# Improved Measurement of Electron-antineutrino Disappearance at Daya bay

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# Neutrino Oscillation Before 2011

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

*Atmospheric*, MINOS, K2K, etc

Reactor, Accelerator

*Solar* ,KamLAND

$0\nu\beta\beta$

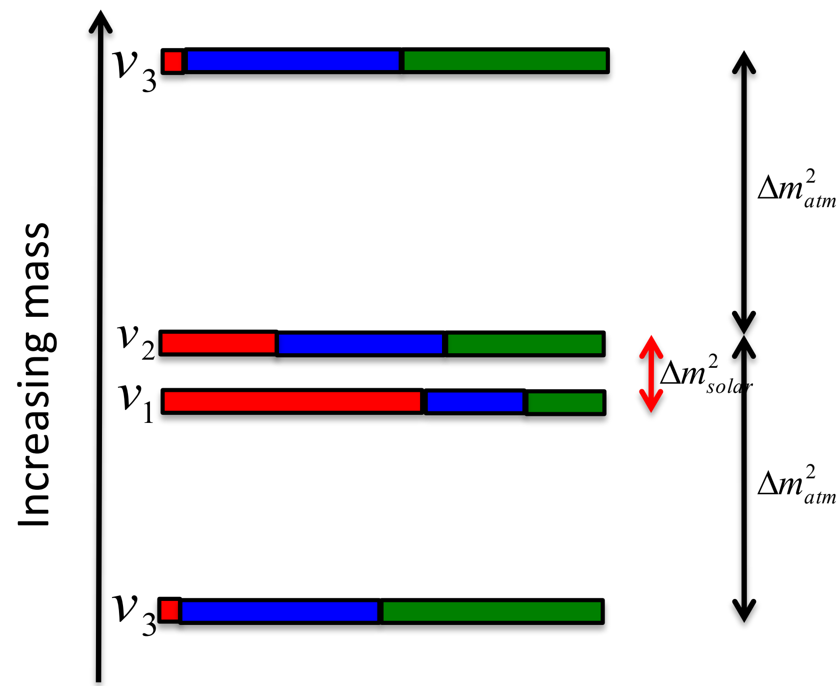
$$\sin^2(2\theta_{12}) = 0.87 \pm 0.03$$

$$\sin^2(2\theta_{23}) > 0.92$$

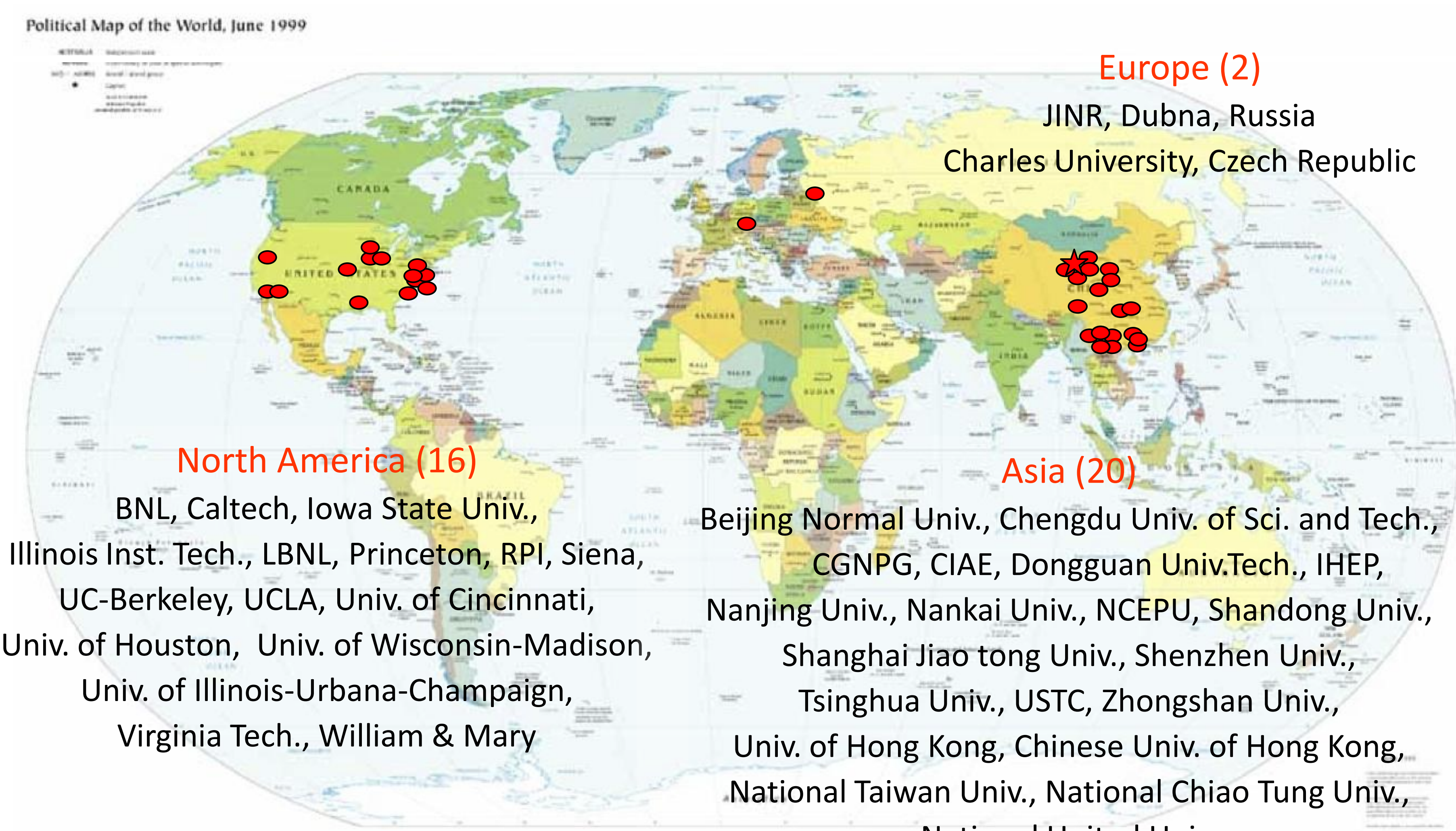
$$\Delta m^2_{21} = m^2_2 - m^2_1 = (7.59^{+0.19}_{-0.21}) \times 10^{-5} eV^2$$

$$\left|\Delta m^2_{32}\right| = \left|m^2_3 - m^2_2\right| = (2.43 \pm 0.13) \times 10^{-3} eV^2$$

- CP violation phase δ
- $\theta_{13}$
  - Gateway to CPV in lepton sector
- Mass hierarchy
- Is it its own antiparticle?



