The Daya Bay Reactor Antineutrino Experiment

measuring the mixing angle θ_{13}

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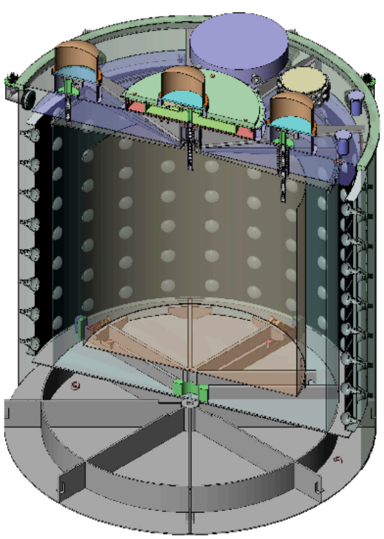



Neutrinos have mass? I didn't even know they were Catholic!

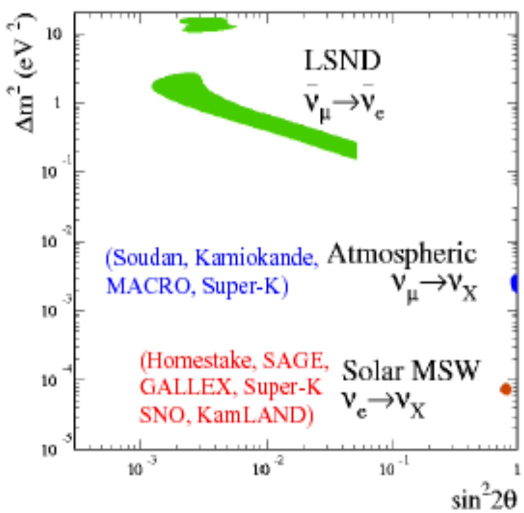
Black Diamond Neutrino Carabiner

Neutrino Oscillation

Neutrino Mixing: PMNS Matrix

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric, K2K, MINOS, T2K, etc.	Reactor Accelerator	Solar KamLAND
$\theta_{23} \sim 45^o$	$\theta_{13} < 12^o$	$\theta_{12} \sim 30^o$

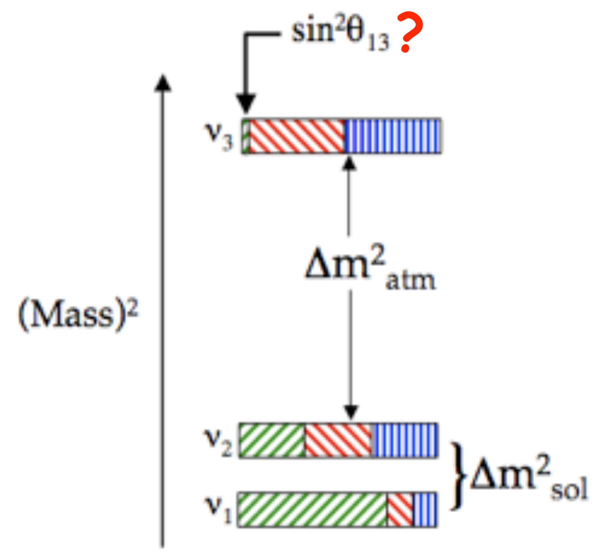


Known: $|\Delta m^2_{32}|$, $\sin^2 2\theta_{23}$, Δm^2_{21}, $\sin^2 2\theta_{12}$

Unknown: $\sin^2 2\theta_{13}$, δ_{CP}, Sign of Δm^2_{32}

Importance of θ_{13}

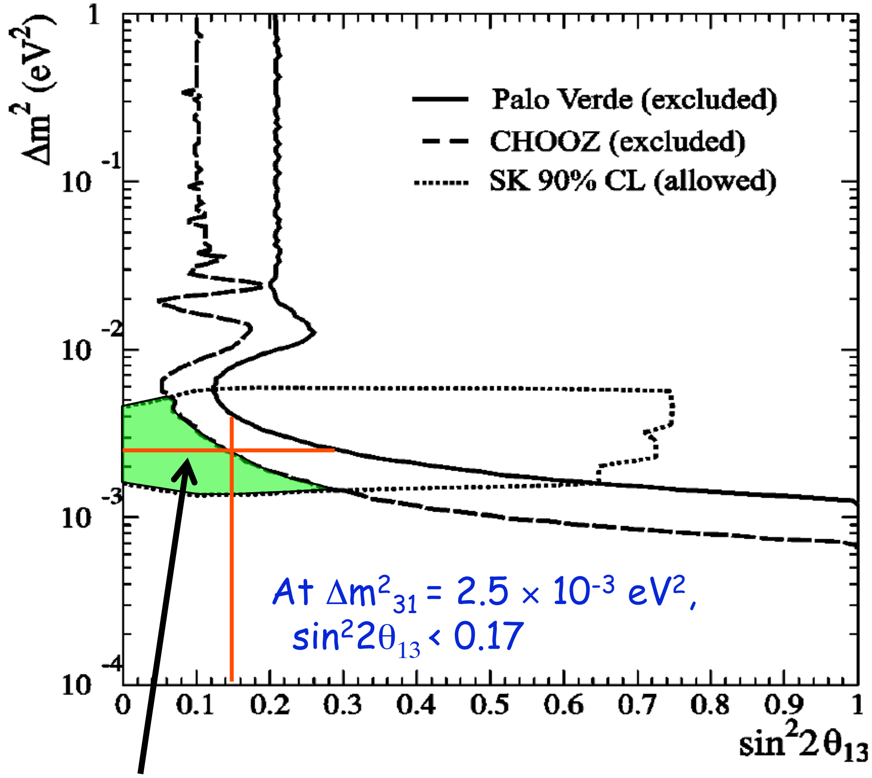
- It is one of the key parameters in determining the leptonic mixing matrix.
- What is ν_e fraction of ν_3?



- U_{e3} is the gateway to CP violation in neutrino sector:

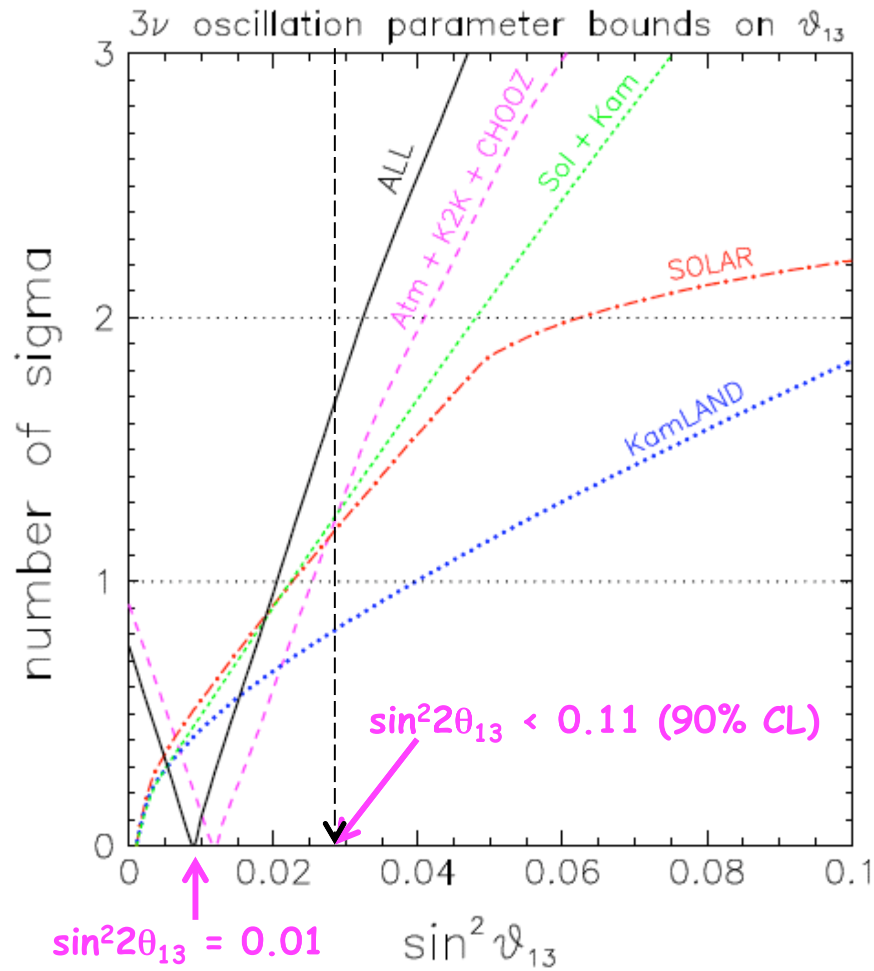
Current Knowledge of θ_{13}

Direct search



allowed region

Global fit



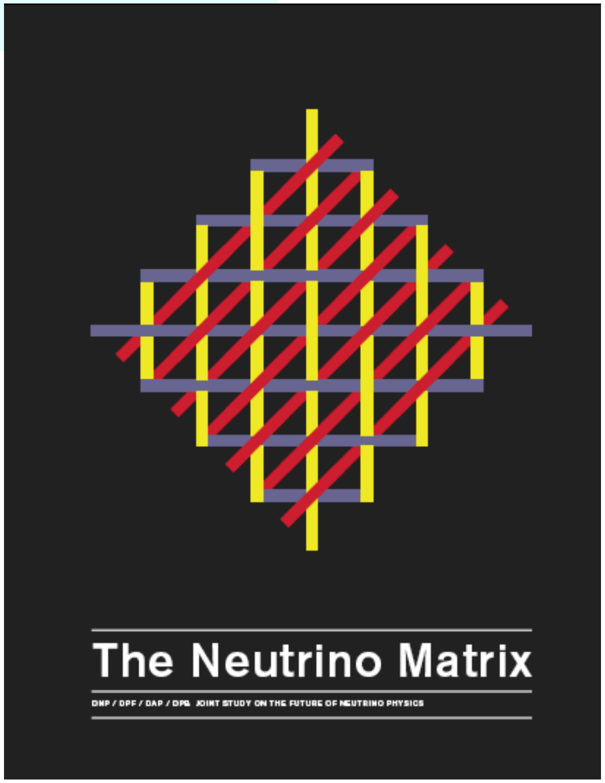
Best fit value of $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2

Fogli etal., hep-ph/0506083

What Should Be Done ?

- **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.*

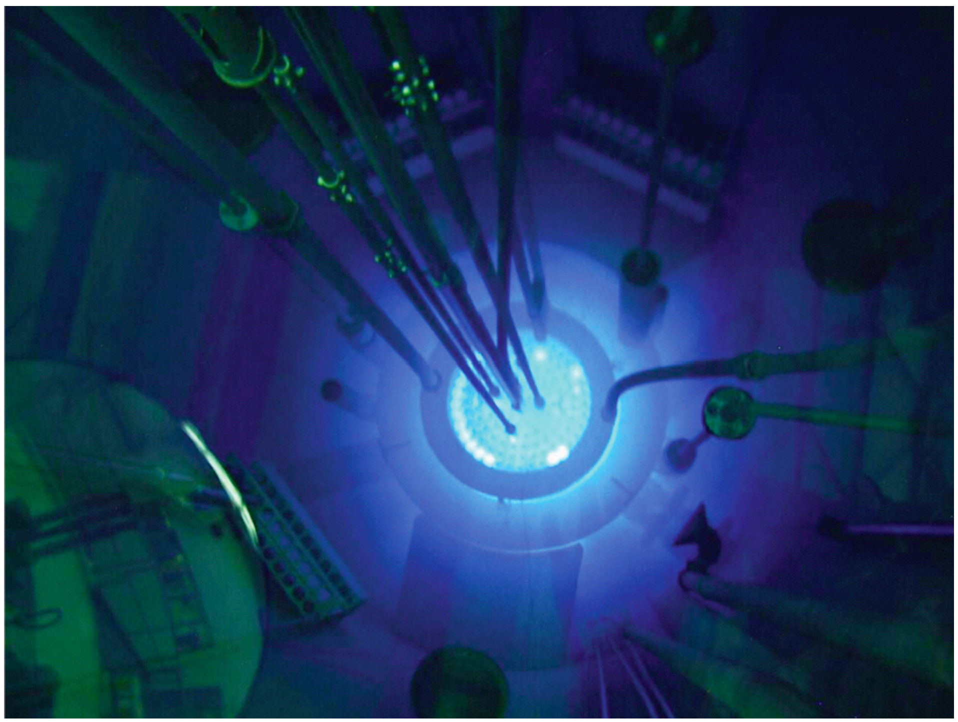


- **Neutrino Scientific Assessment Group:**

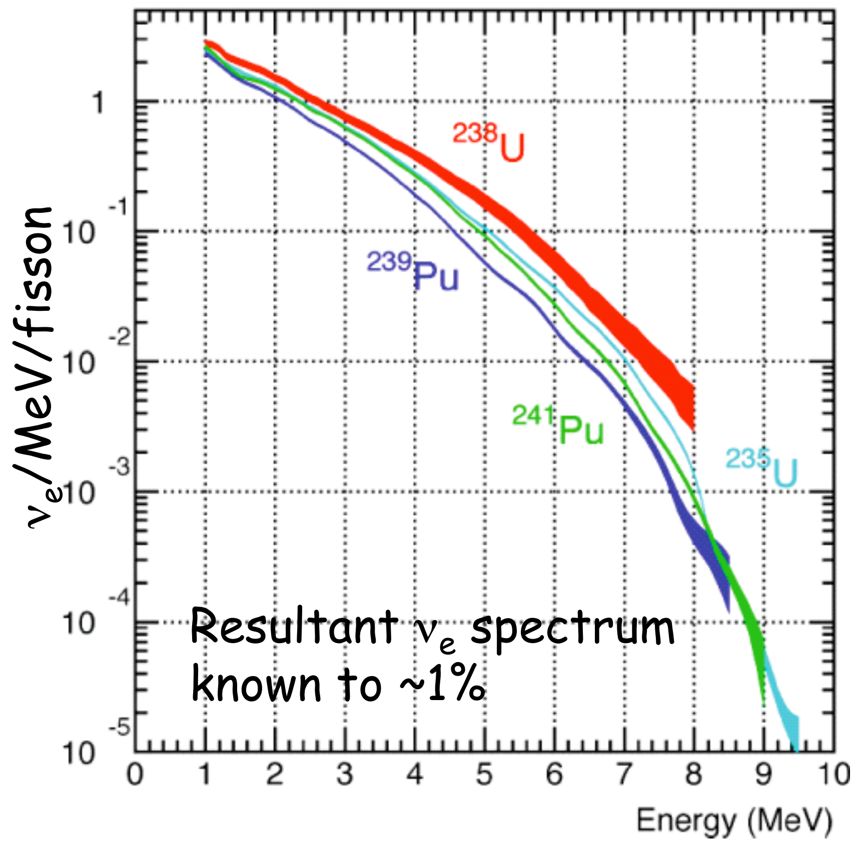
The United States should mount one multi-detector reactor experiment sensitive to $\bar{\nu}_e$ disappearance down to $\sin^2 2\theta_{13}$~0.01.

Reactor Antineutrinos $\overline{\nu}_e$

- Fission processes produce neutron rich isotopes which beta decay quickly, releasing huge numbers of low-energy antineutrinos…



3 GW_{th} generates 6×10^{20} ν_e per sec



Detecting antineutrinos in liquid scintillator

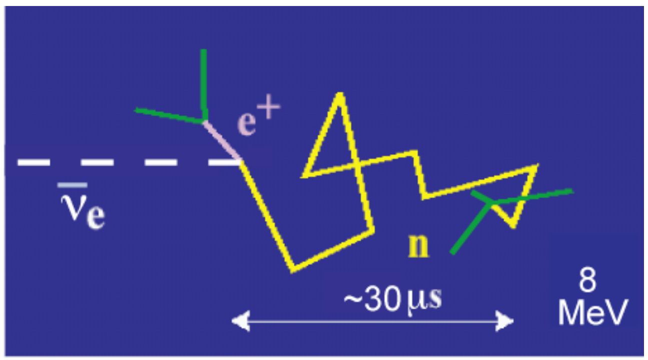
- Detect inverse β-decay reaction in 0.1% Gd-doped liquid scintillator:

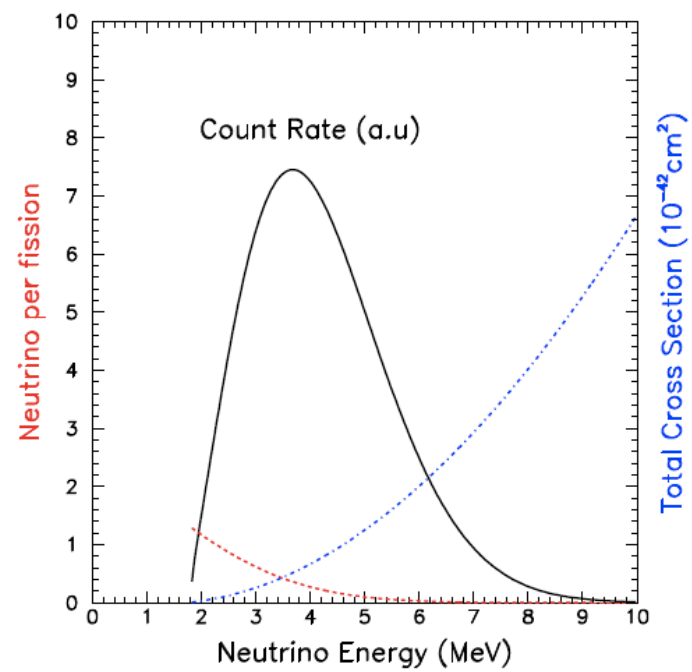
$$\bar{\nu}_e + p \rightarrow e^+ + n \quad \text{(prompt)}$$

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

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

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





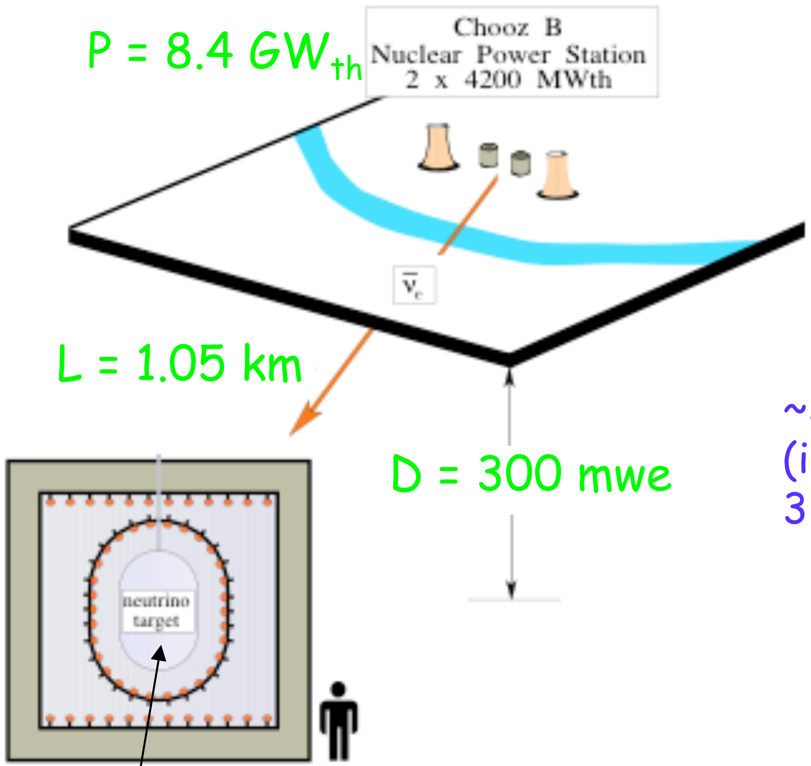
- Time- and energy-tagged signal is a good tool to suppress background events.

