Status Quo and Future Evolution of θ_{13}

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Some Approaches For Measuring θ_{13}

- Accelerator-based ν_e appearance experiments

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

  - Some ambiguities exist in extracting a value for θ_{13}
  - Baseline *O(100-1000 km)*, large detectors
  - MINOS, T2K, NOvA, LBNE,...

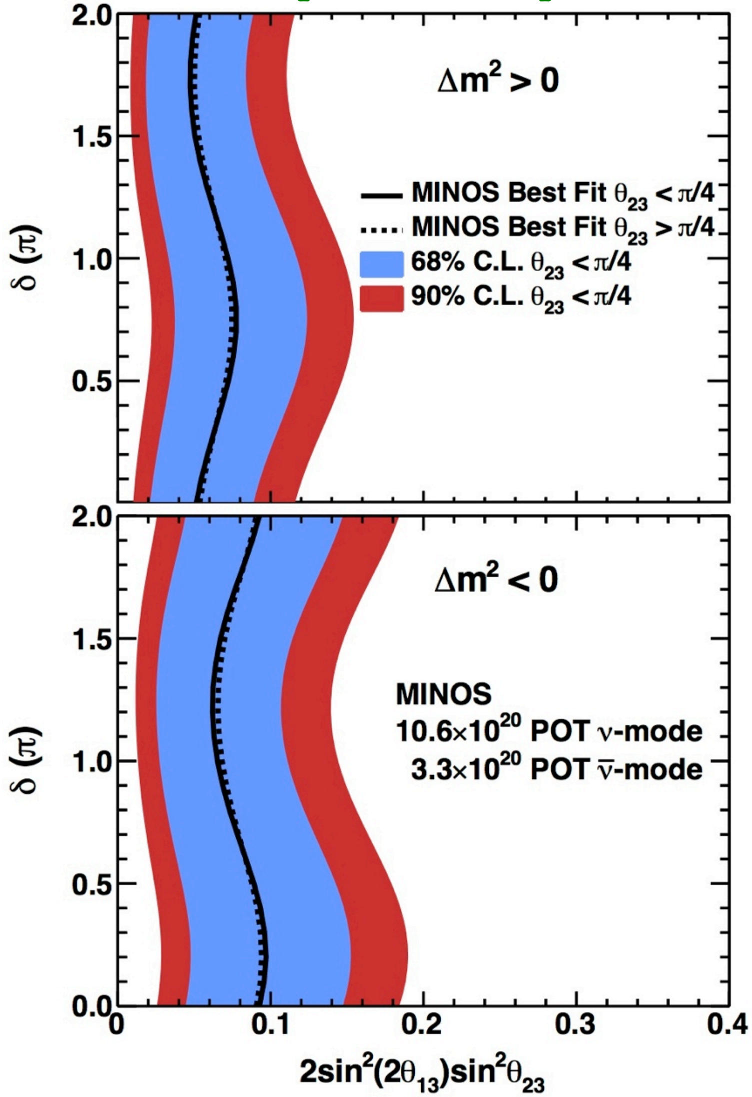
- Reactor-based $\bar{\nu}_e$ disappearance experiments

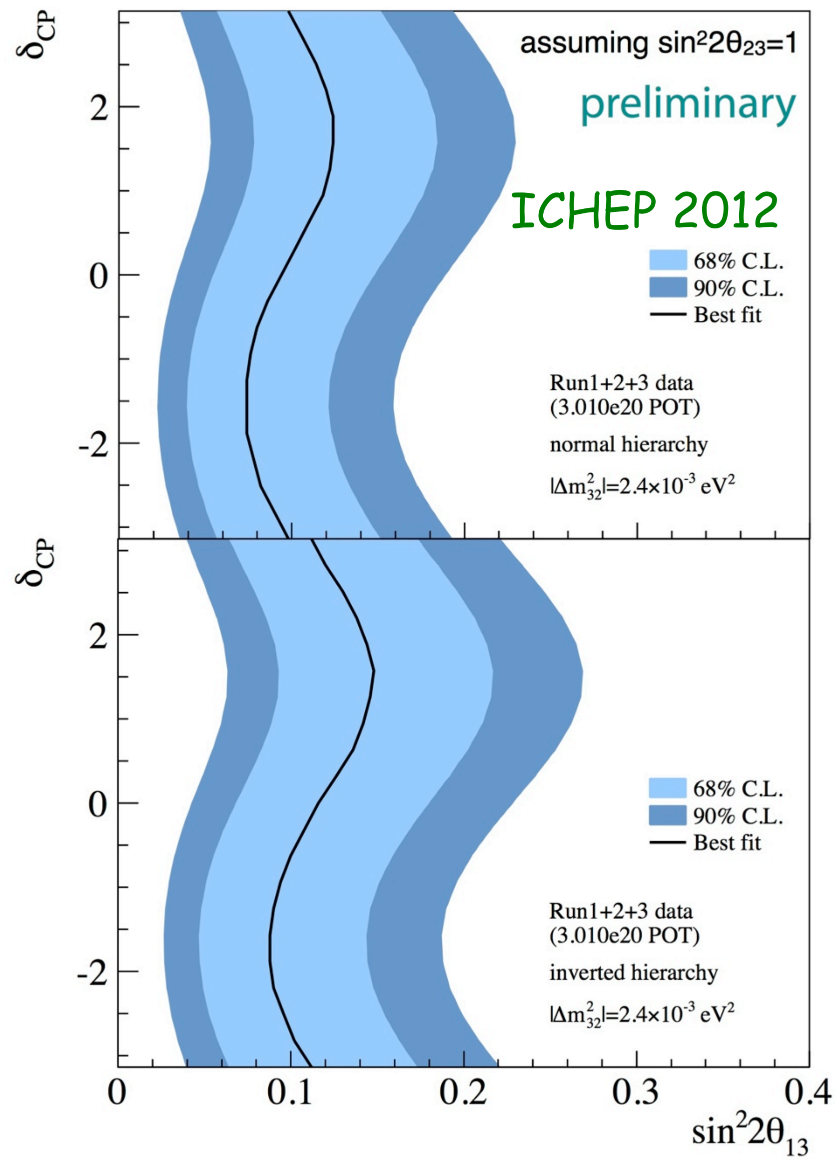
$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right)$$

  - No CP or matter effect.
  - Baseline *O(1 km)*, small detectors
  - Daya Bay, Double Chooz, RENO

$\sin^2 2\theta_{13}$ From MINOS & T2K

[1301.4581]