# The Daya Bay Collaboration




## Europe (2)

JINR, Dubna, Russia
Charles University, Czech Republic

## North America (16)

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

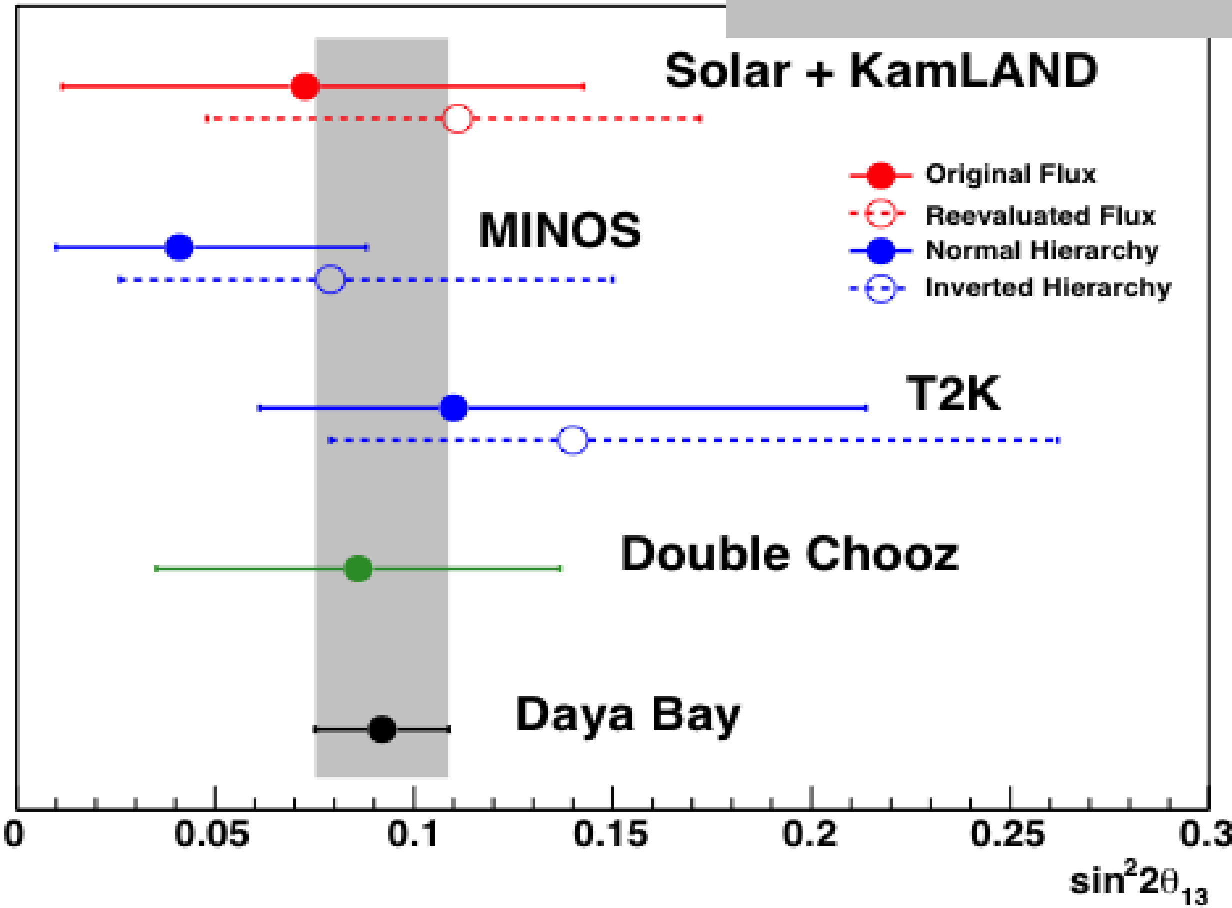
## Asia (20)

Beijing Normal Univ., Chengdu Univ. of Sci. and Tech., CGNPG, CIAE, Dongguan Univ.Tech., IHEP, 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.

**~230 Collaborators**

# The Year of 2012: nonzero $\theta_{13}$

**hints in 2011:**
- **Solar + KamLAND**: G.L.Fogli *et al.*, Phys. Rev. D 84, 053007 (2011)
- **MINOS**: P. Adamson *et al.*, Phys. Rev. Lett. 107, 181802 (2011)
- **T2K**: K. Abe *et al.*, Phys. Rev. Lett. 107 041801 (2011)
- **Double CHOOZ**: Y. Abe *et al.*, arXiv:1112.6353




**2012**: **Daya Bay**: Nonzero $\theta_{13}$ @ 5.2 σ , F. P. An et. al. Phys. Rev. Lett, 108:171803, 2012

**Reno:** Confirms nonzero $\theta_{13}$ arXiv:1204.0626

# Pin Down $\theta_{13}$ by measuring reactor neutrinos

- Neutrinos come from subsequent beta-decays of fission fragment (Free)

$$\bar{\nu}_e + p \rightarrow e^+ + n \quad N_{\det} = \frac{N_p}{4\pi L^2}\int \varepsilon \sigma P_{sur}(E, L, \theta_{13}) S dE$$

- clean measurement
  - no dependence on matter effect or CP violation phase

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

- Beat down the errors:
  - Increase statistics: high neutrino flux & large target mass
  - Relative measurement:

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

    - reduce error on reactor neutrino flux
    - Functionally identical detectors to minimize relative systematic errors
  - Mountain shielding : reduce cosmic ray induced backgrounds
  - Antineutrino detector design to maximize signals/backgrounds

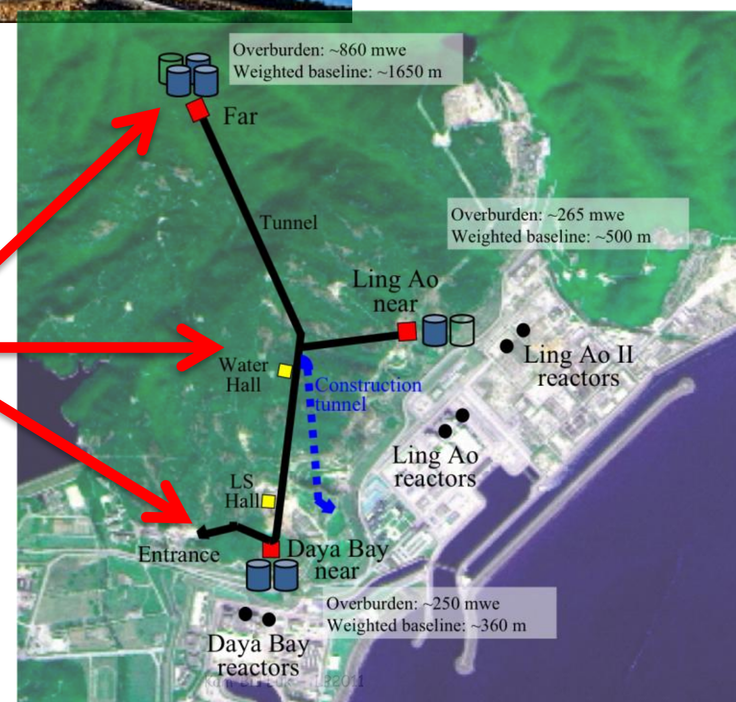
# The Daya Bay Experiment

Adjacent mountains with horizontal access provide 860 (250) m.w.e cosmic shielding.


6 commercial reactor cores with 17.4 $GW_{th}$ total power.

6 Antineutrino Detectors (ADs) give 120 tons total target mass.

Via GPS and modern theodolites, relative detector-core positions known to 3 cm.

