Results on θ_{13} Neutrino Oscillations from Reactor Experiments

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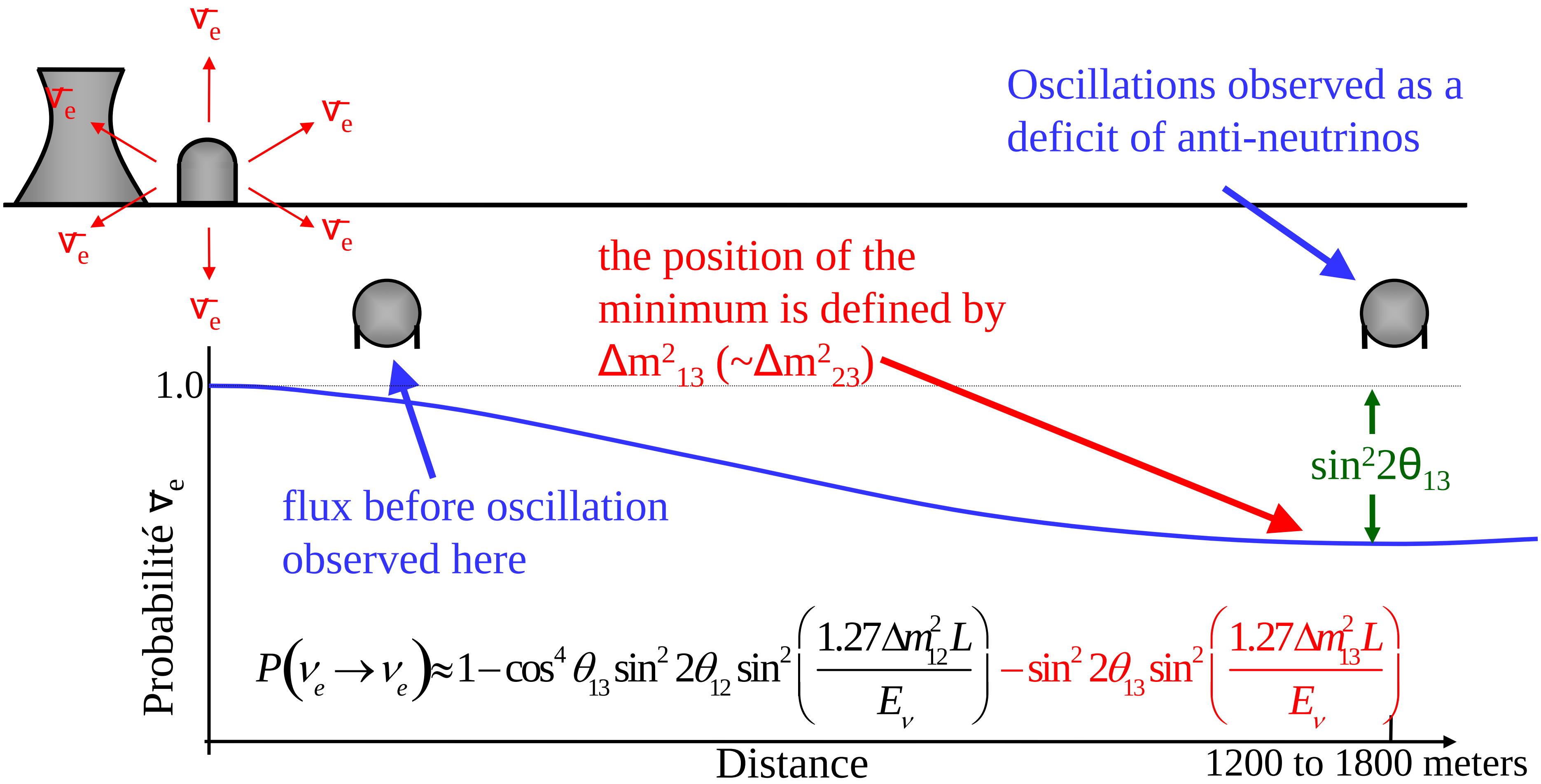
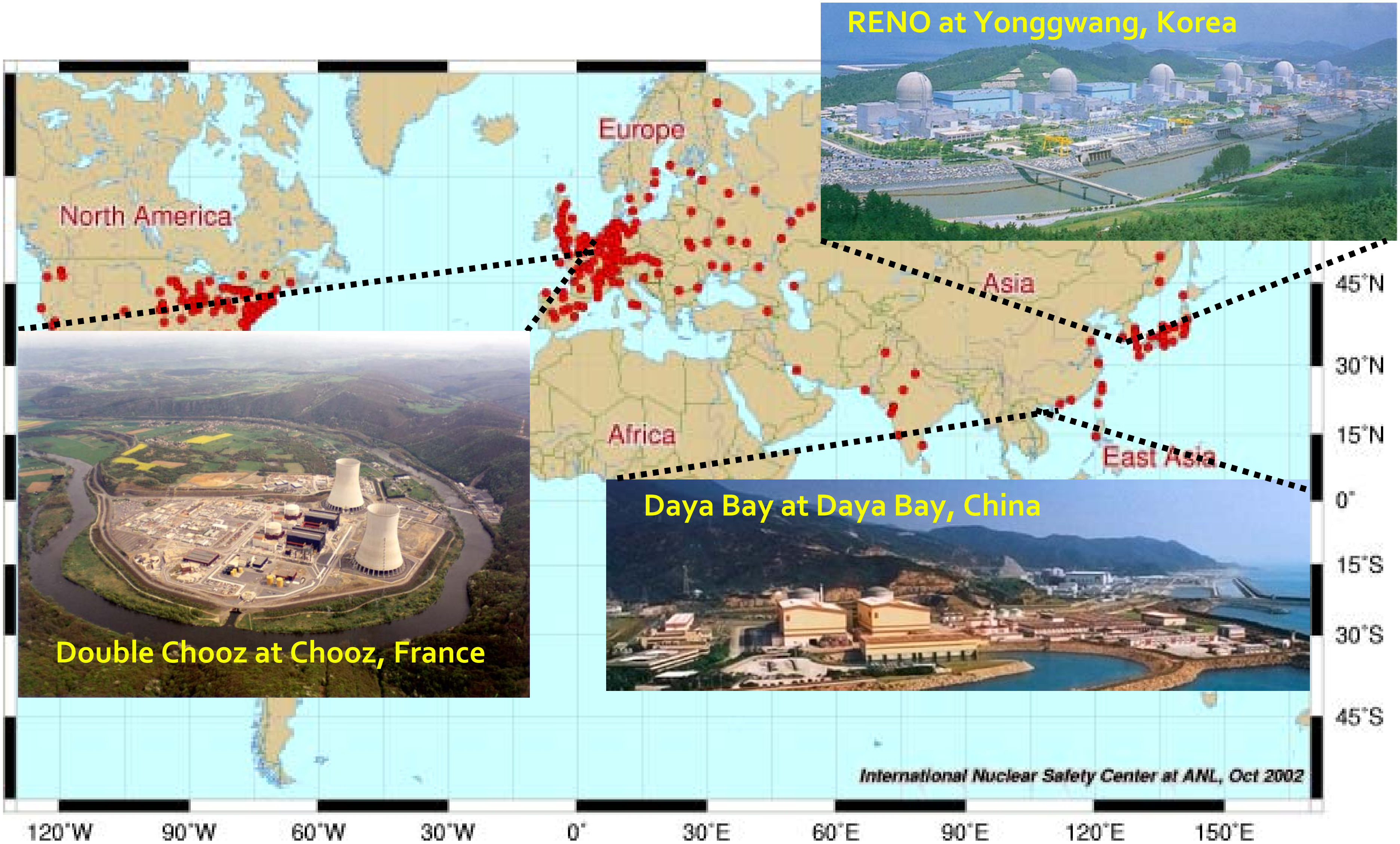
"16th Lomonosov Conference, Moscow, August 22-28, 2013"

Experimental Method of θ_{13} Measurement

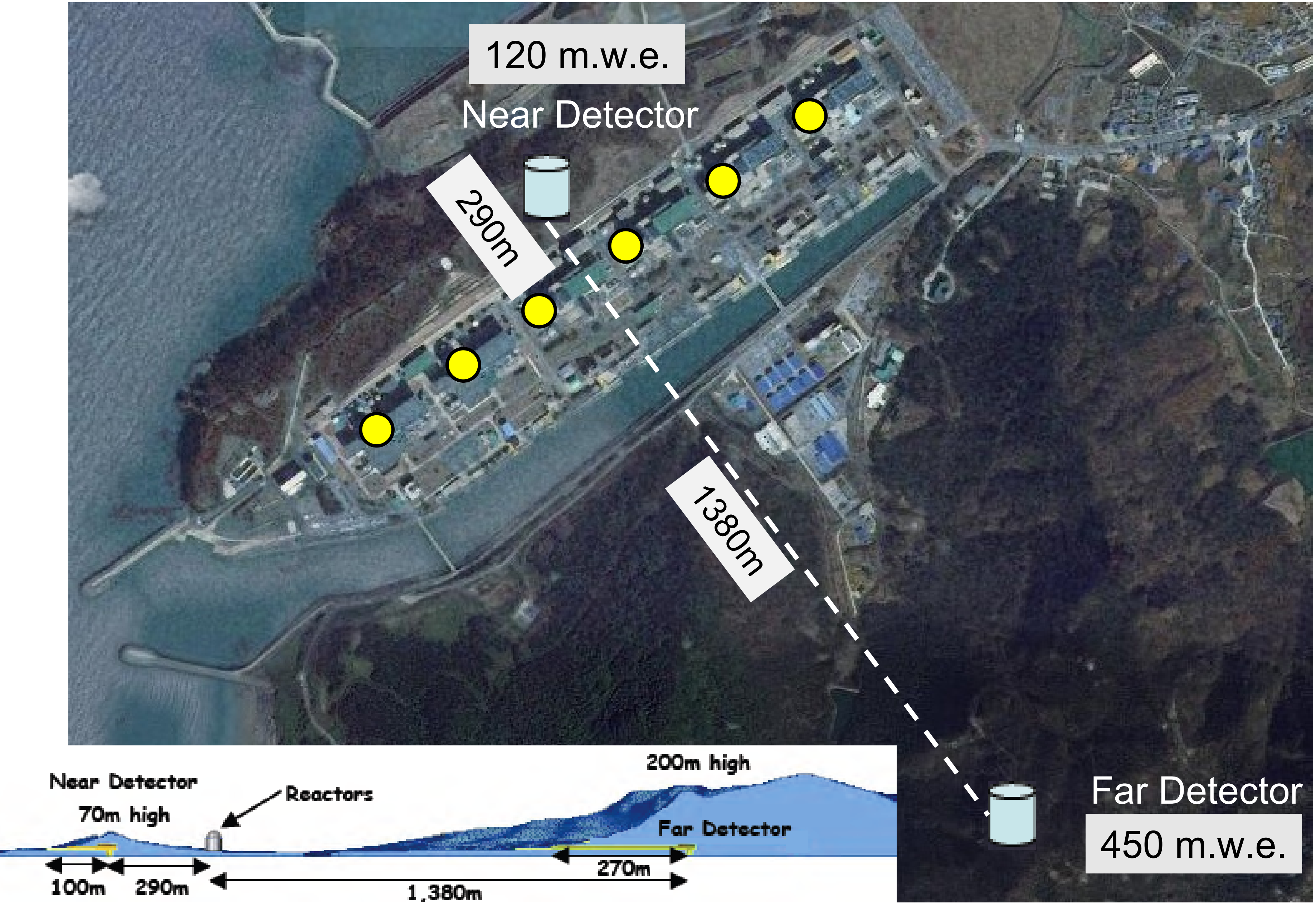


- Find disappearance of $\overline{\nu_e}$ fluxes due to neutrino oscillation as a function of energy using multiple, identical detectors to reduce the systematic errors in 1% level.

