Precise measurement of reactor antineutrino oscillations at Daya Bay

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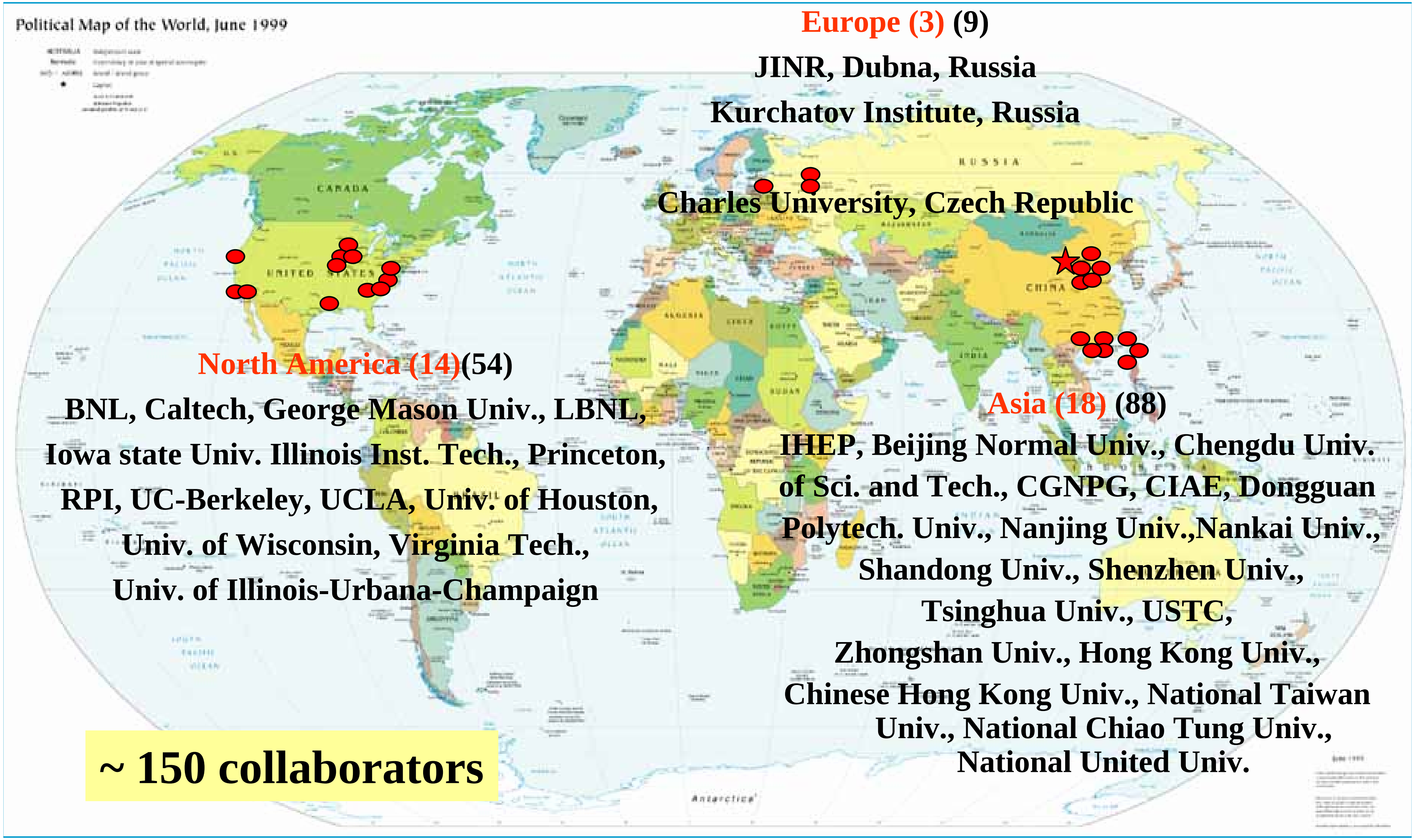
Charles University in Prague

HEP2007 Conference, Manchester, Jul. 19, 2007

The Daya Bay Collaboration



Europe (3) (9)

JINR, Dubna, Russia

Kurchatov Institute, Russia

Charles University, Czech Republic

North America (14)(54)

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 (18) (88)

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.

