Improved Measurement of Electron Antineutrino Disappearance at Daya Bay

Harry Themann (BNL)
on behalf of the Daya Bay Collaboration

RENCONTRES DU VIETNAM
Beyond the standard model in particle physics
July 16, 2012
Quy Nhon, Vietnam

Neutrino Oscillation

Neutrinos change flavor (e,μ,τ) with time
→ non zero mass
→ Not in the Standard Model

Principle: Mass eigenstates ≠ Interaction (flavor) eigenstates

$$P_{\nu_e \to \nu_e}(t) = \left|\langle \nu_e(0) | \nu_e(t) \rangle\right|^2 = \left|\sum_{j=1}^{3} \langle \nu_j(0) | U_{ej}^* \sum_{i=1}^{3} e^{iE_i t} U_{ie} | \nu_i(0) \rangle\right|^2$$

Physical Parameters: (chosen by nature)

θ_{ij}: (appear in U)

3 angles between mass/flavor eigenstates set **oscillation amplitude**

Δm_{ij}^2: (appear in E_i-E_j as a function of p)

Differences in 3 neutrino masses determine **oscillation frequency** (distance)

We want to know all θ and Δm^2

First Evidence of Oscillation:
Davis detects 1/3 expected solar neutrinos (1968)

Mixing Matrix

Many recent measurements of neutrino oscillation

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

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

$\theta_{23} \approx 45^o$
Atmospheric ν
Accelerator ν

$\theta_{13} < 10^o$
Short-Baseline Reactor ν
Accelerator ν

$\theta_{12} \approx 35^o$
Solar ν
Long-Baseline Reactor ν

θ_{13}: Only angle not yet firmly observed. It is the gateway to leptonic CP violation δ

http://arxiv.org/pdf/hep-ph/0108181.pdf

Neutrino Survival Probability

Neutrino survival probability depends on mixing angles and time (baseline)

$$P_{\nu_e \to \nu_e}(t) = \left|\langle \nu_e(0) | \nu_e(t) \rangle\right|^2 = \left|\sum_{j=1}^{3} \langle \nu_j(0) | U_{ej}^* \sum_{i=1}^{3} e^{iE_i t} U_{ie} | \nu_i(0) \rangle\right|^2$$

$$P_{\nu_e \to \nu_e} = (c_{13}c_{12})^2 (c_{13}c_{12})^2 + (c_{13}s_{12})^2 (c_{13}s_{12})^2 (c_{13}s_{12})^2 + (s_{13})^2 (s_{13})^2$$

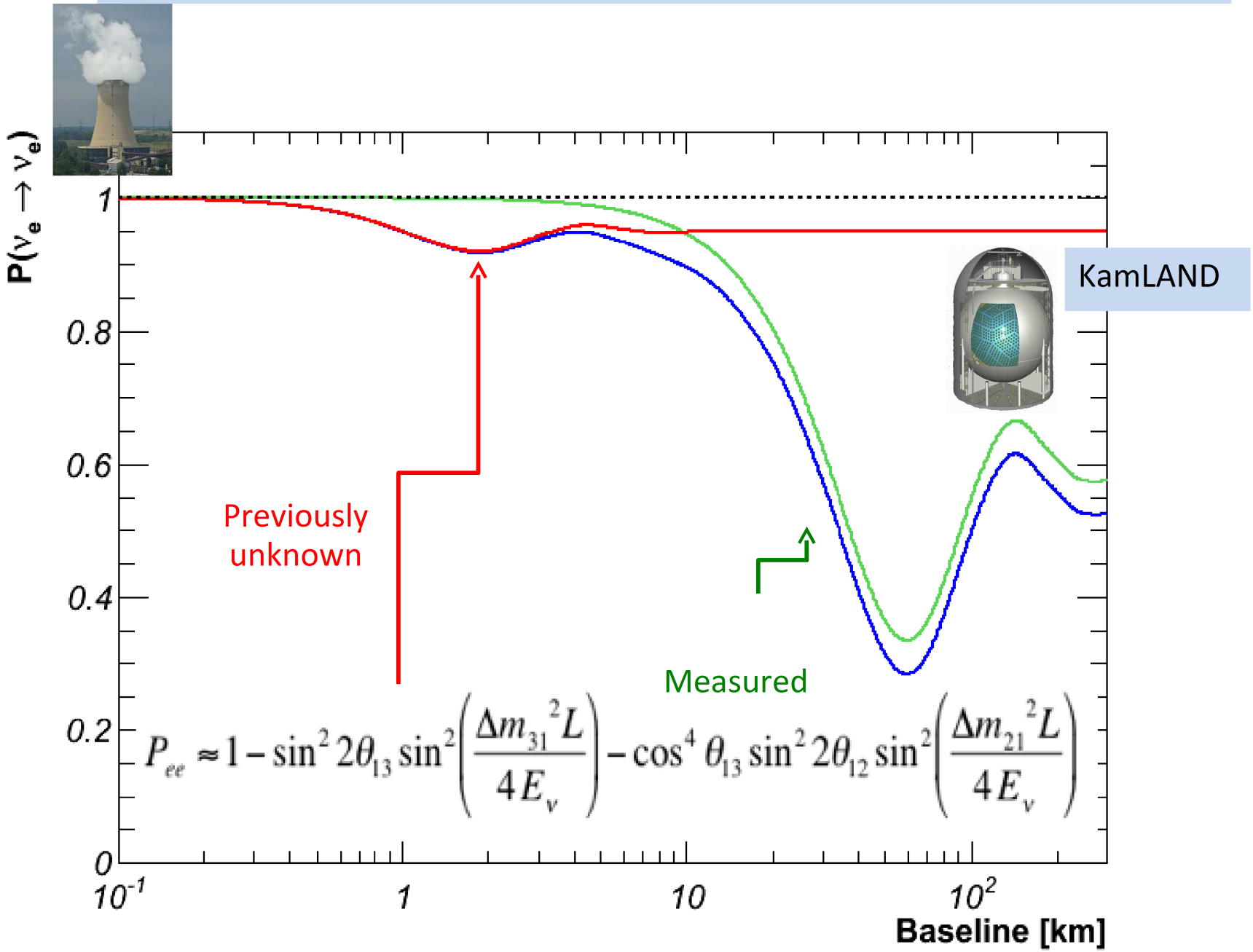
$$+ (c_{13}s_{12})^2 (c_{13}c_{12})^2 2\cos\left(\frac{\Delta m_{21}^2 t}{2p}\right) + (s_{13})^2 (c_{13}c_{12})^2 2\cos\left(\frac{\Delta m_{31}^2 t}{2p}\right)$$

$$+ (s_{13})^2 (c_{13}s_{12})^2 2\cos\left(\frac{\Delta m_{32}^2 t}{2p}\right)$$

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

Reactor Neutrino Oscillation

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



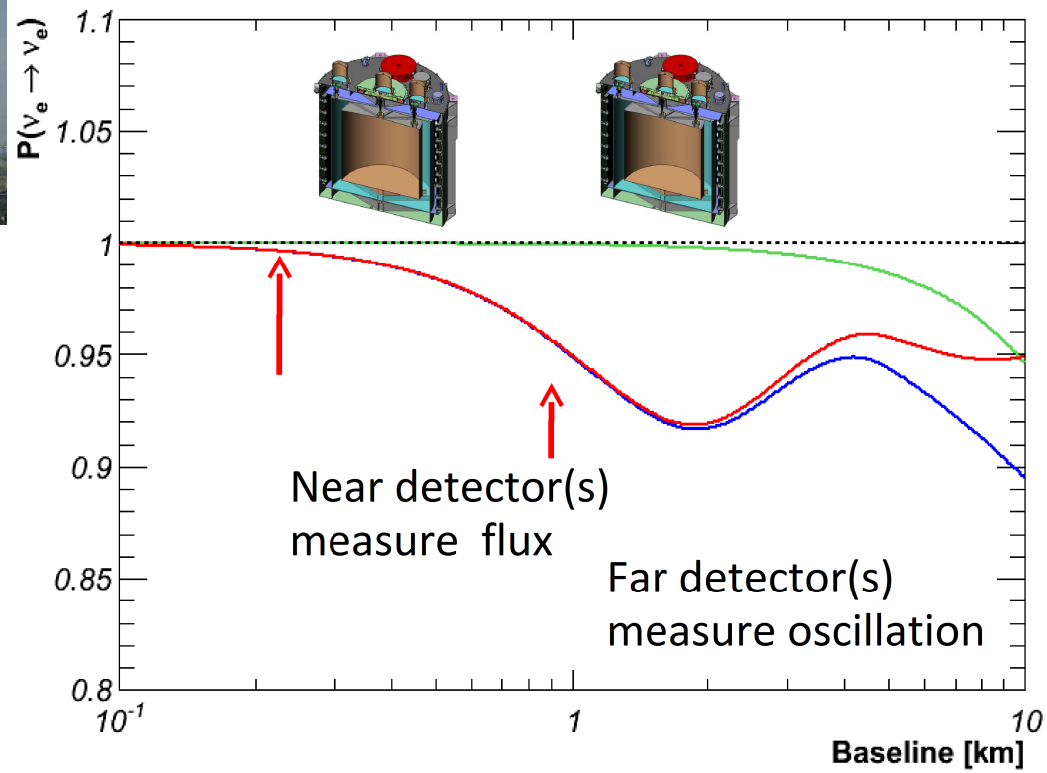
Design principles of Daya Bay

In order to measure the potentially small θ_{13} to levels of 0.01 for $\sin^2 2\theta_{13}$, the experiment was designed to measure relative quantities with multiple functionally identical detectors, paying detailed attention to background rejection and control.

Relative Measurement

Absolute Reactor Flux:
Largest uncertainty in previous measurements (~ 3%)

Relative Measurement:
Removes absolute uncertainties!



Far/Near ve Ratio

Distances from reactor

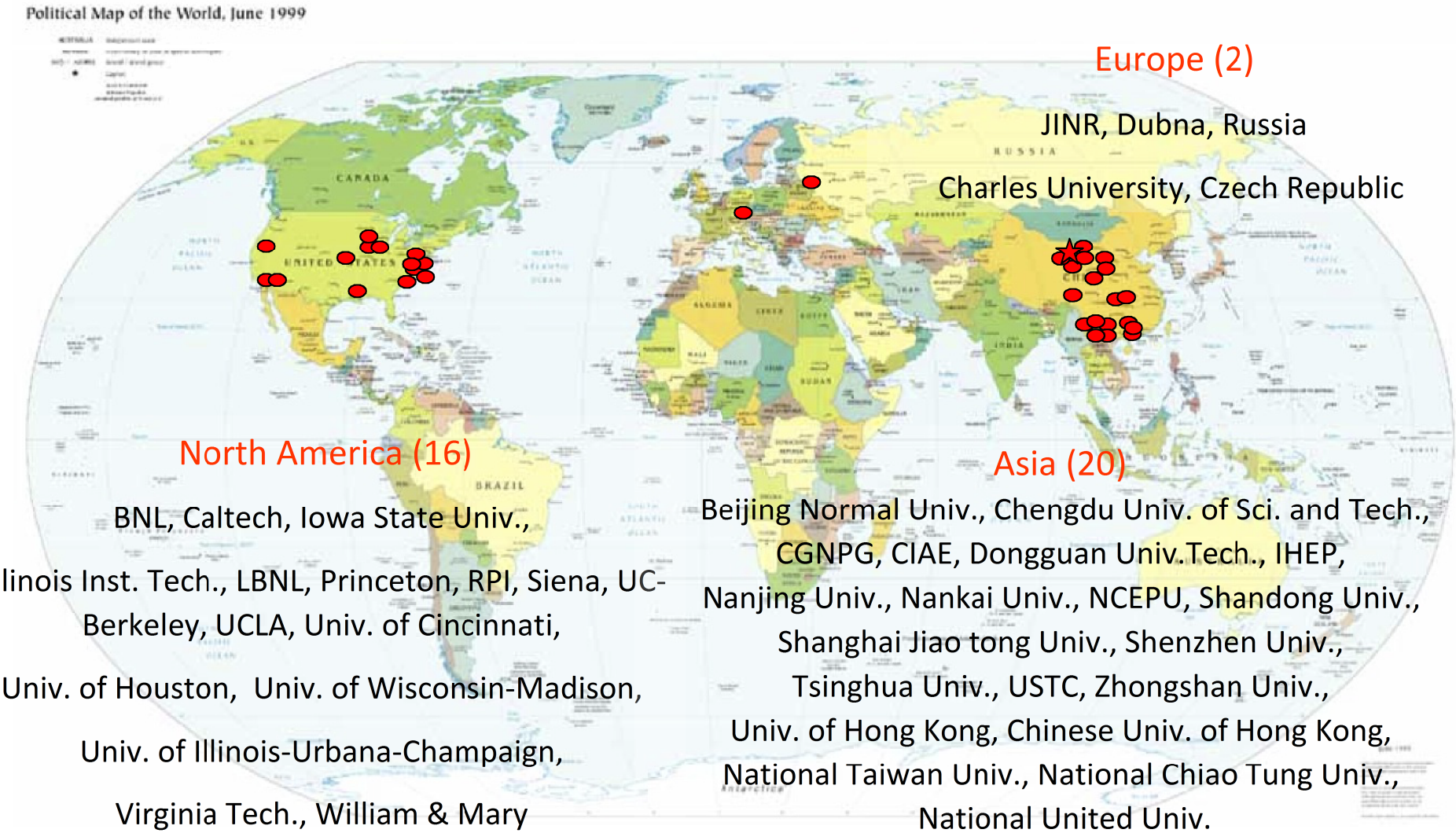
Oscillation deficit

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

Detector Target Mass

Detector efficiency

The Daya Bay Collaboration



Europe (2)

JINR, Dubna, Russia

Charles University, Czech Republic

North America (16)

BNL, Caltech, Iowa State Univ.,

Illinois Inst. Tech., LBNL, Princeton, RPI, Siena, UC-Berkeley, UCLA, Univ. of Cincinnati,

