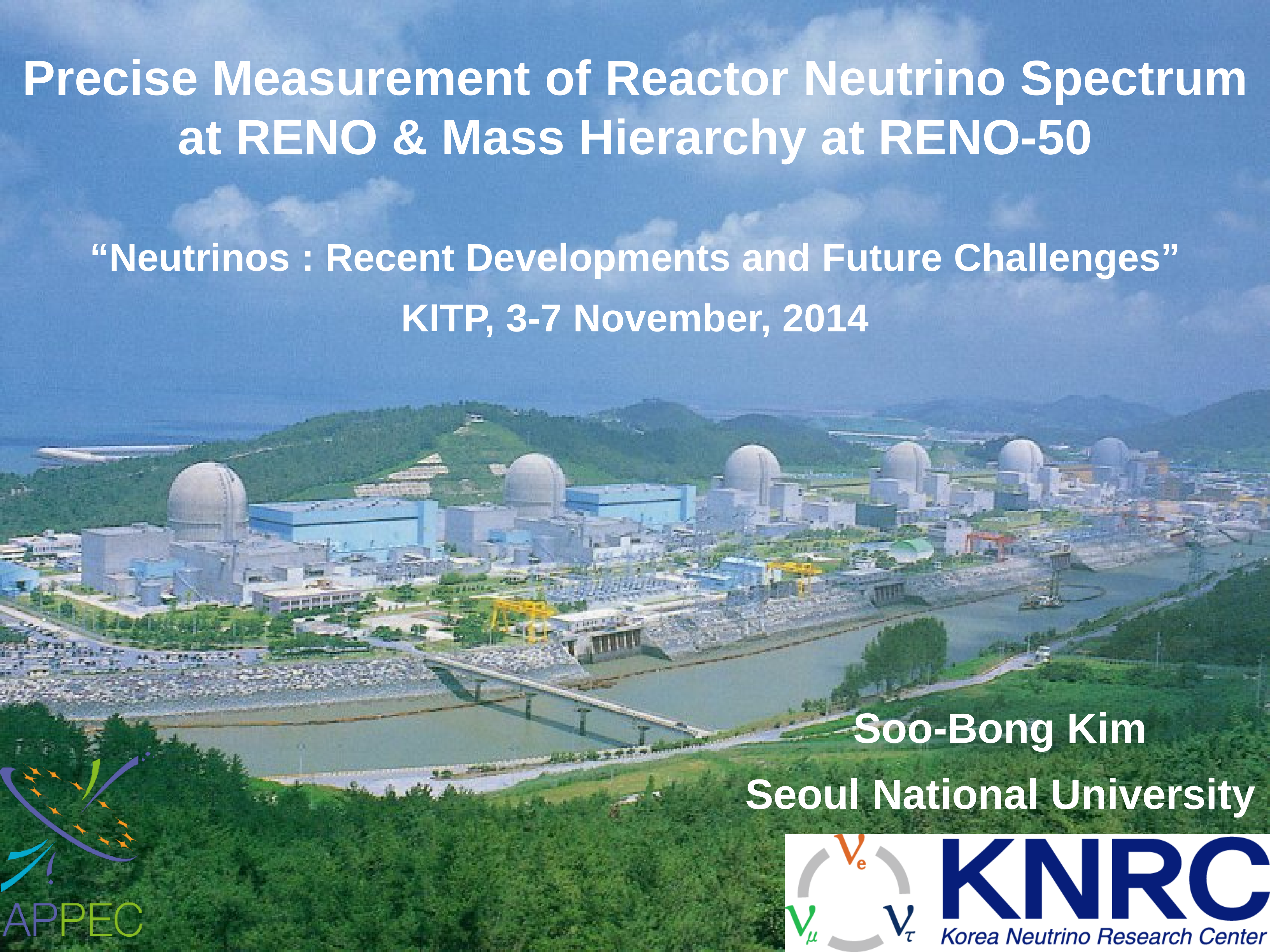


Precise Measurement of Reactor Neutrino Spectrum at RENO & Mass Hierarchy at RENO-50

“Neutrinos : Recent Developments and Future Challenges”

KITP, 3-7 November, 2014

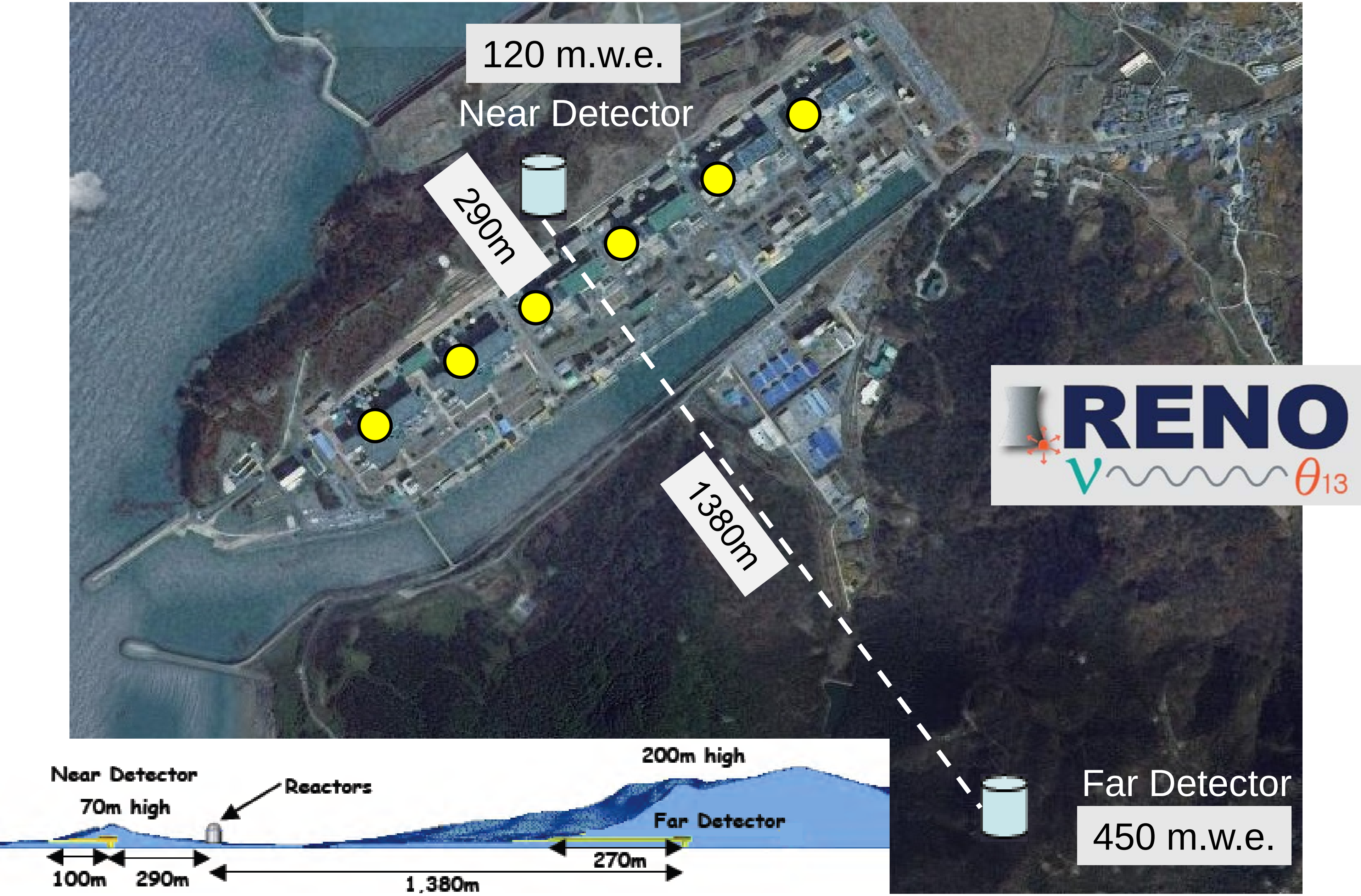
Soo-Bong Kim

Seoul National University

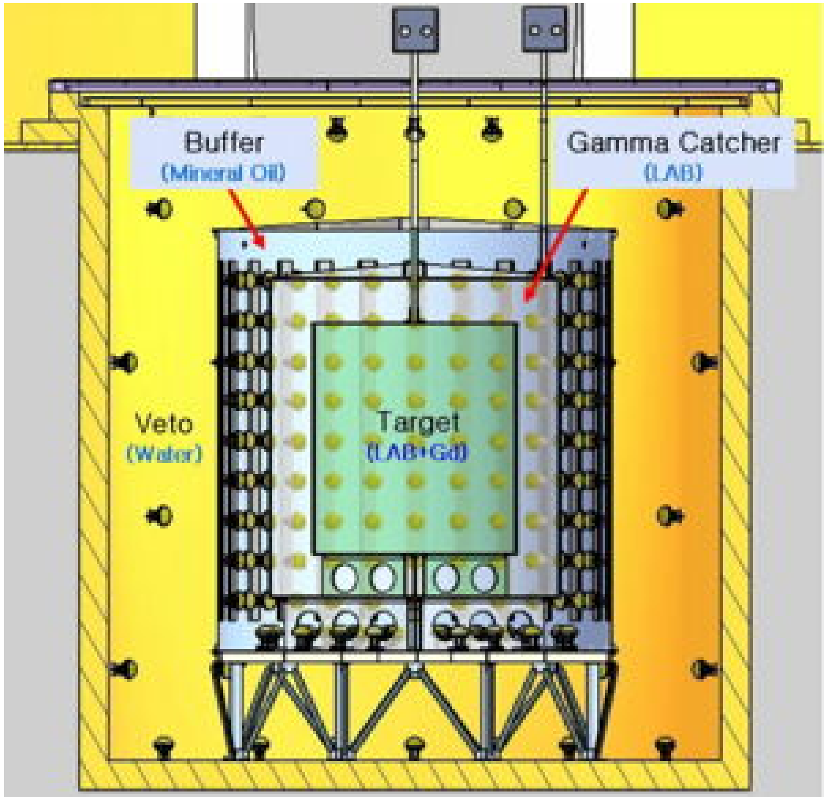
APPEC

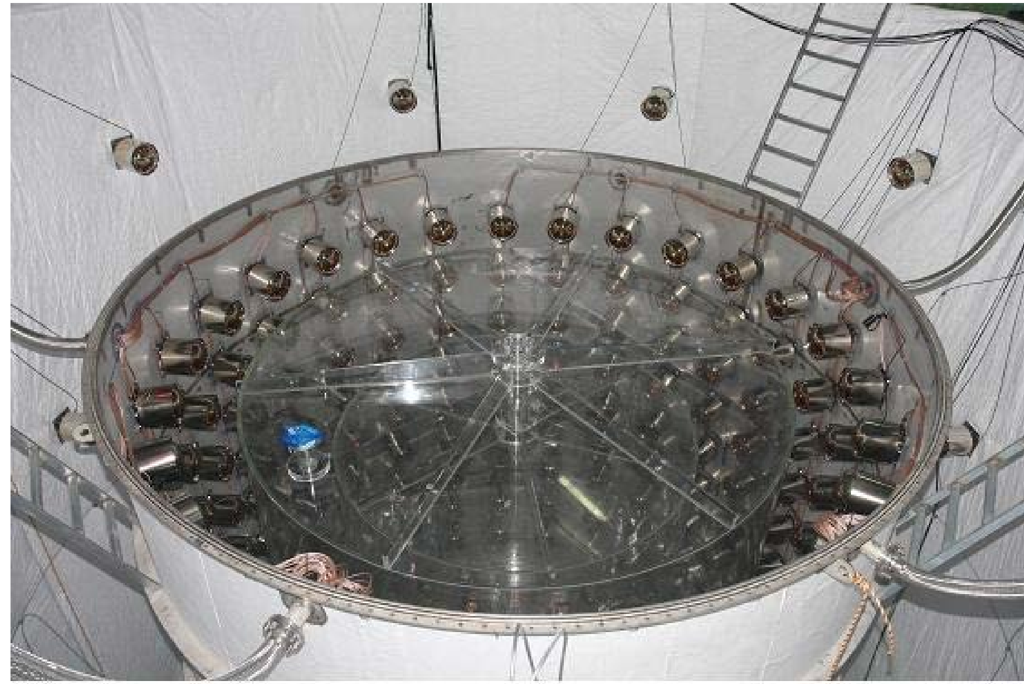
KNRC Korea Neutrino Research Center

RENO Experimental Set-up



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

Recent Results from RENO

- ~800 days of data (11 Aug, 2011~31 Dec, 2013)

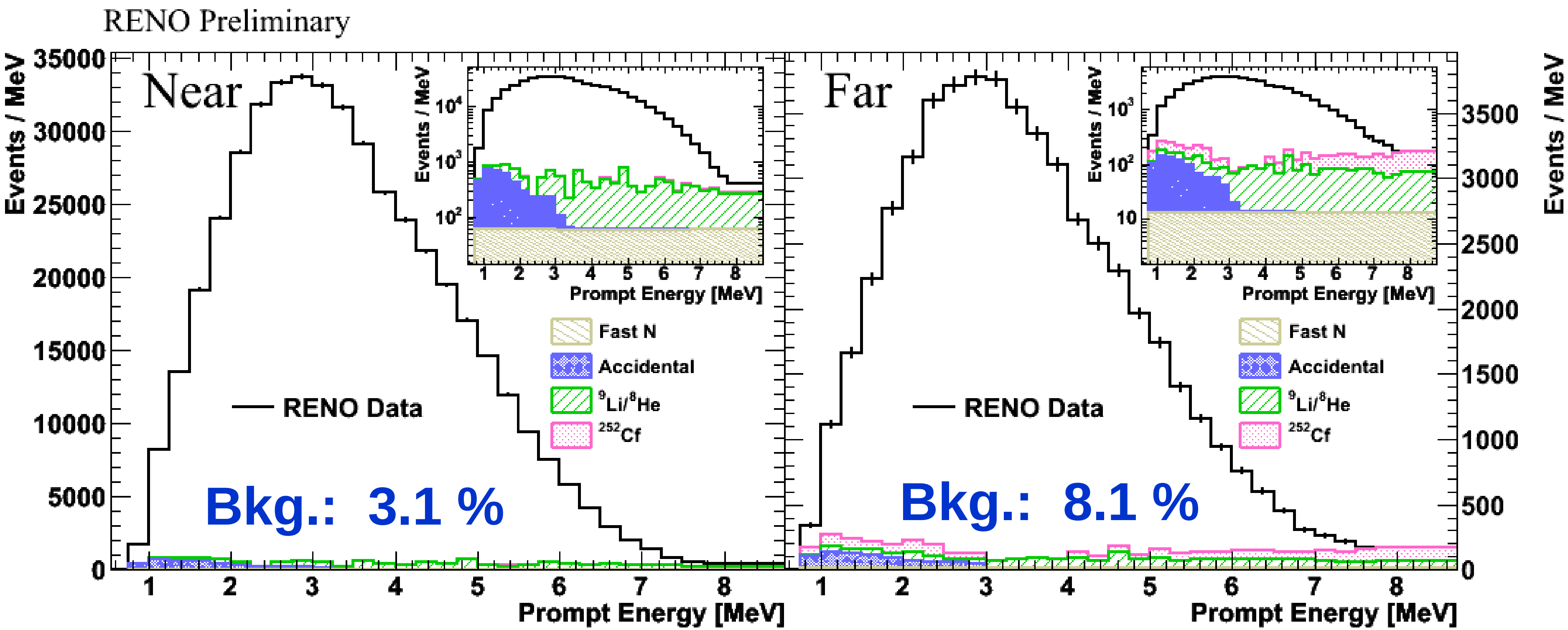
- New measured value of θ_{13} from rate-only analysis
  (Neutrino 2014 ← will be updated with a reduced error)

- Shape analysis in progress [almost ready for publication]

- Observation of a new reactor neutrino component at 5 MeV

- Results of reactor neutrinos with neutron capture on H
  (Significant improvement from Neutrino 2014)

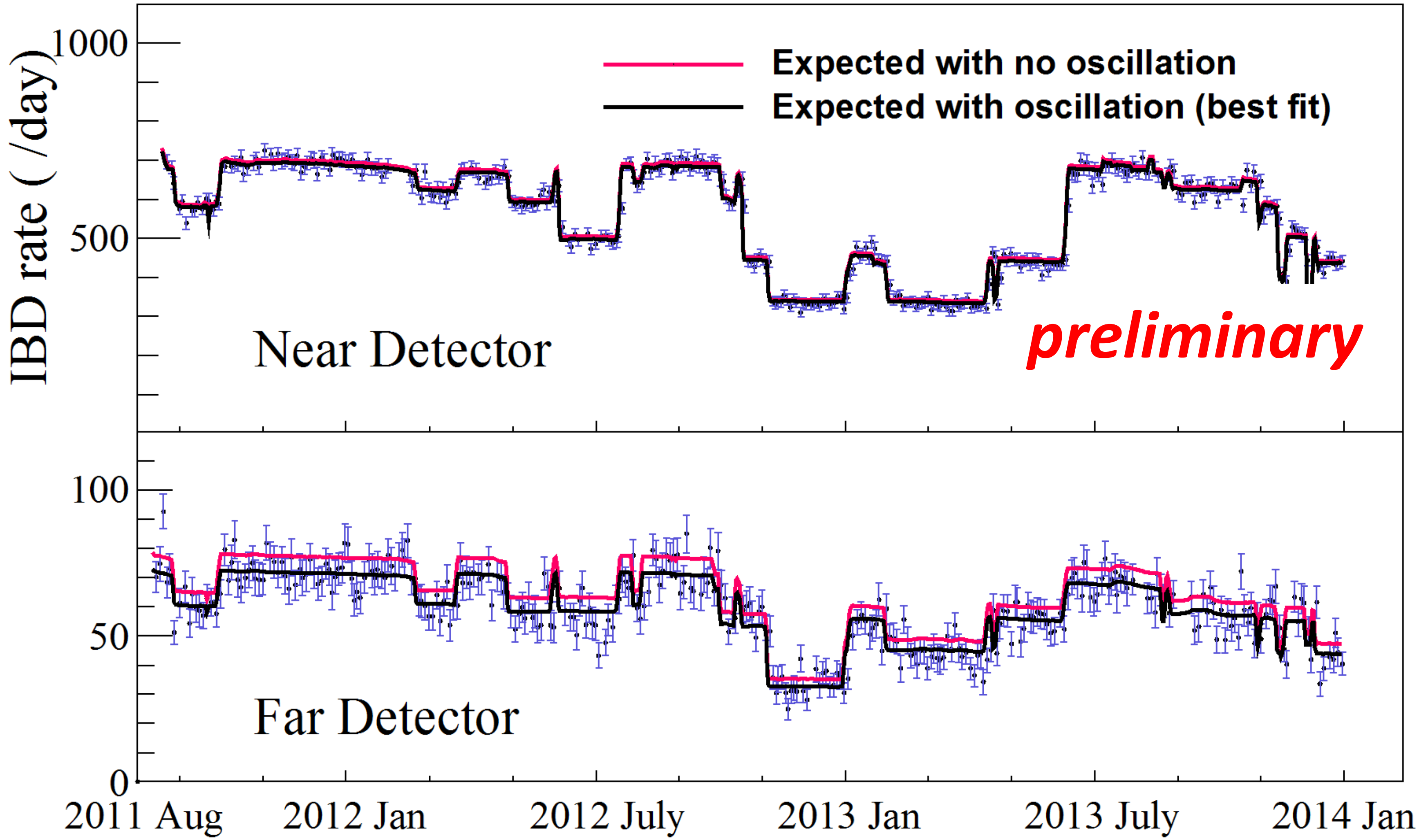
Measured Spectra of IBD Prompt Signal



Near Live time = 761.11 days
# of IBD candidate = 457,176
# of background = 14,165 (3.1 %)

