$\bar{\nu}$ Disappearance at Daya Bay

Brett Viren
For the Daya Bay Collaboration

Physics Department
BROOKHAVEN NATIONAL LABORATORY

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Outline

ν Oscillation Probability

Weak and mass eigenstates need not correspond: $\nu_\alpha = \sum_{i=1}^{3} U_{\alpha,i}\nu_i$

$$U_{\alpha,i} = R_{23}\,(K_{\mathrm{CP}} R_{13} K^*_{\mathrm{CP}})\,R_{12} K_{0\nu\beta\beta}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{pmatrix} \begin{pmatrix} C_{13} & 0 & S_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -S_{13}e^{i\delta_{\mathrm{CP}}} & 0 & C_{13} \end{pmatrix} \begin{pmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} K_{0\nu\beta\beta}$$

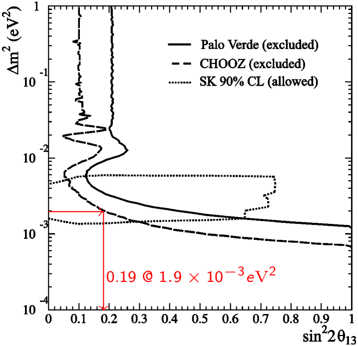
Super–Kamiokande	CHOOZ (+ K2K)	KamLAND + solar
$36.8^\circ < \theta_{23} < 143^\circ$	$\theta_{13} < 13^\circ$	$\theta_{12} = 34.4^\circ \pm 1.3^\circ$
$\sin^2(2\theta_{23}) < 0.92$	$\sin^2(2\theta_{13}) < 0.19$	$\sin^2(2\theta_{12}) = 0.87 \pm 0.03$

KamLAND + solar	MINOS
$\Delta m^2_{21} = (7.6 \pm 0.2) \times 10^{-5}\mathrm{eV}^2$	$\Delta m^2_{32} = (2.43 \pm 0.13) \times 10^{-3}\mathrm{eV}^2$

PDG09 values; limits are 90% errors at 1-σ.

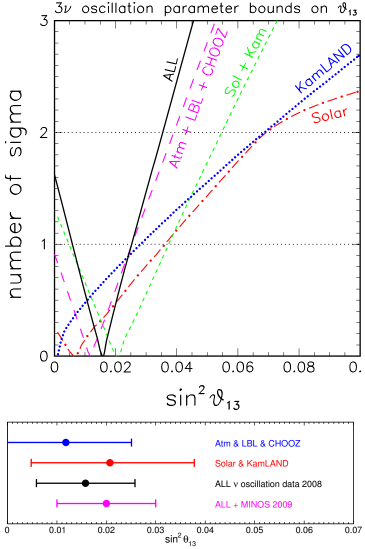
θ_{13} limit from CHOOZ K2K's "1-σ low value": $\Delta m^2_{32,1\sigma-low} = 1.9 \times 10^{-3}\mathrm{eV}^2$

Current Knowledge of θ_{13}



Palo Verde, F.Boehm *et al.*, Phys. Rev. D 62, 072002 (2000).

Hints for $\theta_{13} > 0.0$

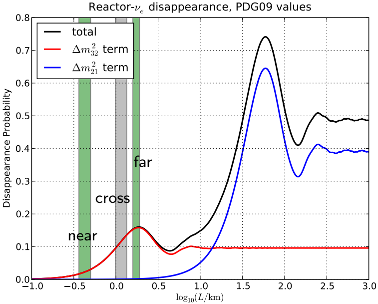


Folgli, *et al.*, arXiv:0905.3549v2.

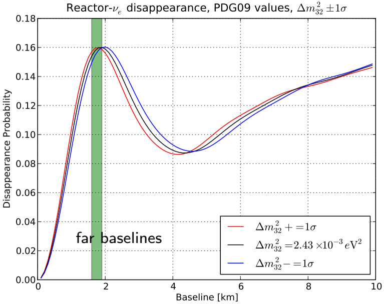
Positioning for $\bar{\nu}_e$ Disappearance

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

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



Maximizing sensitivity to θ_{13}.



Robust against changing Δm^2_{32}.

Probabilities smeared over reactor-$\bar{\nu}$ interaction spectrum.
PDG09 values used.

