Observation of Reactor Antineutrino Disappearance at RENO

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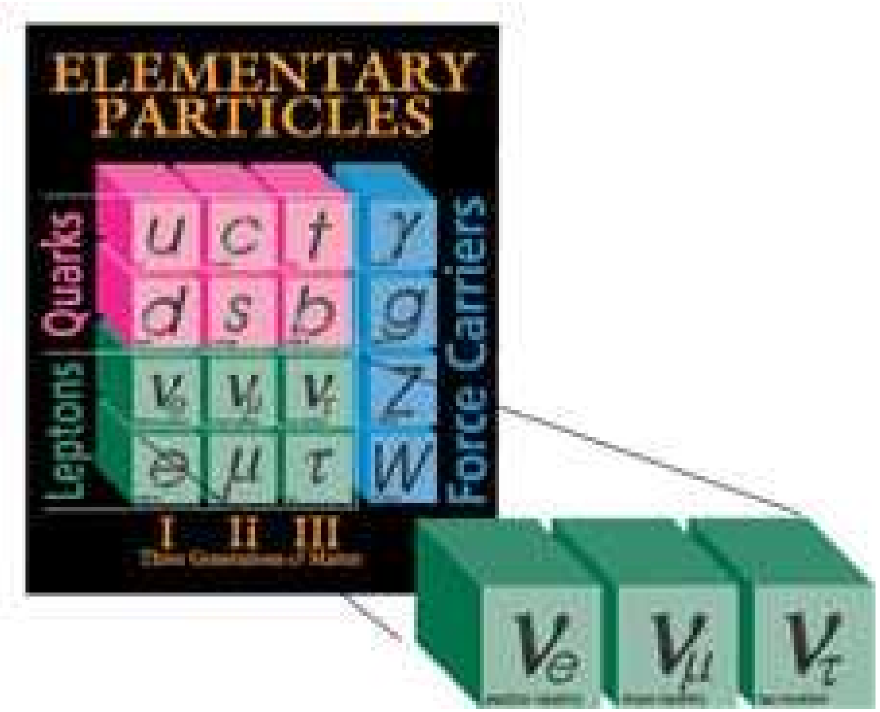
(presented at KEK on May 17, 2012)

Outline

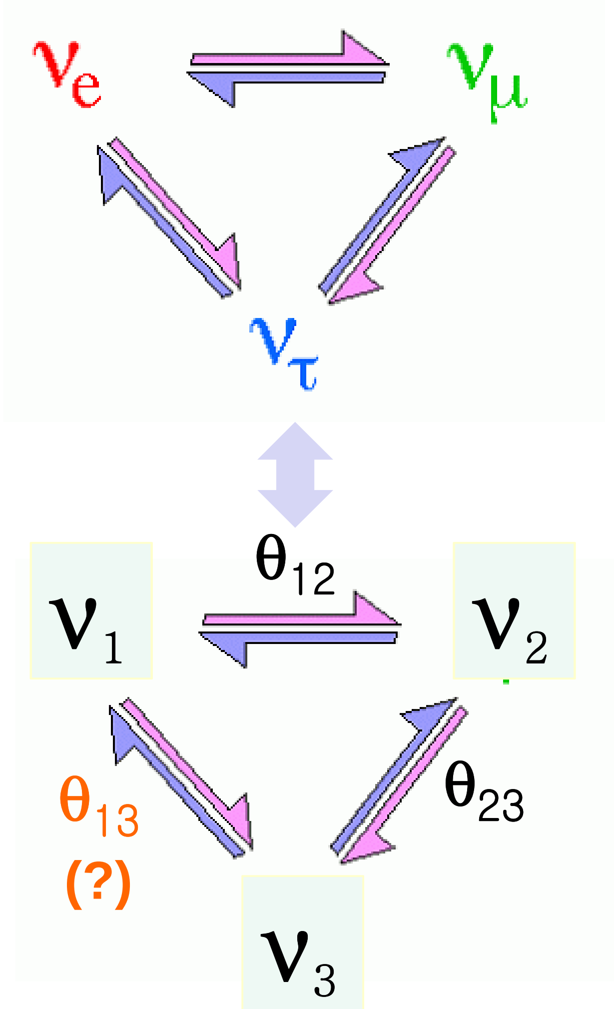
- Introduction
- Experimental setup & detector
- Data-taking & data set
- Calibration
- Event selection
- Efficiency & Background
- Reactor antineutrino prediction
- Systematic uncertainties
- Results
- Summary

YongGwang (靈光) :

Neutrino Oscillation



PMNS Neutrino Mixing Angles and CP Violation



Reactor Antineutrino Oscillation

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{1.27\Delta m^2_{31} L}{E_\nu}\right)$$

θ_{13} from Reactor and Accelerator Experiments

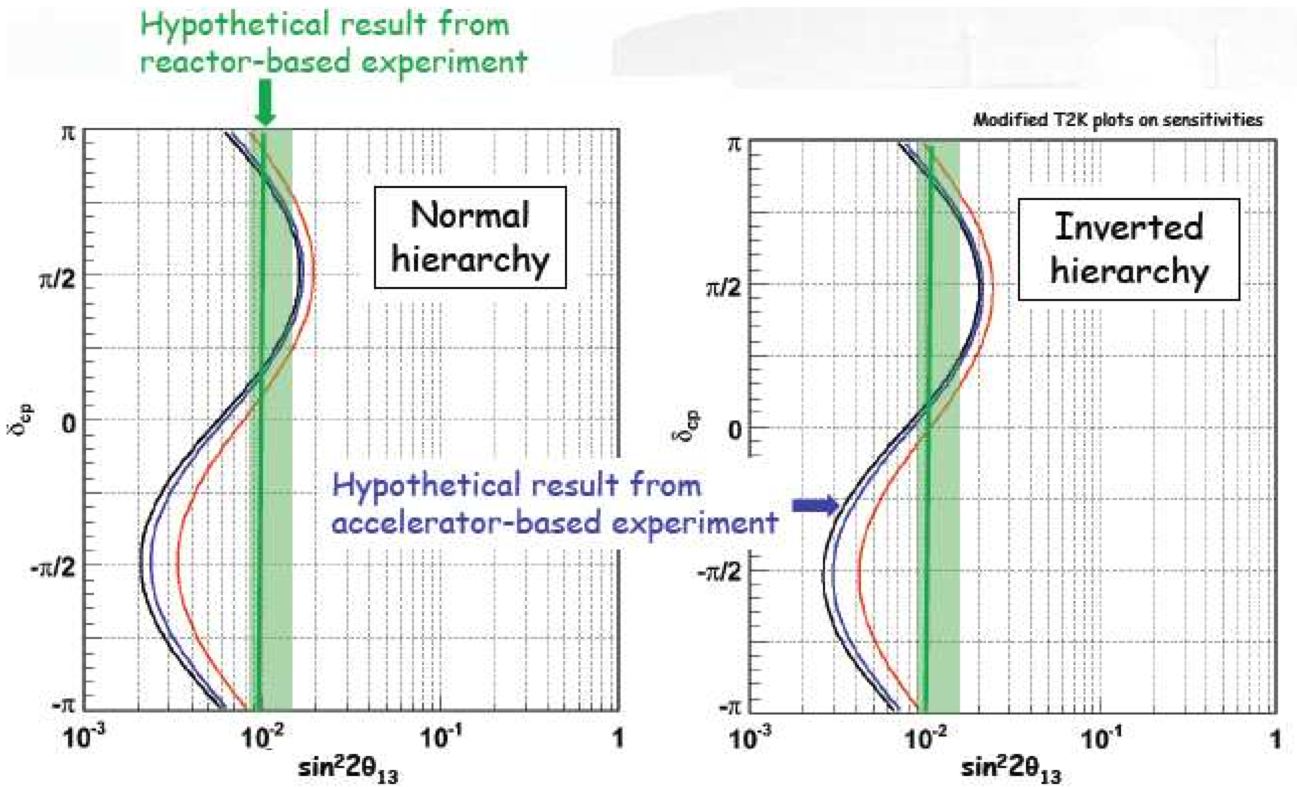
* Reactor

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

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

* Accelerator

- mass hierarchy + CP violation + matter effects



- Complementarity :

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

Efforts for Finding θ_{13}

- Chooz (2003) & Palo Verde (2000): No signal

$\sin^2(2\theta_{13}) < 0.12$ at 90% C.L.

- T2K : 2.5 σ excess (2011)

$0.03 < \sin^2(2\theta_{13}) < 0.28$ at 90% C.L. for N.H.

$0.04 < \sin^2(2\theta_{13}) < 0.34$ at 90% C.L. for I.H.

- MINOS : 1.7 σ excess (2011)

$0 < \sin^2(2\theta_{13}) < 0.12$ at 90% C.L. for N.H.

$0.04 < \sin^2(2\theta_{13}) < 0.19$ at 90% C.L. for I.H.

- Double Chooz : 1.7 σ measurement (2011)

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

- Daya Bay (Mar. 8. 2012)

5.2 σ observation

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

- RENO (Apr. 2. 2012)

4.9 σ observation

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

Published in PRL

- Submitted on Apr. 2, and resubmitted on Apr. 6 after revision
- Accepted on Apr. 23 for publication
- Published on May 11 (Daya Bay PRL : April 27)

To be included in a new edition of Particle Data Listing this year

LEPTONS

Neutrino Mixing

(A) Neutrino fluxes and event ratios

Events (observed/expected) from reactor $\overline{\nu}_e$ experiments.

$0.944 \pm 0.016 \pm 0.040$	[1] ABE	12	DCHZ	Chooz reactors
$0.920 \pm 0.009 \pm 0.014$	[2] AHN	12	RENO	Yonggwang reactors
$0.940 \pm 0.011 \pm 0.004$	[3] AN	12	DAYA	Daya Bay, Ling Ao, Ling Ao-II reactors
$1.08 \pm 0.21 \pm 0.16$	[4] DENIZ	10	TEXO	Kuo-Sheng reactor, 28 m
$0.658 \pm 0.044 \pm 0.047$	[5] ARAKI	05	KLND	Japanese react. $\sim$ 180 km
$0.611 \pm 0.085 \pm 0.041$	[6] EGUCHI	03	KLND	Japanese react. $\sim$ 180 km
$1.01 \pm 0.024 \pm 0.053$	[7] BOEHM	01		Palo Verde react. 0.75–0.89 km
$1.01 \pm 0.028 \pm 0.027$	[8] APOLLONIO	99	CHOZ	Chooz reactors 1 km

(B) Three-neutrino mixing parameters

$\sin^2(2\theta_{13})$

At present time direct measurements of $\sin^2(2\theta_{13})$ are derived from the reactor $\overline{\nu}_e$ disappearance at distances corresponding to the Δm^2_{32} value, i.e. L $\sim$ 1km. Alternatively, limits can also be obtained from the analysis of the solar neutrino data and accelerator-based $\nu_\mu \rightarrow \nu_e$ experiments.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
0.098 ± 0.013 OUR AVERAGE					
$0.086 \pm 0.041 \pm 0.030$		[1] ABE	12	DCHZ	Chooz reactors
$0.113 \pm 0.013 \pm 0.019$		[2] AHN	12	RENO	Yonggwang reactors
$0.092 \pm 0.016 \pm 0.005$		[3] AN	12	DAYA	Daya Bay, Ling Ao, Ling Ao-II reactors
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.85 {+0.04 \atop -0.03}$	68	[4] ABE	11	FIT	KamLAND + global solar
< 0.23	95	[5] ABE	11	FIT	Global solar
0.05 - 0.21	68	[6] ABE	11A	T2K	Normal mass hierarchy
0.06 - 0.25	68	[7] ABE	11A	T2K	Inverted mass hierarchy
0.01 - 0.09	68	[8] ADAMSON	11D	MINS	Normal mass hierarchy
0.03 - 0.15	68	[9] ADAMSON	11D	MINS	Inverted mass hierarchy
0.08 ± 0.03	68	[10] FOGLI	11	FIT	Global neutrino data

RENO Collaboration

RENO

ν θ_{13}

(12 institutions and 40 physicists)

- Chonbuk National University
- Chonnam National University
- Chung-Ang University
- Dongshin University
- Gyeongsang National University
- Kyungpook National University
- Pusan National University
- Sejong University
- Seokyeong University
- Seoul National University
- Seoyeong University
- Sungkyunkwan University

- Total cost : $10M
- Start of project : 2006
- The first experiment running with both near & far detectors from Aug. 2011

서울대 김수봉 교수가 이끄는 RENO 실험팀. 30여년간 관측에 실패한 마지막 중성미자 변환상수를 밝히기 위해 프랑스 중국과 치열한 경주를 벌이고 있다.

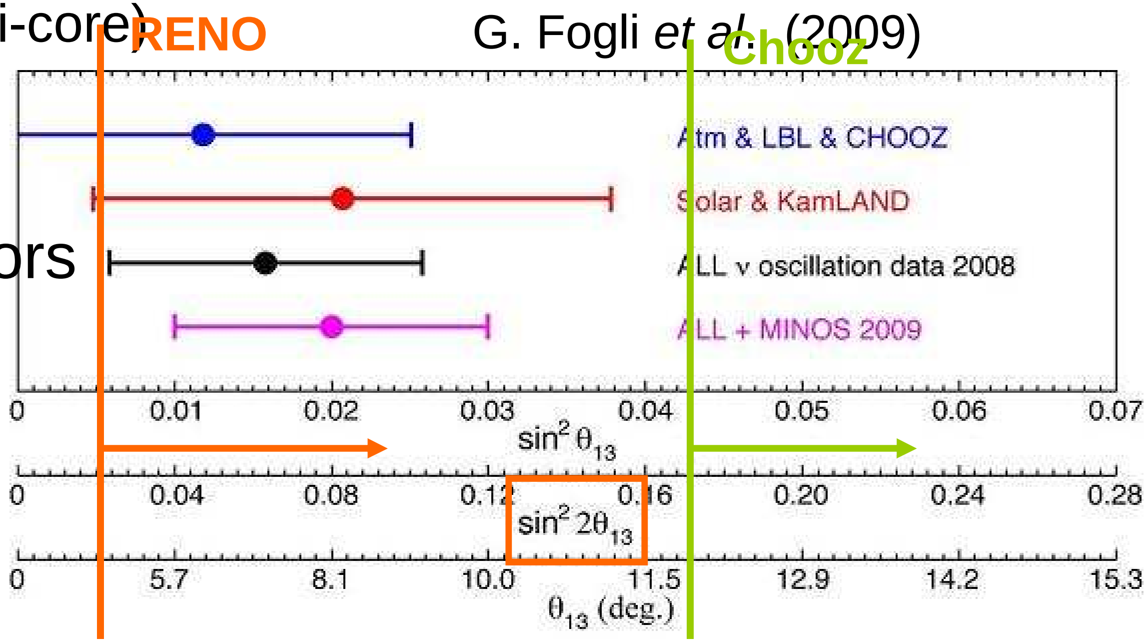
RENO Expected Sensitivity

- **CHOOZ : R_{osc} = 1.01 ± 2.8% (stat) ± 2.7% (syst)**
  $\sin^2(2\theta_{13}) < 0.17$ (90% C.L.)
- **RENO : statistical error : 2.8% → 0.3%**
  systematic error : 2.7% → <0.5%
  $\sin^2(2\theta_{13}) > 0.02$ (for 90% C.L.)
  $\sin^2(2\theta_{13}) > 0.035$ (for 3σ discovery potential)

