Recent Results from RENO & Future Plan: RENO-50

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On behalf of the RENO Collaboration

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Recontre du Vietnam 2013

ICISE Inaugural Conference

Neutrino Oscillation

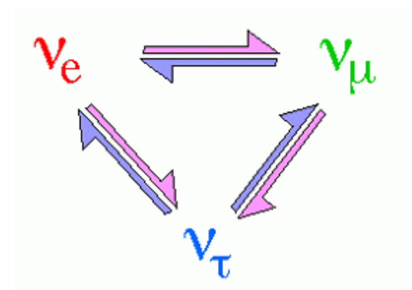
$(\nu_e, \nu_\mu, \nu_\tau)$ $\qquad\qquad$ (ν_1, ν_2, ν_3)

Flavor eigen-state $\neq$ mass eigen-state

creation/detection $\qquad$ travel (oscillation)

Neutrino mixing matrix (PMNS)

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



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

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

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

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

1st result on PRL 108, 19802 (2012)

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

(4.9 σ)

New result (@NuTel 2013)

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

(5.6 σ)

Statistics:

-- about twice more data

Systematics:

-- Improved background estimation/reduction
(Li/He background, fast N, flasher removal)

-- Improved energy scale calibration

RENO Collaboration

RENO ν θ_{13}

<u>12 institutions and 40 physicists</u>

- 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

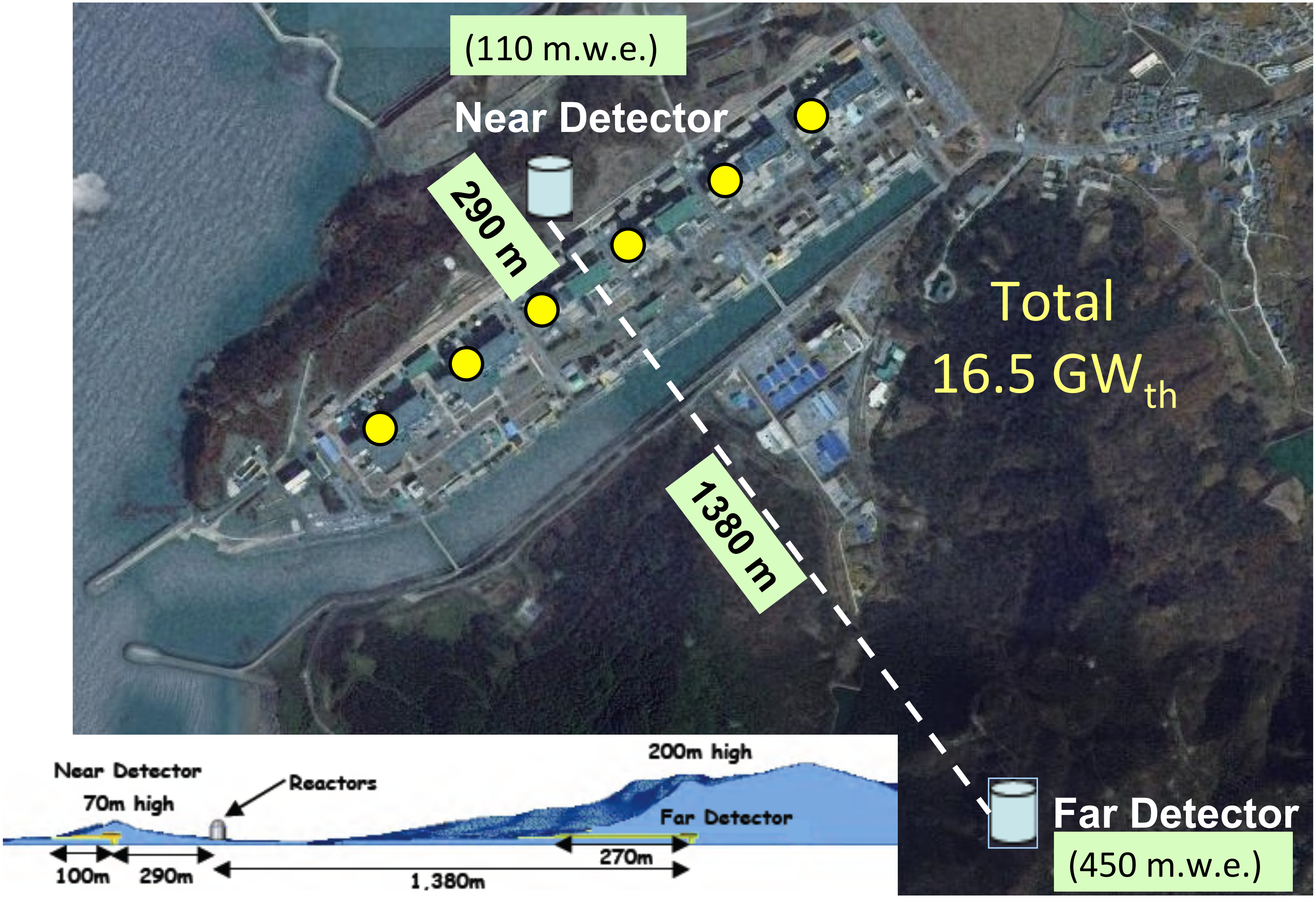
- **Total cost : $10M**
- Start of project : **2006**
- The first experiment running with both near & far detectors from **Aug. 2011**

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

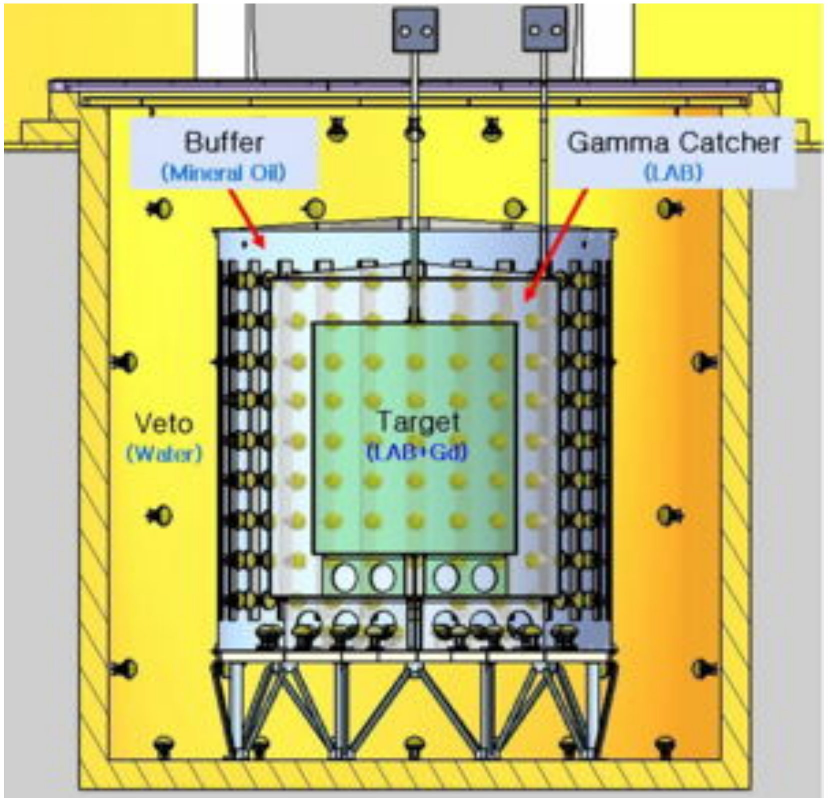
Experimental Site

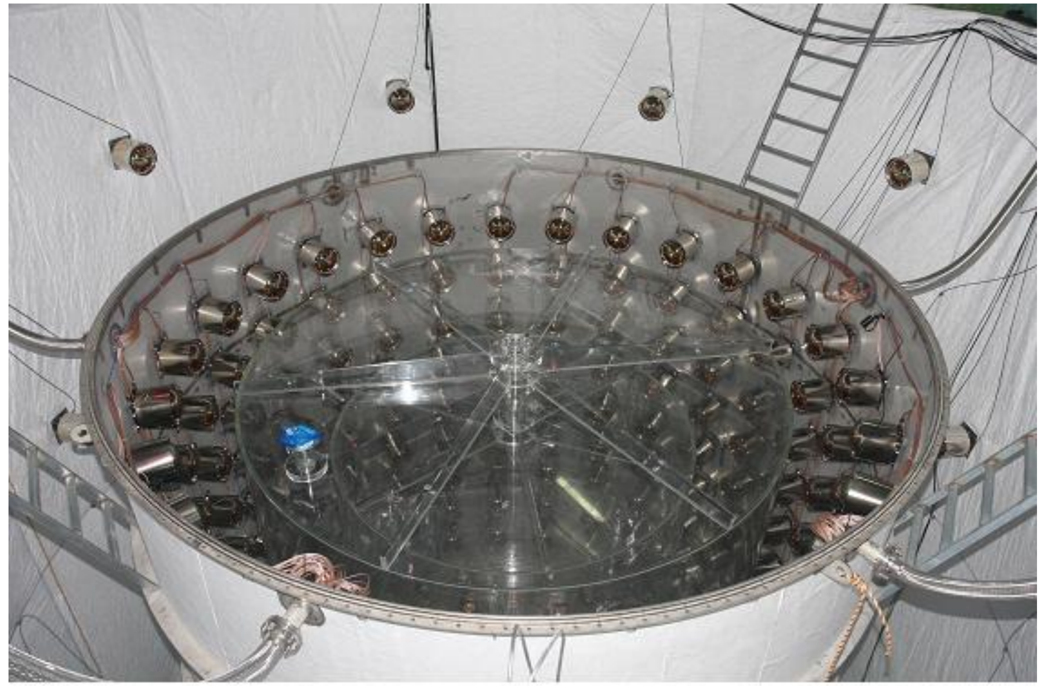
YongGwang: South west of South Korea
~ 300 km from Seoul

