Recent Results from RENO & Future Project RENO-50

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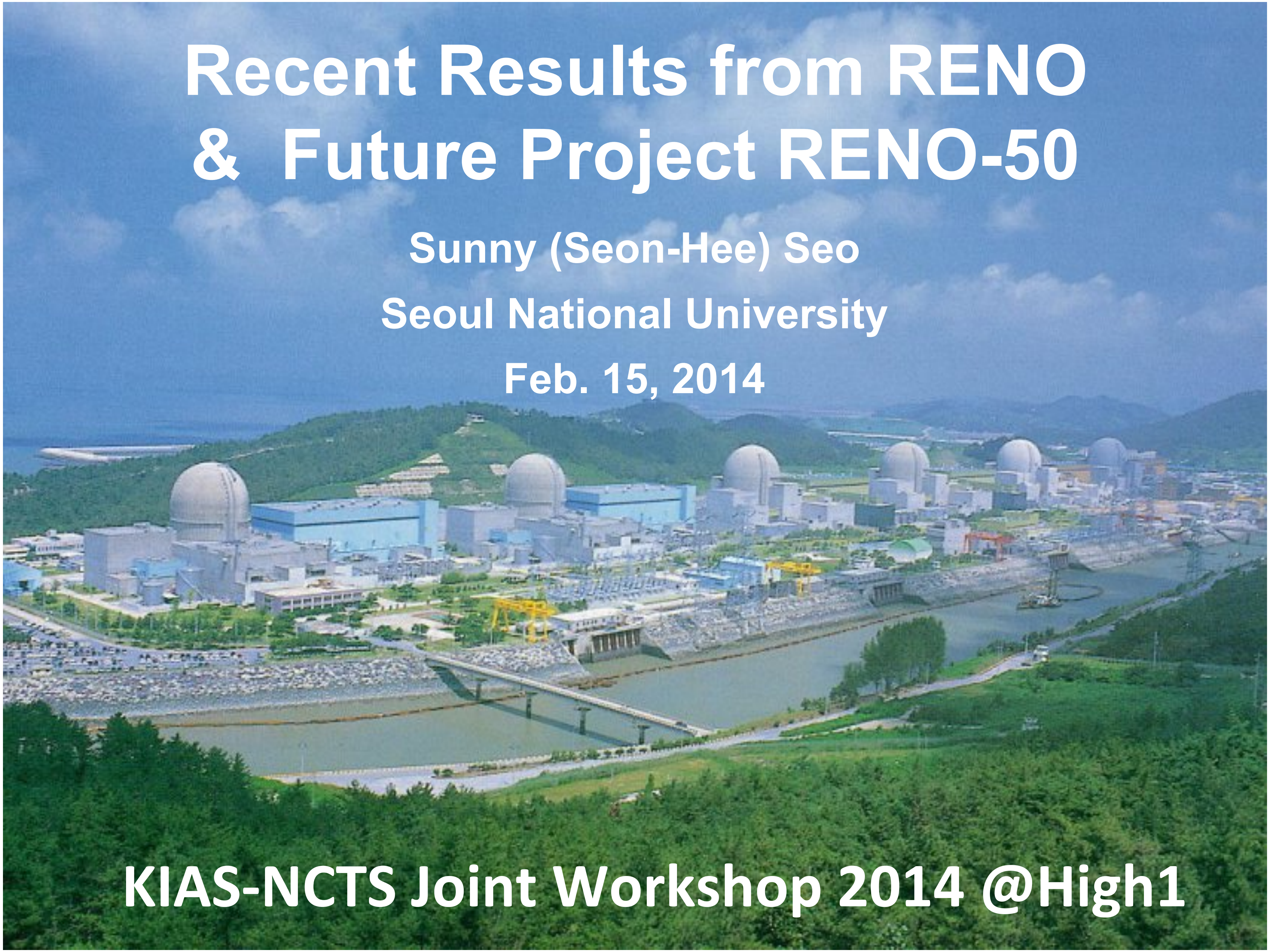
Feb. 15, 2014



KIAS-NCTS Joint Workshop 2014 @High1

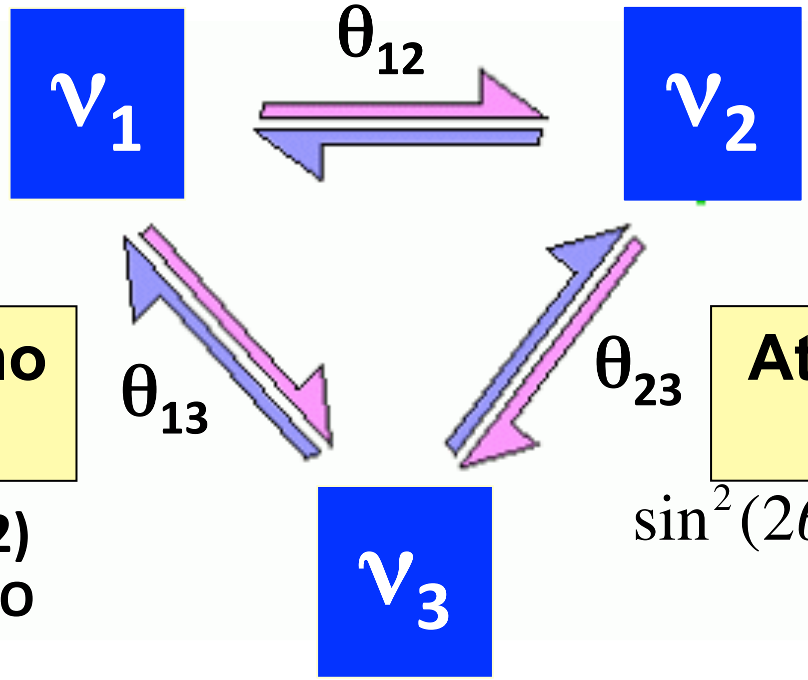
Neutrino Oscillation

Pontecorvo 1957
MNS 1967

Solar Neutrino Oscillation

$\sin^2(2\theta)$ **~80 %** **(2001)**

SNO, **Super-K;** KamLAND



Reactor Neutrino Oscillation

$\sin^2(2\theta)$ **~10 %** **(2012)**

DayaBay, RENO

Atmos. Neutrino Oscillation

$\sin^2(2\theta)$ **~100 %** **(1998)**

Super-K; K2K

$$P(\nu_x \to \nu_x) \approx 1 - \sin^2(2\theta) \cdot \sin^2\left(1.27 \cdot \Delta m^2 \cdot \frac{L(km)}{E(GeV)}\right)$$

Impact of θ_{13} Measurement

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

  LBNO, LBNE, Hyper-K (θ_{13} != 0)

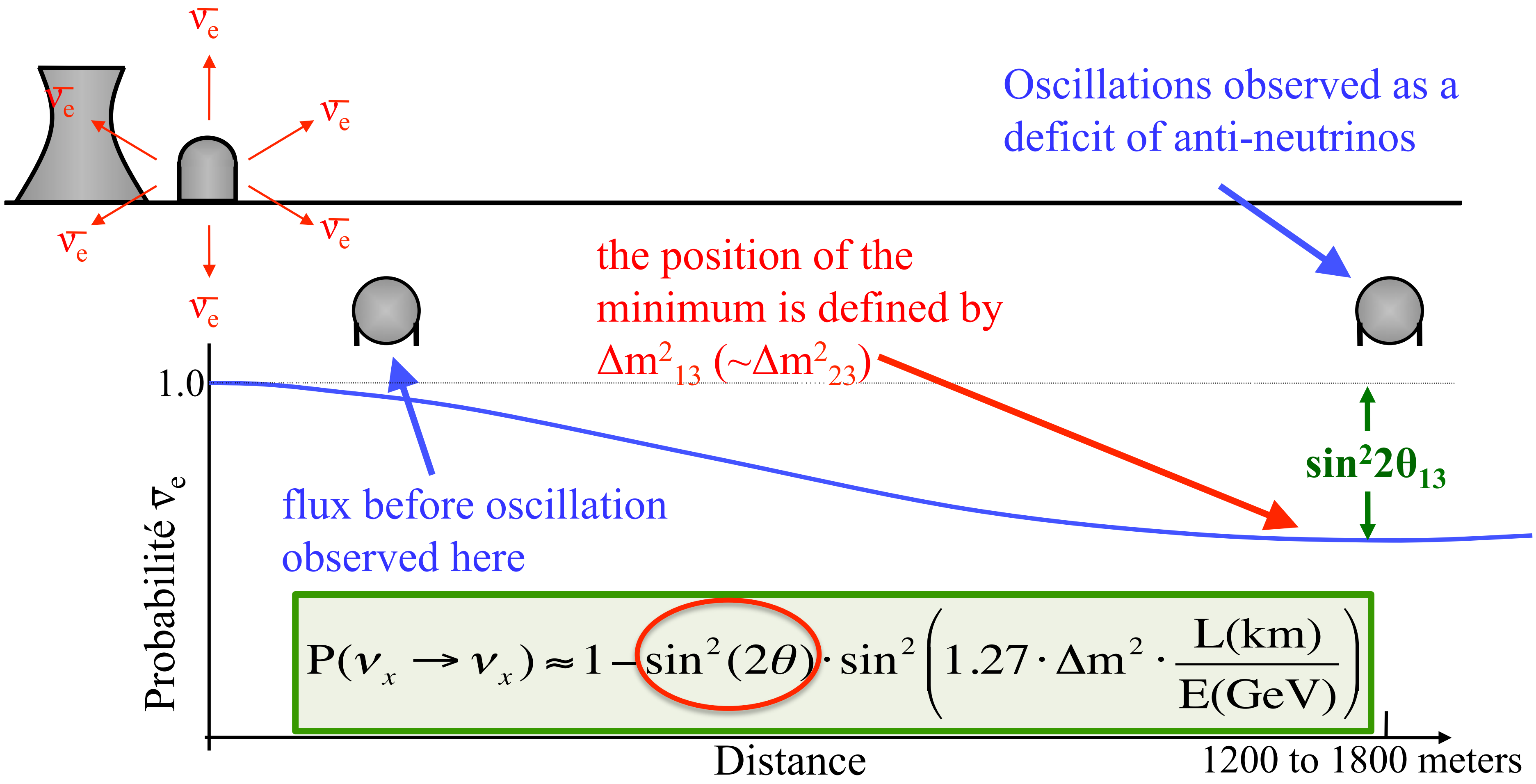
$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) \propto \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos\theta_{13} \sin\delta$$

- ✓ To allow neutrino mass hierarchy measurement

  (← requires not too small θ_{13})
- ✓ To allow precise measurement of atm. neutrino oscillation parameters

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

Concept 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 ν Experiments

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

Construction:

- ✓ **DC** is expected to complete construction in **2014**.
- ✓ **RENO** finished construction in **June 2011**.
- ✓ **Daya Bay** finished construction in **Sept. 2012**.

