Status of Daya Bay

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and
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For
The Daya Bay Collaboration

LAUNCH Workshop at MPI, Heidelberg, Germany, 23 March, 2007

Significance of θ_{13}

U_{MNSP} Matrix

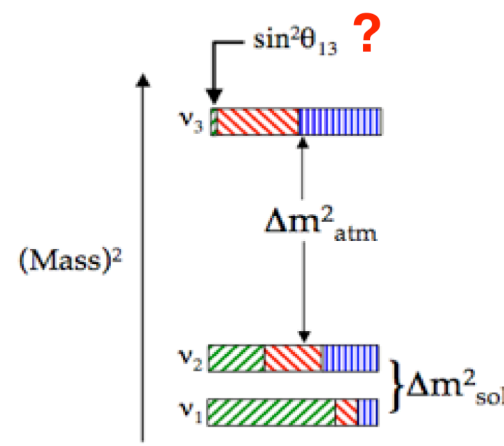
Maki, Nakagawa, Sakata, Pontecorvo

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 0.8 & 0.5 & U_{e3} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \; ?$$

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

atmospheric, accelerator	reactor, accelerator	SNO, solar SK, KamLAND	$0\nu\beta\beta$
$\theta_{23} = \sim 45°$	$\theta_{13} = ?$	$\theta_{12} \sim 32°$	
$\Delta m^2_{32} \approx 2.4 \times 10^{-3}\ eV^2$		$\Delta m^2_{21} \approx 7.9 \times 10^{-5}\ eV^2$	

$\Delta m^2_{31} \approx 2.5 \times 10^{-3}\ eV^2$

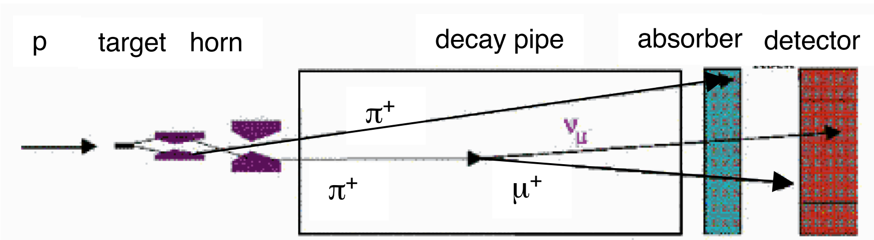


- What is ν_e fraction of ν_3?
- U_{e3} is the gateway to CP violation in neutrino sector:

$$P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \propto \sin(2\theta_{12})\sin(2\theta_{23})\cos^2(\theta_{13})\sin(2\theta_{13})\sin\delta$$

Some Methods For Determining θ_{13}

Method 1: Accelerator Experiments



$$P_{\mu e} \approx \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) + \ldots$$

- $\nu_\mu \rightarrow \nu_e$ appearance experiment
- need other mixing parameters to extract θ_{13}
- baseline *O(100-1000 km)*, matter effects present
- expensive

Method 2: Reactor Experiments

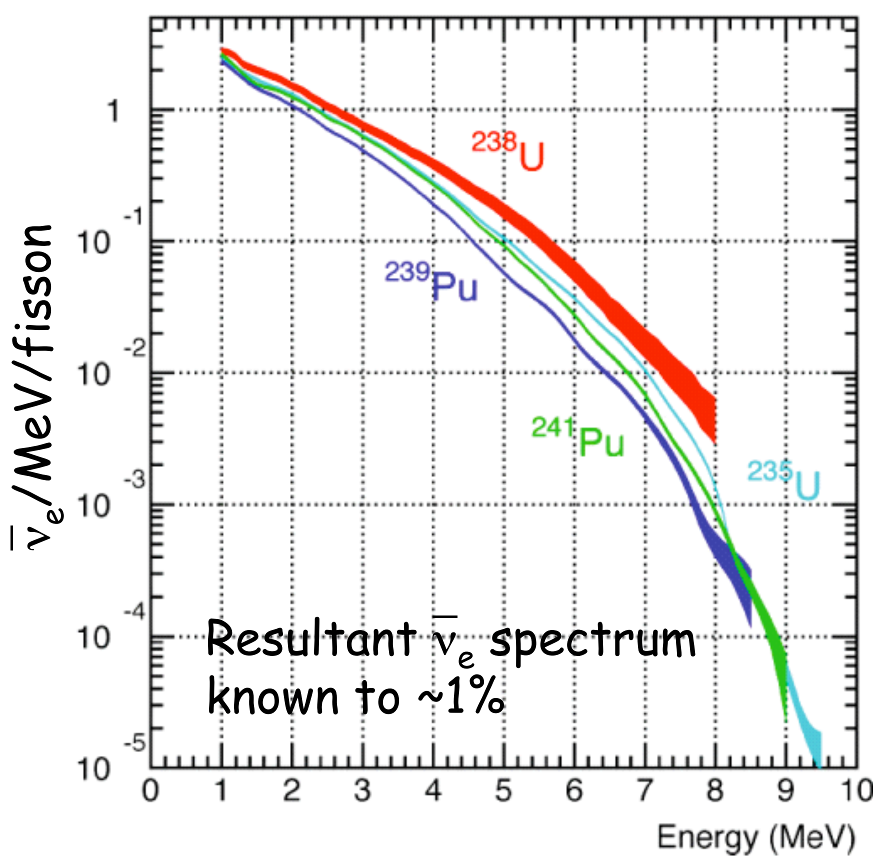
$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

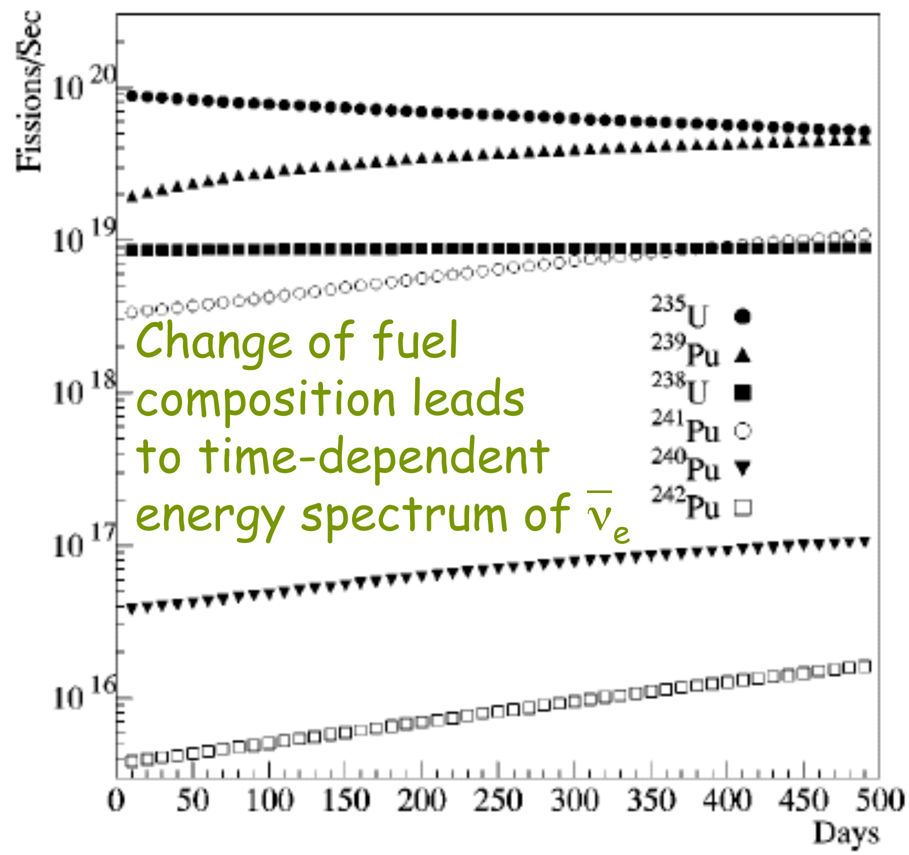
- $\bar{\nu}_e \rightarrow X$ disappearance experiment
- baseline *O(1 km)*, no matter effect, no ambiguity
- relatively cheap

Reactor $\bar{\nu}_e$

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

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





Detecting $\bar{\nu}$ With Liquid Scintillator

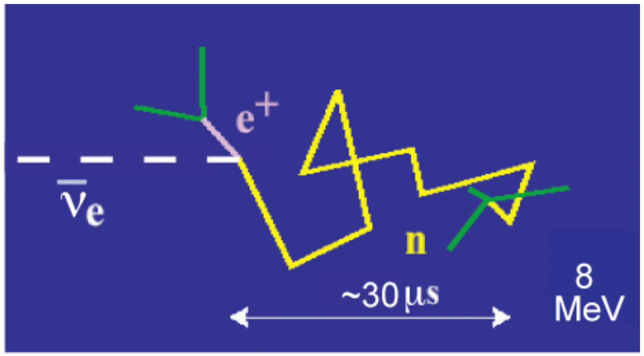
- Use the inverse β-decay reaction in 0.1% Gd-doped liquid scintillator:

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

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)

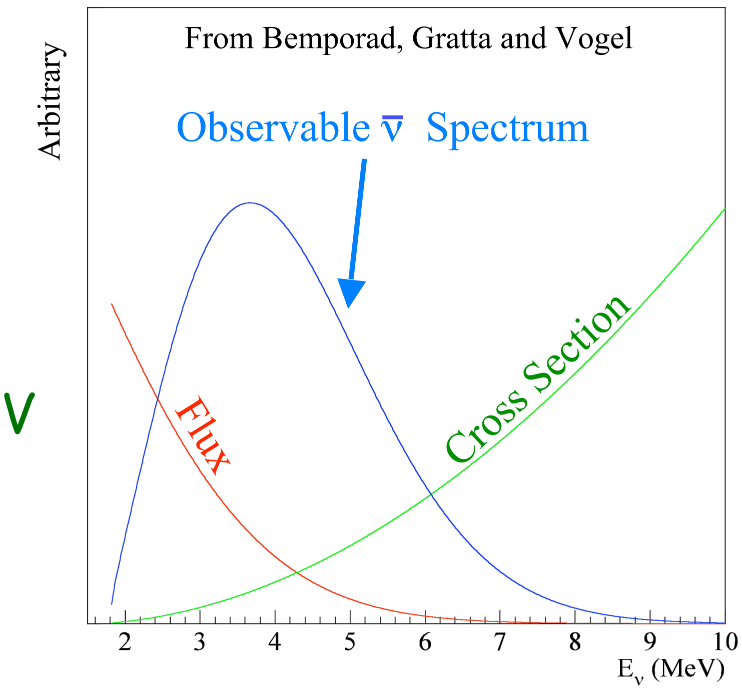


- Time- and energy-tagged signal is a good tool to suppress background events.

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

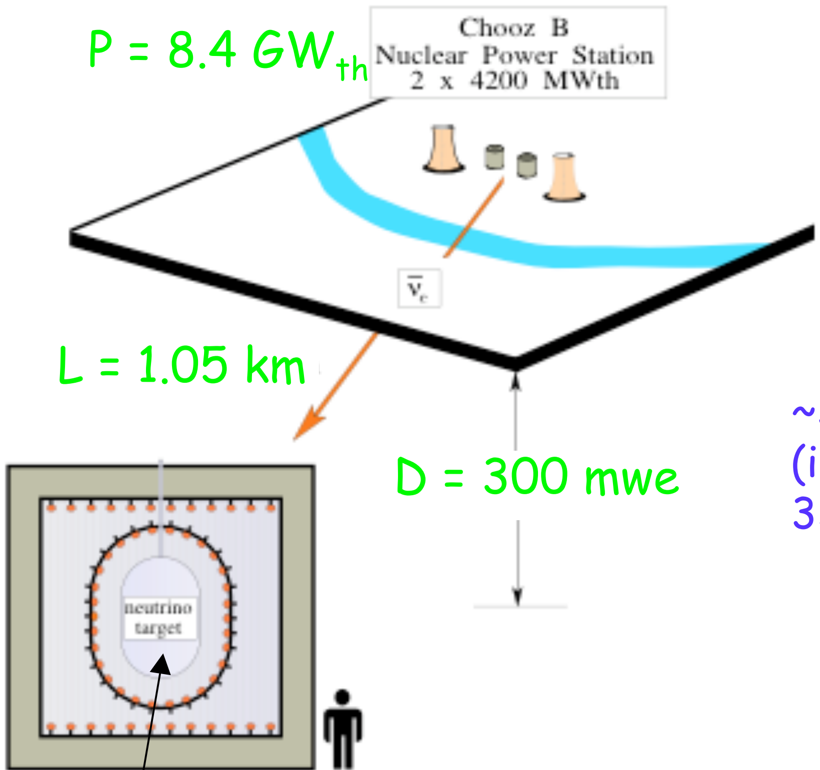
$$E_{\bar{\nu}} \approx T_{e+} + T_n + (m_n - m_p) + m_{e+} \approx T_{e+} + 1.8\ \text{MeV}$$