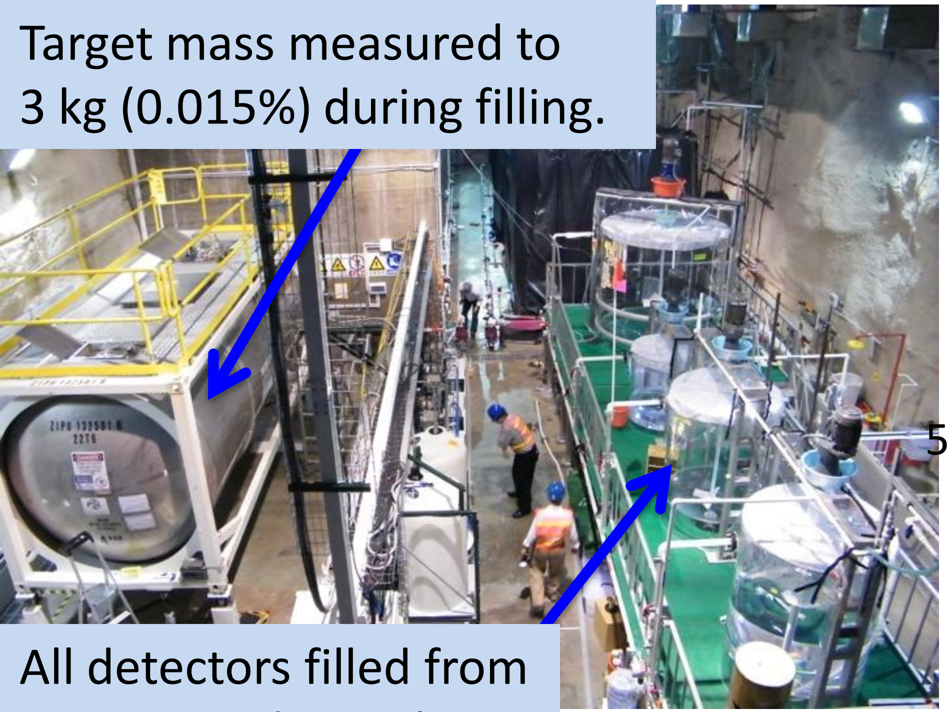


# Antineutrino Detectors

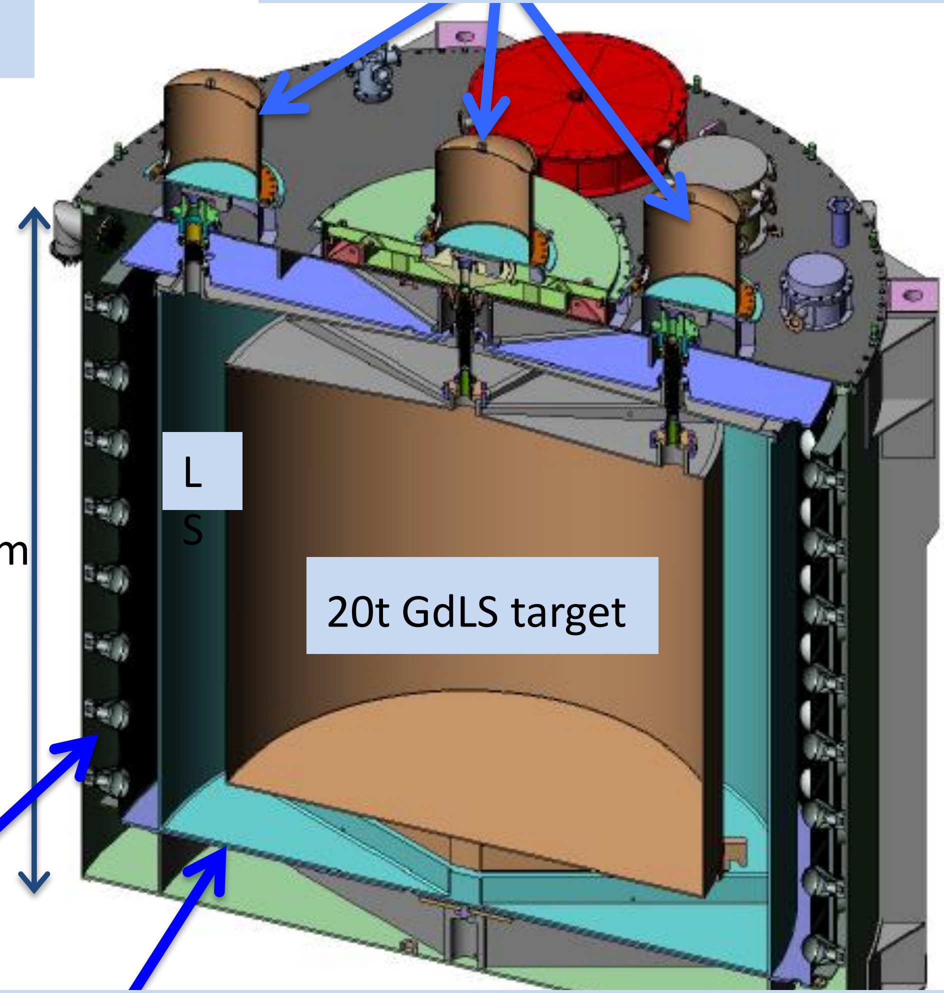
**6 ‘functionally identical’ detectors:**
Reduce systematic uncertainties

Calibration robots insert radioactive sources and LEDs.

Target mass measured to 3 kg (0.015%) during filling.



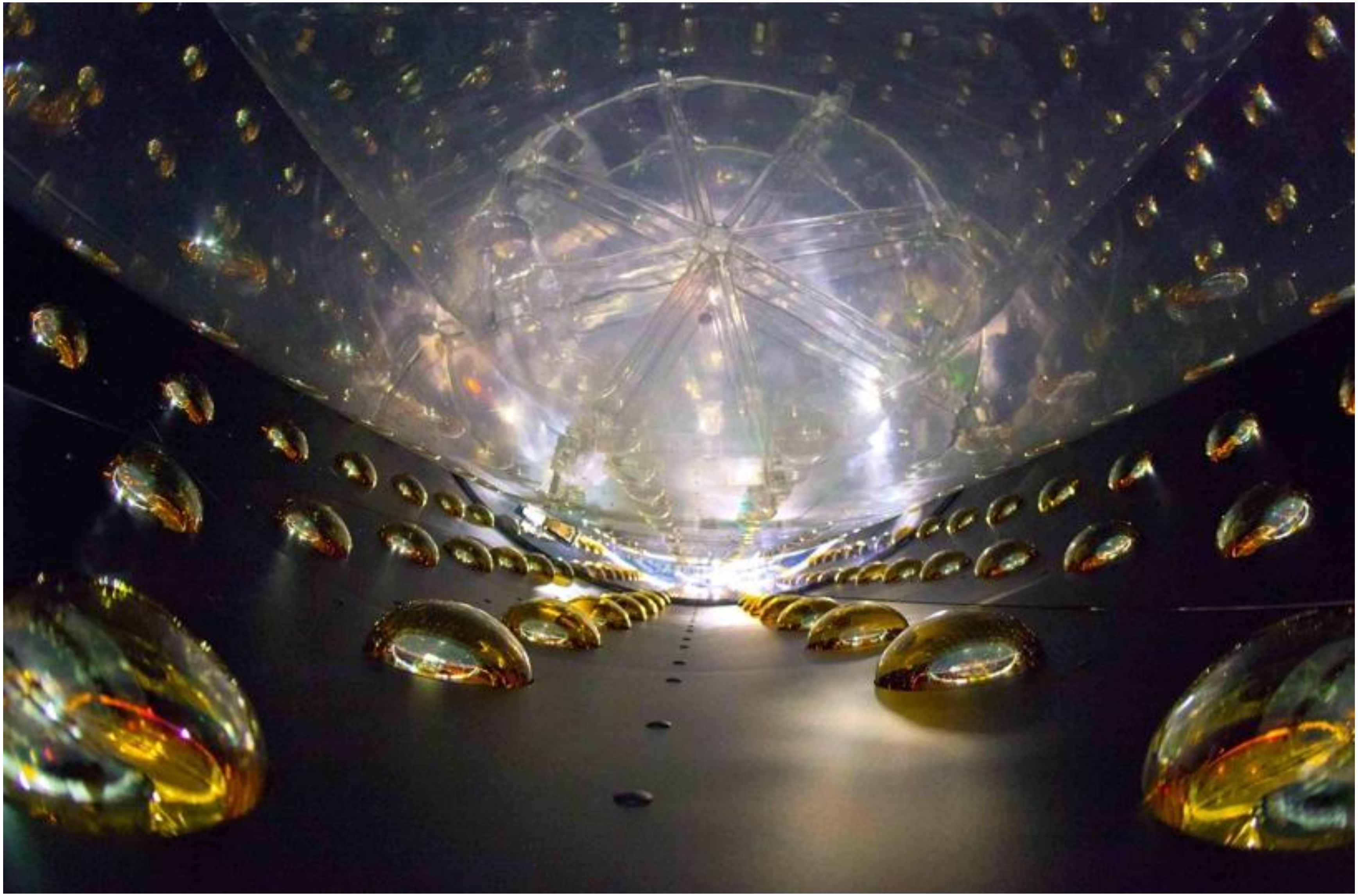
All detectors filled from common GdLS tanks.




192 8” PMTs detect light in target, ~163 p.e./MeV.

