BROOKHAVEN
NATIONAL LABORATORY

The last unknown neutrino mixing angle θ_{13} and the Daya Bay Experiment

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Daya Bay Collaboration

Outline
1. Motivation
2. $\bar{\nu}_e$ source
3. Detector
4. Systematics
5. Sensitivity
6. Status & summary

θ_{13}: The Last Unknown Neutrino Mixing Angle

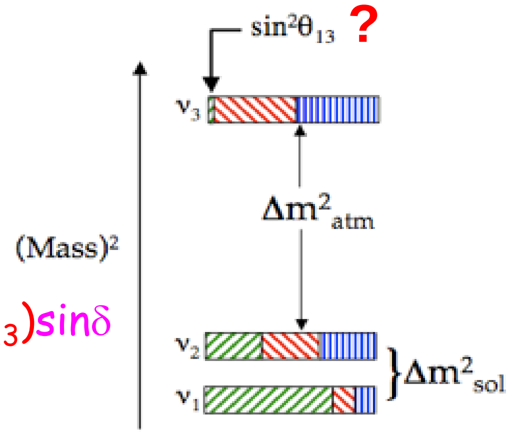
U_{MNSP} Matrix

Maki, Nakagawa, Sakata, Pontecorvo

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

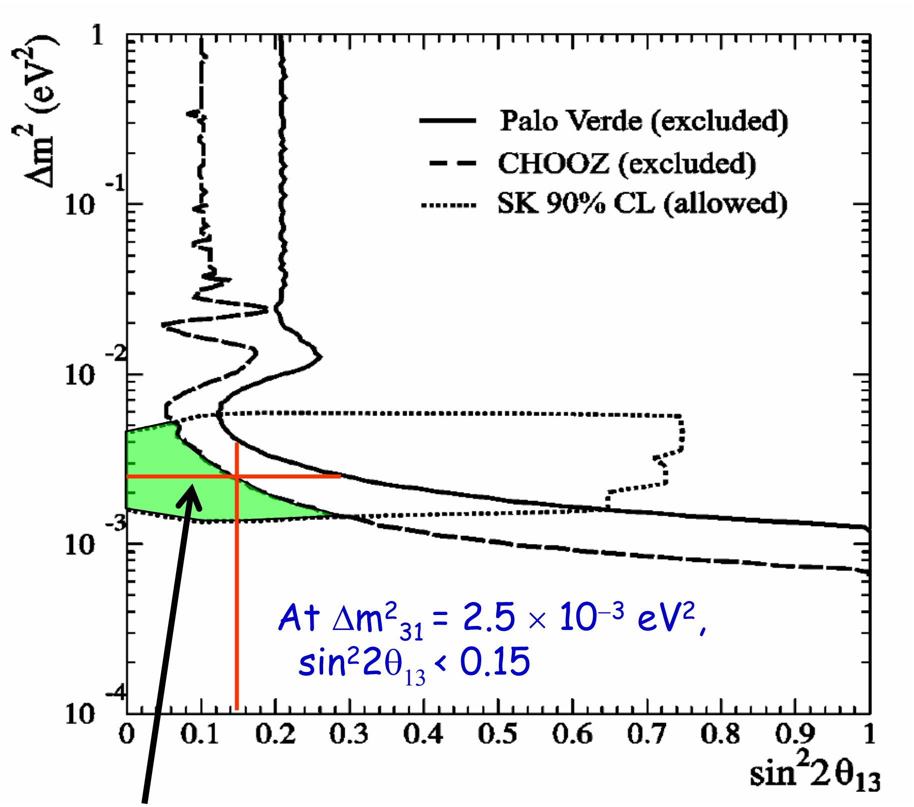
$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\substack{\text{atmospheric,} \\ \text{accelerator} \\ \theta_{23} = \sim 45^\circ}} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\substack{\text{reactor,} \\ \text{accelerator} \\ \theta_{13} = ?}} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\substack{\text{SNO, solar SK,} \\ \text{KamLAND} \\ \theta_{12} \sim 32^\circ}} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}_{0\nu\beta\beta}$$

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



Current Knowledge of θ_{13}

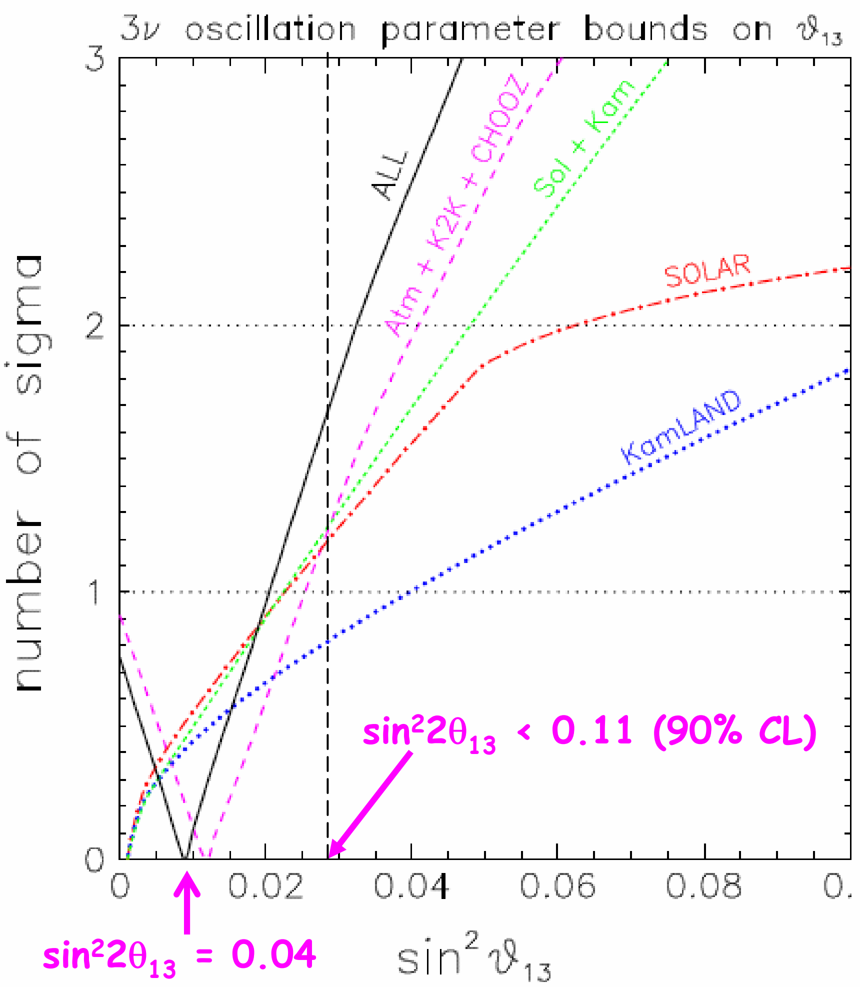
Direct search



At $\Delta m^2_{31} = 2.5 \times 10^{-3}$ eV^2,
$\sin^2 2\theta_{13} < 0.15$

allowed region

Global fit



$\sin^2 2\theta_{13} < 0.11$ (90% CL)

$\sin^2 2\theta_{13} = 0.04$

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

Fogli etal., hep-ph/0506083

Where To Place The Detectors ?