RENO Experimental Setup



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

RENO Data Taking Status

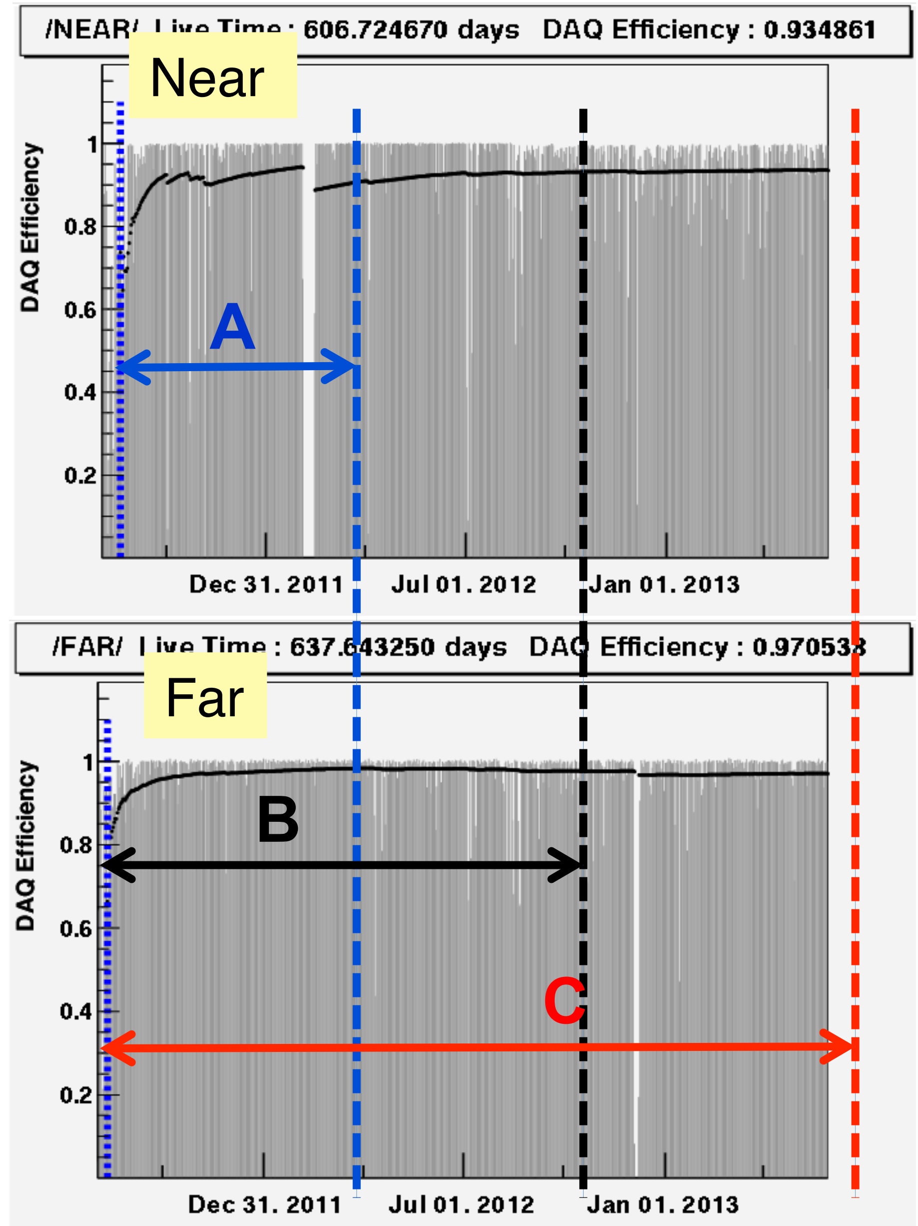
- Data taking began on Aug. 1, 2011 with both near and far detectors. (DAQ efficiency : ~95%)

- **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]

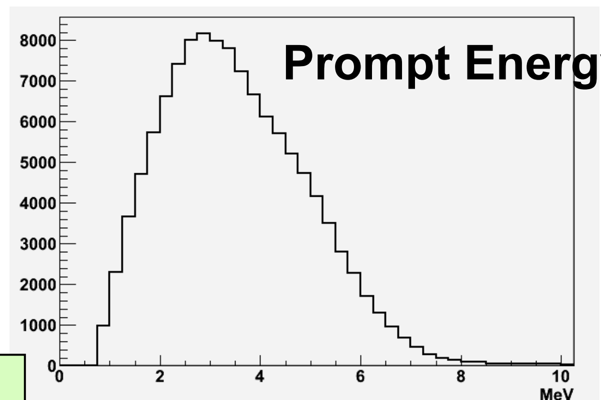


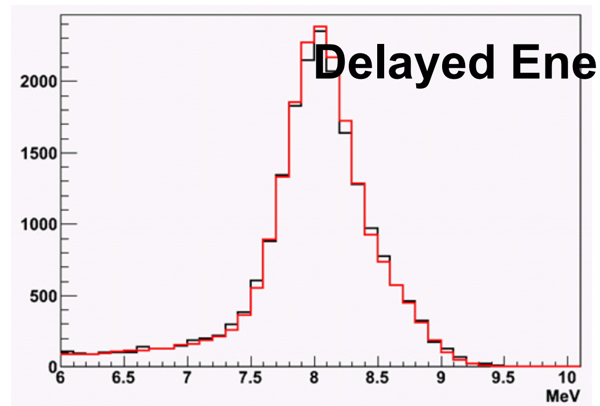
IBD Event Signature and Backgrounds

❑ IBD Event Signature

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

- Prompt signal (e^+) : 1 MeV 2γ's + e^+ kinetic energy (E = 0.8~10 MeV)
- Delayed signal (n) : 8 MeV γ's from neutron's capture by Gd
  ~28 μs (0.1% Gd) in LS♪

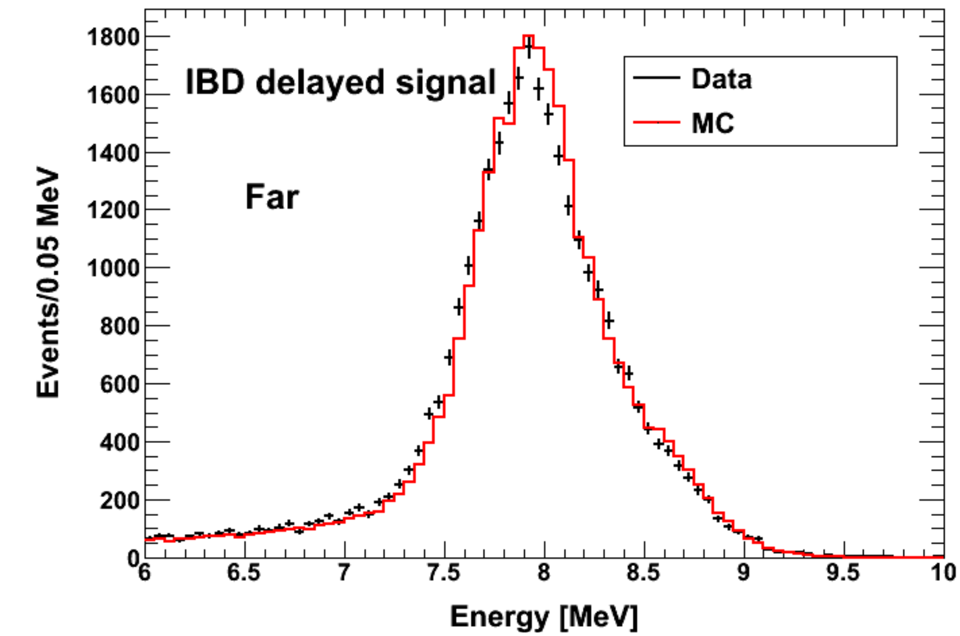


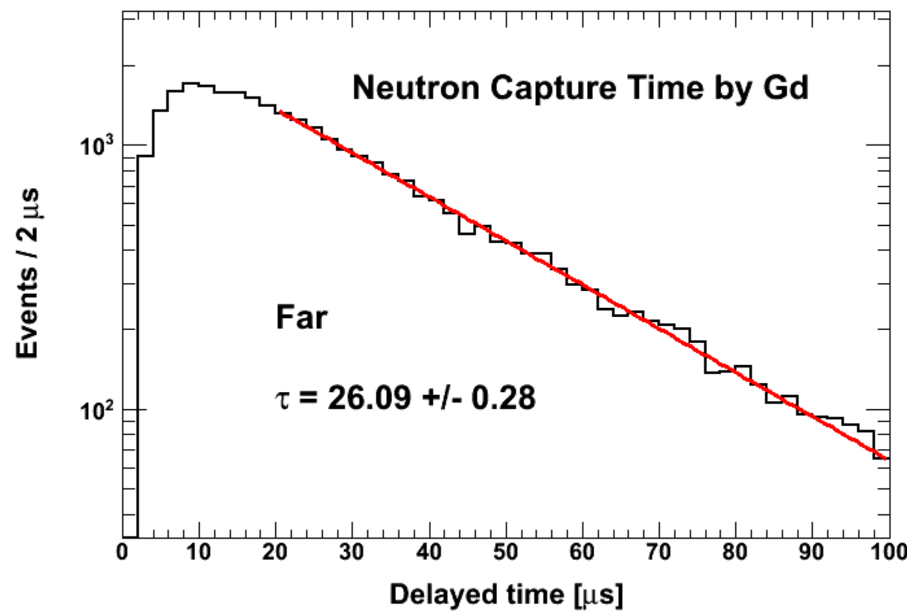


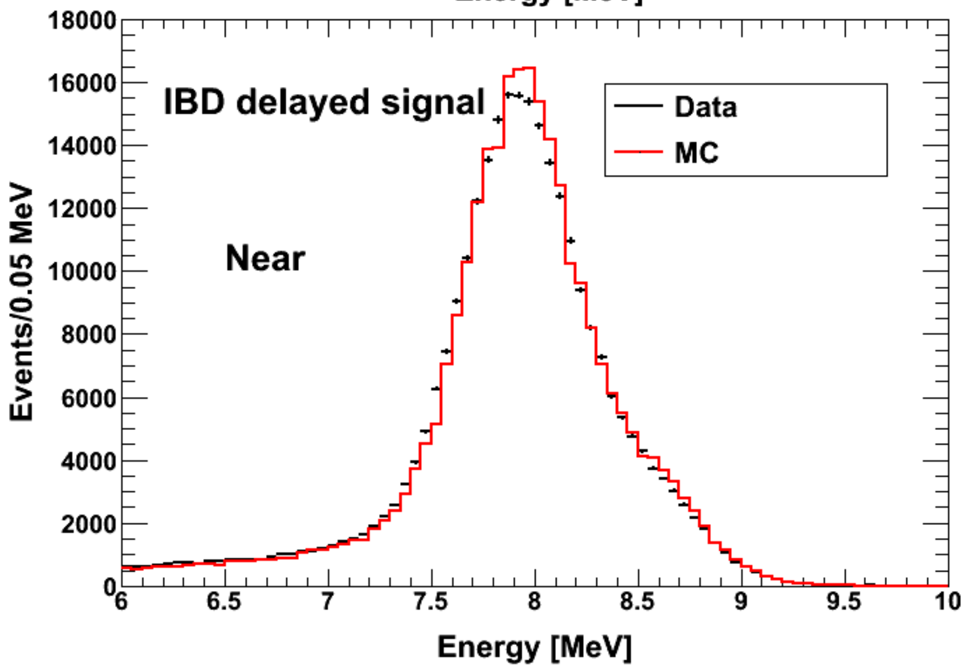
❑ Backgrounds

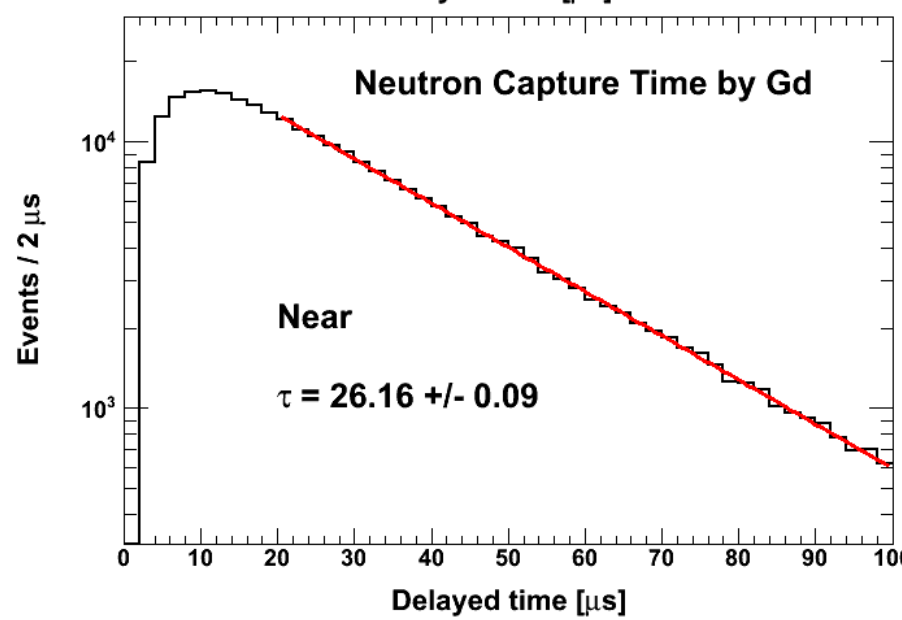
- **Accidental BG**: caused by radioactivity; random coincidence between prompt and delayed signals (uncorrelated)
- **^{9}Li/^{8}He BG**: muon spallation on ^{12}C; β-n followers which mimic signal
- **Fast neutrons:** produced by muons, from surrounding rocks and inside detector (n scattering : prompt, n capture : delayed)

