

To Measure θ_{13} :

The Daya Bay Experiment



Phil Rubin

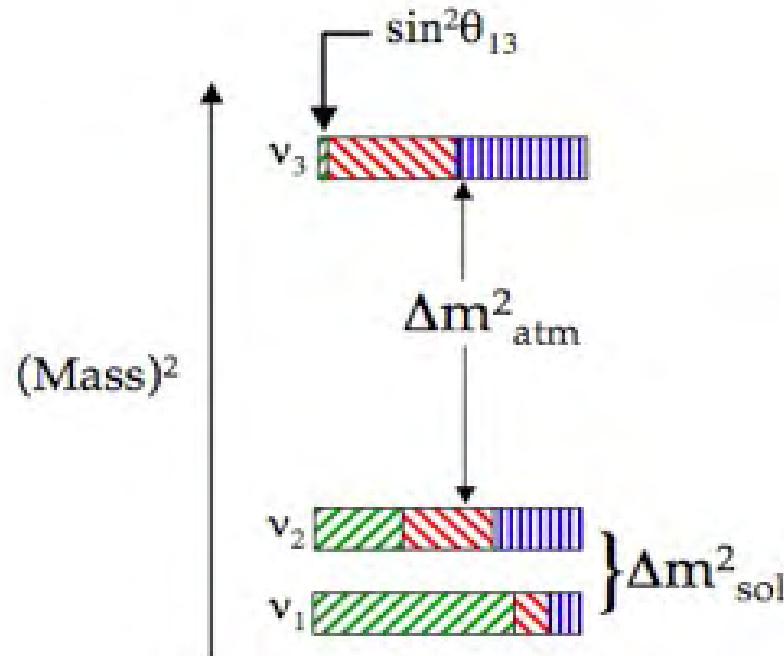


George Mason University
For the Daya Bay Collaboration

“Oscillations”

Neutrino flavors will transform into one another if:

- **Mass Eigenstates Differ**



- **Weak and Mass Eigenstates Mix**

Neutrino Mixing

Weak Eigenstate \neq Mass Eigenstate

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{Pontecorvo-Maki-Nakagawa-Sakata} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} 0.8 & 0.5 & U_{e3} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Pontecorvo–Maki–Nakagawa–Sakata

$$U_{PMNS} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix}}_{atmospheric, \text{accelerator}} \underbrace{\begin{pmatrix} \cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin \theta_{13} e^{i\delta_{CP}} & 0 & \cos \theta_{13} \end{pmatrix}}_{s-b \text{reactor}, \text{future accelerator}} \underbrace{\begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{solar, l-b \text{reactor}}$$

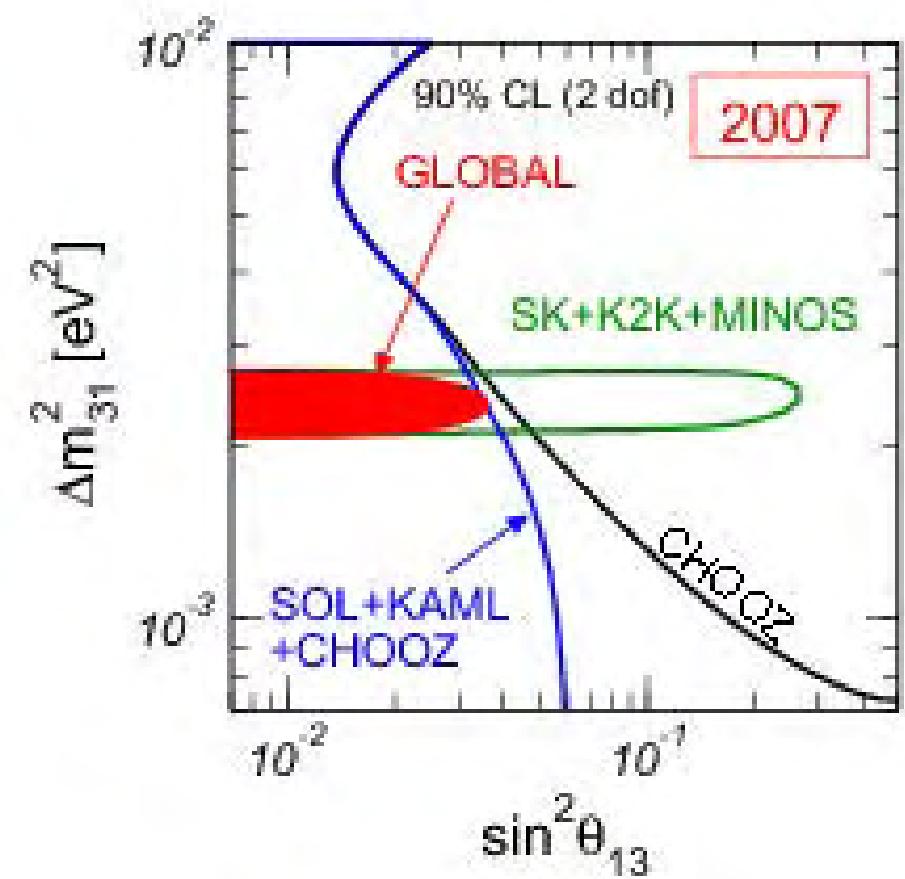
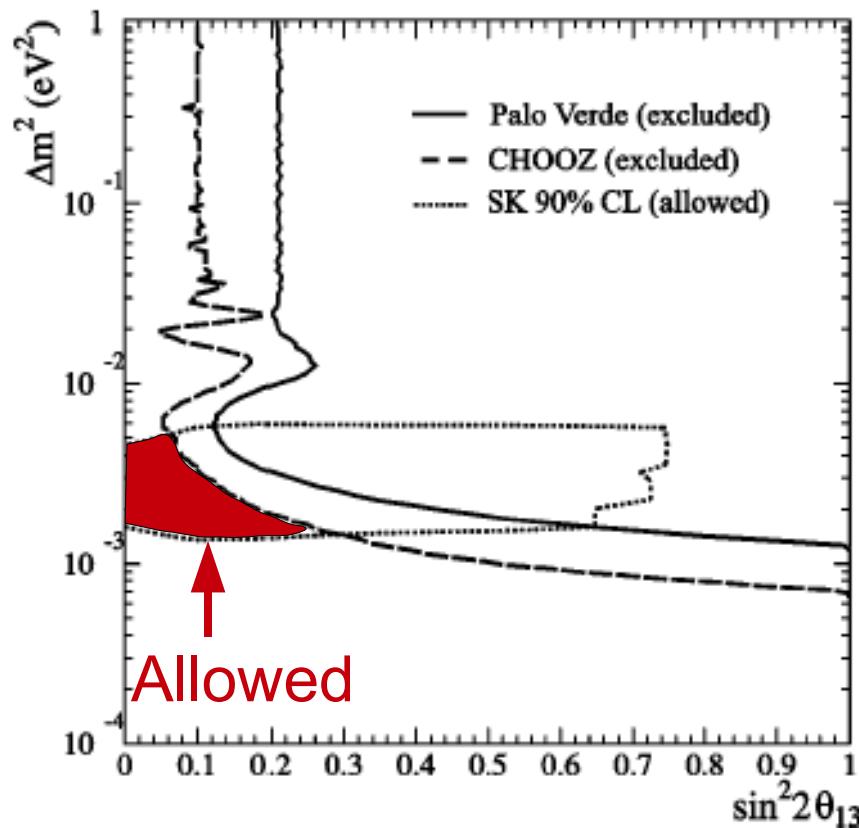
$$\theta_{23} \approx 45^\circ$$

$$\theta_{13} < 10^\circ$$

$$\theta_{12} \approx 32^\circ$$

δ_{CP} accessible only if $\theta_{13} \neq 0$
Daya Bay

Present Status



Best (90% CL) Limit from Chooz: $\sin^2 2\theta_{13} < 0.11$

Theoretical models: $\sin^2 2\theta_{13} \sim 0.001 - 0.01$

Determining θ_{13}

- At short-baseline reactors (electron anti-neutrinos):

