New Results from Daya Bay

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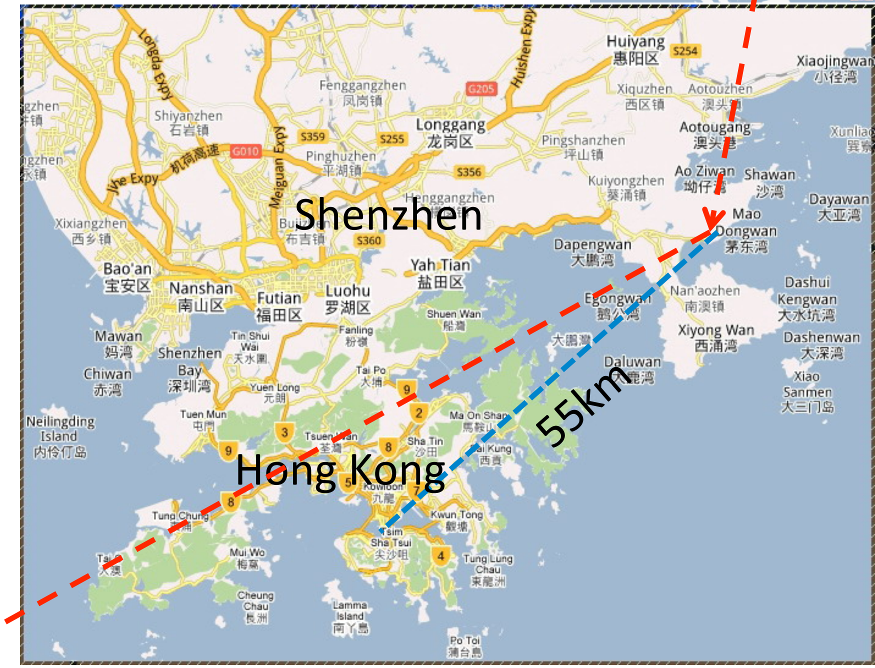
on behalf of the Daya Bay collaboration

PASCOS, Taipei, 2013.11.22

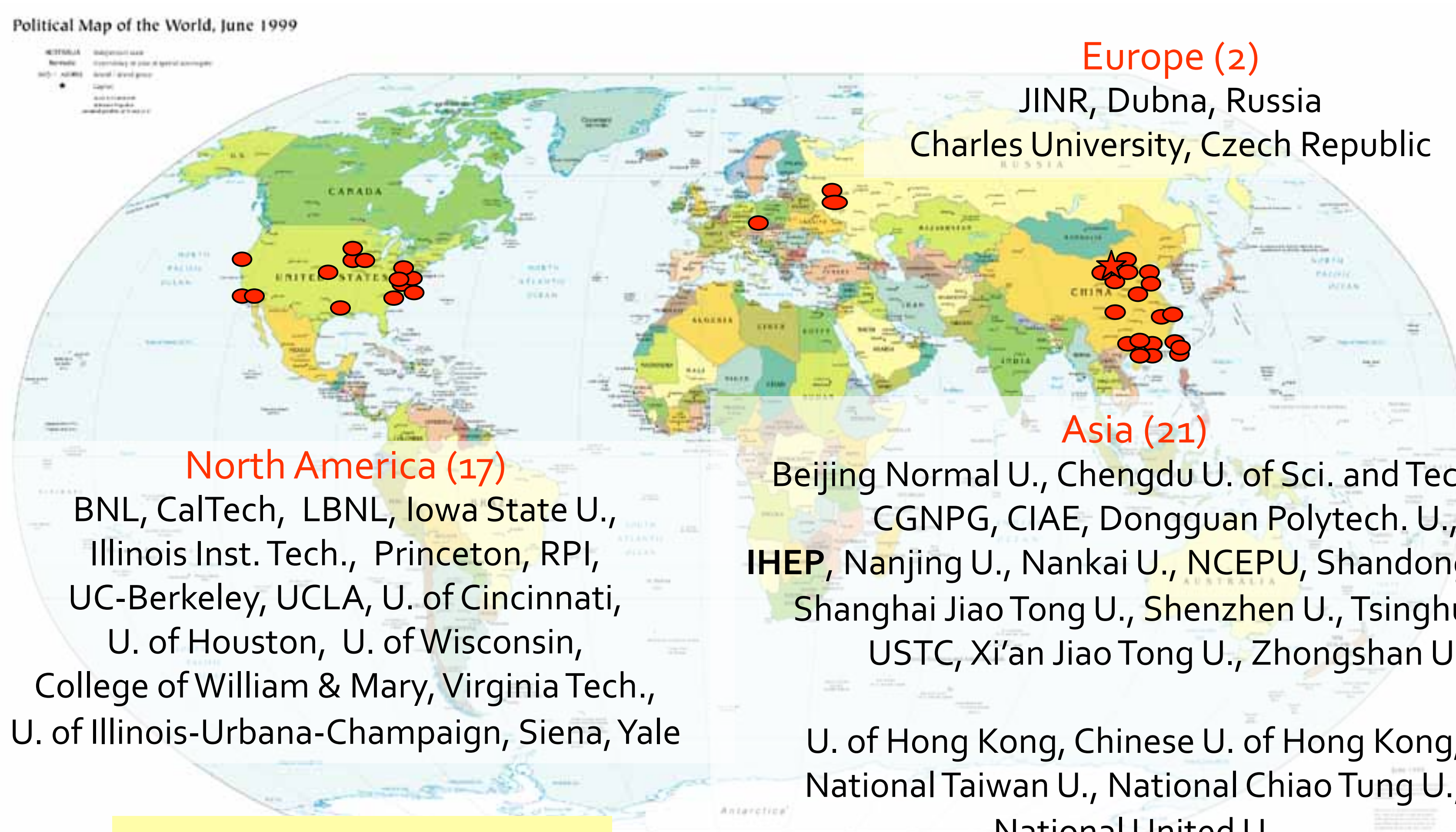
ABOUT DAYA BAY

Why Daya Bay

- Shenzhen, southern China
- powerful nuclear power complex
  - plants: Daya Bay, Ling Ao, Ling Ao II
  - thermal power: 3×2×2.9 GW
- adjacent to mountain
  - easy to build underground labs with tunnel access.
  - sufficient overburden to suppress cosmic rays.



The Daya Bay Collaboration



Europe (2)

JINR, Dubna, Russia
Charles University, Czech Republic

North America (17)

