# Observation of Electron Anti-neutrino Disappearance at Daya Bay

Yifang Wang

Institute of High Energy Physics

CERN， March 20, 2012

F.P. An et al., Daya Bay Coll., " A side-by-side comparison of Daya Bay anti-neutrino detectors", arXiv: 1202.6181[physics.ins-det], submitted to NIM

F.P. An et al., Daya Bay Coll., "Observation of electron anti-neutrino disappearance at Daya Bay", arXiv: 1203.1669[hep-ex], submitted to PRL

# Neutrinos & Neutrino Oscillation

- **Fundamental building blocks of matter:**

$$\begin{pmatrix} e & \mu & \tau \\ \nu_e & \nu_\mu & \nu_\tau \end{pmatrix} \qquad \begin{pmatrix} u & c & t \\ d & s & b \end{pmatrix}$$

- **Neutrino mass: the central issue of neutrino physics**
  - ⇨ **Tiny mass but huge amount**
  - ⇨ **Influence to Cosmology: evolution, large scale structure, …**
  - ⇨ **Only evidence beyond the Standard Model**
- **Neutrino oscillation: a great method to probe the mass**

$$\nu_e \longrightarrow \nu_\mu \longrightarrow \nu_e \longrightarrow \nu_\mu \longrightarrow$$

**Oscillation probability:**

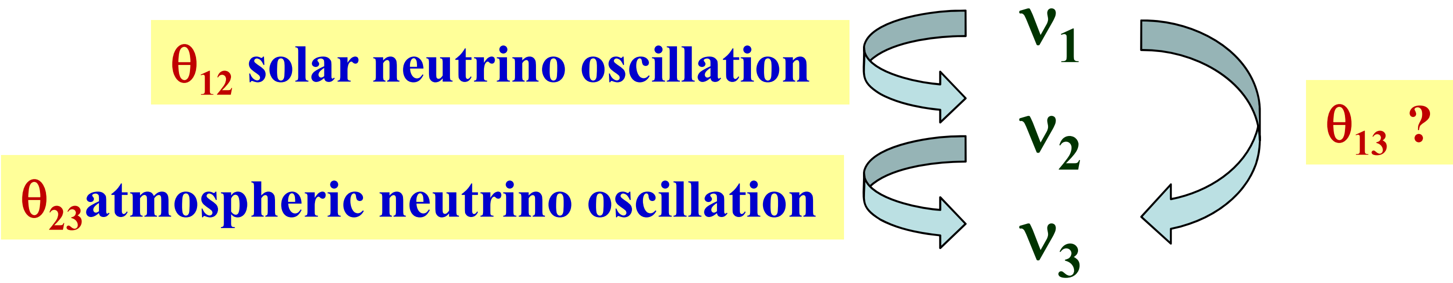
$$P(\nu_e \rightarrow \nu_\mu) = \sin^2(2\theta)\,\sin^2(1.27\Delta m^2 L/E)$$

**Oscillation amplitude** ($\sin^2(2\theta)$)

**Oscillation frequency** ($\Delta m^2$)

# Daya Bay: for a New Type of Oscillation

- **Goal: search for a new oscillation mode $\theta_{13}$ ?**




- **Neutrino mixing matrix:**

$$\mathbf{V} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & e^{-i\delta} & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & e^{i\sigma} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Unknown mixing parameters: $\theta_{13}$, $\delta$ + 2 Majorana phases

Need sizable $\theta_{13}$ for the $\delta$ measurement

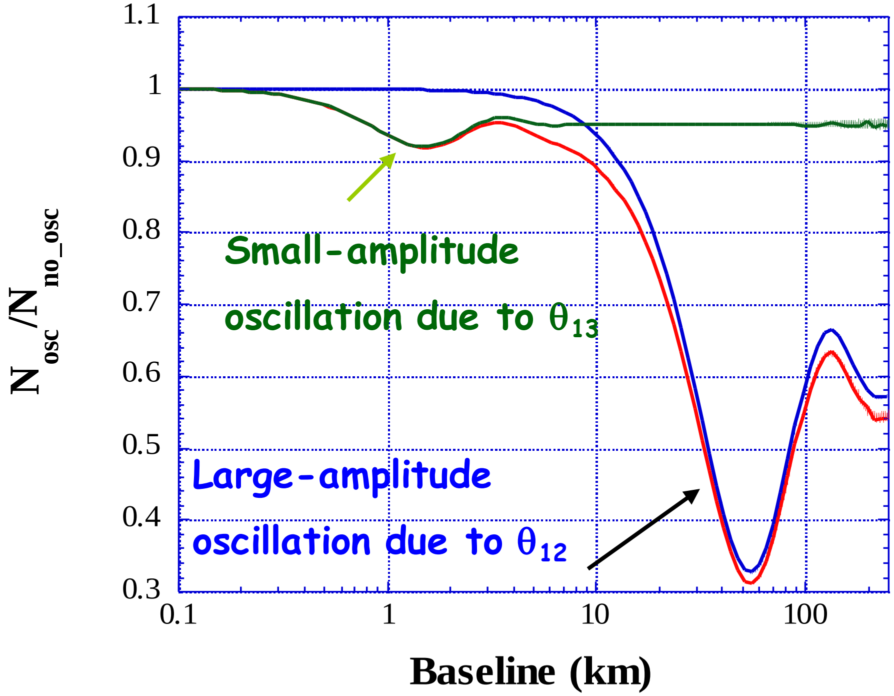
# Two ways to measure $\theta_{13}$

**Reactor experiments:**

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

**Long baseline accelerator experiments:**

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



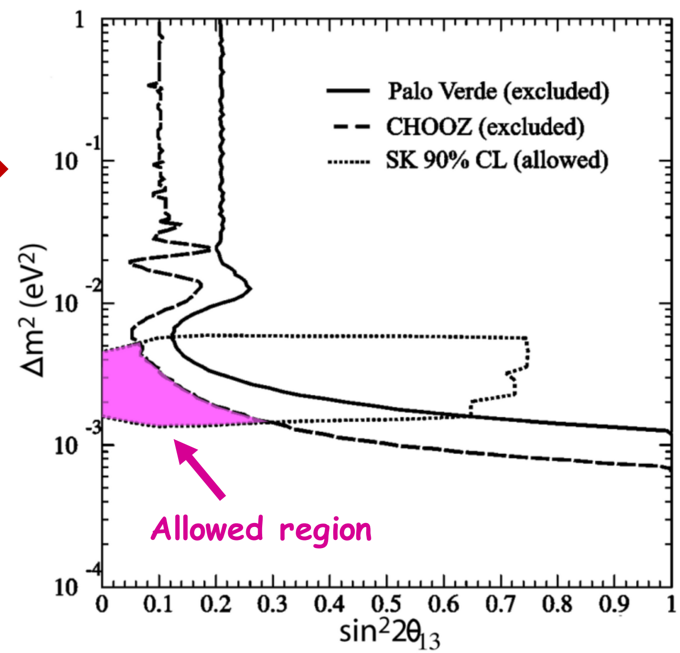

**At reactors:**

- Clean signal, no cross talk with $\delta$ and matter effects
- Relatively cheap compared to accelerator based experiments
- Provides the direction to the future of neutrino physics

# Direct Searches in the Past

- **Palo Verde & Chooz: no signal**

$Sin^2 2\theta_{13} < 0.15$ @ 90% C.L. if $\Delta M^2_{23} = 0.0024\ eV^2$




- **T2K: 2.5 σ over bkg**

$0.03 < Sin^2 2\theta_{13} < 0.28$ @ 90% C.L. for NH

$0.04 < Sin^2 2\theta_{13} < 0.34$ @ 90% C.L. for IH

- **Minos: 1.7 σ over bkg**

$0 < Sin^2 2\theta_{13} < 0.12$ @ 90% C.L. NH

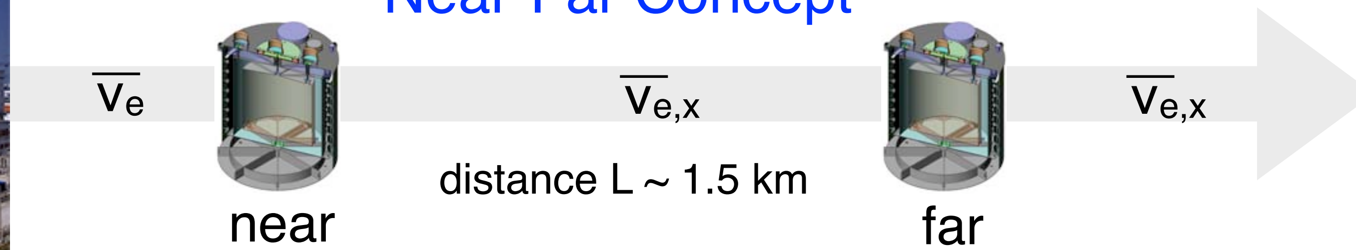
$0 < Sin^2 2\theta_{13} < 0.19$ @ 90% C.L. IH

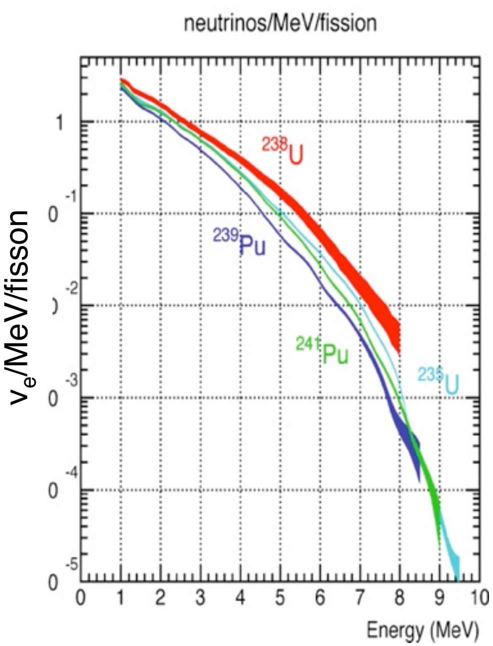
- **Double Chooz: 1.7 σ**

$\sin^2 2\theta_{13} = 0.086 \pm 0.041(stat) \pm 0.030(sys)$

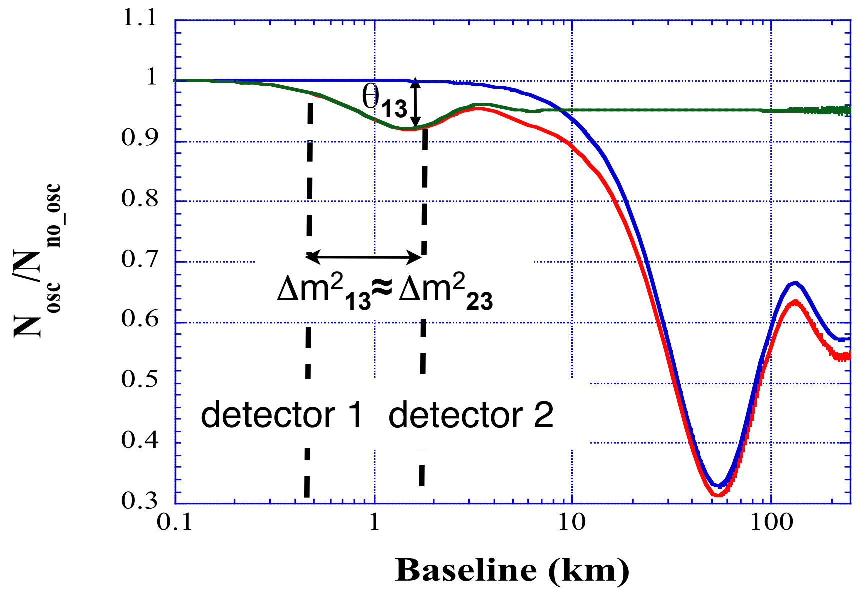
# Measuring $\theta_{13}$ with Reactor Experiments