Outline

Context

The Daya Bay Experiment

Going After θ_{13}

Status and Schedule

Collaboration

Europe (9 in 3):
JINR, Dubna, Russia;
Kurchatov Institute, Russia;
Charles University, Czech Republic

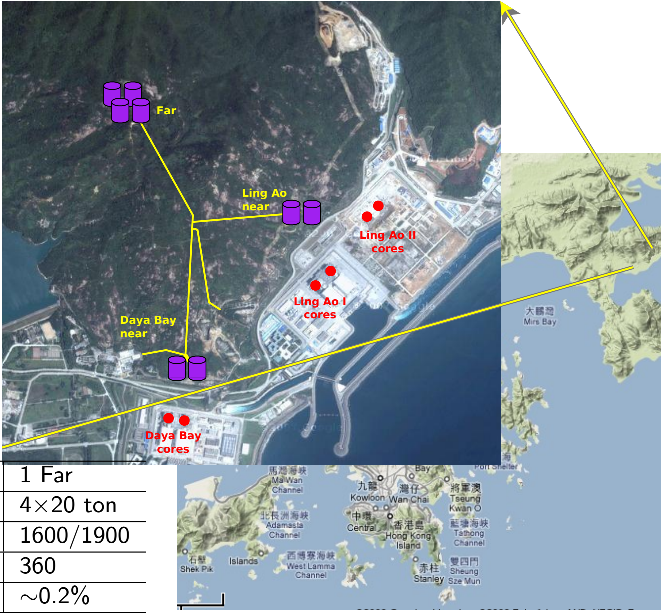
North America (74 in 14):
BNL, Caltech, George Mason Univ.,
LBNL, Iowa state Univ.
Illinois Inst. Tech., Princeton, RPI,
UC-Berkeley, UCLA, Univ. of Houston,
Univ. of Wisconsin, Virginia Tech.,
Univ. of Illinois-Urbana-Champaign

Asia (125 in 18):
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., Hong Kong Univ., Chinese Hong
Kong Univ., National Taiwan Univ., National Chiao
Tung Univ., National United Univ.

Daya Bay Power Plant and Detectors

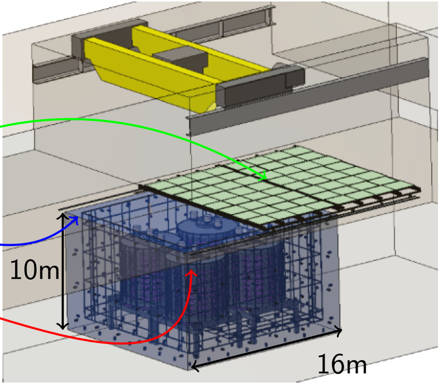
High level numerology:

- 4 cores now
  + 2 more in 2010
- 2.9 GW / core
  (1GW≈ $2 \times 10^{20} \frac{\bar{\nu}_e}{sec}$)
- 3 detector sites:



	2 Near	1 Far
$\bar{\nu}_e$ targets	2×20 ton	4×20 ton
BL (m)	360/500	1600/1900
$\bar{\nu}_e$/day	1680/1480	360
B/S ratios	∼0.4%	∼0.2%

Overview of Detector Elements



Far site example.

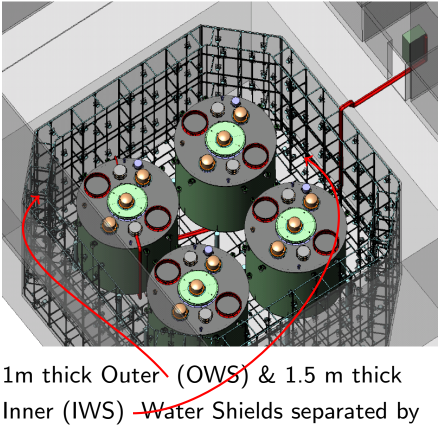
- Slide away RPC roof
- μ-veto / water shields
- $\bar{\nu}$-detector

(Note: current design uses an octagonal pool.)

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 ($^9Li, ^8He$)
  - challenging to obtain enough simulation statistics (1 min sim = 1 CPU-month).