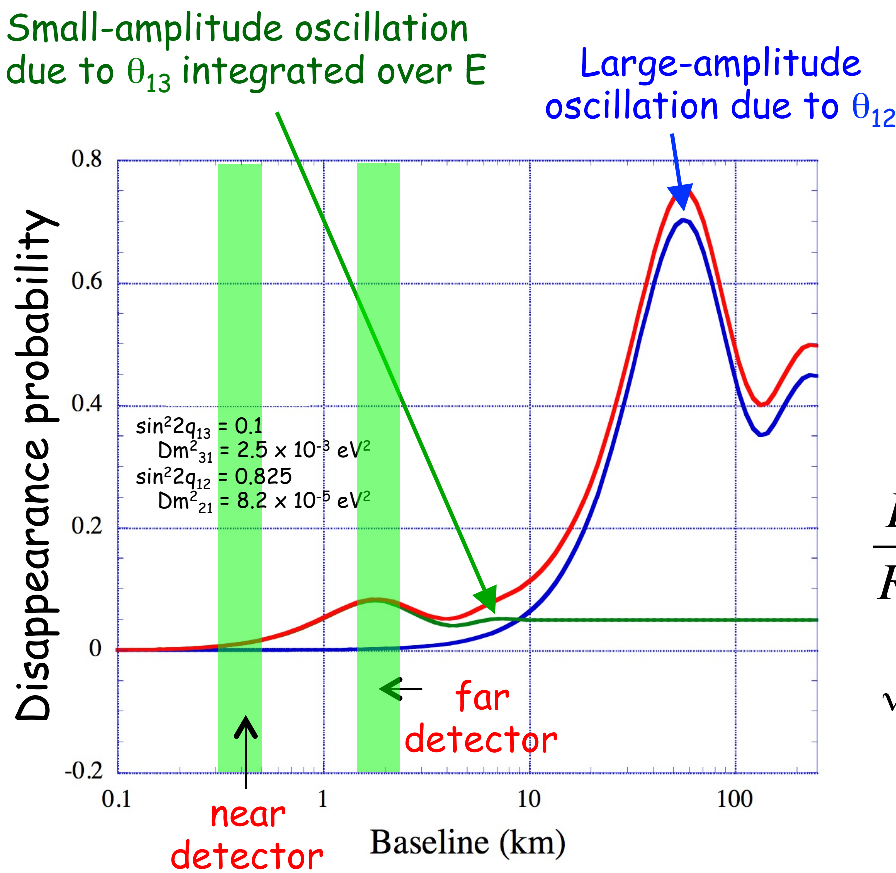
$$2\sin^2 2\theta_{13}\sin^2\theta_{23} = 0.051^{+0.038}_{-0.030} \quad (NH)$$

$$\sin^2 2\theta_{13} = 0.094^{+0.053}_{-0.040} \quad (NH)$$

Precision Determination of θ_{13} With Reactor $\bar{\nu}_e$

- High statistics: powerful nuclear reactors, big detectors, long run-time.
- Optimize baselines:

$$P(\bar{\nu}_e \to x) \approx \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$



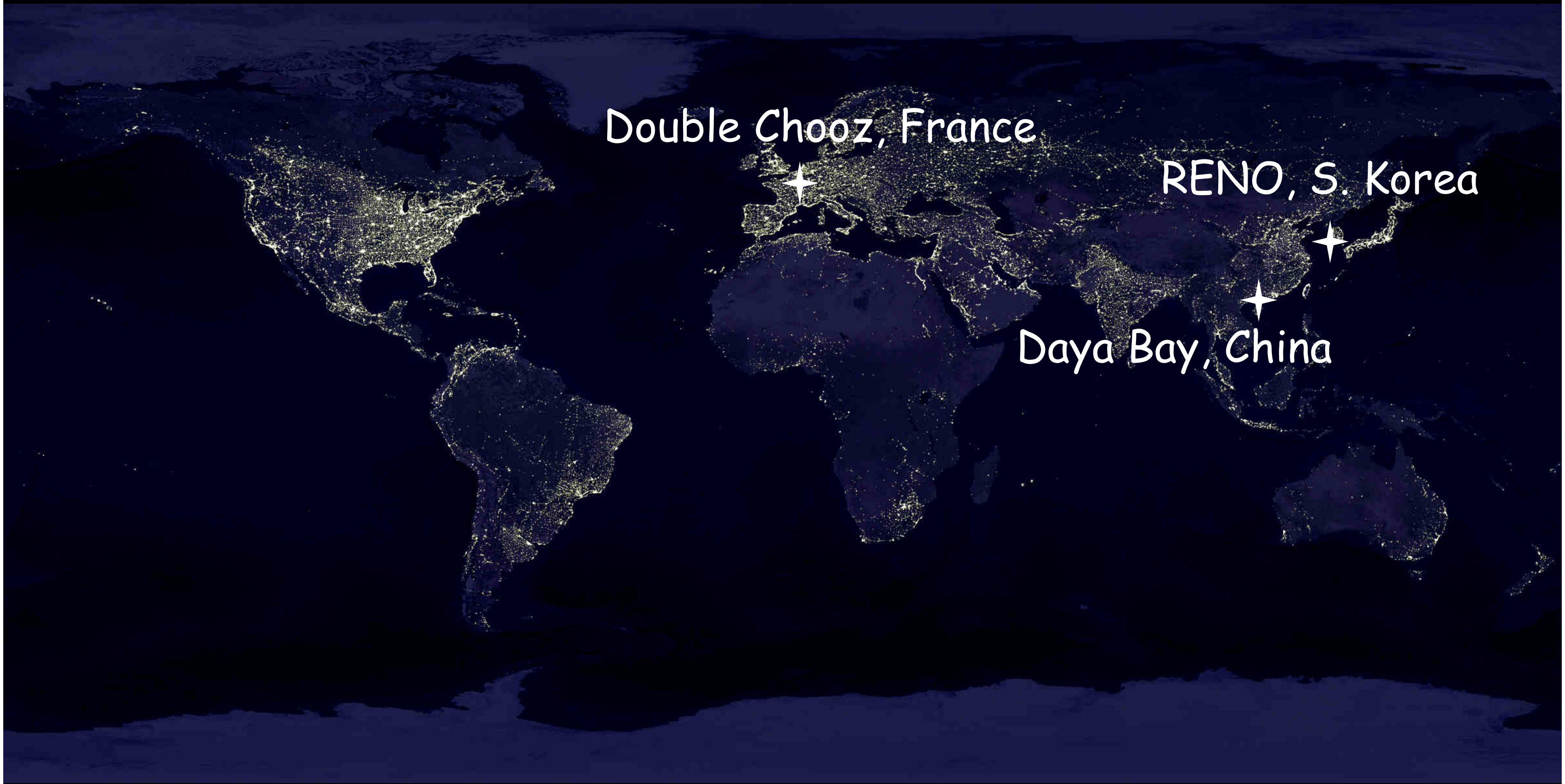
- Reduce systematic uncertainties:
  - detector-related: alike-performance detectors, careful calibration
  - reactor-related: relative measurement with near and far detectors

$$\frac{R_{Far}}{R_{Near}} = \left(\frac{L_{Near}}{L_{Far}}\right)^2 \left(\frac{N_{Far}}{N_{Near}}\right)\left(\frac{\varepsilon_{Far}}{\varepsilon_{Near}}\right)\left(\frac{1-P_{Far}(L_{Far})}{1-P_{Near}(L_{Near})}\right)$$

ν_e flux	$1/r^2$	number of protons	detection efficiency	yield $\sin^2 2\theta_{13}$

