Neutrino-oscillation Experiments with the Daya Bay Nuclear Power Facility

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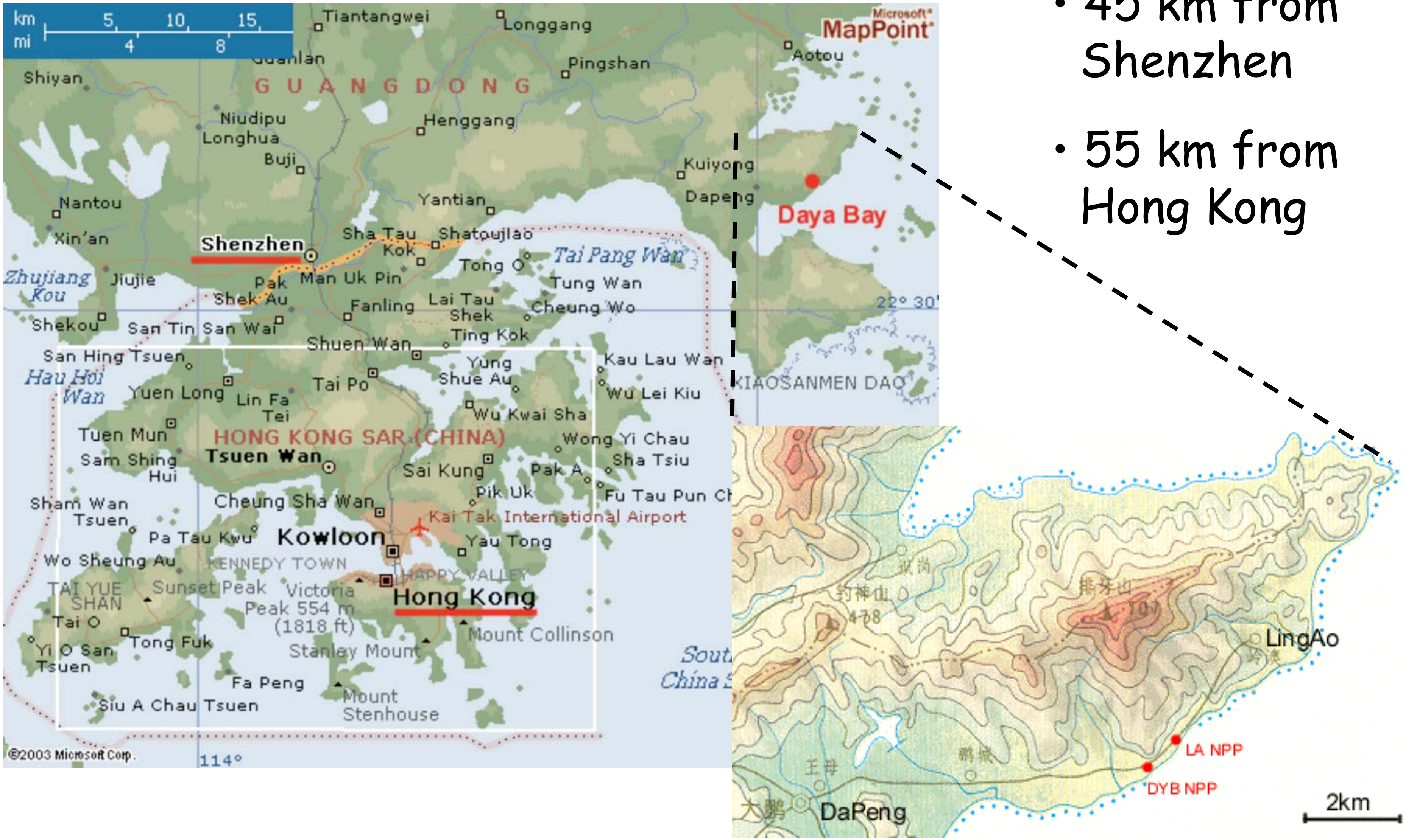
Neutrino Meeting at Santa Fe, October 30, 2005

Location of Daya Bay

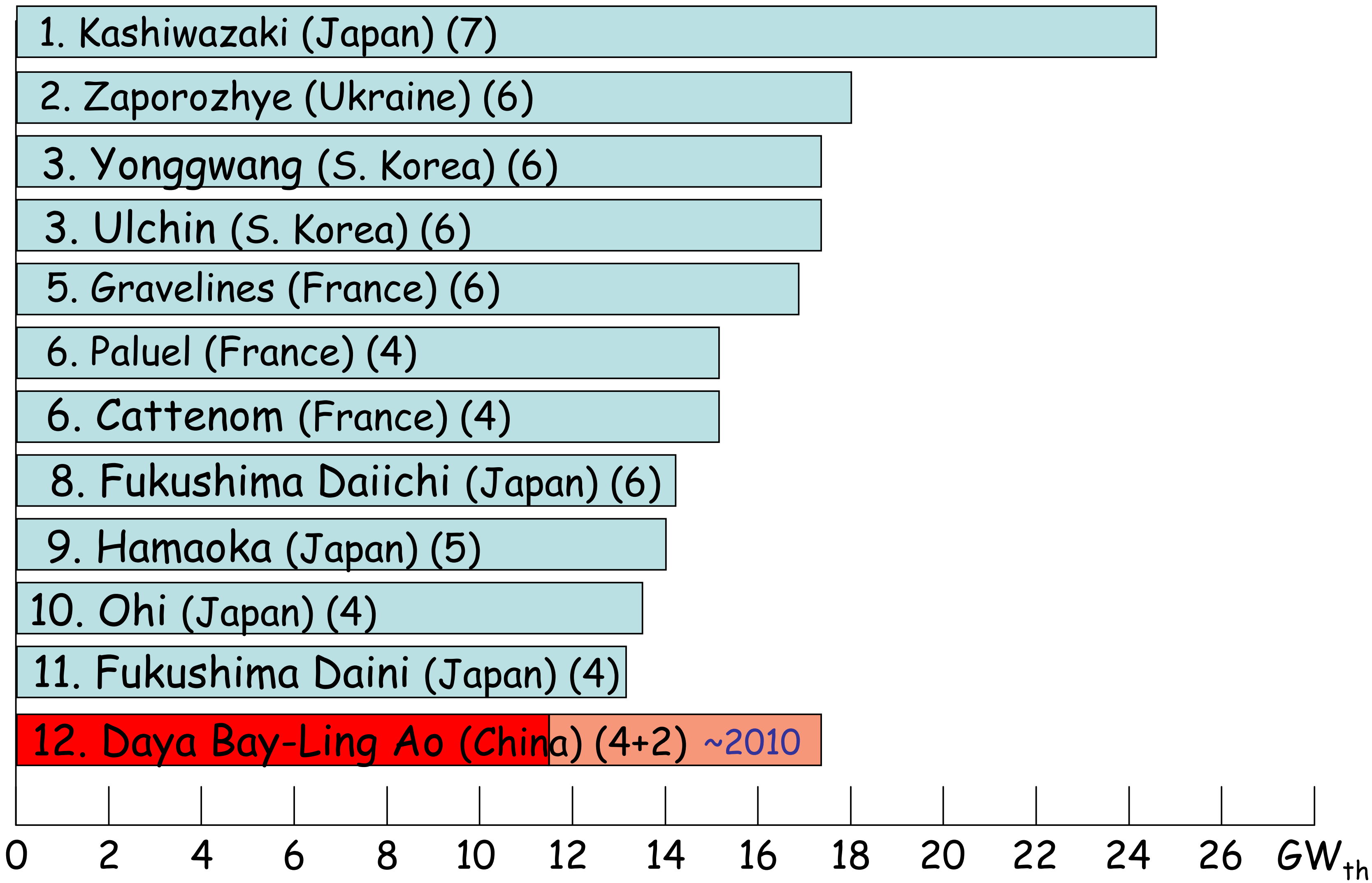


- 45 km from Shenzhen
- 55 km from Hong Kong

The Site


LingAo II NPP:
2 × 2.9 GW$_{th}$
Ready by 2010
Daya Bay NPP:
2 × 2.9 GW$_{th}$
LingAo NPP:
2 × 2.9 GW$_{th}$