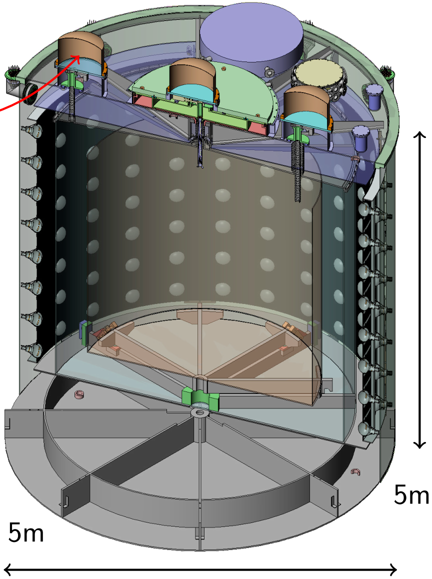


1m thick Outer (OWS) & 1.5 m thick Inner (IWS) Water Shields separated by Tyvek curtain.

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

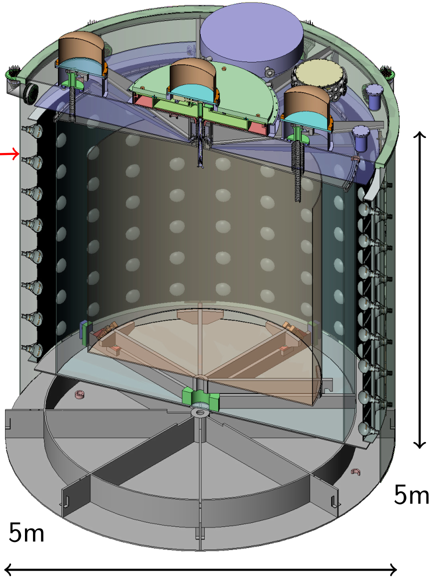
$\bar{\nu}$ Detector (AD) Module

- Automatic calibration units



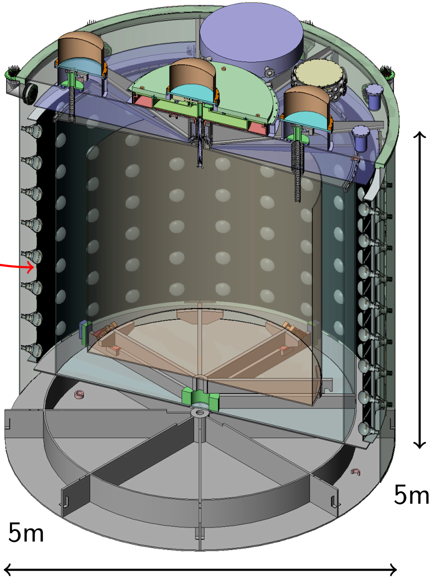
$\bar{\nu}$ Detector (AD) Module

- Automatic calibration units
- Stainless steel vessel



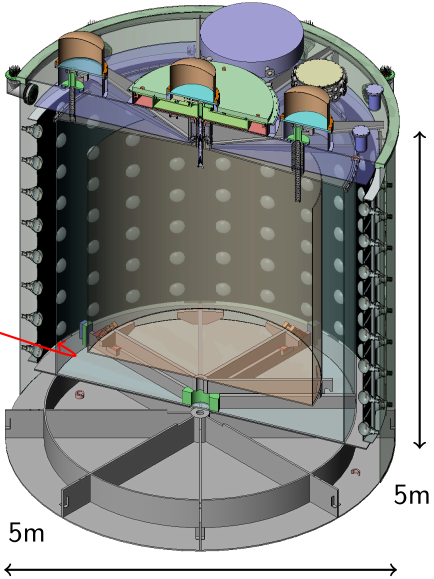
$\bar{\nu}$ Detector (AD) Module

- Automatic calibration units
- Stainless steel vessel
- 192 8" PMTs in mineral oil buffer, black radial shield



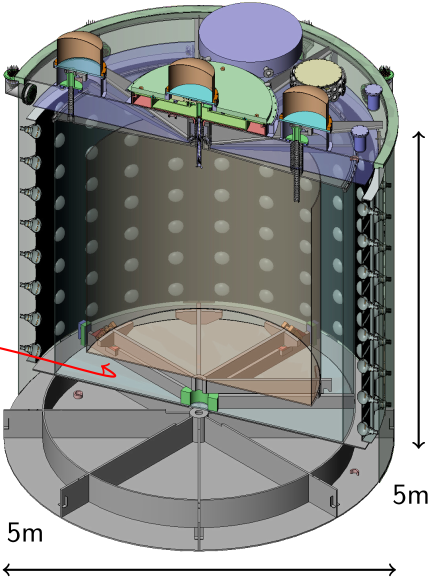
$\bar{\nu}$ Detector (AD) Module

- Automatic calibration units
- Stainless steel vessel
- 192 8" PMTs in mineral oil buffer, black radial shield
- Outer acrylic vessel



