New Results from RENO

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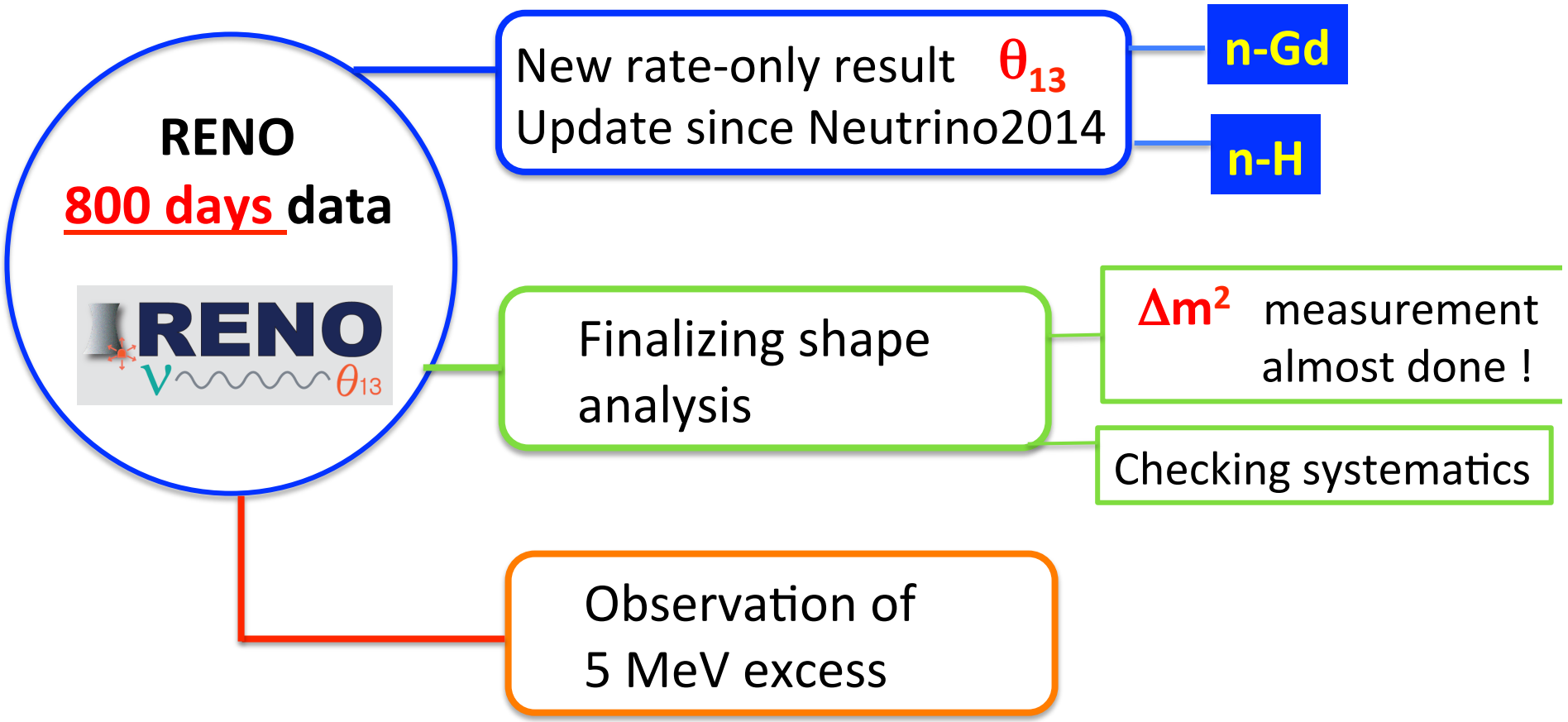
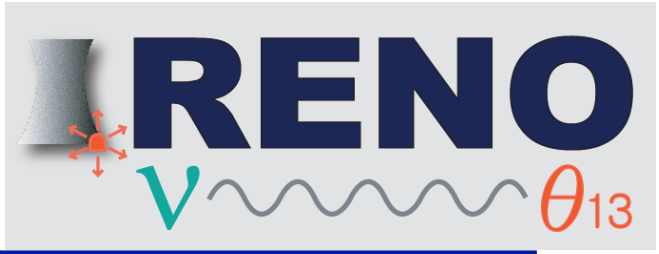
On behalf of the RENO Collaboration

Neutrino Telescopes 2015 Venice Mar. 3, 2015

Quick Overview



RENO Collaboration



11 institutions and 40 physicists in Korea

- Chonbuk National University
- Chonnam National University
- Chung-Ang University
- Dongshin University
- GIST
- Gyeongsang National University
- Kyungpook National University
- Sejong 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**

Reactor **E**xperiment for **N**eutrino **O**scillation

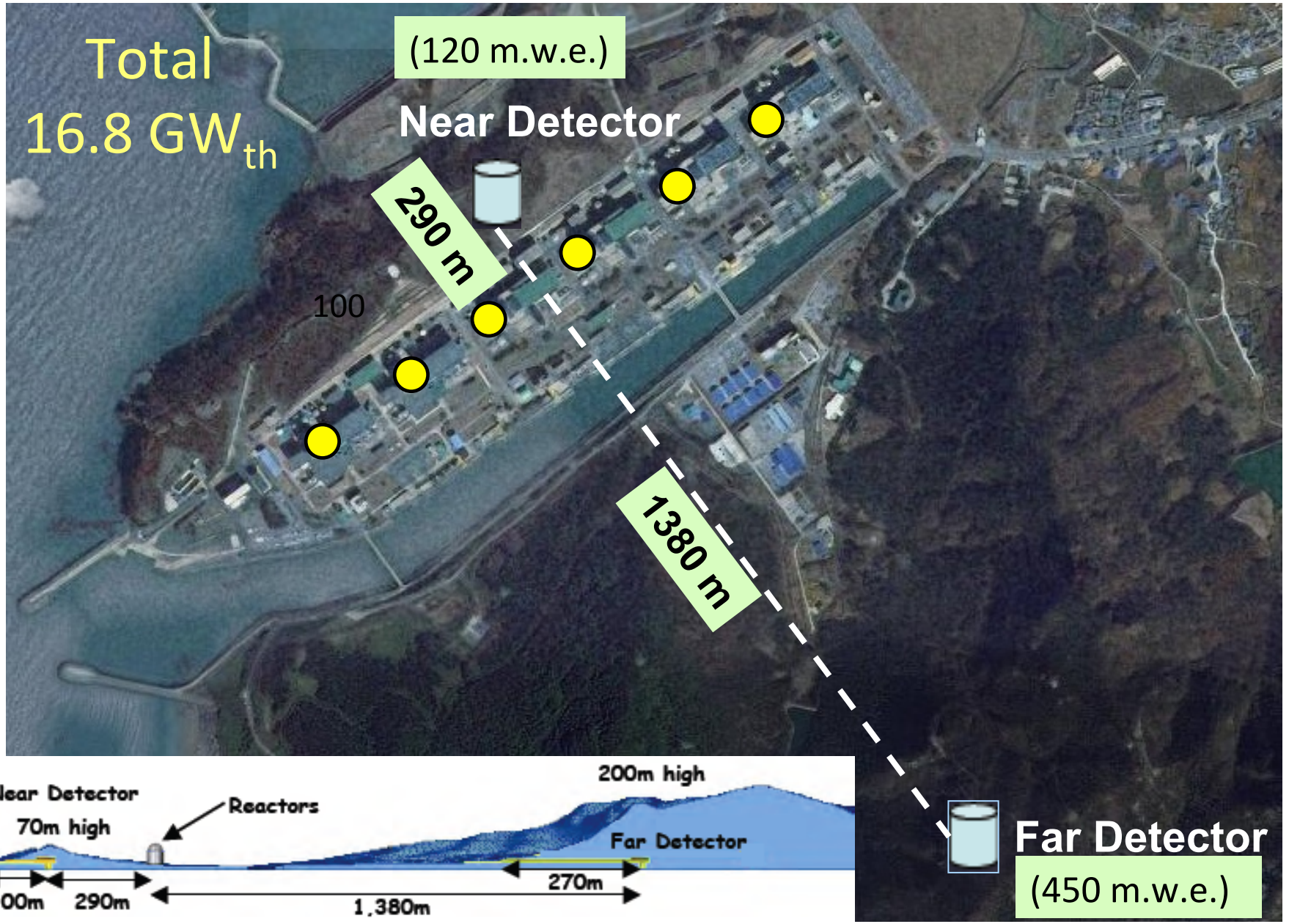
RENO Location: YongGwang S. Korea

YongGwang (靈光) :

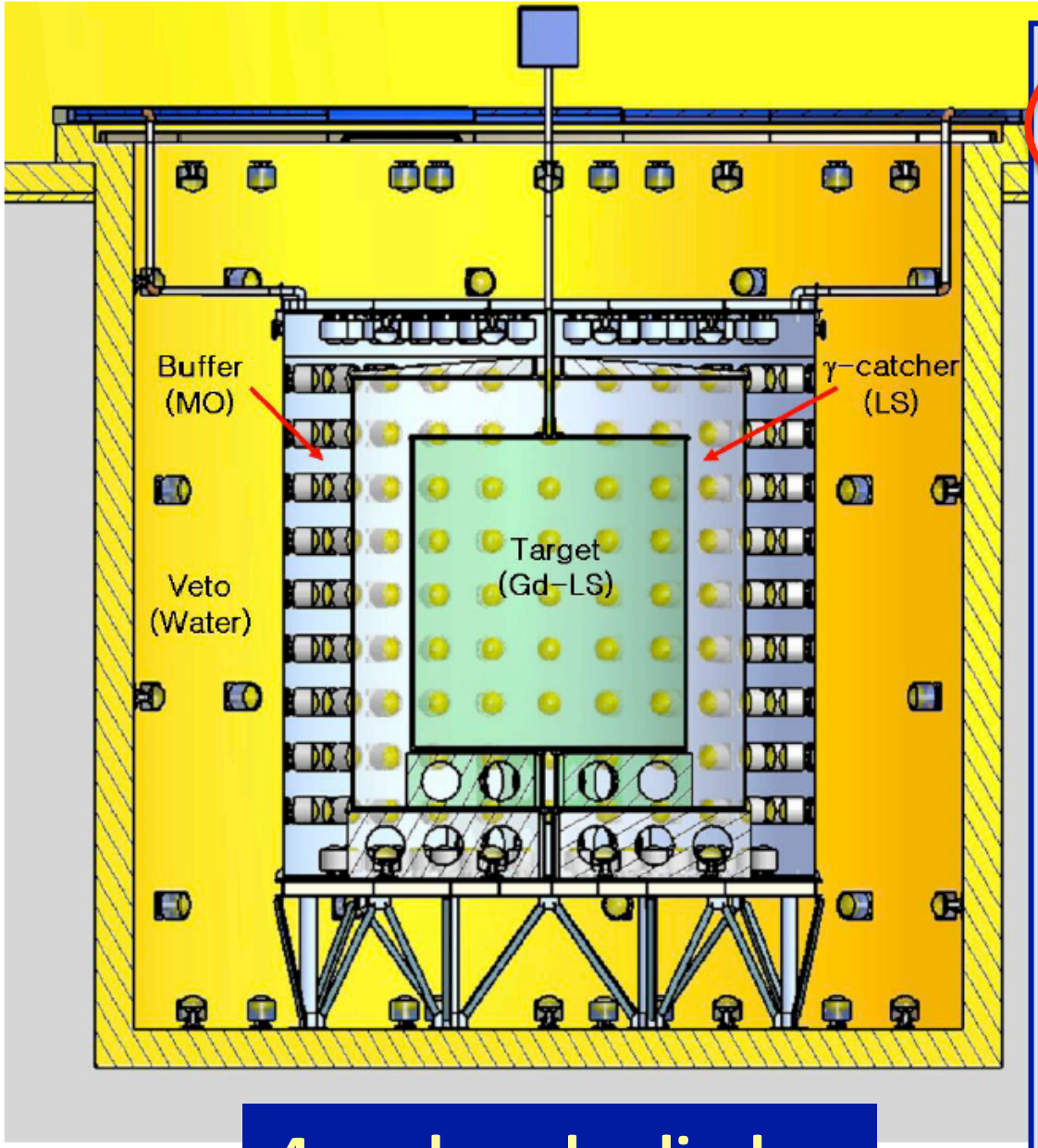
means “Glorious light”

