

Status of Daya Bay Reactors Neutrino Project

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NDM2006, Paris

Neutrino oscillation: PMNS matrix

If Mass eigenstates \neq Weak eigenstates \rightarrow Neutrino oscillation

Oscillation probability:

$$P(\nu_1 \rightarrow \nu_2) \propto \sin^2(1.27 \Delta m^2 L/E)$$

Atmospheric	crossing: CP 与 θ_{13}	solar	$\beta\beta$ decays
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$$V = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & e^{-i\delta} & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & e^{i\sigma} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Super-K

K2K

Minos

T2K

Daya Bay

Double

Chooz

NOVA

Homestake

Gallex

SNO

KamLAND

EXO

Genius

CUORE

NEMO

A total of 6 parameters: 2 Δm^2 , 3 angles, 1 phases
+ 2 Majorana phases

A total of six ν mixing parameters:

Known: $|\Delta m^2_{32}|$, $\sin^2 2\theta_{32}$ --Super-K

Δm^2_{21} , $\sin^2 2\theta_{21}$ --SNO, KamLAND

Unknown: $\sin^2 2\theta_{13}$, δ , sign of Δm^2_{32}

at reactors:

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 (1.27 \Delta m^2_{13} L/E) - \\ \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 (1.27 \Delta m^2_{12} L/E)$$

at LBL accelerators:

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

Importance to know θ_{13}

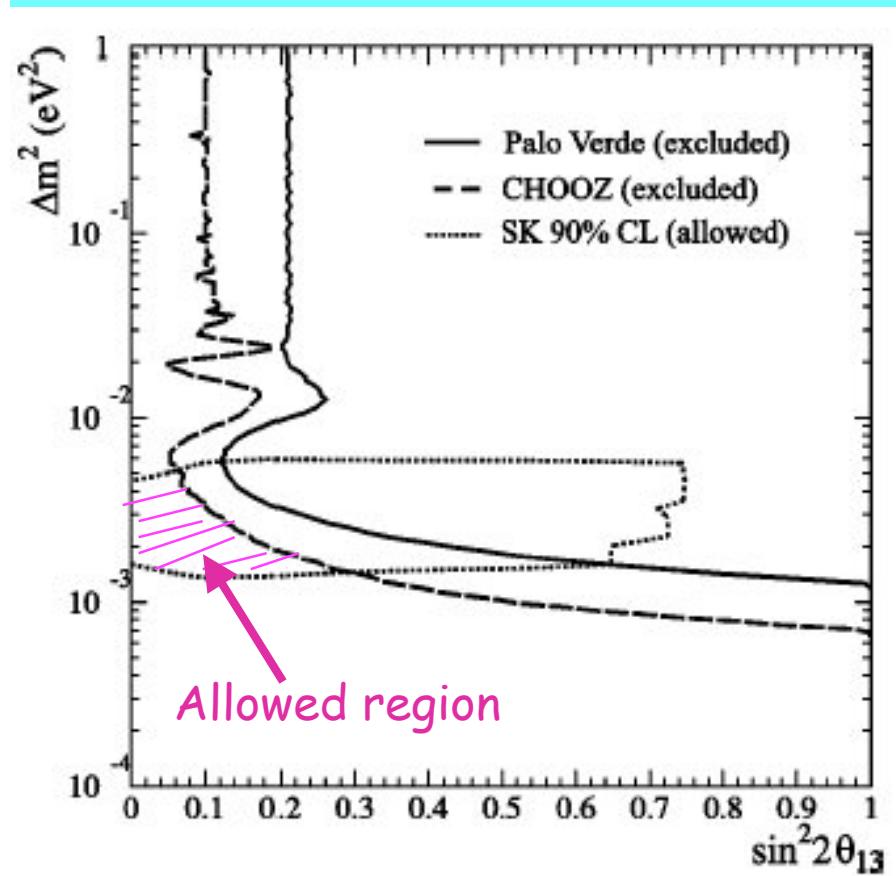
- 1) A fundamental parameter
- 2) important to understand the relation between leptons and quarks, in order to have a grand unified theory beyond the Standard Model

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \quad \longleftrightarrow \quad \begin{pmatrix} \mathbf{v}_e \\ \mathbf{v}_\mu \\ \mathbf{v}_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \mathbf{v}_1 \\ \mathbf{v}_2 \\ \mathbf{v}_3 \end{pmatrix}$$

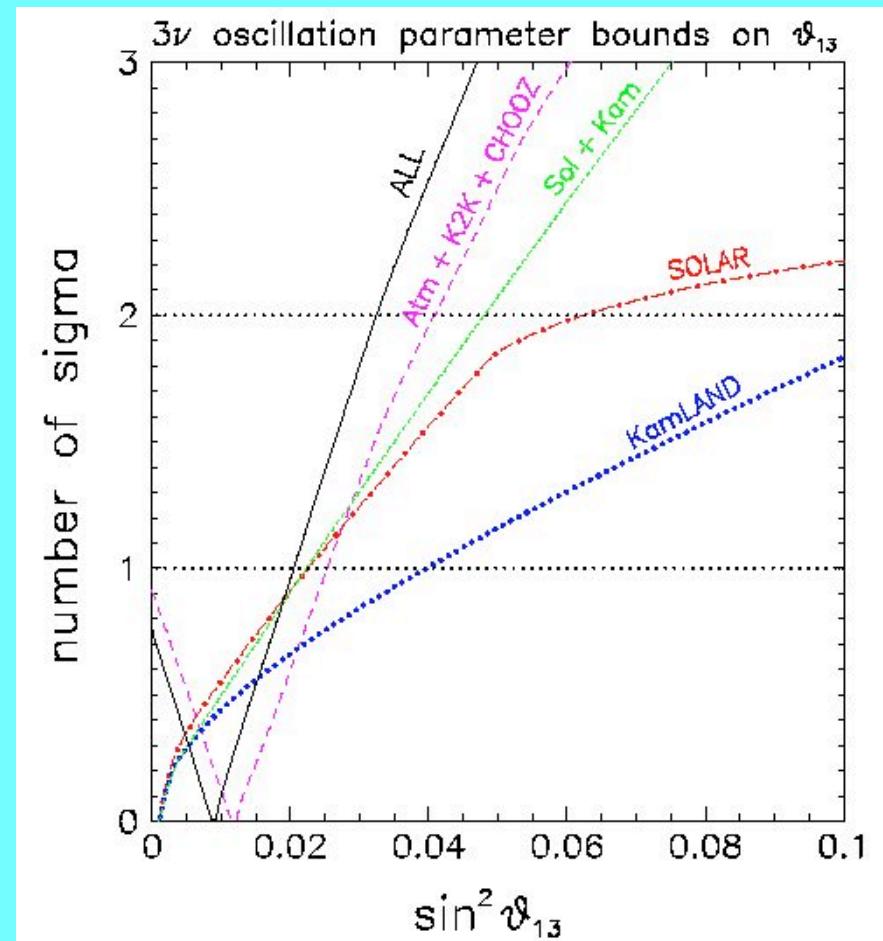
- 3) important to understand matter-antimatter asymmetry
 - If $\sin^2 2\theta_{13} > 0.01$, next generation LBL experiment for CP
 - If $\sin^2 2\theta_{13} < 0.01$, next generation LBL experiment for CP ???
- 4) provide direction to the future of the neutrino physics: super-neutrino beams or neutrino factory ?

