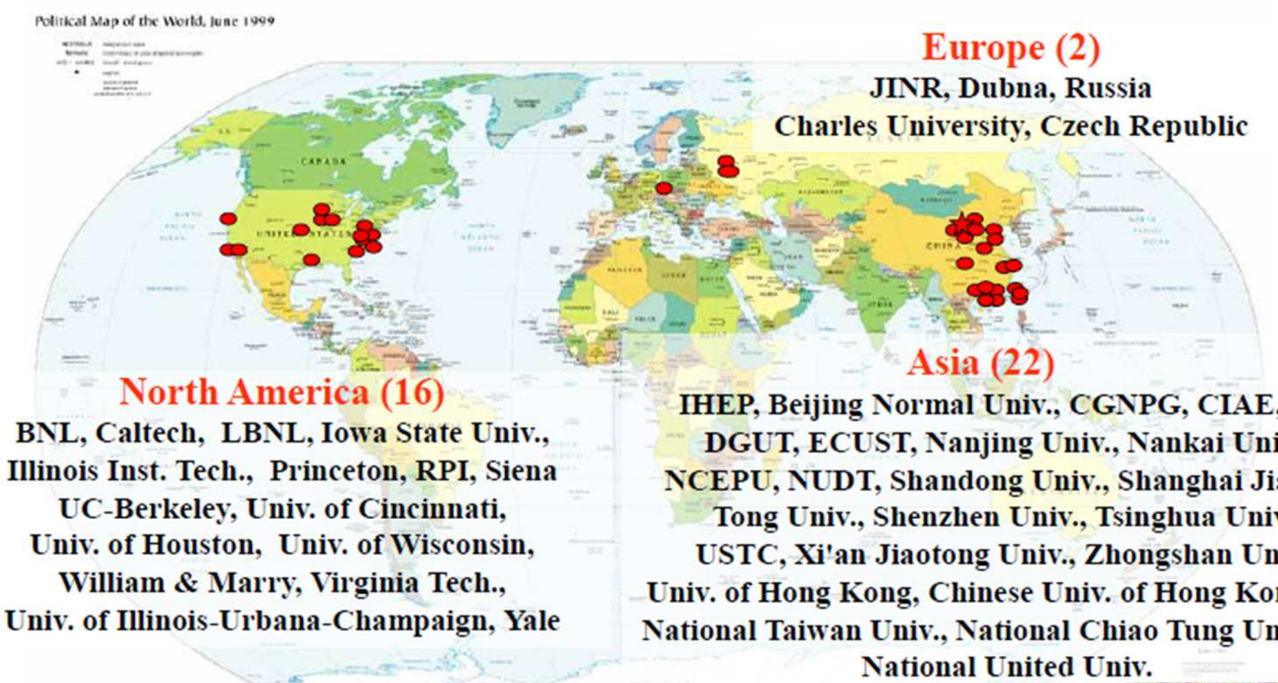
Precise Measurement of Electron Antineutrinos Disappearance with the Daya Bay Experiment

Rupert Leitner (Charles University, Prague)
on behalf of the Daya Bay Collaboration

The Daya Bay Collaboration



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Charles University, Czech Republic

Asia (22)

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North America (16)

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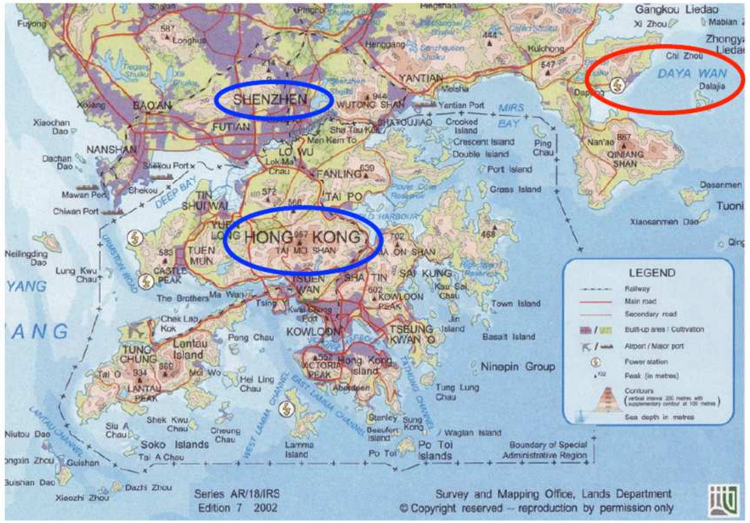
~230 Collaborators

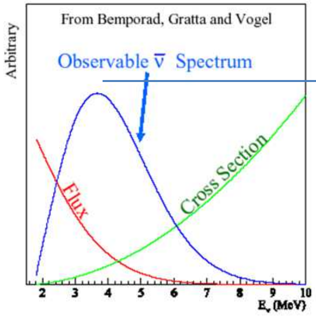


The Daya Bay experiment is designed to measure electron antineutrino oscillations at small distances (~2km) from the reactors.

Such oscillations require a non-zero value of the element $|U_{e3}|$ of the PMNS mixing matrix.

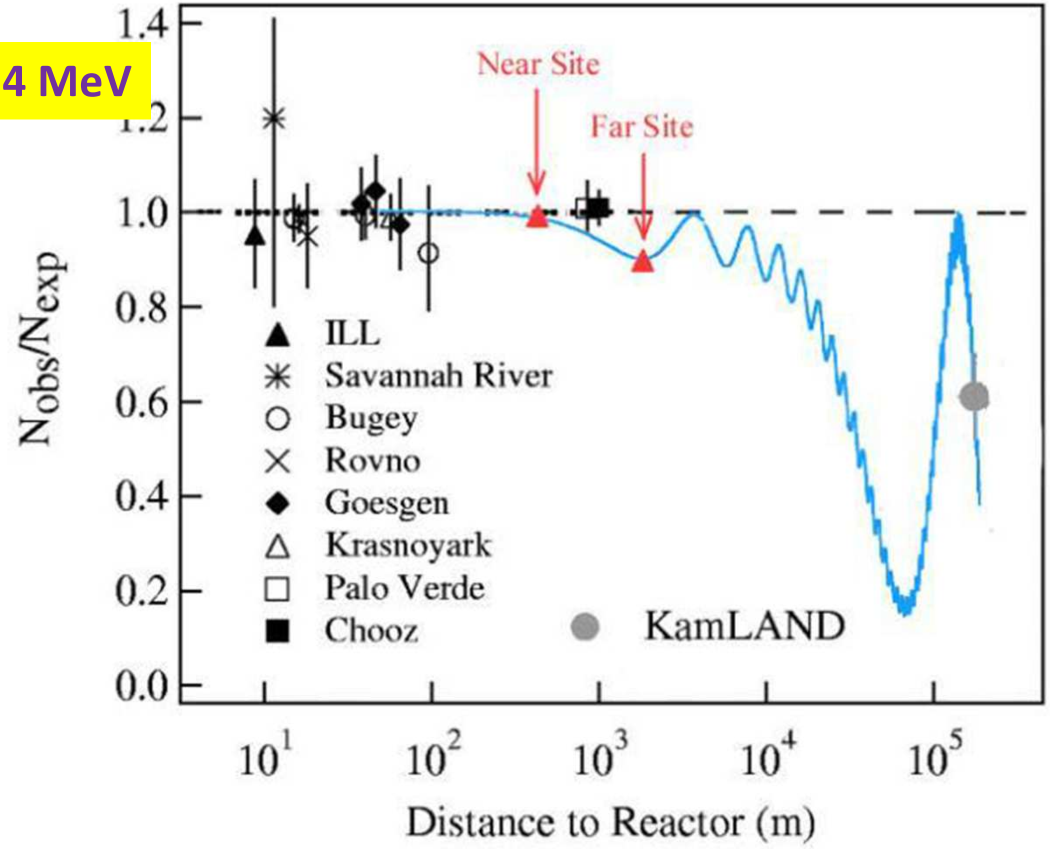
When $|U_{e3}| \neq 0$ then it might be a complex number and be the source of CP violation in neutrino physics.

