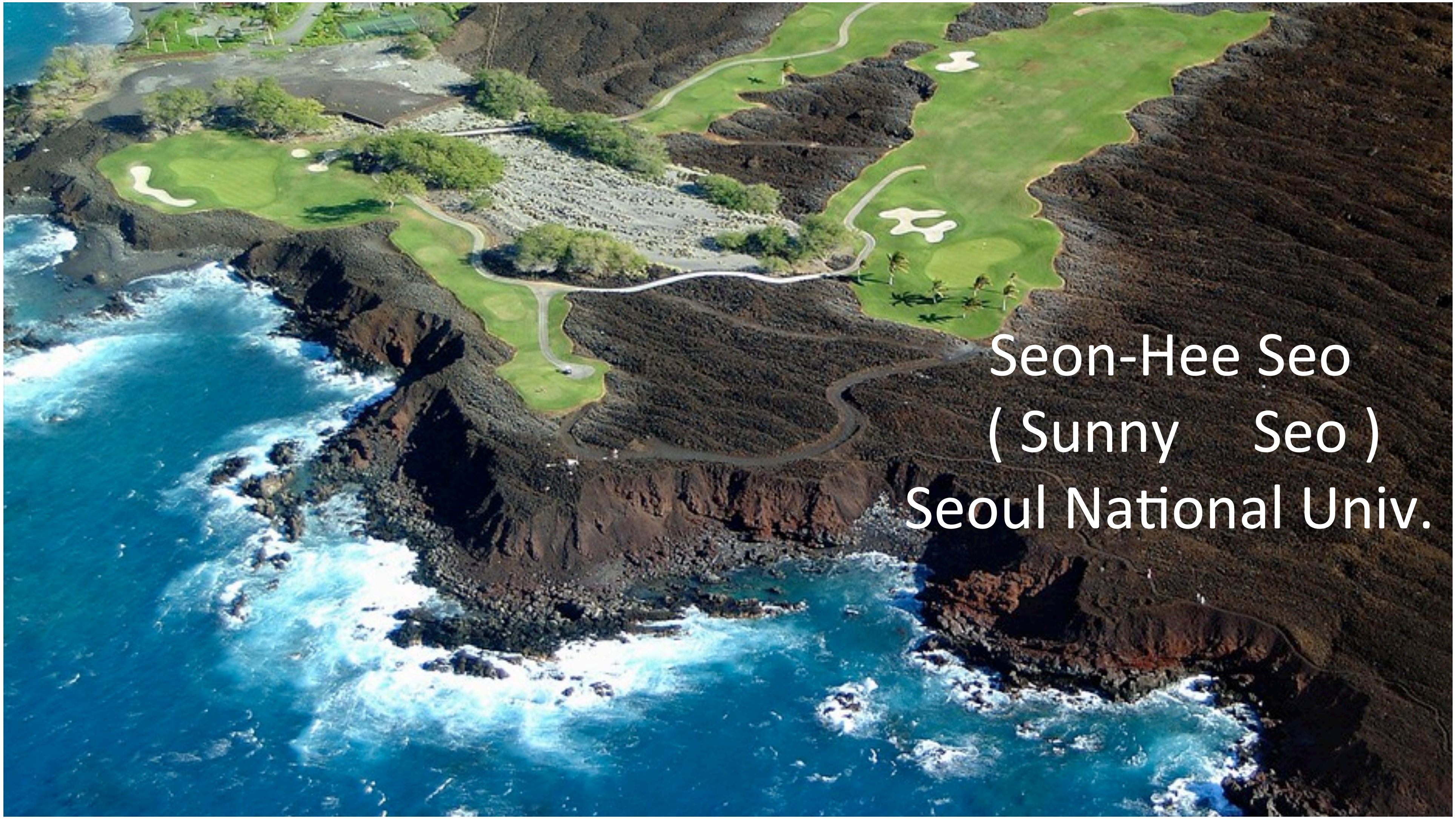
θ_{13} & 5 MeV Excess from Reactor ν



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DBD 2014 Waikoloa, Hawaii Oct. 6, 2014

Outline

This is an experimentalist's report.

- Short Introduction
- Reactor θ_{13} experiments
- Recent θ_{13} results
- The 5 MeV excess
- JUNO, RENO-50 (shortly if time allowed)

$$\left\{ \nu_e \,,\ \nu_\mu \,,\ \nu_\tau \right\} \qquad \left\{ \nu_1 \,,\ \nu_2 \,,\ \nu_3 \right\}$$

Generation, detection	When traveling
3 flavors of ν in SM	3 mass eigen-state of ν

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

- Pontecorvo
- Maki
- Makagawa
- Sakaga

PMNS matrix in 1962

PMNS matrix

$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = \begin{bmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{bmatrix}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$

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

Atmos. (ν_μ, $\overline{\nu}_\mu$ deficit)
Long baseline (ν_μ deficit)

Reactor ($\overline{\nu}_e$ deficit)
Long baseline ($\nu_\mu \rightarrow \nu_e$)

Solar (ν_e deficit)
Reactor ($\overline{\nu}_e$ deficit)

Neutrino Oscillation

Atmos. Neutrino Oscillation	θ_{23}	**~45°** **(1998)** **Super-K;** K2K
↓		↓
Solar Neutrino Oscillation	θ_{12}	**34°** **(2001)** **SNO**, **Super-K;** KamLAND
↓		↓
Reactor Neutrino Oscillation	θ_{13}	**9°** **(2012)** **Daya Bay, RENO**

Why θ_{13} ?

- ✓ To complete 3 ν mixing angle matrix (PMNS).
- ✓ To open a window for leptonic CP phase measurement

  LBNO, LBNE, Hyper-K (θ_{13} != 0)

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

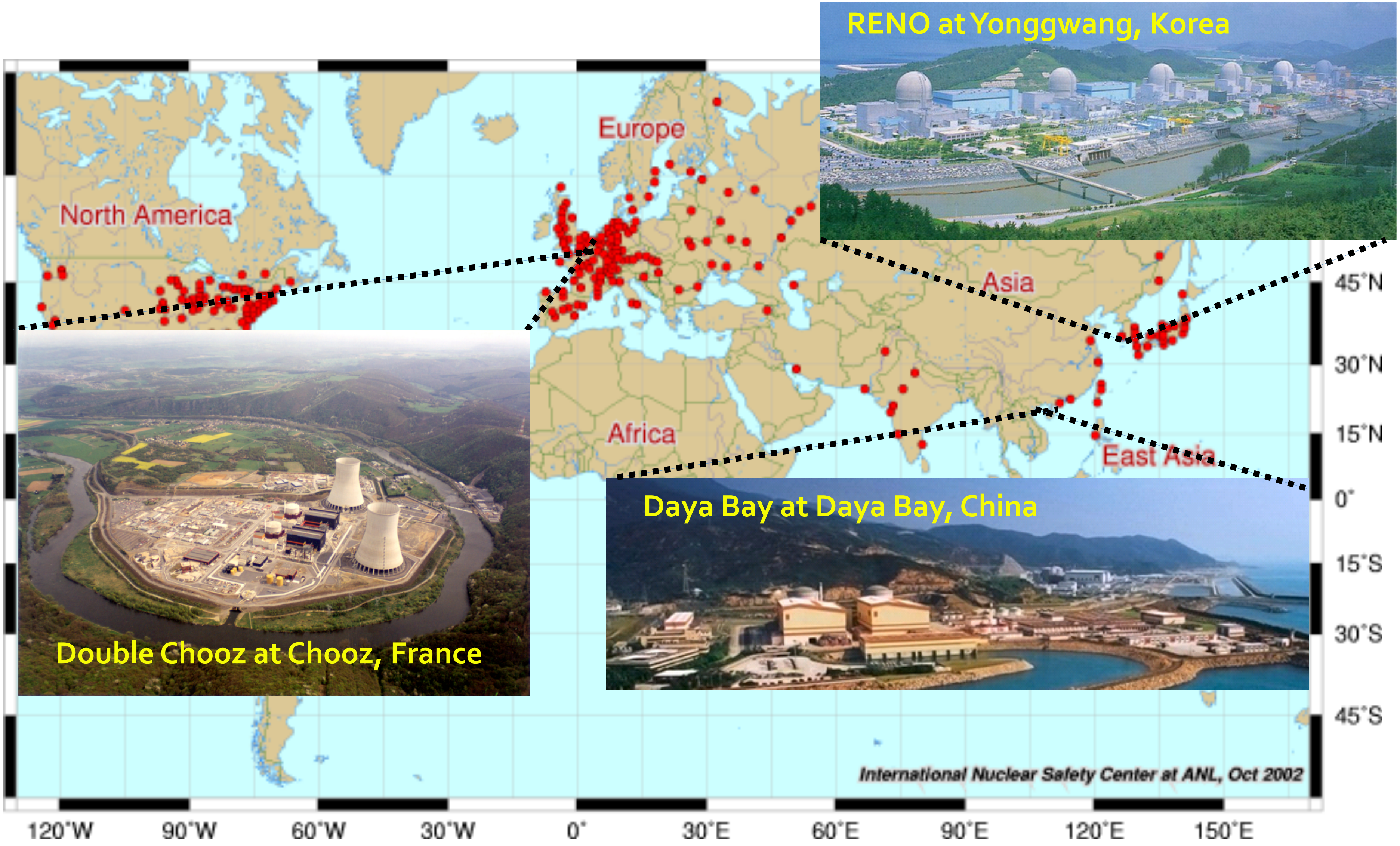
- ✓ To allow neutrino mass hierarchy measurement

  (← requires not too small θ_{13})

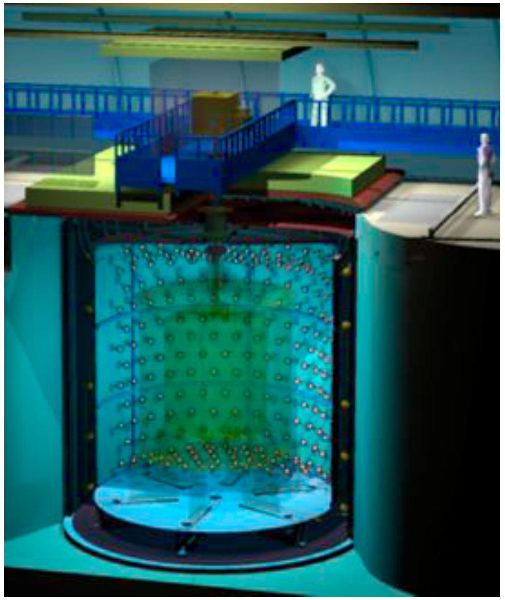
- ✓ To allow precise measurement of atm. neutrino oscillation parameters

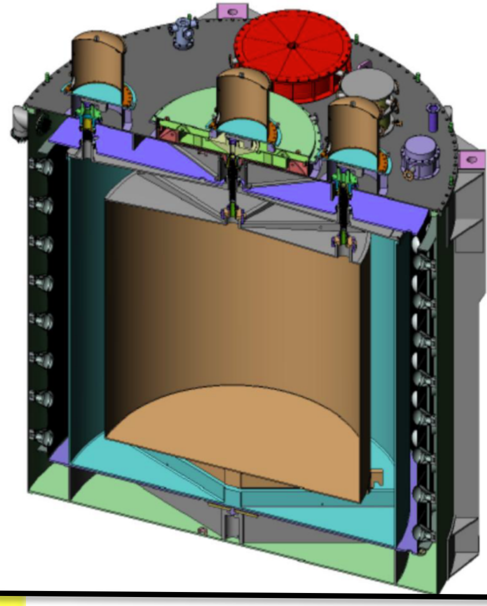
PRD 81, 113008 (2010)
PRD 82, 093011 (2010)

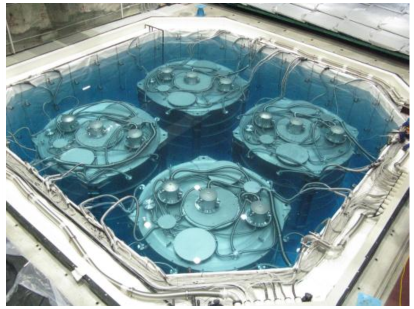
Reactor θ_{13} Experiments

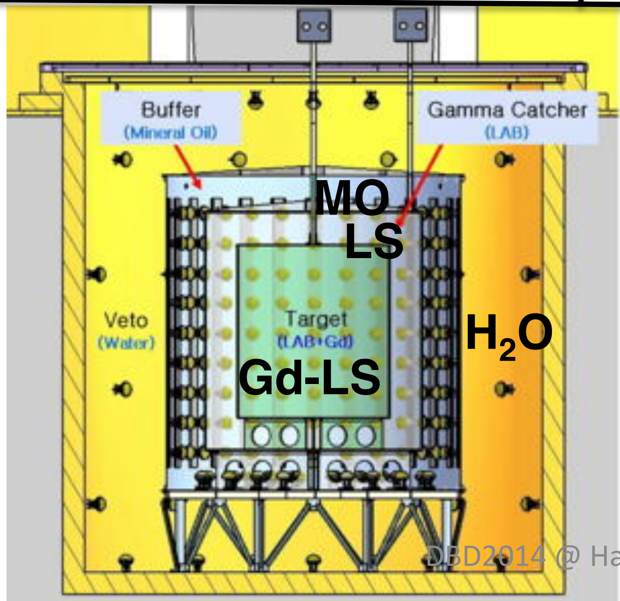


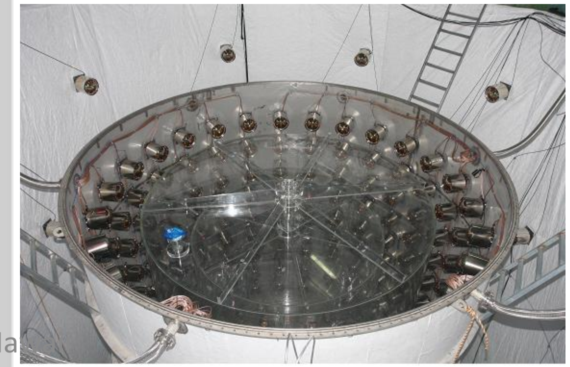
θ_{13} Reactor Neutrino Detectors



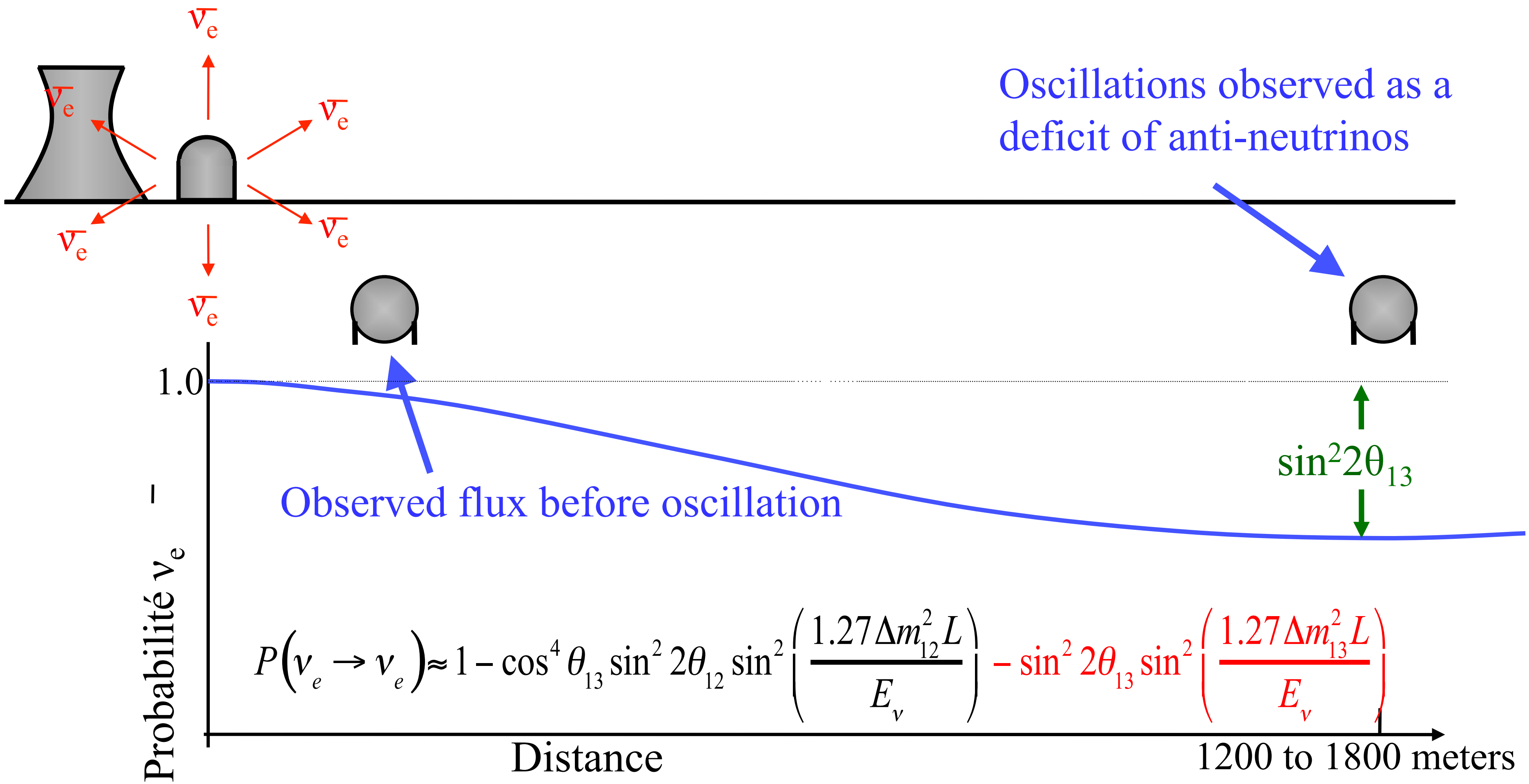








How to measure θ_{13} ?



❑ Find disappearance of $\bar{\nu}_e$ fluxes due to neutrino oscillation as a function of energy using multiple, identical detectors to reduce the systematic errors in 1% level.