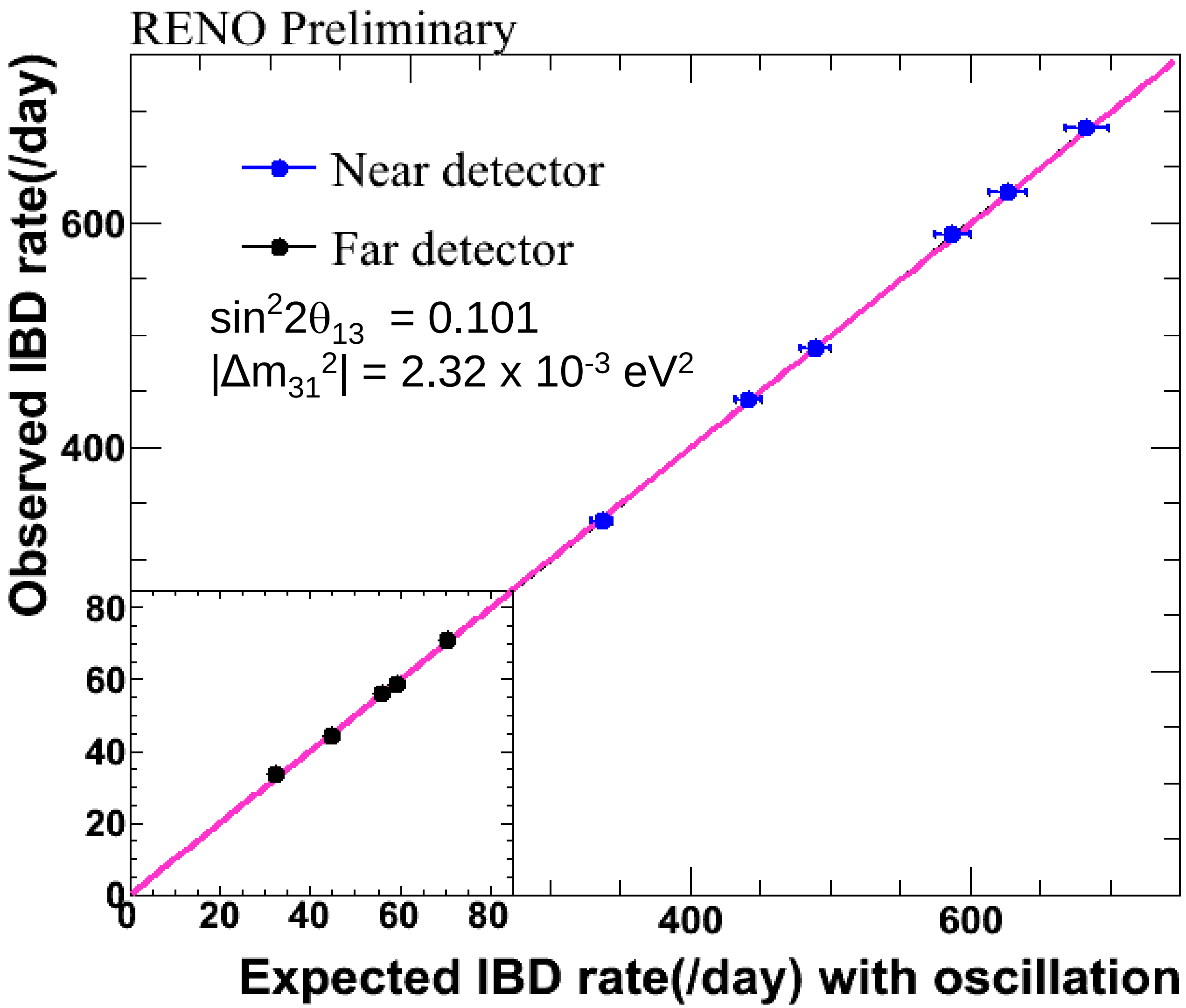
Far Live time = 794.72 days
# of IBD candidate = 53,632
# of background = 4366 (8.1 %)

Observed Daily Averaged IBD Rate



- Good agreement with observed rate and prediction.
- Accurate measurement of thermal power by reactor neutrinos

Observed vs. Expected IBD Rates



- Good agreement between observed rate & prediction
- Indication of correct background subtraction

New θ_{13} Measurement by Rate-only Analysis

(Preliminary)

$$\sin^2 2\theta_{13} = 0.101 \pm 0.008(\text{stat.}) \pm 0.010(\text{syst.})$$

Uncertainties (%)	0.1 0.2 0.3 0.4 0.5 0.6
Statistics (near)	(0.15%)
(far)	(0.43%)
Isotope fraction	(0.28%)
Thermal power	(0.20%)
Detection efficiency	(0.20%)
Backgrounds (near)	(0.21%)
(far)	(0.50%)

$\sin^2 2\theta_{13} = 0.113 \pm 0.023$ 4.9 σ (Neutrino 2012)

$\rightarrow 0.100 \pm 0.016$ 6.3 σ (TAUP/WIN 2013)

$\rightarrow 0.101 \pm 0.013$ 7.8 σ (Neutrino 2014)

Reactor Neutrinos with neutron captures on H

Motivation:

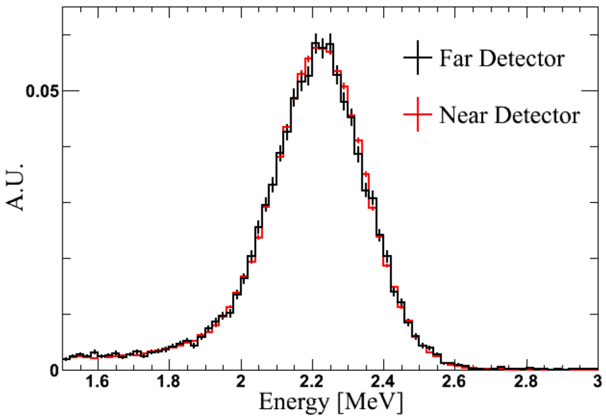
1. Independent measurement of θ_{13} value.
2. Consistency and systematic check on reactor neutrinos.

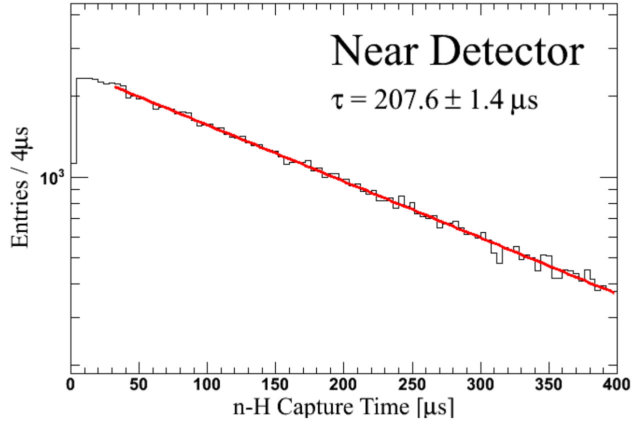
* RENO's low accidental background makes it possible to perform n-H analysis.

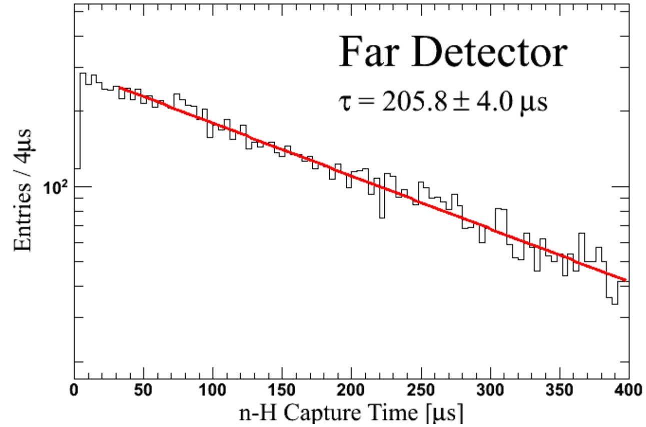
-- low radioactivity PMT
-- successful purification of LS and detector materials.

IBD Sample with n-H

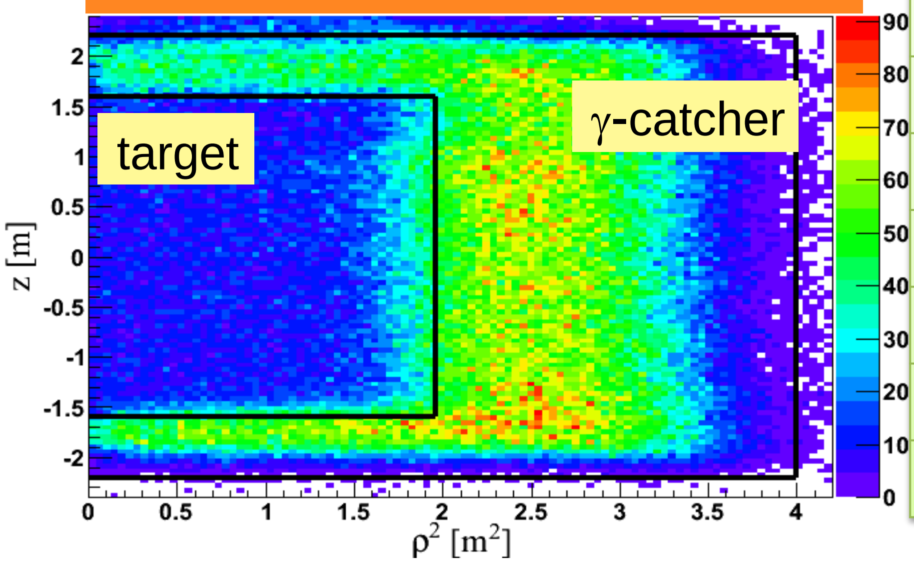
preliminary







n-H IBD Event Vertex Distribution



	Near	Far
Live time(day)	379.663	384.473
IBD Candidate	249,799	54,277
IBD(/day)	619.916	67.823
Accidental (/day)	25.16±0.42	68.90±0.35
Fast Neutron(/day)	5.62±0.30	1.30±0.08
LiHe(/day)	9.87±1.48	3.19±0.37

Results from n-H IBD sample

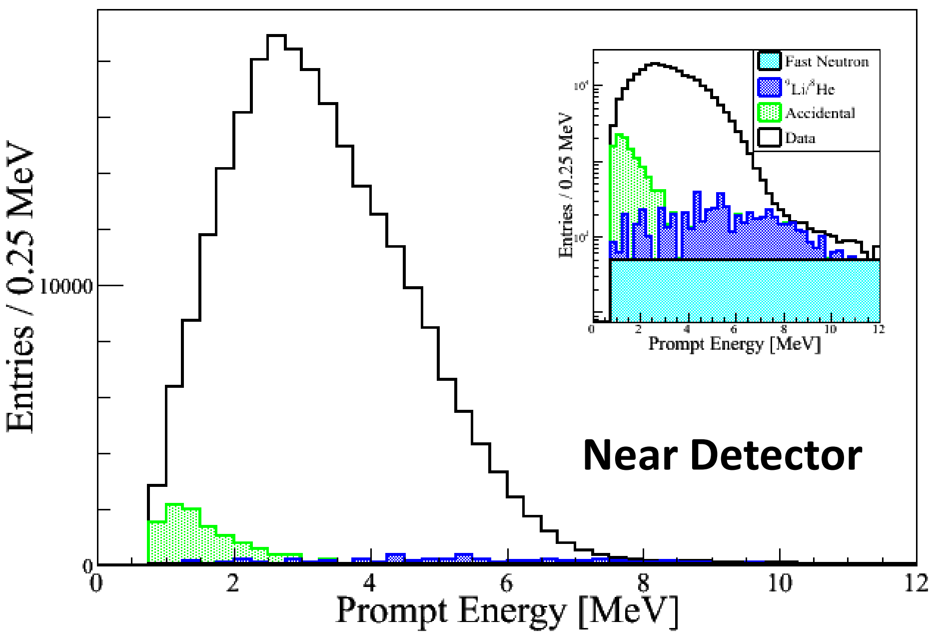
Very preliminary
Rate-only result (~400 days)

$$\sin^2 2\theta_{13} = 0.103 \pm 0.014(\text{stat.}) \pm 0.014(\text{syst.})$$

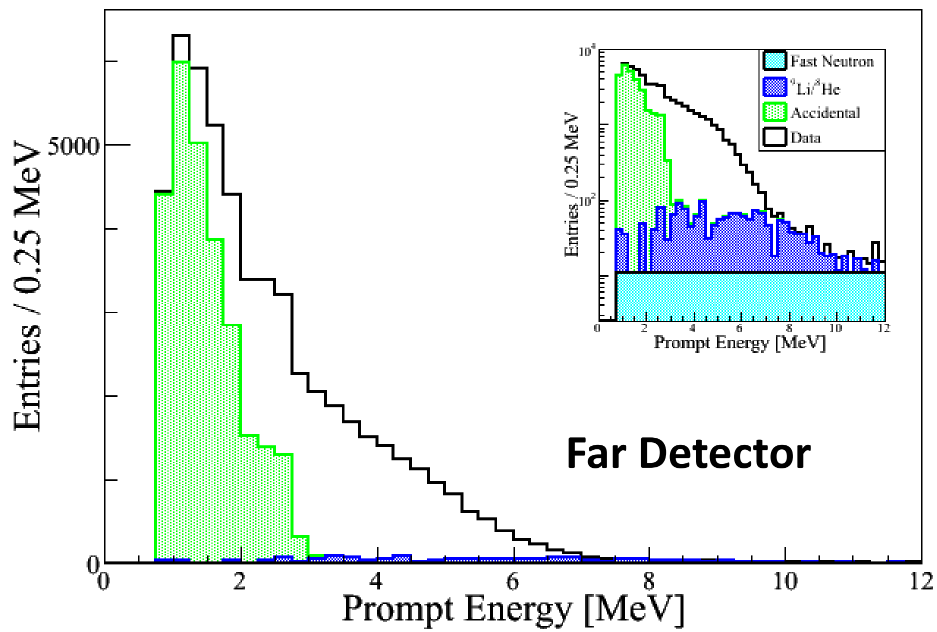
(Neutrino 2014) $\sin^2 2\theta_{13} = 0.095 \pm 0.015(\text{stat.}) \pm 0.025(\text{syst.})$

← *Removed a soft neutron background and reduced the uncertainty of the accidental background*