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

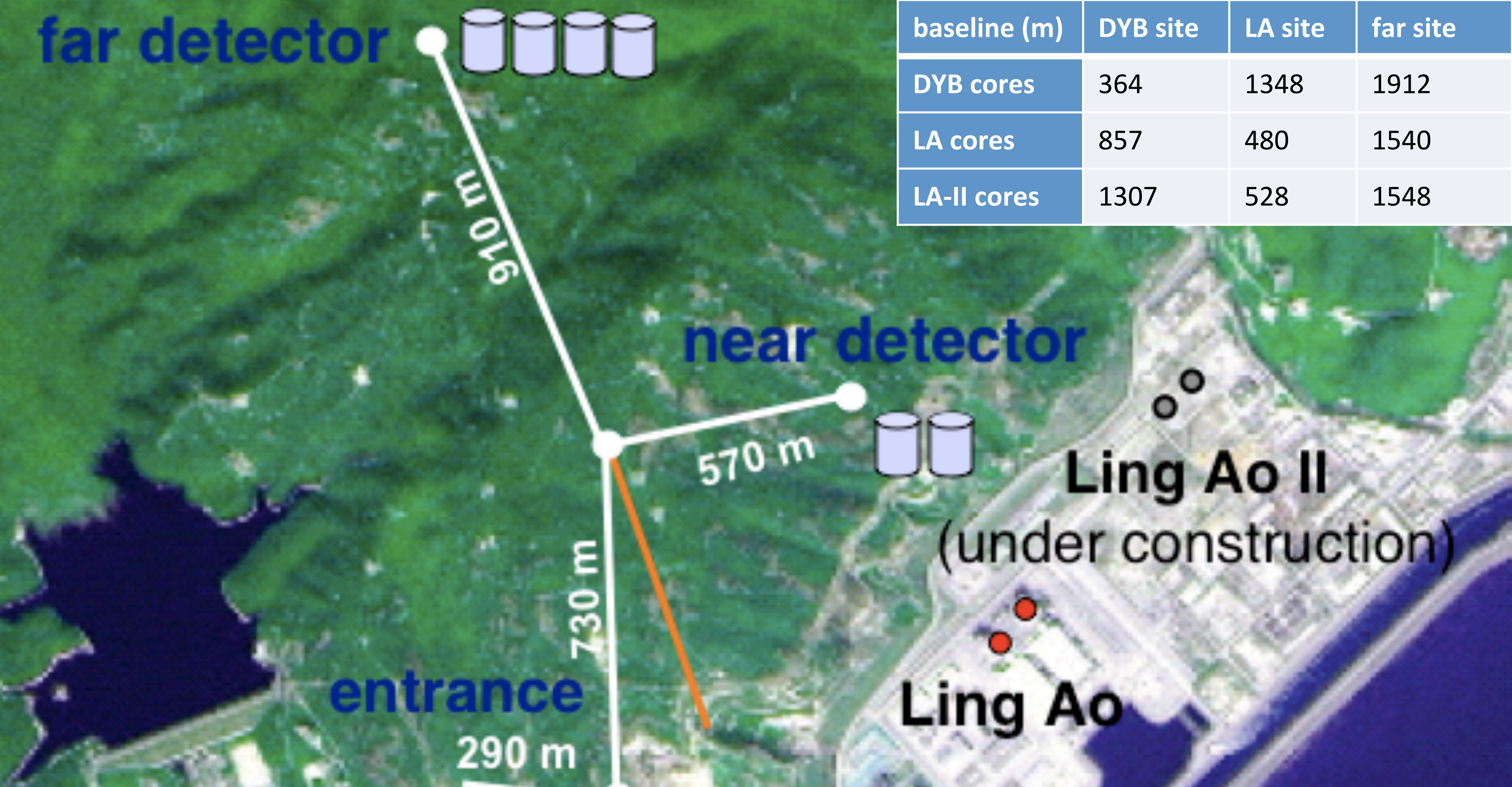
Asia (21)

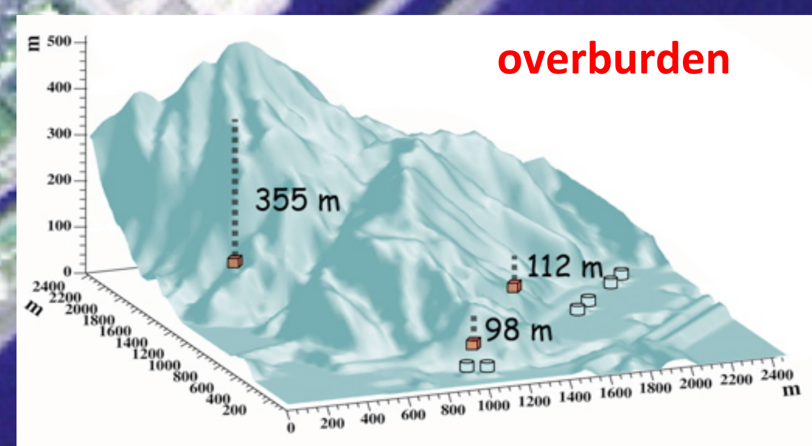
Beijing Normal U., Chengdu U. of Sci. and Tech., CGNPG, CIAE, Dongguan Polytech. U., **IHEP**, Nanjing U., Nankai U., NCEPU, Shandong U., Shanghai Jiao Tong U., Shenzhen U., Tsinghua U., USTC, Xi'an Jiao Tong U., Zhongshan U.

U. of Hong Kong, Chinese U. of Hong Kong, National Taiwan U., National Chiao Tung U., National United U.

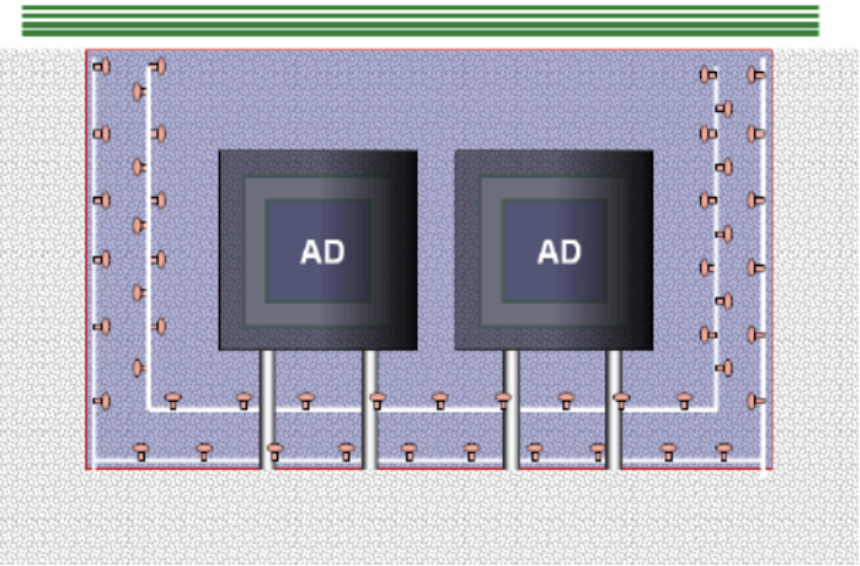
40 institutions
~230 collaborators

baseline (m)	DYB site	LA site	far site
DYB cores	364	1348	1912
LA cores	857	480	1540
LA-II cores	1307	528	1548