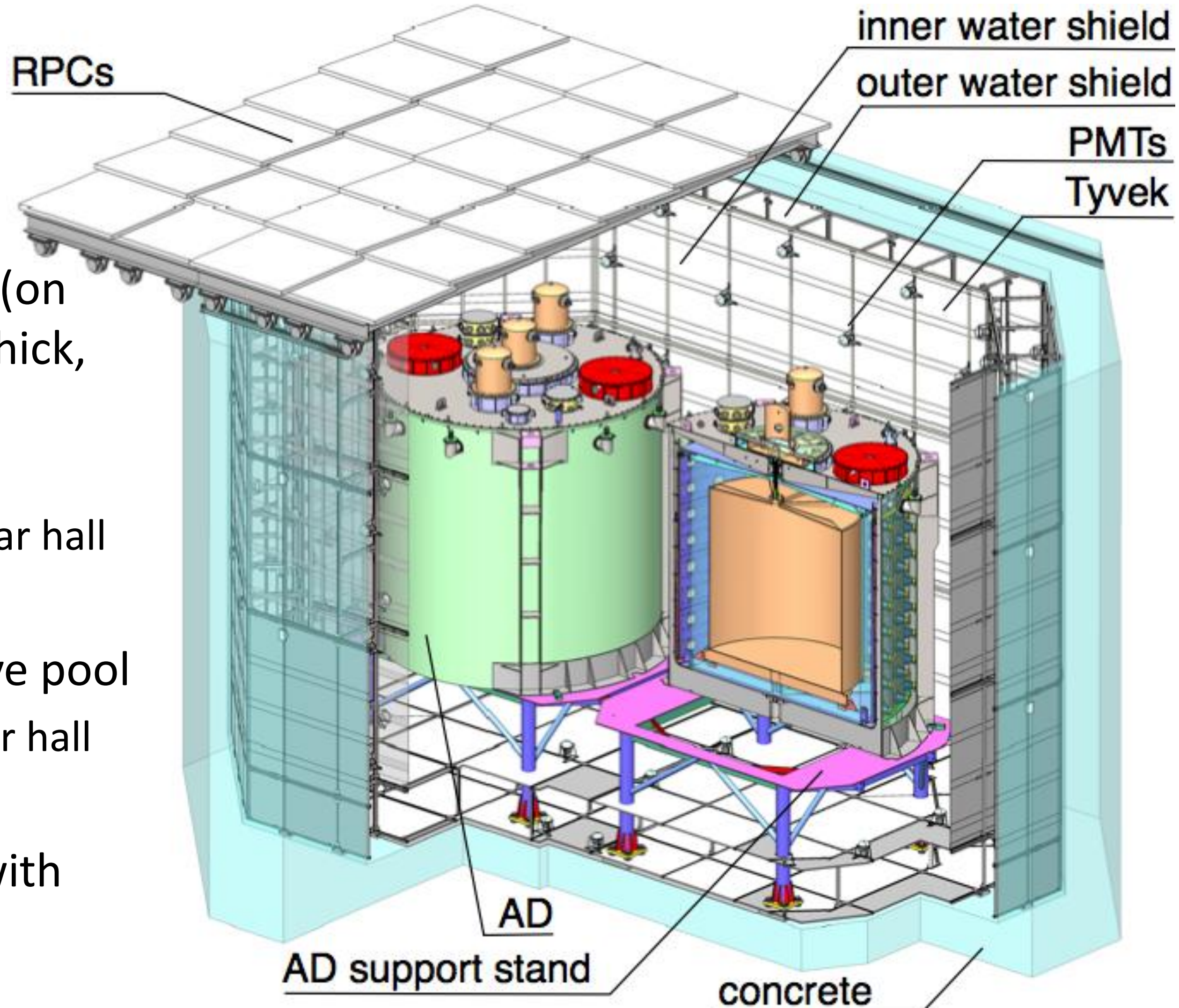
Reflectors improve light collection uniformity.

