DAYA BAY

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On behalf of the Daya Bay Collaboration

NNN08, International Workshop on Next Nucleon Decay and Neutrino Detectors, Paris, France, 11-13 September 2008

Measuring $\sin^2 2\theta_{13}$ with reactors

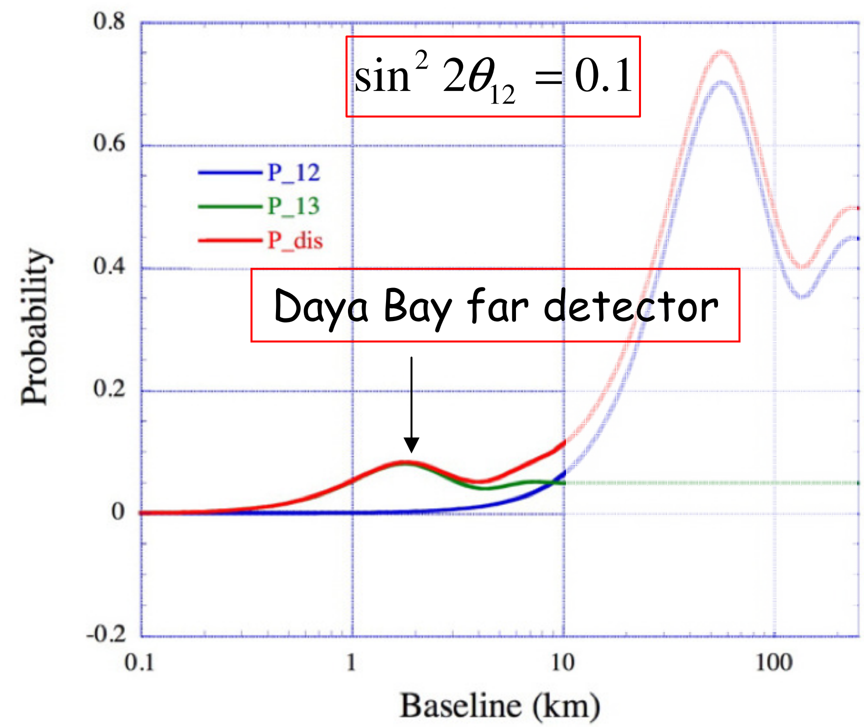
Reactor experiment

$$P_{dis} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(1.27\frac{\Delta m_{12}^2 L}{E_\nu}\right) - \sin^2 2\theta_{13}\sin^2\left(1.27\frac{\Delta m_{31}^2 L}{E_\nu}\right)$$

$$\sin^2 2\theta_{12} \approx 0.86$$

$$\Delta m_{12}^2 \approx 7.6\times10^{-5}\ \text{eV}^2$$

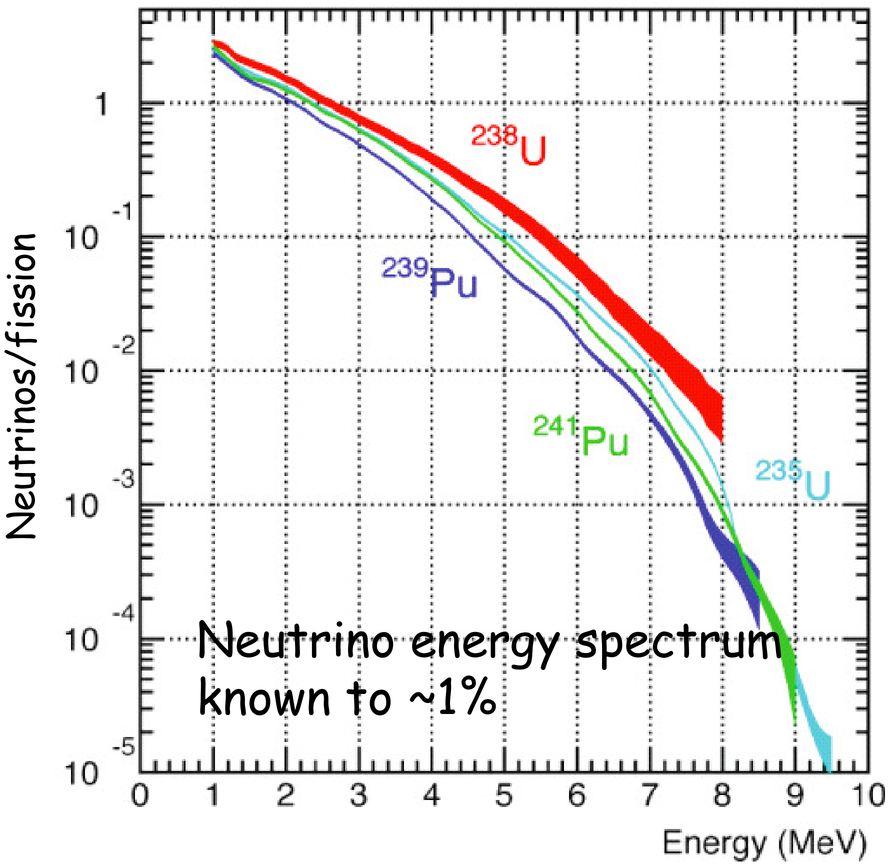
$$\left|\Delta m_{32}^2\right| \approx 2.4\times10^{-3}\ \text{eV}^2$$



- Relatively short baseline (L ~ 2 km)
- Cheap compared to accelerator-based experiments, allowing rapid deployment
- No ambiguity, independent of δ and matter effect

Reactor neutrinos

- Fission processes in nuclear reactors produce ~ 6 neutrinos (anti-electron-neutrinos) per fission
- The Daya Bay Power Plant (17.4 GW_{th}) generates ~3 x 10^{21} neutrinos per sec
- The neutrino energy spectrum is known to ~1% at detector sites
- *A ratio measurement of rates at far to (two) near detectors reduces error due to uncorrelated power fluctuations to ~ 0.1%, comparable to detector site location error.*



$$\Phi_i(E_\nu) \approx e^{a_i - b_i E_\nu - c_i E_\nu^2}$$

Detecting neutrinos in liquid scintillator: Inverse β-decay Reaction

- Detect inverse β-decay reaction in 0.1% Gd-doped liquid scintillator:

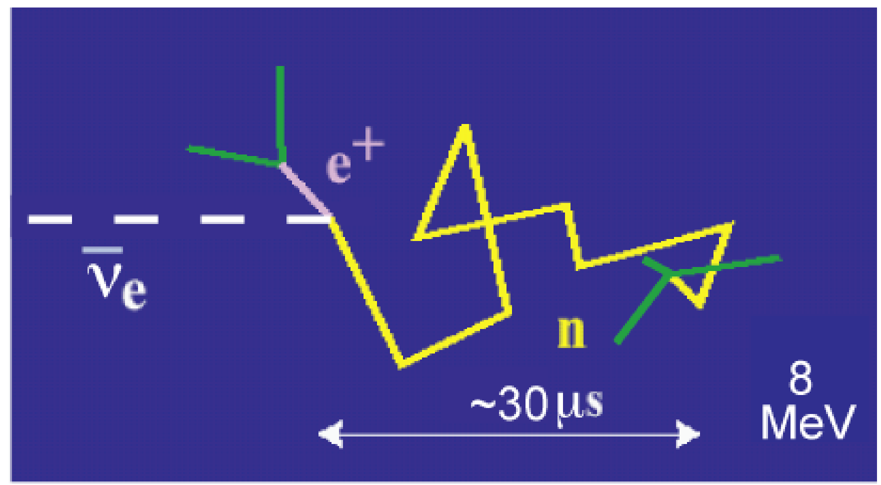
$$\bar{\nu}_e + p \rightarrow e^+ + n \quad \text{(prompt)}$$

0.3b: $\hookrightarrow + p \rightarrow D + \gamma(2.2\ \text{MeV})$ (delayed)

50,000b: $\hookrightarrow + Gd \rightarrow Gd^*$

$\hookrightarrow Gd + \gamma\text{'s}(8\ \text{MeV})$ (delayed)

- Coincidence of prompt positron and delayed neutron signals helps suppress background events
- The energy of the neutrino can be measured by the energy of the positron to the energy resolution of the liquid scintillator



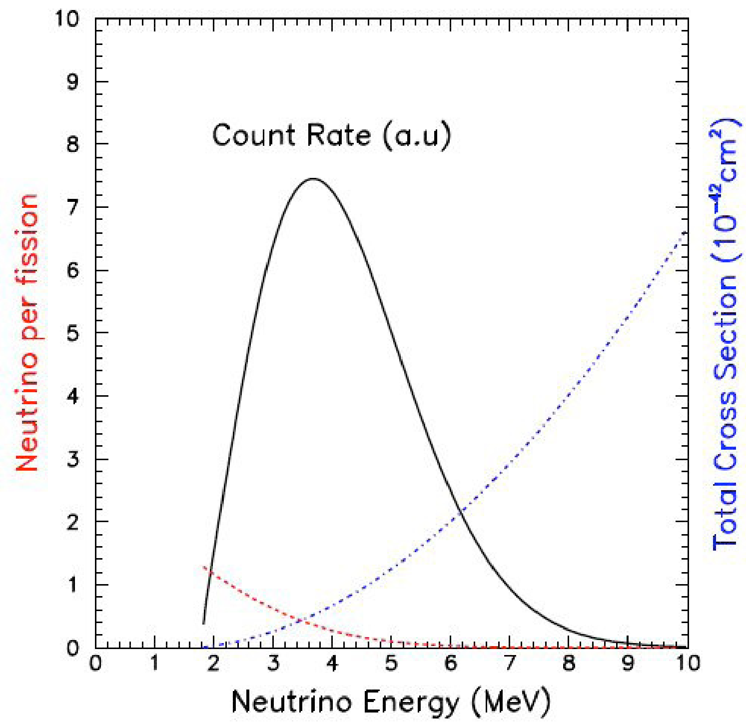
$$E_\nu = E_{e^+} + T_n + (m_n - m_p)$$

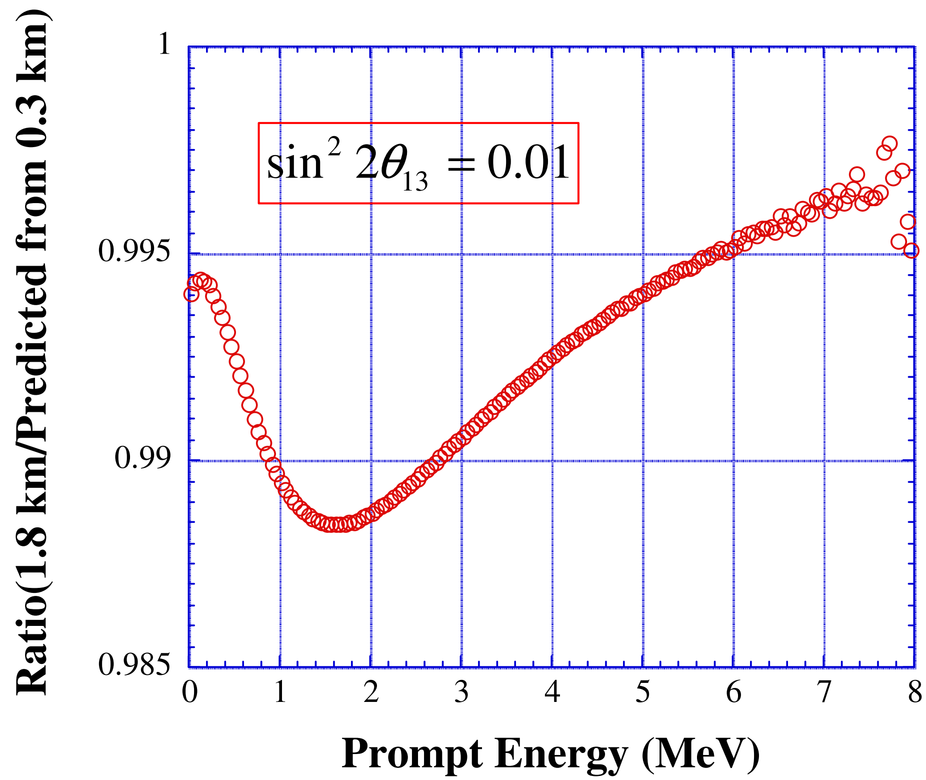
$$\sigma(E_e) = (9.52\times10^{-44}\ \text{cm}^2)E_e p_e$$

