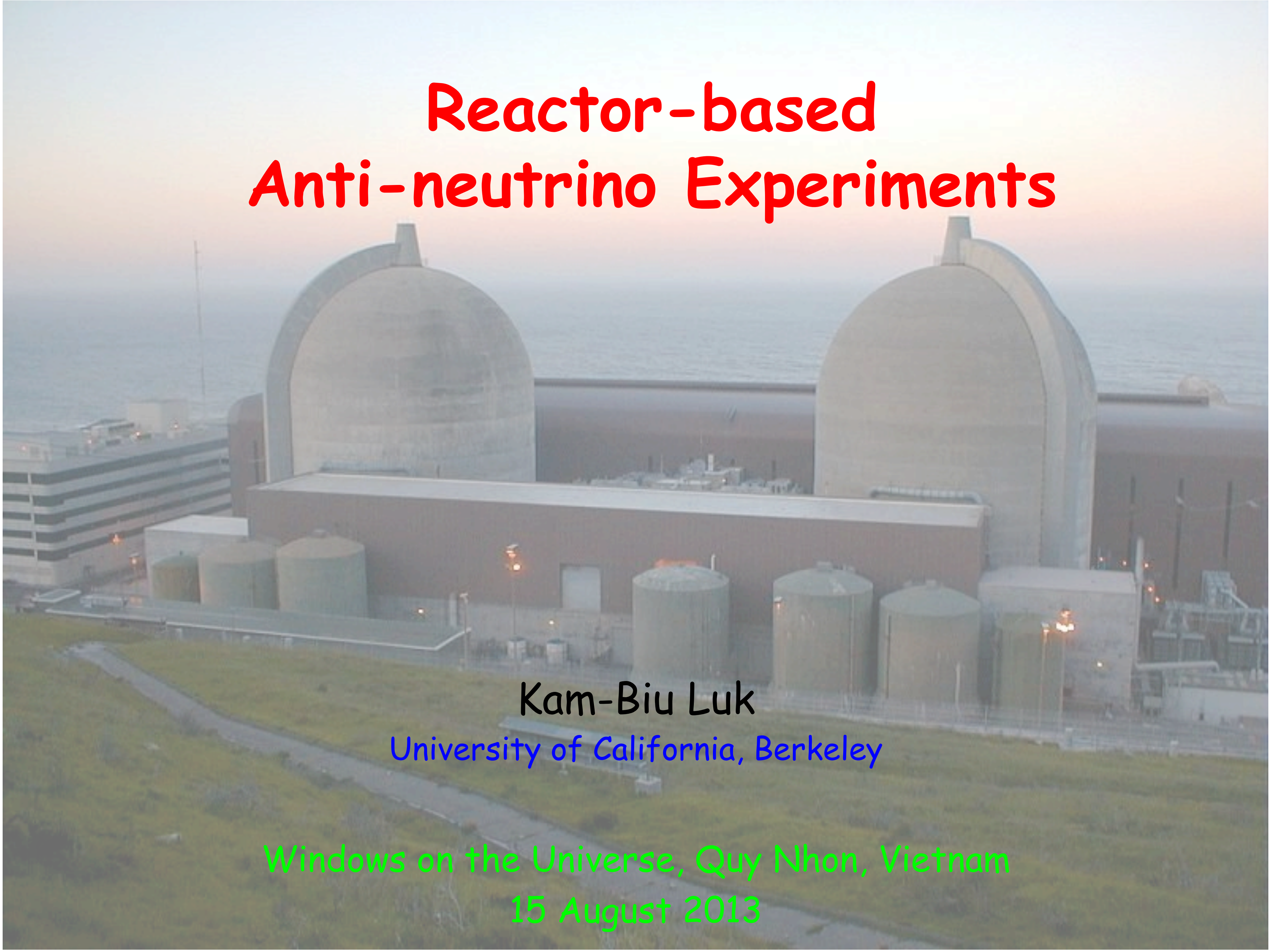


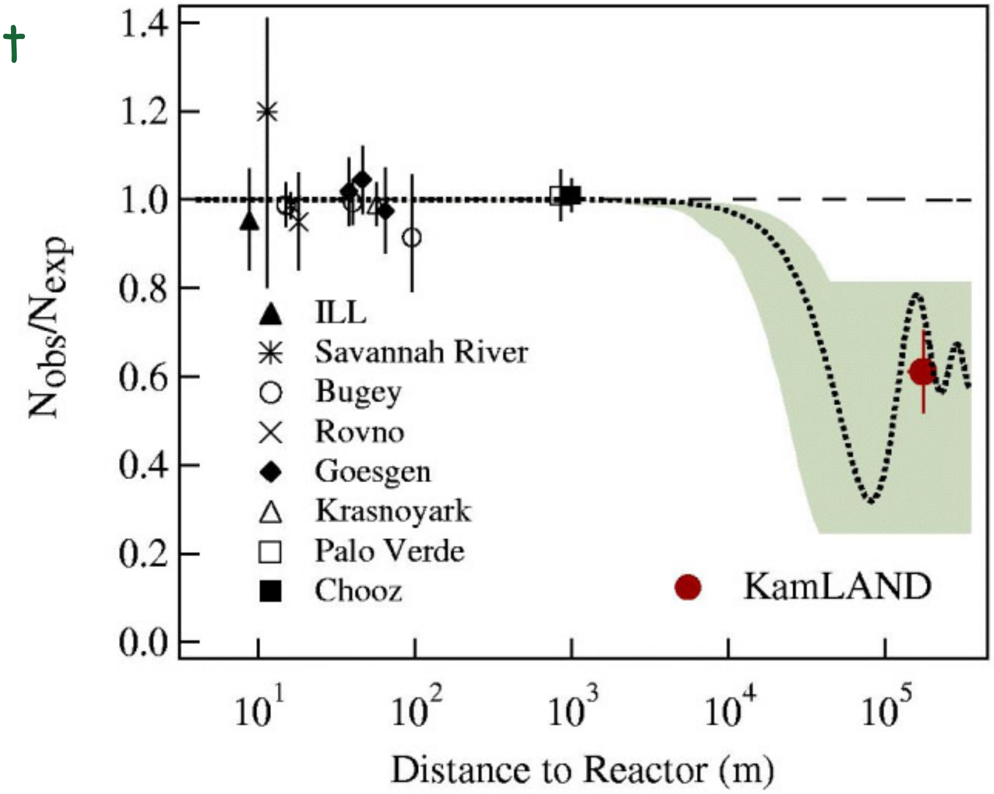
Reactor-based Anti-neutrino Experiments

Kam-Biu Luk
University of California, Berkeley

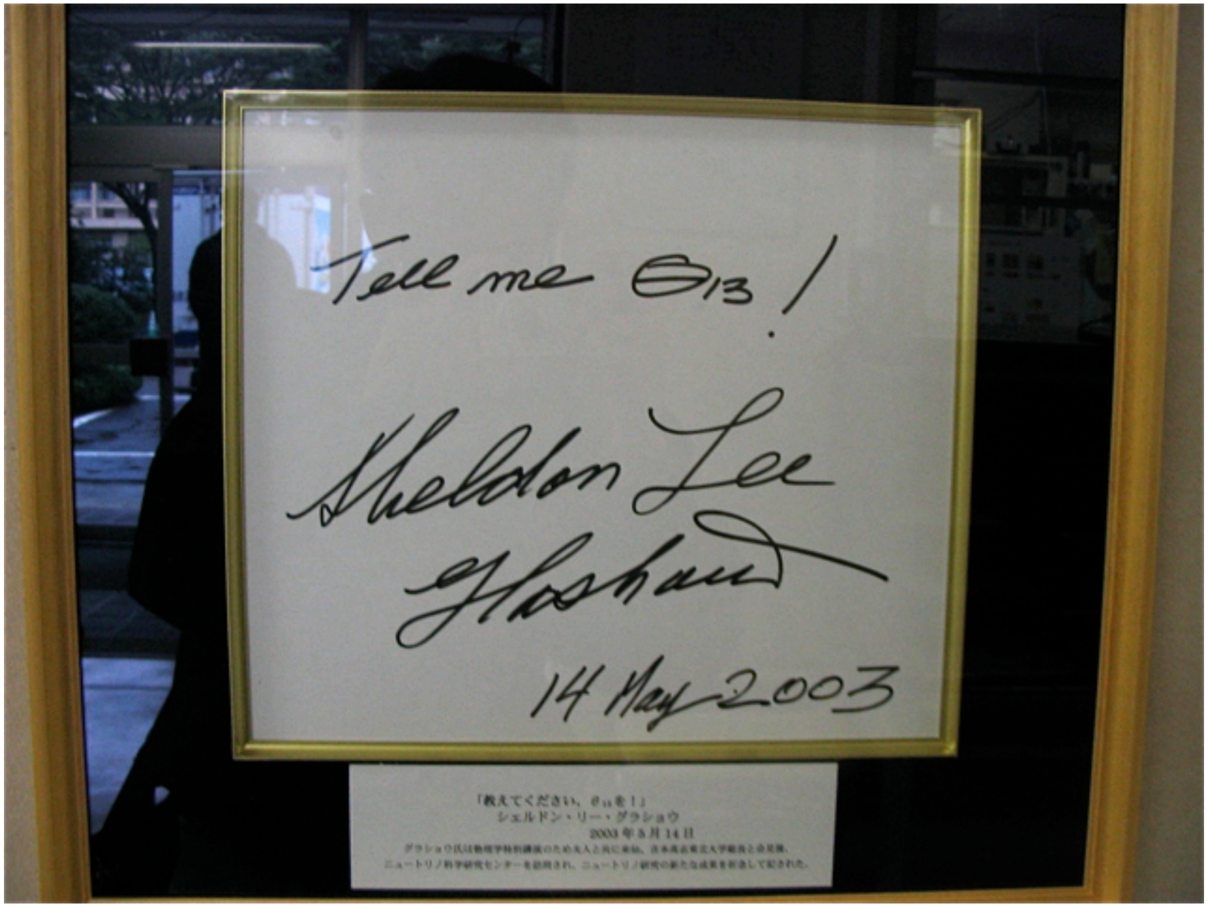
Windows on the Universe, Quy Nhon, Vietnam
15 August 2013

Overview

- Reactor anti-neutrino experiments have significant impacts on the study of neutrinos:
  - The first observation of (anti)neutrino in 1956
  - Low-energy anti-neutrino interaction
    - Neutrino magnetic moment
    - $\sin^2\theta_W$ at low Q^2
  - Investigation of neutrino oscillation
    - First observation of disappearance of $\overline{\nu}_e$
    - Determination of θ_{13}
    - Mass hierarchy
    - Reactor $\overline{\nu}_e$ anomaly



Importance of θ_{13}



Tell me θ_{13} !

Sheldon Lee Glashow

14 May 2003

「教えてください、θ_{13}を！」

シェルドン・リー・グラショウ

2003年5月14日

- It was the last unknown neutrino mixing angle that is the gateway to CP violation in the neutrino sector:

$$P(\nu_\mu \rightarrow \nu_e) - P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e) \propto \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos\theta_{13} \sin\delta$$

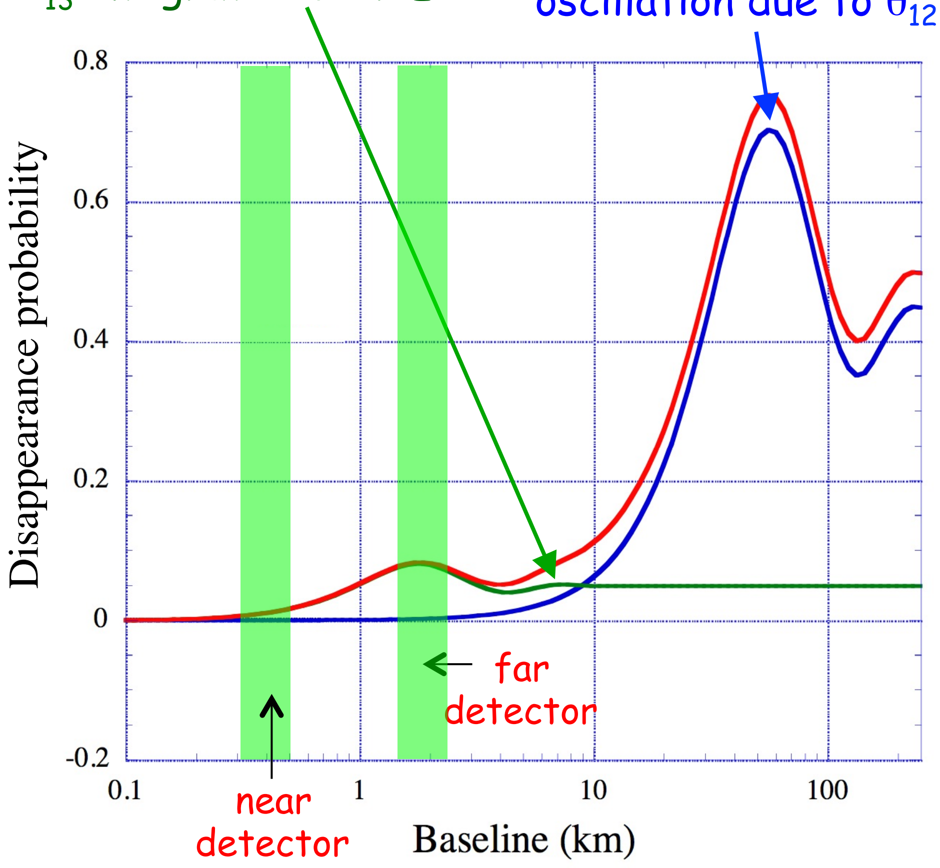
Measure θ_{13} With A Reactor

- Look for $\bar{\nu}_e$ disappearance:

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

Small-amplitude oscillation due to θ_{13} integrated over E

Large-amplitude oscillation due to θ_{12}



Relative measurement using the near-far detectors greatly reduce systematic uncertainties.