- Energy of ν_e is given by:

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

10-40 keV

Chooz: First Attempt In Measuring θ_{13}

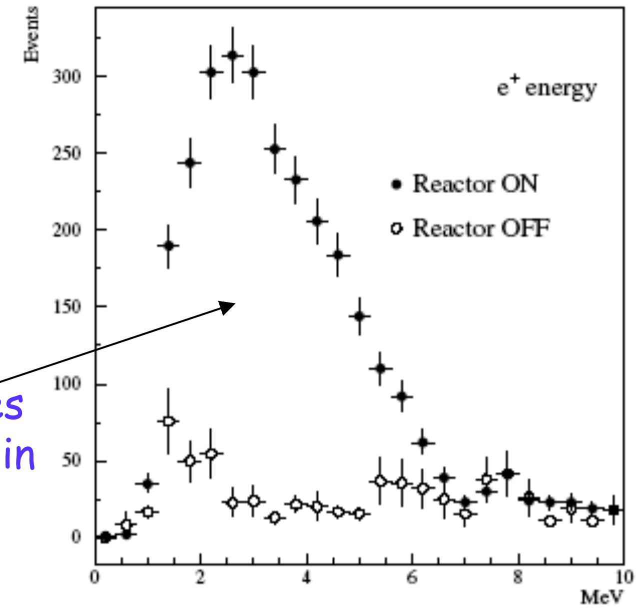


5-ton 0.1% Gd-loaded liquid scintillator to detect $\nu_e + p \rightarrow e^+ + n$

Rate:

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

~3000 ν_e candidates (included 10% bkg) in 335 days

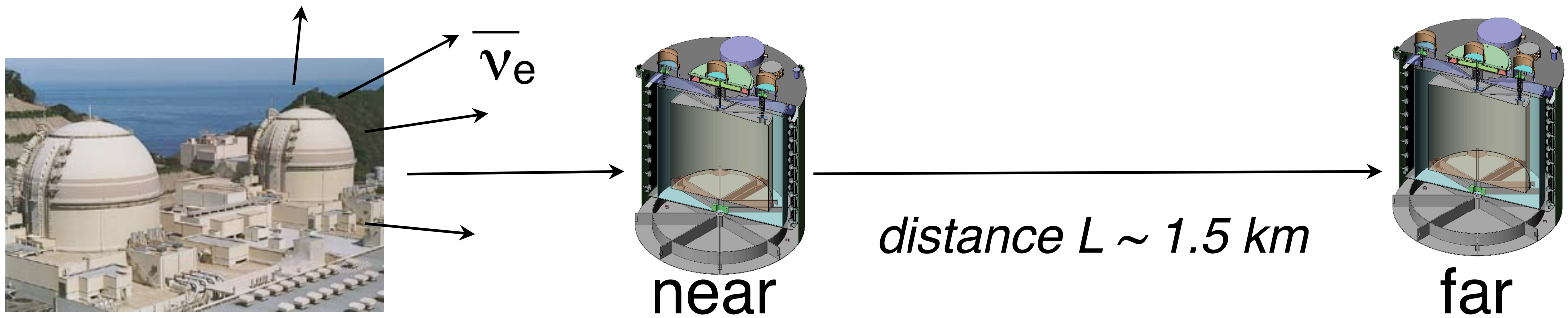


parameter	relative uncertainty (%)	
reaction cross section	1.9	2.5
number of protons	0.8	
detection efficiency	1.5	
reactor power	0.7	0.9
energy released per fission	0.6	
combined	2.7	

$$\frac{N_{obs}}{N_{no-os}} = 1.01 \pm 2.8\%(\text{stat}) \pm 2.7\%(\text{syst})$$

Concept for New Reactor θ_{13} Experiments

Measure ratio of interaction rates in multiple detectors



$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left[\frac{P_{sur}(E,L_f)}{P_{sur}(E,L_n)}\right]$$

Measured Ratio of Rates

Detector Mass Ratio, H/C

Detector Efficiency Ratio

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

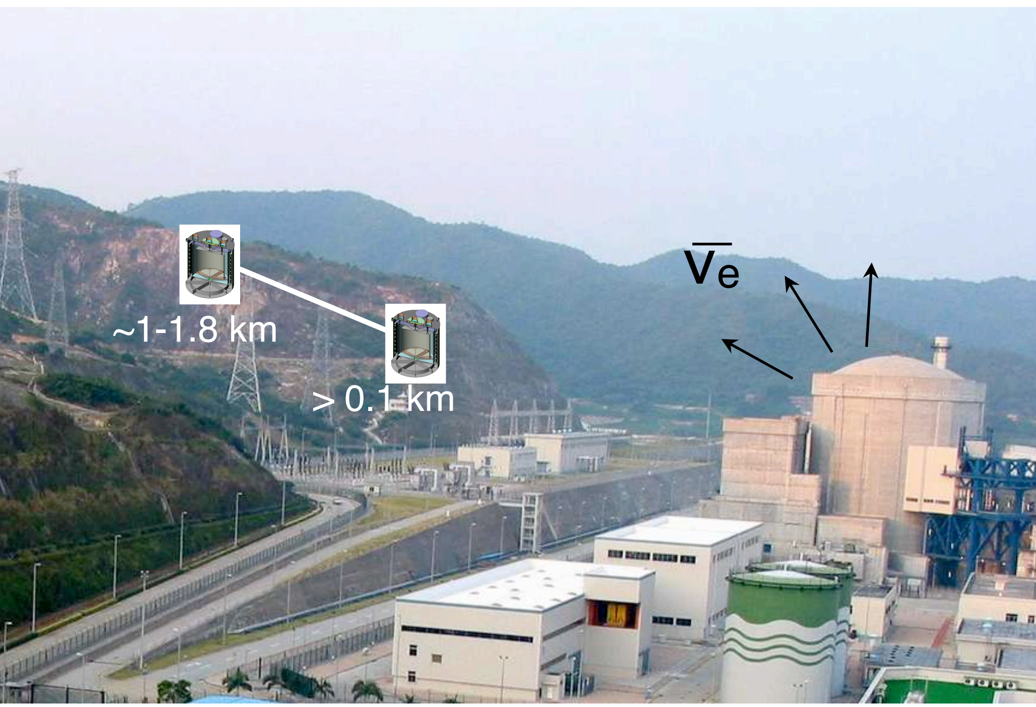
Precision Measurement of θ_{13} with Reactor Antineutrinos

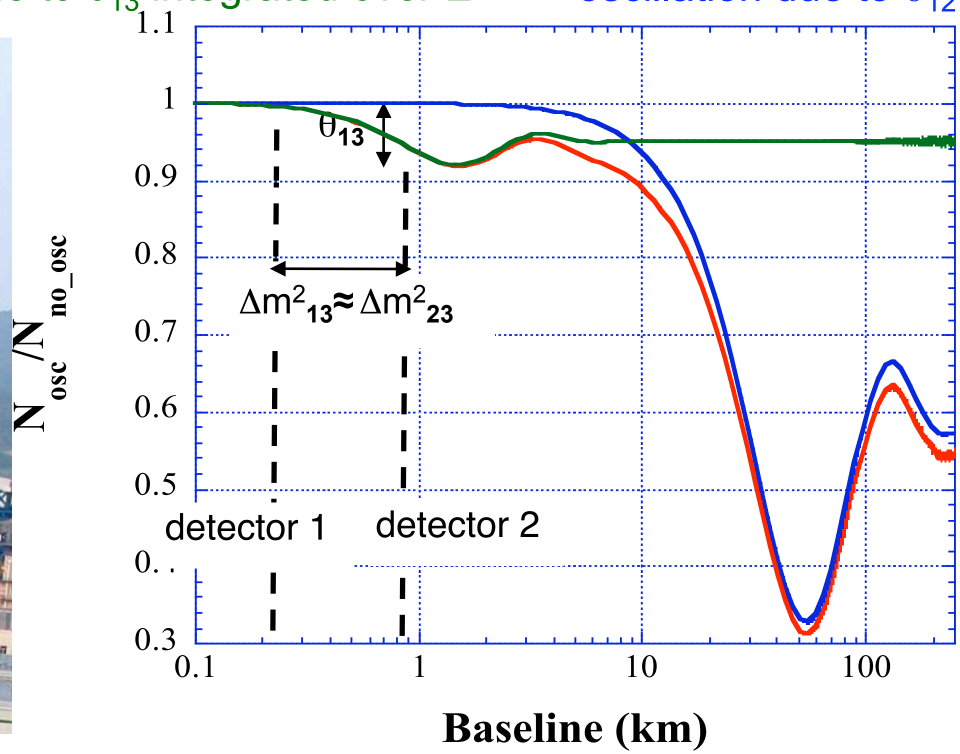
Search for θ_{13} in new oscillation experiment with multiple detectors

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

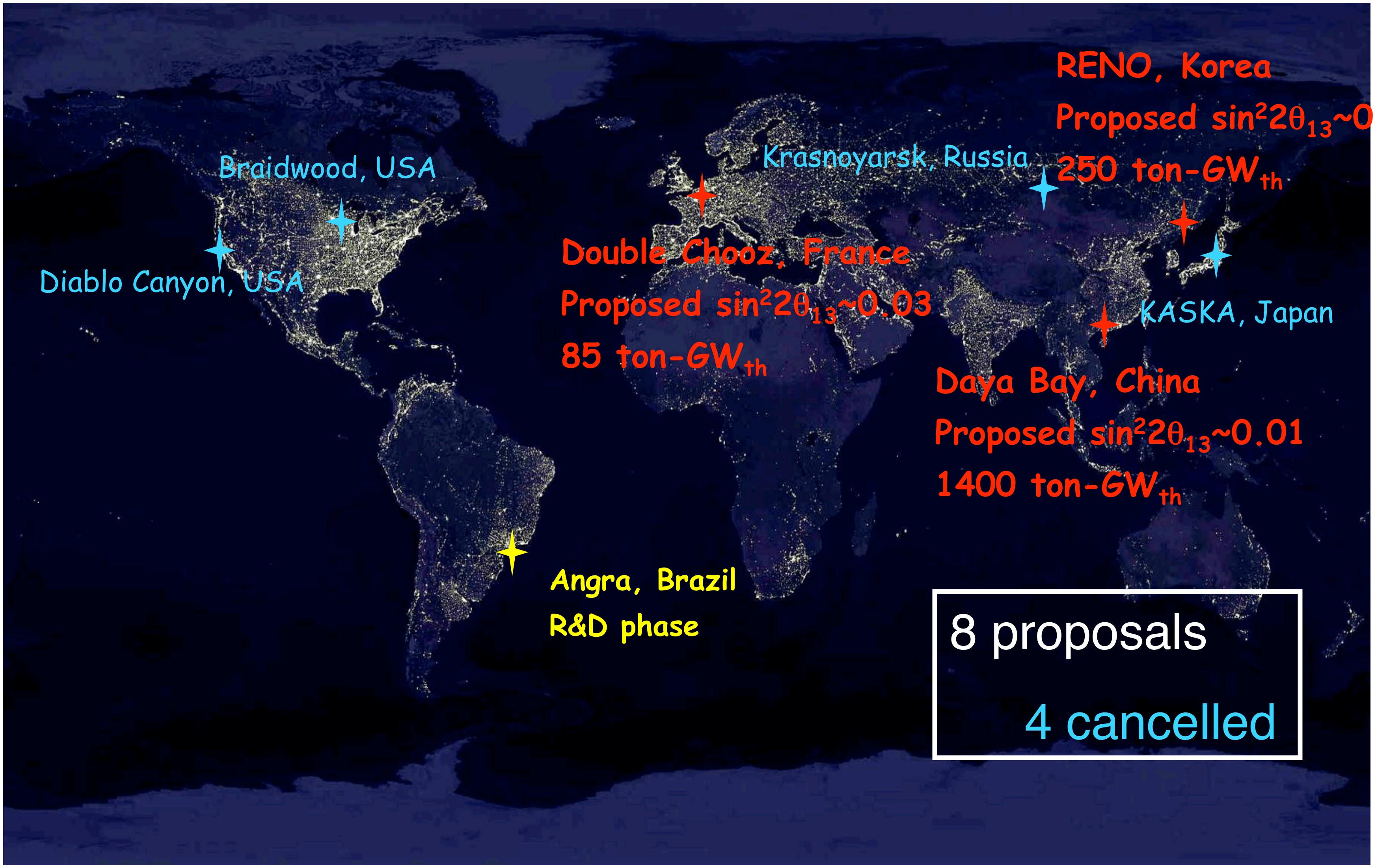
Small-amplitude oscillation due to θ_{13} integrated over E

Large-amplitude oscillation due to θ_{12}

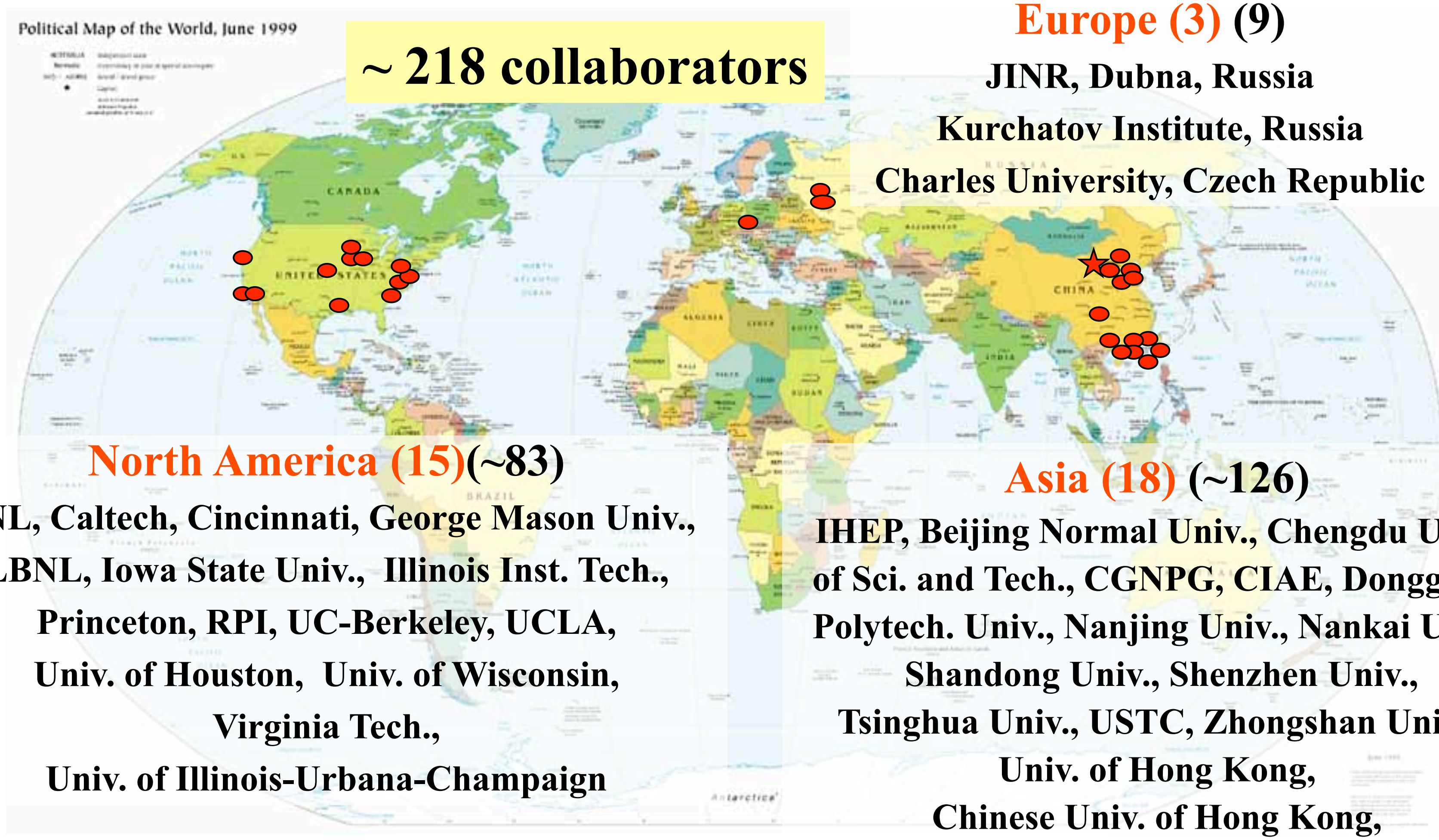




Proposals for measuring θ_{13} at reactors



The Daya Bay Collaboration



~ 218 collaborators

Europe (3) (9)

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

North America (15)(~83)

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

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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.

Map
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Terrain
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深圳市
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Man Kam To
水牛嶺
Shui Ngai Tso
沙頭角
Sha Tau Kok
羅湖
Lo Wu
落馬洲
Lok Ma Chau
水流坑
Shui Lau Hang
鹿頸
Luk Keng
大欖基
Tai Long Kei
石湖墟
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San Tau Yiu
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Lau Fau Shan
天水圍
Tin Shui Wai
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Shuen Wan
十四鄉
Shap Sze Heung
元朗
Yuen Long
元朗
Yuen Long
石崗
Shek Kong
Tsing Long Hwy
沙田
Sha Tin District
龍鼓灘
Lung Kwu Tan
掃管笏
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Tai Lum Chung
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Sai Kung
西貢
Sai Kung District
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九龍灣
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Tseung Kwan O
香港國際機場
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陰澳
Yam O
Lantau Link
大水坑
Tai Shui Hang
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Kwun Tong District
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長洲
Cheung Sha
黃竹坑
Wong Chuk Hang
石壁
Shek Pik
Islands
鴨脷洲
Kam Lo Hom
南丫島
Lamma Island
赤柱
Stanley
5 mi
5 km
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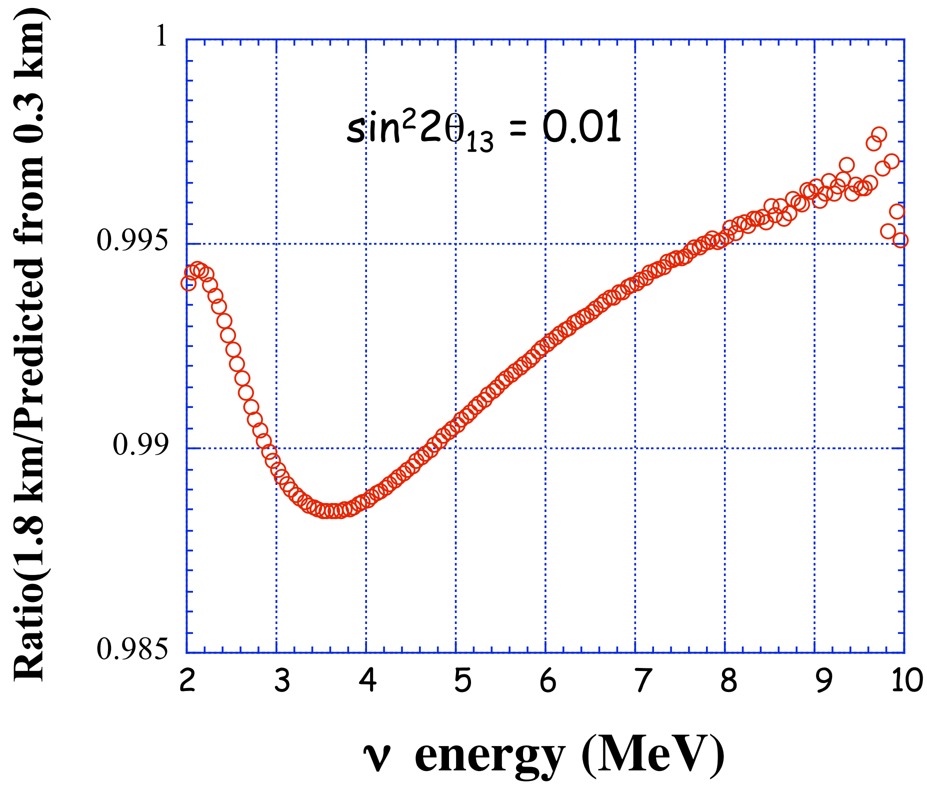
Daya Bay: Goal And Approach

- **Utilize the Daya Bay nuclear power complex to:**

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

  by measuring deficit in ν_e rate and spectral distortion.



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

CHOOZ: R=1.01±2.8%(stat) ±2.7%(syst), $\sin^2 2\theta_{13}<0.17$

Higher statistics

- 40 ton-GW → 1400 ton-GW at Daya Bay
- Statistical error 0.2% in 3 years.