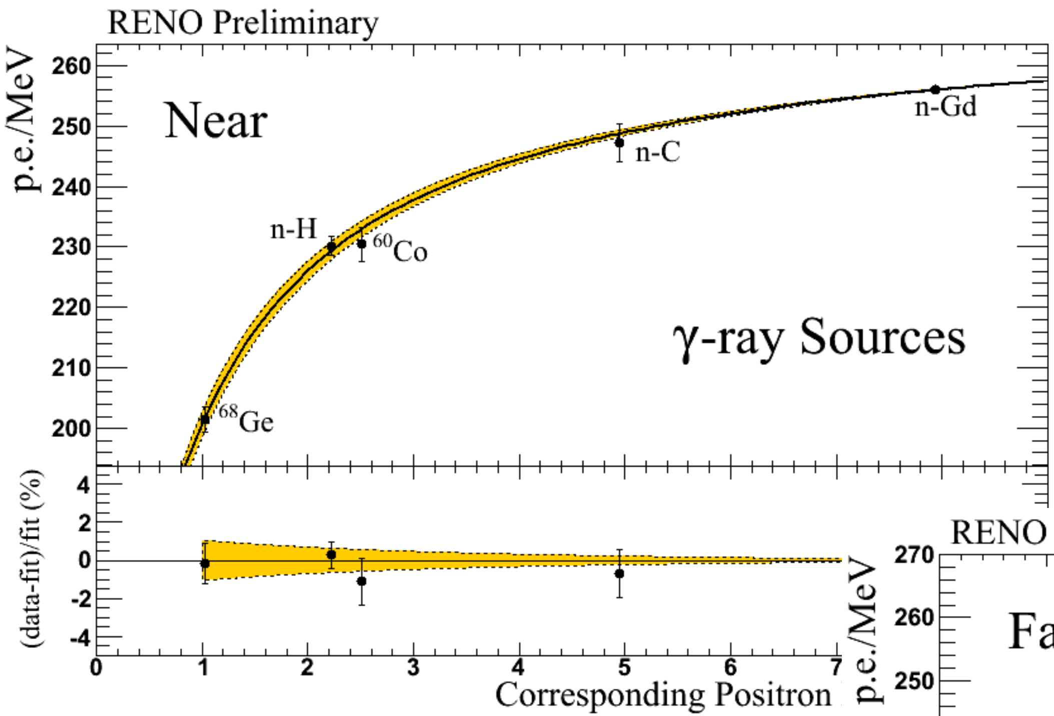
preliminary

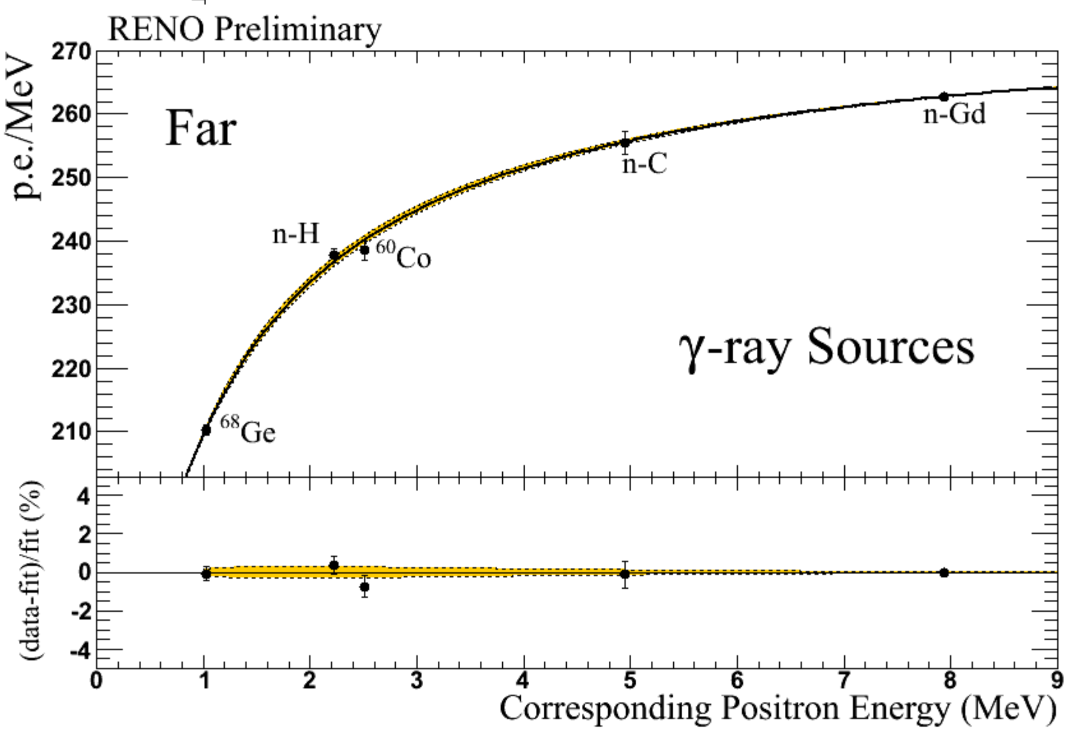


preliminary

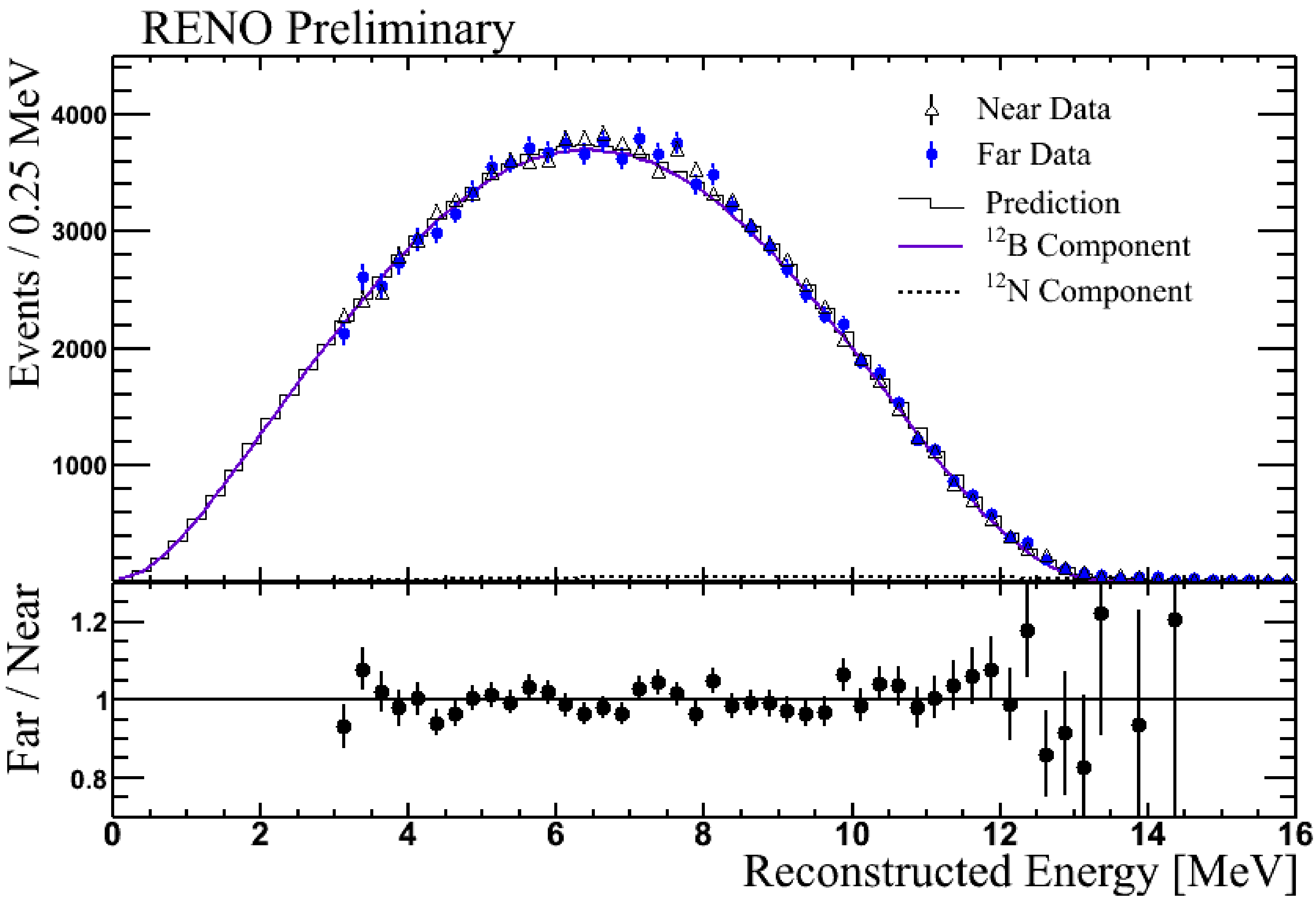


Energy Calibration from γ-ray Sources

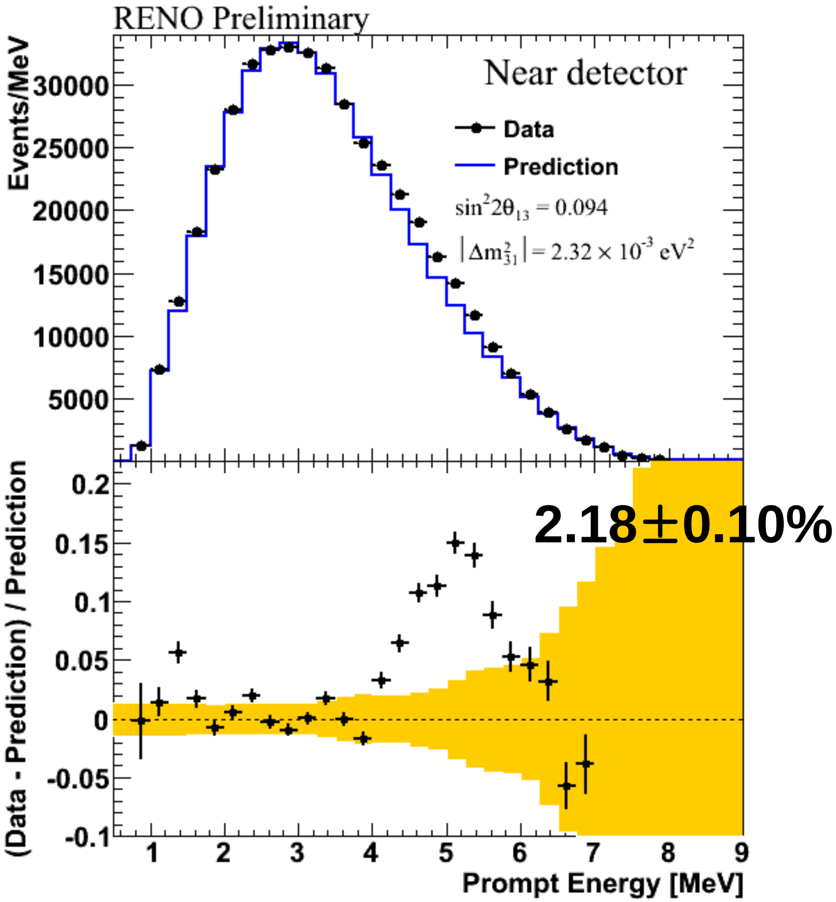


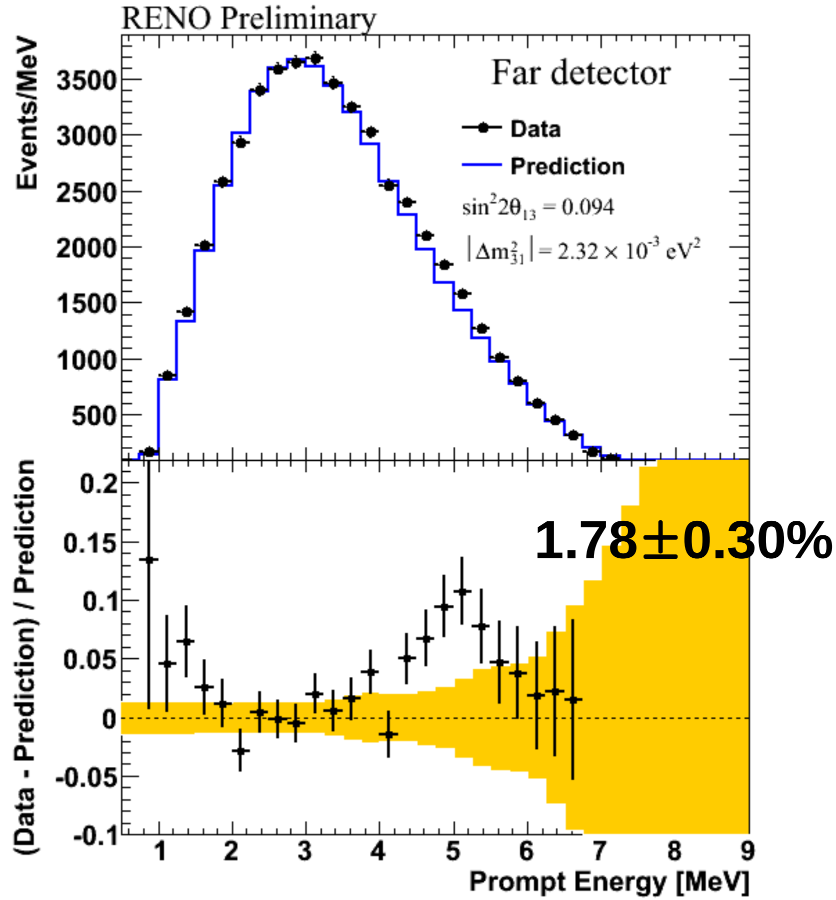


B12 Energy Spectrum (Near & Far)



Observation of a New Reactor Neutrino Component at 5 MeV

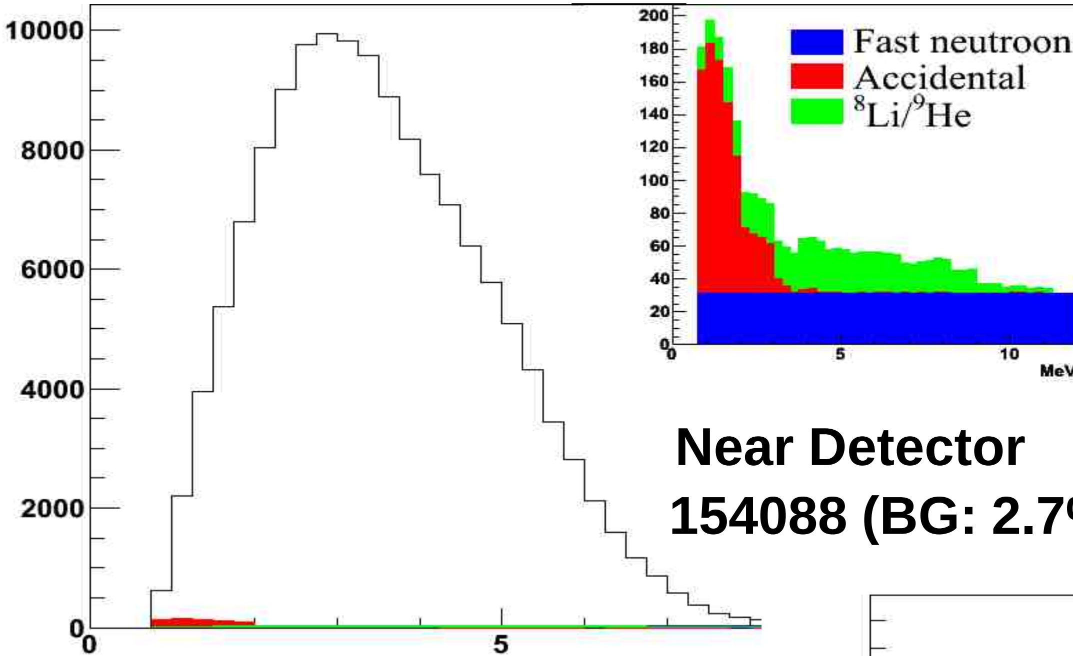




Fraction of 5 MeV excess (%) to expected flux [2011 Huber+Mueller]

- Near : 2.18 ± 0.40 (experimental) ± 0.49 (expected shape error)
- Far : 1.78 ± 0.71 (experimental) ± 0.49 (expected shape error)

Observed Spectra of IBD Prompt Signal



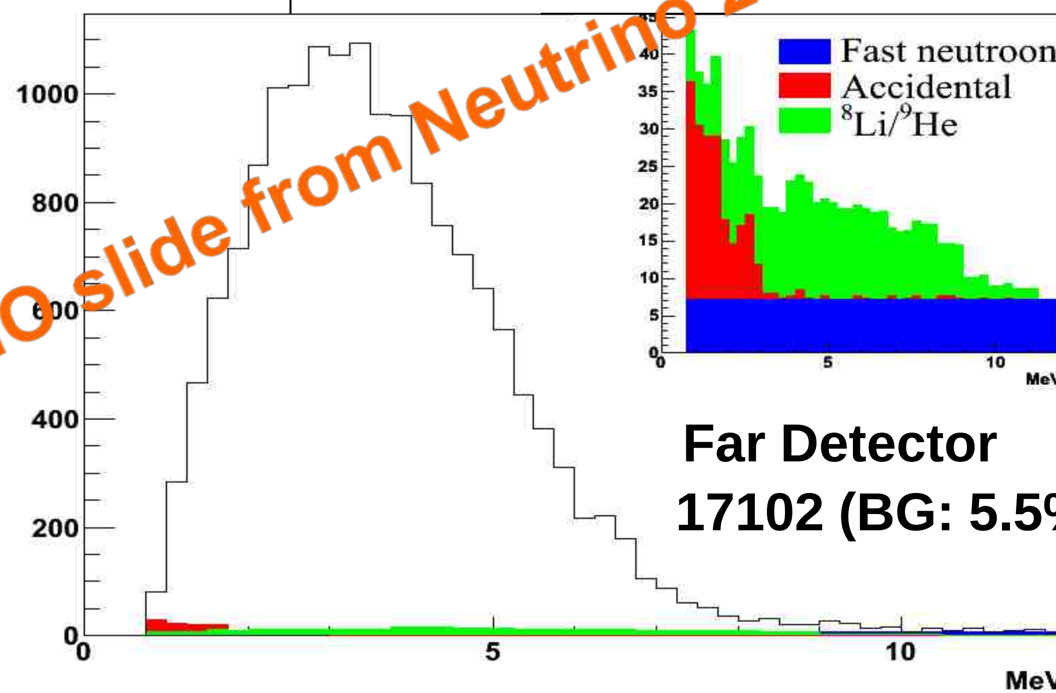
Near Detector
154088 (BG: 2.7%)

▪ 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?

