Antineutrino Detectors for a High-Precision Measurement of θ_{13} at Daya Bay

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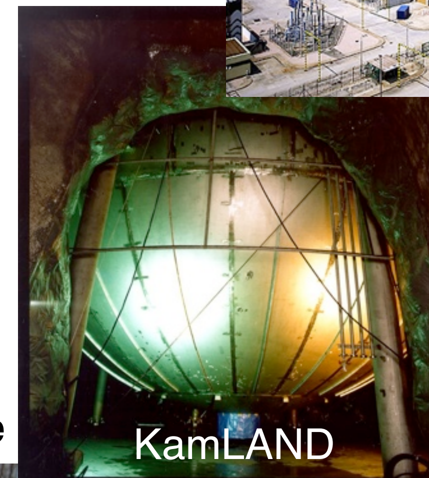
University of Wisconsin
on behalf of the Daya Bay collaboration

TIPP2011, June 11, 2011

Neutrino Physics at Reactors

Next - Discovery and precision measurement of θ_{13}

2008 - Precision measurement of Δm_{12}^2 . Evidence for oscillation

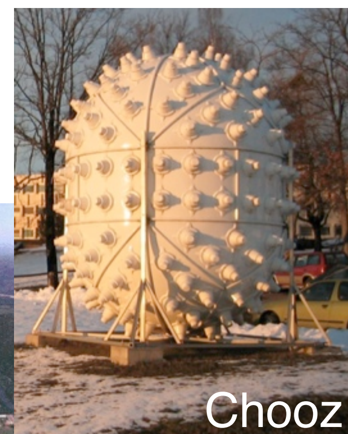


2004 - Evidence for spectral distortion

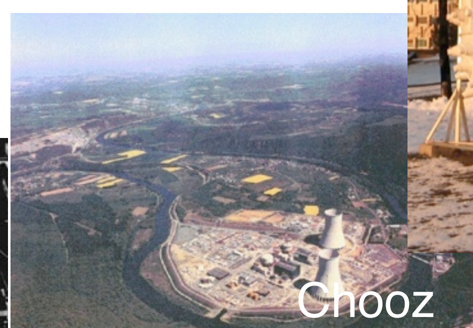
2003 - First observation of reactor antineutrino disappearance

1995 - Nobel Prize to Fred Reines at UC Irvine

1980s & 1990s - Reactor neutrino flux measurements in U.S. and Europe



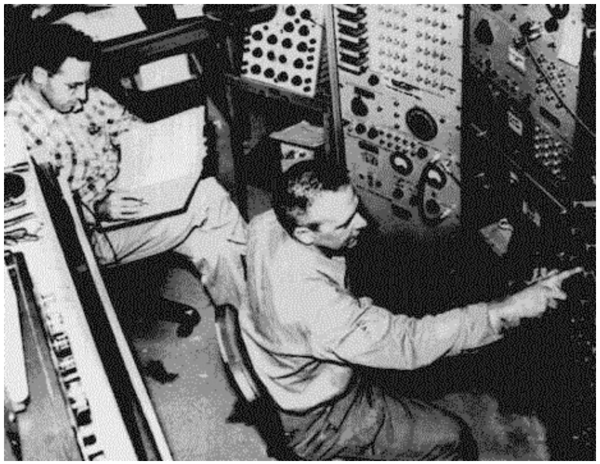
1956 - First observation of (anti)neutrinos

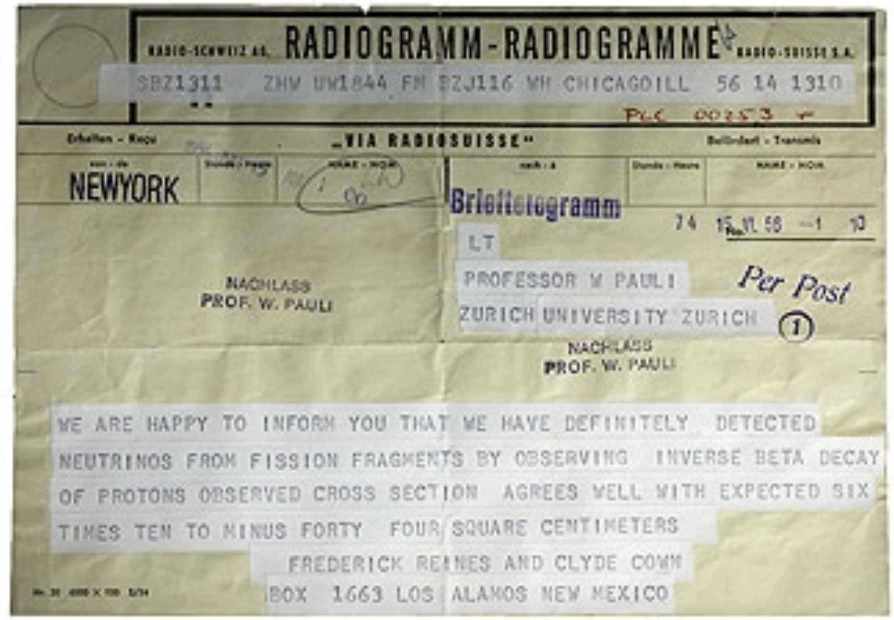


Past Reactor Experiments
Hanford
Savannah River
ILL, France
Bugey, France
Rovno, Russia
Goesgen, Switzerland
Krasnoyark, Russia
Palo Verde
Chooz, France

Discovery of the Neutrino

1956 - "Observation of the Free Antineutrino" by Reines and Cowan





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"VIA RADIOSUISSE"

NEWYORK

Brieftelegramm

LT

PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

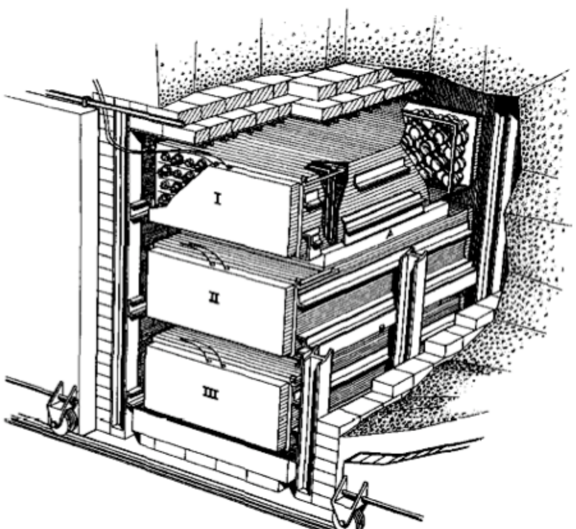
Per Post

NACHLASS PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

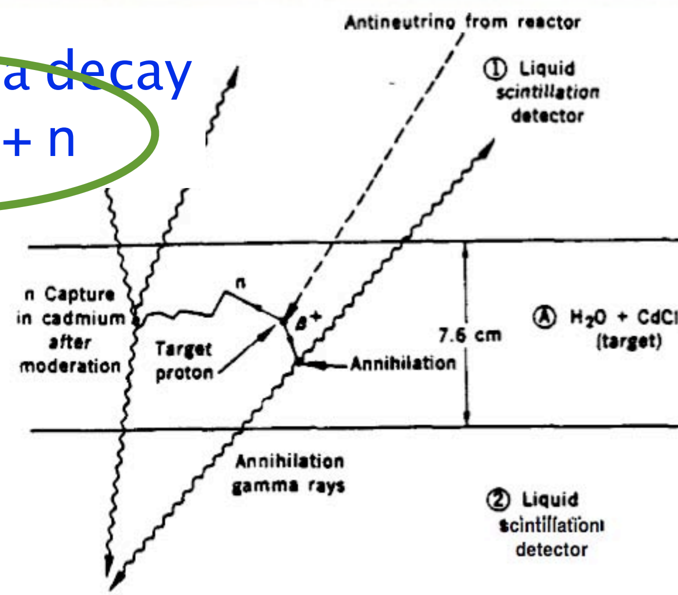
FREDERICK REINES AND CLYDE COWN

BOX 1663 LOS ALAMOS NEW MEXICO



inverse beta decay

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



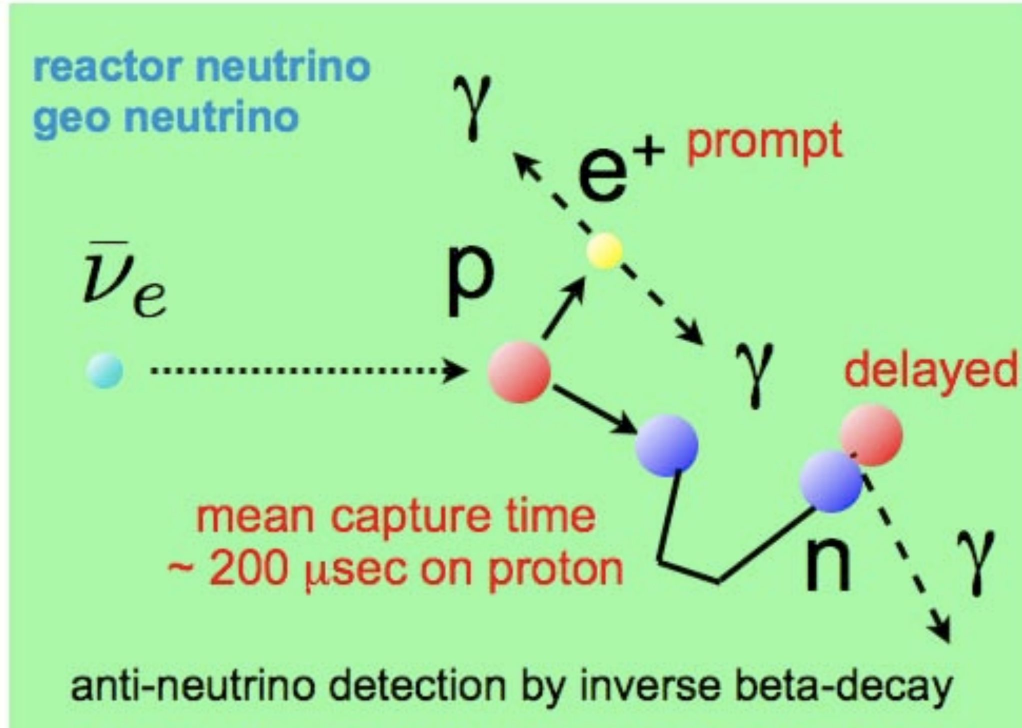
Antineutrino Detection

inverse beta decay

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

coincidence signature

prompt e^+ and delayed neutron capture



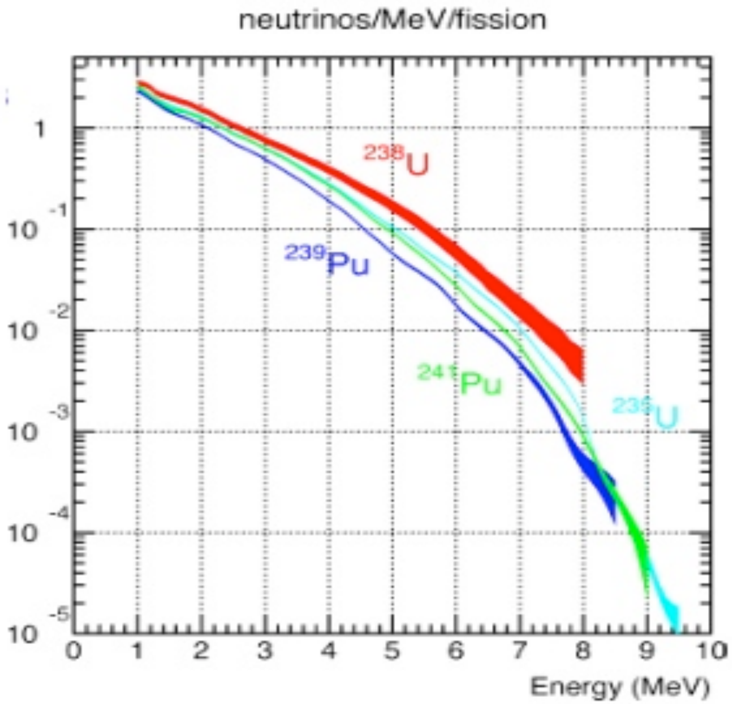
10-100 keV

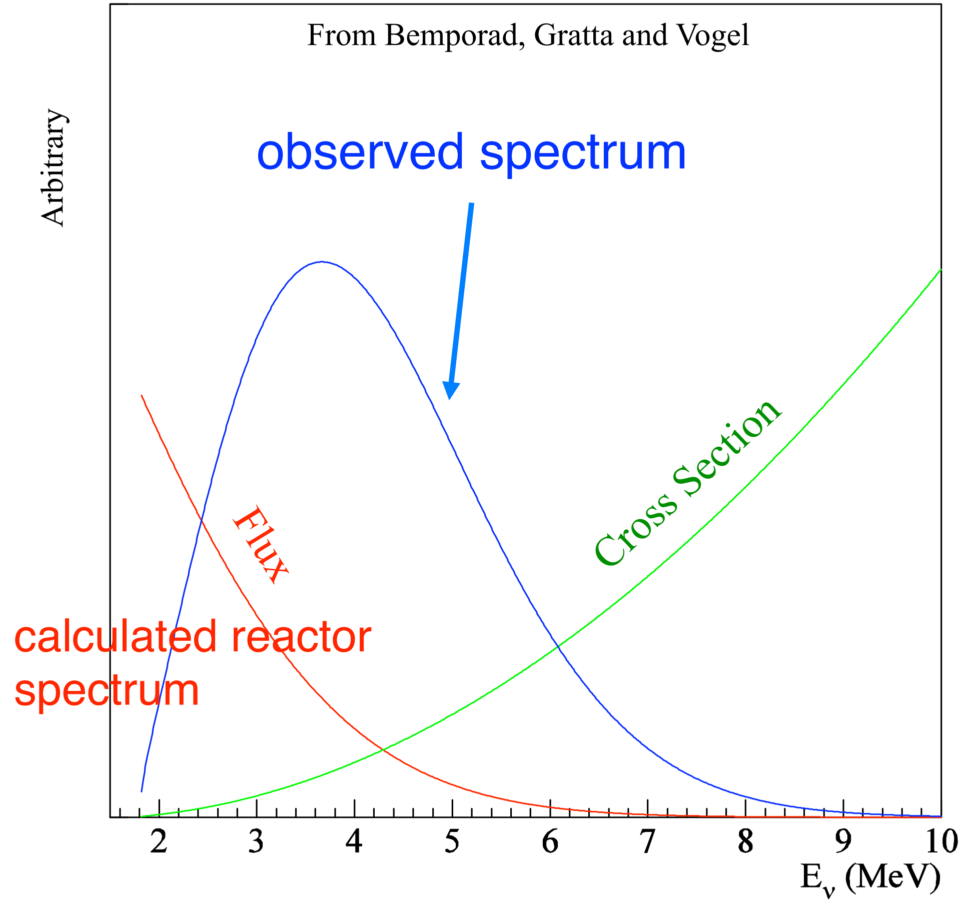
1.805 MeV

$$E_{\bar{\nu}_e} \cong E_{e^+} + E_n + (M_n - M_p) + m_{e^+}$$

including E from e^+ annihilation, $E_{prompt} = E_{\bar{\nu}} - 0.8$ MeV

Reactor Antineutrinos





$\overline{\nu}_e$ from n-rich fission products

~ 200 MeV per fission

~ 6 $\overline{\nu}_e$ per fission

~ 2 x 10^{20} $\overline{\nu}_e$/GW_{th}-sec

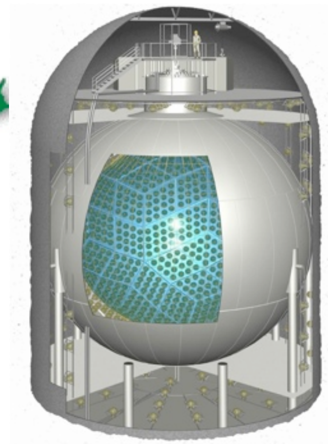
mean energy of $\overline{\nu}_e$: 3.6 MeV