Reactor-based θ_{13} Experiments

Experiment	Reactor Power (GW_{th})	Flux-weight Baseline (m) Near/Far	Target mass (t) Near/Far	Overburden (mwe) Near/Far
Daya Bay	17.4	(470,576)/1650	(40,40)/80	(250,265)/860
Double Chooz	8.5	400/1050	8.3/8.3	120/300
RENO	16.5	409/1444	16.5/16.5	120/450

Detecting Reactor $\bar{\nu}_e$

Inverse β-decay reaction (IBD) in Gd-loaded liquid scintillator:

$\bar{\nu}_e + p \rightarrow e^+ + n$ (prompt signal)

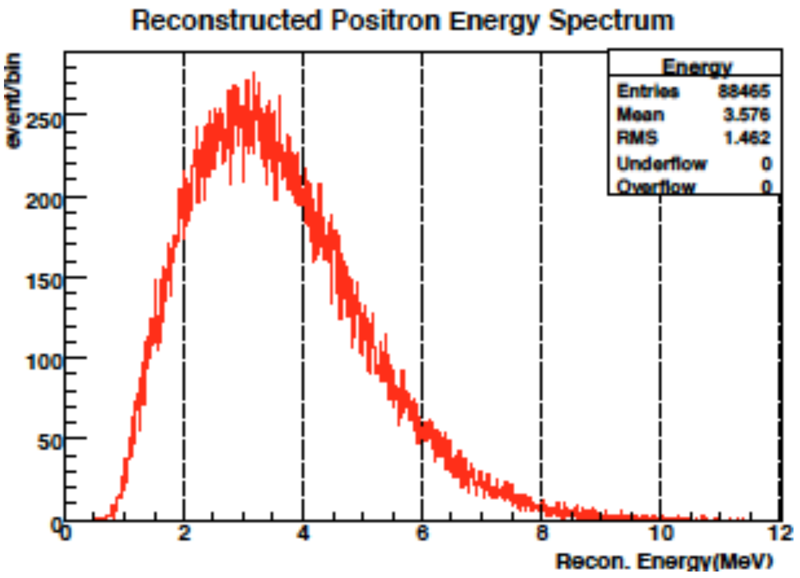
~180μs

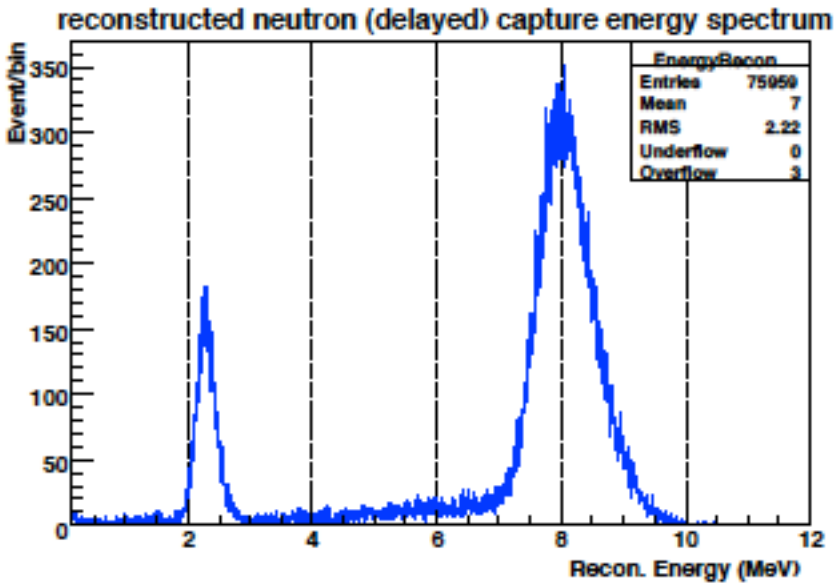
$\rightarrow + p \rightarrow D + \gamma(2.2\ \text{MeV})$ (delayed signal)

$\rightarrow + Gd \rightarrow Gd^*$

~30μs
for 0.1% Gd

$\rightarrow Gd + \gamma$'s(8 MeV) (delayed signal)

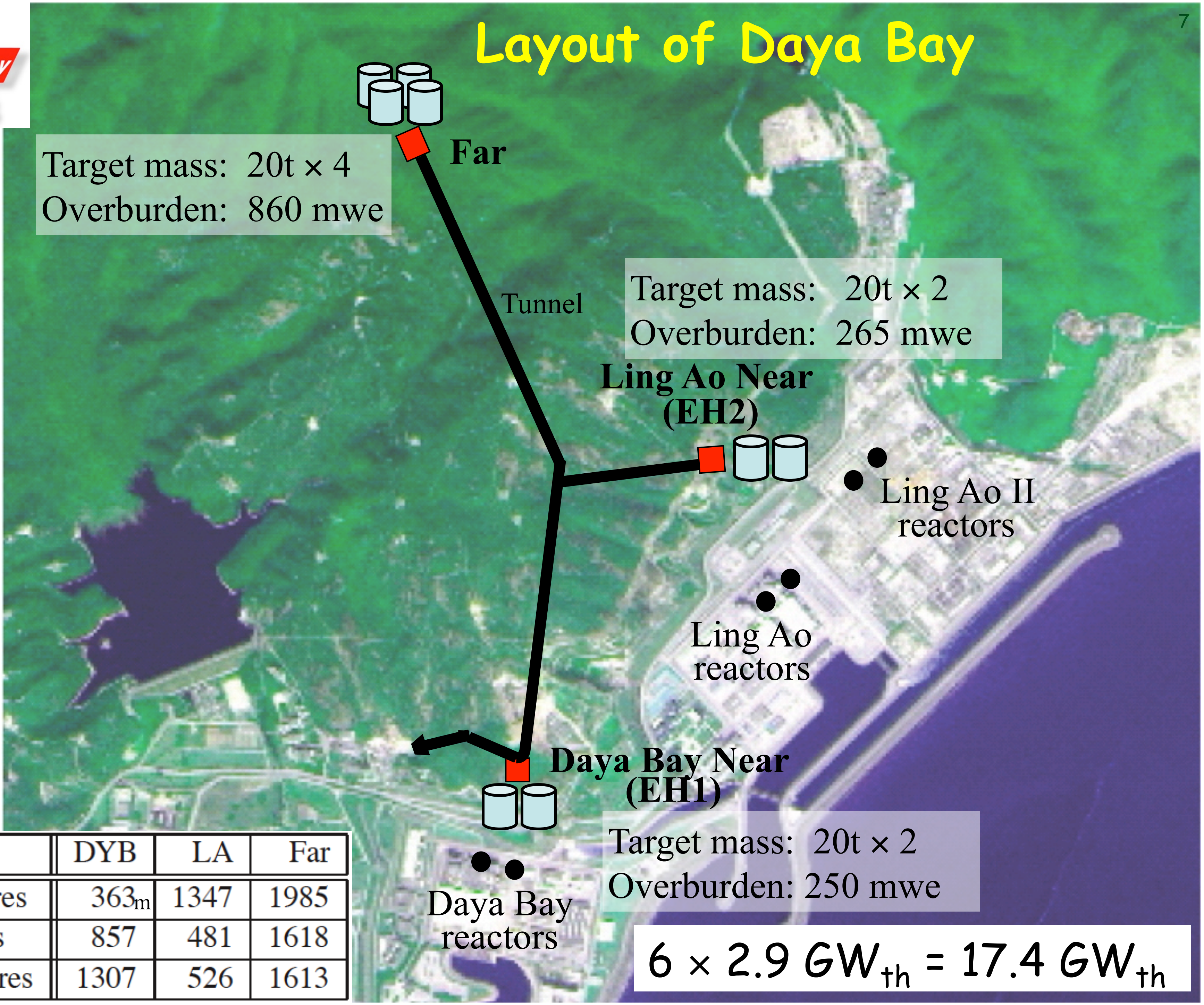




- Energy of $\bar{\nu}_e$ is given by:

$$E_\nu \approx T_{e+} + 1.8\ \text{MeV}$$

Layout of Daya Bay



Target mass: 20t × 4
Overburden: 860 mwe

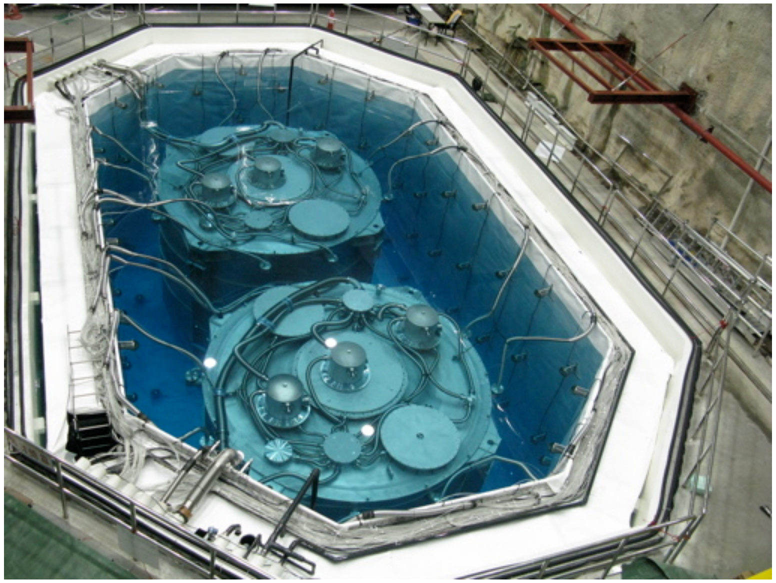
Target mass: 20t × 2
Overburden: 265 mwe

Target mass: 20t × 2
Overburden: 250 mwe

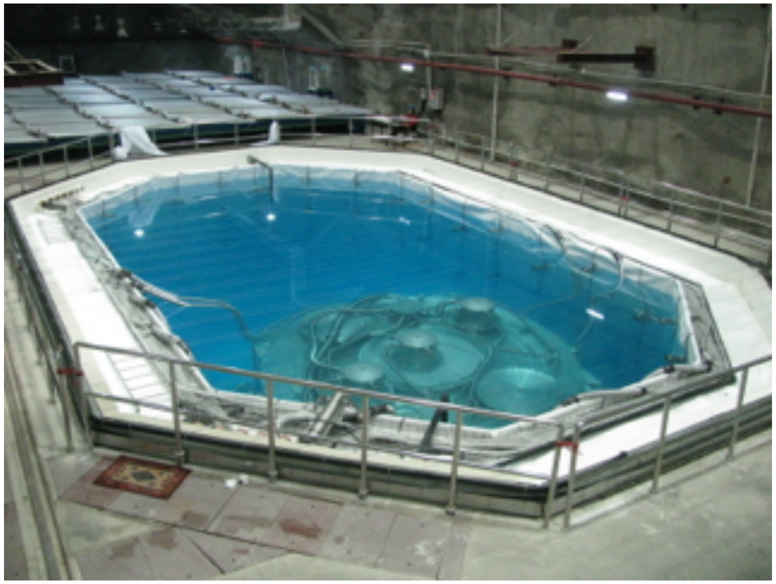
$6 \times 2.9\ GW_{th} = 17.4\ GW_{th}$

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

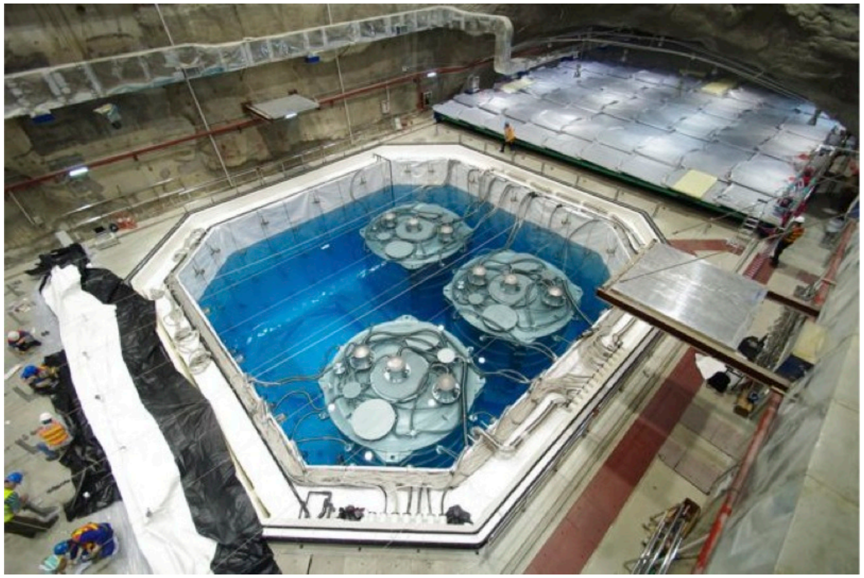
6-Antineutrino Detector (AD) Run



EH1: Data taking began
on 15 Aug 2011



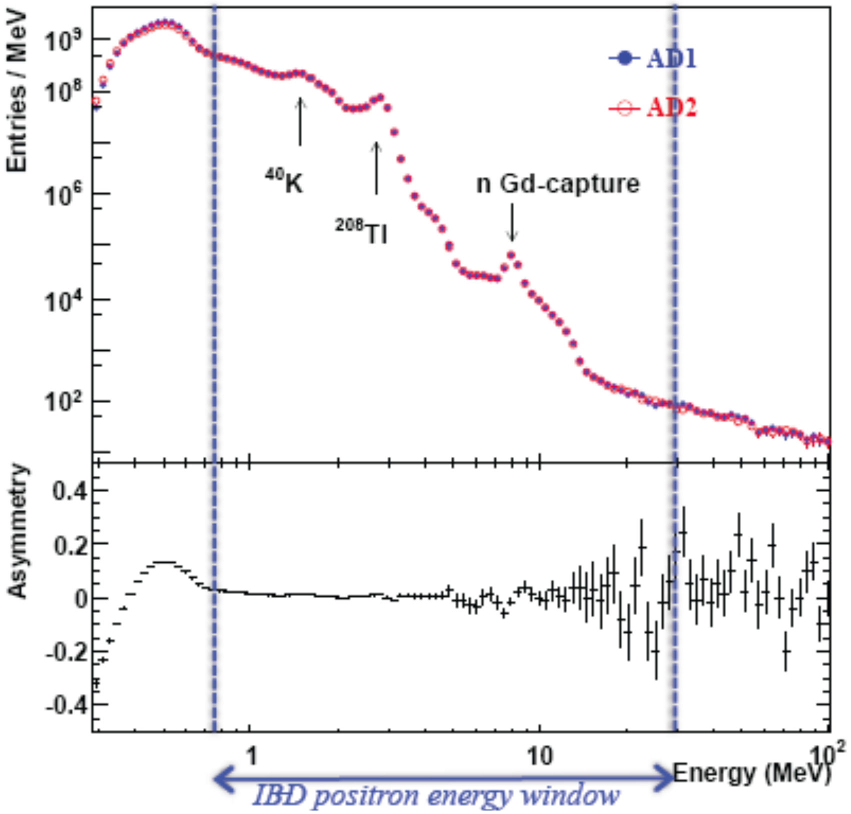
EH2: Data taking began
on 5 Nov 2011



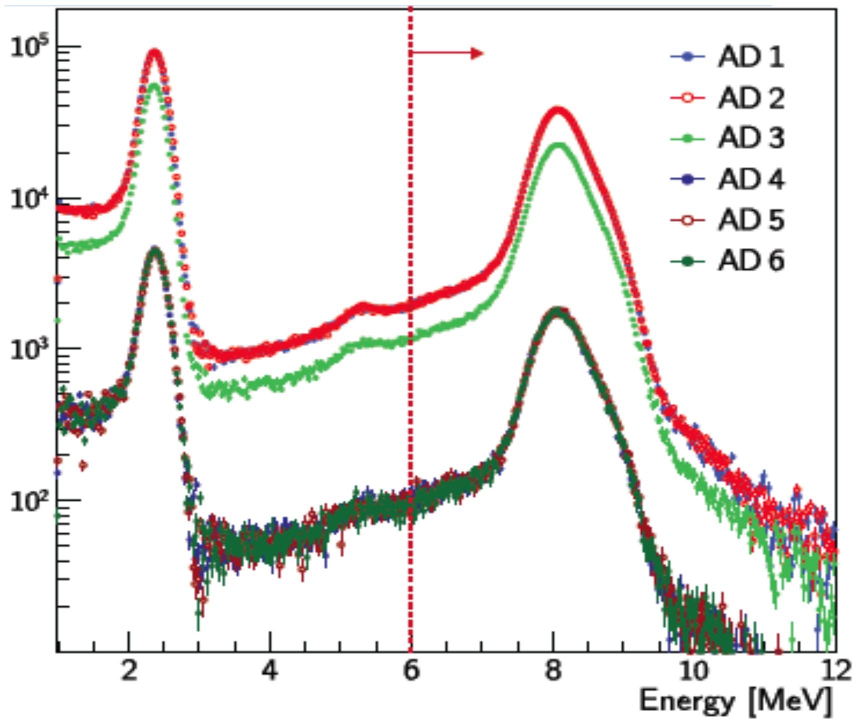
EH3: Data taking began
on 24 Dec 2011

Side-by-side Comparison of ADs

Unique to Daya Bay: Multiple detectors in each hall allows cross-checks and detailed comparison of performance.