Spectra & Capture Time of Delayed Signals



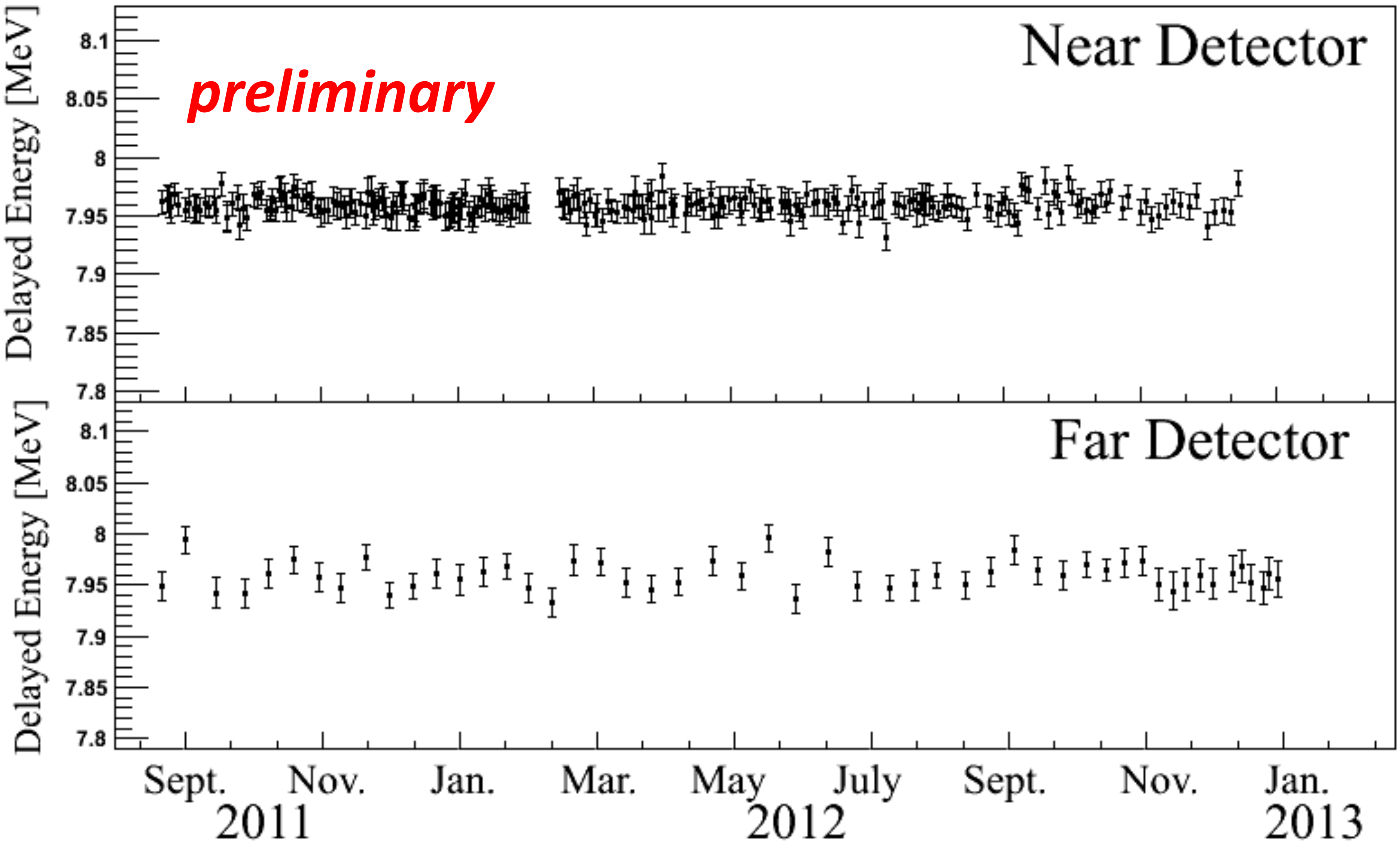


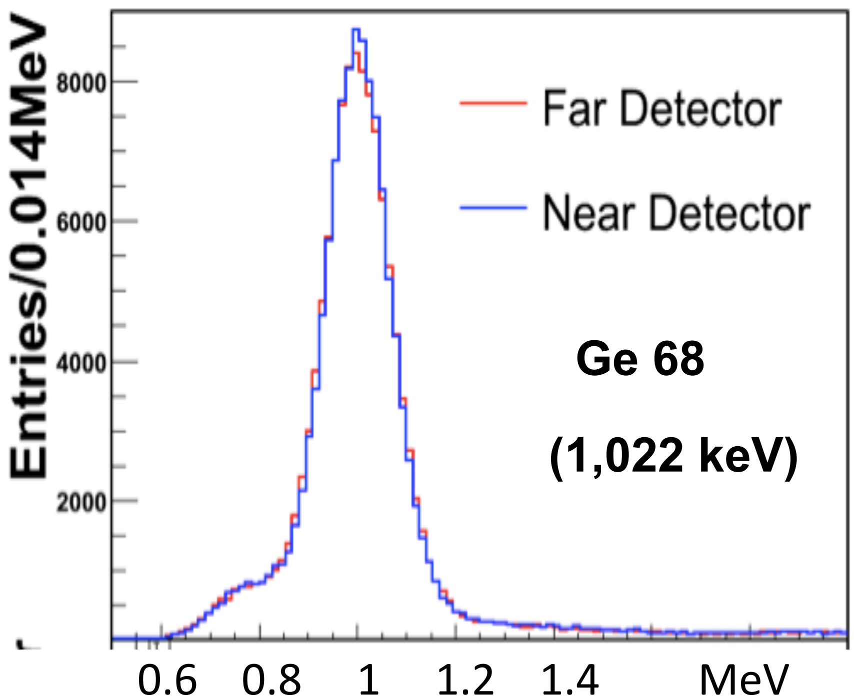


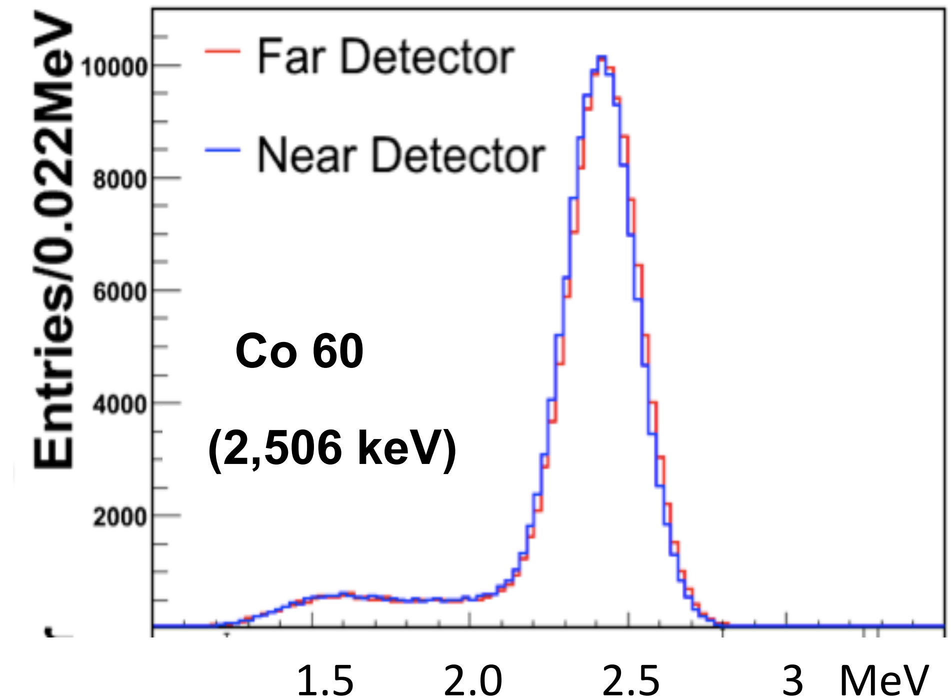


Detector Stability of Energy Scale

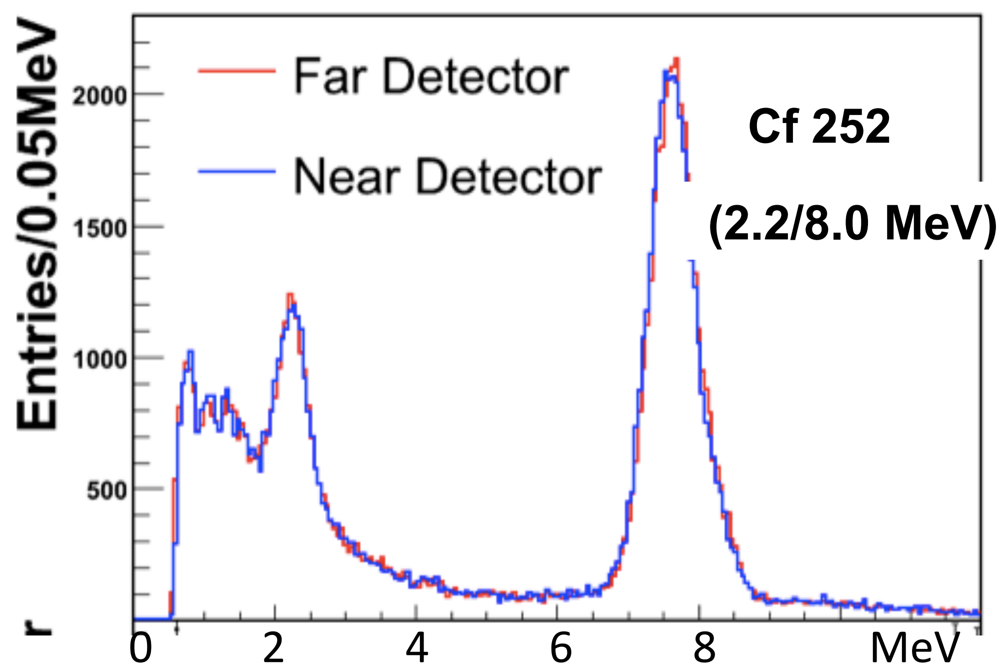
▪ IBD candidate's delayed signals (capture on Gd)





