To Measure θ_{13}: The Daya Bay Experiment

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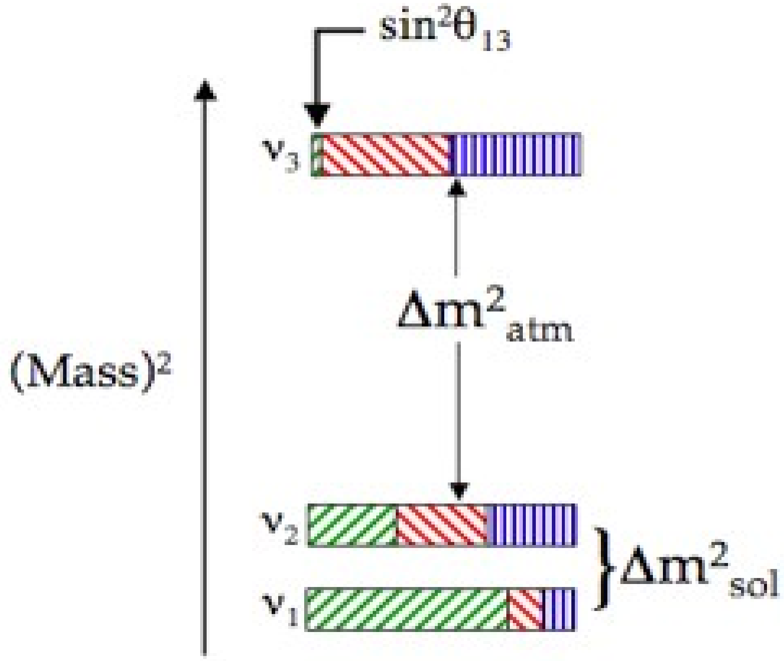
For the Daya Bay Collaboration

“Oscillations”

Neutrino flavors will transform into one another if:

- **Mass Eigenstates Differ**



- **Weak and Mass Eigenstates Mix**

Neutrino Mixing

Weak Eigenstate ≠ Mass Eigenstate

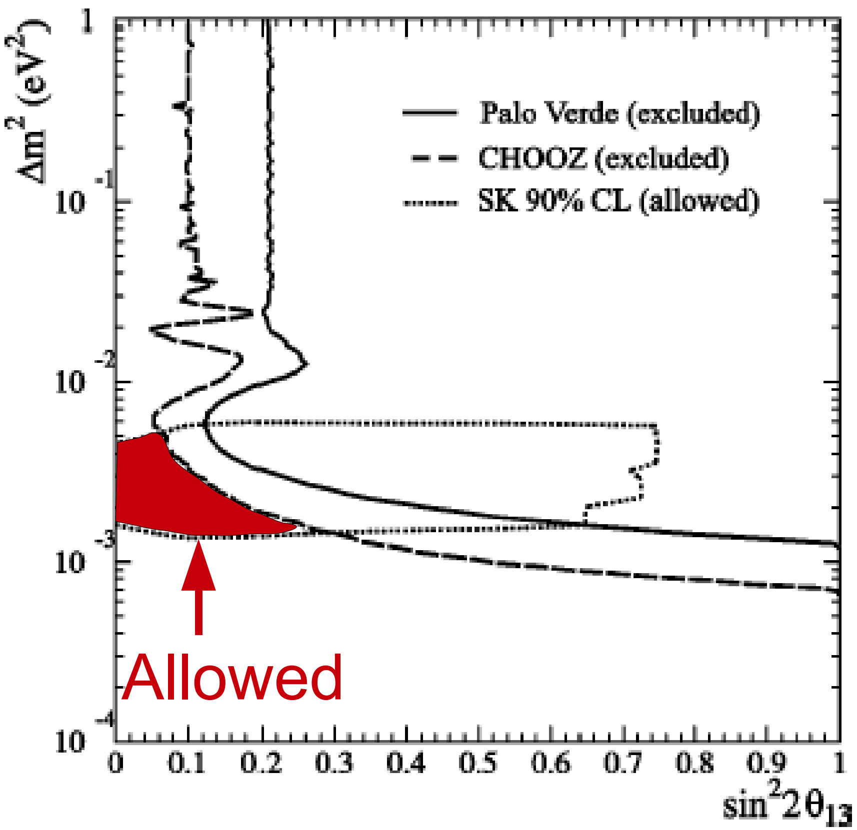
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{Pontecorvo-Maki-Nakagawa-Sakata} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = U_{PMNS}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

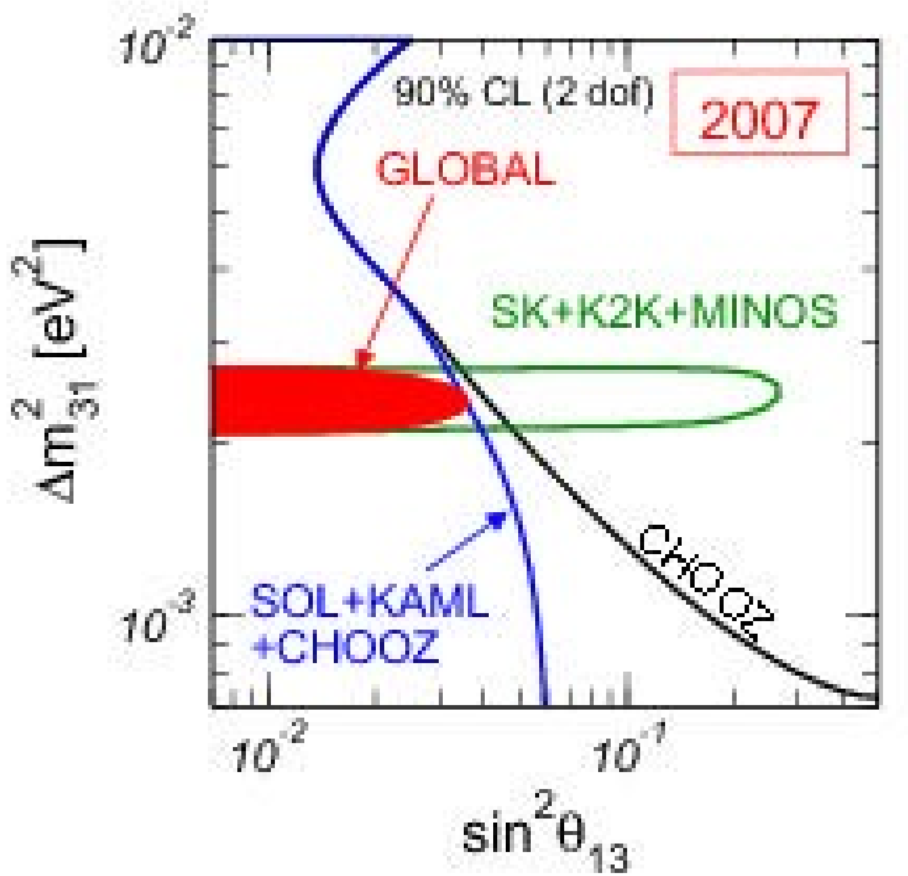
$$U_{PMNS} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{atmospheric,\ accelerator} \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta_{CP}}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

$$\theta_{23} \approx 45^\circ \qquad \theta_{13} < 10^\circ \qquad \theta_{12} \approx 32^\circ$$