Univ. of Houston, Univ. of Wisconsin-Madison,

Univ. of Illinois-Urbana-Champaign,

Virginia Tech., William & Mary

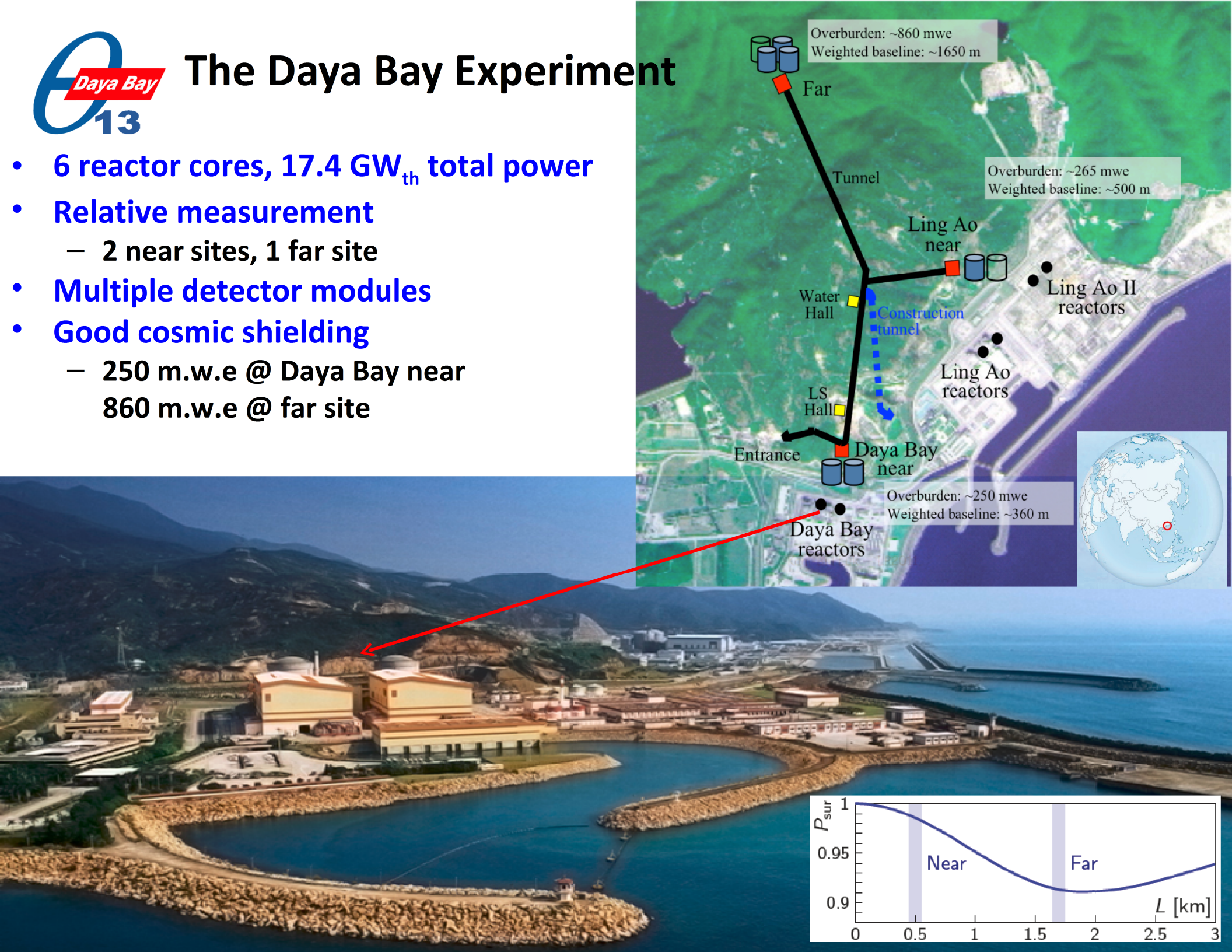
Asia (20)

Beijing Normal Univ., Chengdu Univ. of Sci. and Tech., CGNPG, CIAE, Dongguan Univ.Tech., IHEP, 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.

~230 Collaborators

The Daya Bay Experiment

- 6 reactor cores, 17.4 GW_{th} total power
- Relative measurement
  - 2 near sites, 1 far site
- Multiple detector modules
- Good cosmic shielding
  - 250 m.w.e @ Daya Bay near
    860 m.w.e @ far site



The Daya Bay Detector

Six (at the moment) neutrino detectors, each holding 20 tons of liquid scintillator doped with Gadolinium, are deployed to measure the energy and time of antineutrino interactions electronically. The detectors are submerged in water to shield them from ambient radioactivity background. Active muon detectors are installed to veto residual cosmic muons which can produce cosmogenic background.

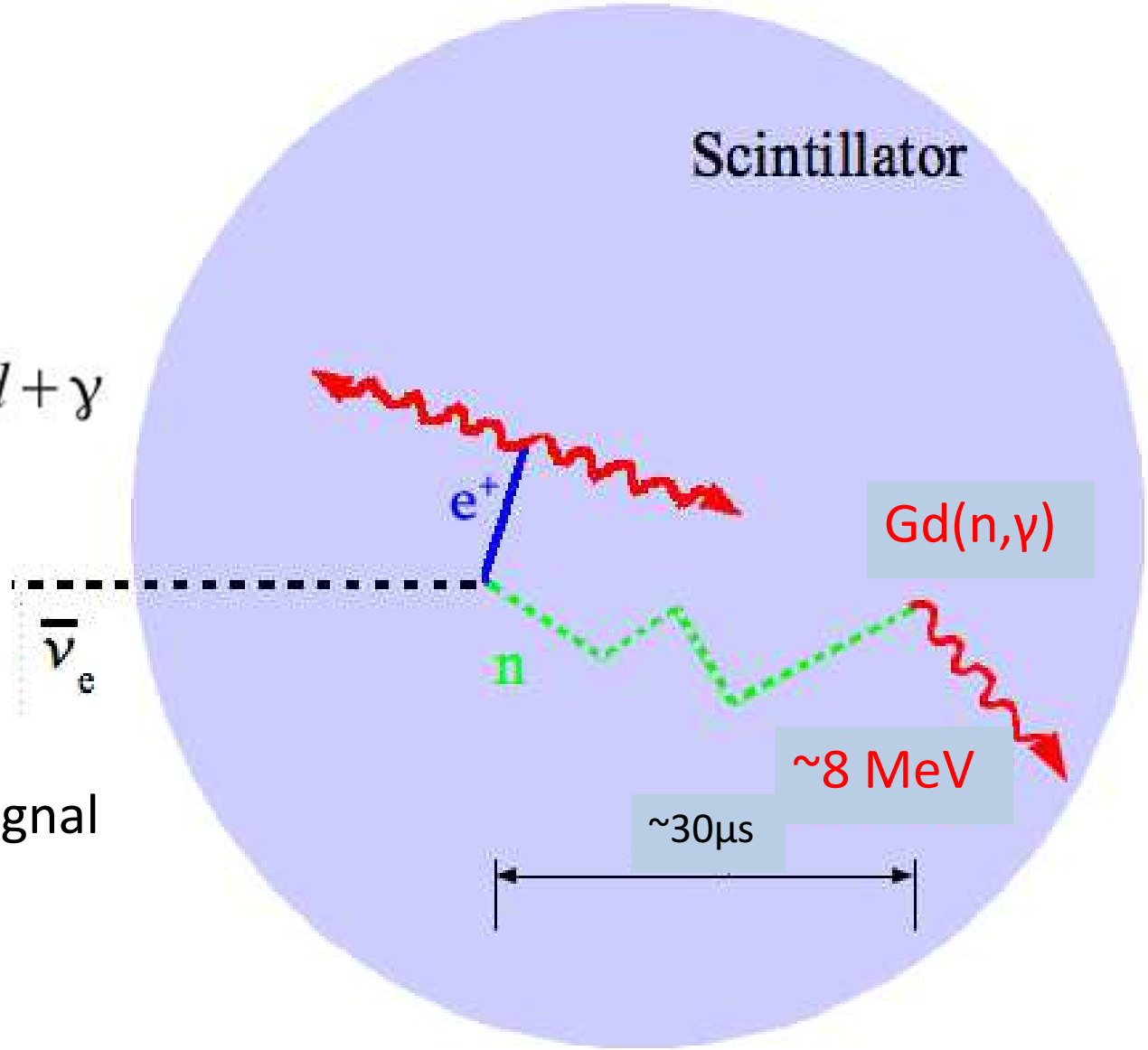
Detection Method

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

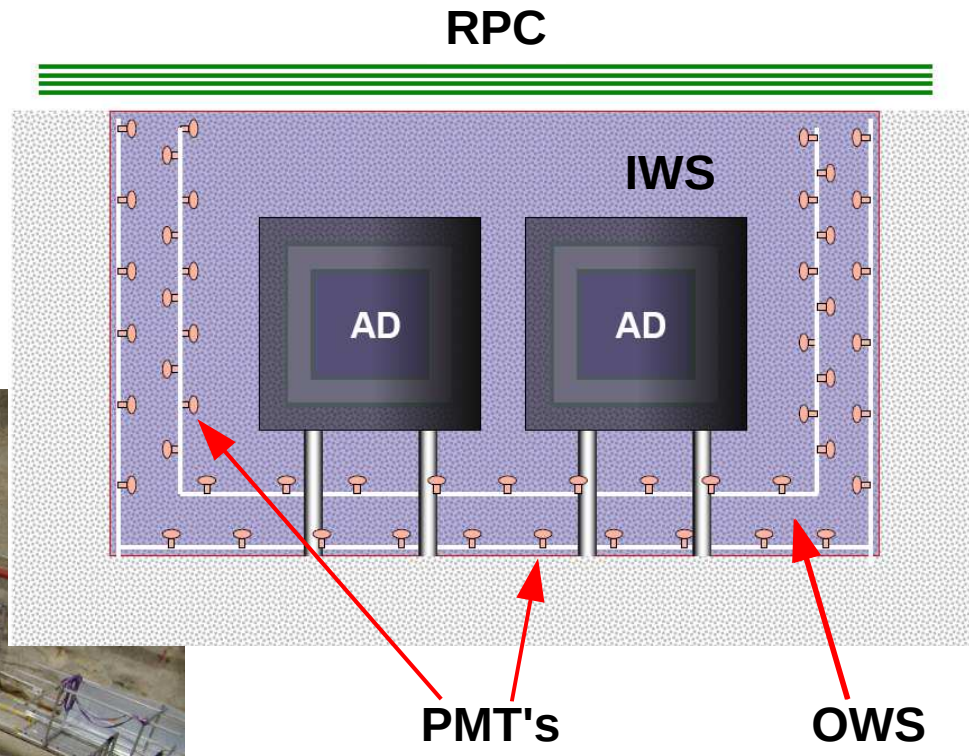
Delayed neutron capture:
Efficiently tags antineutrino signal