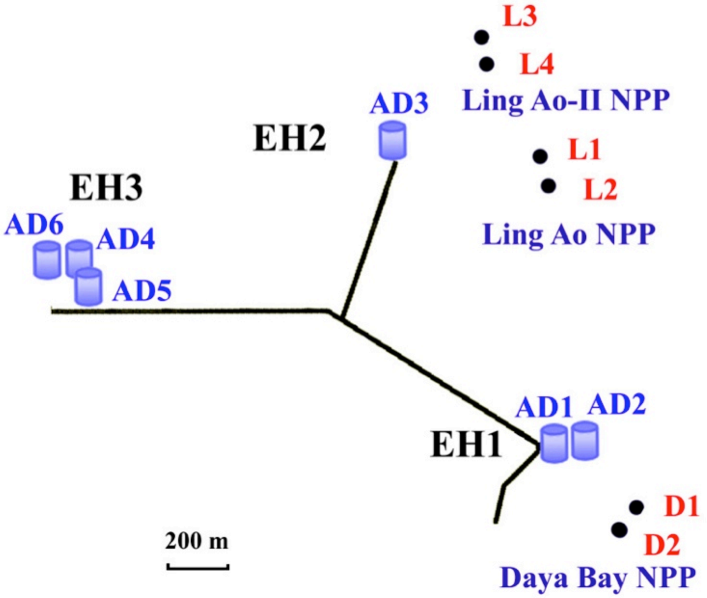
AD1 & AD2 in EH1 have identical response & energy spectra
Nucl. Instru. Meth. A685, 78 (2012)



Spall−n capture

Response of all 6 ADs to spallation neutrons constrains the largest uncorrelated systematic uncertainty

Rate-only Results on $\sin^2 2\theta_{13}$



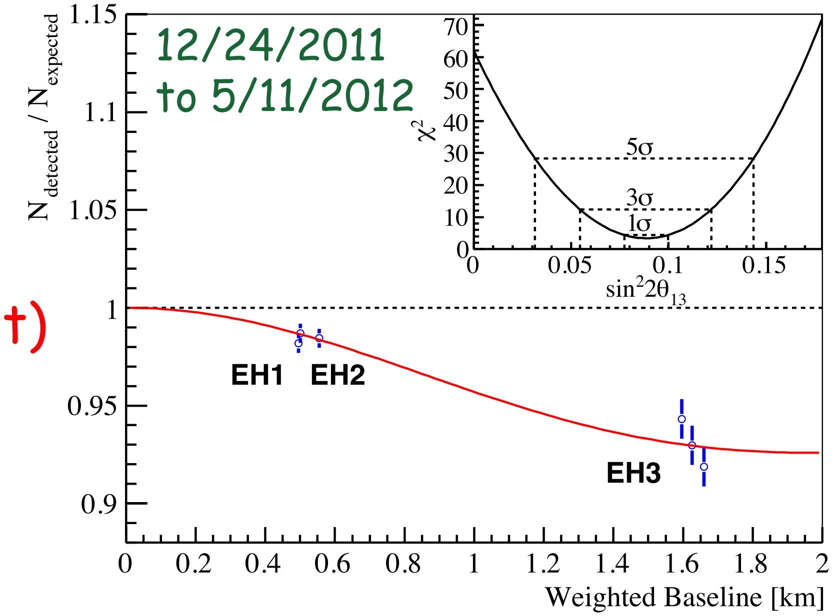
- First >5σ non-zero results from 55 days of data [PRL **108** (2012) 171803]

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

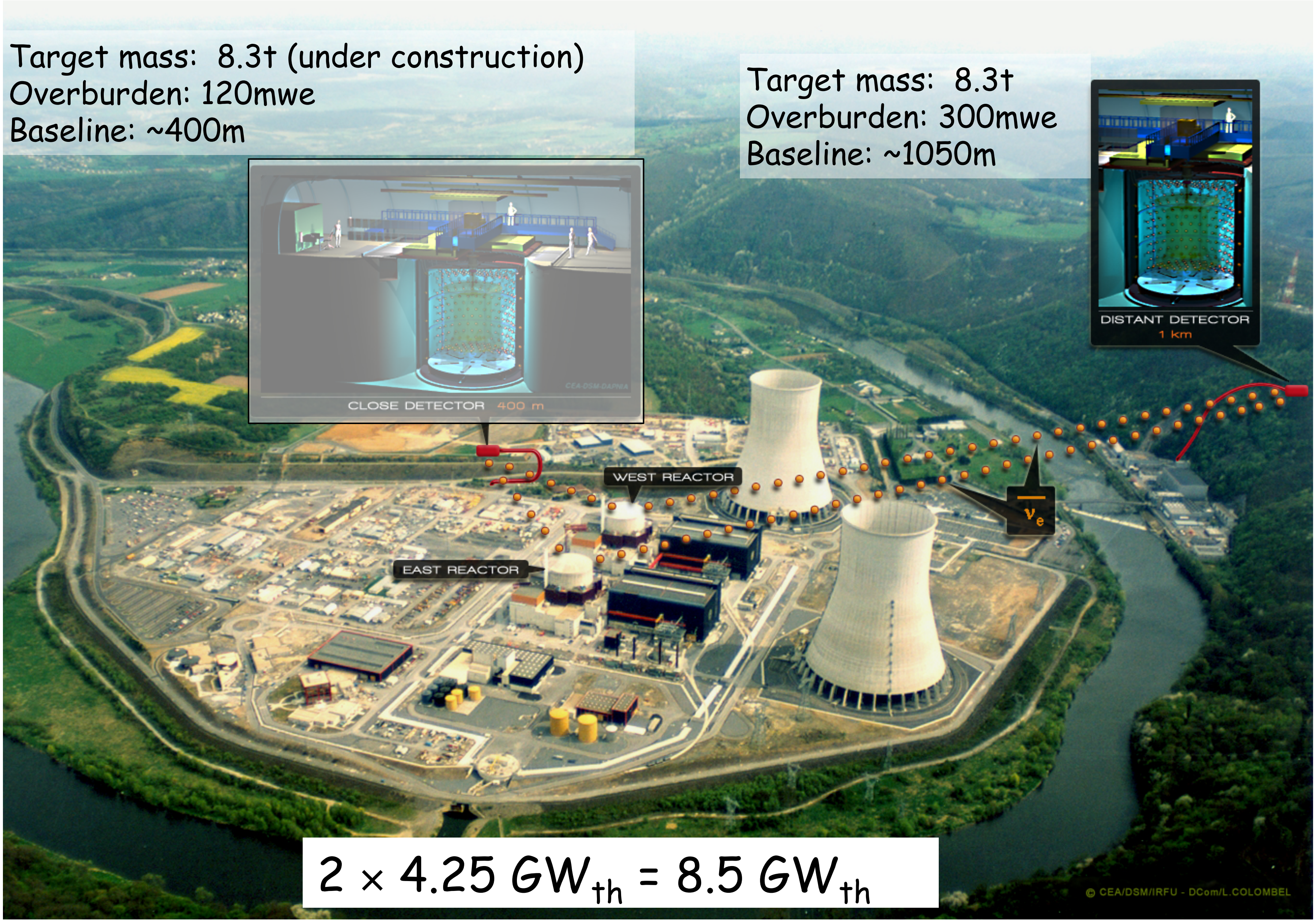
- Updated results (139 days):
  [Chin. Phys. **C37** (2013) 011001]

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

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


12/24/2011
to 5/11/2012

Double Chooz



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

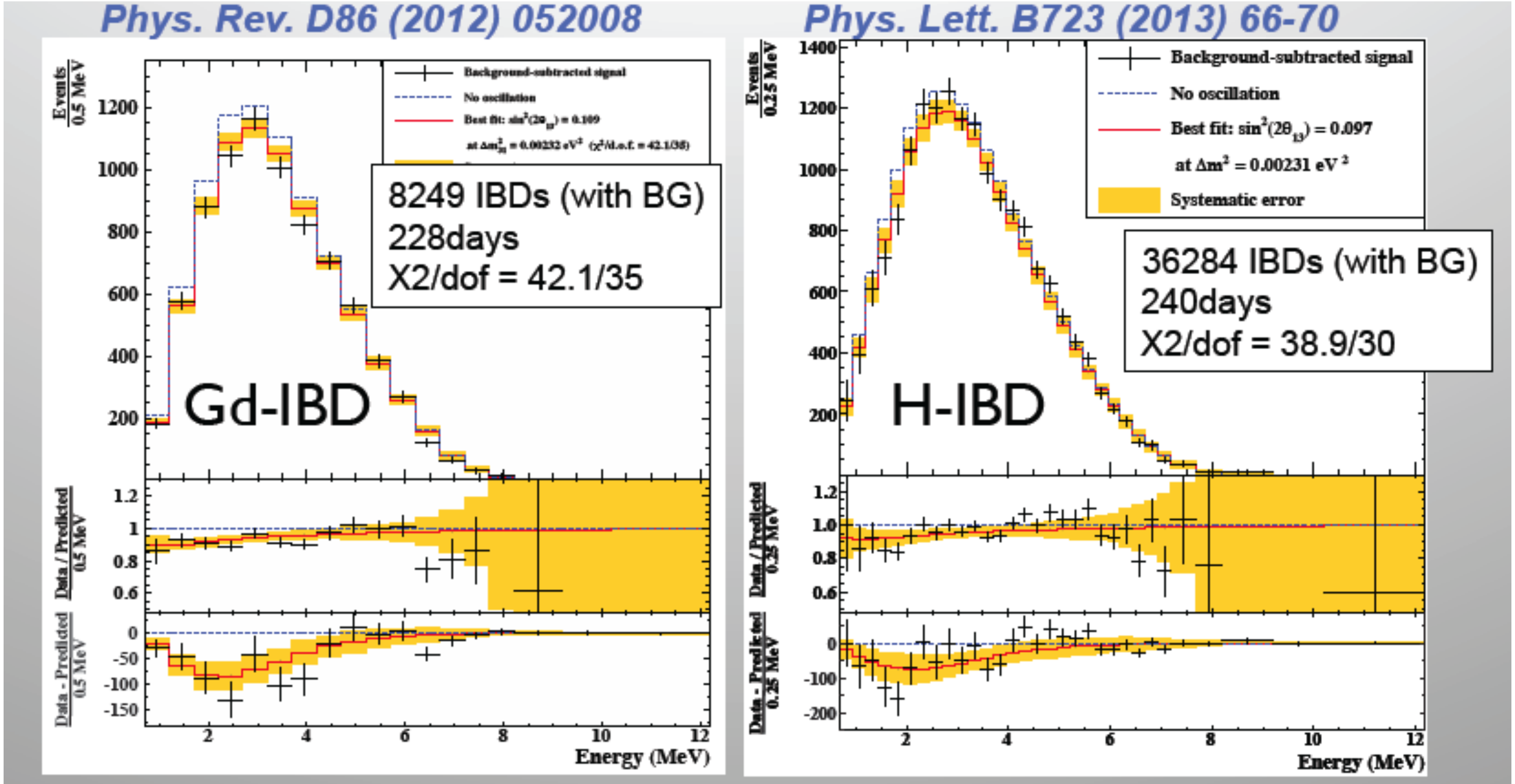
Target mass: 8.3t
Overburden: 300mwe
Baseline: ~1050m

$$2 \times 4.25\ \mathrm{GW}_{th} = 8.5\ \mathrm{GW}_{th}$$

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

Measure $\sin^2 2\theta_{13}$ by fitting rates and energy spectra of positrons using the far detector

Buck, EPS2013



Phys. Rev. D86 (2012) 052008

Phys. Lett. B723 (2013) 66-70

8249 IBDs (with BG)
228days
X2/dof = 42.1/35

36284 IBDs (with BG)
240days
X2/dof = 38.9/30

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

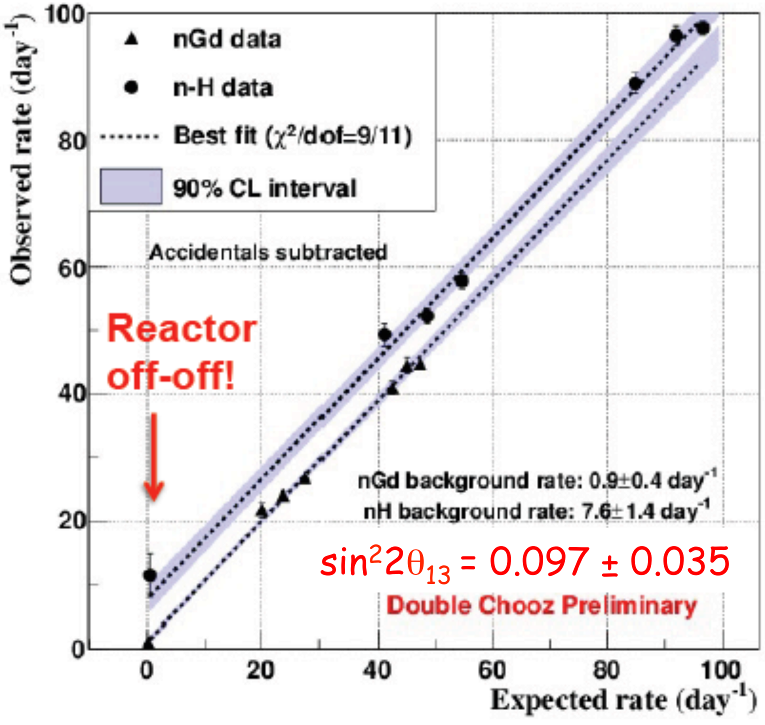
DC-II(H): $\sin^2 2\theta_{13} = 0.097 \pm 0.048\ [0.034^{stat} \pm 0.034^{syst}]$

Reactor-off Results

- Unique to Double Chooz.
- Periods with both reactors off:
  - 0.84 days in October 2011; 6 days in June 2012
- Allowed to measure background directly.
- Carried out a combined rate-only analysis:

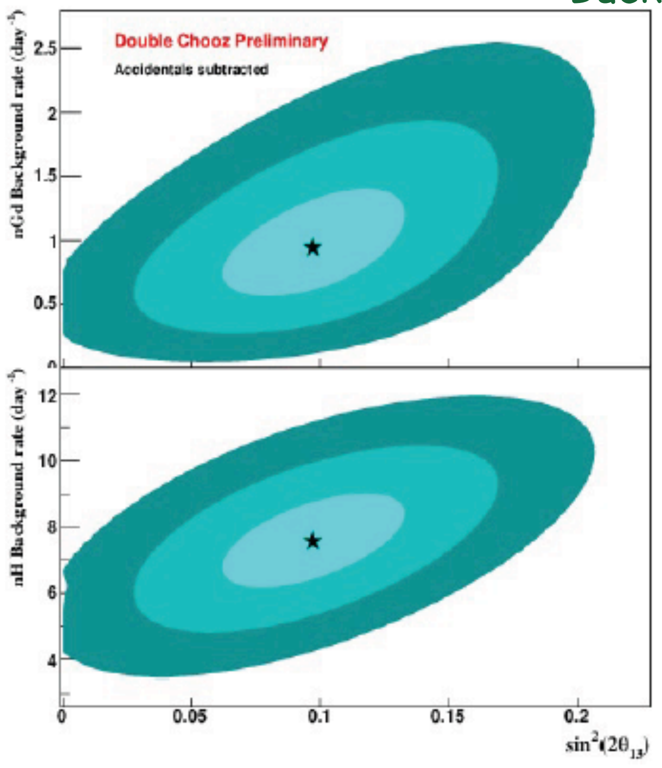
Buck, EPS2013

NEW !!!