## Near-Far Concept

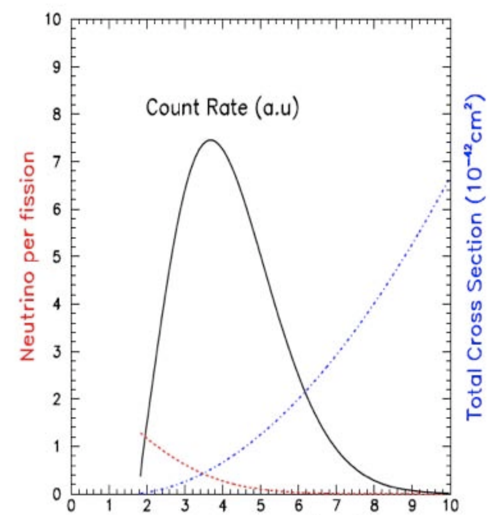



Energy (MeV)



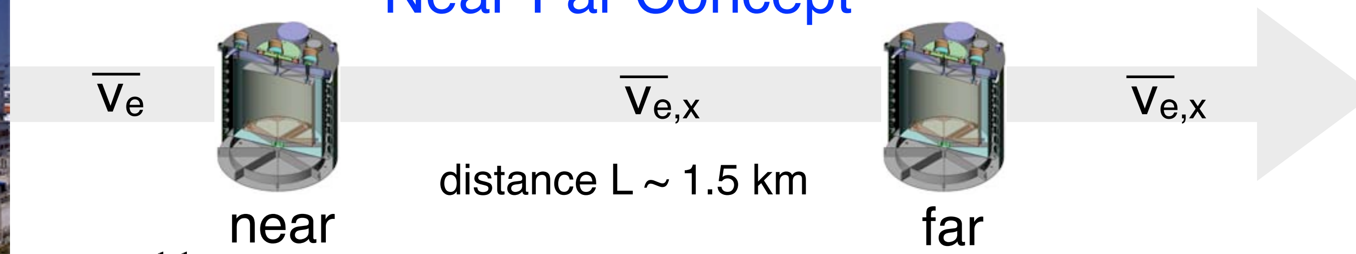

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \cong 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{32} L}{4E}$$

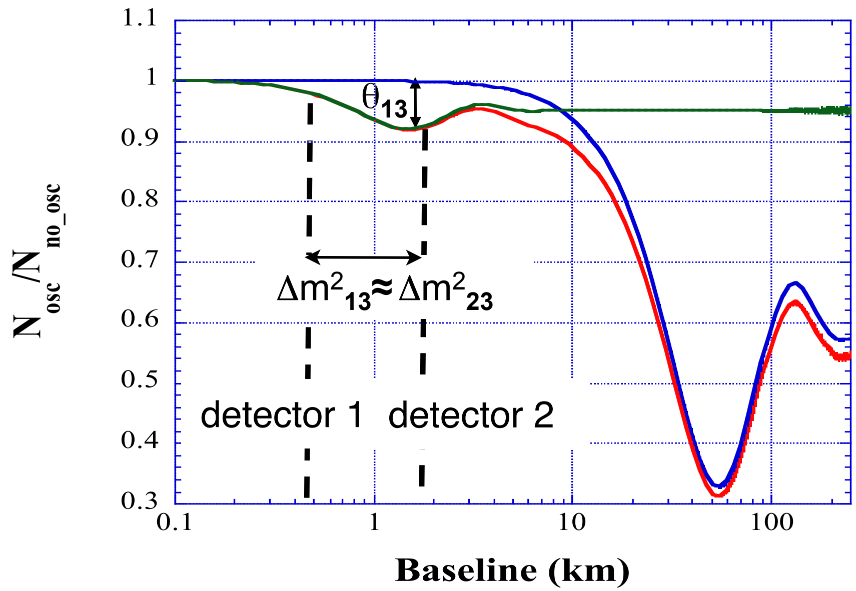



Neutrino Energy (MeV)

# Measuring $\theta_{13}$ with Reactor Experiments

## Near-Far Concept




**Absolute Reactor Flux**
Largest uncertainty in previous measurements

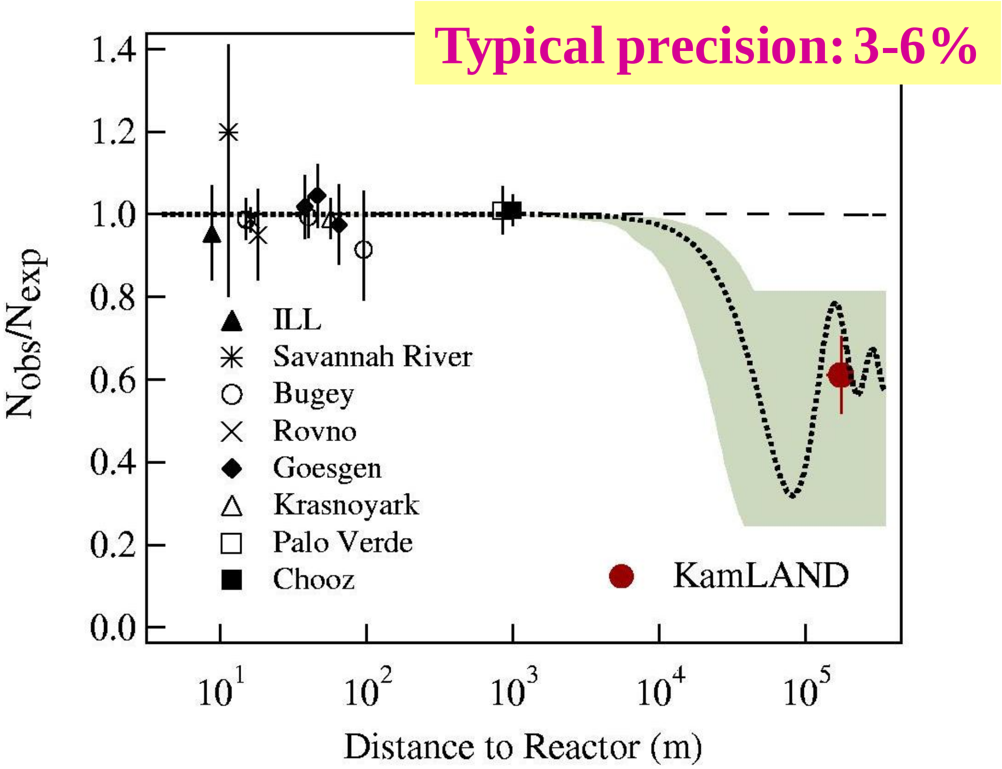
**Relative Measurement**
Removes absolute uncertainties!

First proposed by L. A. Mikaelyan and V.V. Sinev, Phys. Atomic Nucl. 63 1002 (2000)

$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left[\frac{P_{sur}(E,L_f)}{P_{sur}(E,L_n)}\right]$$

far/near $\overline{\nu}_e$ ratio — target mass — distances — efficiency — oscillation deficit