$$\delta_{CP}\ accessible\ only\ if\ \theta_{13} \neq 0$$

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):**

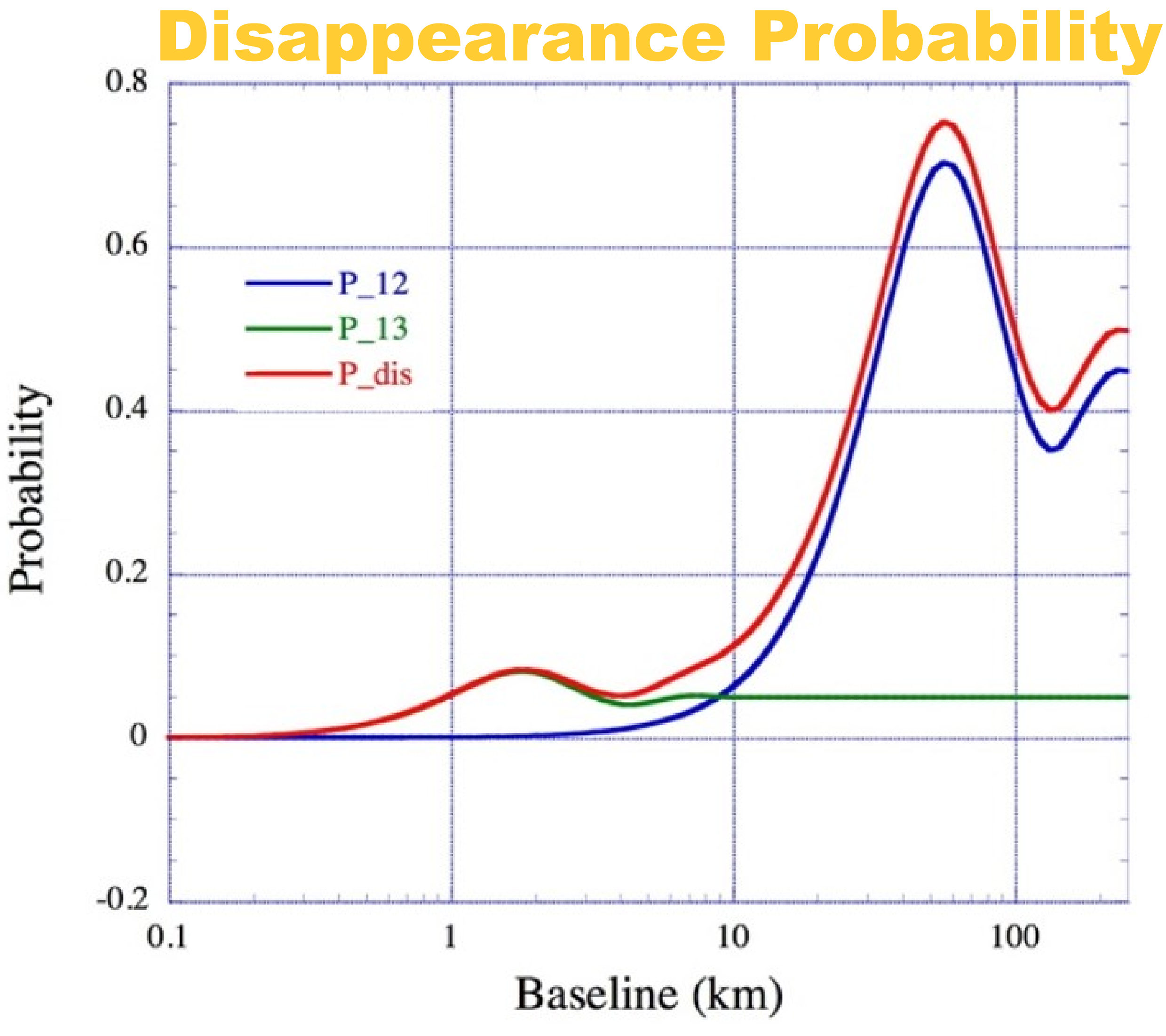
$$\mathbf{P_{e\tau}} = \sin^2 2\theta_{13} \sin^2 (1.27\Delta m^2_{13} L/E) + \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 (1.27\Delta m^2_{12} L/E)$$

- **At long-baseline accelerators:**

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

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

Baseline Optimization



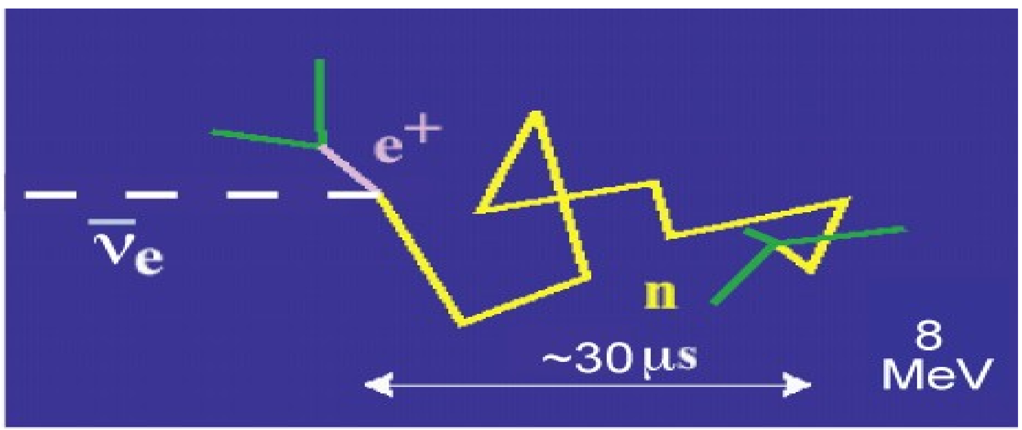
Reactor "Signal"

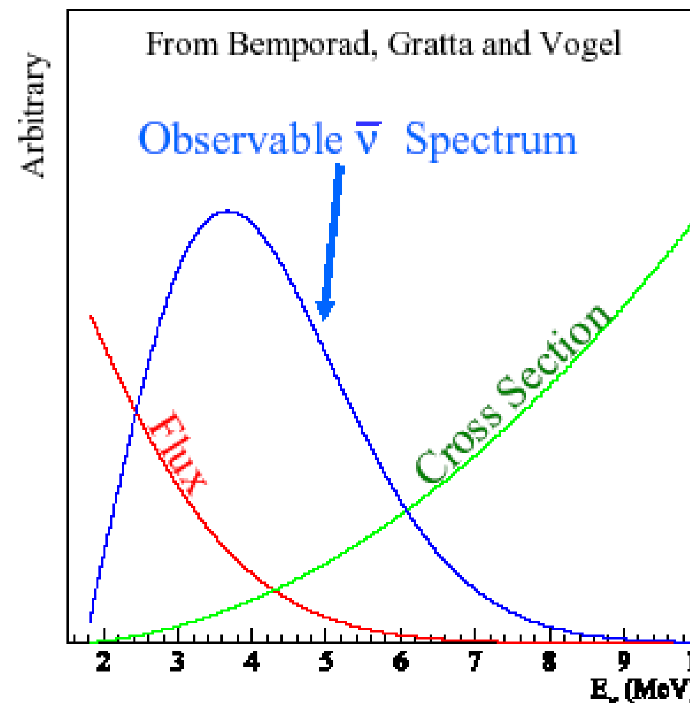
- Reactors produce electron anti-neutrinos