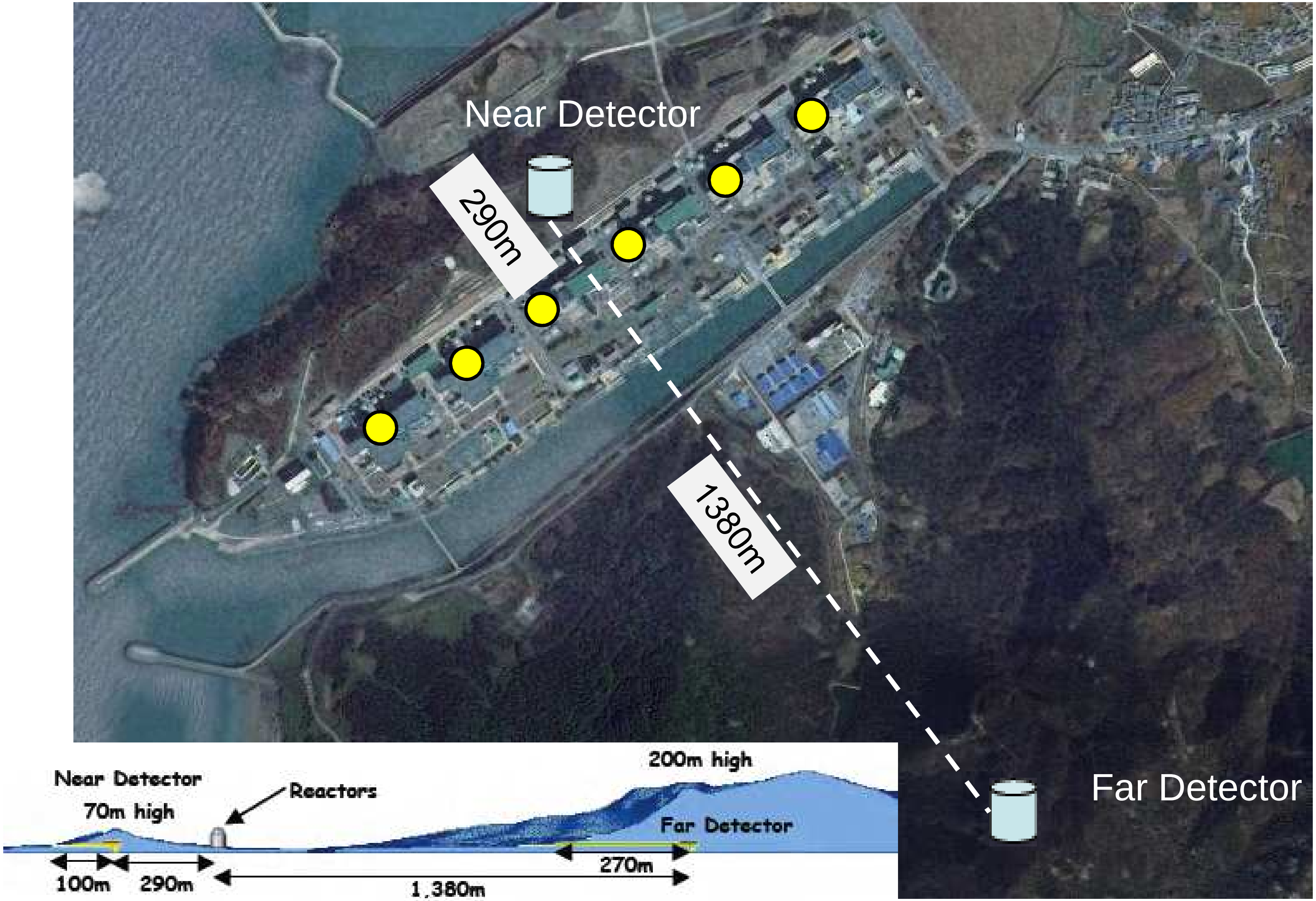
• 10 times better sensitivity

- Larger statistics
  - More powerful reactors (multi-core)
  - Larger detection volume
  - Longer exposure
- Smaller experimental errors
  - Identical multi detectors
- Lower background
  - Improved detector design
  - Increased overburden

G. Fogli *et al.* (2009)



RENO Experimental Setup

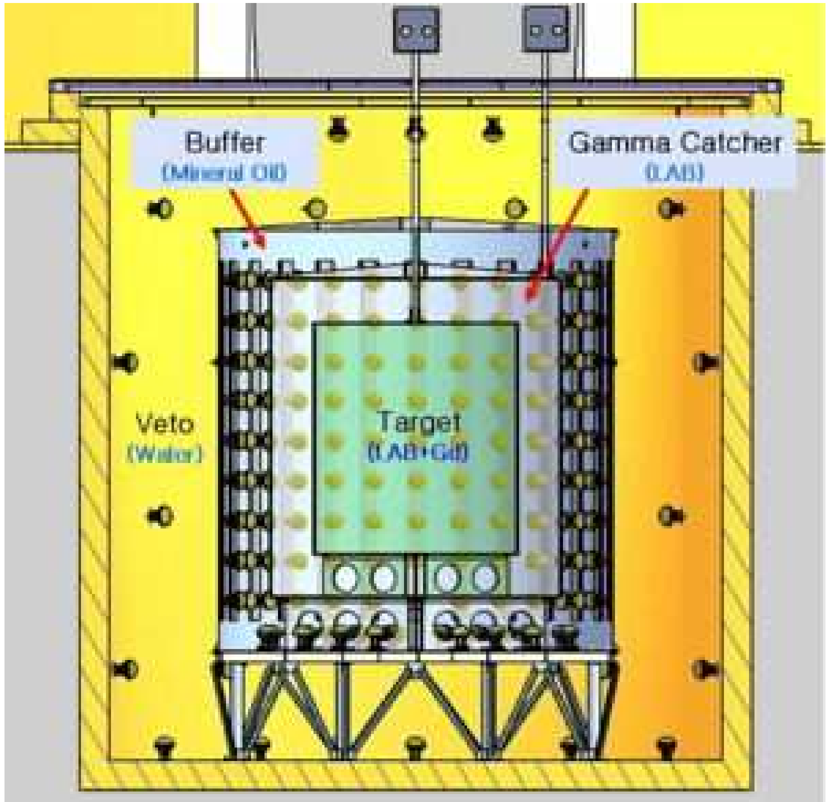


Contribution of Reactor to Neutrino Flux at Near & Far Detectors

Reactor #	Far (%)	Near (%)
1	13.73	6.78
2	15.74	14.93
3	18.09	34.19
4	18.56	27.01
5	17.80	11.50
6	16.08	5.58

- ❑ Accurate measurement of baseline distances to a precision of 10 cm using GPS and total station
- ❑ Accurate determination of reduction in the reactor neutrino fluxes after a baseline distance, much better than 0.1%

RENO Detector



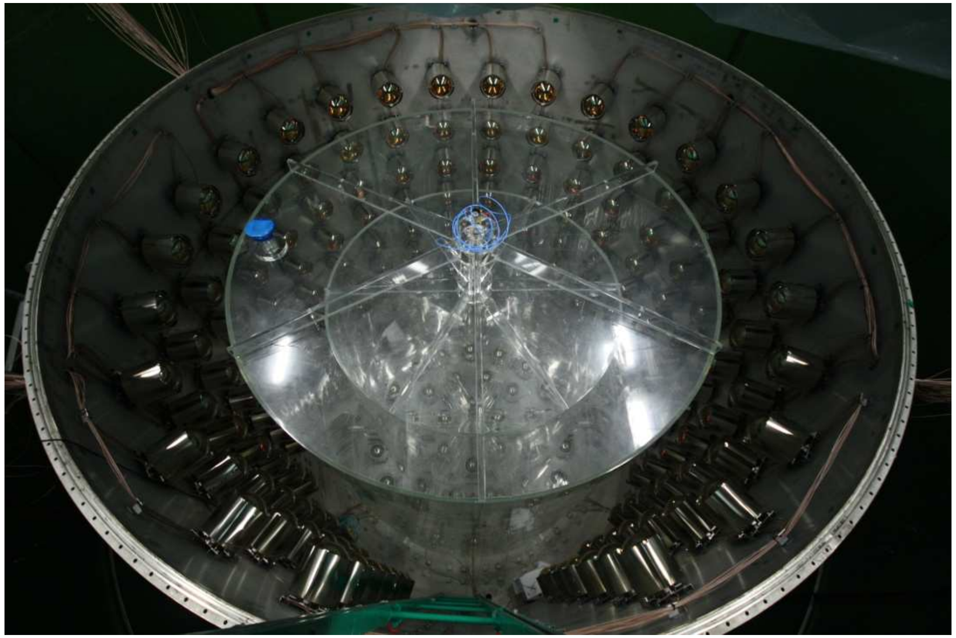
- 354 ID +67 OD 10” PMTs
- Target : 16.5 ton Gd-LS,   R=1.4m, H=3.2m
- Gamma Catcher : 30 ton LS,   R=2.0m, H=4.4m
- Buffer : 65 ton mineral oil,   R=2.7m, H=5.8m
- Veto : 350 ton water,   R=4.2m, H=8.8m

Summary of Detector Construction

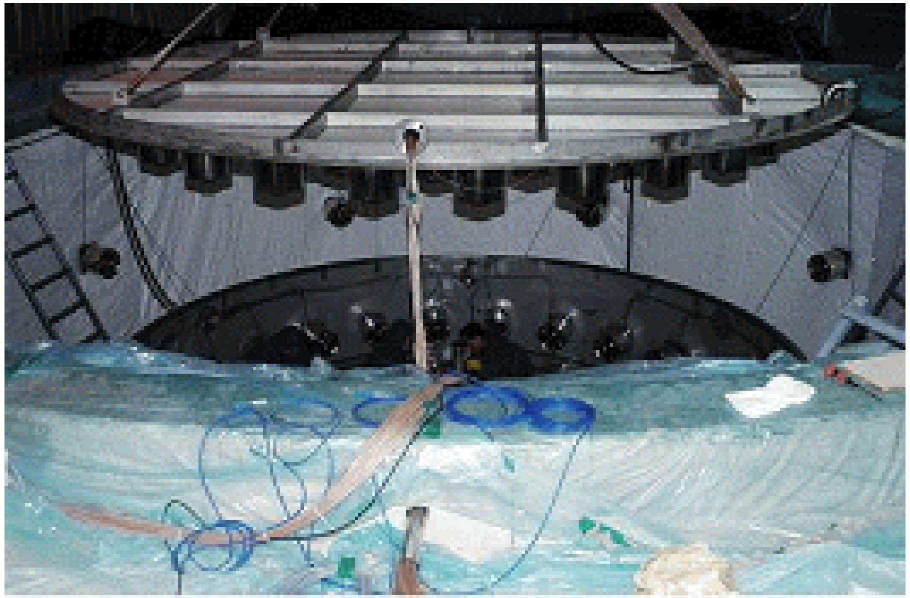
- 2006. 03 : Start of the RENO project
- 2008. 06 ~ 2009. 03 : Civil construction including tunnel excavation
- 2008. 12 ~ 2009. 11 : Detector structure & buffer steel tanks completed
- 2010. 06 : Acrylic containers installed
- 2010. 06 ~ 2010. 12 : PMT test & installation
- 2011. 01 : Detector closing/ Electronics hut & control room built
- 2011. 02 : Installation of DAQ electronics and HV & cabling
- 2011. 03 ~ 06 : Dry run & DAQ debugging
- 2011. 05 ~ 07 : Liquid scintillator production & filling
- 2011. 07 : Detector operation & commissioning
- 2011. 08 : Start data-taking

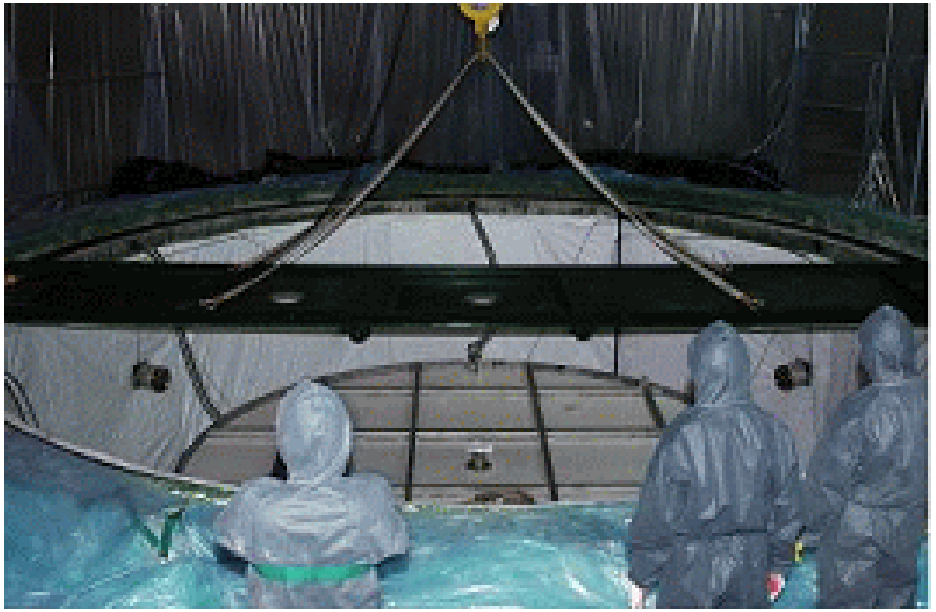
PMT Mounting (2010. 8~10)

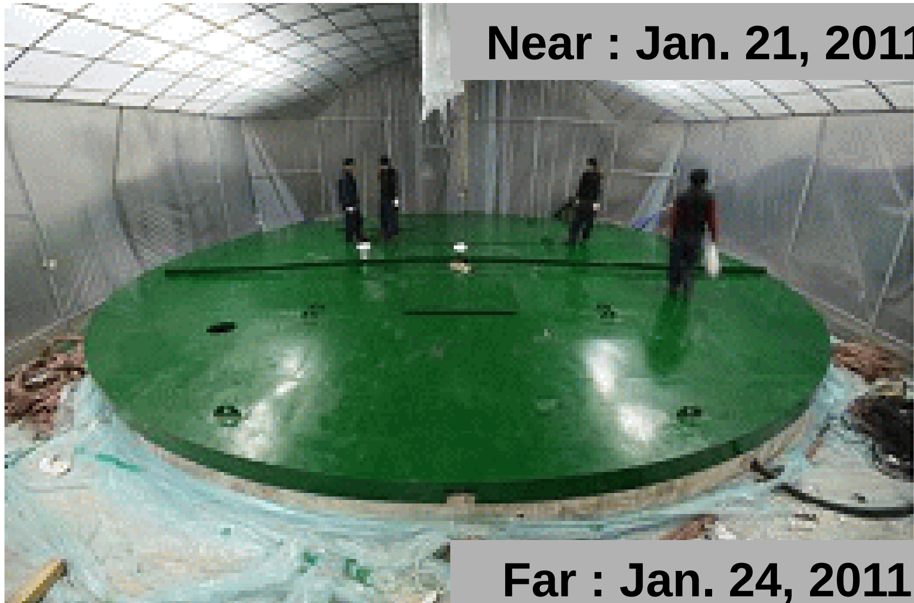
PMT Mounting (2010. 8~10)



Detector Closing (2011. 1)





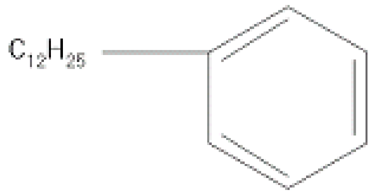


Near : Jan. 21, 2011

Far : Jan. 24, 2011

Detection of Reactor Antineutrinos

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



Linear Alkyl Benzene (LAB)

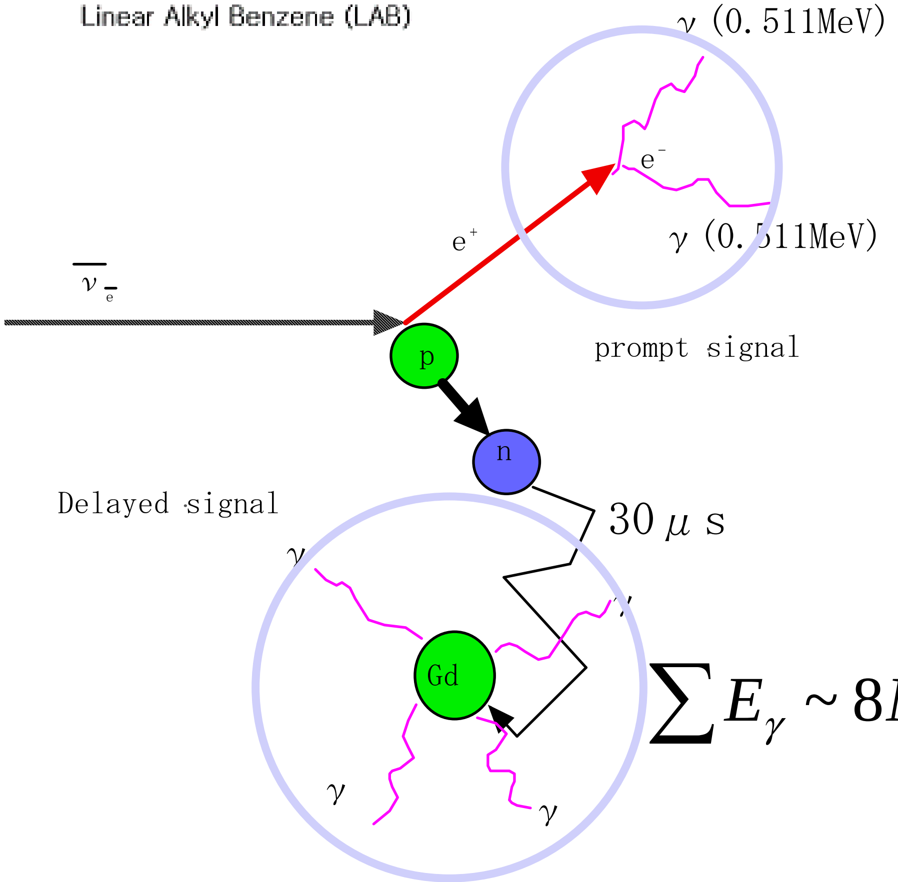
(prompt signal)

