The Daya Bay Reactor Neutrino Experiment

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CP violation in lepton sector

Three-neutrino oscillation

$$\nu_l = \sum_{i=1}^{3} U_{li}\nu_i \quad (l = e, \mu, \tau)$$

To incorporate CP violation into the three-light-neutrino model

Pontecorvo-Maki-Nakagawa-Sakata Matrix

$$\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{12} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} e^{i\phi_1} & 0 & 0 \\ 0 & e^{i\phi_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\sin^2 2\theta_{12} = 0.86^{+0.03}_{-0.04}$ $\sin^2 2\theta_{13} < 0.19$, CL = 90% $\sin^2 2\theta_{23} > 0.92$

CP violation parameters: Dirac phase δ, Majorana phases ϕ_1, ϕ_2

ϕ_1 and ϕ_2 could be manifested in $0\nu\beta\beta$ $\Rightarrow$ extremely hard to measure!

δ may be accessible through oscillation searches.

θ_{13} is the gateway of CP violation in lepton sector!

Theoretical predictions for θ_{13}

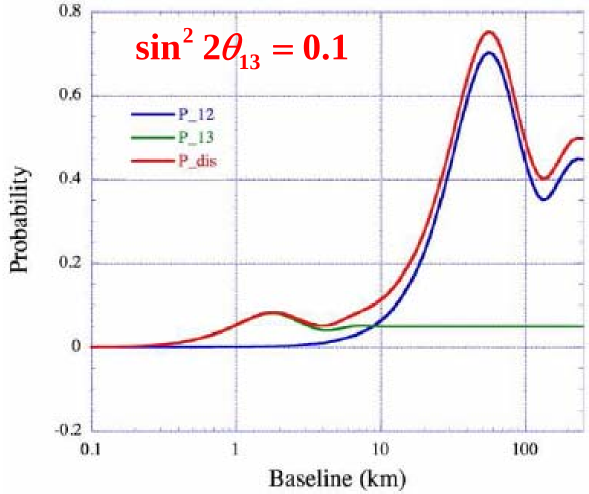
Model(s)	$\sin^2 2\theta_{13}$
Minimal SO(10)	0.13
Orbifold SO(10)	0.04
SO(10)+Flavor Symmetry	1.2×10^{-6}—0.18
SO(10)+Texture	4×10^{-4}—0.04
Flavor symmetries	0—0.15
Textures	4×10^{-4}—0.15
3×2 see-saw	0.04
Anarchy	>0.04
Renormalization group enhancement	0.03—0.04
M-Theory model	10^{-4}

A precise θ_{13} measurement is helpful in understanding the physics beyond the Standard Model.

How to measure θ_{13}?

- **Disappearance searches at reactors:**

$$P_{dis} = P_{12} + P_{13} = \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(1.267\cdot\Delta m_{21}^2\cdot\frac{L}{E}) + \cos^2\theta_{12}\sin^2 2\theta_{13}\sin^2(1.267\cdot\Delta m_{31}^2\cdot\frac{L}{E}) + \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2(1.267\cdot\Delta m_{32}^2\cdot\frac{L}{E})$$



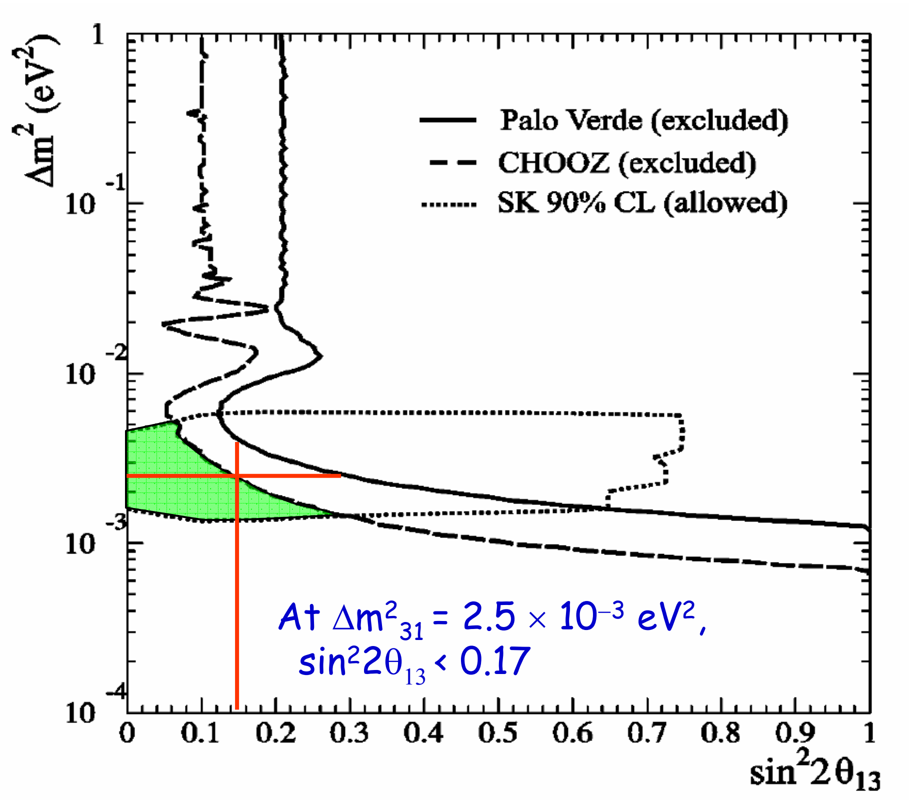
- **Appearance searches at accelerators:**

$$P_{app} \approx \sin^2\theta_{23}\sin^2\theta_{13}\sin^2(1.267\Delta m_{23}^2\frac{L}{E}) + \cos^2\theta_{23}\sin^2\theta_{12}\sin^2(1.267\Delta m_{12}^2\frac{L}{E}) - A(\rho)\cos^2\theta_{13}\sin\theta_{13}\sin\delta$$

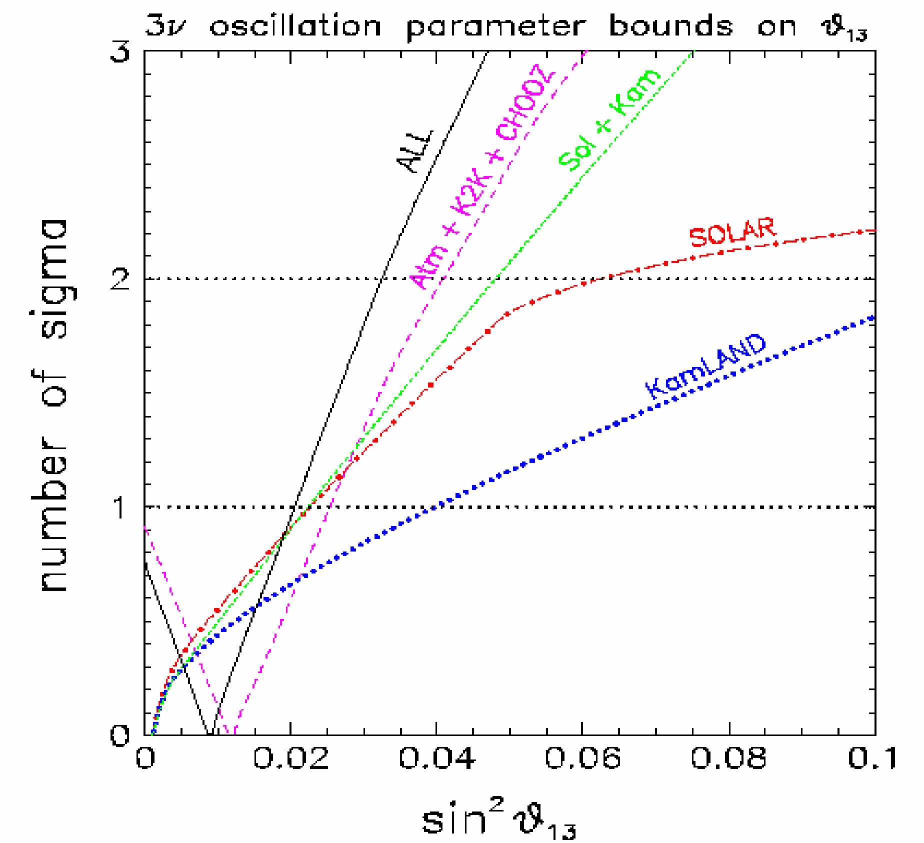
- **Reactor experiments provide a clean environment to measure θ_{13}.**
- **Accelerator experiments give access to both θ_{13} and δ values.**

Current knowledge on θ_{13}

Direct search (PRD 62, 072002)



Global fit (hep-ph/0506083)