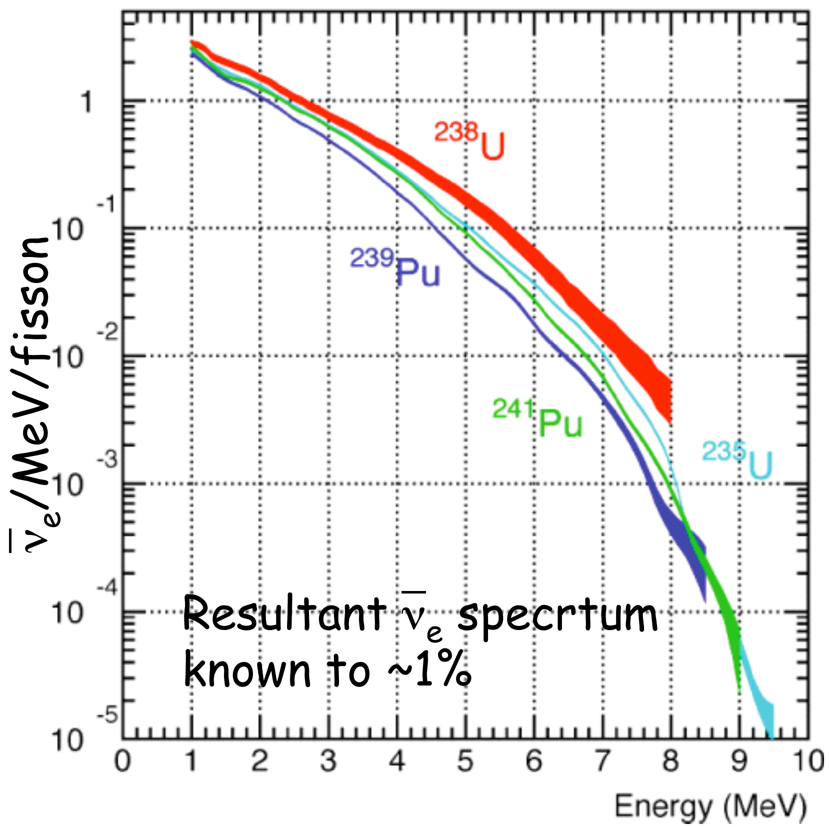
Ranking of Reactors

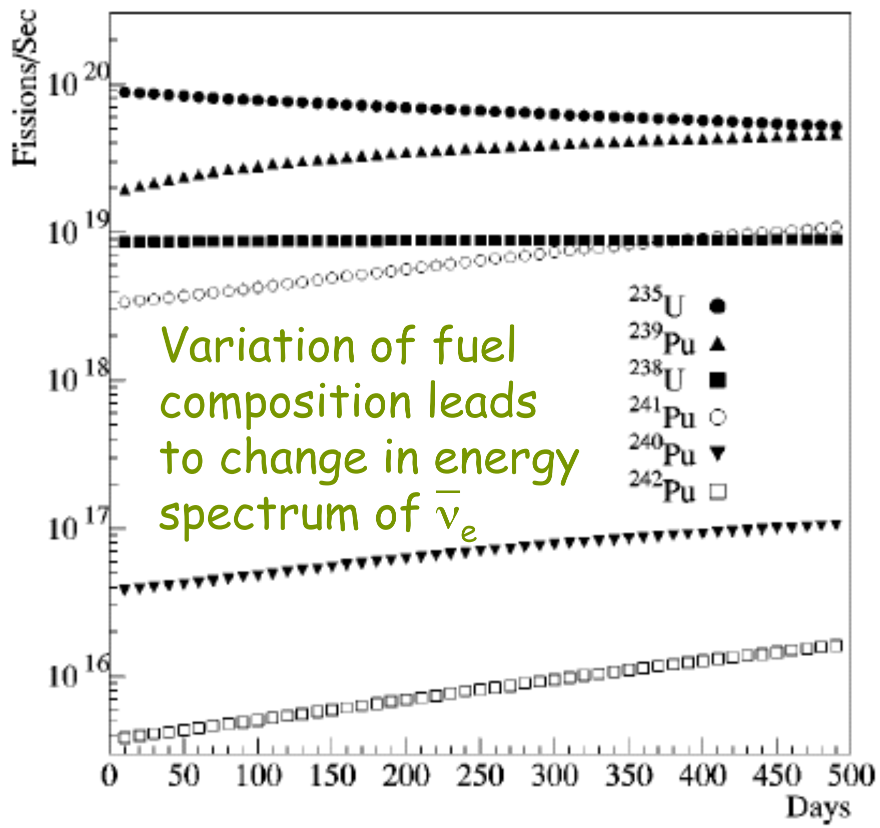


Reactor $\bar{\nu}_e$

- Fission processes in nuclear reactors produce huge number of low-energy $\bar{\nu}_e$:

3 GW_{th} generates 6×10^{20} $\bar{\nu}_e$ per sec





Goals And Approach

- **Utilize the Daya Bay nuclear power facilities to:**

  - determine $\sin^2 2\theta_{13}$ with a sensitivity of 1%
  - measure Δm^2_{31}
  - determine θ_{12} precisely
  - measure Δm^2_{21} as precise as possible

- **Adopt horizontal-access-tunnel scheme:**

  - mature and relatively inexpensive technology
  - flexible in choosing overburden
  - relatively easy and cheap to add expt. halls
  - easy access to underground experimental facilities
  - easy to move detectors between different locations with good environmental control.

The Daya Bay Experiment:
Determination of θ_{13} and Δm^2_{31}
A China-Russia-US Collaboration

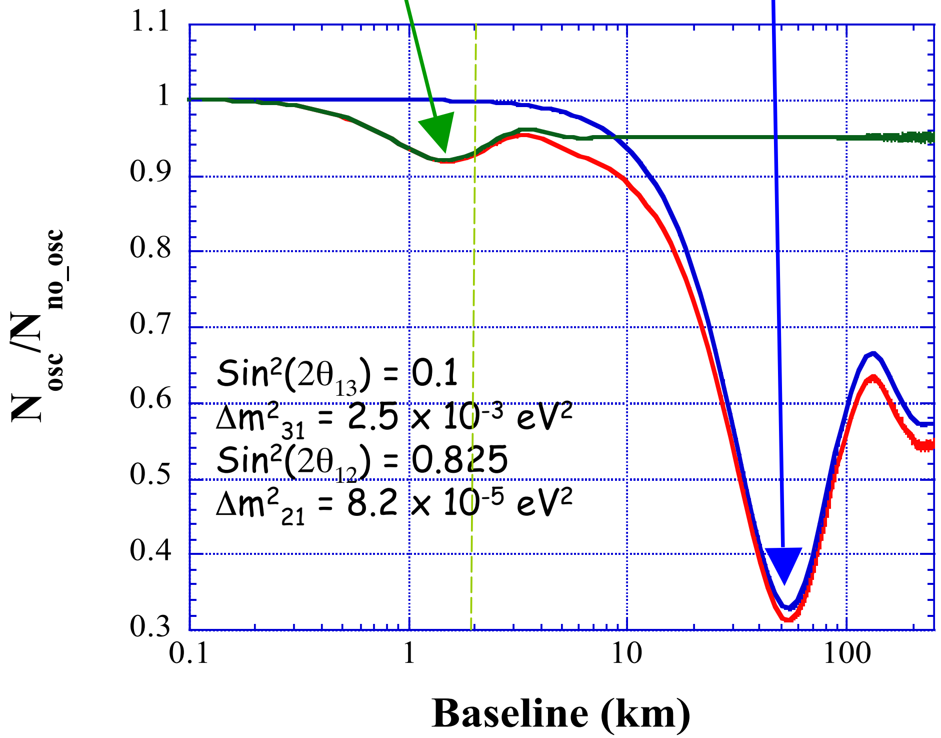
Where To Place The Detectors ?

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

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

Small-amplitude oscillation due to θ_{13}

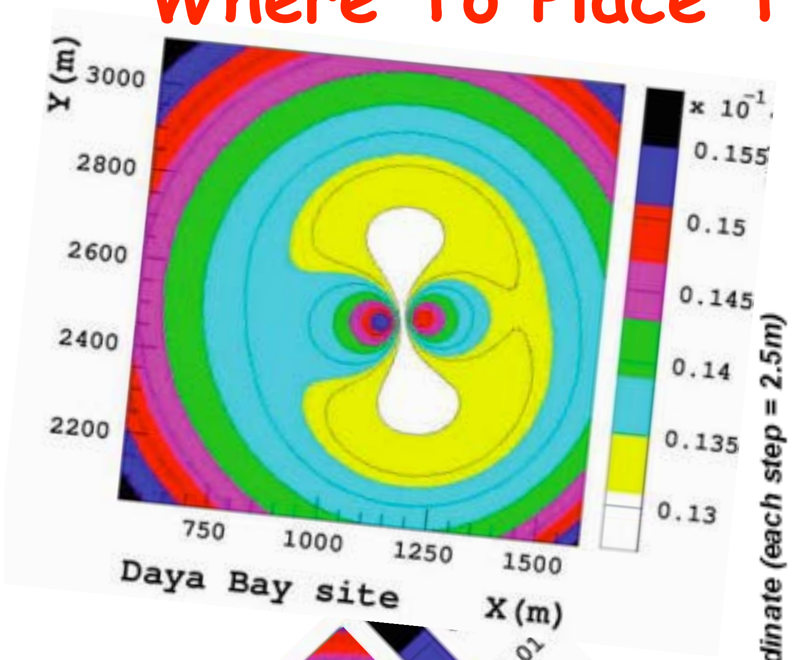
Large-amplitude oscillation due to θ_{12}

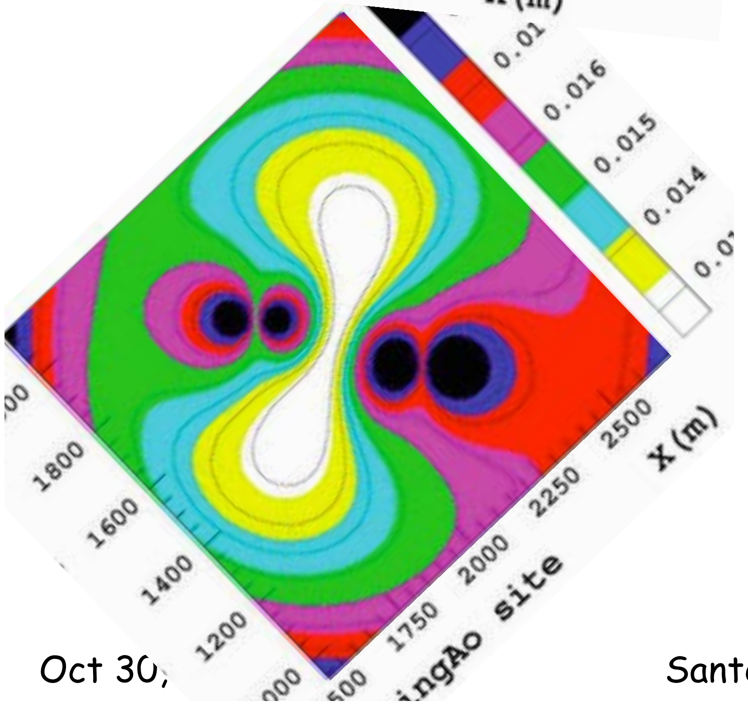


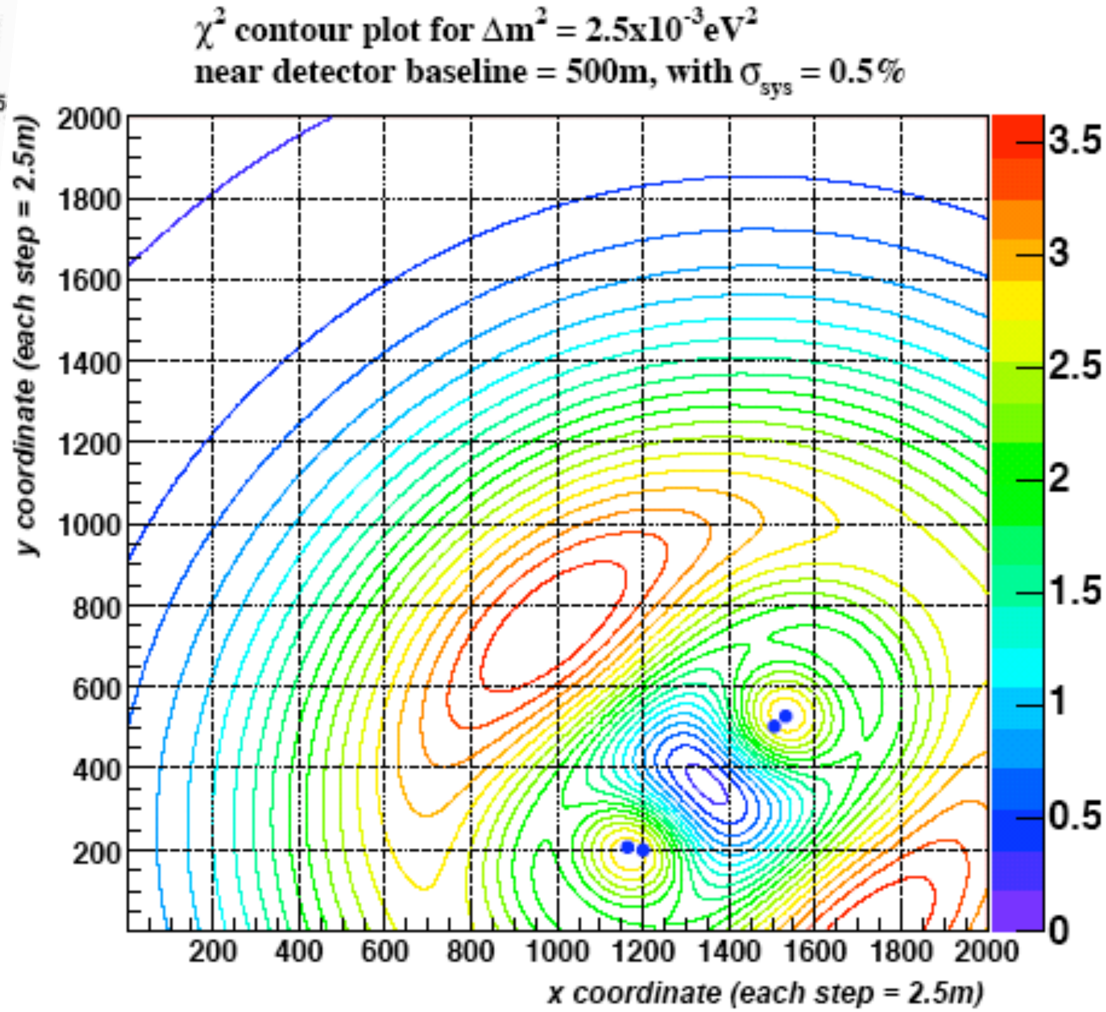
- Place near detector(s) close to reactor(s) to measure raw flux and spectrum of $\bar{\nu}_e$, reducing reactor-related systematic