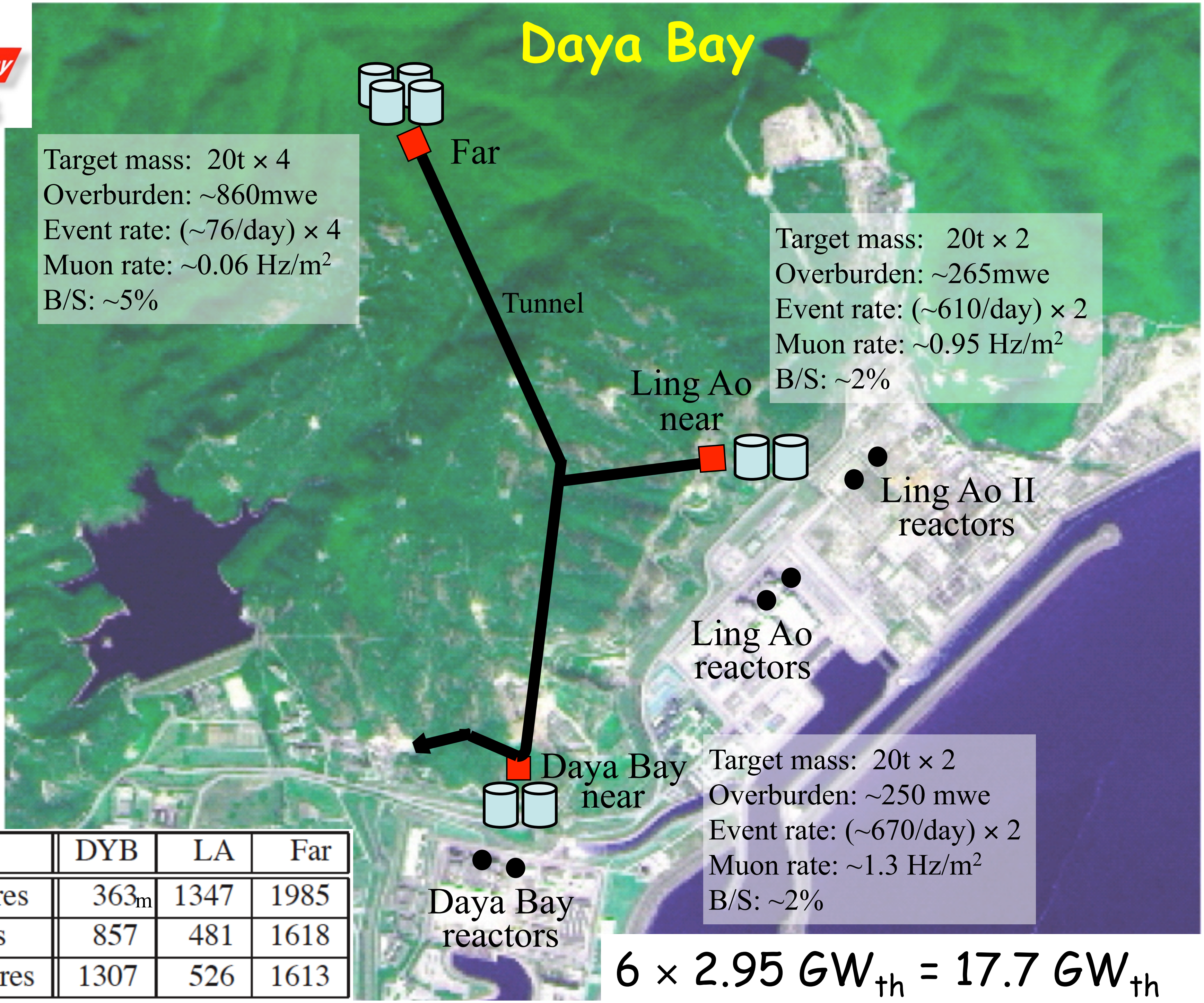
- Reduce background: shield and veto

Current Reactor-based θ_{13} Experiments



What Have Been Accomplished ?

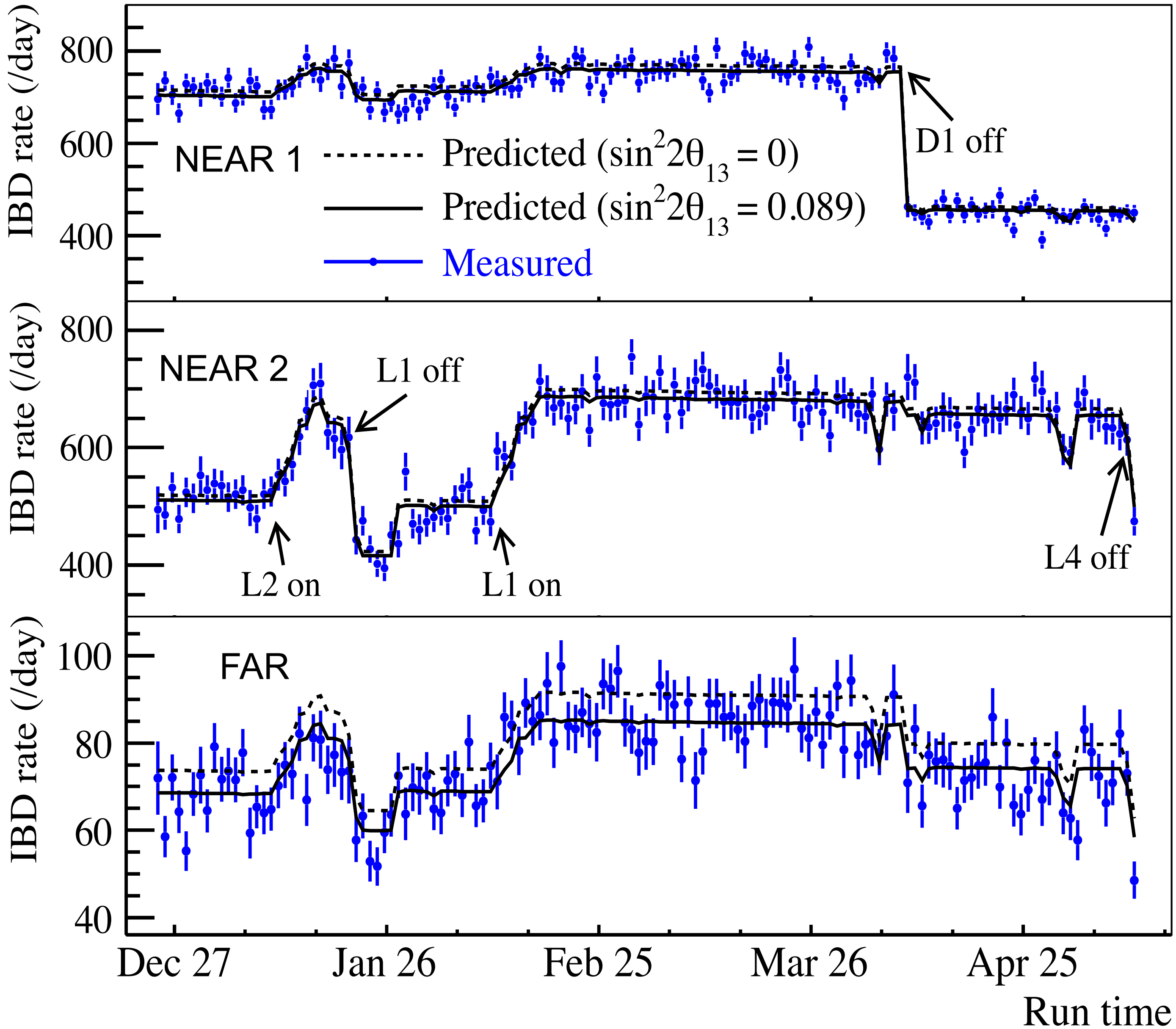
Daya Bay



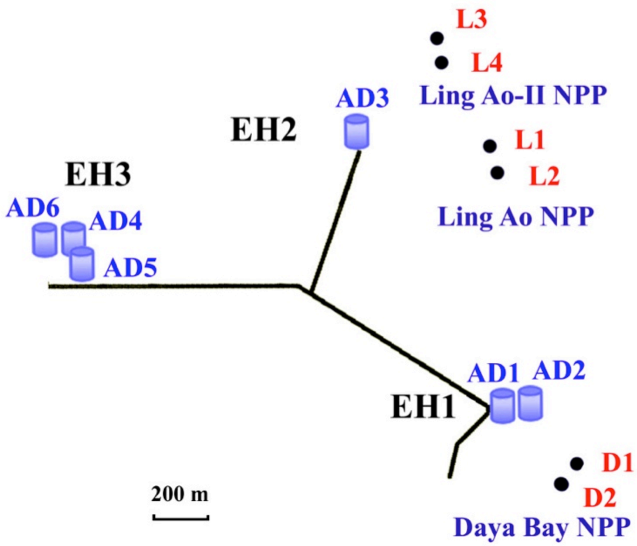
Sites	DYB	LA	Far
DYB cores	363m	1347	1985
LA cores	857	481	1618
LA II cores	1307	526	1613

