Daya Bay Neutrino Oscillation Experiment

大亞灣微中子振盪實驗

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December 28, 2006
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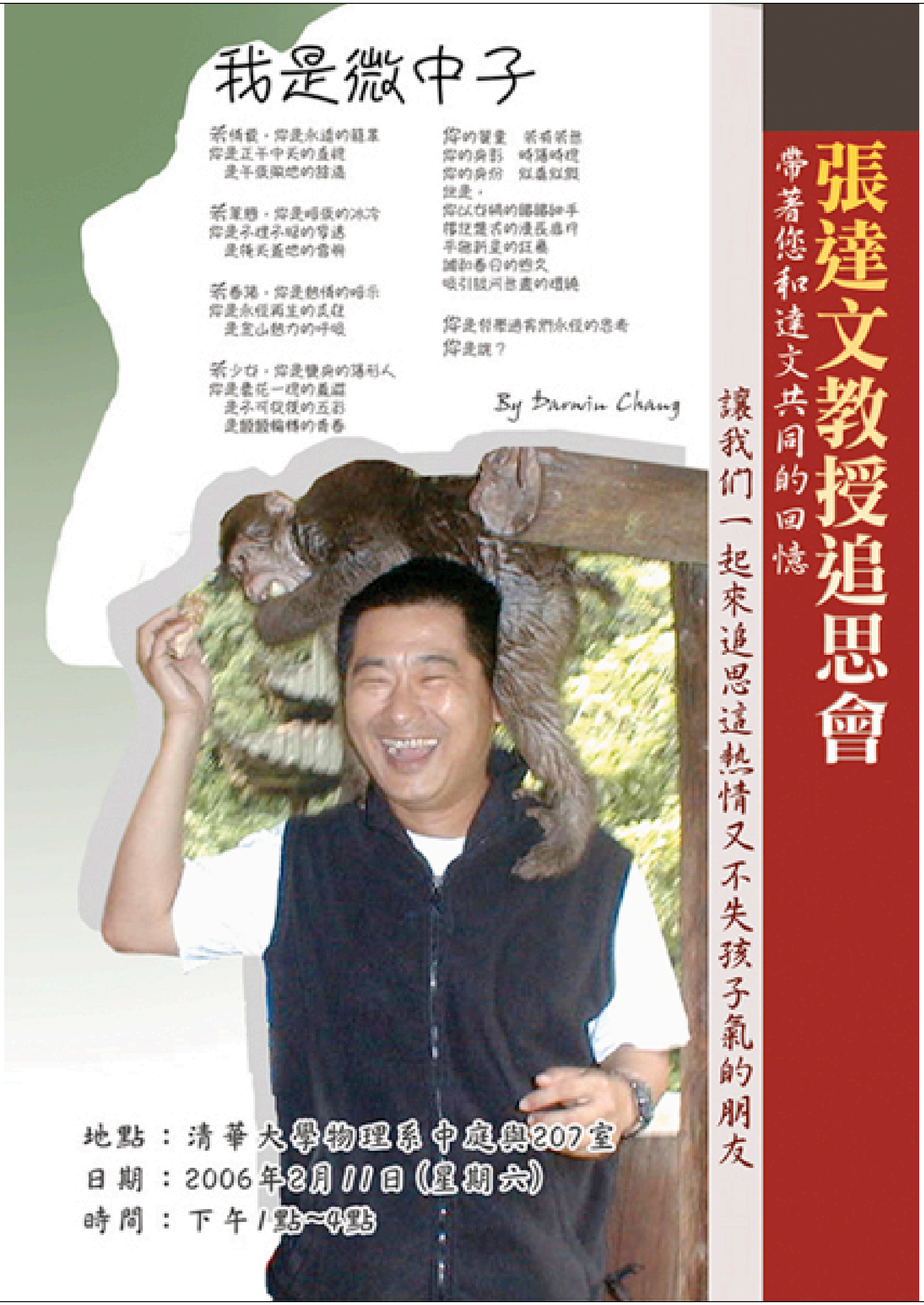


張達文教授追思會

帶著您和達文共同的回憶

讓我們一起來追思這熱情又不失孩子氣的朋友

我是微中子

By Darwin Chang

地點：清華大學物理系中庭與207室
日期：2006年2月11日(星期六)
時間：下午1點~4點

Darwin

you will always
live
in our heart!

We remember
you!

我是微中子

若情愛，你是永遠的籠罩
你是正午中天的直視
　是午夜徹地的餘溫

若單戀，你是暗夜的冰冷
你是不理不睬的穿透
　是掩天蓋地的雪崩

若春陽，你是熱情的暗示
你是永恆再生的支柱
　是金山熱力的呼吸

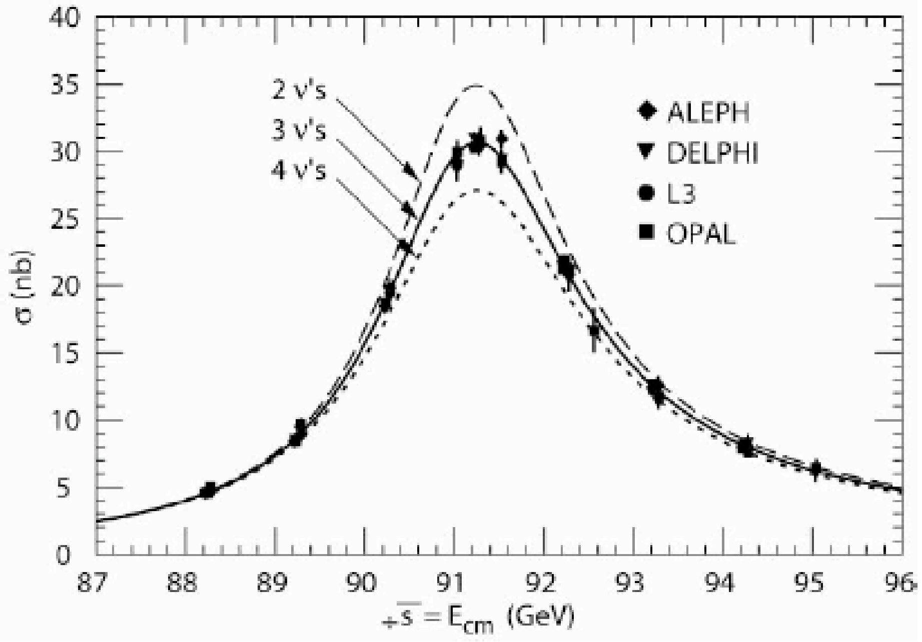
若少女，你是變身的隱形人
你是曇花一現的羞澀
　是不可捉摸的五彩
　是顫顫輪轉的青春

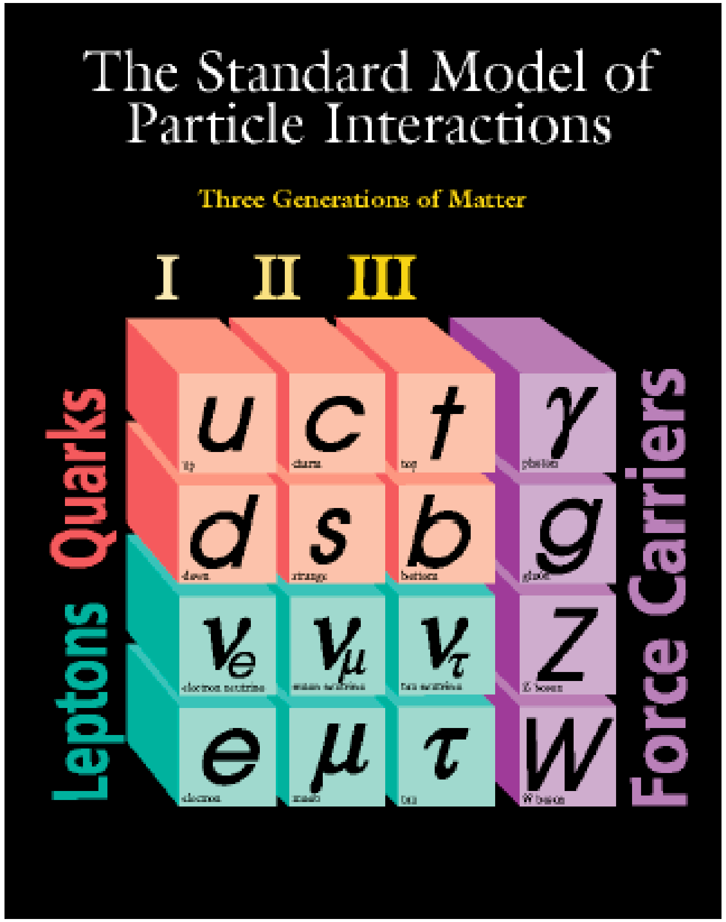
你的質量　　若有若無
你的身影　　時隱時現
你的身份　　似真似假
但是，
你以女媧的纖纖細手
撐住盤古的漫長歲月
平撫新星的狂暴
調和春日的煦久
吸引銀河無盡的環繞

你是哲學過客們永恆的思考
你是誰？

寫於1998年國科會報告

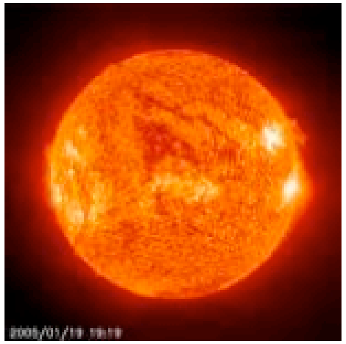
The Elusive Neutrino



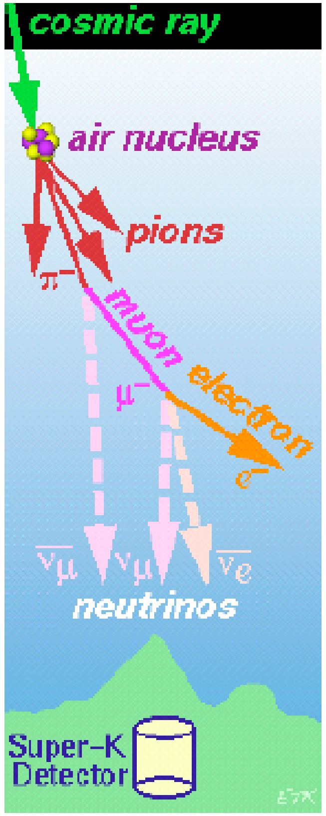


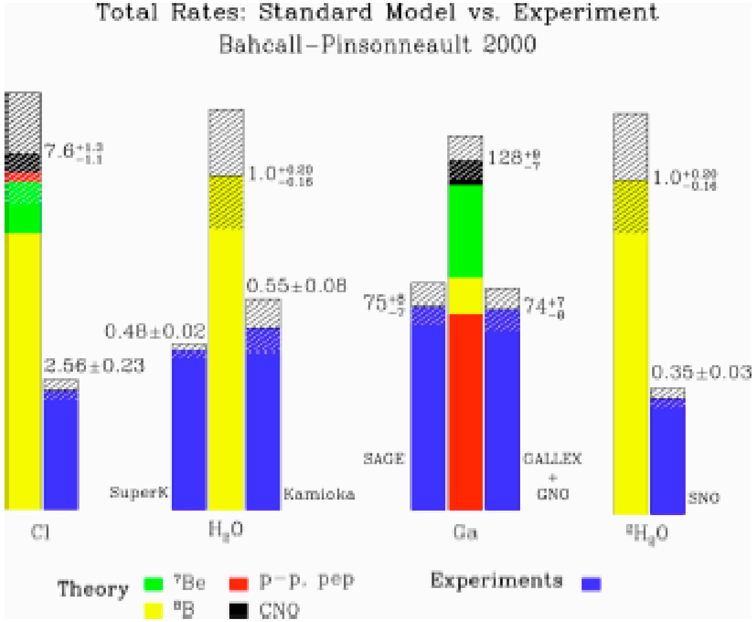
The past two decades have seen the neutrino family take its place in the Standard Model

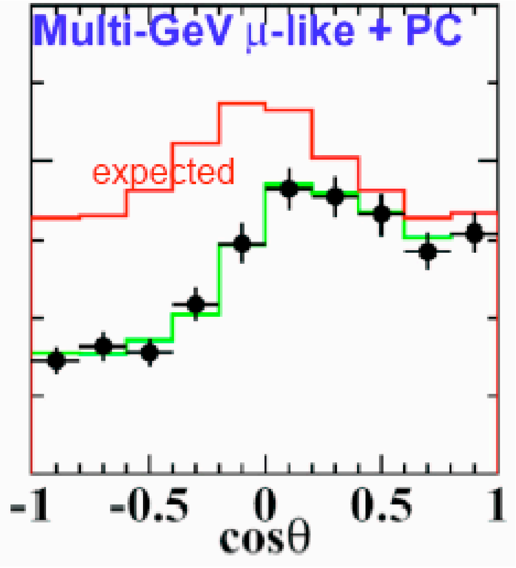
The Elusive Neutrino



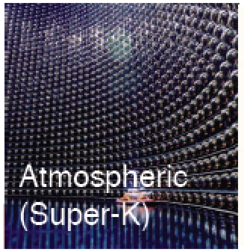
Solar and Atmospheric Neutrinos
Missing in Action

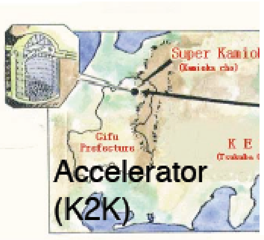


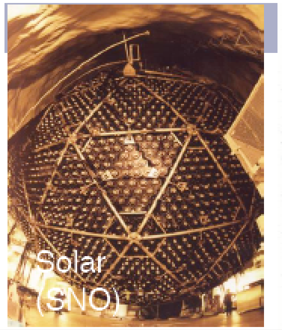


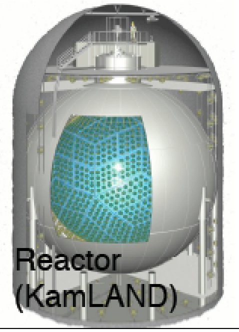


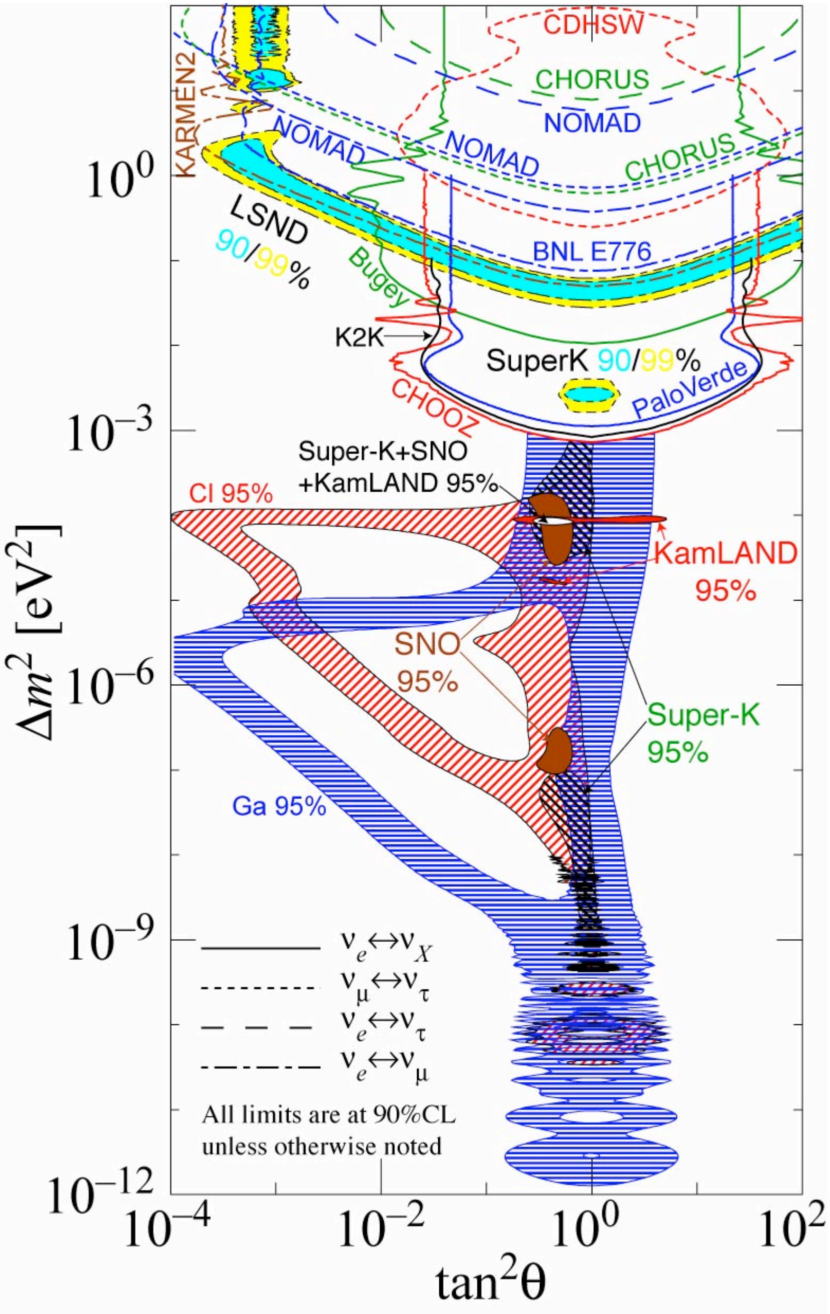
But great progress has been made, and continues in establishing that neutrinos have mass, and in measuring the mass differences and mixing angles…





