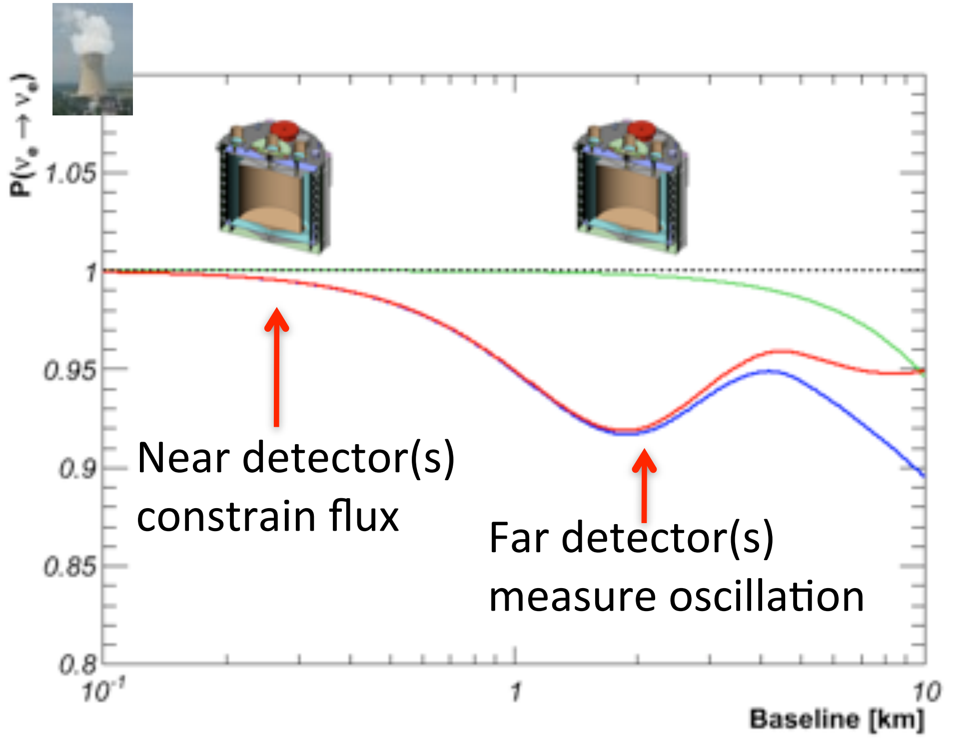
Measured

KamLAND

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

Measurement of θ_{13} with reactor neutrinos

- To measure a small deficit, reducing systematic uncertainty is the key.
- Put "identical" detectors at near and far distances, and make a **relative measurements.**
- Uncertainties for absolute reactor flux (largest error in previous measurements) and absolute detector efficiency cancel.



Near detector(s) constrain flux

Far detector(s) measure oscillation

Far/Near ν_e Ratio

Distances from reactor

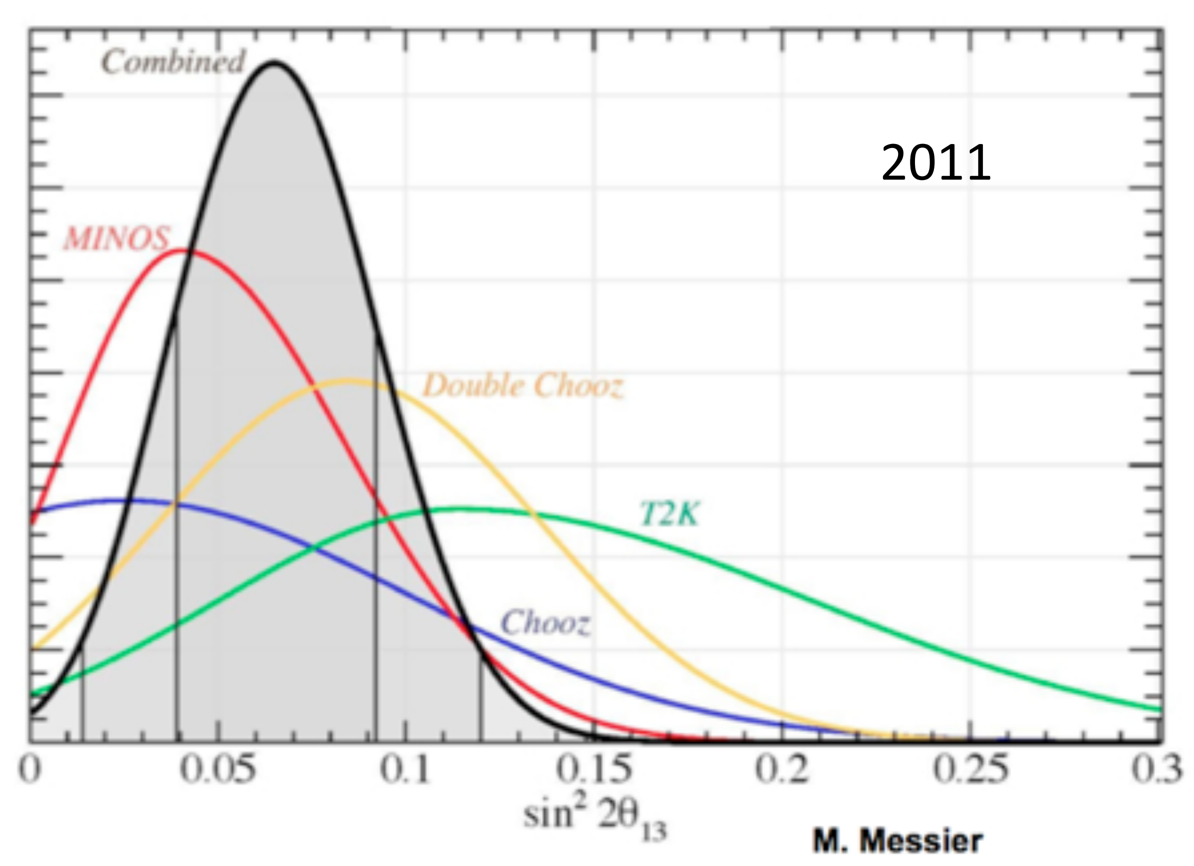
Oscillation deficit

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

Detector Target Mass

Detector efficiency

Indications of non-zero θ_{13}



2011

M. Messier

T2K

$$0.03(0.04) < \sin^2 2\theta_{13} < 0.28(0.34)$$

PRL 107, 041801 (2011)

MINOS

$$2\sin^2(\theta_{23})\sin^2(2\theta_{13}) = 0.041^{+0.047}_{-0.031}$$

PRL. 107, 181802 (2011)

Double Chooz

$\sin^2(2\theta_{13})=0.086 \pm$

$0.041(\text{stat}) \pm 0.030(\text{syst})$

Y. Abe et al. PRL 108 131801 (2012)

- Many hints of non-zero value of θ_{13} in 2011
- No $\theta_{13}=0$ exclusion with > 2.5σ significance before Daya Bay (and RENO)

The Daya Bay Experiment

Daya Bay Collaboration

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

Europe (2)

Charles Univ., Dubna

~230 Collaborators

Location of Daya Bay

Daya Bay Nuclear Power Station

~55 km

Hong Kong International Airport

Series HM20CRS
Edition 7 2002

Survey and Mapping Office, Lands Department
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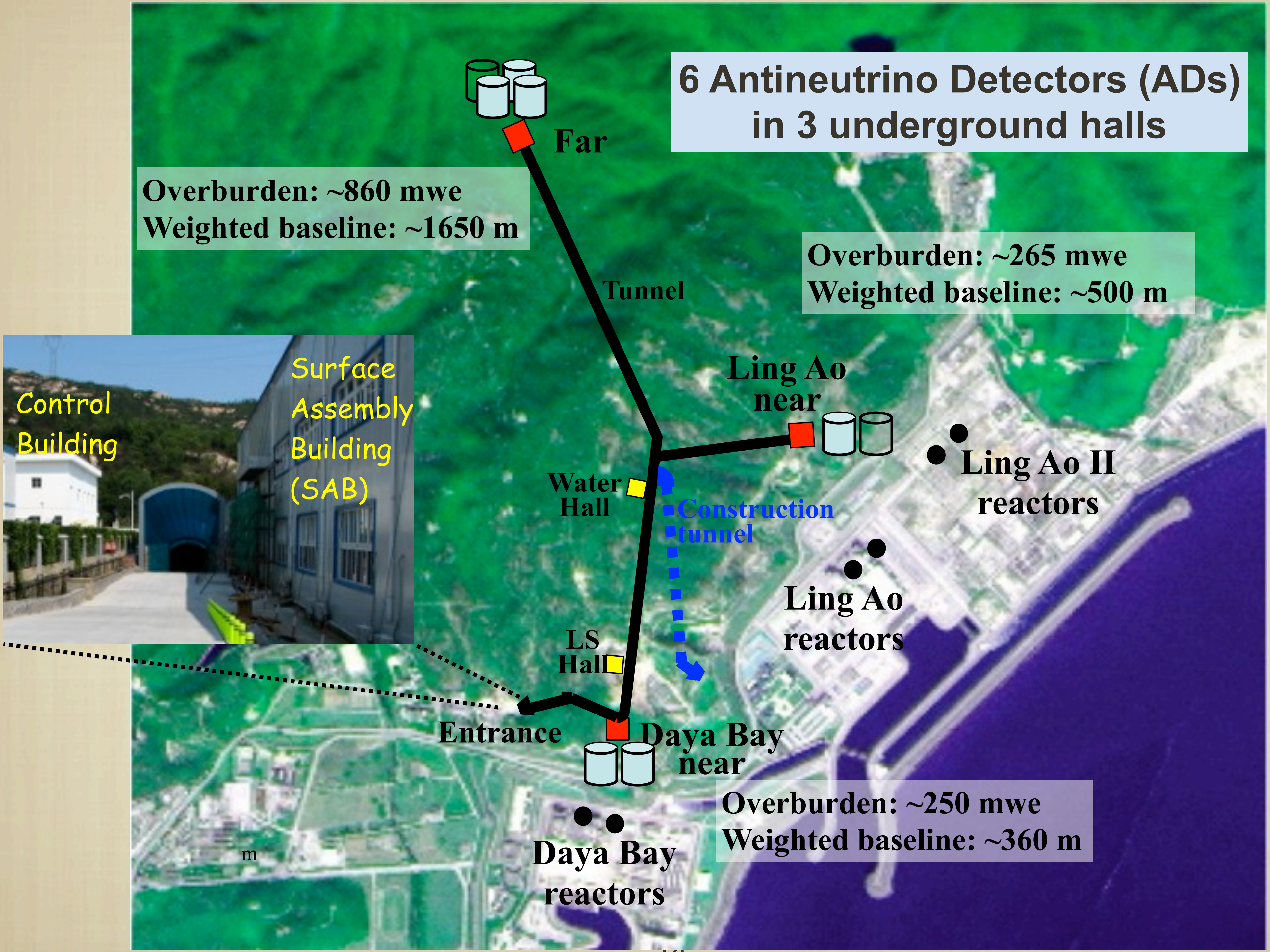
Daya Bay Reactor Complex

- Ranked among the top 5 most powerful complexes in the world, producing 17.4 GW_{th}
- Adjacent to mountains
  - Easy to construct tunnels to reach underground labs with sufficient overburden to suppress cosmic rays

6 Antineutrino Detectors (ADs) in 3 underground halls



Overburden: ~860 mwe
Weighted baseline: ~1650 m

Overburden: ~265 mwe
Weighted baseline: ~500 m

Overburden: ~250 mwe
Weighted baseline: ~360 m

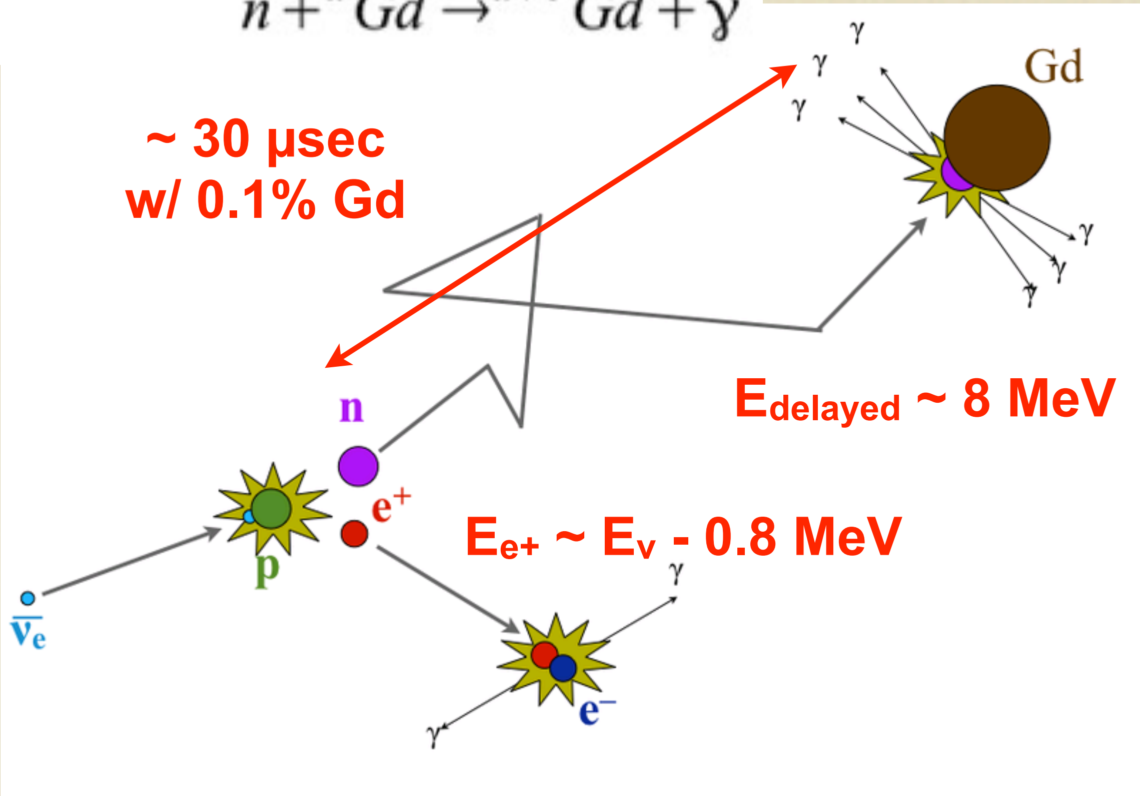
Detection Method

Antineutrinos are detected via inverse beta decay reaction

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

$$\downarrow$$

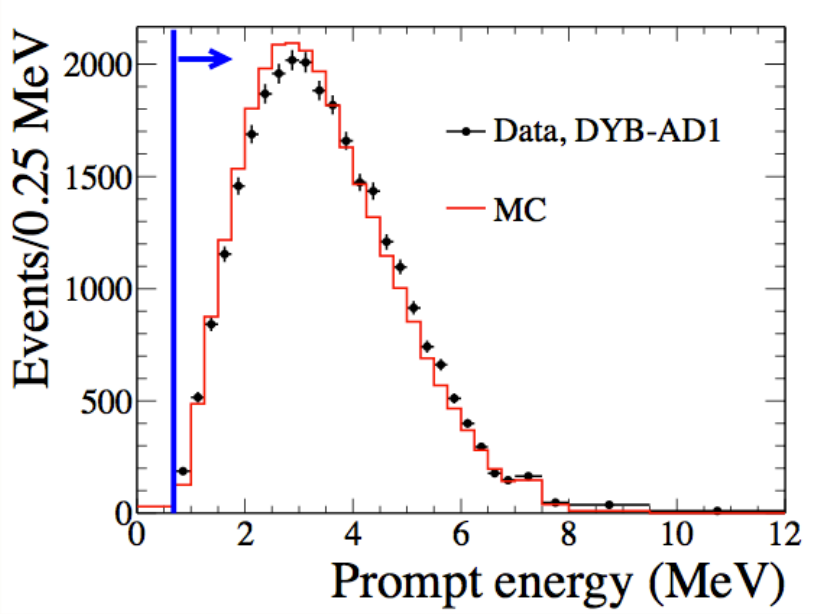
$$n + {}^{x}Gd \rightarrow {}^{x+1}Gd + \gamma$$