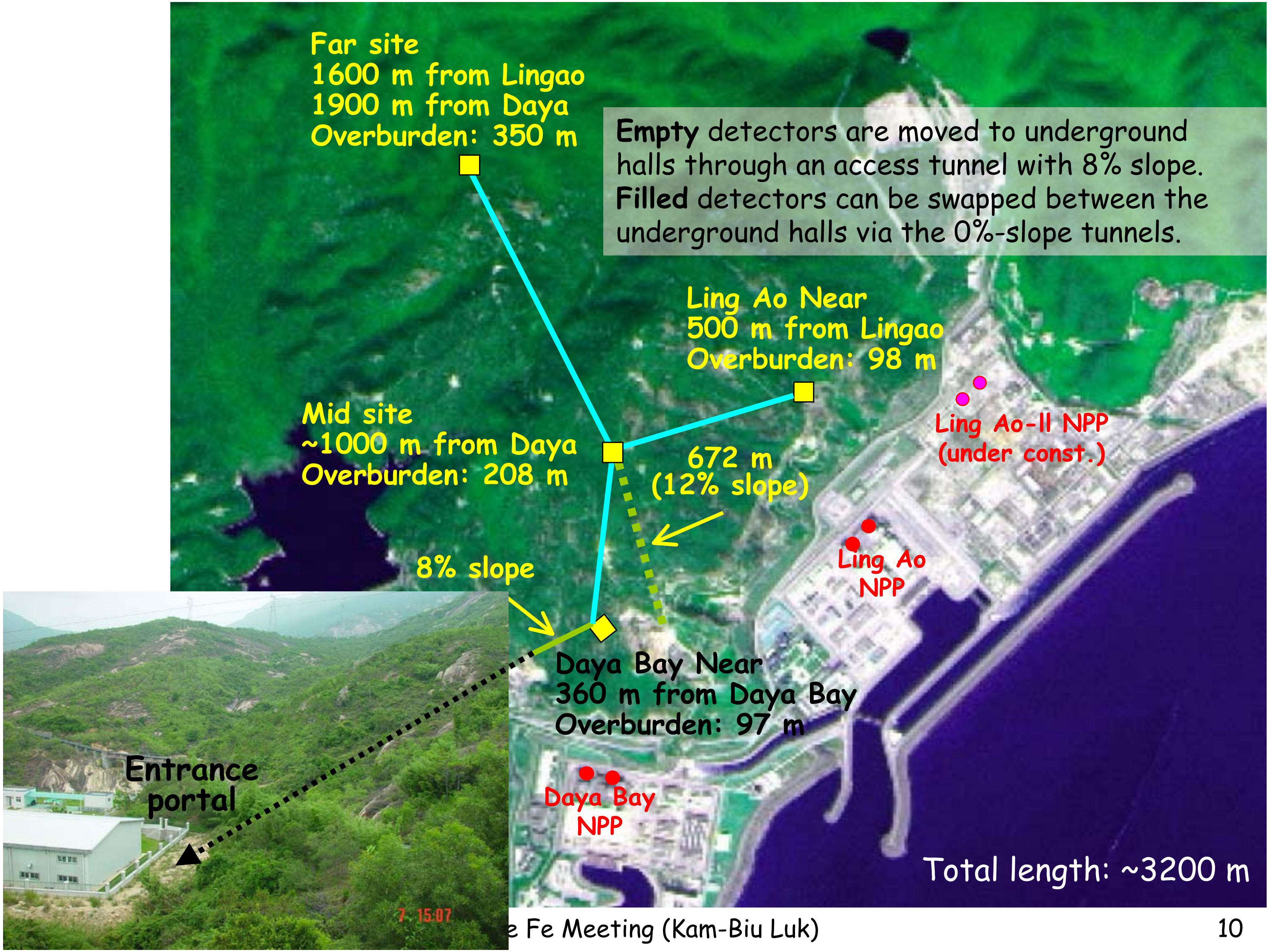
- Position a far detector near the first oscillation maximum to get the highest sensitivity, and also be less affected by θ_{12}

Where To Place The Detectors At Daya Bay?









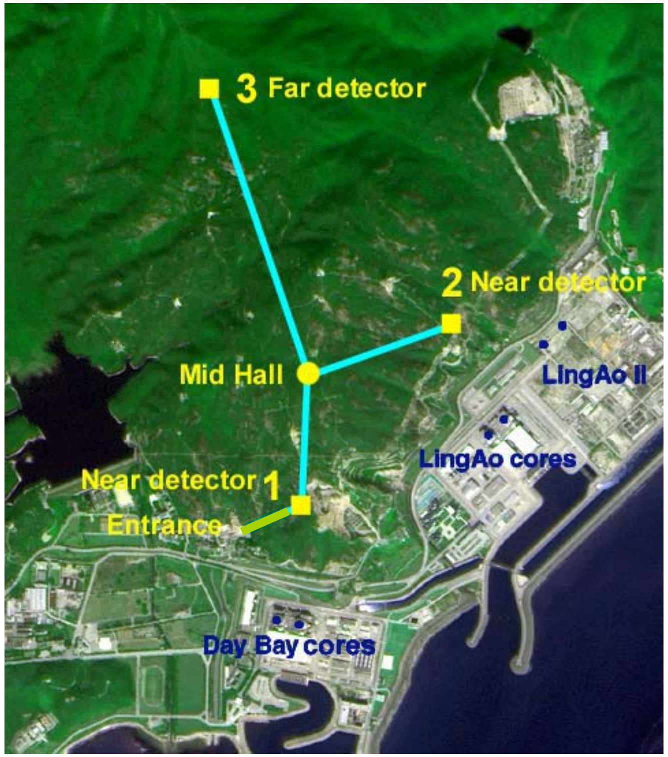
Far site
1600 m from Lingao
1900 m from Daya
Overburden: 350 m
Empty detectors are moved to underground halls through an access tunnel with 8% slope.
Filled detectors can be swapped between the underground halls via the 0%-slope tunnels.
Ling Ao Near
500 m from Lingao
Overburden: 98 m
Mid site
~1000 m from Daya
Overburden: 208 m
672 m
(12% slope)
Ling Ao-II NPP
(under const.)
Ling Ao
NPP
8% slope
Daya Bay Near
360 m from Daya Bay
Overburden: 97 m
Daya Bay
NPP
Total length: ~3200 m
Entrance
portal

A Versatile Site

- **Rapid deployment:**
  - Daya near site + mid site
  - 0.7% reactor systematic error

- **Full operation:**
  (1) Two near sites + Far site
  (2) Mid site + Far site
  (3) Two near sites + Mid site + Far site

Internal checks, each with different systematic



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

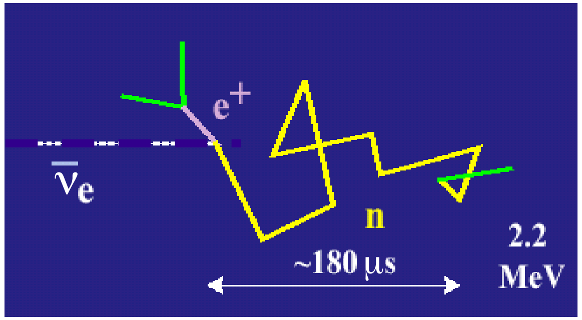
- The reaction is the inverse β-decay in Gd-doped liquid scintillator:

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

$\quad\quad \hookrightarrow + p \rightarrow D + \gamma(2.2\ \text{MeV}) \quad$ (delayed)

$\quad\quad \hookrightarrow + Gd \rightarrow Gd^*$

$\quad\quad\quad\quad \hookrightarrow Gd + \gamma\text{'s}(8\ \text{MeV}) \quad$ (delayed)



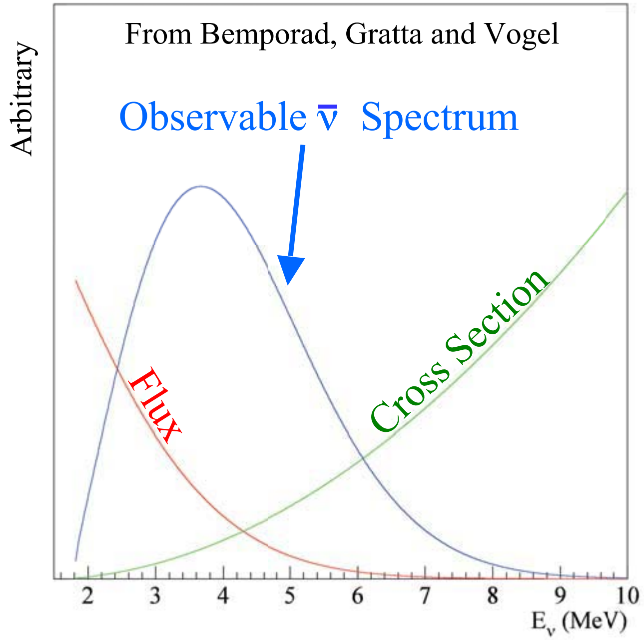
- Time- and energy-tagged signal is a good tool to suppress background events.

