Daya Bay

Pursue of Neutrino Mixing Angle θ_{13}

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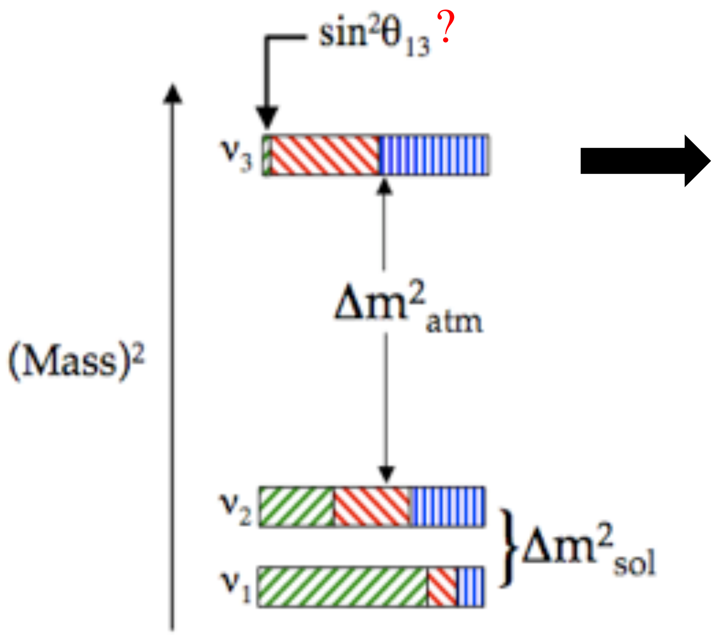
University of California, Berkeley

On behalf of the Daya Bay Collaboration

NuTel 2017, Venice, 13 March 2017

Significance of θ_{13}

- Complete determination of the PMNS matrix
  - guide model building
- Determine ν_e fraction of ν_3



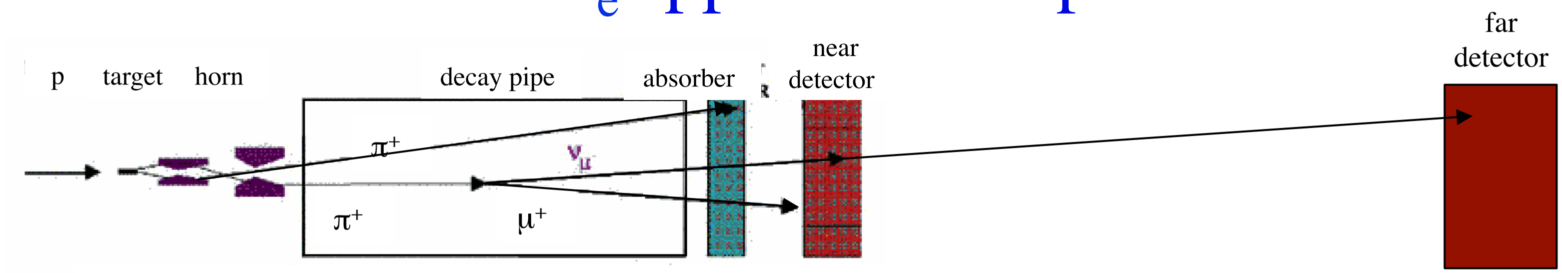
reduce uncertainties in predicting ν phenomena

- Enable determination of mass hierarchy with reactors
- Gateway to explore CP violation in neutrino oscillation:

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

Approaches For Measuring θ_{13}

- Accelerator-based ν_e appearance experiments



$$P_{\mu e} = \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right) + \text{terms}(\delta, \Delta\text{m}_{32}^2, \text{matter effect})$$

- Baseline *O(100-1000 km)*, large detectors
- Some ambiguities exist in extracting a value for θ_{13}

- Reactor-based $\bar{\nu}_e$ disappearance experiments

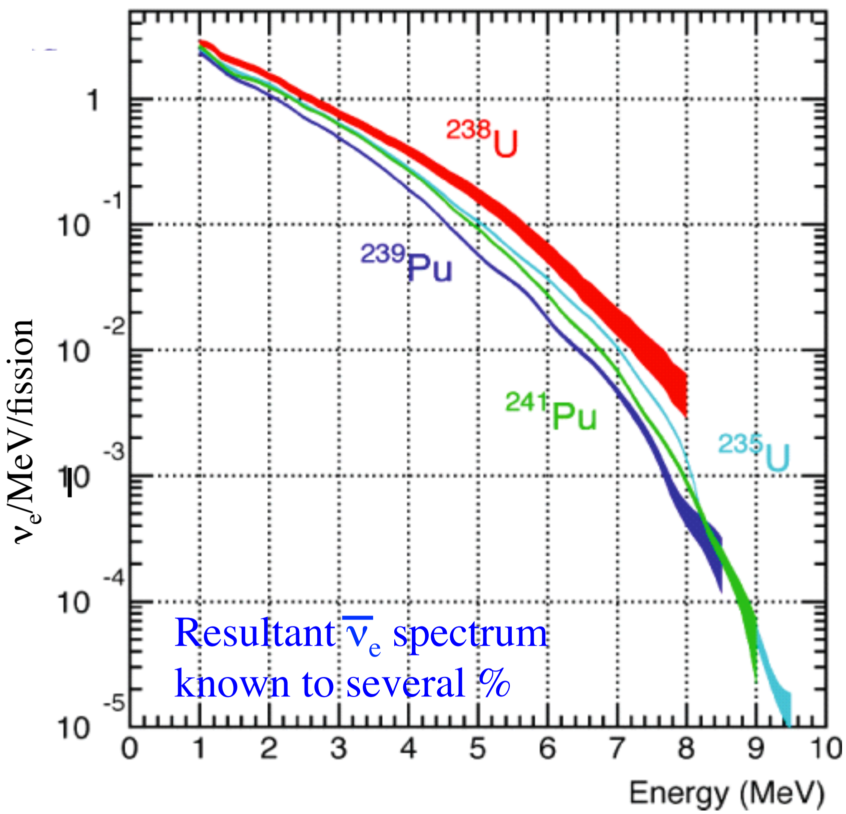
$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right)$$

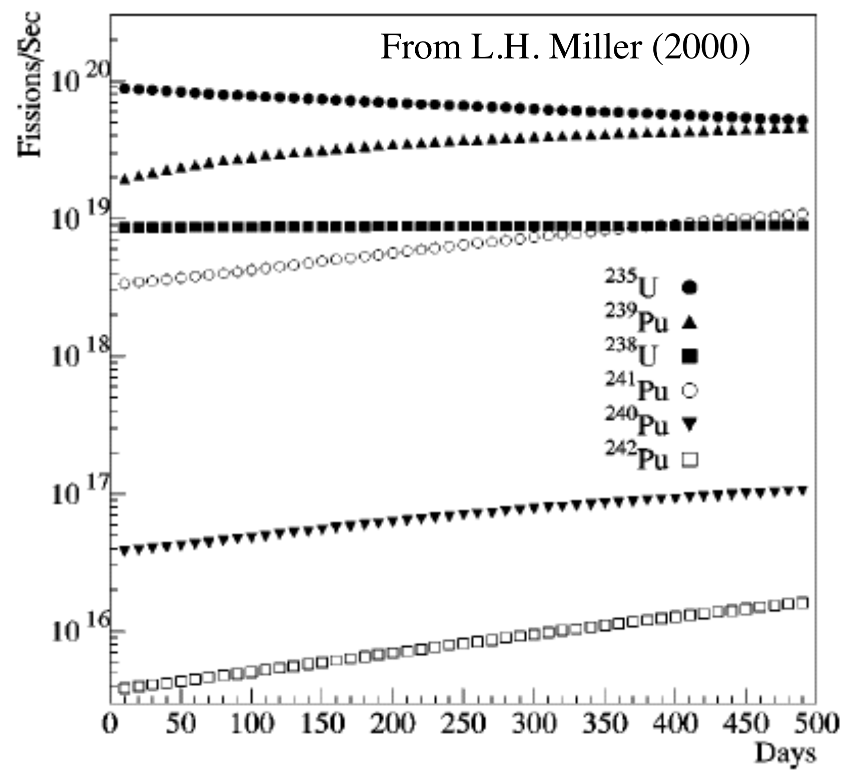
- Baseline *O(1 km)*, no CP or matter effect, small detectors

Production of Reactor $\bar{\nu}_e$

- Fission processes in a nuclear core produce radioactive nuclides that decay rapidly to yield a huge number of low-energy $\bar{\nu}_e$:

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





Resultant spectrum varies with time.

Detecting Reactor $\bar{\nu}_e$

- Use inverse β-decay reaction (IBD) in a liquid scintillator:

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

~180μs

$$\rightarrow + p \rightarrow D + \gamma(2.2\ \mathrm{MeV})$$

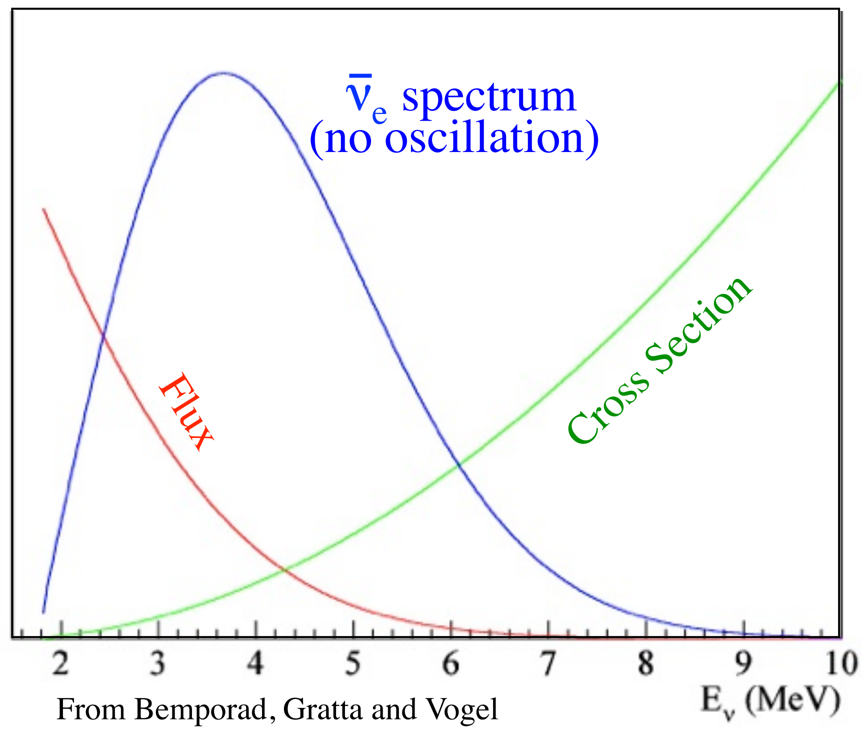
$$\rightarrow + Gd \rightarrow Gd^*$$

~30μs
for 0.1% Gd

$$\rightarrow Gd + \gamma\text{'s}(8\ \mathrm{MeV})$$

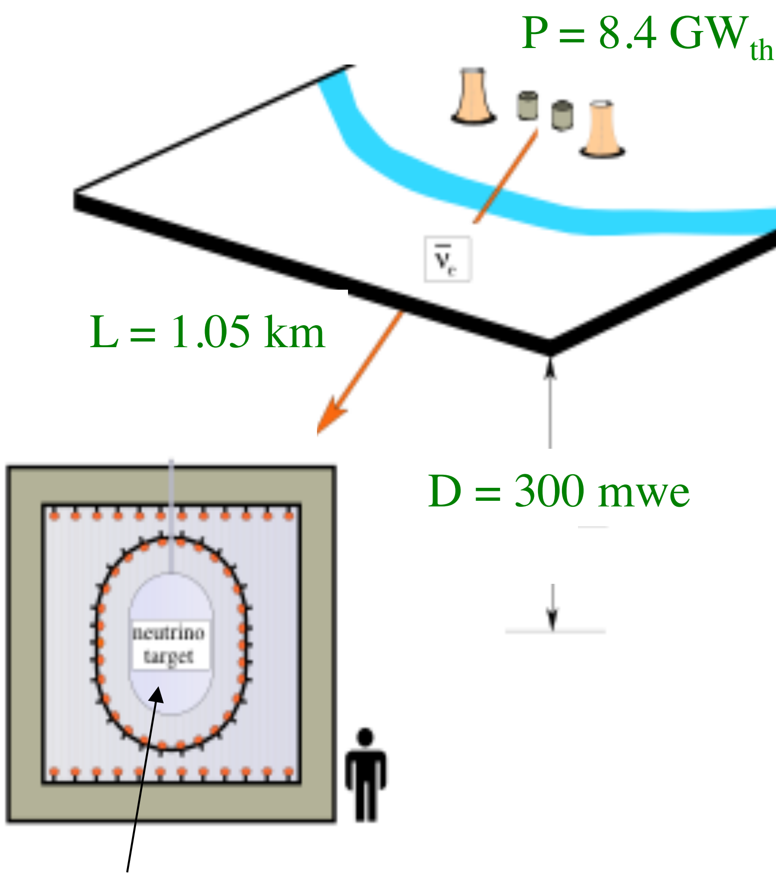
- Energy of $\bar{\nu}_e$ is given by:

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

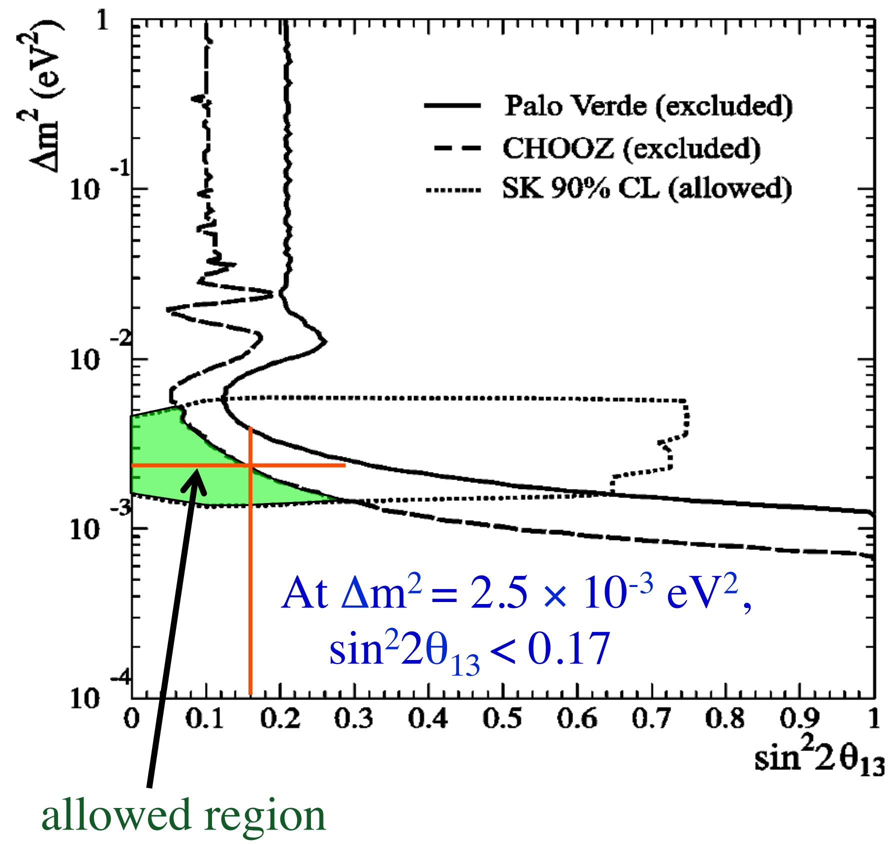


From Bemporad, Gratta and Vogel

Chooz: First Search For θ_{13} in 90's



5-ton 0.1% Gd-loaded liquid scintillator to detect $\bar{\nu}_e + p \rightarrow e^+ + n$



At $\Delta m^2 = 2.5 \times 10^{-3}\ \mathrm{eV}^2$, $\sin^2 2\theta_{13} < 0.17$

parameter	relative uncertainty (%)
reaction cross section	1.9
number of protons	0.8
detection efficiency	1.5
reactor power	0.7
energy released per fission	0.6
combined	2.7

Reaching $\sin^2 2\theta_{13} = 0.01$

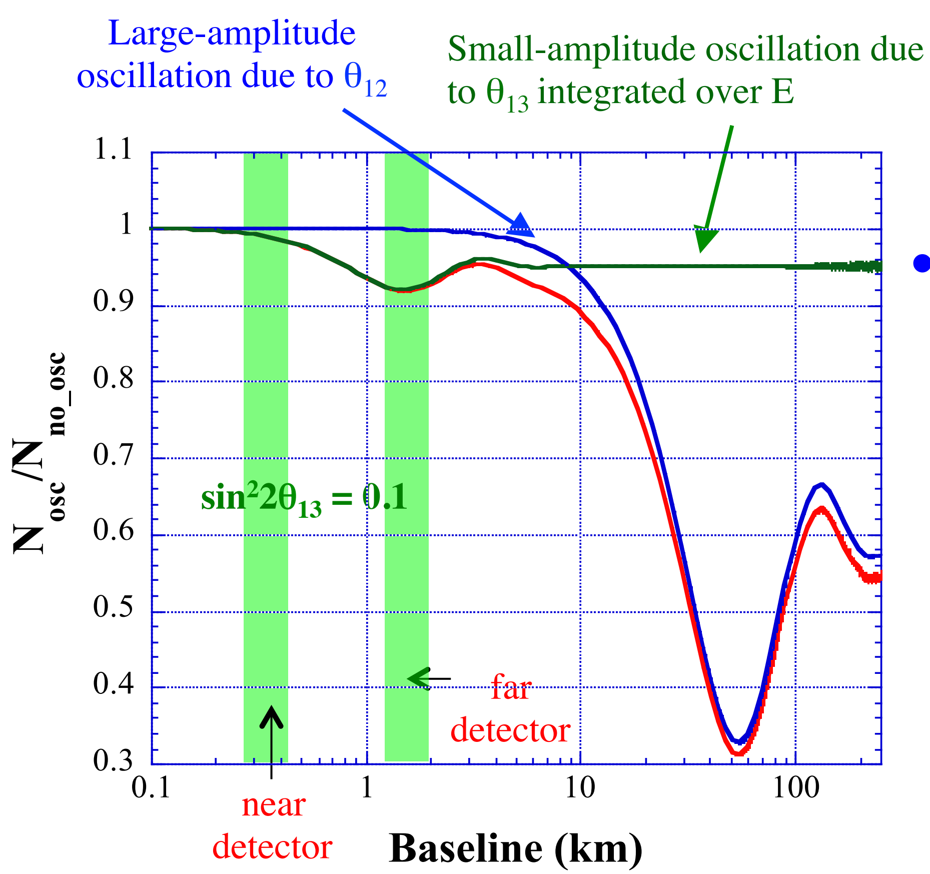
- **Increase statistics:**
  - Utilize powerful nuclear reactors
  - Increase target mass
  - More run time
- **Reduce systematic uncertainties:**
  - **Reactor-related:**
    - Optimize baseline for best sensitivity and smaller residual errors
    - **Use near and far detectors to minimize reactor-related errors**
      [Mikaelyan and Sinev, Phys. Atom. Nucl. 63, 1002 (2000)]
  - **Detector-related:**
    - **Use "Identical" pairs of detectors to do a *relative* measurement**
    - Comprehensive program in calibration/monitoring of detectors
    - Interchange near and far detectors (optional)
  - **Background-related:**
    - Go deep to reduce cosmic ray-induced background
    - Enough active and passive shielding

Determining θ_{13} With Reactor $\bar{\nu}_e$

- Look for disappearance of electron antineutrinos from reactors:

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

$$\sin^2\left(\frac{\Delta m^2_{ee} L}{4E}\right) \equiv \cos^2\theta_{12}\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + \sin^2\theta_{12}\sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$



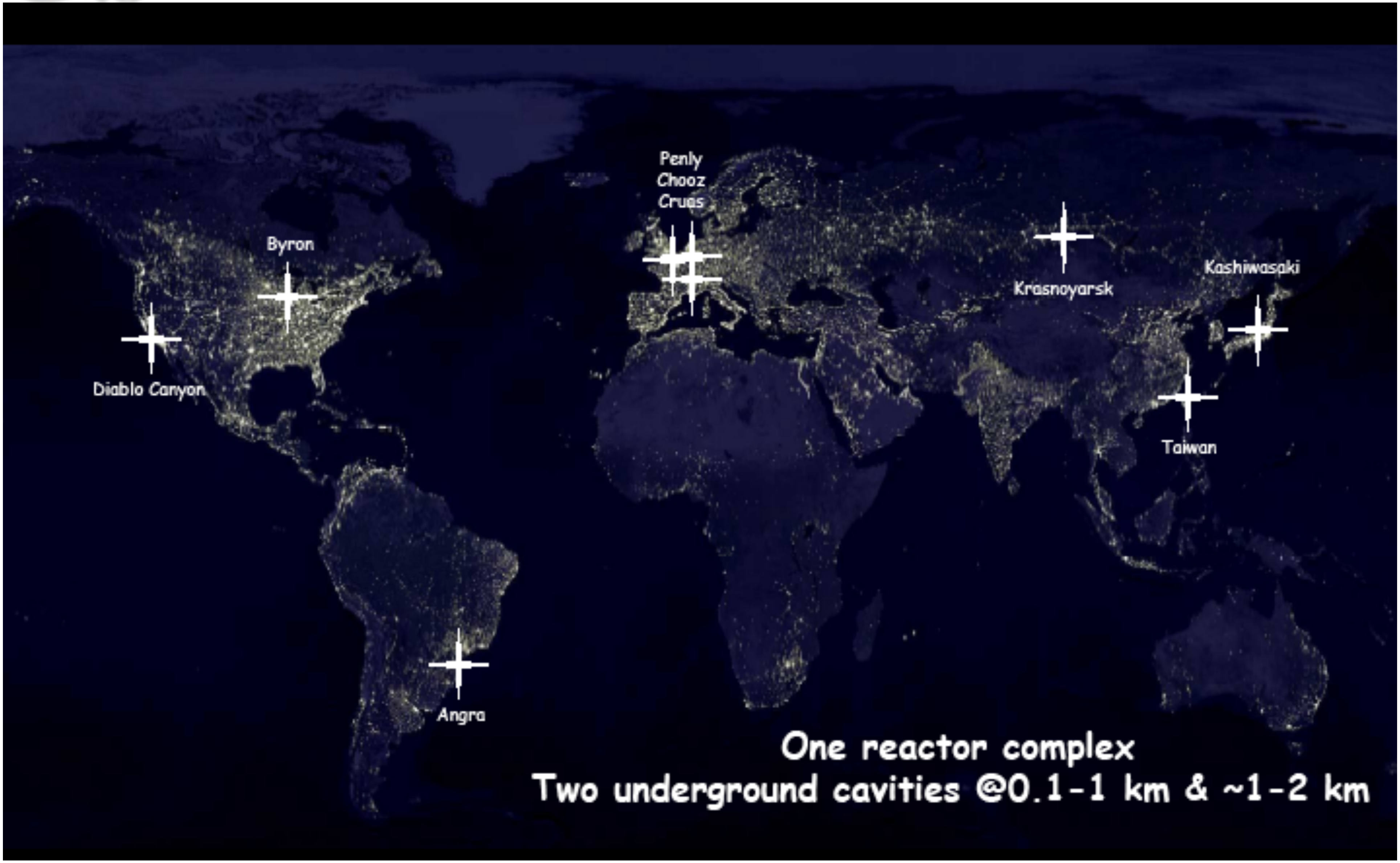
- Perform relative measurement, for a given E :

$$\frac{R_{Far}}{R_{Near}} = \left(\frac{N_{Far}}{N_{Near}}\right)\left(\frac{\varepsilon_{Far}}{\varepsilon_{Near}}\right)\left(\frac{L_{Near}}{L_{Far}}\right)^2\left(\frac{P_{Far}}{P_{Near}}\right)$$

$\bar{\nu}_e$ rate — number of protons — detection efficiency — $1/r^2$ — yield $\sin^2 2\theta_{13}$

Correlated errors are exactly cancelled for only one reactor.

2002-2003: Reactor θ_{13} Proposals



Launching Daya Bay

STUDYING NEUTRINO OSCILLATION
BY USING DAYA BAY NUCLEAR
POWER PLANT
AS THE NEUTRINO SOURCE

November 28-29, 2003

Room 311, Chong Yuet Ming Physics Building,
Department of Physics,
The University of Hong Kong.

Gaining Access To Daya Bay NPP

To: Prof. Kam-Biu Luk

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集團總裁
Andrew Brandler
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16th August, 2004

Professor Kenneth Young,
Pro-Vice-Chancellor,
The Chinese University of Hong Kong
Shatin, New Territories,
Hong Kong

Dear Professor Young,

Thank you very much for your letter dated 22nd July, 2004 which was jointly signed by Professor Paul Tam of the University of Hong Kong, regarding the proposal for an international effort to conduct a neutrino physics experiment related to Daya Bay Nuclear Power Station.

We understand from your letter that the proposed project will not affect the safety and normal operation of the nuclear power station, and that it will not incur any cost to the Guangdong Nuclear Power Joint Venture Company (GNPJVC).

We are pleased to be of assistance to such a meaningful and exciting scientific project that will further our understanding of Nature. We learned from our joint venture partner that the project team is conducting a pre-feasibility study which we are pleased to support. We are developing a common position on the project with our joint venture partner and will arrange GNPJVC to give you a firm reply in due course.

