The Daya Bay Experiment to Measure θ_{13}

Herbert Steiner

UC Berkeley & LBNL

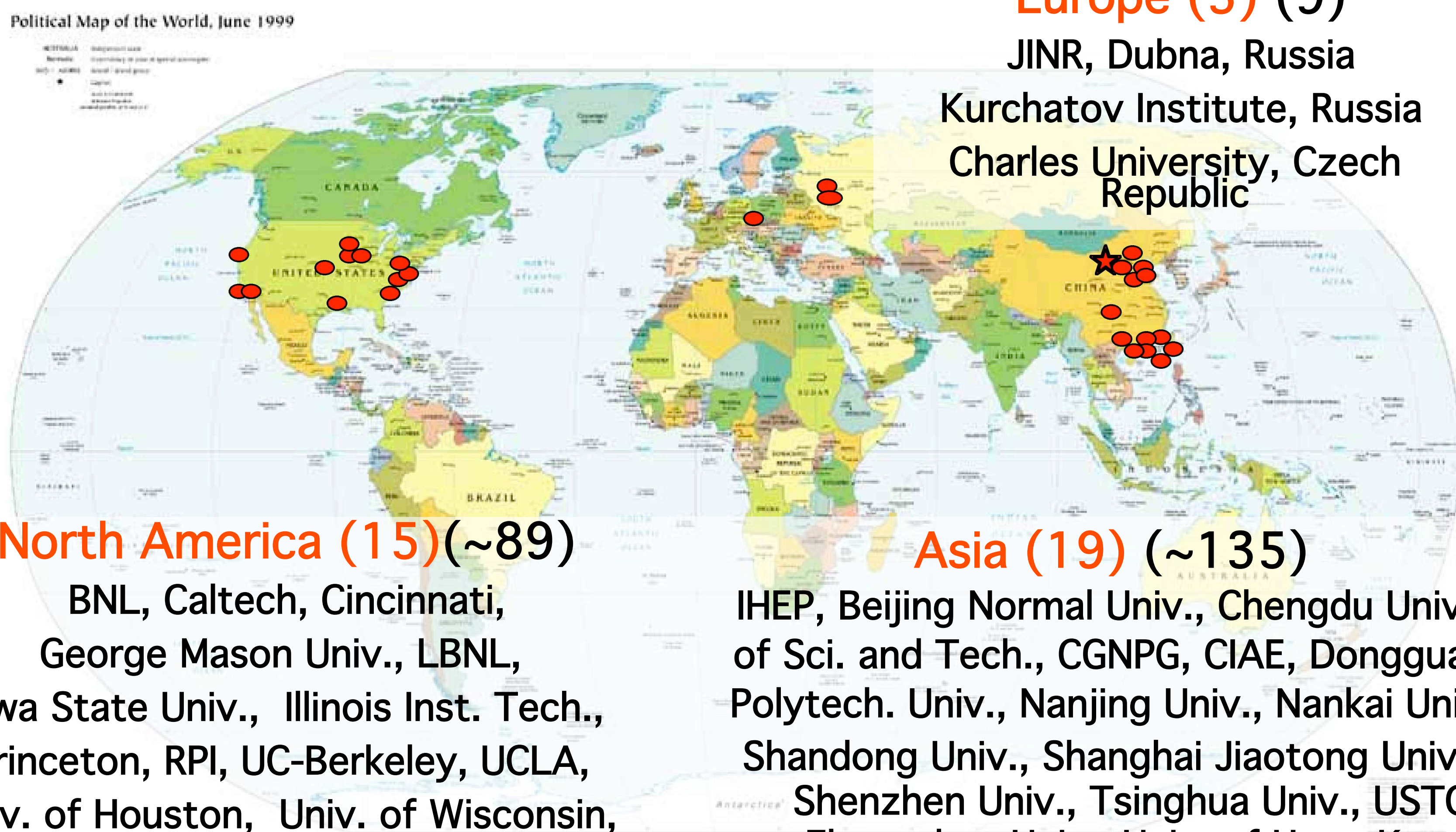
On behalf of the Daya Bay Collaboration

Presented at the Erice School/Workshop on "Neutrinos in Cosmology,in Astro, in Particle and in Nuclear Physics"
Erice/Sicily/Italy, September 21, 2009

Outline

- Overview
- Physics
- Detector
- Backgrounds
- Calibration
- Schedule

The Daya Bay Collaboration



Europe (3) (9)

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

North America (15)(~89)

BNL, Caltech, Cincinnati, 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 (19) (~135)

