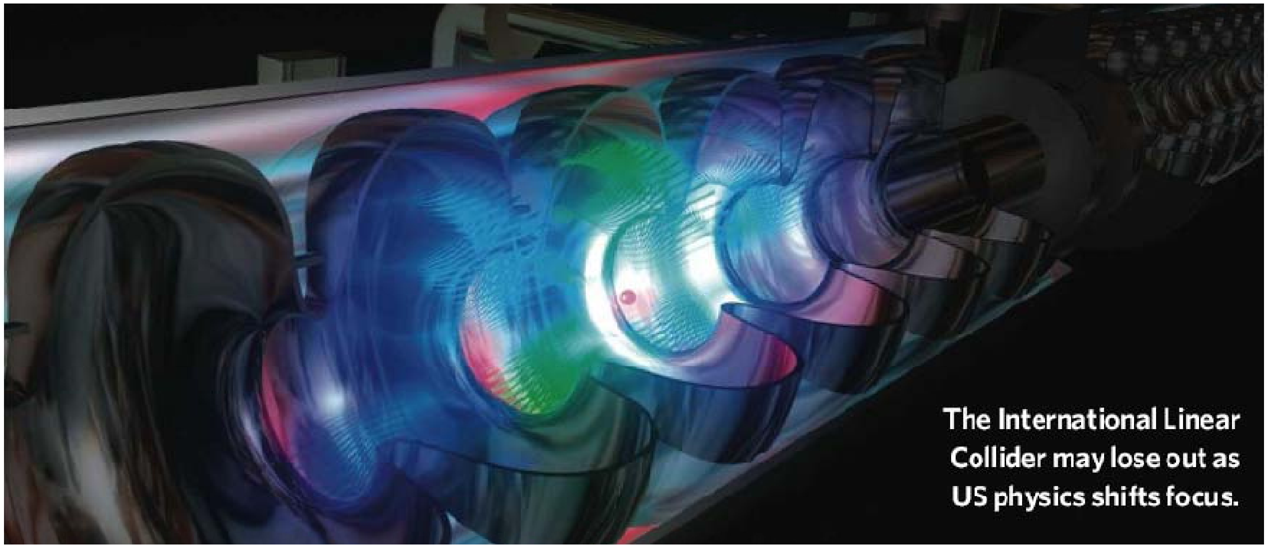
Precise measurement of θ_{13} at Daya Bay

Chu Ming-chung 朱明中
Department of Physics,
The Chinese University of Hong Kong
On behalf of the Daya Bay Collaboration
mcchu@phy.cuhk.edu.hk

ICHEP '08



D.HAMBURG

The International Linear Collider may lose out as US physics shifts focus.

Physicists to target neutrinos

The new focus for America's high-energy physics should be an elusive one: the zippy, chargeless, near-massless neutrino, according to a report that provides the US Department of Energy (DOE) and the National Science Foundation (NSF) with a roadmap for the next decade.

The report, written by the Particle Physics Project Prioritization Panel (P5) and endorsed on 29 May by a DOE and NSF advisory committee, suggests that the US physics programme should concentrate on the fertile terrain of neutrino physics rather than focusing all its efforts on the high-energy frontier explored by colliders.

Instead, the P5 report recommends more work on the neutrino, which was discovered to have mass only a decade ago. Physicists want to understand how the three known neutrino 'flavours' morph from one type to another. Some physicists hope that by understanding neutrinos and their antiparticles, they will be able to explain why the Universe ended up being made of matter rather than antimatter.

θ_{13} plays a key role

Nature **453**, 705 (2008).

The Neutrino Mixing Matrix

Each flavor state = mixture of mass states

3-flavor: $$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

↑ neutrino mixing matrix

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}$$

Maki-Nakagawa-Sakata-Pontecorvo Matrix

Oscillation parameters:

3 mixing angles θ_{12}, θ_{13}, θ_{23}; 1 phase δ_{CP} (CP violation)

2 mass-squared differences

Δm^2_{21}, Δm^2_{32}

always appears with sin θ_{13}

The Neutrino Mixing Parameters

SNO, Solar Neutrinos, KamLAND → $\theta_{12} \sim 34^o$, $\Delta m^2_{21} \sim 7.6 \times 10^{-5}\ eV^2$

atmospheric, accelerator → $\theta_{23} \sim 45^o$, $|\Delta m^2_{32}| \sim 2.4 \times 10^{-3}\ eV^2$

Yet undetermined: δ_{CP} ?

θ_{13} ?

Sign of Δm^2_{32} ?

Chooz Reactor Expt.: $\sin^2(2\theta_{13}) < 0.17$ at 90%

Daya Bay: the most precise determination of θ_{13}

Neutrino Oscillation and θ_{13}

- Major recent discoveries: $m_{\nu_i} \neq 0$, ν mixing
  → new physics beyond the Standard Model
- Value of θ_{13} is critical for:
  - constraining models of physics beyond SM
  - measuring CP violation in neutrinos
    (→ matter-anti-matter asymmetry?)
    δ_{CP} always appears with $\sin\theta_{13}$
- But θ_{13} is small (could even be zero)
  → Daya Bay: Precise determination of θ_{13}

Where To Place The Detectors ?

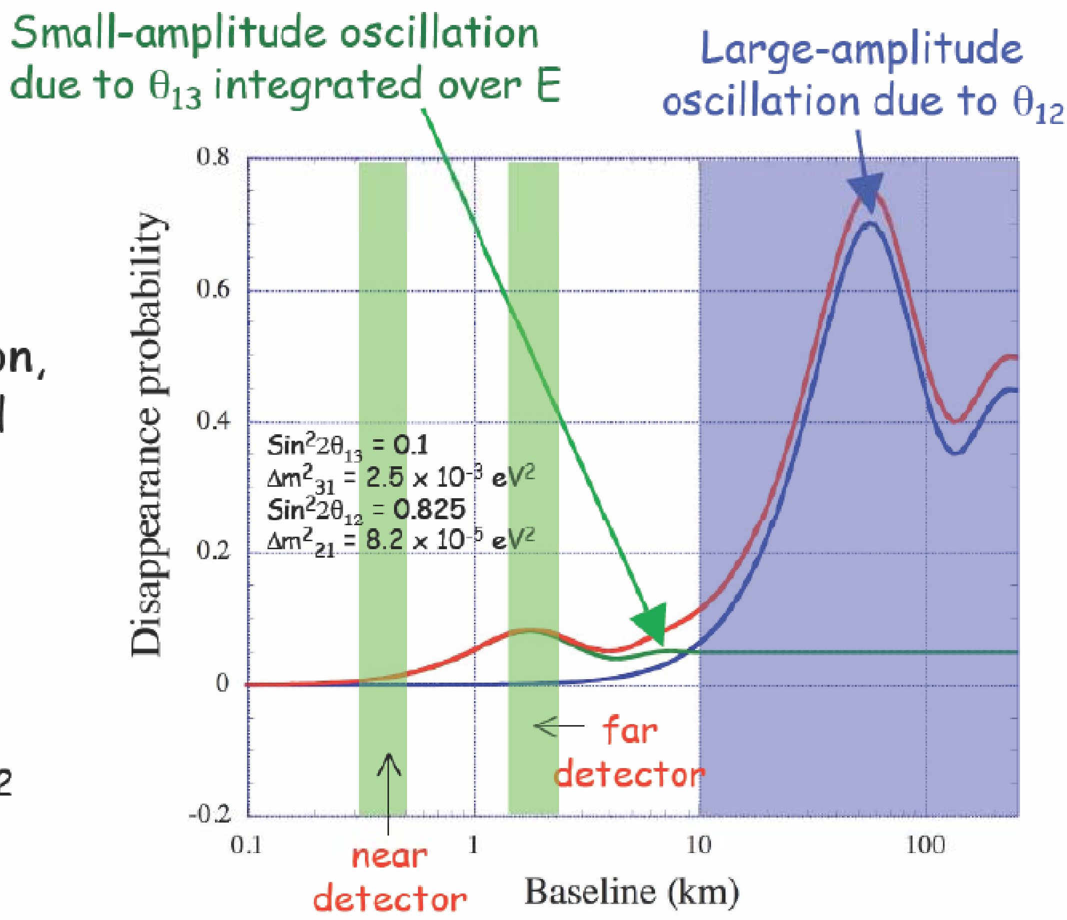
Since reactor $\bar{\nu}_e$ are low-energy, it is a disappearance experiment:

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

Cheap and clean way to determine θ_{13}

Place near detector(s) close to reactor(s) to measure flux and spectrum of $\bar{\nu}_e$ for normalization, hence 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}



The Daya Bay Collaboration

Europe (3) (9)

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

North America (14)(~73)