~ 4 hours driving distance from Seoul

RENO Experimental Setup



The RENO Detector



4 enclosed cylinders

- **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)

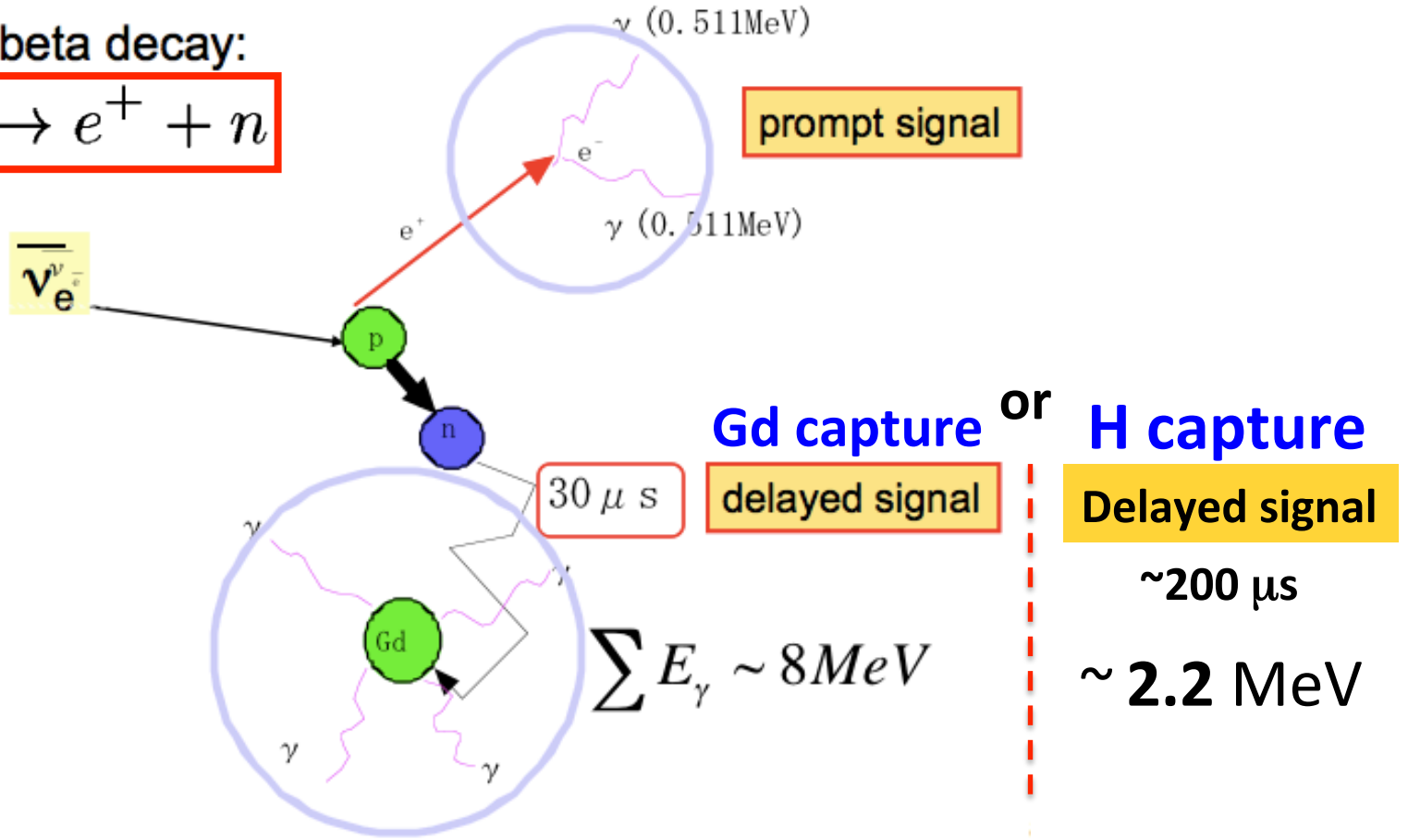
-- 354 ID 10 " PMTs
-- 67 OD 10" PMTs

The RENO Detector

Detection Principle of Reactor Neutrinos

Inverse beta decay:

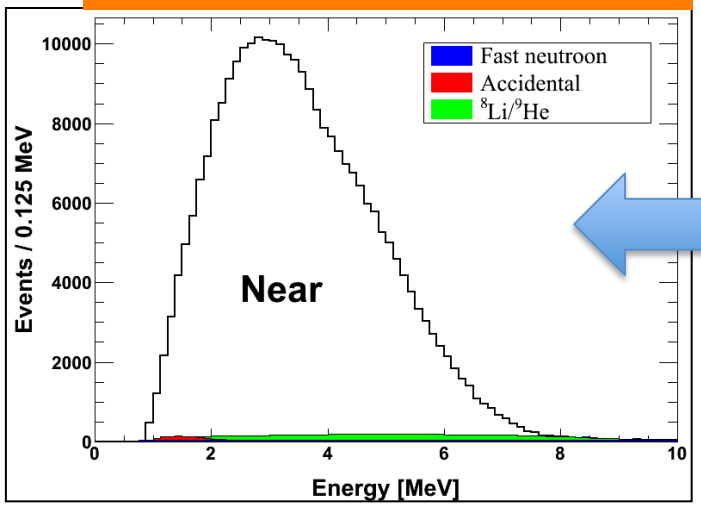
$$\bar{\nu}_e + p \rightarrow e^+ + n$$



- 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** or **H**
  ~30 μs or ~200 μs

Signal: IBD Pair

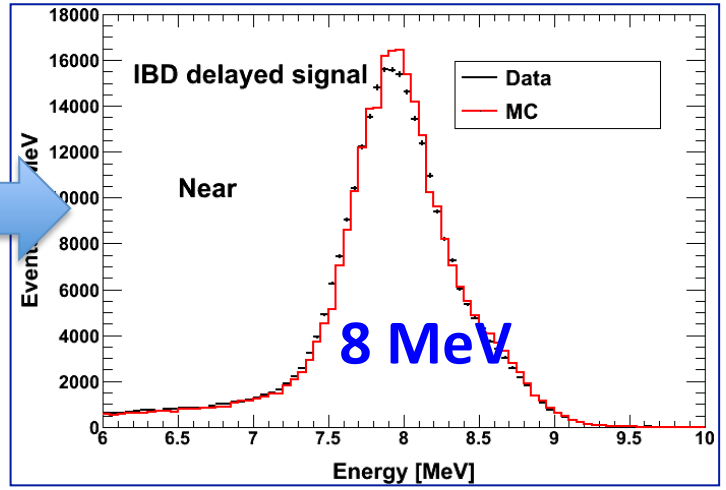
Prompt signal (S1)



n-Gd IBD

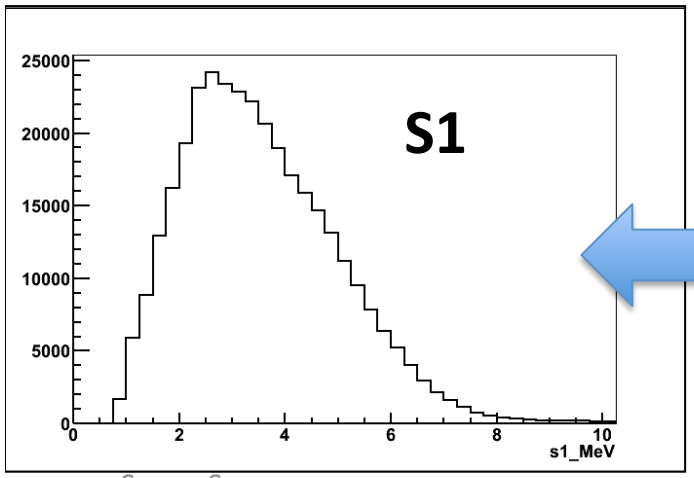
~30 μs

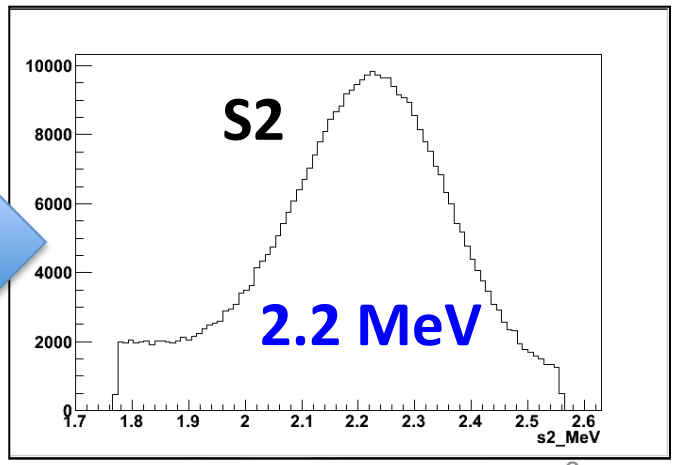
Delayed signal (S2)



n-H IBD

~200 μs





Suppresses background a lot !

RENO Status

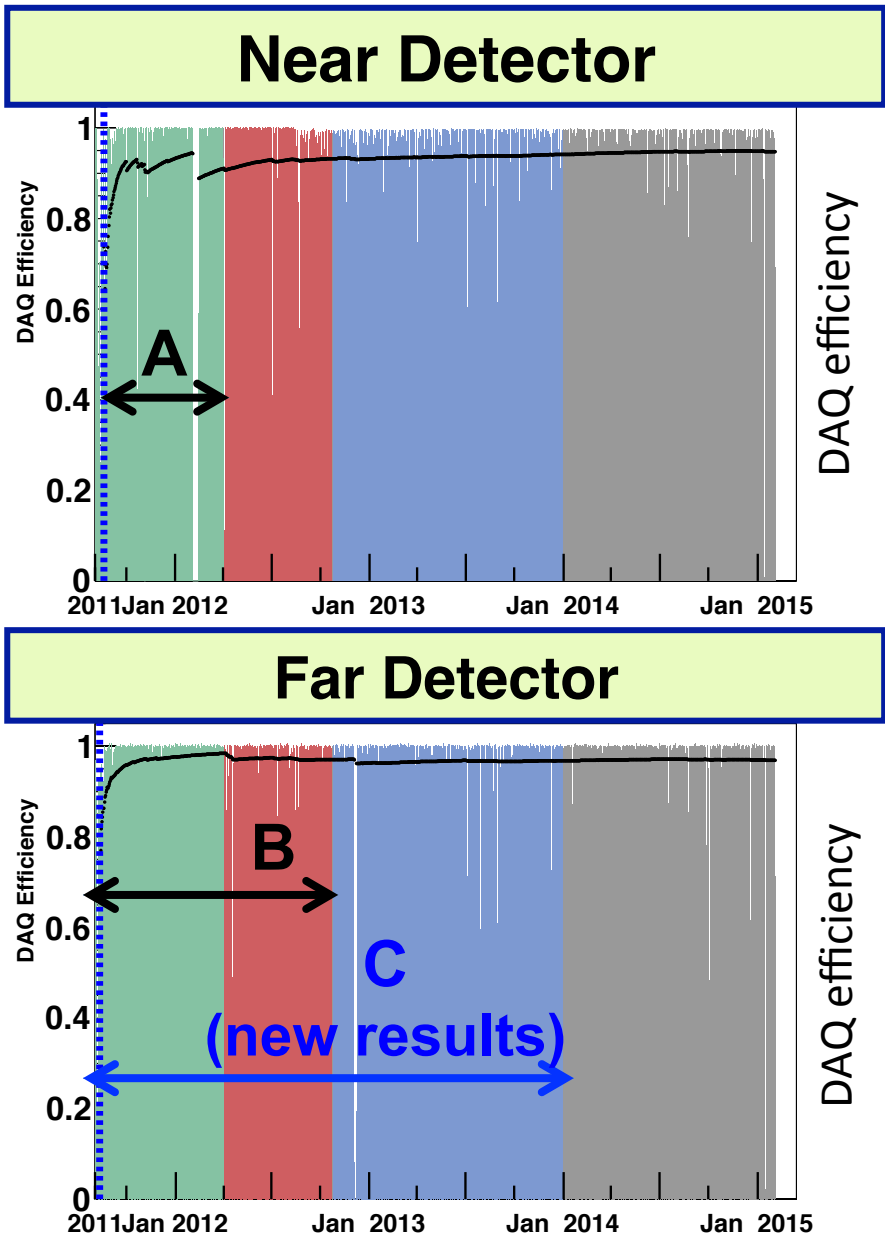
- Data taking began on Aug. 1, 2011 with both near and far detectors.
  (DAQ efficiency : ~95%)