Reactor θ_{13} Experiments

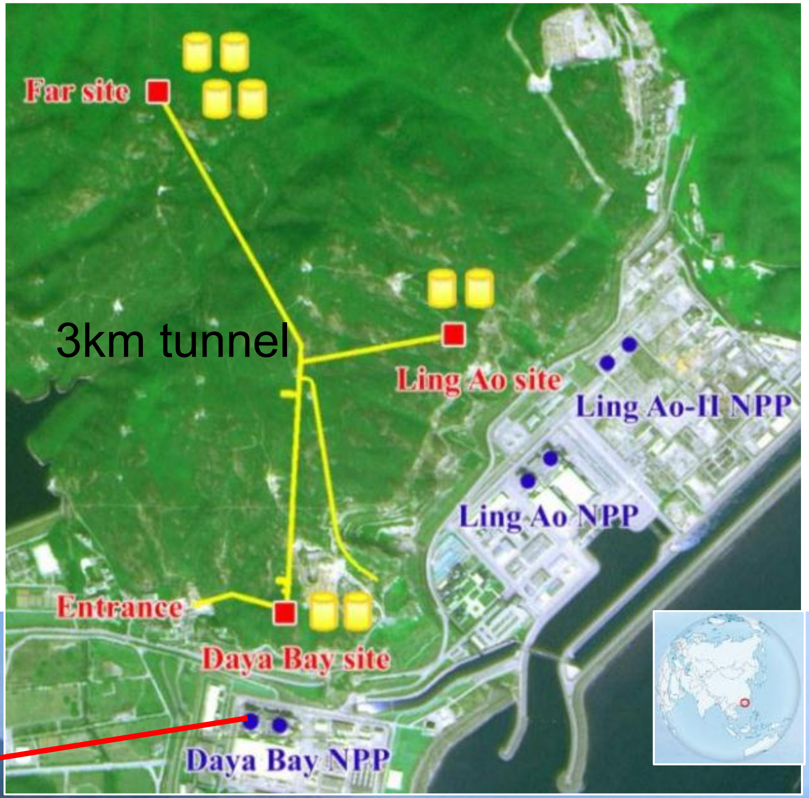


The RENO Experiment

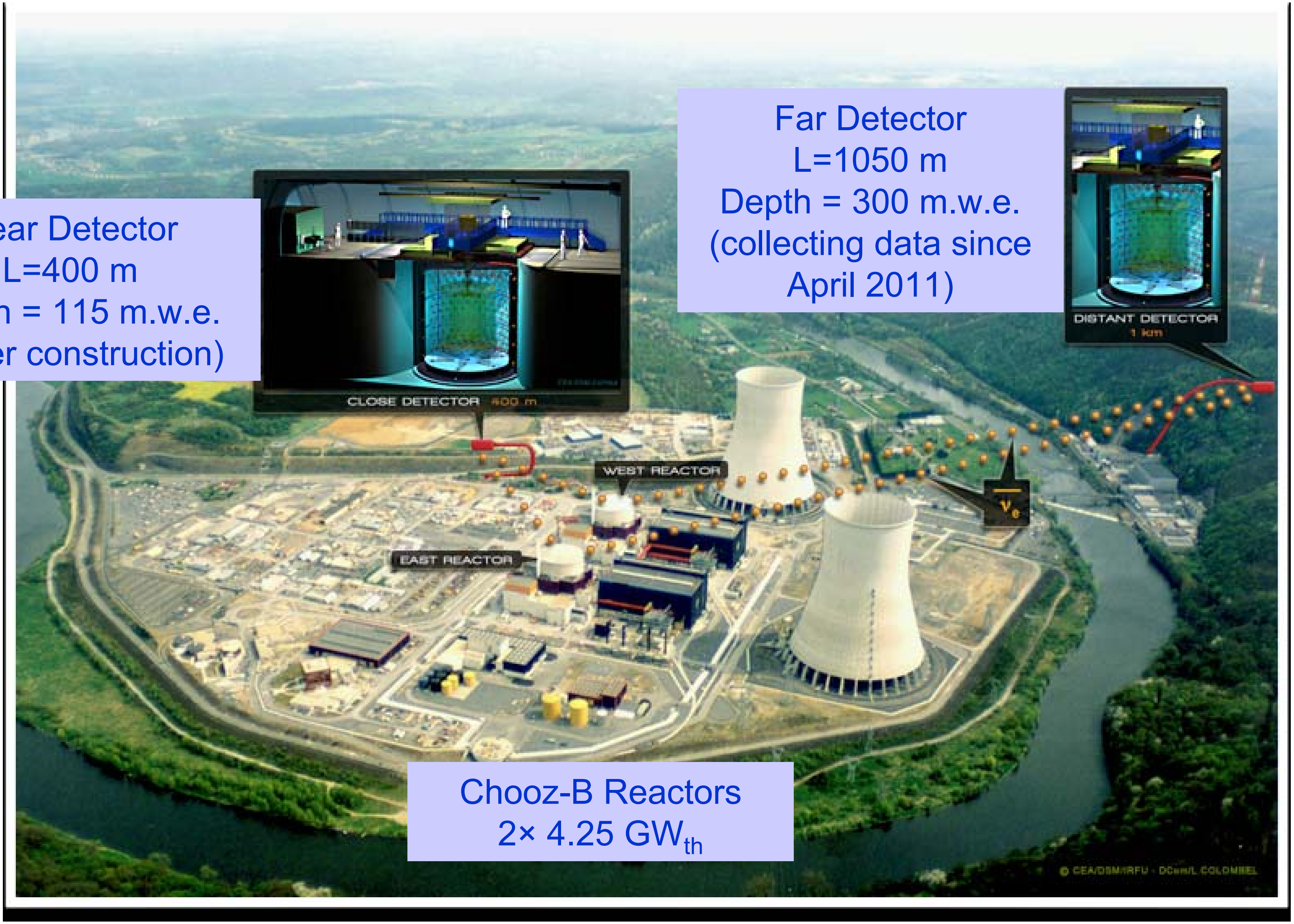


The Daya Bay Experiment

- Measuring neutrino mixing angle θ_{13}
- 6 reactor cores, 17.4 GW_{th}
- Relative measurement
  - ⇨ 2 near sites, 1 far site
- Multiple LS detector modules
  - ⇨ 20 ton target, 110 ton total weight
- Good cosmic shielding
  - ⇨ 250 (860) m.w.e @ near (far) sites



The Double Chooz Experiment

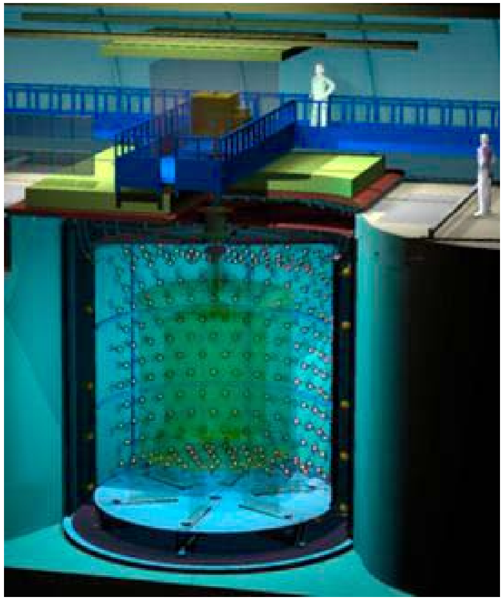


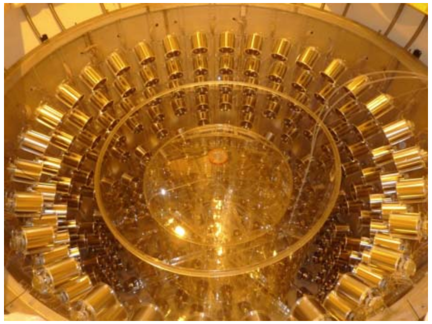
Near Detector
L=400 m
Depth = 115 m.w.e.
(under construction)

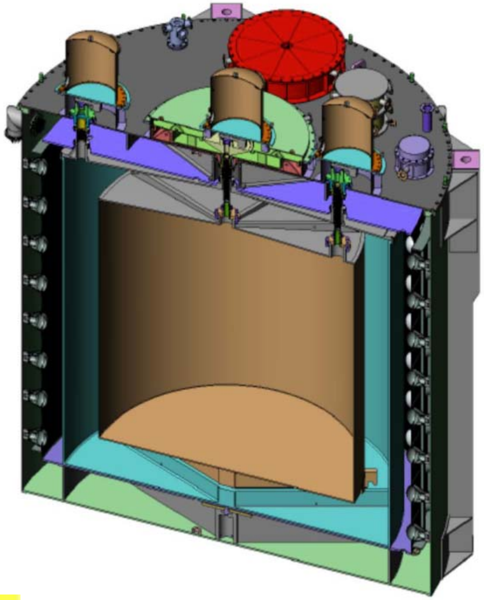
Far Detector
L=1050 m
Depth = 300 m.w.e.
(collecting data since April 2011)

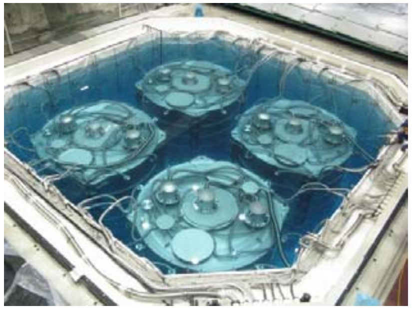
Chooz-B Reactors
2× 4.25 GW_{th}

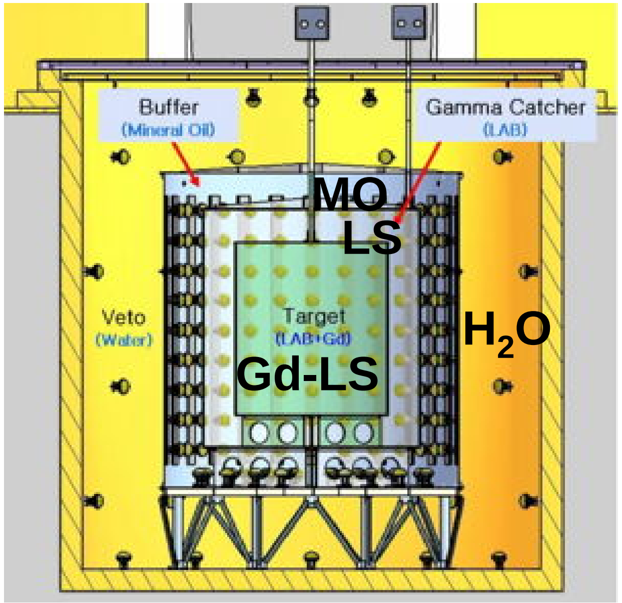
θ_{13} Reactor Neutrino Detectors







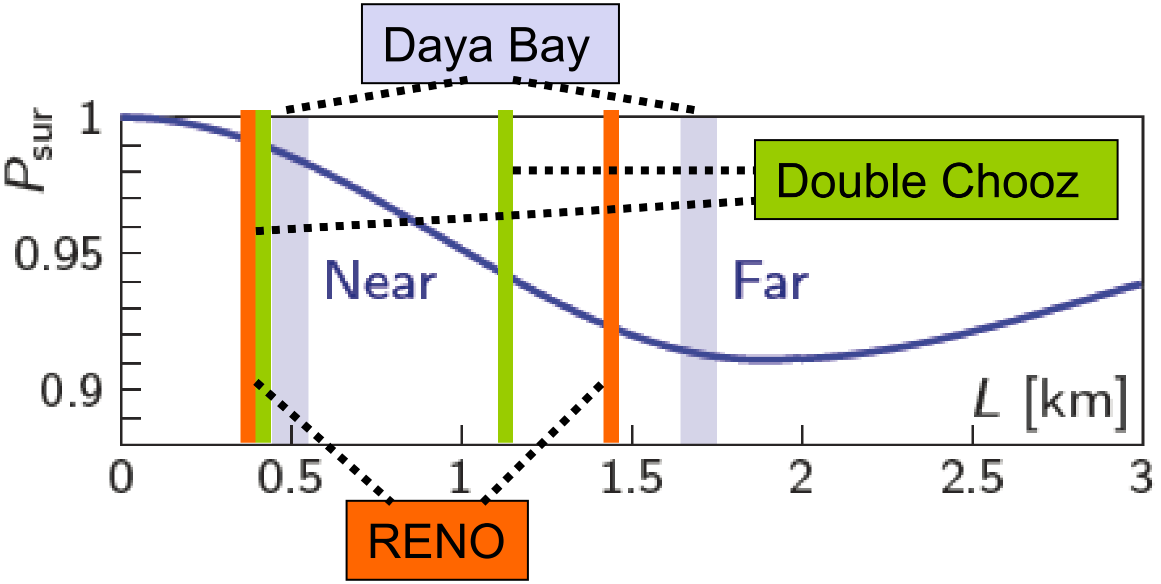




θ_{13} Reactor Neutrino Experiments

Experiments	Location	Thermal Power (GW)	Flux Weighted Baselines Near/Far (m)	Depth Near/Far (mwe)	Target Mass (tons)	Flux*Target per year (GW·ton·yr)
Double Chooz	France	8.5	[410/1050]	120/300	8.6/8.6	73 [1.0]
RENO	Korea	16.7	409/1444	120/450	16/16	267 [3.7]
Daya Bay	China	17.4	470(576)/1648	250/860	40×2/80	1392 [19.1]

	Far	Near
Double Chooz	Apr. 2011	Spring 2014
RENO	Aug. 2011	Aug. 2011
Daya Bay	Dec. 2011	Sep. 2011



RENO Status

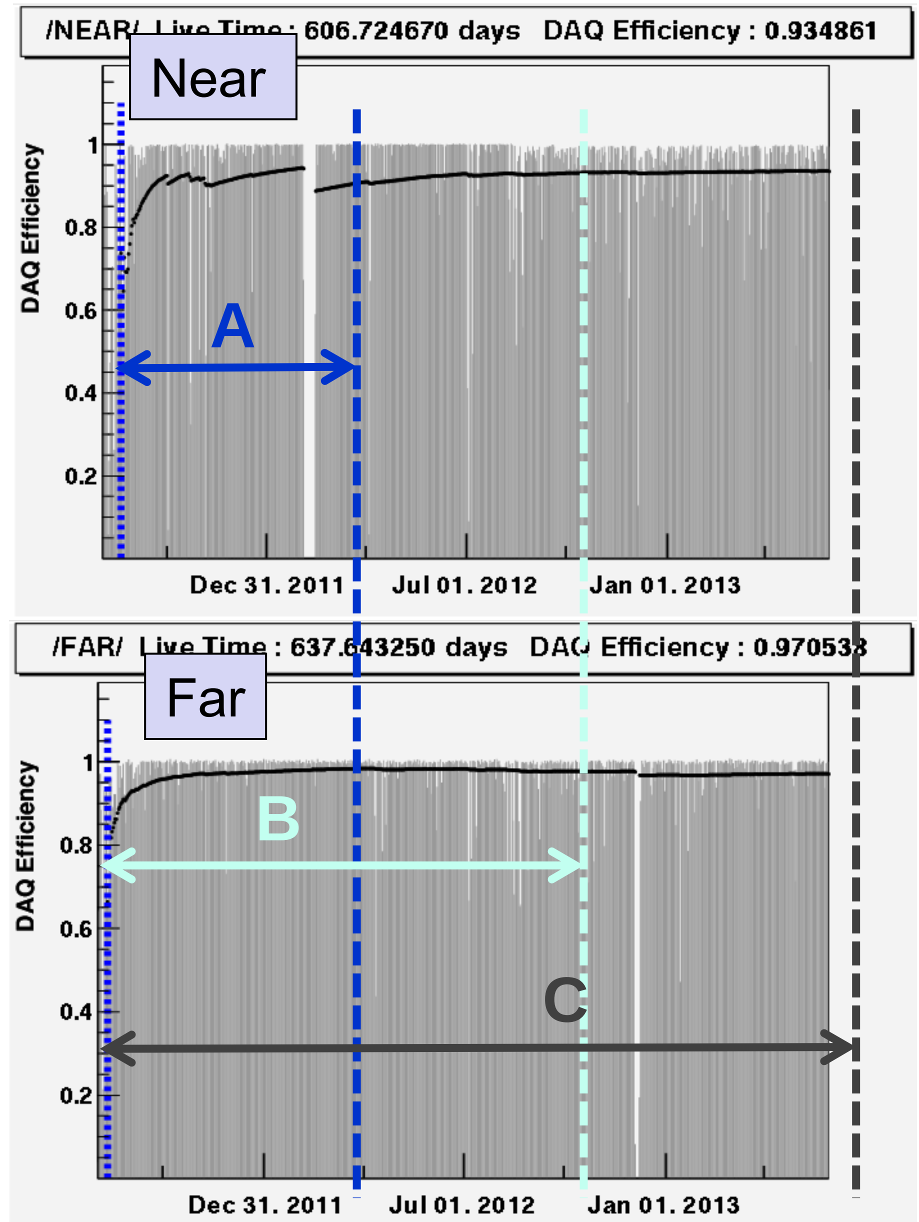
- Data taking began on Aug. 1, 2011 with both near and far detectors. (DAQ efficiency : ~95%)

- **A** (220 days) : **First θ_{13} result**
  [11 Aug, 2011~26 Mar, 2012]
  PRL 108, 191802 (2012)

- **B** (403 days) : **Improved θ_{13} result**
  [11 Aug, 2011~13 Oct, 2012]
  NuTel 2013

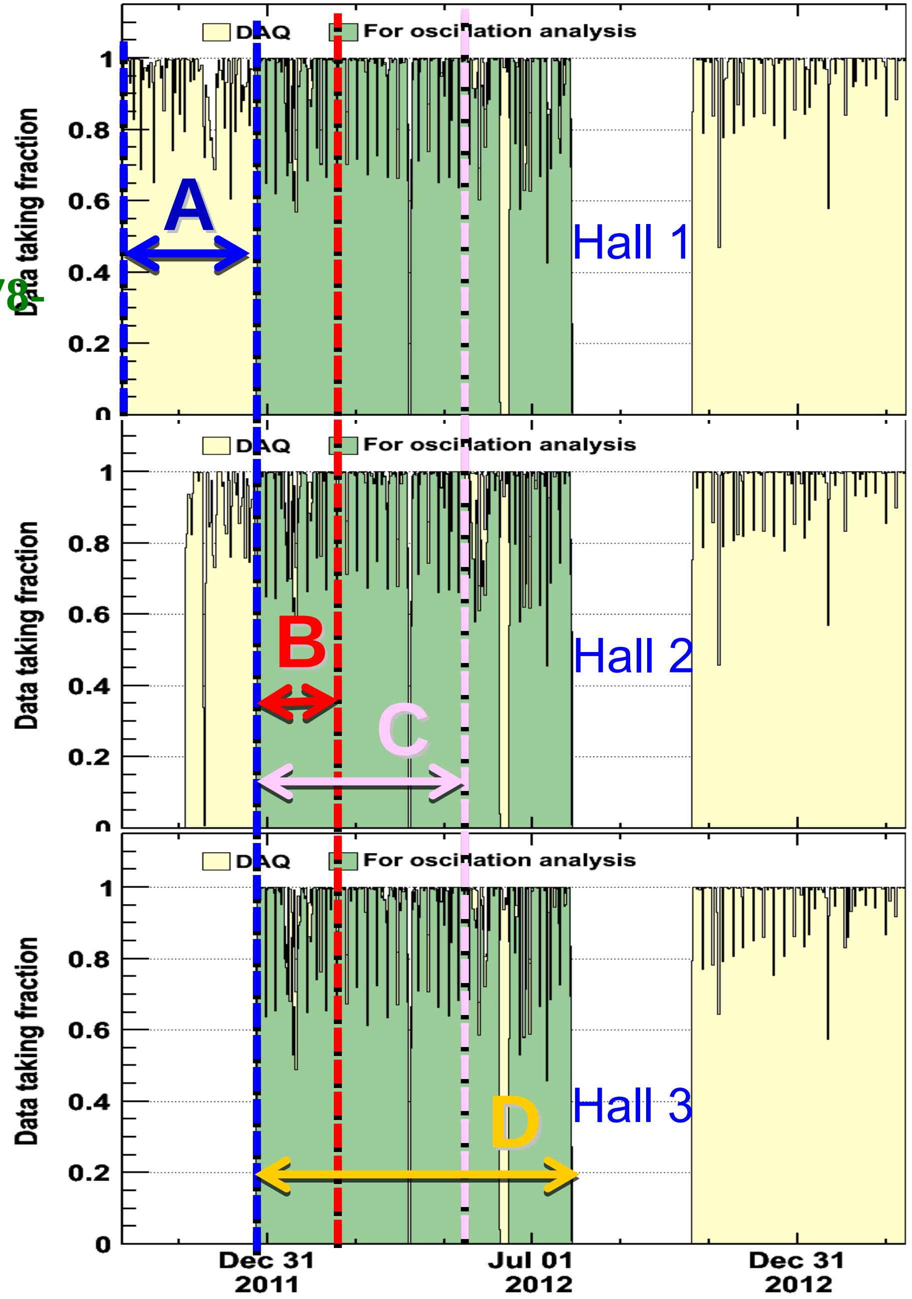
- **C** (~700 days) : **Shape+rate analysis** (in progress)
  [11 Aug, 2011~31 Jul, 2013]