Yours sincerely,

A R Brandler

Andrew Brandler
Group Managing Director

copy to:
Prof MC Chu, CUHK
Prof K S Cheng, HKU

Dear Friends,

I would like to report you the following good news :

The Chinese Academy of Sciences (CAS) sent an official letter to the China Guangdong Nuclear Power Holding Corporation (CGNPC) at the end of July to ask the permission and the assistance for the institute of High Energy Physics (IHEP) to start the feasibility study of the reactor neutrino experiment to measure theta13 at the Daya Bay Nuclear Power Plant.

Last week, CGNPC replied to CAS: CGNPC supports the basic scientific research with the condition of the nuclear safety, and agreed IHEP to start the feasibility study of the reactor neutrino experiment at the Daya Bay Nuclear Power Plant. The Daya Bay Nuclear Power Plant will provide the necessary information and assistance. The conclusion of the feasibility study report should be consulted by the Guangdong Nuclear Electricity Group. Then the feasibility study report will be submitted to the state nuclear safety authority for approval.

This is important step for our effort in the Daya Bay reactor neutrino experiment.

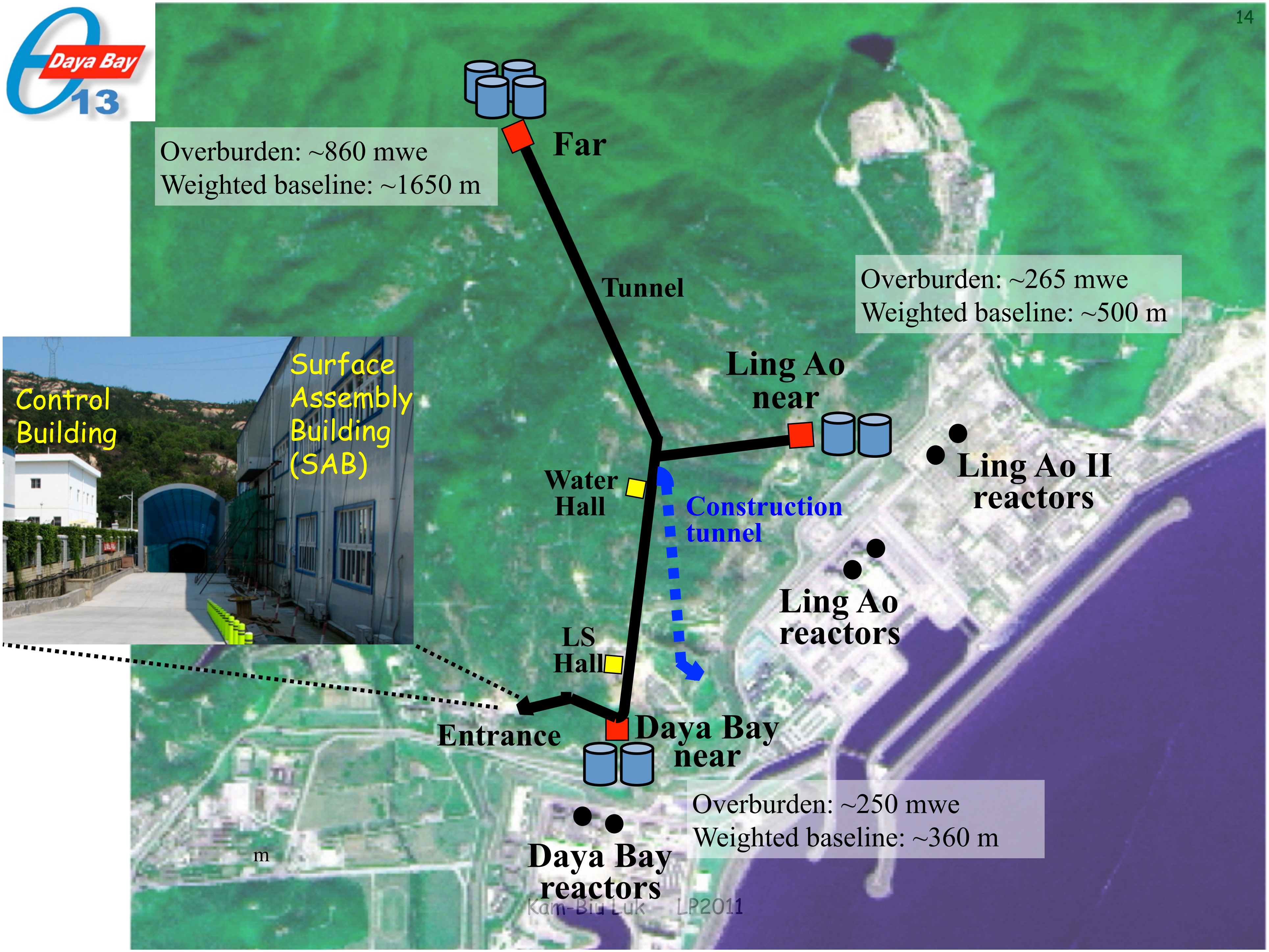
Best regards,

Hesheng Chen
Director of IHEP

21 September 2004

Daya Bay Collaboration Formed

Reactor θ_{13} Experiments in 2006

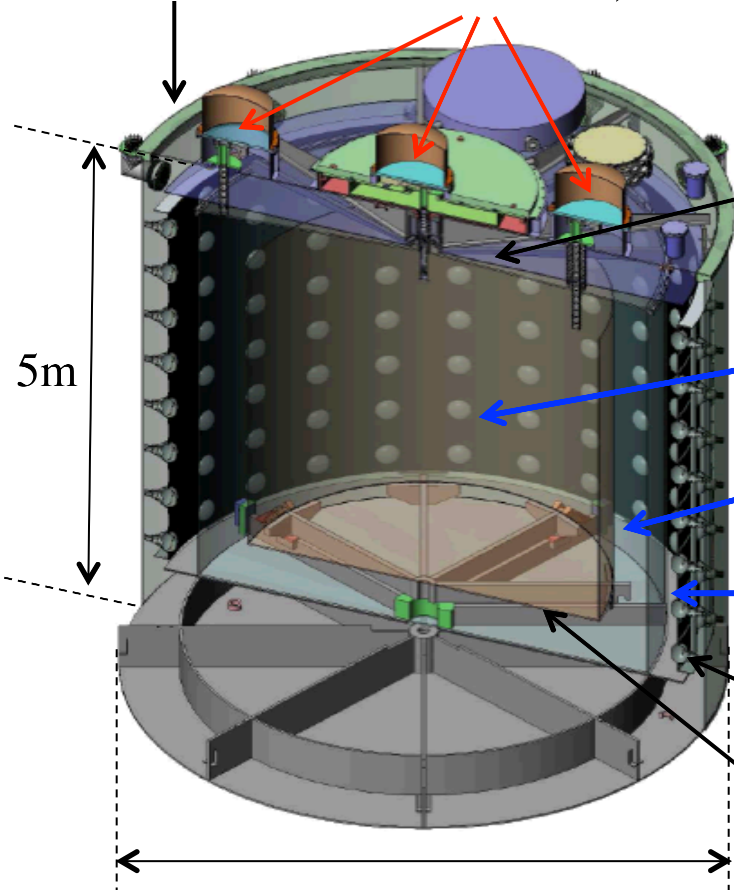


Overburden: ~860 mwe
Weighted baseline: ~1650 m
Far
Tunnel
Overburden: ~265 mwe
Weighted baseline: ~500 m
Ling Ao near
Control Building
Surface Assembly Building (SAB)
Ling Ao II reactors
Water Hall
Construction tunnel
Ling Ao reactors
LS Hall
Entrance
Daya Bay near
Overburden: ~250 mwe
Weighted baseline: ~360 m
m
Daya Bay reactors

Daya Bay Detector Design

Stainless steel tank

Calibration units (LED, ^{68}Ge, AmC-Co)



5m

5m

4m acrylic tank sandwiched between top and bottom reflectors

20-t 0.1% Gd-TMHA LS (target)

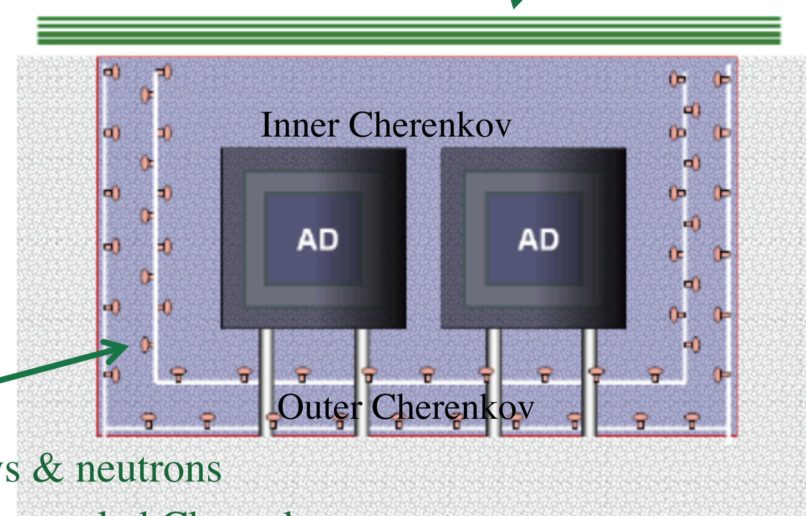
20t LS (gamma catcher)
(LS = LAB + 3 g/l PPO + 15 mg/l Bis-MSB)

40t mineral oil shield

192 PMTs

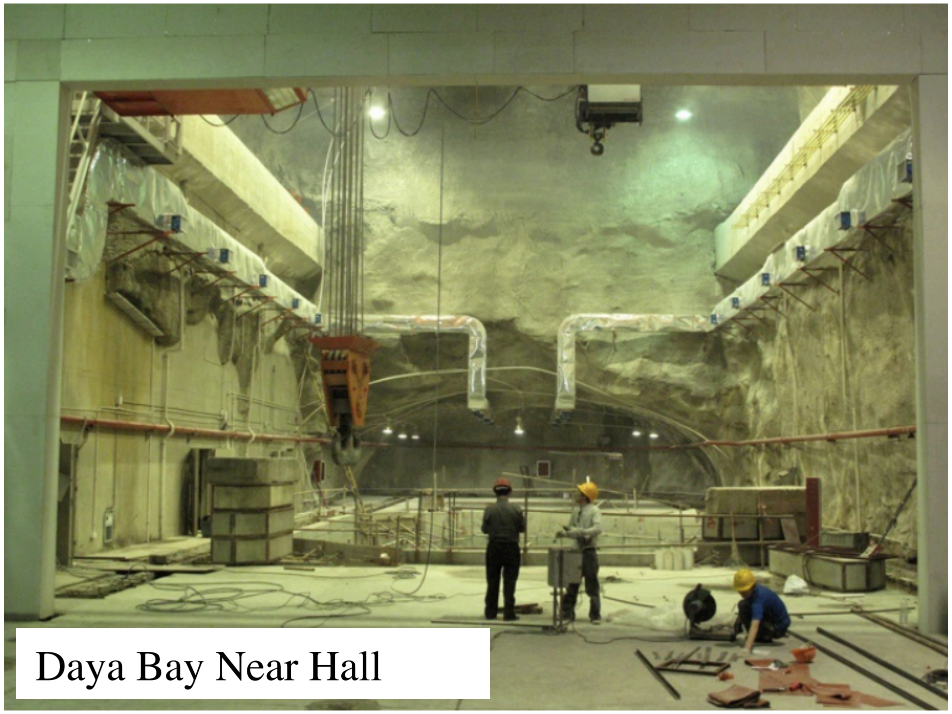
3m acrylic vessel

Four layers of RPC's to tag muons



2.5m water:
- attenuates gamma rays & neutrons
- forms two optically decoupled Cherenkov counters