only disappearance expts possible

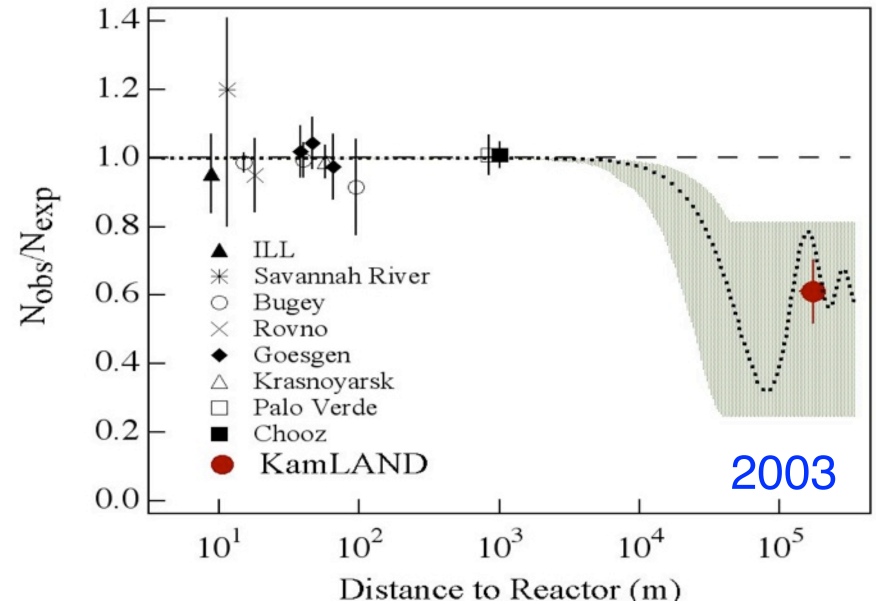
cross-section accurate to +/-0.2%

KamLAND Antineutrino Oscillation (L~180km)

KamLAND

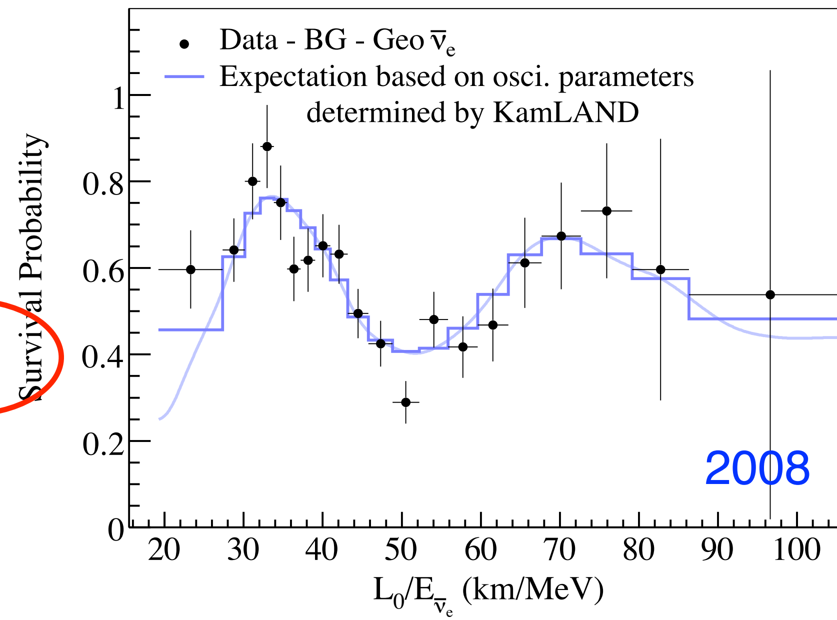


55 reactors



total systematic uncertainty: 4.1%

	Detector-related (%)		Reactor-related (%)	
Δm^2_{21}	Energy scale	1.9	$\overline{\nu}_e$-spectra [7]	0.6
Event rate	Fiducial volume	1.8	$\overline{\nu}_e$-spectra	2.4
	Energy threshold	1.5	Reactor power	2.1
	Efficiency	0.6	Fuel composition	1.0
	Cross section	0.2	Long-lived nuclei	0.3



Precision Measurement of θ_{13} with Reactor Antineutrinos

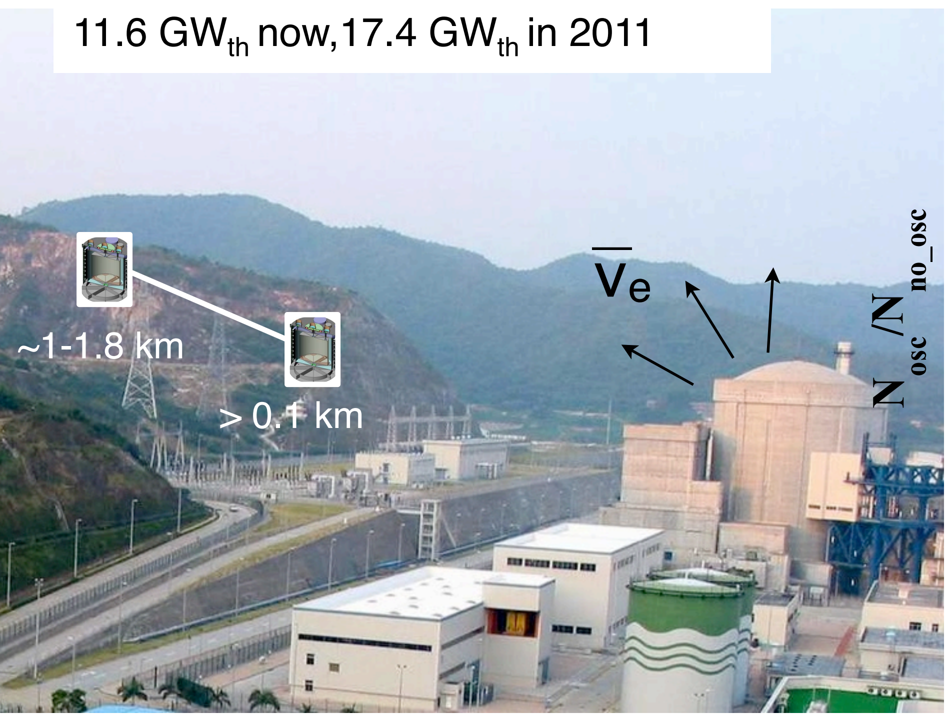
Search for θ_{13} in new oscillation experiment with multiple detectors

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

Daya Bay Reactors:

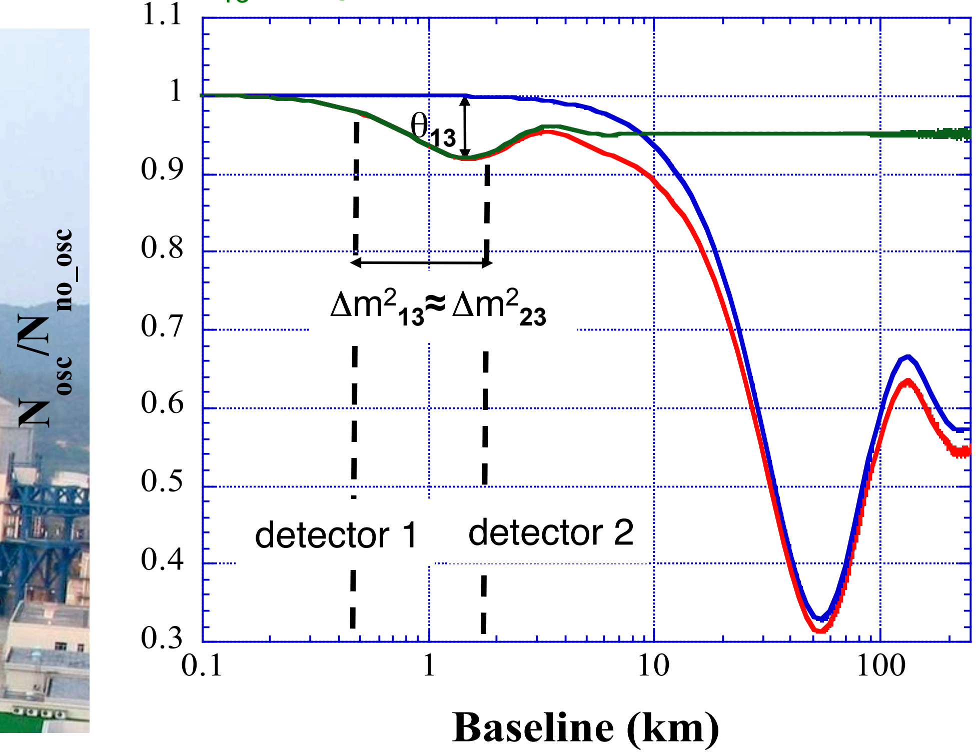
Powerful $\overline{\nu}_e$ source, multiple cores

11.6 GW_{th} now, 17.4 GW_{th} in 2011



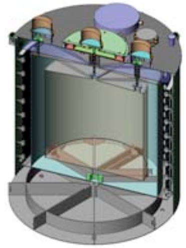
Small-amplitude oscillation due to θ_{13} integrated over E

Large-amplitude oscillation due to θ_{12}

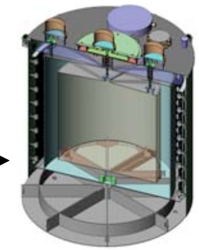


Concept of Reactor θ_{13} Experiments

Measure ratio of interaction rates in multiple detectors



distance L ~ 1.5 km



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

Measured Ratio of Rates

Detector Mass Ratio, H/C → *mass measurement*

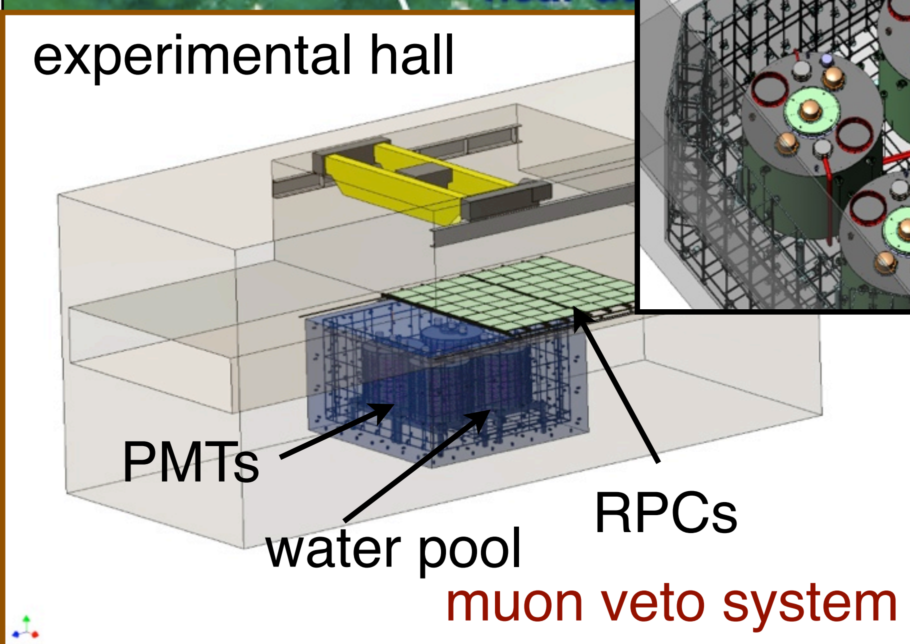
Detector Efficiency Ratio → *calibration*

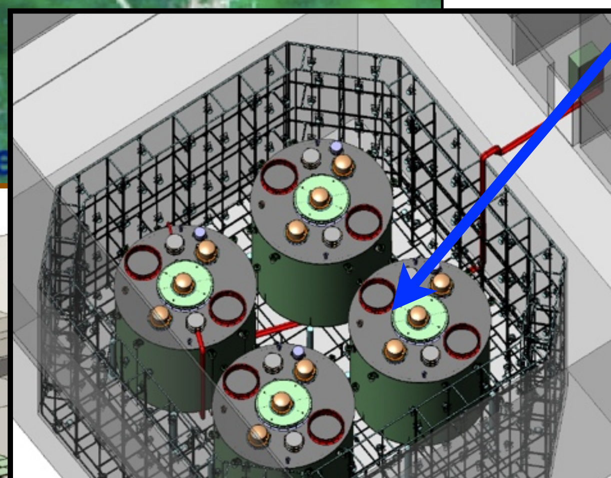
→ $\sin^2 2\theta_{13}$

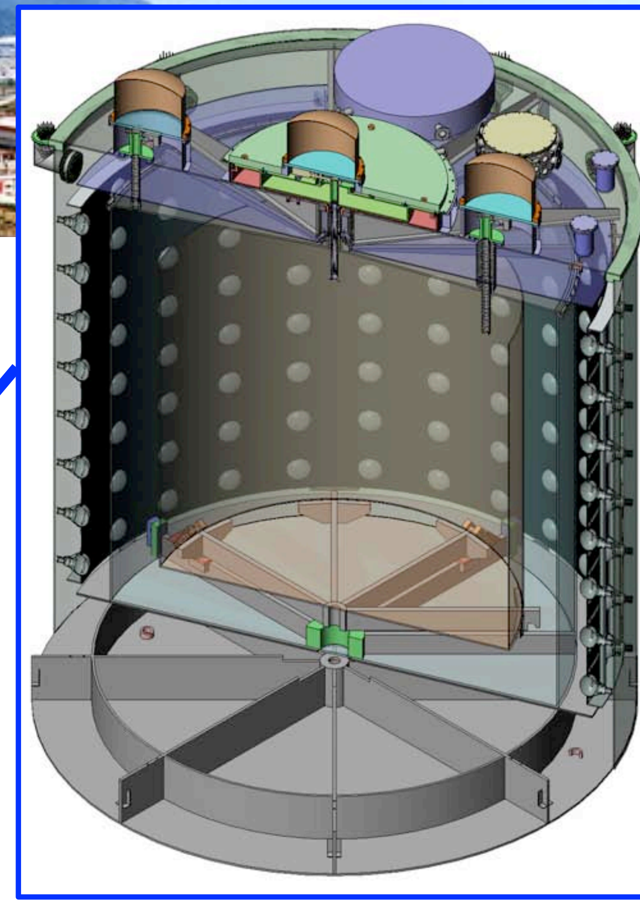
cancel reactor systematics, no fiducial volume cuts

