Наблюдение осцилляций электронных антинейтрино в эксперименте Дая Бэй

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Марковские чтения, 12 мая 2012г.

Neutrino Oscillation

Neutrinos change flavor (e,μ,τ) with time

Principle:

Mass eigenstates ≠ Interaction (flavor) eigenstates

$$|\nu_e\rangle = \sum_{m_i} U_{ei}^{*} |\nu_i\rangle$$

Physical Parameters: (chosen by nature)

θ:

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

Δm^2:

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

We want to know θ and Δm^2

First Evidence of Oscillation:

Davis detects 1/3 expected solar neutrinos (1968)

A Decade of Progress

Clear experimental evidence of neutrino oscillation in recent years

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

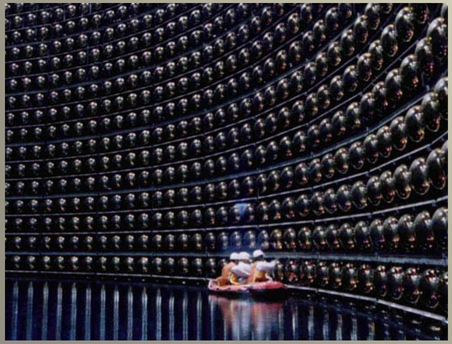
$$U_{if} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

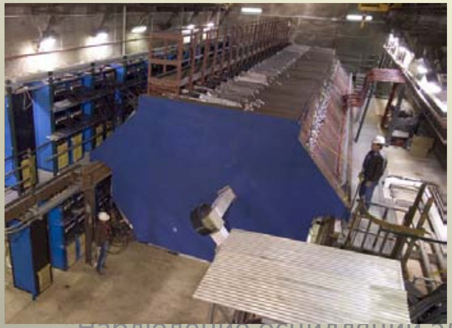
$\theta_{23} \approx 45^o$
Atmospheric ν
Accelerator ν

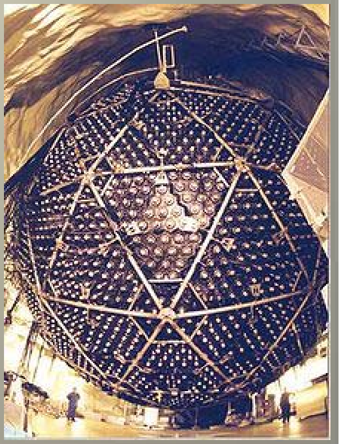
$\theta_{13} < 10^o$
Short-Baseline Reactor ν
Accelerator ν

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

θ_{13}: Only angle not yet firmly observed.







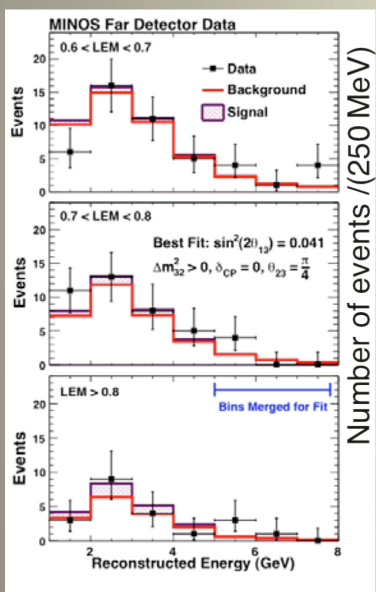
Recent Hints of θ_{13}

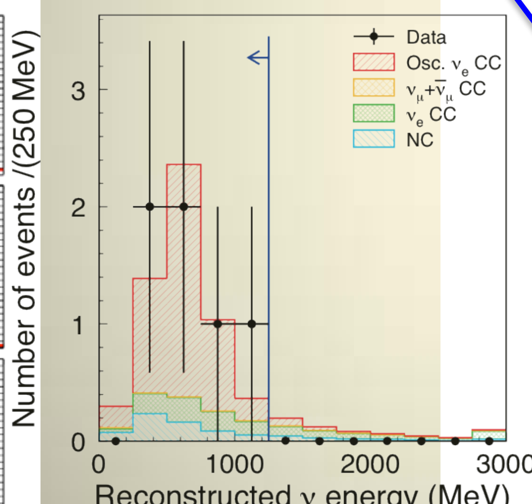
2011 has given many hints:

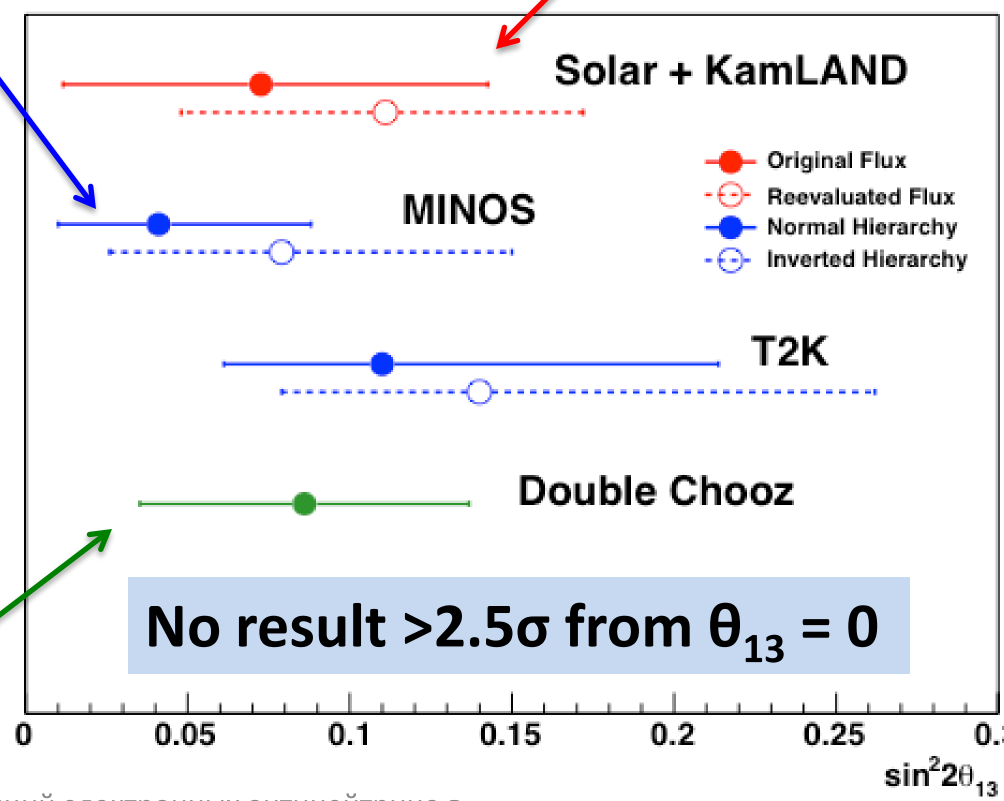
Solar + KamLAND: G.L.Fogli *et al.*, Phys. Rev. D 84, 053007 (2011)
MINOS: P. Adamson *et al.*, Phys. Rev. Lett. 107, 181802 (2011)
T2K: K. Abe *et al.*, Phys. Rev. Lett. 107 041801 (2011)
Double CHOOZ: Y. Abe *et al.*, arXiv:1112.6353

Tension between solar, reactor ν_e oscillations suggest $\theta_{13} > 0$.

Appearance of ν_e in ν_μ accelerator beam





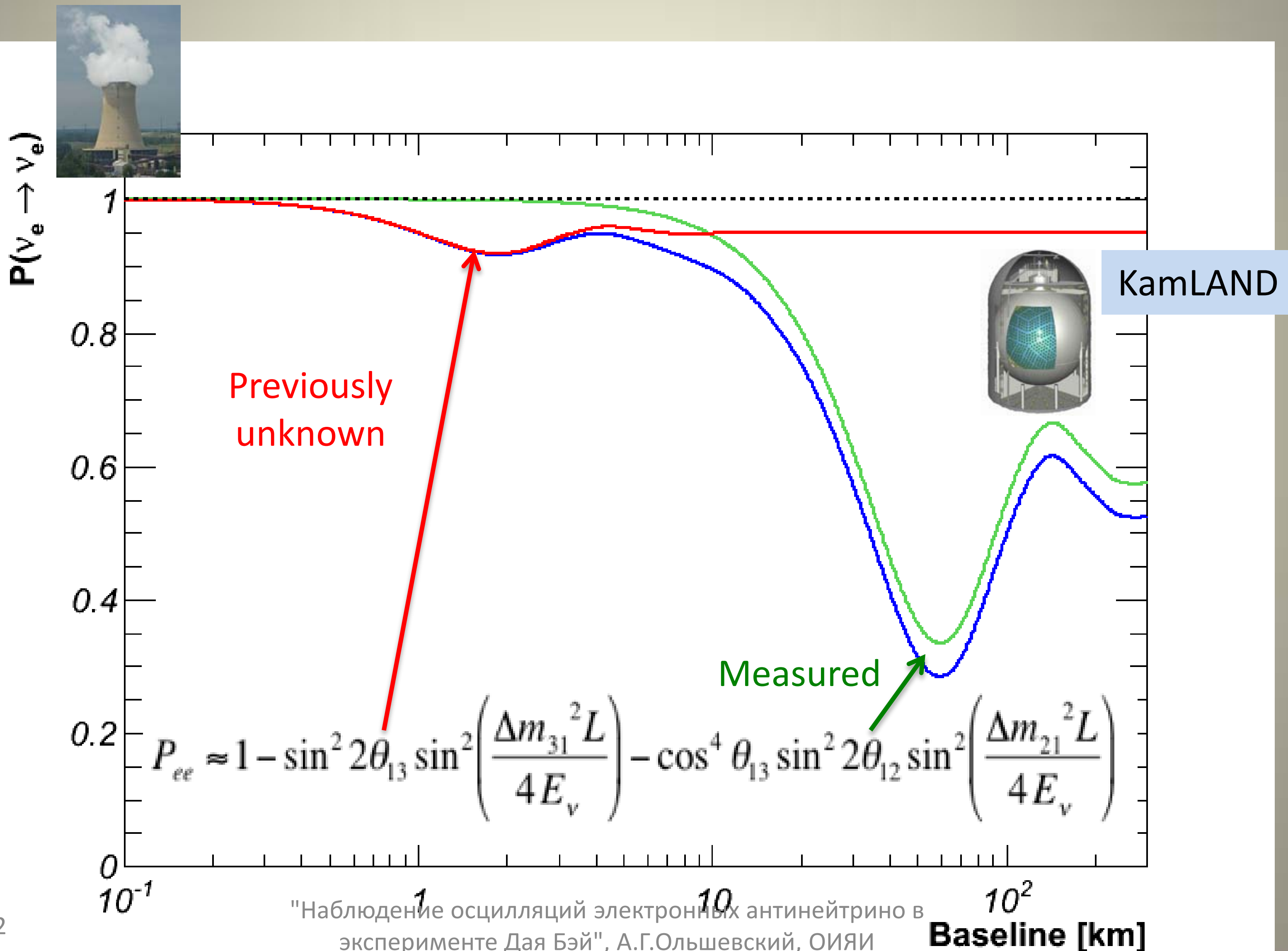


No result >2.5σ from $\theta_{13} = 0$

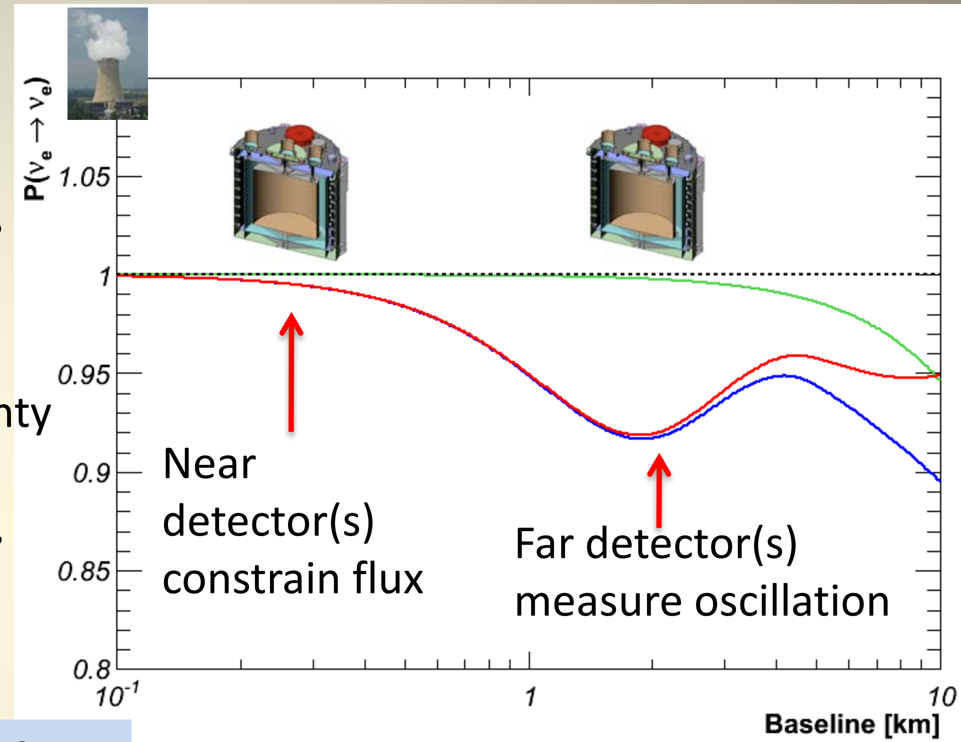
Double Chooz reported improved single detector measurement.

Reactor Neutrino Oscillation

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



Relative Measurement



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

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

Detector Target Mass

Detector efficiency

Daya Bay: An Ideal Location

17.4 GW (thermal) reactor power adjacent to mountains.

Daya Bay NPP
2.9GW×2

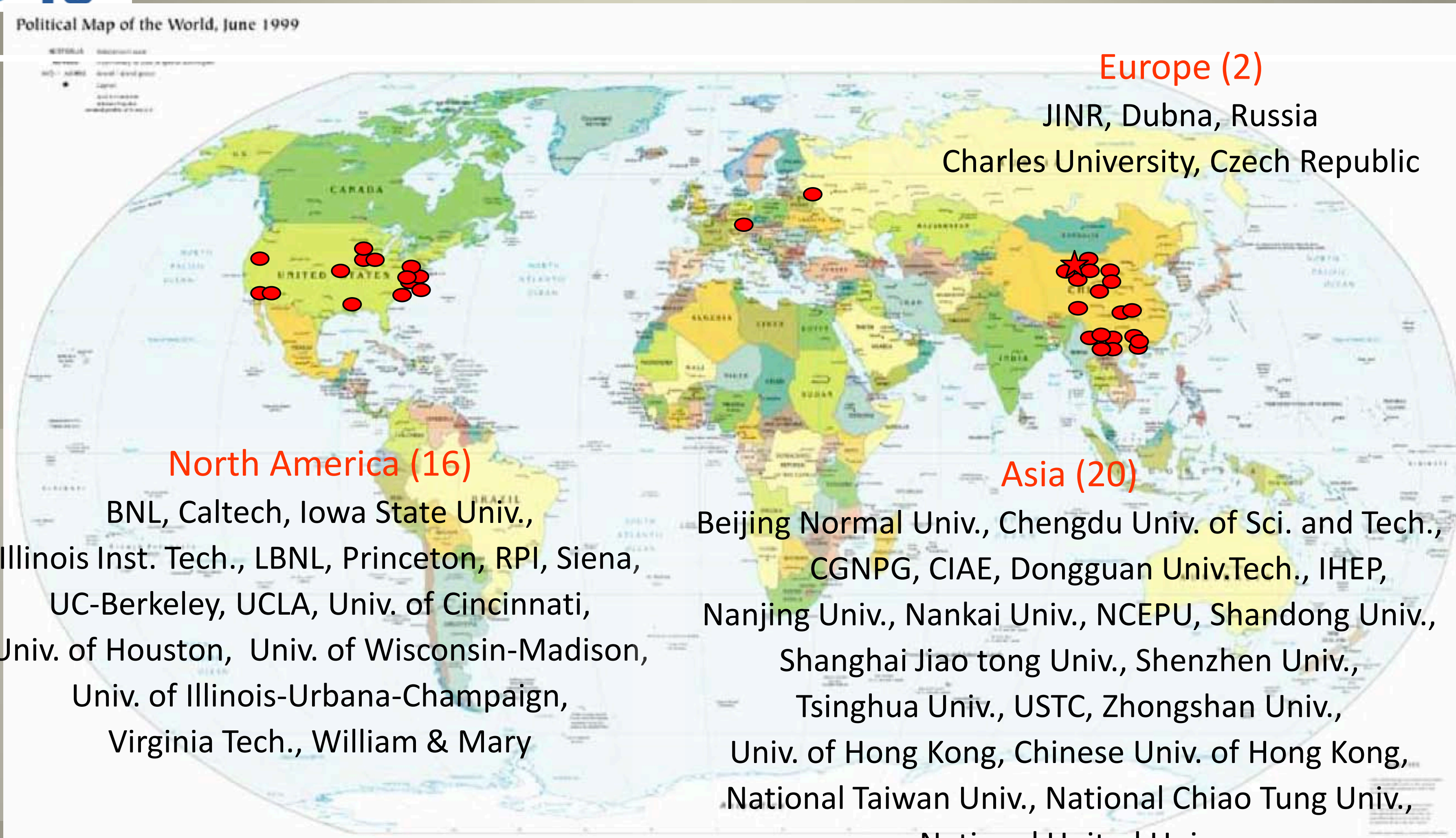
LingAo NPP
2.9GW×2

LingAo II NPP 2.9GW×2

Mountains shield detectors from cosmic ray backgrounds

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

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

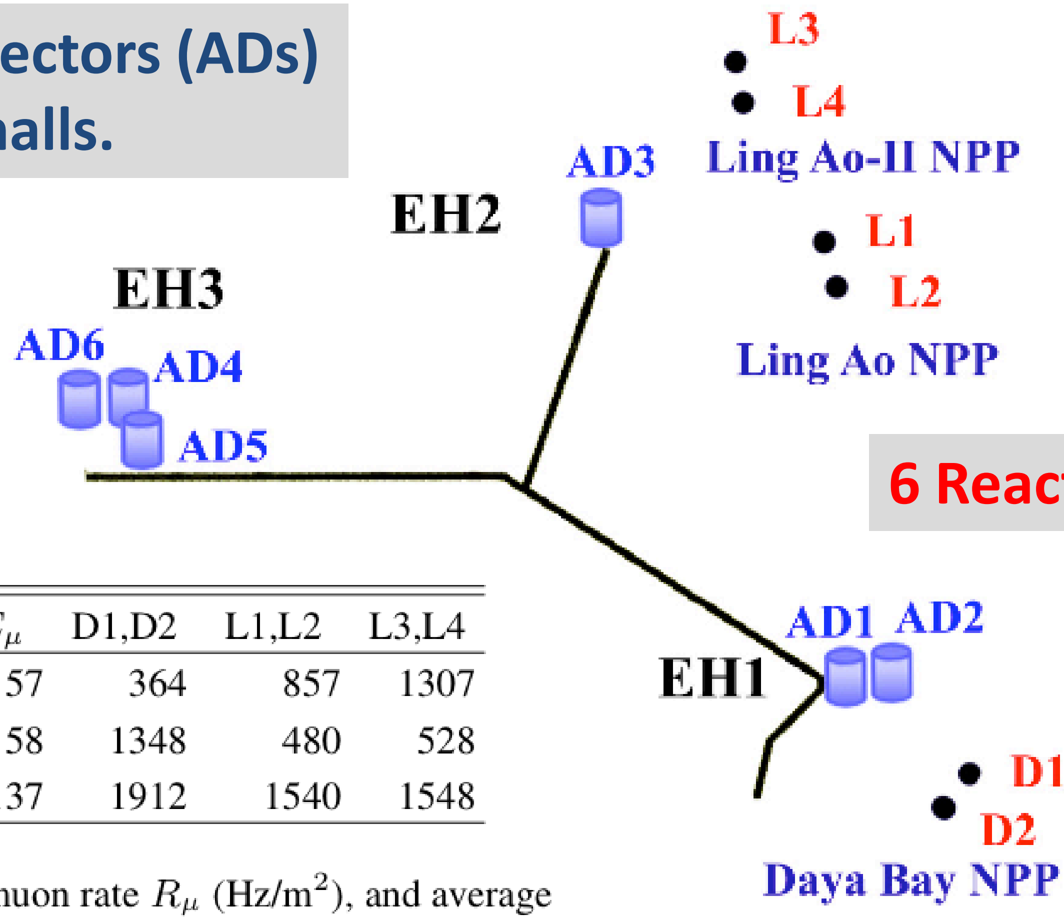
Asia (20)

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

Experiment Layout

6 Antineutrino Detectors (ADs) in 3 underground halls.



6 Reactor Cores

	Overburden	R_μ	E_μ	D1,D2	L1,L2	L3,L4
EH1	280	1.27	57	364	857	1307
EH2	300	0.95	58	1348	480	528
EH3	880	0.056	137	1912	1540	1548

TABLE I. Overburden (m.w.e), muon rate R_μ (Hz/m^2), and average muon energy E_μ (GeV) of the three EHs, and the distances (m) to the reactor pairs.