Spectral distortion

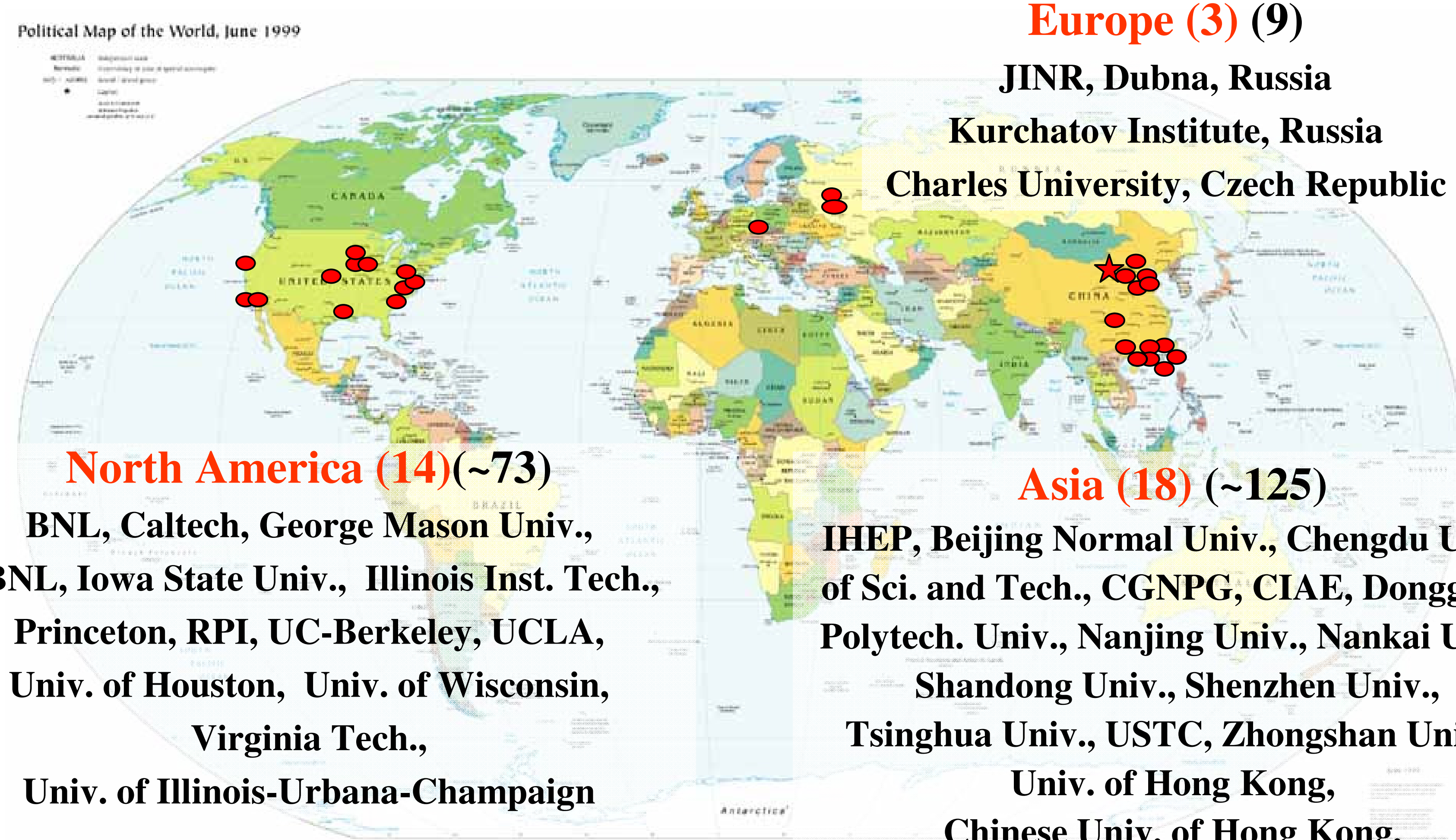
- The spectral distortion between near and far detectors offers additional handle on the deficit measurement

$$\frac{d^2N}{dE_\nu dt} = \Phi(E_\nu)N_H\sigma(E_\nu)P_{dis}(E_\nu)\varepsilon(E_\nu)$$





The Daya Bay Collaboration



Europe (3) (9)

JINR, Dubna, Russia
Kurchatov Institute, Russia
Charles University, Czech Republic

North America (14)(~73)

BNL, Caltech, George Mason Univ., LBNL, Iowa State Univ., Illinois Inst. Tech., Princeton, RPI, UC-Berkeley, UCLA, Univ. of Houston, Univ. of Wisconsin, Virginia Tech., Univ. of Illinois-Urbana-Champaign

Asia (18) (~125)

IHEP, Beijing Normal Univ., Chengdu Univ. of Sci. and Tech., CGNPG, CIAE, Dongguan Polytech. Univ., Nanjing Univ., Nankai Univ., Shandong 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.

~ 207 collaborators

How To Reach A Precision of 0.01 in Daya Bay?

- **Increase statistics:**
  - Use four 20-ton target mass modules at the far site
  - Statistical error in 3 years of running is ~ 0.2%
- **Suppress background:**
  - Deploy near and far detectors in water pools inside mountain to suppress cosmogenic and ambient backgrounds
  - Use active muon tagging at all sites to manage comic-induced bg
- **Reduce systematic uncertainties:**
  - Reactor-related:
    - Use two near detectors to minimize error due to power fluctuations of multiple cores
    - Optimize baseline for best sensitivity and smaller residual reactor-related errors
  - Detector-related:
    - Use "identical" pairs of neutrino detectors to do *relative* measurement
    - Adopt comprehensive program in calibration/monitoring of detectors
    - Interchange near and far detectors (optional)

Location of Daya Bay

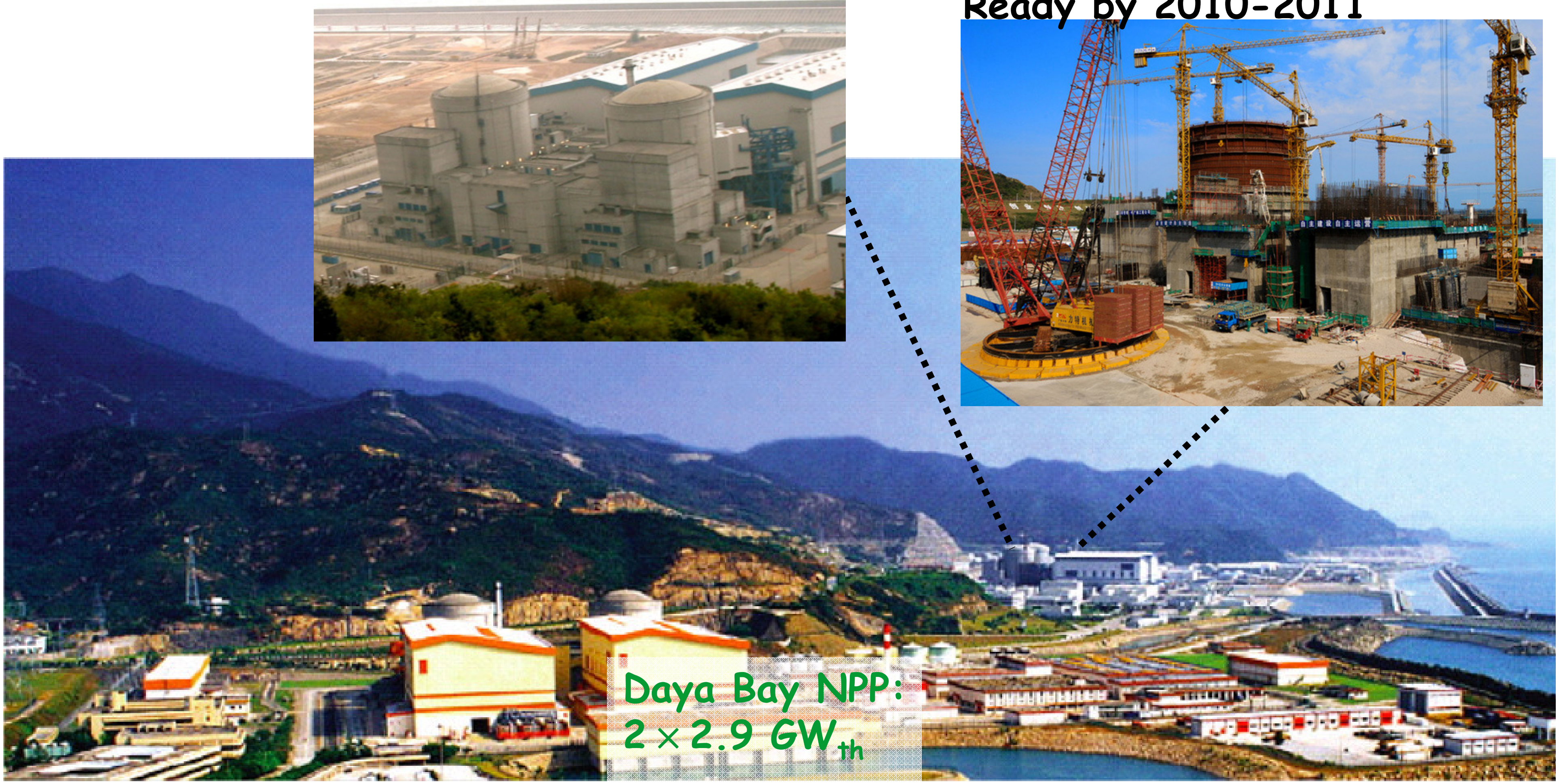
The Daya Bay Nuclear Power Complex

- 12th most powerful in the world (11.6 GW_{th})
- One of the top five most powerful by 2011 (17.4 GW_{th})
- Adjacent to a mountain, easy to construct tunnels to reach underground labs with sufficient overburden to suppress cosmic rays