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

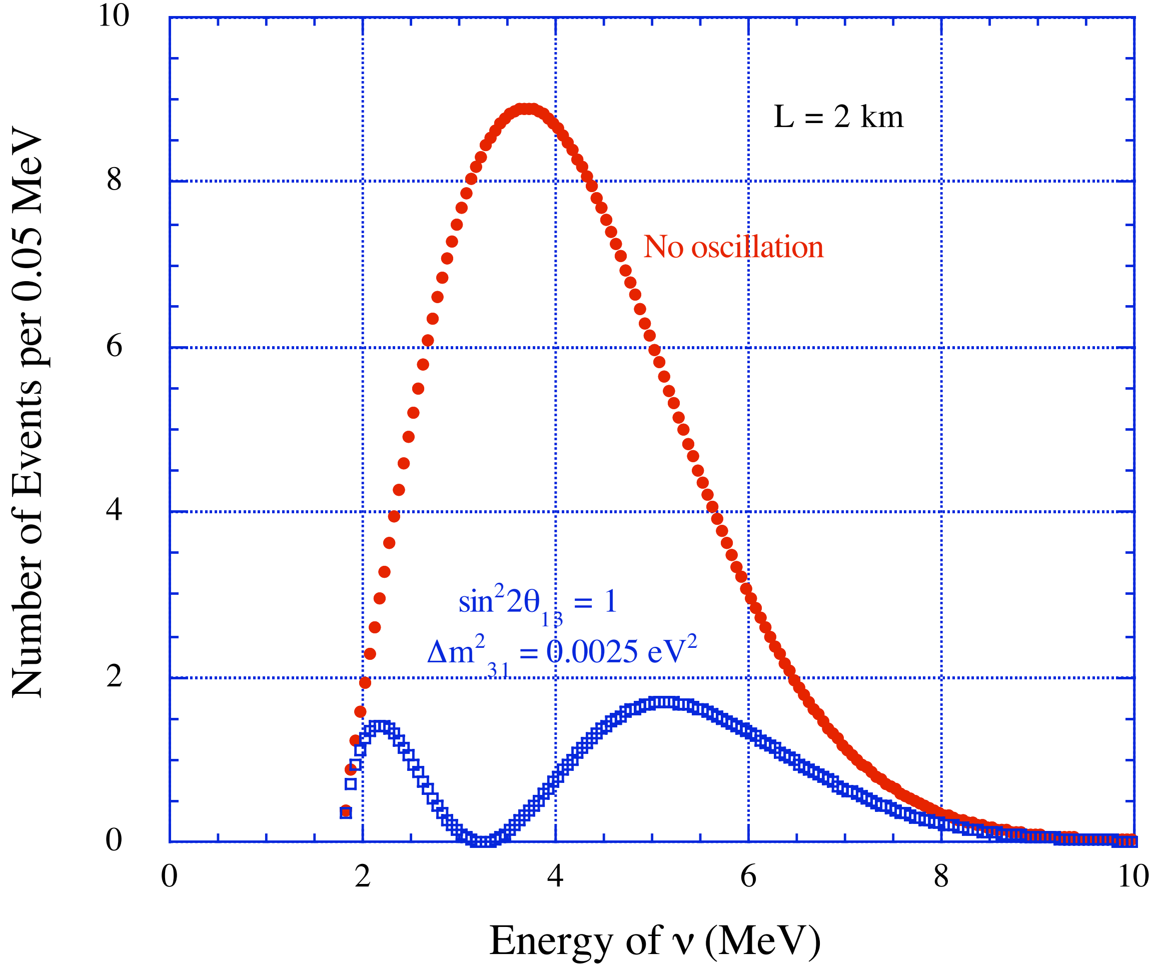
$$E_{\bar{\nu}} \approx T_{e+} + T_n + (m_n - m_p) + m_{e+} \approx T_{e+} + 1.8\ \text{MeV}$$

10-40 keV

- Threshold of inverse β-decay is about 1.8 MeV; thus only about 25% of the reactor $\bar{\nu}_e$ is usable.

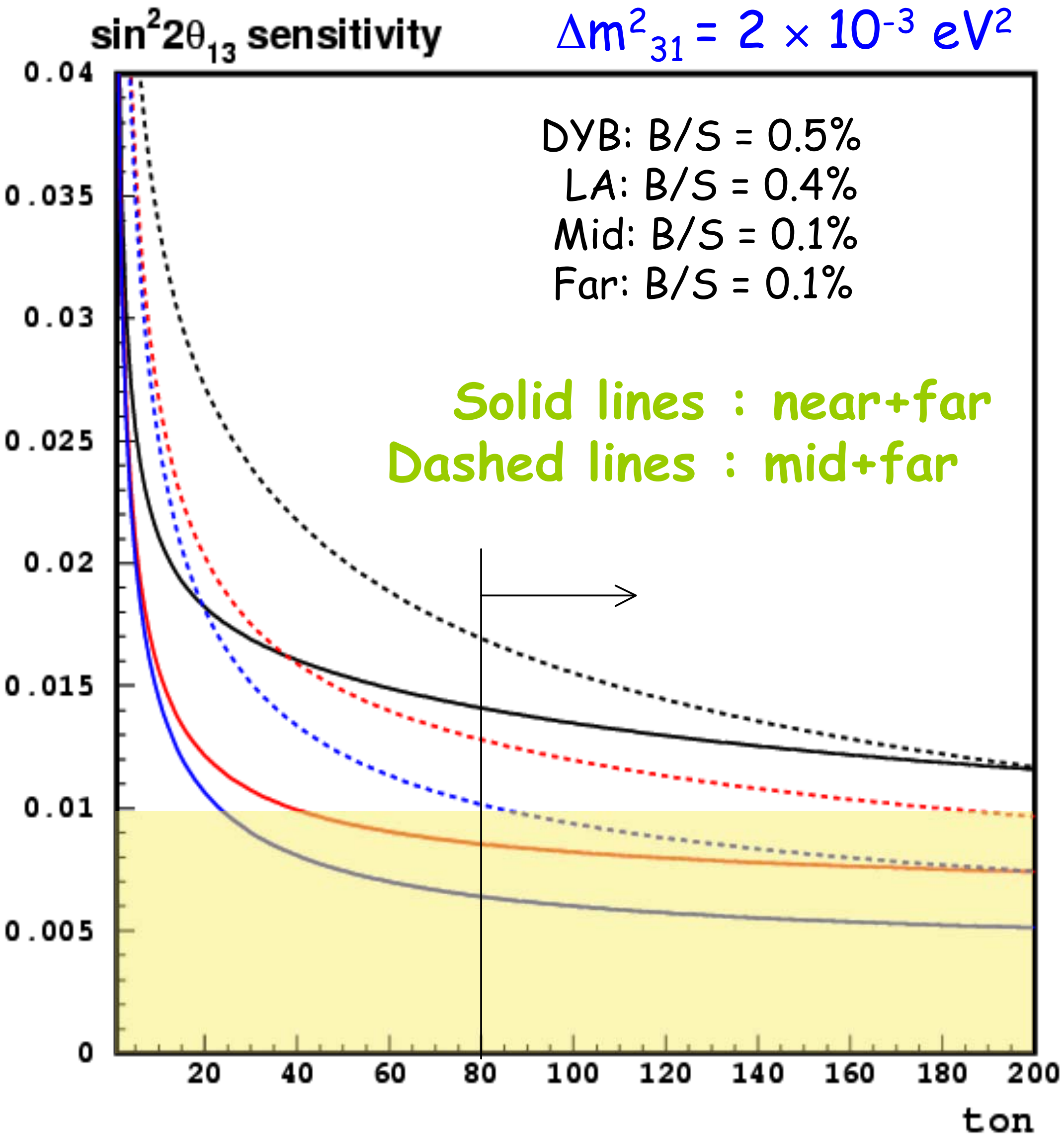


How To Measure θ_{13} With Reactor $\bar{\nu}_e$?



1. Rate deficit: deviation from $1/r^2$ expectation
2. Spectral distortion

What Target Mass Should Be?



Systematic error (per site):

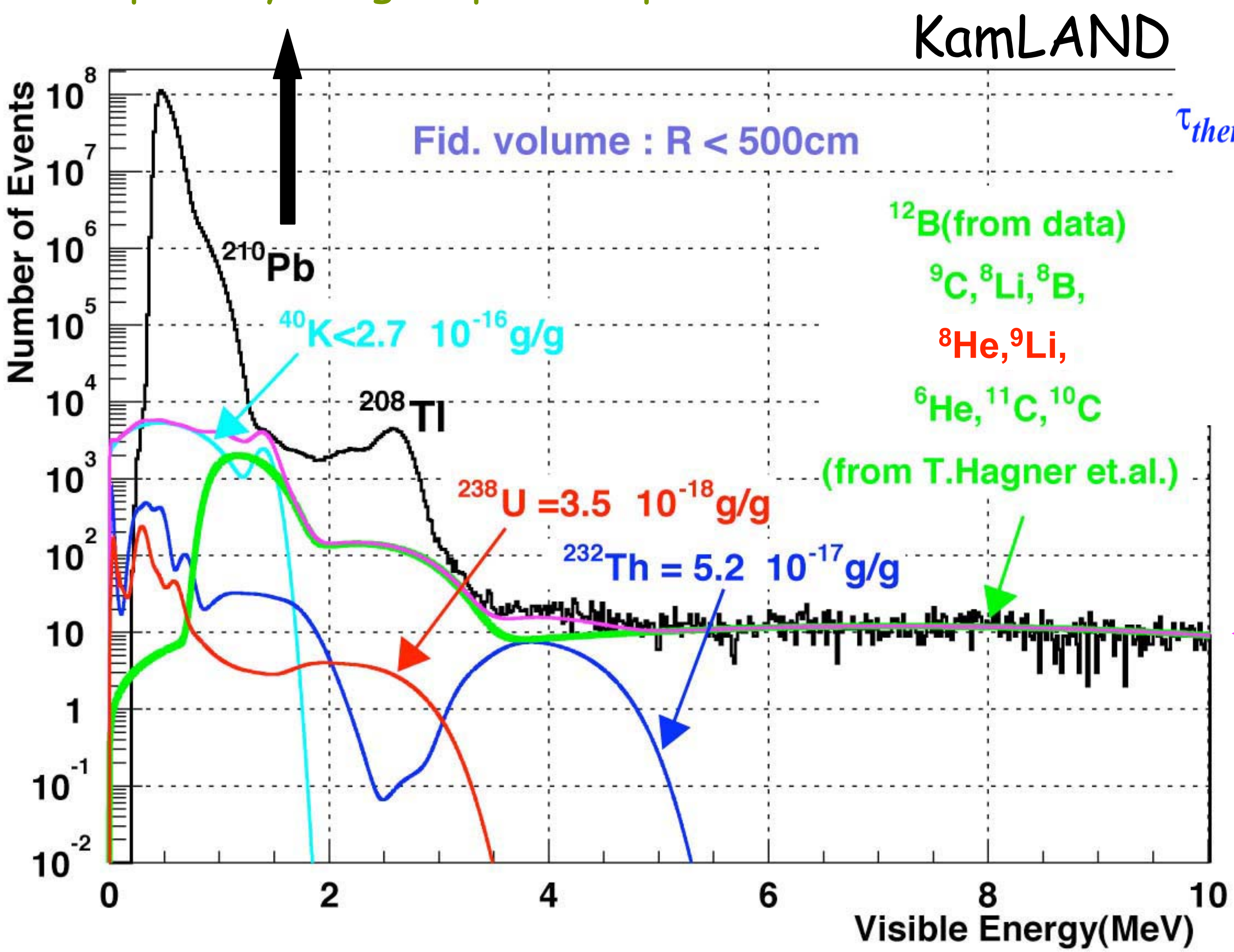
Black : 0.6%

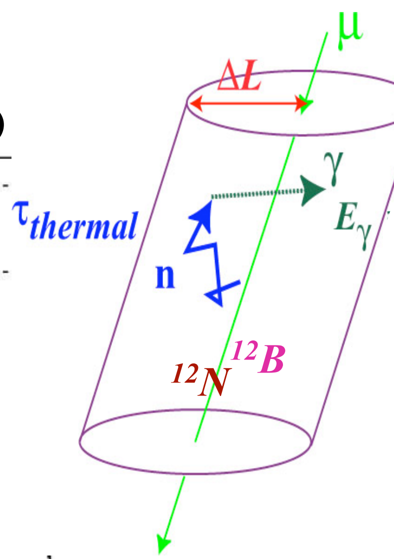
Red : 0.25%

Blue : 0.12%

Beat The Background

Keep everything as pure as possible!