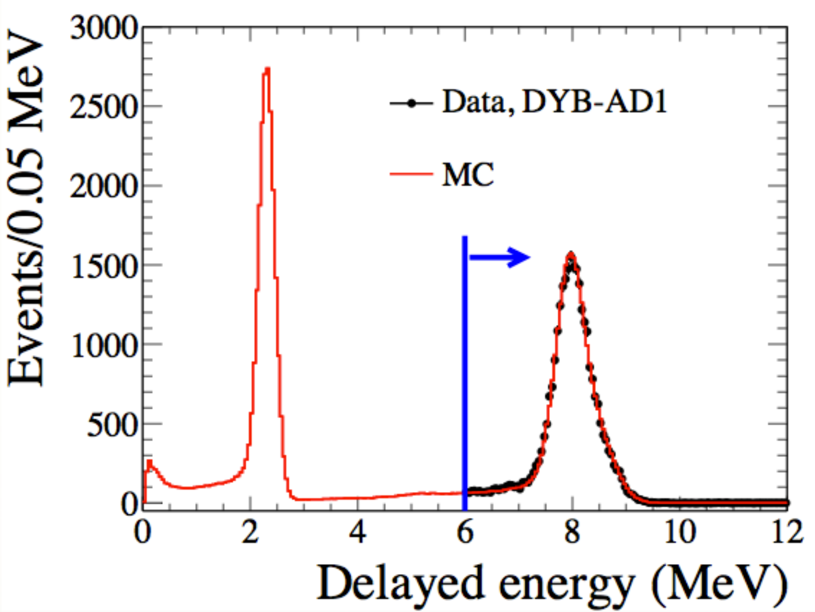


~ 30 µsec
w/ 0.1% Gd

$E_{delayed}$ ~ 8 MeV

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





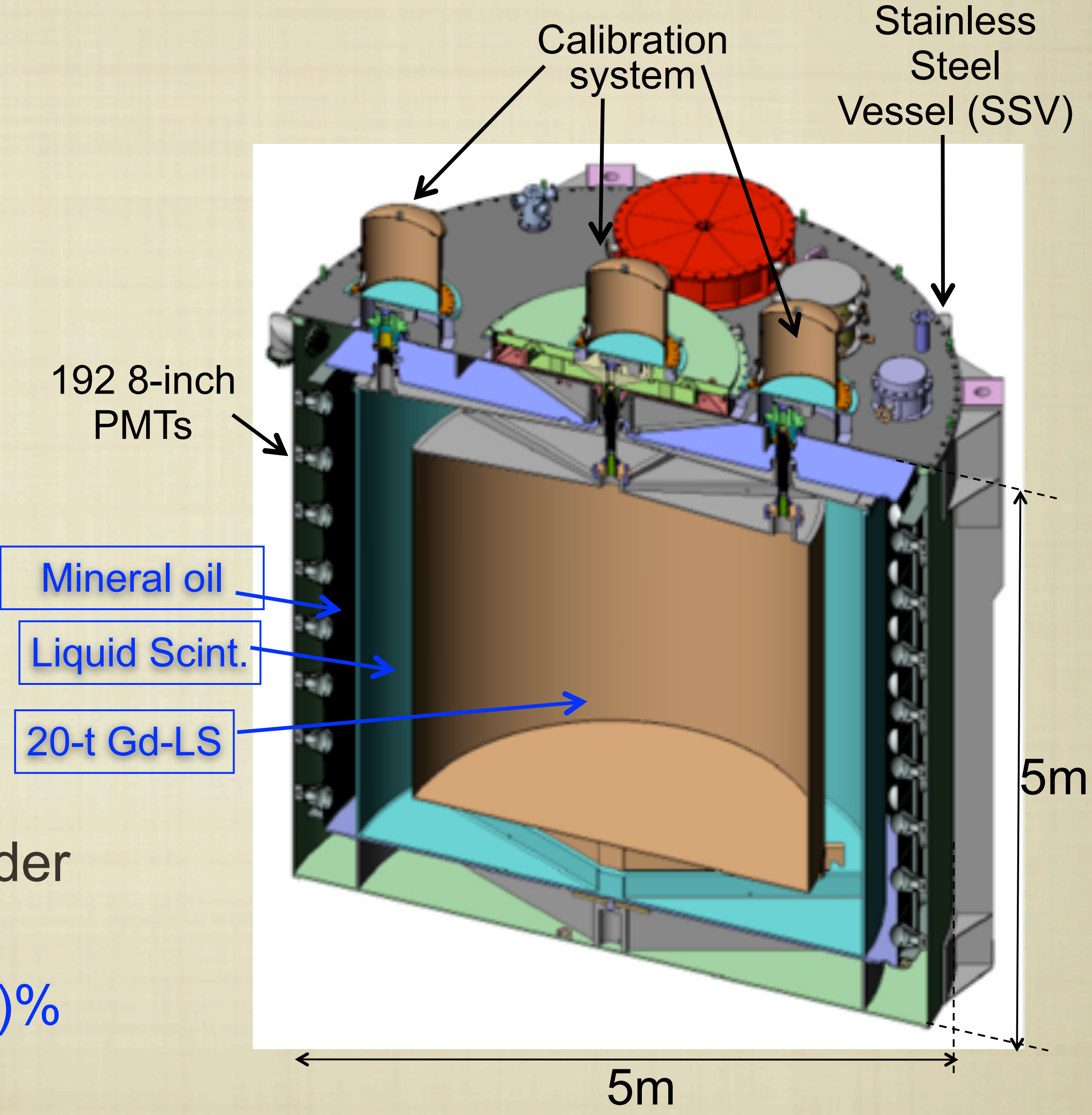
Prompt + Delayed coincidence

- Prompt positron: carries antineutrino energy
- Delayed neutron capture: efficiently tag antineutrino signal.

Antineutrino Detector

- Three zone cylindrical modules:

Zone	Mass	Liquid	Purpose
Inner acrylic vessel	20 t	Gd-doped liquid scintillator	**Anti-neutrino target**
Outer acrylic vessel	20 t	Liquid scintillator	Gamma catcher (from target zone)
Stainless steel vessel	40 t	Mineral Oil	Radiation shielding

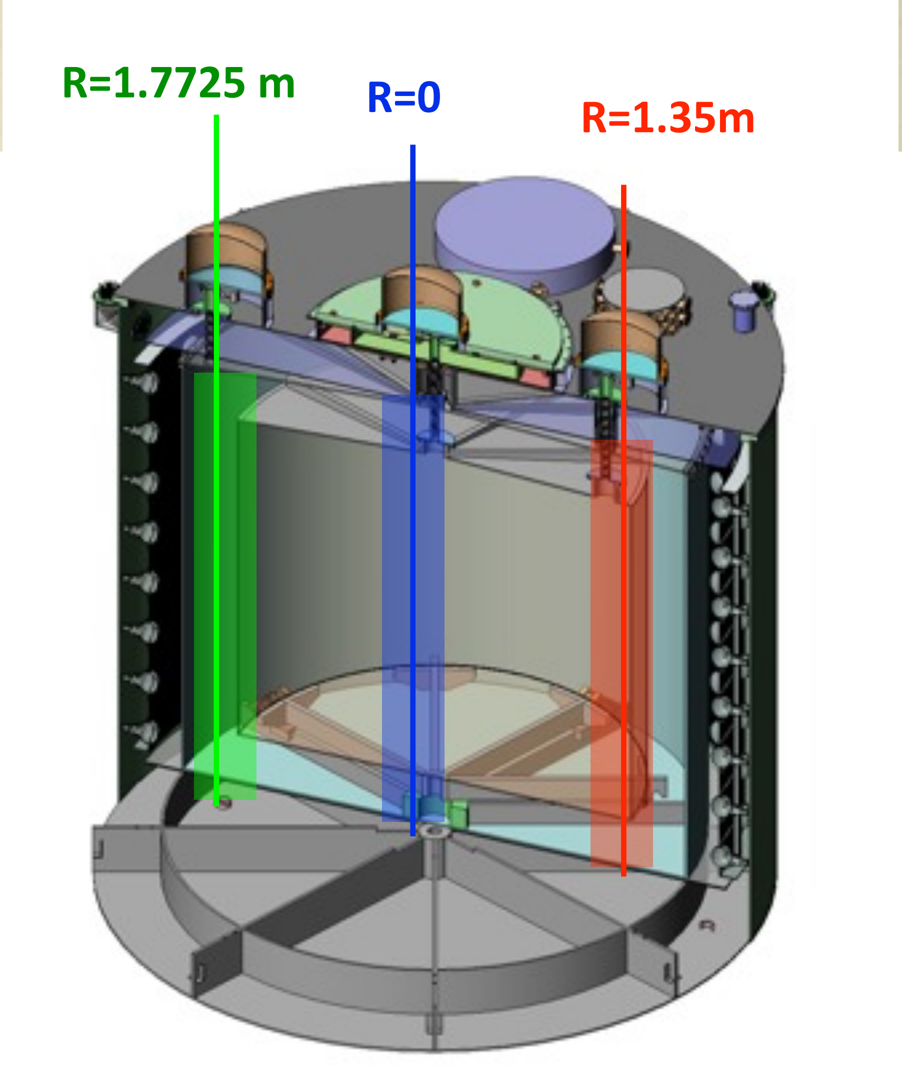


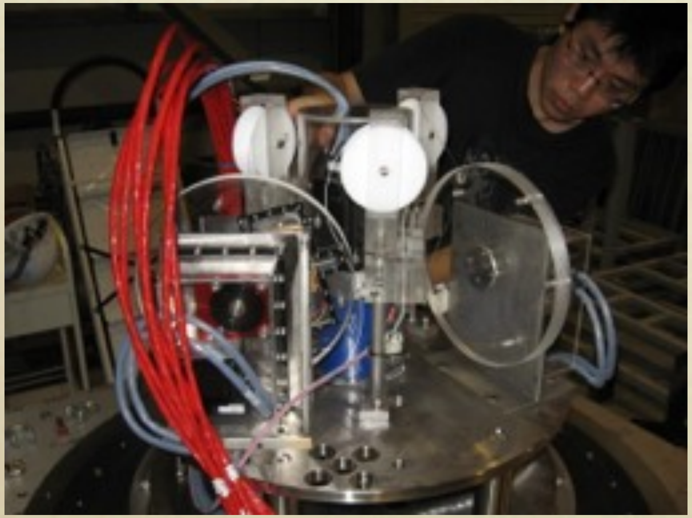
- Reflectors at top/bottom of cylinder are used to increase light yield.
- Energy resolution: $(7.5/\sqrt{E} + 0.9)\%$

Calibration System

- Three Automated Calibration Units (ACUs) per detector.
  - Deploy sources along the z-axis
- Three sources + LED in each ACU, on a turn table.
  - ^{68}Ge (1.02 MeV)
  - ^{60}Co (2.506 MeV)
  - ^{241}Am-^{13}C (8MeV)
  - LED -- Timing and gain calibration

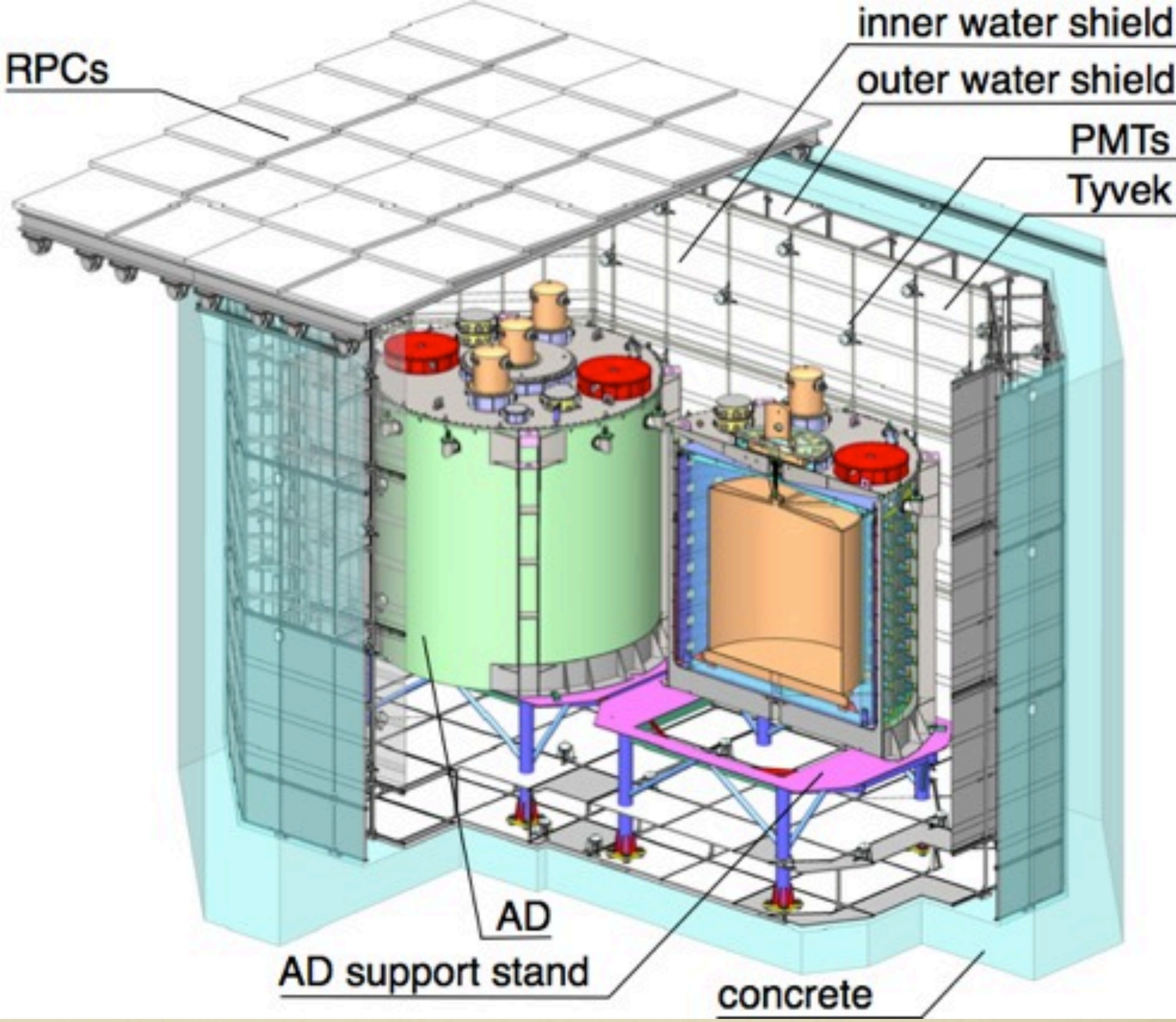
} Energy calibration





Muon Tagging System

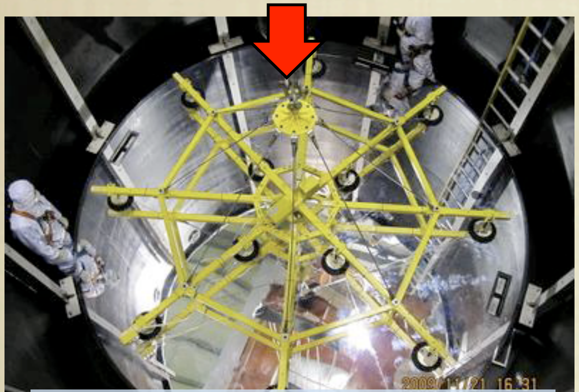
- 2.5 meter thick two-section water shield
  - Cherenkov detector to tag cosmic ray muons.
  - Shield for neutrons and gammas from surrounding materials.
- RPC
  - Covers water pool to provide further muon tagging.
  - Detectors are in commissioning.
  - Not used for “muon veto” in the first analysis, but used for background studies.



Antineutrino Detector Assembly

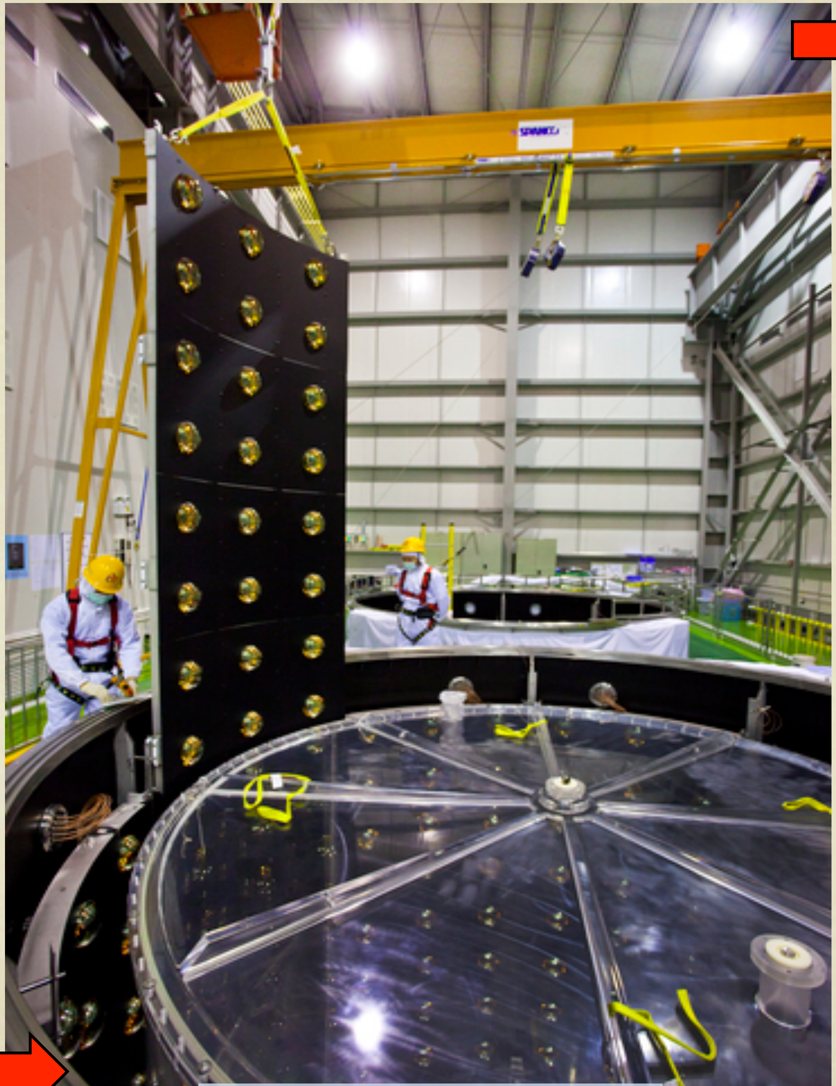
Antineutrino Detectors are assembled at the Surface Assembly Building