Reactor ν Experiments

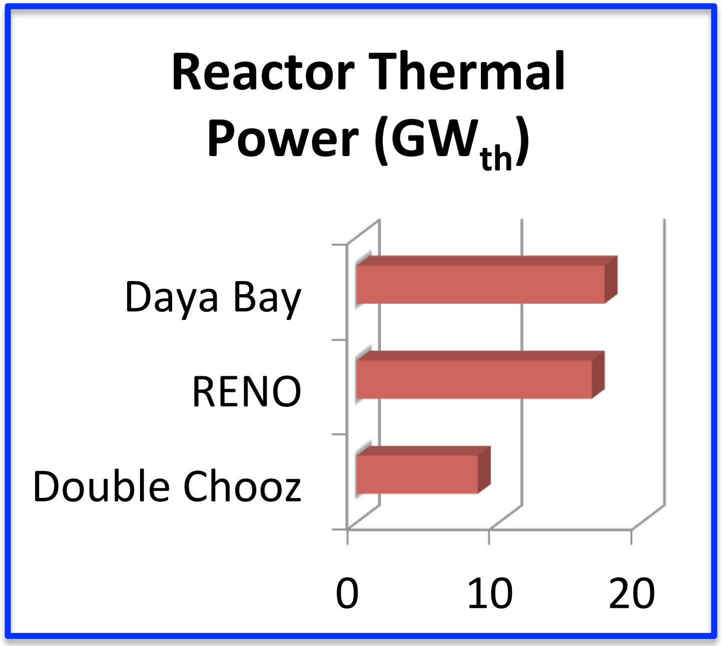
Experiment (location)	$Sin^2 2\theta_{13}$ Sensiti-vity	Thermal Power (GW)	Distance Near/Far	Depth Near/Far (mwe)	Target mass (ton)	Cost (US $)	# of physicists
Double Chooz (France)	> 0.03	8.5	400/1050	120/300	10/10	?	> 160
RENO (Korea)	> 0.02	16.8	290/1380	120/450	16/16	~10 M	40
Daya Bay (China)	> 0.01	17.4	360(500)/ 1985(1613)	260/860	40x2/80	?	> 230

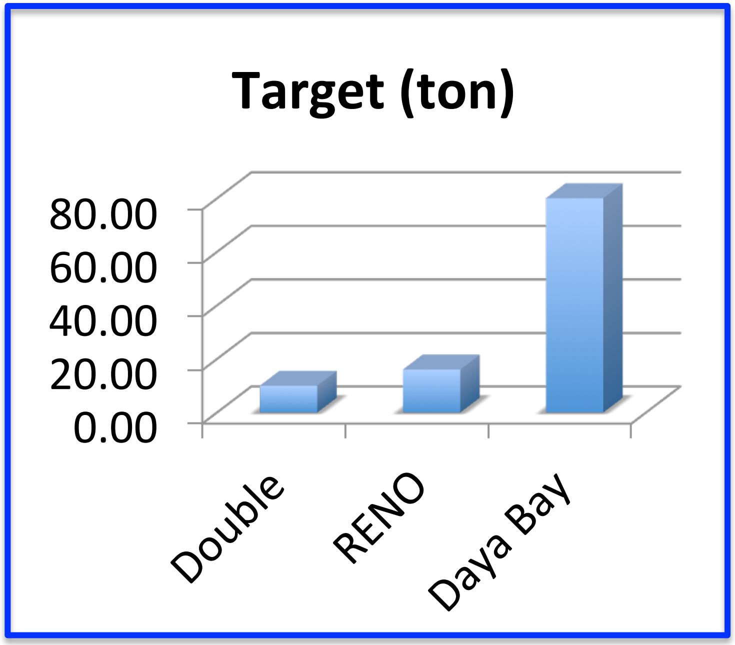
Construction:

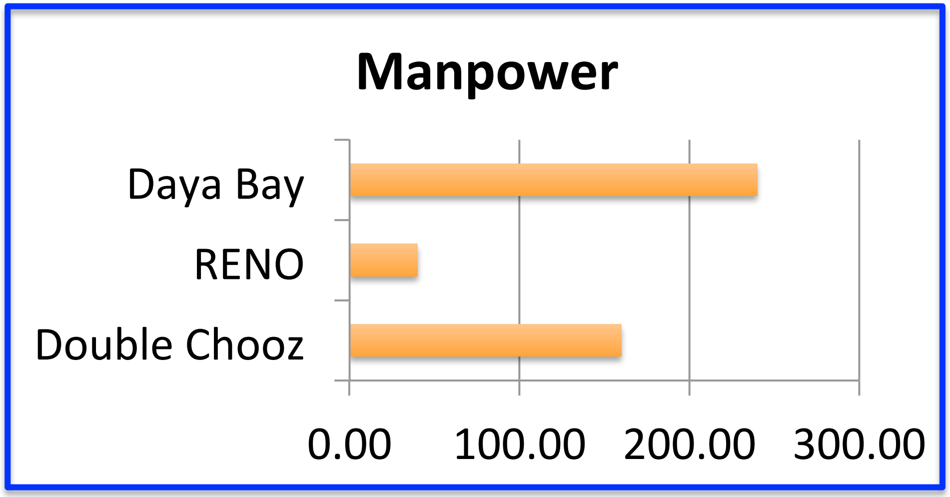
- ✓ **DC** will finish construction in **Oct. 2014**.
- ✓ **RENO** finished construction in **June 2011**.
- ✓ **Daya Bay** finished construction in **Sept. 2012**.

RENO was the 1st exp to take data using both near & far detectors !

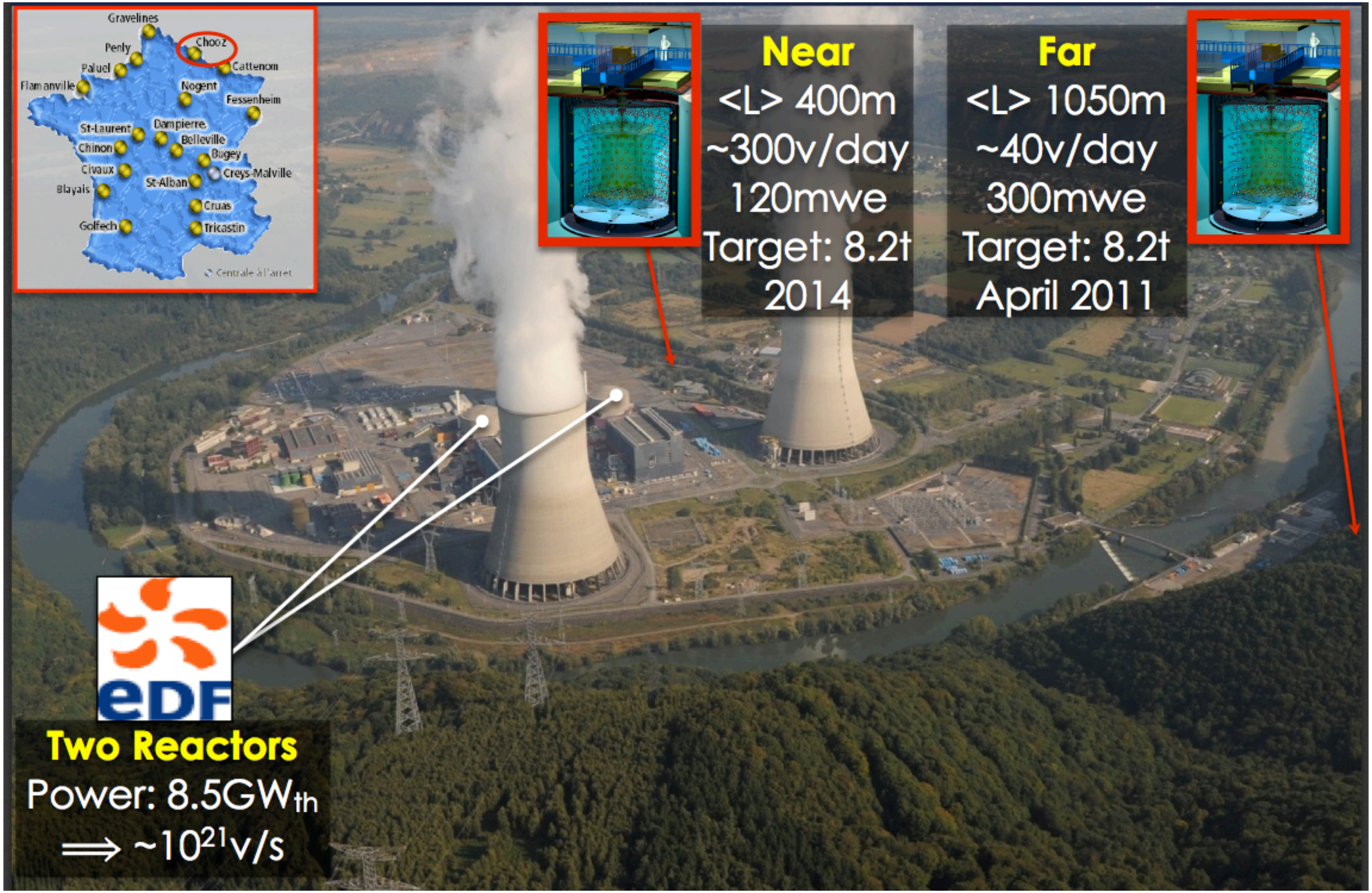
Comparisons



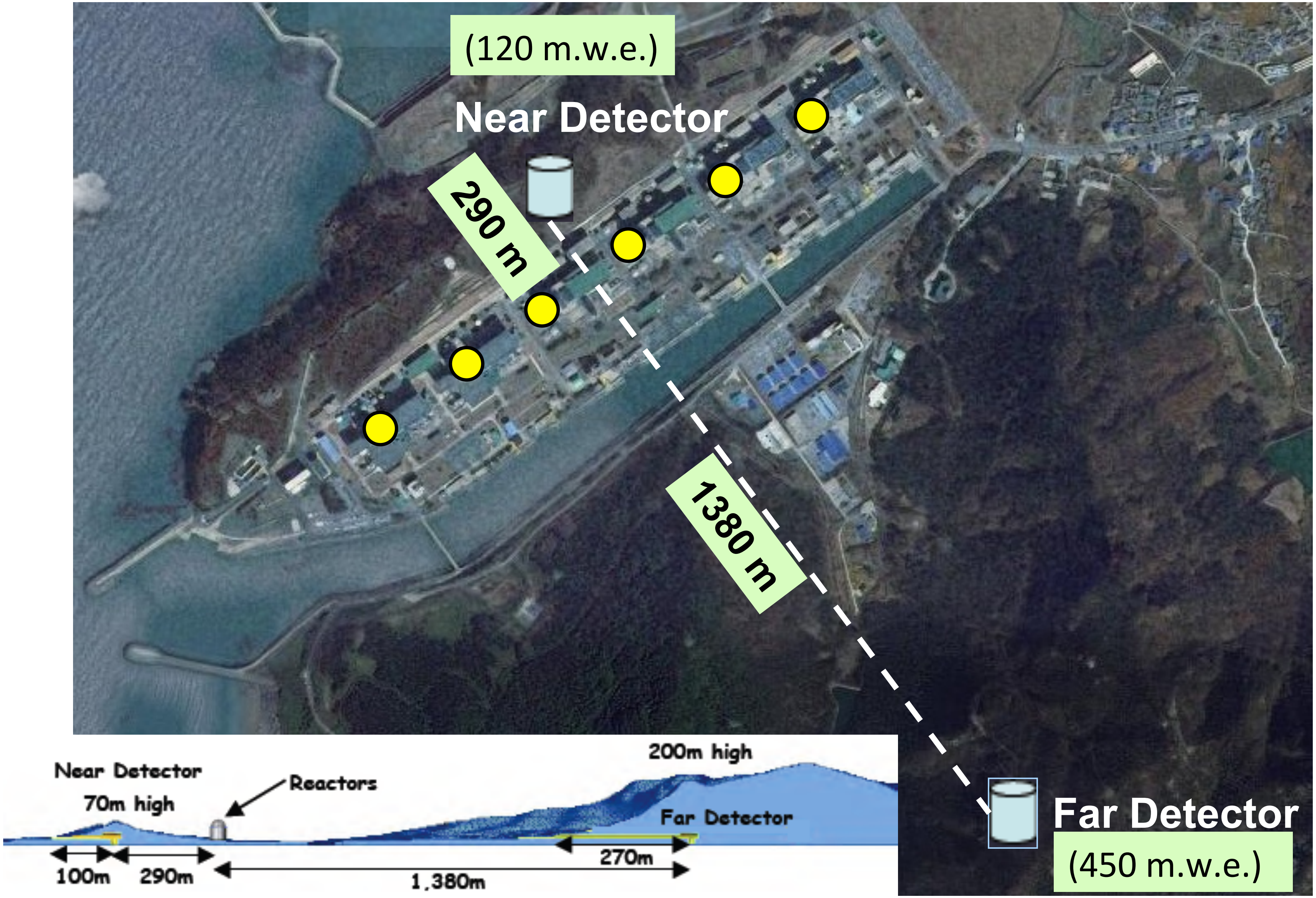




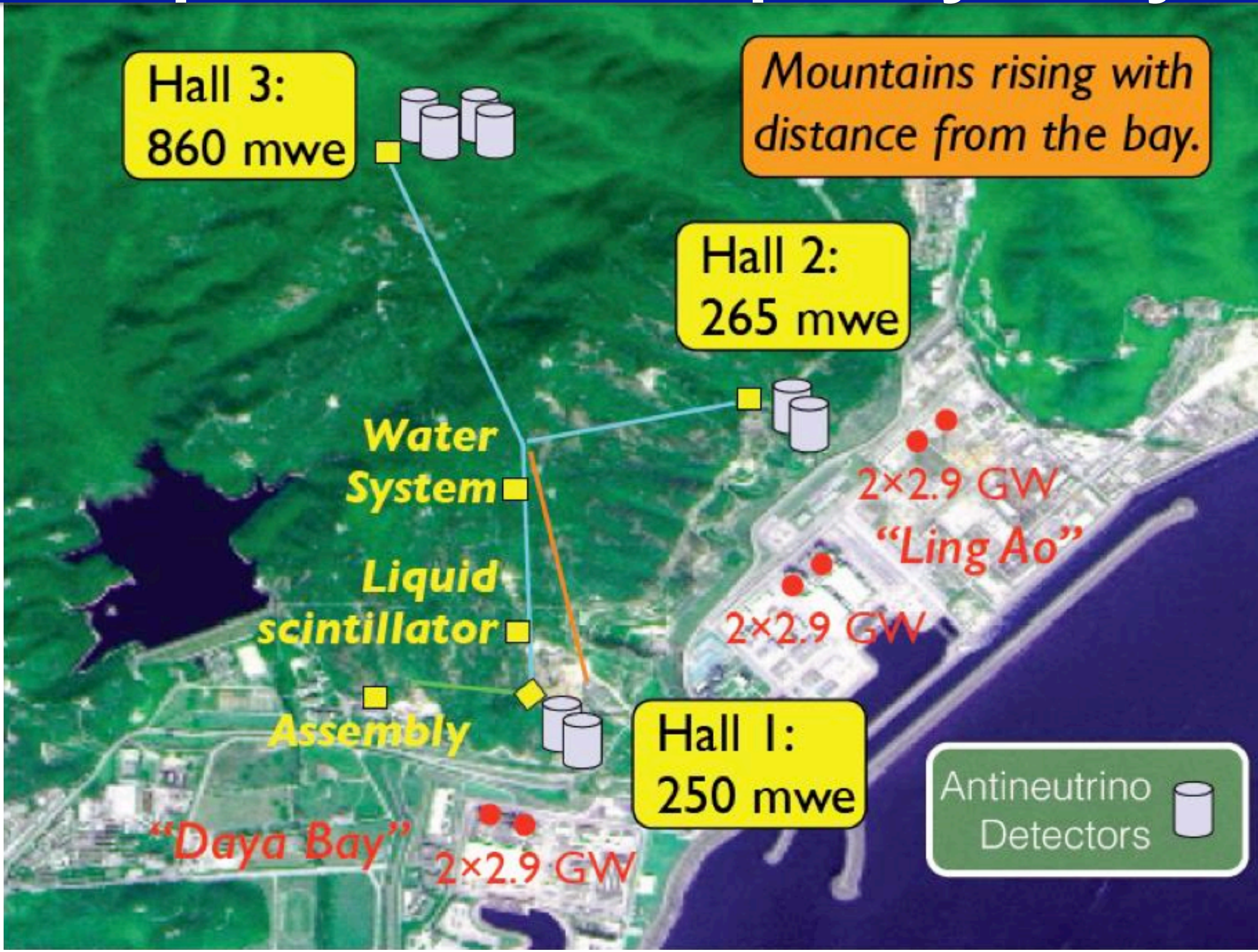
Experimental Setup: Double Chooz



Experimental Setup: RENO



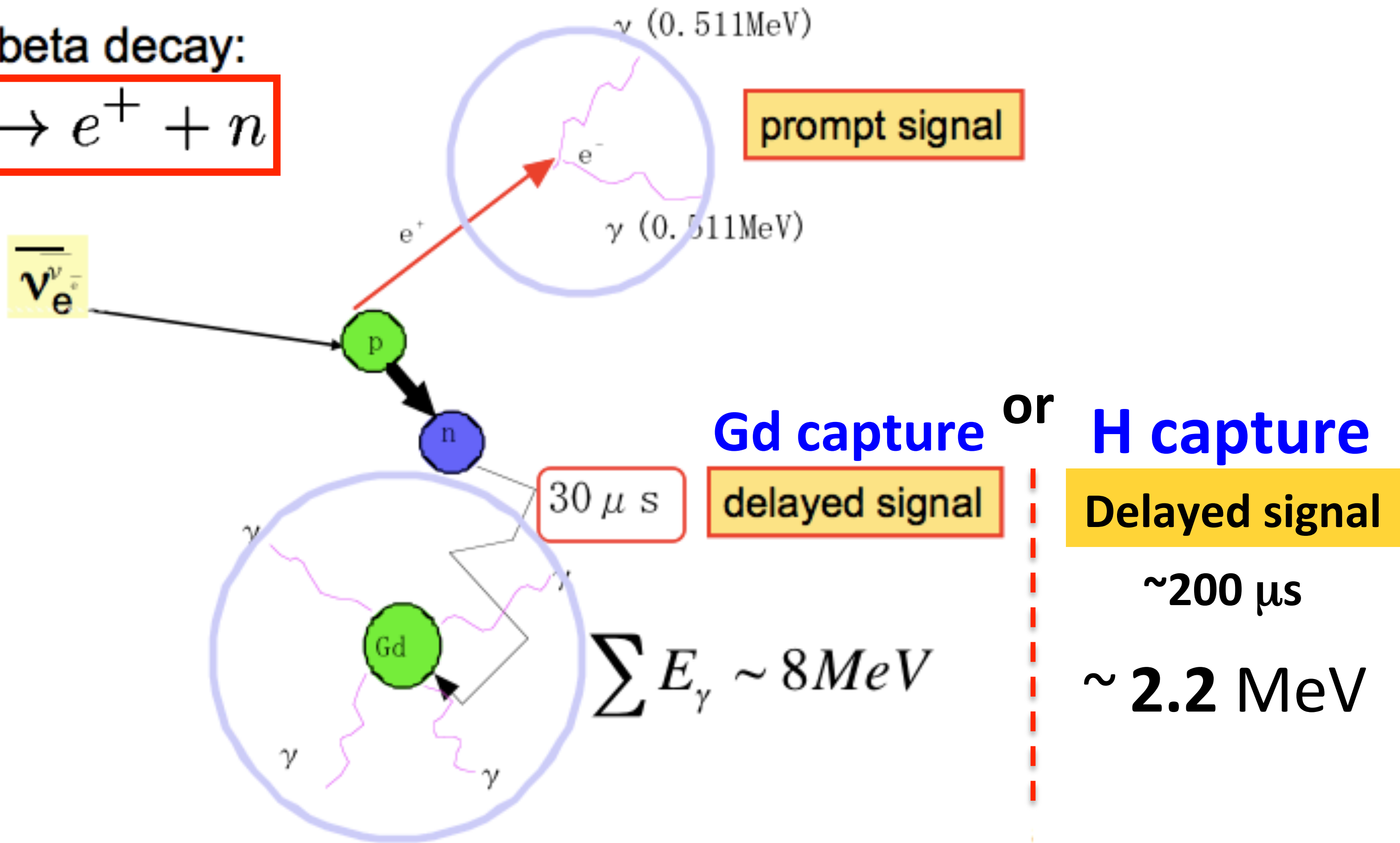
Experimental Setup: Daya Bay



Detection Principle of Reactor Neutrinos

Inverse beta decay:

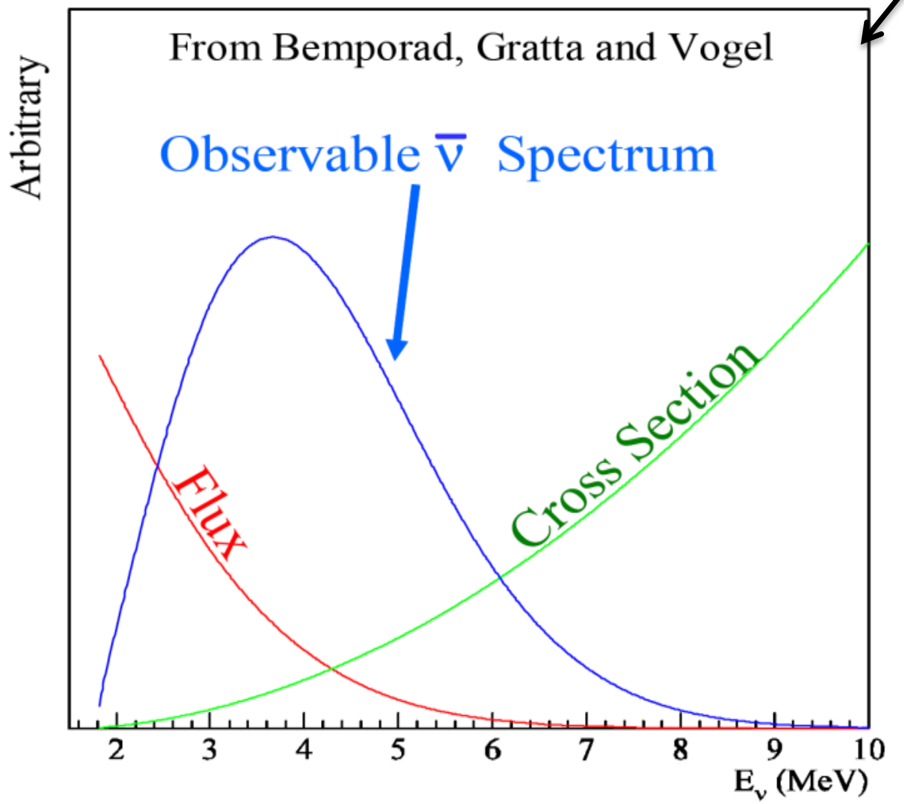
$$\bar{\nu}_e + p \rightarrow e^+ + n$$



- Prompt signal (e^+) : 1 MeV 2γ's + e^+ kinetic energy (E = 1~10 MeV)
- Delayed signal (n) : 8 MeV γ's from neutron's capture by **Gd** or **H**
  ~30 μs or ~200 μs

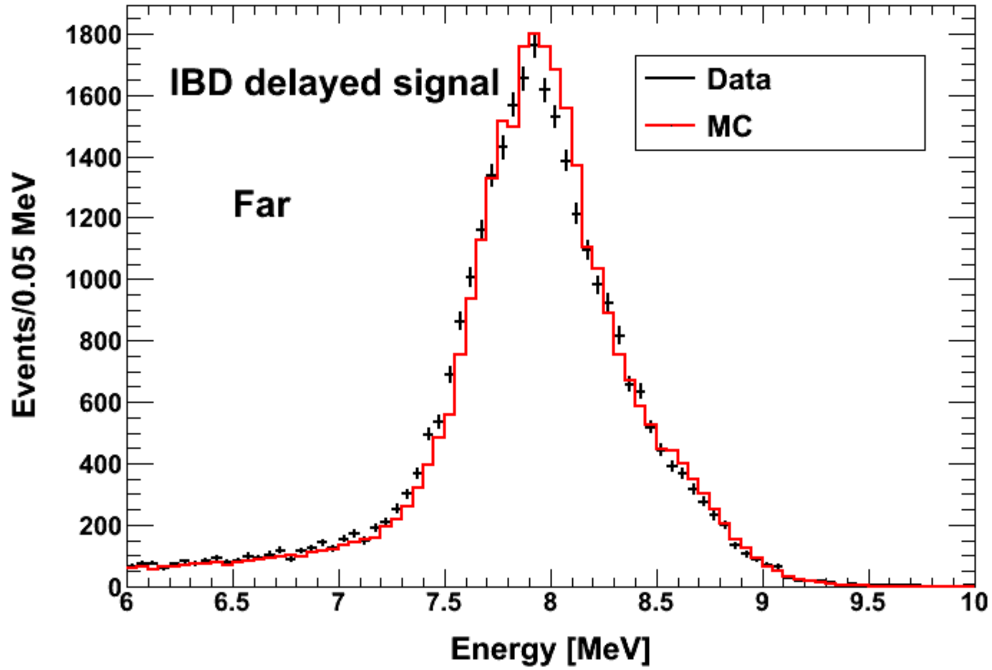
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Prompt signal



$$E_{\bar{\nu}} \cong \underbrace{T_{e^+}}_{} + \underbrace{T_n}_{10\text{-}40\ keV} + \underbrace{(M_n - M_p) + m_{e^+}}_{1.8\ MeV}$$

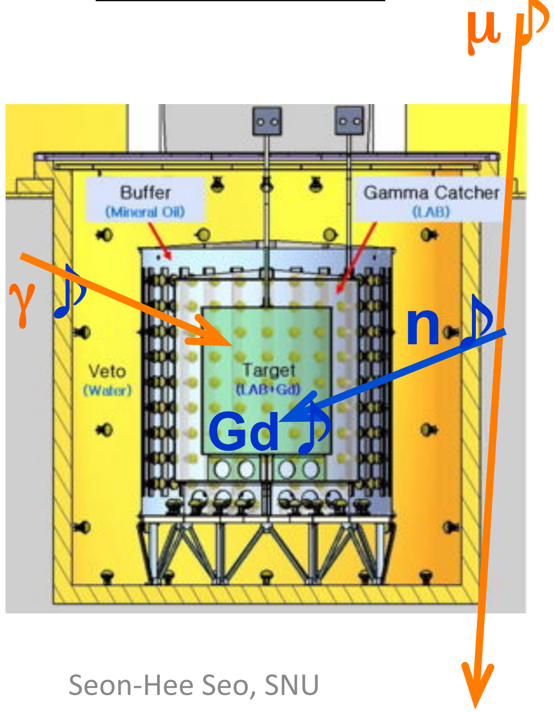
delayed signal



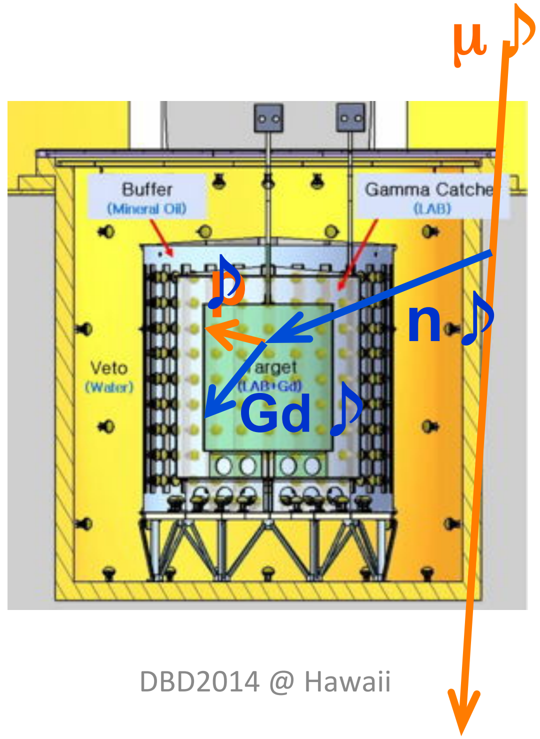
Backgrounds

- Accidental coincidence between prompt and delayed signals
- Fast neutrons produced by muons, from surrounding rocks and inside detector (n scattering : prompt, n capture : delayed)
- **$^{9}Li/^{8}He$** β-n followers produced by cosmic muon spallation

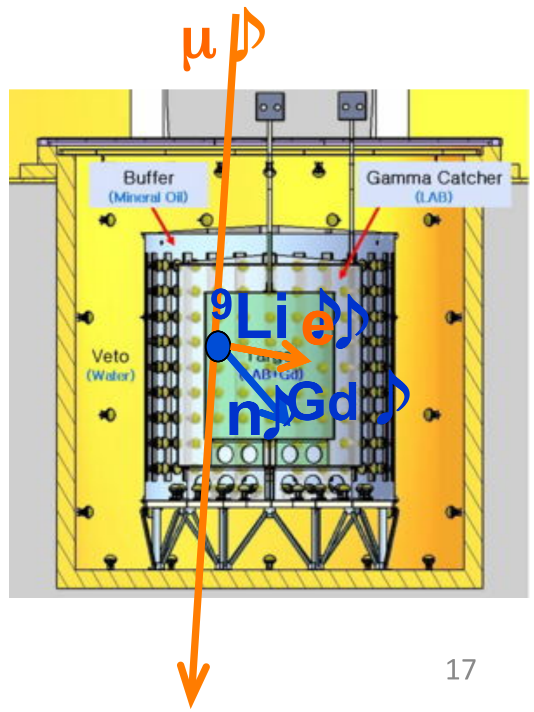
Accidentals



Fast neutrons



$^{9}Li/^{8}He$ β-n followers

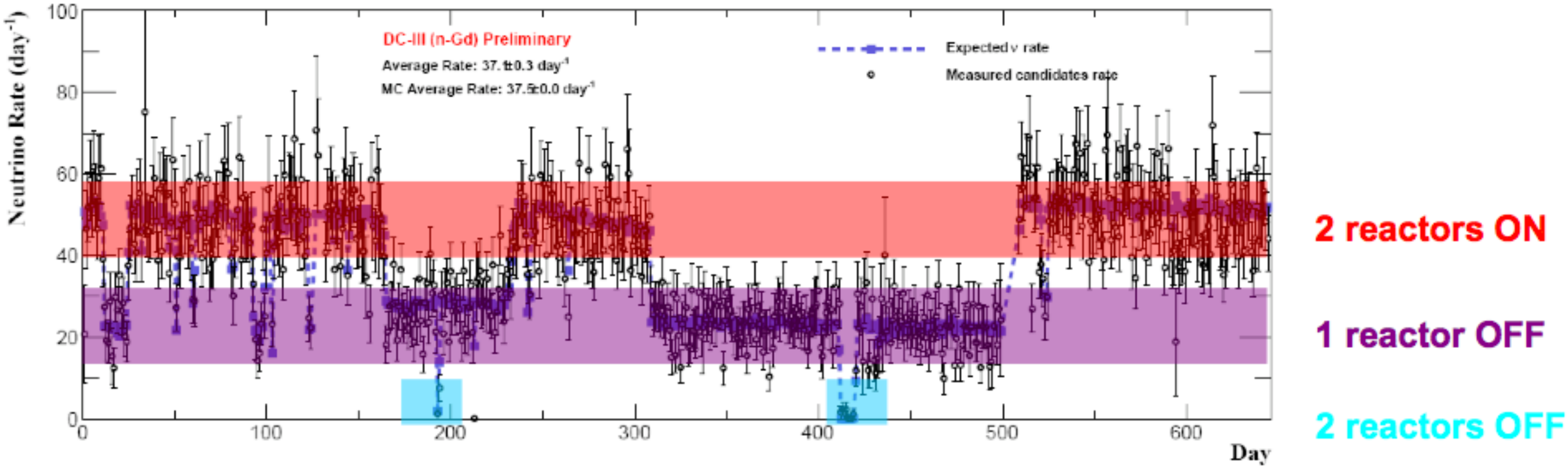


Background Levels

	Double Chooz Far	RENO Near, Far	Daya Bay Near, Far
Total BKG/ Signal	4.4 %	3.3 %, 8.9 %	2 %, 3 %
Accidental/ Signal	0.2 %	0.8 %, 1.4 %	1.4 %, 2.3 %
Fast neutron/ Signal	1.6 %	0.4 %, 0.8 %	0.1 %, 0.1 %
$^{9}Li/^{8}He$/ Signal	2.6 %	2.0 %, 3.5 %	0.4 %, 0.4 %
^{252}Cf source/ Signal	N/A	0.05 %, 3.2 %	N/A
AmC source/ Signal	N/A	N/A	0.03 %, 0.2 %

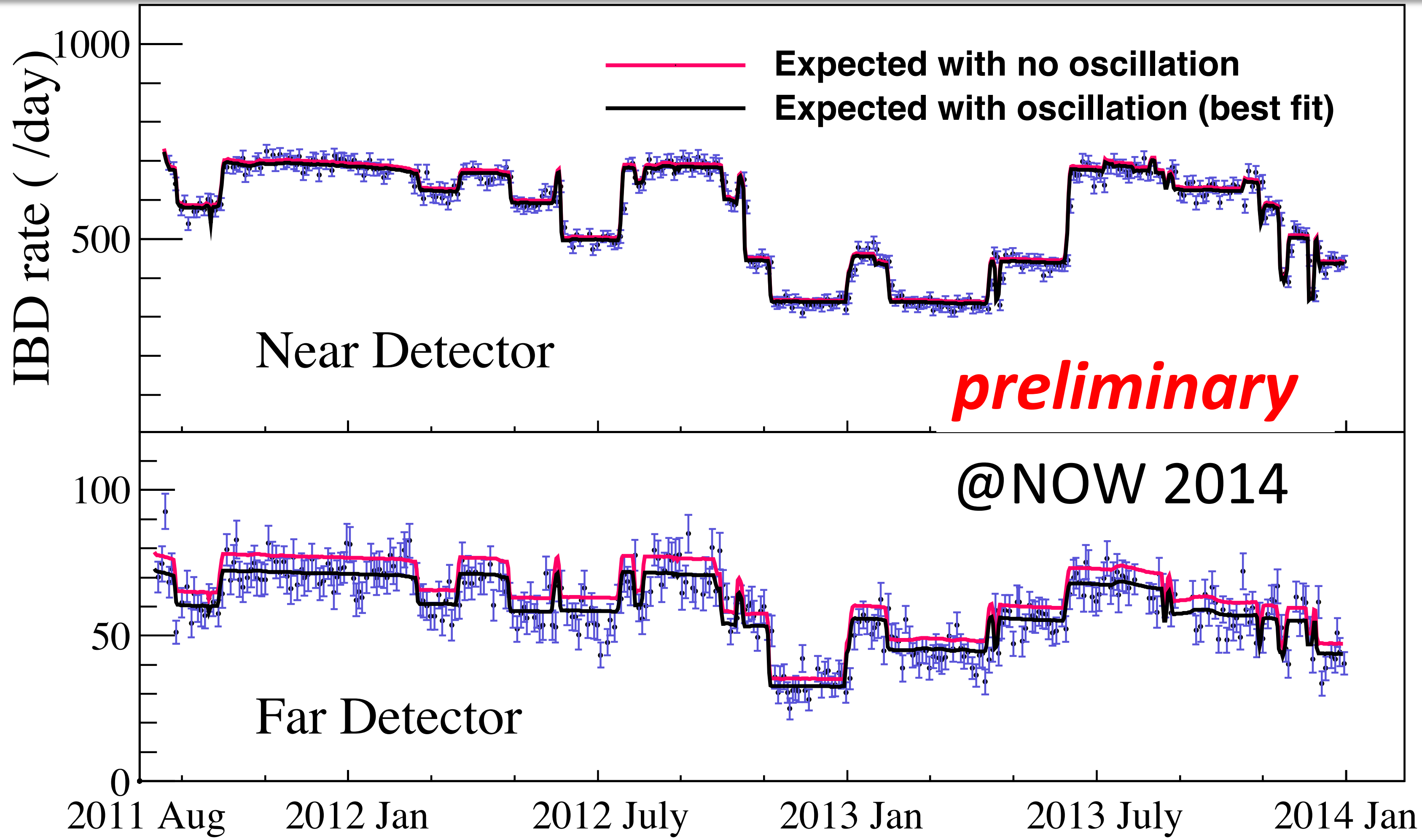
IBD Rate Vs Time: Double Chooz

@NuFact 2014



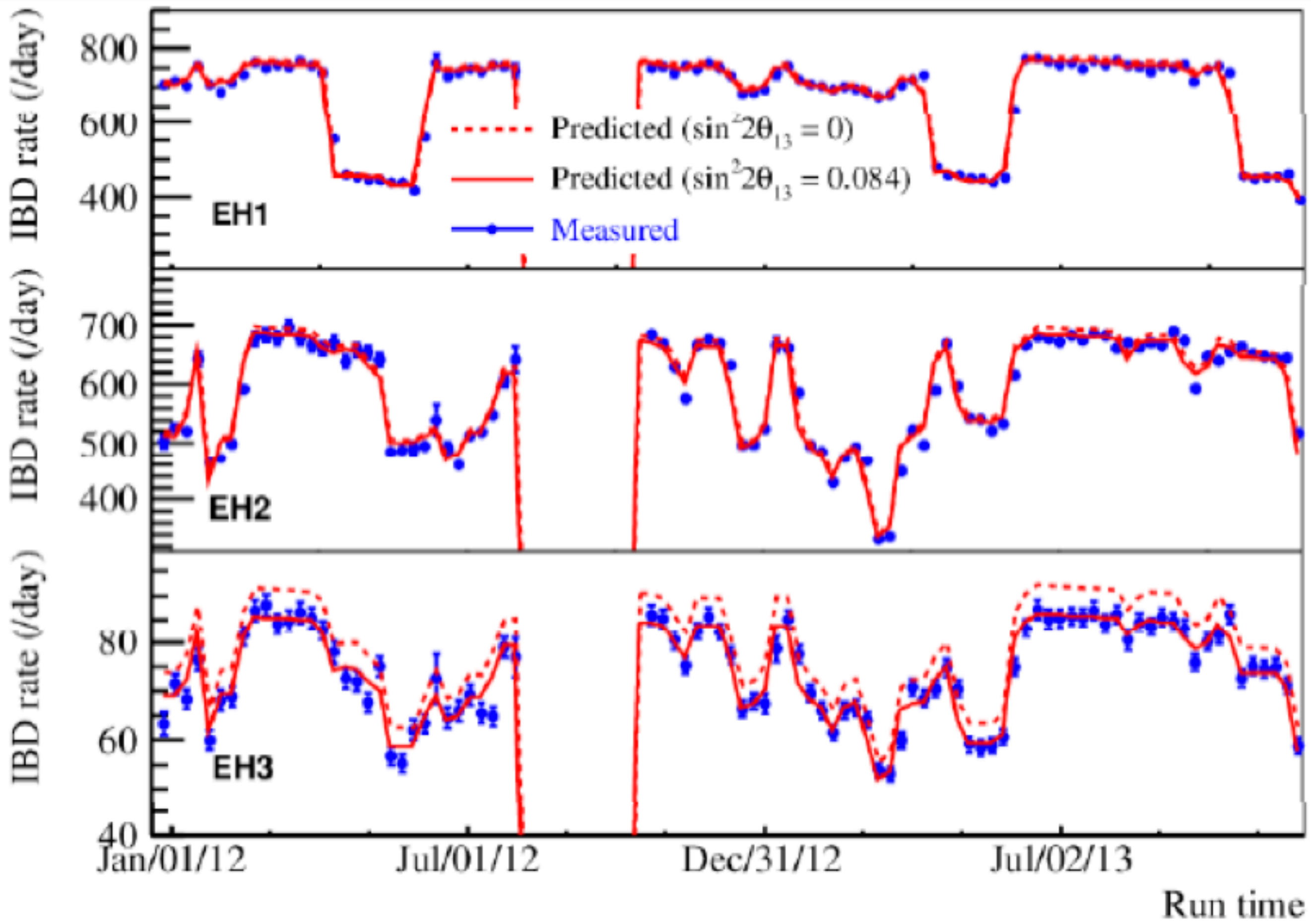
Waiting for Near detector data soon…

IBD Rate Vs Time: RENO



- Observed points have very good agreement with prediction.
- It's the accurate ν flux (or thermal power) measurement.