$$\mathbf{n} \rightarrow \mathbf{p} + \mathbf{e}^- + \bar{\nu}_\mathbf{e}$$

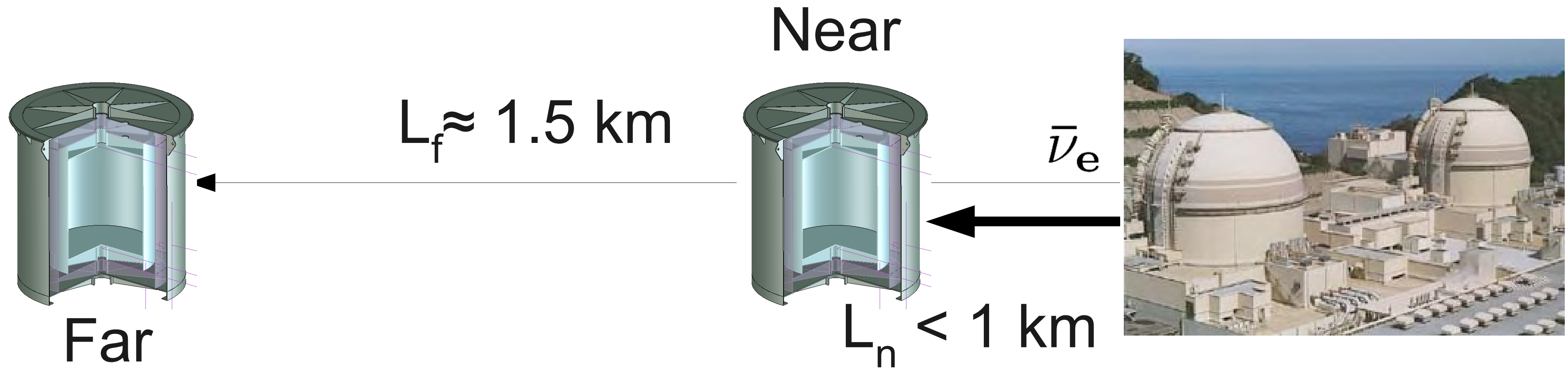
- Signals from inverse beta-decay

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





Paired Detectors



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

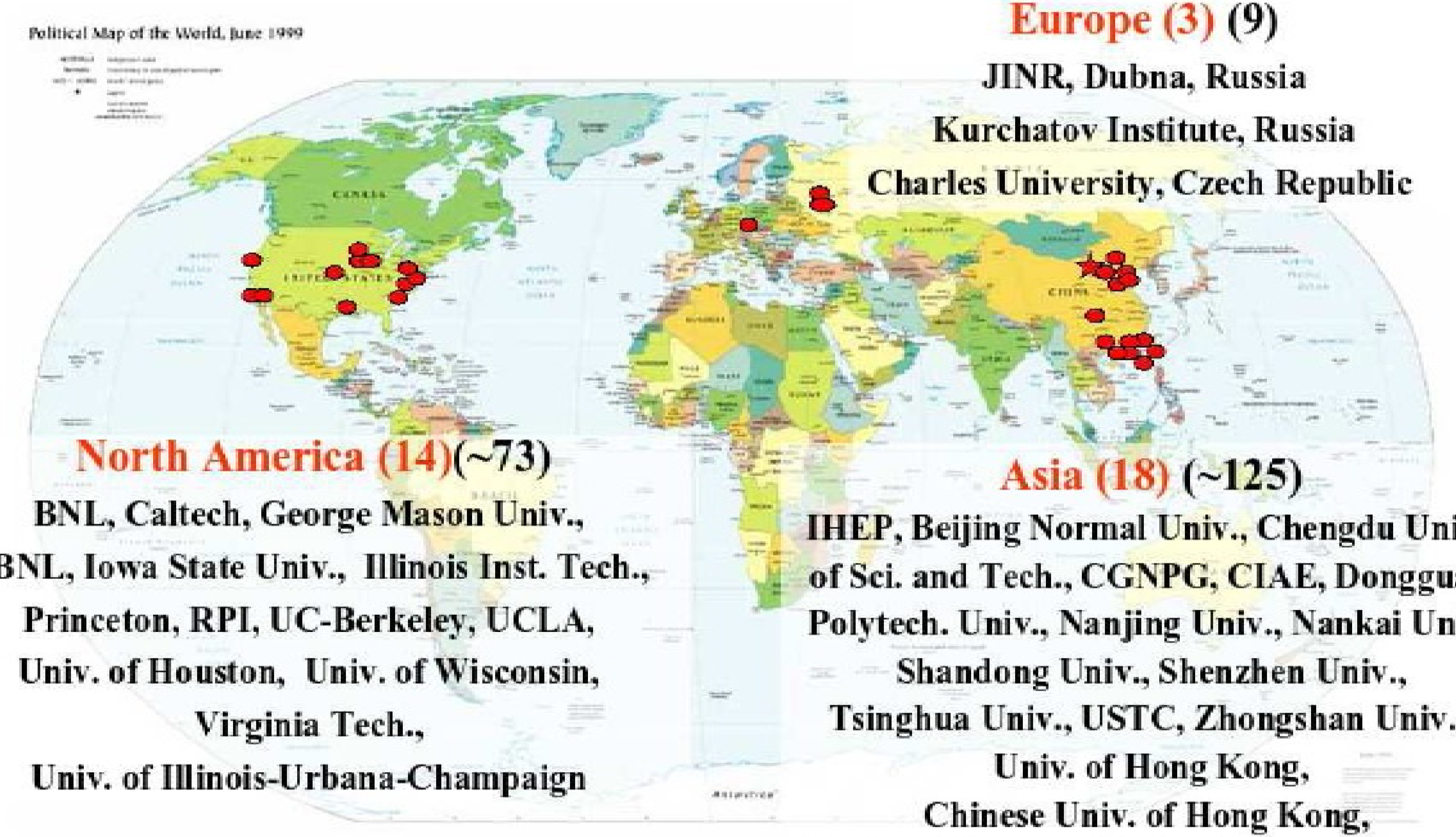
Rate

Target Mass

Efficiency

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

The Daya Bay Collaboration



Europe (3) (9)

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

North America (14)(~73)

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) (~125)

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., Univ. of Hong Kong, Chinese Univ. of Hong Kong, National Taiwan Univ., National Chiao Tung Univ., National United Univ.

≈ 200 collaborators

Daya Bay

Niudipu
Longhua
Buji
Henggang
Kuiyong
Dapeng
Yantian
Daya Bay
Shenzhen
Sha Tau Kok
Shatoujiao
Tai Pang Wan
Tong O
Tung Wan
Man Uk Pin
Pak Shek Au
Fanling
Lai Tau Shek
Cheung Wo
22°
Tin San Wai
Ting Kok
Shuen Wan
Yung Shue Au
Kau Lau Wan
Wu Lei Kiu
XIAOSANMEN DAO
Tai Po
Lin Fa Tei
Wu Kwai Sha
HONG KONG SAR (CHINA)
Tsuen Wan
Wong Yi Chau
Sha Tsiu
Sai Kung
Pak A
Pik Uk
Fu Tau Pun Chau
Cheung Sha Wan
Kai Tak International Airport
Tau Kwu
Kowloon
Yau Tong
KENNEDY TOWN
HAPPY VALLEY
Victoria Peak 554 m (1818 ft)
Hong Kong
Mount Collinson
Stanley Mount
South China Sea
Fa Peng

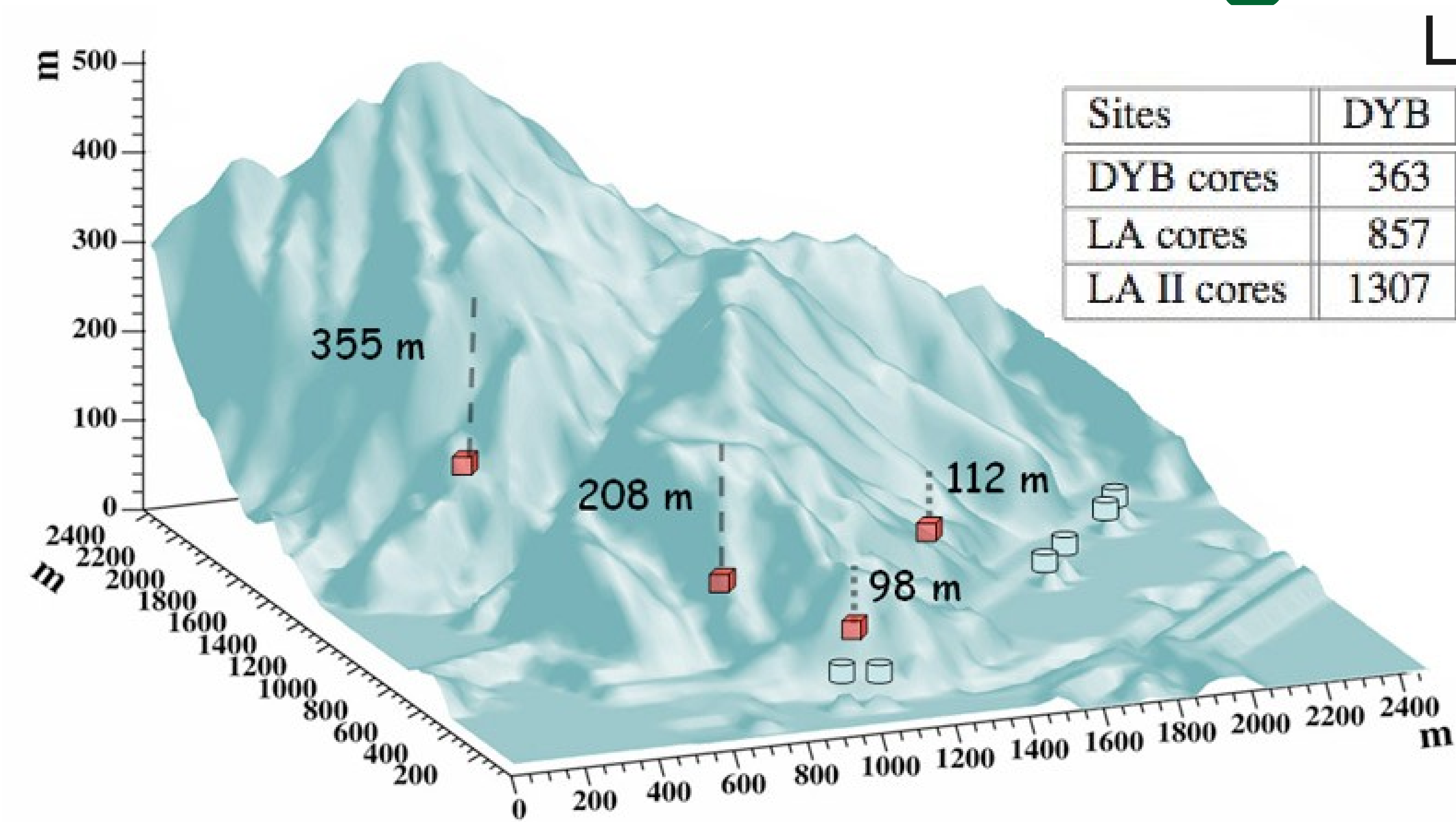
Daya Bay Nuclear Power Station

- 4 reactor cores, 11.6 $\mathrm{GW_{th}}$

$$(1\ \mathrm{GW_{th}} \Leftrightarrow \mathbf{2 \times 10^{20}\frac{\bar{\nu}_e}{s}})$$