- Since reactor $\bar{\nu}_e$ are low-energy, it is a disappearance experiment:

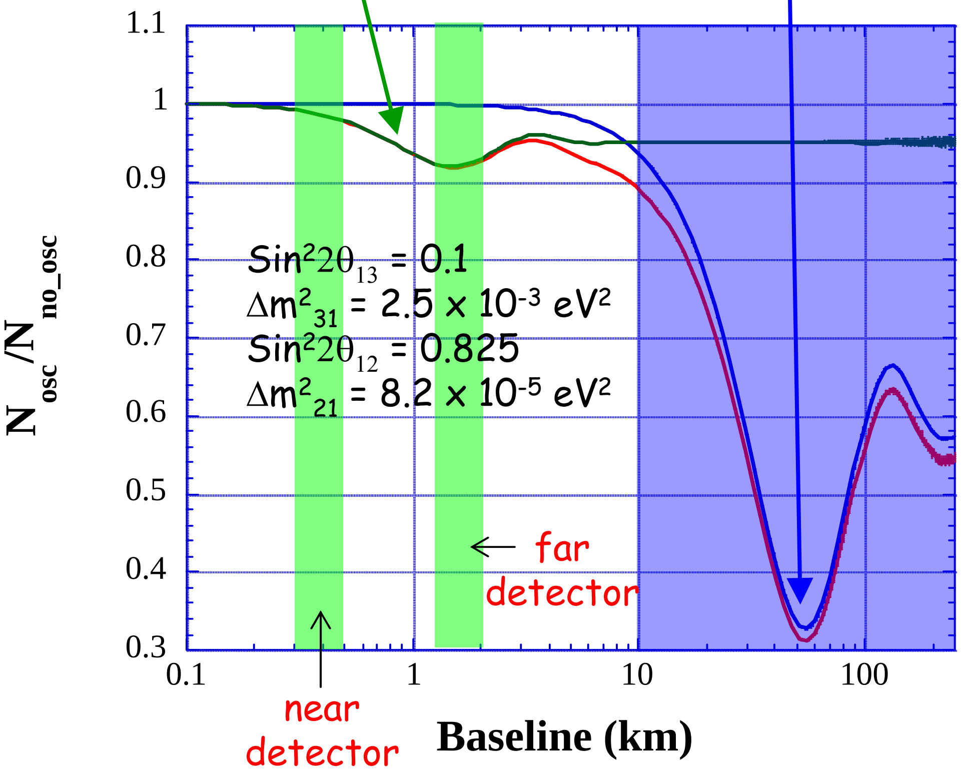
$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

- Place near detector(s) close to reactor(s) to measure raw flux and spectrum of $\bar{\nu}_e$, reducing reactor-related systematic

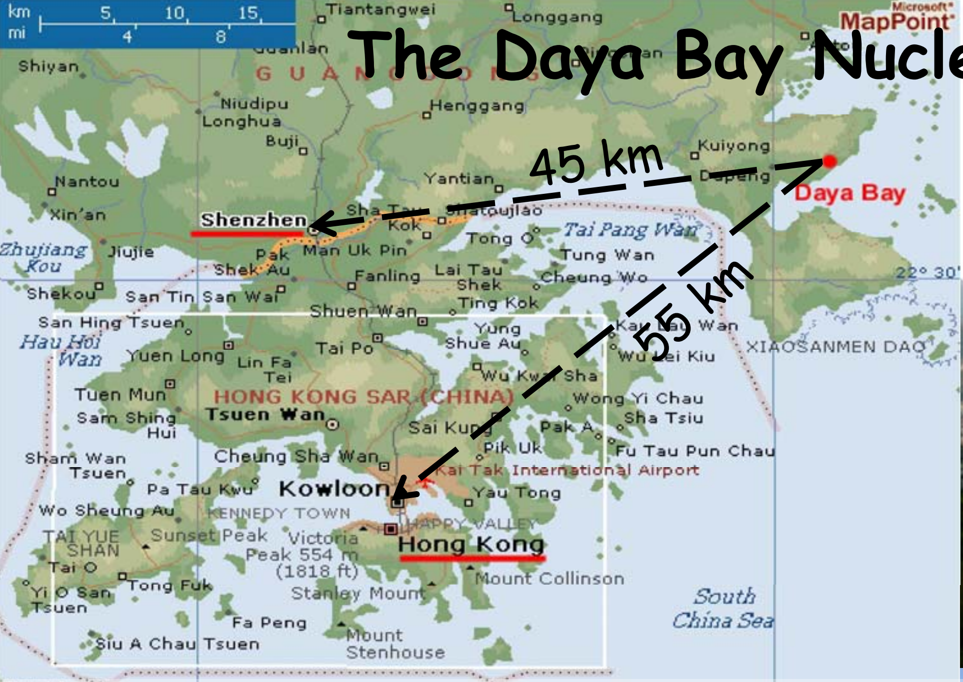
- Position a far detector near the first oscillation maximum to get the highest sensitivity, and also be less affected by θ_{12}

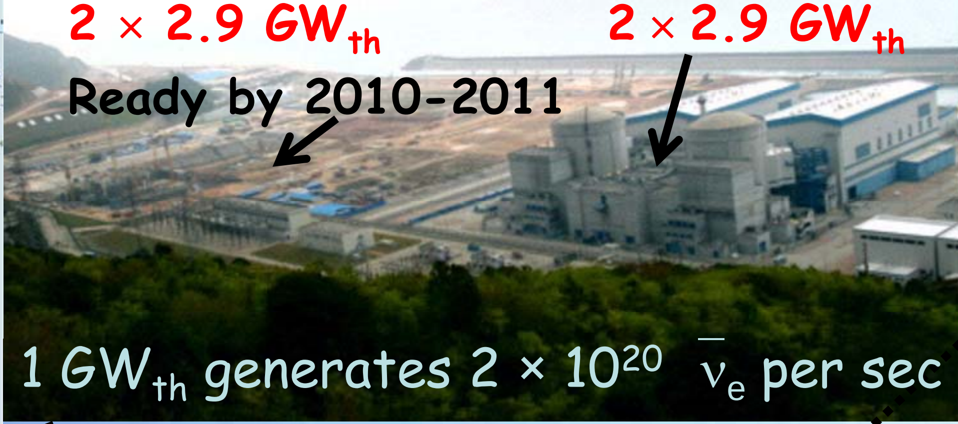
Small-amplitude oscillation due to θ_{13} integrated over E