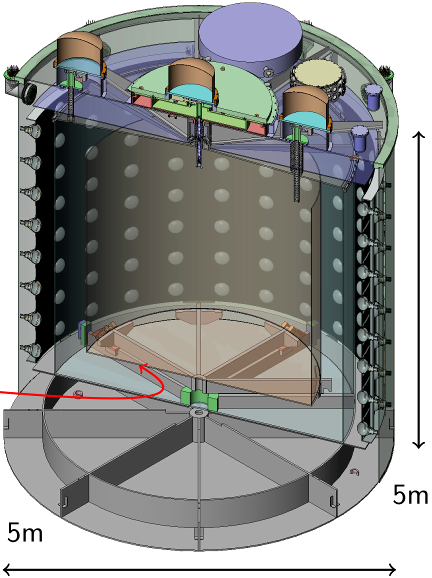
$\bar{\nu}$ Detector (AD) Module

- Automatic calibration units
- Stainless steel vessel
- 192 8" PMTs in mineral oil buffer, black radial shield
- Outer acrylic vessel
- Liquid scintillator γ-catcher



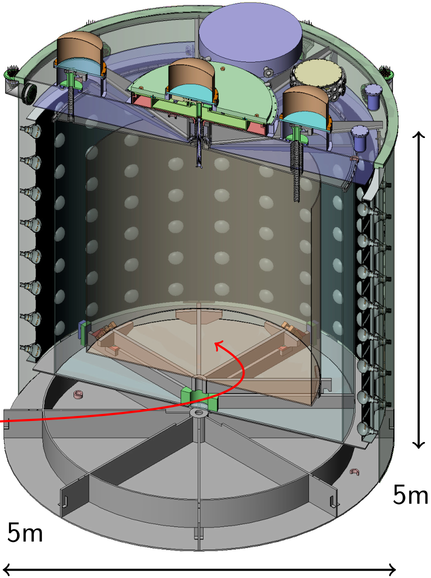
$\bar{\nu}$ Detector (AD) Module

- Automatic calibration units
- Stainless steel vessel
- 192 8" PMTs in mineral oil buffer, black radial shield
- Outer acrylic vessel
- Liquid scintillator γ-catcher
- Inner acrylic vessel



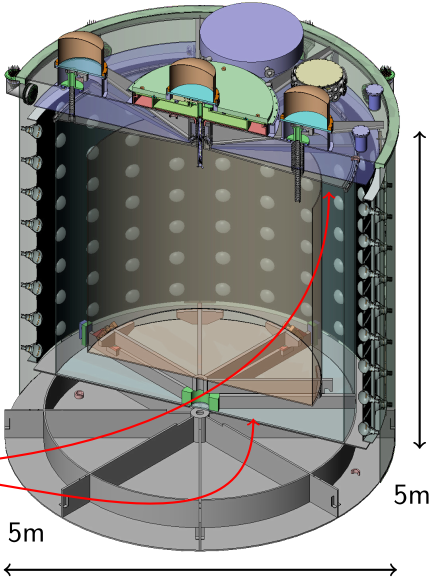
$\bar{\nu}$ Detector (AD) Module

- Automatic calibration units
- Stainless steel vessel
- 192 8" PMTs in mineral oil buffer, black radial shield
- Outer acrylic vessel
- Liquid scintillator γ-catcher
- Inner acrylic vessel
- 20 ton Gd doped LS

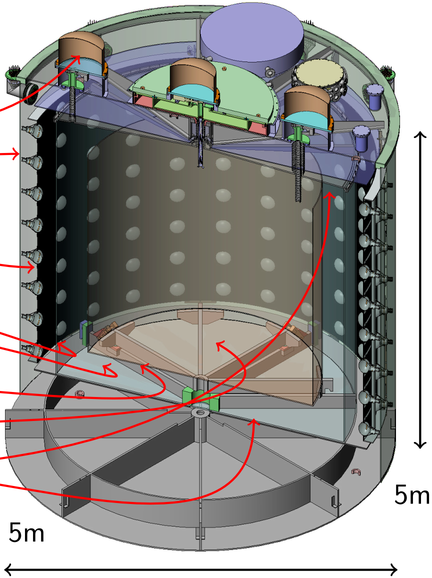


$\bar{\nu}$ Detector (AD) Module

- Automatic calibration units
- Stainless steel vessel
- 192 8" PMTs in mineral oil buffer, black radial shield
- Outer acrylic vessel
- Liquid scintillator γ-catcher
- Inner acrylic vessel
- 20 ton Gd doped LS
- Top/bottom reflectors