# Reactor Experiment: comparing observed/expected neutrinos

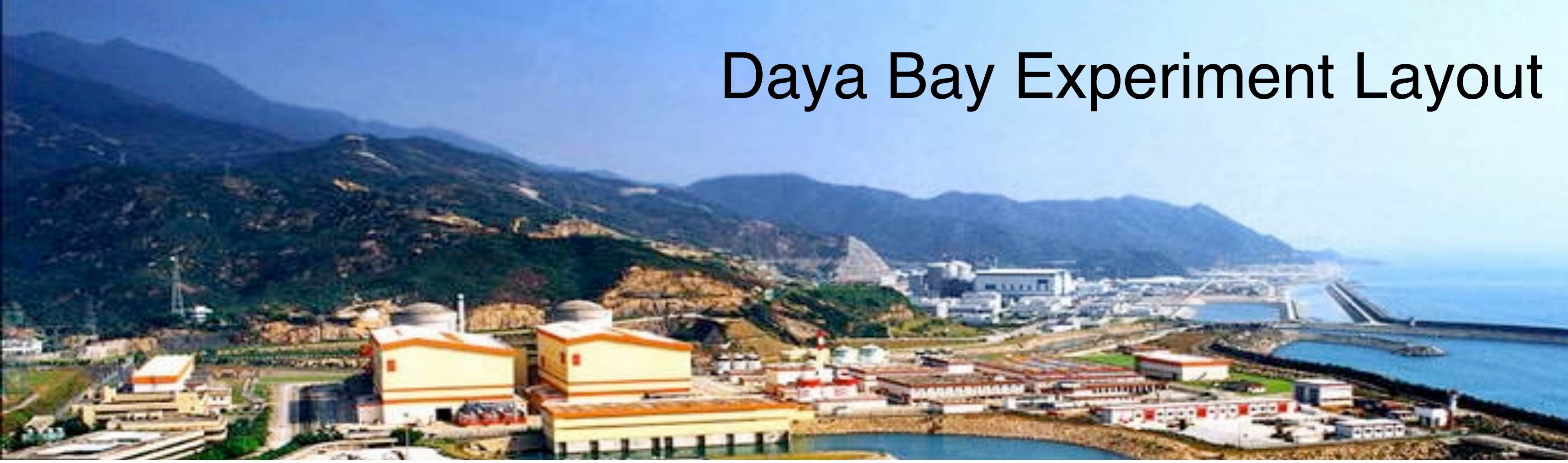


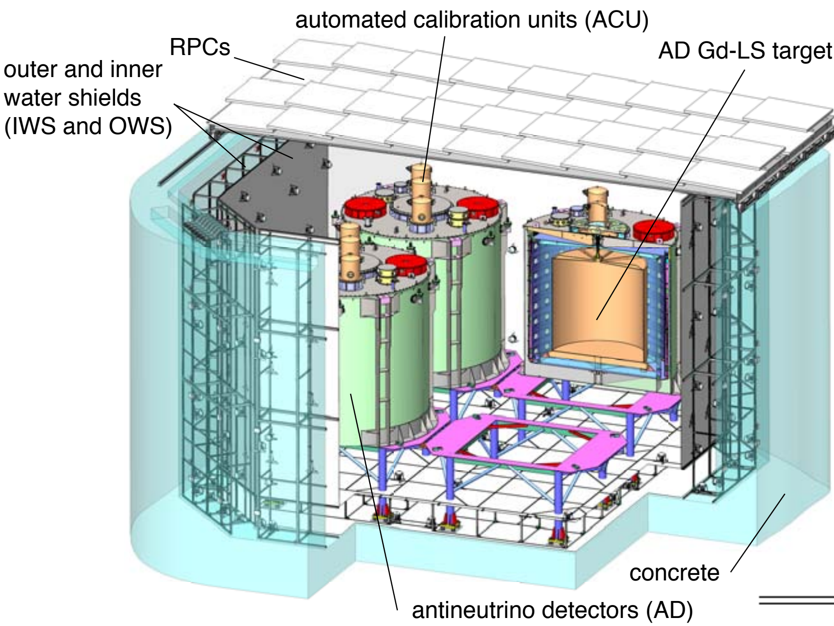

## Precision of past exp.

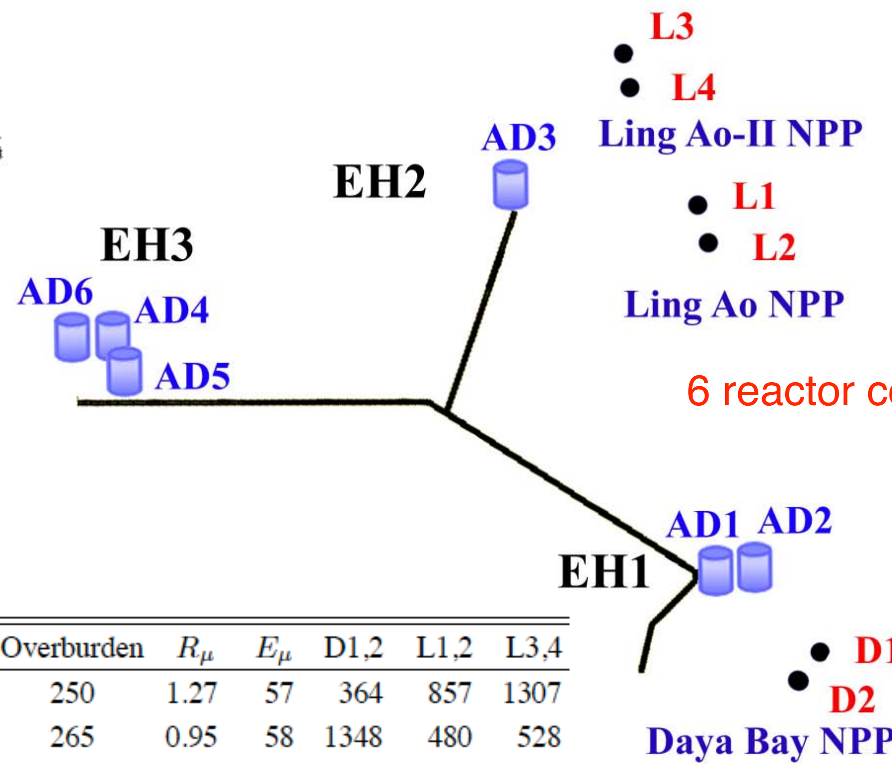
- Reactor power: ~ 1%
- Spectrum: ~ 0.3%
- Fission rate: 2%
- Backgrounds: ~1-3%
- Target mass: ~1-2%
- Efficiency: ~ 2-3%

**Our design goal: a precision of ~ 0.4%**

# Daya Bay Experiment Layout





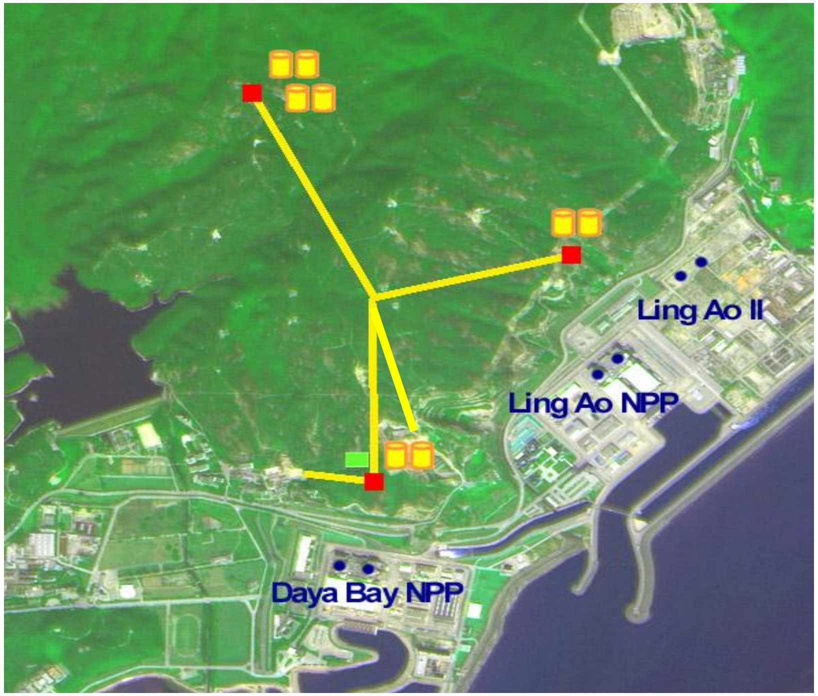



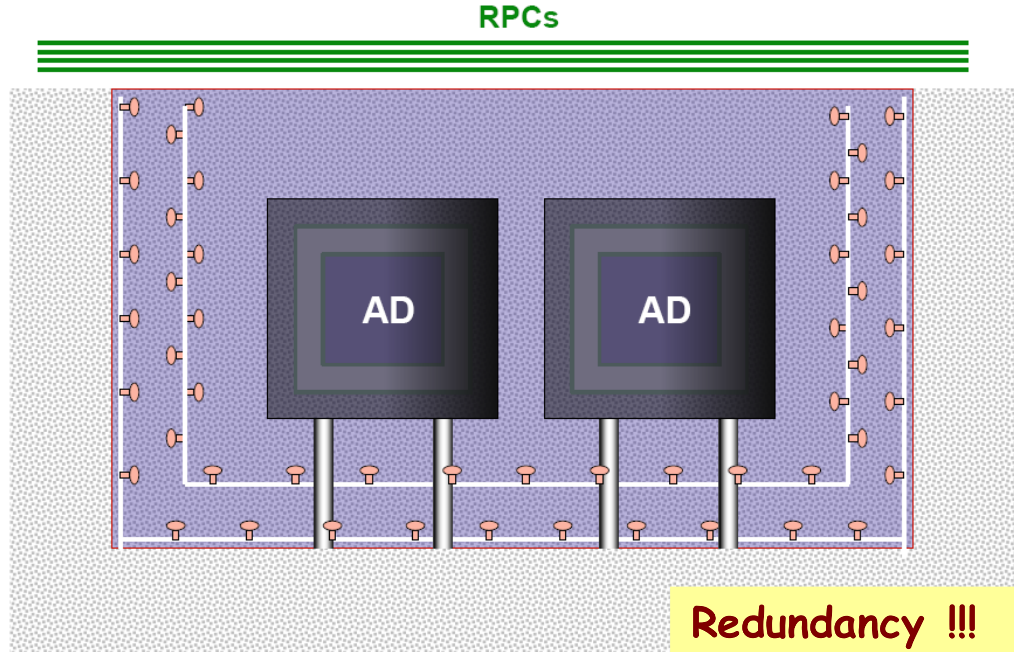

6 reactor cores

| | Overburden | $R_\mu$ | $E_\mu$ | D1,2 | L1,2 | L3,4 |
|---|---|---|---|---|---|---|
| EH1 | 250 | 1.27 | 57 | 364 | 857 | 1307 |
| EH2 | 265 | 0.95 | 58 | 1348 | 480 | 528 |
| EH3 | 860 | 0.056 | 137 | 1912 | 1540 | 1548 |

6 antineutrino detectors in 3 underground experimental halls

# Daya Bay Experiment: Layout



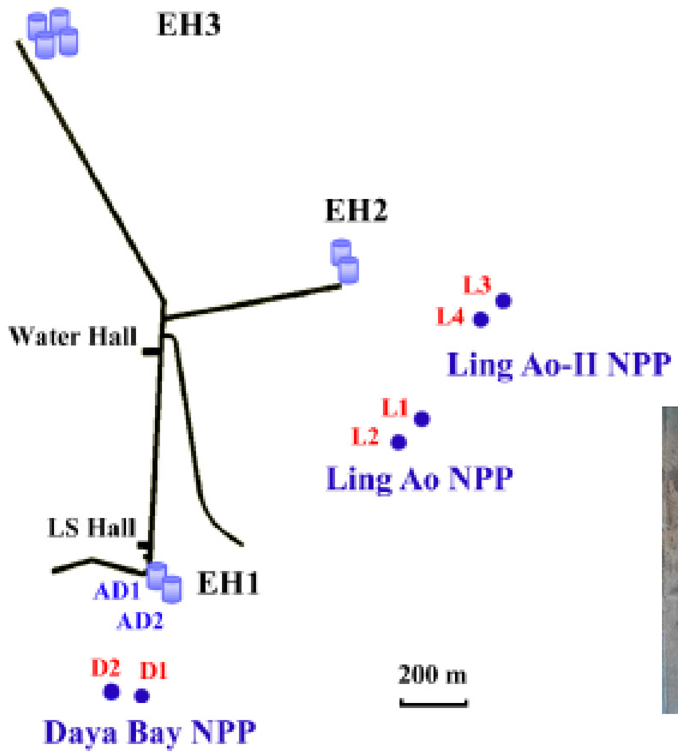




- Relative measurement to cancel Corr. Syst. Err.
  - ⇨ 2 near sites, 1 far site
- Multiple AD modules at each site to reduce Uncorr. Syst. Err.
  - ⇨ Far: 4 modules, near: 2 modules

Cross check; Reduce errors by 1/√N

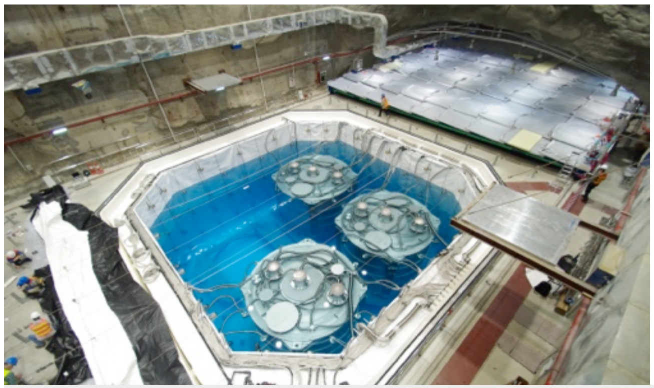
- Multiple muon detectors to reduce veto eff. uncertainties
  - ⇨ Water Cherenkov： 2 layers
  - ⇨ RPC： 4 layers at the top + telescopes

# Underground Labs

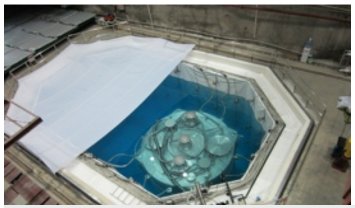



| | Overburden (MWE) | $R_\mu$ (Hz/m²) | $E_\mu$ (GeV) | D1,2 (m) | L1,2 (m) | L3,4 (m) |
|---|---|---|---|---|---|---|
| EH1 | 250 | 1.27 | 57 | 364 | 857 | 1307 |
| EH2 | 265 | 0.95 | 58 | 1348 | 480 | 528 |
| EH3 | 860 | 0.056 | 137 | 1912 | 1540 | 1548 |

