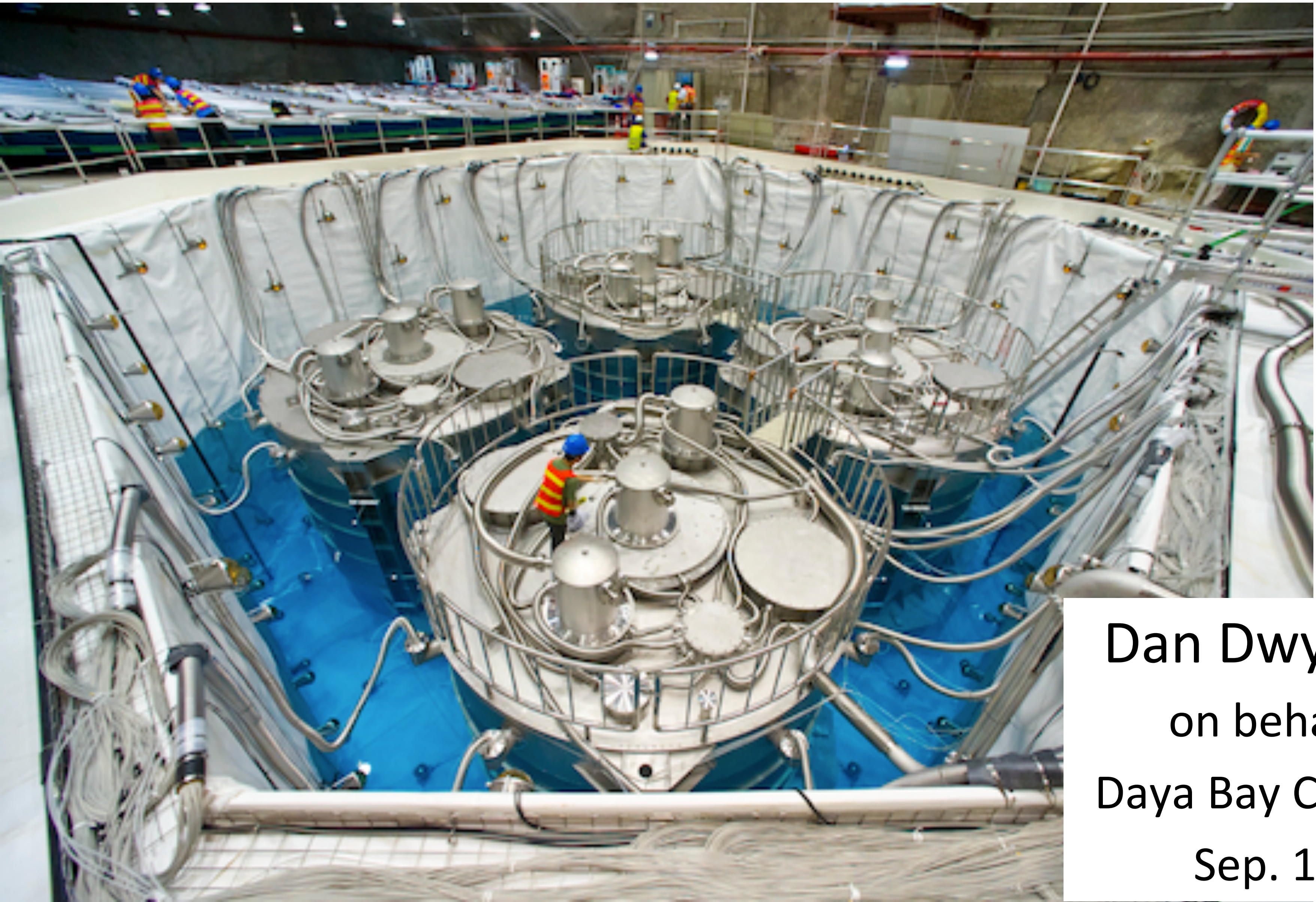
Spectral Measurement of Antineutrino Oscillation Amplitude and Frequency at Daya Bay



Dan Dwyer (LBNL)

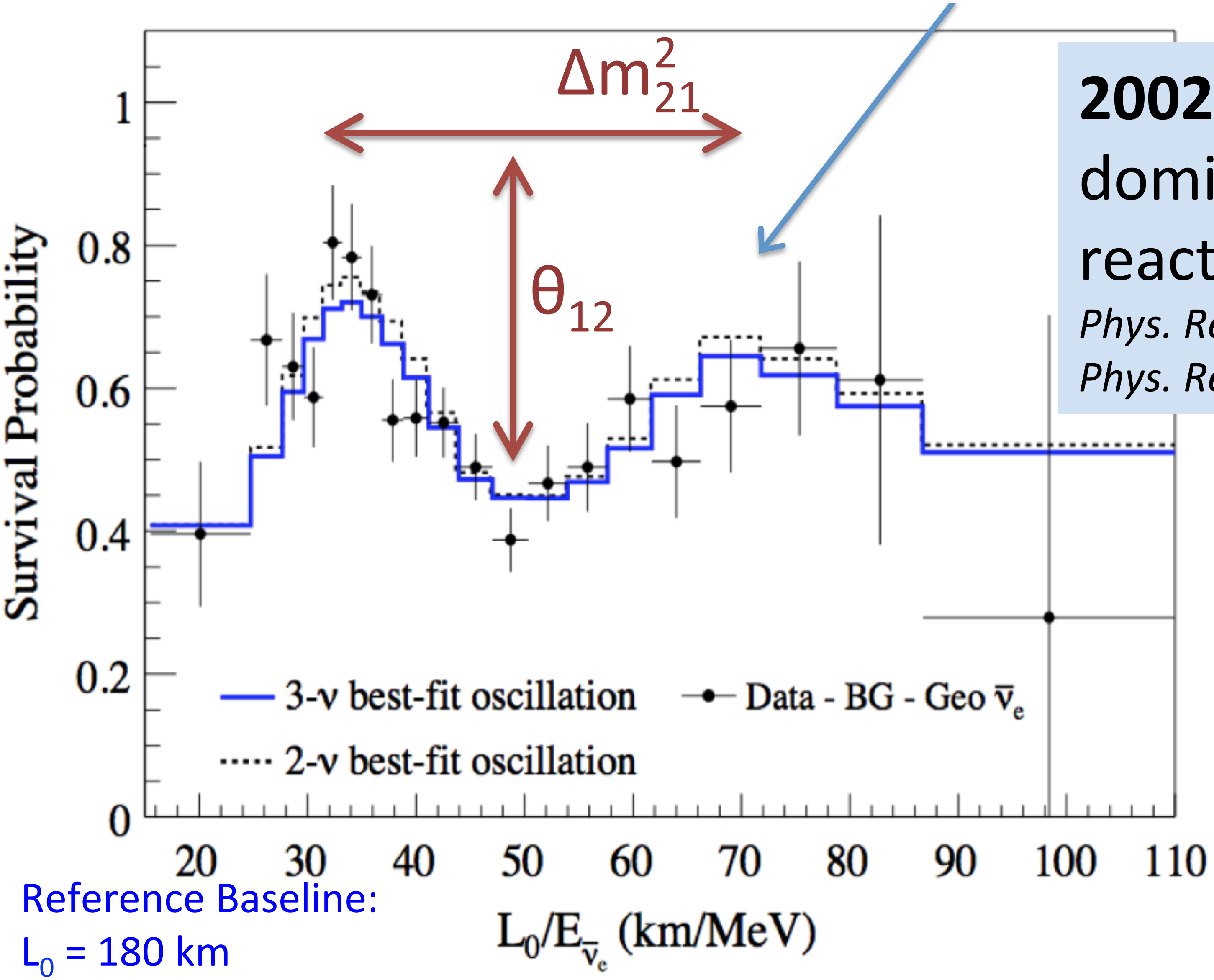
on behalf of the

Daya Bay Collaboration

Sep. 17, 2013

Reactor Antineutrino Oscillation

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



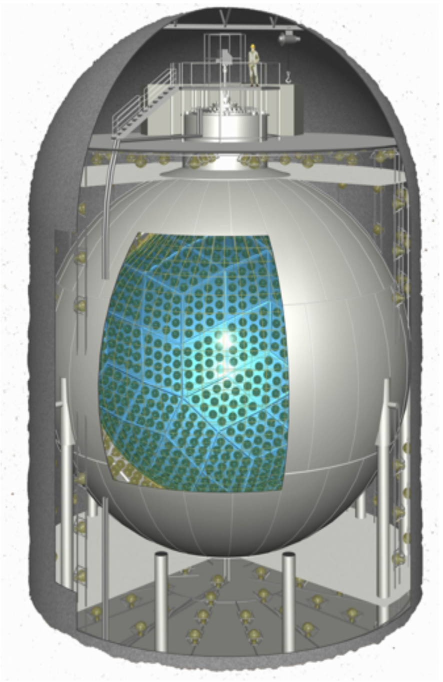
2002: KamLAND shows dominant oscillation of reactor antineutrinos.

Phys. Rev. Lett. 89, 011301 (2002)

Phys. Rev. Lett. 92, 181301 (2004)

Reference Baseline:

L_0 = 180 km



A Decade of Progress

The neutrino mixing matrix only recently measured.

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

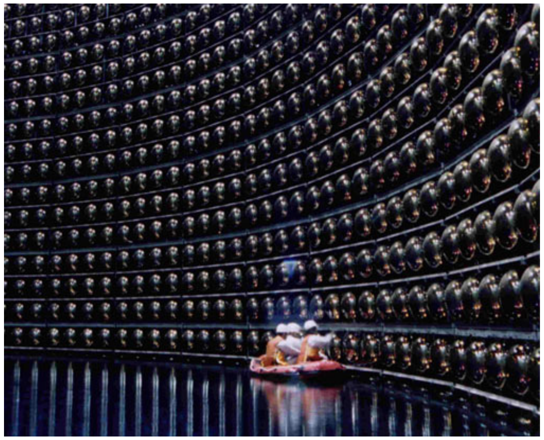
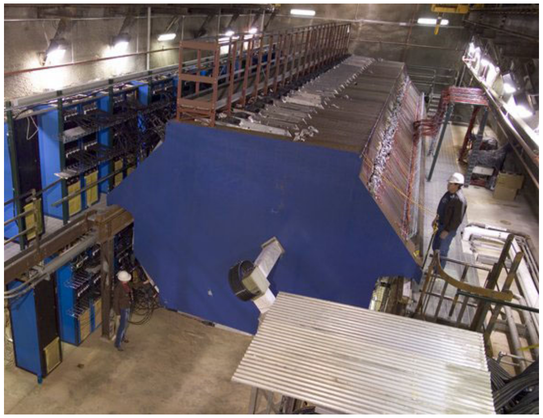
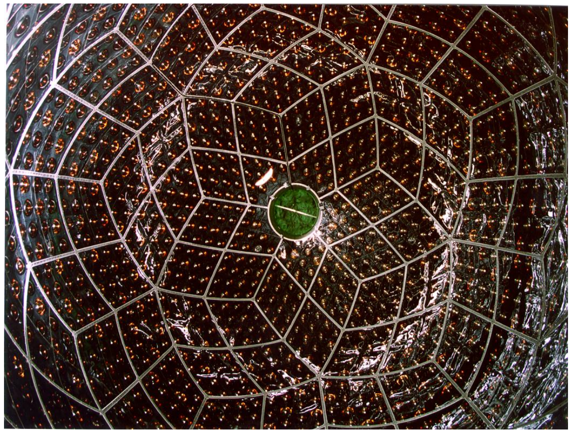
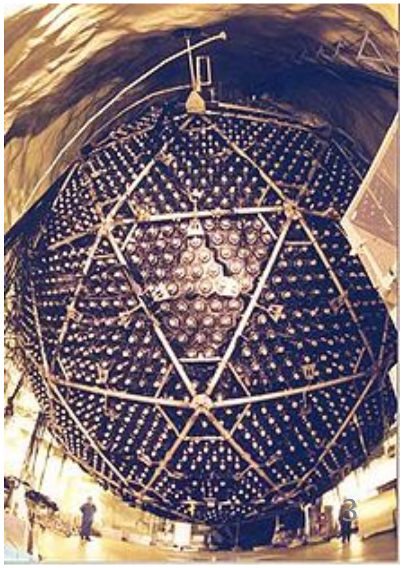
$$U_{if} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha,i}\,|\nu_i\rangle$$

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

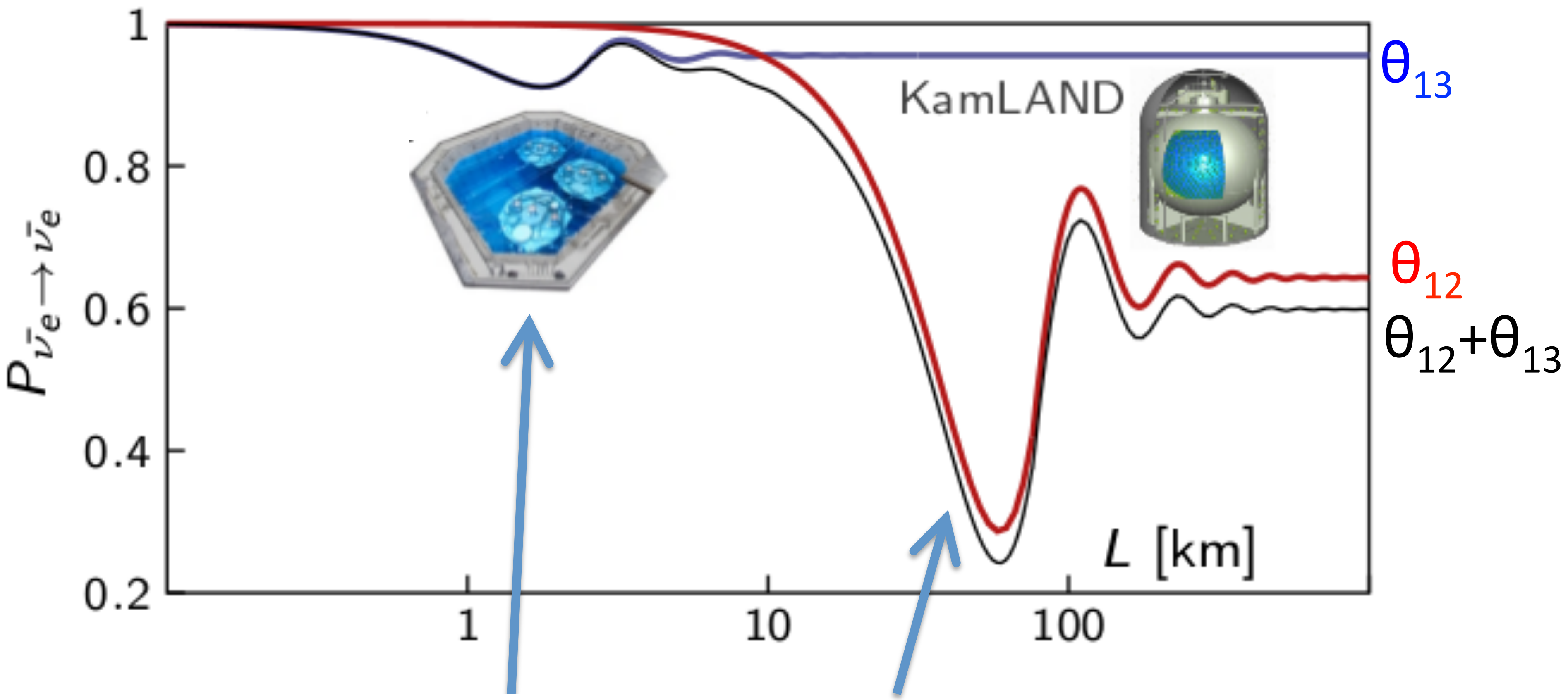
$\theta_{13} \approx 9^\circ$
Short-Baseline Reactor ν
Accelerator ν

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

Searching for θ_{13}

Three-flavor model predicts reactor $\bar{\nu}_e$ oscillation at ~1.8km



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

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

A Relative Measurement

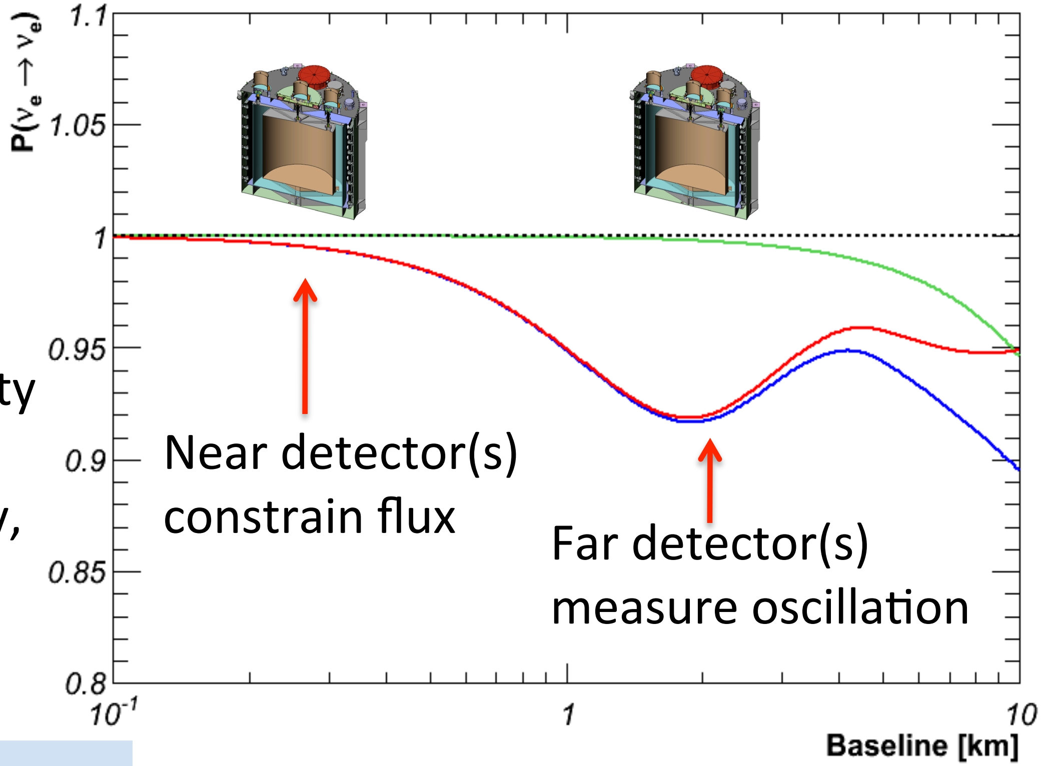
Absolute Reactor Flux:

Largest uncertainty in previous measurements

Relative Measurement:

Multiple detectors remove absolute uncertainty

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



Near detector(s) constrain flux

Far detector(s) measure oscillation

Far/Near ν_e Ratio

Distances from reactor

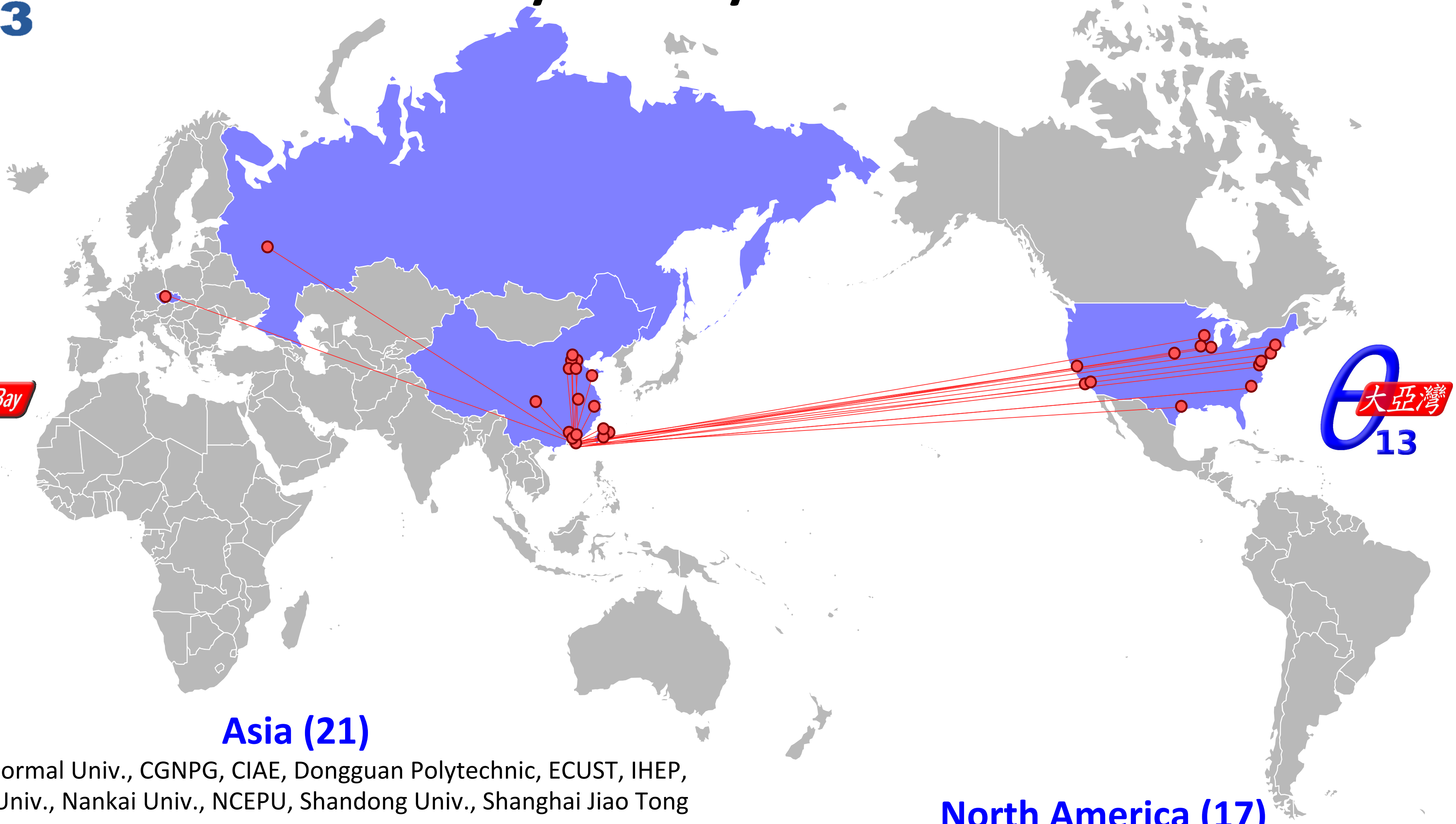
Oscillation deficit

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

Detector Target Mass

Detector efficiency

The Daya Bay Collaboration



Asia (21)

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

Europe (2)

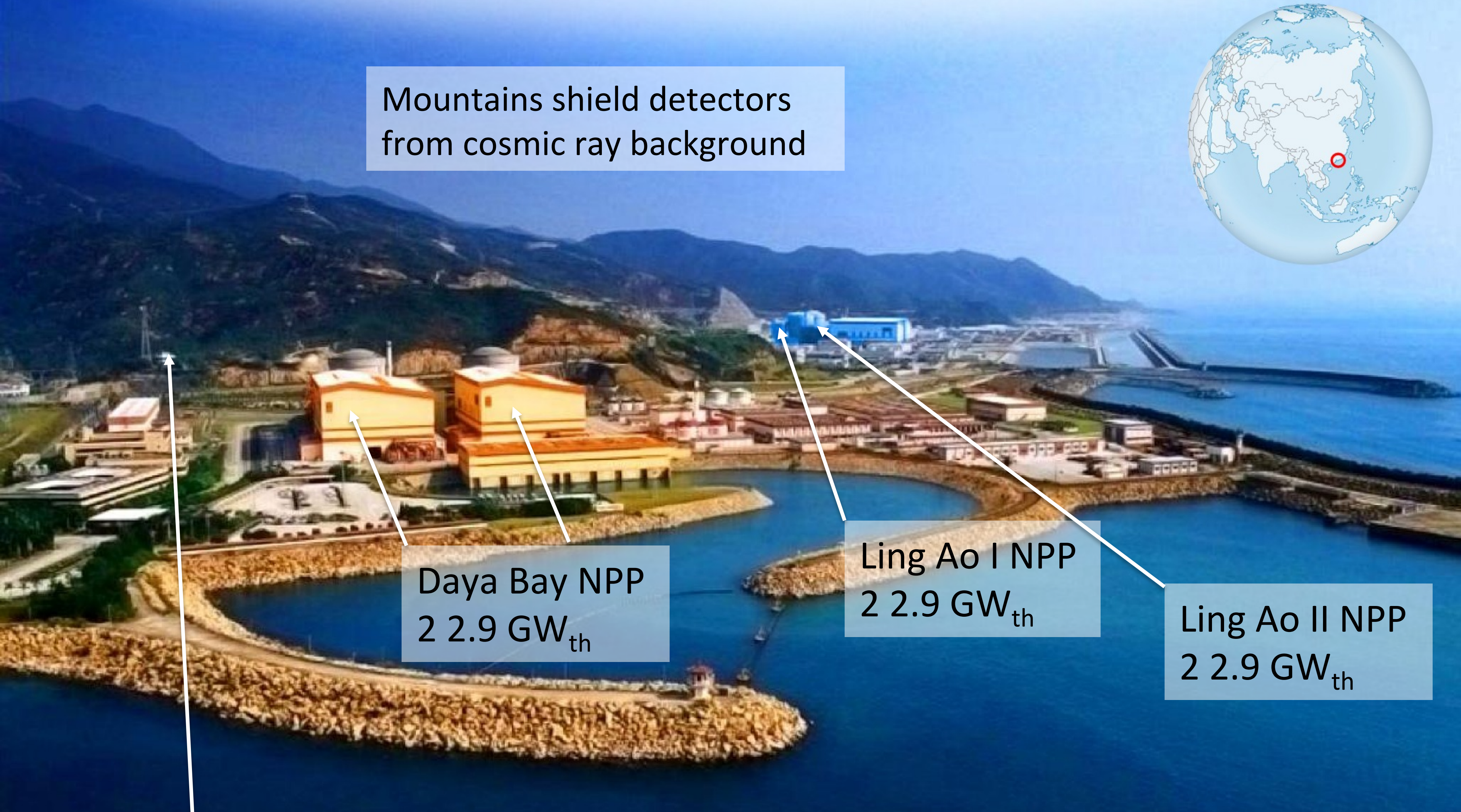
Charles University, JINR Dubna

North America (17)

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

~230 people from 40 institutions

The Daya Bay Experiment



Mountains shield detectors from cosmic ray background

Daya Bay NPP
2 2.9 GW_{th}

Ling Ao I NPP
2 2.9 GW_{th}

Ling Ao II NPP
2 2.9 GW_{th}

Entrance to Daya Bay experiment tunnels

Among the top 5 most powerful reactor complexes in the world, 6 cores produce 17.4 GW_{th} power, 35 × 10^{20} neutrinos per second

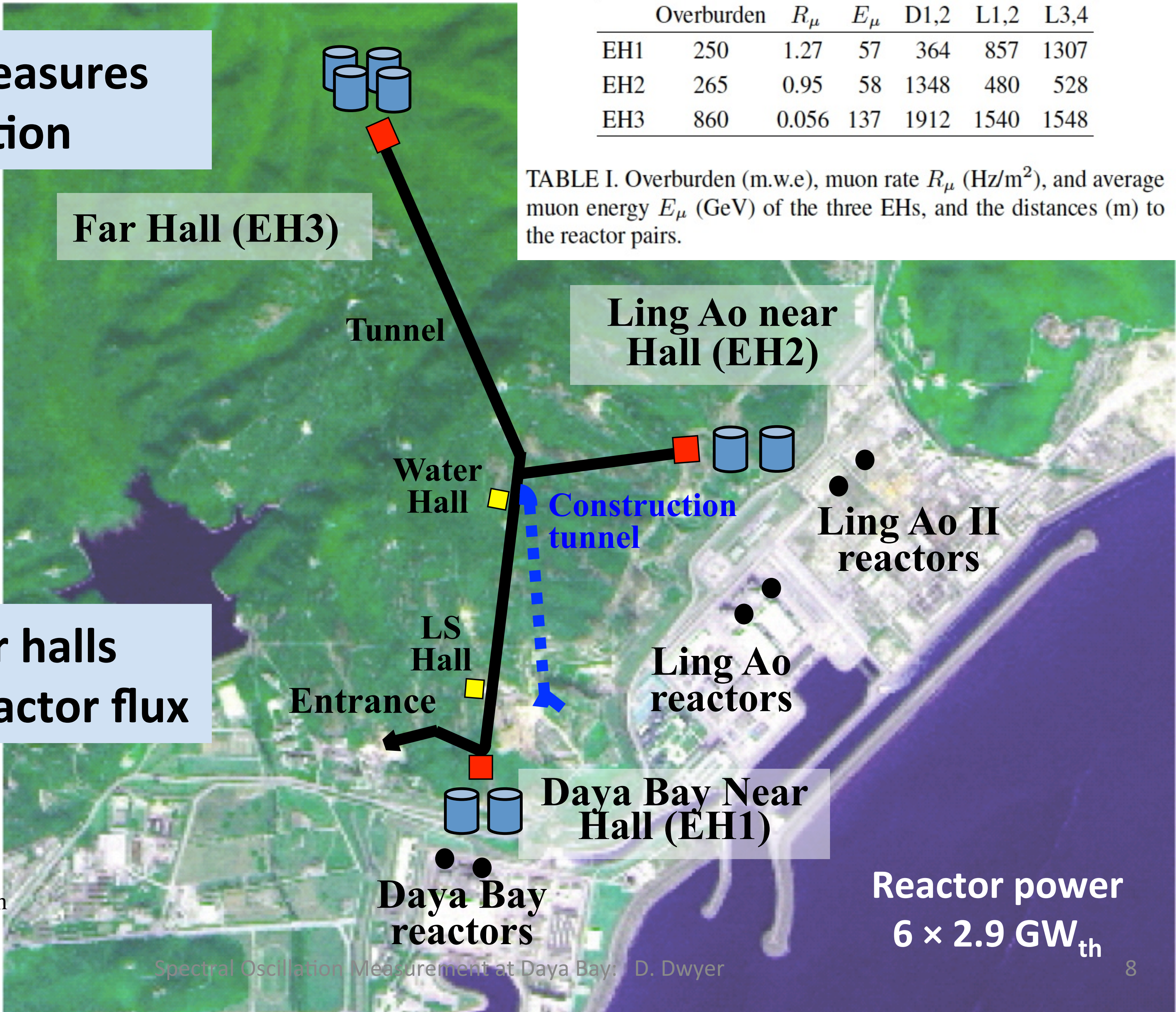
Experiment Layout

Far hall measures oscillation

Two near halls constrain reactor flux

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

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.

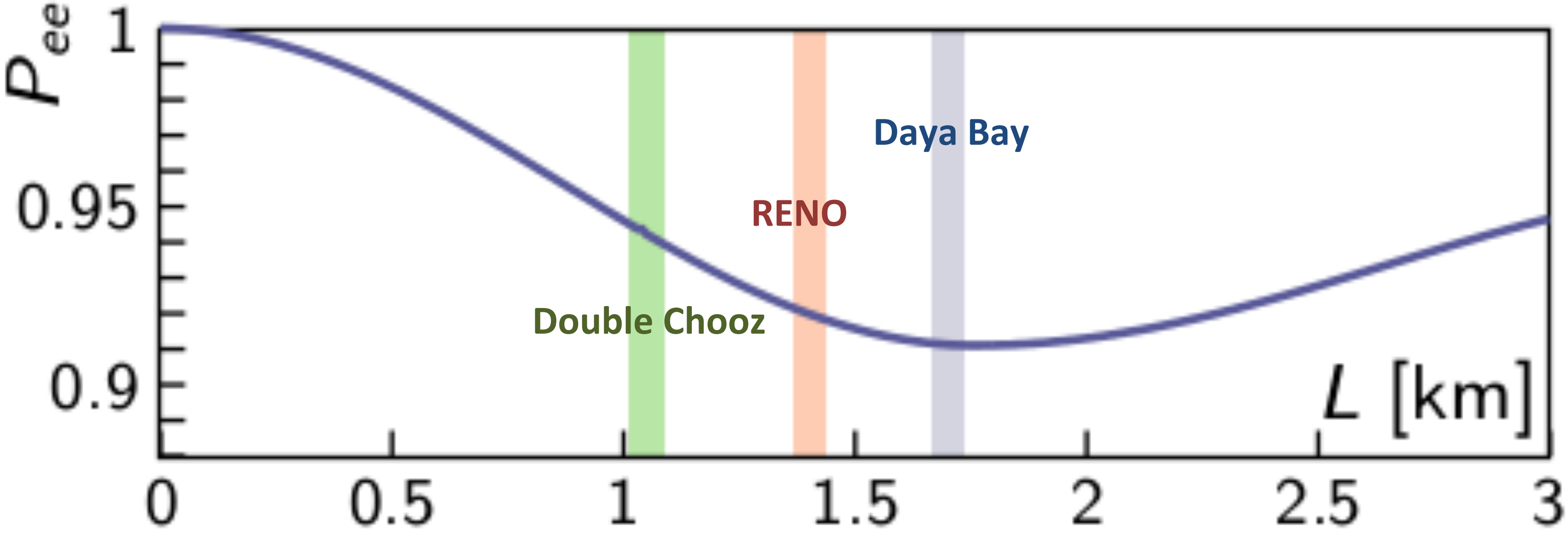


Reactor power
6 × 2.9 GW_{th}

Reactor Experiments

Baseline Optimization

Atmospheric and accelerator ν oscillation $\Delta m^2_{\mu\mu}$ suggest to search at ~1.8 km.



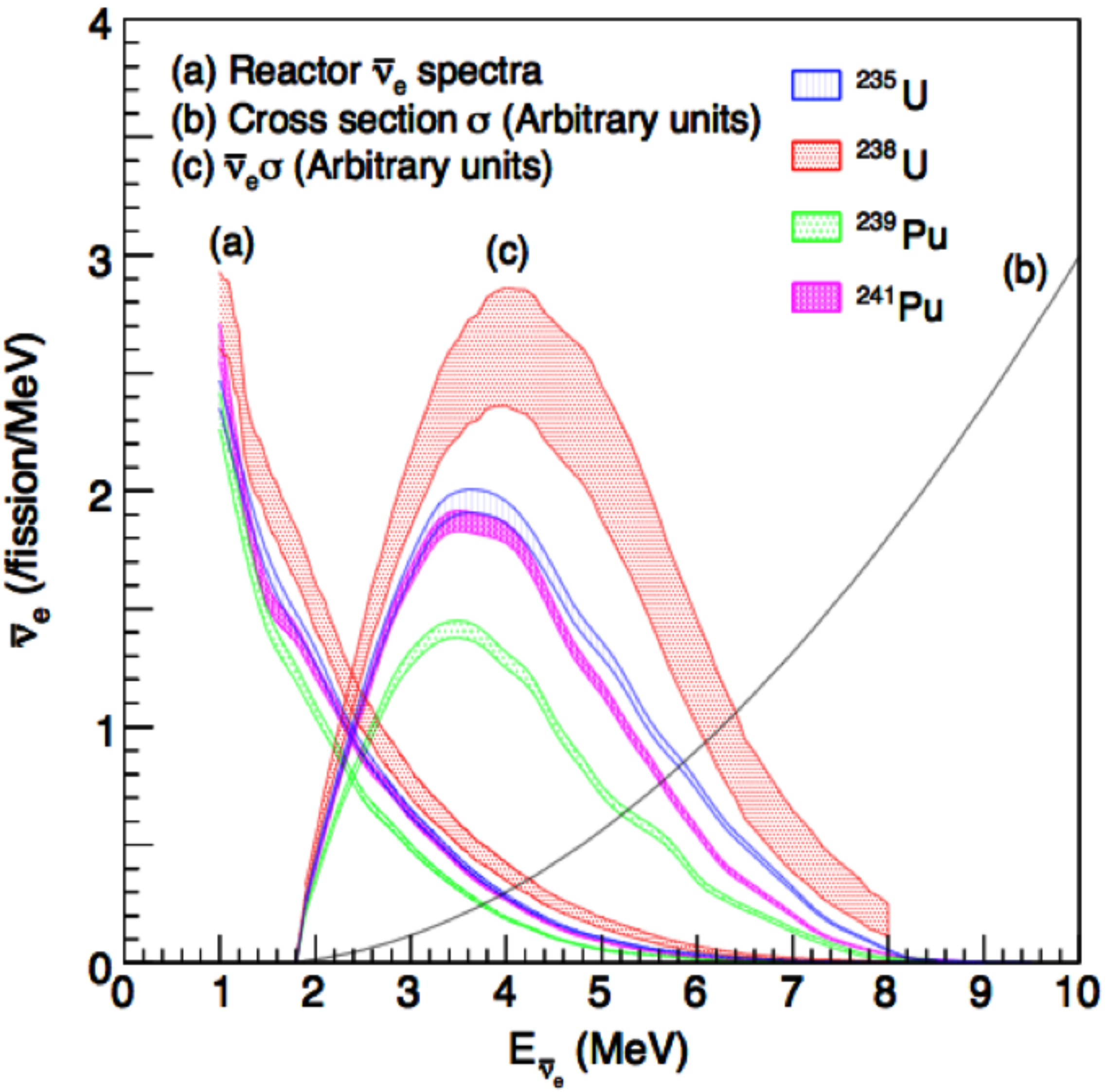
Go strong, big and deep!