13 Oct 2007: Ground Breaking


Daya Bay Near Hall


Liquid Scintillator Hall


Ling Ao Near Hall

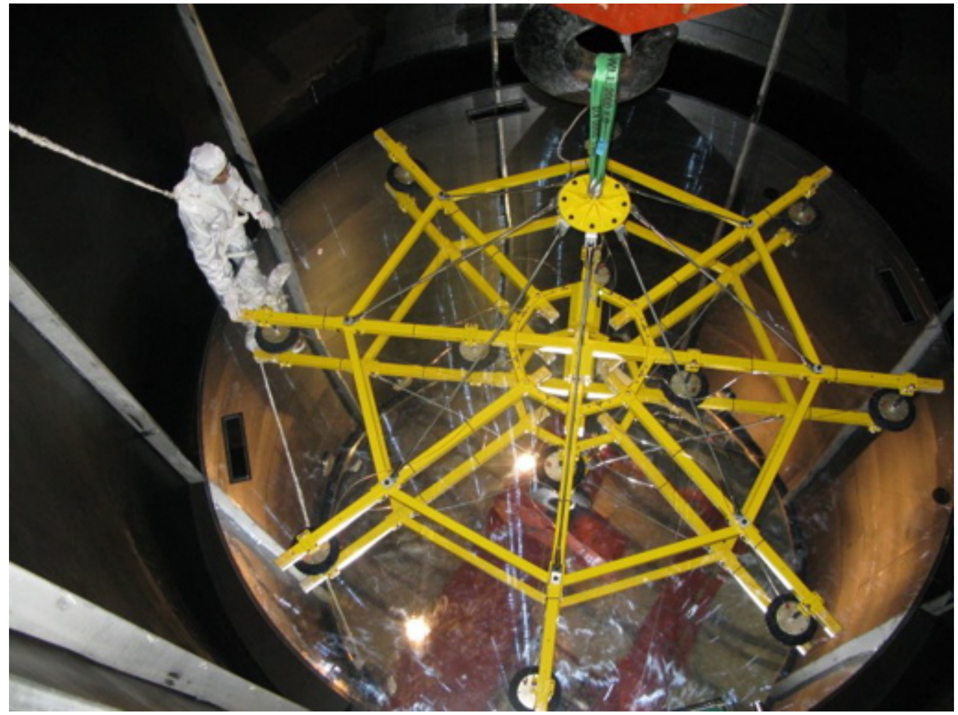
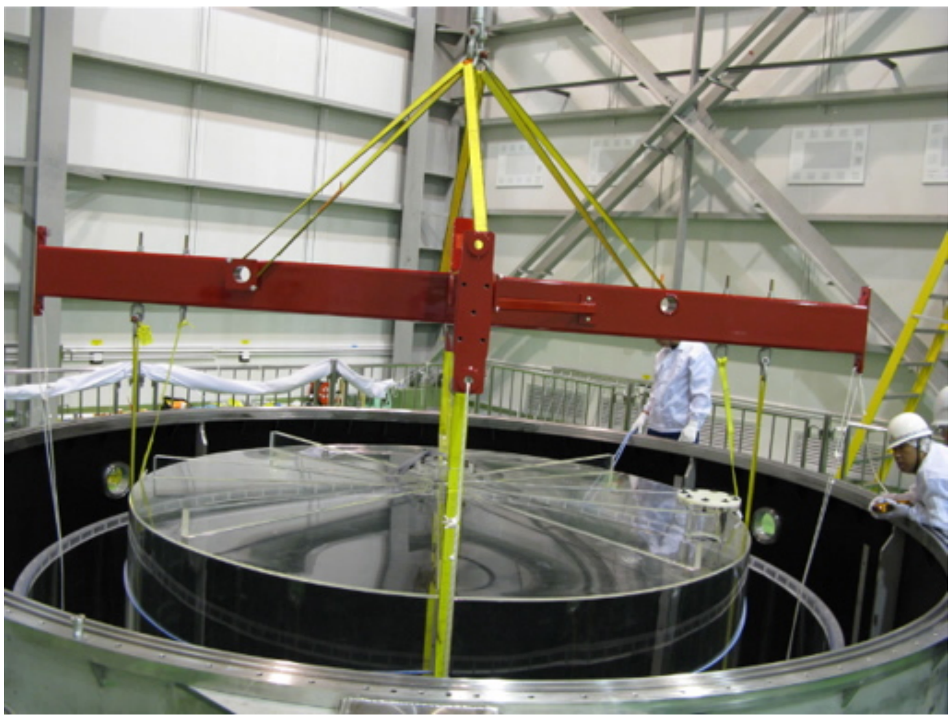

Constructing Tunnel


Entrance Area

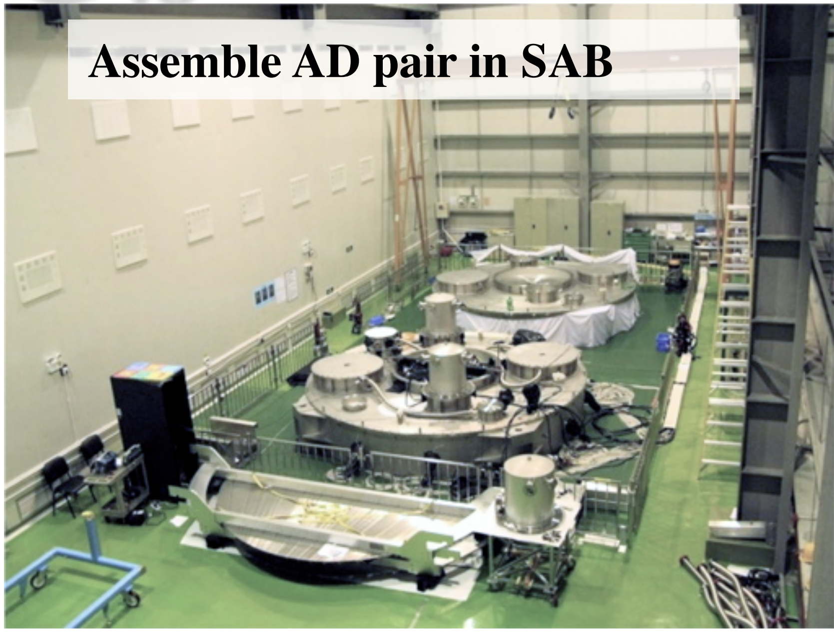
Surface Assembly Building

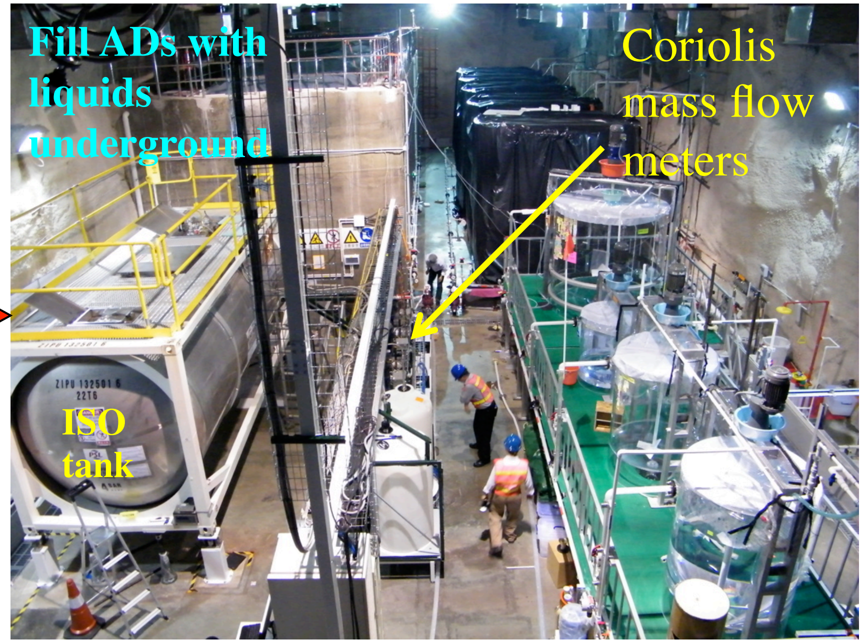
Access Tunnel

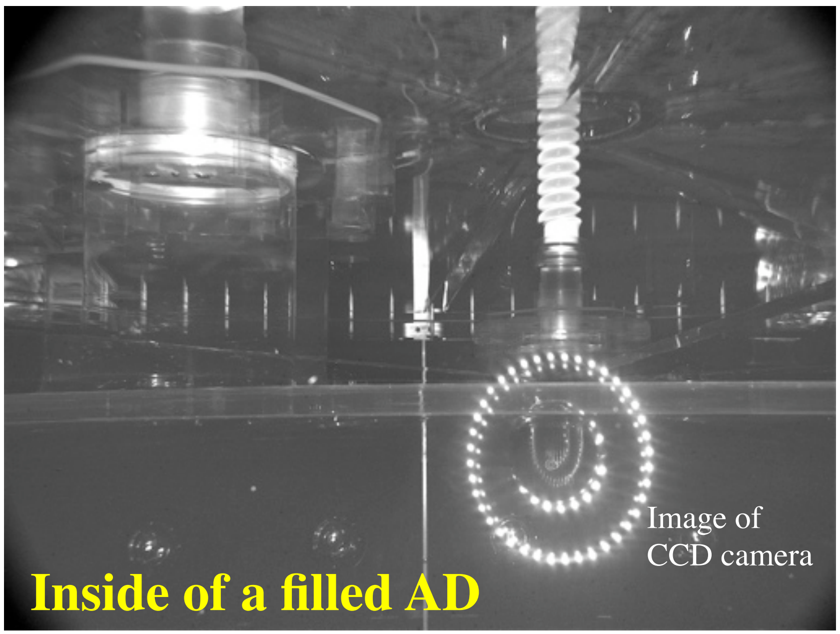

Office Building

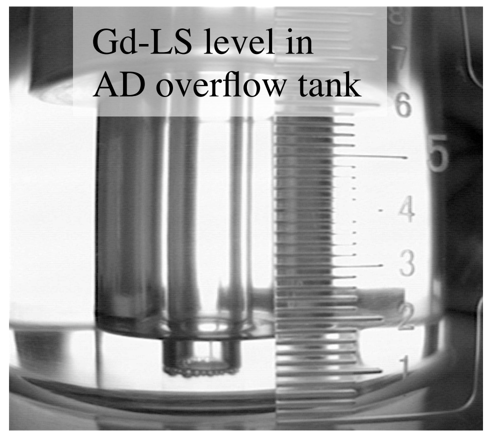

Fill Antineutrino Detectors (ADs)