Stainless Steel Vessel (SSV) in assembly pit

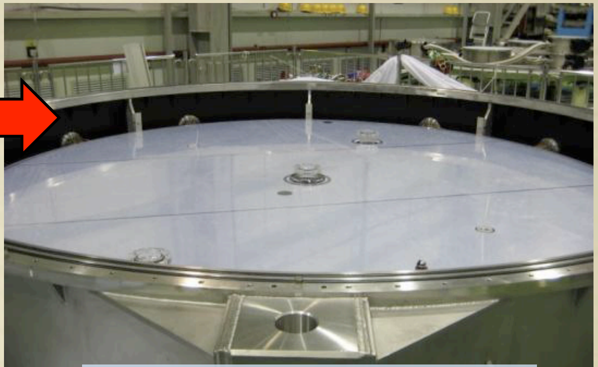


Install lower reflector

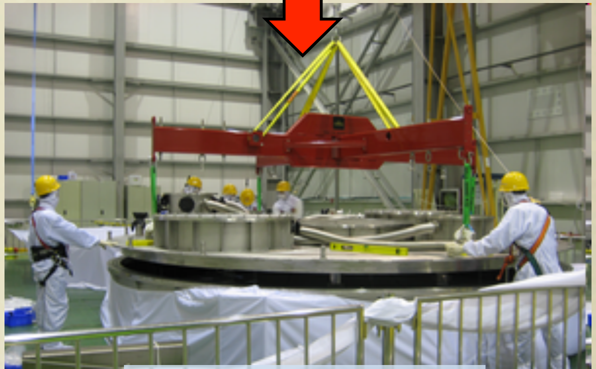
Install Acrylic Vessels



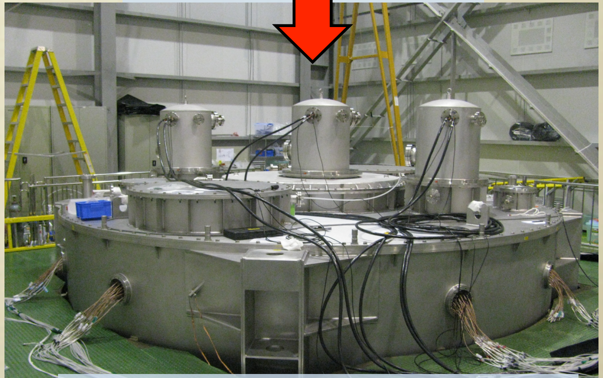
Install PMT ladders



Install top reflector



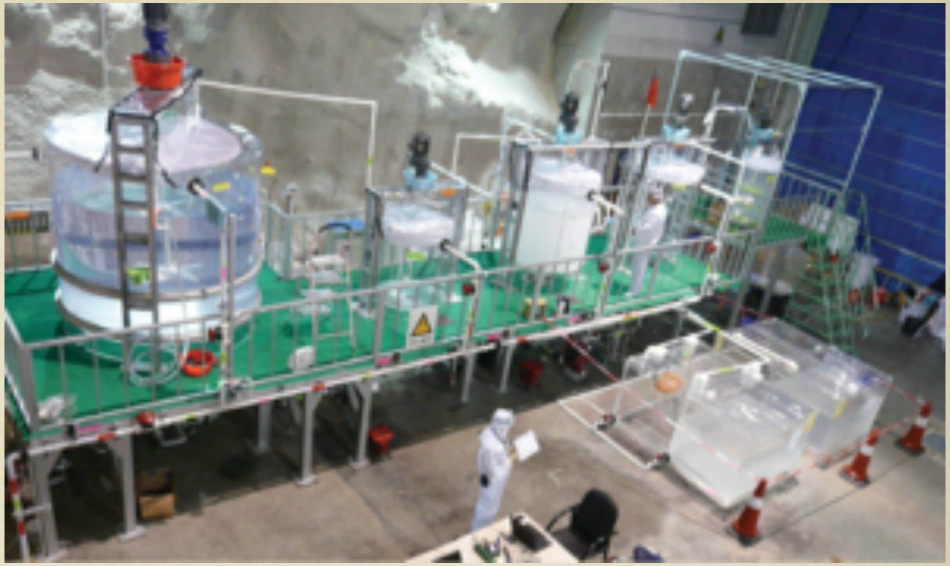
Close SSV lid

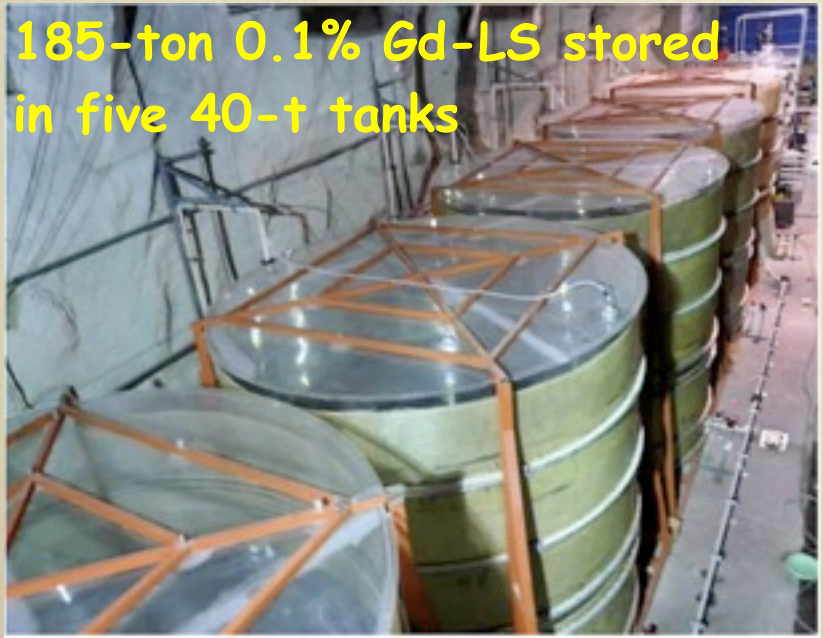


Install calibration units

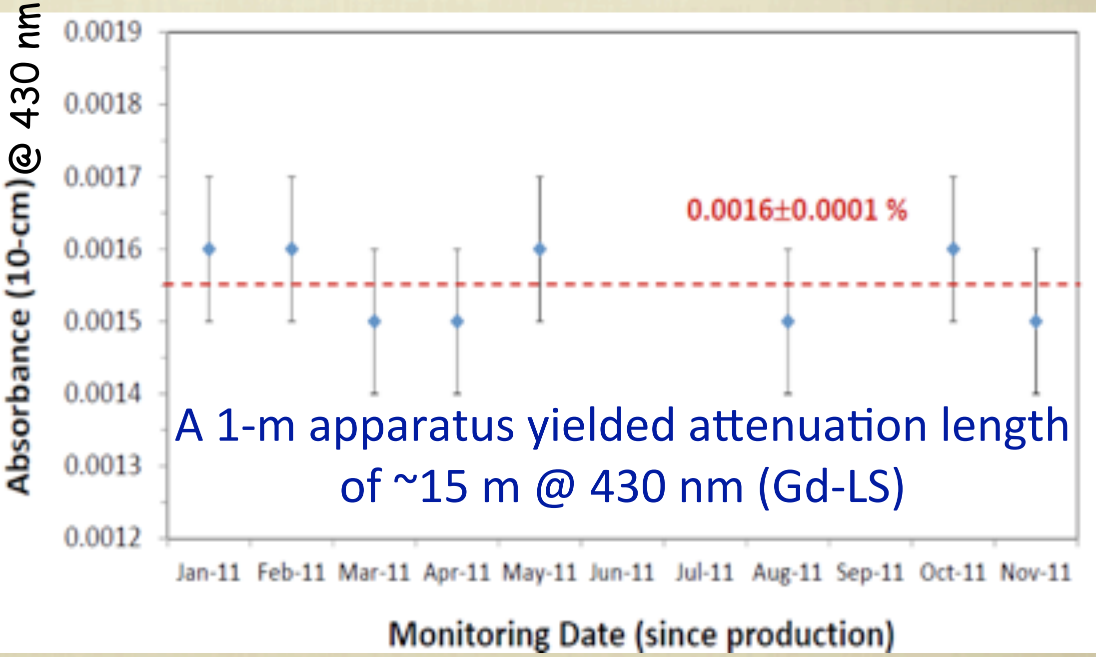
Liquid Scintillators

- The (Gd-)LS is produced in the underground LS hall at Daya Bay.
  - Gd (0.1%) + PPO (3 g/L) + bis-MSB(15mg/L) + LAB
- Produced 185-ton Gd-LS + 196-ton LS
  - Completed early 2011
  - Amount needed for all 8-detectors are produced at the same time to ensure identical detectors





185-ton 0.1% Gd-LS stored in five 40-t tanks



A 1-m apparatus yielded attenuation length of ~15 m @ 430 nm (Gd-LS)

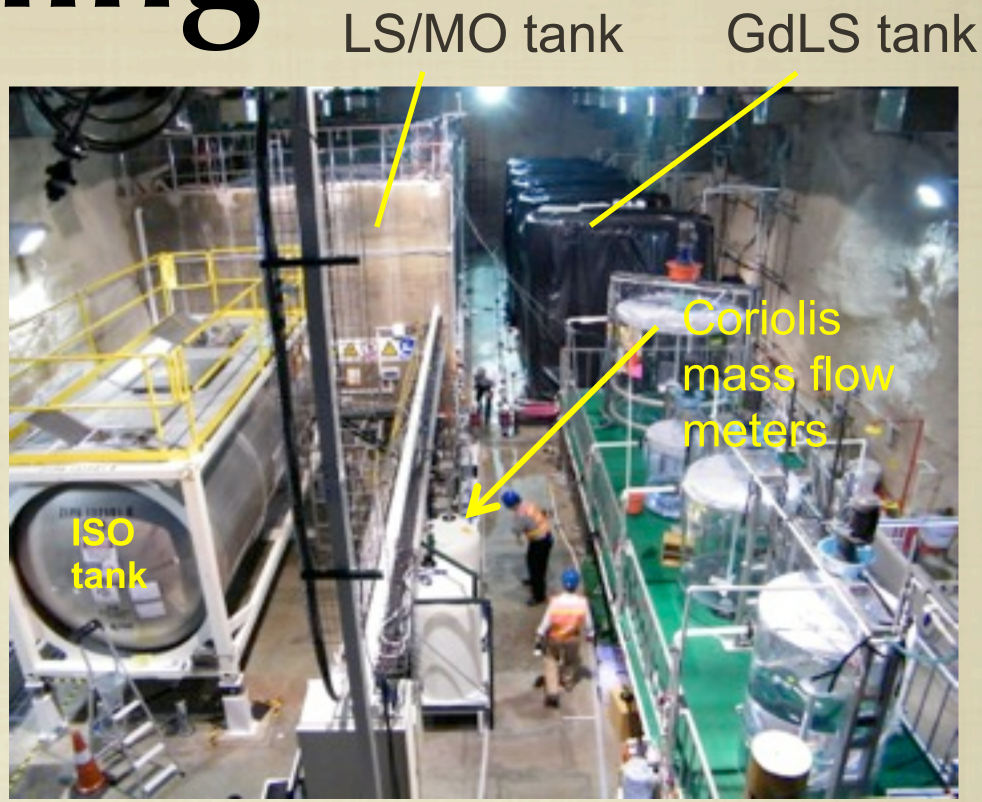
Detector Filling

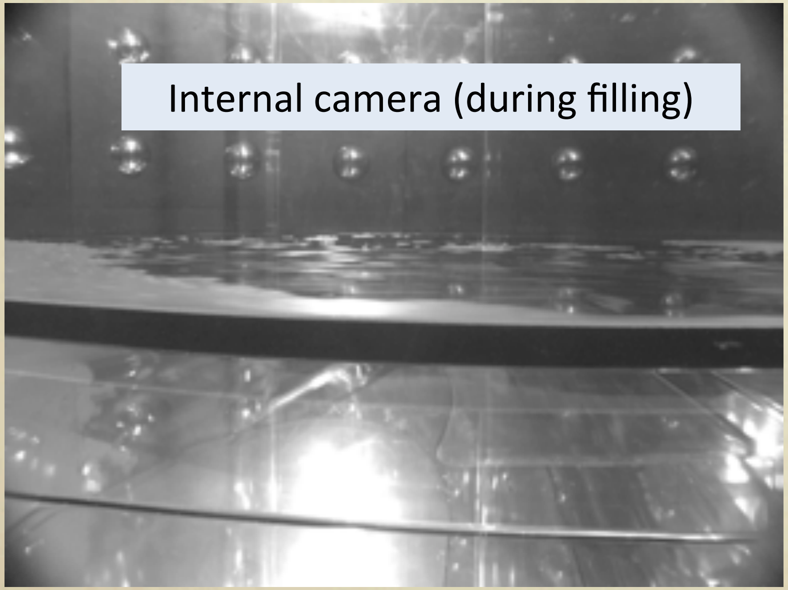
- The detectors are filled with liquid in the underground liquid scintillator hall.
- Target mass is measured with:

(1) 4 load cells supporting 20-ton ISO tank
(2) Coriolis mass flow meters

Uncertainty ~ 3kg in 20t (0.015%)

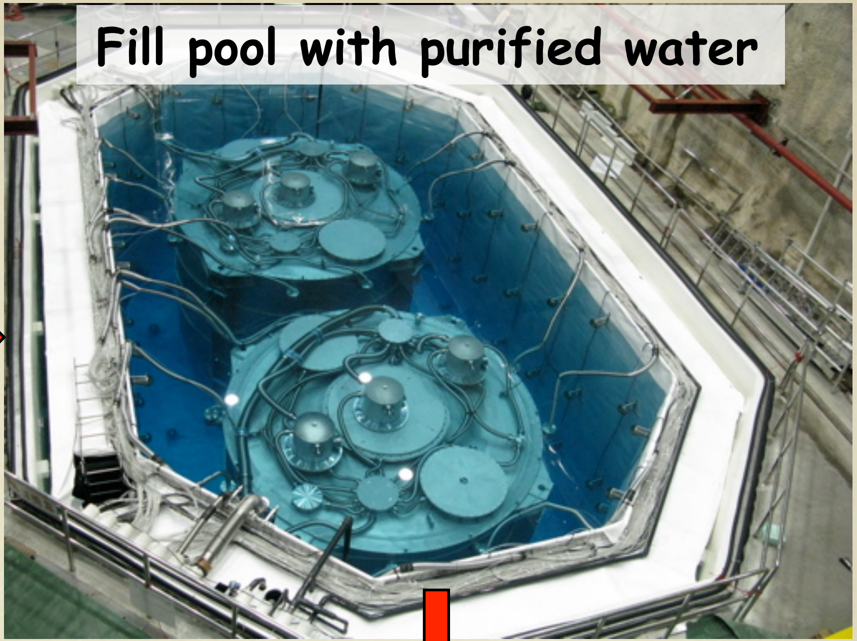
- Monitored with in-situ sensors




Internal camera (during filling)

Near Hall (EH1) Installation

Install filled AD in pool



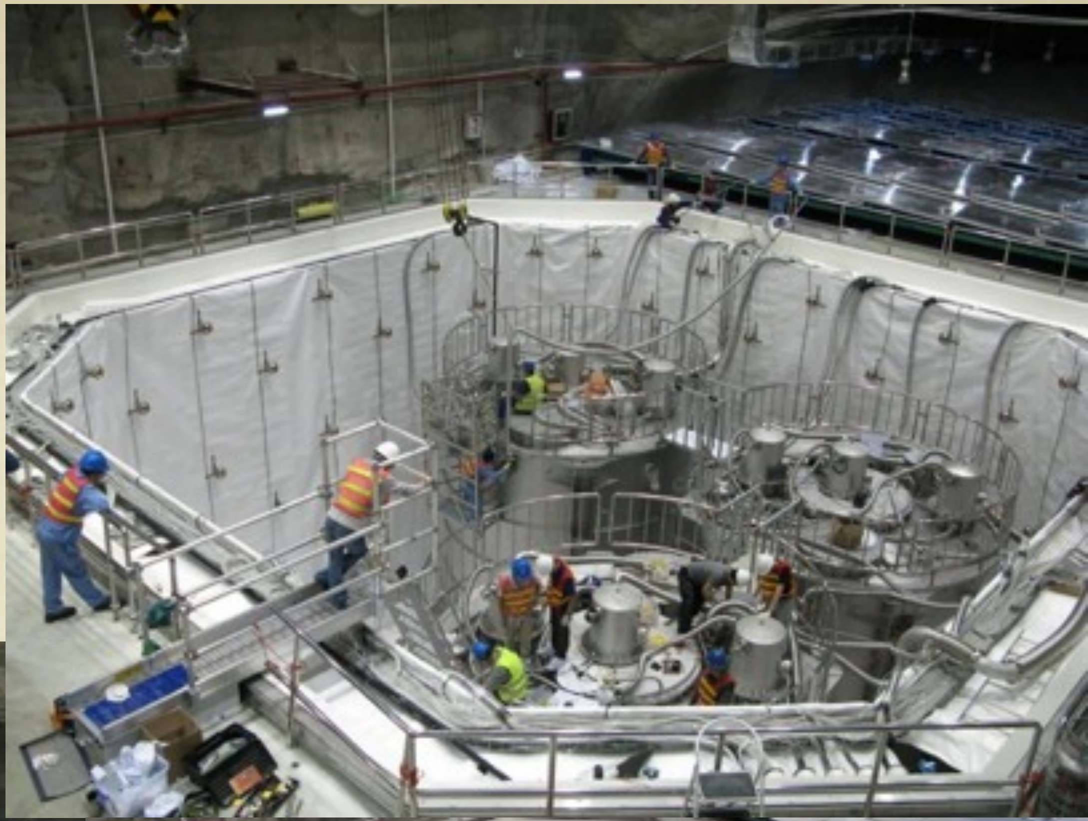
Fill pool with purified water

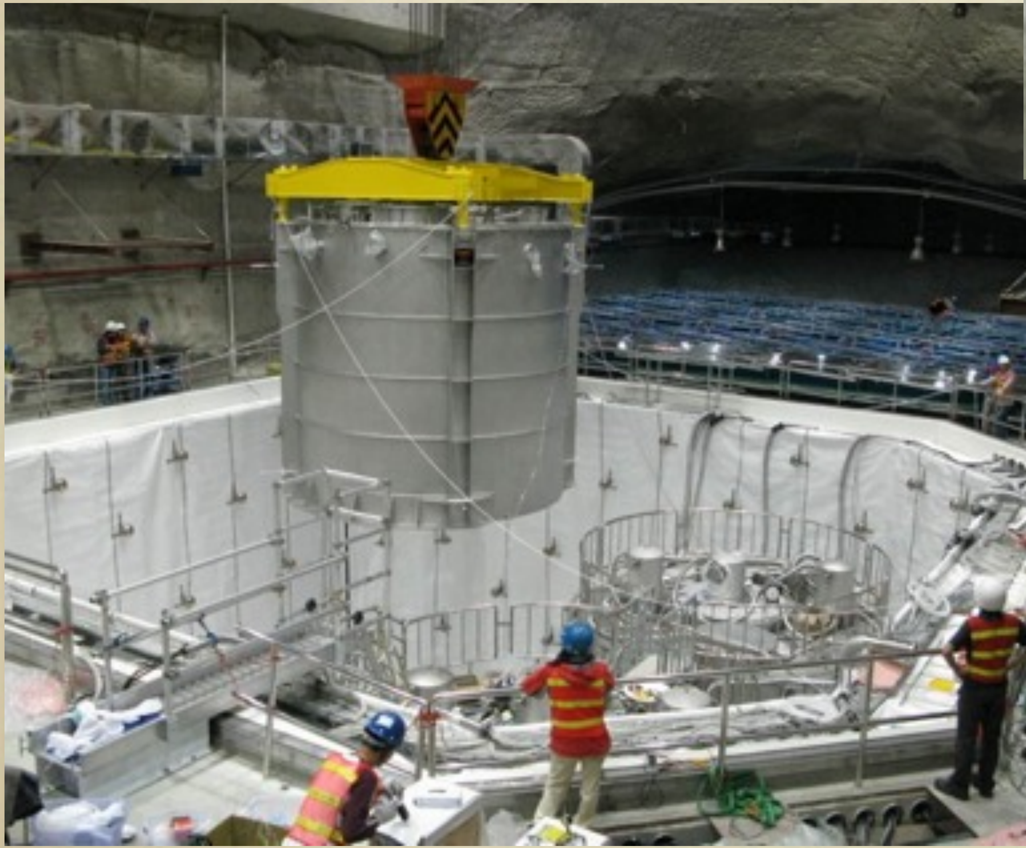
Place cover over pool

Data taking started on 15 Aug 2011

Roll RPC over cover

Far Hall (EH3) Installation





My work at Daya Bay

- In the past year (from April 25, 2011 to April 25, 2012)
  - Stayed in China for ~150 days
    - Assembling and testing of the PMT systems of Antineutrino Detectors
    - Monitoring Liquid Scintillator optical properties.
    - Commissioning of the antineutrino detectors in the experimental halls.
  - Analyses
    - Developing neutrino interaction vertex reconstruction
    - Studying energy scale calibration non-uniformity and systematic uncertainty
    - Independent oscillation analysis within LBNL group