Experiment Survey

Negligible reactor flux uncertainty (<0.02%) from precise survey.

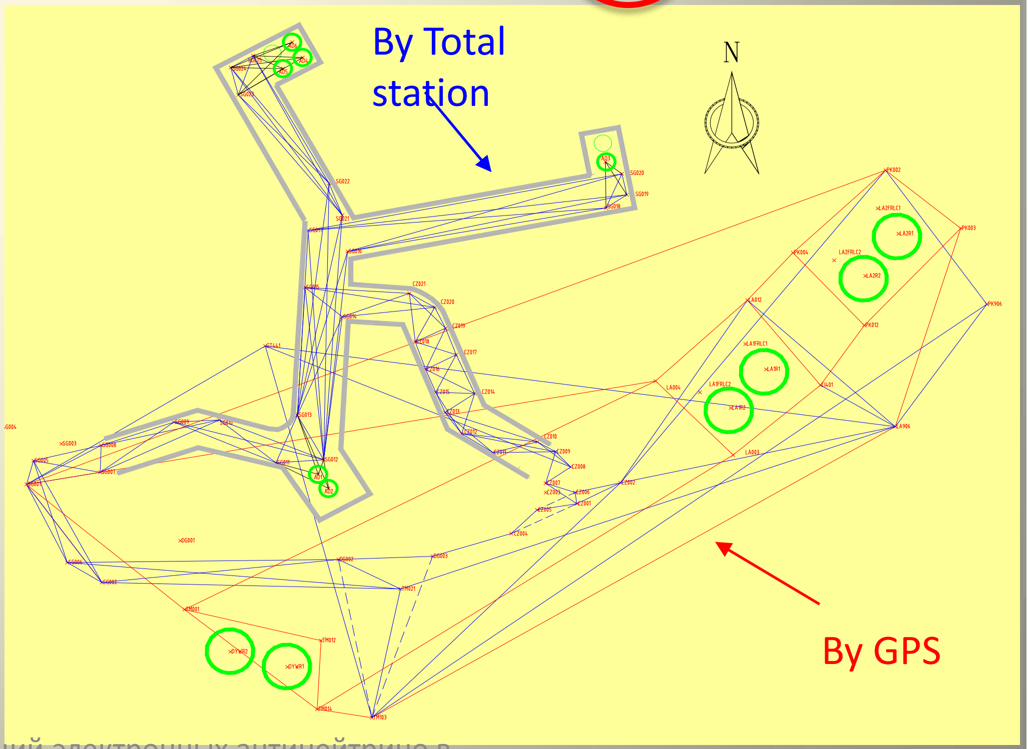
$$\frac{N_{\rm f}}{N_{\rm n}} = \left(\frac{N_{\rm p,f}}{N_{\rm p,n}}\right)\left(\frac{L_{\rm n}}{L_{\rm f}}\right)^2\left(\frac{\epsilon_{\rm f}}{\epsilon_{\rm n}}\right)\left[\frac{P_{\rm sur}(E,L_{\rm f})}{P_{\rm sur}(E,L_{\rm n})}\right]$$

Detailed Survey:

- GPS above ground
- Total Station underground
- Final precision: 28mm

Validation:

- Three independent calculations
- Cross-check survey
- Consistent with reactor plant and design plans



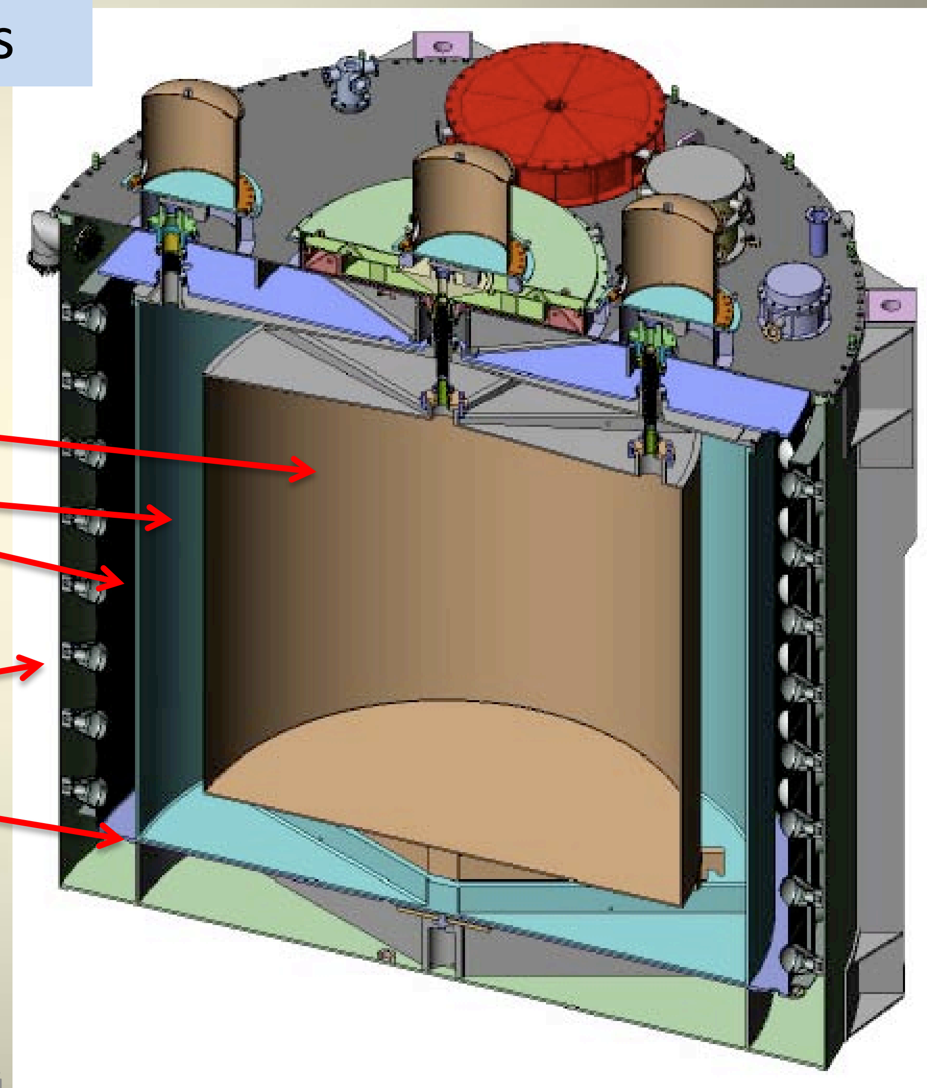
Antineutrino Detectors

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=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

Detection Method

Inverse β-decay (IBD):

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

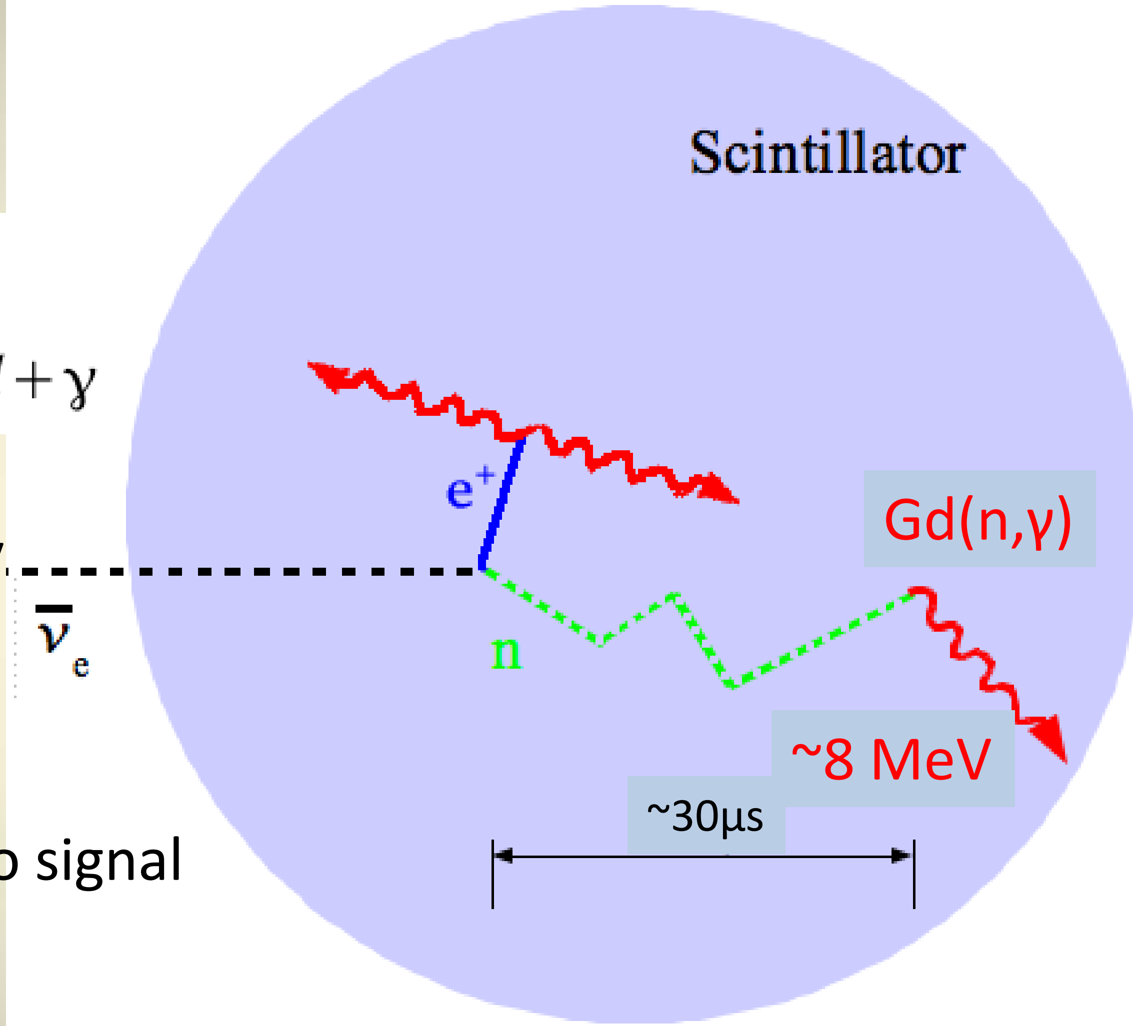
Prompt positron:

Carries antineutrino energy

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

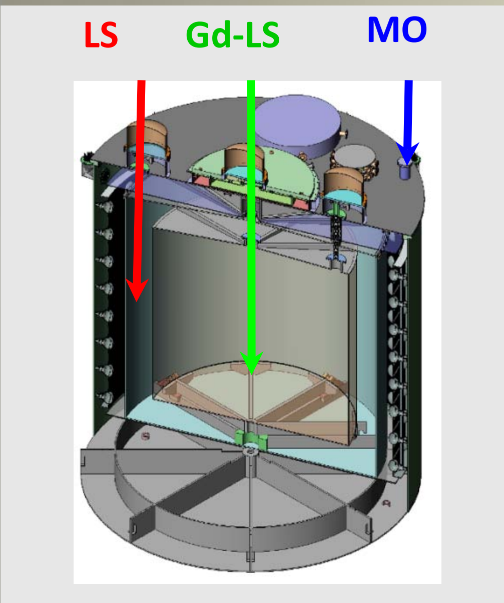
Delayed neutron capture:

Efficiently tags antineutrino signal



Prompt + Delayed coincidence provides distinctive signature

Detector Filling



Detector target filled from GdLS in ISO tank.

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

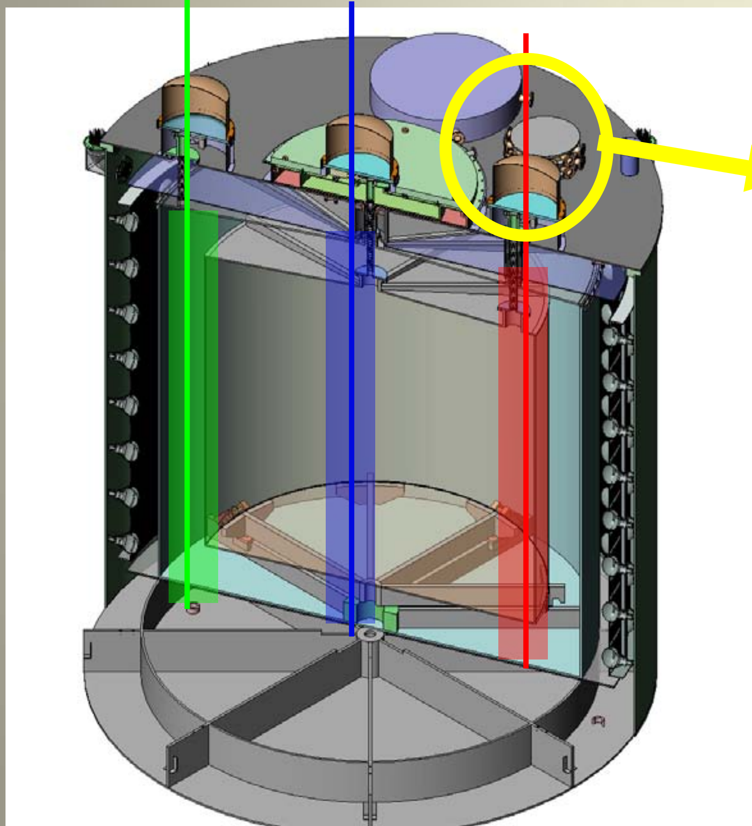
$$\frac{N_{\rm f}}{N_{\rm n}} = \left(\frac{N_{\rm p,f}}{N_{\rm p,n}}\right)\left(\frac{L_{\rm n}}{L_{\rm f}}\right)^2\left(\frac{\epsilon_{\rm f}}{\epsilon_{\rm n}}\right)\left[\frac{P_{\rm sur}(E,L_{\rm f})}{P_{\rm sur}(E,L_{\rm n})}\right]$$

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

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

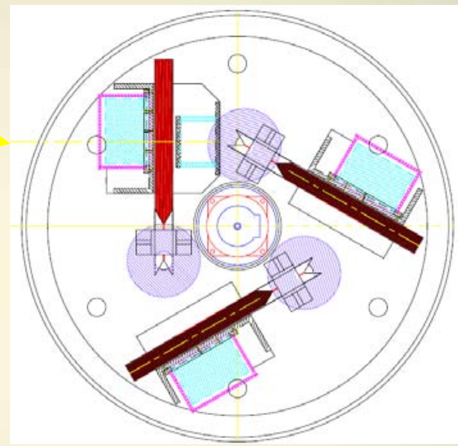
Automated Calibration System

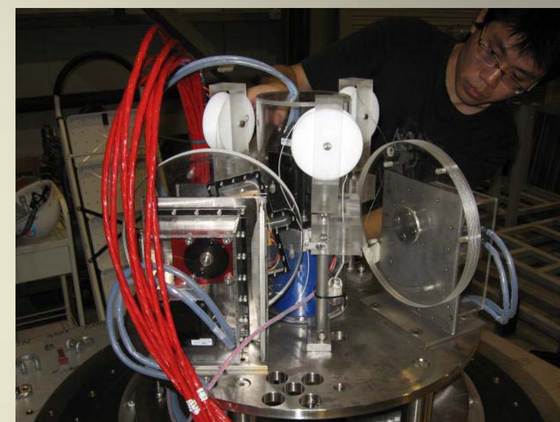
3 Automatic calibration 'robots' (ACUs) on each detector