$6 \times 2.95\ GW_{th} = 17.7\ GW_{th}$

$\sin^2 2\theta_{13}$ From Antineutrino Rate



$\sin^2 2\theta_{13}$ From Daya Bay



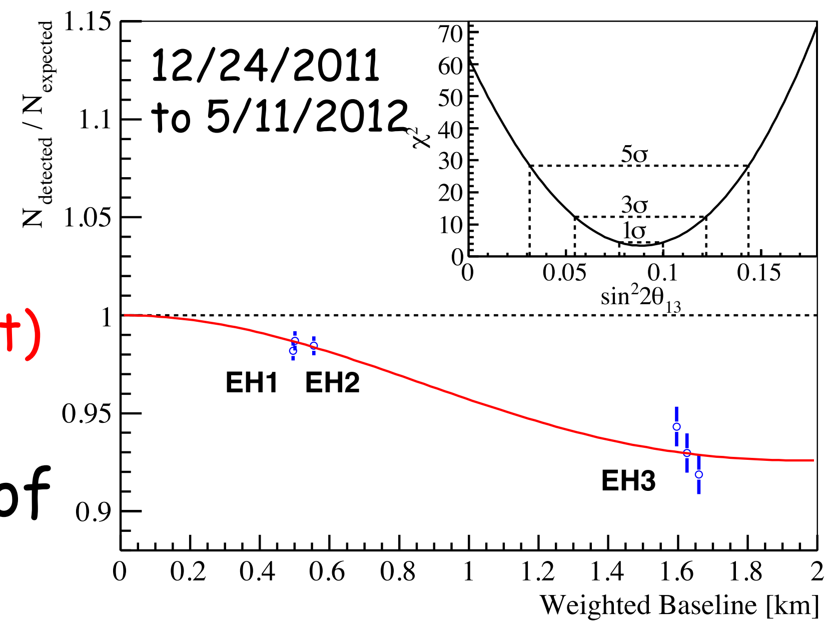
- Based on rate-only analyses.
- First >5σ results from 55 days of data [PRL **108** (2012) 171803]

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

- Updated results (139 days): [Chin. Phys. *C37* (2013) 011001]

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

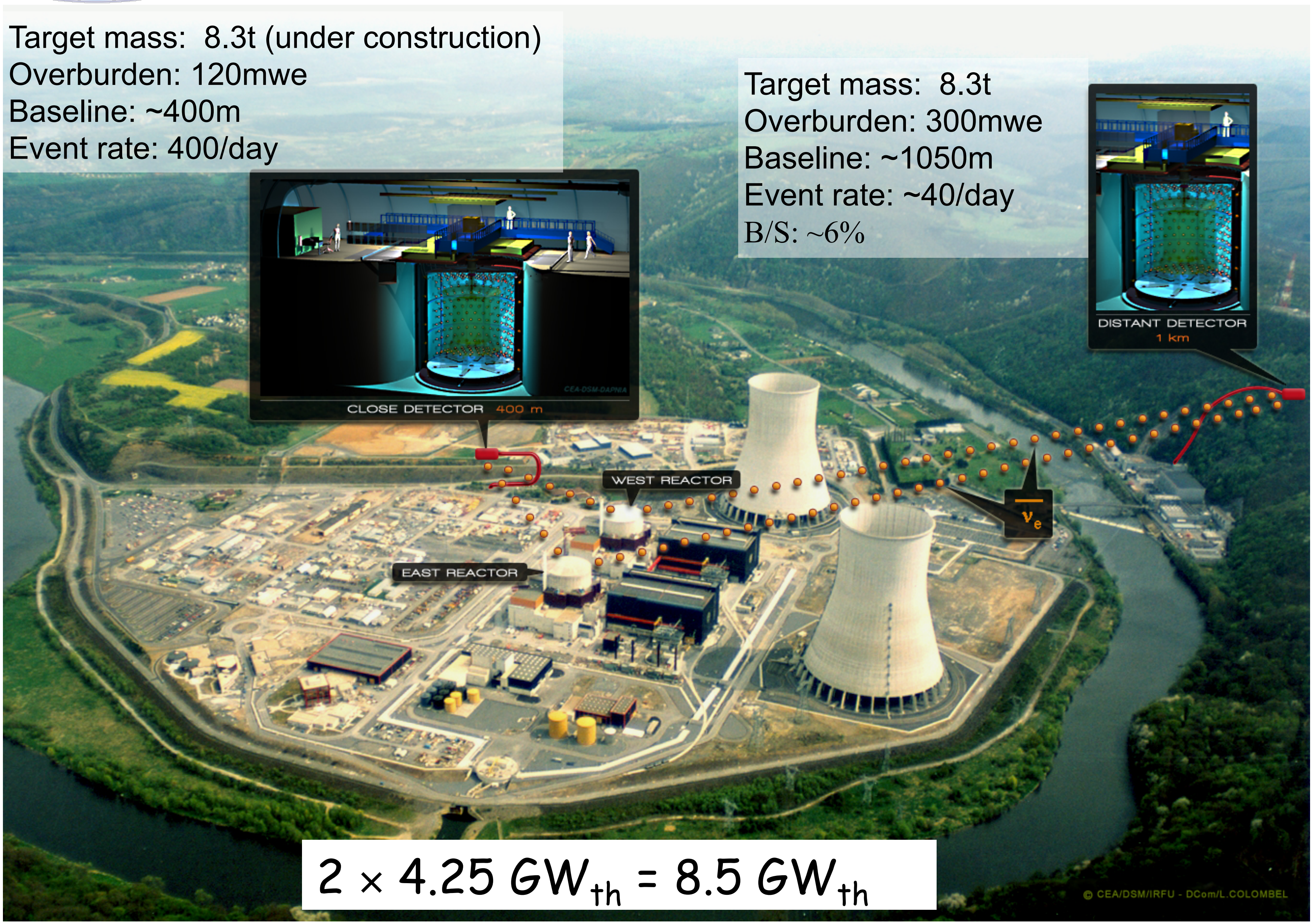
- The most precise measurement of $\sin^2 2\theta_{13}$ to date.



Double Chooz

Target mass: 8.3t (under construction)
Overburden: 120mwe
Baseline: ~400m
Event rate: 400/day

Target mass: 8.3t
Overburden: 300mwe
Baseline: ~1050m
Event rate: ~40/day
B/S: ~6%



$2 \times 4.25\ GW_{th} = 8.5\ GW_{th}$

$\sin^2 2\theta_{13}$ From Double Chooz

- So far, use only the far detector to measure $\sin^2 2\theta_{13}$ by fitting rate and energy spectrum of positrons.
- First measurement based on 101 days of running:

  [PRL **108**, 131801 (2012)]

  $\sin^2 2\theta_{13} = 0.086 \pm 0.041(\text{stat}) \pm 0.030(\text{syst})$

- Updated result using 228 days of data:

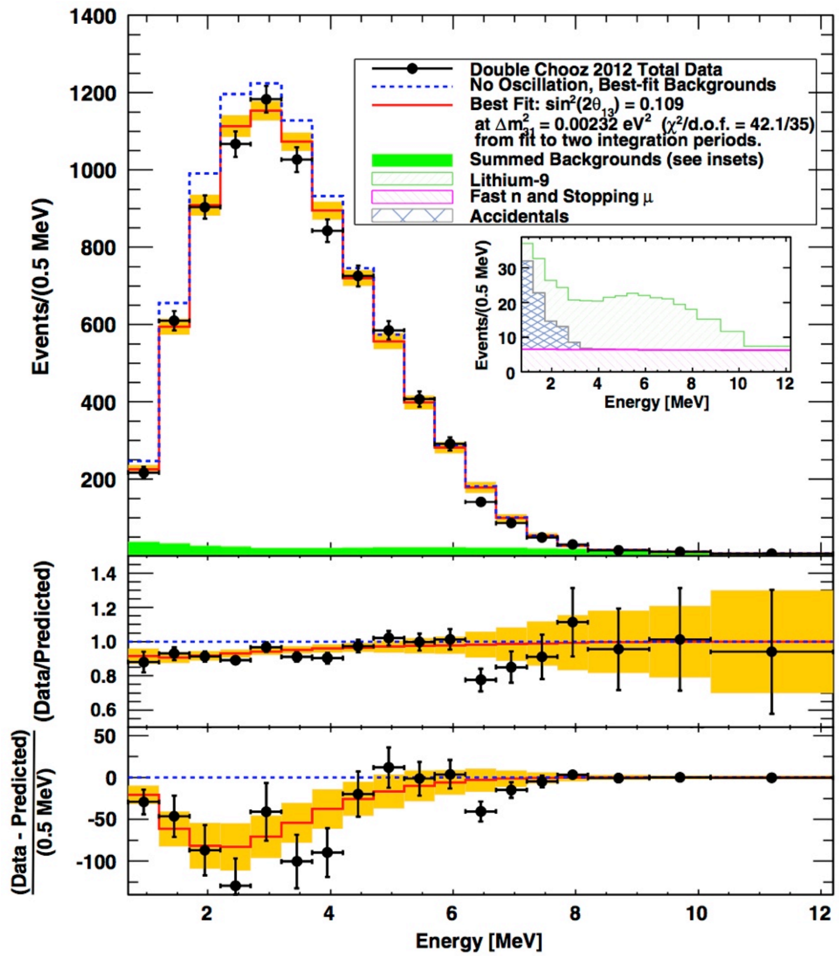
  [PRD **86**, 052008 (2012)]

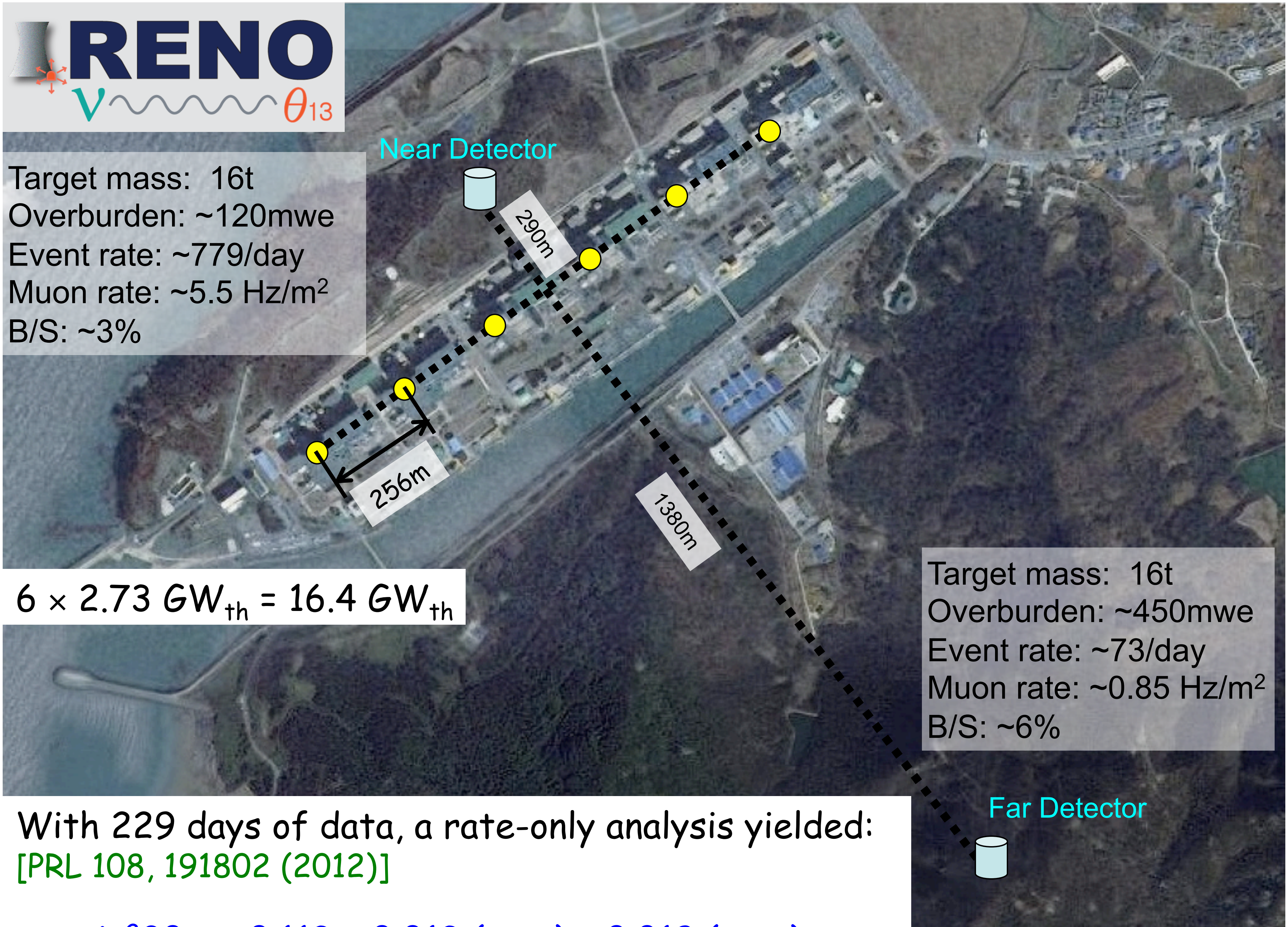
  $\sin^2 2\theta_{13} = 0.109 \pm 0.030(\text{stat}) \pm 0.025(\text{syst})$

- Latest measurement based on n-H capture inverse beta-decay events:

  [1301.2948]