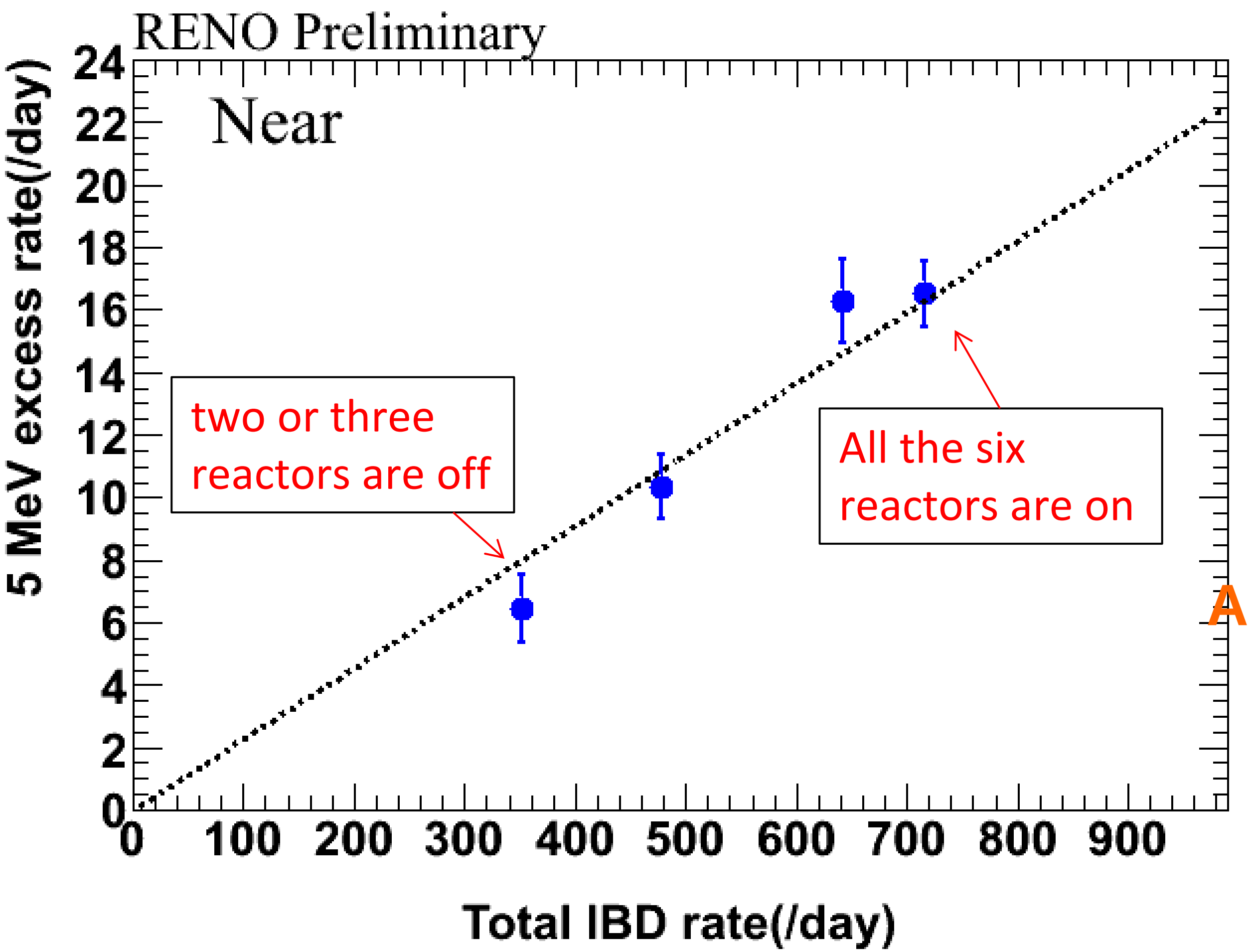
▪ Is the prediction of reactor neutrino spectra correct??



Far Detector
17102 (BG: 5.5%)

RENO slide from Neutrino 2012, Kyoto

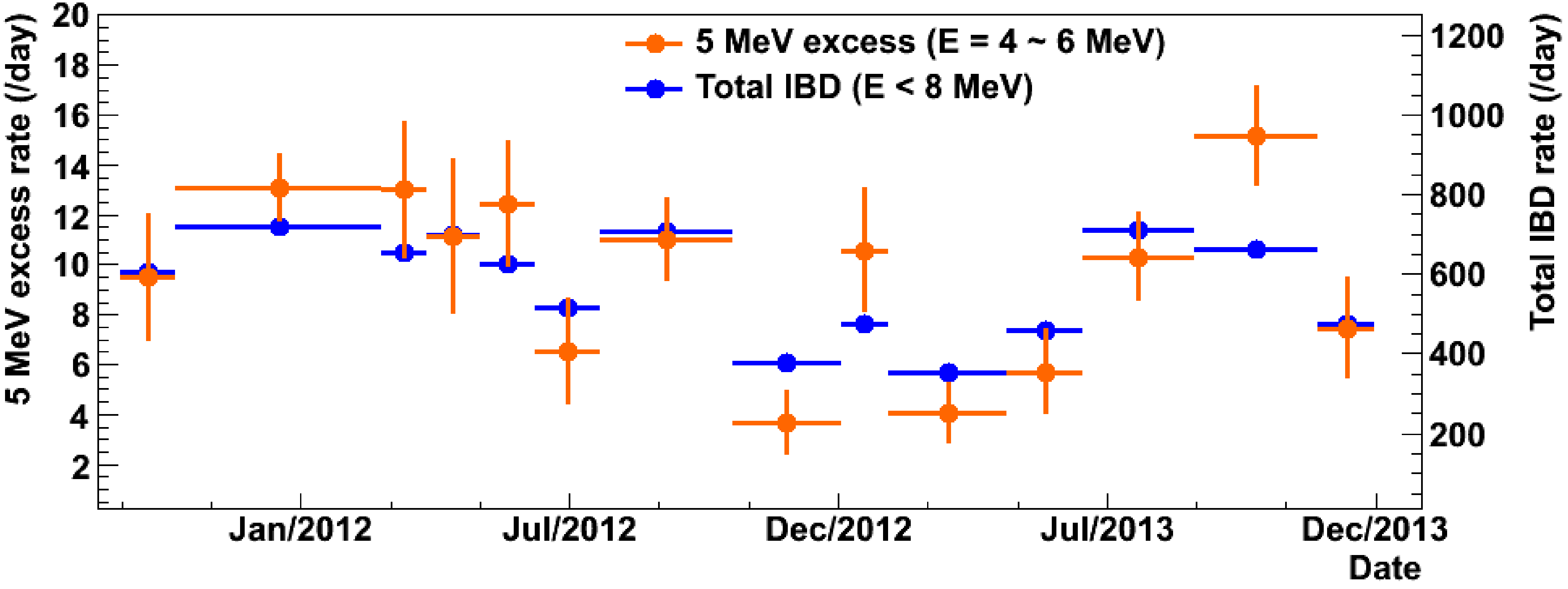
Correlation of 5 MeV Excess with Reactor Power



5 MeV excess has a clear correlation with reactor thermal power !

A new reactor neutrino component !!

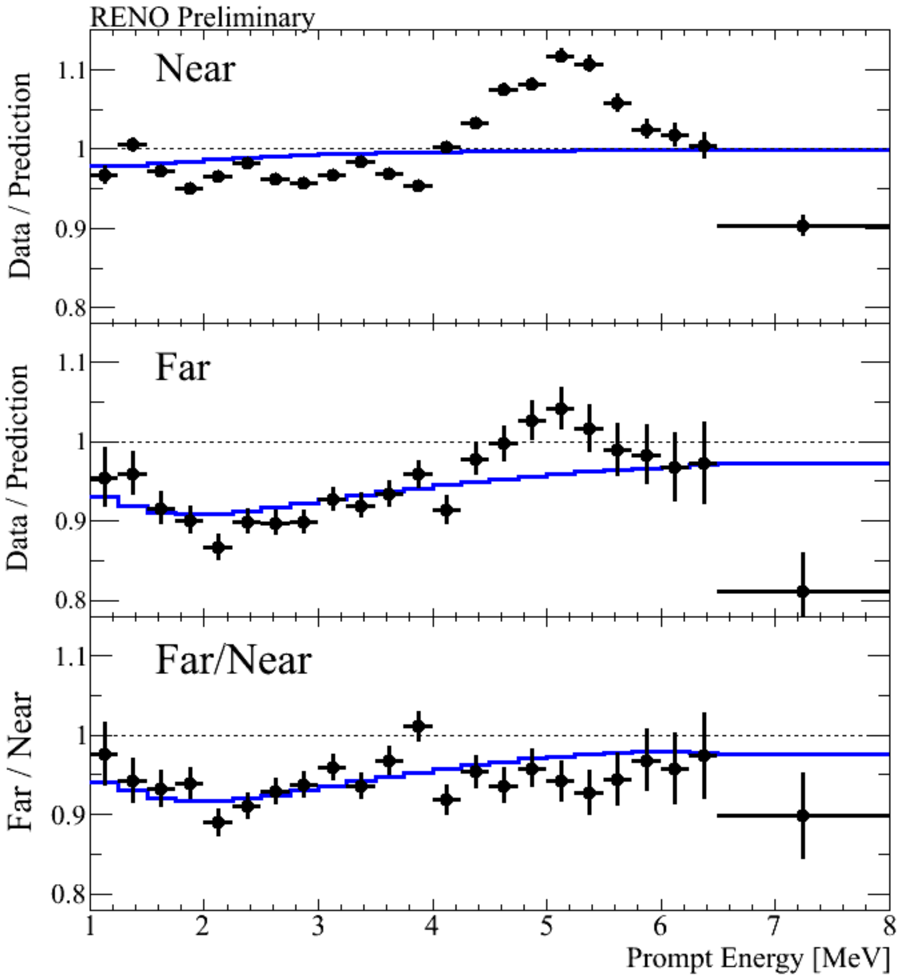
Correlation of 5 MeV Excess with Reactor Power



