Observation of Reactor Antineutrino Disappearance at RENO & Future Plan

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On behalf of the RENO Collaboration

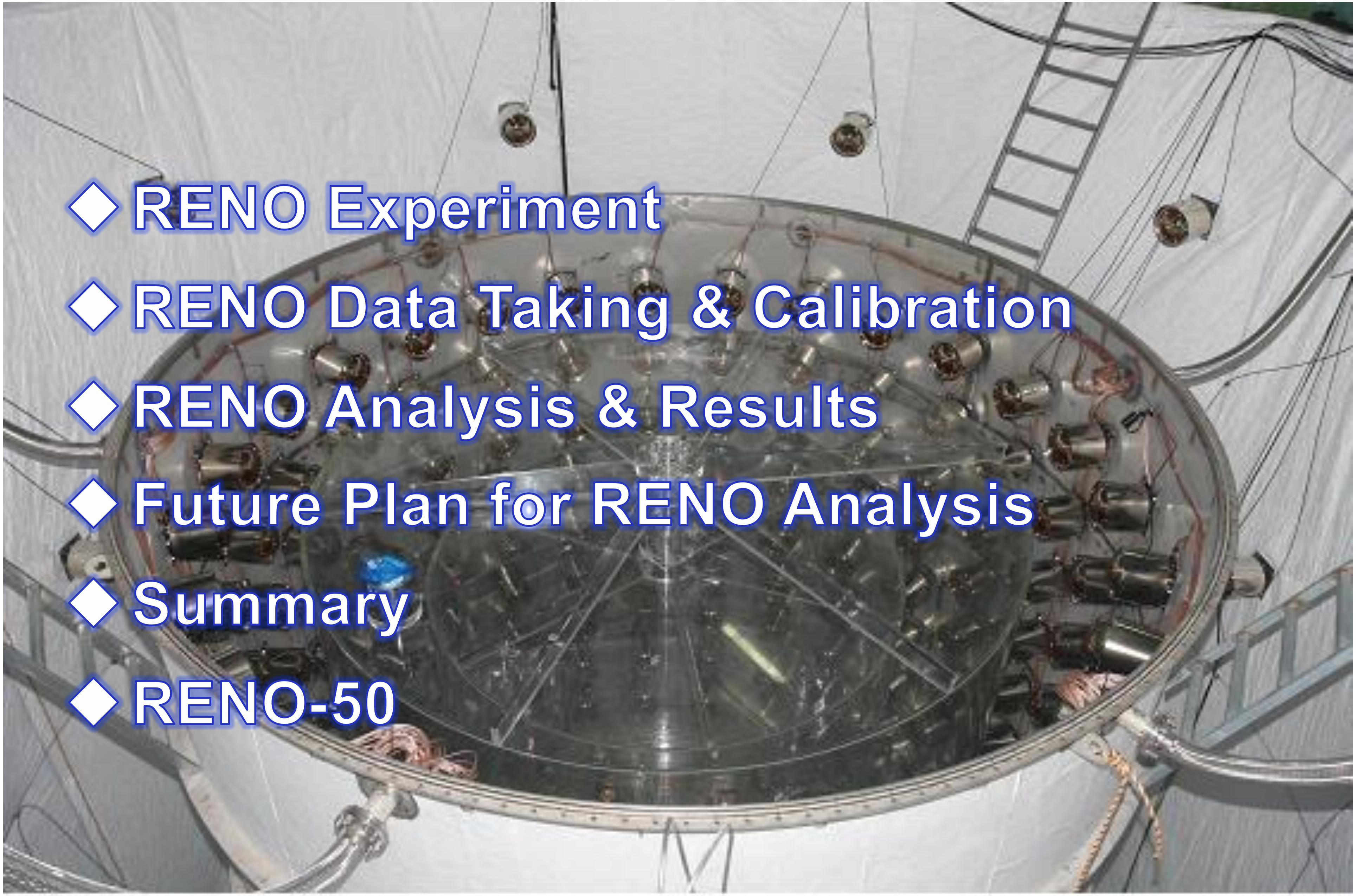
RENO ν θ_{13}

NOW 2012
September 11

ν_e ν_μ ν_τ

KNRC
Korea Neutrino Research Center

Outline



- RENO Experiment
- RENO Data Taking & Calibration
- RENO Analysis & Results
- Future Plan for RENO Analysis
- Summary
- RENO-50

RENO Collaboration

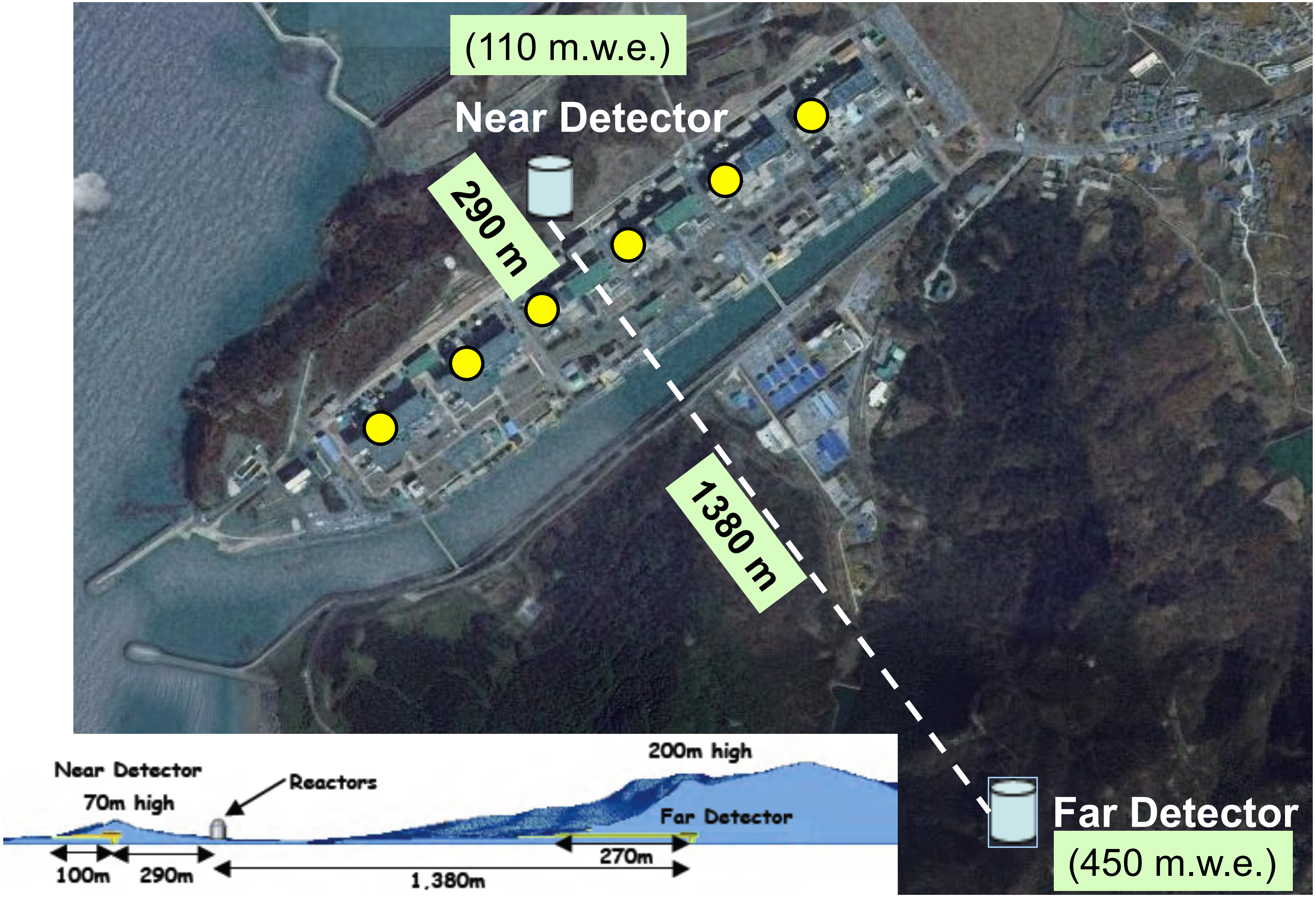
12 institutions and 40 physicists

- 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**

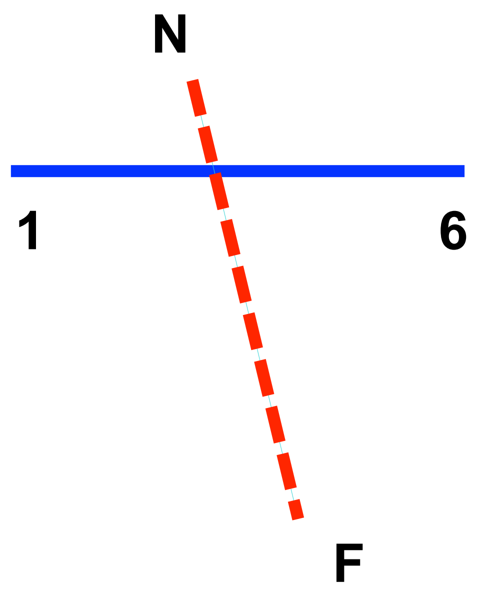
YongGwang (靈光) :

RENO Experimental Setup



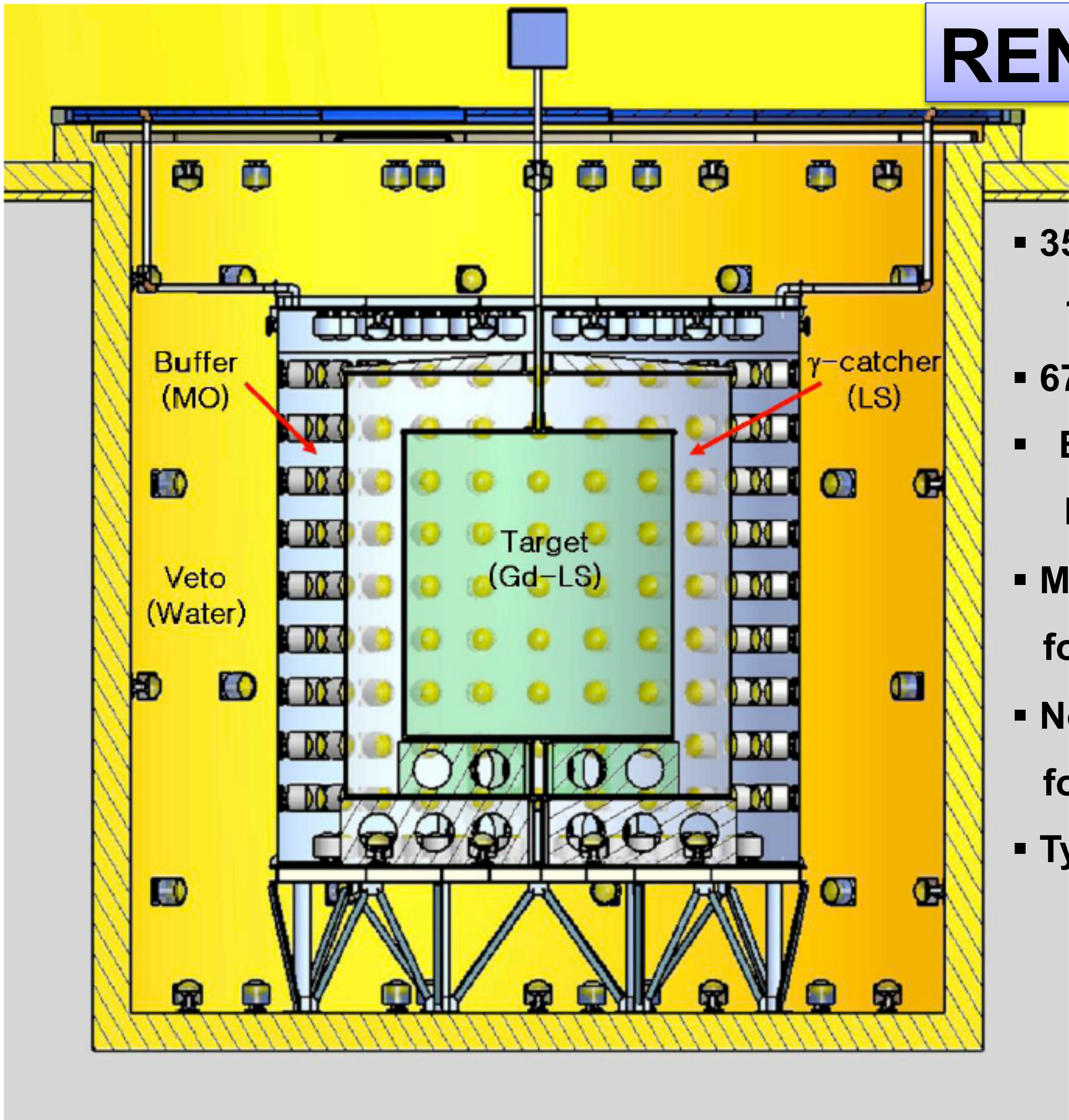
Contribution of Reactor to Neutrino Flux at Near & Far Detectors

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 10” ID PMTs :
  14% surface coverage
- 67 10” OD PMTs
- Both PMTs are
  HAMAMATSU, R7081
- Mu-metal shielding
  for each PMT. (-5cm)
- No special reflector
  for ID
- Tyvek reflector at OD

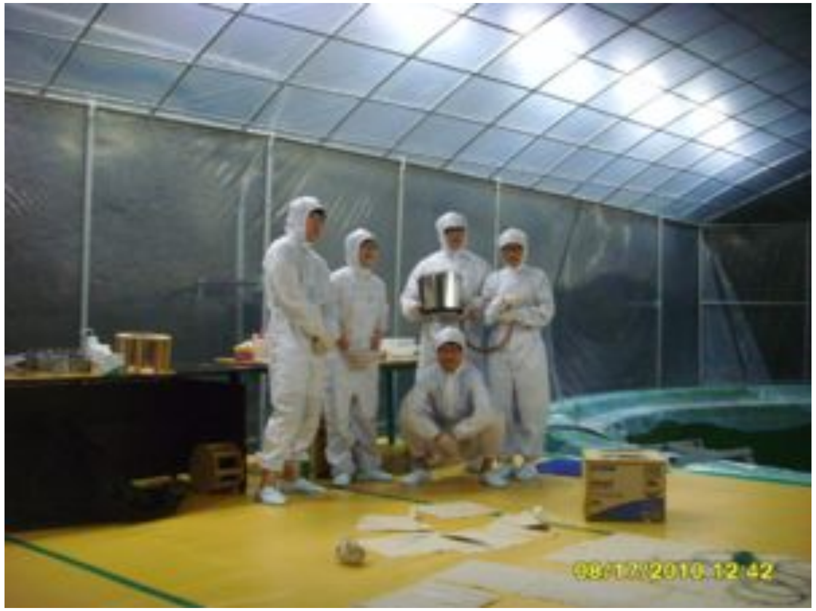
RENO Detector (cont.)

RENO consists of 4 different size cylinders (symmetric & coaxial) for different purposes.