- Absolute reactor neutrino flux measurement in progress
  [reactor anomaly & sterile neutrinos]



Daya Bay Operation

- **A→Two Detector Comparison:**
  Sep. 23, 2011 – Dec. 23, 2011
  Nucl. Inst. and Meth. A 685 (2012), pp. 78-97
- **B→55 days, First Oscillation Result:**
  Dec. 24, 2011 – Feb. 17, 2012
  Phys. Rev. Lett. 108, 171803 (2012)
- **C→Updated analysis:**
  Dec. 24, 2011 – May 11, 2012
  Chinese Physics C37, 011001 (2013)
  - **DAQ eff. ~ 96%**
  - **Eff. for physics: ~ 94%**
- **D→Shape+rate analysis, preparation**
  Dec. 24, 2011 – Jul. 28, 2012
- **E→ 8 AD, double statistics**
  Dec. 24, 2011 – Jul. 2013



Double Chooz Status

Far detector alone

- Data taking has been in progress since April. 2011 with a far detector alone.

- New release in 2003 of rate+shape analysis :
  improved analysis (energy scale, backgrounds) & more statistics

- 2 channels (neutron capture on Gd and on Hydrogen) with a potential for a combined analysis → expect the final sensitivity of 0.03

- Fit oscillation through the nuclear power variation :
  measurement with two reactors, one reactor and zero

Near+Far detectors

- A near detector is under construction until spring 2014.
- The first result of the full experiment will be available in the end of 2014, towards a final sensitivity of 0.01.
  (10% measurement of θ_{13})

A Brief History of θ_{13} from Reactor Experiments

- Nov. 2011 (Double

  $\sin^2(2\theta_{13}) = 0.086 \pm 0.051$

- March 2012 (Daya Bay)

  $\sin^2(2\theta_{13}) = 0.092 \pm 0.017$

- April 2012 (RENO)

  $\sin^2(2\theta_{13}) = 0.113 \pm 0.023$

- June 2012 (Double Chooz)

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

- Oct. 2012 (Daya Bay)

  $\sin^2(2\theta_{13}) = 0.089 \pm 0.011$

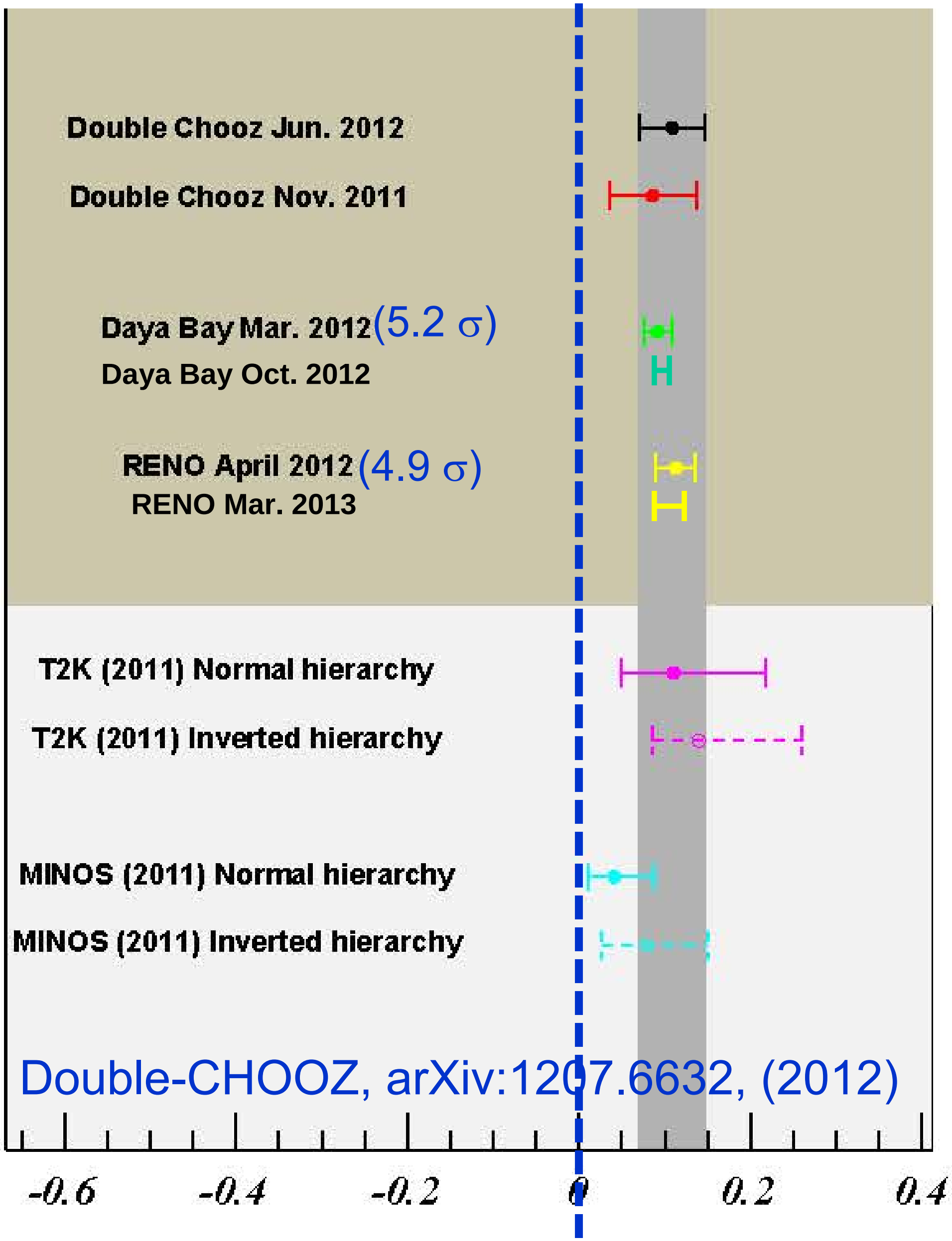
- March 2013 (RENO)

  $\sin^2(2\theta_{13}) = 0.100 \pm 0.018$

- August 2013 (Daya Bay)

  $\sin^2(2\theta_{13}) = 0.090 \pm 0.009$

$\Delta m^2_{31} = (2.54 \pm 0.20) \times 10^{-3}\ eV^2$



- Double-CHOOZ, arXiv:1207.6632, (2012)

θ_{13} from Reactor and Accelerator Experiments

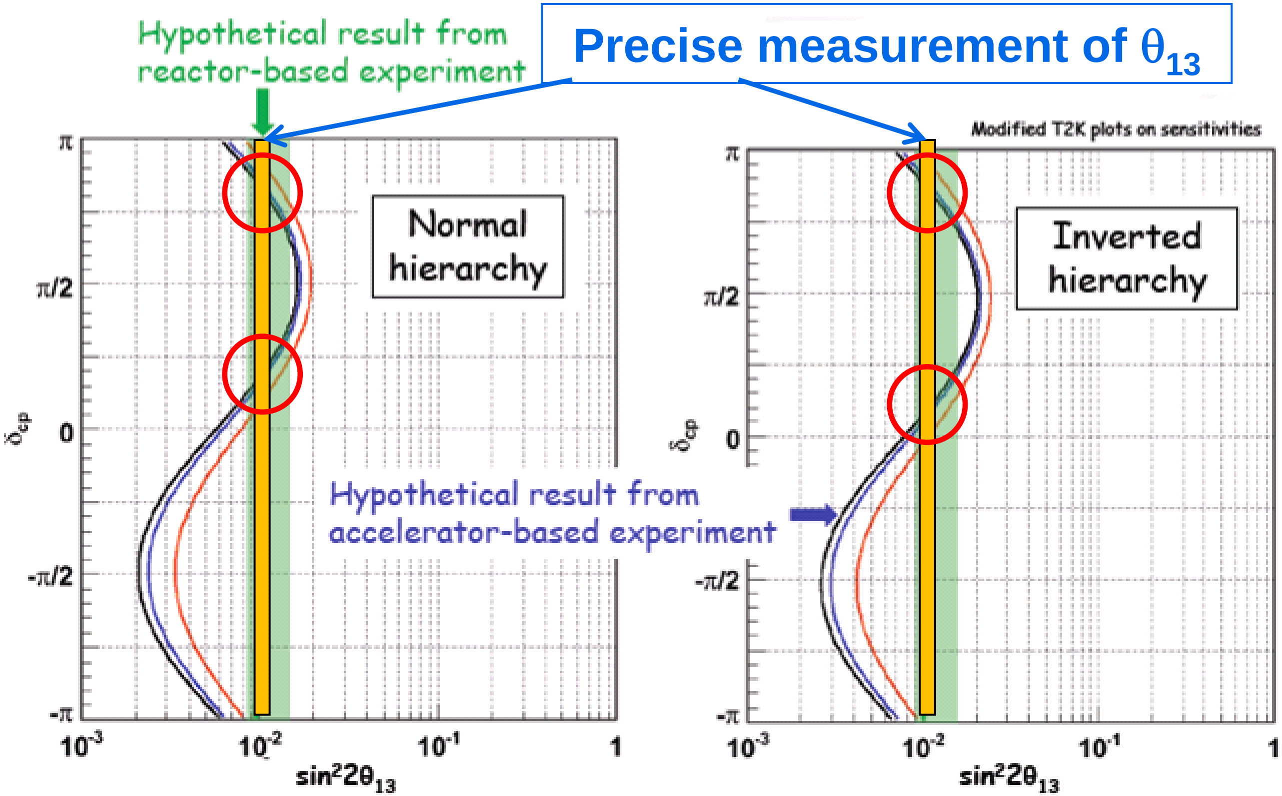
* Reactor

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

- Clean measurement of θ_{13} with no matter effects

* Accelerator

- mass hierarchy + CP violation + matter effects

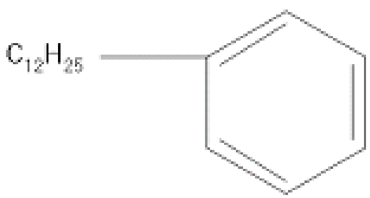


- Complementary :

Combining results from accelerator and reactor based experiments could offer the first glimpse of δ_{CP}.

Detection of Reactor Antineutrinos

C_nH_{2n+1}-C_6H_5 (n=10~14)



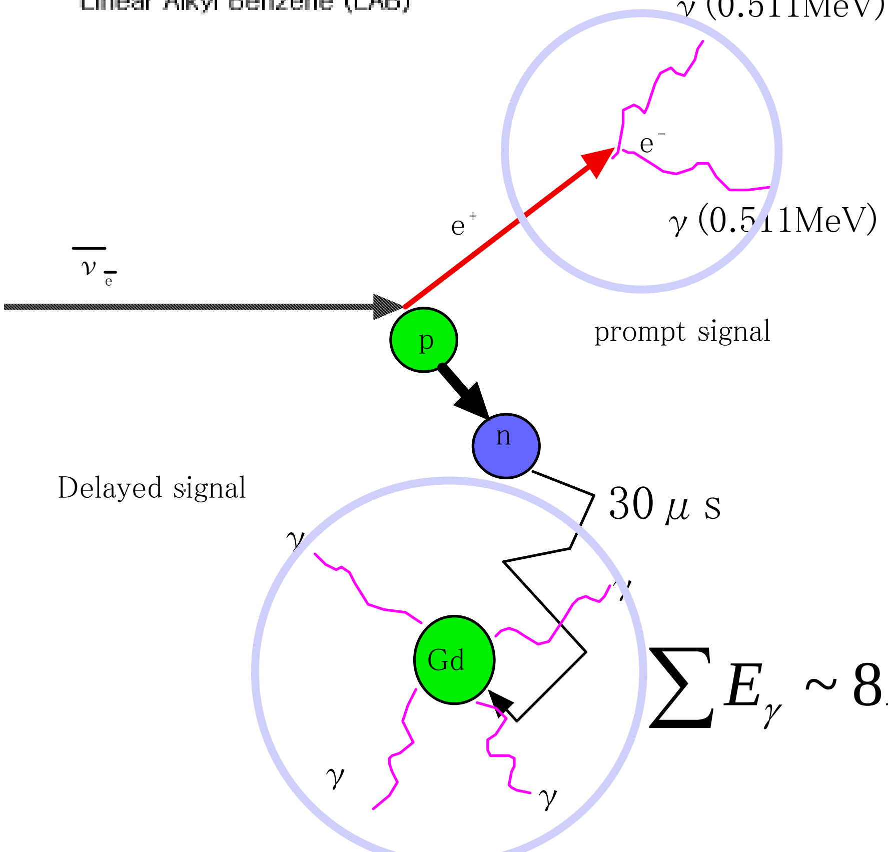
Linear Alkyl Benzene (LAB)

(prompt signal)

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

~180 μs → + p → D + γ (2.2 MeV) (delayed signal)

~28 μs (0.1% Gd) → + Gd → Gd + γ's (8 MeV)