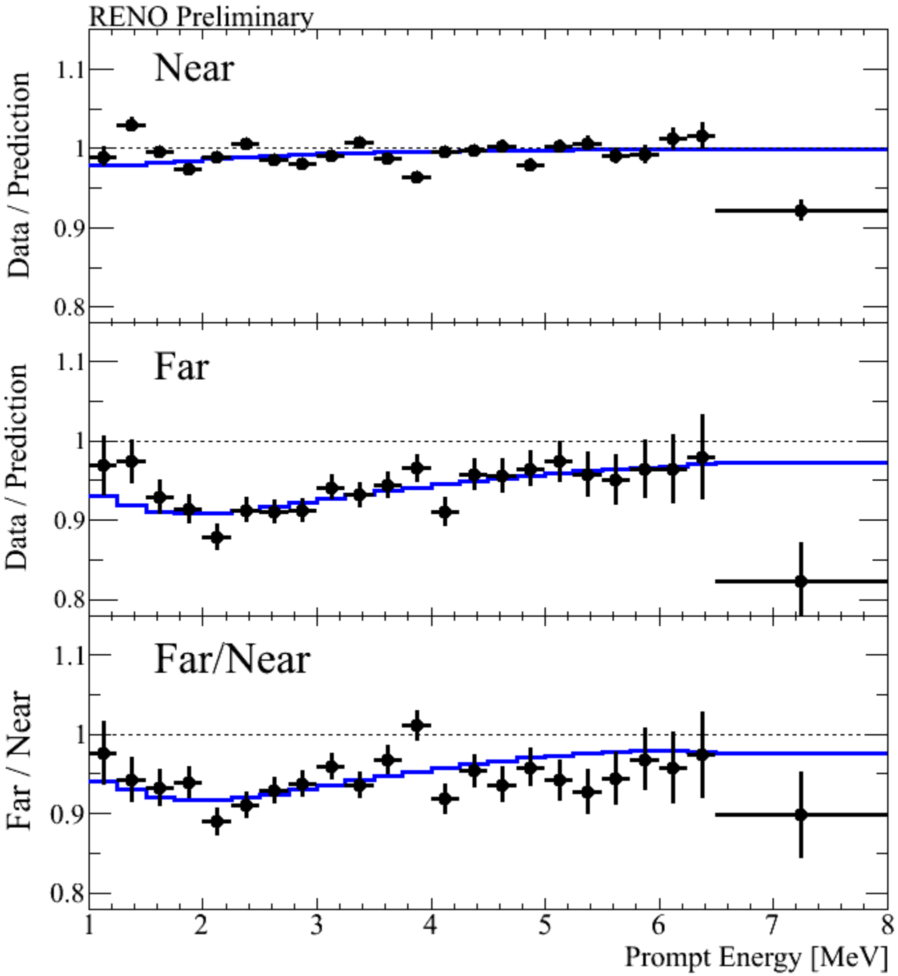
Shape Analysis for Δm_{ee}^2

In progress…. Stay tuned…

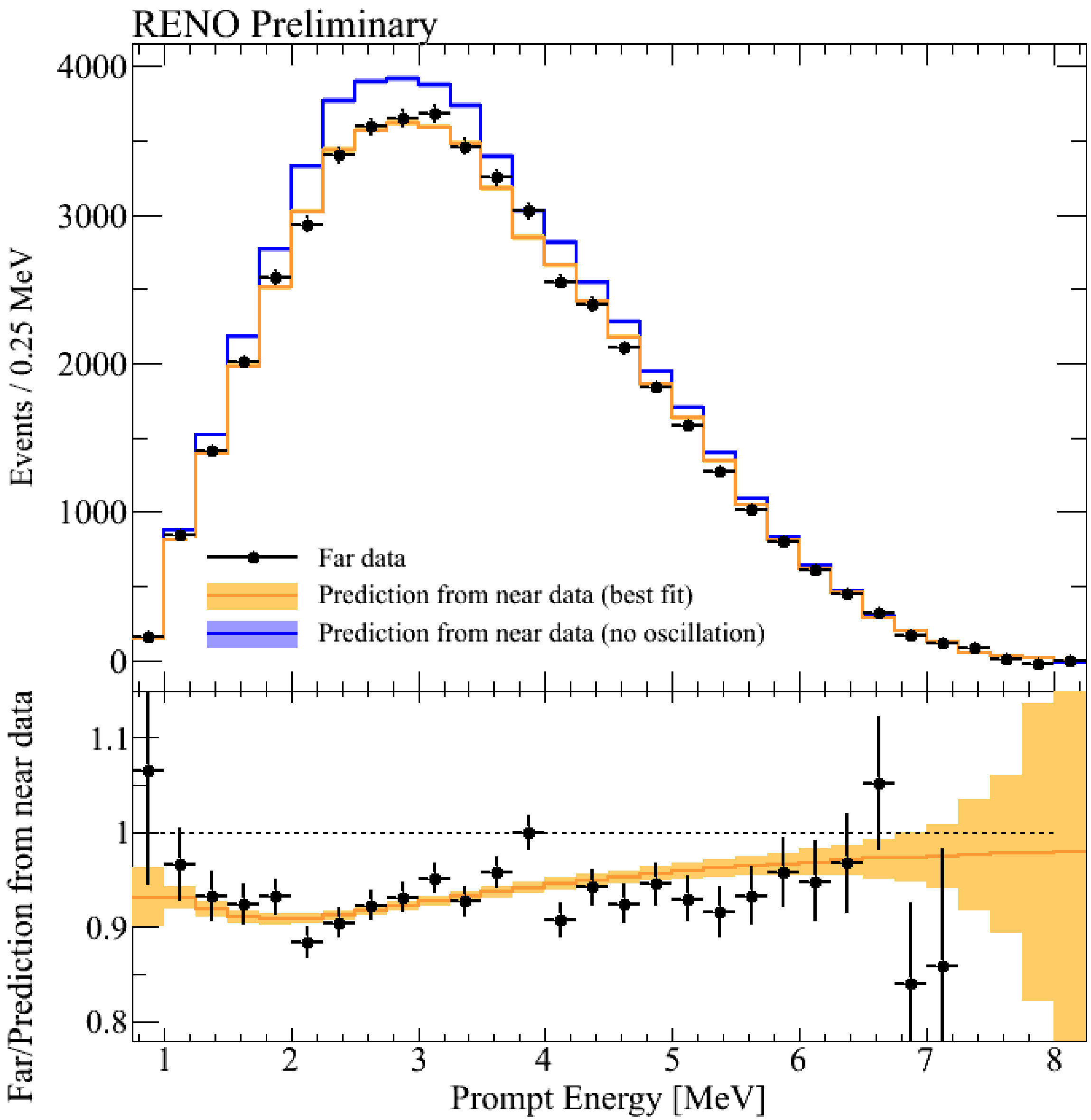
Without 5 MeV excess



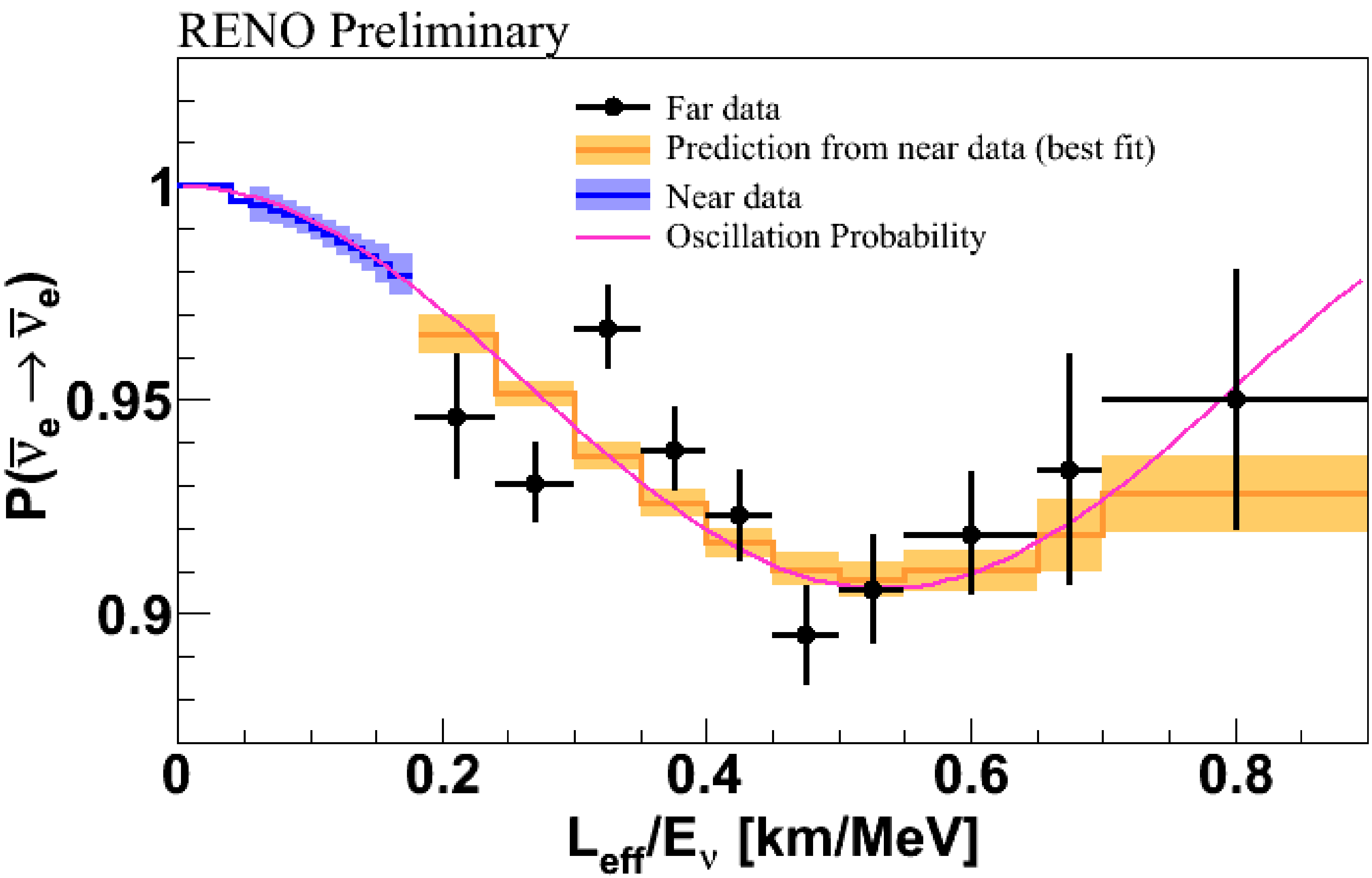
With 5 MeV excess



Far/Near Shape Analysis for Δm_{ee}^2



Reactor Neutrino Disappearance on L/E

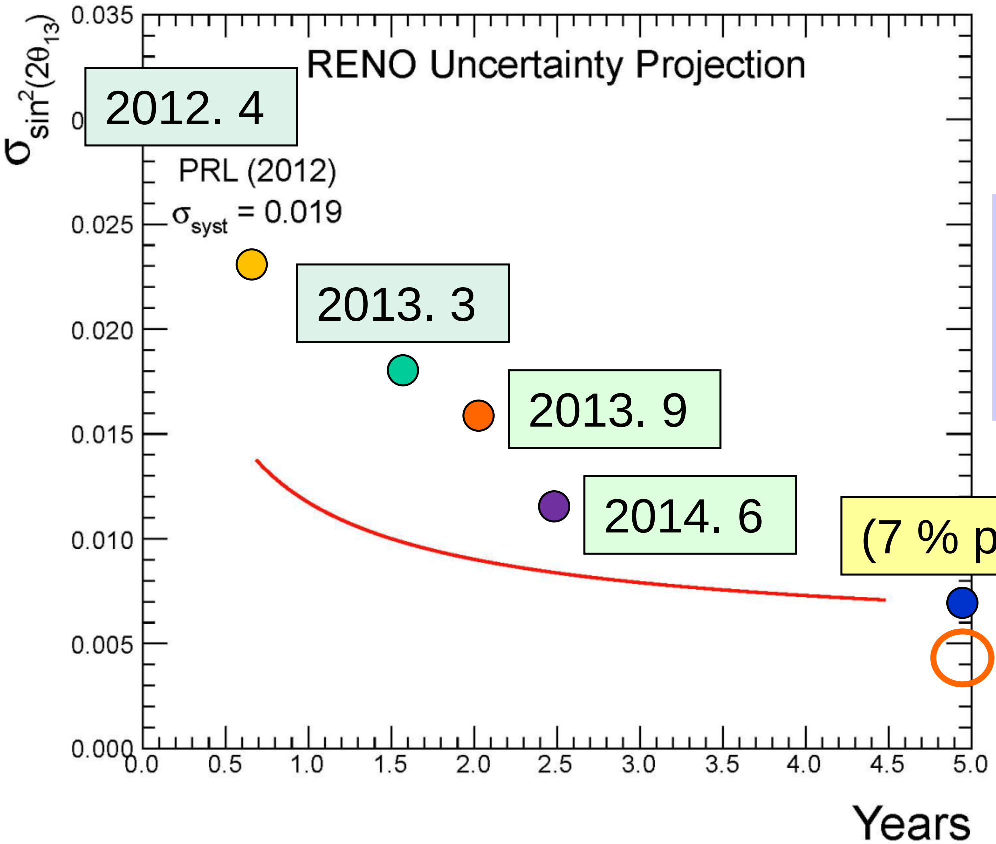


RENO's Projected Sensitivity of θ_{13}

Neutrino 2014 $\sin^2 2\theta_{13} = 0.101 \pm 0.008(stat.) \pm 0.010(syst.)$

(~800 days) 0.101 ± 0.013 (7.8 σ) → ± 0.007 (14 σ) (in 3 years)

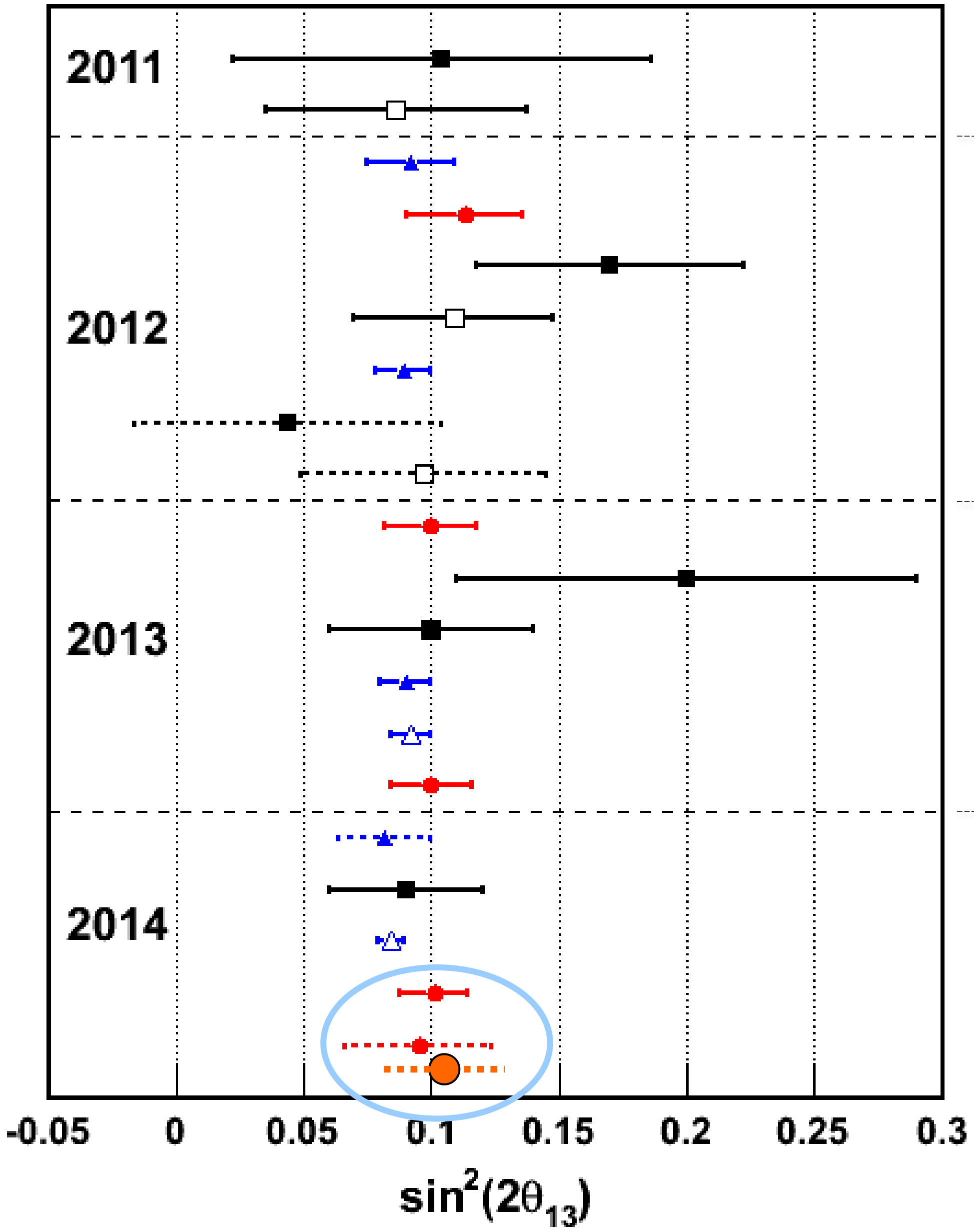
(13 % precision) (7 % precision)



could be possible !!

- 5 years of data : ±7%
  - **- stat. error : ±0.008 → ±0.005**
  - **- syst. error : ±0.010 → ±0.005**

A Brief History of θ_{13} from Reactor Experiments



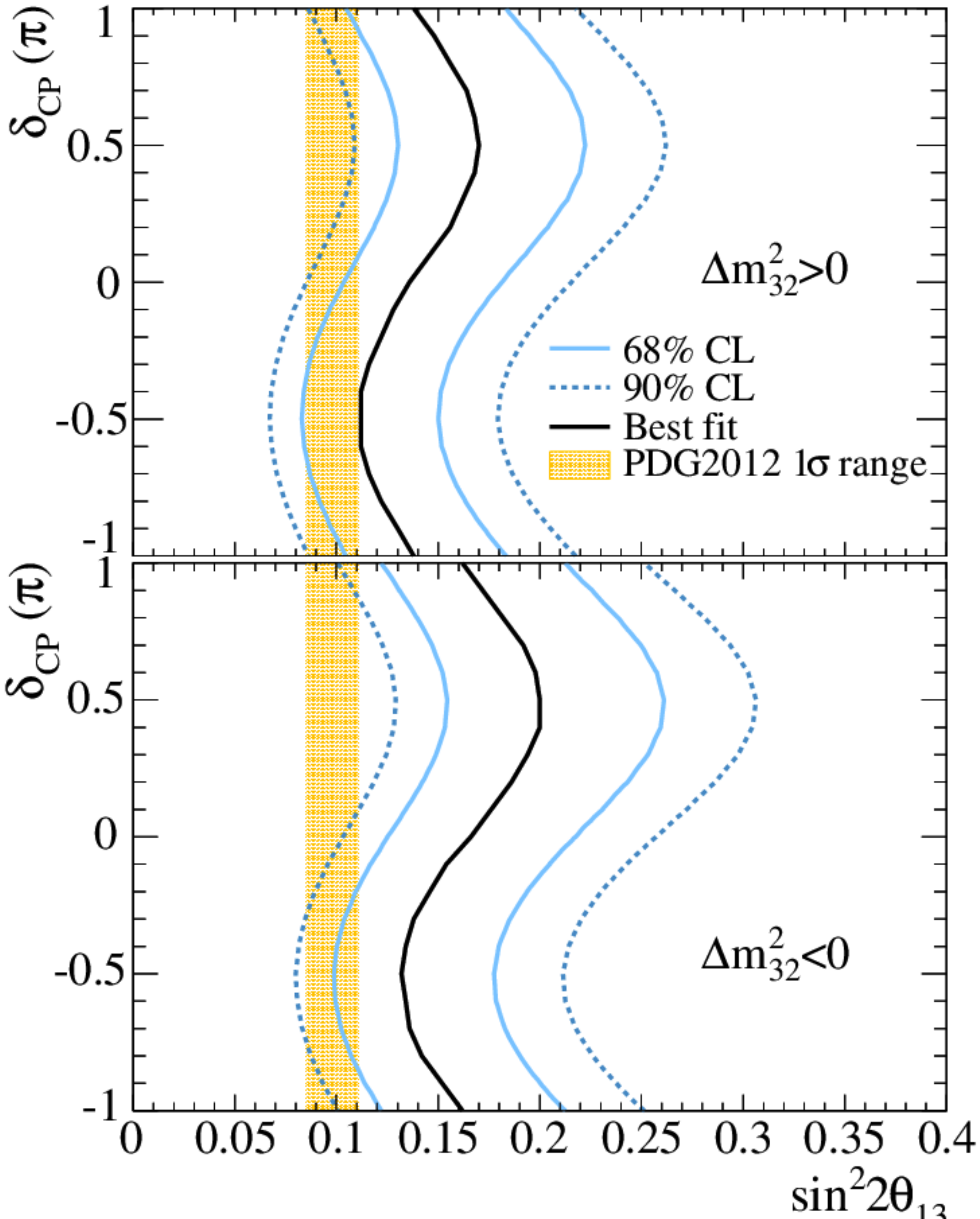
DC: 97 days [1112.6353]
R+S

DB: 49 days [1203.1669]
RENO: 222 days [1204.0626]
DC: 228 days [1207.6632]
R+S
DB: 139 days [1210.6327]
DC: n-H [1301.2948]
R+S

RENO: 403 days [NuTel2013]
DC: RRM analysis [1305.2734]
R+S
DB: 190 days [1310.6732]
R+S
RENO: 403 days [TAUP2013]

DB: 190 days n-H [Moriond2014]
DC: 469 days [ν 2014]
DB: 563 days [ν 2014]
RENO: 795 days [ν 2014]
384 days n-H [ν 2014]
RENO 384 days n-H [NOW 2014]

θ_{13} from Reactor and Accelerator Experiments



First hint of δ_{CP} combining Reactor and Accelerator data

Best overlap is for
Normal hierarchy & δ_{CP} = - π/2

Is Nature very kind to us?
Are we very lucky?
Is CP violated maximally?

Strong motivation for anti-neutrino runs and precise measurements of θ_{13}

Courtesy C. Walter (T2K Collaboration)
Talk at Neutrino 2014

Summary

- We observed a new reactor component at 5 MeV. (3.6 σ)

- New measurement of θ_{13} by rate-only analysis (to be further improved soon)

$$\sin^2 2\theta_{13} = 0.101 \pm 0.008(\text{stat}) \pm 0.010(\text{syst})$$ (preliminary)

- Shape analysis for Δm^2 in progress…(almost ready for publication)

- Improved result on n-H IBD analysis (to be further improved)

$$\sin^2 2\theta_{13} = 0.103 \pm 0.014(\text{stat}) \pm 0.014(\text{syst})$$ (very preliminary)

- $\sin^2(2\theta_{13})$ to 7% accuracy within 3 years
→ will provide the first glimpse of $\delta_{CP.}$
If accelerator results are combined.

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}, Δm^2_{21} and Δm^2_{31}
  - 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** : 2015 ~ 2020 : Facility and detector construction
  2021 ~ : Operation and experiment

Reactor Neutrino Oscillations

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{ee} \frac{L}{4E}\right) - \sin^2 2\theta_{12} \cos^4 2\theta_{13} \sin^2\left(\Delta m^2_{21} \frac{L}{4E}\right)$$

Short Baseline

Long Baseline

$$\sin^2\left(\Delta m^2_{ee} \frac{L}{4E}\right) \equiv \cos^2\theta_{12} \sin^2\left(\Delta m^2_{31} \frac{L}{4E}\right) + \sin^2\theta_{12} \sin^2\left(\Delta m^2_{32} \frac{L}{4E}\right)$$

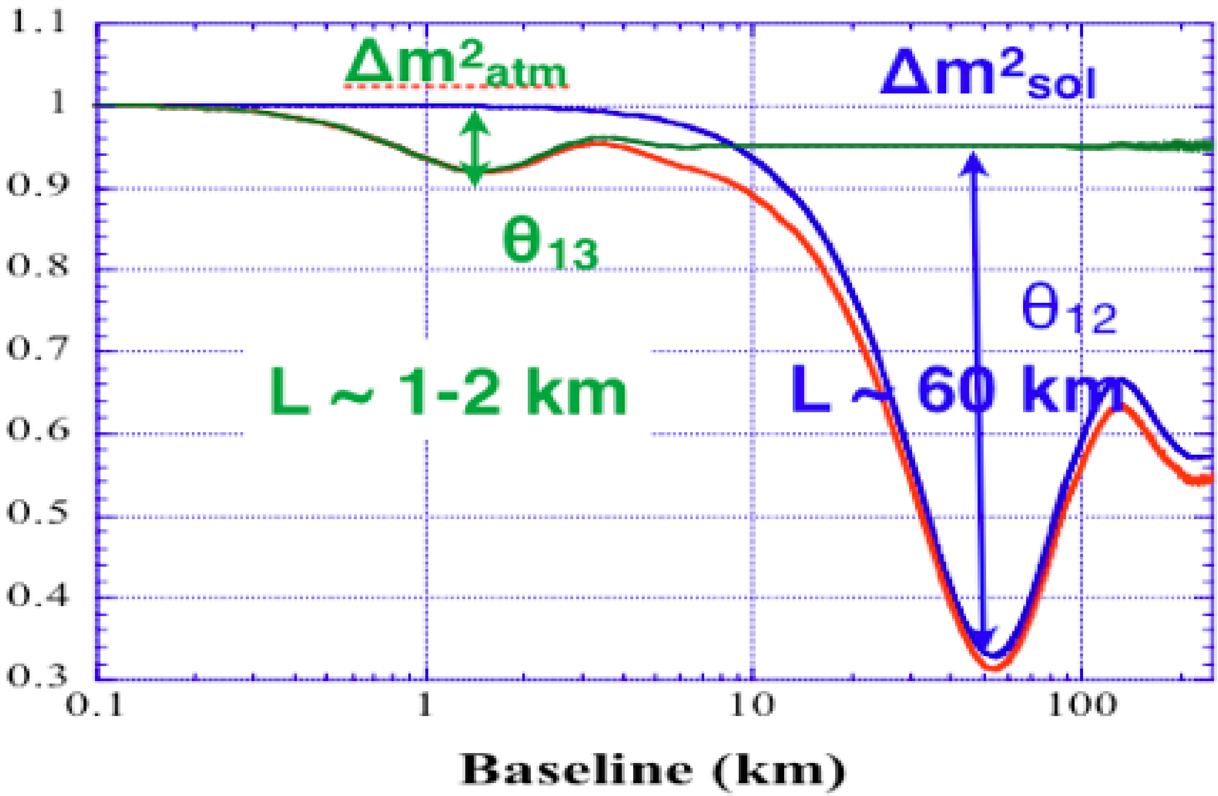
$$|\Delta m^2_{ee}| \simeq |\Delta m^2_{32}| \pm 5.21 \times 10^{-5} \text{eV}^2$$