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

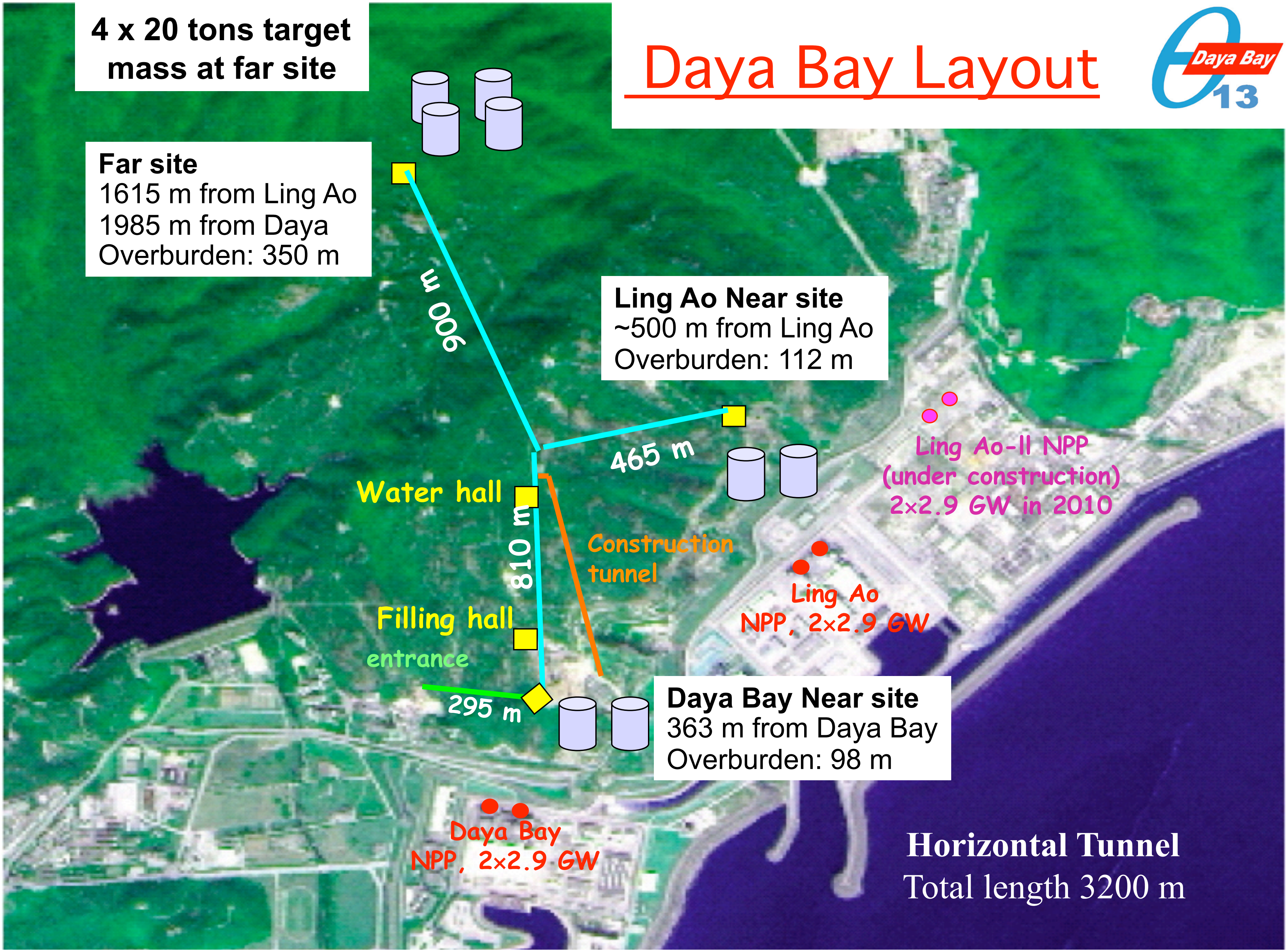
~ 233 collaborators

Location of the Daya Bay Nuclear Power Plant

The Daya Bay Nuclear Power Plant

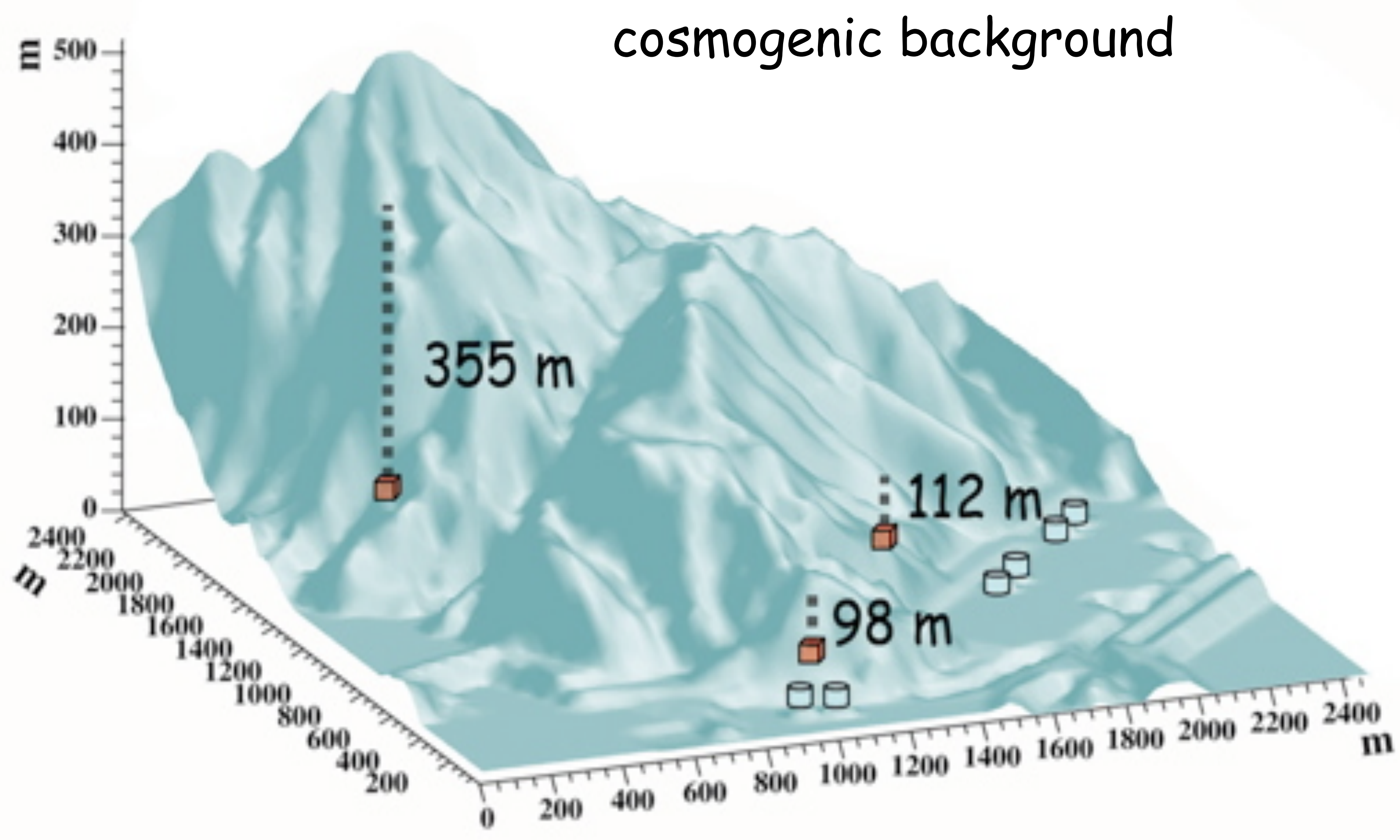
- 12th most powerful in the world (11.6 GW)
- Top five most powerful by 2011 (17.4 GW)
- Adjacent to mountain, easy to construct tunnels to reach underground labs with sufficient overburden to suppress cosmic rays

Daya Bay Layout



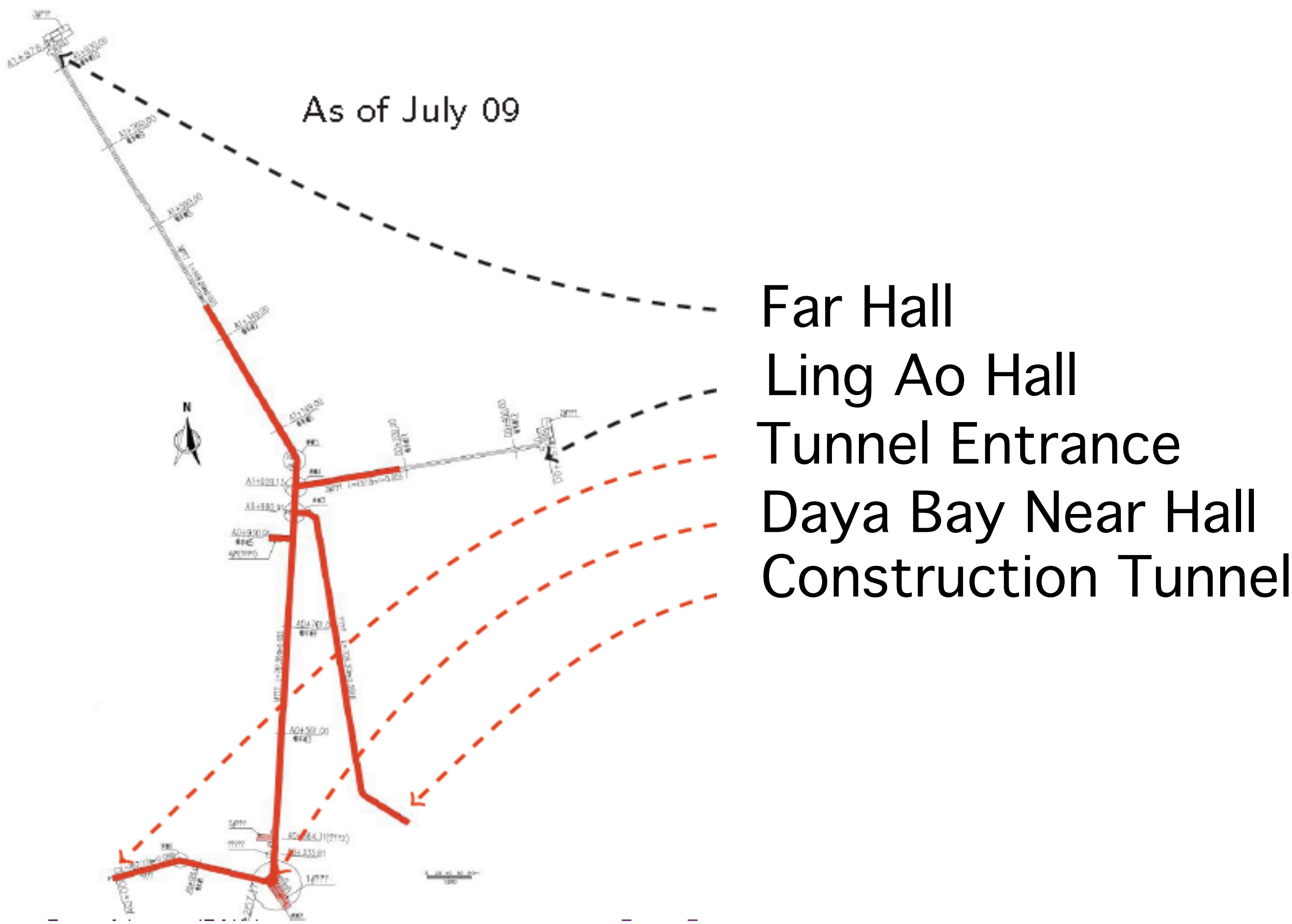
Topography

Excellent overburden to reduce cosmogenic background



Tunnel Construction Status (July '09)

Civil Status - Excavation

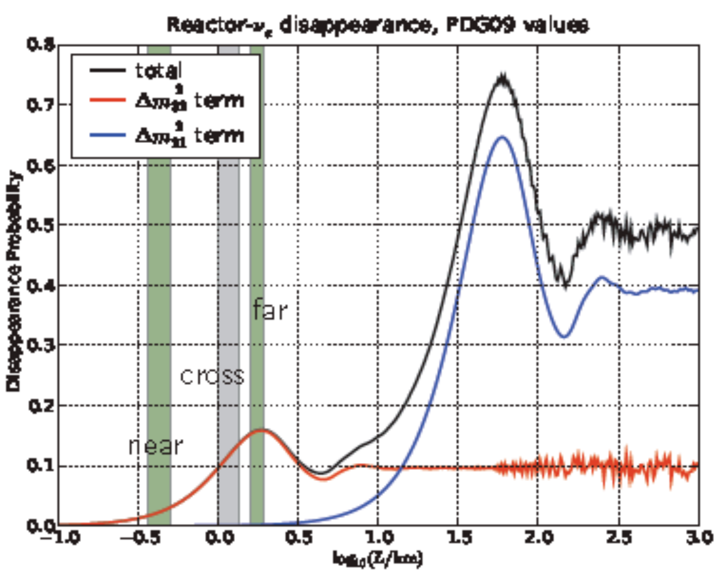


Position Sensitivity

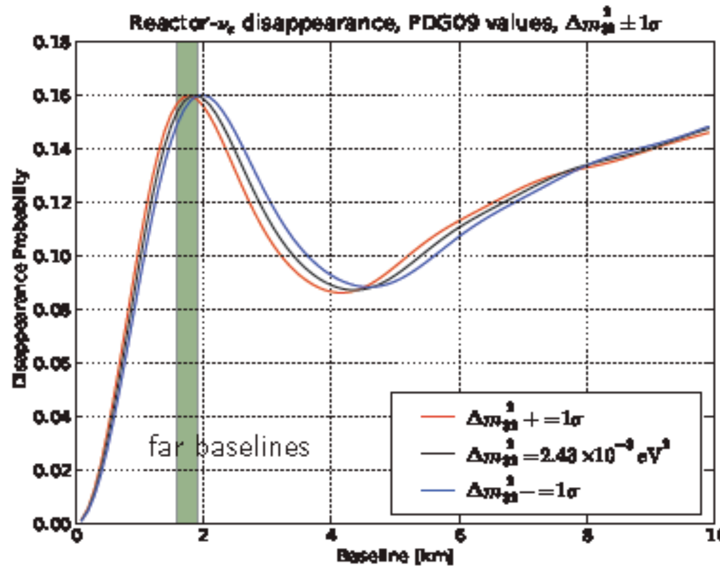
Positioning for $\bar{\nu}_e$ Disappearance