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

Top view





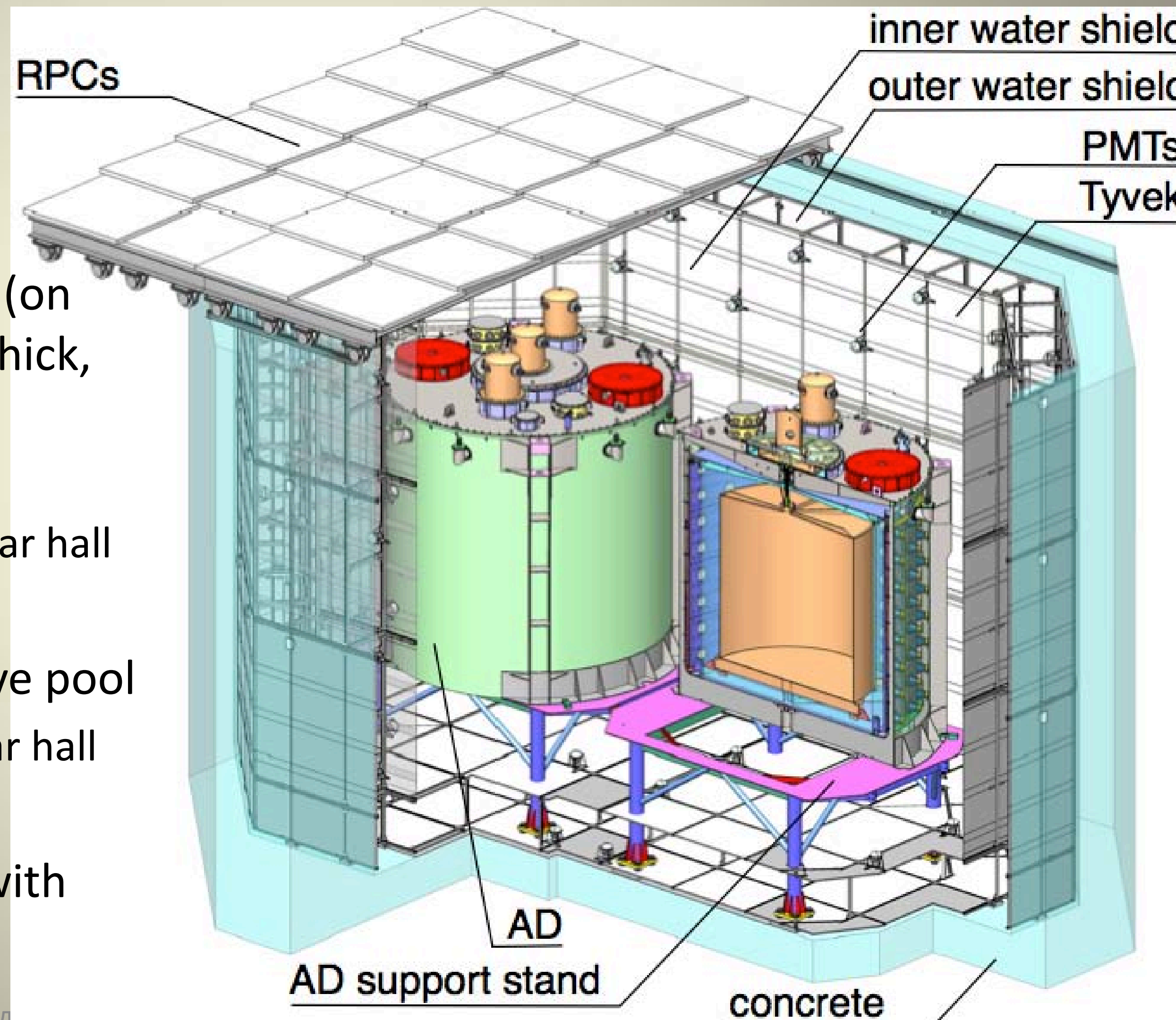
3 sources for each z axis on a turntable (position accuracy < 5 mm):

- 10 Hz ^{68}Ge (0 KE e^+ = 2×0.511 MeV γ's)
- 0.5 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 T_0 and gain

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%



JINR contribution to Daya Bay

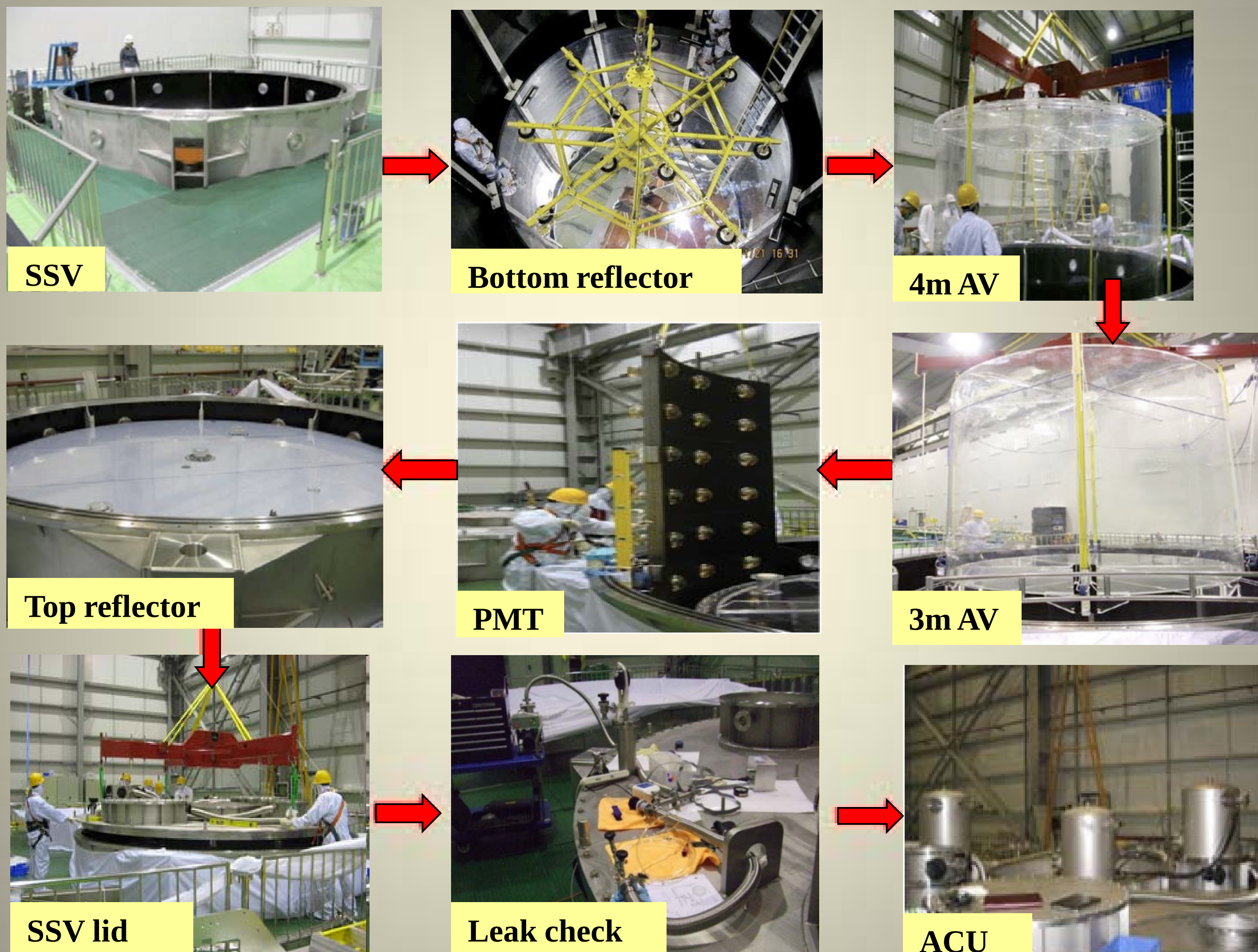
- **Liquid Scintillator measurements and optimization:**
  - Light Yield
  - Transparency
  - Energy Resolution
  - Neutron capture for Gd loaded LS

Scintillator layer height, cm	Total detection efficiency of < 0,4 eV thermal neutrons, %	
	Gd-LS	LS
1	12 ± 2	–
2	19 ± 3	–
3,5	29 ± 4	–
4,5	35 ± 5	17 ± 3

- **Technology of PPO production** was restored in the JINR Member State Ukraine and **1.5t of PPO were produced and delivered to Daya Bay**

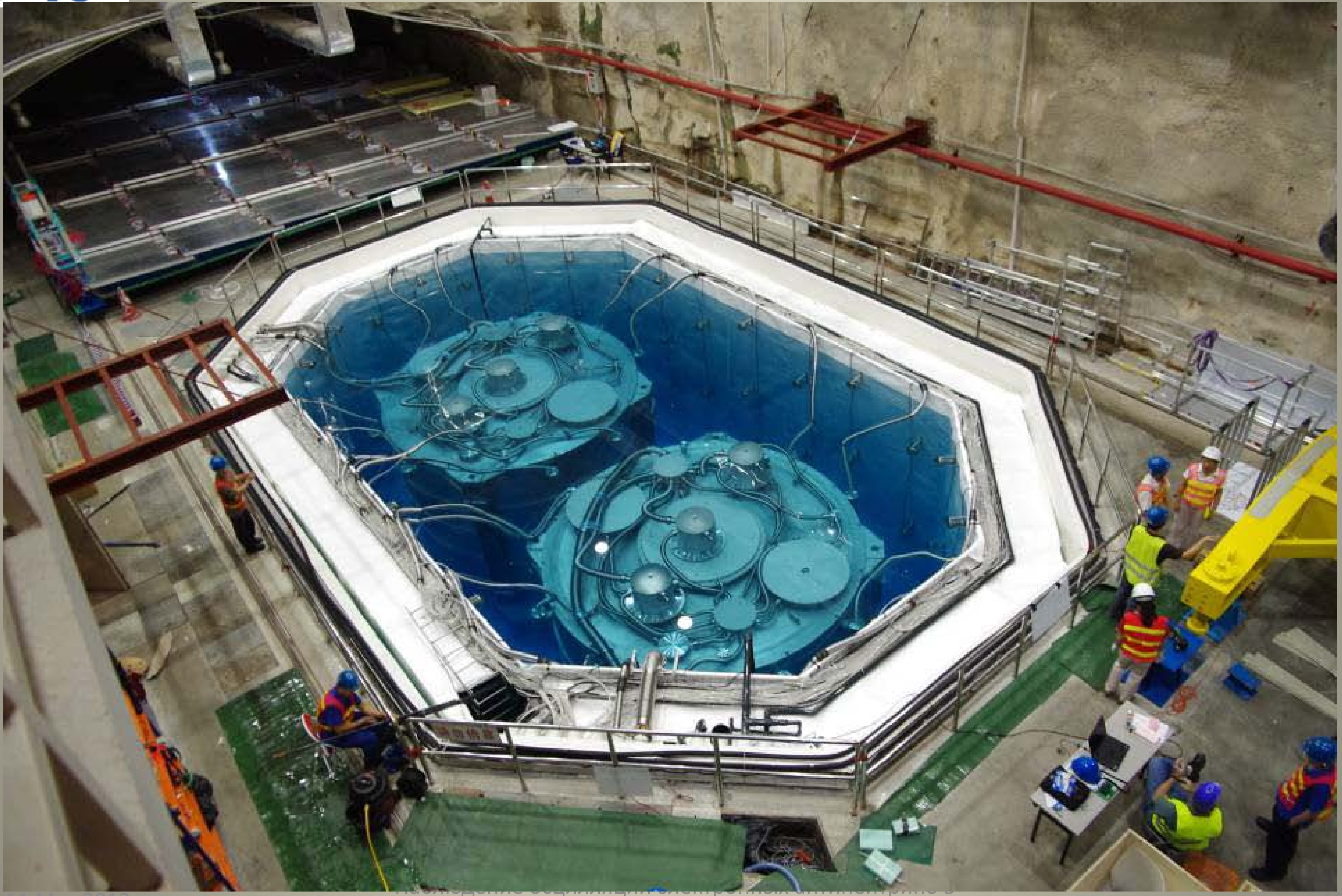
- **Data analysis:**
  - Background simulation
  - Oscillation Analysis

Detector Assembly



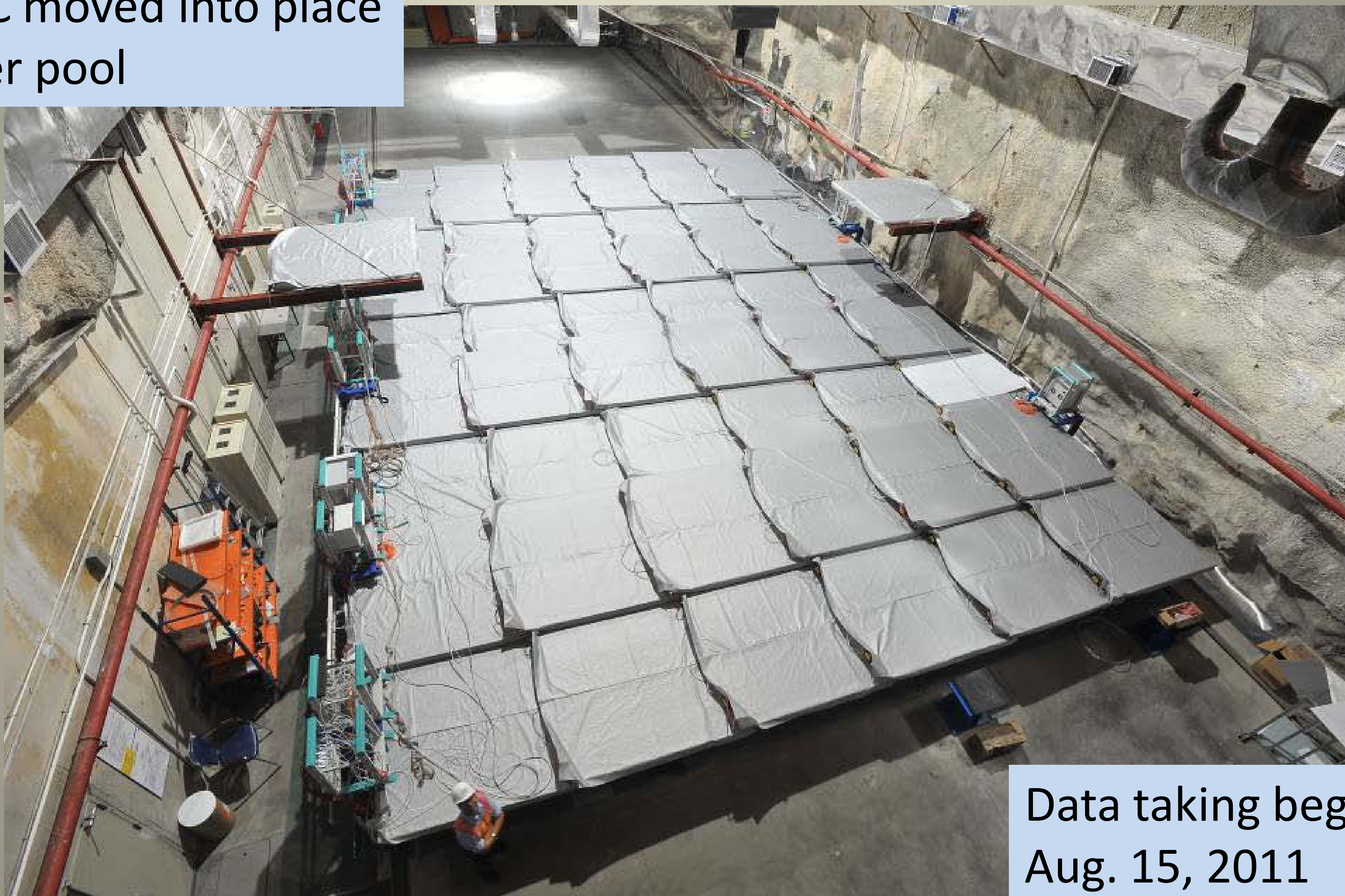
Interior of Antineutrino Detector

EH1: Pool Filled



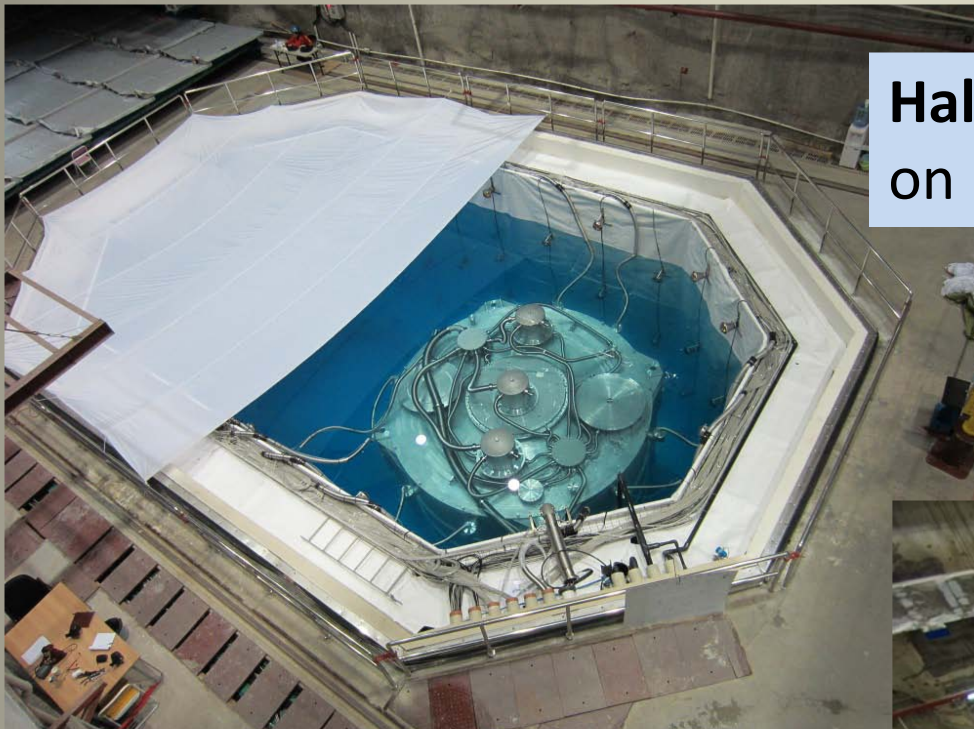
Hall 1: Completed

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

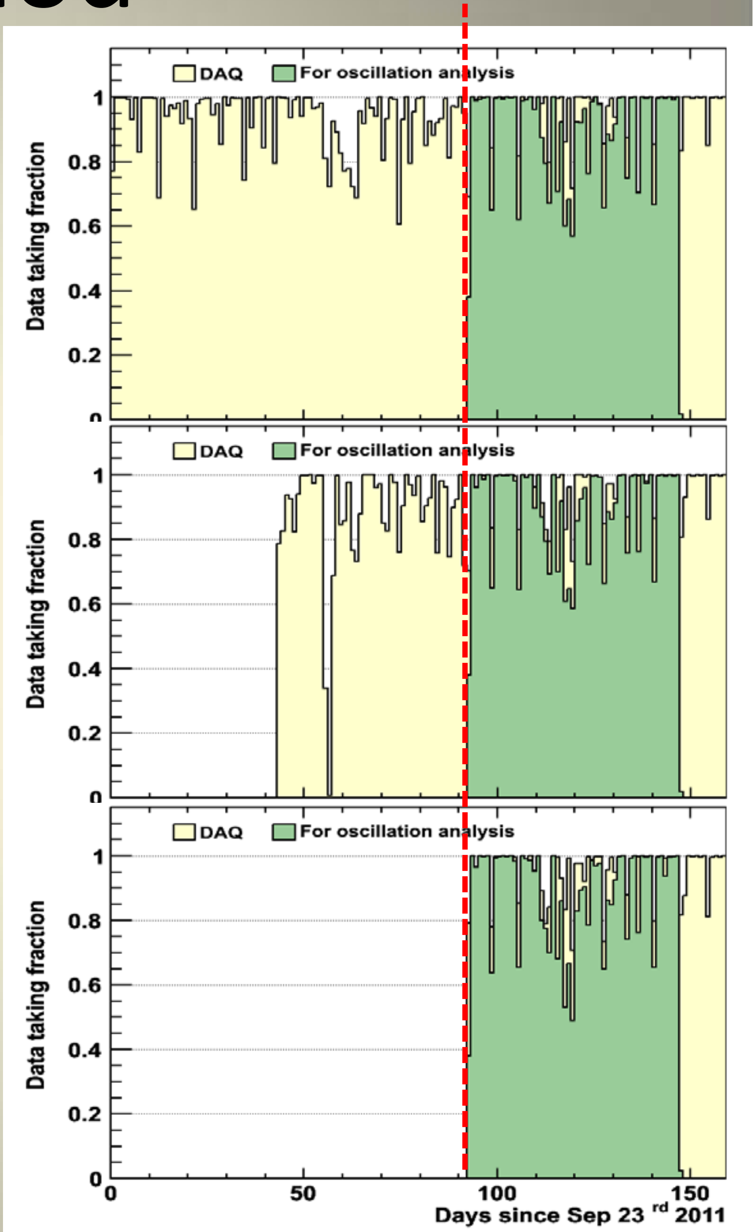
Hall 3: Began 3 AD operation on Dec. 24, 2011