Reactor off-off!

$\sin^2 2\theta_{13} = 0.097 \pm 0.035$



Summary of Double Chooz Results

- Based on rate+shape analyses:
  - Gd-capture samples: $\sin^2 2\theta_{13} = 0.109 \pm 0.039$
  - H-capture samples: $\sin^2 2\theta_{13} = 0.097 \pm 0.048$
  - Combined results: $\sin^2 2\theta_{13} = 0.109 \pm 0.035$
- Based on rate+only analyses including reactor-off data:
  - Gd-capture samples: $\sin^2 2\theta_{13} = 0.10 \pm 0.04$
  - H-capture samples: $\sin^2 2\theta_{13} = 0.13 \pm 0.07$
  - Combined results: $\sin^2 2\theta_{13} = 0.097 \pm 0.035$
- All results are consistent.

RENO

Target mass: 16.5 t
Overburden: ~120 mwe

Target mass: 16.5 t
Overburden: ~450 mwe

$6 \times 2.73\ \mathrm{GW_{th}} = 16.4\ \mathrm{GW_{th}}$

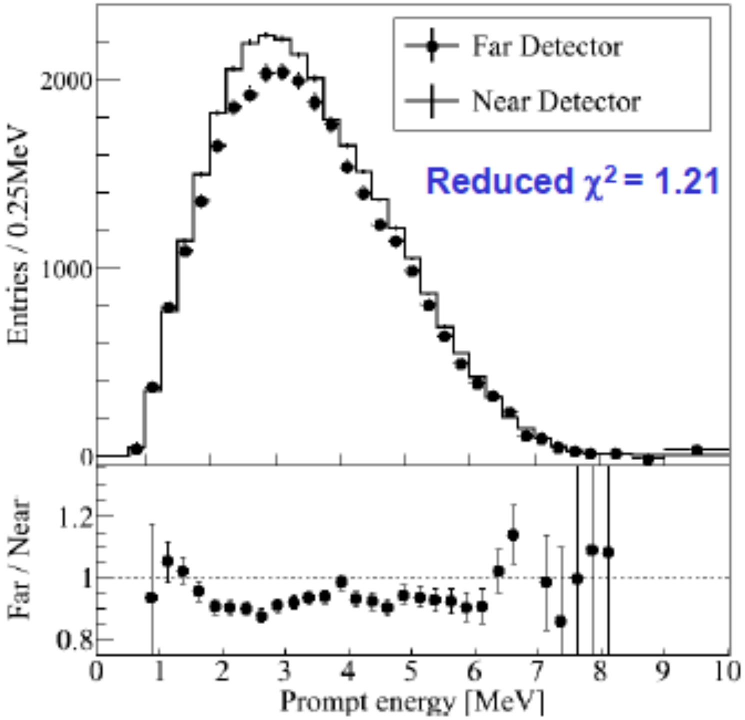
$\sin^2 2\theta_{13}$ From RENO

- First result in April 2, 2012.

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

- A new result reported in March, 2013.

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



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

Statistics:

-- about twice more data

Systematics:

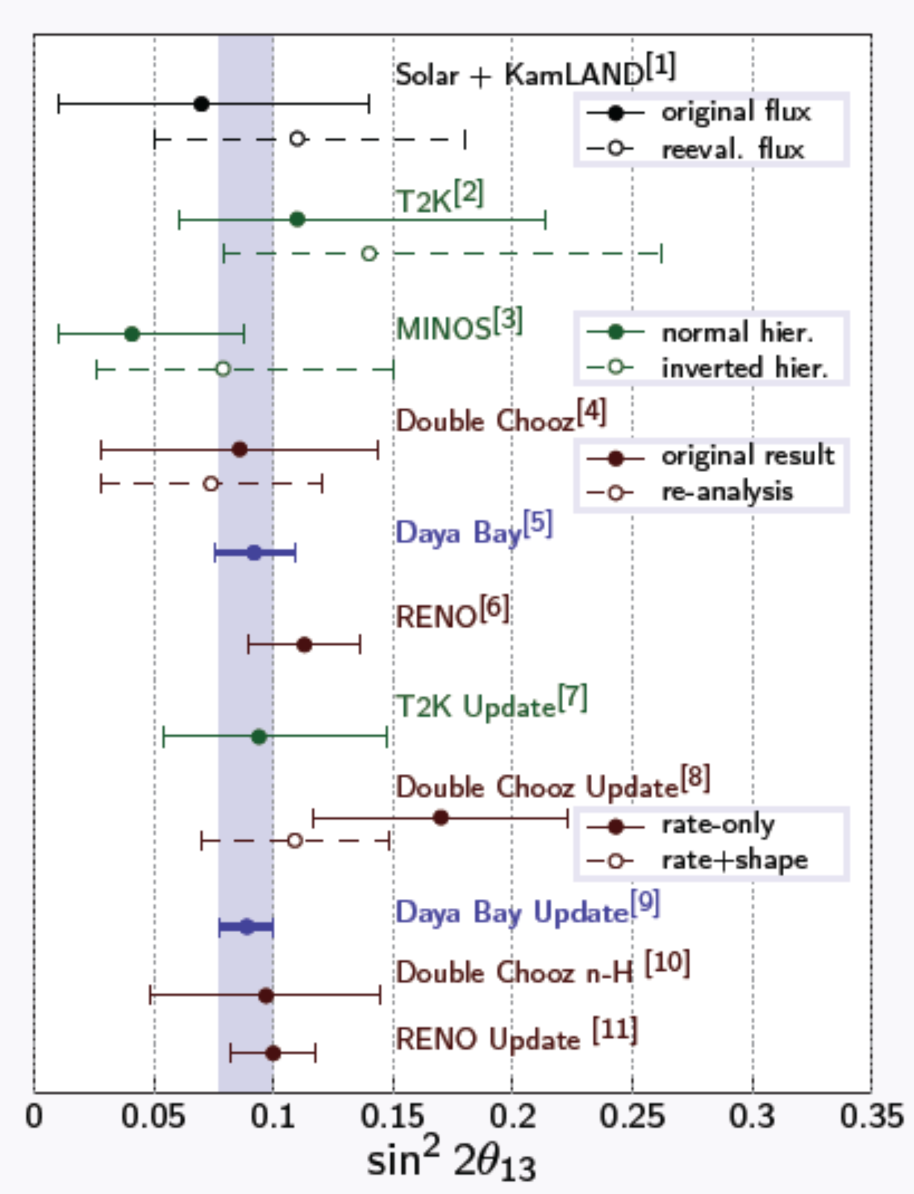
-- Improved background estimation/reduction

(Li/He background, fast N, flasher removal)

-- Improved energy scale calibration

For details, see Seon-Hee Seo's talk at NeuTel'13

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



[1] G.L. Fogli *et al.*, "Evidence of $\theta_{13} > 0$ from global neutrino data analysis," Phys. Rev. D **84** (2011) 053007 arXiv:1106.6028

[2] K. Abe *et al.*, "Indication of Electron Neutrino Appearance from an Accelerator-Produced Off-Axis Muon Neutrino Beam," Phys. Rev. Lett. **107** (2011) 041801, arXiv:1106.2822

[3] P. Adamson *et al.*, "Improved Search for Muon-Neutrino to Electron-Neutrino Oscillations in MINOS," Phys. Rev. Lett. **107** (2011) 181802, arXiv:1108.0015

[4] Y. Abe *et al.*, "Indication of Reactor $\bar{\nu}_e$ Disappearance in the Double Chooz Experiment," Phys. Rev. Lett. **108** (2012), 131801, arXiv:1112.6353

[5] F. P. An *et al.* "Observation of electron-antineutrino disappearance at Daya Bay," Phys. Rev. Lett. **108** (2012), 171803, arXiv:1203.1669

[6] J. K. Ahn *et al.* "Observation of Reactor Electron Antineutrinos Disappearance in the RENO Experiment," Phys. Rev. Lett. **108** (2012) 191802, arXiv:1204.0626

[7] K. Sakashita, "Results from T2K," presented at ICHEP 2012 in Melbourne. Available at T2K.org

[8] Y. Abe *et al.* "Reactor electron antineutrino disappearance in the Double Chooz experiment," Phys. Rev. **D86** (2012) 052008, arXiv:1207.6632

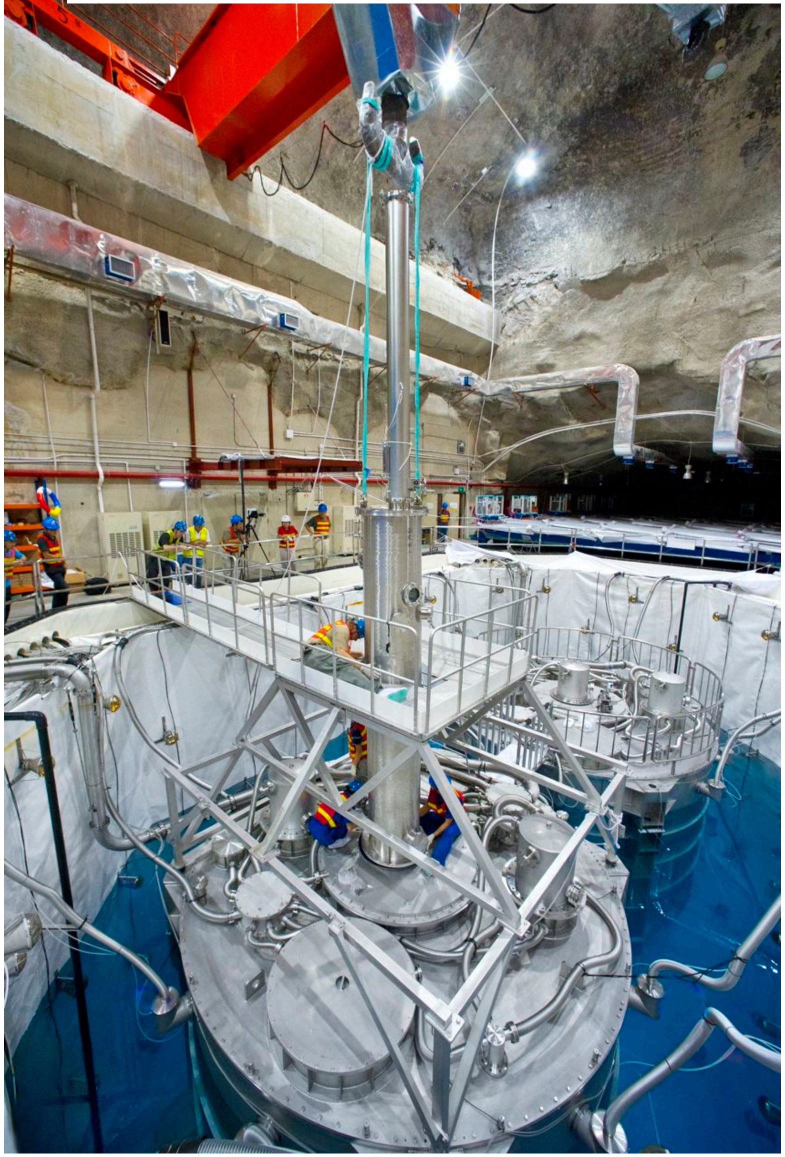
[9] F. P. An *et al.* "Improved measurement of electron antineutrino disappearance at Daya Bay," Chinese Phys. **C37** (2013) 011001 arXiv:1210.6327

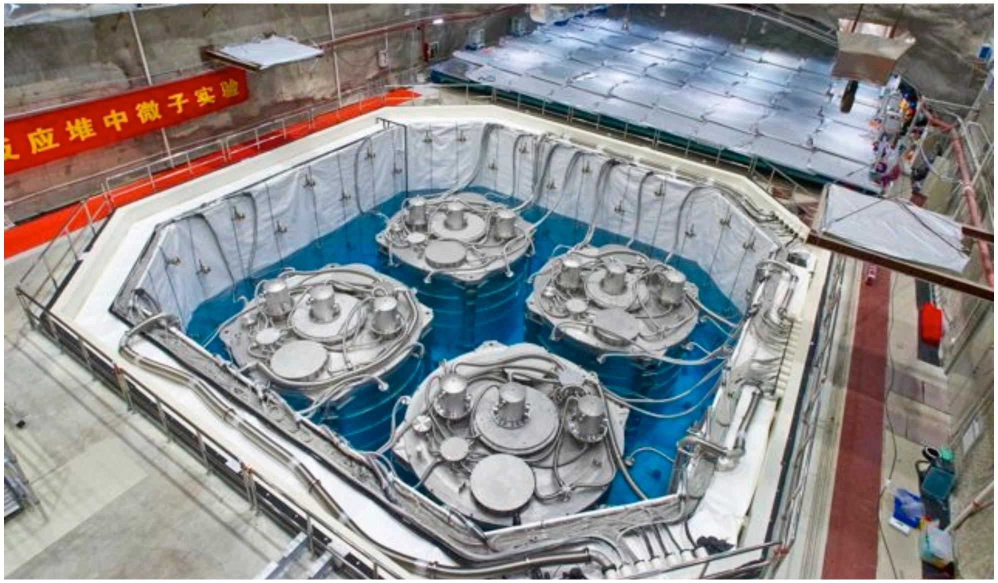
[10] Y. Abe *et al.* "First Measurement of θ_{13} from Delayed Neutron Capture on Hydrogen in the Double Chooz Experiment," Phys.Lett. **B723** (2013) 66-70 arXiv:1301.2948

[11] S.-H. Seo, "New Results from RENO", presented at NuTel 2013 in Venice. Available at NuTel2013

What is Up With Daya Bay?

Started data taking with all eight ADs on 19 Oct 2012.