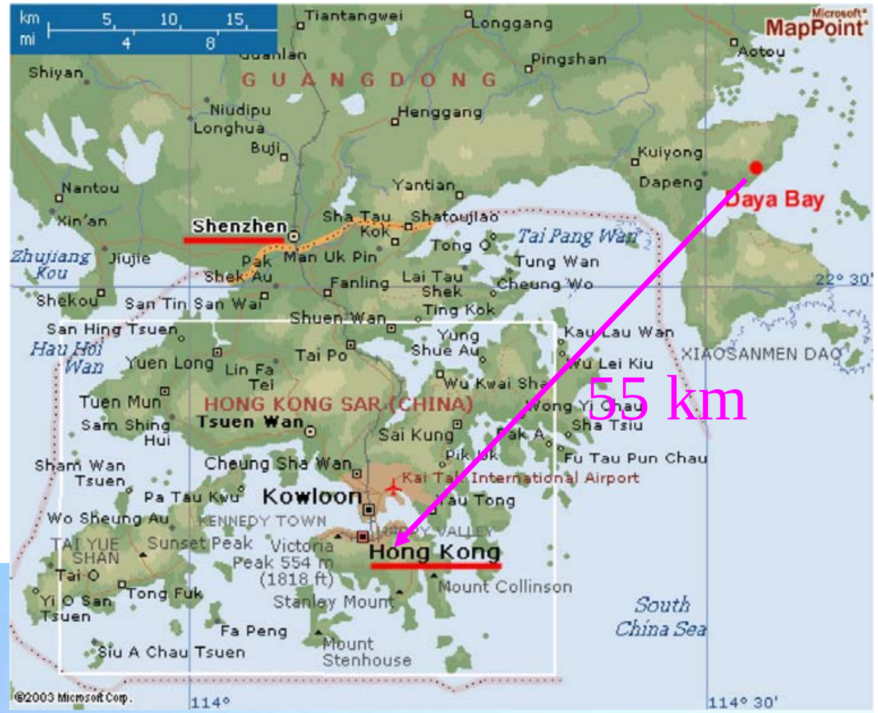
A small θ_{13}(e.g. $\sin^2 2\theta_{13}<0.02$) would make accelerator experimental searches for CP violation become a kind of "Mission: Impossible".

How to reach 1% precision?

- **Increase statistics:**
  - **Need intensive neutrino flux from powerful nuclear reactors**
  - **Utilize larger target mass, hence larger detectors**
- **Reduce systematic uncertainties:**
  - **Reactor-related:**
    - **Optimize baseline for best sensitivity and smaller residual errors**
    - **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**
    - **Interchange near and far detectors (optional)**
  - **Background-related**
    - **Go deeper to reduce cosmic-induced backgrounds**
    - **Enough active and passive shielding**

Daya Bay nuclear power plant

- **4 reactor cores, 11.6 GW**
- **2 more cores in 2011, 5.8 GW**
- **Mountains near by**
- **55 km to Hong Kong**



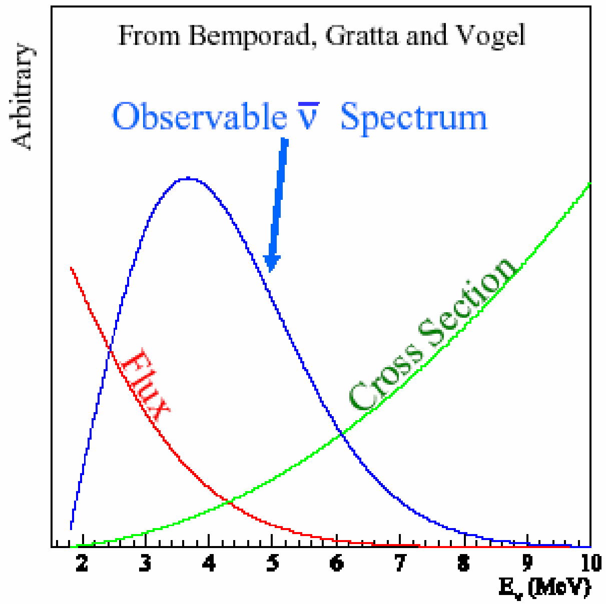
Signature of a signal

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

Prompt signal: $e^+ + e^- \rightarrow 2\gamma's$ $(E_{e^+} > 2m_e = 1.022\text{MeV})$

Delayed signal: $n + Gd \rightarrow Gd' + \gamma's$ $(\sum E_\gamma \sim 8\text{MeV},\ \tau_0 \sim 28\mu s)$

Delayed signal: $n + p \rightarrow d + \gamma$ $(E_\gamma = 2.2\text{MeV},\ \tau_0 \sim 180\mu s)$



Neutrino energy: **Threshold=1.8 MeV**

$$E_{\bar{\nu}} \cong T_{e^+} + T_n + (M_n - M_p) + m_{e^+}$$

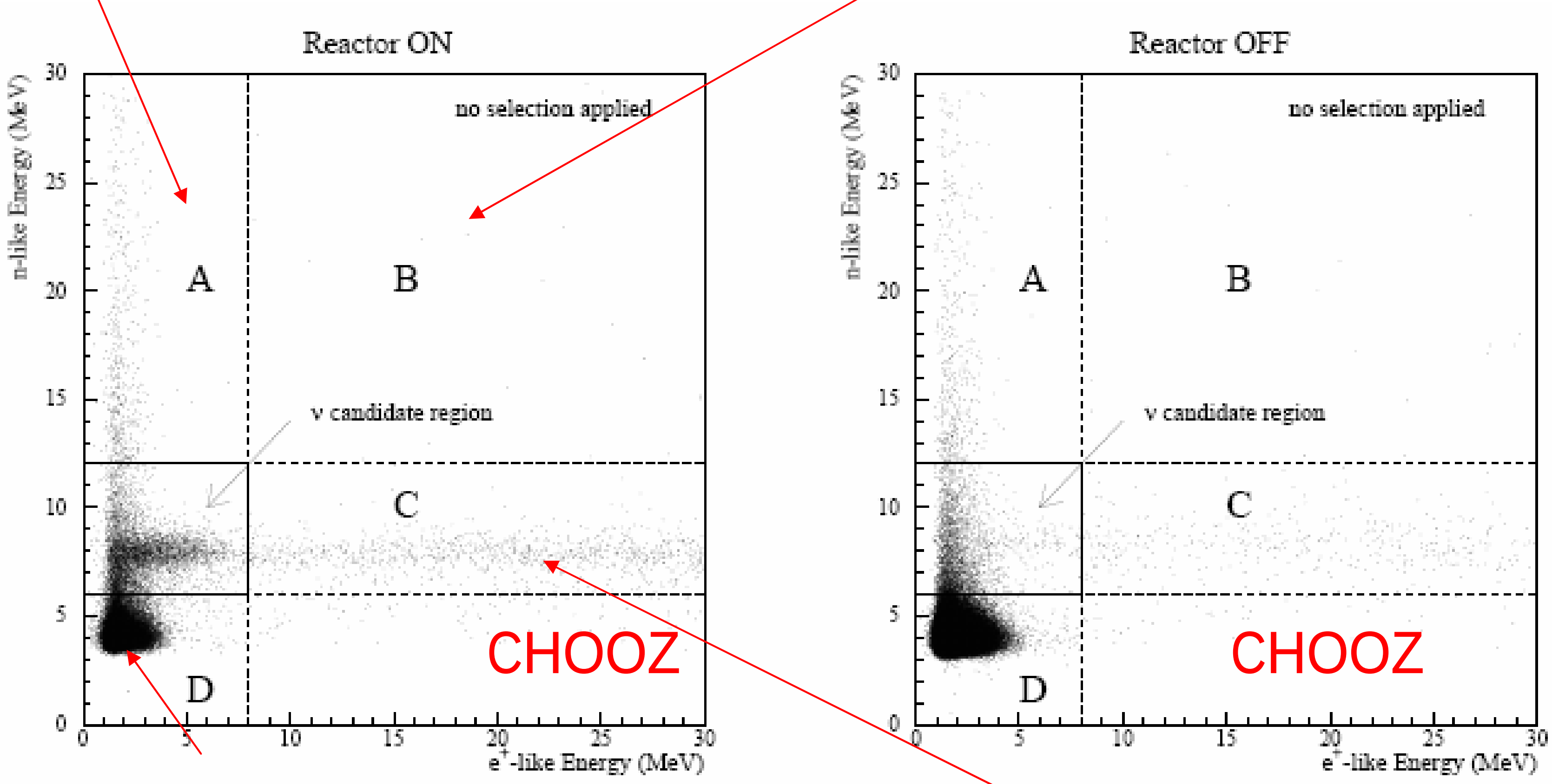
Antineutrino Interaction Rate
(events/day per 20 ton module)