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

Data Period

Two Detector Comparison:
- Sep. 23, 2011 – Dec. 23, 2011
- Side-by-side comparison of 2 detectors
- Demonstrated detector systematics better than requirements.
- Details presented in:
  F.P. An et al., 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%



Trigger Performance

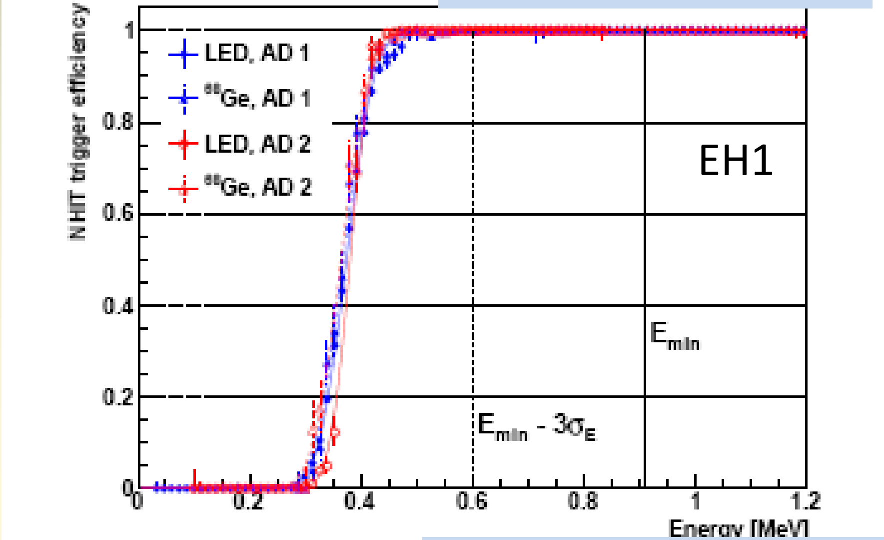
Trigger Thresholds:

- AD: >45 PMTs (digital trigger)
  >0.4 MeV (analog trigger)
- Inner Water Veto: > 6 PMTs
- Outer Water Veto: >7 PMTs
- RPC: ¾ layers in module

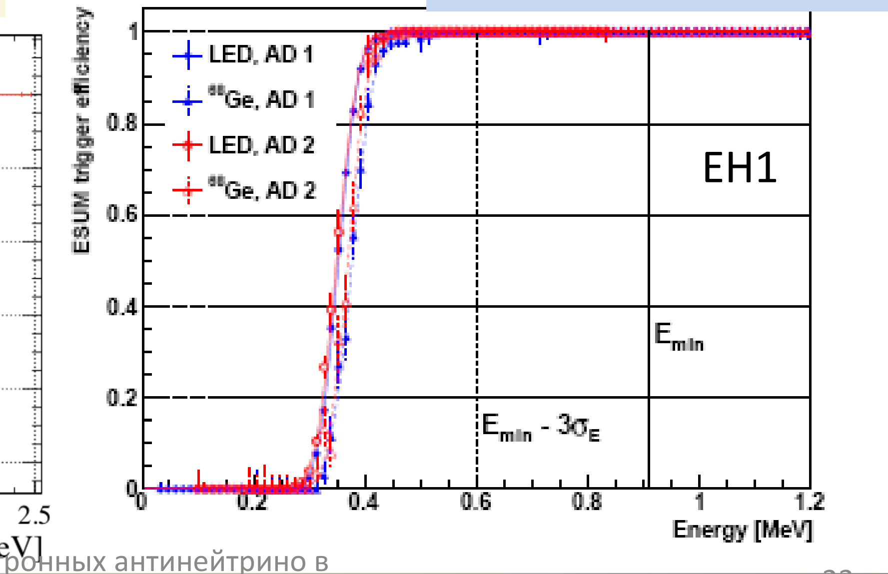
Trigger Efficiency:

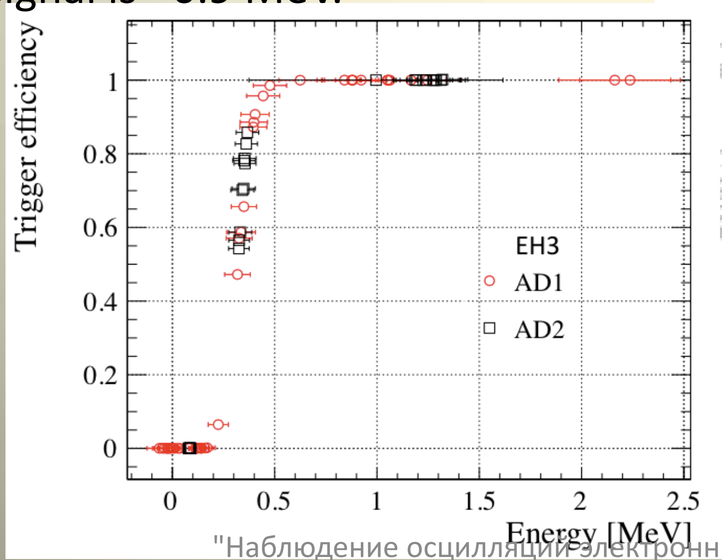
- No measureable inefficiency >0.7 MeV
- Minimum energy expected for prompt antineutrino signal is ~0.9 MeV.

Digital Trigger (Nhit)



Analog Trigger (Esum)



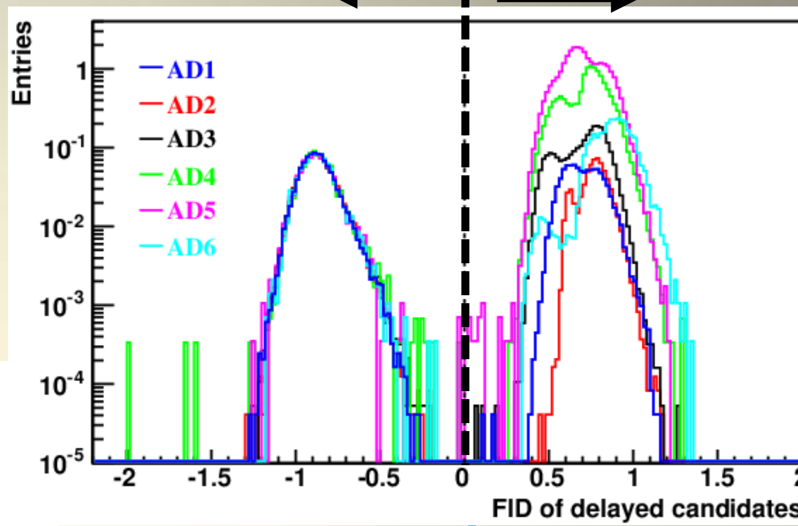


PMT Light Emission (Flashing)

Flashing PMTs:

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

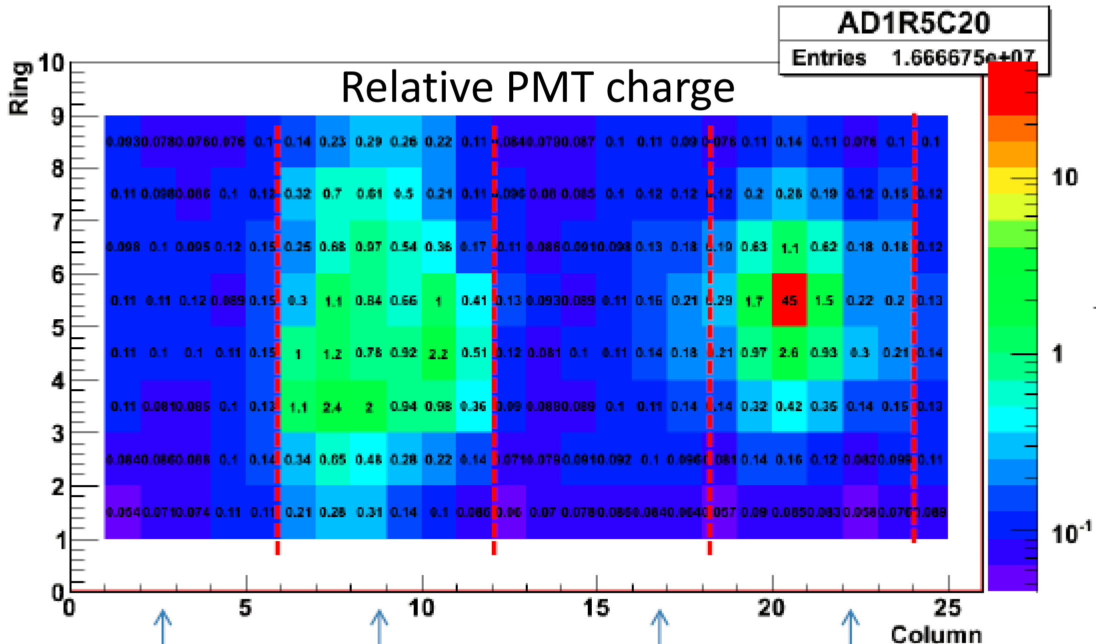
Neutrinos ← → Flashers



$$FID = \log_{10}((MaxQ)^2/(0.45)^2 + (Quad)^2)$$

Quadrant = Q3/(Q2+Q4)

MaxQ = maxQ/sumQ



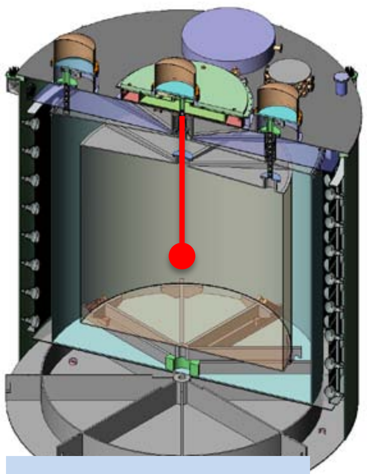
Quadrant 4 Quadrant 3 Quadrant 2 Quadrant 1 (contains ‘hottest’ PMT)

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

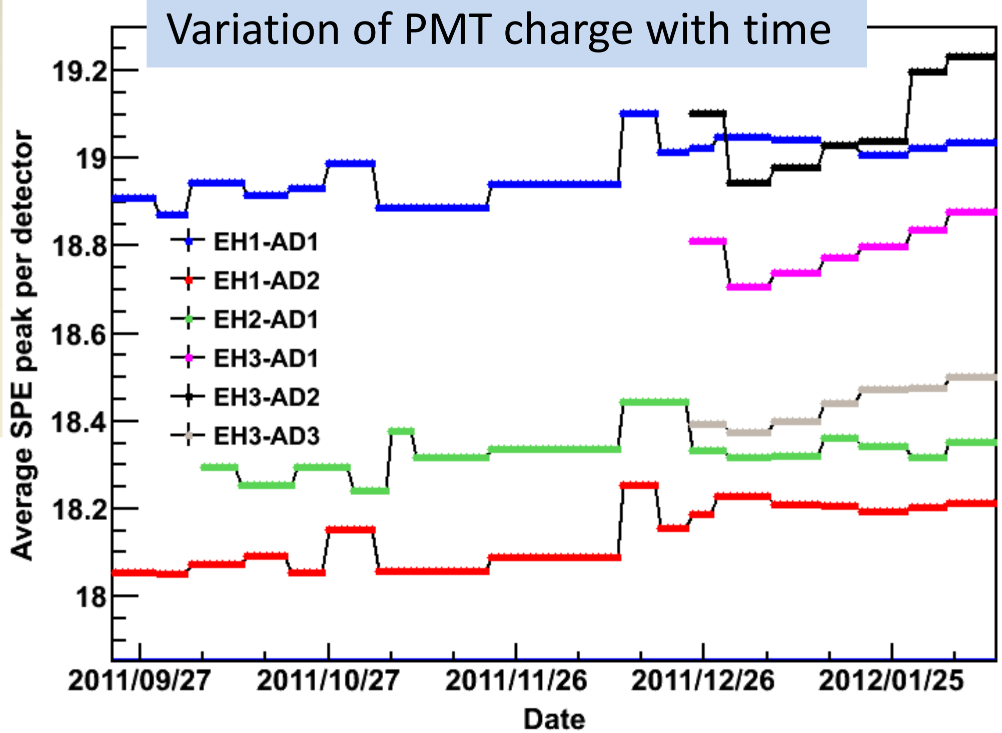
Contamination: < 0.01%

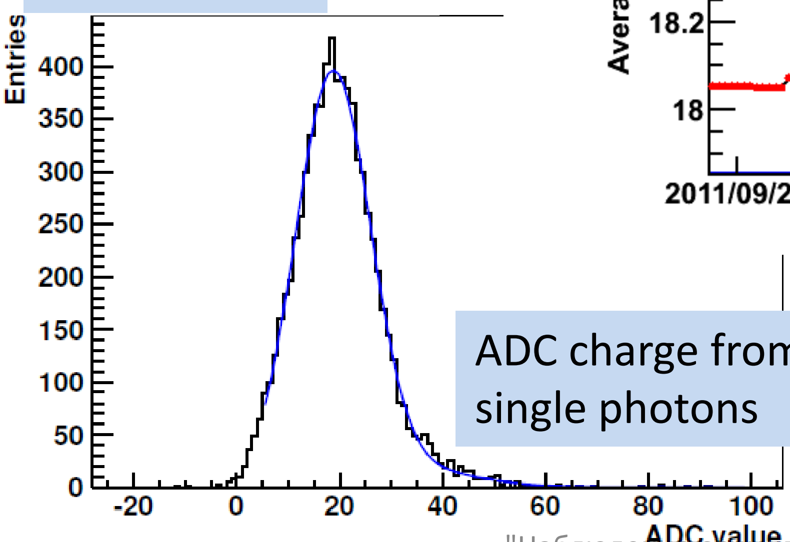
Calibration: PMT Gain

Weekly LED deployments measure charge due to single photons



LED at center



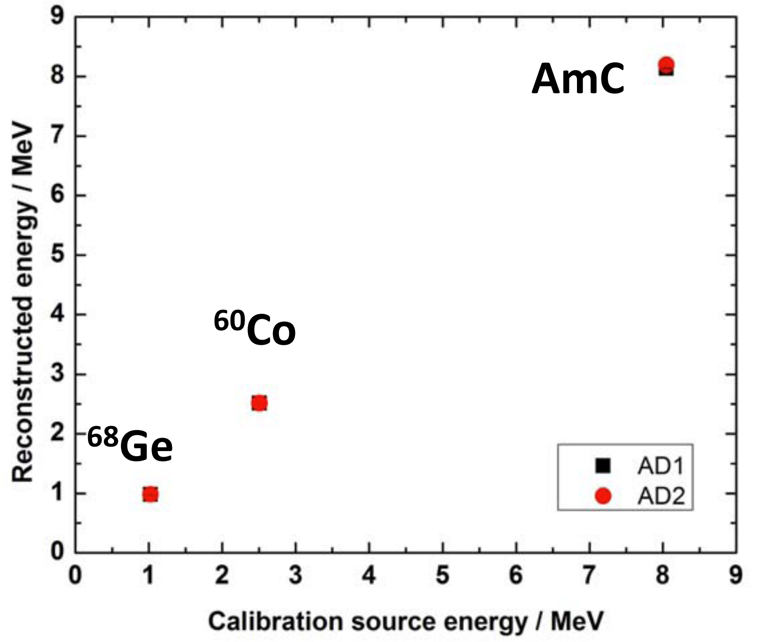


Calibration driven by uncertainty in relative detector efficiency

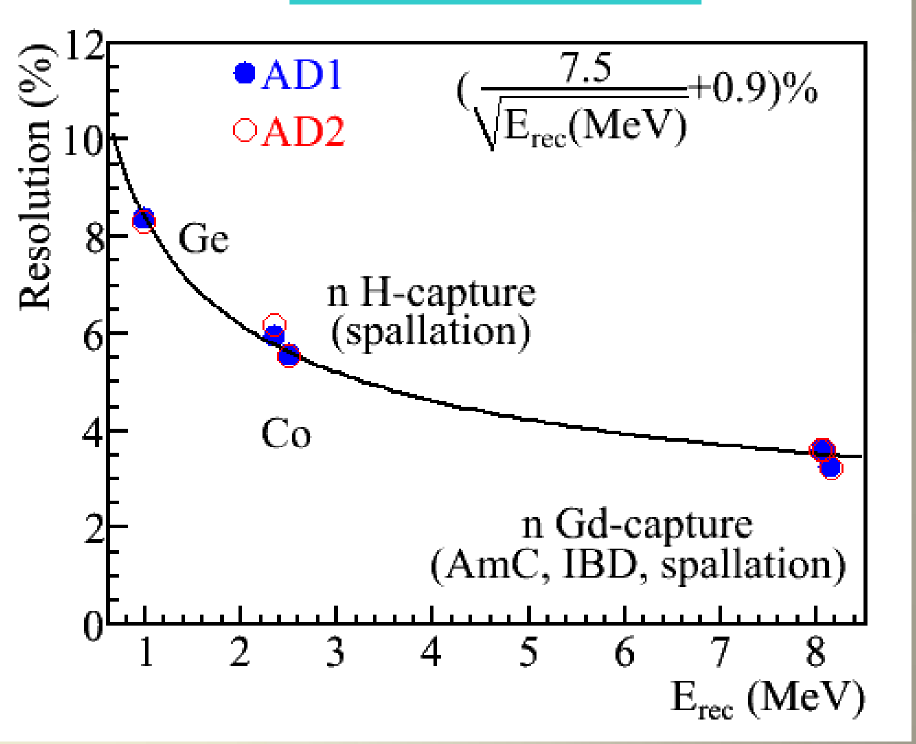
$$\frac{N_{\rm f}}{N_{\rm n}} = \left(\frac{N_{\rm p,f}}{N_{\rm p,n}}\right)\left(\frac{L_{\rm n}}{L_{\rm f}}\right)^2\left(\frac{\epsilon_{\rm f}}{\epsilon_{\rm n}}\right)\left[\frac{P_{\rm sur}(E,L_{\rm f})}{P_{\rm sur}(E,L_{\rm n})}\right]$$