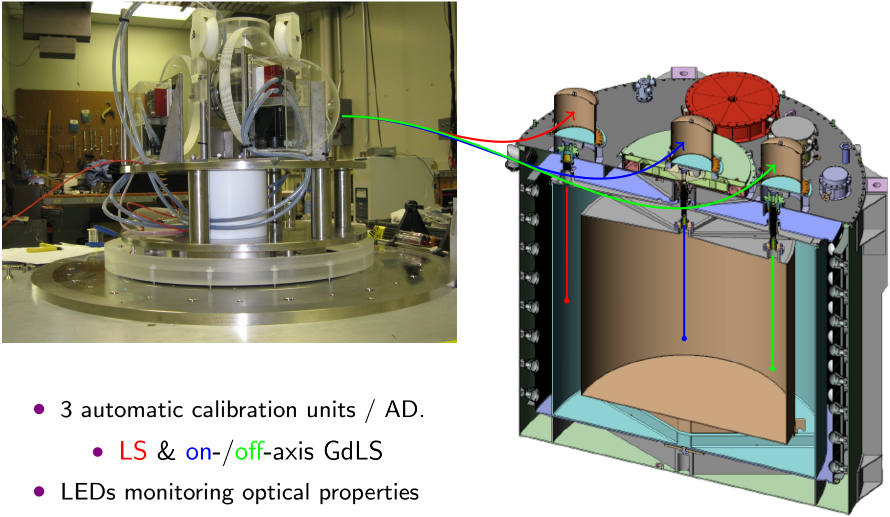


$\bar{\nu}$ Detector (AD) Module



- Automatic calibration units
- Stainless steel vessel
- 192 8" PMTs in mineral oil buffer, black radial shield
- Outer acrylic vessel
- Liquid scintillator γ-catcher
- Inner acrylic vessel
- 20 ton Gd doped LS
- Top/bottom reflectors

Calibration

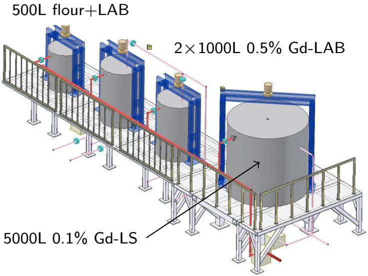


- 3 automatic calibration units / AD.
    - LS & on-/off-axis GdLS
- LEDs monitoring optical properties
- Radioactive sources fix energy
- Additional “free” spallation neutrons

Gd – Liquid Scintillator

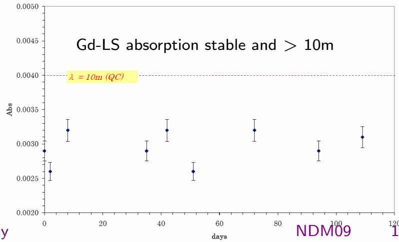
- Require 200 ton 0.1% gadolinium-loaded liquid scintillator (Gd-LS).

4 ton test batch 2009/03



0.1% Gd-LS in 5000L tank.

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



Gd-LS absorption stable and > 10m

Outline

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The Daya Bay Experiment

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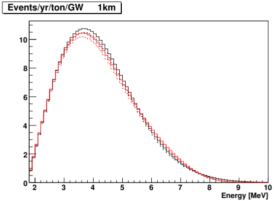
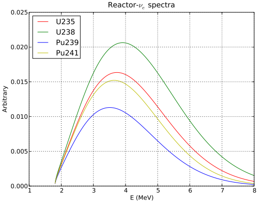
Reactor Neutrino Source

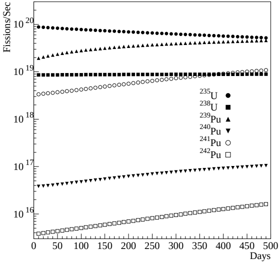


Event rate per year per ton per GW @ 1km. (**Vogel & Engle** and Huber & Schwetz flux models)



Flux × cross section shapes for major fission sources.