IBD Rate Vs Time: Daya Bay



@NuFact 2014

- IBD rates strongly correlate with reactor flux
- Clear signature of oscillation

13

θ_{13}: Double Chooz

- Measure θ_{13} using the rate and spectrum shape.

New features:

- Finer binning.
- Range extended.
- Background shape data-driven.
- New energy model.
- Reactor OFF data included.

Δm^2 from MINOS: $(2.44\ ^{+0.09}_{-0.10}) \times 10^{-3}$ eV^2

$\sin^2(2\theta_{13}) = 0.090\ ^{+0.032}_{-0.029}$

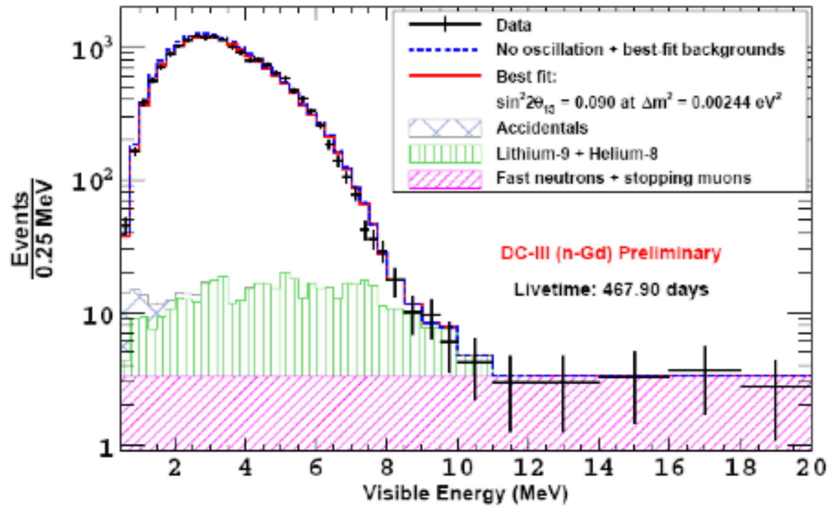
χ^2/ndf = 52.2/40

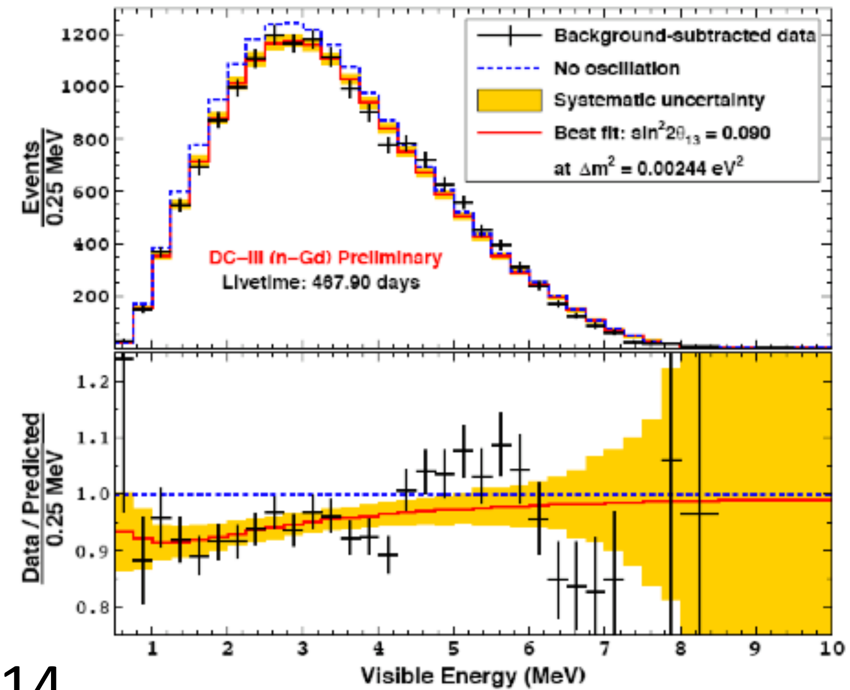
Bkg rate after fit = 1.38 ± 0.14 day^{-1}

Previous: $\sin^2(2\theta_{13}) = 0.109 \pm 0.039$

→ Precision improved 5.3%

Rate-only fit: **$\sin^2(2\theta_{13}) = 0.090\ ^{+0.036}_{-0.037}$**

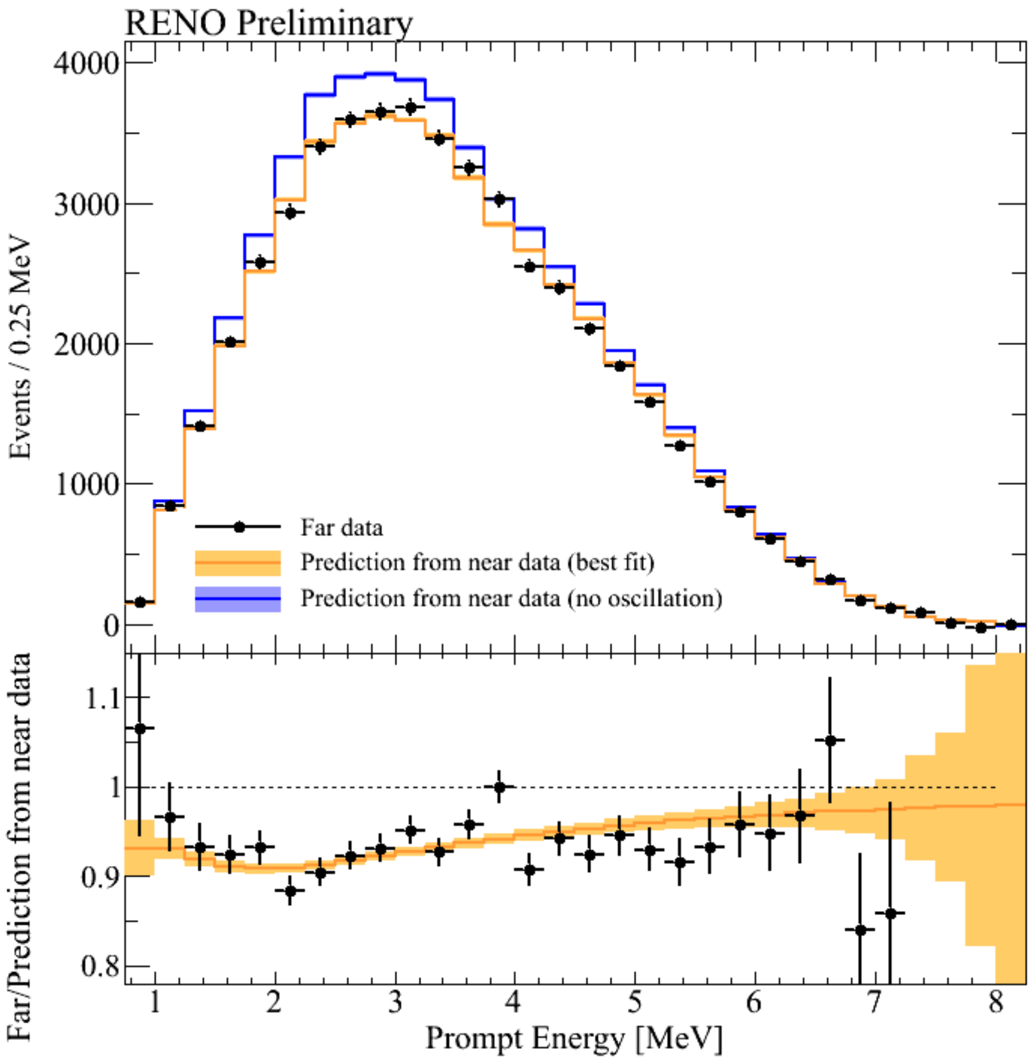




@Neutrino 2014

θ_{13}: RENO

$\sin^2(2\theta_{13}) = 0.101 \pm 0.008\ (\text{stat.}) \pm 0.010\ (\text{sys.})$



Preliminary Rate-only Result

(~800 live days)

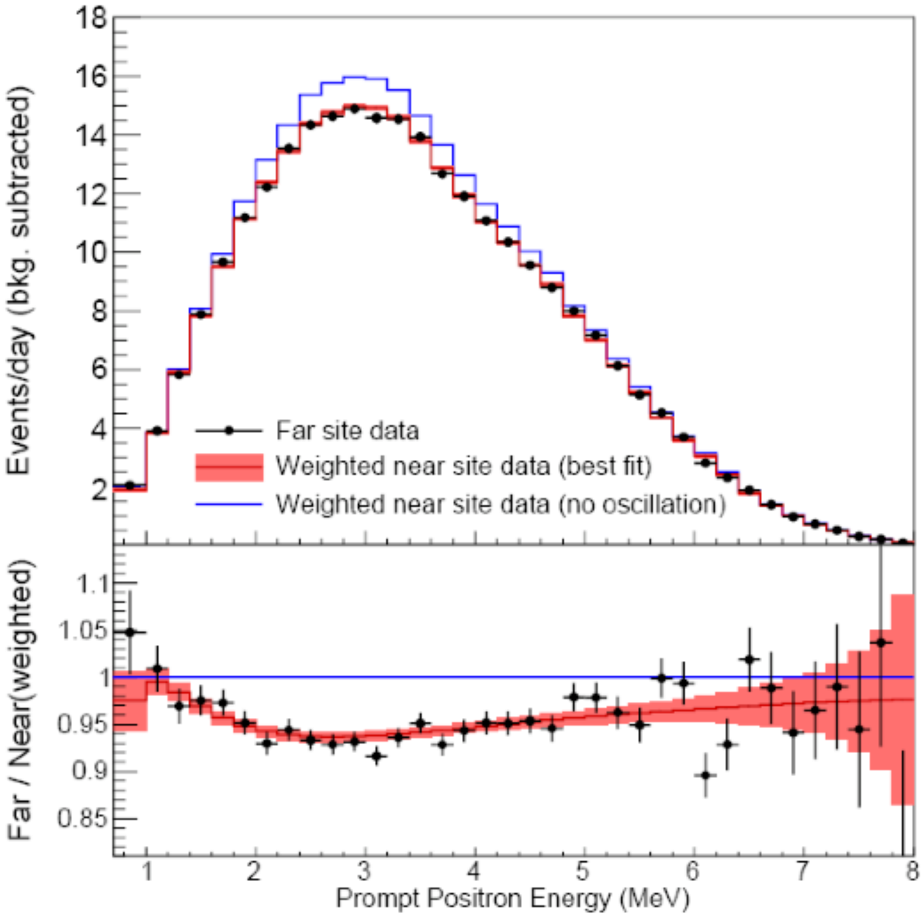
Shape analysis is in progress…

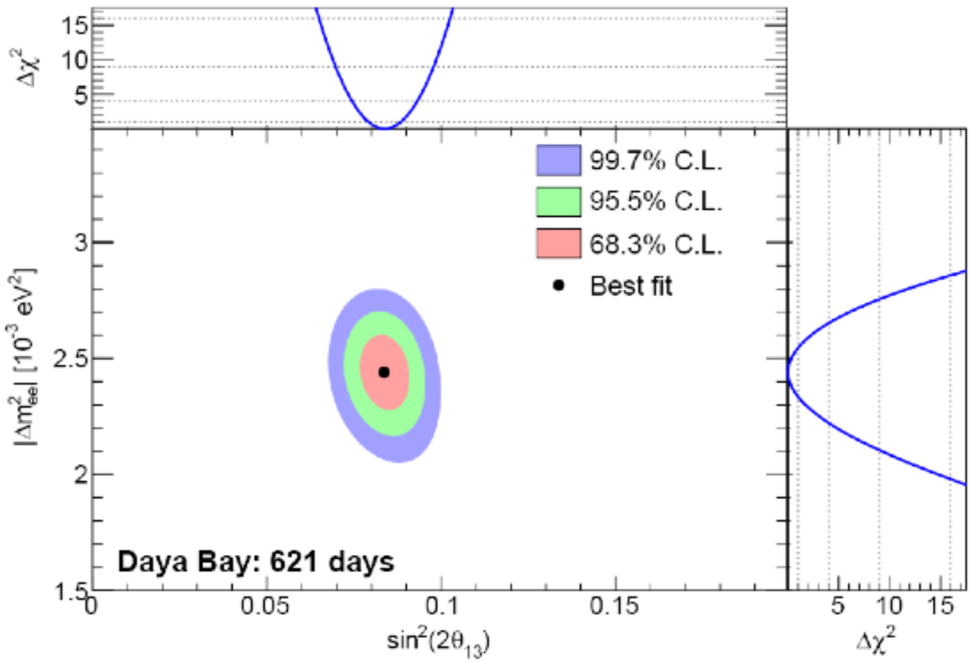
Stay tuned !

The final result will be released soon.

@NOW 2014

θ_{13}: Daya Bay





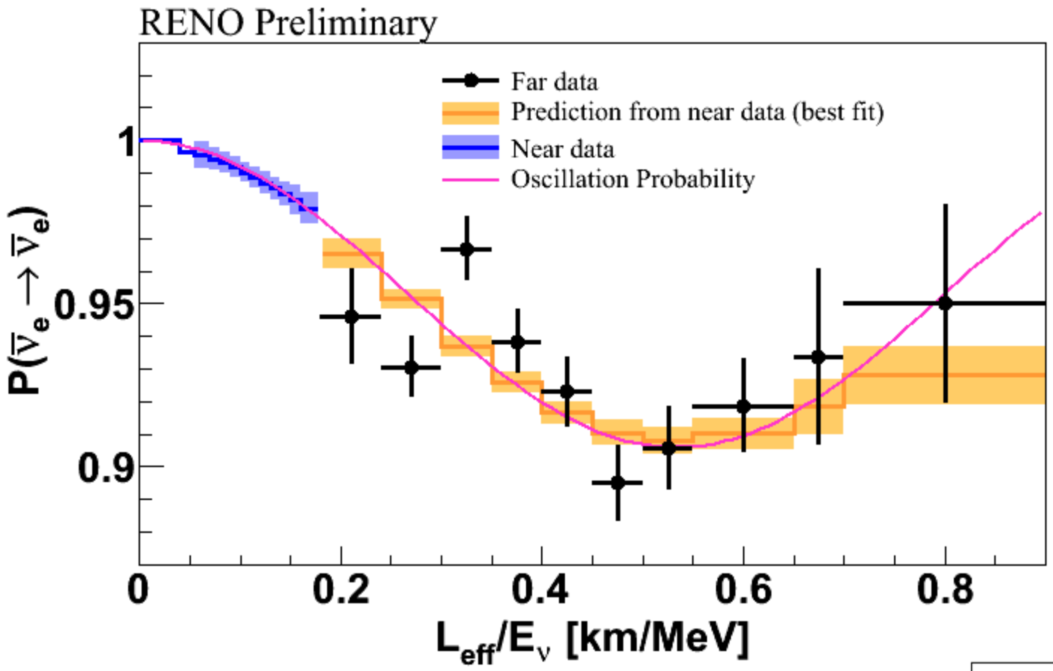
$$\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$$