	Reactor [GW_{th}]	Target [tons]	Depth [m.w.e]
Double Chooz	8.6	16 (2 × 8)	300, 120 (far, near)
RENO	16.5	32 (2 × 16)	450, 120
Daya Bay	17.4	160 (8 × 20)	860, 250
	Large Signal		Low Background

Reactor Antineutrinos

Nuclear fission releases: ~6 antineutrinos/fission

Standard electric power reactor: ~10^{20} fissions/second



Detection Method

Inverse β-decay (IBD):

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

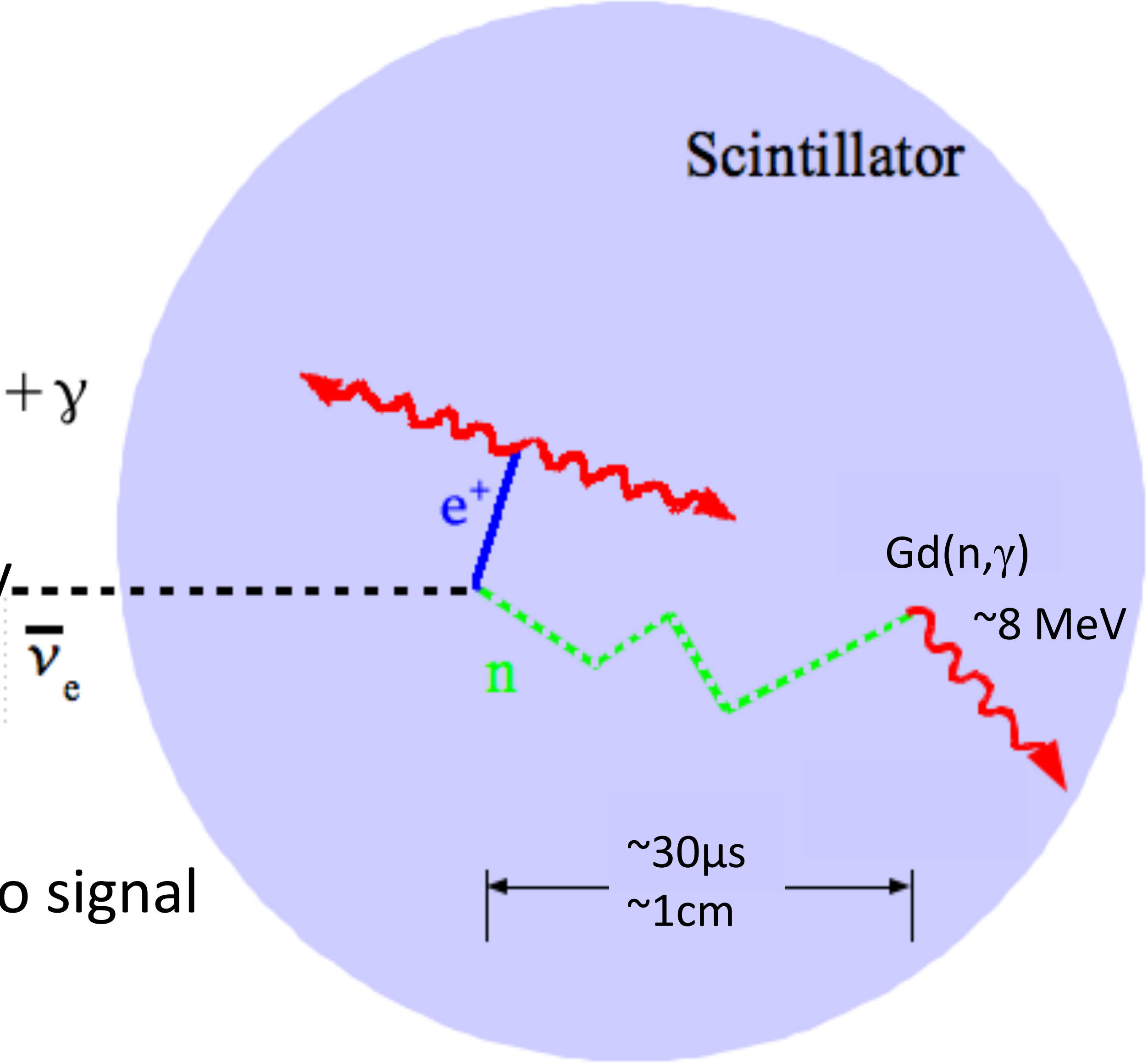
Prompt positron:

Carries antineutrino energy

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

Delayed neutron capture:

Efficiently tags antineutrino signal



Prompt + Delayed coincidence provides distinctive signature

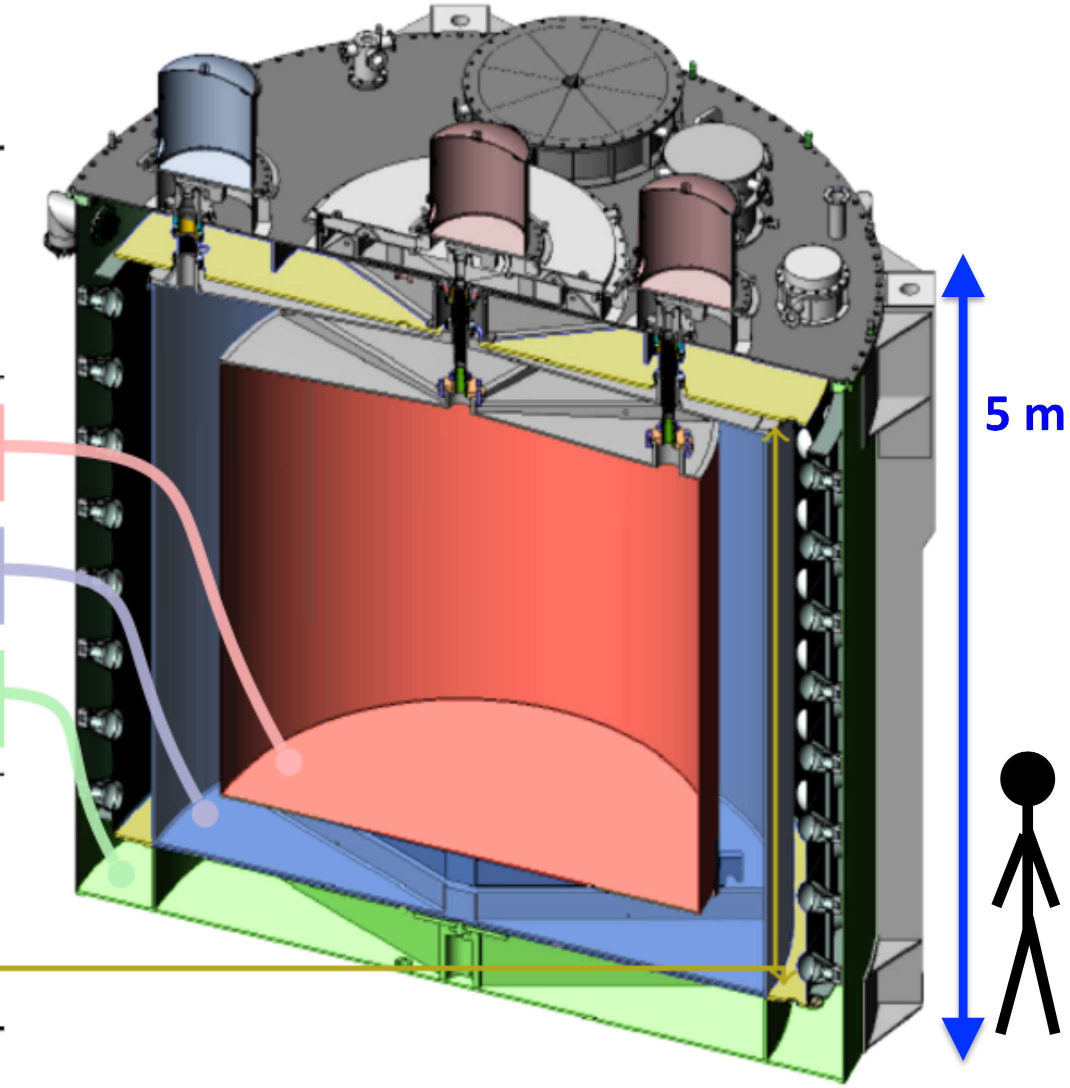
Antineutrino Detector (AD) Design

8 functionally identical detectors
reduce systematic uncertainties

	3 zone cylindrical vessels		
	Liquid	Mass	Function
Inner acrylic	Gd-doped liquid scint.	20 t	Antineutrino target
Outer acrylic	Liquid scintillator	20 t	Gamma catcher
Stainless steel	Mineral oil	40 t	Radiation shielding

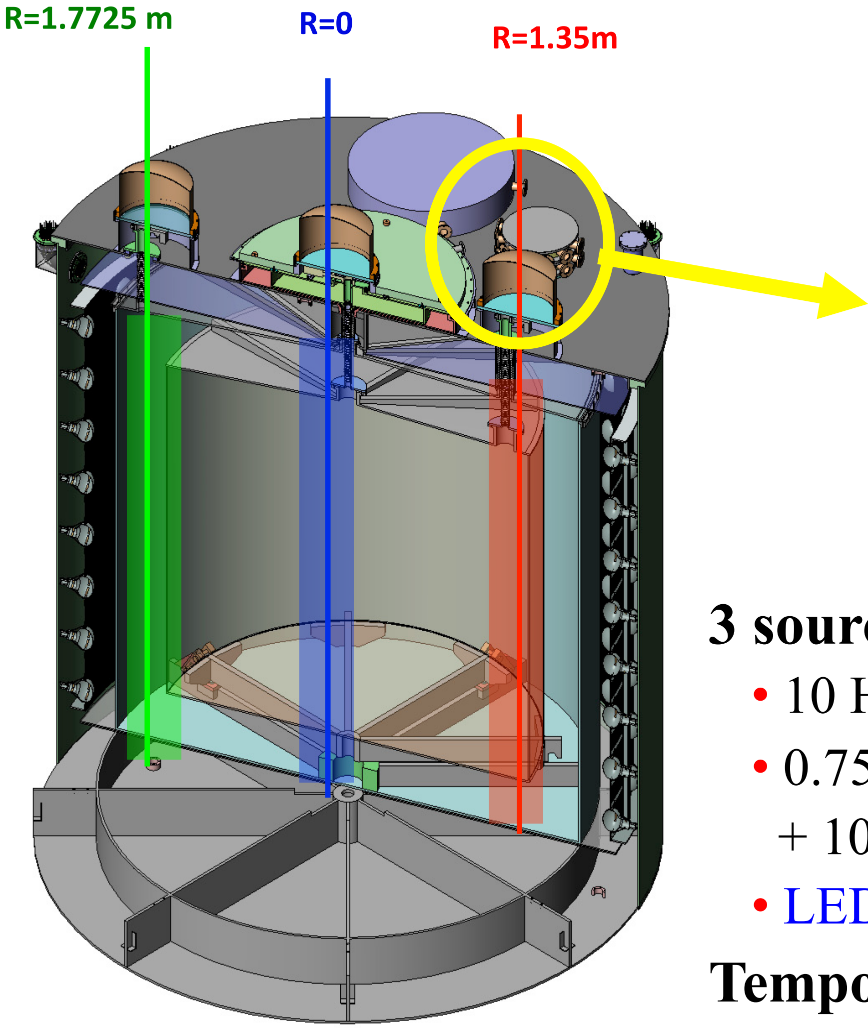
192 8 inch PMTs in each detector

Top and bottom reflectors increase light yield
and flatten detector response

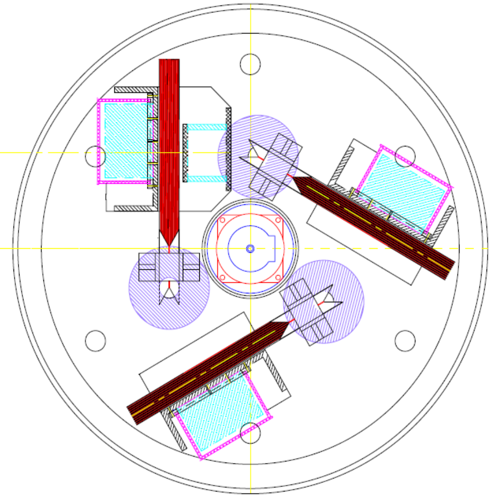


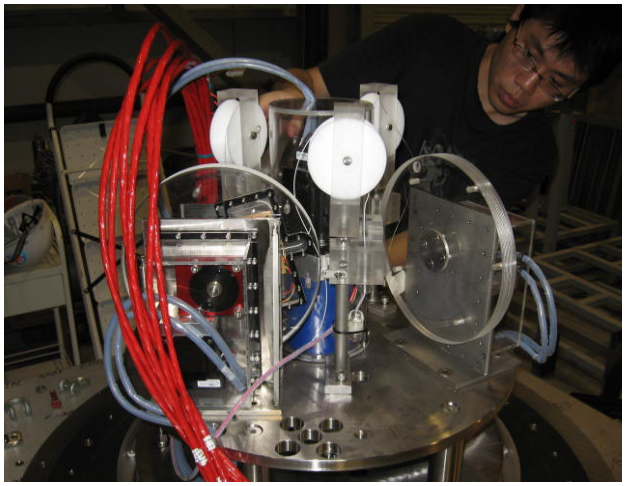
Automated Calibration System

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



Top view





3 sources in each robot, including:

- 10 Hz ^{68}Ge (0 KE $e^+ = 2\times0.511$ MeV γ’s)
- 0.75 Hz ^{241}Am-^{13}C neutron source (3.5 MeV n without γ) + 100 Hz ^{60}Co gamma source (1.173+1.332 MeV γ)
- LED diffuser ball (500 Hz) for time calibration

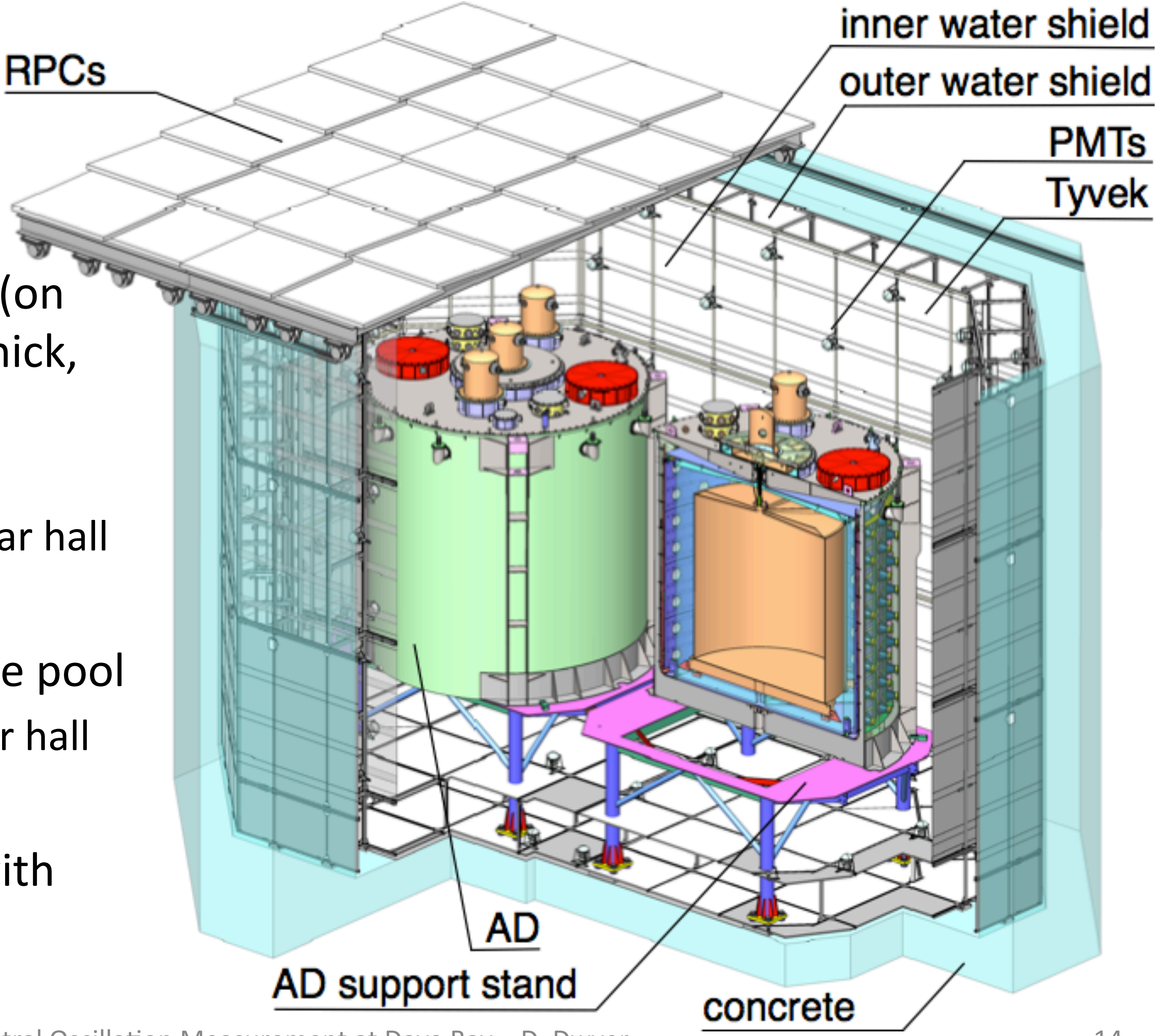
Temporary special calibration sources:

γ: ^{137}Cs (0.662 MeV), ^{54}Mn (0.835 MeV), ^{40}K (1.461 MeV)
n: ^{241}Am-^{9}Be, ^{239}Pu-^{13}C