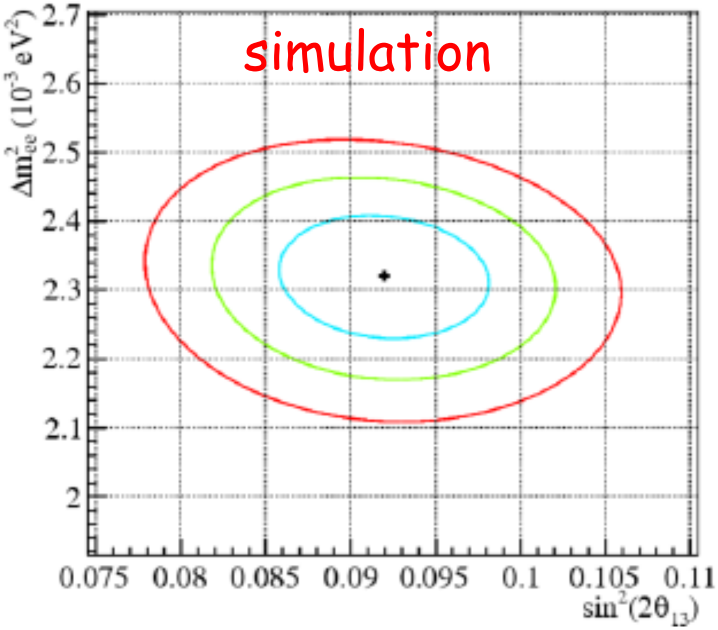




Rate+shape Analyses

- Improve understanding of the energy response of ADs.
- Carry out rate+shape analyses
  - with the entire 6AD data set (24 Dec 2012 – 28 July 2013)
  - update $\sin^2 2\theta_{13}$ and first measurement of Δm^2_{ee}

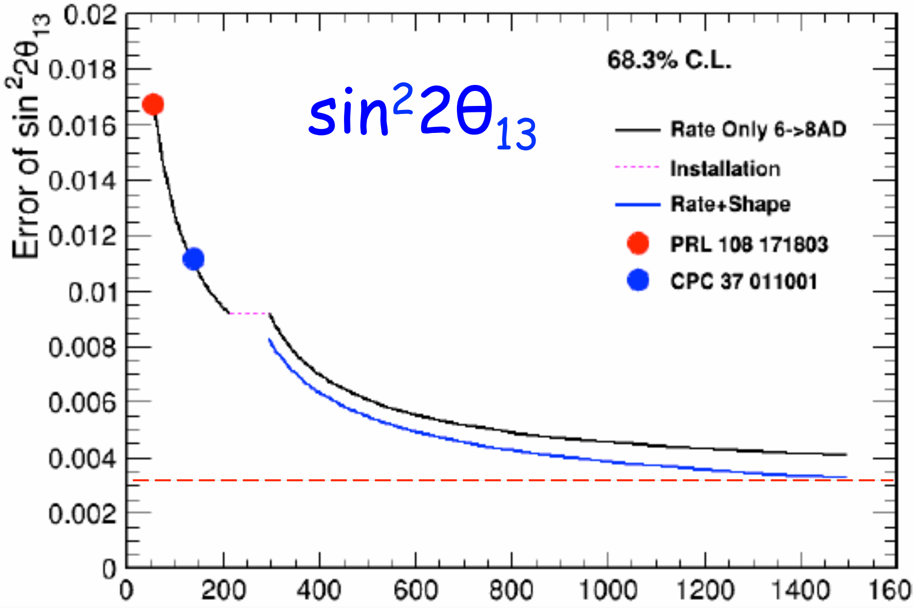
$\Delta m^2_{ee} \approx \Delta m^2_{31}\cos^2\theta_{12} + \Delta m^2_{32}\sin^2\theta_{12}$

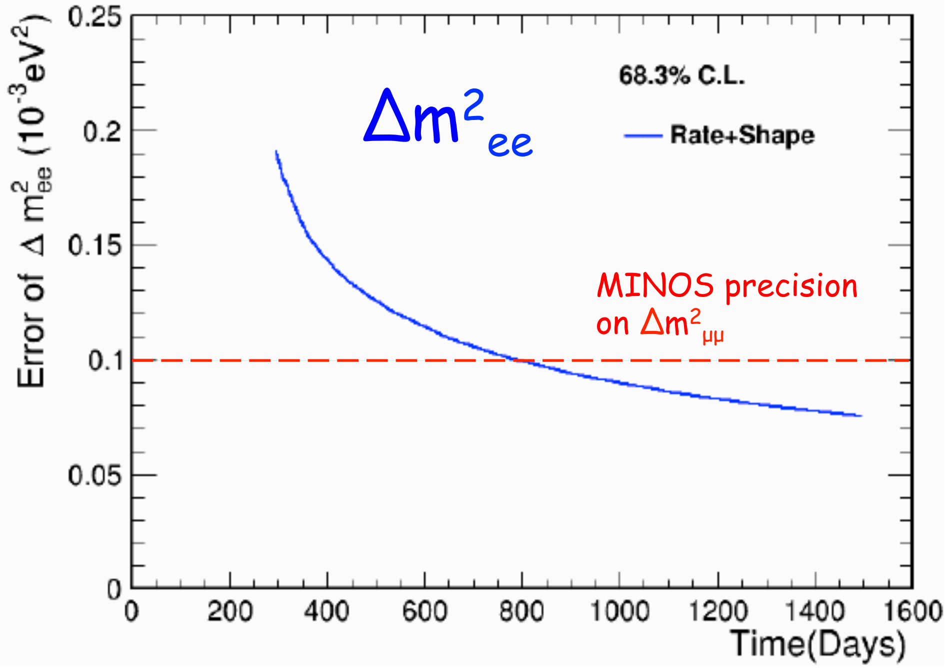


- Results will be released soon.

Scientific Goals of Daya Bay

- Precise measurement of $\sin^2 2\theta_{13}$
  - final precision ≈ 0.003
- Precise measurement of Δm^2_{ee}
  - final precision ≈ 0.08×10^{-3} eV^2
- Precise measurement of reactor $\bar{\nu}_e$ flux and energy spectrum
  - address reactor $\bar{\nu}_e$ anomaly
- Search for supernova neutrinos
  - about to join SNEWS



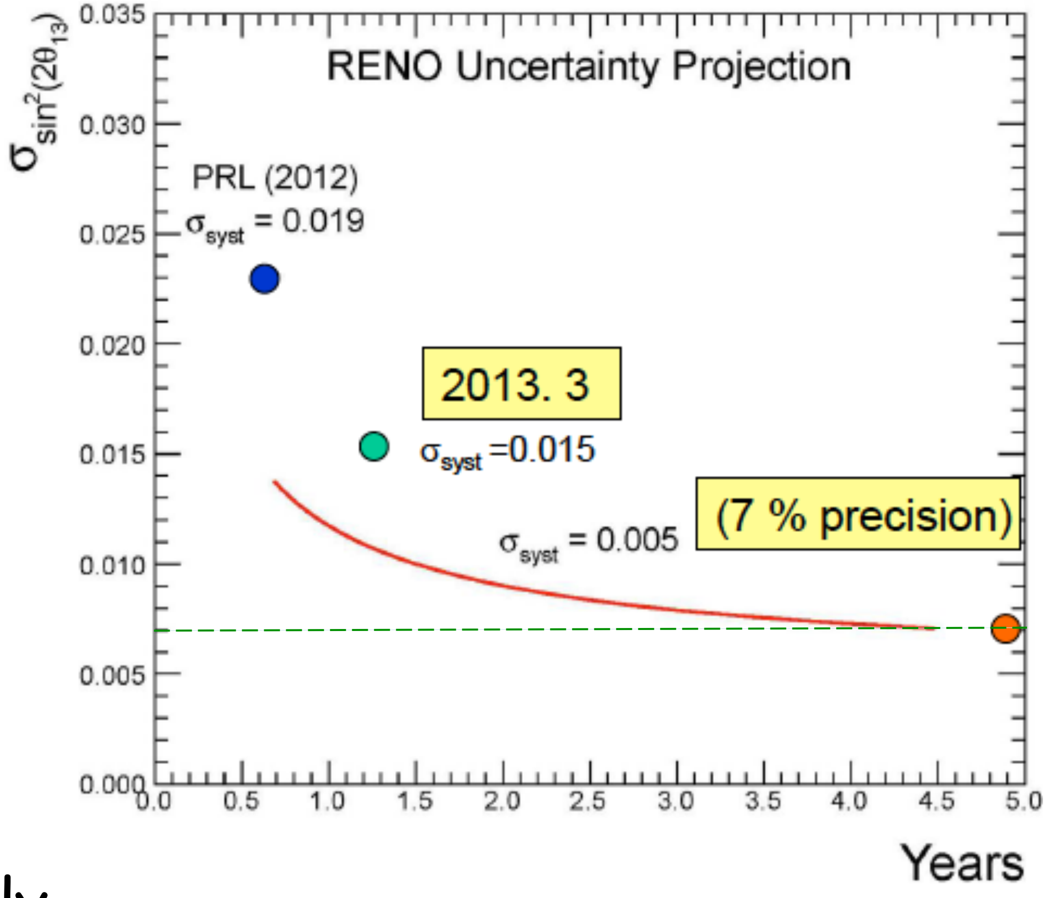


Prospects Of Double Chooz

- Completion of near detector: spring 2014.
- First result using the near and far detectors towards the end of 2014.
- The final precision of $\sin^2 2\theta_{13}$ will be ~10%.

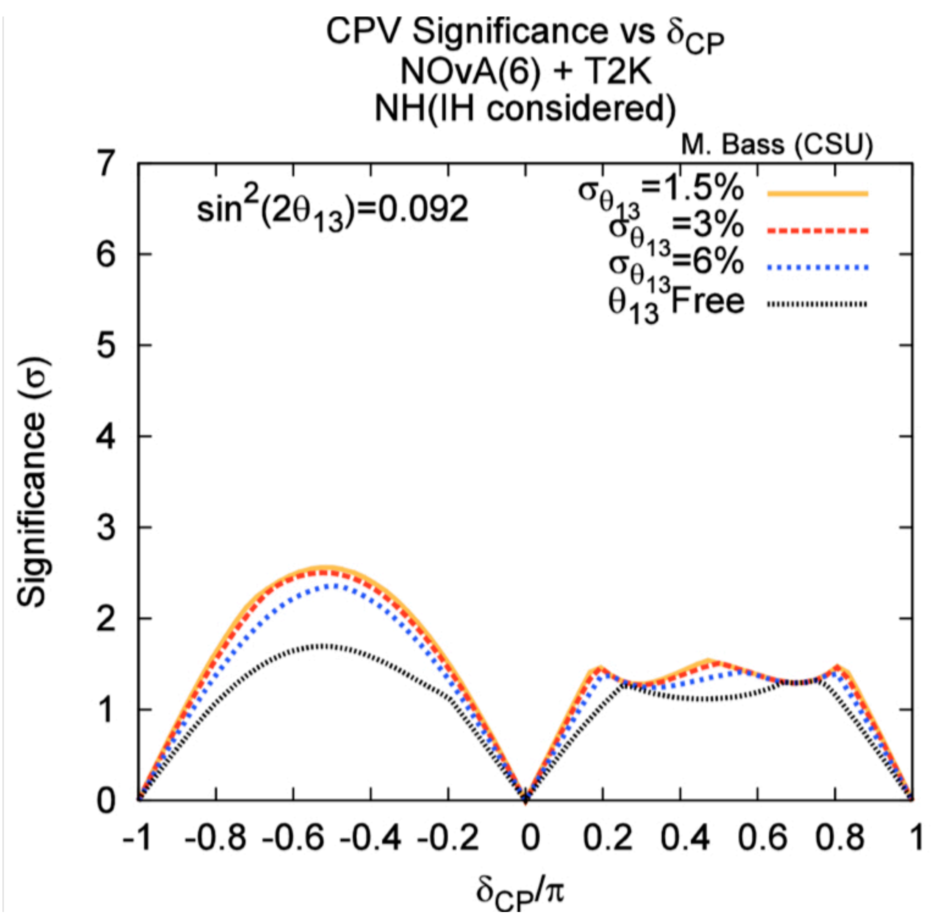
Plan of RENO

- Precise measurement of $\sin^2 2\theta_{13}$
  - final precision ≈ 0.007
- Precise measurement of Δm^2_{ee}
- Precise measurement of reactor $\bar{\nu}_e$ flux and energy spectrum
- Study of reactor $\bar{\nu}_e$ anomaly and sterile neutrinos