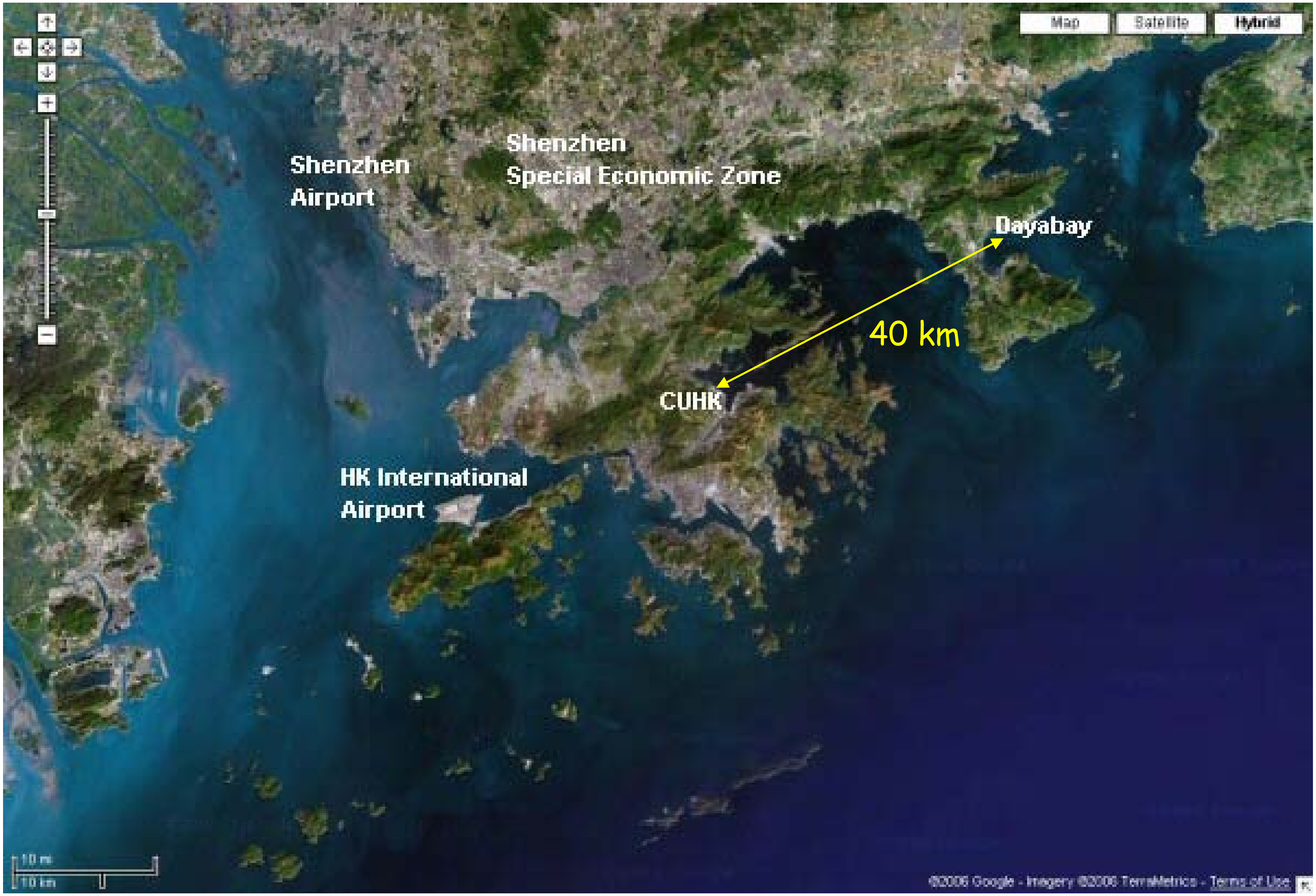
BNL, Caltech, George Mason Univ., LBNL, Iowa State Univ., Illinois Inst. Tech., Princeton, RPI, UC-Berkeley, UCLA, Univ. of Houston, Univ. of Wisconsin, Virginia Tech., Univ. of Illinois-Urbana-Champaign

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.

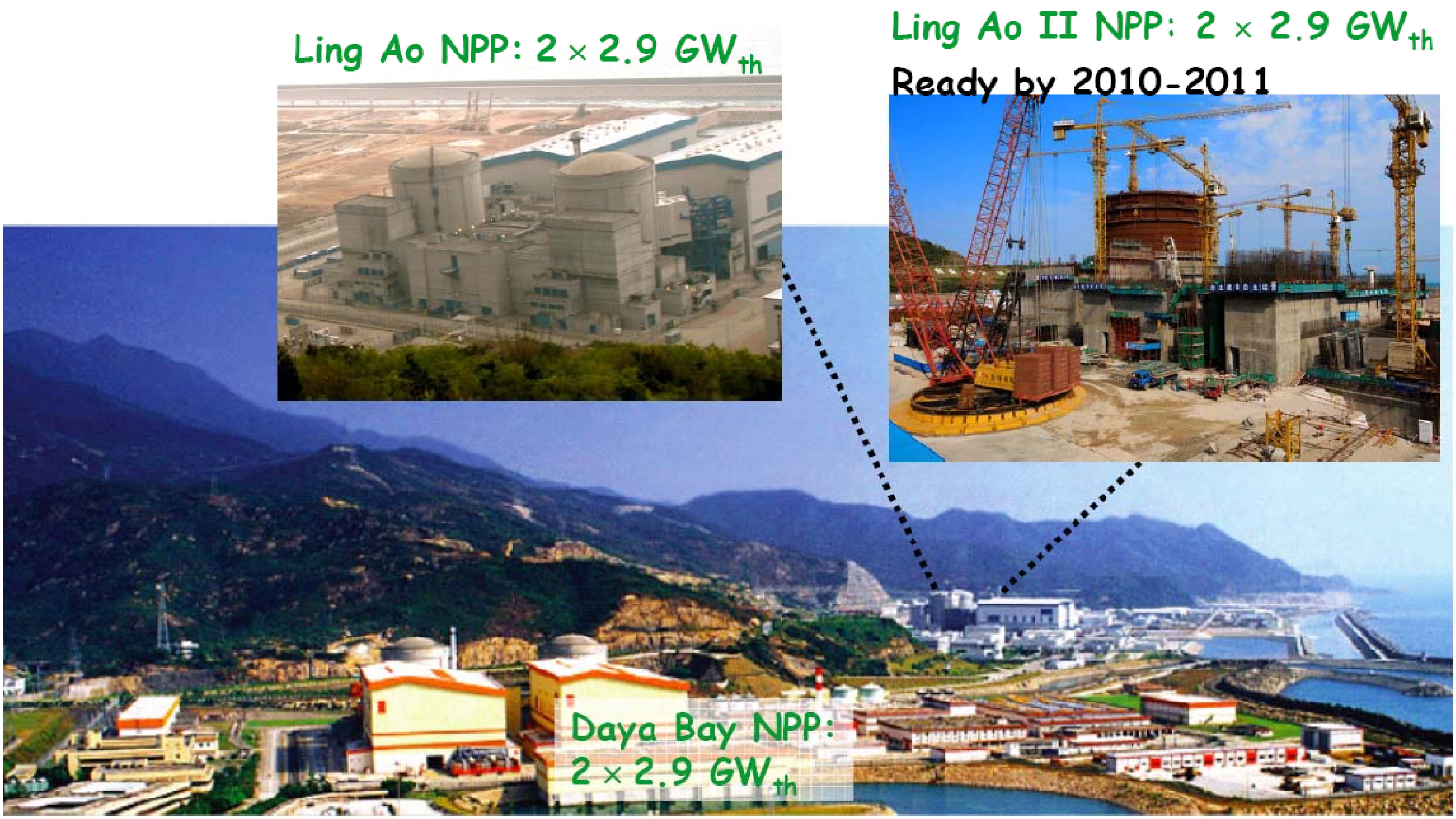
~211 collaborators

大亞灣 Daya Bay (China)

