A High-Precision Measurement of $\sin^2 2\theta_{13}$ with the Daya Bay Reactor Antineutrino Experiment

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Understanding Neutrino Mixing

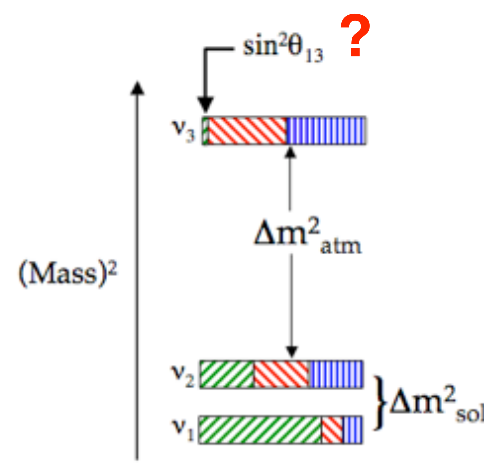
What are the elements of the neutrino mixing matrix U_{MNSP} ?

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

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

What is ν_e fraction of ν_3?

Is there $\mu-\tau$ symmetry in neutrino mixing?



$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23}$$

$$\sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E}L\right)\sin\left(\frac{\Delta m_{13}^2}{4E}L\right)\sin\left(\frac{\Delta m_{23}^2}{4E}L\right)$$

Is there ~~CP~~?

Measuring θ_{13} & Towards the Search for Leptonic CP Violation

Precise measurement of θ_{13}

- key in understanding neutrino mixing

– θ_{13} and θ_{23} are 2 of the 26 parameters of the SM, worthy of precision measurements

$$U_{MNSP} = \begin{pmatrix} 0.8 & 0.5 & U_{e3} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

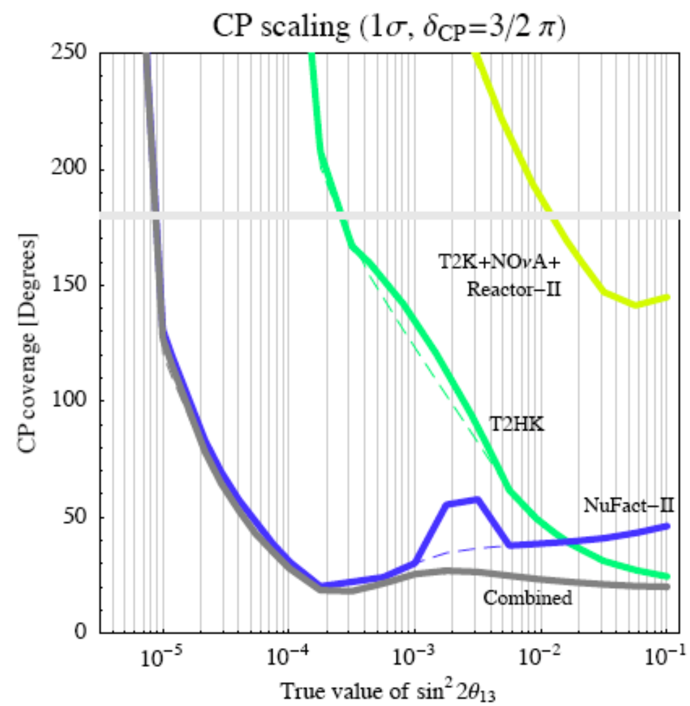
Synergy of reactor + accelerator experiments (NOvA, T2K)

- resolves θ_{23} degeneracy

- early indications of mass hierarchy

- constraints on δ_{CP}

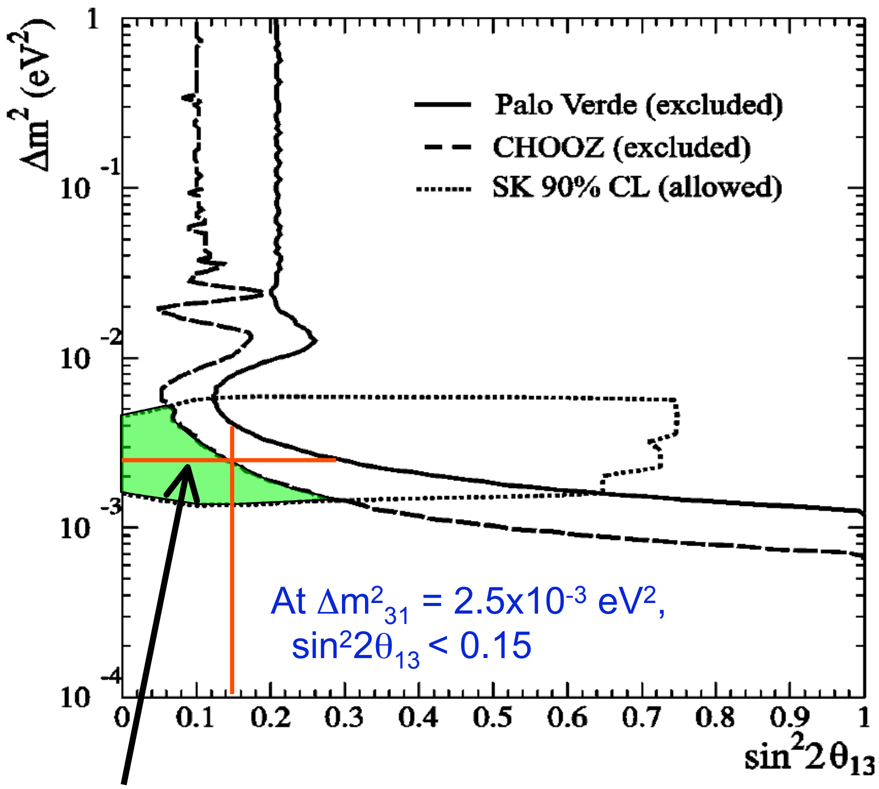
-with enhanced beam rates NOvA+T2K will have good coverage for $\sin^2 2\theta_{13} > 0.02\text{-}0.03$