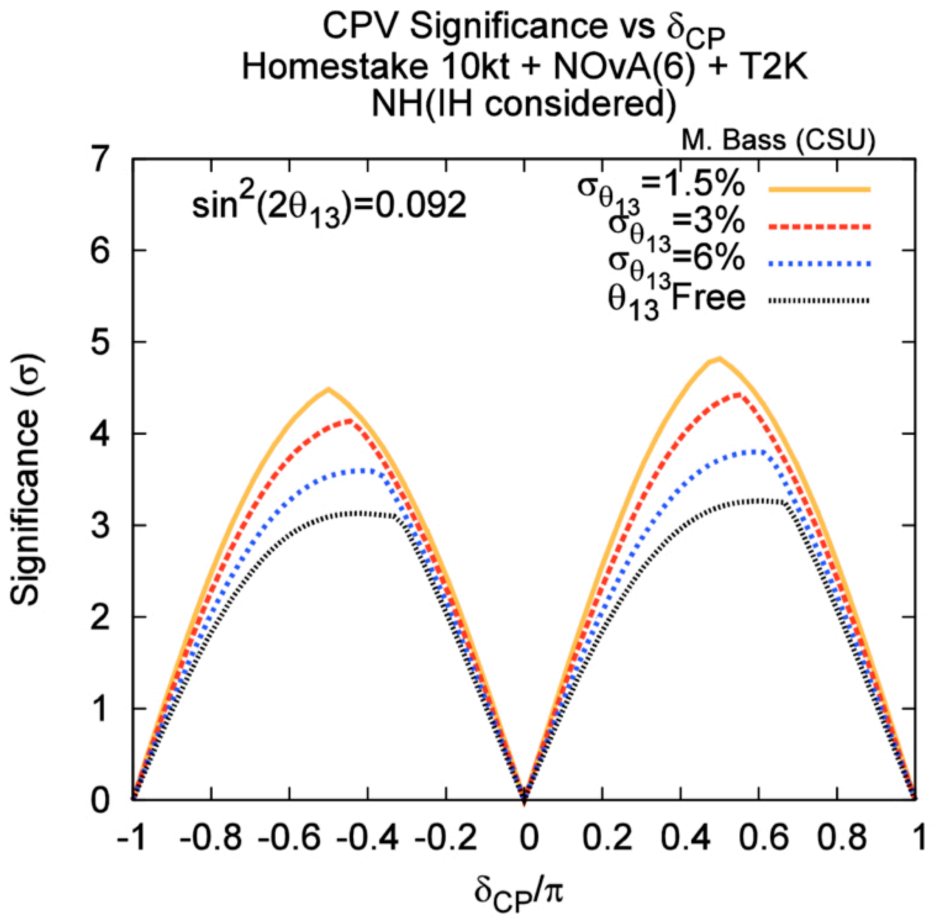


Precision Measurement of $\sin^2 2\theta_{13}$: Impacts

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

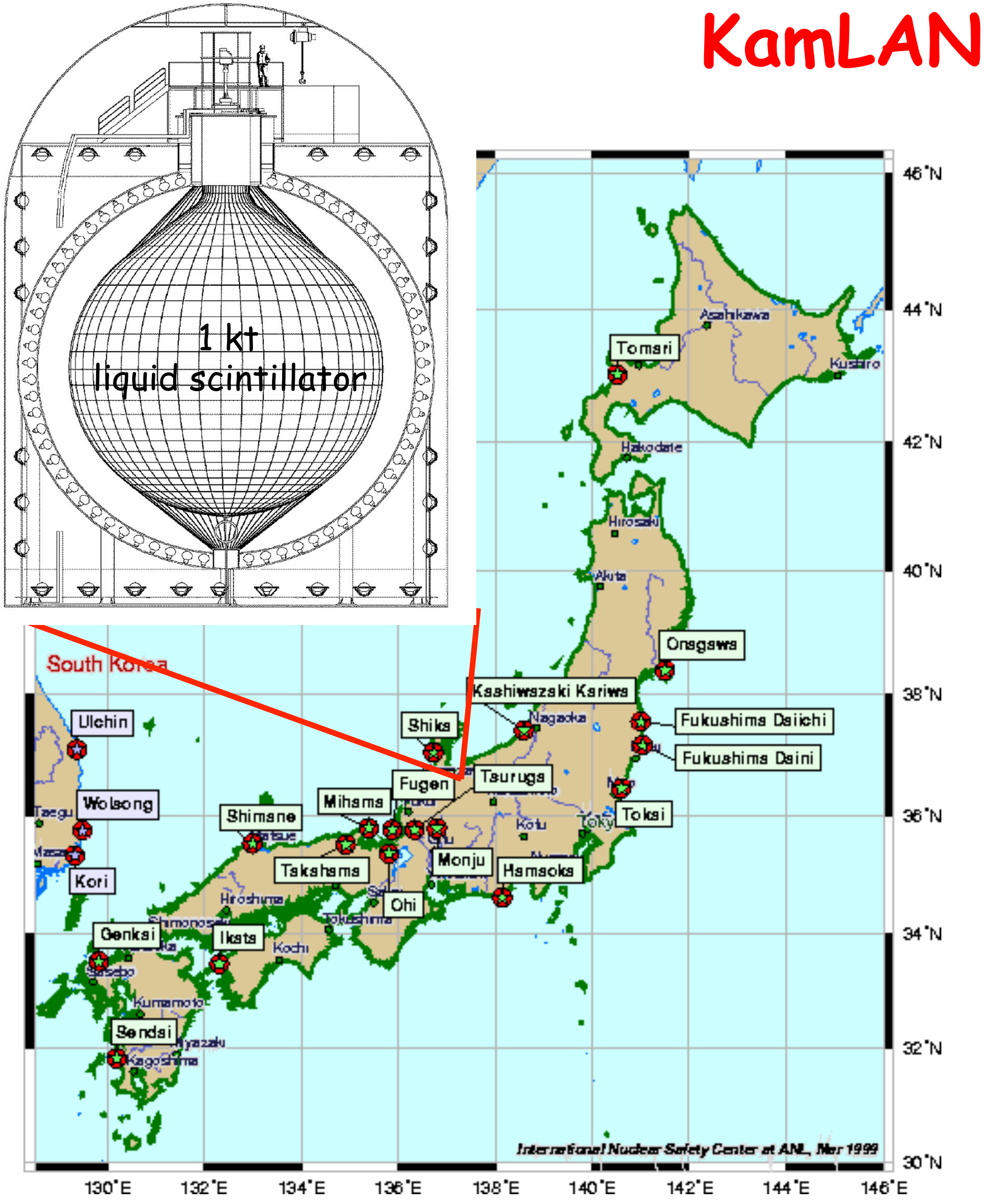


CPV Significance vs δ_{CP}
NOvA(6) + T2K
NH(IH considered)

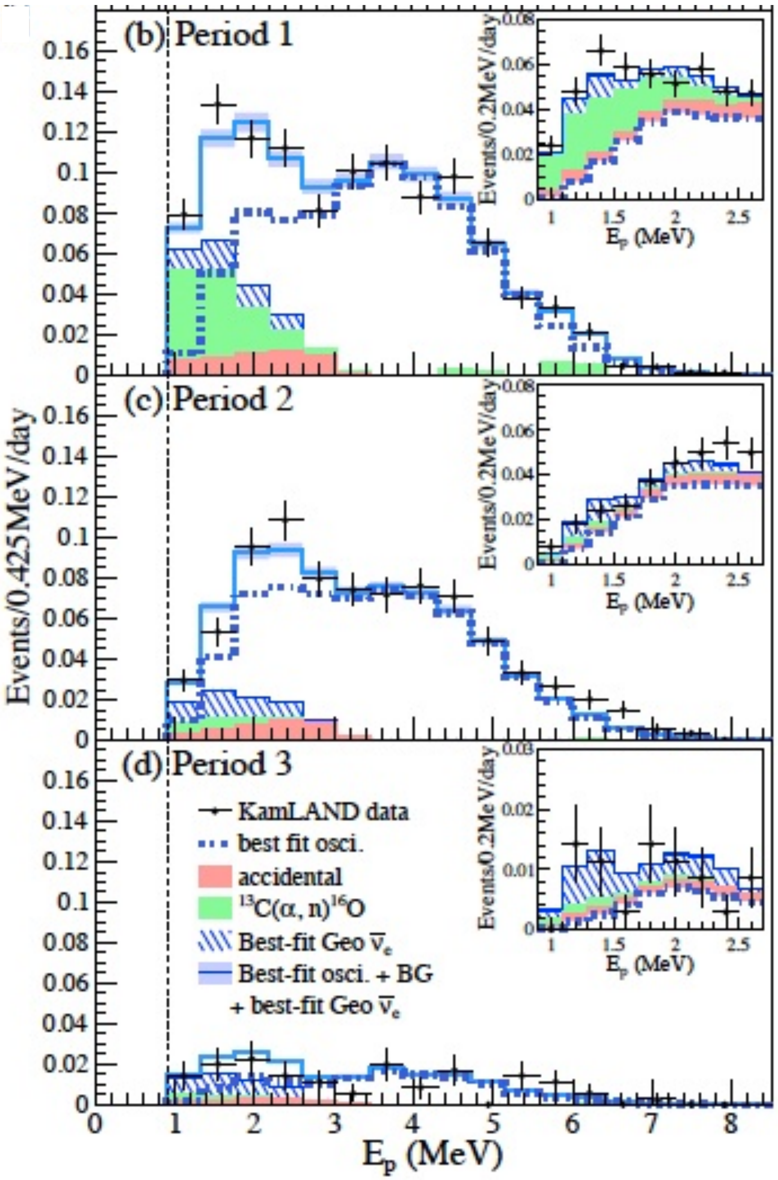


CPV Significance vs δ_{CP}
Homestake 10kt + NOvA(6) + T2K
NH(IH considered)

KamLAND

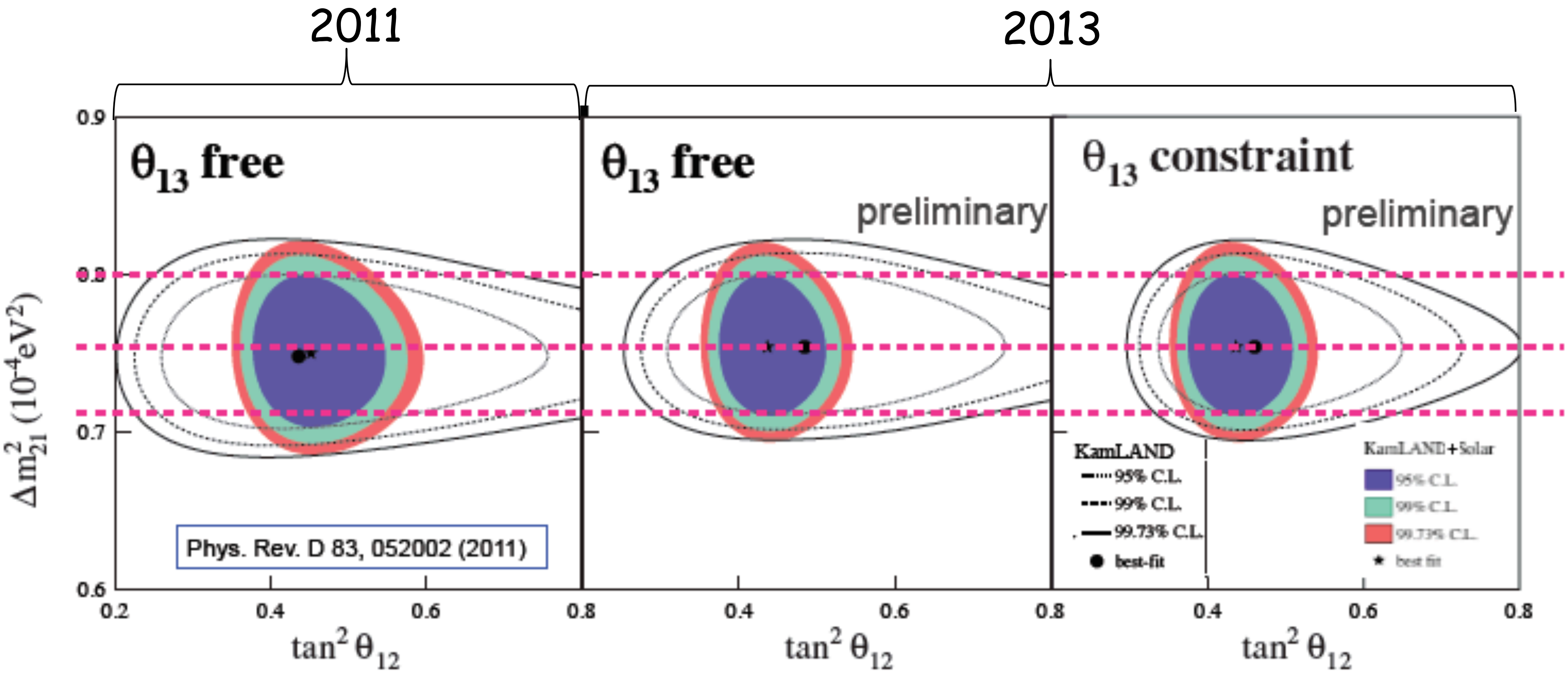


56 Japanese nuclear reactors



Long-term shutdown of reactors allowed better determination of background

Improved θ_{12} From KamLAND



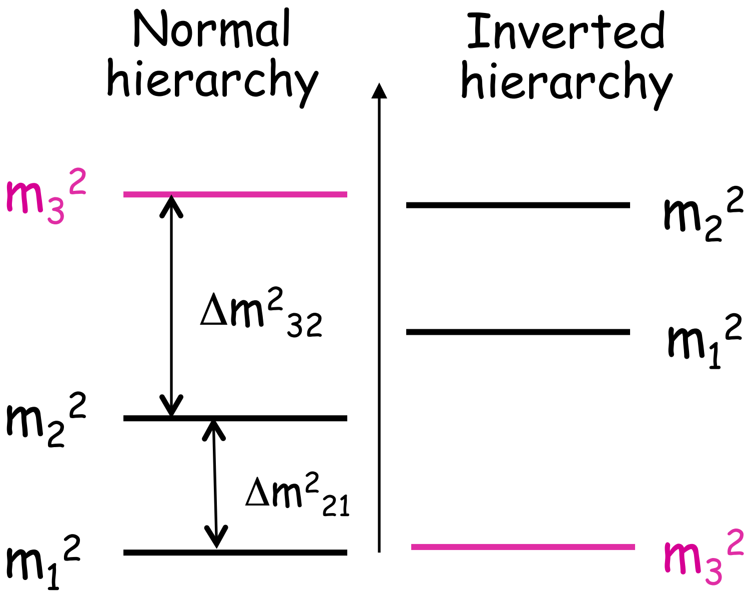
KamLAND+Solar	KamLAND+Solar	KamLAND+Solar+Theta13
$\Delta m^2_{21} = 7.50^{+0.19}_{-0.20} \times 10^{-5}\mathrm{eV}^2$	$\Delta m^2_{21} = 7.53^{+0.19}_{-0.18} \times 10^{-5}\mathrm{eV}^2$	$\Delta m^2_{21} = 7.53^{+0.18}_{-0.18} \times 10^{-5}\mathrm{eV}^2$
$\tan^2\theta_{12} = 0.450^{+0.037}_{-0.031}$	$\tan^2\theta_{12} = 0.437^{+0.029}_{-0.026}$	$\tan^2\theta_{12} = 0.436^{+0.029}_{-0.025}$
$\sin^2\theta_{13} = 0.020^{+0.016}_{-0.016}$	$\sin^2\theta_{13} = 0.023^{+0.015}_{-0.015}$	$\sin^2\theta_{13} = 0.023^{+0.002}_{-0.002}$

- Precision of $\tan^2\theta_{12}$ is improved by 20%

- arXiv: 1303.4667
- Watanabe, NuTel 2013

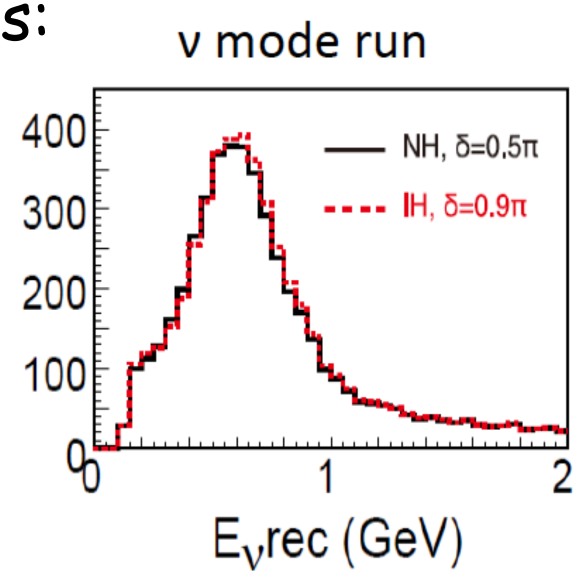
The Mass Hierarchy Problem

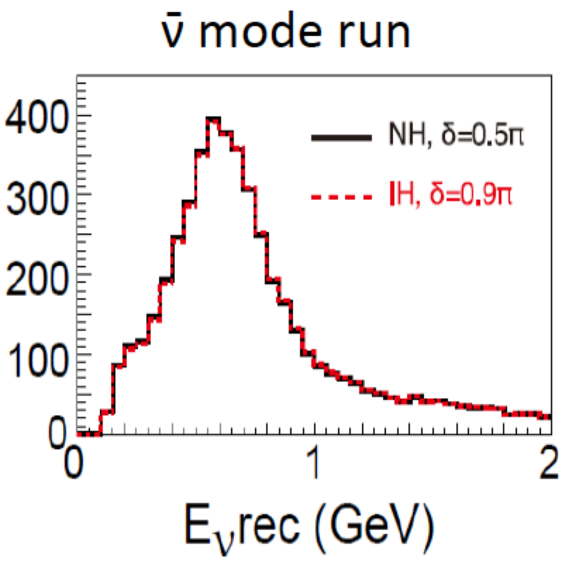
- Which one ?



$$\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21}$$

- Require for removing ambiguities in other key neutrino studies:





Can't tell which is the correct answer for δ if mass hierarchy is unknown !