For $\Delta m^2_{32} \gg \Delta m^2_{21}$:

$$P(\nu_e \nrightarrow \nu_e) \approx \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right) + \sin^2(2\theta_{12}) \cos^4(\theta_{13}) \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$



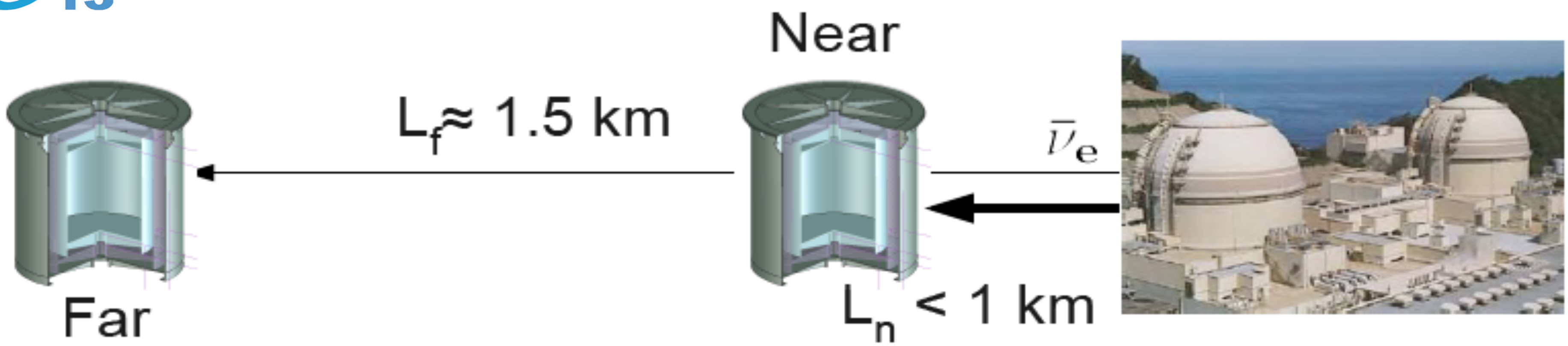
Maximizing sensitivity to θ_{13}.



Robust against changing Δm^2_{32}.

Probabilities smeared over reactor-$\bar{\nu}$ interaction spectrum.

Method



$$\frac{N_{far}}{N_{near}} = \left(\frac{N_{P.far}}{N_{P.near}}\right)\left(\frac{L_{near}}{L_{far}}\right)^2\left(\frac{\varepsilon_{far}}{\varepsilon_{near}}\right)\left(\frac{P_{surv}(E,L_{far})}{P_{surv}(E,L_{near})}\right)$$

Measured ratio of Rates

Proton Number Ratio

Detector Efficiency Ratio

$\sin^2 2\theta_{13}$

Filling Gd-LS and Mass measurement

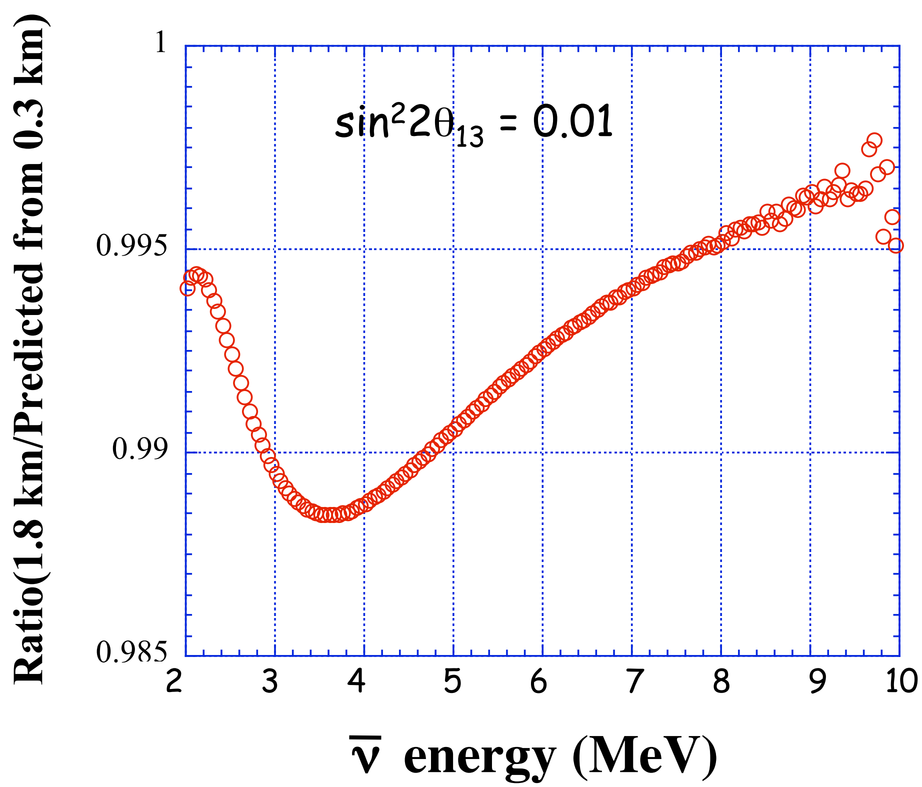
Calibration Systems

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.



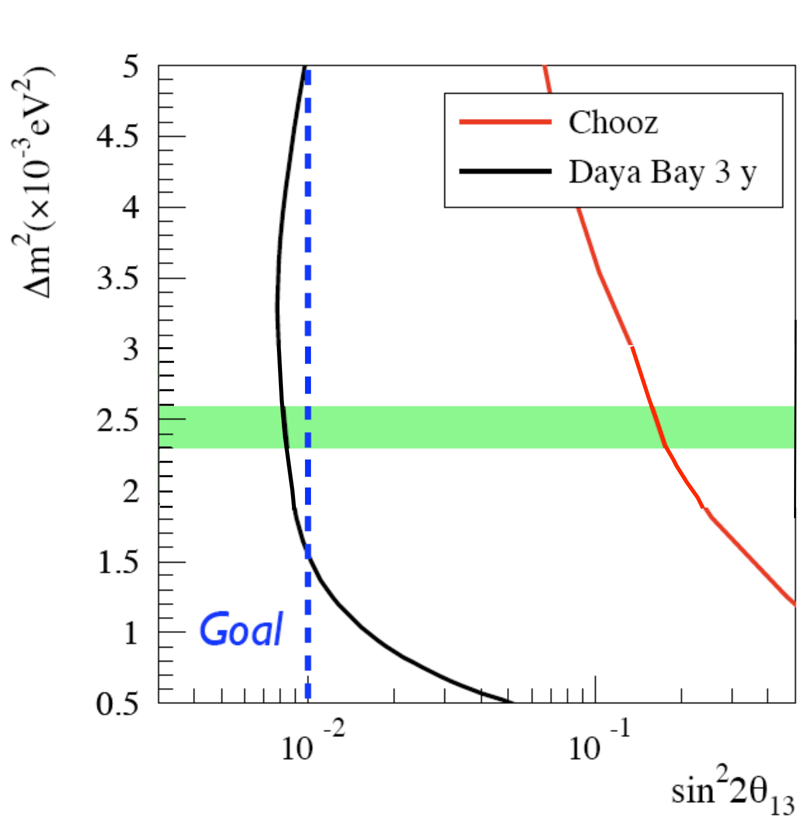
How to measure $\sin^2 2\theta_{13}$ to 0.01