$$|\Delta m^2_{ee}| = 2.44^{+0.10}_{-0.11} \times 10^{-3}\mathrm{eV}^2$$

$$\chi^2/NDF = 134.7/146$$

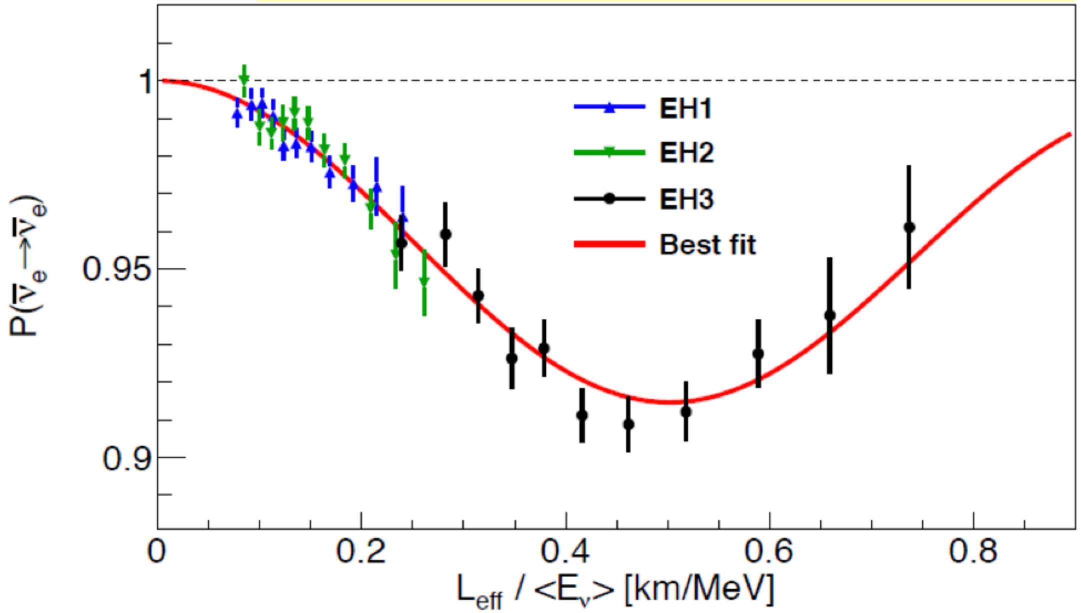
@NuFact 2014

Reactor Neutrino Disappearance on L/E



RENO @NOW 2014

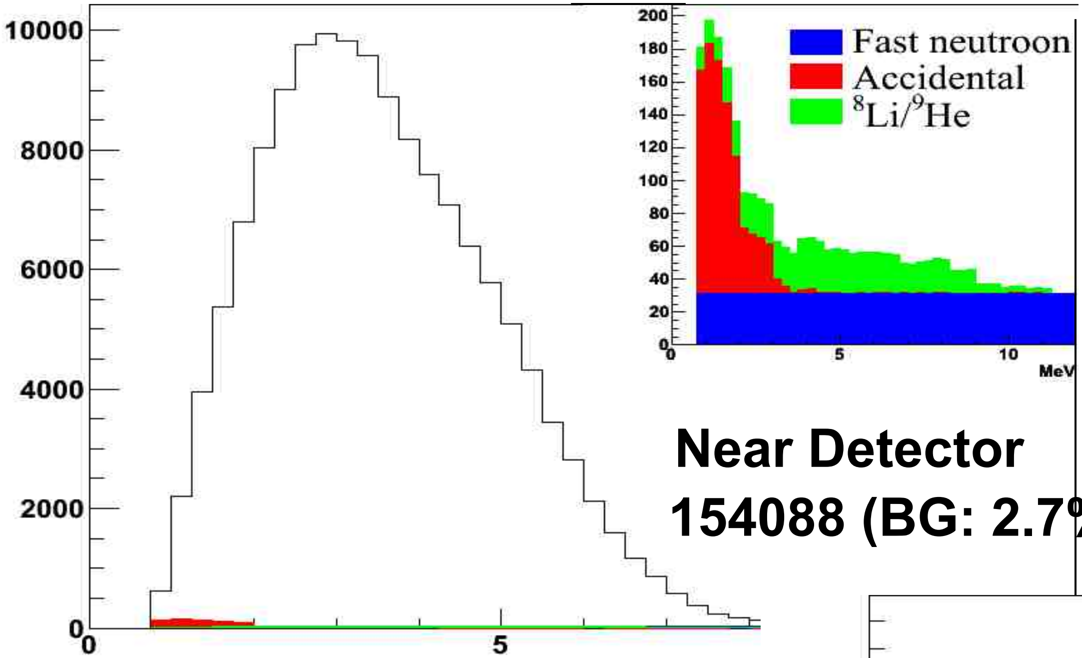
Daya Bay @Neutrino 2014



Quick Summary of the 5 MeV Excess

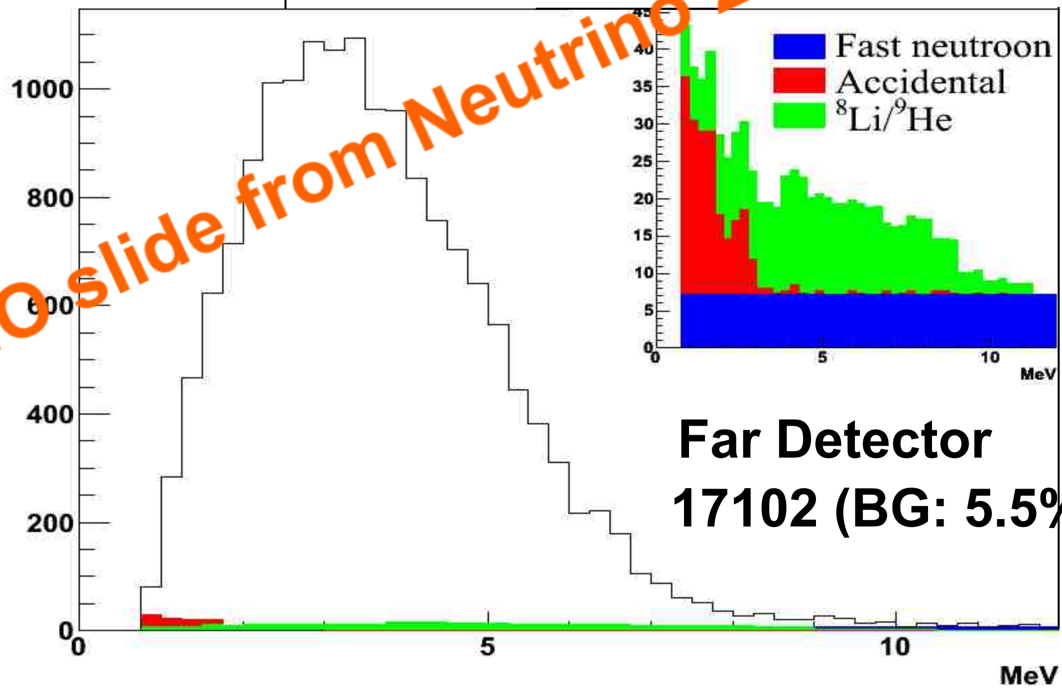
- The 5 MeV excess was mentioned by RENO in Neutrino 2012 (Kyoto) for the first time.
- In Neutrino 2014 (Boston) RENO announced the clear observation of the 5 MeV excess and claimed it as due to reactor neutrinos.
- Double Chooz also showed the 5 MeV excess in the Neutrino 2014 but the significance was weak.
- Daya Bay showed the 5 MeV excess in the ICHEP 2014 but could not show its relation with reactor neutrinos.

Observed Spectra of IBD Prompt Signal



Near Detector
154088 (BG: 2.7%)

- The expected IBD prompt spectra from the RENO MC do not reproduce the shape in the energy region of 4~6 MeV.....

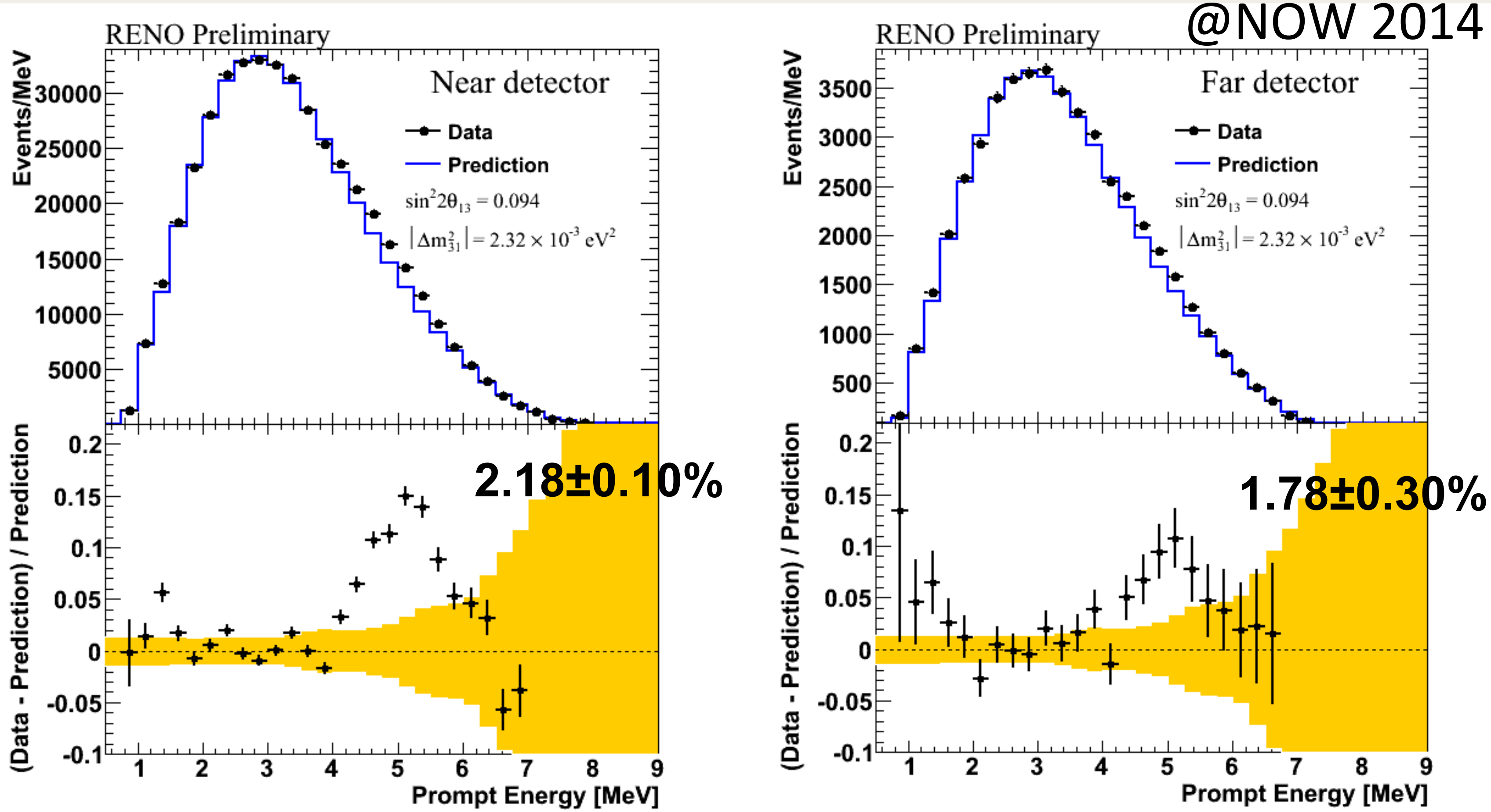


Far Detector
17102 (BG: 5.5%)

- Need more detailed energy calibration between 3 and 8 MeV using new radioactive sources.
- Any new components of background sources?
- Is the prediction of reactor neutrino spectra correct??

Observation of a New Reactor Neutrino Component at 5 MeV in RENO

@NOW 2014

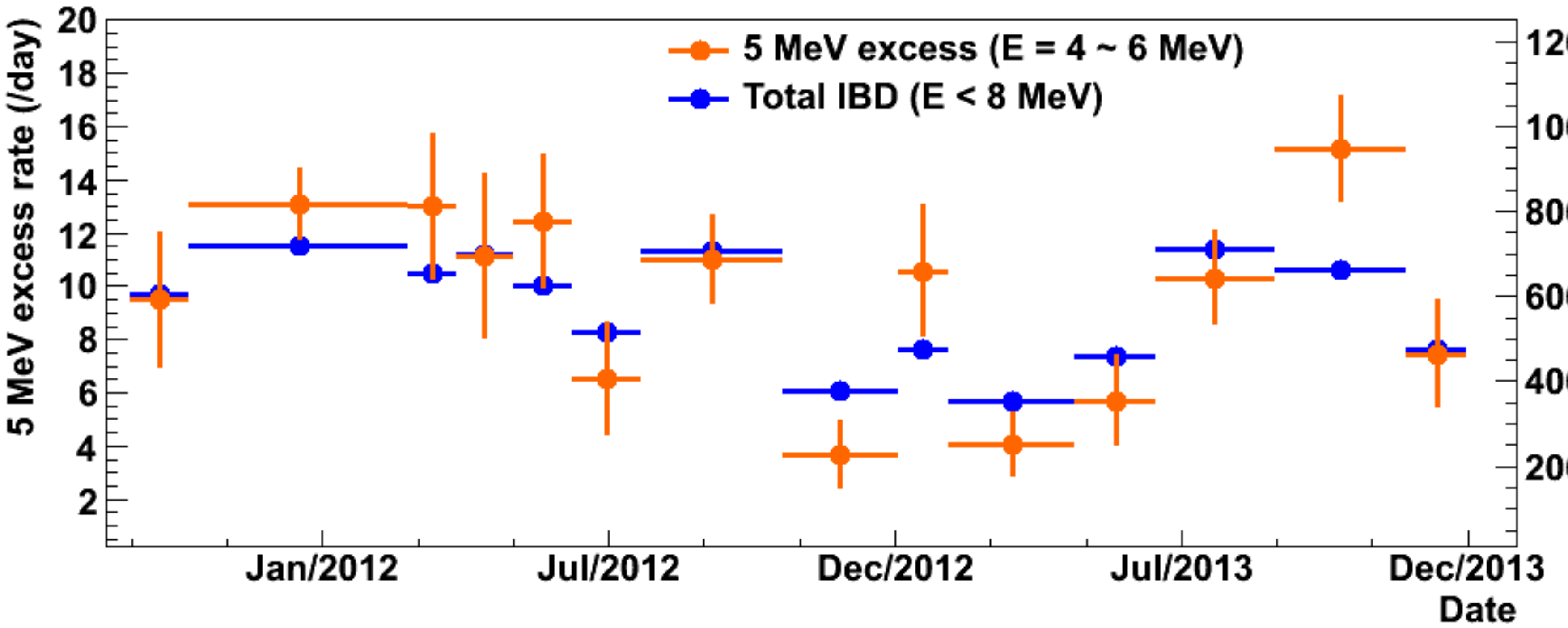


<u>Fraction of 5 MeV excess (%) to expected flux</u> **[2011 Huber+Mueller]**

- Near : 2.18 ± 0.40 (experimental) ± 0.49 (expected shape error)
- Far : 1.78 ± 0.71 (experimental) ± 0.49 (expected shape error)

Correlation of 5 MeV Excess with Reactor Power

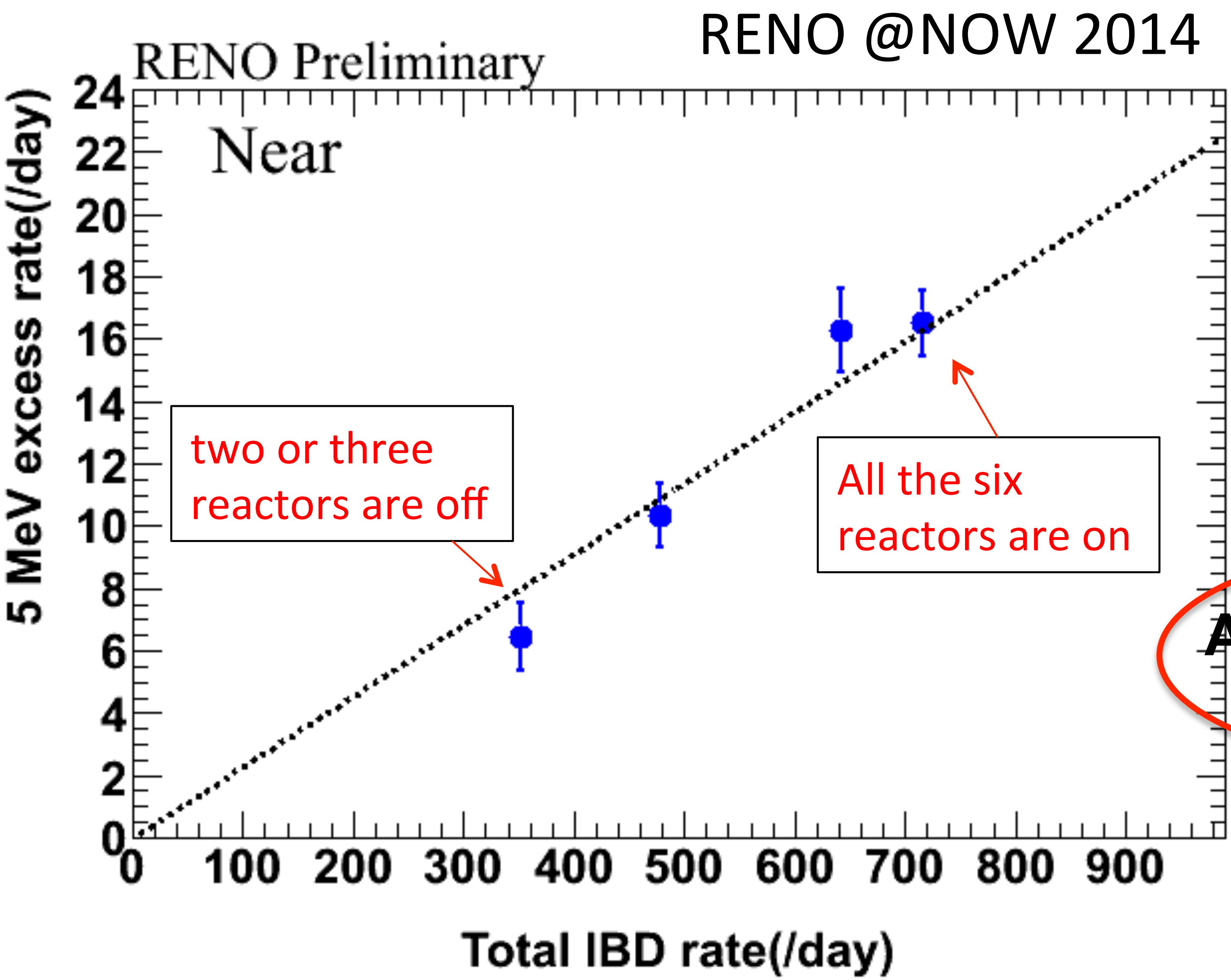
RENO @NOW 2014



5 MeV excess has a clear correlation with reactor thermal power !

A new reactor neutrino component !!

Correlation of 5 MeV Excess with Reactor Power



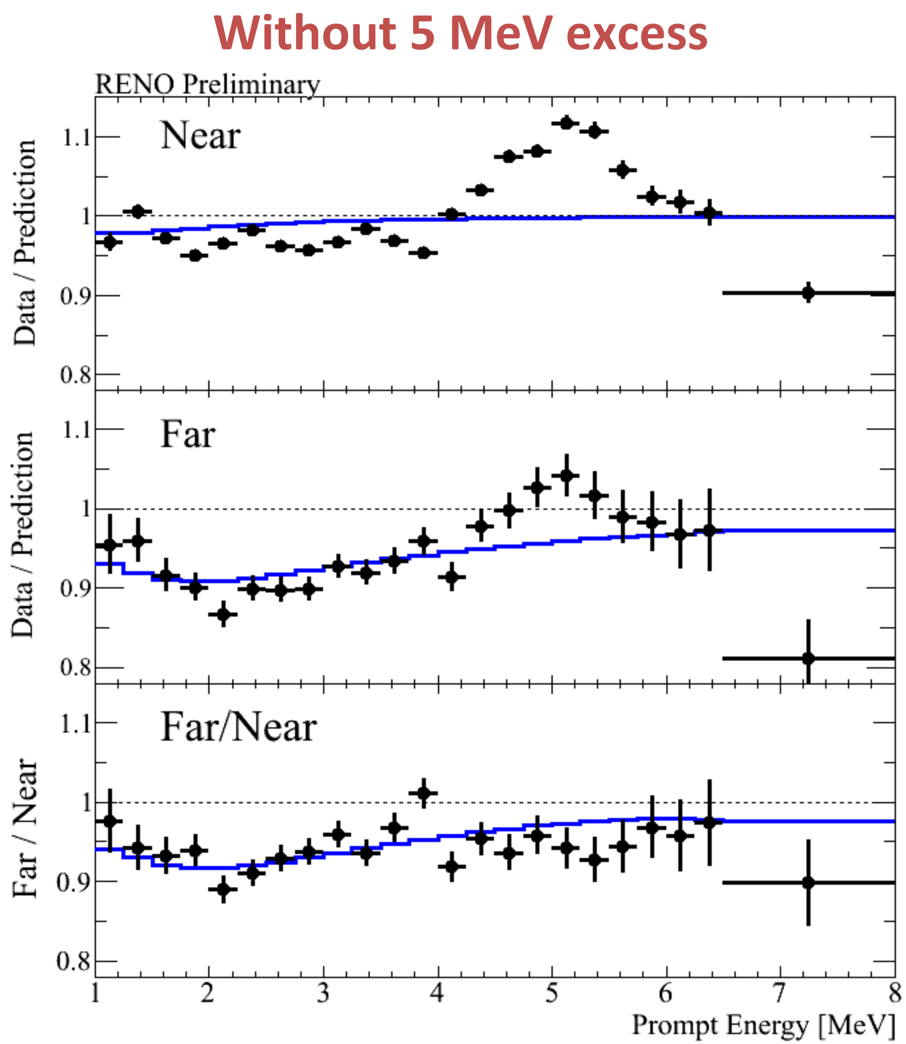
5 MeV excess has a clear correlation with reactor thermal power !