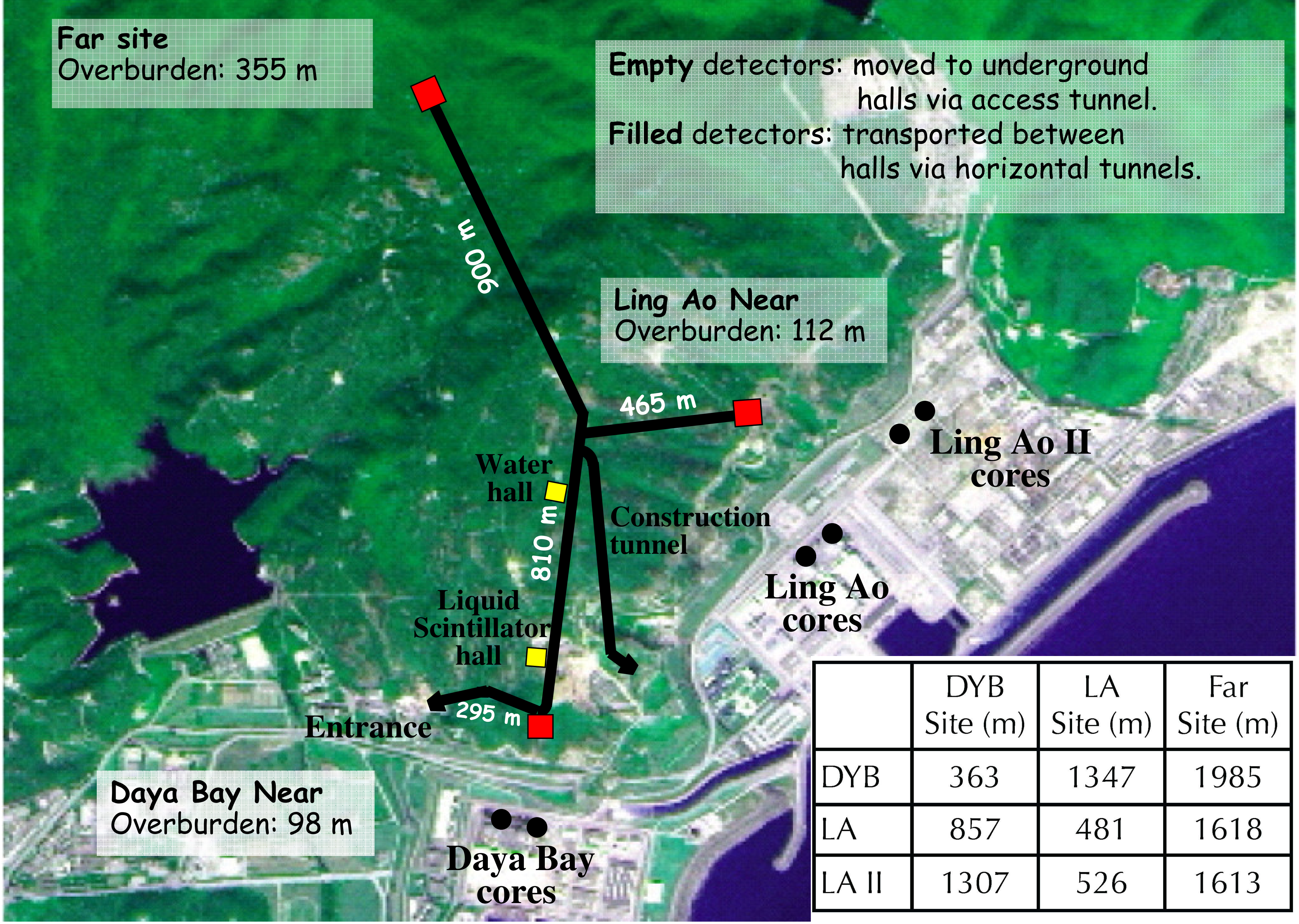
Ling Ao NPP: 2×2.9 GW_{th}

Ling Ao II NPP: 2×2.9 GW_{th}

Ready by 2010-2011



Daya Bay: Experimental Setup



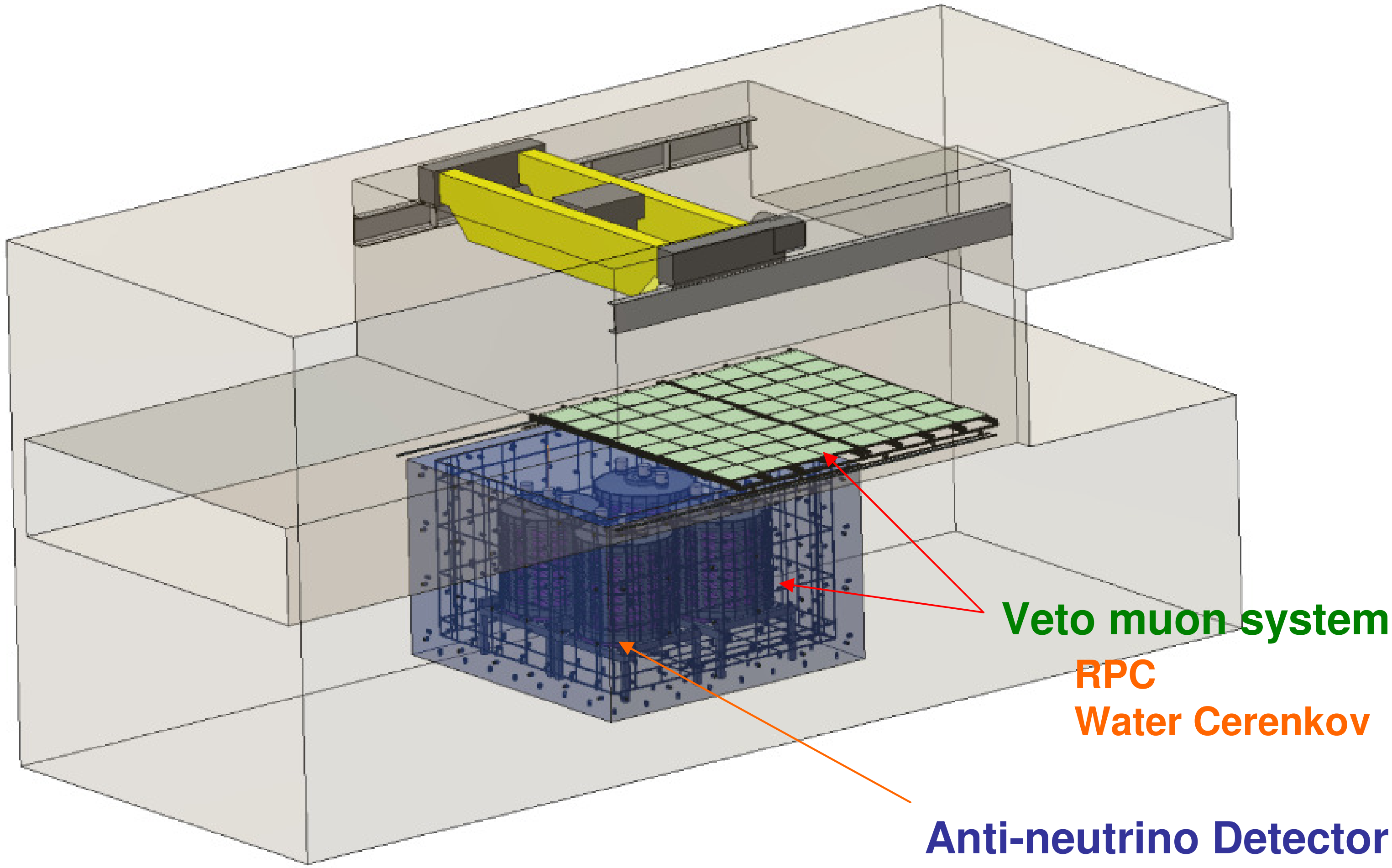
	DYB Site (m)	LA Site (m)	Far Site (m)
DYB	363	1347	1985
LA	857	481	1618
LA II	1307	526	1613

Daya Bay Is Moving Forward Quickly

Excavation of access and construction tunnels is progressing rapidly since ground breaking (Oct 13, 2007)

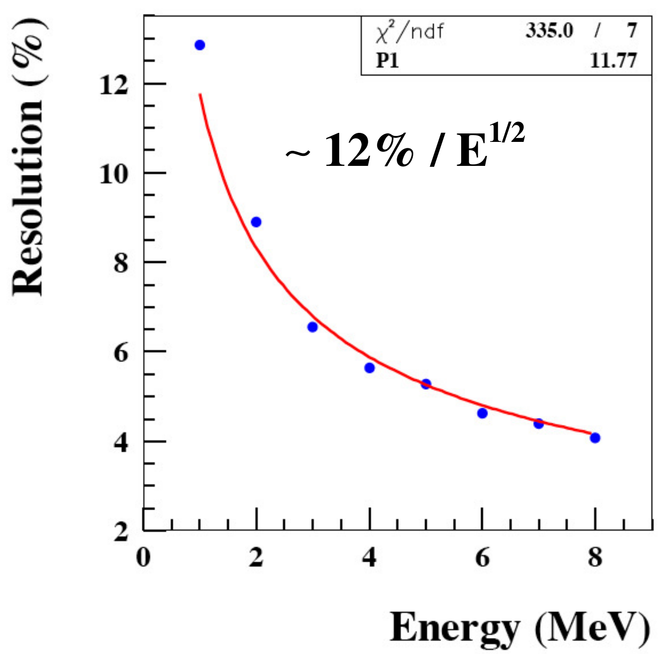
Construction of various detector subsystems is also moving forward quickly

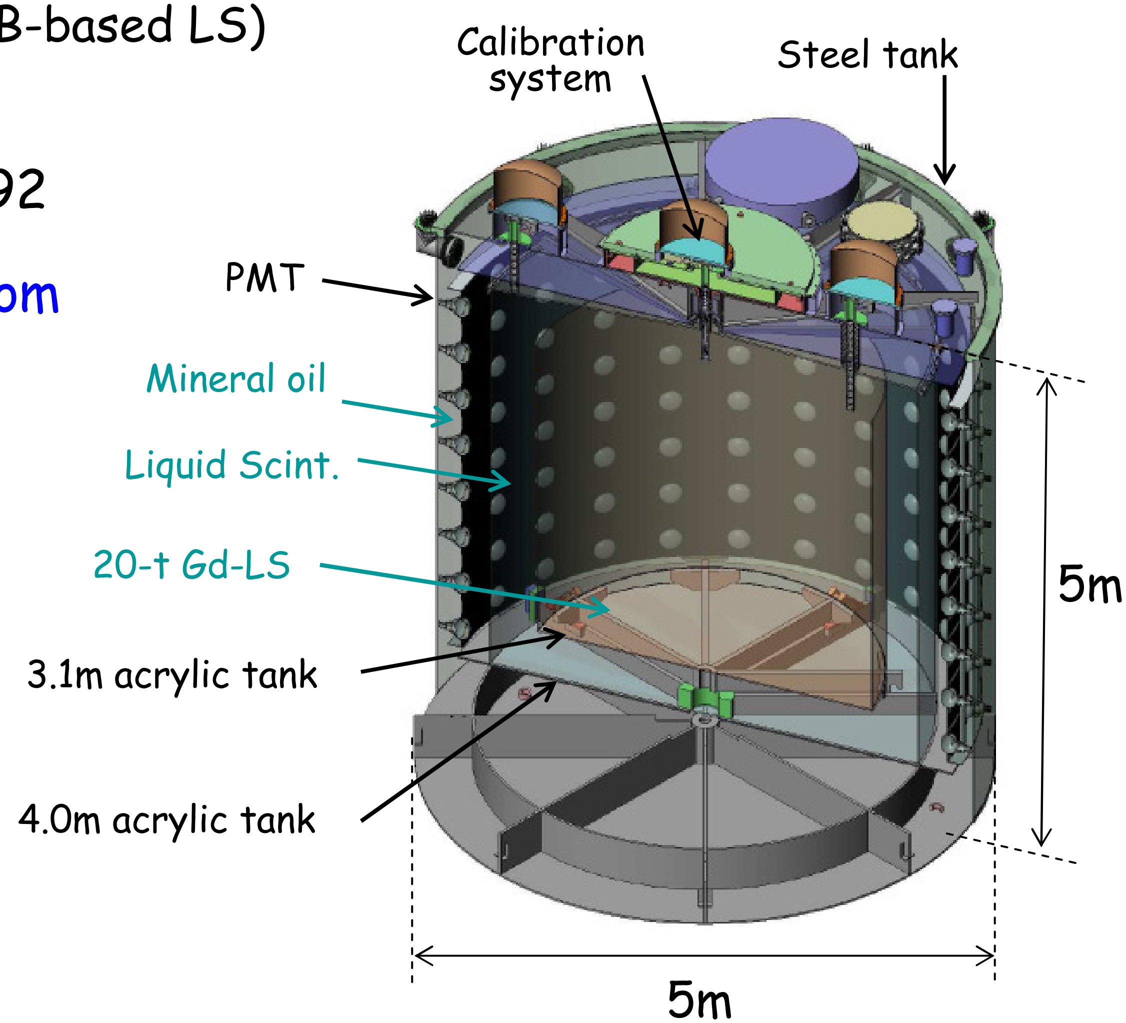
Daya Bay far Detector



Antineutrino Detectors

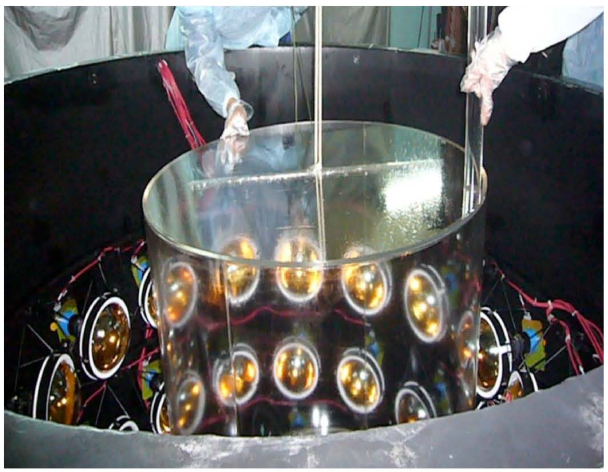
- Three-zone cylindrical detector design
  - Target: 20 t (0.1% Gd LAB-based LS)
  - Gamma catcher: 20 t (LAB-based LS)
  - Buffer : 40 t (mineral oil)
- Low-background 8" PMT: 192
- Reflectors at top and bottom

