Reactor-based Neutrino Experiment

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Outline

- Introduction
- Reactor-based neutrino experiment
- Results from reactor neutrino experiment
- Future and prospects
- Summary

Reactor Neutrino Physics

Now - Discovery and precision measurement of θ_{13}

2008 - Precision measurement of Δm_{12}^2. Evidence for oscillation

2003 - First observation of reactor antineutrino disappearance

1995 - Nobel Prize to Fred Reines at UC Irvine

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

1956 - First observation of (anti)neutrinos

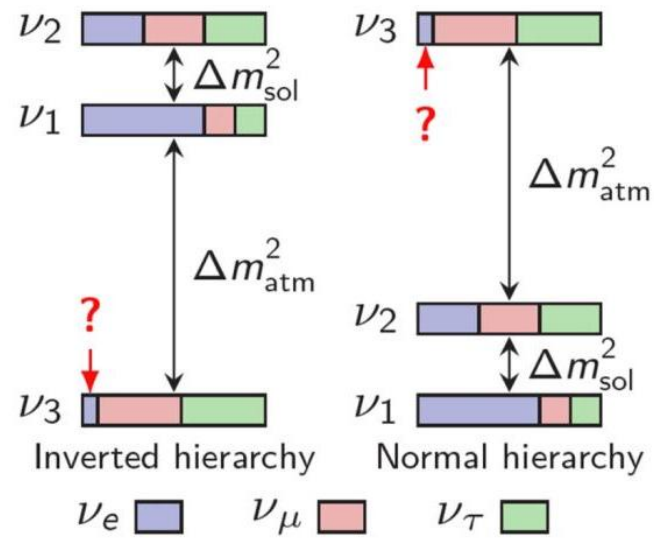
Past Reactor Experiments
Hanford
Savannah River
ILL, France
Bugey, France
Rovno, Russia
Goesgen, Switzerland
Krasnoyark, Russia
Palo Verde
Chooz, France

56 years of liquid scintillator detectors
a story of varying baselines...

Neutrino Mixing

In a 3-ν framework

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



$\Delta m^2_{sol} : \Delta^2 m_{21}$ $\Delta m^2_{atm} : \Delta^2 m_{31}, \Delta^2 m_{32}$

$$\mathrm{NH} : |\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}|, \quad |\Delta m^2_{31}| > |\Delta m^2_{32}|$$

$$\mathrm{IH} : |\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}|, \quad |\Delta m^2_{31}| < |\Delta m^2_{32}|$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

θ_{23} ~ 45°
Atmospheric
Accelerator

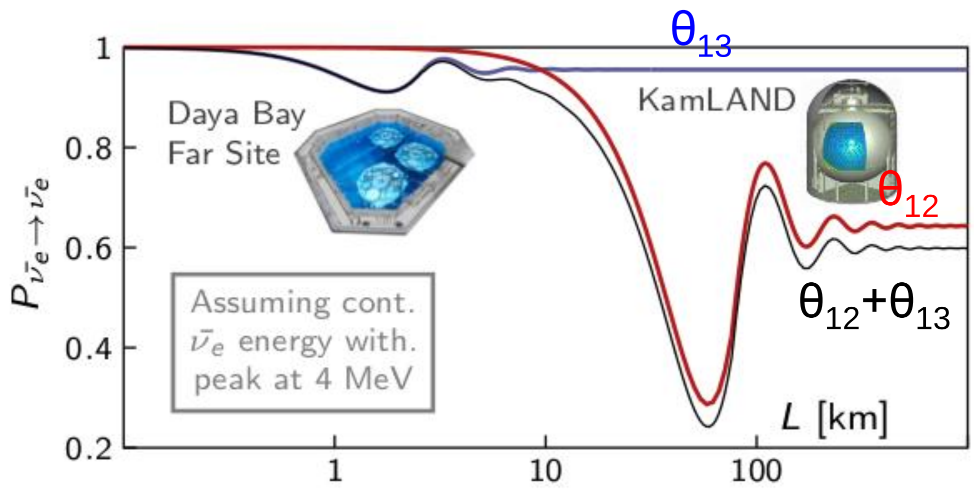
θ_{13} = ?
Reactor
Accelerator

θ_{12} ~ 34°
Solar
Reactor

Reactor Neutrino Oscillation

Benefits of reactor neutrinos:

- Pure $\overline{\nu}_e$ source
- Intense source (>10^{20} $\overline{\nu}_e$/s)
- Clean detection signal
- No effects from CP phase, or matter interactions



- **θ_{13} revealed by deficit of reactor antineutrinos at ~2 km. Mixing angle θ_{13} governs overall size of $\overline{\nu}_e$ deficit.**
- **Short-baseline reactor experiments insensitive to mass hierarchy can not discriminate 2 frequencies contributing to oscillation:** $\Delta m^2_{31}, \Delta m^2_{32}$
- **One effective oscillation frequency** Δm^2_{ee} **is measured:**

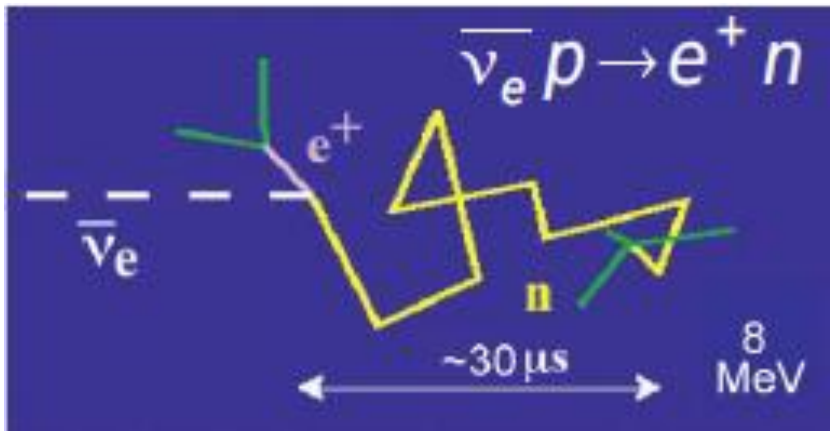
$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{ee} \frac{L}{4E}\right) - \sin^2 2\theta_{12} \cos^4\theta_{13} \sin^2\left(\Delta m^2_{21} \frac{L}{4E}\right)$$

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

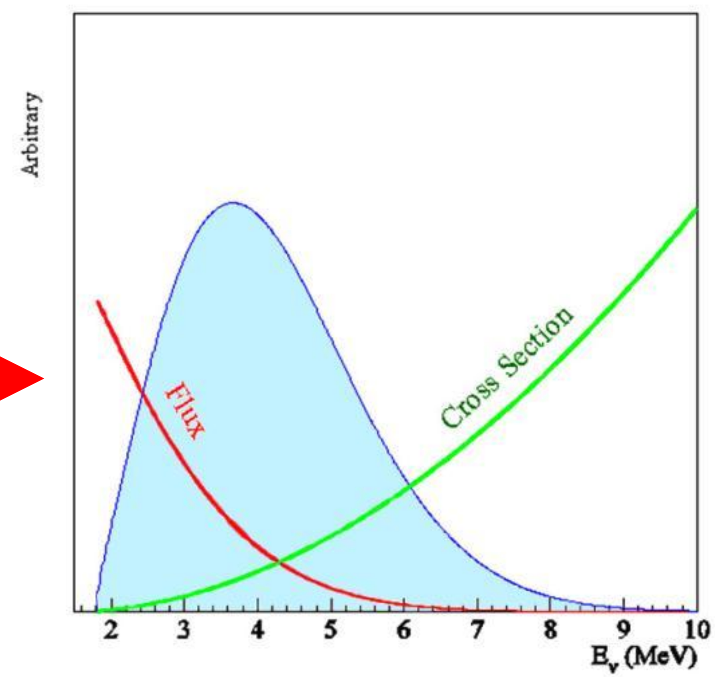
$$\Delta m^2_{ee} \sim \Delta m^2_{31} \sim \Delta m^2_{32} \sim \Delta m^2_{atm} \sim (\sim \Delta m^2_{uu})$$

Detecting Reactor Antineutrino

Inverse beta decay in Gd-doped liquid scintillator



<u>**Peak at ~4 MeV**</u>



Prompt signal

$$e^+ + e^- \rightarrow 2\gamma$$

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

Delayed signal, Capture on Gd (8 MeV), ~30μs

Proposed Reactor Experiments

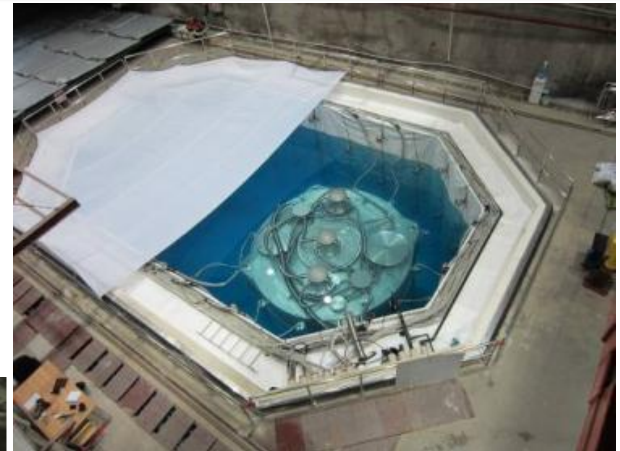
Three active experiments:

DayaBay, RENO, Double Chooz

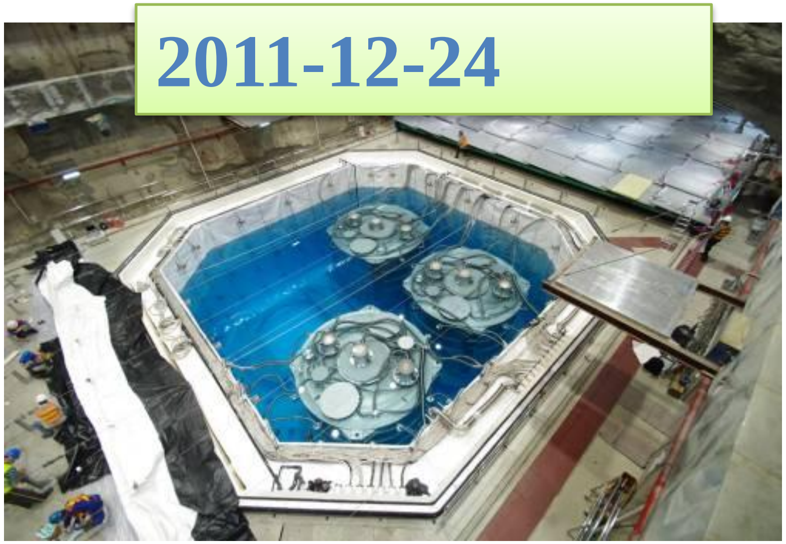
Experiment layout

Daya Bay

2011-11-5



2011-12-24

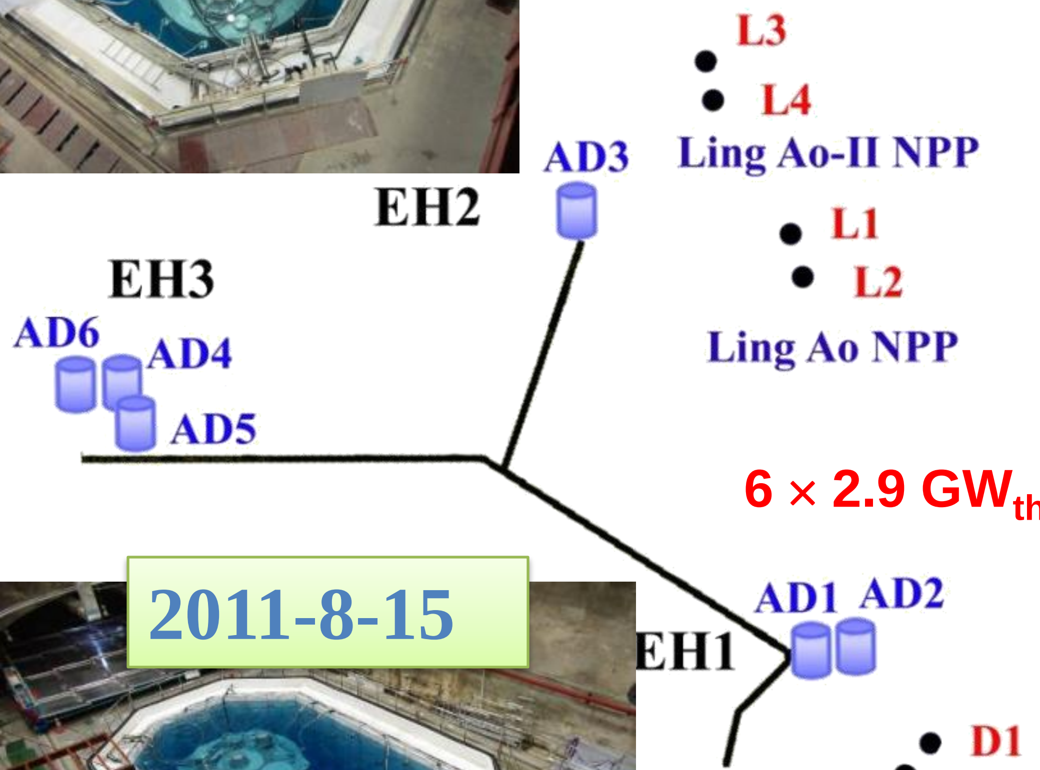


8 identical ADs for Daya Bay.

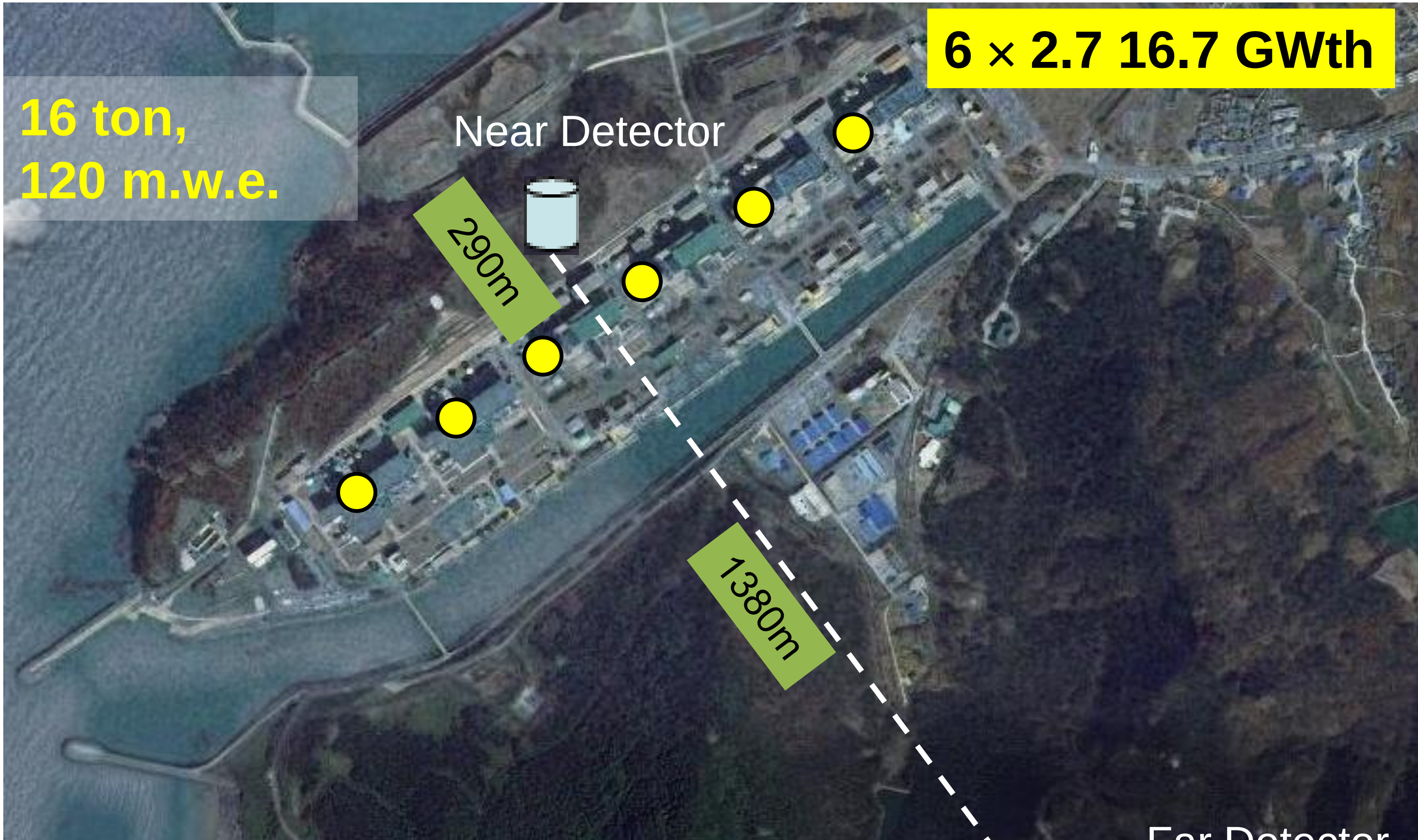
6 AD installed for data collection at first stage.

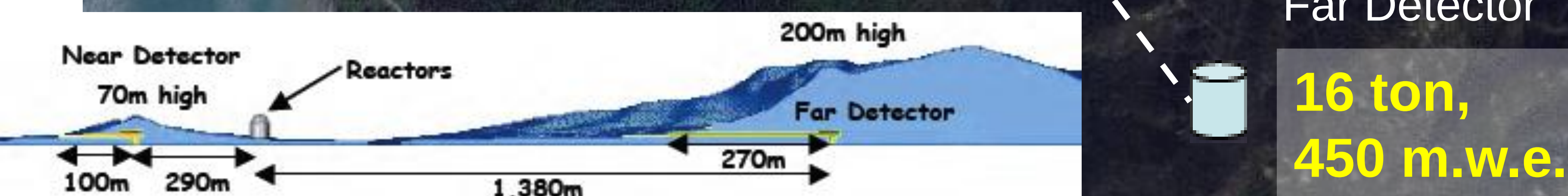
After Oct. 2012, 8 ADs installation was finished.