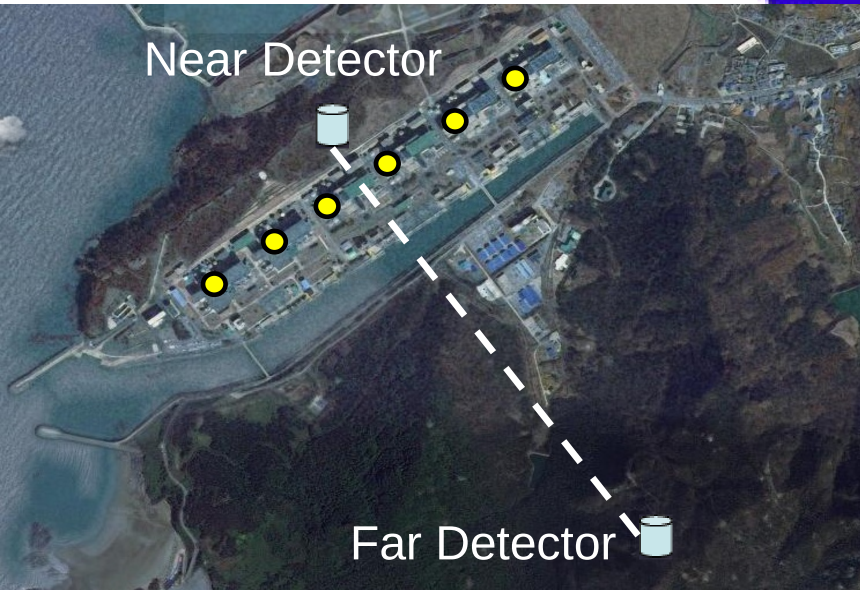
$\cos^2\theta_{12}|\Delta m^2_{21}|$

+: Normal Hierarchy

−: Inverted Hierarchy

[Nunokawa & Parke (2005)]

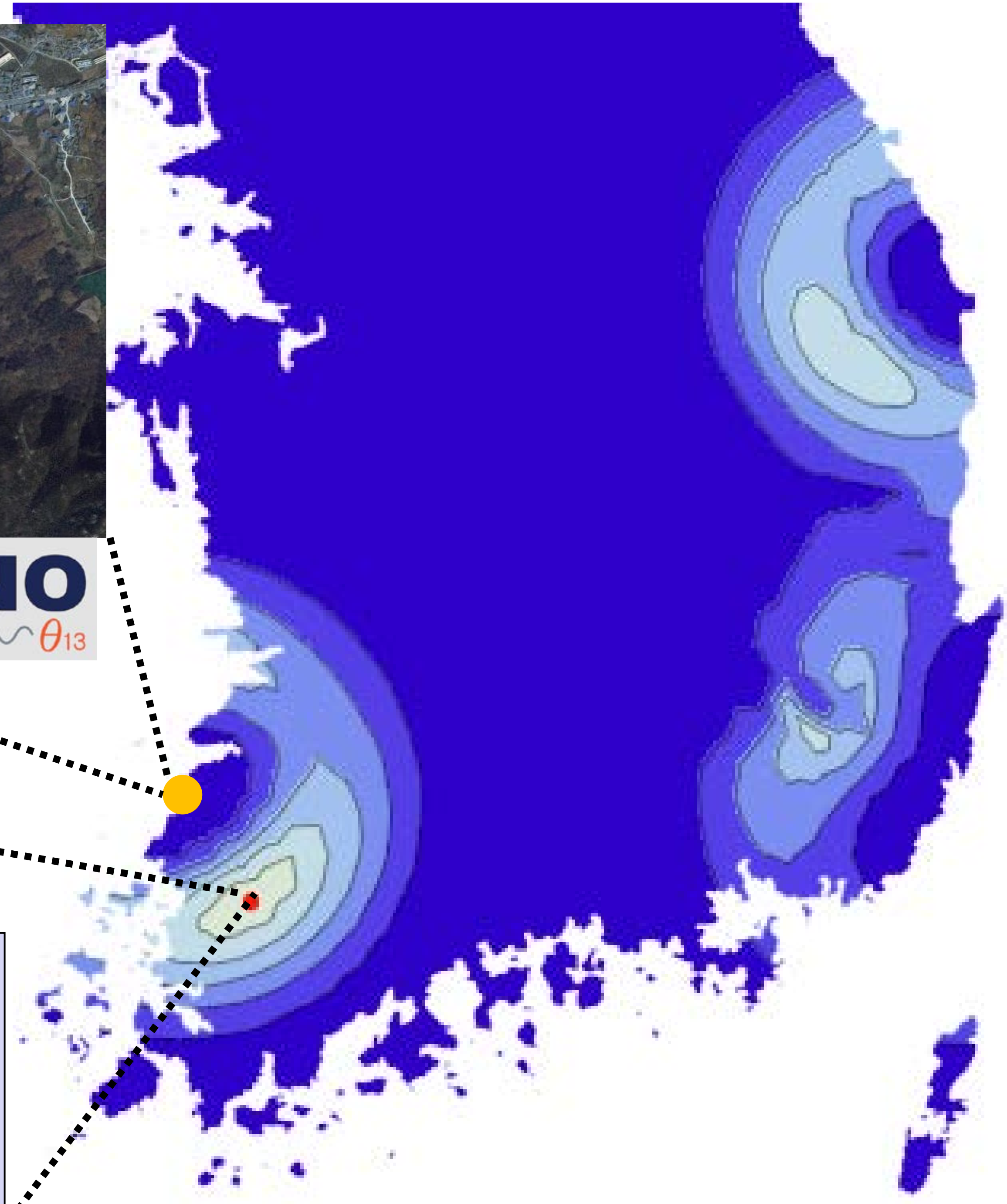




RENO

(NEAR Detector)

(FAR Detector)



RENO-50

10 kton LS Detector
~47 km from YG reactors

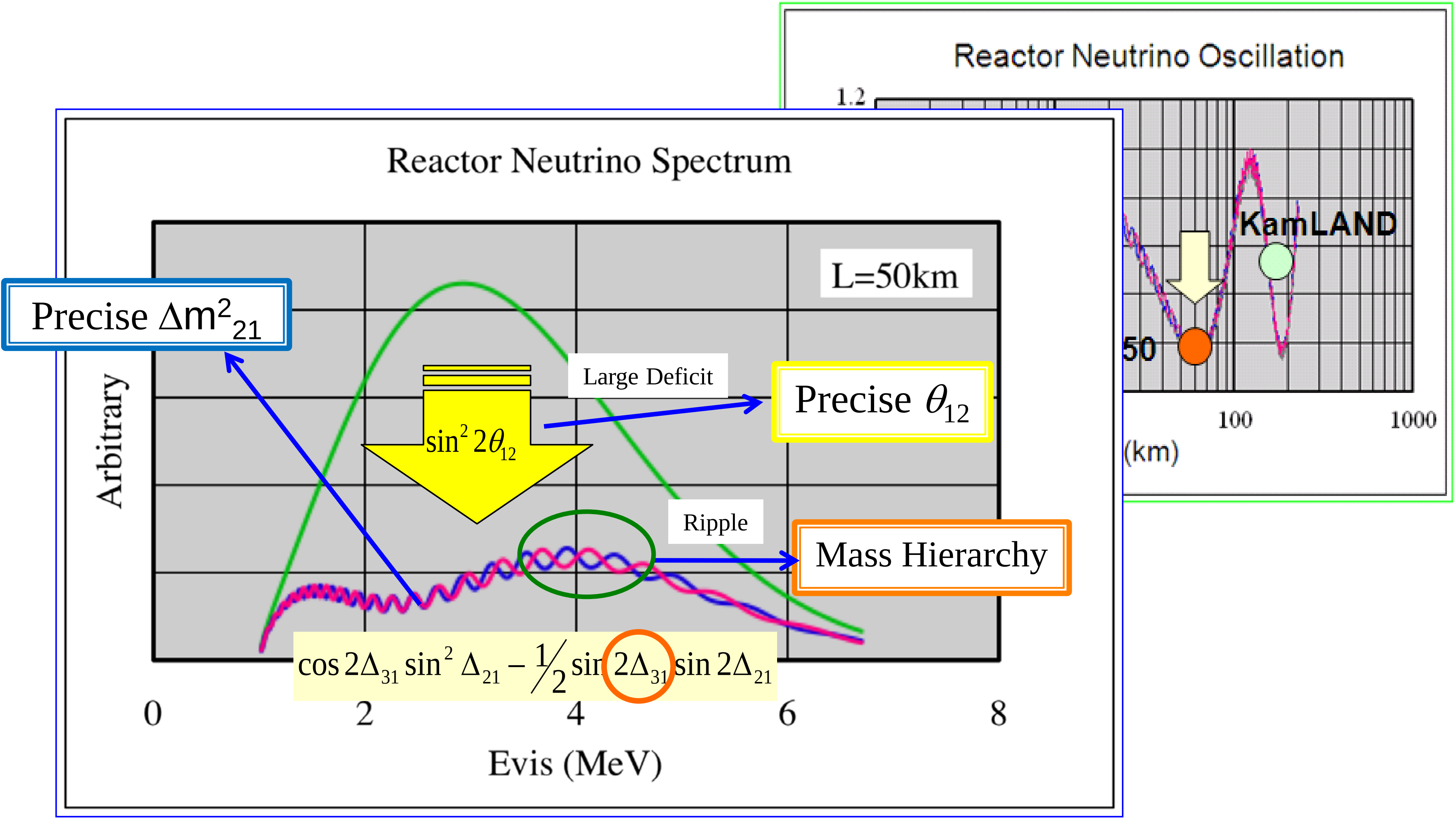
Mt. Guemseong (450 m)
~900 m.w.e. overburden

RENO-50 Candidate Site

RENO-50 Candidate Site

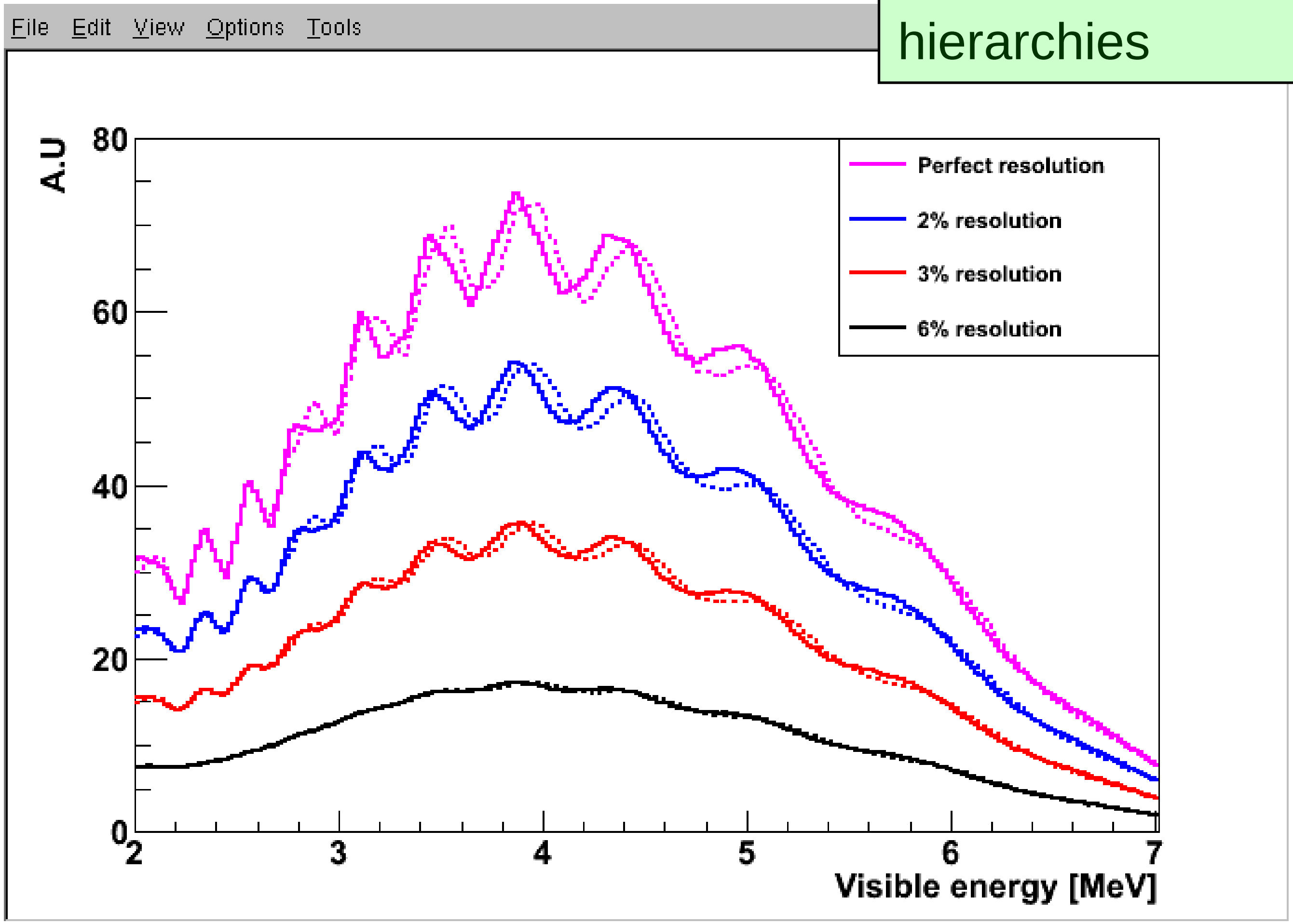
Reactor Neutrino Oscillations at 50 km

Neutrino mass hierarchy (sign of Δm^2_{31})+precise values of θ_{12}, Δm^2_{21} & Δm^2_{31}

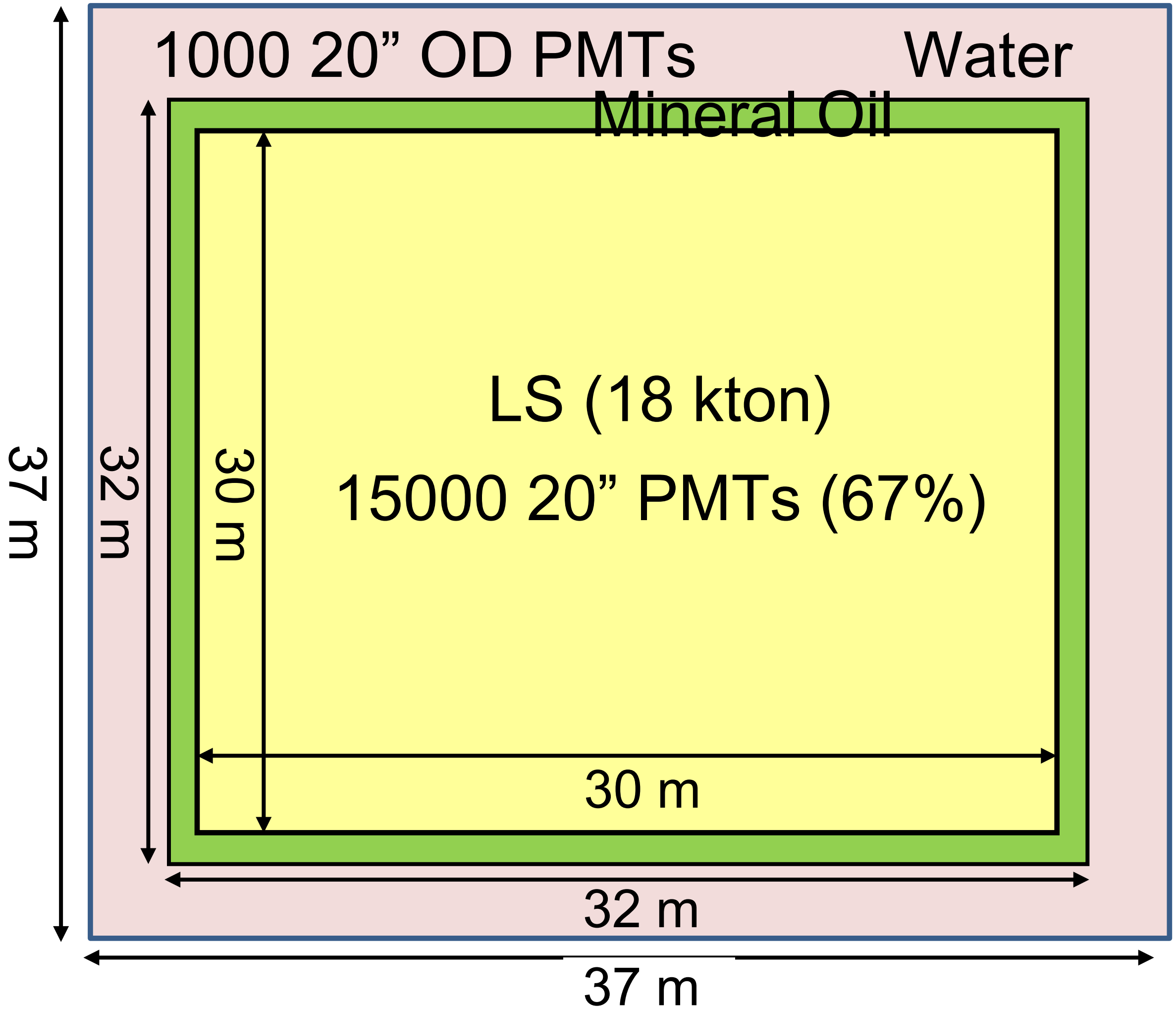


Energy Resolution for Mass Hierarchy

3% energy resolution essential for distinguishing the oscillation effects between normal and inverted mass hierarchies



Conceptual Design of RENO-50

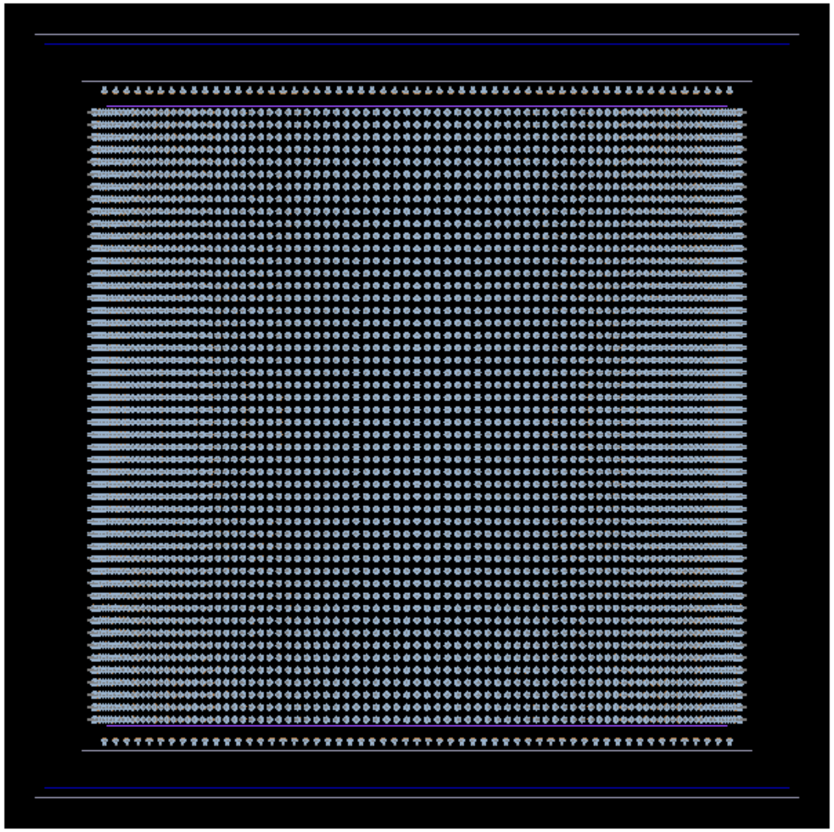


Technical Challenges

	KamLAND	RENO-50
LS mass	~1 kt	18 kt
Energy resolution	6.5%/√E	3%/√E
Light yield	500 p.e./MeV	>1000 p.e./MeV
LS attenuation length	~16 m	~25 m

- R&D for 3% energy resolution :
  - High transparency LS : 15 m → 25 m (purification & better PPO)
  - Large photocathode coverage : 34% → 67% (15,000 20” PMT)
  - High QE PMT : 20% → 35% (Hamamatsu 20” HQE PMT)
  - High light yield LS : ×1.5 (1.5 g/ℓ PPO → 5 g/ℓ PPO)

MC Simulation of RENO-50



• R&D with optimization of detector design by a MC study

• Increase of photosensitive area up to ~60% using 15,000 20” PMTs to maximize the light collection

▪ PMT arrangement scheme.