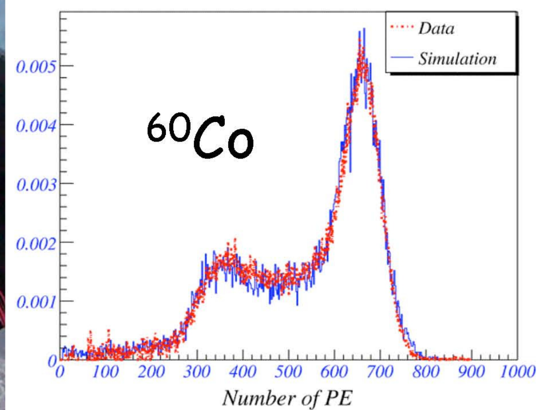


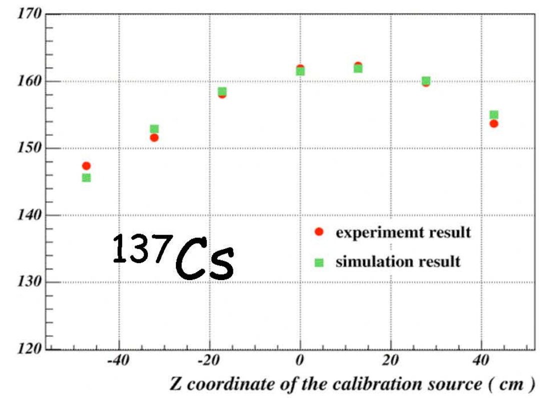


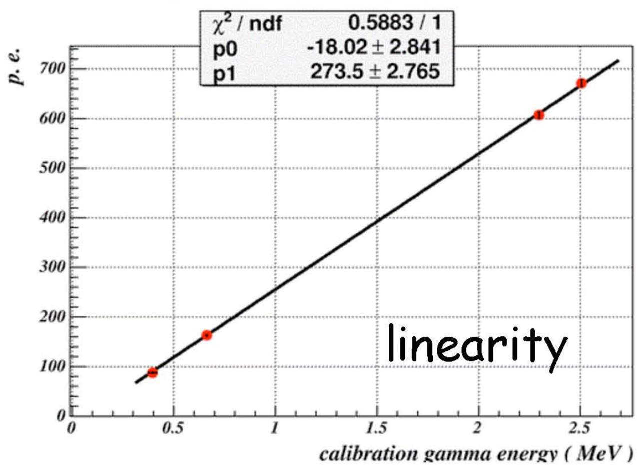
2-zone Prototype at IHEP

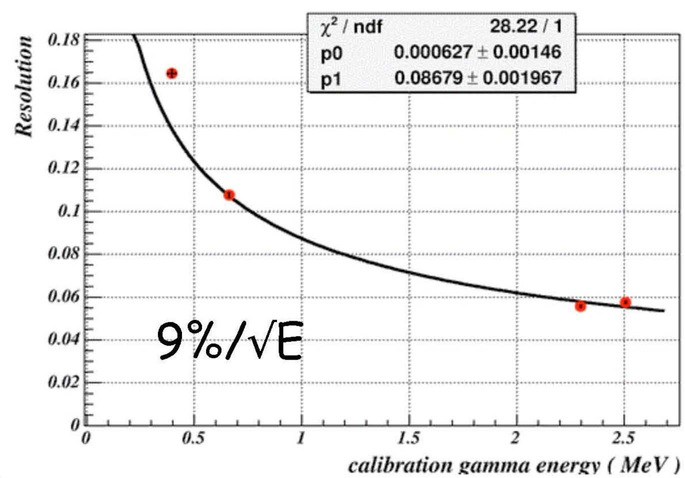
- 0.5 ton unloaded LS
- 45 8" PMTs with reflecting top and bottom







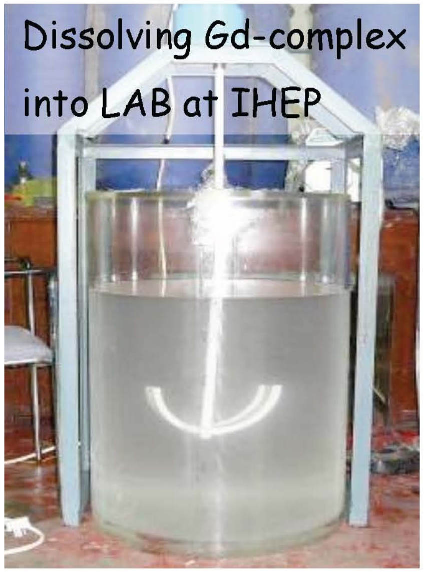


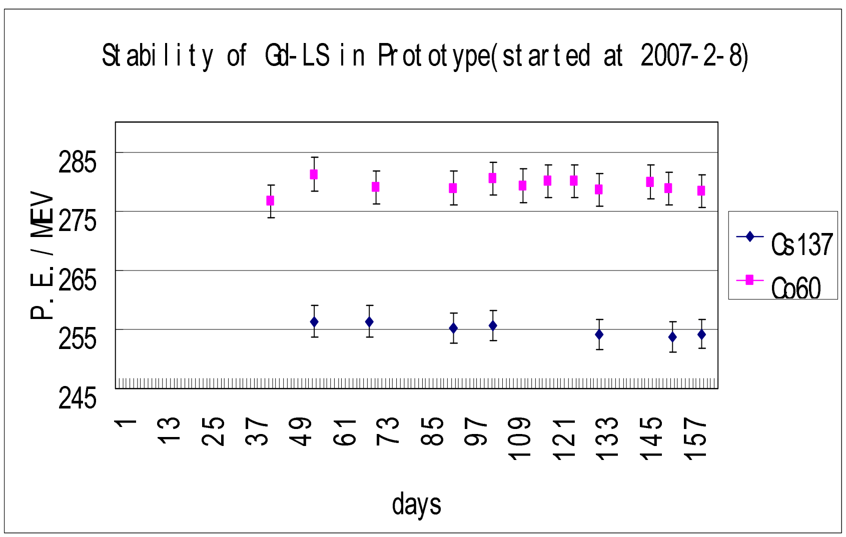


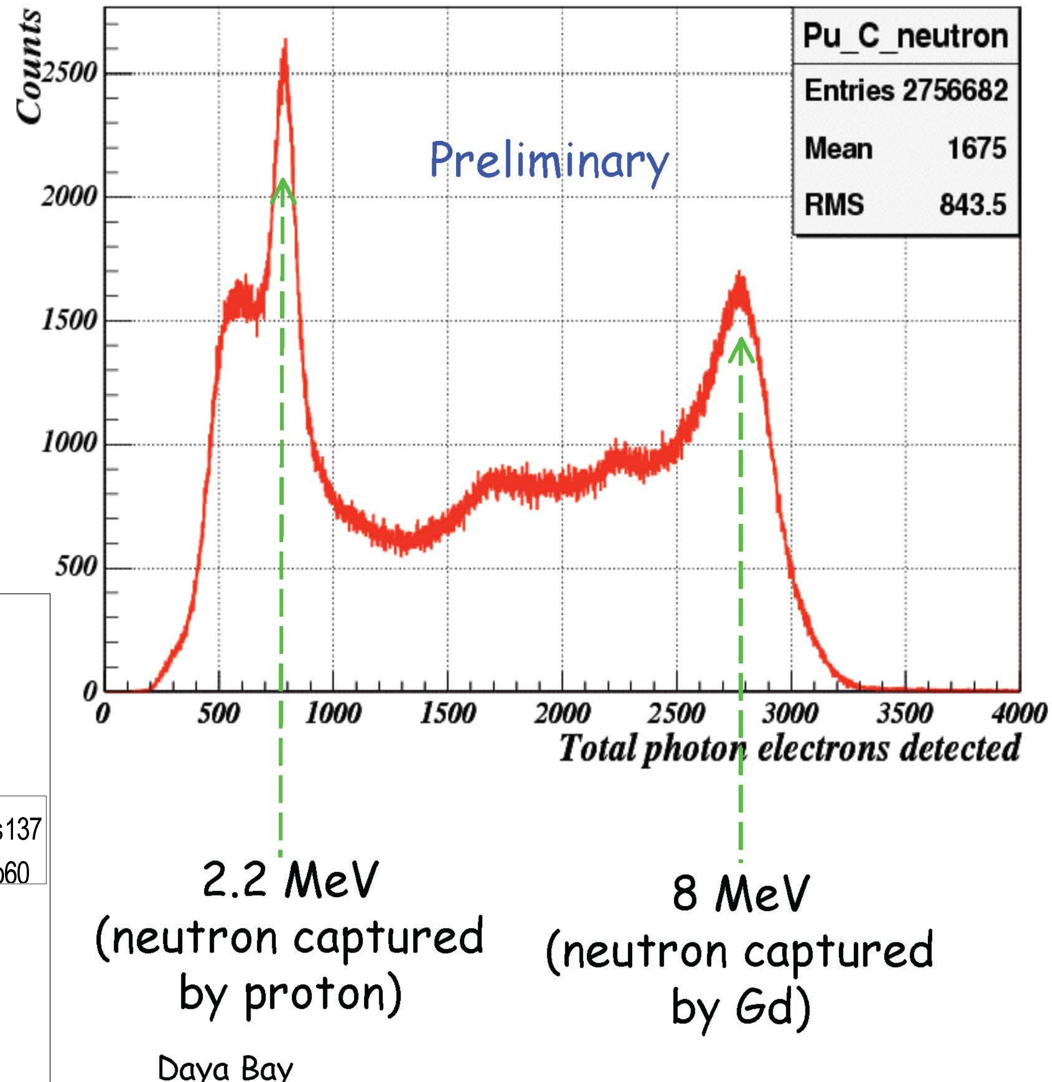
Kam-Biu Luk

Daya Bay

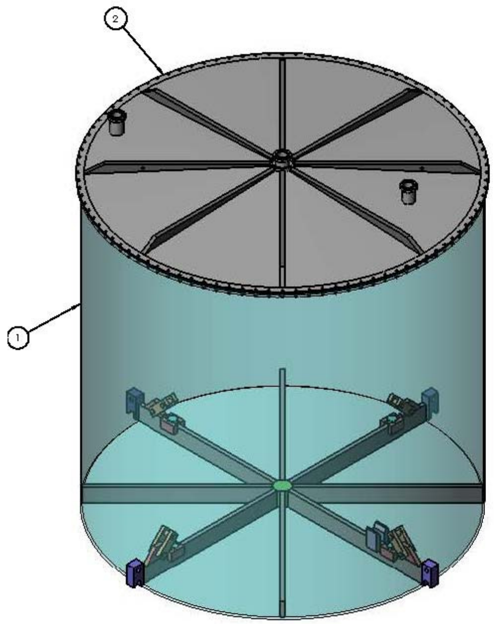
IHEP Prototype Filled With 0.1% Gd-LS







AV Prototypes Under Construction



4-m prototype in the U.S.

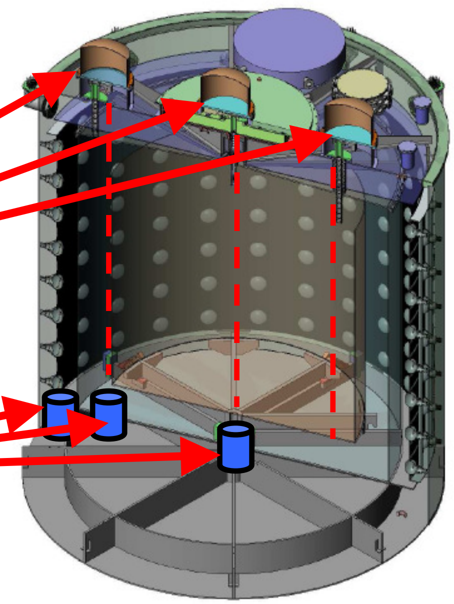
3-m prototype in Taiwan

AD Systematic Uncertainty Control

- **Acrylic vessel and liquid scintillator**
  - Manufactured and filled in pairs with a common storage tank
- **Target mass**
  - Load cells to measure the target mass to 0.1%
  - Flow meter during filling to 0.1%
  - Overflow tank liquid level monitoring with ultrasonic devices
- **Energy calibration to reach relative uncertainty of 0.1%:**
  - Automated calibration with γ (LED), e^+ (^{68}Ge), and neutrons
  - Sources being practiced on the prototype: ^{133}Ba (0.356 MeV), ^{137}Cs (0.662 MeV), ^{60}Co (1.17 + 1.33 MeV), ^{22}Na (1.022+1.275 MeV), Pu-C (6.13 MeV), and ^{252}Cf(neutron)

Calibration/Monitoring Program

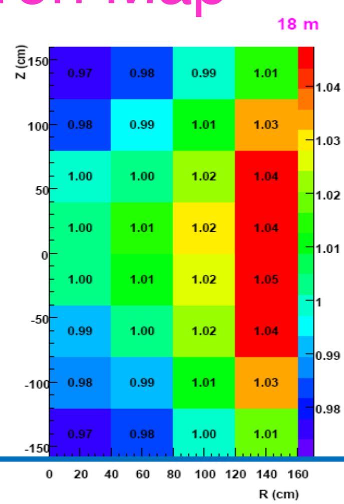
- **Initial commissioning of detector module:**
  - complete characterization of detector properties
  - manual deployment system
- **Routine monitoring of detector modules**:
  - weekly or monthly procedure
  - **3** <u>automated</u> systems per detector, <u>each</u> can deploy γ (LED), e^+ (^{68}Ge), and neutron
  - monitoring system for optical properties
  - supplement with spallation product (e.g., neutrons) measurements