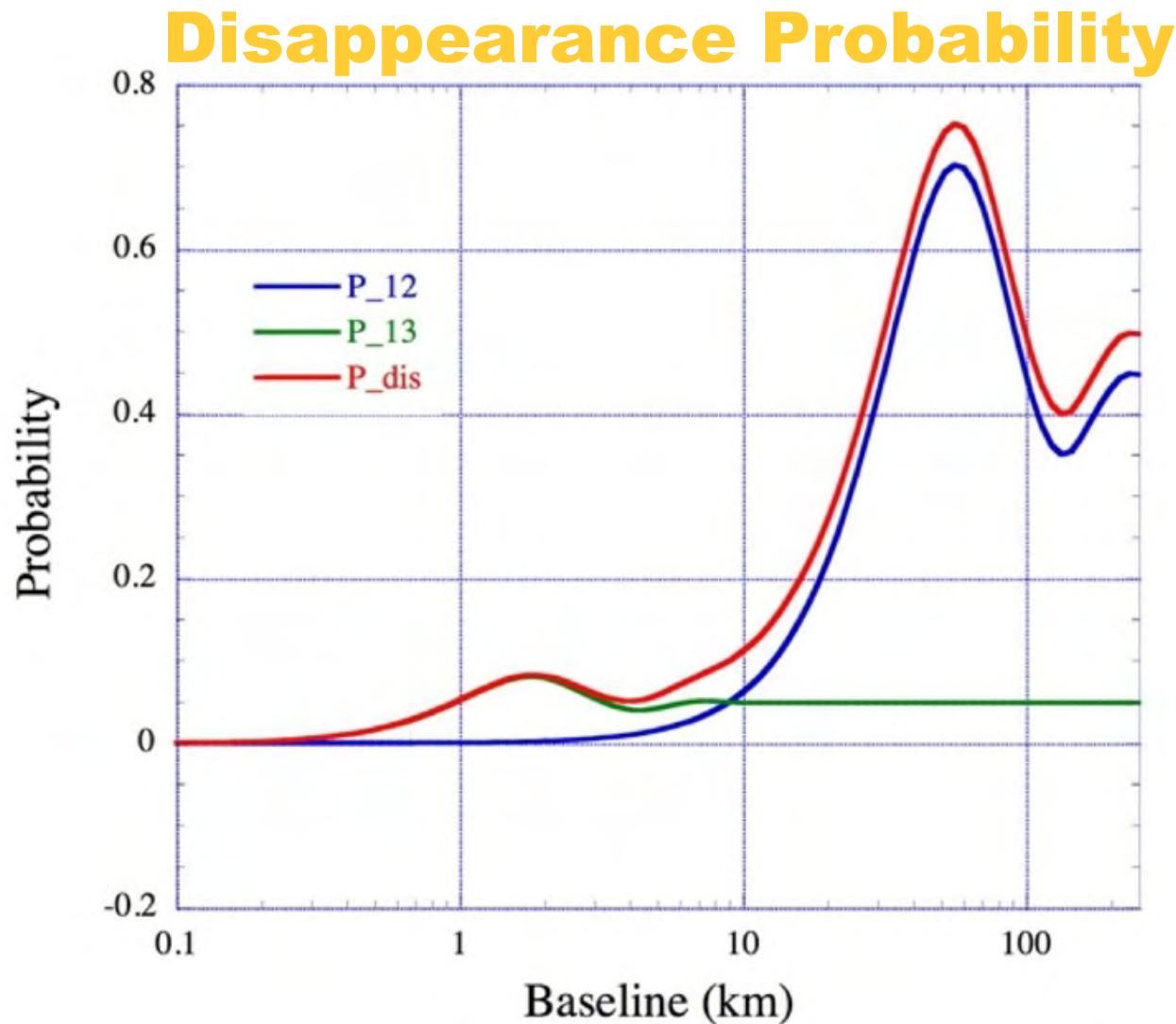
$$P_{e\tau} = \sin^2 2\theta_{13} \sin^2 (1.27 \Delta m_{13}^2 L/E) + \\ \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 (1.27 \Delta m_{12}^2 L/E)$$

- At long-baseline accelerators:

$$P_{\mu e} \approx \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 (1.27 \Delta m_{23}^2 L/E) + \\ \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 (1.27 \Delta m_{12}^2 L/E) - \\ A(\rho) \cos^2 \theta_{13} \sin \theta_{13} \sin \delta_{CP}$$

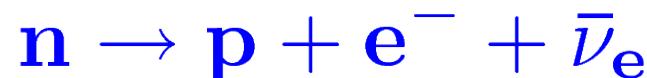
$$[m] = \text{eV} \quad [L] = \text{m} \quad [E] = \text{MeV}$$

Baseline Optimization

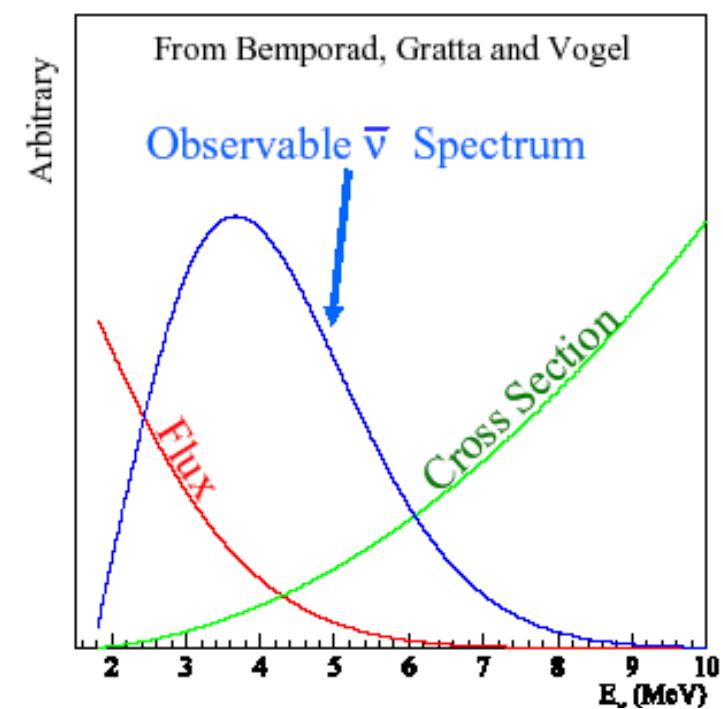
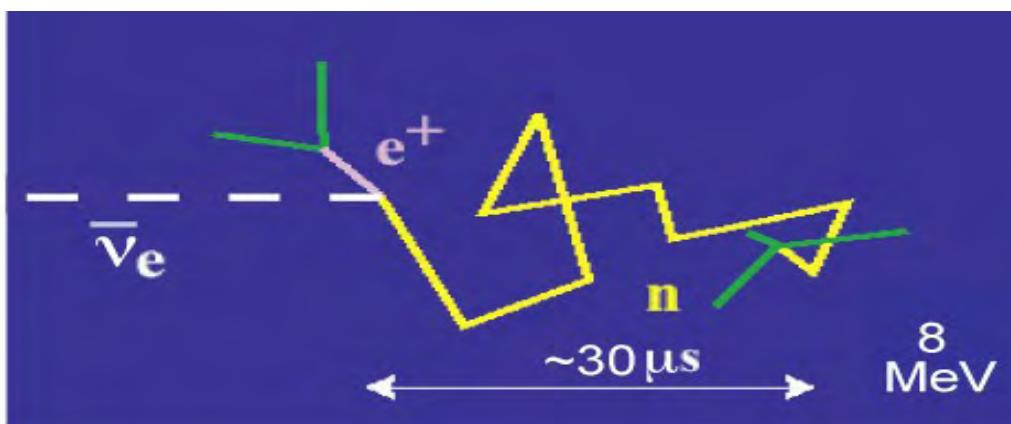


Reactor “Signal”

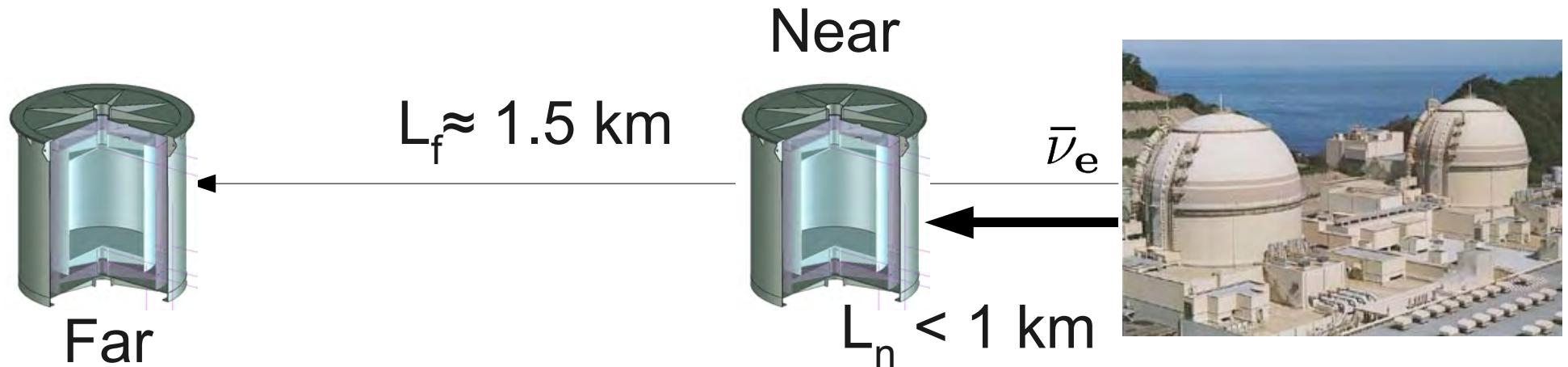
- Reactors produce electron anti-neutrinos