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

Origins of background

Accidental coincidences

Stop muons



Two accidental coincidences

Fast neutrons

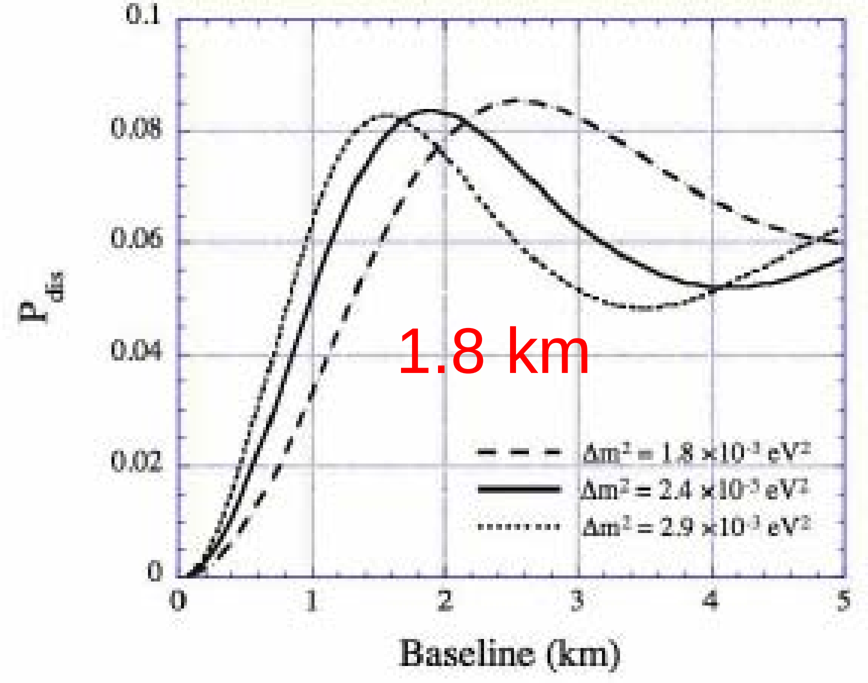
Primary design considerations

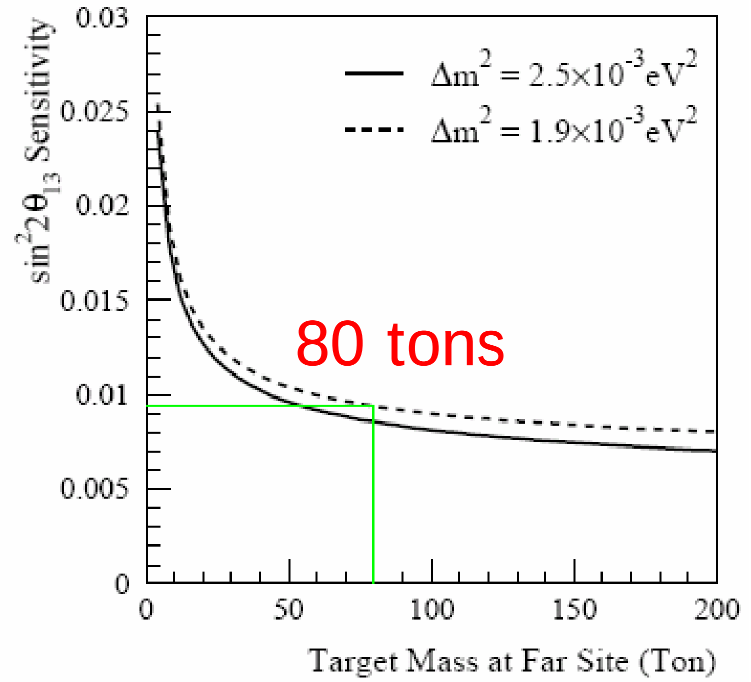
- ✓ *Identical near and far detectors* **to cancel reactor-related errors**
- ✓ *Multiple modules* **for reducing detector-related errors and cross checks**
- ✓ *Three-zone detector modules* **to reduce detector-related errors**
- ✓ *Overburden and shielding* **to reduce backgrounds**
- ✓ *Multiple muon detectors* **for reducing backgrounds and cross checks**
- ✓ *Movable detectors* **for swapping**

Baseline and target mass

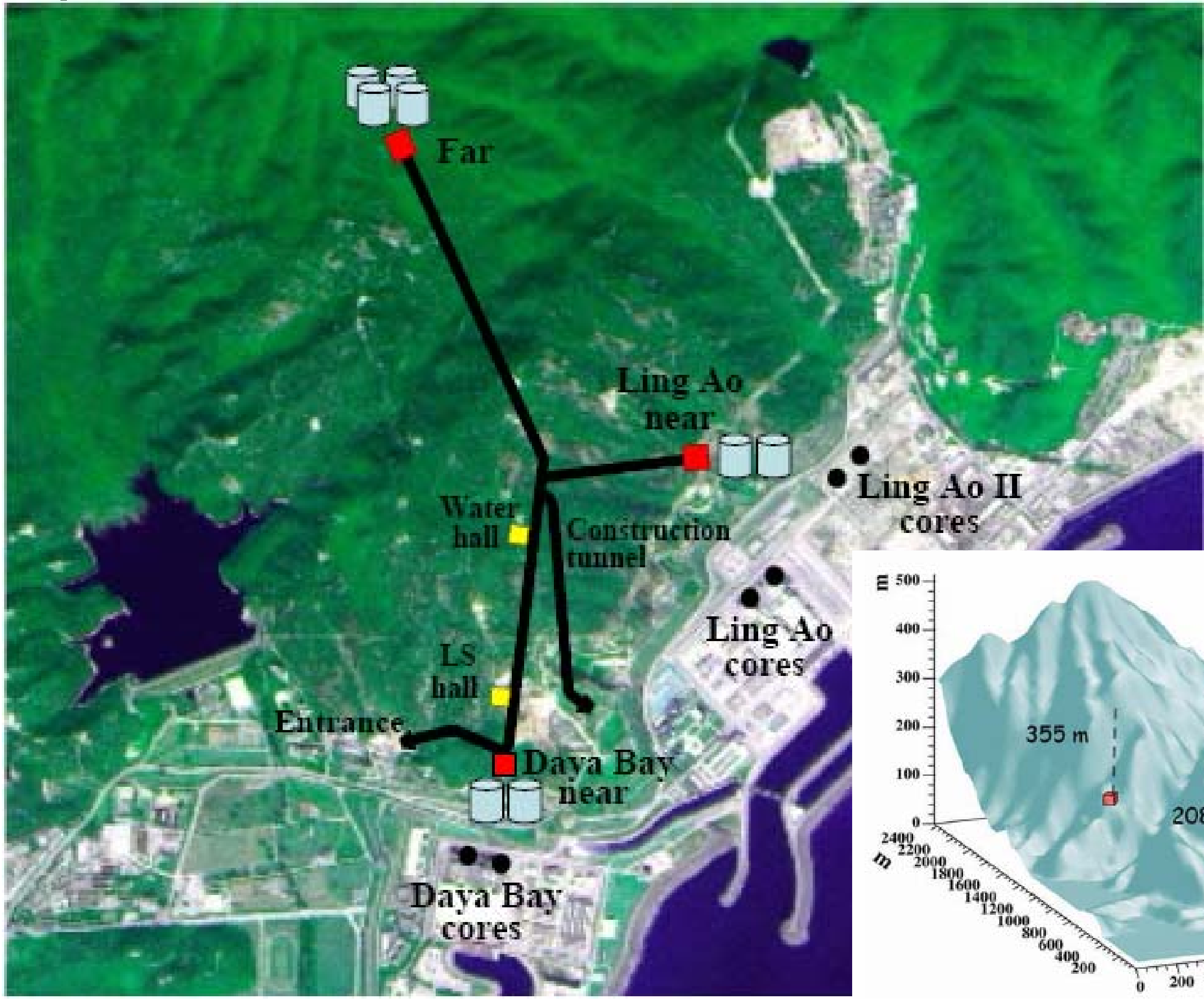
Input to the process:

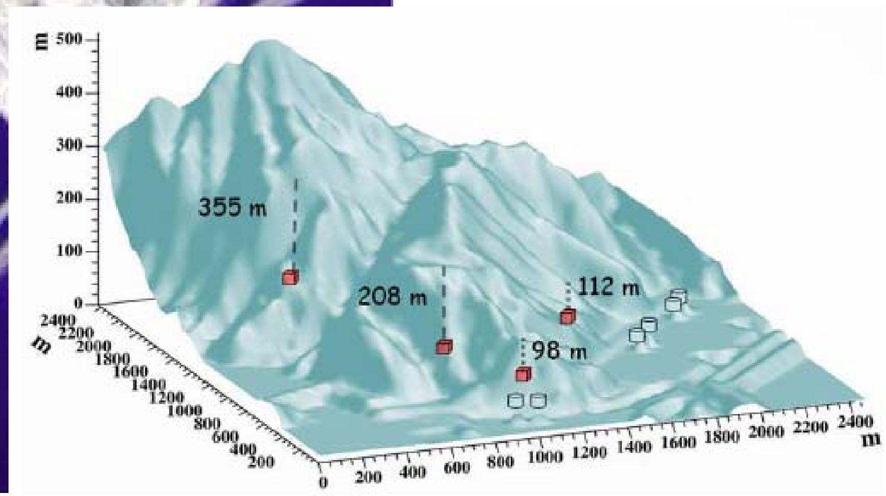
- $\bar{\nu}_e$ flux, oscillation and energy spectrum
- Systematic uncertainties of reactors and detectors
- Overburden, ambient background and uncertainties
- e^+ dependent rates and spectra of cosmogenic neutrons and ^{8}Li





Experimental Layout





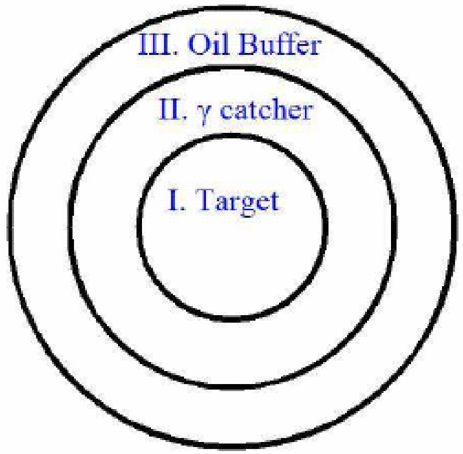
Far site
1615 m from Ling Ao
1985 m from Daya Bay
Overburden: 350 m

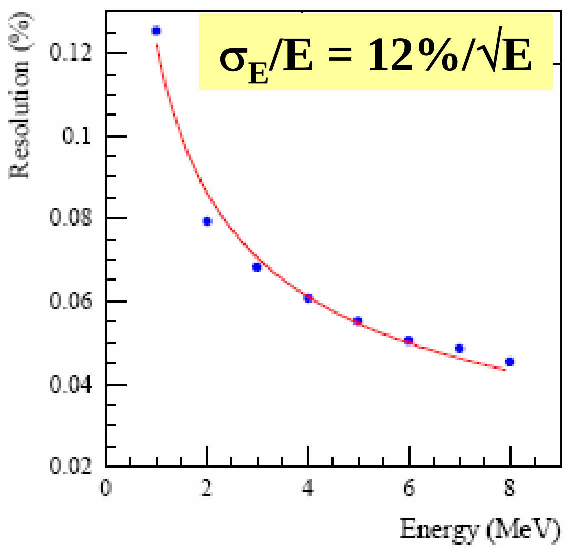
Ling Ao Near site
~500 m from Ling Ao
Overburden: 112 m

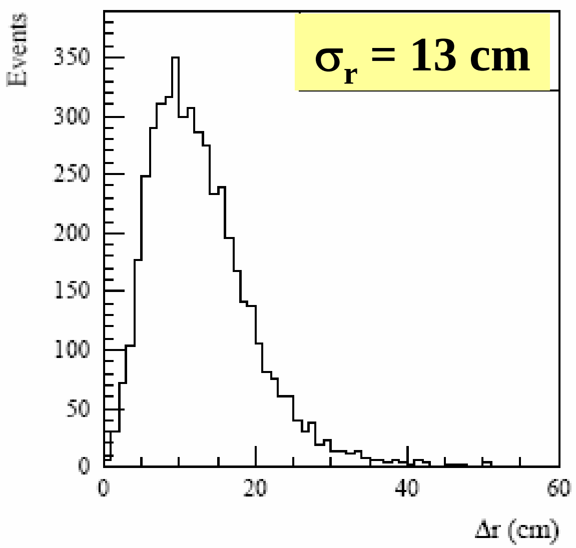
Daya Bay Near site
363 m from Daya Bay
Overburden: 98 m

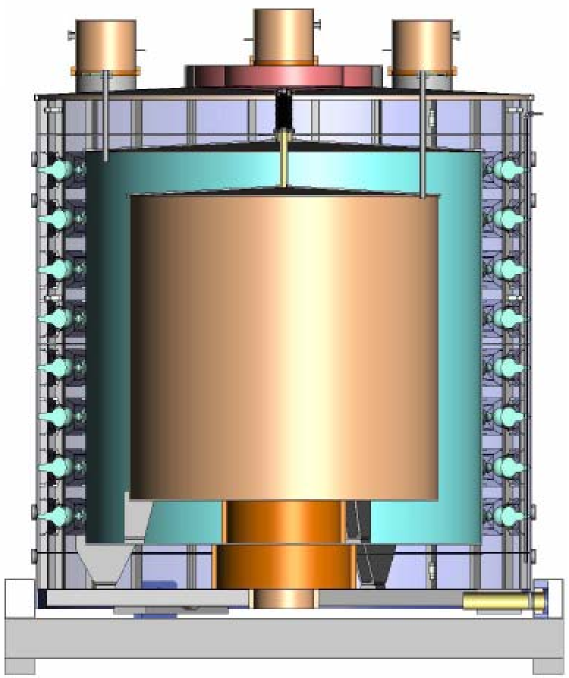
Anti-neutrino detector design

- Three zones modular structure:
  - **I.** Target: 20t, 1.6m Gd-loaded scintillator
  - **II.** γ-catcher: 20t, 45cm normal scintillator
  - **III.** Buffer shielding: 40t, 45cm oil
- Reflector at top and bottom
- 192 8"PMT/module
- PMT coverage: 12%(with reflector)