- 2 additional cores in 2011, + 5.8 $\mathrm{GW_{th}}$
- Mountainous overburden nearby

Natural Shielding



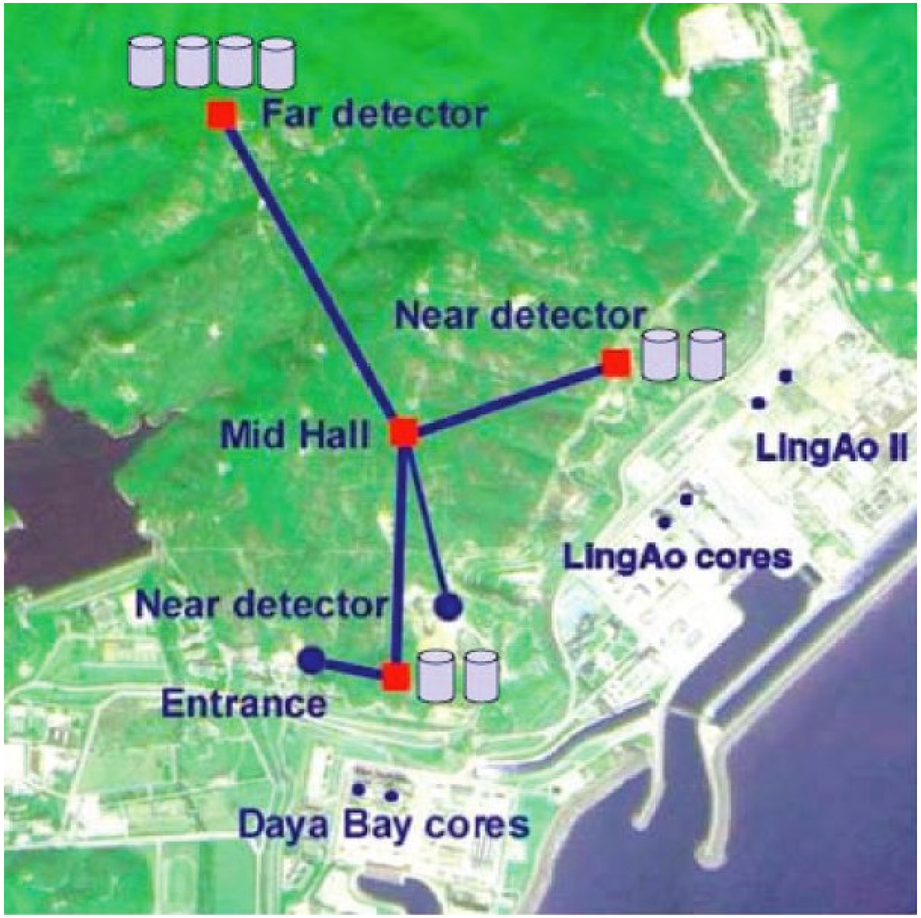
L [m]