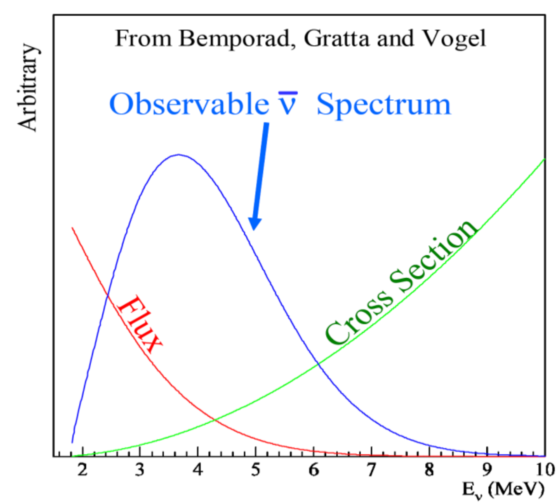


$$\sum E_\gamma \sim 8MeV$$

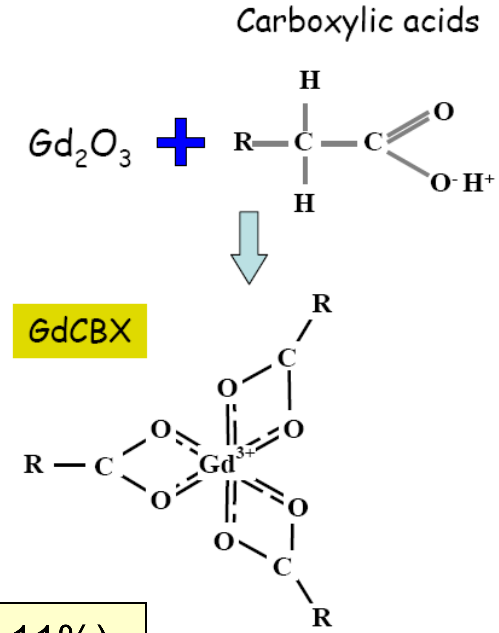
- **Neutrino energy measurement**

$$E_{\bar{\nu}} \cong T_{e^+} + T_n + (M_n - M_p) + m_{e^+}$$

T_n: 10-40 keV; $(M_n - M_p) + m_{e^+}$: 1.8 MeV



Gd Loaded Liquid Scintillator

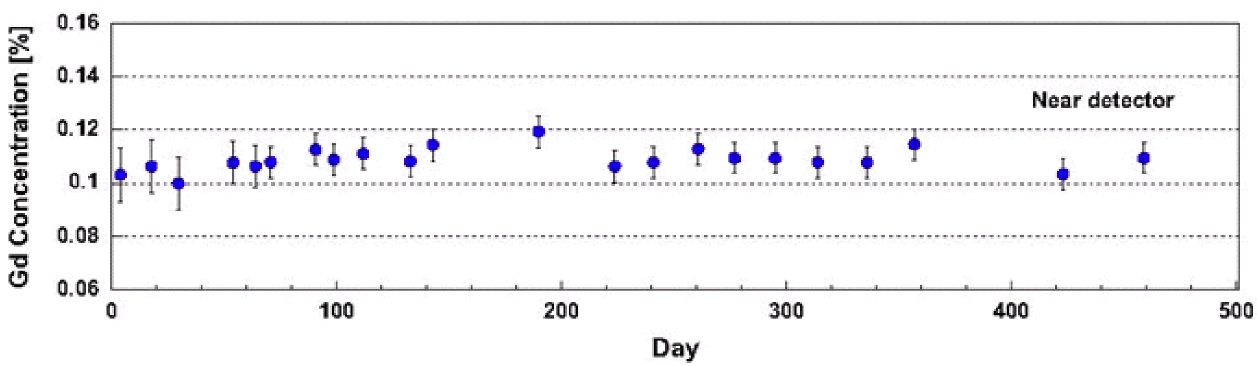


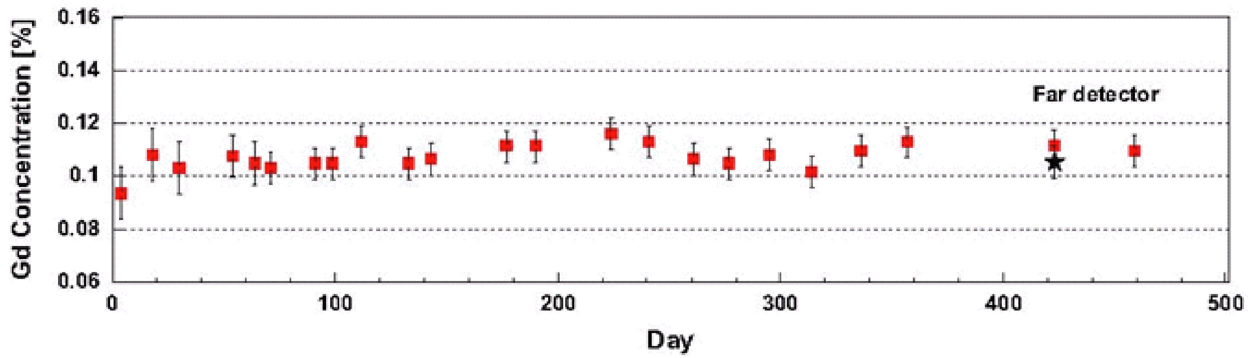
❑ Recipe of Liquid Scintillator

Solvent & Flour	WLS	Gd−compound
LAB	PPO + Bis−MSB	0.1% Gd + (TMHA)³

❑ Steady properties of Gd-LS

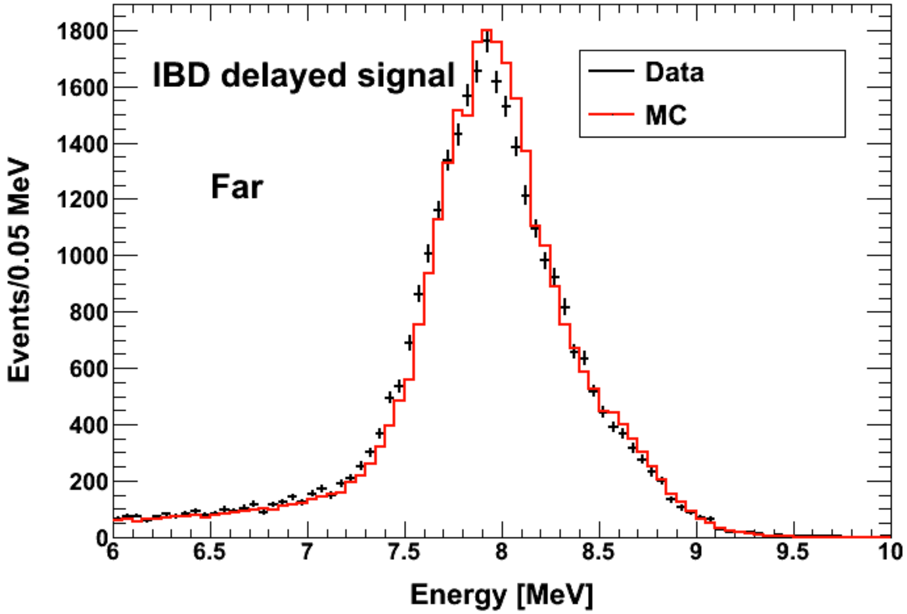
• Stable light yield (~250 pe/MeV) , transparency & Gd concentration (0.11%)

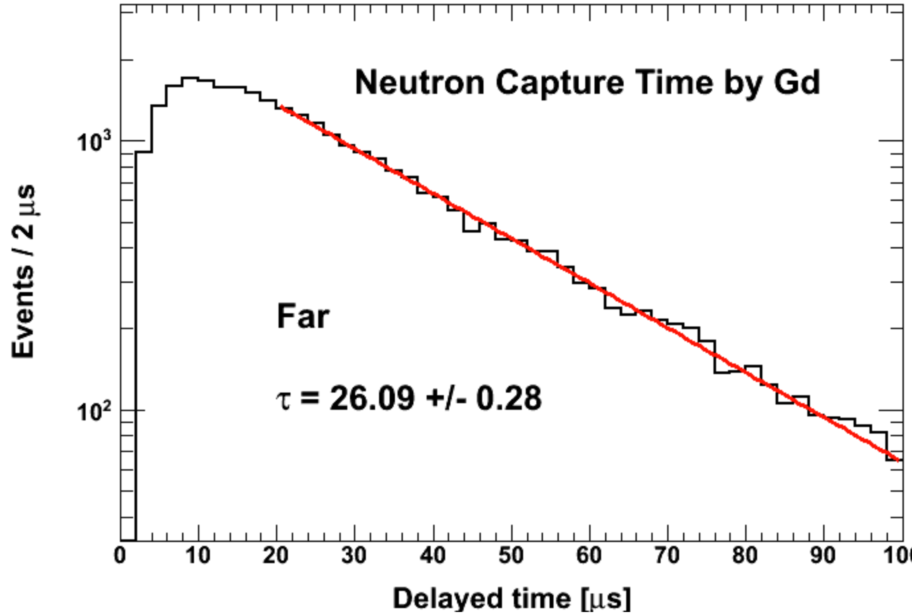


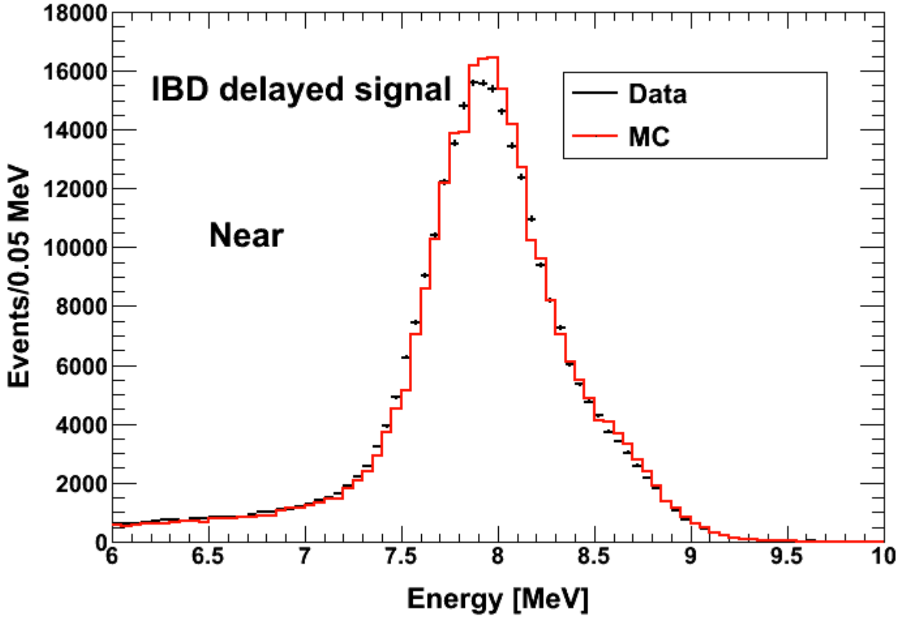


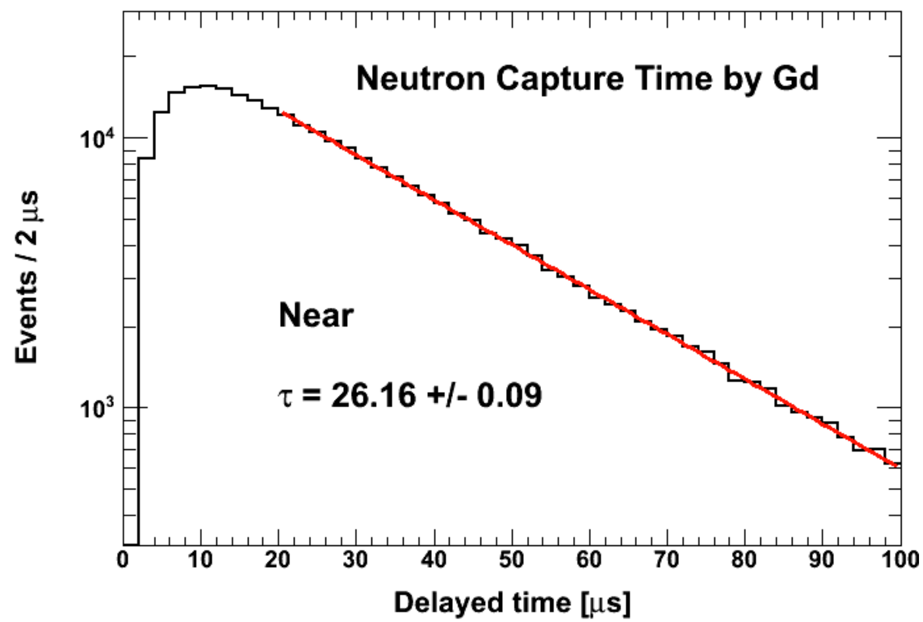
NIM A, 707, 45-53 (2013. 4. 11)