Large-amplitude oscillation due to θ_{12}



The Daya Bay Nuclear Power Facilities





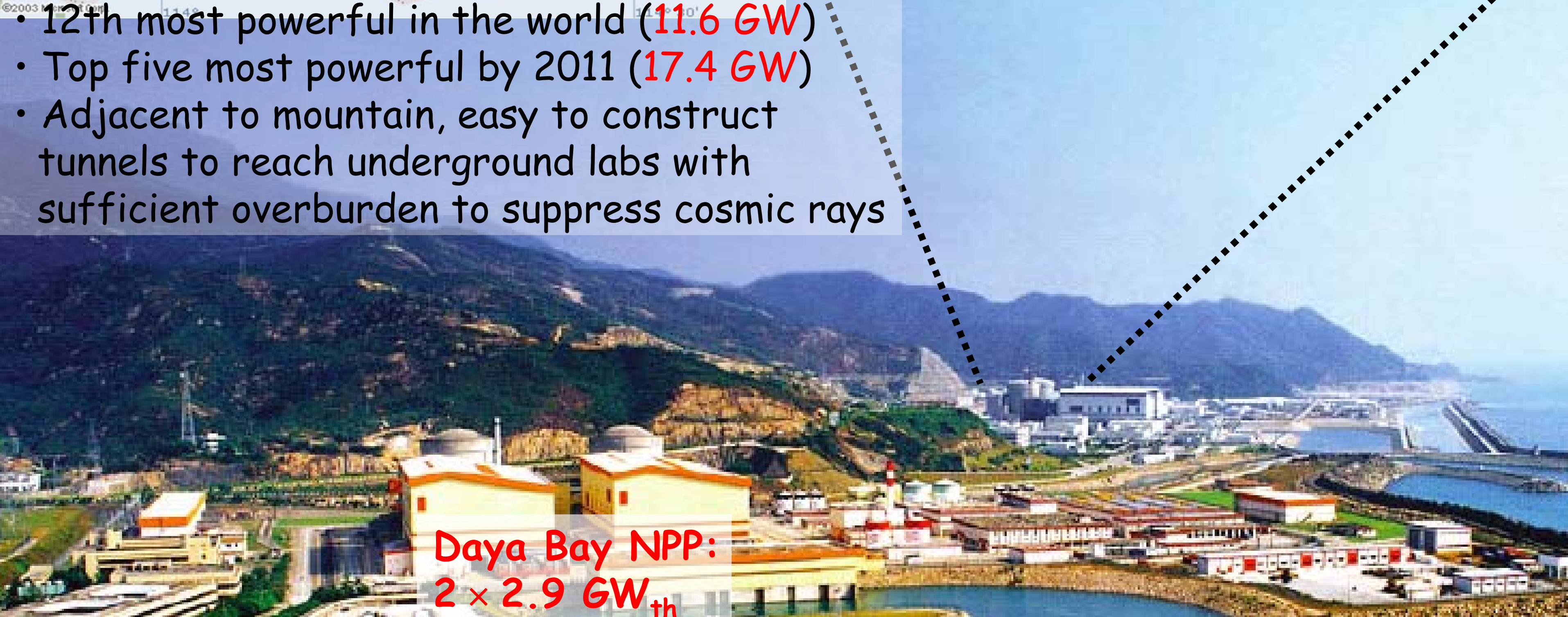
Ling Ao II NPP:
2×2.9 GW$_{th}$

Ready by 2010-2011

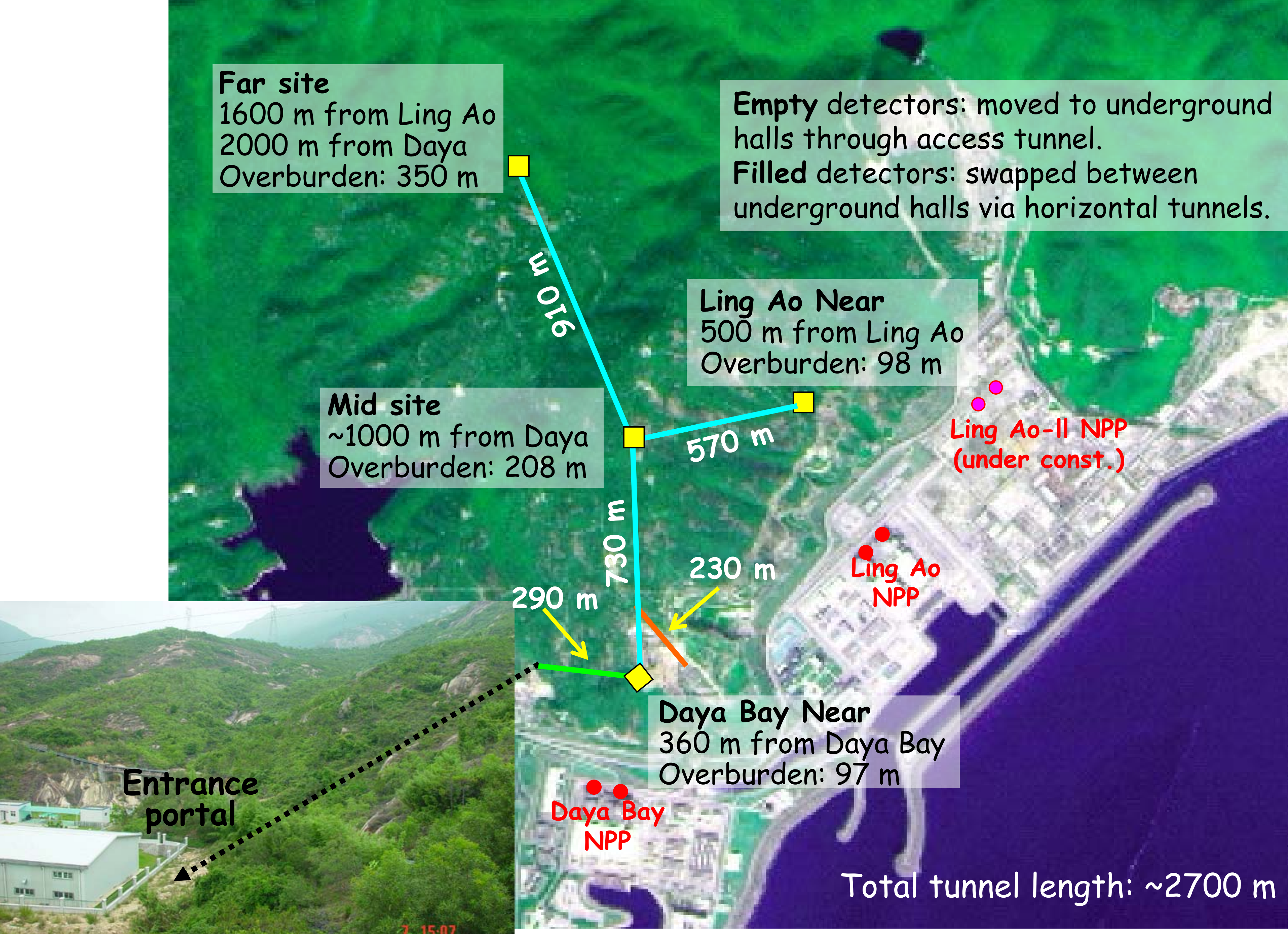
Ling Ao NPP:
2×2.9 GW$_{th}$

1 GW$_{th}$ generates 2×10^{20} $\overline{\nu}_e$ per sec

- 12th most powerful in the world (11.6 GW)
- Top five most powerful by 2011 (17.4 GW)
- Adjacent to mountain, easy to construct tunnels to reach underground labs with sufficient overburden to suppress cosmic rays



Daya Bay NPP:
2×2.9 GW$_{th}$



Far site
1600 m from Ling Ao
2000 m from Daya
Overburden: 350 m

Empty detectors: moved to underground halls through access tunnel.
Filled detectors: swapped between underground halls via horizontal tunnels.