10-40 keV



Chooz: Finding θ_{13}

$P = 8.4\ GW_{th}$



$L = 1.05$ km

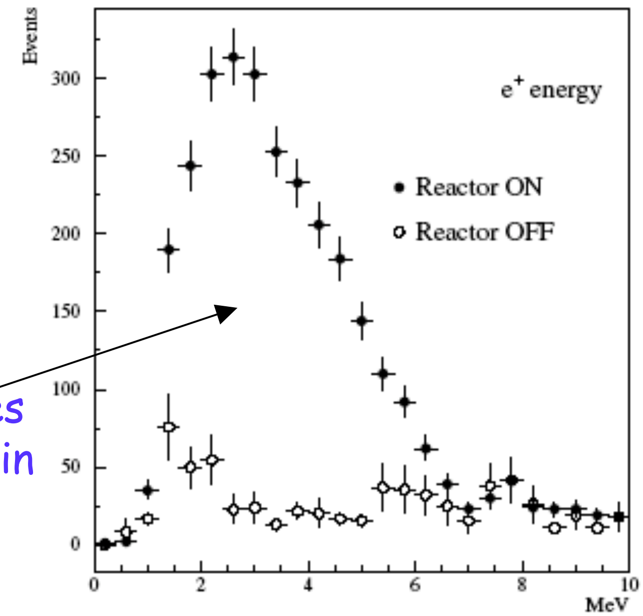
$D = 300$ mwe

5-ton 0.1% Gd-loaded liquid scintillator to detect $\bar{\nu}_e + p \rightarrow e^+ + n$

Rate:

~5 evts/day/ton (full power)
including 0.2-0.4 bkg/day/ton

~3000 $\bar{\nu}_e$ candidates (included 10% bkg) in 335 days

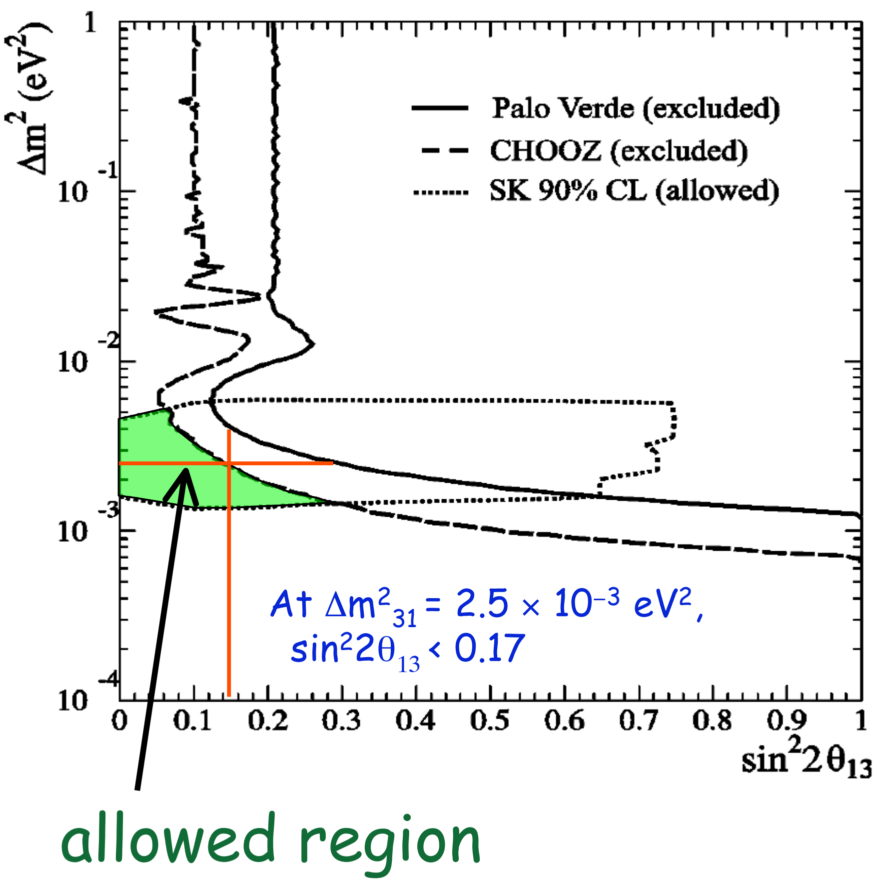


Systematic uncertainties

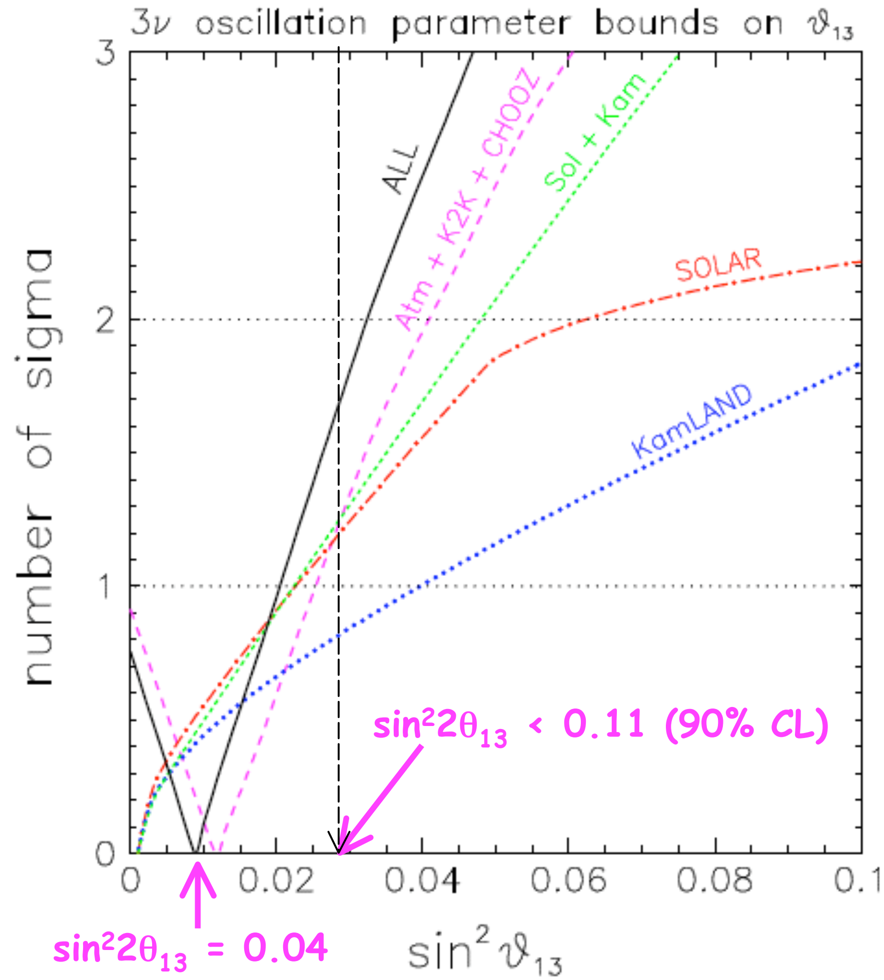
parameter	relative uncertainty (%)
reaction cross section	1.9
number of protons	0.8
detection efficiency	1.5
reactor power	0.7
energy released per fission	0.6
combined	2.7

Current Knowledge of θ_{13}

Direct search



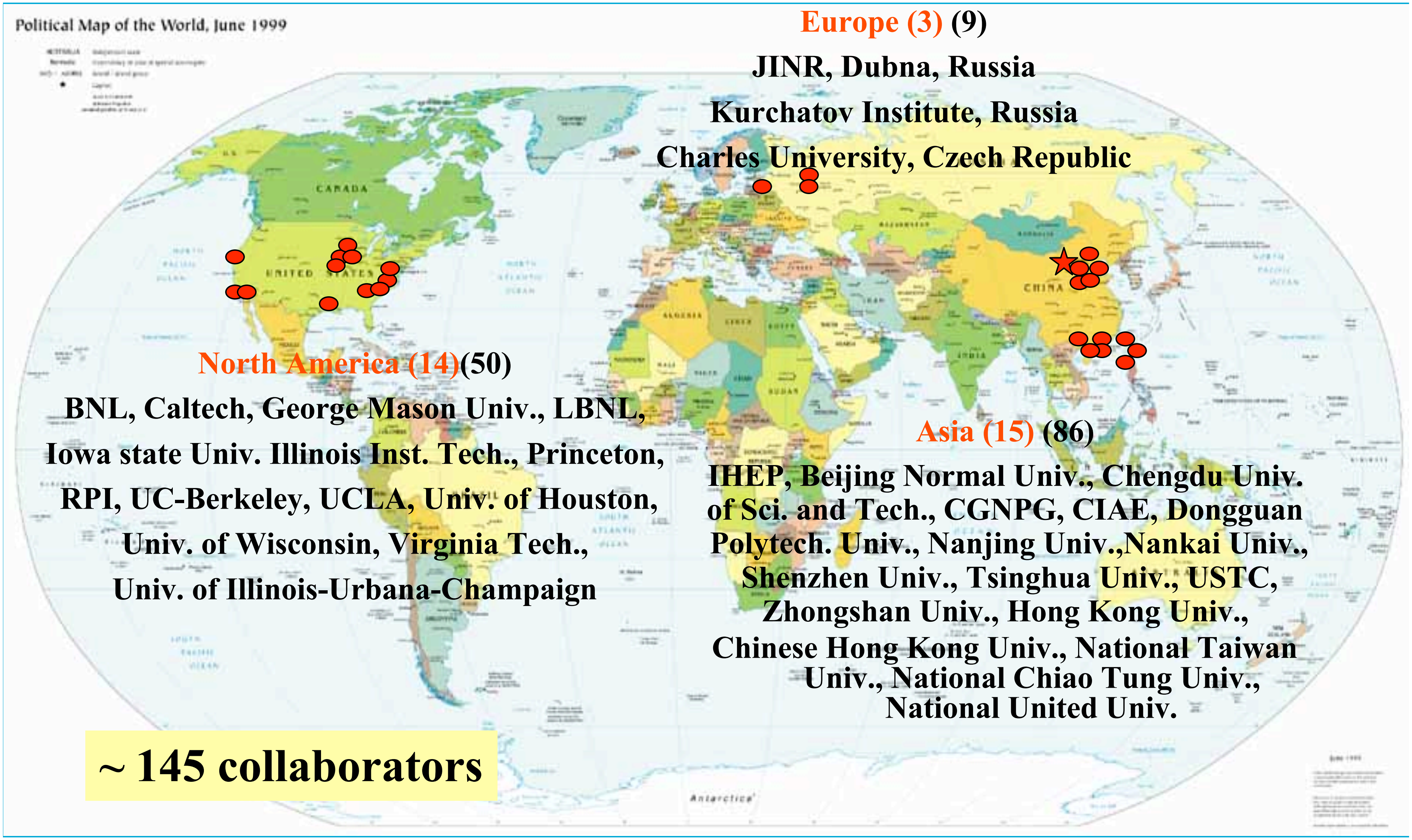
Global fit



Best fit value of $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2

Fogli etal., hep-ph/0506083

Daya Bay Collaboration



Europe (3) (9)

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

North America (14)(50)

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 (15) (86)

IHEP, Beijing Normal Univ., Chengdu Univ. of Sci. and Tech., CGNPG, CIAE, Dongguan Polytech. Univ., Nanjing Univ.,Nankai Univ., Shenzhen Univ., Tsinghua Univ., USTC, Zhongshan Univ., Hong Kong Univ., Chinese Hong Kong Univ., National Taiwan Univ., National Chiao Tung Univ., National United Univ.

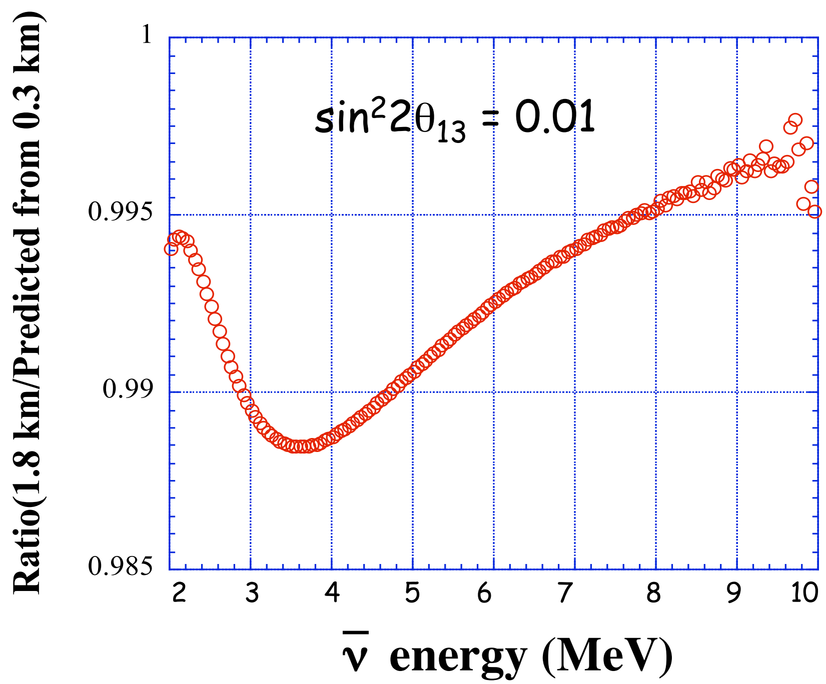
~ 145 collaborators


12-14 Jan, 2007 at HKU

Daya Bay: Goal And Approach

- Determine $\sin^2 2\theta_{13}$ with a sensitivity of ≤ 0.01

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



- Recommendation of the APS Neutrino Study Group:

  - *An expeditiously deployed multidetector reactor experiment with sensitivity to $\bar{\nu}_e$ disappearance down to $\sin^2 2\theta_{13} = 0.01$, an order of magnitude below present limits.*

How To Reach A Precision of 0.01 in Daya Bay?