Daya Bay, China

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



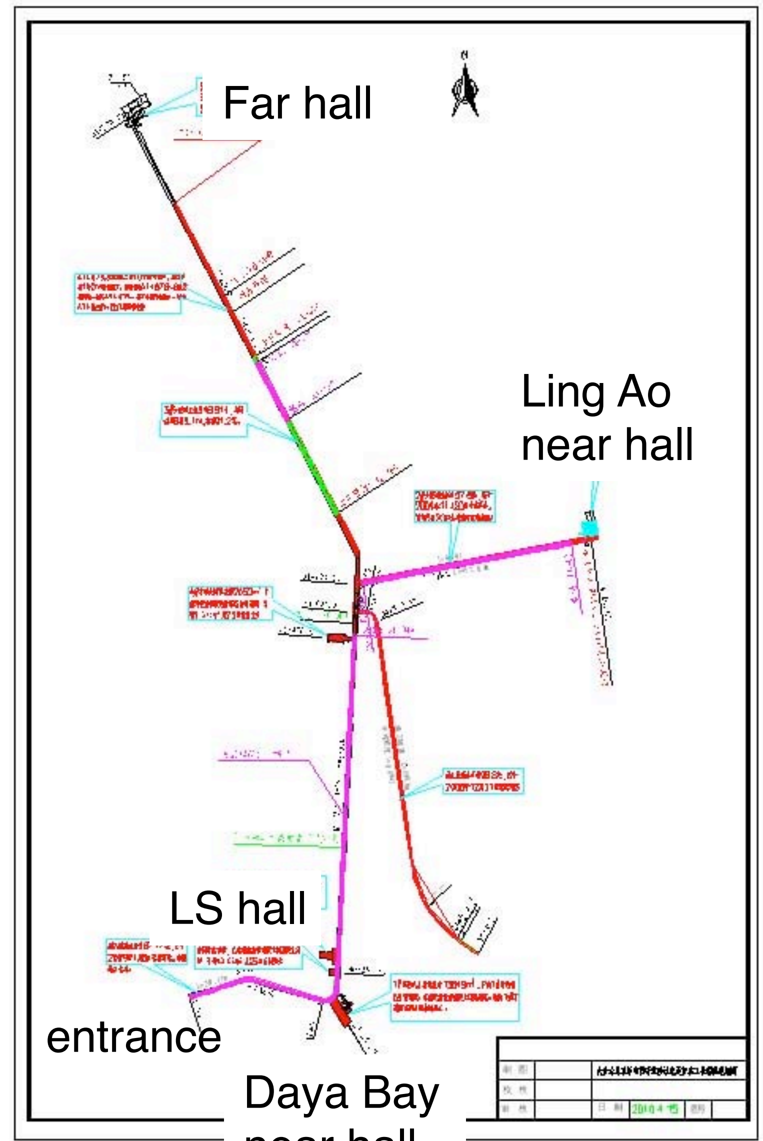




antineutrino detectors

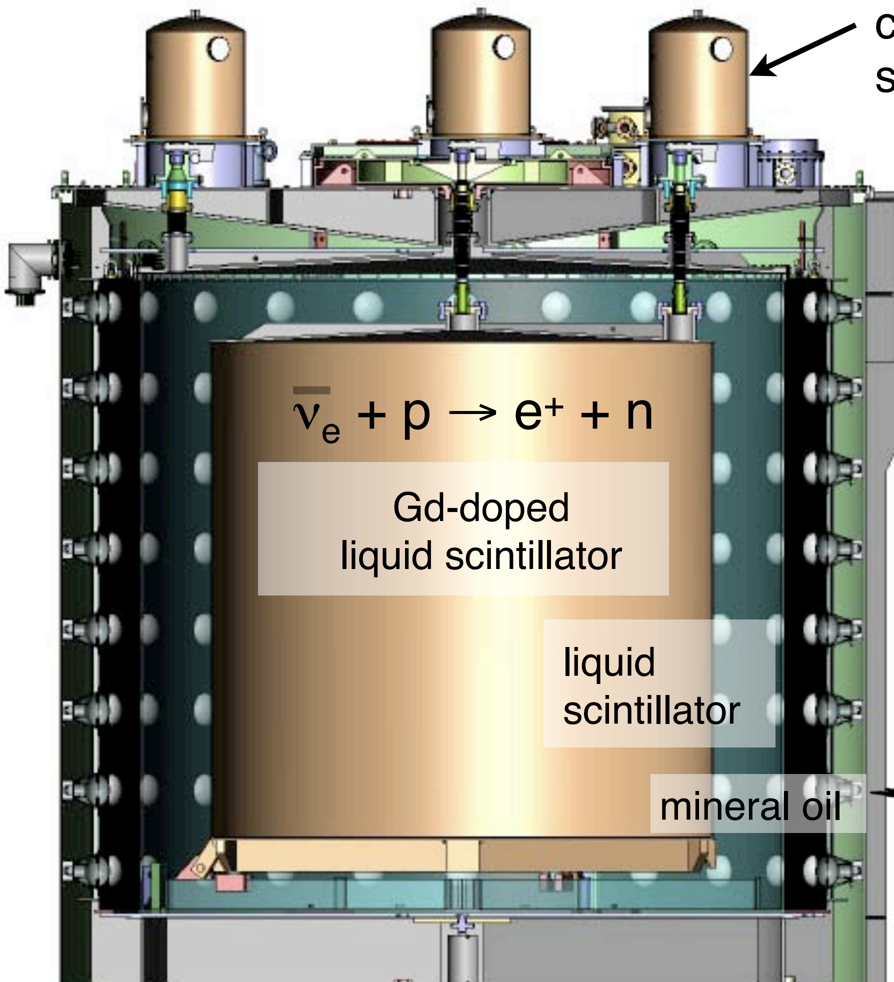
multiple detectors per site
cross-check efficiency

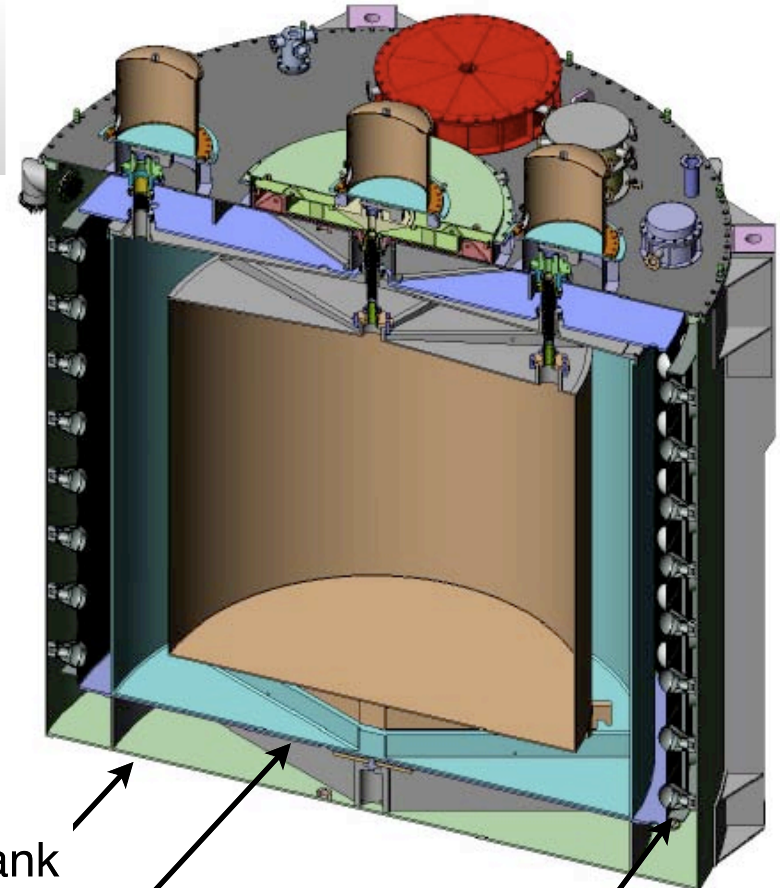
Daya Bay Underground Laboratory



Daya Bay Antineutrino Detectors

- 8 “identical”, 3-zone detectors
- no position reconstruction, no fiducial cut





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

Daya Bay Antineutrino Detectors

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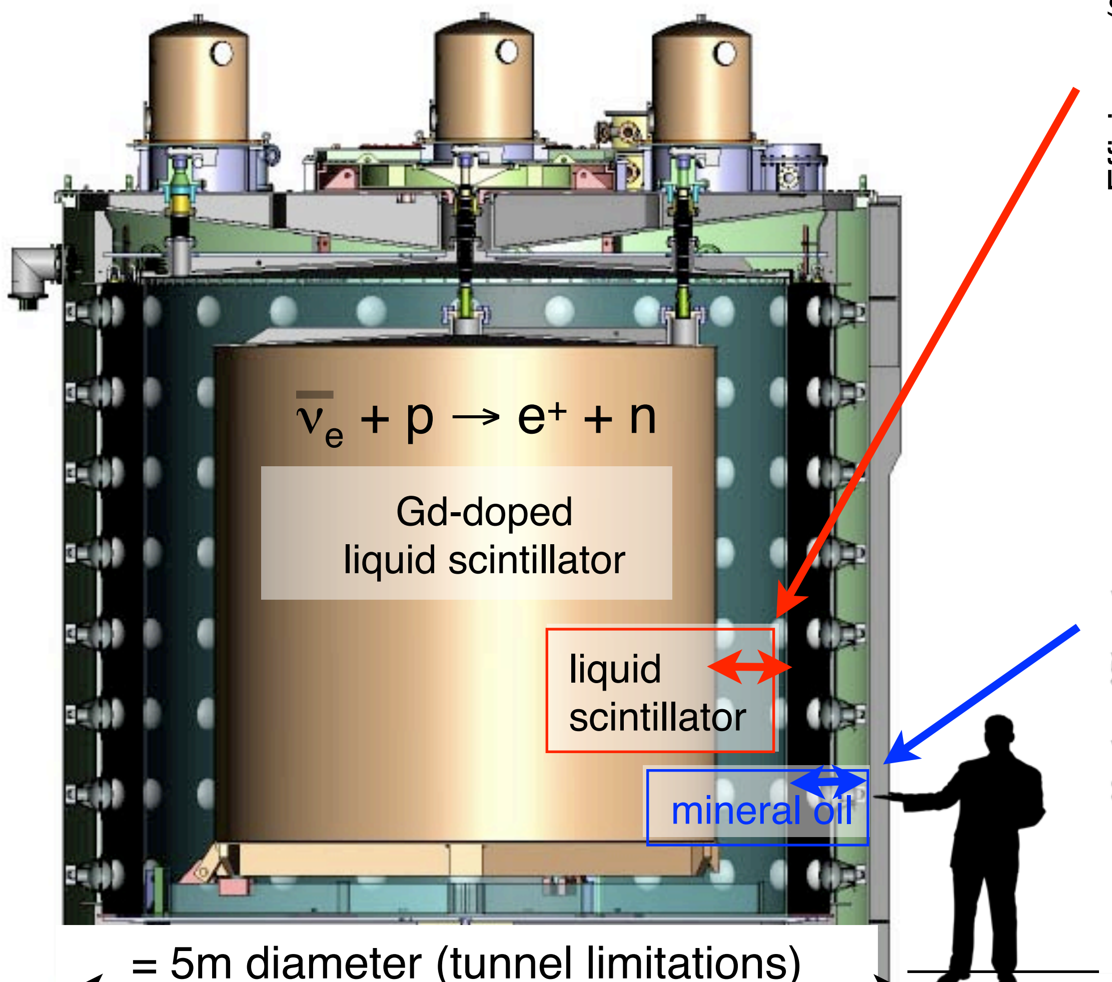
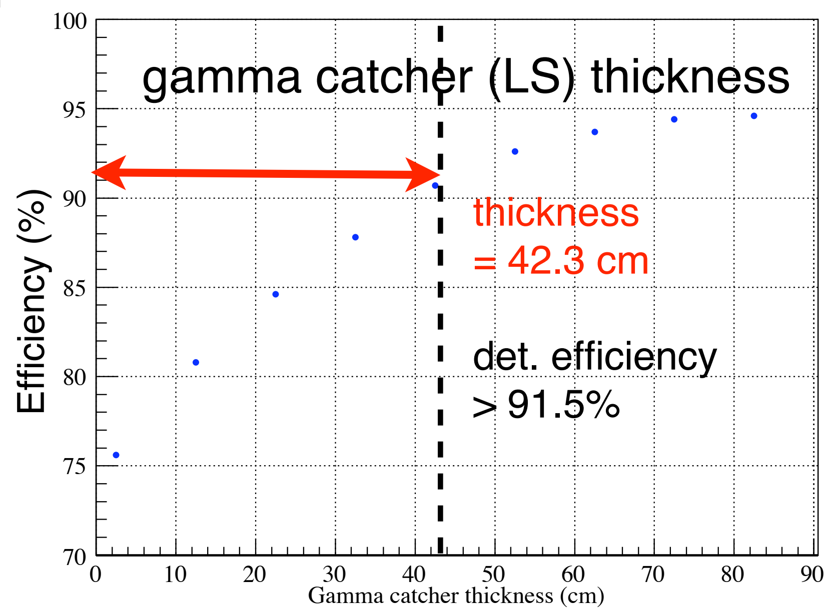
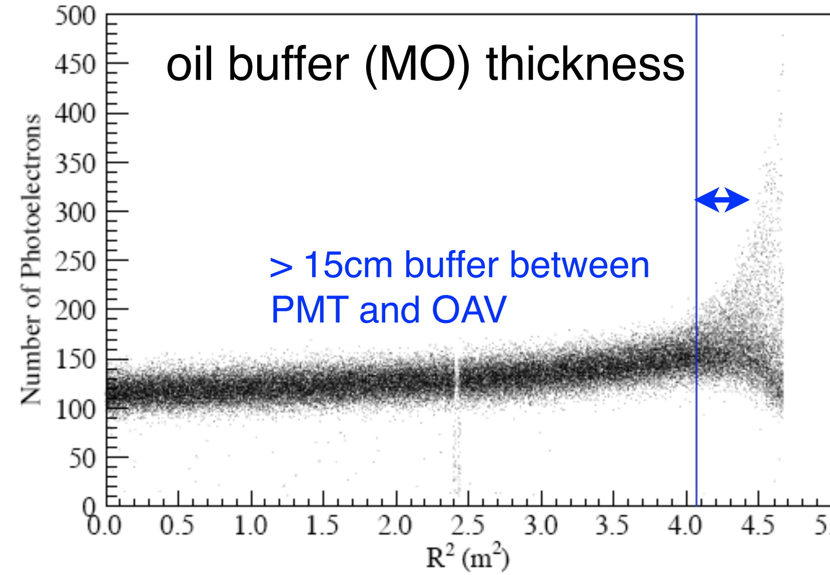
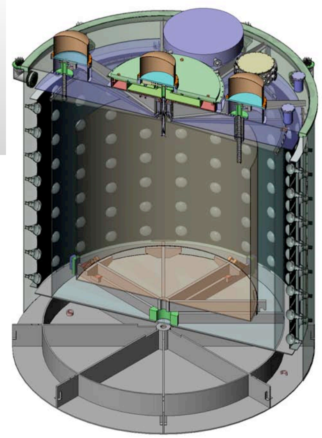
- no position reconstruction, no fiducial cut