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

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

Experiment Design

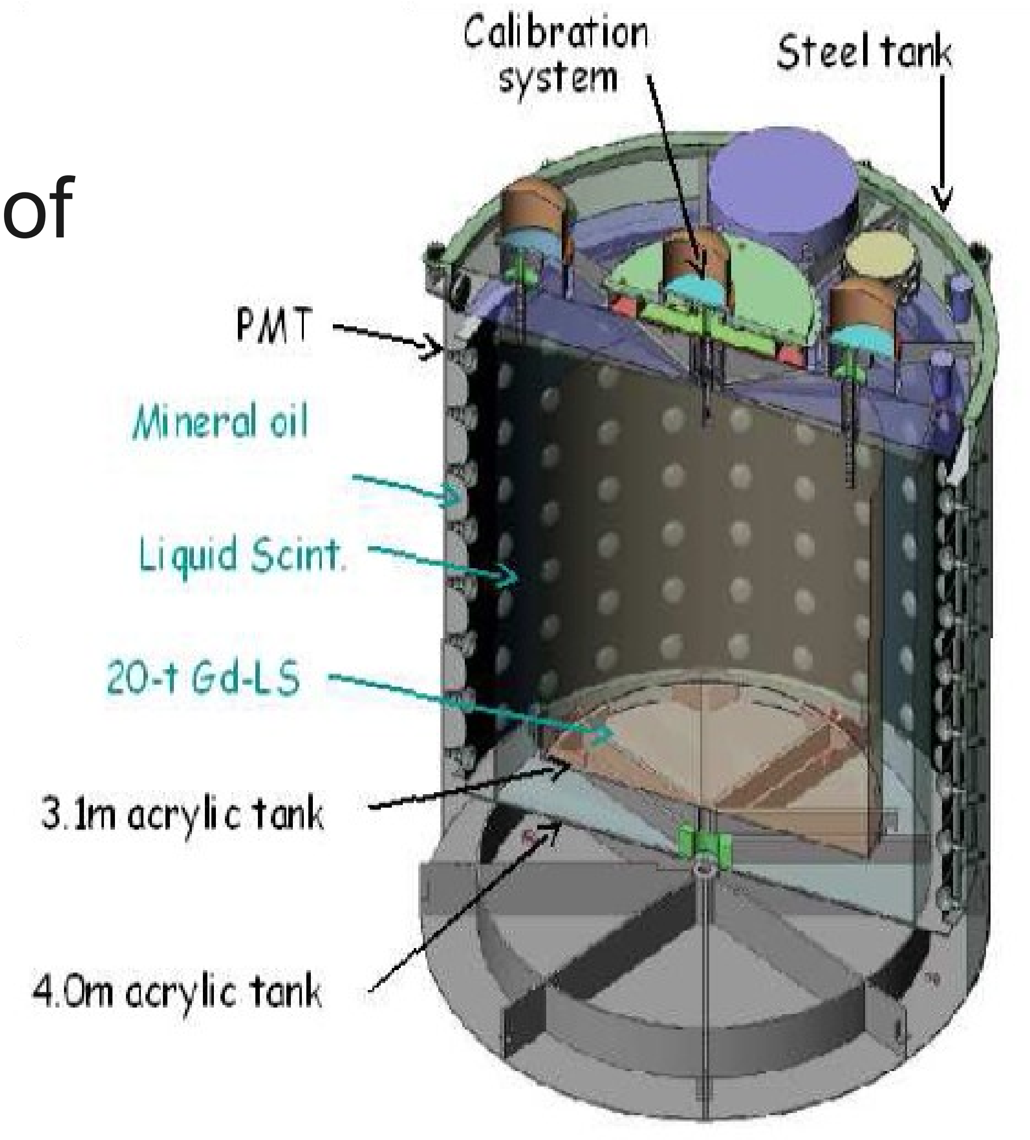
DOE CD3-b Approval: 6 August 2008



- 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

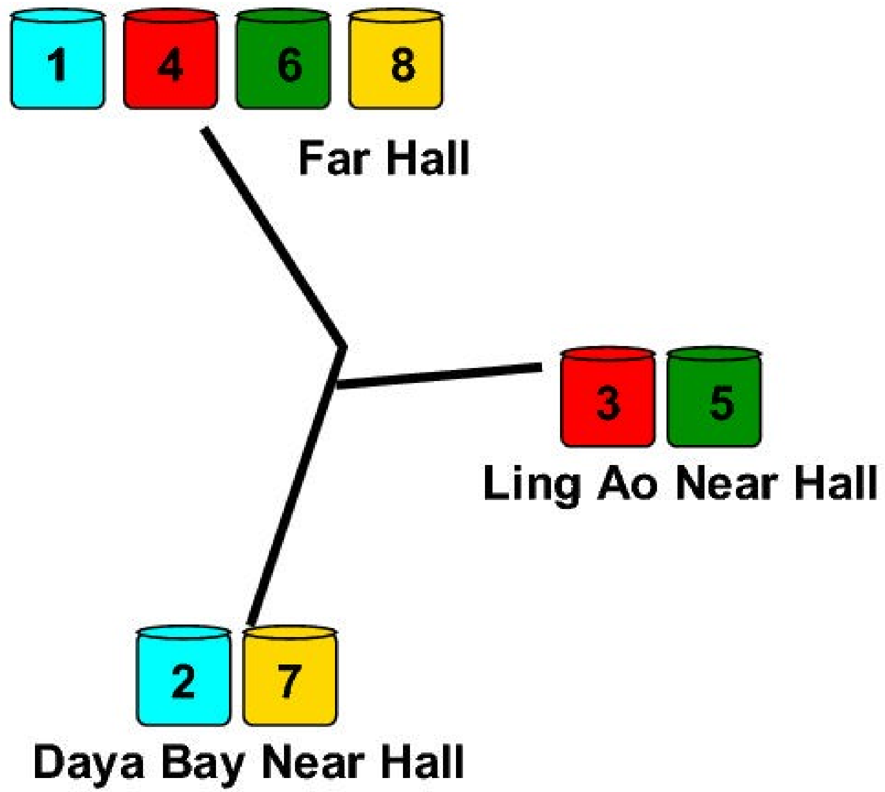
Anti-Neutrino Detector (AD)

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



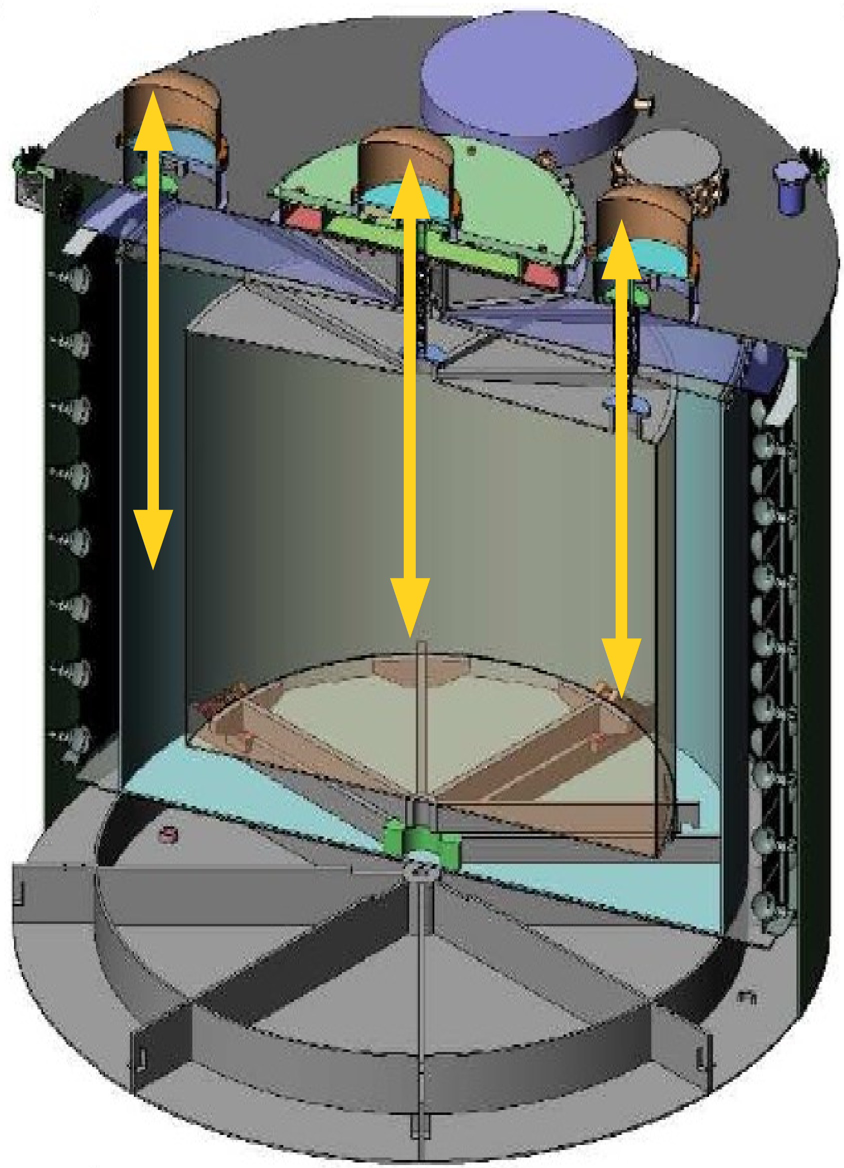
AD Filling and Deployment

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



AD Calibration & Monitoring

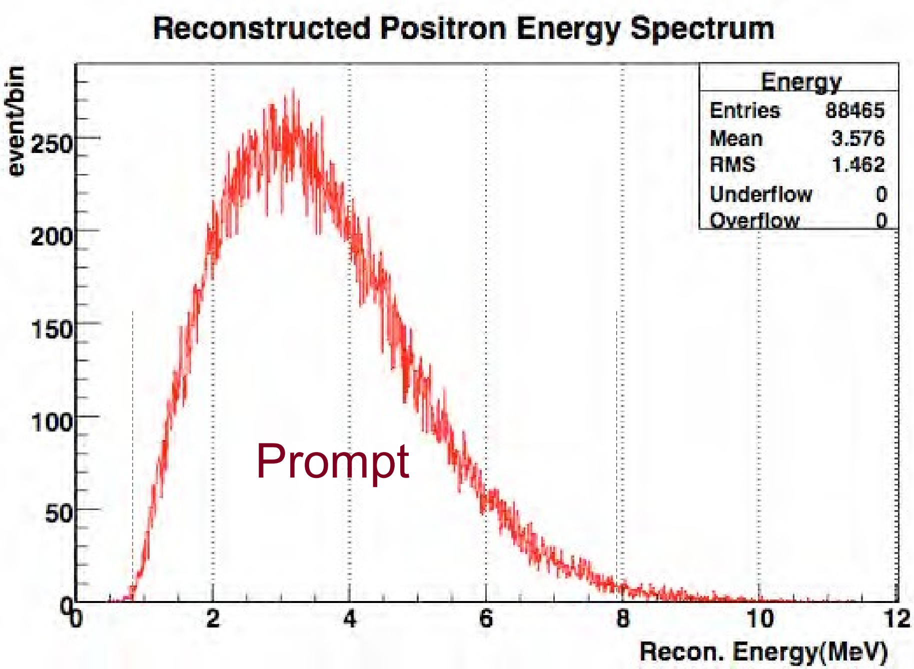
- Load cells and mass-flow meters when filling
- Automated Systems
  - γ
  - β^+
  - n
  - LED
- Deployed for each zone