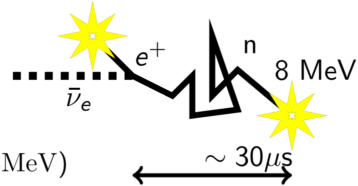
$1\text{GW}_{\text{thermal}} \approx 2 \times 10^{20} \frac{\bar{\nu}_e}{sec}$



Fission rates during burnup Palo Verde (L.H.Miller Ph.D. Thesis).

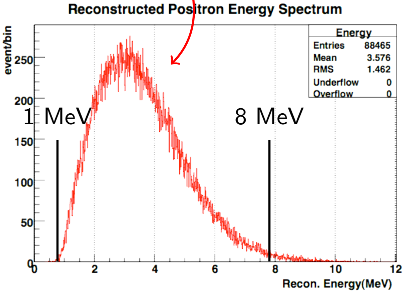
Will receive information from power plant officials. We assume 2%/2% (corr./uncorr) uncertainty in the power per core (can actually handle much higher uncertainties) and 30 cm uncorr. uncertainties in the core positions.

Signal: Inverse β-Decay Signature

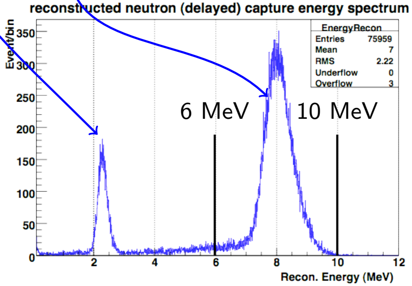


$$\bar{\nu}_e + \mathrm{p} \to e^+ + \mathrm{n}$$

0.3 b	$\mathrm{n} + \mathrm{p} \to \mathrm{D} + \gamma(2.2\mathrm{MeV})$
50 Kb	$\mathrm{n} + \mathrm{Gd} \to \mathrm{Gd}^* \to \mathrm{Gd} + \gamma's(8\mathrm{MeV})$



Prompt positron spectrum



30 μs delayed neutron capture spectrum

Events per day per 20 ton AD module	
Daya Bay near site	840
Ling Ao near site	760
Far site	90

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	760	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

Controlling Systematic Uncertainties

One could try to dead reckon far event rate:

$$N = N_{\mathrm{P}} \int \epsilon \sigma \Phi(E, L) \mathrm{P}(\nu_e \rightarrow \nu_e | E, L) dE$$

But, many uncertainties cancel by doing a relative measurement.
Consider the measured far/near event rate ratio at one energy:

$$\frac{N_f}{N_n} = \left(\frac{N_{\mathrm{P},f}}{N_{\mathrm{P},n}}\right) \left(\frac{L_n}{L_f}\right)^2 \left(\frac{\epsilon_f}{\epsilon_n}\right) \left(\frac{\mathrm{P}(\nu_e \rightarrow \nu_e | E, L_f)}{\mathrm{P}(\nu_e \rightarrow \nu_e | E, L_n)}\right)$$

Proton number ratio

- Flow & mass measurements
- N/F module pairs filled from same batch
- 0.3% uncertainty

Detector efficiency ratio

- Calibration systems
- 0.2% uncertainty
- Potential for detector swapping

Probability ratio

- Gives $\sin^2(2\theta_{13})$

Additional complexity due to cross flux in near detectors from distant reactors.

Estimated Systematic Uncertainties

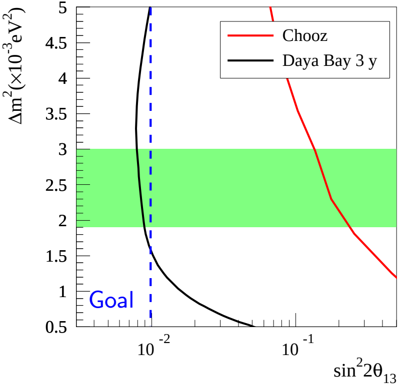
Detector Uncertainties (relative, %):

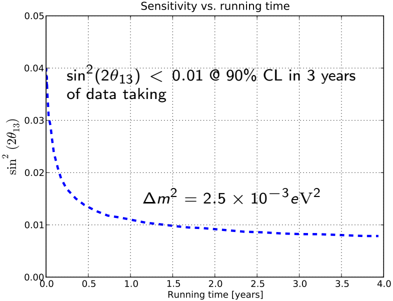
Source of uncertainty		Conservative	Goal
# protons		0.3	0.1
Detector Efficiency	Energy cuts	0.2	0.1
	Position cuts	0.0	0.0
	Time cuts	0.1	0.03
	H/Gd ratio	0.1	0.1
	n multiplicity	0.05	0.05
	Trigger	0.01	0.01
	Live time	<0.01	<0.01
Total detector-related uncertainty		0.38%	0.18%

Reactor Uncertainties

Reactors online	Power	Location	Total
Daya Bay & Ling Ao I	0.035%	0.08%	0.087%
Daya Bay & Ling Ao I & II	0.097%	0.08%	0.126%

Sensitivity





Start date expected summer 2011.