~ 150 collaborators

θ_{13}: The Last Unknown Neutrino Mixing Angle

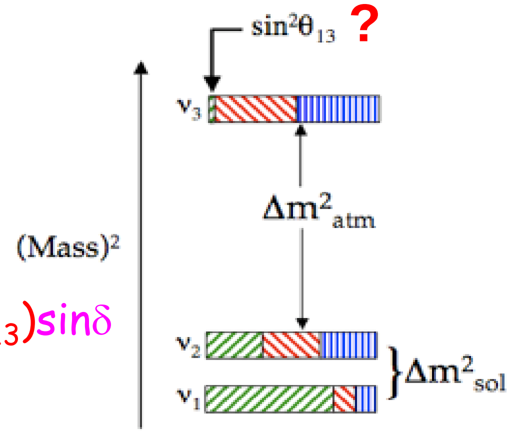
U_{MNSP} Matrix
Maki, Nakagawa, Sakata, Pontecorvo

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

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

atmospheric, accelerator	reactor, accelerator	SNO, solar SK, KamLAND	$0\nu\beta\beta$
θ_{23} = ~ 45°	θ_{13} = ?	θ_{12} ~ 32°	

- What is ν_e fraction of ν_3?
- U_{e3} is the gateway to CP violation in neutrino sector: $P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) \propto \sin(2\theta_{12})\sin(2\theta_{23})\cos^2(\theta_{13})\sin(2\theta_{13})\sin\delta$



Measuring θ_{13} Using Reactor Anti-neutrinos

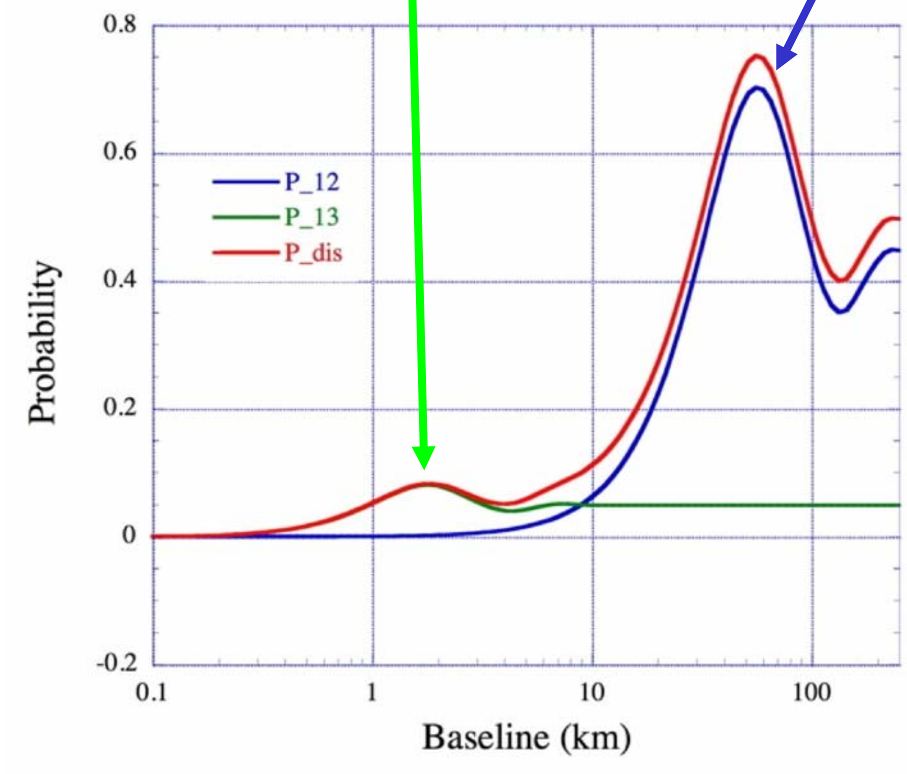
Electron anti-neutrino disappearance probability

$$P_{dis} \approx \sin^2 2\theta_{13} \cdot \sin^2\left(\frac{\Delta m^2_{13} L}{4E_\nu}\right) + \cos^4\theta_{13} \cdot \sin^2 2\theta_{12} \cdot \sin^2\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right)$$

Small oscillation due to θ_{13}
< 2 km

Large oscillation due to θ_{12}
> 50 km

Osc. prob. (integrated over E_ν) vs distance



$\bar{\nu}_e$ disappearance at short baseline(~2 km): unambiguous measurement of θ_{13}

$\sin^2 2\theta_{13} = 0.1$
$\Delta m^2_{31} = 2.5 \times 10^{-3}$ eV^2
$\sin^2 2\theta_{12} = 0.825$
$\Delta m^2_{21} = 8.2 \times 10^{-5}$ eV^2