# Interior of Antineutrino Detector



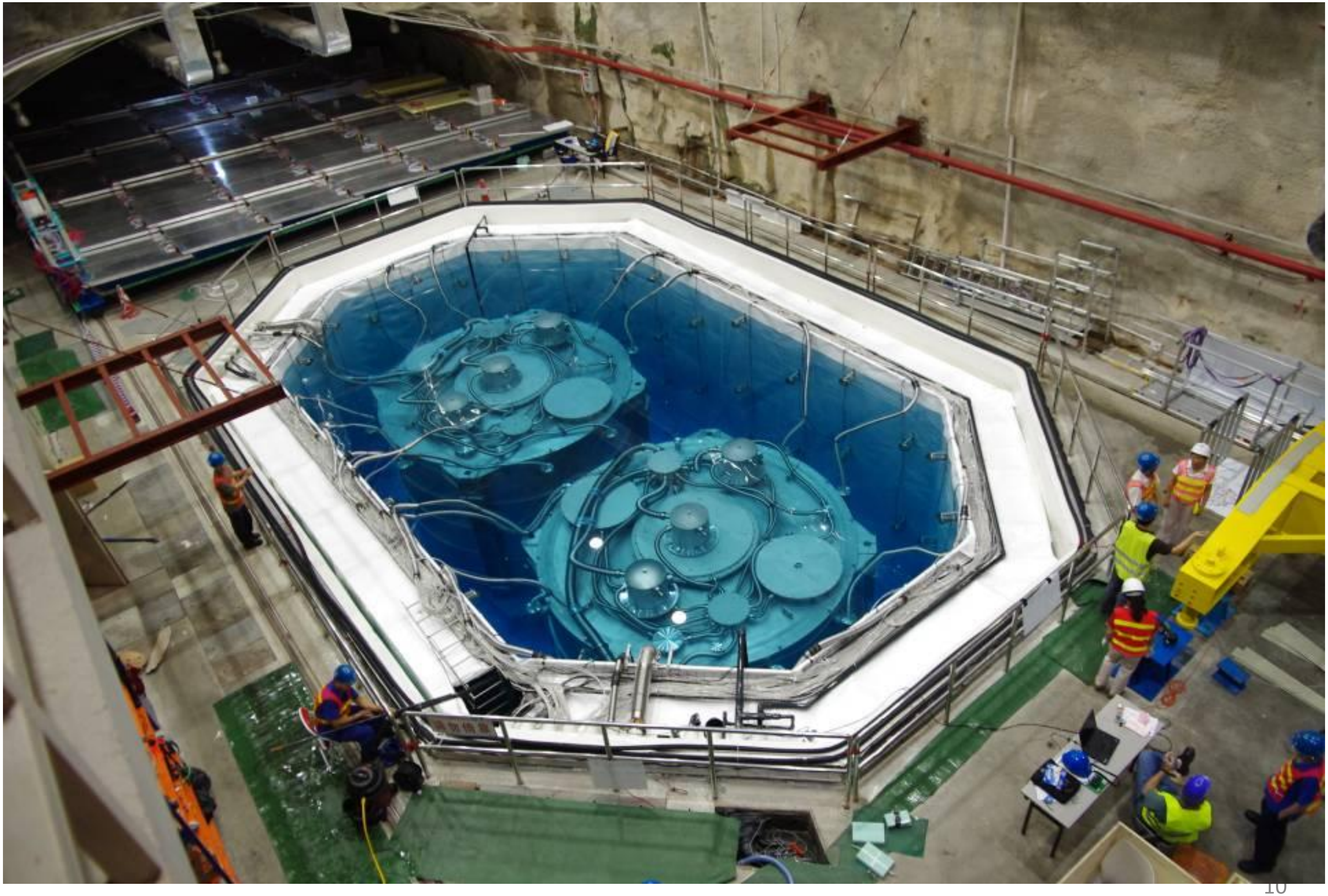
# Muon Tagging System

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



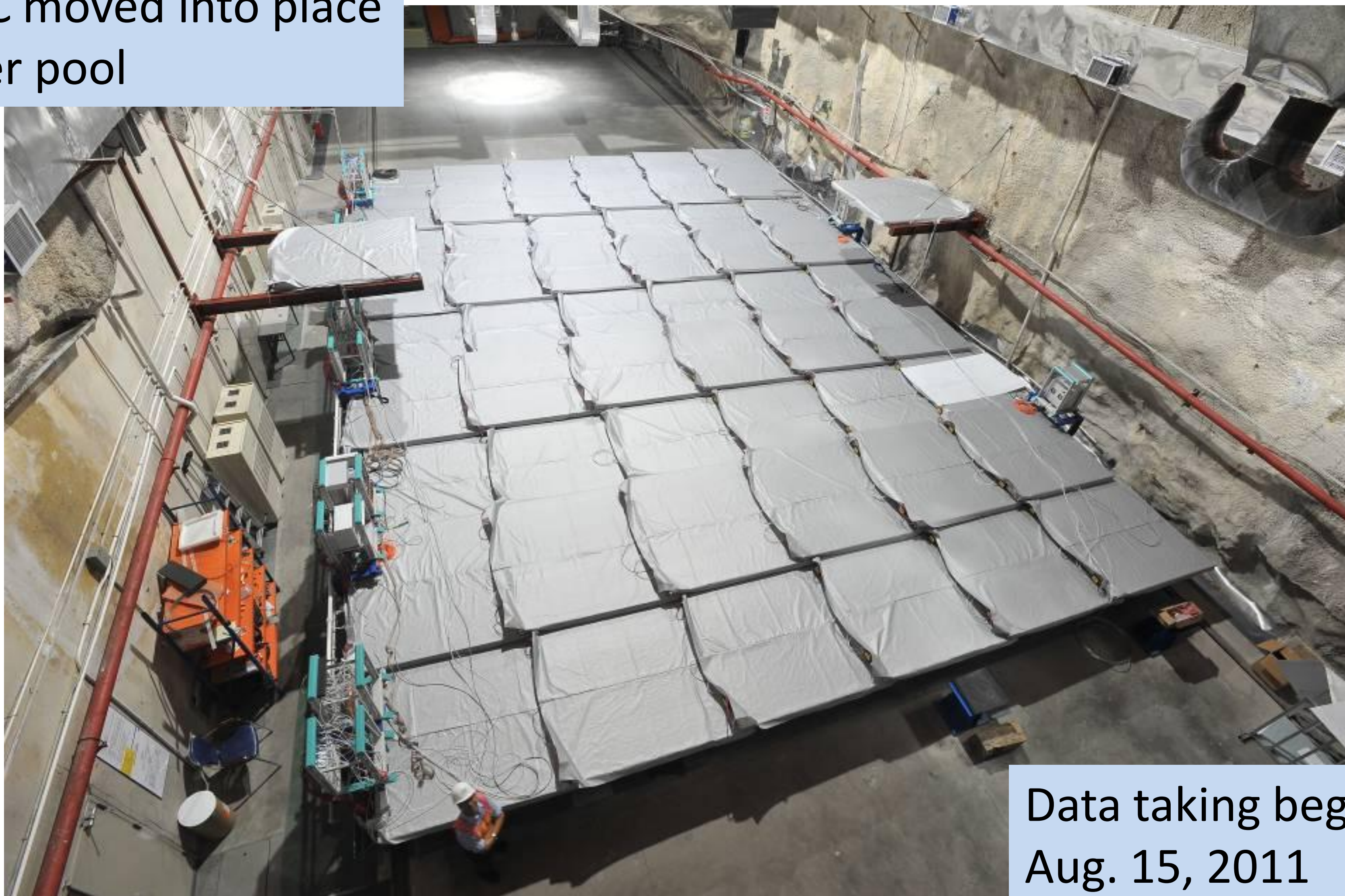

- Outer layer of water veto (on sides and bottom) is 1m thick, inner layer >1.5m. Water extends 2.5m above ADs
  - 288 8" PMTs in each near hall
  - 384 8" PMTs in Far Hall
- 4-layer RPC modules above pool
  - 54 modules in each near hall
  - 81 modules in Far Hall
- Goal efficiency: > 99.5% with uncertainty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

# EH1: Pool Filled



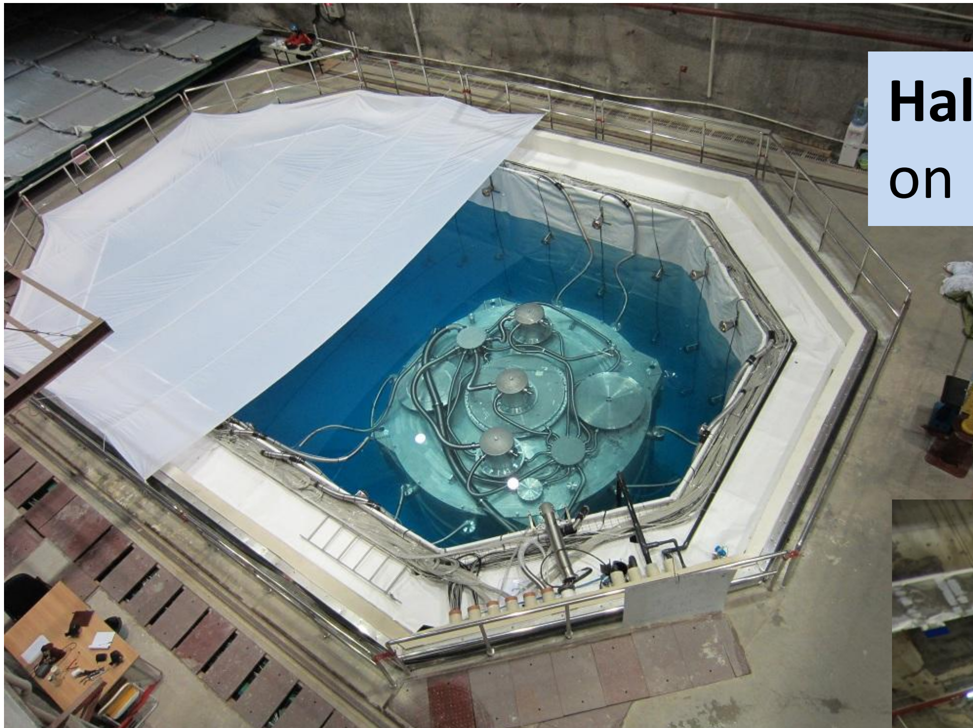
# Hall 1: Completed

RPC moved into place over pool



Data taking began Aug. 15, 2011

# Hall 2 and Hall 3



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

**Hall 3:** Began 3 AD operation on Dec. 24, 2011

2 more ADs assembled during summer of 2012

# Data Period

**A. Two Detector Comparison:** arXiv:1202:6181

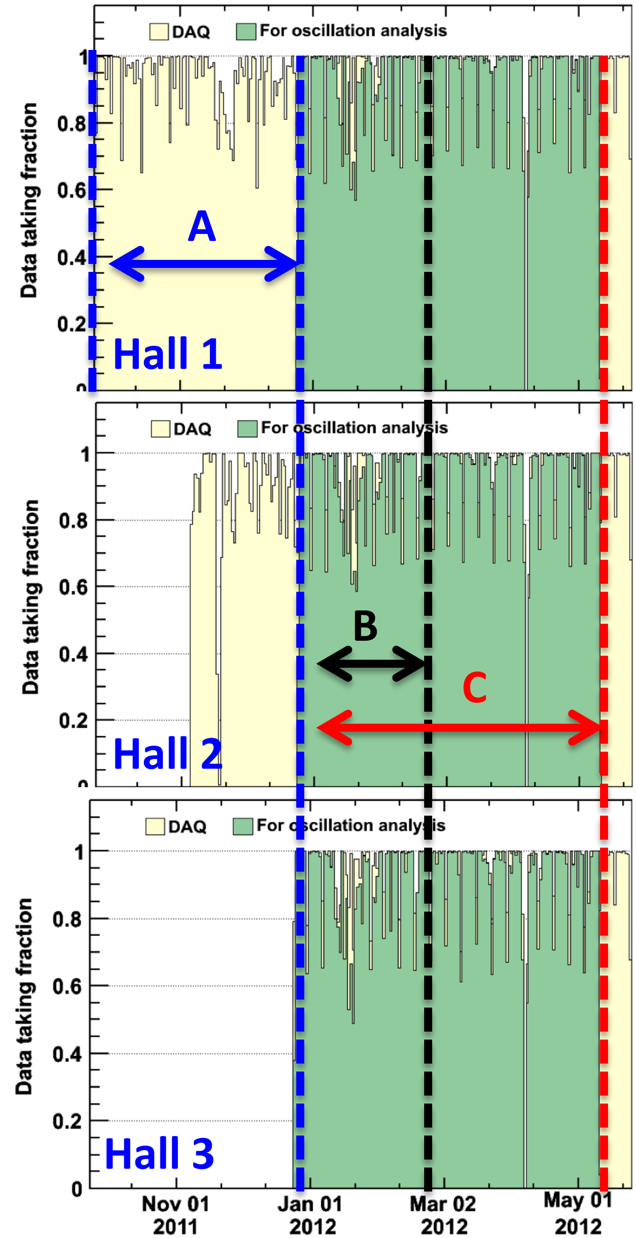
- Sep. 23, 2011 – Dec. 23, 2011
- Side-by-side comparison of 2 detectors in Hall 1
- Demonstrated detector systematics better than requirements.
- Nucl. Inst. and Meth. **A685**,78 (2012)

**B. First Oscillation Result:** arXiv:1203:1669

- Dec. 24, 2011 – Feb. 17, 2012
- All 3 halls (6 ADs) operating
- First observation of $\bar{\nu}_e$ disappearance
- Phys. Rev. Lett. **108**, 171803 (2012)