Calibration: Energy Scale

Energy scale



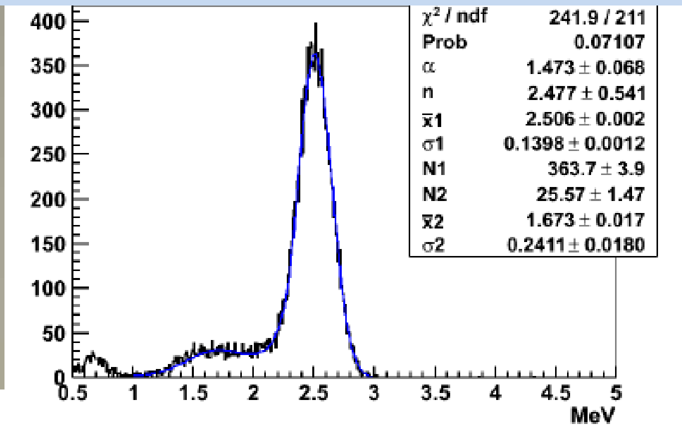
Energy resolution

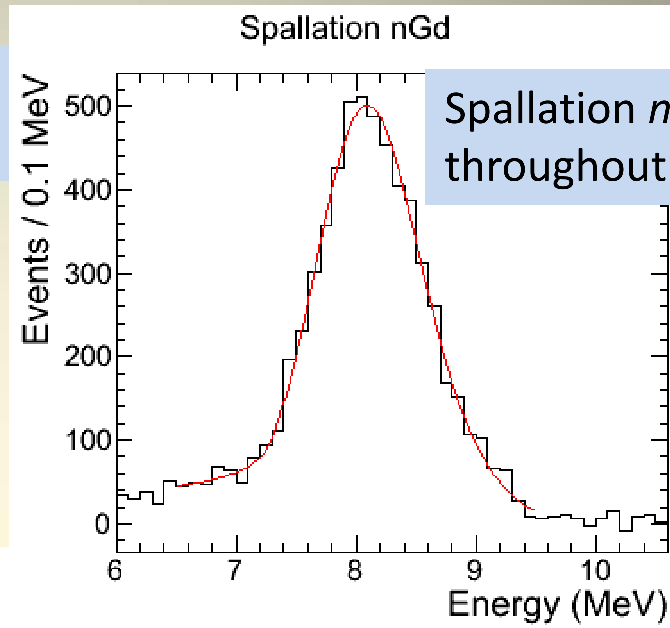


- Energy linearity at detector centre with ^{68}Ge, ^{60}Co, AmC neutron
- Photon electron yield: ~170PE/MeV
- Resolution (RMS/E_{MeV}): ~7.5%/sqrt(E_{MeV})+0.9%

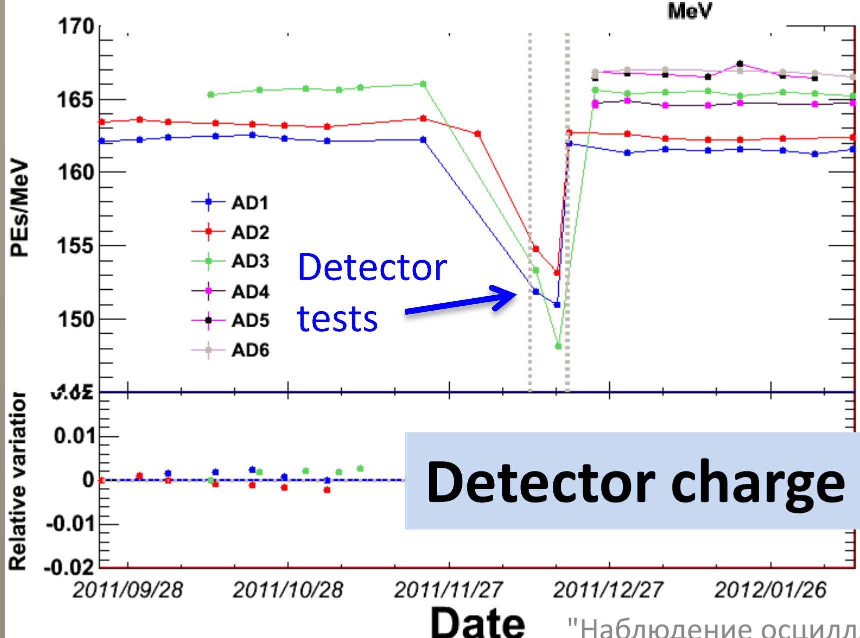
Calibration: Energy Scale

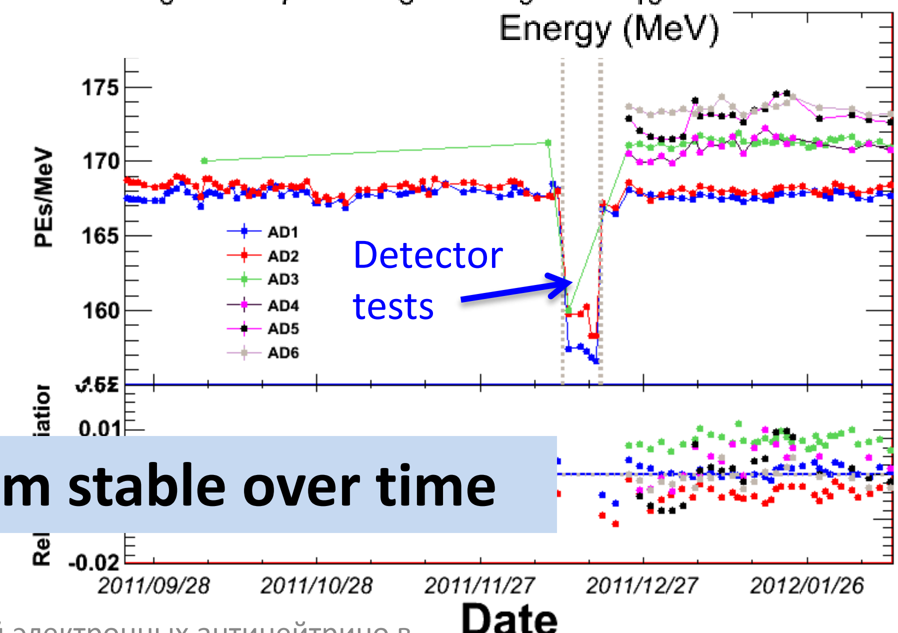
Weekly deployments of ^{60}Co at detector center:
Monitor photoelectrons collected per MeV





Spallation *n*Gd capture throughout detector



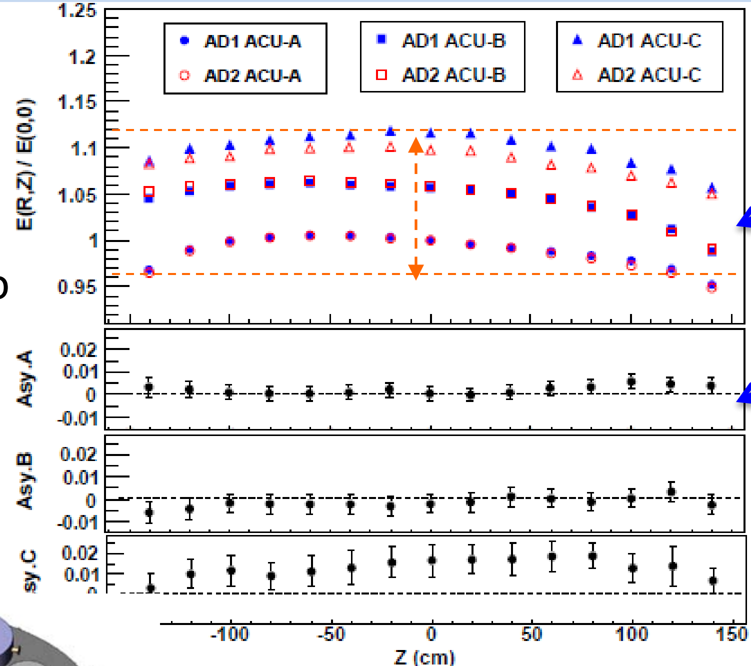


Detector charge sum stable over time

Calibration: Detector Uniformity

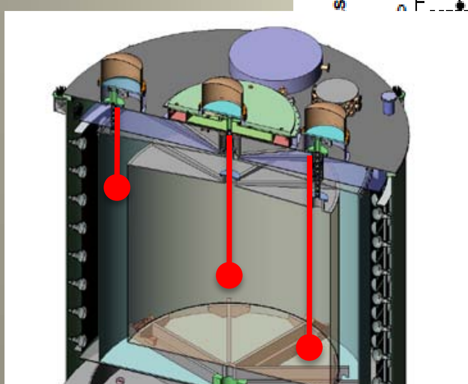
Multiple sources placed along three axes measure uniformity

Example: ^{60}Co



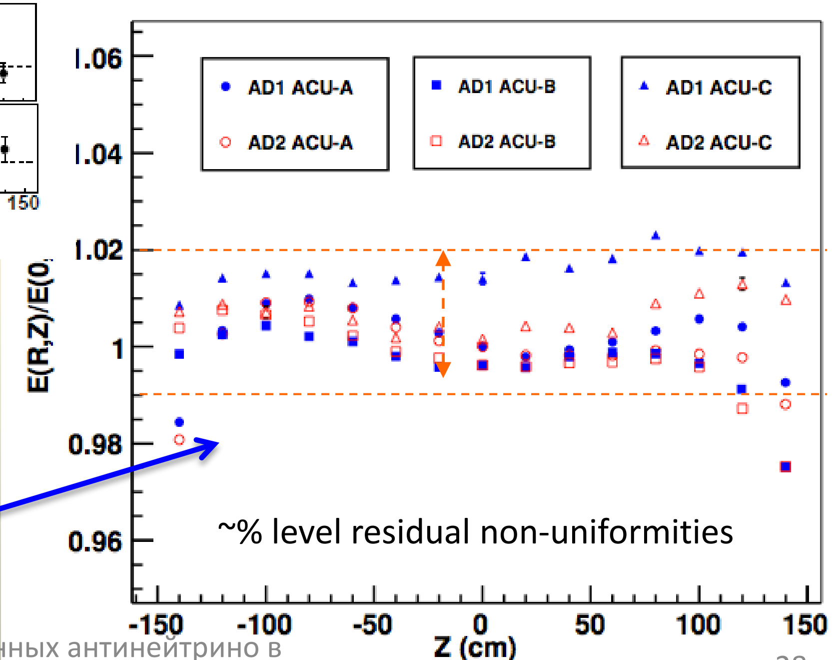
Energy response varies across detector…

…but still consistent between detectors



3 sources along 3 axes

After first-order correction, energy is more uniform.

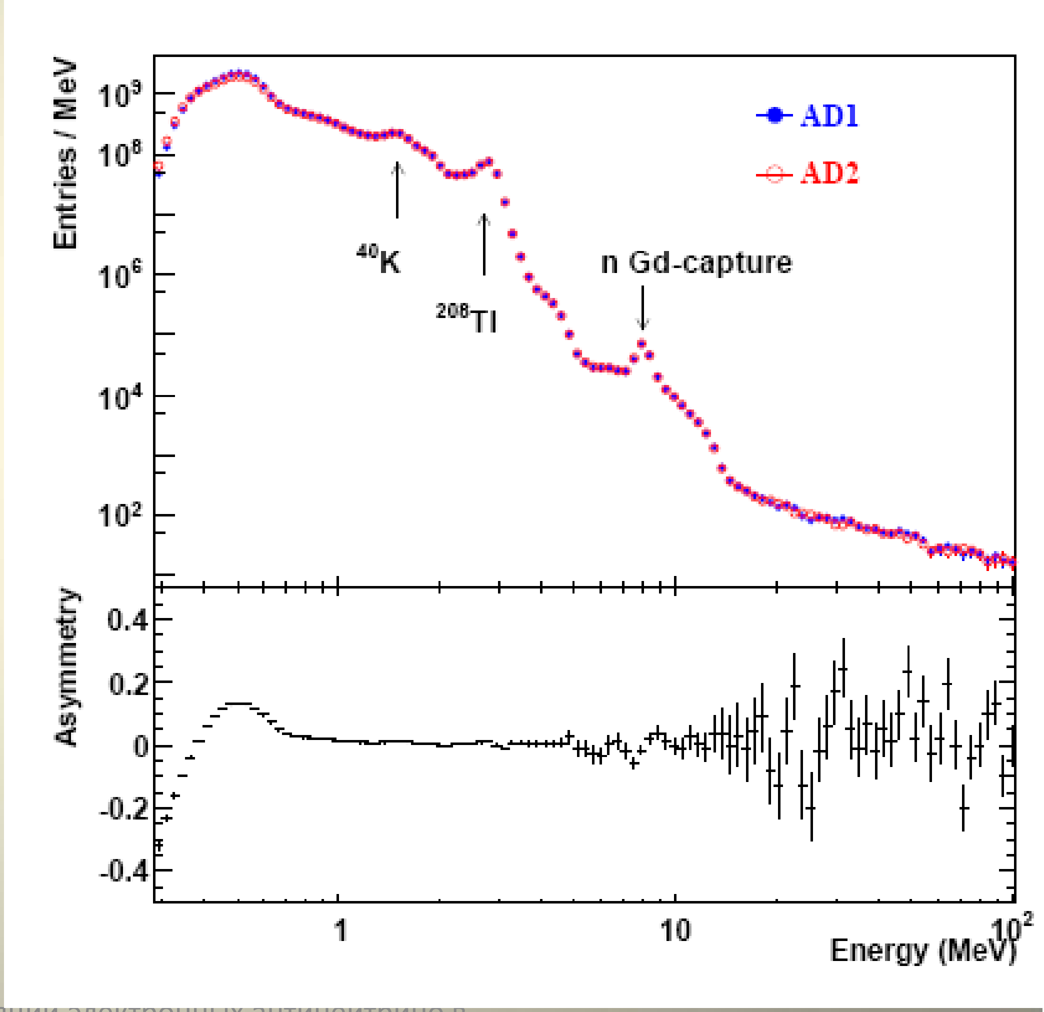


Singles Spectrum

Triggered signals dominated by low-energy radioactivity

Measured Rates:
~65 Hz in each detector
(>0.7 MeV)

Sources:
Stainless Steel: U/Th chains
PMTs: 40K, U/Th chains
Scintillator: Radon/U/Th chains



Antineutrino (IBD) Selection

Use IBD Prompt + Delayed correlated signal to select antineutrinos

Selection:

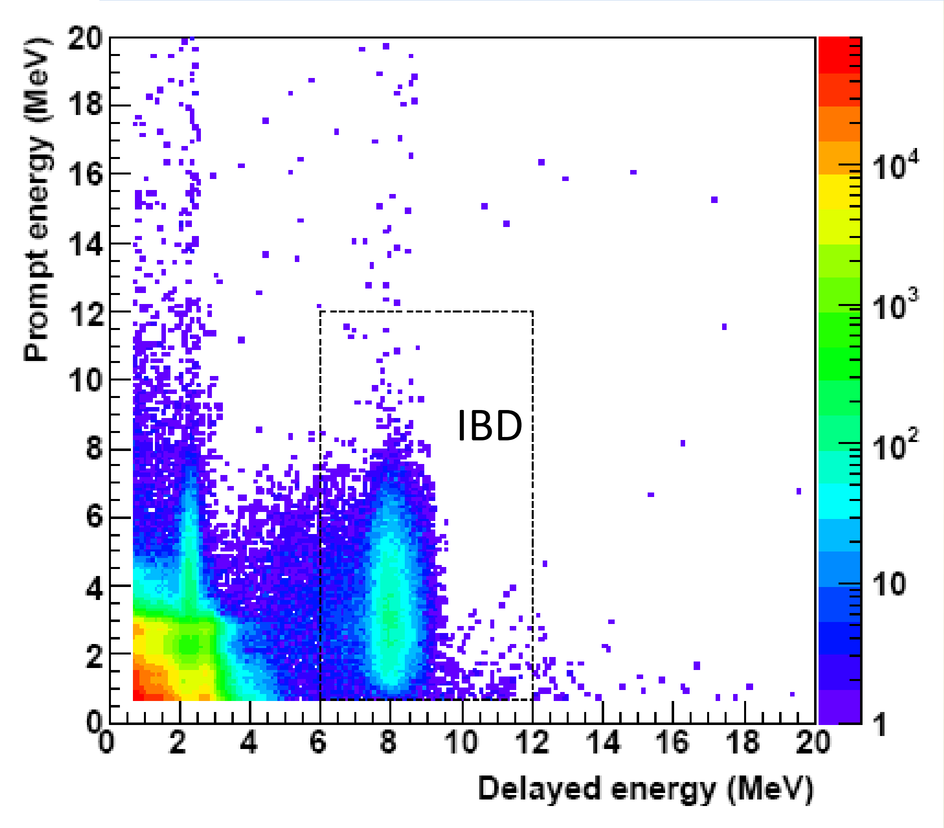
- Reject Flashers
- Prompt Positron: 0.7 MeV < E_p < 12 MeV
- Delayed Neutron: 6.0 MeV < E_d < 12 MeV
- Capture time: 1 μs < Δt < 200 μs
- Muon Veto:
  - Pool Muon: Reject 0.6ms
  - AD Muon (>20 MeV): Reject 1ms
  - AD Shower Muon (>2.5GeV): Reject 1s
- Multiplicity:
  No other signal > 0.7 MeV
  in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

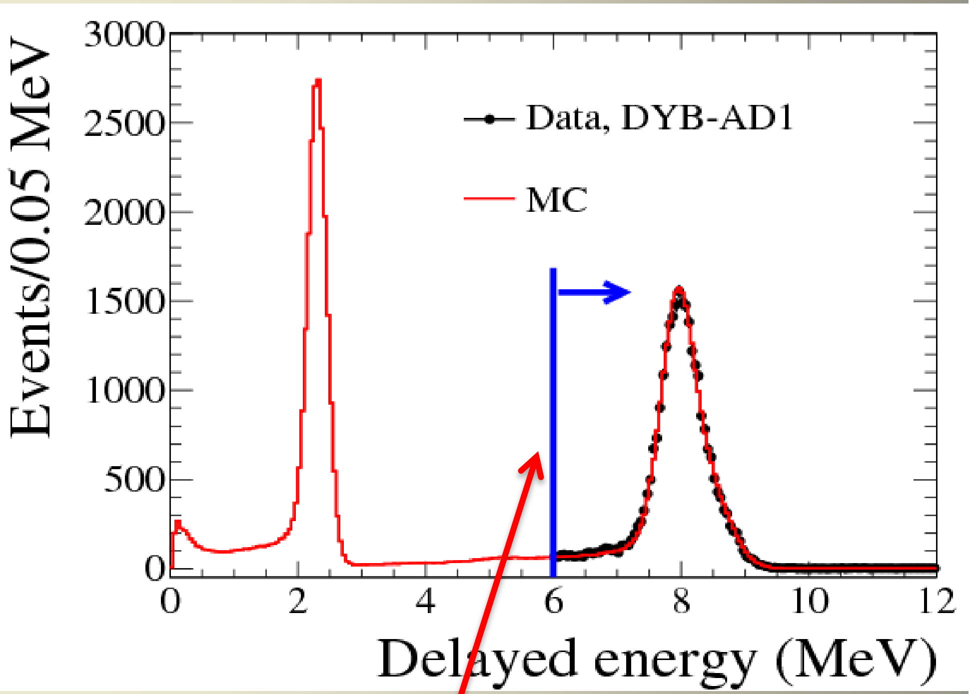
Selection driven by uncertainty in relative detector efficiency

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

Prompt/Delayed Energy

Clear separation of antineutrino events from most other signals



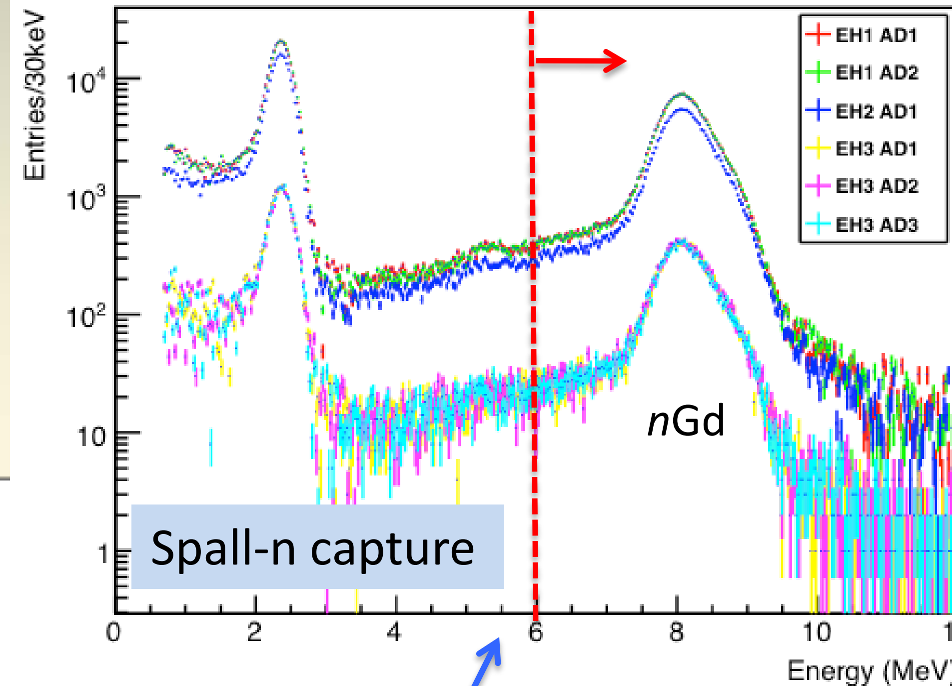


Uncertainty in relative E_d efficiency (0.12%) between detectors is largest systematic.