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

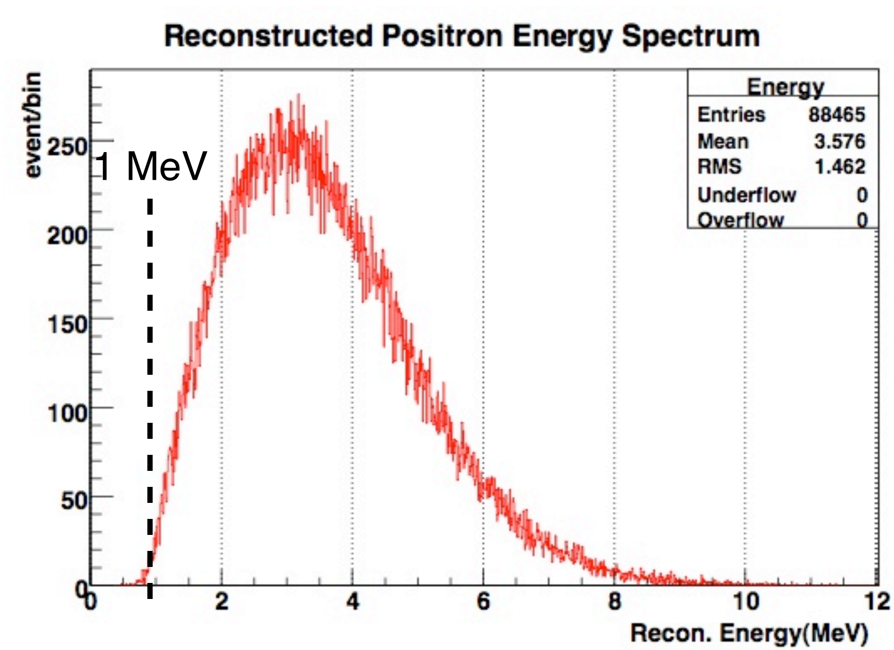
high-statistics experiment!

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

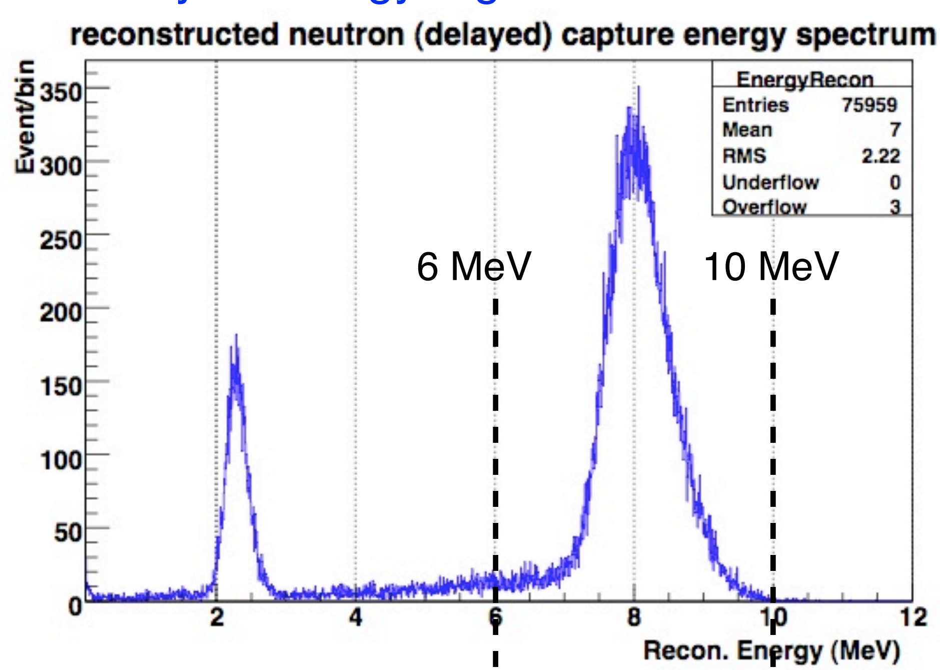
0.3 b $\mapsto + p \rightarrow D + \gamma$ (2.2 MeV) (delayed)

49,000 b $\mapsto + Gd \rightarrow Gd^* \rightarrow Gd + \gamma$'s (8 MeV) (delayed)