Tackling Mass Hierarchy With Reactor $\overline{\nu}_e$

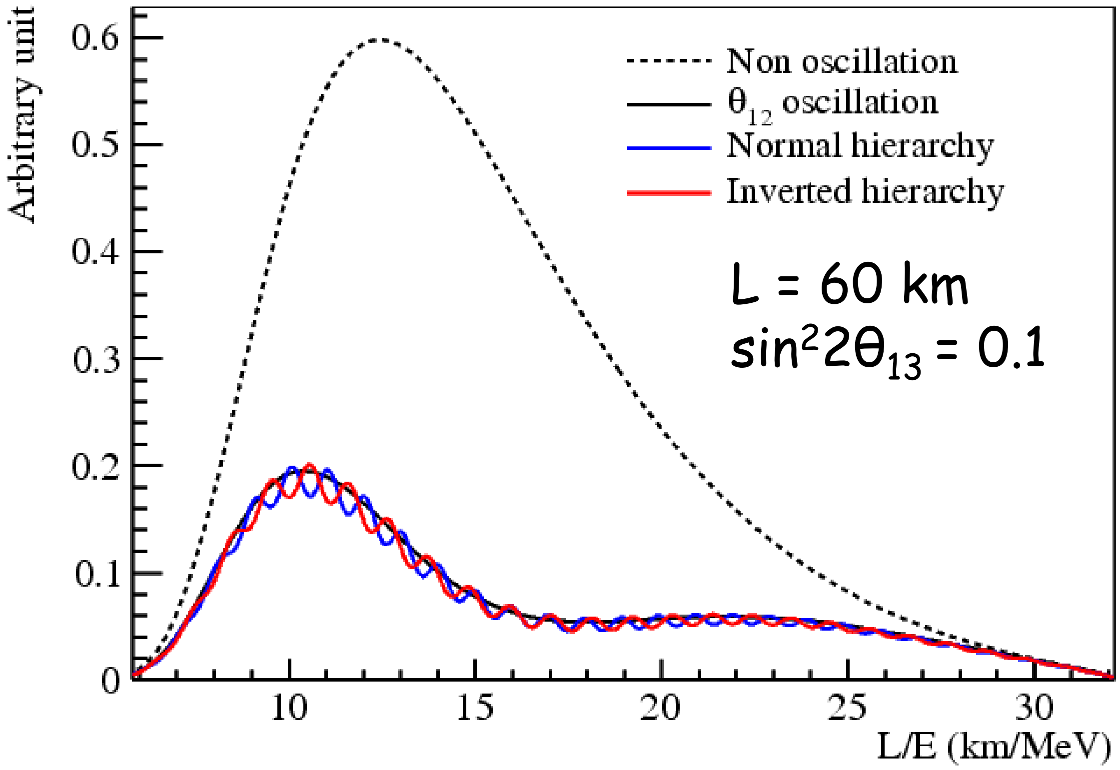
- The survival probability of $\overline{\nu}_e$ is given by:

$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = 1 - P_{21} - P_{31} - P_{32}$$

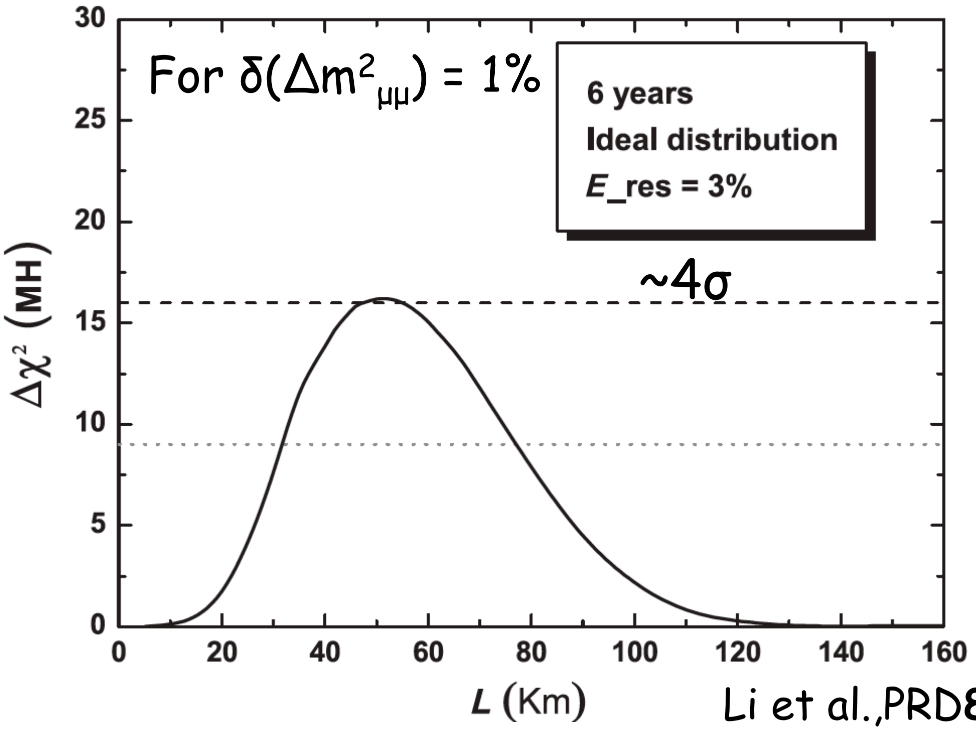
$$P_{21} = \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

Large θ_{13} enables the possibility

$$P_{31} = \cos^2\theta_{12}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) \qquad P_{32} = \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m_{32}^2 L}{4E}\right)$$

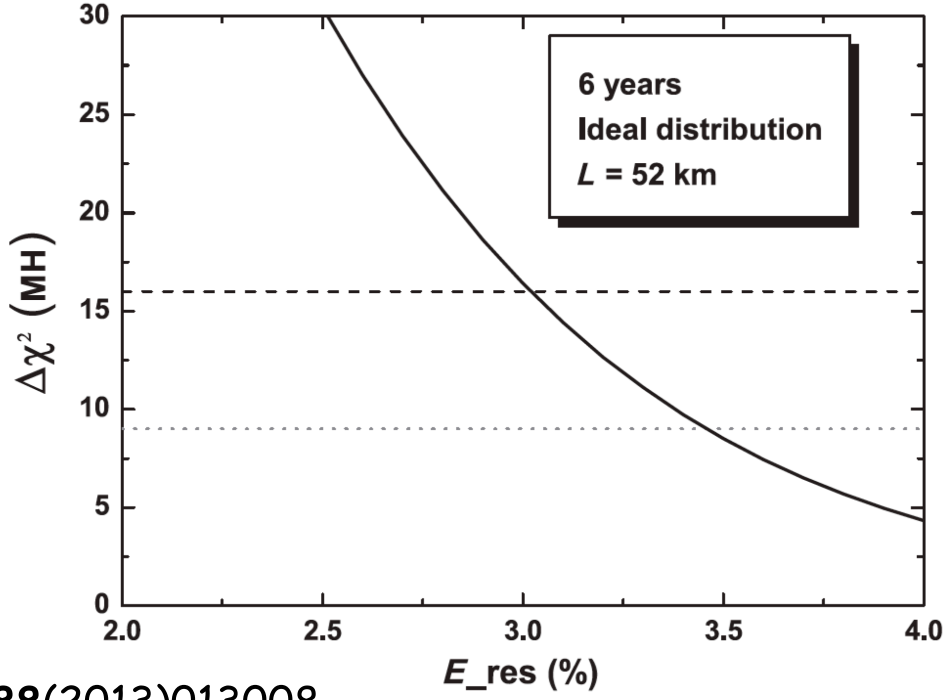


Requirements



For $\delta(\Delta m^2_{\mu\mu}) = 1\%$

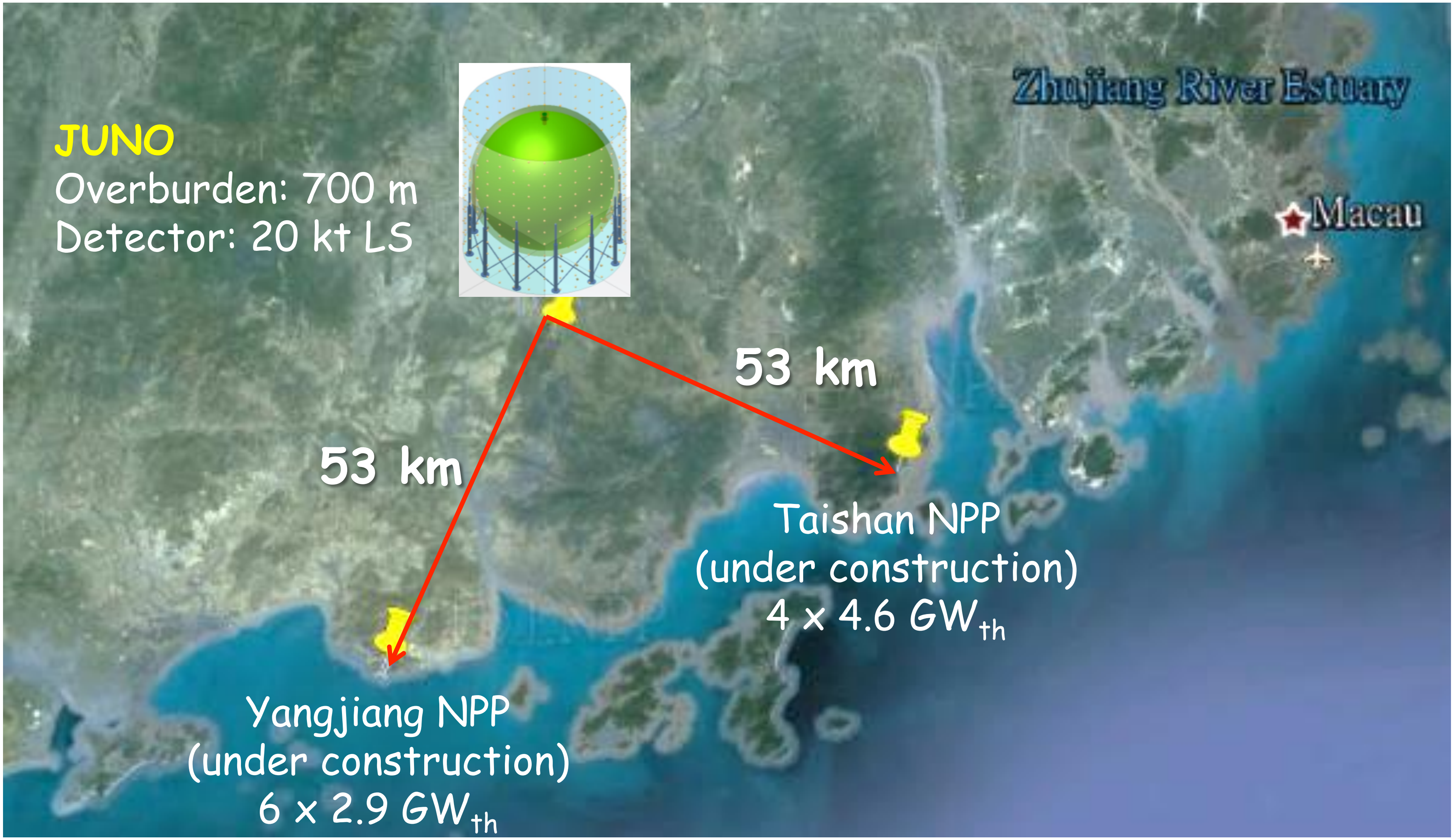
~4σ



Li et al.,PRD**88**(2013)013008

- Requirements:
  - High statistics
    - powerful nuclear reactors with proper orientation w.r.t. the detector
    - a large detector
  - Excellent energy measurement
    - energy resolution : better than 3%/√E
    - accurate determination of the energy scale

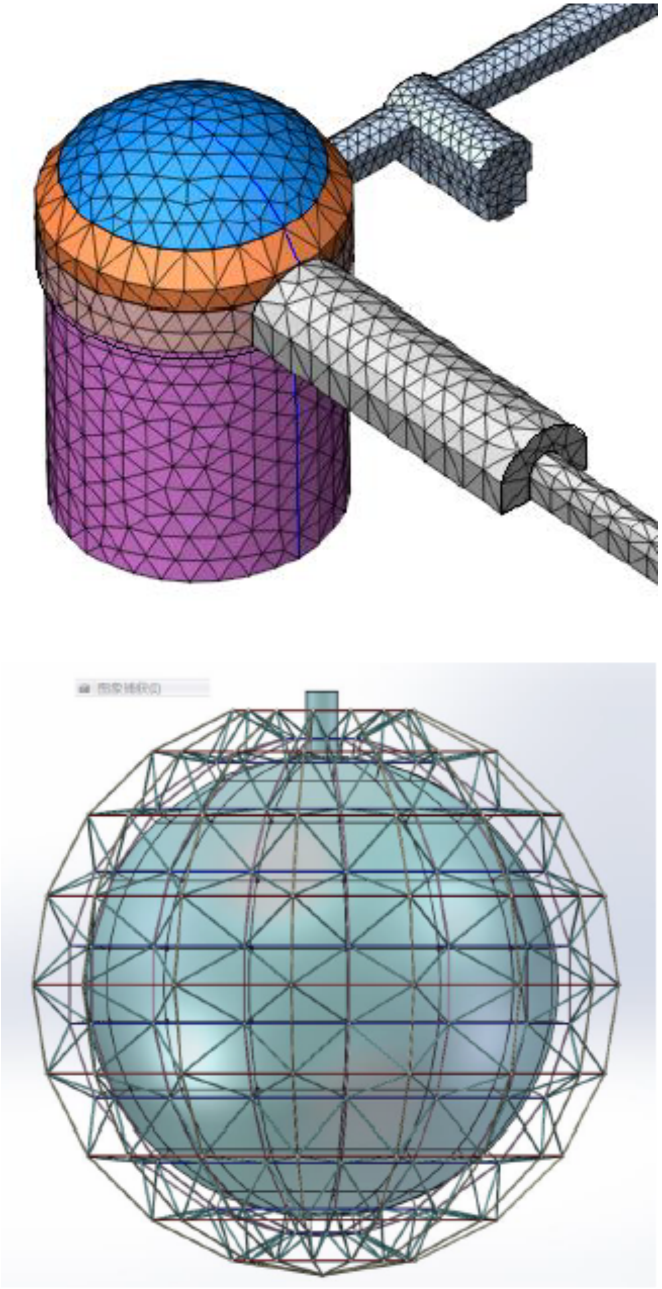
JUNO

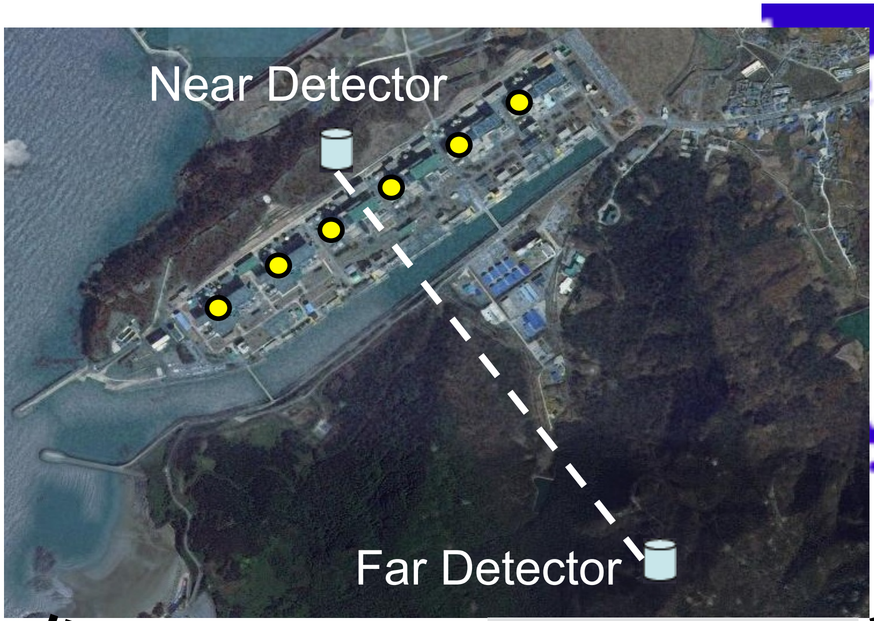


X. Li, this meeting

Status & Plan of JUNO

- Received funding for R&D & conceptual design in China.
- Geotechnical survey will be done by the end of summer.
- Detailed civil design underway.
- R&D on
  - prototyping detector
  - LAB-based liquid scintillator
  - photo-detectors
  - readout electronics
- Detector design underway.
- Form collaboration by the end of 2013.
- Begin data taking in 2020.