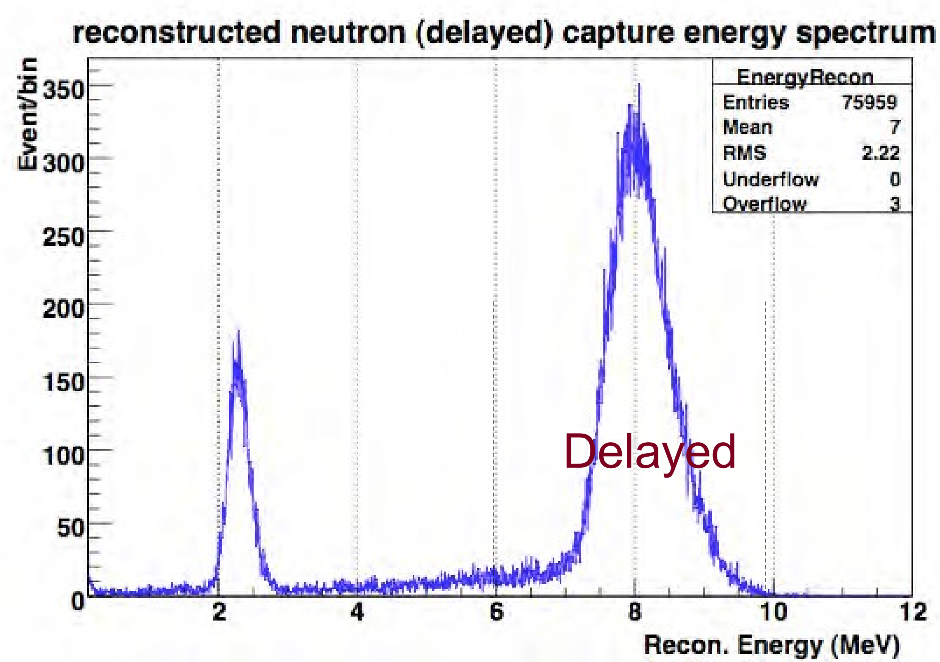


Event Rates

/day/module

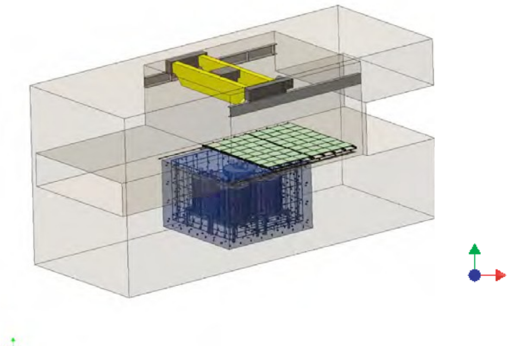
Daya Bay Near Site:	960
Ling Ao Near Site:	760
Far Site:	90

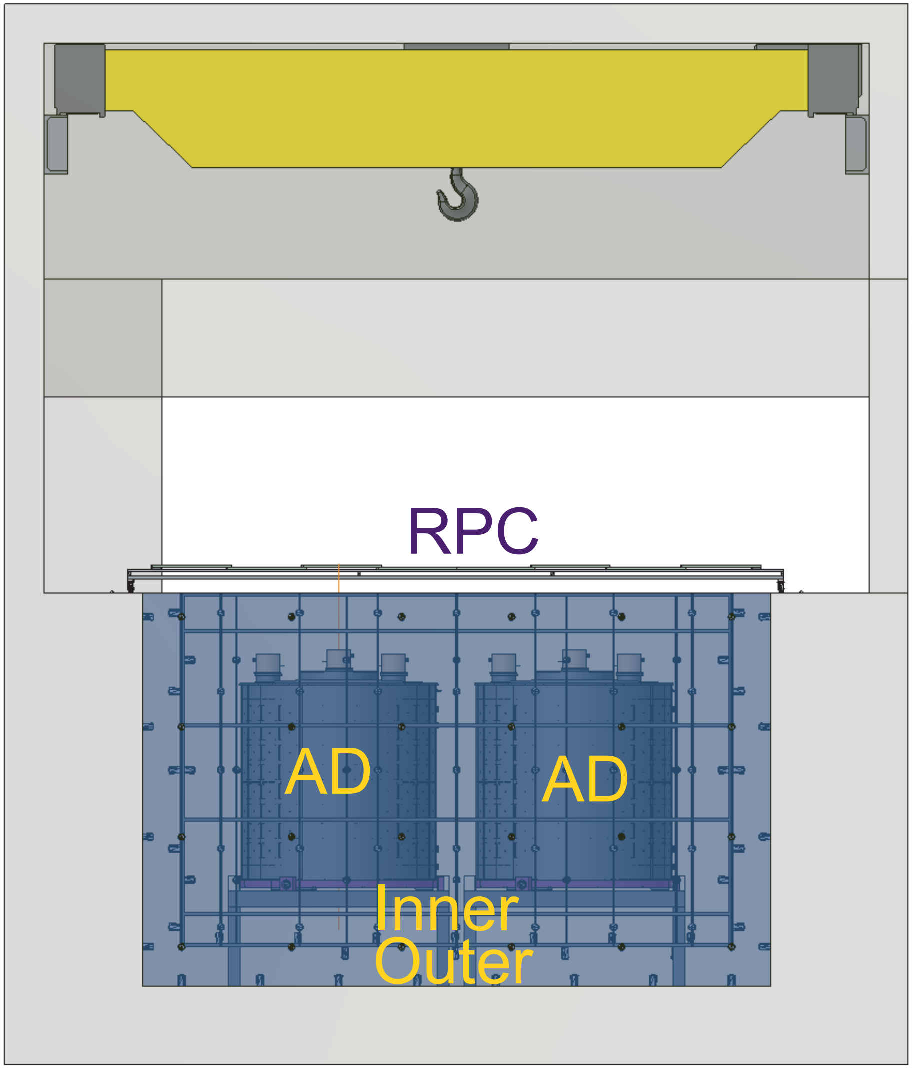




Water Shield and Muon Veto

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





Backgrounds

Thick water shield reduces neutrons and γs 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
^{8}He-^{9}Li/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%