VV1

Objective of Near Term θ_{13} Measurement

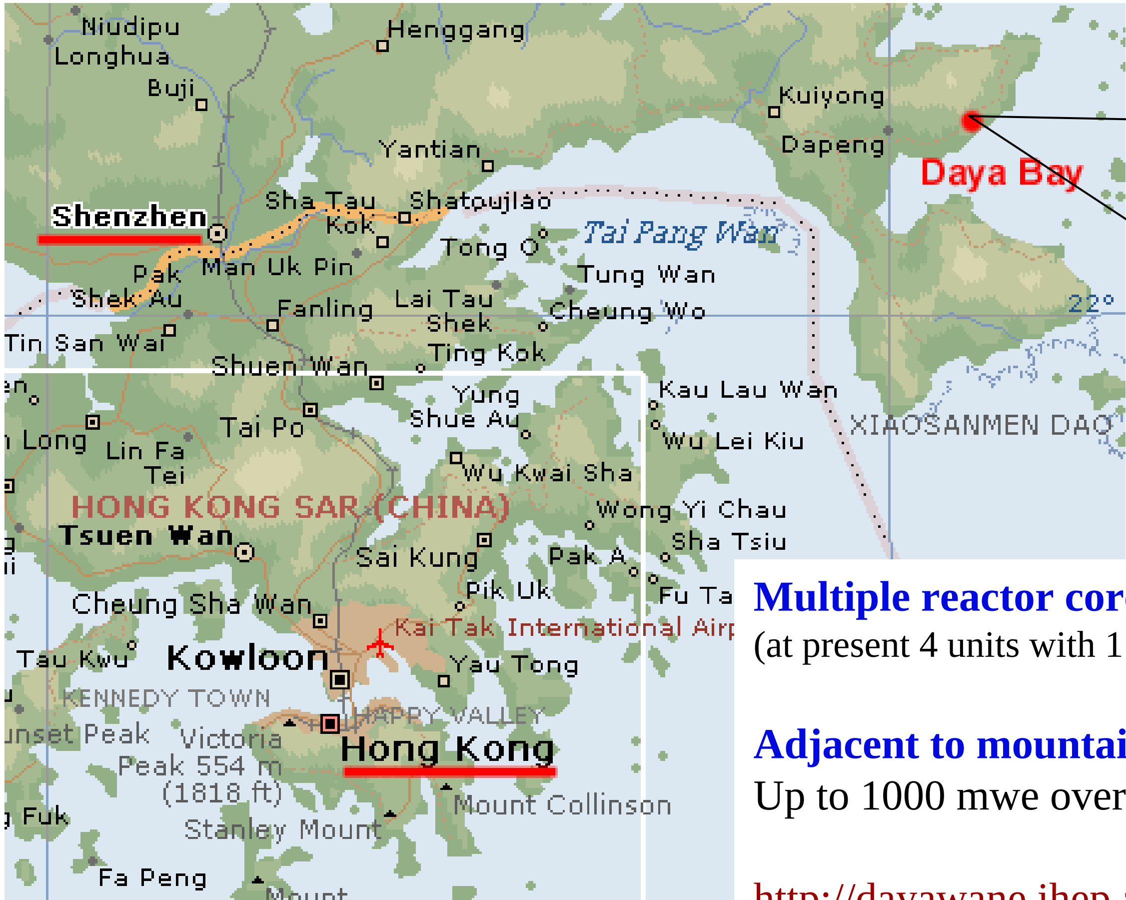
Previous best experimental limit from Chooz:
$\sin^2(2\theta_{13}) < 0.17$ ($\Delta m^2_{31} = 2.5\times10^{-3}$ eV, 90% c.f.)

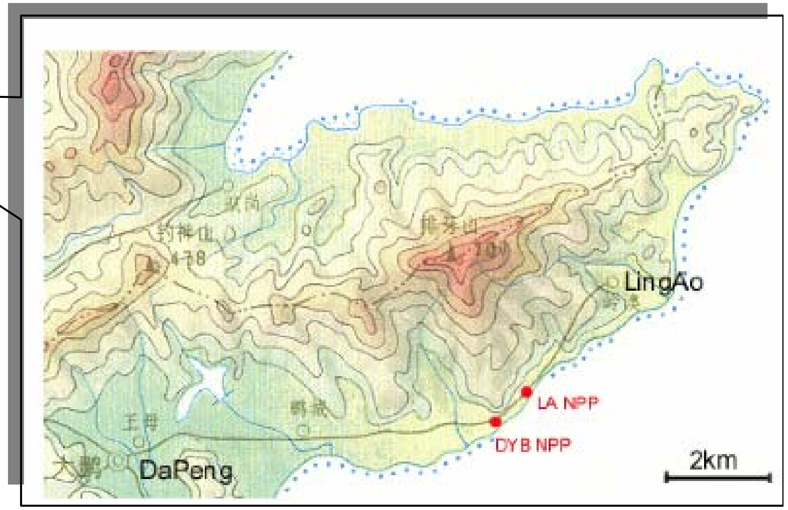
Build an experiment with sensitivity of ≤ 0.01 in $\sin^2(2\theta_{13})$