Majority of sensitivity gain in first 6 months!

Outline

Context

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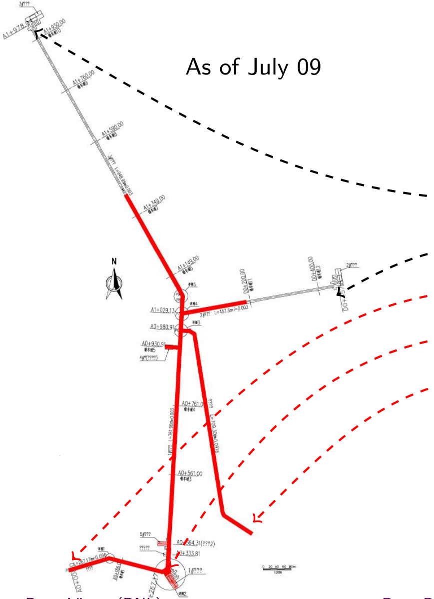
Status and Schedule

Civil Status - Excavation



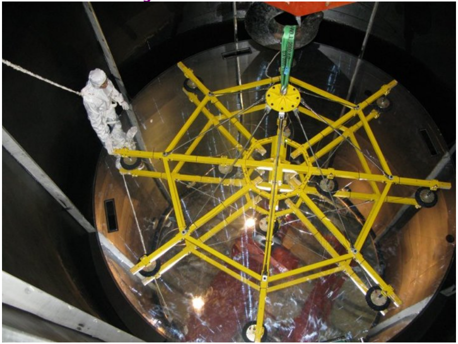
As of July 09

- Far site location
- Ling Ao near site location
- Main entrance
- Daya Bay site
- Construction entrance

Excavation marked in red.

Fabrication and Delivery of Detector Components

Assembly



Past and Future Milestones

October 2007	Ground Breaking
Spring 2008	CD3 review completed
March 2009	Surface Assembly Building occupancy
Summer 2010	Daya Bay Near Hall ready for data taking
Summer 2011	All three halls ready for data taking

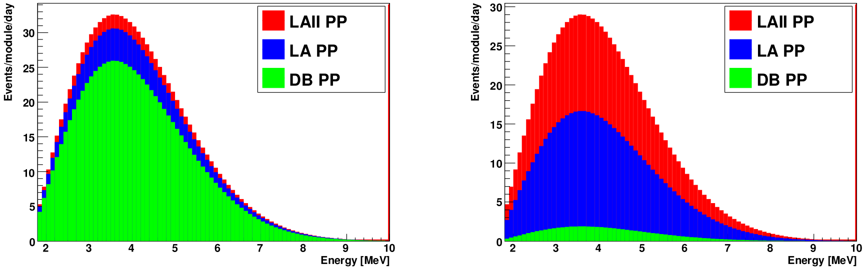
Summary

- The Daya Bay experiment is the most sensitive reactor θ_{13} experiment currently under construction.
- It is designed to reach an ultimate sensitivity to $\sin^2(2\theta_{13})$ of 0.01 @ 90% CL in three years.
- It is on track for taking initial data with one near site in one year and with all sites running in two years.

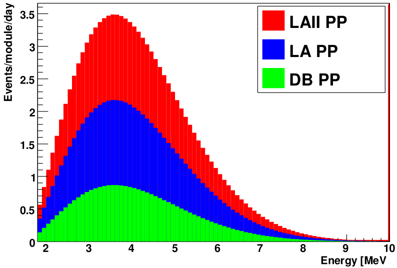
Thanks.