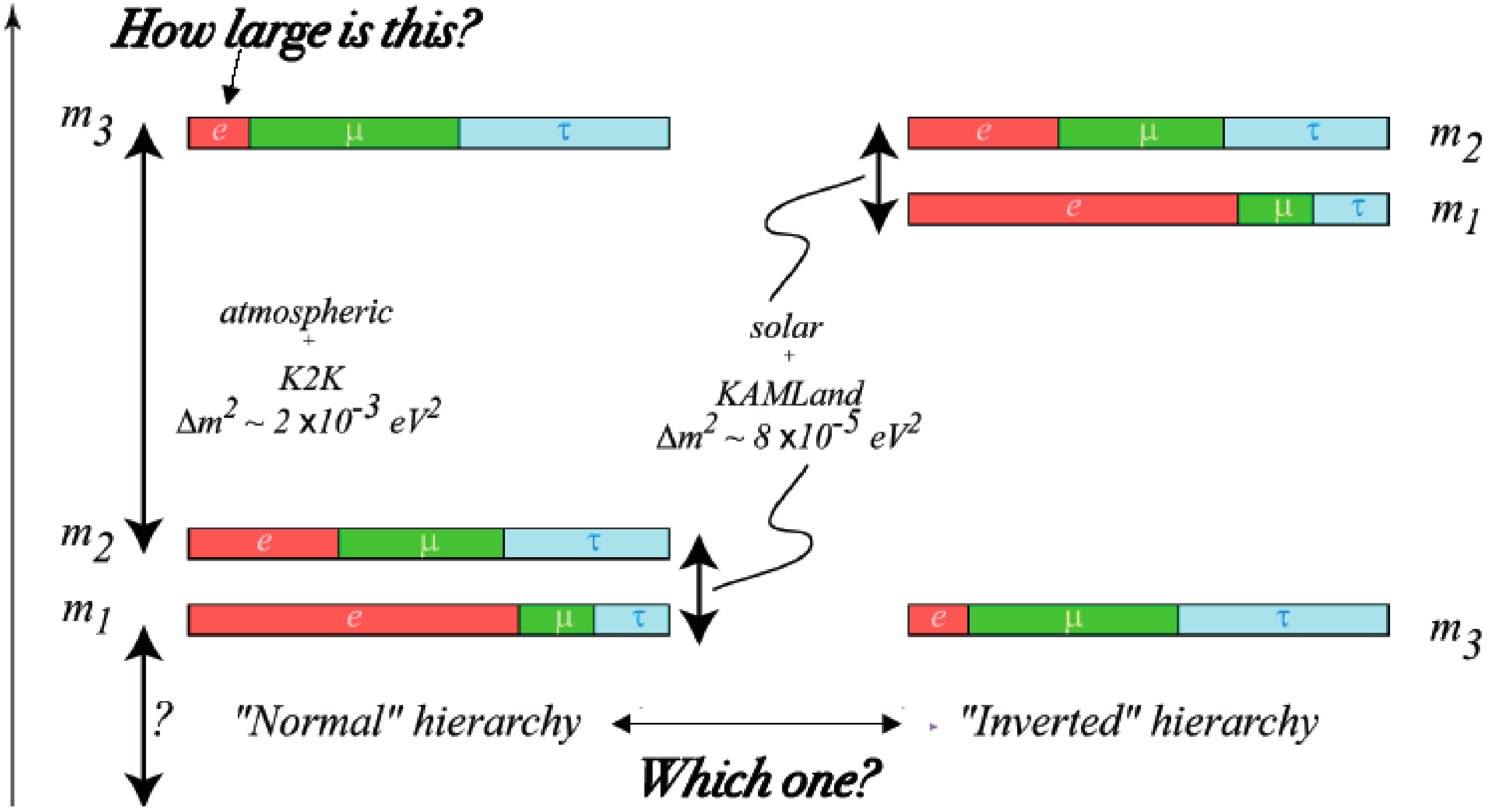






http://hitoshi.berkeley.edu/neutrino

Mass mixing parameters



How large is this?

atmospheric
+
K2K
$\Delta m^2 \sim 2 \times 10^{-3}\ eV^2$

solar
+
KAMLand
$\Delta m^2 \sim 8 \times 10^{-5}\ eV^2$

"Normal" hierarchy ↔ *"Inverted" hierarchy*

Which one?

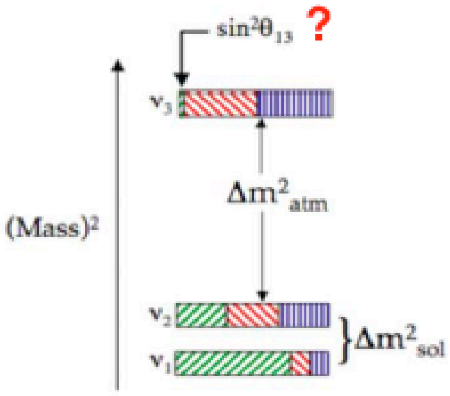
θ_{13}: The Last Unknown Neutrino Mixing Angle

U_{MNSP} Matrix

Maki, Nakagawa, Sakata, Pontecorvo

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

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

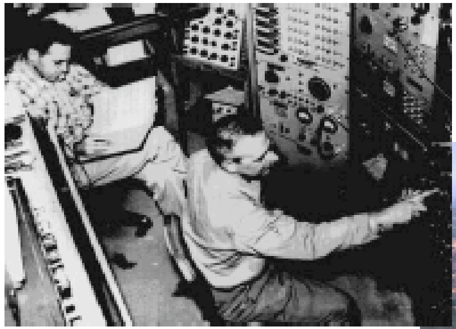


- What is ν_e fraction of ν_3?
- U_{e3} is the gateway to CP violation in neutrino sector:

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) \propto \sin(2\theta_{12})\sin(2\theta_{23})\cos^2(\theta_{13})\sin(2\theta_{13})\sin\delta$$

Neutrino Physics at Reactors

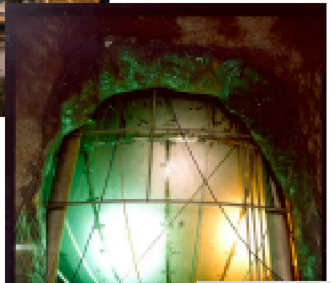
Past Experiments
Hanford
Savannah River
ILL, France
Bugey, France
Rovno, Russia
Goesgen, Switzerland
Krasnoyark, Russia
Palo Verde
Chooz, France
Reactors in Japan



1956
First observation
of neutrinos

1980s & 1990s
Reactor neutrino flux
measurements in U.S. and Europe

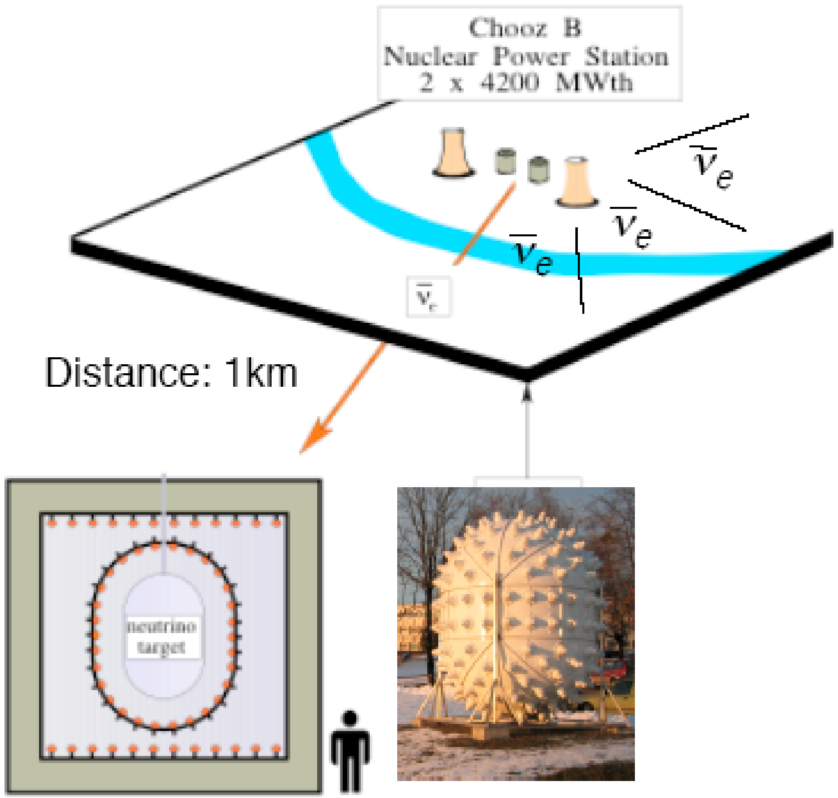
1995
Nobel Prize to Fred Reines
at UC Irvine



2002
Discovery of reactor
antineutrino oscillation

2006 and beyond
Precision measurement of θ_{13}
Exploring feasibility of CP violation studies

Oscillation Searches at Chooz + Palo Verde:



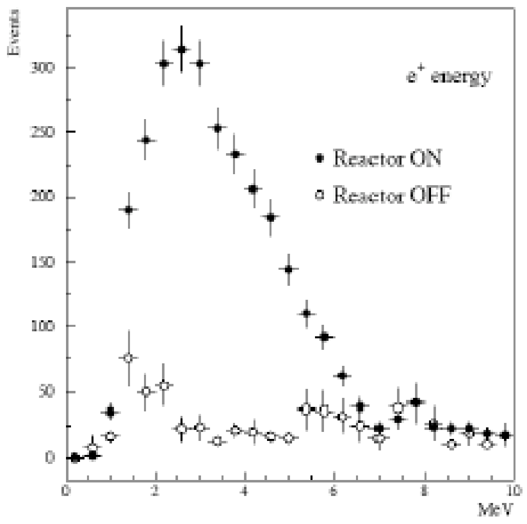
Chooz B
Nuclear Power Station
2 x 4200 MWth

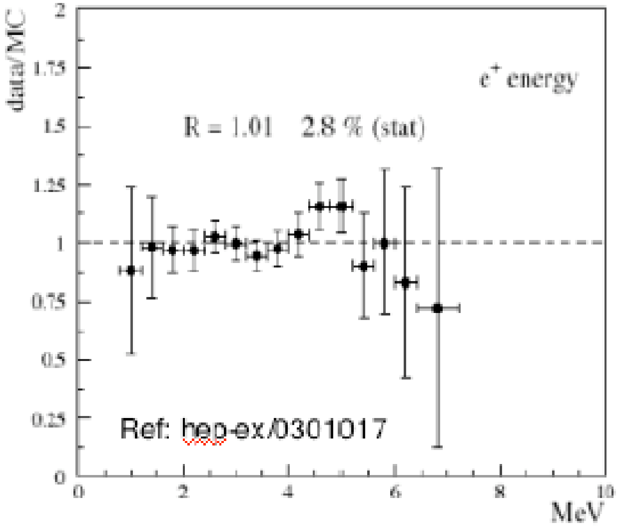
Distance: 1km

Chooz Underground Neutrino Laboratory
Ardennes, France

Absolute measurement with 1 detector

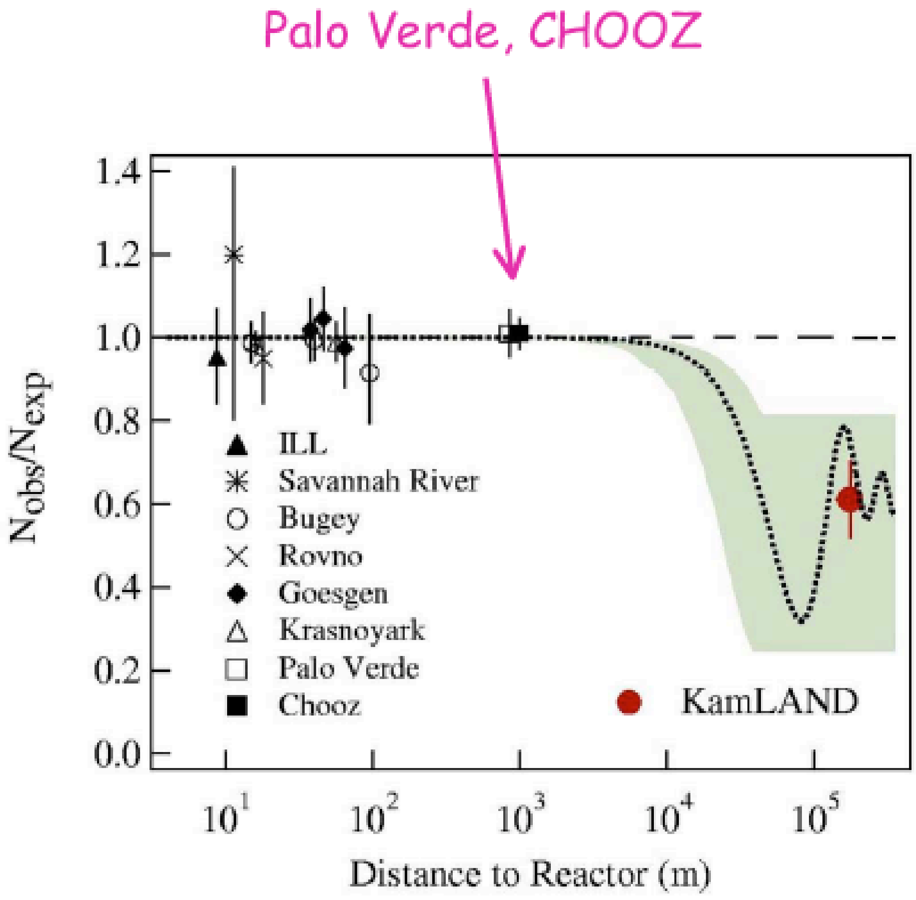
$\overline{\nu}_e \rightarrow \overline{\nu}_x$





Ref: hep-ex/0301017

Limitations of Past and Current Reactor Neutrino Experiments

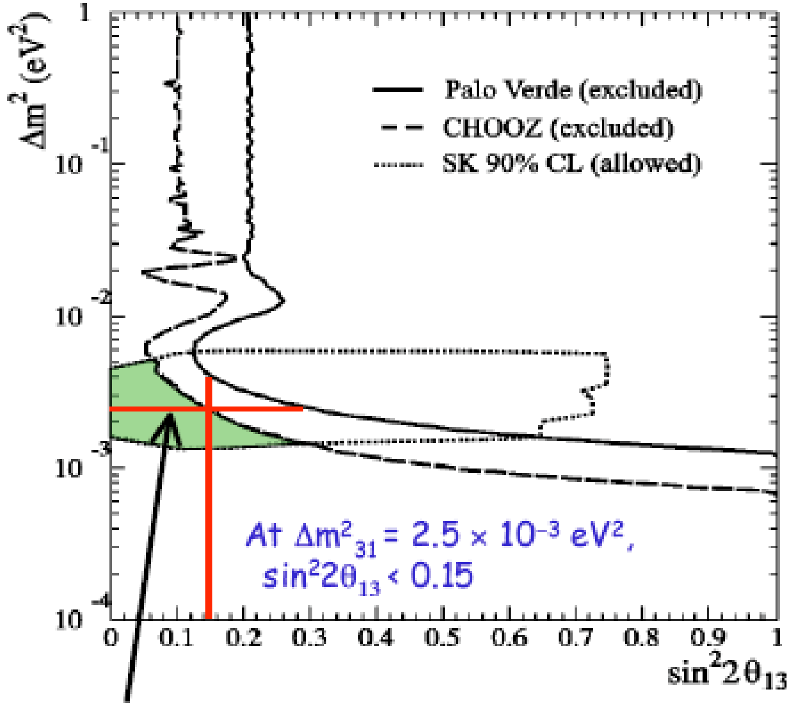


Typical precision is 3-6% due to

- limited statistics
- reactor-related systematic errors:
  - energy spectrum of $\overline{\nu}_e$ (~2%)
  - time variation of fuel composition (~1%)
- detector-related systematic error (1-2%)
- background-related error (1-2%)