Neutron Capture by Gd



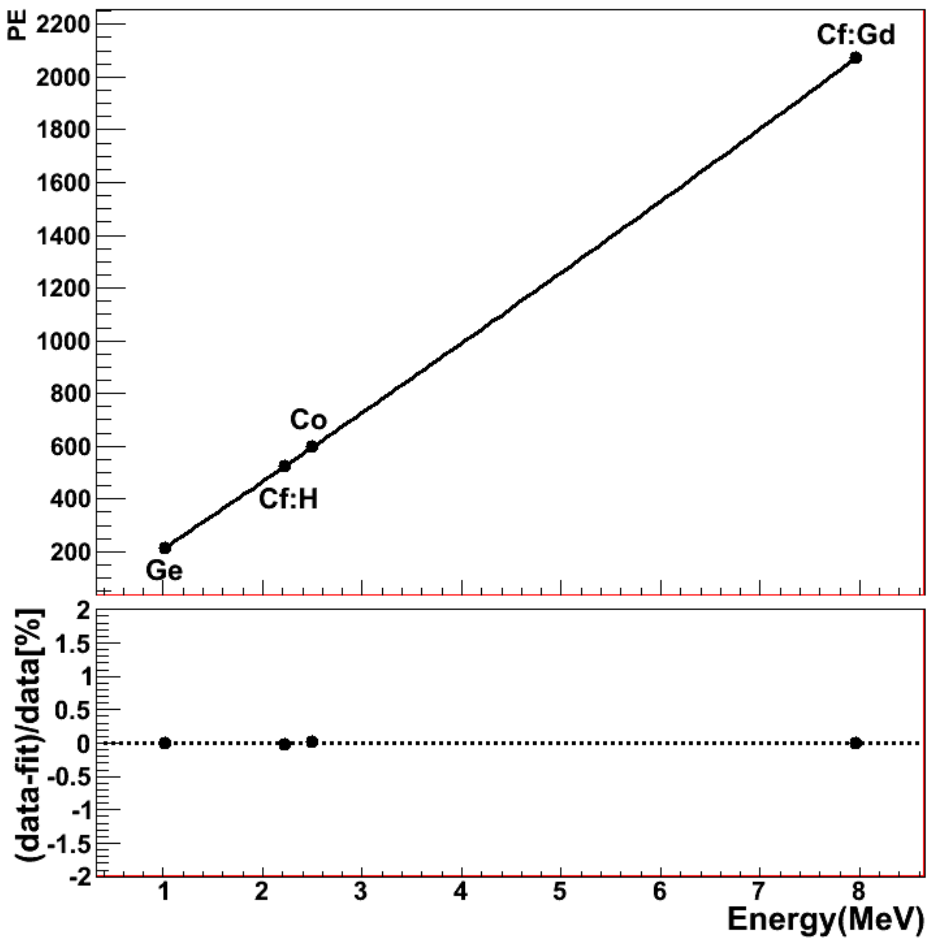




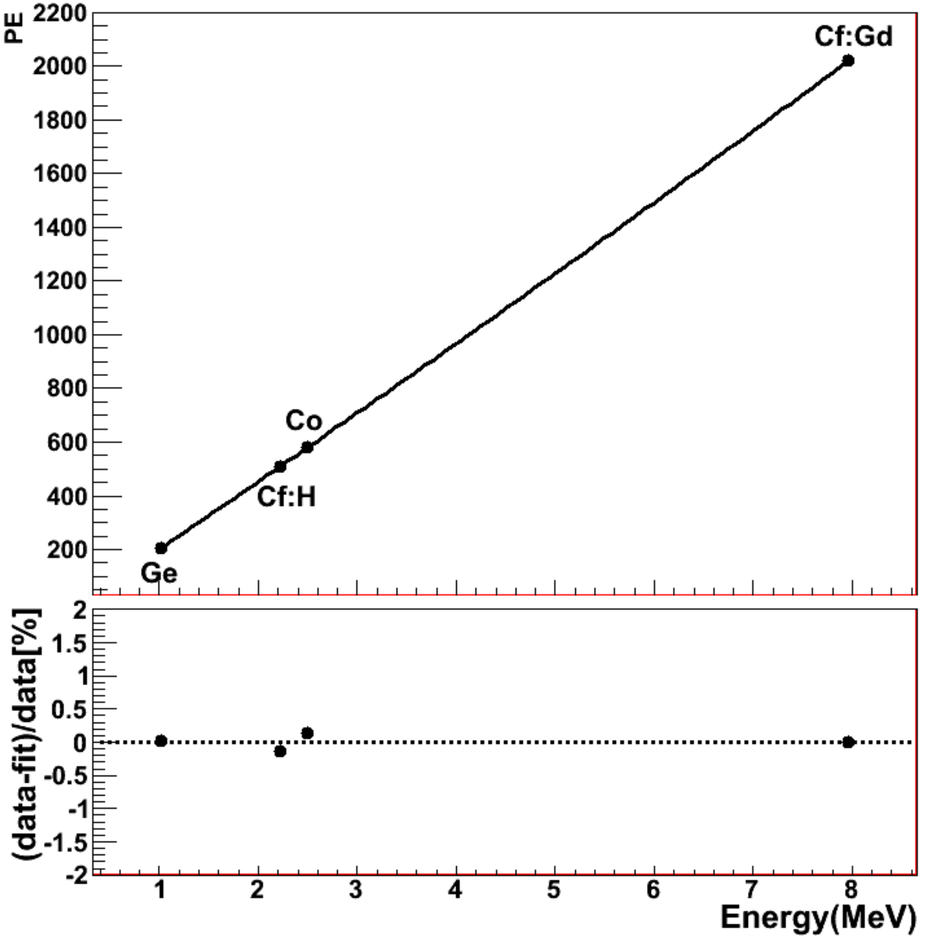


Energy Calibration

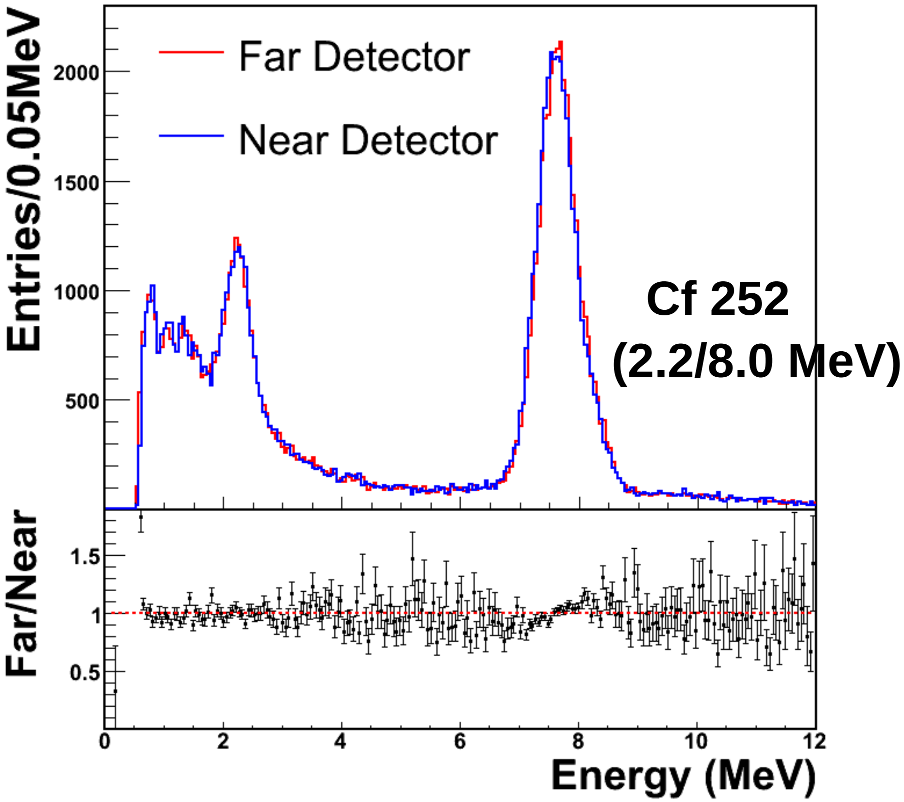
Far Detector

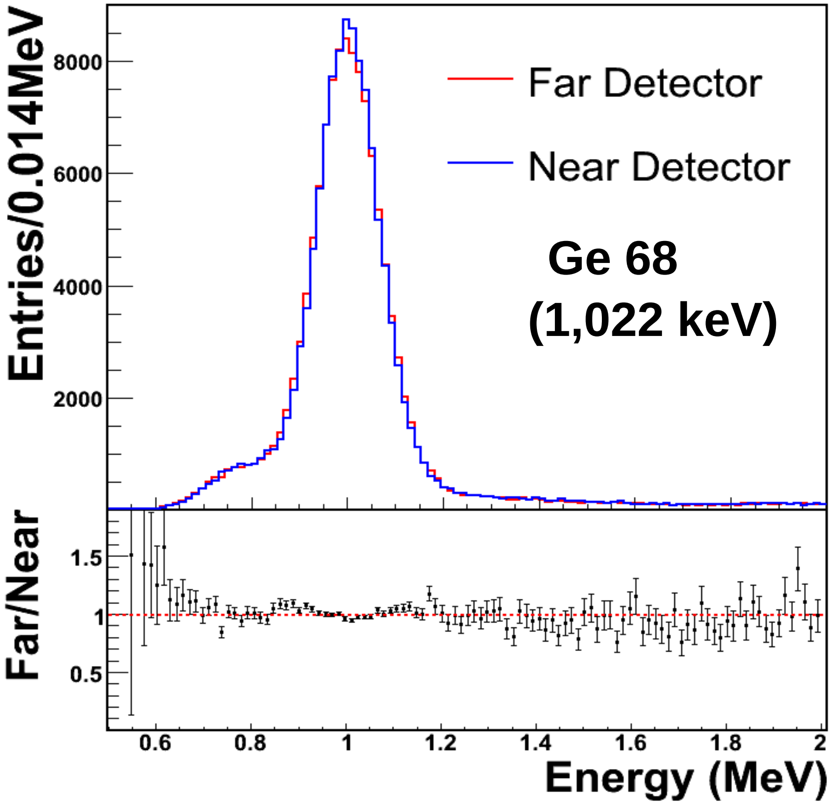


Near Detector



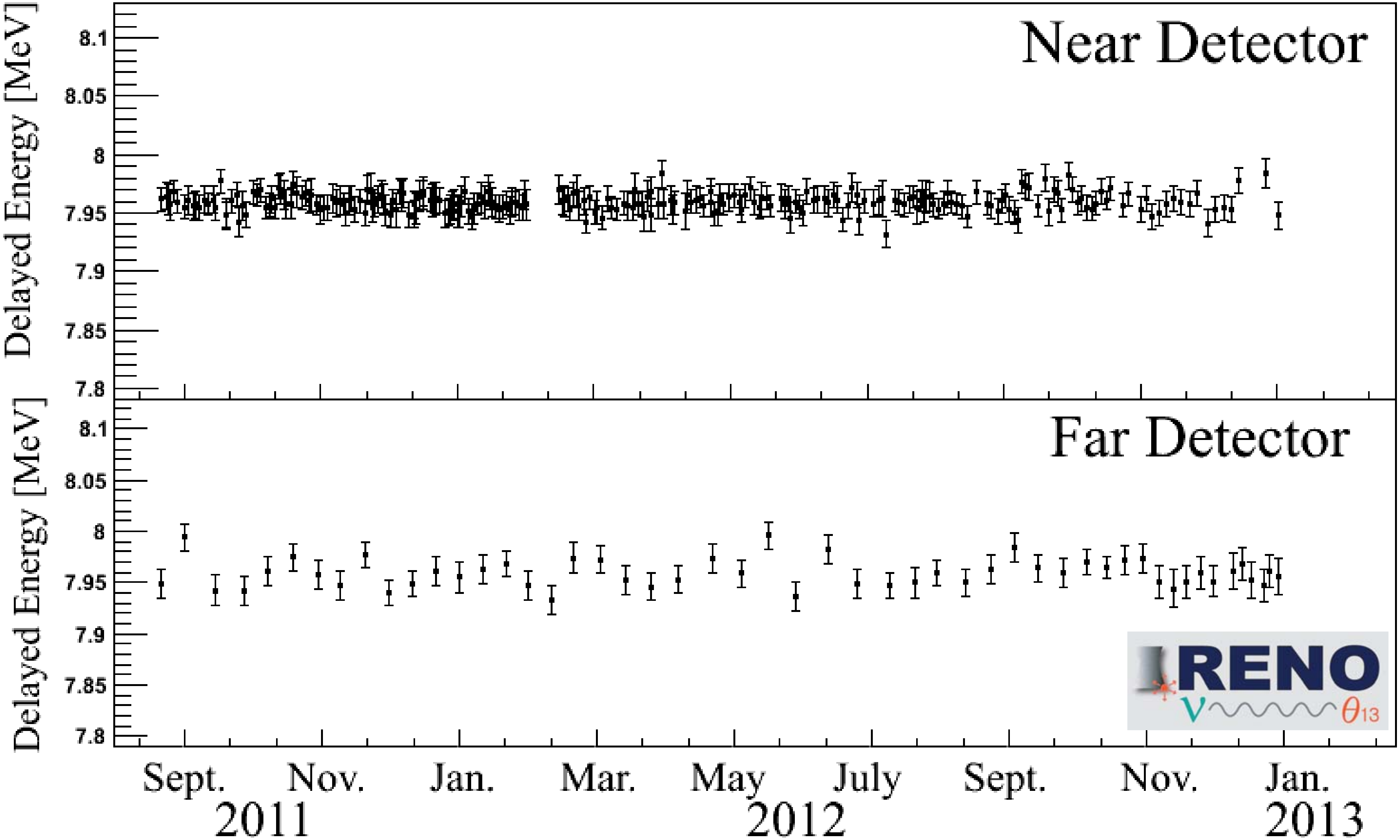
Energy Calibration





Detector Stability of Energy Scale

- IBD candidate's delayed signals (neutron capture by Gd)



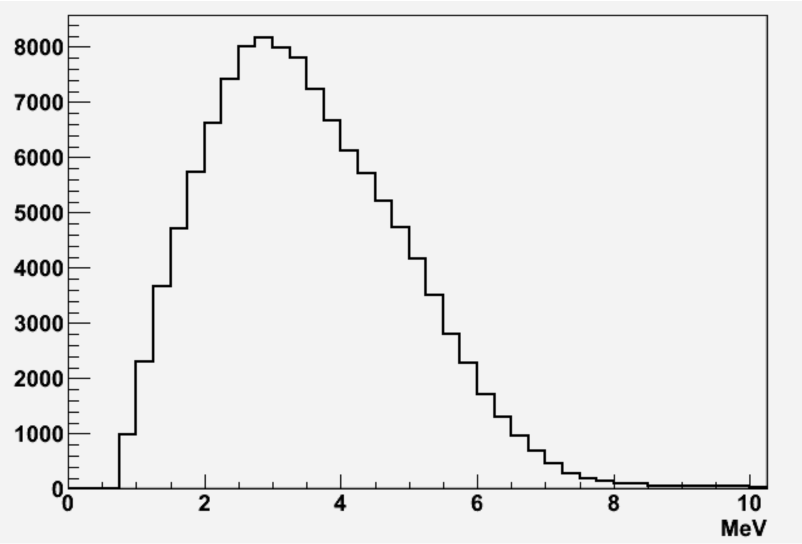
IBD Event Signature

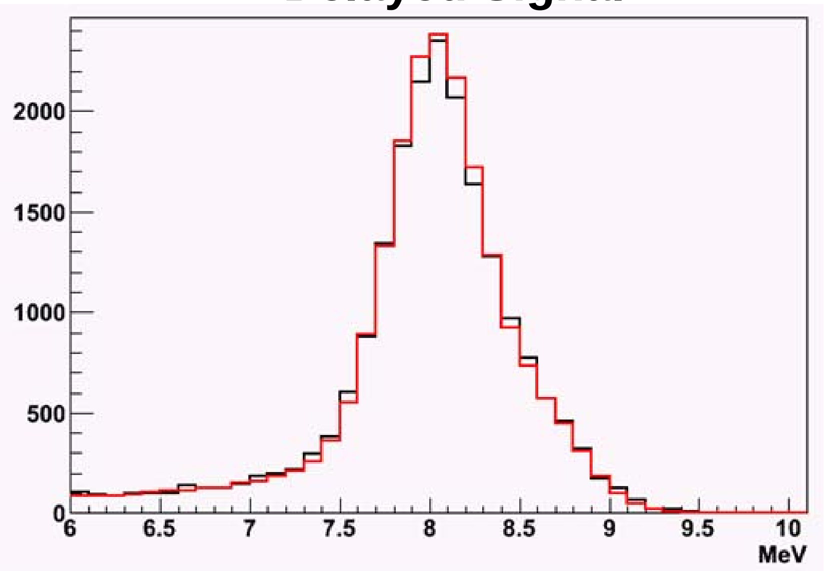
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