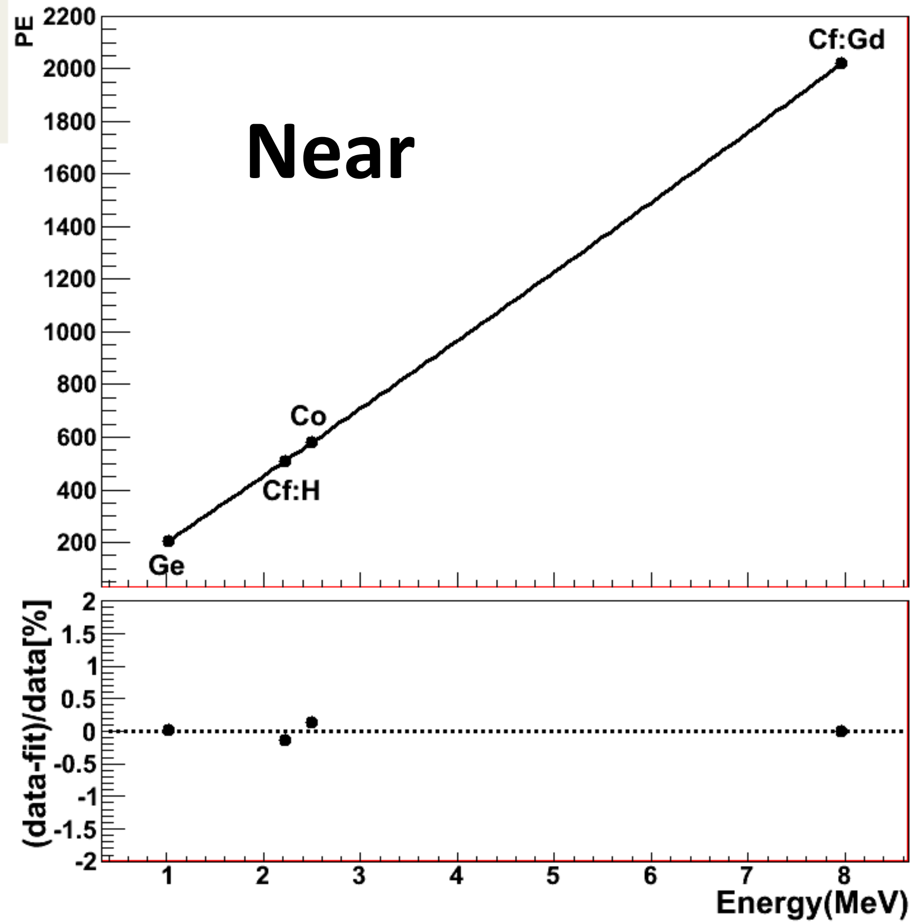


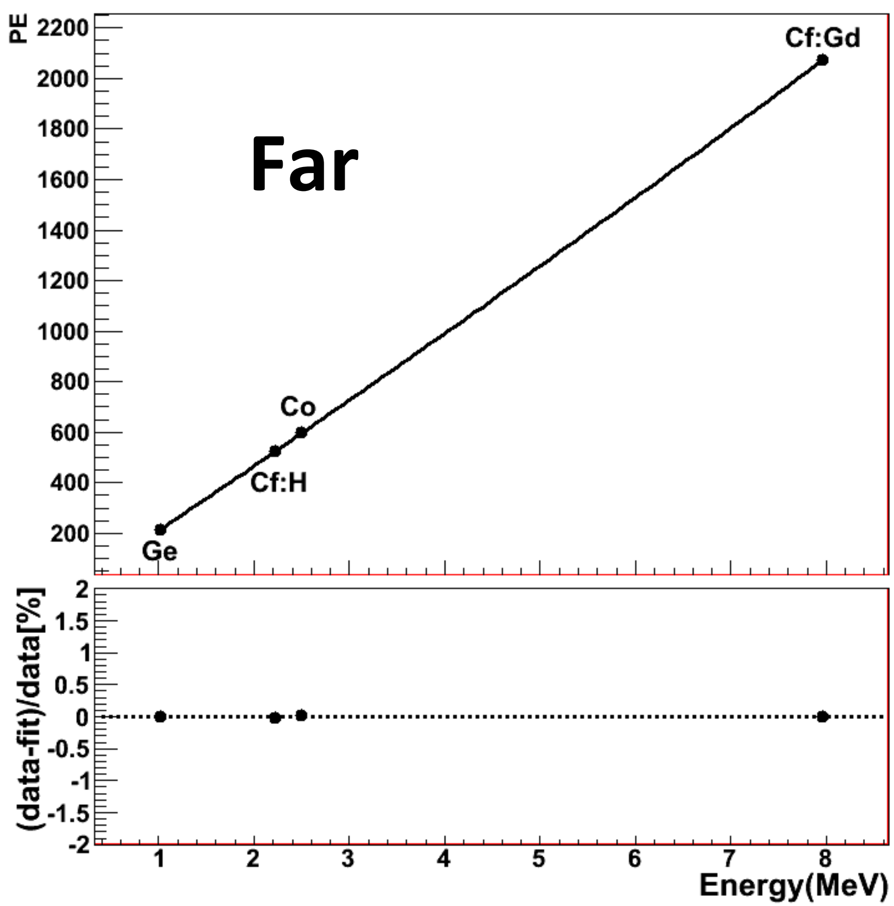
Energy Calibration



Energy Calibration

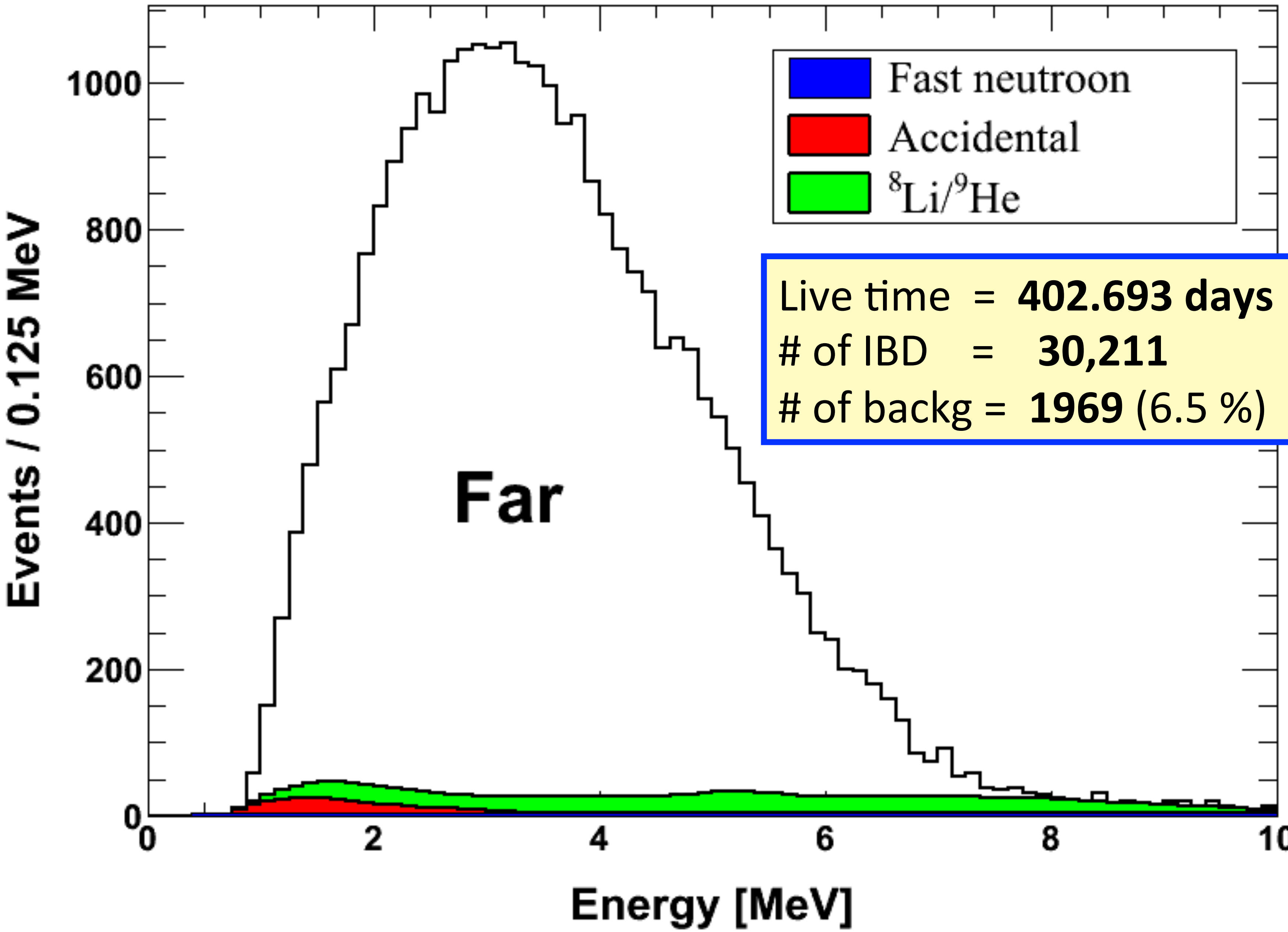
PE → MeV conversion fnc





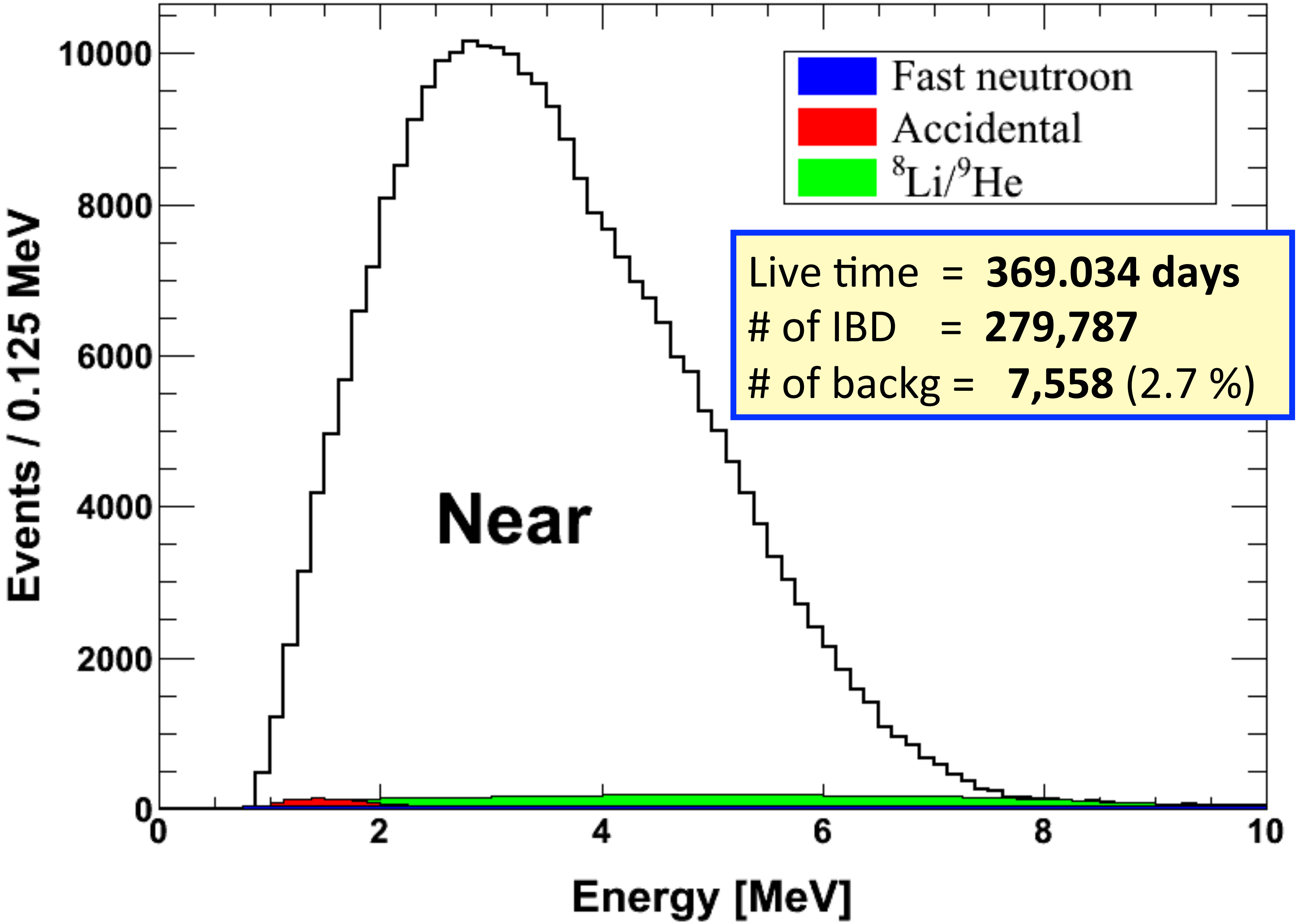
Fitting accuracy: 0.1 %

Measured Spectra of IBD Prompt Signal

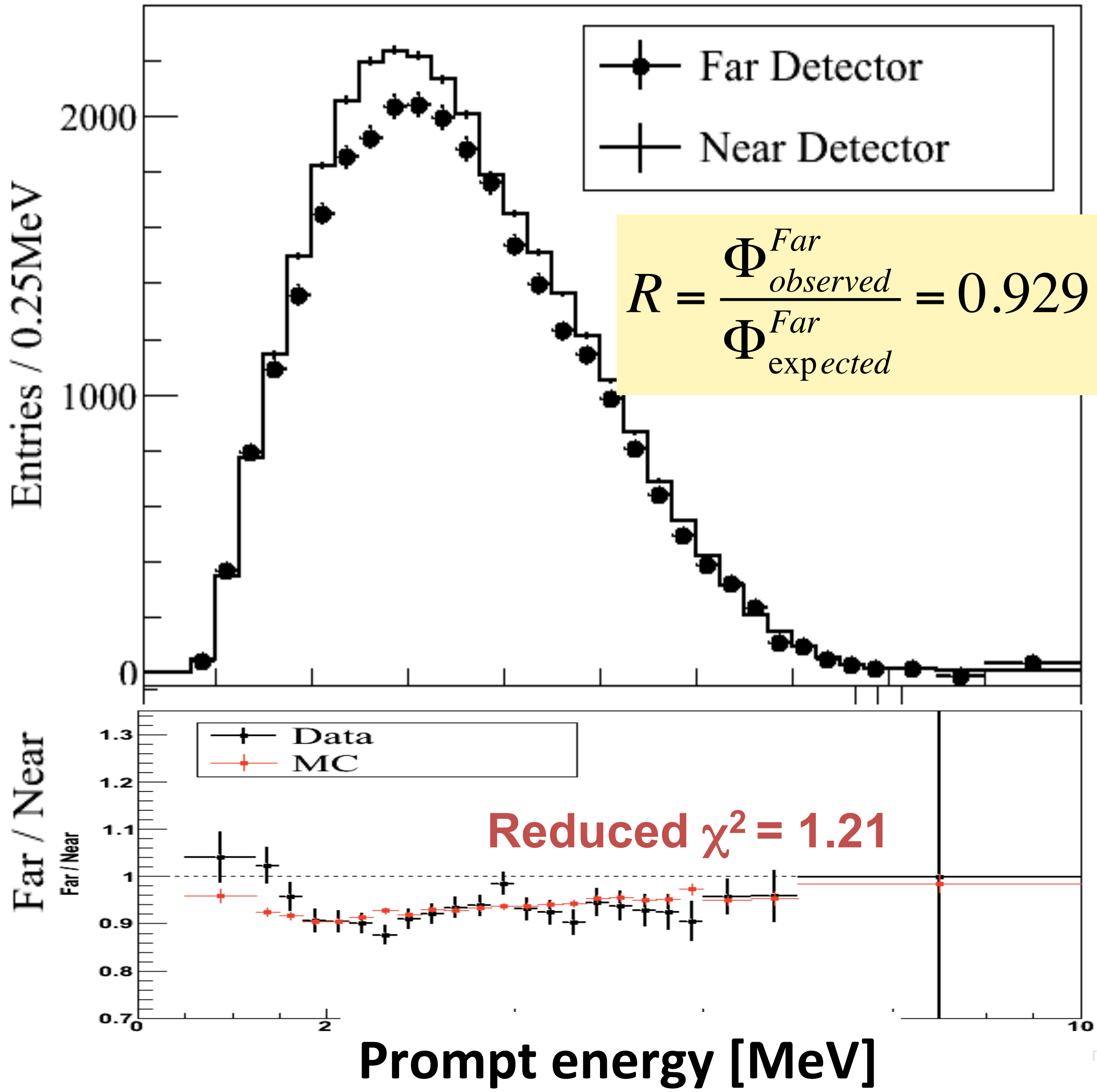