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

θ_{13} Measurements Status

Double Chooz

$\sin^2(2\theta_{13})$ = 0.085 +- 0.051 (2011) rate + shape 1.7 σ

→0.109 +- 0.035 (2013) rate + shape 3.1 σ

RENO

$\sin^2(2\theta_{13})$ = 0.113 +- 0.023 (2012) rate 4.9 σ

→ 0.100 +- 0.016 (2013) rate 6.3 σ

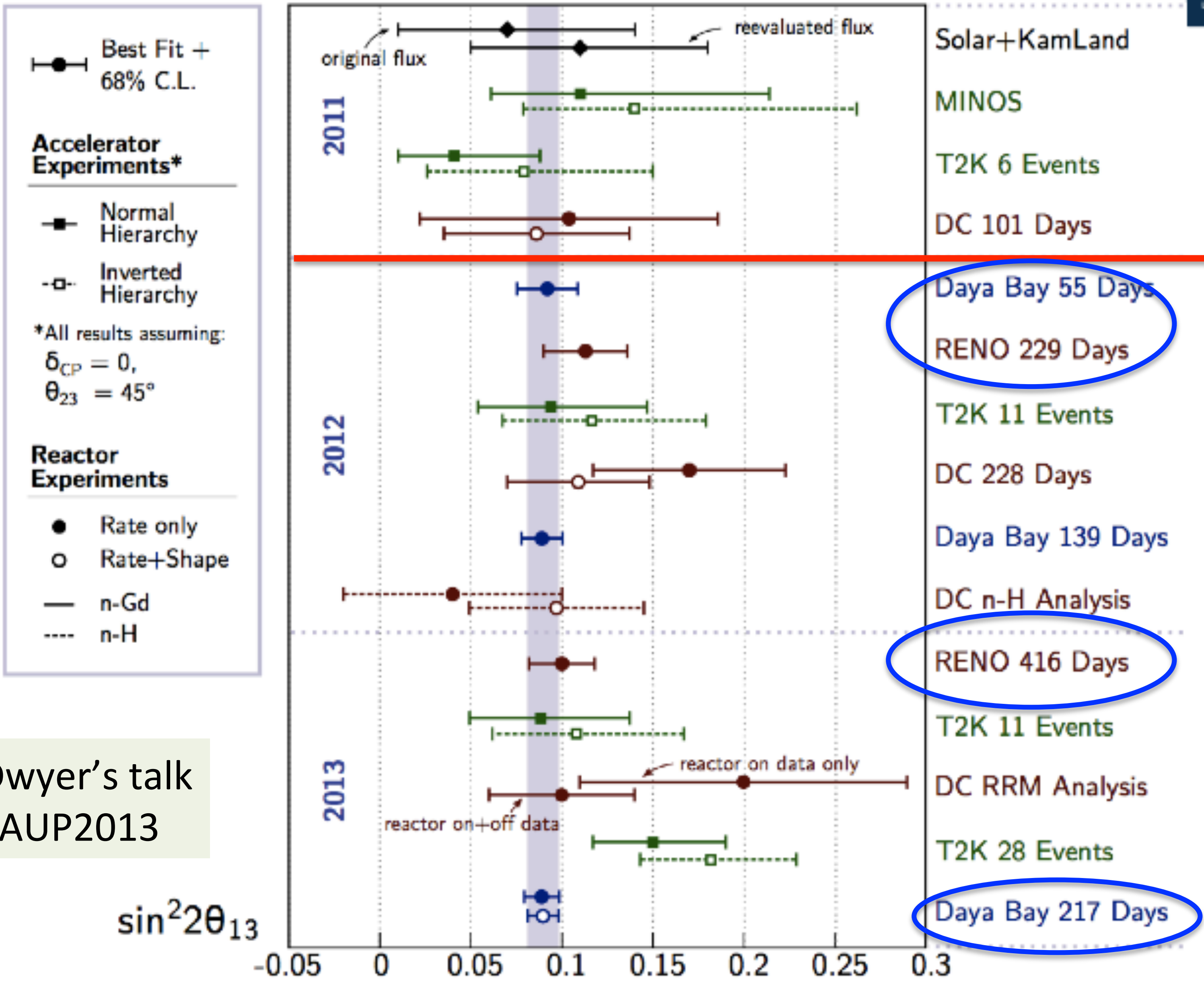
Daya Bay

$\sin^2(2\theta_{13})$ = 0.092 +-0.017 (2012) rate 5.4 σ

→ 0.090 +- 0.009 (2013) rate + shape 10 σ

$$|\Delta m^2_{ee}| = 2.59^{+0.19}_{-0.20} \times 10^{-3} (eV^2)$$

State of θ_{13} Measurements



Dan Dwyer's talk @ TAUP2013

RENO's 1st Measurement of θ_{13} (I)

PRL 108, 19802 (2012)

PRL **108,** 191802 (2012) PHYSICAL REVIEW LETTERS week ending 11 MAY 2012

Observation of Reactor Electron Antineutrinos Disappearance in the RENO Experiment

J. K. Ahn,[7] S. Chebotaryov,[6] J. H. Choi,[4] S. Choi,[10] W. Choi,[10] Y. Choi,[12] H. I. Jang,[11] J. S. Jang,[2] E. J. Jeon,[8] I. S. Jeong,[2] K. K. Joo,[2] B. R. Kim,[2] B. C. Kim,[2] H. S. Kim,[1] J. Y. Kim,[2] S. B. Kim,[10] S. H. Kim,[7] S. Y. Kim,[7] W. Kim,[6] Y. D. Kim,[8] J. Lee,[10] J. K. Lee,[7] I. T. Lim,[2] K. J. Ma,[8] M. Y. Pac,[4] I. G. Park,[5] J. S. Park,[10] K. S. Park,[9] J. W. Shin,[10] K. Siyeon,[3] B. S. Yang,[10] I. S. Yeo,[2] S. H. Yi,[12] and I. Yu[12]

(RENO Collaboration)

citation : **666 (Inspires),**
373 (web of science)

as of 13th Feb., 2014

RENO's 1st Measurement of θ_{13} (II)

Our PRL value was included in 2012 Particle Data Book.

LEPTONS

Neutrino Mixing

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

$\Delta m^2_{21} = (7.50 \pm 0.20) \times 10^{-5}$ eV^2

$\sin^2(2\theta_{23}) > 0.95$ [i]

$\Delta m^2_{32} = (2.32^{+0.12}_{-0.08}) \times 10^{-3}$ eV^2 [j]

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

(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 ~ 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±0.041±0.030		[1] ABE	12	DCHZ	Chooz reactors
0.113±0.013±0.019		[2] AHN	12	RENO	Yonggwang reactors
0.092±0.016±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. • • •					
$0.85^{+0.04}_{-0.03}$	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}

<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 since **Aug. 2011**

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

Experimental Site

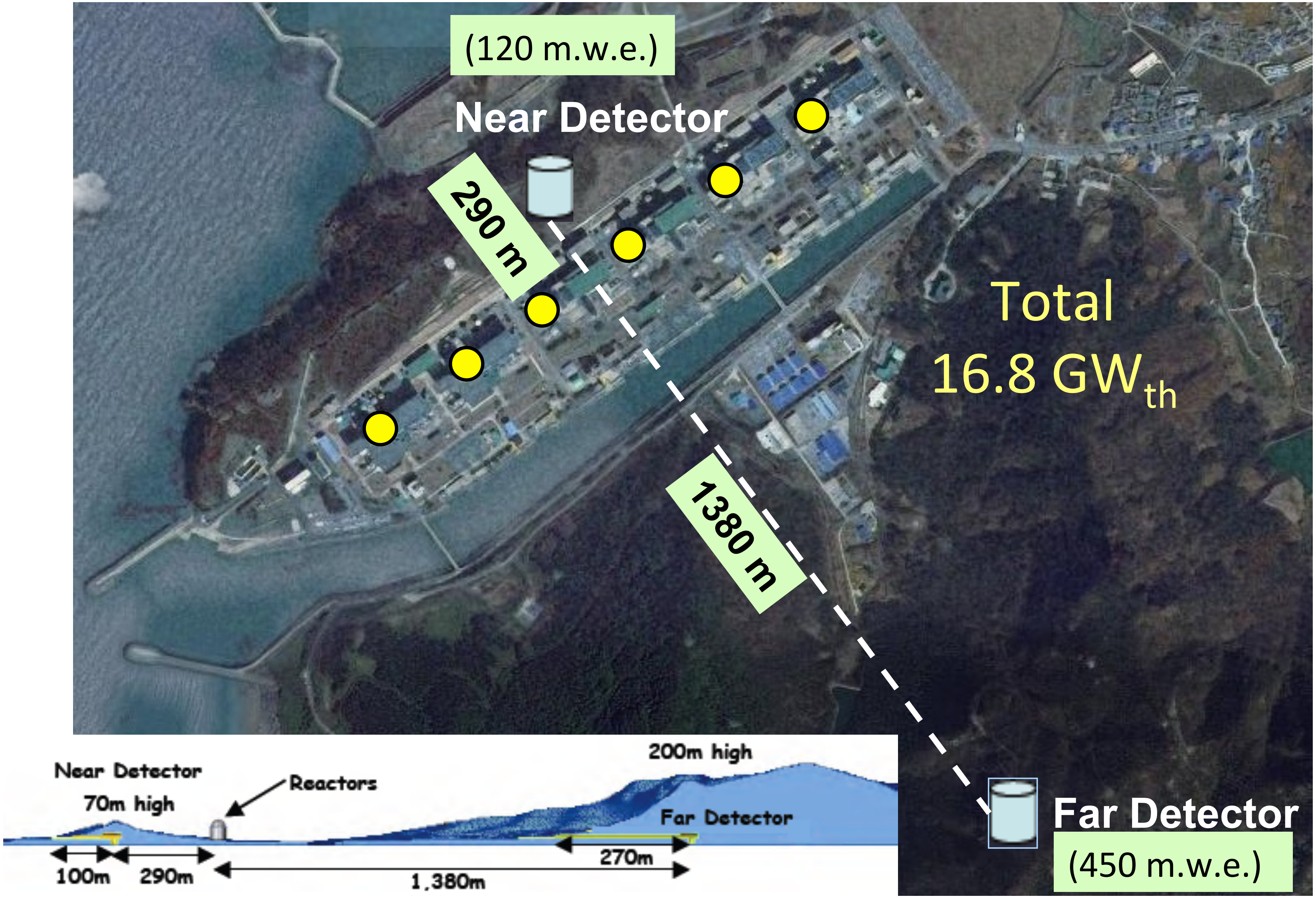
YongGwang: South west of South Korea
~ 300 km from Seoul

"YongGwang" reactor site

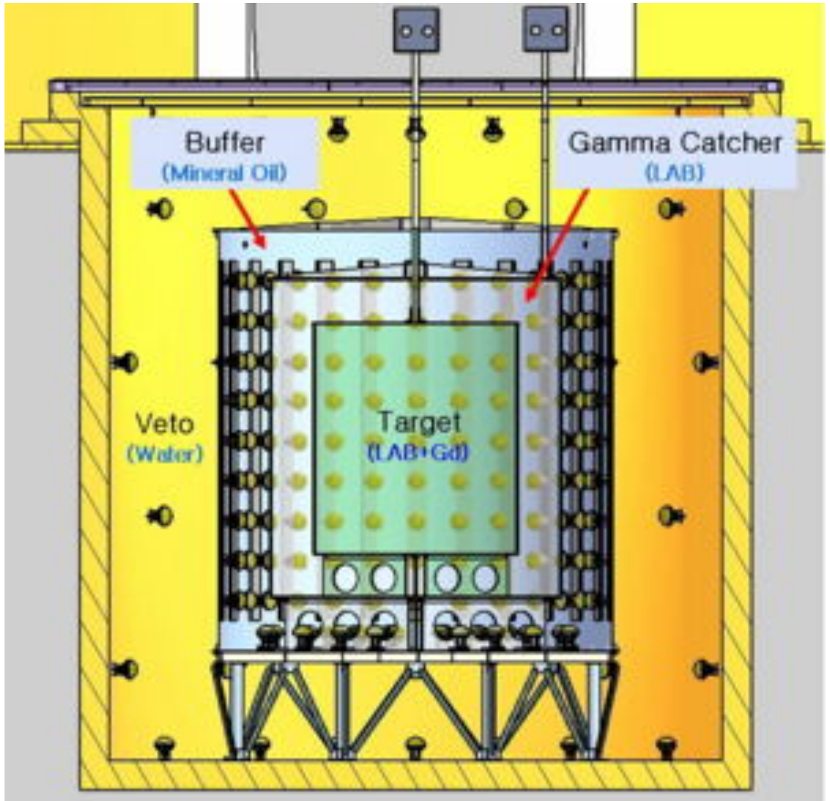
→ "Hanbit" reactor site (new name)

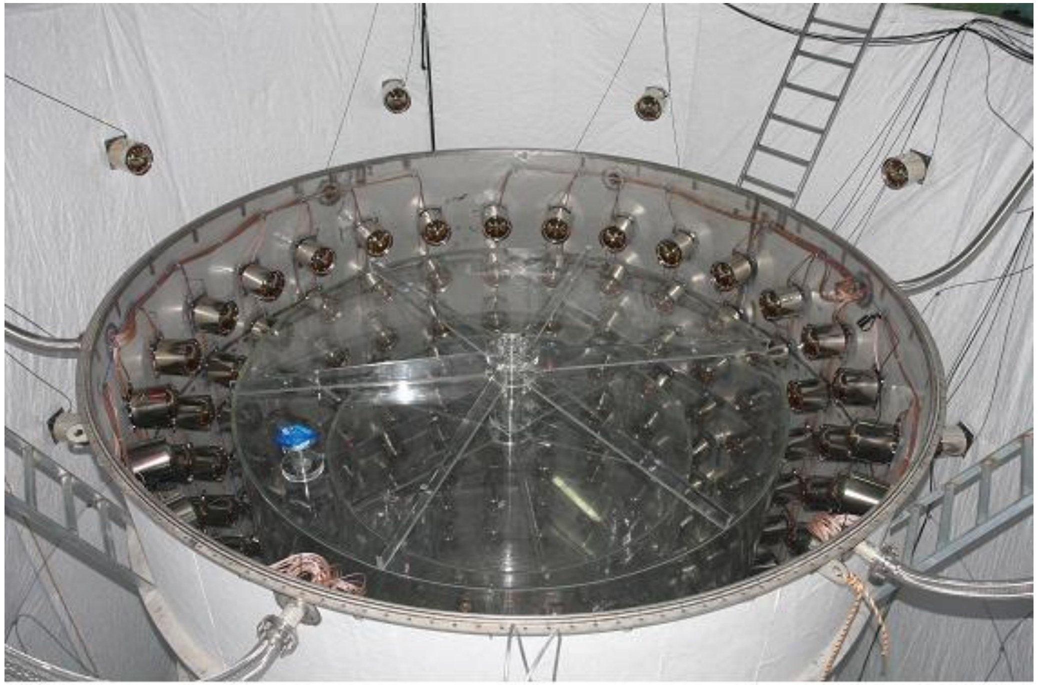
YongGwang (靈光) :