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

(delayed signal)

~180 μs: + p → D + γ (2.2 MeV)

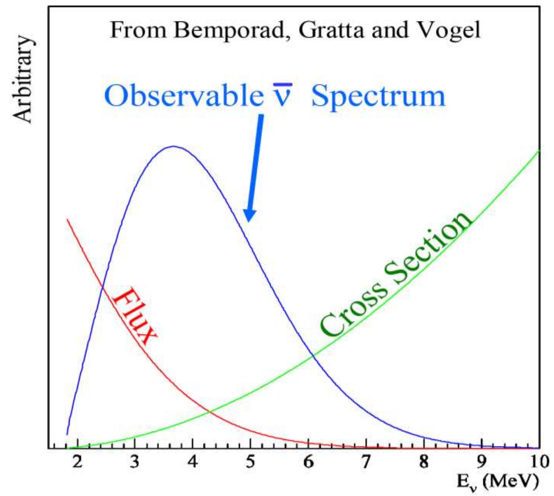
~28 μs (0.1% Gd): + Gd → Gd + γ's (8 MeV)



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

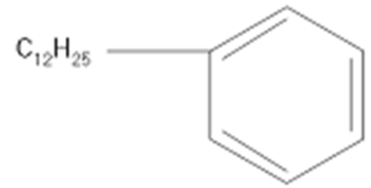
- **Neutrino energy measurement**

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

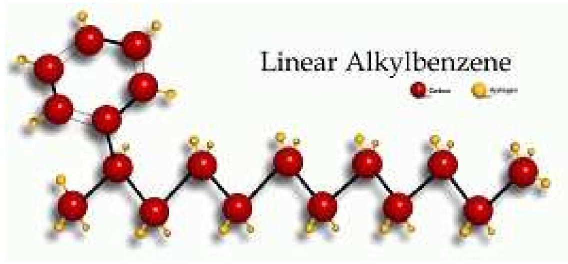


Gd Loaded Liquid Scintillator

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



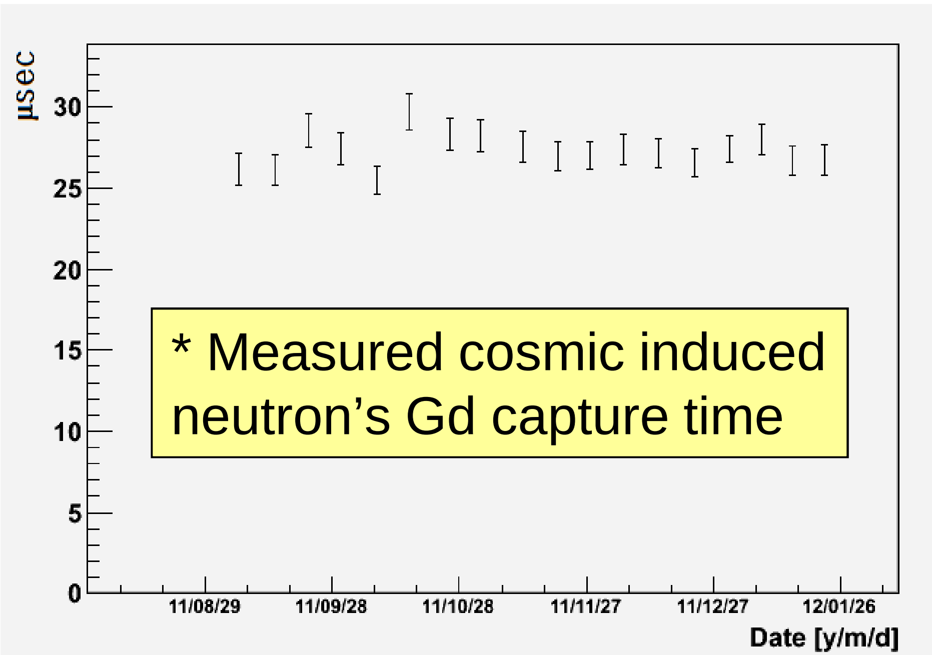
Linear Alkyl Benzene (LAB)



❑ Recipe of Liquid Scintillator

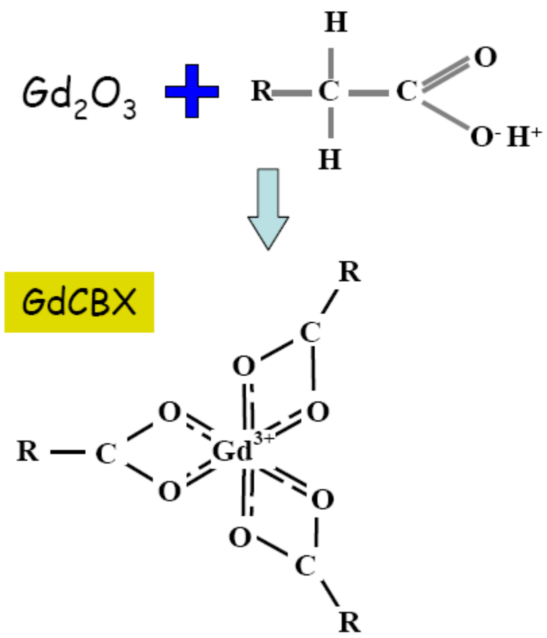
Aromatic Solvent & Flour	WLS	Gd−compound
LAB	PPO + Bis−MSB	0.1% Gd+(TMHA)^3 (trimethylhexanoic acid)

* Stable light yield over the time period : ~250 pe/MeV



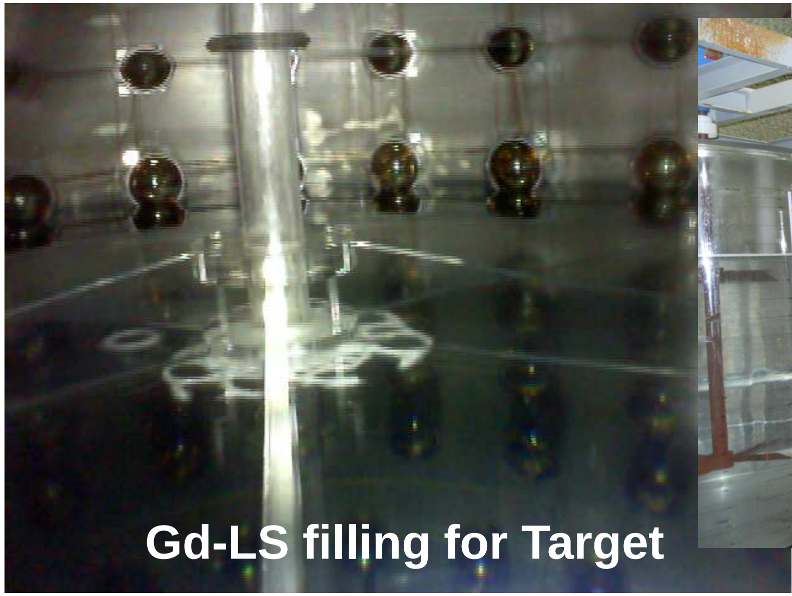
* Measured cosmic induced neutron's Gd capture time

Carboxylic acids



Liquid(Gd-LS/LS/MO/Water) Production & Filling (May-July 2011)

Gd Loaded Liquid Scintillator

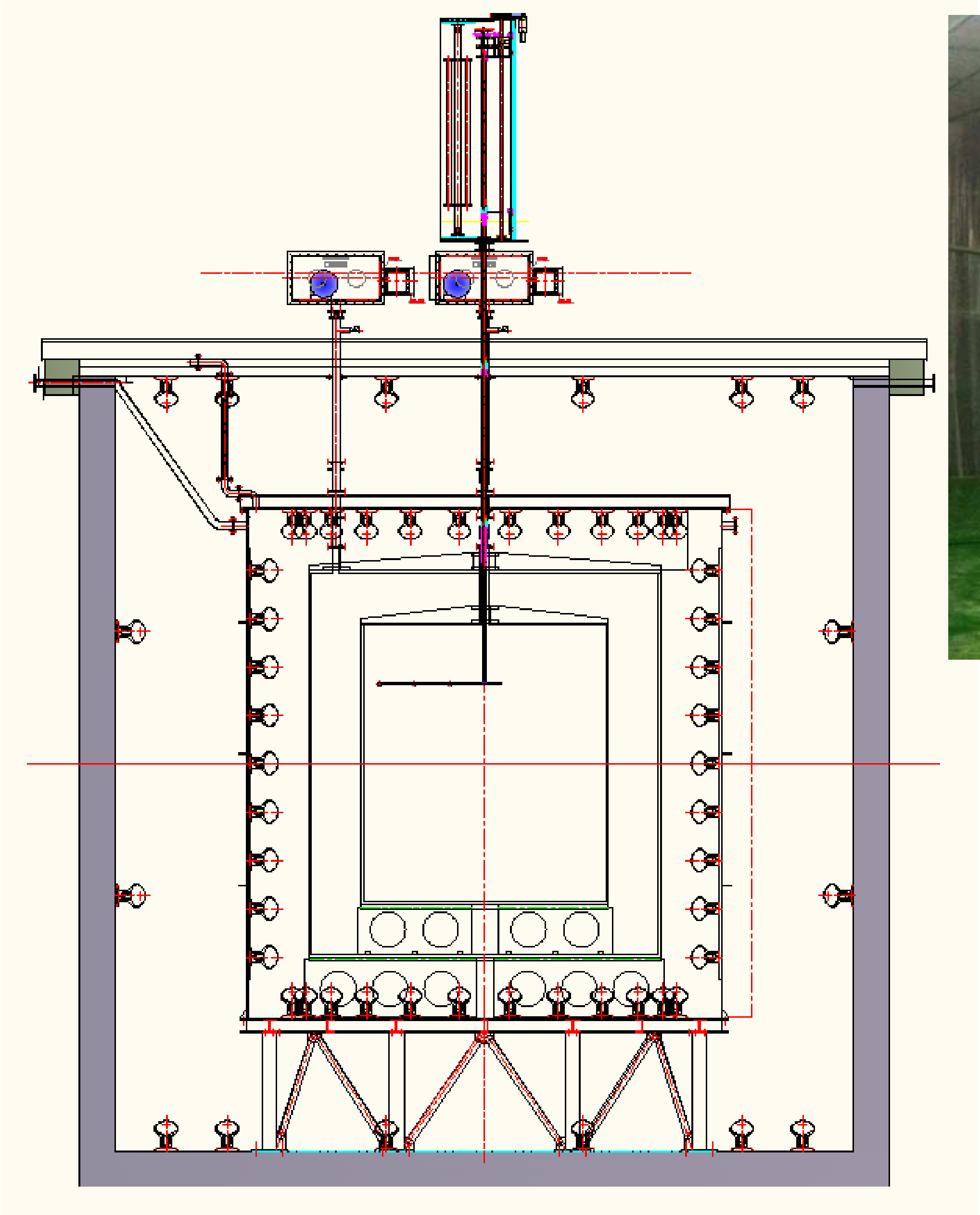


Gd-LS filling for Target

Water filling for Veto

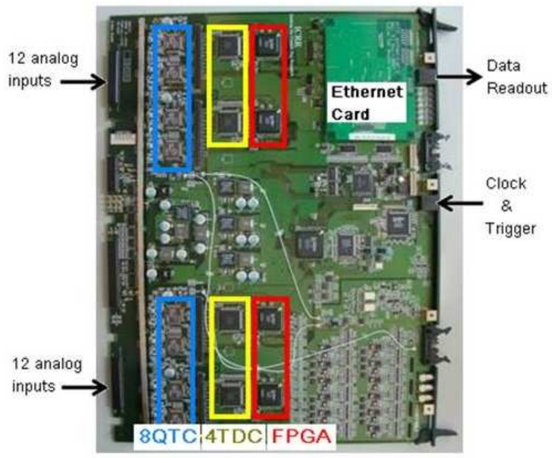
LS filling for Gamma Catcher

1D/3D Calibration System

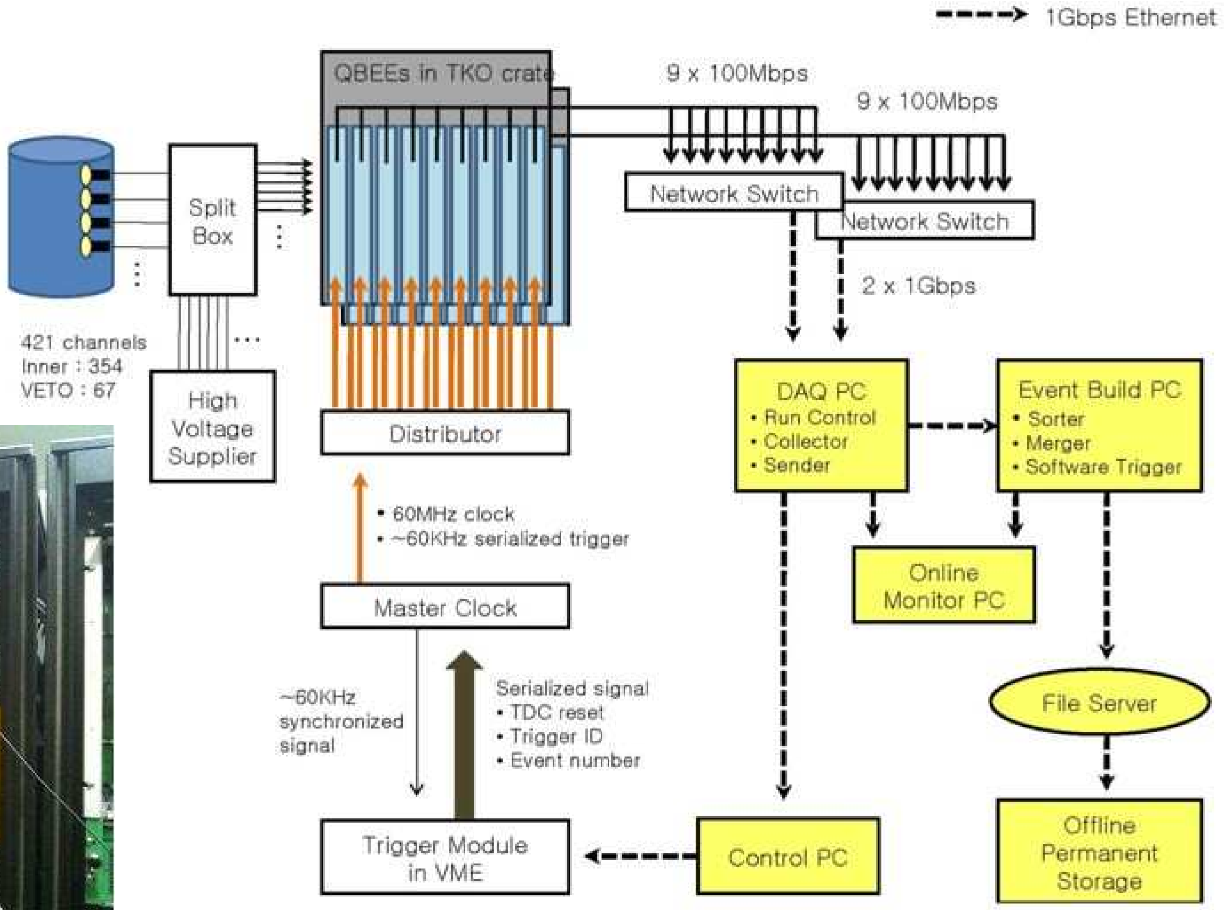


- ❑ Calibration system to deploy radioactive sources in 1D & 3D directions
- ❑ Radioactive sources : ^{137}Cs, ^{68}Ge, ^{60}Co, ^{252}Cf
- ❑ Laser injectors