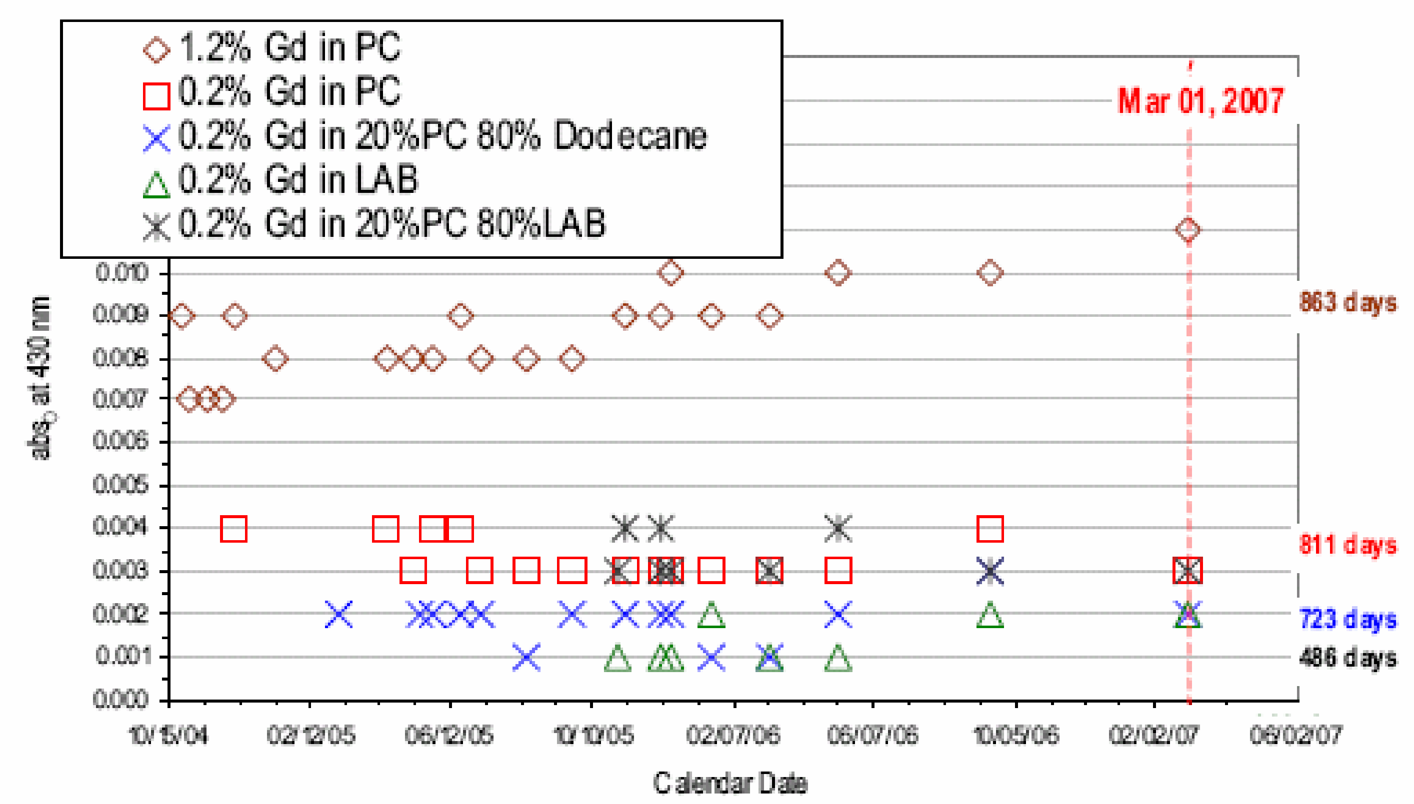






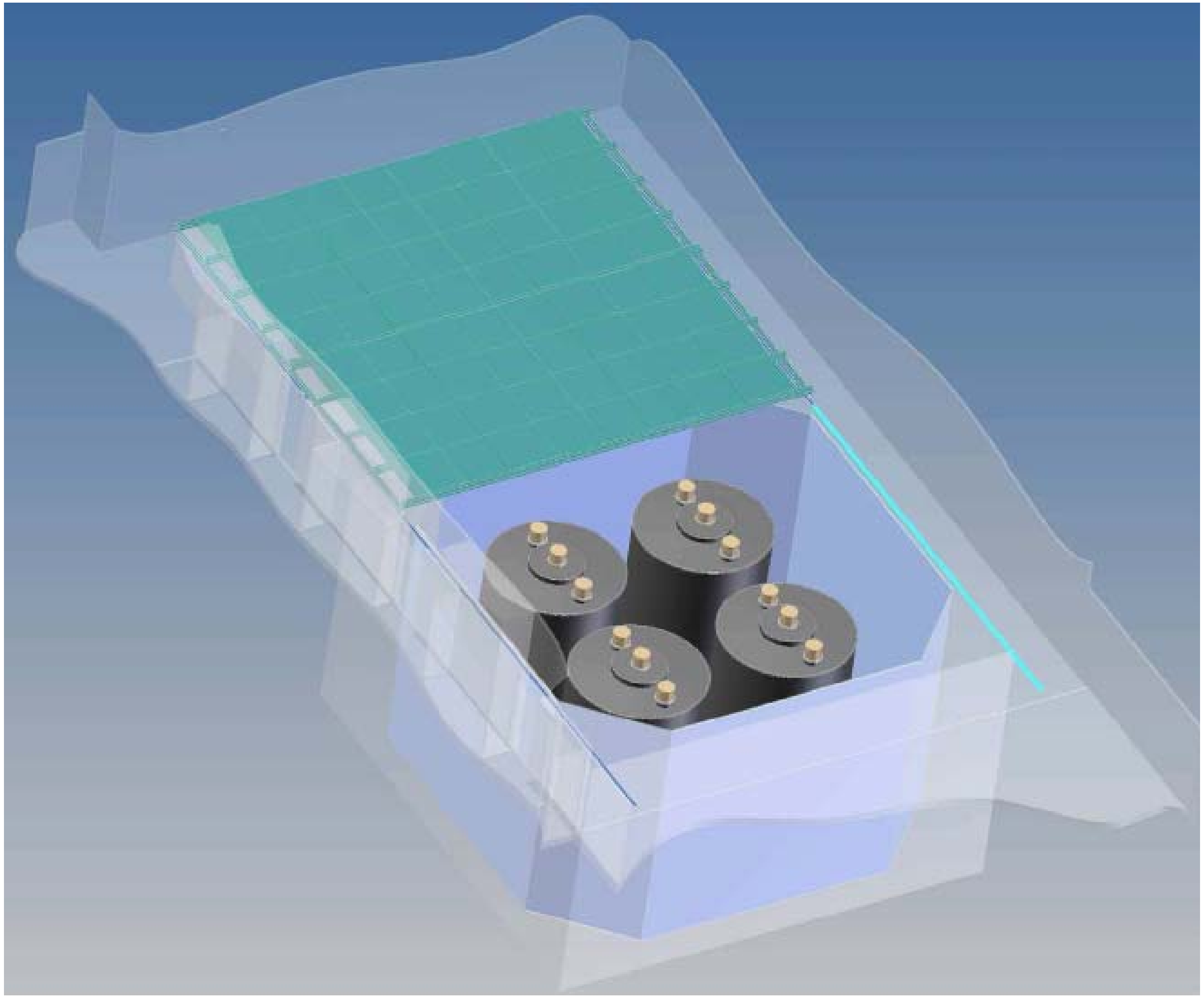
Gd-loaded liquid scintillator

- **Linear Alkyl Benzene (LAB) doped with organic Gd complex (0.1% Gd mass concentration)**



- **Gd-LS and LS mixed in storage pool and distributed to all sites**

AD modules in far site



Calibrations and monitoring

- **Full manual calibration procedures**

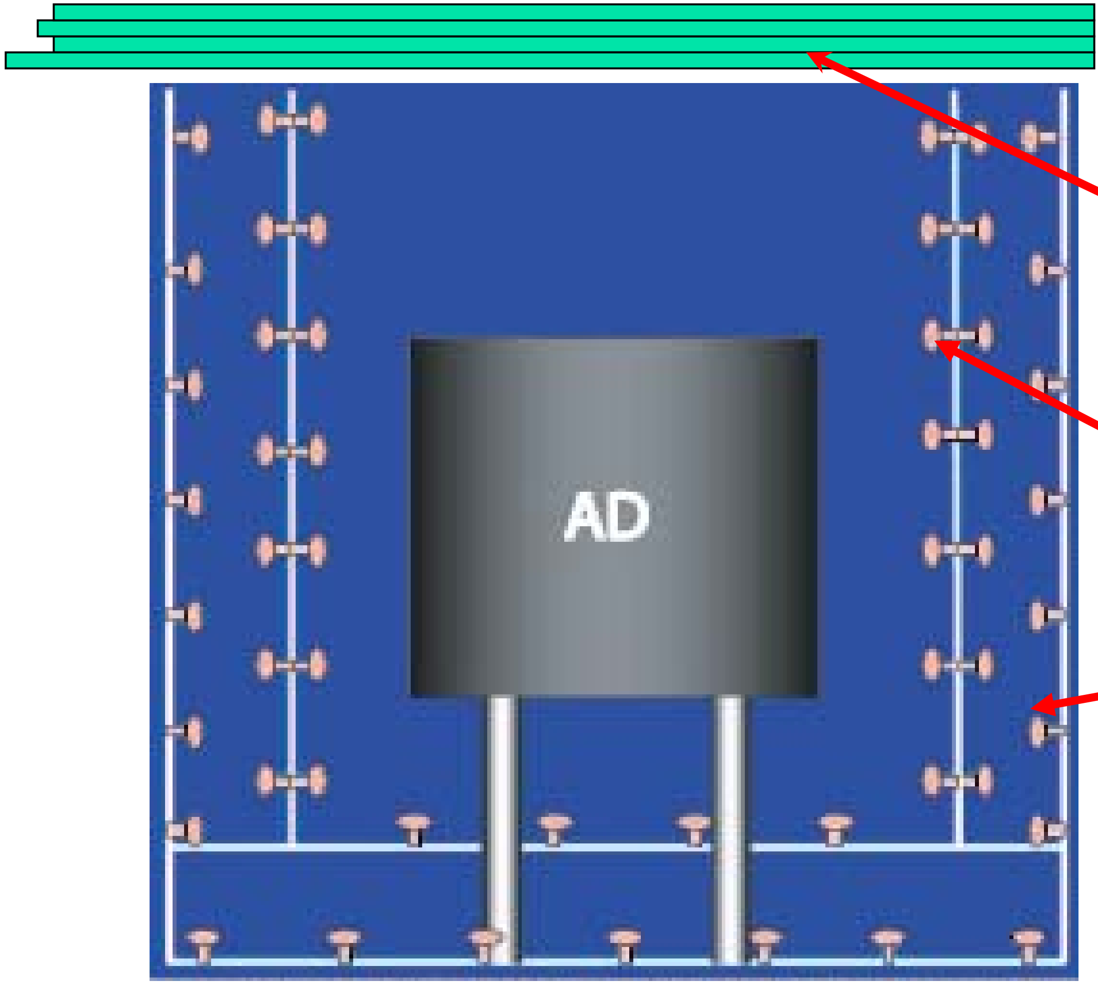
Requirement	Description	Proposed Solution(s)
Optical Integrity	Spatial uniformity of response, light attenuation	LED, γ sources
PMT gains	Match gains of all PMTs	LED - single p.e. matching
PMT timing	$\sim$1 ns timing calibration for each PMT	Pulsed LED
Energy scale	Set scale of energy deposition	Gamma sources
H/Gd ratio	Measure relative Gd fraction	neutron source