Ling Ao Near
500 m from Ling Ao
Overburden: 98 m

Mid site
~1000 m from Daya
Overburden: 208 m

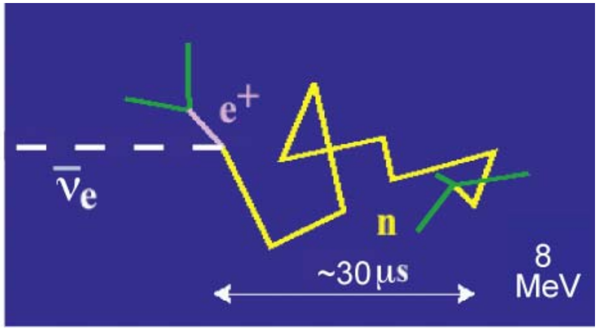
Daya Bay Near
360 m from Daya Bay
Overburden: 97 m

Total tunnel length: ~2700 m

Detecting Low-energy $\bar{\nu}_e$

- The reaction is the inverse β-decay in 0.1% Gd-doped liquid scintillator:

$$\bar{\nu}_e + p \rightarrow e^+ + n \quad \text{(prompt)}$$



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

50,000b $\rightarrow$ + Gd $\rightarrow$ Gd*

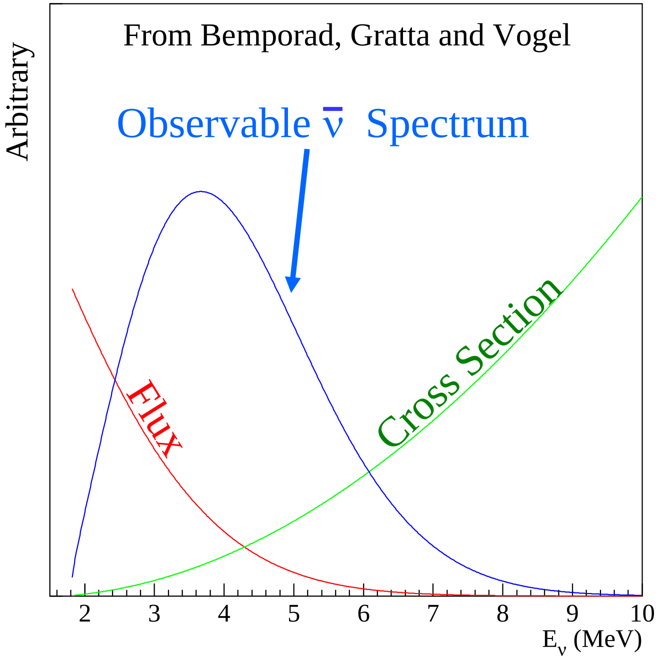
$\rightarrow$ Gd + γ's(8 MeV) (delayed)

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

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

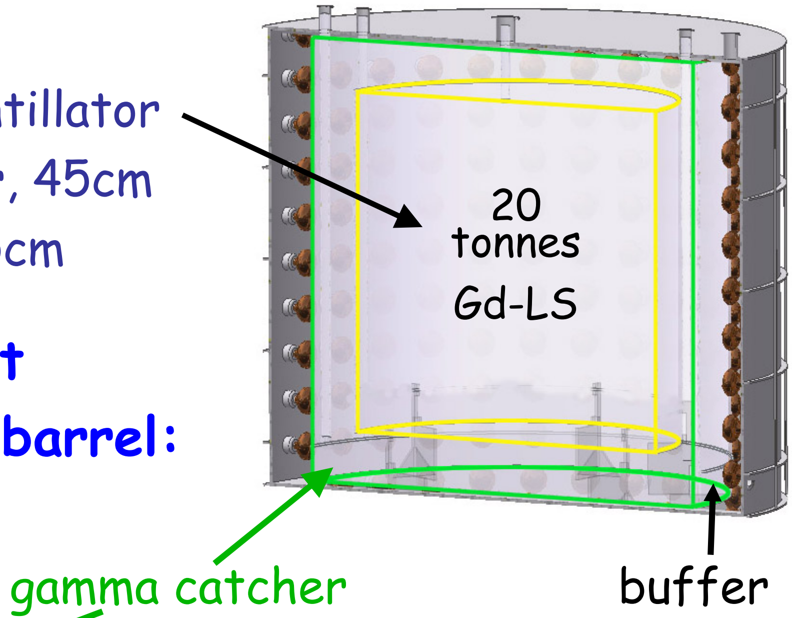
$$E_{\bar{\nu}} \approx T_{e+} + \underbrace{T_n}_{10\text{-}40\text{ keV}} + (m_n - m_p) + m_{e+} \approx T_{e+} + 1.8\text{ MeV}$$

- n-capture vertex resolution ~20cm (CHOOZ)


From Bemporad, Gratta and Vogel

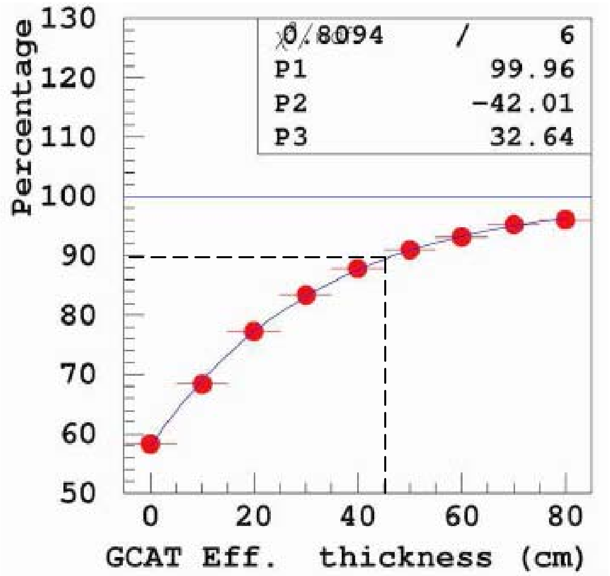
Design of Antineutrino Detectors

- **Three-zone structure:**
  - I. Target: 0.1% Gd-loaded liquid scintillator
  - II. Gamma catcher: liquid scintillator, 45cm
  - III. Buffer shielding: mineral oil, ~45cm



- **Possibly with diffuse reflection at ends. For 200 PMT's around the barrel:**

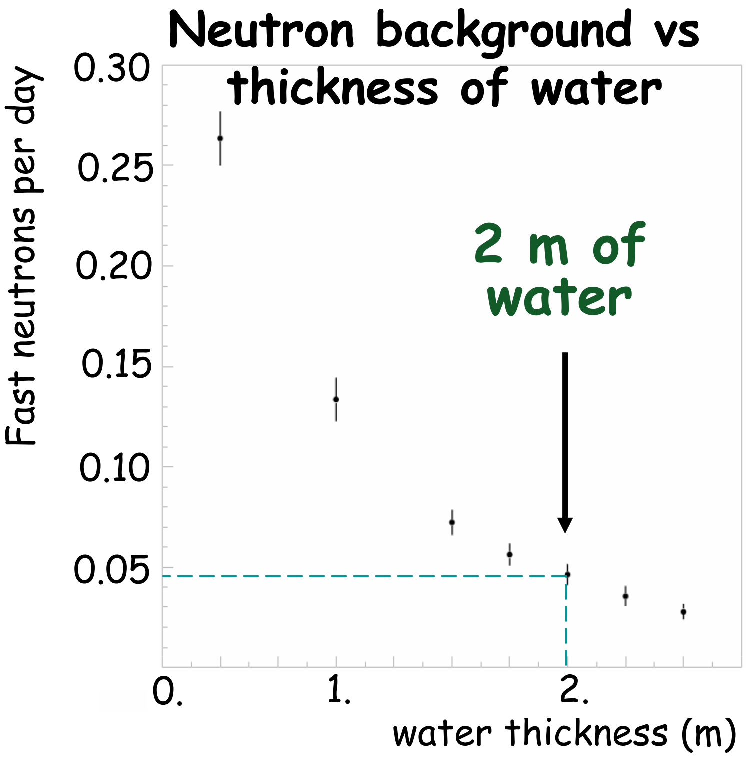
$$\frac{\sigma}{E} \sim \frac{14\%}{\sqrt{E(\text{MeV})}}, \quad \sigma_{\text{vertex}} = 14\text{cm}$$