- **Increase statistics: Use powerful reactors & large target mass**
- **Suppress background:**
  - Go deeper underground
  - High performance veto detector to MEASURE the background
- **Reduce systematic uncertainties:**
  - Reactor-related:
    Utilize 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

VV1 Vit Vorobel, 2007-6-19

Daya Bay, China





Multiple reactor cores.

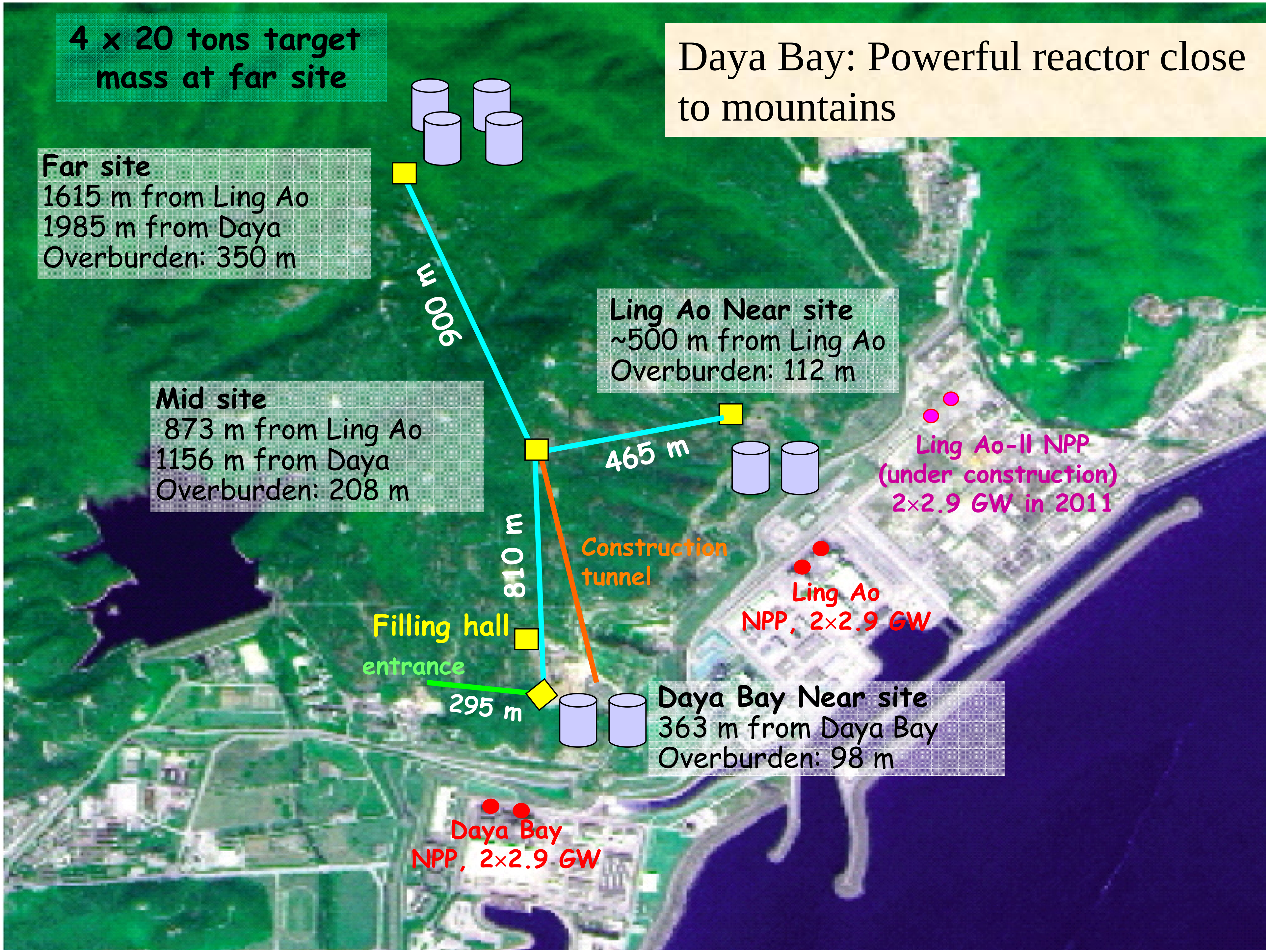
(at present 4 units with 11.6 GW_{th}; in 2011, 6 units with 17.4 GW_{th})

Adjacent to mountains.