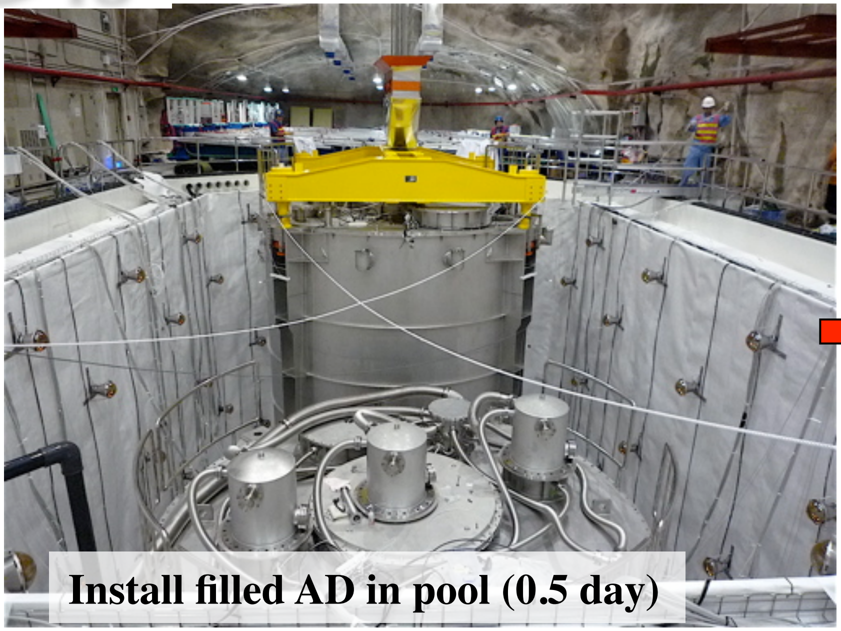


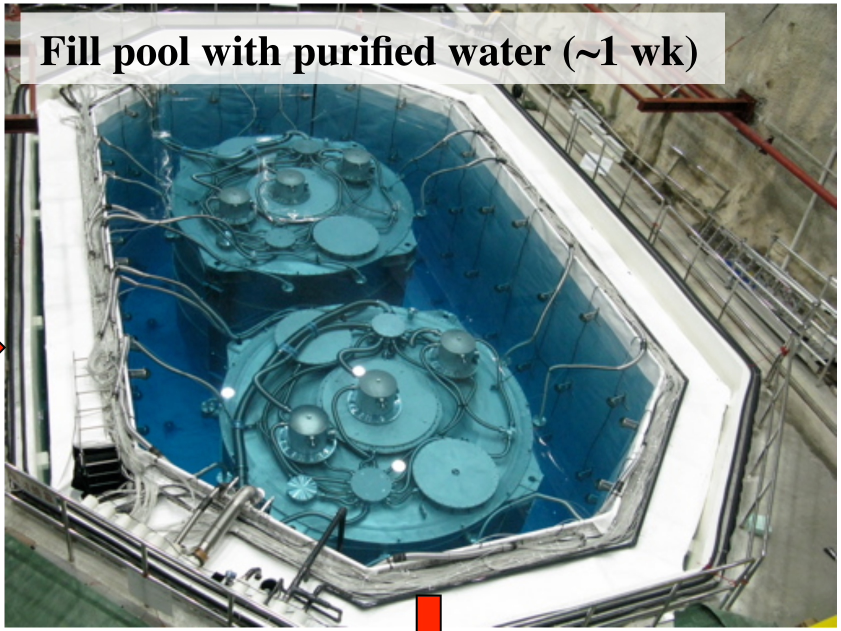


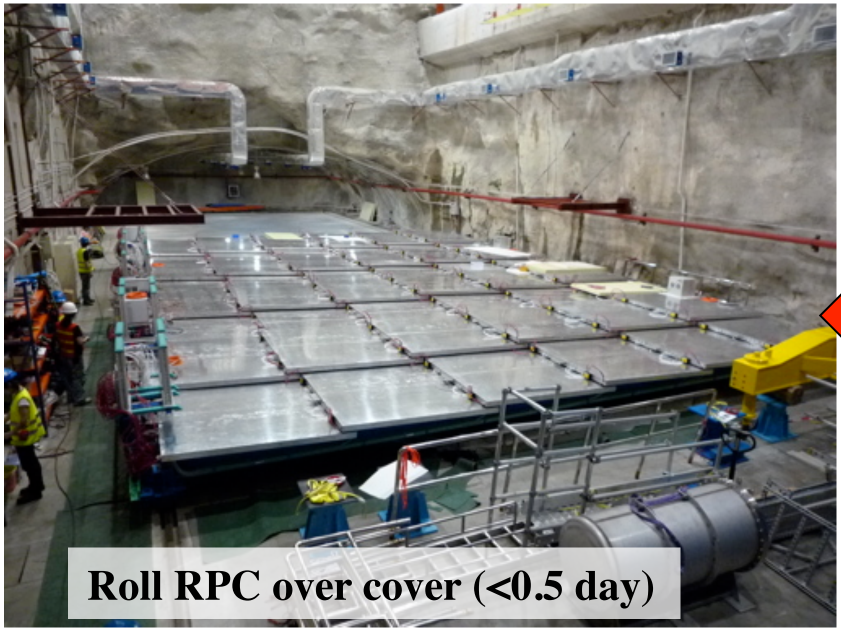
- Target mass is measured with:
  (1) 20-t ISO tank
  (2) Coriolis mass flow meters
  Uncertainty: 4kg in 20t
- Temperature is maintained constant
- Filling is monitored with in-situ sensors
- A pair of detectors is filled sequentially in <2 weeks.



Commissioning EH1



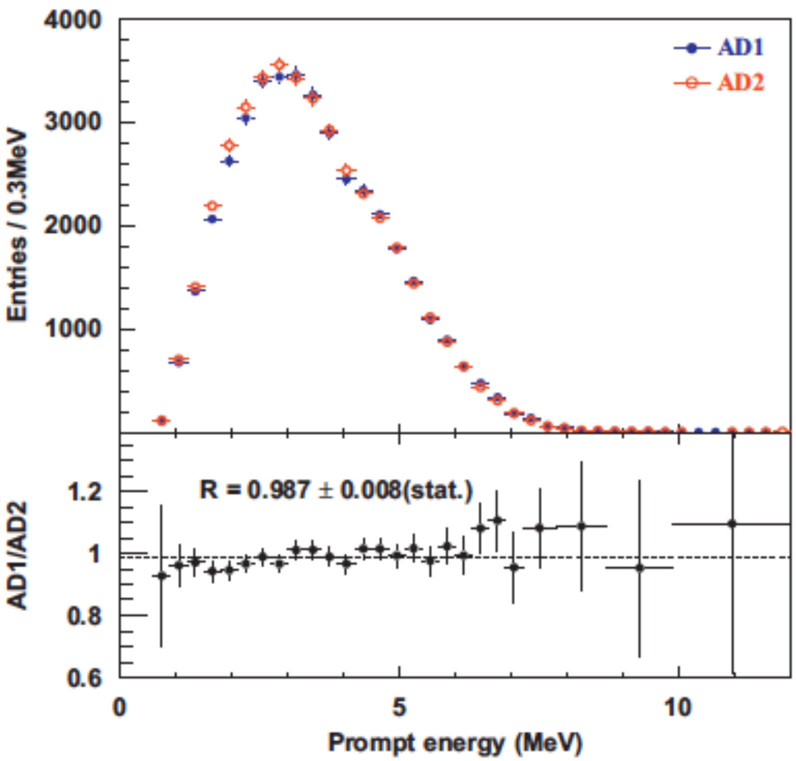


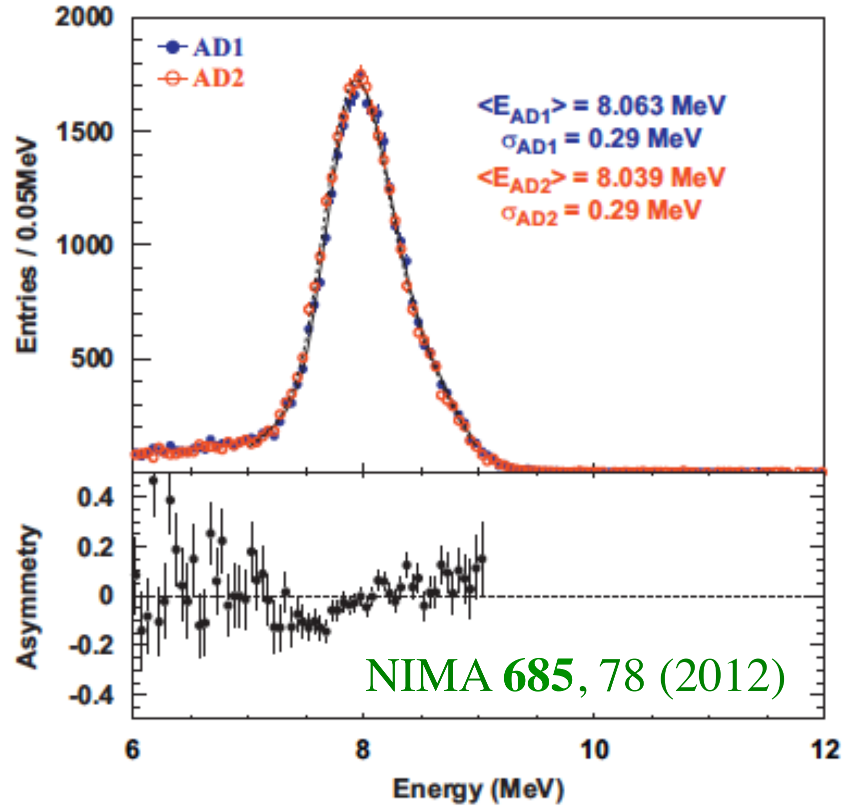


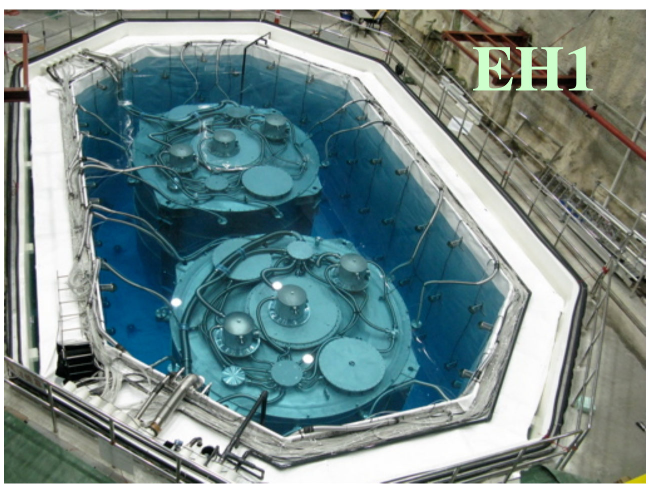
Operation of Daya Bay

- 15 August 2011 First two ADs in EH1
- 24 December 2011 6ADs: 2 in EH1, 1 in EH2, and 3 in EH3
- 28 July 2012 Shutdown
  - installed last 2 ADs
  - comprehensive calibration
- 19 October 2012 All 8 ADs
- 21 December 2016 Shutdown
  - special calibration
  - liquid scintillator R&D
- 26 January 2017 7 ADs: 1 in EH1, 2 in EH2, and 4 in EH3

Performance of First Two ADs



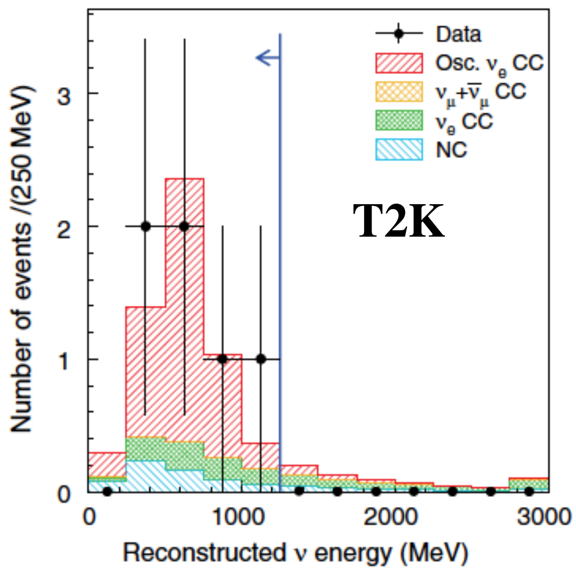




Uncertainty of the relative antineutrino detection efficiency was 0.2%, significantly better than the design value of 0.38%.

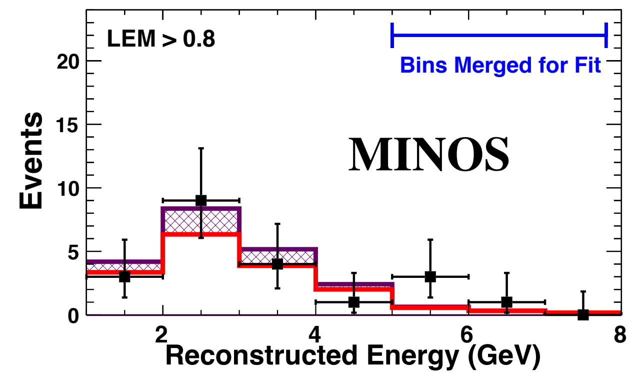
θ_{13} Circa March 2012

PRL**107,**041801 (2011)

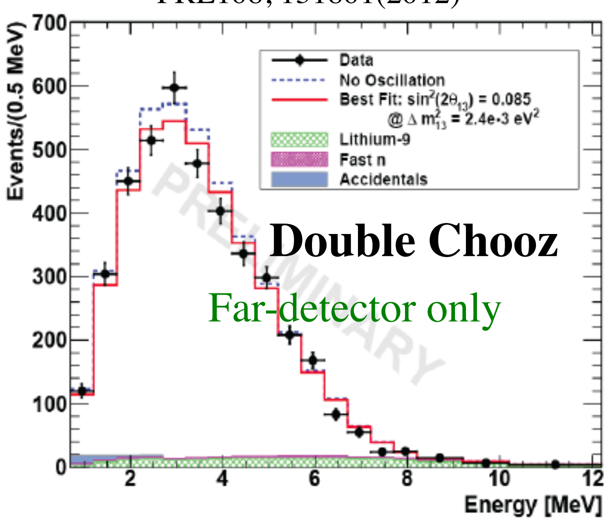


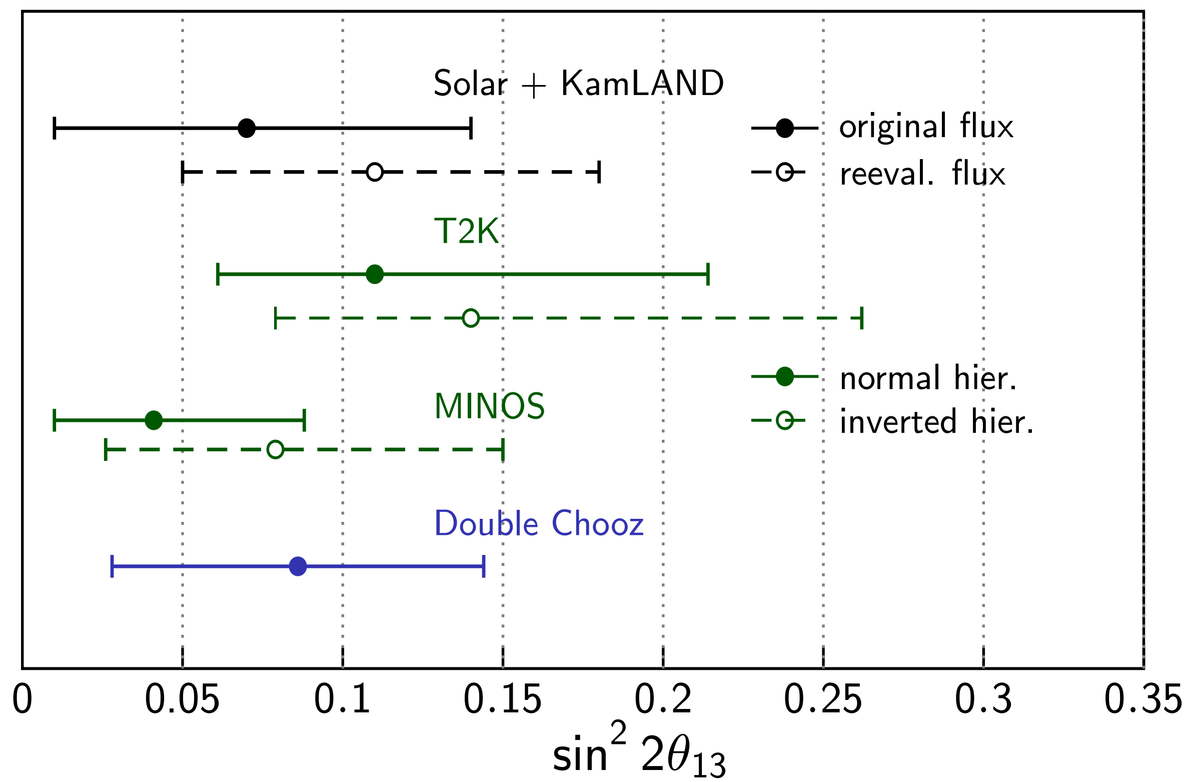
Some hints of a non-zero θ_{13}

PRL107, 181802 (2011)