2011-8-15



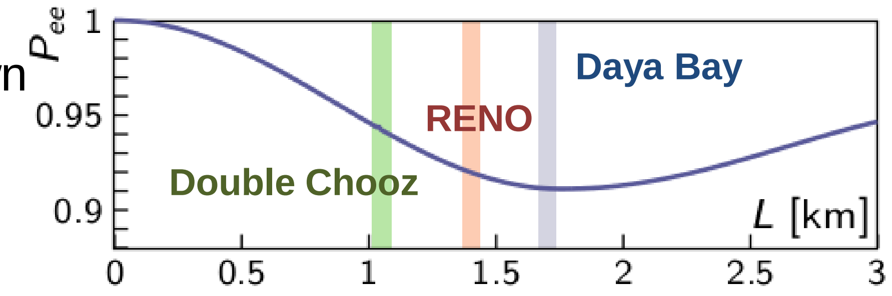
RENO


6 × 2.7 16.7 GWth
16 ton,
120 m.w.e.
Near Detector
290m
1380m
Far Detector
16 ton,
450 m.w.e.


Near Detector
70m high
Reactors
200m high
Far Detector
100m
290m
270m
1,380m

Double Chooz

- **Baseline Optimization**
  - Detector locations optimized to known parameter space of $|\Delta m^2_{ee}|$
  - Far site maximizes term dependent on $\sin^2 2\theta_{13}$

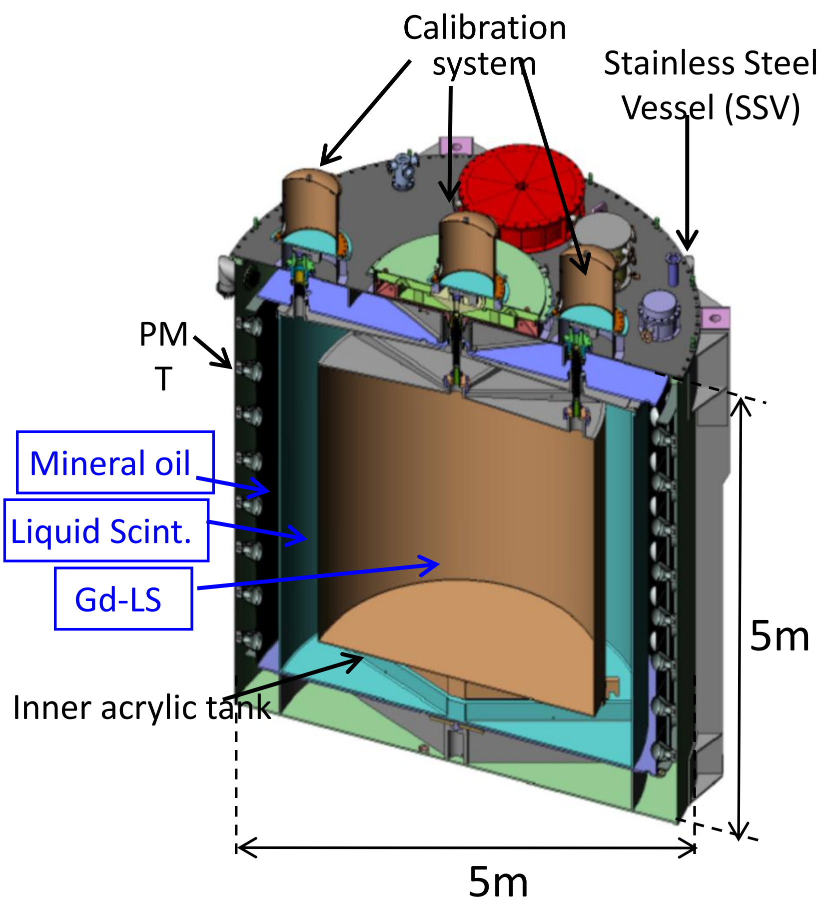


Experiment	Power (GW_{th})	Detector(t) Near/Far	Overburden (m.w.e.) Near/Far	Sensitivity (3y, 90% C.L.)
Double Chooz	8.5	8/8	120/300	~0.03
RENO	16.5	16/16	120/450	~0.02
Daya Bay	17.4	80/80	250/860	~0.008

Detector design

- Absolute reactor flux single largest uncertainty in previous measurements

Cancels in near/far ratio: $$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left(\frac{P_{sur}(E, L_f)}{P_{sur}(E, L_n)}\right)$$

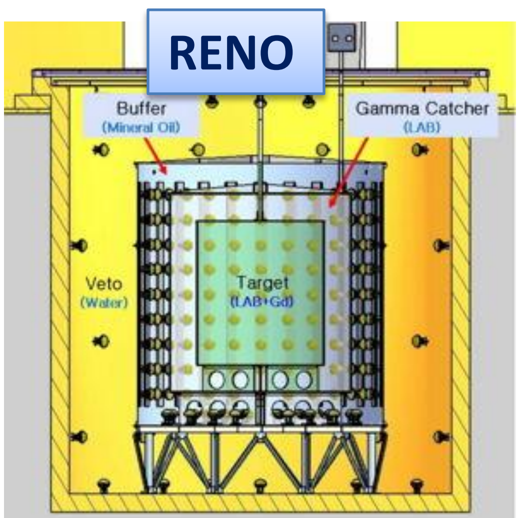


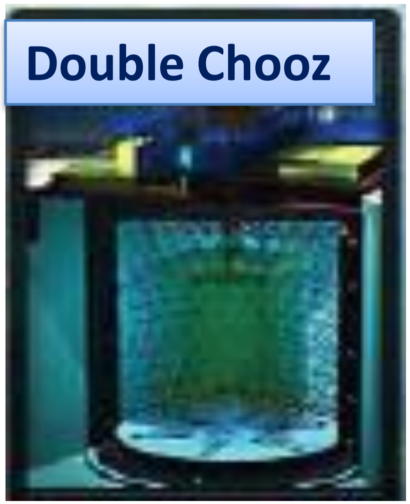
Daya Bay Antineutrino Detectors (AD)

- 8 functionally identical detectors to reduce the detector relative errors
- Three zones modular structure
- Reflector at top and bottom:

Reflectors improve light collection and uniformity

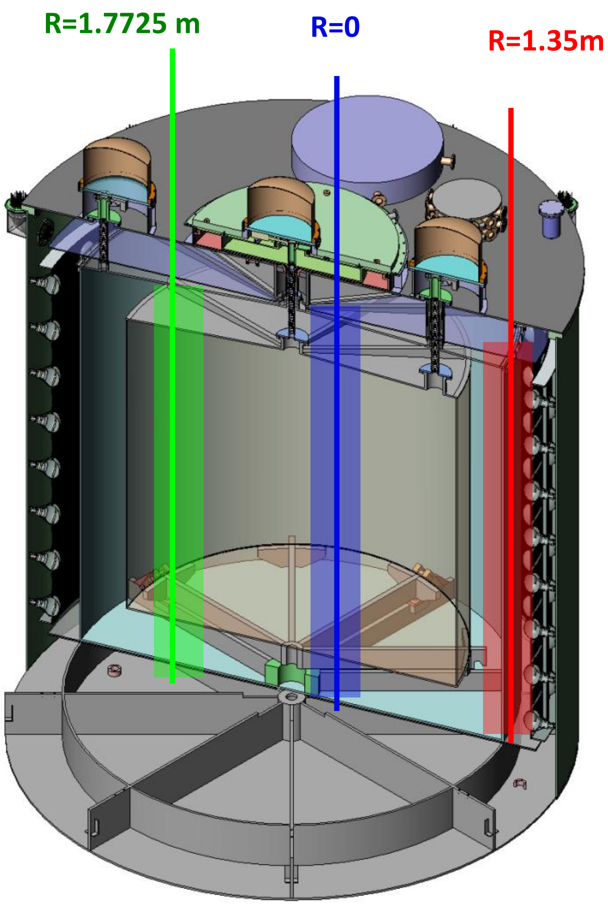
RENO and Double Chooz detector: similar structure





Automated Calibration System

3 Automatic calibration units (ACUs) on each detector



ACU source for weekly calibration:

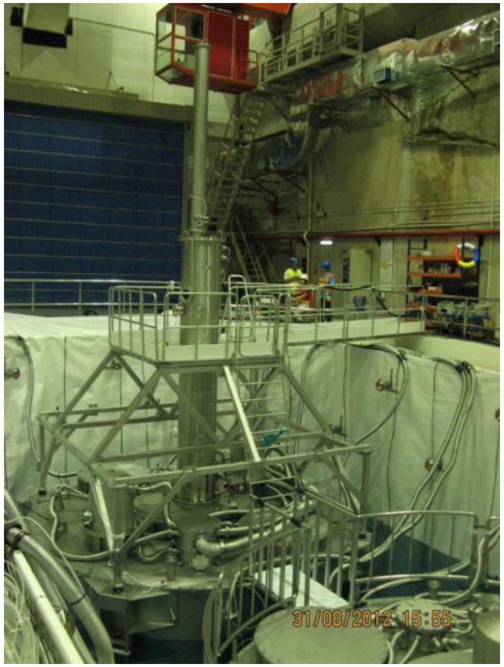
- 10 Hz ^{68}Ge (0 KE e^+ = 2×0.511 MeV γ's)
- 0.5 Hz ^{241}Am-^{13}C neutron source (3.5 MeV n without γ)
  + 100 Hz ^{60}Co gamma source (1.173+1.332 MeV γ)
- LED diffuser ball (500 Hz) for time calibration

Special ACU:

- γ: ^{137}Cs (0.662 MeV), ^{54}Mn (0.835 MeV), ^{40}K (1.461 MeV),Co
- n: ^{241}Am-^{9}Be, ^{238}Pu-^{13}C

Manual(4 π):

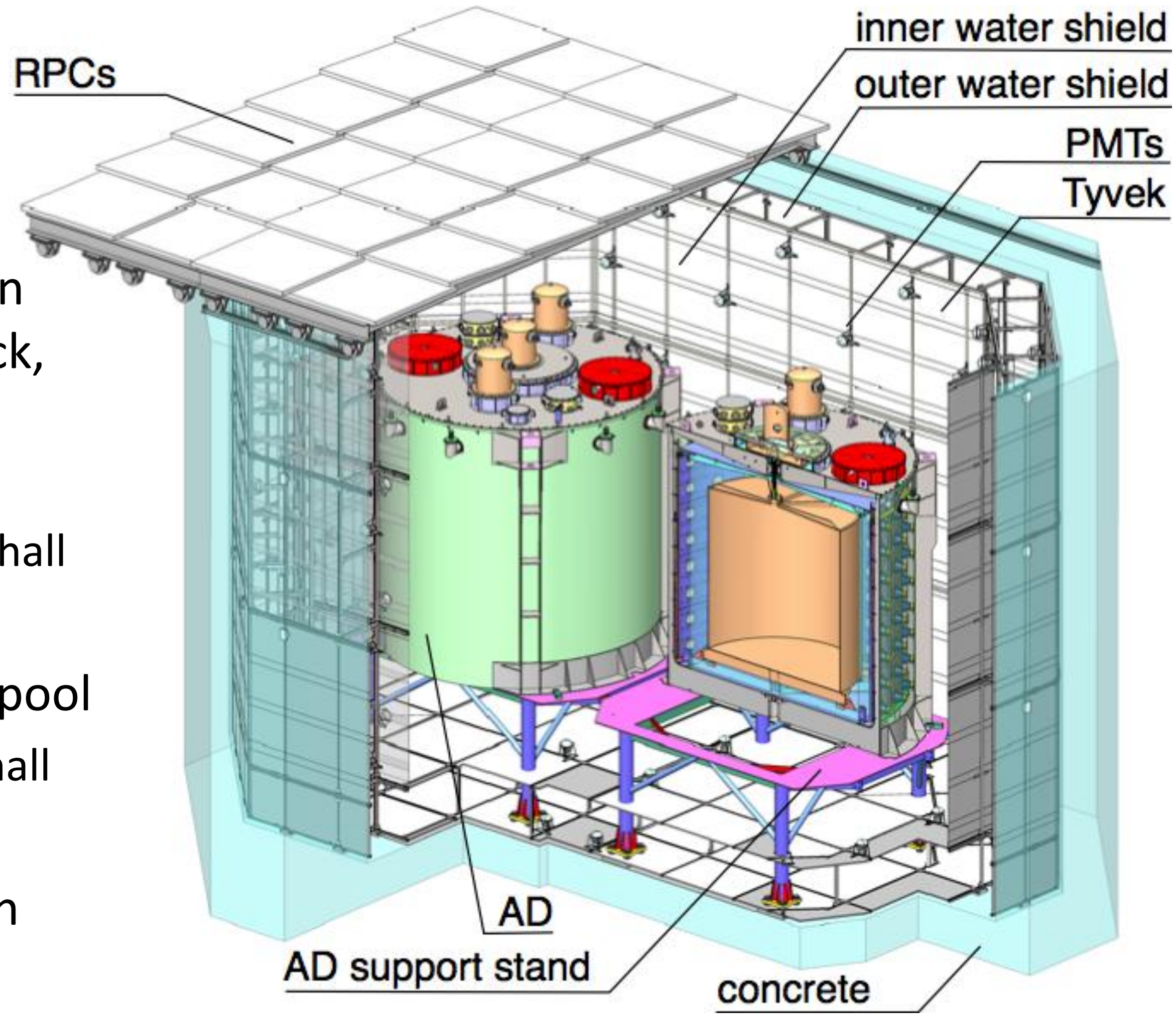
- Co / ^{238}Pu-^{13}C



Muon Tagging System

Dual tagging systems: 2.5 meter thick two-section water shield and RPCs

- Outer layer of water veto (on sides and bottom) is 1m thick, inner layer >1.5m. Water extends 2.5m above ADs
  - 288 8” PMTs in each near hall
  - 384 8” PMTs in Far Hall
- 4-layer RPC modules above pool
  - 54 modules in each near hall
  - 81 modules in Far Hall
- Goal efficiency: > 99.5% with uncertainty <0.25%



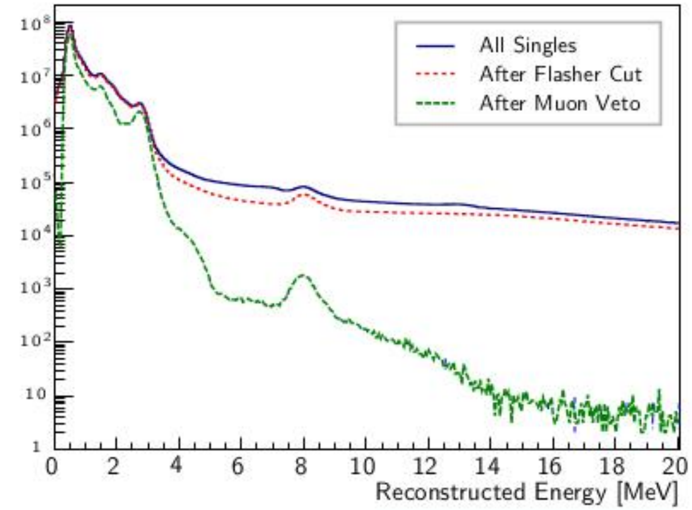
Two-zone ultrapure water cherenkov detector

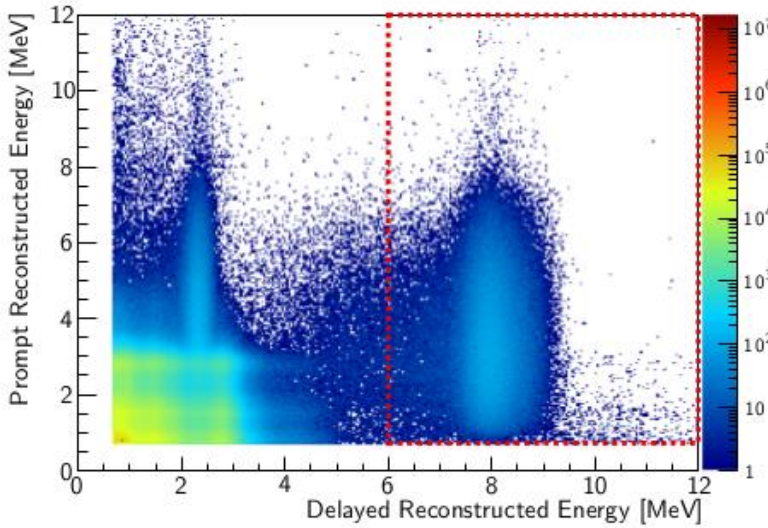
Event Selection and analysis(Daya Bay)

Anti-neutrino events(IBD) Selection

① Reject spontaneous PMT light emission ("flashers")
② Prompt positron:
0.7 MeV < Ep < 12 MeV
③ Delayed neutron:
6.0 MeV < Ed < 12 MeV
④ Neutron capture time:
1 μ s < t < 200 μ s
⑤ Muon veto:
- Water pool muon (>12 hit PMTs): Reject [-2μs; 600μs]
- AD muon (>20 MeV): Reject [-2 μs; 1400μs]
- AD shower muon (>2.5 GeV): Reject [-2 μs; 0.4s]

⑥ Multiplicity:
- No additional prompt-like signal 400μs before delayed neutron
- No additional delayed-like signal 400μs after delayed neutron





Backgrounds: $^{9}Li/^{8}He$

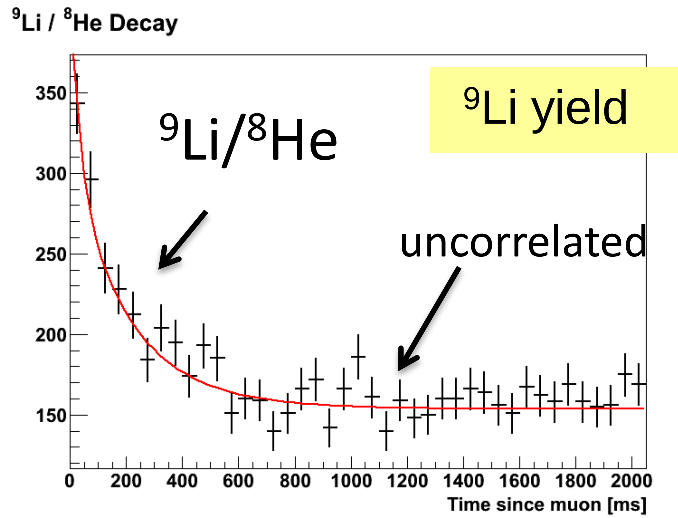
- Cosmic μ produced $^{9}Li/^{8}He$ in LS

  β-decay + neutron emitter

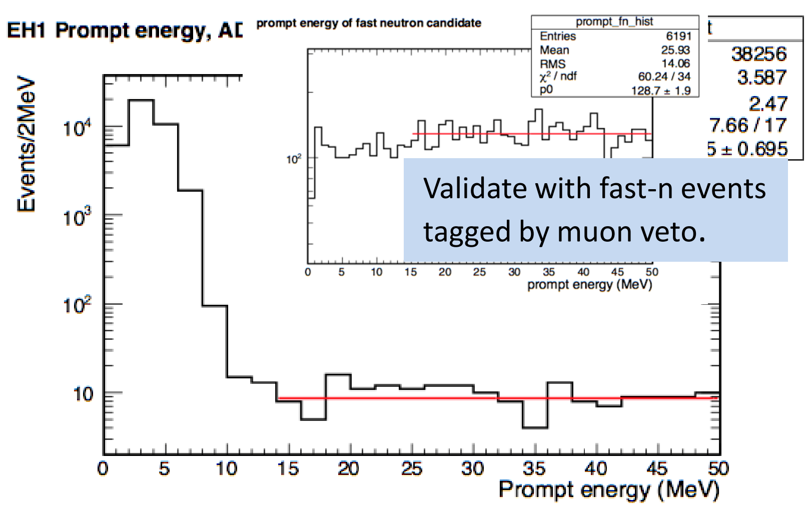
- **Measurement:**
  – Time-since-last-muon fit method

Analysis muon veto cuts control B/S to ~0.3±0.1%.