Up to 1000 mwe overburden at the far site.

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

Daya Bay: Powerful reactor close to mountains



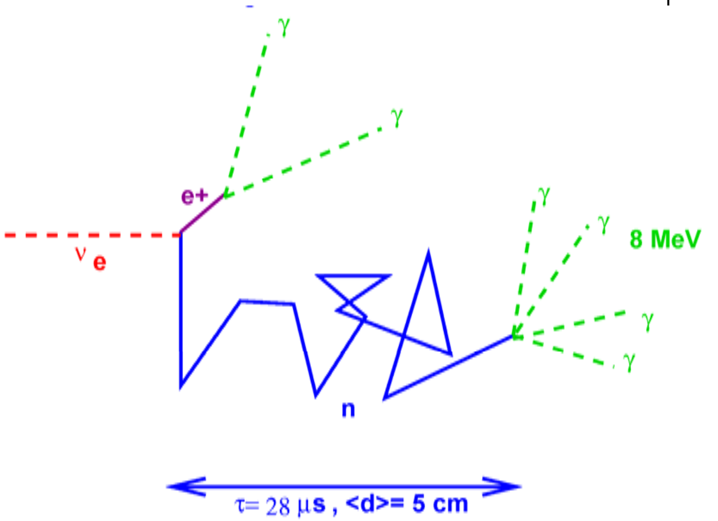
Detection of $\bar{\nu}_e$

Inverse β-decay in Gd-doped liquid scintillator:

$$\overline{\nu_e} + p \rightarrow e^+ + n$$

$\rightarrow + p \rightarrow D + \gamma(2.2\ MeV)$ (t~180 μs) 0.3b

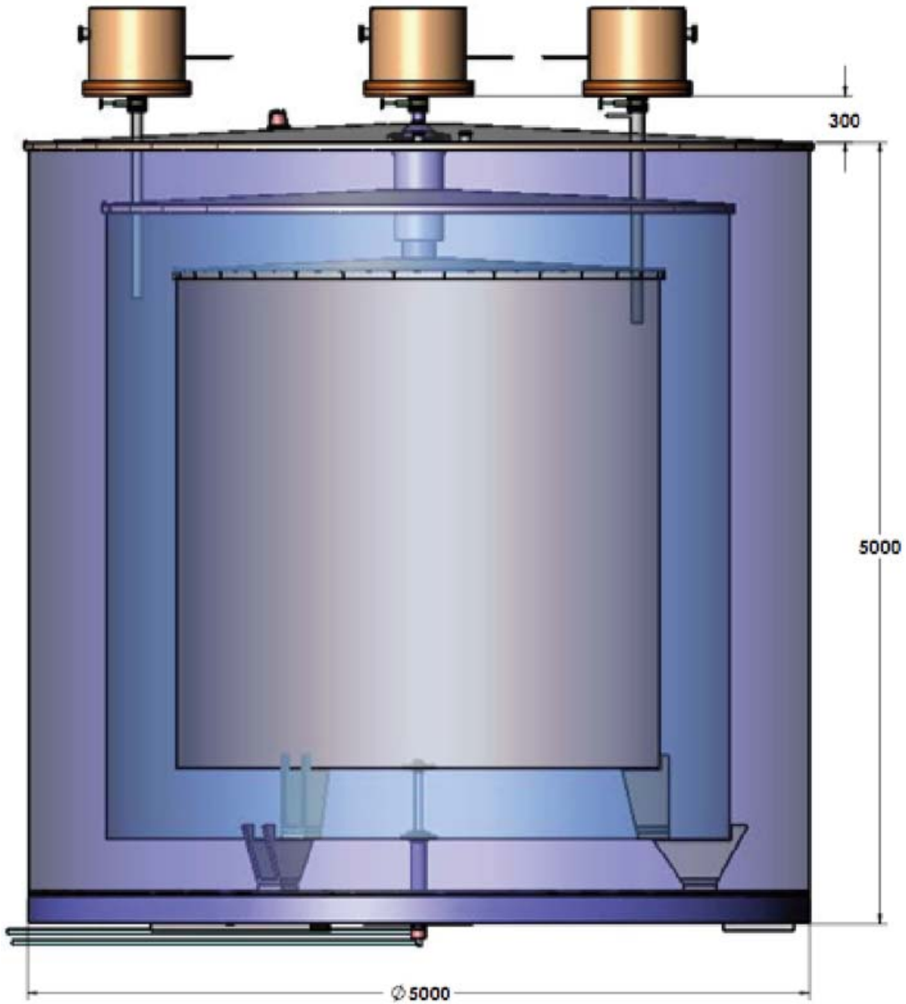
$\rightarrow + Gd \rightarrow Gd^* \rightarrow Gd + \gamma\text{'s}(8\ MeV)$ (t~30 μs) 50,000b



Time, space and energy-tagged signal
⇒ suppress background events.