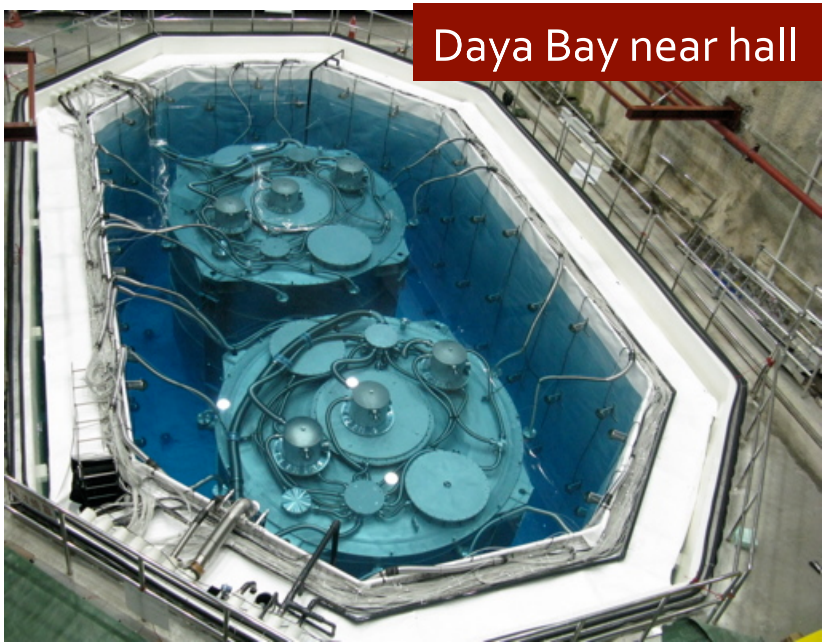




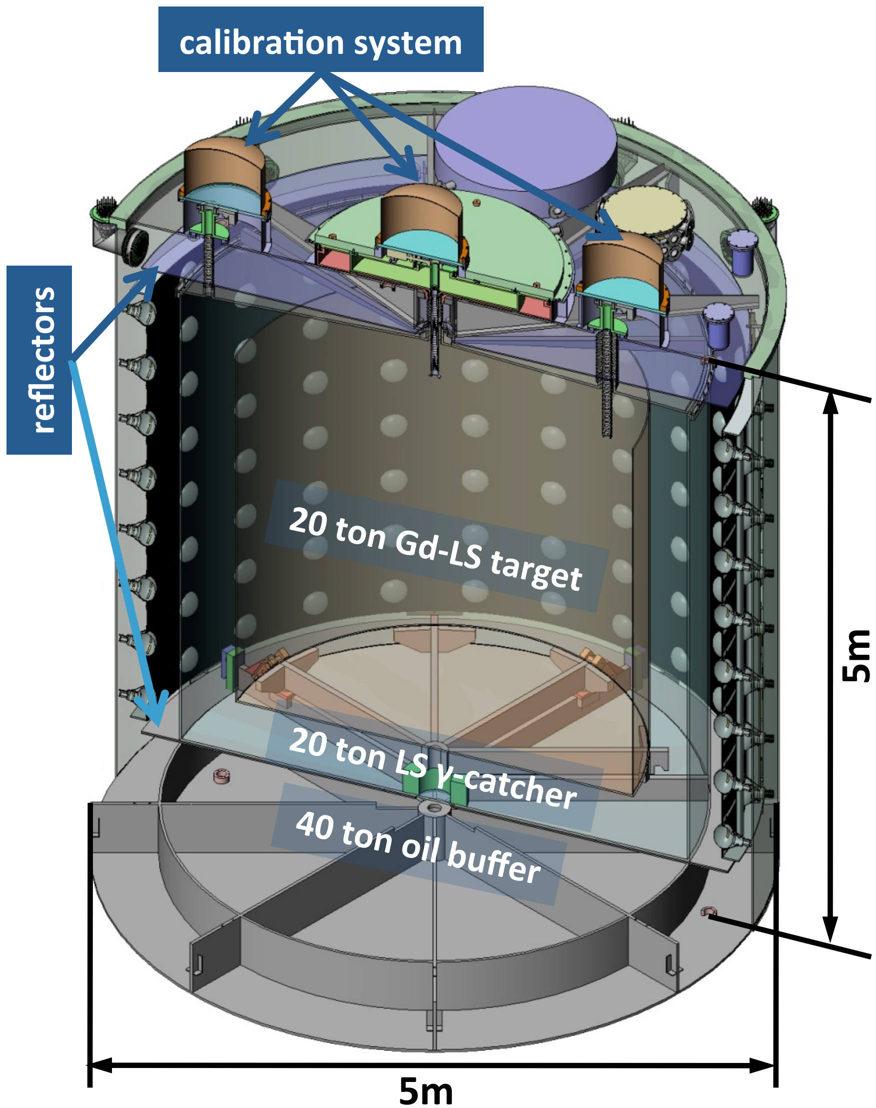
Detection System



- modularized functional identical ***antineutrino detectors*** (ADs)
  - 4 for far site, 2 for each near site
- ADs immersed in a water pool, serving dual purpose:
  - attenuate ambient neutrons and γs
  - instrumented with PMTs as a water Cerenkov detector
- water pool covered with RPC detector for redundant cosmic muon detection



Antineutrino Detector



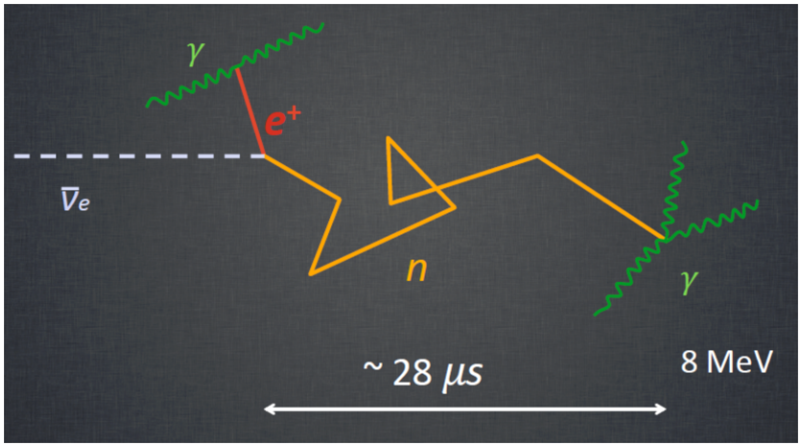
total weight: 110 ton

- design
  - 3-zone modular structure
  - 192 8” PMTs per module
  - 2 optical reflectors to increase PMT coverage: 5.6% → 12%
  - 8 functional identical modules (**6** for this analysis)
- performance
  - trigger: 45 hit PMTs or summed charge ~65 p.e. → 0.4 MeV in Gd-LS
  - light yield: ~165 p.e./MeV
  - $\sigma_E/E \approx 8\%$ @ 1 MeV

Detection of Electron Antineutrinos

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

$\tau \approx 28\ \mu s$ (0.1% Gd)



$n + p \rightarrow d + \gamma$ (2.2 MeV)

$n + Gd \rightarrow Gd^* + \gamma$'s (8 MeV)

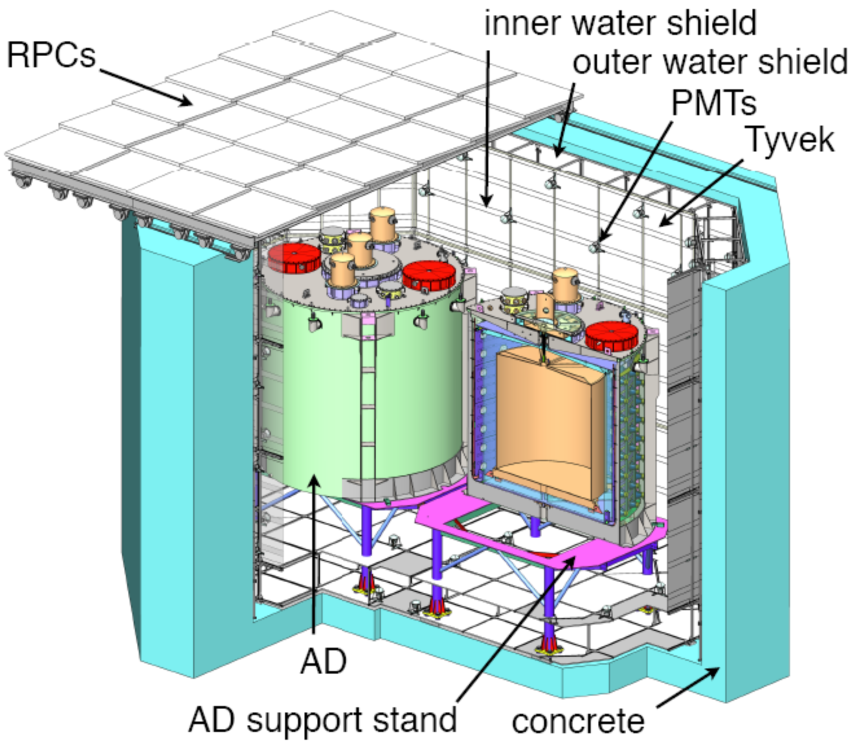
$$E_{\bar{\nu}_e} = E_{\text{prompt}} + T_n + 0.78\,\text{MeV}$$

$$E_{\text{prompt}} = T_{e^+} + 2m_e$$

$$T_n \sim 10\text{–}40\,\text{keV}$$

- via inverse β-decay (IBD)
  - prompt signal: e^+
  - delayed signal: n-capture on Gd ~ 8 MeV → powerful background suppression
  - coincidence in time, space and energy
- prompt light giving an estimate of the incident $\bar{\nu}_e$ energy

Muon Veto System



two active cosmic-muon veto's

- water Cerenkov: ε > 97%
- RPC muon tracker: ε > 88%

- RPCs
  - 4 layers/module
  - 54 modules/near hall, 81 modules/far hall
  - 2 telescope modules/hall
- water Cerenkov detector
  - Two layers, separated by Tyvek/PE/Tyvek film
  - 288 8" PMTs for near halls
    384 8" PMTs for the far hall
- water processing
  - high purity de-ionized water in pools also for shielding
  - first stage water production in hall 4
  - local water re-circulation & purification