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

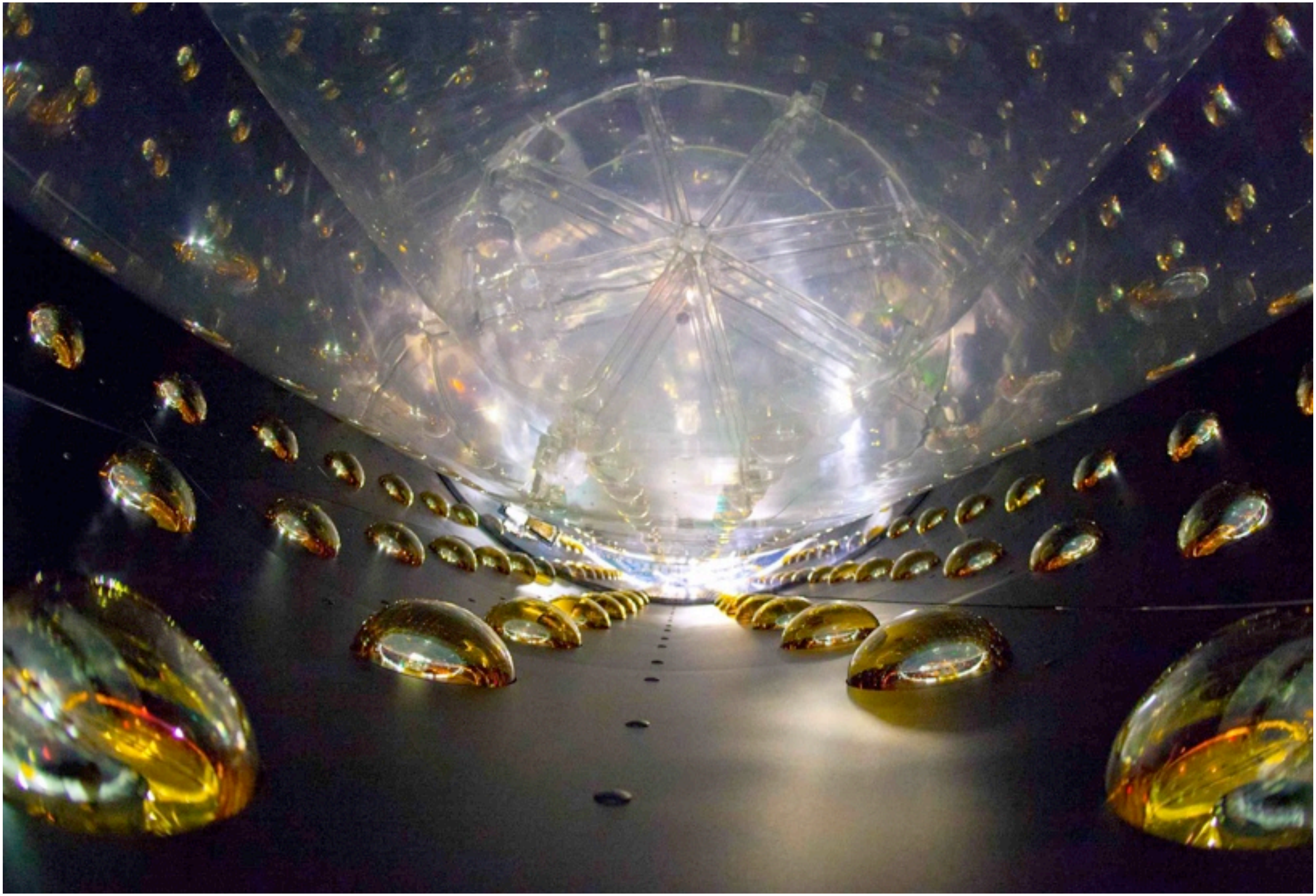
Muon Detector System

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

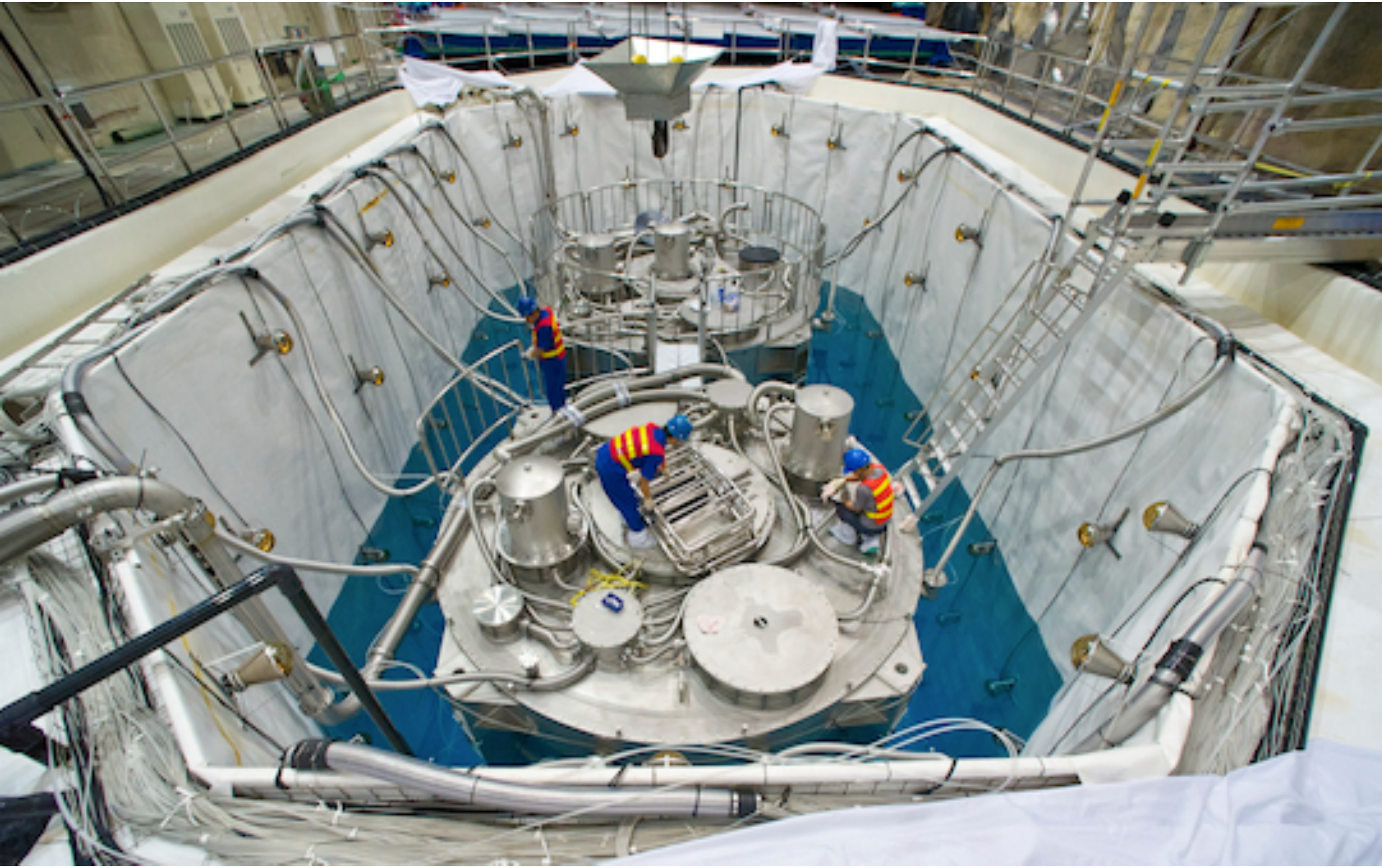


- Outer layer of water veto (on sides and bottom) is 1m thick, inner layer >1.5m. Water extends 2.5m above ADs
    - 288 8” PMTs in each near hall
    - 384 8” PMTs in Far Hall
- 4-layer RPC modules above pool
    - 54 modules in each near hall
    - 81 modules in Far Hall
- Goal efficiency: > 99.5% with uncertainty <0.25%

Interior of Antineutrino Detector



Installed Underground



Analyzed Data Sets

Two detector comparison [1202.6181]

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

First oscillation analysis [1203:1669]

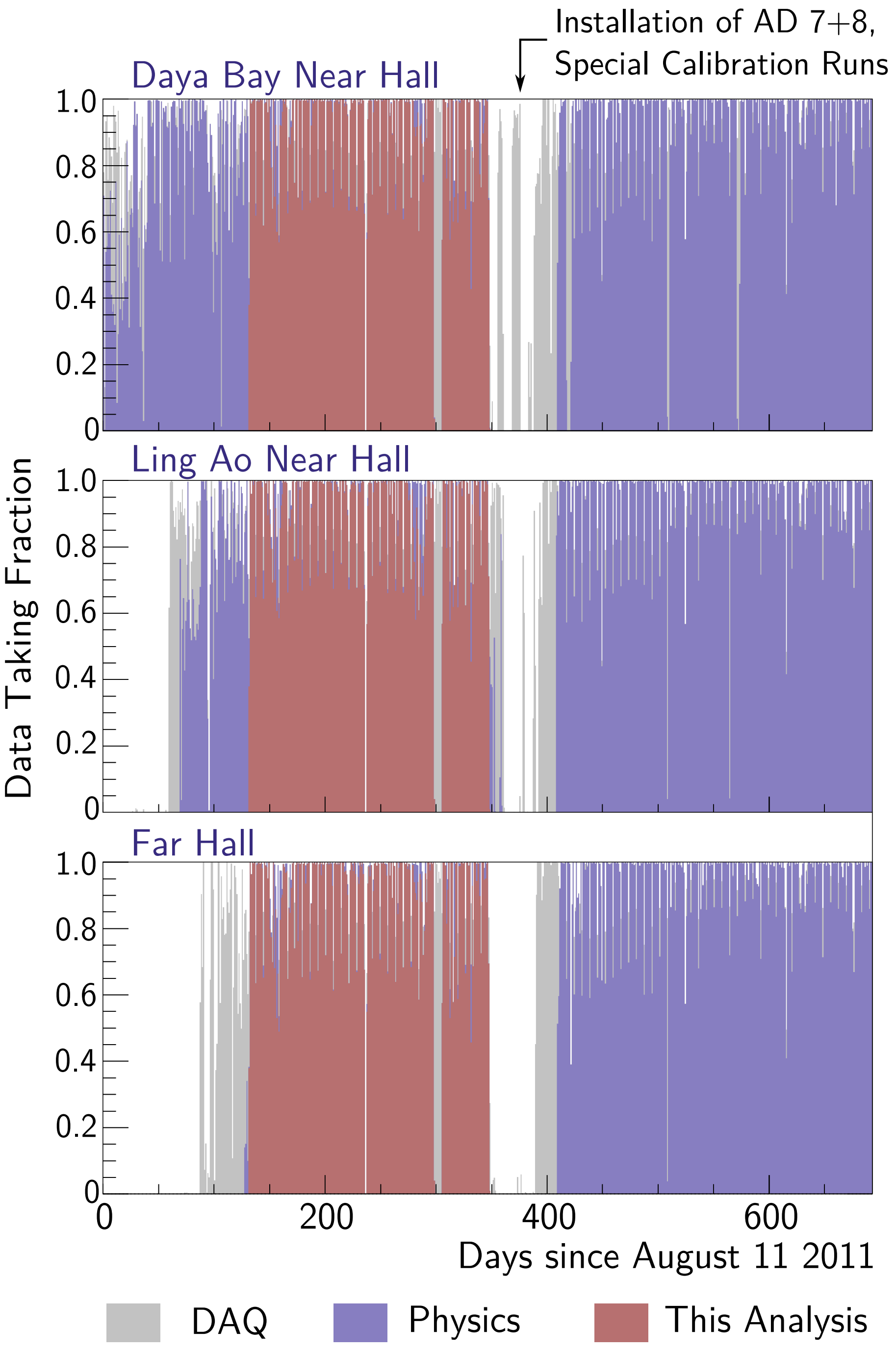
- 55 days of data, 6 ADs near+far
- PRL **108** (2012), 171803

Improved oscillation analysis [1210.6327]

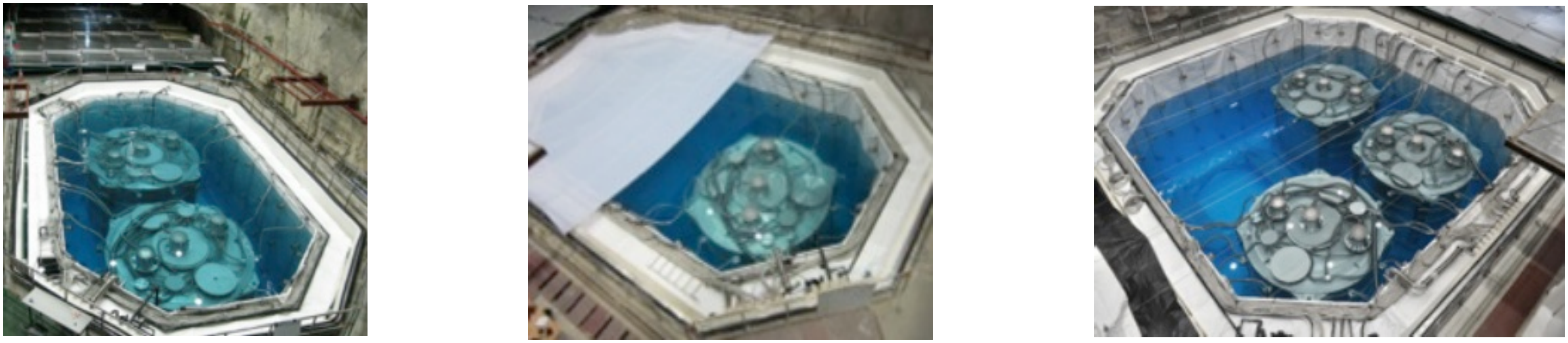
- 139 days of data, 6 ADs near+far
- CP C **37** (2013), 011001

Spectral Analysis

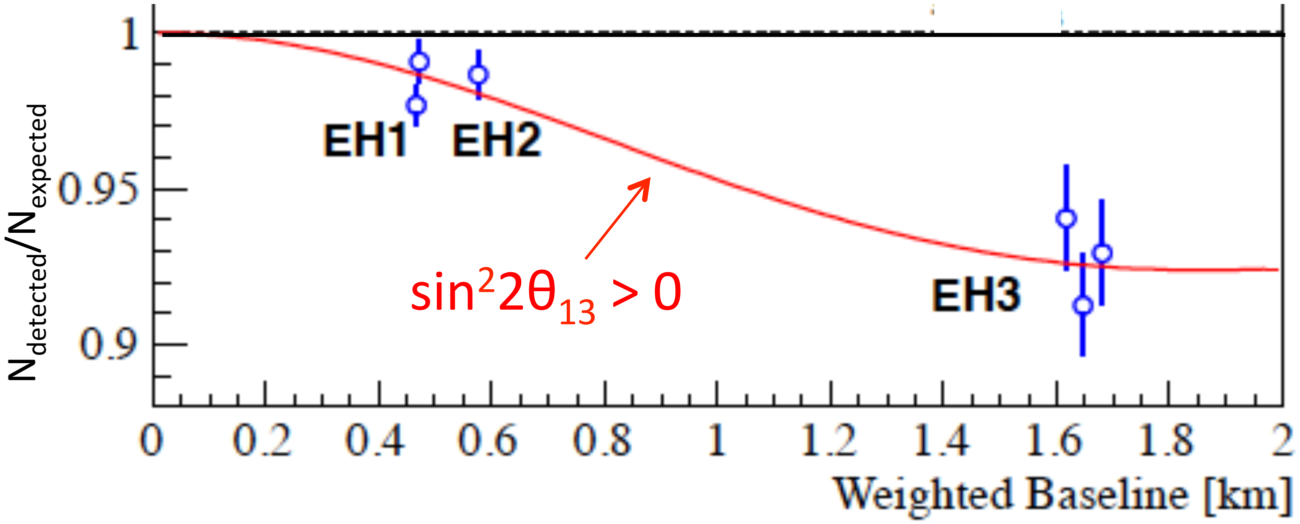
- 217 days, complete 6 AD period
- 55% more statistics than CPC result



Initial Results



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



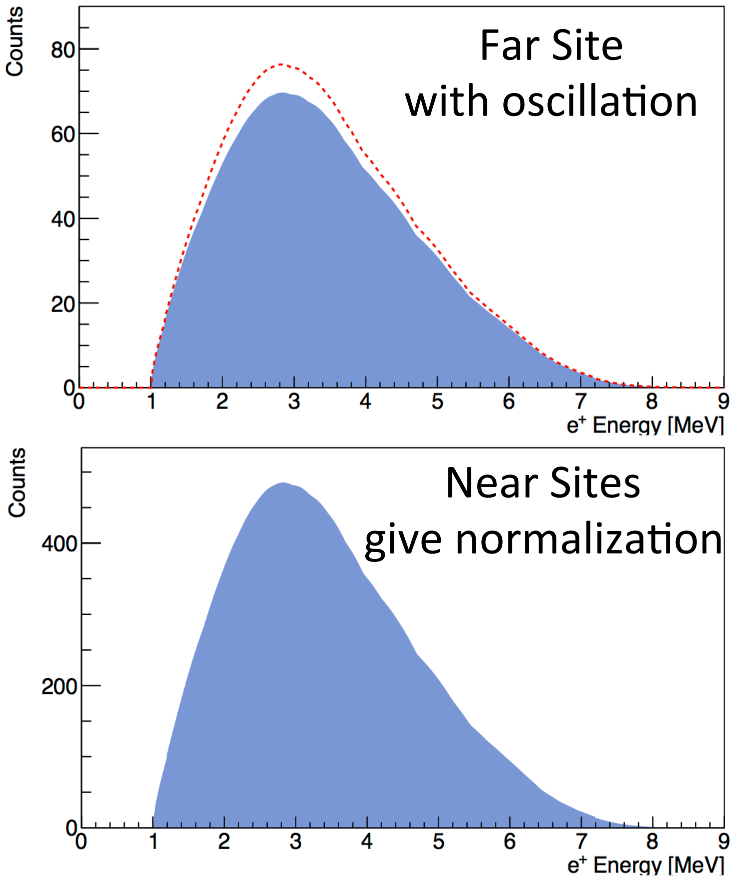
Obtained the most precise value of θ_{13} in Jun. 2012:

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

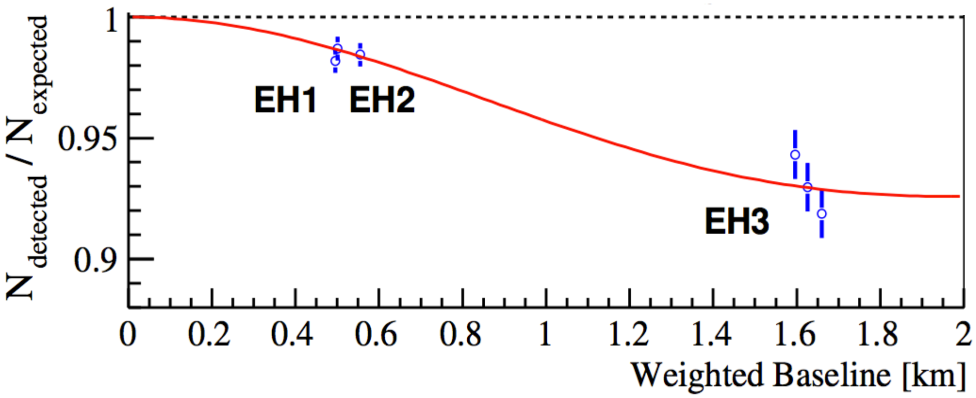
Rate vs. Spectral Information

Rate-only Analysis:

Previously reported



Integrate
all energies



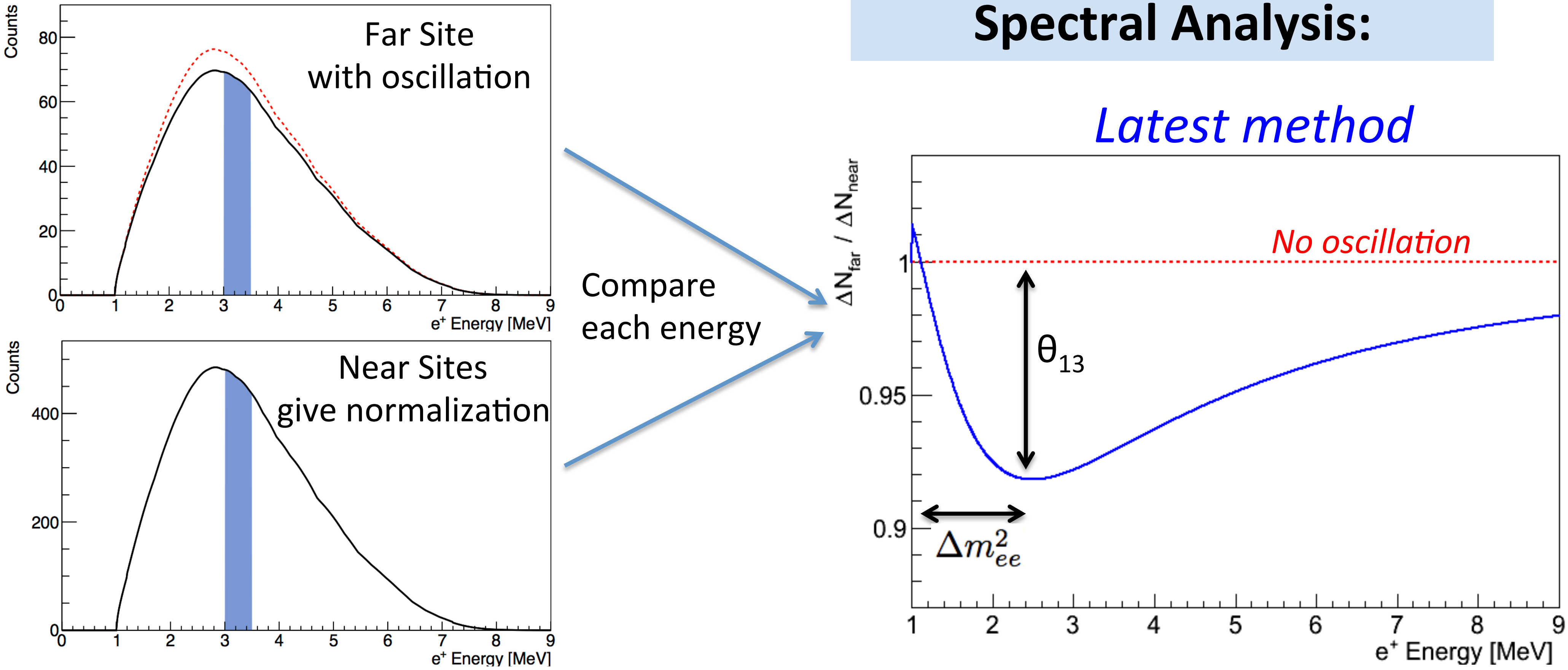
Advantages: Fewer systematic uncertainties

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

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

Rate vs. Spectral Information

Spectral Analysis:



Latest method

Compare each energy

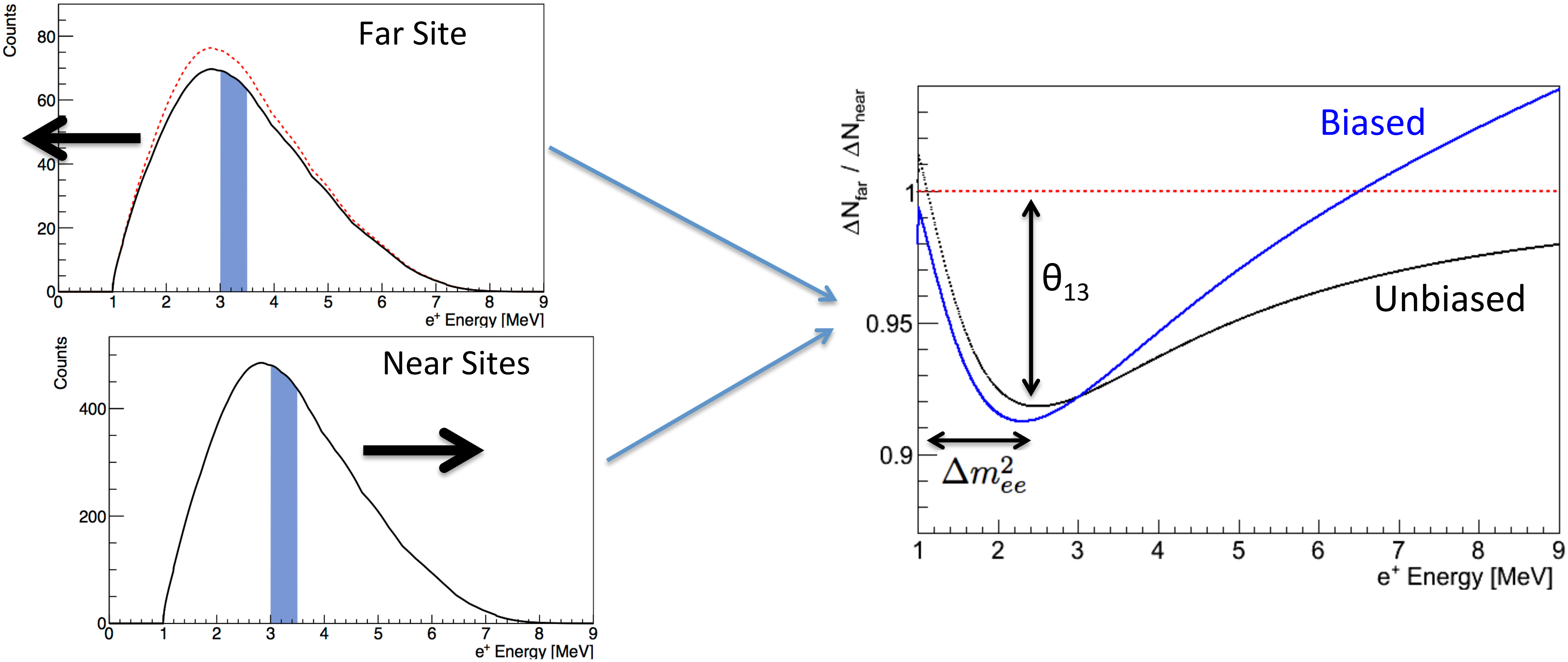
Advantages: Each energy bin is an independent oscillation measurement, Δm^2_{ee}
Disadvantages: Requires detailed understanding of detector energy response.

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

Wading into the thick…

Energy Scale Systematics

Relative shift in energy between detectors can bias oscillation



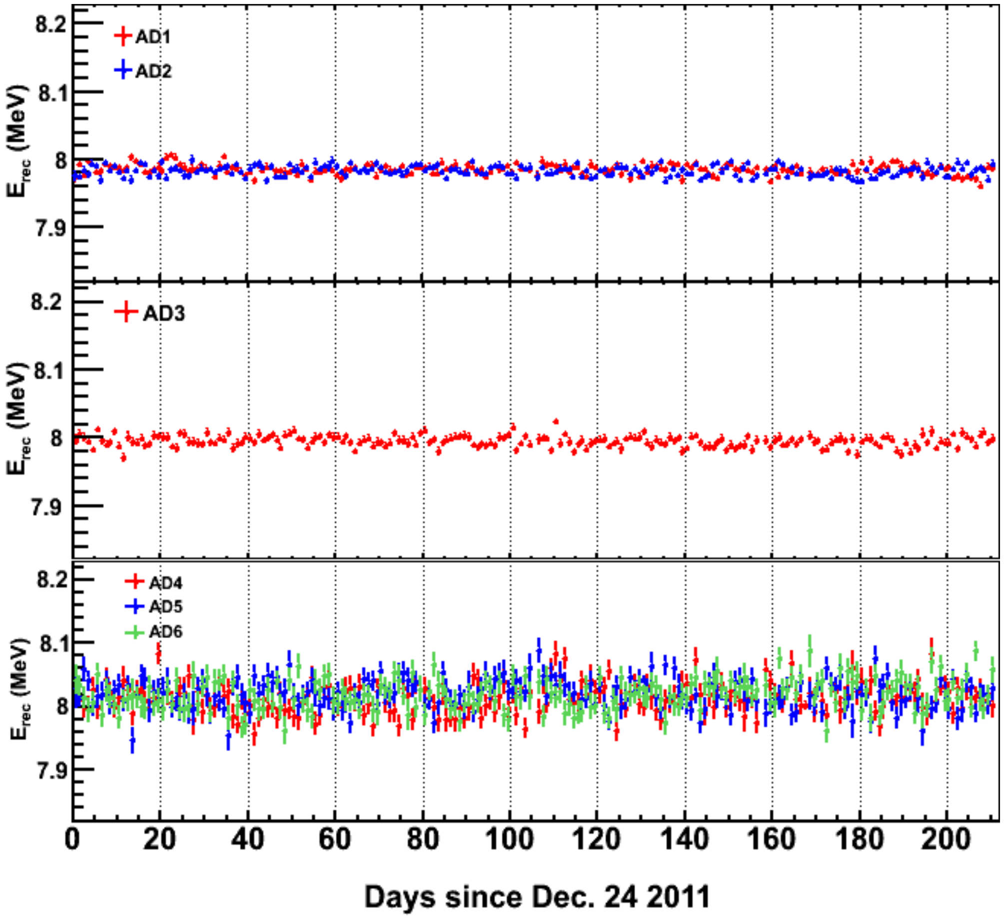
Requires careful detector calibration

Calibration: Performance

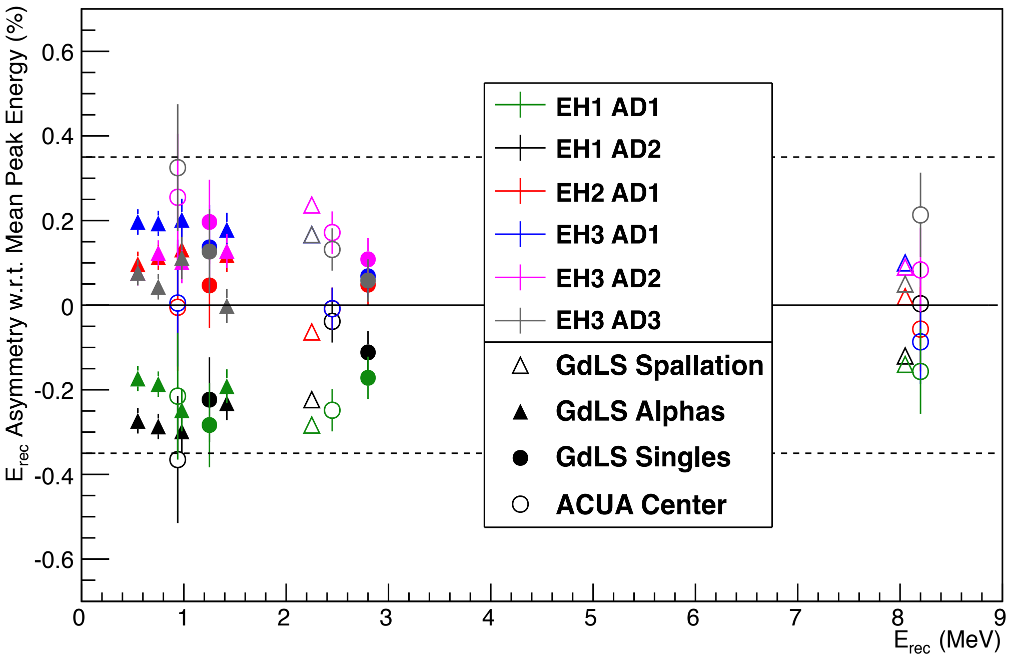
Obtain a stable and consistent Energy Response

After calibration, Daya Bay detectors are **stable to ~0.1%**, with **relative uncertainty of 0.35%**.

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

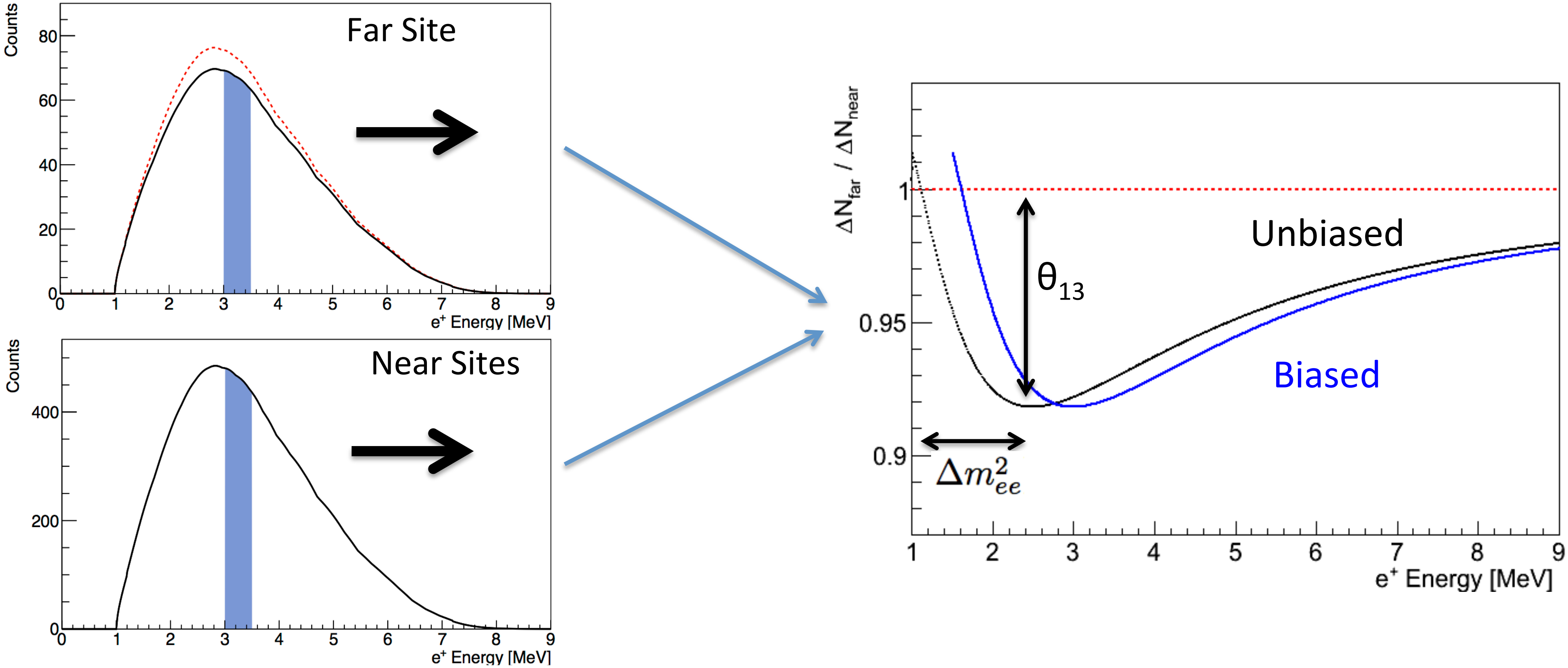


Relative energy peaks in all detectors (after calibration)



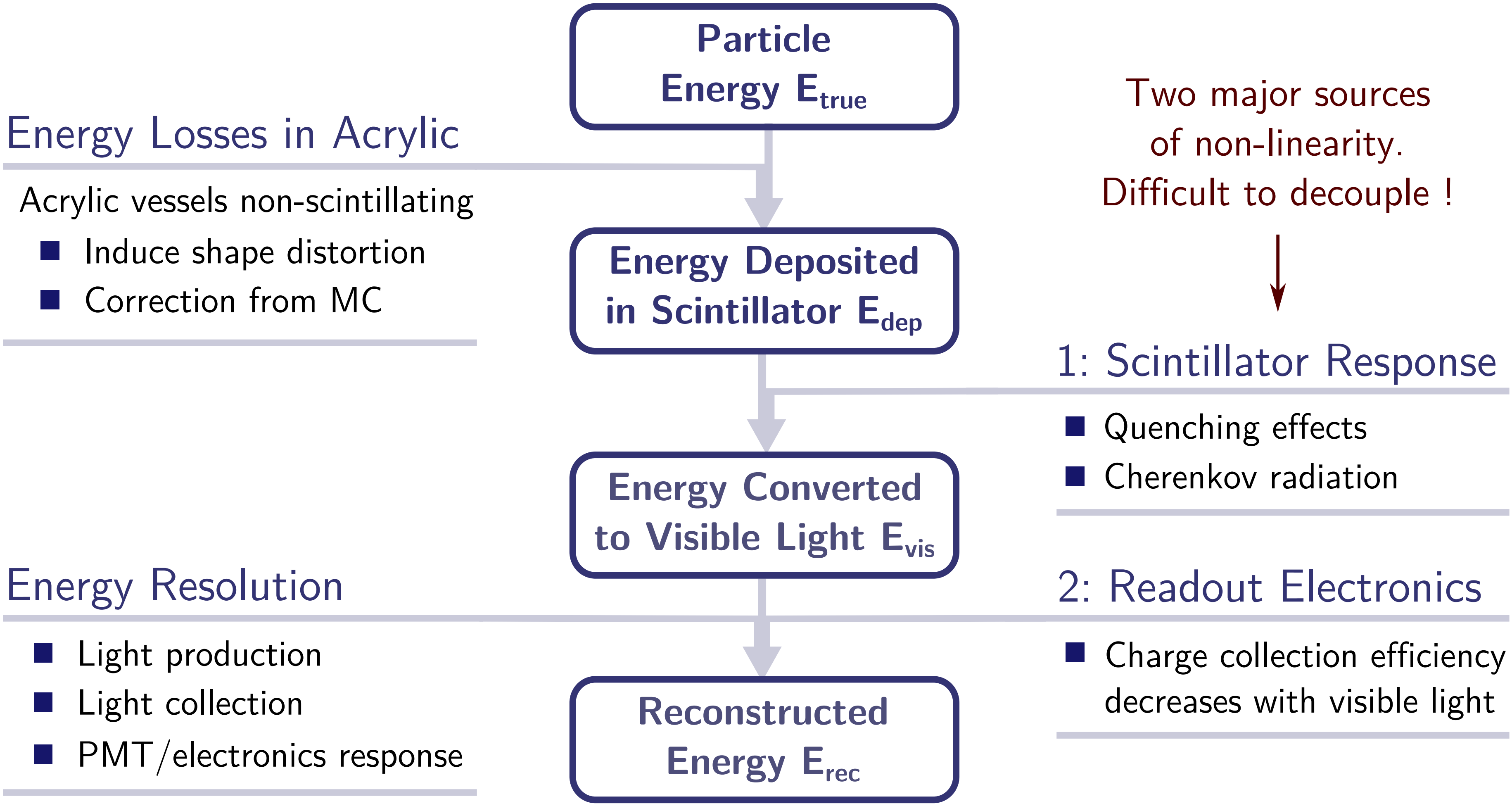
Energy Scale Systematics

Absolute shift in energy common to detectors can bias oscillation



Requires detailed translation between true and detected $\overline{\nu}_e$ energy

Modeling the Energy Response



Particle Energy E_{true}

Energy Losses in Acrylic

Acrylic vessels non-scintillating

- Induce shape distortion
- Correction from MC

Energy Deposited in Scintillator E_{dep}

Two major sources of non-linearity. Difficult to decouple !