Data Set for Oscillation Analysis

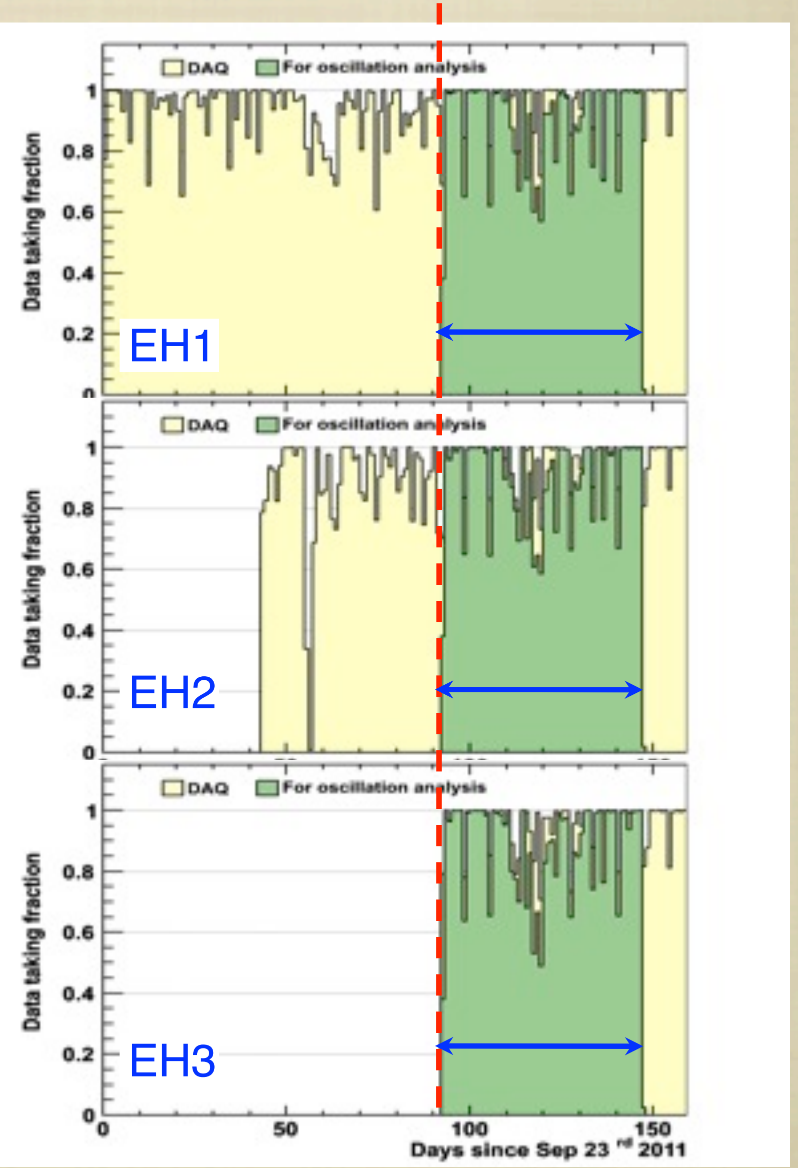
Data Taking Period

- Two Detector Side-by-Side Comparison
  - Sep. 23, 2011 - Dec. 23, 2011
  - Side-by-side comparison of 2 detectors in EH1
  - Demonstrated detector systematics better than requirements.

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

- Current Oscillation Analysis
  - Dec. 24, 2011 - Feb. 17, 2012
  - All 3 halls (6 ADs) operating
  - DAQ uptime > 97%
  - Antineutrino data: ~89%

Daya Bay Collab.
Phys. Rev. Lett. 108, 171803 (2012)



Data Analysis Approach

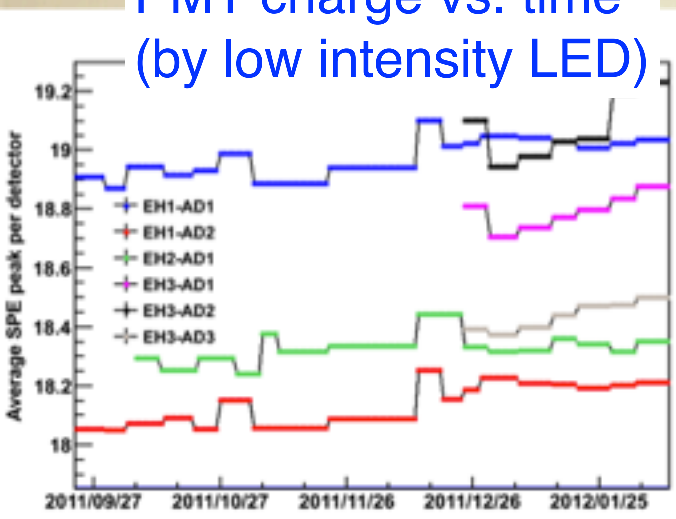
- Multiple independent analyses are performed to cross-check the results
- Difference between analyses
  - Energy calibration & reconstruction
    - Calibration source (^{60}Co, 2.5 MeV)
    - Spallation neutron (8-MeV Gd-capture peak)
  - Antineutrino selection
    - Different muon veto
    - Different multiplicity cut
  - Background studies
  - Oscillation fit method
- Blind analysis
  - Target mass, baselines and reactor flux information were blinded.
  - Cross-checked between analyses before unblinding.
- All analysis gave a consistent results

Only results from one analysis are presented here

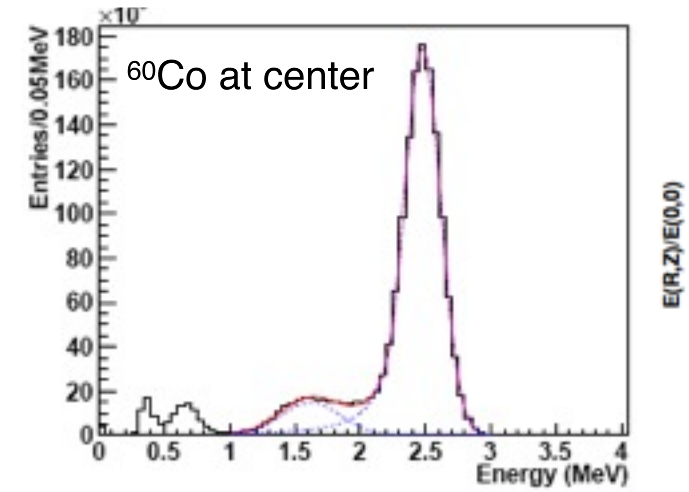
Energy Calibration

PMT Gain (PE/ADC) → Energy scale (MeV/PE) → Non-uniformity correction

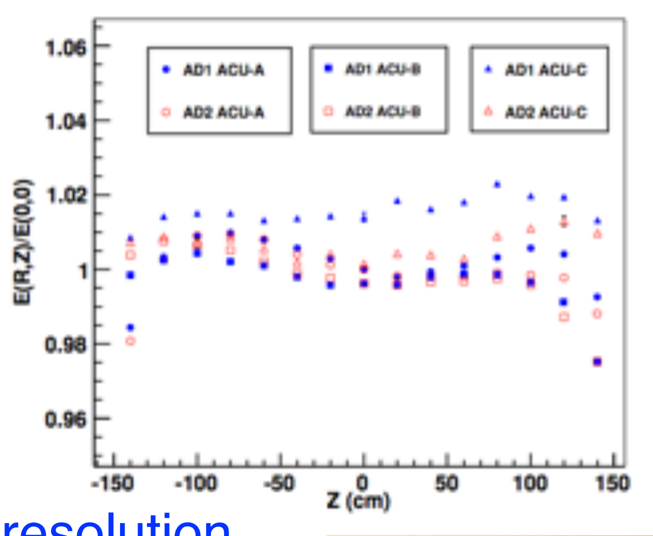
PMT charge vs. time (by low intensity LED)

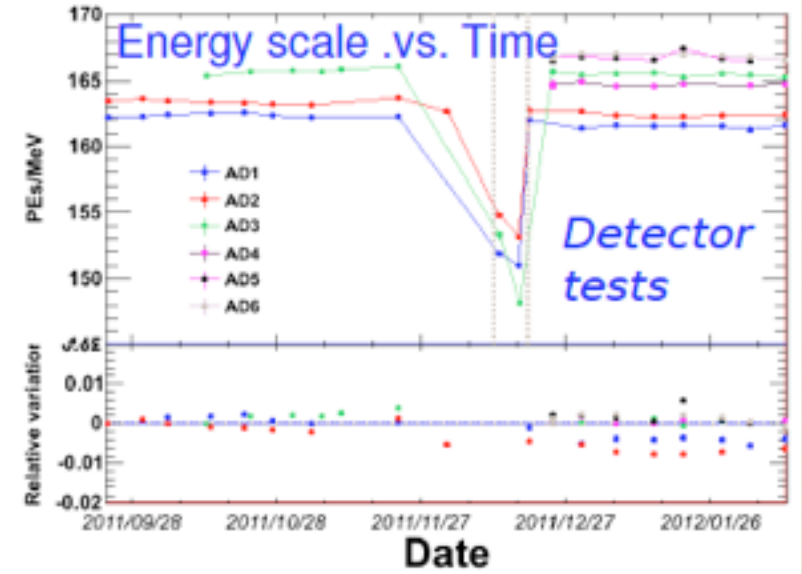


Energy Calibration

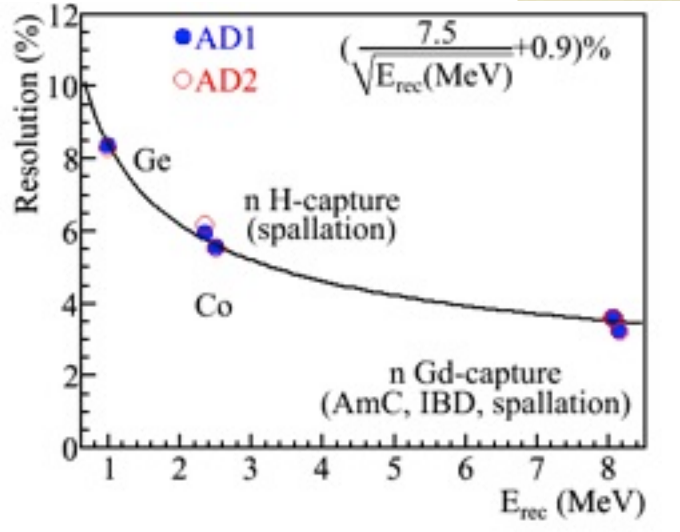


Energy vs. position





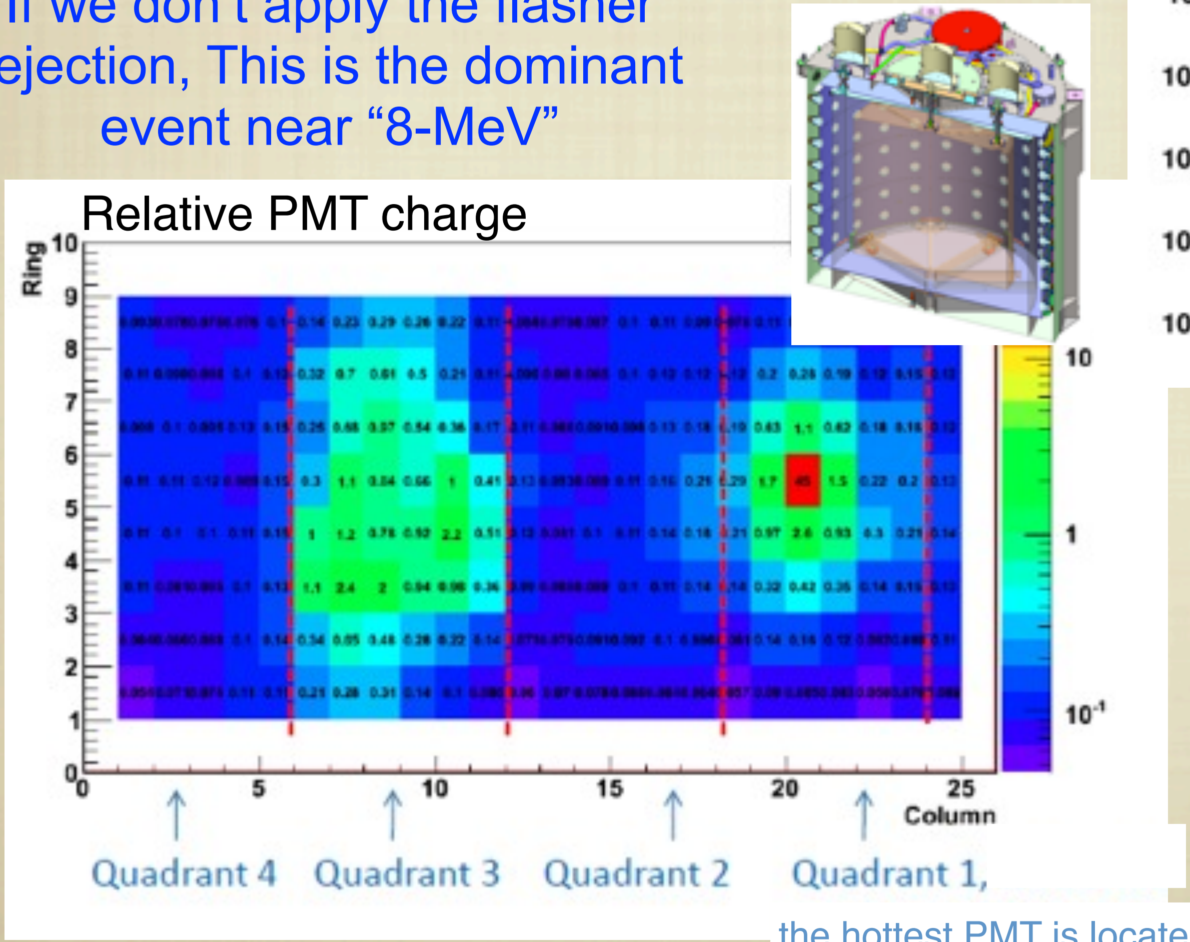
Energy resolution



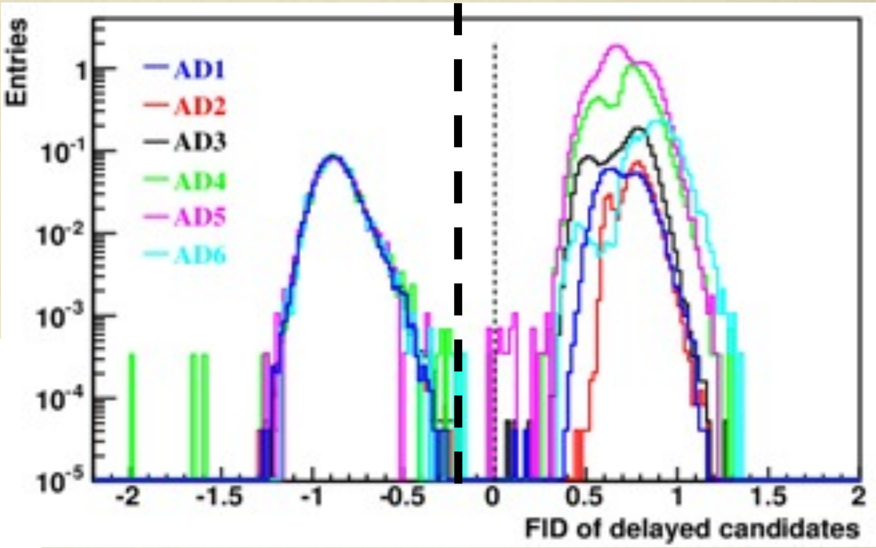
PMT Light Emission (Flashing)

- Instrumental background from ~5% of PMTs.
- ‘Shines’ light to opposite side of the detector
- Easily discriminated from normal signals

If we don’t apply the flasher rejection, This is the dominant event near “8-MeV”



the hottest PMT is located



$$log10\left(\text{Quadrant}^2+\left(\frac{\text{MaxQ}}{0.45}\right)^2\right)<0$$

Quadrant = Q3/(Q2+Q4)
MaxQ = maxQ/sumQ

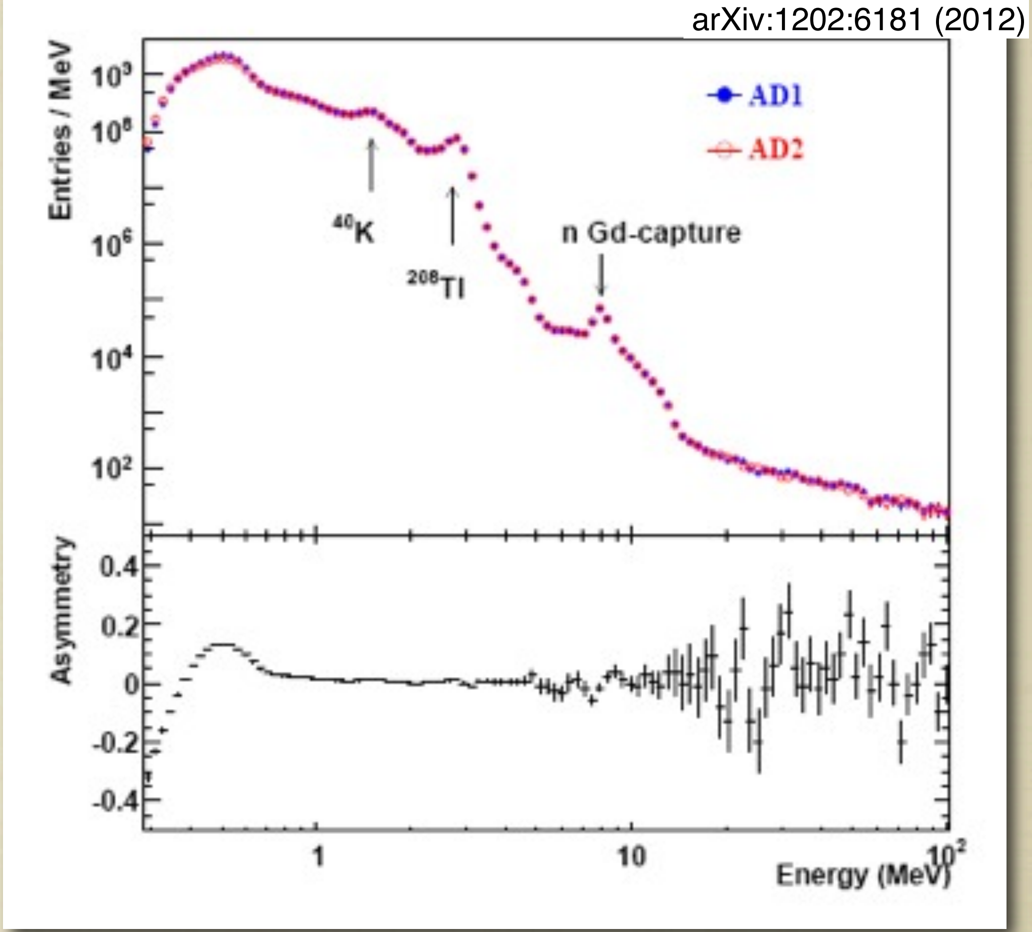
Inefficiency to antineutrinos signal: 0.024% ± 0.006%(stat)
Contamination: < 0.01%