- **A** (220 days) : **First θ_{13} result**
  [11 Aug, 2011~26 Mar, 2012]
  PRL 108, 191802 (2012)

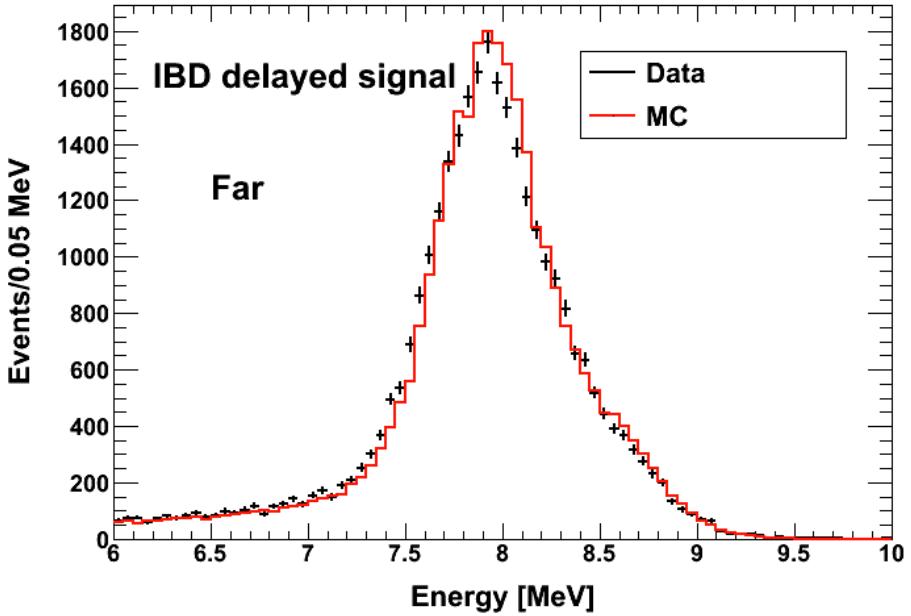
- **B** (403 days) : **Improved θ_{13} result**
  [11 Aug, 2011~13 Oct, 2012]
  NuTel 2013, TAUP 2013, WIN 2013

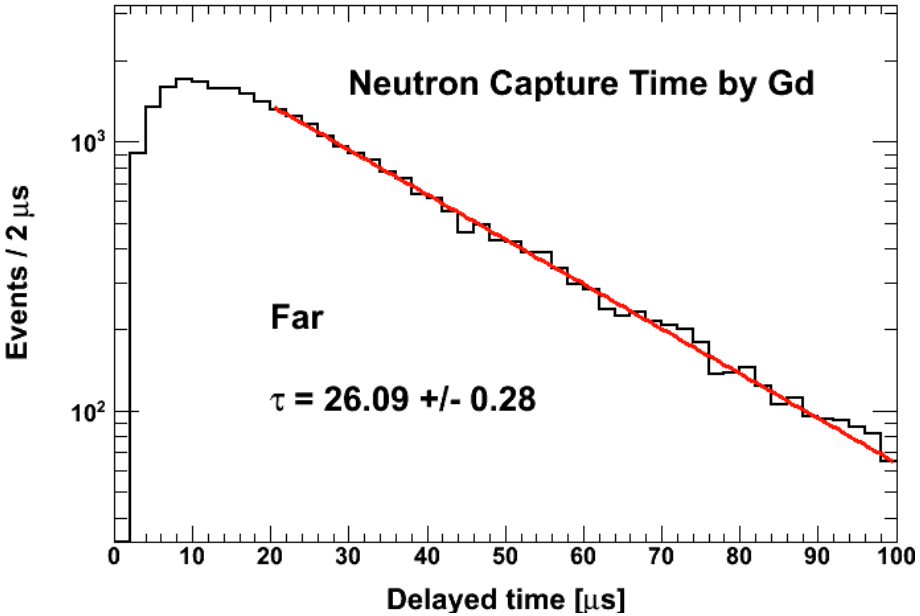
- **C** (~800 days) : **New θ_{13} result**
  Shape+ Rate analysis (in progress)
  [11 Aug, 2011~31 Dec, 2013]

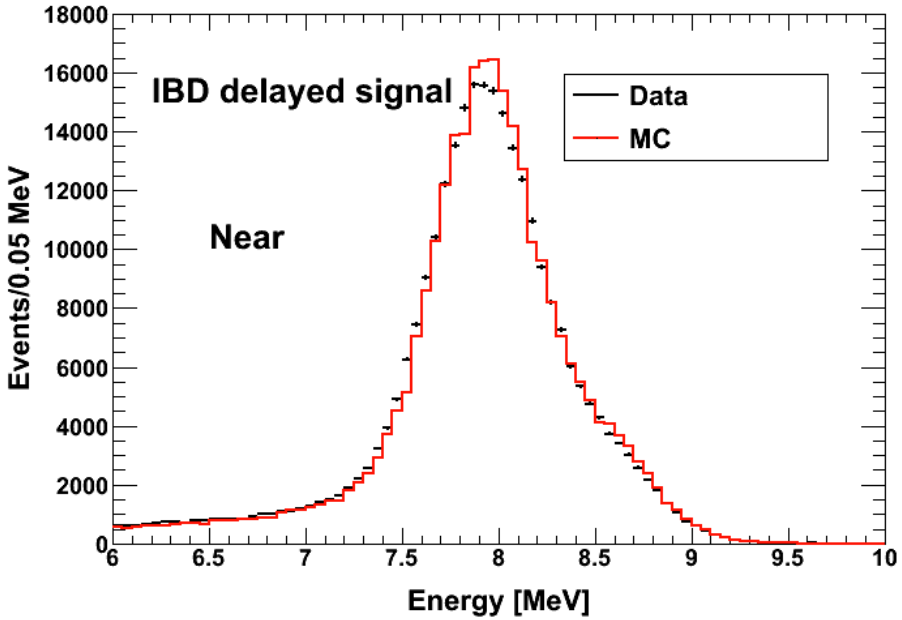
- Total observed reactor neutrino events as of today : **~ 1.5M** (Near), **~ 0.15M** (Far)
  → Absolute reactor neutrino flux measurement in progress
  [reactor anomaly & sterile neutrinos]

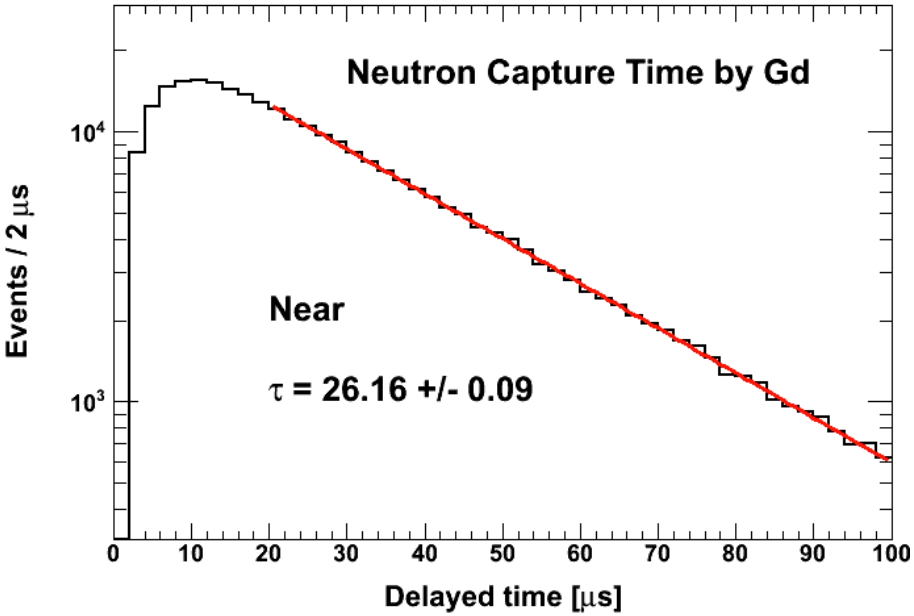


Neutron Capture by Gd









Rate-only Analysis Results

Improved since Neutrino 2014

by background systematic error reduction applying new criteria.

- Li/He BKG: ~30% reduction
- Cf contamination: ~35 %

Note:

background estimation is data (not MC) driven.

→ More data taking leads more reduction of both stat. & sys. errors

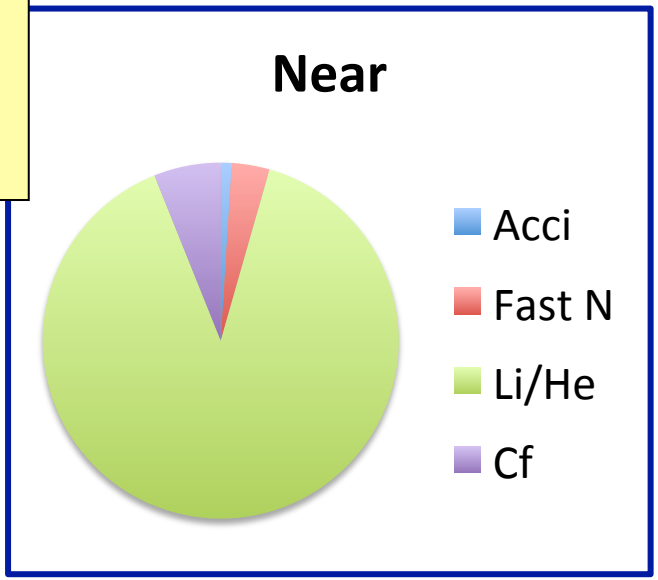
Backgrounds

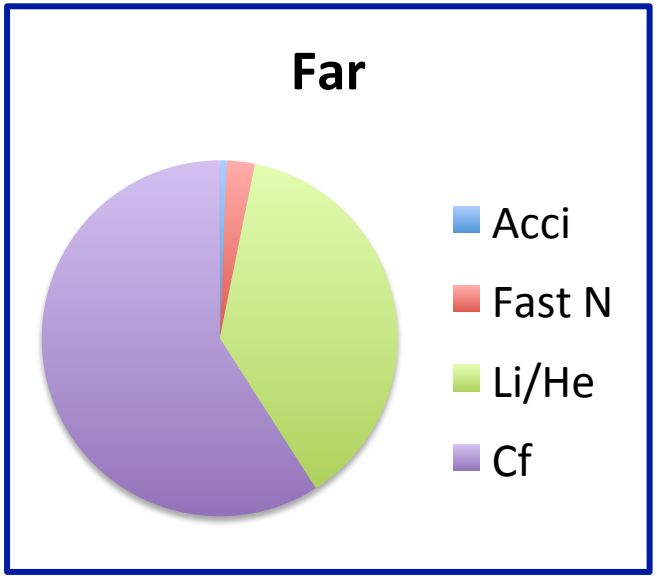
- After Neutrino 2014, Q_{max}/Q_{tot} cut : 0.03 → 0.04
- allow more accidentals to increase acceptance of signal and minimize any bias to the spectral shape.