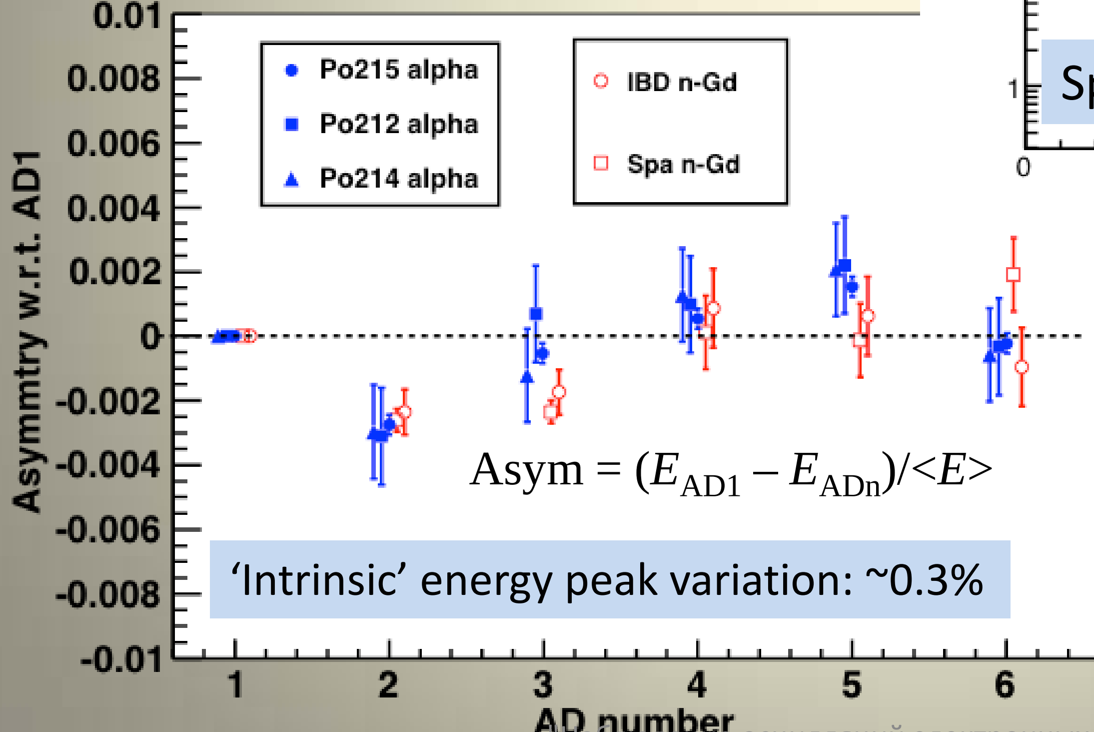
Delayed Energy Cut

Largest uncertainty between detectors

Some *n*Gd gammas escape scintillator region, visible as tail of *n*Gd energy peak.

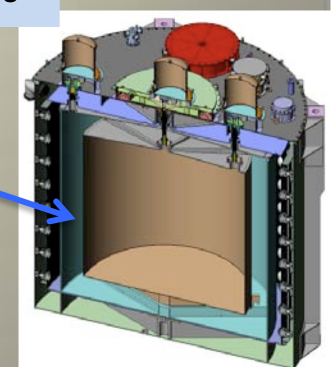


Use variations in energy peaks to constrain relative efficiency.



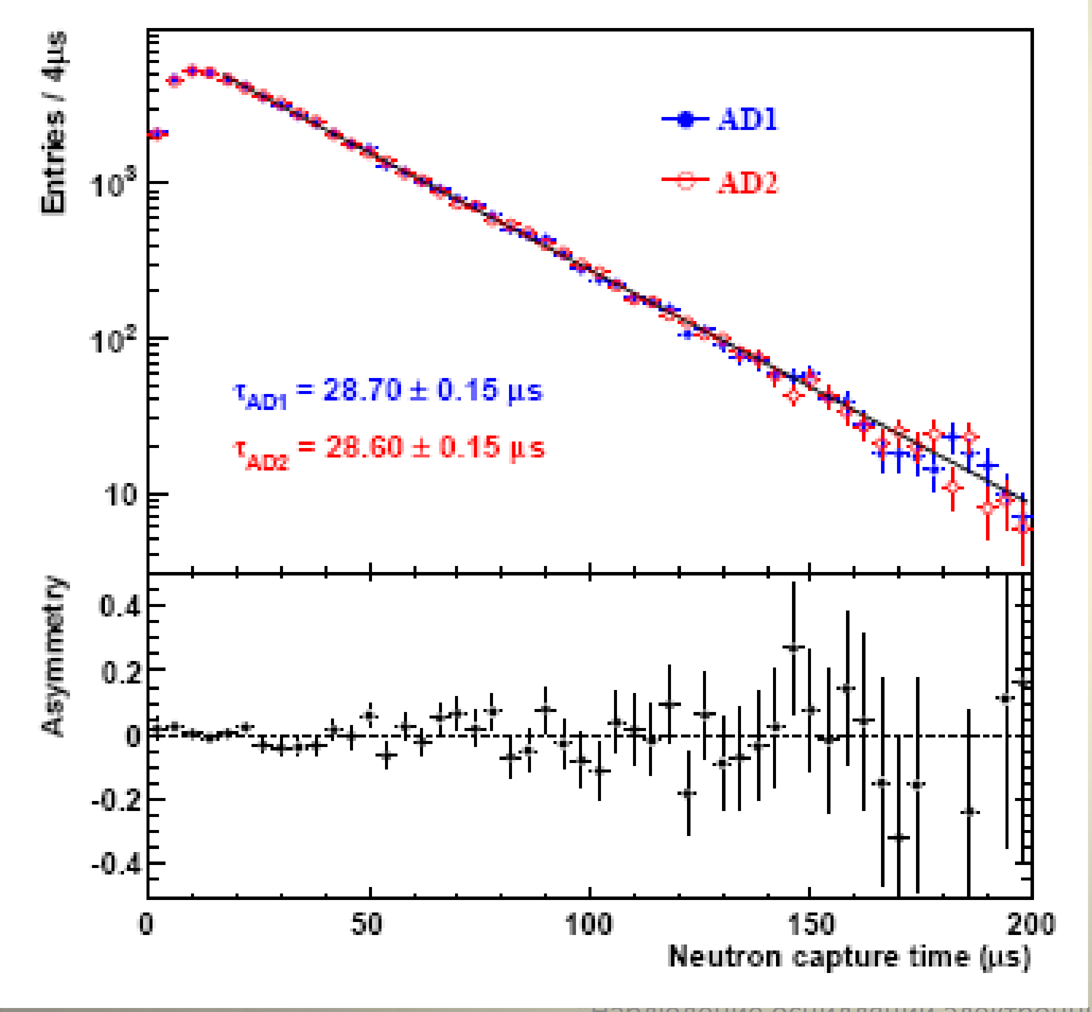
Efficiency variations estimated at 0.12%

Motivation for 3-zone design



Gd Capture Ratio

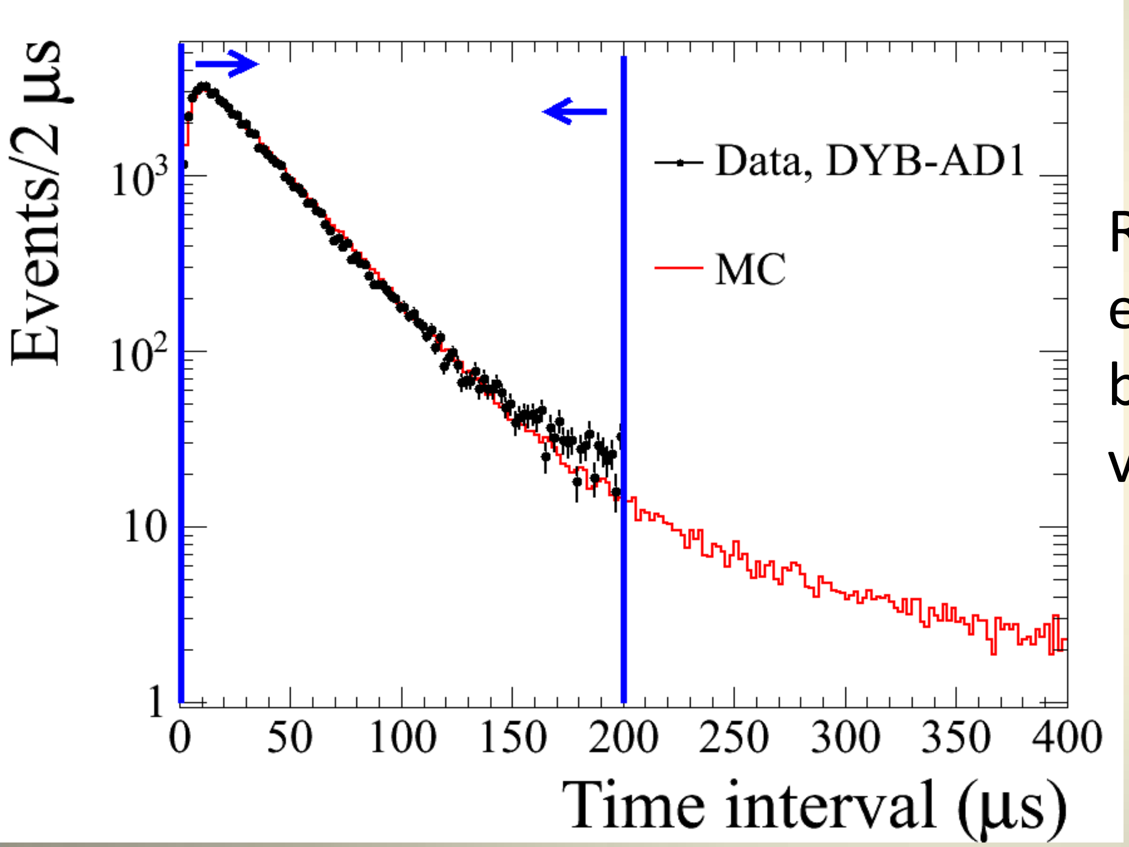
Capture time in each detector constrains H/Gd capture ratio



Measurement of Am-C source neutron capture time distributions constrain uncertainty in relative H/Gd capture efficiency to < 0.1% between detectors.

Capture Time

Consistent IBD capture time measured in all detectors

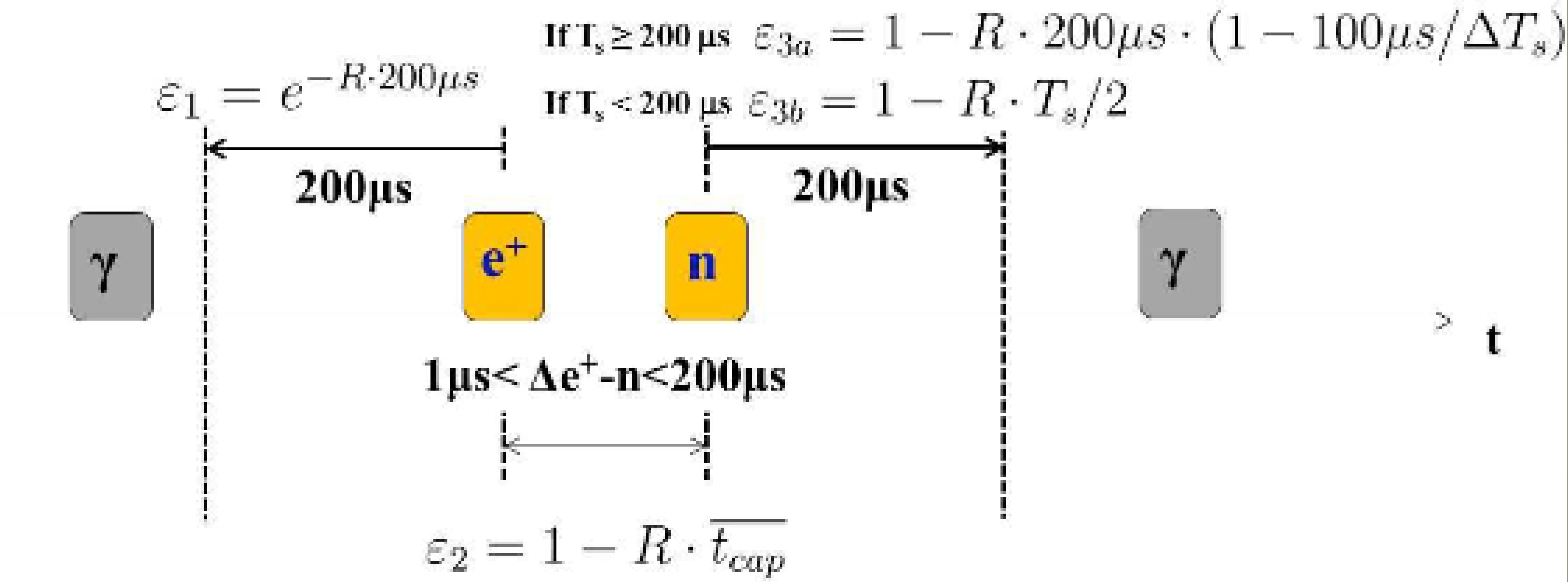


Relative detector efficiency estimated within 0.01% by considering possible variations in Gd concentration.

Simulation contains no background (deviates from data at >150 μs)

Multiplicity

Ensure exactly one prompt-delayed coincidence



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

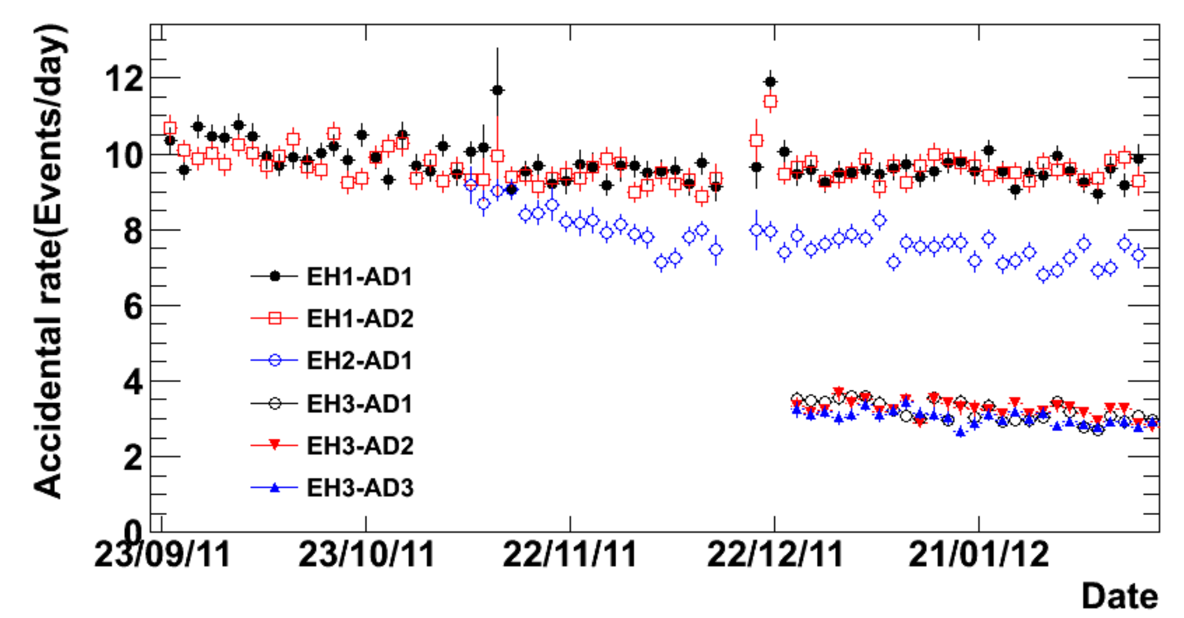
-> Reject all IBD with >2 triggers above 0.7 MeV in -200µs to +200µs.
Introduces ~2.5% IBD inefficiency, with negligible uncertainty

Background: Accidentals

Two single signals can accidentally mimic an antineutrino (IBD) signal

Rate and spectrum can be accurately predicted from singles data.

Multiple analyses/methods estimate consistent rates.