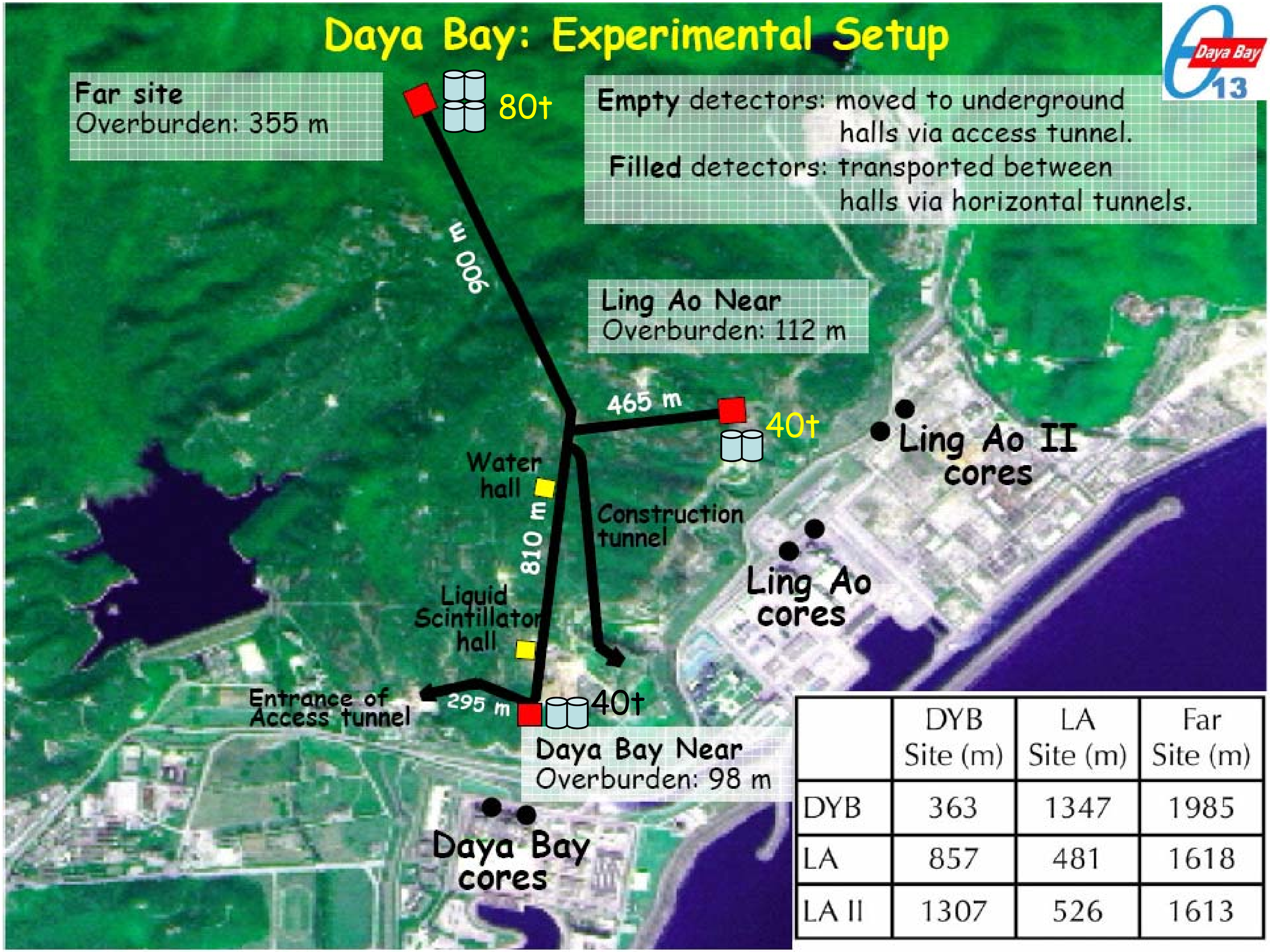


The Daya Bay Nuclear Power Complex

- 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 mountain, easy to construct tunnels to reach underground labs with sufficient overburden to suppress cosmic rays



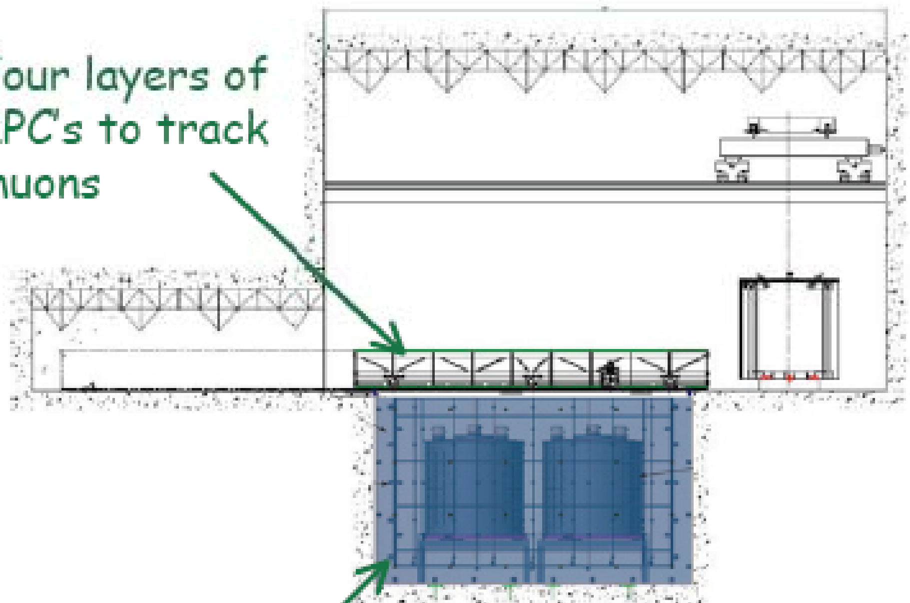
Daya Bay: Experimental Setup



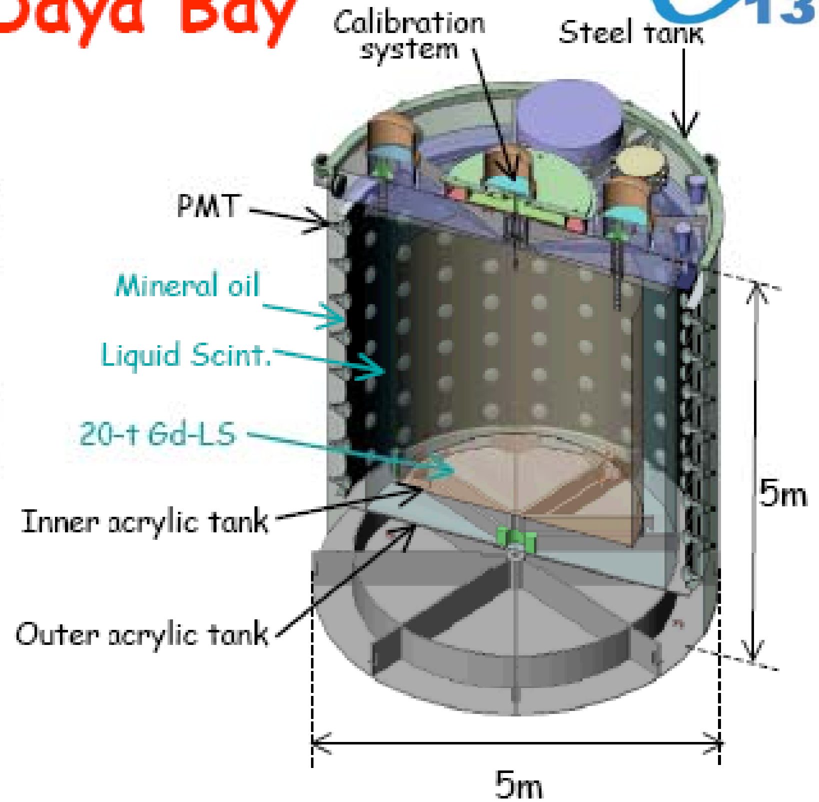
	DYB Site (m)	LA Site (m)	Far Site (m)
DYB	363	1347	1985
LA	857	481	1618
LA II	1307	526	1613

Detector Of Daya Bay

Four layers of RPC's to track muons



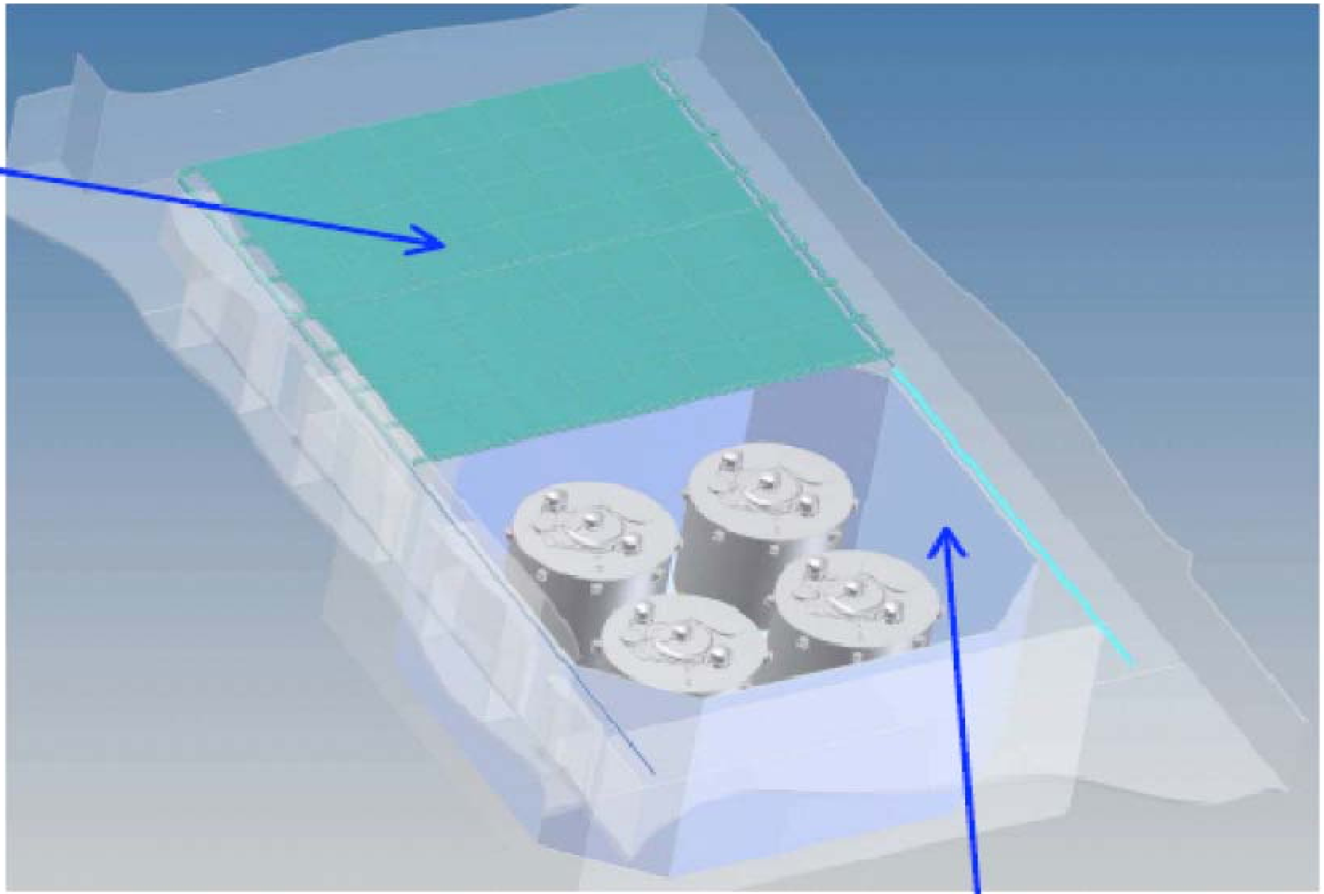
2.5m water shield also serves as Cherenkov counter for tagging muons