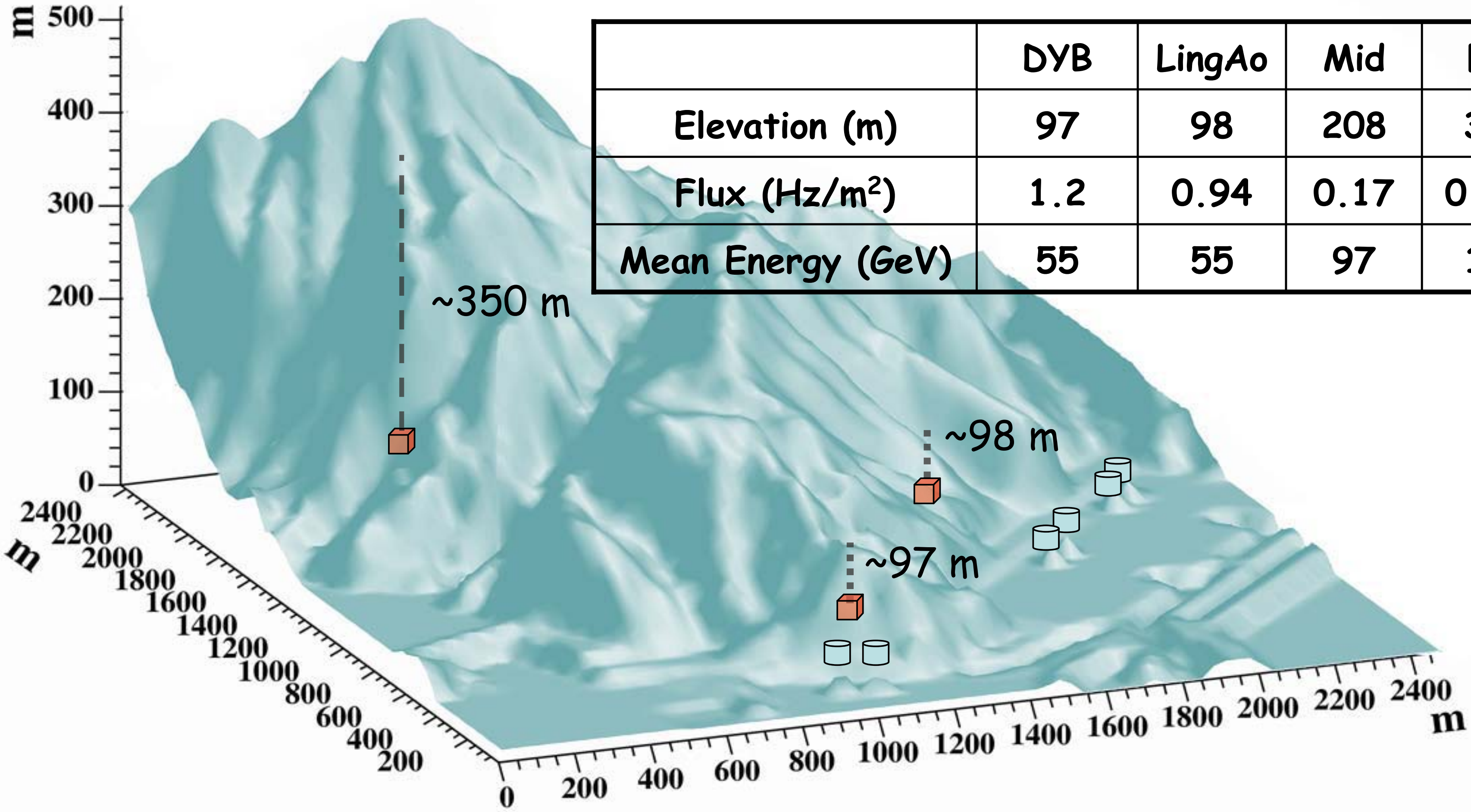


Depends on the flux of cosmic muons in the vicinity of the detector

Cosmic-ray Muon

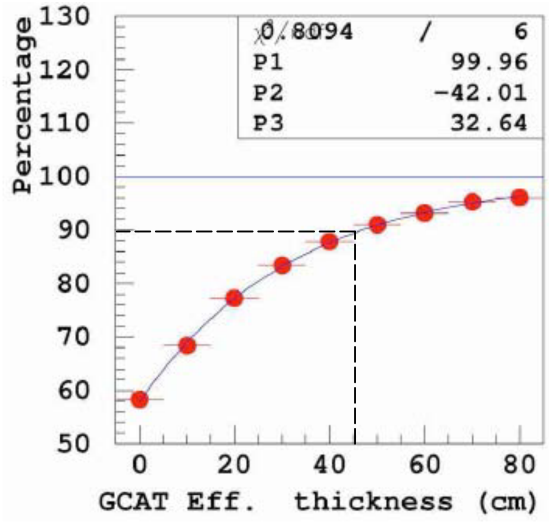
- Apply the Geiser parametrization for cosmic-ray flux at surface
- Use MUSIC and mountain profile to estimate muon flux & energy

	DYB	LingAo	Mid	Far
Elevation (m)	97	98	208	347
Flux (Hz/m^2)	1.2	0.94	0.17	0.045
Mean Energy (GeV)	55	55	97	136



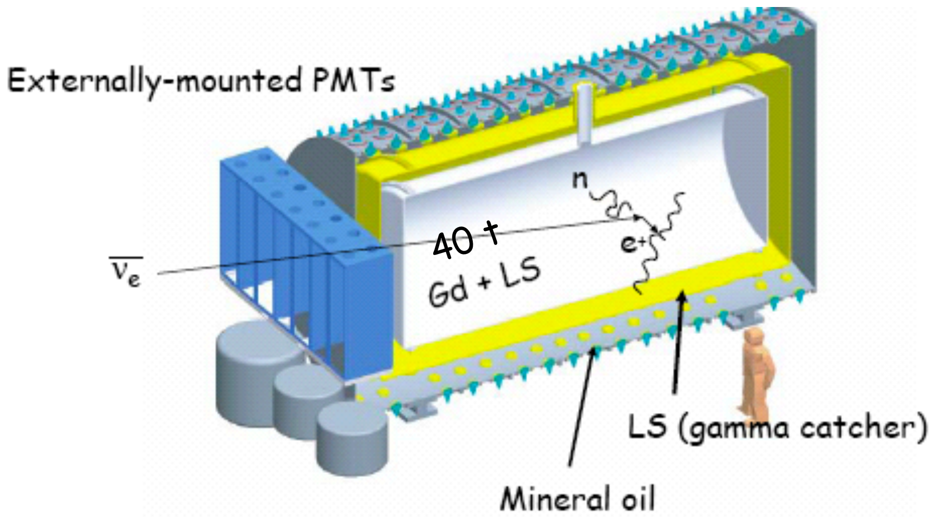
Conceptual Design of Detector Modules

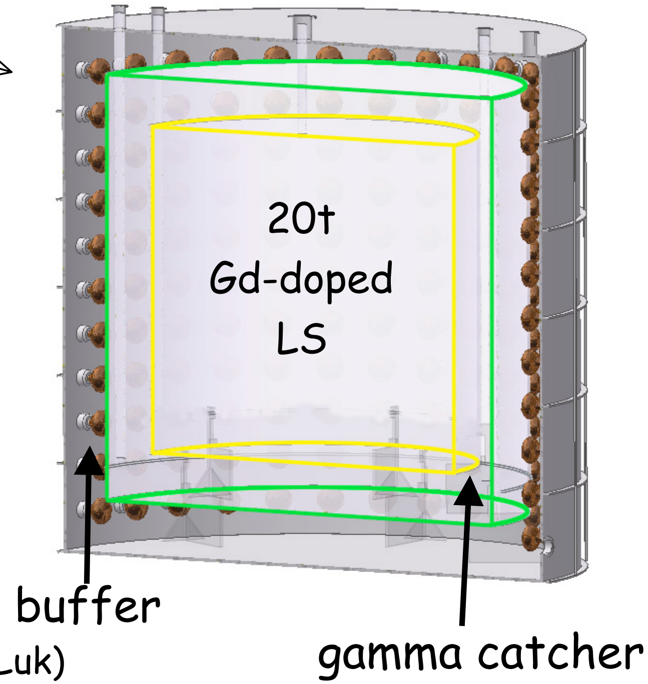
- **Three-layer structure:**
  I. Target: Gd-loaded liquid scintillator
  II. Gamma catcher: liquid scintillator, 45cm
  III. Buffer shielding: mineral oil, ~45cm



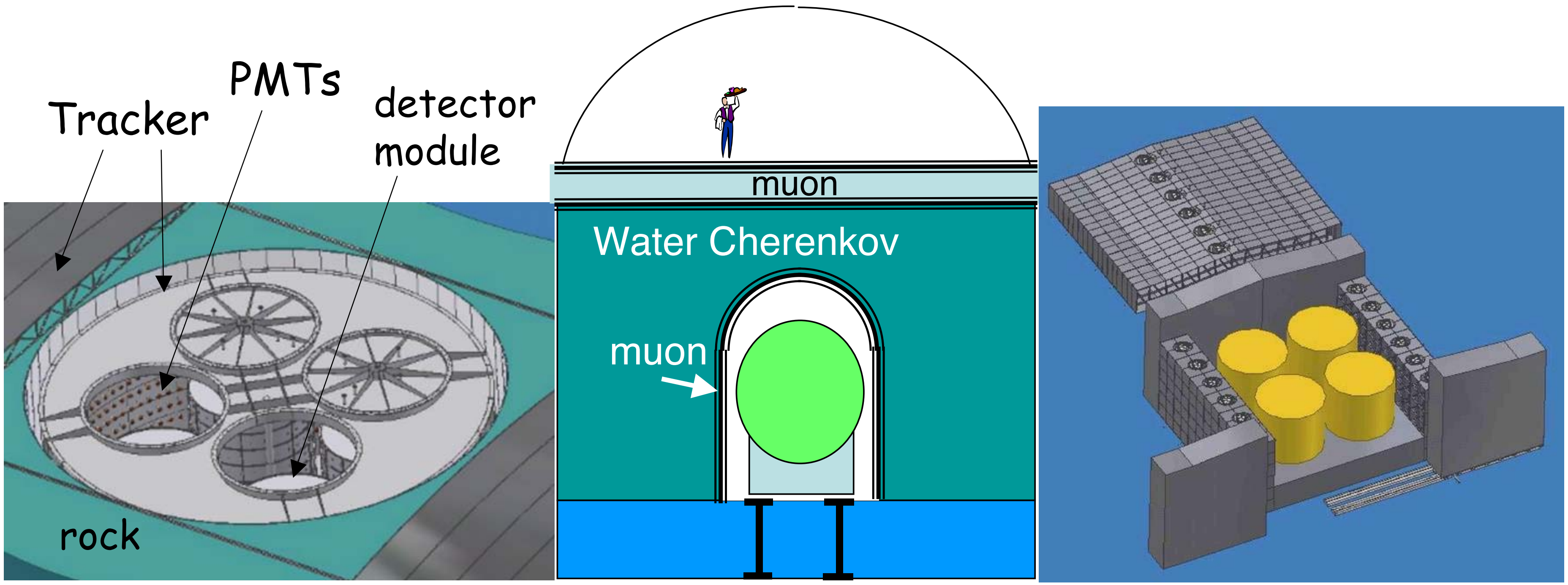
- **Possibly with diffuse reflection at ends. For ~200 PMT's around the barrel:**