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



From Bemporad, Gratta and Vogel

E=4 MeV



Expected amplitude of oscillations is few %

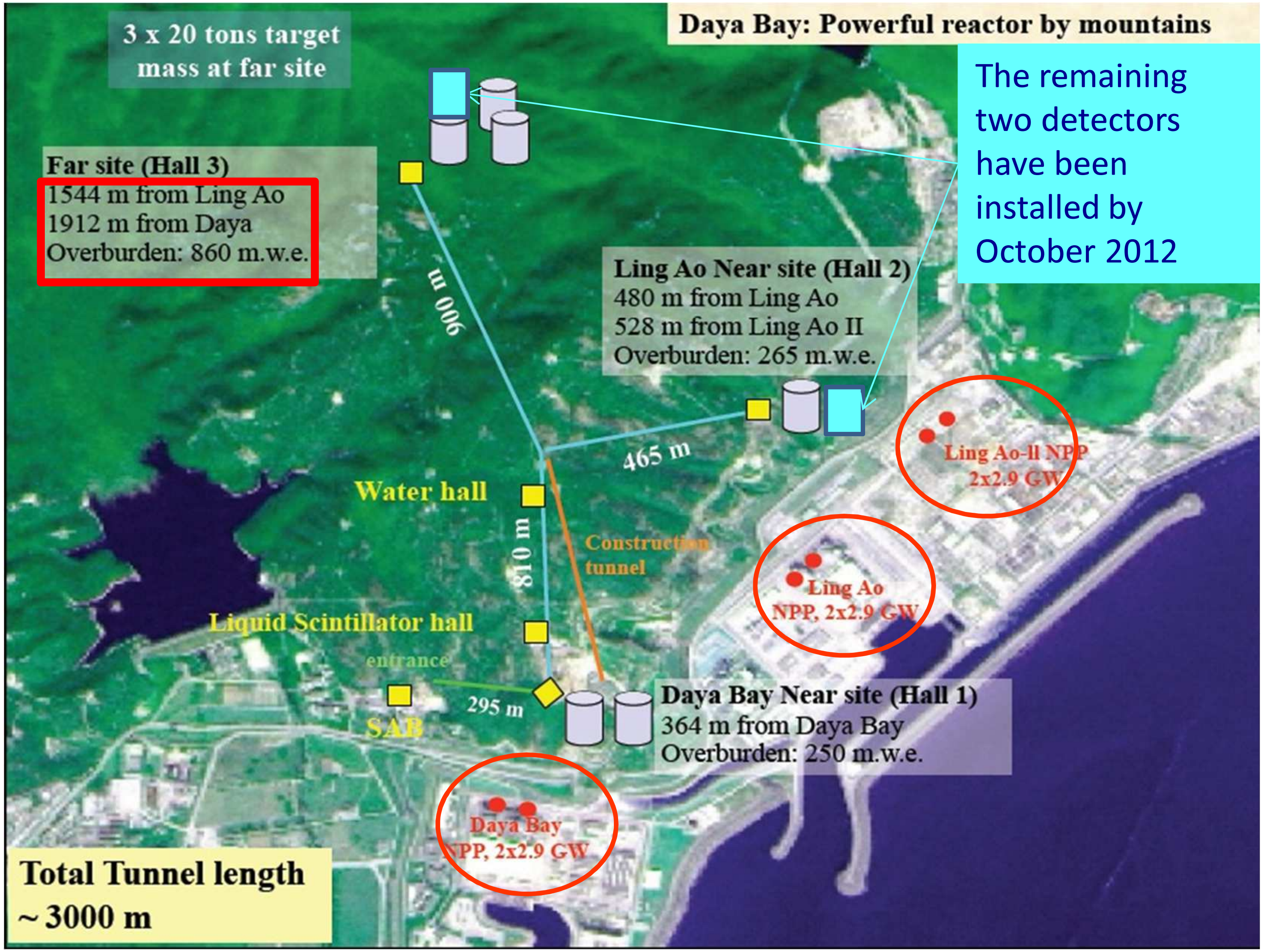
- High reactor power and detector mass is needed to collect enough data
- Far/Near detectors configuration and large overburden significantly reduce systematic uncertainties and backgrounds

Layout of the Daya Bay experiment

6 reactors:
17.4 GW total
(thermal) power

A total of eight functionally identical and moveable detectors in three detector halls.

6 of the 8 detectors have been taking physics data since Dec. 2011



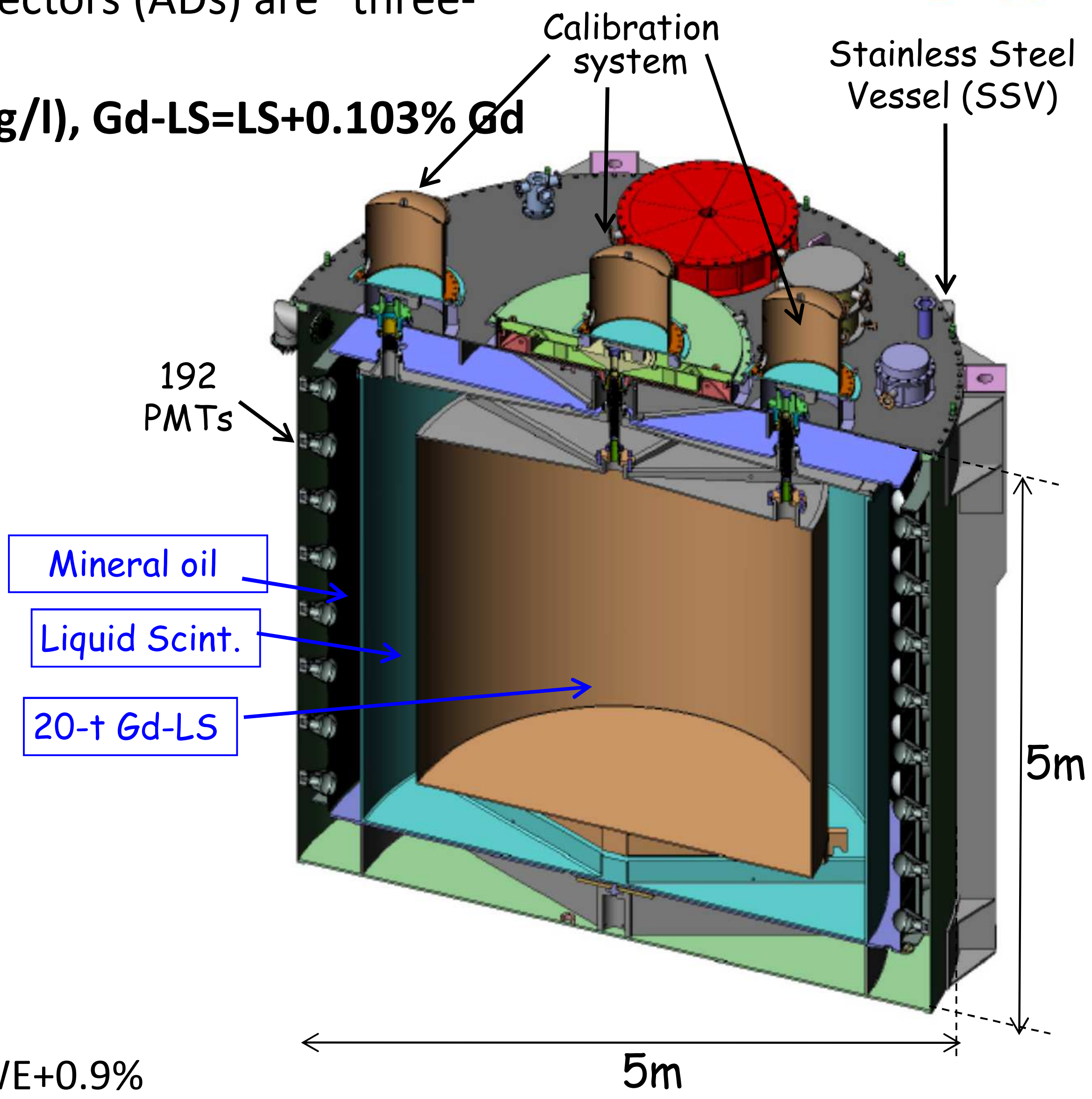
The remaining two detectors have been installed by October 2012