Current Knowledge of θ_{13}

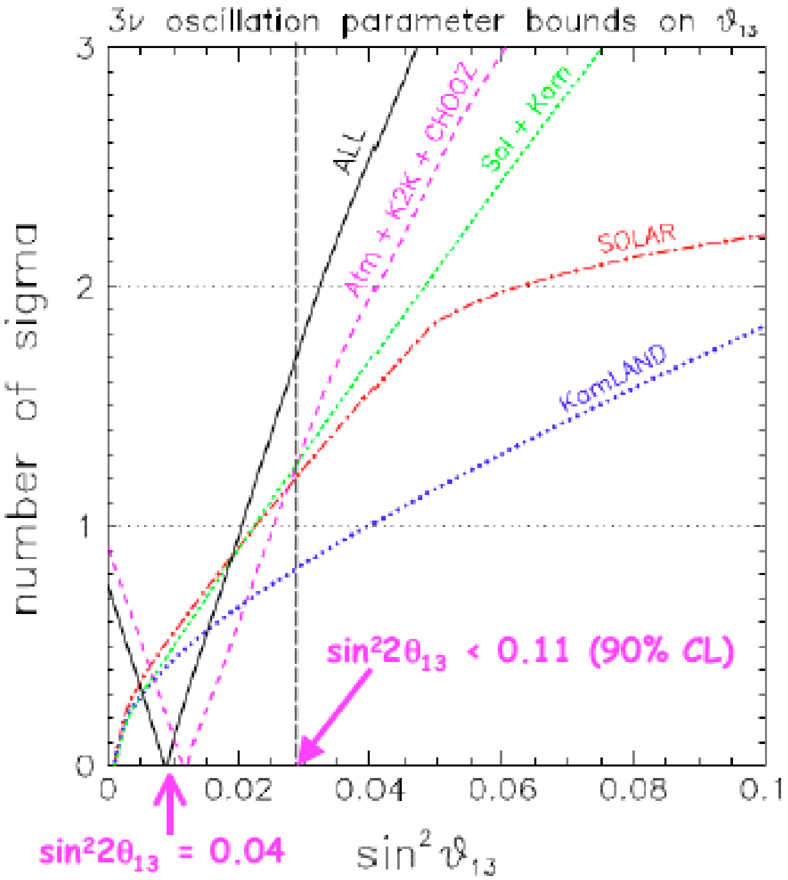
Direct search



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)

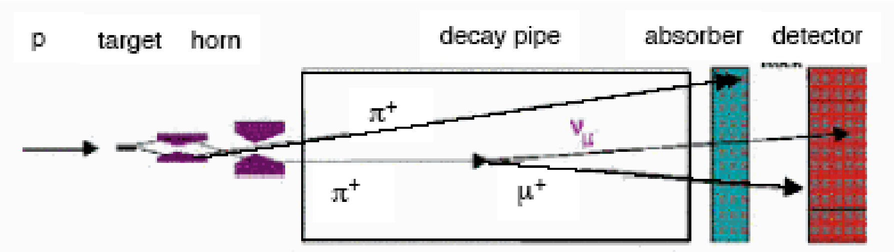
$\sin^2 2\theta_{13} = 0.04$

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

Fogli etal., hep-ph/0506083

Measuring θ_{13}

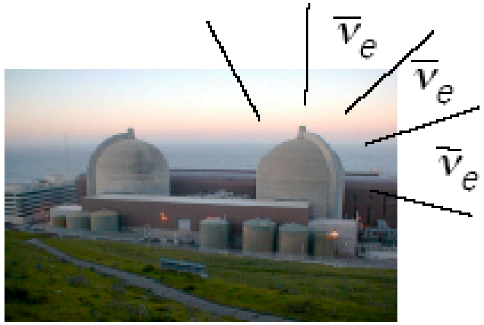
Method 1: Accelerator Experiments



$$P_{\mu e} \approx \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 \frac{\Delta m_{31}{}^2 L}{4 E_\nu} + \dots$$

- appearance experiment $\nu_\mu \rightarrow \nu_e$
- measurement of $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ yields θ_{13}, δ_{CP}
- baseline *O(100 -1000 km),* matter effects present

Method 2: Reactor Neutrino Oscillation Experiment



$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4 E_\nu}\right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4 E_\nu}\right)$$

- disappearance experiment $\overline{\nu}_e \rightarrow \overline{\nu}_e$
- look for rate deviations from $1/r^2$ and spectral distortions
- observation of oscillation signature with 2 or multiple detectors
- baseline *O(1 km),* no matter effects

How To Reach A Precision of 0.01 ?

- Powerful nuclear plant
- Larger detectors
- "Identical" detectors
- Near and far detectors to minimize reactor-related errors
- Optimize baseline for best sensitivity and smaller residual reactor-related errors
- Interchange near and far detectors – cancel detector systematic errors
- Sufficient overburden/shielding to reduce background
- Comprehensive calibration/monitoring of detectors

Where To Place The Detectors ?

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

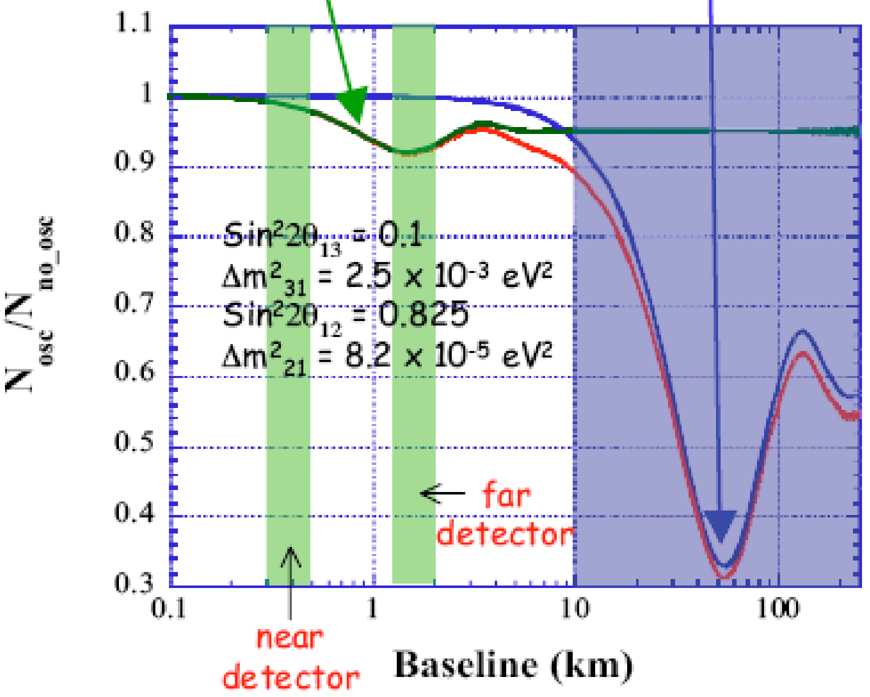
$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

- 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}



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

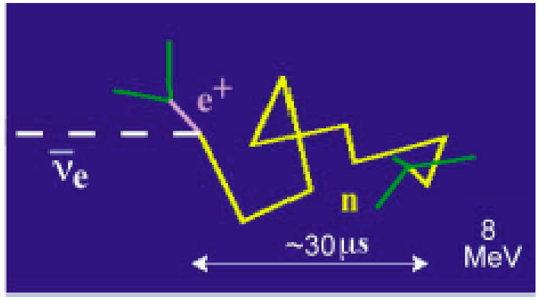
- The reaction is the inverse β-decay in 0.1% Gd-doped liquid scintillator:

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

0.3b ↳ $+ p \rightarrow D + \gamma(2.2\ \text{MeV})$ (delayed)

50,000b ↳ $+ Gd \rightarrow Gd^*$

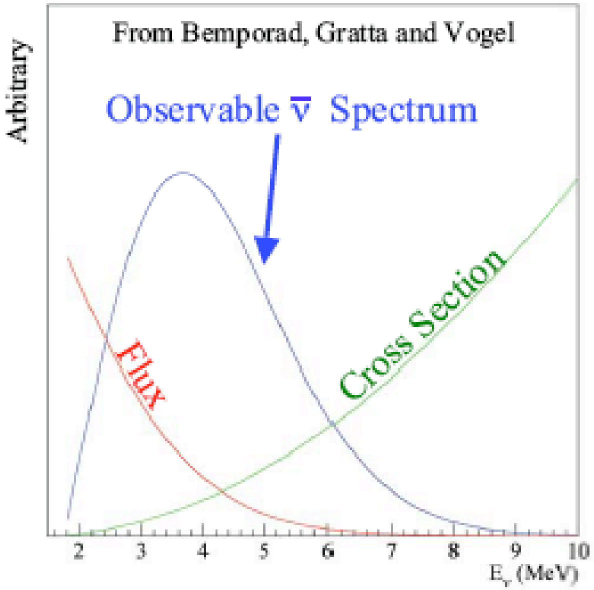
↳ $Gd + \gamma\text{'s}(8\ \text{MeV})$ (delayed)



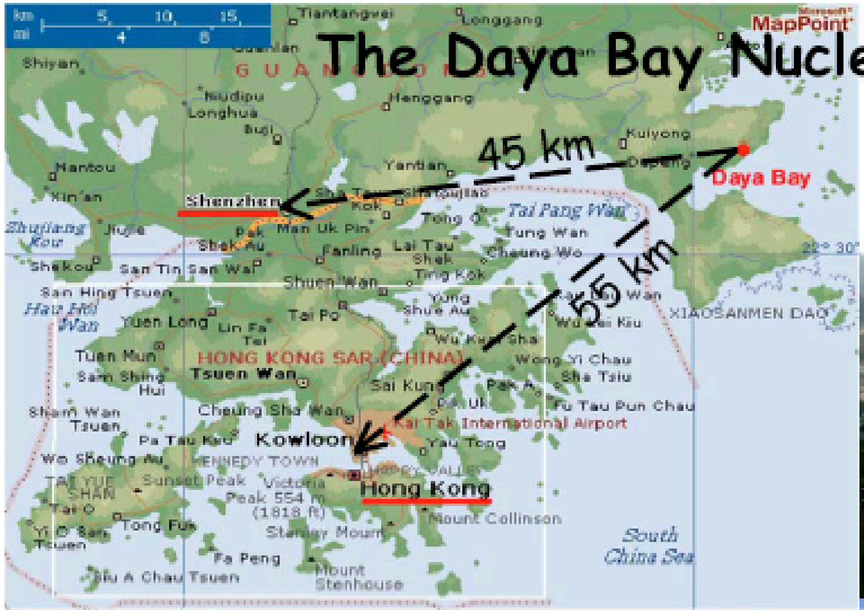
- Time- and energy-tagged signal is a good tool to suppress background events.

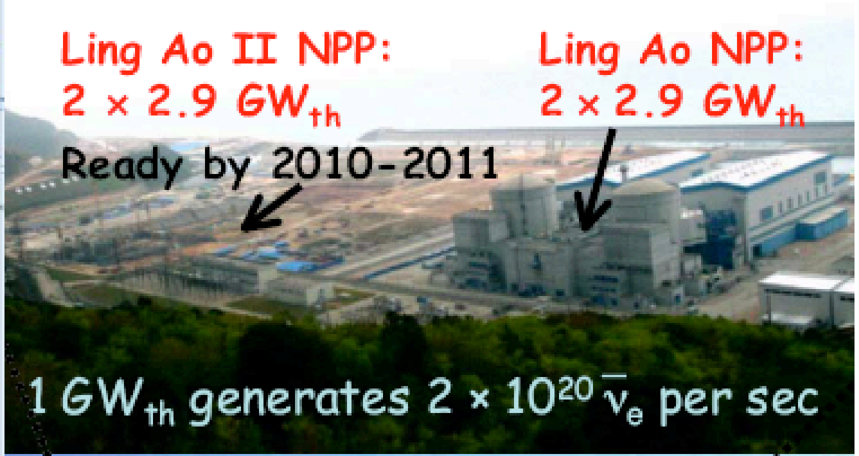
- Energy of $\bar{\nu}_e$ is given by:

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


From Bemporad, Gratta and Vogel

The Daya Bay Nuclear Power Facilities





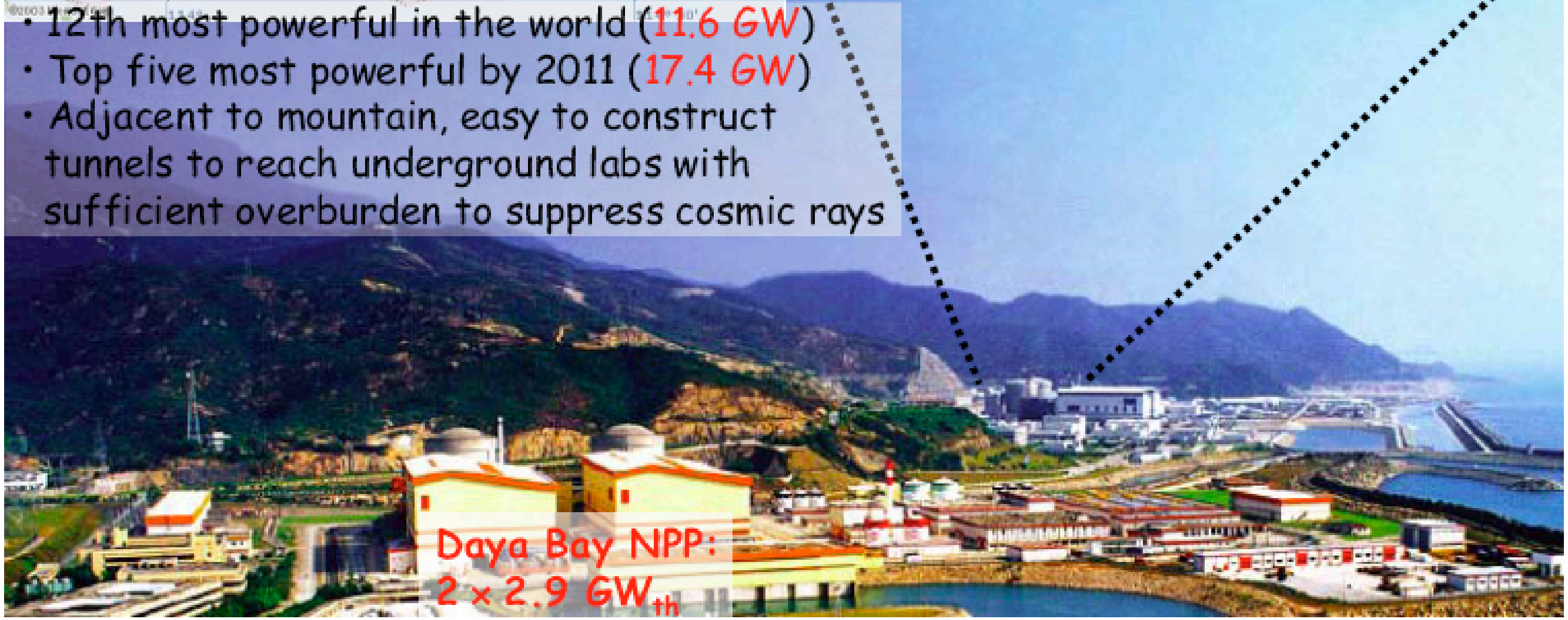
Ling Ao II NPP:
2×2.9 GW$_{th}$

Ready by 2010-2011

Ling Ao NPP:
2×2.9 GW$_{th}$

1 GW$_{th}$ generates 2×10^{20} $\bar{\nu}_e$ 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 length: ~2700 m

Daya Bay site geology survey

Bore Samples

Zk2 (depth: ~180 m)

Zk4 (depth: 133 m)

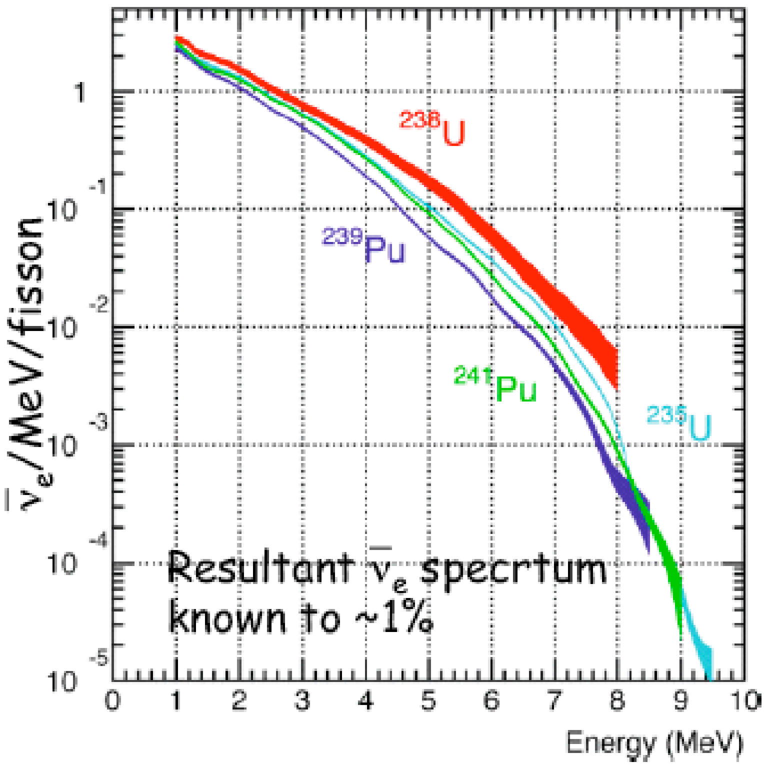
Zk1 (depth: 210 m)