Backgrounds		Rate (/day)
Accidentals	Near	1.82±0.11 → **4.475±0.009**
	Far	0.36±0.01 → **0.672±0.003**
Fast Neutron	Near	2.67±0.08 → **2.210±0.031**
	Far	0.56±0.02 → **0.422±0.012**
Li/He	Near	9.18±0.67 → **11.14 ±0.81**
	Far	2.07±0.21 → **1.215±0.179**
^{256}Cf contamination	Near	0.45±0.07 → **0.337±0.055**
	Far	3.17±0.28 → **1.252±0.191**
Total	Near	14.18±0.69 → **18.163±0.814**
	Far	6.17±0.35 → **3.561±0.280**

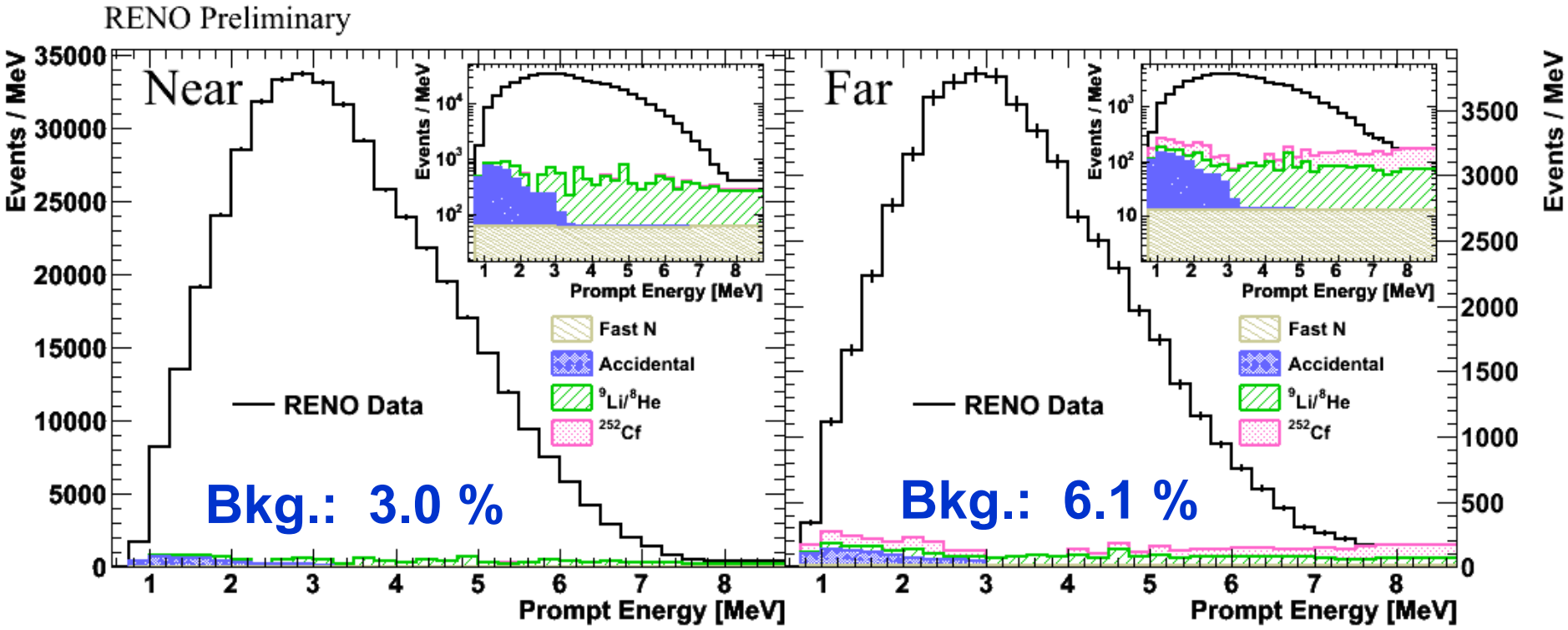
Fraction to total IBD: 3.0 % (Near)
6.1% (Far)

BKG Uncertainties



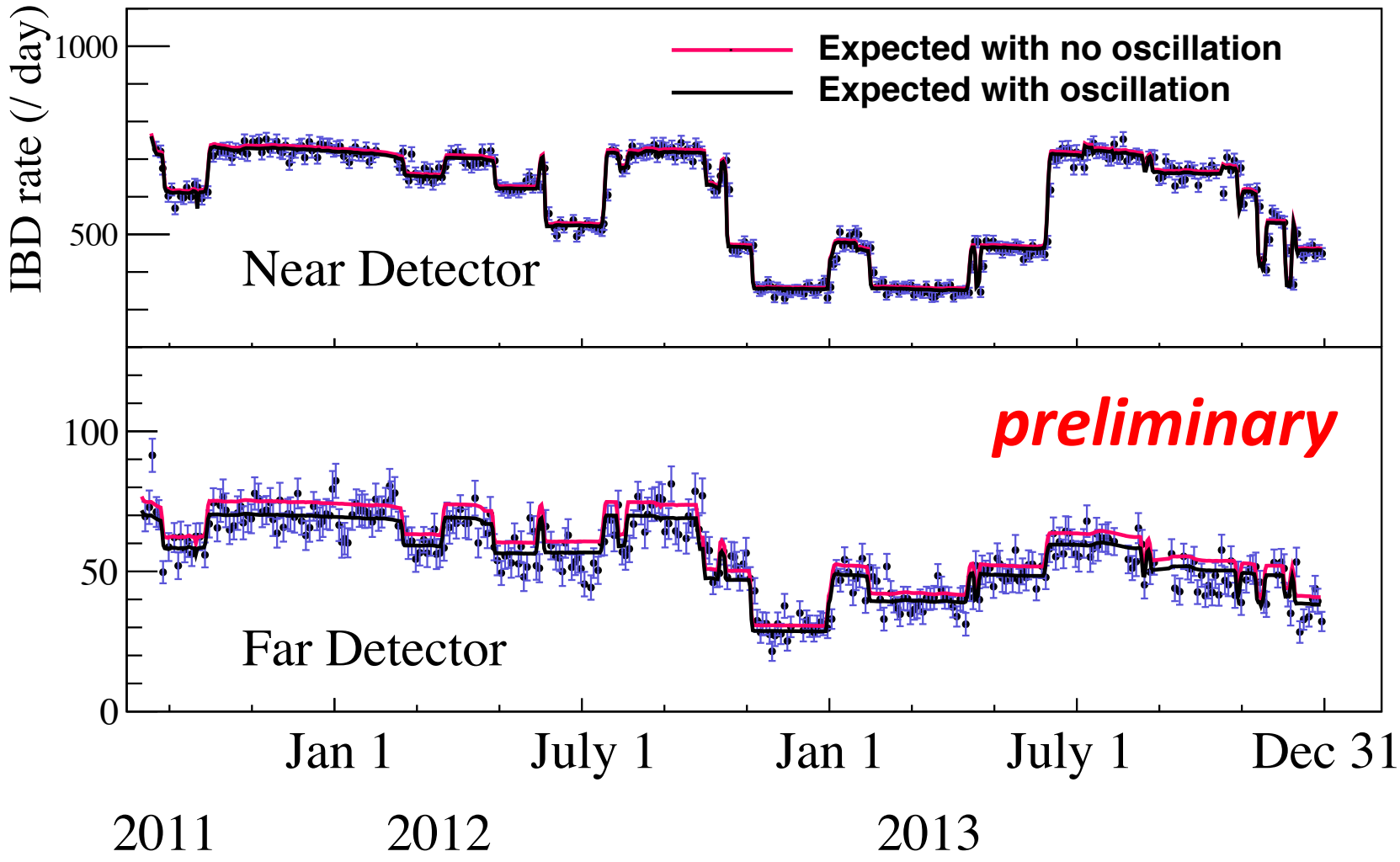


Measured Spectra of IBD Prompt Signal



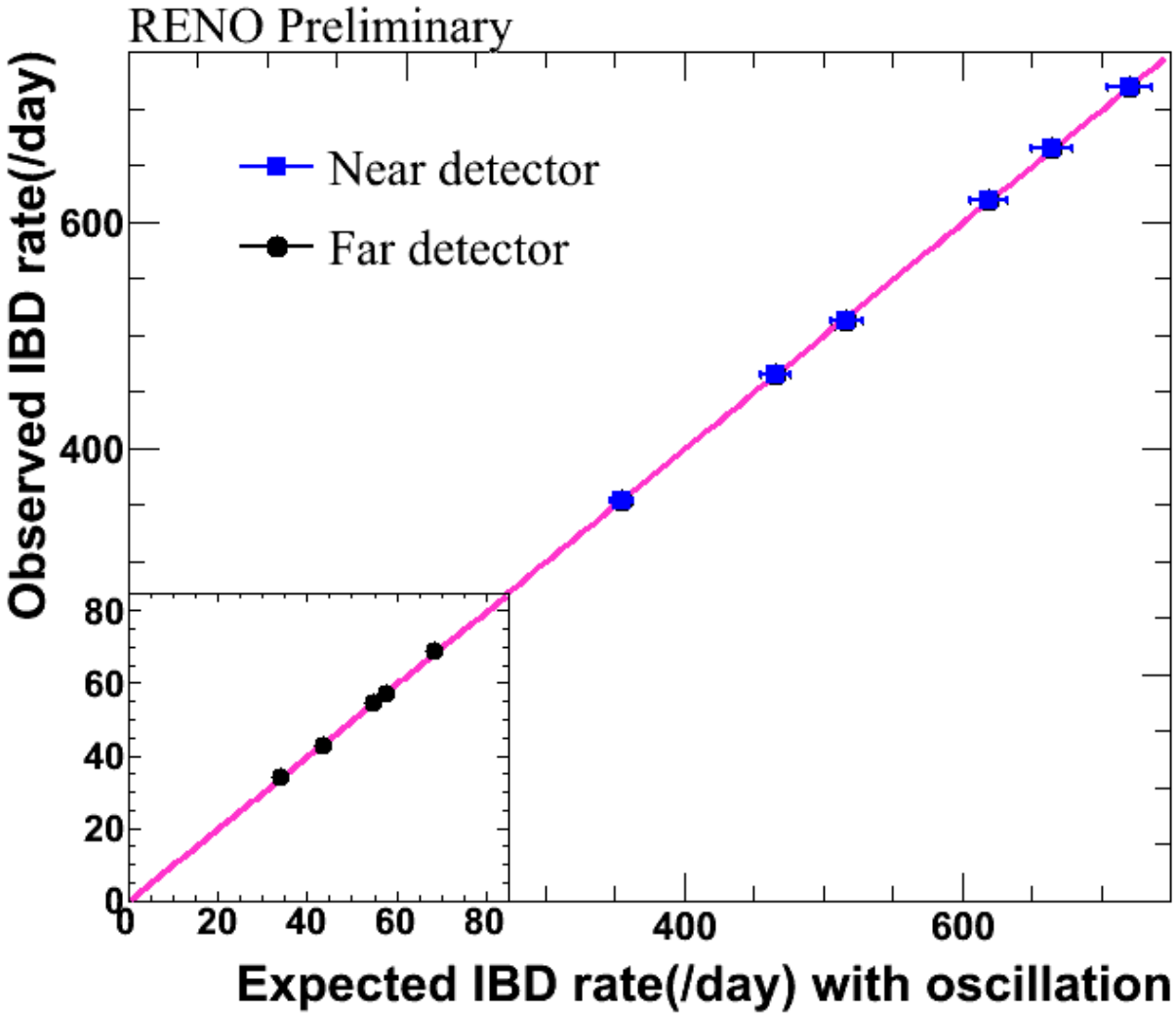
Near	Far
Live time = 761.11 days	Live time = 794.72 days
# of IBD candidate = 459,292	# of IBD candidate = 46,670
# of background = 13,824 (3.0 %)	# of background = 2830 (6.1 %)