Current Knowledge of θ_{13}

Direct search
PRD 62, 072002

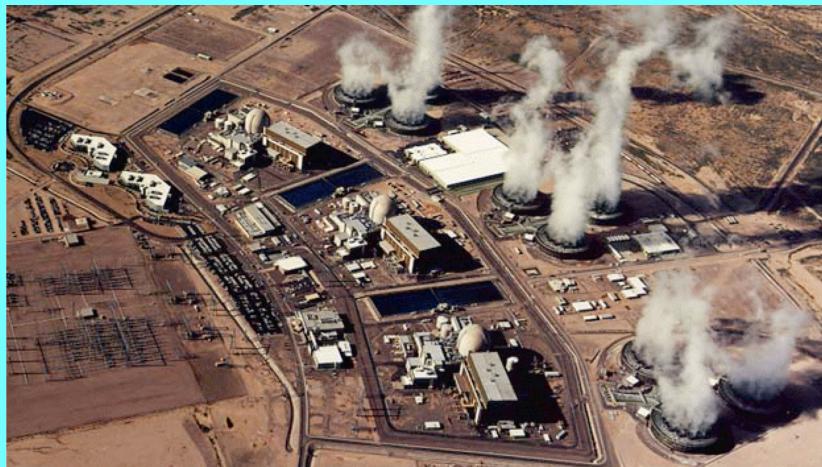


Global fit fogli et al
.hep-ph/0506083

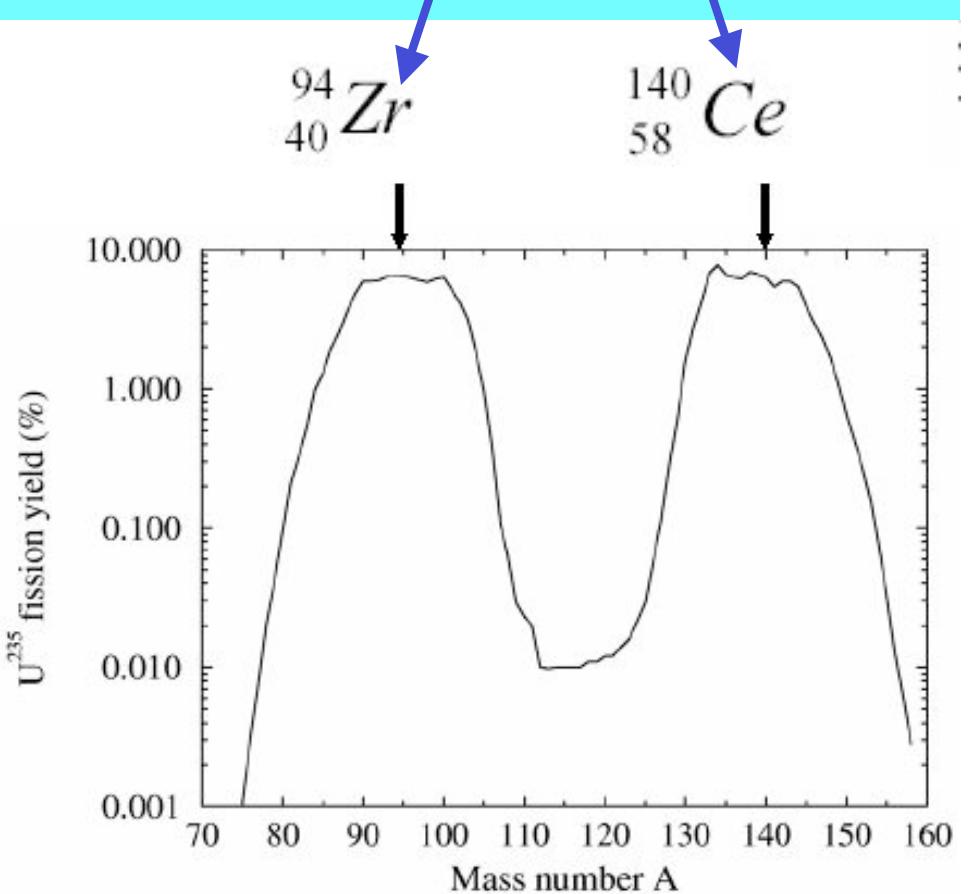
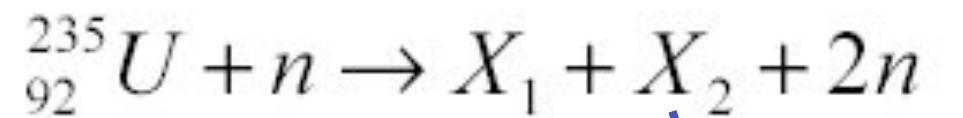


Best fit value of $\Delta m^{232} = 2.4 \times 10^{-3} \text{ eV}^2$

Reactors Neutrinos



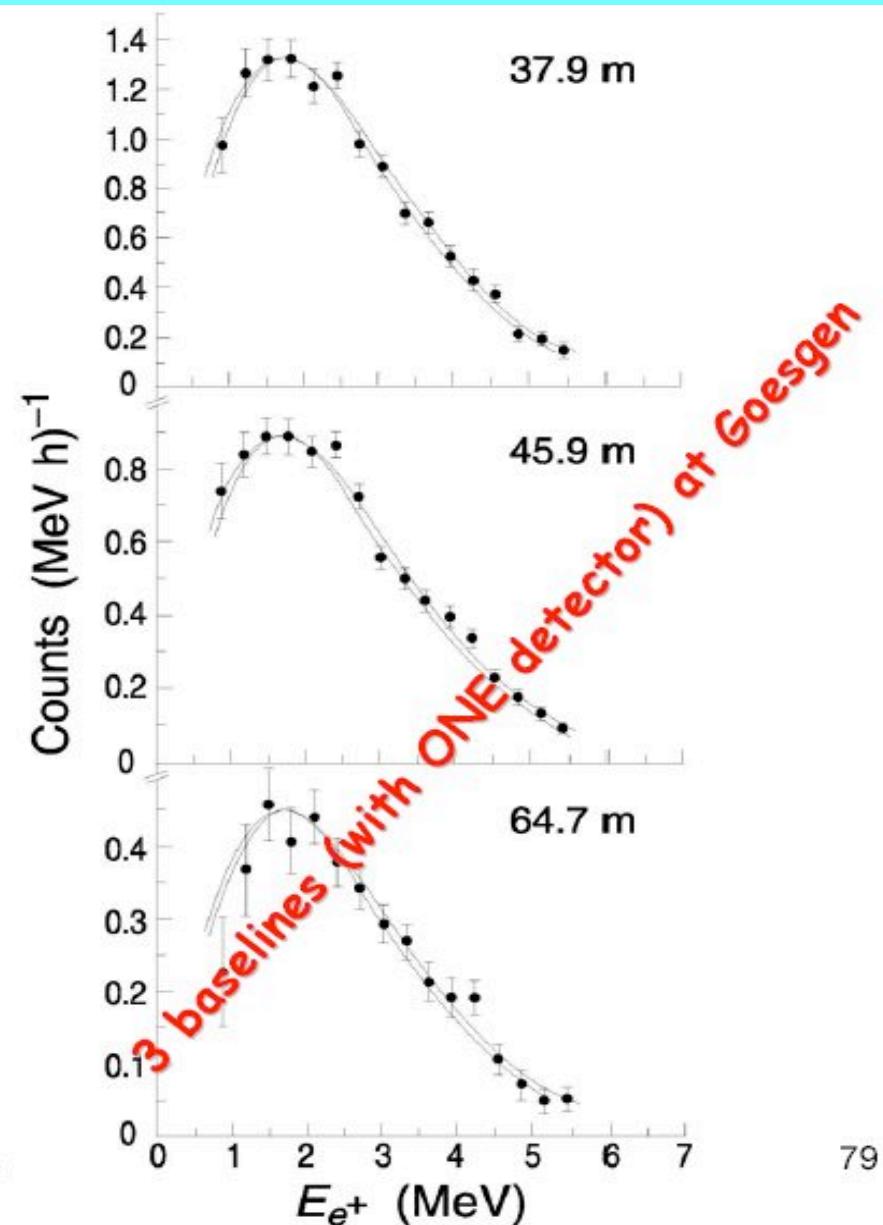
The most likely fission products have a total of 98 protons and 136 neutrons, hence on average there are 6 n which will decay to 6p, producing 6 neutrinos



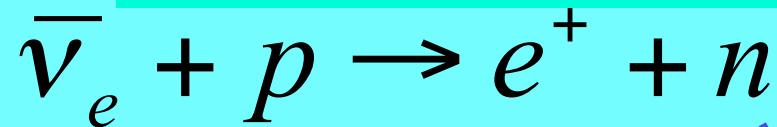
Neutrino flux of a commercial reactor with 3 GW_{thermal} : $6 \times 10^{20} \bar{\nu}/\text{s}$

Prediction of reactor neutrino spectrum

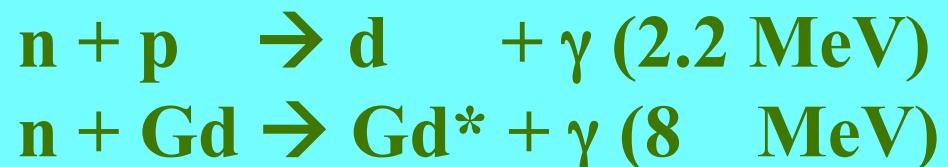
- Three ways to obtain reactor neutrino spectrum:
 - Direct measurement
 - First principle calculation
 - Sum up neutrino spectra from ^{235}U , ^{239}Pu , ^{241}Pu and ^{238}U
 ^{235}U , ^{239}Pu , ^{241}Pu from their measured β spectra
 $^{238}\text{U}(10\%)$ from calculation (10%)
- They all agree well within 3%



Neutrino Detection: Inverse- β reaction in liquid scintillator

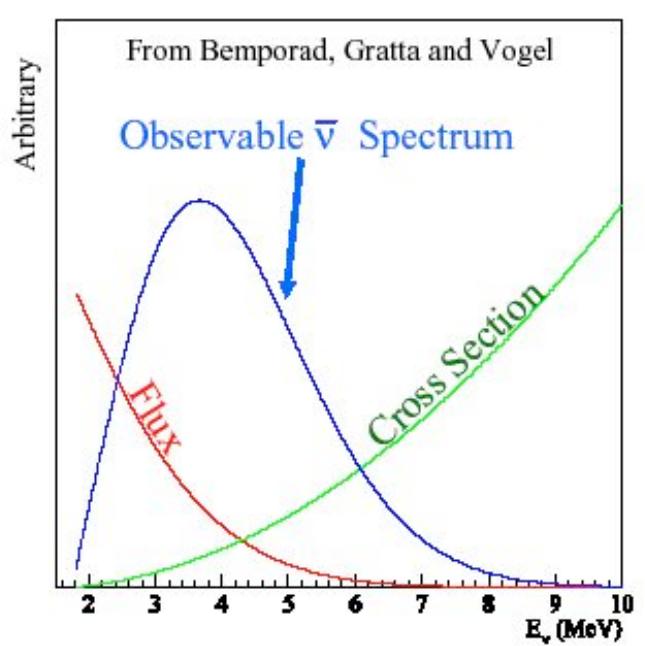


$\tau \approx 180 \text{ or } 28 \mu\text{s} (0.1\% \text{ Gd})$



Neutrino Event: coincidence in time, space and energy

Neutrino energy:



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

10-40 keV

1.8 MeV: Threshold

How to reach 1% precision ?