Live time = **402.693 days**
# of IBD = **30,211**
# of backg = **1969** (6.5 %)

Measured Spectra of IBD Prompt Signal



Reactor Antineutrino Disappearance



preliminary

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

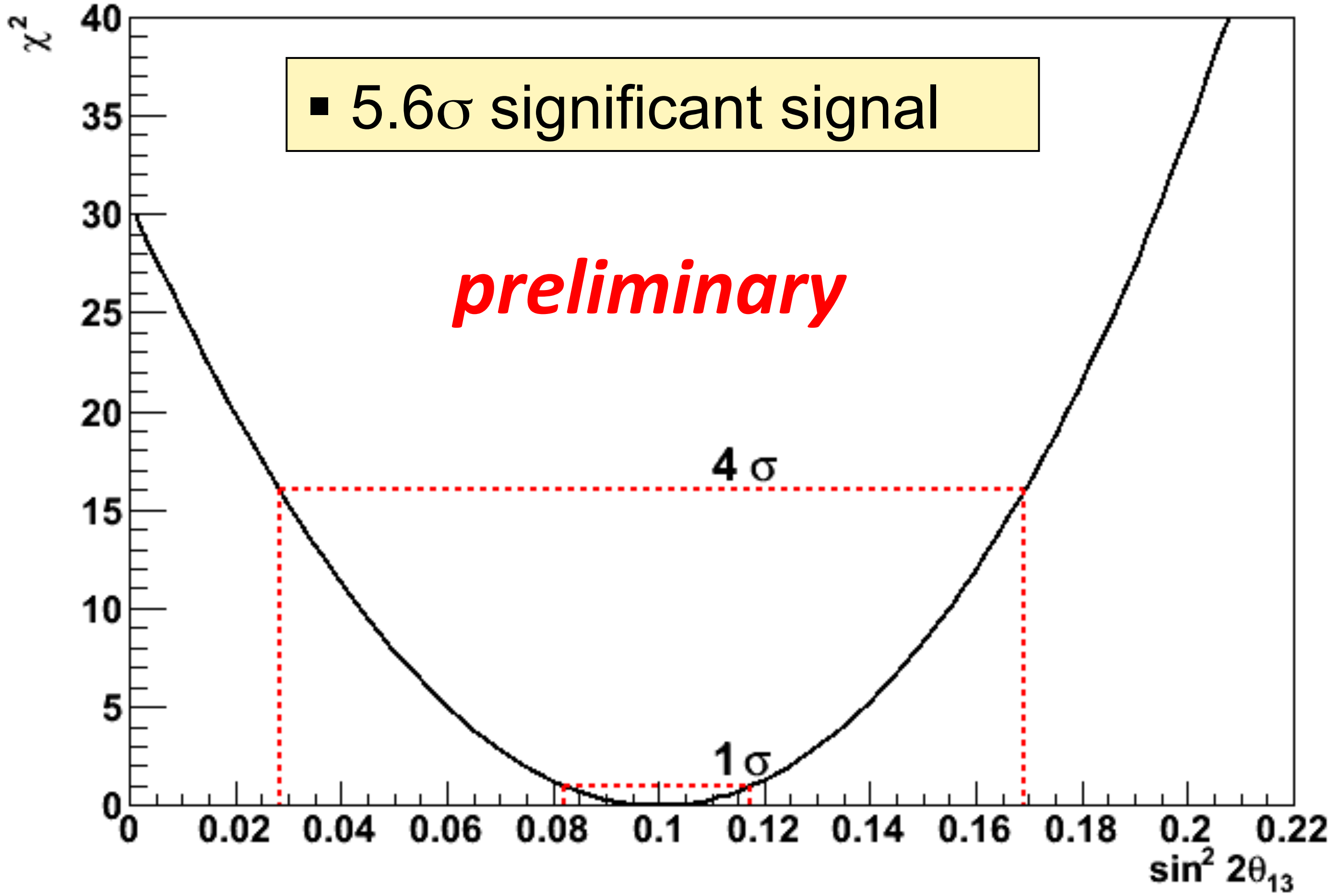
- A clear deficit in rate

  (7 % reduction)