1: Scintillator Response

- Quenching effects
- Cherenkov radiation

Energy Converted to Visible Light E_{vis}

Energy Resolution

- Light production
- Light collection
- PMT/electronics response

2: Readout Electronics

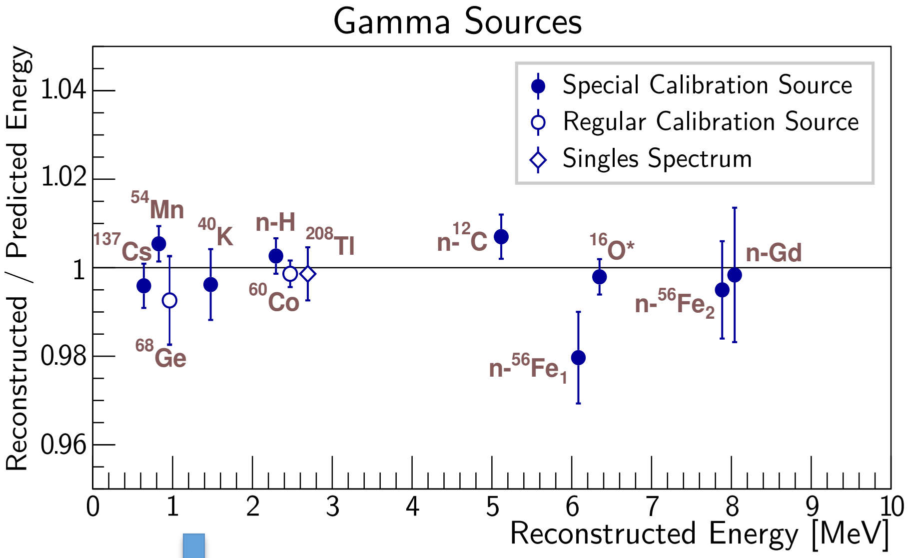
- Charge collection efficiency decreases with visible light

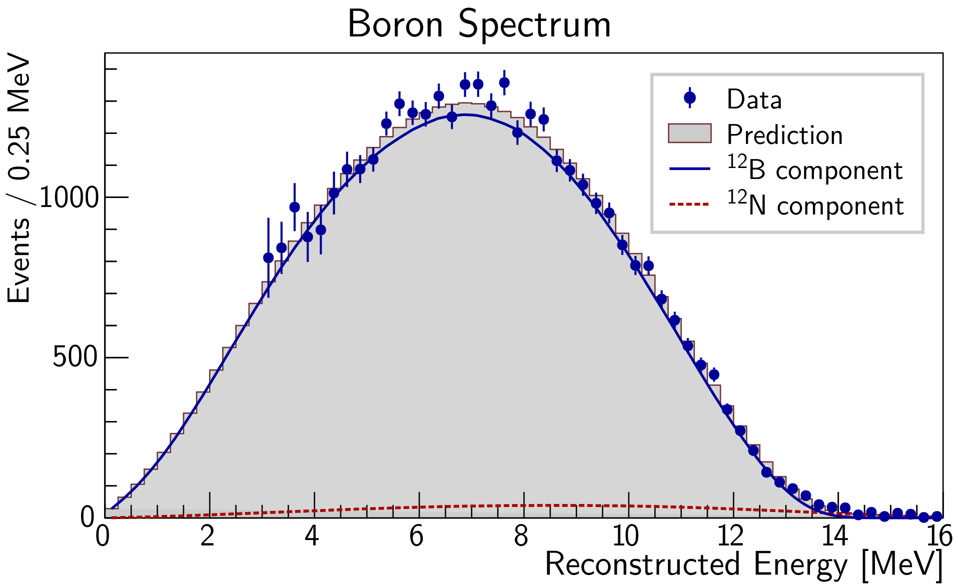
Reconstructed Energy E_{rec}

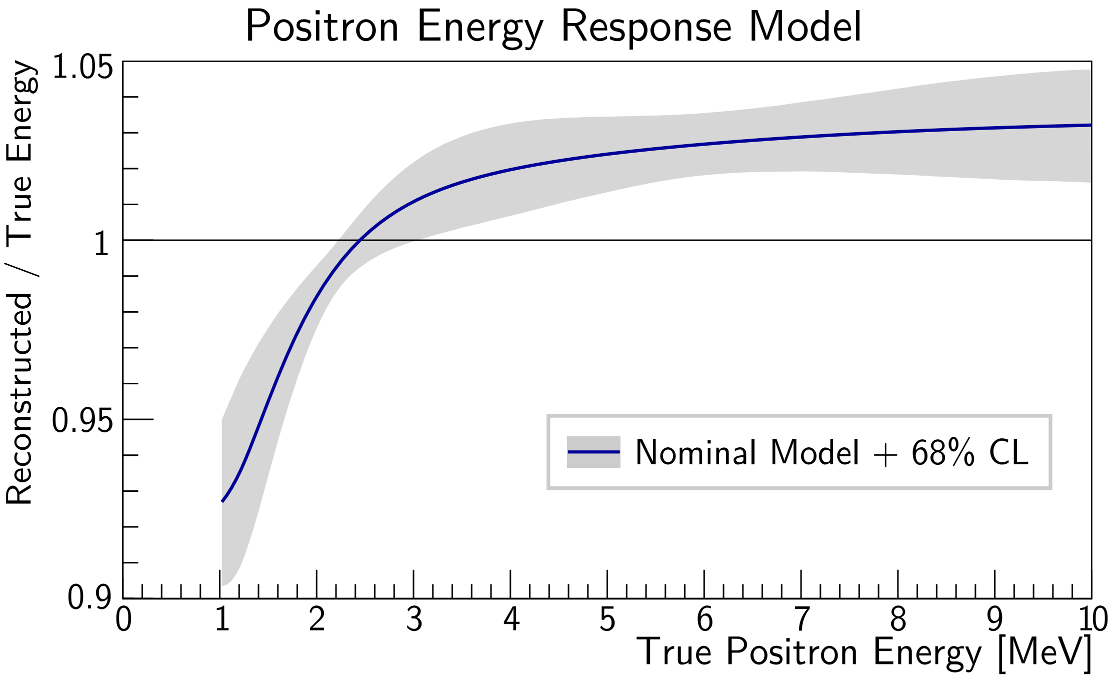
Model maps true energy E_{true} to reconstructed kinetic energy E_{rec}

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

Modeling the Energy Response

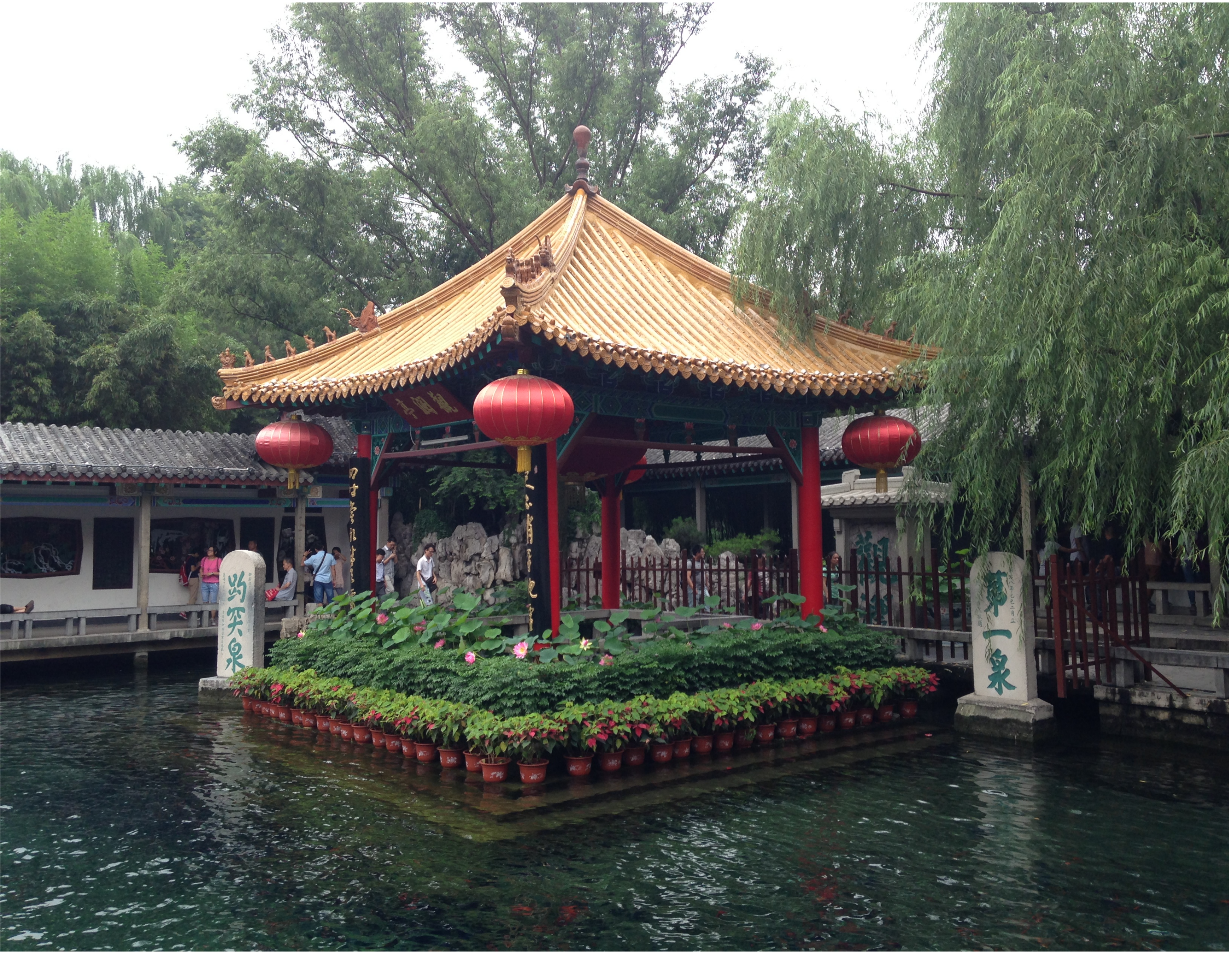

Gamma Sources


Boron Spectrum


Positron Energy Response Model

Detector response to γ and e$^-$ used to predict response to e$^+$

Out of the Swamp…



Antineutrino (IBD) Selection

Antineutrino interactions cleanly separated from backgrounds

① Reject spontaneous PMT light emission (“flashers")

② Prompt positron:
0.7 MeV < Ep < 12 MeV

③ Delayed neutron:
6.0 MeV < Ed < 12 MeV

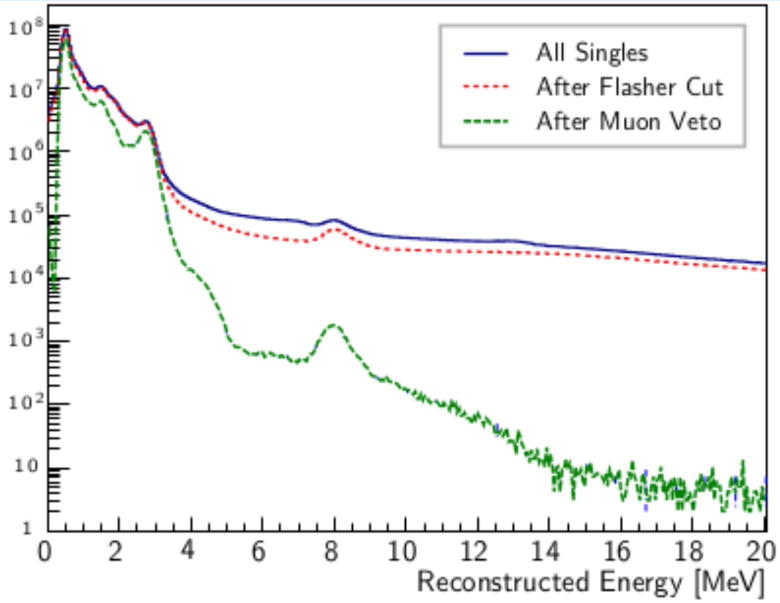
④ Neutron capture time:
1 μs < t < 200 μs

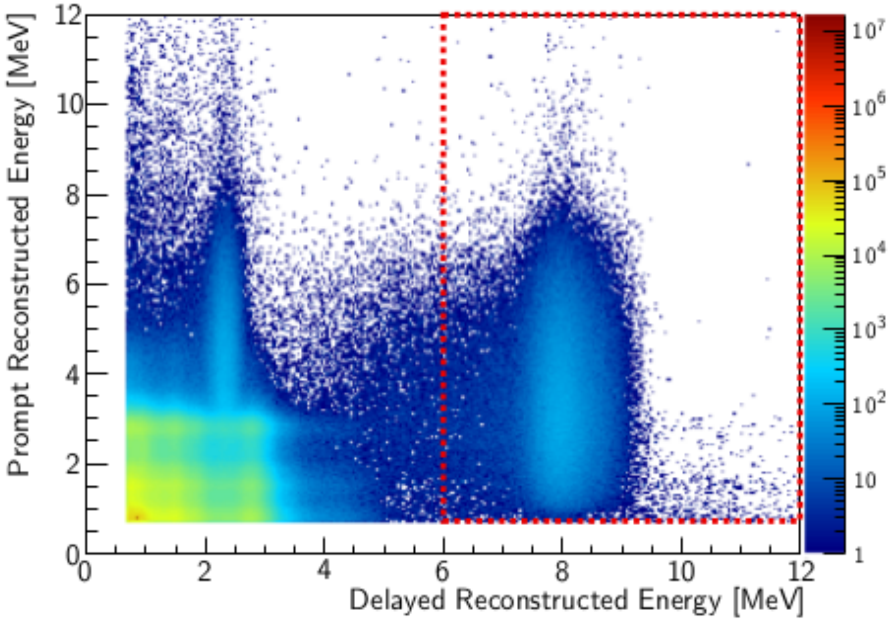
⑤ Muon veto:

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

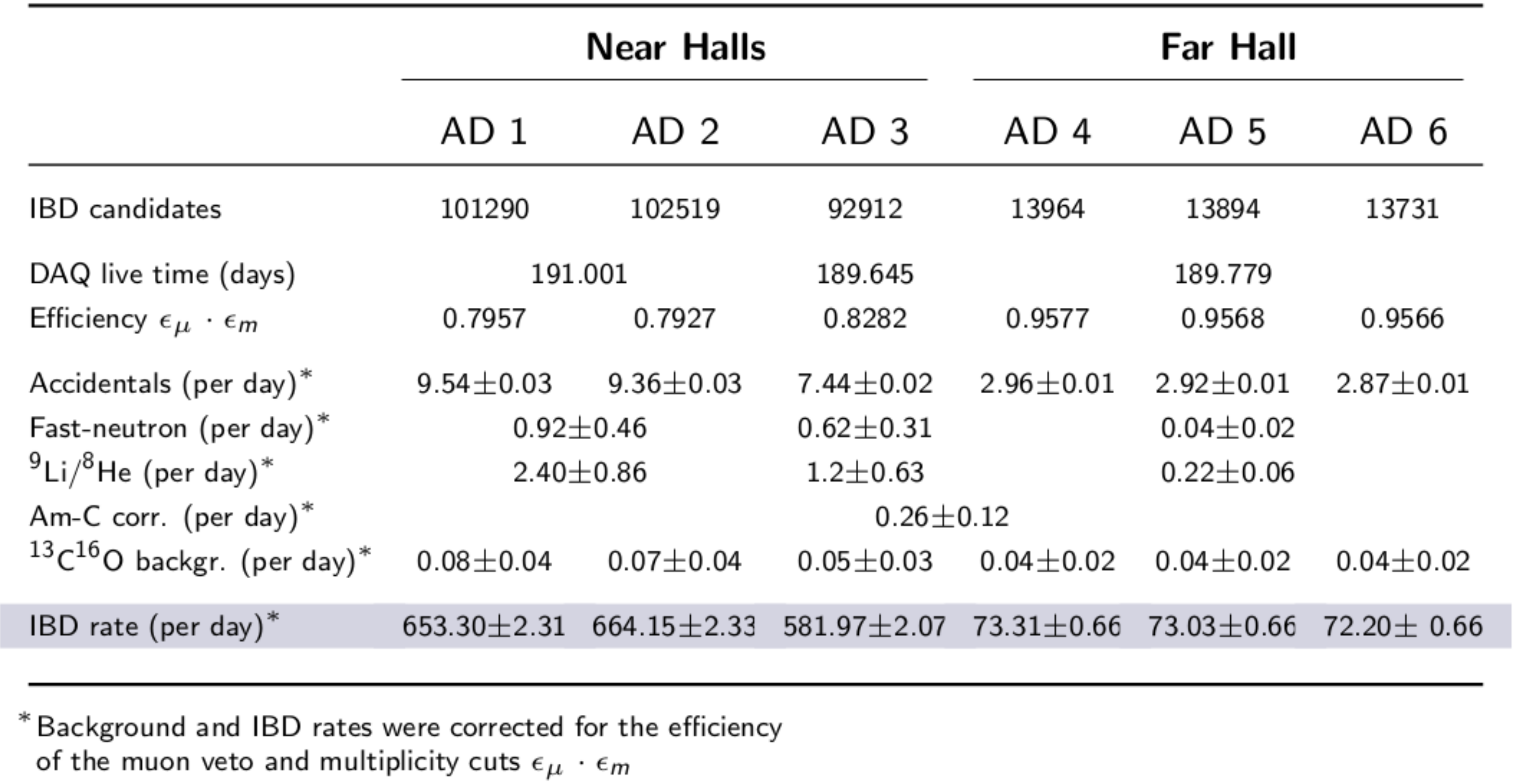
⑥ Multiplicity:

- No additional prompt-like signal
  400μs before delayed neutron
- No additional delayed-like signal
  200μs after delayed neutron