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





Conceptual Design of Shield-Muon Veto



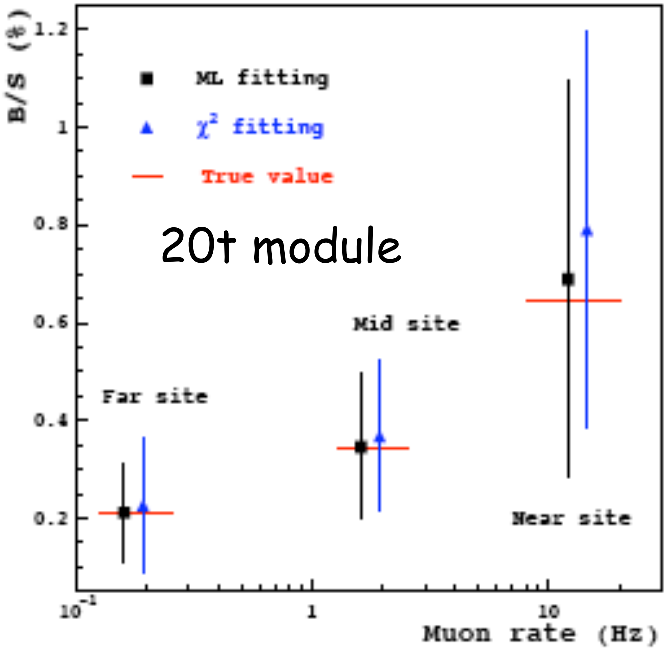
- Detector modules enclosed by 2m+ of water to shield neutrons and gamma-rays from surrounding rock
- Water shield also serves as a Cherenkov veto
- Augmented with a muon tracker: scintillator strips or RPCs
- Combined efficiency of Cherenkov and tracker > 99.5%

Background

- **Natural Radioactivity**: PMT glass, Rock, Radon in the air, etc
- **Slow neutron, and fast neutron**
  - Neutrons produced in rock and water shielding (99.5% veto efficiency)
- **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 detector with muon rate ~ 10 Hz.
- **Use a modified Palo-Verde-Geant3-based MC to model response of detector:**

	Near Site	Far Site
Radioactivity (Hz)	<50	<50
Accidental B/S	<0.05%	<0.05%
Fast Neutron background B/S	0.15%	0.1%
$^{8}He/^{9}Li$ B/S	0.55%	0.25%

The above number is before shower-muon cut.



Systematic Uncertainty

Systematic error	Chooz	Daya Bay
Reaction Cross Section	1.9%	0, near-far cancellation
Energy released per fission	0.6%	0, near-far cancellation
Reactor Power	0.7%	0.06%, near-far cancellation
Number of Protons	0.8%	0, detector swapping
Detection efficiency*	1.5%	~0.2%, fewer cuts, detector swapping
Total	2.75%	~0.2%

*

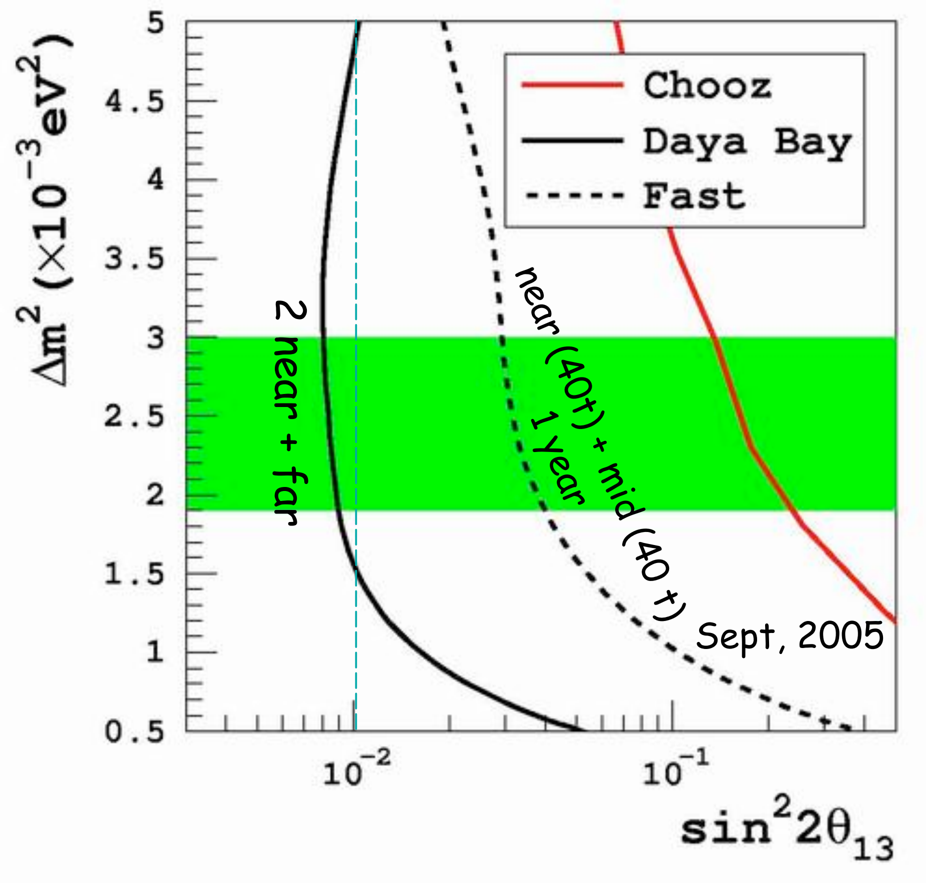
- No Vertex cut.
- Residual detection error is dominated by the **neutron energy cut** at 6 MeV - arises mainly from the energy-scale uncertainties. It is ~0.2% for a 1% energy-scale error at 6 MeV.
- **Positron energy cut** is negligible.

Statistical Error (3 years): 0.2%
Residual systematic error: ~ 0.2%
Background: B/S ~ 0.6%

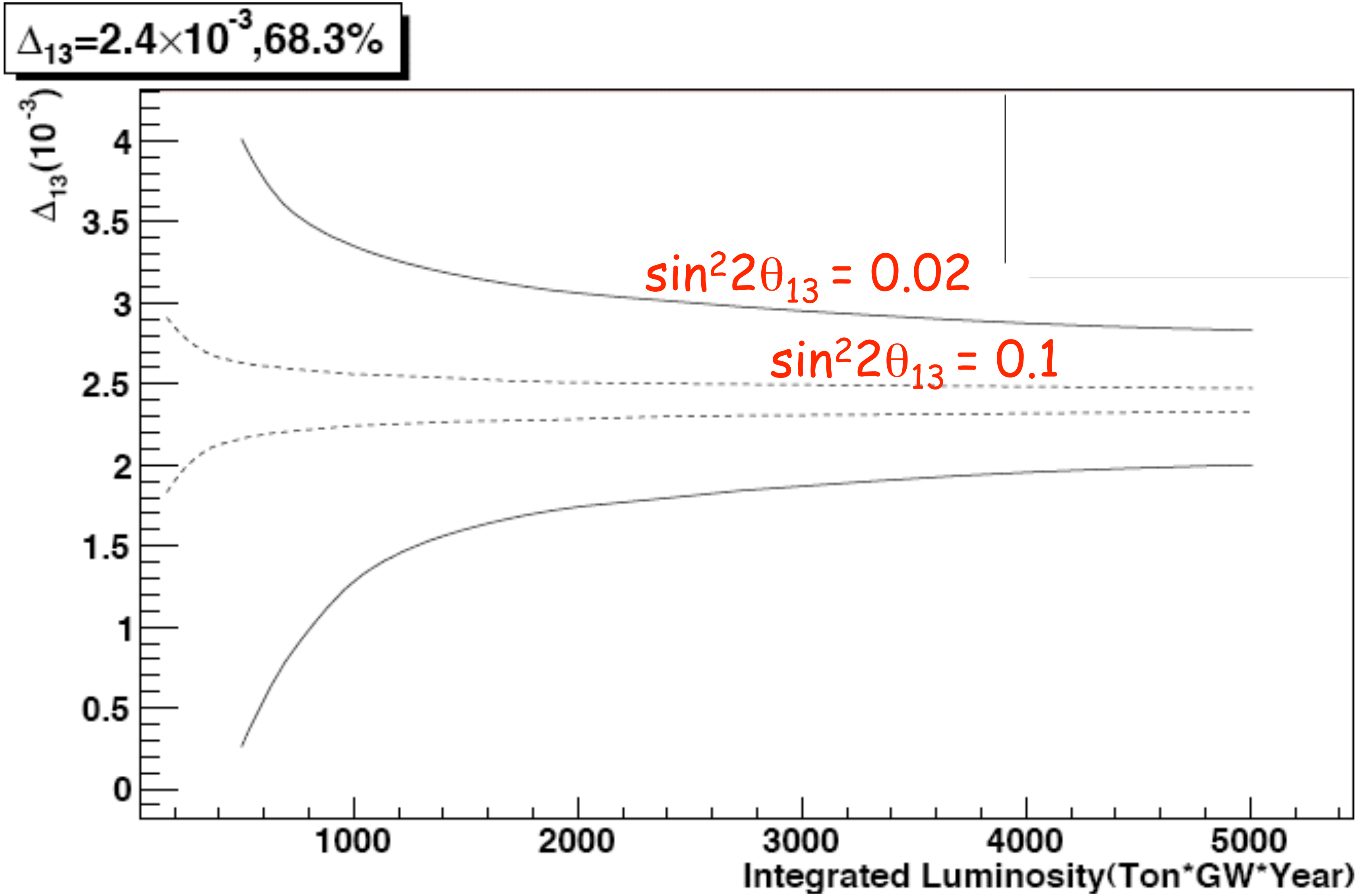
Sensitivity of $\sin^2 2\theta_{13}$

- Daya Bay site
  - baseline = 360 m
  - target mass = 40 ton
  - B/S = ~0.5%
- LingAo site
  - baseline = 500 m
  - target mass = 40 ton
  - B/S = ~0.5%
- Far site
  - baseline = 1900 m to DYB cores
    1600 m to LA cores
  - target mass = 80 ton
  - B/S = ~0.2%
- Three-year run (0.2% statistical error)
- Detector residual error = 0.2%
- Use rate and spectral shape