Lessons from past experience:

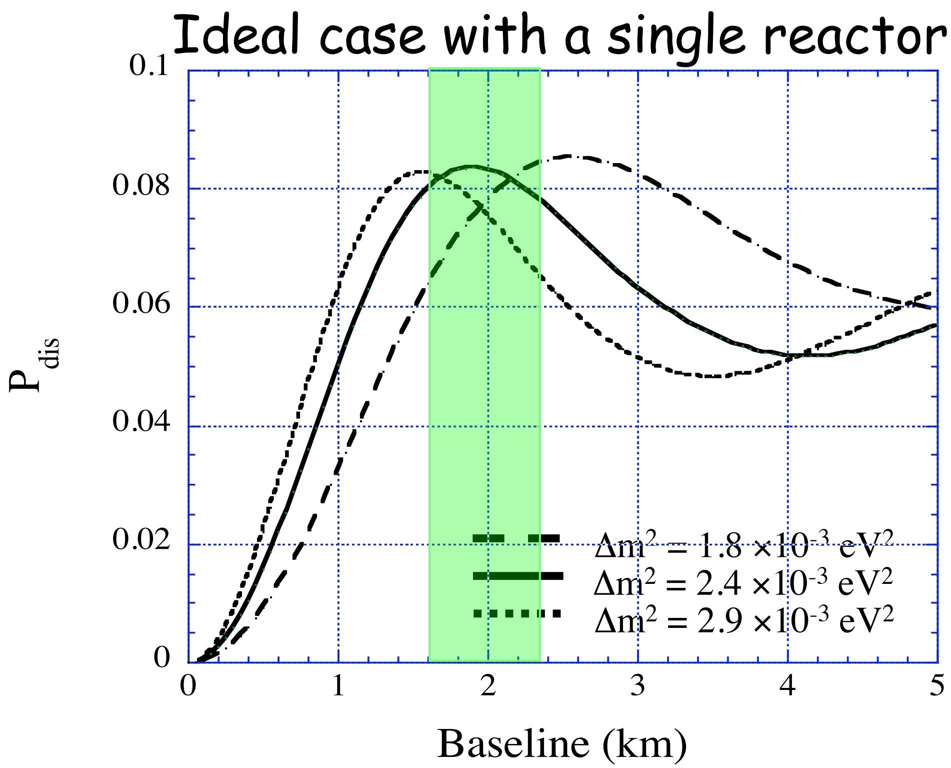
- Need near and far detectors
- Chooz: Good Gd-LS
- Palo Verde: Go deeper, good muon system
- KamLAND: No fiducial cut, lower threshold

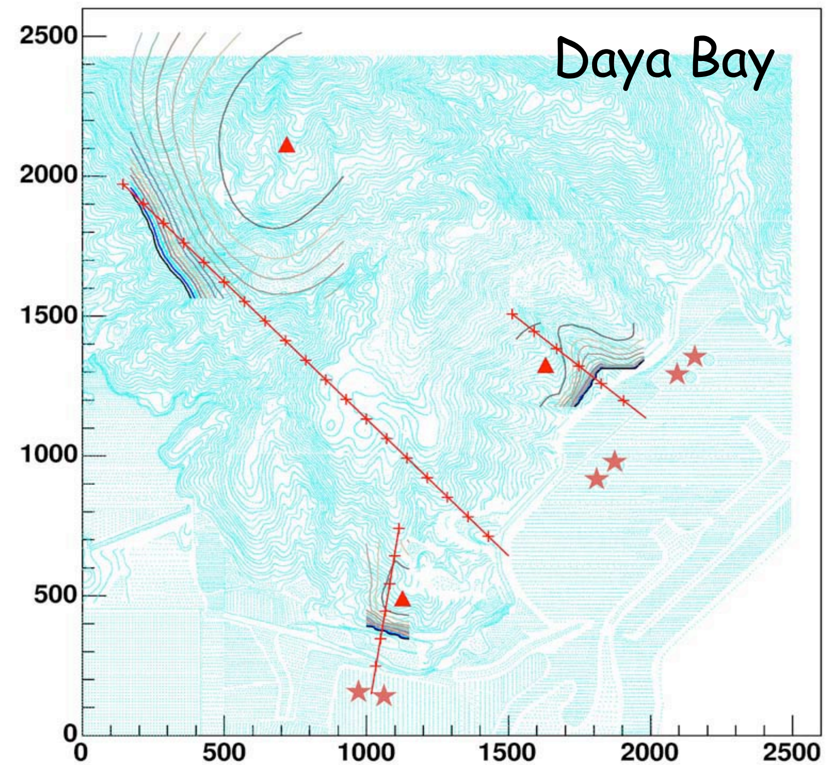
Parameter	Relative error	Daya Bay
Reaction cross section	1.9 %	Cancel out, Near/far
Number of protons	0.8 %	Reduced to <0.3%, filling tank with load cell
Detection efficiency	1.5 %	Reduced to ~0.2%, 3-layer detector
Reactor power	0.7 %	Reduced to ~0.1%, Near/far
Energy released per fission	0.6 %	Cancel out, Near/far
Chooz Combined	2.7 %	

Baseline optimization and site selection

Inputs to the process:

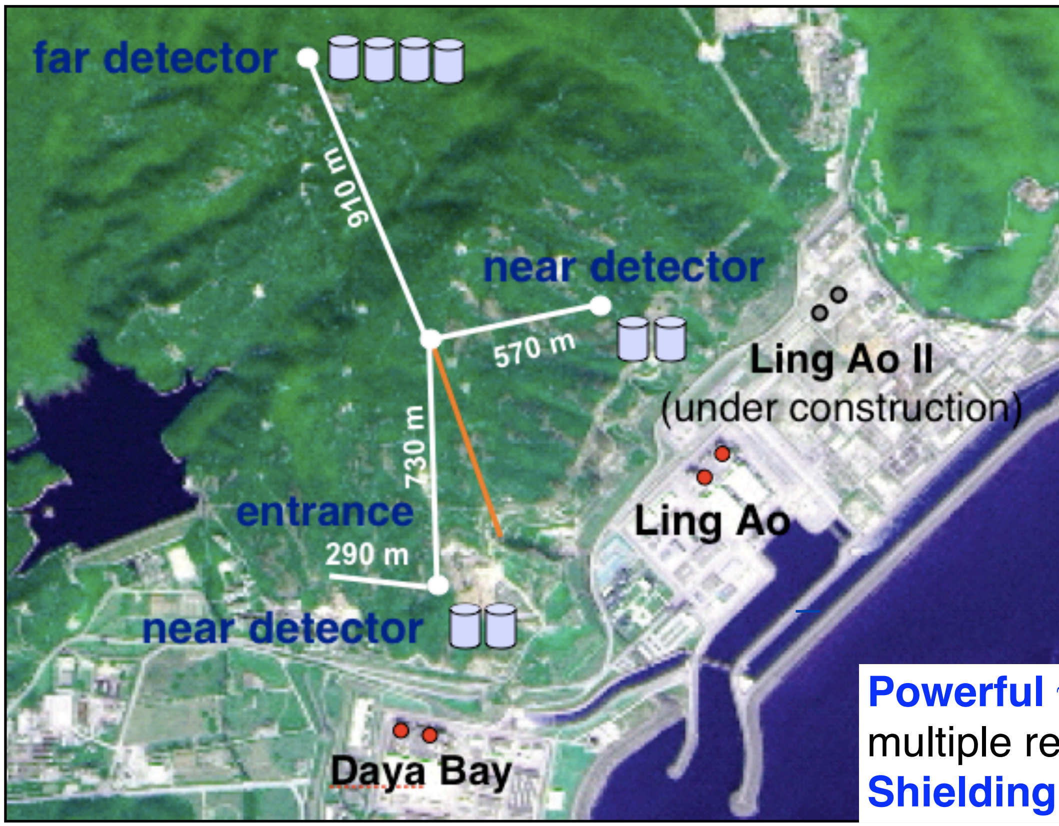
- Flux and energy spectrum of reactor antineutrino
- Systematic uncertainties of reactors and detectors
- Ambient background and uncertainties
- Position-dependent rates and spectra of cosmogenic neutrons and ^{9}Li

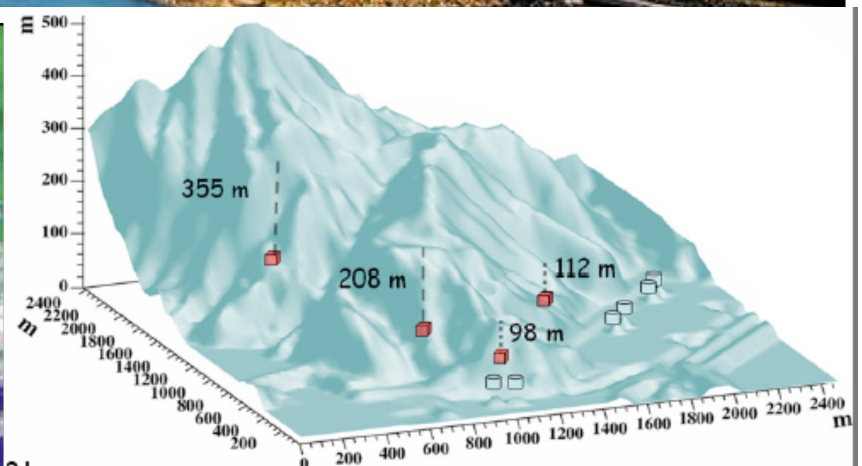




Daya Bay, China

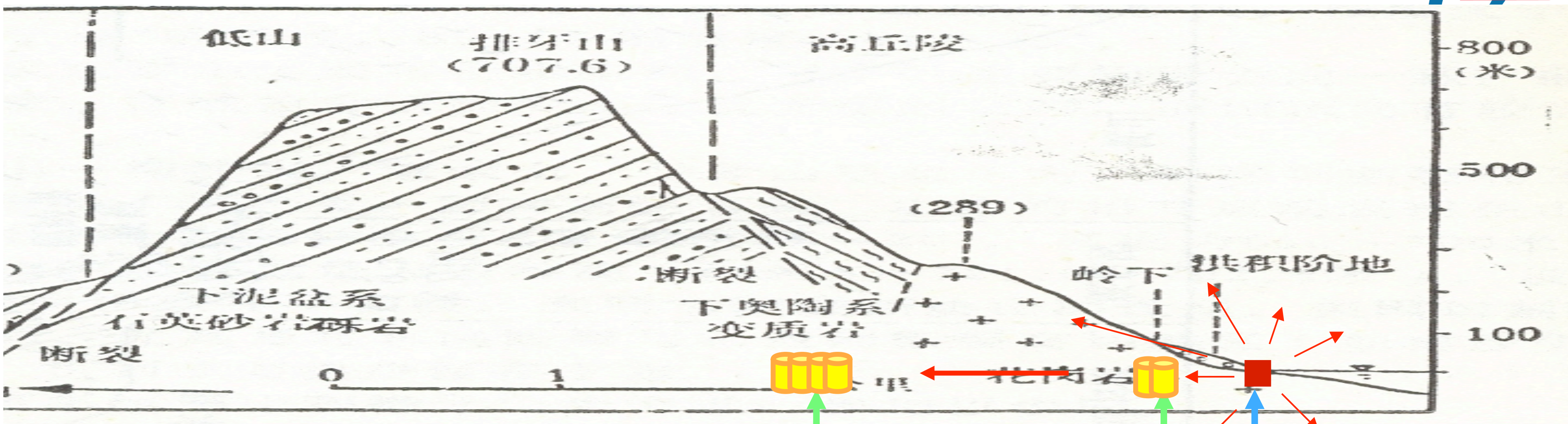
http://dayawane.ihep.ac.cn/





Sites	DYB	LA	Far
DYB cores	363	1347	1985
LA cores	857	481	1618
LA II cores	1307	526	1613

Powerful ν_e Source:
multiple reactor cores, 11.6 GW_{th} now, 17.4 GW_{th} in 2011
Shielding from Cosmic Rays: up to 1000 mwe



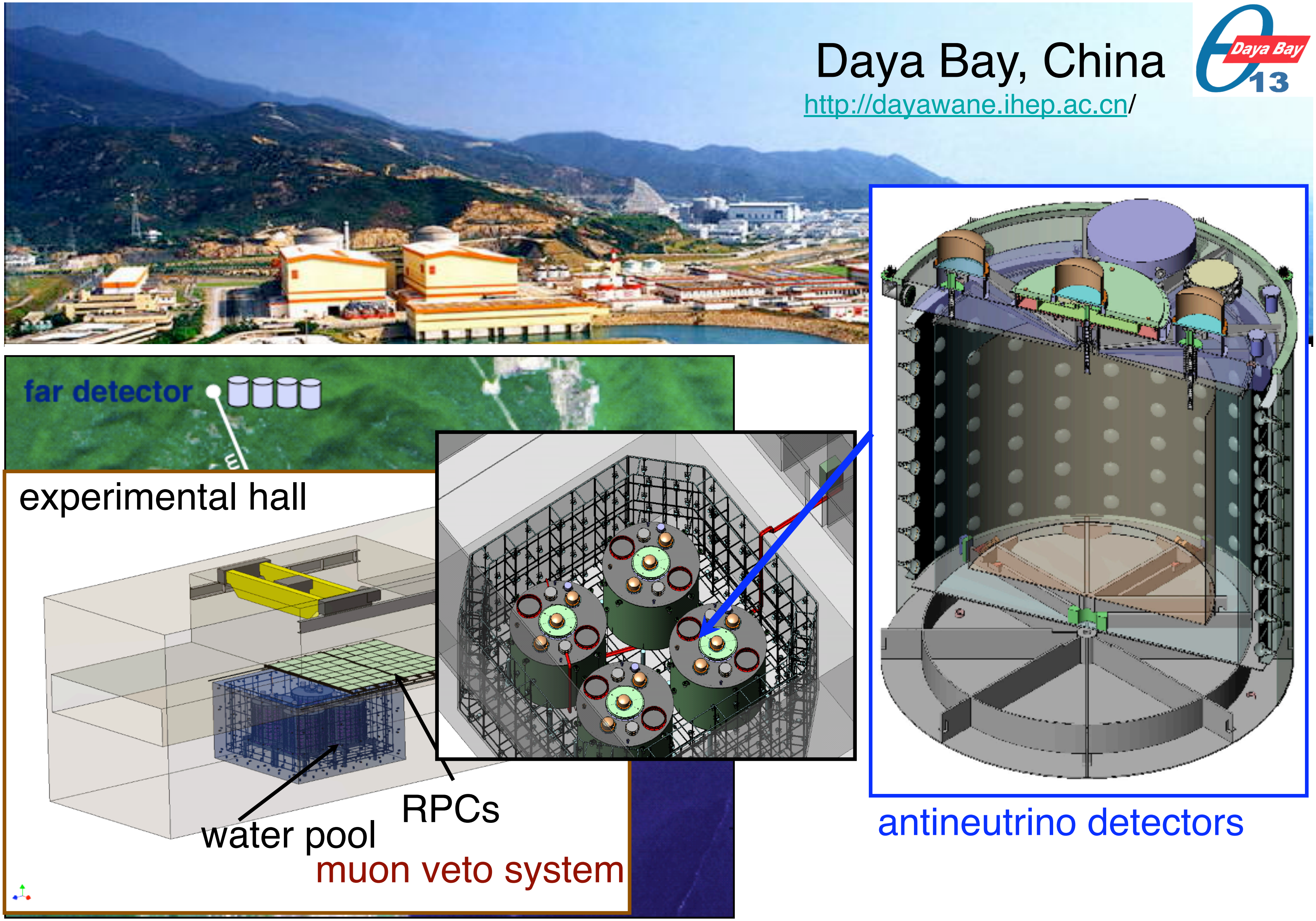
Far Site

Near Site

Reactor

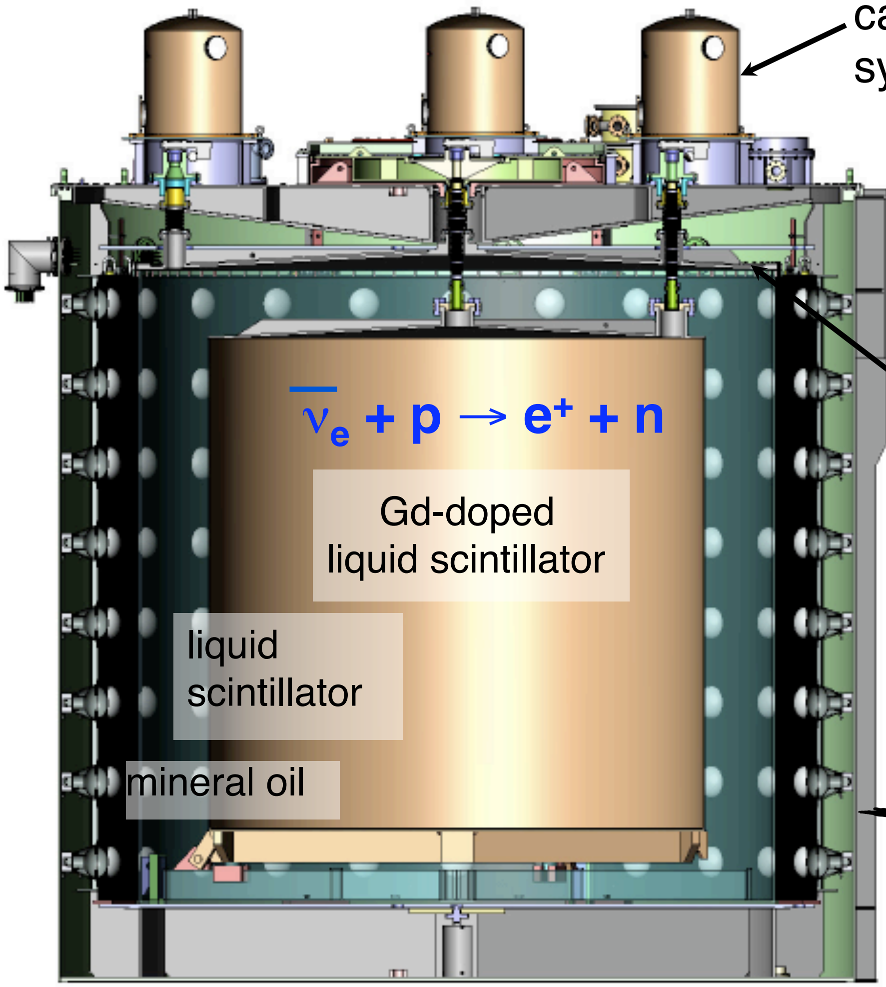
Daya Bay, China

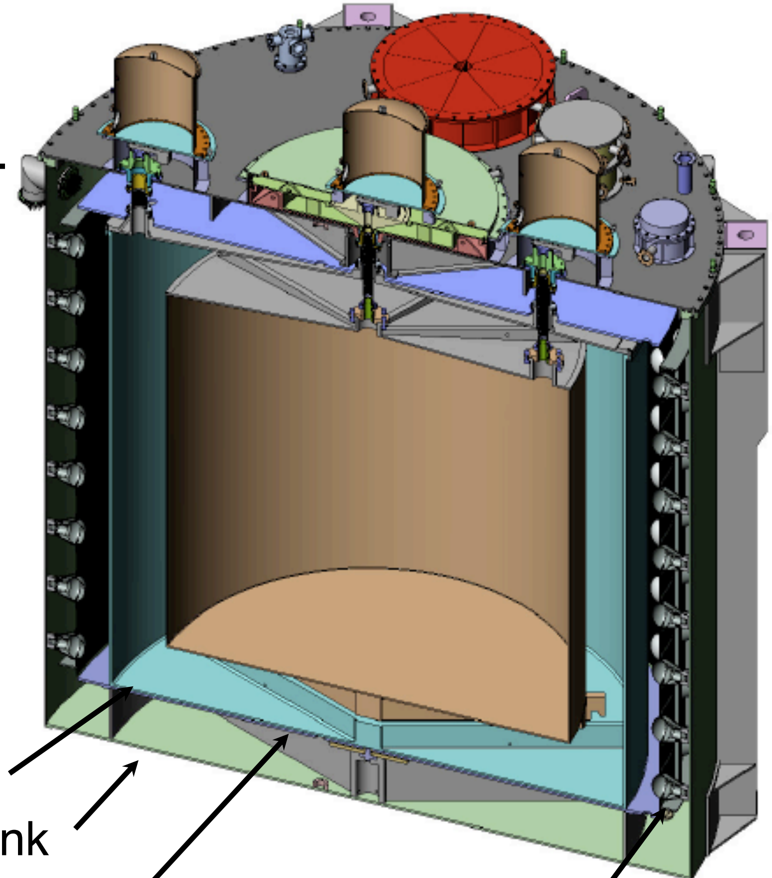
http://dayawane.ihep.ac.cn/



Daya Bay Antineutrino Detectors

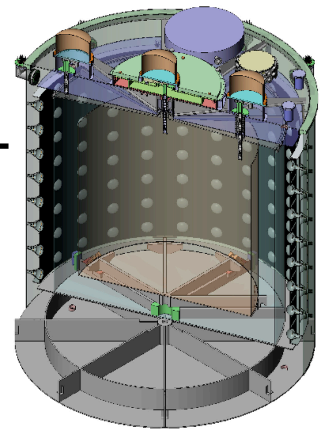
Eight “identical”, 3-zone detectors





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

Antineutrino Detection



Signal and Event Rates

Daya Bay near site	840
Ling Ao near site	760
Far site	90

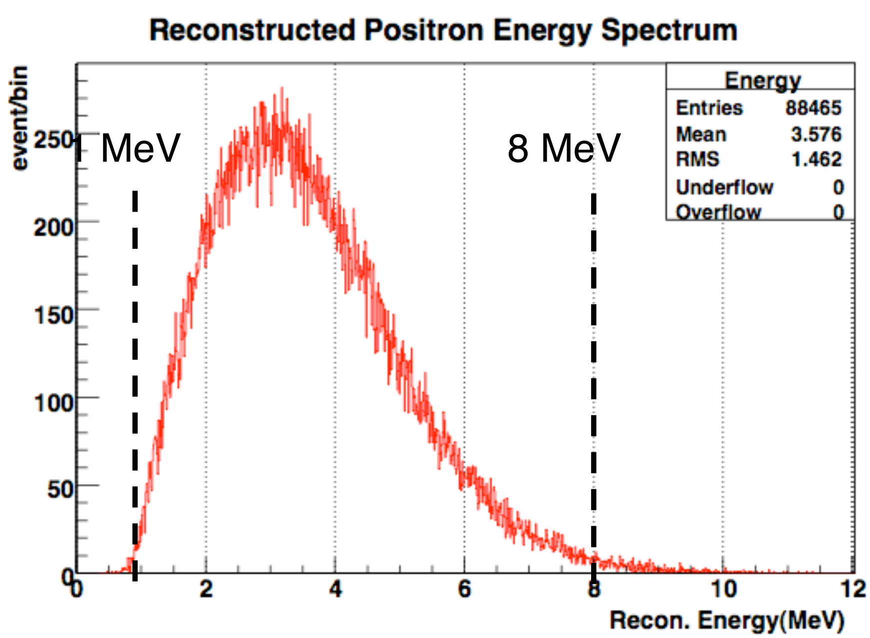
events/day per 20 ton module

$\overline{\nu}_e$ **+ p →** **e⁺ + n**

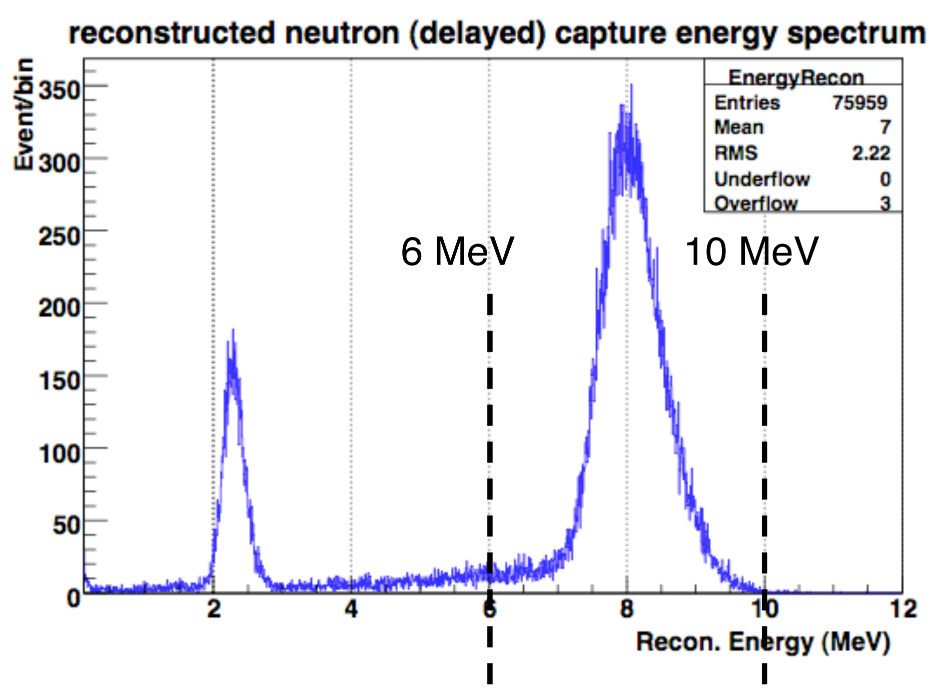
0.3 b → + p → D + γ (2.2 MeV) (delayed)