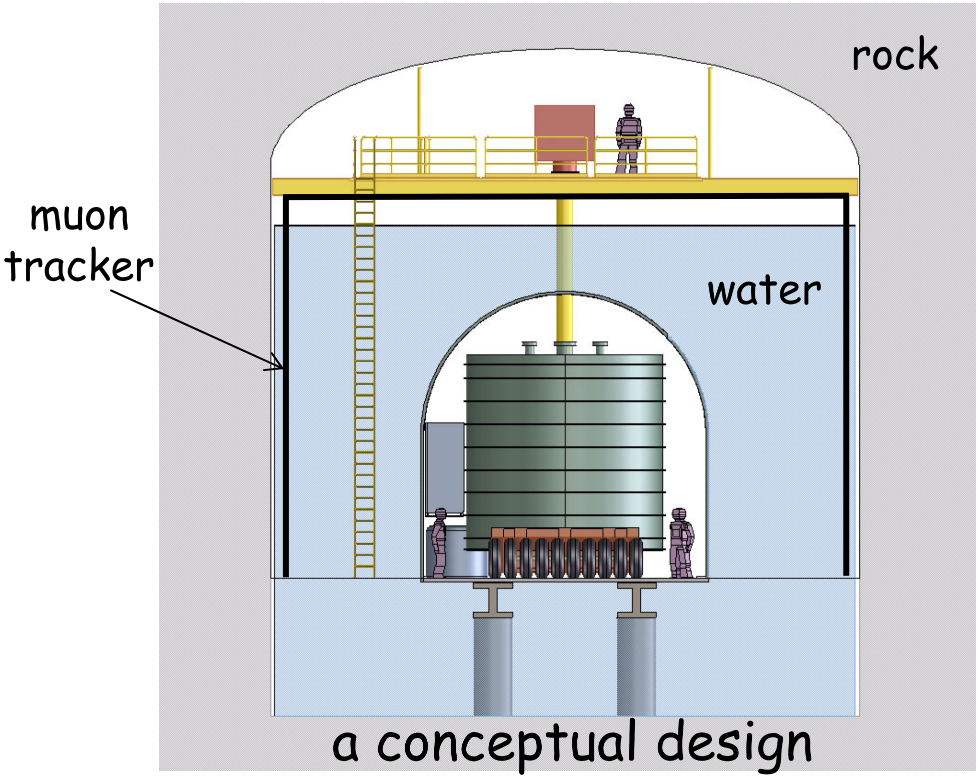


Oil buffer thickness

Isotopes (from PMT)	Purity (ppb)	20cm (Hz)	25cm (Hz)	30cm (Hz)	40cm (Hz)
^{238}U(>1MeV)	50	2.7	2.0	1.4	0.8
^{232}Th(>1MeV)	50	1.2	0.9	0.7	0.4
^{40}K(>1MeV)	10	1.8	1.3	0.9	0.5
Total		5.7	4.2	3.0	1.7

Design of Shield-Muon Veto





- Detector modules enclosed by 2 m of water to shield neutrons produced by cosmic-ray muons and gamma-rays from the surrounding rock
- Water shield also serves as a Cherenkov veto for tagging muons
- Augmented with a muon tracker: scintillator or RPCs
- Combined efficiency of Cherenkov and tracker > 99.5%

Sources of Systematic Uncertainty

1. Background-related uncertainties
2. Reactor-related uncertainties
3. Detector-related uncertainties

Systematic uncertainties are controlled and/or measured by use of

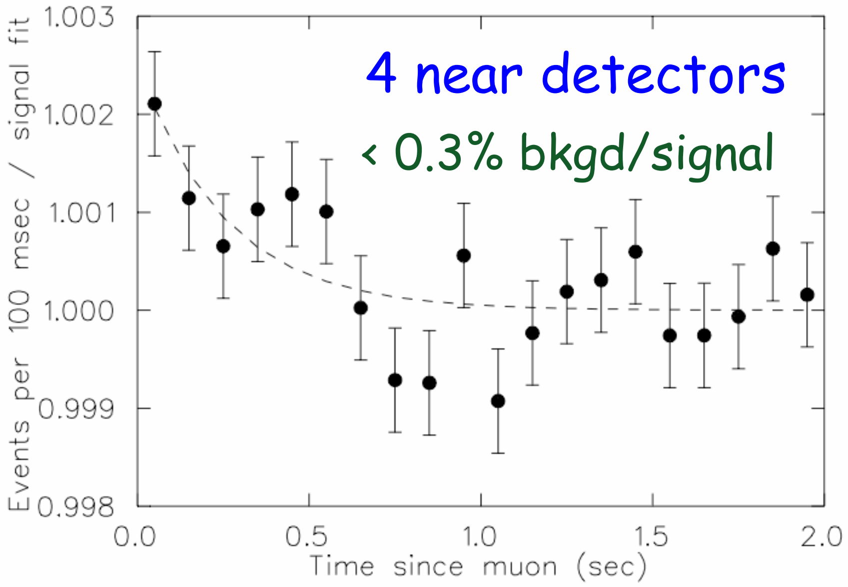
- overburden and active shielding,
- multiple sites with multiple identical detectors per site,
- optimized baseline,
- 3-zone detector modules,
- swapping of detectors between sites,
- calibration and monitoring

Background sources

- **Natural Radioactivity**: PMT glass, Rock, Radon in the air, etc
- **Slow and fast neutrons produced in rock & shield by cosmic muons**
- **Muon-induced cosmogenic isotopes: ^{8}He/^{9}Li which can β-n decay**
  - Cross section measured at CERN (Hagner et. al.)
  - Can be measured in-situ, even for near detectors with muon rate ~ 10 Hz:

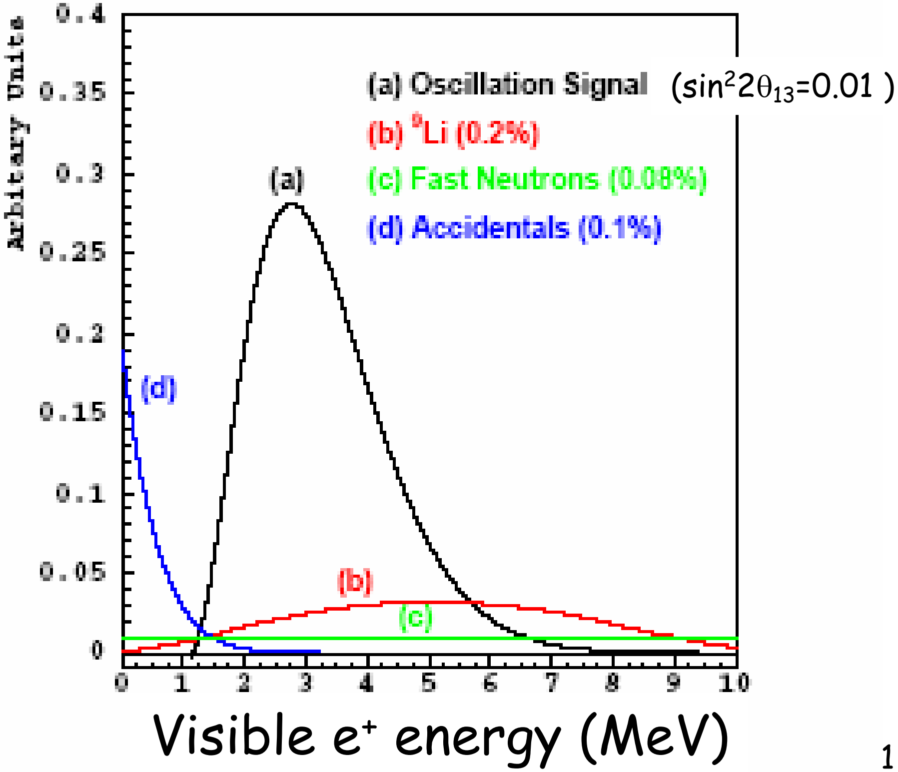
Half-life of ^{9}Li = 0.18s

β-n decay of ^{9}Li mimics signal



4 near detectors

< 0.3% bkgd/signal



Summary of Background

- **Use a modified Palo Verde-Geant3-based MC to model response of detector**

- **Muon-induced background estimate uses the measured overburden, spectra from modified Gaisser parametrization & muon transport with the MUSIC package**

	Near Site	Far Site
$\bar{\nu}_e$ rate/day	560	80
Radioactivity (Hz)	<50	<50
Accidental B/S	<0.05%	<0.05%
Fast neutron B/S	0.14% ± 0.16%	0.08 ± 0.1%
^{8}He/^{9}Li B/S	0.41% ± 0.18%	0.2% ± 0.08%

Further rejection of background may be possible by vetoing $\bar{\nu}_e$ candidates preceded by showering muons. (KamLAND)

Reactor-related uncertainties

Define ρ=near/far event ratio:

Flux at unit distance from reactor r

$$\rho = \alpha \sum_r \frac{\phi_r}{L_{r1}^2} \Big/ \sum_r \frac{\phi_r}{L_{rf}^2} + \sum_r \frac{\phi_r}{L_{r2}^2} \Big/ \sum_r \frac{\phi_r}{L_{rf}^2} = \alpha\rho_1 + \rho_2$$

Calculable parameter based on power, baseline, livetime

Baseline from reactor r to near site 2

Uncertainty due to $\sigma_\phi \approx 2\%$=uncorrelated reactor power uncertainties:

$$\sigma_\rho = \sqrt{\sum_r \left[\frac{1}{\rho}\frac{\partial\rho}{\partial\phi_r}\delta\phi_r\right]^2} = \sigma_\phi \sqrt{\sum_r \left[\frac{\alpha\rho_1(f_1^r - f_f^r) + \rho_2(f_2^r - f_f^r)}{\alpha\rho_1 + \rho_2}\right]^2}$$

Fraction of events at site 1 due to reactor r

Reactor Cores	σ_ρ(power)	σ_ρ (core position)	σ_ρ(Total)
4	0.035%	0.08%	0.087%
6	0.097%	0.08%	0.126%

Assumes ±30cm uncertainty in core positions

Detector-related Uncertainties

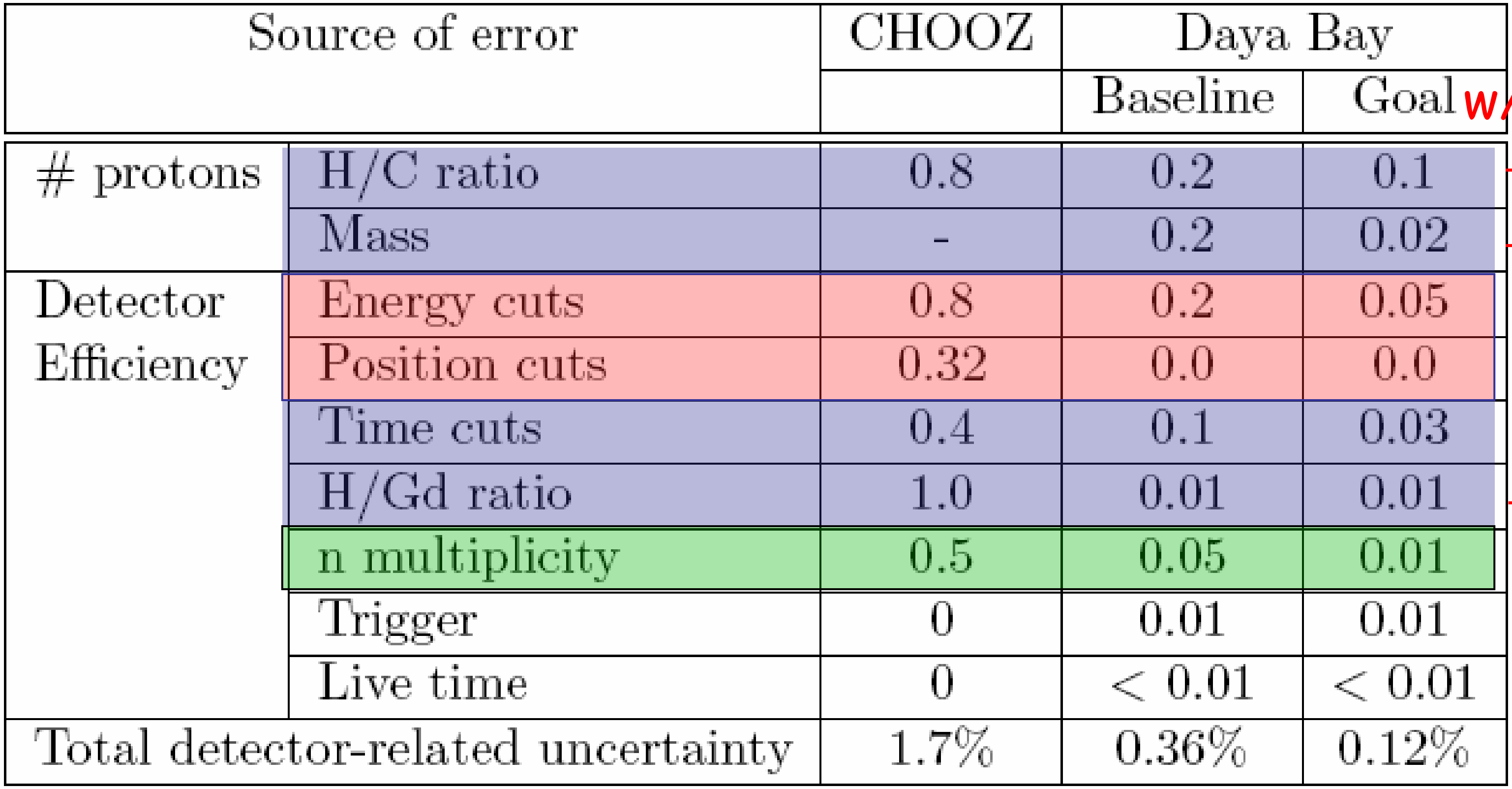
Multiple, identical detectors/site

Overburden/shielding

3-zone design

Absolute measurement

Relative measurement



Source of error		CHOOZ	Daya Bay		
			Baseline	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	0.05	
	Position cuts	0.32	0.0	0.0	
	Time cuts	0.4	0.1	0.03	
	H/Gd ratio	1.0	0.01	0.01	→ 0
	n multiplicity	0.5	0.05	0.01	
	Trigger	0	0.01	0.01	
	Live time	0	< 0.01	< 0.01	
Total detector-related uncertainty		1.7%	0.36%	0.12%	→ 0.06%