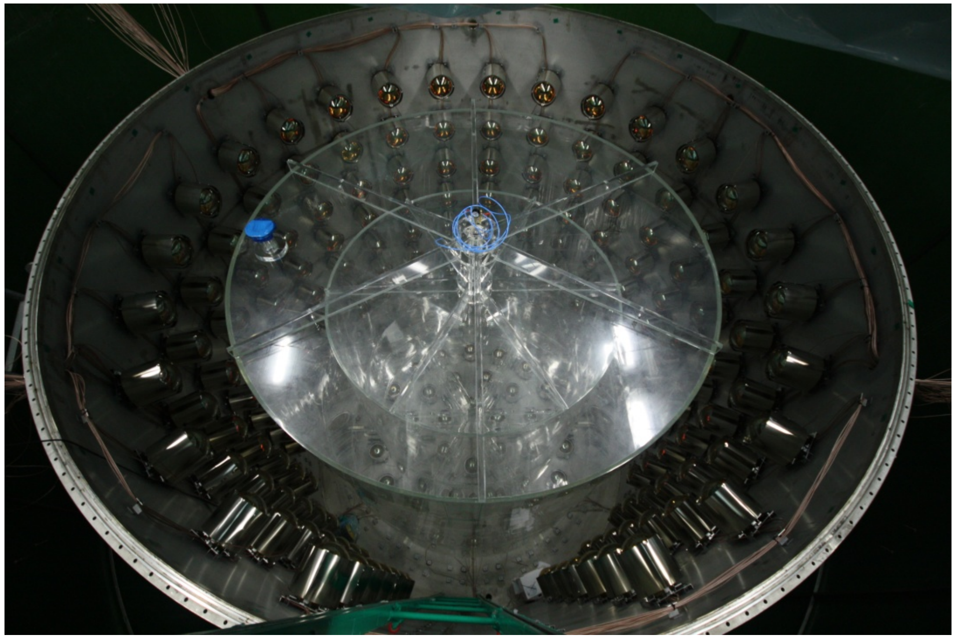
Inner detector	Inner Diameter (cm)	Inner Height (cm)	Container Material	Filled with	Mass (ton)
Target vessel	280	320	Acryl	Gd (0.1%) + LS	16.5
Gamma catcher	400	440	Acryl	LS	30.0
Buffer tank	540	580	Stainless steel	Mineral oil	64.4
Veto tank	840	880	concrete	Water	352.6

outer detector

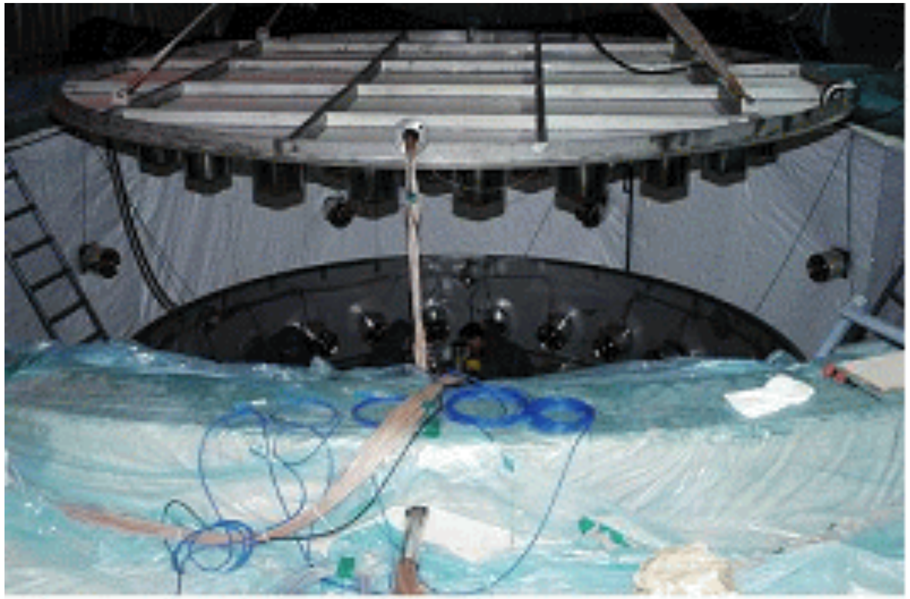
PMT Mounting (2010. 8~10)

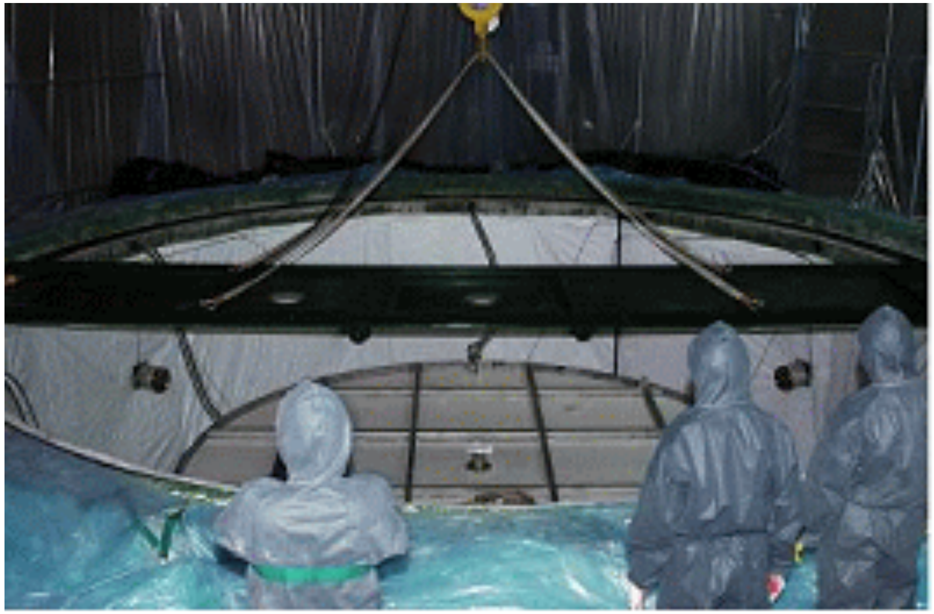


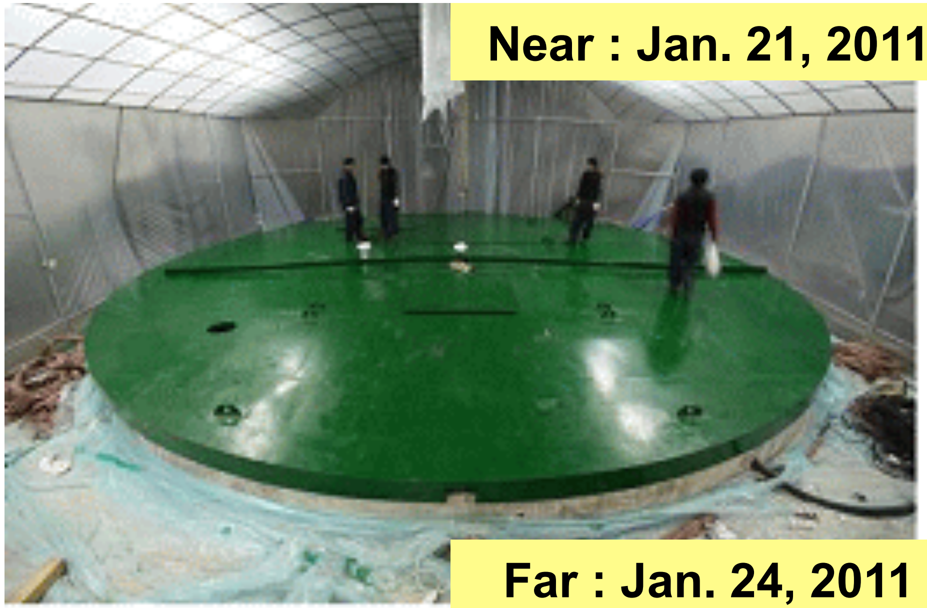
PMT Mounting (2010. 8~10)



Detector Closing (2011. 1)







Near : Jan. 21, 2011

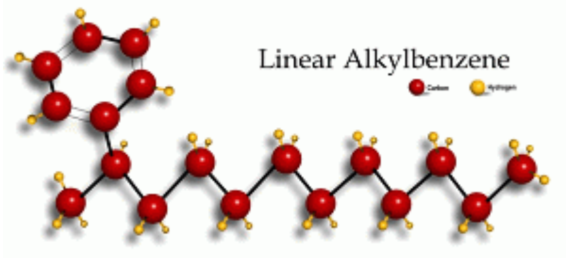
Far : Jan. 24, 2011

Gd Loaded Liquid Scintillator

❑ Recipe of Liquid Scintillator

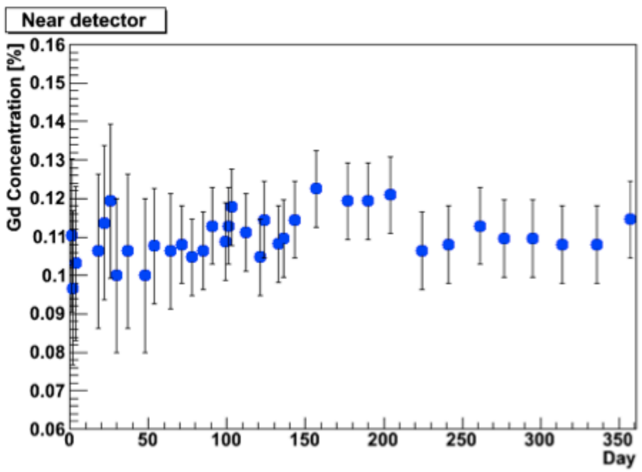
Aromatic Solvent & Flour	WLS	Gd-compound
LAB	PPO + bis-MSB	0.1% Gd+(TMHA)^3 (trimethylhexanoic acid)

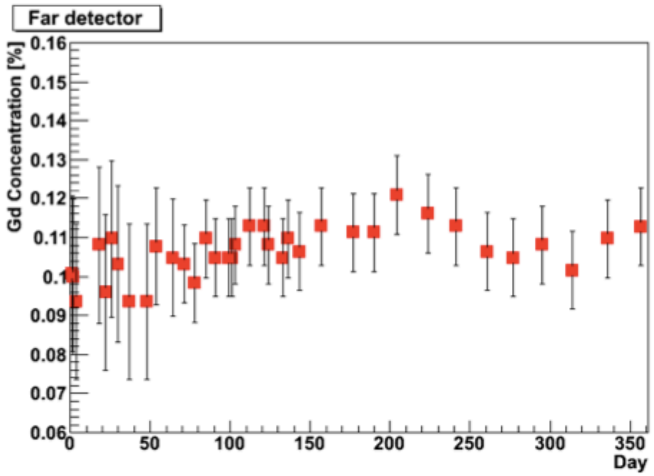
C_nH_{2n+1}-C_6H_5 (n=10~14)

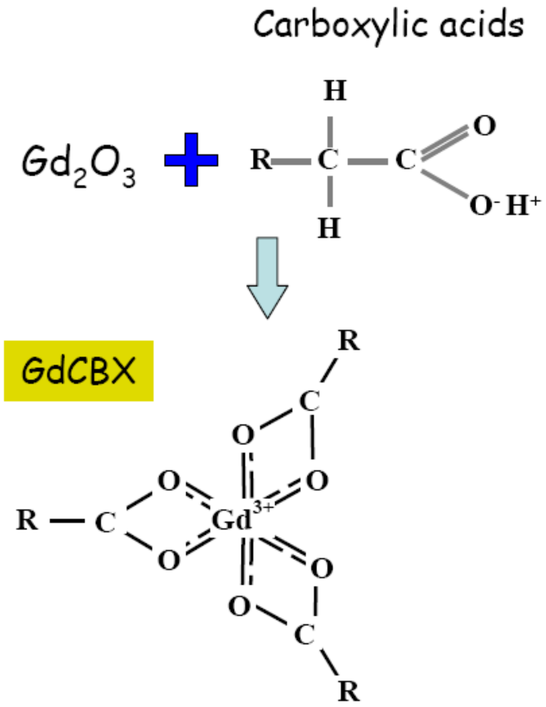


❑ Steady properties of Gd-LS

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







Data-Taking & Data Set

- Data taking began on Aug. 1, 2011 with both near and far detectors.

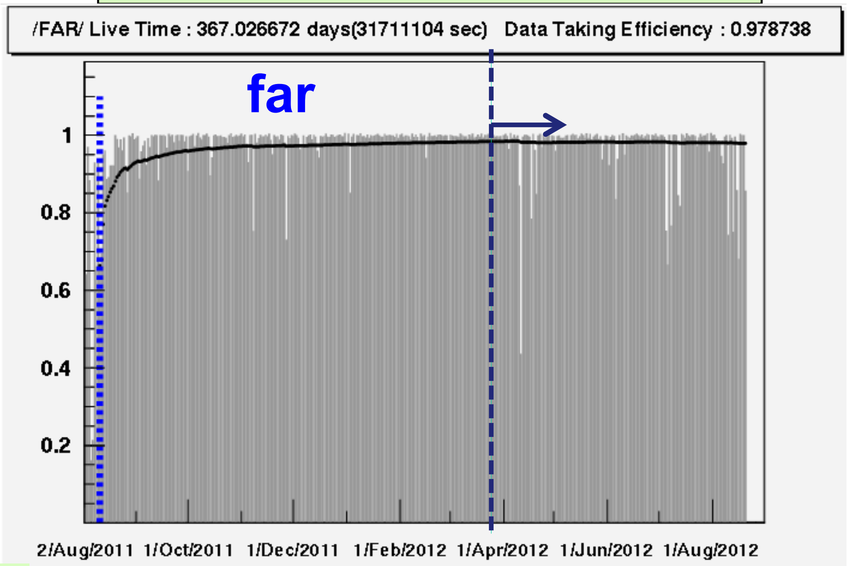
- Data-taking efficiency > 90%.

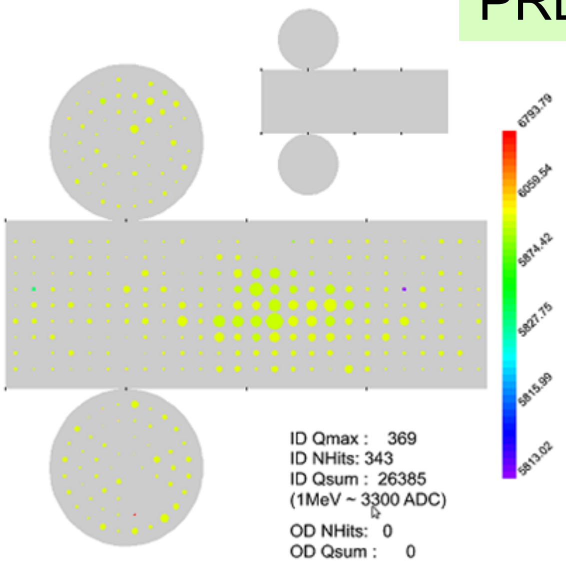
- Trigger rate at the threshold energy of 0.5~0.6 MeV : 80 Hz

- Data-taking period : 228 days
  Aug. 11, 2011 ~ Mar. 25, 2012

PRL 108, 191802 (2012)