49,000 b → + Gd → Gd* → Gd + γ's (8 MeV) (delayed)

Prompt Energy Signal



Delayed Energy Signal



Antineutrino Detector Performance

Geant4-based simulations

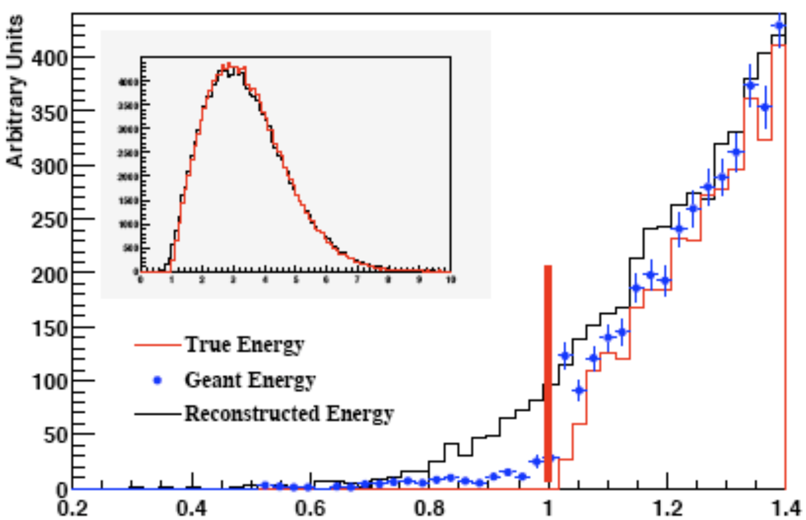
Detection Efficiencies

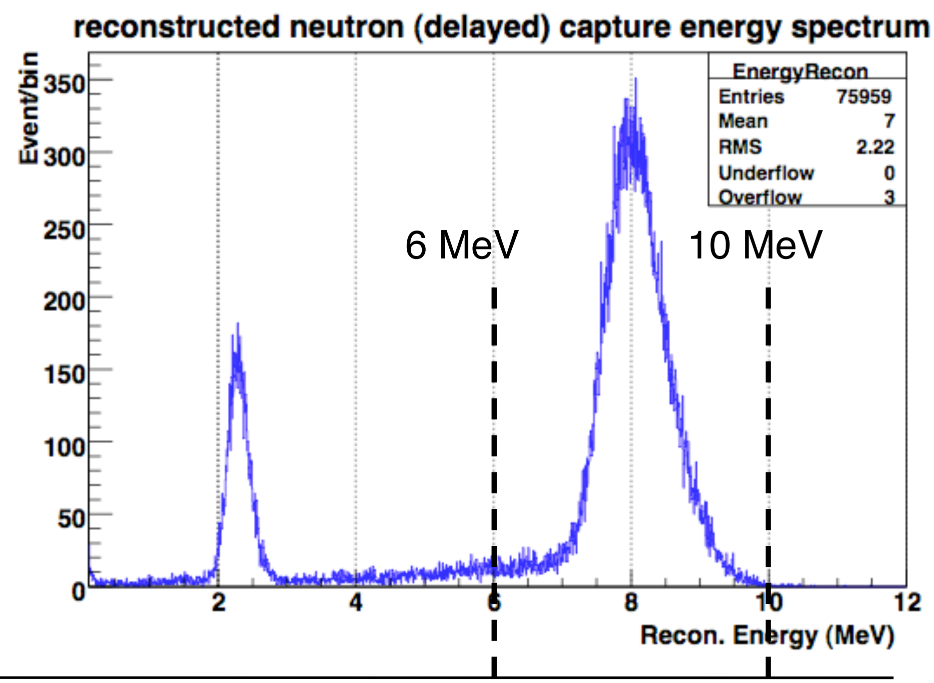
Prompt e^+ Signal

1 MeV cut for prompt positrons: >99%

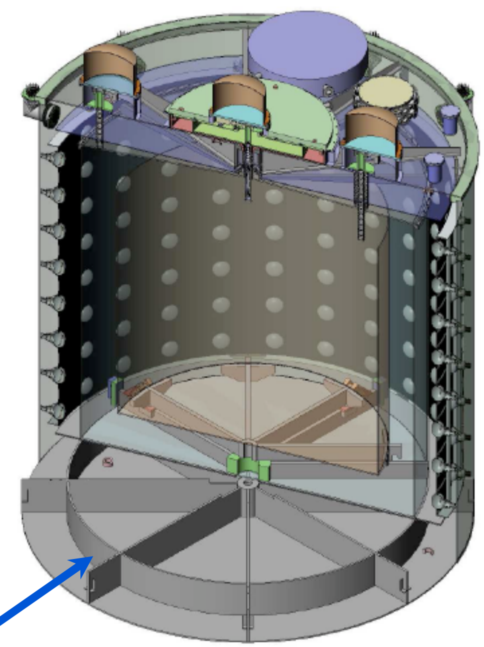
Delayed n Signal

6 MeV cut for delayed neutrons: 91.5%
0.22% uncertainty assuming ΔE = 1%



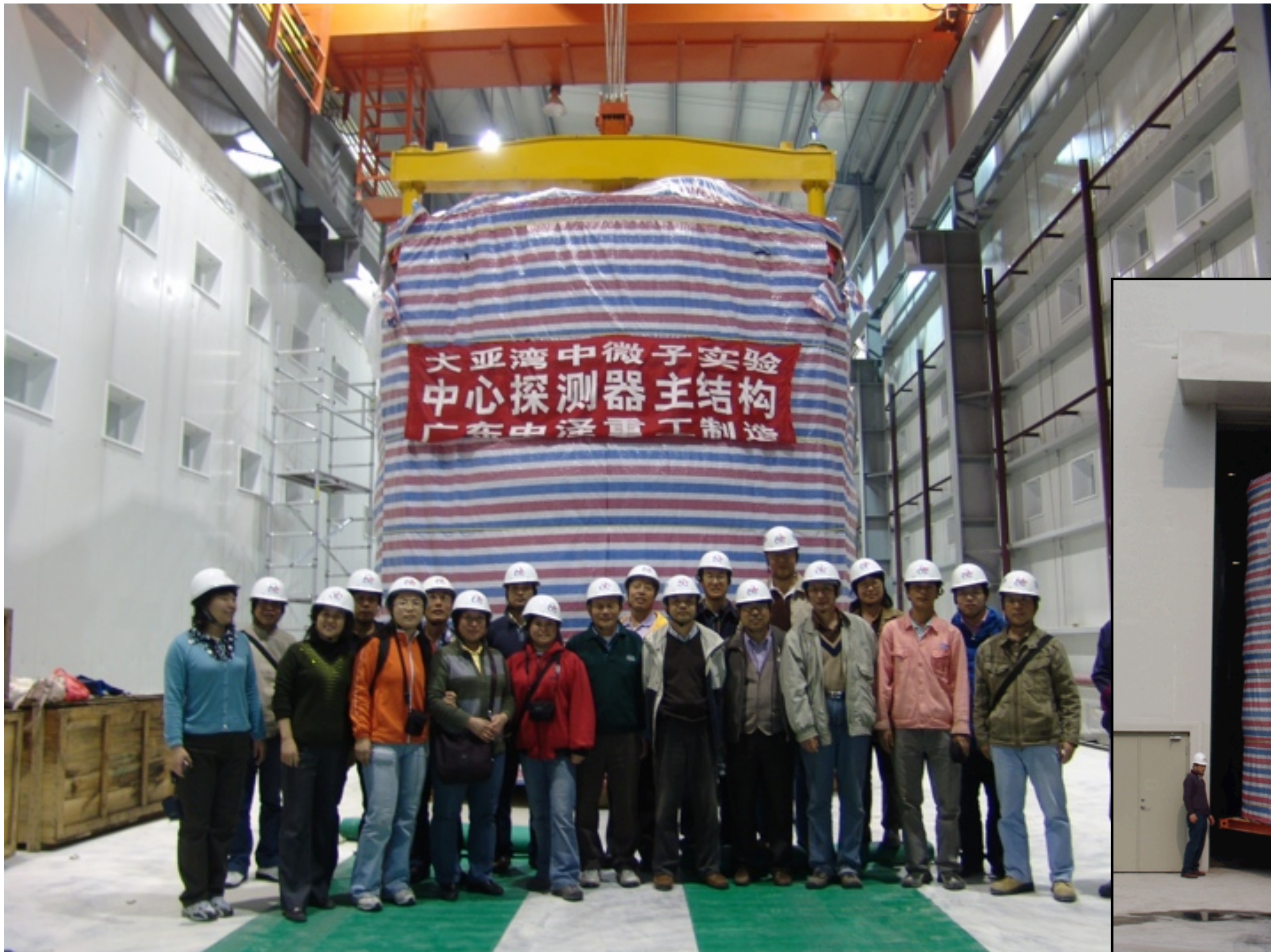


Detector Steel Tank



Detector Steel Tank

Delivery of first detector steel tank to Daya Bay Assembly Building

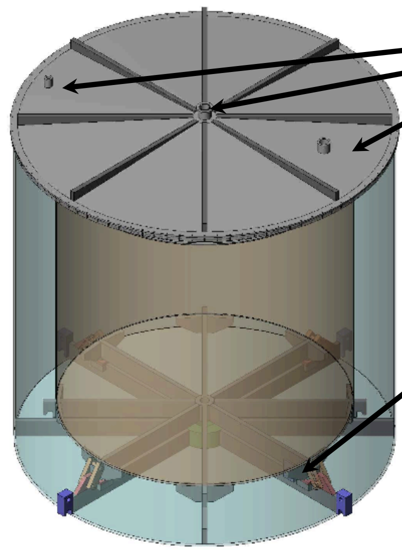


March 13, 2009

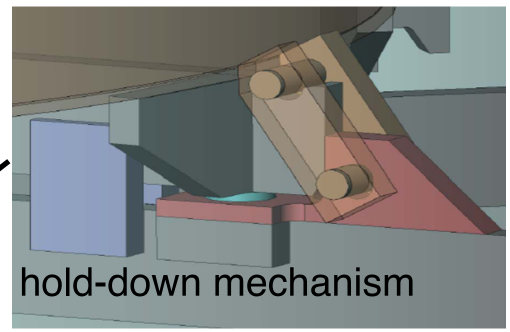
Detector Acrylic Vessel System

Pair of nested acrylic vessels

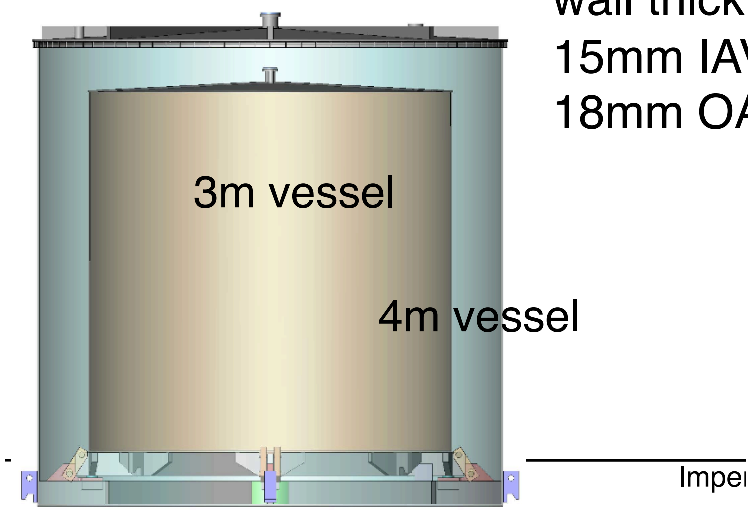
3.1-m and 4-m diameter, fabricated from UVT acrylic

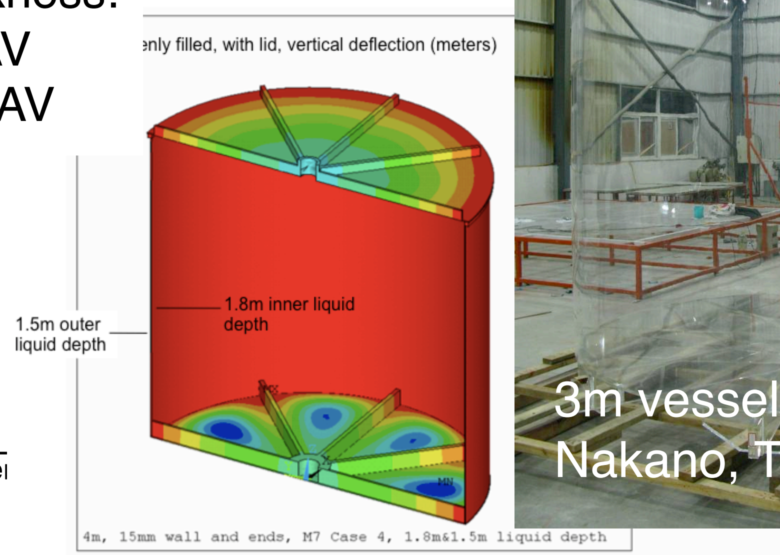


3 calibration pipe connections



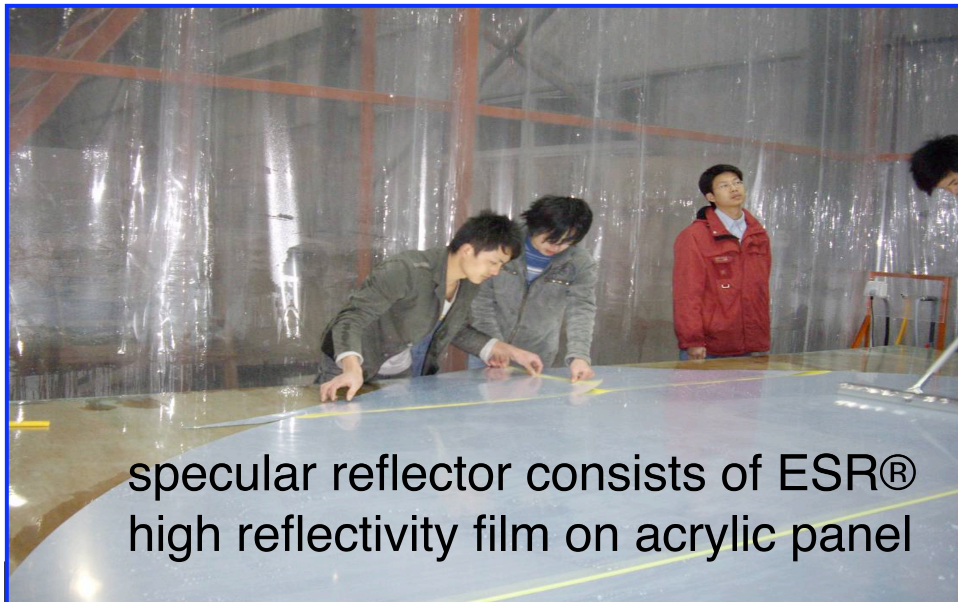
wall thickness:
15mm IAV
18mm OAV



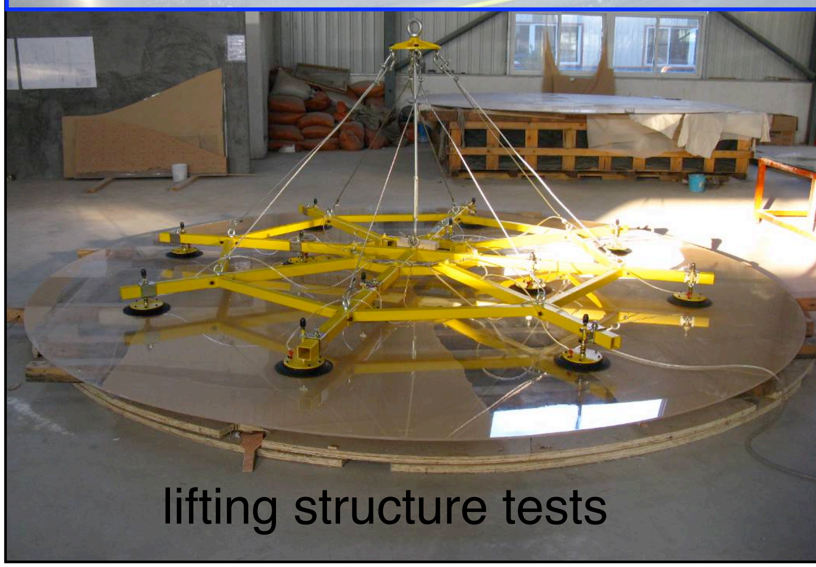


Assembly of 4m Acrylic Vessel Prototype

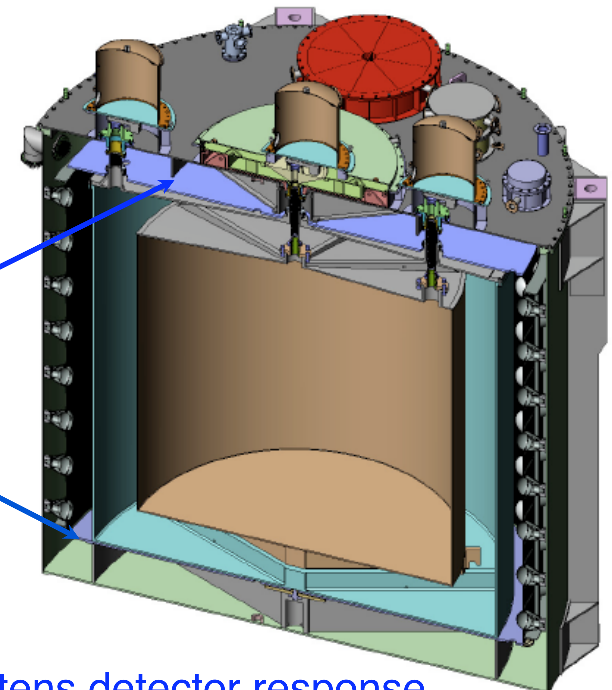
Detector Reflective Panels



specular reflector consists of ESR® high reflectivity film on acrylic panel

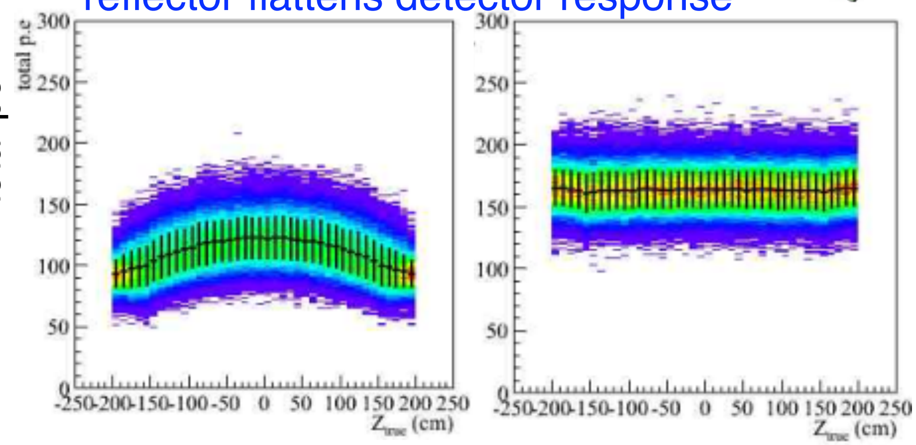


lifting structure tests



reflector flattens detector response

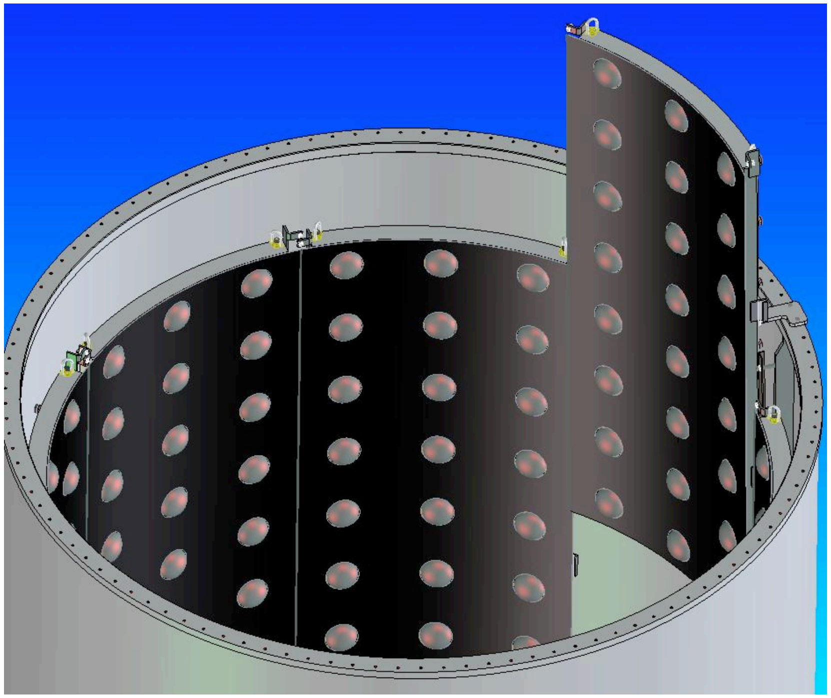
total pe

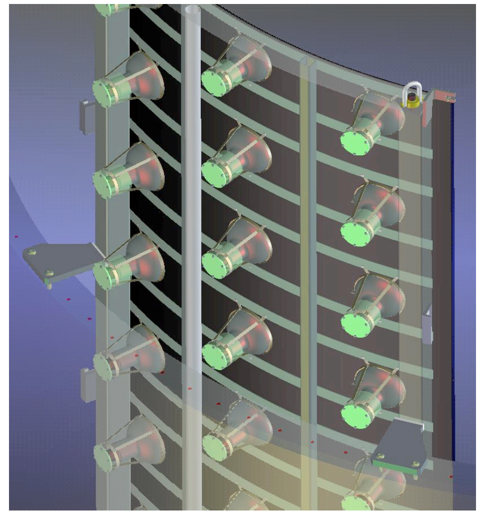


z (cm)