- **Increase statistics:**
  - Use more powerful nuclear reactors
  - Utilize larger target mass, hence larger detectors
- **Suppress background:**
  - Go deeper underground to gain overburden for reducing cosmogenic background
  - Use active shield around the target
- **Reduce systematic uncertainties:**
  - Reactor-related:
    - Optimize baseline for best sensitivity and smaller residual reactor-related errors
    - Near and far detectors to minimize reactor-related errors
  - Detector-related:
    - Use "Identical" pairs of detectors to do ***relative*** measurement
    - Comprehensive program in calibration/monitoring of detectors
    - Interchange near and far detectors (optional)


55 km
Gangkou Liedao
Xi Zhou
Mabian
Chi Zhou
DAYA WAN
Dalajia
Dapeng
Nan'ao
867
QINIANG SHAN
Dasanmen
Tuoni
Xiaosanmen Dao
Shiyan
Fuyong
Pingshan
587
Longhua
Henggang
444
Kuichong
547
214
Buji
YANTIAN
Meisha
SHENZHEN
944
WUTONG SHAN
Yantian Port
MIRS BAY
Xixiang
BAO'AN
LUOHU
FUTIAN
SHATOUJIAO
Crooked Island
Crescent Island
Double Island
Xiaochan Dao
NANSHAN
Sha Tau Kok
Man Kam To
LO WU
Lok Ma Chau
Dachan Dao
Shekou Port
FANLING
639
Mawan Port
Shekou
DEEP BAY
TIN SHUI WAI
572
566
TAI PO
Plover Cove Reservoir
Chiwan Port
TOLO HARBOUR
YUEN LONG
HONG KONG
957
TAI MO SHAN
702
MA ON SHAN
468
Neilingding Dao
583
TUEN MUN
CASTLE PEAK
URMSTON ROAD
TSUEN WAN
SHA TIN
SAI KUNG
High Island Reservoir
Lung Kwu Chau
Kau Sai Chau
The Brothers
Ma Wan
602
KOWLOON PEAK
Town Island
Chek Lap Kok
Kwai Chung Port
Jin Island
KOWLOON
TSEUNG KWAN O
Basalt Island
Peng Chau
VICTORIA HARBOUR
TUNG CHUNG
Lantau Island
552
VICTORIA PEAK
Hong Kong Island
Ninepin Group
Tai O
934
869
Mui Wo
Hei Ling Chau
Aberdeen
Tung Lung Chau
LANTAU PEAK
EAST LAMMA CHANNEL
TATHONG CHANNEL
Shek Kwu Chau
Cheung Chau
WEST LAMMA CHANNEL
Stanley
Sung Kong
Waglan Island
Niutou Dao
Siu A Chau
Soko Islands
Beaufort Island
Po Toi Islands
Tai A Chau
Lamma Island
Po Toi
Boundary of Special Administrative Region
LANTAU CHANNEL
Guishan
Guishan Dao
Dazhi Zhou
Xiaozhi Zhou
LEGEND
Railway
Main road
Secondary road
Built-up area / Cultivation
Airport / Major port
Power station
Peak (in metres)
Contours
(vertical interval 200 metres with supplementary contour at 100 metres)
Sea depth in metres
Series AR/18/IRS
Edition 7 2002
Survey and Mapping Office, Lands Department
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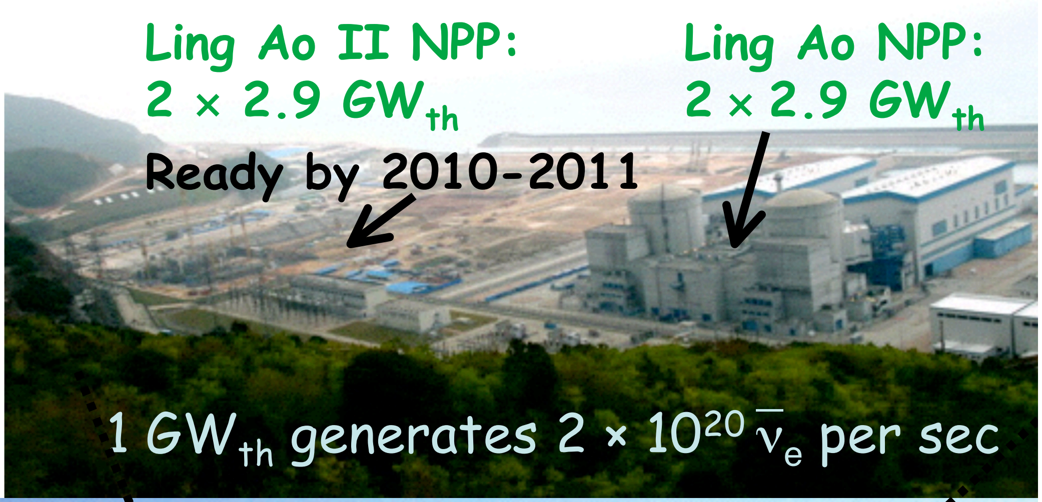
The Daya Bay Nuclear Power Complex

- 12th most powerful in the world (11.6 GW_{th})
- Fifth 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



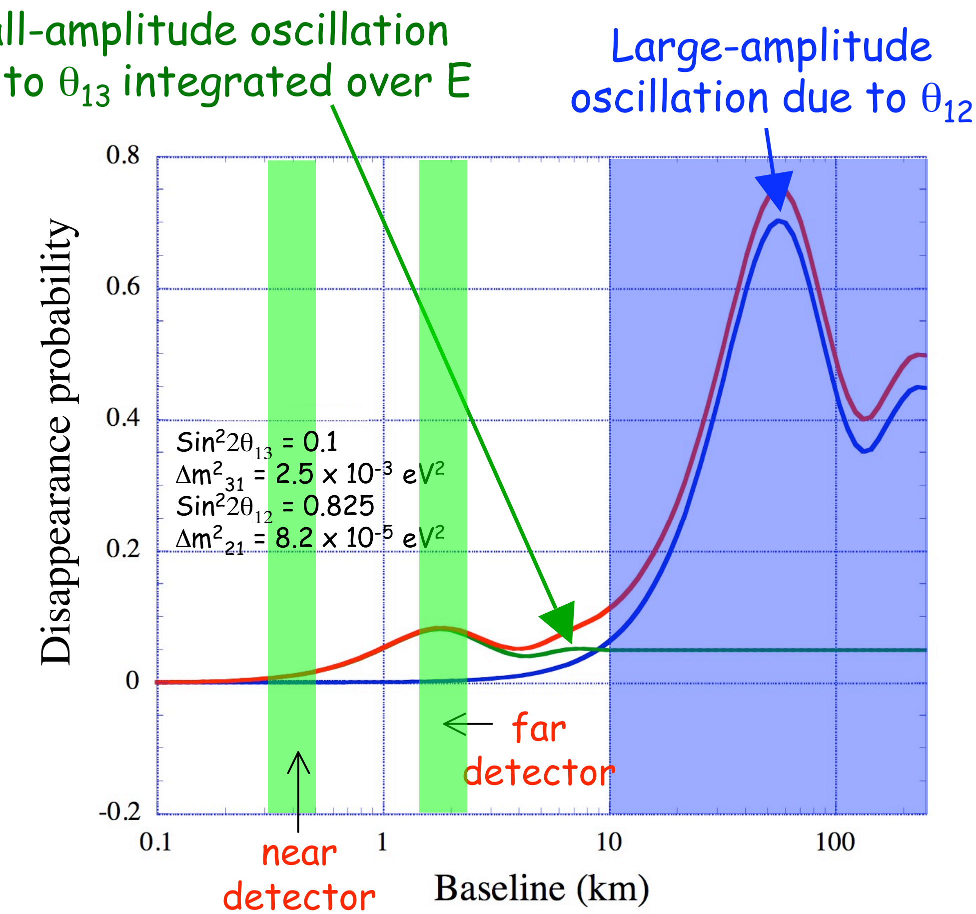
Where To Place The Detectors ?

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

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

- 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}

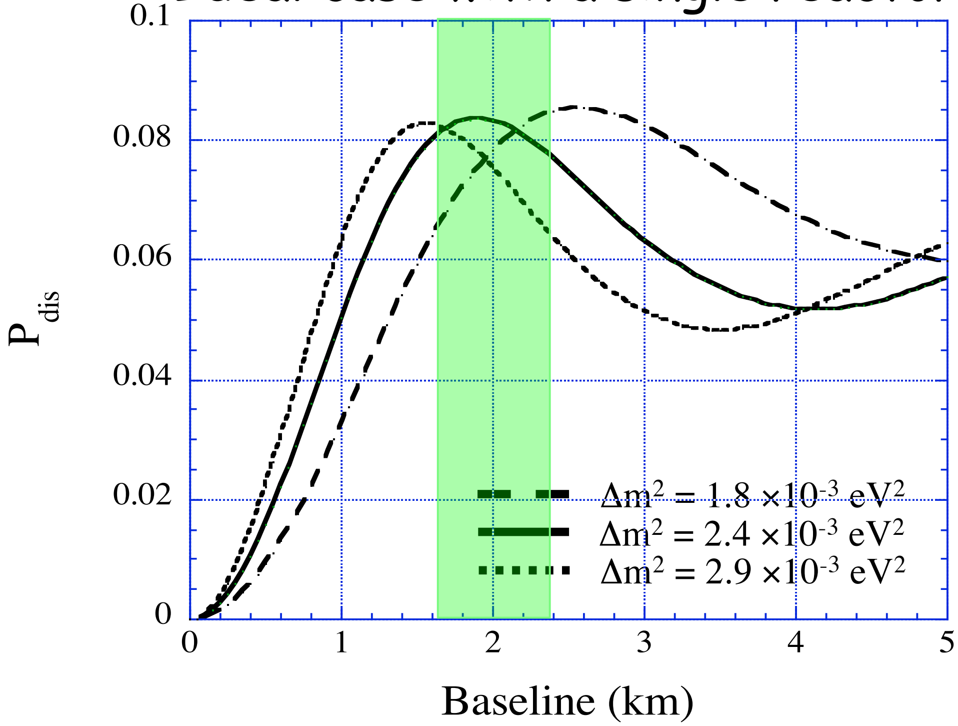


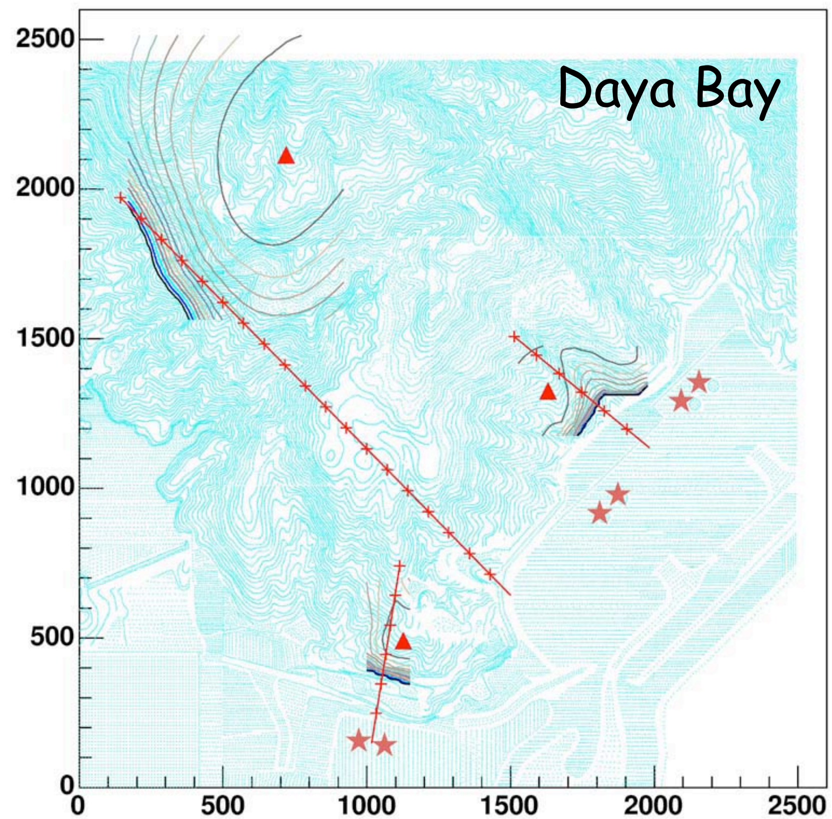
Baseline optimization and site selection