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

Antineutrino Detector



Cylindrical 3-Zone Structure separated by acrylic vessels:

- **I. Target: 0.1% Gd-loaded liquid scintillator, diameter=height= 3.1 m, 20 ton**
- **II. γ-catcher: liquid scintillator, 42.5 cm thick**
- **III. Buffer shielding: mineral oil, 48.8 cm thick**

With 192 PMT's on circumference and reflective reflectors on top and bottom:

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

Inverse-beta Signals

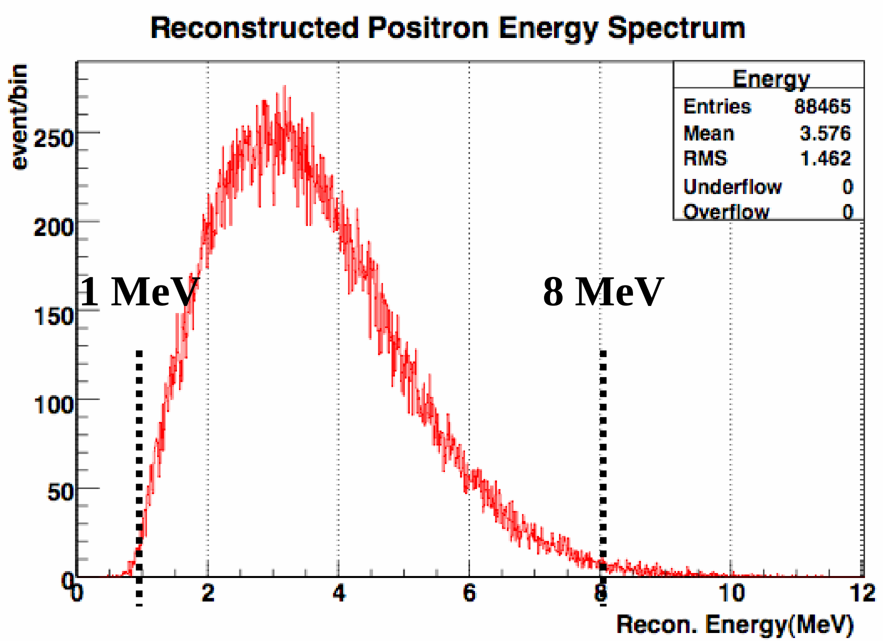
Antineutrino Interaction Rate (events/day per 20 ton module)	
Daya Bay near site	960
Ling Ao near site	760
Far site	90

E_{e+}("prompt") $\in$[1,8] MeV

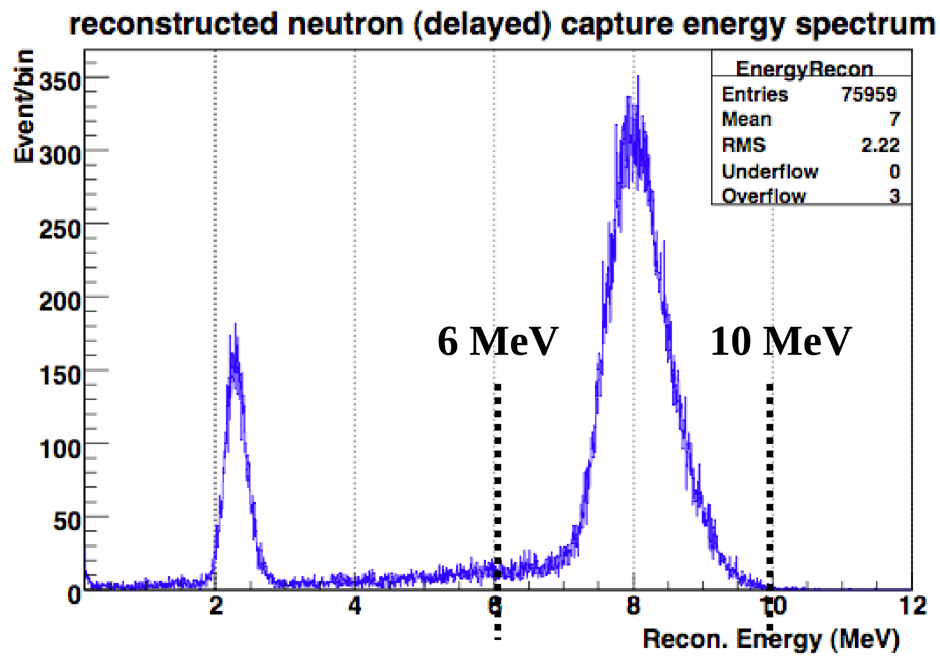
$E_{n\text{-}cap}$ ("delayed") $\in$ [6,10] MeV