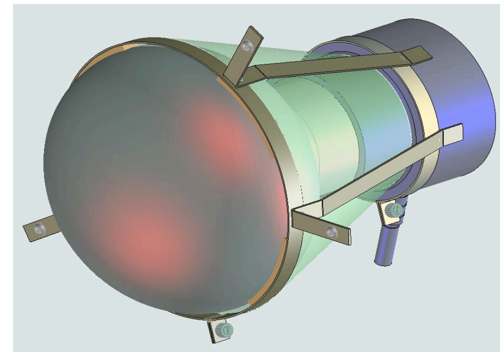
z (cm)

PMT Ladders with Radial Light Shield





individual conical magnetic shields from 16 μm-thick Finemet→ foil

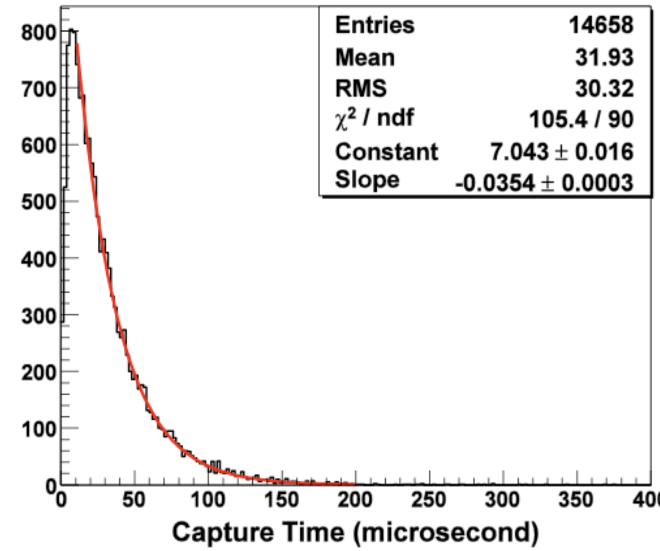


3 mm thick P-95 acrylic
(black matte) as radial shield

eight PMT ladders with 192 8”-PMTs (R5912)

magnetic shield reduces charge variation due to the local magnetic field from 25% to 5%.

Liquid Scintillator Detector Target



0.1% Gadolinium-Liquid Scintillator

- Proton-rich target
- Easily identifiable n-capture signal above radioactive backgrounds
- Short capture time (τ~28 μs)
- Good light yield

$\overline{\nu}_e + p \rightarrow e^+ + n$

0.3 b → $+ p \rightarrow D + \gamma$ (2.2 MeV) (delayed)

49,000 b → $+ Gd \rightarrow Gd^*$

→ $Gd + \gamma$'s (8 MeV) (delayed)

	fraction by weight
C	0.8535
H	0.1288
N	0.0003
O	0.0164
Gd	0.0010

Isotopic Abundance

Gd(152)	*0.200*
Gd(154)	*2.18*
Gd(155)	*14.80*
Gd(156)	*20.47*
Gd(157)	*15.65*
Gd(158)	*24.84*
Gd(160)	*21.86*

^{155}Gd $\Sigma\gamma$=7.93 MeV

^{157}Gd $\Sigma\gamma$=8.53 MeV

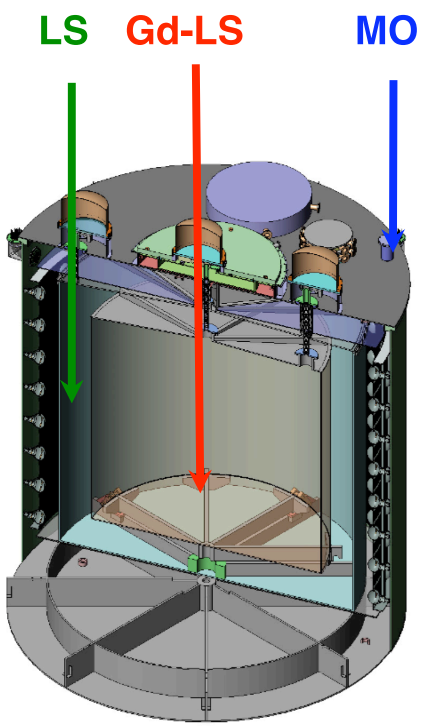
other Gd isotopes with high abundance have very small neutron capture cross sections

Gd capture	86.7%
H capture	13.2%
C capture	0.08%

Gd-LS

- Daya Bay experiment will use 200 ton normal liquid scintillator and 200 ton 0.1% gadolinium-loaded liquid scintillator (Gd-LS) .
  Gd-TMHA + LAB + 3g/L PPO + 15mg/L bis-MSB
- The stability of the Gd-LS has been tested for two years with IHEP prototype detector (half ton Gd-LS) and high temperature aging tests in lab.
- All Gd-LS will be produced as one batch on-site, to ensure IDENTICAL detectors. The mixing equipment has been tested at IHEP and will be re-assembled on-site.
- 4-ton production test is on-going.

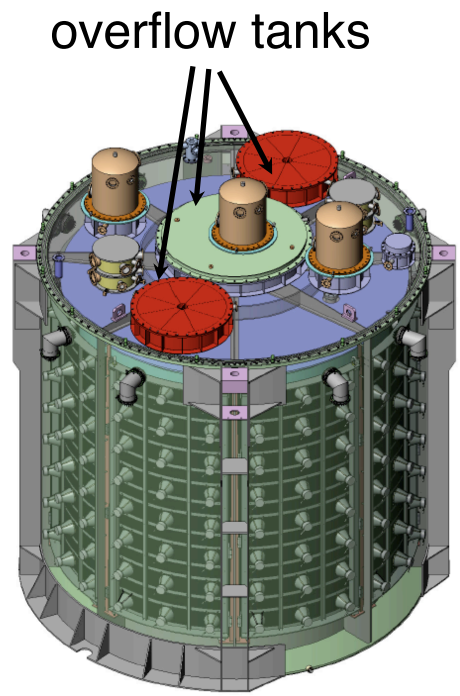
AD Filling and Target Mass Measurement



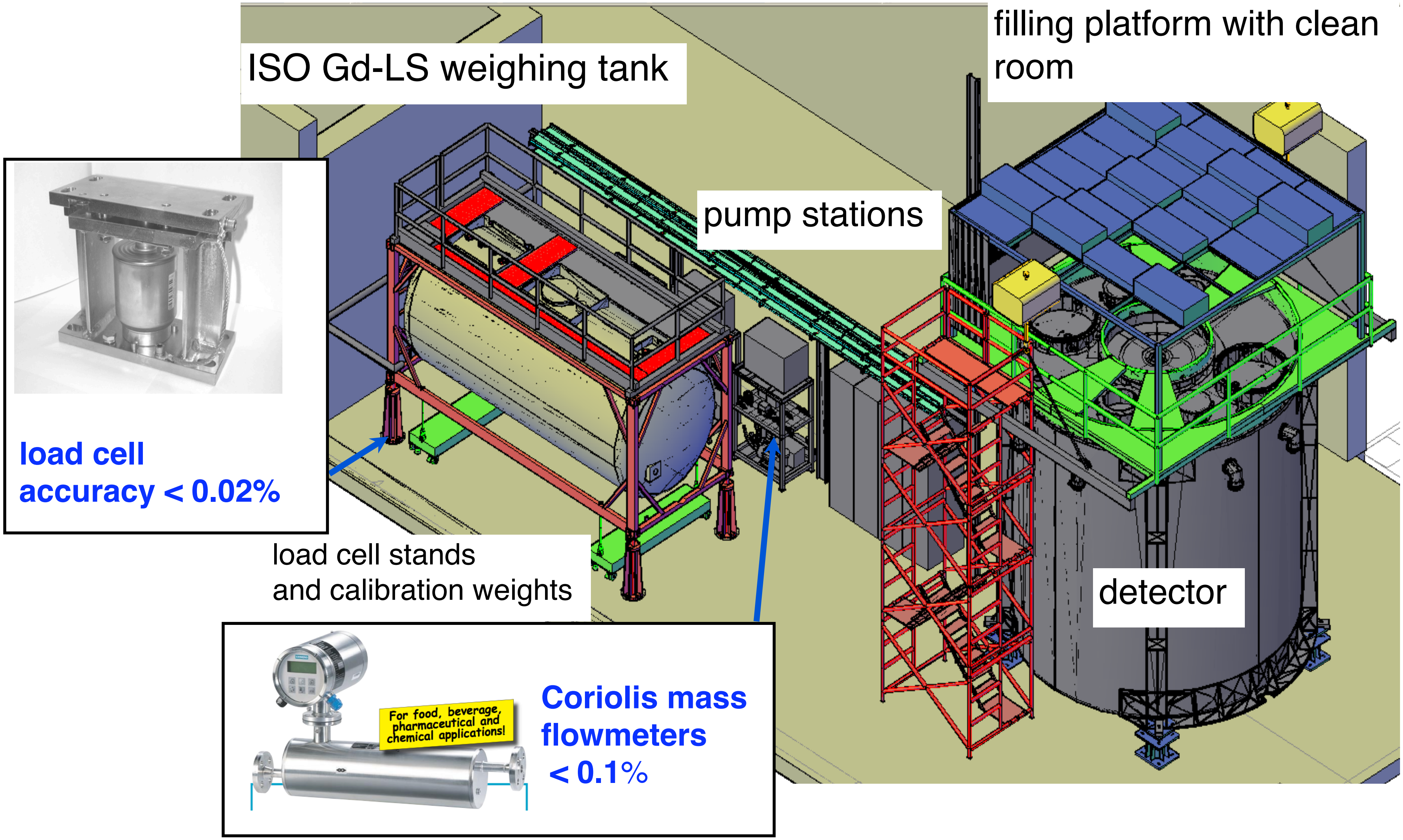
AD is filled with liquids from three reservoirs: GD-LS, LS, and MO

3-zones of detector have to be filled simultaneously to avoid stresses on the acrylic vessels

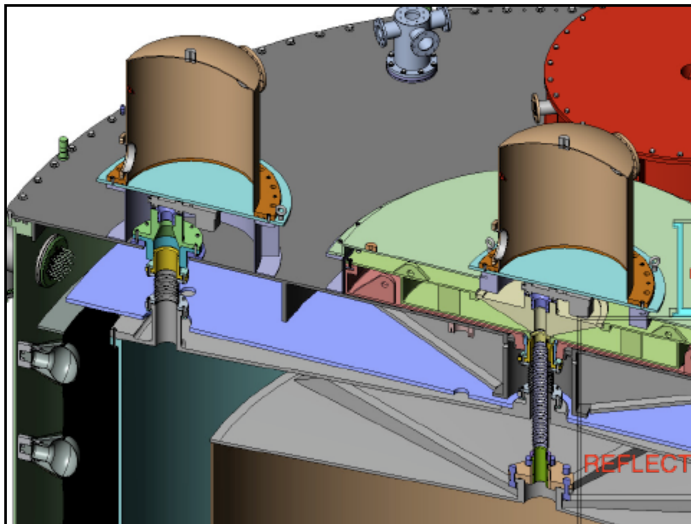
We assemble and fill pairs of detectors. Filling within ~2 weeks from each other.

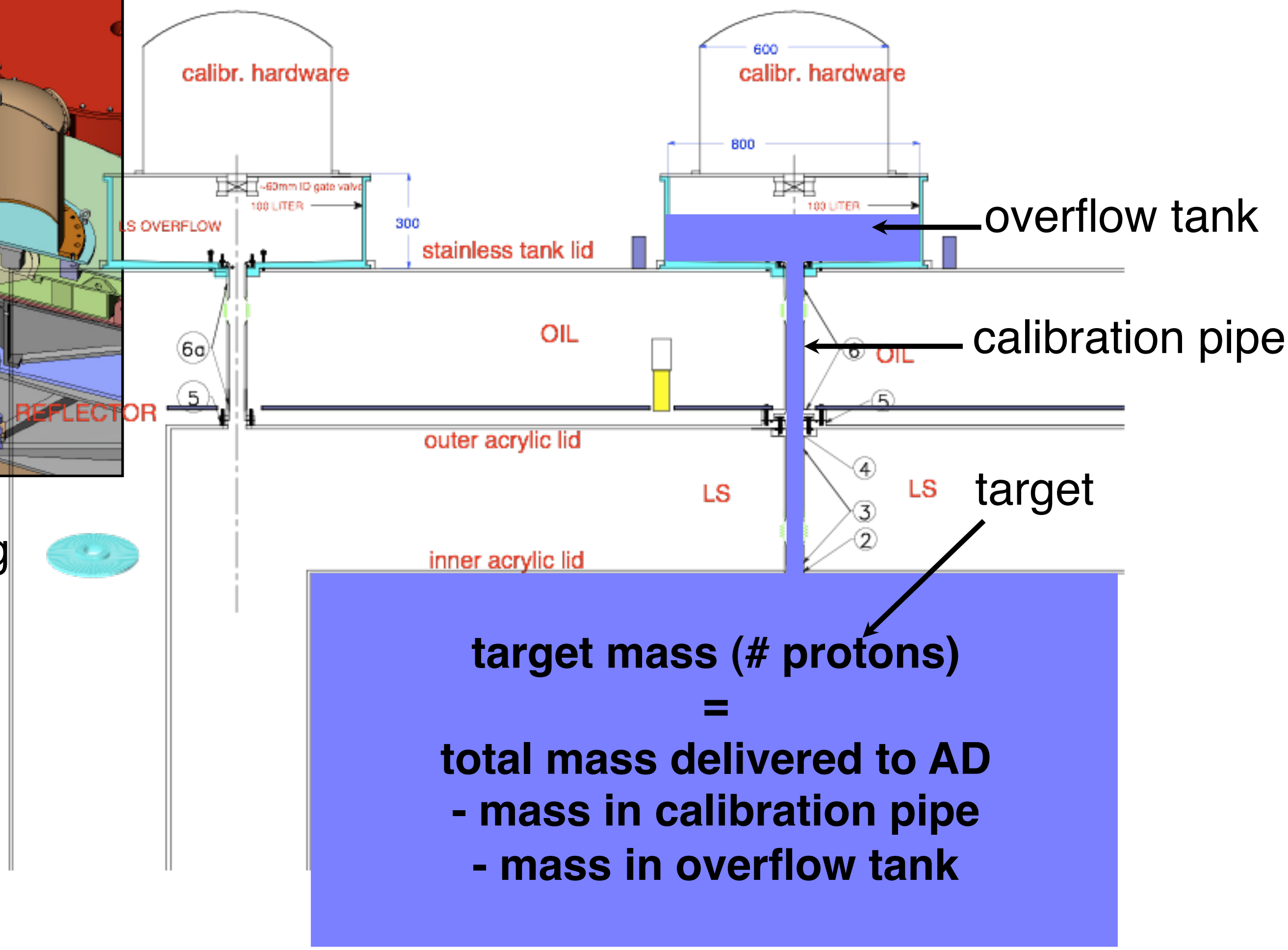


AD Filling and Target Mass Measurement



Monitoring the Detector’s Effective Target Mass





precise liquid level sensing in overflow tanks

Antineutrino Detector Design Requirements

Design criteria from physics considerations

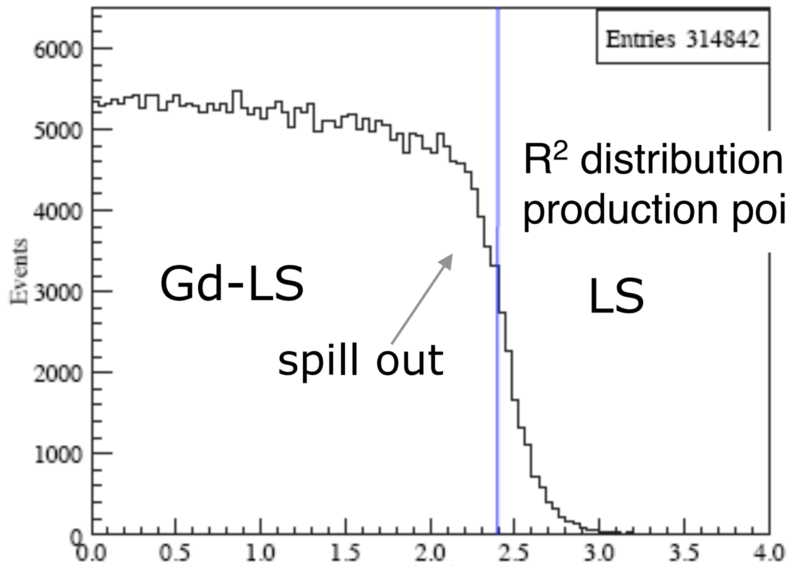
Item	Requirement	Justification
Target mass at far site	$\geq$80 T	Achieve sensitivity goal in three years over allowed Δm^2_{31} range
Precision on target mass	$\leq$0.3%	Meet detector systematic uncertainty baseline per module
Energy resolution	$\leq 15\%/\sqrt{E}$	Assure accurate calibration to achieve required uncertainty in energy-threshold cuts (dominated by energy threshold cut)
Detector efficiency error	<0.2%	Should be small compared to target mass uncertainty
Positron energy threshold	$\leq$1 MeV	Fully efficient for positrons of all energies
Radioactivity singles rate	$\leq$50 Hz	Limit accidental background to less than other backgrounds and keep data rate manageable

key feature of experiment: "identical detectors" at near and far sites

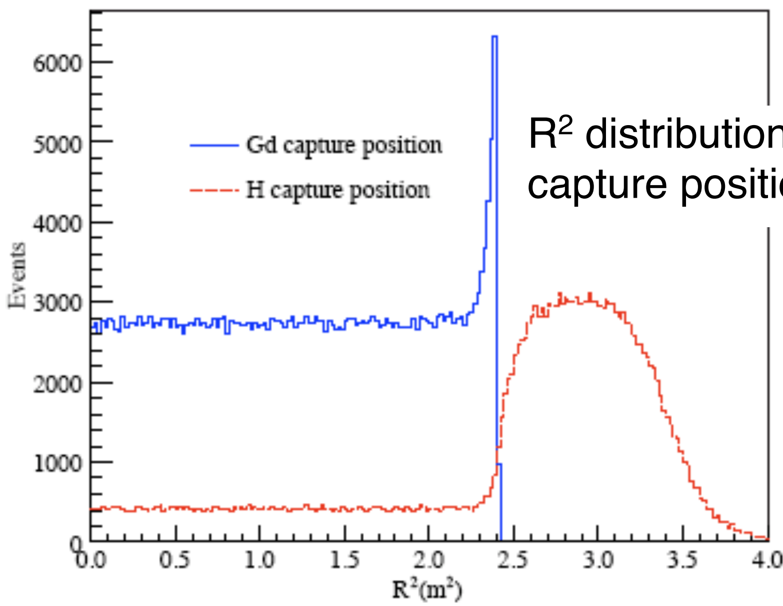
detectors will never be identical but we can control