- 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

~26 μs (0.1% Gd) in LS

Prompt Signal → **Delayed Signal**

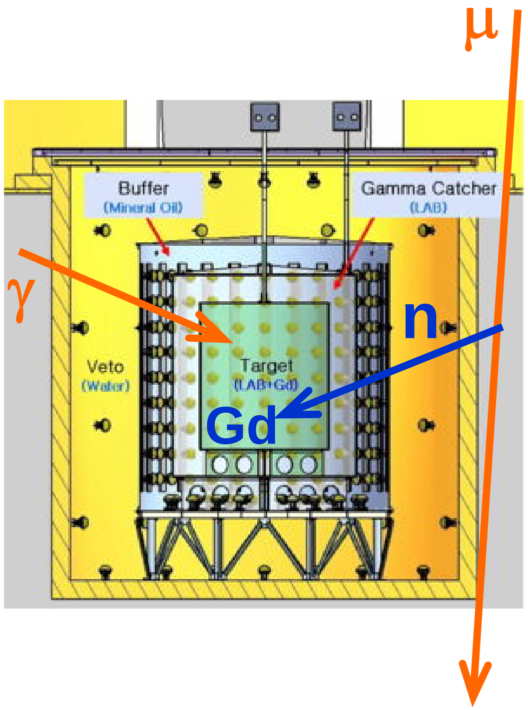




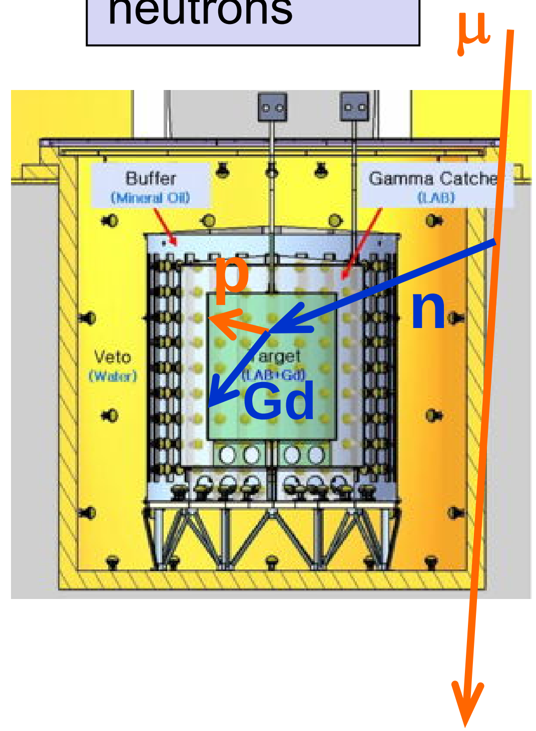
Backgrounds

- 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

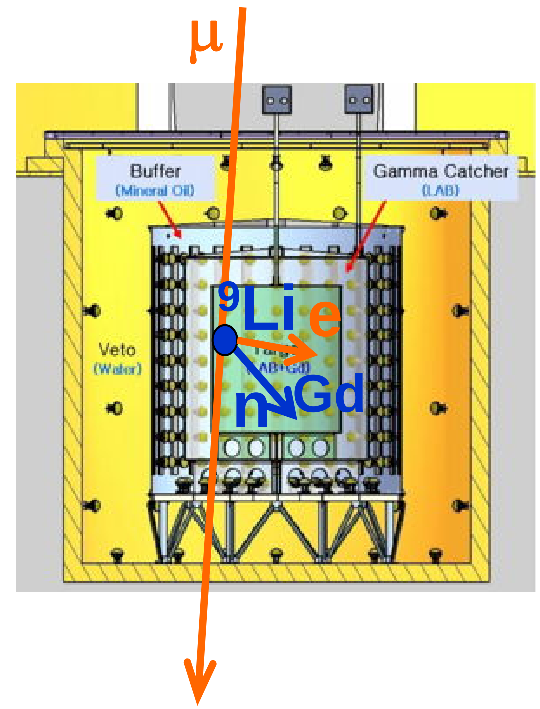
Accidentals



Fast neutrons

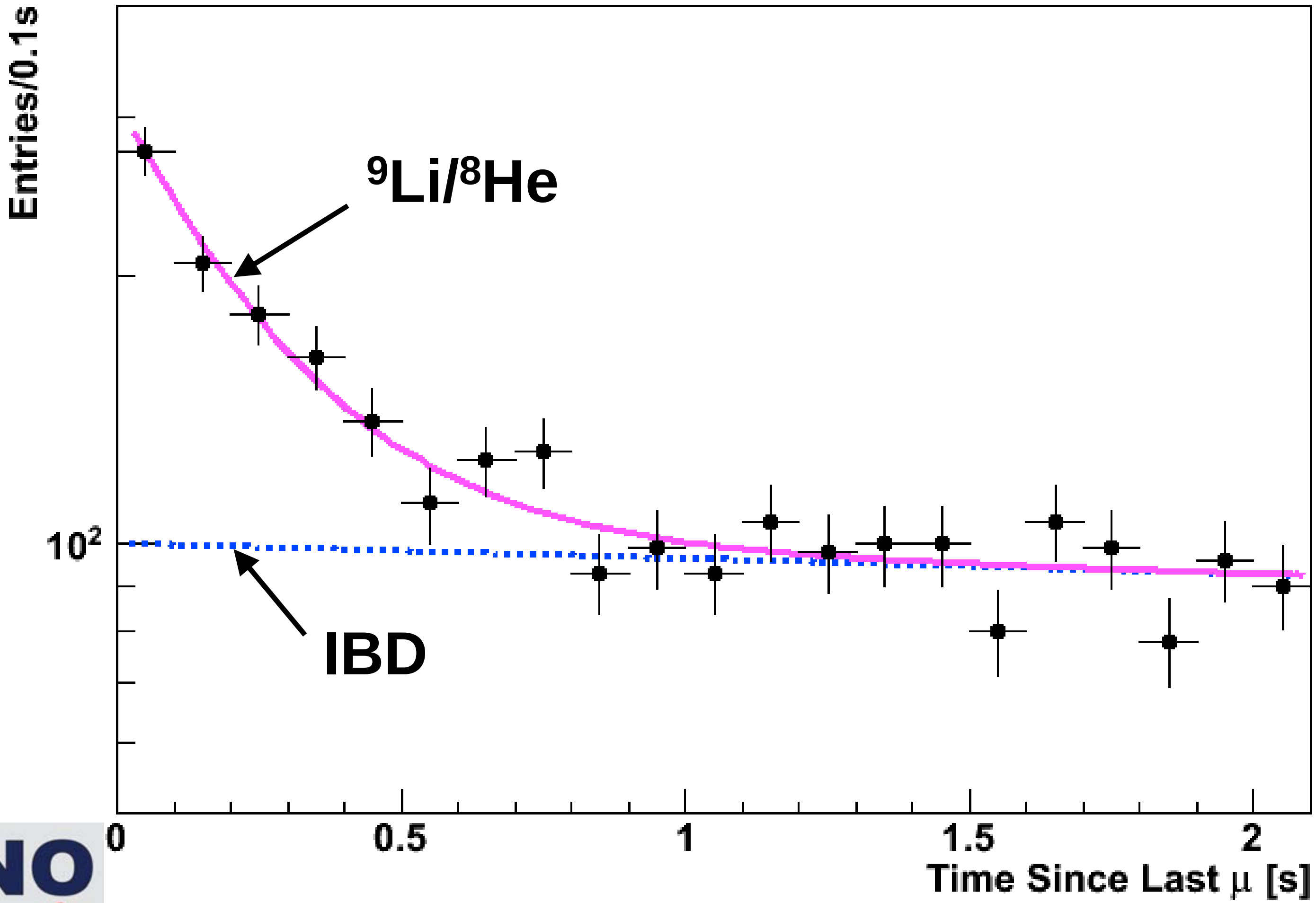


^{9}Li/^{8}He β-n followers



$^{9}Li/^{8}He$ Background

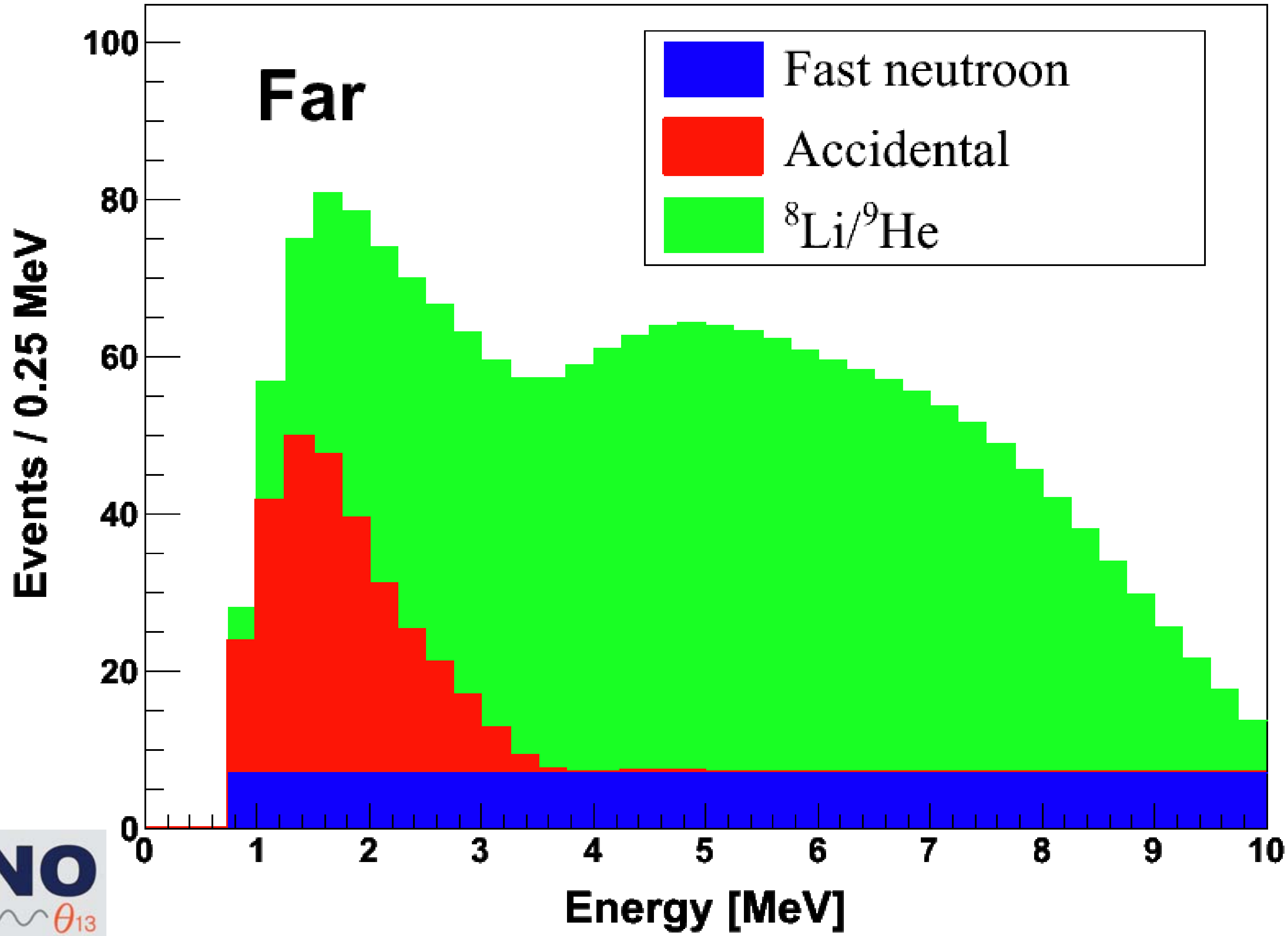
- $^{9}Li/^{8}He$ are unstable isotopes emitting (β,n) followers and produced when a muon interacts with carbon in the LS.



Background Spectra

- Background shapes and rates are well understood

- Total backgrounds : 6.5% at Far
  2.7% at Near



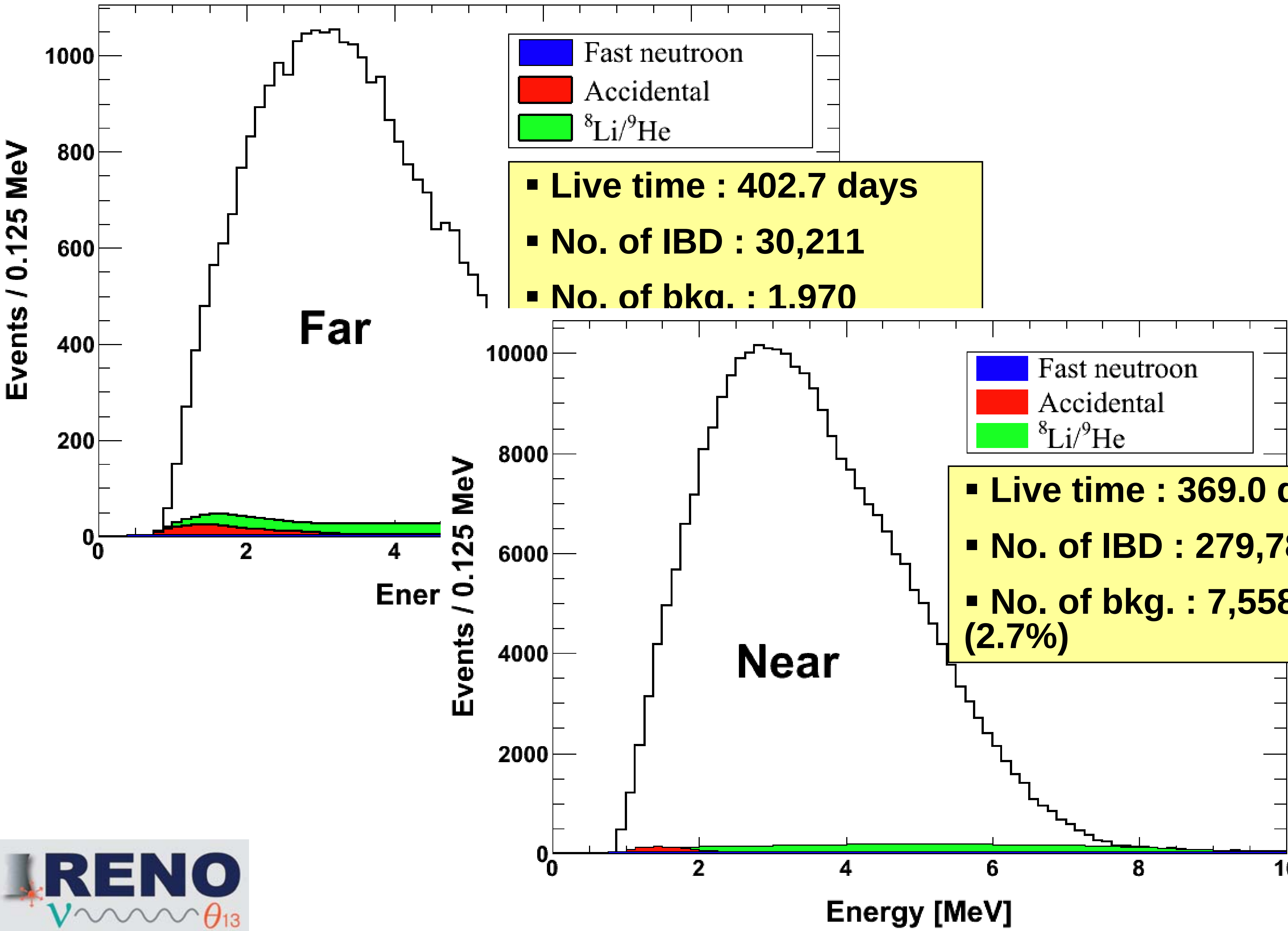
Summary of Final Data Sample

(Prompt energy < 10 MeV)

Detector	Near	Far
Selected events	279787	30211
Total background rate (per day)	20.48± 2.13	4.89± 0.60
IBD rate after background subtraction (per day)	737.69± 2.58	70.13± 0.75
DAQ Live time (days)	369.03	402.69
Detection efficiency (ϵ)	62.0± 0.014	71.4± 0.014
Accidental rate (per day)	3.61± 0.05	0.60± 0.03
^{9}Li/^{8}He rate (per day)	13.73± 2.13	3.61± 0.60
Fast neutron rate (per day)	3.14± 0.09	0.68± 0.04