Anti-neutrino detectors

- The Daya Bay anti-neutrino detectors (ADs) are “three-zone” cylindrical modules.
- **LS=LAB+PPO(3 g/l)+MSB(15 mg/l), Gd-LS=LS+0.103% Gd**
  - Zones are separated by acrylic vessels:

Zone	Mass	Liquid	Purpose
Inner acrylic vessel	20 t	Gd-doped liquid scintillator	**Anti-neutrino target**
Outer acrylic vessel	20 t	Liquid scintillator	Gamma catcher (from target zone)
Stainless steel vessel	40 t	Mineral Oil	Radiation shielding

  - Top and bottom reflectors are used to increase light yield
  - Energy resolution: $\sigma_E/E = 7.5\%/\sqrt{E}+0.9\%$



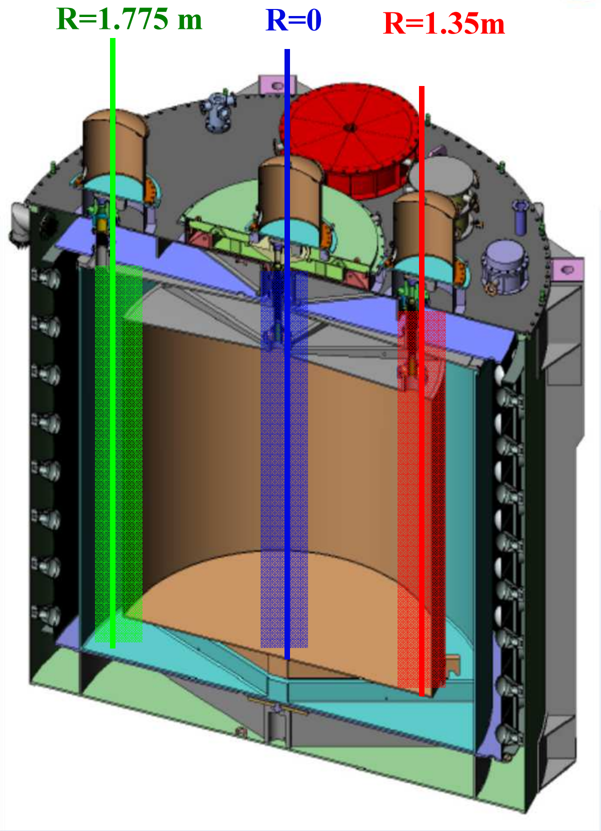
Detector calibration

- Three sources + LED in each calibration unit, on a turn-table:
    - ○ ^{68}Ge (1.02MeV)
    - ○ ^{60}Co (2.5MeV)
    - ○ ^{241}Am-^{13}C (8MeV)
    - ○ LED

Energy calibration (linearity, detector response… etc)

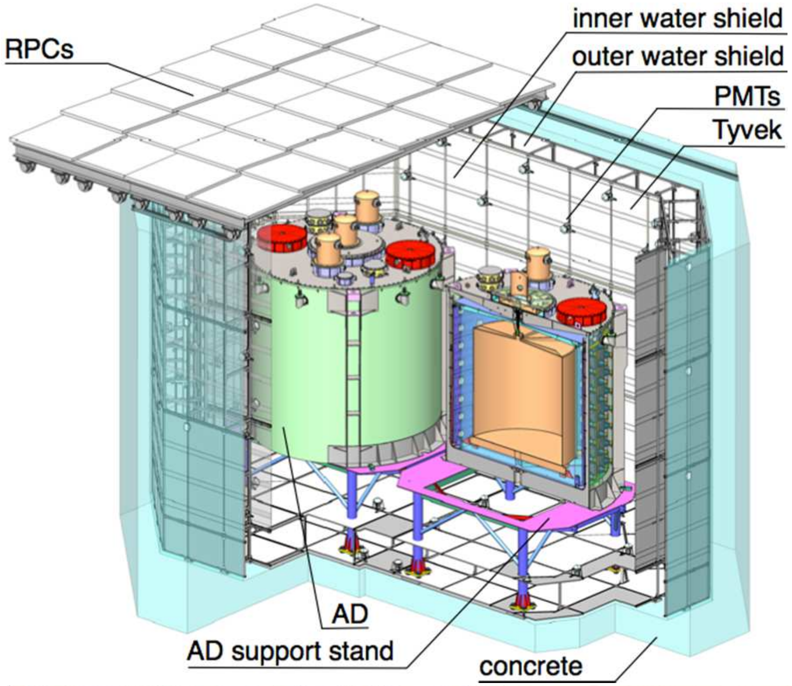
Timing, gain and relative QE

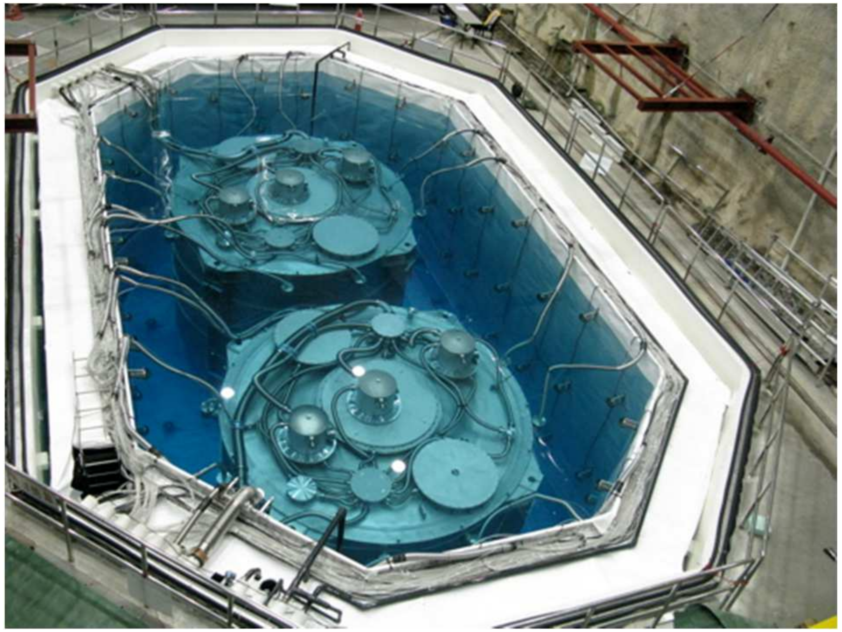
- Can also use spallation neutrons (uniformity, stability, calibration, … etc).