**C. This Update:** arXiv:1210.6327

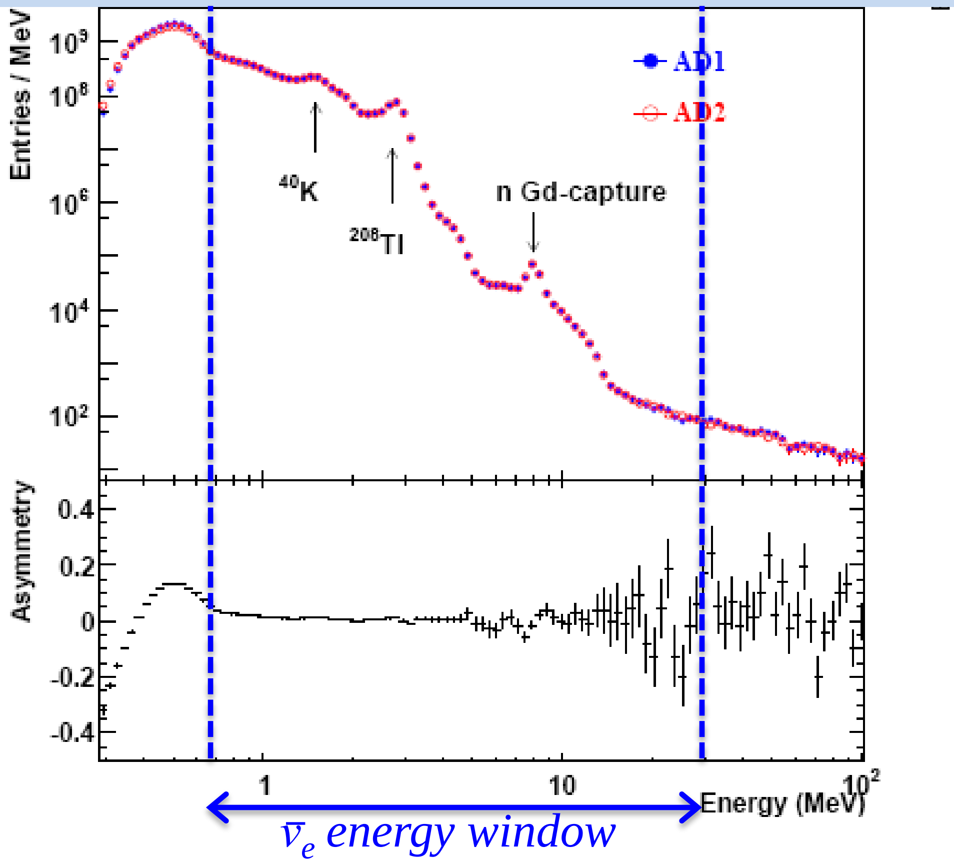
- Dec. 24, 2011 – May 11, 2012
- More than 2.5x the previous data set
- Submitted to Chinese Physics C

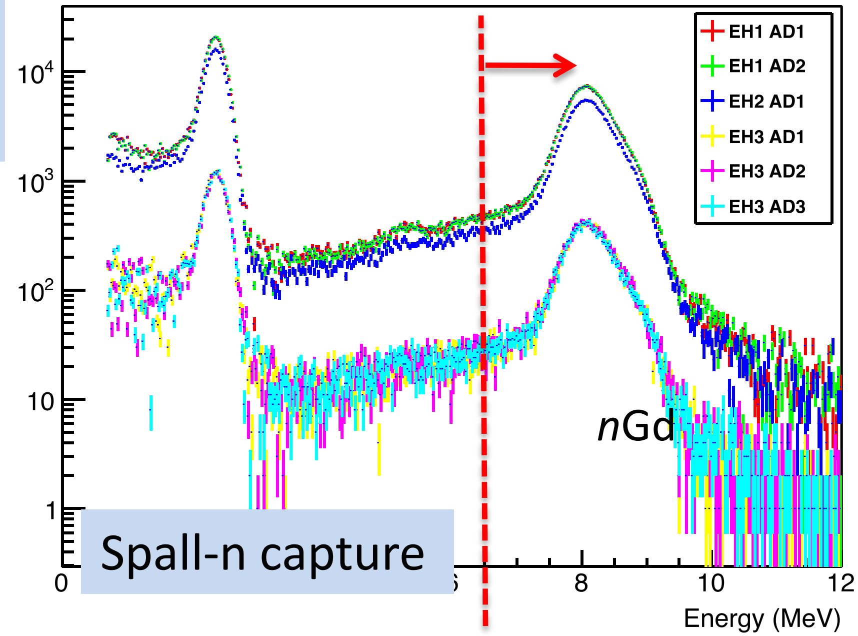


# Side-by-Side Comparison

**Multiple detectors allows detailed comparison and cross-checks.**

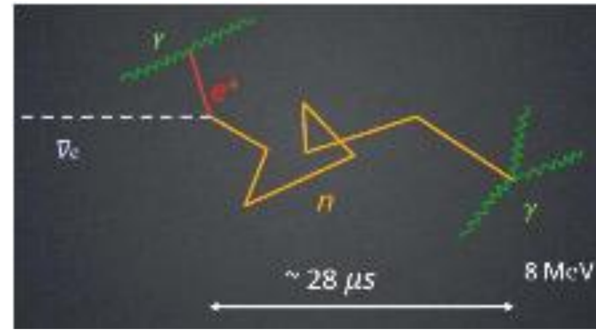
**Two ADs in Hall 1 have functionally identical spectra and response.**




**Response of all detectors to neutrons constrains largest systematic uncertainty.**

# The Signals & Backgrounds




- Signals ( Inverse Beta Decay) in AD

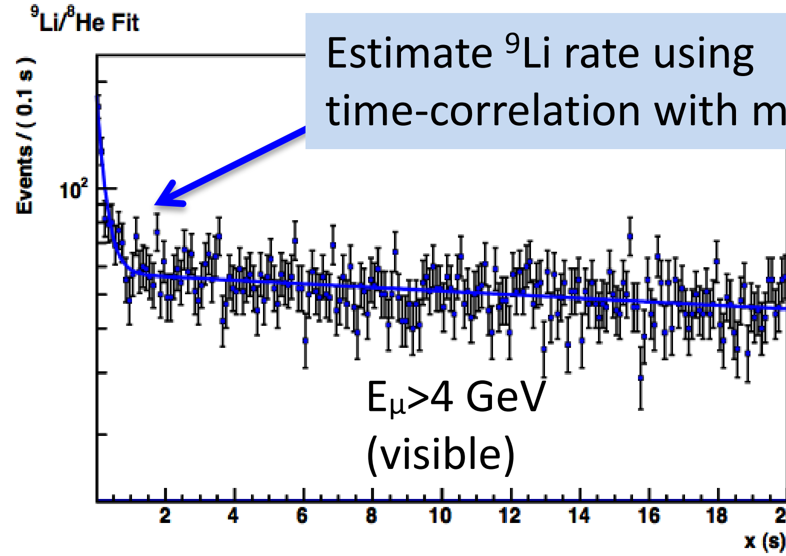
$$\bar{\nu}_e + p \rightarrow e^+ + n$$
$$\downarrow$$
$$n + {}^{x}Gd \rightarrow {}^{x+1}Gd + \gamma$$

  - Prompt positron carries antineutrino energy: $E_{e+} \approx E_\nu - 0.8$ MeV
  - Delayed neutron capture has distinct energy (~ 8MeV) and time correlation with prompt signal
- Backgrounds:
  - Accidentals
  - Fast n: prompt: n scattering, delayed: n Capture
  - 8He/9Li: prompt: βdecay, delayed: n Capture
  - Am-C source: prompt:γrays, delayed:n Capture
  - α n: 13C(α,n)16O