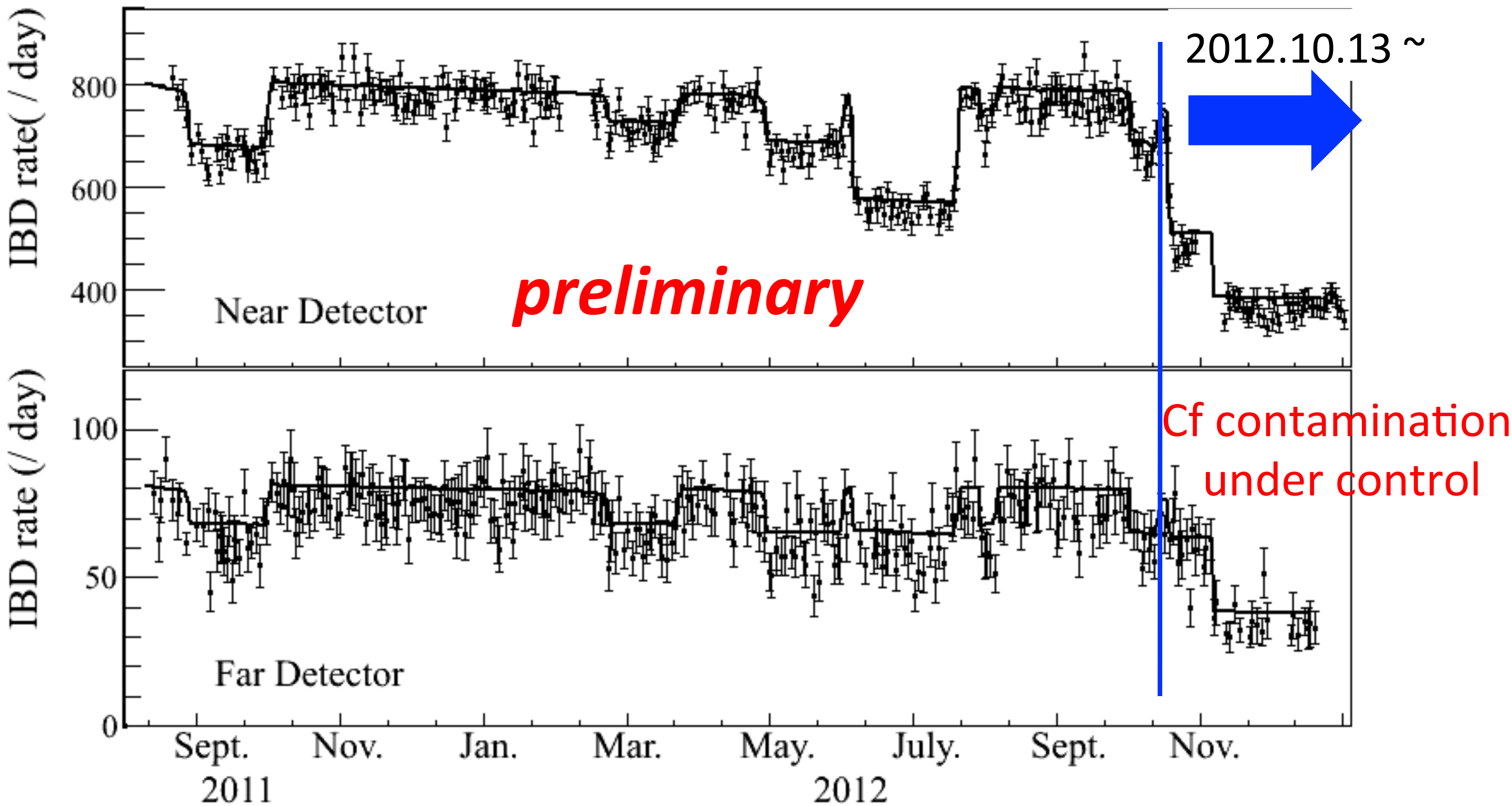
- Consistent with neutrino oscillation in the spectral distortion

Definitive Measurement of θ_{13}

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



Observed Daily IBD Rate



- Solid line is predicted rate from the neutrino flux calculation.
- Observed points have very good agreement with prediction.
- It’s the accurate flux measurement.

Summary

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

- RENO has collected about 700 days of neutrino data so far and improved systematic uncertainties and energy calibration.

- RENO observed a clear disappearance of reactor antineutrinos.

$$R = 0.929 \pm 0.006(stat.) \pm 0.009(syst.)$$ ***preliminary***

- RENO's new result (402 live days):

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

**** There is a room to improve sys. error (to be improved soon).**

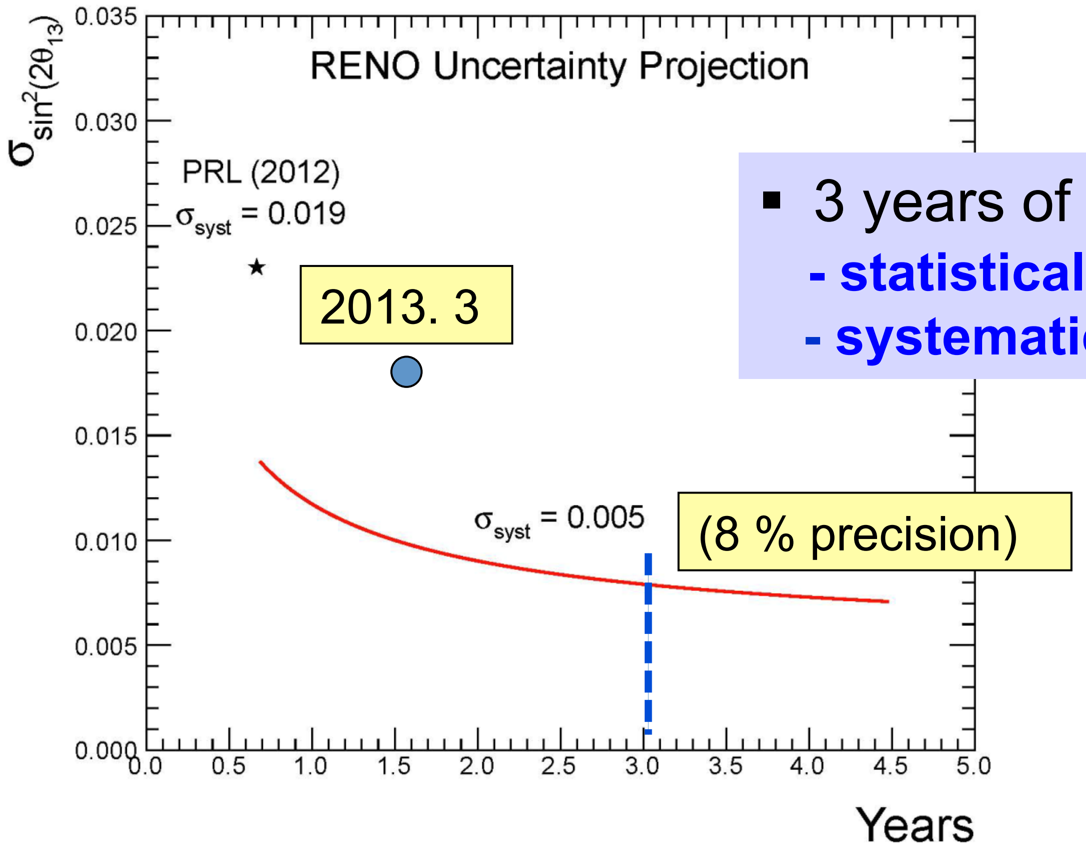
RENO's Projected Sensitivity of θ_{13}

RENO

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

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

± 0.008 (~ 12 σ) (3 years) (8 % precision)



- 3 years of data : ±0.008 (8% precision)
  - **statistical error : ±0.010 → ±0.006**
  - **systematic error : ±0.015 → ±0.005**

Other Ongoing Analyses

- H capture analysis
- Direct measurement of Δm_{13}^2
- Precise measurement of reactor neutrino flux and spectrum
- Reactor anomaly and sterile neutrinos

Overview of RENO-50

- **RENO-50** : An underground detector consisting of 18 kton ultra-low-radioactivity liquid scintillator & 15,000 20” PMTs, at 50 km away from the Hanbit(Yonggwang) nuclear power plant

- **Goals** : - Determination of neutrino mass hierarchy

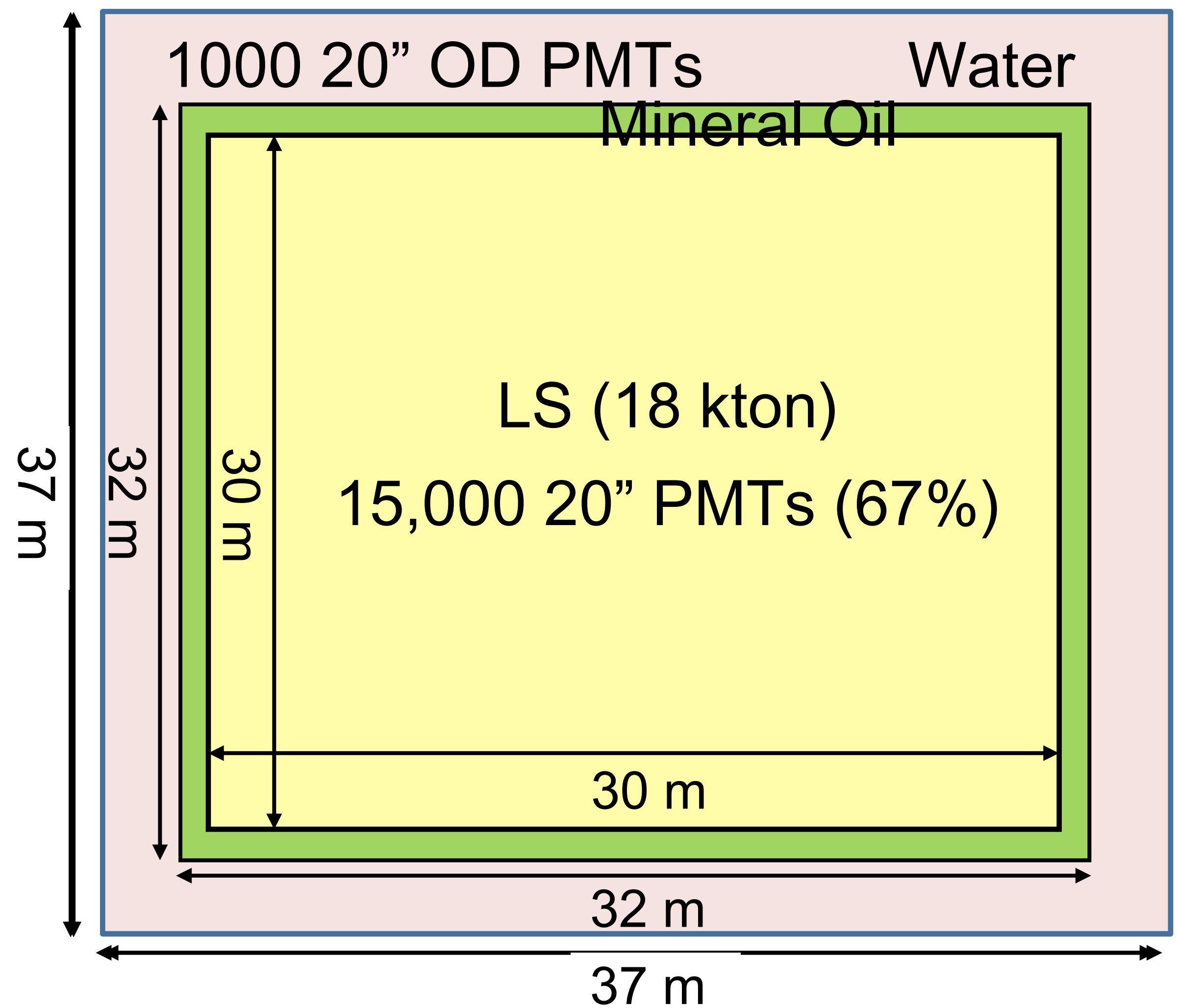
  - High-precision measurement of θ_{12} and Δm^2_{21}
  - Study neutrinos from reactors, (the Sun), the Earth, Supernova, and any possible stellar objects