This background is directly measured by fitting the distribution of IBD candidates vs. time since last muon.



Backgrounds: Fast neutrons



Fast neutron from muon:

- **prompt signal :proton recoil:**
- **delayed signal: neutron capture**

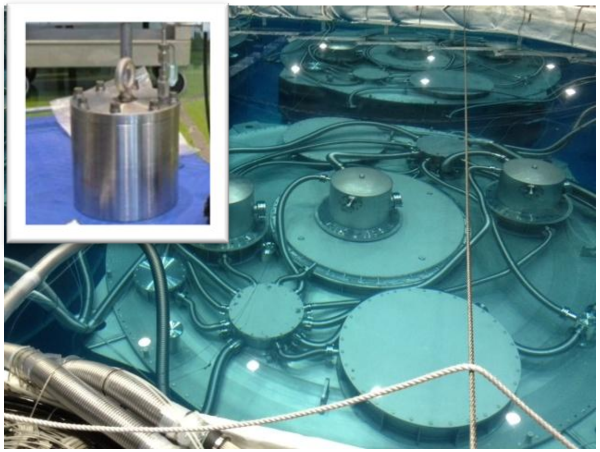
- **Method:**
  - ➢Evaluated by extraploation
  - ➢Spectrum and rate cross checked with fast-n tagged by muonveto

B/S to 0.06% (0.1%) of far (near) signal.

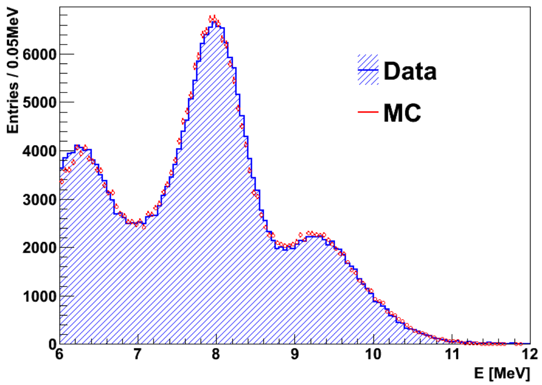
Background rate and shape constrained using intense source

^{241}Am-^{13}C background

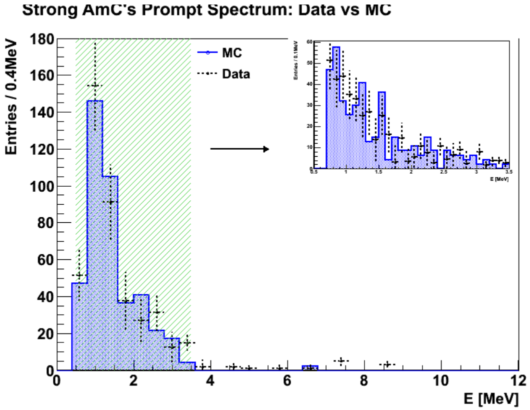
A special x80 stronger ^{241}Am-^{13}C source placed on the AD



Single n-like



Correlated prompt spectrum



Backgrounds summary

	Near Halls		Far Hall	
	B/S %	$\sigma_{B/S}$ %	B/S %	$\sigma_{B/S}$ %
Accidentals	**1.5**	0.01	**4.0**	0.04
Fast neutrons	0.1	0.07	0.06	0.03
^{9}Li/^{8}He	0.4	**0.1**	0.3	**0.08**
^{241}Am-^{13}C	0.04	0.02	0.36	**0.16**
^{13}C(α, n)^{16}O	0.01	0.01	0.05	0.03

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 by far vs. near measurement.

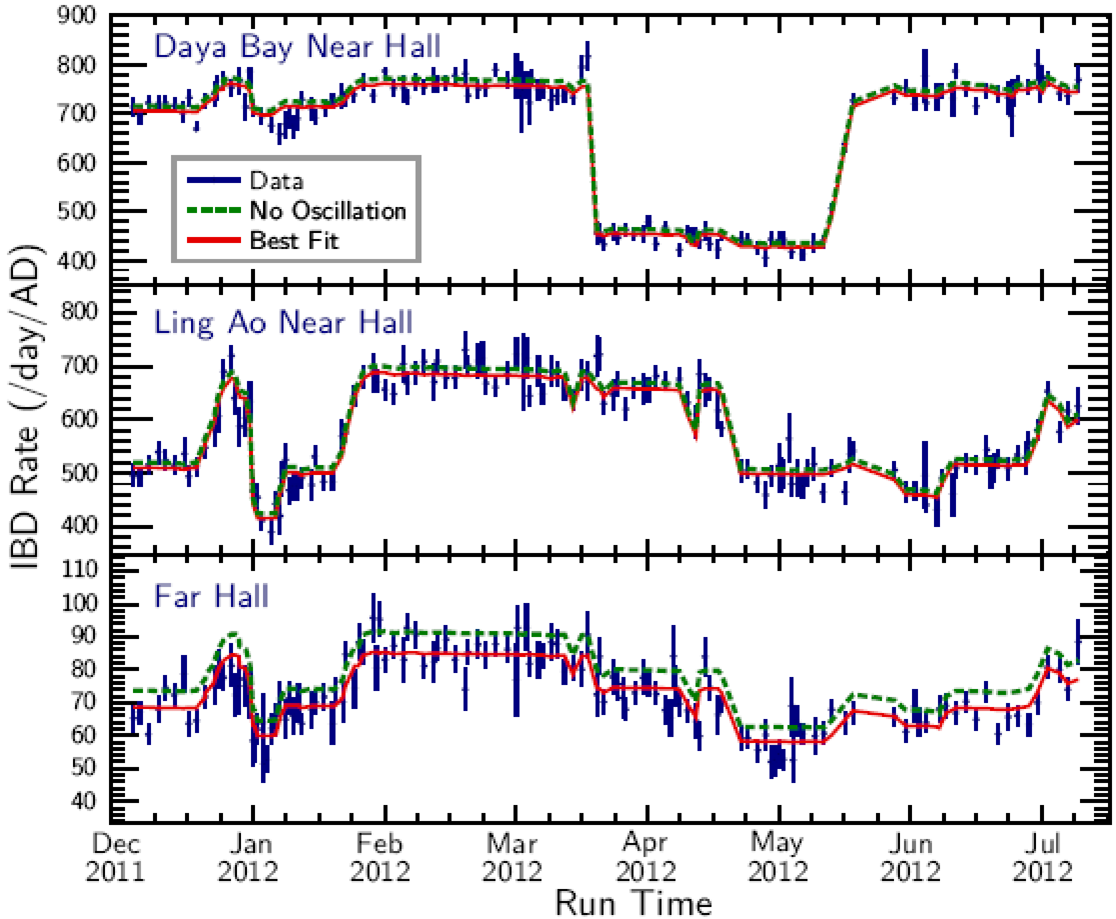
Signal and background summary

	Near Halls			Far Hall		
	AD 1	AD 2	AD 3	AD 4	AD 5	AD 6
IBD candidates	101290	102519	92912	13964	13894	13731
DAQ live time (days)	191.001		189.645		189.779	
Efficiency $\epsilon_{\mu} \cdot \epsilon_m$	0.7957	0.7927	0.8282	0.9577	0.9568	0.9566
Accidentals (per day)*	9.54±0.03	9.36±0.03	7.44±0.02	2.96±0.01	2.92±0.01	2.87±0.01
Fast-neutron (per day)*	0.92±0.46		0.62±0.31		0.04±0.02	
$^{9}Li/^{8}He$ (per day)*	2.40±0.86		1.2±0.63		0.22±0.06	
Am-C corr. (per day)*			0.26±0.12			
$^{13}C^{16}O$ backgr. (per day)*	0.08±0.04	0.07±0.04	0.05±0.03	0.04±0.02	0.04±0.02	0.04±0.02
IBD rate (per day)*	653.30±2.31	664.15±2.33	581.97±2.07	73.31±0.66	73.03±0.66	72.20± 0.66

*Background and IBD rates were corrected for the efficiency of the muon veto and multiplicity cuts $\epsilon_{\mu} \cdot \epsilon_m$

- **Collected more than 300k antineutrino interactions**
- **Consistent rates for side-by-side detectors (expected AD1/AD2 ratio 0.981)**
- **Uncertainties still dominated by Far Hall statistics 0.9%**

Antineutrino Rate vs. Time



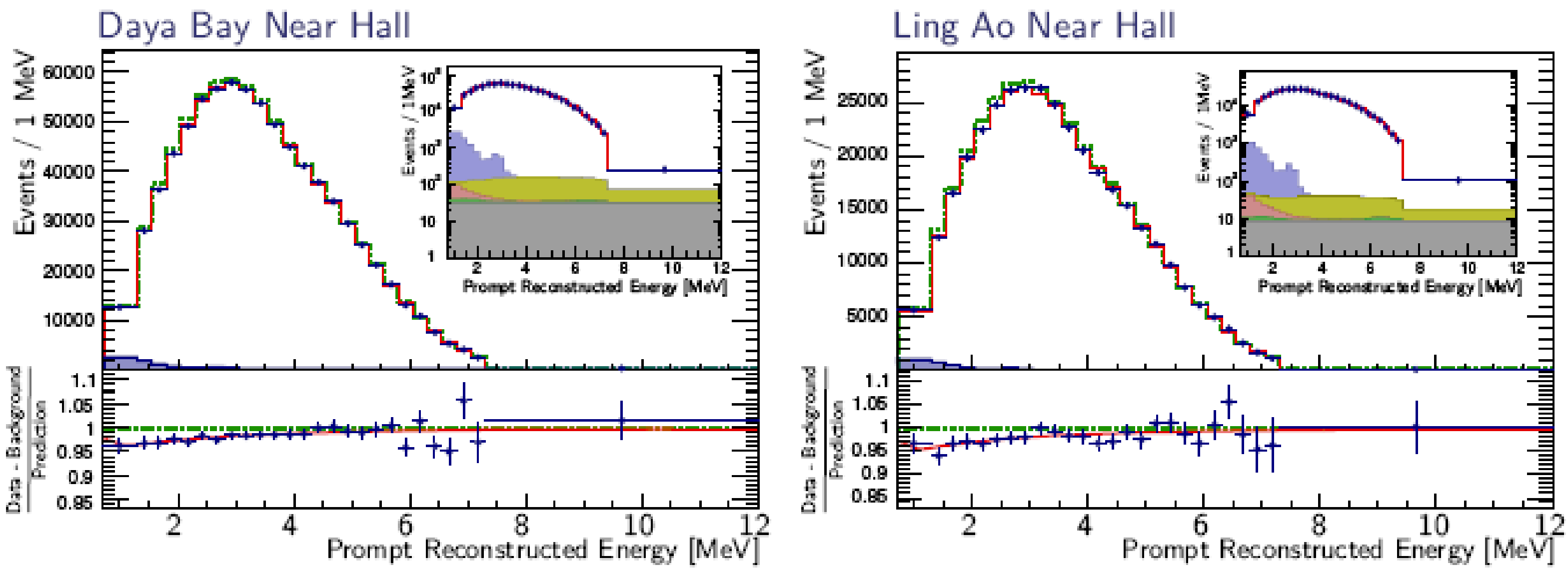
Predicted Rate:

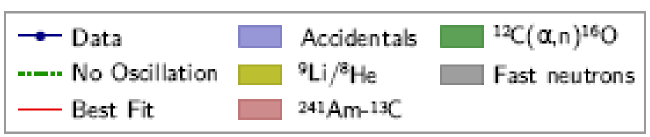
- Assume no oscillation
- Absolute normalization is determined by data fit.
- Normalization is within a few percent of expectations.

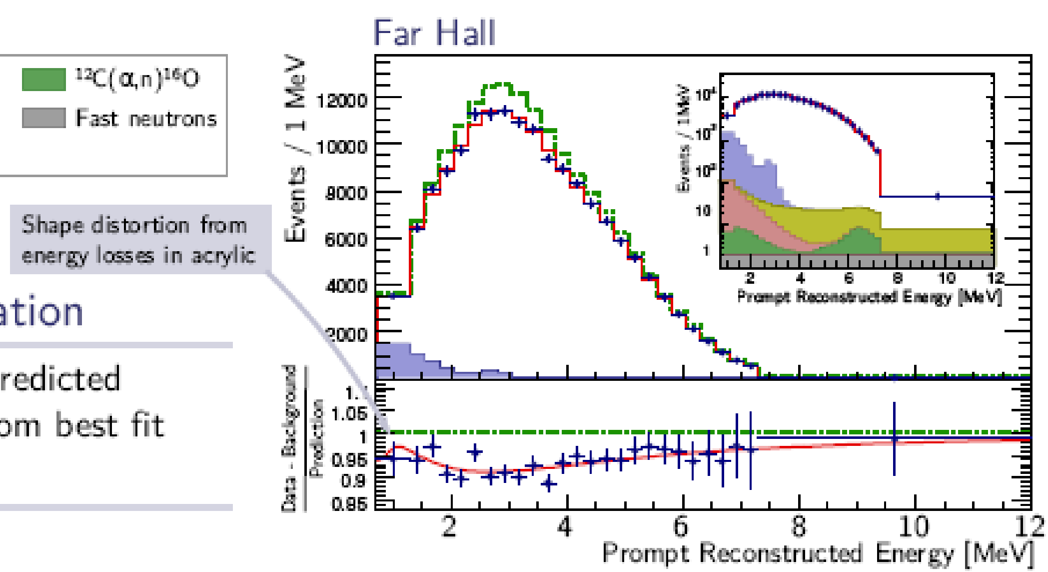
Detected rate strongly correlated with reactor flux expectations.