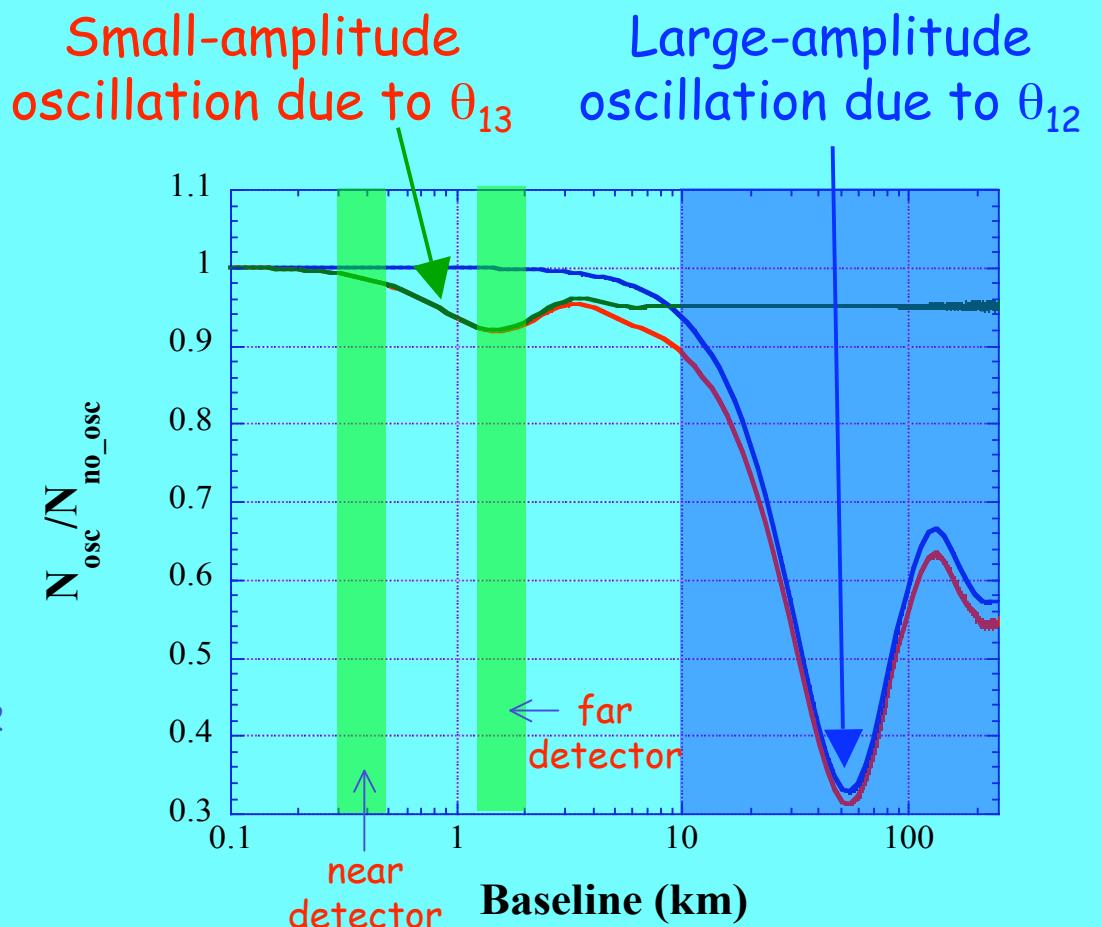
- Three main types of errors: reactor related(~2-3%), background related (~1-2%) and detector related(~1-2%)
- Use far/near detector to cancel reactor errors
- Movable detectors, near ↔ far, to cancel part of detector systematic errors
- Optimize baseline to have best sensitivity and reduce reactor related errors
- Sufficient shielding to reduce backgrounds
- Comprehensive calibration to reduce detector systematic errors
- Careful design of the detector to reduce detector systematic errors
- Large detector to reduce statistical errors

Optimize baseline

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

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

- 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}



Systematic error comparison

		Chooz	Palo Verde	KamLAND	Daya Bay
Reactor power		0.7	0.7	2.05	<0.1%
Reactor fuel/v spectra		2.0	2.0	2.7	
ν cross section		0.3	0.2	0.2	0
No. of protons	H/C ratio	0.8	0.8	1.7	0.2 → 0
	Mass	-	-	2.1	0.2 → 0
Efficiency	Energy cuts	0.89	2.1	0.26	0.2
	Position cuts	0.32		3.5	0
	Time cuts	0.4		0.	0.1
	P/Gd ratio	1.0		-	0.1
	n multiplicity	0.5		-	<0.1
background	correlated	0.3	3.3	1.8	0.2
	uncorrelated	0.3	1.8	0.1	<0.1
Trigger		0	2.9	0	<0.1
Live time		0	0.2	0.2	0.03

Currently Proposed Experiments

Site (proposal)	Power (GW)	Baseline Near/mid//F ar (m)	Detector Near/Mid. /Far(t)	Overburden Near/Mid/Fa r (MWE)	Sensitivity (90%CL)
Double Chooz (France)	8.7	150/1067	10/10	60/300	~ 0.03
Daya Bay (China)	11.6	360/500/1800	40/40/80	260/260/910	~ 0.008
Kaska (Japan)	24.3	350/1600	6/6/2 ×6	90/90/260	~ 0.02
Reno (S. Korea)	17.3	150/1500	20/20	230/675	~ 0.03

Daya Bay nuclear power plant

- 4 reactor cores, 11.6 GW
- 2 more cores in 2011, 5.8 GW
- Mountains near by, easy to construct a lab with enough overburden to shield cosmic-ray backgrounds



DYB region - Location and Surrounding



Convenient
Transportation,
Living
conditions,
communications

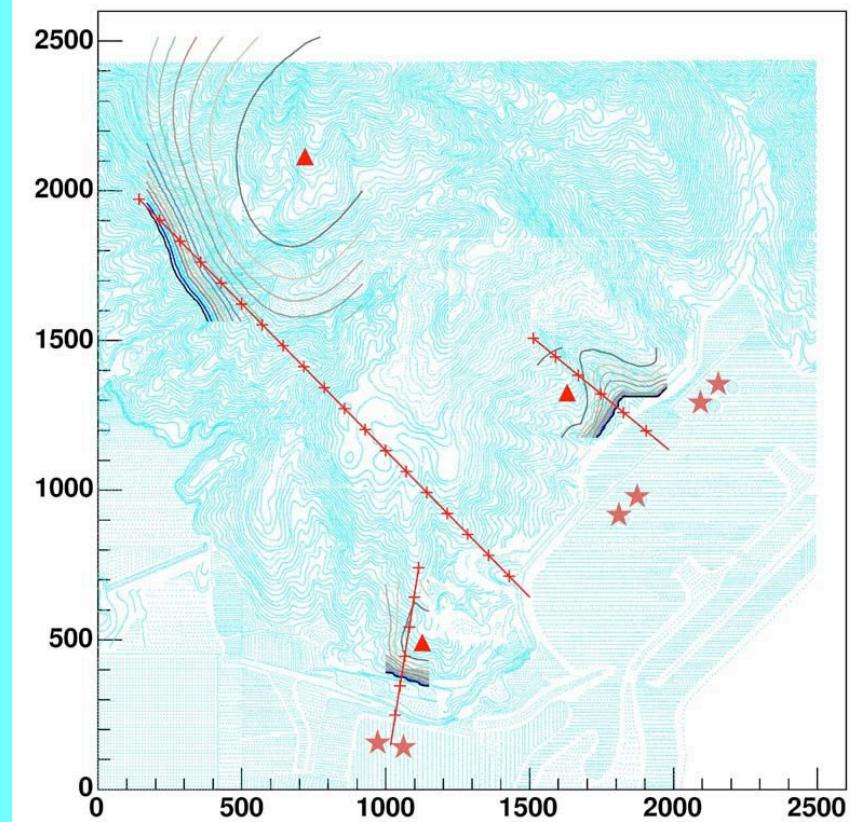


Baseline Optimization and Site Selection

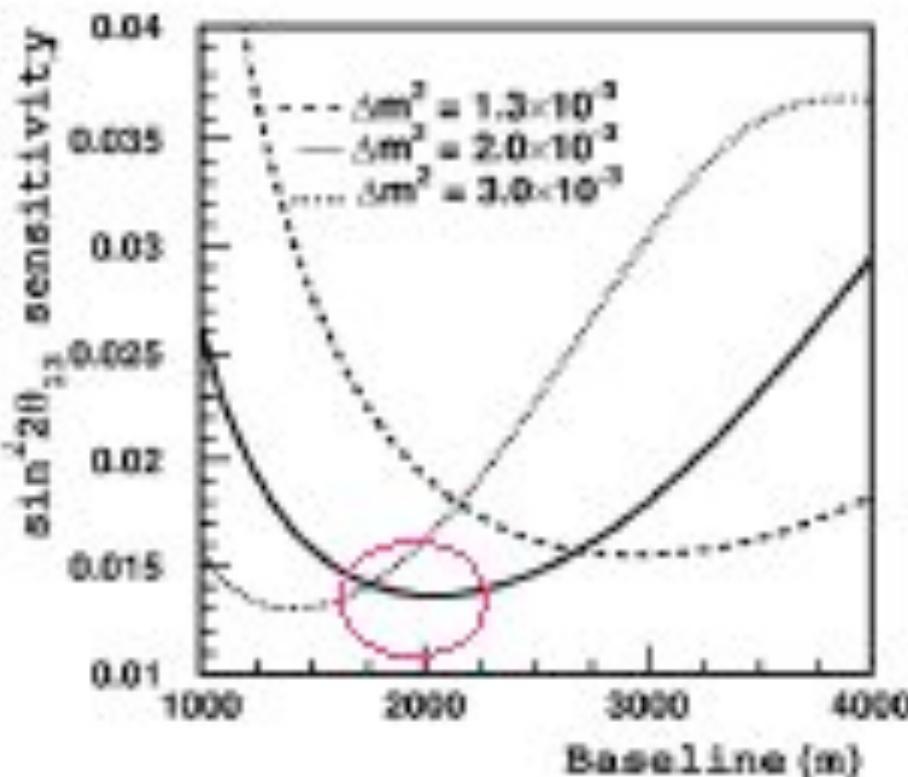
$$\chi^2 = \min_{\alpha's} \sum_{i=1}^{Nbin} \sum_{A=1,3} \frac{\left[M_i^A - T_i^A (1 + \alpha_D + \alpha_c + \alpha_d^A + c_i + \sum_r \frac{T_i^{rA}}{T_i^A} \alpha_r) - b^A B_i^A \right]^2}{T_i^A + T_i^{A2} \sigma_b^2 + B_i^A}$$

$$+ \frac{\alpha_D^2}{\sigma_D^2} + \frac{\alpha_c^2}{\sigma_c^2} + \sum_r \frac{\alpha_r^2}{\sigma_r^2} + \sum_{i=1}^{Nbin} \frac{c_i^2}{\sigma_{shape}^2} + \sum_{A=1,3} \left(\frac{\alpha_d^{A2}}{\sigma_d^2} + \frac{b^{A2}}{\sigma_B^2} \right)$$