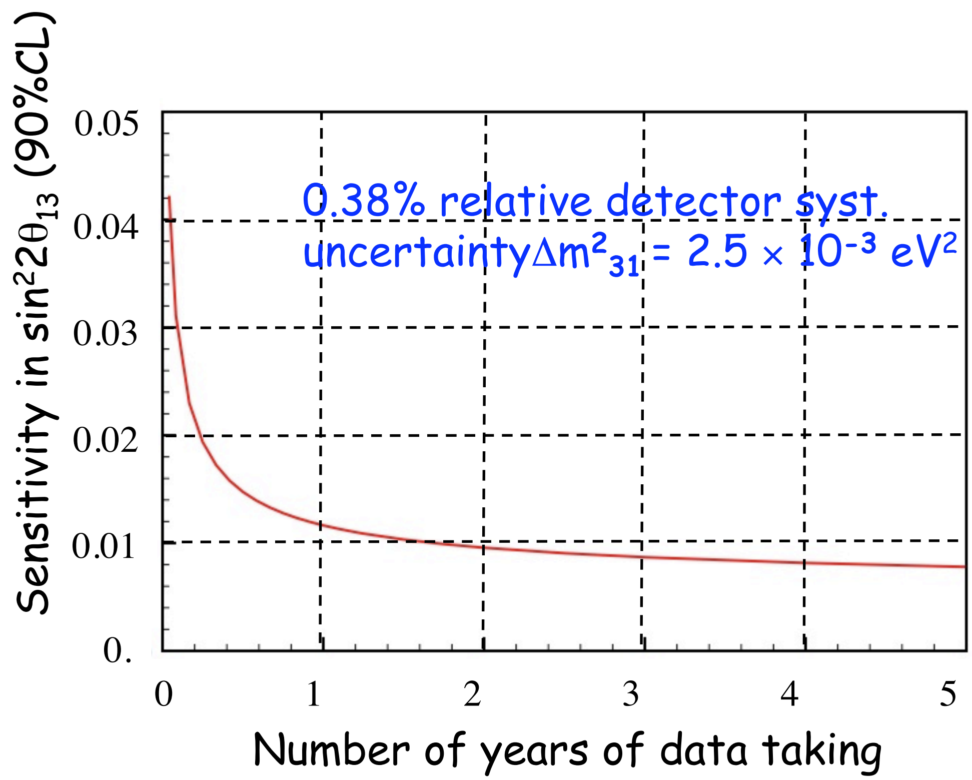
Reduce systematic uncertainties:

- Reactor-related:
  - Optimize baseline for best sensitivity and lowest residual errors
  - Near and far detectors to minimize reactor-related errors
- Detector-related:
  - Use "Identical" pairs of detectors to do relative measurement
    - Fill all detectors with same batch of Gd-LS.
  - Comprehensive program in calibration/monitoring
    - Side-by-side calibration
- Background-related
  - Go as deep as possible to reduce cosmic-induced backgrounds
  - Enough active and passive shielding
    - B/S ~0.4% Near
    - B/S ~0.2% Far

Sensitivity of Daya Bay

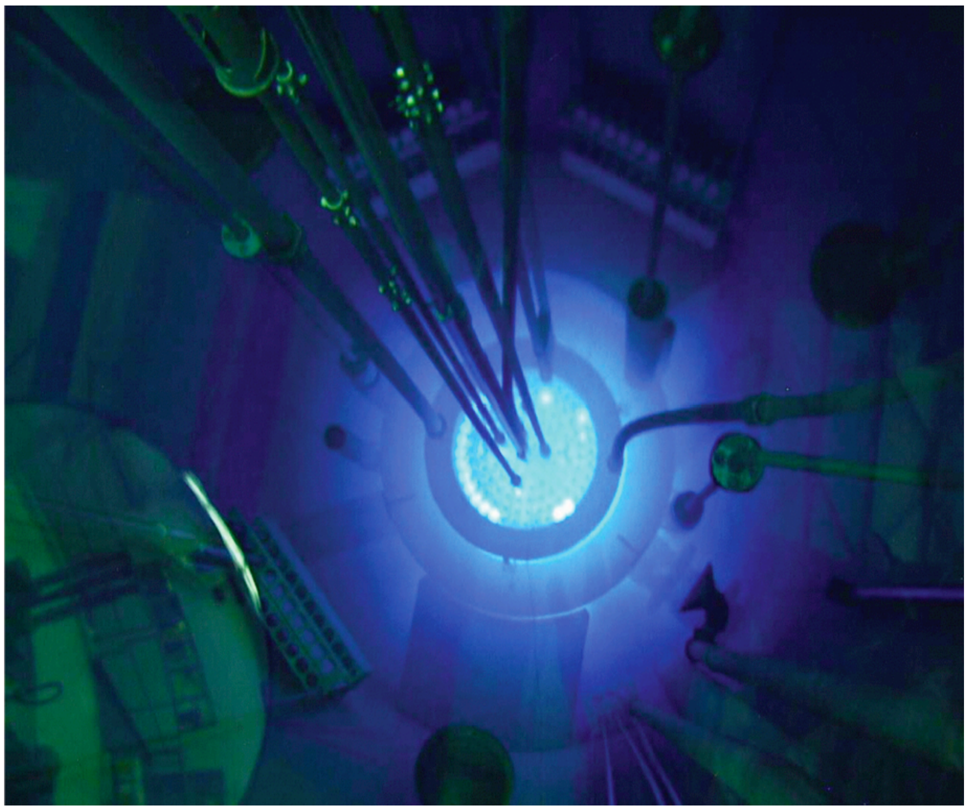
$\sin^2 2\theta_{13} < 0.01$ @ 90% CL in 3 years of data taking



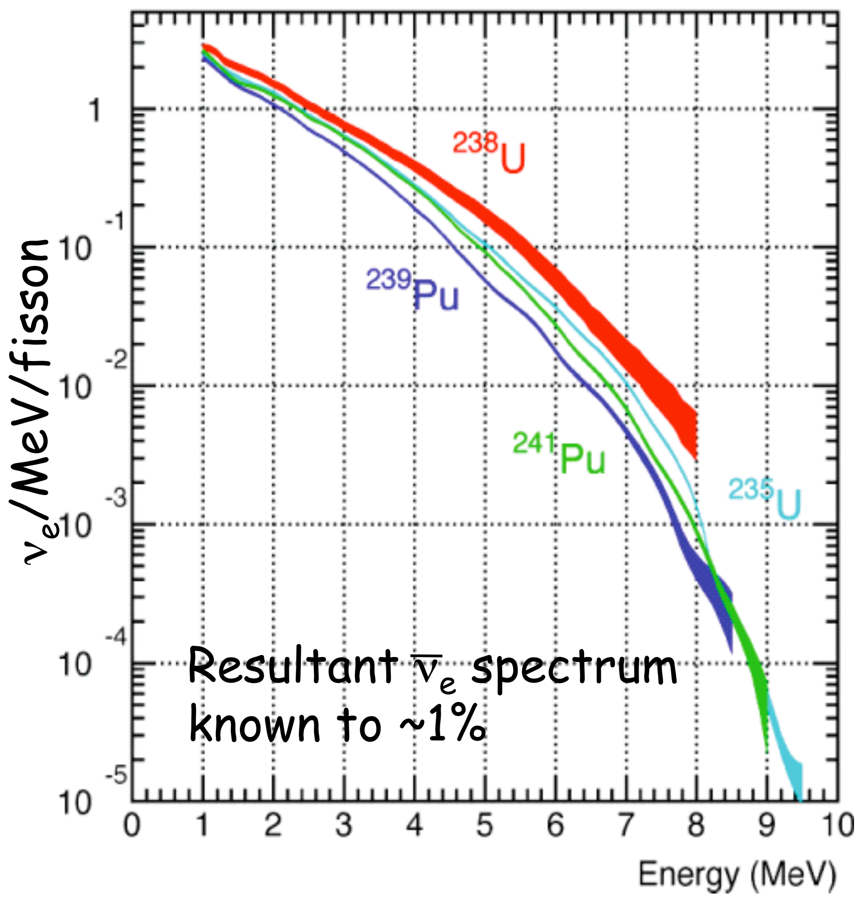


Reactor $\bar{\nu}_e$

- Fission processes in nuclear reactors produce a huge number of low-energy $\bar{\nu}_e$



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



Detecting $\bar{\nu}_e$ in liquid scintillator

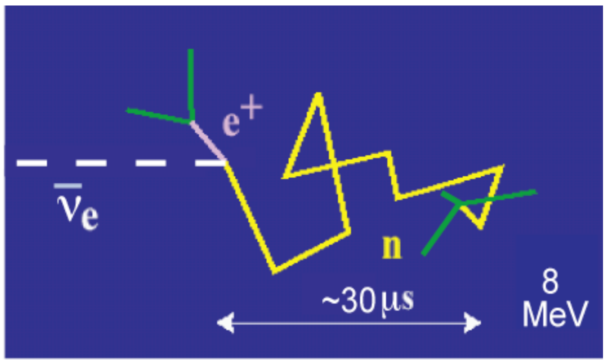
- Detect inverse β-decay reaction in 0.1% Gd-doped liquid scintillator:

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

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)