Energy Spectrum of All Events

- Measured rate:
    - ~65 Hz in each detector (>0.7 MeV)
- Dominated by low-energy radioactivity
    - U/Th chains: Stainless steel, PMT, scintillator
    - ^{40}K: PMT
    - Radon: Scintillator
- Around "8-MeV":
    - IBD neutron
    - Muon spallation products
    - Am-C neutron in ACU
    - positron from IBD

Task: Select IBD from these

Singles spectrum after muon veto and flasher cut



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

asymmetry $A = 2 \times \frac{AD1 - AD2}{AD1 + AD2}$

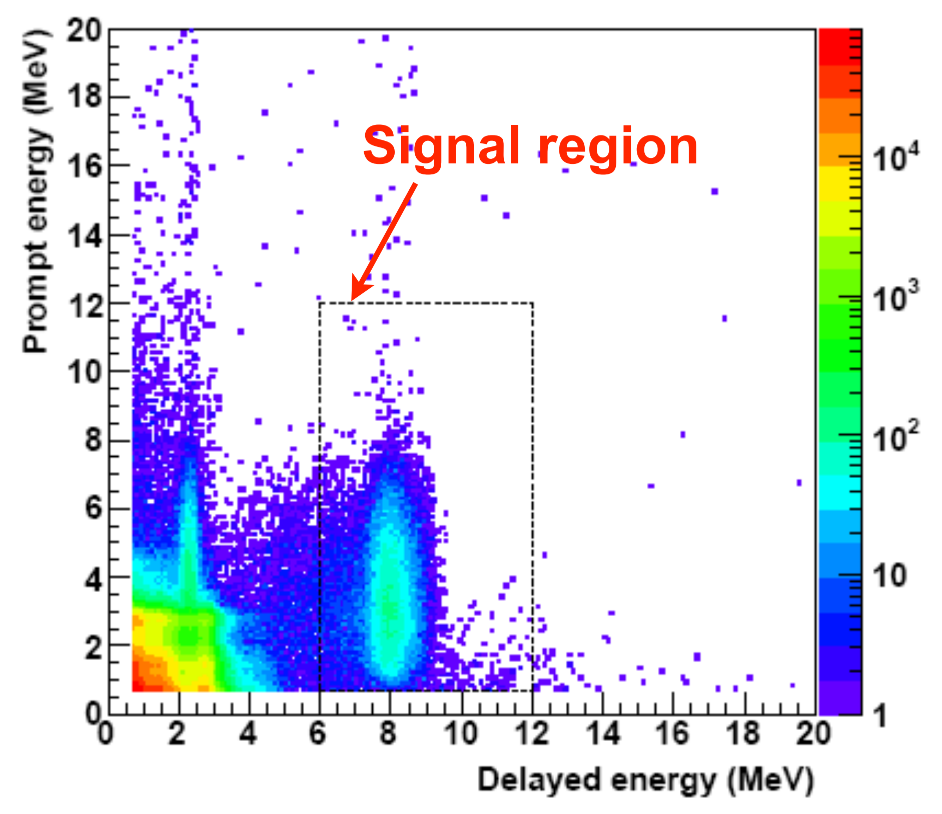
Antineutrino Selection

Prompt + Delayed coincidence

- Prompt: 0.7 MeV < E_p < 12 MeV
- Delayed: 6.0 MeV < E_d < 12 MeV
- Capture time: 1 μs < Δt < 200 μs
- Reject flashers
- Muon veto
  - Pool muon: Reject 0.6 ms
  - AD Muon (>20 MeV): Reject 1 ms
  - AD Shower Muon (>2.5 GeV): Reject 1s
- Multiplicity :
  - No other signal > 0.7 MeV in -200 μs to 200 μs of IBD

$$\begin{array}{l} \bar{\nu}_e + p \rightarrow e^+ + n \\ \qquad\qquad\quad \downarrow \\ \qquad\qquad\quad n + {}^{x}Gd \rightarrow {}^{x+1}Gd + \gamma \end{array}$$

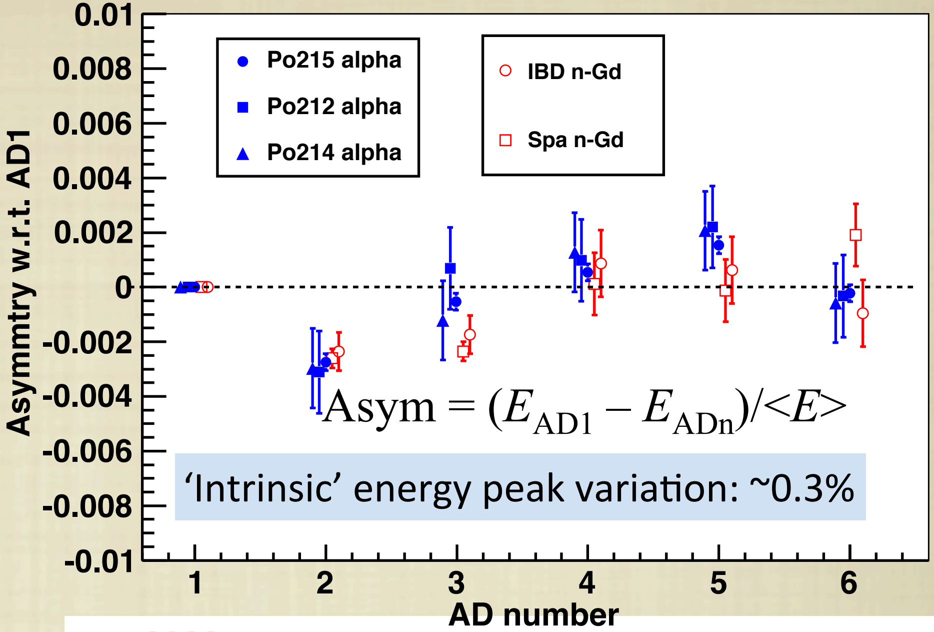
Clear separation of antineutrino events from backgrounds



Signal region

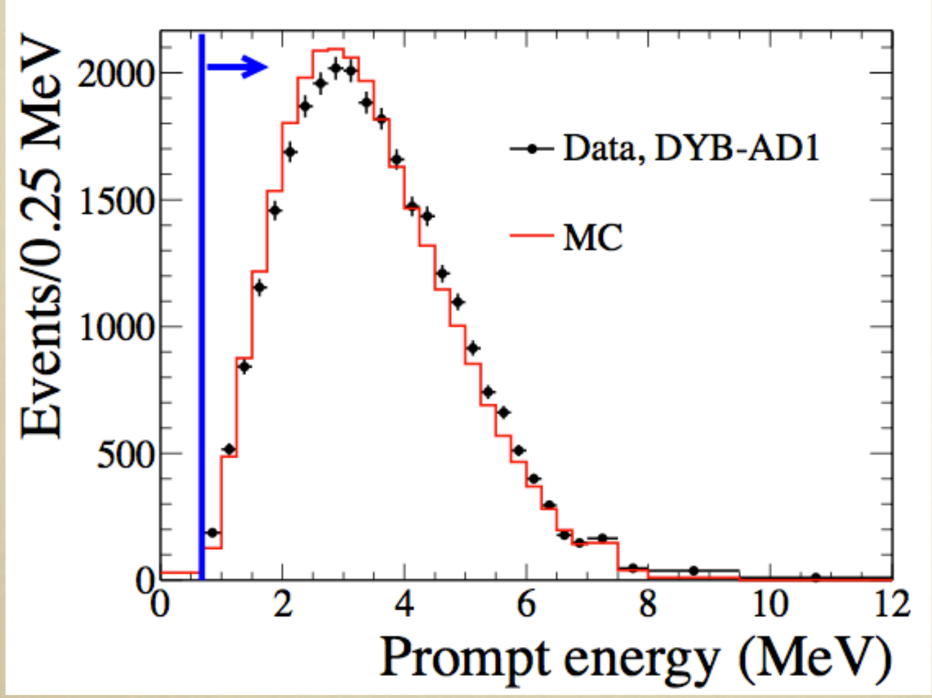
Prompt and Delayed Energy

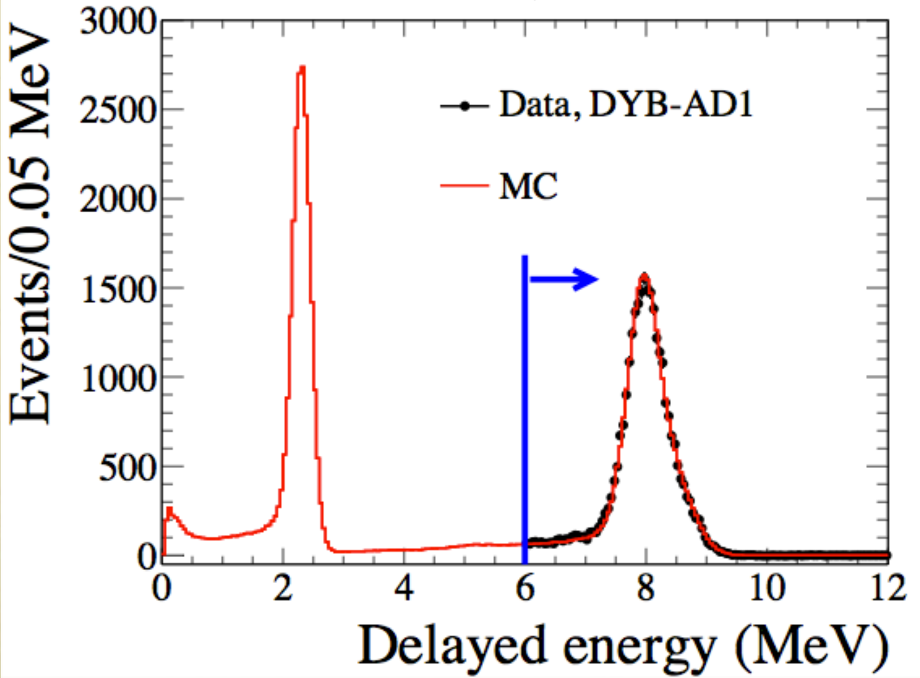
- Uncertainty of prompt energy cut efficiency: **negligible**
- Uncertainty of delayed energy cut efficiency: **0.12%**
  - Largest detector related uncertainty.