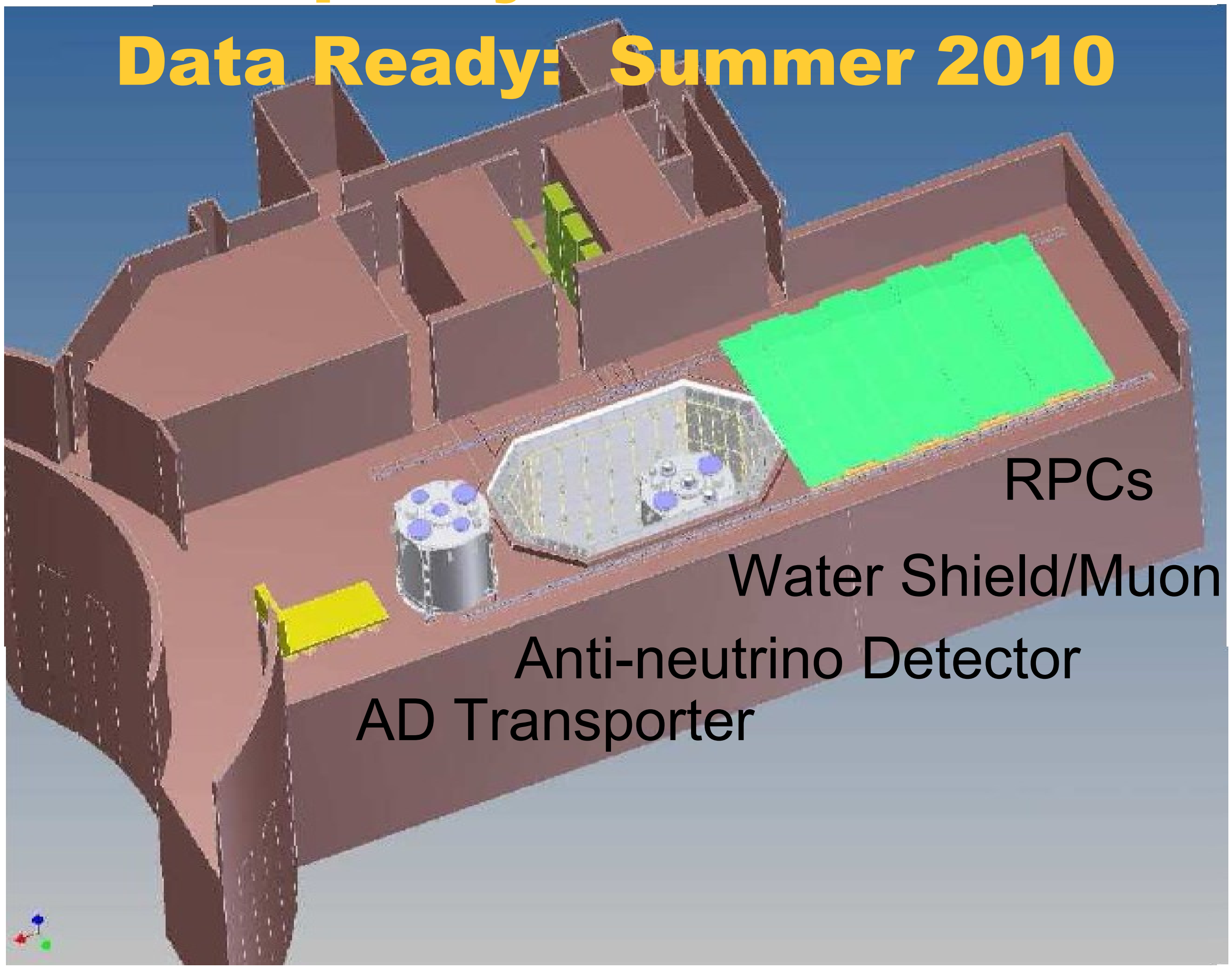
Tunneling

Groundbreaking:
October 2007

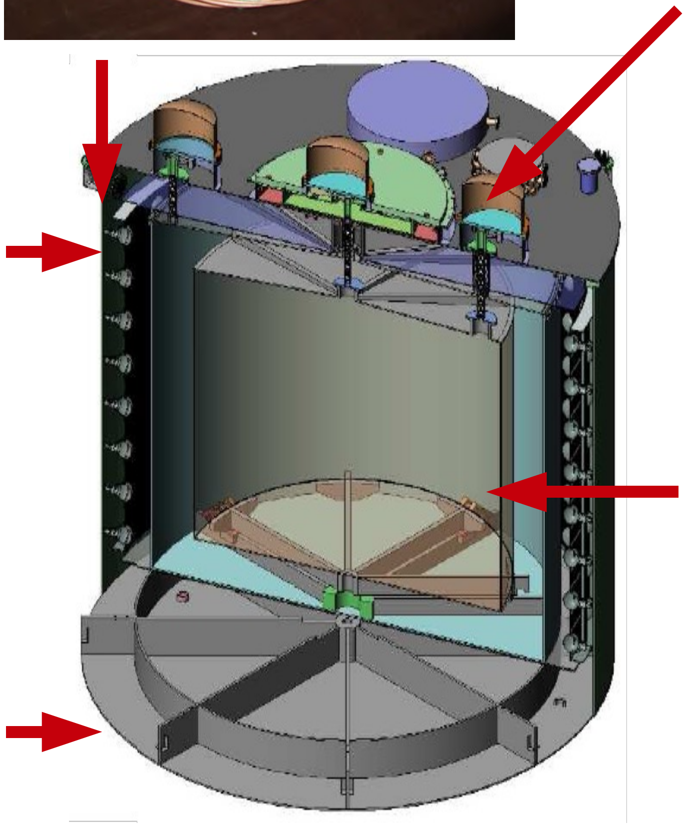
Near Hall Layout

Occupancy: Summer 2009

Data Ready: Summer 2010



AD Construction



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

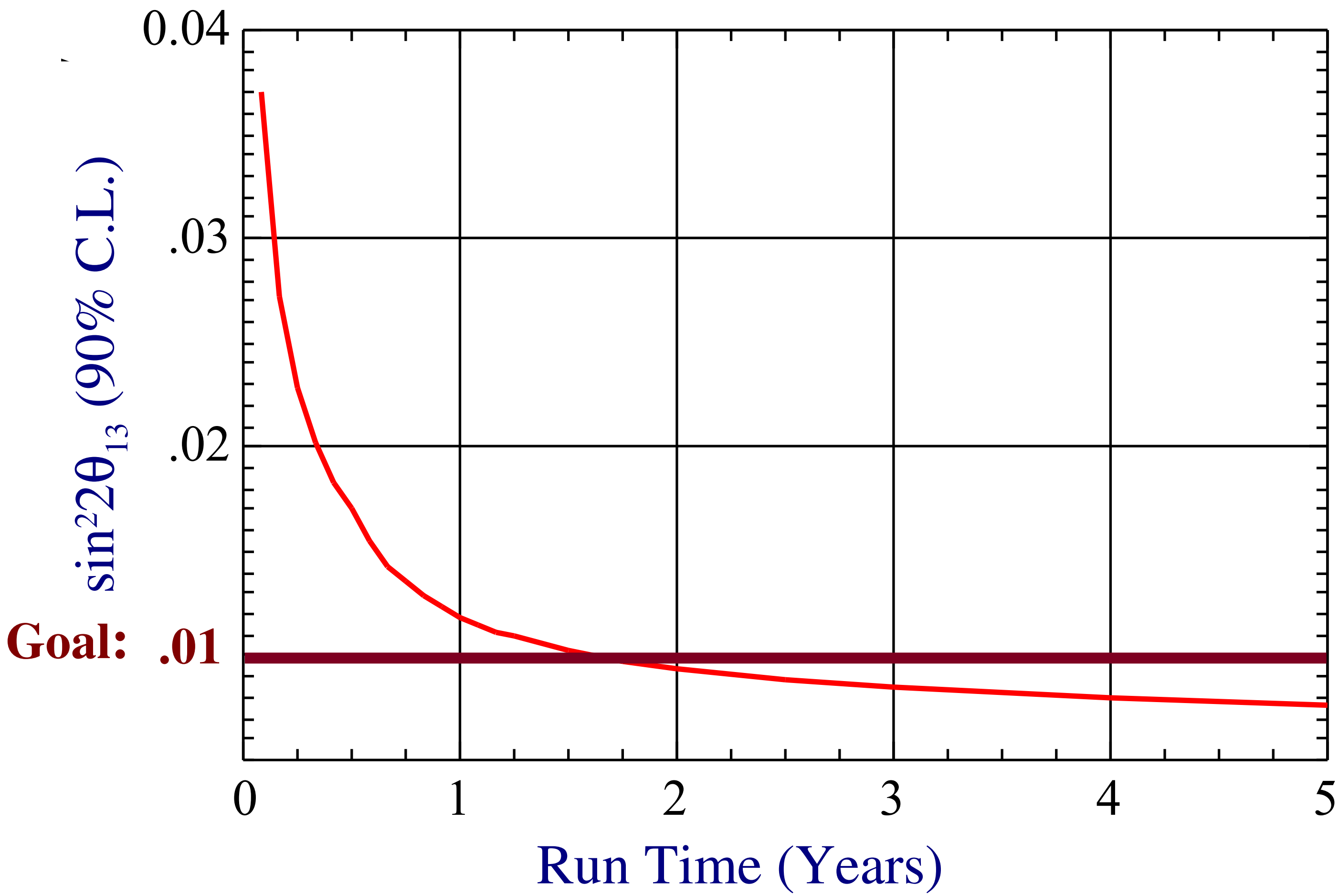
First AD "Dry Test": Fall 2009

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

$$\mathcal{R} = \left[\alpha \sum_{\mathbf{r}} \frac{\phi_{\mathbf{r}}}{\mathbf{L}^2_{\mathbf{r},\mathbf{DB}}} + \sum_{\mathbf{r}} \frac{\phi_{\mathbf{r}}}{\mathbf{L}^2_{\mathbf{r},\mathbf{LA}}} \right] / \sum_{\mathbf{r}} \frac{\phi_{\mathbf{r}}}{\mathbf{L}^2_{\mathbf{r},\mathbf{f}}}$$

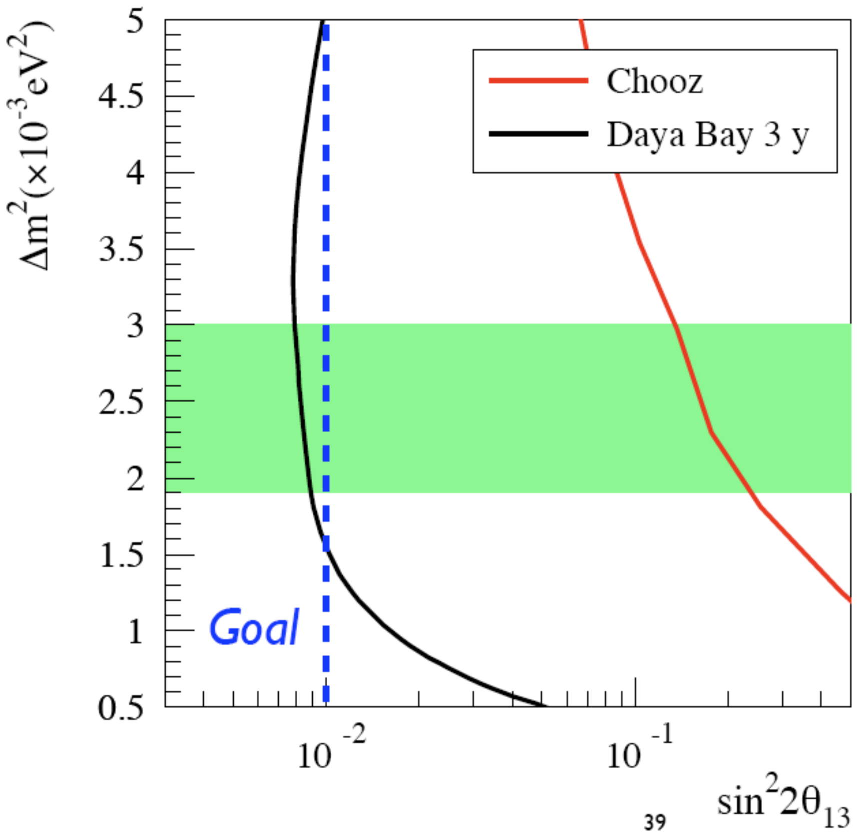
Cores	α	$\sigma_{\Re}$(power)	$\sigma_{\Re}$(location)	$\sigma_{\Re}$(total)
4	0.338	0.035%	0.080%	0.087%
6	0.392	0.097%	0.080%	0.128%