Data Acquisition System



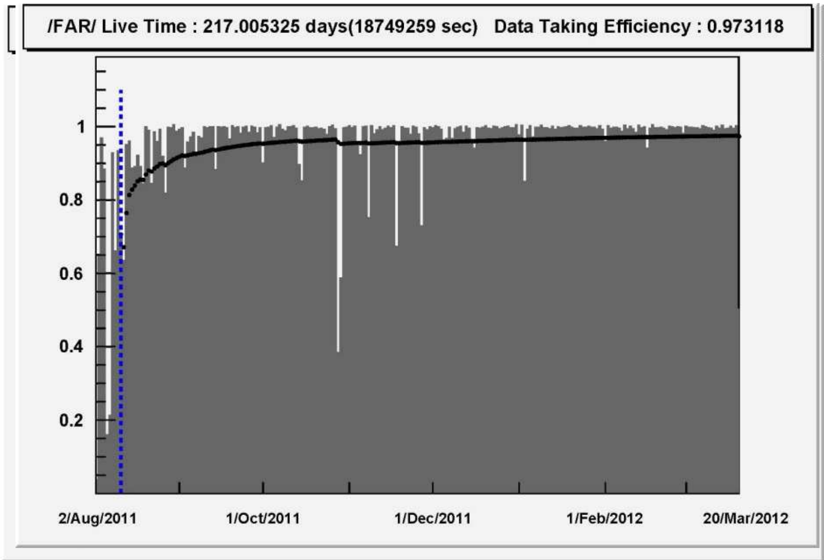
- 24 channel PMT input to ADC/TDC
- 0.1pC, 0.52nsec resolution
- ~2500pC/ch large dynamic range
- No dead time (w/o hardware trigger)
- Fast data transfer via Ethernet R/W

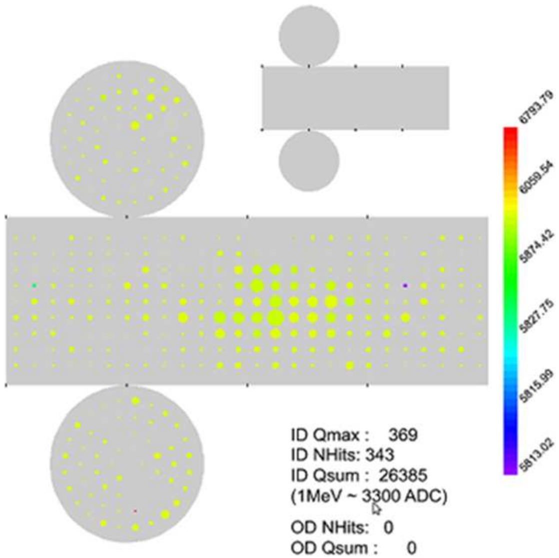


Data-Taking & Data Set

- Data taking began on Aug. 1, 2011 with both near and far detectors.
- Data-taking efficiency > 90%.
- Trigger rate at the threshold energy of 0.5~0.6 MeV : 80 Hz
- Data-taking period : 228 days
  Aug. 11, 2011 ~ Mar. 25, 2012

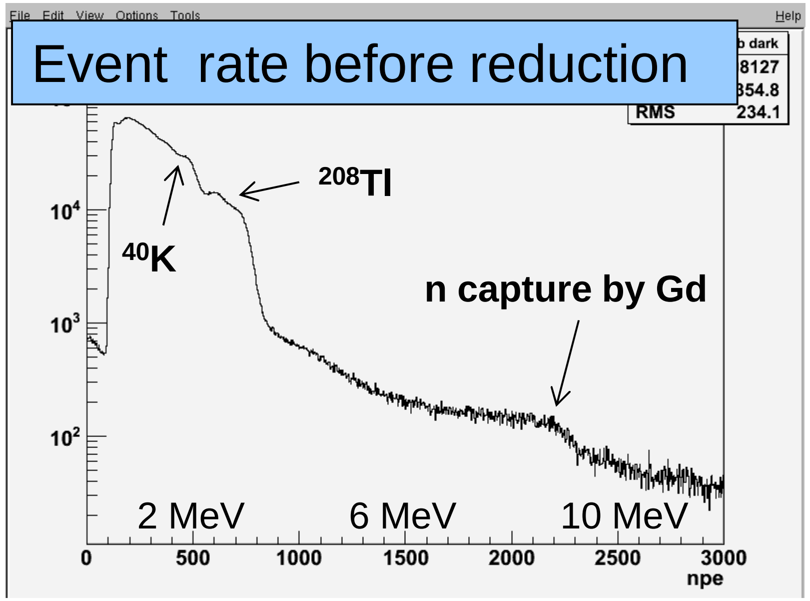
- Data-taking efficiency





A candidate for a neutron capture by Gd

Event rate before reduction



RENO's Status & Plan

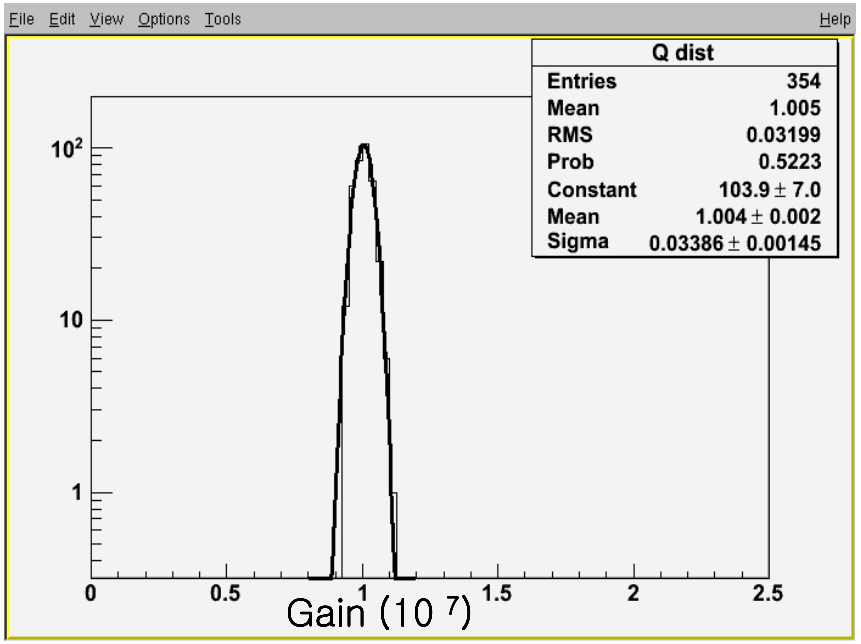
- RENO was the first reactor neutrino experiments to search for θ_{13} with both near & far detectors running, from the early August 2011.

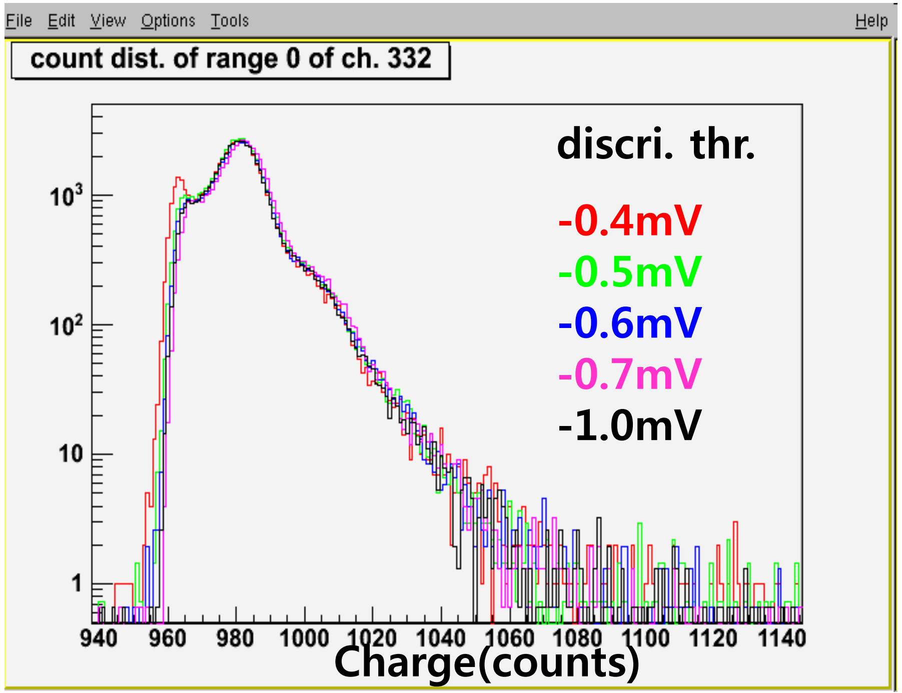
- RENO started to see a signal of reactor neutrino disappearance from the late 2011.

- According to reported schedules of the other experiments, RENO was thought to present a result first soon. We planned to publish our first results in April without a hurry and to present them in the Neutrino 2012.
- But …..

PMT Threshold & Gain Matching

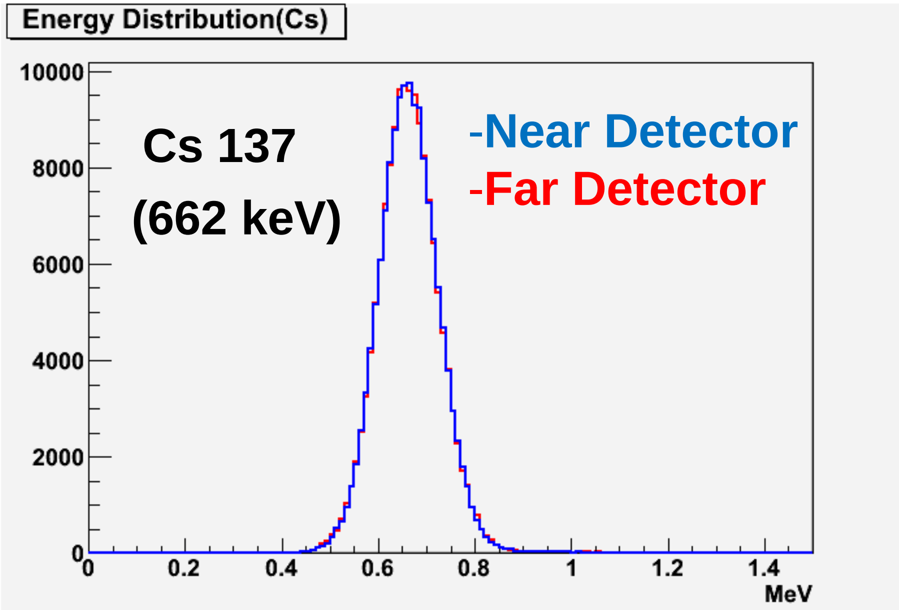
- PMT gain : set 1.0×10^7 using a Cs source at center
- Gain variation among PMTs : 3% for both detectors.

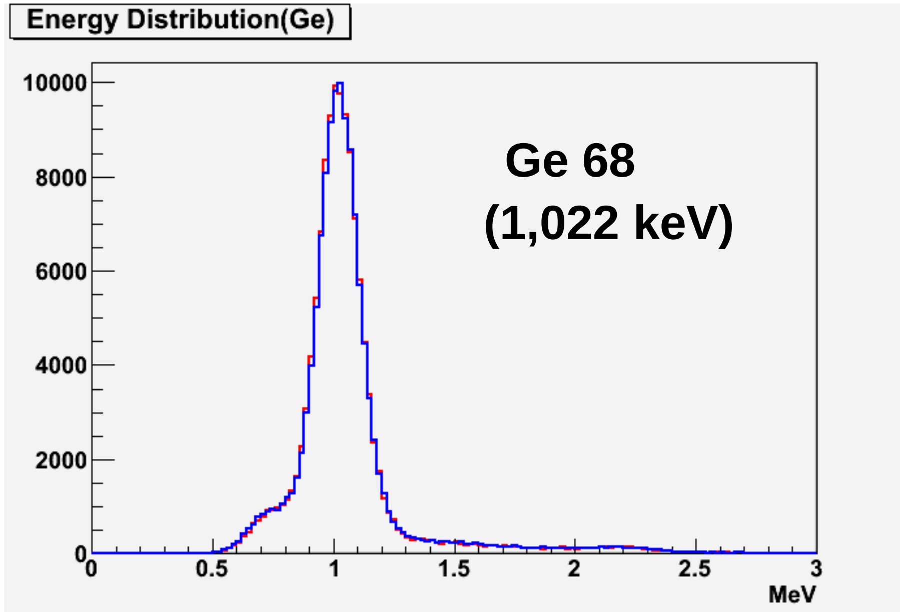


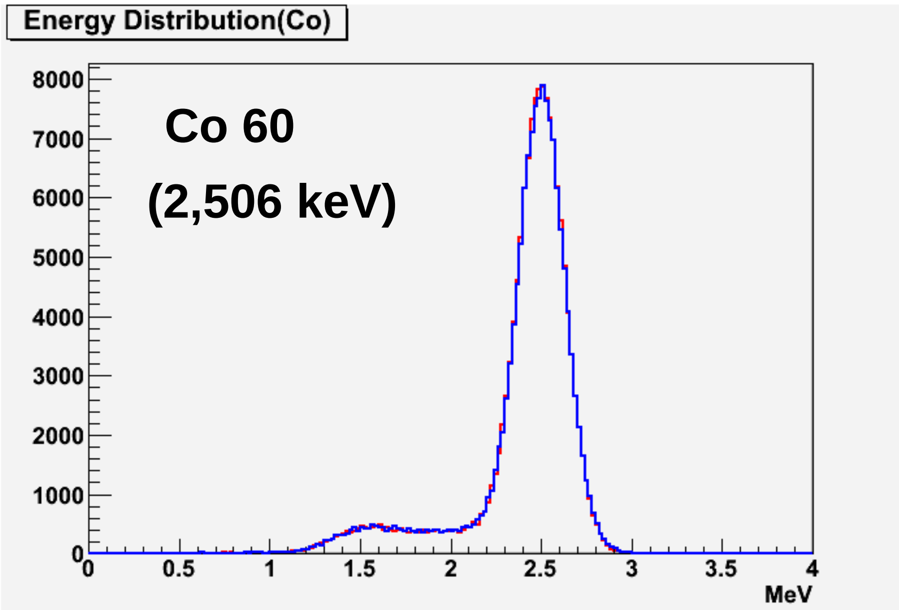


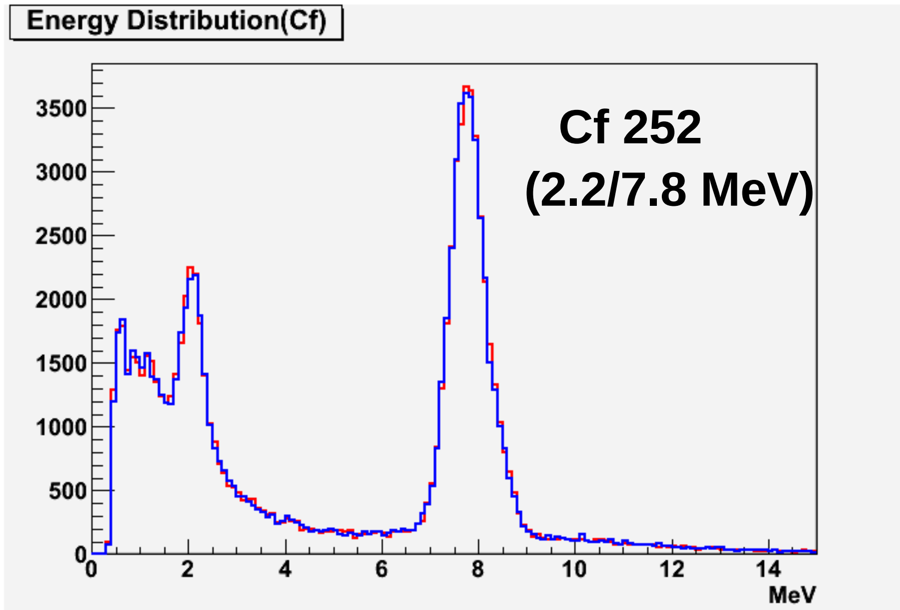
- PMT threshold : determined by a single photoelectron response using a Cs source at the center