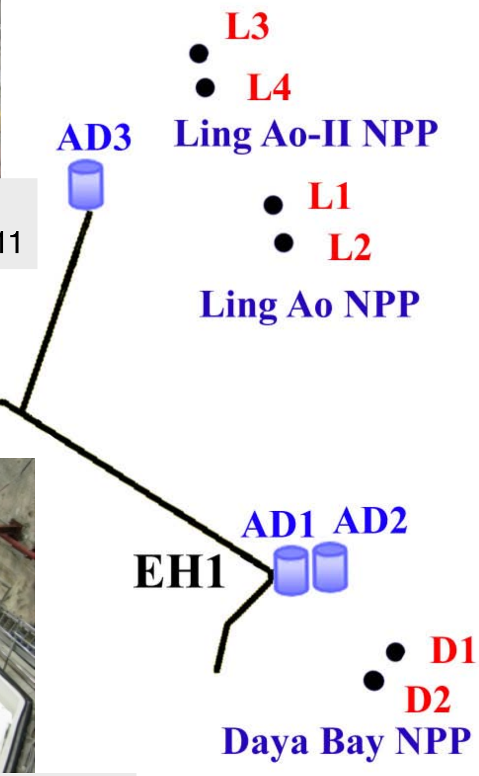
# Daya Bay Experiment Layout

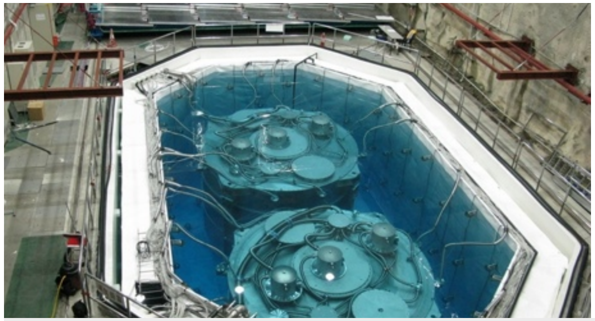


Hall 3: began 3 AD operation on Dec. 24, 2011



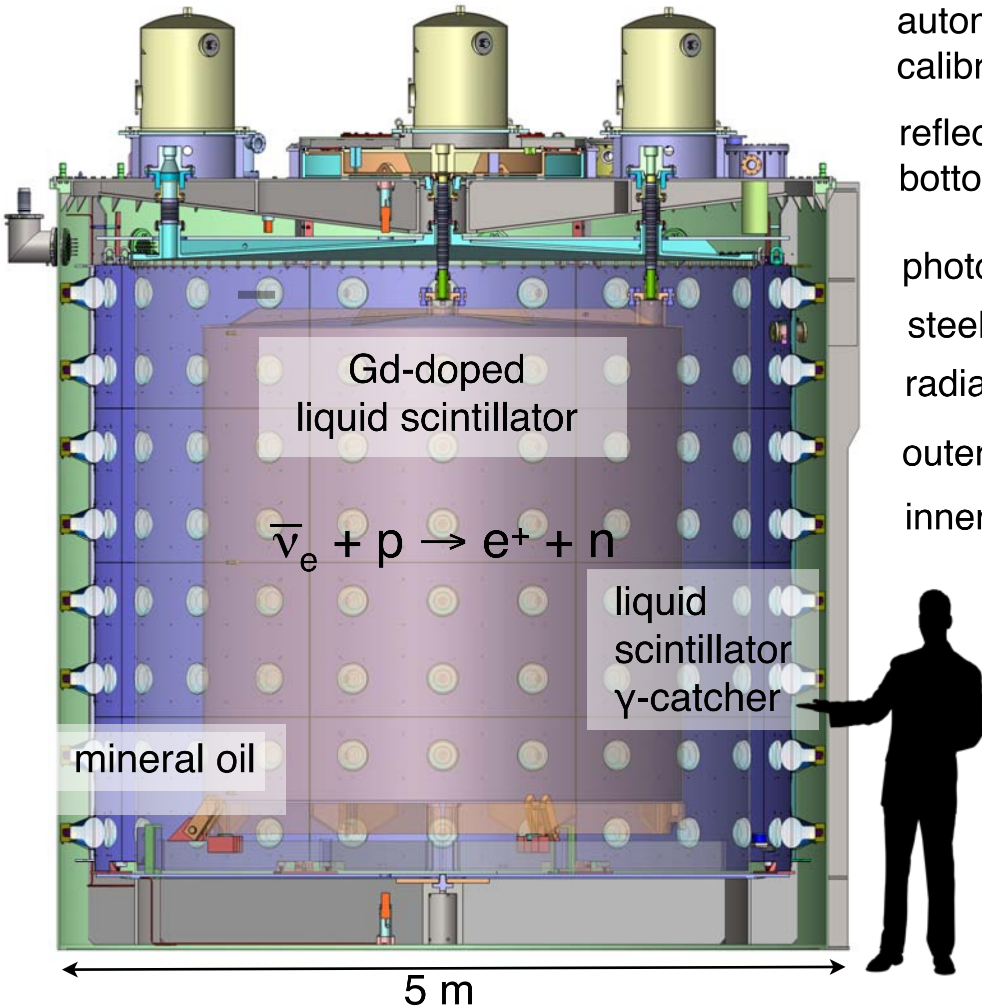
Hall 2: began 1 AD operation on Nov. 5, 2011

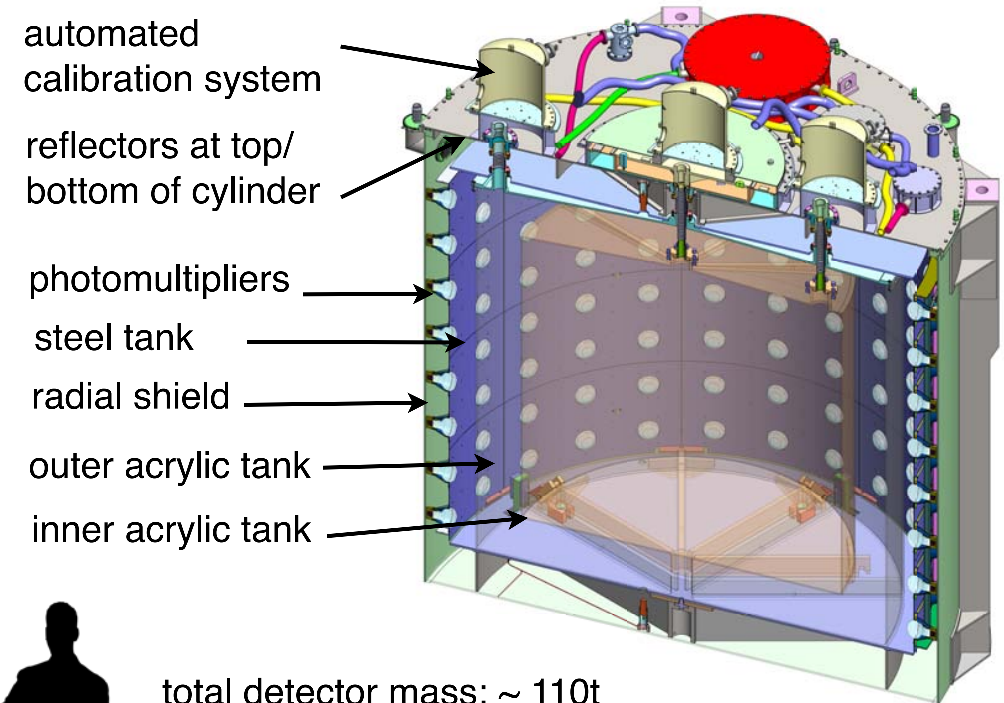


Hall 1: began 2 AD operation on Sep. 23, 2011

# Daya Bay Antineutrino Detectors




total detector mass: ~ 110t

- inner: 20 tons Gd-doped LS (d=3m)
- mid: 20 tons LS (d=4m)
- outer: 40 tons mineral oil buffer (d=5m)

photosensors: 192 8”-PMTs

energy resolution: $(7.5 / \sqrt{E} + 0.9)\%$

6 “functionally identical”, 3-zone detectors reduces systematic uncertainties

$$\frac{N_{\mathrm{f}}}{N_{\mathrm{n}}} = \left(\frac{N_{\mathrm{p,f}}}{N_{\mathrm{p,n}}}\right)\left(\frac{L_{\mathrm{n}}}{L_{\mathrm{f}}}\right)^2\left(\frac{\epsilon_{\mathrm{f}}}{\epsilon_{\mathrm{n}}}\right)\left[\frac{P_{\mathrm{sur}}(E,L_{\mathrm{f}})}{P_{\mathrm{sur}}(E,L_{\mathrm{n}})}\right]$$

# Daya Bay Antineutrino Detection

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

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

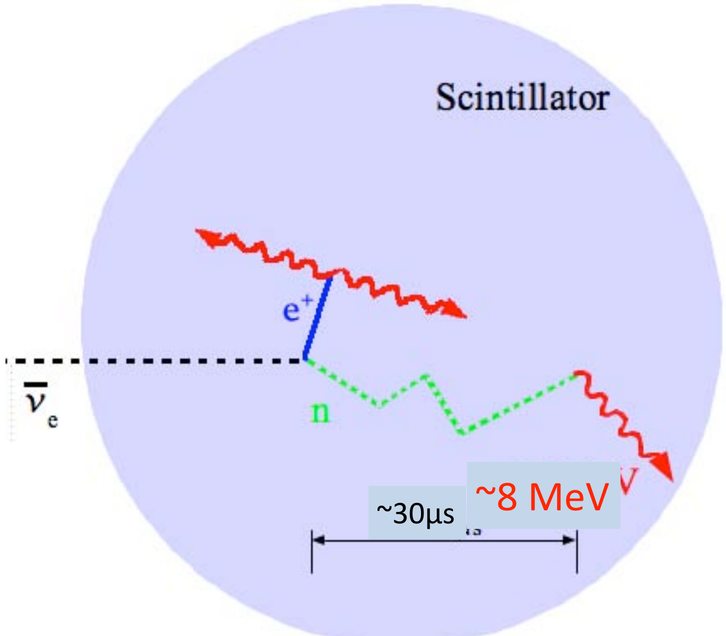
49,000 b → $+ Gd \rightarrow Gd^* \rightarrow Gd + \gamma$'s (8 MeV) (delayed)

prompt+delayed coincidence provides distinctive signature

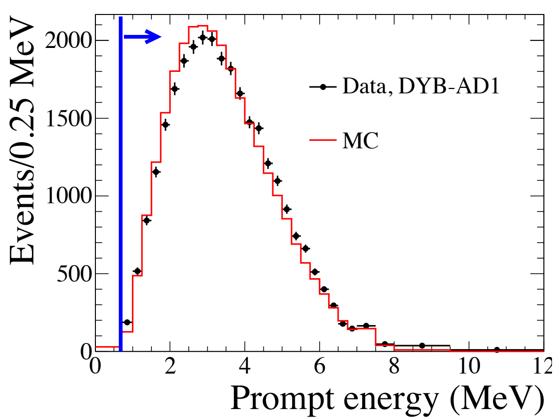
Prompt positron: carries antineutrino energy

$E_{e+} \approx E_\nu - 0.8$ MeV

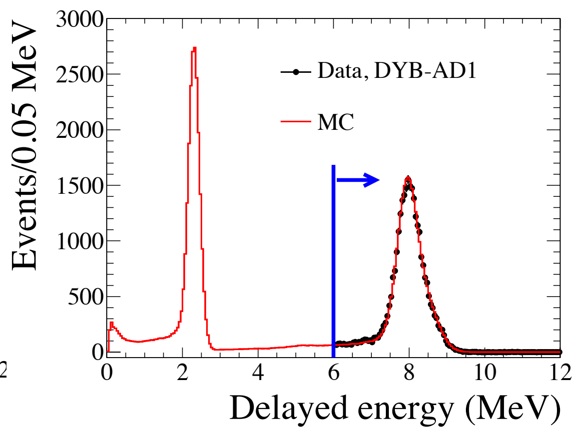
Delayed neutron capture: tags antineutrino signal