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

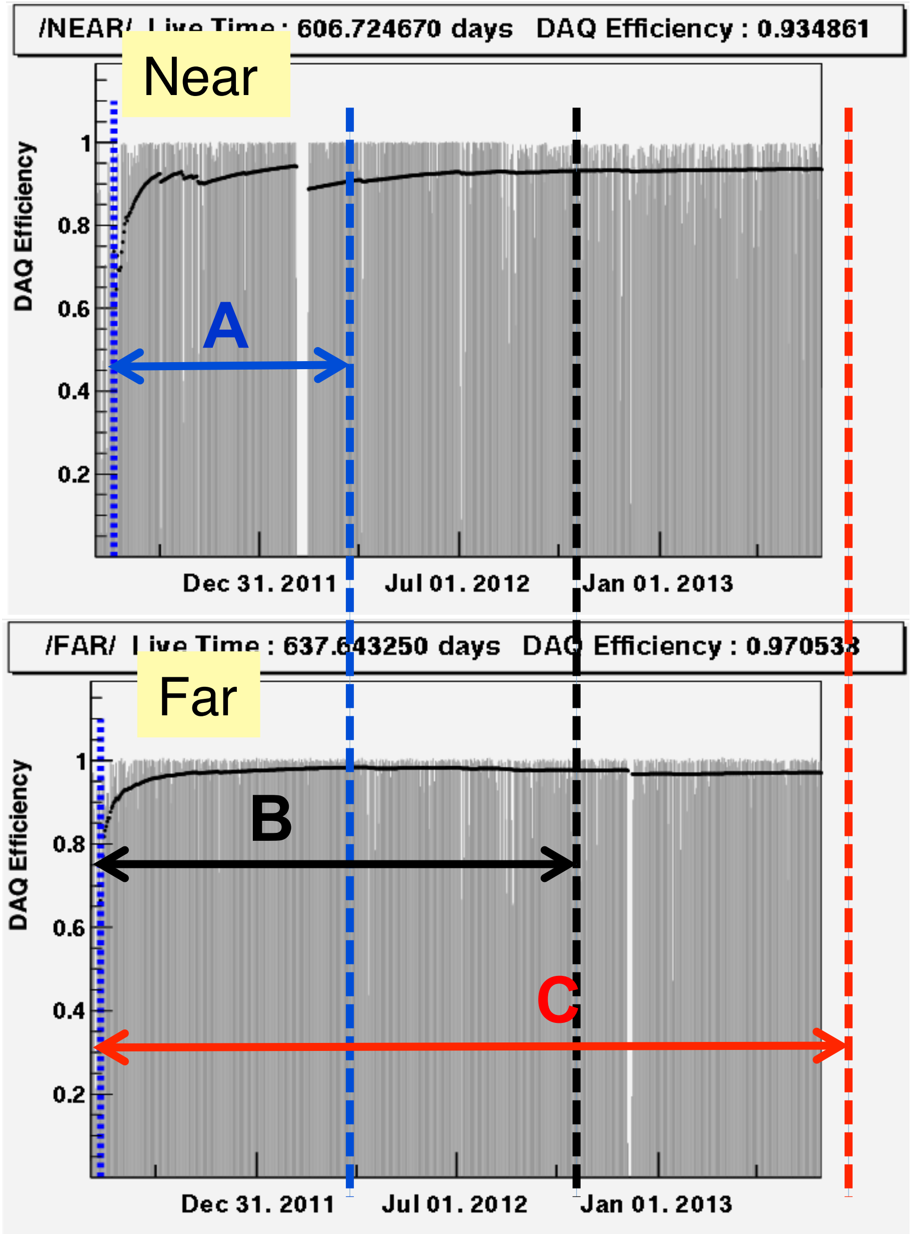
- Data taking began on Aug. 1, 2011 with both near and far detectors. (DAQ efficiency : ~95%)

- **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, TAUP 2013, WIN 2013

- **C** (~795 days) : **Shape+rate analysis** (in progress)
  [11 Aug, 2011~31 Dec, 2013]

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



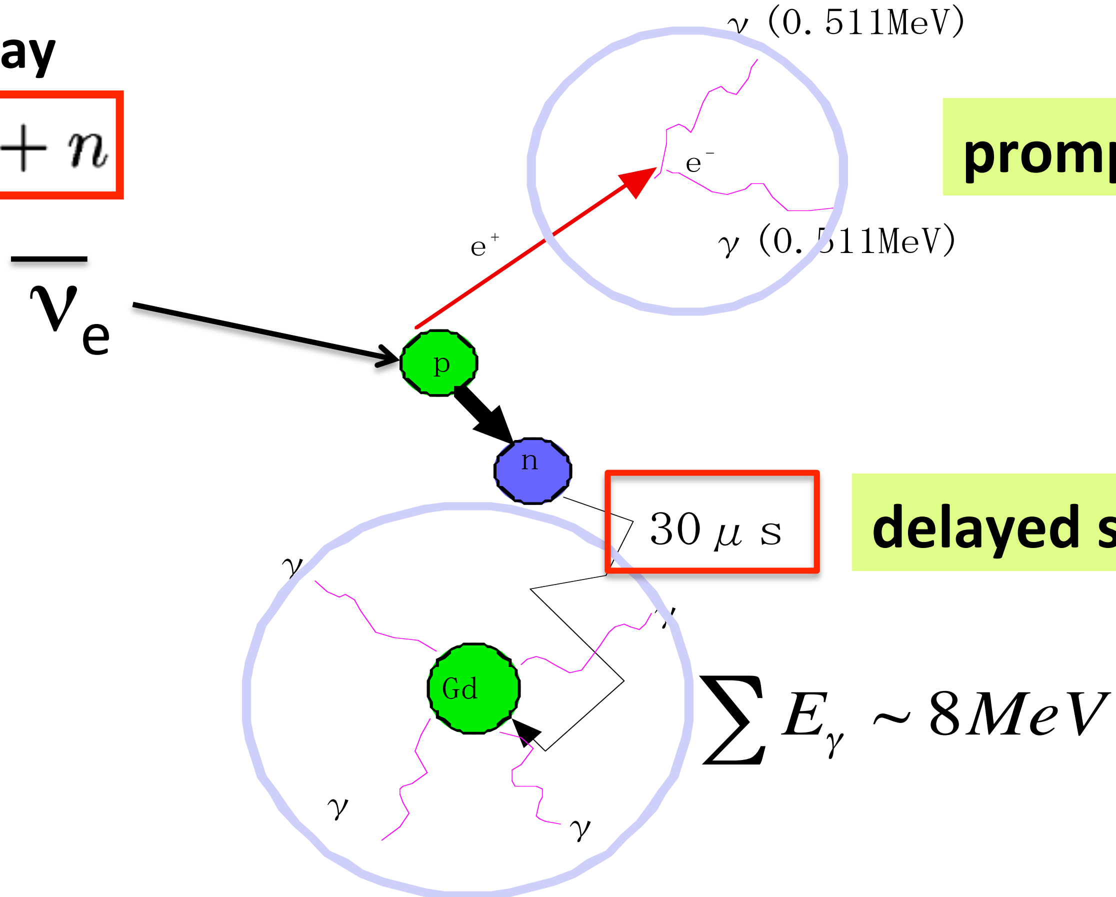
IBD Event Signature

- 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

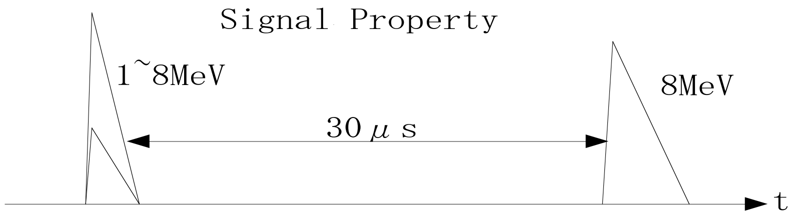
  ~28 μs (0.1% Gd) in LS♪

Inverse Beta Decay

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

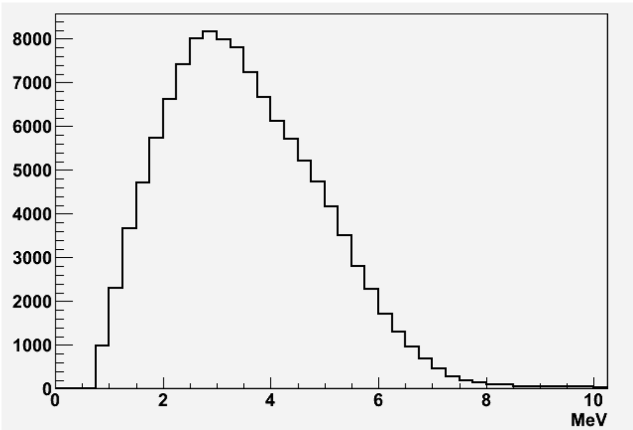


Signal: IBD pair
(= a pair of prompt & delayed signals)

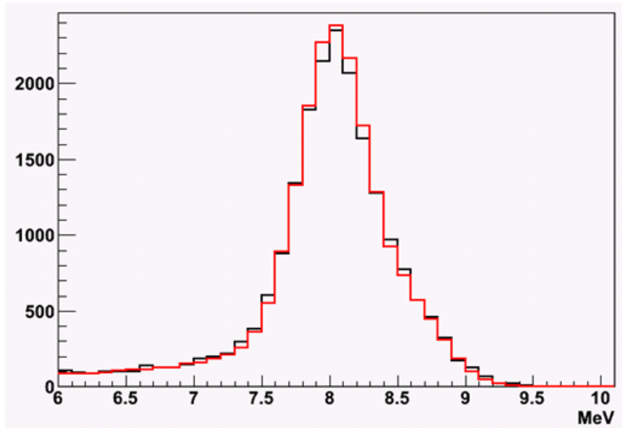


prompt signal

delayed signal



ΔT
~30 usec



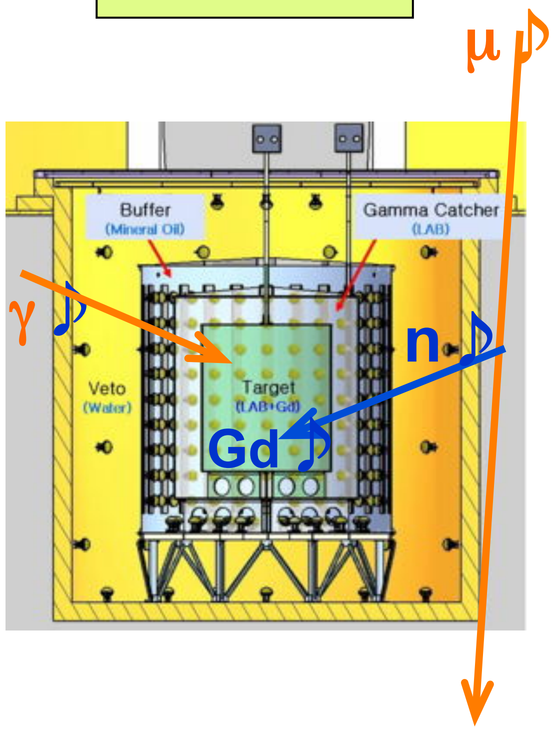
$(1)\ 0.7 < E_{prompot} < 10\ MeV$

$(2)\ 6 < E_{delayed} < 10\ MeV$

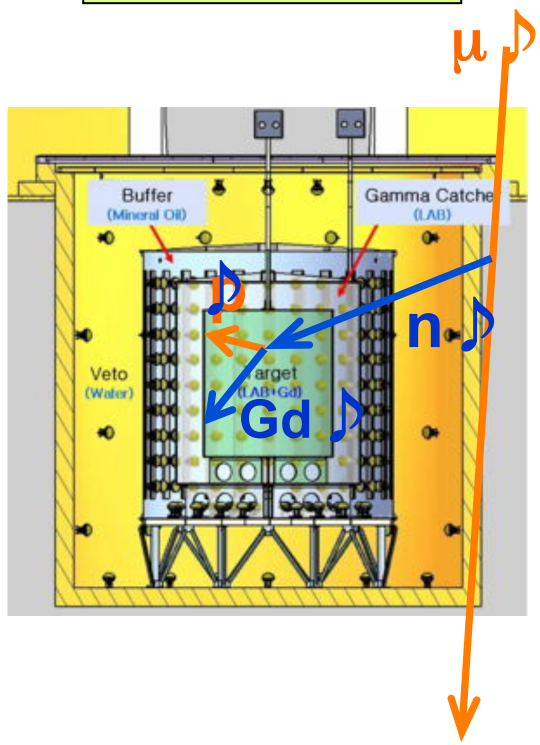
Backgrounds

- **Accidental background** caused by radioactivity; random coincidence between prompt and delayed signals (uncorrelated)
- **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 on ^{12}C