Energy Calibration



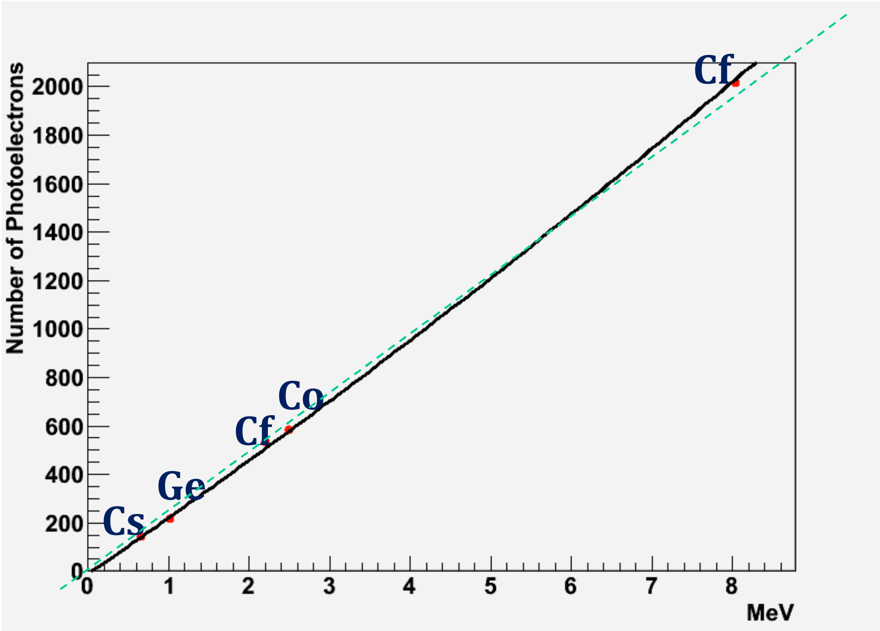




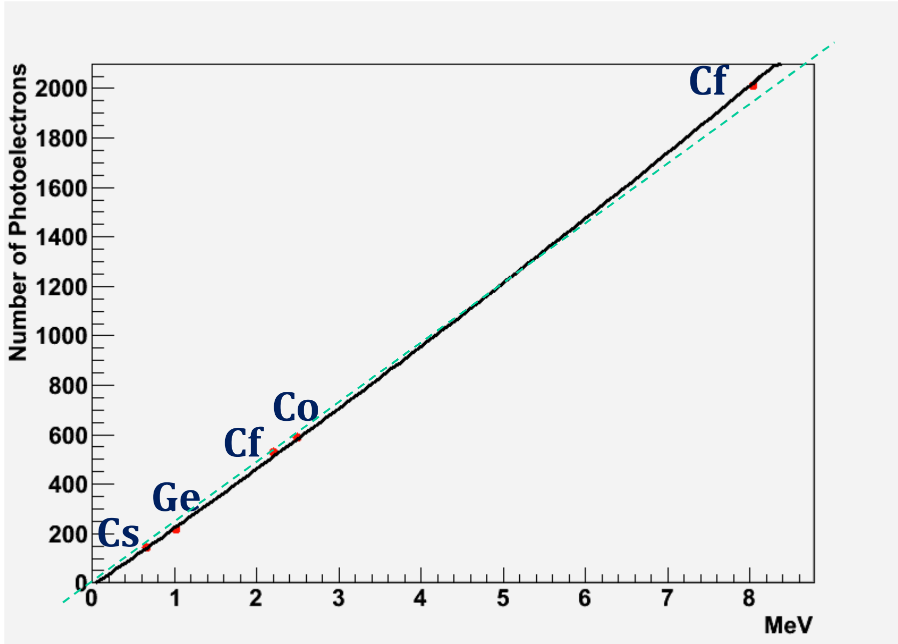


Energy Scale Calibration

Near Detector



Far Detector

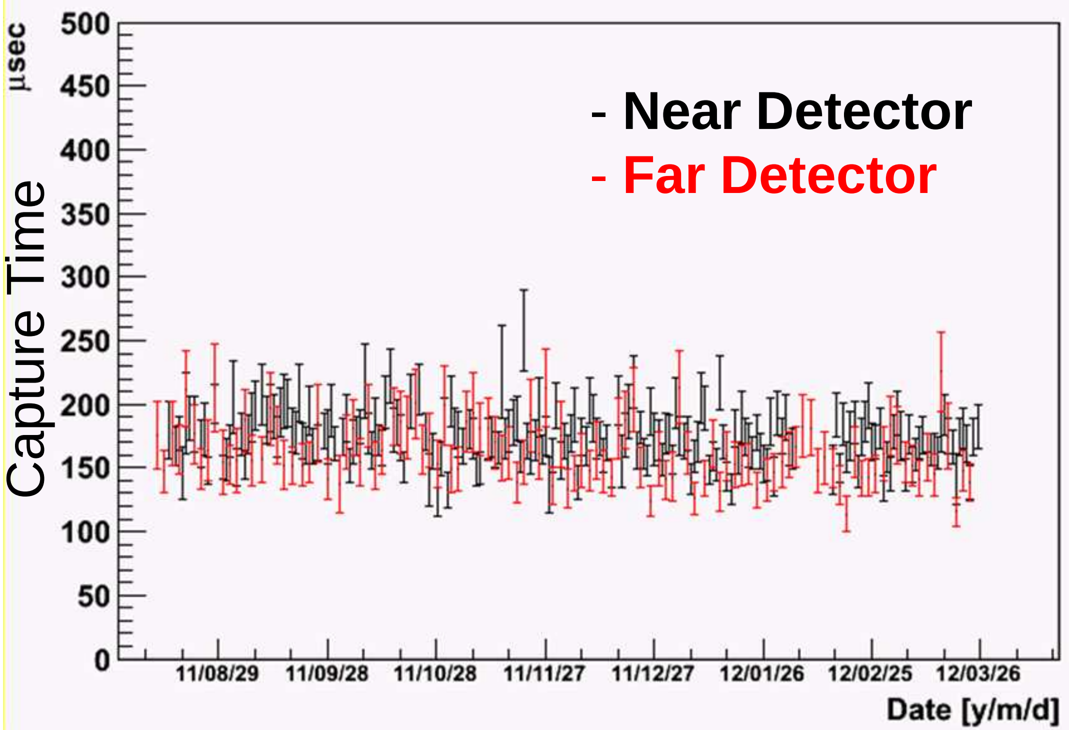


$$\delta E = \frac{5.9\%}{\sqrt{E(MeV)}} + 1.1\%$$

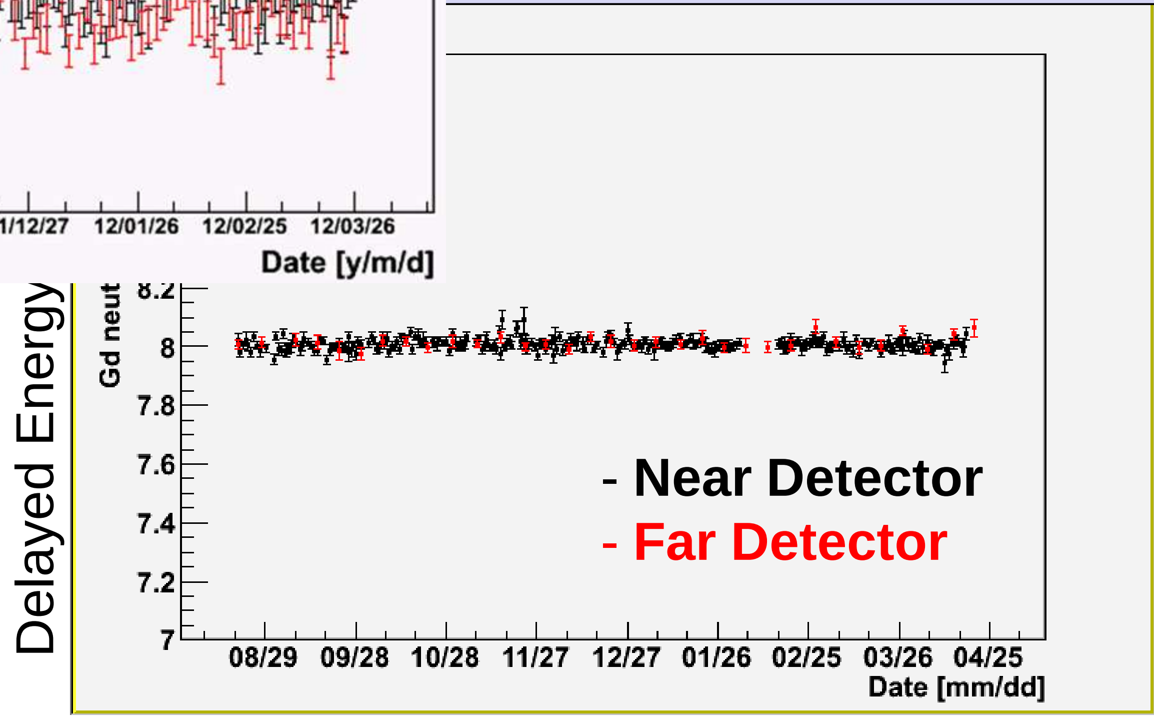
- ~ 250 pe/MeV (sources at center)
- Identical energy response (< 0.1%) of ND & FD
- Slight non-linearity observed

Detector Stability & Identity

- Cosmic muon induced neutron's capture by H



delayed signals (capture on Gd)

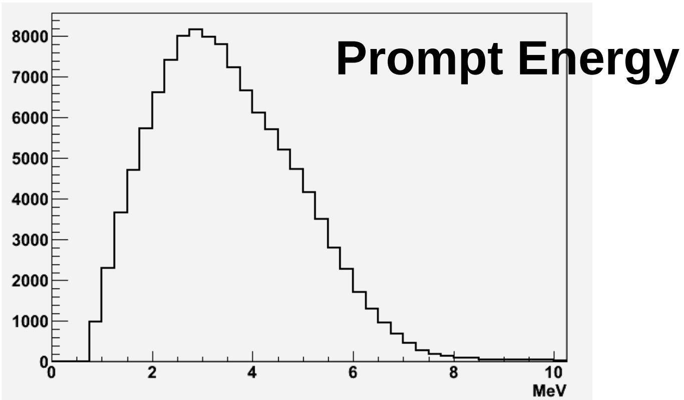


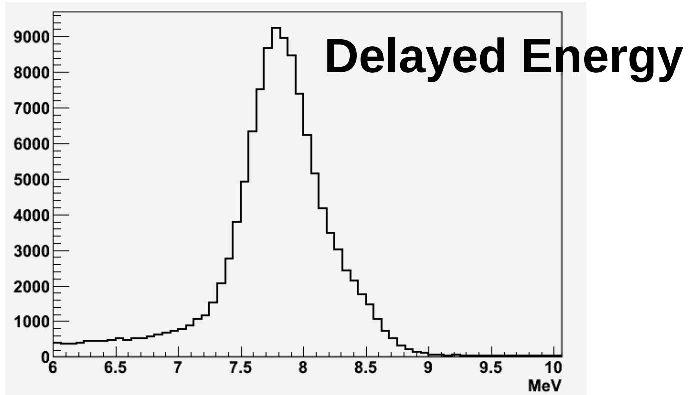
IBD Event Signature and Backgrounds

❑ 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
  ~28 μs (0.1% Gd) in LS





❑ Backgrounds

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

IBD Event Selection

- Reject flashers and external gamma rays : $Q_{max}/Q_{tot} < 0.03$
- Muon veto cuts : reject events after the following muons

  (1) 1 ms after an ID muon with E > 70 MeV, or with 20 < E < 70 MeV and OD NHIT > 50

  (2) 10 ms after an ID muon with E > 1.5 GeV

- Coincidence between prompt and delayed signals in 100 μs

  - E_{prompt} : 0.7 ~ 12.0 MeV, $E_{delayed}$: 6.0 ~ 12.0 MeV

  - coincidence : $2\ \mu s < \Delta t_{e+n} < 100\ \mu s$

- Multiplicity cut : reject pairs if there is a trigger in the preceding 100 ms window

Random Coincidence Backgrounds

❑ Calculation of accidental coincidence

$$N_{accidental} = N_{delayed} \times \left(1 - \exp^{[-R_{prompt}(Hz) \times \Delta T(s)]}\right) \pm \frac{N_{accidental}}{\sqrt{N_{delayed}}}$$

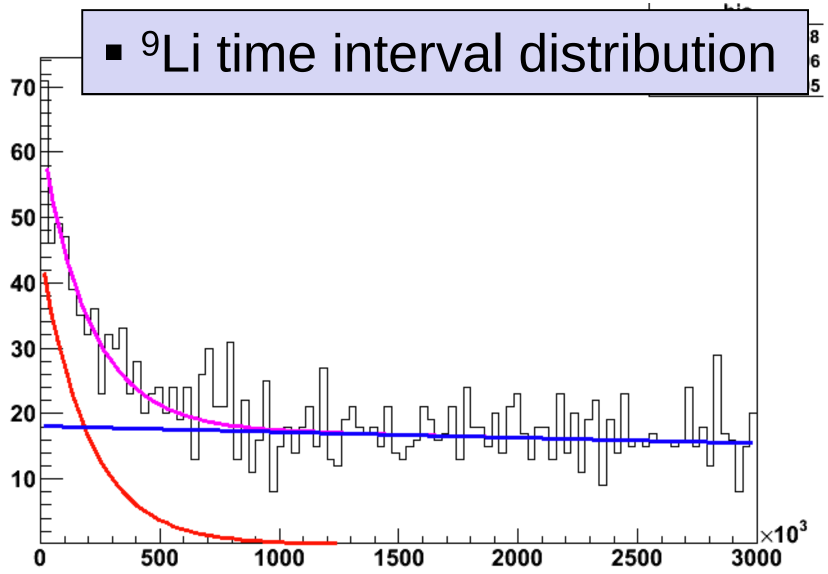
- ΔT = 100 μs time window
- Near detector :

  R_{prompt} = 8.8 Hz, N_{delay} = 4884/day $\rightarrow$ $BG^{near}_{accidental} = 4.30 \pm 0.06 / day$
- Far detector :

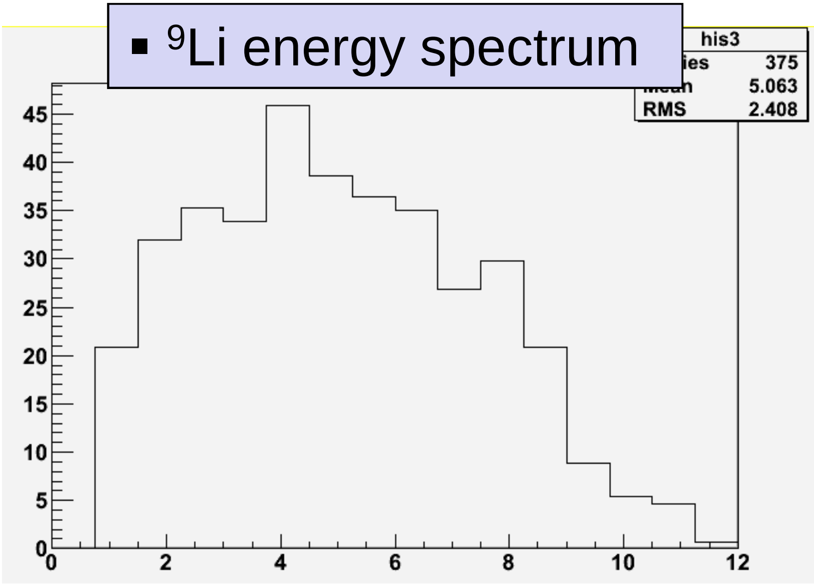
  R_{prompt} = 10.6 Hz, N_{delay} = 643/day $\rightarrow$ $BG^{far}_{accidental} = 0.68 \pm 0.03 / day$

$^9Li/^8He$ β-n Backgrounds

❑ Find prompt-delay pairs after muons, and obtain their time interval distribution with respect to the preceding muon.