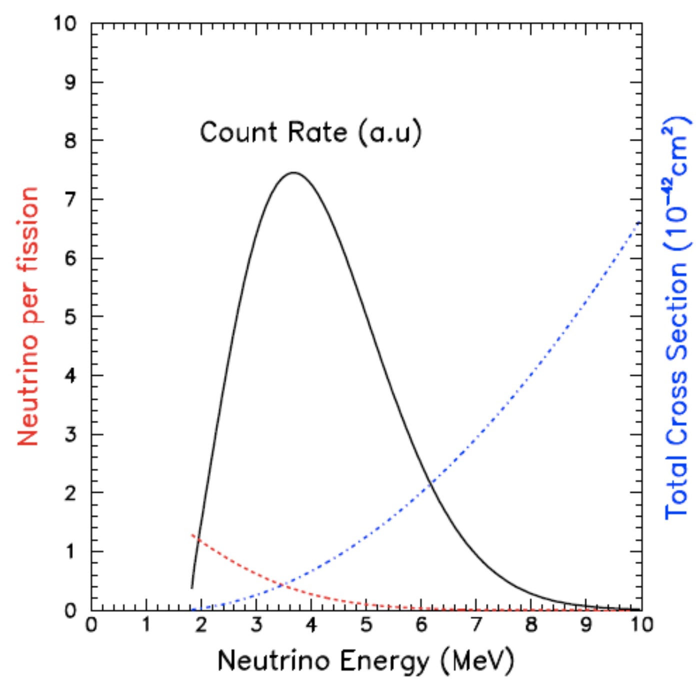


- Time- and energy-tagged signal is a good tool to suppress background events.

- Energy of $\bar{\nu}_e$ is given by:

$$E_{\bar{\nu}} \approx T_{e+} + T_n + (m_n - m_p) + m_{e+} \approx T_{e+} + 1.8\text{ MeV}$$

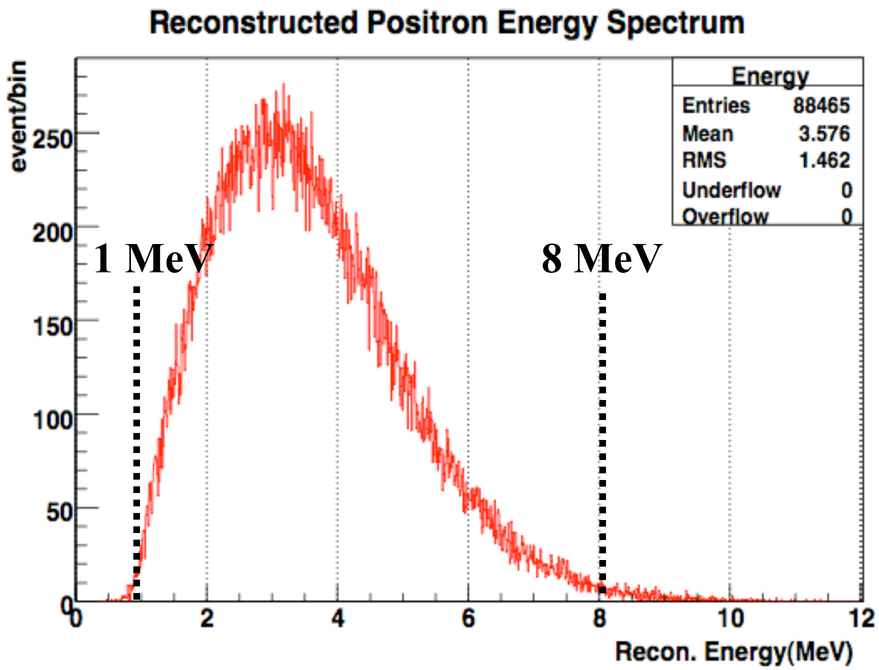
10-40 keV



Detection of $\bar{\nu}_e$

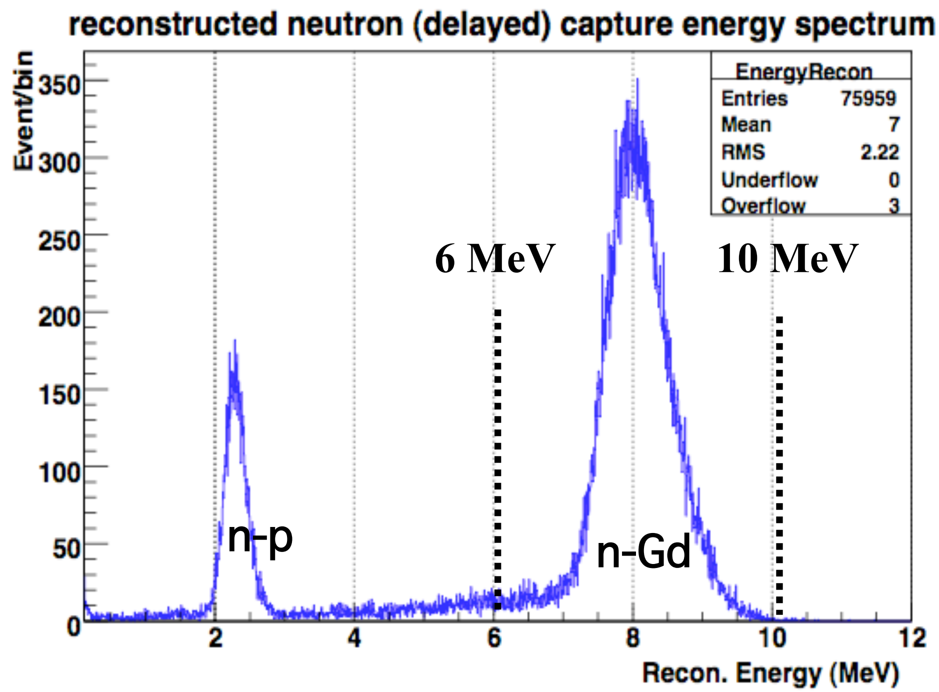
Inverse β-decay in Gd-doped liquid scintillator:

Prompt Energy Signal



- E_{e+}(“prompt”) ∈[1,8] MeV
- $E_{n\text{-}cap}$ (“delayed”) ∈ [6,10] MeV
- $t_{delayed}$-t_{prompt} ∈ [0.3,200] μs

Delayed Energy Signal



Coincidence of prompt positron and delayed neutron signals helps to suppress background events

Expected Antineutrino Rates

(Per Day per Module)

Site	Rate
DYB	840
LA	740
Far	90

Systematic Uncertainty Control

- Acrylic vessels 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 0.1%
  - overflow tank liquid level monitoring with ultrasonic devices
- Energy calibration to reach relative uncertainty 0.1%
  - 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)

Sources of Uncertainty

Detector Uncertainty Source		Baseline	Goal	Chooz Experience
Number of protons		0.3%	0.1%	0.8%
Detection Efficiency	Energy cuts	0.2%	0.1%	0.8%
	H/Gd ratio	0.1%	0.1%	1.0%
	Time cut	0.1%	0.03%	0.4%
	Neutron mult.	0.05%	0.05%	0.5%
	Trigger	0.01%	0.01%	0.01%
	Live time	$< 0.01\%$	$< 0.01\%$	$< 0.01\%$
Total Uncertainty		0.38%	0.18%	1.7%
		Two detector **relative** uncertainty		One detector **absolute** uncertainty

Backgrounds

Backgrounds

Backgrounds arise from cosmic-μs:

Accidental coincidence :