- Three-zone cylindrical detector design
  - Target: 20 t (0.1% Gd-doped LAB LS), 3.1 m
  - Gamma catcher: 20 t (LAB LS), 0.42 m
  - Buffer : 40 T (mineral oil) , 0.48 m
- Low-background 8" PMT: 192
- Reflectors at top and bottom of outer acrylic vessel
- Photocathode coverage:
  5.6 % → 12% (with reflectors)

Shielding and veto

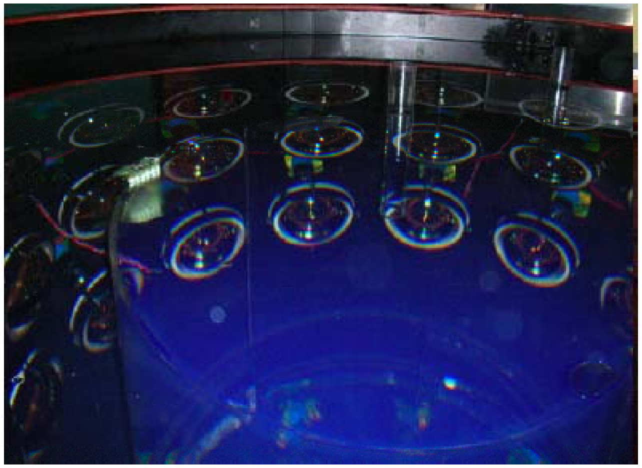
Four RPC's for tracking muons

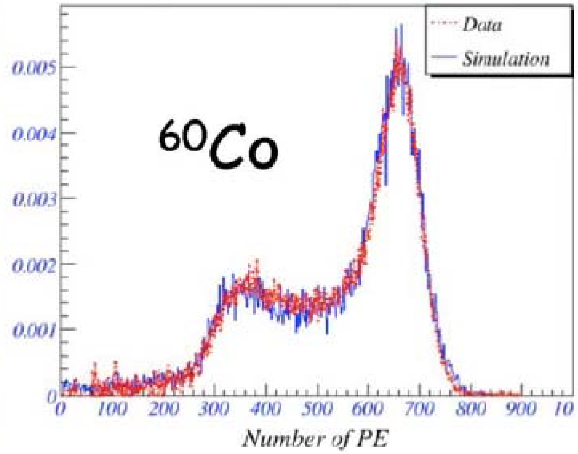


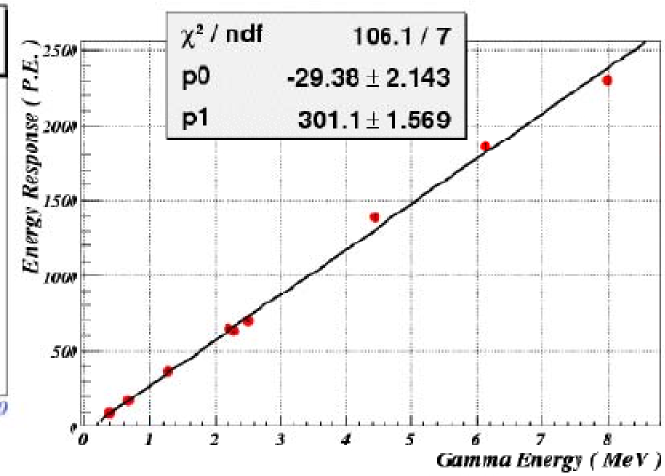
- At least 2.5 m of water surrounding AD's to attenuate ambient gamma rays and spallation neutrons from rock
- Instrumented to serve as water Cherenkov counters

Two-zone Prototype At IHEP

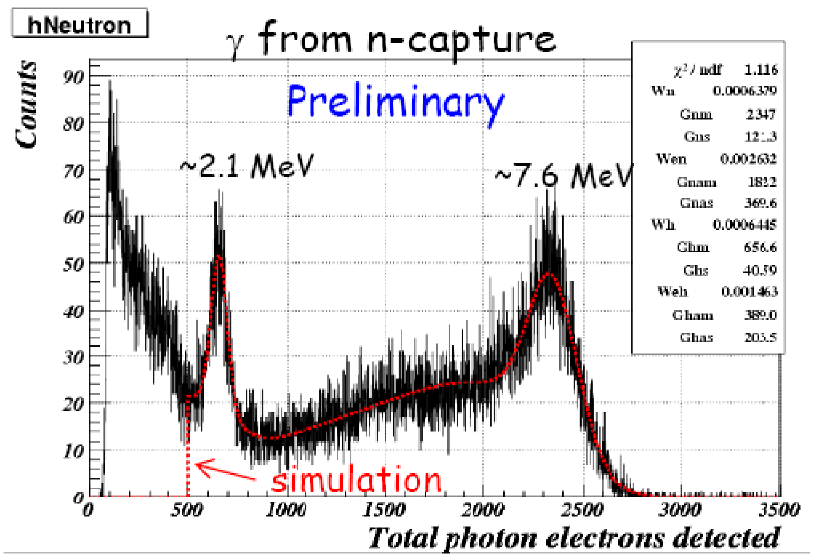
- 45 8" PMTs with reflectors at top and bottom
- Phase 1: 0.5 tonne **unloaded LAB-based LS** + mineral oil

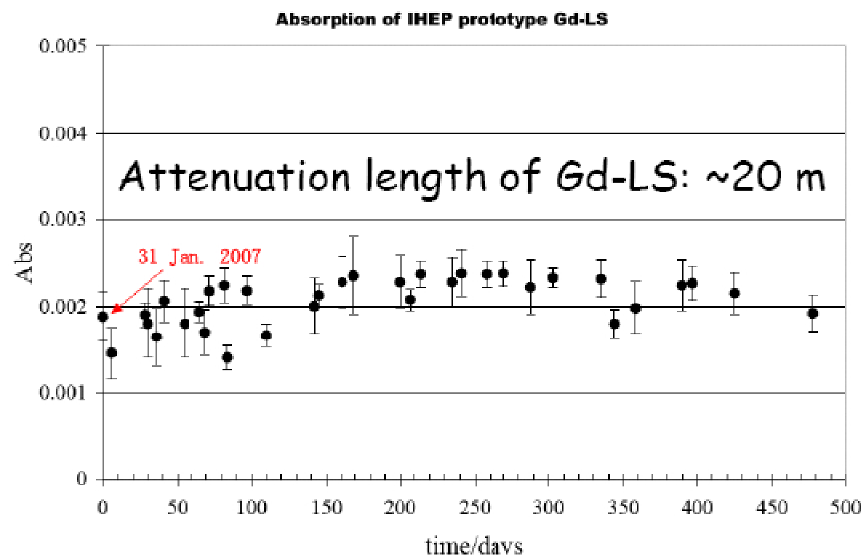






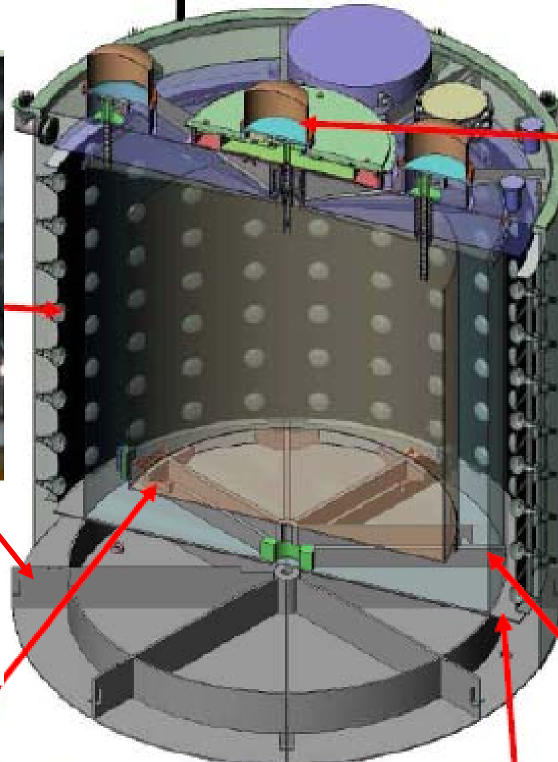
- Phase 2: 0.5 tonne **0.1% Gd-loaded LAB-based LS** + mineral oil