Baseline: currently achievable **relative** uncertainty without R&D

Goal: expected **relative** uncertainty after R&D

Swapping: can reduce **relative** uncertainty further

Summary of Systematic Uncertainties

- Reactor-related systematic uncertainties are:

  0.09% (4 cores)
  0.13% (6 cores)

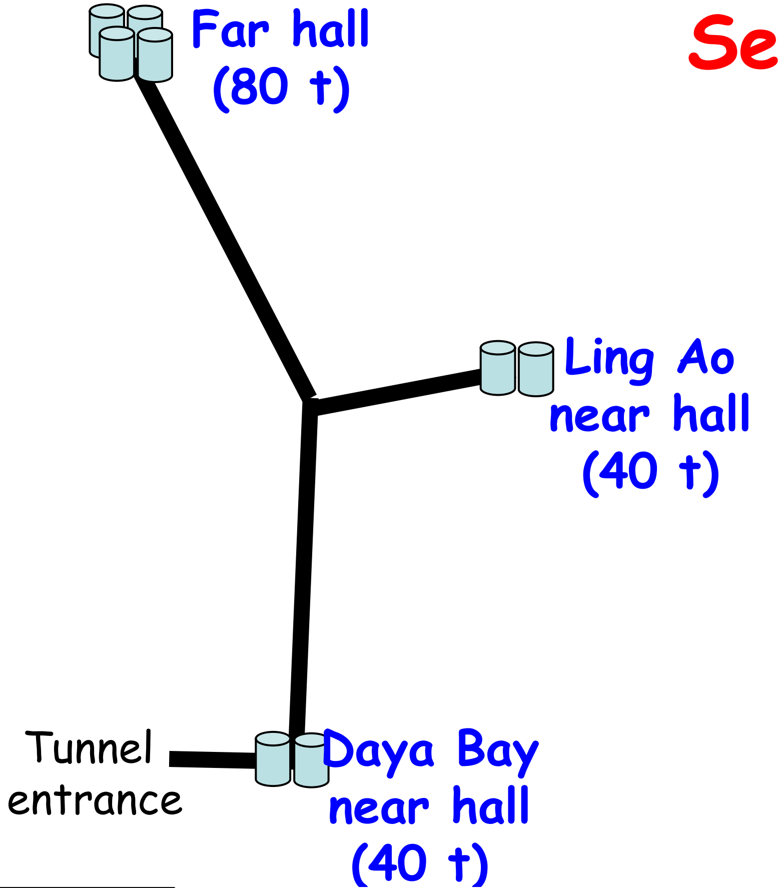
- Relative detector systematic uncertainties are:

  0.36% (baseline)
  0.12% (goal)
  0.06% (with swapping)

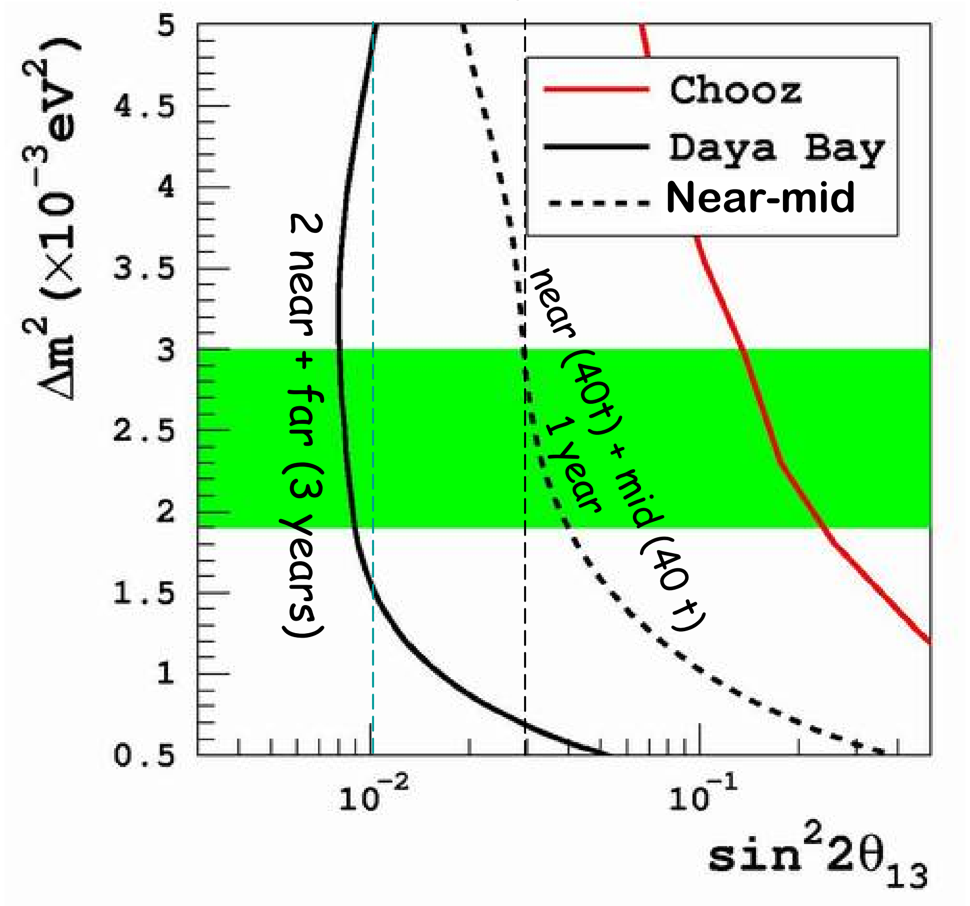
- Assume backgrounds are measured

- These are input to sensitivity calculations

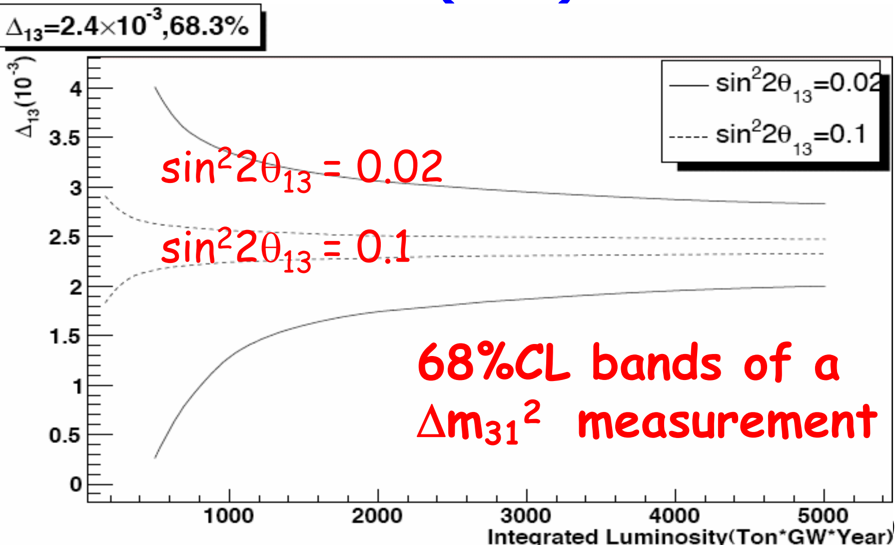
Sensitivity of Daya Bay



90% confidence level



- *Use rate and spectral shape*
- *input relative detector systematic error of 0.2%*