Zk3 (depth: ~64 m)

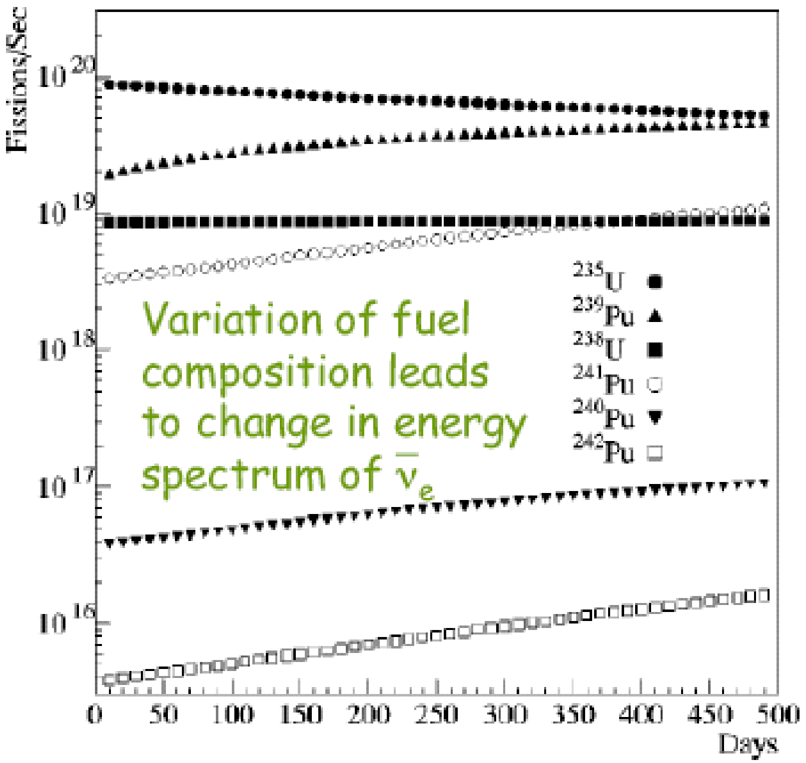
Reactor $\bar{\nu}_e$

- 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

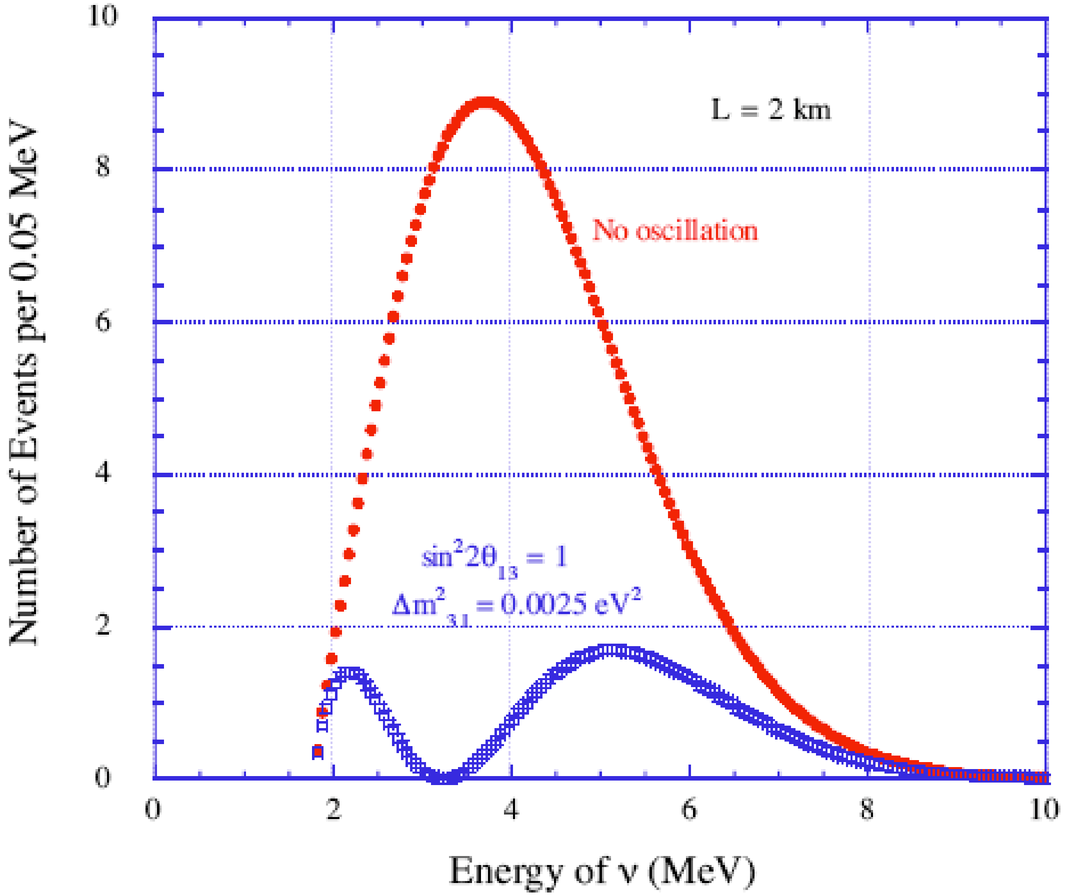


Resultant $\bar{\nu}_e$ specrtum known to ~1%



Variation of fuel composition leads to change in energy spectrum of $\bar{\nu}_e$

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



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

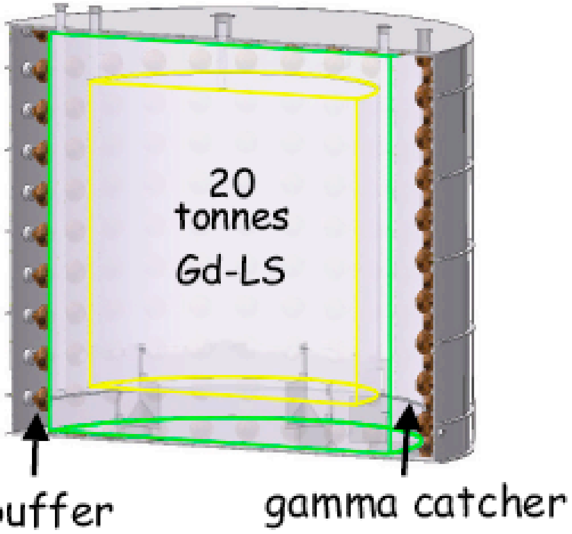
Design considerations

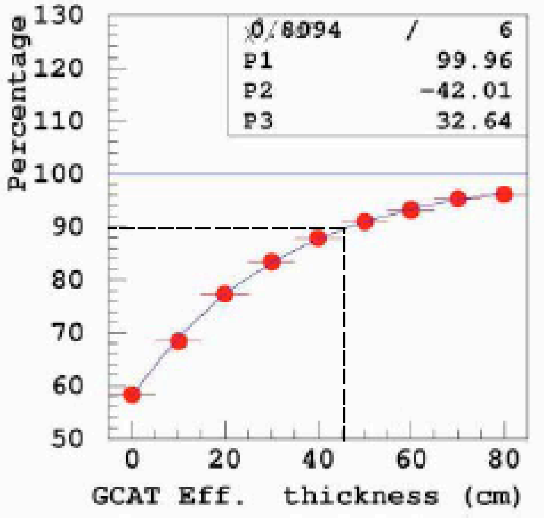
- ***Identical near and far detectors*** to cancel reactor-related errors
- ***Multiple modules*** for reducing detector-related errors and cross checks
- ***Three-zone detector modules*** to reduce detector-related errors
- ***Overburden and shielding*** to reduce backgrounds
- ***Multiple muon detectors***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

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:

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



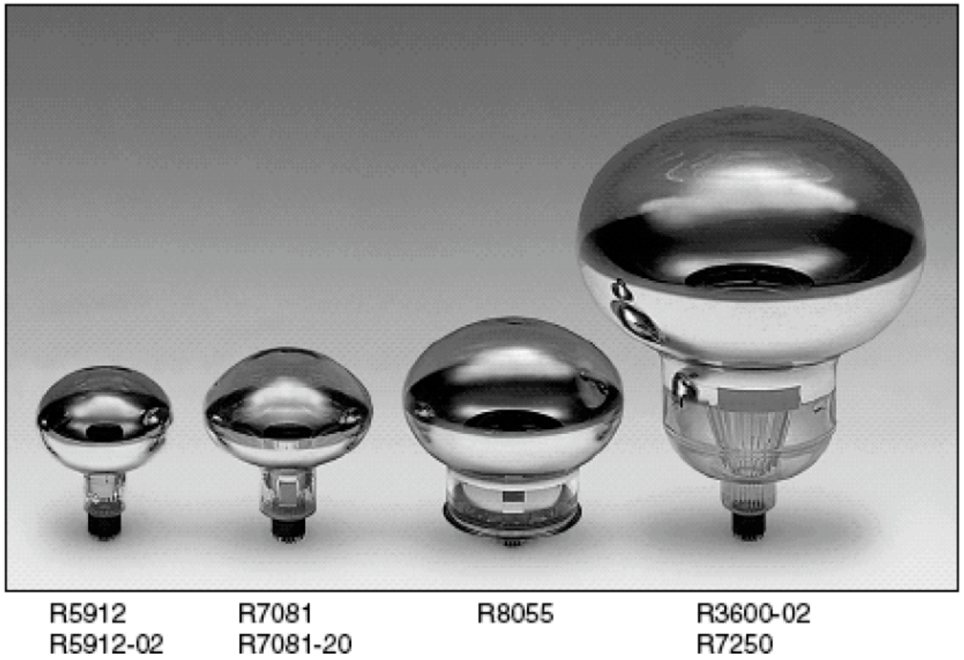


Oil buffer thickness

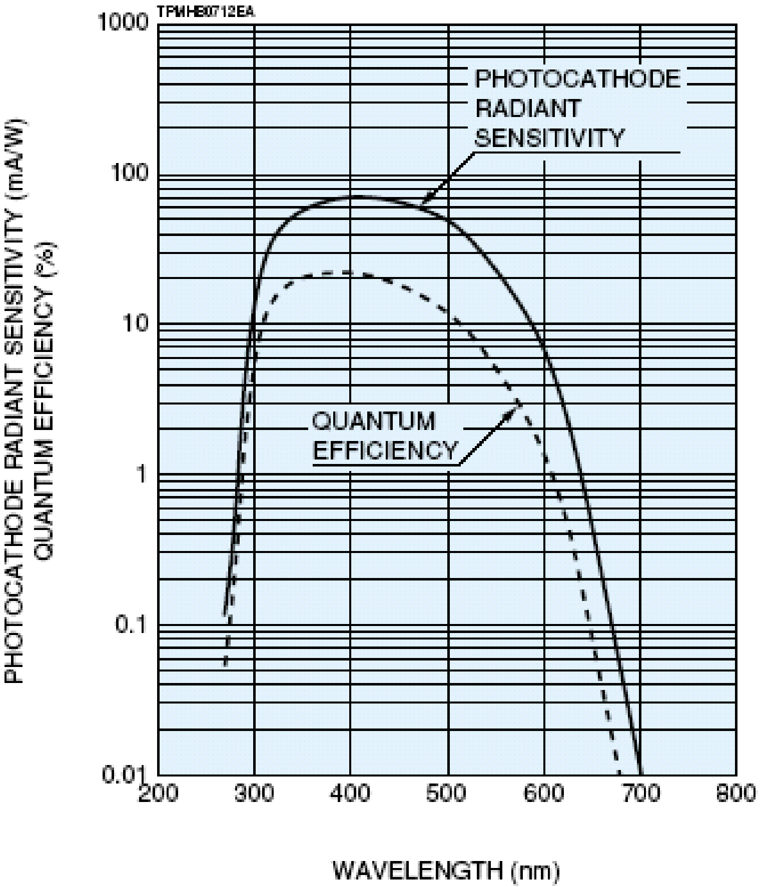
Isotopes (from PMT)	Purity (ppb)	20cm (Hz)	25cm (Hz)	30cm (Hz)	40cm (Hz)
^{238}U(>1MeV)	50	2.7	2.0	1.4	0.8
^{232}Th(>1MeV)	50	1.2	0.9	0.7	0.4
^{40}K(>1MeV)	10	1.8	1.3	0.9	0.5
Total		5.7	4.2	3.0	1.7

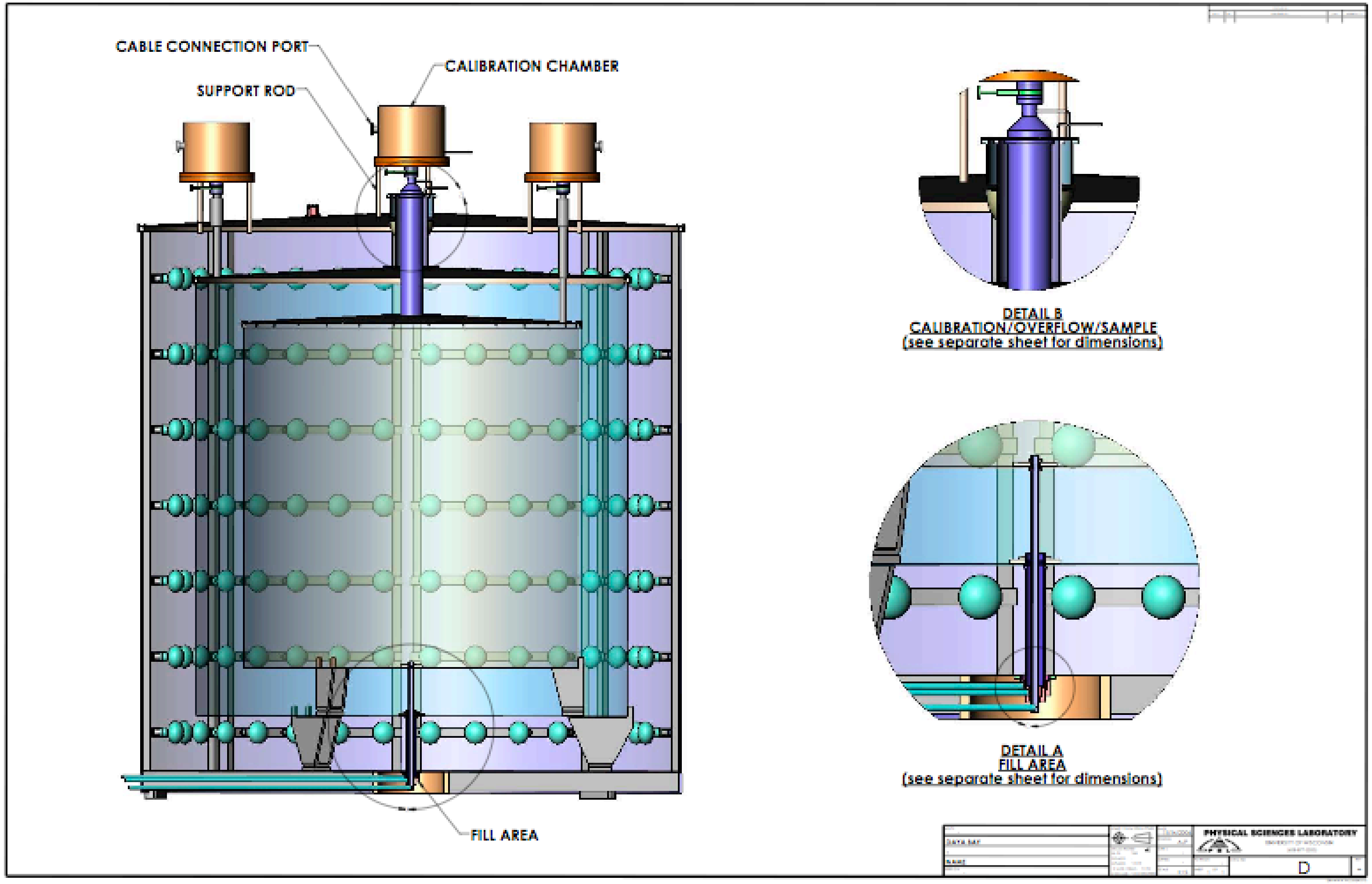
Large Area PMT to collect photons from the LS detectors