  $\sin^2 2\theta_{13} = 0.097 \pm 0.034(\text{stat}) \pm 0.034(\text{syst})$

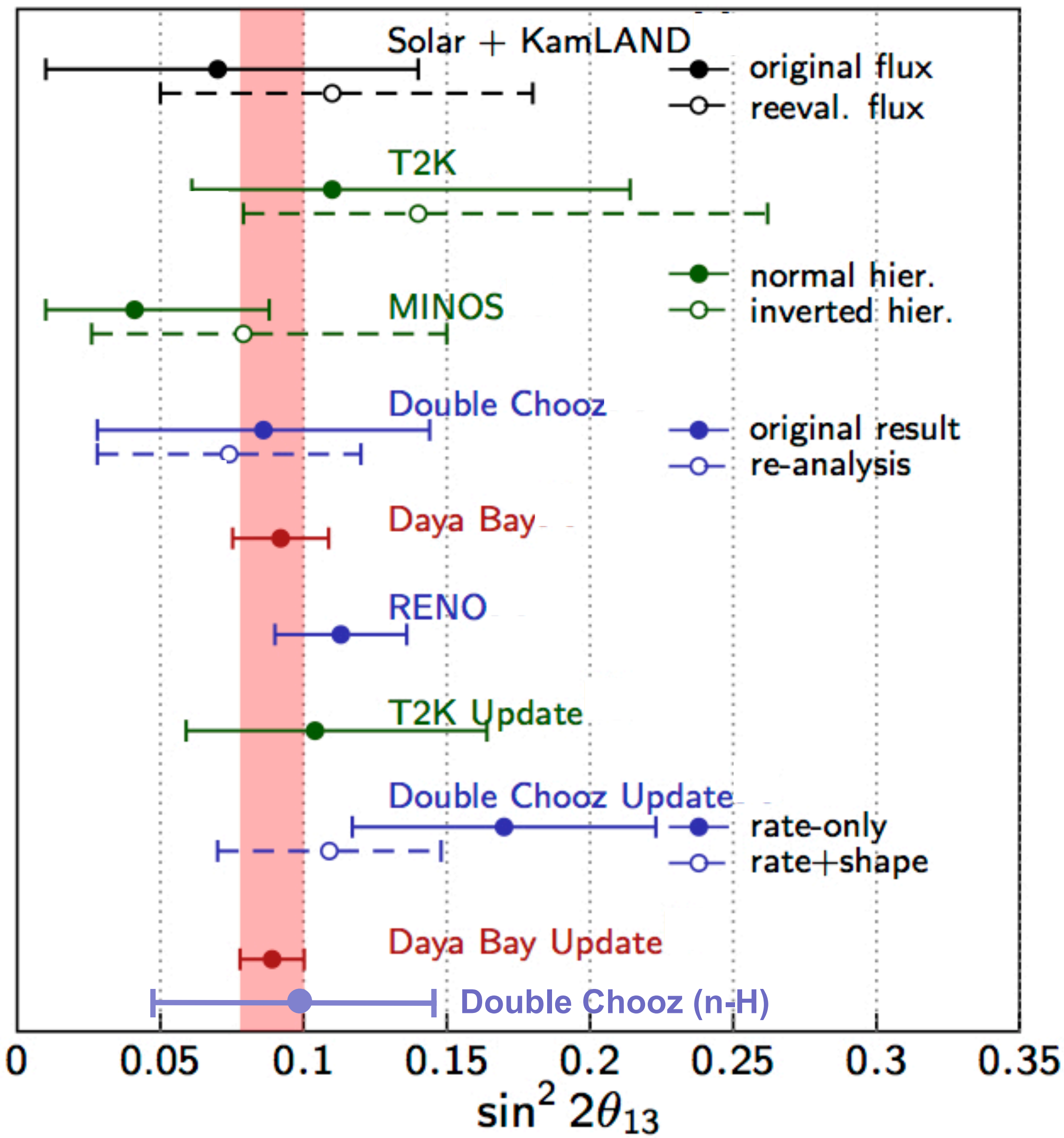




With 229 days of data, a rate-only analysis yielded:
[PRL 108, 191802 (2012)]

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

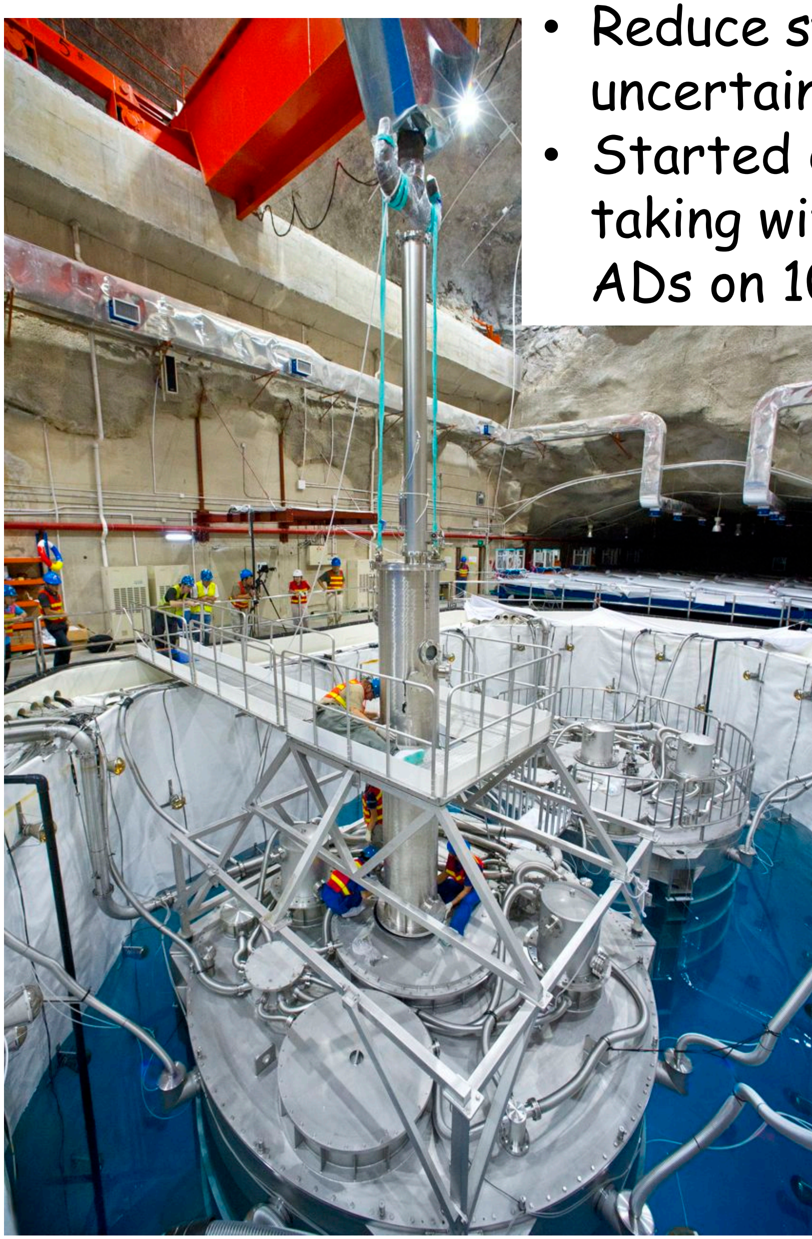
Global Landscape of $\sin^2 2\theta_{13}$