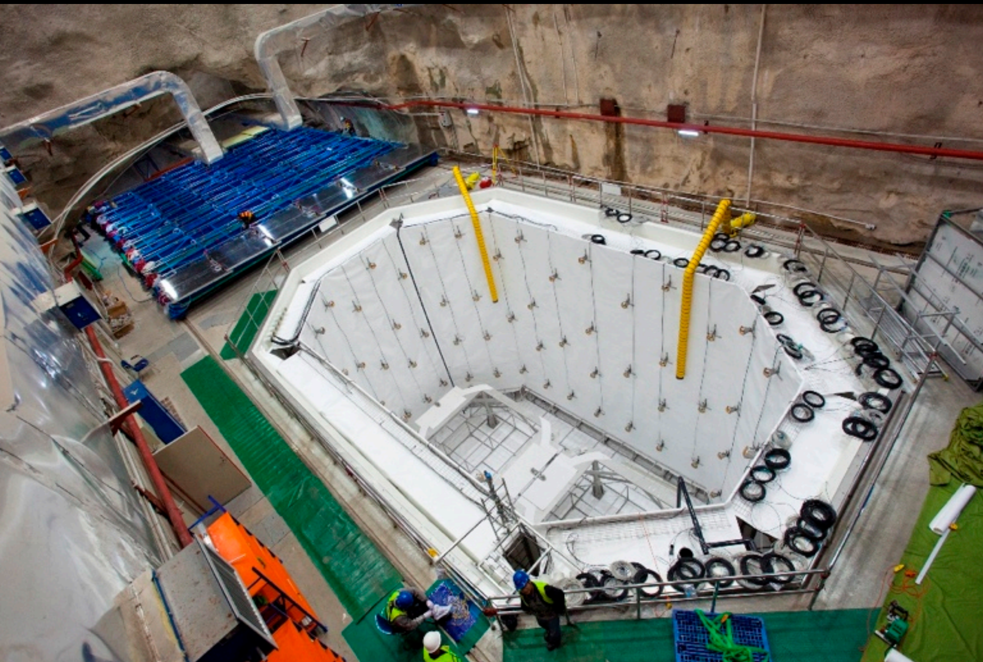

Prompt Energy Signal

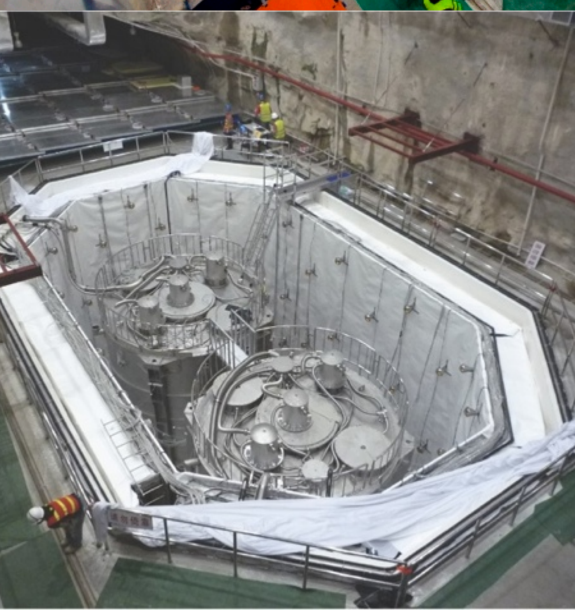
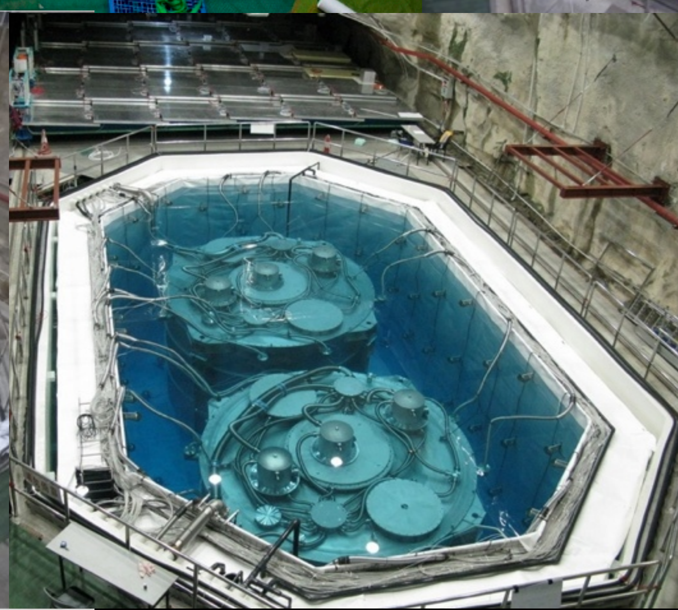



Delayed Energy Signal

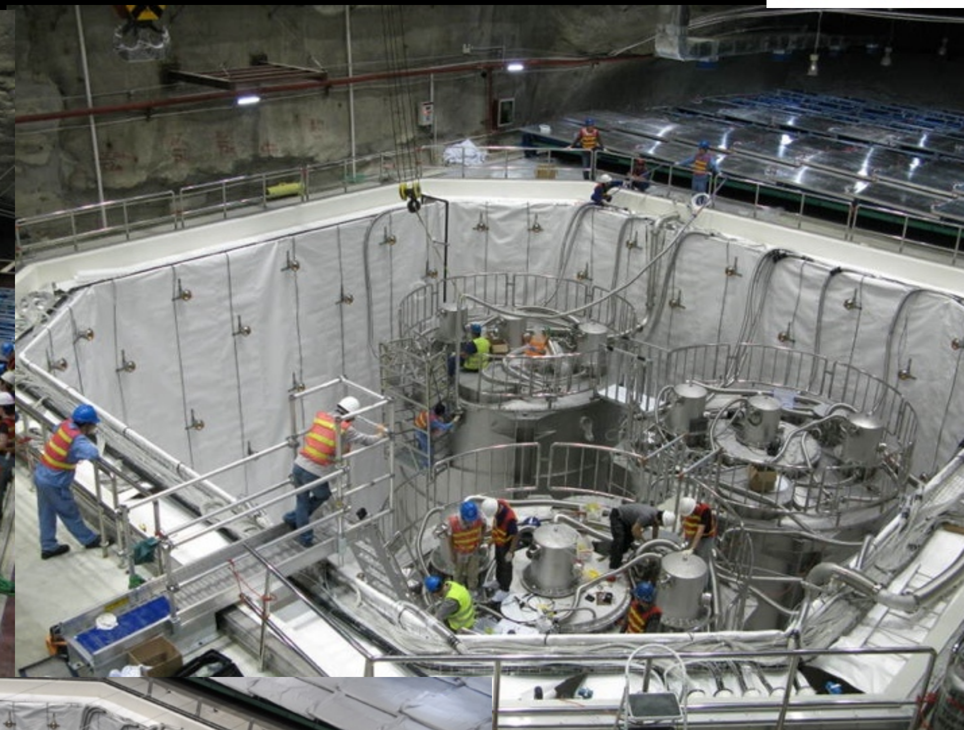


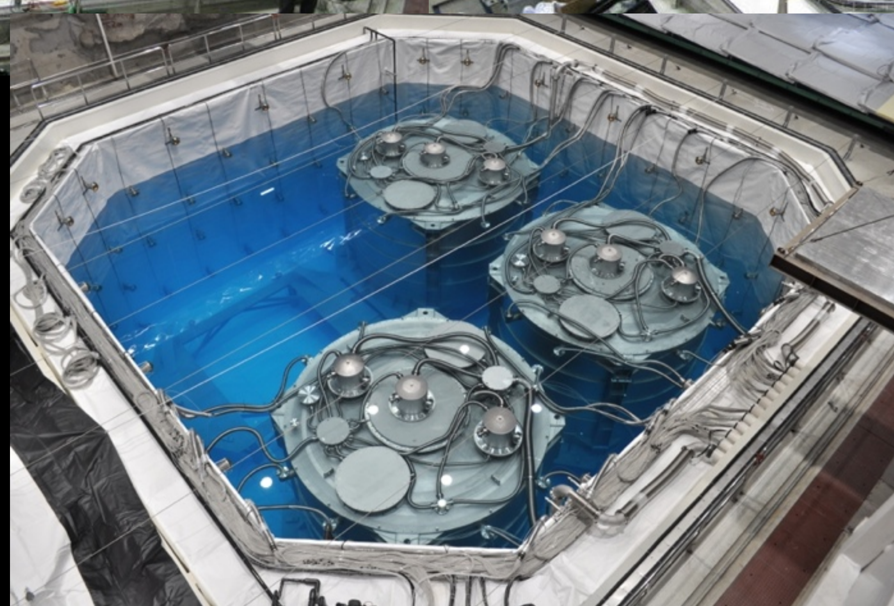
# Antineutrino Detector Installation - Near Hall