Reactor experiments set the scale for future studies.

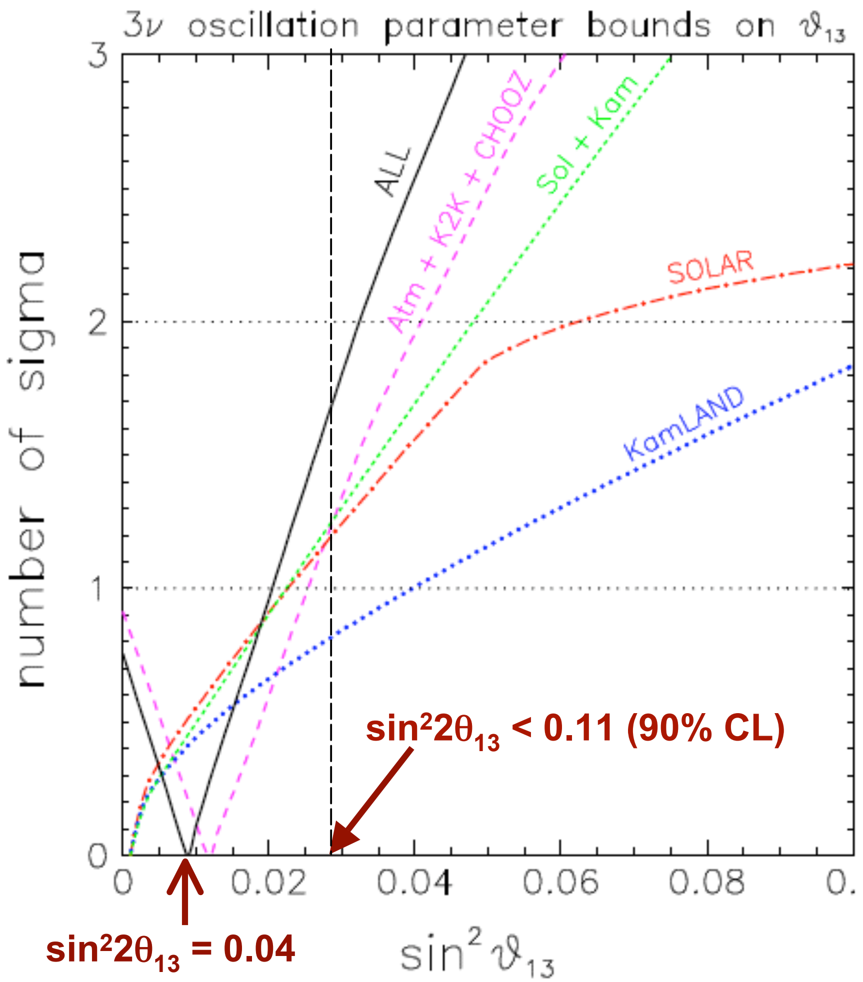
Current Knowledge of θ_{13}

Direct search



allowed region

Global fit



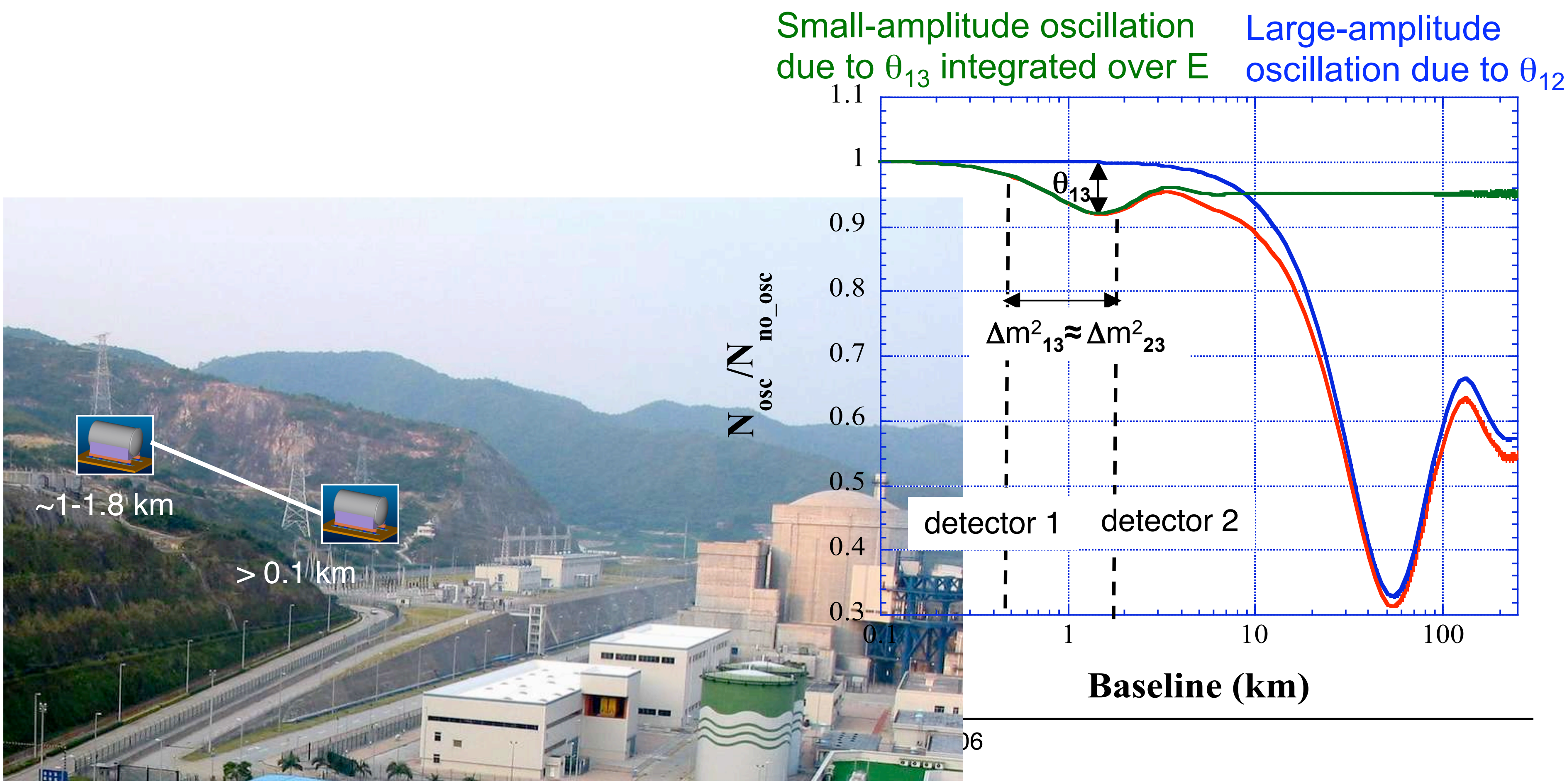
Best fit value of $\Delta m^2_{32} = 2.4\text{x}10\text{-}^{3}\ eV^2$

Ref: Fogli et al., hep-ph/0506083

Measuring θ_{13} with Reactor Antineutrinos

Search for θ_{13} in new $\bar{\nu}_e$ disappearance experiment

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



How To Reach A Precision of $\sin^2 2\theta_{13} < 0.01$?

Concepts of a Next-Generation Reactor Neutrino Experiment