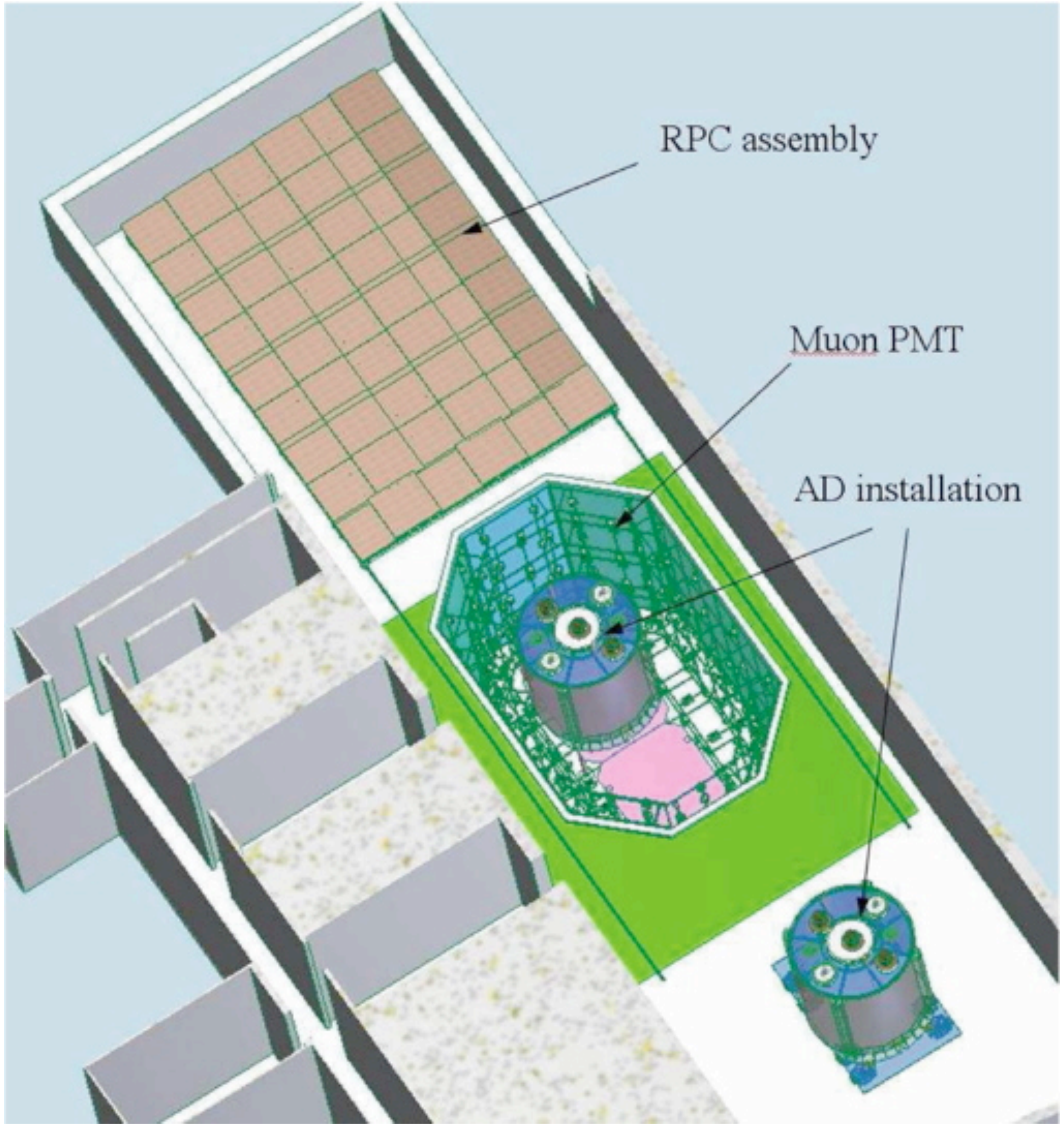
- natural radioactivity + neutrons from cosmic-μ.

Correlated events :

- Fast cosmogenic neutrons (recoil proton + n-capture),
- β+n decays of cosmogenic produced ^{9}Li and ^{8}He.
- Measurable by μ-tagging.

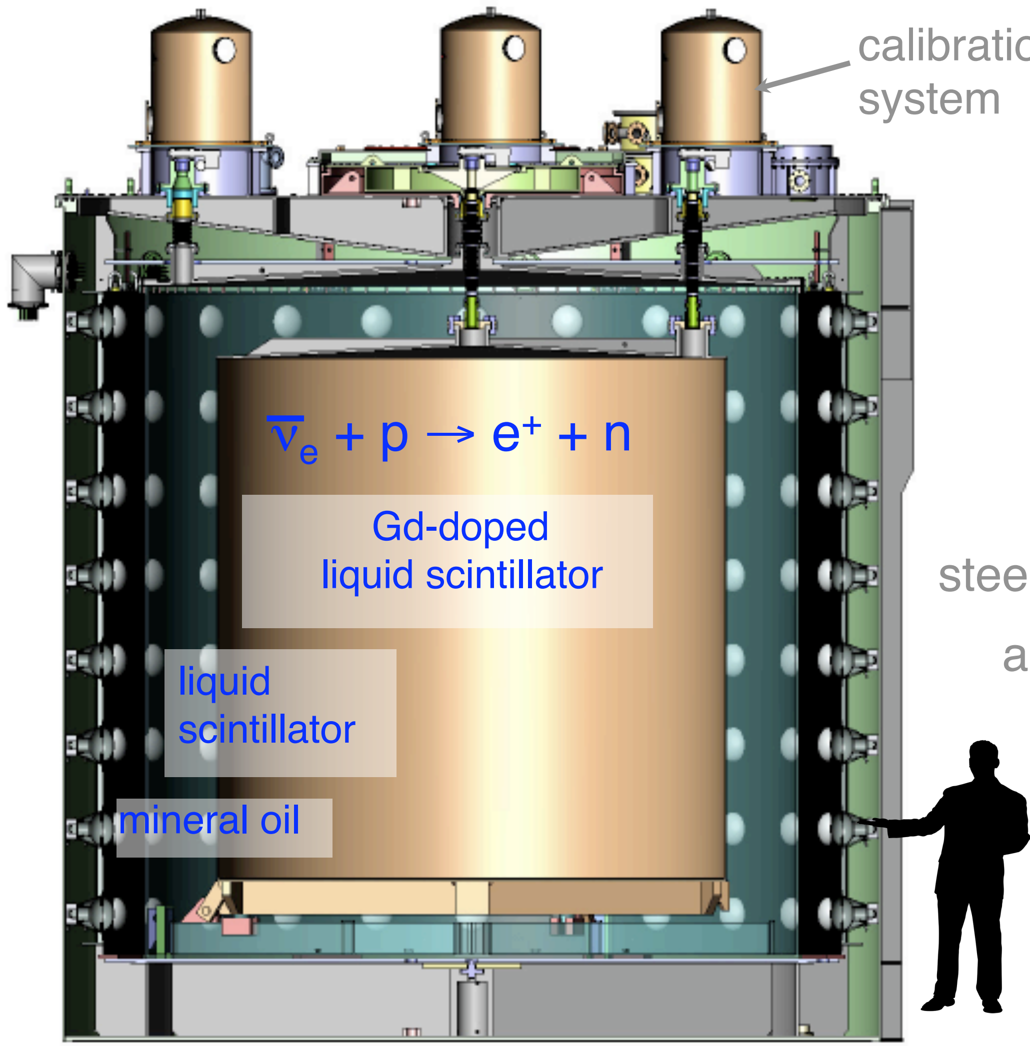
	Daya Bay Near	Ling Ao Near	Far Hall
Radioactivity (Hz)	<50	<50	<50
Muon rate / AD (Hz)	36	22	1.2
$\bar{\nu}_e$-Signal (events/day)	840	740	90
Accidental B/S (%)	<0.2	<0.2	<0.1
Fast neutron B/S (%)	0.1	0.1	0.1
^{8}He+^{9}Li B/S (%)	0.3	0.2	0.2