Daya Bay results

IBD prompt spectrum







Spectral distortion consistent with oscillation

- Both background and predicted no-oscillation spectra from best fit
- Statistical errors only

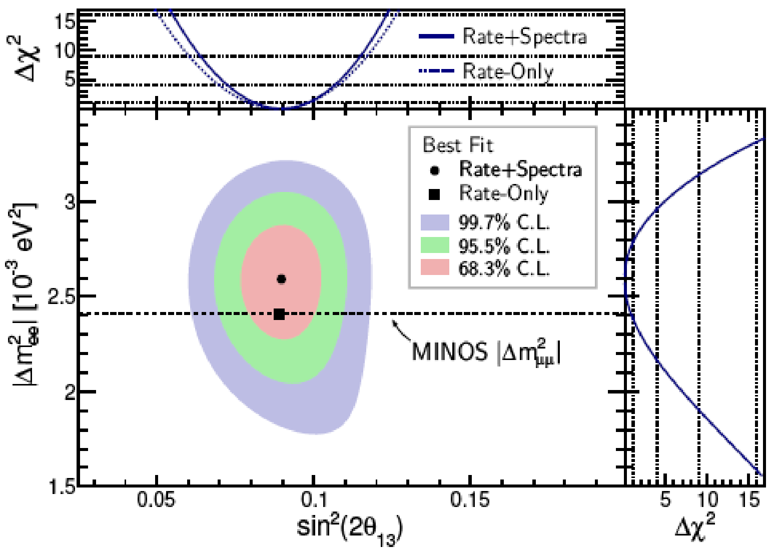
Mar.8, 2012, with 55 day data, $\sin^2 2\theta_{13}$=0.092±0.016(stat)±0.005(syst)

5.2 σ for non-zero θ_{13}

Jun.4, 2012, with 139 day data, $\sin^2 2\theta_{13}$=0.089±0.010(stat)±0.005(syst)

7.7 σ for non-zero θ_{13}

Rate+shape analysis(NuFact2013)



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

$$|\Delta m^2_{ee}| = 2.59^{+0.19}_{-0.20} \cdot 10^{-3}\text{eV}^2$$

$$\chi^2/N_{\text{DoF}} = 162.7/153$$

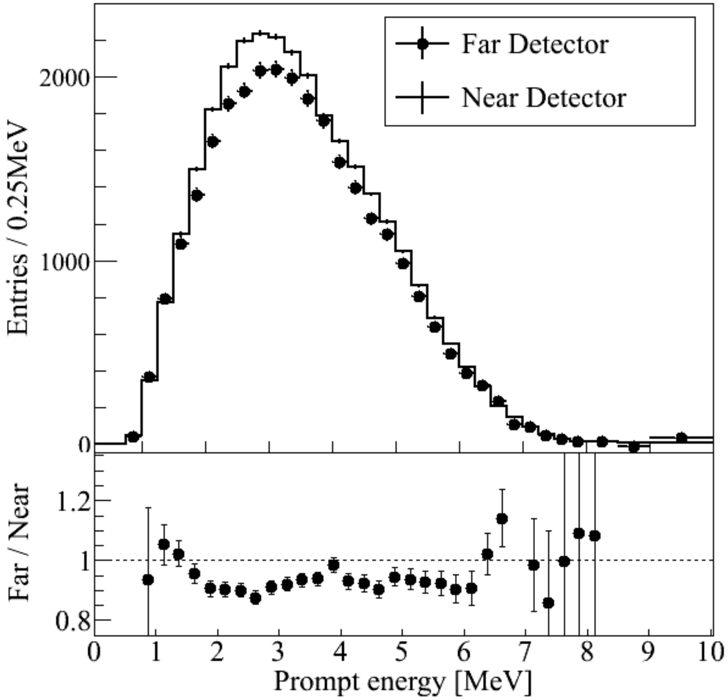
Strong confirmation of observed anti-neutrino deficit.

	Normal MH Δm^2_{32} [10^{-3}eV^2]	Inverted MH Δm^2_{32} [10^{-3}eV^2]
From Daya Bay Δm^2_{ee}	$2.54^{+0.19}_{-0.20}$	$-2.64^{+0.19}_{-0.20}$
From MINOS $\Delta m^2_{\mu\mu}$	$2.37^{+0.09}_{-0.09}$	$-2.41^{+0.11}_{-0.09}$

RENO results(NuTel2013)

▪RENO published their first result on April 2, 2012.

$$\sin^2 2\theta_{13} = 0.113 \pm 0.013(stat) \pm 0.019(syst)$$



- Total 6.5% background at Far and 2.7% background at Near.

▪ RENO has continued data-taking & data-analysis in a steady state, and reported a new result in March, 2013.

$$\sin^2 2\theta_{13} = 0.100 \pm 0.010(stat) \pm 0.015(syst)$$

$$R = \frac{\Phi^{Far}_{observed}}{\Phi^{Far}_{expected}} = 0.929 \pm 0.006(stat) \pm 0.009(syst)$$

▪ A clear deficit in rate (7.1% reduction)

▪ Consistent with neutrino oscillation in the spectral distortion

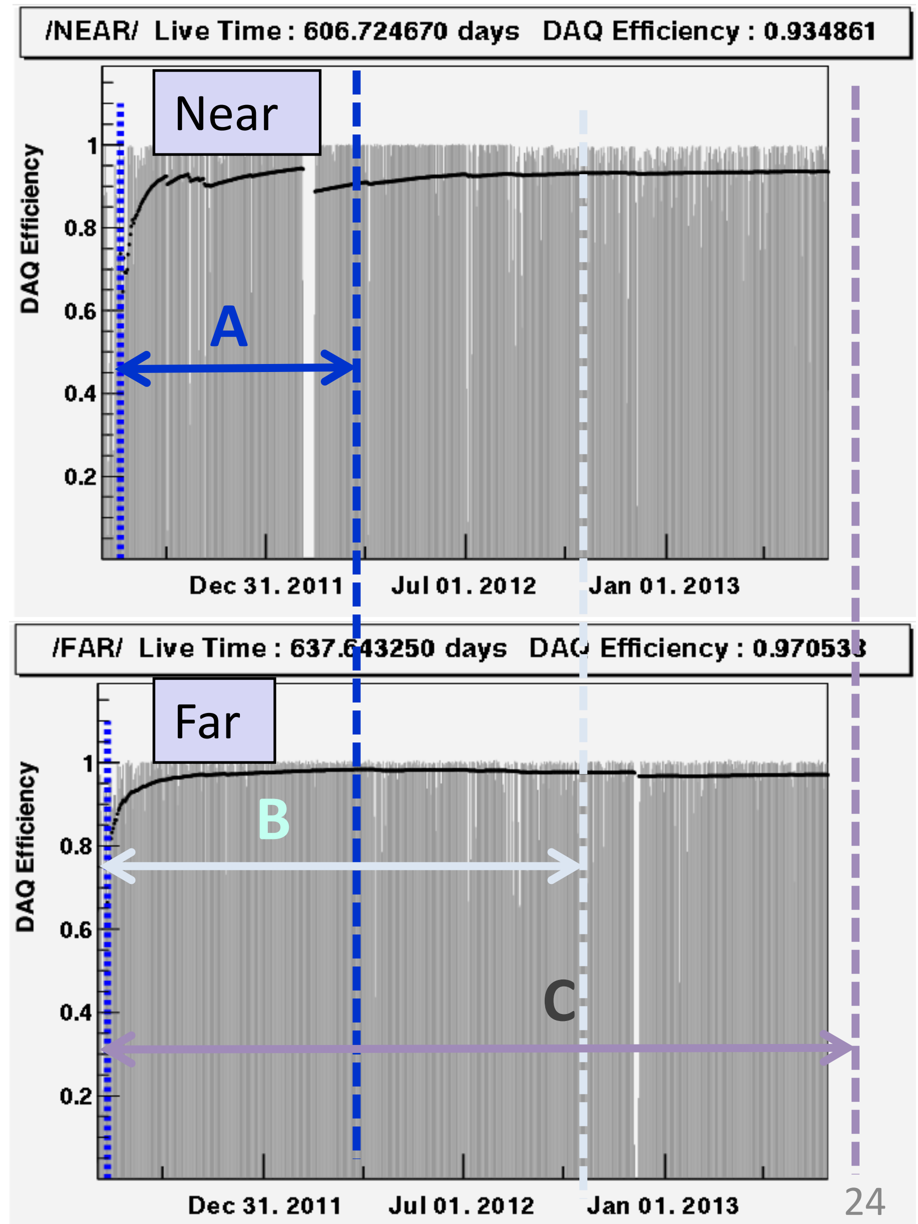
RENO Status and Plan

- Data taking began on Aug. 1, 2011 with both near and far detectors.
  (DAQ efficiency : ~95%)

- **A** (220 days) : **First theta13 result**
  [11 Aug, 2011~26 Mar, 2012]
  PRL 108, 191802 (2012)

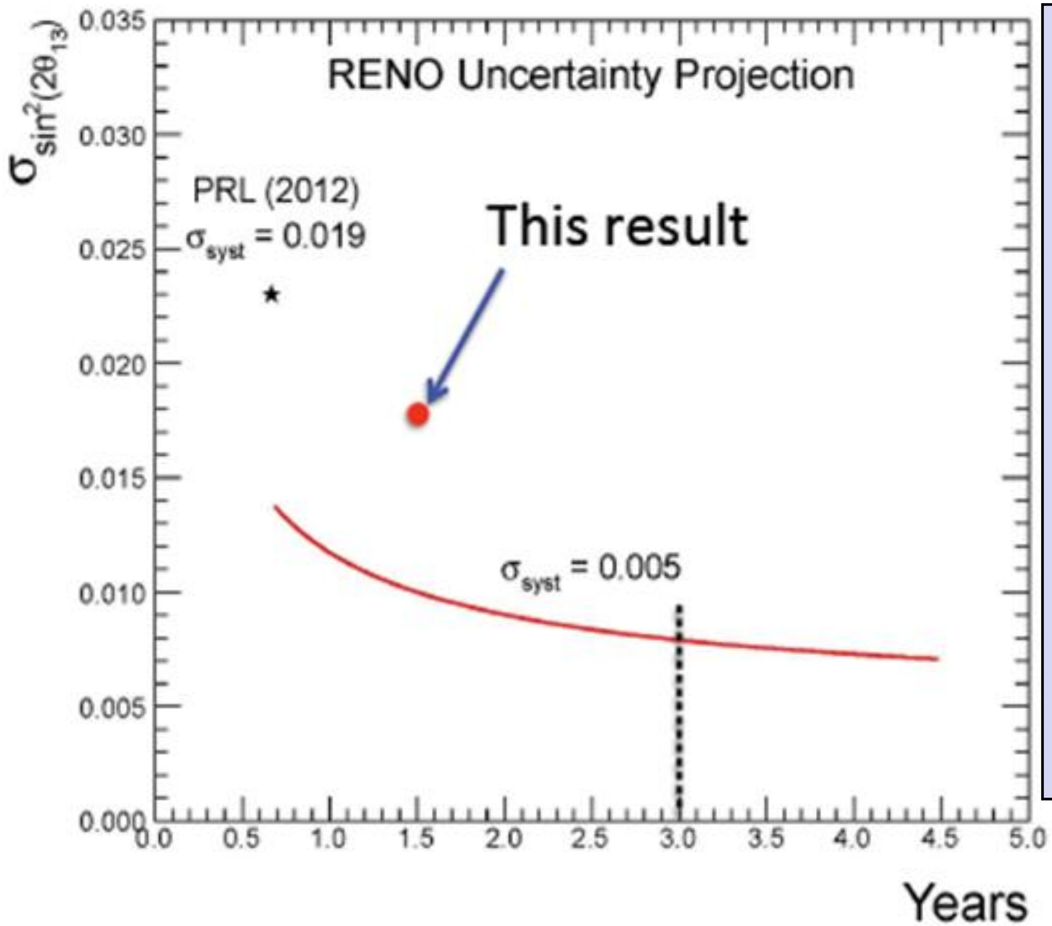
- **B** (403 days) : **Improved theta13 result**
  [11 Aug, 2011~13 Oct, 2012]
  NuTel 2013

- **C** (~700 days) : **Shape+rate analysis**
  (in progress)
  [11 Aug, 2011~31 Jul, 2013]



$$\sin^2 2\theta_{13} = 0.100 \pm 0.010(stat.) \pm 0.015(syst.)$$

(402 days) 0.100 ± 0.018 (5.6 σ) → ± 0.01 (10 σ) (3 years)



- **w/3 years of data:**
  - **Stat. error:0.006**
  - **Sys. Error:<0.011**
- **Goals**

  - $\sin^2 2\theta_{13}$ **to 7% precision**

  - direct measurement of Δm^2_{31}

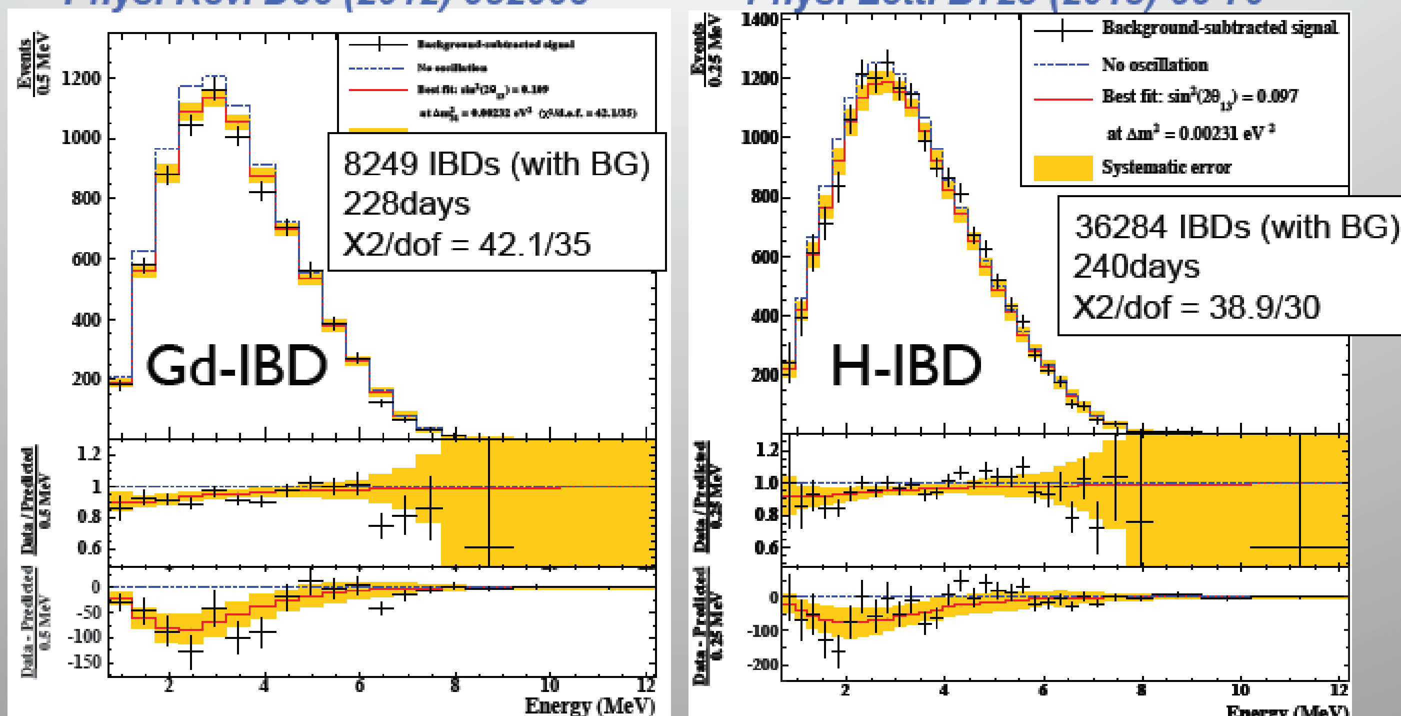
  - precise measurement of reactor neutrino flux and spectrum

  - study for reactor anomaly and sterile neutrinos

Double Chooz(NuFact2013)

Θ_{13}: rate + shape results

Phys. Rev. D86 (2012) 052008 *Phys. Lett. B723 (2013) 66-70*

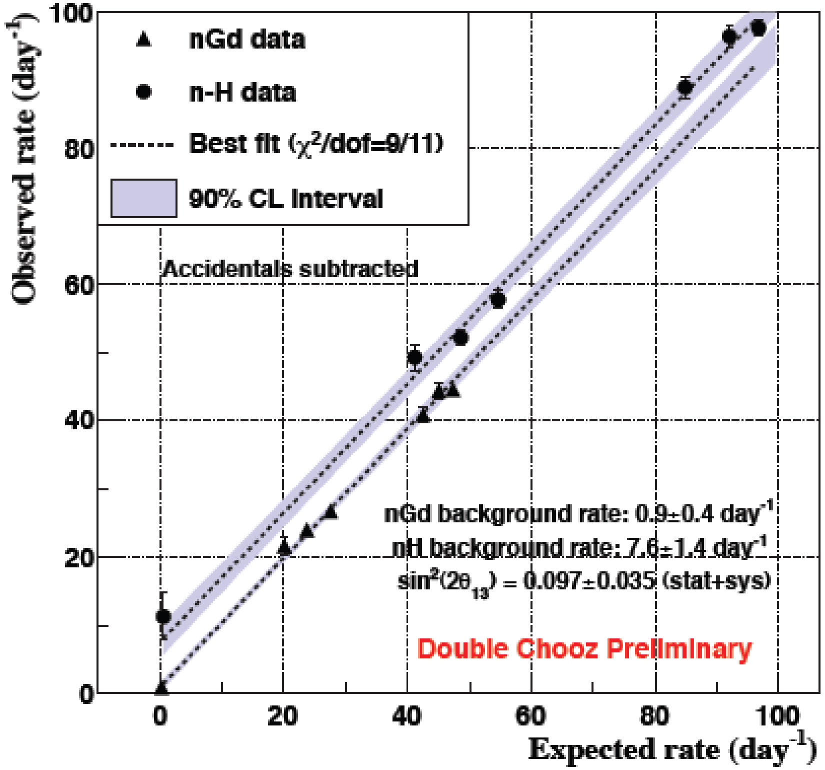


DC-II(Gd): $\sin^2 2\theta_{13} = 0.109 \pm 0.039$ [$0.030^{stat} \pm 0.025^{syst}$]

DC-II(H): $\sin^2 2\theta_{13} = 0.097 \pm 0.048$ [$0.034^{stat} \pm 0.034^{syst}$]