Automated Calibration Units (Daya Bay)

Three calibration units per detector that deploy sources along z-axis

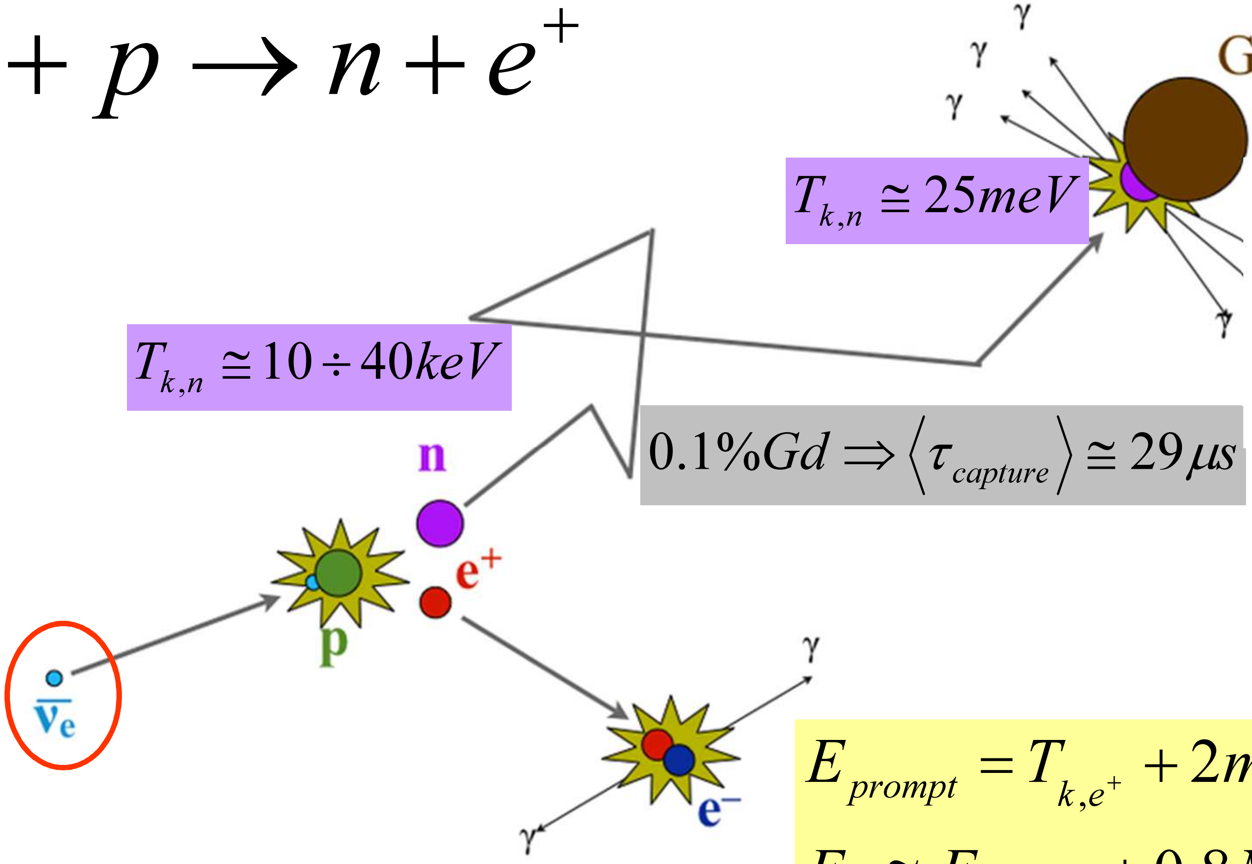




- Outer layer of water Čerenkov detector (on sides and bottom) is 1m thick, inner layer >1.5m. Water extends 2.5m above ADs
  - 288 8” PMTs in each near hall
  - 384 8” PMTs in Far Hall
- 4-layer RPC modules above pool
  - 54 modules in each near hall
  - 81 modules in Far Hall

Detection of antineutrinos via Inverse Beta Decay (IBD) is performed by the coincidence of prompt signal from positron and delayed signal of neutron capture on Gd.

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

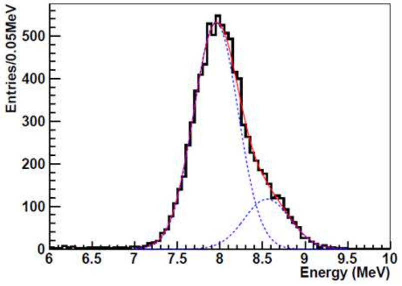


$$\left\langle \sum E_\gamma \right\rangle = 8.05\,MeV$$

$$T_{k,n} \cong 25\,meV$$

$$T_{k,n} \cong 10 \div 40\,keV$$

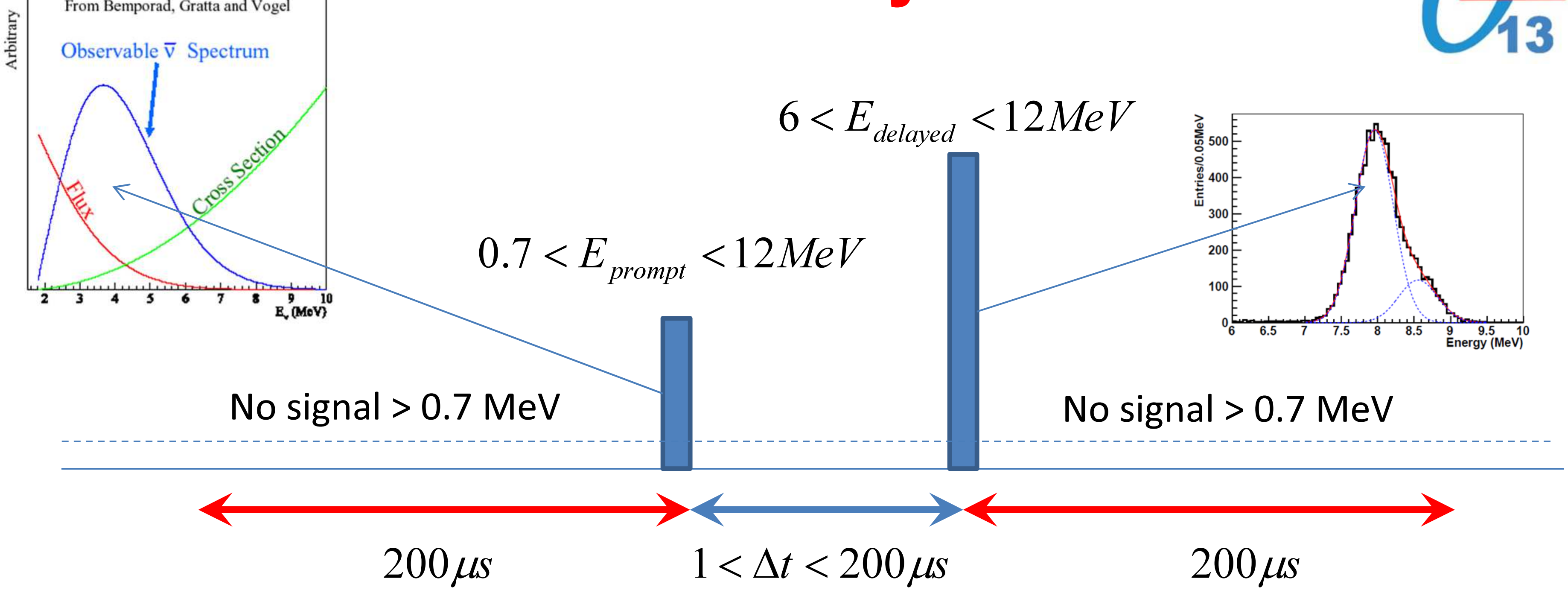
$$0.1\%Gd \Rightarrow \left\langle \tau_{capture} \right\rangle \cong 29\,\mu s$$