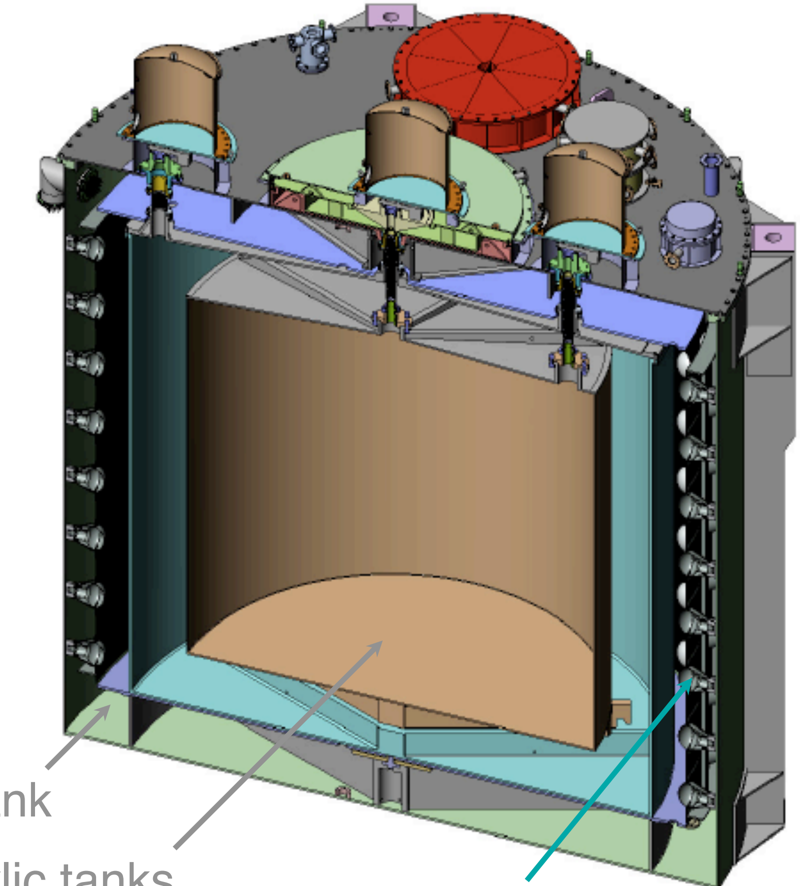
Layout in DBY Hall



Daya Bay Antineutrino Detector

- 8 “identical”, 3-zone detectors



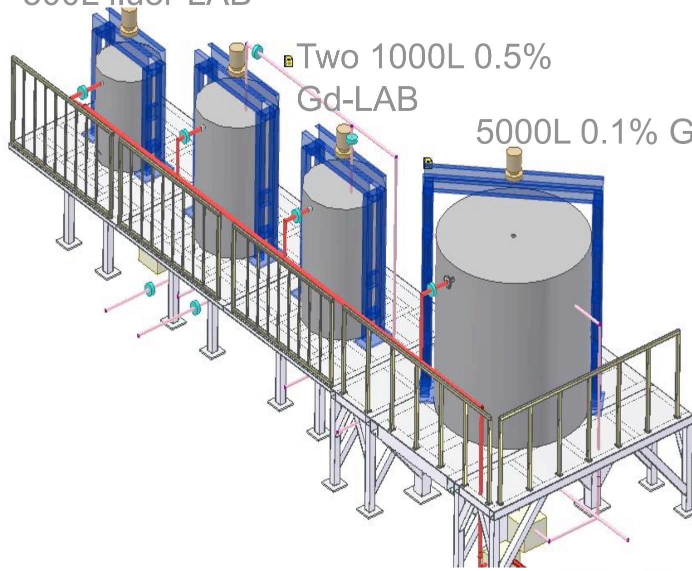


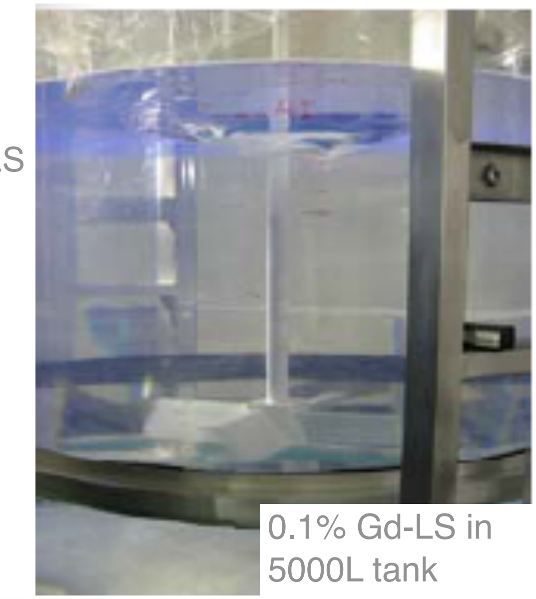
target mass:	20t per detector
detector mass:	~ 110t
photosensors:	192 PMTs
energy resolution:	12%/√E

Gd-Liquid Scintillator Test Production

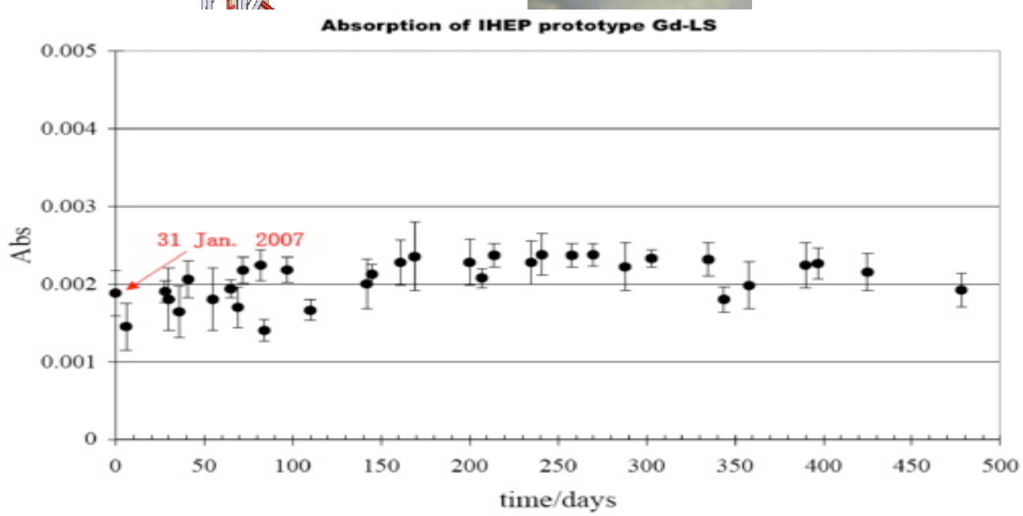
Daya Bay experiment uses 200 ton 0.1% gadolinium-loaded liquid scintillator (Gd-LS). Gd-TMHA + LAB + 3g/L PPO + 15mg/L bis-MSB

4-ton test batch production in April 2009.





0.1% Gd-LS in 5000L tank



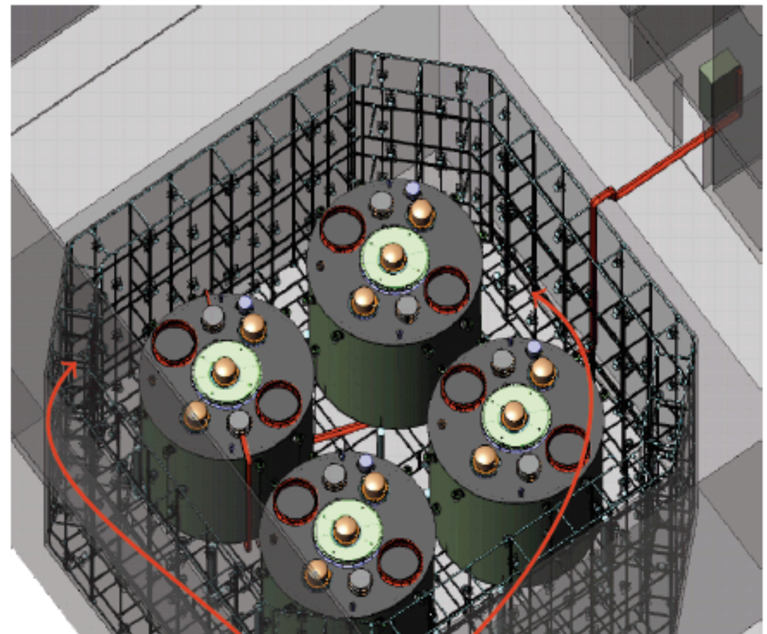
Gd-LS will be produced in multiple batches but mixed in reservoir on-site, to ensure identical detectors.

Water Cherenkov Detector to Tag Muons

Muon Veto Detectors

Efficiencies to tag all muons and muons leading to activity in ADs

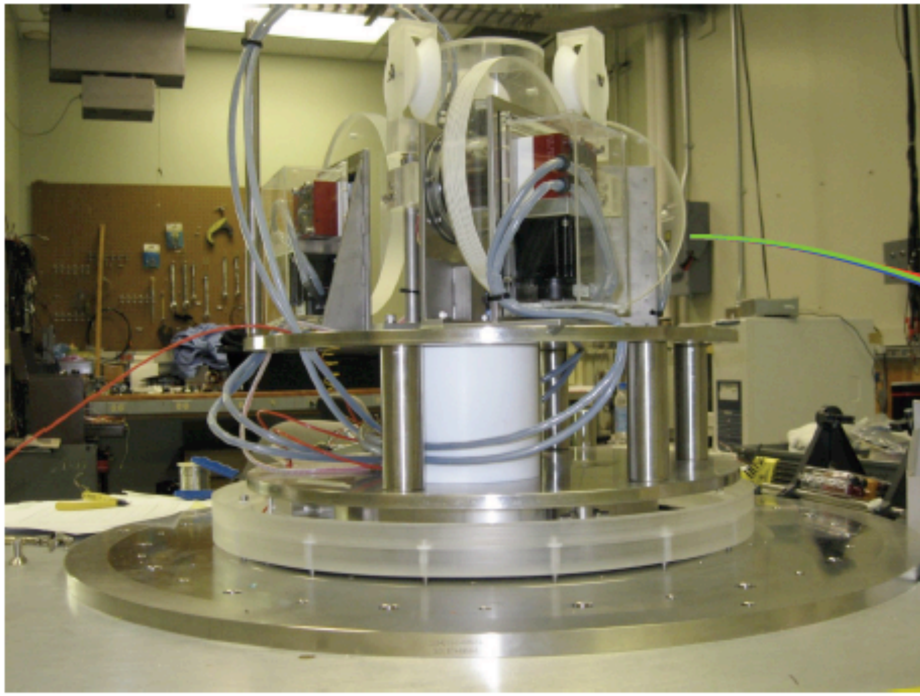
- Overall veto efficiency goal $99.5\% \pm 0.25\%$.
- OWS+IWS alone $> 99\%$ eff for μ in IWS or AD.
- Less eff. for μ in OWS or rock
    - less likely to make bkg
- Ongoing studies of ineff. μ:
    - fast neutrons
    - radioactive isotopes production (^{9}Li,^{8}He)
    - challenging to obtain enough simulation statistics (1 min sim = 1 CPU-month).