- Signals from inverse beta-decay



Paired Detectors



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

Rate

Target Mass

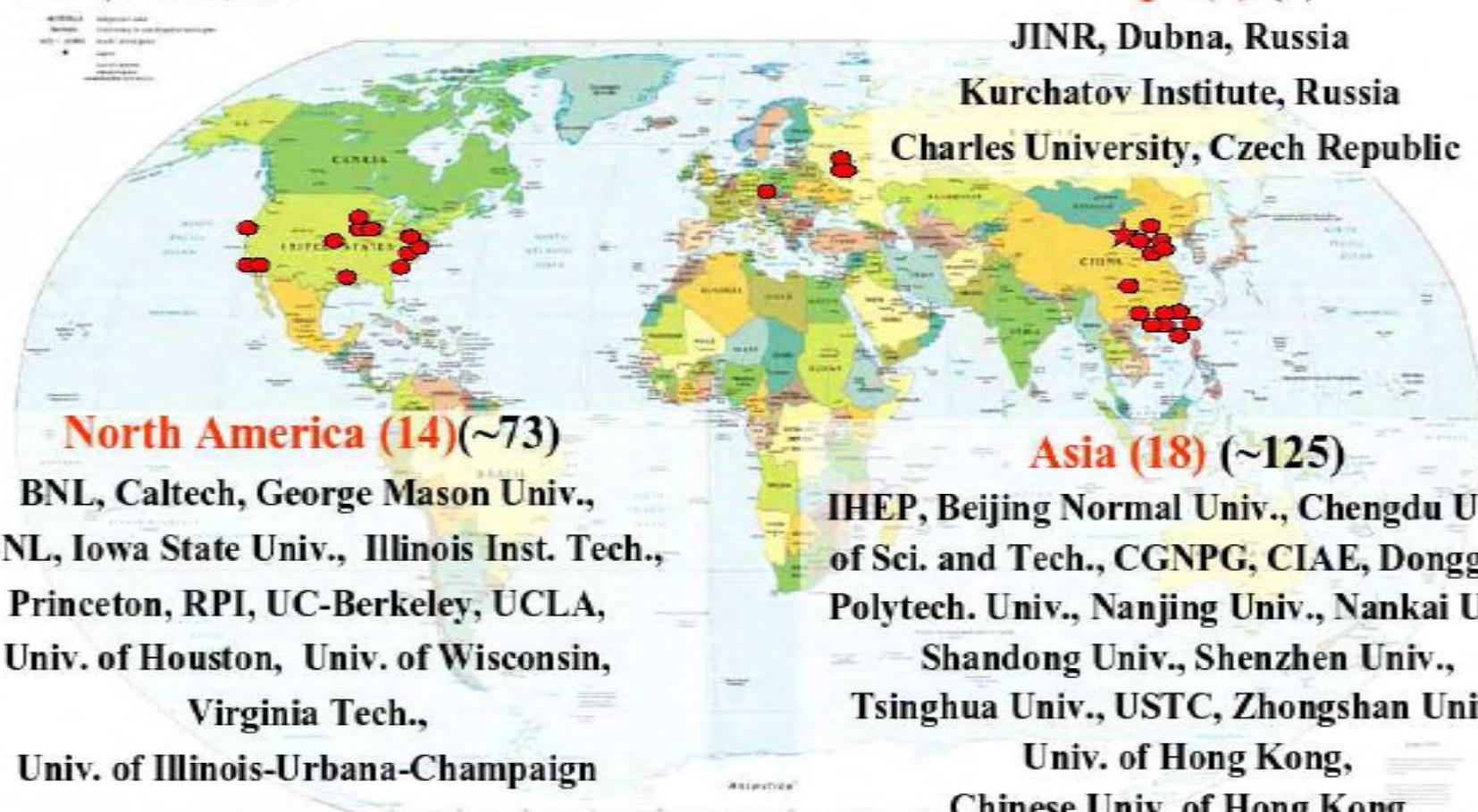
Efficiency

\downarrow

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

The Daya Bay Collaboration

Political Map of the World, June 1999



≈ 200 collaborators

Daya Bay

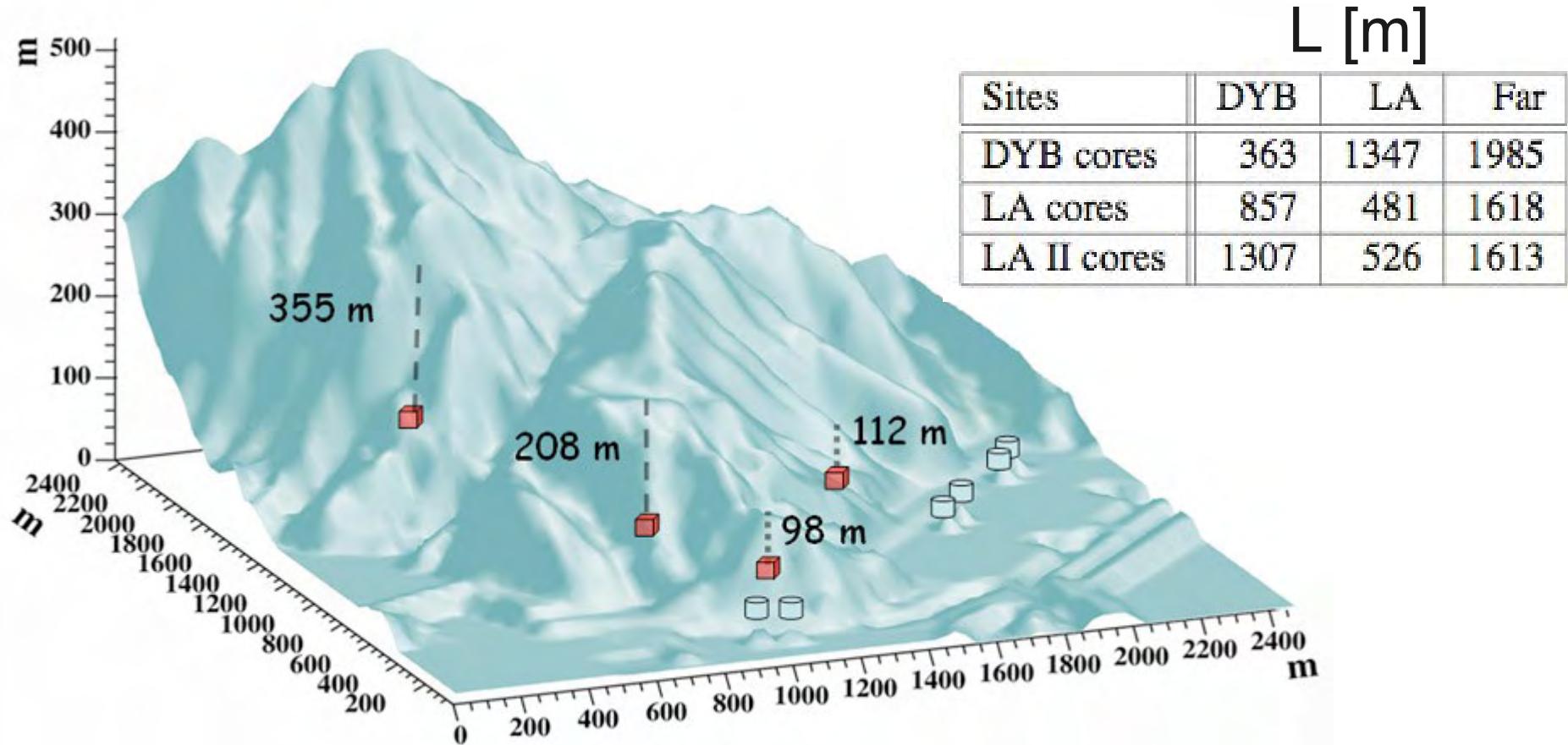


Daya Bay Nuclear Power Station



- 4 reactor cores, $11.6 \text{ GW}_{\text{th}}$
$$(1 \text{ GW}_{\text{th}} \Leftrightarrow 2 \times 10^{20} \frac{\bar{\nu}_e}{\text{s}})$$
- 2 additional cores in 2011, + $5.8 \text{ GW}_{\text{th}}$
- Mountainous overburden nearby