- Barrel : 50 raw * 200 column
- Top & Bottom: 2500 PMTs for each region

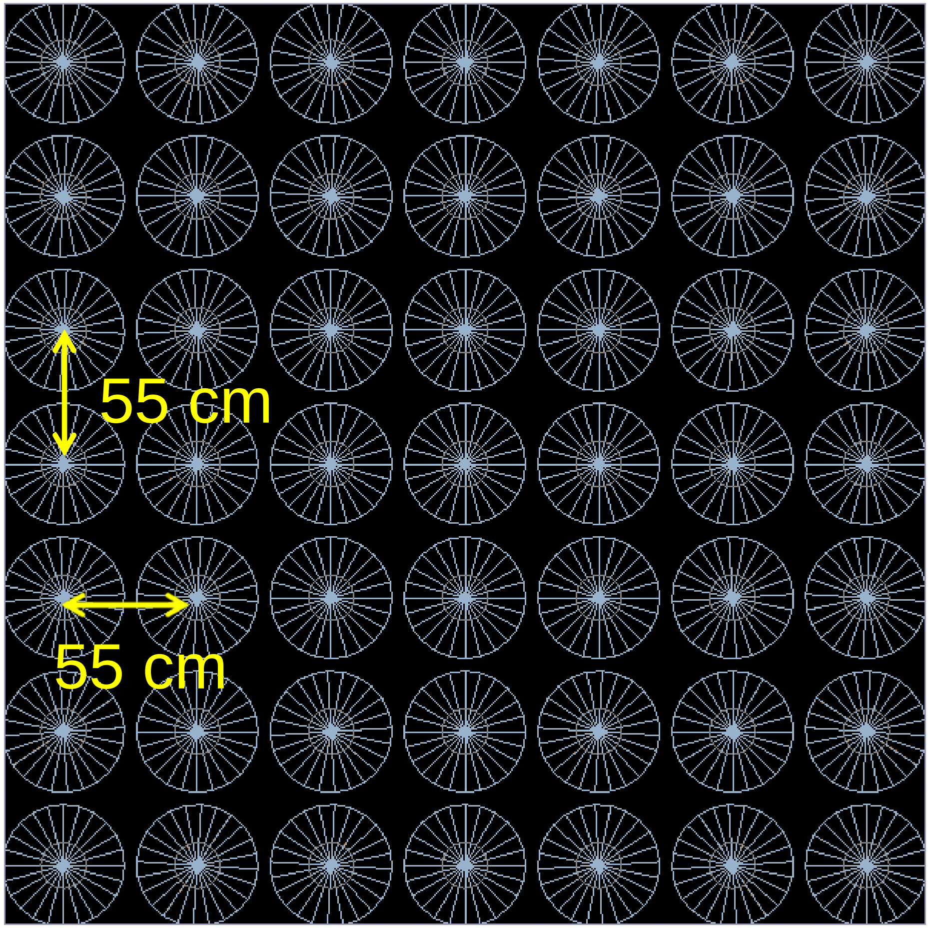
Target : Acrylic, 30m*30m

Buffer : Stainless-Steel, 32m*32m

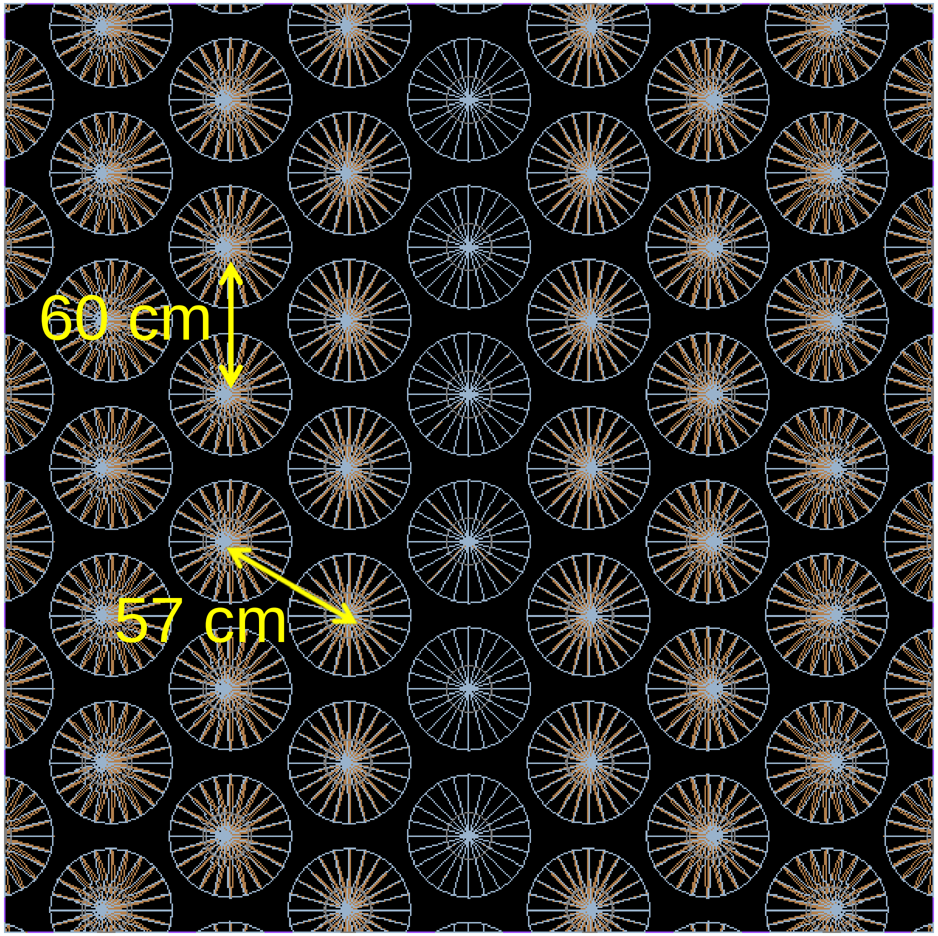
Veto   : Concrete, 37m*37m

RENO-50 PMT Arrangement

Top & Bottom

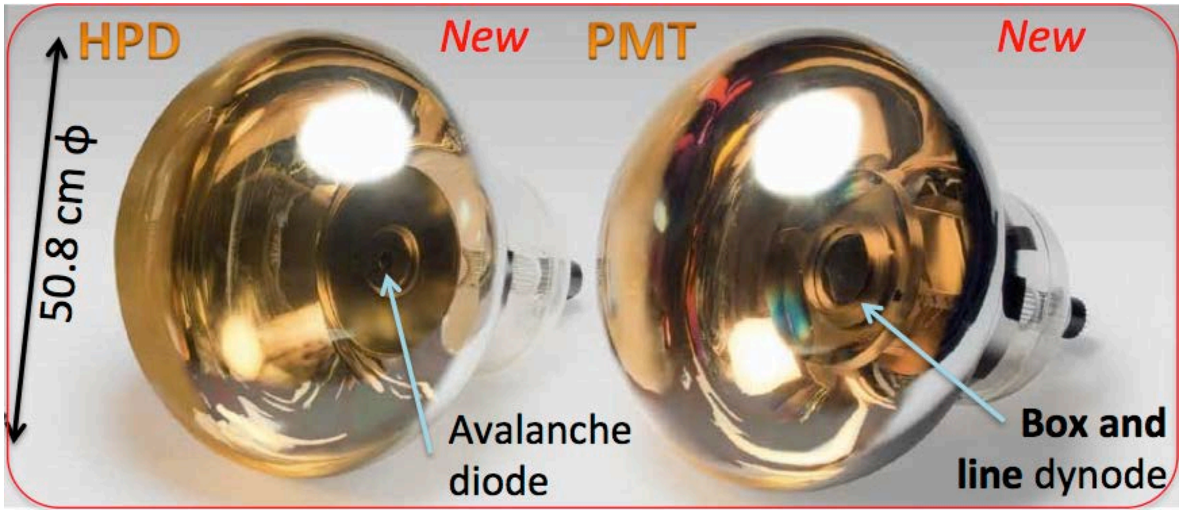


Barrel

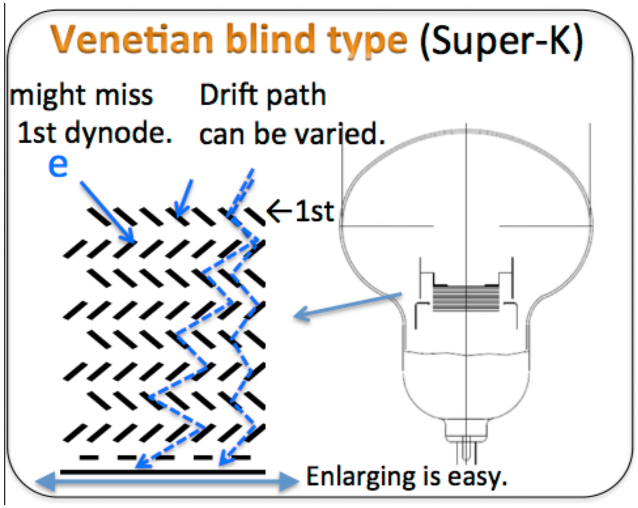


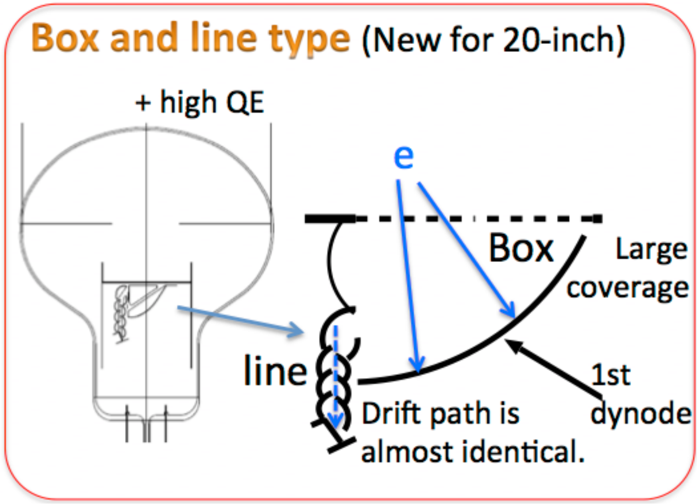
High QE PMTs

• Use of high, 35%, quantum efficiency PMTs in development



Hamamatsu HQE PMT, R12860





LS Purification Scheme

- Develop efficient methods for mass purification of radioactivity in LS

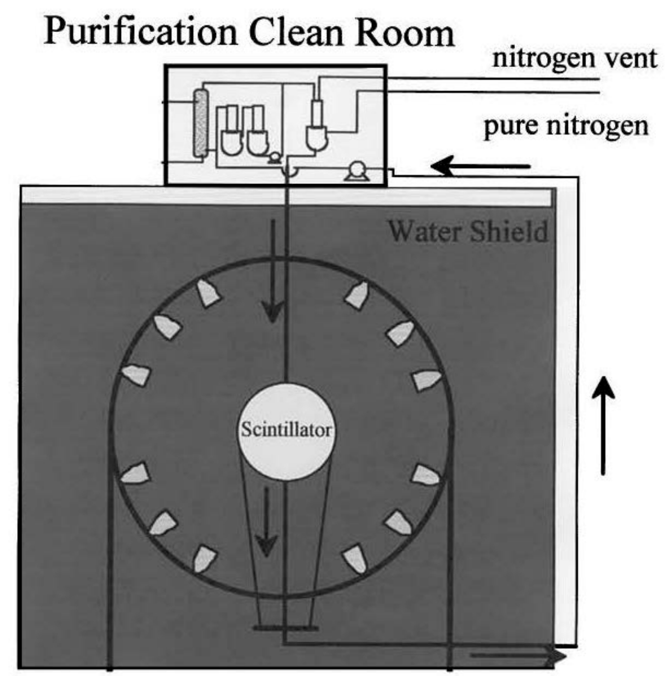
Radio-isotopes	Source	Typical concentration	Required concentration	Strategy for reduction
^{14}C	Cosmogenic bombardment of ^{14}N	$^{14}C/^{12}C \leq 10^{-12}$	$^{14}C/^{12}C \leq 10^{-18}$	**Use of LAB from petroleum derivative (old carbon)**
^{7}Be	Cosmogenic bombardment of ^{12}C	3×10^{-2} Bq/t-carbon	$<10^{-6}$ Bq/t-carbon	**Distillation, or underground storage of scintillator**
^{238}U ^{232}Th	Dust or surface contamination	2×10^{-5} g/g-dust	$<10^{-16}$ g/g LAB	**Water extraction +Distillation +Filtration +pH control**
^{40}K	Dust or contamination in fluor	2×10^{-6} g/g-dust	$<10^{-13}$ g/g in LAB $<10^{-11}$ g/g in fluor	**Water extraction**
^{222}Rn	Air and emanation from material	100 Rn atom/t-LAB	1 Rn atom/t-LAB	**Nitrogen stripping**

From a Borexino paper

LS Purification & Test Facility

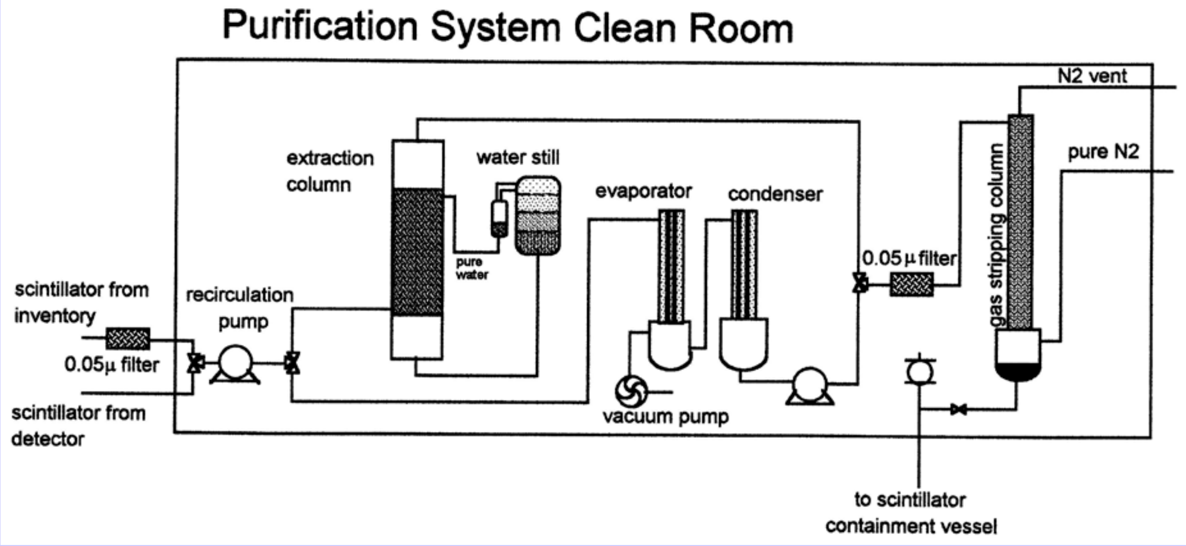
- Develop a test purification facility of ~5 ton LS and build a water shield tank of scintillation detector to measure radioactivity in LS

- Water extraction: removal of polar and charged impurities
- Vacuum distillation: removal of radioactive and chemical impurities
- Filtration with a 0.05 mm Teflon filter: removal of particulates
  (* suspended dust particles that may contain U, Th and K)
- Nitrogen stripping: removal of water and dissolved noble gases of Kr