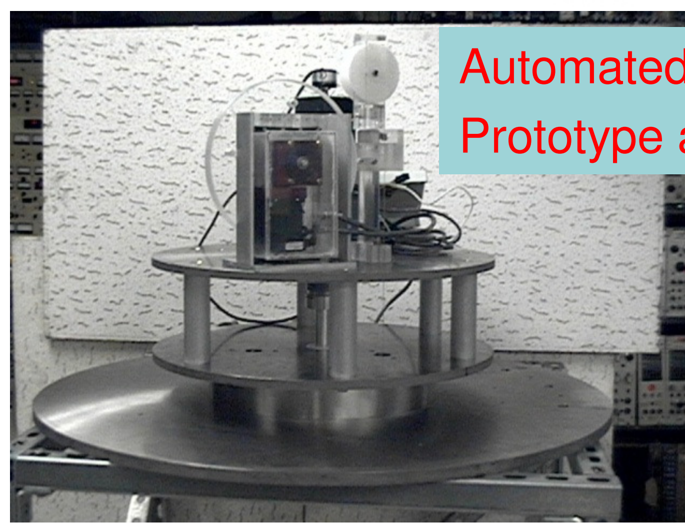


Spallation Neutron Map

σ/E = 0.5% per pixel requires:

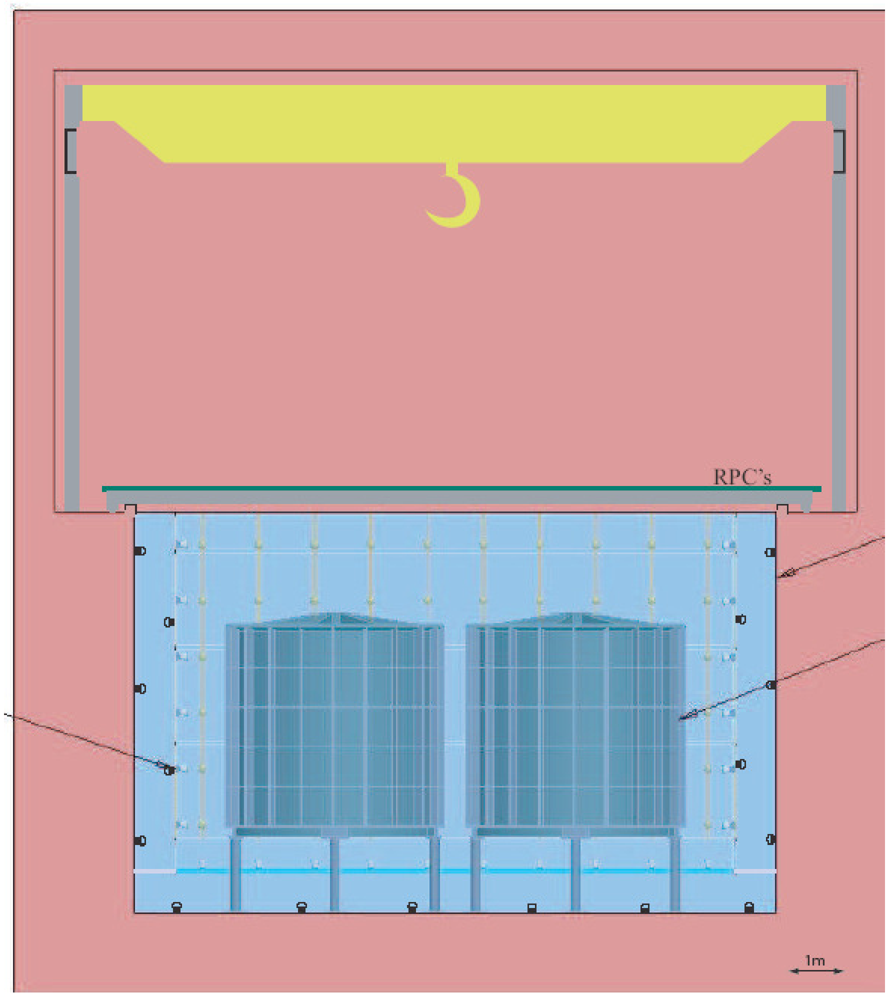
1 day (near)
10 days (far)





Automated System Prototype at Caltech

The muon system

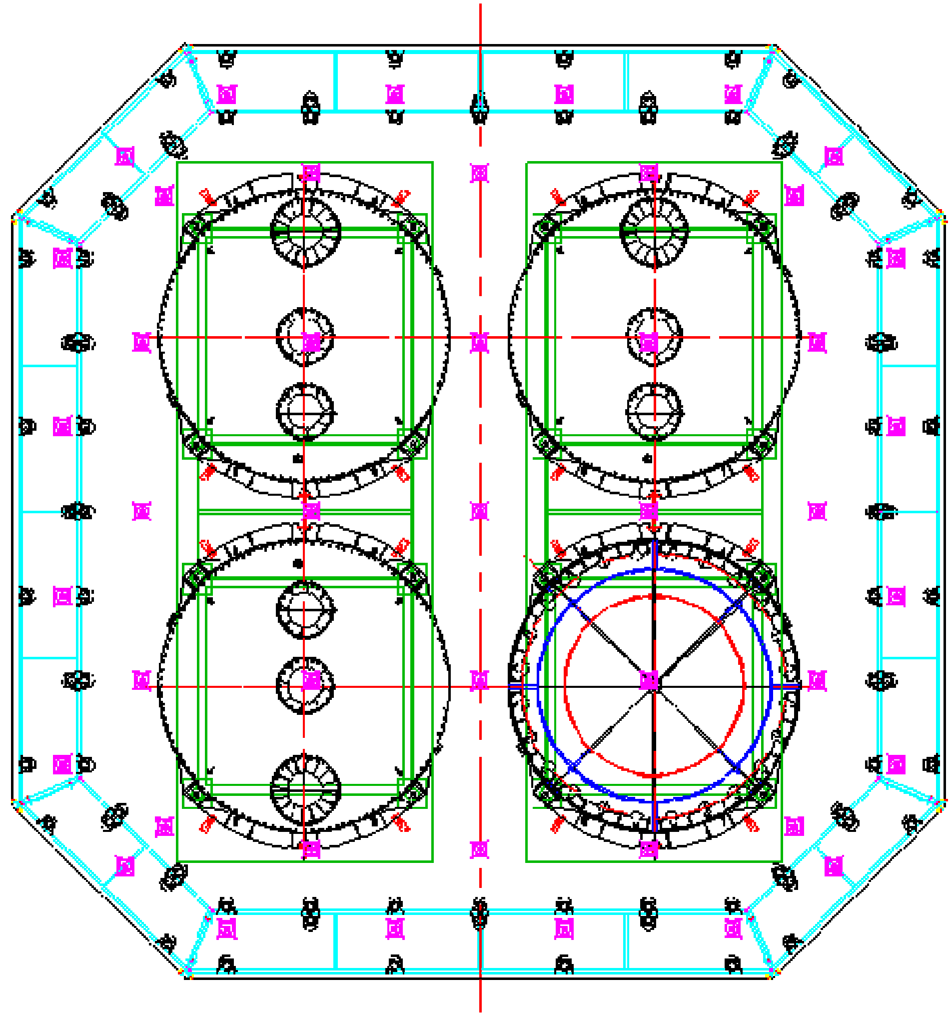


- Multiple muon tagging detectors:
  - Segmented water pool as Cherenkov counter
  - RPC muon detectors at the top of water pool
- Combined muon tagging efficiency > (99.5 ± 0.25) %
- Use neutron background measured by tagged muons to normalize simulation on neutron background due to untagged muons
- ADs surrounded by 2.5 m of water to attenuate neutrons and gammas

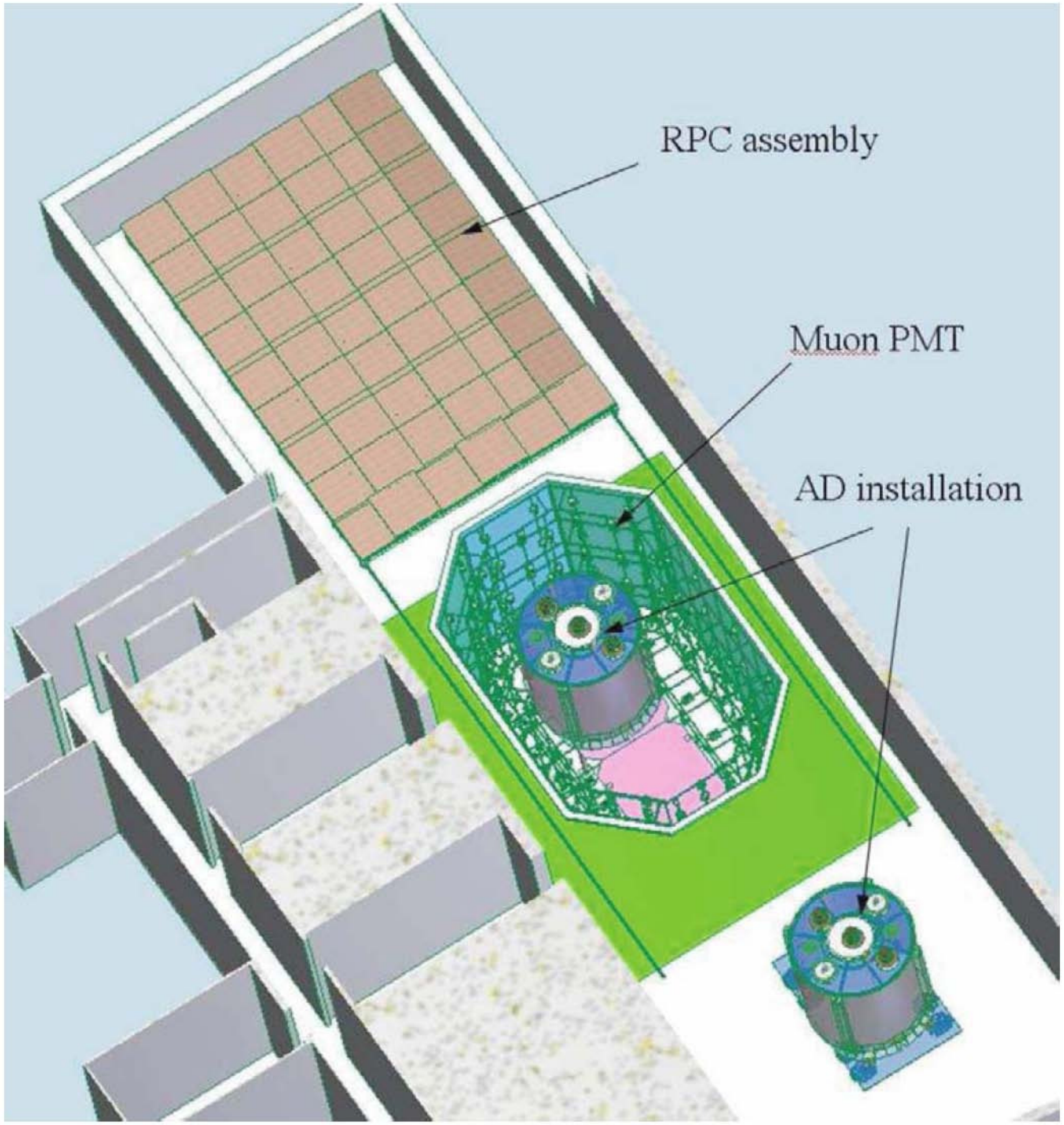
Far detector water pool Cerenkov detector

- Divided by Tyvek into Inner and Outer regions
- Reflective Paint on ADs improves efficiency
- Calibration LEDs placed according to simulations

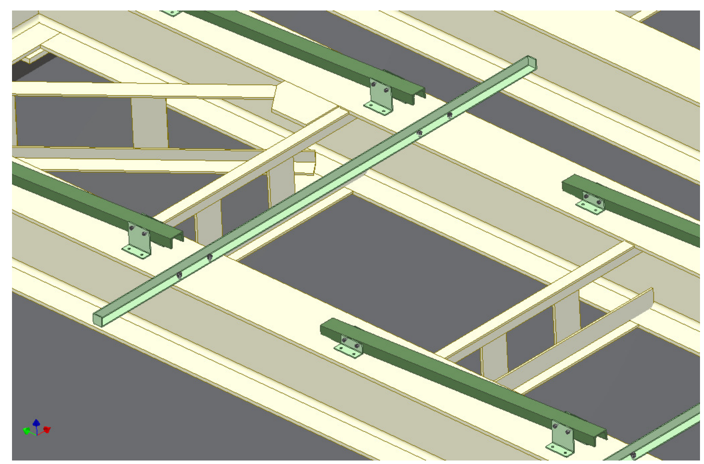
160 PMTs (Inner)
224 PMTs (Outer)