$\text{Asym} = (E_{\text{AD1}} - E_{\text{ADn}})/\langle E\rangle$

'Intrinsic' energy peak variation: ~0.3%

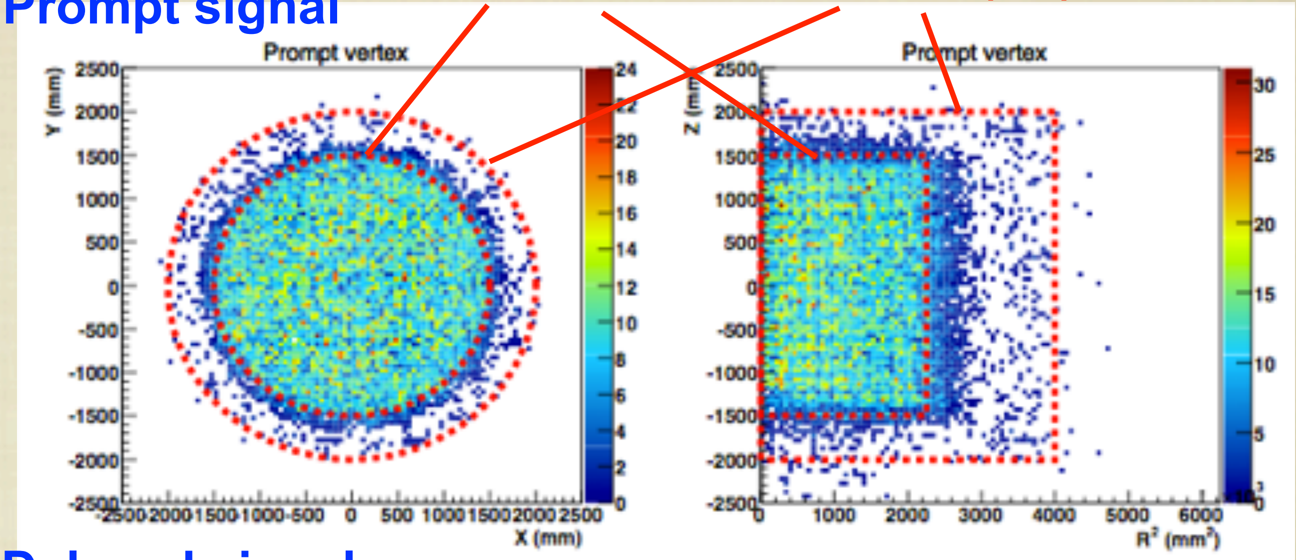




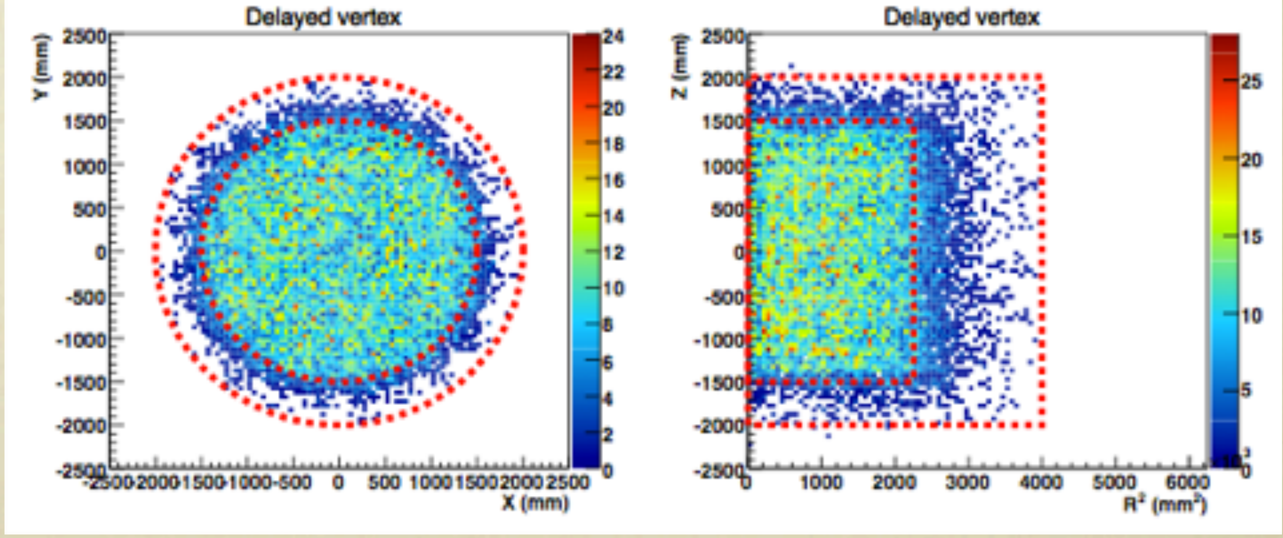
Spacial Distribution of IBD candidates

- IBD candidates are uniformly distributed in Gd-LS volume

Prompt signal

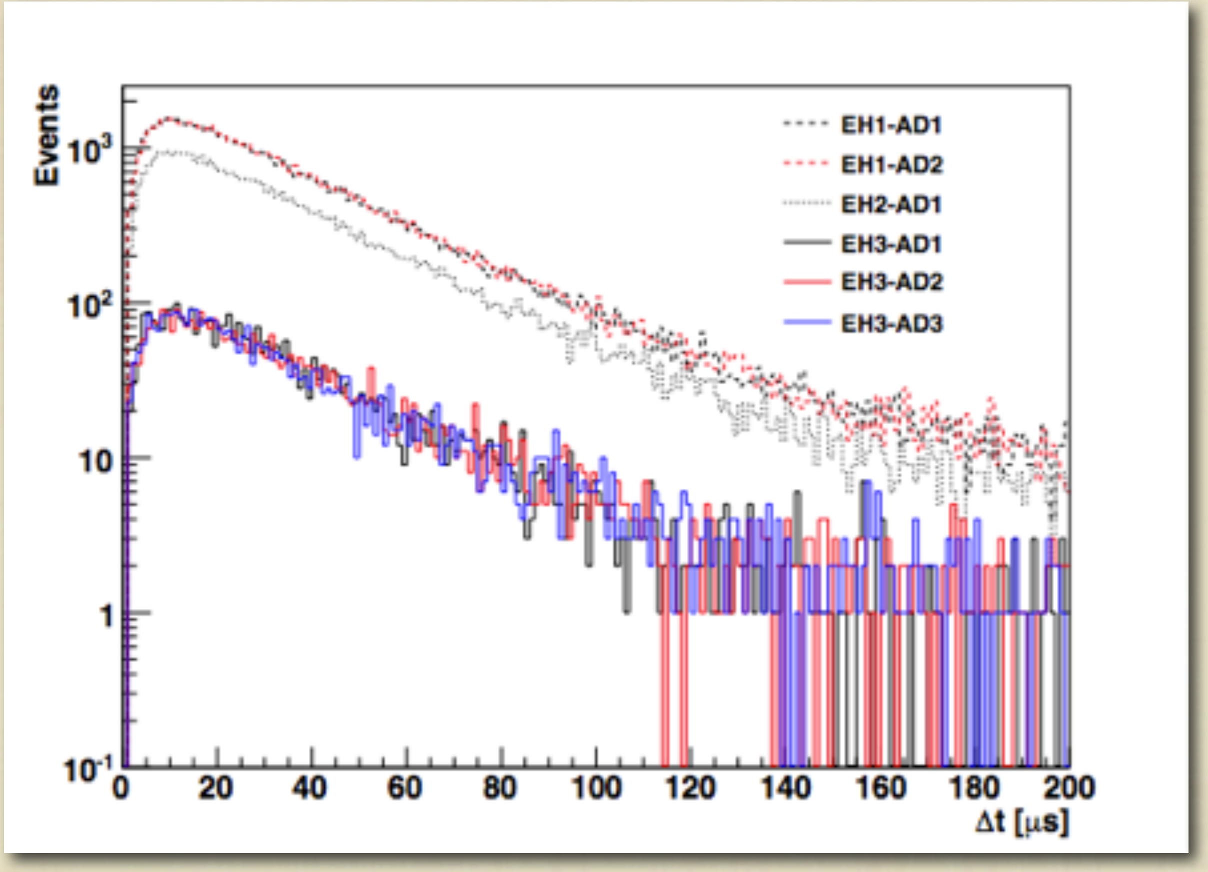

3m-IAV (GdLS)
4m-OAV (LS)
EH1 AD1

Delayed signal



Neutron Capture Time

Consistent IBD capture time measured in all detectors



Capture time cut:
1μs to 200μs

Relative H/Gd capture efficiencies between ADs differ by less than 0.1%

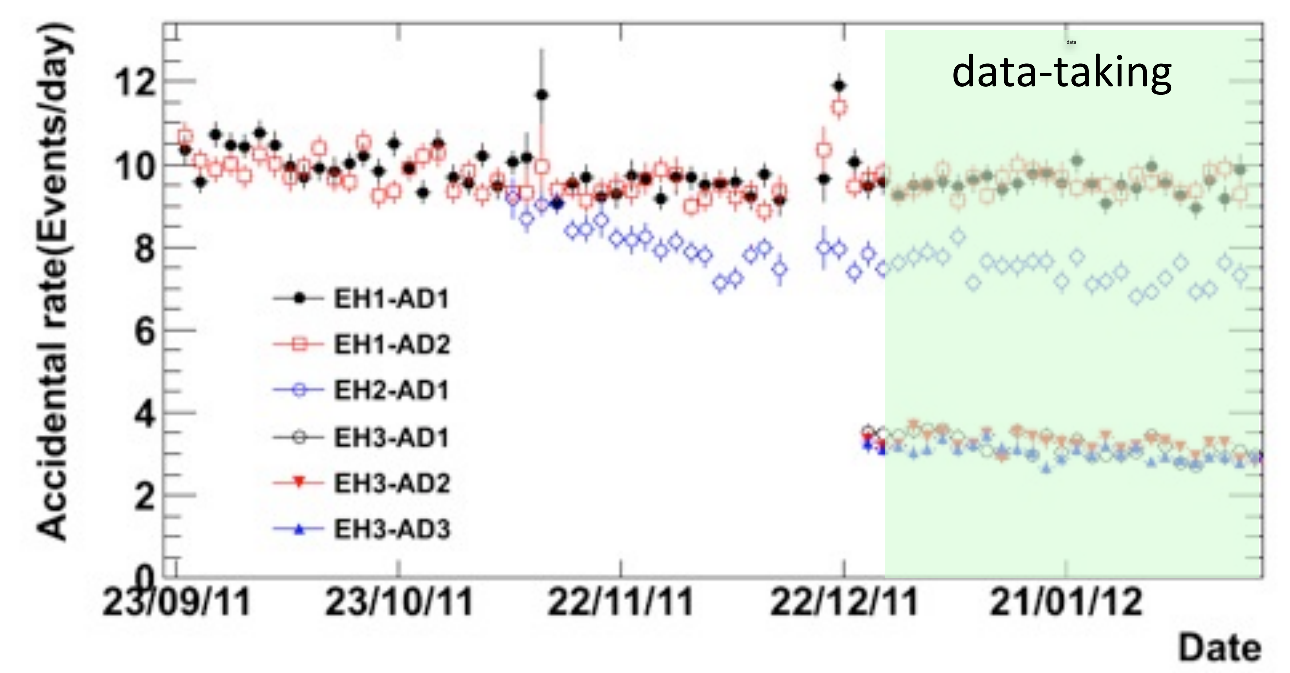
Backgrounds

- Uncorrelated background
  - Accidentals: two uncorrelated events accidentally happened with short time separation and mimic IBD event.

- Correlated (from largest to smallest)
  - Muon spallation products
    - β-n decay isotopes (^{9}Li/^{8}He)
    - Fast neutrons
  - Correlated signal from ^{241}Am-^{13}C calibration source
  - ^{13}C(α,n)O reaction

Backgrounds: Accidental

- The largest background
- Rate and spectrum can be accurately measured from data

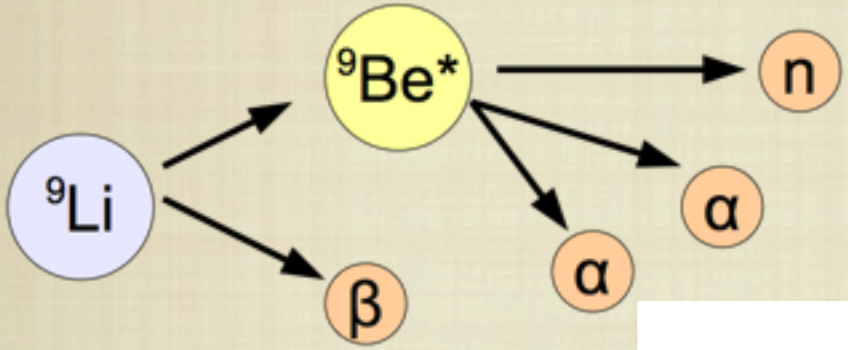


	EH1-AD1	EH1-AD2	EH2-AD1	EH3-AD1	EH3-AD2	EH3-AD3
Accidental rate(/day)	9.82±0.06	9.88±0.06	7.67±0.05	3.29±0.03	3.33±0.03	3.12±0.03
B/S	1.37%	1.38%	1.44%	4.58%	4.77%	4.43%

Background: β-n decay

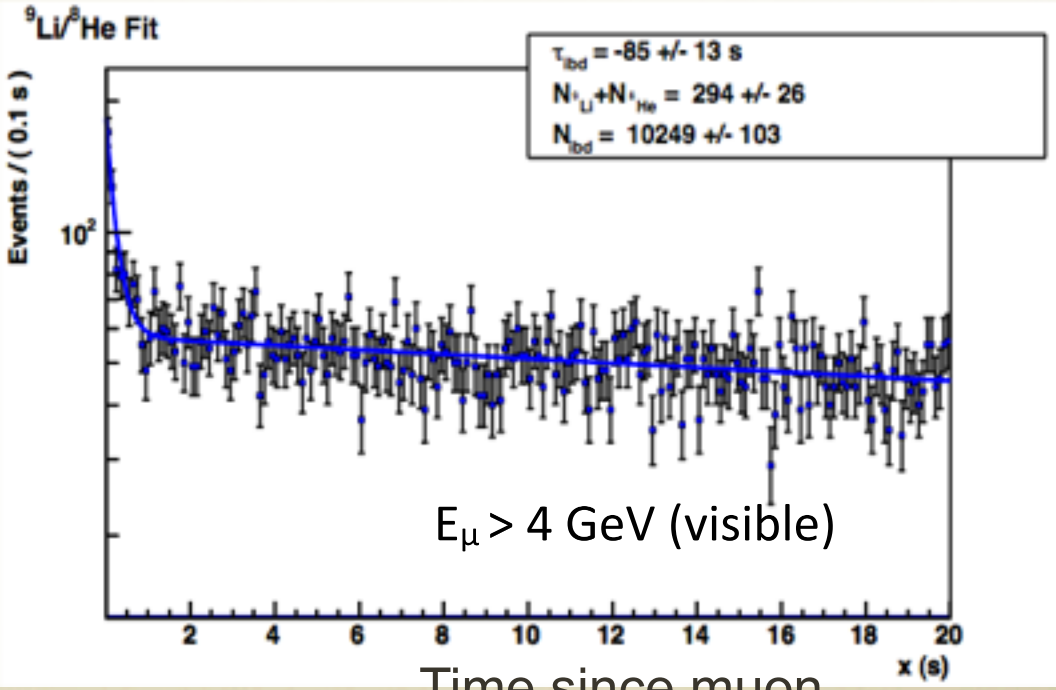
β-n decay:

- Prompt: β-decay
- Delayed: neutron capture



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

^{9}Li: $\tau_{½}$ = 178 ms, Q = 13. 6 MeV
^{8}He: $\tau_{½}$ = 119 ms, Q = 10.6 MeV



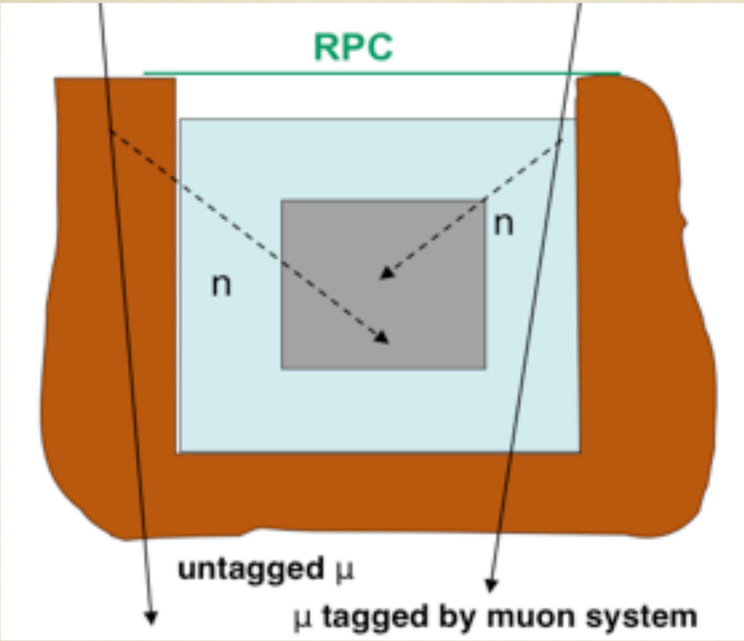
E_μ > 4 GeV (visible)

Time since muon

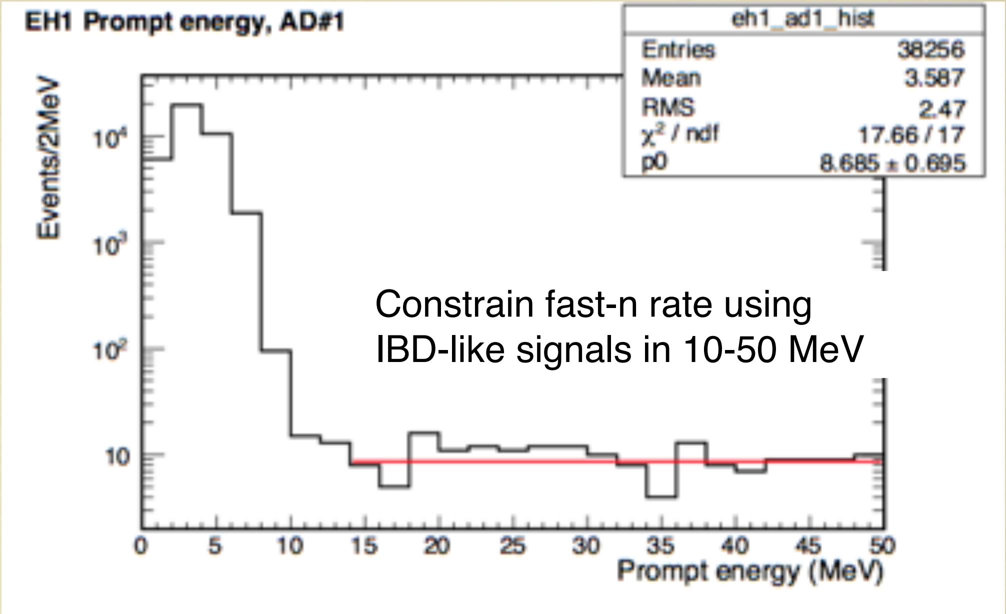
Analysis muon veto cuts control B/S to ~0.2% (0.4%) of far (near) signal

Background: Fast Neutron

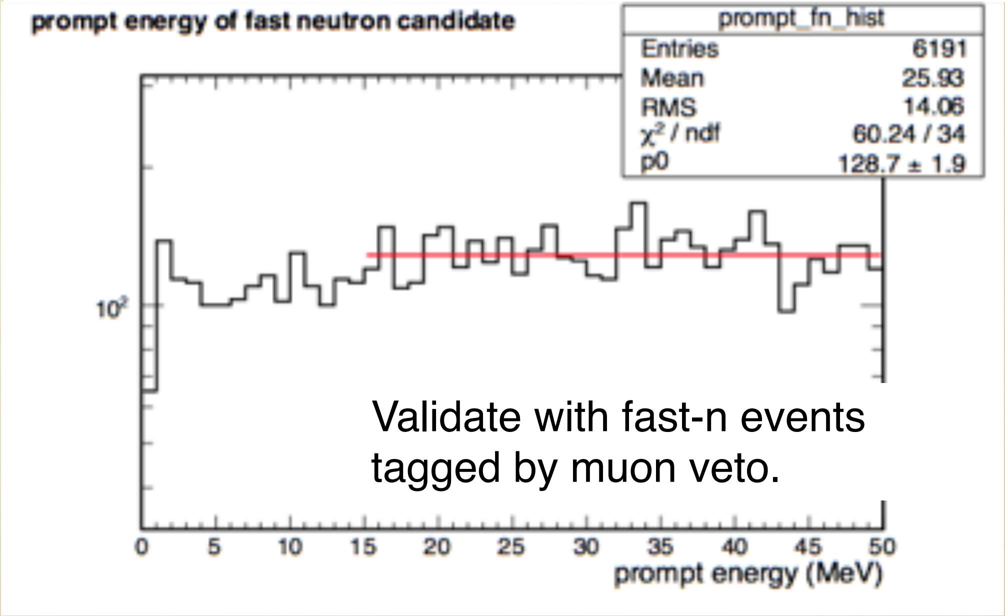
- Energetic neutrons produced by cosmic-rays
- Mimic an IBD signal:
  - Prompt: Neutron recoils/stops in target
  - Delayed: Neutron capture on Gd



After muon veto cuts, B/S is ~0.06% (0.1%) of far (near) signal.



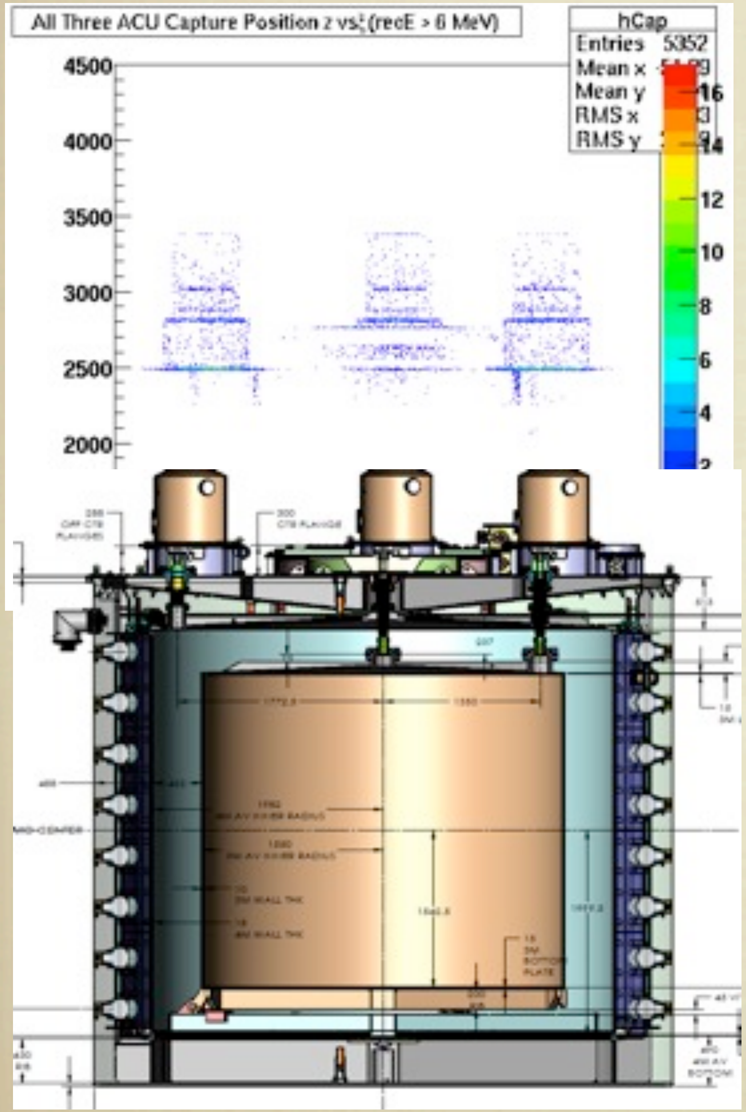
Constrain fast-n rate using IBD-like signals in 10-50 MeV

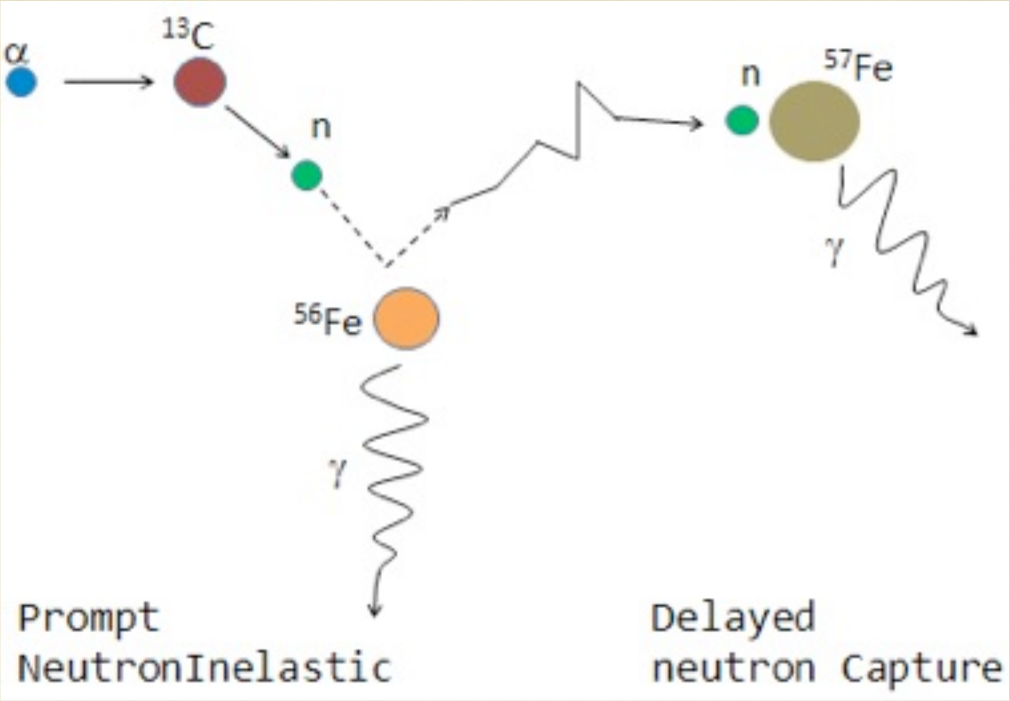


Validate with fast-n events tagged by muon veto.