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



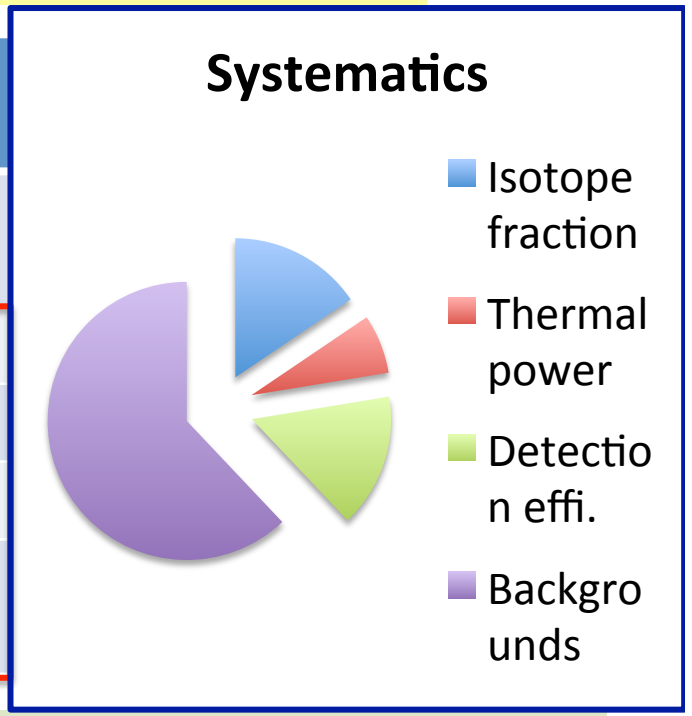
- Good agreement between observed rate & prediction
- Indication of correct background subtraction

New θ_{13} Measurement by Rate-only Analysis

(Preliminary)

$$\sin^2 2\theta_{13} = 0.090 \pm 0.008(\text{stat.}) \pm 0.008(\text{syst.})$$

Uncertainties sources	Uncertainties (%)	Errors of $\sin^2 2\theta_{13}$ Error (fraction)
Statistics (near) (far)	0.21 % 0.54 %	0.008
Isotope fraction	0.7 %	0.003 → 15.6 %
Thermal power	0.5 %	0.002 → 6.9 %
Detection efficiency	0.2 %	0.003 → 15.6 %
Backgrounds (near) (far)	0.14 % 0.51 %	0.006 → 62.3 %



$\sin^2 2\theta_{13} = 0.113 \pm 0.023$ 4.9 σ (Neutrino 2012)
→ 0.100 ± 0.016 6.3 σ (TAUP/WIN 2013)
→ 0.101 ± 0.013 7.8 σ (Neutrino 2014)
→ 0.090 ± 0.011 8.2 σ (Singapore 2015)

Energy Calibration & 5 MeV Excess

Confident energy calibration

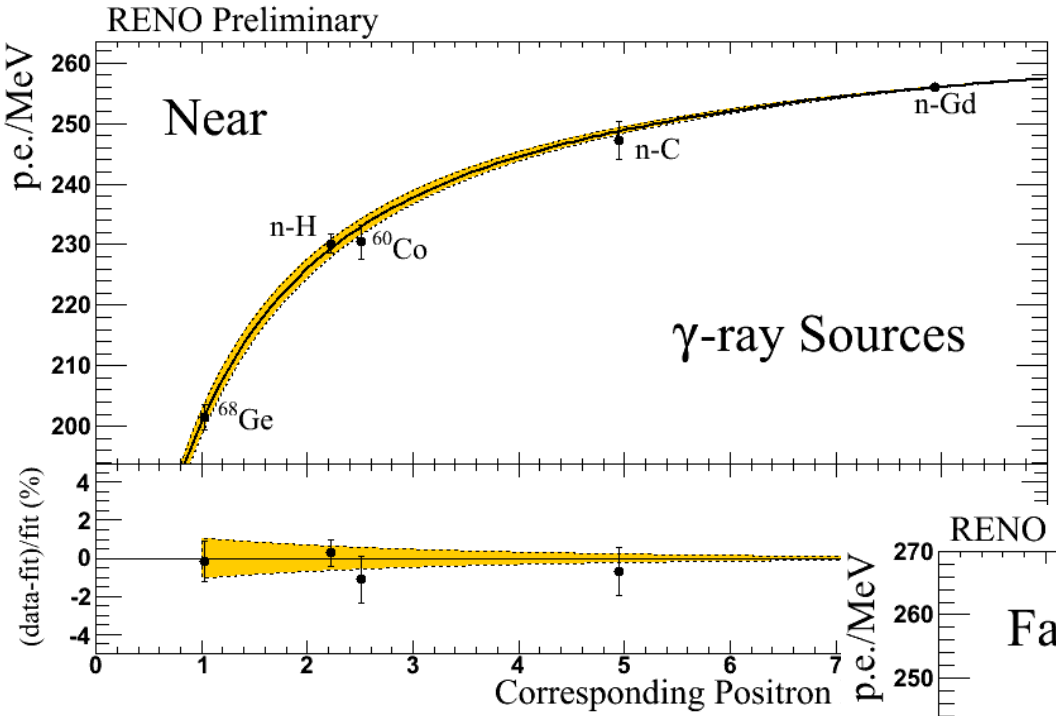
- sys. uncertainty on spectral analysis is well under-control.
- Confidence in the 5 MeV excess

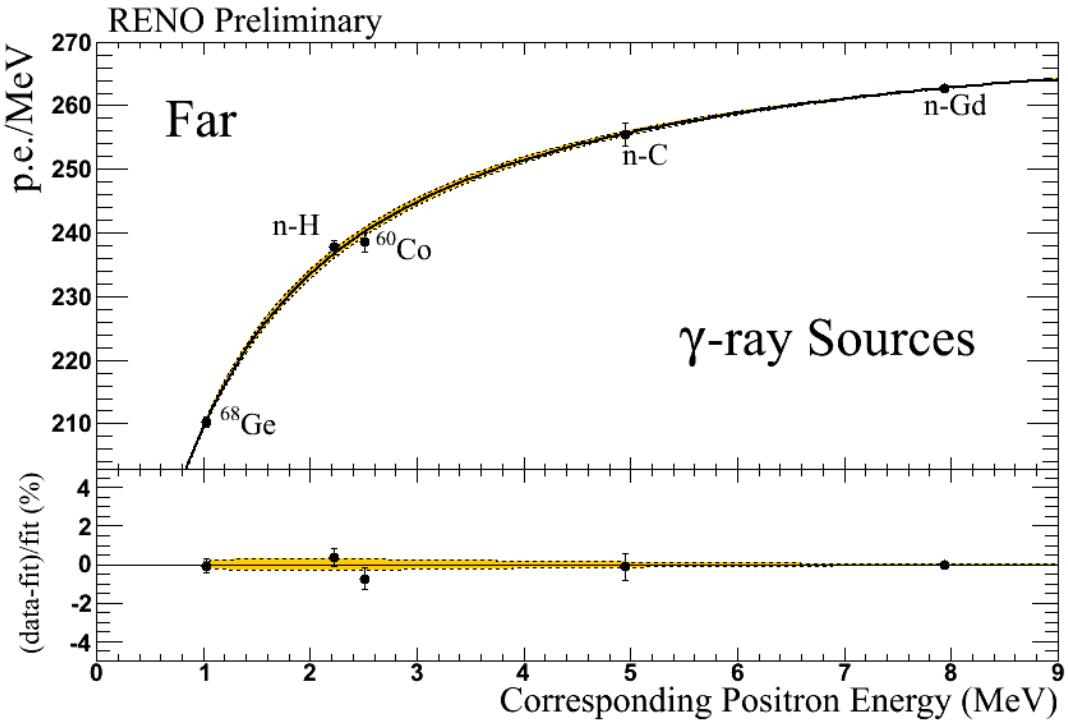
The 5 MeV Excess:

- Observed ~2% excess.
- It has strong positive correlation w/ reactor power.
  → Need re-evaluation of reactor ν model.
- Explained by additional several fission isotopes.

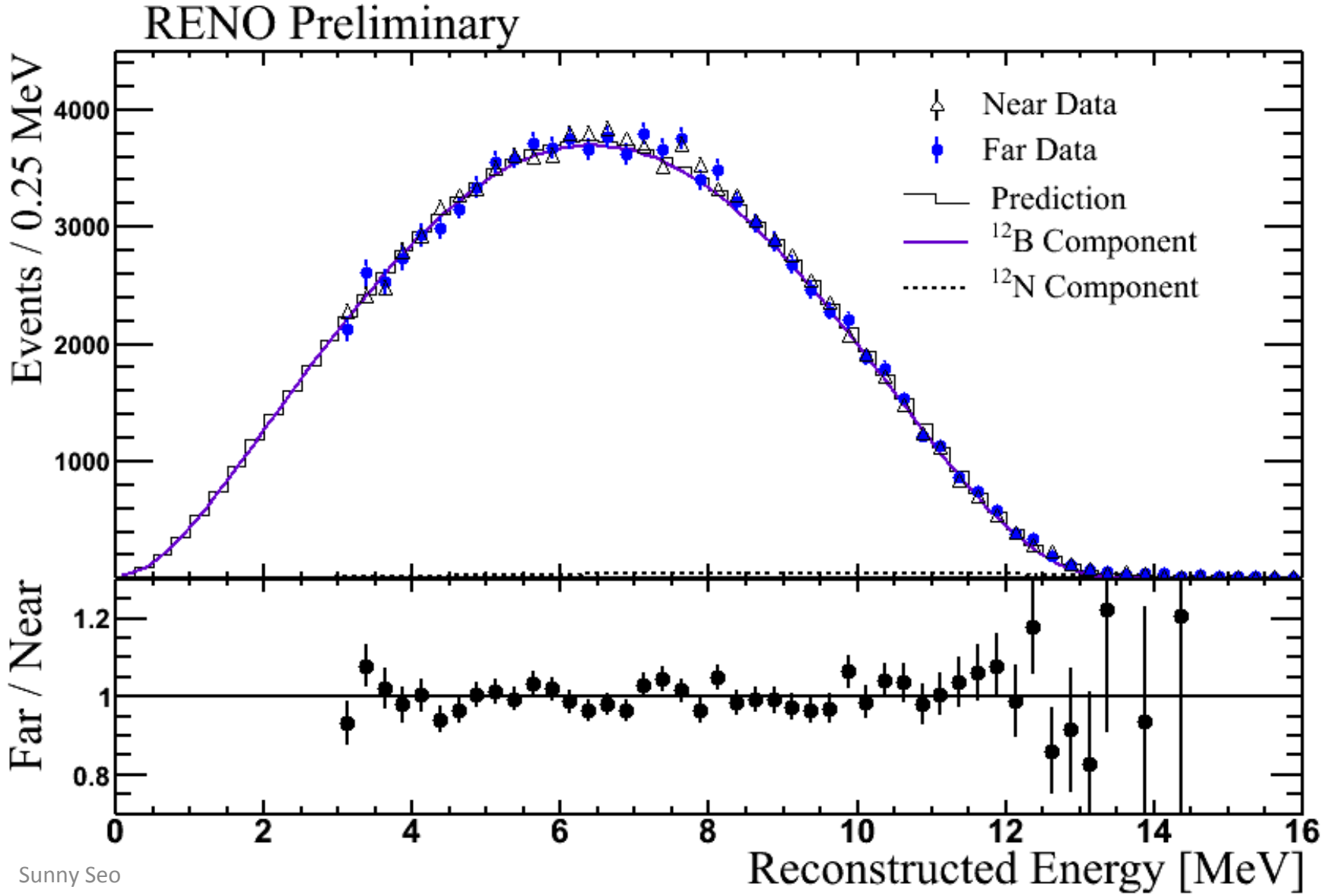
  (D. Dwyer, T. Langford PRL 114, 012502)