Precision Measurement Strategy

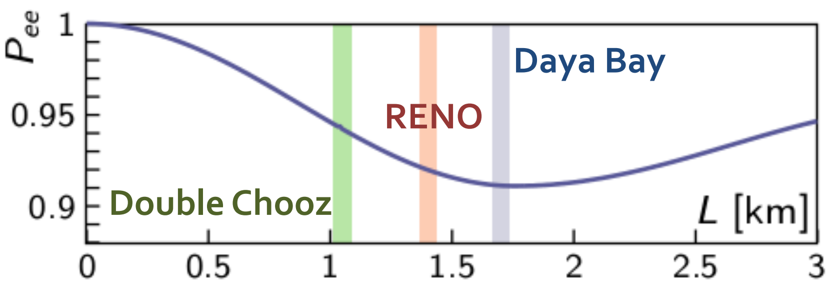
Relative measurement with 8 functionally identical detectors

- Absolute reactor flux single largest uncertainty in previous measurements

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

Baseline Optimization

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



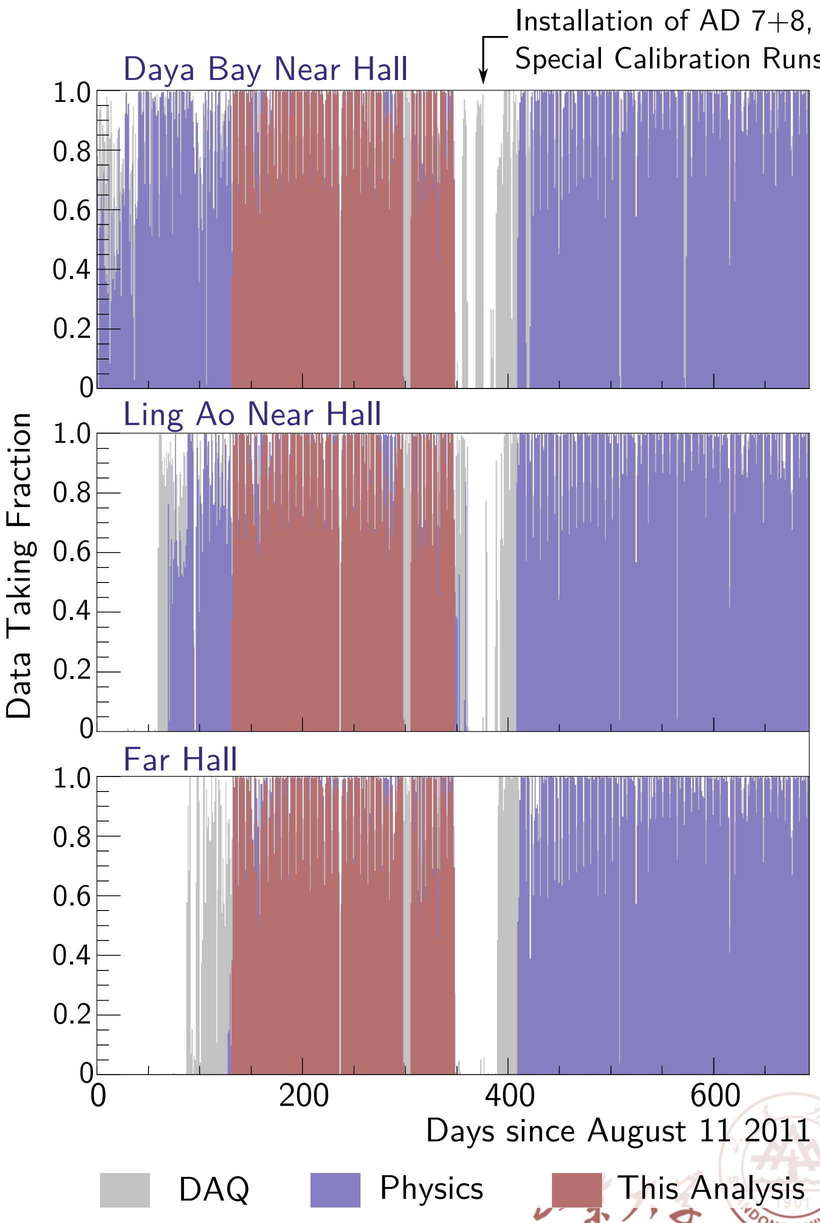
Go strong, big and deep!

	Reactor [GW_{th}]	Target [tons]	Depth [m.w.e]
Double Chooz	8.6	16 (2 × 8)	300, 120 (far, near)
RENO	16.5	32 (2 × 16)	450, 120
Daya Bay	17.4	160 (8 × 20)	860, 250

Large Signal — Low Background

Physics Accomplishments

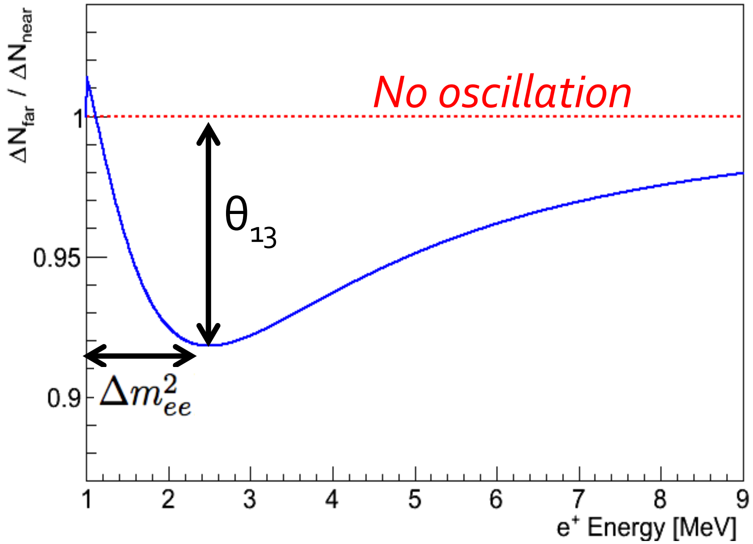
- two detector comparison [1202.6181]
  - 90 days of data, Daya Bay near only
  - *NIM **A685** (2012) 78-97*
- first oscillation result [1203.1669]
  - 55 days of data, 6 ADs near + far
  - first observation of $\bar{\nu}_e$ disappearance
  - *PRL **108** (2012) 171803*
  - ***Top 10 breakthrough '2012 by Science***
- improved oscillation analysis [1210.6327]
  - 139 days of data, 6 ADs near + far
  - *CP **C37** (2013) 011001*
- **spectral analysis [1310.6732]**
  - 217 days complete 6 AD period
  - 55% more statistics than CPC result



SPECTRAL ANALYSIS

Spectral Measurement

- possible to measure the mass splitting
- require good understanding of the detectors' ***energy response***!