High Statistics

- Powerful source of $\overline{\nu}_e$: commercial nuclear plant
- Large detectors

Optimization of Detector Locations

- Optimize baseline for best sensitivity and smaller residual reactor-related errors

Control of Systematics

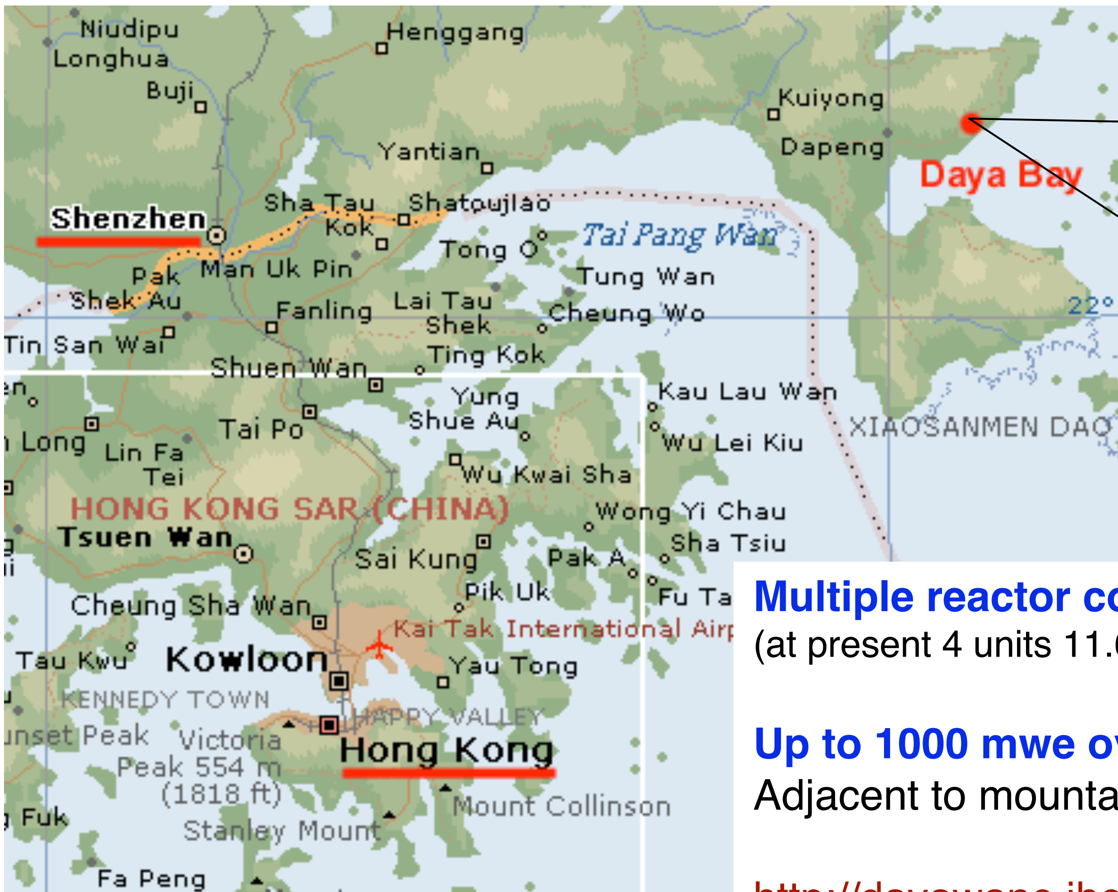
- Minimize reactor-related errors:
  - → Use multiple, "identical" near and far detectors
  - → Relative measurement
- Cancel detector systematic uncertainties:
  - → no position cuts for event selection
  - → Interchange near and far detectors
- Ensuring high detector efficiency through multi-zone antineutrino detector