Time interval (ms)



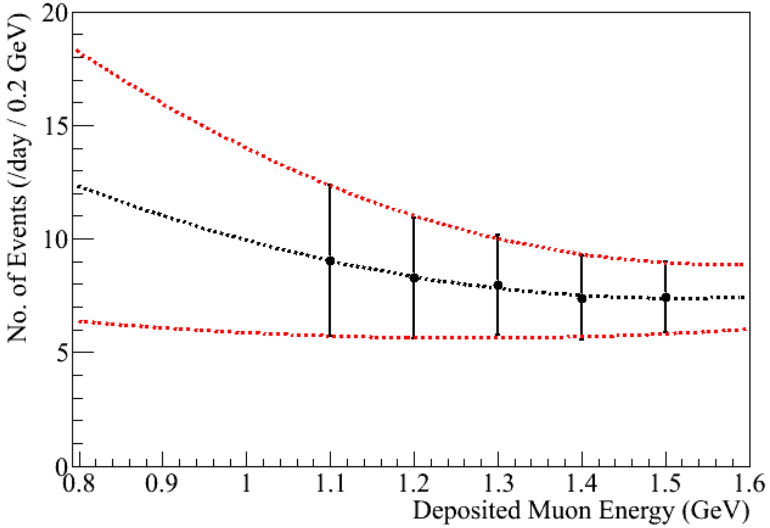
Energy (MeV)

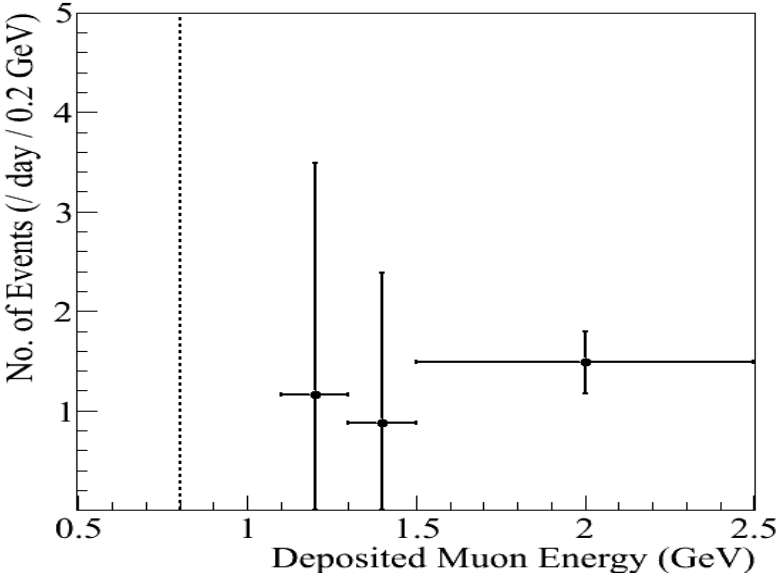
▪ Near detector : $$BG^{near}_{Li/He} = 12.45 \pm 5.93 / day$$

▪ Far detector : $$BG^{far}_{Li/He} = 2.59 \pm 0.75 \ / day$$

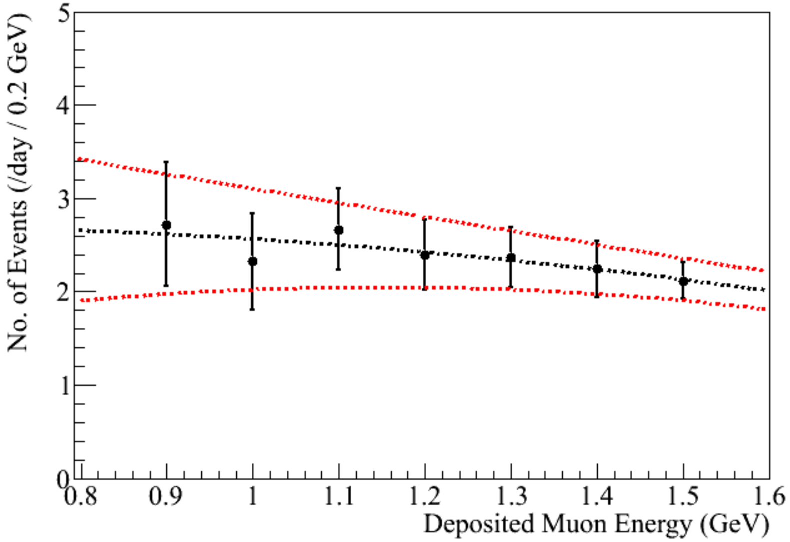
^{9}Li/^{8}He β-n Backgrounds

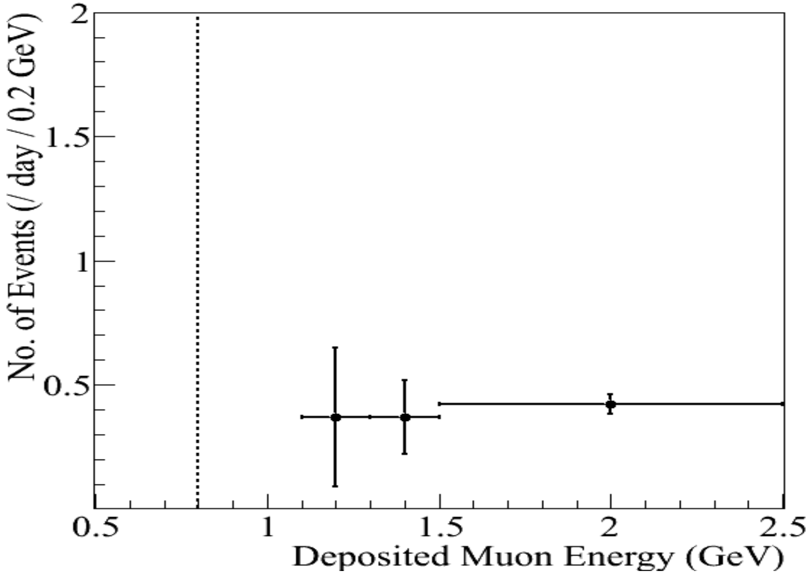
- ^{9}Li production at near detector





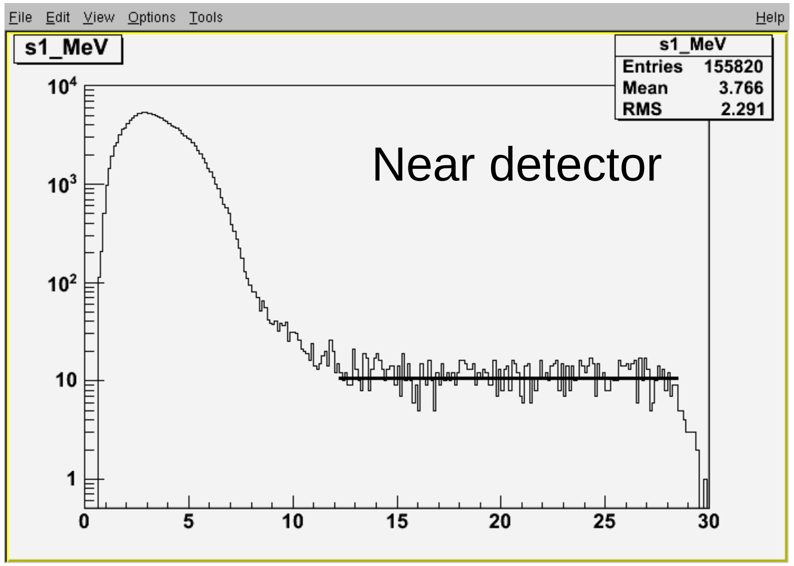
- ^{9}Li production at far detector

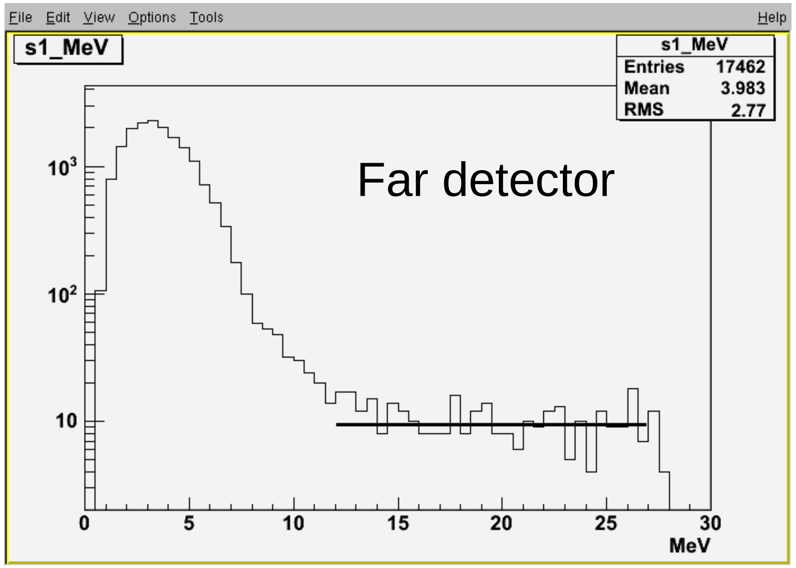




Fast Neutron Backgrounds

❑ Obtain a flat spectrum of fast neutron's scattering with proton, above that of the prompt signal.

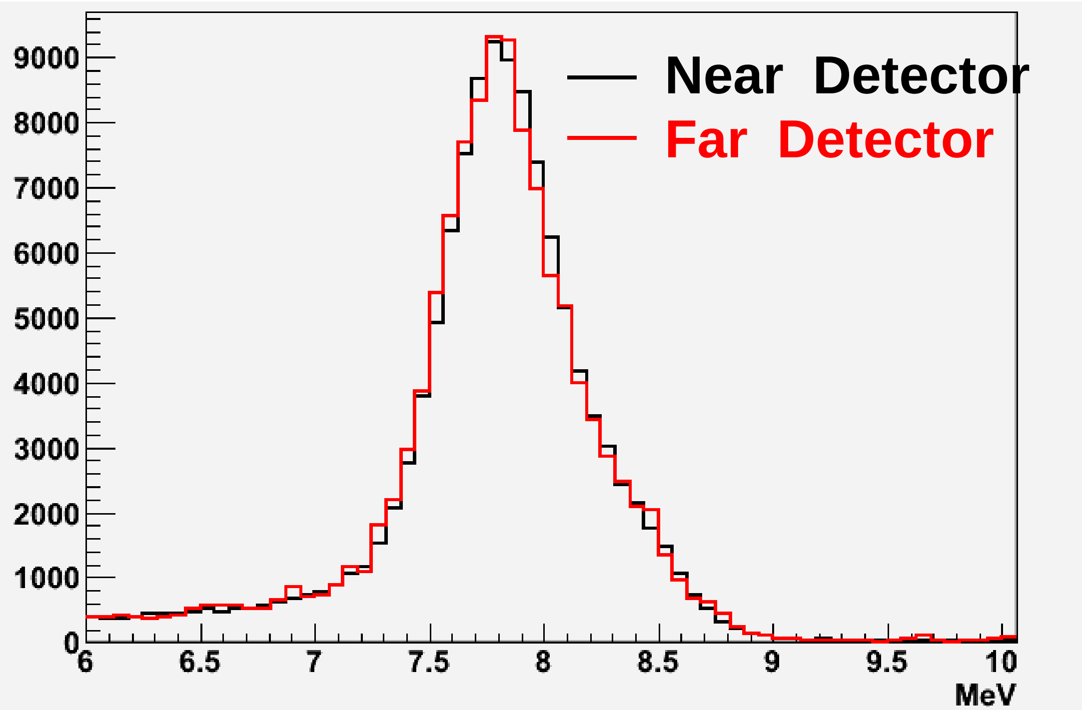




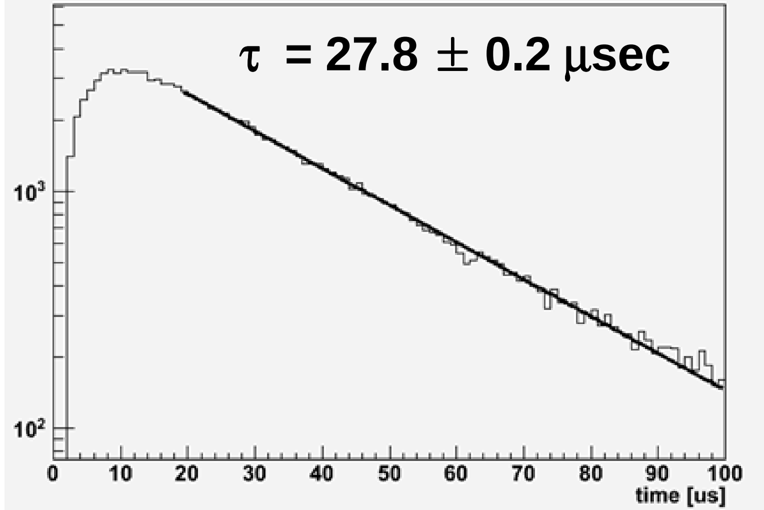
- Near detector : $BG^{near}_{neutron} = 5.00 \pm 0.13 \quad / \, day$
- Far detector : $BG^{far}_{neutron} = 0.97 \pm 0.06 \quad / \, day$

Spectra & Capture Time of Delayed Signals

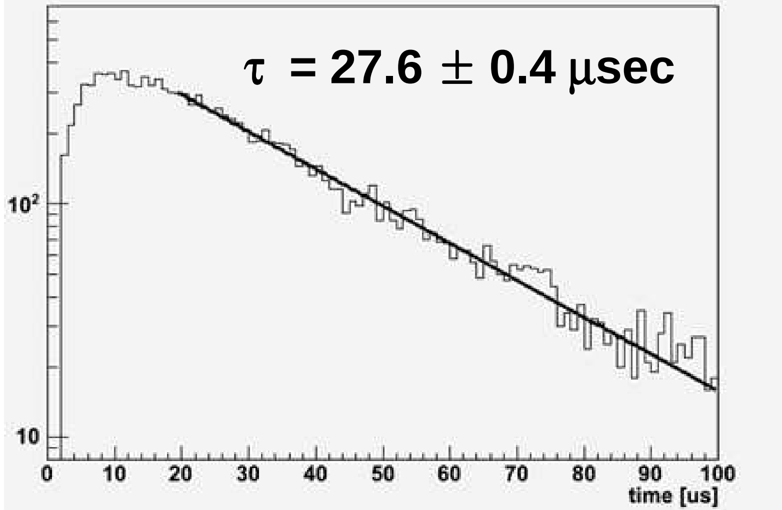
❑ Observed spectra of IBD delayed signals