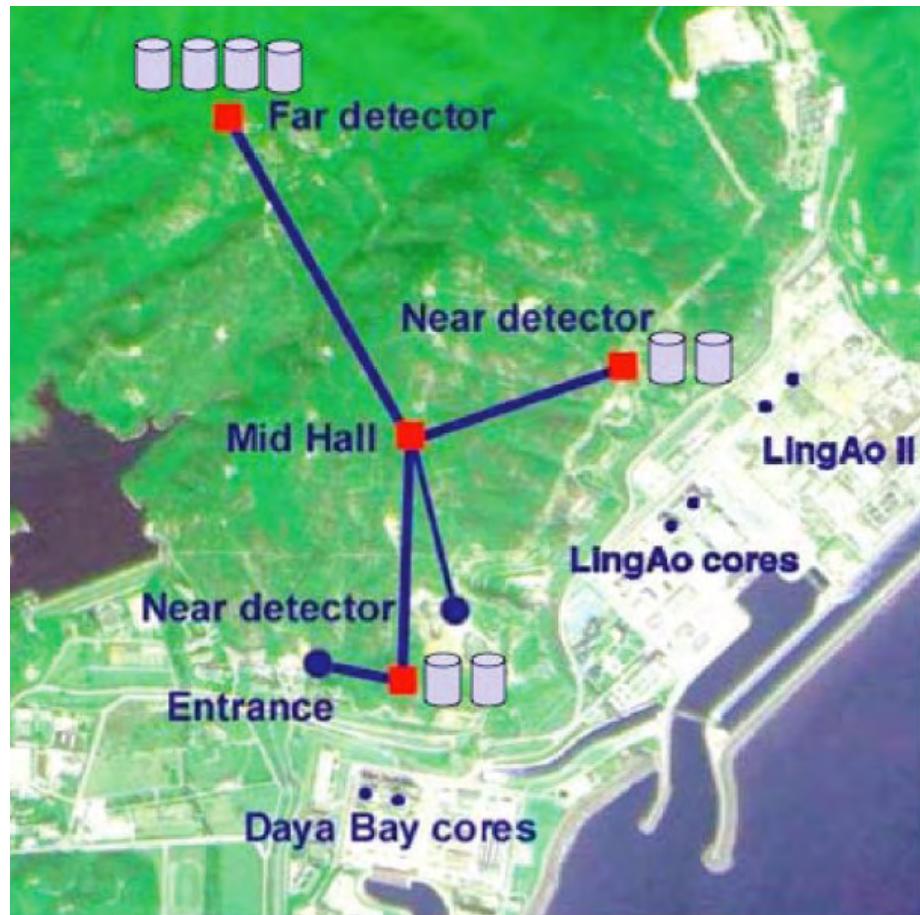
Natural Shielding



Overburden increases with distance from source ⇒
Signal/noise ≈ constant

Experiment Design

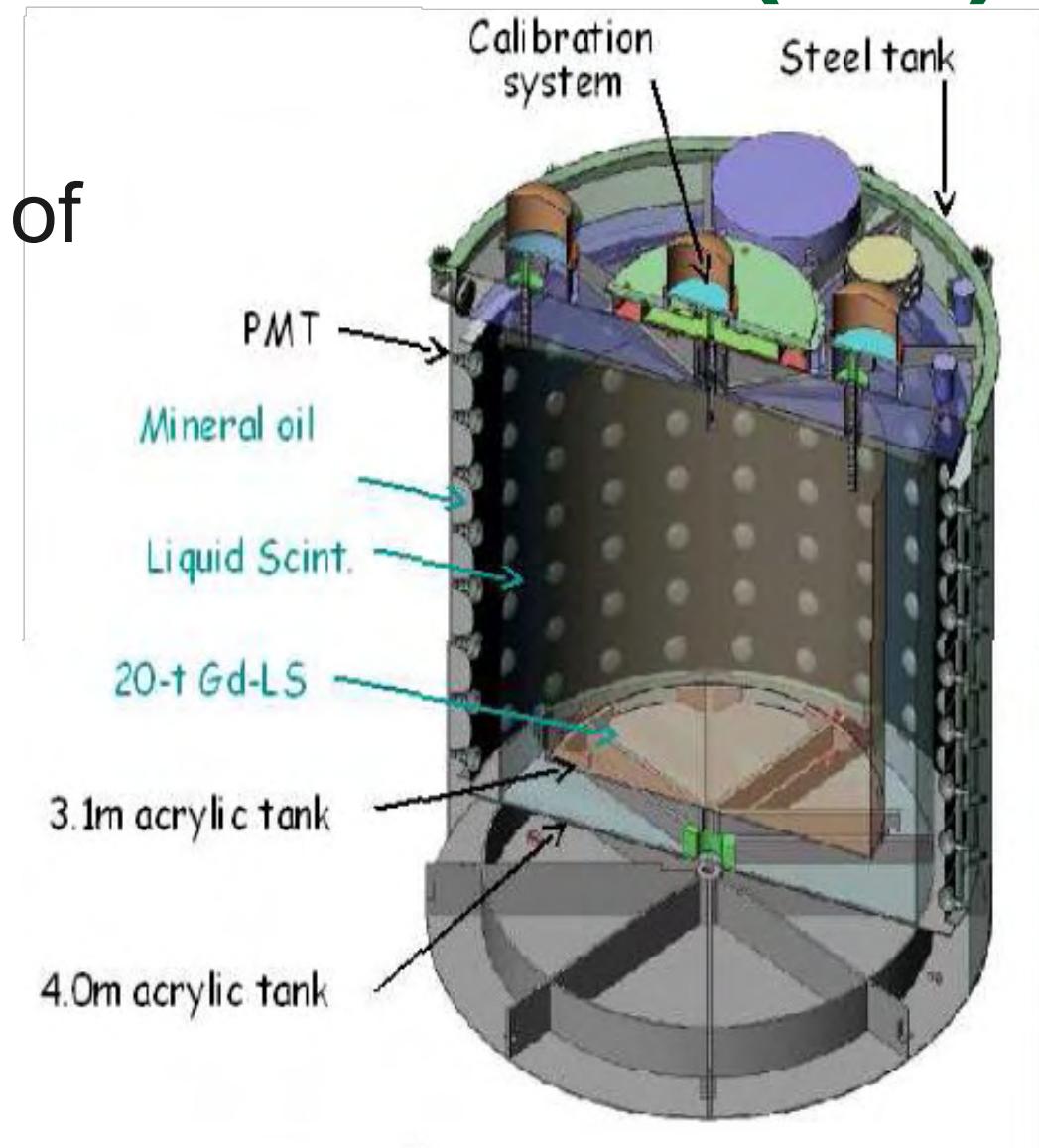
DOE CD3-b Approval: 6 August 2008



- Objective: $\sin^2 2\theta_{13} < 1\%$ (@ 90% CL)
- Multiple detectors:
 - 8 “Identical”
 - 2+2 Near
 - 4 Far
 - Filled in pairs
 - Sophisticated calibration
- About 3 km of tunnels

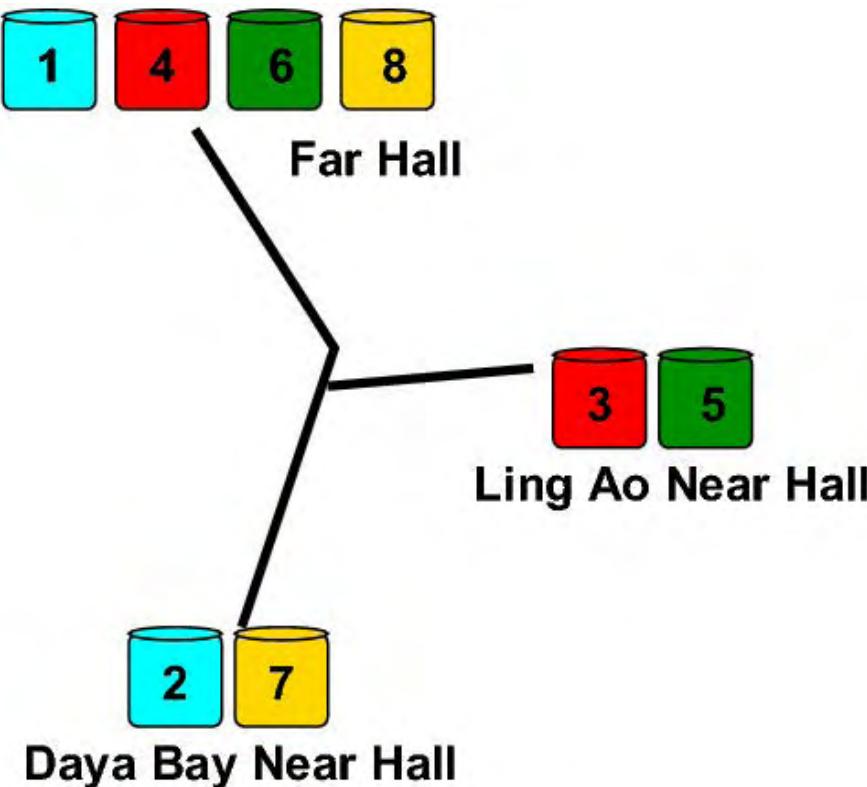
Anti-Neutrino Detector (AD)