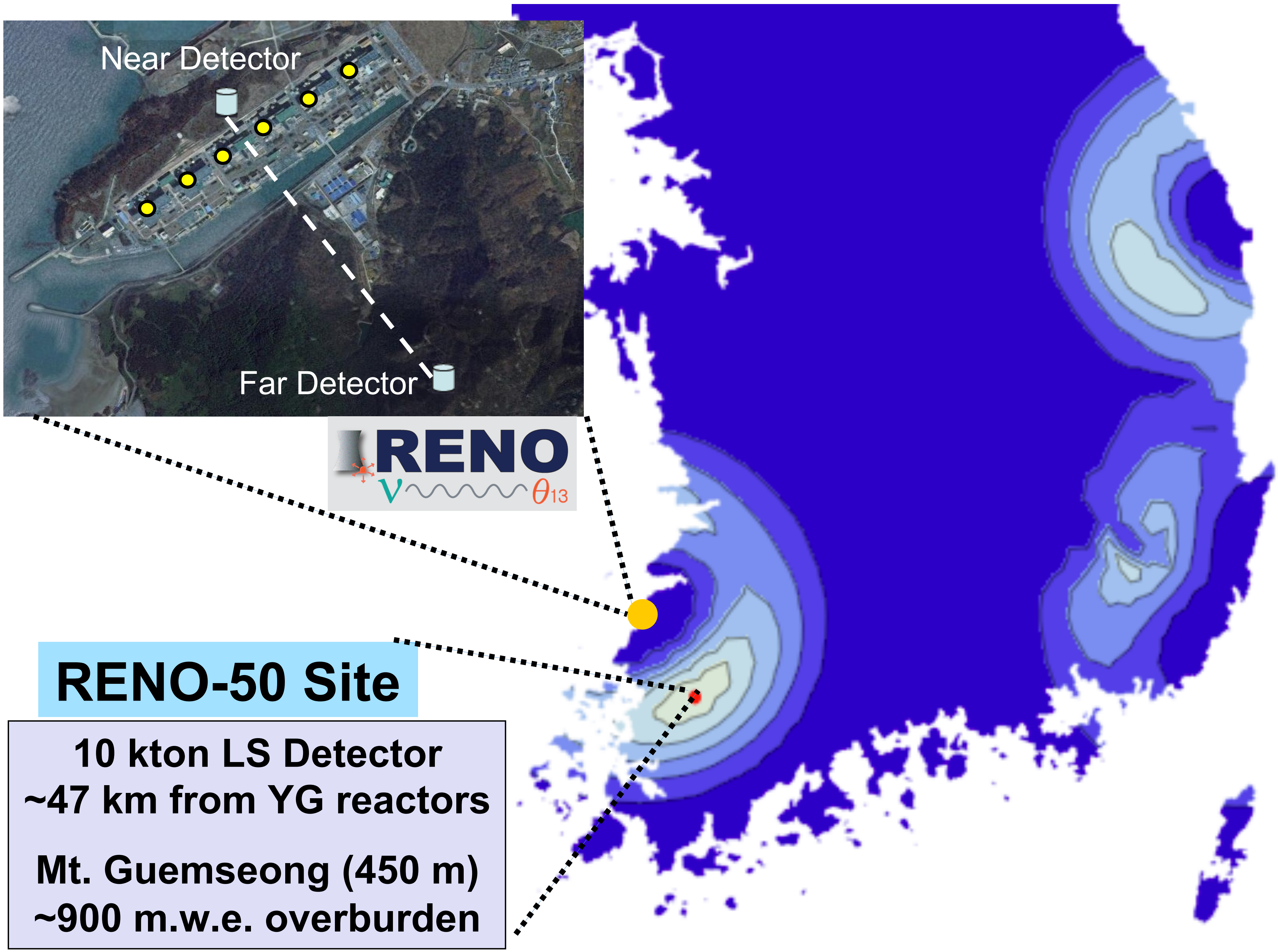
- **Budget** : $ 100M for 6 year construction

  (Civil engineering: $ 15M, Detector: $ 85M)

- **Schedule** : 2013 ~ 2018 : Facility and detector construction
  2019 ~ : Operation and experiment

Conceptual Design of RENO-50




Near Detector
Far Detector
RENO
ν θ_{13}
RENO-50 Site
10 kton LS Detector
~47 km from YG reactors
Mt. Guemseong (450 m)
~900 m.w.e. overburden

International collaborators are very welcome to join RENO-50 !

Thank you !

Backup slides

Trigger & Data rates

Trigger rate	Near	Far
Inner Det. (> 90 hits)	300 Hz	100 Hz
Outer Det. (> 10 hits)	530 Hz	60 Hz

Data rate	Near	Far
Raw data	215 GB/day	75 GB/day

IBD Event Selection

- Reject flashers and external gamma rays : $Q_{max}/Q_{tot} < 0.03$
- Extra flasher cut :R >0.26 && n_{max}/n_{tot} >0.06, R > 0.26 && n_{max}/n_{tot} > 0.06
- 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 any trigger in the preceding 100 μs window (→ to remove spallation multiple-neutrons)
- Multiplicity cut 2: reject pairs if there is any S1 or S2 candidates in [-300, 1000] μs (→ to remove neutrons from Cf252 source)

Detection Efficiency & Systematic Uncertainties

Criteria	Detection efficiency (%)
The fraction of neutron captures on Gd	86.52 ± 0.7
Flasher cut & Prompt energy cut	95.19 ± 0.1
The 6.0M	
Time coi	
The spill	
Commo	
Muon ve	
Multiplic	
The tota	

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	0.10	0.5
Prompt energy cut	0.01	0.1
Flasher cut	0.01	0.11
Gd capture ratio	0.10	0.7
Delayed energy cut	0.10	0.46
Time coincidence cut	0.01	0.44
Spill-in	0.08	0.71
Muon veto cut	0.02	0.02
Multiplicity cut	0.04	0.06
Combined	0.20	1.31

New Result

preliminary

(prompt energy < 10 MeV)

	Near (PRL)	Near (New)	Far (PRL)	Far (New)
# of IBD events	**153,807**	**279,787**	**17,062**	**30,211**
Total Background rate (/day)	**21.73 +- 5.93**	**20.48 +- 2.13**	**4.3 +- 0.75**	**4.89 +- 0.60**
Accidental backgr ound (/day)	**4.30 +- 0.06**	**3.61 +- 0.05**	**0.68 +- 0.03**	**0.60 +- 0.03**
Fast neutron backg round (/day)	**4.98 +- 0.16**	**3.14 +- 0.09**	**1.03 +- 0.07**	**0.68 +- 0.04**
Li/He background (/day)	**12.45 +- 5.93**	**13.73 +- 2.13**	**2.59 +- 0.75**	**3.61+- 0.60**
DAQ Live-time (days)	**192.42**	**369.034**	**222.06**	**402.693**
Detector efficiency (%)	**64.7 +- 0.14**	**61.99 %**	**74.5 +- 0.14**	**71.37 %**

Physics Goals

- Determination of mass hierarchy (sign of Δm^2_{31} or Δm^2_{32})

  - Quite challenging : requires extremely good energy resolution

- Precise measurement of θ_{12}, Δm^2_{21} and Δm^2_{31}

$$\frac{\delta \sin^2\theta_{12}}{\sin^2\theta_{12}} < 1.0\%(1\sigma) \quad \frac{\delta\Delta m^2_{21}}{\Delta m^2_{21}} < 1.0\%(1\sigma) \quad \frac{\delta\Delta m^2_{31}}{\Delta m^2_{31}} < 1.0\%(1\sigma)$$

(← 5.4%) (← 2.6%) (← 5.2%)

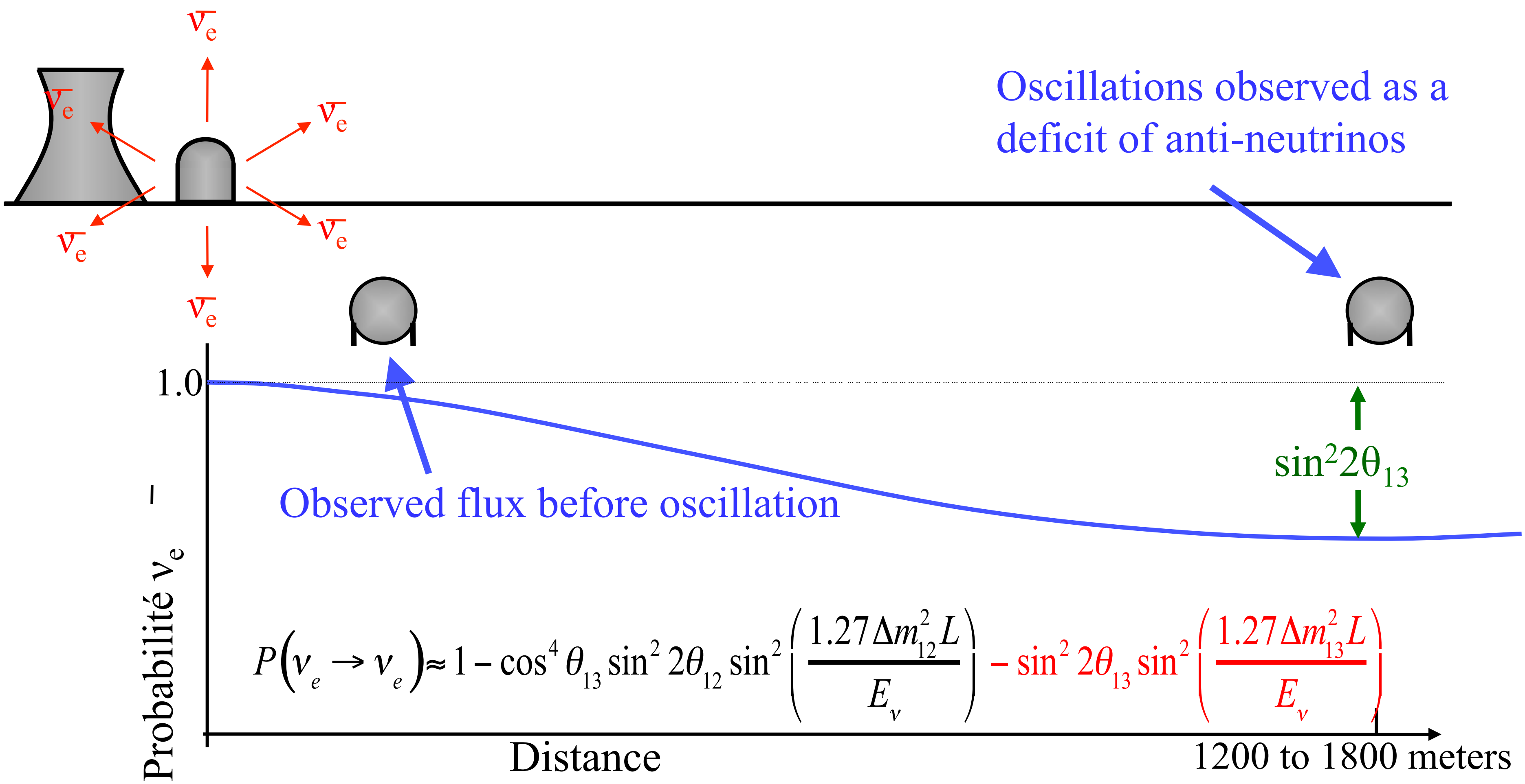
- Neutrino burst from a Supernova in our Galaxy

  - ~5400 events (@8 kpc)
  - A long-term neutrino telescope

- Geo-neutrinos : ~ 900 geo-neutrinos for 5 years

  - Study the heat generation mechanism inside the Earth

How to measure θ_{13}?



$$P(\nu_e \to \nu_e) \approx 1 - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{1.27\Delta m_{12}^2 L}{E_\nu}\right) - \sin^2 2\theta_{13} \sin^2\left(\frac{1.27\Delta m_{13}^2 L}{E_\nu}\right)$$

- ❑ 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.