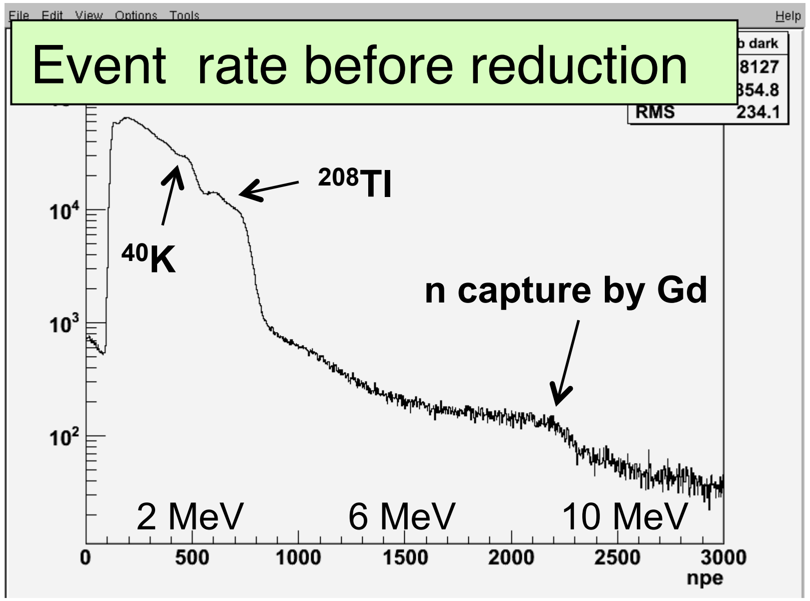
- Data-taking efficiency



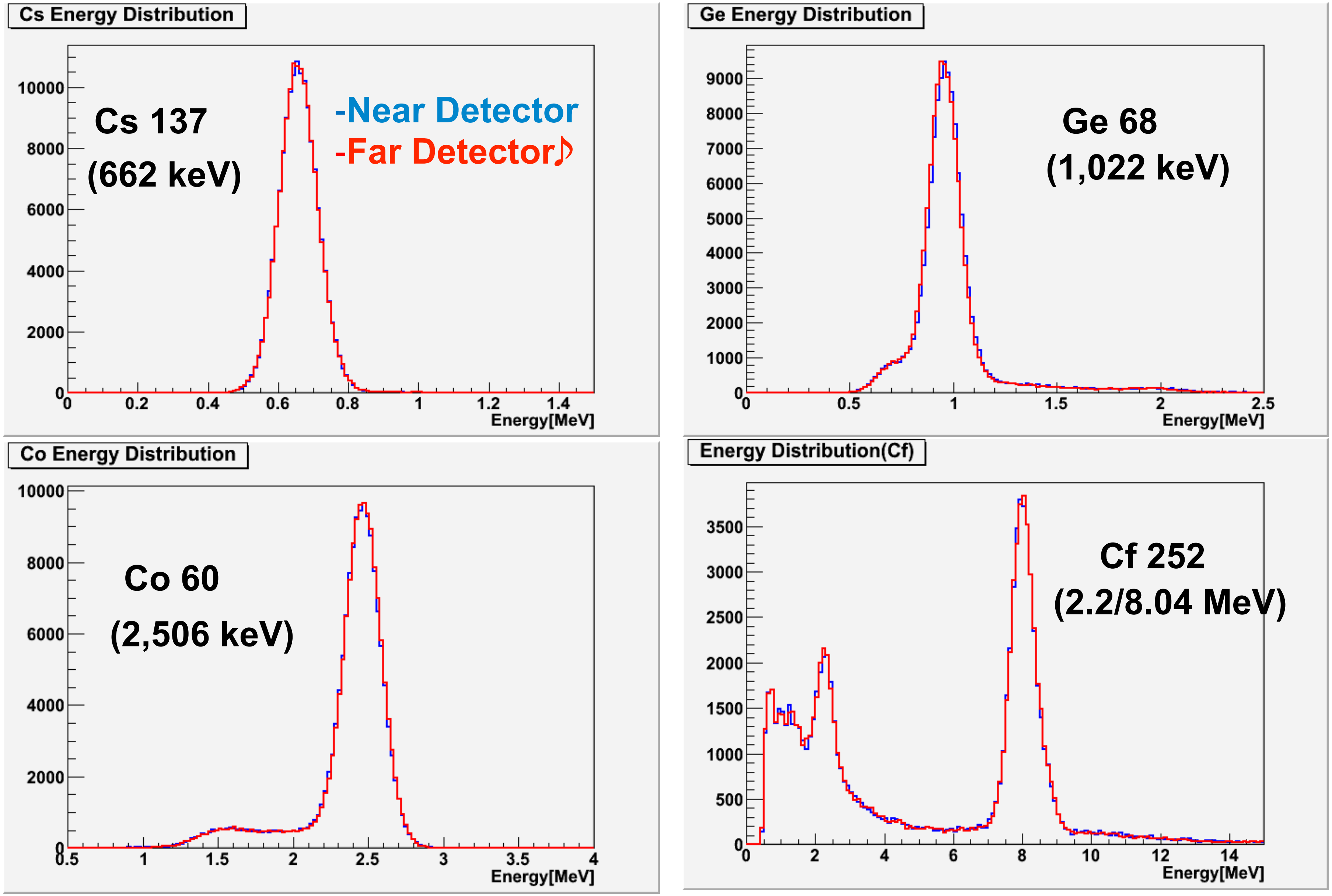


A candidate for a neutron capture by Gd

Event rate before reduction

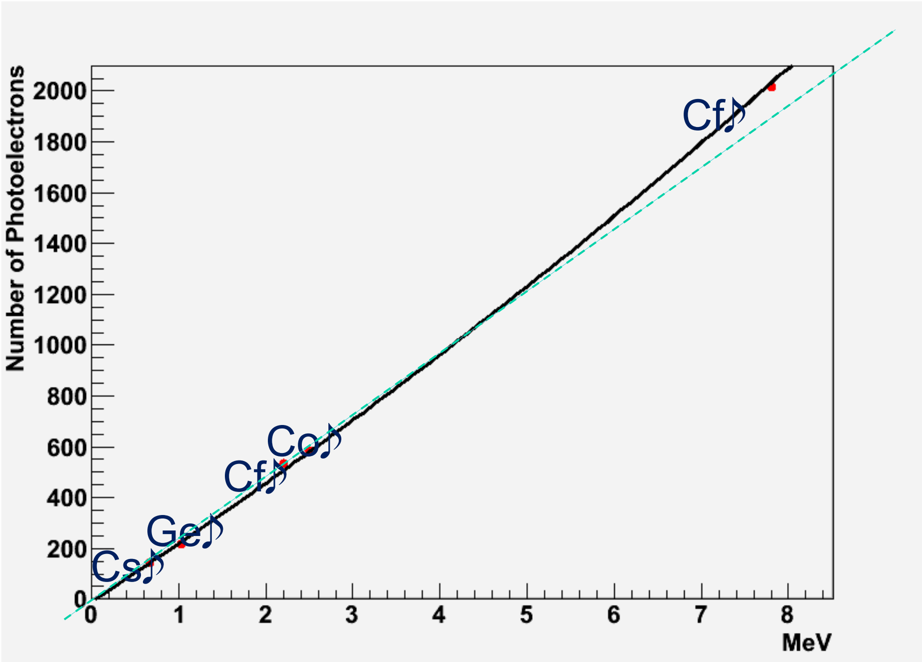


Energy Calibration

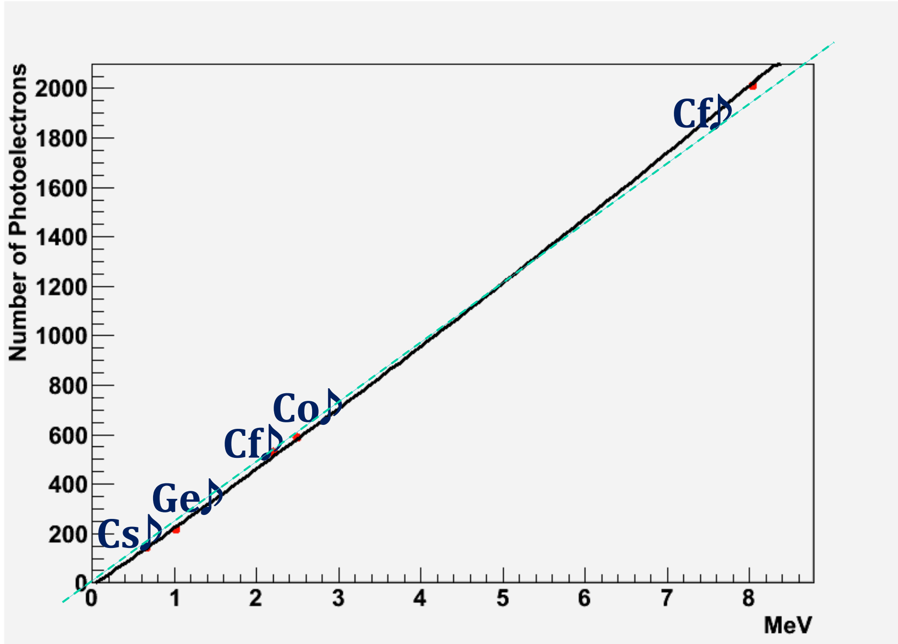


Energy Scale Calibration

Near Detector♪



Far Detector♪



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

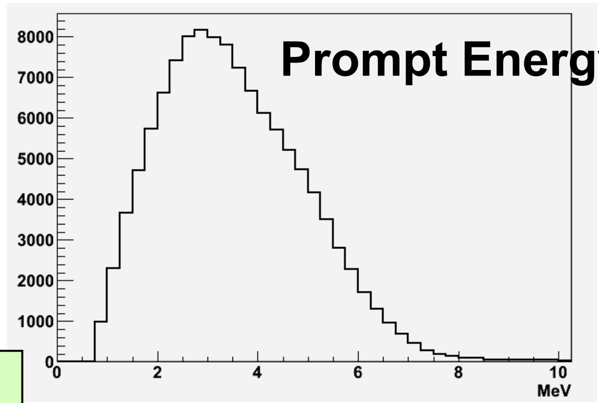
- ~ 250 pe/MeV (sources at center)
- Identical energy response (< 0.1%) of ND & FD
- Slight non-linearity observed

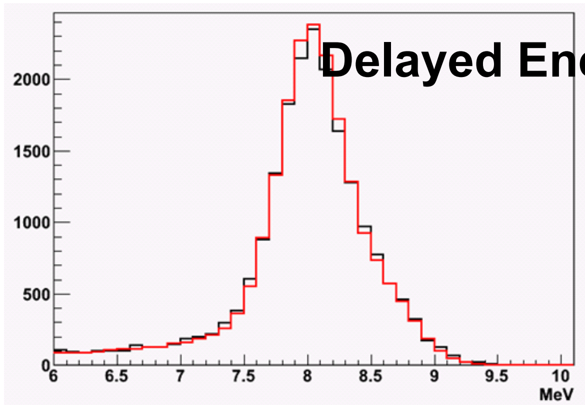
IBD Event Signature and Backgrounds

❑ 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)
- **$^9Li/^8He$** 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

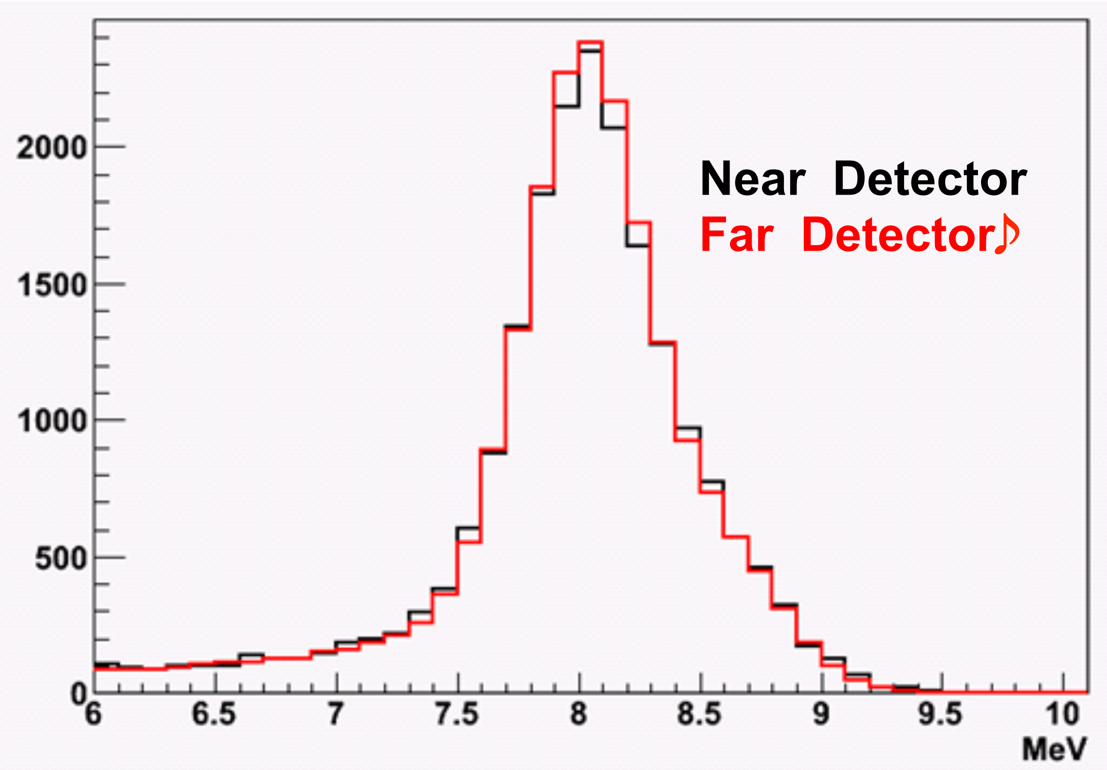
  (1) 1 ms after an ID muon with E > 70 MeV, or with 20 < E < 70 MeV and OD NHIT > 50 (→ to remove fast neutrons)

  (2) 10 ms after an ID muon with E > 1.5 GeV (→ to remove Li/He)
- Coincidence between prompt and delayed signals in 100 μs

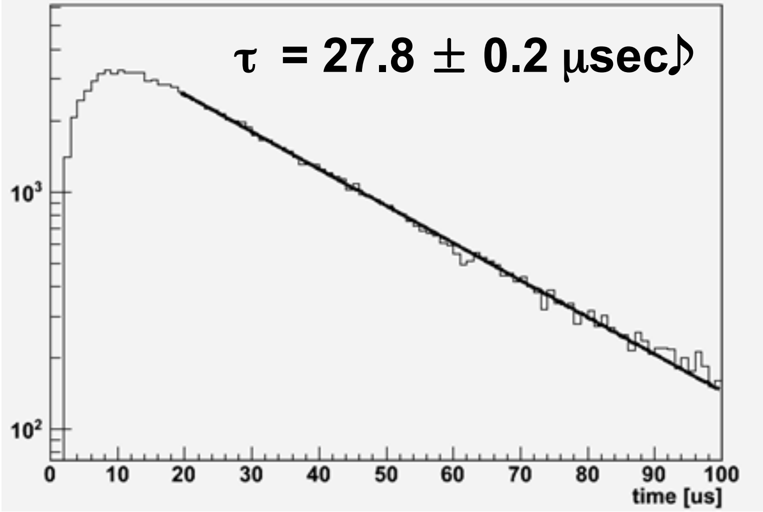
  - E_{prompt} : 0.7 ~ 12.0 MeV, $E_{delayed}$: 6.0 ~ 12.0 MeV
  - coincidence : $2\ \mu s < \Delta t_{e+n} < 100\ \mu s$
- Multiplicity cut : reject pairs if there is a trigger in the preceding 100 μs window (→ to remove spallation multiple-neutrons)

Spectra & Capture Time of Delayed Signals

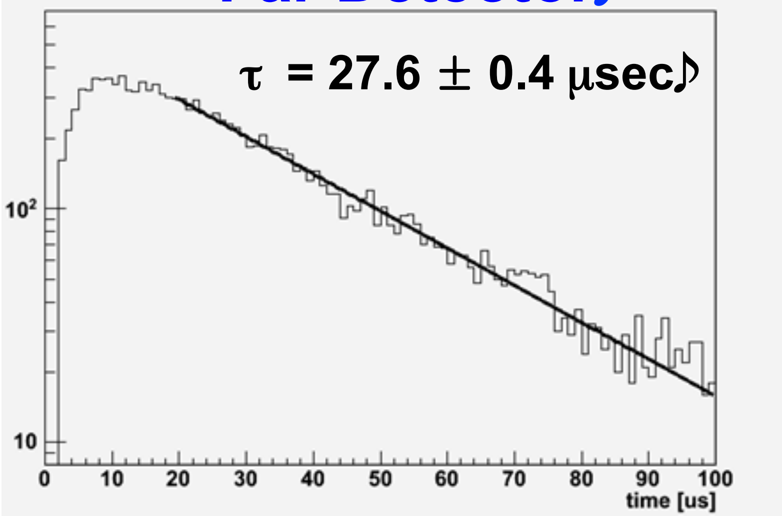
- ❑ Observed spectra of IBD delayed signals