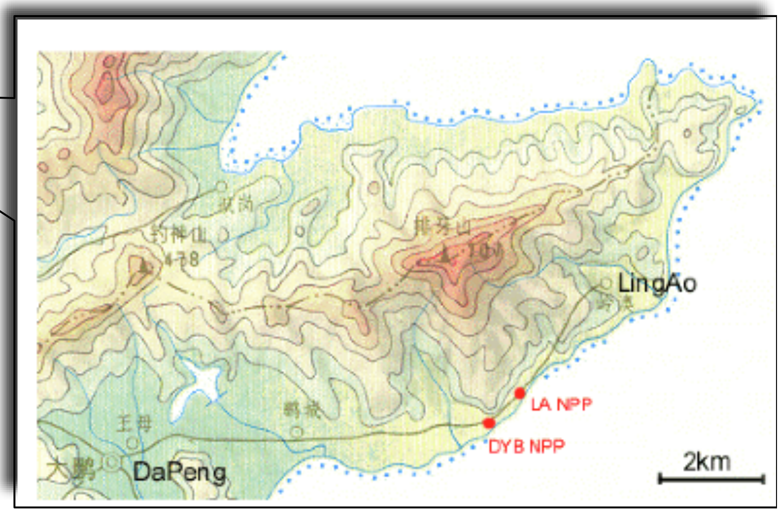
⇒ Comprehensive calibration/monitoring of detectors

Reduction of Backgrounds

- Reduce background-related uncertainties through sufficient overburden and active shielding

Daya Bay, China





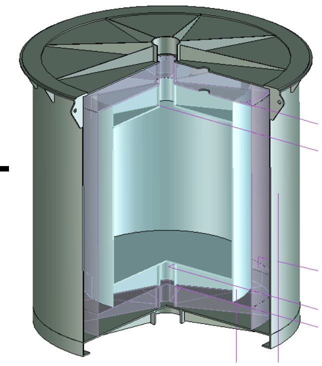
Multiple reactor cores.
(at present 4 units 11.6 $GW_{th,}$ in 2011 6 units with 17.4 GW_{th})

Up to 1000 mwe overburden nearby.
Adjacent to mountains.

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

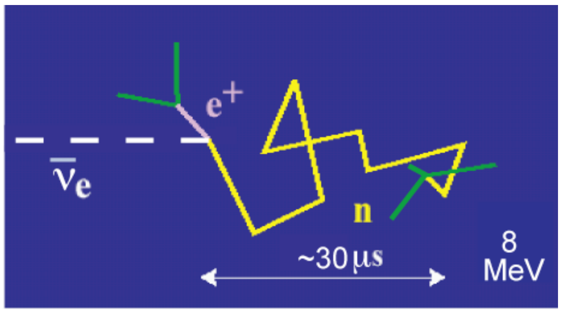
Daya Bay - Site Layout

Detecting Reactor $\bar{\nu}_e$



Inverse β-decay in 0.1% Gd-doped liquid scintillator

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

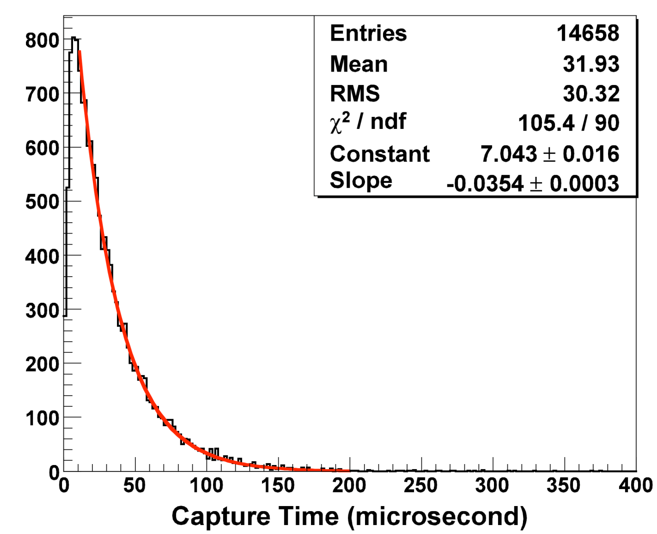


0.3b → $+ p \rightarrow D + \gamma$ (2.2 MeV) (delayed)