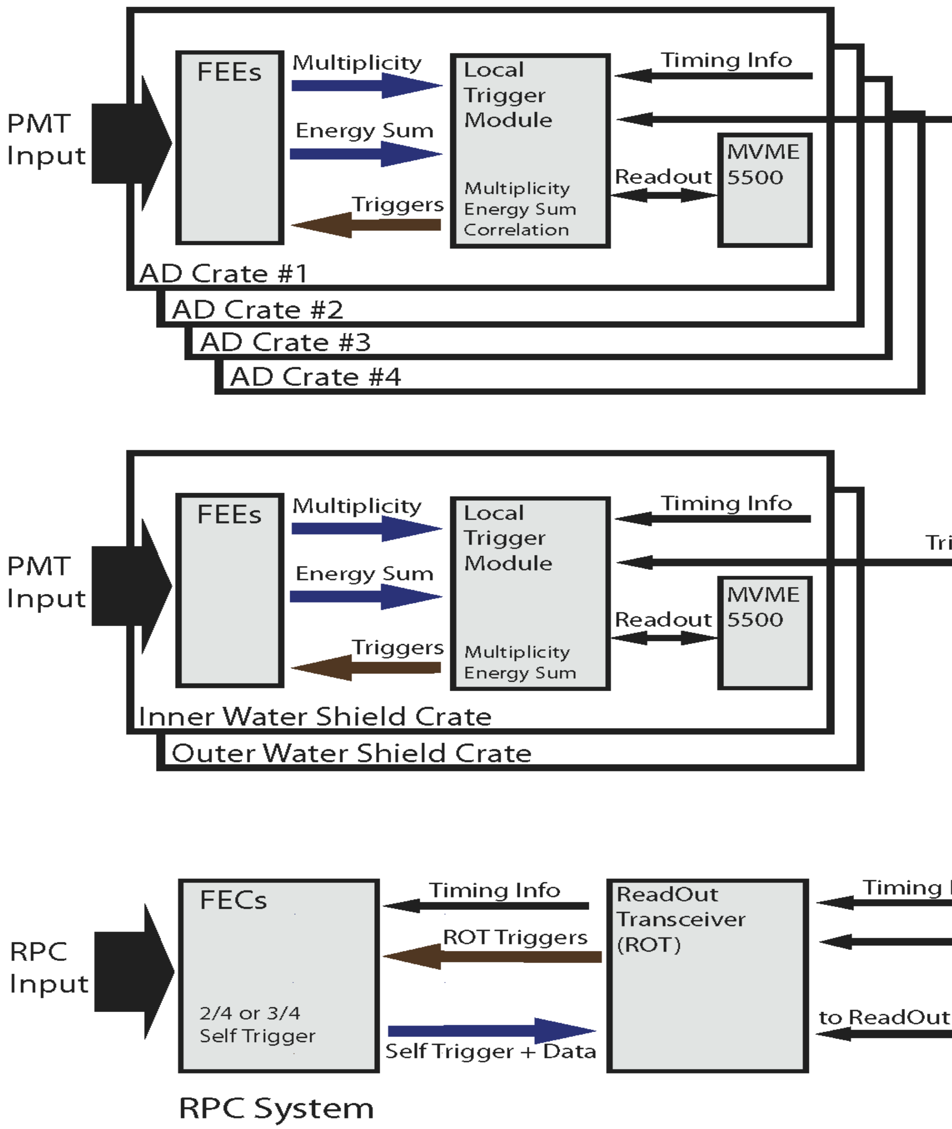
RPC muon detector over Water Pool

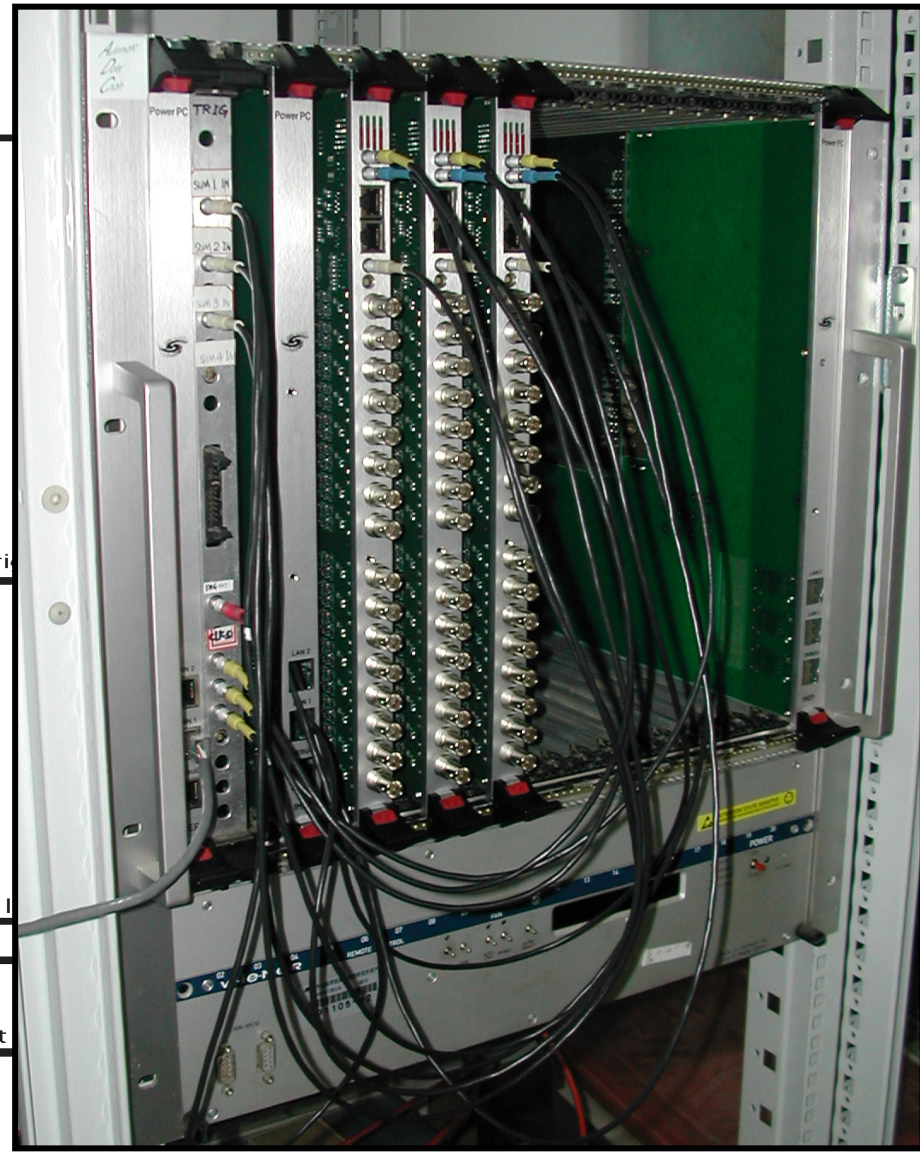


Mockup of 2m x 2m RPC module



Electronics and Readout System





Signal, Background, and Systematic

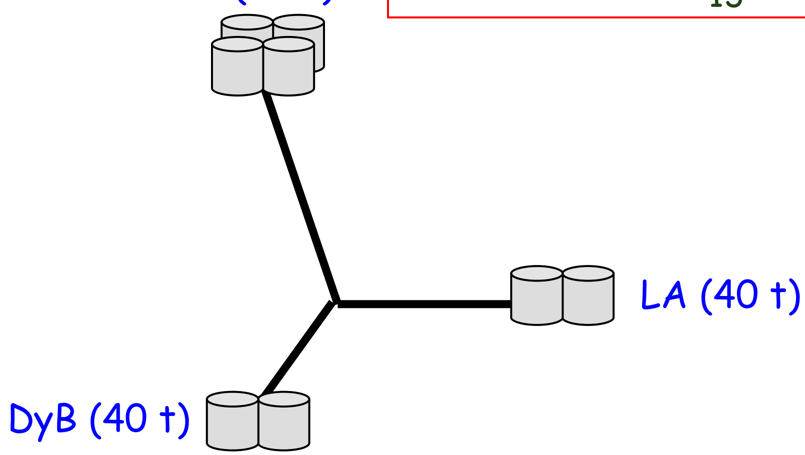
- Summary of signal and background:

	Daya Bay	Ling Ao Near	Far Hall
Baseline (m)	363	481 from Ling Ao 526 from Ling Ao II	1985 from Daya Bay 1615 from Ling Ao
Overburden (m)	98	112	350
Radioactivity (Hz)	< 50	< 50	< 50
Muon rate (Hz)	36	22	1.2
Antineutrino signal (events/day)	840	740	90
Accidental background /signal (%)	< 0.2	< 0.2	< 0.1
Fast neutron background/signal (%)	0.1	0.1	0.1
^{8}He+^{9}Li background/signal (%)	0.3	0.2	0.2

- Summary of statistical and systematic error budgets:

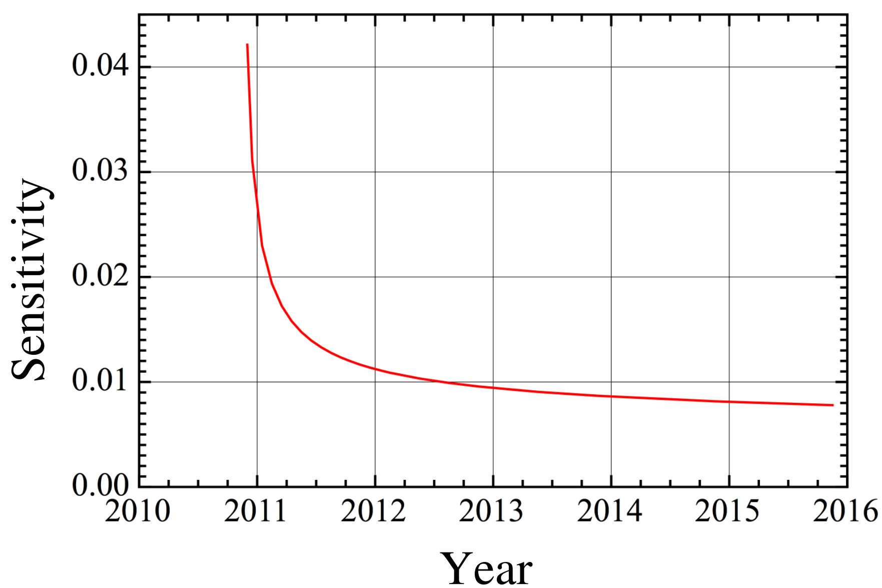
Source	Uncertainty (%)
Reactor power	0.13
Detector (per module)	0.38 (baseline), 0.18 (goal)
Signal statistics	0.2

Sensitivity of Daya Bay

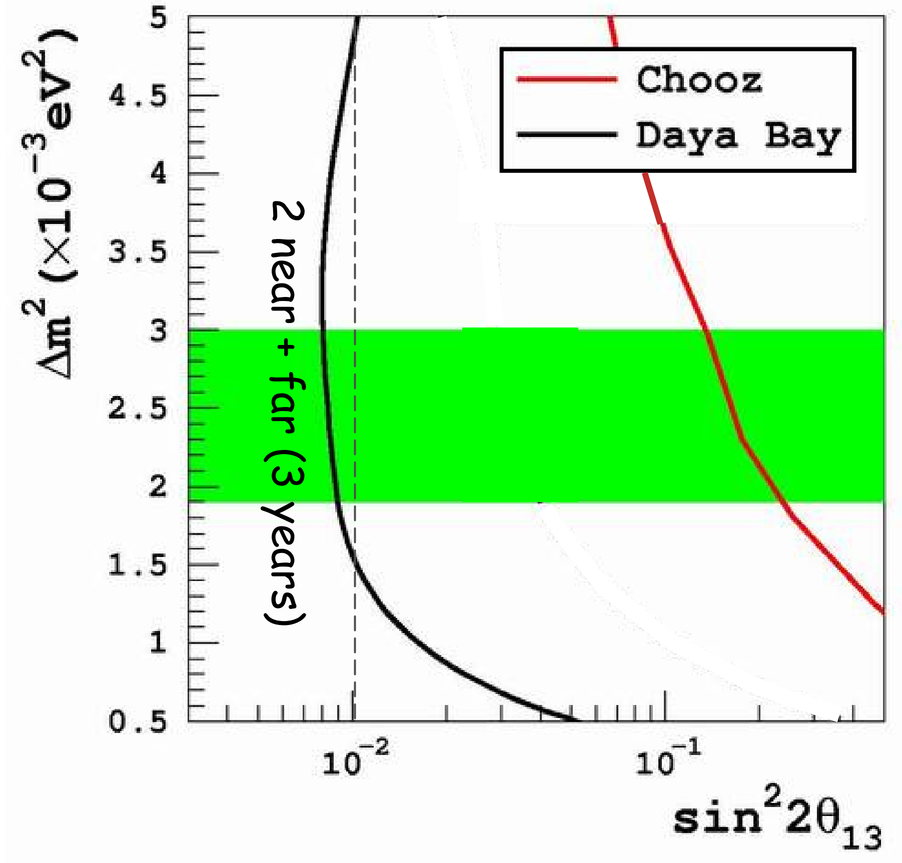


Goal: $\sin^2 2\theta_{13} < 0.01$

- Use rate and spectral shape
- input relative detector syst. error of 0.38%/detector