- 3-zones
- 20-ton target mass of Gd-doped liquid scintillator
- 192 photomultiplier tubes
- $12\%/\sqrt{E}$ resolution
- No fiducial cut or position reconstruction



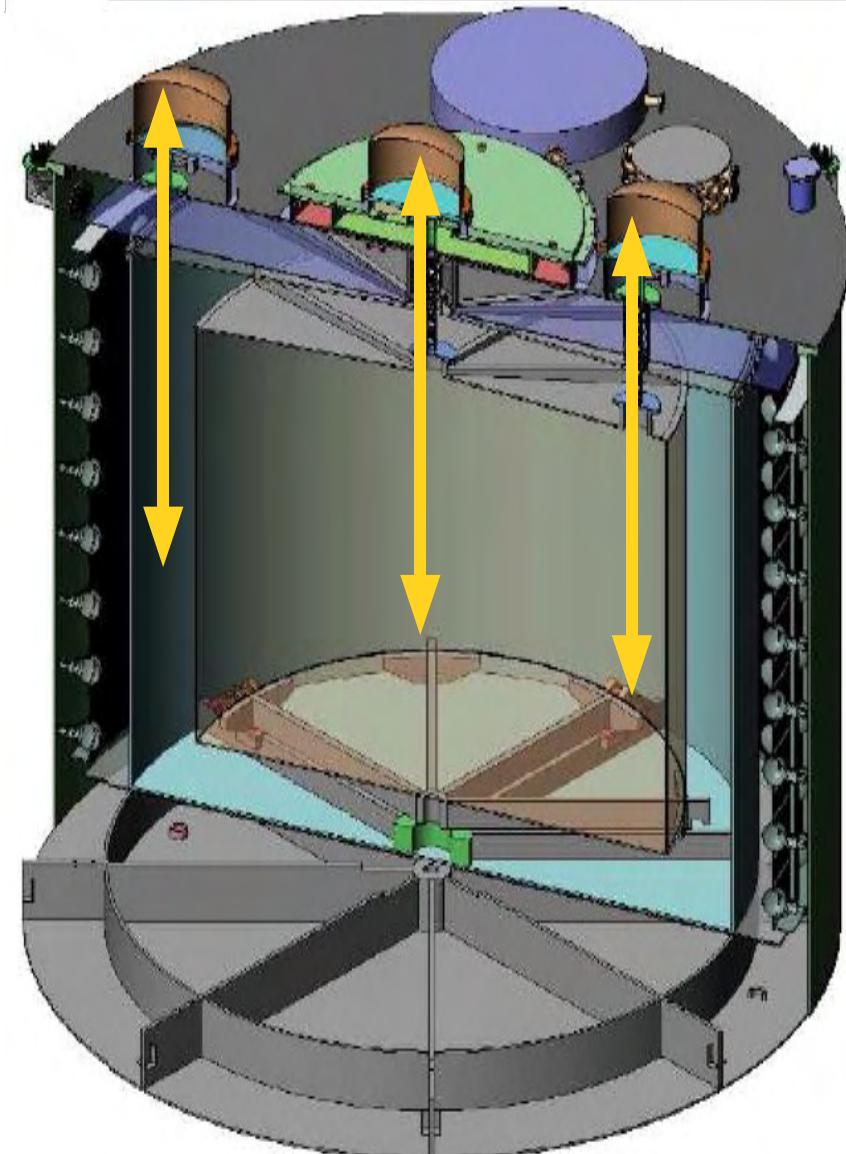
AD Filling and Deployment

- Filled and commissioned in pairs
- Deployed one near, one far



AD Calibration & Monitoring

- Load cells and mass-flow meters when filling
- Automated Systems
 - γ
 - β^+
 - n
 - LED
- Deployed for each zone



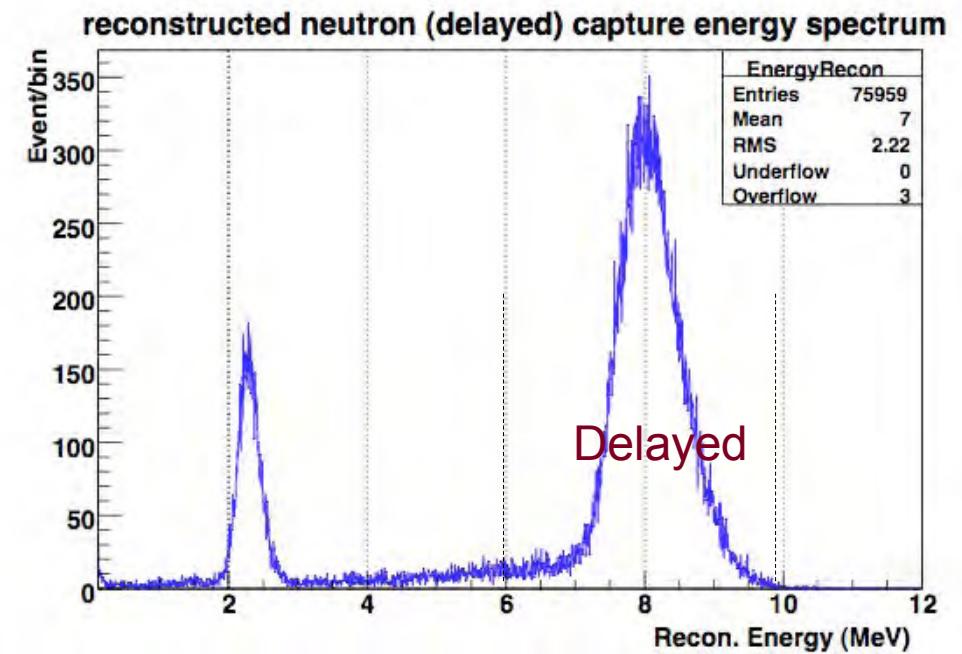
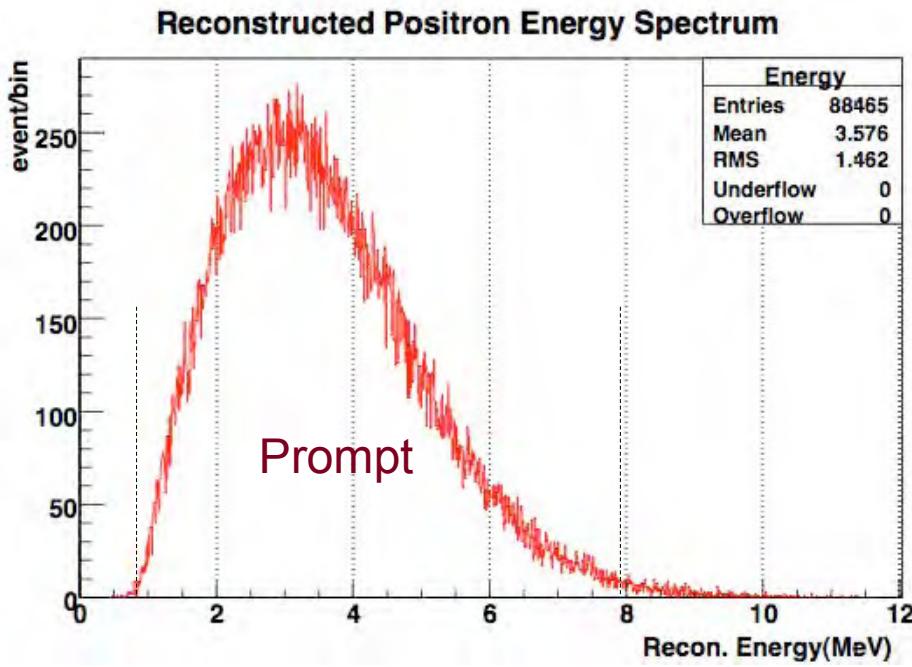
Event Rates