50,000b → $+ Gd \rightarrow Gd^*$

→ $Gd + \gamma$'s (8 MeV) (delayed)

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



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

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

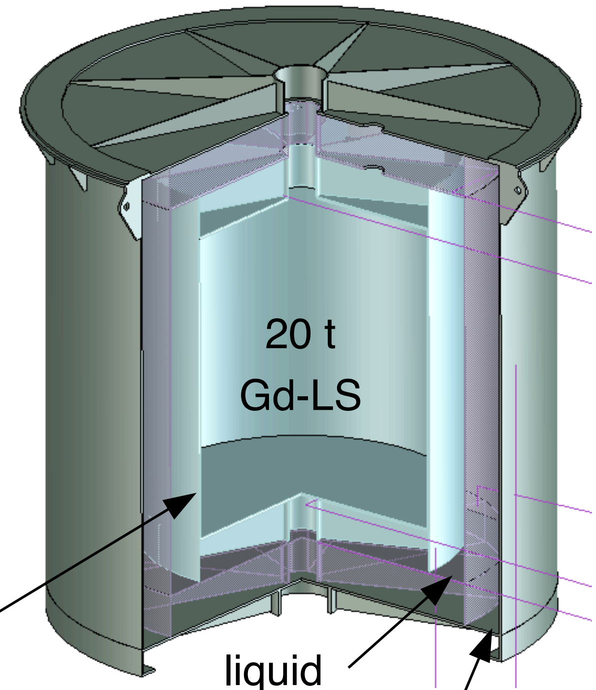
10-40 keV

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

Antineutrino Detector Design

Cylindrical 3-Zone Structure

I. **Target: 0.1% Gd-loaded liquid scintillator, 1.6m**
II. **γ-catcher: liquid scintillator, 45cm**
III. Buffer shielding: mineral oil, ~45cm

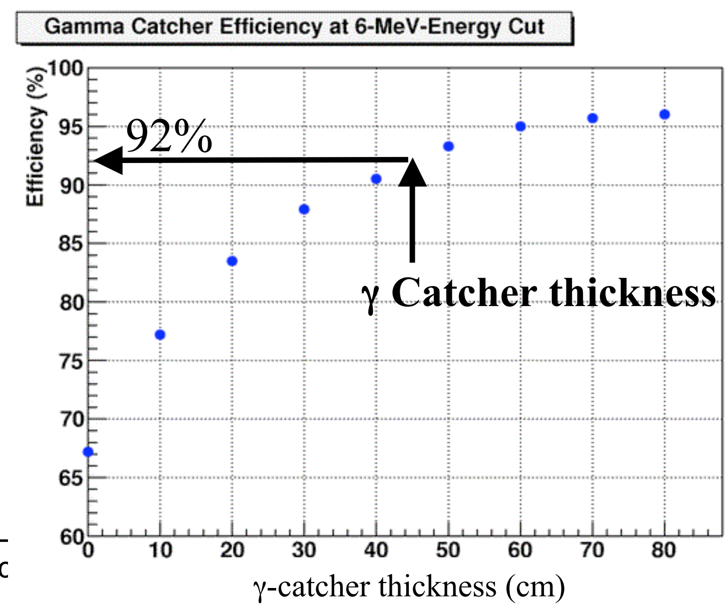


Resolution

With 224 PMT's on circumference and diffuse reflector on top and bottom:

$$\frac{\sigma}{E} \sim \frac{12.2\%}{\sqrt{E(\mathrm{MeV})}}, \quad \sigma_{\mathrm{vertex}} = 13\mathrm{cm}$$