90% confidence level



Summary

- Daya Bay will reach a sensitivity of ≤ 0.01 for $\sin^2 2\theta_{13}$
- Civil construction has begun
- Subsystem prototypes exist
- Long-lead orders initiated
- Daya Bay is rapidly moving forward:
  - Surface Assembly Building - Fall 2008
  - DB Near Hall - installation activities begin early in 2009
  - Assembly of first AD pair - Spring 2009
  - Commission Daya Bay Hall by Winter 2009/2010
  - LA Near and Far Hall - installation activities begin late in 2009
  - Data taking with all eight detectors in three halls by Dec. 2010

Backup slides

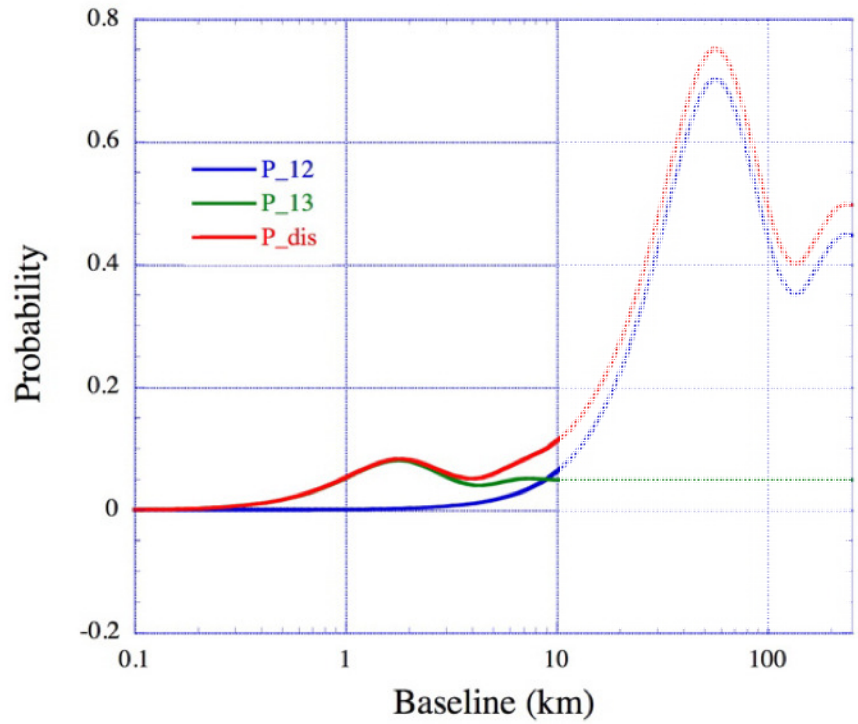
Measuring $\sin^2 2\theta_{13}$ with reactors

Long-baseline accelerator exp.

$$P_{\mu e} \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2(1.27\Delta m^2_{23}L/E) + \cos^2\theta_{23}\sin^2 2\theta_{12}\sin^2(1.27\Delta m^2_{12}L/E) - A(\rho)\bullet\cos^2\theta_{13}\sin\theta_{13}\bullet\sin(\delta)$$

Reactor experiment

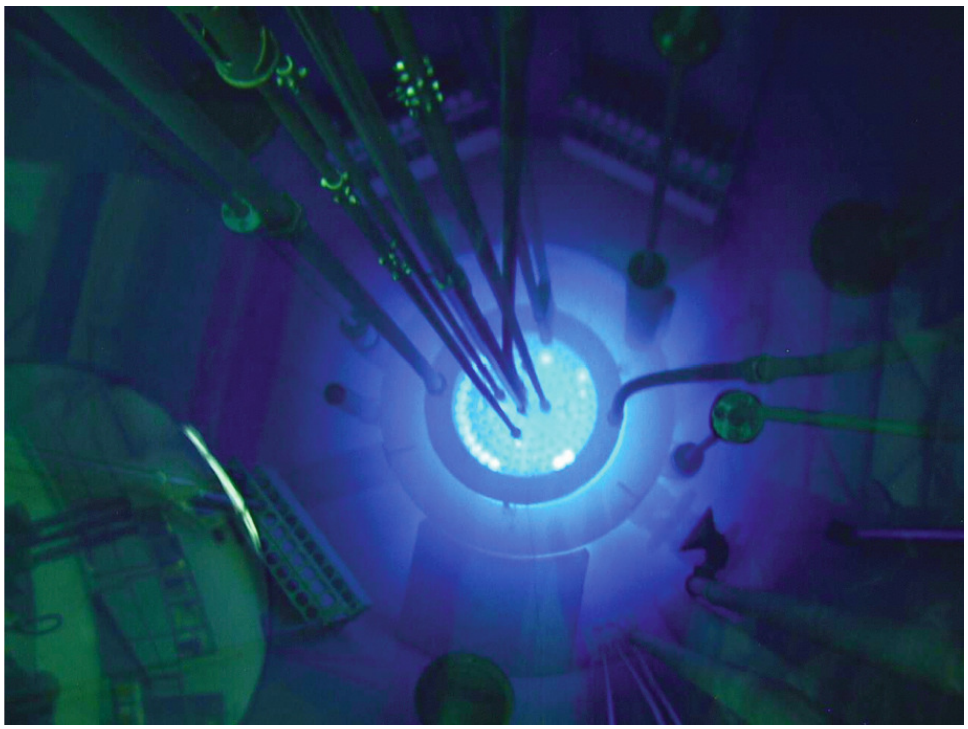
$$P_{ex} \approx \sin^2 2\theta_{13}\sin^2(1.27\Delta m^2_{13}L/E) + \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(1.27\Delta m^2_{12}L/E)$$



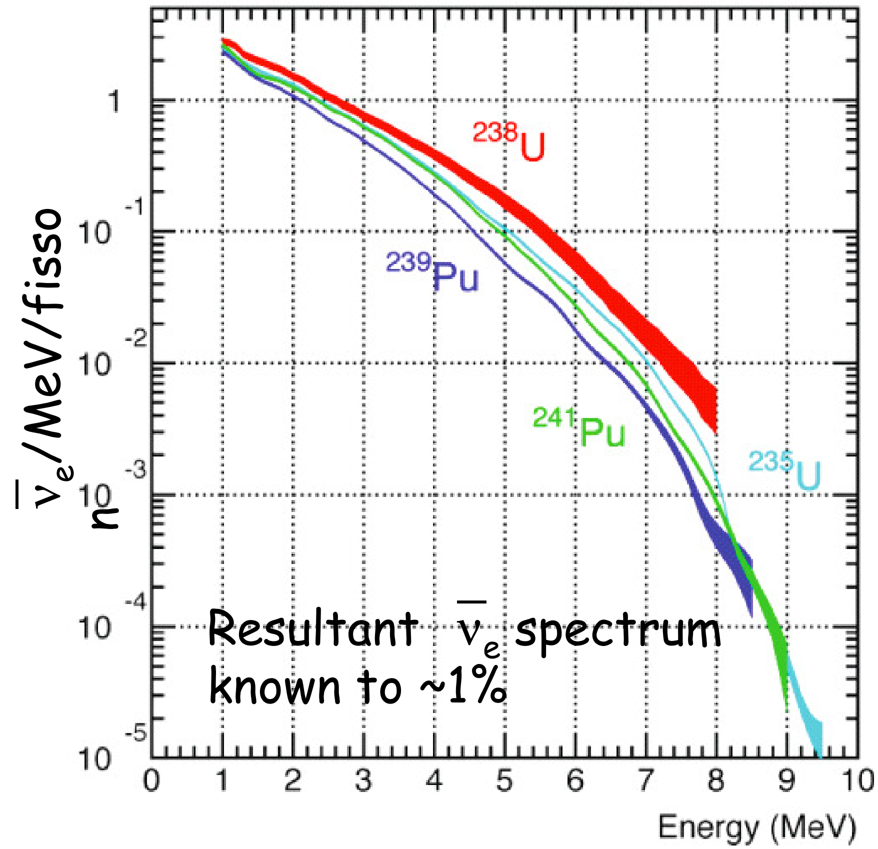
- No ambiguity, independent of δ and matter effect $A(\rho)$
- Relatively cheap compared to accelerator-based experiments
- Rapid deployment possible

Reactor neutrinos

- Fission processes in nuclear reactors produce ~ 6 neutrinos per fission



3 GW_{th} generates 6×10^{20} $\bar{\nu}_e$ per sec

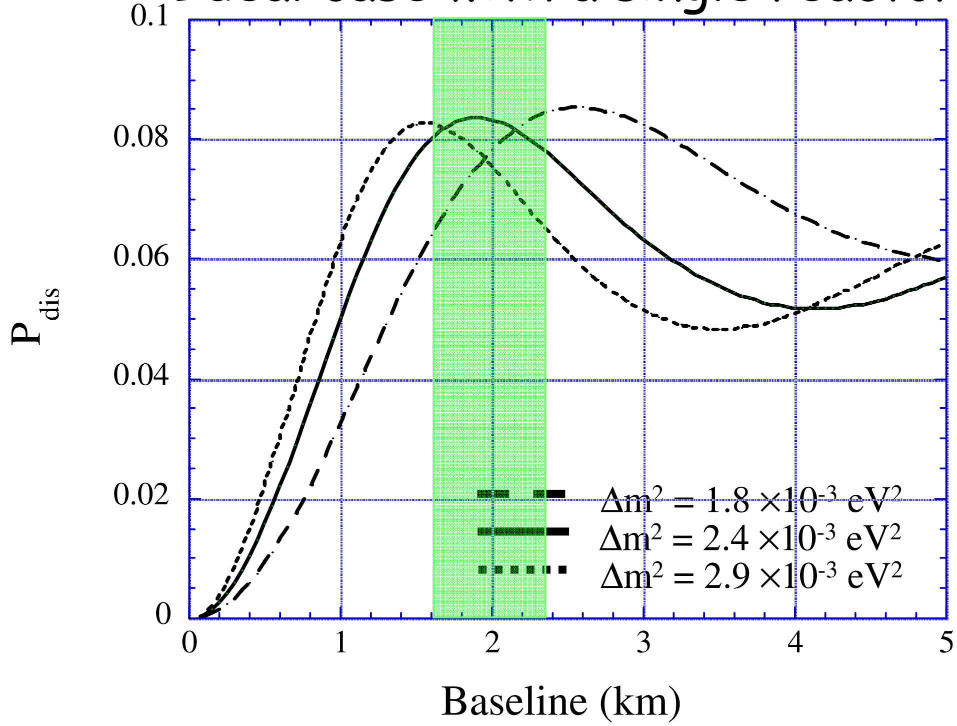


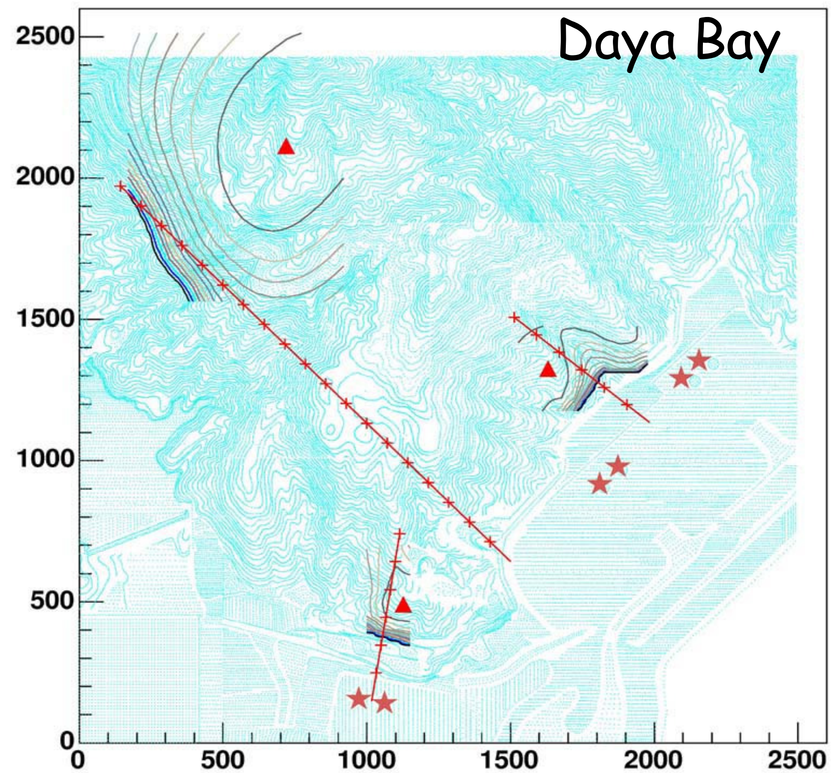
Baseline optimization and site selection