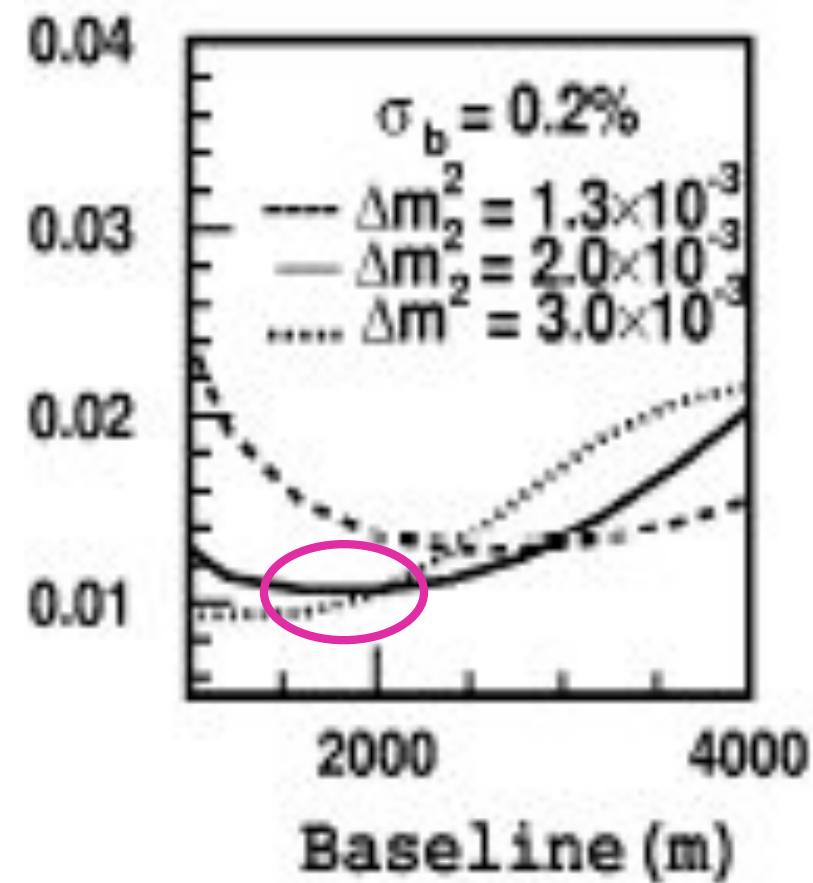
- Neutrino spectrum and their error
- Neutrino statistical error
- Reactor residual error
- Estimated detector systematical error:
total, bin-to-bin
- Cosmic-rays induced background
(rate and shape) taking into mountain
shape: fast neutrons, ${}^9\text{Li}$, ...
- Backgrounds from rocks and PMT glass



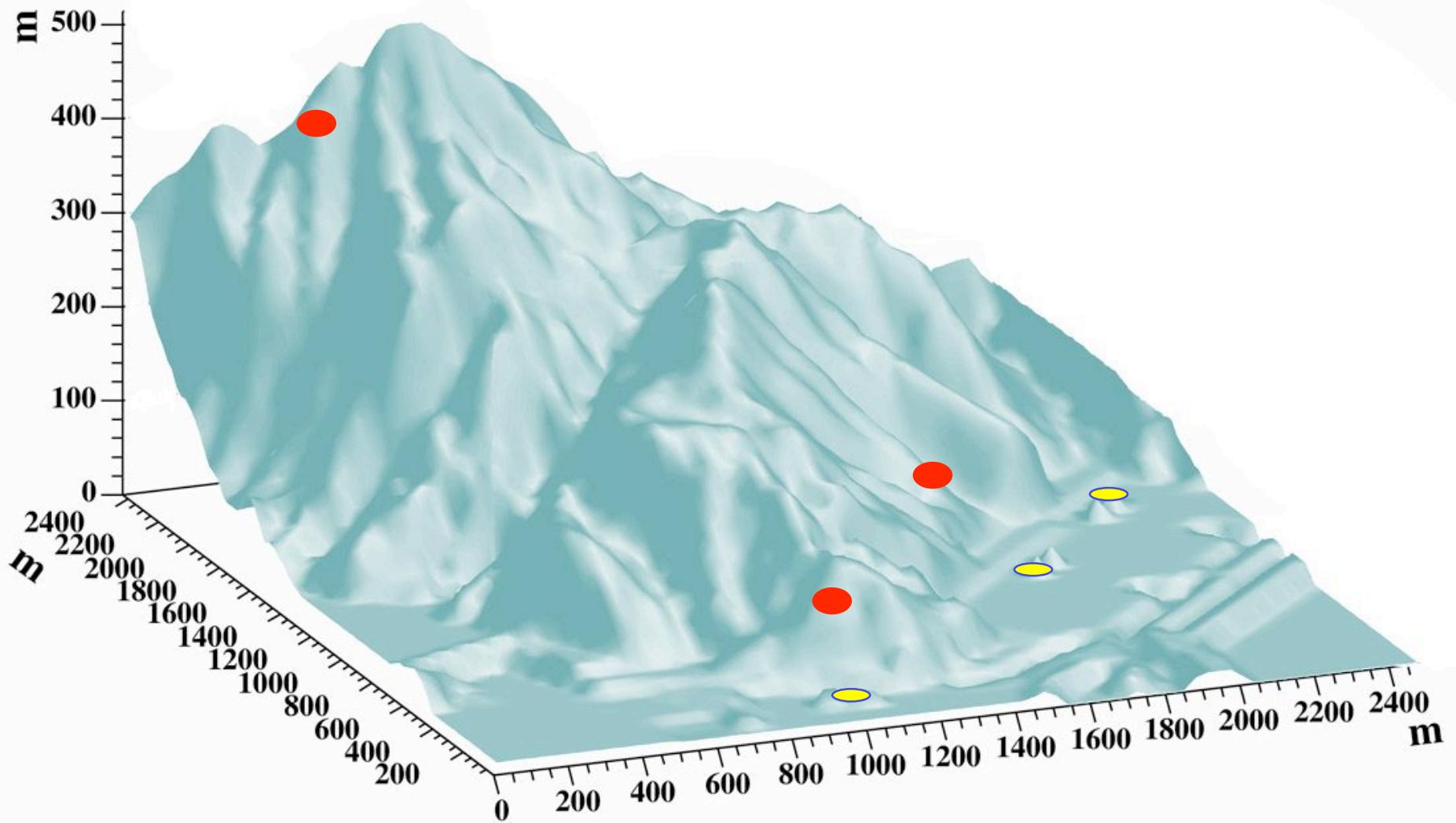
Best location for far detectors



Rate only

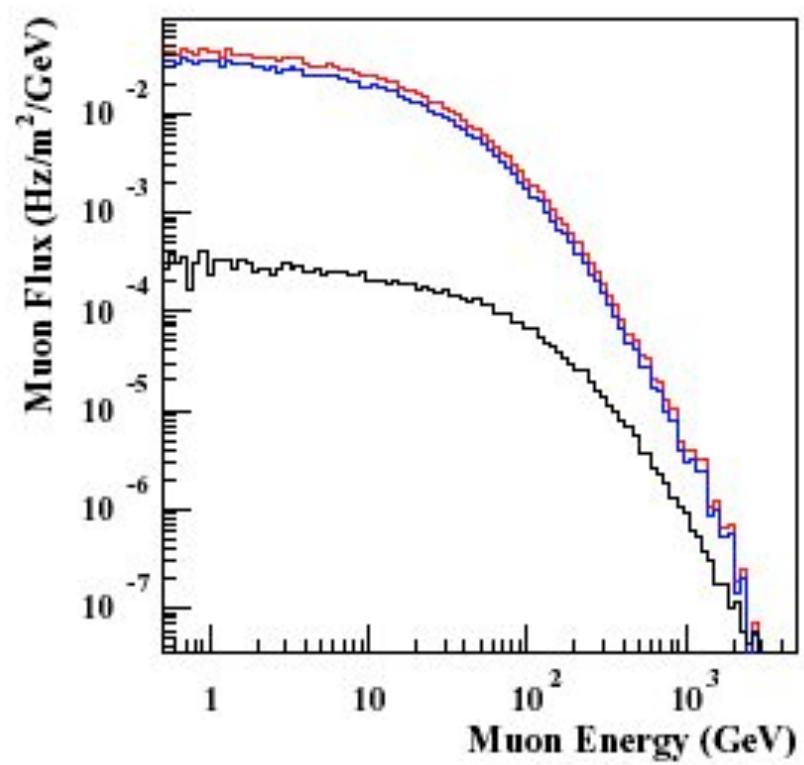
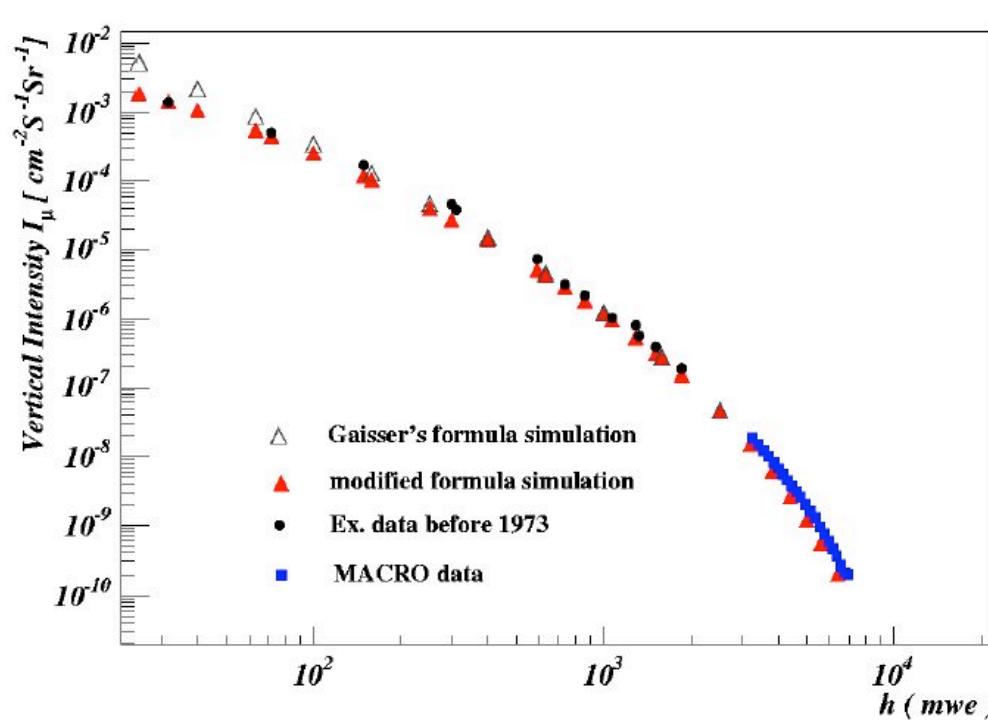