Hammamatsu 8” PMT

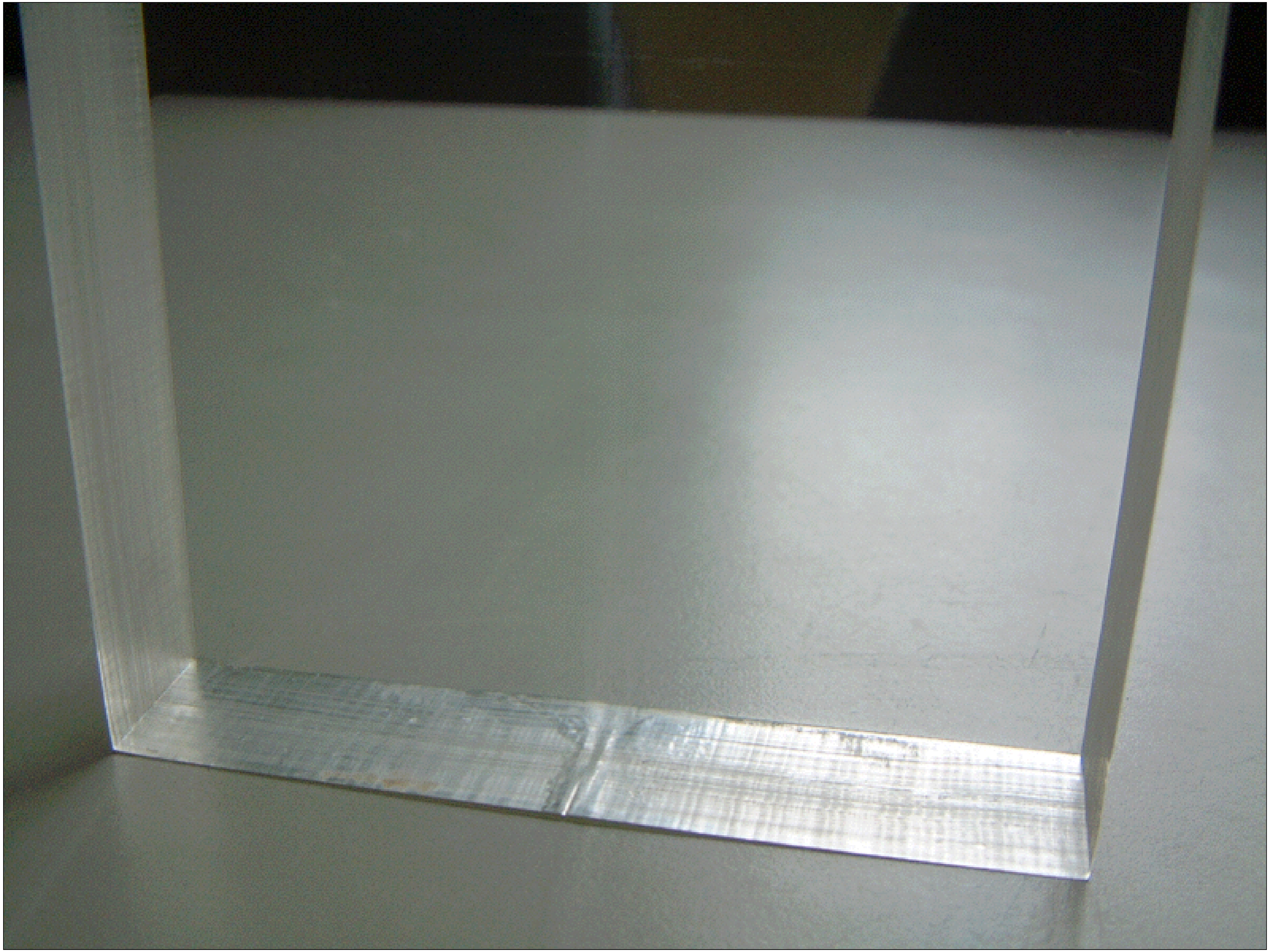


●R5912, R5912-02




CABLE CONNECTION PORT
CALIBRATION CHAMBER
SUPPORT ROD
FILL AREA
DETAIL B
CALIBRATION/OVERFLOW/SAMPLE
(see separate sheet for dimensions)
DETAIL A
FILL AREA
(see separate sheet for dimensions)
DAYA BAY
NAME
PHYSICAL SCIENCES LABORATORY
D

Gold Aqua and Nakano Co.,
Kaoshiung, Taiwan



- Acrylic plexiglass material (PMMA + ingredients to prevent aging and absorbing UV) is very good in light transmission and mechanically strong material than PC, PVC or glass.

- Best acrylic to resist chemical attack is plate sheets. Extruded tube and casting with centrifugal method are not as good due to added ingredients.

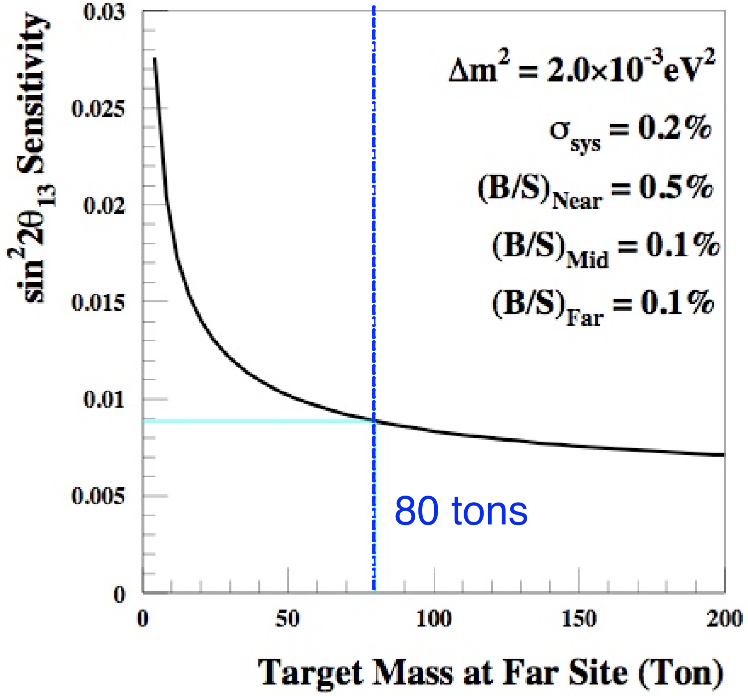
- Plate sheets can be molded in desired shape easily and glued together with polymerization method with same material as acrylic sheets.

- The glue joint usually a few mm has the same chemical, mechanical and optical properties as the acrylic material.

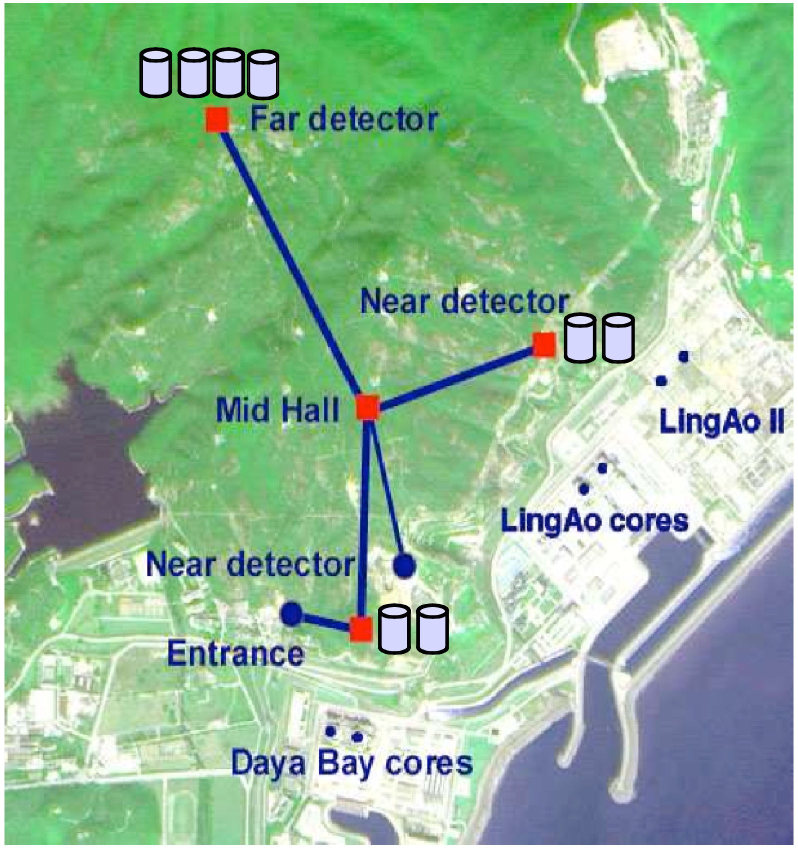
Antineutrino Detector Target Mass

Sensitivity after 3 years

Required target mass > 80 tons



4 x 20 tons at far site to achieve target mass

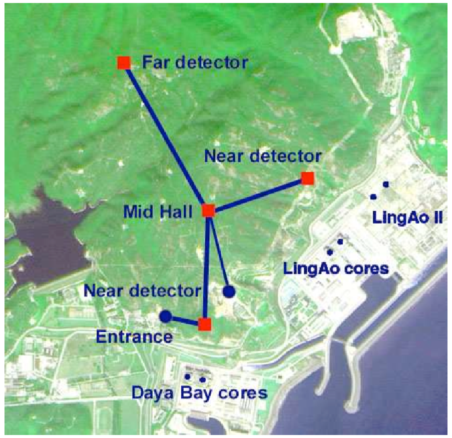


Event Rates and Signal

Antineutrino Interaction Rate

(events/day per 20 ton module)

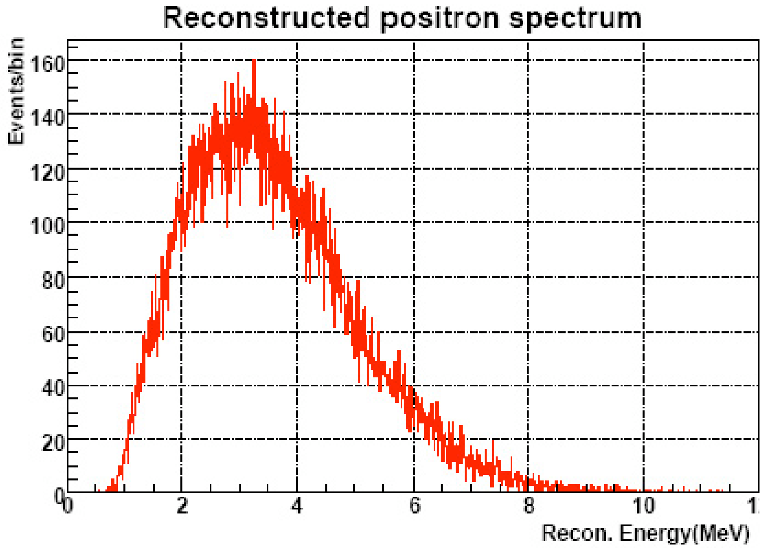
Daya Bay near site	960
Ling Ao near site	760
Far site	90



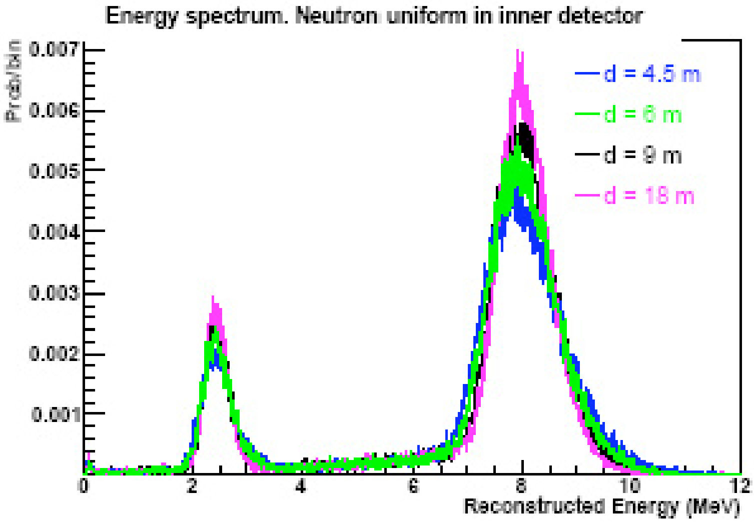
Distances (m)

Daya Bay near	363
Ling Ao near	481
Far site	~1800

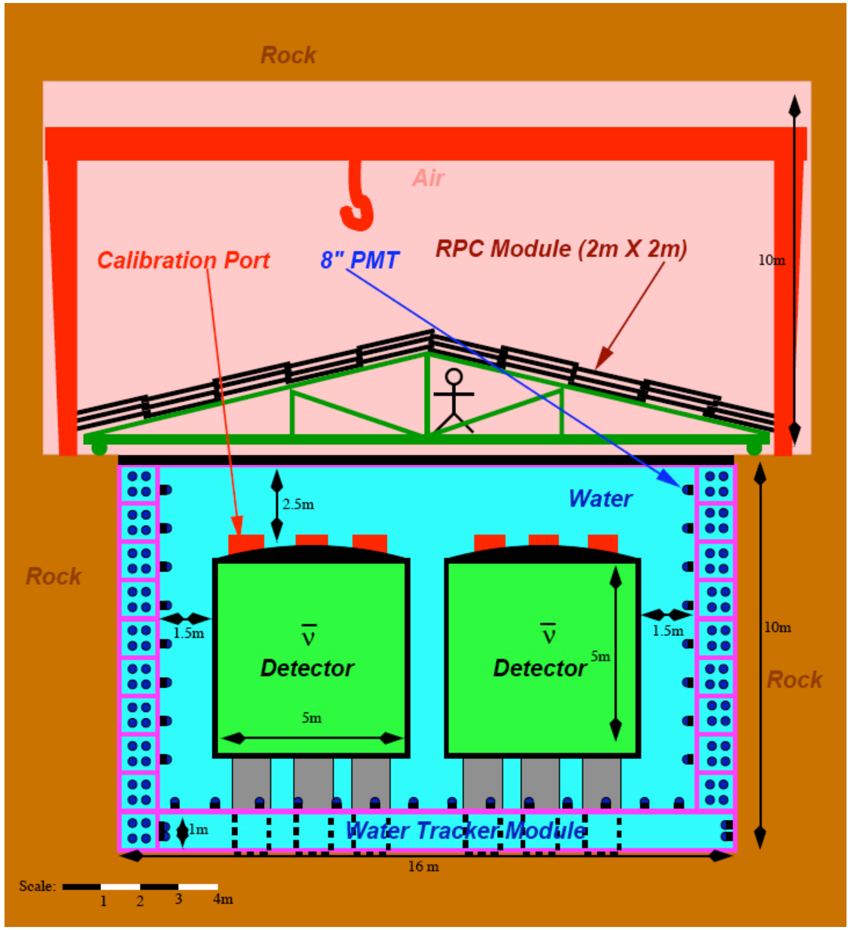
Prompt Signal



Delayed Signal



Baseline detector design: multiple neutrino modules and multiple vetos



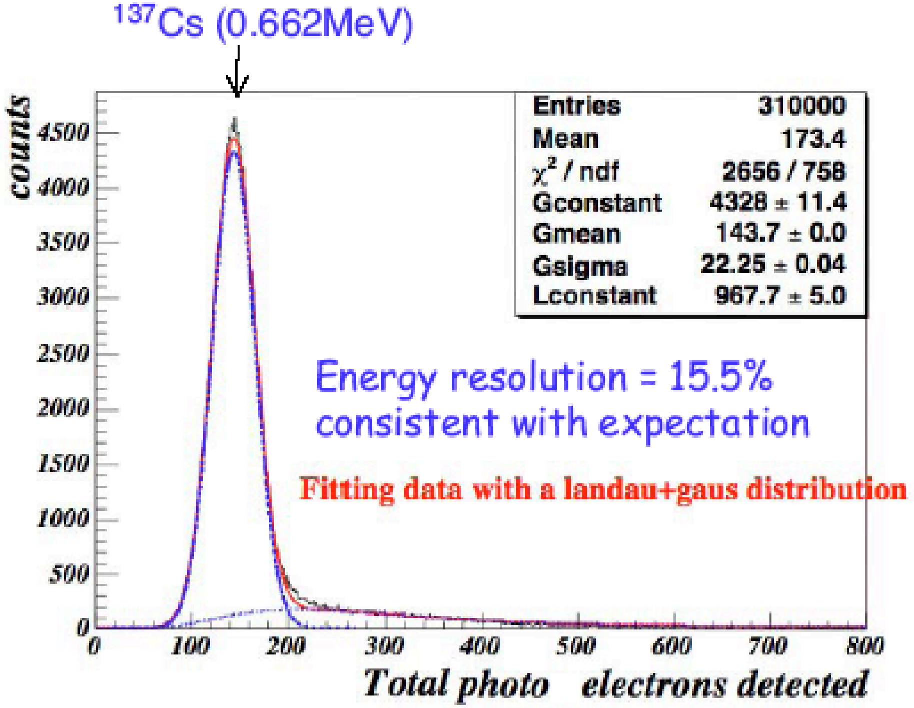
- Multiple anti-neutrino detector modules for side-by-side cross check
- Multiple muon tagging detectors:
  - Water pool as Cherenkov counter
  - Water modules along the walls and floor as muon tracker
  - RPC at the top as muon tracker
  - Combined efficiency