Background: ^{241}Am-^{13}C neutrons

- Weak (0.5 Hz) neutron source in ACU can also mimic IBD via inelastic scattering and capture on iron.



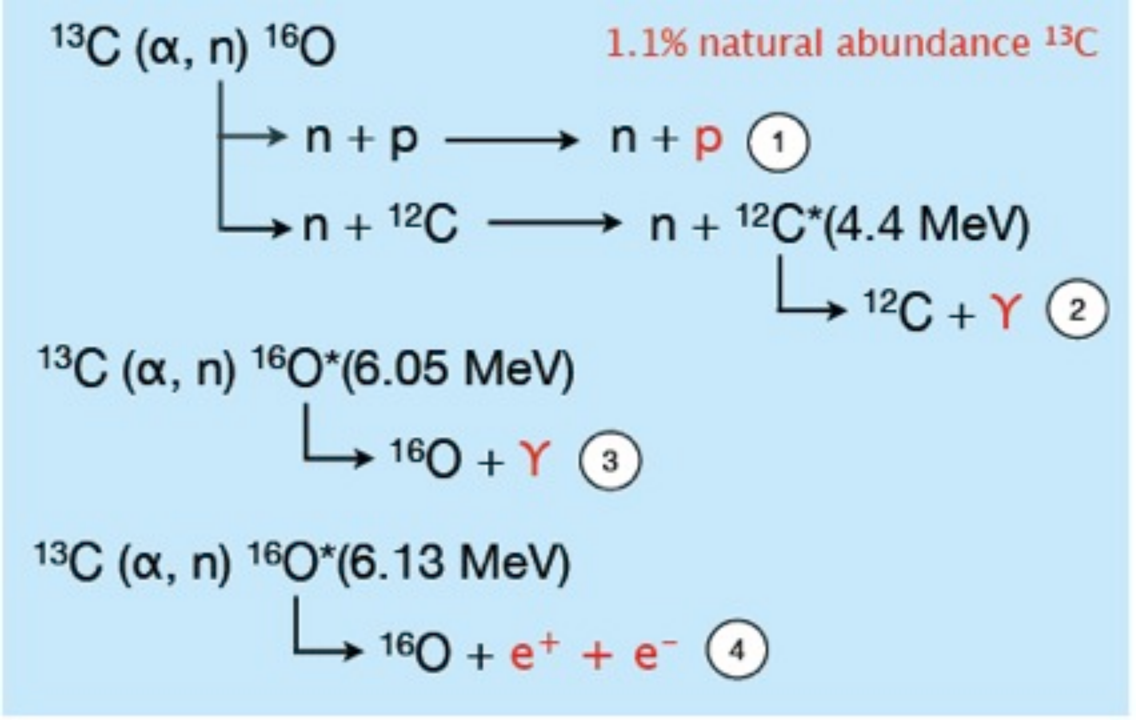


Estimation Procedure:

- Measure uncorrelated gamma rays from ACU in data
- Estimate ratio of correlated/uncorrelated rate using simulation
- Assume 100% uncertainty from simulation

Constrain far site B/S to 0.3±0.3%

Background:



Potential alpha source:
^{238}U, ^{232}Th, ^{235}U, ^{210}Po:

Each of them are measured in-situ:

U&Th: cascading decay of
Bi(or Rn) – Po – Pb

^{210}Po: spectrum fitting

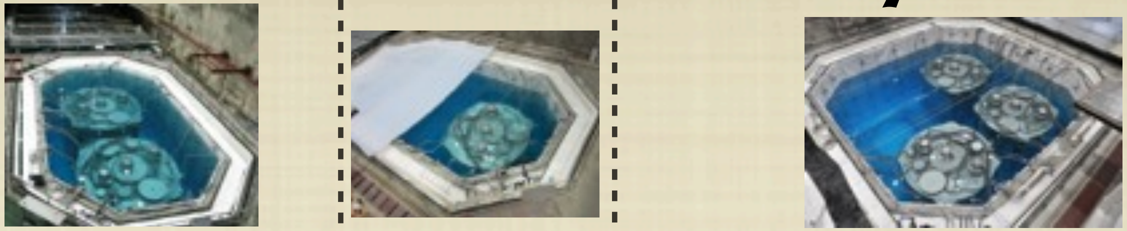
Example alpha rate in AD1	^{238}U	^{232}Th	^{235}U	^{210}Po
Bq	0.05	1.2	1.4	10

Combining (α,n) cross-section, correlated background rate is determined from MC.

Near Site: 0.04±0.02 per day, B/S (0.006±0.004)%

Far Site: 0.03±0.02 per day, B/S (0.04±0.02)%

Data Summary



	AD1	AD2	AD3	AD4	AD5	AD6
Antineutrino candidates	28935	28975	22466	3528	3436	3452
DAQ live time (day)	49.5530		49.4971	48.9473		
Efficiency	0.8019	0.7989	0.8363	0.9547	0.9543	0.9538
Accidentals (/day)	9.82±0.06	9.88±0.06	7.67±0.05	3.29±0.03	3.33±0.03	3.12±0.03
Fast neutron (/day)	0.84±0.28	0.84±0.28	0.74±0.44	0.04±0.04	0.04±0.04	0.04±0.04
^{8}He/^{9}Li (/day)	3.1±1.6		1.8±1.1	0.16±0.11		
Am-C corr. (/day)	0.2±0.2					
^{13}C(α, n)^{16}O (/day)	0.04±0.02	0.04±0.02	0.035±0.02	0.03±0.02	0.03±0.02	0.03±0.02
Antineutrino rate (/day)	**714.17 ±4.58**	**717.86 ±4.60**	**532.29 ±3.82**	**71.78 ±1.29**	**69.80 ±1.28**	**70.39 ±1.28**

- Consistent antineutrino rate for the detectors in the same hall
- Uncertainty is currently dominated by statistics

Oscillation Analysis

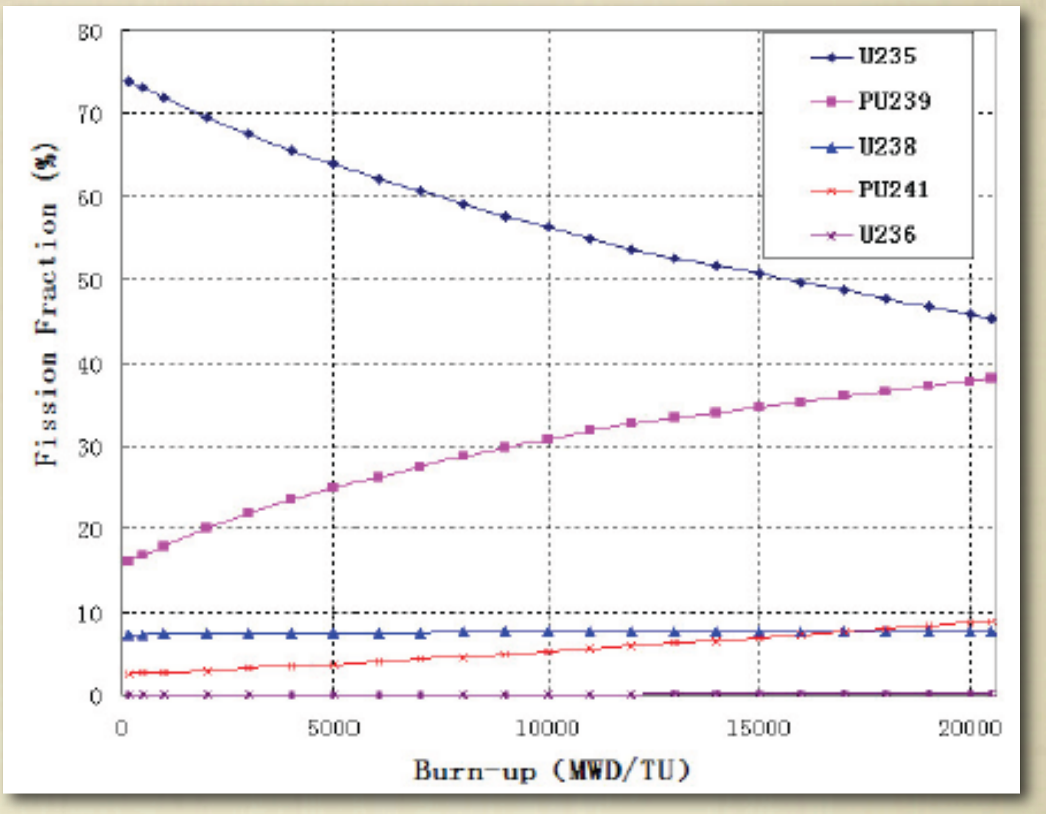
Flux Prediction

Reactor neutrino spectrum:

$$S(E_\nu) = \frac{W_{th}}{\sum_i (f_i/F) e_i} \sum_i^{istopes} (f_i/F) S_i(E_\nu)$$

- Reactor operators provide:
  - Thermal power data: W_{th}
  - Relative isotope fission fraction f_i
- Energy released per fission: e_i

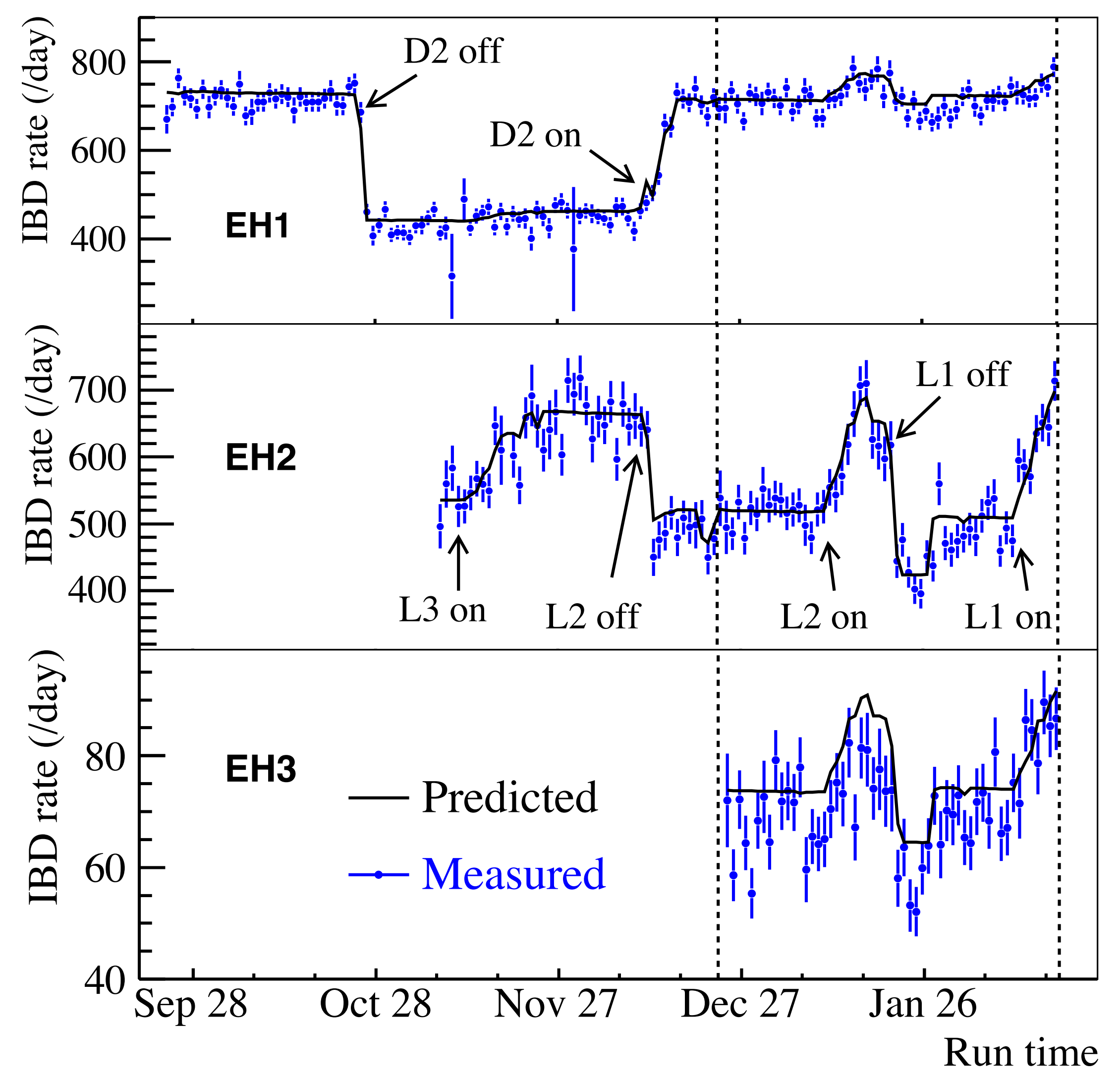
V. Kopekin et al., Phys. Atom. Nucl. 67, 1892 (2004)



- Antineutrino spectra per fission: $S_i(E_\nu)$

K. Schreckenbach et al., Phys. Lett. B160, 325 (1985)
A. A. Hahn et al., Phys. Lett. B218, 365 (1989)
P. Vogel et al., Phys. Rev. C24, 1543 (1981)
T. Mueller et al., Phys. Rev. C83, 054615 (2011)
P. Huber, Phys. Rev. C84, 024617 (2011)

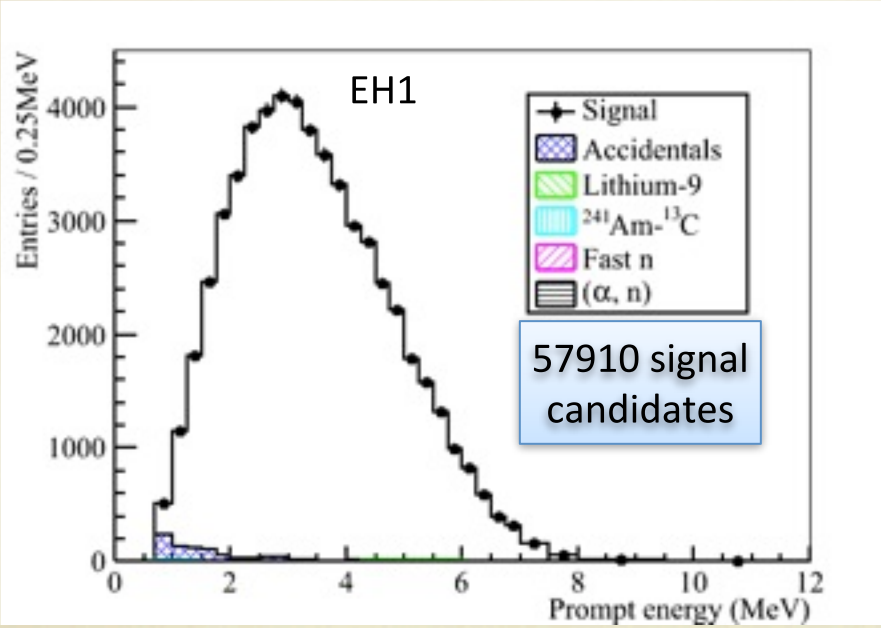
Daily Antineutrino Rate



- Predicted rate:
  - Assumes no oscillation
  - Normalization is determined by fit to the data.

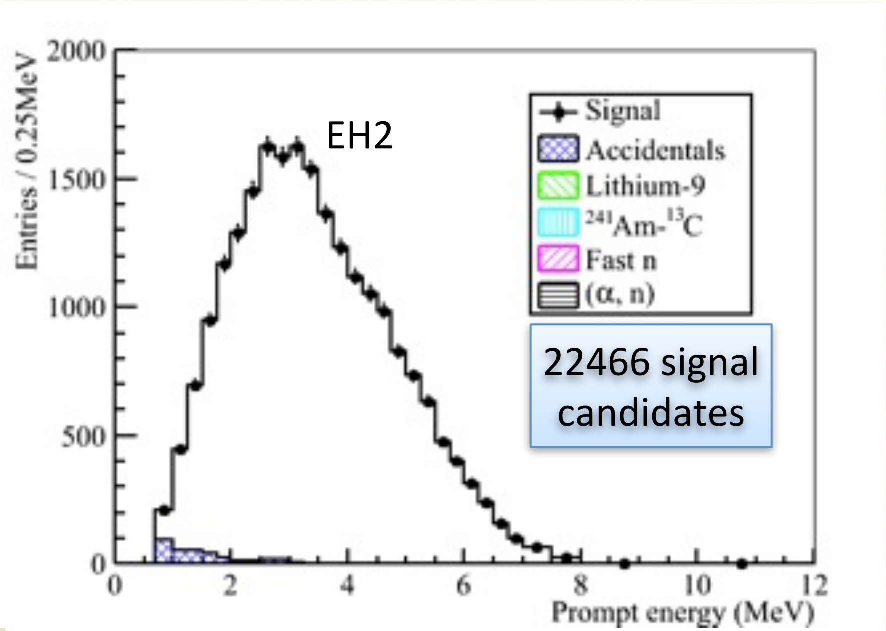
- Measured rate tracks the reactor power variation.