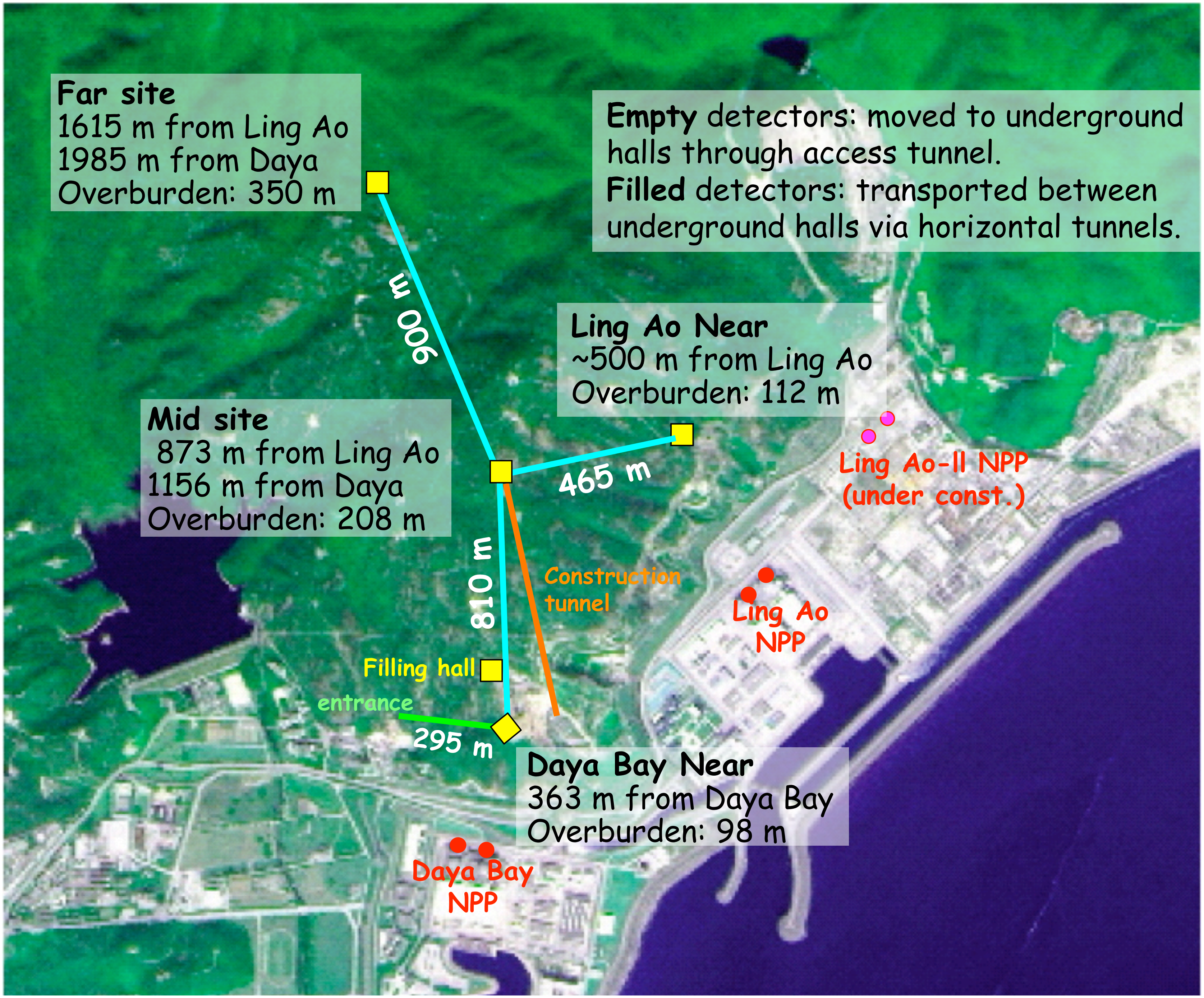
Inputs to the process:

- 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

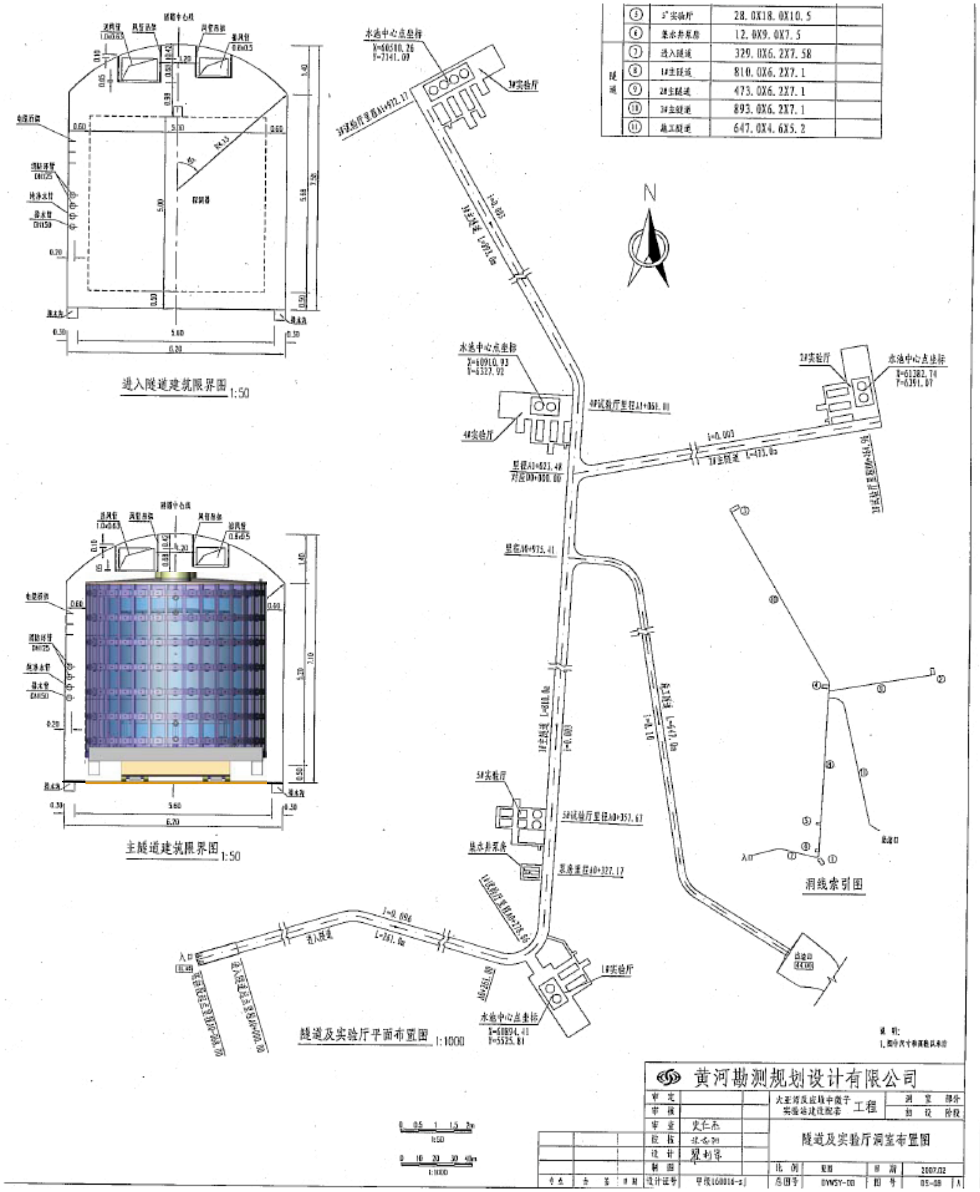






Far site
1615 m from Ling Ao
1985 m from Daya
Overburden: 350 m
Empty detectors: moved to underground halls through access tunnel.
Filled detectors: transported between underground halls via horizontal tunnels.
900 m
Ling Ao Near
~500 m from Ling Ao
Overburden: 112 m
Mid site
873 m from Ling Ao
1156 m from Daya
Overburden: 208 m
465 m
Ling Ao-II NPP
(under const.)
810 m
Construction tunnel
Ling Ao NPP
Filling hall
entrance
295 m
Daya Bay Near
363 m from Daya Bay
Overburden: 98 m
Daya Bay NPP

Civil Design Almost Complete

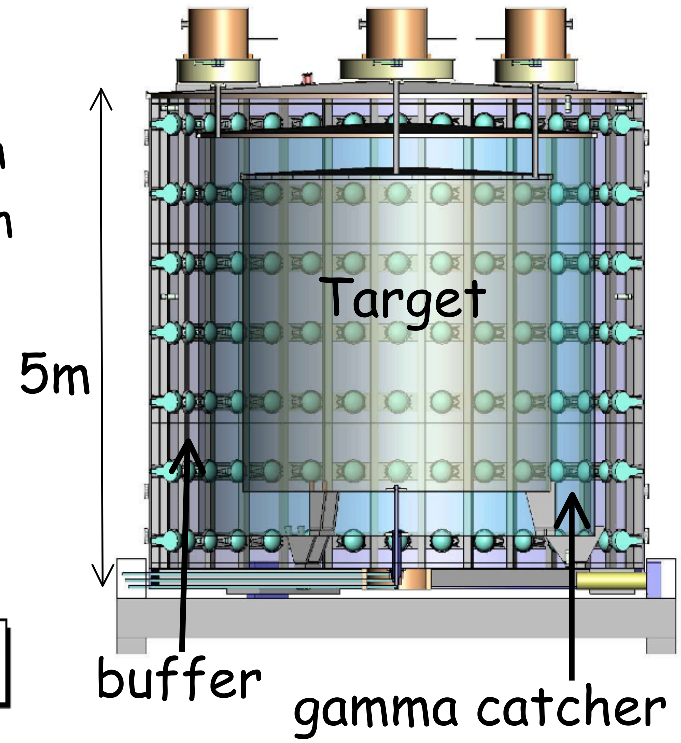


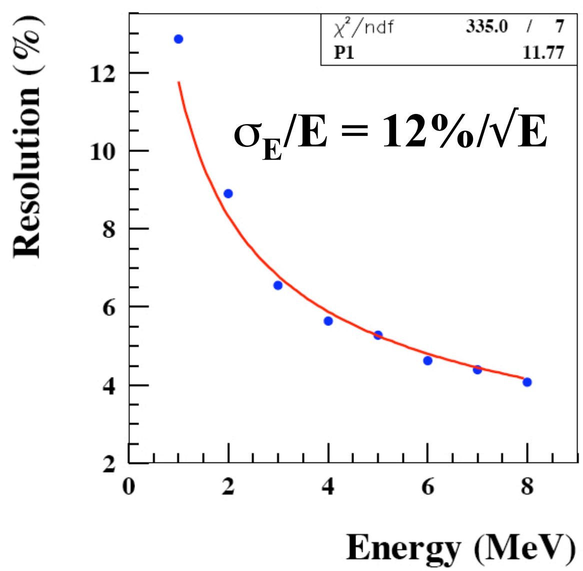
- Total tunnel length is about 3100 m
- Estimated total construction cost is ~$11 M
- Construction will start this summer
- First experimental hall is available after 13 months
- Construction time is ~22 months

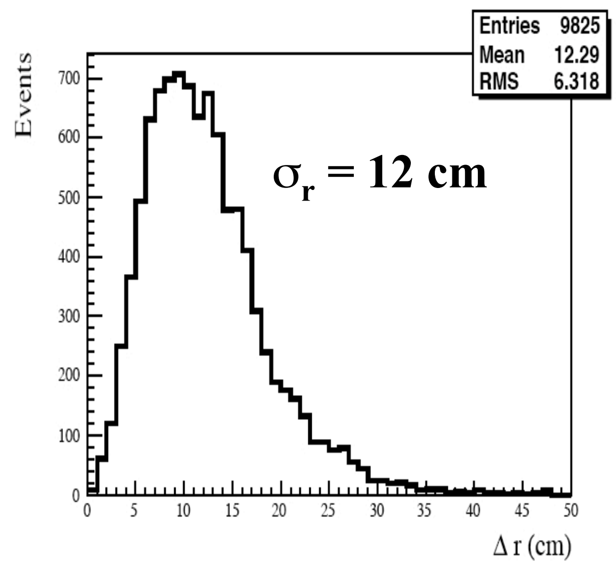
Antineutrino Detectors

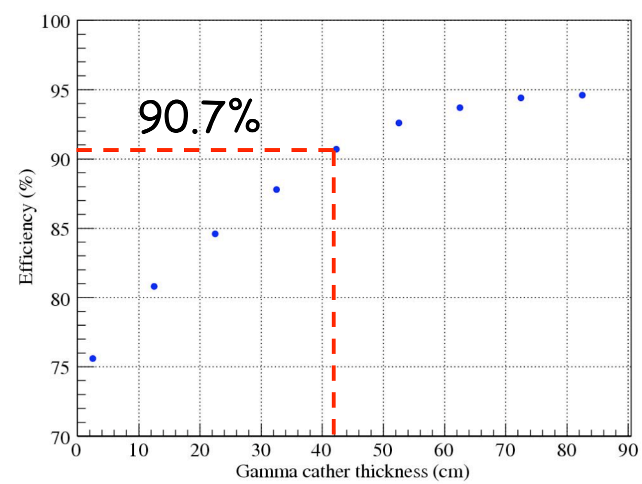
- Three-zone cylindrical detector design
  - Target: 20 T (0.1% Gd-LS), radius = 1.55 m
  - Gamma catcher: 20 T (LS), thickness = 0.42 m
  - Buffer : 40 T (mineral oil) , thickness = 0.48 m
- Low-background 8" PMT: 192
- Reflectors at top and bottom
- Photocathode coverage:

  5.6 % → 12% (with reflectors)





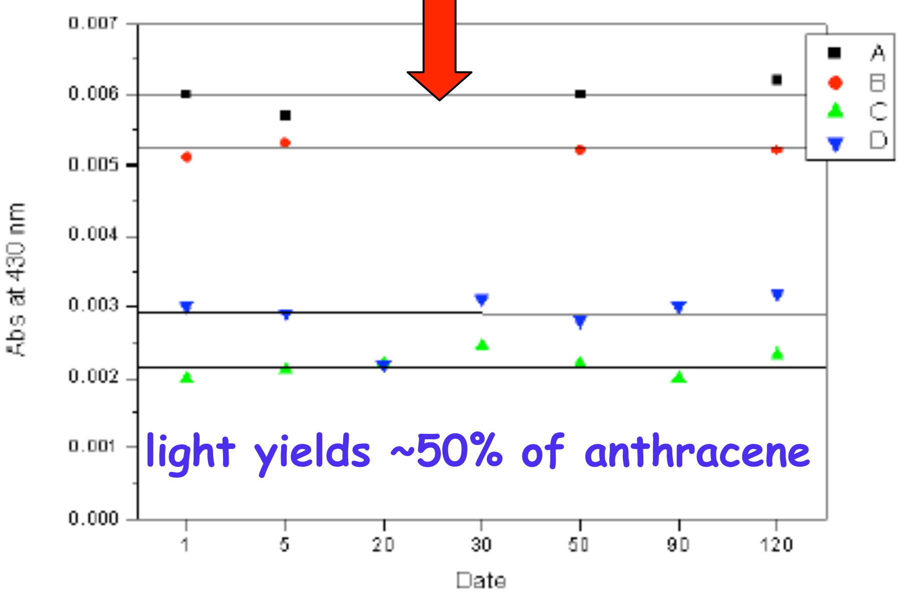




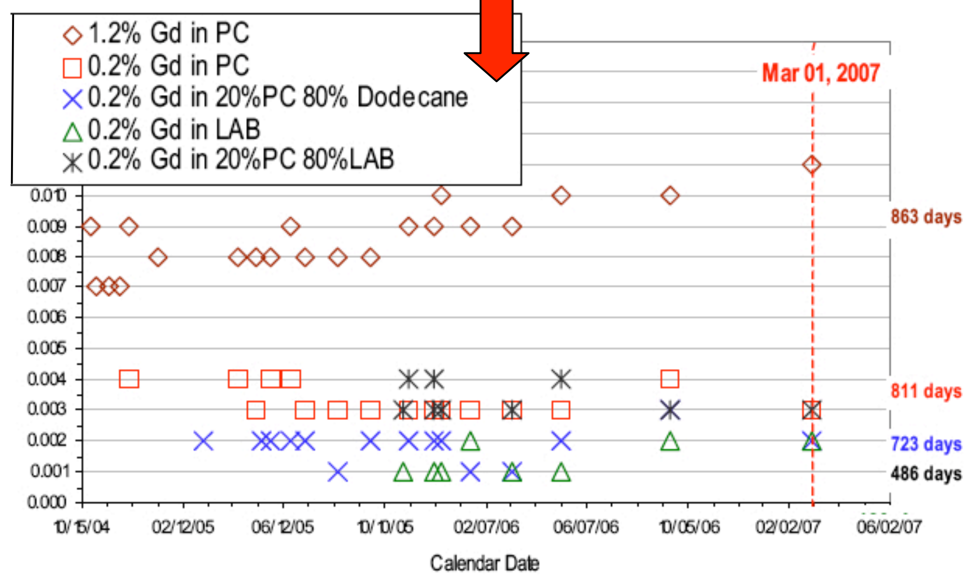
- Eight 'identical' detector modules

Gd-Liquid Scintillator

IHEP Gd-LS

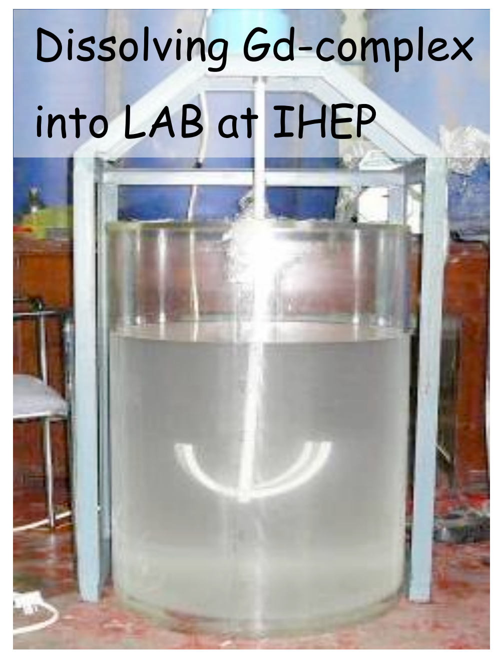


BNL Gd-LS



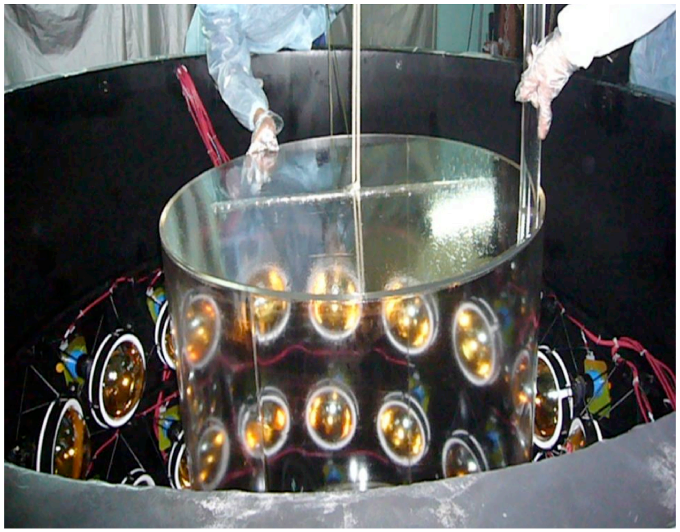
A. Gd-isonanoate in 4: 6 mesitylene/dodecane
B. Gd-ethylhexanoate in 2: 8 mesitylene/dodecane
C. Gd-isonanoate in LAB
D. Gd-ethylhexanoate in 2: 8 mesitylene/LAB

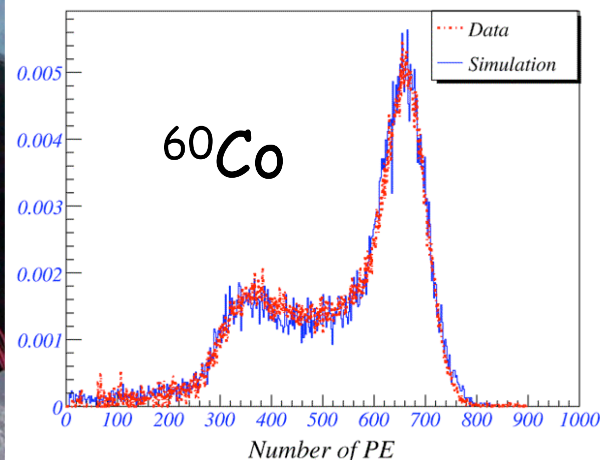
- Use LAB (Linear Alkyl Benzene):
  - good stability
  - high flash point
  - used in bio. sc.
  - high light yield
  - no EH&S issues
  - cheap (raw material for making detergent)

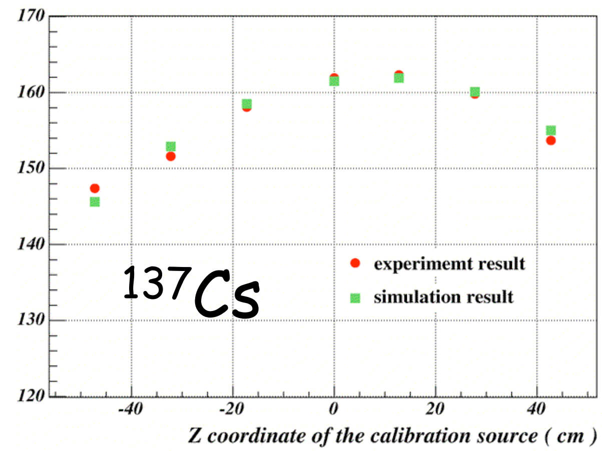


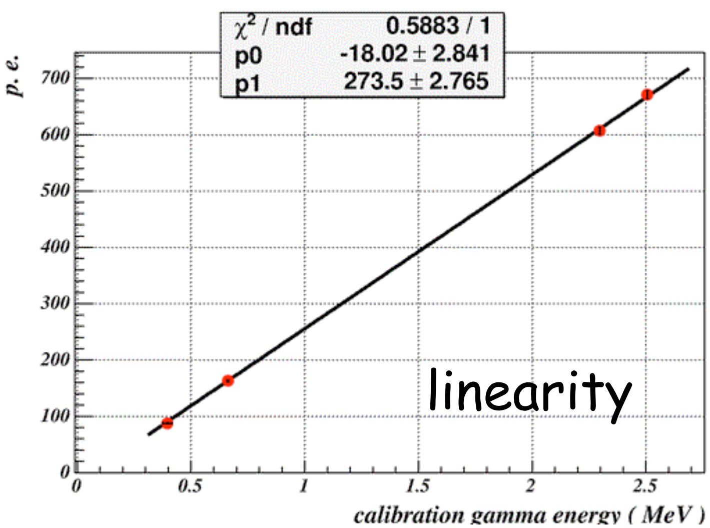
2-zone Prototype at IHEP

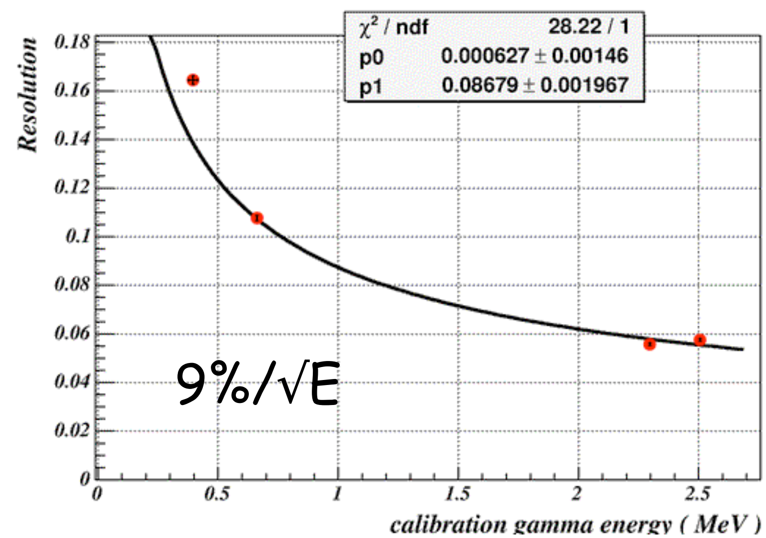
- 0.5 ton unloaded LS (now replaced with Gd-LS)
- 45 8" PMTs with reflecting top and bottom