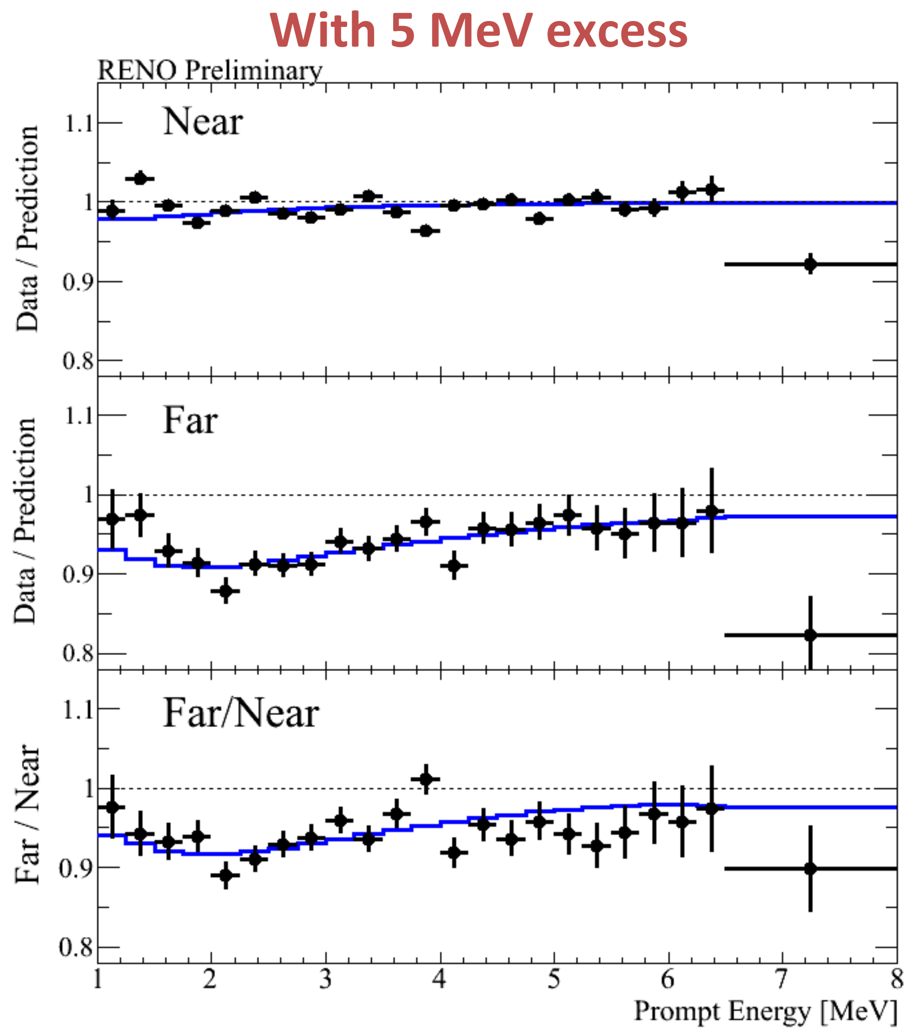
A new reactor neutrino component !!

RENO: Shape Analysis for Δm_{ee}^2

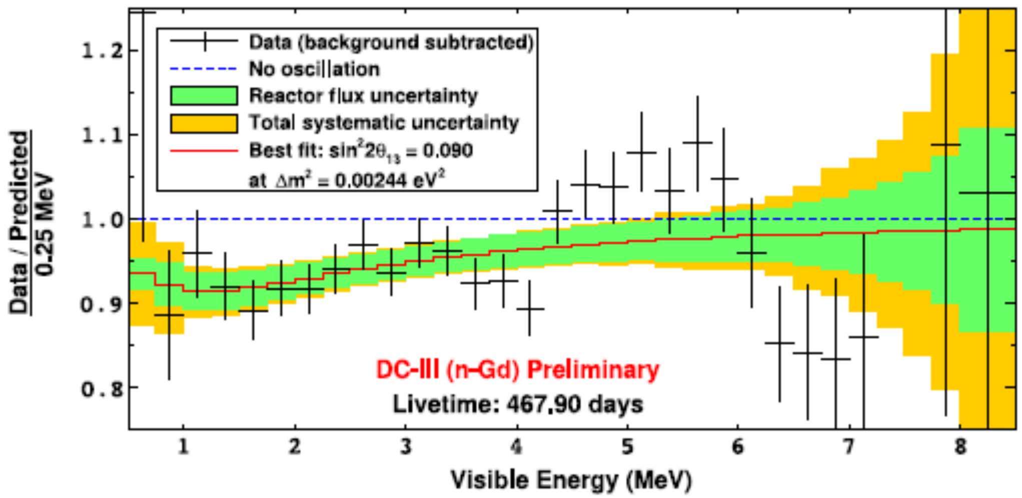
In progress…. Stay tuned…

@NOW 2014



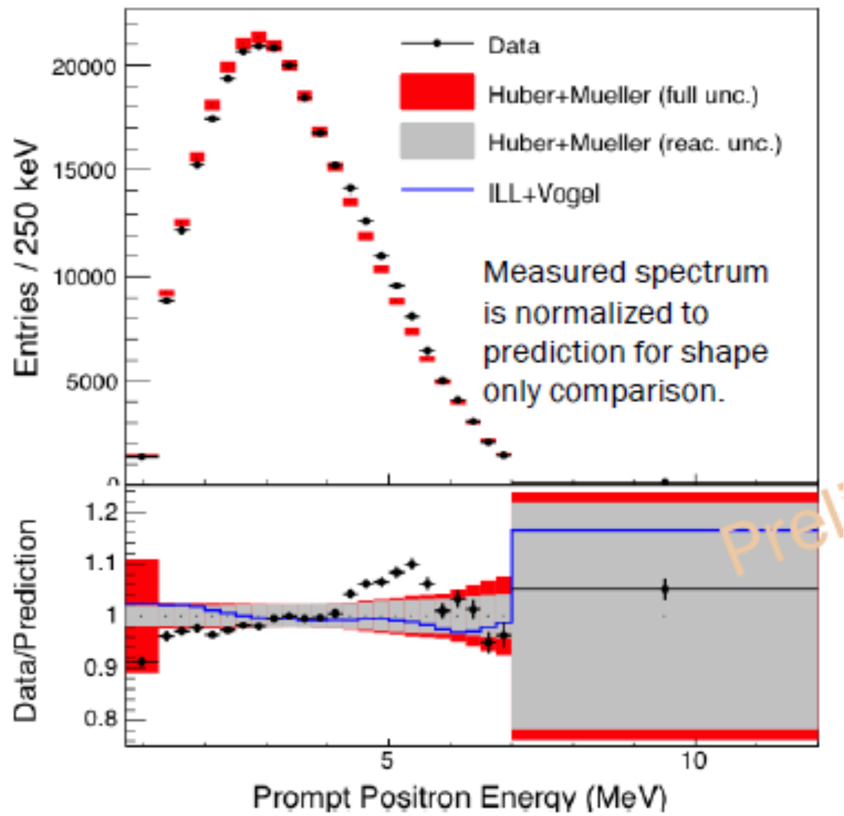


The 5 MeV Excess Seen at Double-Chooz and Daya Bay



Double Chooz @Neutrino 2014

Daya Bay @ICHEP 2014

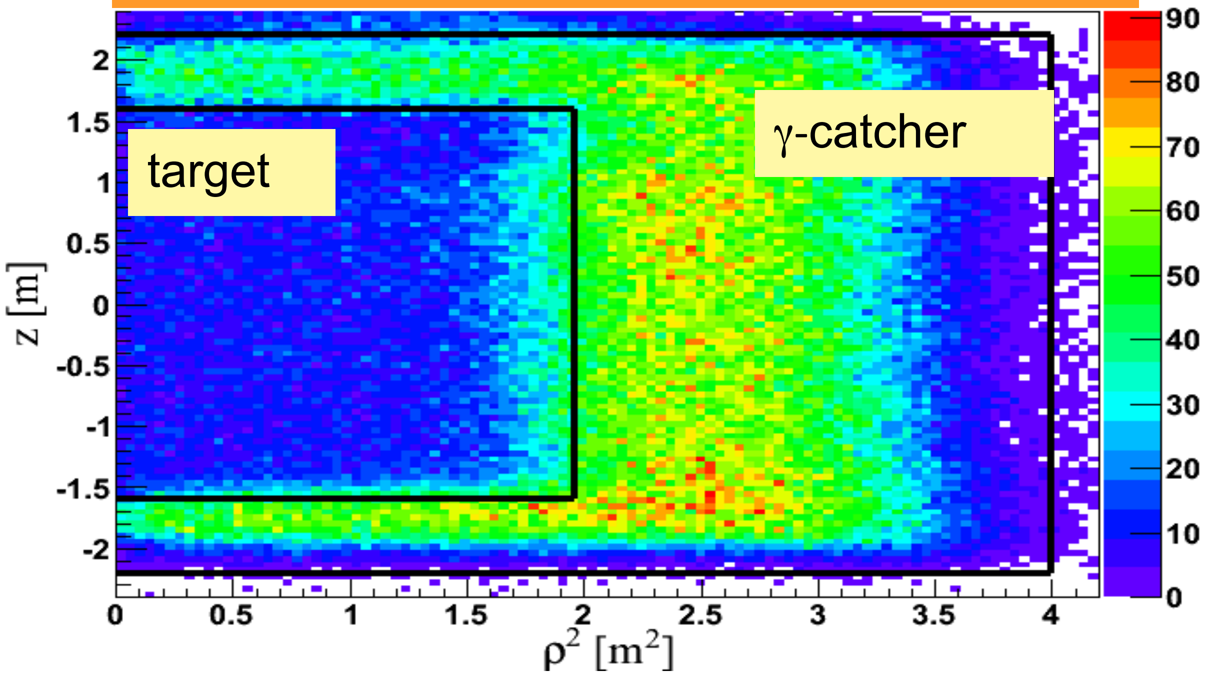


n-H Analysis

Motivation:

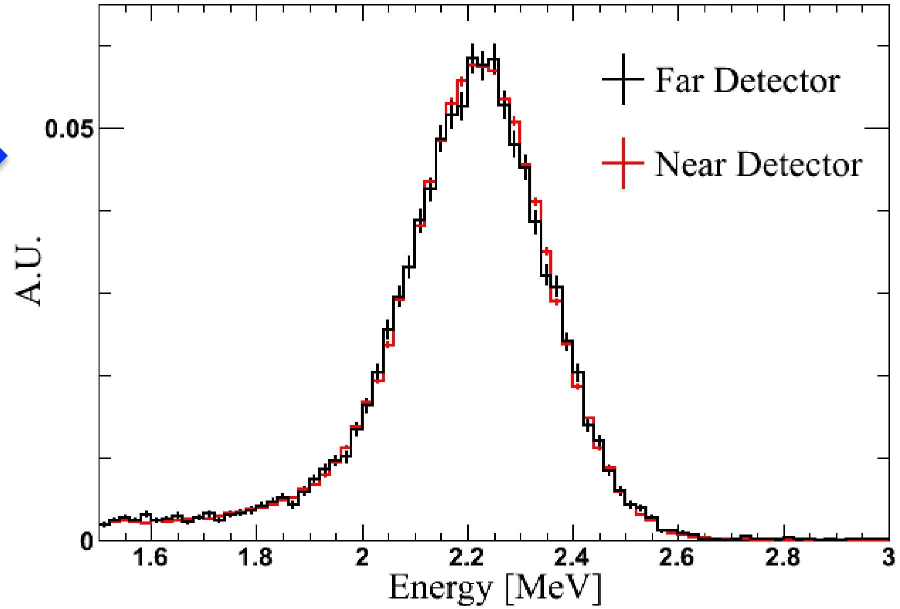
1. Independent measurement of θ_{13} value.
2. Consistency and systematic check on reactor neutrinos.

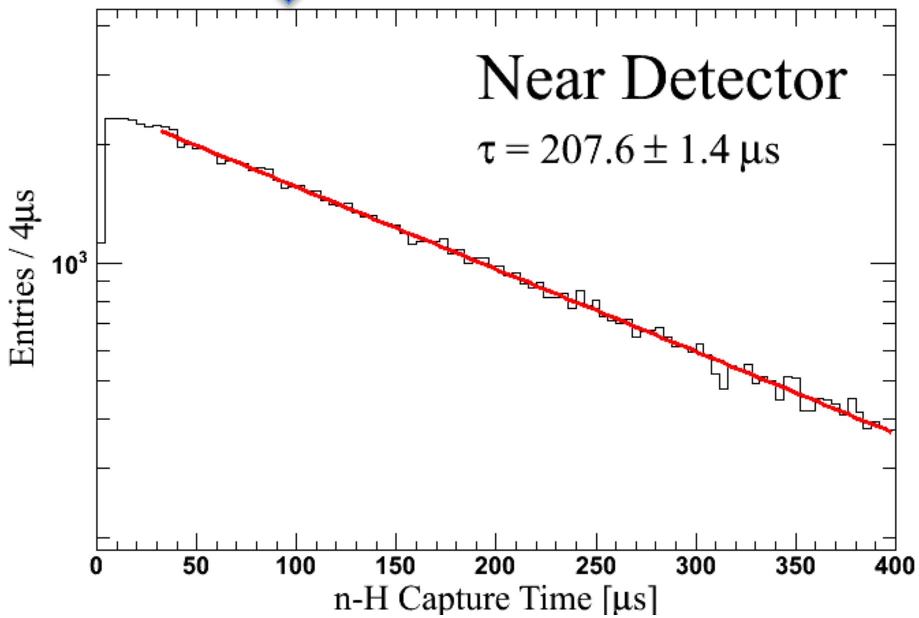
n-H IBD Event Vertex Distribution

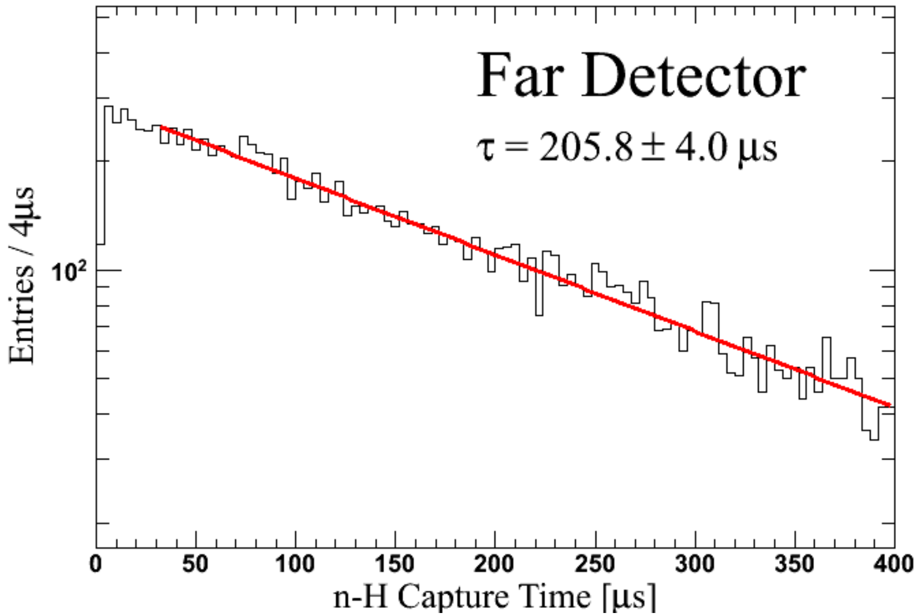


Features of n-H Events

- Delayed signal peak:
  2.2 MeV
- Mean coincidence time:
  ~ 200 μs



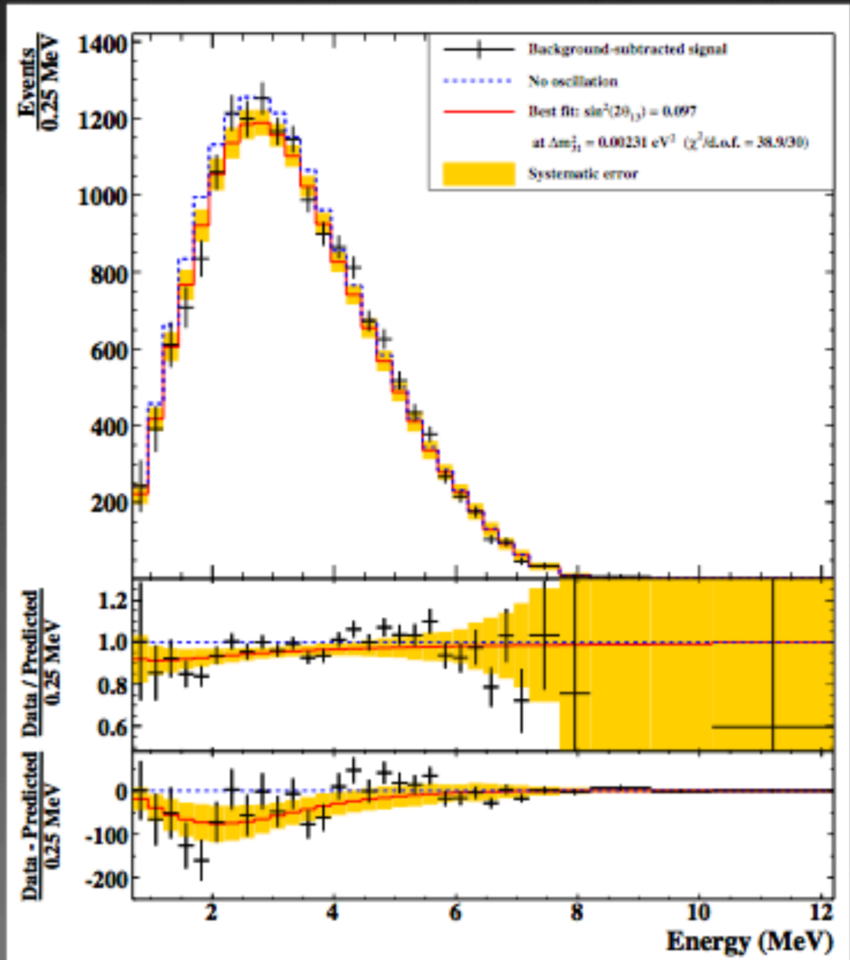




n-H Analysis: Double Chooz

H analysis, December 2012

Phys. Lett. B 723 (2013)



$$\sin^2 2\theta_{13} = 0.097 \pm 0.048$$

n-H Analysis: RENO

Very preliminary
Rate-only result

(~400 days)