Rate + shape



Cosmic-muons at the laboratory

	DYB near site	LA near site	Far site
Baseline (m)	360	500	1980/1620
Elevation (m)	97	98	356
Muon Flux (Hz/m ²)	1.19	0.94	0.041
Muon Mean Energy (GeV)	55	55	138



The Layout



Total Tunnel length

3200 m

Detector swapping

in a horizontal tunnel cancels
most detector systematic error.
Residual error ~0.2%

Backgrounds

B/S of DYB,LA ~0.5%

B/S of Far ~0.2%

Fast Measurement

DYB+Mid, 2008-2009

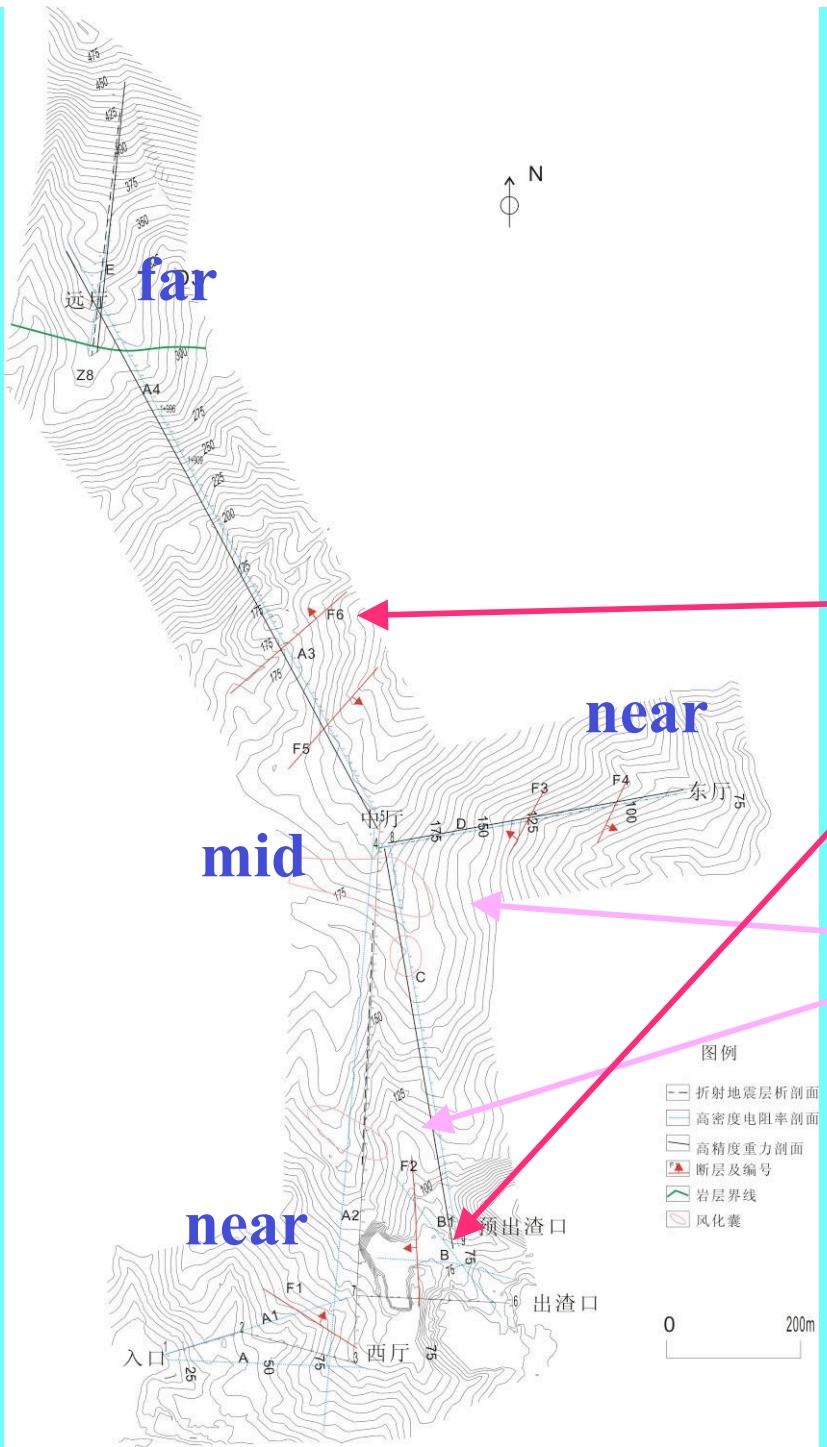
Sensitivity (1 year) ~0.03

Full Measurement

DYB+LA+Far, from 2010

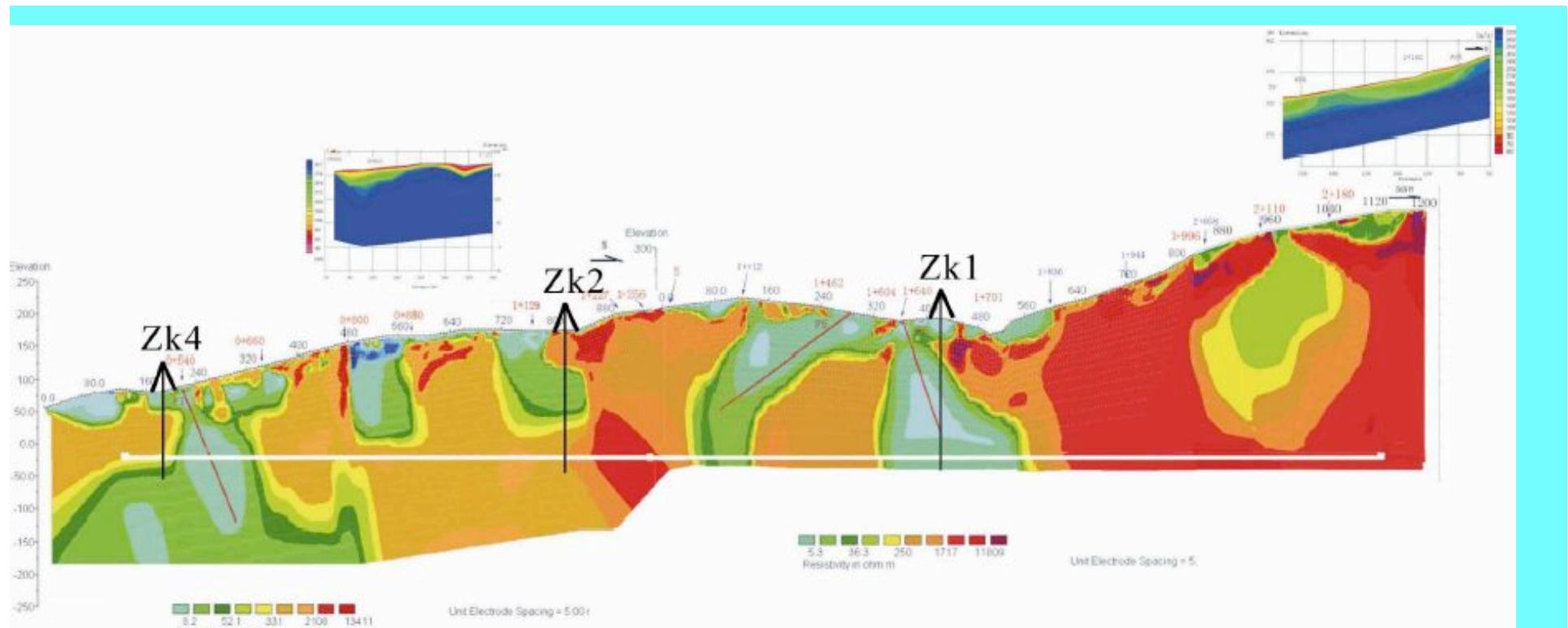
Sensitivity (3 year) <0.01

Geologic survey completed, including boreholes



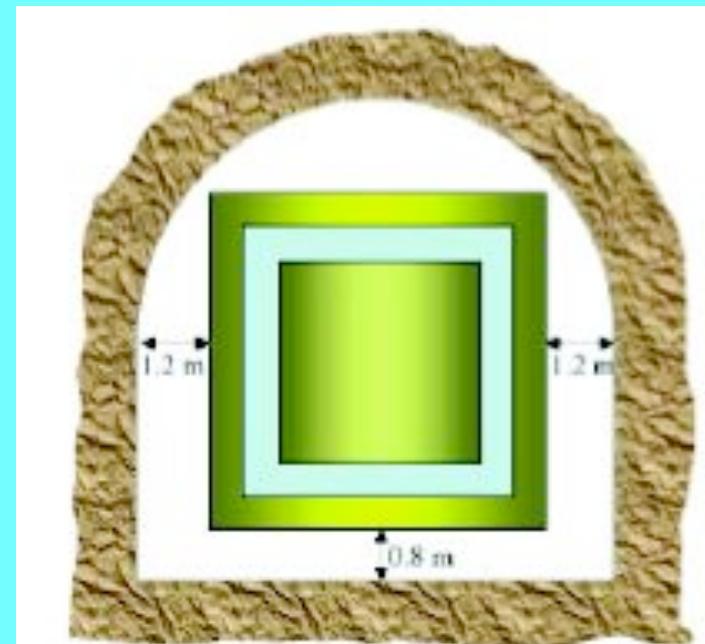
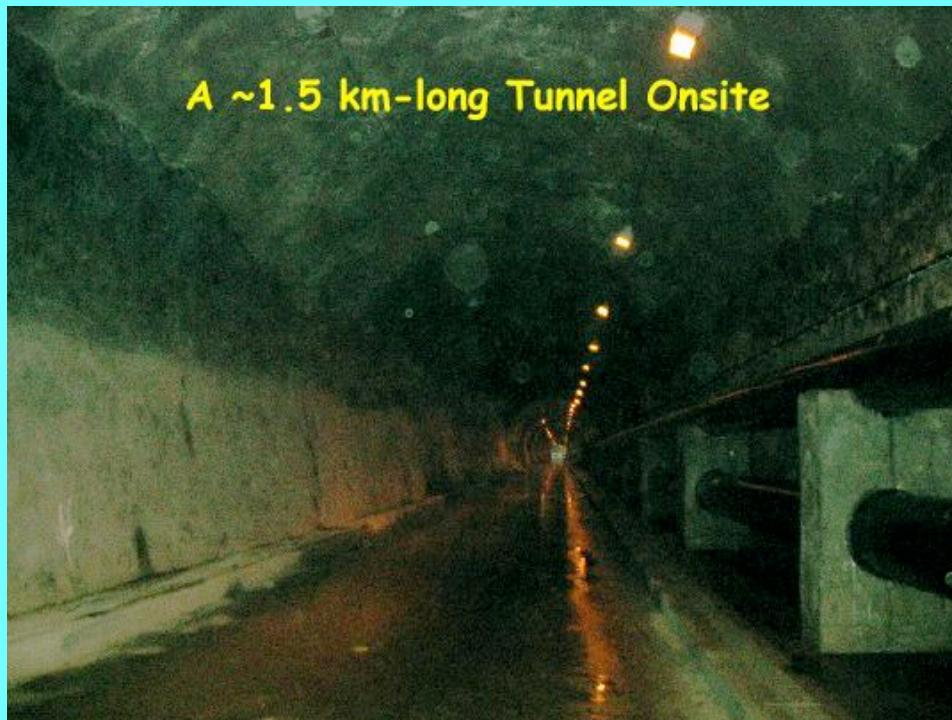
Faults(small)