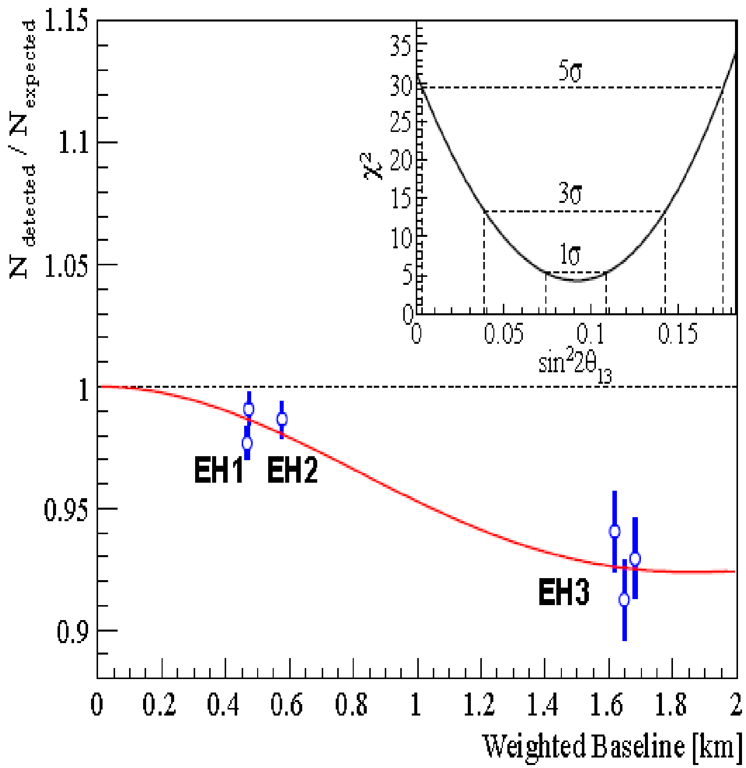



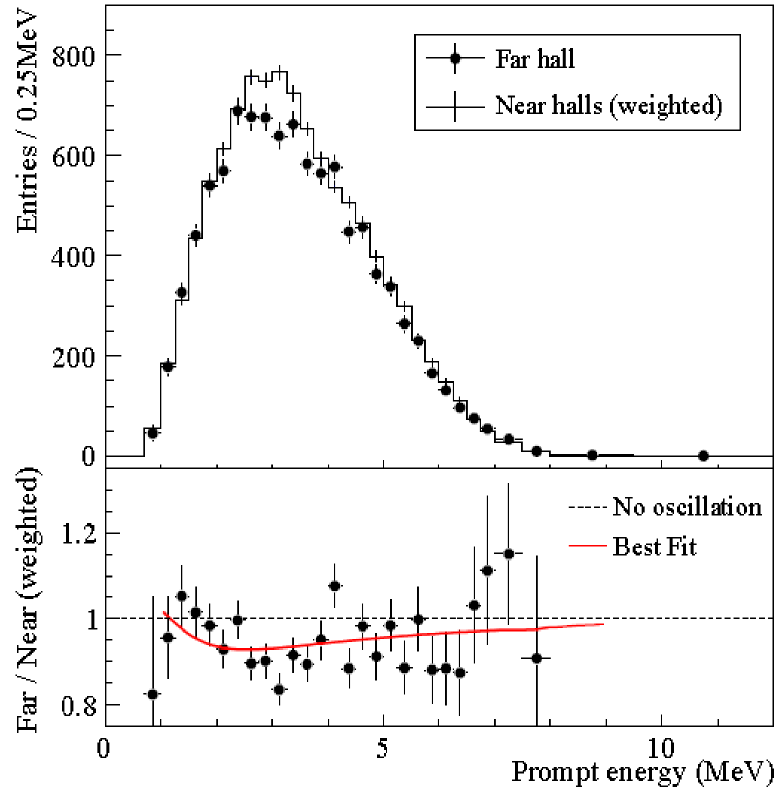

# Antineutrino Detector Installation - Far Hall





# March 8, 2012 : Daya Bay results



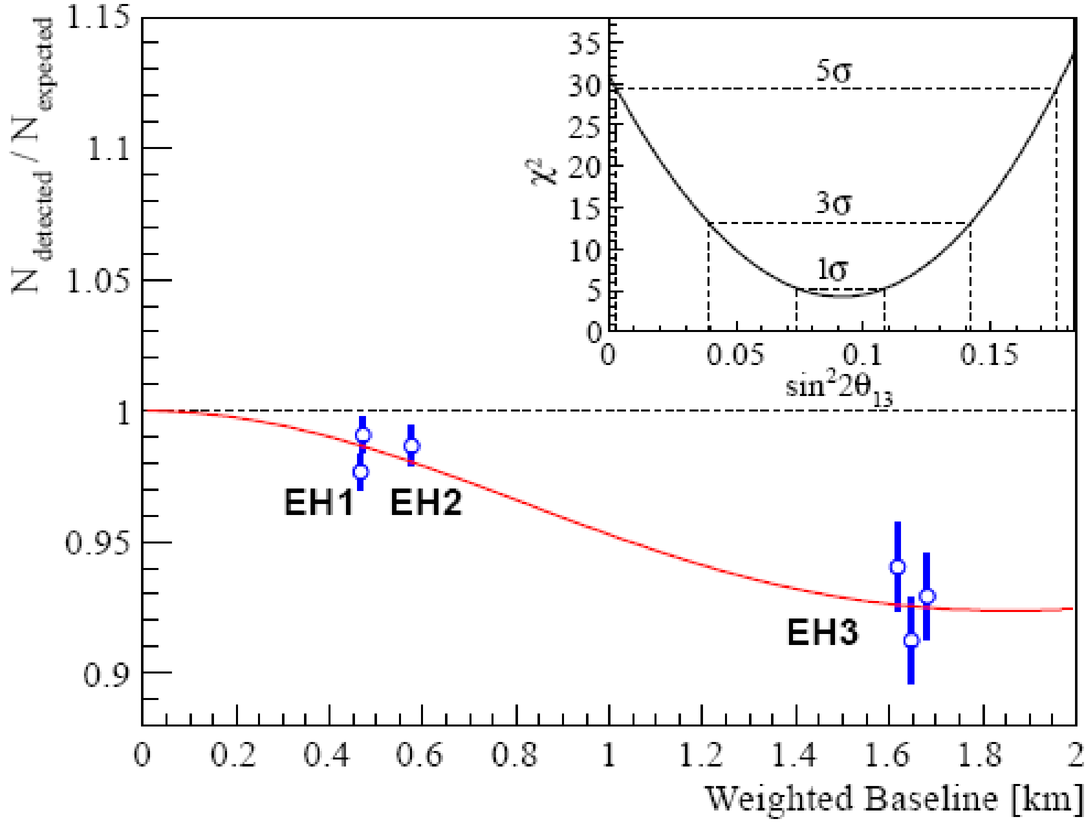

hall. Comparing with the prediction based on the near-hall measurements, a deficit of 6.0% was found. A rate-only analysis yielded $\sin^2 2\theta_{13} = 0.092 \pm 0.016(\mathrm{stat}) \pm 0.005(\mathrm{syst})$. The neutrino mixing angle $\theta_{13}$ is non-zero with a significance of 5.2 standard deviations.

# $\chi^2$ Analysis

$$\chi^2 = \min_{\gamma} \sum_{d=1}^{6} \frac{\left[M_d - T_d\left(1 + \sum_r \omega_r^d \epsilon_r + \epsilon + \epsilon_d\right) - B_d\left(1 + \eta_d\right)\right]^2}{M_d}$$

$$+ \sum_r \frac{\epsilon_r^2}{\sigma_r^2} + \sum_{d=1}^{6}\left[\frac{\epsilon_d^2}{\sigma_d^2} + \left(\frac{\eta_d}{\sigma_B^d}\right)^2\right] + \frac{\epsilon^2}{\sigma^2}$$

**No constrain on absolute normalization. Fit on the near-far relative measurement.**



# $\chi^2$ Analysis

$\chi^2 =$ m…

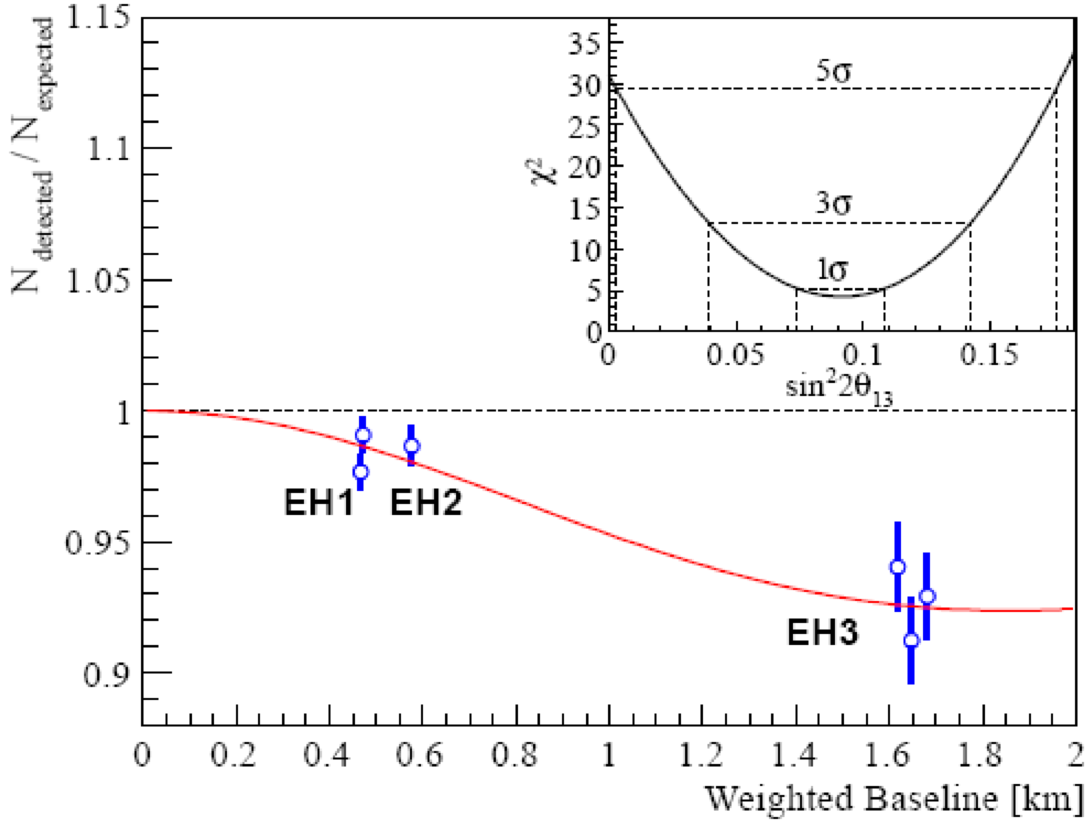
$+ \sum$ …

**$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$**

**$\chi^2/NDF = 4.26/4$**

**5.2 σ for non-zero $\theta_{13}$**

…ute
…the near-
…ent.



# Uncertainty Summary

| Detector | | | |
|---|---|---|---|
| | Efficiency | Correlated | Uncorrelated |
| Target Protons | | 0.47% | 0.03% |
| Flasher cut | 99.98% | 0.01% | 0.01% |
| Delayed energy cut | 90.9% | 0.6% | 0.12% |
| Prompt energy cut | 99.88% | 0.10% | 0.01% |
| Multiplicity cut | | 0.02% | $<$0.01% |
| Capture time cut | 98.6% | 0.12% | 0.01% |
| Gd capture ratio | 83.8% | 0.8% | $<$0.1% |
| Spill-in | 105.0% | 1.5% | 0.02% |
| Livetime | 100.0% | 0.002% | $<$0.01% |
| Combined | 78.8% | 1.9% | 0.2% |

| Reactor | | | |
|---|---|---|---|
| Correlated | | Uncorrelated | |
| Energy/fission | 0.2% | Power | 0.5% |
| $\overline{\nu}_e$/fission | 3% | Fission fraction | 0.6% |
| | | Spent fuel | 0.3% |
| Combined | 3% | Combined | 0.8% |

For near/far oscillation, only uncorrelated uncertainties are used.