Detection of Reactor Antineutrinos

Inverse beta decay

(prompt signal)

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

~180 μs

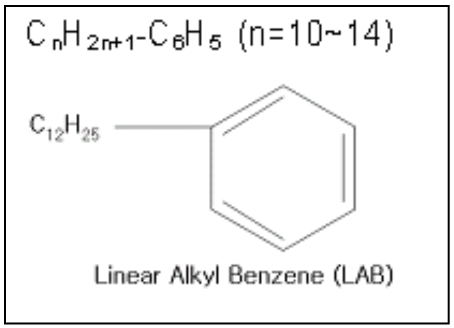
+ p → D + γ (2.2 MeV)

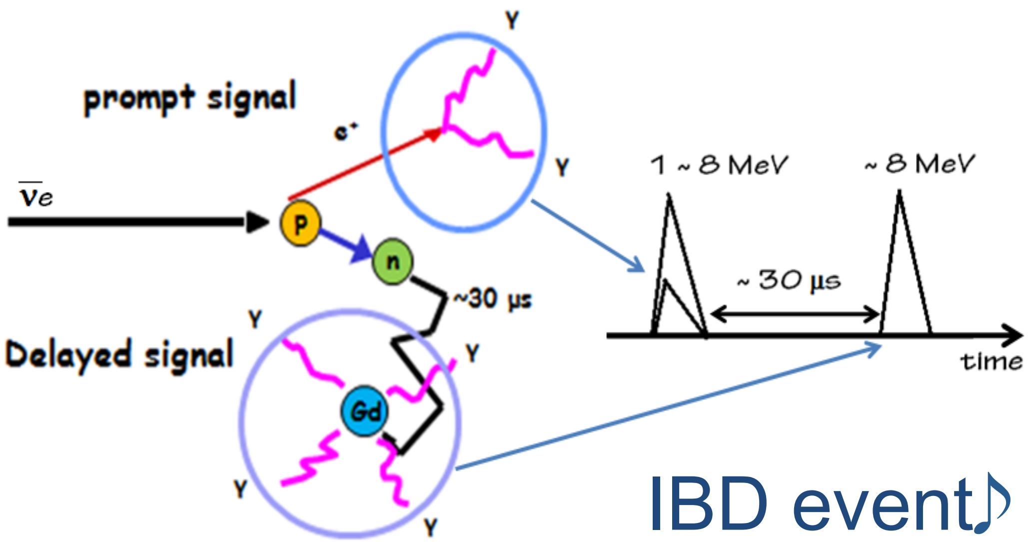
~30 μs
(0.1% Gd)

+ Gd → Gd + γ's (~8 MeV)

(delayed signal)

Higher captured cross section
& Additional gammas in Gd-LS detector

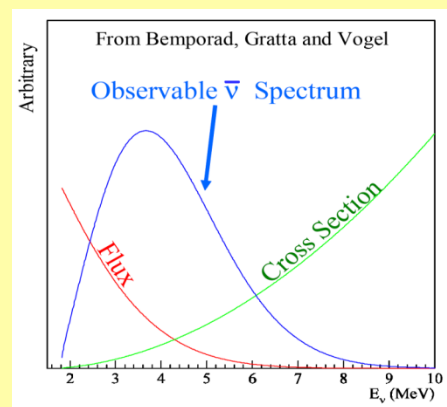




IBD event♪

Neutrino energy measurement♪

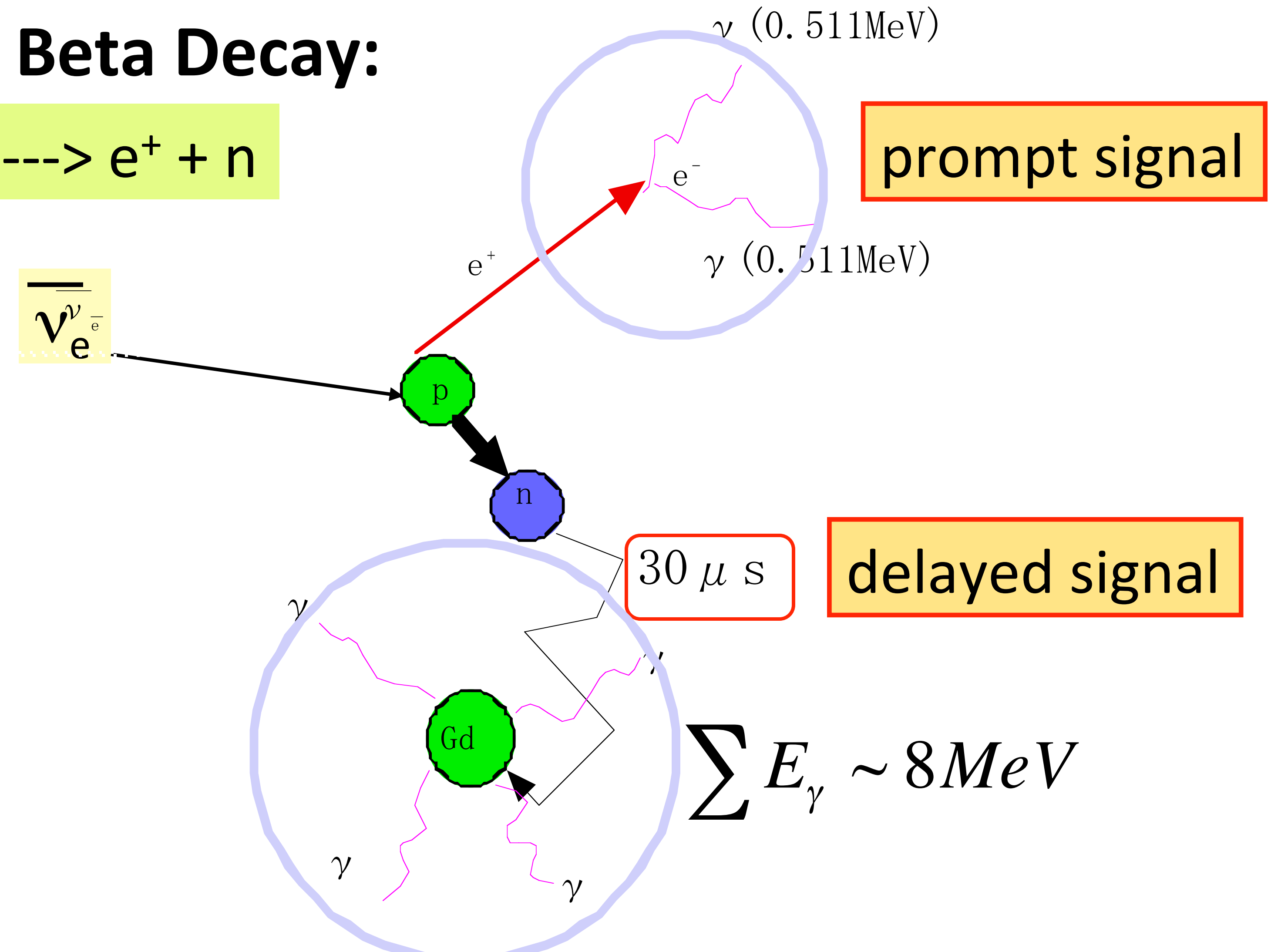
$$E_{\bar{\nu}} \cong T_{e^+} + \underbrace{T_n}_{10\text{-}40\ keV} + \underbrace{(M_n - M_p) + m_{e^+}}_{1.8\ MeV}$$



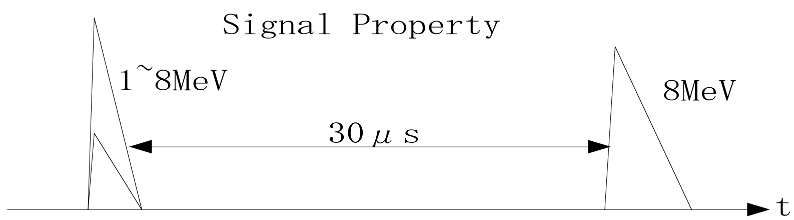
Detection of Reactor Neutrinos

Inverse Beta Decay:

$\overline{\nu}_e + p \dashrightarrow e^+ + n$

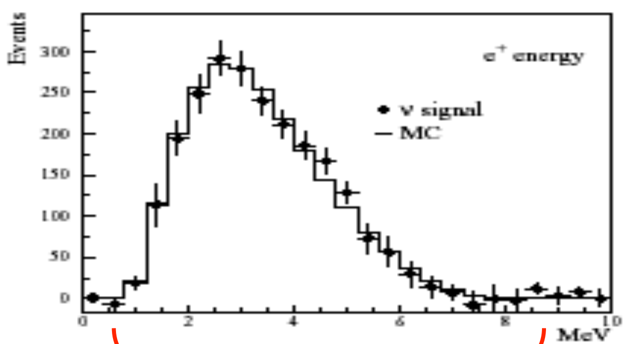


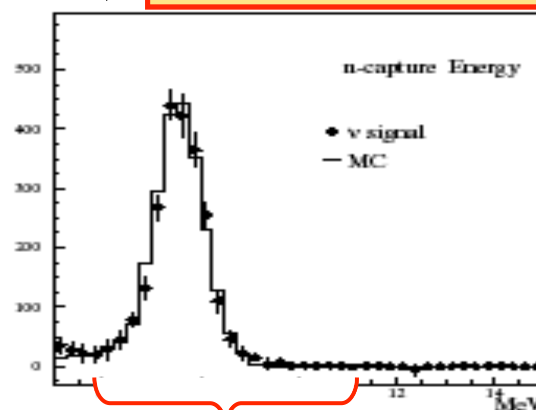
Signal: IBD pair



prompt signal

delayed signal





$(1)\ 0.7 < E_{prompot} < 10\ MeV$

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