    > (99.5 ± 0.25) %

Redundancy is a key for the success of this experiment

Prototype at IHEP

- Built a 2-zone prototype with reflective surfaces at the top & bottom, 0.5 t (Gd-doped) LS enclosed in 5 t of mineral oil, and 40 8" PMTs to evaluate some design issues at IHEP, Beijing



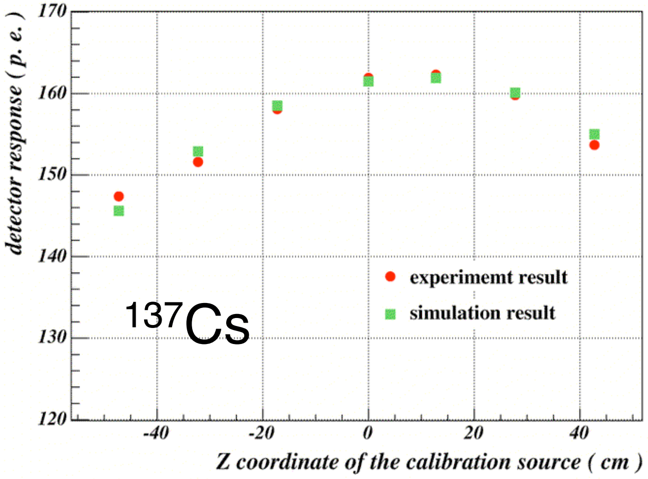
Energy resolution = 15.5%
consistent with expectation

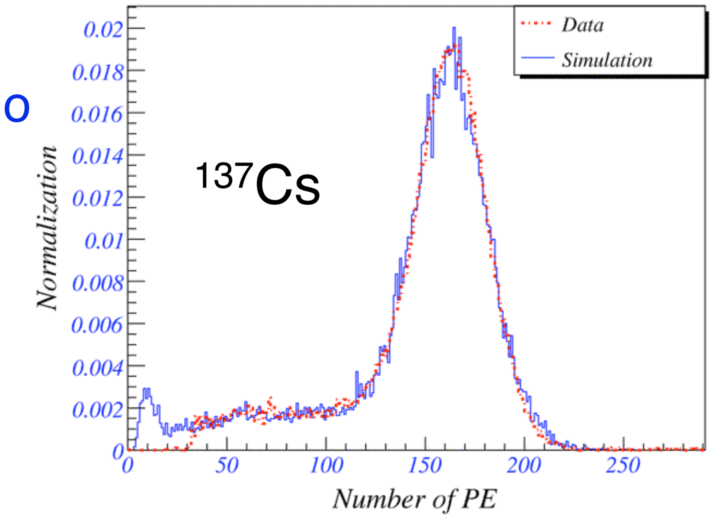
Fitting data with a landau+gaus distribution

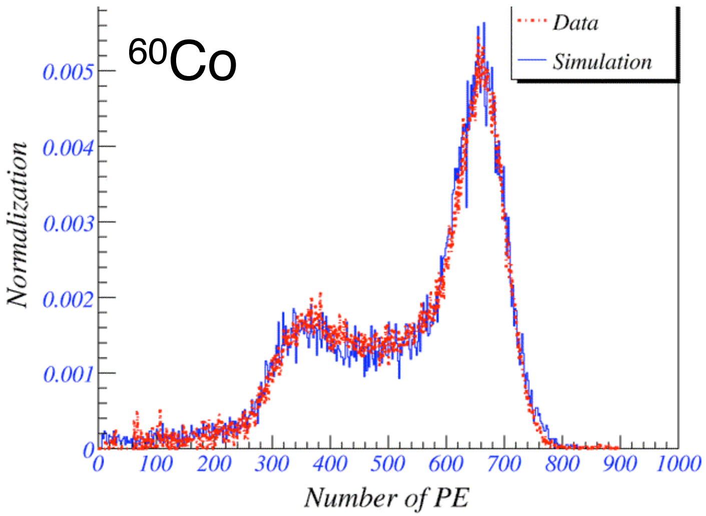
Prototype Performance

Testing the Energy Response: Comparison of data and Monte Carlo

- 0.5ton IHEP prototype
- L=1.0m, Φ=0.9m

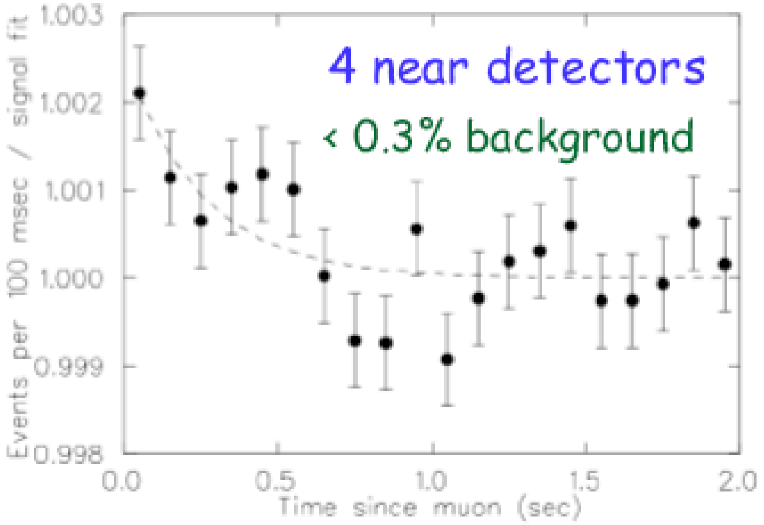






Background

- **Natural Radioactivity**: PMT glass, Rock, Radon in the air, etc
- **Slow and fast neutrons produced by cosmic muons**
  - Neutrons produced in rock
- **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:



4 near detectors

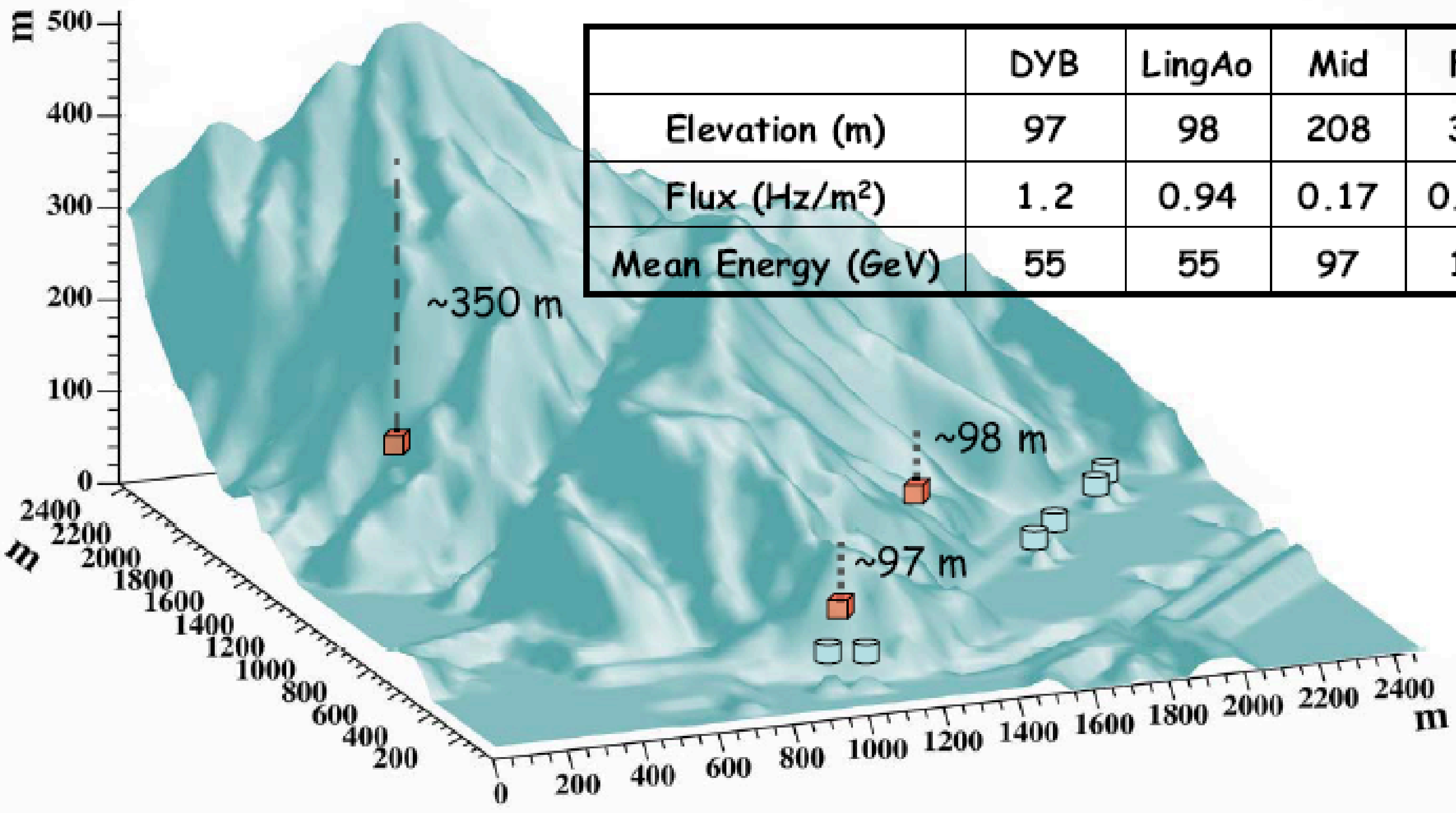
< 0.3% background

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

β-n decay of ^{9}Li mimics signal

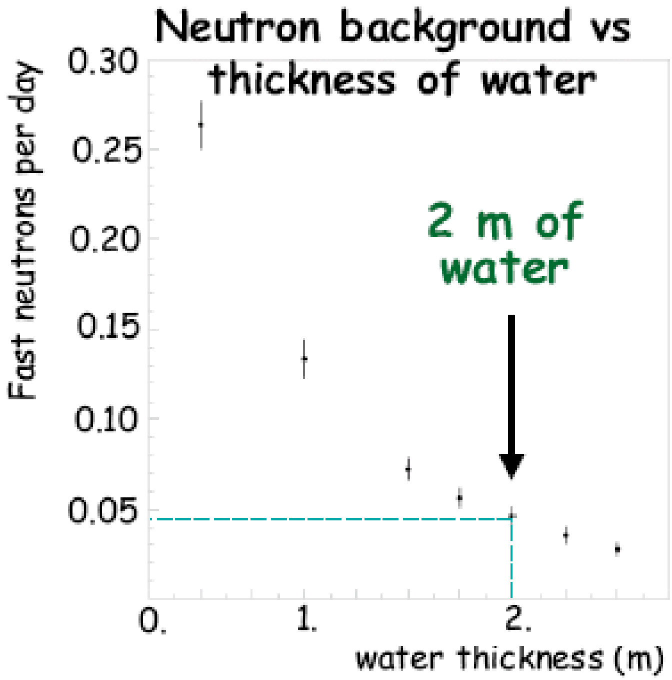
Cosmic-ray Muon

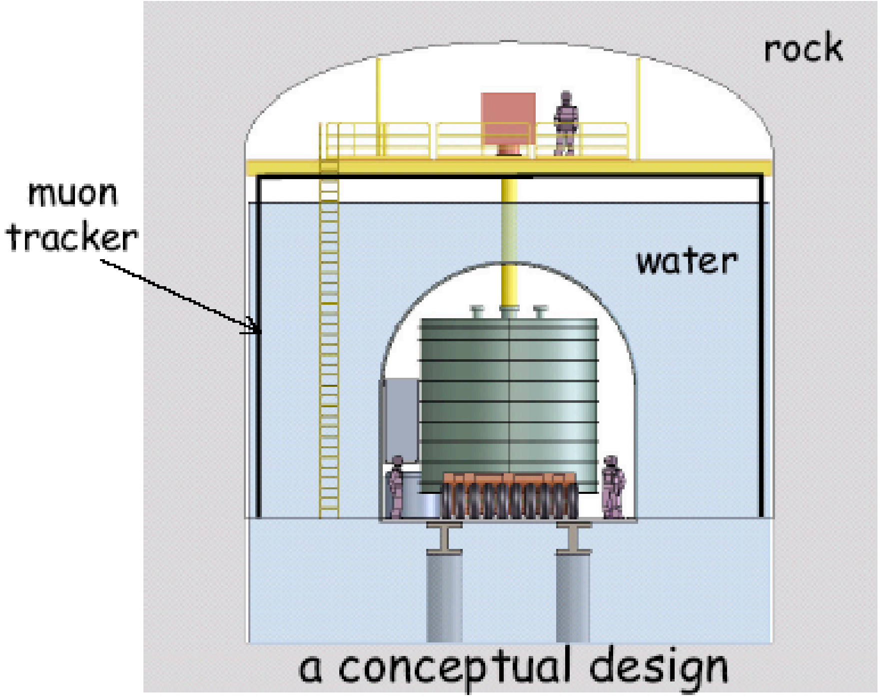
- Apply the Geiser parametrization for cosmic-ray flux at surface
- Use MUSIC and mountain profile to estimate muon flux & energy



	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

Design of Shield-Muon Veto





a conceptual design

- 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%

Summary of Background

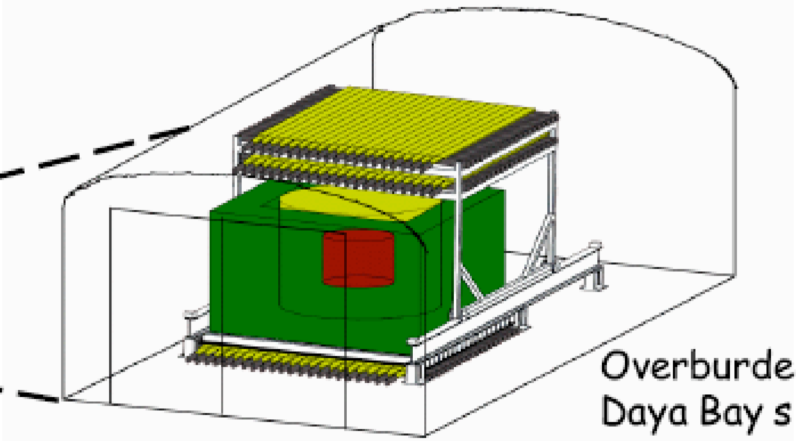
- Use a modified Palo Verde-Geant3-based MC to model response of detector:

	Near Site	Far Site
Radioactivity (Hz)	<50	<50
Accidental B/S	<0.05%	<0.05%
Fast neutron B/S	0.14% ± 0.16%	0.08 ± 0.1%
^{8}He/^{9}Li B/S	0.41% ± 0.18%	0.2% ± 0.08%

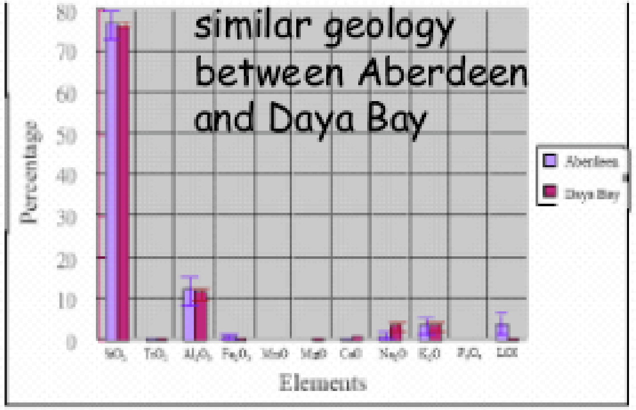
Further rejection of background may be possible by cutting showering muons.