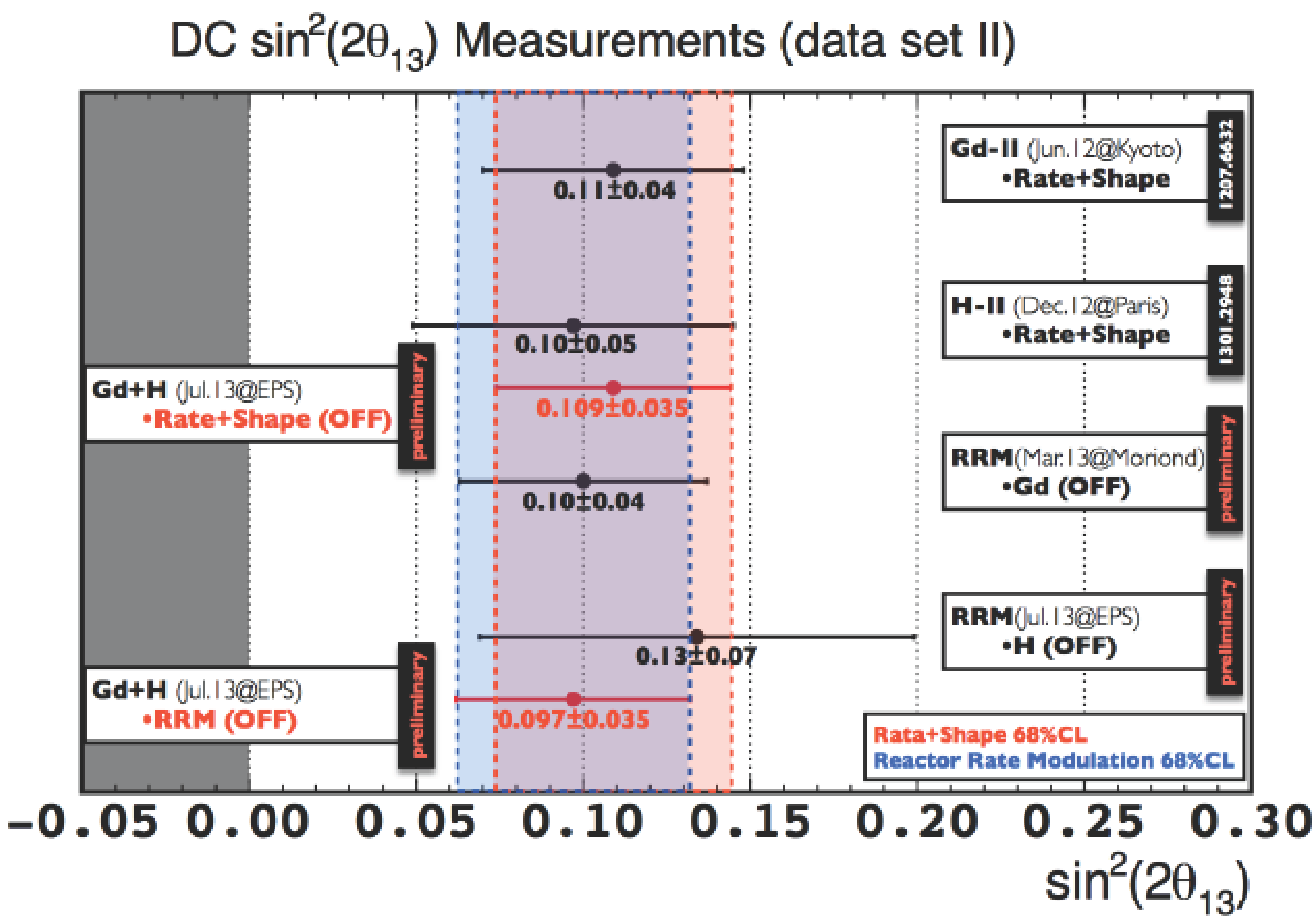
Combined Gd and H fit: $\sin^2 2\theta_{13} = 0.109 \pm 0.035$

Results of analysis with reactor rate modulation $\sin^2 2\theta_{13} = 0.097 \pm 0.035$

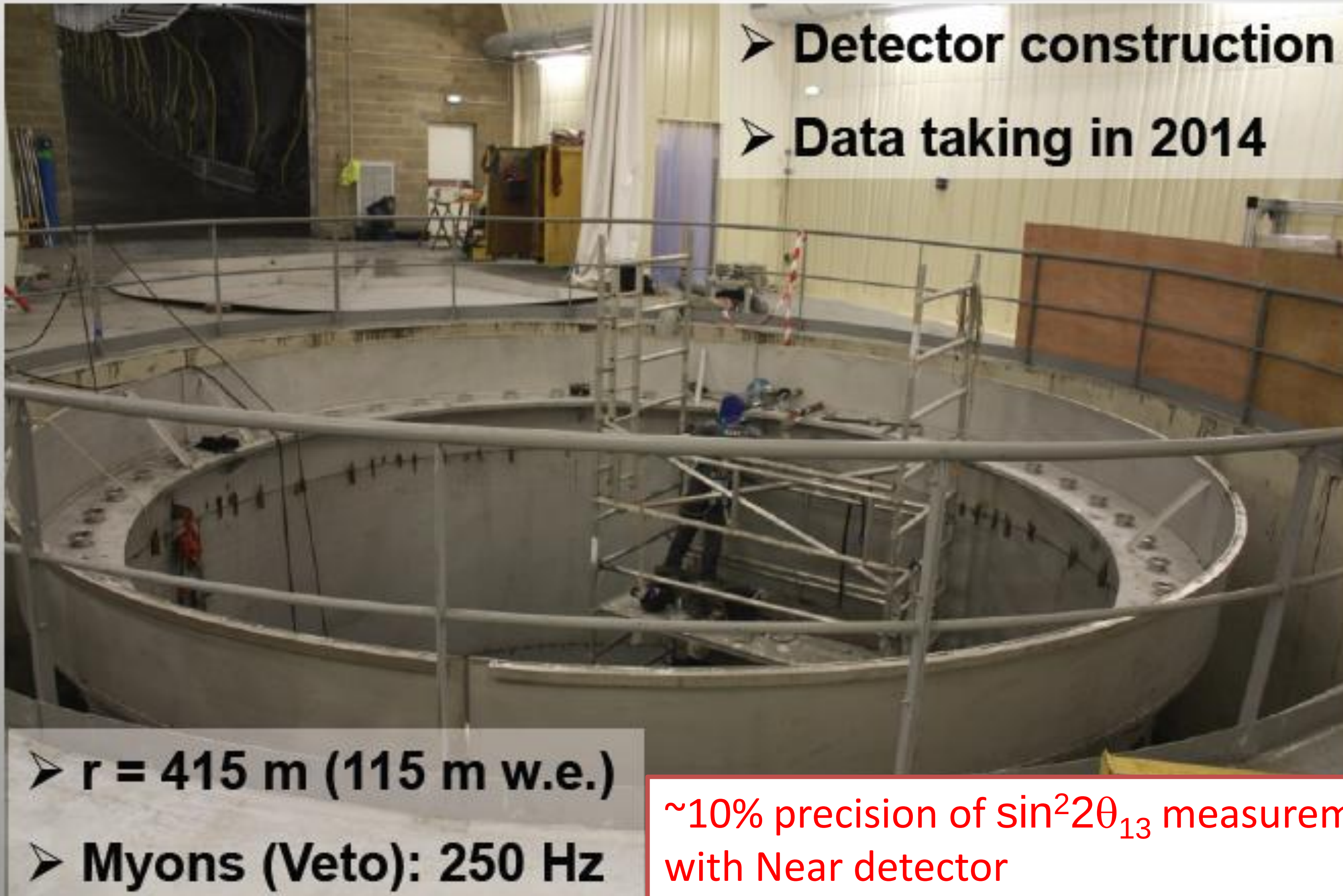


- Data: April 2011 - March 2012
- Using dependence of ν rate on reactor power
- Independent of BG estimation
- Best fit: $\sin^2 2\theta_{13} = 0.097 \pm 0.035$
- Consistent with Double Chooz rate+shape results

Double Chooz Status and plan



Near detector



~10% precision of $\sin^2 2\theta_{13}$ measurement with Near detector

DayaBay Status and Plan

A. Two AD Comparison: arXiv:1202:6181

- Sep. 23, 2011 – Dec. 23, 2011 NIM **A685**:78
- Side-by-side comparison of 2 detectors

B. First Oscillation result: arXiv:1203:1669

- Dec. 24, 2011 – Feb. 17, 2012 (6 ADs)

-1st observation of ν_e dis. **PRL108:171803**

C. Improved Result: arXiv:1210:6327

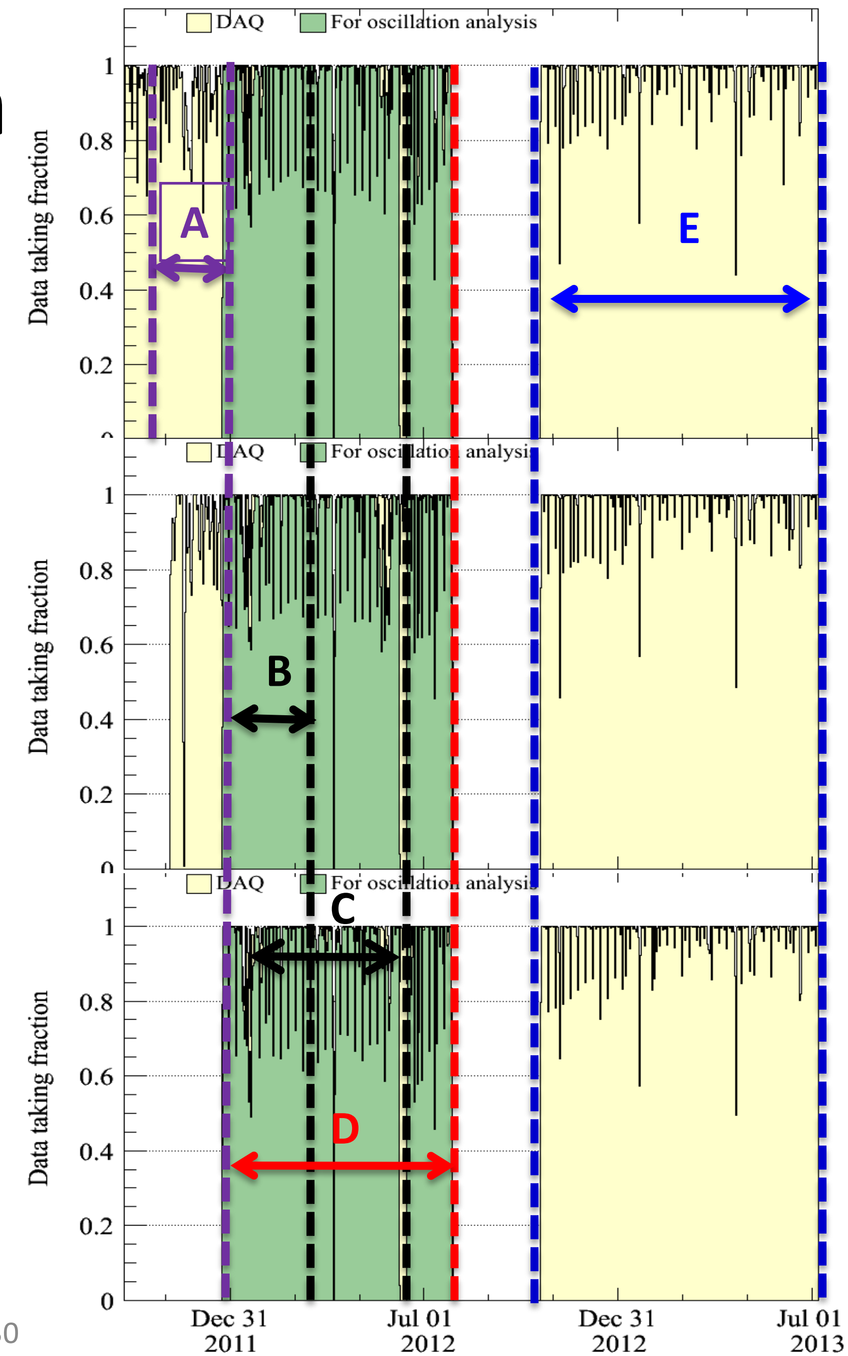
- Dec. 24, 2011 – May 11, 2012
- 2.5x original data, **CPC37:011001**

D. New analysis

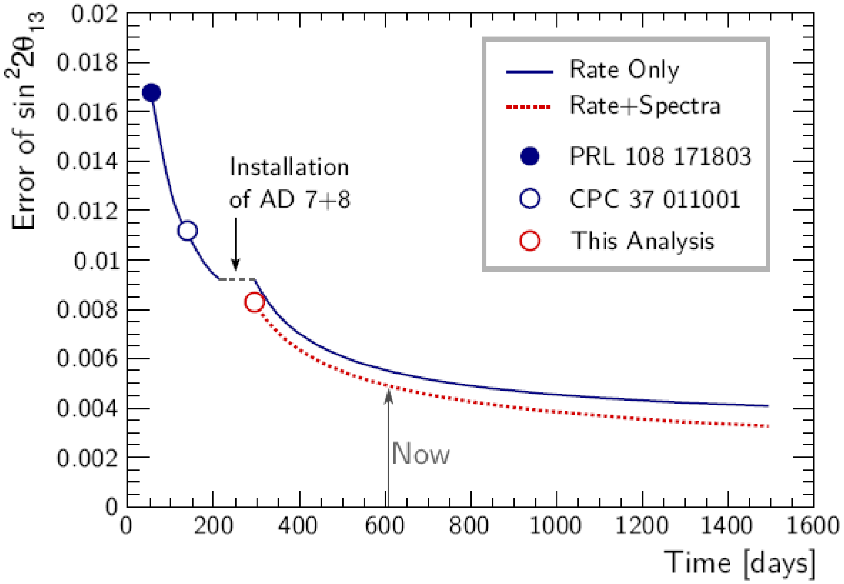
- Dec. 24, 2011 – July 28, 2012
- 4x original data; shape, Δm^2_{ee} analysis

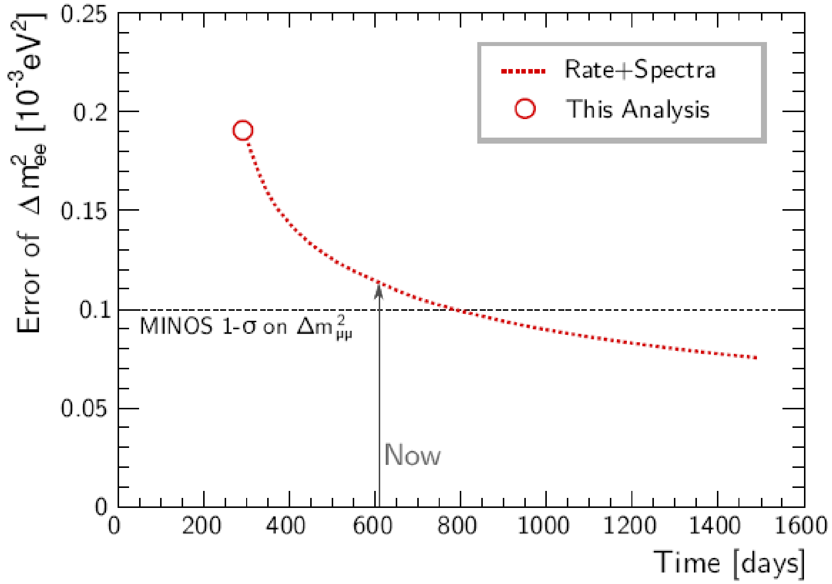
E. Full experiment (8 AD)

- Oct. 19, 2012 – present

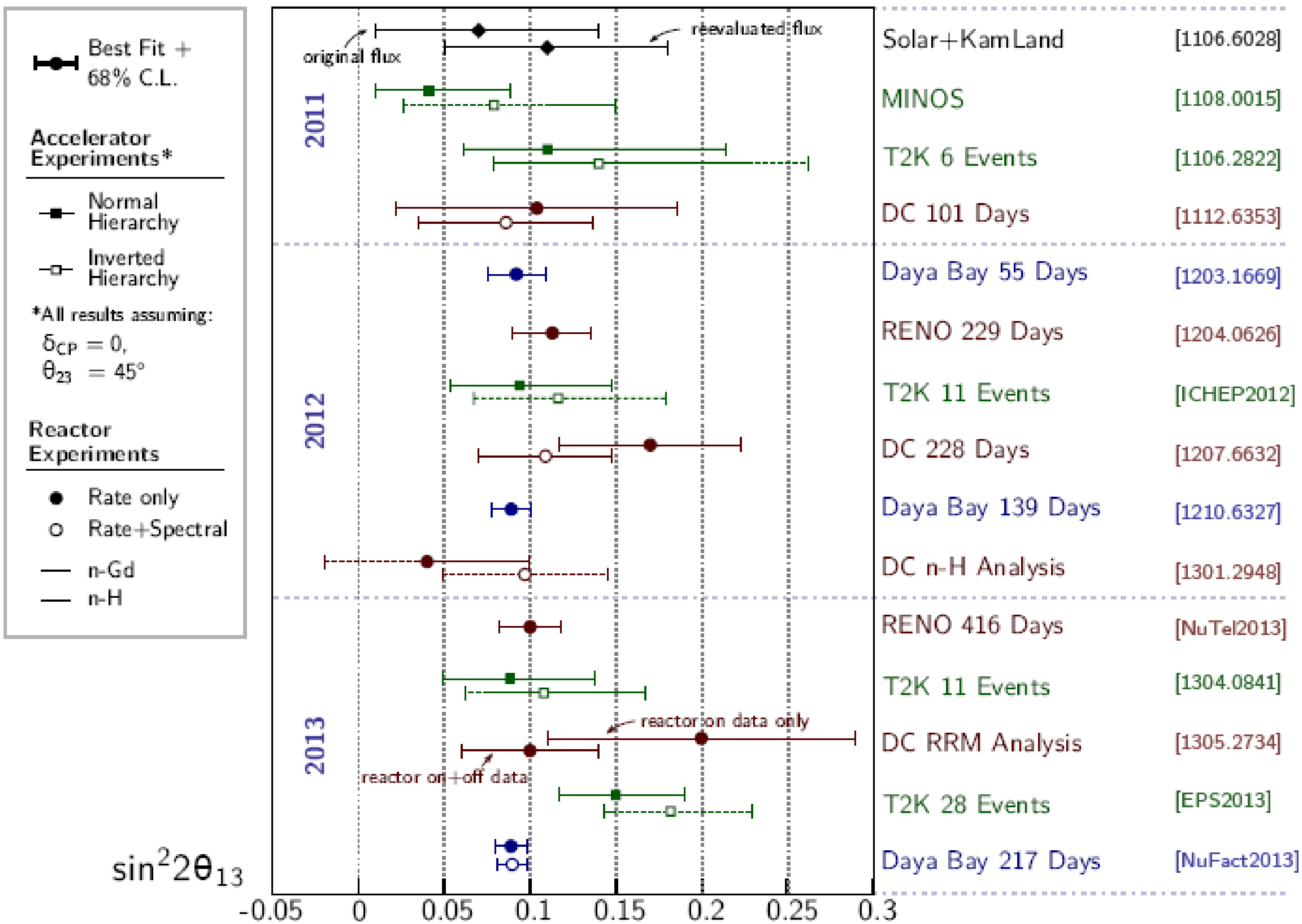


- **Measure of θ_{13} with high precision:**
  - Uncertainty of $\sin^2 2\theta_{13}$<4%.
- **Measure Δm_{ee}^2 complementary to accelerator-based experiments.**
- Further scientific goals:
  - Measure reactor flux/spectrum: possibly resolve ambiguities in reactor predictions and anomaly.
  - Measure neutron and spallation production for various muon energies in different depths.