Full-size AD Component Prototypes

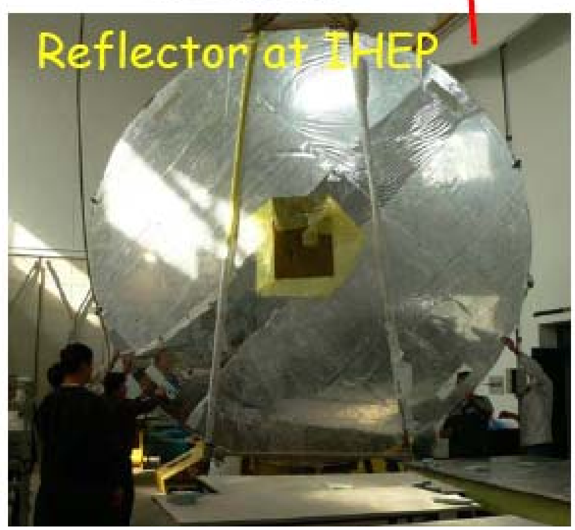
Stainless steel tank in China



Automatic calibration system

4-m prototype in the U.S.

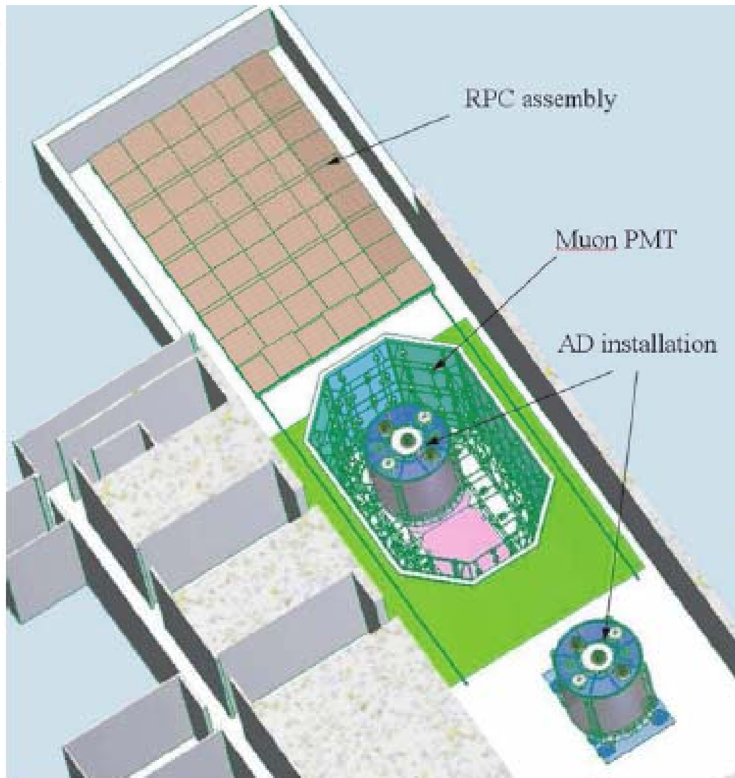
3-m prototype in Taiwan



Prototyping Muon System

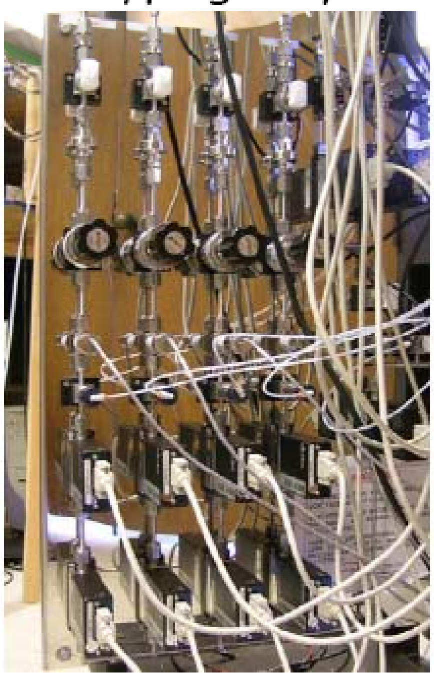
RPC module

- RPC on top of water pool
- Cherenkov detectors inside the water pool

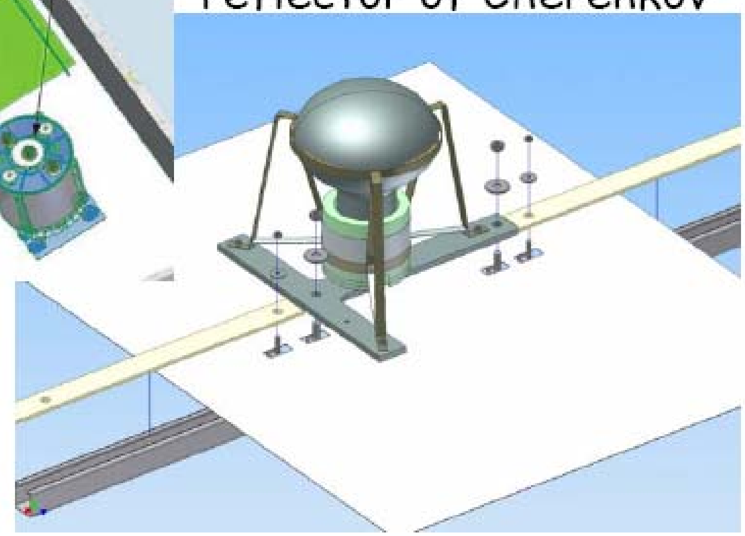


Water-proof 8" PMT

Prototype gas system



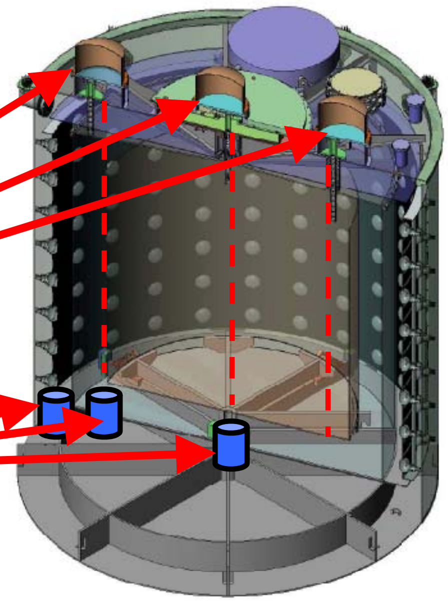
PMT mount and Tyvek reflector of Cherenkov



Calibration/Monitoring Program

- Initial commissioning of detector module:
  - complete characterization of detector properties
  - manual deployment system

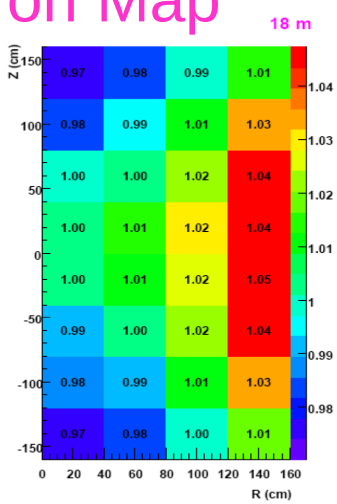
- Routine monitoring of detector modules:
  - weekly or monthly procedure
  - **3** <u>automated</u> systems per detector, <u>each</u> can deploy LED, ^{252}Cf, ^{68}Ge
  - monitoring system for optical properties
  - supplement with spallation product (e.g., neutrons) measurements:

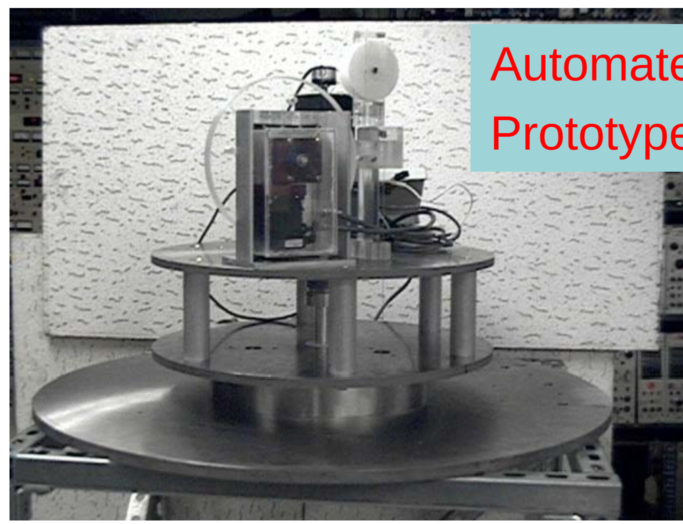


Spallation Neutron Map

σ/E = 0.5% per pixel requires:

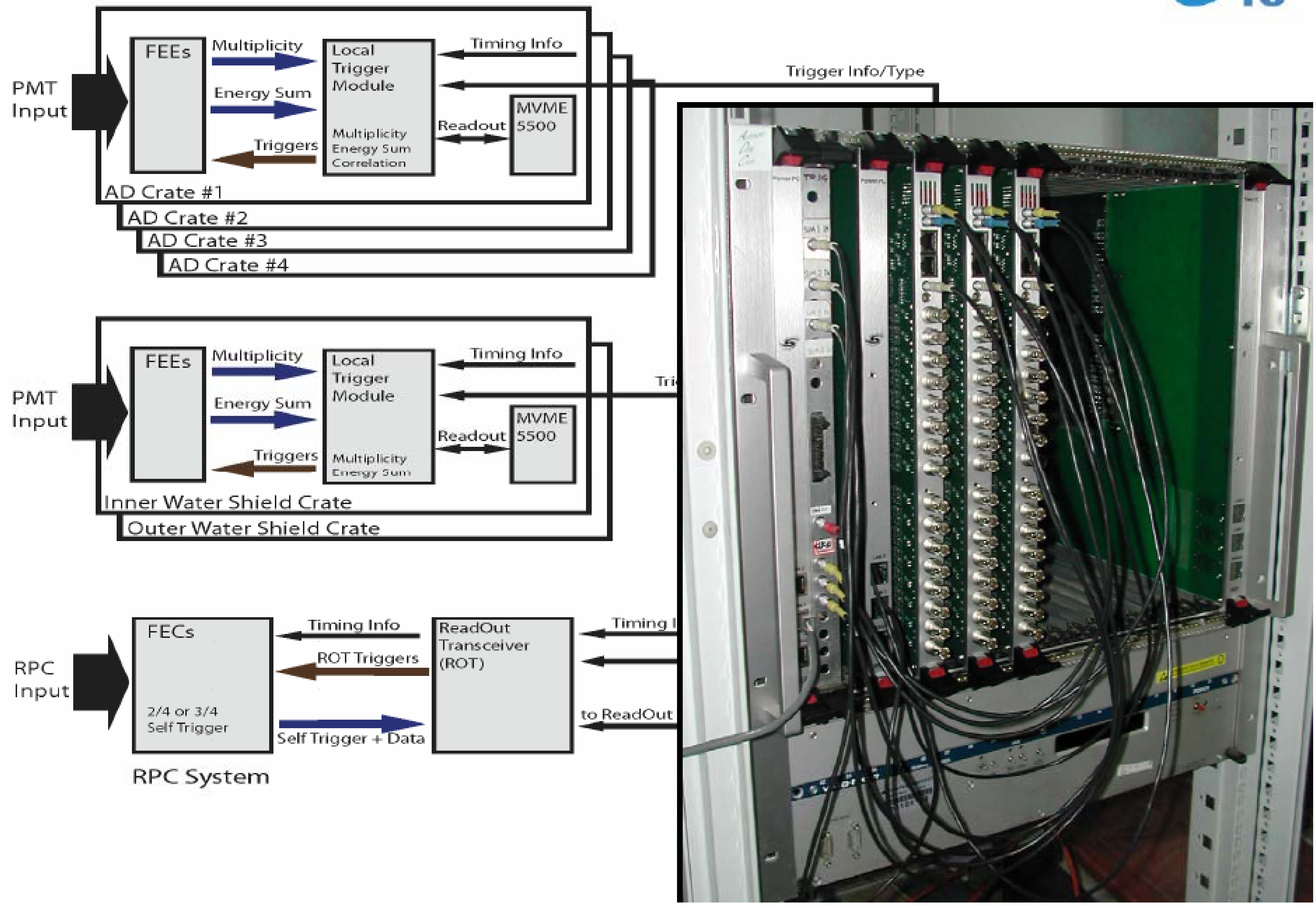
1 day (near)
10 days (far)





Automated System Prototype at Caltech

Front-end And Readout Electronics



Signal, Background, and Systematic

- Summary of signal and background:

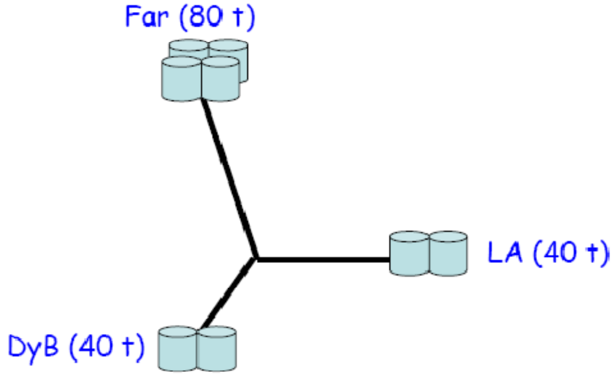
	Daya Bay Near	Ling Ao Near	Far Hall
Baseline (m)	363	481 from Ling Ao 526 from Ling Ao II	1985 from Daya Bay 1615 from Ling Ao
Overburden (m)	98	112	350
Radioactivity (Hz)	<50	<50	<50
Muon rate (Hz)	36	22	1.2
Antineutrino Signal (events/day)	930	760	90
Accidental Background/Signal (%)	<0.2	<0.2	<0.1
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 budgets:

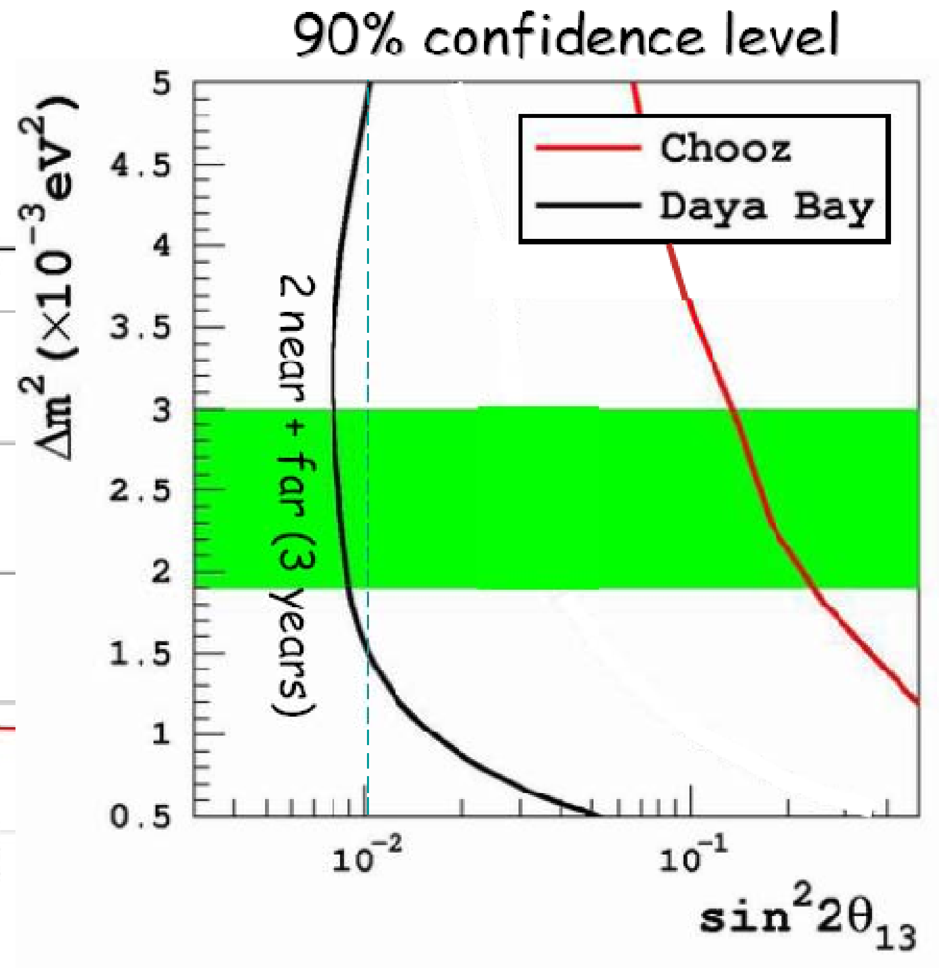
Source	Uncertainty
Reactor power	0.13%
Detector (per module)	0.38% (baseline) 0.18% (goal)
Signal statistics	0.2%

Sensitivity of Daya Bay

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



- Combine rate and spectral shape with a relative detector syst. uncertainty of 0.38%



Important Milestones

- Surface Assembly Building - Summer 2008
- DB Near Hall - installation activities begin early in 2009
- Assembly of first AD pair - Spring 2009
- Commission Daya Bay Hall by November 2009
- LA Near and Far Hall - installation activities begin late in 2009
- Data taking with all eight detectors in three halls by Dec. 2010

Daya Bay is moving forward quickly

Summary

- θ_{13}: key to future measurements of the CP violating phase, fundamental importance to particle physics/astrophysics/cosmology
- Daya Bay will reach a sensitivity of ≤ 0.01 for $\sin^2 2\theta_{13}$
- Civil construction has begun
- Almost all subsystem prototypes completed
- Long-lead orders initiated
- Daya Bay will start data-taking in Dec. 2010