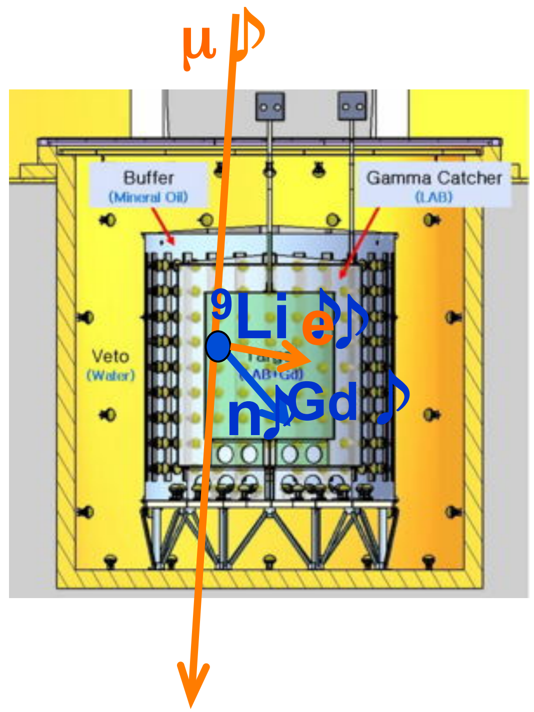
Accidentals

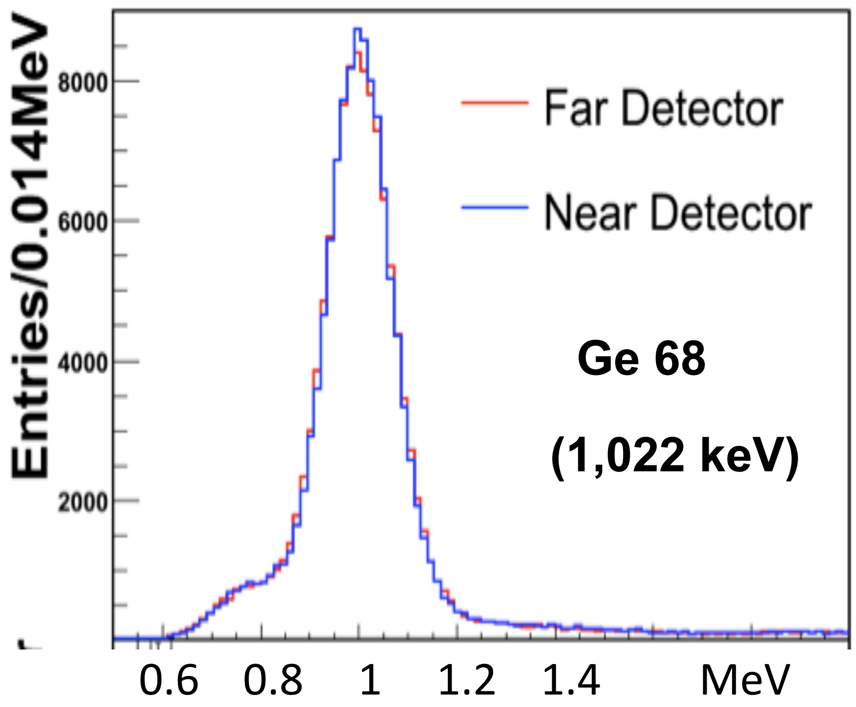


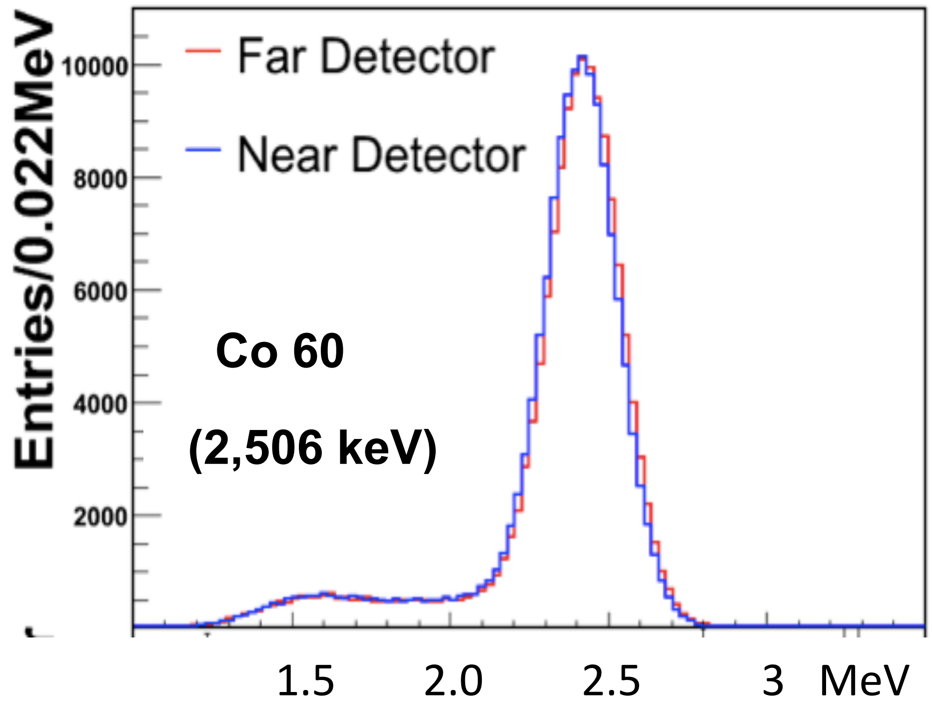
Fast neutrons



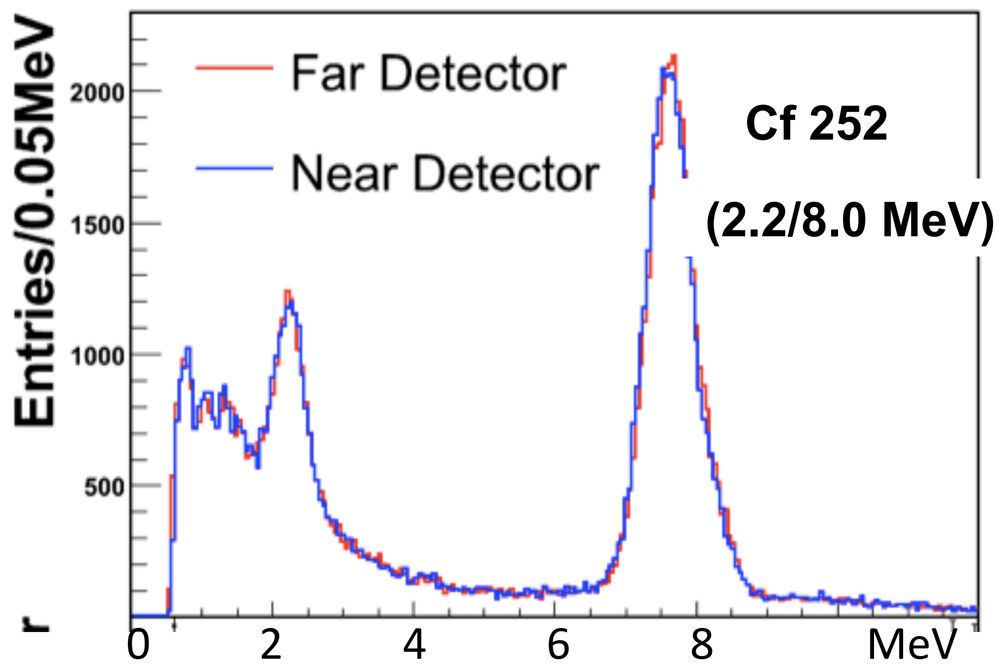
^{9}Li/^{8}He β-n followers





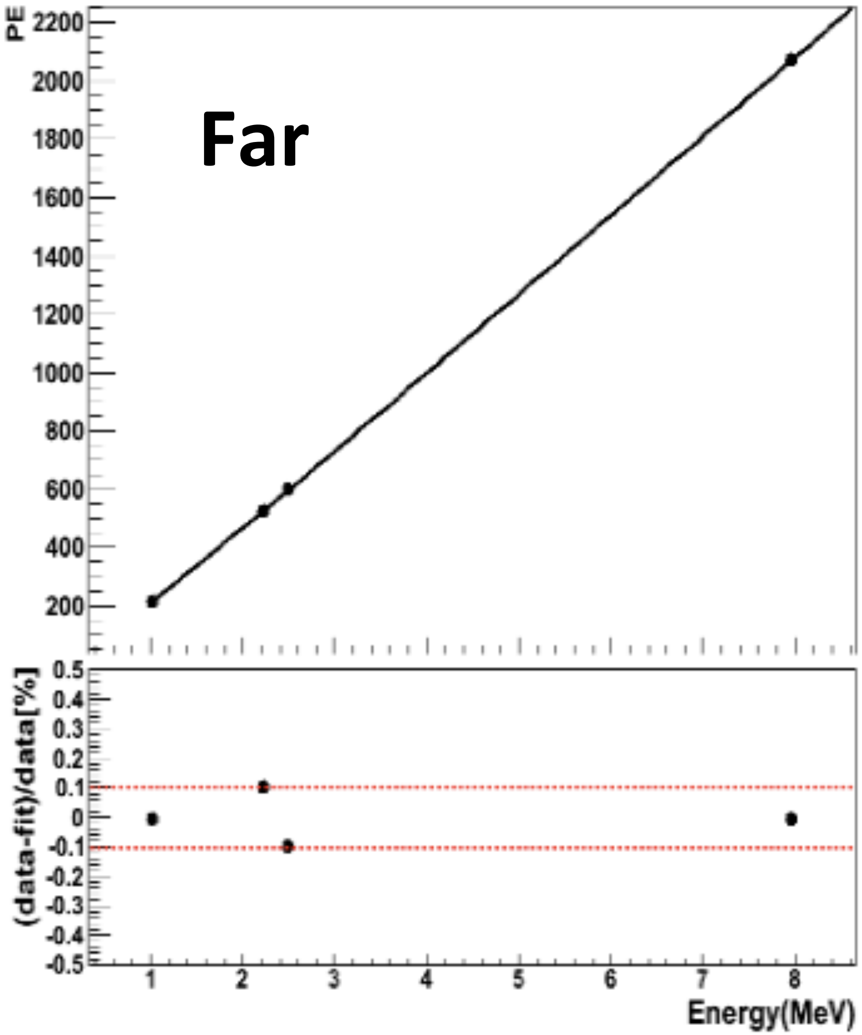


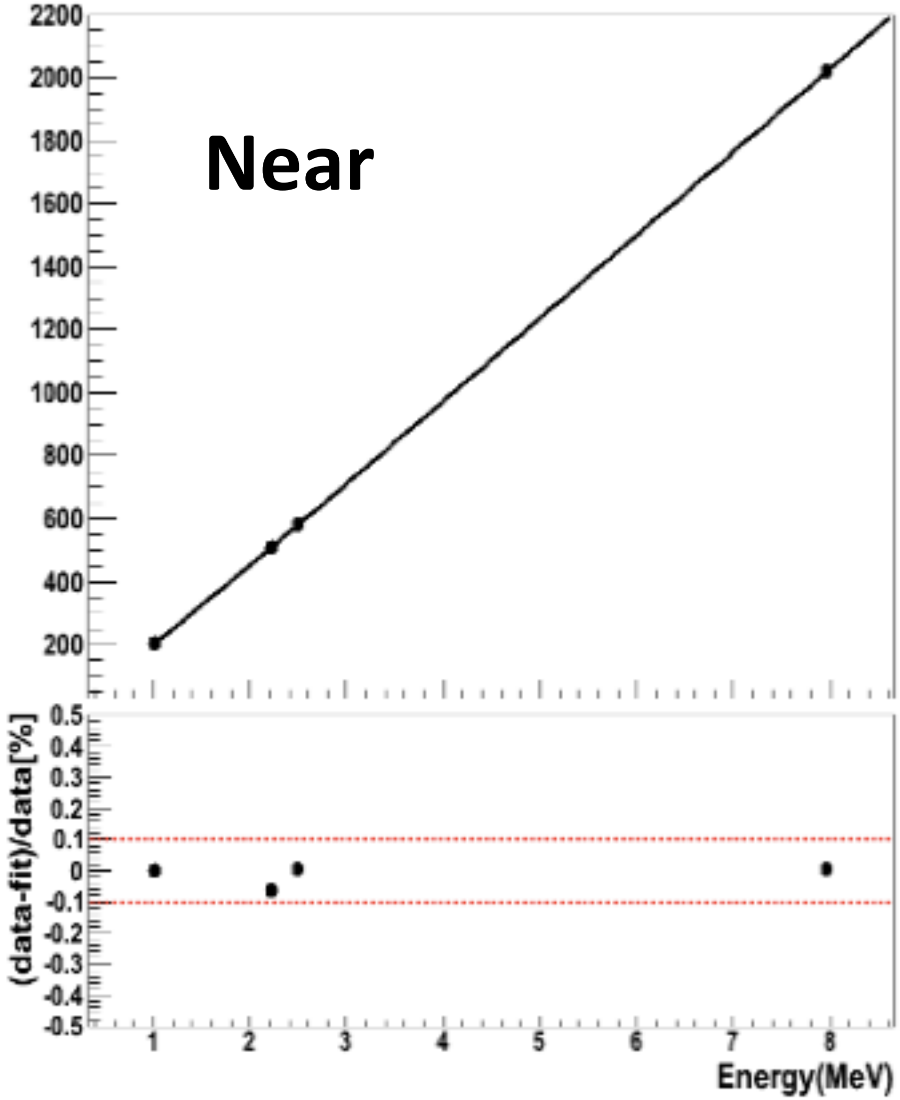
Energy Calibration



Energy Calibration