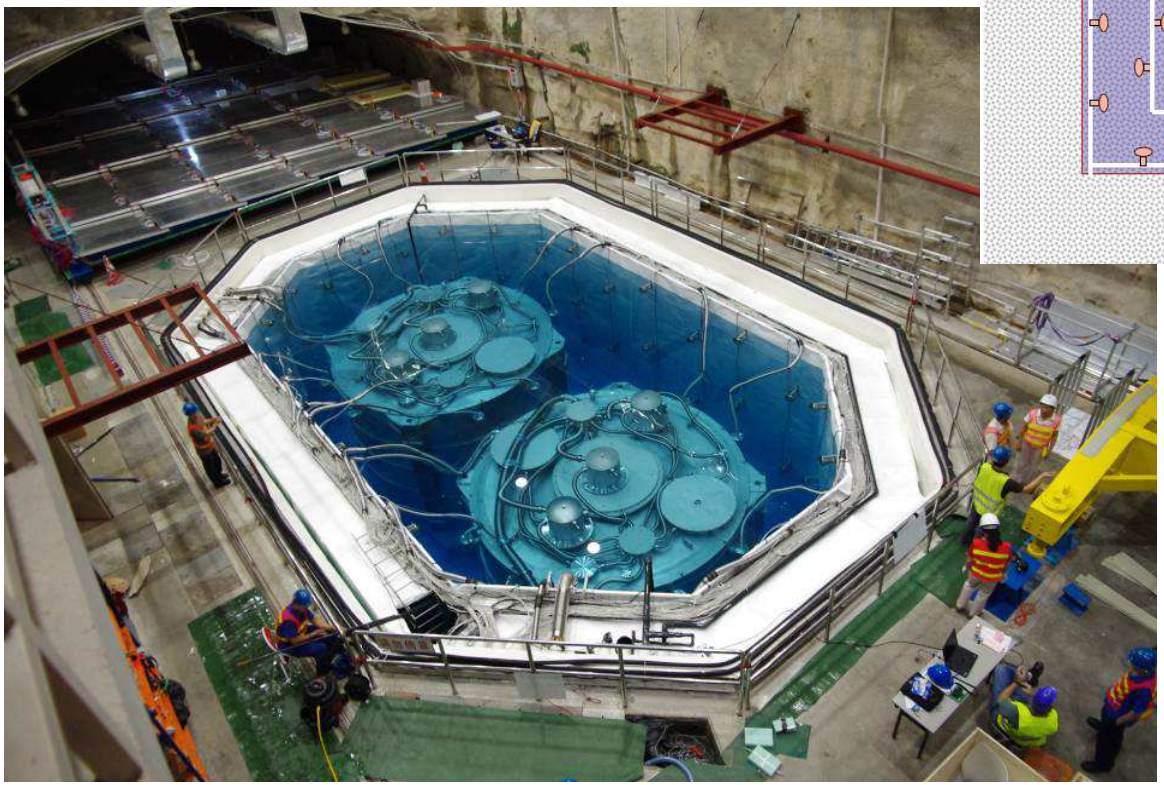


Prompt + Delayed coincidence provides distinctive signature

Daya Bay Experiment Hall

- Water pool muon veto
- Water attenuates background
- RPC additional tracking





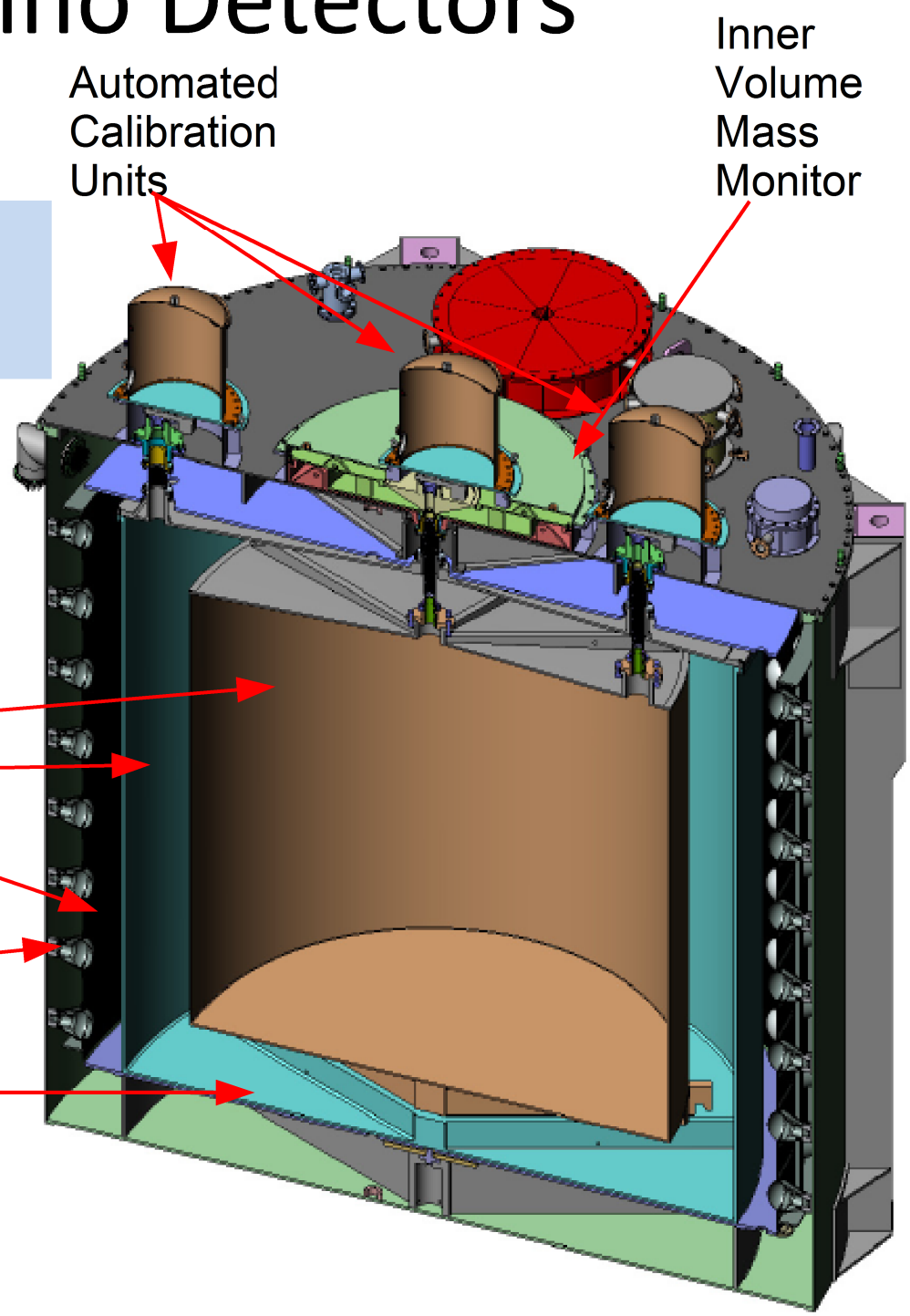
Antineutrino Detectors

6 'functionally identical' detectors:
Reduce systematic uncertainties

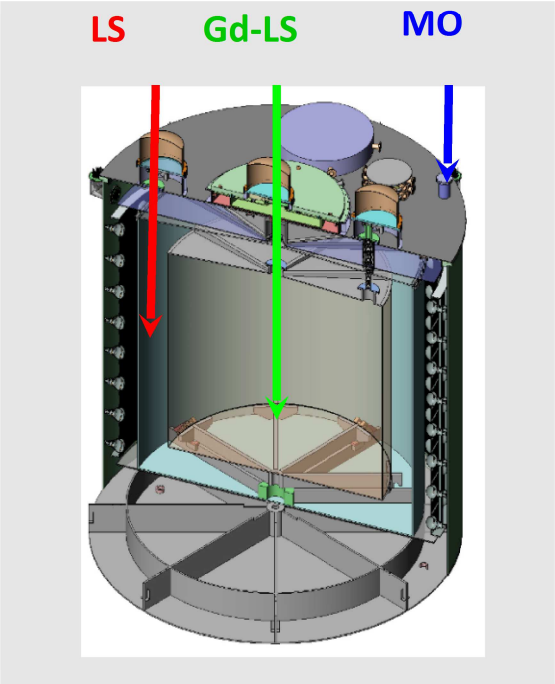
$$\frac{N_{\mathrm{f}}}{N_{\mathrm{n}}} = \left(\frac{N_{\mathrm{p,f}}}{N_{\mathrm{p,n}}}\right)\left(\frac{L_{\mathrm{n}}}{L_{\mathrm{f}}}\right)^2\left(\frac{\epsilon_{\mathrm{f}}}{\epsilon_{\mathrm{n}}}\right)\left[\frac{P_{\mathrm{sur}}(E,L_{\mathrm{f}})}{P_{\mathrm{sur}}(E,L_{\mathrm{n}})}\right]$$

3 nested cylinders:
Inner: 20 tons Gd-doped LS (d=3m)
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

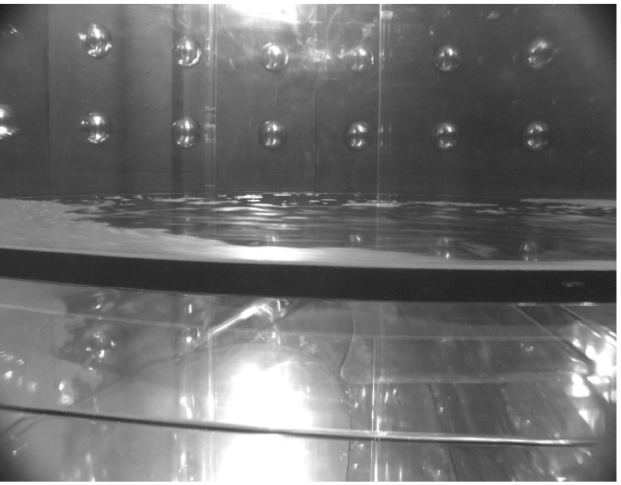


Detector Filling



Detector target filled from GdLS in ISO tank.

Load cells measure 20 ton target mass to 3 kg (0.015%)



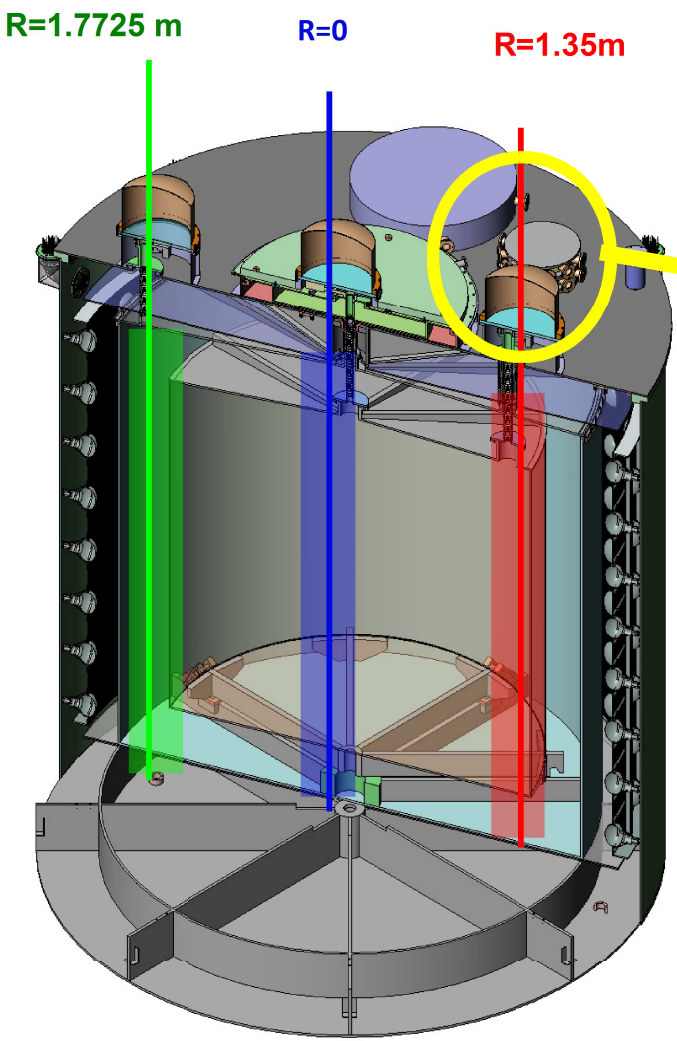
$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left[\frac{P_{sur}(E,L_f)}{P_{sur}(E,L_n)}\right]$$

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

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

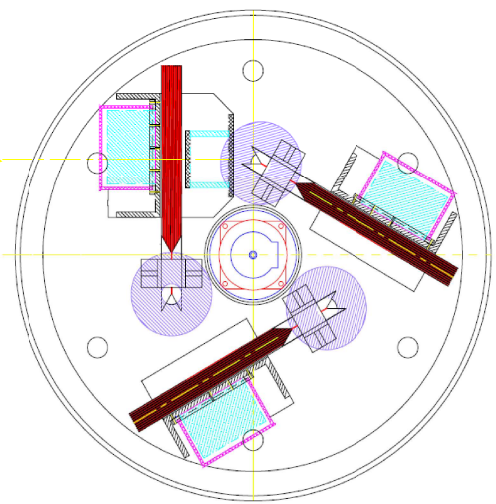
Automated Calibration System

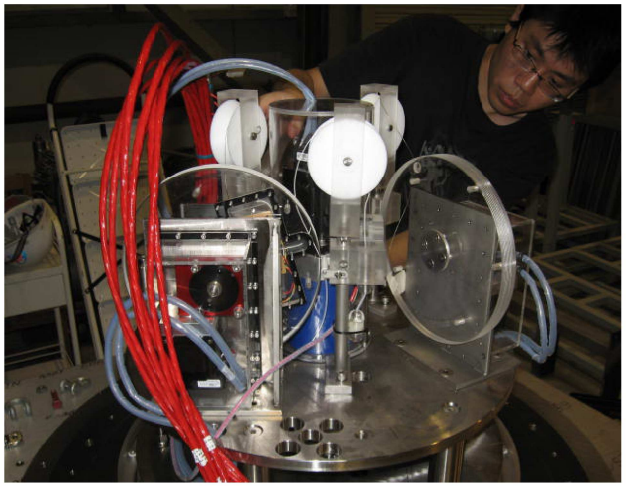
3 Automated calibration 'robots' (ACUs) on each detector



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

Top view

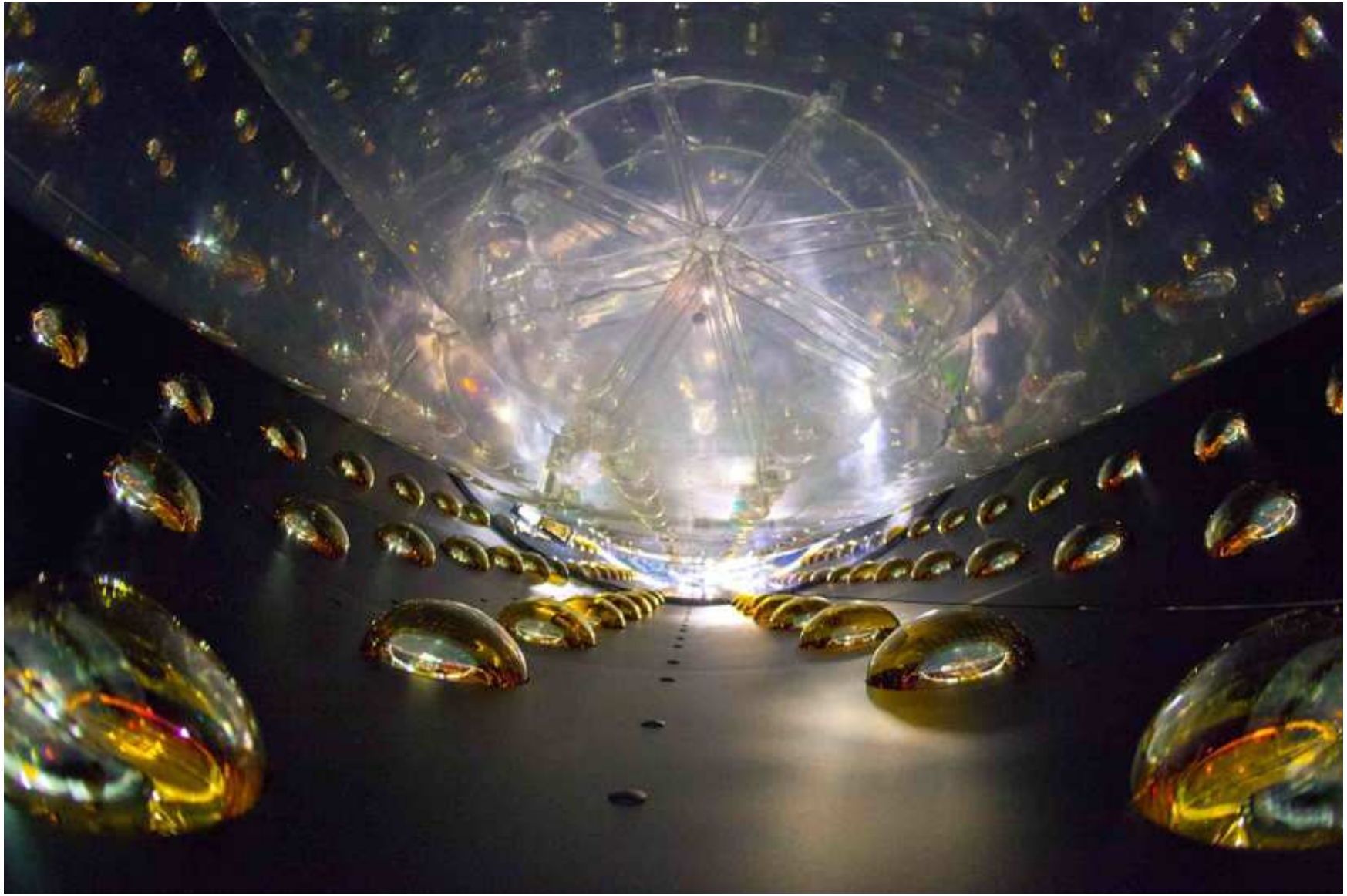




3 sources for each z axis on a turntable (position accuracy < 5 mm):