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



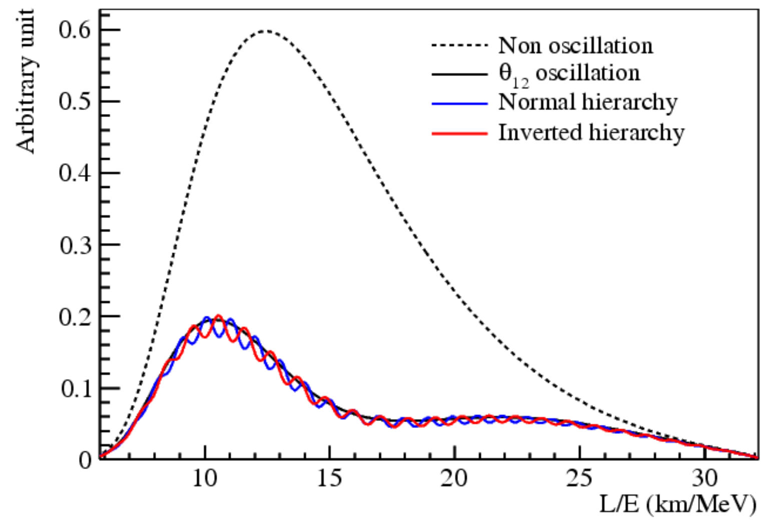
Future prospects

- **Next generation experiment :**
  - Main focus: Mass hierarchy and CP phase
- **Measuring Mass Hierarchy by Reactor neutrinos**
  - Method: distortion of energy spectrum
  - Mass hierarchy independent of the CP phase

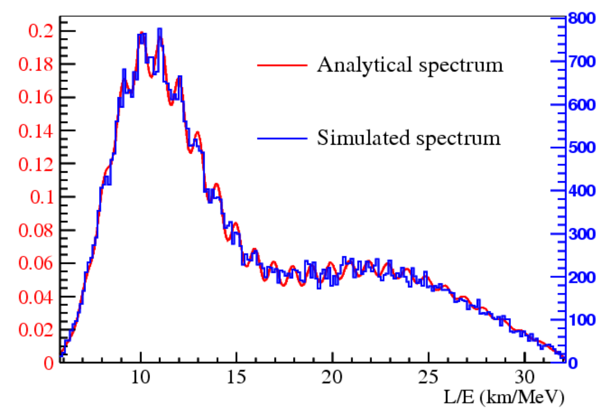
$$F(L/E) = \phi(E)\sigma(E)P_{ee}(L/E)$$

$$\begin{aligned} P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\ P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\ P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\ P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32}) \end{aligned}$$

$$\Delta_{21} << \Delta_{31} \approx \Delta_{32}$$



S.T. Petcov et al., PLB533(2002)94
S.Choubey et al., PRD68(2003)113006
J. Learned et al., hep-ex/0612022
L. Zhan, Y. Wang, J. Cao, L. Wen, PRD78:111103, 2008
PRD79:073007, 2009



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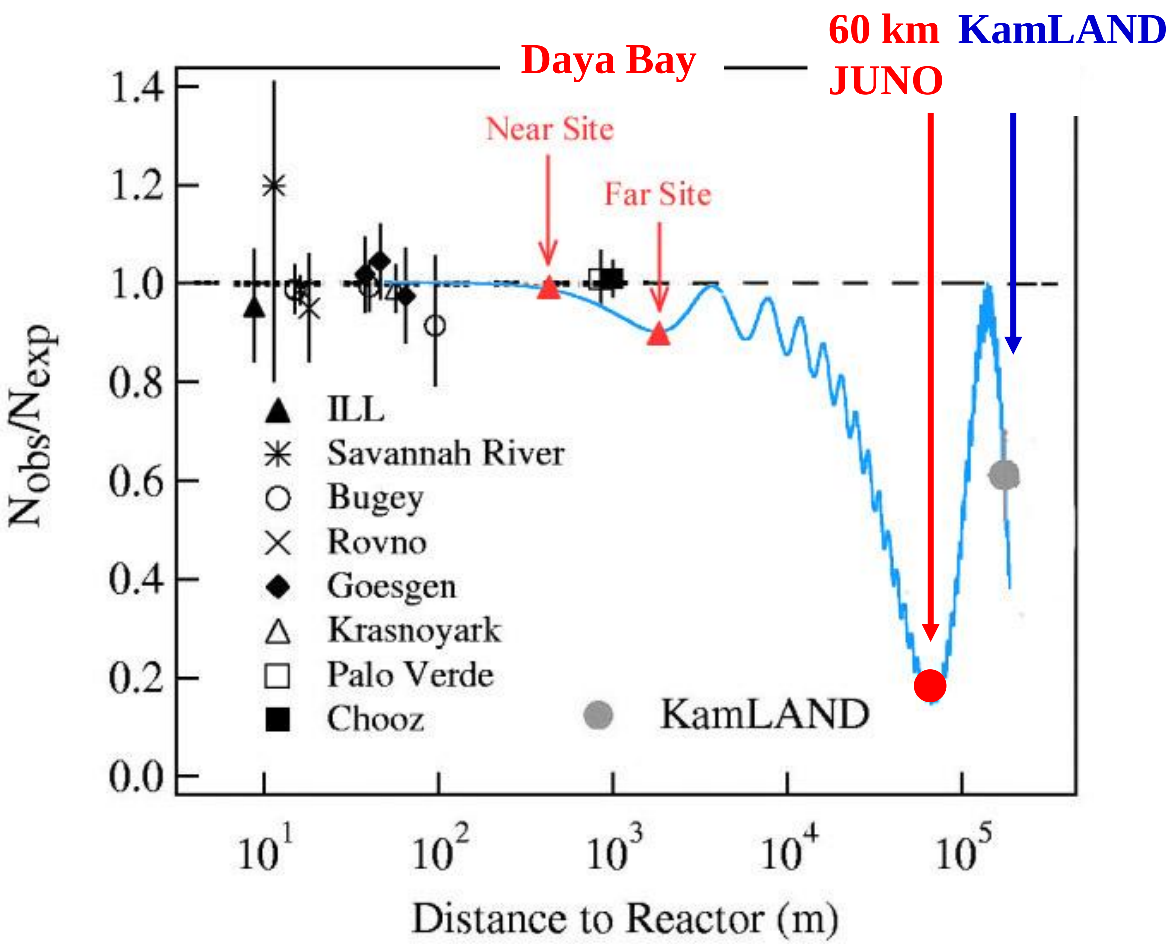
The Jiangmen Underground Neutrino Observatory

(JUNO, known as Daya Bay II)

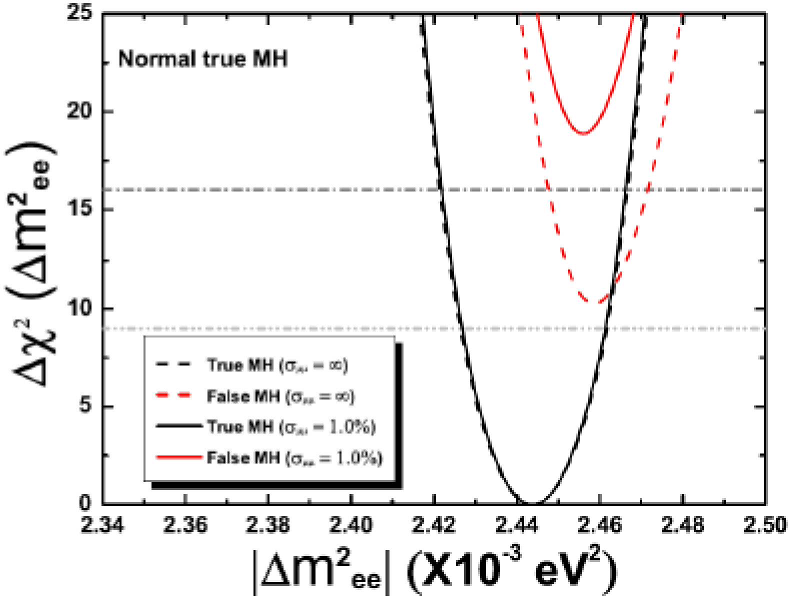


- **20 kton LS detector**
- **3% energy resolution**
- Rich physics possibilities
  - ⇨ **Mass hierarchy**
  - ⇨ **Precision measurement of 4 mixing parameters**
  - ⇨ **Supernovae neutrino**
  - ⇨ **Geoneutrino**
  - ⇨ **Sterile neutrino**
  - ⇨ **Atmospheric neutrinos**
  - ⇨ **Exotic searches**

Talk by Y.F. Wang at ICFA seminar 2008, Neutel 2011; by J. Cao at Nutel 2009, NuTurn 2012 ;
Paper by L. Zhan, Y.F. Wang, J. Cao, L.J. Wen, PRD78:111103,2008; PRD79:073007,2009

Physics prospective of JUNO

Y.F Li *et al*, arXiv:1303.6733



Probing the unitarity of U_{PMNS} to ~1%

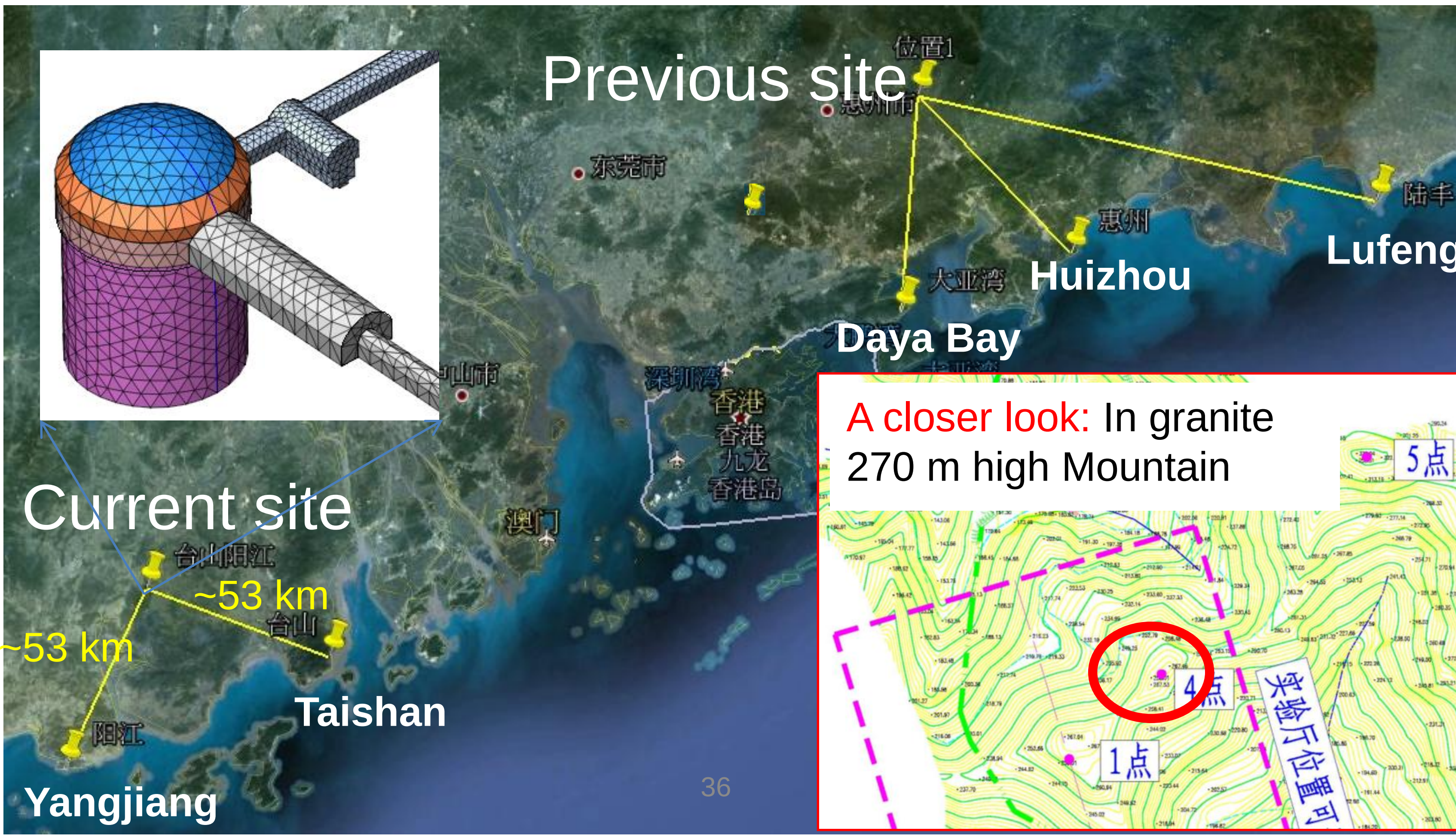
	Current	JUNO
Δm^2_{12}	~3%	~0.6%
Δm^2_{23}	~5%	~0.6%
$\sin^2\theta_{12}$	~6%	~0.7%
$\sin^2\theta_{23}$	~20%	N/A
$\sin^2\theta_{13}$	~14% → ~4%	~ 15%

MH sensitivity with 6 years' data of JUNO (*arXiv:1303.6733*)**:**

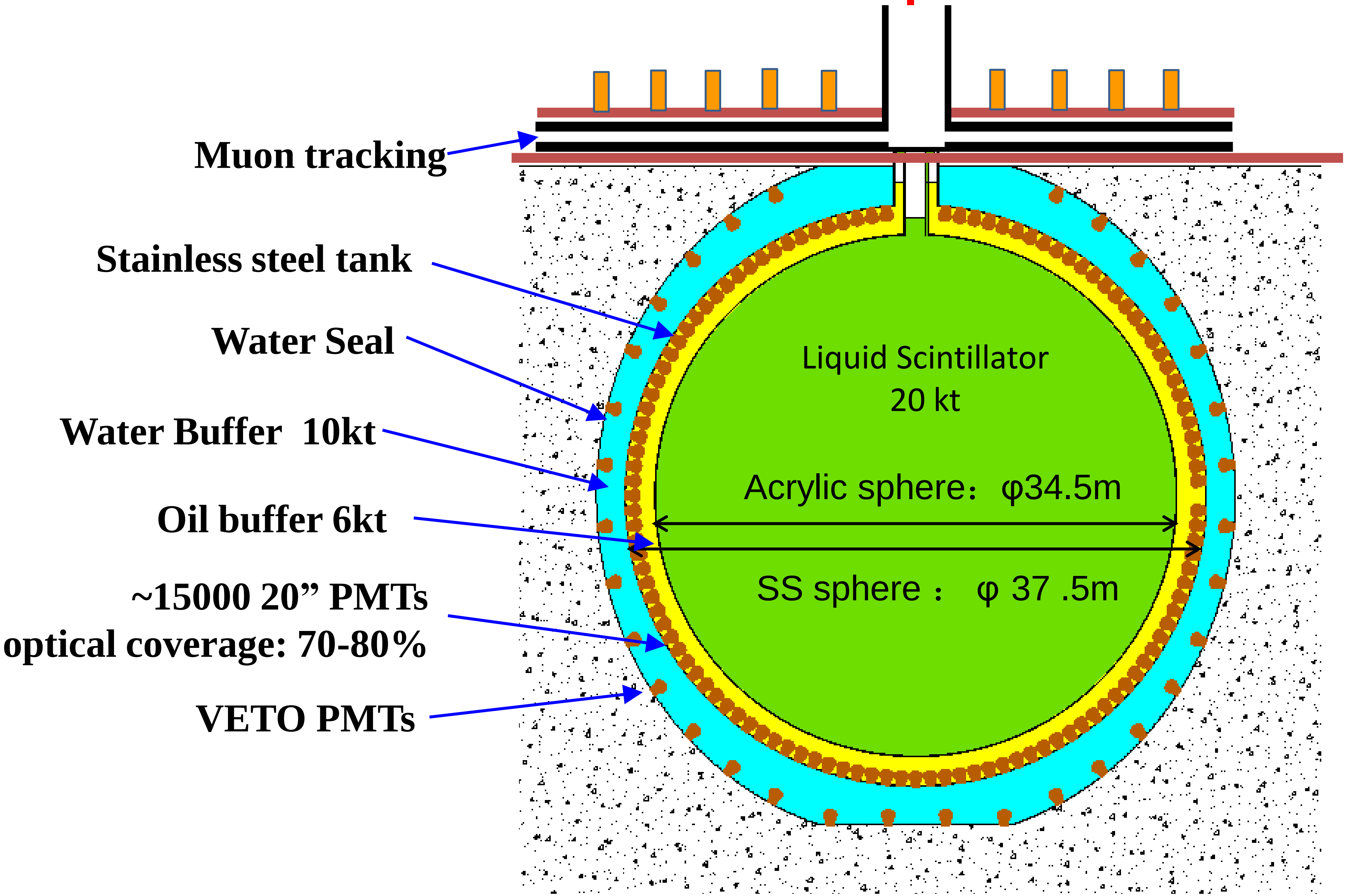
- **Taking into account the spread of reactor cores, uncertainties from energy non-linearity, etc.**
  - **Δχ2>9(3sigma) with relative measurement**
  - **Δχ2>16(4sigma) with absolute Δm2 measurement**