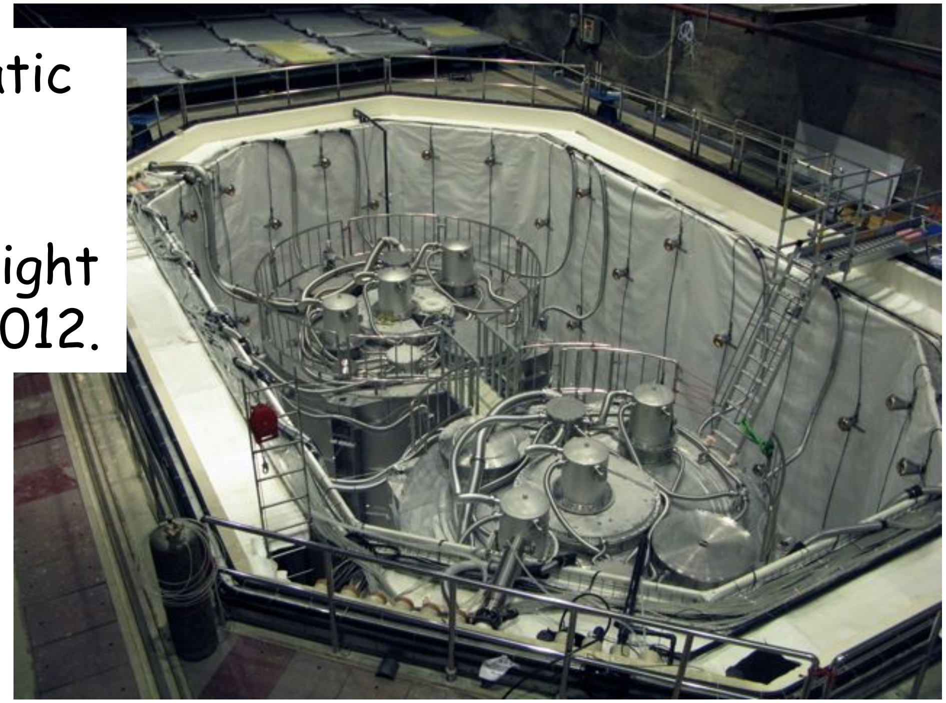


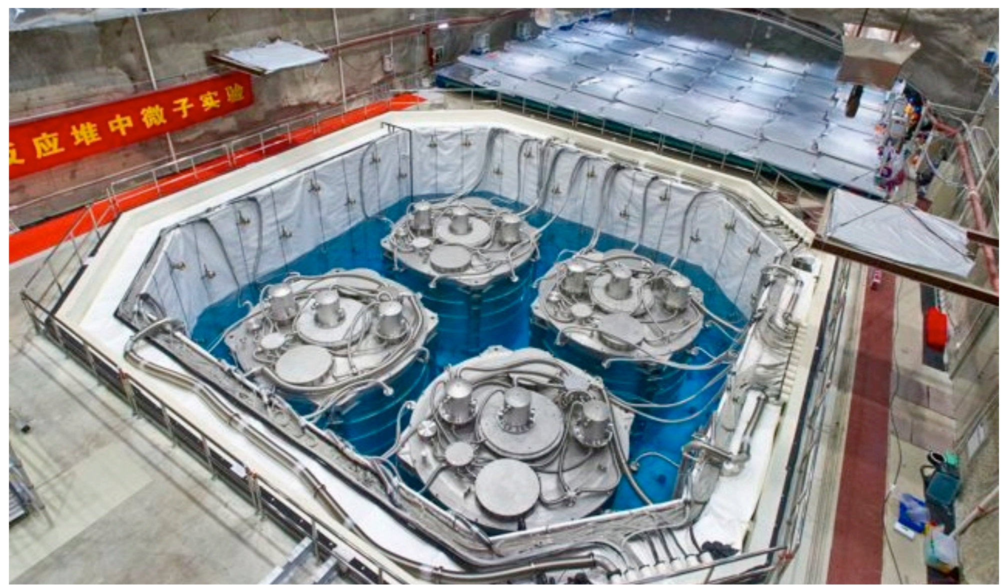
What Lies Ahead ?

What is Next For Daya Bay?

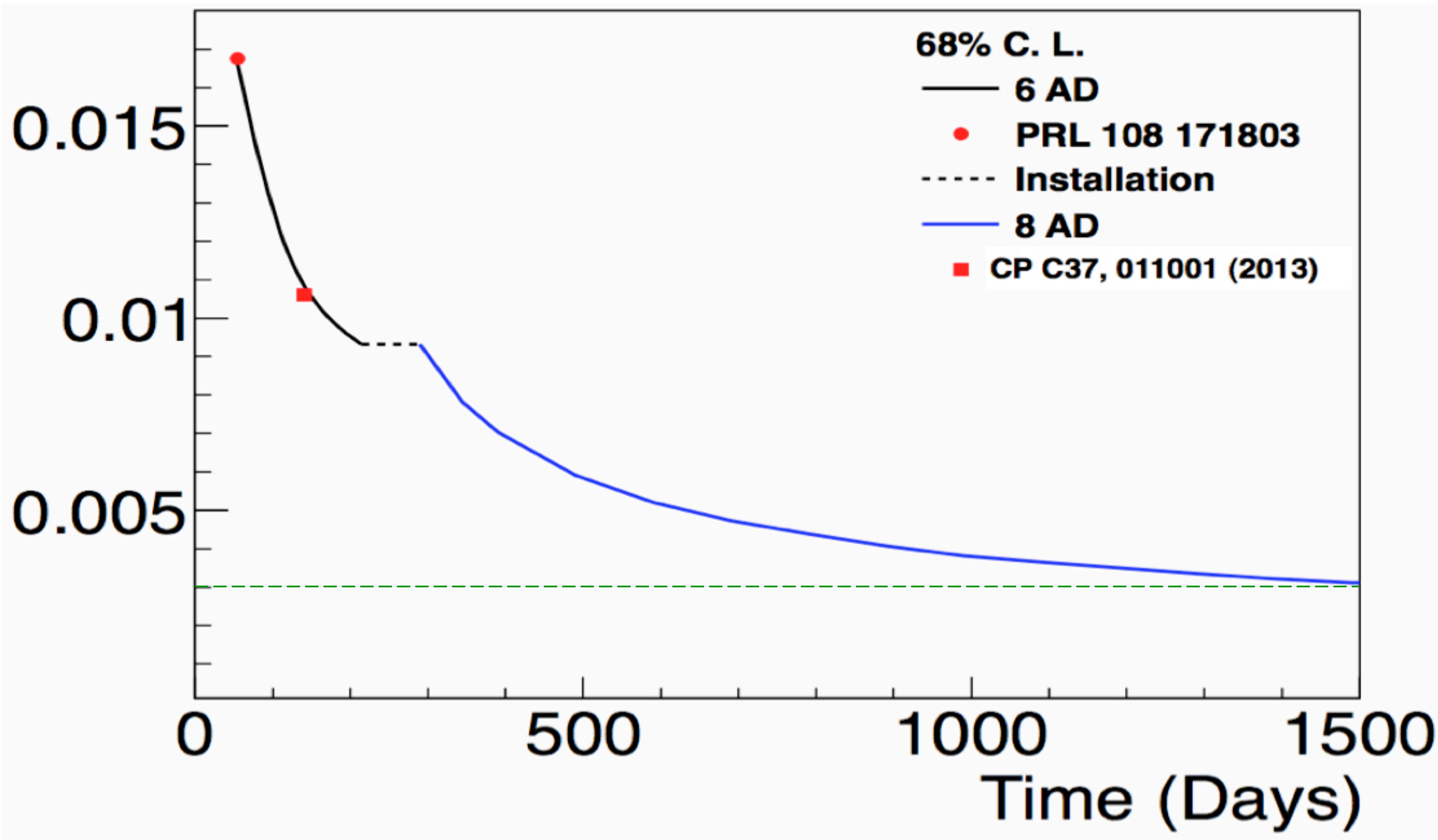
- Reduce systematic uncertainties.
- Started data taking with all eight ADs on 10/19/2012.







Daya Bay: Projected Precision of $\sin^2 2\theta_{13}$



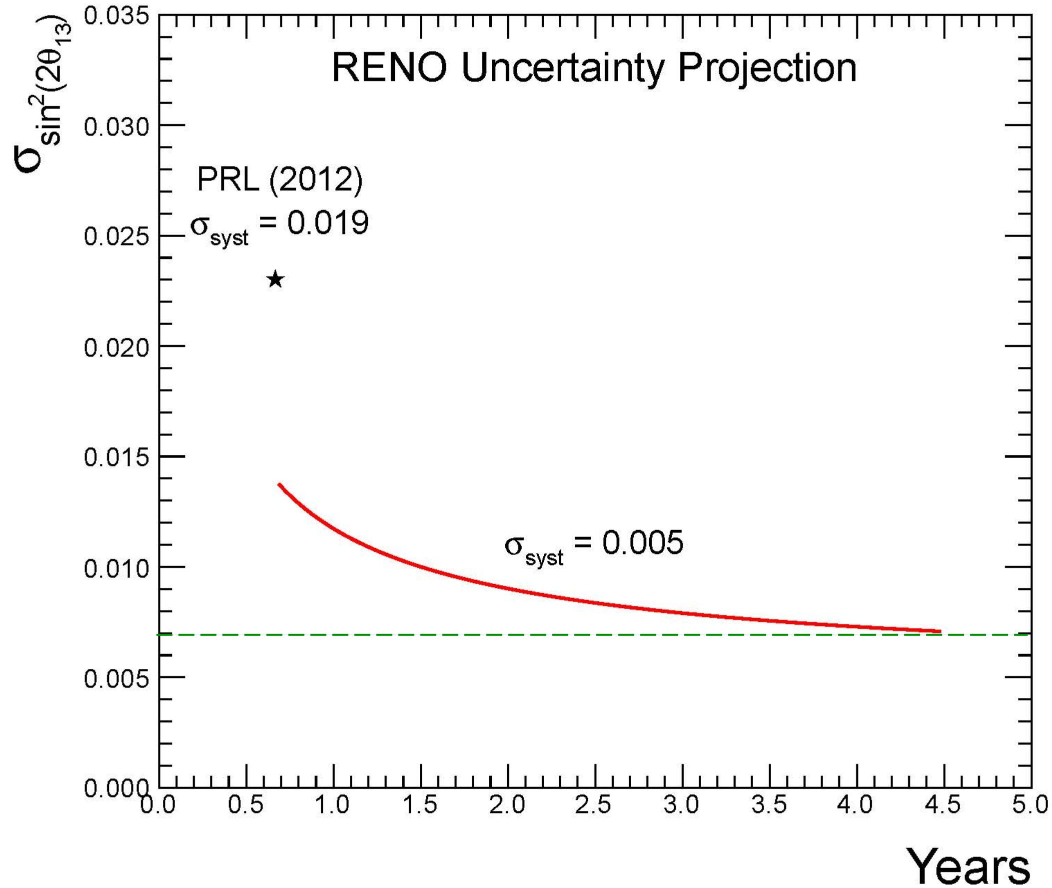
- Carry out rate-and-spectral analyses.