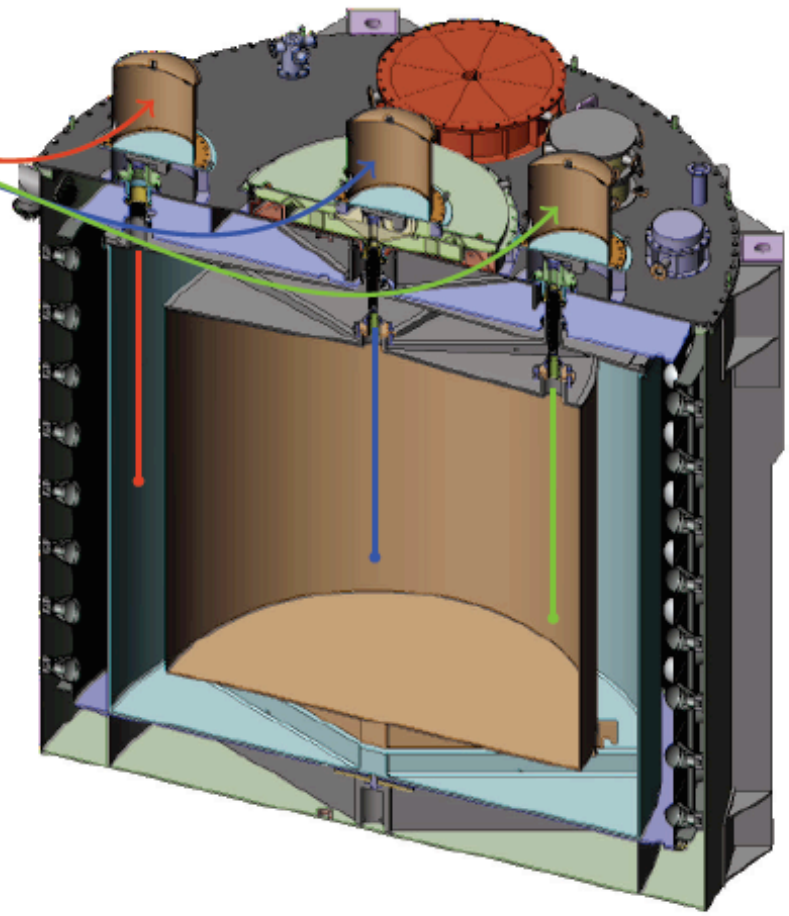


1m thick Outer (OWS) & 1.5 m thick Inner (IWS) Water Shields separated by Tyvek curtain.

Muon rate (Hz)	DB	LA	Far
per AD module	36	22	1.2

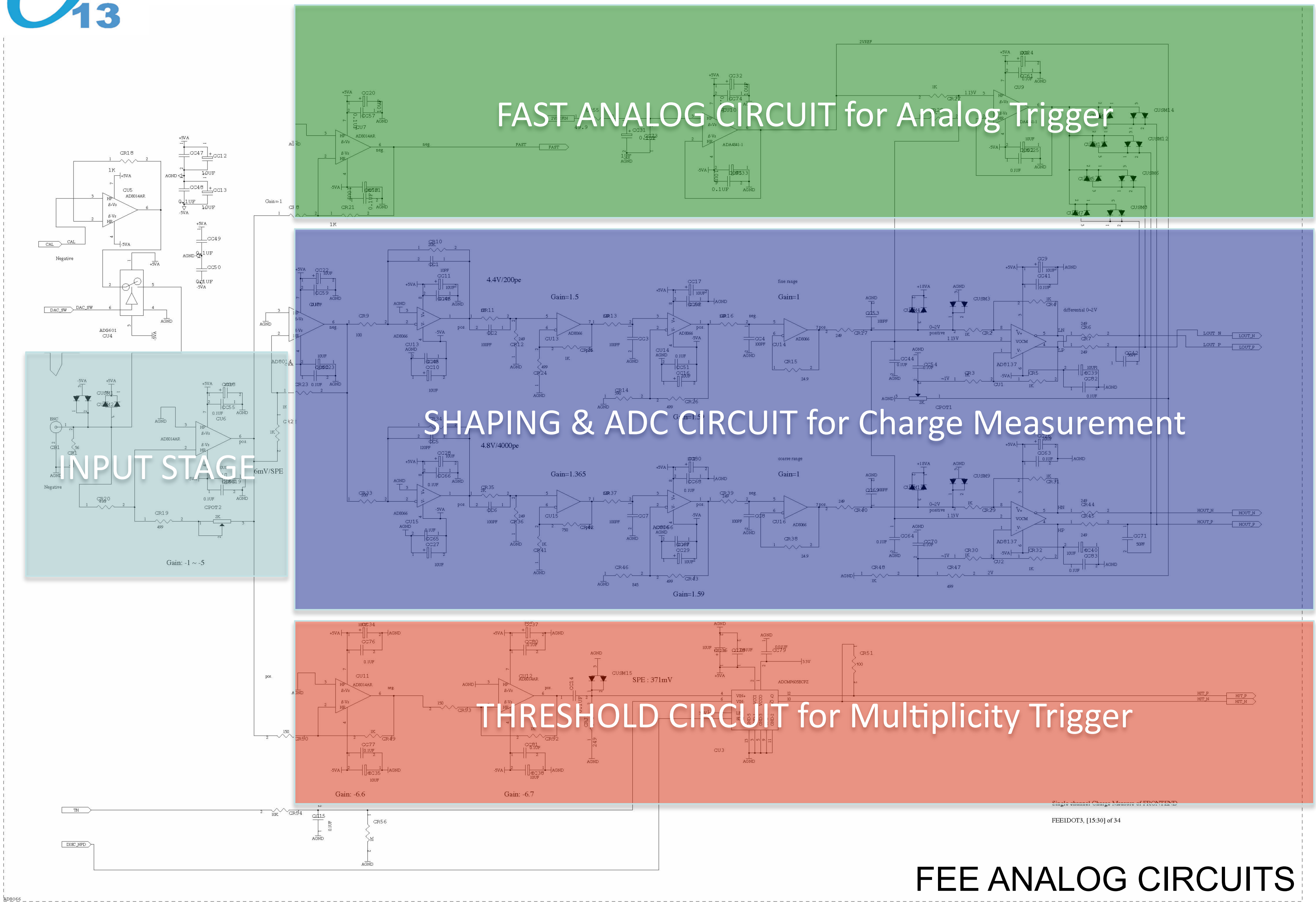
Calibration





- 3 automatic calibration units / AD.
  - LS & on-/off-axis GdLS
- LEDs monitoring optical properties
- Radioactive sources fix energy
- Additional "free" spallation neutrons

Front End Electronics

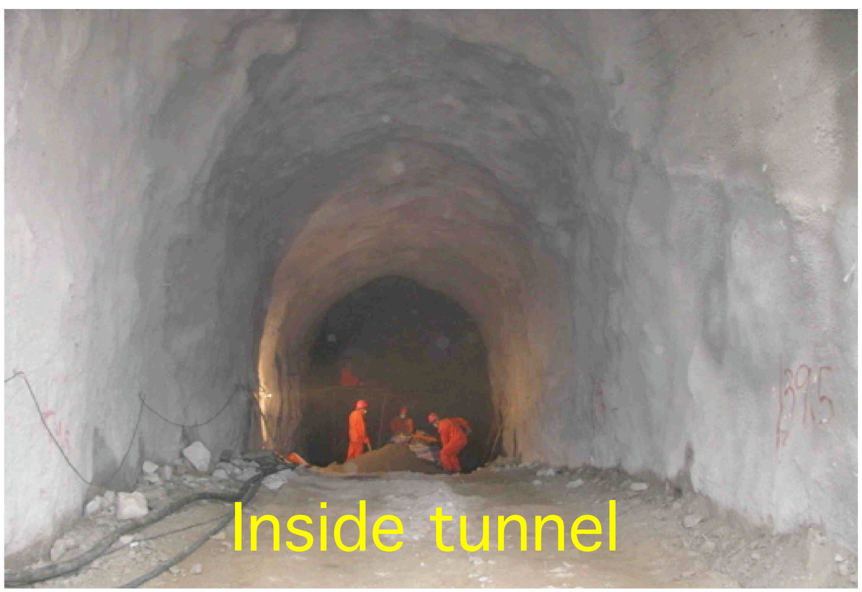


FEE ANALOG CIRCUITS

Civil Construction

Entrance

Surface Assembly Bldg



Inside tunnel

Control Room

Tunnel Construction Status

Pool Excavation in DBY Hall - Aug 09

Main Tunnels Join - June 09

Detector Assembly


Stainless steel tank in China


3-m acrylic vessel in Taiwan


4-m vessel in the U.S.

SS Tank delivery


Delivery of 4m AV


Stainless steel tank in SAB

AD Components


4-meter acrylic vessel arrives


Unpacked 4-m acrylic vessel


PMT Ladder


Mounting of non-reflecting panels on ladder

AD Assembly

Schedule

- 2003-2007: Proposal, R&D, engineering design etc.
- October 2007: Ground Breaking
- March 2009: Surface Assembly Building occupancy
- Summer 2010: Daya Bay Near Hall ready for data taking
- Summer 2011: All near and far halls ready for data taking

Three years' data taking to reach full sensitivity.

Thank You !