Near Detector



Far Detector

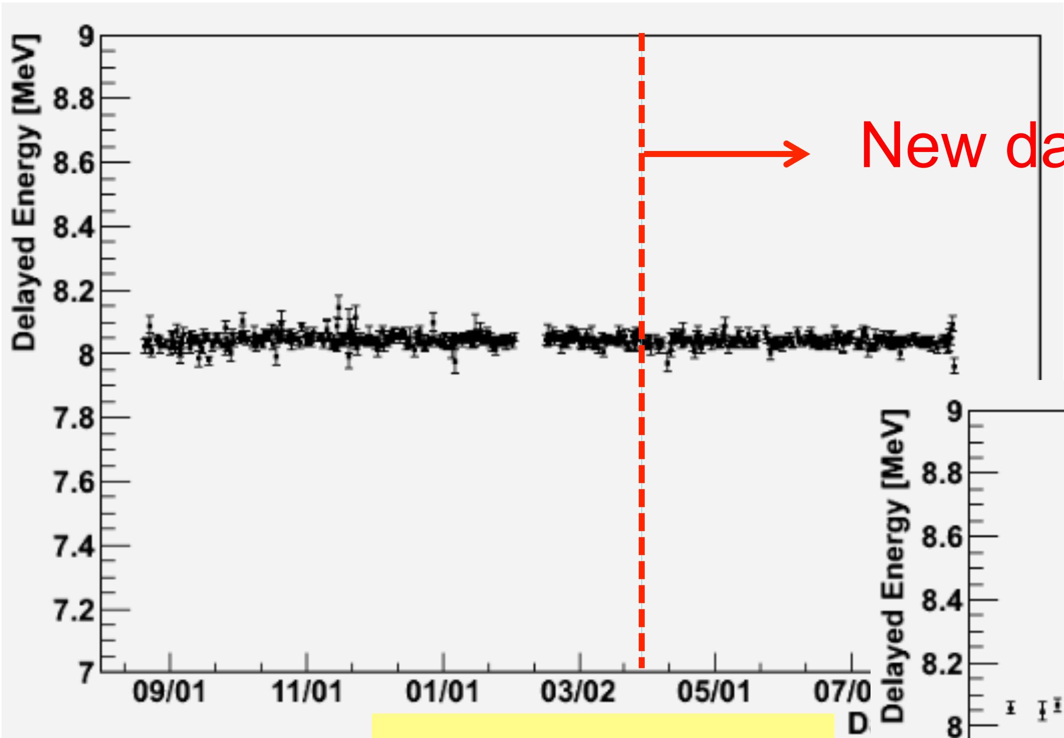


Detector Stability & Identical Performance

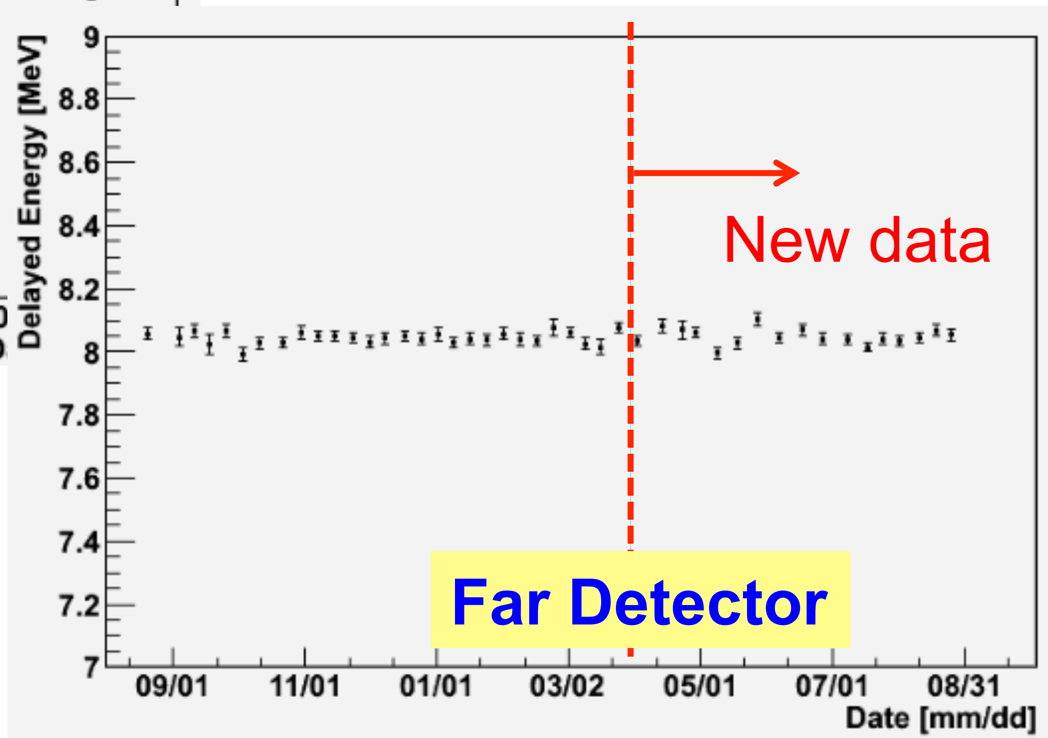
- IBD candidate's delayed signals (capture on Gd)

New data (after PRL release in May)

Ahn et al (RENO collab.), PRL 108, 191802 (2012)



Near Detector



Far Detector

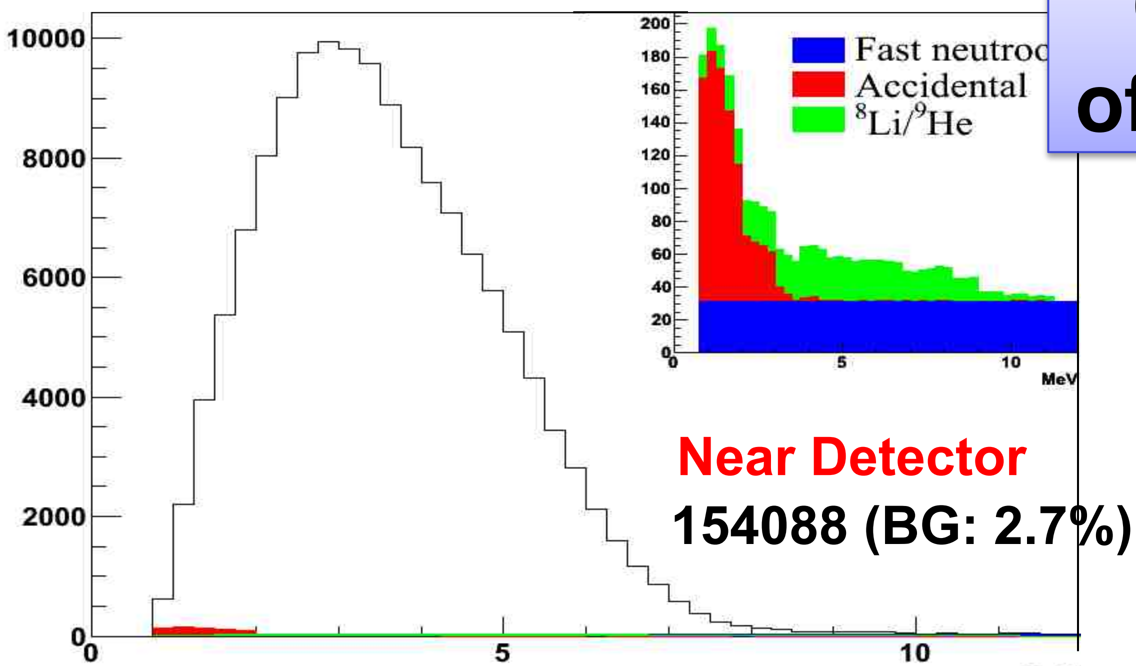
Summary of Final Data Sample

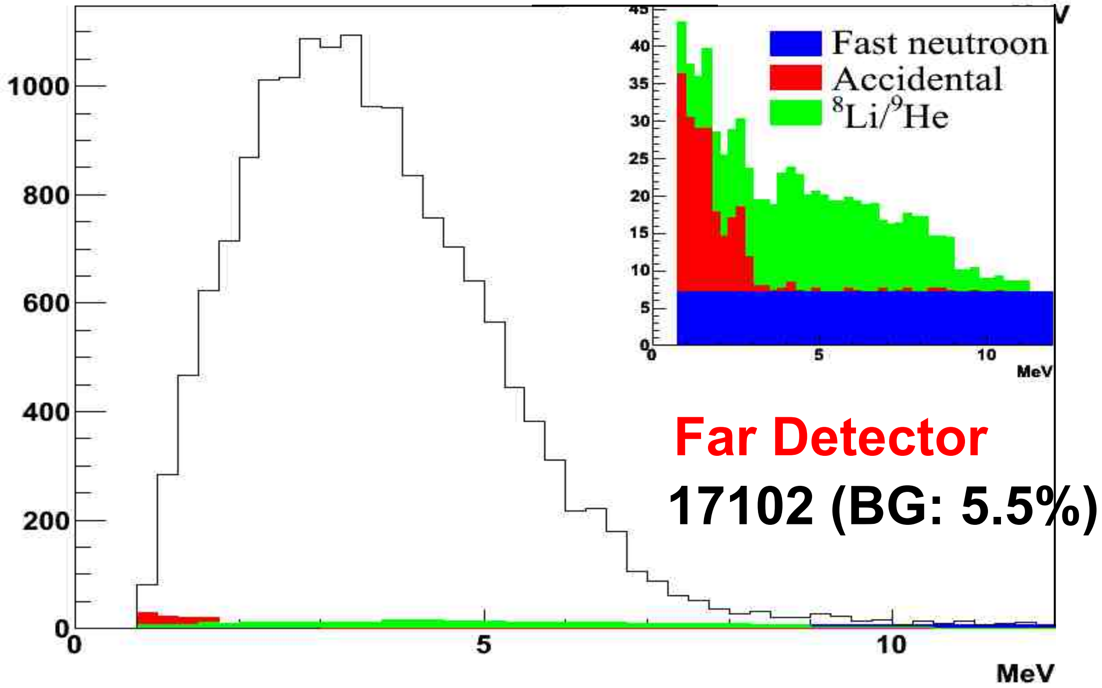
PRL data [with 192 (near), 222 (far) live-days data]

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

About 100 live-days more data (not included here) are currently being analyzed.

Observed Spectra of IBD Prompt Signal





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

- 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??

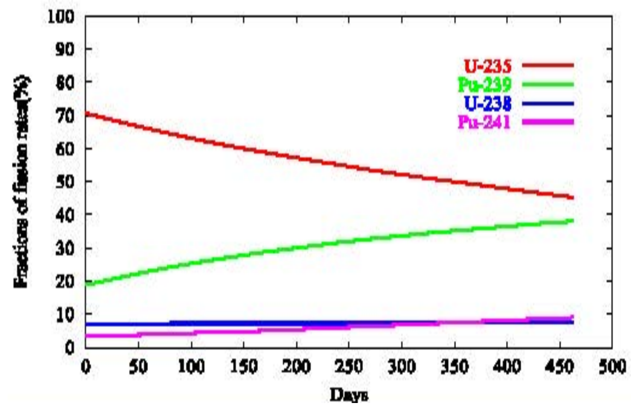
Expected Reactor Antineutrino Fluxes

- Reactor neutrino flux

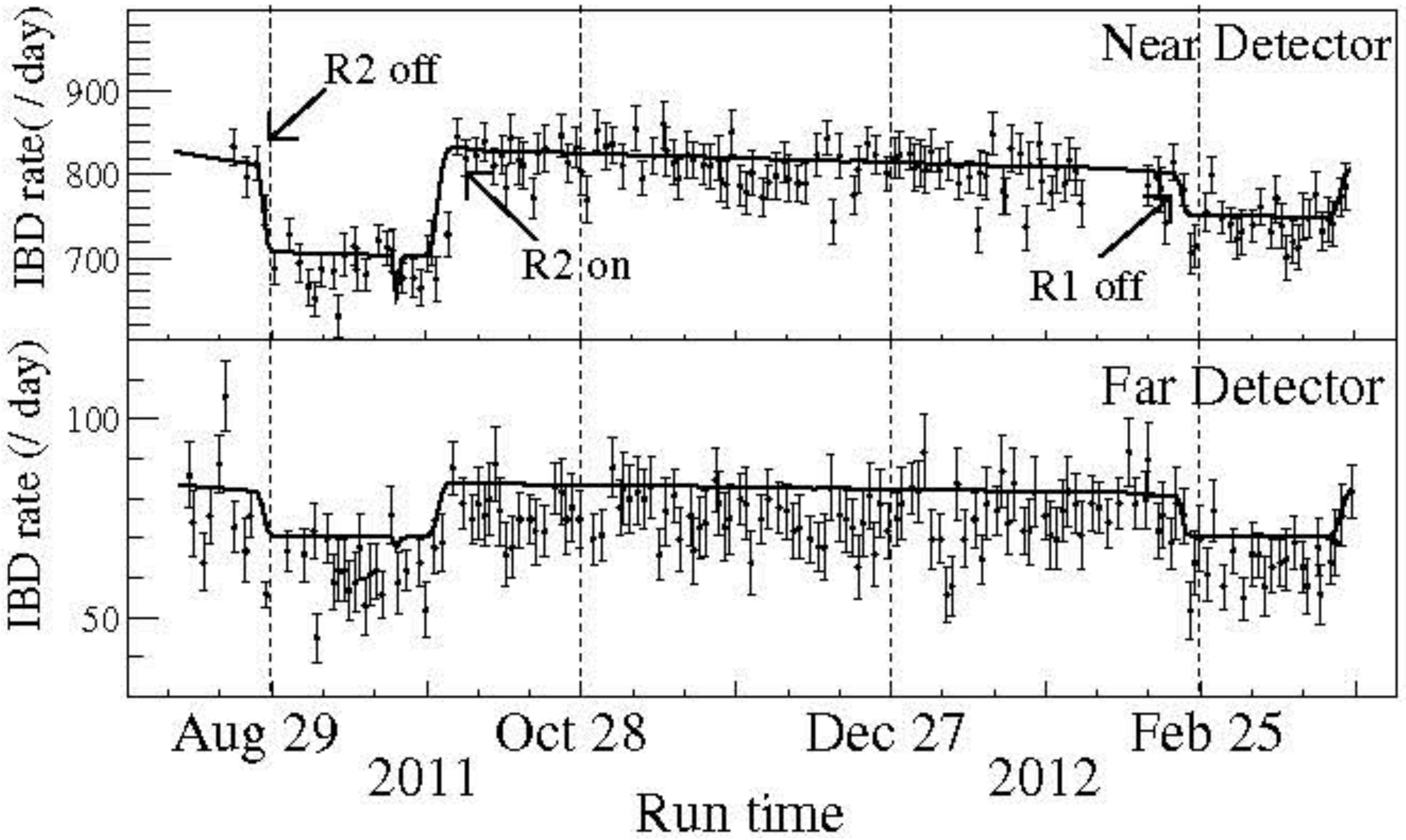
$$\Phi(E_\nu) = \frac{P_{th}}{\sum_i^{isotopes} f_i \cdot E_i} \sum_i^{isotopes} f_i \cdot \phi_i(E_\nu)$$

- 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



Expected and observed rates match very well!