Signal and Background Summary



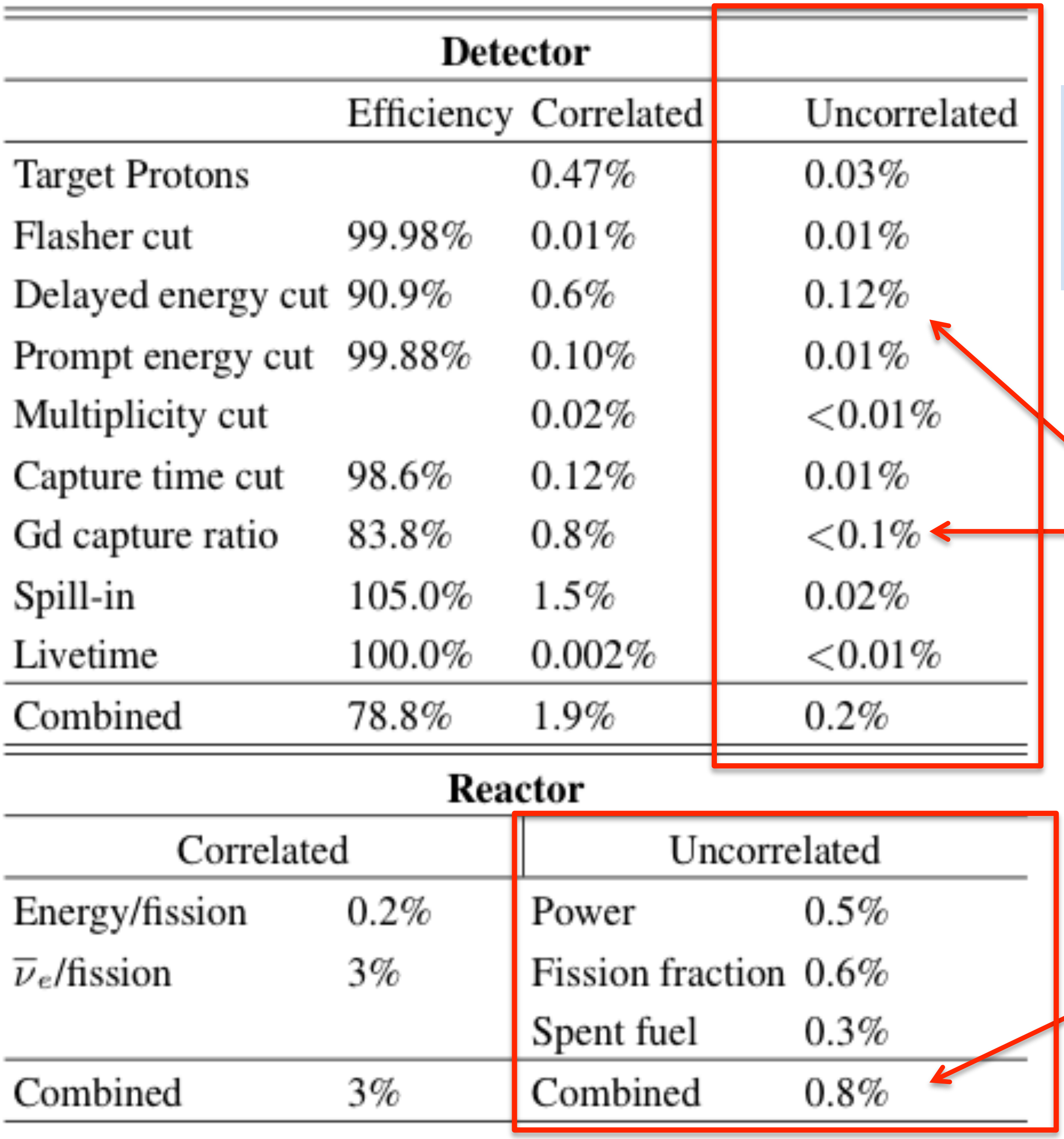
	Near Halls			Far Hall		
	AD 1	AD 2	AD 3	AD 4	AD 5	AD 6
IBD candidates	101290	102519	92912	13964	13894	13731
DAQ live time (days)	191.001		189.645	189.779		
Efficiency $\epsilon_\mu \cdot \epsilon_m$	0.7957	0.7927	0.8282	0.9577	0.9568	0.9566
Accidentals (per day)*	9.54±0.03	9.36±0.03	7.44±0.02	2.96±0.01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

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

Collected more than 300k antineutrino interactions

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

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

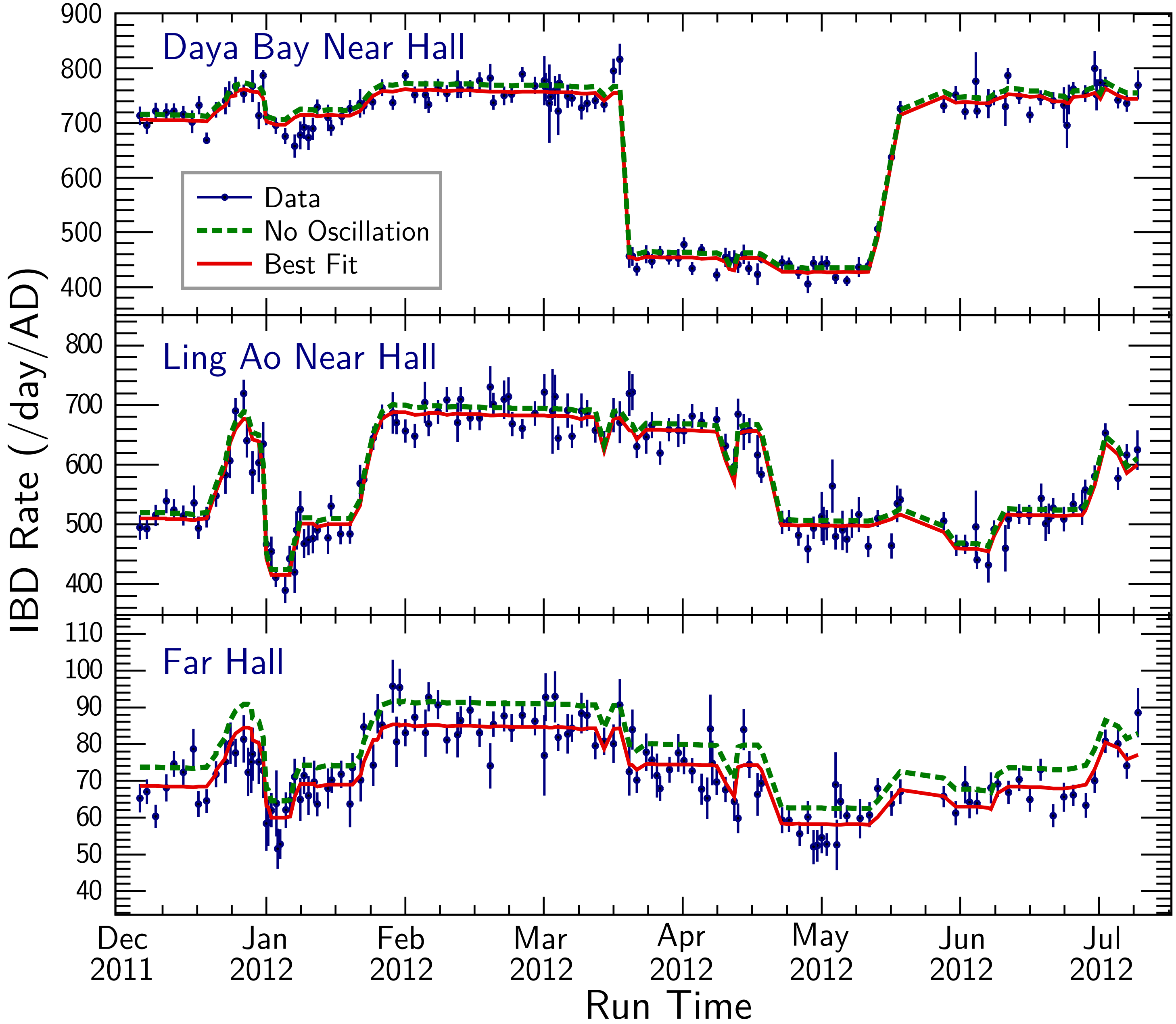
Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
$\overline{\nu}_e$/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%

For near/far rate analysis, only uncorrelated uncertainties impact measurement.

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

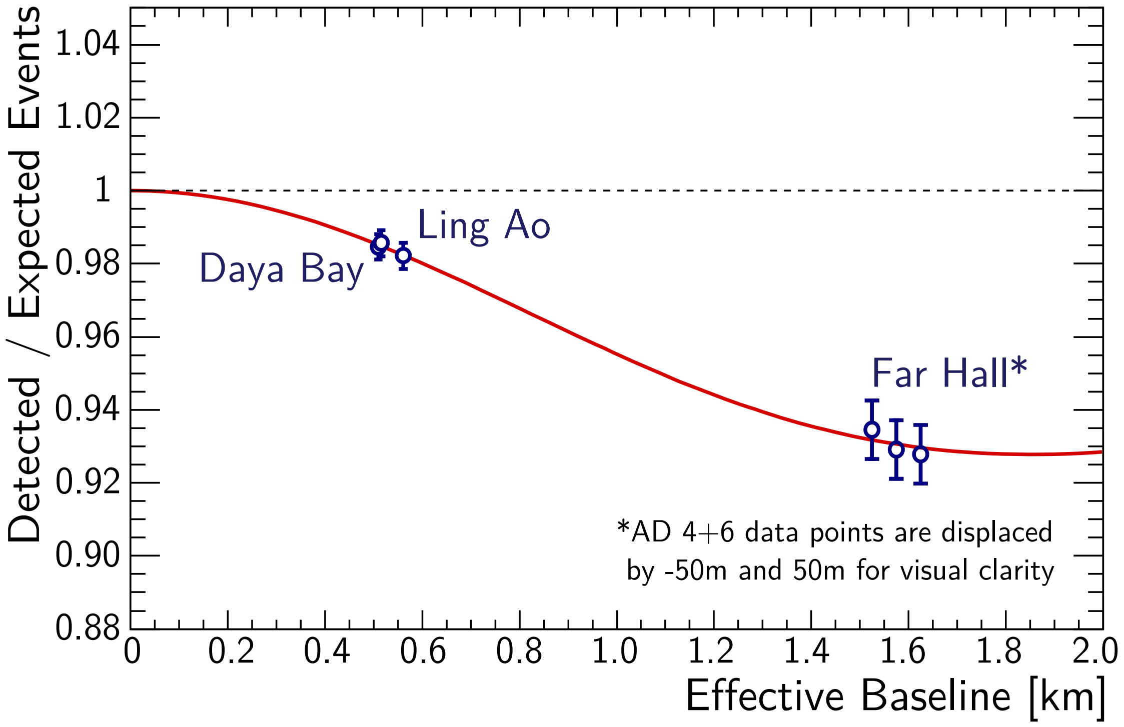
Influence of uncorrelated reactor systematics reduced by far vs. near measurement.

Antineutrino Rate vs. Time

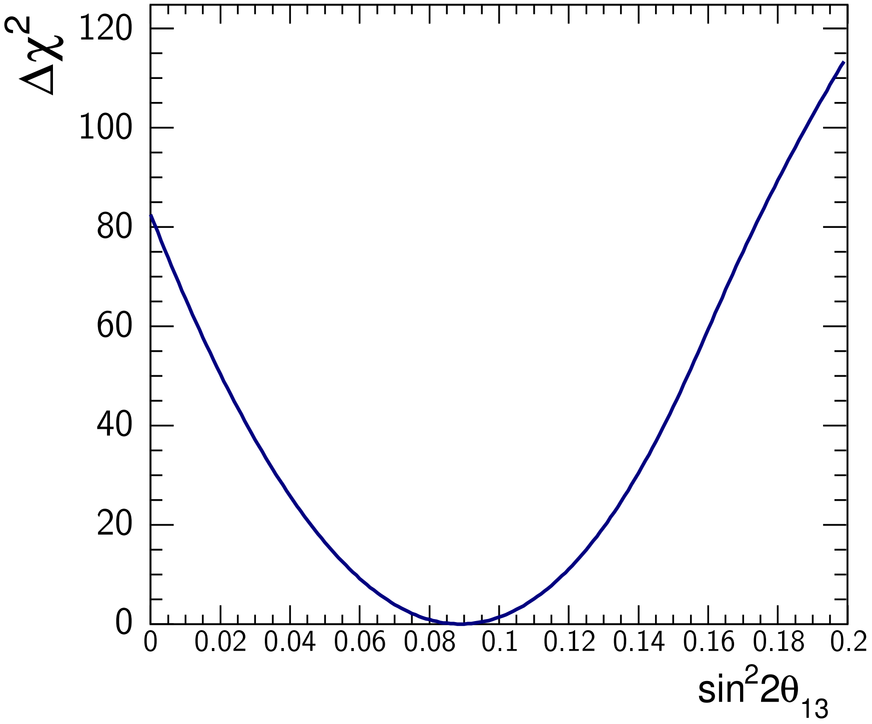


Detected rate strongly correlated with reactor flux expectations

Rate-Only Oscillation Results



*AD 4+6 data points are displaced by -50m and 50m for visual clarity

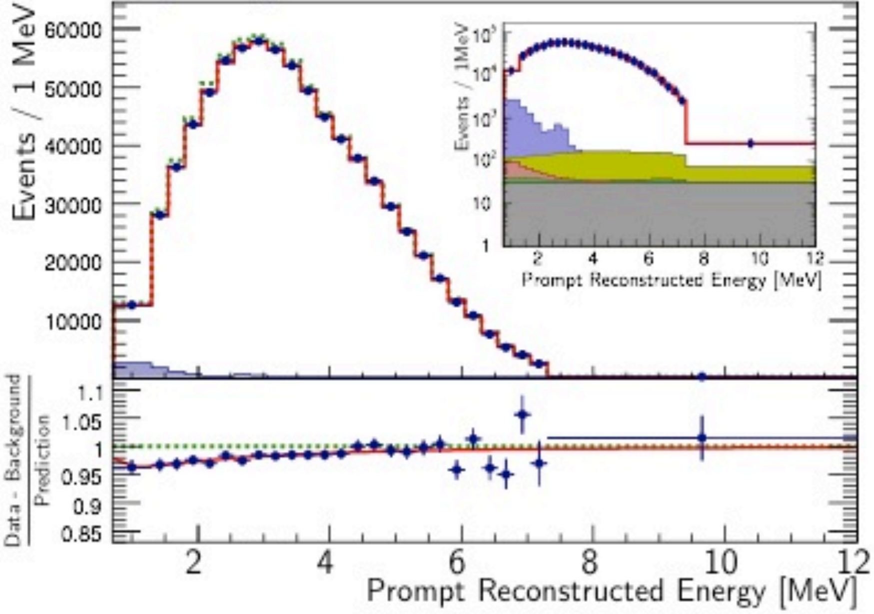


$\sin^2 2\theta_{13} = 0.089 \pm 0.009$

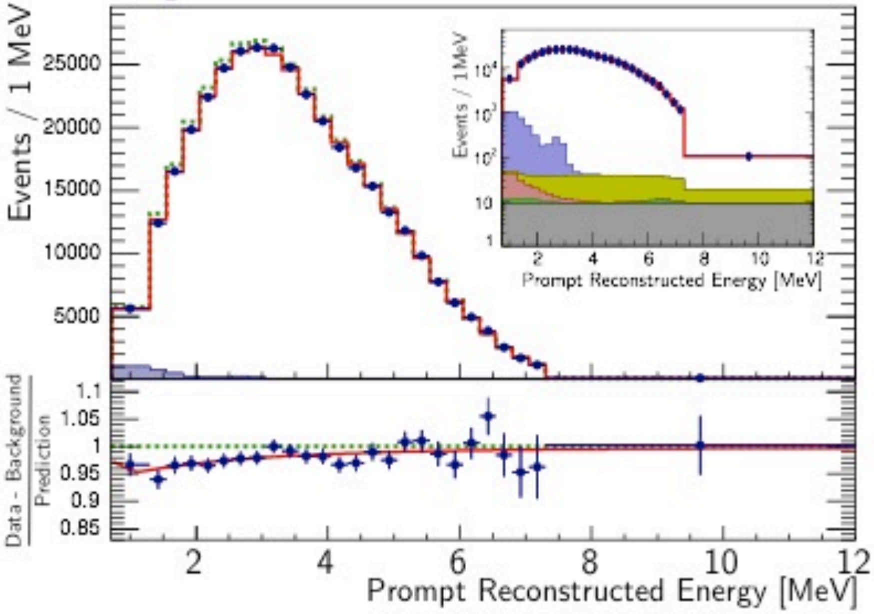
- Uncertainty reduced by statistics of complete 6 AD data period
- Standard approach: $\chi^2/N_{DoF} = 0.48/4$
- $|\Delta m^2_{ee}|$ constrained by MINOS result for $|\Delta m^2_{\mu\mu}|$
- Far vs. near relative measurement: absolute rate not constrained
- Consistent results from independent analyses, different reactor flux models

Prompt IBD Spectra

Daya Bay Near Hall

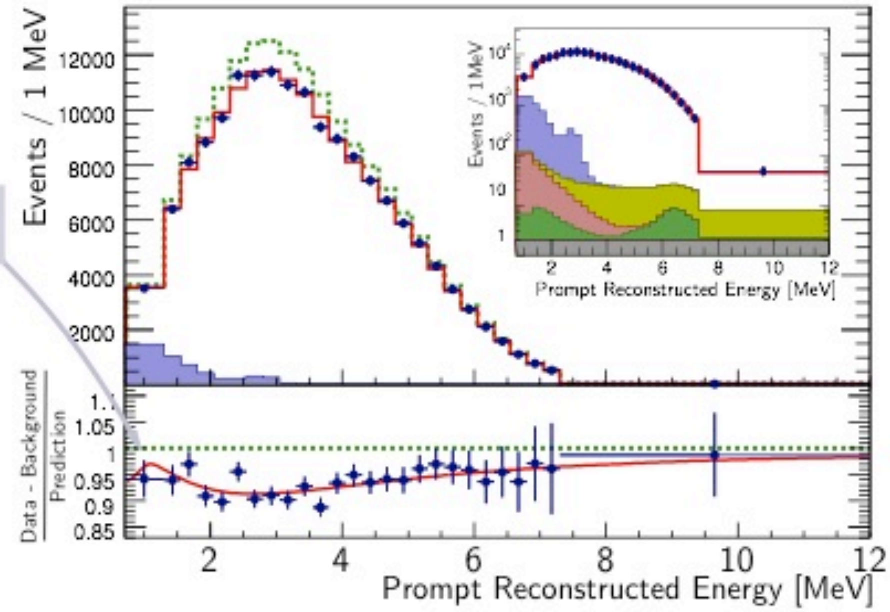


Ling Ao Near Hall



- ● Data
- ⋯ No Oscillation
- — Best Fit
- ▨ Accidentals
- ▨ ^{9}Li/^{8}He
- ▨ ^{241}Am-^{13}C
- ▨ ^{12}C(α,n)^{16}O
- ▨ Fast neutrons

Far Hall



Shape distortion from energy losses in acrylic

Spectral distortion consistent with oscillation

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

A Comment on Δm^2

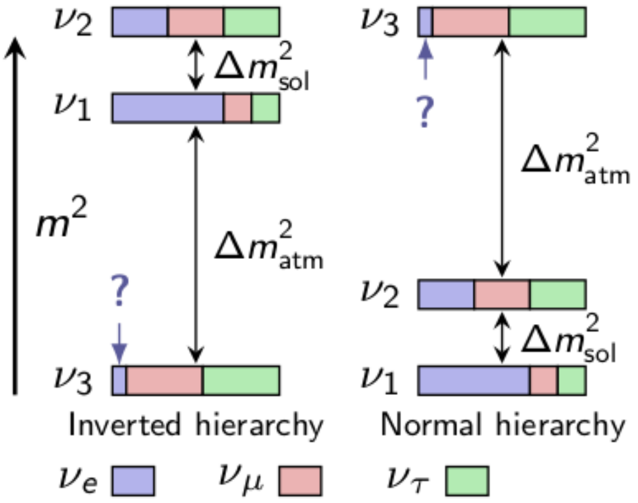
Short-baseline reactor experiments insensitive to neutrino mass hierarchy.