/day/module

Daya Bay Near Site: 960

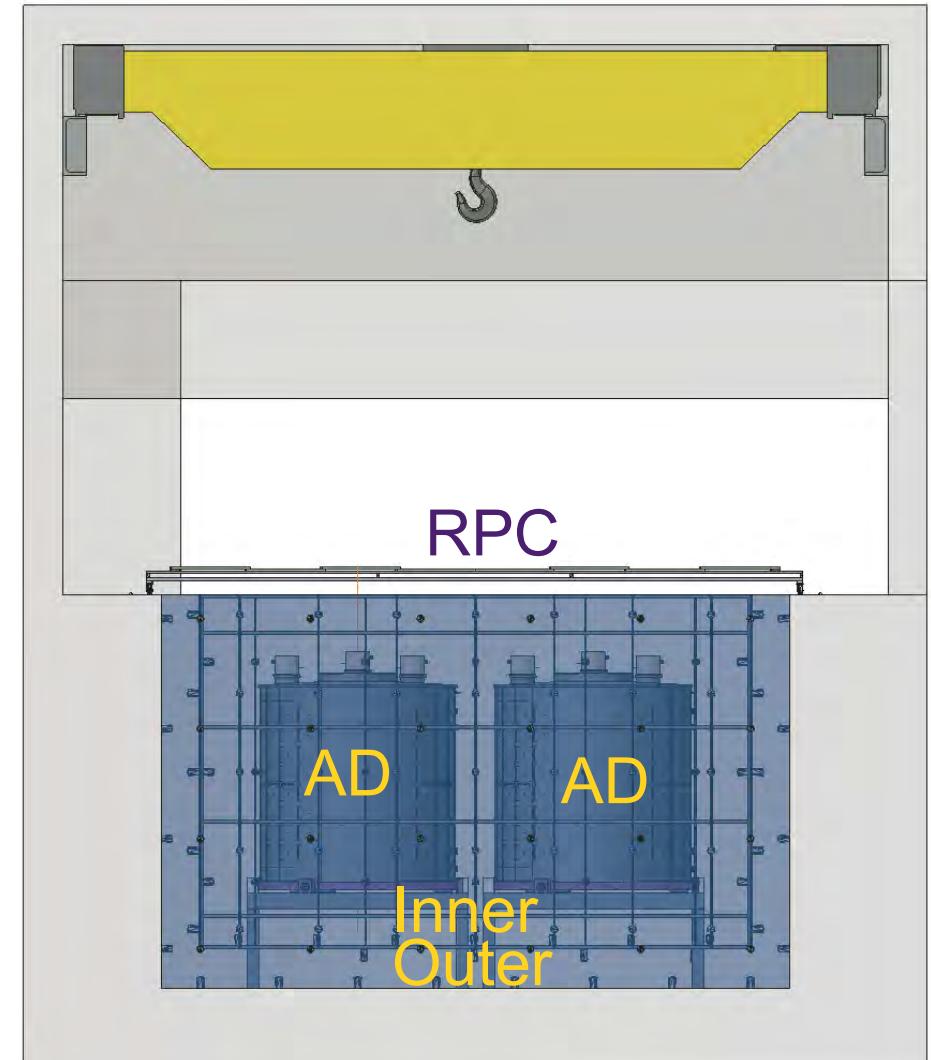
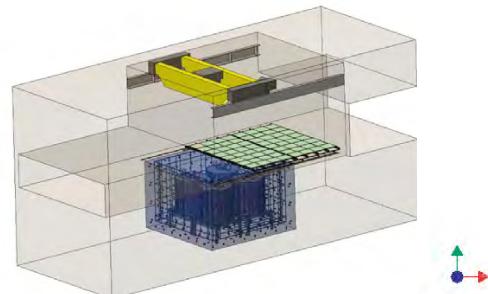
Ling Ao Near Site: 760

Far Site: 90



Water Shield and Muon Veto

- AD thermal bath
- Passive and active shield
 - RPC
 - Inner & outer water Čerenkov
- > 99.5% Efficient



Backgrounds

Thick water shield reduces neutrons and γ s from external sources

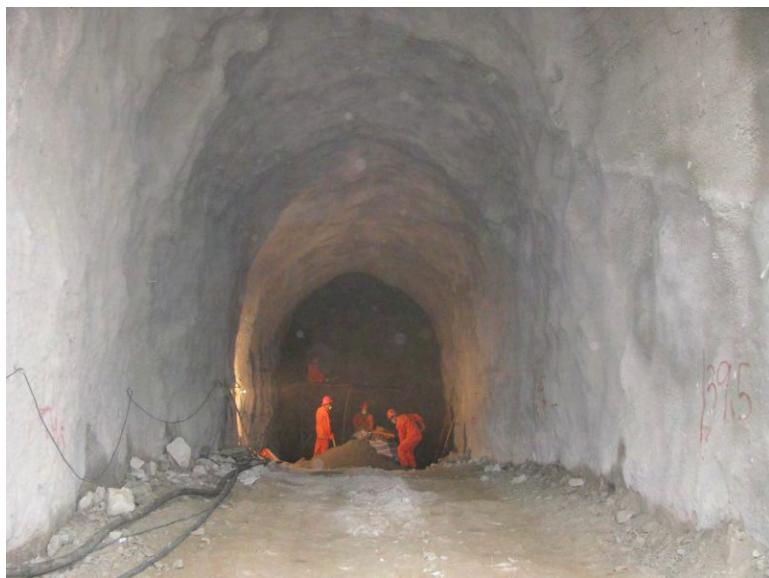
Source	Daya Bay Near	Ling Ao Near	Far
Natural Radiation [Hz]	<50	<50	<50
Single Neutron [/day/module]	18	12	1.5
Isotope β -Emission [/day/module]	210	141	14.6
Accidental/Signal	<0.002	<0.002	<0.001
Fast Neutron/Signal	0.001	0.001	0.001
^8He - ^9Li /Signal	0.003	0.002	0.002

Design Uncertainties

Source	Uncertainty
Flux	0.087% (4 cores) 0.13% (6 cores)
Detector (per module)	0.38% 0.18% (objective)
Backgrounds	0.32% (Daya Bay near) 0.22% (Ling Ao near) 0.22% (far)
Signal Statistics	0.2%