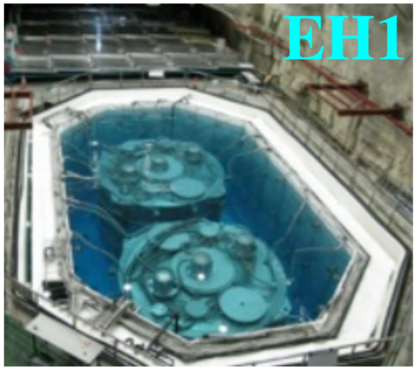


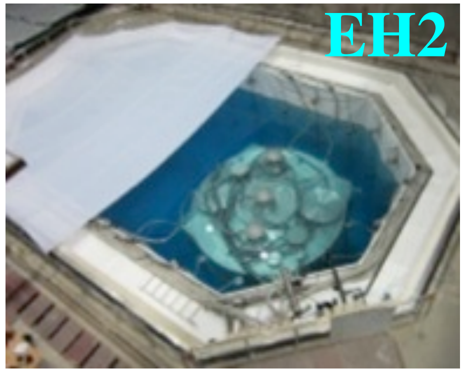
PRL108, 131801(2012)

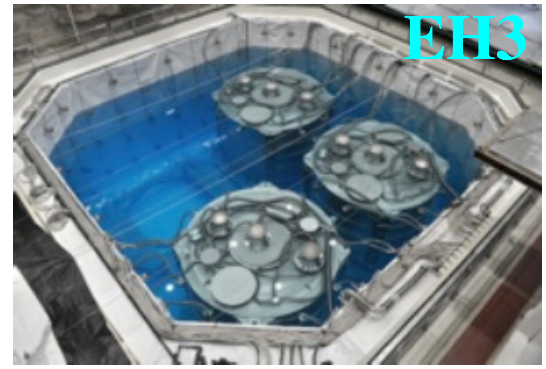




Definitive Result on θ_{13} (2012)

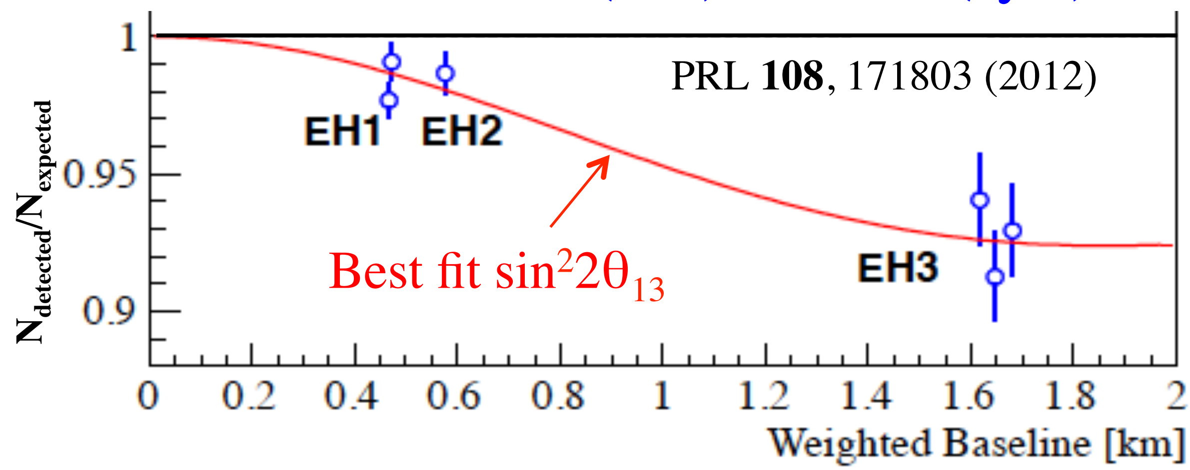






With 55 days of data, discovered disappearance of reactor $\bar{\nu}_e$ at short baseline in March 2012:

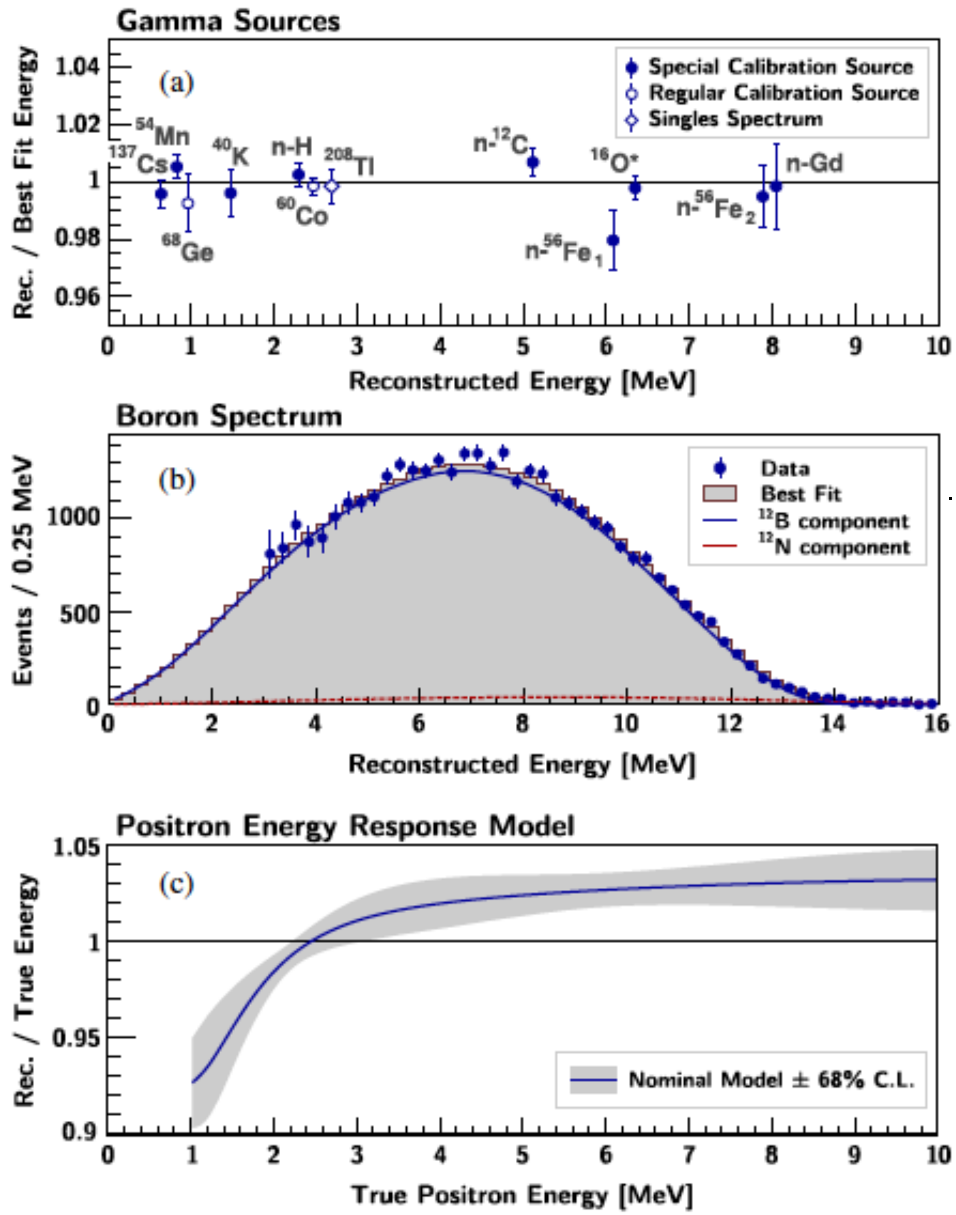
$$R = 0.940 \pm 0.011\ (\mathrm{stat}) \pm 0.004\ (\mathrm{syst})$$

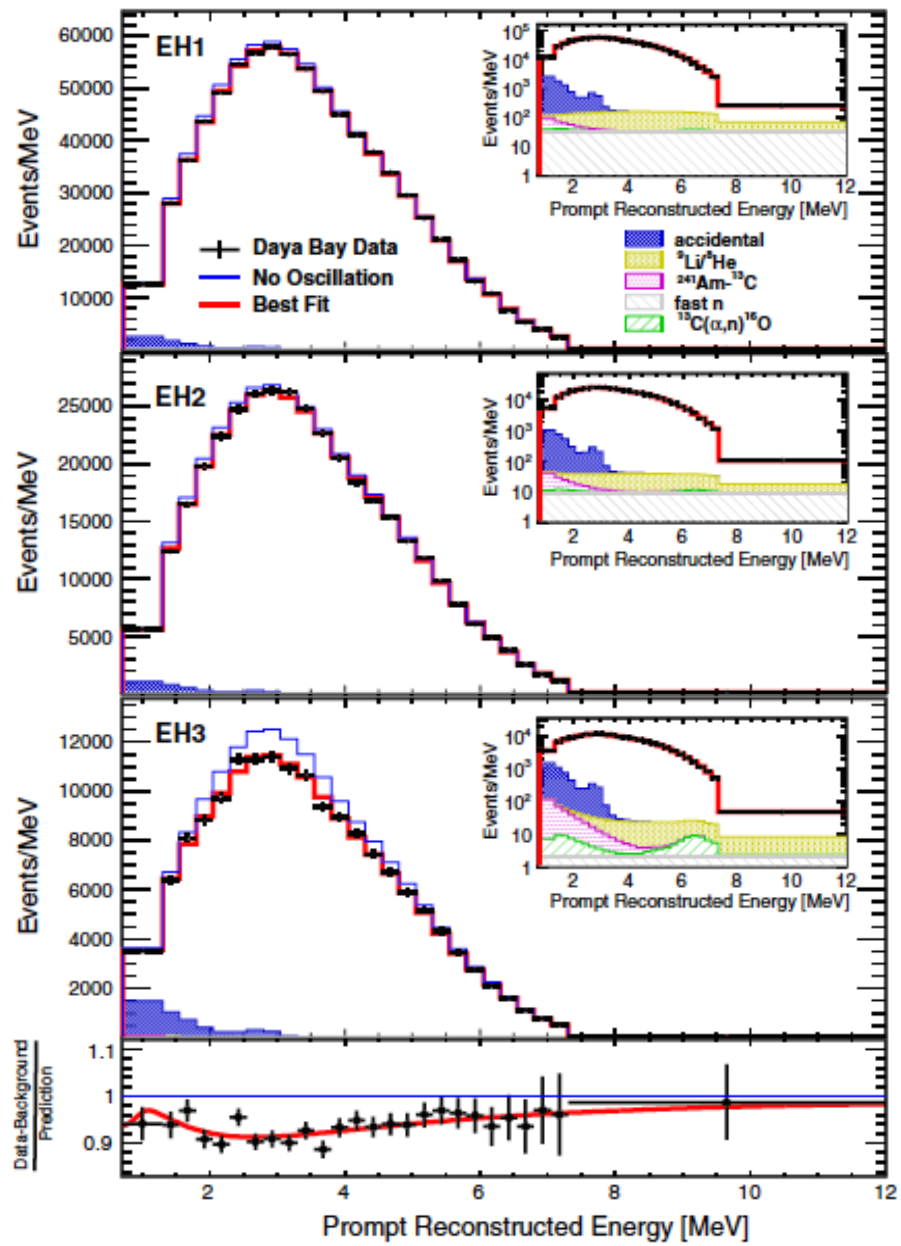


$$\boxed{\sin^2 2\theta_{13} = 0.092 \pm 0.016(\mathrm{stat}) \pm 0.005(\mathrm{syst})}$$