Backup slides

Detecting $\bar{\nu}$ in liquid scintillator: Inverse β Decay

- The reaction is the inverse β-decay in 0.1% Gd-doped liquid scintillator:

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

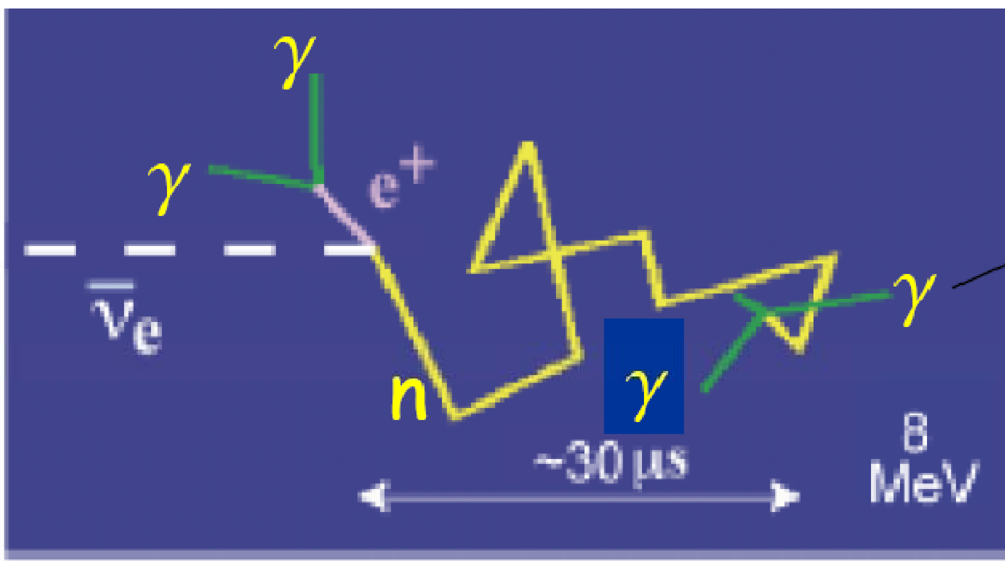
0.3b: $\rightarrow + p \rightarrow D + \gamma(2.2\ \text{MeV})$ (delayed)

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

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

Gd (Gadolinium) increases both the neutron capture efficiency and the gamma energy dramatically.

- Time- and energy-tagged signal is a good tool to suppress background events.

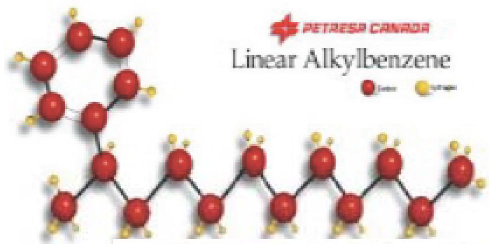


A 1 MeV gamma is converted to ~ 9,000 visible photons in liquid scintillator

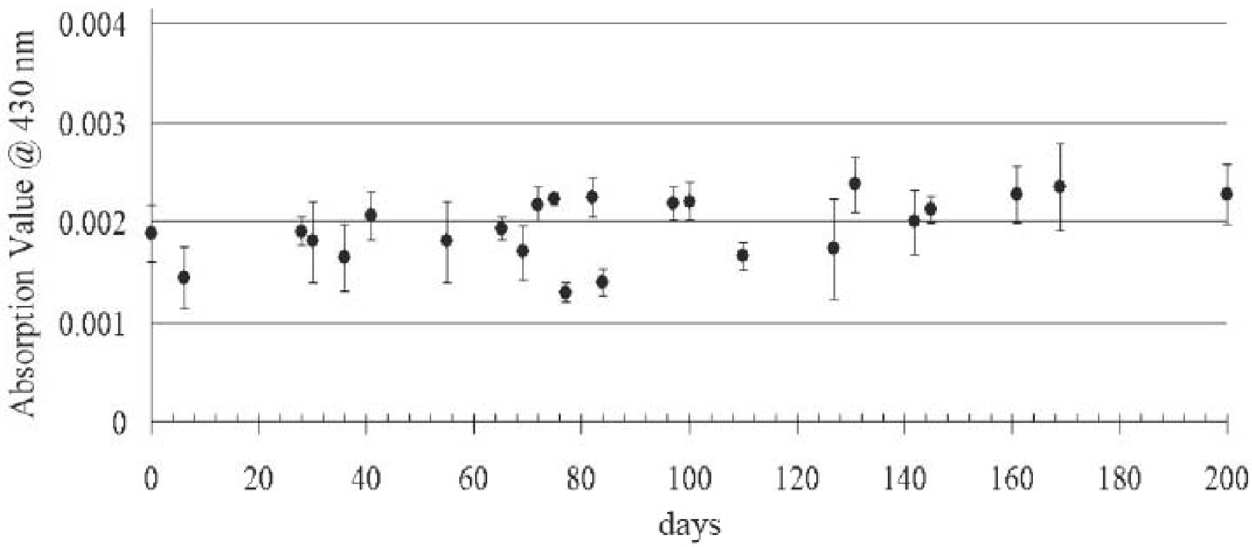
Detected by PMTs (Photomultiplier Tubes)

Gd-Liquid Scintillator

- Use LAB (Linear Alkyl Benzene):
  - high light yield, ~50% of anthracene
  - long attenuation length, > 10 m @ 430 nm
  - high flash point, ~130 °C
  - no EH&S issues
  - compatible with many plastics
  - cheap (raw material for making detergent)



- 0.1% Gd-LAB with 3 g/l PPO and 15 mg/l Bis-MSB



Systematic Uncertainties

- Reactor-related:

Near detectors really help !

Number of cores	α	σ_ρ(power)	σ_ρ(location)	σ_ρ(total)
4	0.338	0.035%	0.08%	0.087%
6	0.392	0.097%	0.08%	0.126%

- Detector-related:

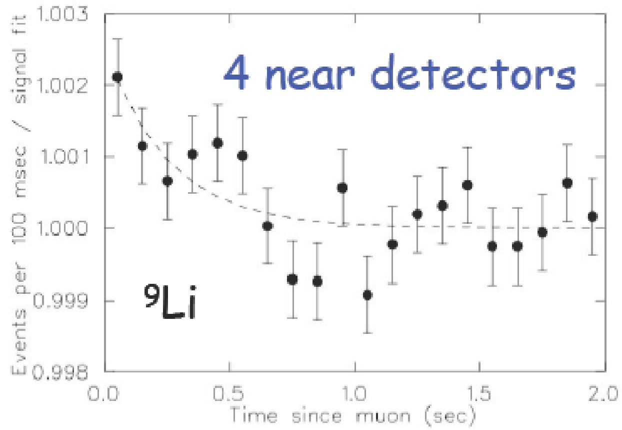
Source of uncertainty		Chooz *(absolute)*	Daya Bay *(relative)* Baseline	Goal	Goal w/Swapping
# protons	H/C ratio	0.8	0.2	0.1	0
	Mass	-	0.2	0.02	0.006
Detector Efficiency	Energy cuts	0.8	0.2	0.1	0.1
	Position cuts	0.32	0.0	0.0	0.0
	Time cuts	0.4	0.1	0.03	0.03
	H/Gd ratio	1.0	0.1	0.1	0.0
	n multiplicity	0.5	0.05	0.05	0.05
	Trigger	0	0.01	0.01	0.01
	Live time	0	< 0.01	< 0.01	< 0.01
Total detector-related uncertainty		1.7%	0.38%	0.18%	0.12%

anticipated

with R&D

Background

- Uncorrelated background:
  Sources: U/Th/K/Rn/neutron
  Single gamma rate @ 0.9MeV < 50Hz/module
  Single neutron rate < 1000/day/module
- Correlated backgrounds: $n \propto E_{\mu}^{0.75}$
  Fast Neutrons: double coincidence
  $^{8}He/^{9}Li$: beta-neutron emitting decays
- All these background events can be measured and corrected