PE → MeV conversion fnc

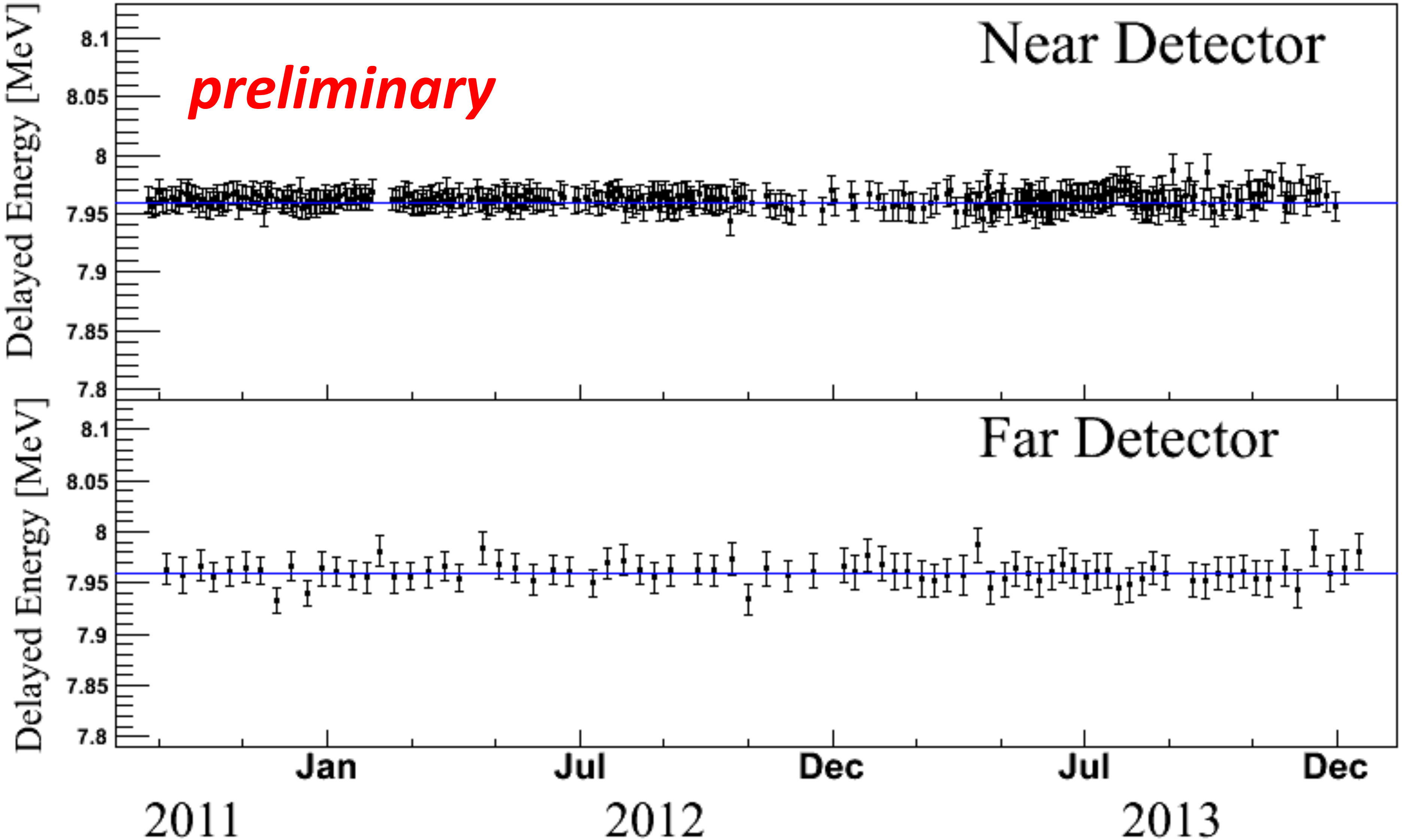




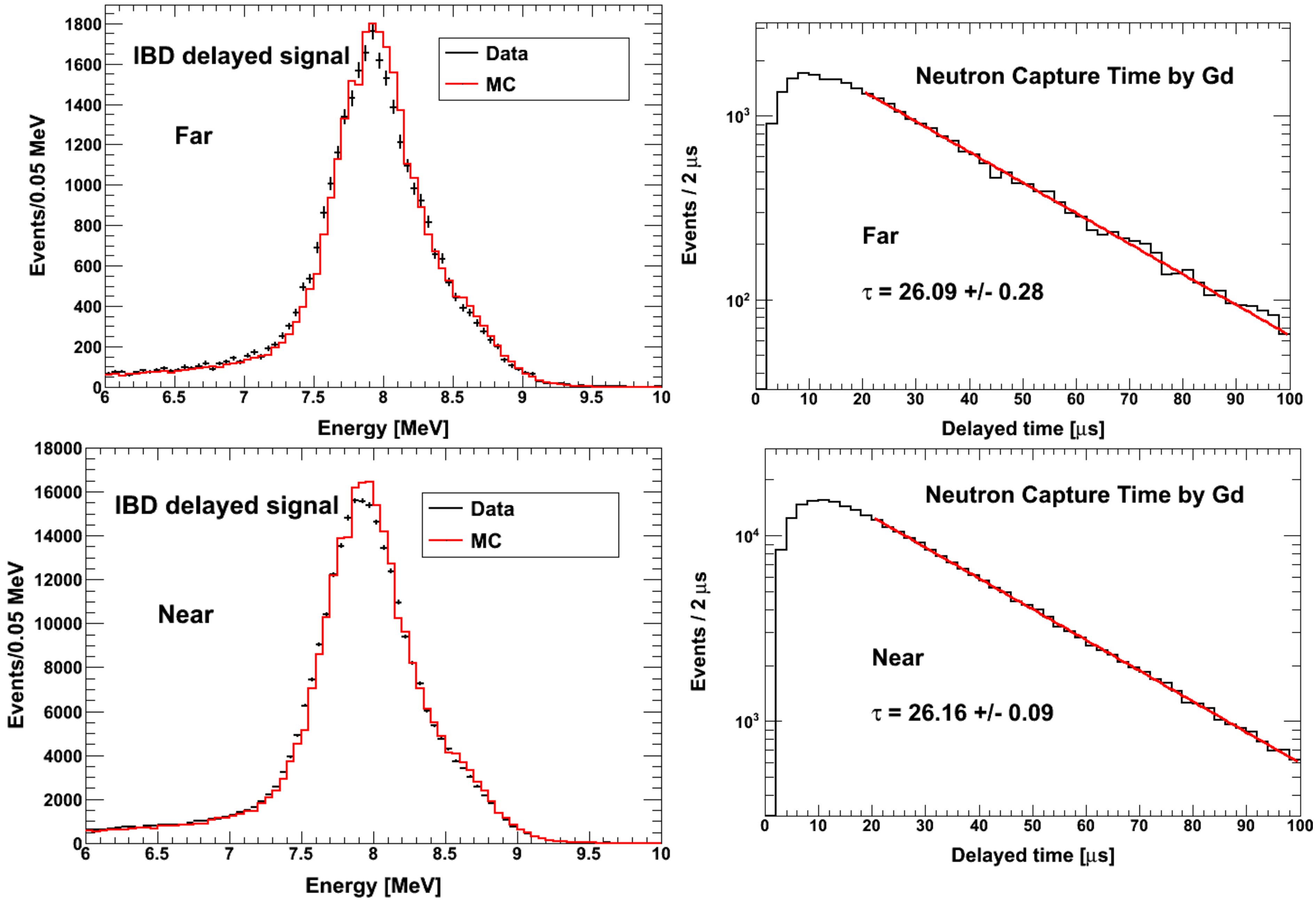
Fitting accuracy: 0.1 %

Detector Stability of Energy Scale

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



Spectra & Capture Time of Delayed Signals



Recent Results (Sept. 2013)

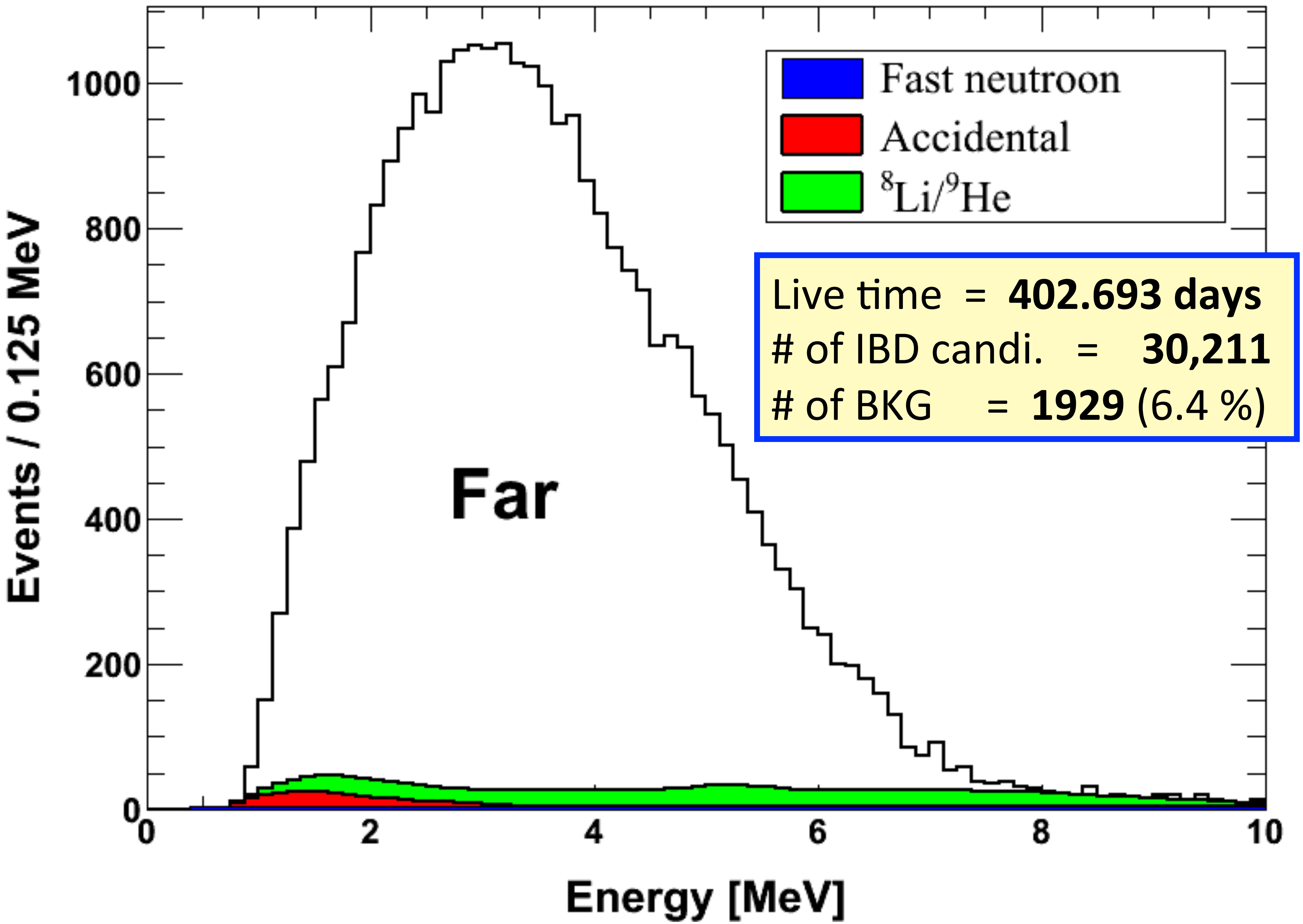
(prompt energy < 10 MeV)