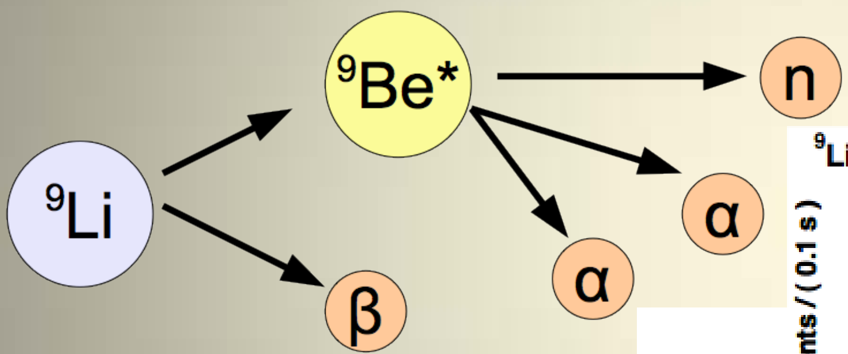


	EH1-AD1	EH1-AD2	EH2-AD1	EH3-AD1	EH3-AD2	EH3-AD3
Accidental rate(/day)	9.82±0.06	9.88±0.06	7.67±0.05	3.29±0.03	3.33±0.03	3.12±0.03
B/S	1.37%	1.38%	1.44%	4.58%	4.77%	4.43%

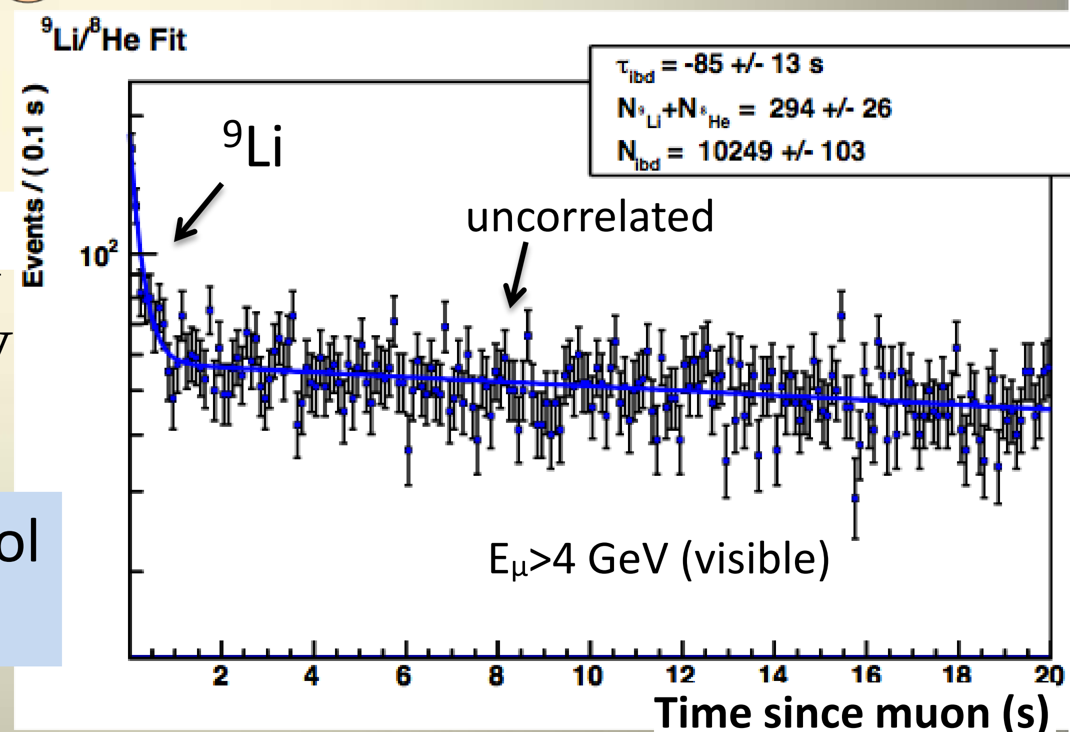
Background: β-n decay

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

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



^{9}Li: $\tau_{1/2}$ = 178 ms, Q = 13. 6 MeV
^{8}He: $\tau_{1/2}$ = 119 ms, Q = 10.6 MeV



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

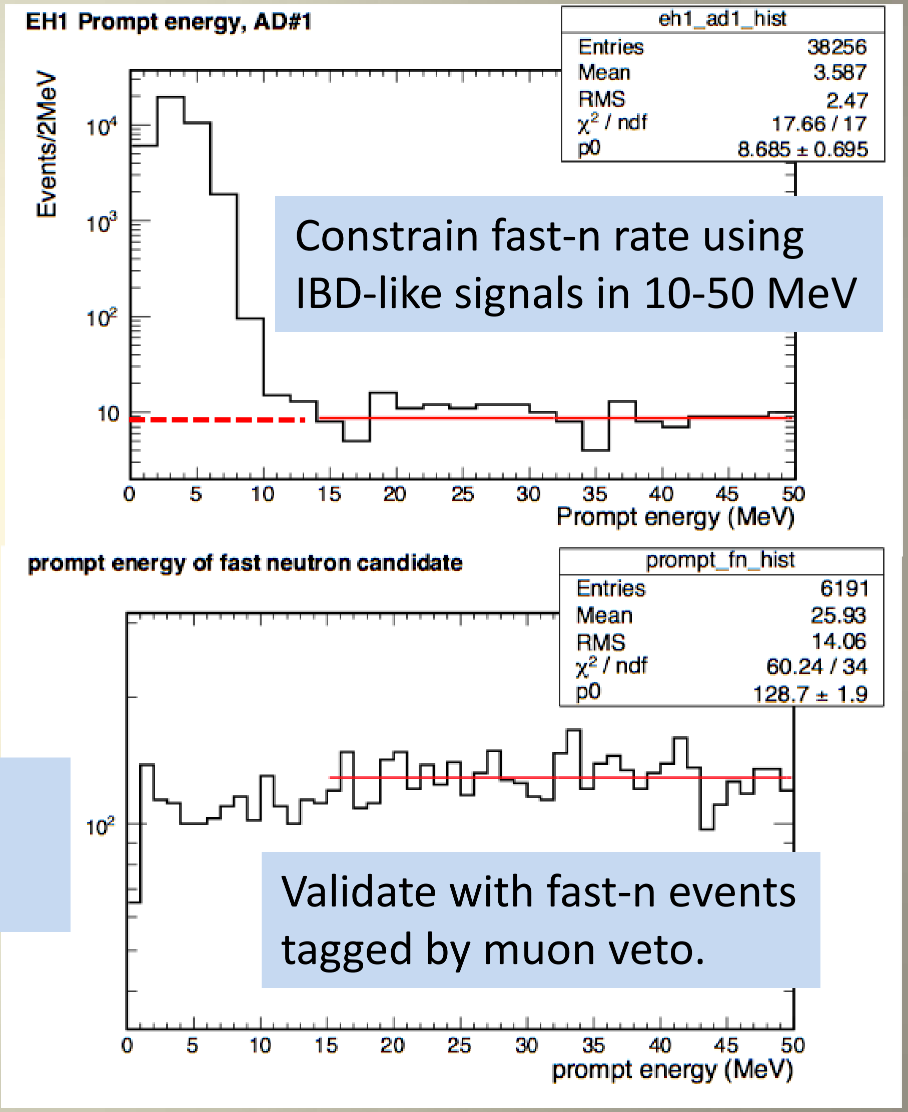
Background: Fast neutrons

Fast Neutrons:

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

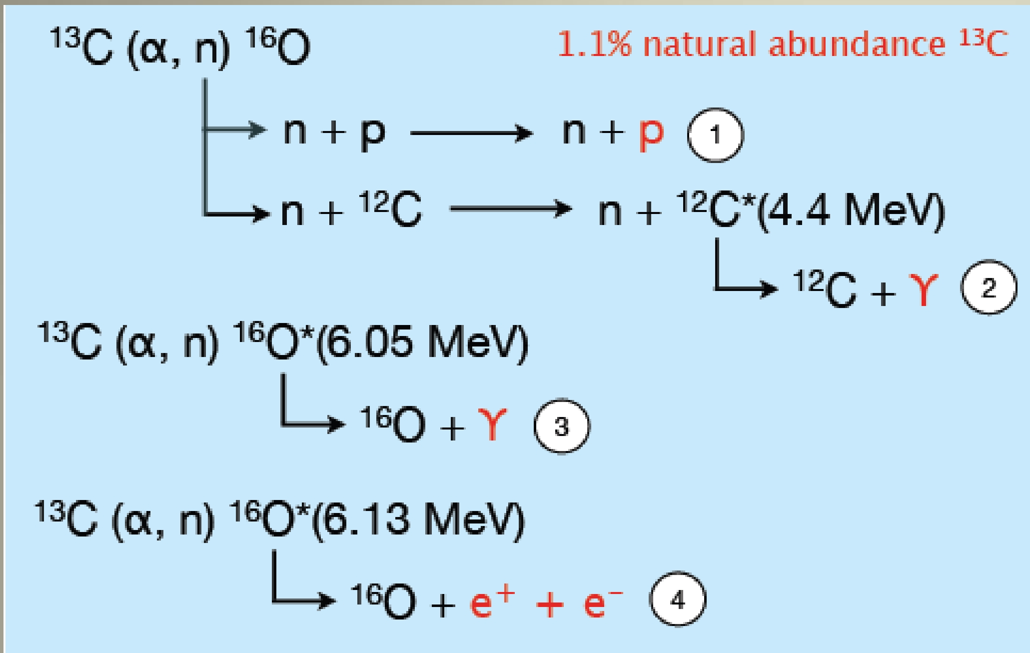
Mimics antineutrino (IBD) signal:

- 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.

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



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

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

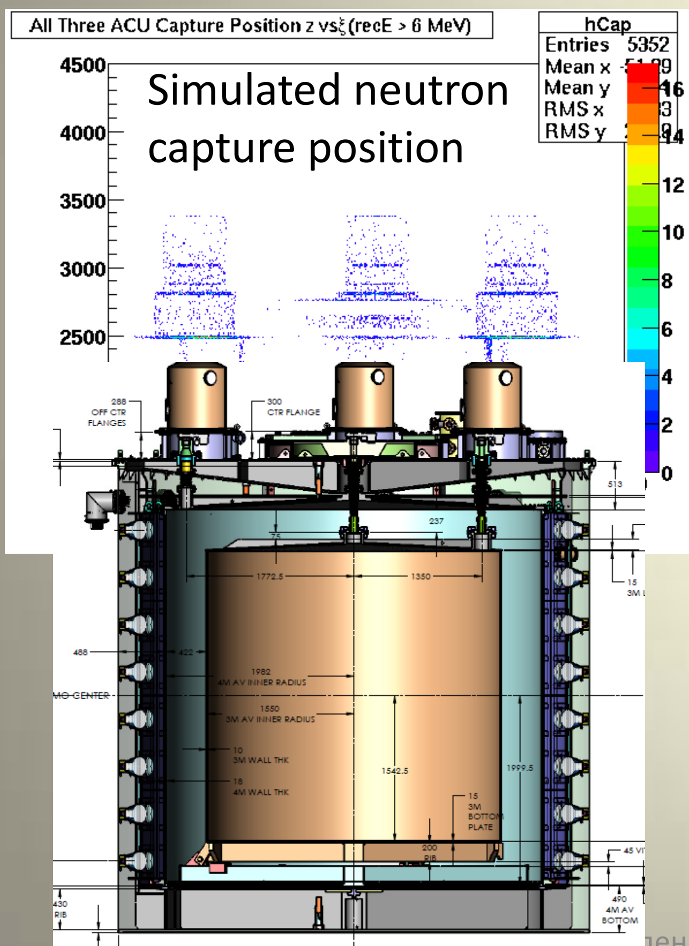
Combining (α,n) cross-section, correlated background rate is determined.

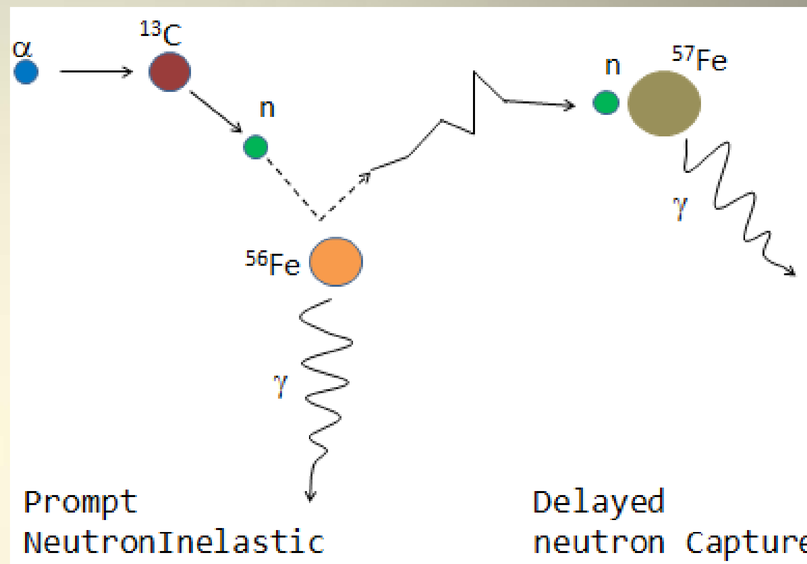
Near Site: 0.04+-0.02 per day, B/S (0.006±0.004)%

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

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

Data Set 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 rates for side-by-side detectors

Uncertainty currently dominated by statistics

Reactor Flux Expectation

Antineutrino flux is estimated for each reactor core

Flux estimated using:

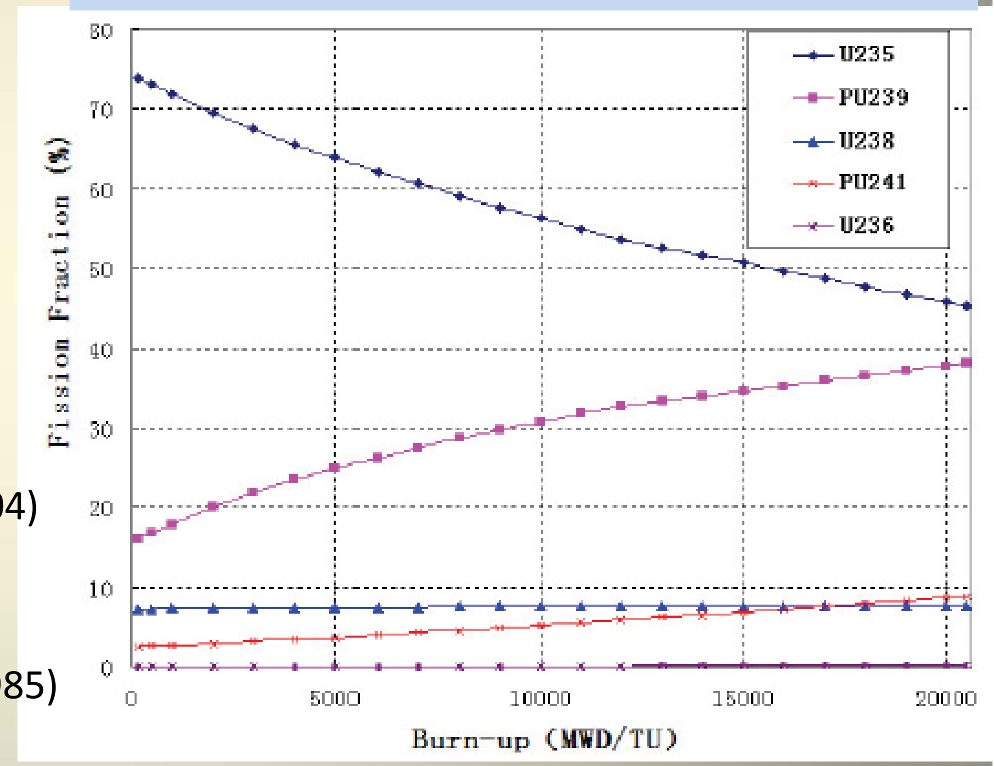
$$S(E_\nu) = \frac{W_{th}}{\sum_i (f_i/F)e_i} \sum_i^{istopes} (f_i/F) S_i(E_\nu)$$

Reactor operators provide:
- Thermal power data: W_{th}
- Relative isotope fission fractions: f_i

Energy released per fission: e_i
V. Kopekin et al., Phys. Atom. Nucl. 67, 1892 (2004)

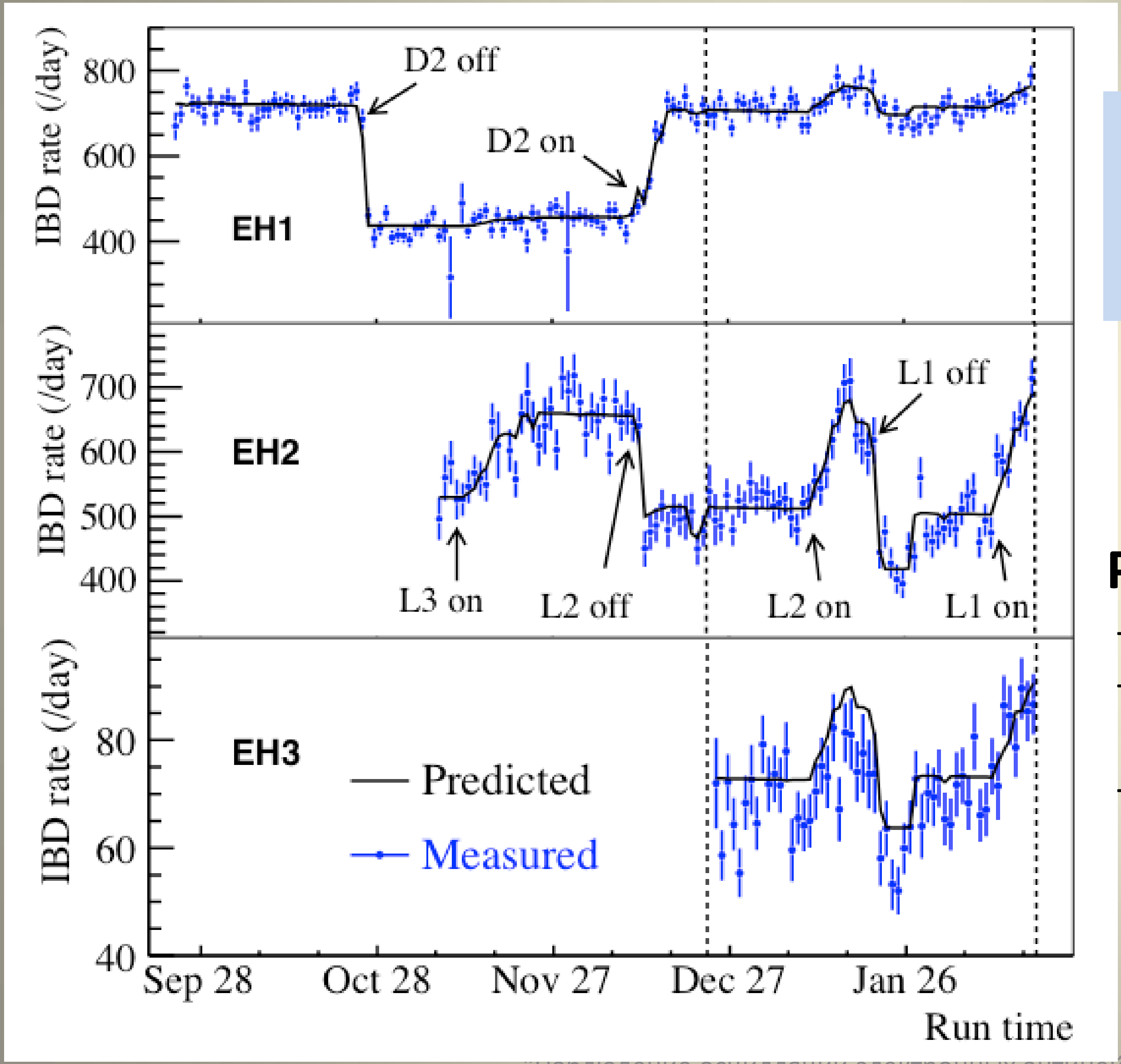
Antineutrino spectra per fission: $S_i(E_\nu)$
K. Schreckenbach et al., Phys. Lett. B160, 325 (1985)
A. A. Hahn et al., Phys. Lett. B218, 365 (1989)
P. Vogel et al., Phys. Rev. C24, 1543 (1981)
T. Mueller et al., Phys. Rev. C83, 054615 (2011)
P. Huber, Phys. Rev. C84, 024617 (2011)