Near Detector



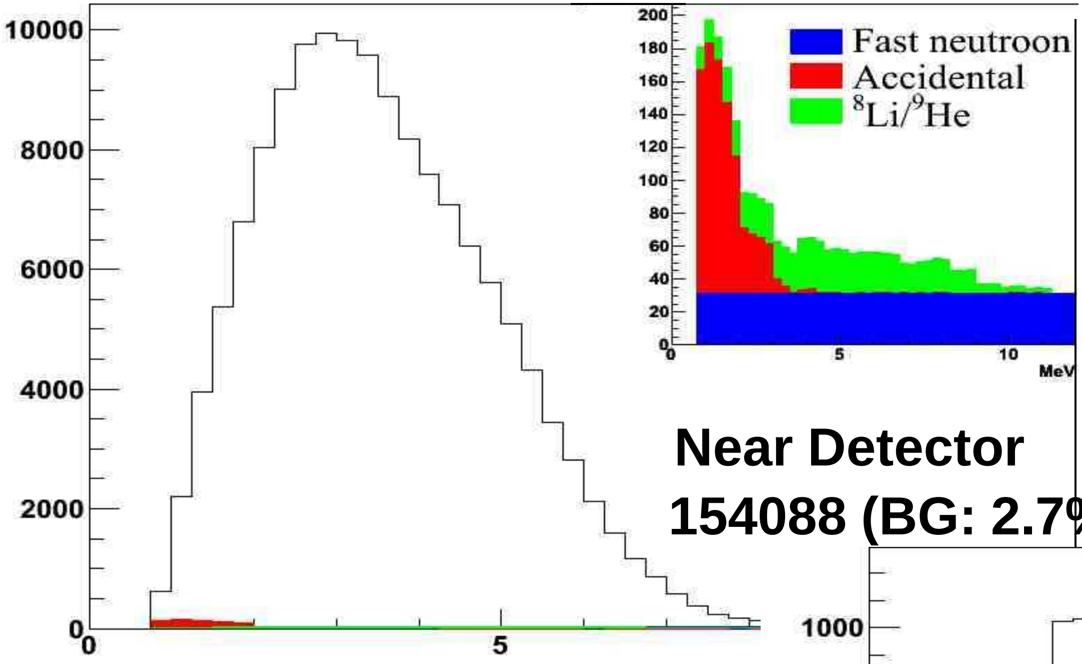
Far Detector



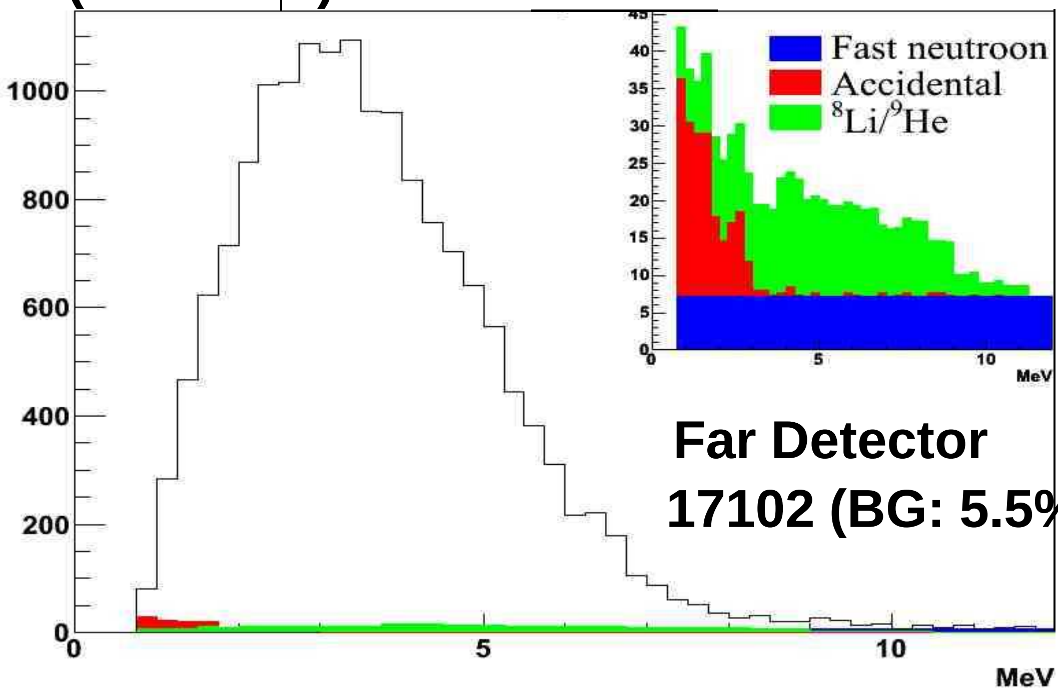
Summary of Final Data Sample

Detector	Near	Far
Selected events	154088	17102
Total background rate (per day)	21.75 ± 5.93	4.24 ± 0.75
IBD rate after background subtraction (per day)	779.05 ± 6.26	72.78 ± 0.95
DAQ Live time (days)	192.42	222.06
Detection efficiency (ϵ)	0.647 ± 0.014	0.745 ± 0.014
Accidental rate (per day)	4.30 ± 0.06	0.68 ± 0.03
^{9}Li/^{8}He rate (per day)	12.45 ± 5.93	2.59 ± 0.75
Fast neutron rate (per day)	5.00 ± 0.13	0.97 ± 0.06

Measured Spectra of IBD Prompt Signal



Near Detector
154088 (BG: 2.7%)



Far Detector
17102 (BG: 5.5%)

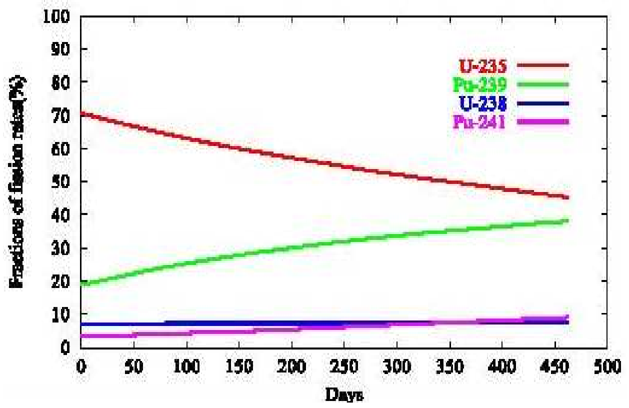
Expected Reactor Antineutrino Fluxes

- Reactor neutrino flux

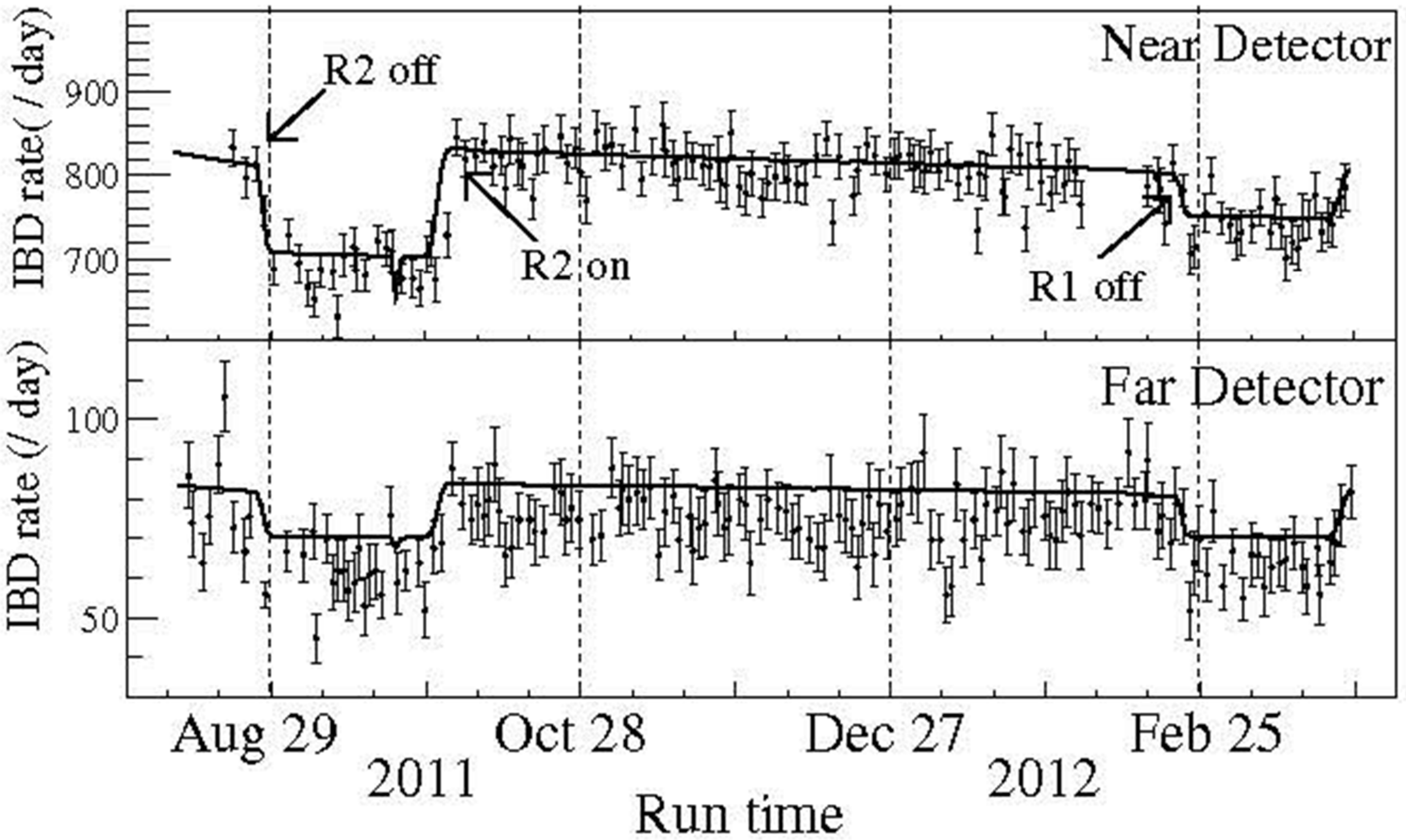
$$\Phi(E_\nu) = \frac{P_{th}}{\sum_i^{isotopes} f_i \cdot E_i} \sum_i^{isotopes} f_i \cdot \phi_i(E_\nu)$$

- 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



Reduction of Systematic Uncertainties

- **Detector related :**
  - **"Identical" near and far detectors**
  - **Careful calibration**

- **Reactor related :**
  - **Relative measurements with near and far detectors**

$$\frac{N^{\nu}_{far}}{N^{\nu}_{near}} = \left(\frac{L_{near}}{L_{far}}\right)^2 \left(\frac{N^{p}_{far}}{N^{p}_{near}}\right) \left(\frac{\epsilon_{far}}{\epsilon_{near}}\right) \left[\frac{P(\bar{\nu}_e \rightarrow \bar{\nu}_e; E, L_{far})}{P(\bar{\nu}_e \rightarrow \bar{\nu}_e; E, L_{near})}\right]$$

Neutrino events	$1/r^2$	Number of protons	Detection efficiency	Yield of $\sin^2(2\theta_{13})$

- **Maury Goodman's neutrino newsletter (5/5/2012):**
F. Darwin said "In Science the credit goes to the man who convinces the world, not to the man to whom the idea first occurred."
But he wishes to give credit to Russians who first proposed a two detector neutrino reactor disappearance experiment : L. Mikaelyan & V. Sinev.

Efficiency & Systematic Uncertainties

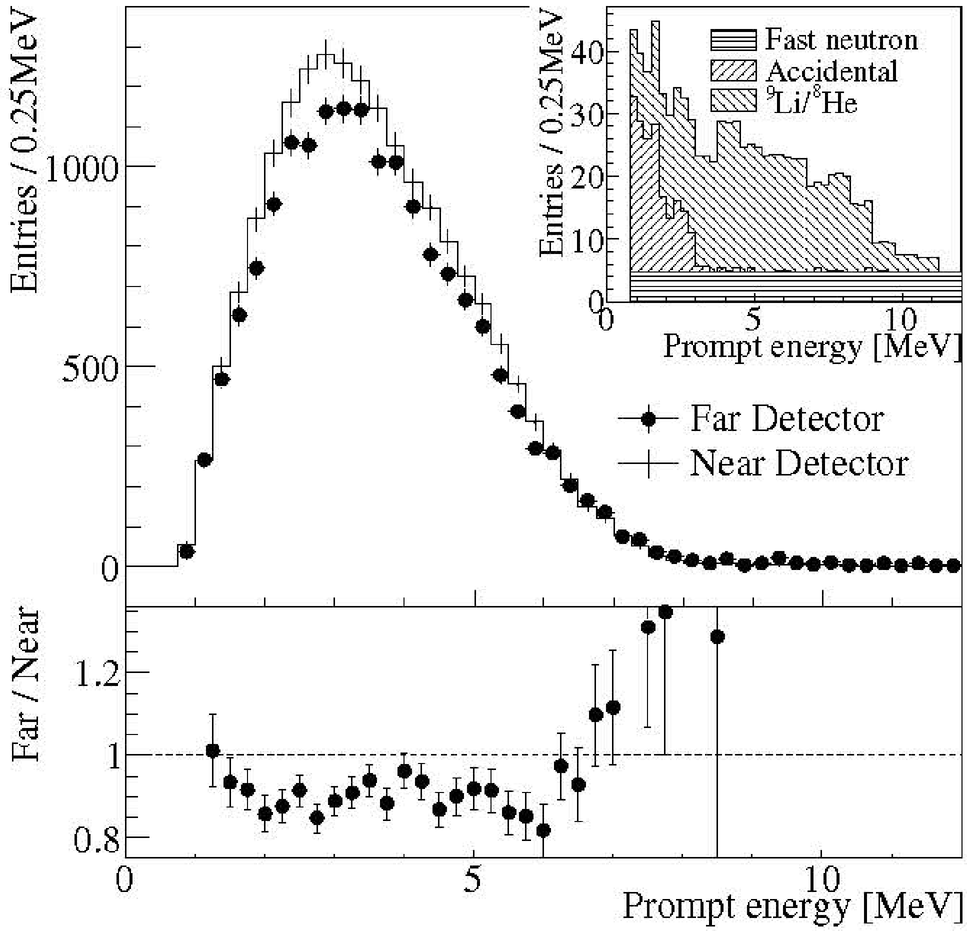
Prompt energy cut	
Flasher cut	
Gd capture fraction	
Delayed energy cut	
Time coincidence cut	
Spill-in	
Common	

Muon veto loss ($\delta_{\mu-veto}$)	(11.
Multiplicity cut loss (δ_{multi})	(4.
Total	((

Reactor		
	Uncorrelated	Correlated
Thermal power	0.5%	—
Fission fraction	0.7%	—
Fission reaction cross section	—	1.9%
Reference energy spectra	—	0.5%
Energy per fission	—	0.2%
Combined	0.9%	2.0%
Detection		
	Uncorrelated	Correlated
IBD cross section	—	0.2%
Target protons	0.1%	0.5%
Prompt energy cut	0.01%	0.1%
Flasher cut	0.01%	0.1%
Gd capture ratio	0.1%	0.7%
Delayed energy cut	0.1%	0.5%
Time coincidence cut	0.01%	0.5%
Spill-in	0.03%	1.0%
Muon veto cut	0.02%	0.02%
Multiplicity cut	0.04%	0.06%
Combined (total)	0.2%	1.5%

Reactor Antineutrino Disappearance

$$R = \frac{\Phi^{Far}_{observed}}{\Phi^{Far}_{expected}} = 0.920 \pm 0.009(stat.) \pm 0.014(syst.)$$



- A clear deficit in rate (8.0% reduction)
- Consistent with neutrino oscillation in the spectral distortion

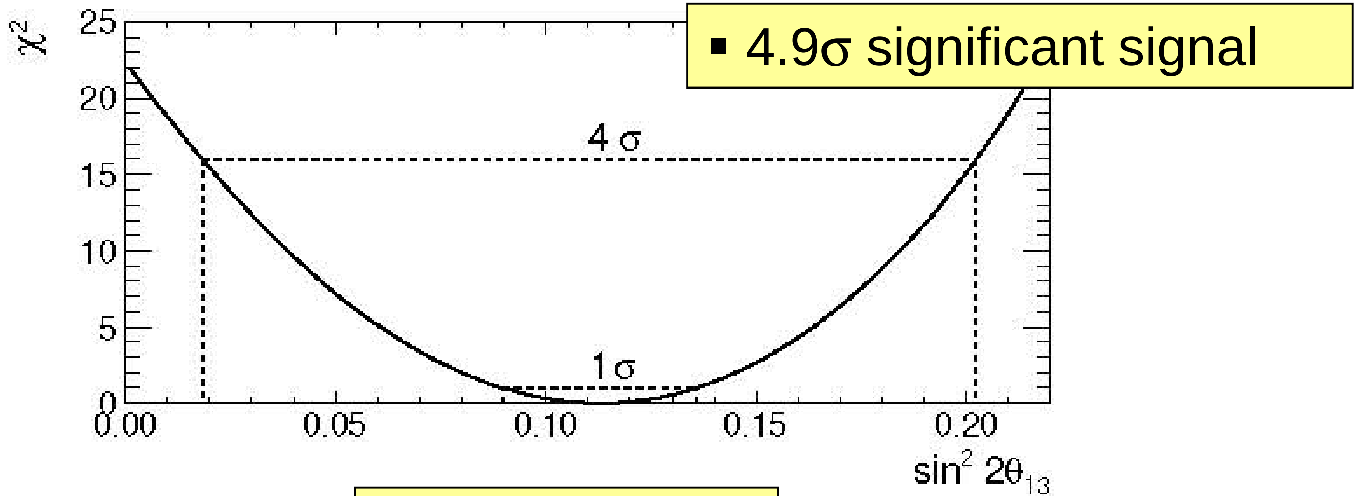
χ^2 Fit with Pulls

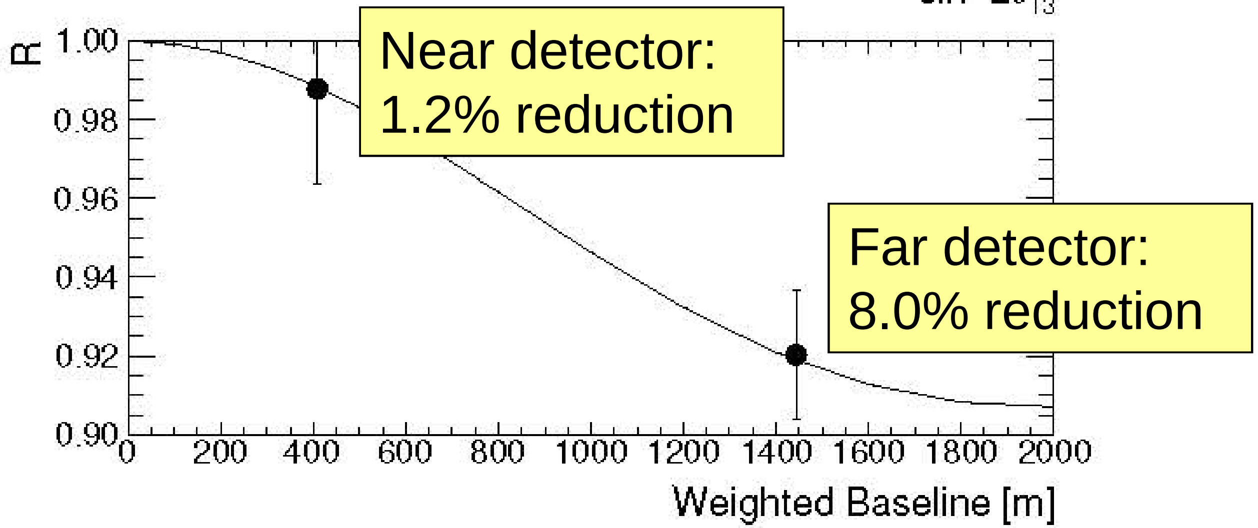
$$\chi^2 = \sum_{d=N,F} \frac{\left[N_{obs}^{d} + b_d - (1 + a + \xi_d) \sum_{r=1}^{6} (1 + f_r) N_{\exp}^{d,r}\right]^2}{N_{obs}^{d}}$$

$$+ \sum_{d=N,F} \left(\frac{\xi_d^2}{\sigma_d^{\xi\,2}} + \frac{b_d^2}{\sigma_d^{b\,2}} \right) + \sum_{r=1}^{6} \left(\frac{f_r}{\sigma_r} \right)^2$$