- **Automated calibration procedures**

Requirement	Description	Proposed Solution(s)
Mechanical/thermal	Verify these properties are stable	Load sensors, thermometers, etc.
Optical stability	Track variations in light yield	Gamma sources, spallation products
Uniformity, light attenuation	Monitor spatial distribution of light	Gamma sources, spallation products
Detection efficiency	Monitor ϵ for neutrons and positrons	Gamma sources, neutron sources
PMT gains	Monitor 1 p.e. peaks	LED source

- **And maybe more calibration procedures to come…**

Muon veto detector design



Multiple muon veto detectors:

- **RPC's at the top as muon tracker**
- **Water pool as Cherenkov counter has inner/outer regions**
- **Combined eff.**
  > (99.5 ± 0.25) %

Estimated efficiencies

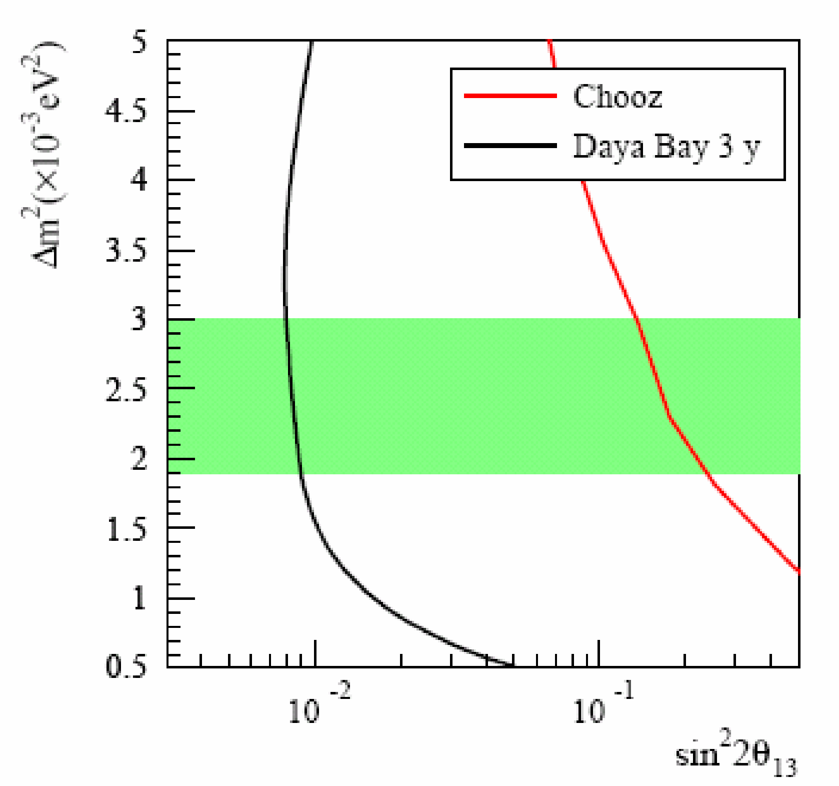
Source	Efficiency	
	Near	Far
Neutron detection	0.78	0.78
Positron detection	0.98	0.98
Muon Veto deadtime	0.95	0.95
Calibration runs	0.99	0.99
Reactor/experiment downtime	0.82	0.82

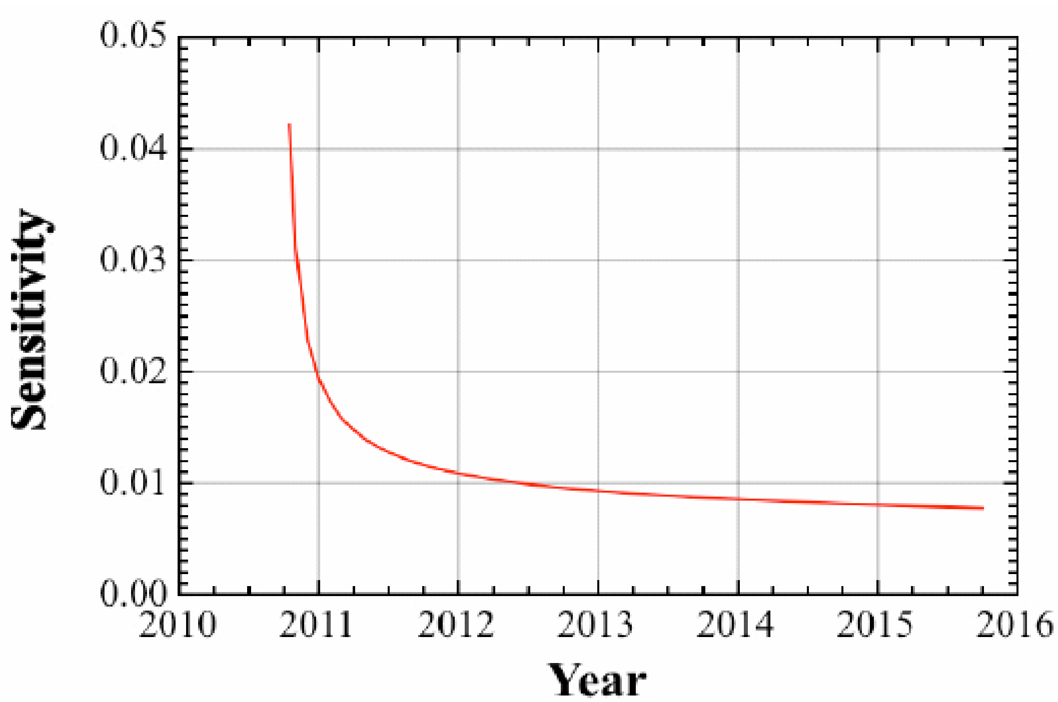
Neutron detection efficiency is a product of 85% Gd fraction and 93% energy cut.

Summary of uncertainties

Sources	Uncertainty
Neutrinos from Reactor	0.087% (4 cores) 0.13% (6 cores)
Detector (per module)	0.38% (baseline) 0.18% (goal)
Backgrounds	0.32% (Daya Bay near) 0.22% (Ling Ao near) 0.22% (far)
Signal statistics	0.2%

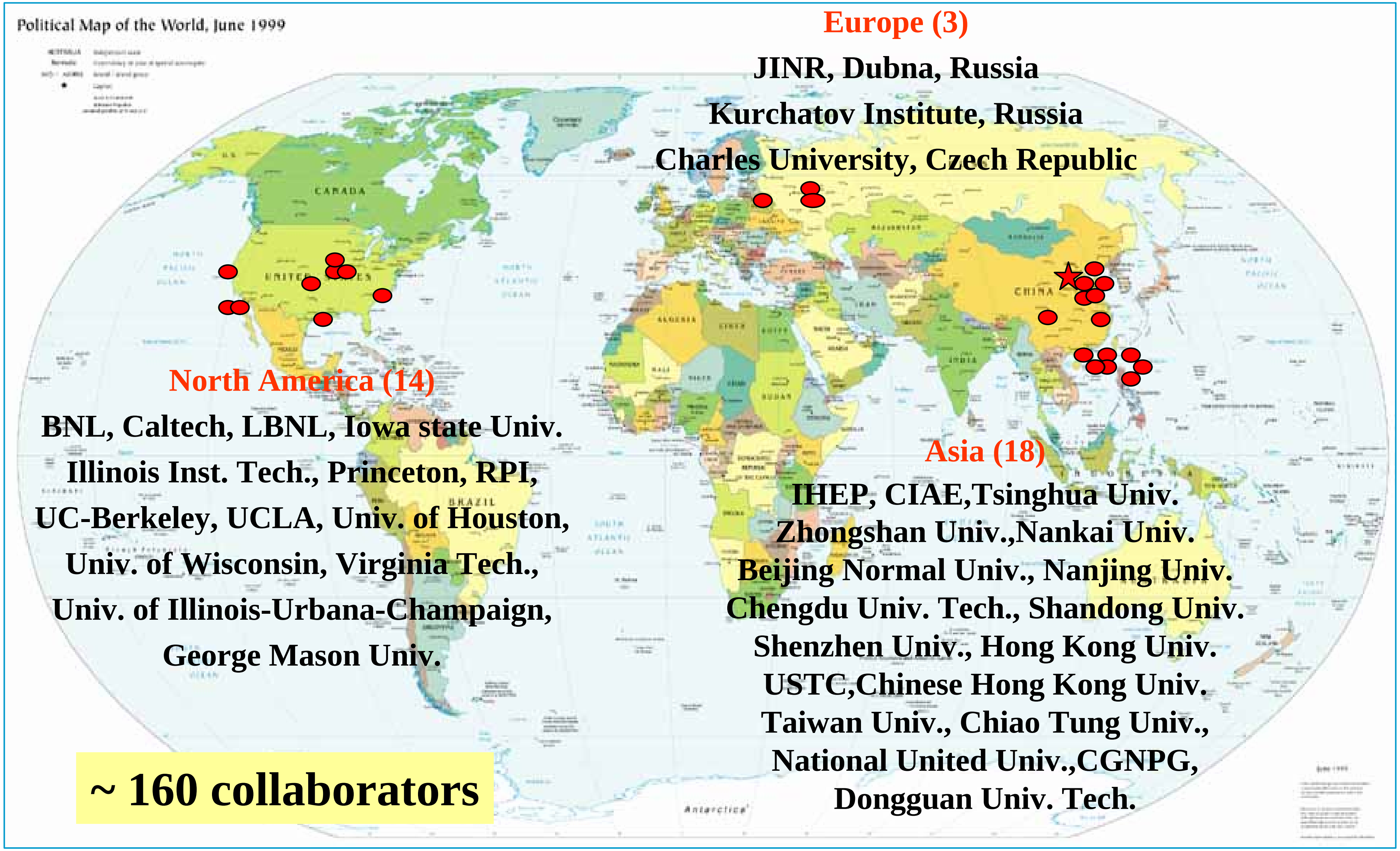
Goal to be reached at Daya Bay





The sensitivity of ≤ 0.01 for $\sin^2 2\theta_{13}$ will be reached in 2013.