Efficiency & Systematic Uncertainties

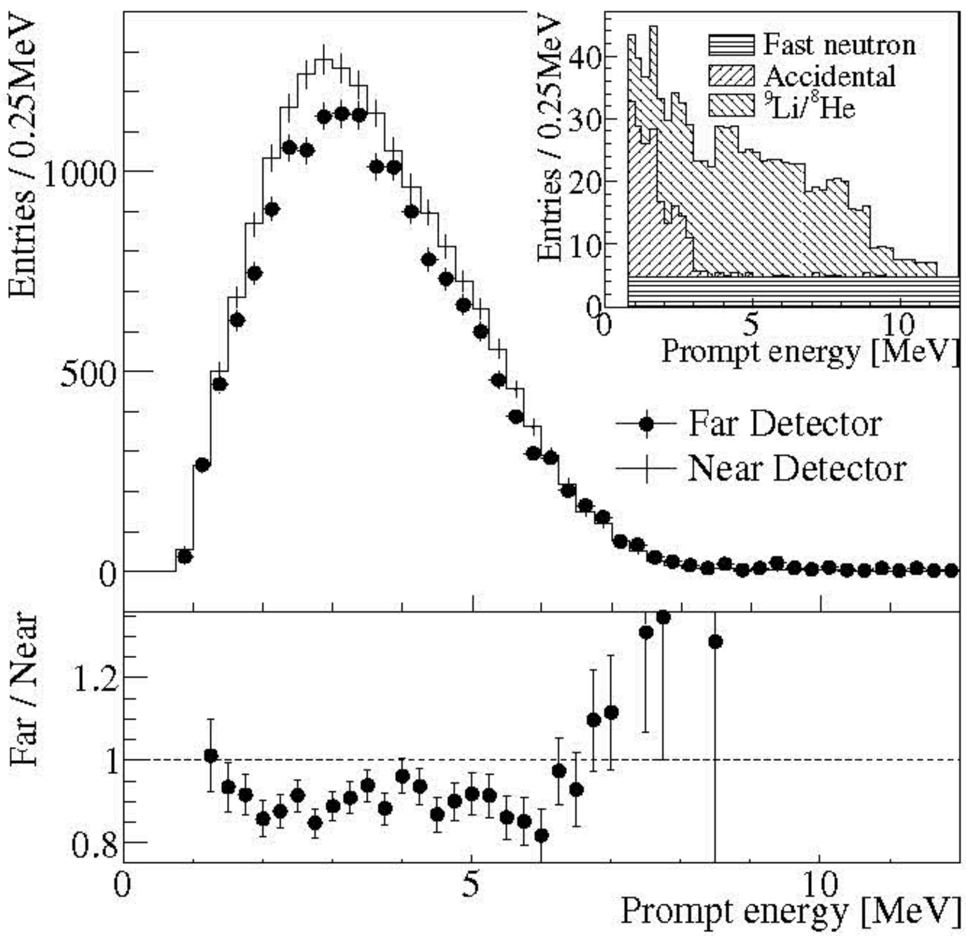
Prompt energy cut	
Flasher cut	
Gd capture fraction	
Delayed energy cut	
Time coincidence cut	
Spill-in	
Common	

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

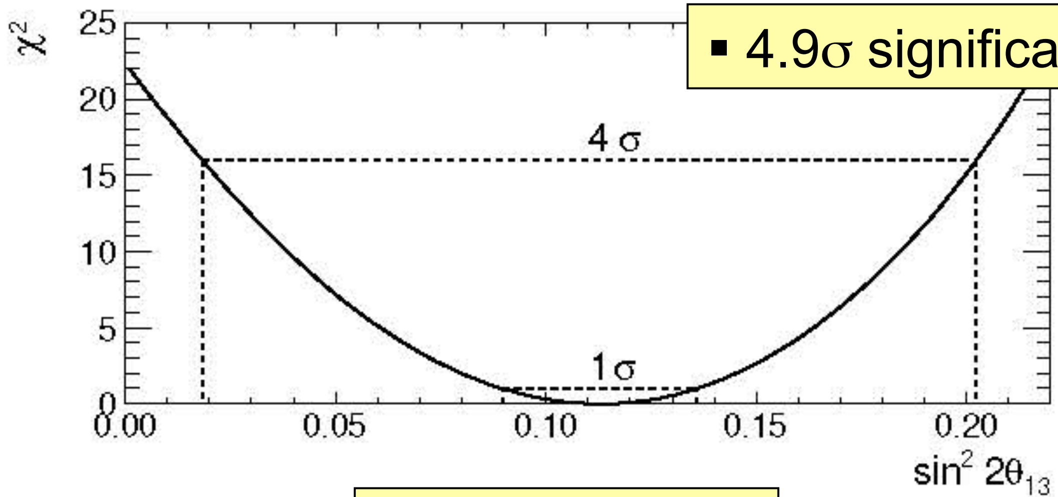
$$R = \frac{\Phi^{Far}_{observed}}{\Phi^{Far}_{expected}} = 0.920 \pm 0.009(stat) \pm 0.014(syst)$$



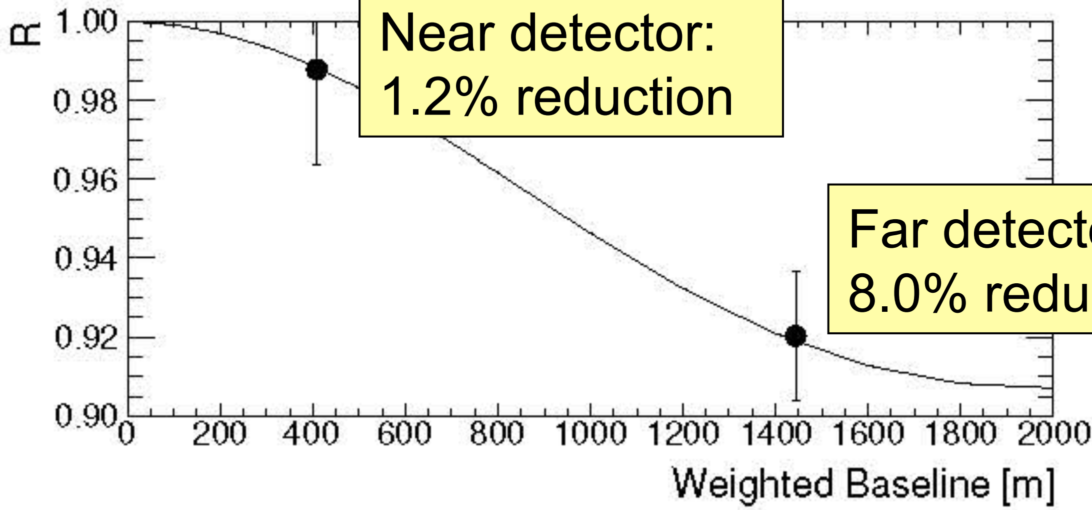
- A clear deficit in rate (8.0% reduction)
- Consistent with neutrino oscillation in the spectral distortion
- E>6 MeV distortion is not understood yet.

Definitive Measurement of θ_{13}

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



- 4.9σ significant signal



Near detector:
1.2% reduction

Far detector:
8.0% reduction

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 (11 σ)

(220 days) → (3 years)

- 3 yr of data : **~ 1%** for the total measurement error

- **statistical error : 1.3%** (~220 days) → **0.6%**

- **systematic error : 1.9%**

  1.4% (by background reduction)

  1.0% (by reduction of reactor uncertainty + shape analysis)

  0.5% (by reduction of detection efficiency uncertainty)

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

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

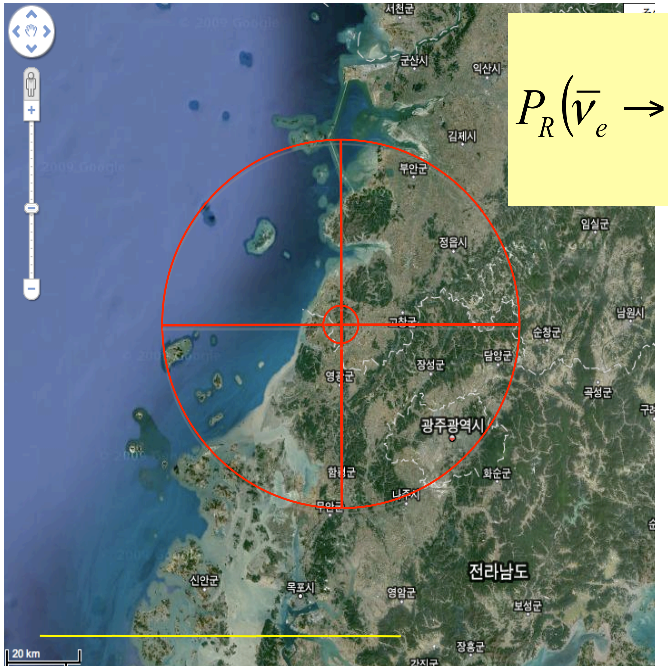
~220 d data

so far

- Data-taking (**~320 days**) & data-analysis in a steady state.
- Shape analysis and background reduction under progress.

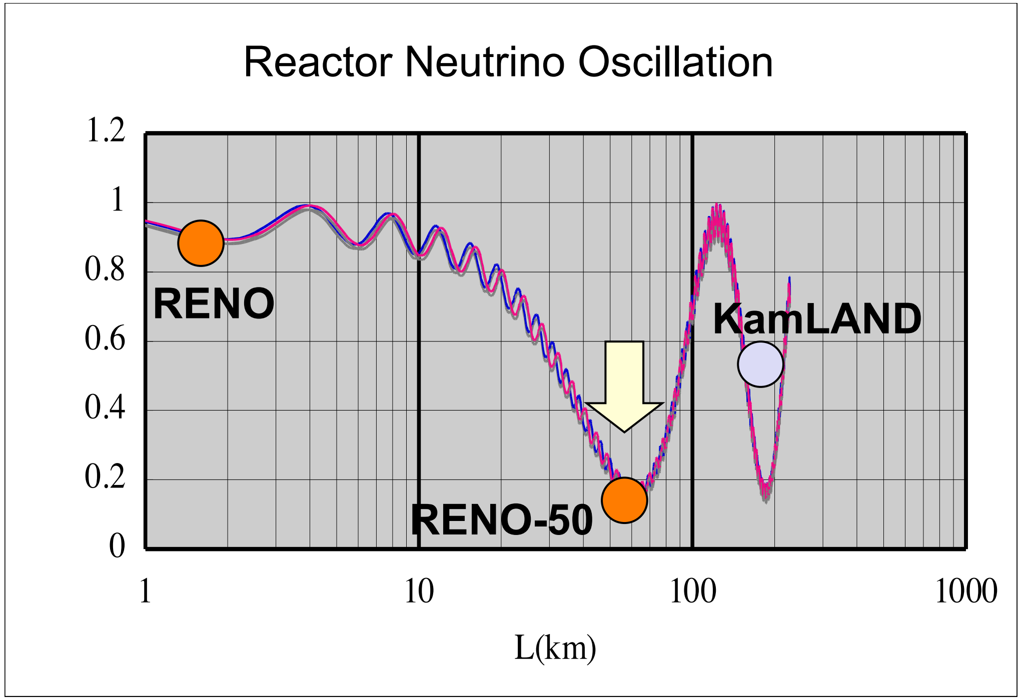
RENO-50

- Large θ_{12} neutrino oscillation effects at 50 km + 5kton liquid scintillator detector
- RENO can be used as near detectors. → Precise reactor neutrino fluxes
- Negligible contribution from other nuclear power plants.



$$P_R\left(\bar{\nu}_e \to \bar{\nu}_e\right) = 1 - \left\{ \begin{array}{l} \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} \\ +\sin^2 2\theta_{13}\sin^2\theta_{12}\left(\cos 2\Delta_{31}\sin^2\Delta_{21} - \tfrac{1}{2}\sin 2\Delta_{31}\sin 2\Delta_{21}\right) \end{array} \right\}$$

L~50km experiment could be a natural extension of current RENO θ_{13} experiment. (2018 ~)



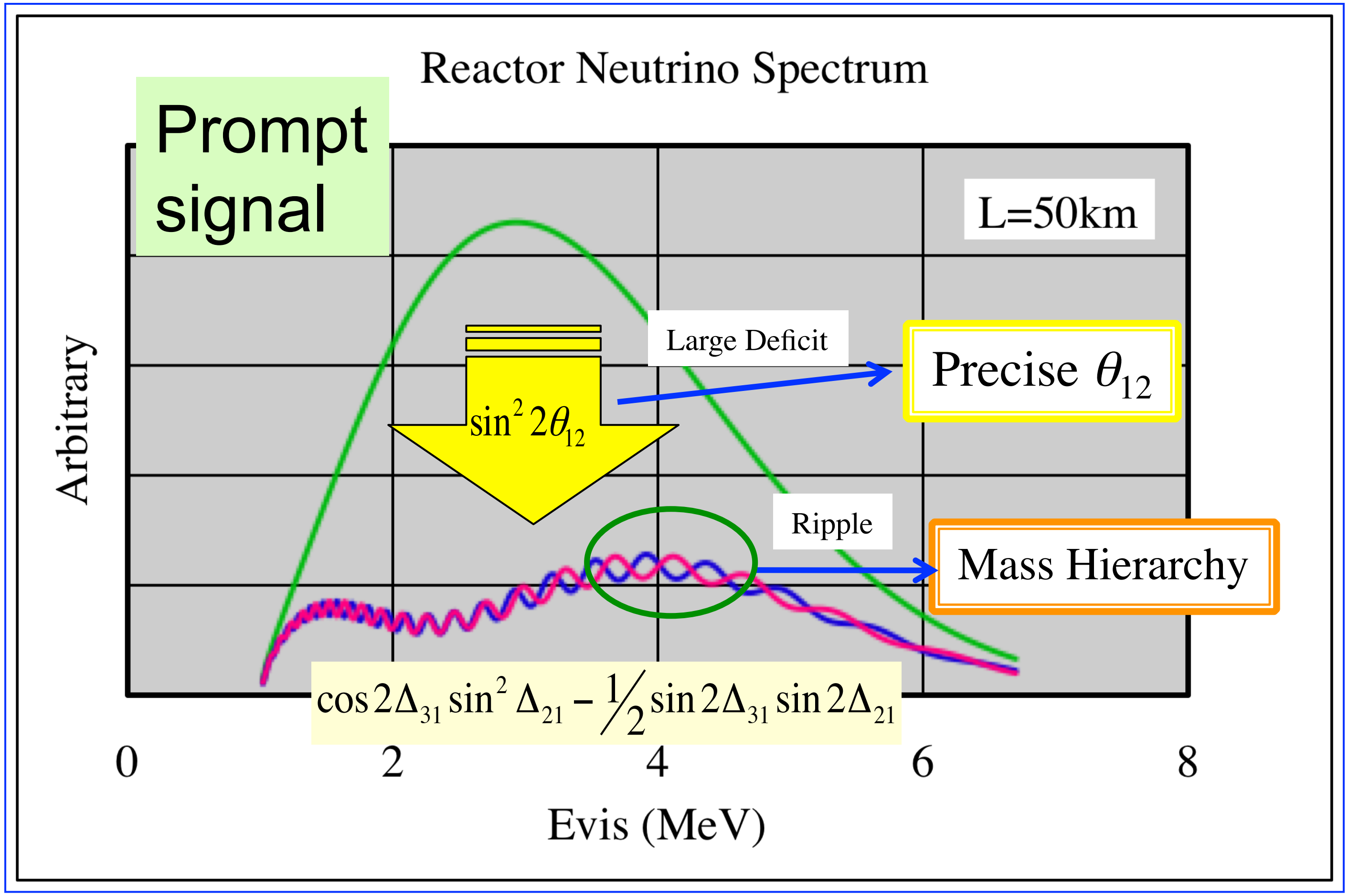
1st Δm^2_{21} Maximum (L~50km) ;

precise value of θ_{12} & Δm^2_{21} + mass hierarchy (Δm^2_{31})

$$P_R(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \left\{ \begin{array}{l} \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} \\ +\sin^2 2\theta_{13}\sin^2\theta_{12}\left(\cos 2\Delta_{31}\sin^2\Delta_{21} - \frac{1}{2}\sin 2\Delta_{31}\sin 2\Delta_{21}\right) \end{array} \right\}$$

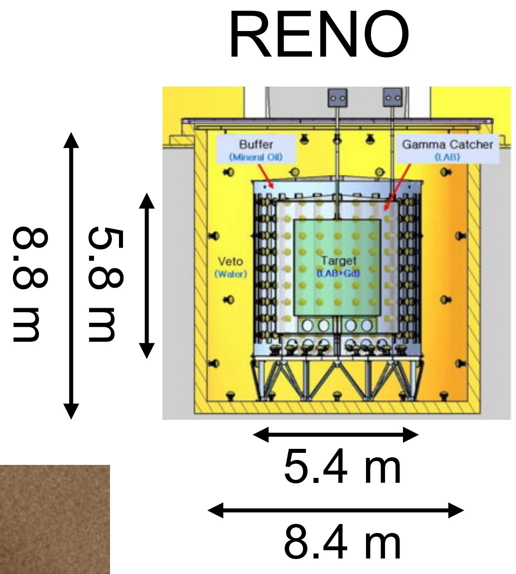
Minakata et al, PRD 68,033017 (2003)