γ Catcher Efficiency



Event Rates and Signal

Antineutrino Interaction Rate

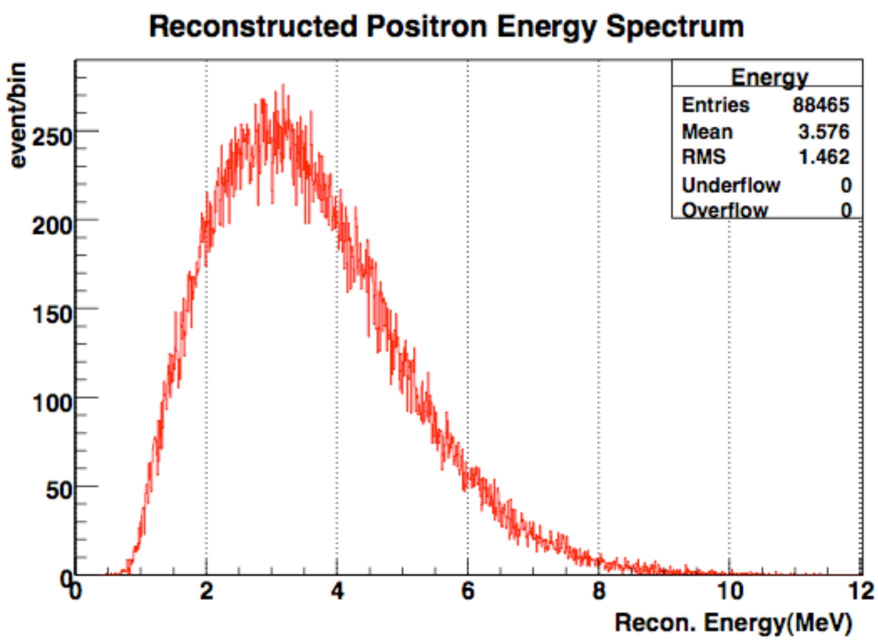
(events/day per 20 ton module)

Daya Bay near site	960
Ling Ao near site	760
Far site	90

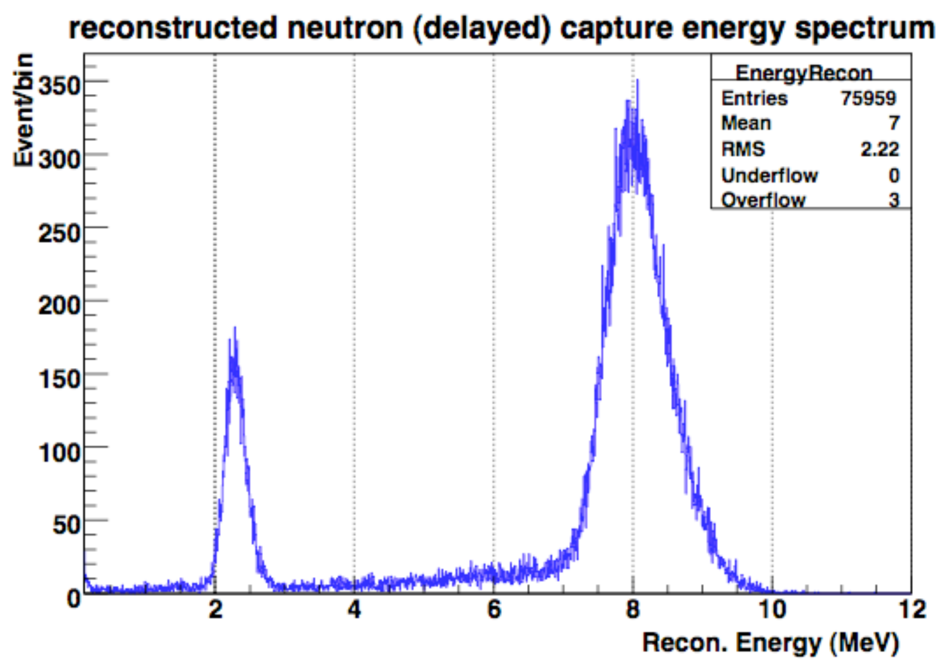
Distances to Sites (m)

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

Prompt Energy Signal



Delayed Energy Signal



Statistics comparable to single detector in far hall

Systematic Errors from the Detector

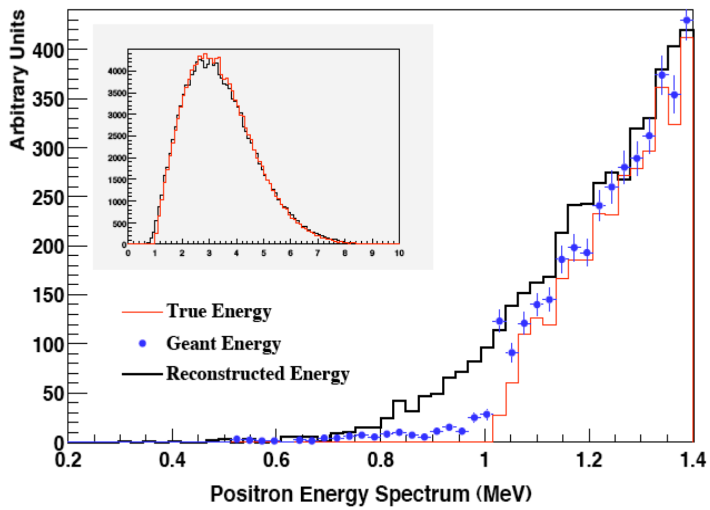
Number of Protons

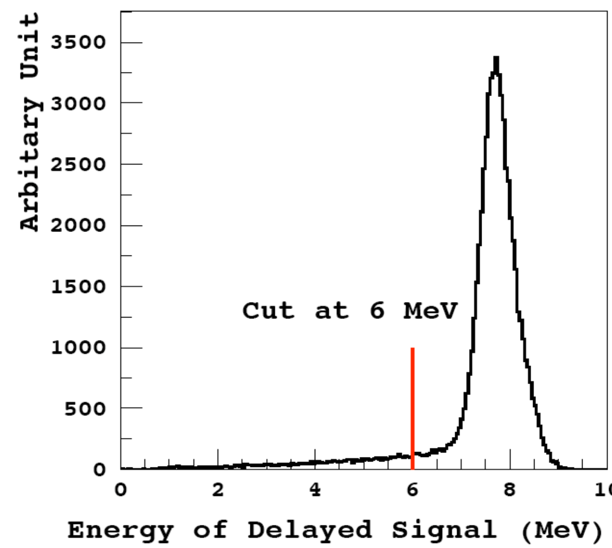
- reproducability: volume flow < 0.02%, mass flow < 0.1%
- combustion analysis, NMR or neutron beam to determine H/C ratio