$$E_{prompt} = T_{k,e^+} + 2m_e$$

$$E_\nu \cong E_{prompt} + 0.8\,MeV$$

Inverse Beta Decay Selection



$$0.7 < E_{prompt} < 12 MeV$$

$$6 < E_{delayed} < 12 MeV$$

$$200 \mu s \qquad 1 < \Delta t < 200 \mu s \qquad 200 \mu s$$

Prompt-delayed coincidence:

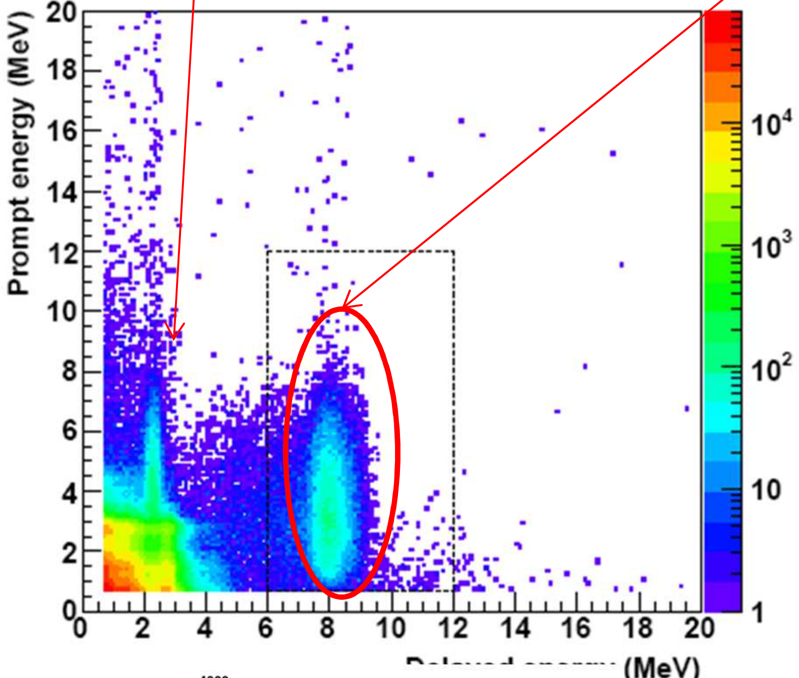
- Prompt positron: 0.7 MeV < E_p < 12 MeV Delayed neutron: 6.0 MeV < E_d < 12 MeV
- Capture Time: 1 μs < Δt< 200 μs

Multiplicity:

- No signal 200 μs around IBD

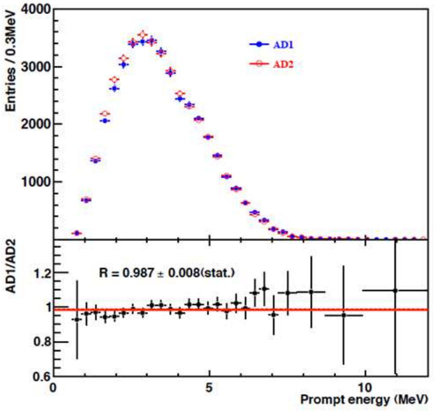
Muon Veto:

Pool muon (muon detected in water pool): veto following 0.6 ms
Muon signal (> 20 MeV) detected in AD: veto following 1 ms
High energy muon signal (AD shower muon >2.5 GeV): veto following 1 s that is >5 $T_{1/2}$ of ^{9}Li / ^{8}He isotopes



Capture on H

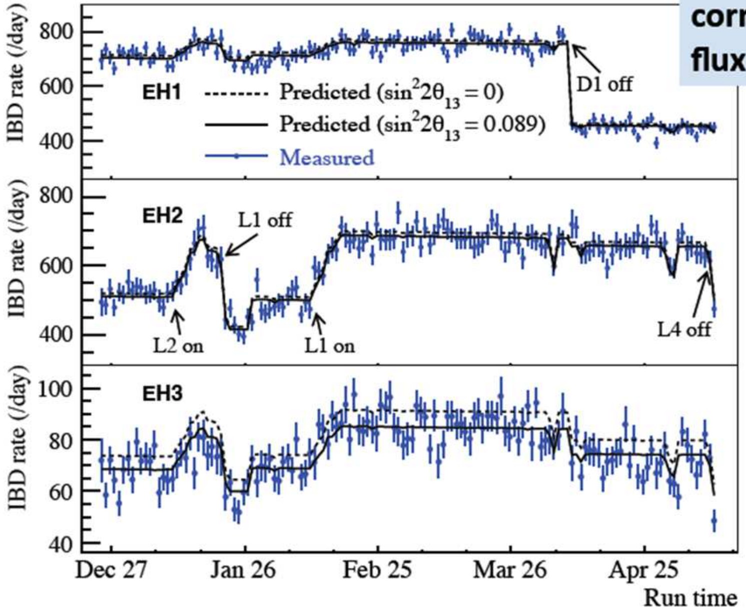
IBD candidates capture on Gd



	Near	Far
IBD candidates/day	662+671(EH1) 614 (EH2)	78+77+75

Antineutrino Rate vs. Time

Detected rate strongly correlated with reactor flux expectations.



Predicted Rate:

- Normalization is determined by data fit.
- Absolute normalization is within a few percent of expectations.