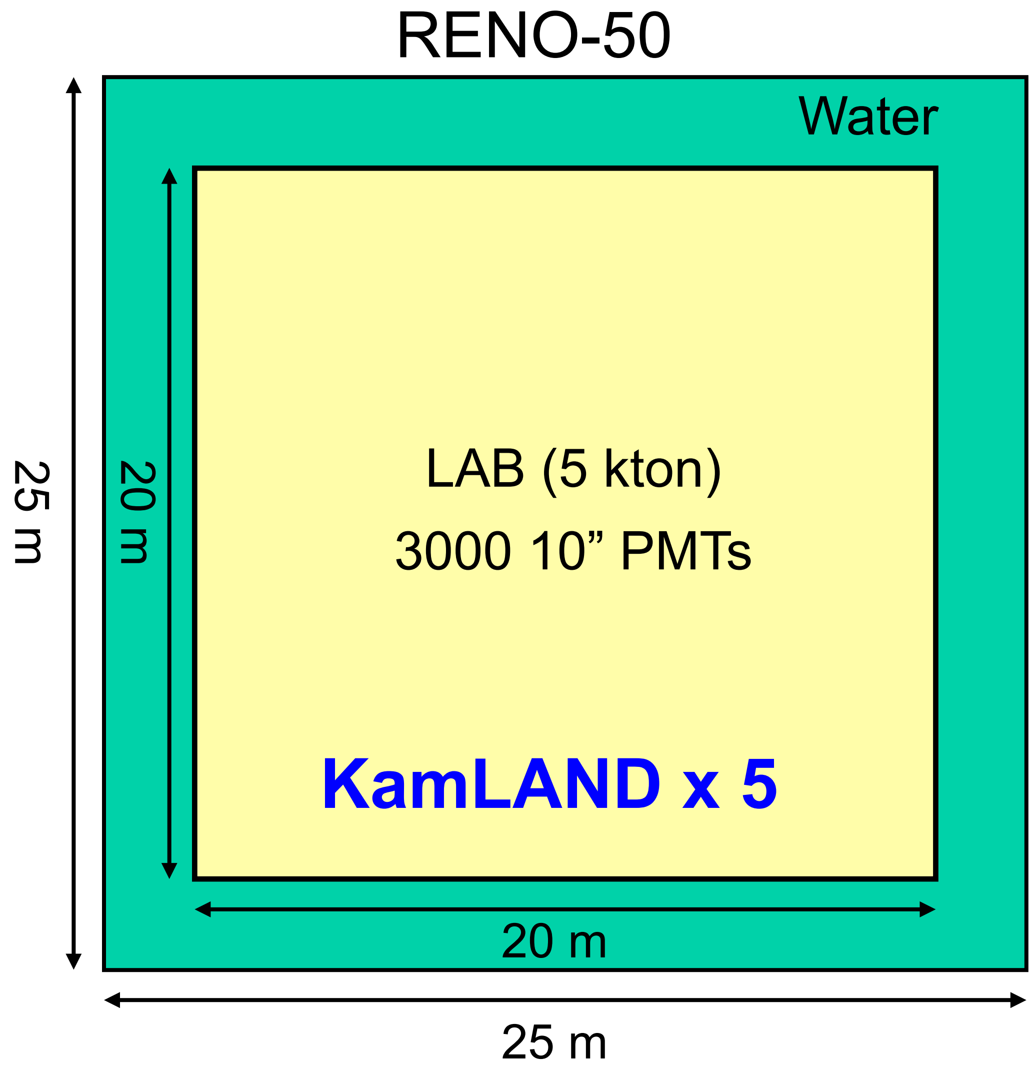
Akhmedov et al, JHEP 04, 078 (2004)

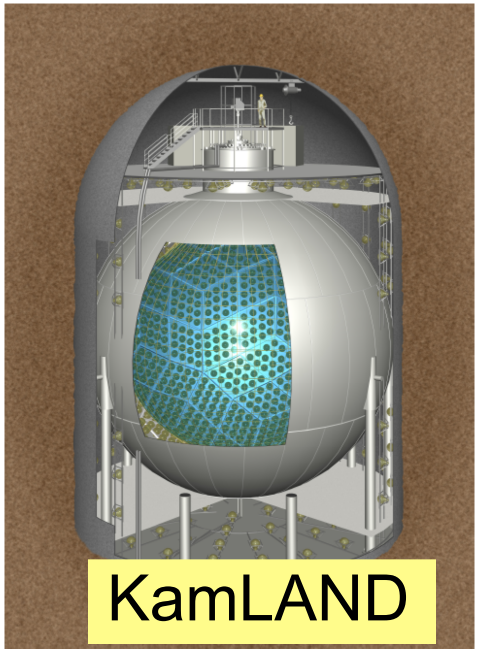


RENO-50 Detector

- 5000 tons ultra-low-radioactivity Liquid Scintillation Detector







RENO-50 vs. KamLAND

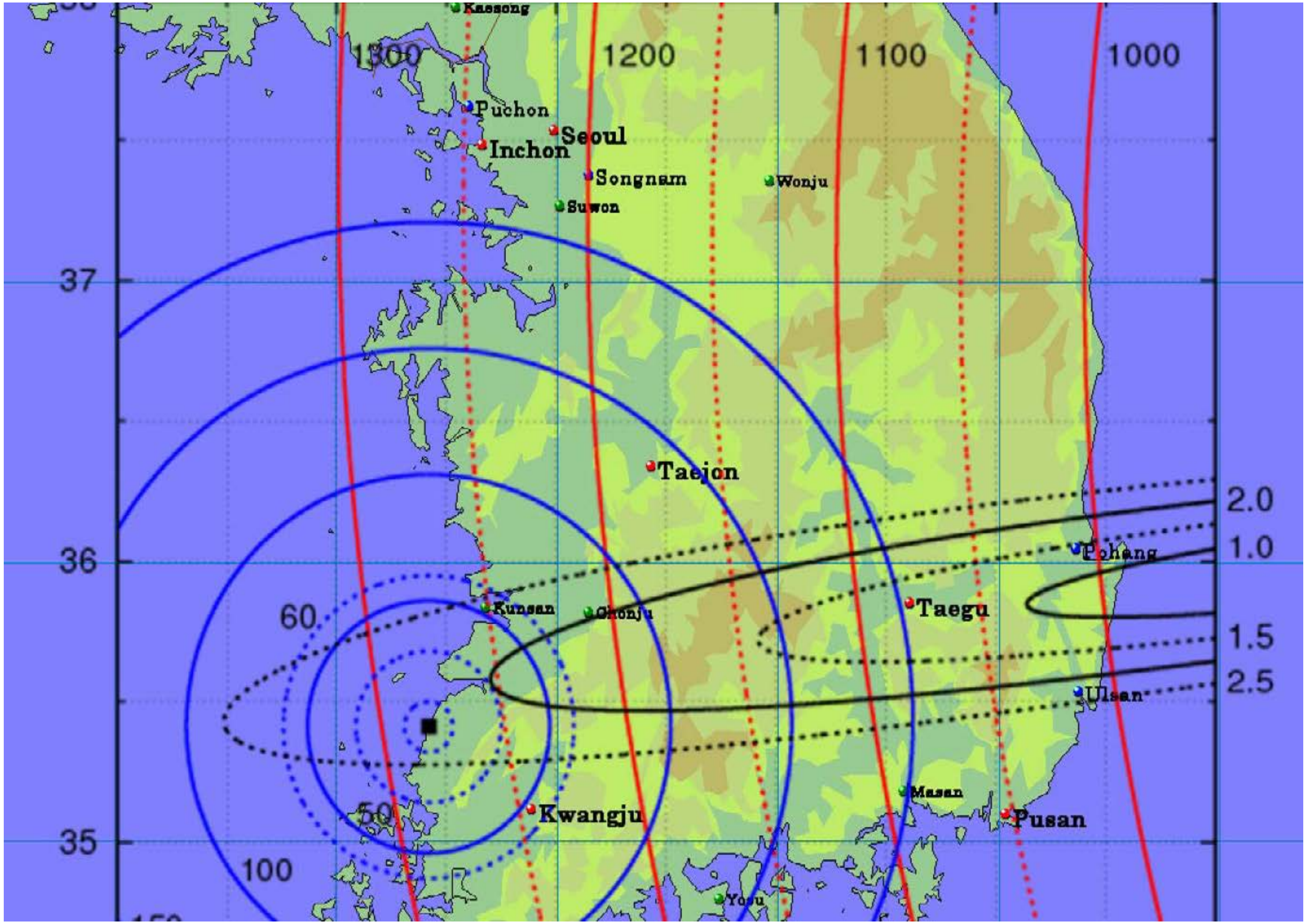
RENO-50

* RENO-50 is dedicated to the Yonggwang power plant. (negligible contribution from the other nuclear power plants)
* RENO can be used as near detectors.
* Precise reactor neutrino fluxes : **systematic error from ~3% to ~0.1%**

* KamLAND uses the entire Japanese nuclear power plants as a source

J-PARC neutrino beam

Dr. Okamura & Prof. Hagiwara



Physics with RENO-50

■ Precise measurement of θ_{12} and Δm^2_{21}

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

$$\frac{\delta \Delta m^2_{12}}{\Delta m^2_{12}} \sim 1\%\ (1\sigma)$$ in 2~3 years (← 2.6%)

■ Determination of mass hierarchy : challenging

✓ Requires extremely good energy resolution.

✓ **Plan B**: to build additional 200-ton detector at 10 km.

(L : 300 m + 1.4 km + 10 km + 50 km)

■ Neutrino burst from a Supernova in our Galaxy :

-- ~1500 events (@8 kpc)

-- a long-term neutrino telescope

Physics with RENO-50 (cont.)

- Solar neutrinos : with ultra low radioacitivity (Borexino level)

-- Matter effects on neutrino oscillation

-- Probe the center of the Sun and test the solar models

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

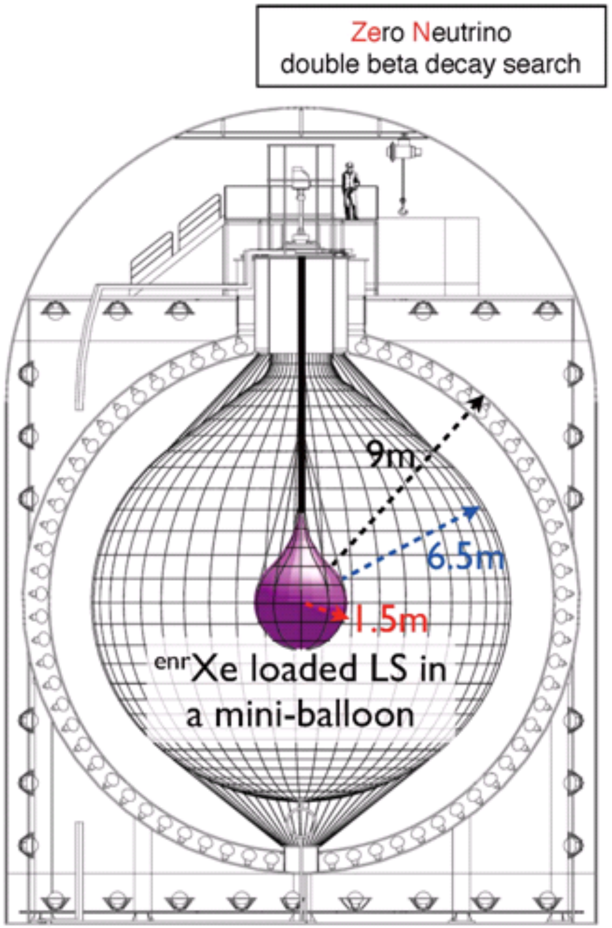
-- Study the heat generation mechanism inside the Earth

- Reactor physics : to check nuclear non-proliferation treaty
- Detection of T2K beam : ~120 events/year
- Test of non-standard physics : sterile/mass varying neutrinos

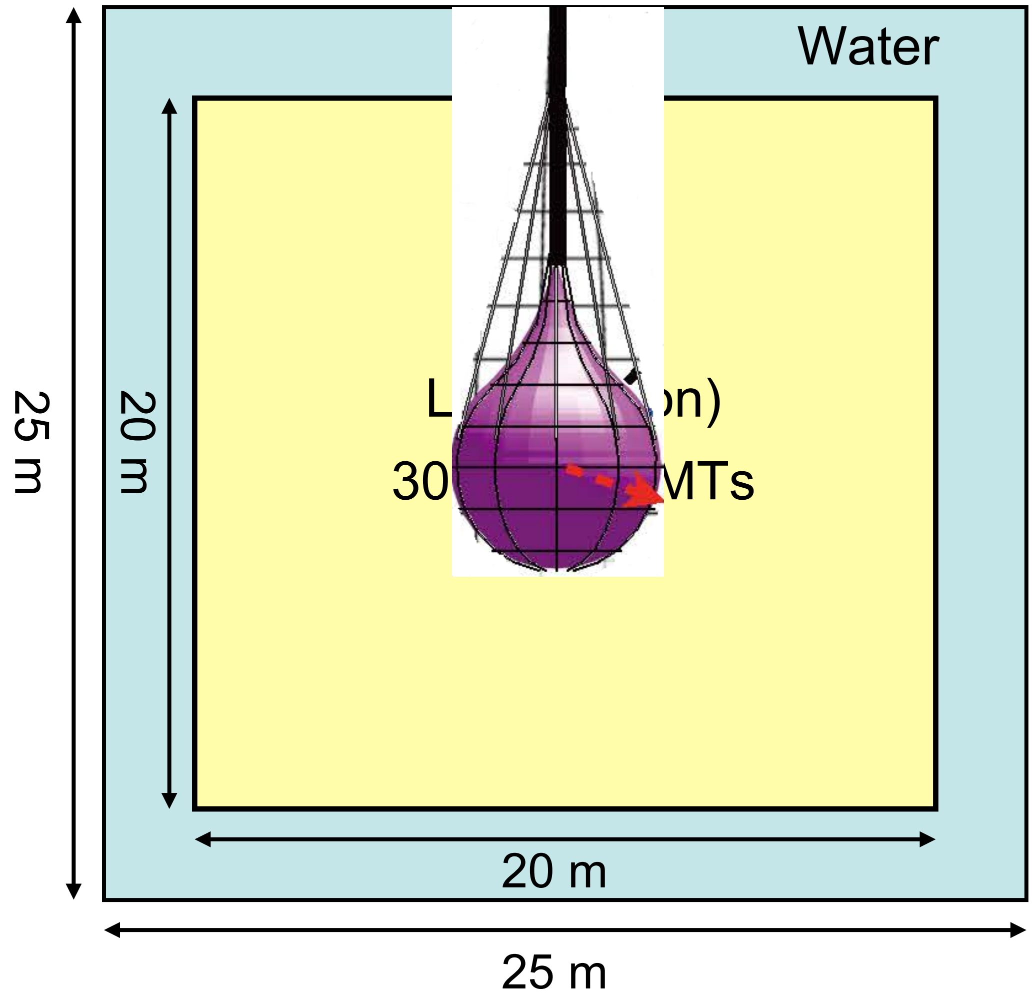
Physics with RENO-50 (cont.)