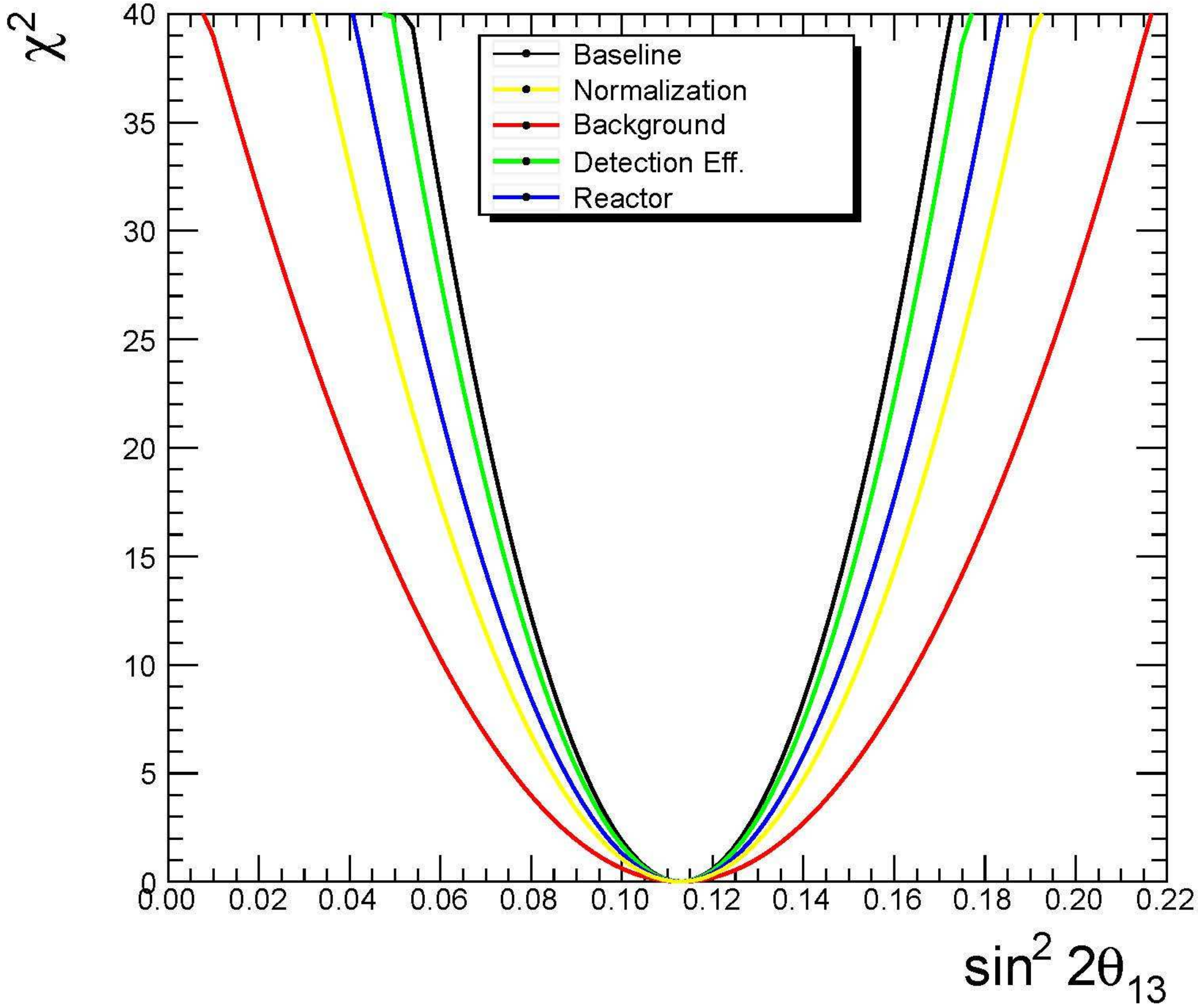
Definitive Measurement of θ_{13}

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





χ^2 Distributions for Uncertainties



Future Plan for Precision Measurement of θ_{13}

RENO

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

0.113 ± 0.023 (4.9 σ) ⇨ ± 0.01

Daya Bay

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

0.092 ± 0.018 (5.2 σ)

- Contributions of the systematic errors :
  - Background uncertainties : 0.0165
    (far : 5.5%×17.7% = 0.97%, near : 2.7%×27.3% = 0.74%)
  - Reactor uncertainty (0.9%) : 0.0100
  - Detection efficiency uncertainty (0.2%) : 0.0103
  - Absolute normalization uncertainty (2.5%) : 0.0104

- Remove the backgrounds !
- Spectral shape analysis

Summary

- RENO was the first experiment to take data with both near and far detectors, from August 1, 2011.

- RENO observed a clear disappearance of reactor antineutrinos.

$$R = 0.920 \pm 0.009(stat.) \pm 0.014(syst.)$$

- RENO measured the last, smallest mixing angle θ_{13} unambiguously that was the most elusive puzzle of neutrino oscillations

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

- Surprisingly large !!!
  $\rightarrow$ A plenty of tasks ahead for neutrino physicists

Prospective Future

- A surprisingly large value of θ_{13} :
  (Save a lot of dollars for the future neutrino experiments which may need reconsideration of their designs!!)

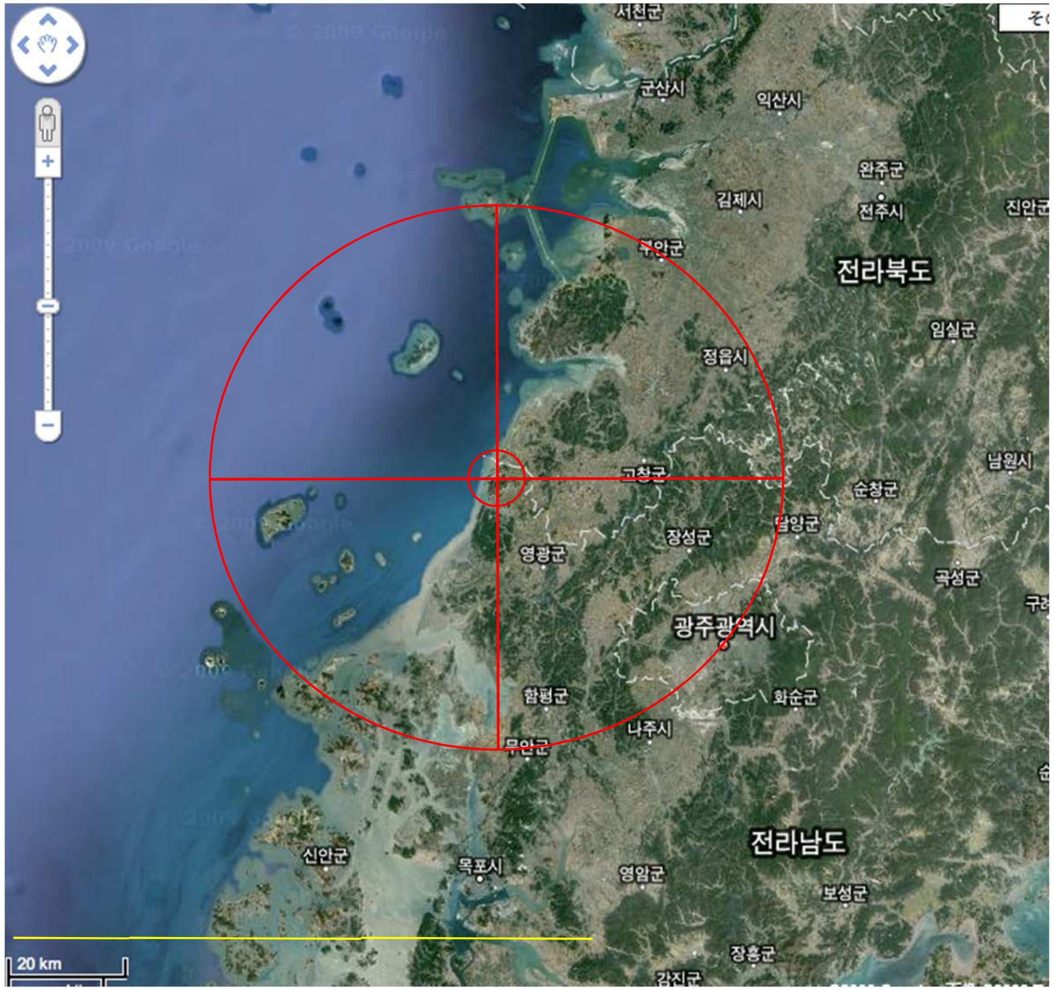
→ (1) Provides a complete picture of neutrino oscillations
  (2) Open a bright window of understanding why there is much more matter than antimatter in the Universe today

A prospective future for neutrino physics due to a large value of θ_{13} !!!

- Our measurement will strongly promote the next round of neutrino experiments to find the CP phase.
- Complimentary measurements between accelerator experiments and reactor experiments will provide significant information on the CP phase.

RENO-50

RENO-50



L~50km experiment may be a natural extension of current Reactor-θ_{13} Experiments

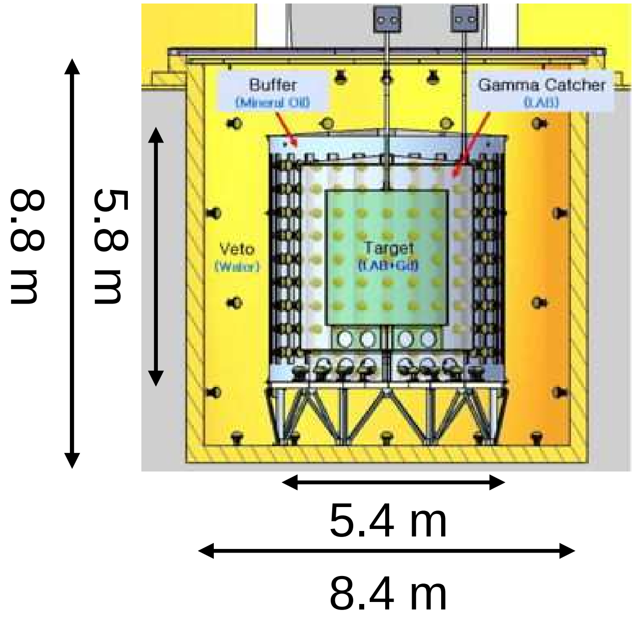
* θ_{13} detectors can be used as near detector

* Small background from other reactors.

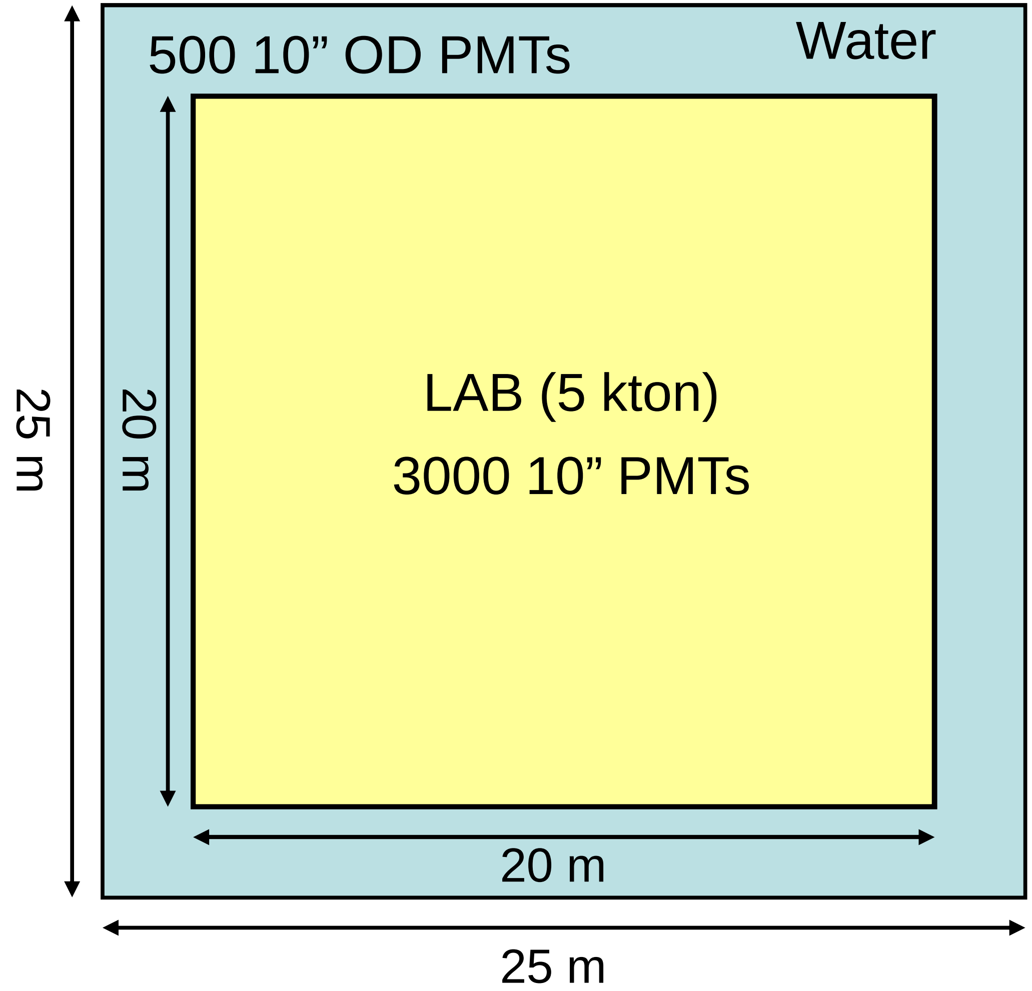
RENO-50

- 5000 tons ultra-low-radioactivity Liquid Scintillation Detector

RENO



RENO-50



Physics with RENO-50

- Precise measurement of θ_{12}

$$\frac{\delta \sin^2\theta_{12}}{\sin^2\theta_{12}} \sim 1.0\%(1\sigma)$$ in a year $\leftarrow$ current accuracy : 5.4%

- Determination of mass hierarchy Δm^2_{13}

- Neutrino burst from a Supernova in our Galaxy :

  ~1500 events (@8 kpc)

- Geo-neutrinos : ~ 300 geo-neutrinos for 5 years

- Solar neutrinos : with ultra low radioacitivity

- Reactor physics : non-proliferation

- Detection of T2K beam : ~120 events/year

- Test of non-standard physics : sterile/mass varying neutrinos

RENO-50 & J-PARC Neutrino Beam

Dr. Naotoshi Okamura & Prof. K. Hagiwara