The Aberdeen Tunnel Experiment

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

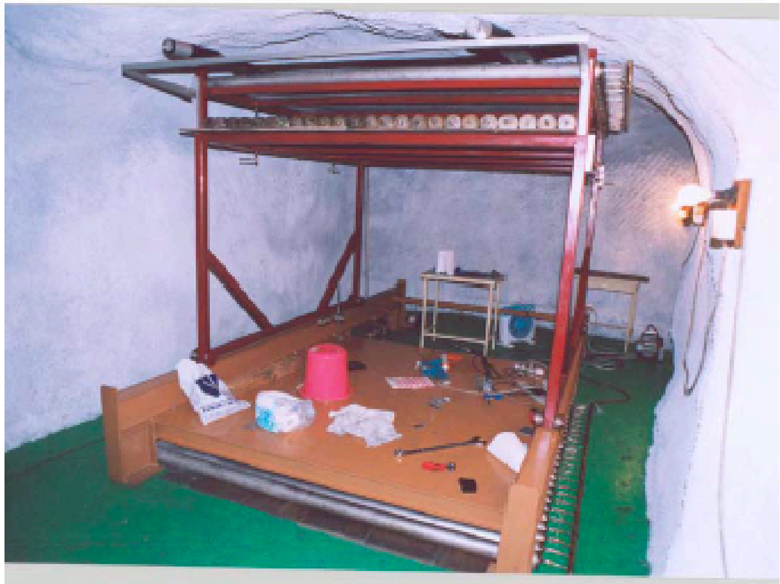


Overburden ~
Daya Bay sites



similar geology between Aberdeen and Daya Bay

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



Reactor-related Uncertainties of Daya Bay

- The error due to power fluctuations of the reactors is given by:

$$\sigma_{sys} = \sigma_p \sqrt{\sum_r \left(f_F^r - f_N^r\right)^2}$$

Based on experience of past experiments, due to uncertainty in measuring the amount of thermal power produced, the uncorrelated error per reactor core $\sigma_p \approx 2\%$.

f^r_F and f^r_N are fractions of the events at the far and near site from reactor r respectively.

# Reactor Cores	Syst. error due to Power Fluctuations	Syst. error due to Core Positions	Total syst. error
4	0.035%	0.08%	0.087%
6	0.097%	0.08%	0.126%

Summary of Systematic Errors

- Reactor-related systematic errors are:

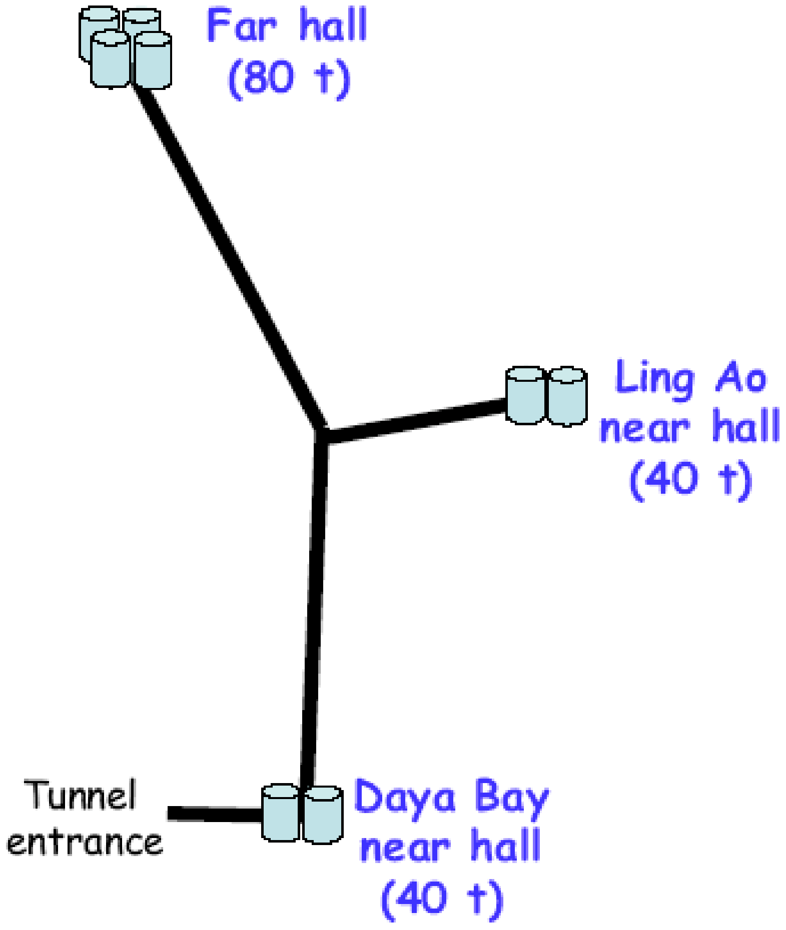
  0.09% (4 cores)
  0.13% (6 cores)

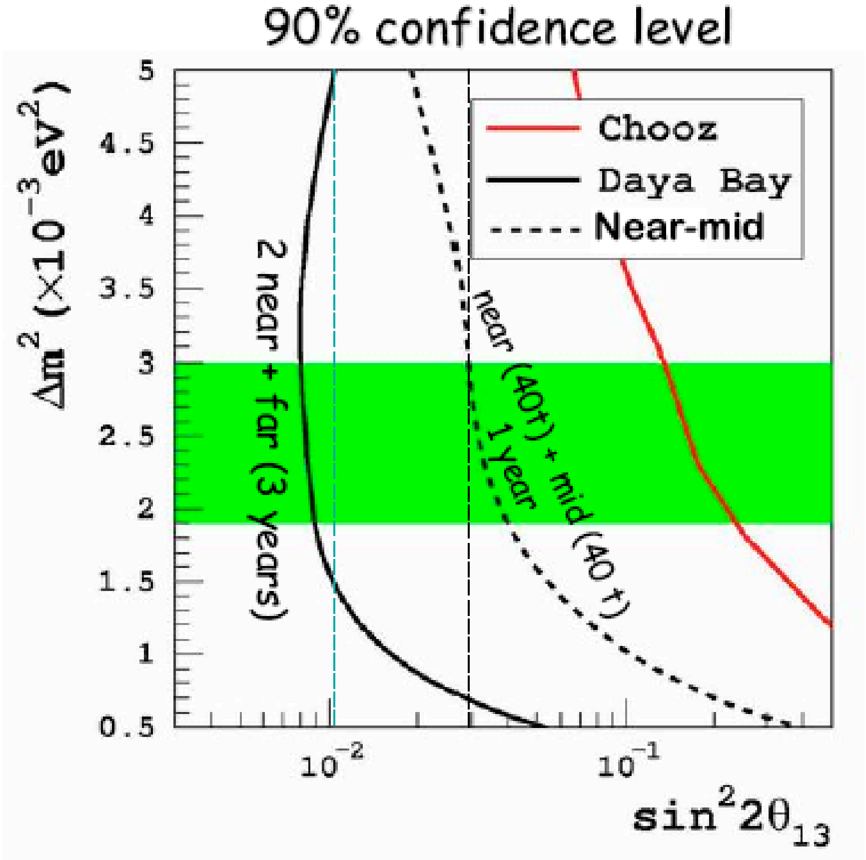
- Relative detector systematic errors are:

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

- These are input to sensitivity calculations

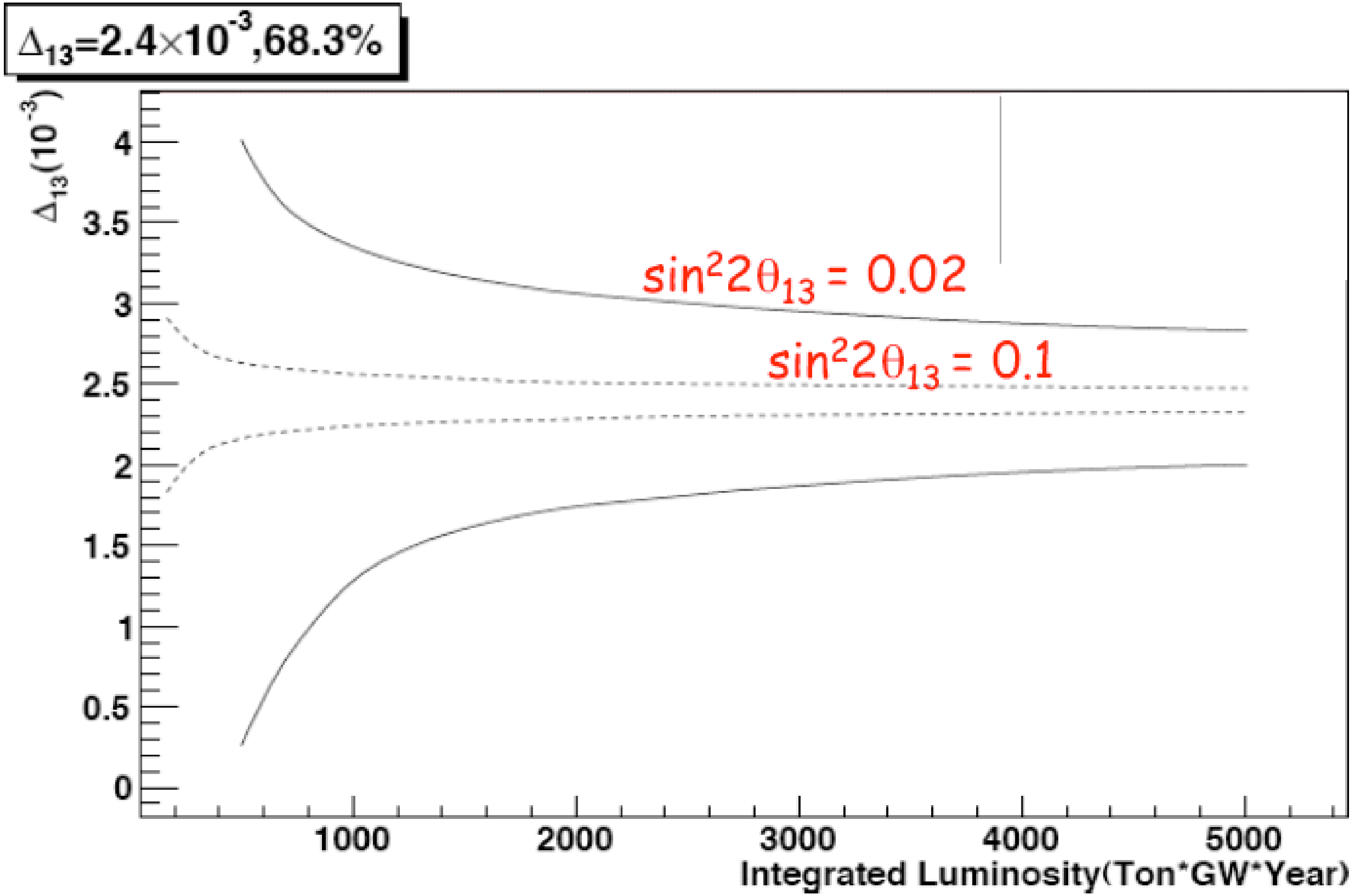
Sensitivity of Daya Bay in $\sin^2 2\theta_{13}$





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

Precision of Δm^2_{31}

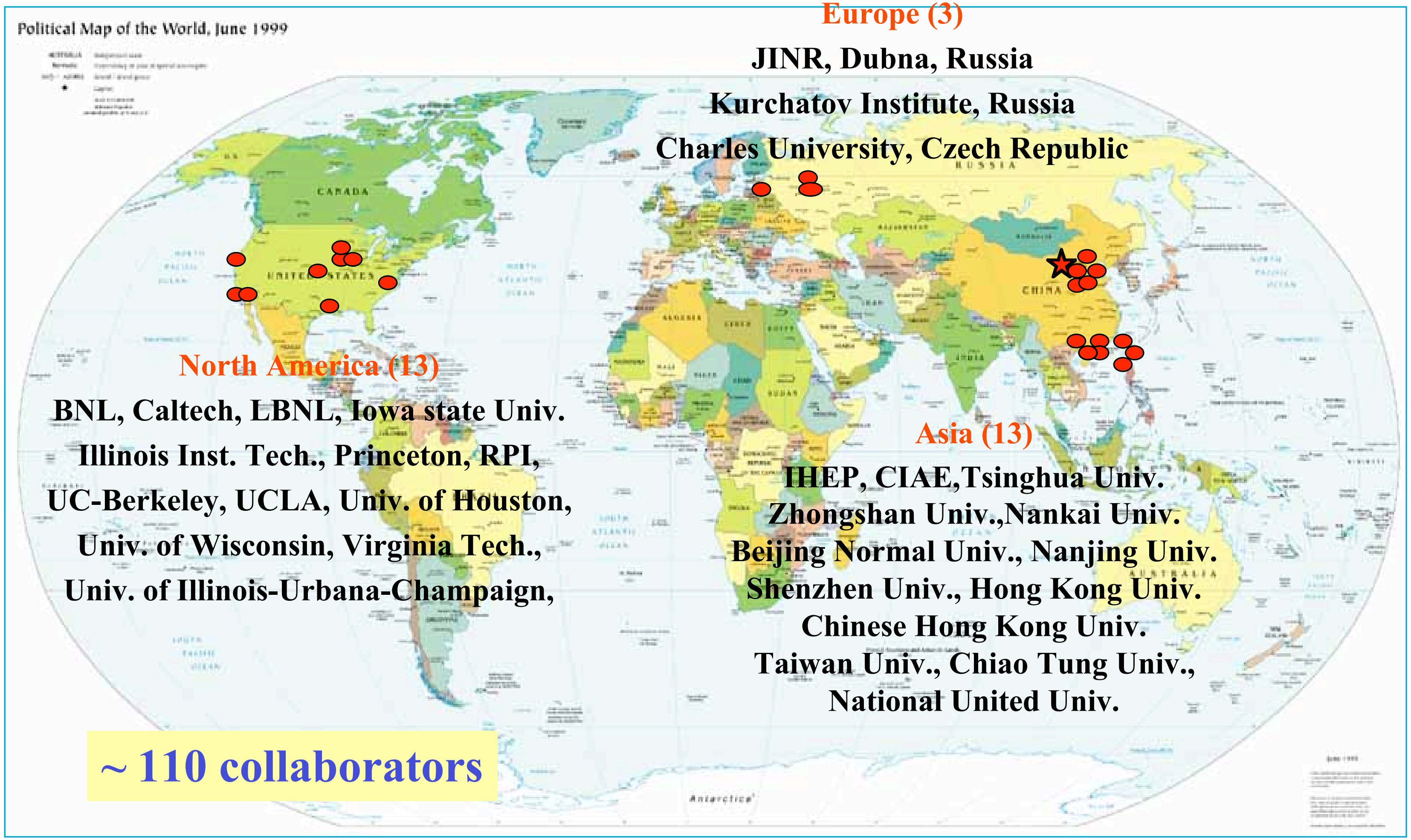


Schedule

• begin civil construction	April 2007
• Bring up the first pair of detectors	Jun 2009
• Begin data taking with the Near-Mid configuration	Sept 2009
• Begin data taking with the Near-Far configuration	Jun 2010


Daya Bay Collaboration Meeting
IHEP,Beijing,Feb.13-15,2006

Daya Bay collaboration



Europe (3)

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

North America (13)

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,

Asia (13)

IHEP, CIAE,Tsinghua Univ.
Zhongshan Univ.,Nankai Univ.
Beijing Normal Univ., Nanjing Univ.
Shenzhen Univ., Hong Kong Univ.
Chinese Hong Kong Univ.
Taiwan Univ., Chiao Tung Univ.,
National United Univ.