Prompt Energy Signal



Delayed Energy Signal



Daya Bay Antineutrino Detectors

Detection Efficiencies

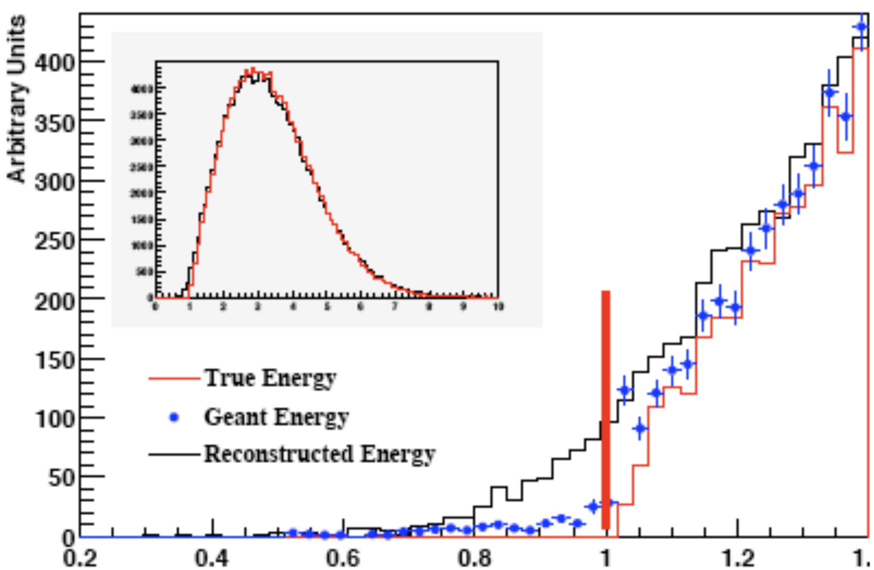
no position reconstruction

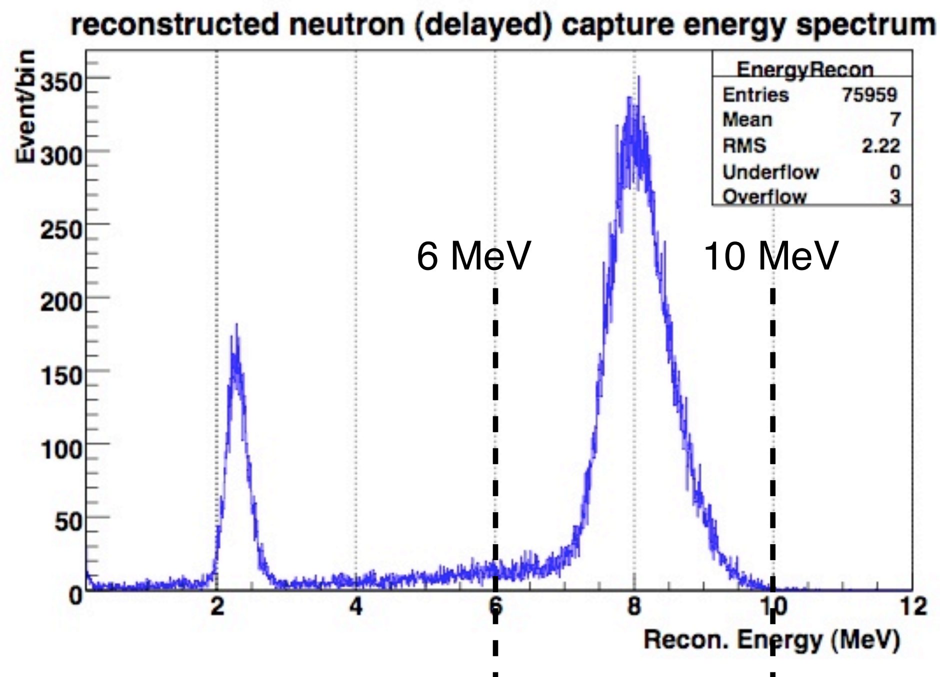
Prompt e+ Signal

1 MeV cut for prompt positrons: >99%, uncertainty negligible

Delayed n Signal

6 MeV cut for delayed neutrons: 91.5%, uncertainty 0.22% assuming 1% energy uncertainty

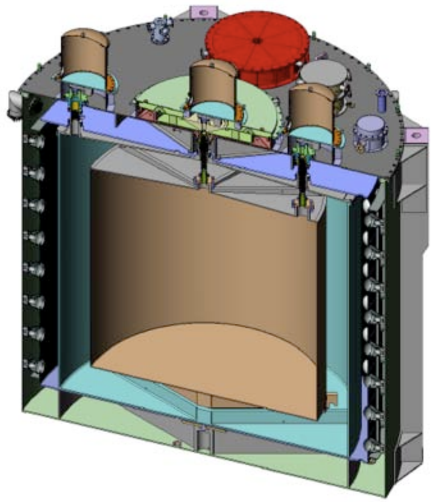


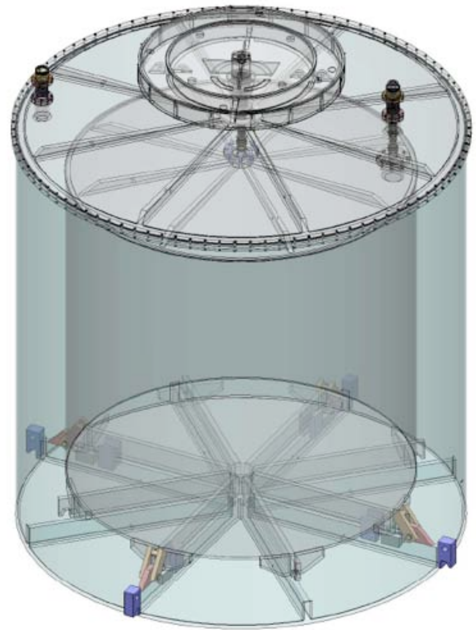


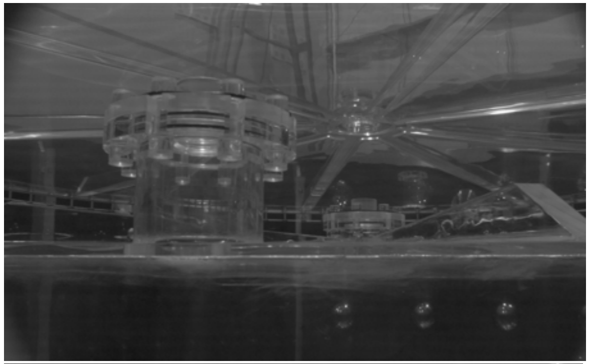
Daya Bay Antineutrino Detectors

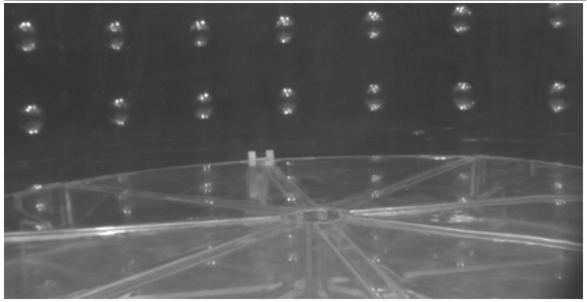
Detector Acrylic Target Vessels

design and integration





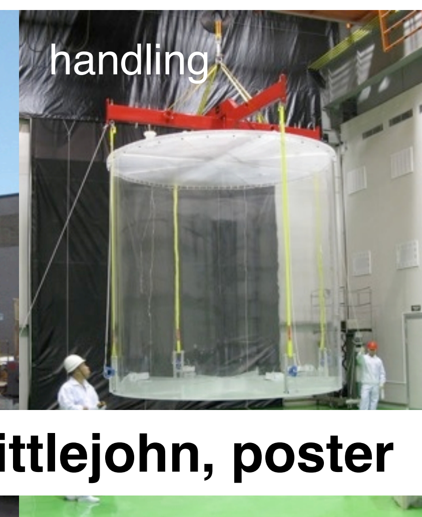




pairwise fabrication, cleaning, and QA

shipment and transport

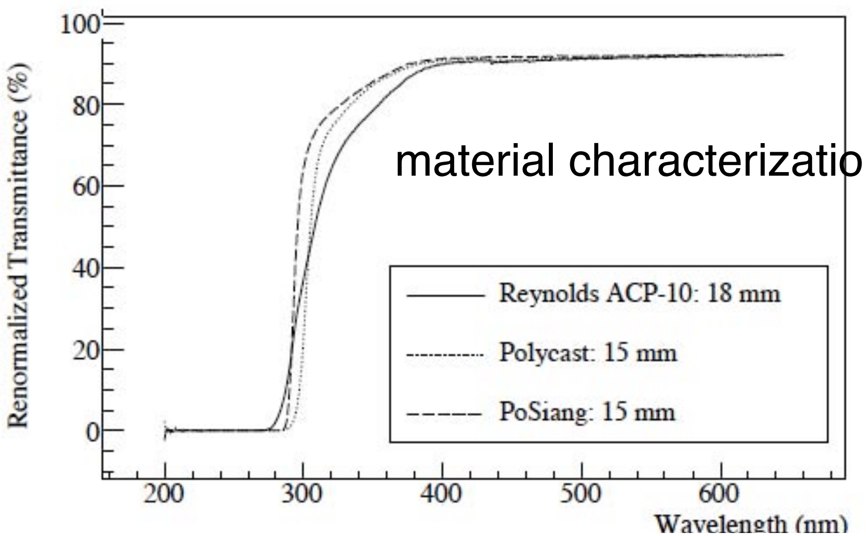
handling



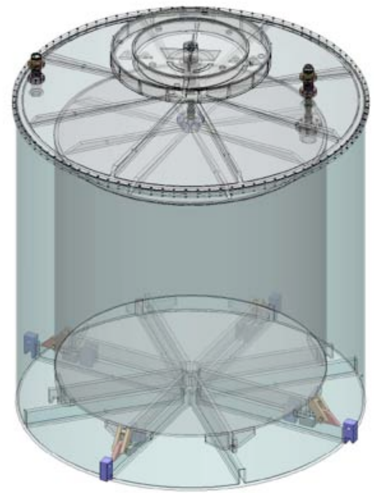
Bryce Littlejohn, poster

Daya Bay Antineutrino Detectors

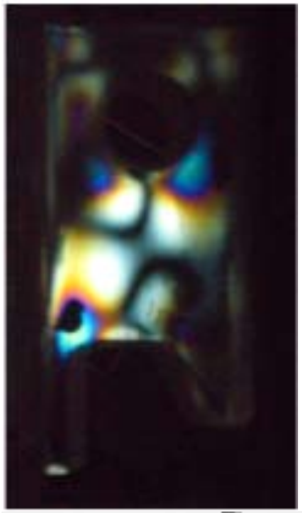
Detector Acrylic Target Vessels

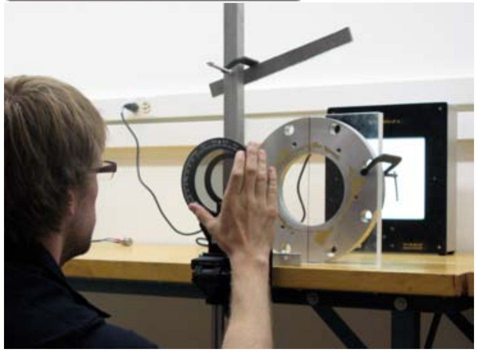


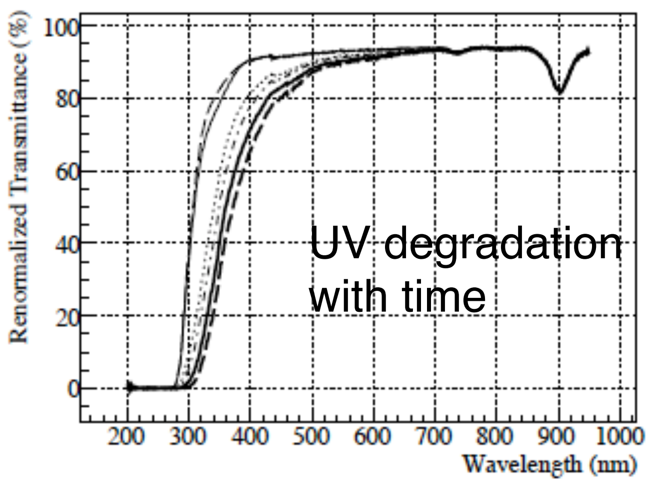
material characterization



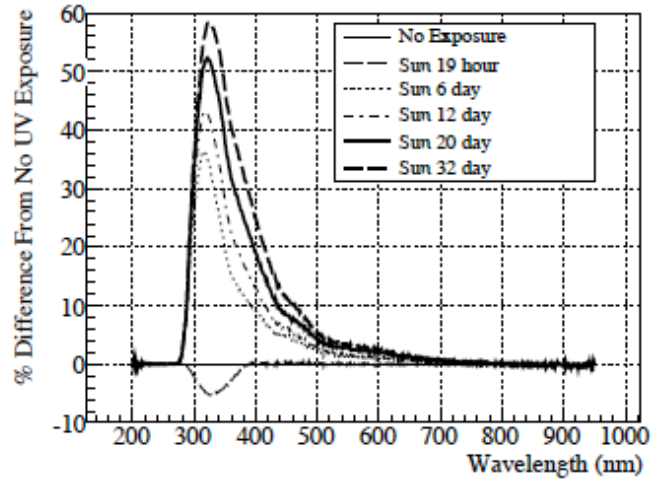
stress analysis







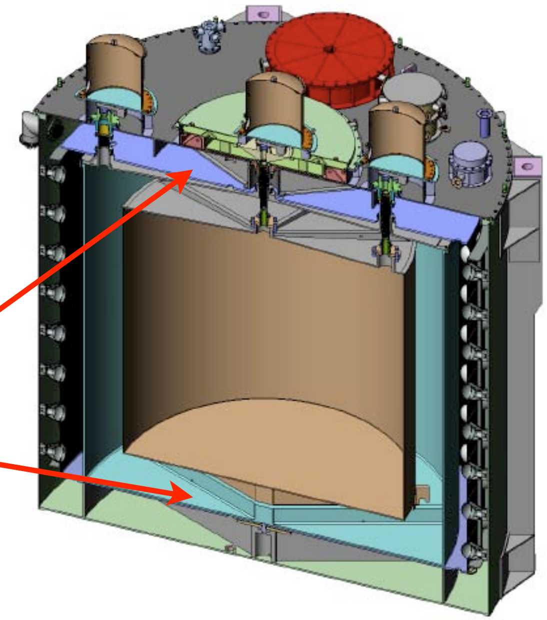
UV degradation with time



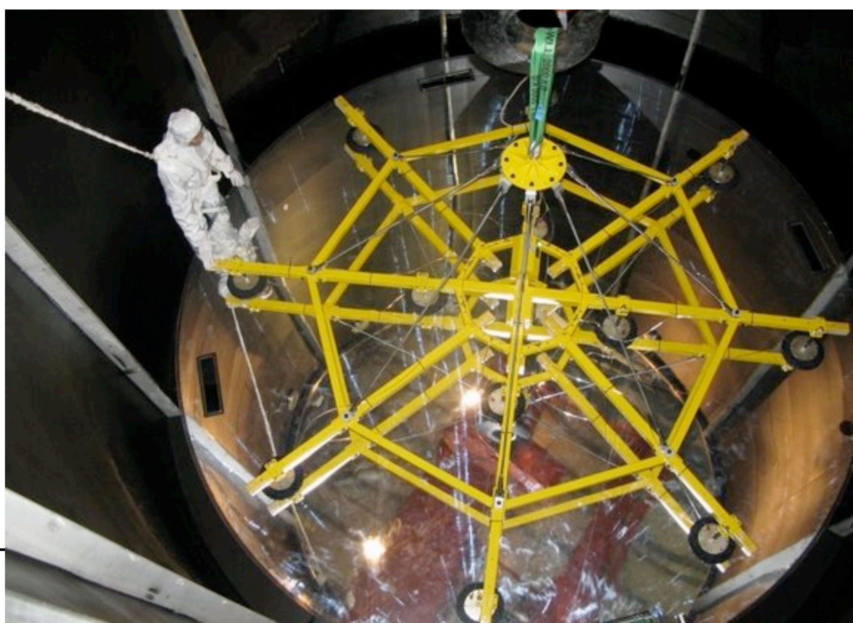
Bryce Littlejohn, poster

Daya Bay Antineutrino Detectors

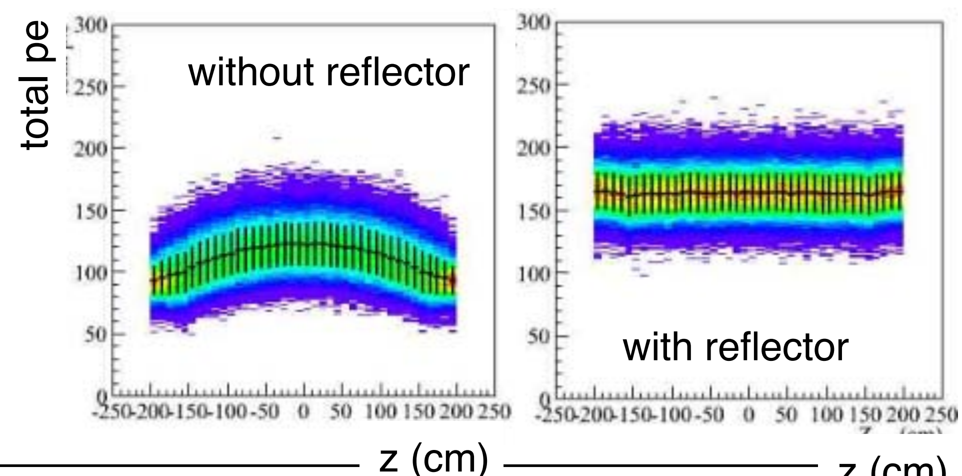
Top/Bottom Reflectors



specular reflectors consist of ESR® high reflectivity film on acrylic panels



reflector flattens detector response

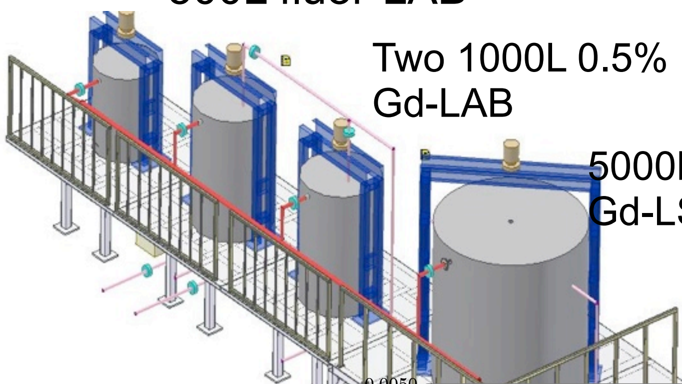


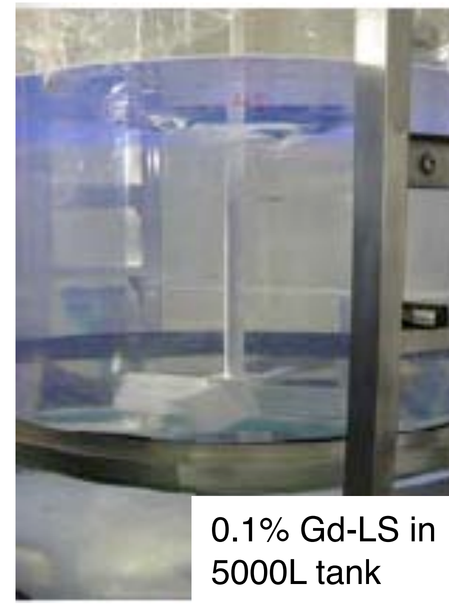
Daya Bay Antineutrino Detectors

Gd-Liquid Scintillator Production

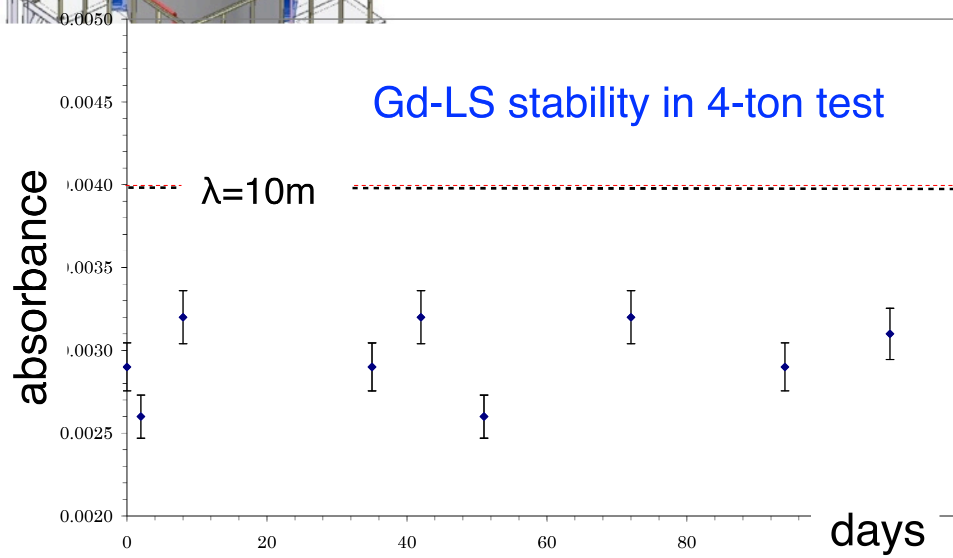
Daya Bay experiment uses 185 ton 0.1% gadolinium-loaded liquid scintillator (Gd-LS).

Gd-TMHA + LAB + 3g/L PPO + 15mg/L bis-MSB





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.

Systematic Uncertainties

Detector-Related Uncertainties

Absolute measurement **Relative measurement**

Source of uncertainty		Chooz	Daya Bay (*relative*)		
		(*absolute*)	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

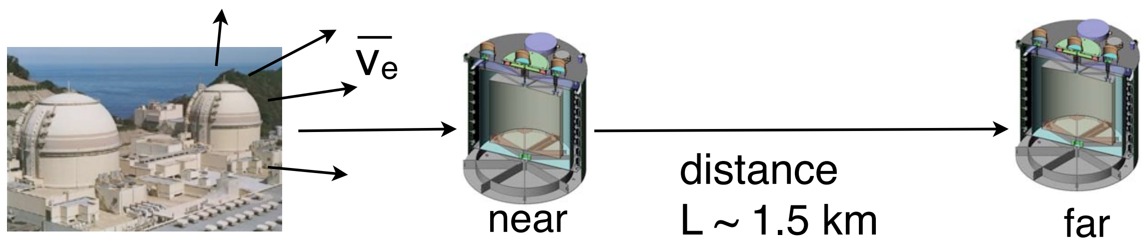
O(0.2-0.3%) precision for relative measurement between detectors at near and far sites