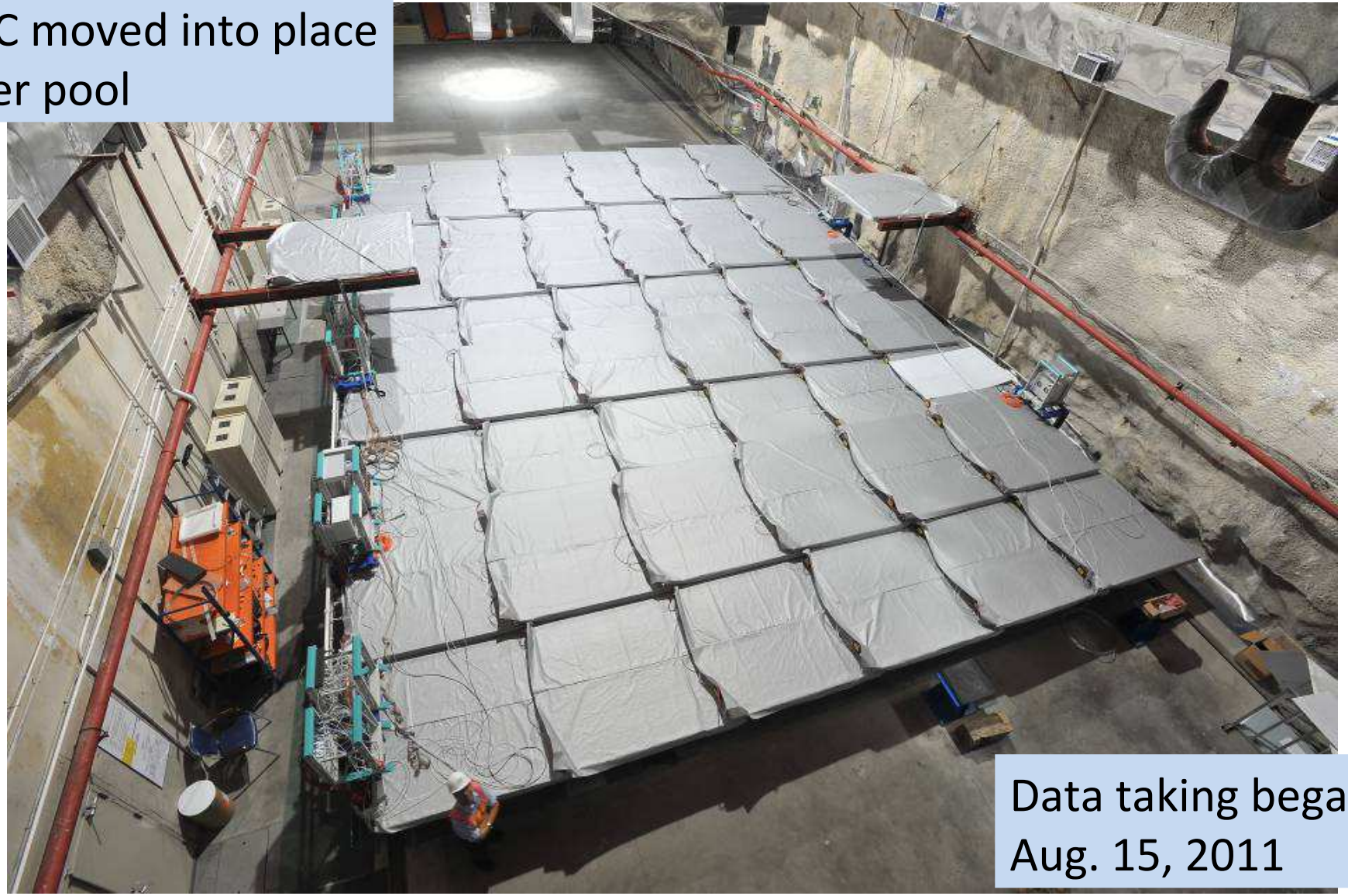
- 10 Hz 68Ge (0 KE e+ = 2×0.511 MeV γ's)
- 0.5 Hz 241Am-13C neutron source (3.5 MeV n without γ) + 100 Hz 60Co gamma source (1.173+1.332 MeV γ)
- LED diffuser ball (500 Hz) for T_0 and gain

Interior of Antineutrino Detector



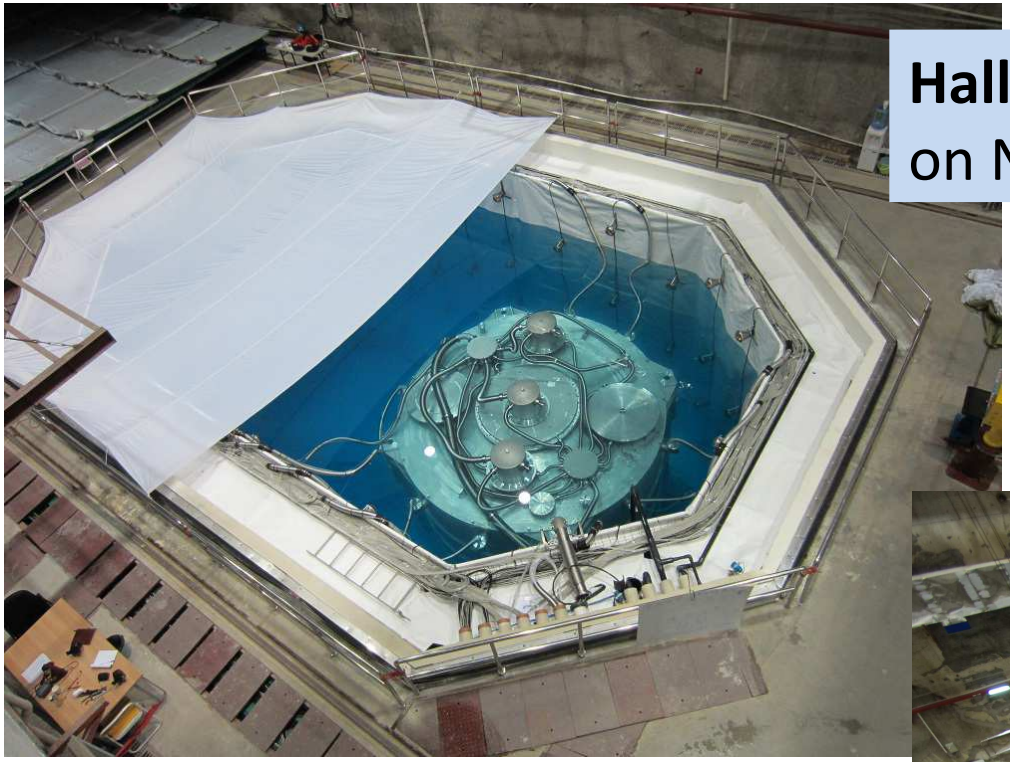
Hall 1: Completed

RPC moved into place over pool



Data taking began Aug. 15, 2011

Hall 2 and Hall 3



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

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

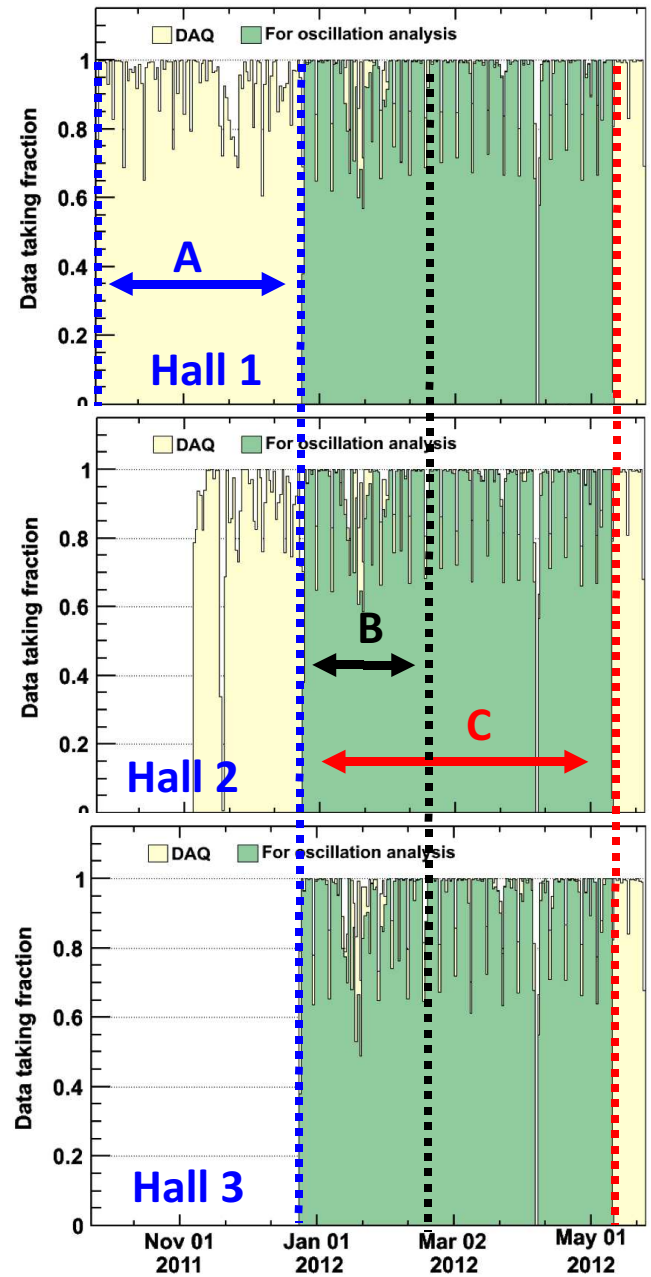
2 more ADs still in assembly; installation planned for late 2012

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.
- Nucl. Inst. and Meth. A685, 78 (2012)

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



Antineutrino IBD Event Selection

Use IBD Prompt + Delayed correlated signal to select antineutrinos

Selection:

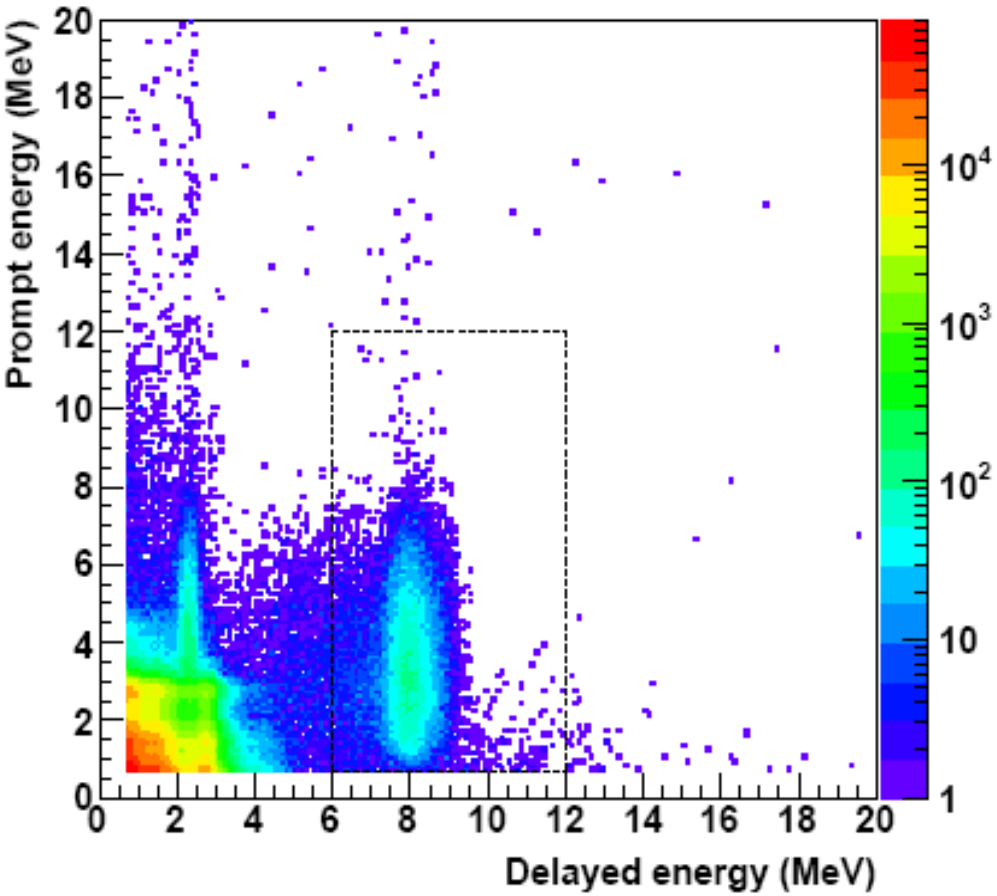
- Reject Flashers
- Prompt Positron: 0.7 MeV < Ep < 12 MeV
- Delayed Neutron: 6.0 MeV < Ed < 12 MeV
- Capture time: 1 μs < Δt < 200 μs
- Muon Veto:
  - Pool Muon: Reject 0.6ms
  - AD Muon (>20 MeV): Reject 1ms
  - AD Shower Muon (>2.5GeV): Reject 1s
- Multiplicity:
  - No other signal > 0.7 MeV in ±200 μs of IBD.

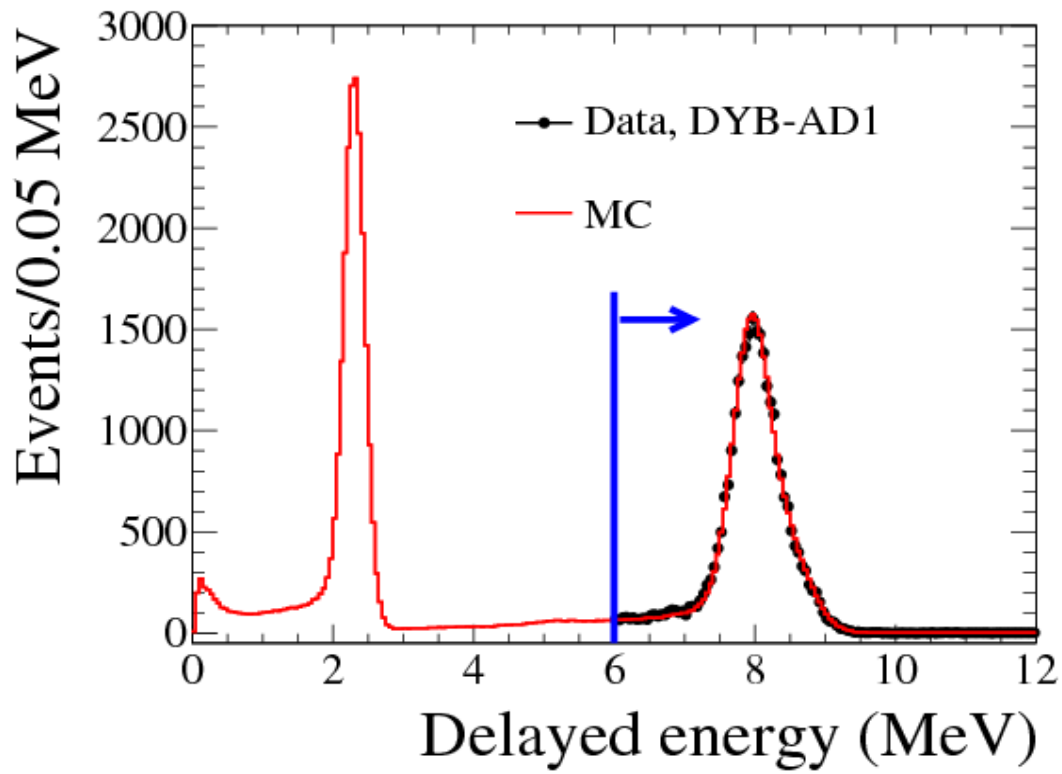
Selection driven by uncertainty in relative detector efficiency

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

Prompt/Delayed Energy

Clear separation of antineutrino events from most other signals





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

Backgrounds

Accidentals:

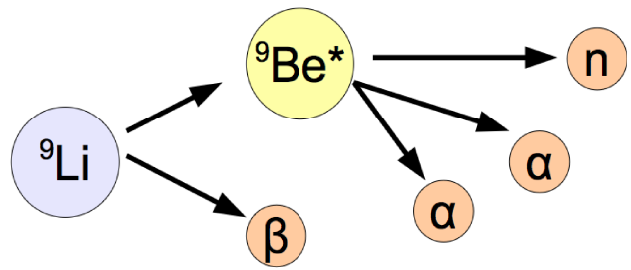
- Random coincidence of neutron-like singles and prompt singles

Fast Neutrons:

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

^{9}Li/^{8}He :

- Generated by cosmic rays

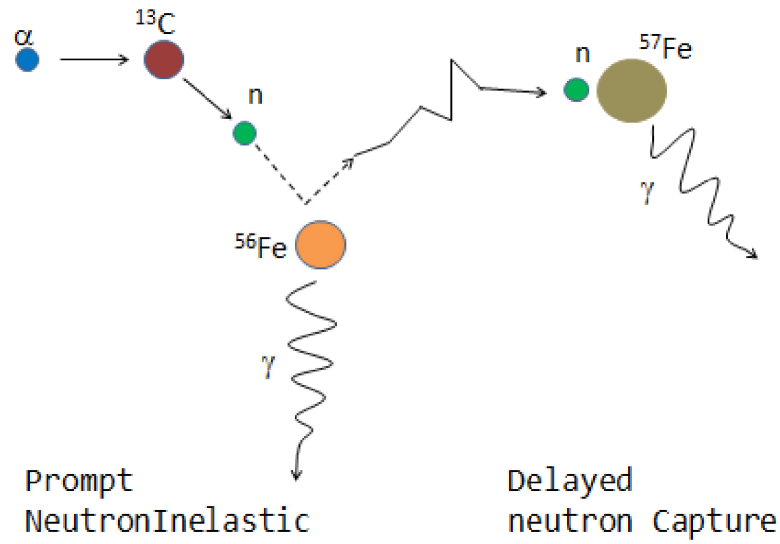


^{241}Am-^{13}C :

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

^{13}C(α,n)^{16}O :

- Alpha emitters interact with ^{13}C in scintillator.