IBD candidates and backgrounds

~200 000 events in near detectors

~30 000 events in far detectors

	AD1	AD2	AD3	AD4	AD5	AD6
IBD candidates	69121	69714	66473	9788	9669	9452
Expected IBDs	68613	69595	66402	9922.9	9940.2	9837.7
DAQ livetime (days)	127.5470		127.3763	126.2646		
ϵ_μ	0.8231	0.8198	0.8576	0.9813	0.9813	0.9810
$\overline{\epsilon}_m$	0.9738	0.9742	0.9753	0.9737	0.9734	0.9732
Accidentals (per day)	9.73±0.10	9.61±0.10	7.55±0.08	3.05 ±0.04	3.04 ± 0.04	2.93 ±0.03
Fast-neutron (per day)	0.77±0.24	0.77±0.24	0.58±0.33	0.05±0.02	0.05±0.02	0.05±0.02
^{9}Li/^{8}He (per AD per day)	2.9±1.5		2.0±1.1	0.22±0.12		
Am-C correlated (per AD per day)	0.2±0.2					
(α, n) background (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)	662.47±3.00	670.87±3.01	613.53±2.69	77.57±0.85	76.62±0.85	74.97±0.84

$$^8_2He \xrightarrow{119ms\ 16\%} \boxed{{}^7_3Li + e^- + \bar{\nu}_e + n}$$

$$^8_2He \xrightarrow{84\%} {}^8_3Li^* + e^- + \bar{\nu}_e$$

$$^8_3Li^* \rightarrow {}^8_3Li + 0.98MeV\gamma$$

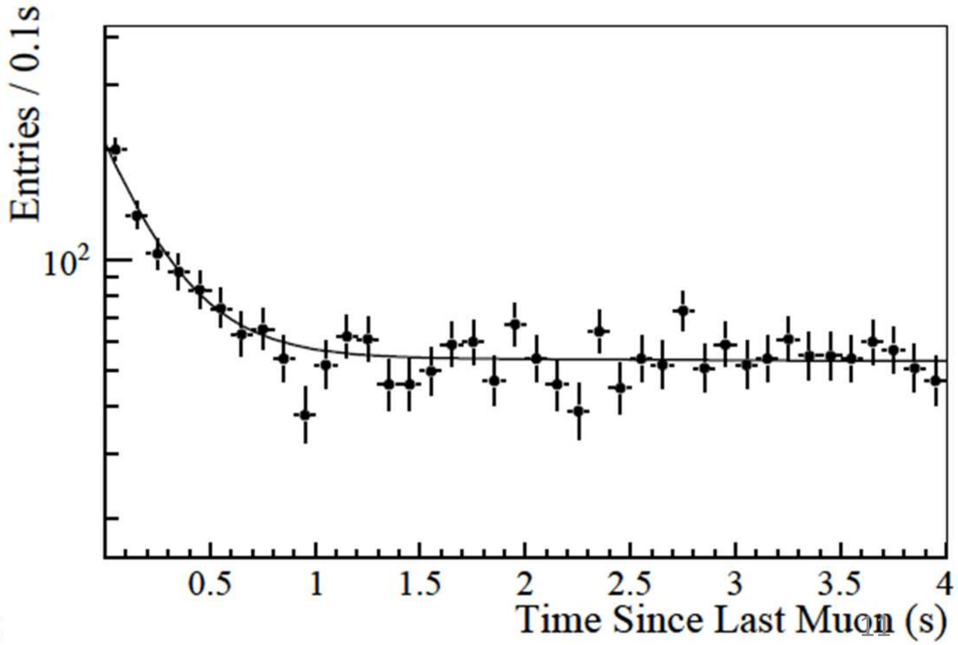
$$^8_3Li \xrightarrow{840ms} {}^8_4Be + e^- + \bar{\nu}_e$$

$$^8_4Be \rightarrow \alpha + \alpha$$

$$^9_3Li \xrightarrow{178ms\ 50\%} \boxed{{}^8_4Be + e^- + \bar{\nu}_e + n}$$

$$^8_4Be \rightarrow \alpha + \alpha$$

$$^9_3Li \xrightarrow{178ms\ 50\%} {}^9_4Be + e^- + \bar{\nu}_e$$

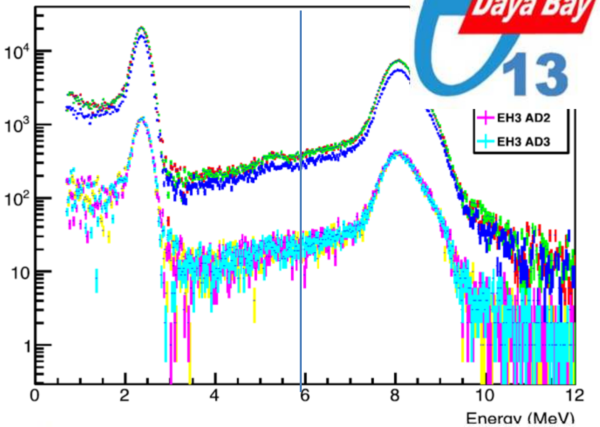


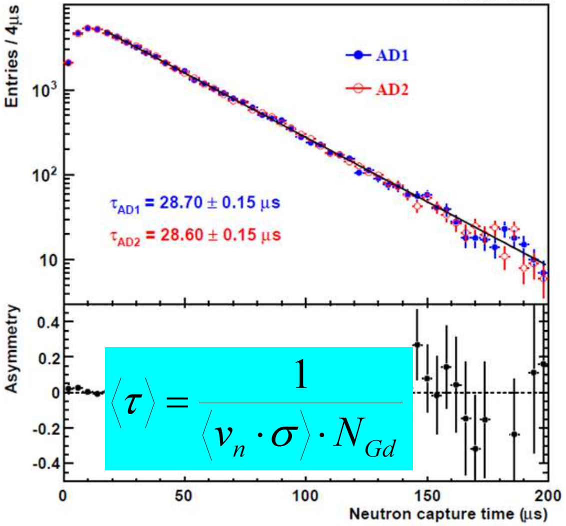
Detectors related uncertainties

	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 fraction	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%

Reactors related uncertainties

Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
IBD reaction/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%