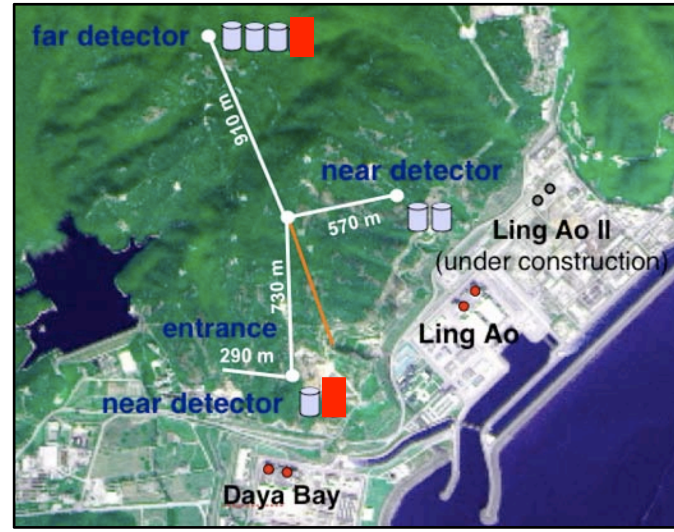
Daya Bay Antineutrino Detectors

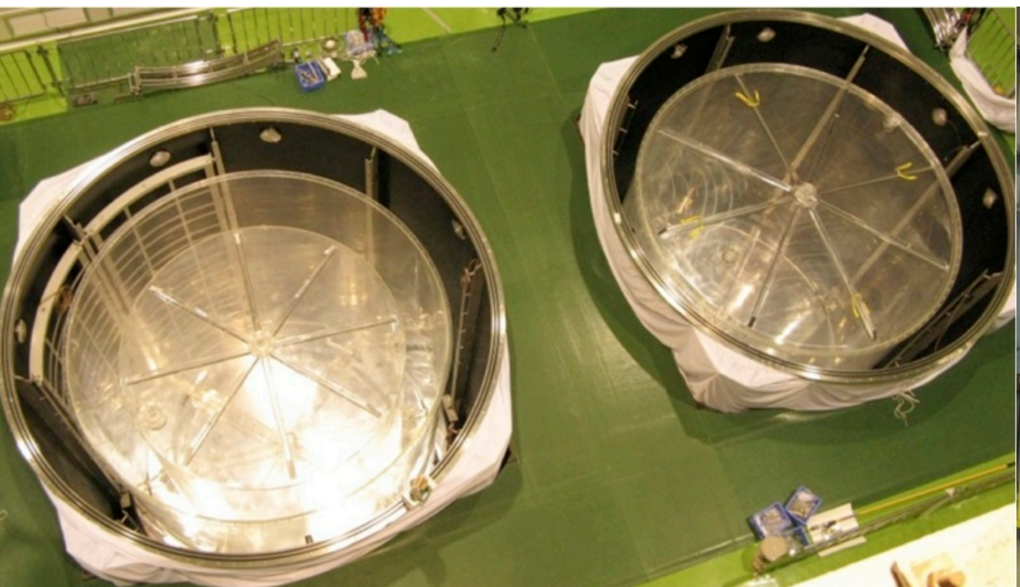
Detector Assembly in Pairs

Daya Bay Antineutrino Detectors

Antineutrino Detector Pairs







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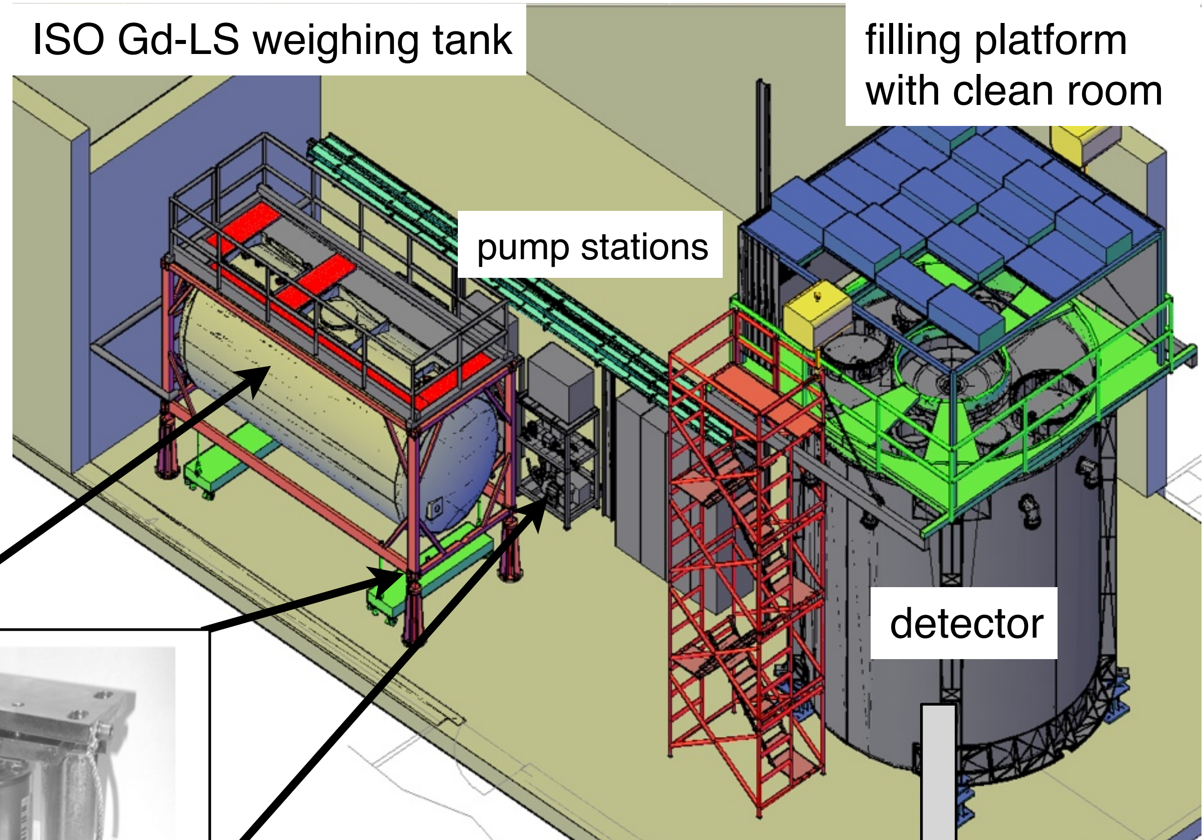
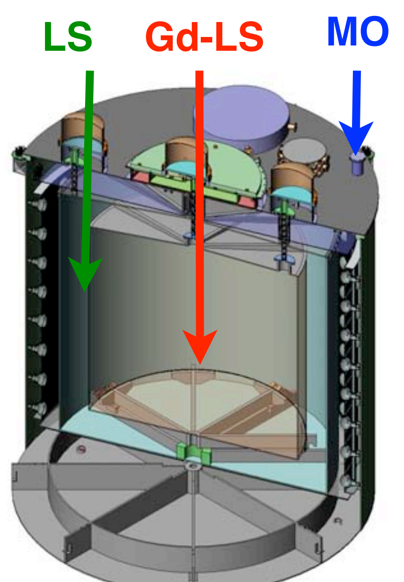
Detector Filling & Target Mass Measurement

200-ton Gd-LS reservoir

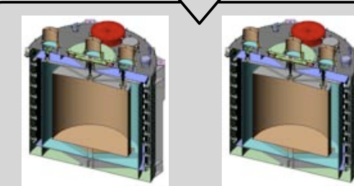
20-ton ISO tank





load cell
accuracy < 0.02%

Coriolis mass
flowmeters < 0.1%

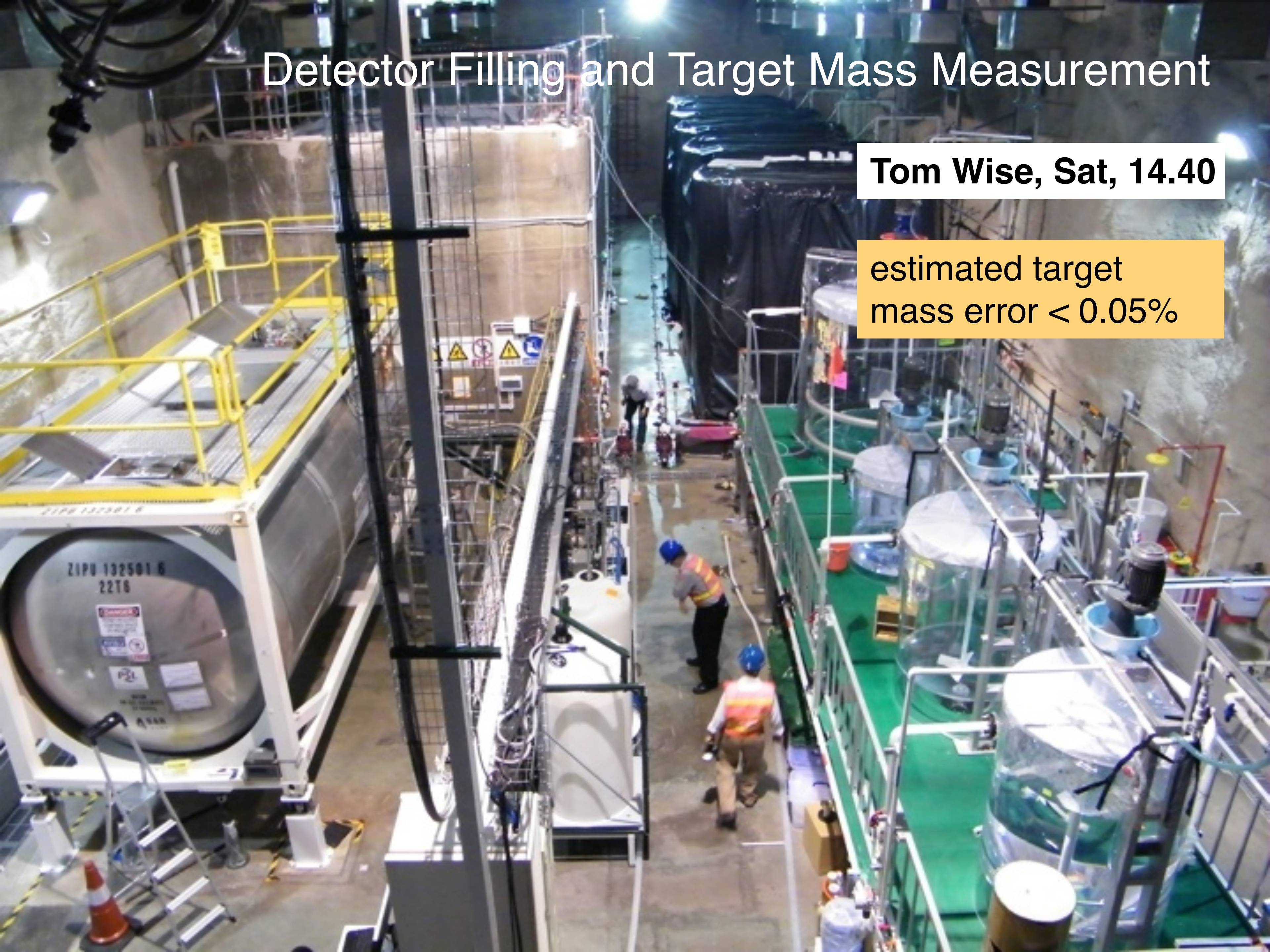


filling “pairs” of detectors

Detector Filling and Target Mass Measurement

Tom Wise, Sat, 14.40

estimated target
mass error < 0.05%



Systematic Uncertainties

Detector-Related Uncertainties

Absolute measurement **Relative measurement**

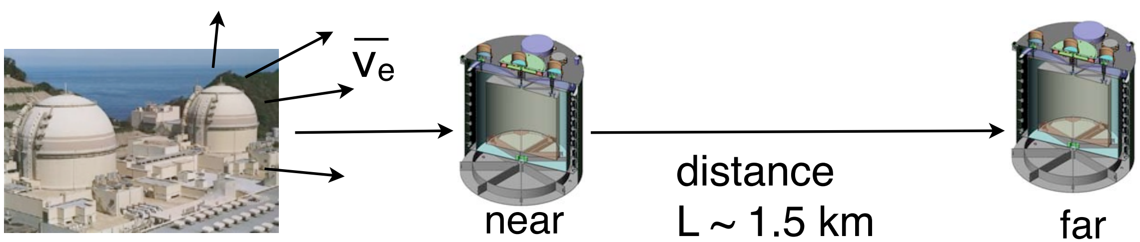
Source of uncertainty		Chooz (*absolute*)	Daya Bay (*relative*) Baseline	Goal	Goal w/Swapping
# protons		0.8	0.3	0.1	0.006
Detector Efficiency	Energy cuts	0.8	0.2	0.1	0.1
	Position cuts	0.32	0.0	0.0	0.0
	Time cuts	0.4	0.1	0.03	0.03
	H/Gd ratio	1.0	0.1	0.1	0.0
	n multiplicity	0.5	0.05	0.05	0.05
	Trigger	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%

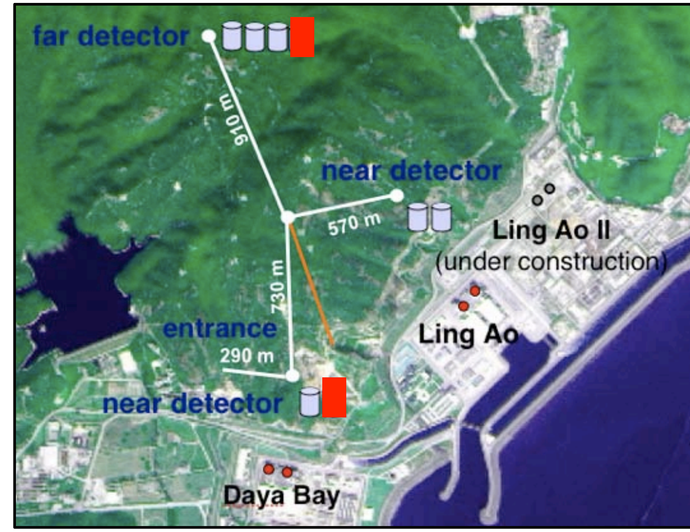
Ref: Daya Bay TDR

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

Daya Bay Antineutrino Detectors

Antineutrino Detector Pairs





n detection efficiency

n efficiency uncertainty

light yield

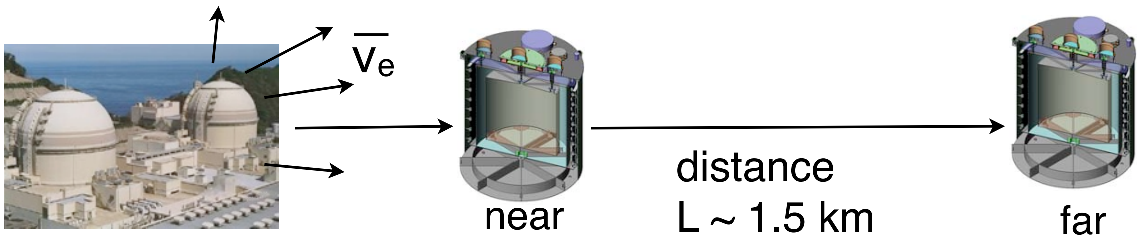
Component	Parameter	Variation between As-Built ADs	Resultant Variation in Respnose Metric			
Acrylic Vessels	Shape/dimensions	Target volumes vary by ¡0.5% Avg. thicknesses <1 mm different Concentric to <5 mm	<0.1	<0.01	-	-
	Optical Properties	Attn. lengths for QA from 1 m to 10 m	<0.1	<0.01	4.4	-
Target Liquids	Shape	GC Non-scint. volume varies by <1%	<0.2	<0.01	-	-
	...erties	Unknown				
	...tio	2% between batches and storage tanks				
	H/C Ratio	Unknown, but likely <0.1%				
Reflector	Dimensions	Diameter <2 mm				
	Reflectivity	<2%				
	Shape	<2 cm sag				
PMTs	Dist. to AD center	<2 cm				
	Dist. to radial shield	<3 mm				
	Dead PMTs	None yet observed	-	-	-	-
etc	Reflectivity	Likely <10%	Negl.	Negl.	<1.0	-
	Shape	Surface area >0.5%	Negl.	Negl.	<0.1	-
	Radioactivity	All materials pass QA testing	-	-	-	No Predicted Variation

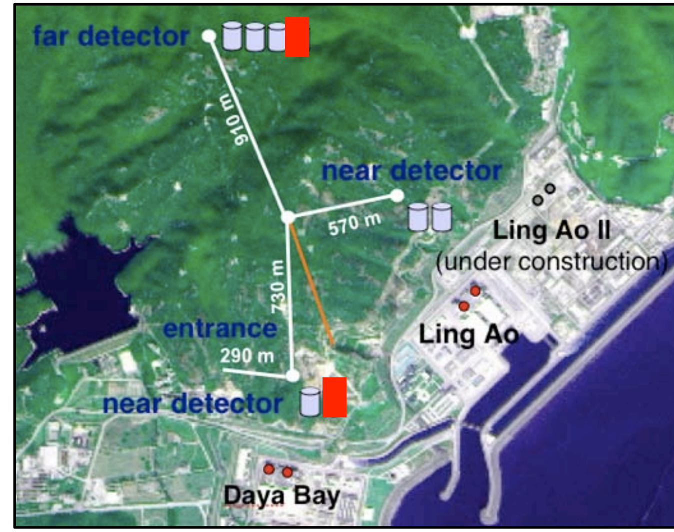
evaluate changes in detector response metrics