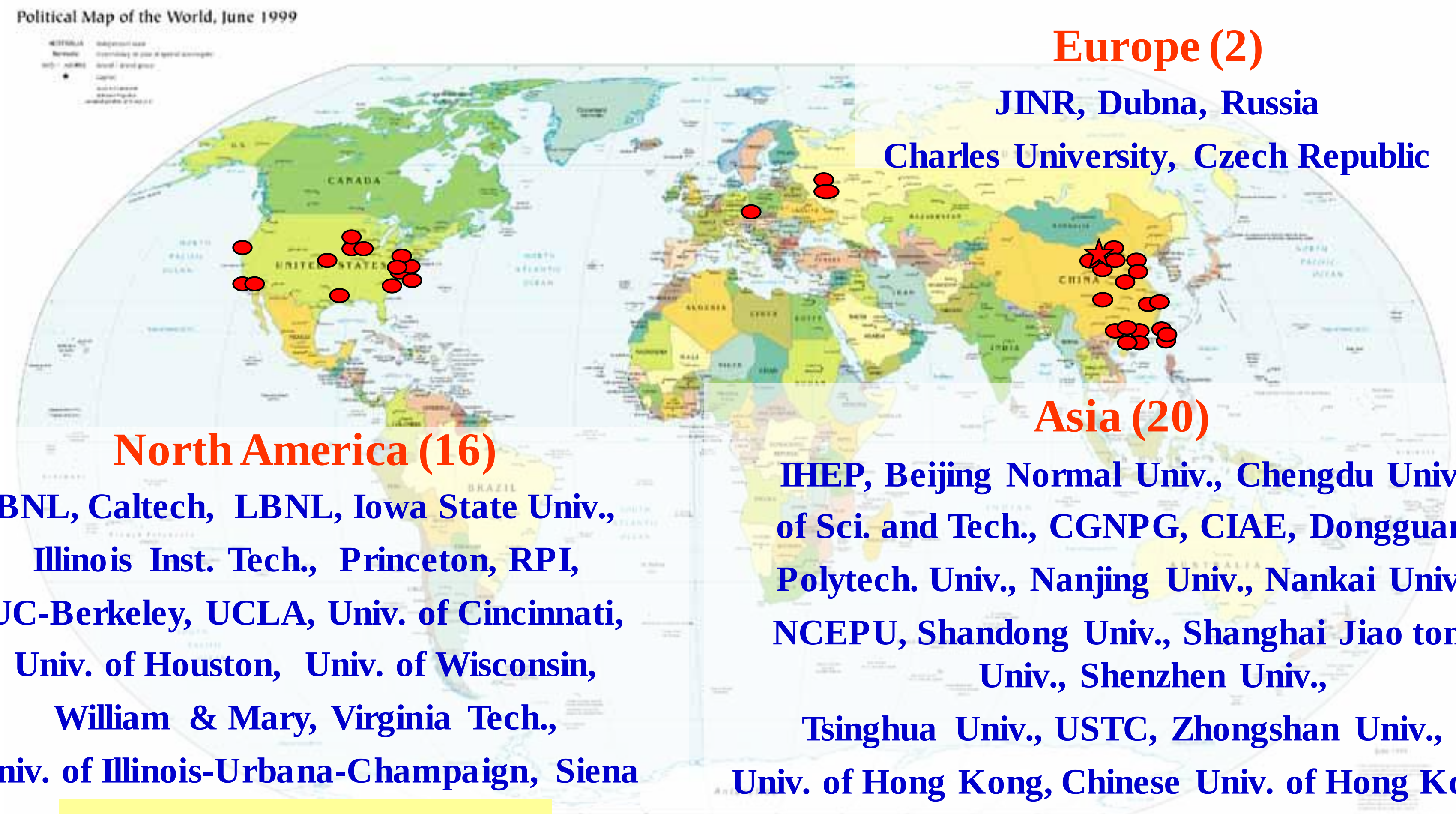
Largest systematics are smaller than far site statistics (~1%)

Influence of uncorrelated reactor systematics reduced (~1/20) by far vs. near measurement.

# Future plan

- Assembly of AD7 and AD8 is underway now, to be completed before summer
- Current data taking will continue until the summer
- Summer activities:
  - Installation of AD7 & AD8
  - Detector calibration
- Re-start data taking after summer

# The Daya Bay Collaboration




## Europe (2)

JINR, Dubna, Russia
Charles University, Czech Republic

## North America (16)

BNL, Caltech, LBNL, Iowa State Univ., Illinois Inst. Tech., Princeton, RPI, UC-Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, Univ. of Wisconsin, William & Mary, Virginia Tech., Univ. of Illinois-Urbana-Champaign, Siena

**~250 Collaborators**

## Asia (20)

IHEP, Beijing Normal Univ., Chengdu Univ. of Sci. and Tech., CGNPG, CIAE, Dongguan Polytech. Univ., Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiao tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Zhongshan Univ., Univ. of Hong Kong, Chinese Univ. of Hong Kong, National Taiwan Univ., National Chiao Tung Univ., National United Univ.

# Summary

- **Electron anti-neutrino disappearance is observed at Daya Bay,**

$$R = 0.940 \pm 0.011\ (\text{stat}) \pm 0.004\ (\text{syst}),$$

**together with a spectral distortion**

- **A new type of neutrino oscillation is thus discovered**

**$\sin^2 2\theta_{13} = 0.092 \pm 0.016\ (\text{stat}) \pm 0.005 (\text{syst})$**

**$\chi^2/NDF = 4.26/4$**

**5.2 $\sigma$ for non-zero $\theta_{13}$**

# $\theta_{13}$ measurement is a milestone in HEP

- $\theta_{13}$ was one of the few standard model parameters still unknown.
- It is one of the most discriminant parameters to select neutrino mass matrixes, a key ingredient to decide grand unified theories (if any).
- Non-zero $\theta_{13}$ is necessary to build-up leptonic CP violation. The value (order of magnitude) of $\theta_{13}$ is necessary to optimize new facilities to measure leptonic CP violation.

# A refresher on neutrino mixing

The flavor state of the neutrino, $\nu_\alpha$, is related to the mass states, $\nu_i$, by a mixing matrix, $U_{\alpha i}$

$$|\nu_i> = \sum U_{\alpha i}|\nu_\alpha>$$

Since there are three observed flavors of neutrinos ($\nu_e$, $\nu_\mu$, $\nu_\tau$), U contains three mixing angles ($\theta_{12}$, $\theta_{23}$, $\theta_{13}$) and a CP violating phase $\delta$.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$

$$U_{\alpha i} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

"Atmospheric": $\theta_{23}$ ~37°-53°

"CP sector": $\theta_{13}$ <11°

"Solar": $\theta_{12}$ ~34°

Rather different from quark mixing:

- Nearly diagonal unitary matrix
- Small angles:
  $\theta^{CKM}_{12}$~13.0°, $\theta^{CKM}_{23}$~2.3°, $\theta^{CKM}_{13}$~0.2°

Open questions:

- Is $\theta_{23}$ exactly 45 degrees, or not?
- Is $\theta_{13}$ zero, or just small?
- Is there CP violation in the neutrino sector?

# Reactors vs Accelerators

**Accelerators: $\nu_e$ appearance**

$$P_{\nu_\mu \to \nu_e} = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \frac{\Delta m_{13}^2 L}{4E} \times \left[1 \pm \frac{2a}{\Delta m_{13}^2}(1-2s_{13}^2)\right] \qquad \theta_{13} \text{ driven}$$

$$+ 8c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} cos\delta - s_{12} s_{13} s_{23}) \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} \text{CPev}$$

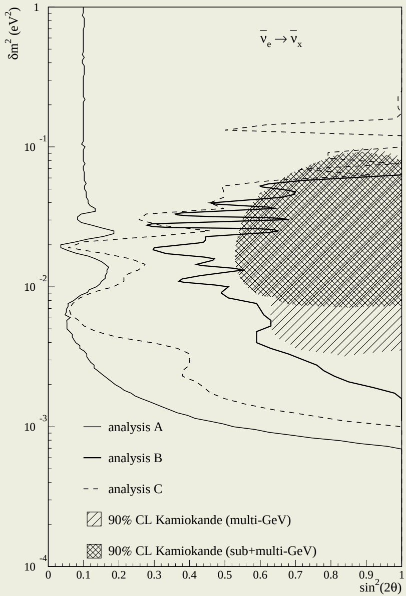
$$\mp 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \sin \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} \qquad \text{CPodd}$$

$$+ 4s_{12}^2 c_{13}^2 \{c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} cos\delta\} \sin \frac{\Delta m_{12}^2 L}{4E} \qquad \text{solar driven}$$

$$\mp 8c_{12}^2 s_{13}^2 s_{23}^2 \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \frac{aL}{4E}(1-2s_{13}^2) \qquad \text{matter effect (CP odd)}$$

**Reactors: $\overline{\nu}_e$ disappearance**

$$1 - P_{\overline{\nu}_e - \overline{\nu}_e} \simeq \sin^2 2\theta_{13} \sin^2(\Delta m_{31}^2 L/4E) + (\Delta m_{21}^2/\Delta m_{31}^2)^2 (\Delta m_{31}^2 L/4E)^2 \cos^4 \theta_{13} \sin^2 2\theta_{12}$$



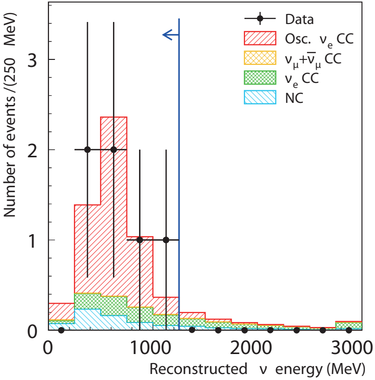

# CHOOZ final results

- **Analysis A** $\overline{\nu}_e$ spectrum after background subtraction. Both the absolute rate and the spectrum are used.
- **Analysis B** Uses the different baseline ($\Delta L = 117.7\ m$) of the two reactors. Many systematic errors cancel, but statistical errors are bigger and the $\Delta m^2$ sensitivity is reduced by the shorter baseline.
- **Analysis C** Only spectrum information is used.

**1450 citations:**
**the top cited null result in hep ever !**

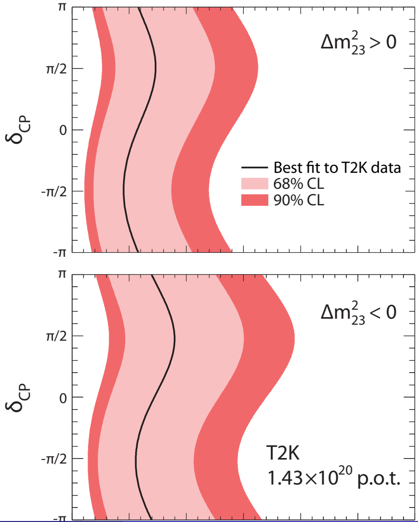
# The T2K Experiment

# T2K result, PRL 107 (2011) 041801




Expected: 1.5 +/- 0.3

Measured: 6

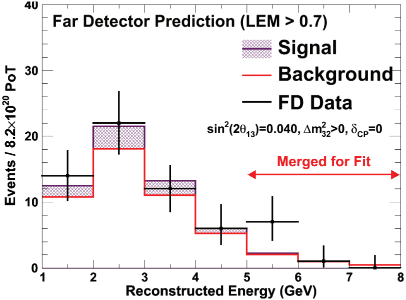



## Systematic errors

| Source | $\sin^2 2\theta_{13} = 0$ | $\sin^2 2\theta_{13} = 0.1$ |
|---|---|---|
| (1) neutrino flux | ± 8.5% | ± 8.5% |
| (2) near detector | $^{+5.6}_{-5.2}\%$ | $^{+5.6}_{-5.2}\%$ |
| (3) near det. statistics | ± 2.7% | ± 2.7% |
| (4) cross section | ± 14.0% | ± 10.5% |
| (5) far detector | ± 14.7% | ± 9.4% |