# Backgrounds

**Total backgrounds are 5% (2%) in far (near) halls.**

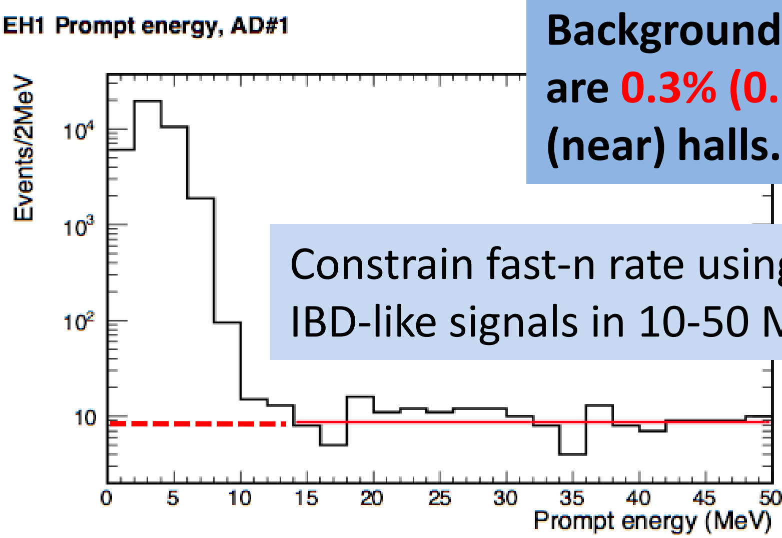
| | Near Halls | | Far Hall | |
|---|---|---|---|---|
| | B/S % | $\sigma_{B/S}$ % | B/S % | $\sigma_{B/S}$ % |
| **Accidentals** | 1.5 | 0.02 | 4.0 | 0.05 |
| **Fast neutrons** | 0.12 | 0.05 | 0.07 | 0.03 |
| **$^{9}Li/^{8}He$** | 0.4 | 0.2 | 0.3 | 0.2 |
| **$^{241}Am\text{-}^{13}C$** | 0.03 | 0.03 | 0.3 | 0.3 |
| **$^{13}C(\alpha, n)^{16}O$** | 0.01 | 0.006 | 0.05 | 0.03 |



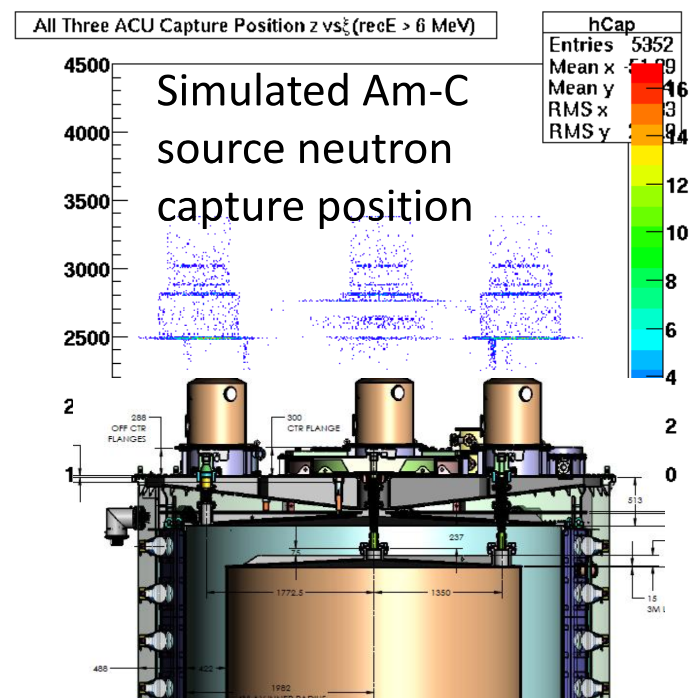

Estimate $^{9}$Li rate using time-correlation with muon

$E_{\mu}$>4 GeV (visible)

**Background uncertainties are 0.3% (0.2%) in far (near) halls.**




Constrain fast-n rate using IBD-like signals in 10-50 MeV




Simulated Am-C source neutron capture position

# Data Set Summary

**> 200k antineutrino interactions!**

| | AD1 | AD2 | AD3 | AD4 | AD5 | AD6 |
|---|---|---|---|---|---|---|
| Antineutrino candidates | 69121 | 69714 | 66473 | 9788 | 9669 | 9452 |
| DAQ live time (day) | 127.5470 | | 127.3763 | | 126.2646 | |
| Efficiency | 0.8015 | 0.7986 | 0.8364 | 0.9555 | 0.9552 | 0.9547 |
| Accidentals (/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 (/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 |
| $^{8}He/^{9}Li$ (/day) | 2.9±1.5 | | 2.0±1.1 | | 0.22±0.12 | |
| Am-C corr. (/day) | 0.2±0.2 | | | | | |
| $^{13}C(\alpha, n)^{16}O$ (/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 |
| **Antineutrino rate (/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** |

**Consistent rates for side-by-side detectors**

Uncertainty currently dominated by statistics

# 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% |

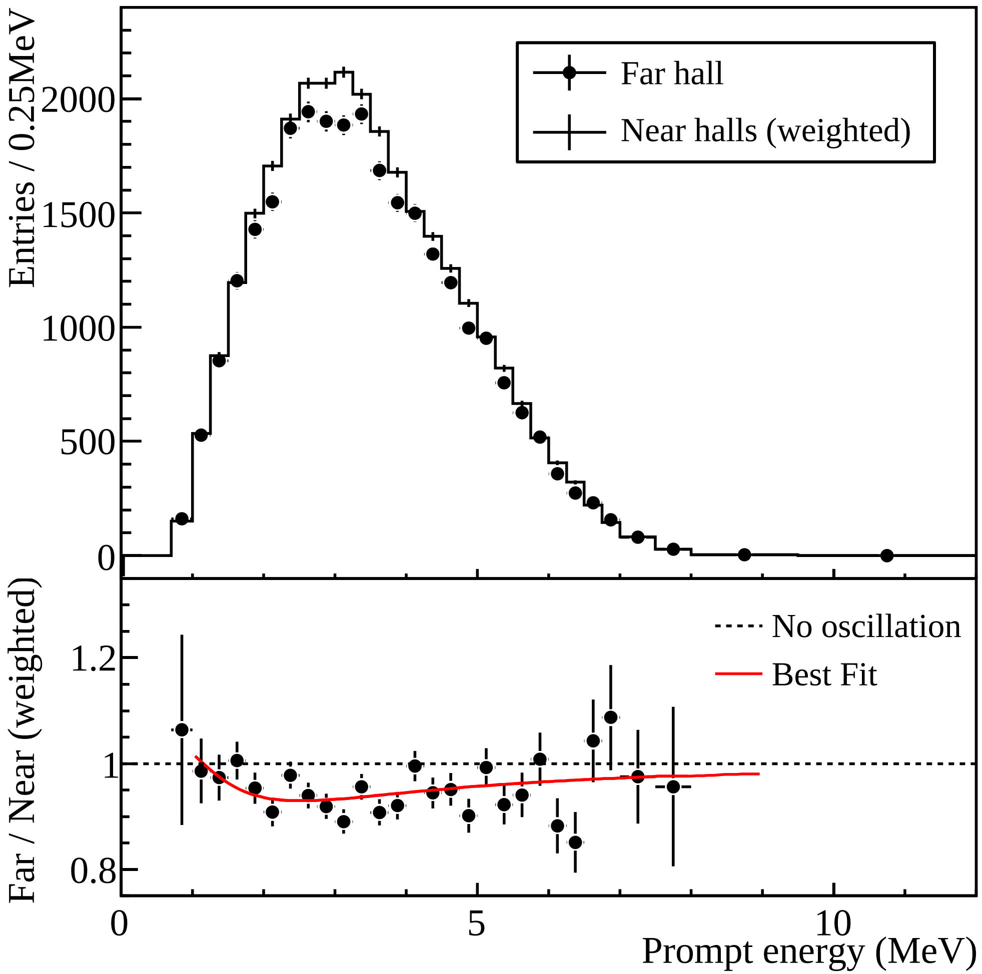
**For near/far oscillation, only uncorrelated uncertainties are used.**

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

Influence of uncorrelated reactor systematics reduced by far vs. near measurement.

# Far vs. Near Comparison

Compare the far/near measured rates and spectra




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

$M_n$ are the measured rates in each detector. Weights $\alpha_i$,$\beta_i$ are determined from baselines and reactor fluxes.