Antineutrino Detector Event Distributions

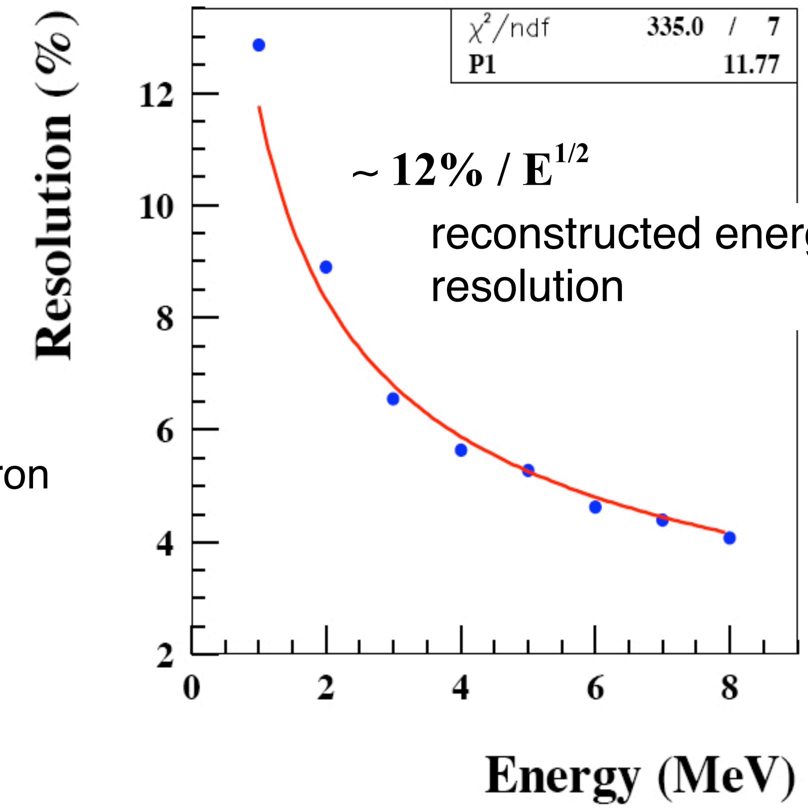
Geant4-based simulations



R^2 distribution of neutron production point



R^2 distribution of neutron capture position

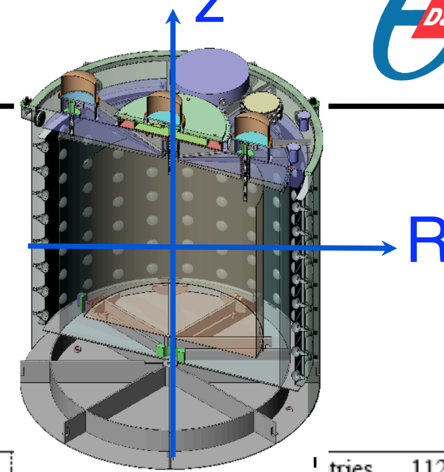


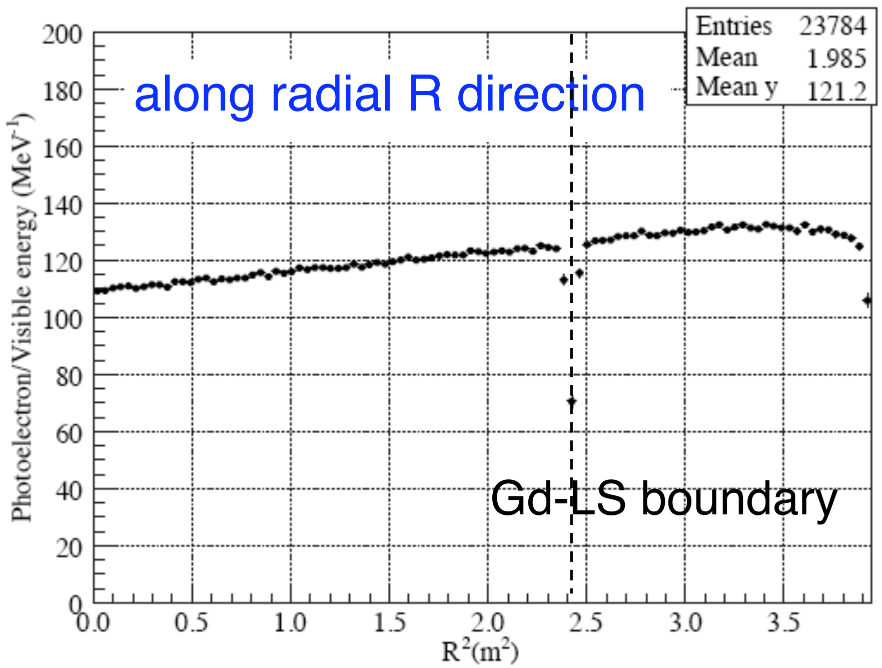
reconstructed energy resolution

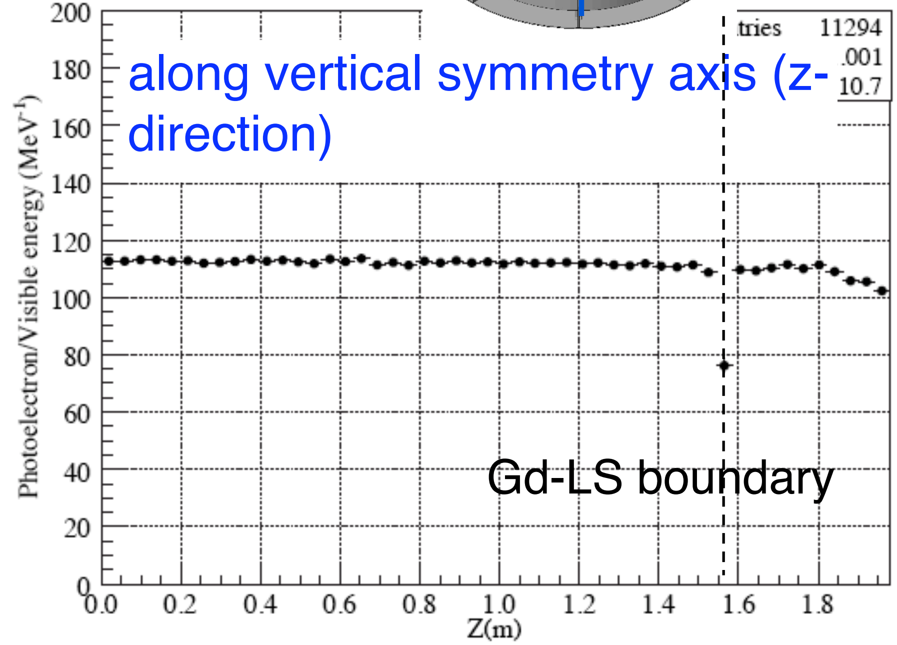
Antineutrino Detector Response

Detector Uniformity

Geant4-based simulations







reflectors help with detector uniformity

Daya Bay Systematic Uncertainties

Detector-Related Uncertainties

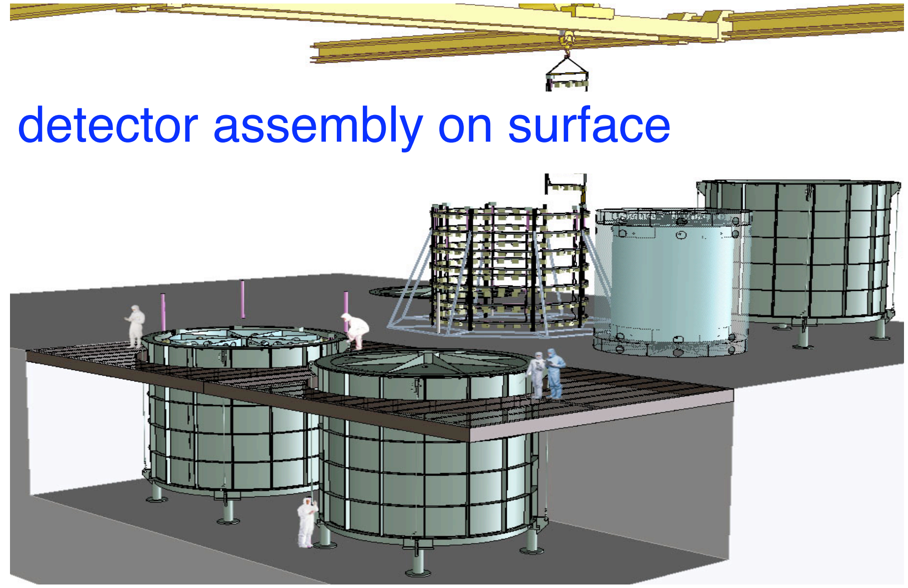
Absolute measurement **Relative measurement**

Source of uncertainty		Chooz (*absolute*)	Daya Bay (*relative*) Baseline	Goal	Goal w/Swapping
# protons		0.8	0.3	0.1	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%

Ref: Daya Bay TDR

O(0.2-0.3%) precision for relative measurement between detectors at near and far sites

Antineutrino Detector Assembly at Daya Bay



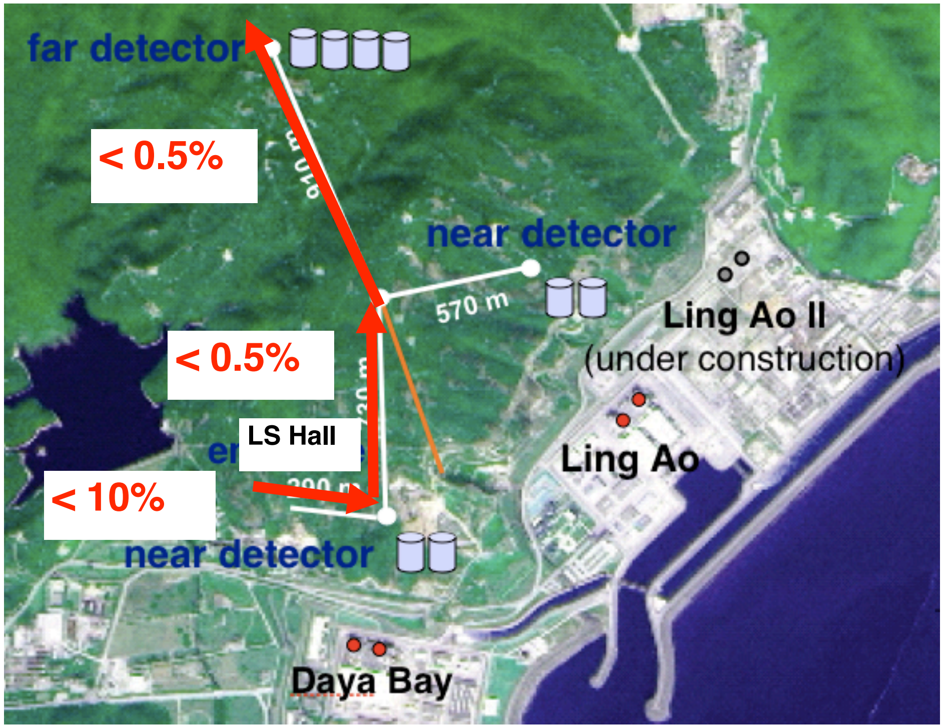
March 2009:
Assembly building occupancy

Summer 2009: Near Hall occupancy

Summer 2010: Near Hall ready for data

Summer 2011: Far Hall ready for data

Deployment of Antineutrino Detectors



1. Moving detectors underground on < 10% grade when empty (20t)

2. Filling detectors underground with liquids

3. Moving on < 0.5% tunnel grade when full (~110 t)

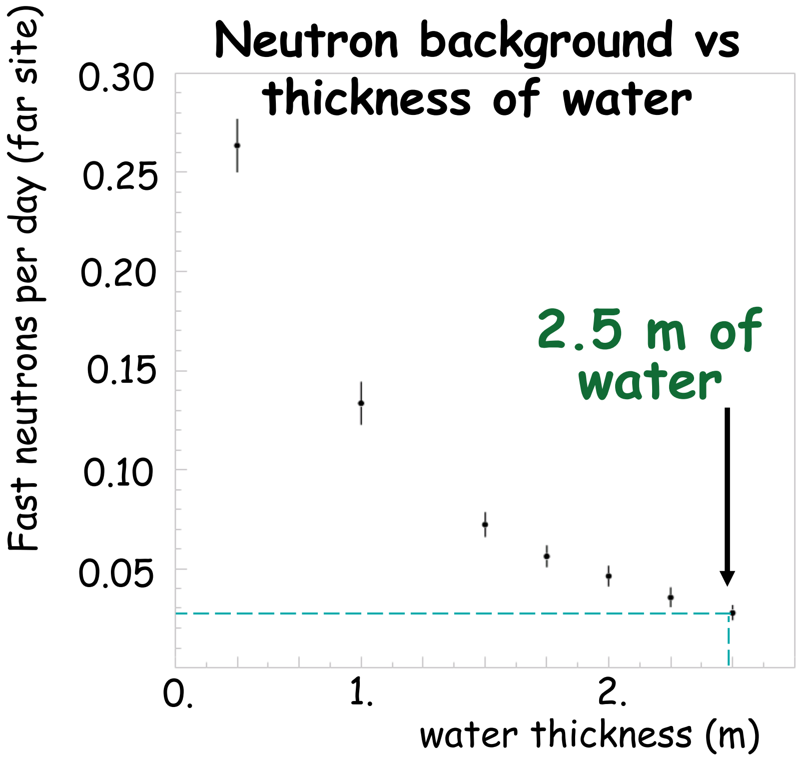
4. Lifting full detector (~110t) into water pool

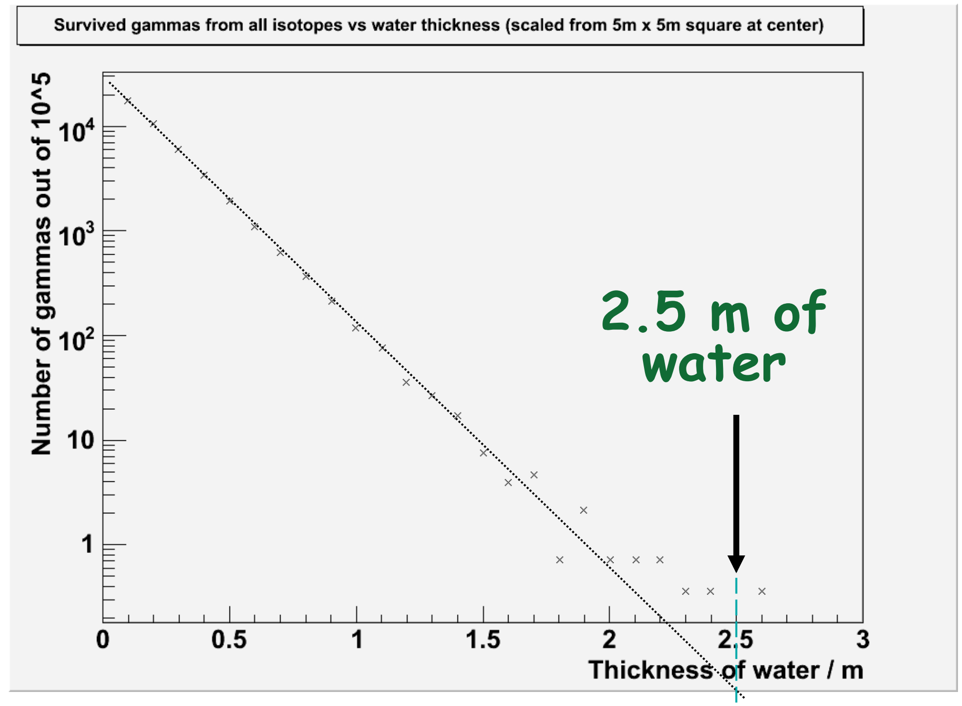
5. Swapping detectors optional

Automatic Guide Vehicle for detector transport

120 t overhead crane

Shielding Antineutrino Detectors

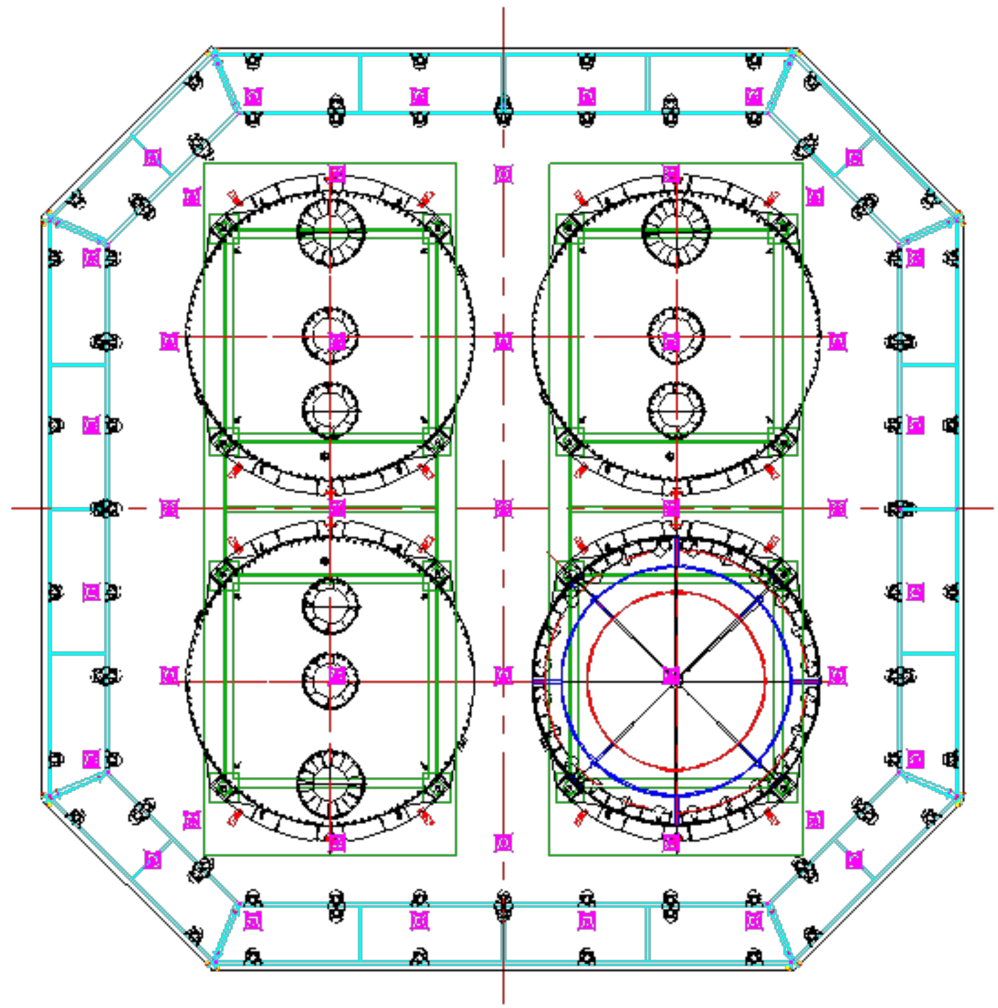




- Detector modules enclosed by 2.5 m of water to shield energetic neutrons produced by cosmic-ray muons and gamma-rays from the surrounding rock

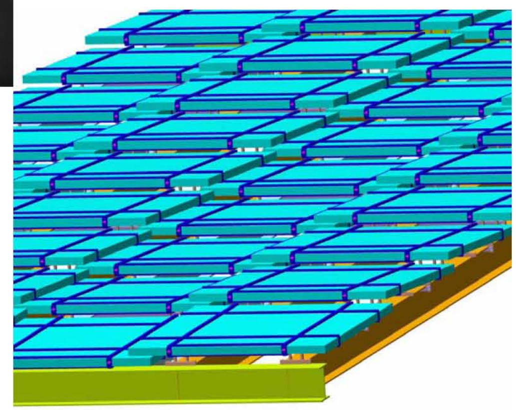
Water Pool – Two Regions

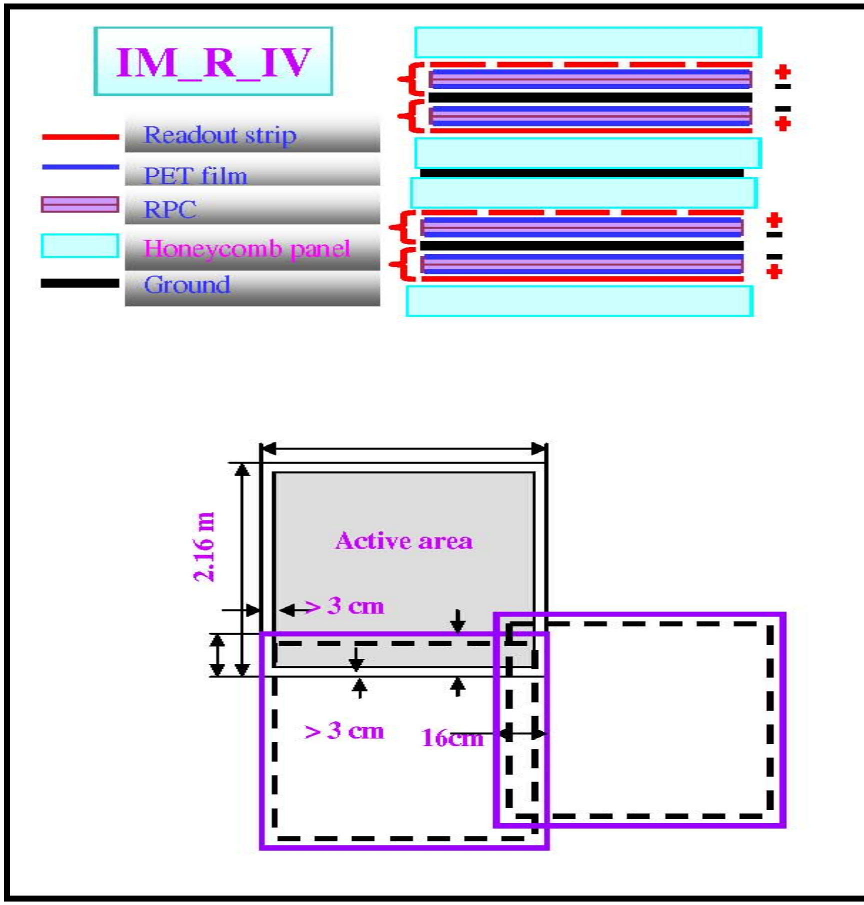
- Divided by Tyvek into Inner and Outer regions
- Reflective Paint on ADs improves efficiency
- Calibration LEDs placed according to simulations