Per module	Daya Bay Near	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's
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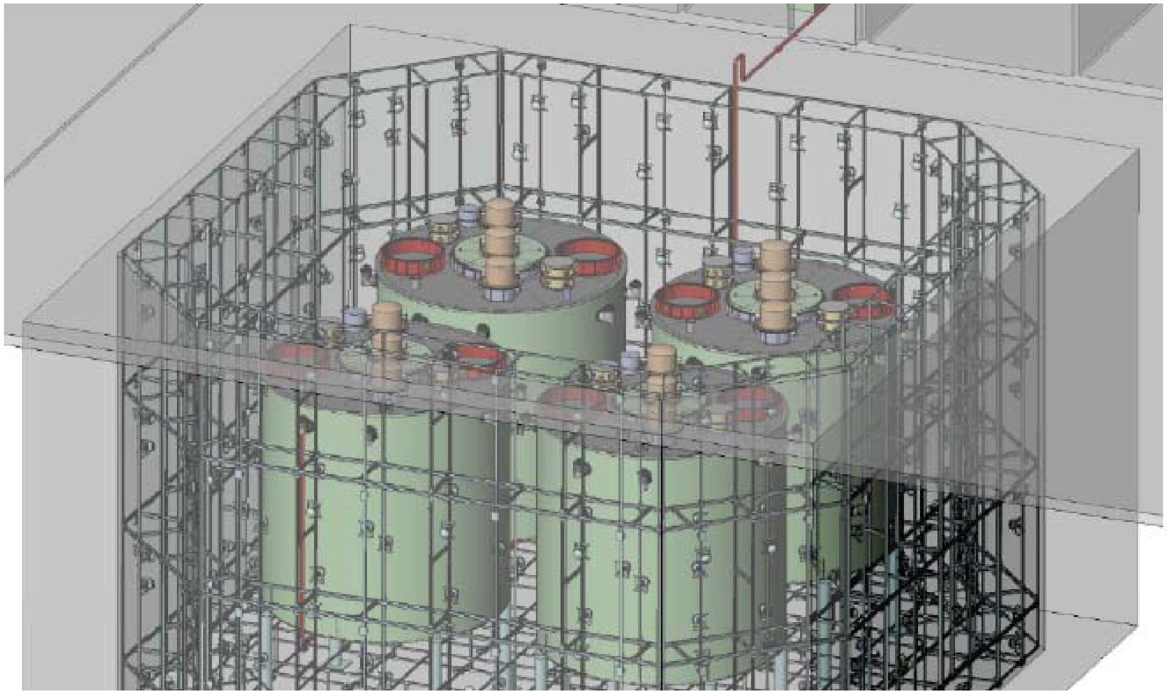
Water Pool - Two Regions

- Divided by Tyvek into Inner and Outer regions
- Reflective Paint on ADs improves efficiency
- Calibration LEDs placed around the pool for calibration

160 PMTs (Inner)
224 PMTs (Outer)

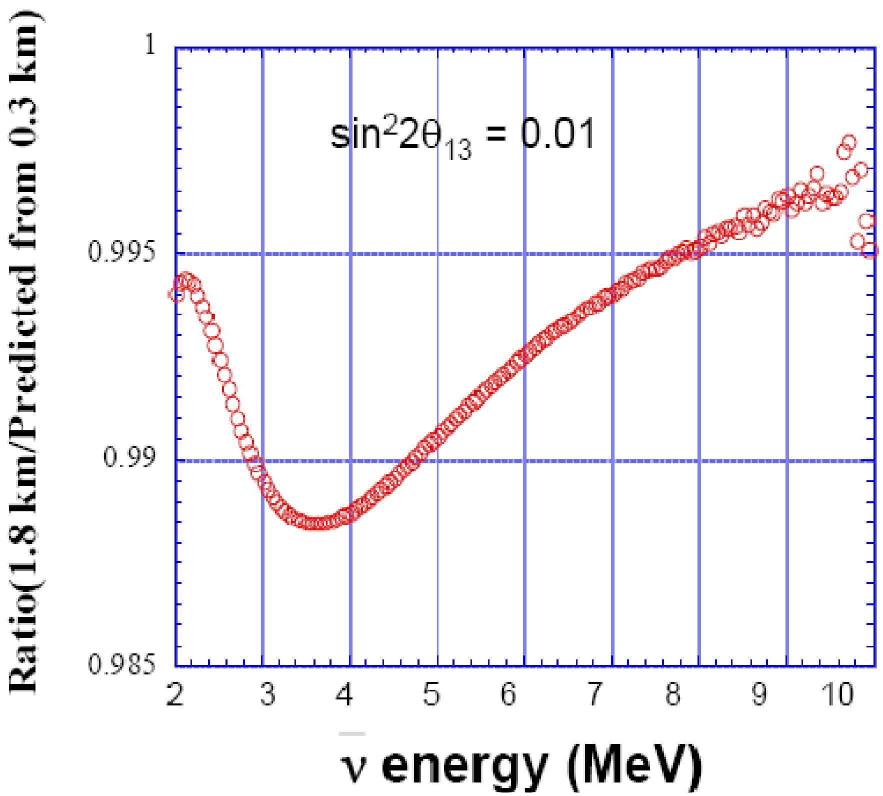


Daya Bay: Goal And Approach

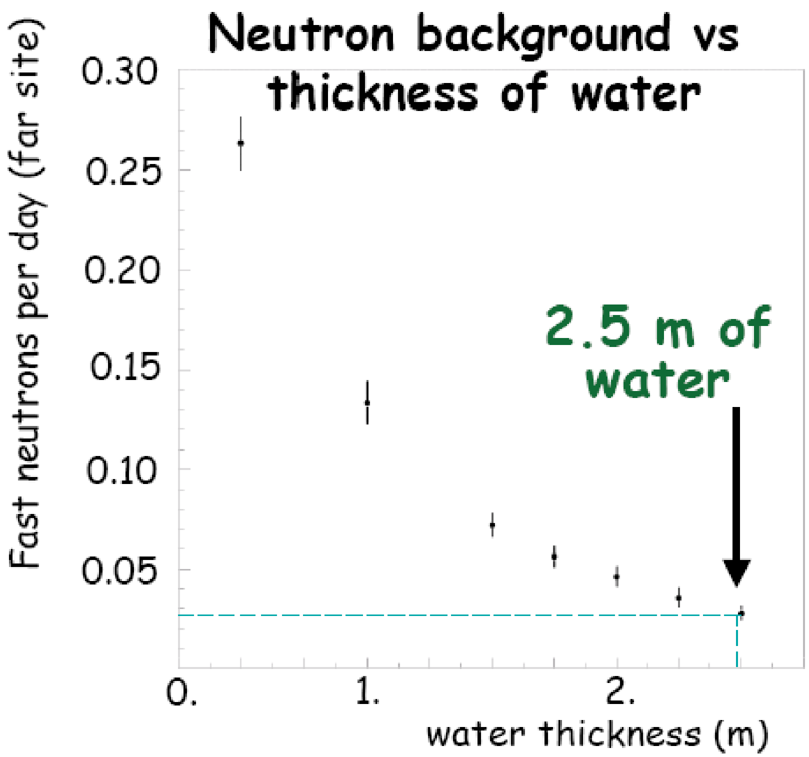
Utilize the Daya Bay nuclear power complex to:

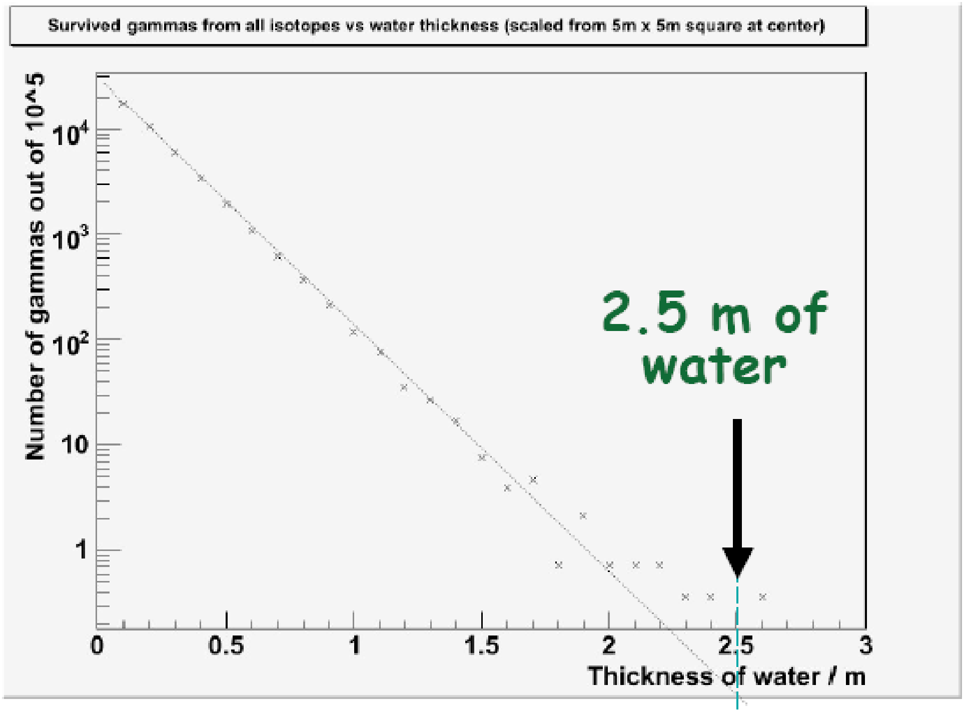
determine $\sin^2 2\theta_{13}$ with a sensitivity of 0.01

by measuring deficit in $\bar{\nu}_e$ rate and spectral distortion.



Shielding Antineutrino Detectors





- Detector modules enclosed by 2.5 m of water to shield energetic neutrons produced by cosmic-ray muons and gamma-rays from the surrounding rock

Borrowed from Kam-biu Luk

Detector Systematic Uncertainty Control

Some examples:

- Acrylic vessels and liquid scintillator
  - manufactured and filled in pairs with a common storage tank
- Target mass
  - load cells to measure target mass to 0.1%
  - flow meter during filling 0.1%
  - overflow tank liquid level monitoring
- Energy calibration to reach 0.1% relative uncertainty
  - automated calibration: ^{68}Ge(positron), ^{252}Cf(neutron) & LED
  - 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), ^{252}Cf(neutron)