This needs a team effort!



Europe (3)

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

North America (14)

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,
George Mason Univ.

Asia (18)

IHEP, CIAE,Tsinghua Univ.
Zhongshan Univ.,Nankai Univ.
Beijing Normal Univ., Nanjing Univ.
Chengdu Univ. Tech., Shandong Univ.
Shenzhen Univ., Hong Kong Univ.
USTC,Chinese Hong Kong Univ.
Taiwan Univ., Chiao Tung Univ.,
National United Univ.,CGNPG,
Dongguan Univ. Tech.

~ 160 collaborators

Recommendations

第250次香山科学会议简报（2005）

Meeting brief for the 250th Xiangshan Scientific Meeting

…

2．中微子混合角θ$_{13}$是自然界的基本参数之一，…是一个急需解决的关键问题。

Neutrino mixing angle θ$_{13}$ is one of the fundamental parameters in nature,…a key issue to be resolved.

3．…条件已经基本成熟，而且实验得到了大亚湾核电站有关方面的大力支持。…准备充分，完全有能力和实力完成这项实验。

…have mature technology and get strong support from Daya Bay Nuclear Power Plant. … get preparations well done and have capability and strength to complete this experiment.

4．确定θ$_{13}$…在国际上竞争激烈，…项目在年内立项是赢得国际竞争的关键。

International competition in determining θ$_{13}$ is very vigorous,…getting the project approved promptly is a key to win the competition.

…

This is an usual way to initiate a giant research project in China.

Roadmap

➢ Passed DOE scientific review	Oct. 2006
➢ CDR released (hep-ex/0701029)	Jan. 2007
➢ Passed US CD-1 review	April 2007
➢ Passed final nuclear safety review in China	April 2007
➢ Received funding from Chinese agencies	April 2007
➢ TDR to PAP released	Sept. 2007
➢ Ground breaking ceremony	Oct. 2007
➢ Anticipate US CD-2/3a review	Nov. 2007
➢ Deployment of the first detector	July 2009
➢ Data taking with final configuration	Sept. 2010

Summary

- **An ultimate sensitivity of $\leqslant$ 0.01 for $\sin^2 2\theta_{13}$ is designed to be reached at the Daya Bay experiment.**
- **Detector design is close to complete.**
- **Received commitment from Chinese funding agencies.**
- **US CD-2/3a Physics Review scheduled for Nov. 2007.**
- **Civil construction will start from Oct. 2007, detectors will be deployed in 2009, and full operation expected in 2010.**

And more…

We already know GuangDong province is a place for providing one of the most delicious foods and the cheapest "Made in China" products in the world.

We are anticipating it will also be an excellent place for us to have the most precise "Made in China" θ_{13} .

Thank you!

Back-up slides

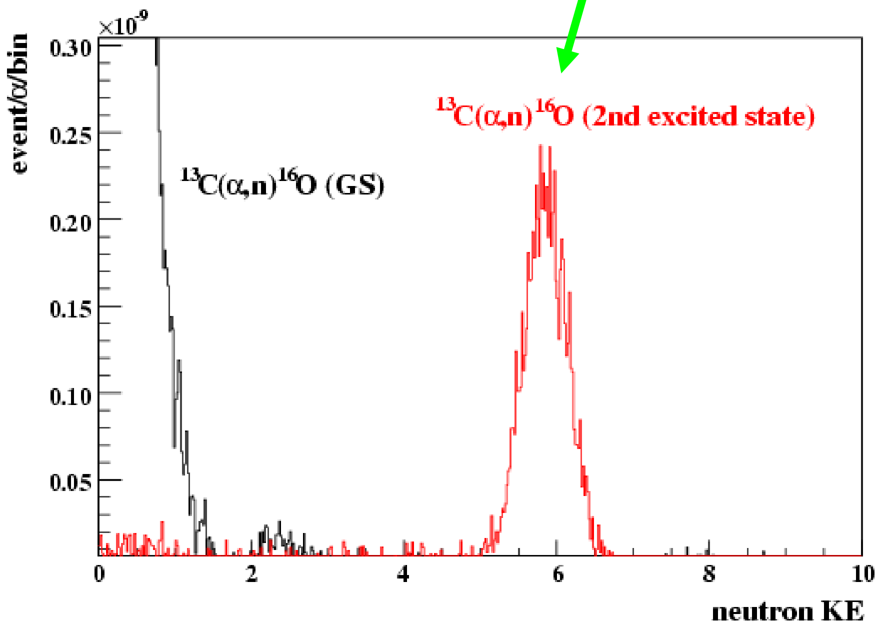
Reactor neutrino spectrum

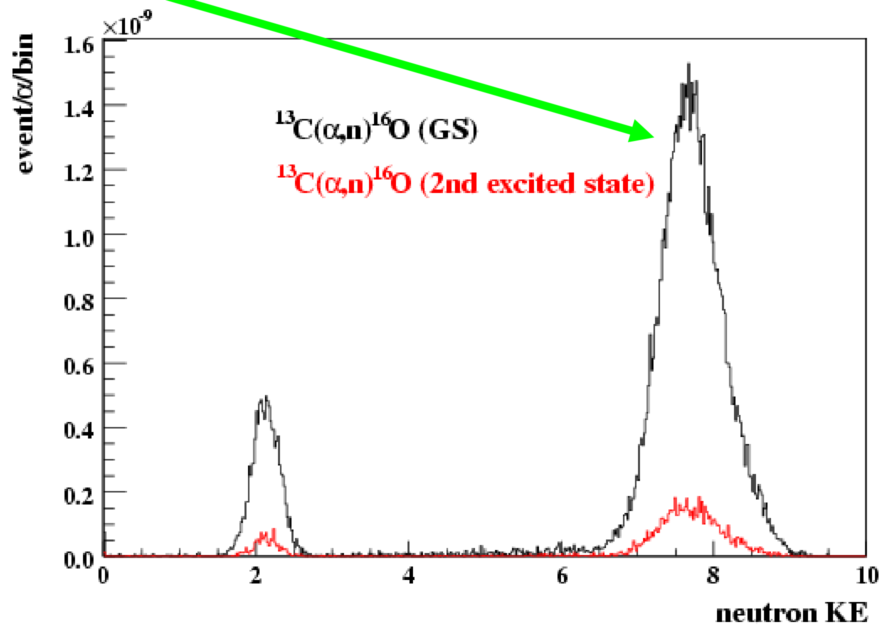
- **Reactor neutrino rate and spectrum depends on:**
  - **The fission isotopes and their fission rate, uncorrelated ~ 1-2%**
  - **Fission rate depends on thermal power, uncorrelated ~ 1%**
  - **Energy spectrum of weak decays of fission isotopes, correlated ~ 1%**
- **Three ways to obtain reactor neutrino spectrum:**
  - **Direct measurement at near site**
  - **First principle calculation**
  - **Sum up neutrino spectra of ^{235}U, ^{239}Pu, ^{241}Pu(from measurement) and ^{238}U(from calculation, ~ 1%)**
- **They all agree well within 3%**

Calibrating Energy Cuts

Automated deployed radioactive sources to calibrate the detector energy and position response within the entire range.