- Search for neutrinoless double beta decay

KamLAND-Zen



RENO-50



Backup

Random Coincidence Backgrounds

❑ Calculation of accidental coincidence

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

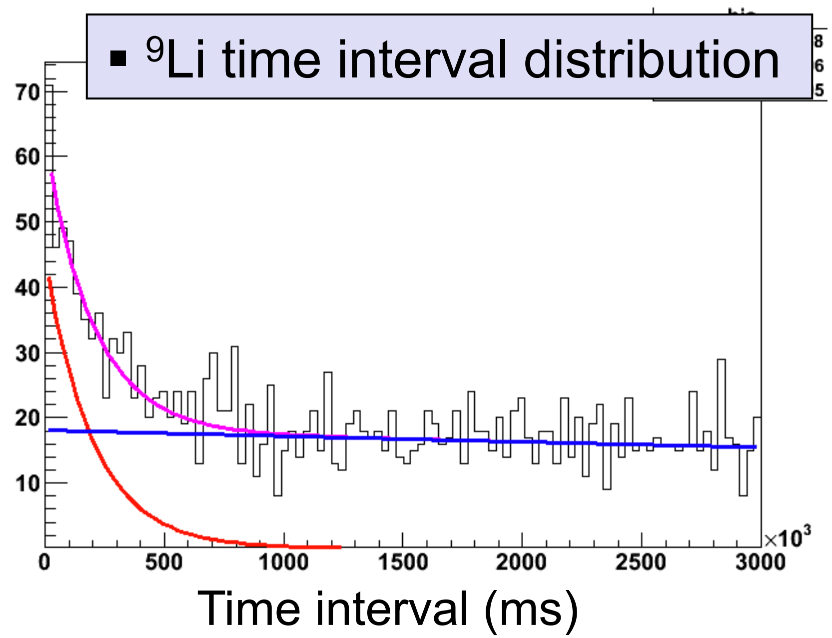
- ΔT = 100 μs time window
- Near detector :

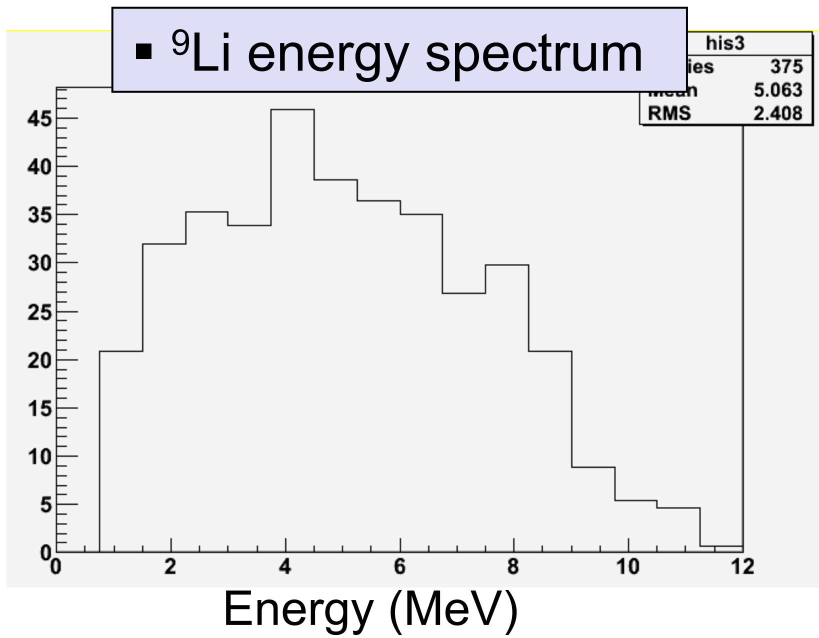
  R_{prompt} = 8.8 Hz, N_{delay} = 4884/day $\rightarrow BG^{near}_{accidental} = 4.30 \pm 0.06 / day$
- Far detector :

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

$^{9}Li/^{8}He$ β-n Backgrounds

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



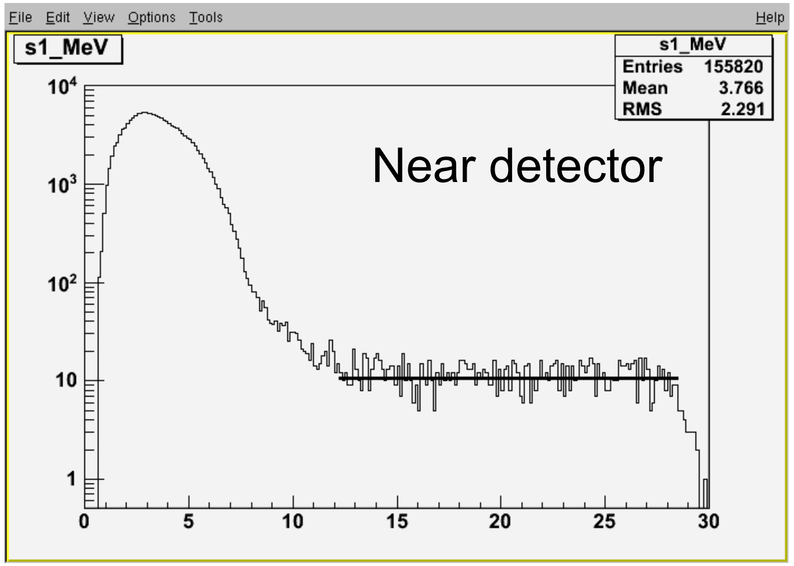


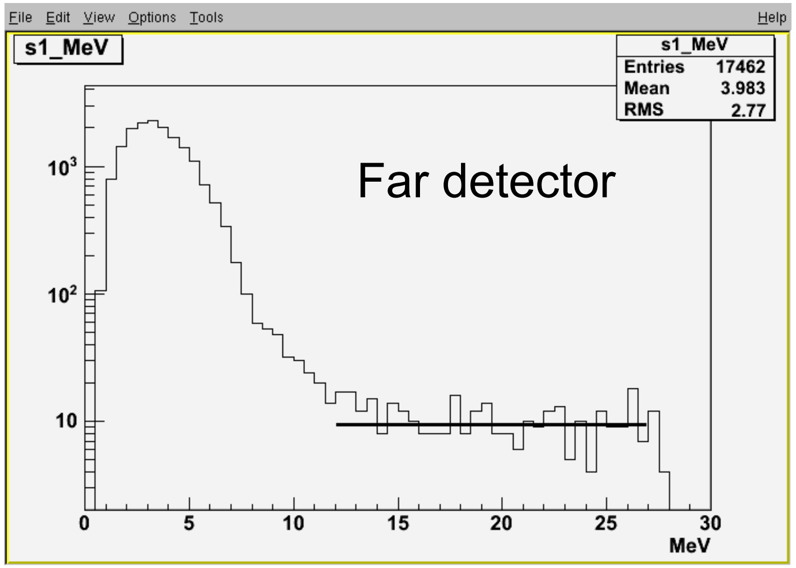
- Near detector : $$BG^{near}_{Li/He} = 12.45 \pm 5.93 / day$$

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

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 : $BG^{far}_{neutron} = 0.97 \pm 0.06 \quad / day$

Reduction of Systematic Uncertainties

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

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

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

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.

θ_{13} from Reactor and Accelerator Experiments

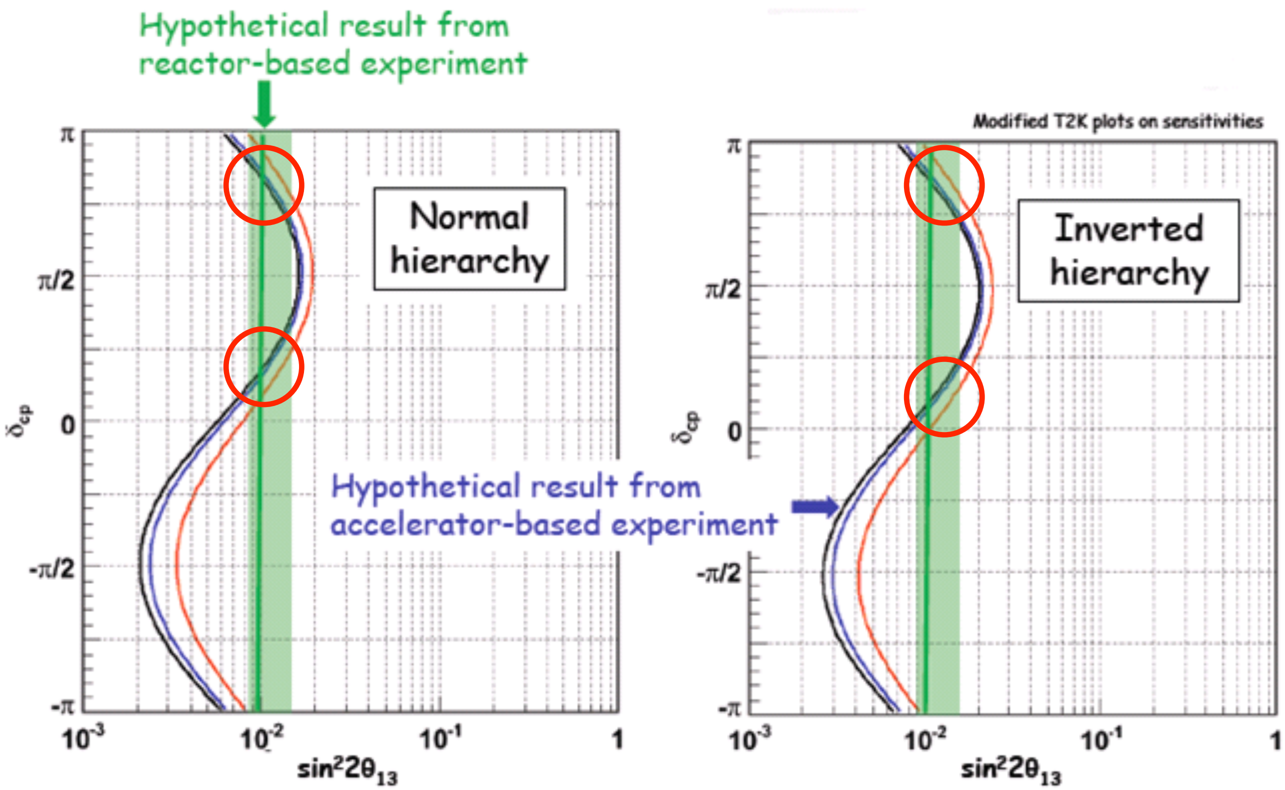
* Reactor

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

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

* Accelerator

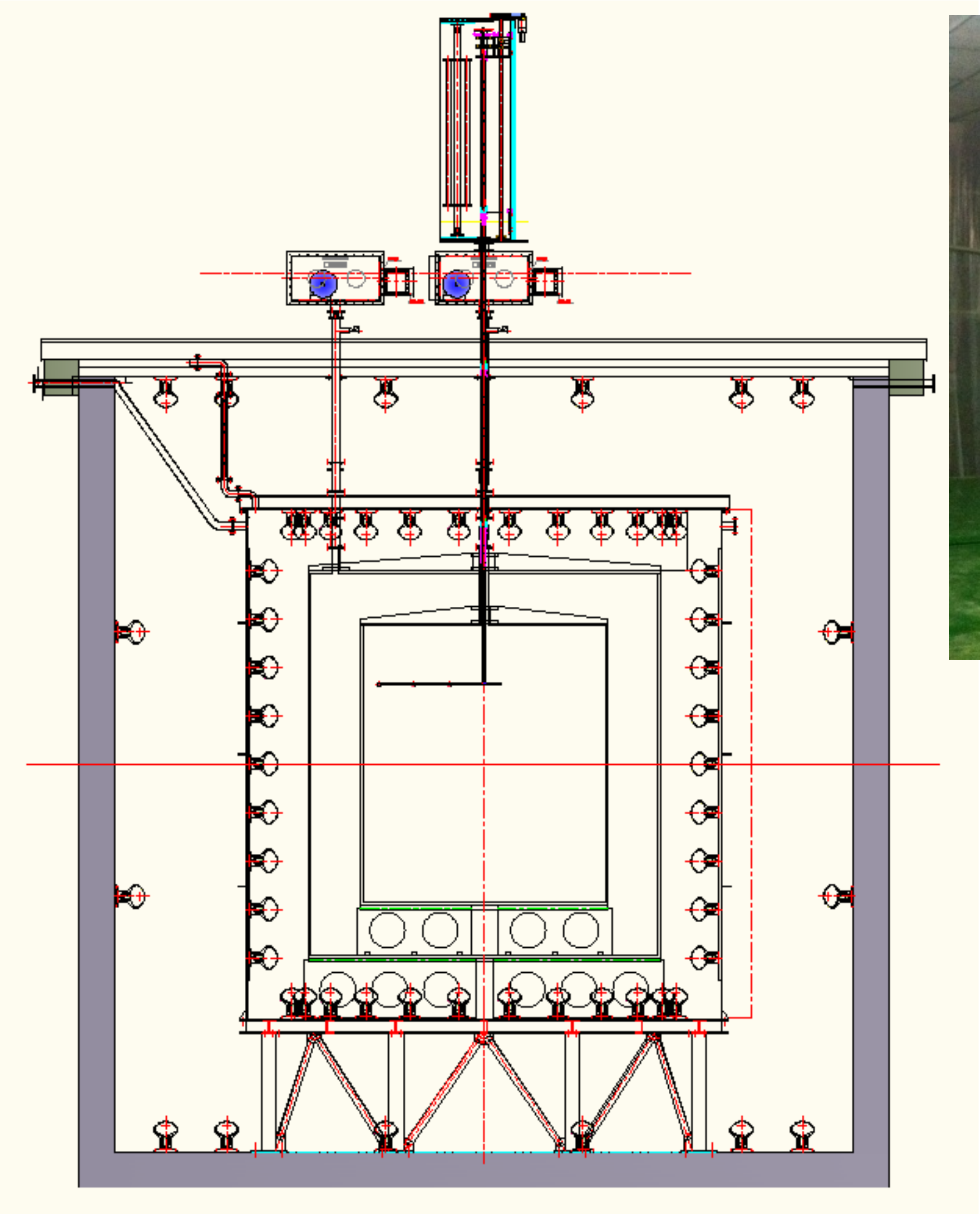
– mass hierarchy + CP violation + matter effects



- Complementarity :

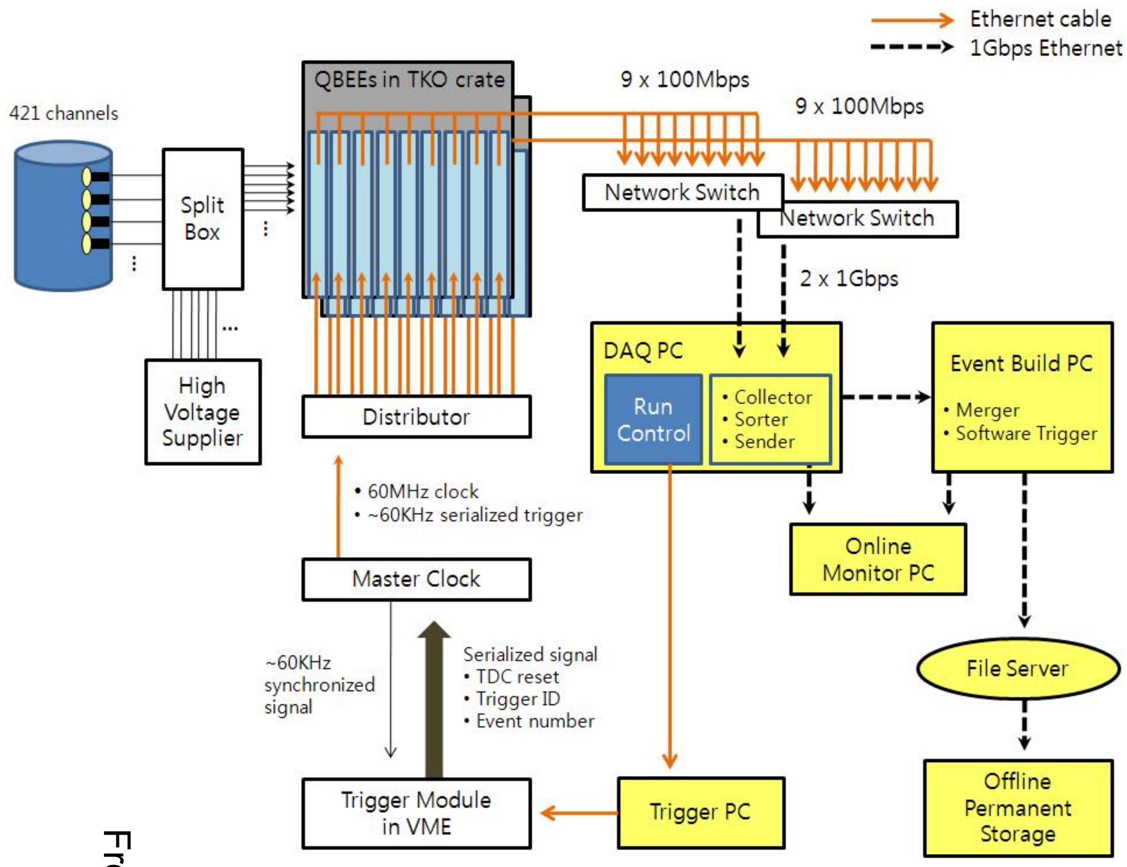
Combining results from accelerator and reactor based experiments could offer the first glimpse of $\delta_{CP.}$

1D/3D Calibration System

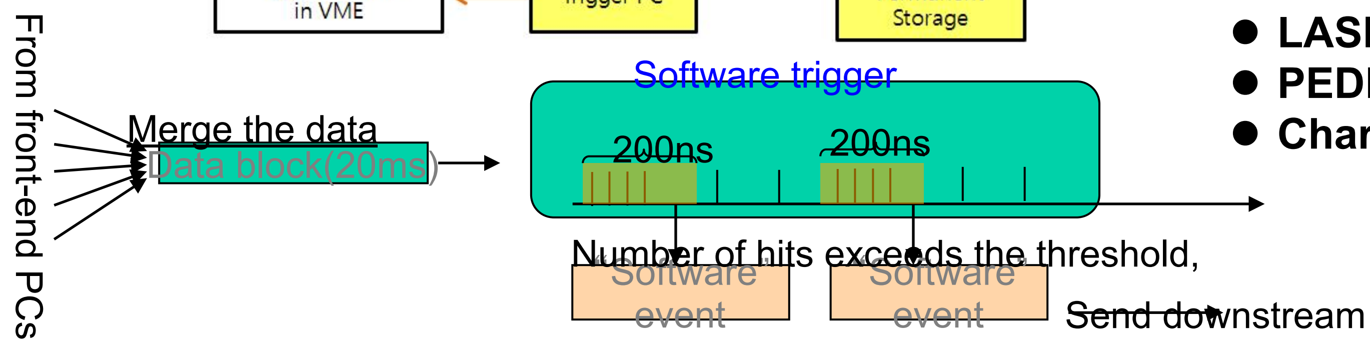


- ❑ Calibration system to deploy radioactive sources in 1D & 3D directions
- ❑ Radioactive sources : ^{137}Cs, ^{68}Ge, ^{60}Co, ^{252}Cf
- ❑ Laser injectors