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

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

for: $\Delta m^2_{21} \ll |\Delta m^2_{31}| \approx |\Delta m^2_{32}|$

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

$+$: normal hierachy

$-$: inverted hierachy

Energy Response Model

Particle Energy E_{true} → Energy Deposited in Scintillator E_{dep} → Energy Converted to Visible Light E_{vis} → Reconstructed Energy E_{rec}

$$f = \frac{E_{rec}}{E_{true}}(E_{true}) = \frac{E_{vis}}{E_{true}}(E_{true}) \cdot \frac{E_{rec}}{E_{vis}}(E_{vis})$$

Scintillator energy response

- Quenching effects
- Cherenkov radiation

Readout electronics response

- Charge collection efficiency decreases with visible light
- Empirical parameterization: exponential

e⁻ response

- 2 parameterizations:

$$\frac{E_{vis}}{E_{true}} = \frac{1 + p_3 \cdot E_{true}}{1 + p_1 \cdot e^{-p_2 \cdot E_{true}}}$$

$$\frac{E_{vis}}{E_{true}} = f_q(E_{true}; k_B) + k_C \cdot f_C(E_{true})$$

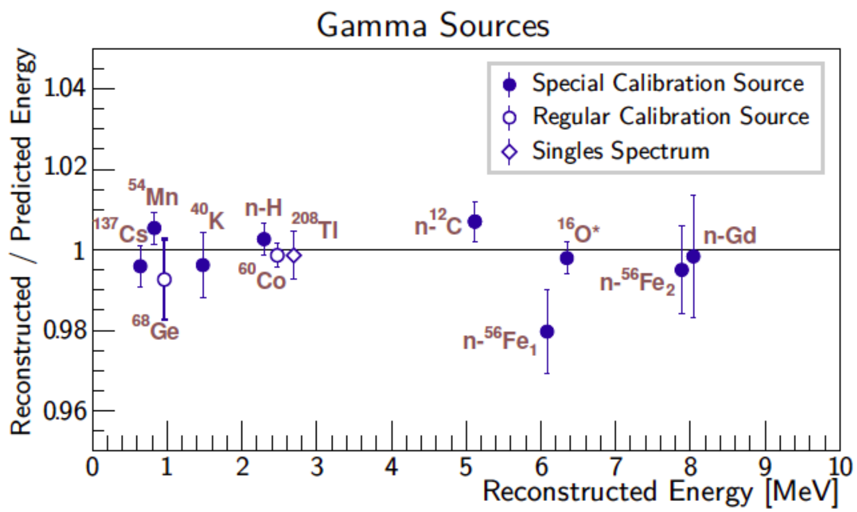
k_B : Birk's constant

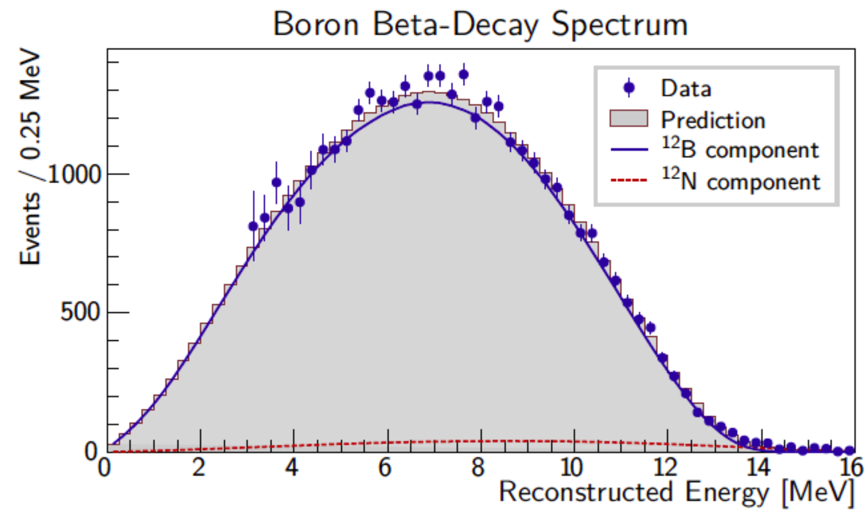
k_C : Cherenkov contribution

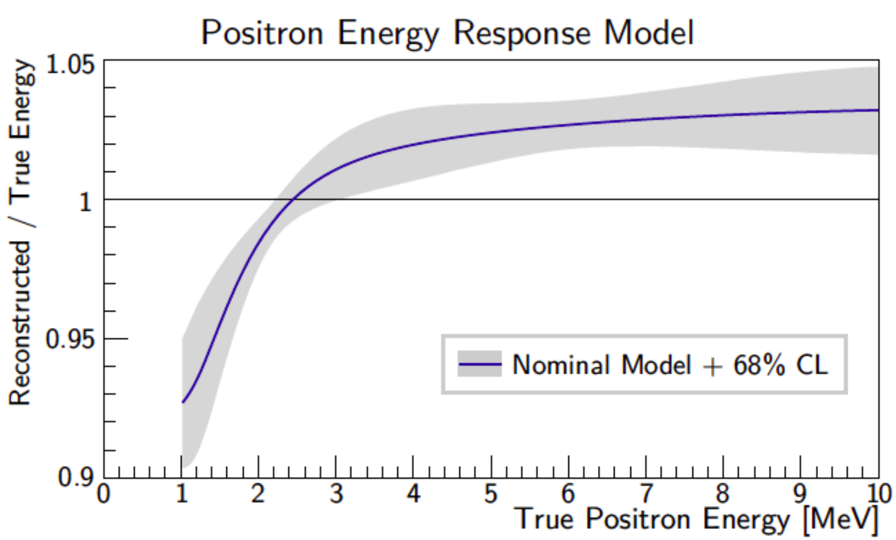
γ and e⁺

- Gammas and Positrons connected to electron model through MC.

Constraining Non-Linearity







- non-linearity parameters constrained by γ sources and ^{12}B spectrum
- all models contained in 68% CL region
- total positron energy response uncertainty within 1.5%

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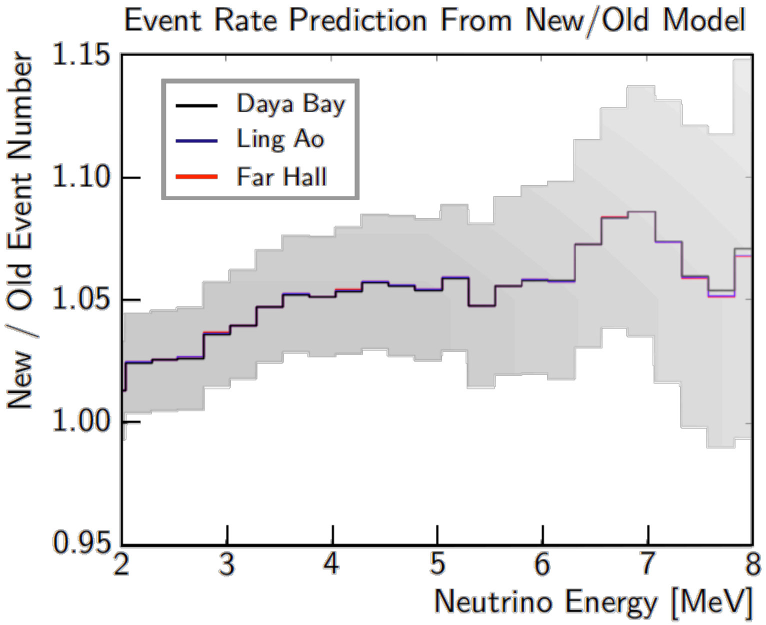
IBD Event Selection

- reject spontaneous PMT light emission ("flasher")
- select prompt-delayed coincidence signals
  - e+: 0.7 MeV < E_{prompt} < 12.0 MeV
  - n-Gd capture: 6.0 MeV < $E_{delayed}$ < 12.0 MeV
  - 1 μs < $\Delta t_{e\text{-}n}$ < 200 μs
- muon veto (efficiency: ε_{μ}), one of the following:
  - (-2 μs—600 μs) w.r.t. IWS/OWS trigger $N_{PMT} > 12$
  - (-2 μs—1400 μs) w.r.t. same AD with Esum > 3000 p.e.
  - (-2 μs—0.4 s) w.r.t. same AD with Esum > 3×10^{5} p.e.
- multiplicity cut (efficiency: ε_{m})
  - NO prompt-like signals 400 μs before the delayed event
  - NO delayed-like signals 200 μs after the delayed event
- efficiencies ε_{μ} and ε_{m} calculated directly from data with negligible uncertainties for each AD

Five Sources of Background

- accidental: any pair of otherwise uncorrelated signals happen to satisfy the IBD selection criteria
  - largest background
  - accurately determined by using the singles in data
  - relative uncertainty dominated by statistics of delayed-like signals
- correlated β-n decays from cosmogenic ^{9}Li/^{8}He
  - estimated by fitting the time elapsed since the last muon
- neutrons from the 0.7 Hz Am-C calibration sources
  - inelastical scattering in shielding + capturing on Fe, etc
  - use MC to estimate the rate
  - a special ×80 stronger Am-C source to benchmark the MC and to improve uncertainty by a factor of 2
- energetic (fast) neutrons produced by cosmic rays
  - proton-recoil (prompt) signal, a flat spectrum up to 50 MeV, extrapolated into IBD energy region
- ^{13}C(α, n)^{16}O background
  - determined with simulation