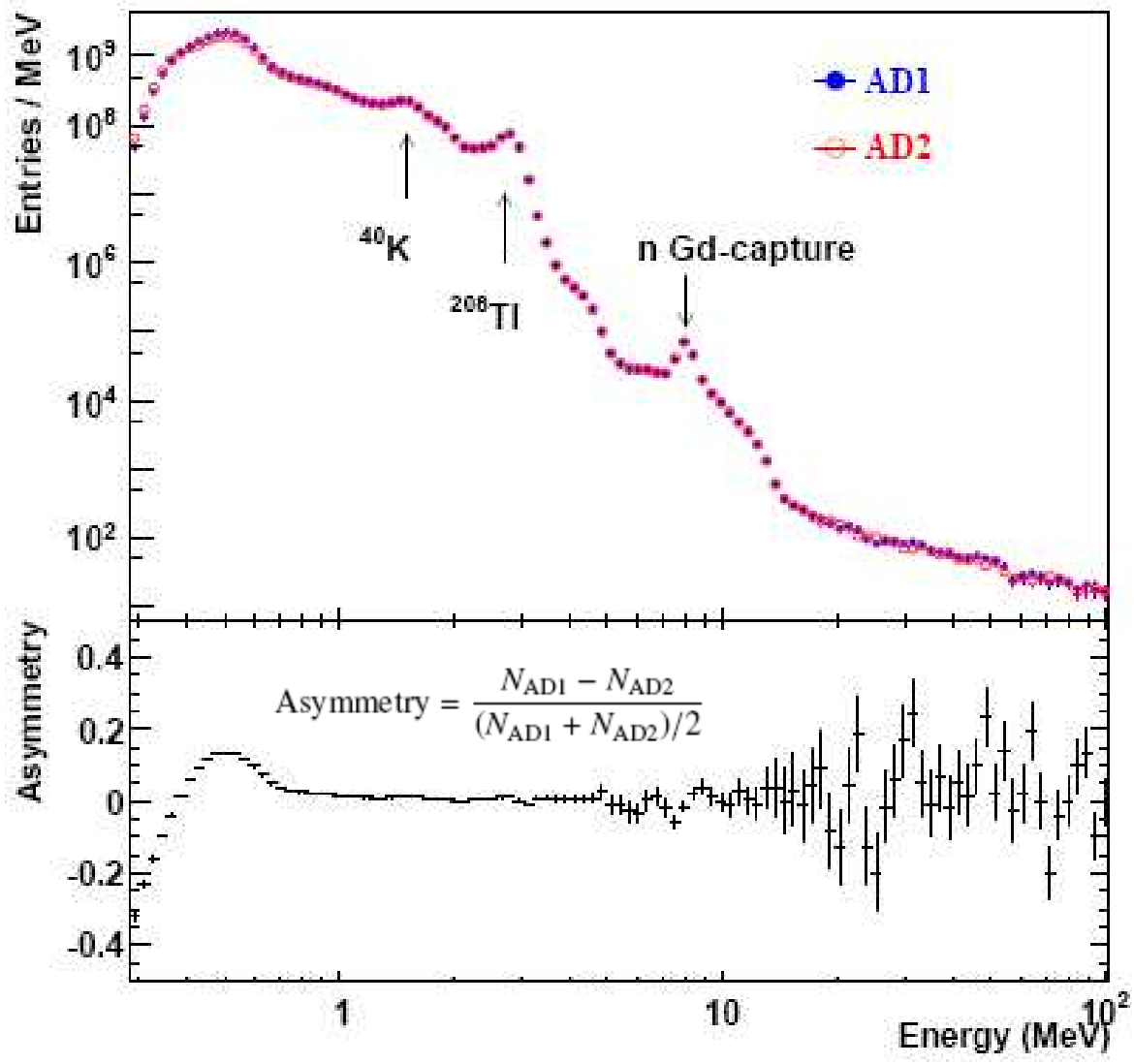


Singles Spectrum

- Design: ~50Hz above 1 MeV
- Data: ~60Hz above 0.7 MeV, ~40Hz above 1 MeV

- From sample purity and MC simulation, each of the following component contribute to singles
  - ⇨ ~ 5 Hz from SSV
  - ⇨ ~ 10 Hz from LS
  - ⇨ ~ 25 Hz from PMT
  - ⇨ ~ 5 Hz from rock

- All numbers are consistent



Side-by-side Comparison

- **Expected ratio of neutrino events: R(AD1/AD2) = 0.982**
  - **The ratio is not 1 because of baseline difference**
  - **target mass contributes 0.15%**
- **Measured ratio: 0.987 ± 0.008(stat) ± 0.003(syst)**

Data Set Summary

> 200k antineutrino interactions!

	Daya Bay Near		Ling Ao Near	Far		
	AD1	**AD2**	**AD3**	**AD4**	**AD5**	**AD6**
Antineutrino candidates	69121	69714	66473	9788	9669	9452
DAQ live time (days /AD)	127.55		127.38	126.26		
Efficiency	0.8015	0.7986	0.8364	0.9555	0.9552	0.9547
Antineutrino Candidates (/day)	676.12	684.40	623.92	81.13	80.17	78.41
Accidentals (/AD/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 (/AD/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 (/AD/day)	2.9±1.5		2.0±1.1	0.22±0.12		
Am-C corr. (/AD/day)	0.2±0.2					
^{13}C(α, n)^{16}O (/AD/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
Sum Backgrounds (/AD/day)	13.68	13.55	10.38	3.56	3.55	3.44
Antineutrino rate (/AD/day)	**662.47 ±3.00**	**670.87 ±3.01**	**613.53 ±3.60**	**77.57 ±0.85**	**76.62 ±0.85**	**74.97 ±0.84**

Consistent rates for side-by-side detectors

Uncertainty currently dominated by statistics

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%

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

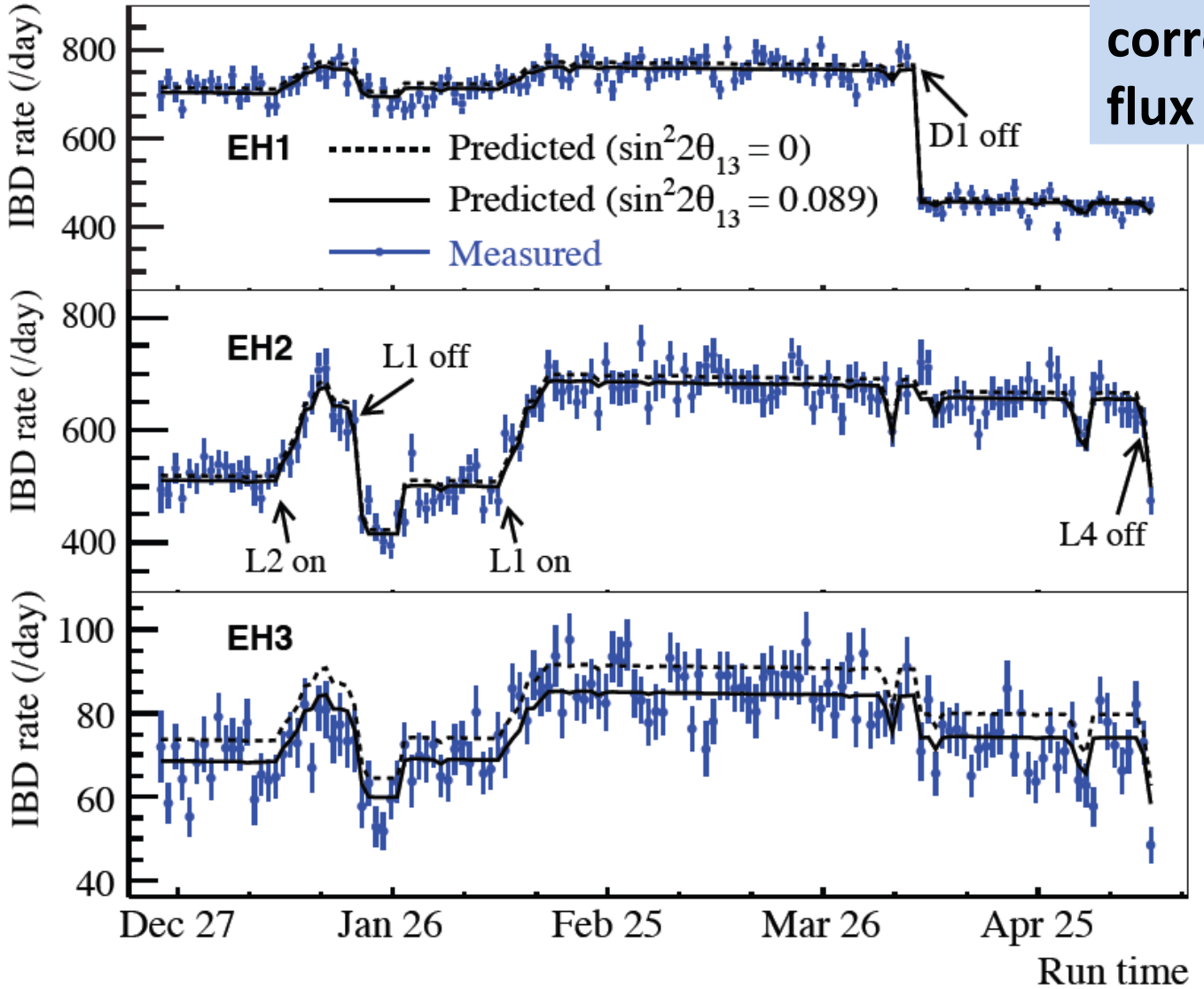
Largest systematics are smaller than far site statistics (~1%)

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%

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

Antineutrino Rate vs. Time

Detected rate strongly correlated with reactor flux expectations.

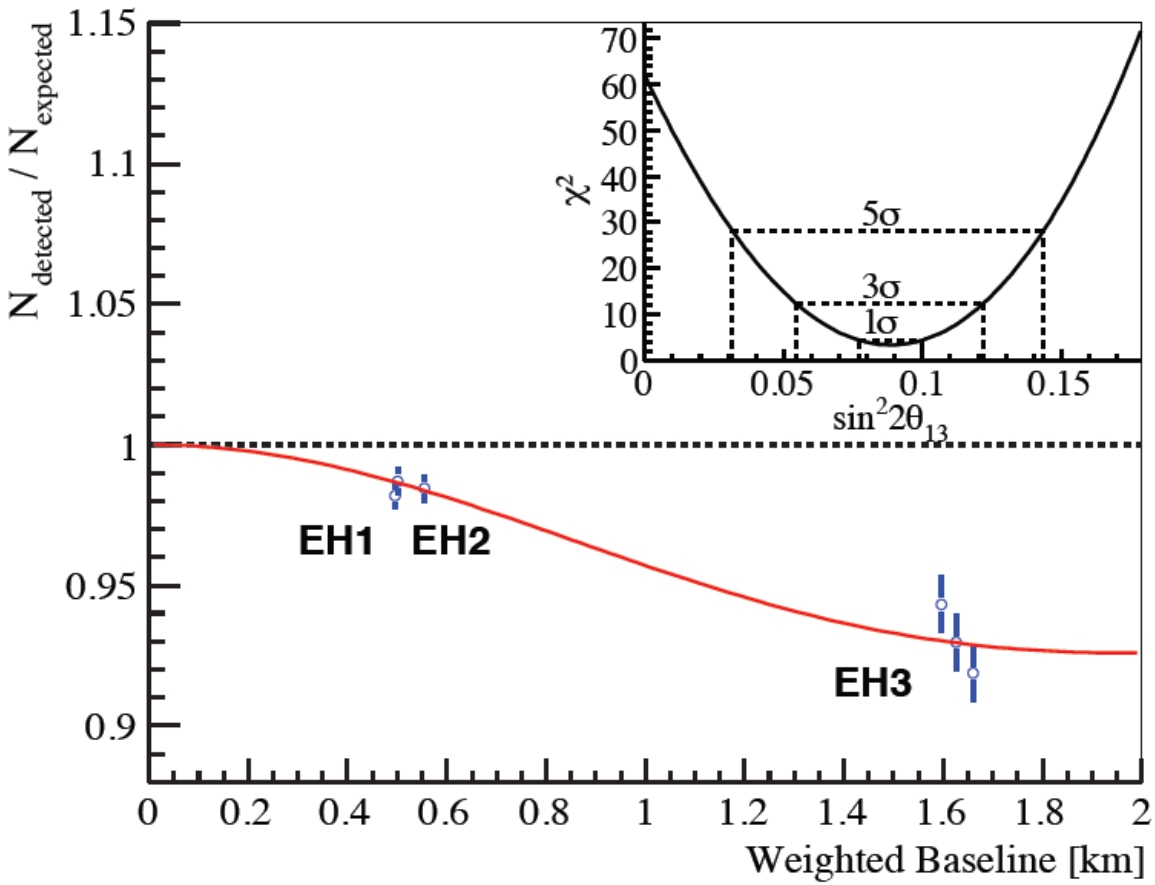


Predicted Rate:

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

Rate Analysis

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



Uses standard χ2 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.

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

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.