Isotope fission rates vs. reactor burnup



Flux model has negligible impact on far vs. near oscillation measurement

Antineutrino Rate vs. Time

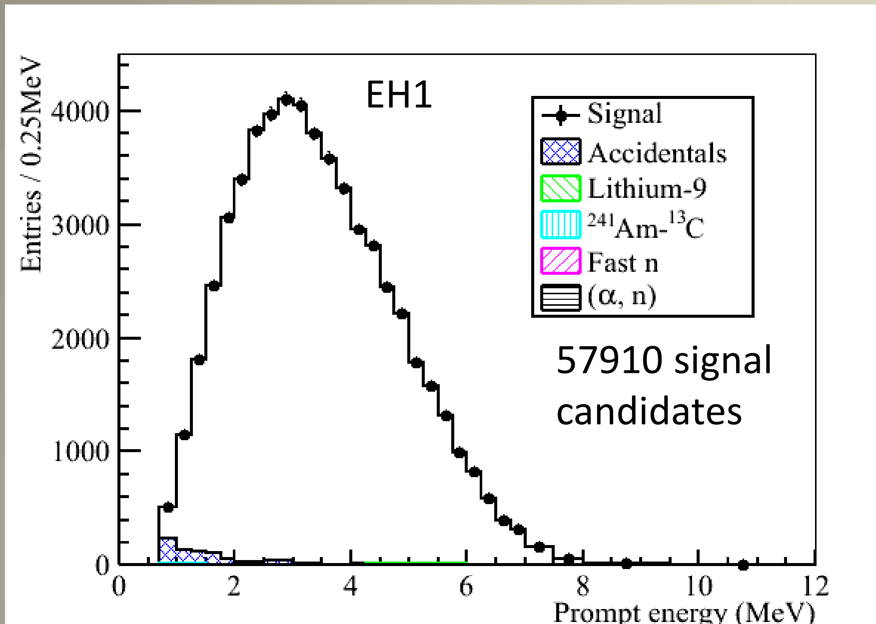


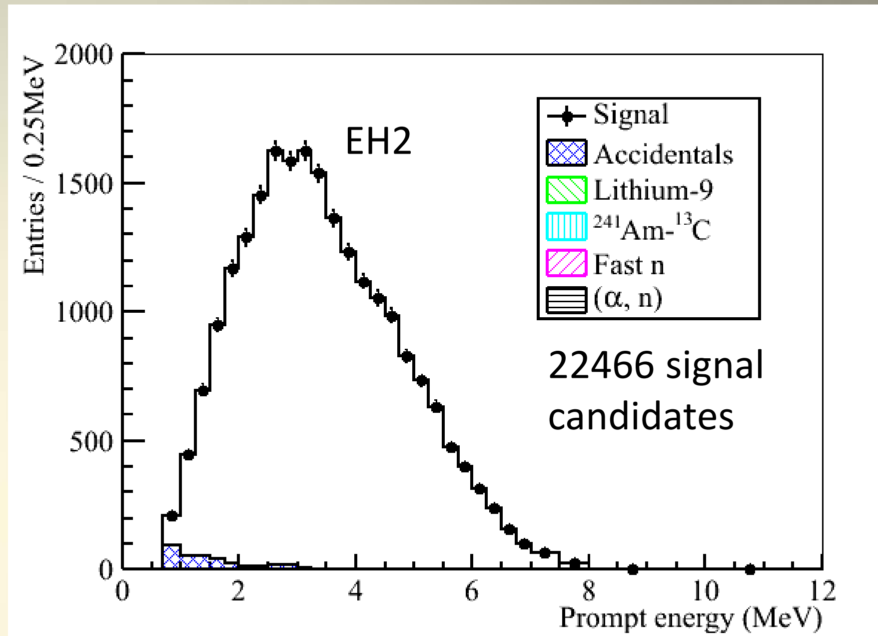
Detected rate strongly correlated with reactor flux expectations.

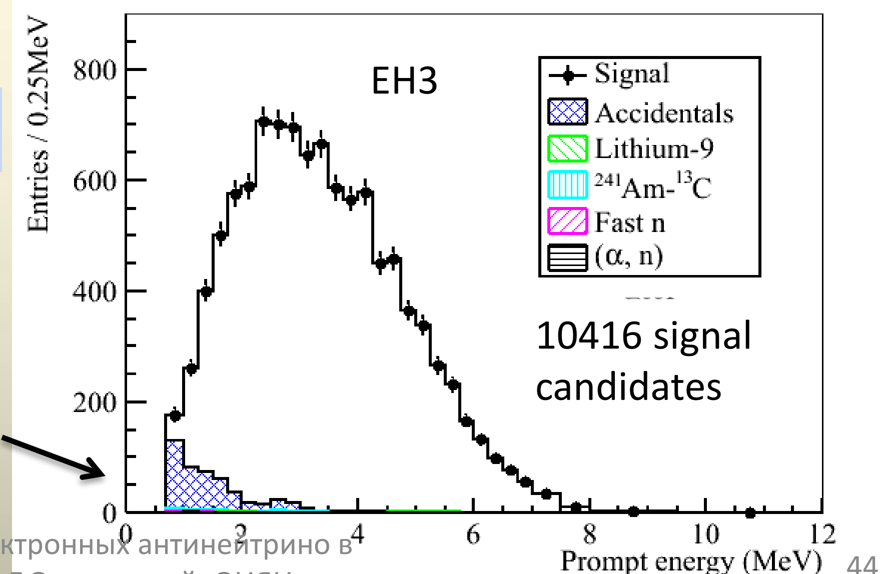
Predicted Rate: (in figure)

- Assumes no oscillation.
- Normalization is determined by fit to data.
- Absolute normalization is within a few percent of expectations.

Prompt Positron Spectra







High-statistics reactor antineutrino spectra.

B/S ratio is 5% (2%) at far (near) sites.

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%

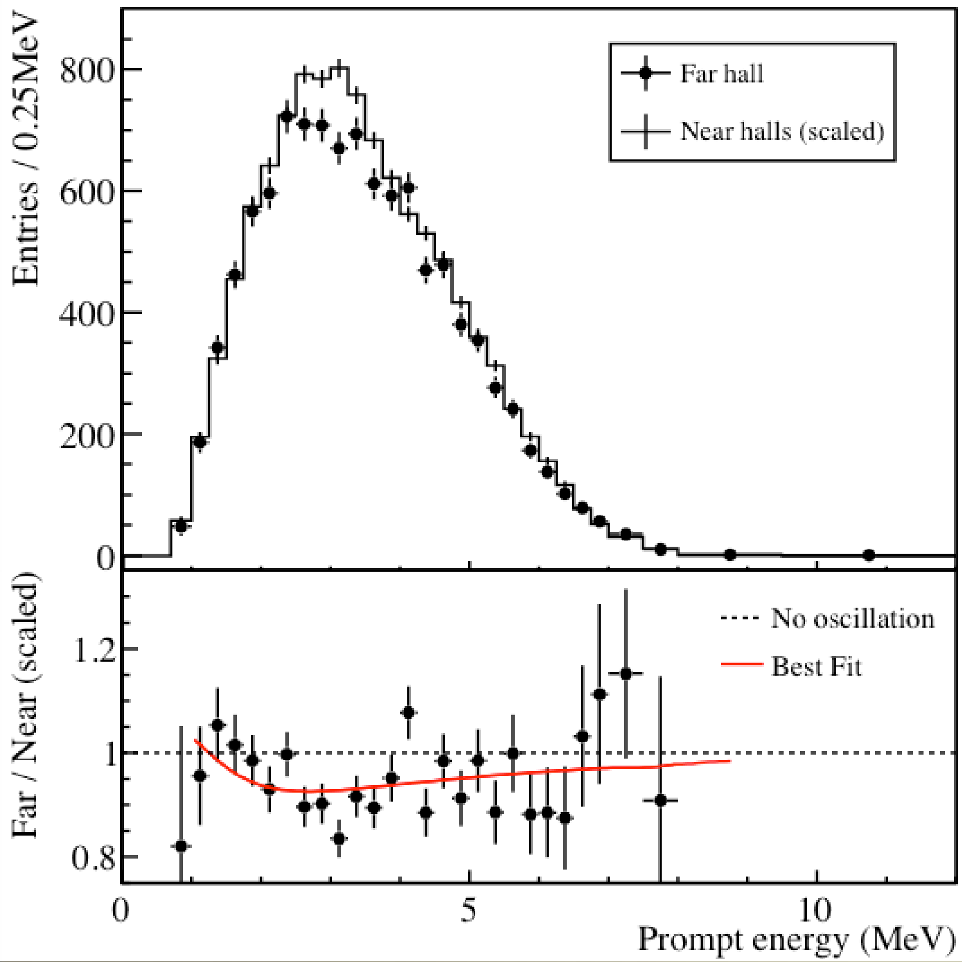
For near/far oscillation, only uncorrelated uncertainties are used.

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

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

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 = 0.940 ± 0.011 (stat) ± 0.004 (syst)

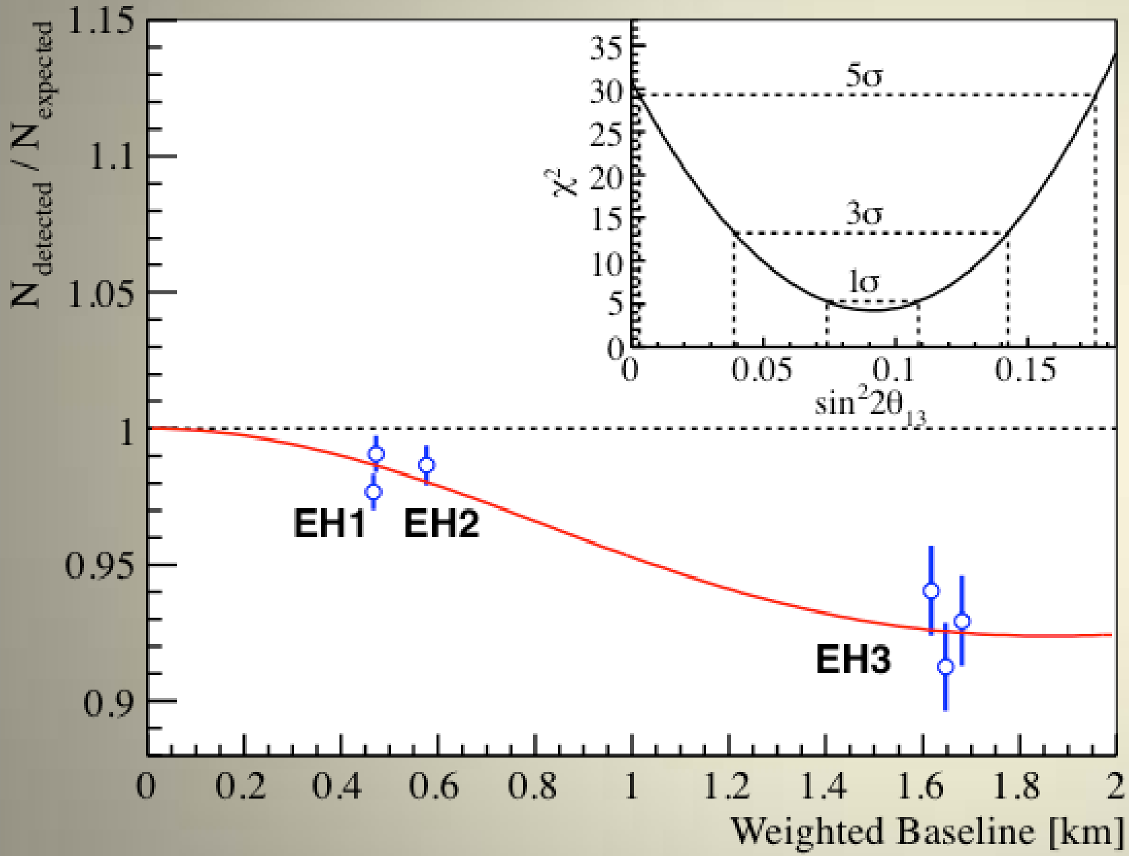
Clear observation of far site deficit.

Spectral distortion consistent with oscillation.*

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

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.]

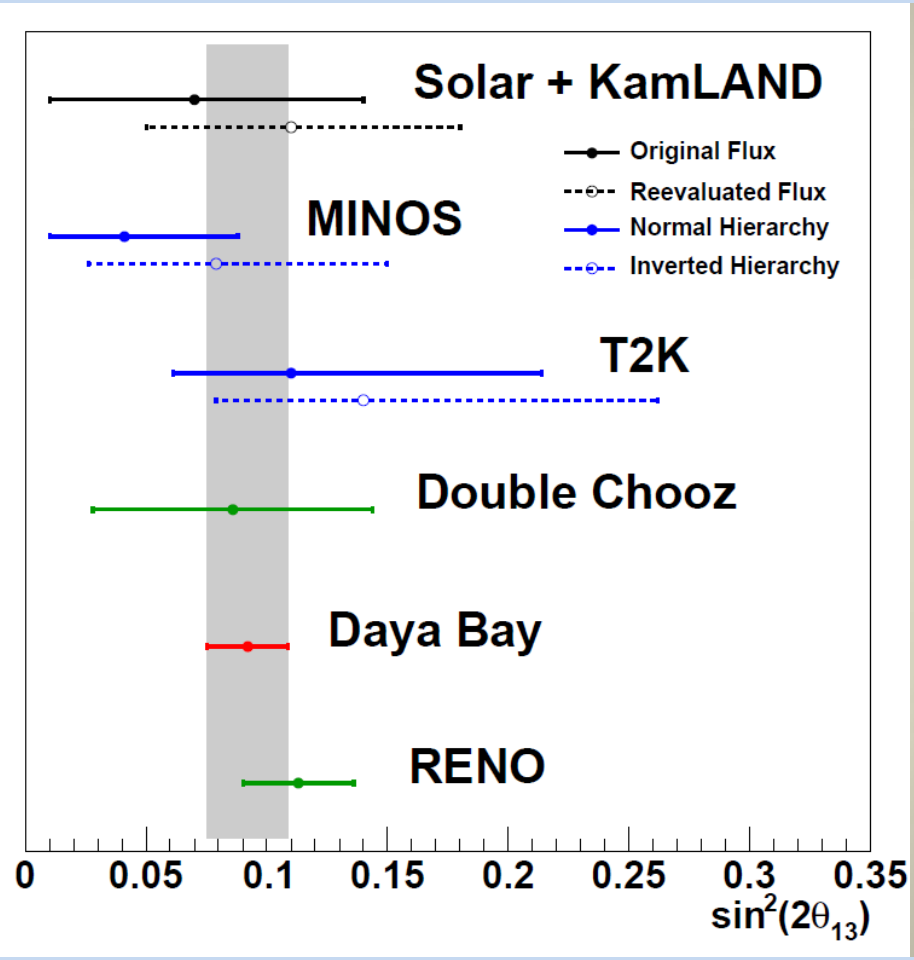
Consistent results obtained by independent analyses, different reactor flux models.

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

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

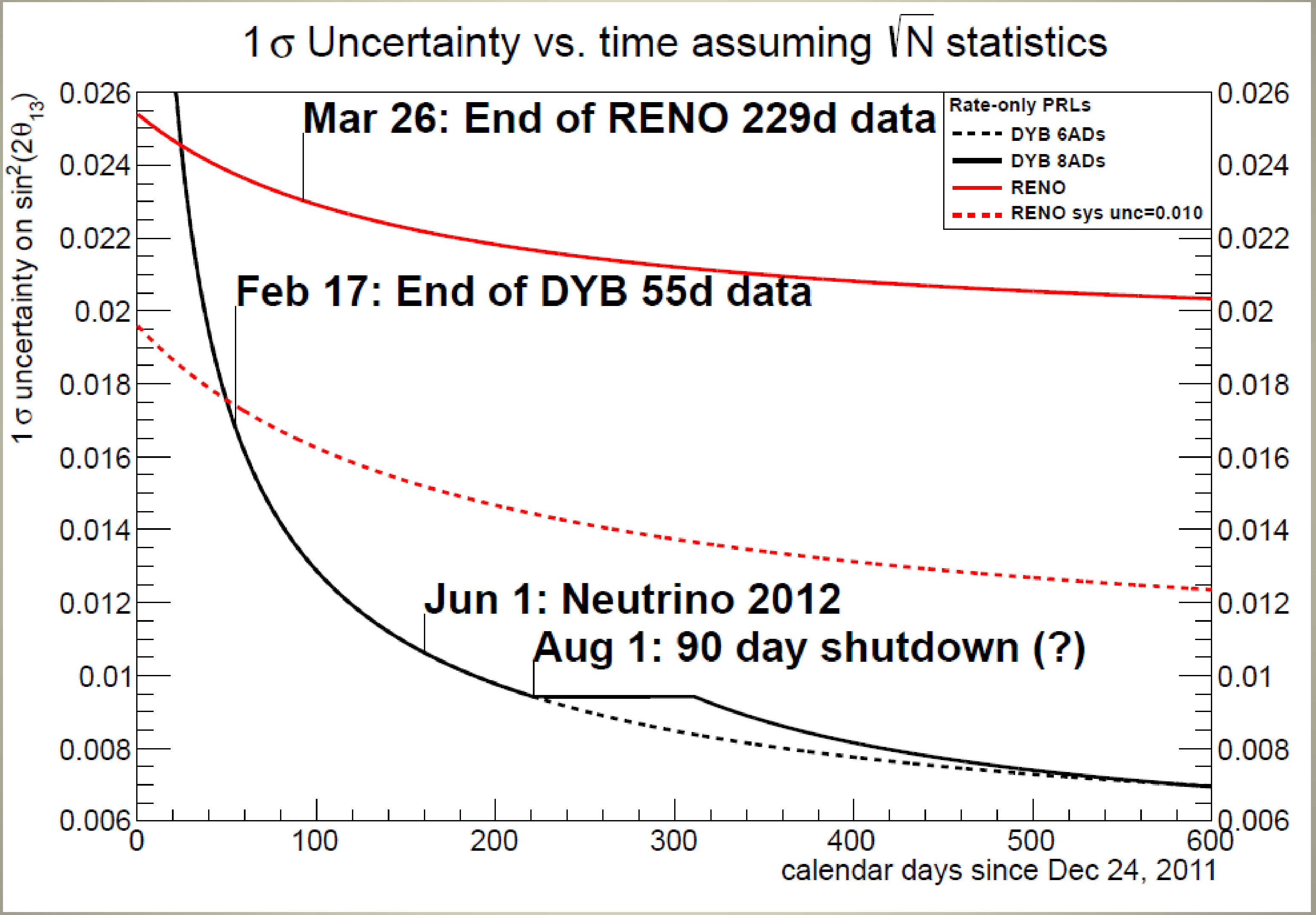
θ_{13}

Daya Bay precision surpasses all existing estimates.



Expect more statistics and further improvements in analysis.

Projected sensitivity to θ_{13}



Summary

- The Daya Bay reactor neutrino experiment has made an unambiguous observation of reactor electron-antineutrino disappearance at ~2 km:

R = 0.940 ± 0.011 (stat) ± 0.004 (syst)

- Interpretation of disappearance as neutrino oscillation yields:

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

ruling out zero at 5.2 standard deviations.

- Installation of final pair of antineutrino detectors this summer