Energy Calibration from γ-ray Sources

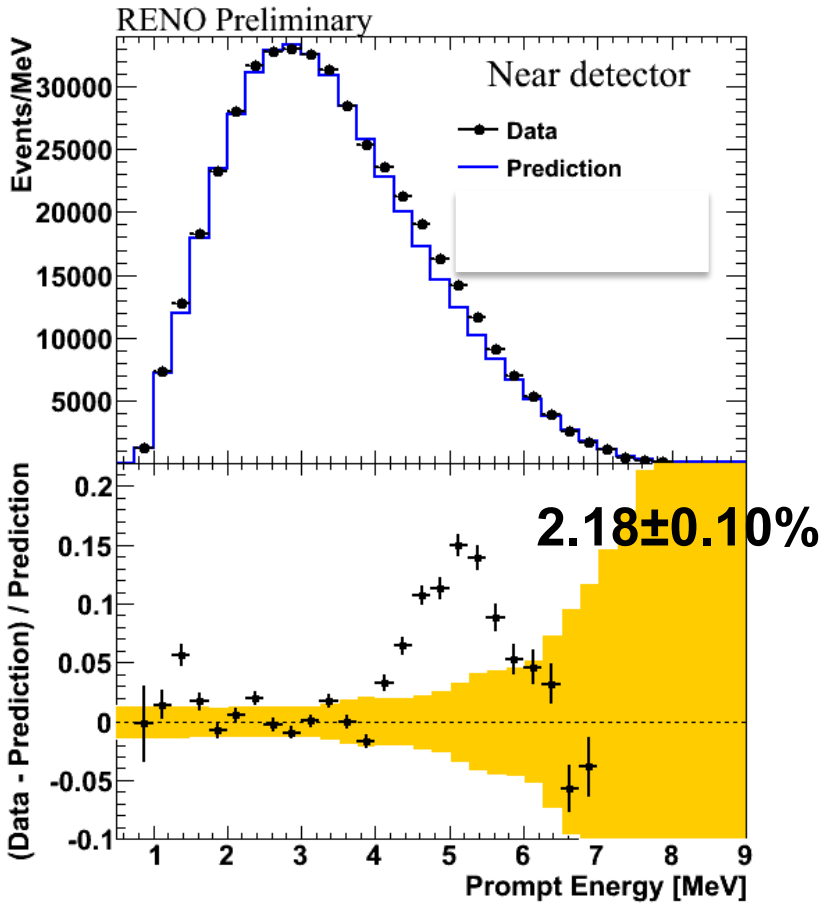


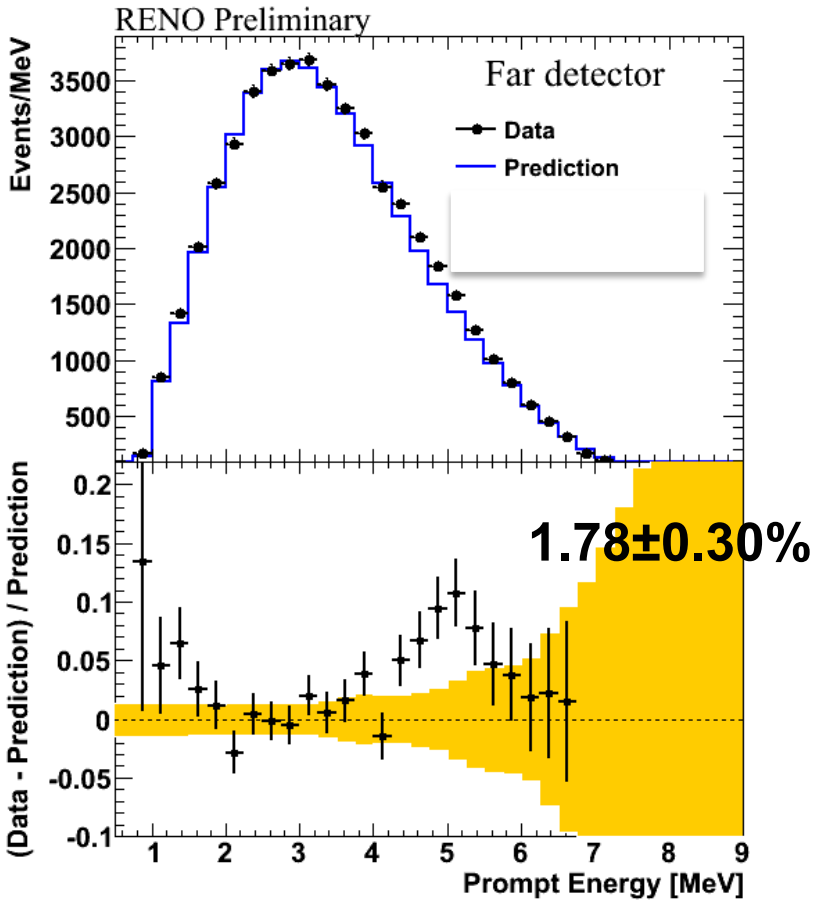


^{12}B Energy Spectrum (Near & Far)



Observation of a New Reactor Neutrino Component at 5 MeV

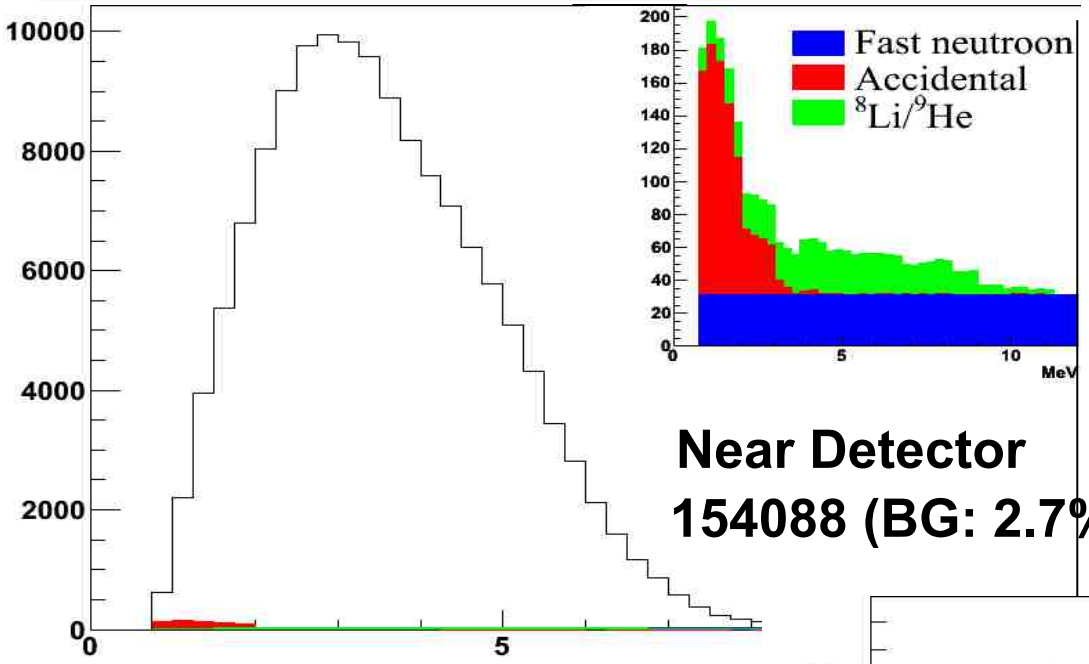




Fraction of 5 MeV excess (%) to expected flux **[2011 Huber+Mueller]**

- 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

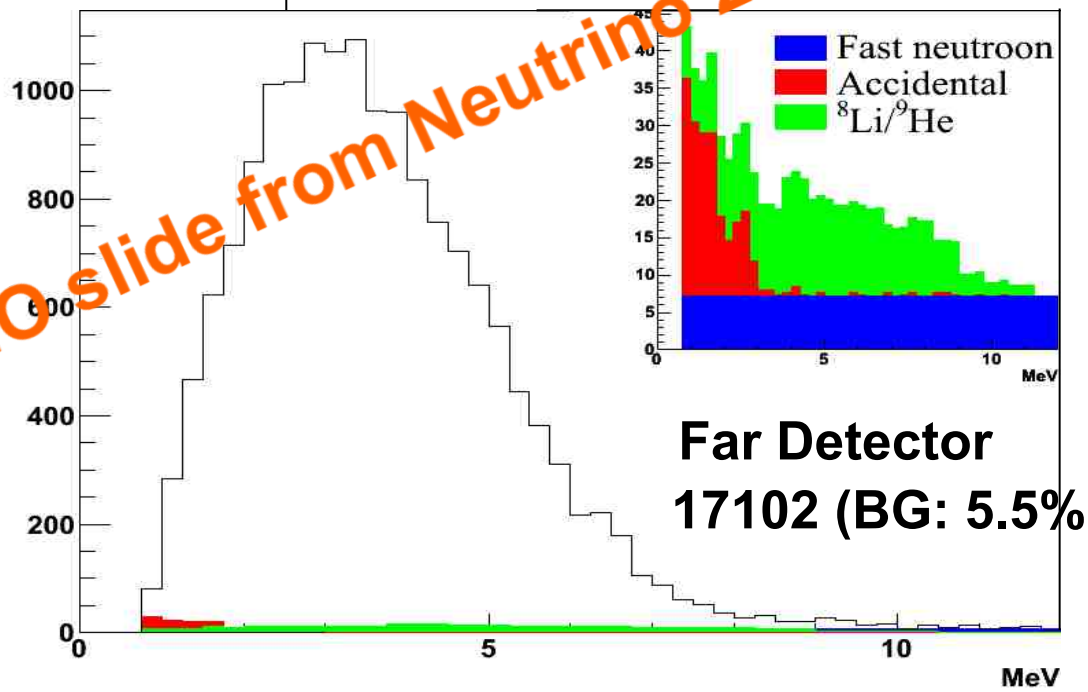


Near Detector
154088 (BG: 2.7%)