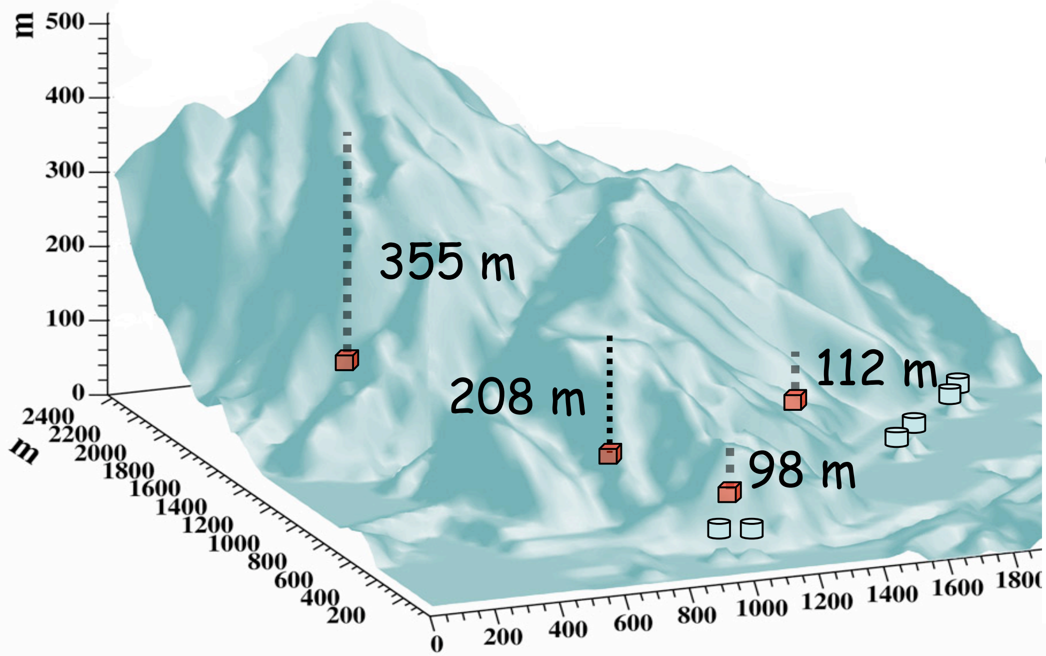


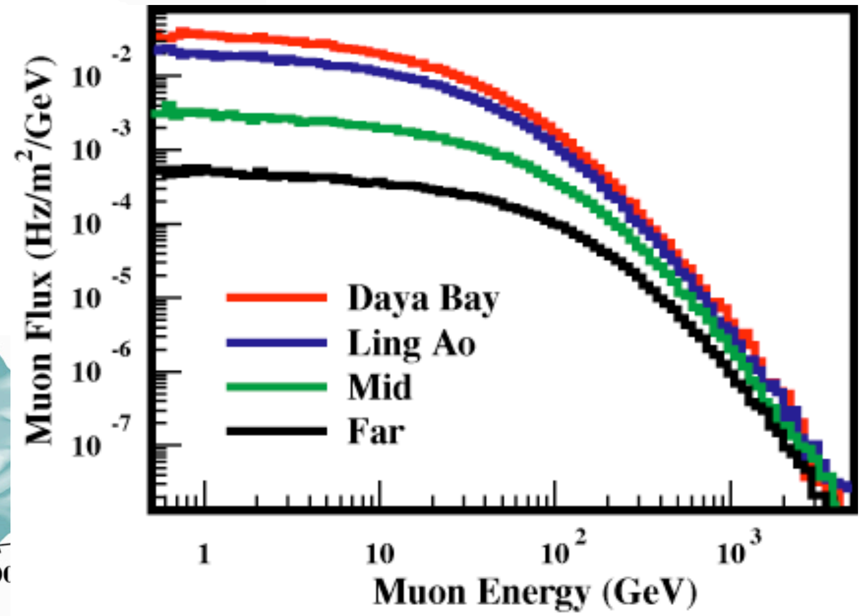




Cosmic-ray Muon

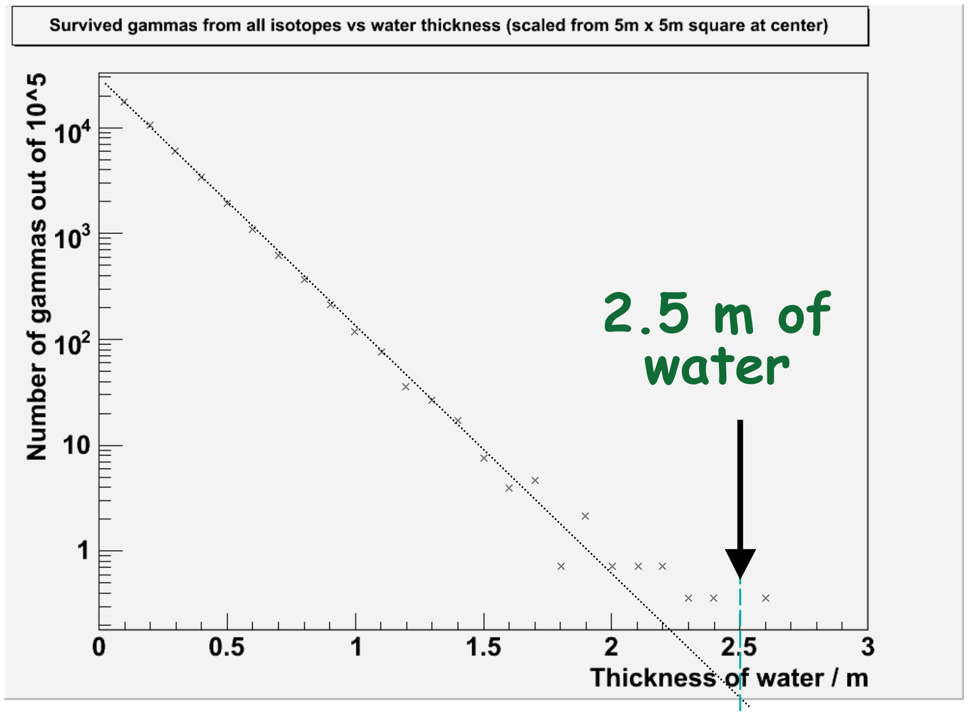
- Use a modified Gaisser parametrization for cosmic-ray flux at surface
- Apply MUSIC and mountain profile to estimate muon intensity & energy

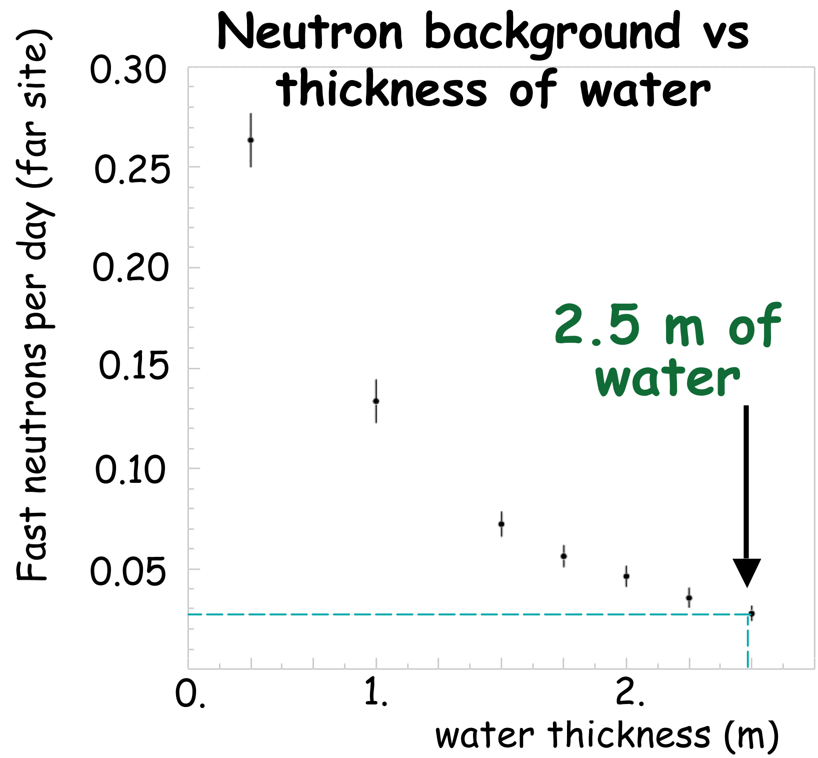




	DYB	LingAo	Mid	Far
Overburden (m)	98	112	208	355
Muon intensity (Hz/m²)	1.16	0.73	0.17	0.041
Mean Energy (GeV)	55	60	97	138

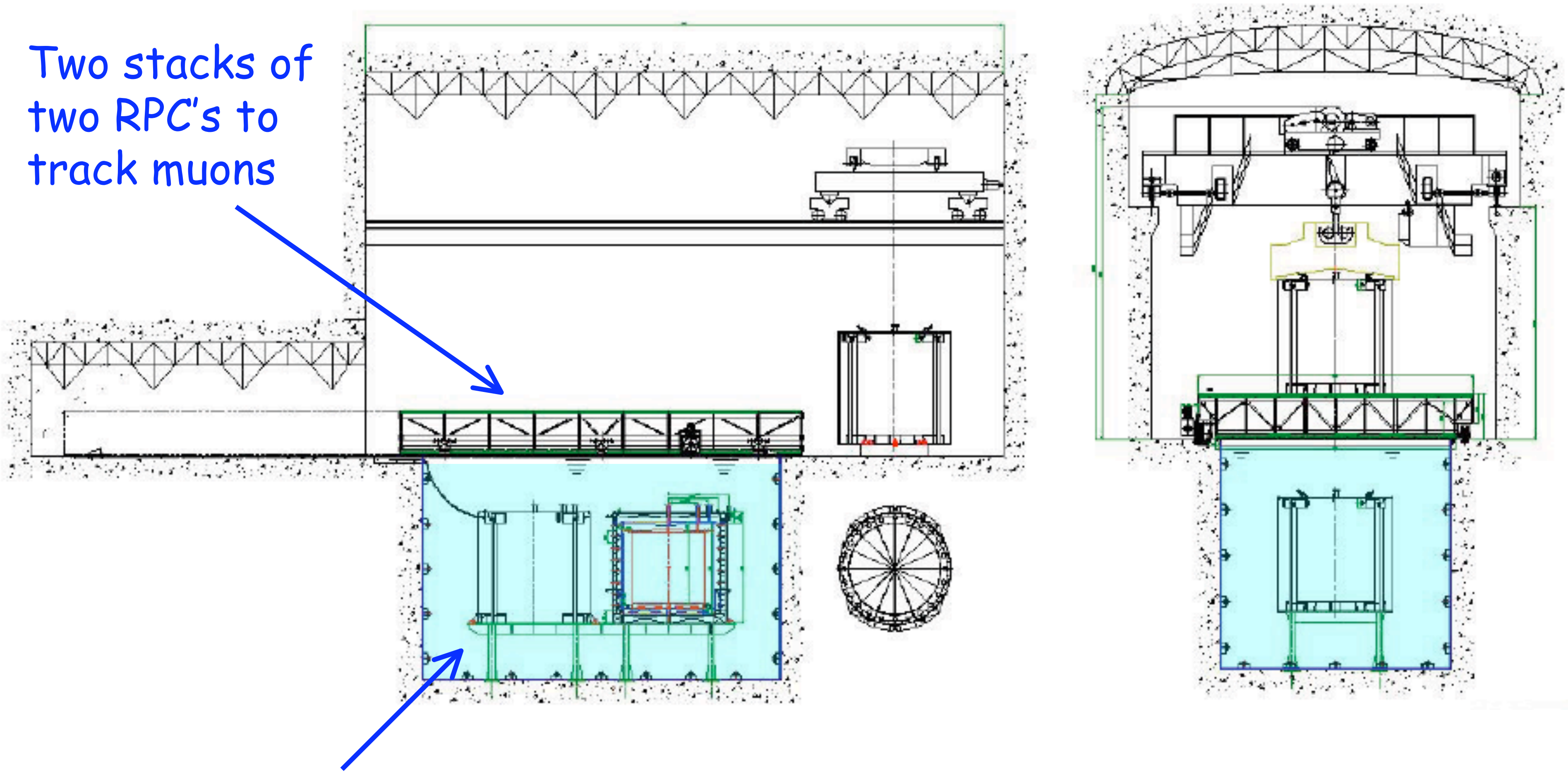
Shielding Antineutrino Detectors





- 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

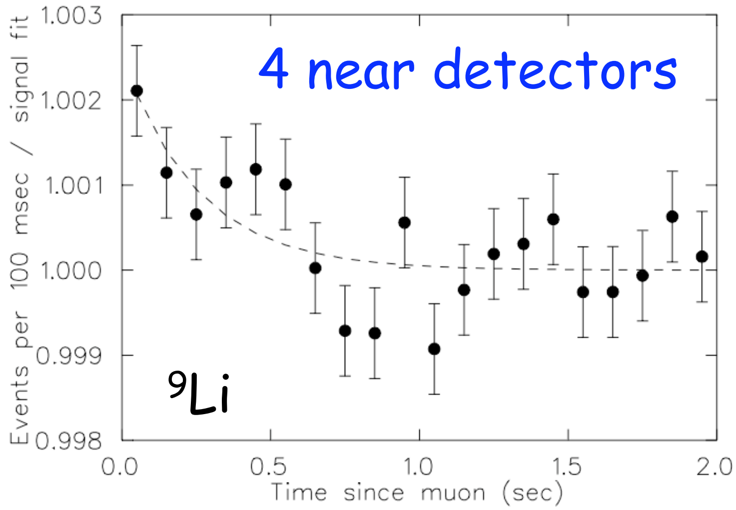
An Example of the Muon System



- Combined efficiency of Cherenkov and tracker > 99.5% with error measured to better than 0.25%