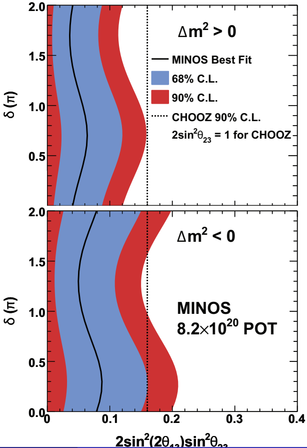
# MINOS, PRL 107 (2011) 181802

**Results on appearance of electron-neutrinos with $8.2 \times 10^{20}$ POT**



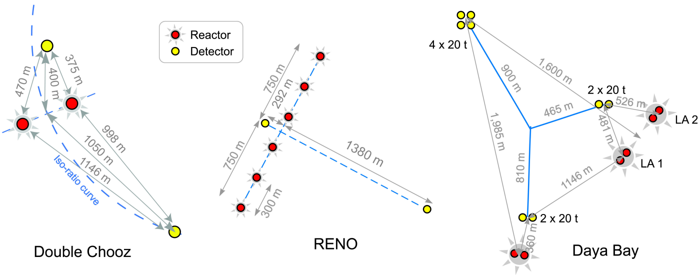

| Year | pot | Expected | Detected |
|---|---|---|---|
| 2009 | $3.1\ 10^{20}$ | 27 | 35 |
| 2010 | $7.0\ 10^{20}$ | 49 | 54 |
| 2011 | $8.2\ 10^{20}$ | 49 | 62 |

| | MINOS | T2K |
|---|---|---|
| pot | $8.2\ 10^{20}$ | $1.45\ 10^{20}$ |
| tjoule | 1.57 | 0.07 |
| tjoule kton | 7.85 | 1.57 |



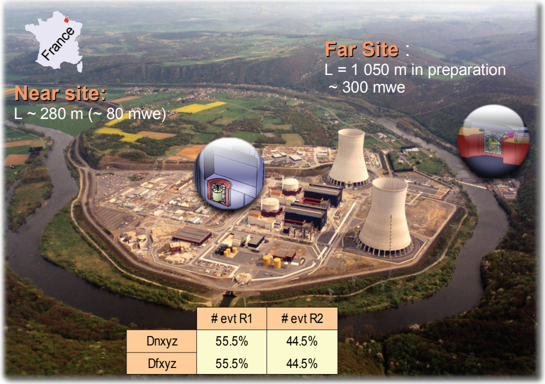
# The three reactor players

| Setup | $P_{\mathrm{Th}}$ [GW] | $L$ [m] | $m_{\mathrm{Det}}$ [t] | Events/year | Backgrounds/day |
|---|---|---|---|---|---|
| Daya Bay | 17.4 | 1700 | 80 | $10 \cdot 10^4$ | 0.4 |
| Double Chooz | 8.6 | 1050 | 8.3 | $1.5 \cdot 10^4$ | 3.6 |
| RENO | 16.4 | 1400 | 15.4 | $3 \cdot 10^4$ | 2.6 |



# Double Chooz

Talk by J. Dawson




| | # evt R1 | # evt R2 |
|---|---|---|
| Dnxyz | 55.5% | 44.5% |
| Dfxyz | 55.5% | 44.5% |

**2 cores – 1 site – 8.5 $GW_{th}$**

**1 near position, 1 far**

- target: 2 x 8.3 t

**Civil engineering**

- 1 near lab ~ Depth 40 m, Ø 6 m
- 1 available lab

**Statistics (including ε)**

- far: ~ 40 evts/day
- near: ~ 460 evts/day

**Systematics**

- reactor : ~ 0.2%
- detector : ~ 0.5%

**Backgrounds**

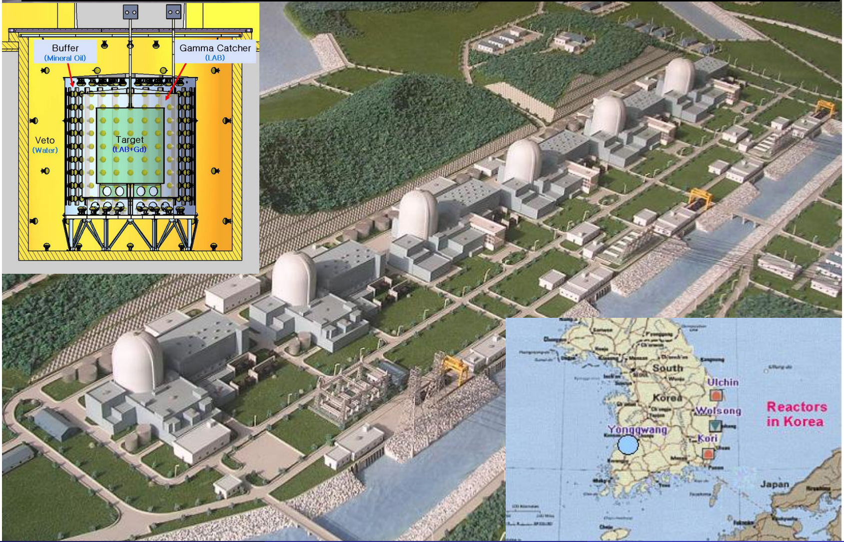
- $\sigma_{b2b}$ at far site: ~ 1%
- $\sigma_{b2b}$ at near site: ~ 0.5%

**Planning**

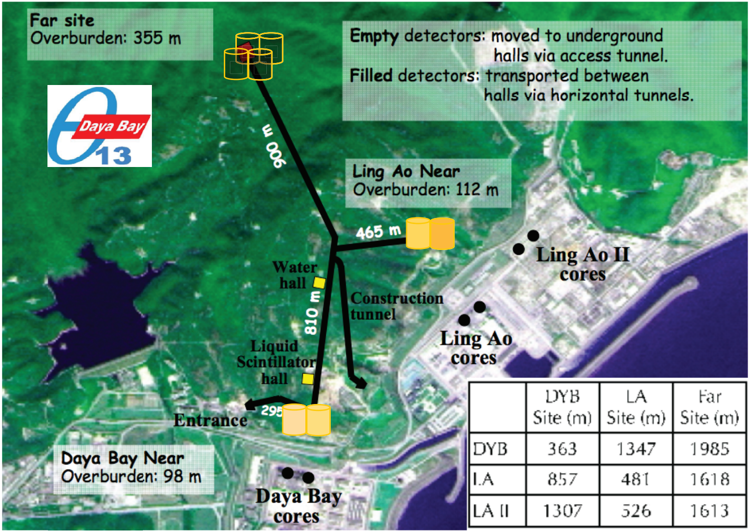
1. Far detector only
   - Sensitivity (1.5 ans) ~ 0.06
2. Far + Near sites
   - available from 2010
   - Sensitivity (3 years) ~ 0.025

# RENO

| | Location | Thermal Power | Distances Near/Far (m) | Depth (mwe) | Target Mass (tons) | Cost |
|---|---|---|---|---|---|---|
| RENO | Korea | 17.3 GW | 290/1380 | 120/450 | 16/16 ton | ~10M$ |

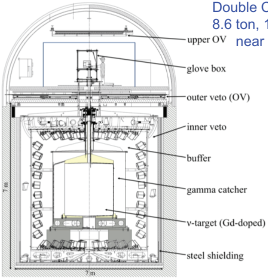


# Daya Bay

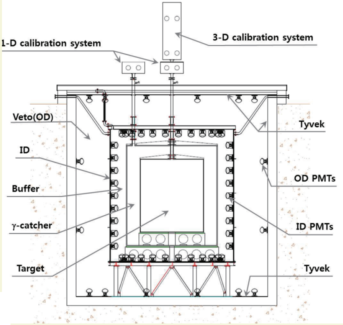



| | DYB Site (m) | LA Site (m) | Far Site (m) |
|---|---|---|---|
| DYB | 363 | 1347 | 1985 |
| LA | 857 | 481 | 1618 |
| LA II | 1307 | 526 | 1613 |

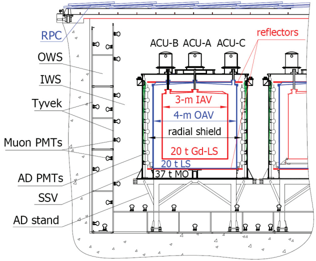
# Reactor detectors




Double Chooz
8.6 ton, 1 detector (far)
near detector by 2013




RENO
16 ton, 2 detectors (near + far)




Daya Bay
20 ton, 6 detectors (3 far, 3 near)
8 detectors by 2013 (4+4)

# Experimental Results

**T2K ($\theta_{13} > 0$ @ $2.5\sigma$)**
Expected events: 1.5, Detected 6

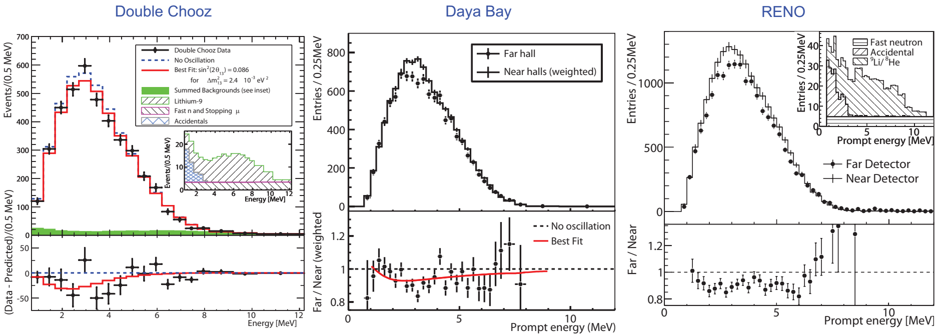
**Double Chooz ($1.3\sigma$)**
Expected events: 4344, Detected 4101
$R_{DC} = 0.944 \pm 0.016(\mathrm{stat}) \pm 0.040(\mathrm{syst})$

**Daya Bay ($5.2\sigma$)**
Expected events: 85506, Detected 80376
$R_{DB} = 0.940 \pm 0.011(\mathrm{stat}) \pm 0.004(\mathrm{syst})$

**RENO ($4.9\sigma$)**
Expected events:149905, Detected 137912
$R_R = 0.920 \pm 0.009(\mathrm{stat.}) \pm 0.014(\mathrm{syst.})$

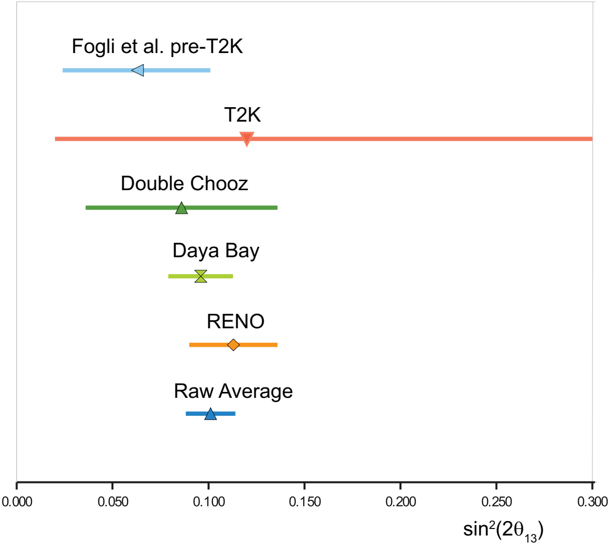
# Spectral information

## Not used in the fit



# Summary of $\theta_{13}$ results

Computed for $\Delta m^2_{23} = 2.4 \cdot 10^{-3}$ eV$^2$



# Conclusions

The measurement of $\theta_{13}$ solves one of the few question marks still left in the standard model. Among the many fondamental consequences, it opens the door to future long-baseline neutrino experiments addressing leptonic CP violation.

Five experimental results in the past 9 months, coming from accelerators and reactors, provided exciting information about $\theta_{13}$.

Leptonic CP violation, measurable only at accelerators, will require challenging experimental improvements. The optimization of future facilities is now possible by knowing the $\theta_{13}$ value.

A worldwide effort is ongoing with multiple proposals in three different continents.