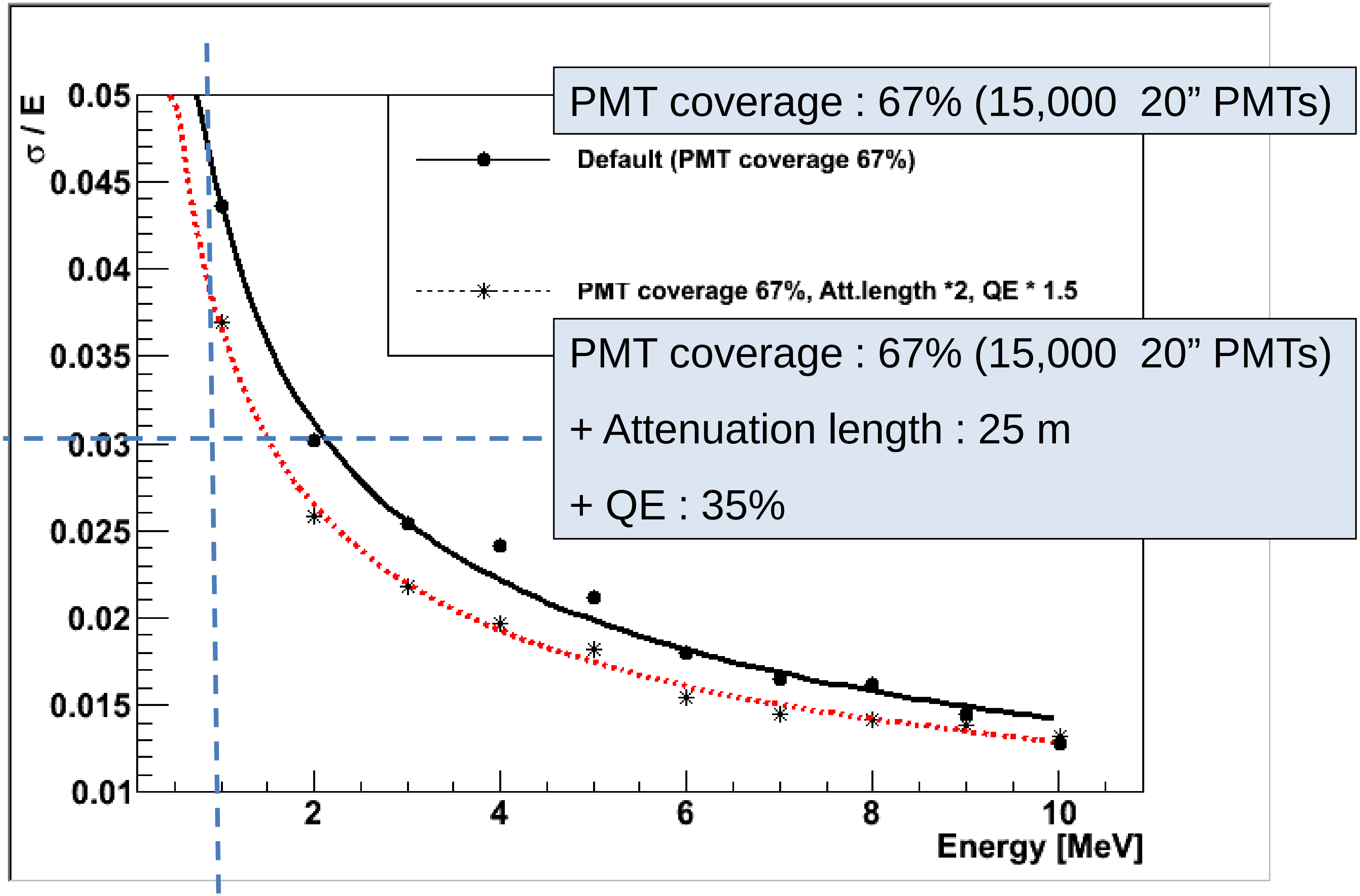


Test facility of Borexino

Ref. J.B. Benzinger *et al.*, NIM A 417, 278-296 (1998)



Expected Energy Resolution



RENO-50 vs. KamLAND

	Oscillation Reduction	Reactor Neutrino Flux	Detector Size	Syst. Error on ν Flux	Error on $\sin^2\theta_{12}$
RENO-50 (50 km)	80%	$13\times6\times\phi_0$ [6 reactors]	18 kton	~ 0.3%	< 1%
KamLAND (180 km)	40%	$0.6\times55\times\phi_0$ [55 reactors]	1 kton	3%	5.4%
Figure of Merit	×2	×2.4	×18	×10	

$(50\text{ km} / 180\text{ km})^2 \approx 13$

Observed Reactor Neutrino Rate

- RENO-50 : ~ 15 events/day
- KamLAND : ~ 1 event /day

Determination of mass ordering:
~ 3σ with 5 year data

2012 Particle Data Book

LEPTONS

Neutrino Mixing

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

$\Delta m^2_{21} = (7.50 \pm 0.20) \times 10^{-5}$ eV^2 **(±2.7%)**

$\sin^2(2\theta_{23}) > 0.95$ [i] **(±3.1%)**

$\Delta m^2_{32} = (2.32^{+0.12}_{-0.08}) \times 10^{-3}$ eV^2 [j] **(+5.2-3.4%)**

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

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

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

- Precise measurement of θ_{12}, Δm^2_{21} and Δm^2_{32}

$$\frac{\delta \sin^2\theta_{12}}{\sin^2\theta_{12}} < 1.0\%(1\sigma)$$
(← 5.4%)

$$\frac{\delta \Delta m^2{}_{21}}{\Delta m^2{}_{21}} < 1.0\%(1\sigma)$$
(← 2.7%)

$$\frac{\delta \Delta m^2{}_{32}}{\Delta m^2{}_{32}} < 1.0\%(1\sigma)$$
(← 5.2%)

Additional Physics with RENO-50

- Neutrino burst from a Supernova in our Galaxy
  - ~5,600 events (@8 kpc) (* NC tag from 15 MeV deexcitation γ)
  - A long-term neutrino telescope

- Geo-neutrinos : ~ 1,000 geo-neutrinos for 5 years
  - Study the heat generation mechanism inside the Earth

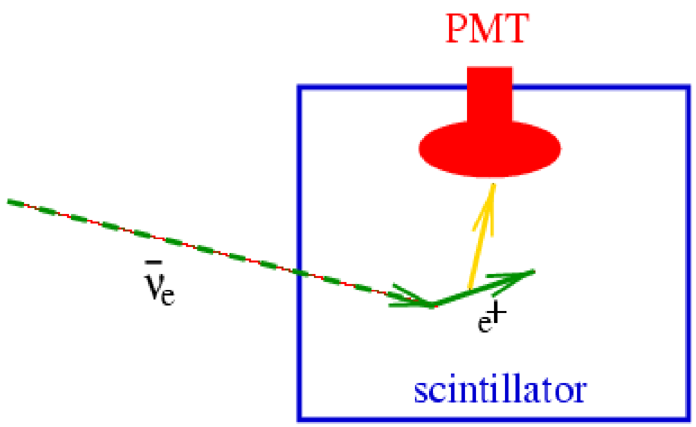
- Solar neutrinos : with ultra low radioacitivity
  - MSW effect on neutrino oscillation
  - Probe the center of the Sun and test the solar models

- Detection of J-PARC beam : ~200 events/year

- Neutrinoless double beta decay search : possible modification like KamLAND-Zen

Scintillation detectors

(by Kate Scholberg, Neutrino 2014)



Liquid scintillator C_nH_{2n} volume surrounded by photomultipliers

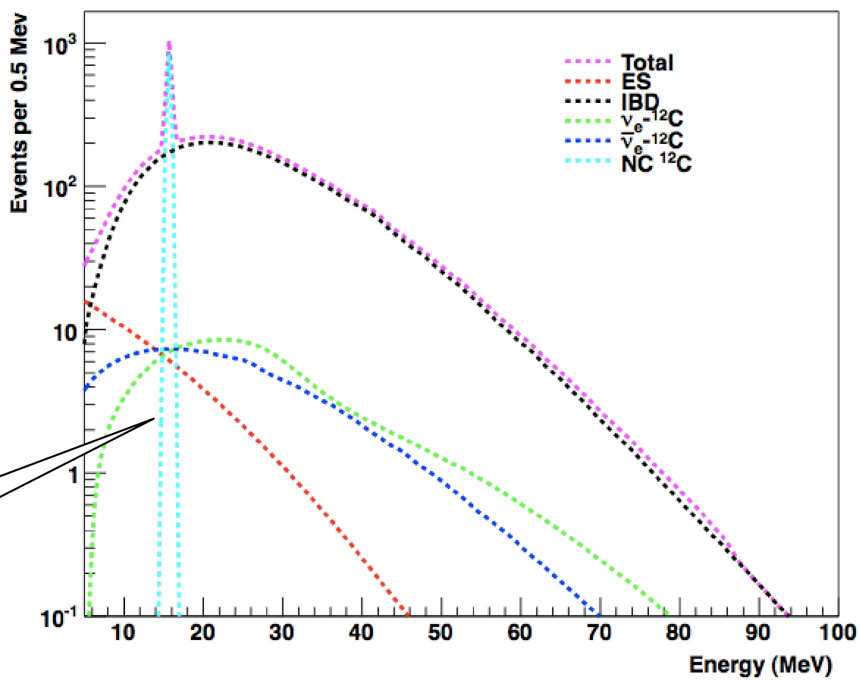
- few 100 events/kton (IBD)

- low threshold, good neutron tagging possible

- little pointing capability (light is ~isotropic)

- coherent elastic NC scattering on protons for ν spectral info

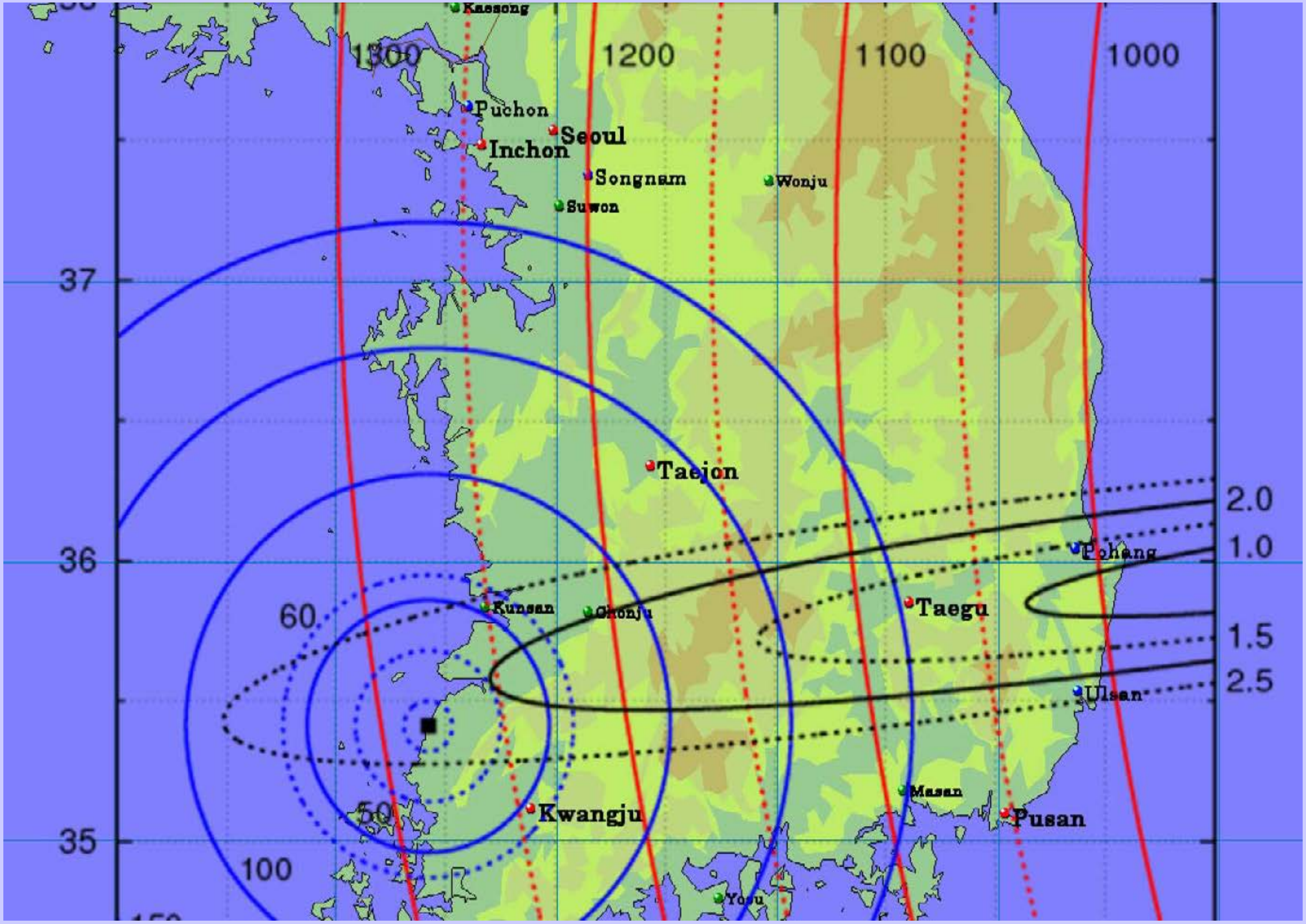
NC tag from 15 MeV deexcitation γ (no ν spectral info)



50 kt @ 10 kpc

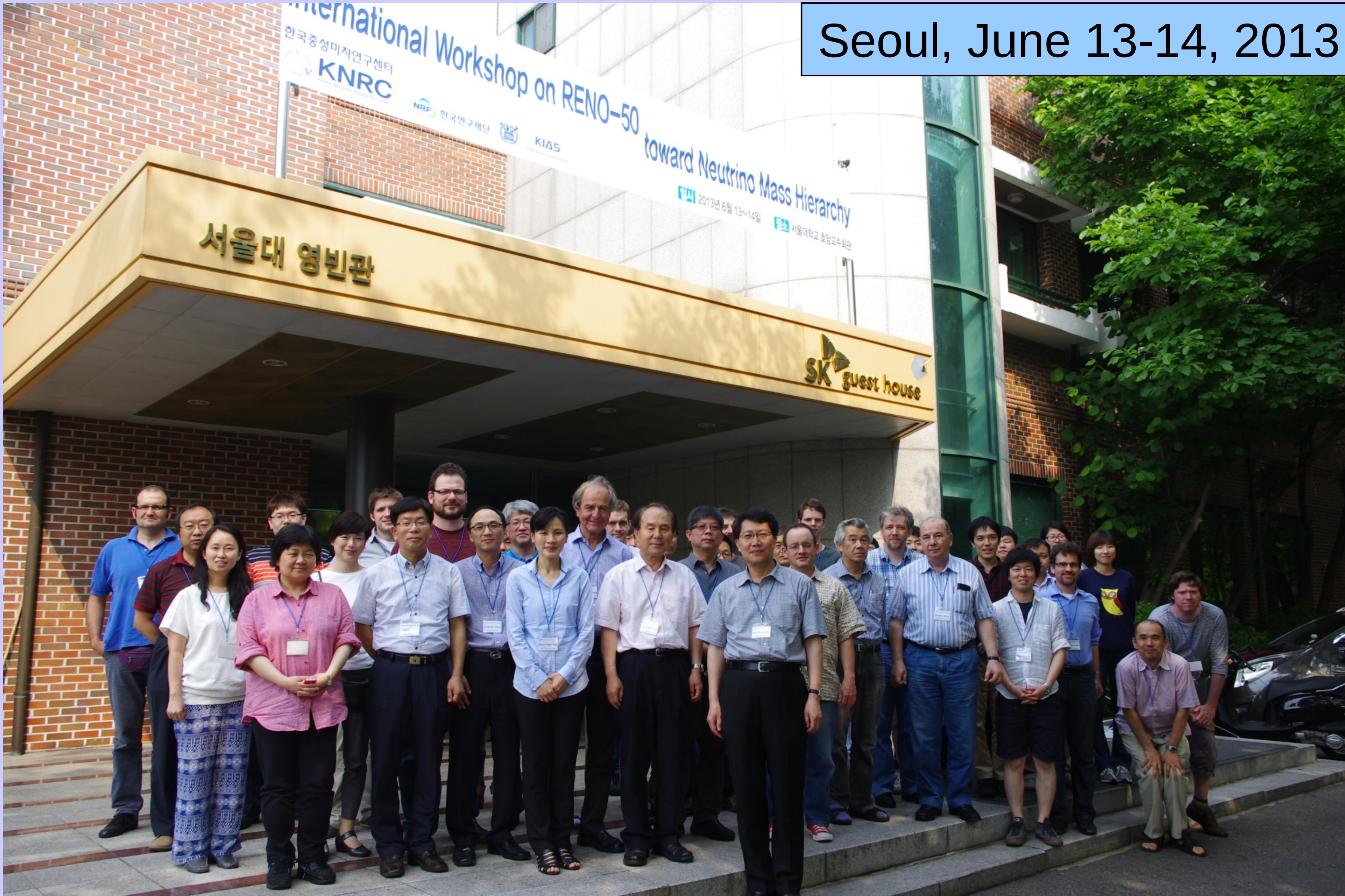
J-PARC neutrino beam

Dr. Okamura & Prof. Hagiwara



International Workshop on RENO-50

Seoul, June 13-14, 2013



Schedule

- 2015 : Group organization
  Detector simulation & design
  Geological survey
- 2016 ~ 2017 : Civil engineering for tunnel excavation
  Underground facility ready
  Structure design
  PMT evaluation and order,
  Preparation for electronics, HV, DAQ & software tools,
  R&D for liquid scintillator and purification
- 2018 ~ 2020 : Detector construction
- 2021 ~ : Data taking & analysis

Summary

- Longer baseline (~50 km) reactor experiments is under pursuit to determine the mass hierarchy in 3σ for 5 years of data-taking, and to perform high-precision (<1%) measurements of θ_{12}, Δm^2_{21}, & Δm^2_{31} .

- Domestic and international workshops held in 2013 to discuss the feasibility and physics opportunities

- An R&D funding (US $ 2M in next 3 years) will be given by the Samsung Science & Technology Foundation.

- A proposal have been submitted to obtain full funding.

Thanks for your attention!