Background

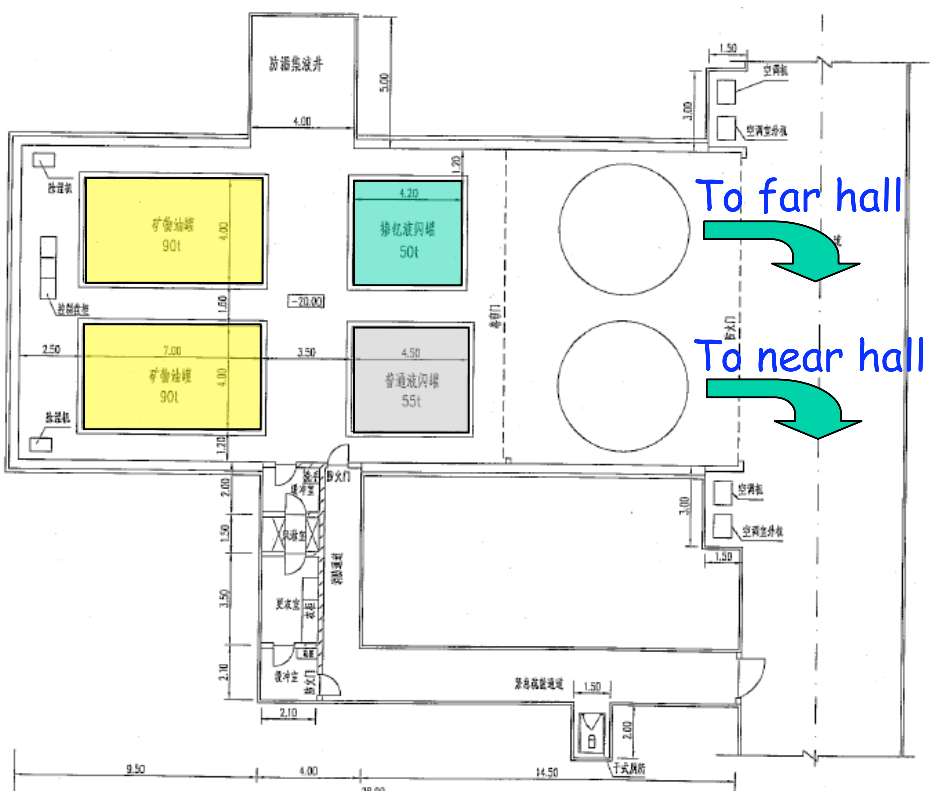
- Uncorrelated background:
  Sources: U/Th/K/Rn/neutron
  Single gamma rate @ 0.9MeV < 50Hz/module
  Single neutron rate < 1000/day/module
- Correlated backgrounds: $n \propto E_{\mu}^{0.75}$
  Fast Neutrons: double coincidence
  $^{8}He/^{9}Li$: beta-neutron emitting decays
- All these background events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

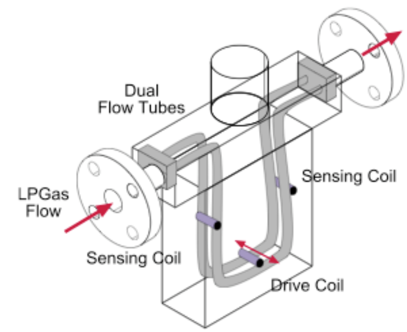


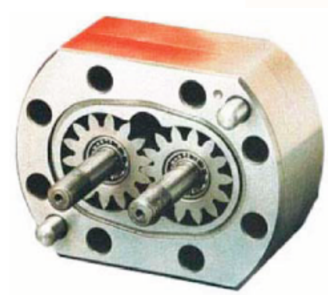
Per module	Daya Bay Near	Ling Ao Near	Far Hall
Baseline (m)	363	481 from Ling Ao 526 from Ling Ao II	1985 from Daya Bay 1615 from Ling Ao's
Overburden (m)	98	112	350
Radioactivity (Hz)	<50	<50	<50
Muon rate (Hz)	36	22	1.2
Antineutrino Signal (events/day)	930	760	90
Accidental Background/Signal (%)	<0.2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

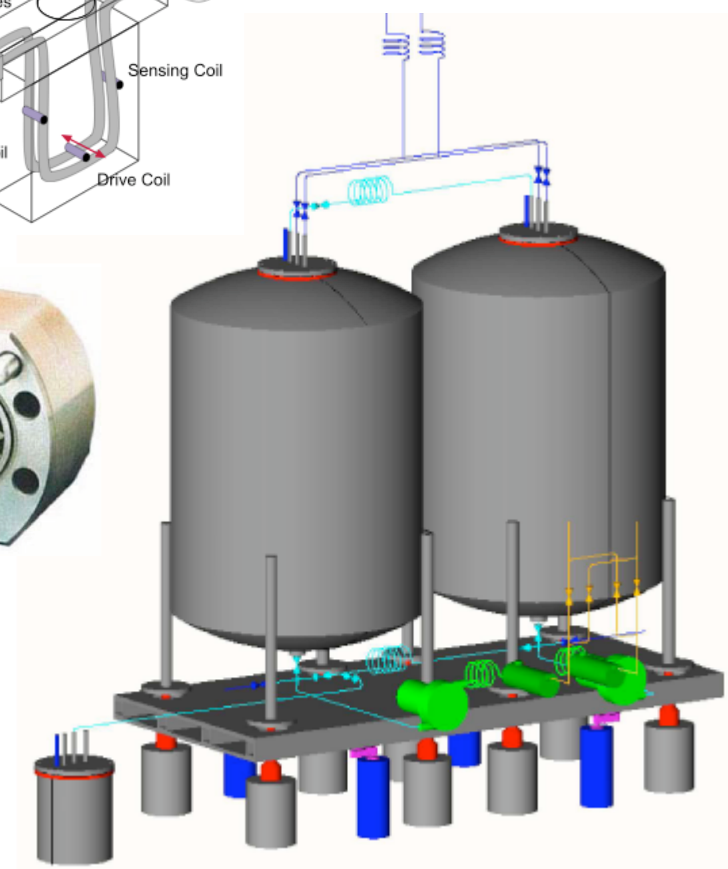
Controlling Target Mass & Composition

- Store one batch of pure LAB in a 200-T tank
- Mix and fill a pair of detector at a time underground with controls of Coriolis mass flow meters (reproducible at 0.1%), load cells (0.008% accuracy), and volume flow meters (good to 0.02%), as well as temperature monitoring :

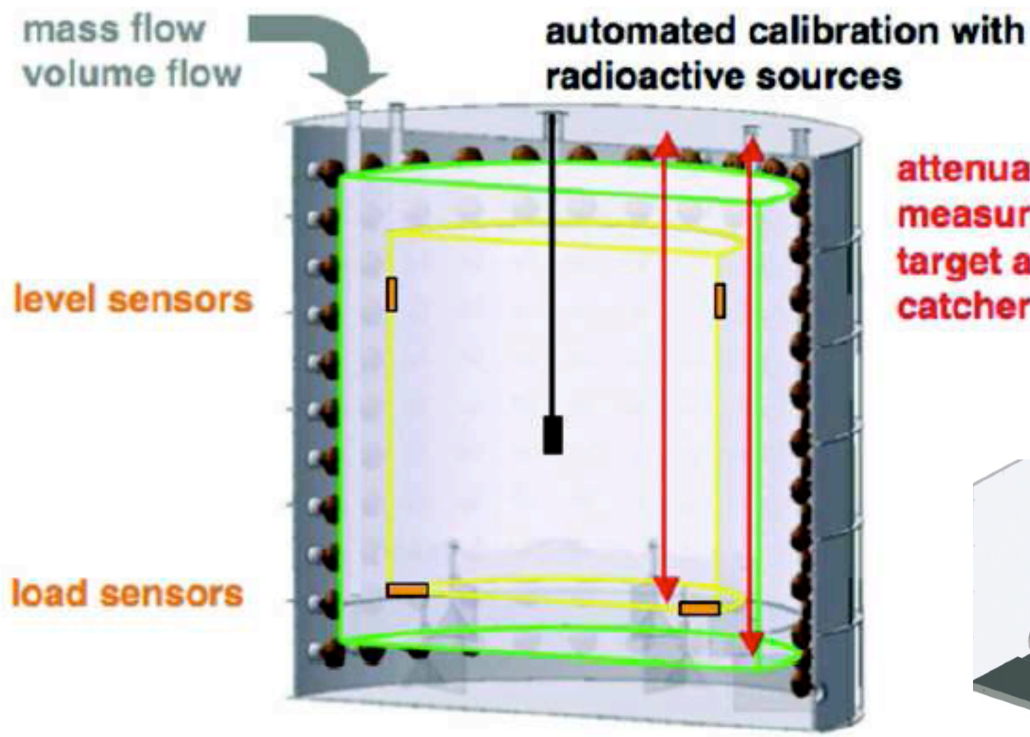


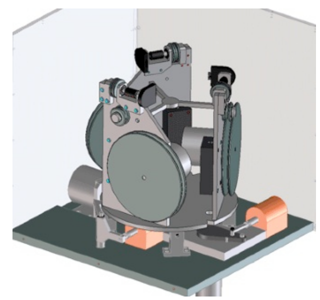


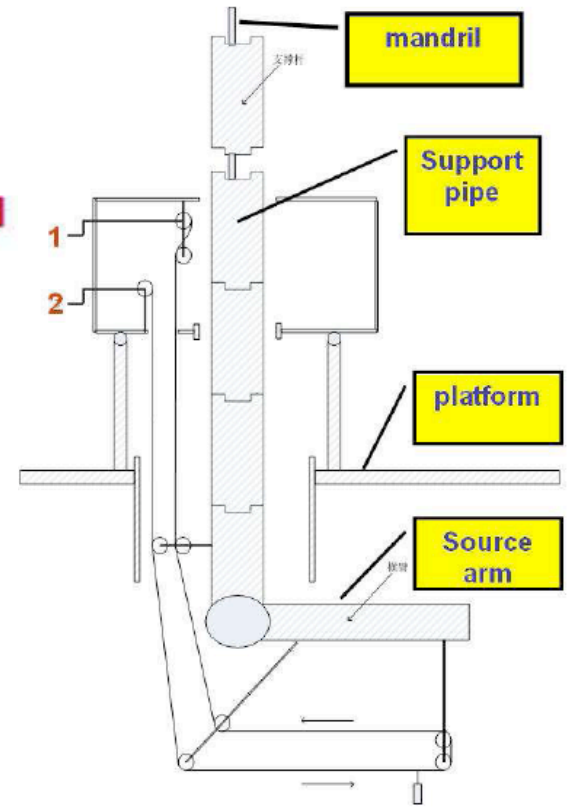




Calibration And Monitoring

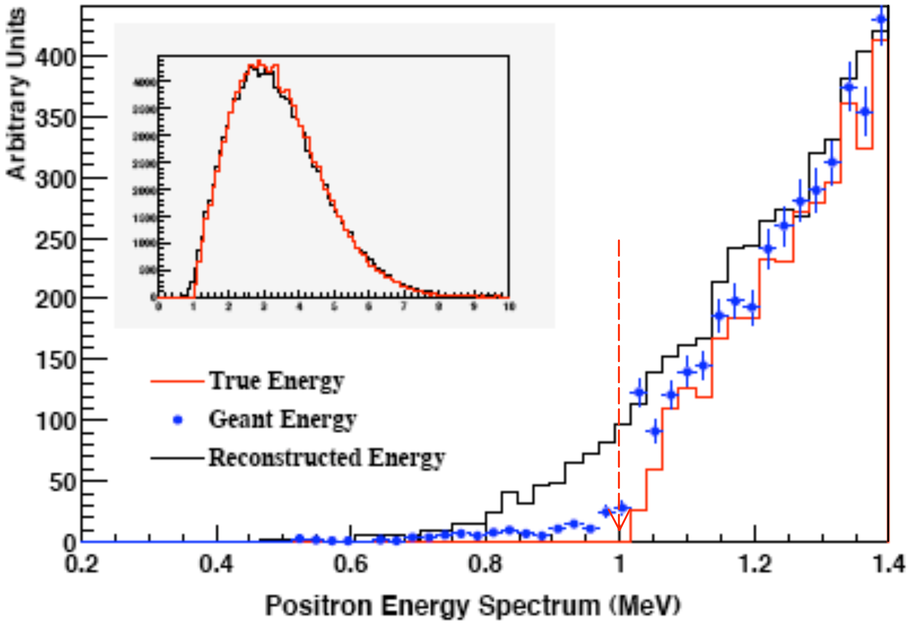


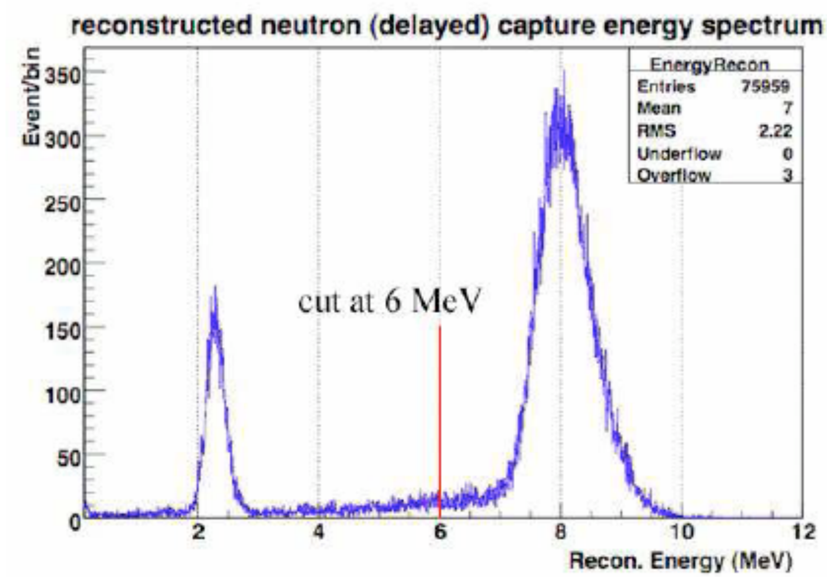




- Use a manual system to do full-volume calibrations
- Monitor level, load and temperature sensors regularly
- Weekly calibration with radioactive sources and LED along vertical axes with an automated calibration system