- ^{68}Ge (0 KE e^+ = 2×0.511 MeV γ's)
- ^{60}Co (2.506 MeV γ's)
- ^{238}Pu-^{13}C (6.13 MeV γ's, 8 MeV n-capture)



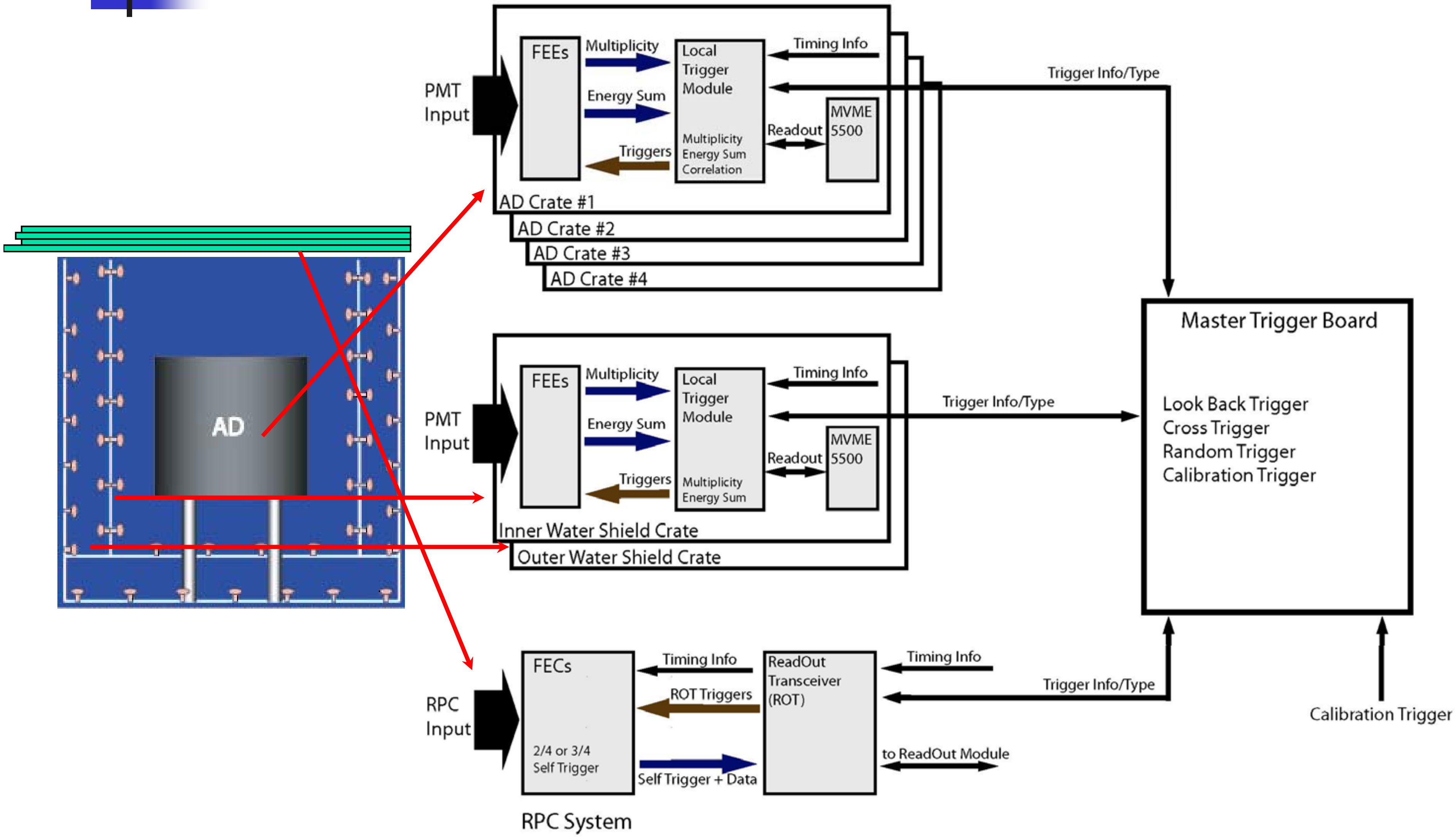


Estimated event rates

Detector	Description	Trigger Rates (Hz) DB	LA	Far	Occ	Ch No.	data rate (kB/s)
$\bar{\nu}$ module	cosmic-μ	36×2	22×2	1.2×4	100%	192	1408
	Rad.	50×2	50×2	50×4			
Inner water shield	Rad & noise	50	50	50	10%	123/169	31
	cosmic-μ	250	160	15	70%		526
Outer water shield	Rad & noise	50	50	50	10%	168/212	41
	cosmic-μ	250	160	15	30%		309
RPC	Rad.	2000	2000	3000	10%	32/module	217
	cosmic-μ	186	117	11			11
site totals	(kB/s)	1042	788	714			2544

The total event rate in each site is less than 3.5 kHz and is therefore affordable in the readout-every-hit scheme.

FEE and trigger system



Sources of systematics

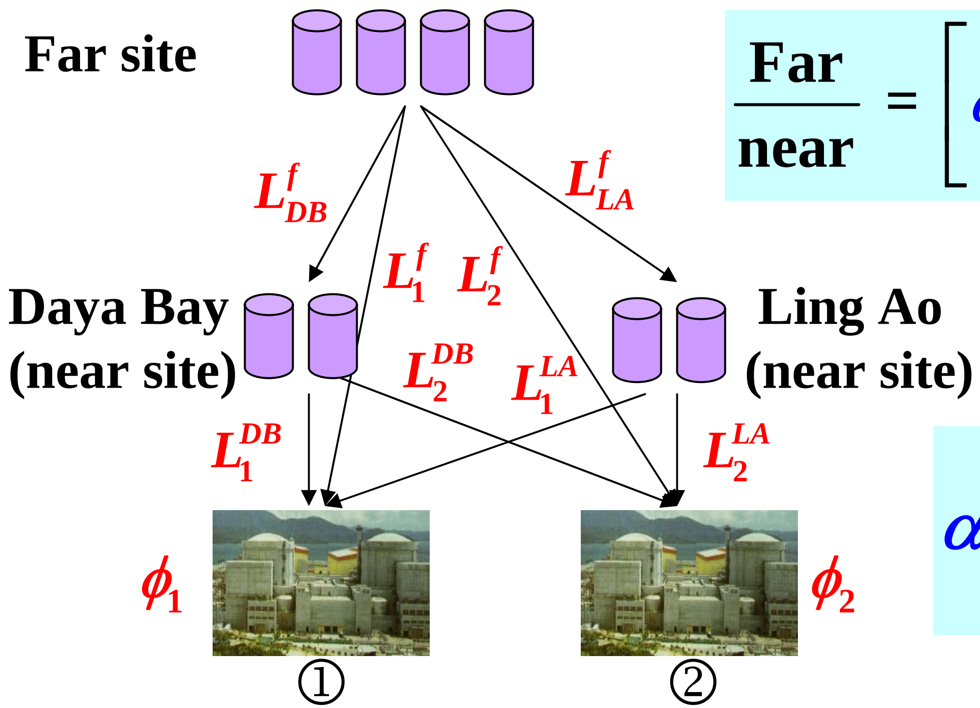
Detector-related

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%

Reactor-related

Number of cores	α	σ_ρ(power)	σ_ρ(location)	σ_ρ(total)
4	0.338	0.035%	0.08%	0.087%
6	0.392	0.097%	0.08%	0.126%

Reactor-related uncertainties



$$\frac{\text{Far}}{\text{near}} = \left[\alpha \sum_r \frac{\phi_r}{(L_r^{DB})^2} + \sum_r \frac{\phi_r}{(L_r^{LA})^2} \right] \Big/ \sum_r \frac{\phi_r}{(L_r^f)^2}$$

$$\alpha = \frac{(L_2^{LA} \cdot L_{DB}^f)^{-2} - (L_1^{LA} \cdot L_{LA}^f)^{-2}}{(L_1^{DB} \cdot L_{LA}^f)^{-2} - (L_2^{DB} \cdot L_{DB}^f)^{-2}}$$

Assuming 30 cm precision in core position

Number of cores	α	σ_ρ(power)	σ_ρ(location)	σ_ρ(total)
4	0.338	0.035%	0.08%	0.087%
6	0.392	0.097%	0.08%	0.126%

Background-related errors

- **Uncorrelated backgrounds:**

  U/Th/K/Rn/neutron

  Single gamma rate @ 0.9MeV < 50Hz

  Single neutron rate < 1000/day

- **Correlated backgrounds:**

  Fast Neutrons: double coincidence

  ^{8}He/^{9}Li: neutron emitting decays

	DYB site	LA site	far site
Antineutrino rate (/day/module)	930	760	90
Natural radiation (Hz)	<50	<50	<50
Single neutron (/day/module)	18	12	1.5
β-emission isotopes	210	141	14.6
Accidental/Signal	<0.2%	<0.2%	<0.1%
Fast neutron/Signal	0.1%	0.1%	0.1%
^{8}He^{9}Li/Signal	0.3%	0.2%	0.2%