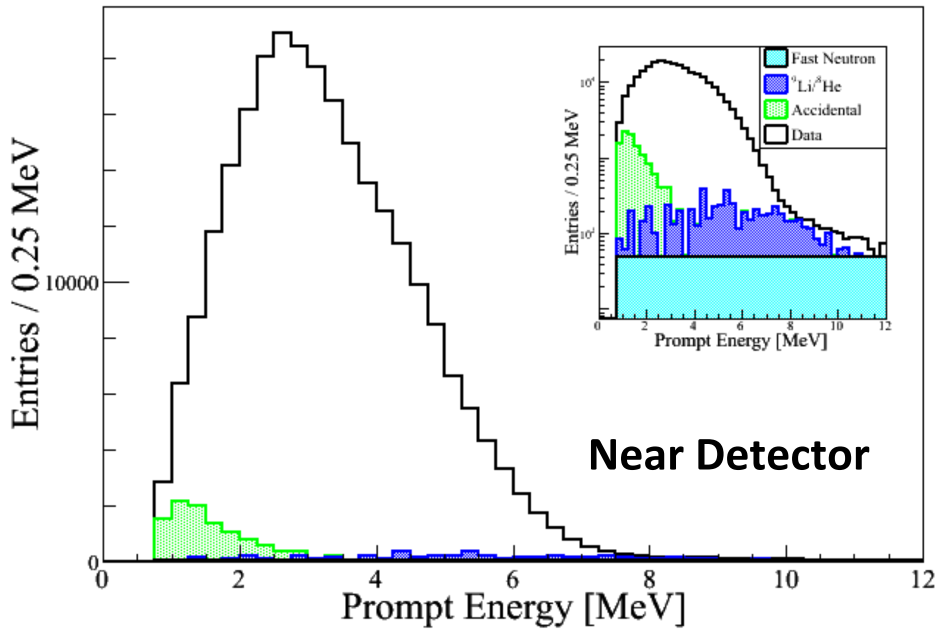
@NOW 2014

$$\sin^2 2\theta_{13} = 0.103 \pm 0.014(\text{stat.}) \pm 0.014(\text{syst.})$$

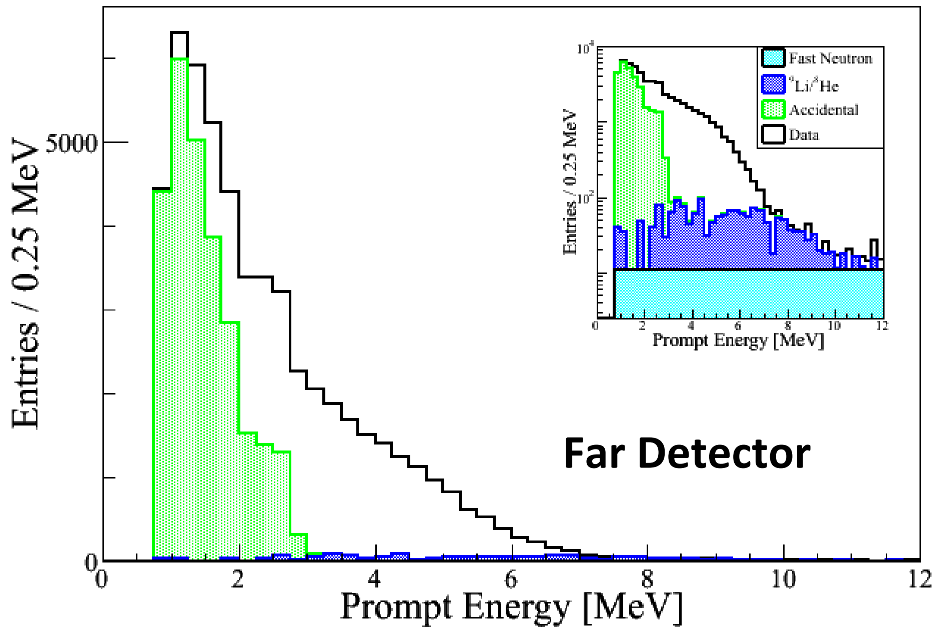
(Neutrino 2014) $\sin^2 2\theta_{13} = 0.095 \pm 0.015(\text{stat.}) \pm 0.025(\text{syst.})$

← *Removed a soft neutron background and reduced the uncertainty of the accidental background*

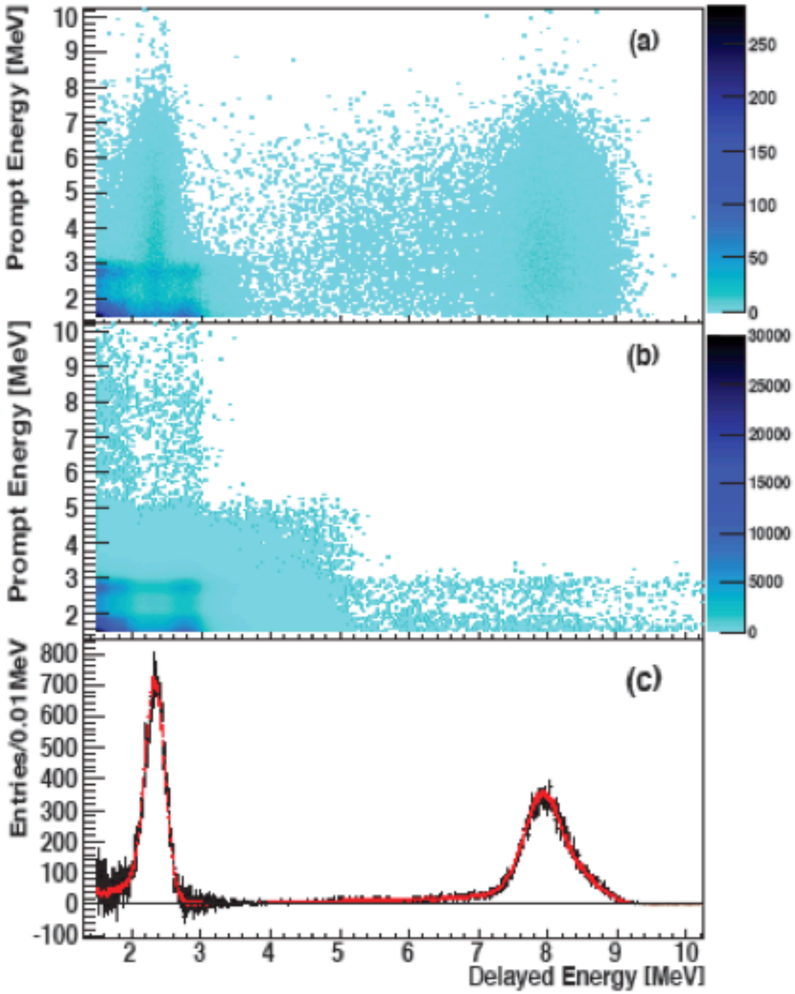
preliminary

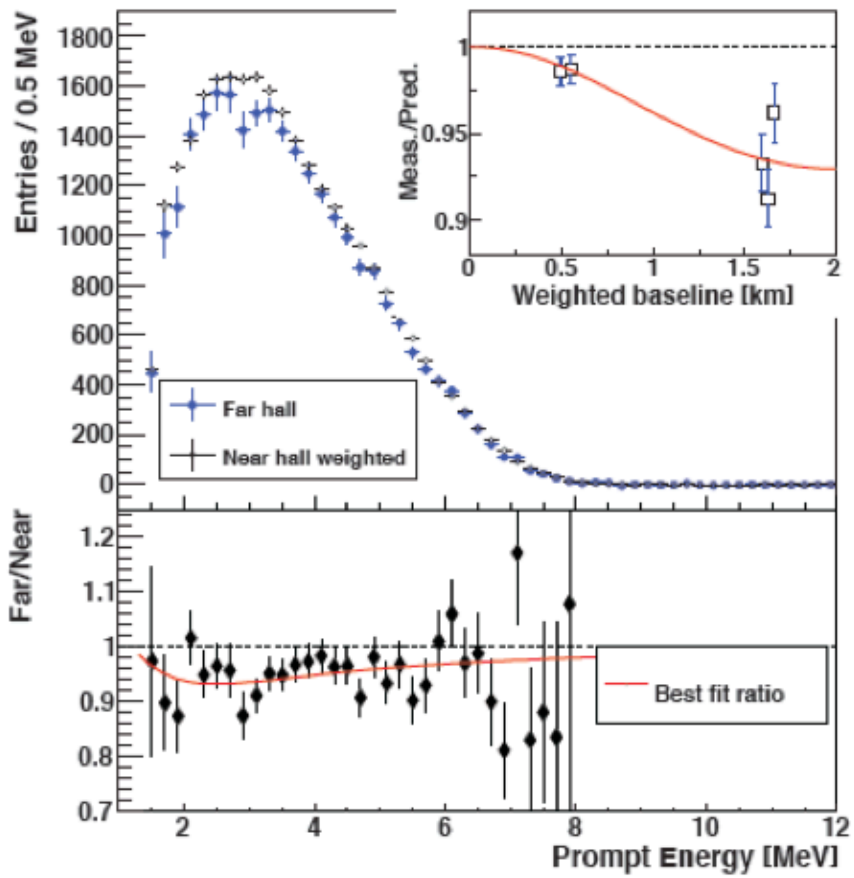


preliminary



n-H Analysis: Daya Bay





$$\sin^2 2\theta_{13} = 0.083 \pm 0.018$$

@Neutrino 2014

(arXiv: 1406.6468)

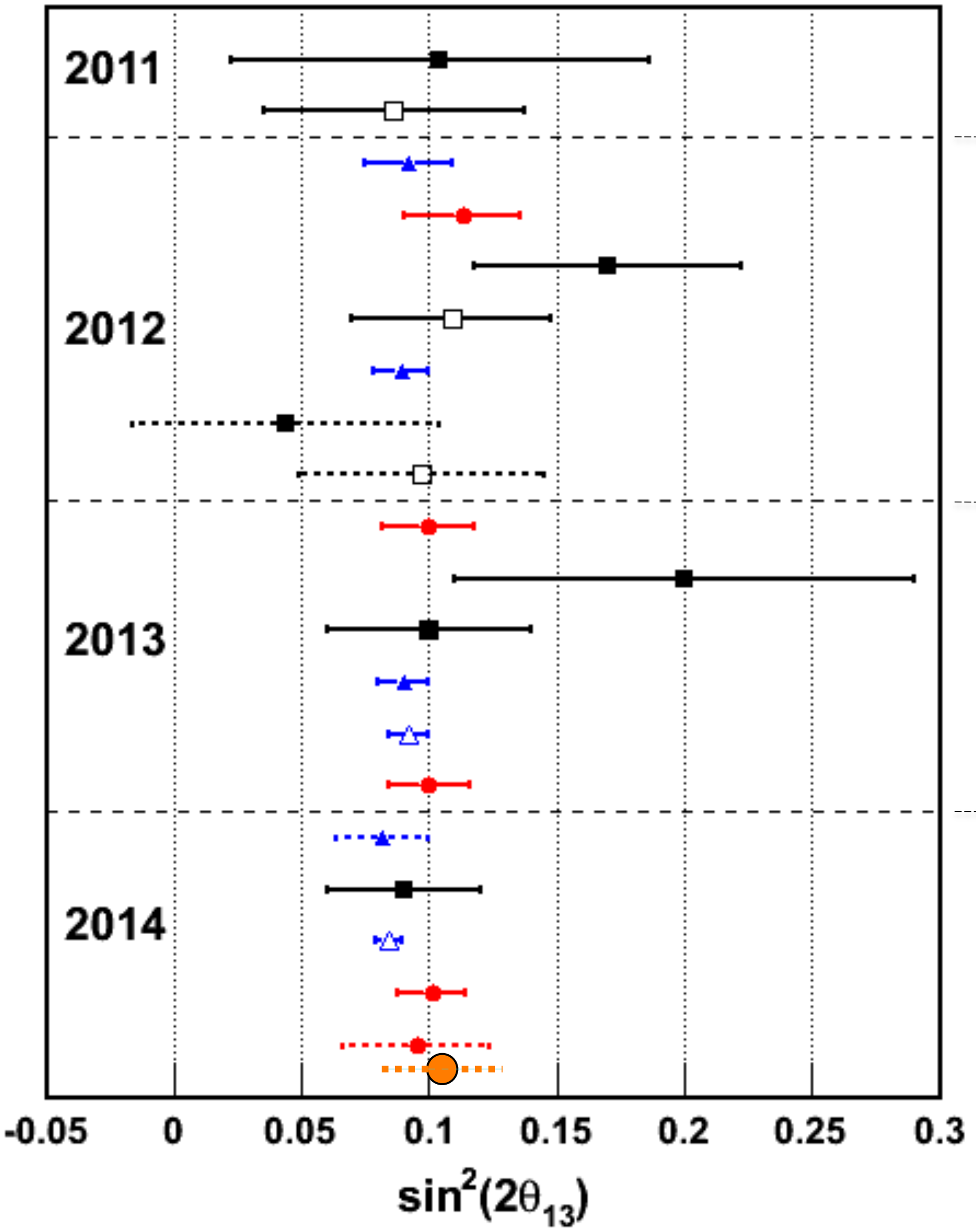
Experiment	n-Gd: $\sin^2(2\theta_{13})$	method
Double Chooz	$0.090^{+0.032}_{-0.029}$ (33 %)	Rate + Shape
RENO	0.101 +/- 0.013 (13 %)	Rate only
Daya Bay	0.084 +/- 0.005 (6 %)	Rate + Shape

n-Gd

Experiment	n-H: $\sin^2(2\theta_{13})$	method
Double Chooz	0.097 +/- 0.048 (49 %)	Rate + Shape
RENO	0.103 +/-0.013 (19 %)	Rate only
Daya Bay	0.083 +/- 0.018 (21 %)	Rate + Shape

n-H

A Brief History of θ_{13} from Reactor Experiments



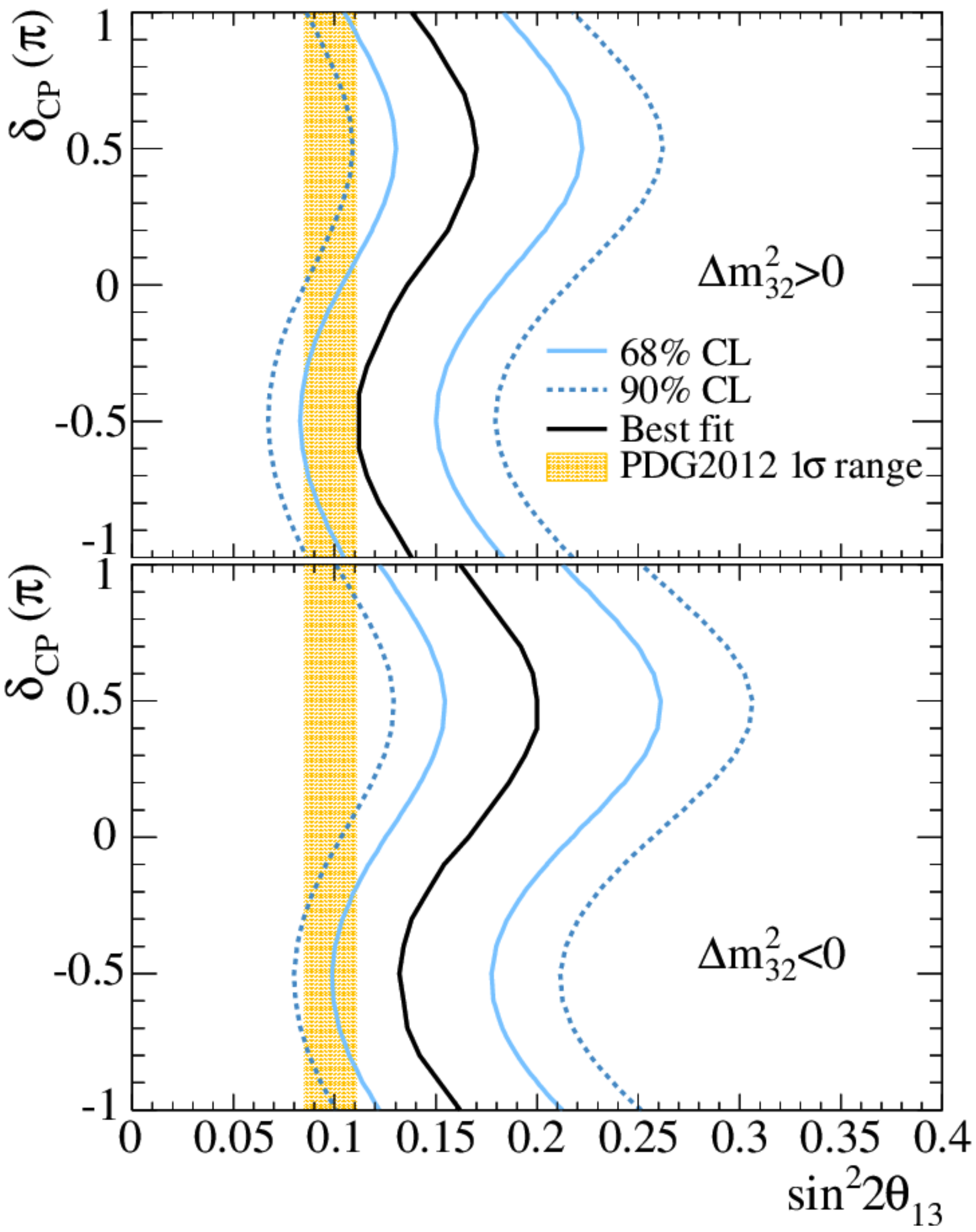
DC: 97 days [1112.6353]
R+S

DB: 49 days [1203.1669]
RENO: 222 days [1204.0626]
DC: 228 days [1207.6632]
R+S
DB: 139 days [1210.6327]
DC: n-H [1301.2948]
R+S

RENO: 403 days [NuTel2013]
DC: RRM analysis [1305.2734]
R+S
DB: 190 days [1310.6732]
R+S
RENO: 403 days [TAUP2013]

DB: 190 days n-H [Moriond2014]
DC: 469 days [ν 2014]
DB: 563 days [ν 2014]
RENO: 795 days [ν 2014]
384 days n-H [ν 2014]
RENO 384 days n-H [NOW 2014]

θ_{13} from Reactor and Accelerator Experiments



First hint of δ_{CP} combining Reactor and Accelerator data

Best overlap is for Normal hierarchy & $\delta_{CP} = -\pi/2$

Is Nature very kind to us?
Are we very lucky?
Is CP violated maximally?