~ 110 collaborators

Summary and prospect

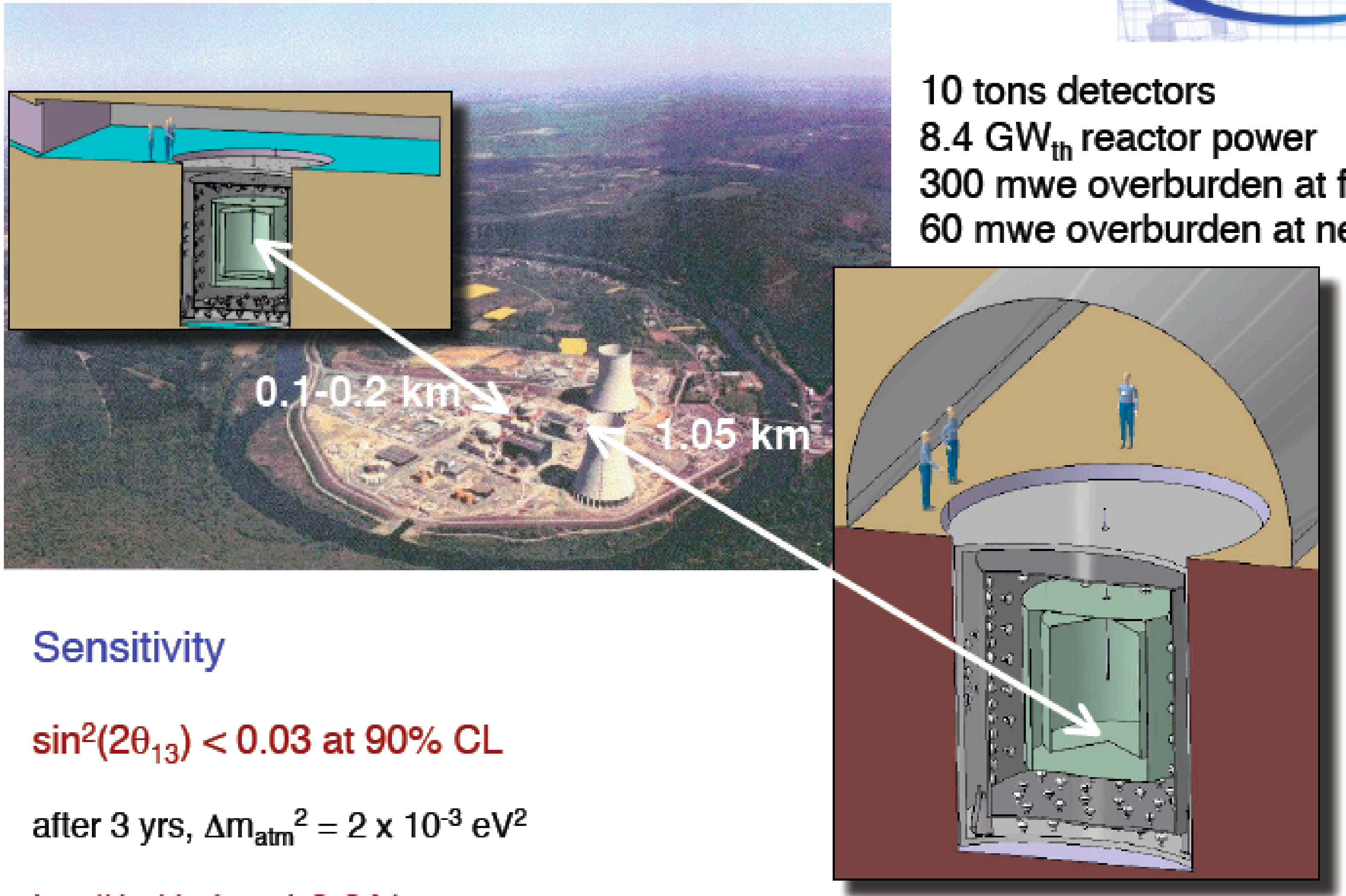
- The Daya Bay nuclear power facility in China and the mountainous topology in the vicinity offer an excellent oppertunity for carrying out a reactor neutrino program using horizontal tunnels.
- The Daya Bay neutrino experiment has excellent potential to reach an sensitivity of 0.01 for $\sin^2 2\theta_{13}$.
- Design of the detector is in progress and R&D is ongoing.
- Detailed engineering design of tunnels and experimental halls has begun.
- The collaboration has continued to grow this year. Received funding commitment from Chinese funding agencies and US DOE for R&D fund.
- Plan to start civil construction in 2007, deploying detectors in 2009 and begin full operation in 2010.

World of Proposed Reactor Neutrino Experiments

θ_{13} proposals

	Country	Reactor Power (GW_{th})	Distance (m)	Depth (mwe)	Far Target mass (t)	Sensitivity (90% u. l.)	Expected start date	Funding
Double CHOOZ	France	8.7	280 1050	80 300	10.2	0.03	2008 f 2009 f+n	○
KASKA	Japan	24.3	350 1600	90 260	8	0.025	2009/2010	△
RENO	Korea	17.3	150 1500	230 675	20x2	0.02	2009/2010	△
Daya Bay	China	11.6 17.4 (2011~)	360 (500) 1750	260 910	20x4	0.01	2009 n+m 2010 full	○
Angra	Brazil	4.1	300 1500	250 2000	500	0.005	-	-

Double Chooz



10 tons detectors
8.4 GW_{th} reactor power
300 mwe overburden at far site
60 mwe overburden at near site

Sensitivity

$\sin^2(2\theta_{13}) < 0.03$ at 90% CL

after 3 yrs, $\Delta m_{atm}^2 = 2 \times 10^{-3}\ eV^2$

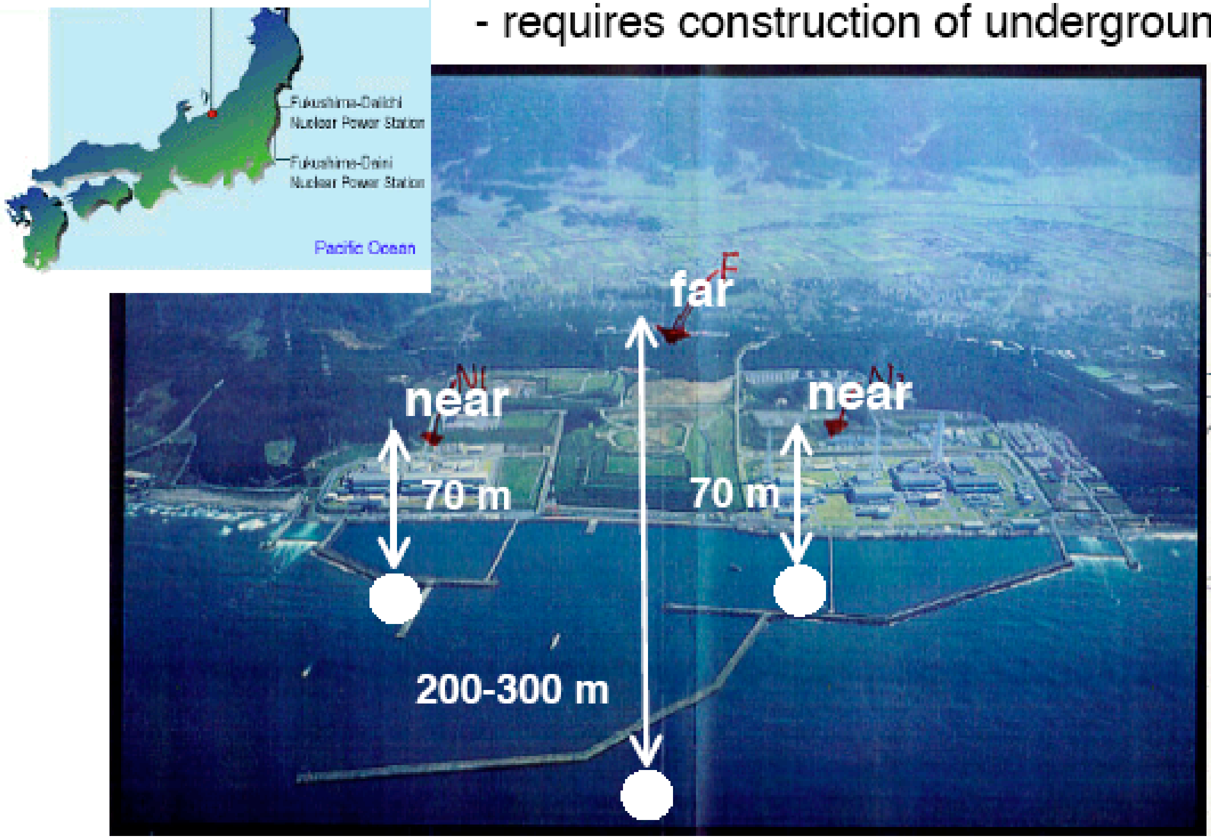
http://doublechooz.in2p3.fr/

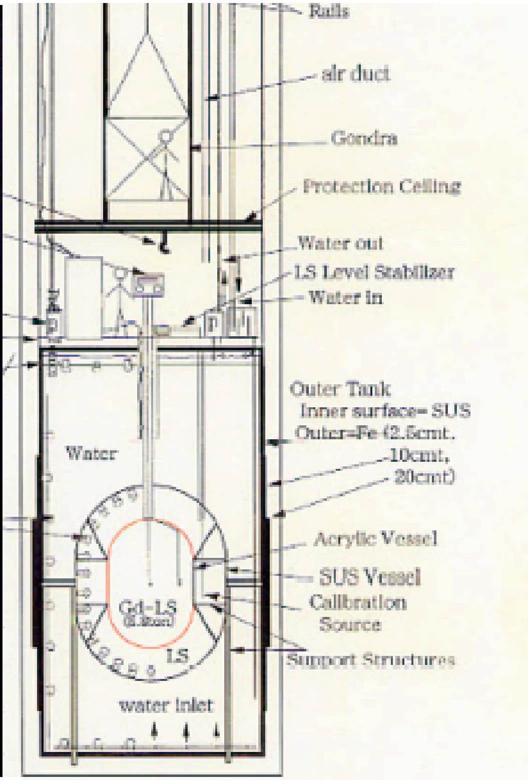
[illegible]

KASKA at Kashiwazaki, Japan

Kashiwazaki-Kariwa Nuclear Power Station

- 7 nuclear power stations, World's most powerful reactors
- requires construction of underground shaft for detectors





6 m shaft hole,
200-300 m depth

$\sin^2(2\theta_{13}) < 0.02$

http://kaska.hep.sc.niigata-u.ac.jp/

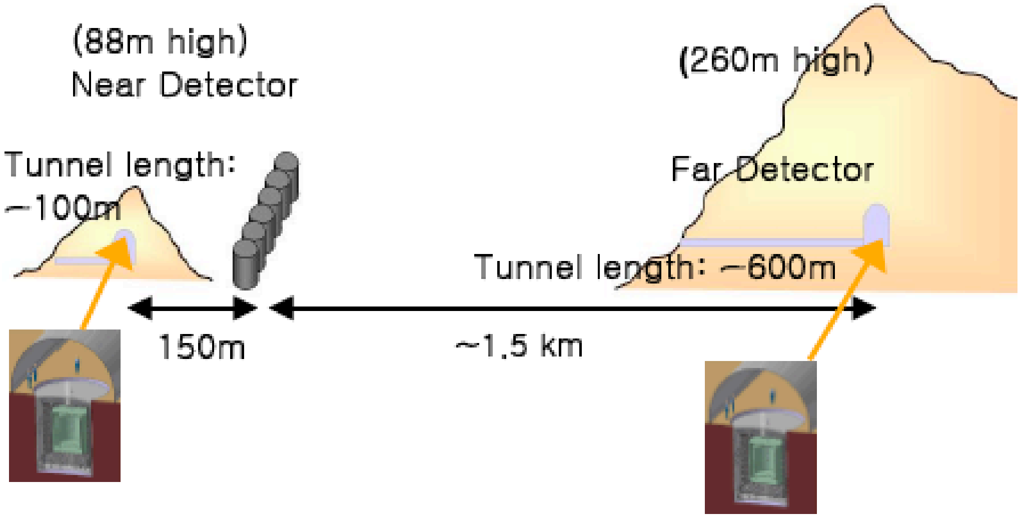
Reactor Experiment for Neutrino Oscillations (RENO) at YongGwang, Korea

20tons (fid. vol.) of liquid scintillator detectors

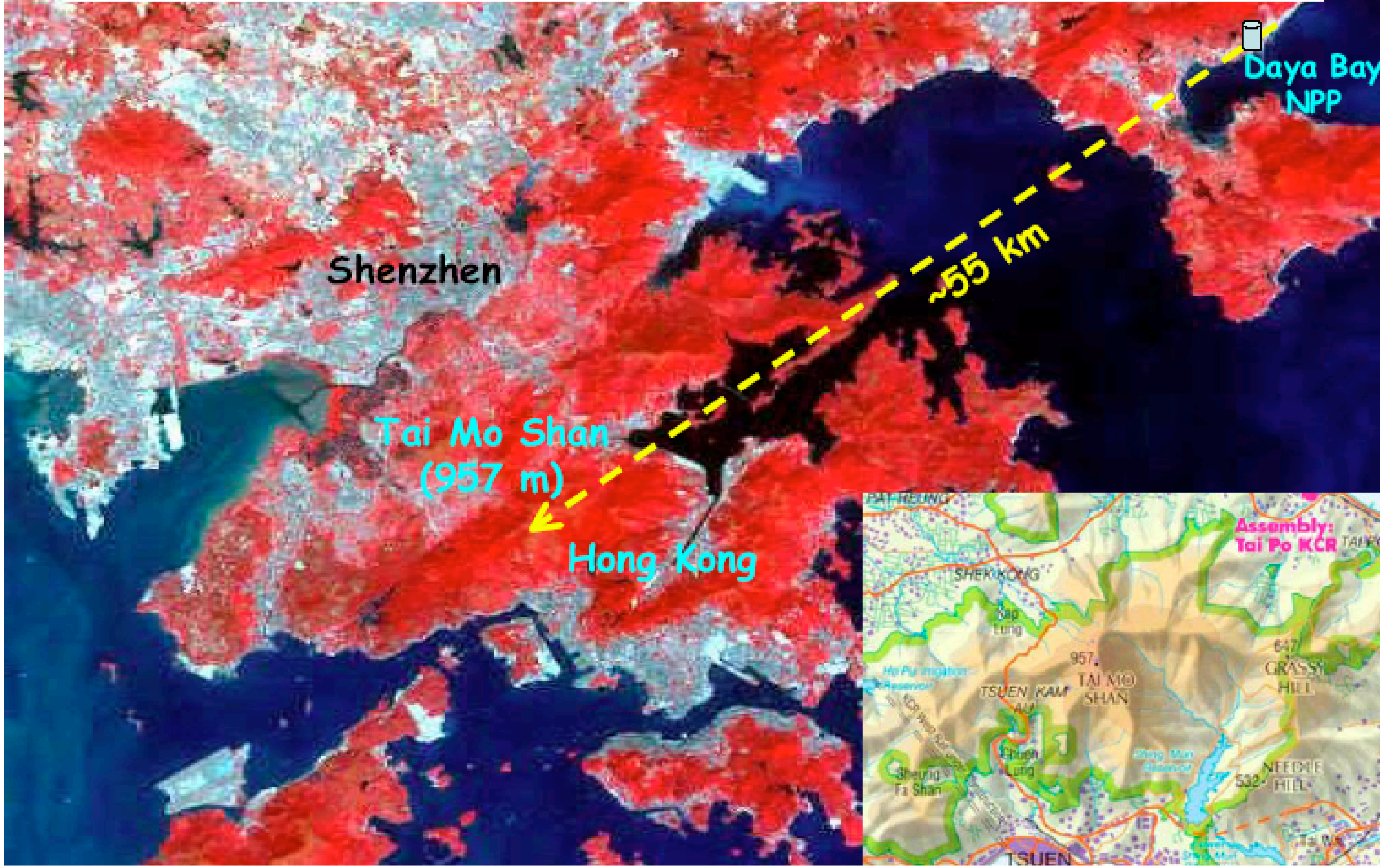
3 nearest detectors of 200~300kg scintillators

Begin of data taking 2009/2010

$\sin^2(2\theta_{13}) < 0.02$



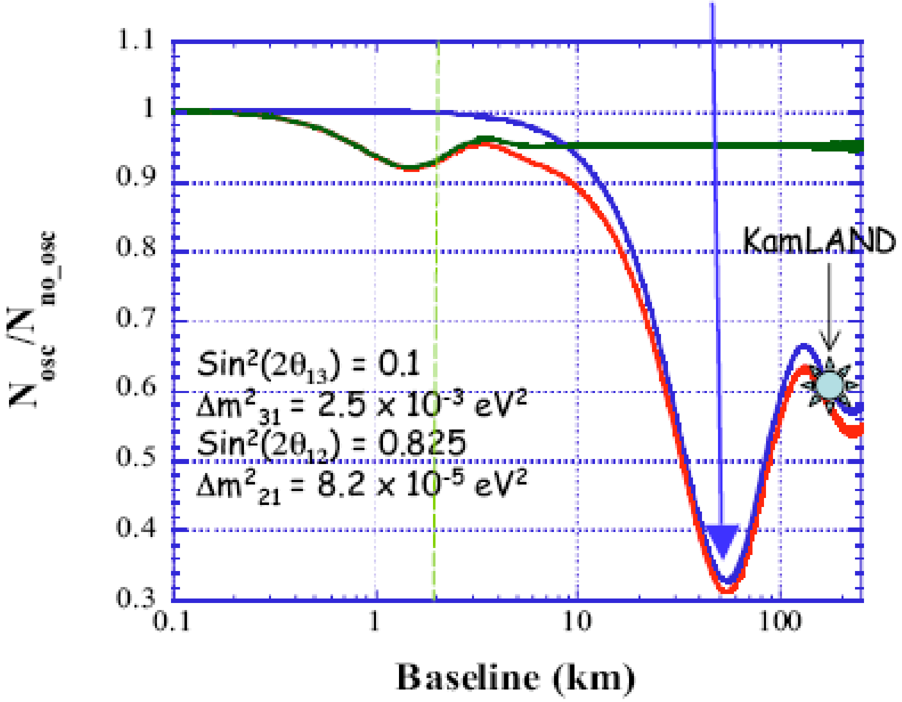
Location of Hong Kong Site For θ_{12} Measurement



Precise Measurement of θ_{12}

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

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



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}

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