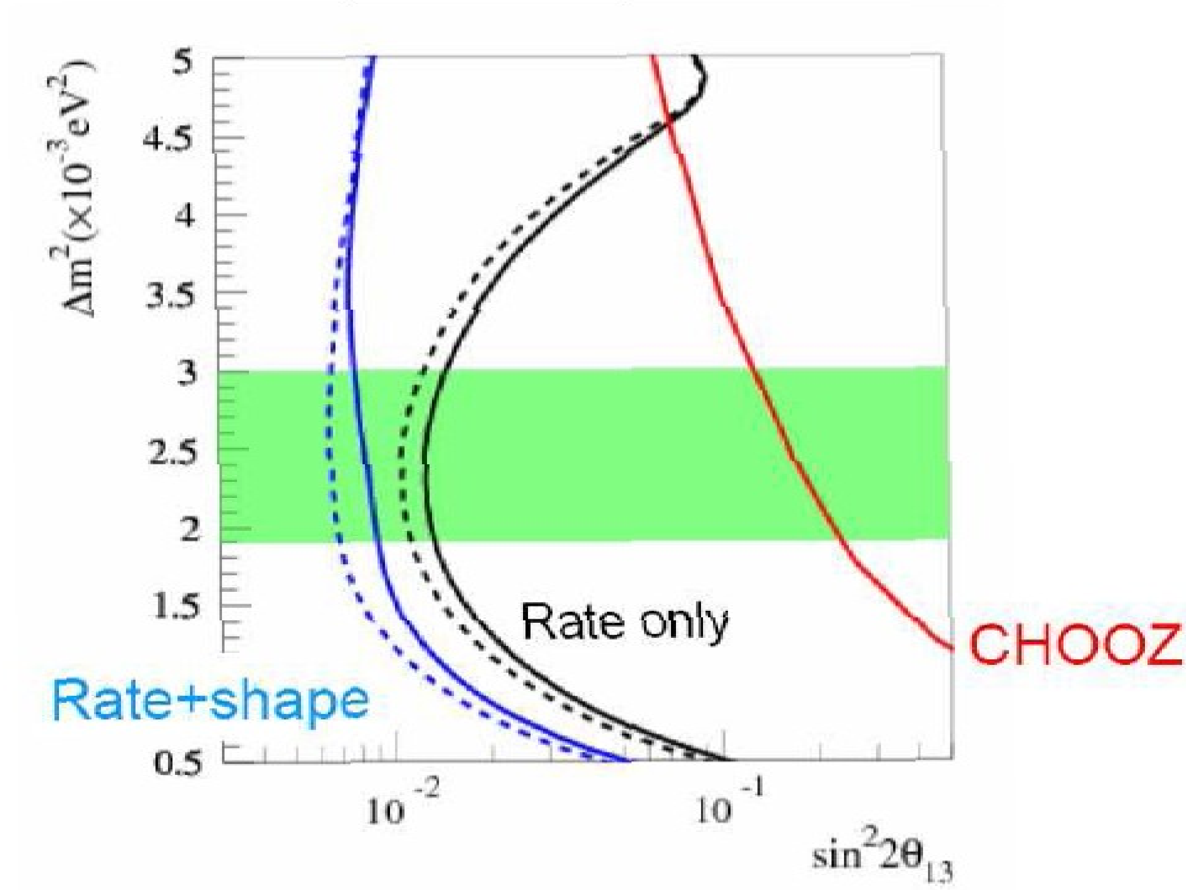
Detector Systematics

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

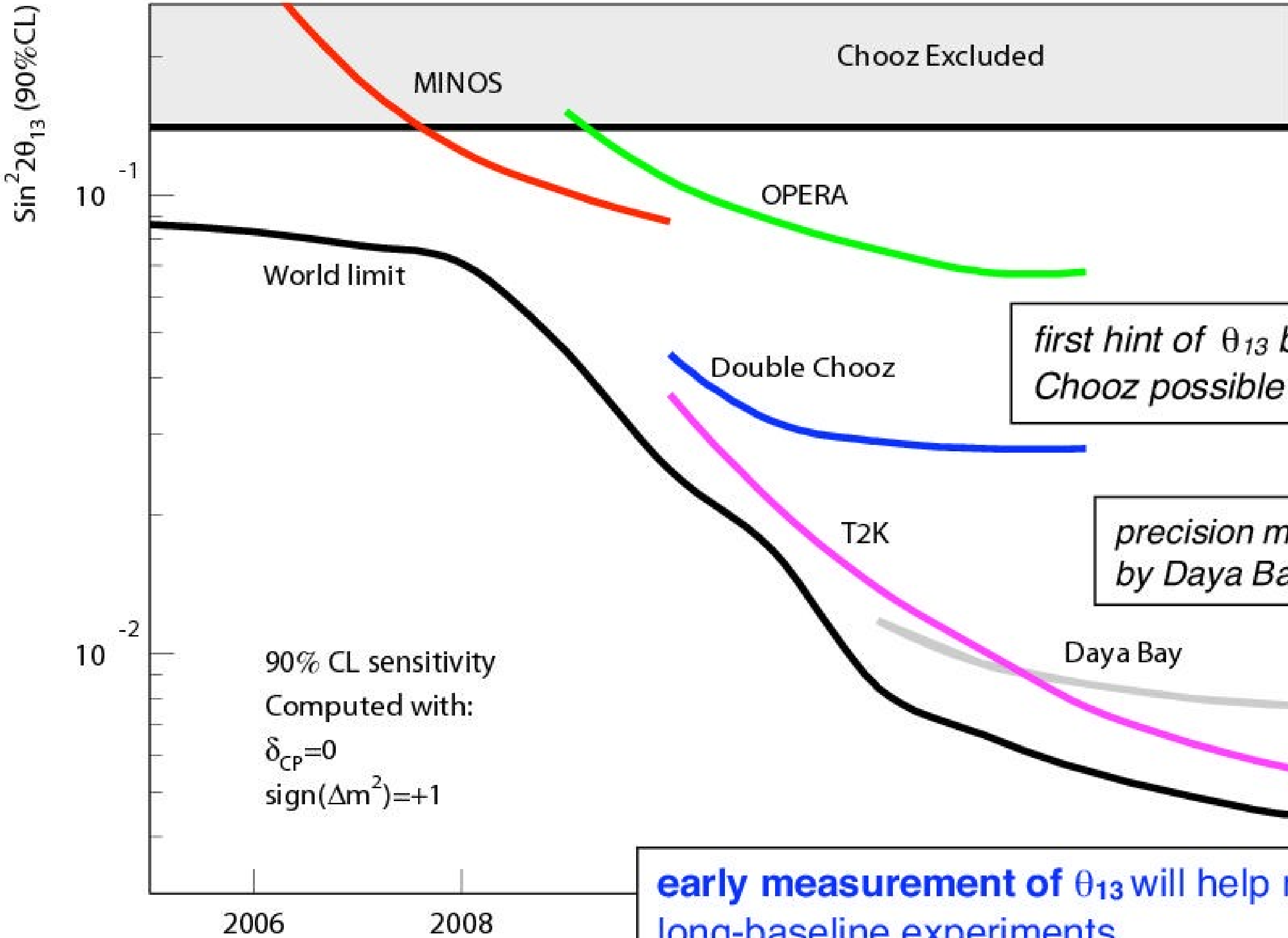


Fig: M. Mezzetto

first hint of θ_{13} by Double Chooz possible if θ_{13} large

precision measurement at 1% level by Daya Bay

early measurement of θ_{13} will help make decision on future long-baseline experiments

precision measurement of θ_{13} for unambiguous discovery and combined analysis with T2K and NOvA