Tunneling

**Groundbreaking:
October 2007**



13/03/09



Daya Bay

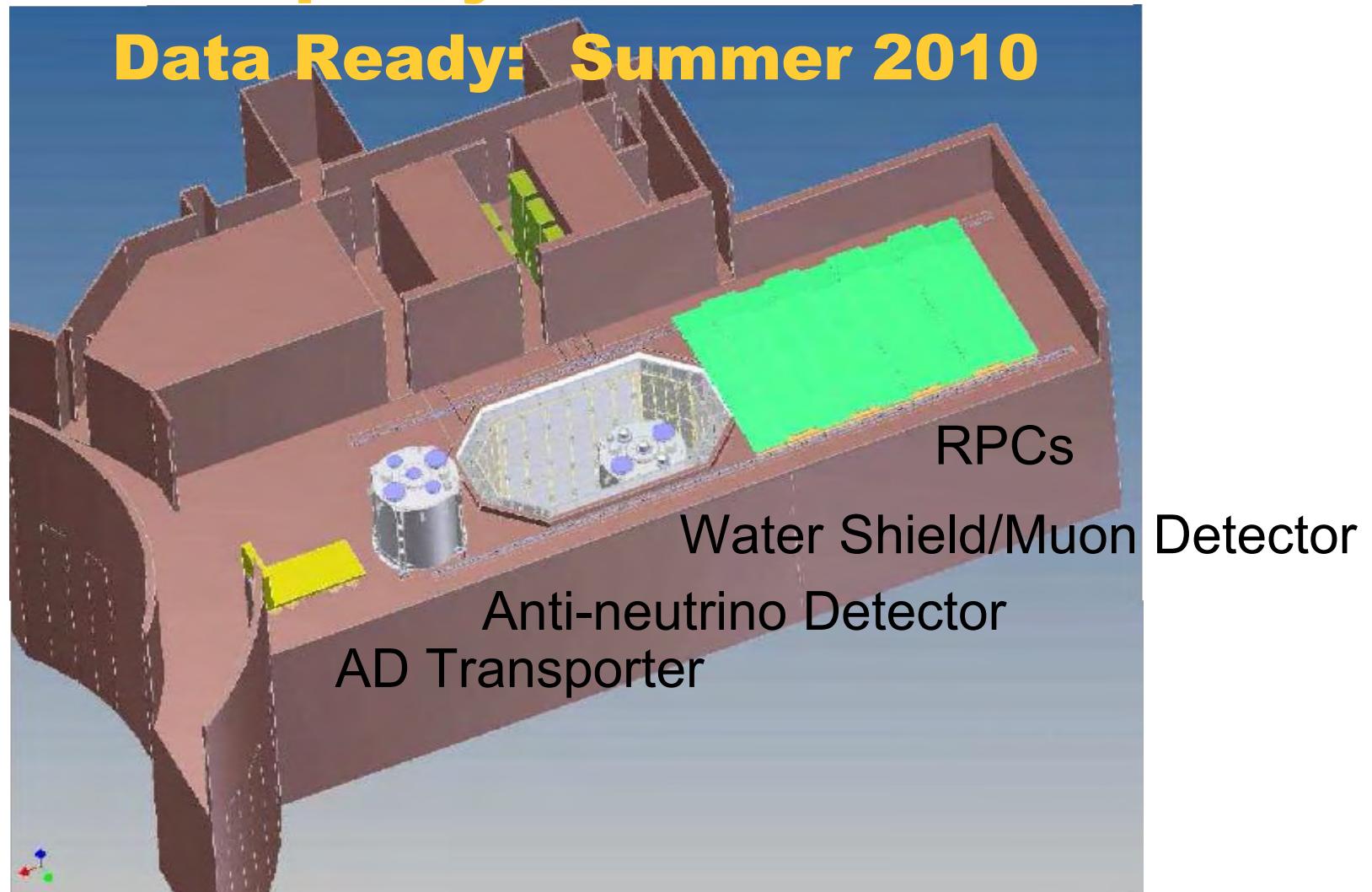


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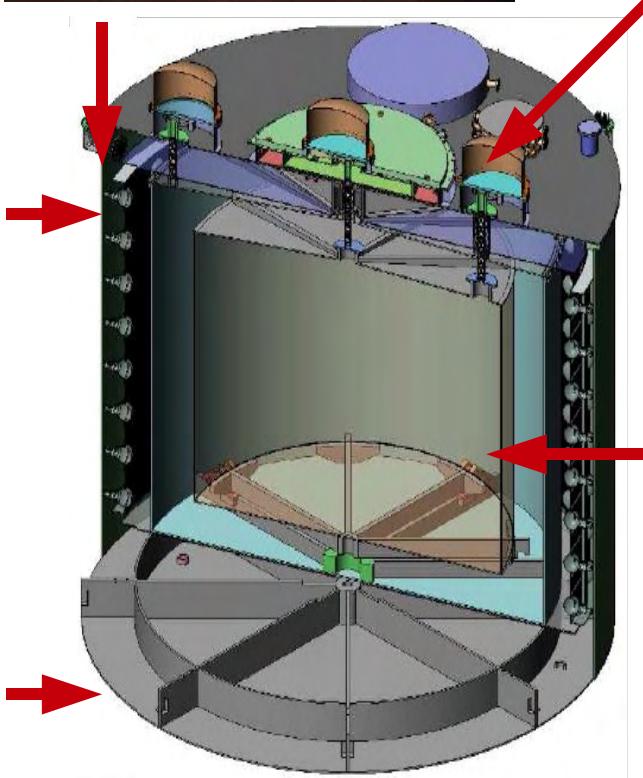
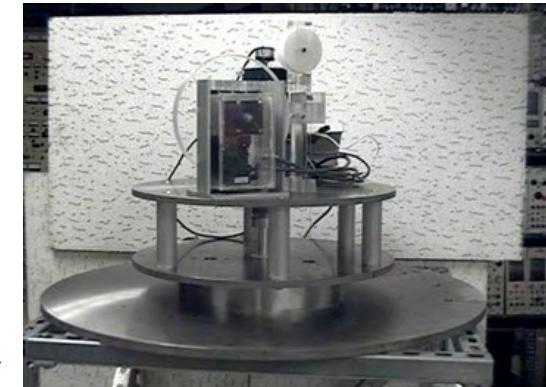
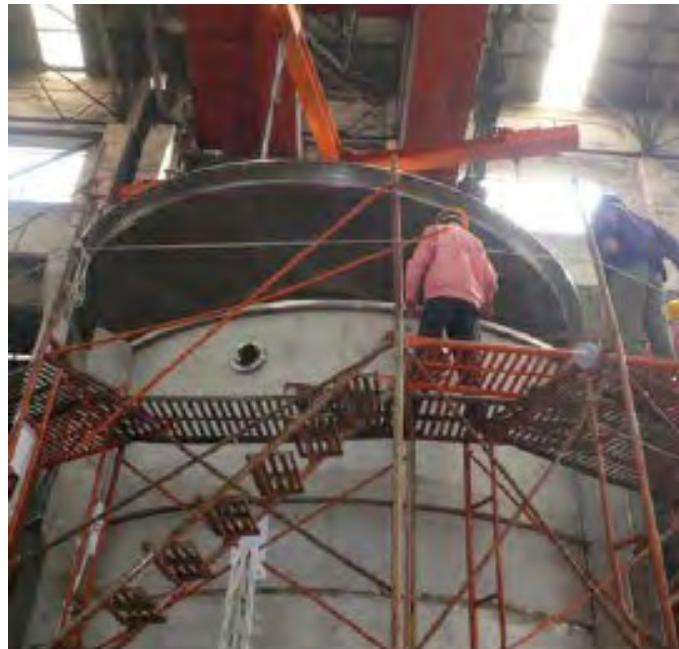
Near Hall Layout

Occupancy: Summer 2009

Data Ready: Summer 2010



AD Construction



13/03/09

Daya Bay

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AD Production

- Prototyping complete (China/US)
- Subsystems' design complete (China/US)
- Stainless vessels under construction (China)
- Acrylic vessels under construction (Taiwan/US)
- PMT production tests underway (China/US)