RENO ν θ_{13}

Measured Spectra of IBD Prompt Signal

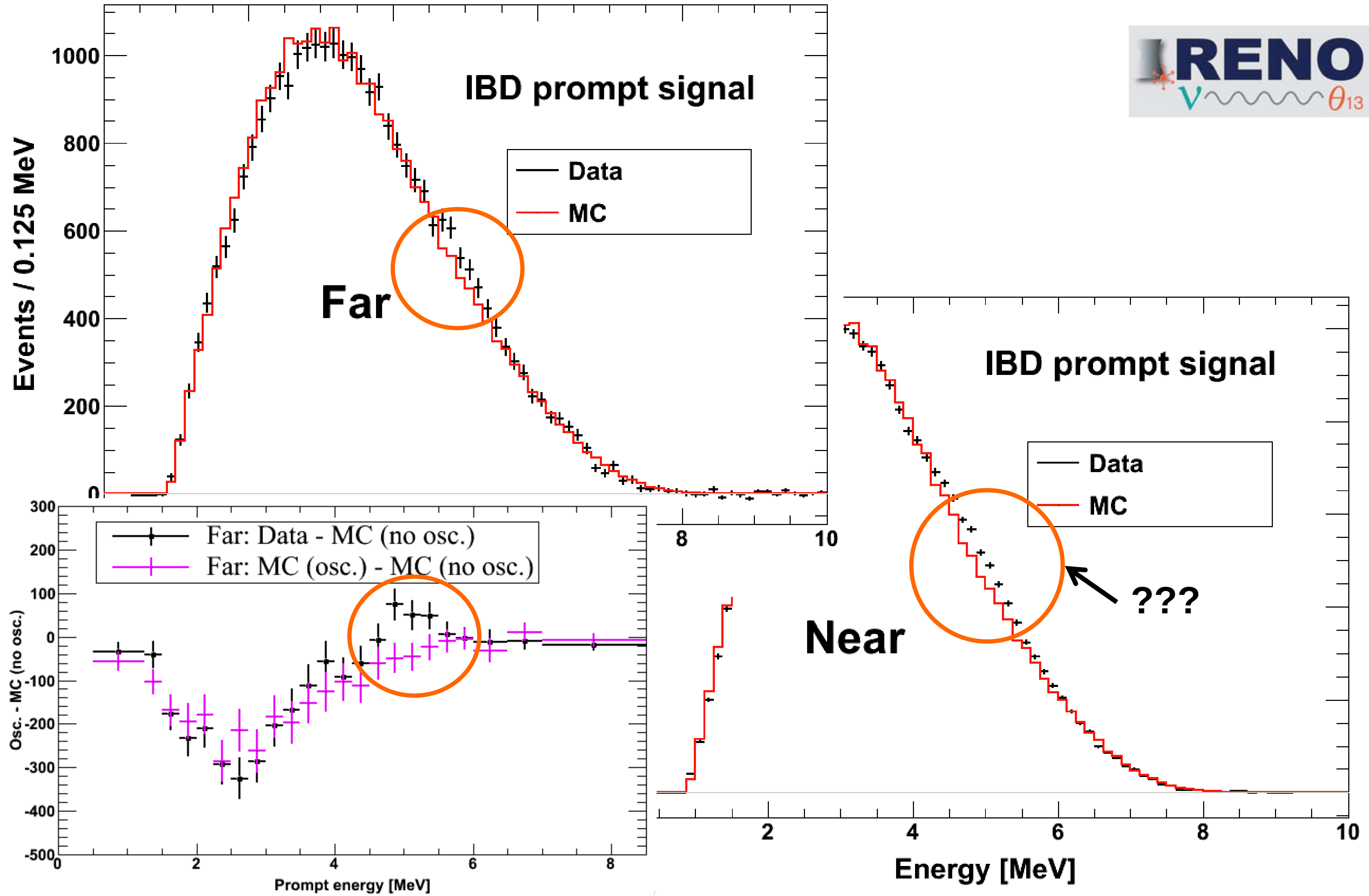


- Live time : 402.7 days
- No. of IBD : 30,211
- No. of bkg. : 1,970

- Live time : 369.0 days
- No. of IBD : 279,787
- No. of bkg. : 7,558 (2.7%)

RENO

IBD Prompt Signal (Data vs. MC)



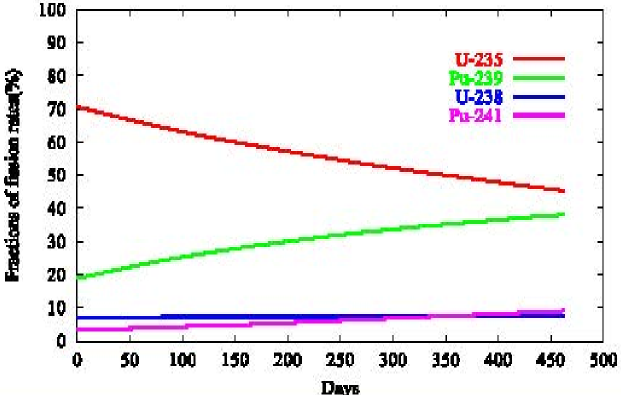
Expected Reactor Antineutrino Fluxes

- Reactor neutrino flux

$$\Phi(E_\nu) = \frac{P_{th}}{\sum_i^{isotopes} f_i \cdot E_i} \sum_i^{isotopes} f_i \cdot \phi_i(E_\nu)$$

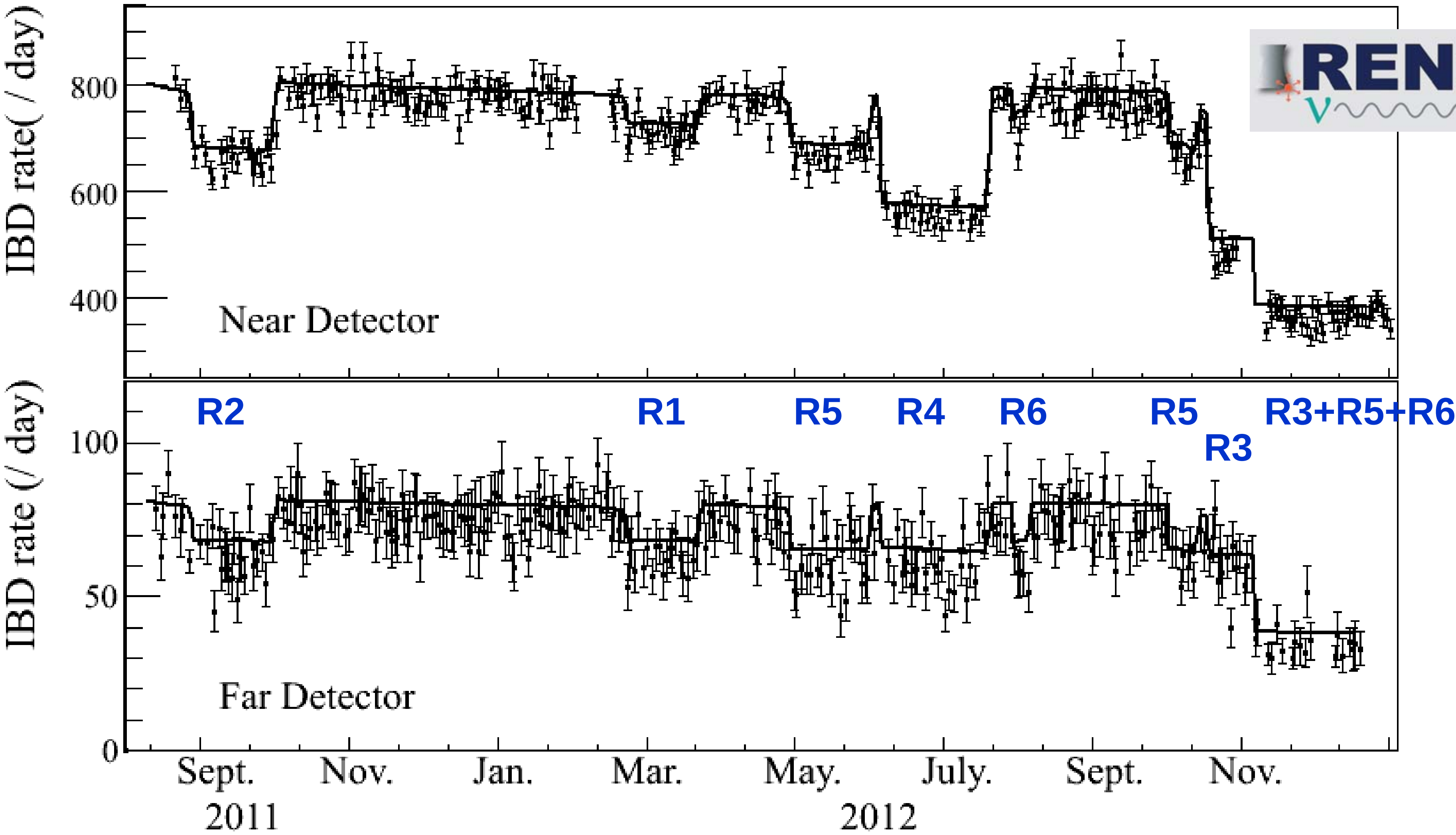
- P_{th} : Reactor thermal power provided by the YG nuclear power plant
- f_i : Fission fraction of each isotope determined by reactor core simulation of Westinghouse ANC
- $\phi_i(E_\nu)$: Neutrino spectrum of each fission isotope
  [* P. Huber, Phys. Rev. C84, 024617 (2011)
  T. Mueller *et al*., Phys. Rev. C83, 054615 (2011)]
- E_i : Energy released per fission
  [* V. Kopeikin *et al*., Phys. Atom. Nucl. 67, 1982 (2004)]

Isotopes	James	Kopeikin
^{235}U	201.7±0.6	201.92±0.46
^{238}U	205.0±0.9	205.52±0.96
^{239}Pu	210.0±0.9	209.99±0.60
^{241}Pu	212.4±1.0	213.60±0.65

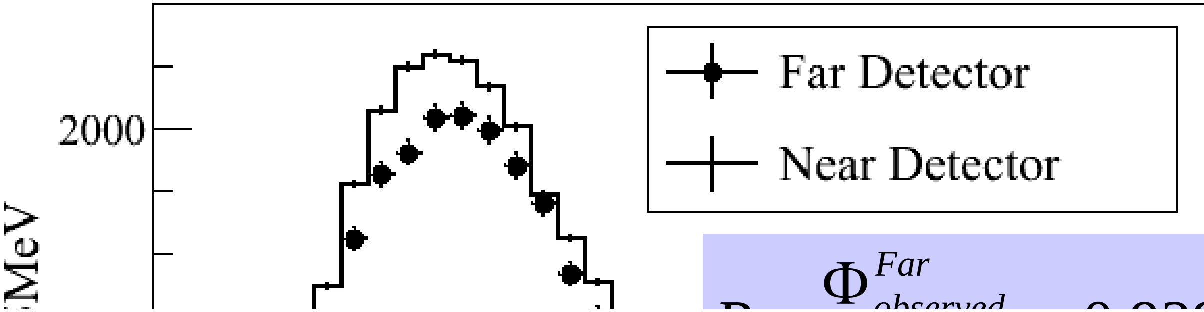


Observed Daily Averaged IBD Rate

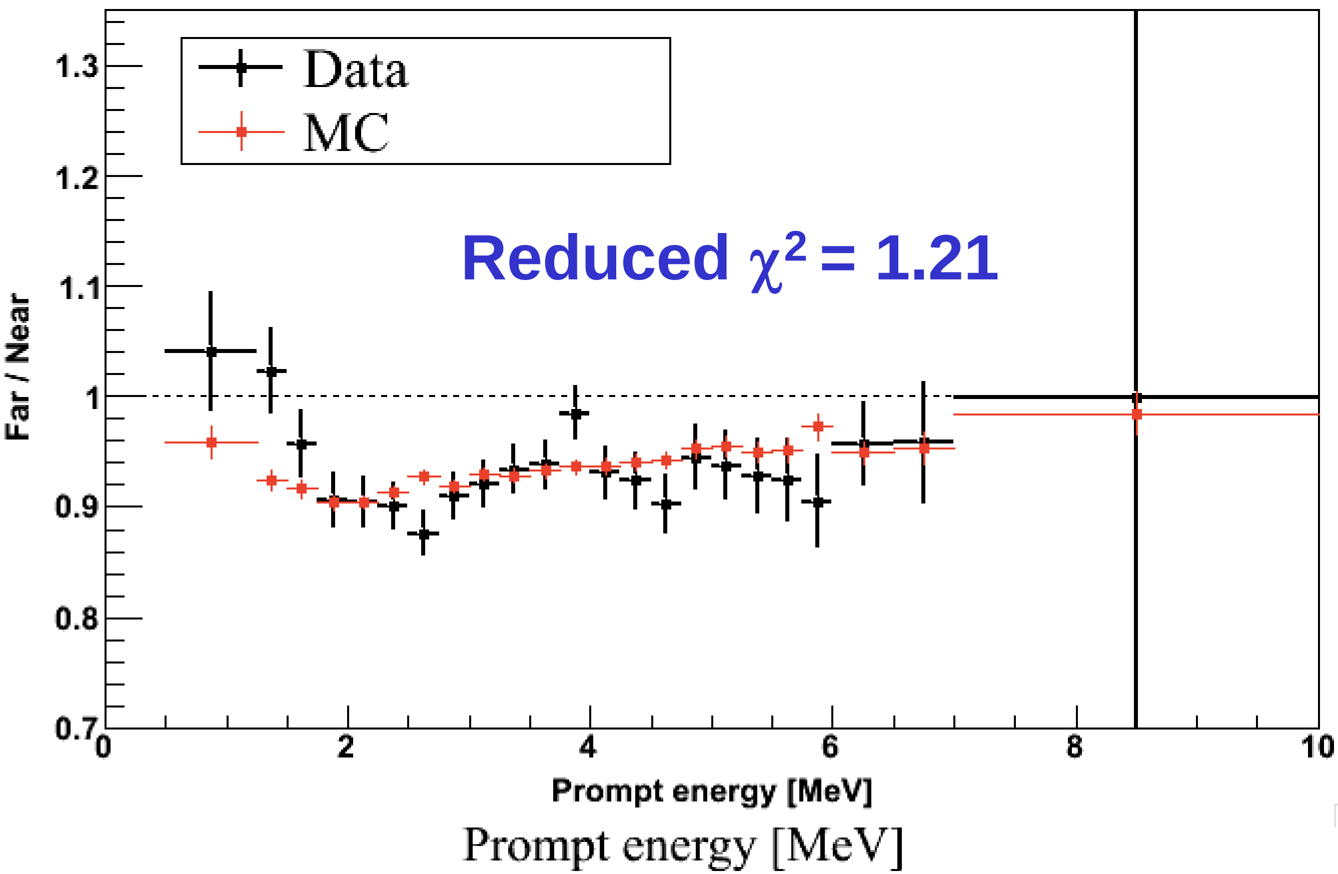
- A new way to measure the reactor thermal power remotely!!!



Reactor Antineutrino Disappearance



$\Phi^{Far}_{observed}$ ... $006(stat) \pm 0.009(syst)$

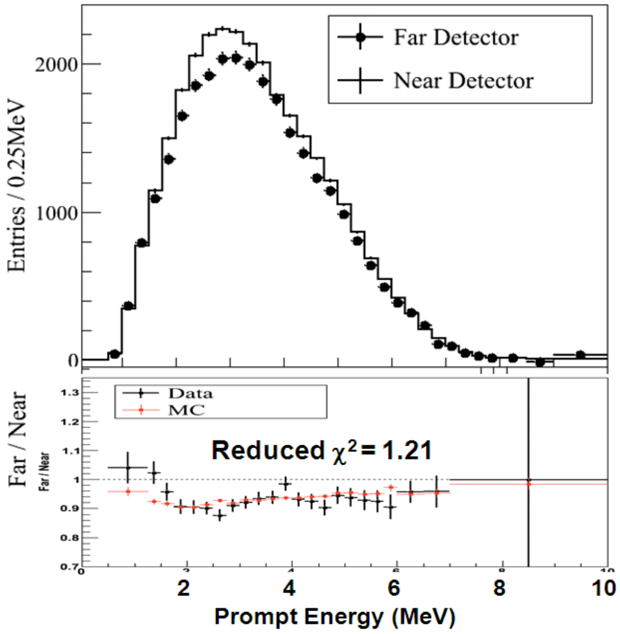


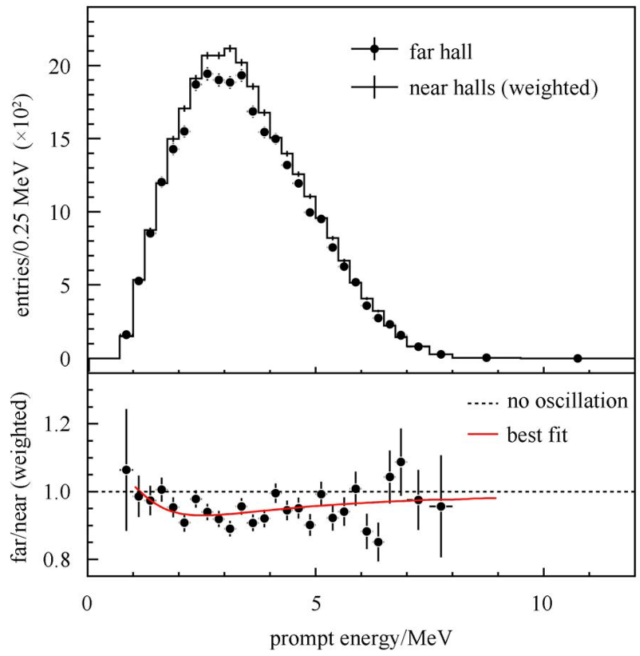
clear deficit in rate
% reduction)