Inputs to the process:

- Flux and energy spectrum of reactor antineutrino
- Systematic uncertainties of reactors and detectors
- Ambient background and uncertainties
- Position-dependent rates and spectra of cosmogenic neutrons and ^{9}Li

Ideal case with a single reactor





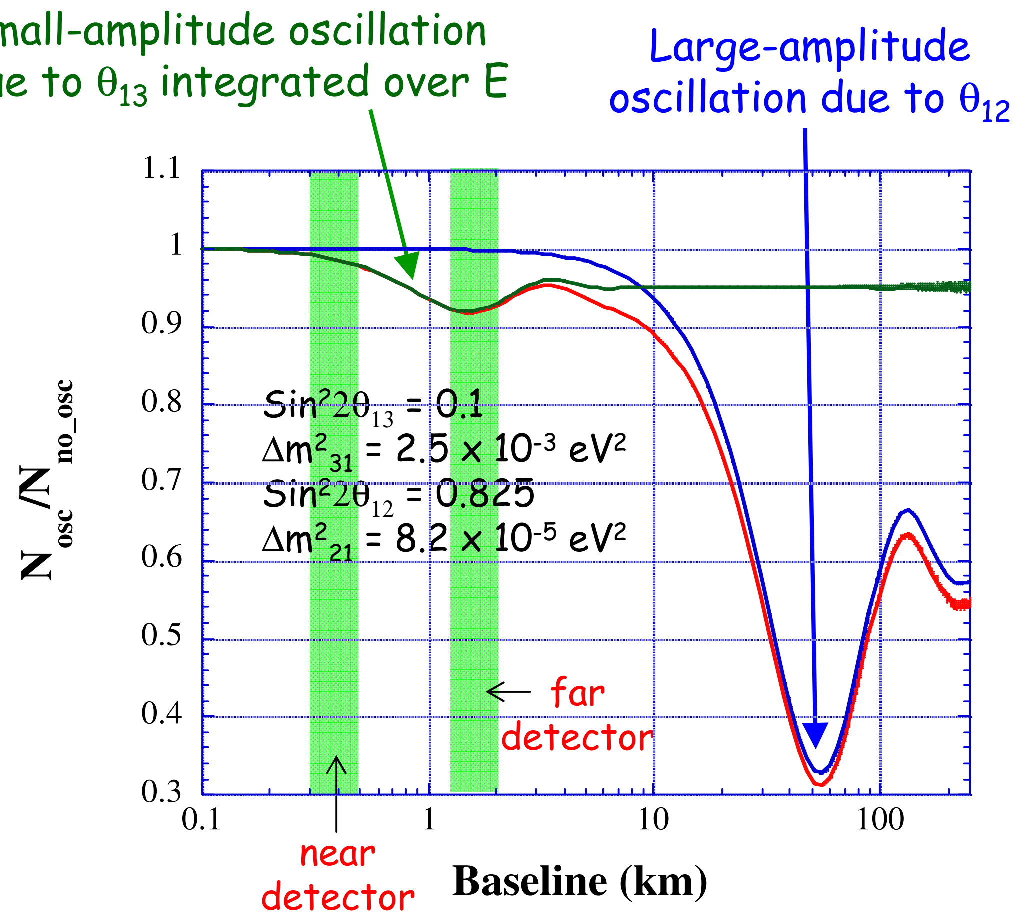
Where To Place The Detectors ?

- Since reactor $\bar{\nu}_e$ are low-energy, it is a disappearance experiment:

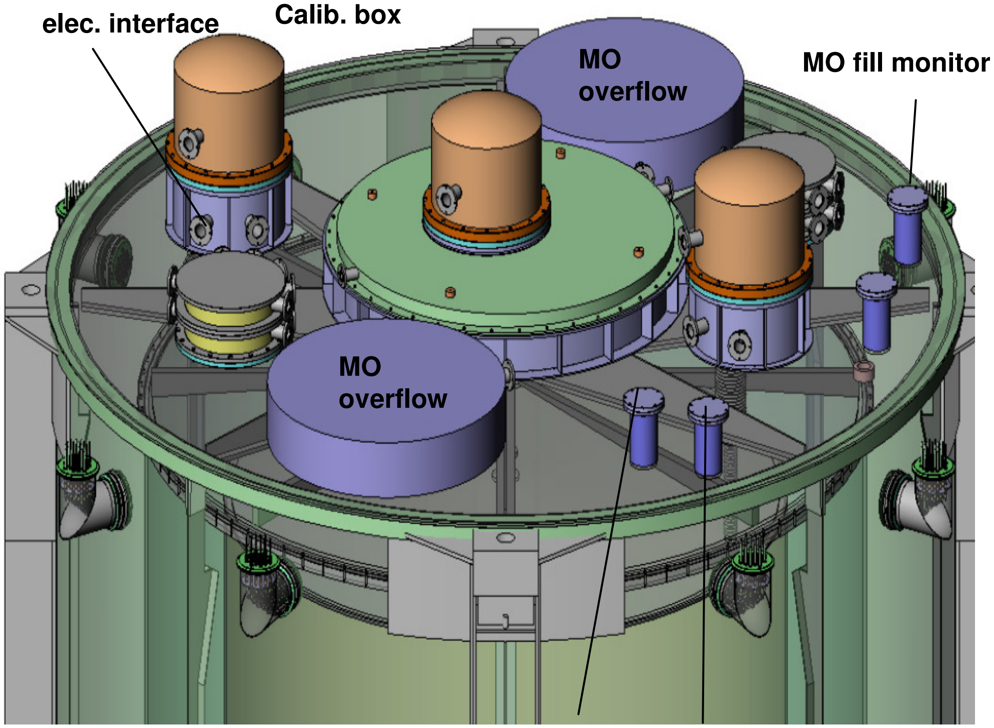
$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

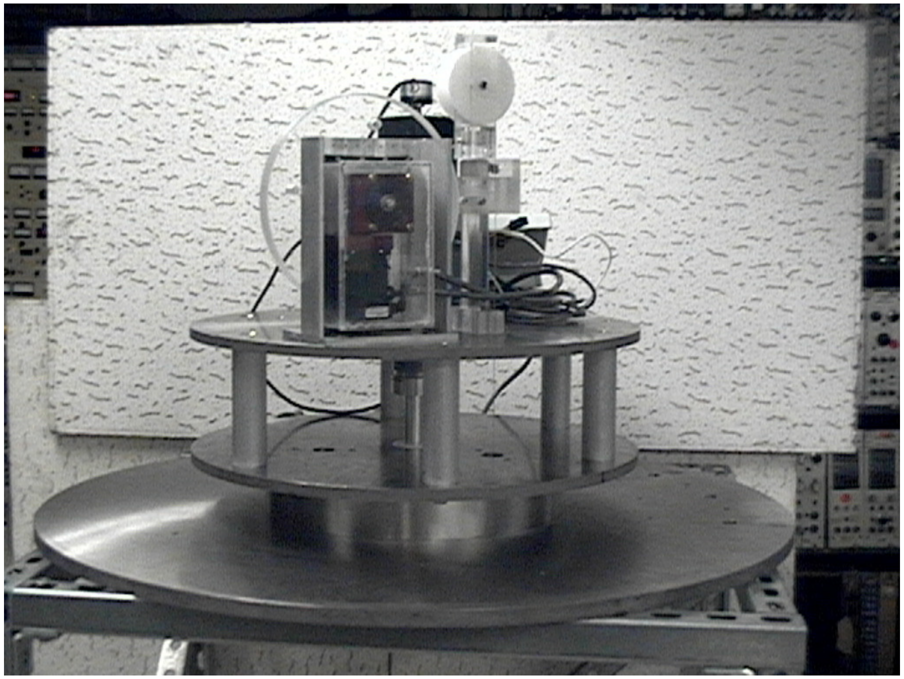
- Place near detector(s) close to reactor(s) to measure raw flux and spectrum of $\bar{\nu}_e$, reducing reactor-related systematic

- Position a far detector near the first oscillation maximum to get the highest sensitivity, and also be less affected by θ_{12}



Automated Calibration System



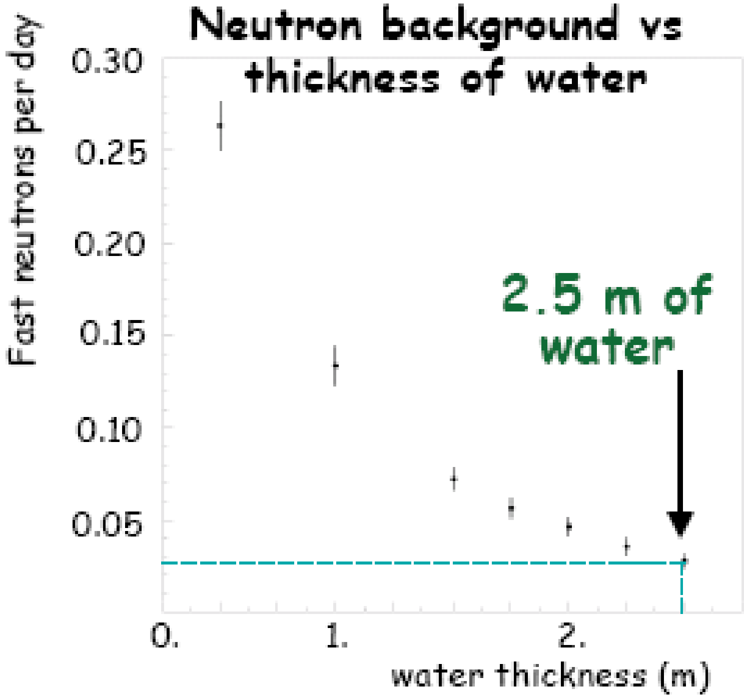


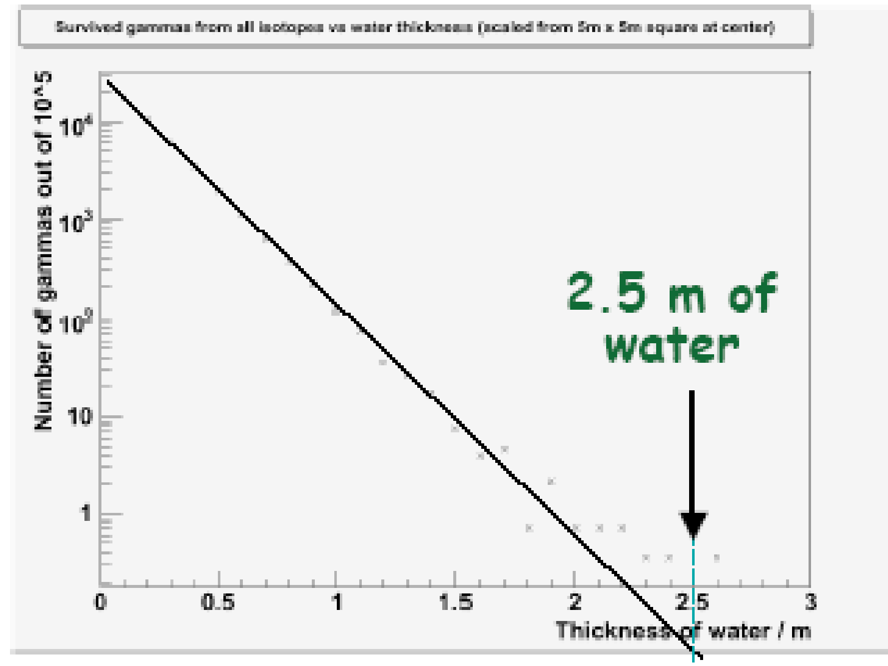
Each unit deploys 3 sources: ^{68}Ge, ^{252}Cf, LED

Status:

- Completed >20 years worth of cycling
- No liquid dripping problem
- Tested limit switch precision and reliability

Water Shield & Cherenkov





- Antineutrino detectors enclosed by 2.5 m of water to shield energetic neutrons produced by muons and gamma-rays from the surrounding rock
- Tagging requirements:
  - Inefficiency < 0.5% and known to < 0.25%
- Use multiple detectors to provide cross check

Daya Bay Is Moving Forward Quickly

Groundbreaking Ceremony: Oct 13, 2007

Daya Bay Is Moving Forward Quickly