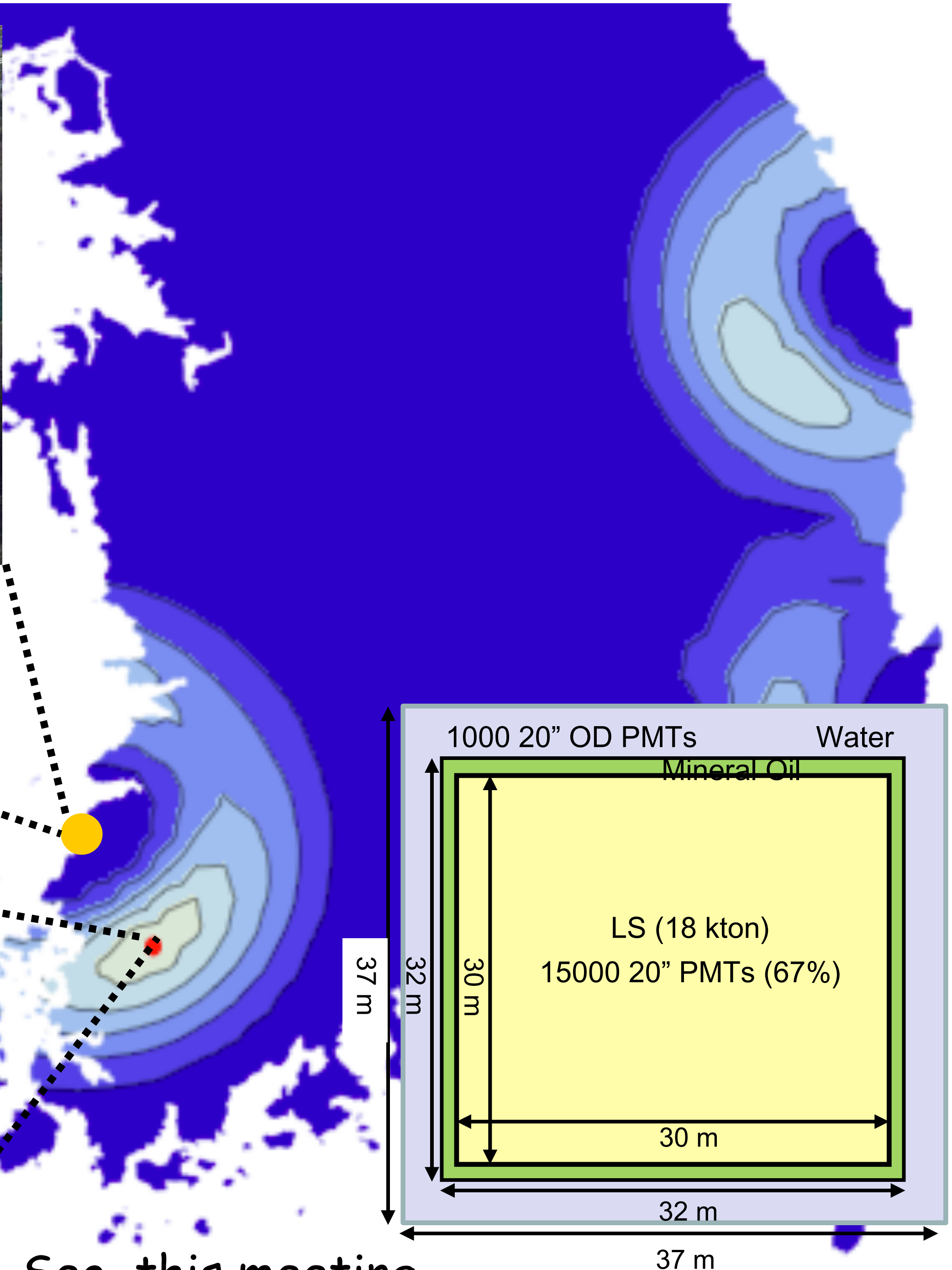


RENO

RENO-50

18 kton LS Detector
~47 km from YG reactors

Mt. Guemseong (450 m)
~900 m.w.e. overburden



S. Seo, this meeting

Scientific Potential of JUNO/RENO-50

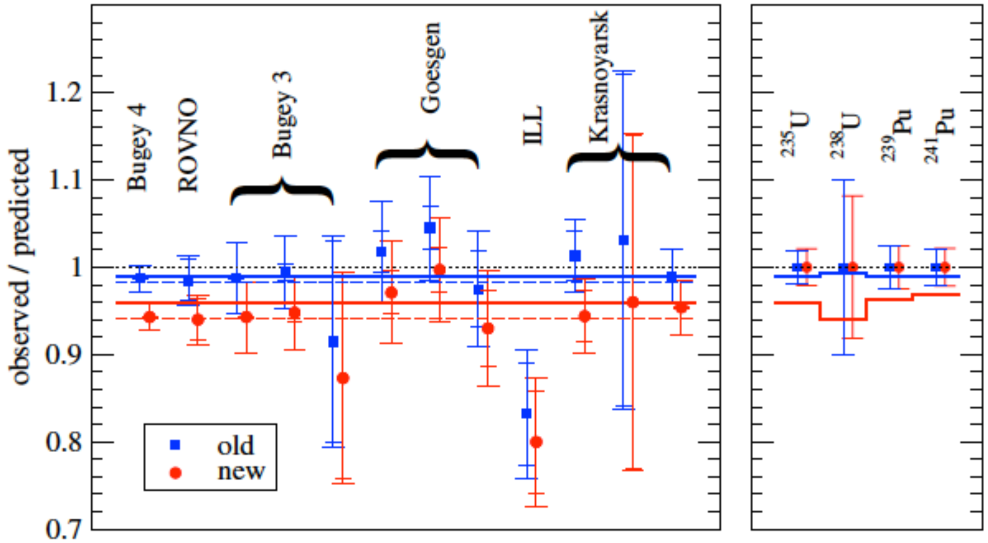
- Resolve the mass hierarchy
  - ~4 standard-deviation discrimination in 6 years
- Precision determination of neutrino-mixing parameters

	Current fractional precision	**JUNO/ RENO-50**
$\sin^2 2\theta_{12}$	5%	0.7%
$\sin^2 2\theta_{23}$	5%	NA
$\sin^2 2\theta_{13}$	10%	~15%
Δm^2_{21}	3%	0.6%
Δm^2_{31}	5%	0.6%

- Search for supernova neutrinos
  - ~5000 events for supernovae occur at 8 kpc
- Study geo-neutrinos
  - ~1000 events in a 5-year run

Reactor Antineutrino Anomaly

- Reactor antineutrino flux at short distance is 6% smaller
  - New calculations yielded 3% more flux
    - Mention etal., PRD**83**(2011)054615 and update (2012)
    - Huber PRC**84**(2011)024617
  - Included contributions from long-lived isotopes
  - Measured neutron lifetime has decreased, leading to larger σ(IBD).

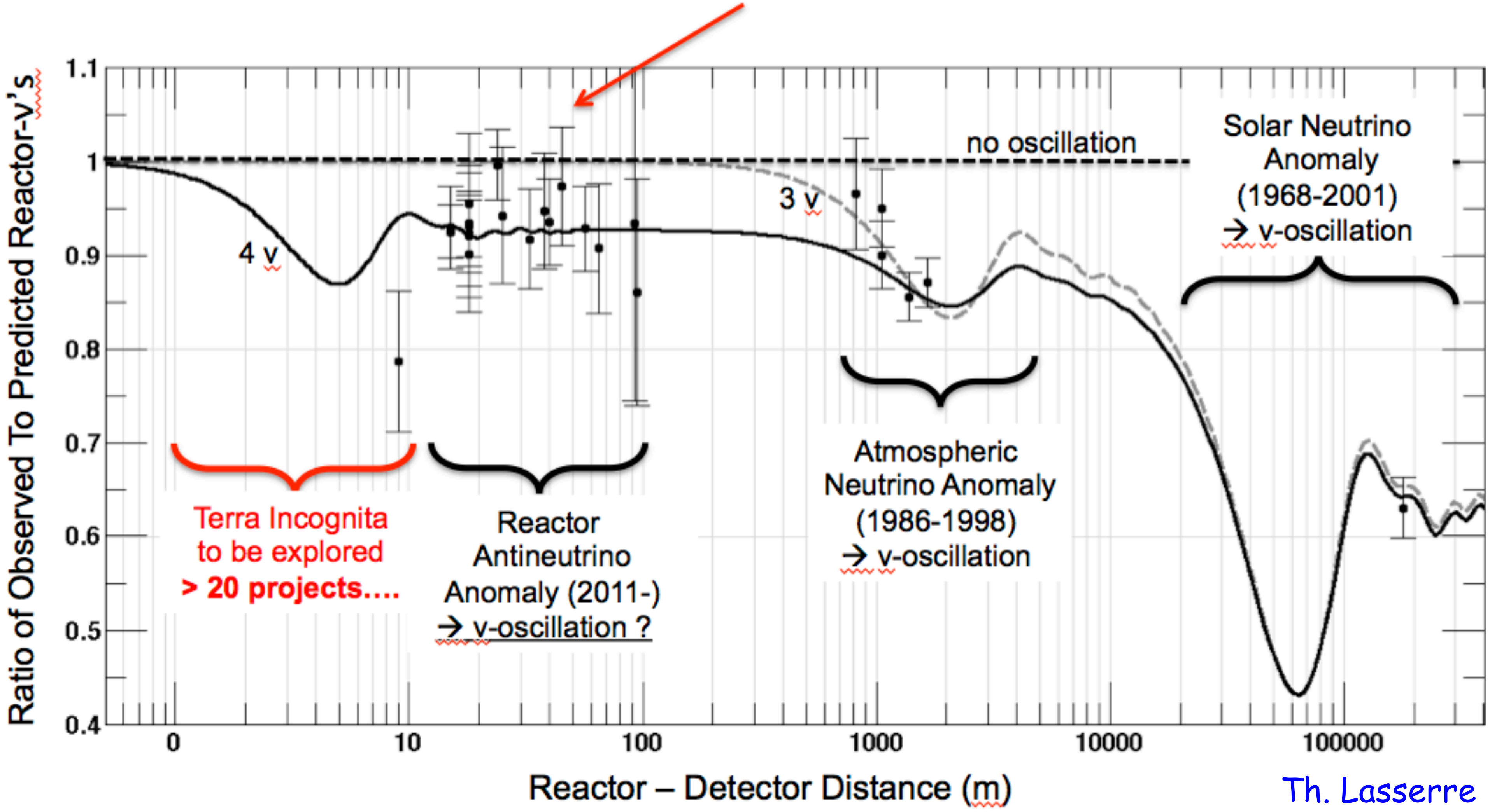


Schwetz etal,
NJP13(2011)063004

- Re-analyses of 19 measured fluxes using $\sin^2 2\theta_{13} = 0.089$
  - R = 0.959±0.028 (1.4 standard deviations) [Zhang et al., PRD**87**,073018]
  - R = 0.93±0.022 (> 3 standard deviations) [Saclay]
- Need further investigation.

Sterile Neutrino As A Solution

- Reactor anti-neutrino anomaly may be due to sterile-neutrino oscillation with $\Delta m^2 \sim 1\ eV^2$:
  - **Observed/predicted averaged event ratio: R=0.927±0.023 (3.0 σ)**

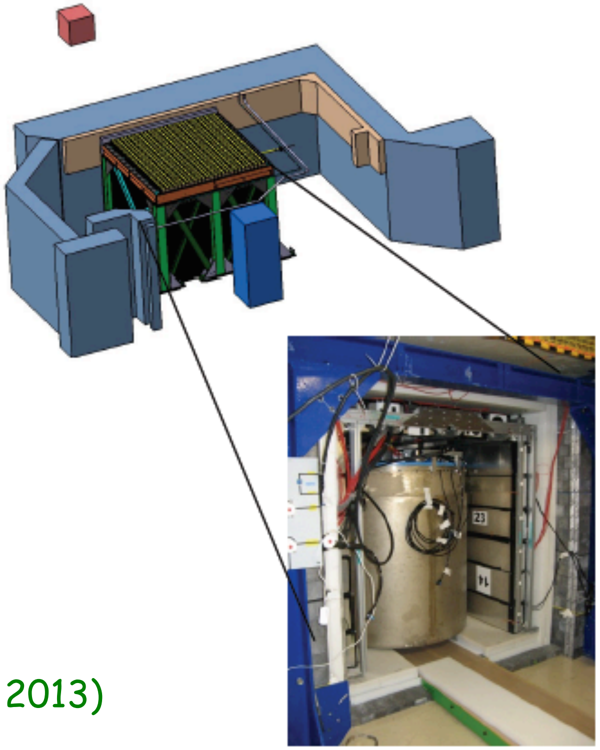


Th. Lasserre

Search For Sterile Neutrino

- Very short baseline reactor neutrino-oscillation experiments:
  - Nucifer (~7m from Osiris research reactor at Saclay – taking data)
  - DANSS (~7-12m from the core of Kalinin NPP – prototyping)
  - Stereo, Solid (~8m at ILL)
  - and more …

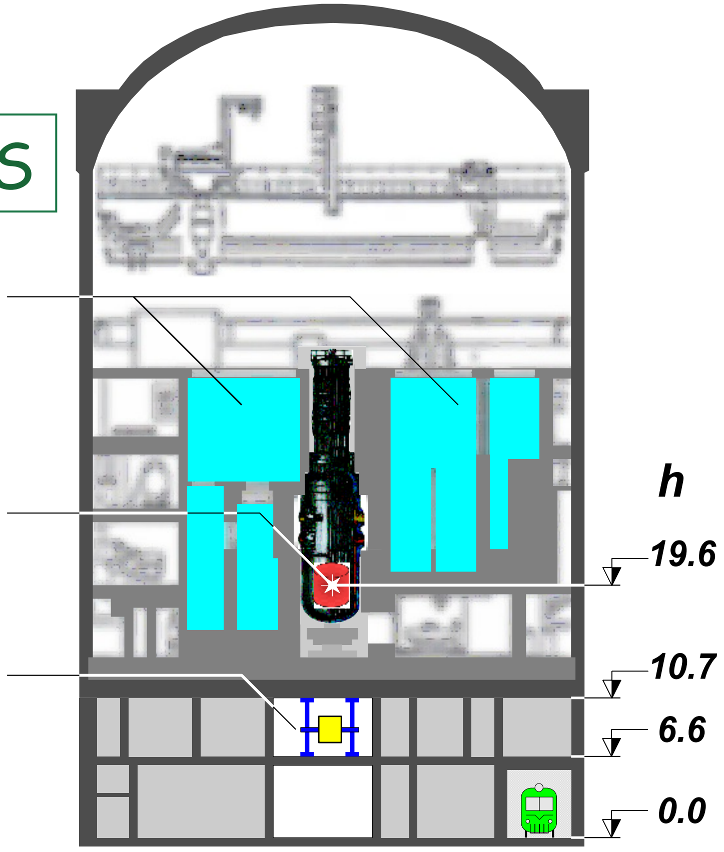
Nucifer



Cribier (NuTel 2013)

DANSS

Danilov (This meeting)



Summary

- Nuclear reactors are excellent tools and have played a key role for studying neutrino physics.
- Current generation of reactor antineutrino experiments are essential for precision determination of the mixing parameters θ_{12}, θ_{13}, Δm^2_{21}, and Δm^2_{ee} .
- Next generation of reactor antineutrino experiments will address the mass hierarchy problem in the next decade.
- Investigation of the reactor $\bar{\nu}_e$ anomaly might lead to a surprise – existence of sterile neutrino.
- The future of reactor antineutrino experiment is bright!