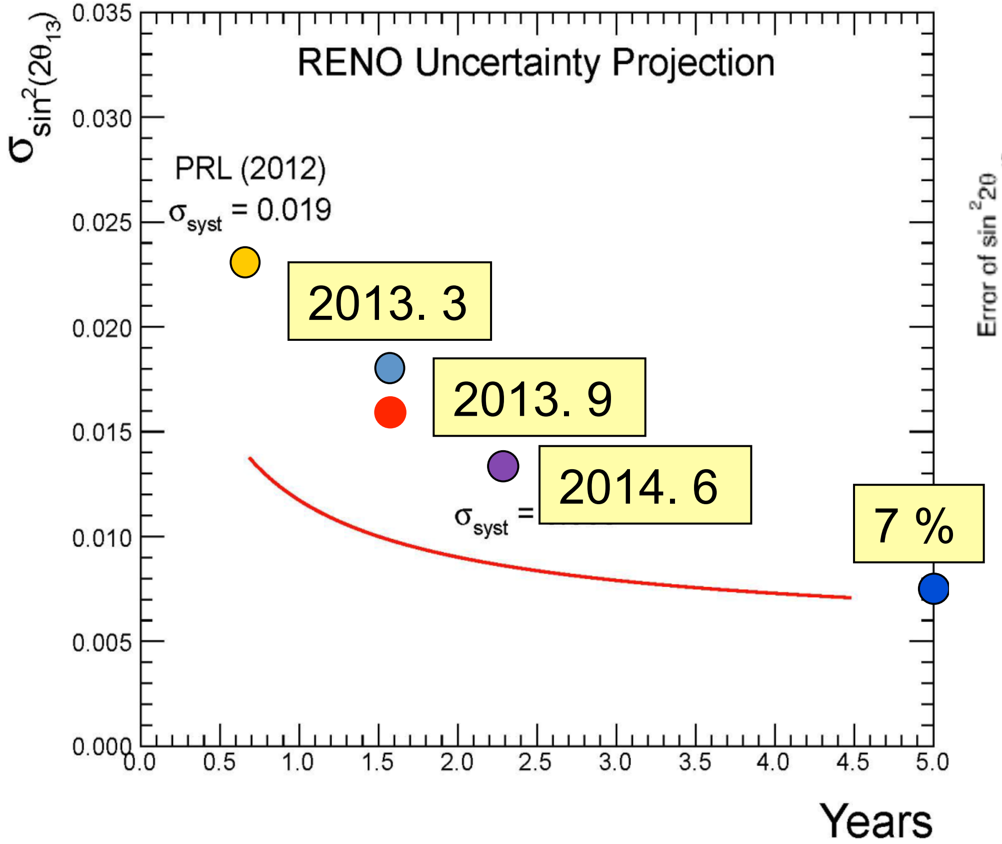
Strong motivation for anti-neutrino runs and precise measurements of θ_{13}

Courtesy C. Walter (T2K Collaboration)
Talk at Neutrino 2014

Future Prospects on θ_{13}

RENO

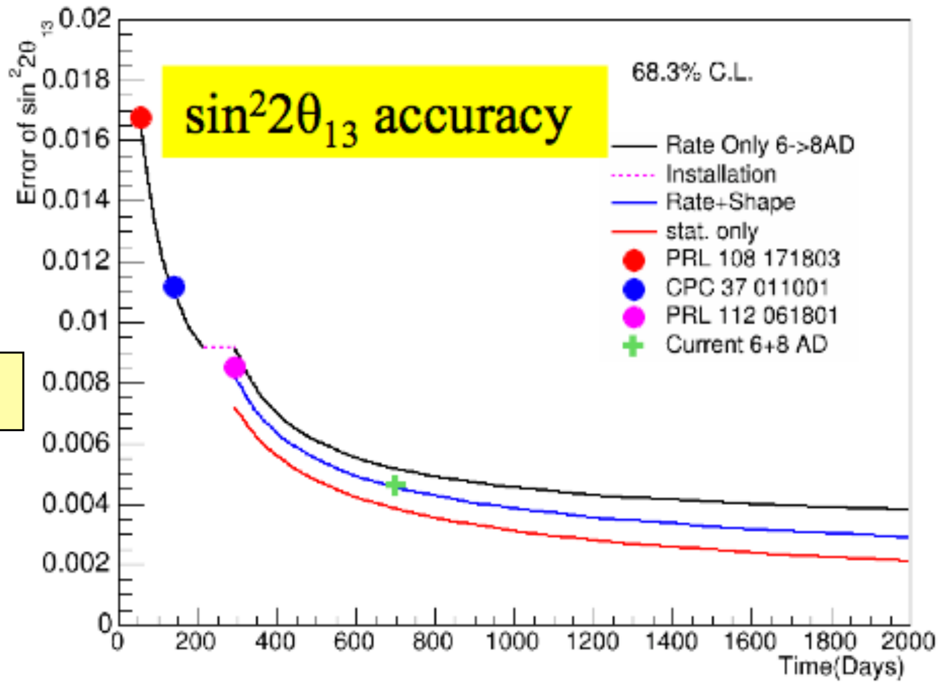
- 5 years of data : 7 %
  - stat. error : $\pm 0.008 \rightarrow \pm 0.005$
  - sys. error : $\pm 0.010 \rightarrow \pm 0.005$



Daya Bay

- 2017 (6 years of data) : 3 %

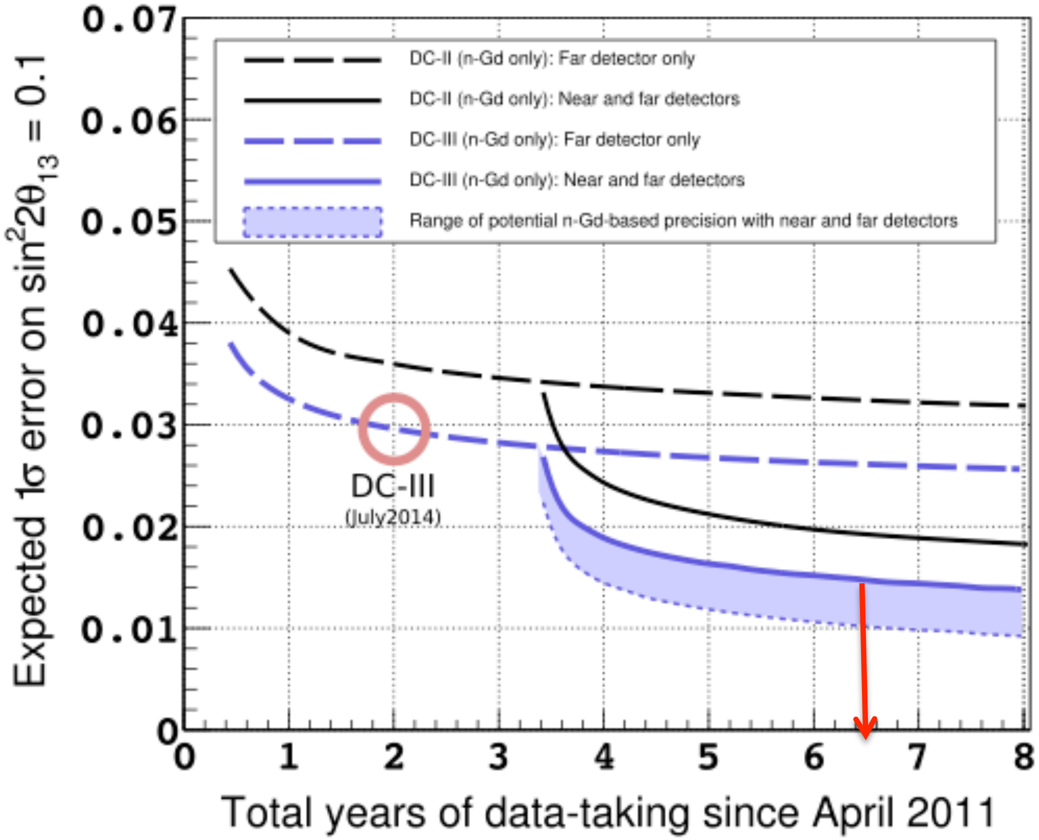
$\delta(\sin^2\theta_{13})\sim 0.003$, $\delta(\Delta m^2_{ee})\sim 0.07$



Future Prospects on θ_{13}

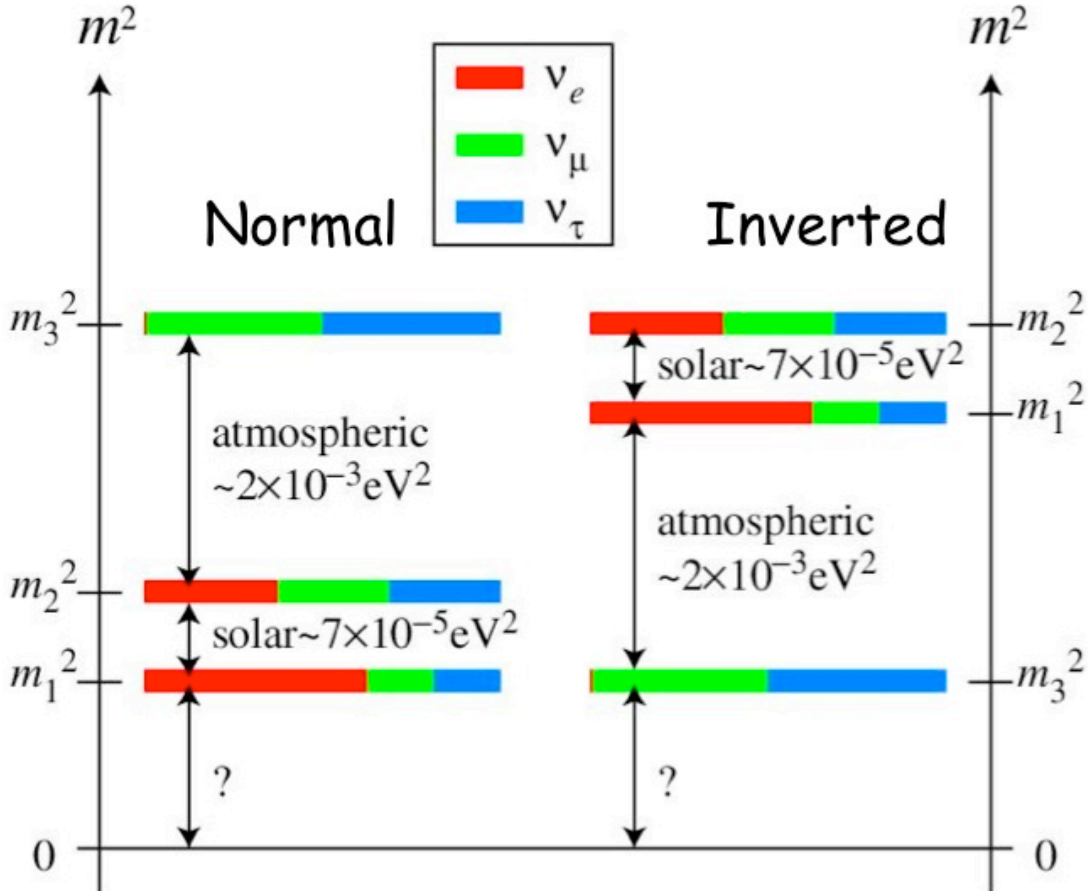
Double Chooz

- 3 years of Far & Near data : 15 -10 %

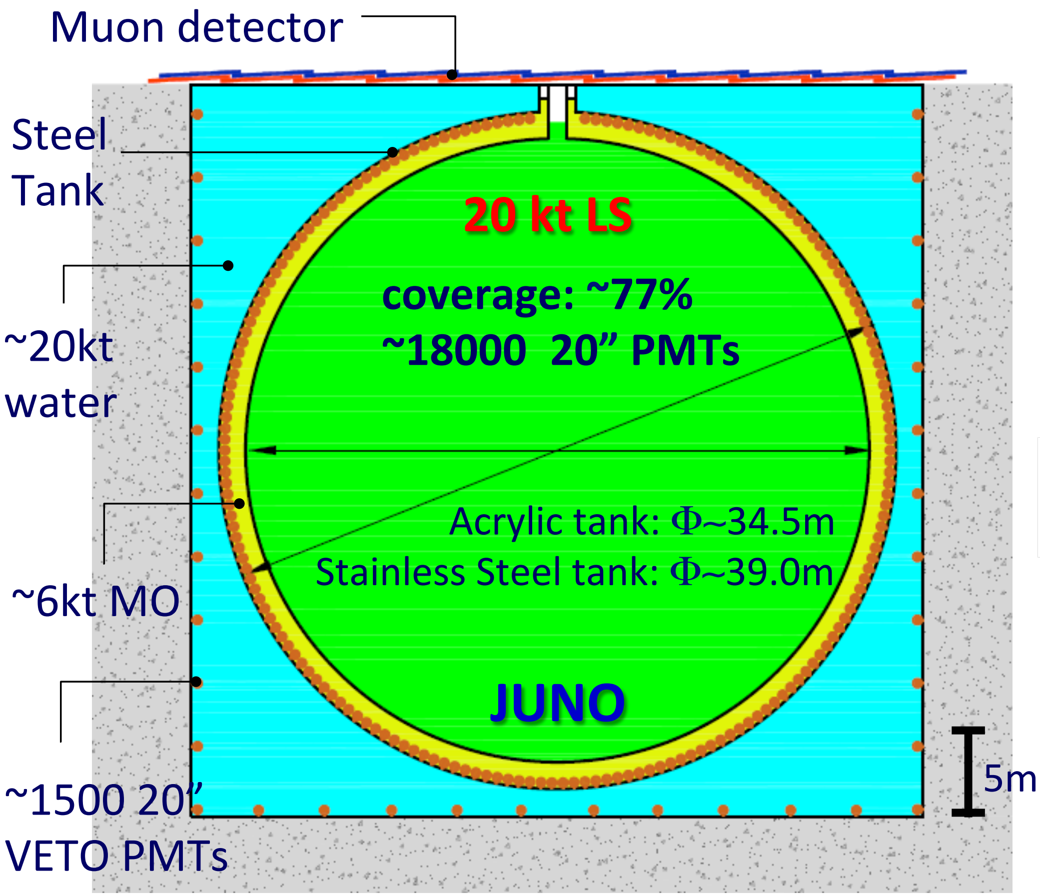


Towards Neutrino Mass Hierarchy: RENO-50 & JUNO

Which ?



Challenge: high-precision, giant LS detector



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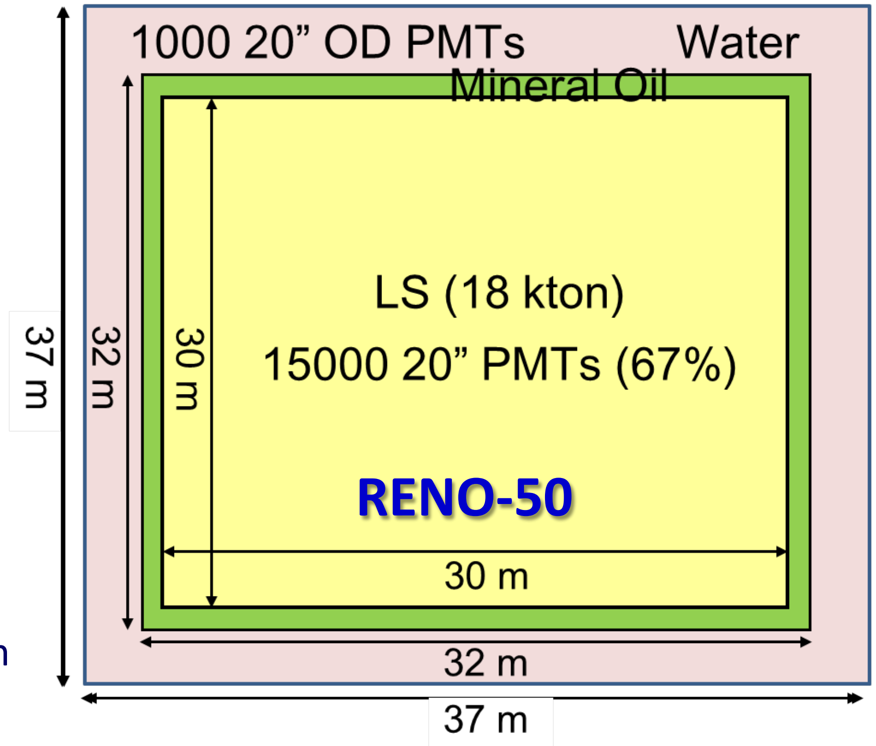
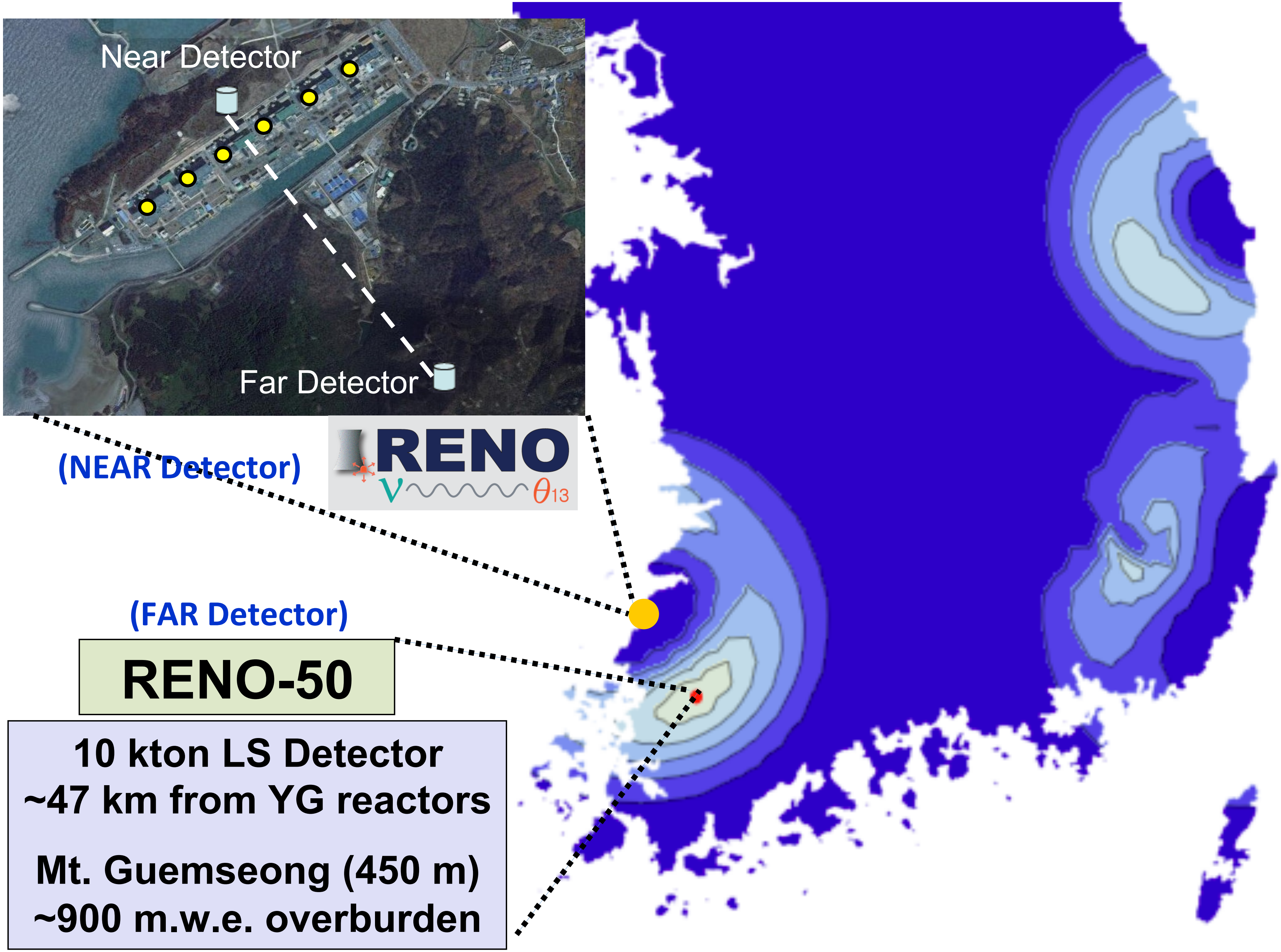


	KamLAND	JUNO	RENO-50
LS mass	~1 kt	20 kt	18 kt
Energy Resolution	6%/	~3%/	~3%/
Light yield	250 p.e./MeV	1200 p.e./MeV	>1000 p.e./MeV


Near Detector
Far Detector
RENO
ν θ13
(NEAR Detector)
(FAR Detector)
RENO-50
10 kton LS Detector
~47 km from YG reactors
Mt. Guemseong (450 m)
~900 m.w.e. overburden

◆ RENO can be used as near detector for RENO-50.
→ Reduces systematic error of nu flux.

While JUNO can not use Daya Bay detector as near detector.
→ To reduce neutrino interference effect from other reactors.

✧ Baseline difference should be < 500 m.

Li, Cao, Wang, Zhan: arXiv: 1303.6733

Ciuffoli, Evslin, Zhan: arXiv: 1302.0624

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

@Recontre du Vietnam 2013

Fresh Good News

- $ 2 M grant from Samsung was awarded for RENO-50 R&D.

This grant will be used for R&D of

① Liquid scintillator purification.

② High QE PMT performance to reach 3% resolution.

→ RENO-50 needs your collaboration !

(personal slide)