Calibrating Energy Cuts





- Routine calibration with
  - ^{68}Ge: e^+ annihilation yields two 0.511 MeV γ's
  - ^{60}Co: 2.6 MeV in γ's
  - ^{238}Pu-^{13}C (α-n source):

$$\alpha\ (^{238}\mathrm{Pu}) + {}^{13}\mathrm{C} \rightarrow {}^{17}\mathrm{O}$$

~ 5.48 MeV

→ ^{16}O + n

→ ^{16}O* + n

→ ^{16}O + γ (6.13 MeV)

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:

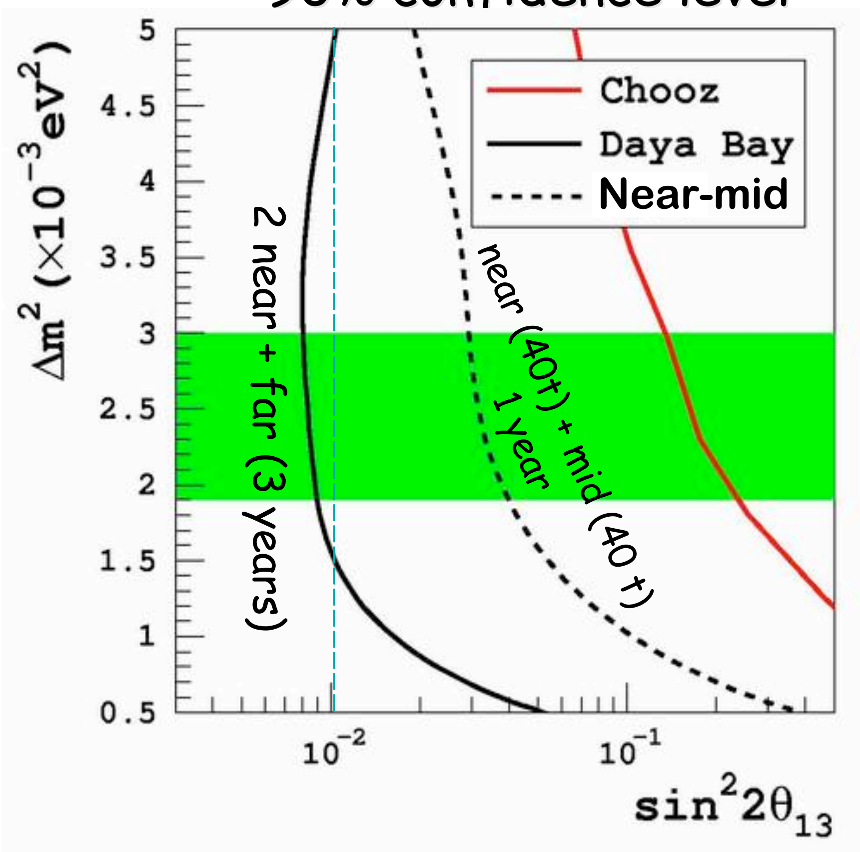
Source of uncertainty		Chooz *(absolute)*	Daya Bay *(relative)* Baseline	Goal	Goal w/Swapping
# protons	H/C ratio	0.8	0.2	0.1	0
	Mass	-	0.2	0.02	0.006
Detector Efficiency	Energy cuts	0.8	0.2	0.1	0.1
	Position cuts	0.32	0.0	0.0	0.0
	Time cuts	0.4	0.1	0.03	0.03
	H/Gd ratio	1.0	0.1	0.1	0.0
	n multiplicity	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%

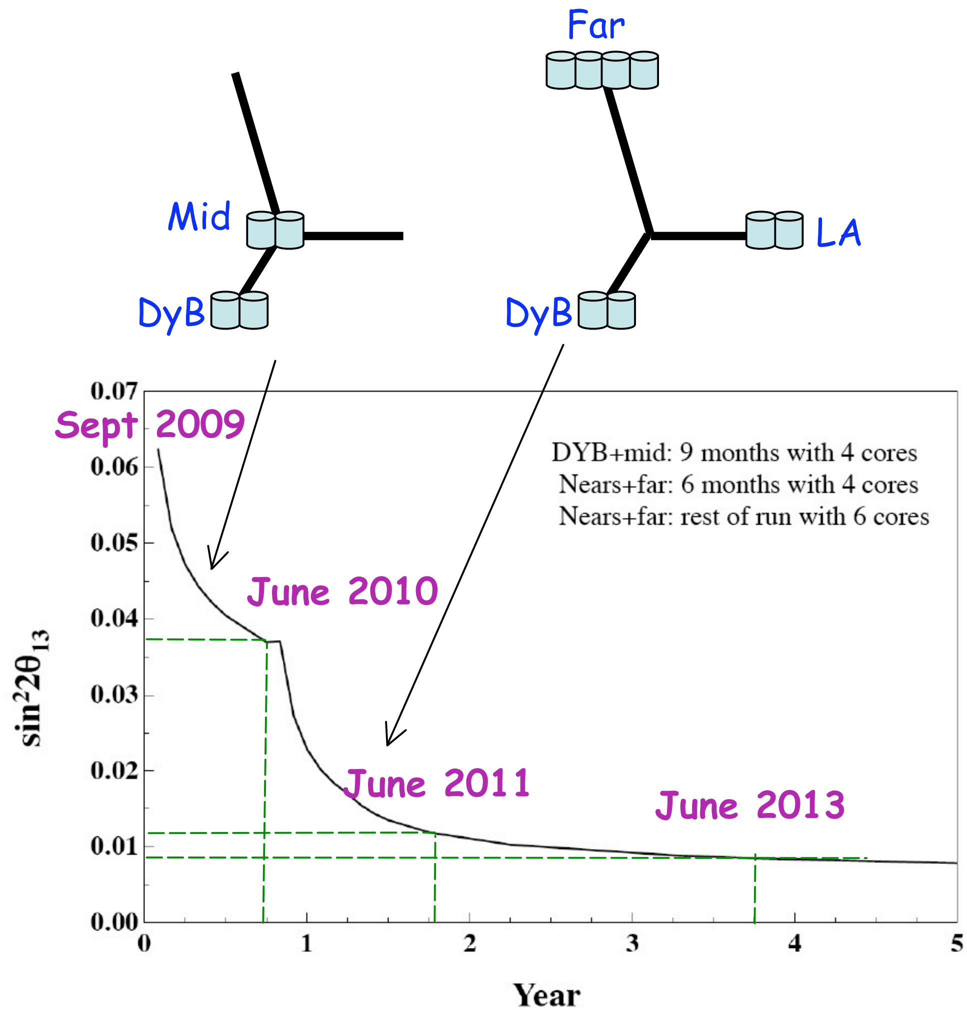
anticipated

with R&D

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

90% confidence level





- Use rate and spectral shape
- input relative detector systematic error of 0.38%

Sensitivity of 9 months running with near-mid, 3 years with near-far

Funding And Support

- Funding Committed from
  - Chinese Academy of Sciences,
  - Ministry of Science and Technology
  - Natural Science Foundation of China
  - China Guangdong Nuclear Power Group
  - Shenzhen municipal government
  - Guangdong provincial government
- Strong support from:
  - China Guangdong Nuclear Power Group
  - China atomic energy agency
  - China nuclear safety agency

- Supported by BNL/LBNL LDRD funds
- Supported by DOE $1M R&D to date
- Support by funding agencies from other countries & regions
- China plans to provide civil construction and ~half of the detector systems; U.S.plans to bear ~half of the detector cost

Summary

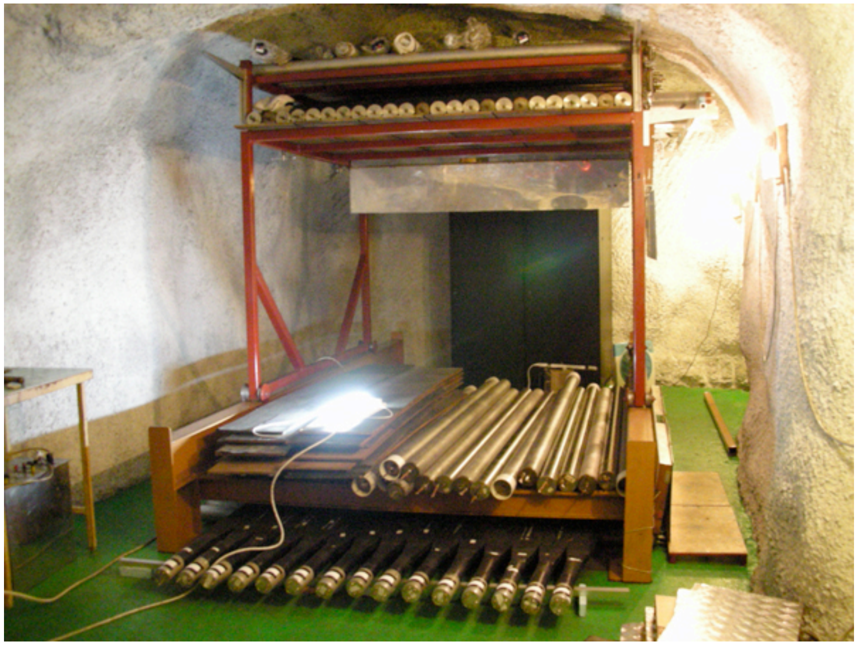
- The Daya Bay experiment will reach a sensitivity of ≤ 0.01 for $\sin^2 2\theta_{13}$
- Design of detectors is in progress and R&D is ongoing
- Completed DOE scientific review, and is preparing for DOE CD-1 review in April, 2007
- Detailed design of tunnels and infrastructures is in progress
- The Daya Bay Collaboration continues to grow
- Received commitments from Chinese agencies and power plant
- Plan to start civil construction in 2007, deploying detectors in 2009, begin full operation in 2010, and reach the designed sensitivity by 2013

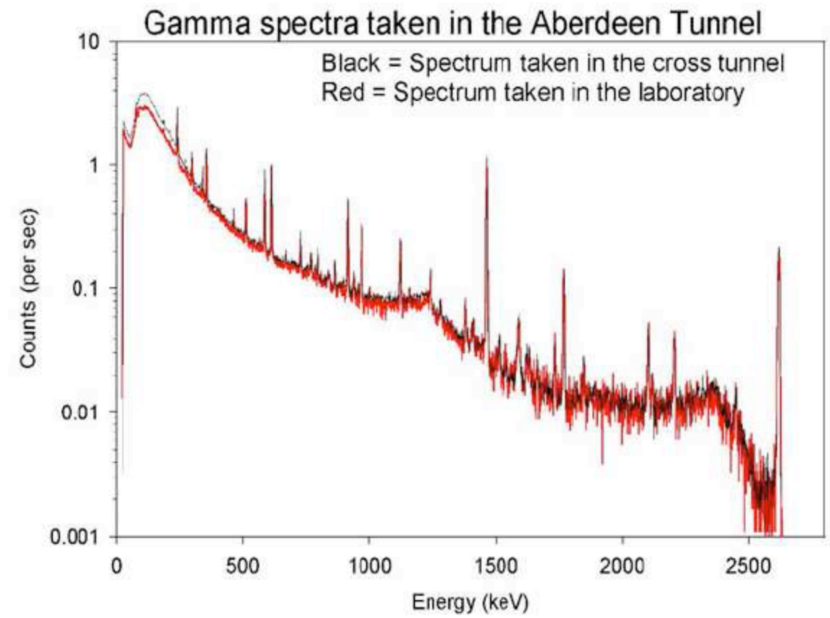
Schedule

• Will begin civil construction	Jun 2007
• Bring up the first pair of detectors	Jun 2009
• Begin data taking with the Near-Mid configuration	Sept 2009
• Begin data taking with the Near-Far configuration	Jun 2010
• Reach $\sin^2 2\theta_{13} < 0.01$	Jun 2013

Aberdeen Tunnel Experiment (Hong Kong)

For studying cosmic muons, spallation neutrons, and gamma background





similar overburden/geology between Aberdeen and Daya Bay

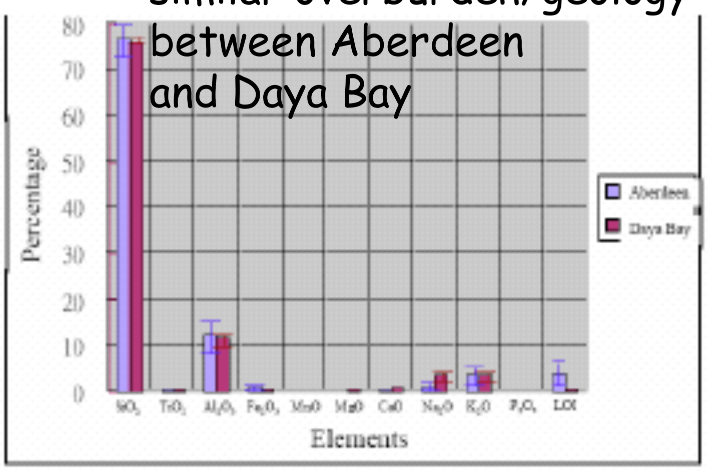


Fig. 1 A comparison of rock compositions at Daya Bay and Aberdee