160 PMTs (Inner)
224 PMTs (Outer)

RPC Cover over Water Pool

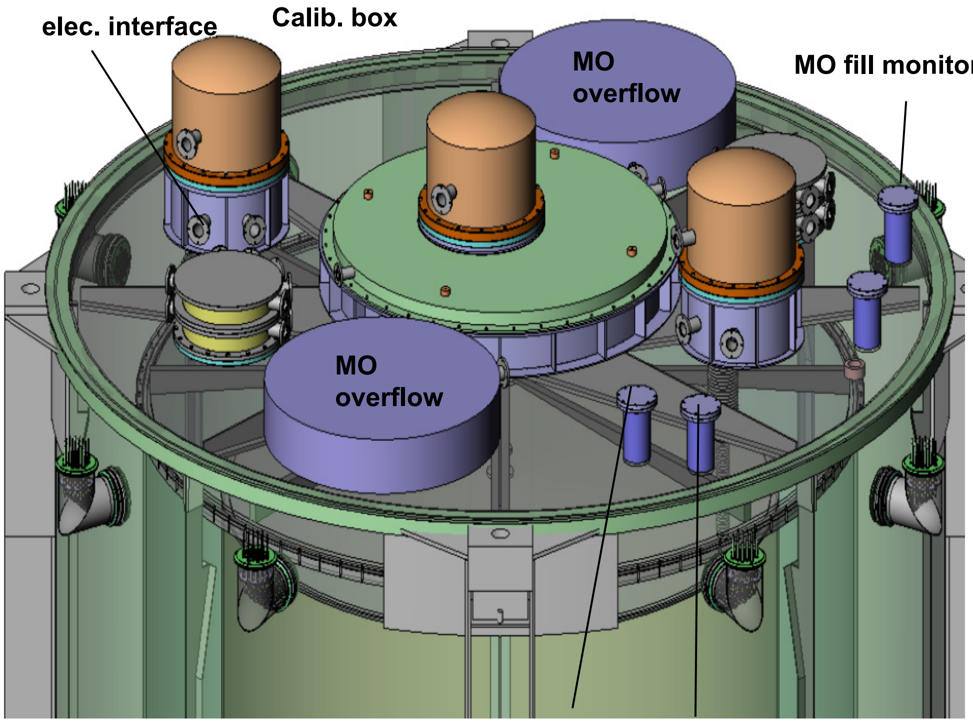


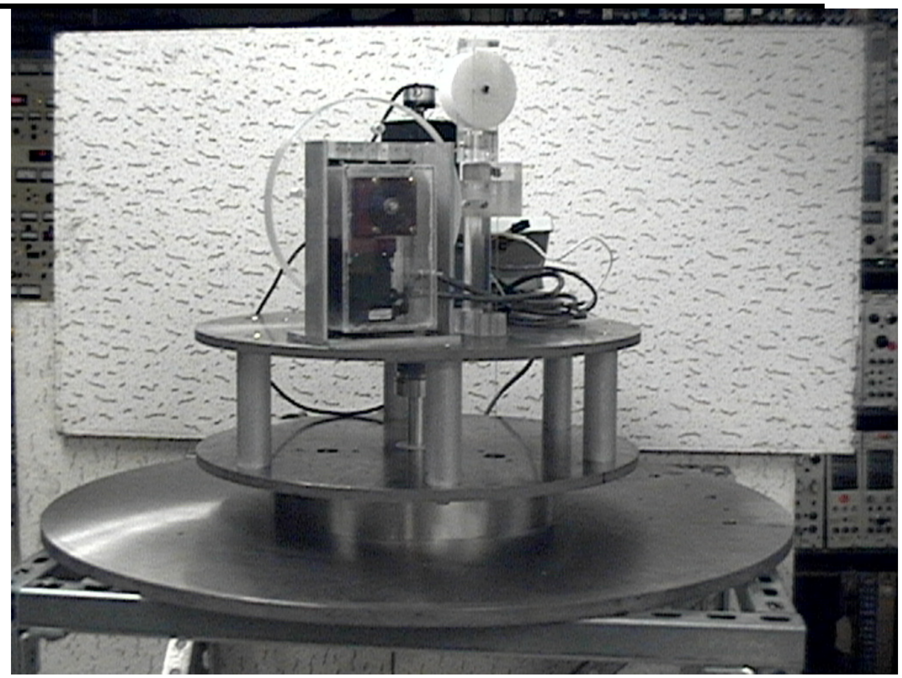


RPC Assembly

RPC module delivering table, which can lift the module to the height on module rack. Gas system is behind the module rack.

Automated Calibration System



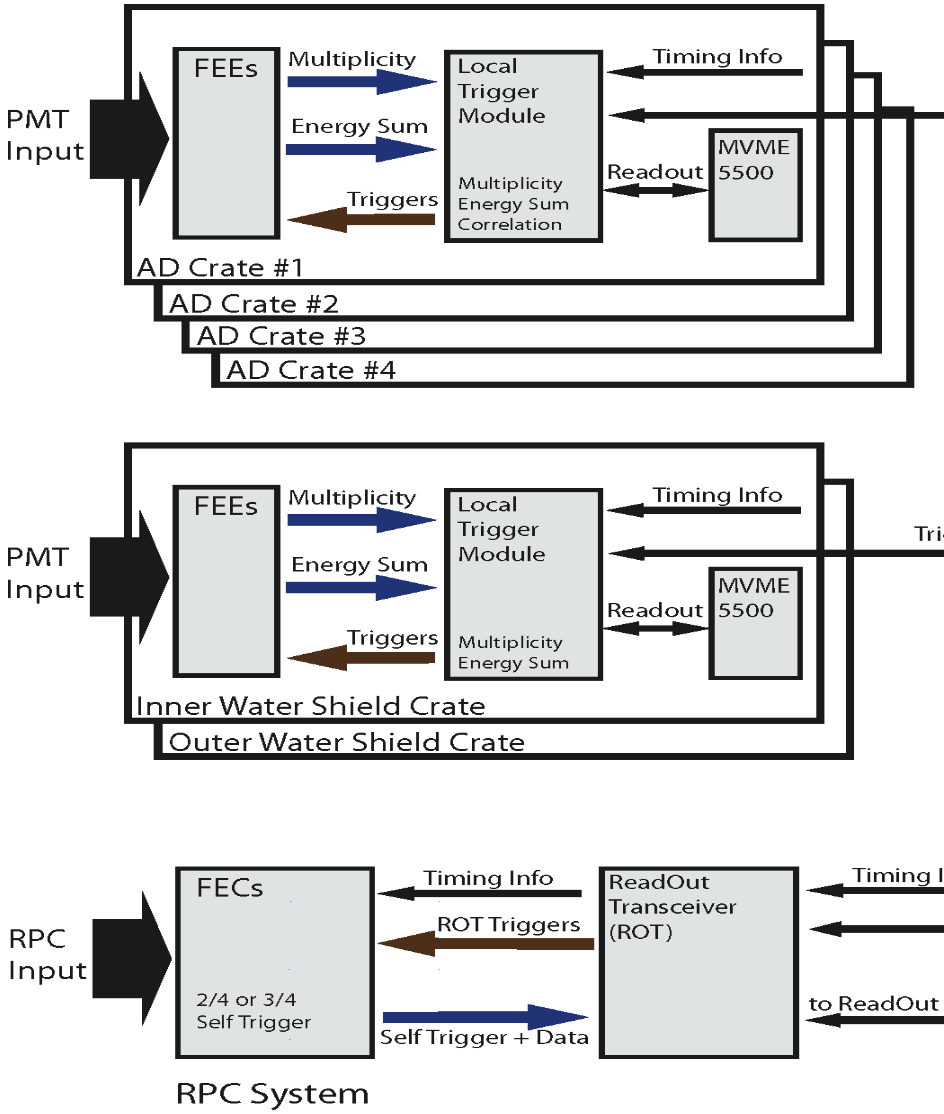


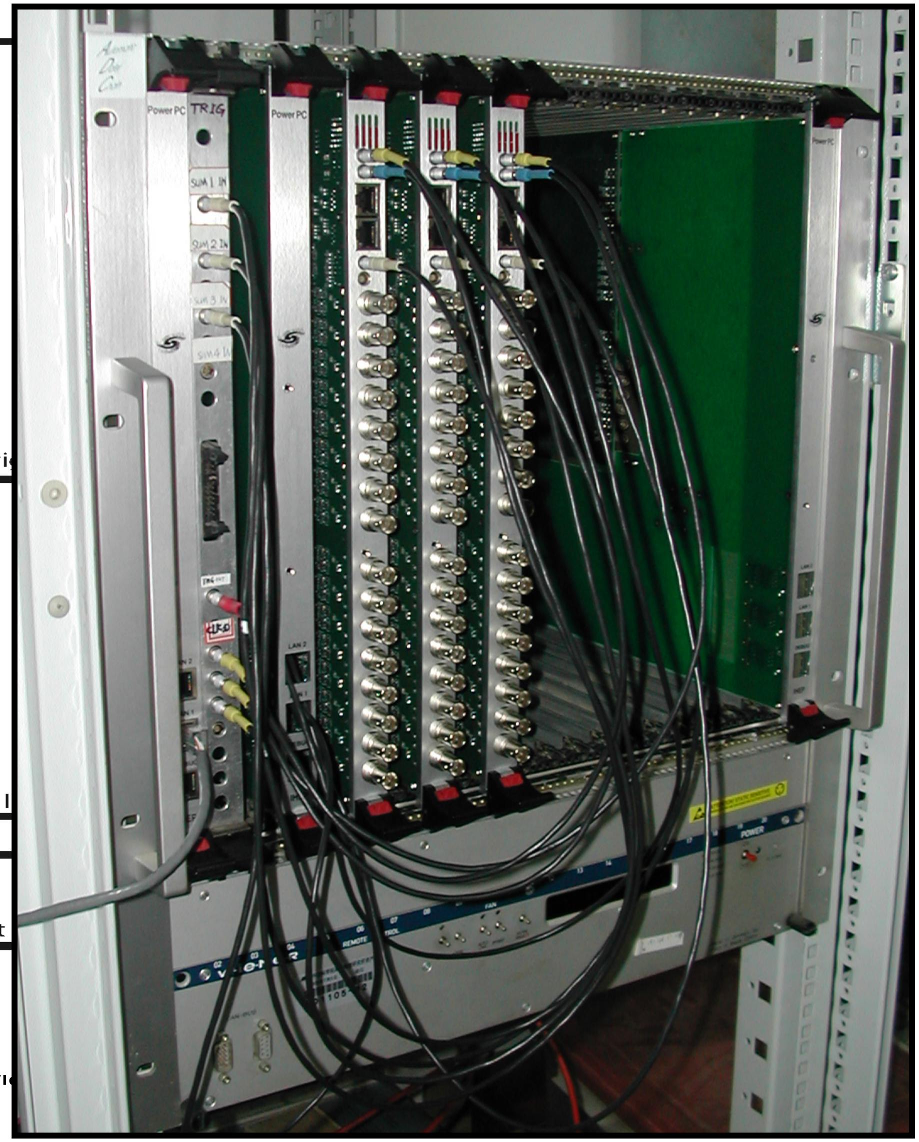
Each unit deploys 3 sources:
^{68}Ge, ^{252}Cf, LED

Major Prototype Test Results:

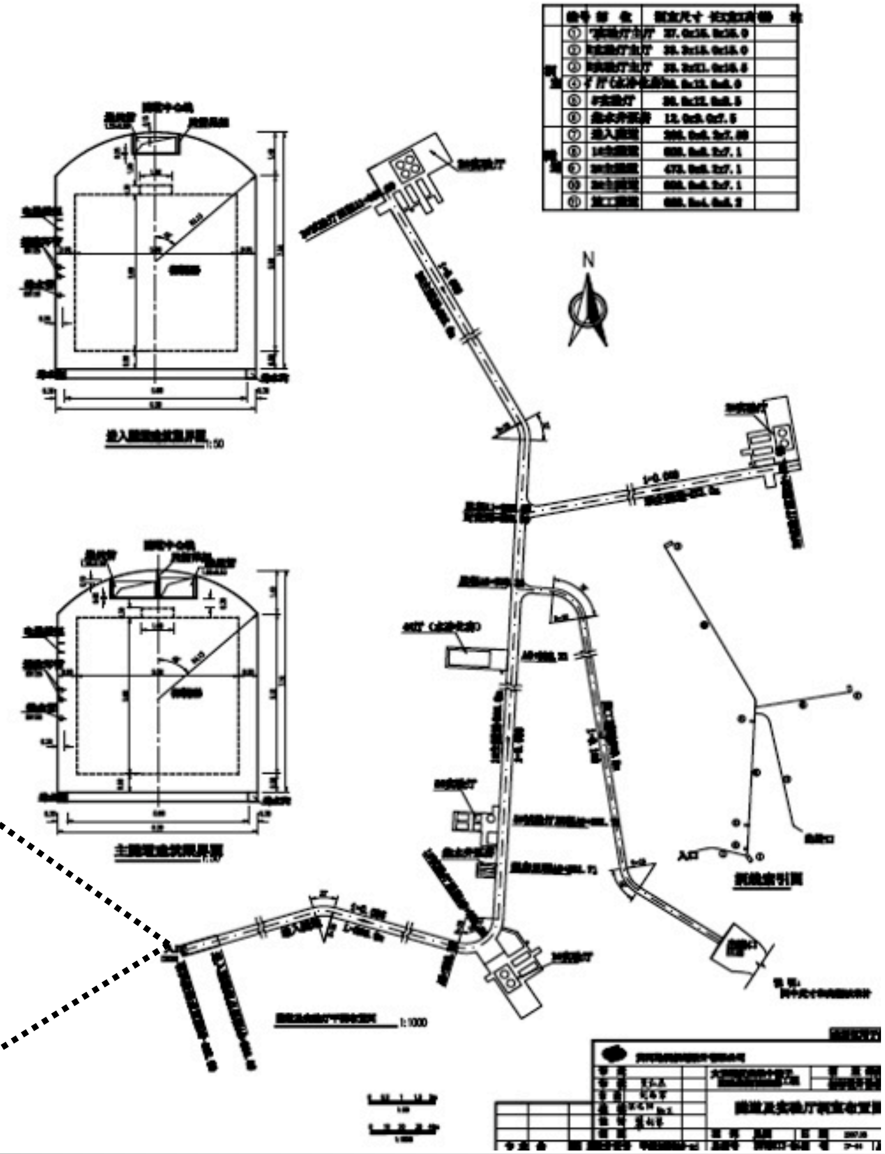
- Completed >20 years worth of cycling
- No liquid dripping problem
- Tested limit switch precision and reliability

ctronics and Readout System





Civil Construction



Civil Construction

Large clean room allows two AD assembly

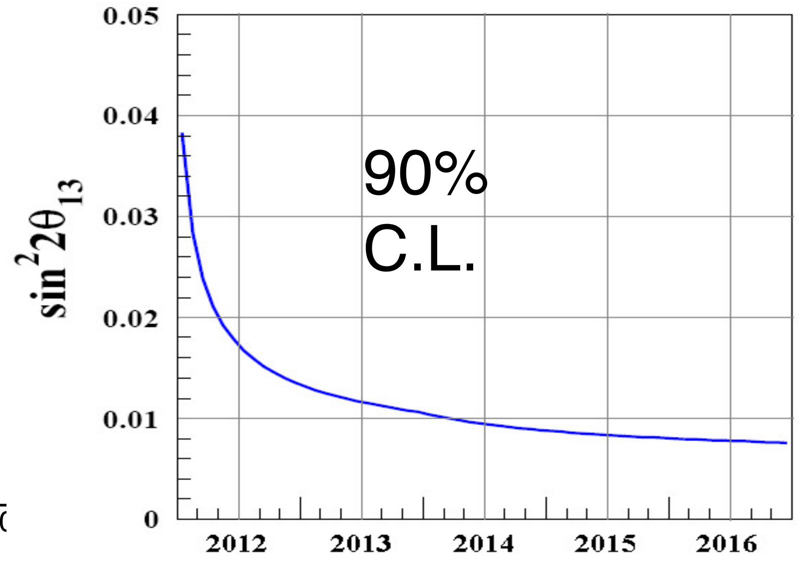
Daya Bay Is Moving Forward Quickly

Groundbreaking Ceremony: Oct 13, 2007

Tentative Schedule

- October 2007, Ground Breaking
- March 2009, Surface Assembly Building Occupancy
  - Antineutrino detector (AD) test assembly
- Summer 2009, Daya Bay Near Hall Occupancy
- Fall 2009, the first AD complete, Dry-run test starts
- Summer 2010, Daya Bay Near Hall Ready for Data
- Summer 2011, Far Hall Ready for Data

- Three years' data taking reach full sensitivity.