preliminary

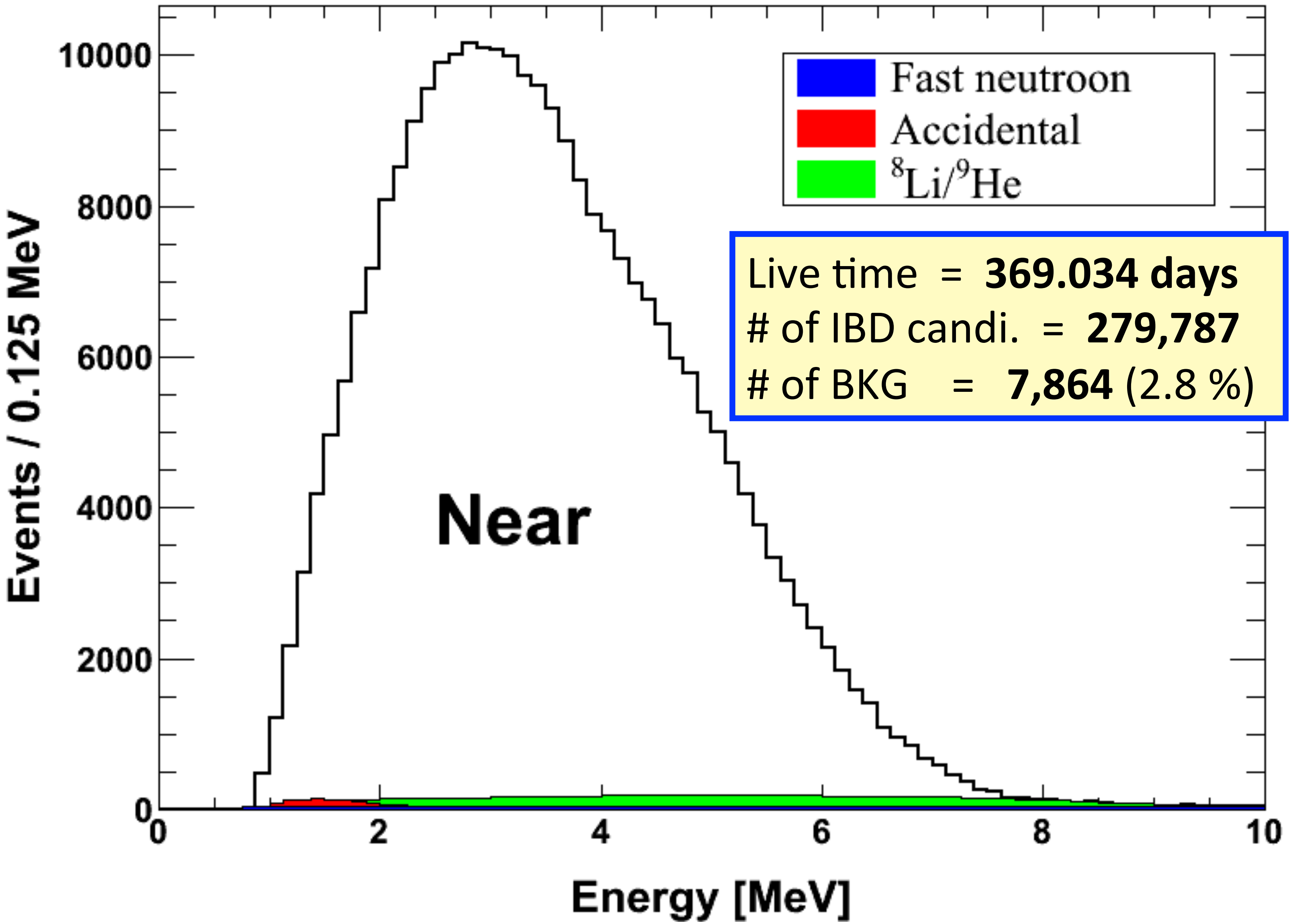
Rate +- Sys. err +- Stat. err

	Near	Far
# of IBD events	**279,787**	**30,211**
Total BKG rate (/day)	**21.31 +- 1.79 +- 0.26**	**4.80 +- 0.45 +- 0.12**
Total IBD rate after BKG Subtraction (/day)	**737 +- 2.31**	**70.22 +- 0.64**
Accidental background (/day)	**3.61 +- 0.05 +- 0.10**	**0.60 +- 0.03 +- 0.04**
Fast neutron background (day)	**3.59 +- 0.94 +- 0.10**	**0.65 +- 0.09 +- 0.04**
Li/He background (/day)	**13.97 +- 1.52 +- 0.22**	**3.55 +- 0.44 +- 0.11**
DAQ Live-time (days)	**369.034**	**402.693**
Detector efficiency (%)	**61.99 +- 1.40**	**71.37 +- 1.19**