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 ± 0.010 (stat) ± 0.005 (syst)

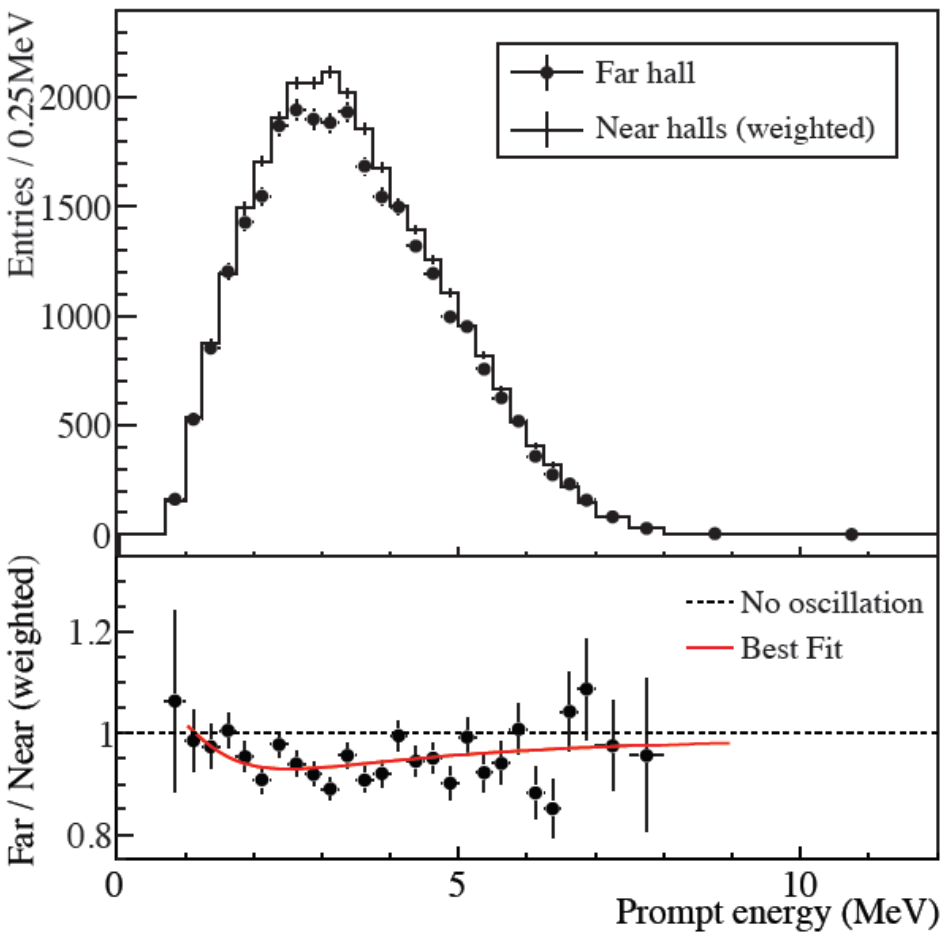
[Previous value: $\sin^2 2\vartheta_{13}$ = 0.092 ± 0.016 (stat) ± 0.005 (syst)]

- Installation of final pair of antineutrino detectors this year

Back up

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)

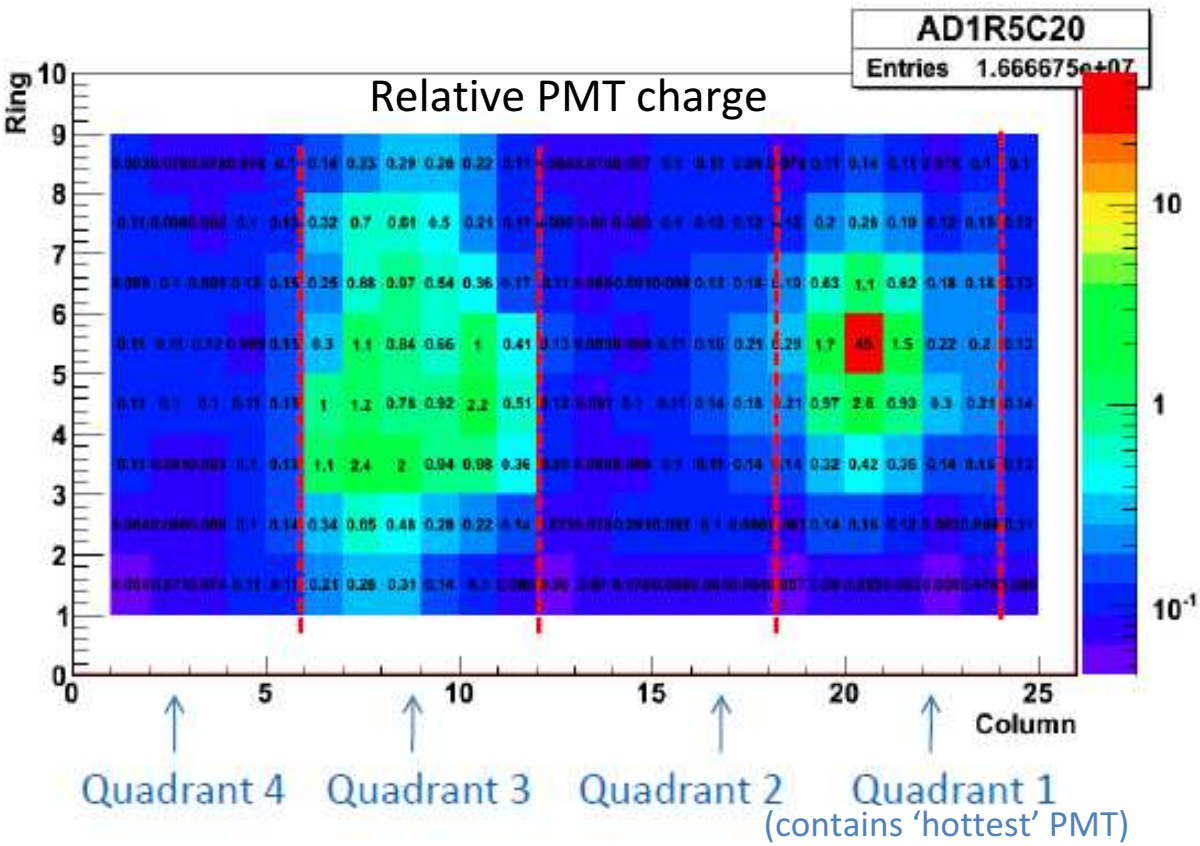
Clear observation of far site deficit.

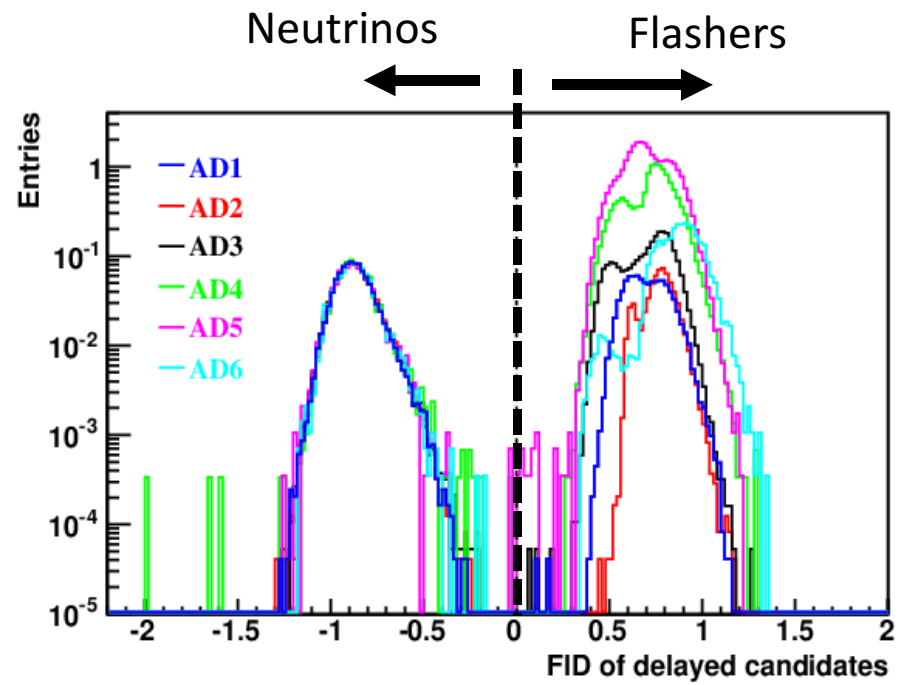
Spectral distortion consistent with oscillation.*

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

PMT Light Emission (Flashing)

Flashing PMTs:
- Instrumental background from ~5% of PMTS
- 'Shines' light to opposite side of detector
- Easily discriminated from normal signals





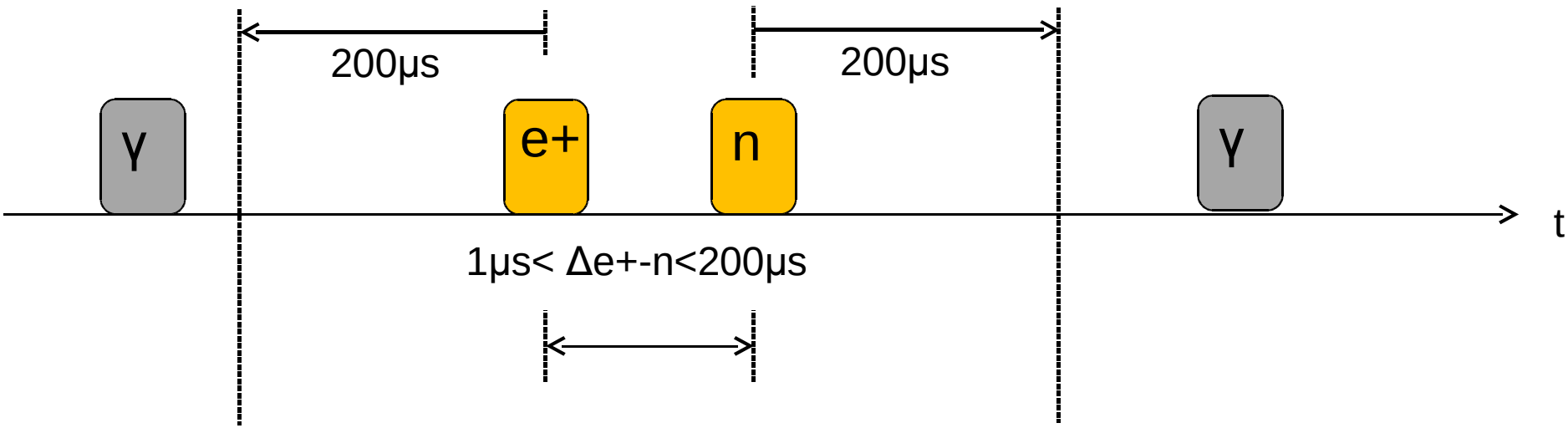
$$\mathrm{FID} = \log_{10}\left[\left(\frac{\mathrm{Quadrant}}{1.0}\right)^2 + \left(\frac{\mathrm{MaxQ}}{0.45}\right)^2\right] < 0$$

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

Inefficiency to antineutrinos signal:
$0.024\% \pm 0.006\%$(stat)
Contamination: < 0.01%

Multiplicity

Ensure exactly one prompt-delayed coincidence



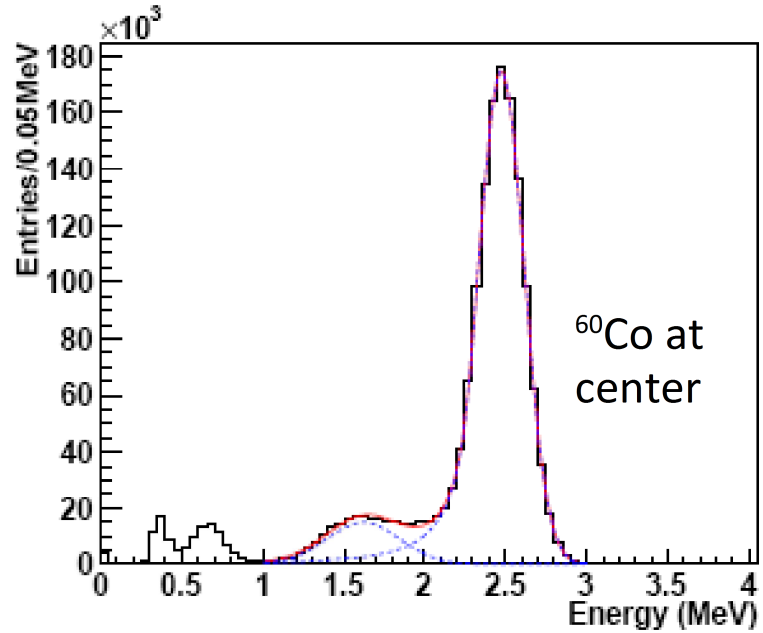
Uncorrelated background and IBD signals result in ambiguous prompt, delayed signals.

-> Reject all IBD with >2 triggers above 0.7 MeV in -200μs to +200μs.
Introduces ~2.5% IBD inefficiency, with negligible uncertainty

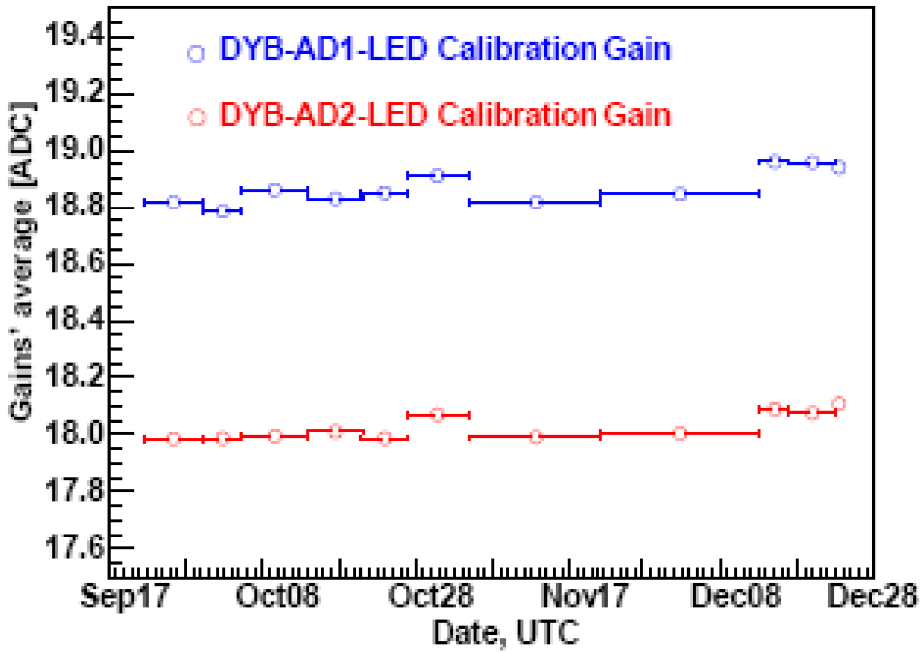
Calibration

Calibration driven by uncertainty in relative detector efficiency

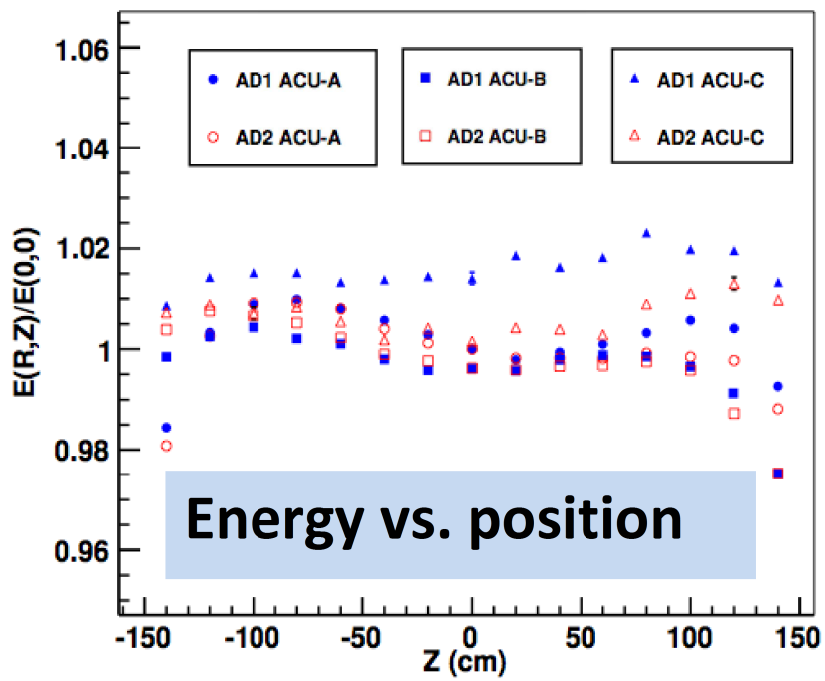
$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left[\frac{P_{sur}(E,L_f)}{P_{sur}(E,L_n)}\right]$$