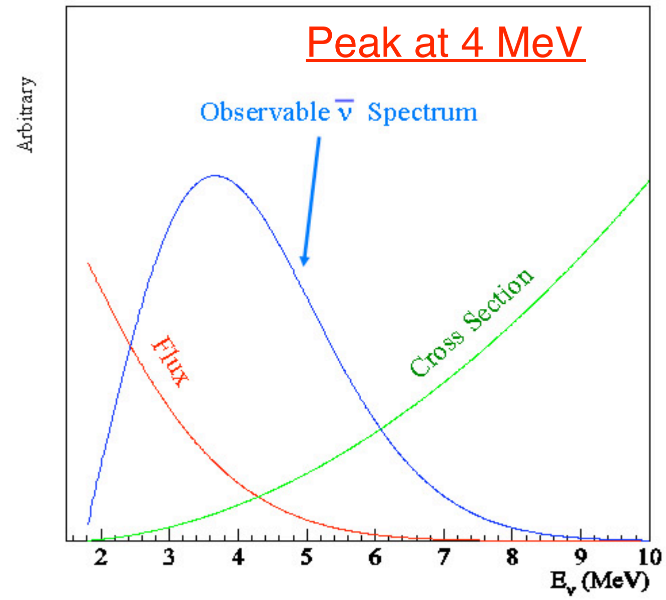
Signal and Backgrounds in detector

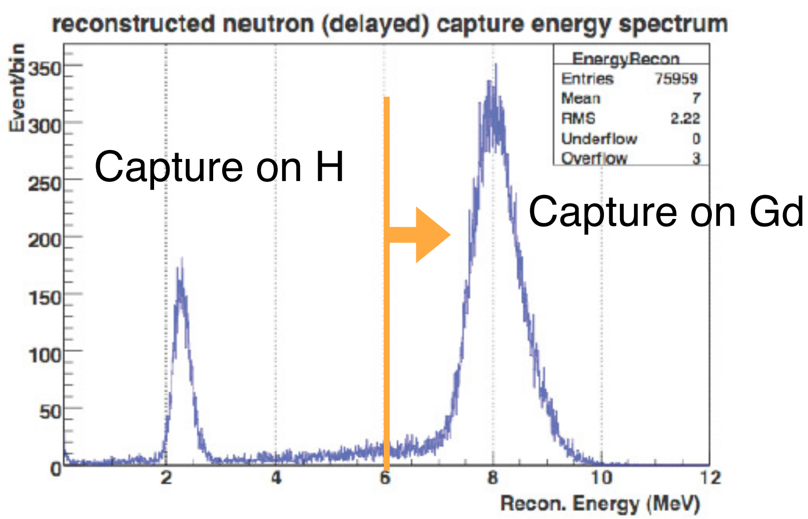
Prompt signal

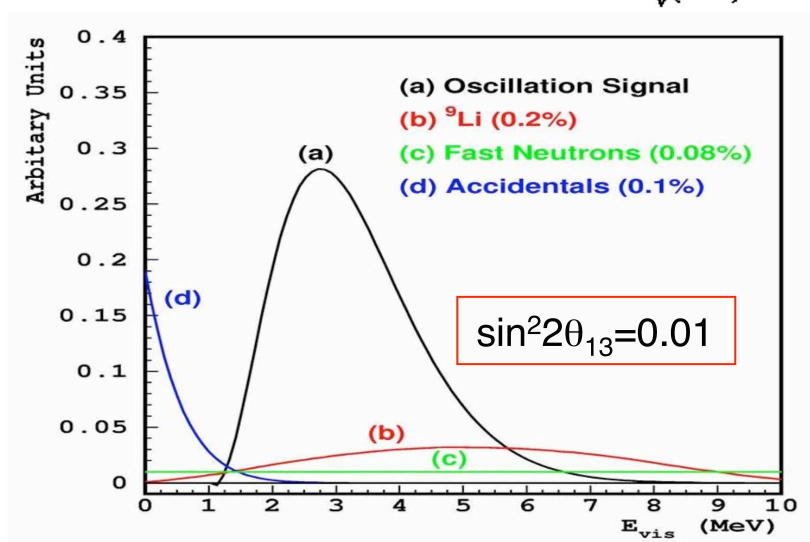
$$e^{+} + e^{-} \rightarrow 2\gamma$$

$$\bar{\nu}_e + p \rightarrow e^{+} + n$$

Capture on H or Gd,
Delayed signal, 2.2, 8 MeV

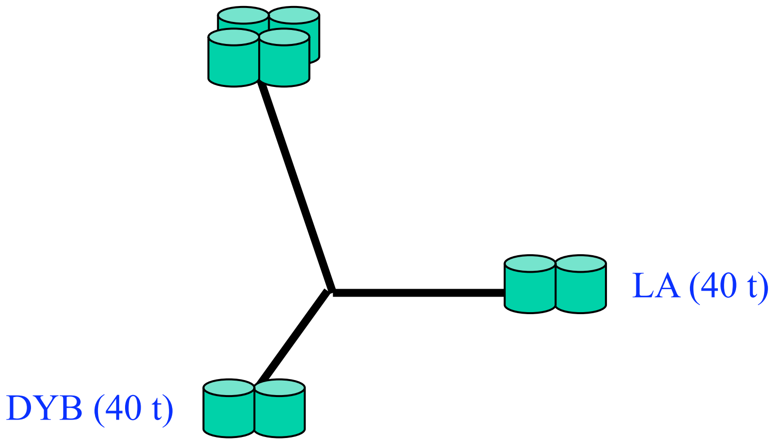




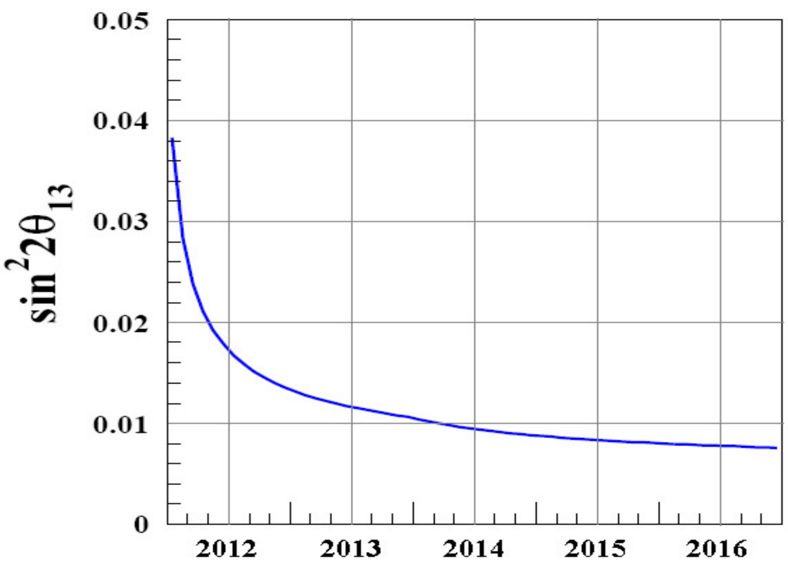


Sensitivity of Daya Bay

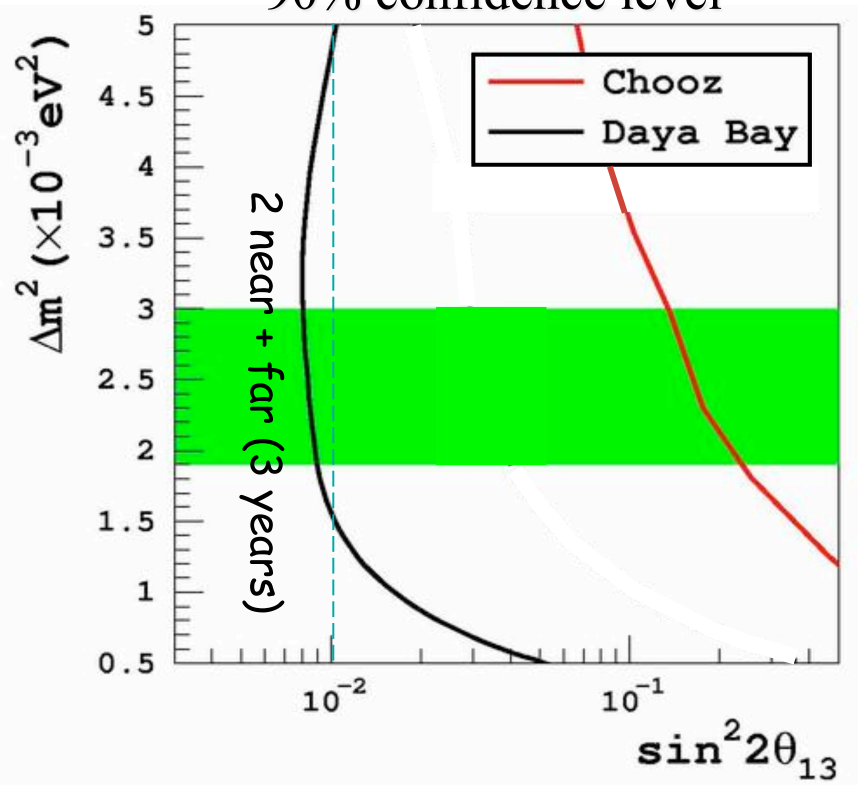
Goal: $\sin^2 2\theta_{13} < 0.01$



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



90% confidence level



Summary and Conclusions

Daya Bay experiment is designed to measure $\sin^2 2\theta_{13} < 0.01$ at 90% CL in 3 years of data taking.

Daya Bay is the most sensitive reactor θ_{13} experiment.

- Day Bay is funded, civil and detector construction are progressing. Data taking at near site will begin in 2010.

- 3-zone detector design allows observation of antineutrino signal without event reconstruction.

- Daya Bay will use eight "identical" antineutrino detectors Relative detector systematic error < 0.38%.

- Detectors are movable. Swapping is an option but not required to reach baseline sensitivity.

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:

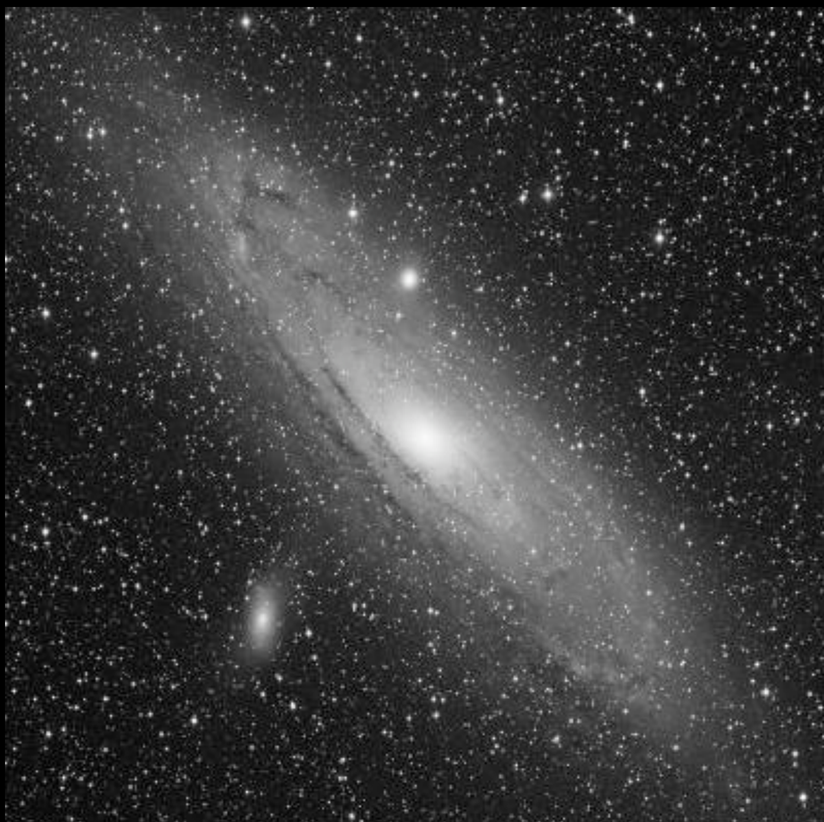
Source	Uncertainty
Reactor power	0.13%
Detector (per module)	0.38% (baseline) 0.18% (goal)
Signal statistics	0.2%

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 moving forward:
  - Surface Assembly Building - end of 2008
  - DB Near Hall - installation activities begin middle of 2009
  - Assembly of first AD pair – end of 2009
  - Commission Daya Bay Hall by Spring 2010
  - LA Near and Far Hall - installation activities begin early in 2010
  - Data taking with all eight detectors in three halls by early 2011

If $\sin^2 2\theta_{13} > 0.01$, Then:

- Study CP violation in the neutrino sector



- **How can we exist?**

Thank You

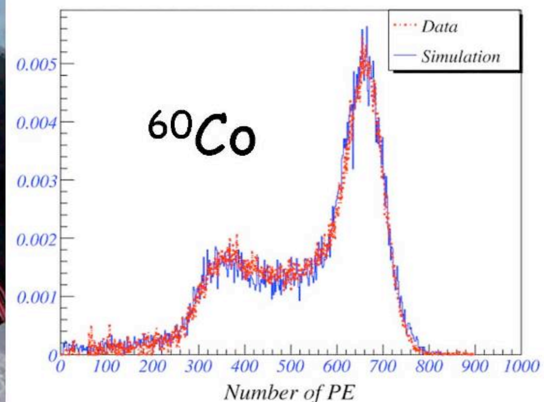
大亚湾反应堆中微子实验奠基
Daya Bay Reactor Neutrino Experiment Foundation Stone

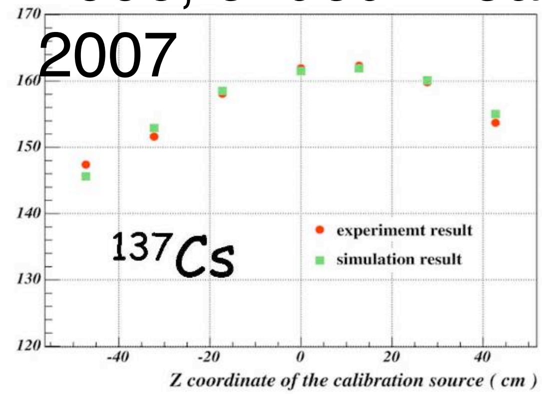
[redacted]

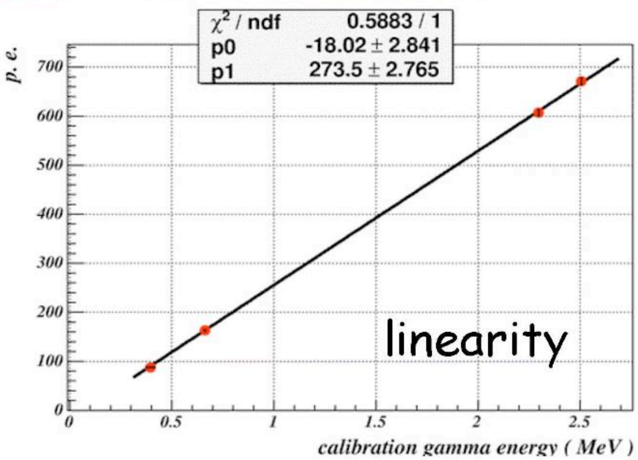
2-zone Prototype at IHEP

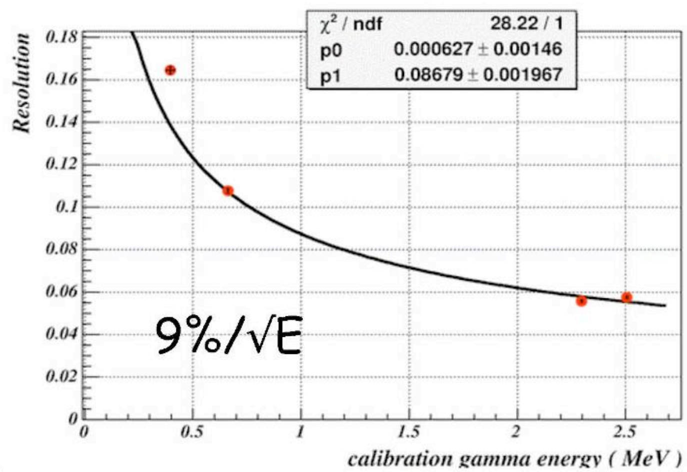
- 0.5 ton unloaded LS
- 45 8" PMTs with reflecting top and bottom

Phase-I, started in 2006, ended in Jan. 2007









Kam-Biu Luk

Daya Bay

2-zone Prototype at IHEP

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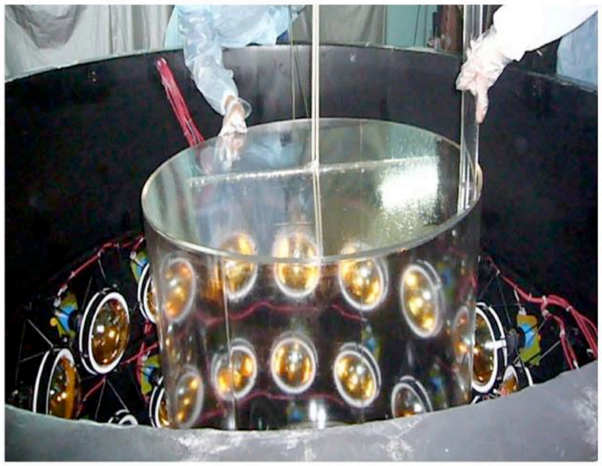
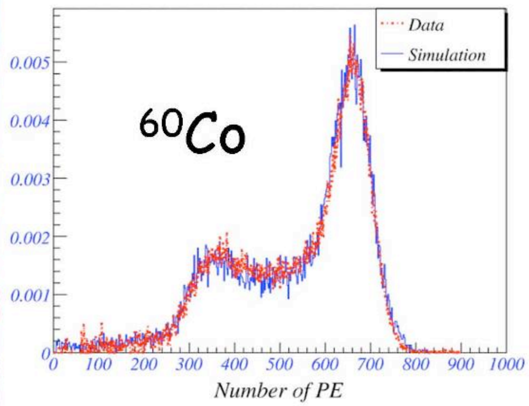
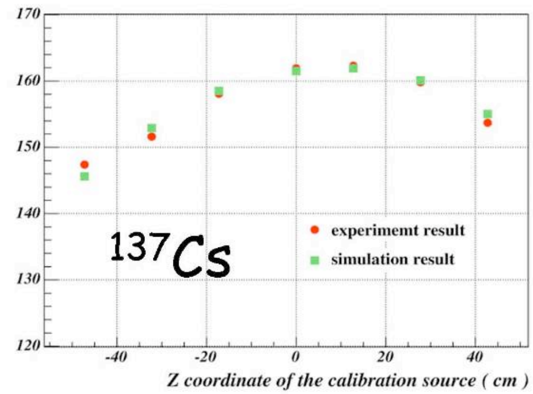
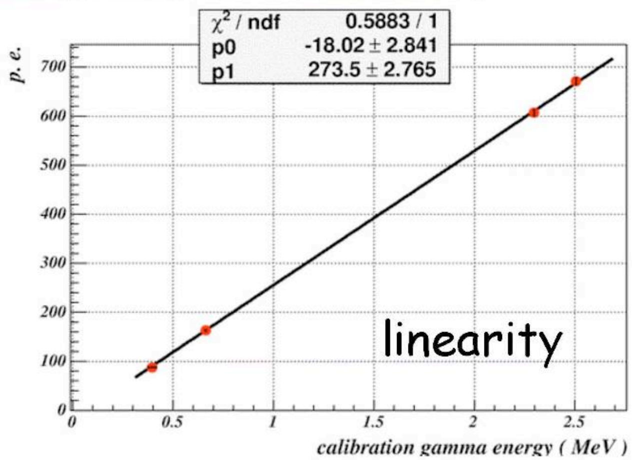
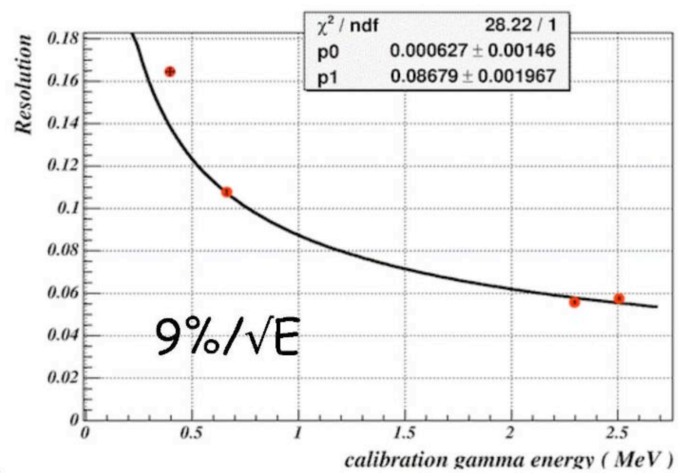








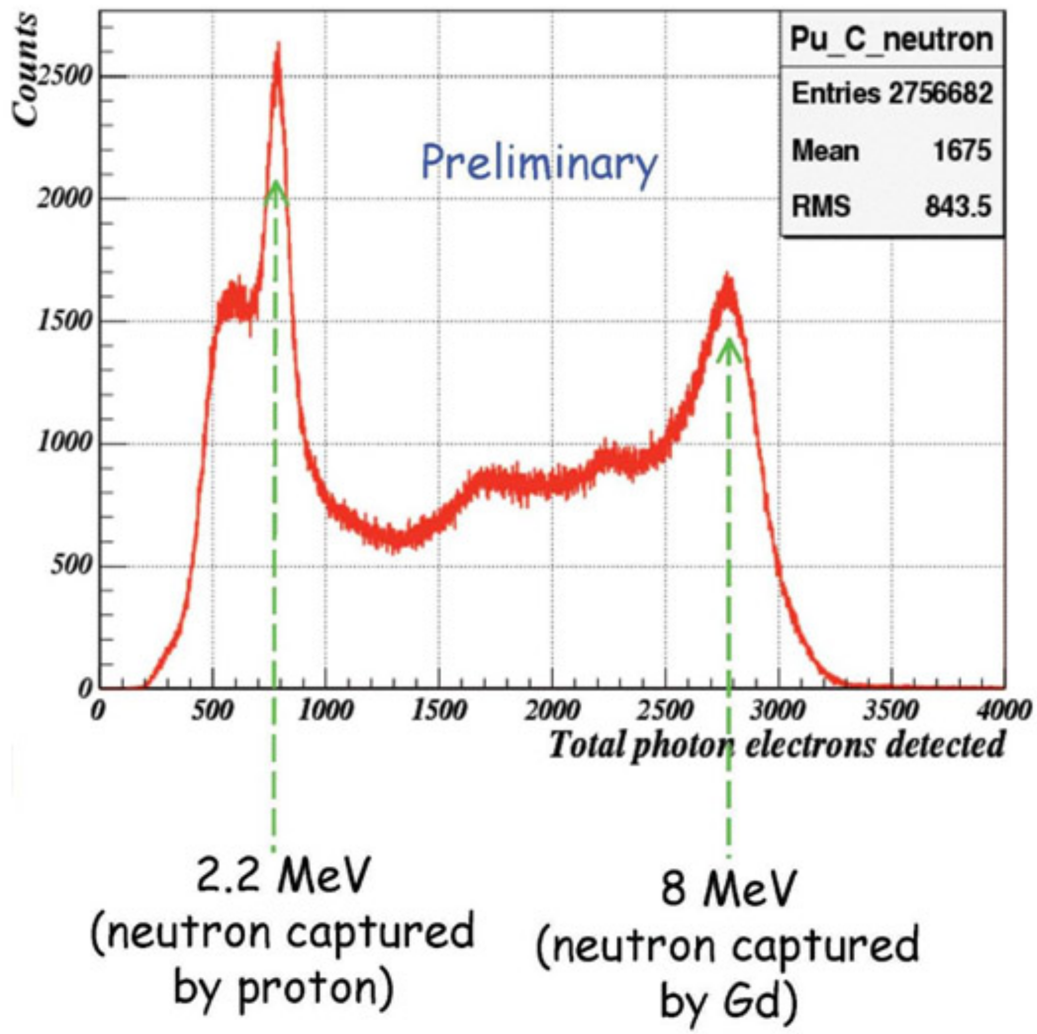


IHEP Prototype filled with 0.1% Gd-LS

Gd-TMHA complex synthesis

Phase-II, filled with half-ton 0.1% Gd-LS, started in Jan. 2007 and keep running until now.

The prototype is also used for the FEE and Trigger boards testing.



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

Ling Ao NPP: 2×2.9 GW_{th}

Ling Ao II NPP: 2×2.9 GW_{th}

Ready by 2010-2011