90% confidence level

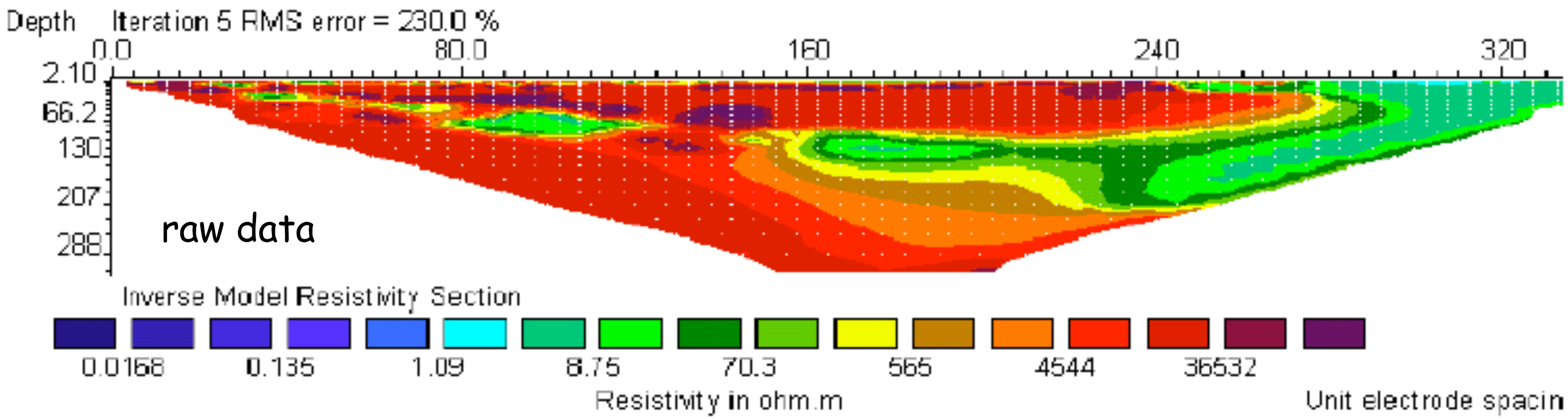


Precision of Δm^2_{31}



Geotechnical Survey

- Topography survey: Completed
- Geological Survey: Completed
  - Verified topographic information
  - Generated new map covering 7.5 km^2
- Geological Physical Survey: Completed
  - High-resolution electric resistance
  - Seismic
  - Micro-gravity
- Bore-Hole Drilling: November-December, 2005

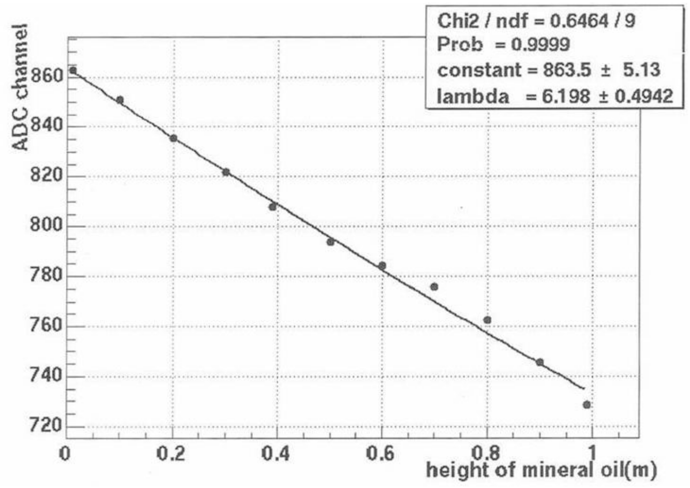


Synthesis of Gd-loaded Liquid Scintillator

- Investigating a few candidates at IHEP:

  One candidate:

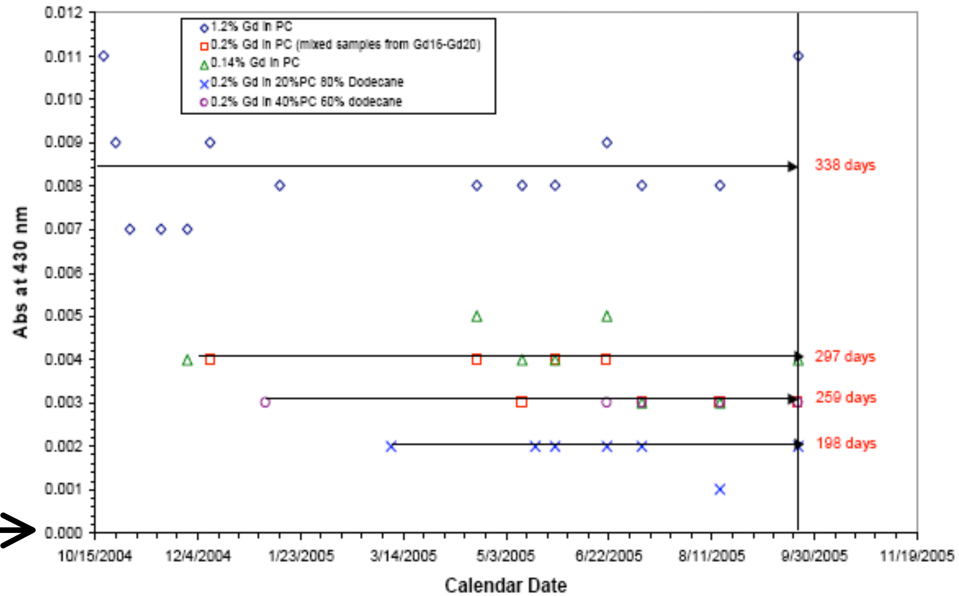
  - 0.1% Gd (D2EHP-ligand) in 20% mesitylene-80% dodecane
  - Light yield: 91% of pure LS
  - attenuation length = 6.2 m
  - stable for more than two months:



Date	2005. 06.13	2005. 08.01	2005. 08.26
Gd (%)	0.1	0.098	0.1

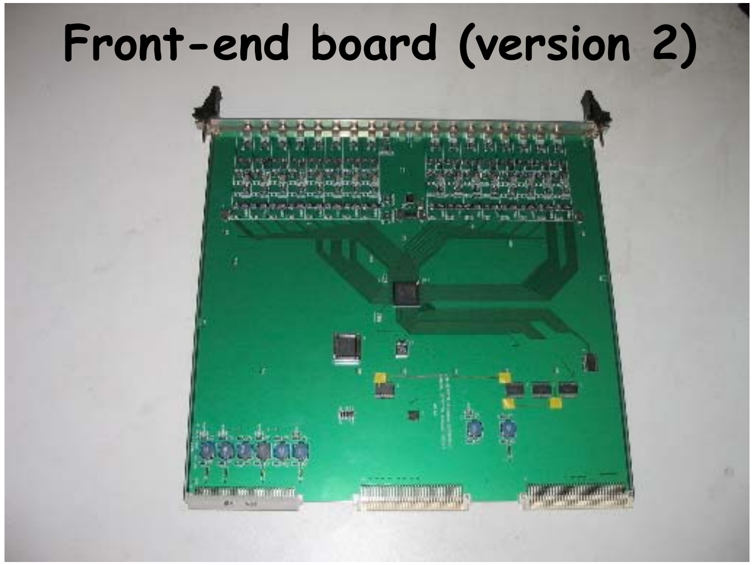
  - no effect on acrylic

- R&D collaborative effort at BNL:
  - Gd (carboxylate ligands) in PC and dodecane
  - all stable for almost a year →



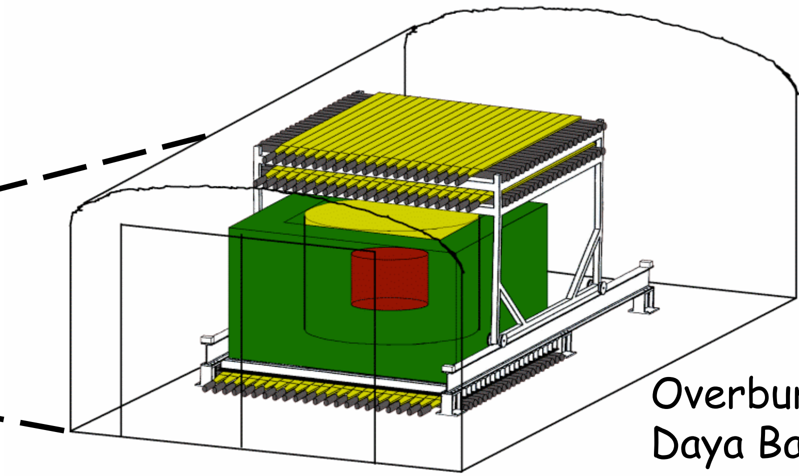
Prototype Detector at IHEP

- Constructing a 2-layer prototype with 0.5 t Gd-doped LS enclosed in 5 t of mineral oil, and 45 8" PMTs to evaluate design issues at IHEP, Beijing



The Aberdeen Tunnel Experiment

- Study cosmic muons & cosmogenic background in Aberdeen Tunnel, Hong Kong.



Overburden ~ Daya Bay sites

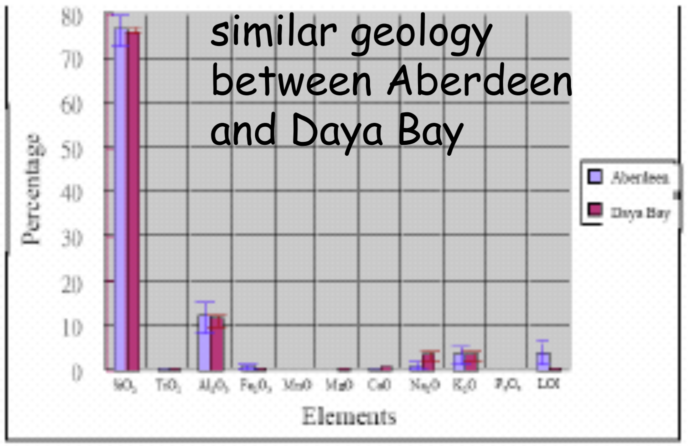


Fig. 1 A comparison of rock compositions at Daya Bay and Aberdeen.