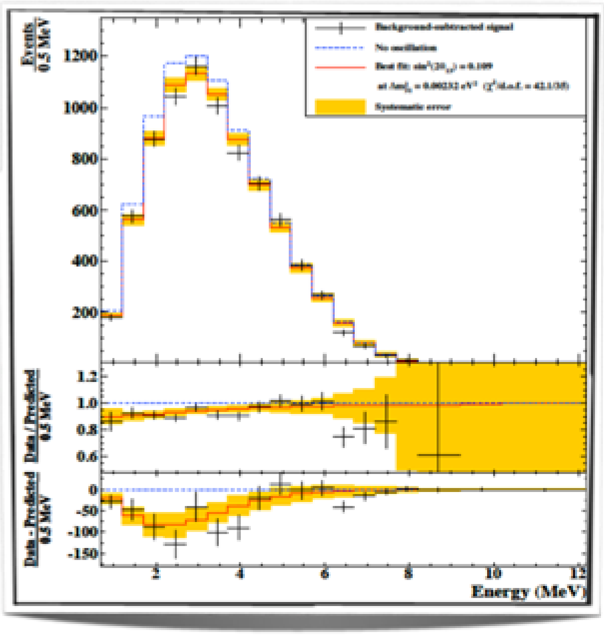
onsistent with neutrino
illation in the spectral
ortion

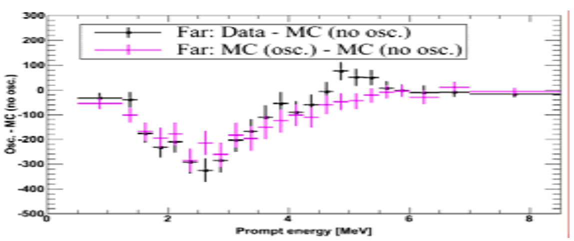
RENO ν θ_{13}

Reactor Antineutrino Oscillations







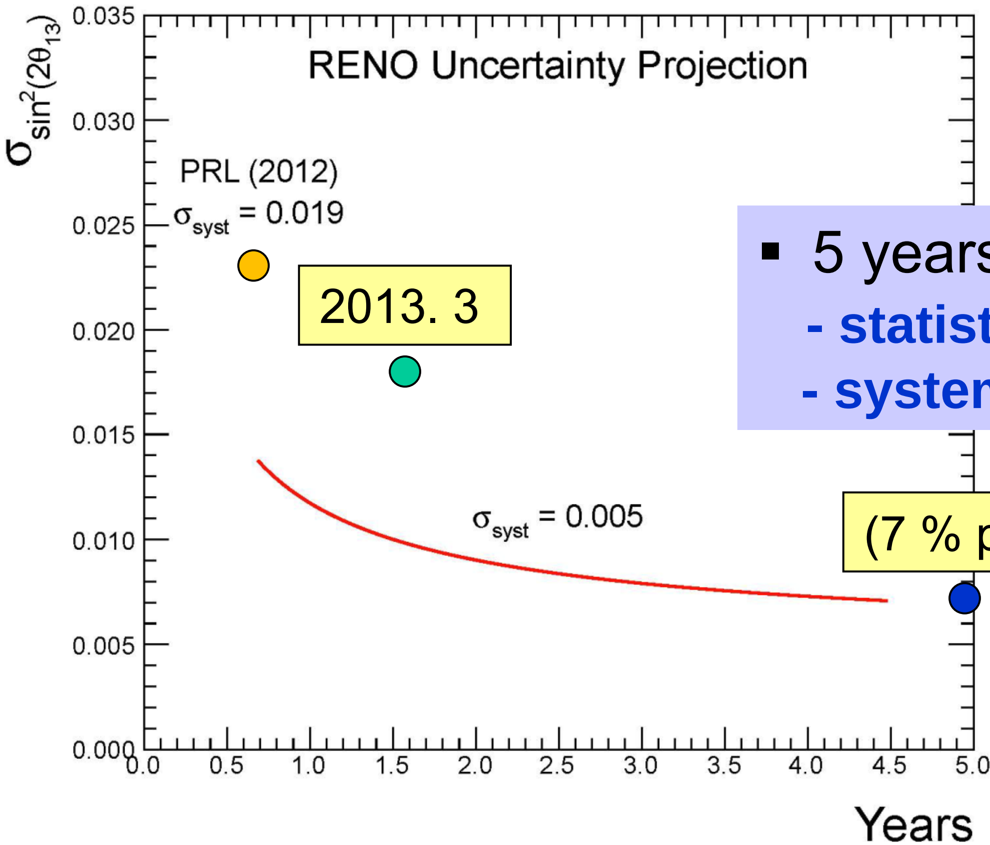


RENO's Projected Sensitivity of θ_{13}

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

(402 days) 0.100 ± 0.018 (5.6 σ) (18 % precision)

→ ± 0.007 (~ 13 σ) (5 years) (7 % precision)

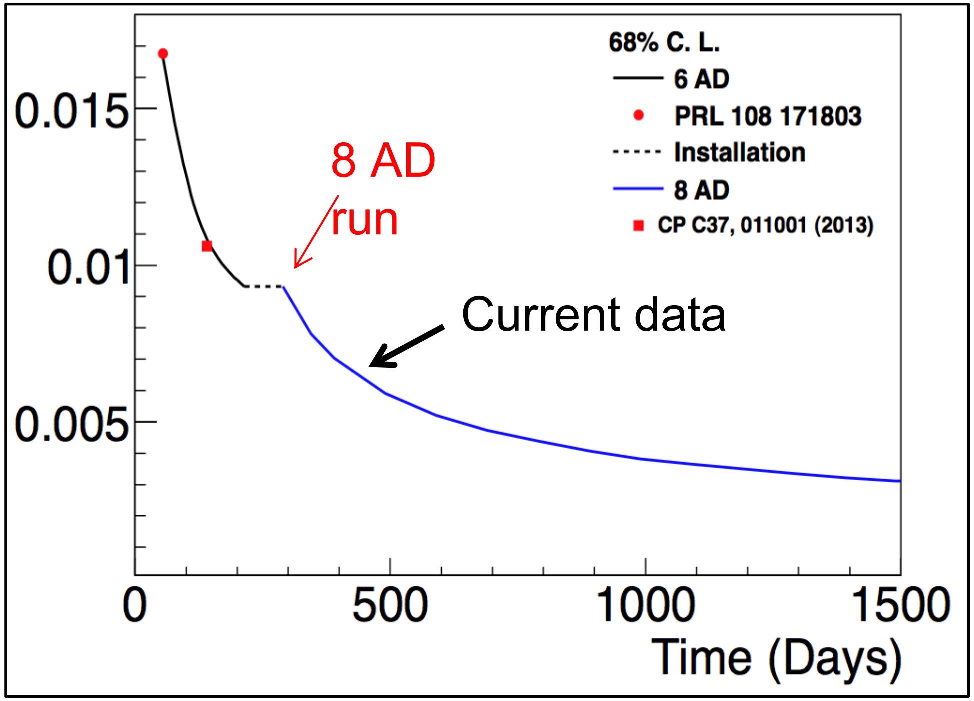


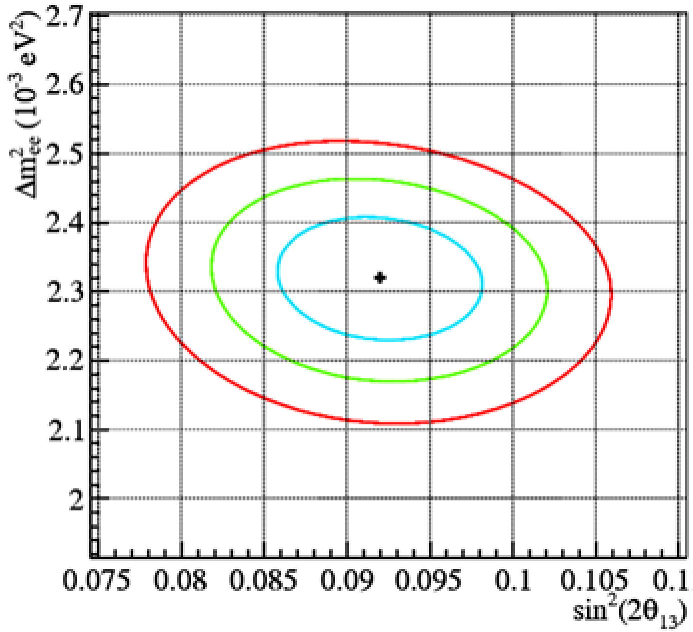
2013. 3

(7 % precision)

- 5 years of data : ± 0.007 (7% precision)
  - **- statistical error : $\pm 0.010 \rightarrow \pm 0.005$**
  - **- systematic error : $\pm 0.015 \rightarrow \pm 0.005$**

Daya Bay Projected Senstivity

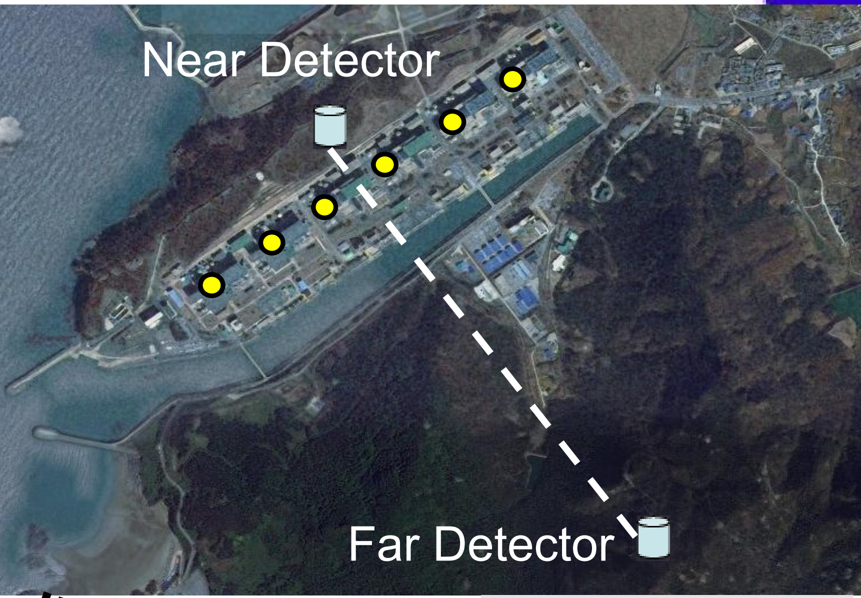


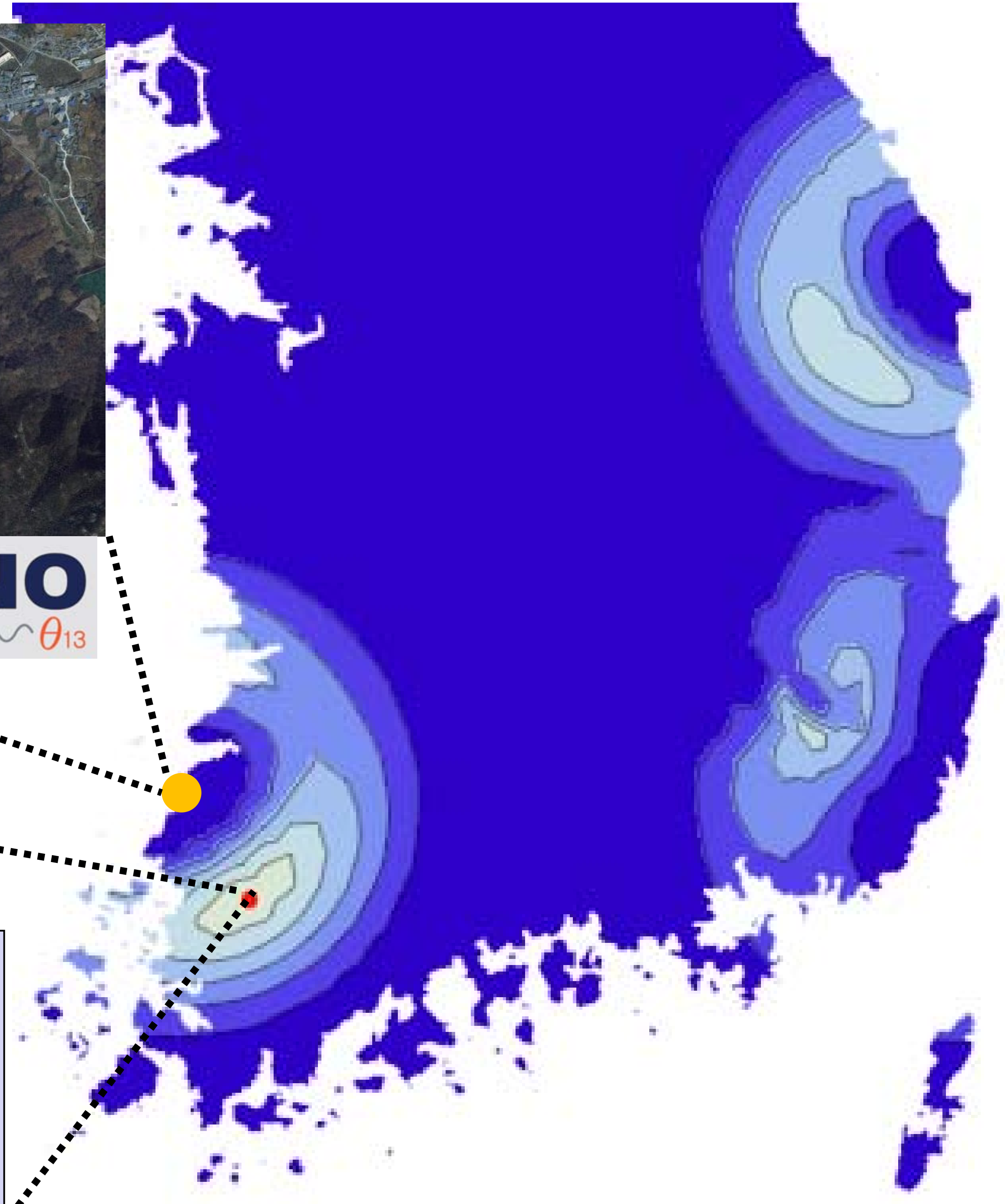


- Released: 12.5% precision
  - ⇨ $\sin^2 2\theta_{13} = 0.089 \pm 0.011$
- Projected: 4%
- At least 5 years' operation

Physics:

1. measure $\sin^2 2\theta_{13}$ to 4% precision
2. Precise reactor ν spectrum
3. Direct measurement of Δm^2_{31}
4. Cosmogenic neutrons, isotopes
5. Exotic searches





RENO-50

18 kton LS Detector
~47 km from YG reactors

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

Summary

- A clear disappearance of reactor antineutrinos is observed. The smallest mixing angle θ_{13} that was the most elusive puzzle of neutrino oscillations, is firmly measured by the reactor experiments.

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

$$\sin^2 2\theta_{13} = \sin^2 2\theta_{13} = 0.090 \pm 0.009 \; 005(syst)$$ (Daya Bay)

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

- A surprisingly large value of θ_{13} will strongly promote the next round of neutrino experiments to find the CP phase and determine the mass hierarchy.

- Precise measurement of θ_{13} by the reactor experiments [Daya Bay: 4%, RENO: 7%, Double Chooz: 10% from 5 years of data] will provide the first glimpse of $\delta_{CP.}$ if accelerator results are combined.