Prompt (Positron) Spectra

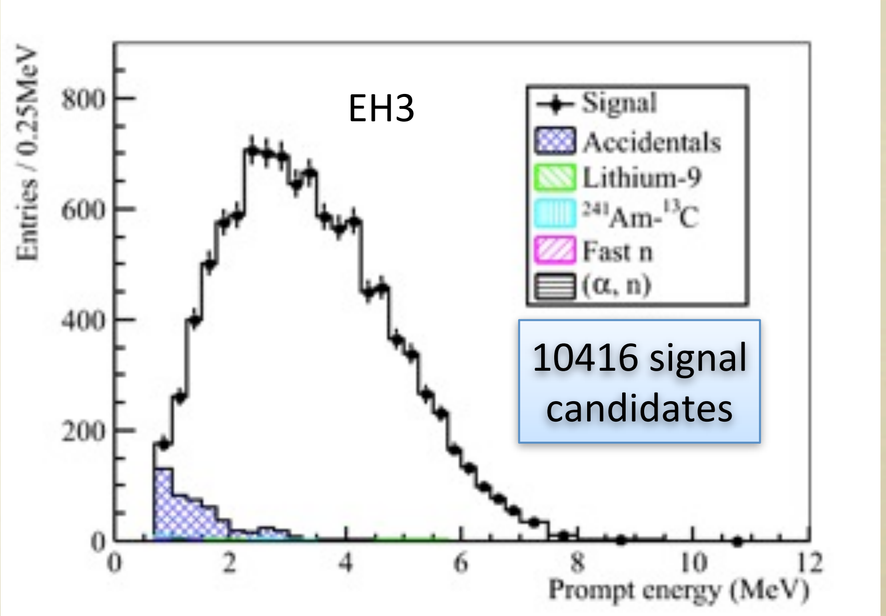


57910 signal candidates

	B/S @ EH1/2	B/S @ EH3
Accidentals	~1.4%	~4.5%
Fast neutrons	~0.1%	0.06%
^{8}HE/^{9}Li	~0.4%	~0.2%
Am-C	~0.03%	~0.3%
α-n	~0.01%	~0.04%
Total	~2%	~5%

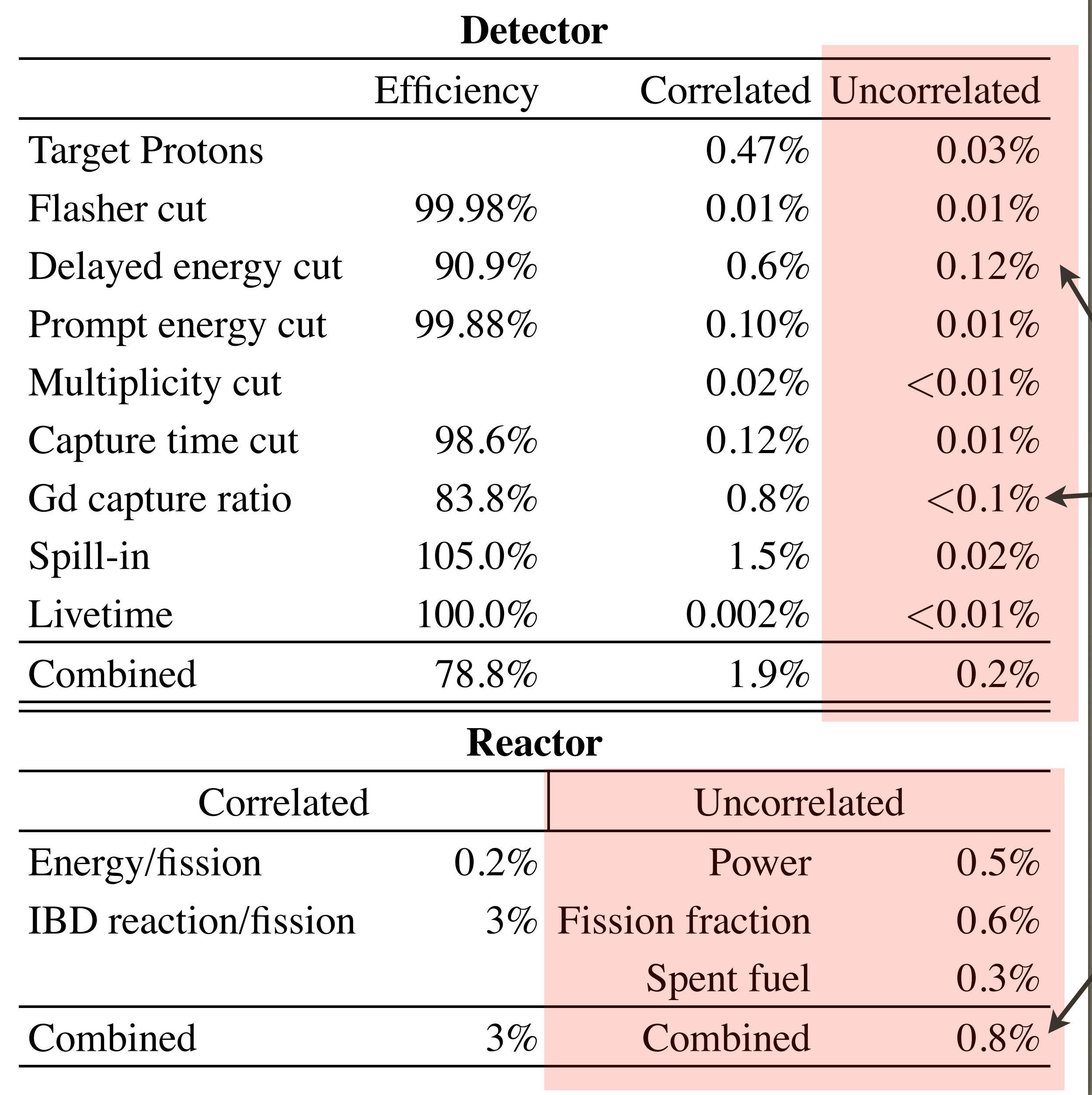


22466 signal candidates



10416 signal candidates

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

- For near/far oscillation analysis, the correlated uncertainties cancel.
- Only uncorrelated uncertainties are used.

Largest systematics are smaller than far site statistics (~1%)

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

Far vs. Near Comparison

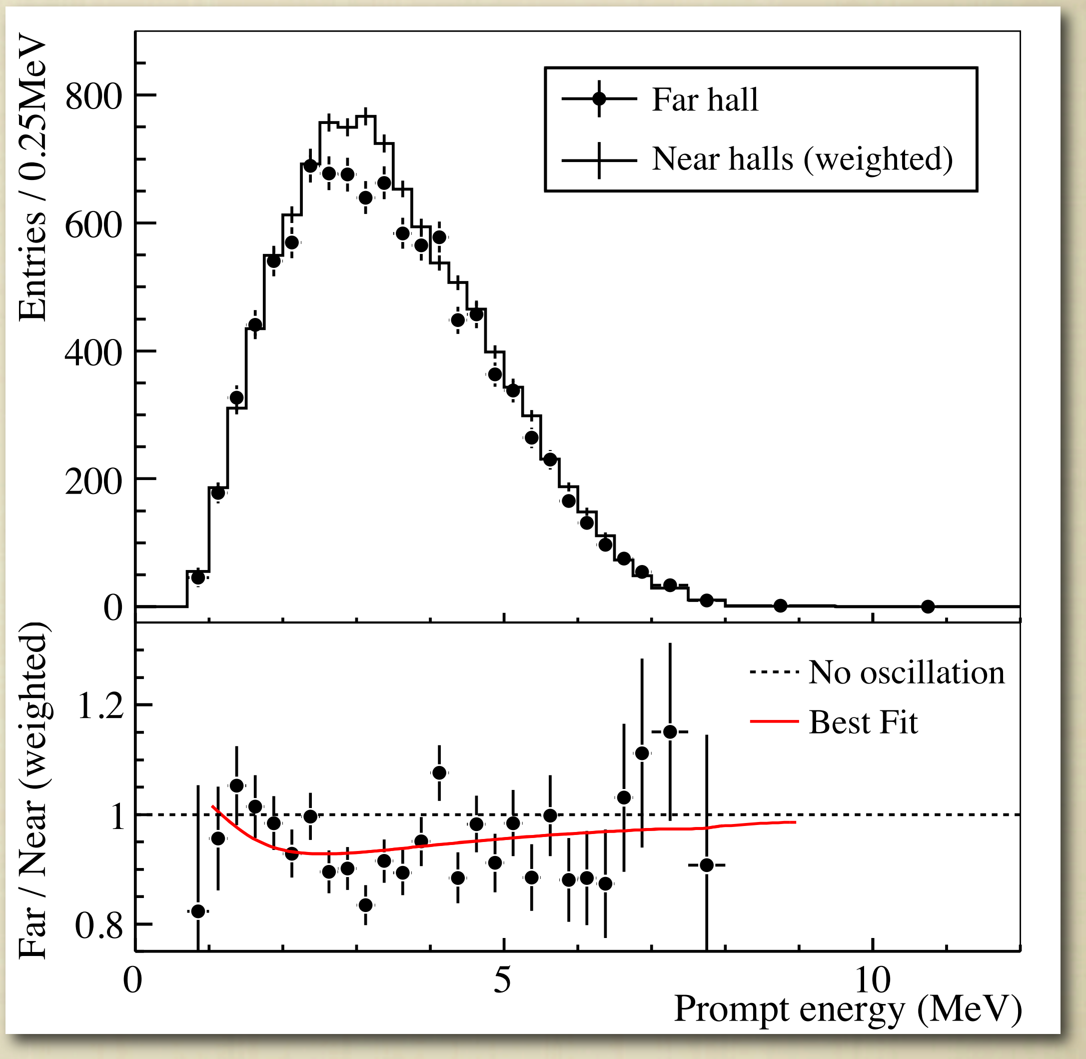
- Compare the far/near measured rate and spectra.

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

M_n: measured rates after background subtraction and efficiency correction.
α_i, β_i : Weights determined from baselines and reactor fluxes.

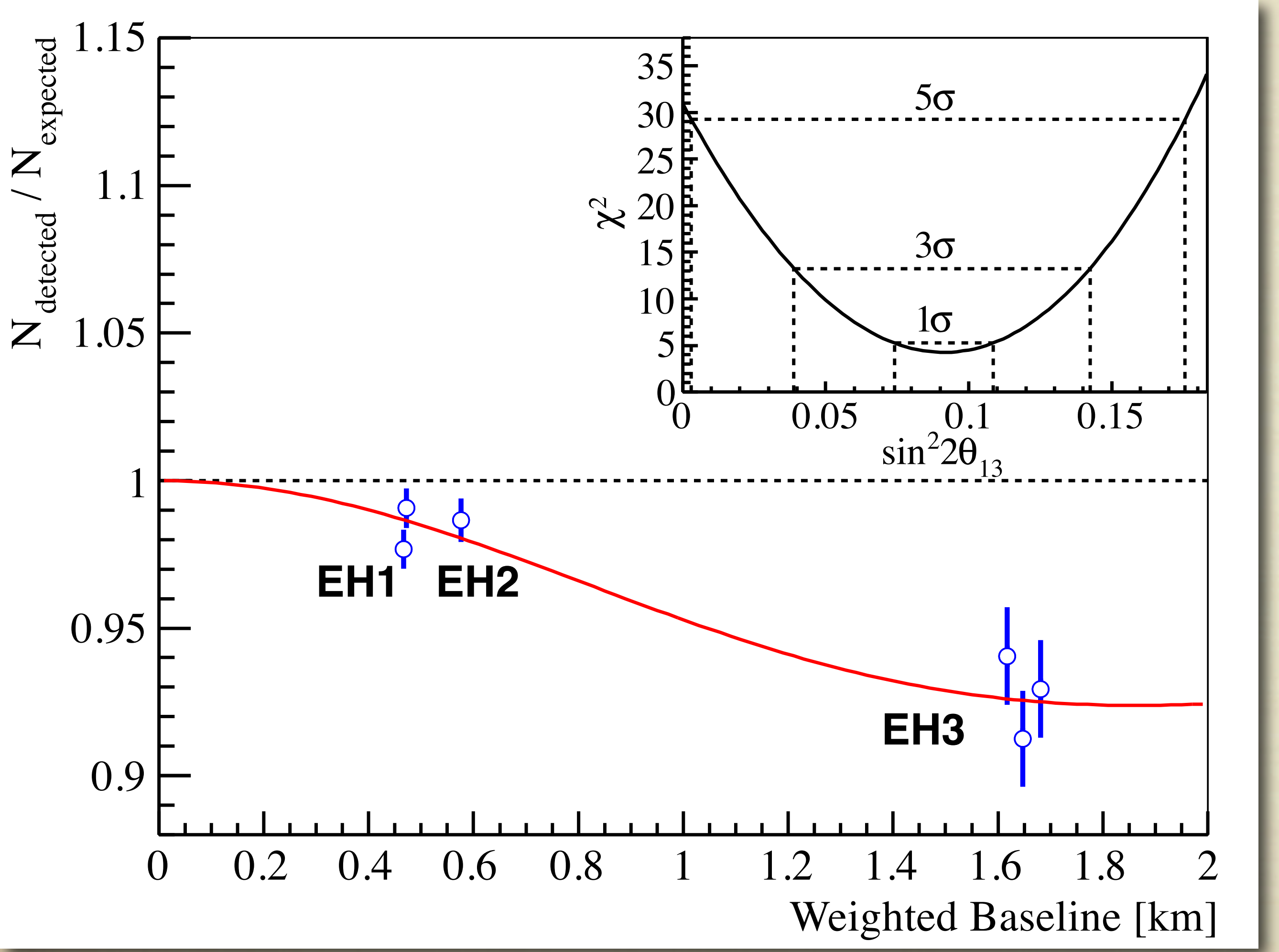
R = 0.940 ± 0.011(stat) ± 0.004(sys)

- Clear observation of far site deficit
- Spectrum distortion consistent with oscillation



Rate Analysis

$\sin^2(2\theta_{13}) = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{sys})$



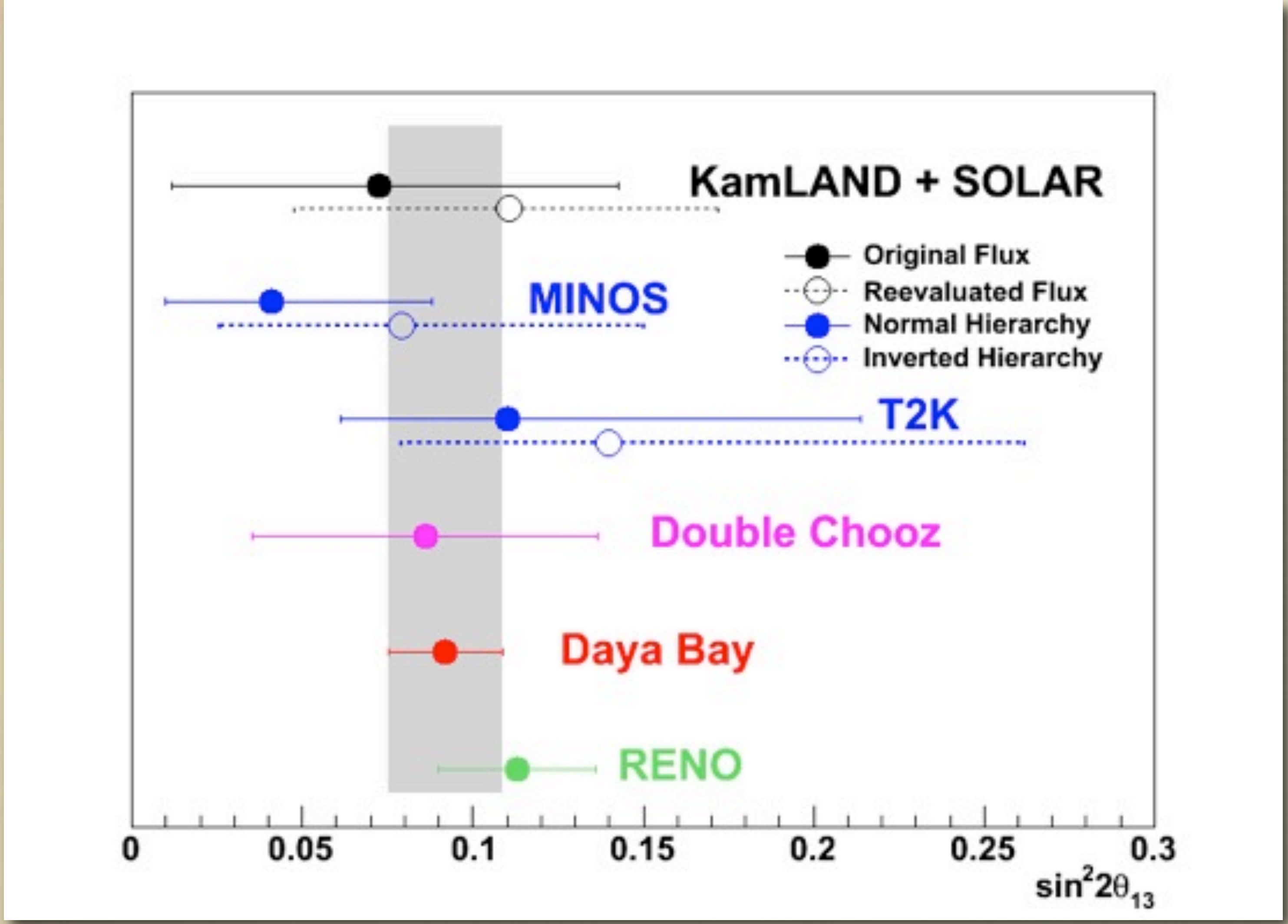
- Value of θ_{13} extracted by using measured rates in each detector.
- Uses standard χ^2 approach.

$$\chi^2 = \sum_{d=1}^{6} \frac{\left[M_d - T_d\left(1 + \varepsilon + \sum_r \omega_r^d \alpha_r + \varepsilon_d\right) + \eta_d\right]^2}{M_d} + \sum_r \frac{\alpha_r^2}{\sigma_r^2} + \sum_{d=1}^{6}\left(\frac{\varepsilon_d^2}{\sigma_d^2} + \frac{\eta_d^2}{\sigma_B^2}\right),$$

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

$\sin^2(2\theta_{13}) = 0$ excluded at 5.2σ

Current Landscape



- RENO also released their results (~ a month after us)

arXiv:1204.0626v2

Summary

- The Daya Bay reactor neutrino experiment has observed reactor electron - antineutrino disappearance at ~2 km:

R = 0.940 ± 0.011(stat) ± 0.004(sys)

- Interpretation of disappearance as neutrino oscillation yields:

$$\sin^2(2\theta_{13}) = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{sys})$$

$$\sin^2(2\theta_{13}) = 0 \text{ excluded at } 5.2\sigma$$

Of course, this is not an end for us....

- Improved analysis including spectrum shape information is in progress
- Install remaining the final pair of antineutrino detectors this summer.
- Continue making precision measurement of θ_{13} with (much) more statistics.