Reactor Flux Models



	Ratio of $\bar{\nu}_e$ from isotope [%]			
	^{235}U	^{238}U	^{239}Pu	^{241}Pu
AD 1	63.3	12.2	19.5	4.8
AD 2	63.3	12.2	19.5	4.8
AD 3	61.0	12.5	21.5	4.9
AD 4	61.5	12.4	21.5	4.9
AD 5	61.5	12.4	21.5	4.9
AD 6	61.5	12.4	21.5	4.9

Flux model has negligible impact on oscillation measurement

- Flux from each reactor used to predict IBDs at each detector

1. New model:
   - P. Huber, Phys. Rev. C84, 024617 (2011),
   - T. Mueller et al., Phys. Rev. C83, 054615 (2011)
2. Old model:
   - A. A. Hahn et al., Phys Rev Lett. B218, 365 (1989)
   - P. Vogel et al. Phys. Rev. C24, 1543 (1981)
   - K. Schreckenbach et al., Phys. Lett. B160, 325 (1985)

Signal and Backgrounds 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%

Systematic Uncertainties

	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%**

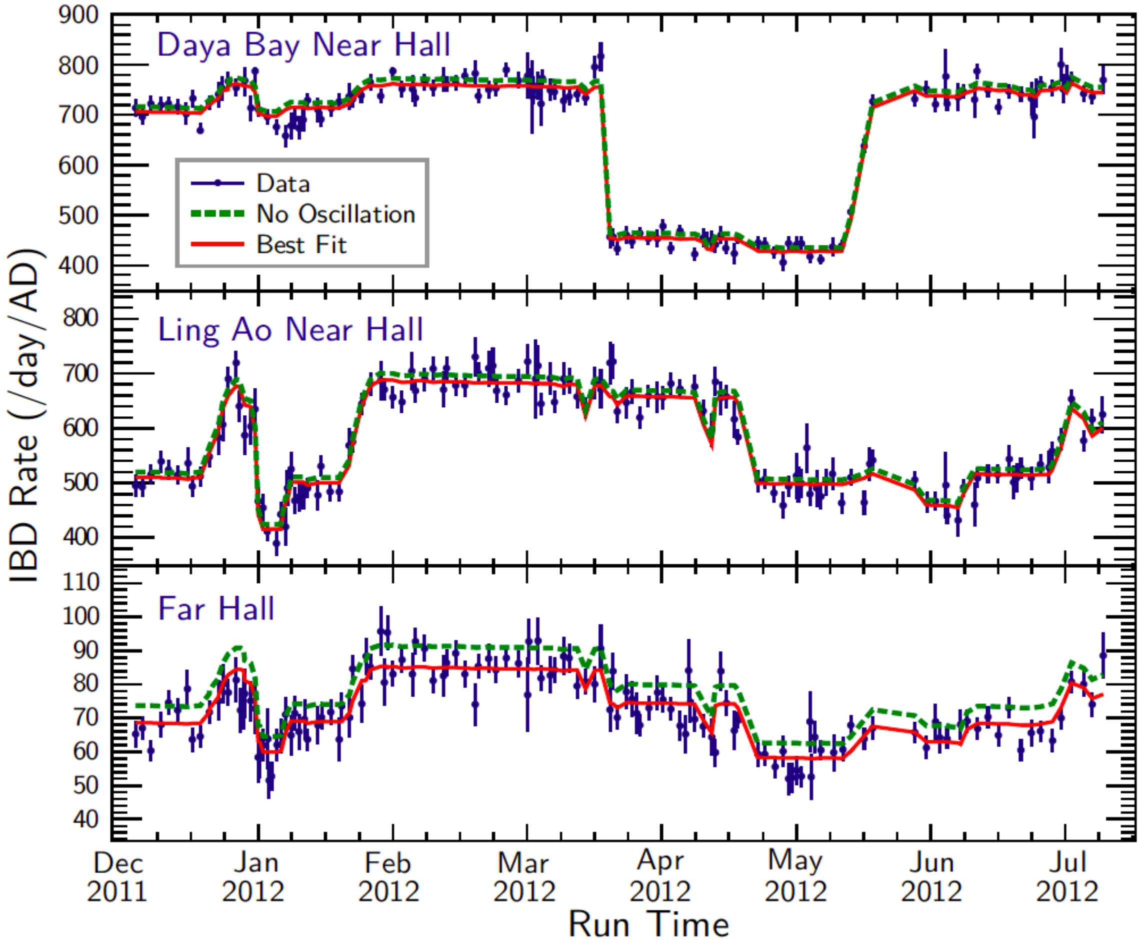
Reactor			
Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
IBD/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	**Combined**	**0.8%**

only uncorrelated uncertainties relevant to near/far oscillation analysis

largest systematics smaller than far site statistics (~0.9%)

impact of uncorrelated reactor systematics reduced relative measurement

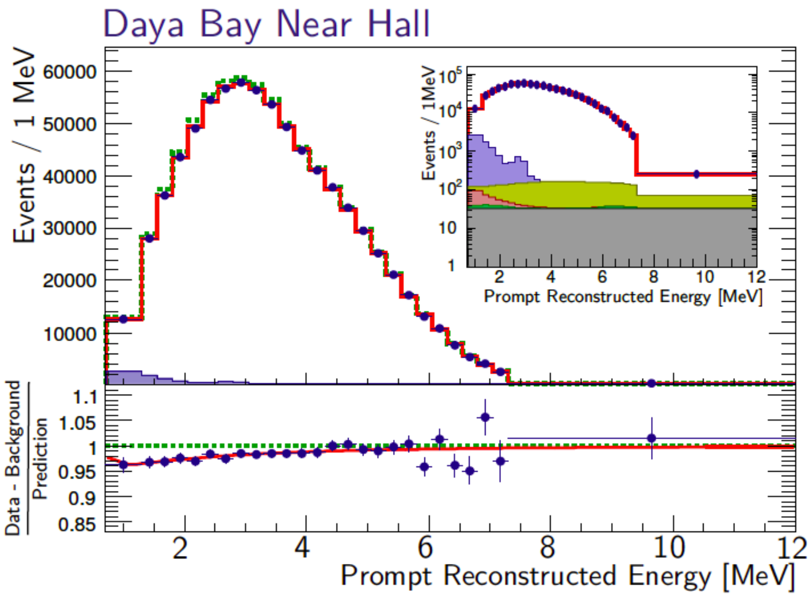
Antineutrino Rate vs. Time



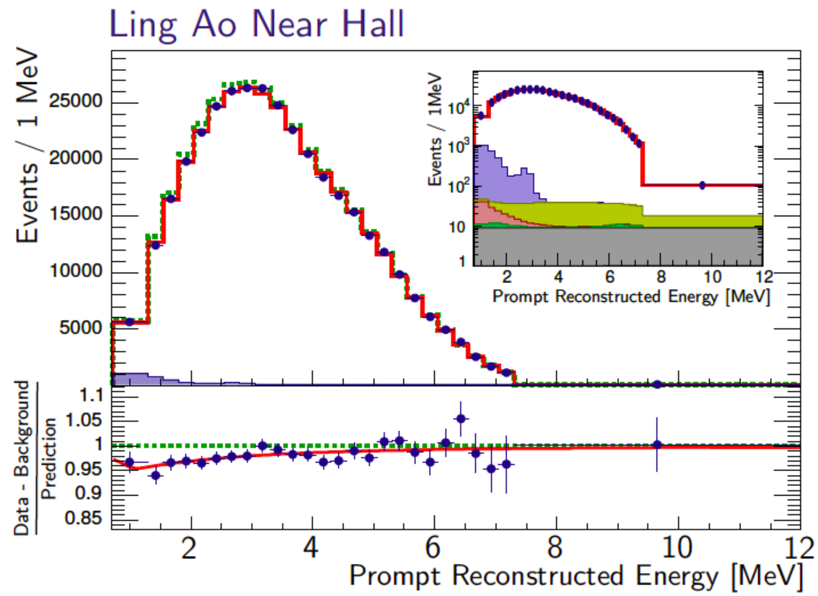
- detected rate strongly correlated with reactor flux expectations
  - predicted rate assumed NO oscillation
  - absolute normalization determined by fit to data
  - normalization within a few percent of expectations