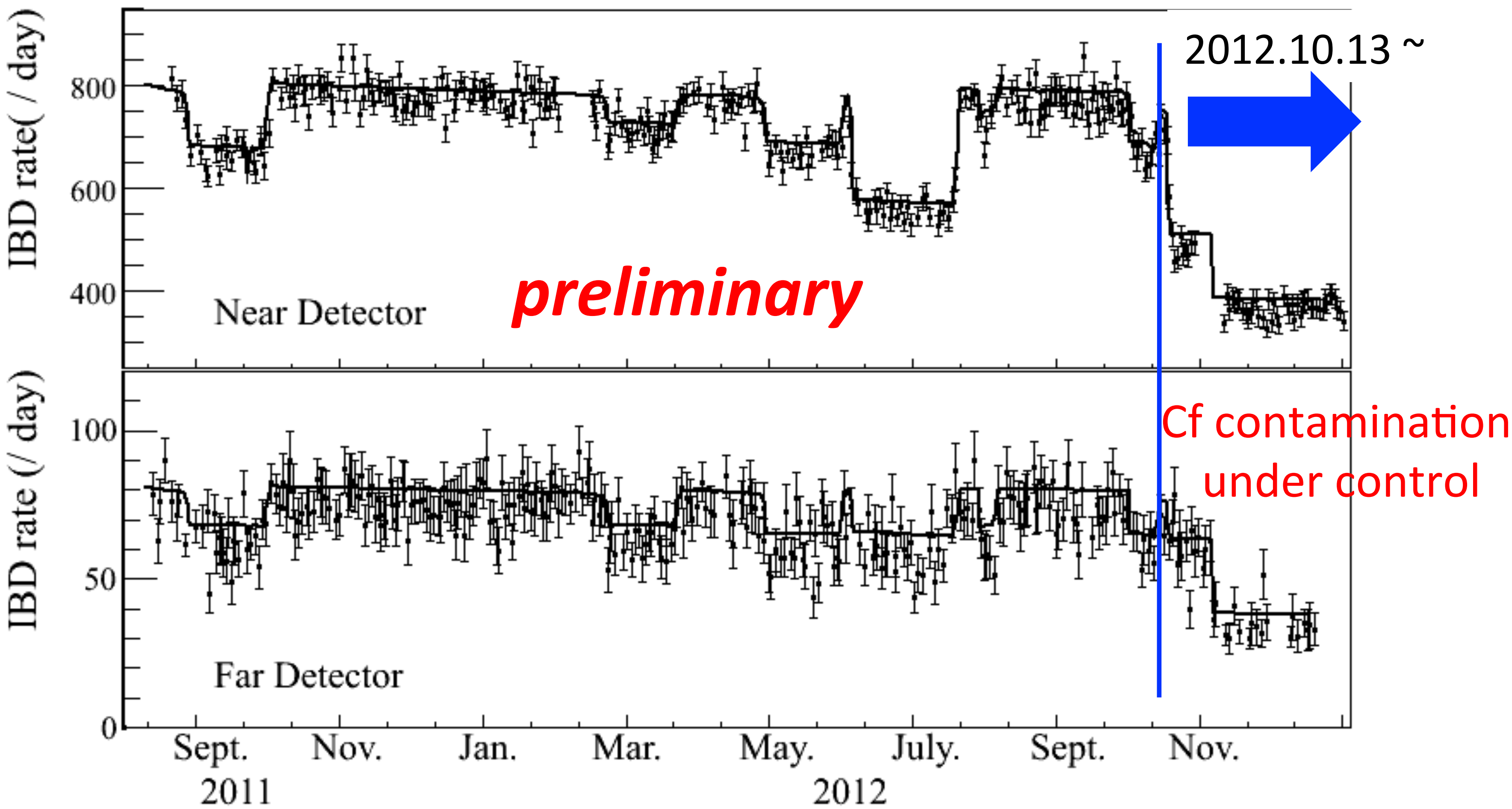
Measured Spectra of IBD Prompt Signal



Measured Spectra of IBD Prompt Signal

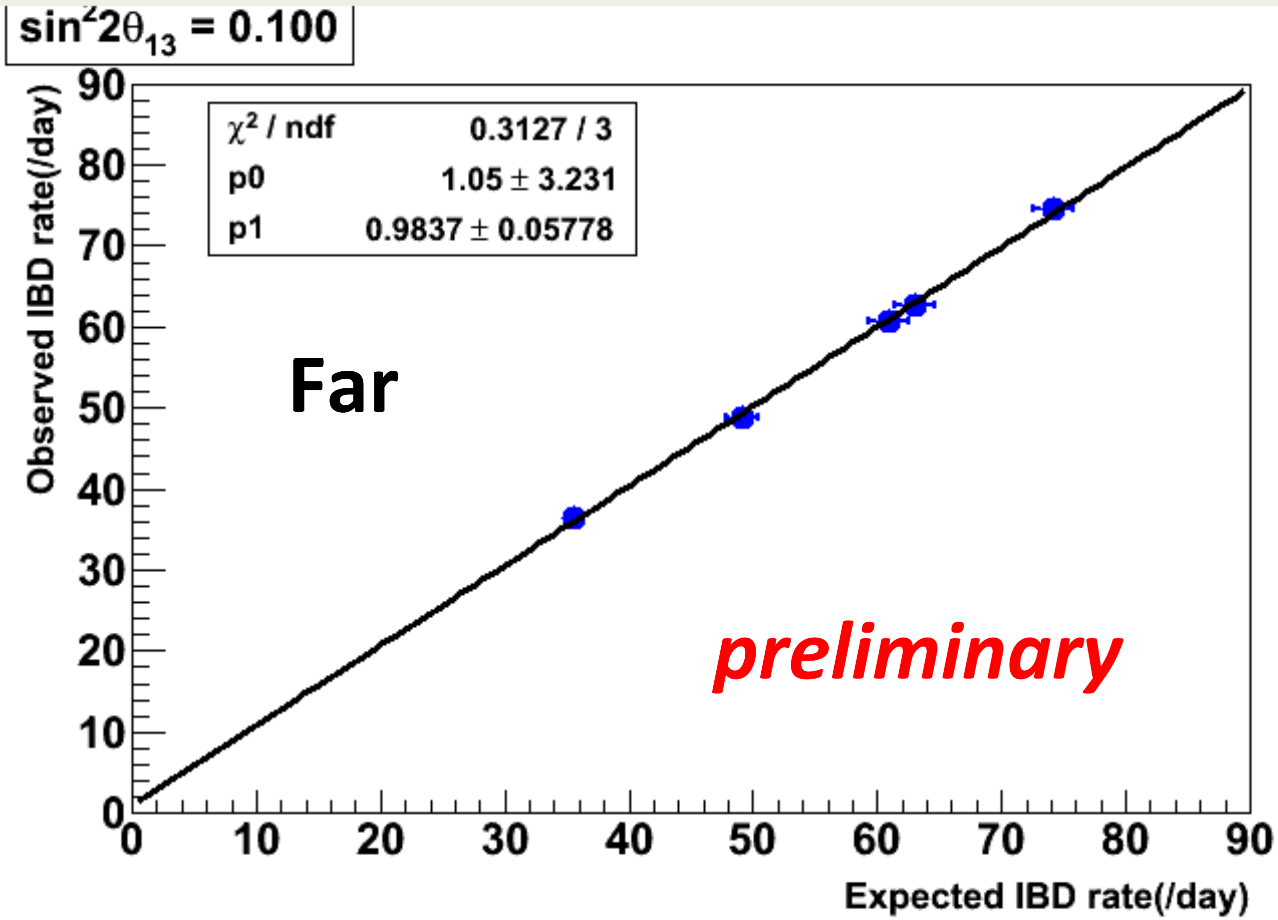


Observed Daily IBD Rate



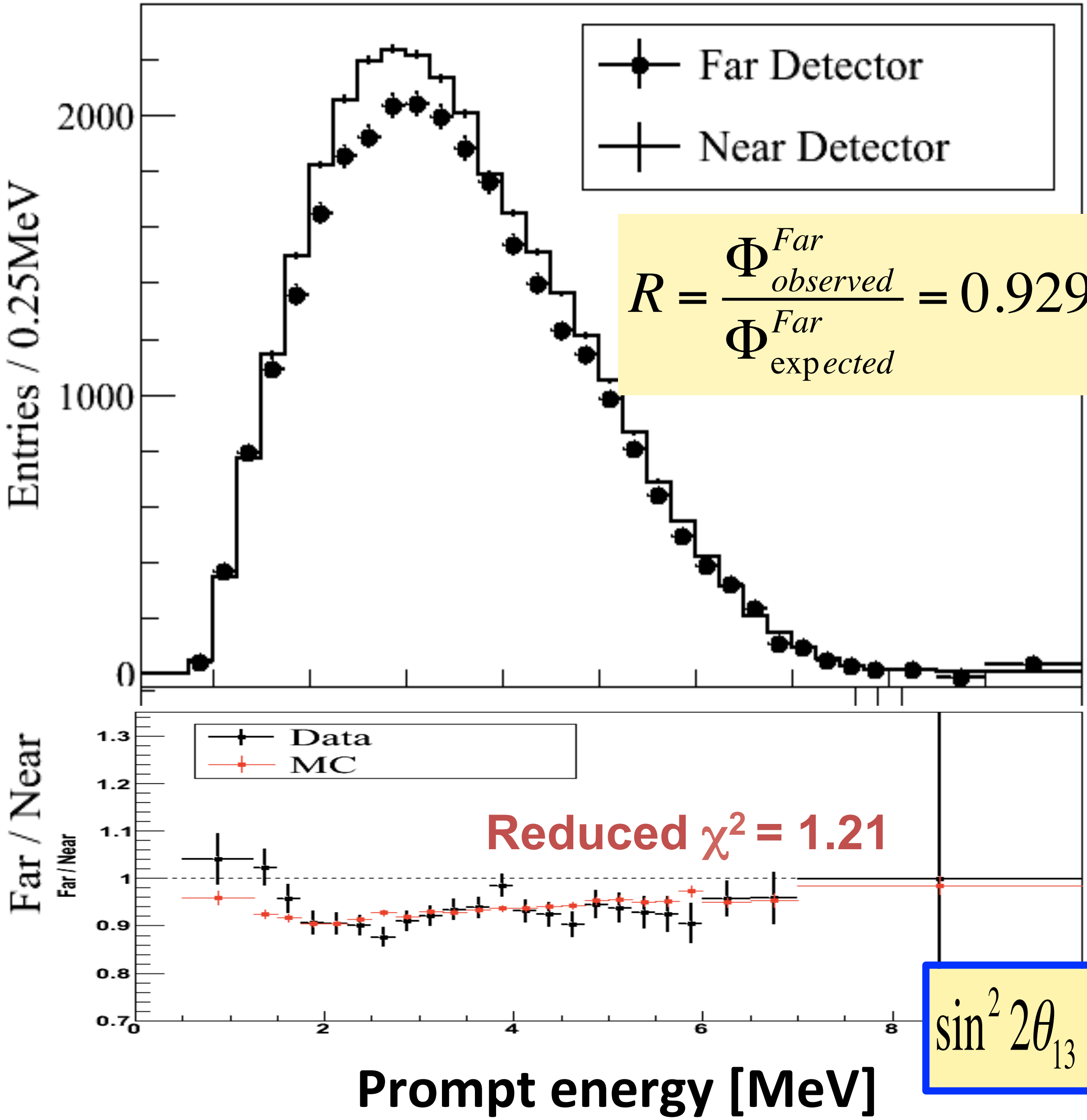
- Solid line is predicted rate from the neutrino flux calculation.
- Observed points have very good agreement with prediction.
- It's the accurate flux measurement.

Observed vs. Expected IBD Rates



- ✓ Observed and expected IBD rates match well within oscillation hypothesis.
- ✓ Background subtraction is correctly done.

Reactor Antineutrino Disappearance



preliminary

$$R = \frac{\Phi^{Far}_{observed}}{\Phi^{Far}_{expected}} = 0.929 \pm 0.006(stat.) \pm 0.007(syst.)$$

- A clear deficit in rate

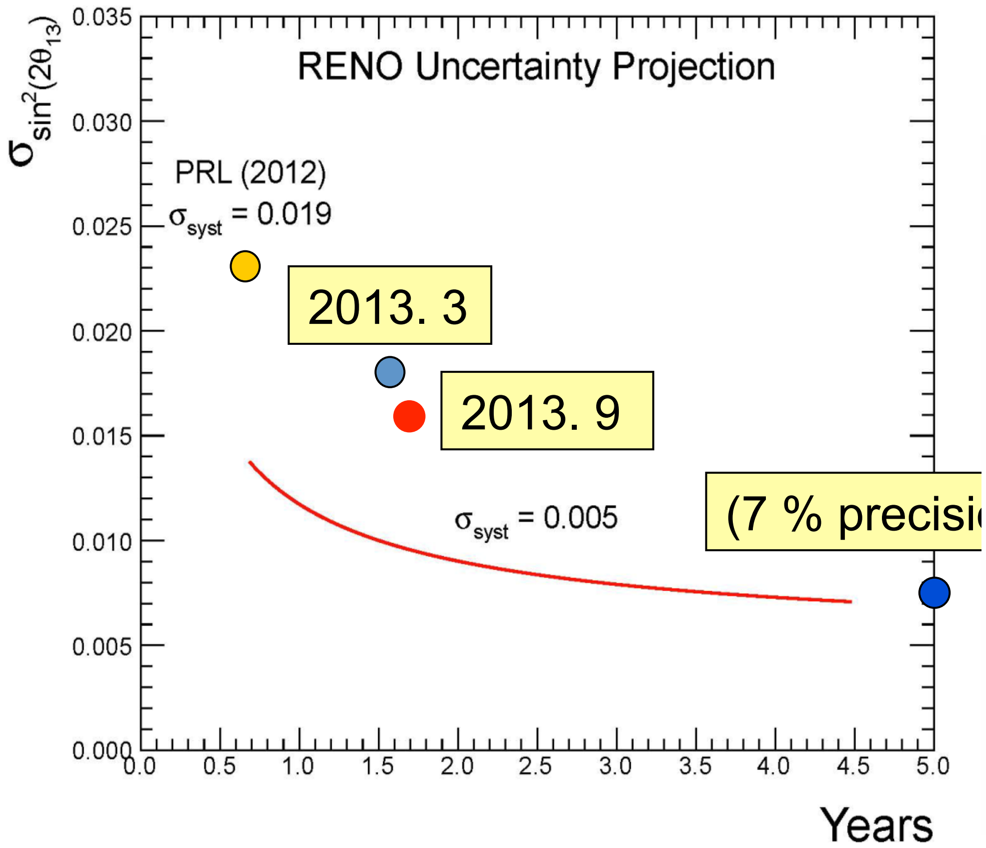
  (~ 7 % reduction)
- Consistent with neutrino oscillation in the spectral distortion

$$\sin^2 2\theta_{13} = 0.100 \pm 0.010(stat.) \pm 0.012(syst.)$$

Goal for θ_{13}

RENO

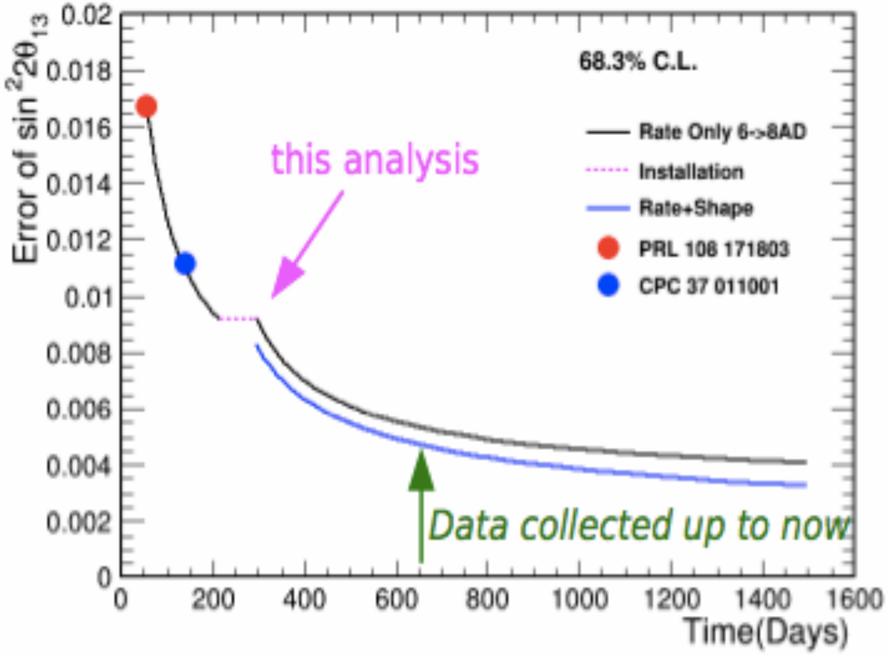
- 5 years of data : 7 %
  - **- stat. error : ±0.010 → ±0.005**
  - **- sys. error : ±0.012 → ±0.005**



Daya Bay

- 4 years of data : 4 %

$|\Delta m^2_{ee}|$ final precision <0.1x10^{-3}



Expected (Upcoming) Results from RENO

- $\mathbf{\Delta m^2_{31}}$ directly from reactor neutrinos :
  ← spectral disappearance of reactor antineutrinos

- Precise measurement of reactor antineutrino flux & spectra :
  → study reactor anomaly or sterile neutrinos

- Observation of reactor neutrinos based on neutron capture by Hydrogen

- $\mathbf{\sin^2(2\theta_{13})}$ to 7% accuracy within 3 years :
  → determination of CP phase with accelerator results

Past

Present

Future

θ_{13}

Change gear !