Confirmed by RENO in April 2012

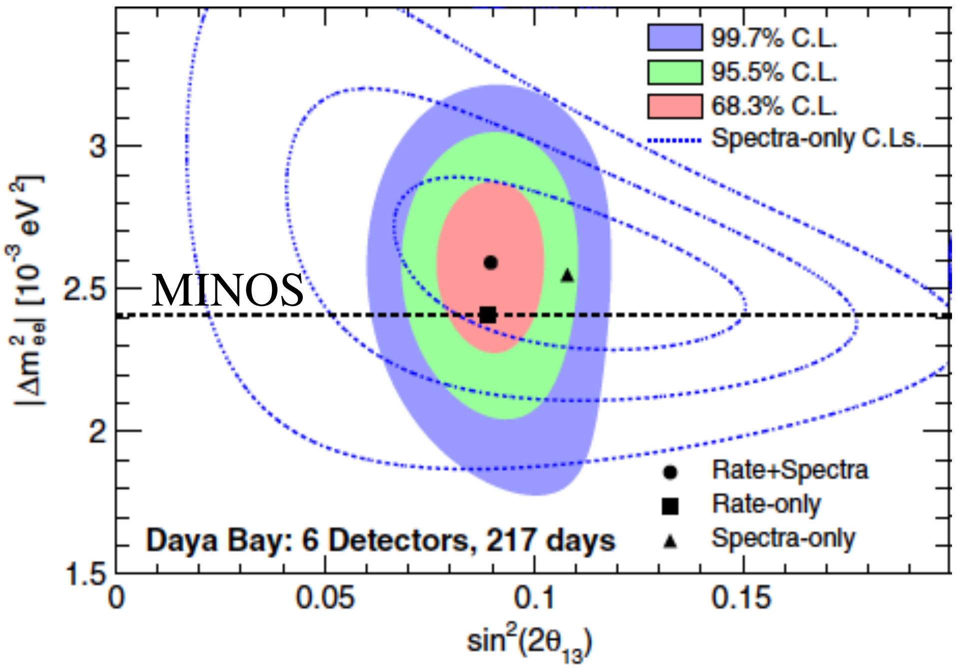
Accurate Energy Spectra

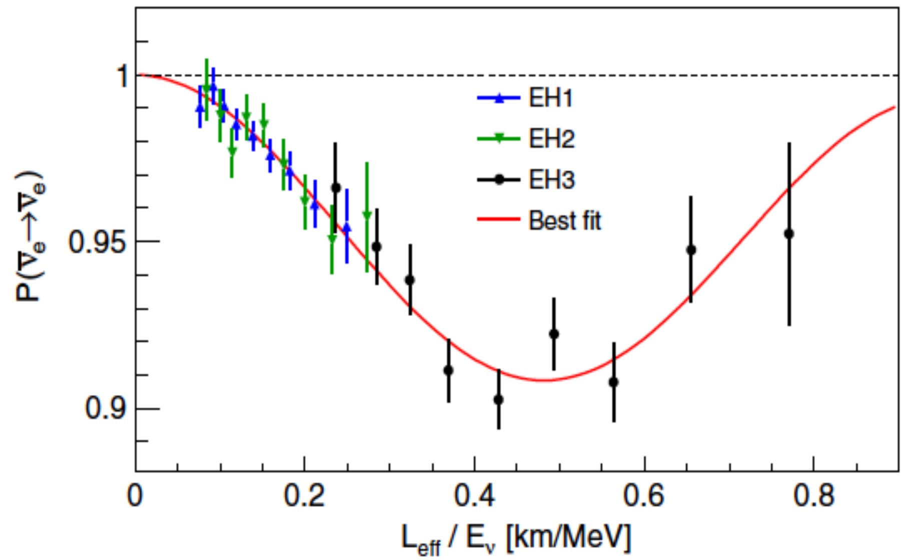




First Measurement of $|\Delta m^2_{ee}|$

PRL **112**, 061801(2014)



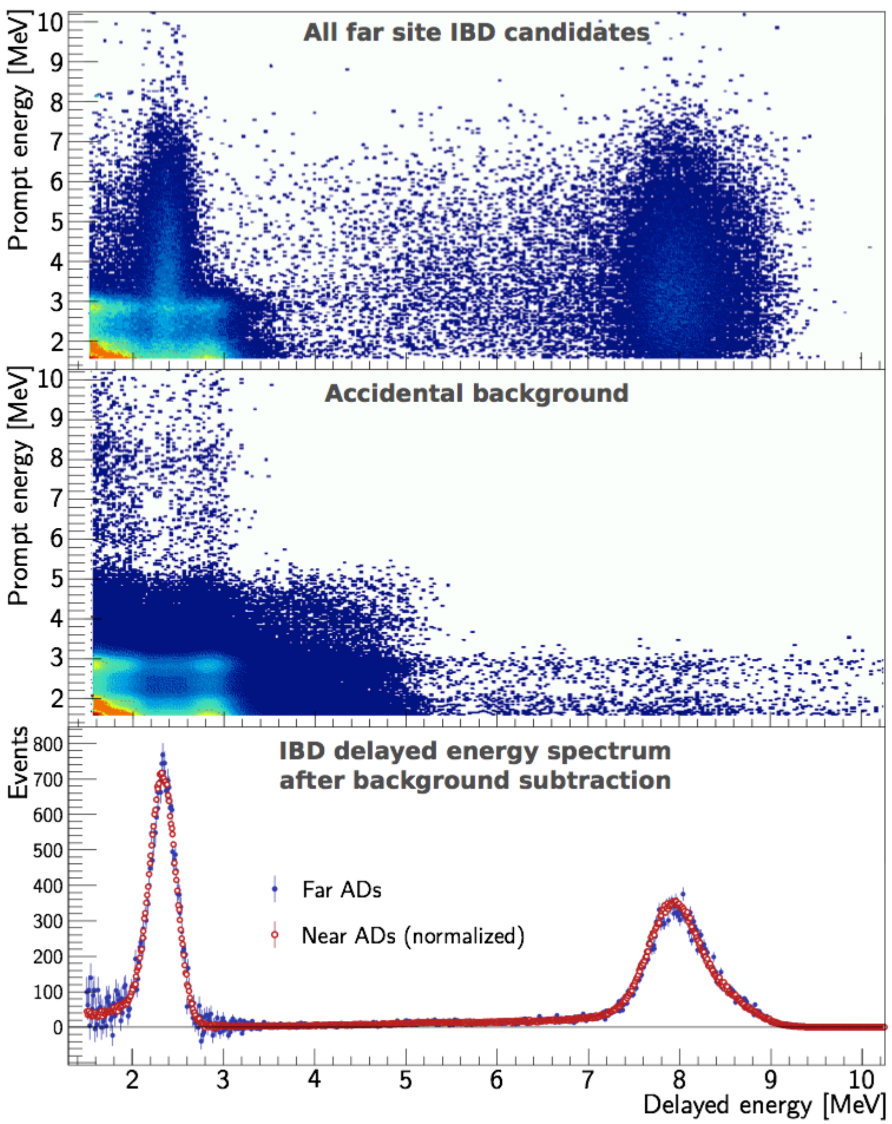


$$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$$

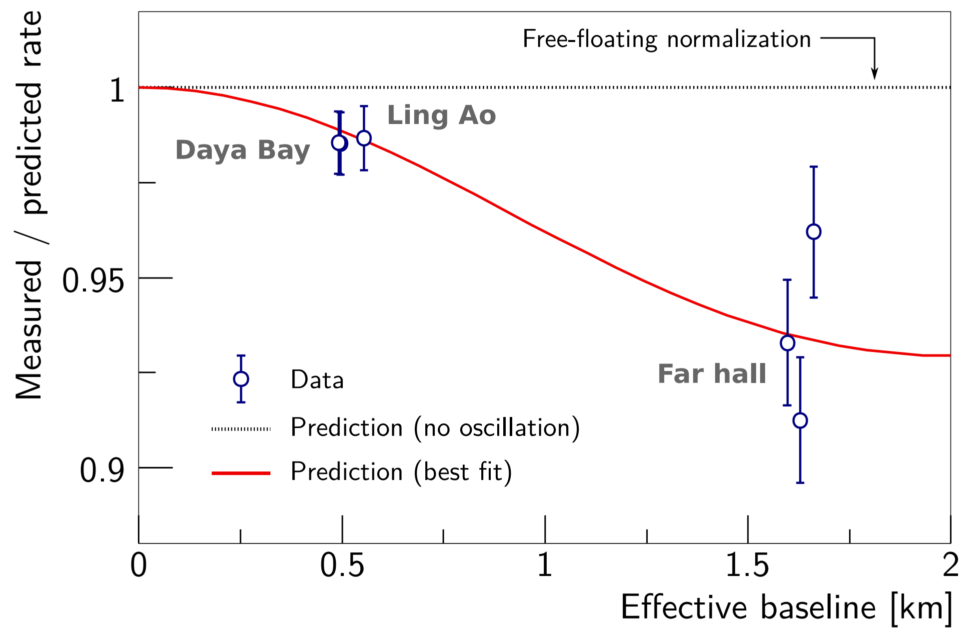
$$|\Delta m^2_{ee}| = (2.59^{+0.19}_{-0.20}) \times 10^{-3}\ \mathrm{eV}^2$$

Measurement of $\sin^2\theta_{13}$ with nH Data

neutron-capture on hydrogen: 217 days of data with 6 ADs



Rate-only analysis

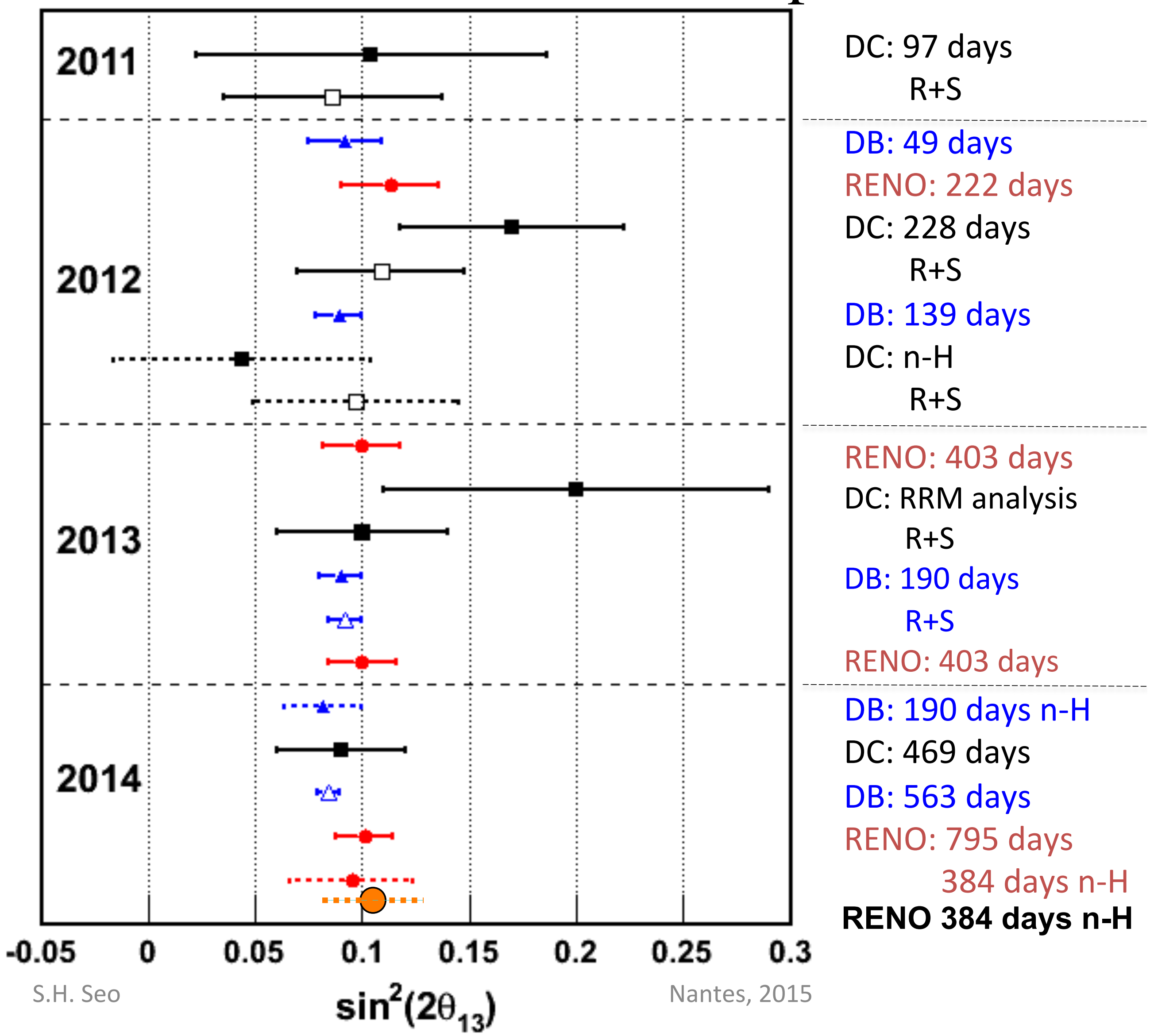


$$\sin^2 2\theta_{13} = 0.083 \pm 0.018$$
$$\chi^2/N_{\mathrm{DoF}} = 4.5/4$$

PRD **90**, 071101(R) (2014)

$\sin^2 2\theta_{13}$ Circa 2015

Results from reactor-based experiments



Most Precise $\sin^2 2\theta_{13}$

- Analyzed 1230 days of data using
  - complete 217 days of 6-AD data set
  - 1013 days of 8-AD data sample
  - improved energy response model and energy calibration
  - reduced uncertainties in background events
  - >2.2 million IBD events in EH1+EH2, >0.3 million in EH3
- Results:
  - Uncertainty in relative antineutrino detection efficiency reduced from 0.2% to 0.13%
  - Deficit in antineutrino rate: R = 0.949±0.002(stat)±0.002(syst)

$$\sin^2 2\theta_{13} = 0.0841 \pm 0.0027(\text{stat}) \pm 0.0019(\text{syst})$$

$$|\Delta m^2_{ee}| = [2.50 \pm 0.06(\text{stat}) \pm 0.06(\text{syst})] \times 10^{-3}\,\text{eV}^2$$

$$|\Delta m^2_{32}| = [2.45 \pm 0.06(\text{stat}) \pm 0.06(\text{syst})] \times 10^{-3}\,\text{eV}^2 \quad (\text{NH})$$

$$|\Delta m^2_{32}| = [-2.56 \pm 0.06(\text{stat}) \pm 0.06(\text{syst})] \times 10^{-3}\,\text{eV}^2 \quad (\text{IH})$$

- See Naumov's talk for details and other results.