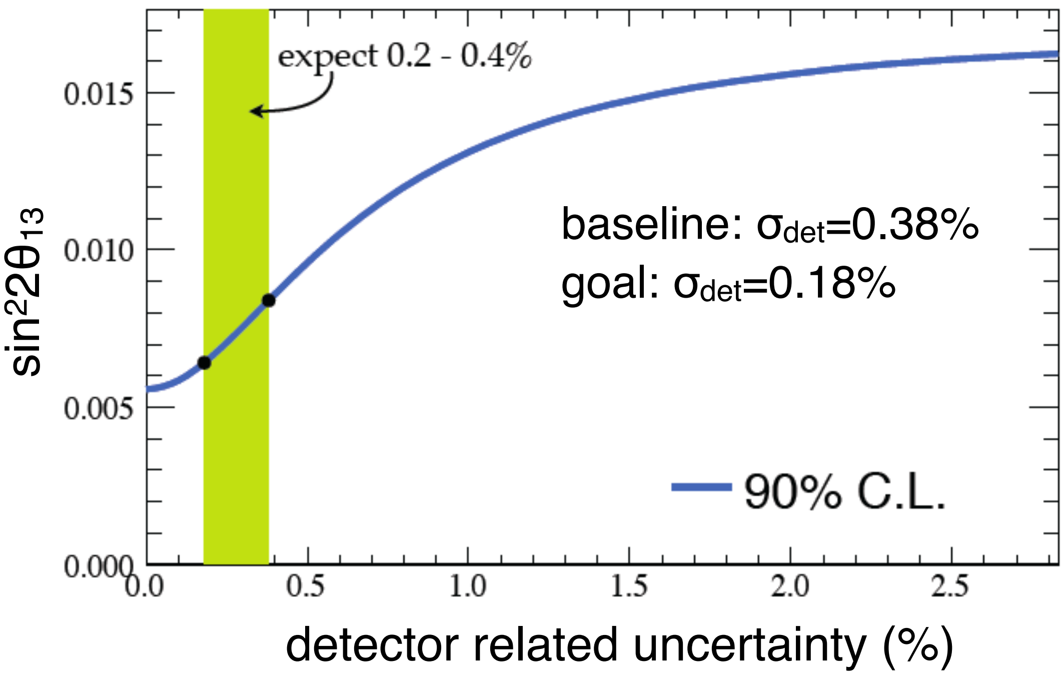
calibration sources will determine detector response

Detector Systematics and Sensitivity to θ_{13}

Antineutrino Detector Pairs

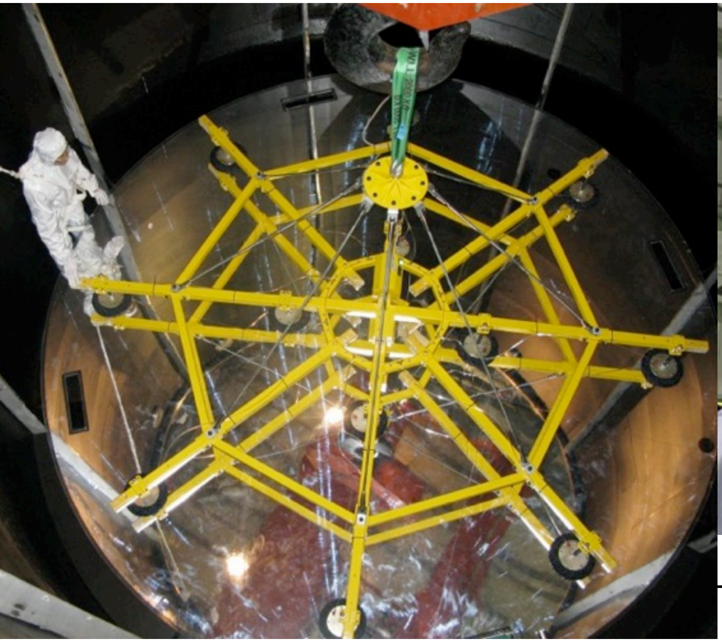


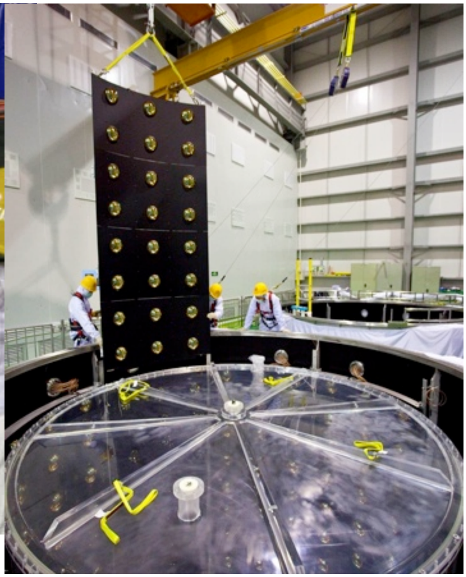




How sensitive is the Daya Bay experiment to relative detector systematics?

Antineutrino Detector Assembly





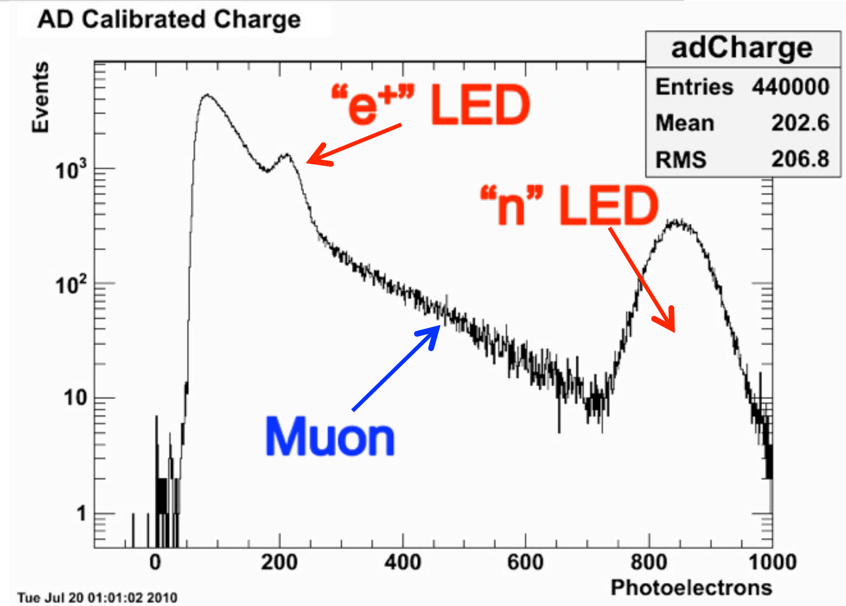
Henry Band, Thurs, 15.00

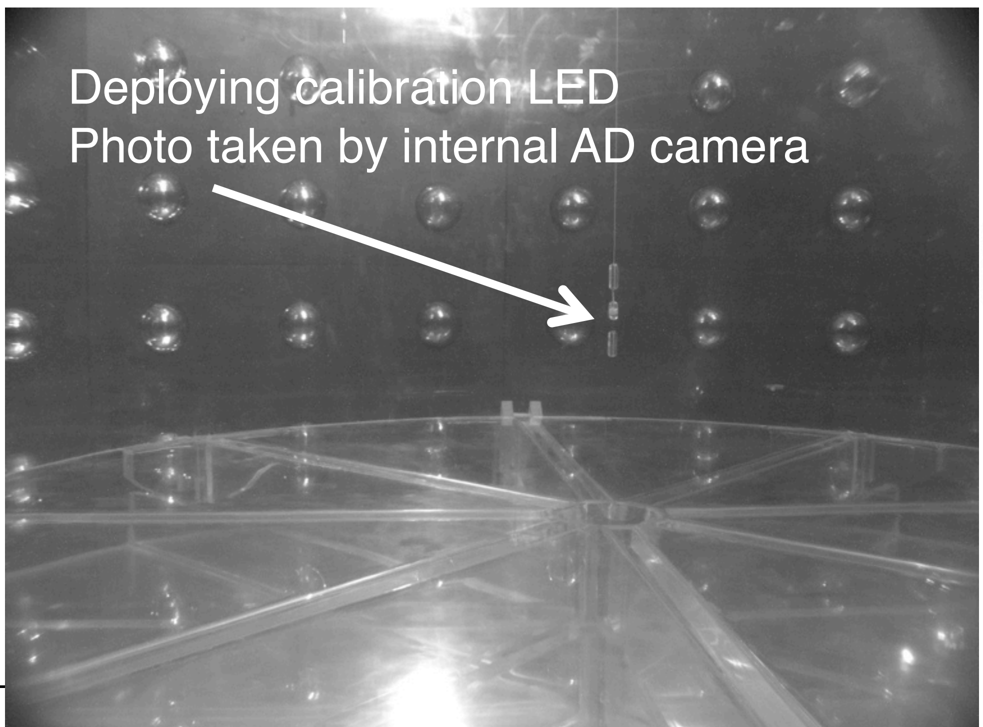
Antineutrino Detector Dry Run

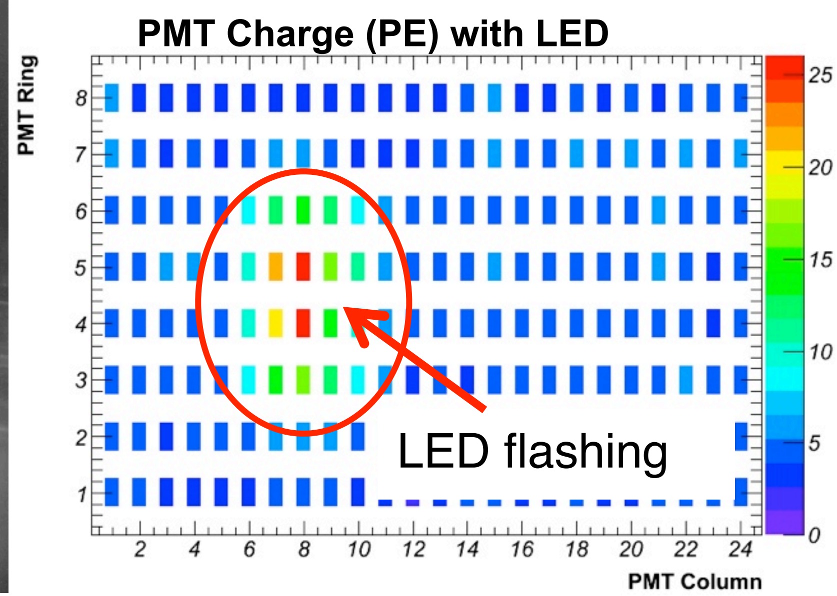
First Detector Data

Double-pulse LED to mimic $\overline{\nu}$ interaction

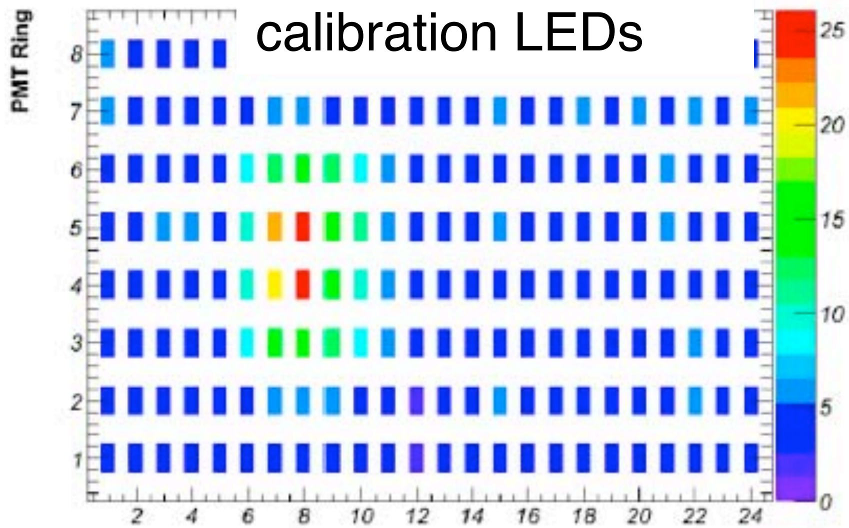
Detector dry run took place in assembly building (above ground). Can see muon events.