Weathering bursa
(风化囊)

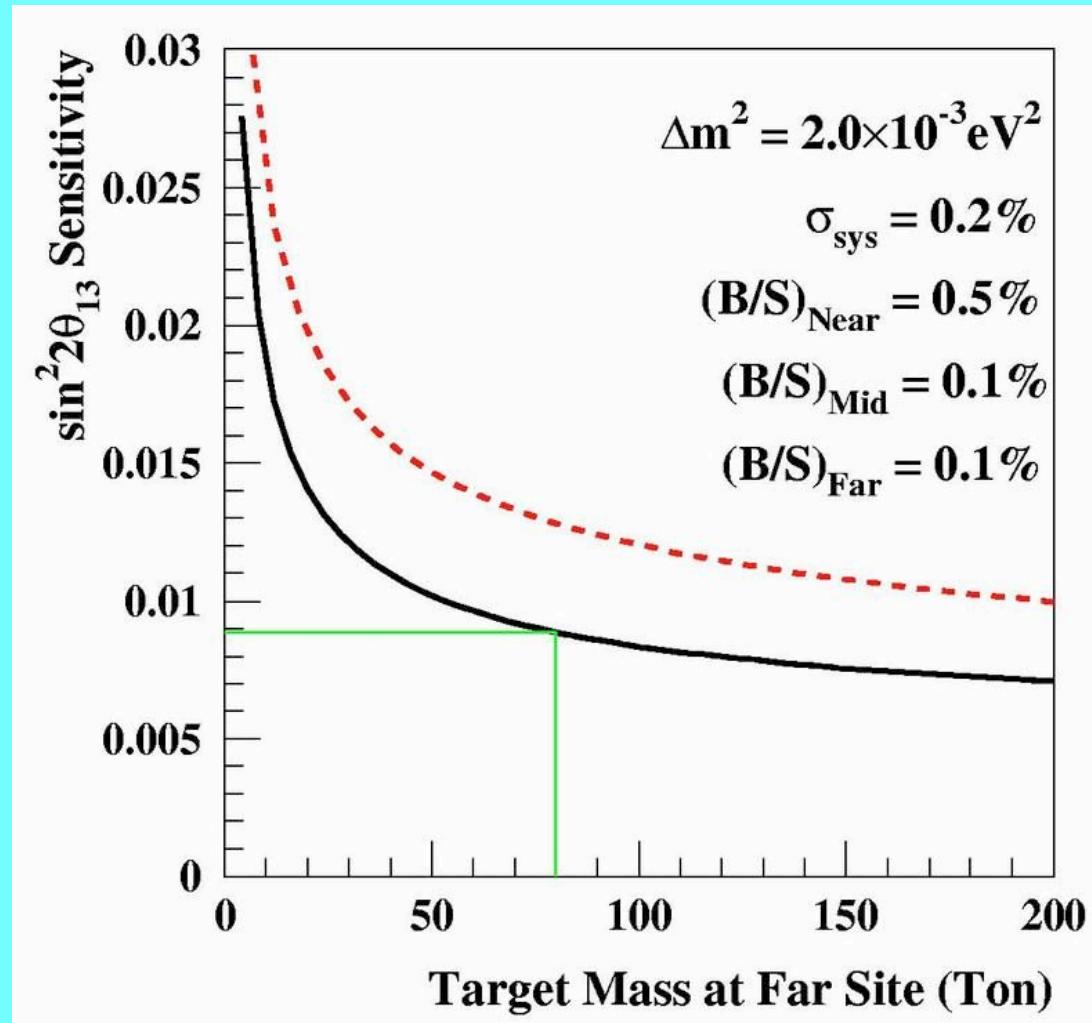


Tunnel Construction

- The tunnel length is about 3000m
- Local railway construction company has a lot of experience (similar cross section)
- Cost estimate by professionals, $\sim 3K$ \$/m
- Construction time is $\sim 15\text{-}24$ months
- A similar tunnel on site as a reference

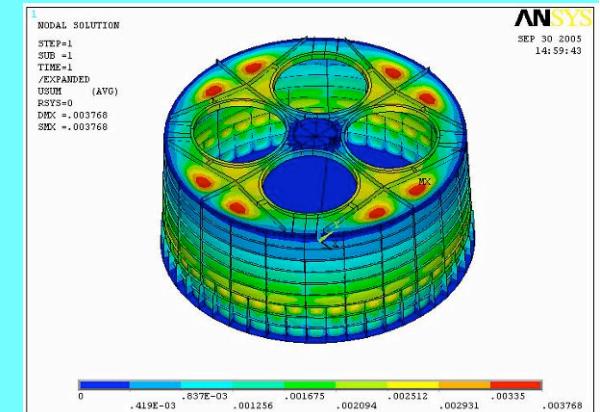
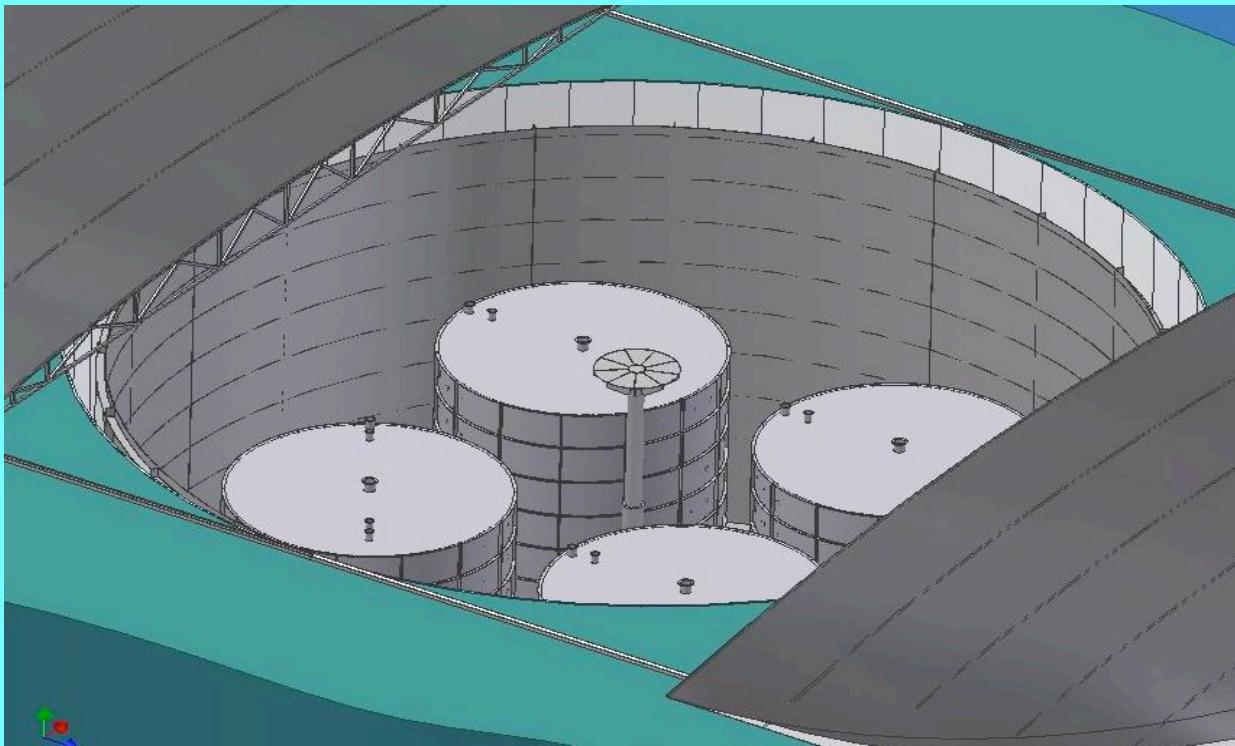


How large the detector should be ?