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

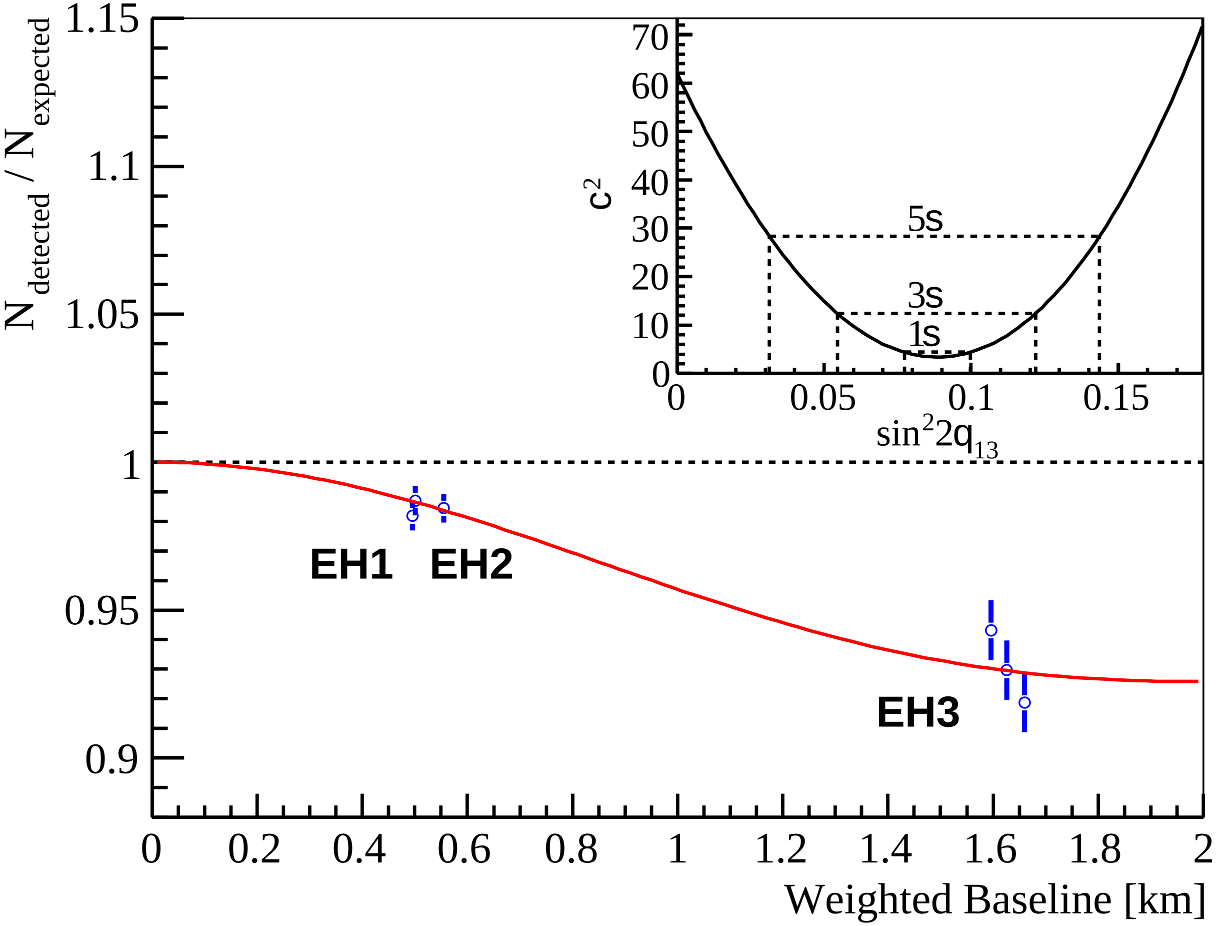
Clear observation of far site deficit.

Spectral distortion consistent with oscillation.*

* Caveat: Spectral systematics not fully studied; $\theta_{13}$ value from shape analysis is not recommended.

# Rate Analysis

**Estimate $\theta_{13}$ using measured rates in each detector.**




Uses standard $\chi^2$ approach.

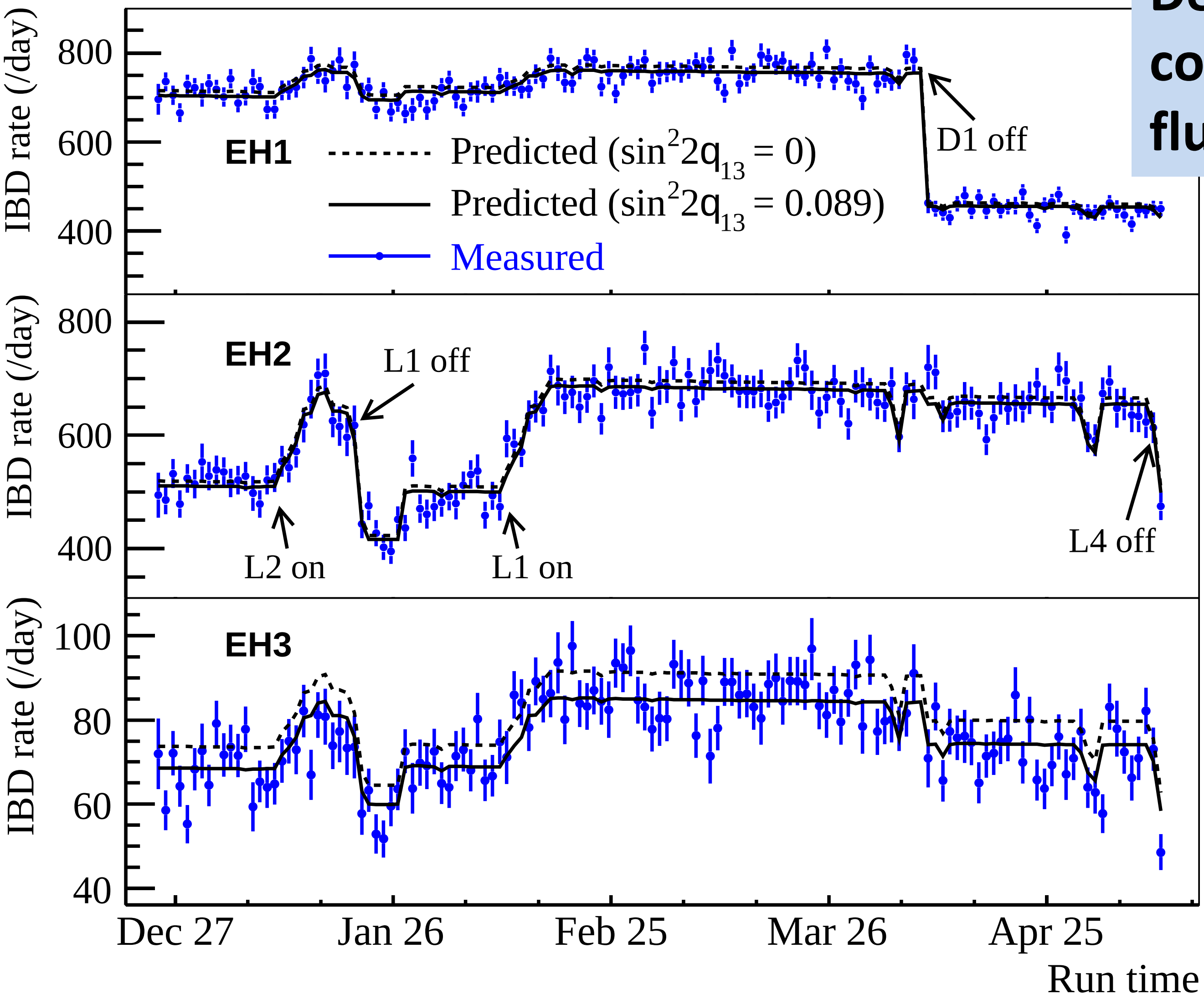
Far vs. near relative measurement.
[Absolute rate is not constrained.]

Consistent results obtained by independent analyses, different reactor flux models.

**Most precise measurement of $\sin^2 2\theta_{13}$ to date.**

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

# 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.

# More Work for Daya Bay

## Primary Science Goals

- Definitive precision measurement of $\sin^2 2\theta_{13}$
- Measurement of $\Delta m^2_{31}$

## Additional Science Goals

- Precise reactor flux and spectra measurements**.** Will have largest reactor antineutrino data set collected.
- Measurement of cosmogenic neutrons & isotopes over a range of muon energies and (modest) depths.
- Search for new, non-standard antineutrino interactions

## Technical studies

- Demonstrate multi-year operation of "functionally identical detectors". Track performance versus time.
- Verify long term GdLS stability.

# Summary

- With 2.5x more data, the Daya Bay reactor neutrino experiment measures a far/near antineutrino deficit at ~2 km:

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

*[Previous value: R = 0.940 ± 0.011 (stat) ± 0.004 (syst)]*

- Interpretation of disappearance as neutrino oscillation yields:

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

*[Previous value: $\sin^2 2\vartheta_{13} = 0.092 \pm 0.016$ (stat) ± 0.005 (syst)]*

- Final two ADs are installed during this summer.