IBD Prompt Spectra

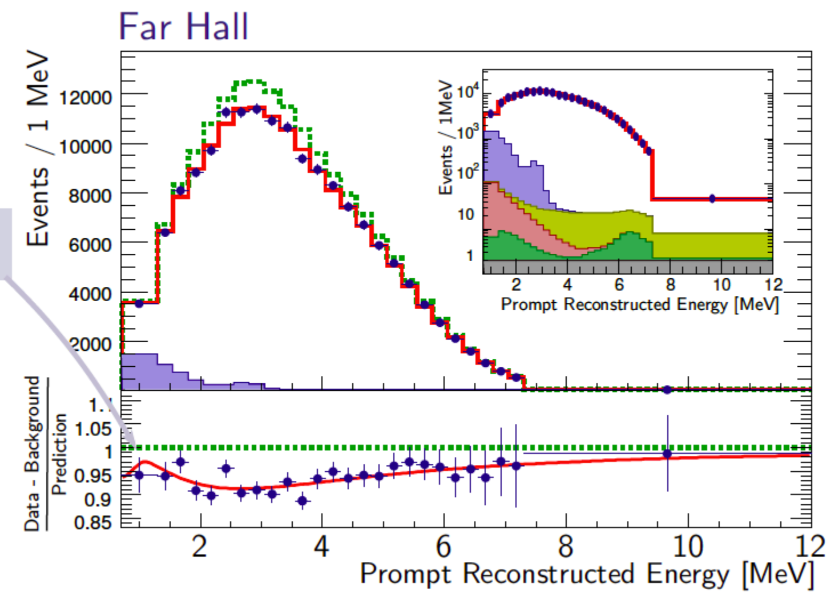
Daya Bay Near Hall



Ling Ao Near Hall



Far Hall



Data | Accidentals | $^{12}C(\alpha,n)^{16}O$
No Oscillation | $^{9}Li/^{8}He$ | Fast neutrons
Best Fit | $^{241}Am\text{-}^{13}C$

Shape distortion from energy losses in acrylic

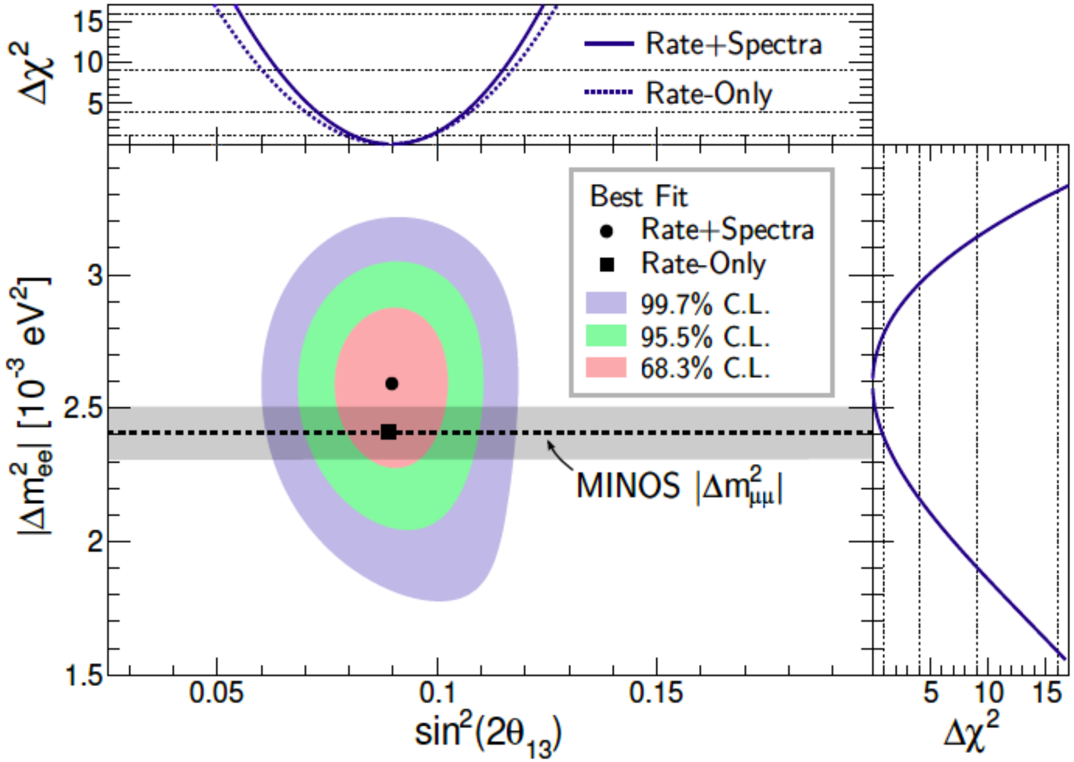
Spectral distortion consistent with oscillation

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

王萌/Wa

RESULTS AND PROSPECT

Spectral Analysis Results



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

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

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

strong confirmation of oscillation-interpretation of observed $\overline{\nu}_e$ deficit

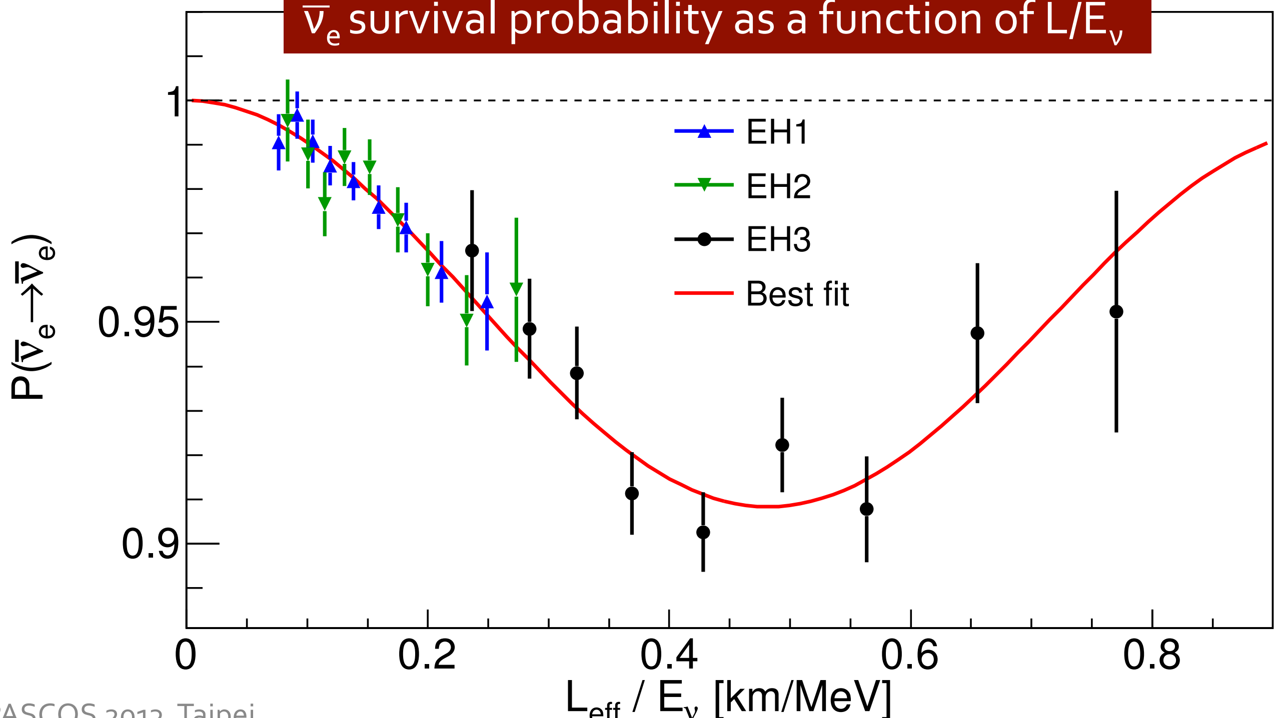
	Normal MH Δm^2_{32} [10^{-3}eV^2]	Inverted MH Δm^2_{32} [10^{-3}eV^2]
From Daya Bay Δm^2_{ee}	$2.54^{+0.19}_{-0.20}$	$-2.64^{+0.19}_{-0.20}$
From MINOS $\Delta m^2_{\mu\mu}$	$2.37^{+0.09}_{-0.09}$	$-2.41^{+0.12}_{-0.09}$