Experiment site: Kaiping county, Jiangmen city

	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	approved	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW



Detector Concept



Project status

Funding

Great support from CAS: “special fund for advancement”

Approved on Feb.1, 2013

Brief schedule

Construction: 2013-2019

Filling & data taking： 2020

Overview of RENO-50

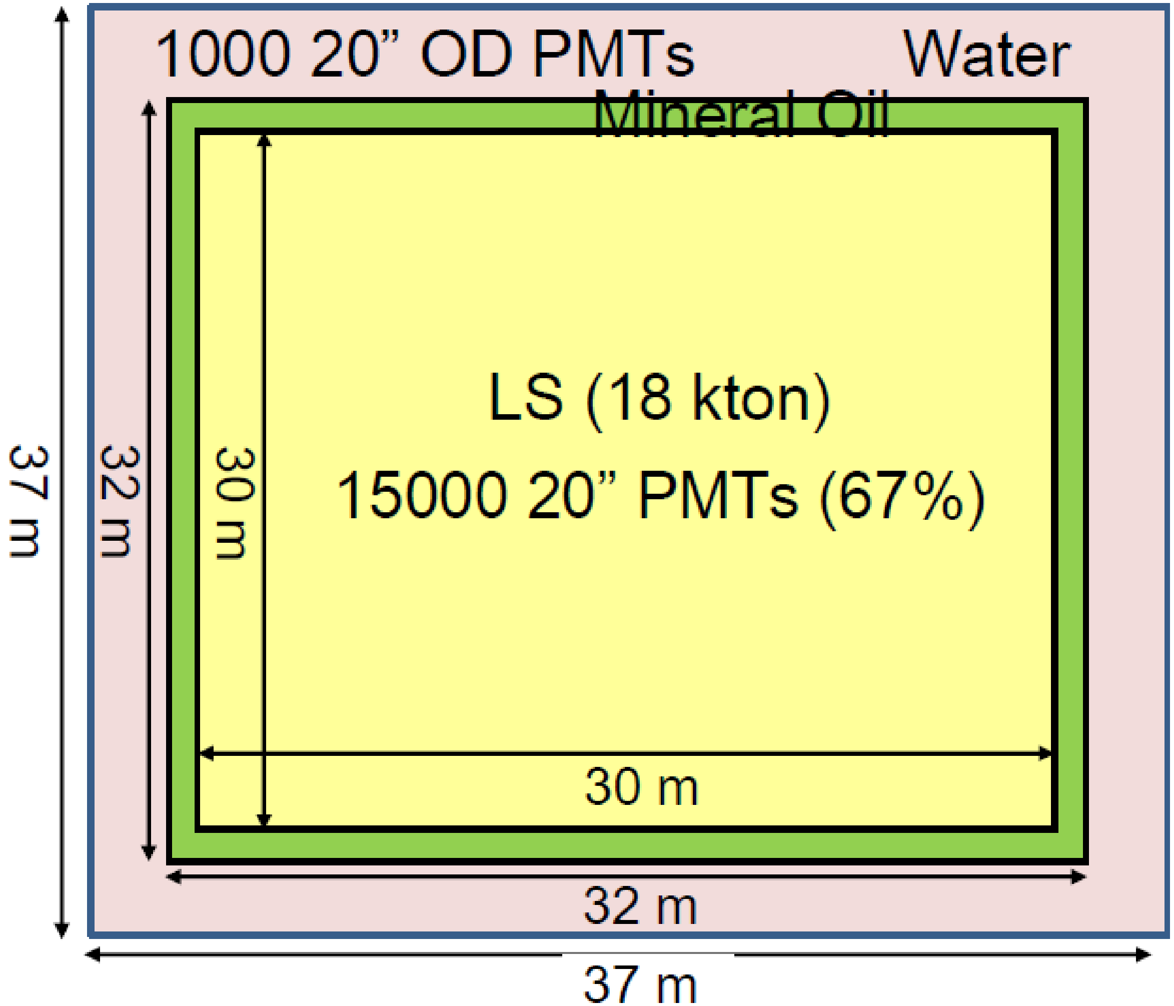
- **RENO-50** : An underground detector consisting of 18 kton ultra-low-radioactivity liquid scintillator & 15,000 20" PMTs, at 50 km away from the Hanbit(Yonggwang) nuclear power plant

- **Goals** : - High-precision measurement of θ_{12} and Δm^2_{21}
  - Determination of neutrino mass hierarchy
  - Study neutrinos from reactors, (the Sun), the Earth, Supernova, and any possible stellar objects

- **Budget** : $ 100M for 6 year construction
  (Civil engineering: $ 15M, Detector: $ 85M)

- **Schedule** : 2013 ~ 2018 : Facility and detector construction
  2019 ~ : Operation and experiment

Conceptual Design of RENO-50



Summary

- Reactor neutrino experiments have obtained a big achievement in θ_{13} measurement in past two years:
  - Daya Bay experiment discovered the new oscillation and proved θ_{13} is quite large.
  - RENO and Double Chooz experiments get the consist results.
  - The precision on $\sin^2 2\theta_{13}$ will be improved to ~4%
- Future prospects:
  - The reactor neutrinos will continue to play an important role:
    - Mass hierarchy
    - Precision measurement of mixing parameters up to < 1% level ➔ unitarity test of the mixing matrix

Thanks

Backup

Relative Measurement

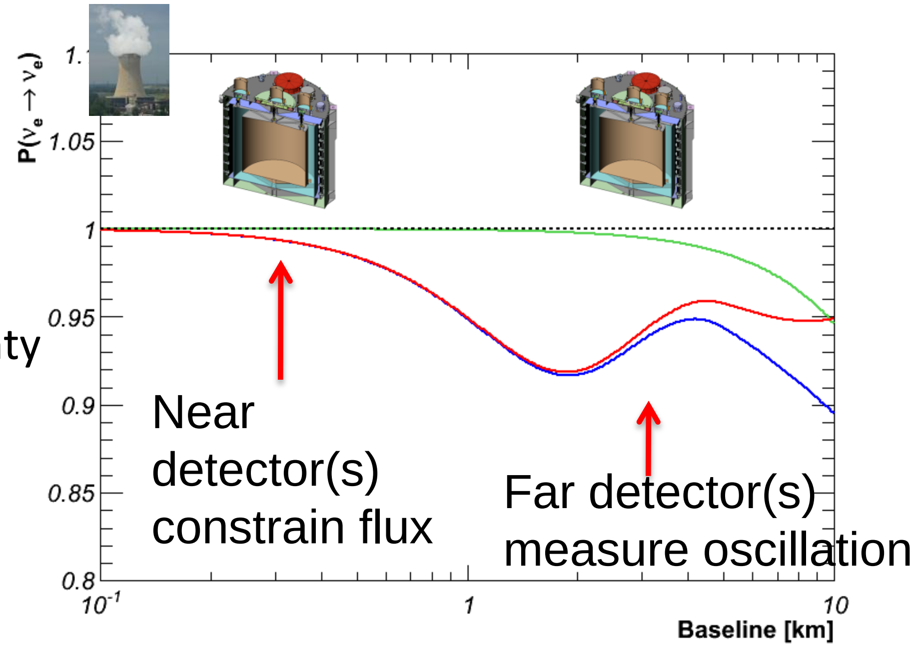
Absolute Reactor Flux:

Largest uncertainty in previous measurements

Relative Measurement:

Multiple detectors removes absolute uncertainty

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



Far/Near ν_e Ratio

Distances from reactor

Oscillation deficit

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

Detector Target Mass

Detector efficiency

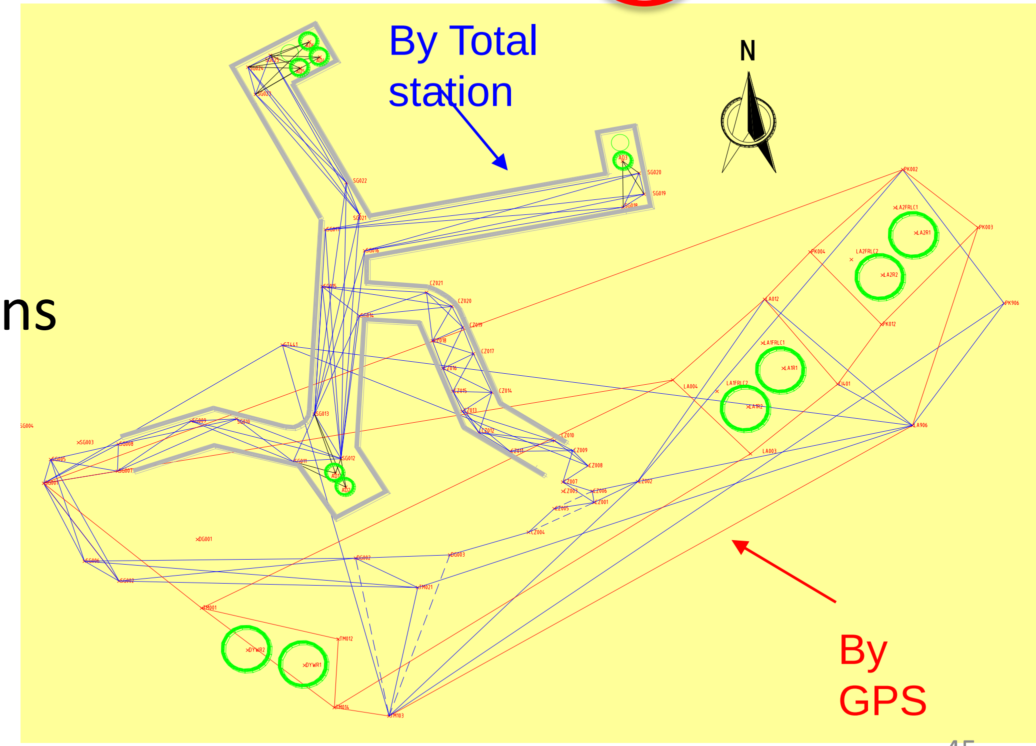
Experiment Survey

Negligible reactor flux uncertainty (<0.02%) from precise survey.

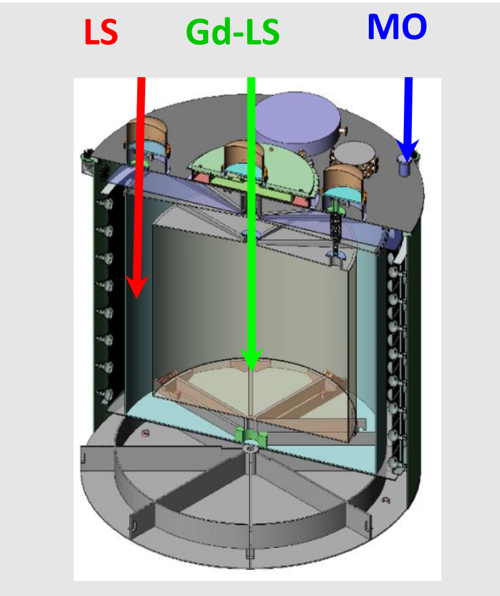
$$\frac{N_{\rm f}}{N_{\rm n}} = \left(\frac{N_{\rm p,f}}{N_{\rm p,n}}\right)\left(\frac{L_{\rm n}}{L_{\rm f}}\right)^2\left(\frac{\epsilon_{\rm f}}{\epsilon_{\rm n}}\right)\left[\frac{P_{\rm sur}(E,L_{\rm f})}{P_{\rm sur}(E,L_{\rm n})}\right]$$

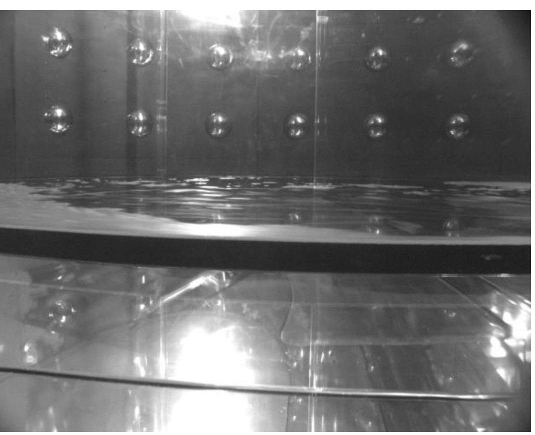
Detailed Survey:
- GPS above ground
- Total Station underground
- Final precision: 28mm

Validation:
- Three independent calculations
- Cross-check survey
- Consistent with reactor plant and design plans



Detector Filling





Detector target filled from GdLS in ISO tank.

Load cells measure 20 ton target mass to 3 kg (0.015%)

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

3 fluids filled simultaneously, with heights matched to minimize stress on acrylic vessels

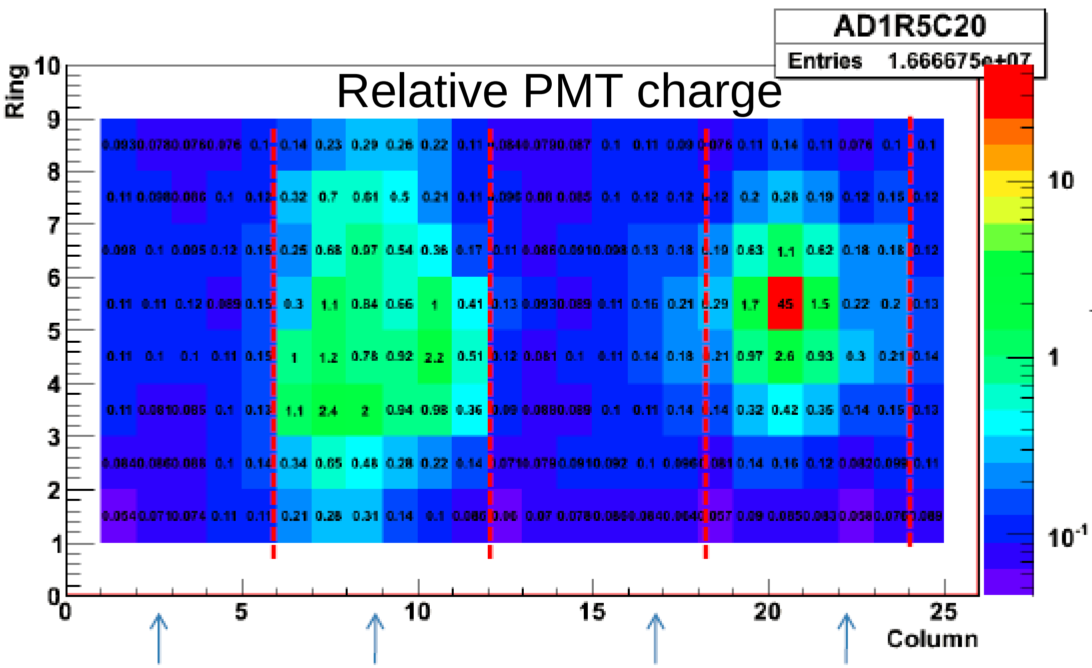
- **Gadolinium-doped Liquid Scintillator (GdLS)**
- **Liquid Scintillator (LS)**
- **Mineral Oil (MO)**

Liquid Scintillator Hall

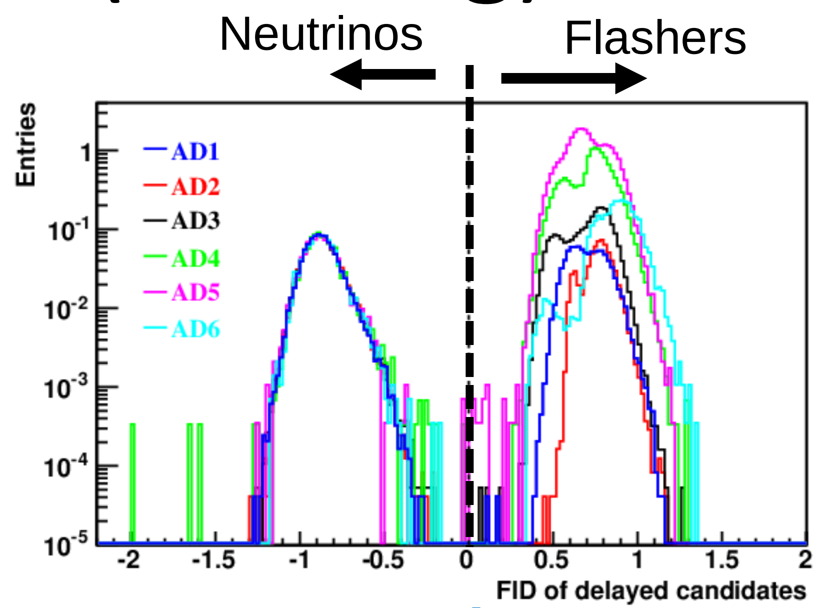
PMT Light Emission (Flashing)

Flashing PMTs:

- Instrumental background from ~5% of PMTS
- ‘Shines’ light to opposite side of detector
- Easily discriminated from normal signals