Position & Time Cuts

- no position cuts: volume defined by neutron capture on Gd.
- time cuts: time window 1-200μs, precision <10ns, uncertainty < 0.03%

Energy Cuts





Low-energy threshold: Routine calibration using positron annihilation source (^{68}Ge)

Calibrate the 6 MeV cut → relative uncertainty in neutron efficiency <0.2%.

Gd/H Ratio

1% mass uncertainty causes 0.12% change in n-capture efficiency

Detector-Related Uncertainties

Absolute measurement **Relative measurement**

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%

Ref: Daya Bay CDR

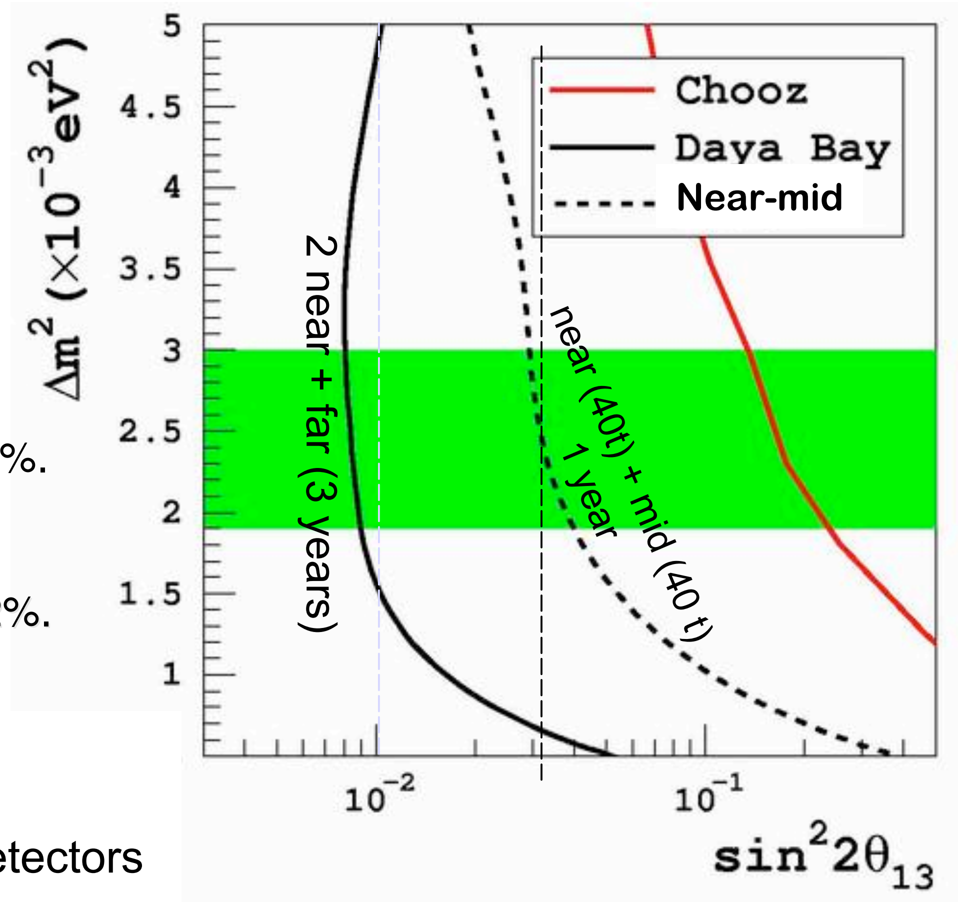
Baseline: currently achievable **relative** uncertainty without R&D
Goal: expected **relative** uncertainty after R&D
Swapping: can reduce **relative** uncertainty further

Sensitivity of Daya Bay Reactor θ_{13} Experiment

Source	Uncertainty
Reactor Power	0.087% (4 cores) 0.13% (6 cores)
Detector (per module)	0.38% (baseline) 0.18% (goal)
Signal Statistics	0.2%

Assume backgrounds are measured to < 0.2%.

Use rate and spectral shape.
Input relative detector systematic error of 0.2%.