Mass hierarchy

&

Leptonic CP phase angle

Overview of RENO-50

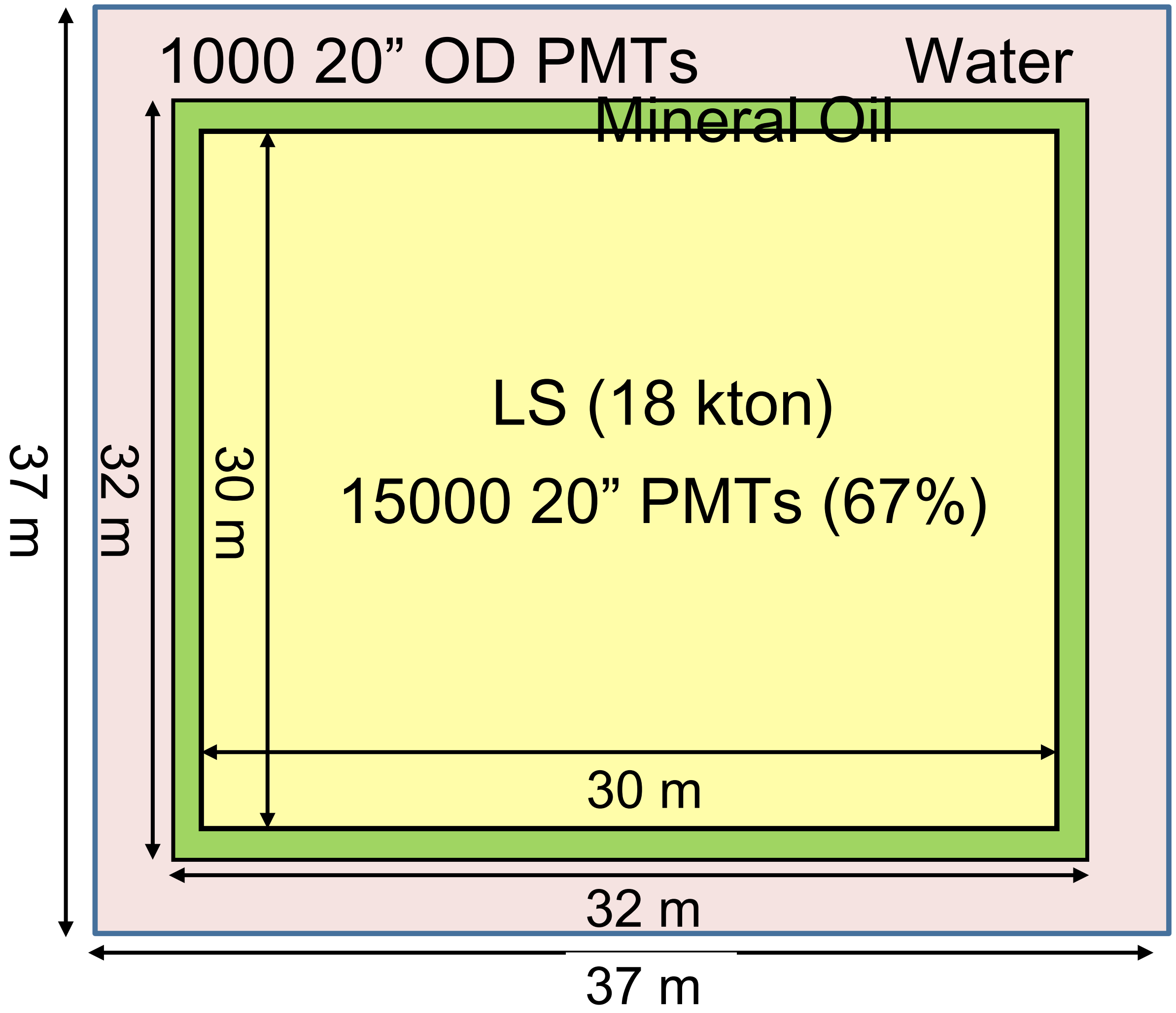
- **RENO-50** : An underground detector consisting of 18 kton ultra-low-radioactivity liquid scintillator & 15,000 20” PMTs, at 50 km away from the Hanbit(Yonggwang) nuclear power plant

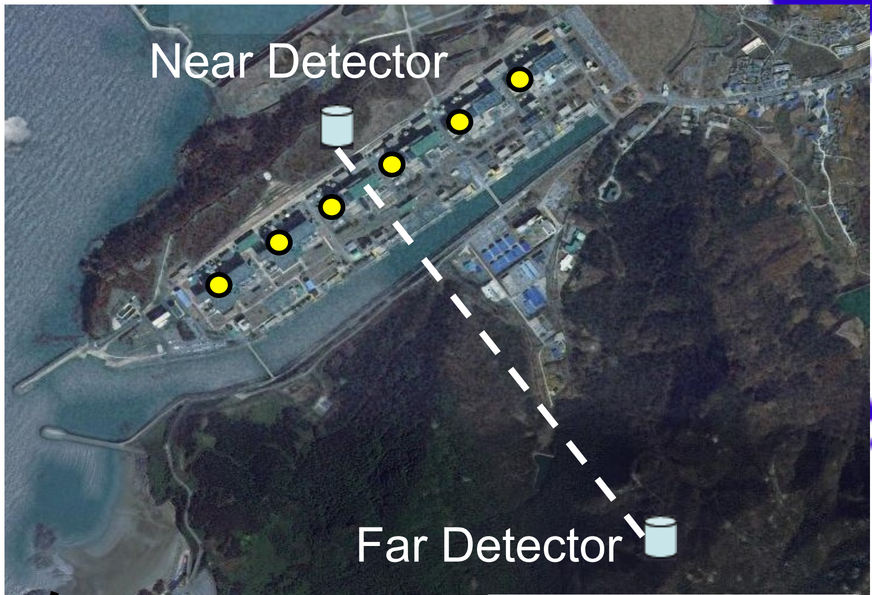
- **Goals** : - High-precision measurement of θ_{12} and Δm^2_{21}
  - Determination of neutrino mass hierarchy
  - Study neutrinos from reactors, (the Sun), the Earth, Supernova, and any possible stellar objects

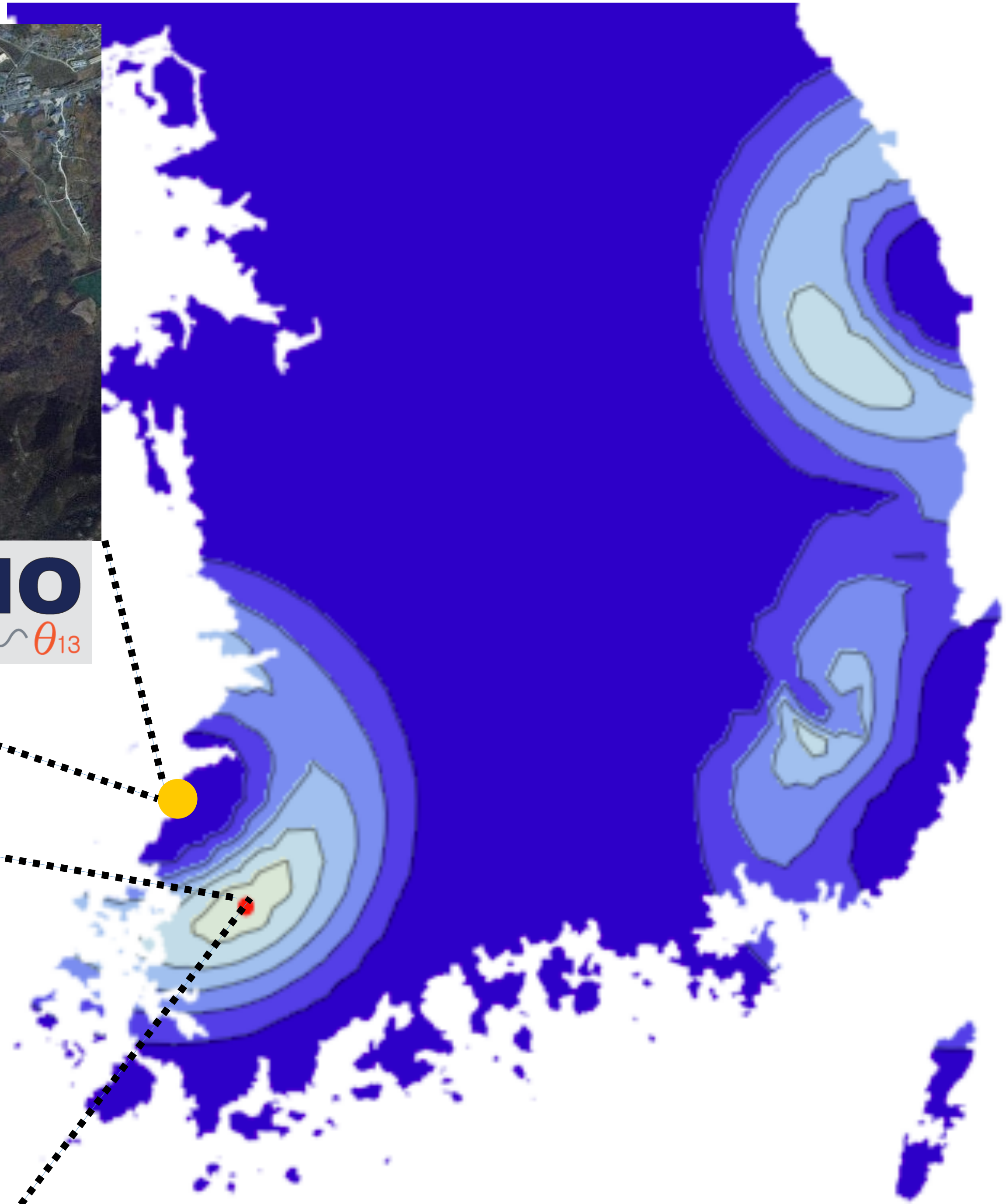
- **Budget** : $ 100M for 6 year construction
(Civil engineering: $ 15M, Detector: $ 85M)

- **Schedule** : 2014 ~ 2019 : Facility and detector construction
  2019 ~ : Operation and experiment

Conceptual Design of RENO-50







RENO-50

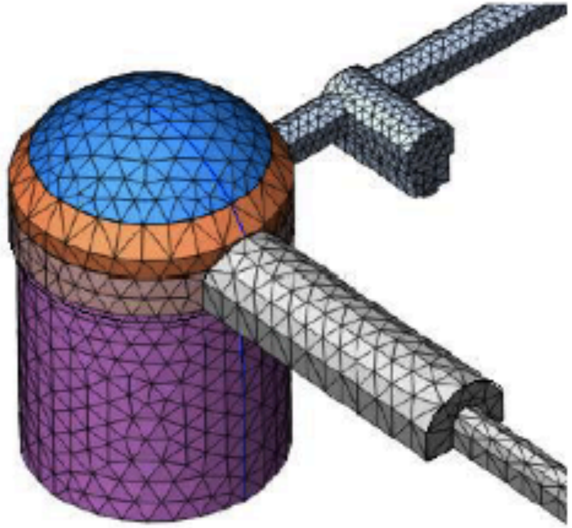
18 kton LS Detector
~47 km from YG reactors

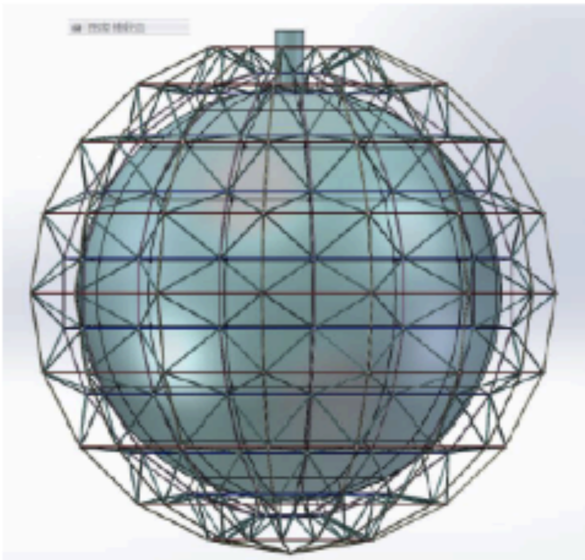
Mt. Guemseong (450 m)
~900 m.w.e. overburden

Overview of JUNO

- Received funding for R&D & conceptual design in China.
- Geotechnical survey ~~will be~~ done ~~by the end of summer~~.
- Detailed civil design underway.
- R&D on
  - prototyping detector
  - LAB-based liquid scintillator
  - photo-detectors
  - readout electronics
- Detector design underway.
- Form collaboration by the end of 2013.
- Begin data taking in 2020.

Luk's talk @Recontre du Vietnam 2013





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

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

✧ Baseline difference should be < 500 m.

Li, Cao, Wang, Zhan: arXiv: 1303.6733

Ciuffoli, Evslin, Zhan: arXiv: 1302.0624

Scientific Potential of JUNO/RENO-50

- Resolve the mass hierarchy
  - ~4 standard-deviation discrimination in 6 years
- Precision determination of neutrino-mixing parameters

	Current fractional precision	JUNO/ RENO-50
$\sin^2 2\theta_{12}$	5%	0.7%
$\sin^2 2\theta_{23}$	5%	NA
$\sin^2 2\theta_{13}$	10%	~15%
Δm^2_{21}	3%	0.6%
Δm^2_{31}	5%	0.6%

- Search for supernova neutrinos
  - ~5000 events for supernovae occur at 8 kpc
- Study geo-neutrinos
  - ~1000 events in a 5-year run

Luk's talk
@Recontre du Vietnam 2013