Systematic
error
Black : 0.25%
Red: 0.6%

Detector: Multiple Modules



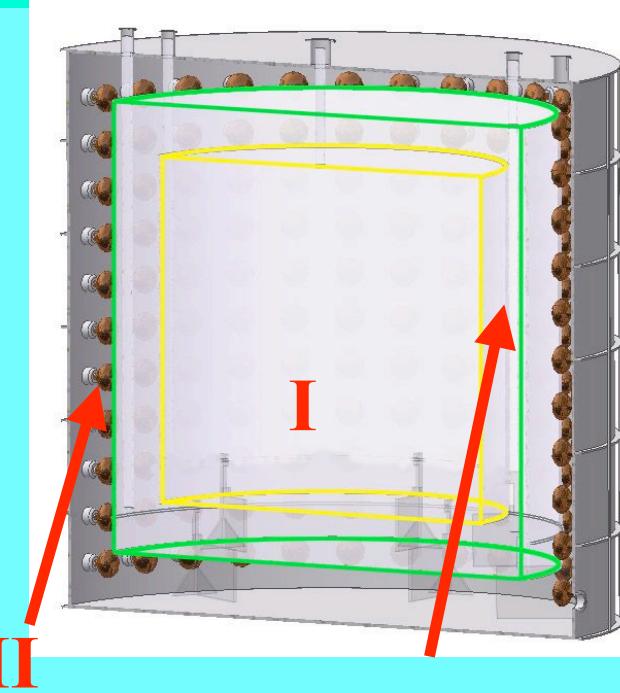
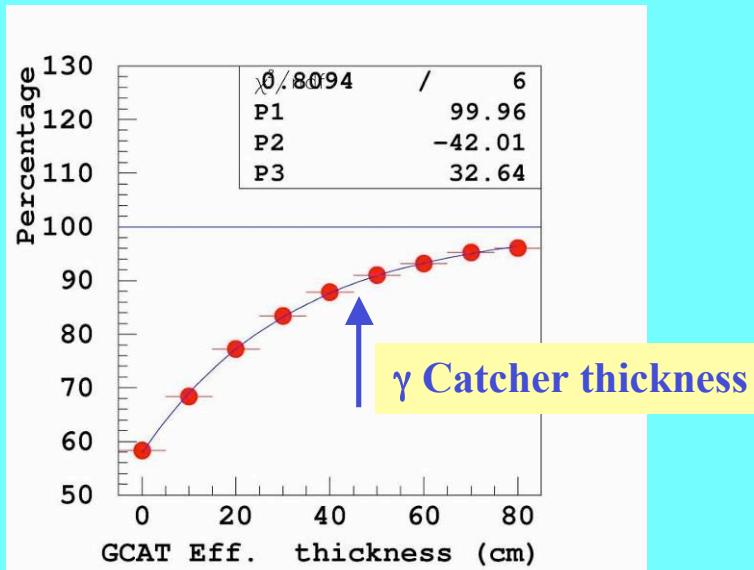
Two modules at near sites
Four modules at far site:
Side-by-side cross checks

- **Multiple modules for cross check, reduce uncorrelated errors**
- **Small modules for easy construction, moving, handing, ...**
- **Small modules for less sensitive to scintillator aging**
- **Scalable**

Detector Modules

- Three zones modular structure:
 - I. target: Gd-loaded scintillator
 - II. γ -ray catcher: normal scintillator
 - III. Buffer shielding: oil
- Reflection at two ends
- 20t target mass, ~200 8"PMT/module

$$\sigma_E = 5\% \text{ @ 8MeV}, \quad \sigma_s \sim 14 \text{ cm}$$



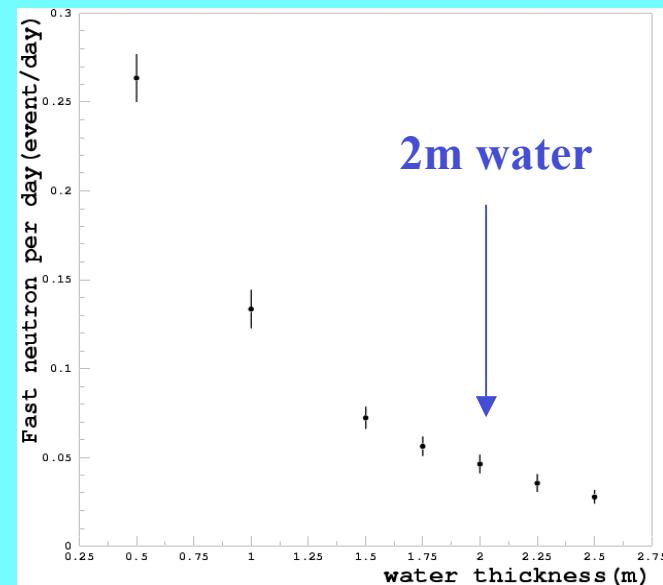
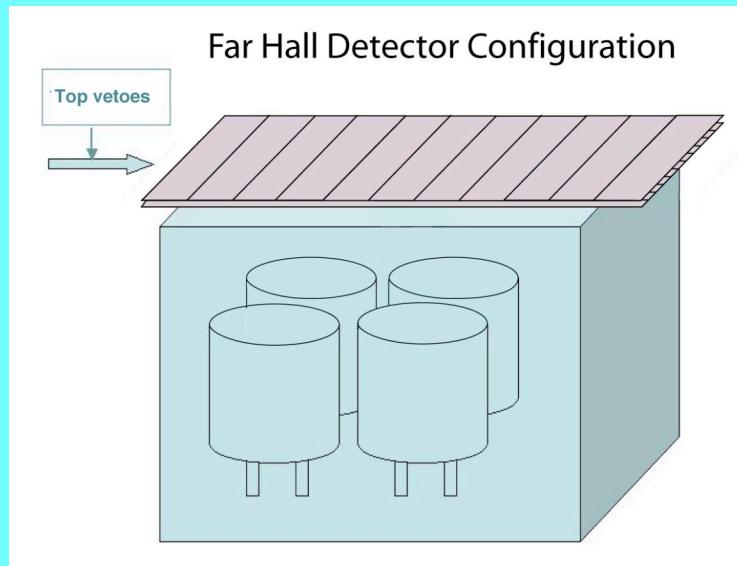
Oil buffer thickness

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

Water Shield and Muon Veto

- Specifications

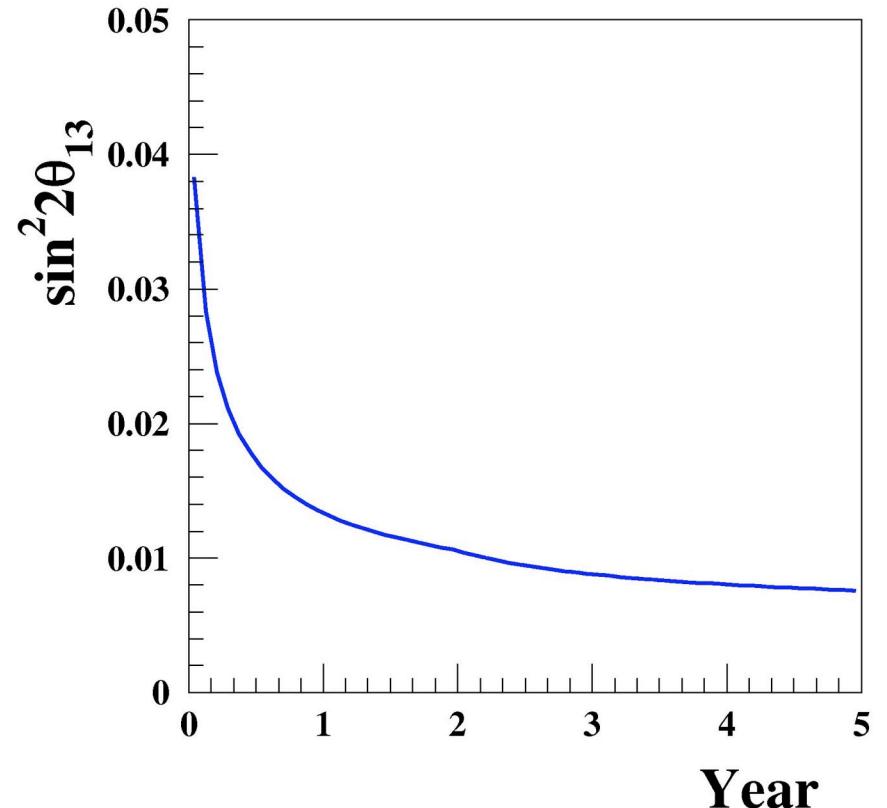
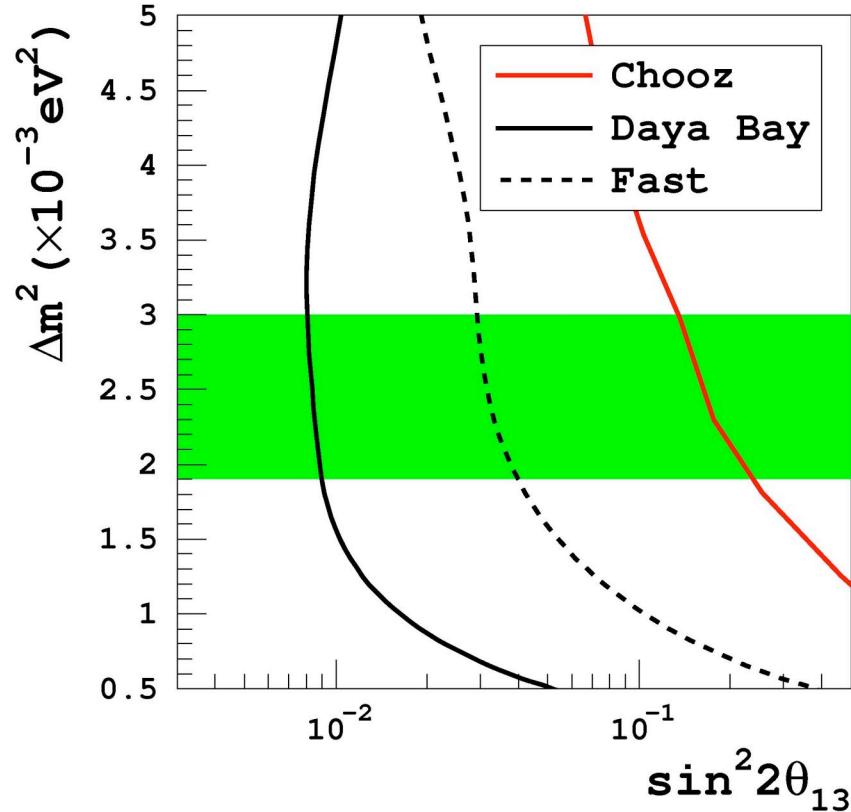
- High efficiency muon tracker; less than 0.3% inefficiency when combined with the muon water Cherenkov
- Good (ns) timing resolution to reduce accidentals due to ambient radioactivity background
- Muon tracker can be deployed in water pool
- Robust, good long-term stability



Background estimated by GEANT MC simulation

	Near	far
Neutrino signal rate(1/day)	560	80
Natural backgrounds (Hz)	45.3	45.3
Single neutron(1/day)	24	2
Accidental BK/signal	0.04%	0.02%
Correlated fast neutron Bk/signal	0.14%	0.08%
${}^8\text{He}+{}^9\text{Li}$ BK/signal	0.5%	0.2%

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

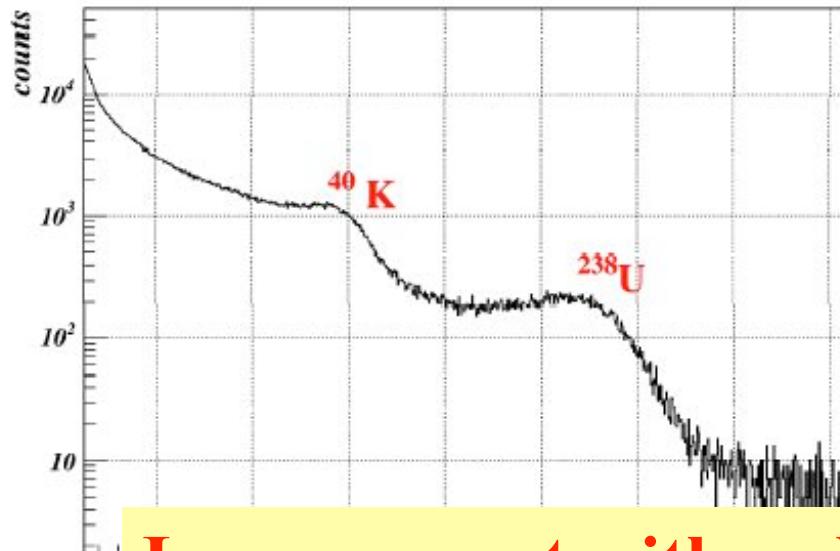


Other physics capabilities:
Supernova watch, Sterile neutrinos, ...