Installing proptubes in Sept, 2005

Precision Measurement of θ_{12} and Δm^2_{21}

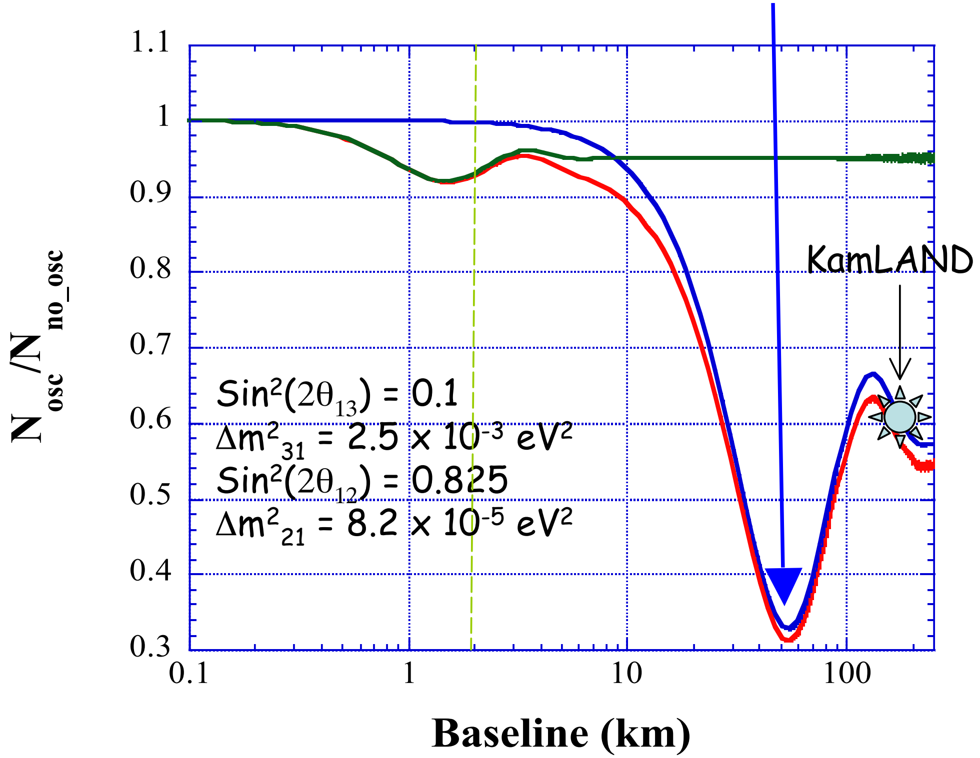
HKU, CUHK, and Berkeley

Precise Measurement of θ_{12}

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

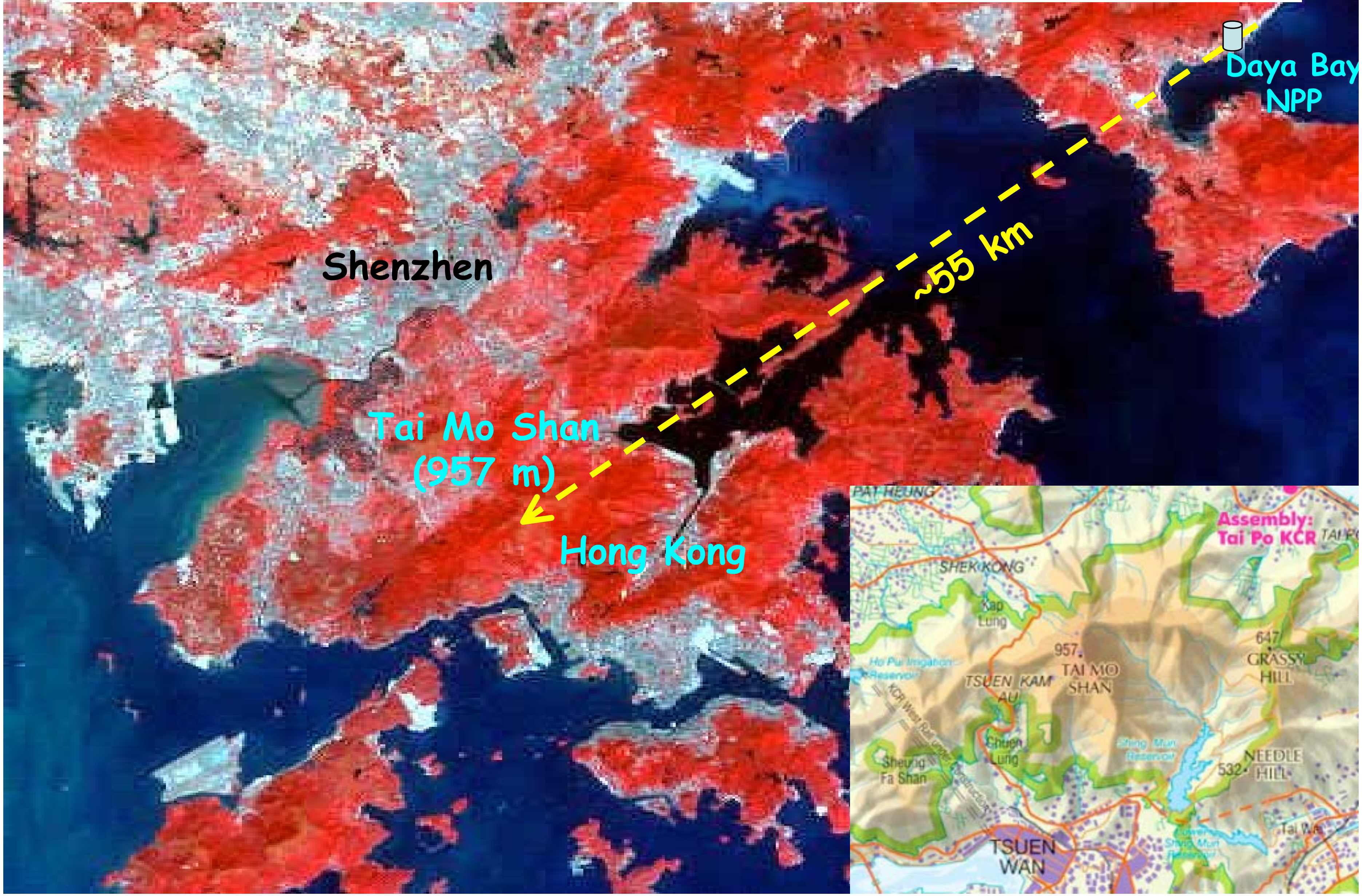
$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

Large-amplitude oscillation at ~55 km due to θ_{12}



- Near detectors close to reactors 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 of θ_{12}

Location of Hong Kong Site For θ_{12} Measurement



Precision of θ_{12} With The Daya Bay Facility

Inputs:

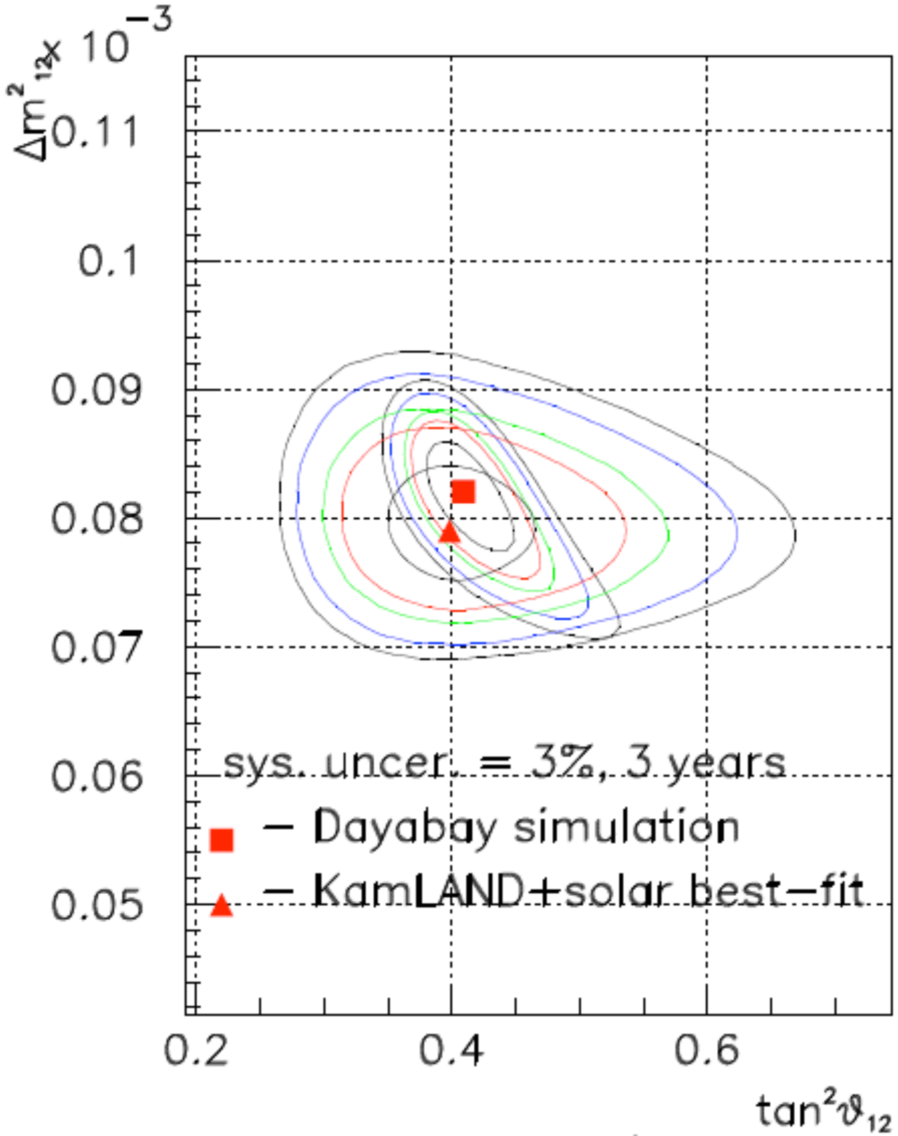
- Thermal power = 17.4 GW
- Baseline = 55 km
- Target mass = ~ 500 ton LS
- Mixing parameters:

  $\sin^2 2\theta_{12} = 0.825$

  $\sin^2 2\theta_{13} = 0.1$

  $\Delta m^2_{12} = 8.2 \times 10^{-5}\ eV^2$

  $\Delta m^2_{13} = 2.5 \times 10^{-3}\ eV^2$



Summary and Prospects

- The Daya Bay nuclear power facility in China and the mountainous topology in the vicinity offer an excellent opportunity for carrying out a reactor neutrino program using horizontal tunnels.
- The Daya Bay experiment has excellent potential to reach a sensitivity of 0.01 for $\sin^2 2\theta_{13}$.
- The three Chinese funding agencies are discussing cost-sharing of a request of RMB$200 million.
- The US team is waiting for the NuSAG's decision.
- Will complete detailed design of detectors, tunnels and underground facilities in 2006.
- Plan to commission the Fast Deployment scheme in 2007-2008, and Full Operation in 2009.
- **Welcome more collaborators to join.**