Prospects Of Double Chooz

- With only the far detector, the precision in 2013 will be about 0.03
- Plan to begin taking data with the near and far detectors in Spring 2014
  - with 6 months of running, the error will be 0.015
- The final precision of $\sin^2 2\theta_{13}$ will be less than 0.01

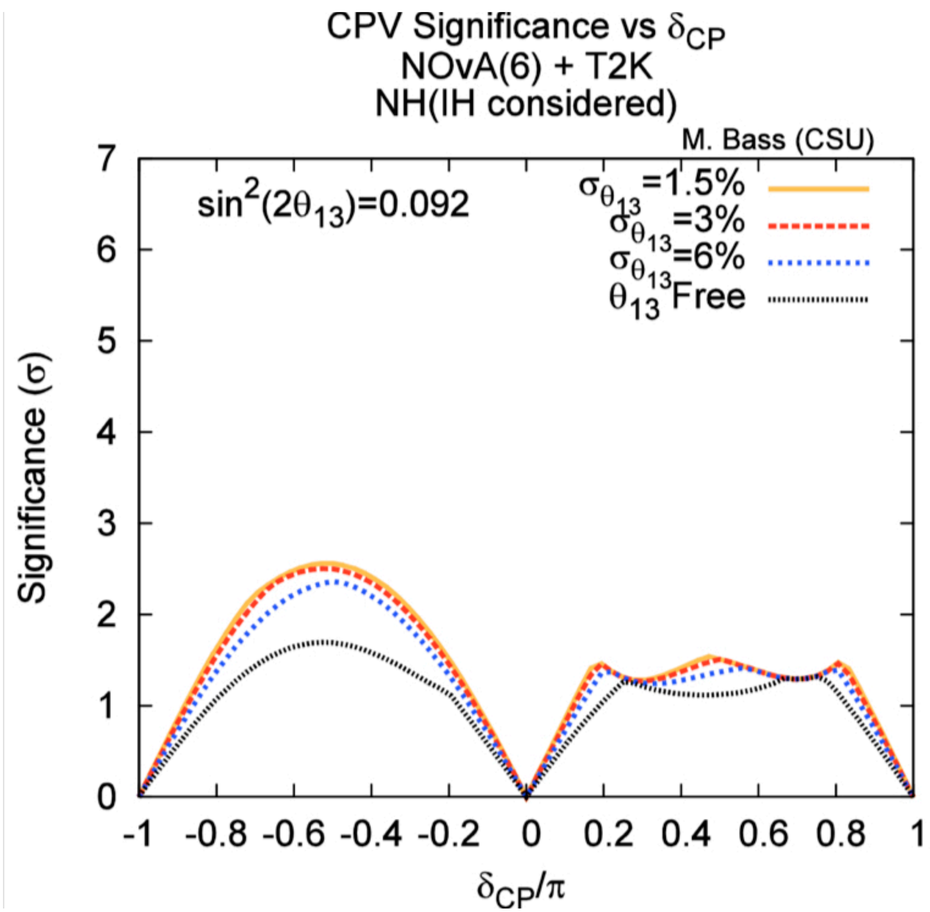
Projected Precision of $\sin^2 2\theta_{13}$

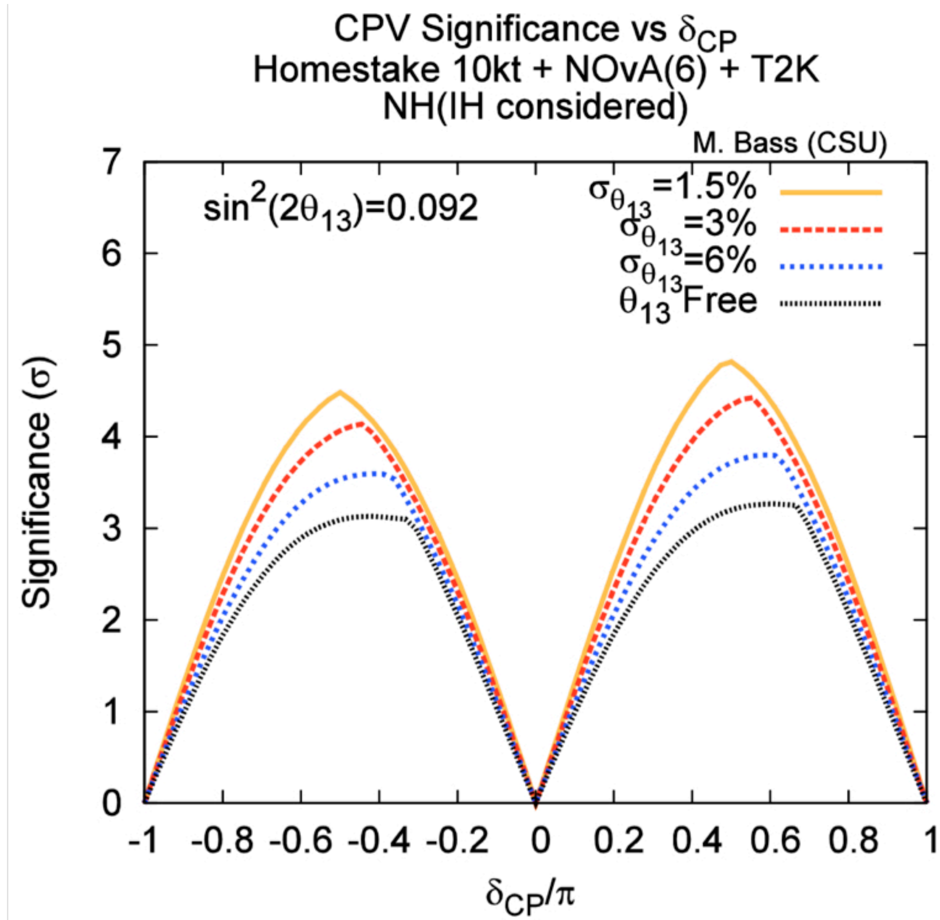
- Reduce systematic uncertainties
  - background
  - reactor-related (flux)
  - relative detector efficiency
- Improve energy calibration.
- Carry out spectral shape analysis.



Precise Measurement of $\sin^2 2\theta_{13}$: Impacts

- Check the unitary condition of the neutrino mixing matrix.
- Reduce uncertainties in predicting neutrino phenomena.
- Constrain model building.
- Extend the CP reach of long baseline accelerator experiments





Summary

- Reactor neutrino experiments are ideal for determining the value of θ_{13}.
- Daya Bay's measurement of $\sin^2 2\theta_{13}$ will likely remain the most precise for the foreseeable future.
  - will reach a precision of ~3%.
- Precise determination of θ_{13} is important for future theoretical and experimental investigations of the neutrinos.