Surface Assembly Building

Occupancy: March 2009

First AD “Dry Test”: Fall 2009



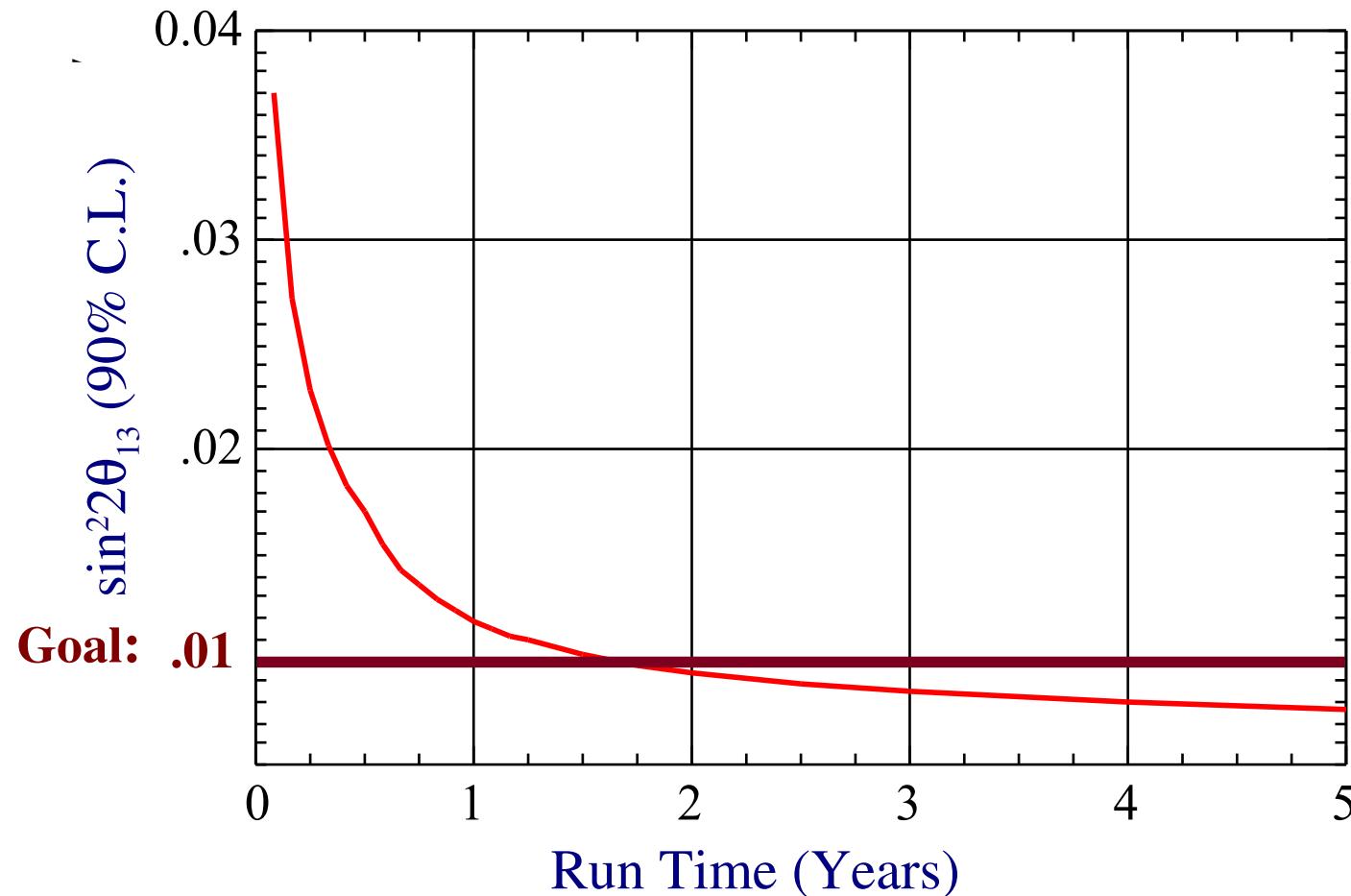
AD Assembly

First SST Delivered: 13 March 2009



Status and Sensitivity

Far Hall Data Ready: Summer 2011



Extra

Rate with Multiple Detectors

Weight Detector-Pair Contributions

$$\mathcal{R} = \left[\alpha \sum_r \frac{\phi_r}{L_{r,DB}^2} + \sum_r \frac{\phi_r}{L_{r,LA}^2} \right] / \sum_r \frac{\phi_r}{L_{r,f}^2}$$

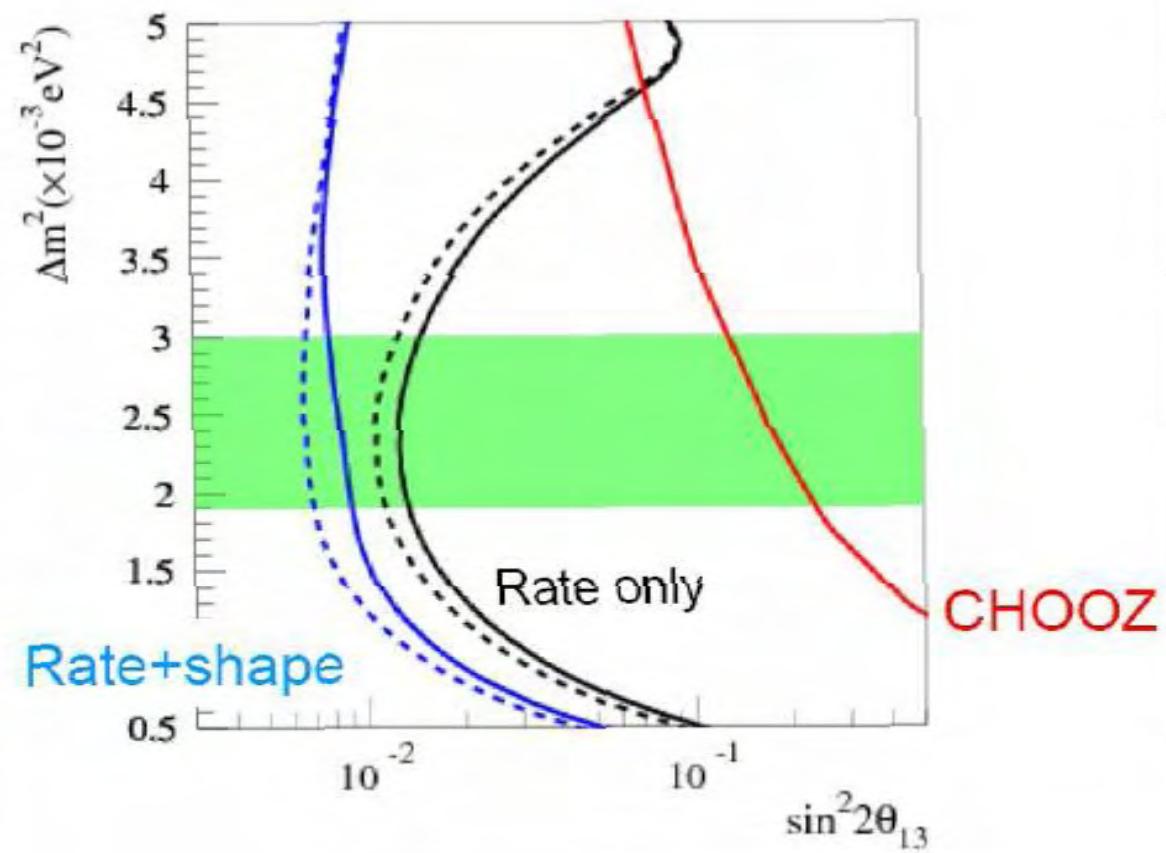
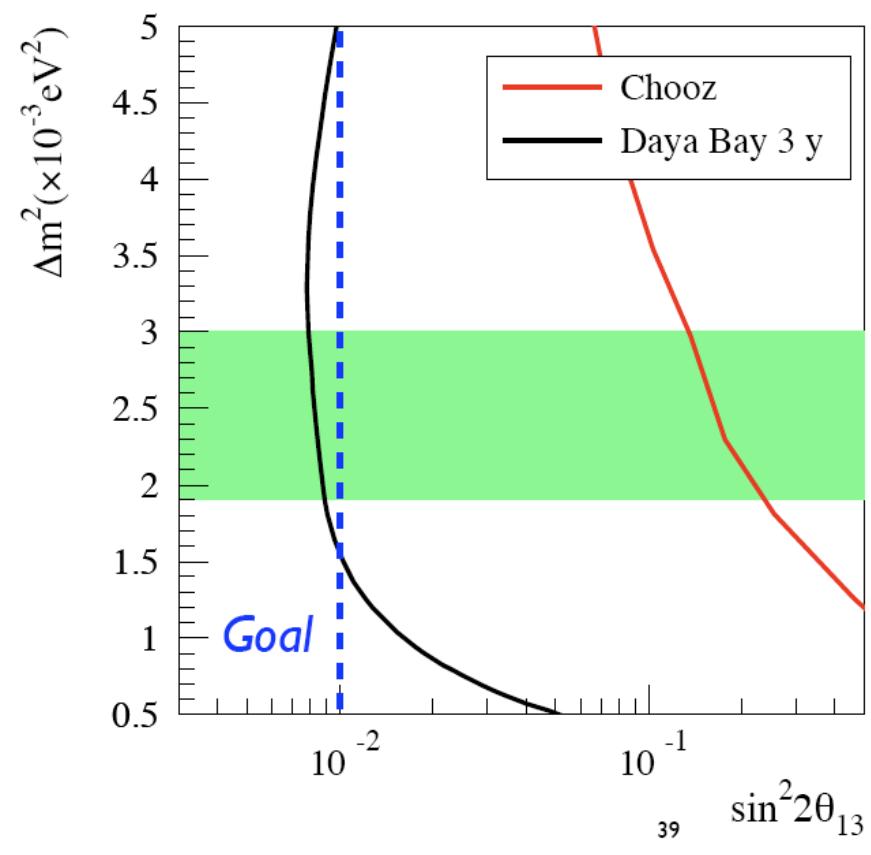
Cores	α	$\sigma_{\mathcal{R}}(\text{power})$	$\sigma_{\mathcal{R}}(\text{location})$	$\sigma_{\mathcal{R}}(\text{total})$
4	0.338	0.035%	0.080%	0.087%
6	0.392	0.097%	0.080%	0.128%

Detector Systematics

Near/Far Relative %

Source		Design	Objective	Strategy
Proton count	H/C	<0.1	<0.1	Pair filling/calibration
	Mass	<0.3	<0.1	Fill monitoring
Efficiency	Energy	0.2	0.1	Low threshold/calibration
	Position	0	0	AD 3-zone design
	Time	0.1	0.03	Common clock (~10 ns)
	H/Gd	0.1	0.1	Pair filling/calibration
	n multiplicity	0.05	0.05	Overburden/muon veto
	Trigger	0.01	0.01	Redundancy
	Live Time	<0.01	<0.01	Common GPS clock
Total		0.38	0.18	

Sensitivity Comparison



Search for θ_{13} : A Possible Scenario