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

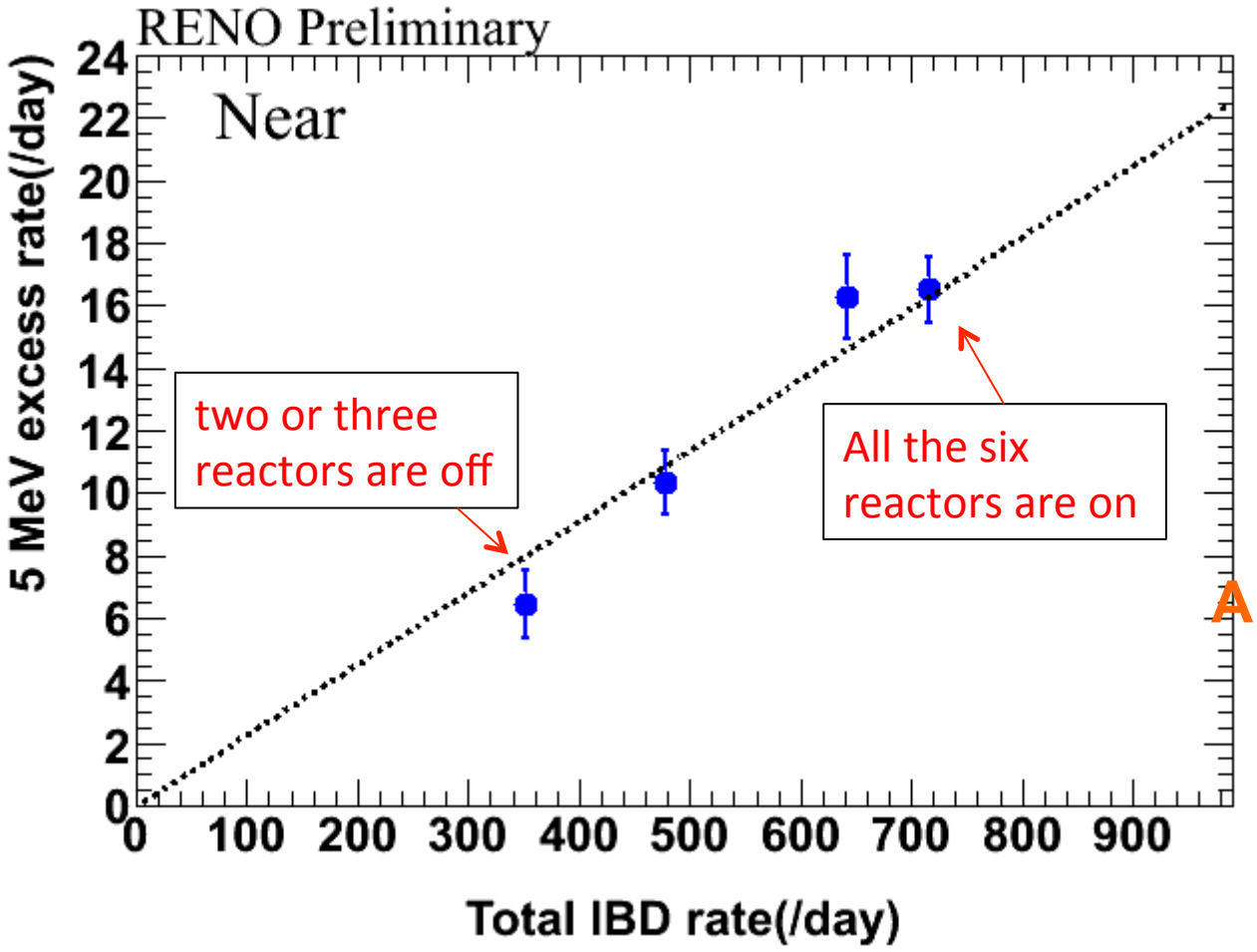
- Need more detailed energy calibration between 3 and 8 MeV using new radioactive sources.
- Any new components of background sources?
- Is the prediction of reactor neutrino spectra correct??

RENO slide from Neutrino 2012, Kyoto



Far Detector
17102 (BG: 5.5%)

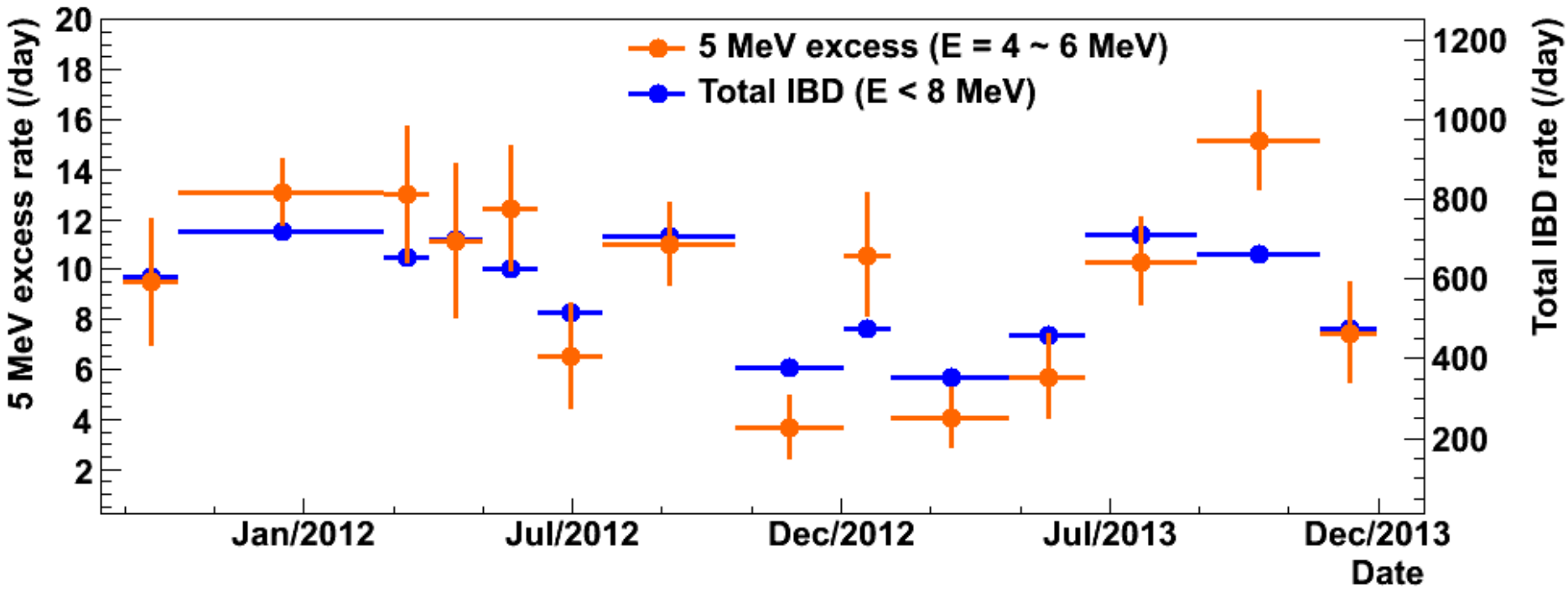
Correlation of 5 MeV Excess with Reactor Power



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

A new reactor neutrino component !!

Correlation of 5 MeV Excess with Reactor Power



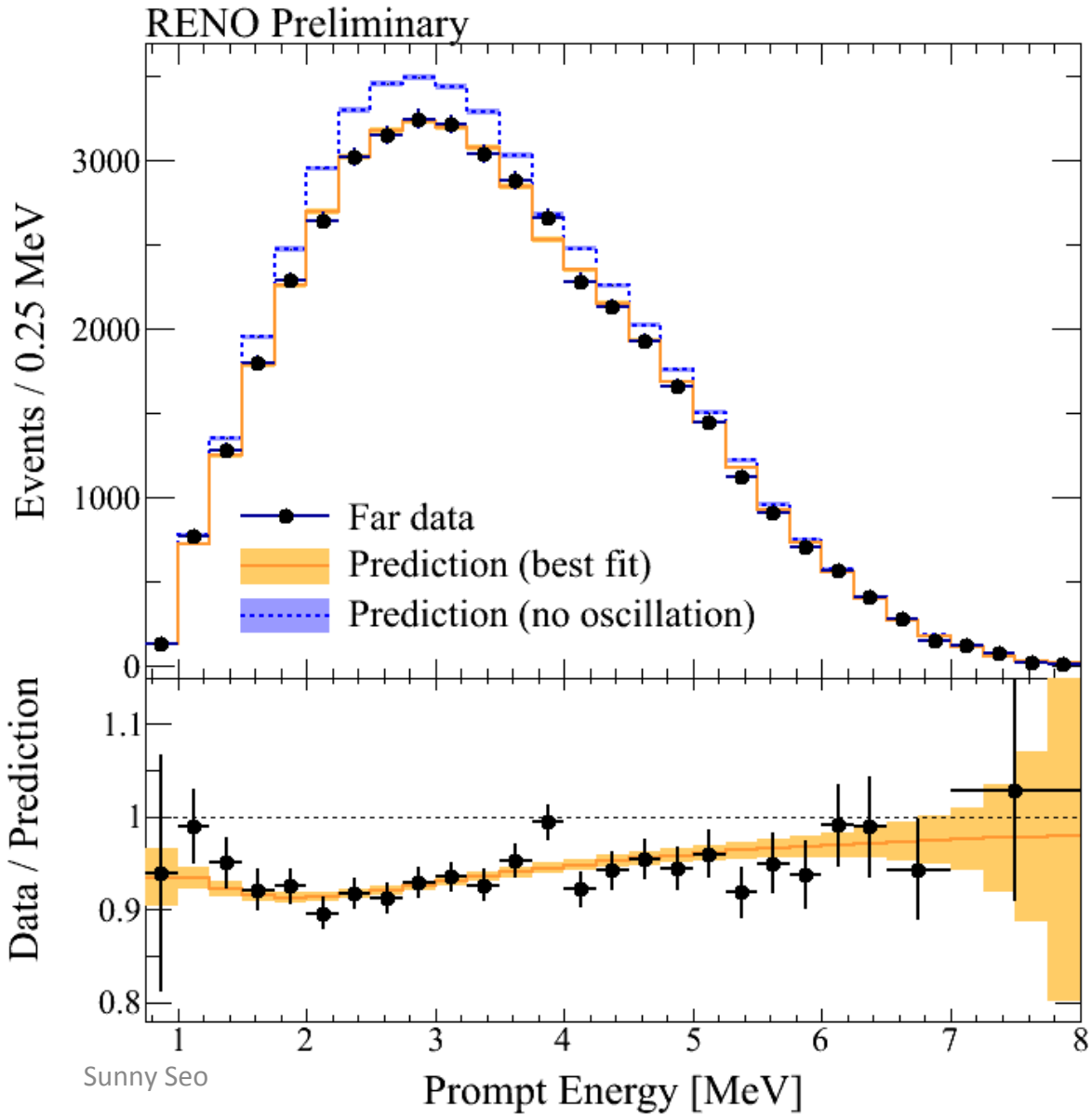
Shape Analysis Status

Δm^2 measurement is almost done.

- Systematic uncertainty is well understood and in well under-control by now.
- We will soon publish our paper.

Stay tuned !