PMT gain vs. time



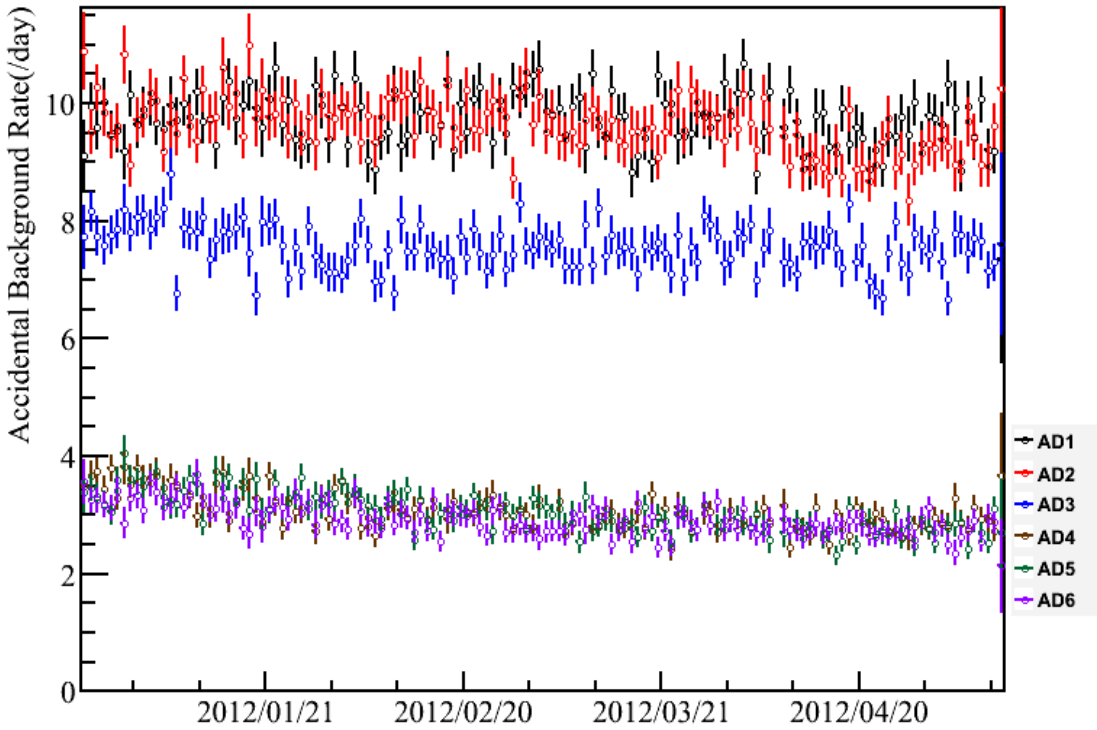
Calibrations run weekly



Energy vs. position

Accidental Background

- Calculation:
  - Random coincidence of neutron-like singles and prompt signals
  - periodic trigger
- Cross check:
  - Prompt-delayed distance distribution. Check the fraction of prompt-delayed with distance >2m.



Accidental background rates (per day), muon veto and multiplicity cut eff corrected

	AD1	AD2	AD3	AD4	AD5	AD6
Accidentals (per 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

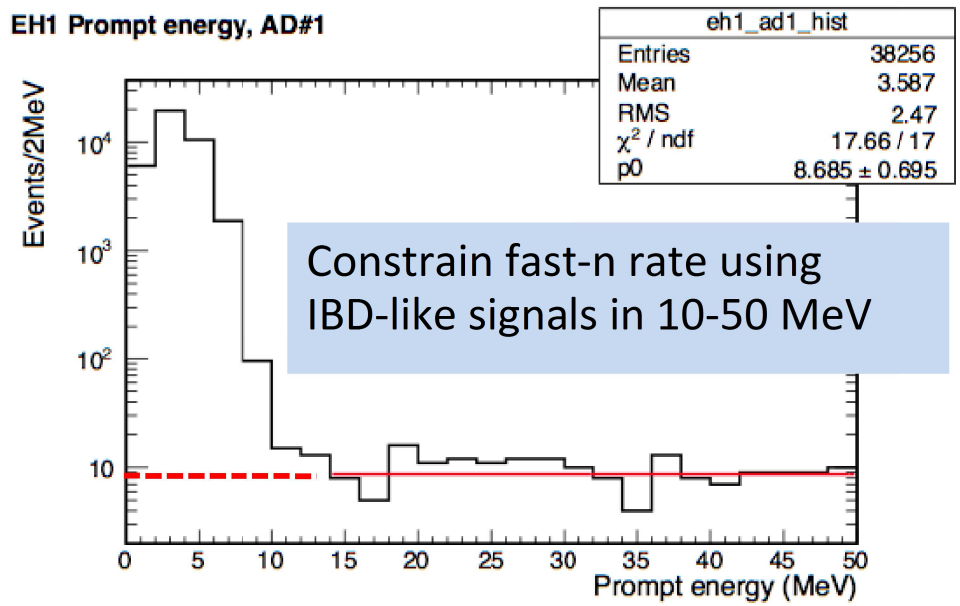
Fast neutron Background

Fast Neutrons:

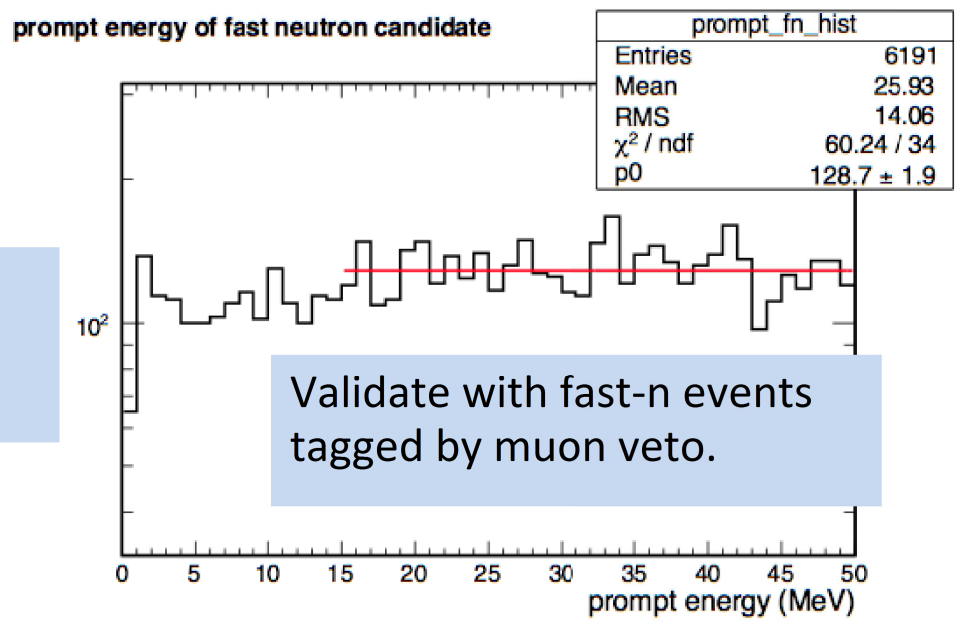
Energetic neutrons produced by cosmic rays (inside and outside of muon veto system)

Mimics antineutrino (IBD) signal:

- Prompt: Neutron collides/stops in target
- Delayed: Neutron captures on Gd



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



Validate with fast-n events tagged by muon veto.

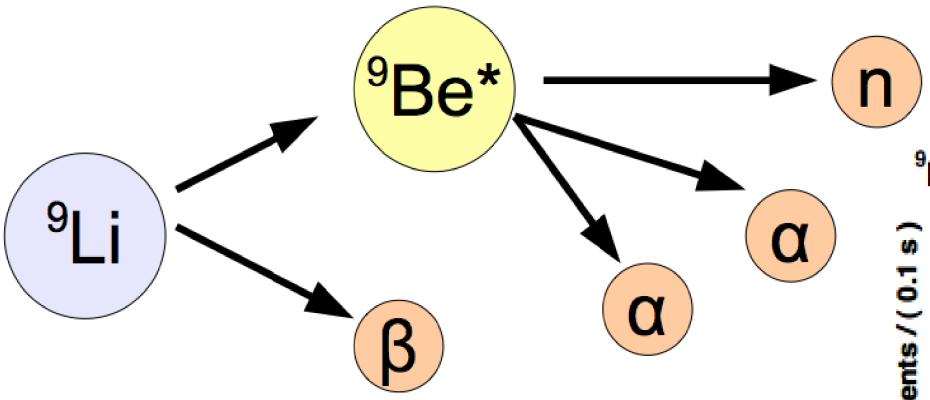
Background uncertainties are 0.3% (0.2%) in far (near) halls.

β-n decay Background

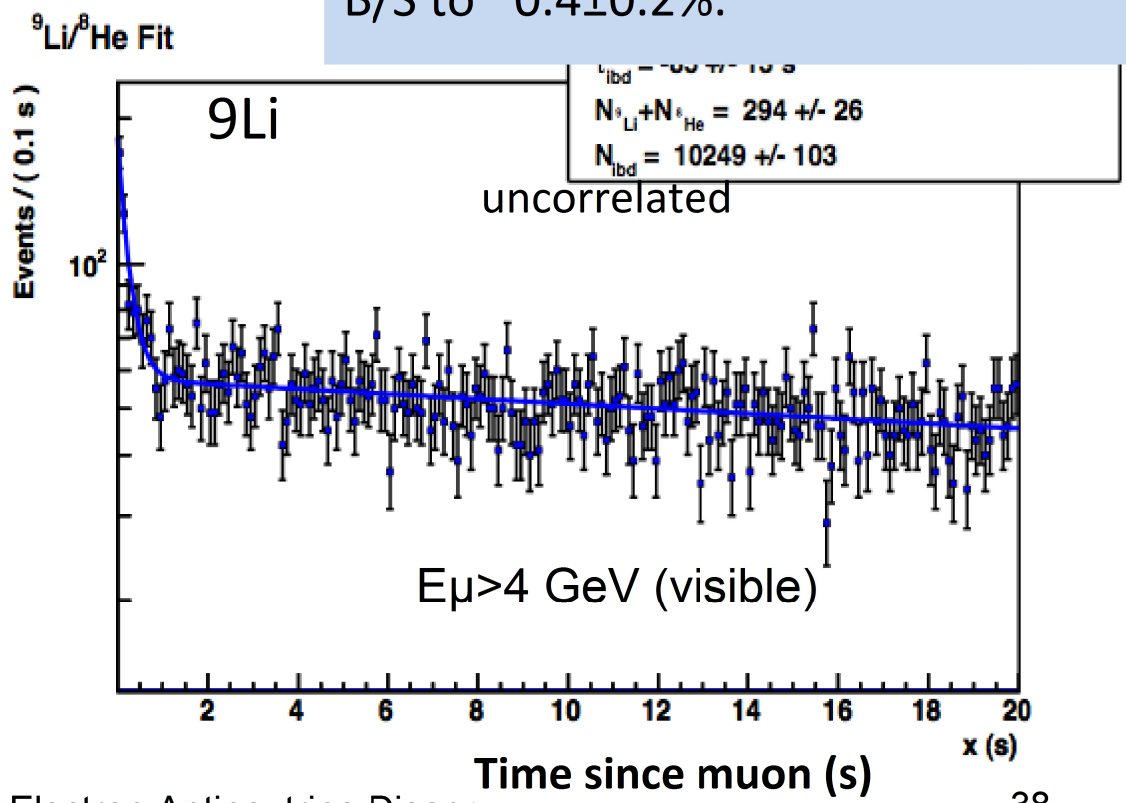
- Generated by cosmic rays
- Long-lived
- Mimic antineutrino signal
- Estimate 9Li rate using time-correlation with muon

β-n decay:

- Prompt: β-decay
- Delayed: neutron capture



Analysis muon veto cuts control B/S to ~0.4±0.2%.