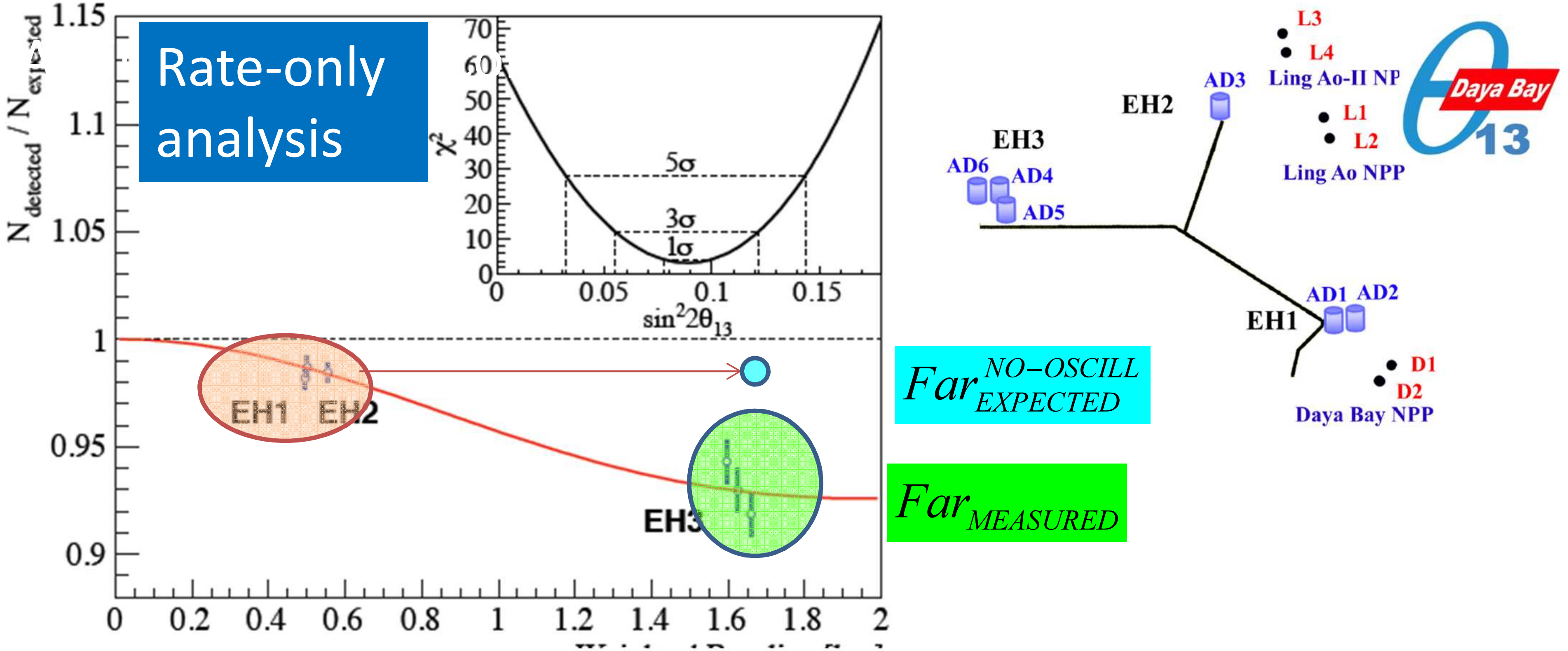




$$\langle \tau \rangle = \frac{1}{\langle v_n \cdot \sigma \rangle \cdot N_{Gd}}$$

Thanks to far/near detectors configuration it contributes only by ~0.04% to the resulting uncertainty.

Rate-only analysis



- Near/Far rate comparison:

$$R = \frac{Far_{measured}}{Far_{expected}} = \frac{M_4 + M_5 + M_6}{\sum_{i=4}^{6}(\alpha_i(M_1 + M_2) + \beta_i M_3)}$$

M_n : measured rates in each detector.
Weights α_i, β_i : determined from baselines and reactor fluxes, no oscillations assumed.

R = 0.944 ± 0.007 (stat) ± 0.003 (syst)

- **Unambiguous observation (7.7 σ) antineutrino deficit at the far site!**

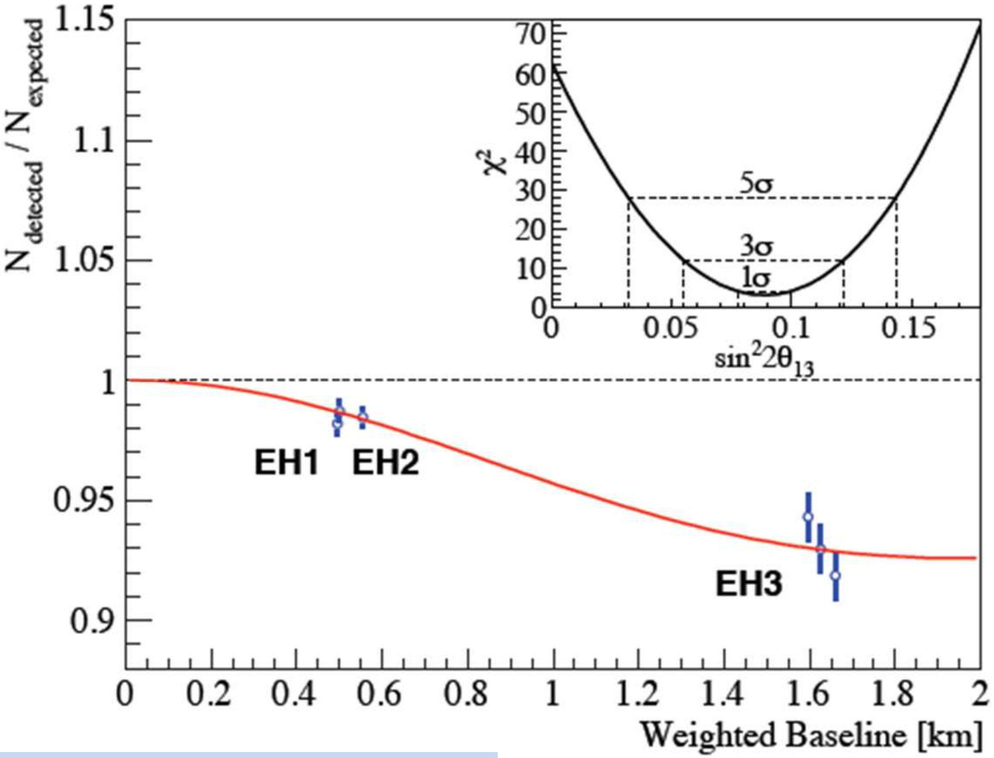
Rate-only analysis

- Determine θ_{13} using measured rates in each detector:

Uses standard χ^2 approach (χ^2/NDF=4.26/4)

$$\chi^2 = \sum_{d=1}^{6} \frac{[M_d - T_d(1 + \varepsilon + \sum_r \omega_r^d \alpha_r + \varepsilon_d) + \eta_d]}{M_d + B_d} + \sum_r \frac{\alpha_r^2}{\sigma_r^2} + \sum_{d=1}^{6} \left(\frac{\varepsilon_d^2}{\sigma_d^2} + \frac{\eta_d^2}{\sigma_B^2} \right),$$

Far vs. near relative measurement.
[Absolute rate is not constrained.]
Consistent results obtained by independent analyses, different reactor flux models.



$\sin^2 2\theta_{13} = 0.089 \pm 0.010$ (stat) ± 0.005 (syst)

our first result of March 2012:

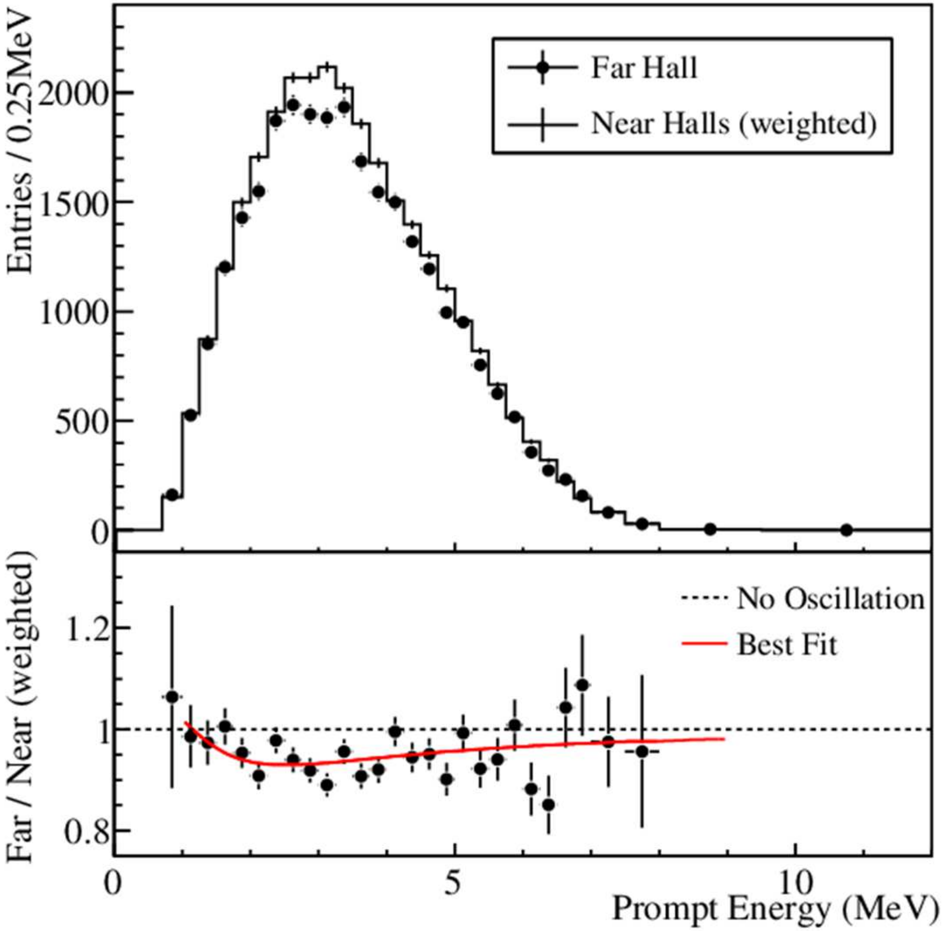
$\sin^2 2\theta_{13} = 0.092 \pm 0.016$ (stat) ± 0.005 (syst)

$\theta_{13} \cong 8.7^o$ The smallest lepton mixing angle is comparable to the largest (Cabibbo) quark mixing angle.

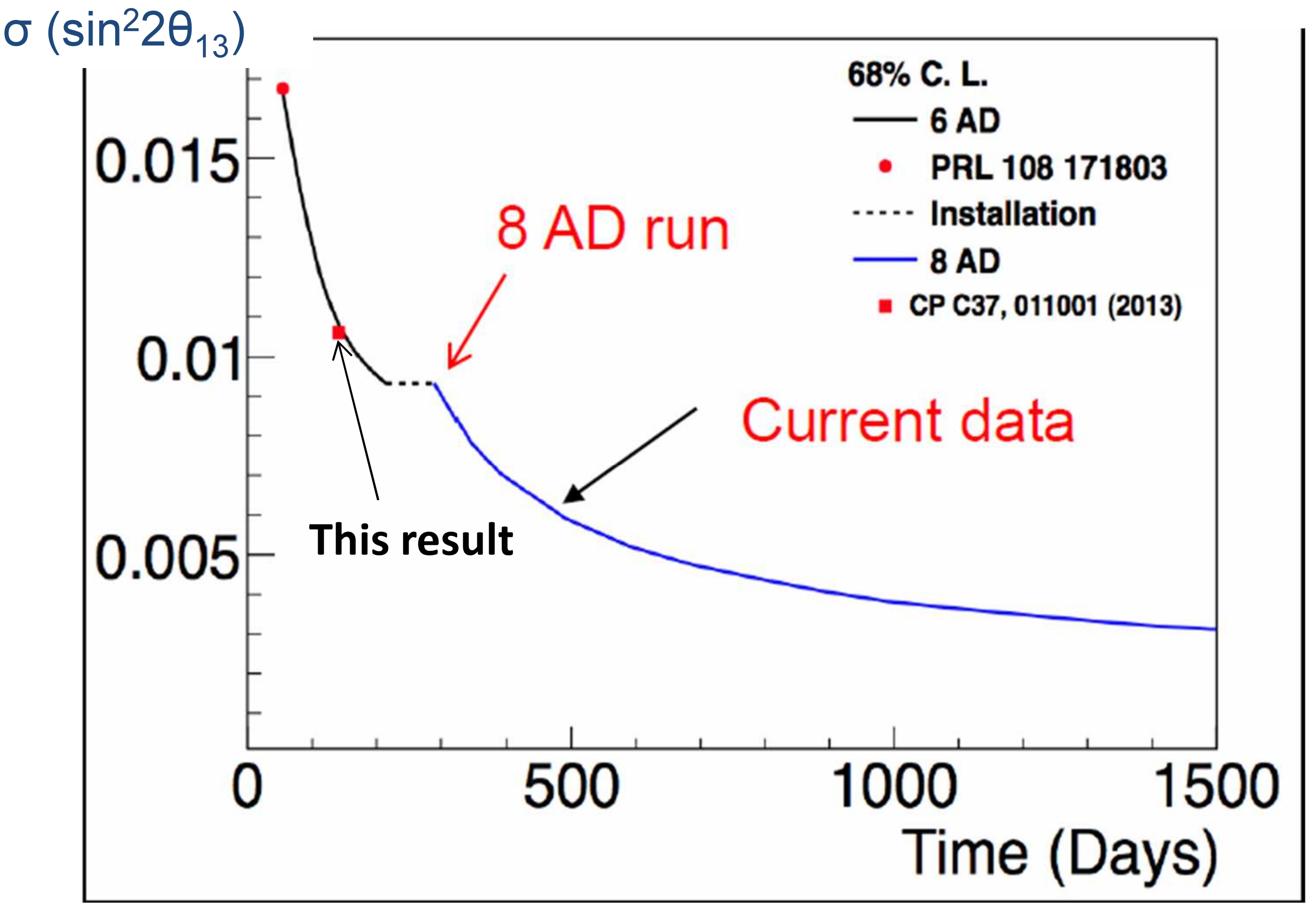
The disagreement of the spectra in far and near hall provides further evidence of neutrino oscillation.

The ratio of the spectra is consistent with the best-fit oscillation solution of $\sin^2 2\theta_{13} = 0.089$ (red curve) obtained from the rate-only analysis.

Currently the result is only from rate analysis!



Projected Daya Bay sensitivity



SUMMARY

-In March 2012 the Daya Bay experiment observed and published (in PRL) the observation of reactor antineutrinos disappearance with the significance of 5.2 standard deviations. Improved result with the significance of 7.7 standard deviations:

$$\sin^2 2\theta_{13} = 0.089 \pm 0.010\ (\text{stat}) \pm 0.005\ (\text{syst})$$

presented here was reported in Neutrino 2012 and published in CPC.

-To date it is the most precise result of all θ_{13} measurements in terms of both statistical(*) and systematic uncertainties.

(*) At NuTel workshop in March 2013, the RENO collaboration has reported a new result on $\sin^2 2\theta_{13} = 0.100 \pm 0.010$ (stat) ± 0.015 (syst) with the same value of the statistical error of 0.010 as that of the Daya Bay result.

-Relatively large value of θ_{13} opens the possibility to check the CP invariance in neutrino oscillation experiments.

-Rate and shape analysis of the full Daya Bay data set taken with 6 detectors is in preparation.

-In October 2012 the Daya Bay Experiment has been completed by two remaining detectors and started to take data.

-In 3 years the Daya Bay Experiment will measure the value of **$\sin^2 2\theta_{13}$** with **~4%** precision.

- Large statistics of data will permit other analyses such as
  precise measurement of the reactor antineutrino flux and spectrum,
  measurement of the value of Δm^2_{ee} with the precision close to 4%
  and others.