$t_{delayed}$-t_{prompt} $\in$ [0.3,200] μs

Prompt Energy Signal



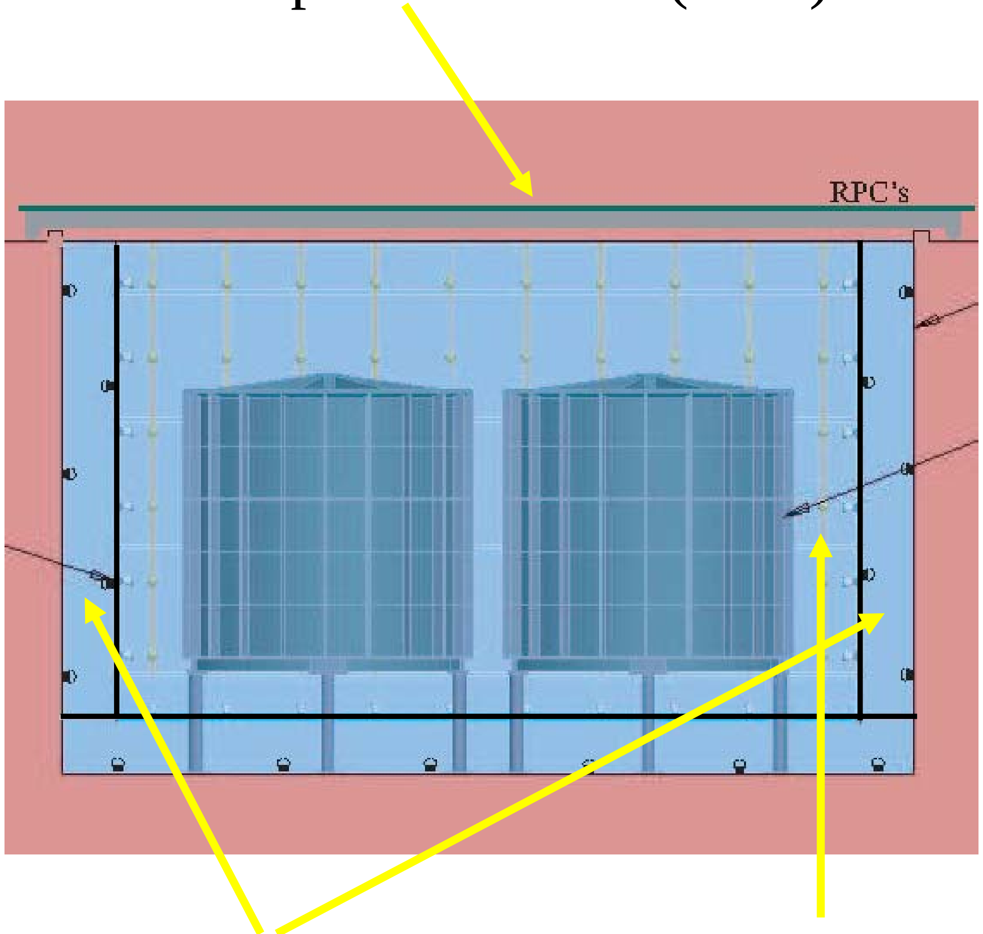
Delayed Energy Signal



MC statistics corresponds to a data taking with a single module at far site in 3 years.