Quadrant 4 Quadrant 3 Quadrant 2 Quadrant 1
(contains ‘hottest’ PMT)



$$FID = \log_{10}((MaxQ)^2/(0.45)^2 + (Quad)^2)$$

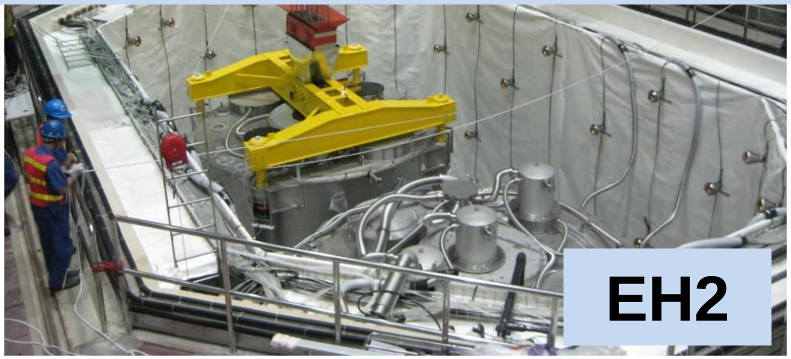
Quadrant = Q3/(Q2+Q4)

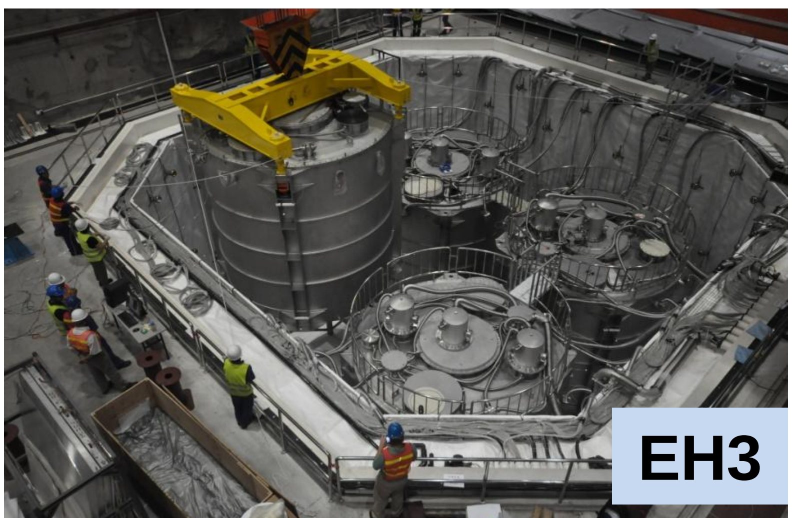
MaxQ = maxQ/sumQ

Inefficiency to antineutrinos signal:
0.024% ± 0.006%(stat)
Contamination: < 0.01%

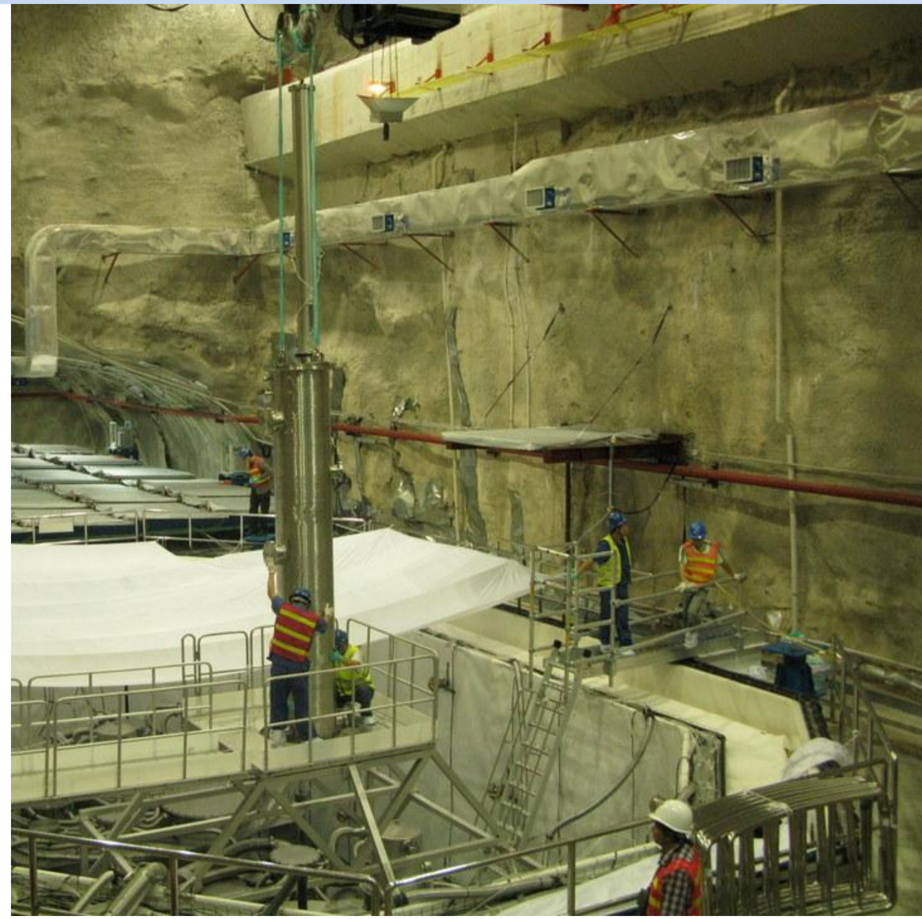
Daya Bay Onsite Progress

Final two detectors installed, operating since Oct. 2012.



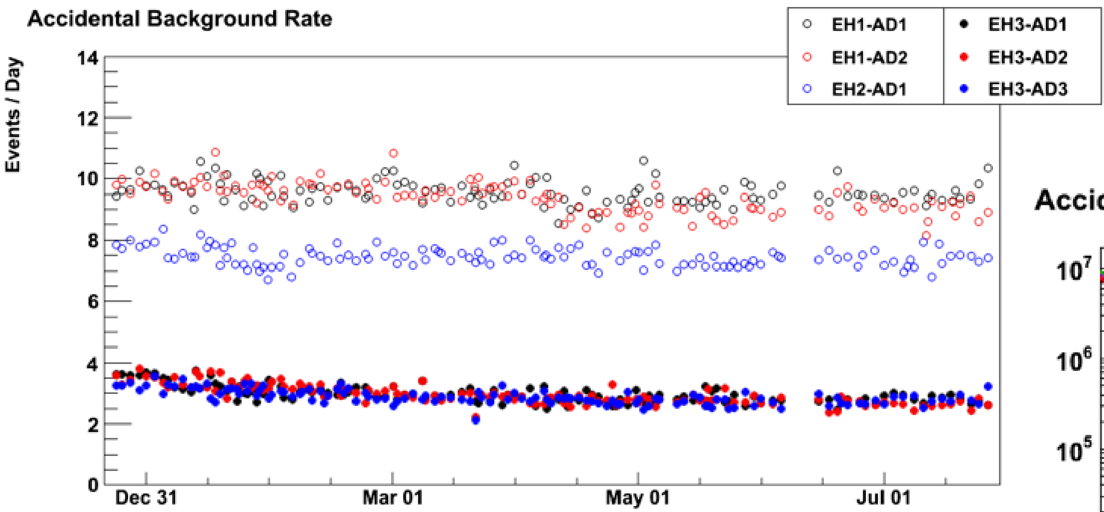


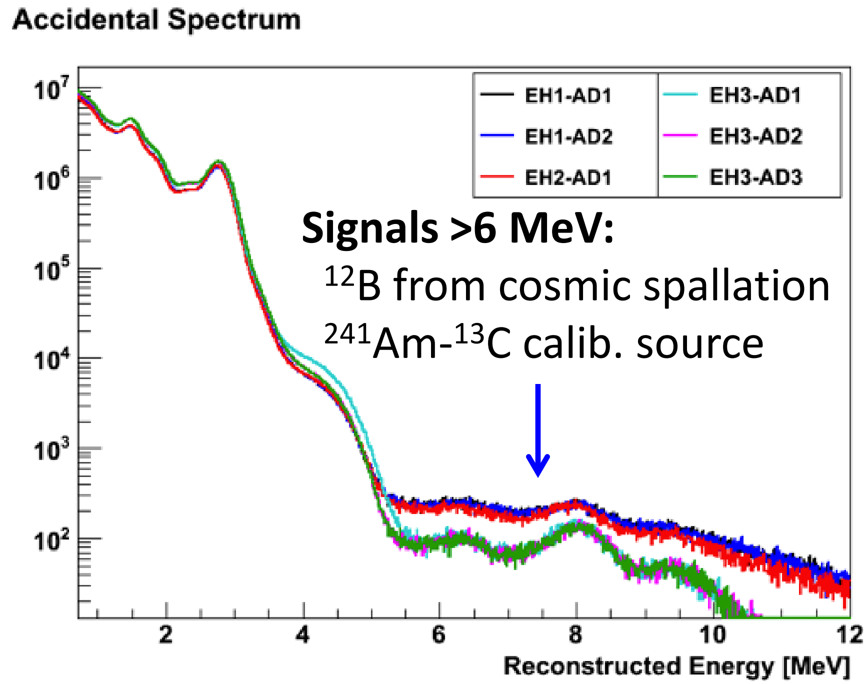
Full 4π detector calibration in Sep. 2012.



Accidental Background

Two uncorrelated signals can accidentally mimic an antineutrino signal.





Accidental B/S is 4% (1.5%) of far (near) signal.

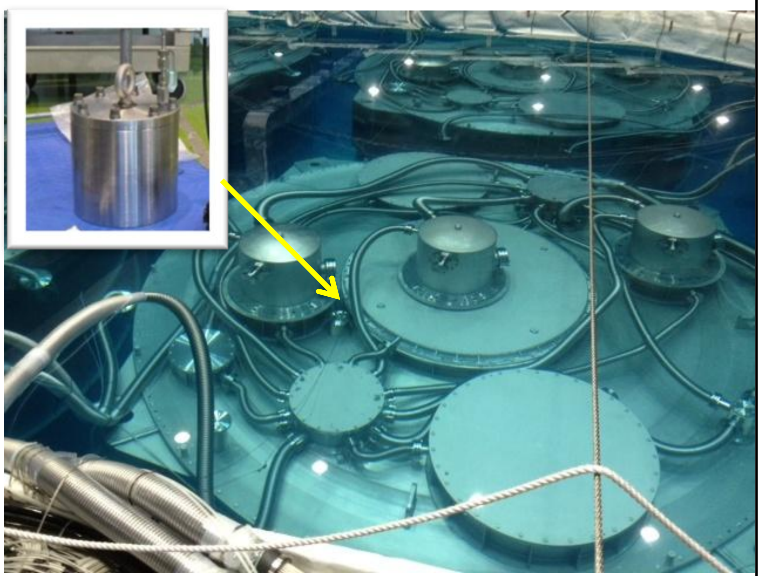
Accidental background be accurately modeled using uncorrelated signals in data.

➔ Negligible uncertainty in background rate or spectra.

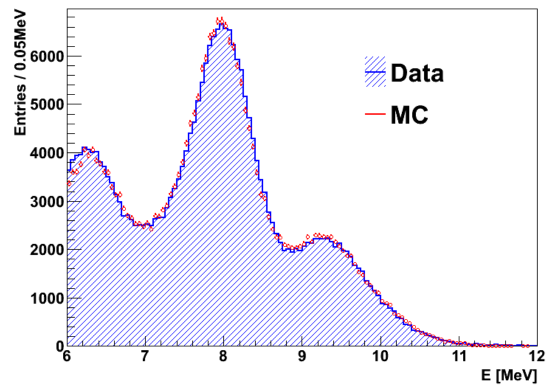
^{241}Am-^{13}C Background

Background rate and shape constrained using intense source

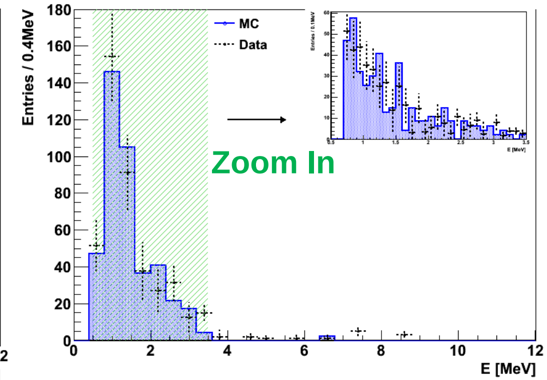
A special x80 stronger ^{241}Am-^{13}C source placed on the AD



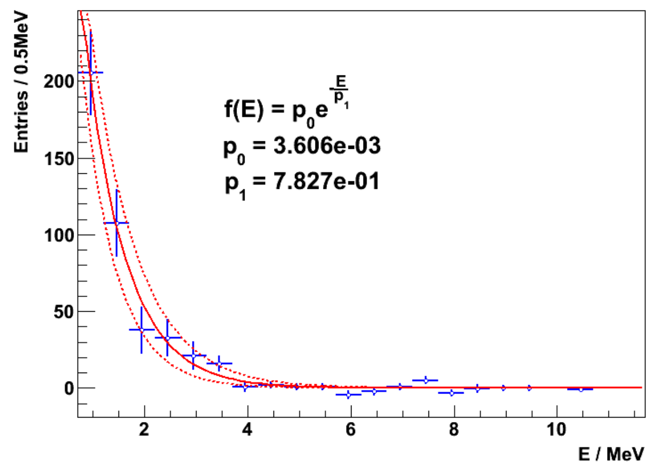
Single n-like



Correlated prompt spectrum



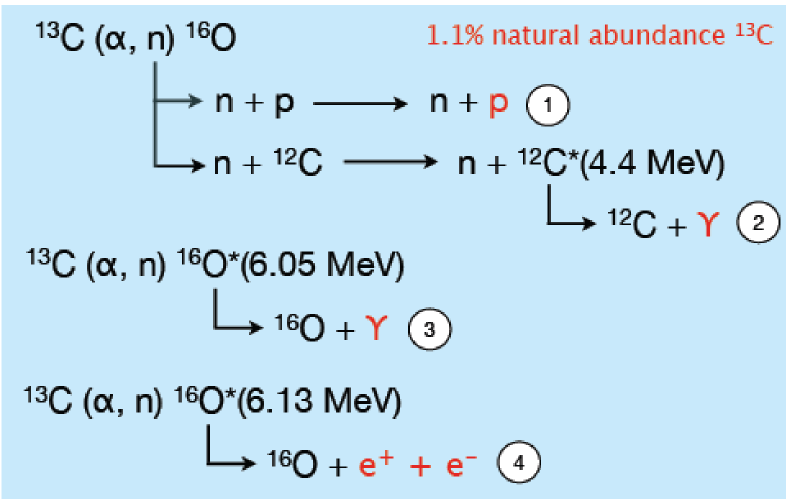
Correlated background in physics run = single n-like in physics run (rate) x correlated/single ratio in strong AmC (spectrum)



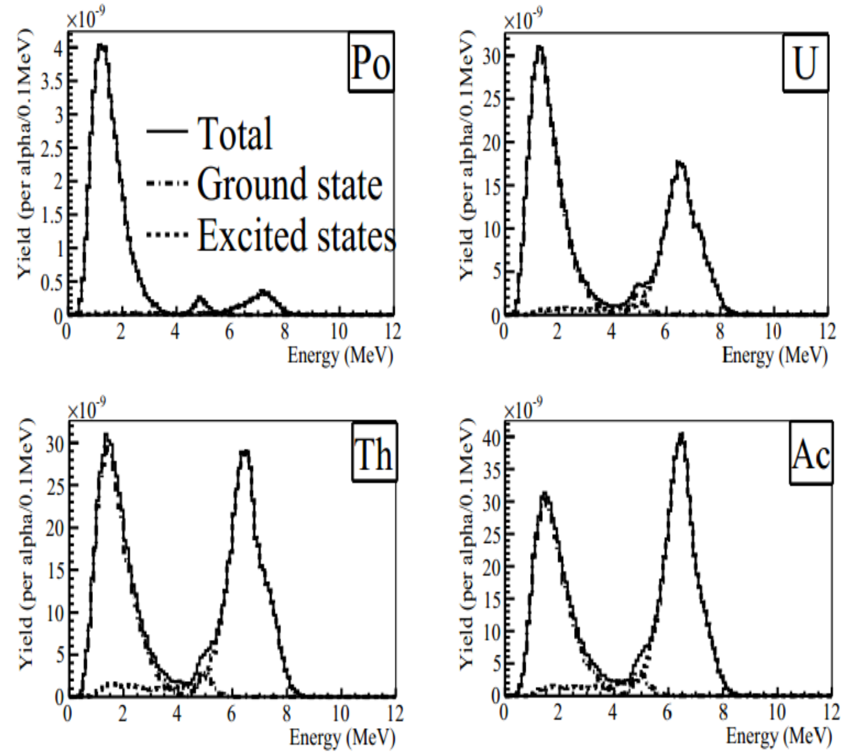
- Rate: 0.26/day/module (global uncert. 45%
- Spectrum: exponential (global uncert 15%)

Background: $^{13}C(\alpha,n)^{16}O$

Alphas from intrinsic radioactivity (^{238}U, ^{232}Th, ^{235}U, ^{210}Po) measured in-situ.
Background rate and spectra modeled using known $^{13}C(\alpha,n)^{16}O$ cross-section.



Example alpha rate in AD1	^{238}U	^{232}Th	^{235}U	^{210}Po
Bq	0.05	1.2	1.4	10



Near Sites: (0.05 to 0.08)±0.04 per day, B/S (0.01±0.006)%

Far Site: 0.04±0.02 per day, B/S (0.05±0.03)%

A Comment on Δm^2

Short-baseline reactor experiments insensitive to neutrino mass hierarchy.

Cannot discriminate two frequencies contributing to oscillation: Δm^2_{31}, Δm^2_{32}

One effective oscillation frequency is measured:

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

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

Result can be easily related to actual mass splitting, based on true hierarchy:

$$|\Delta m^2_{ee}| \simeq |\Delta m^2_{32}| \pm 5.21 \times 10^{-5} \mathrm{eV}^2$$

+: Normal Hierarchy

-: Inverted Hierarchy

Hierarchy discrimination requires ~2% precision on both Δm^2_{ee} and $\Delta m^2_{\mu\mu}$