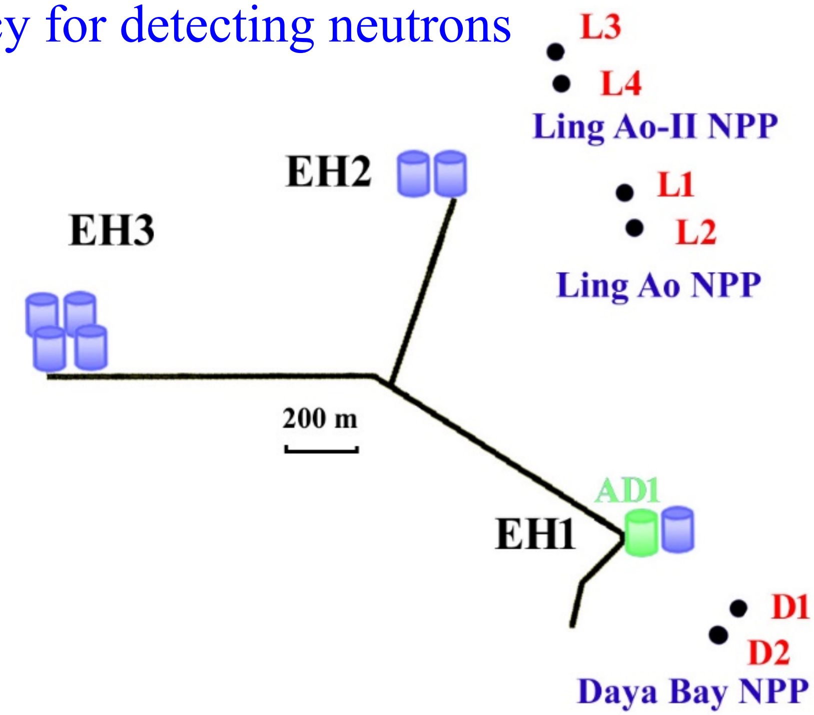
Current Status

- Installed FADCs running in parallel with default front-end electronics to improve understanding of electronics non-linearity.

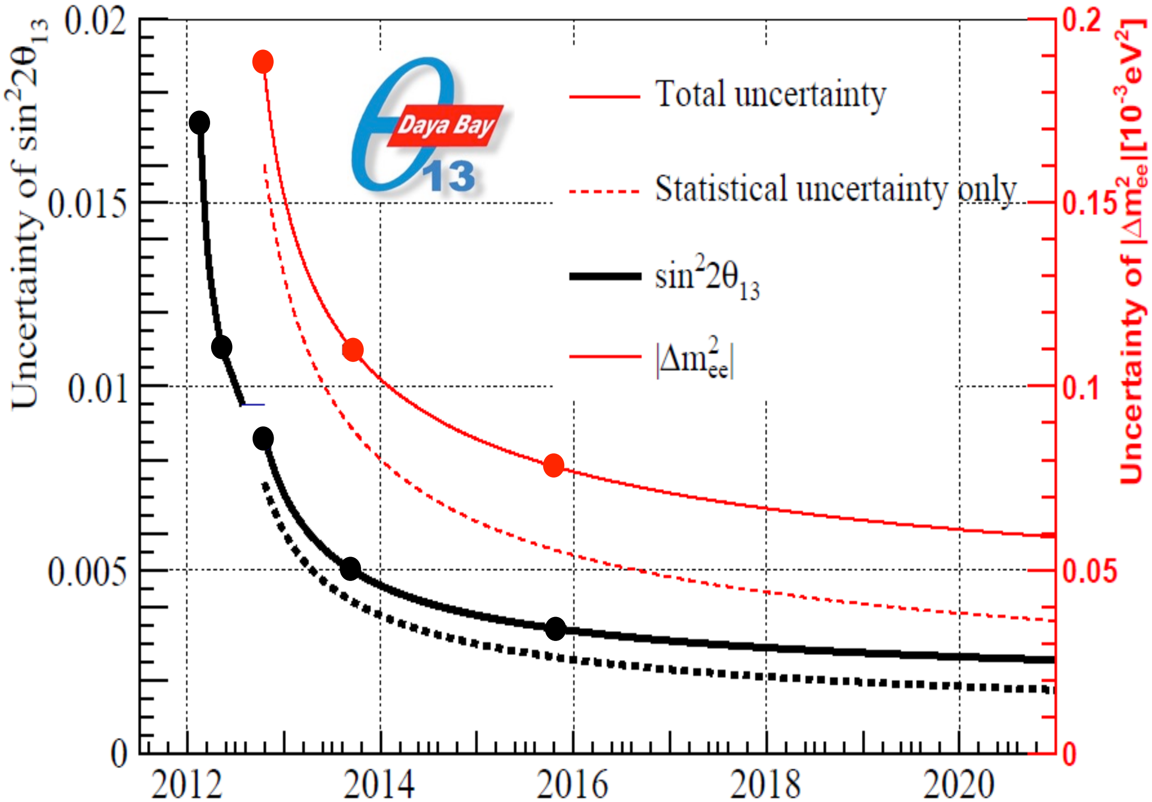
- Carried out a special calibration of AD1 with ^{60}Co, new Am-Be and Am-C sources in EH1
  - Study the effects of shadowing with different source configuration
  - Refine measurement of absolute efficiency for detecting neutrons

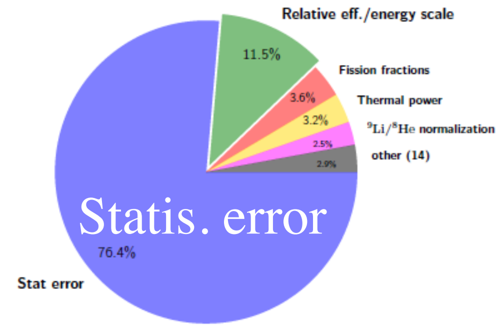
- Replaced the Gd-loaded liquid scintillator in AD1 for carrying out liquid scintillator R&D.

- Continue stable data taking with 7 ADs since 26 January 2017.

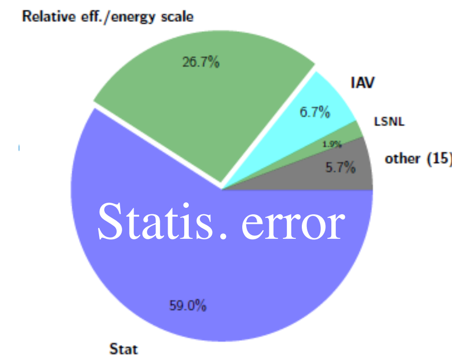


Prospects For $\sin^2 2\theta_{13}$ & $|\Delta m^2_{ee}|$





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



$|\Delta m^2_{ee}|$

By 2020 : $\sigma(\sin^2 2\theta_{13}) = 0.0025$

$\sigma(|\Delta m^2_{ee}|) = 0.06 \times 10^{-3}\,\text{eV}^2$

Continue to reduce systematic uncertainties and background.

Summary

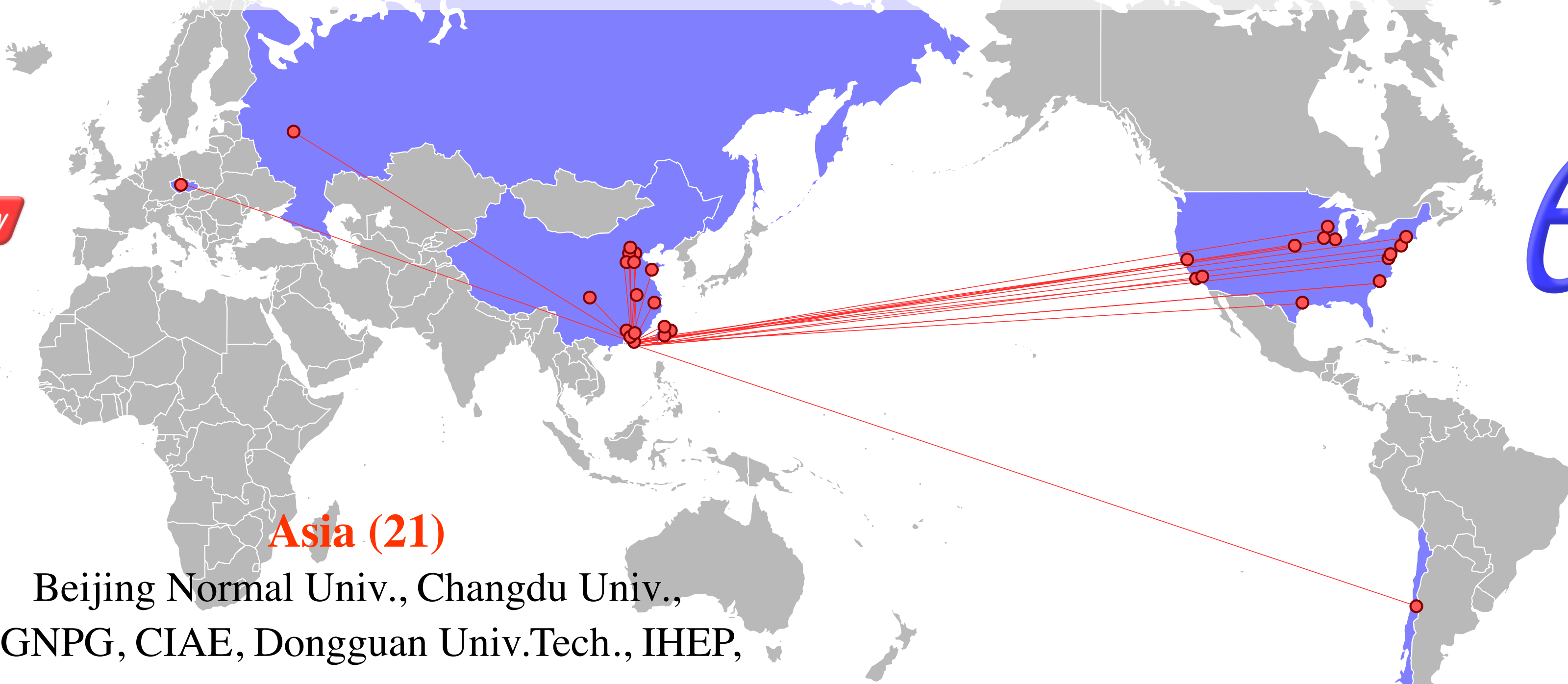
Daya Bay

- has acquired the largest sample of reactor antineutrinos to date.
- provides world's most precise determination of
  - $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$
- continues to yield leading results on other topics such as
  - measurement of absolute flux and spectrum of reactor antineutrinos with unprecedented statistics
  - search for a light sterile neutrino with $\sim 10^{-3}$ eV^2 $< \Delta m^2_{41} <$ $\sim 10^{-1}$ eV^2

Stay tuned:

D. Naumov: 'New Results from the Daya Bay Reactor Neutrino Experiment'

The Daya Bay Collaboration



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Nanjing Univ., Nankai Univ., NCEPU,
Shandong Univ., Shanghai Jiaotong Univ.,
Shenzhen Univ., Tsinghua Univ., USTC,
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Virginia Tech., William & Mary, Yale

South America (1)

Cath. Univ. of Chile

Thank You