[João, NuFact2013]

Antineutrinos in Oscillation

- almost one full oscillation cycle being visible
  - L_{eff} determined for each experimental hall
  - background-subtracted positron spectrum converted into antineutrino spectrum
  - x-axis position given by <L_{eff}/E_ν> in each bin

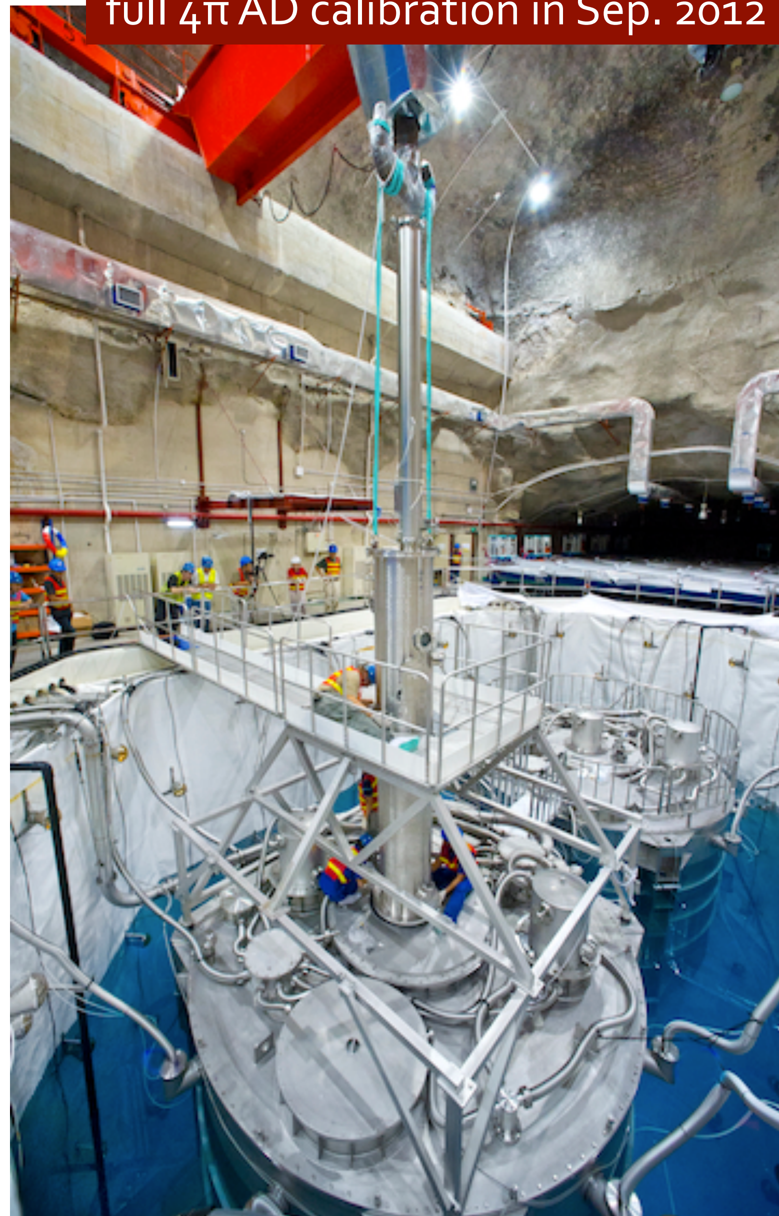
$\overline{\nu}_e$ survival probability as a function of L/E_ν



Daya Bay Still in Progress

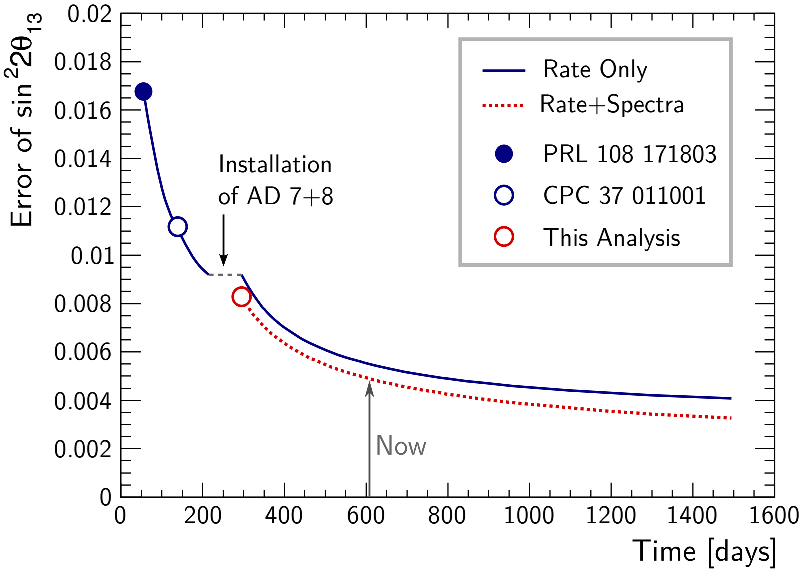
two final ADs installed
operating since Oct. 2012

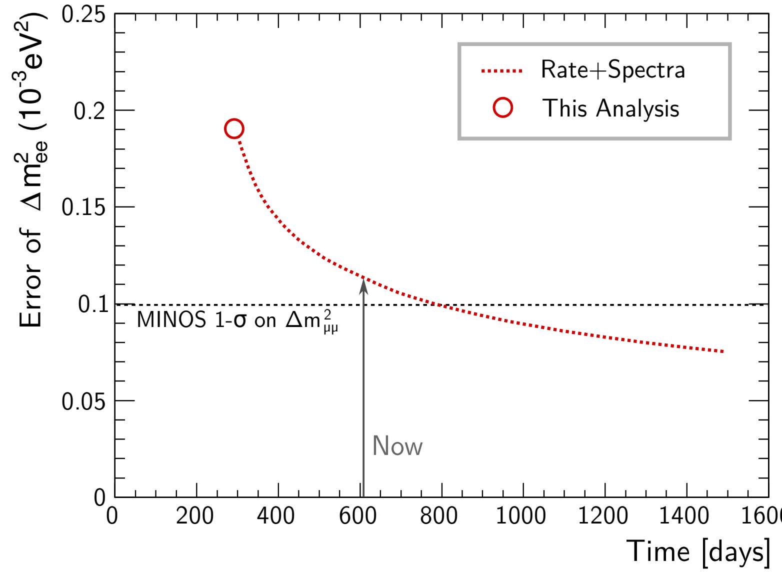
full 4π AD calibration in Sep. 2012



The Future

- increased precision in oscillation parameters: θ_{13} and Δm^2_{ee}





produce world's most precise measurement of the two oscillation parameters

  - constrain non-standard oscillation models
  - improve reach of next-generation experiments
- absolute reactor antineutrino flux and shape measurement
  - probe reactor models and explore reactor antineutrino 'anomaly'
- others: cosmogenic production, supernovae, …

Summary

- Daya Bay provides the first direct measurement of the mass-squared difference from relative deficit and spectral distortion observed between far and near detectors,

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

- and the most precise estimate of the mixing angle.

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

- … more exciting results to be continued from Daya Bay!