Prototype: 45 PMT for 0.6 t LS

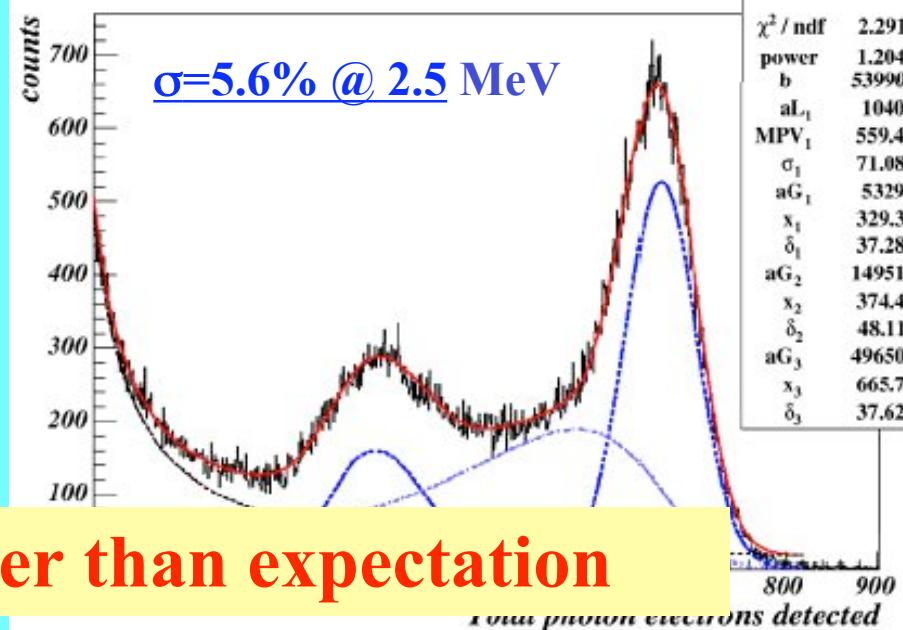


Backgrounds

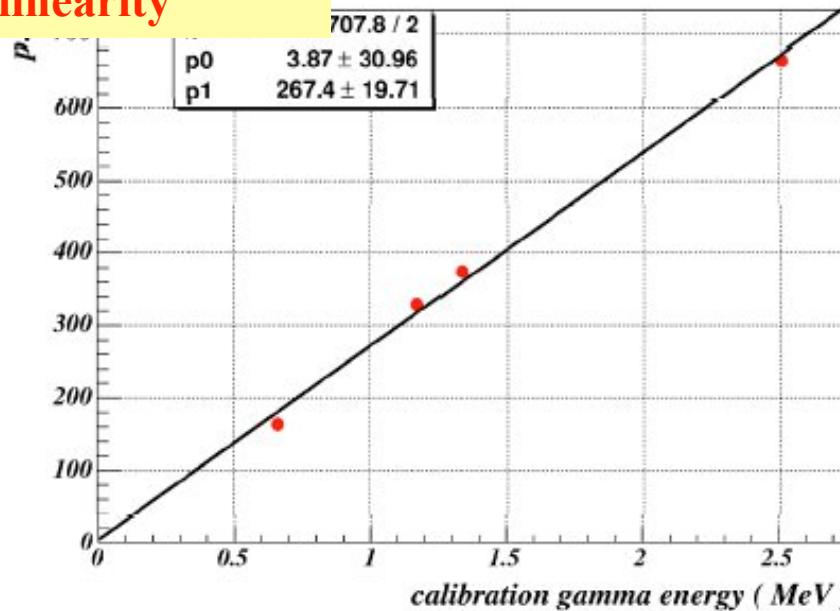


In agreement with or better than expectation

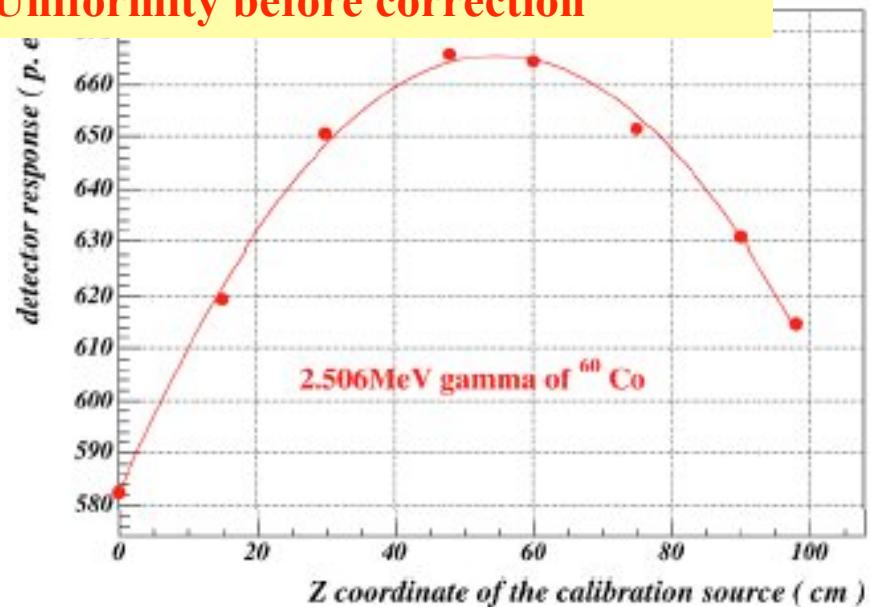
⁶⁰Co spectrum



linearity

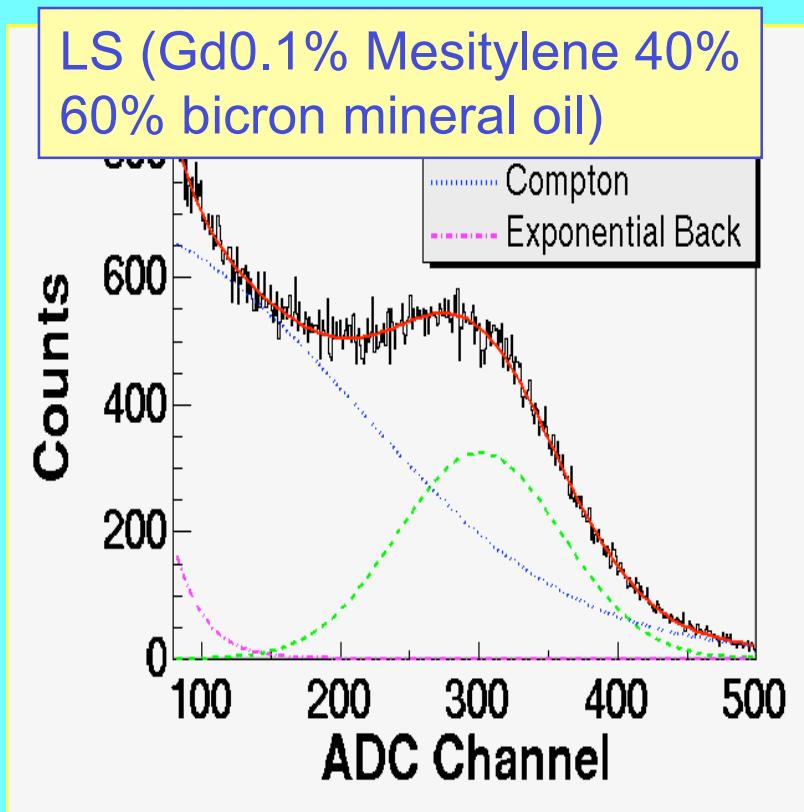


Uniformity before correction



Development of Gd-loaded LS

Sample	Attenuation Lengths (m)
2: 8 mesitylene: dodecane (LS)	15.0
PPO 5g/L bis-MSB 10mg/L in LS	11.3
0.2% Gd-EHA in LS	8.3
0.2% Gd-TMHA in LS	7.2
LAB	~
PPO 5g/L bis-MSB 10mg/L in LAB	23.7
0.2% Gd-TMHA PPO 5g/L bis-MSB 10mg/L in LAB	19.1
0.2% Gd-EHA PPO 5g/L bis-MSB 10mg/L in 2: 8 mesitylene: LAB	14.1



IHEP and BNL both developed Gd-loaded LS using LAB:
high light yield, high flash point,
low toxicity, cheap,
long attenuation length

Status of the Project

- CAS officially approved the project
- Chinese Atomic Energy Agency and the Daya Bay nuclear power plant are very supportive to the project
- Funding agencies in China are supportive, R&D funding in China approved and available
- R&D funding from DOE approved
- Site survey including bore holes completed
- R&D started in collaborating institutions, the prototype is operational
- Review by governments under preparation
- Good collaboration among China, US and other countries

Schedule of the Project

- 2004-2006 R&D, engineering design,
secure , funding
- 2007-2008 proposal, construction
- 2009 installation
- 2010 running

Daya Bay Collaboration

Political Map of the World, June 1999



The Daya Bay Collaboration

20 institutions, 89 collaborators

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Thanks!