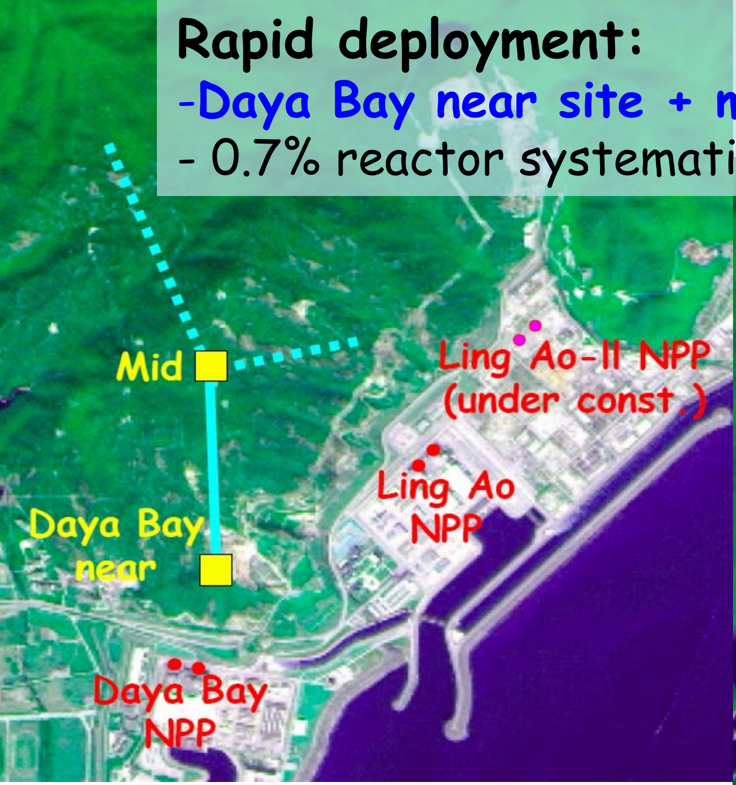


68%CL bands of a Δm_{31}^2 measurement

Versatility of the Daya Bay experiment

Rapid deployment:

- Daya Bay near site + mid site
- 0.7% reactor systematic error



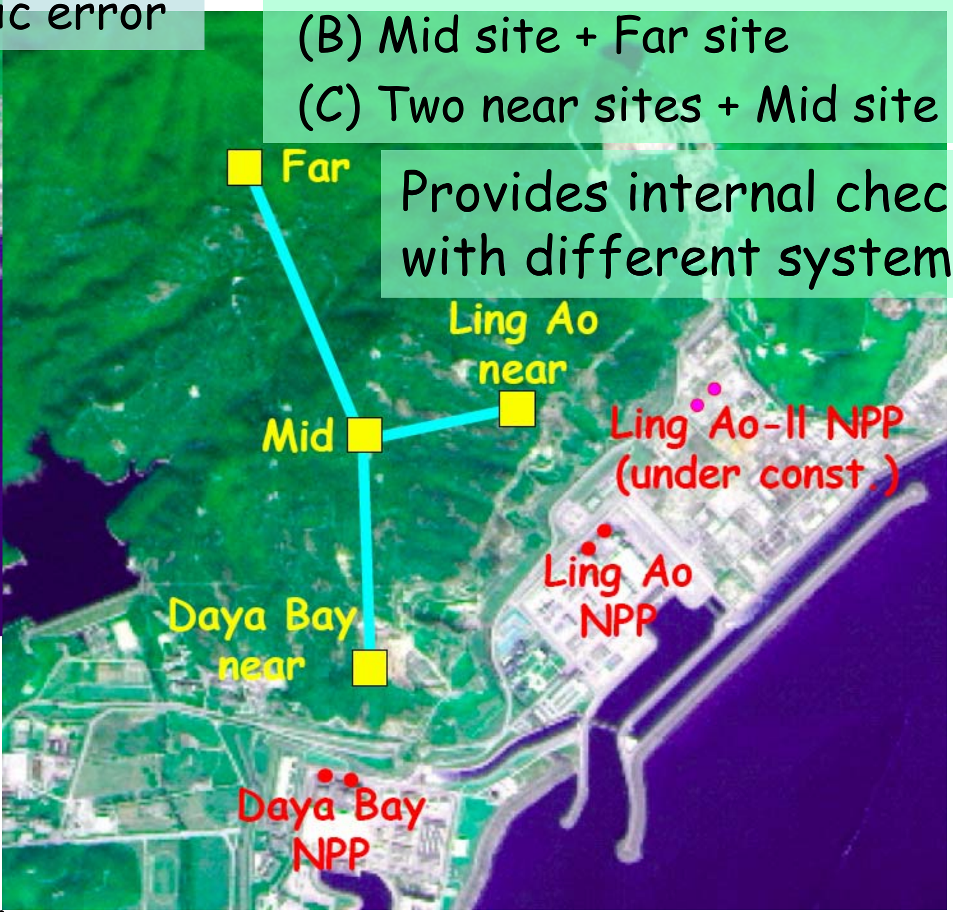
Full operation:

(A) Two near sites + Far site

(B) Mid site + Far site

(C) Two near sites + Mid site + Far site

Provides internal checks, each with different systematic



Preliminary schedule

June 06 Begin civil design

July 07 Begin civil construction

June 08 Daya Bay near & mid halls complete

Dec 08 Ling Ao near & far halls complete

Oct 09 Begin Daya Bay near, mid data taking

Aug 10 Begin data taking with far & near halls

Mar 13 Measure $\sin^2 2\theta_{13}$ to ≤ 0.01

Summary and status

- The Daya Bay reactor neutrino experiment is designed to reach a sensitivity of ≤ 0.01 for $\sin^2 2\theta_{13}$ and have the versatility to perform internal systematic checks of a $\sin^2 2\theta_{13}$ measurement.
- The Daya Bay project has been approved by the Chinese Academy of Science for 50M RMB. Other Chinese agencies are expected to contribute another ~100M RMB
- The US DOE has provided 0.8M$ for R&D for FY06. We are working towards a US project start in FY08.
- We are seeking new collaborators
- Will complete preliminary design of detectors and detailed design of tunnels and underground facilities in 2006.
- Plan to start with the near-mid data taking in 2009, and begin full operation in 2010.

Thanks to my Daya Bay colleagues for help in preparing this presentation.