Muon "Veto" System

Resistive plate chamber (RPC)



Outer water shield   Inner water shield

- Surround detectors with at least 2.5m of water, which shields the external radioactivity and cosmogenic background
- Water shield is divided into two optically separated regions (with reflective divider, 8" PMTs mounted at the zone boundaries), which serves as two active and independent muon tagger
- Augmented with a top muon tracker: RPCs
- Combined efficiency of tracker > 99.5% with error measured to better than 0.25%

Backgrounds

Background = "prompt"+"delayed" signals that fake inverse-beta events

Three main contributors, **all can be measured:**

Background type	Experimental Handle
Muon-induced fast neutrons (prompt recoil, delayed capture) from water or rock	>99.5% parent "water" muons tagged ~1/3 parent "rock" muons tagged
$^{9}Li/^{8}He$ ($T_{1/2}$= 178 msec, β decay w/neutron emission, delayed capture)	Tag parent "showing" muons
Accidental prompt and delay coincidences	Single rates accurately measured

Background/Signal:

	DYB site	**LA site**	**Far site**
Fast n / signal	0.1%	0.1%	0.1%
^{9}Li-^{8}He / signal	0.3%	0.2%	0.2%
Accidental/signal	<0.2%	<0.2%	<0.1%

Systematic Budget

Detector-related

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%

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

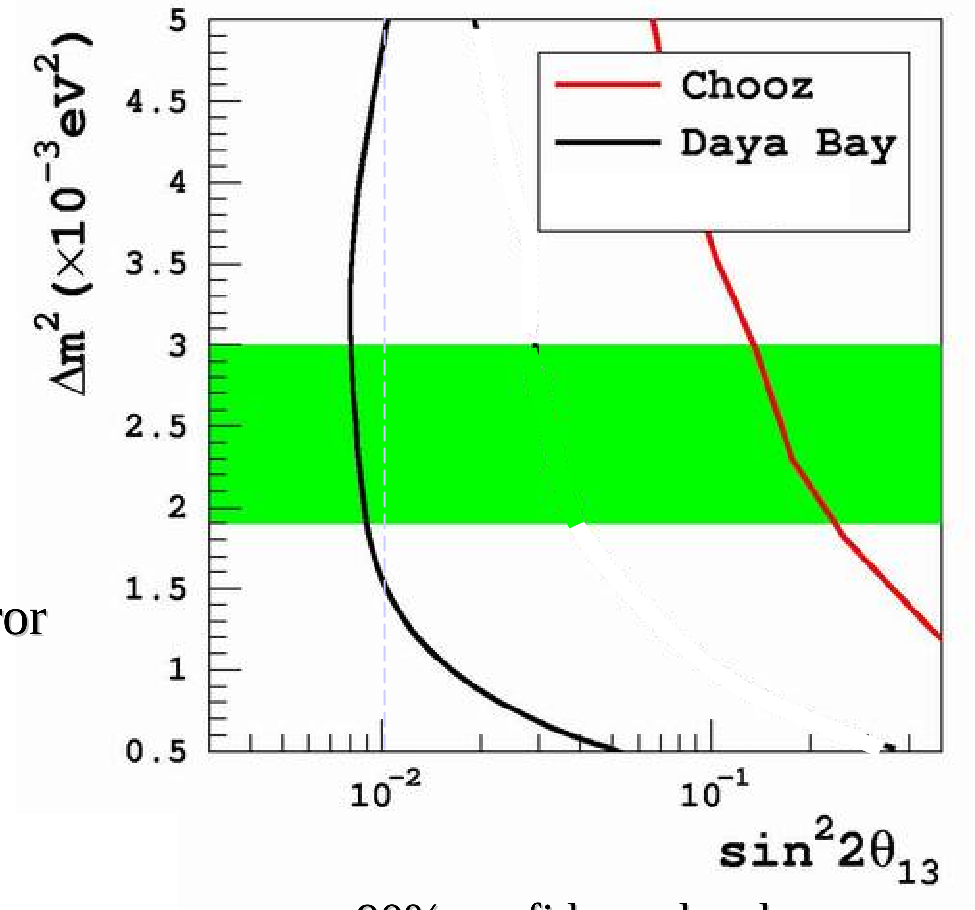
Reactor-related

Number of cores	σ_ρ(power)	σ_ρ(location)	σ_ρ(total)
4	0.035%	0.08%	0.087%
6	0.097%	0.08%	0.126%

Daya Bay Sensitivity

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

3 year of data taking

Milestones

Fall 07 Begin civil construction

June 09 Start commissioning first two detectors

June 10 Begin data taking with near-far

Daya Bay: Status and Plan

• Passed DOE scientific review	Oct 06
• Passed US CD-1 review	Apr 07
• Passed final nuclear safety review in China	Apr 07
• Began to receive committed project funding for 3 years from Chinese agencies	Apr 07
• Start civil construction	Oct 07
• Anticipate US CD-2/3a review	Oct 07
• Start data taking with 2 detectors at Daya Bay near hall	May 09
• Begin data taking with 8 detectors in final configuration	Apr 10