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

One effective oscillation frequency is measured:

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

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



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

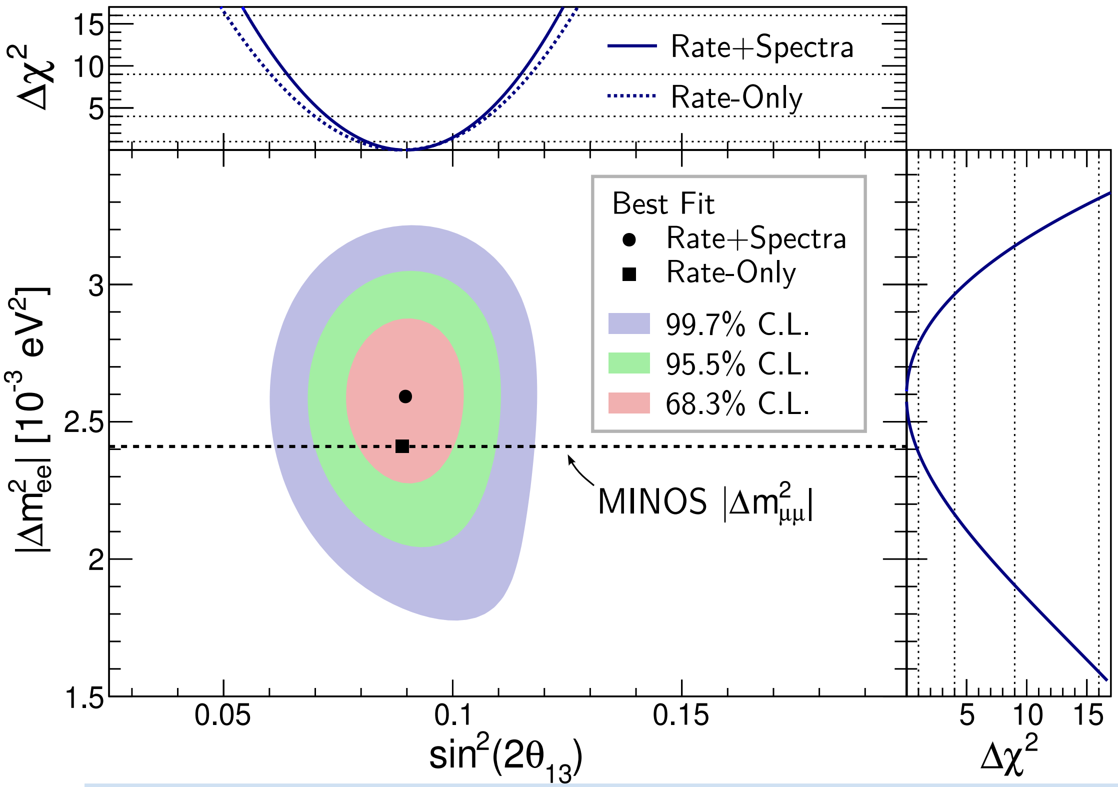
$$\left|\Delta m^2_{ee}\right| \simeq \left|\Delta m^2_{32}\right| \pm 5 \times 10^{-5} \mathrm{eV}^2$$

+: Normal Hierarchy

–: Inverted Hierarchy

Hierarchy discrimination requires ~1% precision on both Δm^2_{ee} and $\Delta m^2_{\mu\mu}$

Rate+Spectra Oscillation Results



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

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

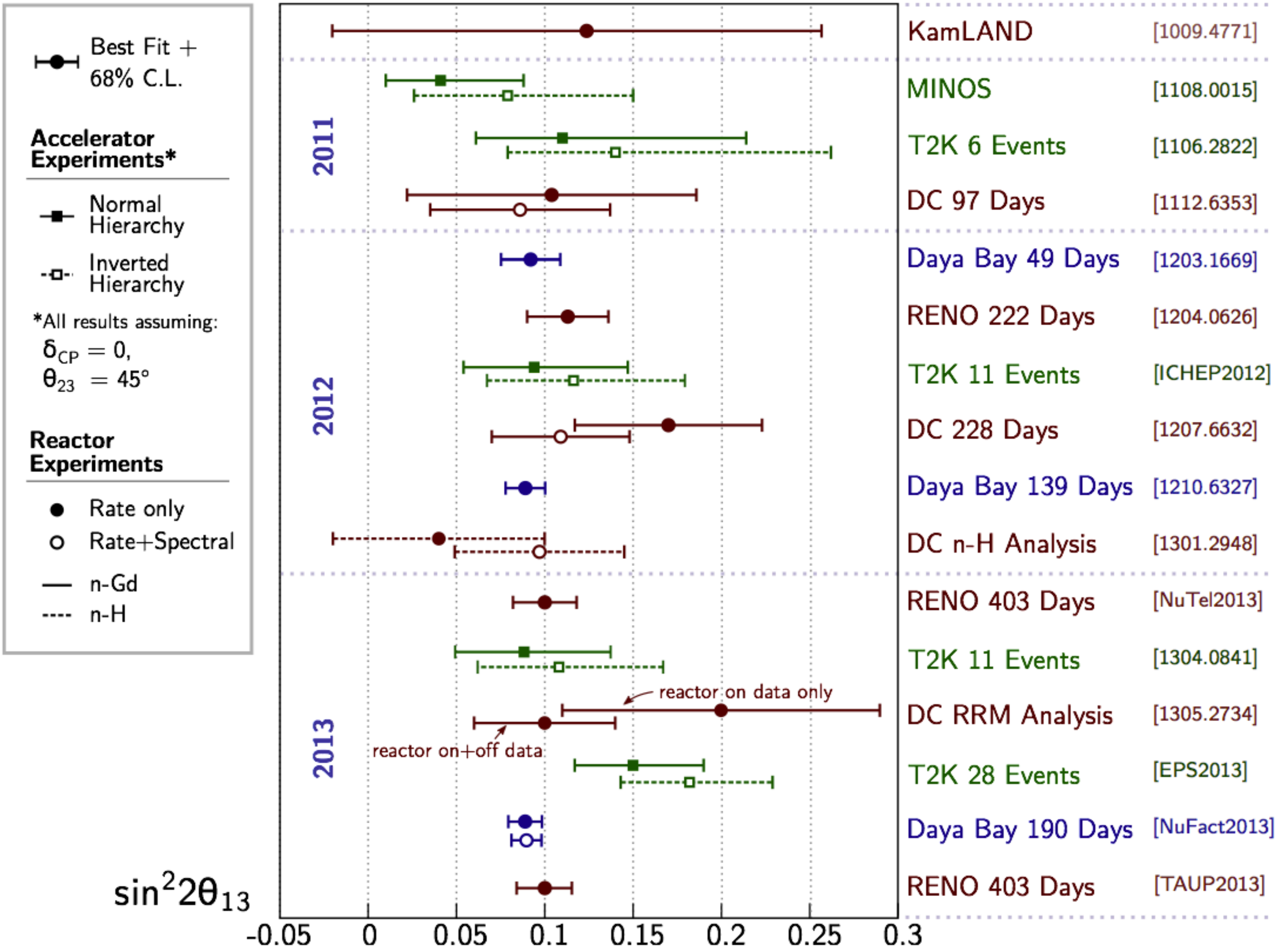
$$\chi^2/N_{\text{DoF}} = 162.7/153$$

Strong confirmation of three-flavor oscillation model

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

A. Radovic, DPF2013

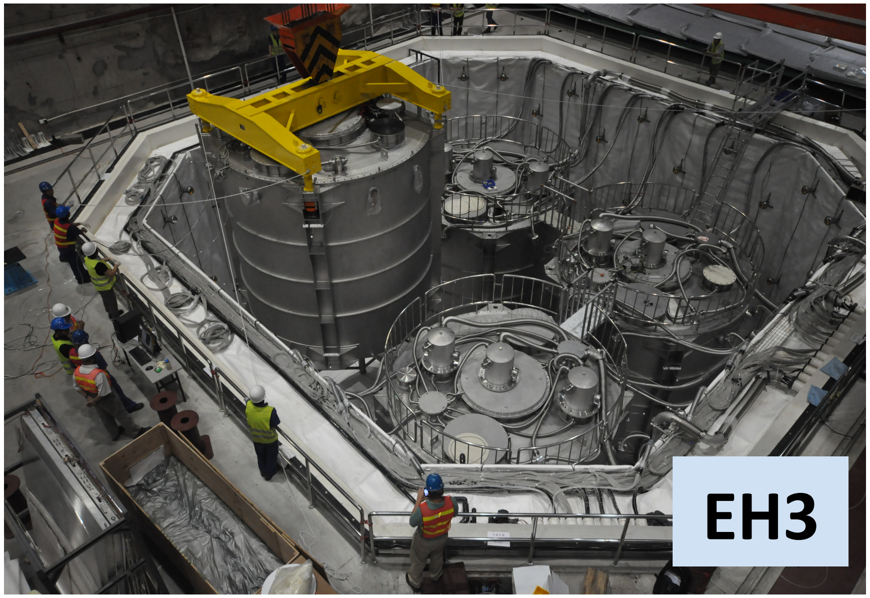
Global Comparison of θ_{13} Measurements



Daya Bay Onsite Progress

Final two detectors installed, operating since Oct. 2012.

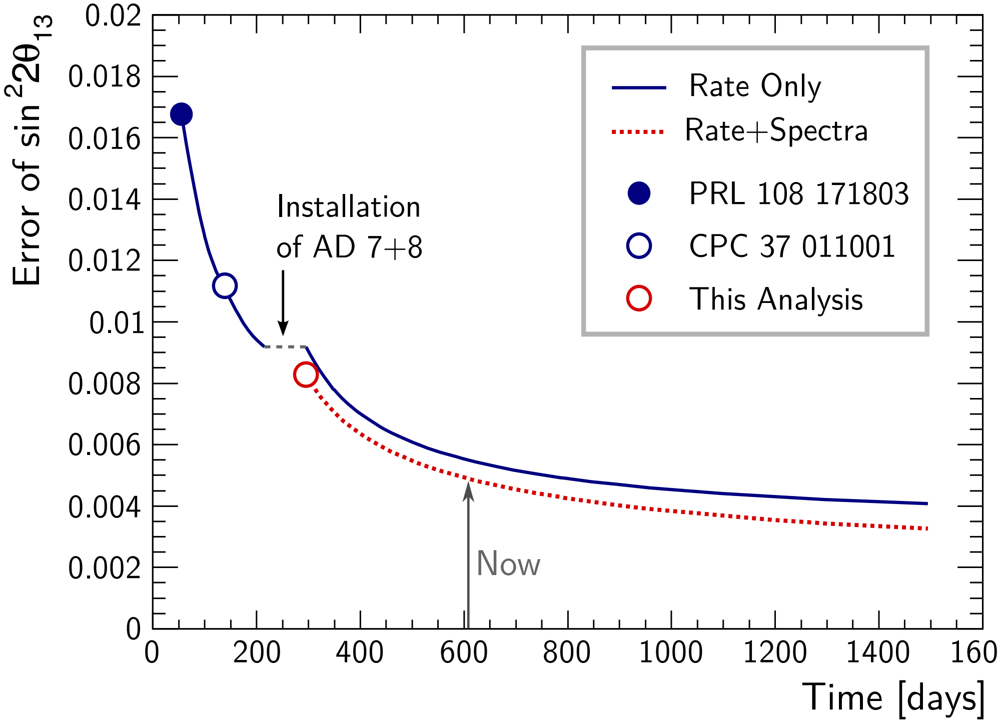
EH2

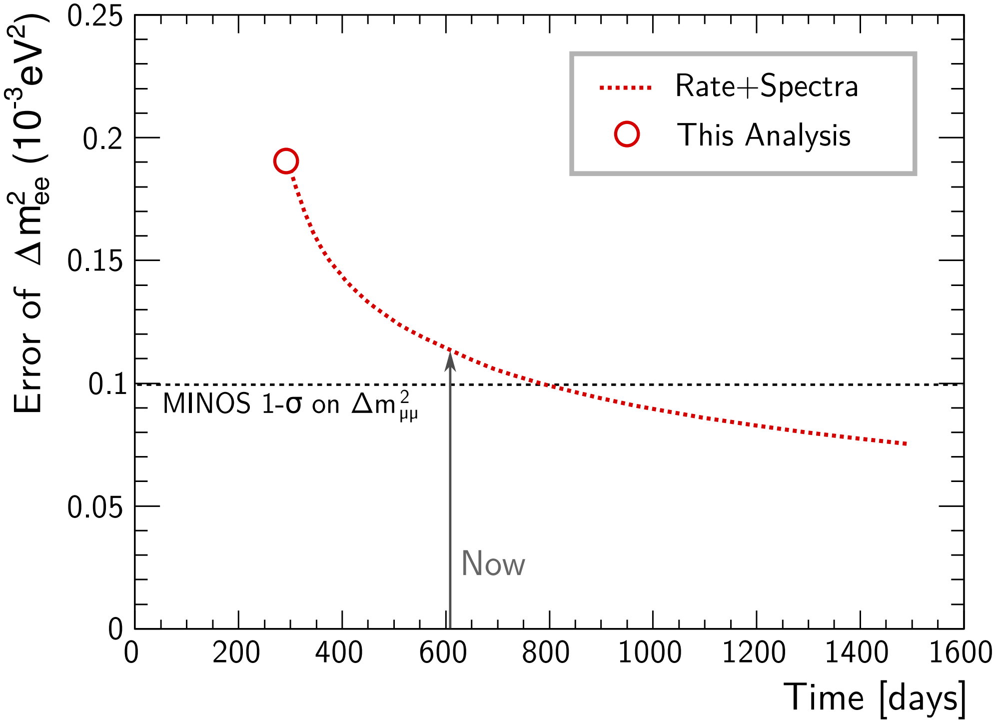


EH3

Full 4π detector calibration in Sep. 2012.

Sensitivity Projection





Over 1 million antineutrinos detected as of now!

Precision will soon be dominated by systematic uncertainties

Daya Bay Future

Improved precision on oscillation parameters

- Constrains non-standard oscillation models
- Improves reach of future neutrino experiments

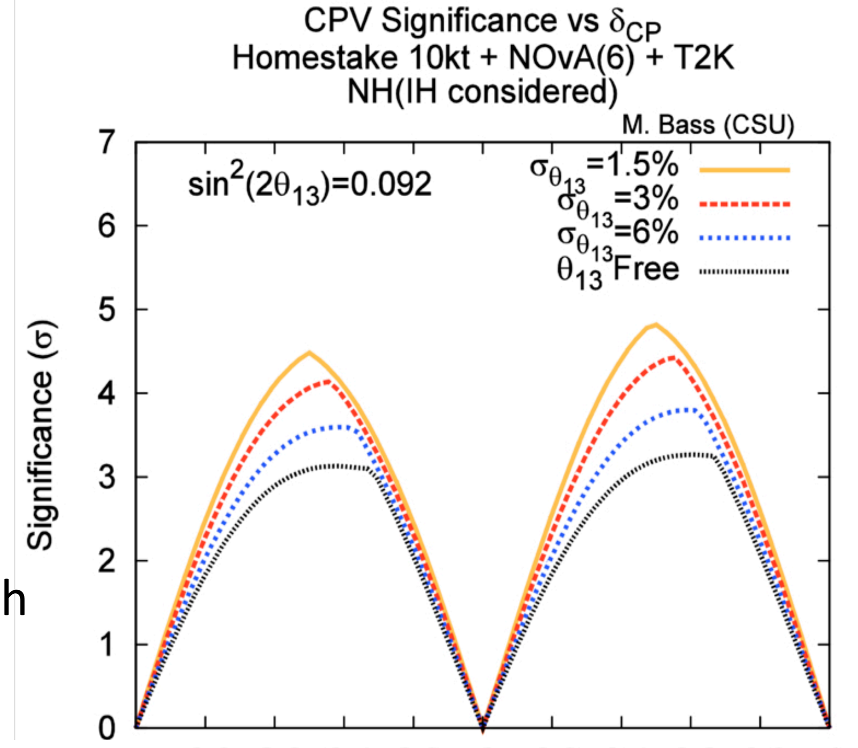
Measure absolute reactor neutrino flux

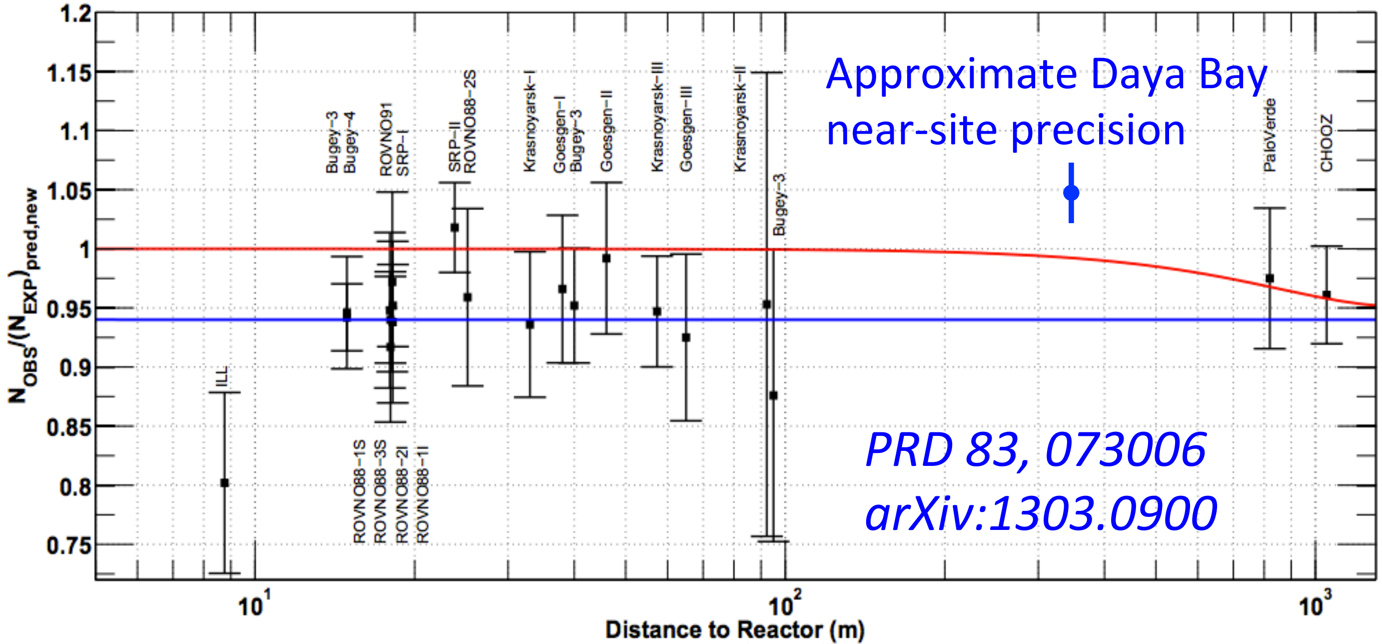
- Explore the ‘reactor antineutrino anomaly’
- Precise spectrum probes reactor models

Cosmogenic Backgrounds

- Measurement of cosmogenic production vs. depth

Supernova Neutrinos





Approximate Daya Bay near-site precision

PRD 83, 073006
arXiv:1303.0900

Summary

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

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

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

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

Expect more from Daya Bay:

- Measurement of the absolute reactor flux, addressing the reactor anomaly
- Constraints on non-standard neutrino models
- Significantly increased precision (all 8 detectors, >2 years of operation)