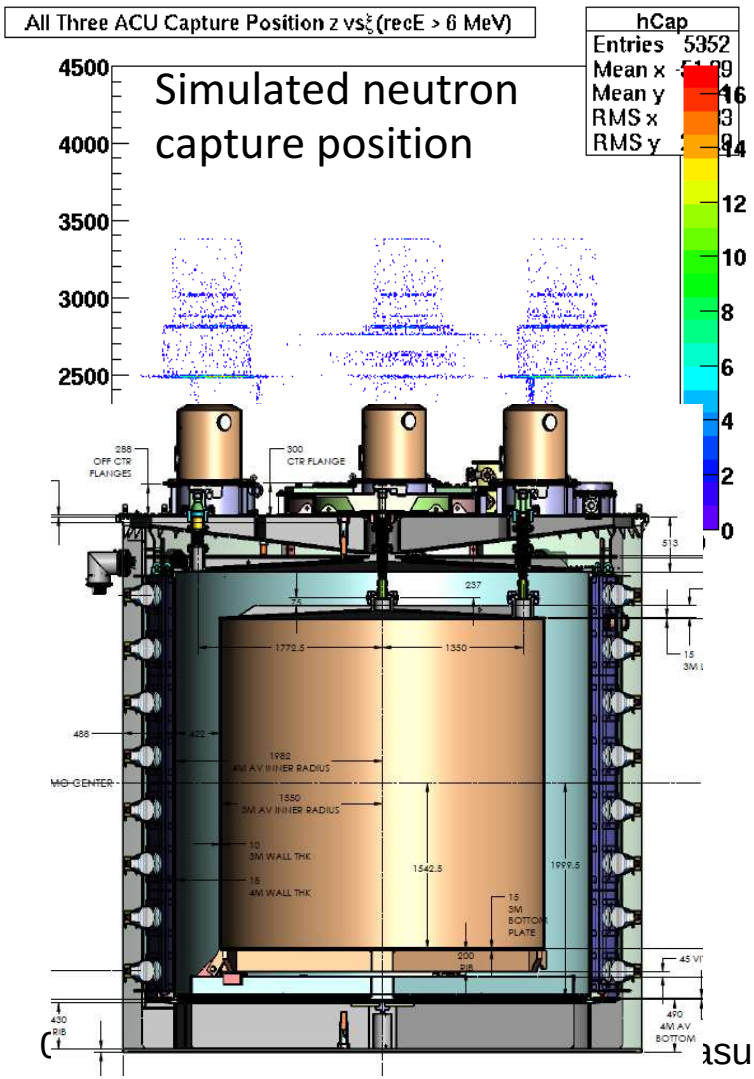


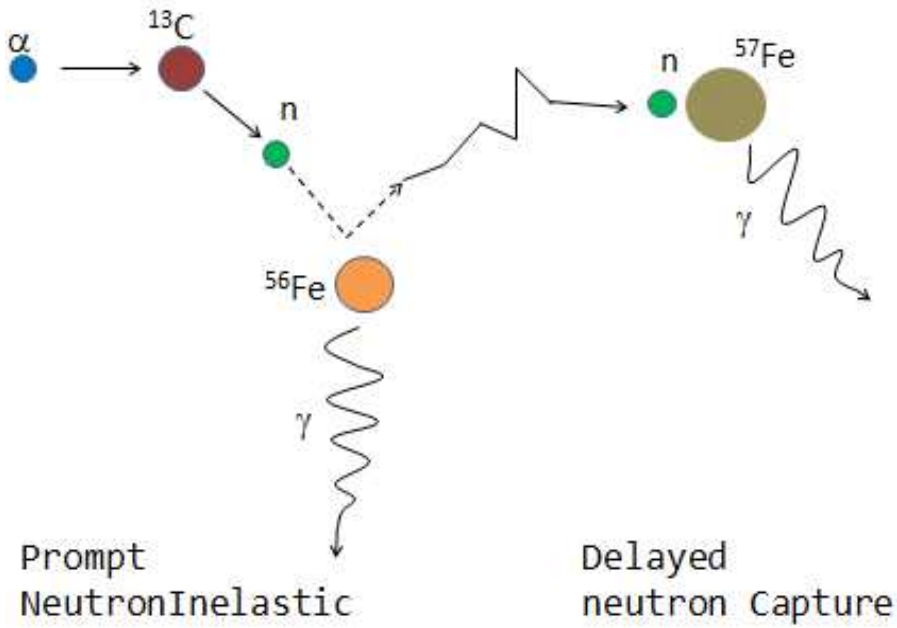
9Li: $\tau_{1/2}$ = 178 ms, Q = 13.6 MeV

8He: $\tau_{1/2}$ = 119 ms, Q = 10.6 MeV

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

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

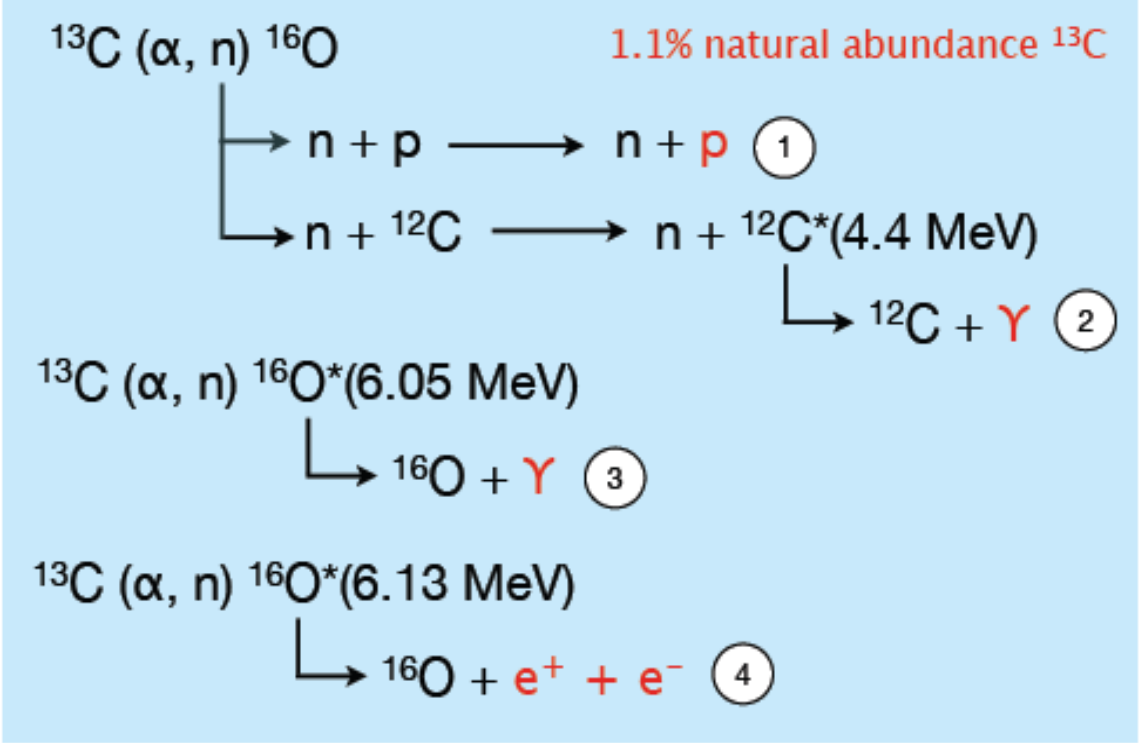




Constrain far site B/S to 0.3 ± 0.3%:

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

Background: $^{13}C(\alpha,n)^{16}O$



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

Potential alpha source:

238U, 232Th, 235U, 210Po:

Each of them are measured in-situ:

U&Th: cascading decay of

Bi(or Rn) – Po – Pb

210Po: spectrum fitting

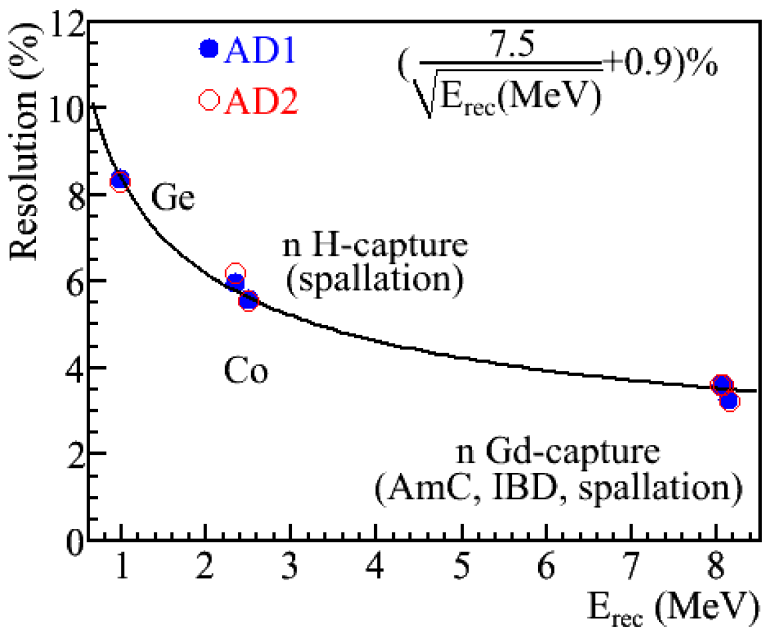
Combining (α,n) cross-section, correlated background rate is determined.

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)%

All detectors use one common batch of target scintillator

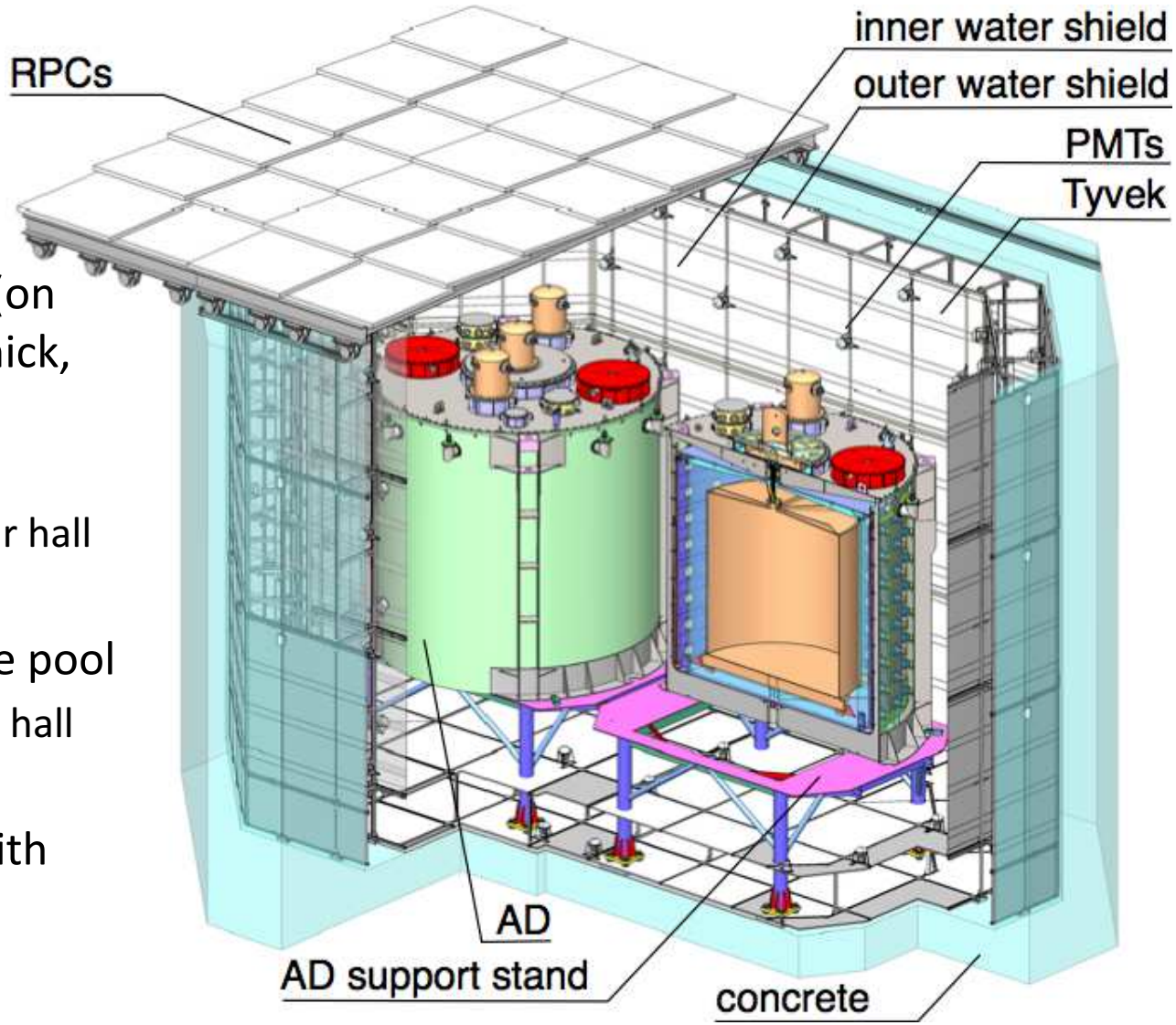
Quantity	Relative	Absolute
Free protons/kg	neg.	0.47%
Density	neg.	0.0002%
Total mass	0.015%	0.015%
Bellows	0.0025%	0.0025
Overflow tank	0.02%	0.02%
Total	0.03%	0.47%

Target Protons Uncertainty



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
- Goal efficiency: > 99.5% with uncertainty <0.25%

Reactor Neutrinos

- **Reactor neutrino spectrum**

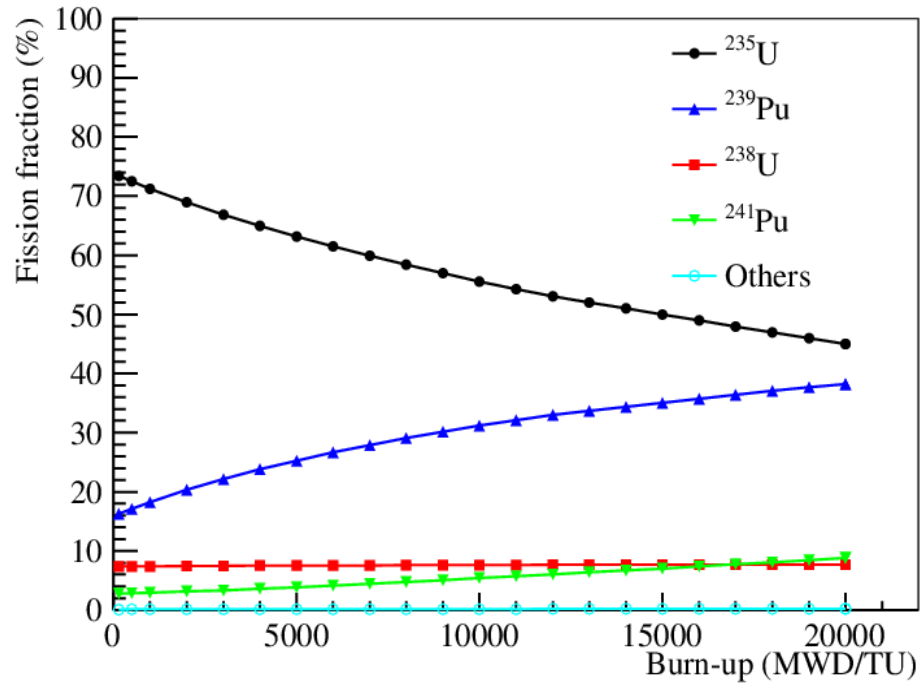
$$S(E) = \sum_i F_i S_i(E)$$

neutrino spectra per fission of each isotope

simulated fission rate

The measured thermal power W_{th} is used for normalization when simulating fission rate

$$F_i = W_{th} f_i / \sum_k f_k e_k$$



Energy release per fission

Isotope	E_{fi}, MeV/fission
^{235}U	201.92 ± 0.46
^{238}U	205.52 ± 0.96
^{239}Pu	209.99 ± 0.60
^{241}Pu	213.60 ± 0.65

Kopeikin et al, Physics of Atomic Nuclei, Vol. 67, No. 10, 1892 (2004)

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%

Relative measurement → flux model has negligible impact on far v.s near oscillation measurement