Backup Slides

Per site, per reactor rates (C. Lewis)

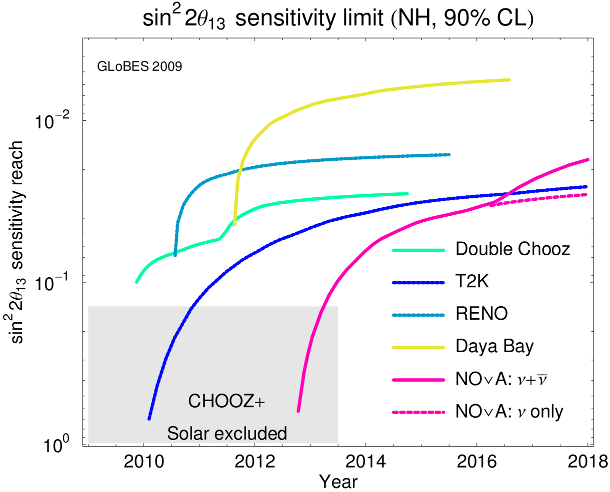


Far detector



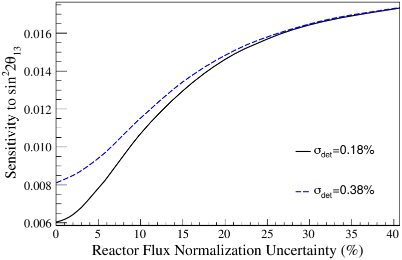
Rates per day per 20t detector module at each detector site, assuming Vogel and Engel flux and zeroth order cross sections. These plots show only the proportion of events coming from a given reactor pair, they are not corrected for any efficiencies.

Sensitivity Comparison



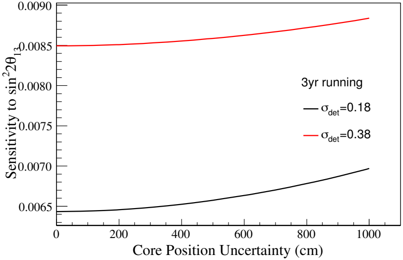
P. Huber, M. Lindner, T. Schwetz, W. Winter, arXiv:0907.1896.

Robust Against Reactor Uncertainties



Assume 2% correlated / 2% uncorrelated.

(CHOOZ and Palo Verde achieve power uncertainties of 0.6-0.7%)



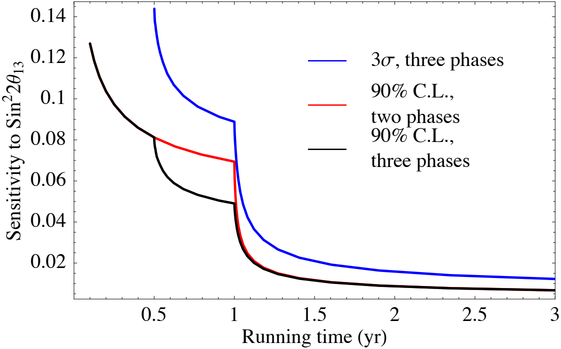
Assume 30 cm, uncorrelated.

(GLOBES study by UW group)

Near Running

GLOBES study:

Results

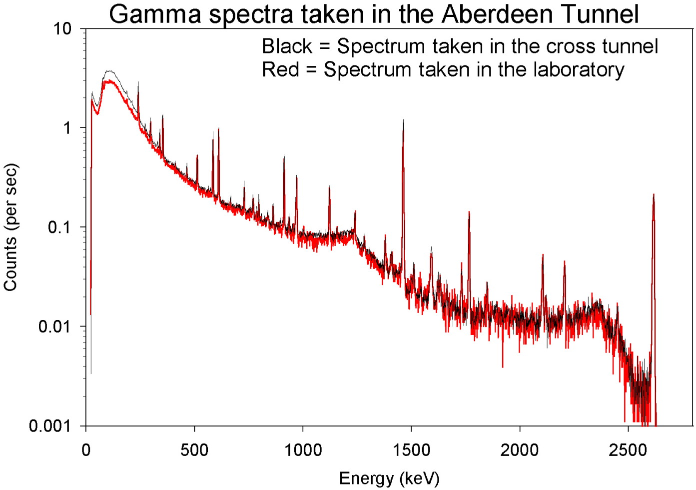


Time Dependence

0-6 months	6-12 months (A)	6-12 months (B)	1-3 years
Daya Bay near site Daya Bay and Ling Ao I	No change No change	Both near sites No change	All detectors All cores
Sensitivity=0.08	0.07	0.05	0.007

Michael McFarlane, Wisconsin   Daya Bay Sensitivity, 11 December 2008   p. 6

Aberdeen Tunnel γ Radioactivity



5 order of magnitude reduction of 1-2 MeV γs with 2.5 meter water.