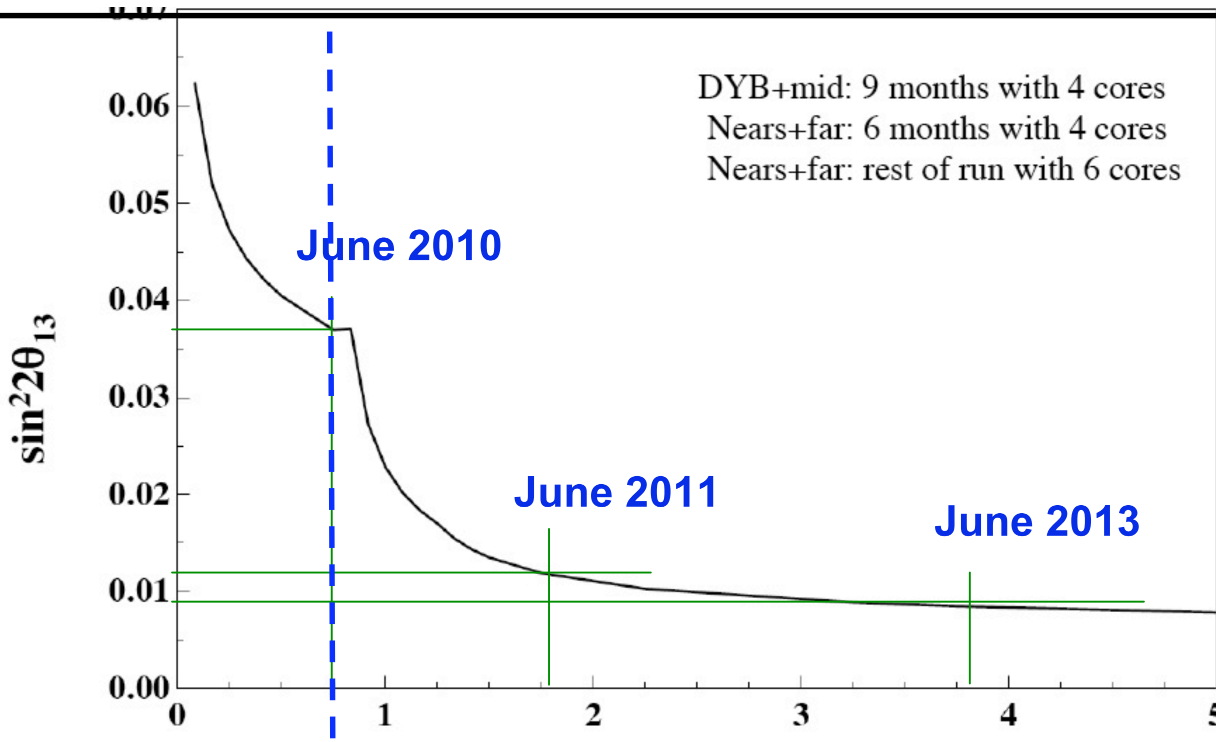
90% confidence level

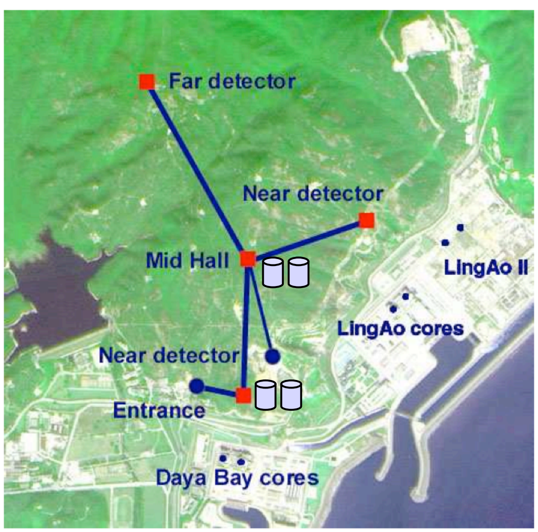
Milestones

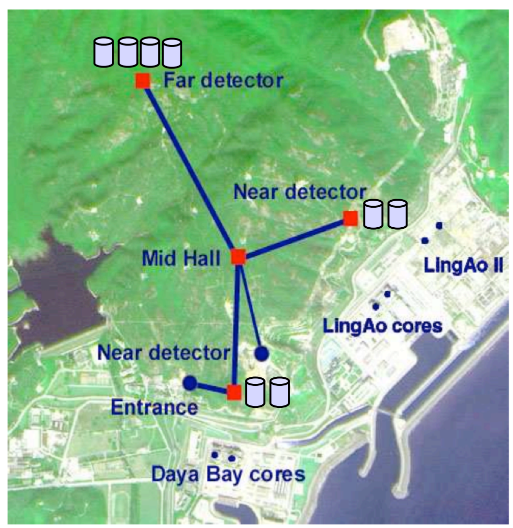
April 07 Begin civil construction
June 09 Start commissioning first two detectors
Sep 09 Begin data taking with near-mid
June 10 Begin data taking with near-far

1 year of data taking = 300 days

Daya Bay Sensitivity by Year



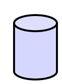




Baseline Configuration

9 months with near-mid

3 years with near-far

 20 t detector module

Daya Bay Collaboration

Europe (3)

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

North America (13)

BNL, Caltech, 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 (13)

IHEP, CIAE,Tsinghua Univ., Zhongshan Univ.,Nankai Univ., Beijing Normal Univ., Nanjing Univ., Shenzhen Univ., Hong Kong Univ., Chinese Hong Kong Univ., Taiwan Univ., Chiao Tung Univ., National United Univ.

~ 125 collaborators

[redacted]