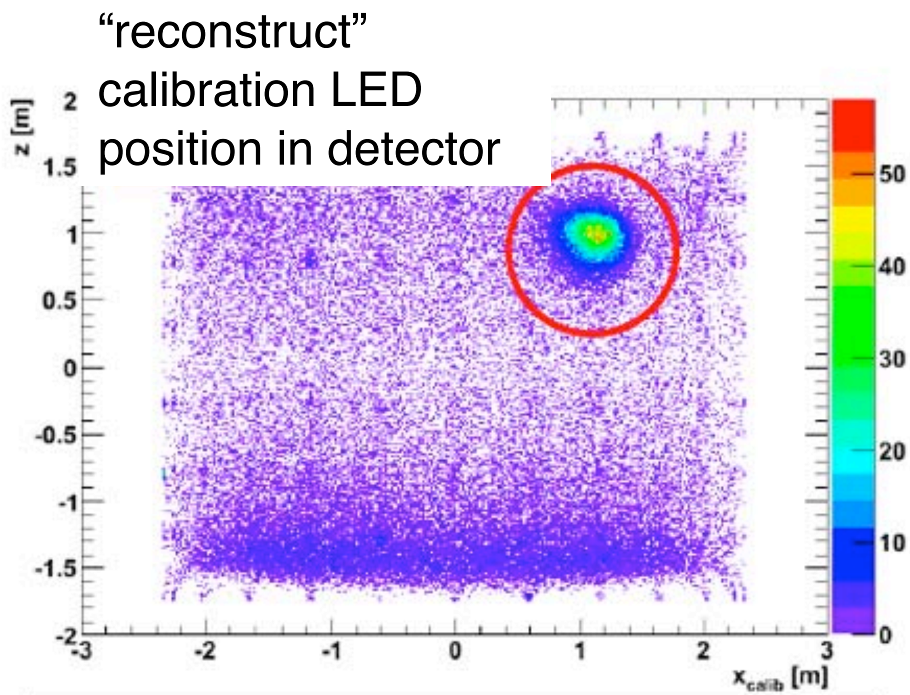


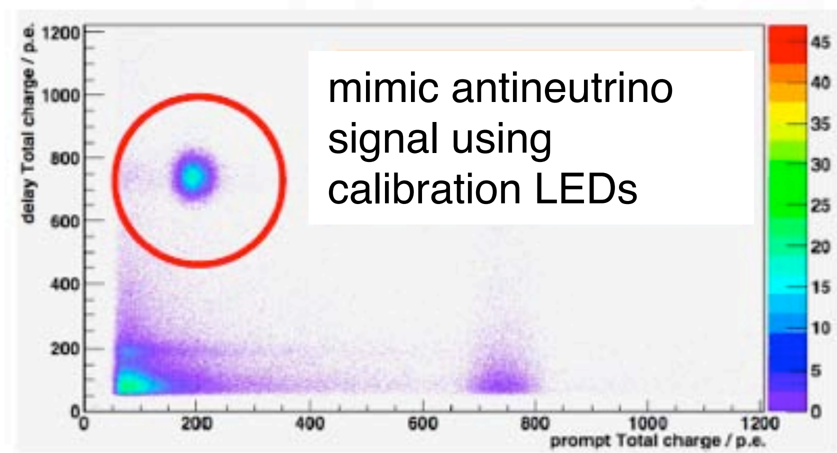




Antineutrino Detector Dry Run

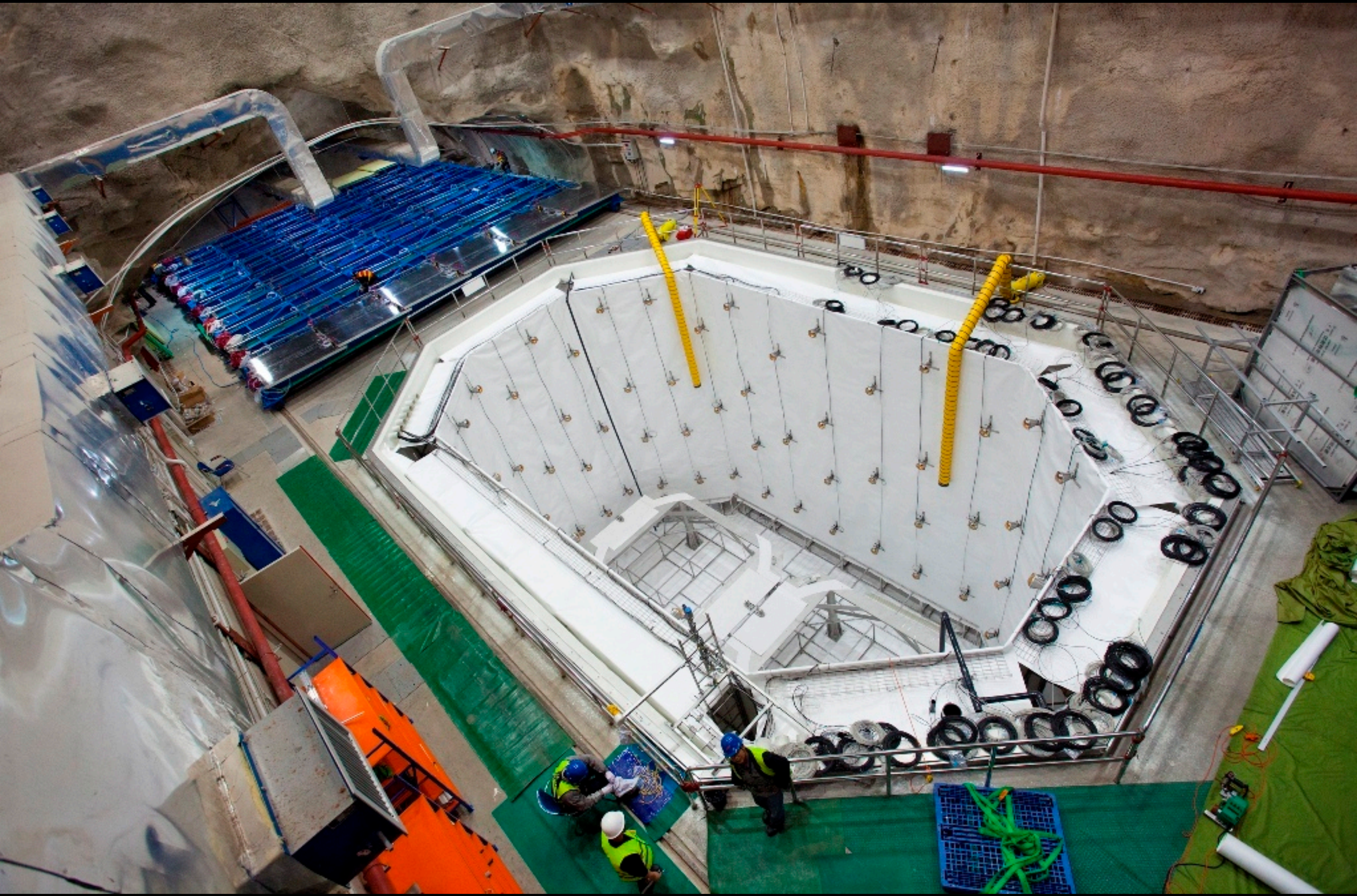


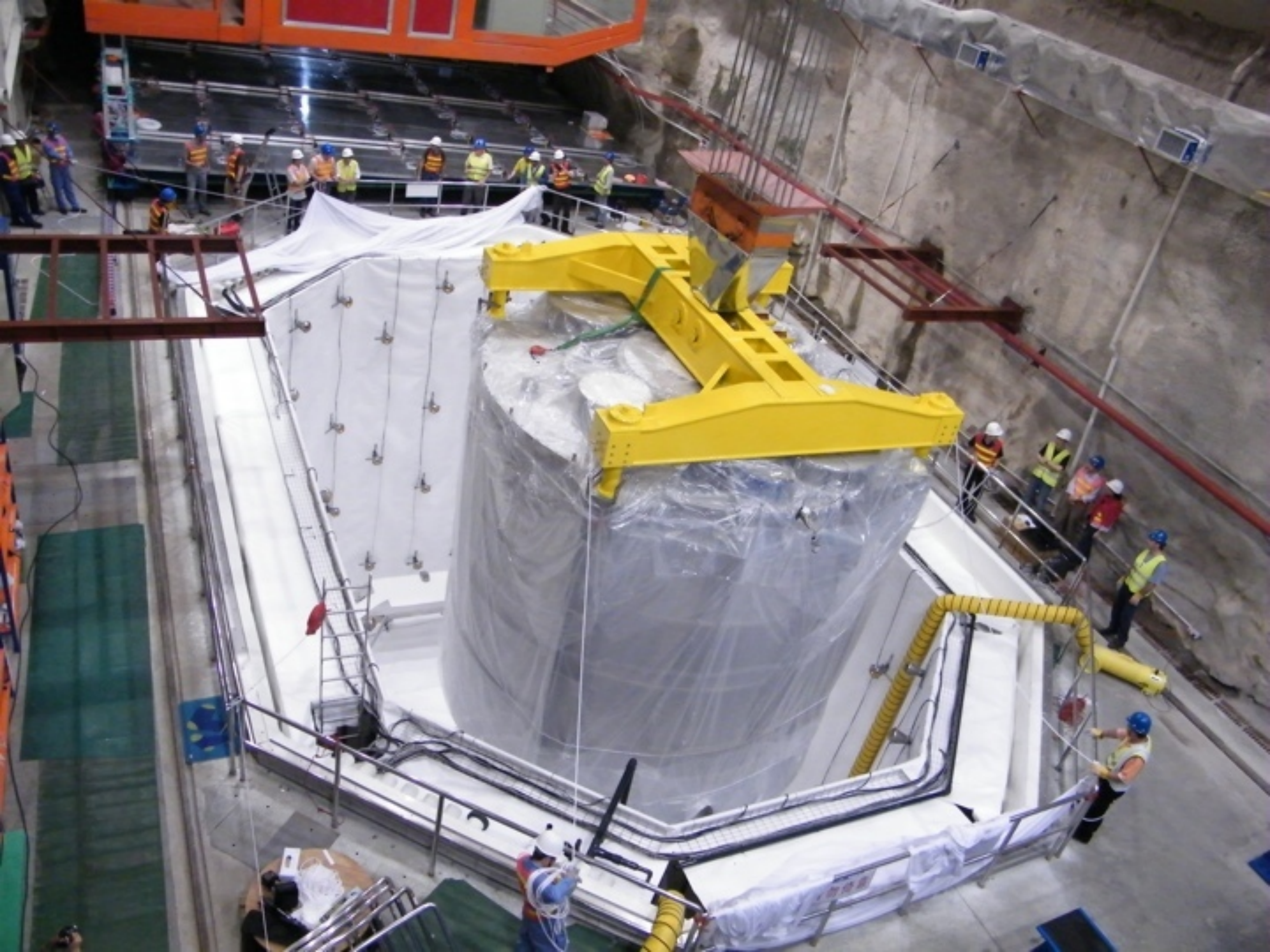




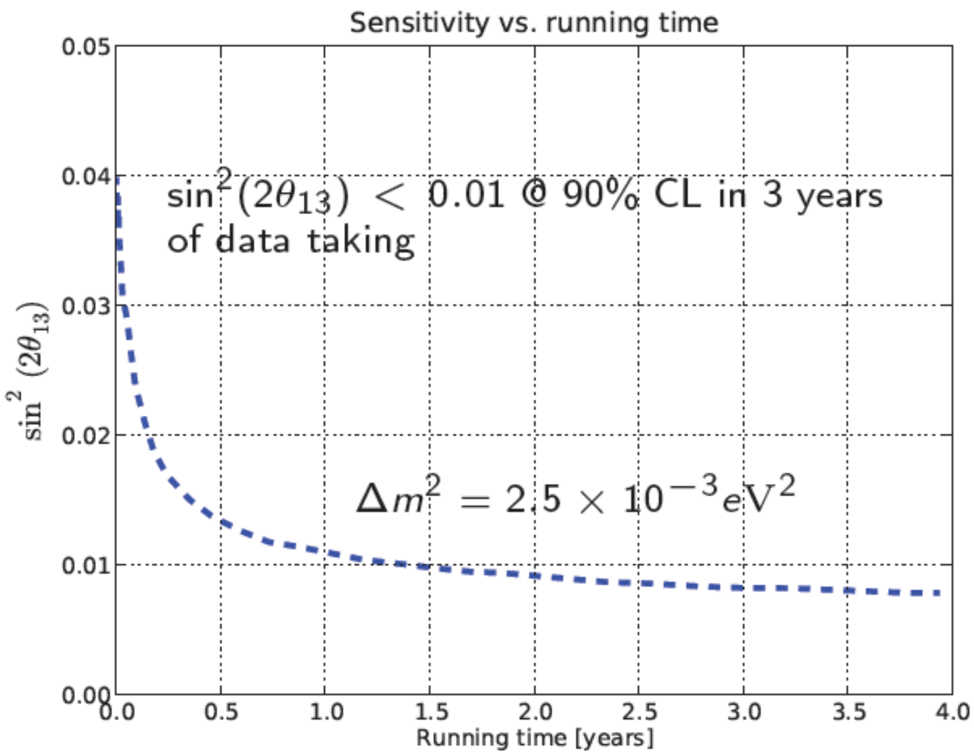
Commissioning experience
- detector and electronics can stably operate for several days
- commissioning calibration system
- improvement of PMT electronics
- processing data online and offline detector and analysis experience

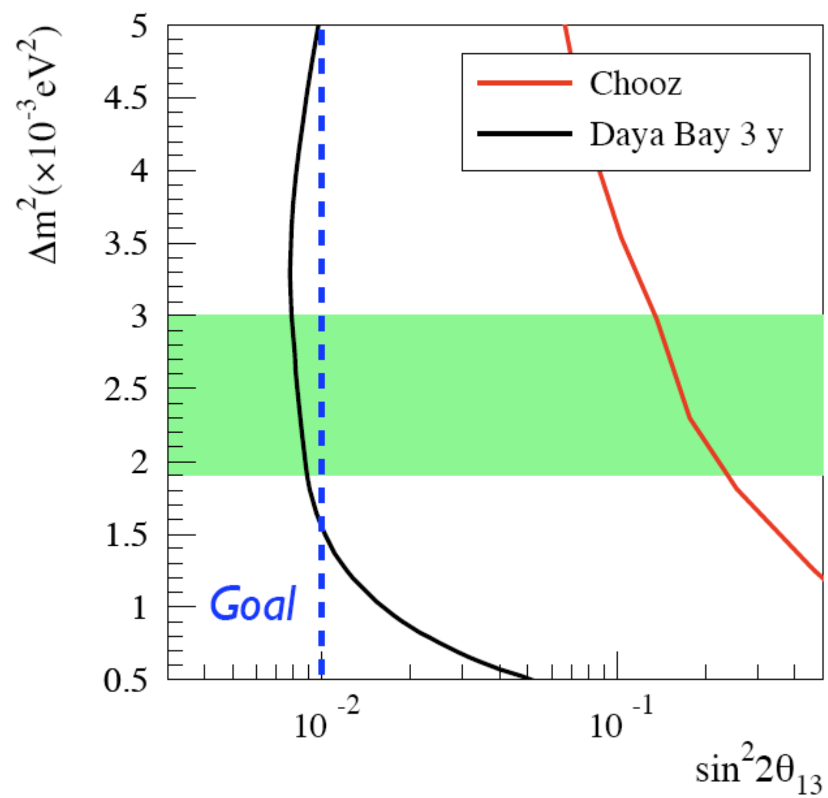
Antineutrino Detector Test Transport





Sensitivity of Daya Bay





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

Jul 2011 start data taking with near site
2012 start data taking with full experiment

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

Daya Bay Talks at TIPP2011

Detector Talks

- *Antineutrino Detectors for a High-Precision Measurement of θ_{13} at Daya Bay* (K. Heeger Saturday 12:00)
- *Daya Bay Antineutrino Detector Assembly and Installation* (H. Band. Thursday, 14.00)
- *High Precision Measurement of the Target Mass of the Daya Bay Detectors* (T. Wise, Saturday 14:40)

Electronics Talks

- *The DAQ and Trigger Systems for the Daya Bay Reactor Neutrino Experiment* (C. White, Saturday 15:00)
- *The Front-end Electronics for the Daya Bay Reactor Neutrino Experiment* (Z. Wang, Saturday 14:00)

Posters

- *Development and Characterization of the Acrylic Target Vessels for the Daya Bay ν Detectors* (B. Littlejohn, poster)
- *Detector Control System Design of Daya Bay Neutrino Experimen*t (M. YE, poster)

Summary and Conclusions

- Reactor experiments have played central role in history of neutrino physics

- Daya Bay antineutrino detectors optimized for high-precision measurement of θ_{13} with
  - cancellation of systematics between multiple detectors
  - relative detector uncertainties of $\leq 0.4\%$
  - novel 3-zone design with no fiducial volume cut or position reconstruction
  - pairwise detector filling and installation of identical, matched detector pairs

- Upcoming reactor experiments will measure θ_{13}. Key to neutrino model building. Measurement of $\sin^2 2\theta_{13} > 0.01$ is key to planning leptonic CPV searches in long-baseline ν oscillation experiments.

Daya Bay Collaboration

United States (15)(~89)

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

Europe (3) (9)

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

Asia (19) (~135)

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

~ 230 collaborators