Electronics & Trigger



- QBEE : each channel digitized if over threshold.
- All the hits are sorted in time and grouped into an event if number of hits exceeds preset trigger condition. (ID:90, OD:10)
- Pedestal hits are collected realtime
- Intrinsic charge Injector into each channel for electronics calibration.
- Types of Trigger :
  - ID
  - OD
  - LASER
  - PEDESTAL
  - Charge Injector



Summary of Measured Neutrino Parameters

J. Beringer et al. (Particle Data Group), PR D86, 010001 (2012) (URL: http://pdg.lbl.gov)

- Mixing Angles

$\sin^2(2\theta_{12}) = 0.857 \pm 0.024$ (2.8%)

$\sin^2(2\theta_{23}) = 0.97 \pm 0.03$ (3.1%) or > 0.95 (CL=90%)

$\sin^2(2\theta_{13}) = 0.098 \pm 0.013$ (13.3%)

$\theta_{12} \approx \pi/5.4$

$\theta_{23} \approx \pi/4$

$\theta_{13} \approx \pi/20$

$\sin^2\theta_{12} = 0.312 \pm 0.017$ (5.4%)

$\sin^2\theta_{23} = 0.42 {+0.08} {-0.03}$ (+19.0 -7.1%)

$\sin^2\theta_{13} = 0.0251 \pm 0.0034$ (13.5%)

$\sin^2\theta_{12} \sim 1/3$

$\sin^2\theta_{23} \sim 1/2$

$\sin^2\theta_{13} \sim 1/40$

Deviated from TBM

- Mass Differences

$\Delta m_{21}^2 = (7.50 \pm 0.20) \times 10^{-5}\ \mathrm{eV}^2$ (2.7%)

$\Delta m_{32(31)}^2 = (2.32 {+0.12} {-0.08}) \times 10^{-3}\ \mathrm{eV}^2$ (+5.2-3.4%)

$|\Delta m_{21}^2| / |\Delta m_{31(32)}^2| \approx 0.03$

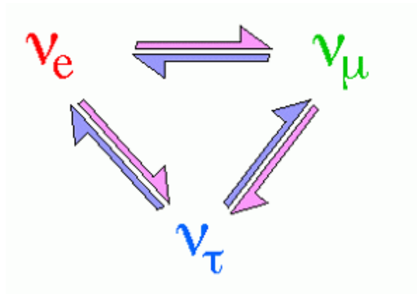
Neutrino Oscillation

$(\nu_e, \nu_\mu, \nu_\tau)$ Flavor eigen-state ≠ (ν_1, ν_2, ν_3) mass eigen-state

creation/detection — travel (oscillation)

Neutrino mixing matrix

$$U = \begin{array}{c} \\ e \\ \mu \\ \tau \end{array} \begin{array}{c} \begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \end{array} \\ \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \end{array}$$



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

↓ Atmospheric, Long baseline

↓ Reactor, Long baseline

↓ Solar, Reactor exp

Neutrino Oscillation Parameters

Before 2011

$\Delta m_{12}^2 \sim +7.6 \times 10^{-5}\ eV^2$, $\theta_{12} \sim 34^o$

$\Delta m_{23}^2 \sim \pm 2.5 \times 10^{-3}\ eV^2$, $\theta_{23} \sim [38^o \sim 52^o]$

$\theta_{13} < 10^o$

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

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

θ_{13} was least known oscillation parameter.

Neutrino Oscillation Parameters

Since 2011

- T2K : 2.5 σ excess (2011)

$\sin^2(2\theta_{13})$ = 0.104$^{+0.060}_{-0.045}$ (δ_{CP}=0 for N.H.)

$\sin^2(2\theta_{13})$ = 0.128$^{+0.070}_{-0.055}$ (δ_{CP}=0 for I.H.)

(Neutrino 2012)

- 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)

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

(rate+shape) **(Neutrino 2012)**

- Daya Bay (Mar. 8. 2012)

5.2 σ observation

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

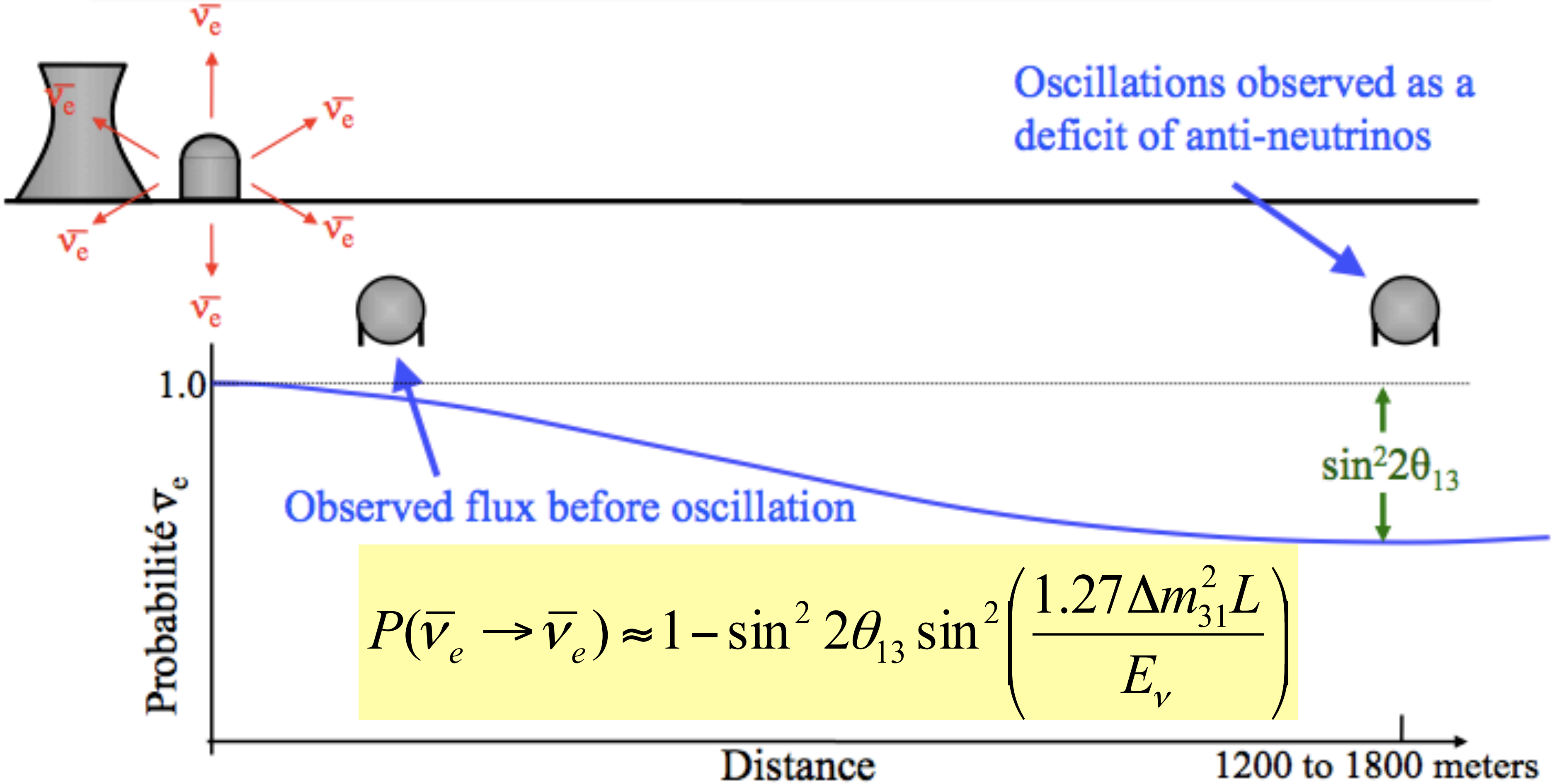
(Neutrino 2012)

- RENO (Apr. 2. 2012)

4.9 σ observation

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

Concept of Reactor θ_{13} Measurement

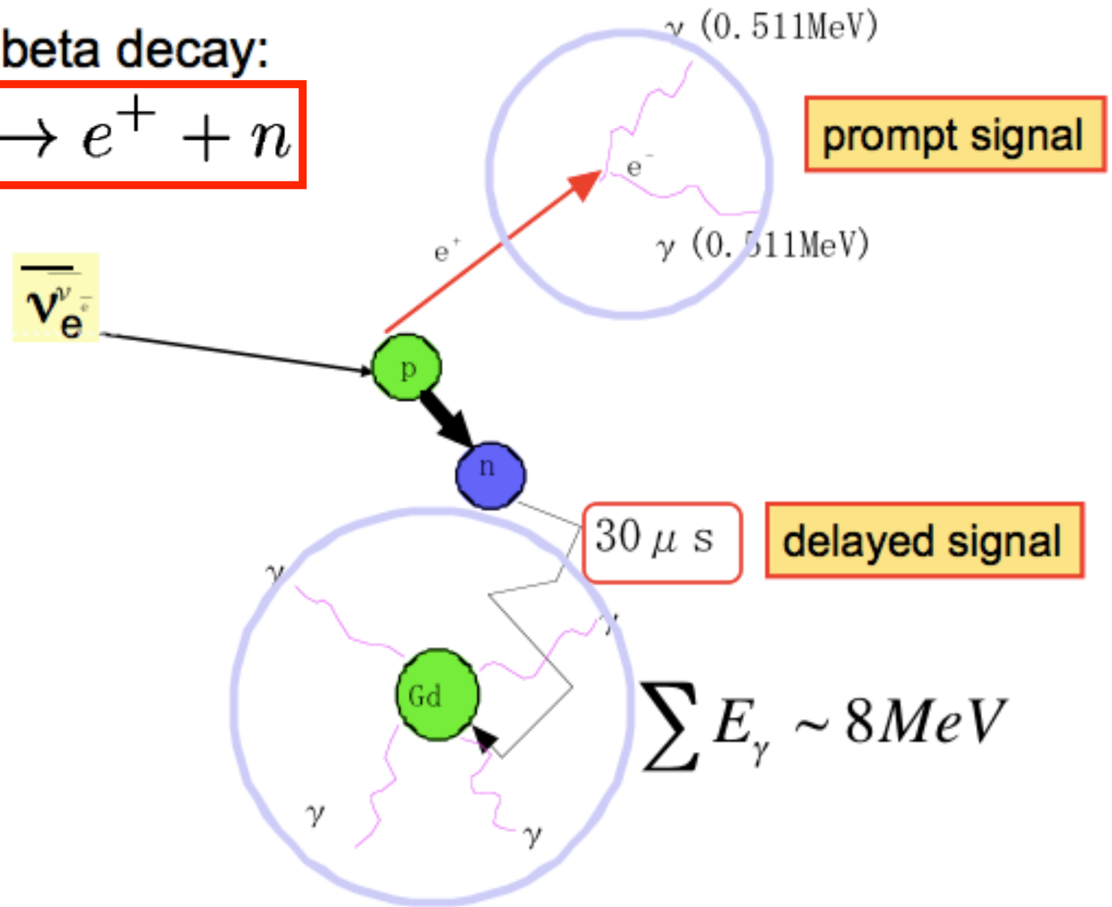


Find disappearance of ν_e fluxes due to neutrino oscillation as a function of energy using multiple, identical detectors to reduce the systematic errors in 1% level.

Detection Principle of Reactor Neutrinos

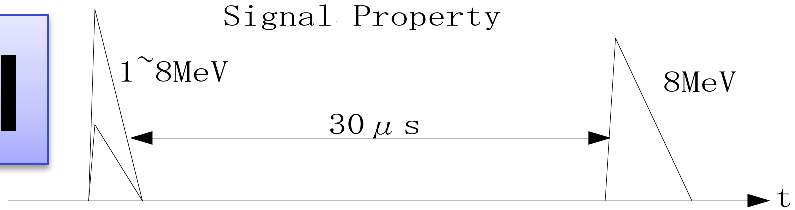
Inverse beta decay:

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

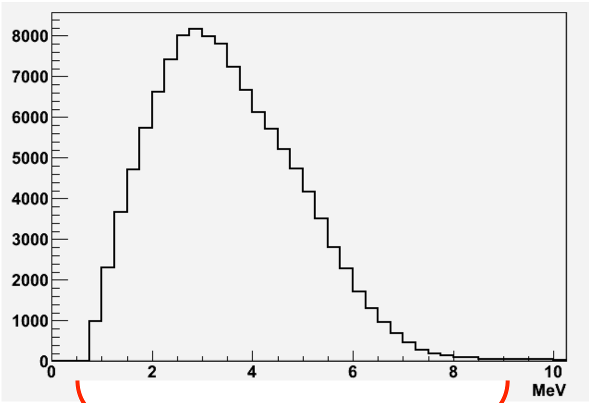


- Prompt signal (e^+) : 1 MeV 2γ's + e^+ kinetic energy (E = 1~10 MeV)
- Delayed signal (n) : 8 MeV γ's from neutron's capture by Gd
  ~28 μs (0.1% Gd) in LS

IBD signal

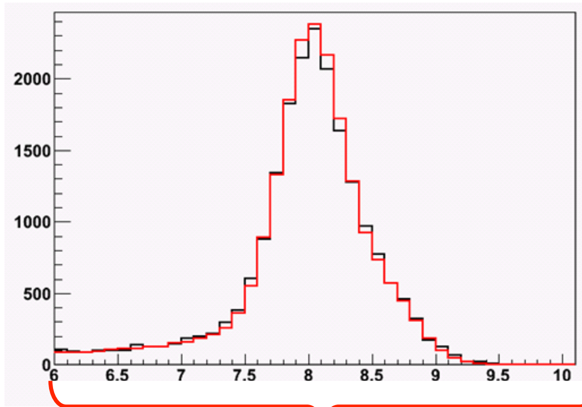


prompt signal

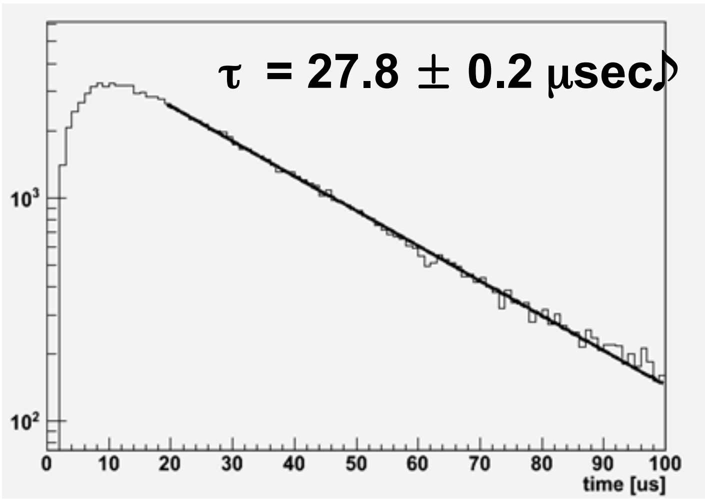


(1) $0.7 < E_{prompot} < 12 MeV$

delayed signal



(2) $6 < E_{delayed} < 12 MeV$



χ^2 Fit with Pulls

$\pm 2.5\%$ (correlated uncertainties)

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

(uncorrelated detection uncertainties) $\pm 0.2\%$

$\pm 17.7\% \,(Far)$

$\pm 27.3\% \,(Near)$

(background uncertainties)

$\pm 0.9\%$

(uncorrelated reactor uncertainties)