Far/Near Shape Analysis for Δm^2_{ee}

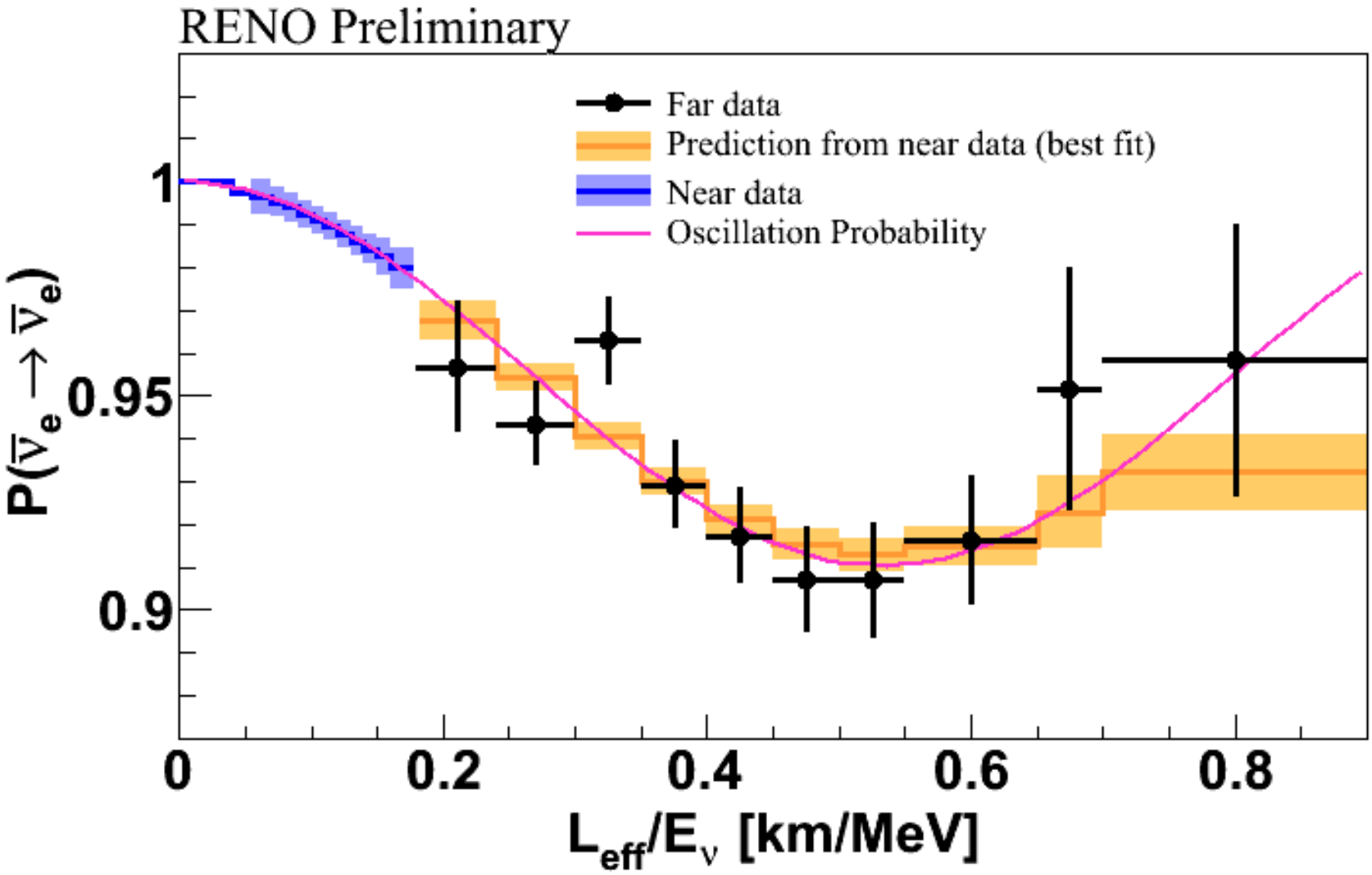


Far/Near Rate+Shape

- $\mathrm{Sin}^2 2\theta_{13}$ = ?
- $|\Delta m^2_{ee}|$ = ?

→ **Coming Soon !!**

Reactor Neutrino Disappearance on L/E

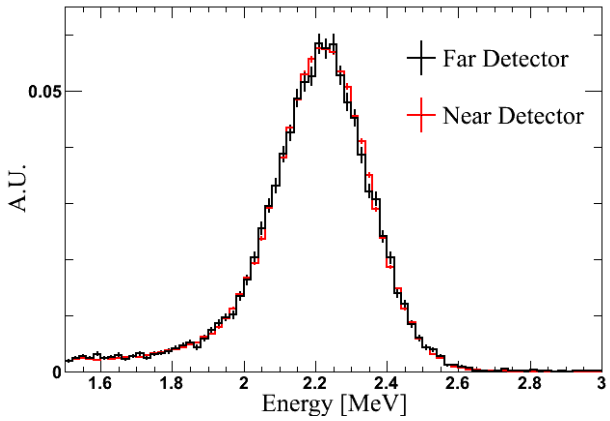


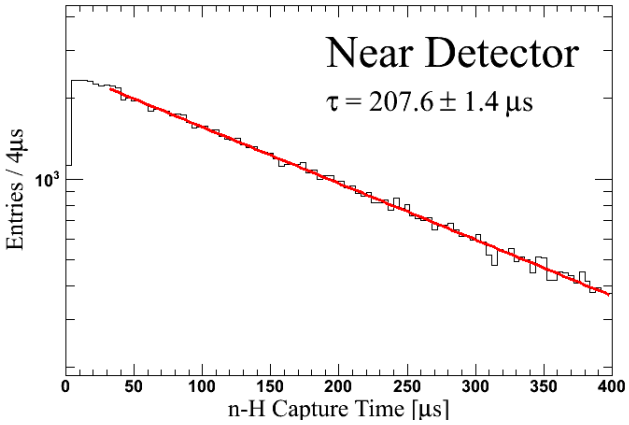
n-H Analysis

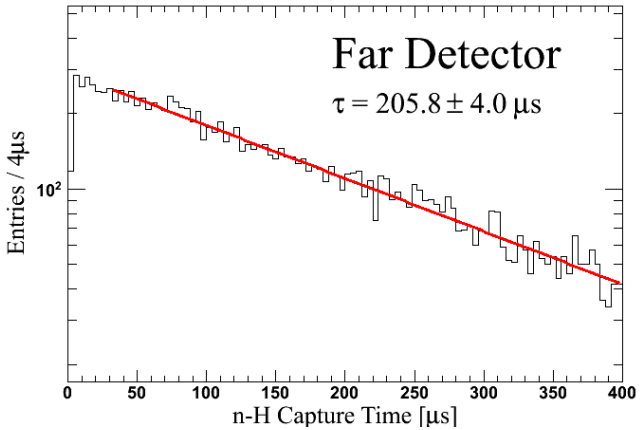
- **Independent θ_{13} measurement**
- **Improved since Neutrino 2014**
  by better understanding of our background.

IBD Sample with n-H

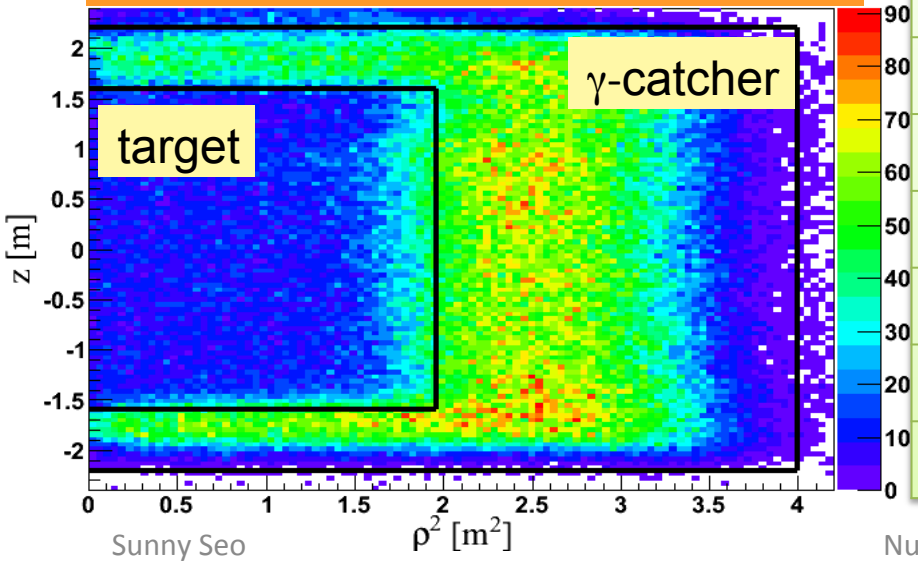
preliminary







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

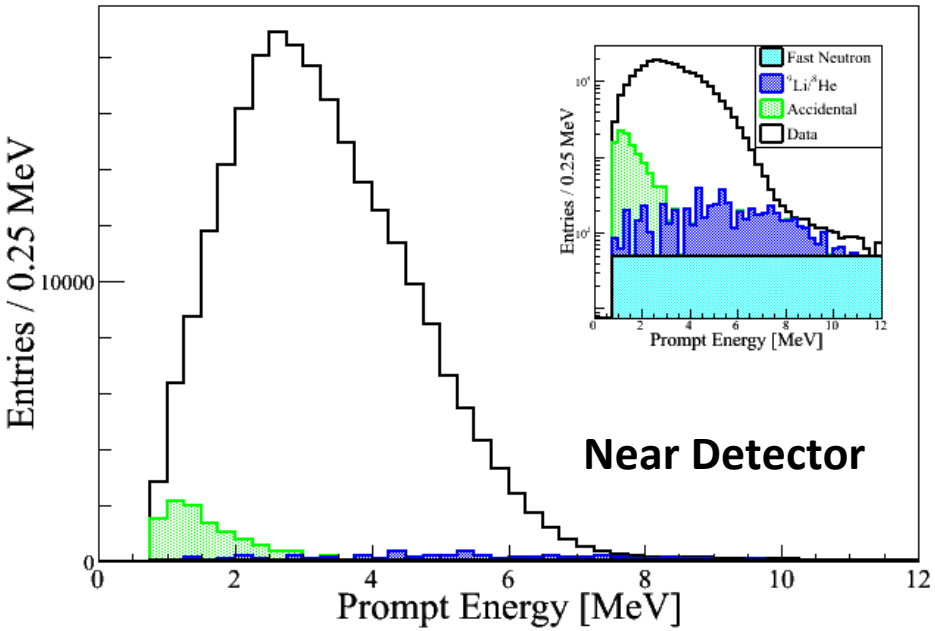
(B data set, ~400 days)

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

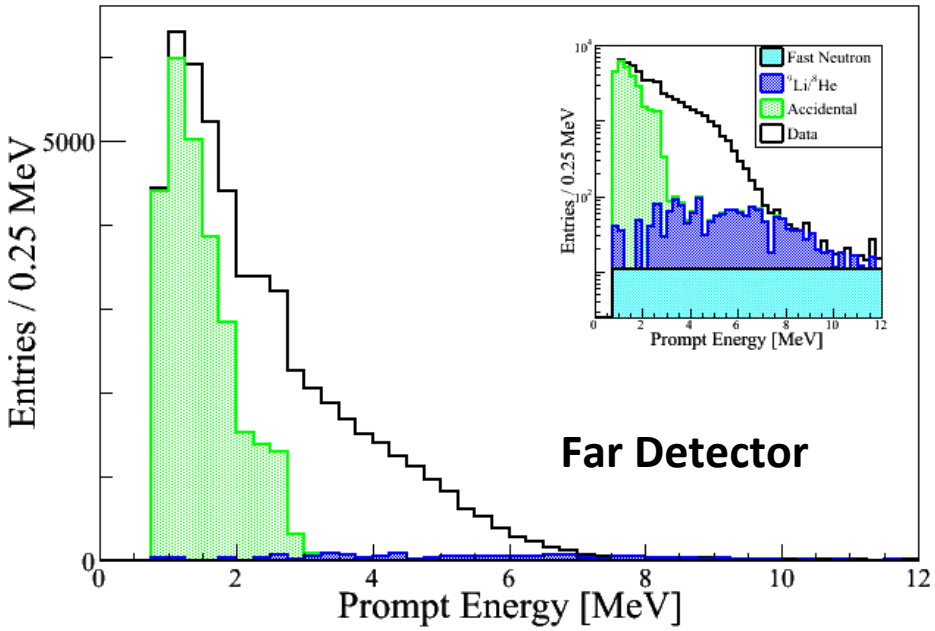
(Neutrino 2014) $\sin^2 2\theta_{13} = 0.095 \pm 0.015(\text{stat.}) \pm 0.025(\text{syst.})$

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

preliminary



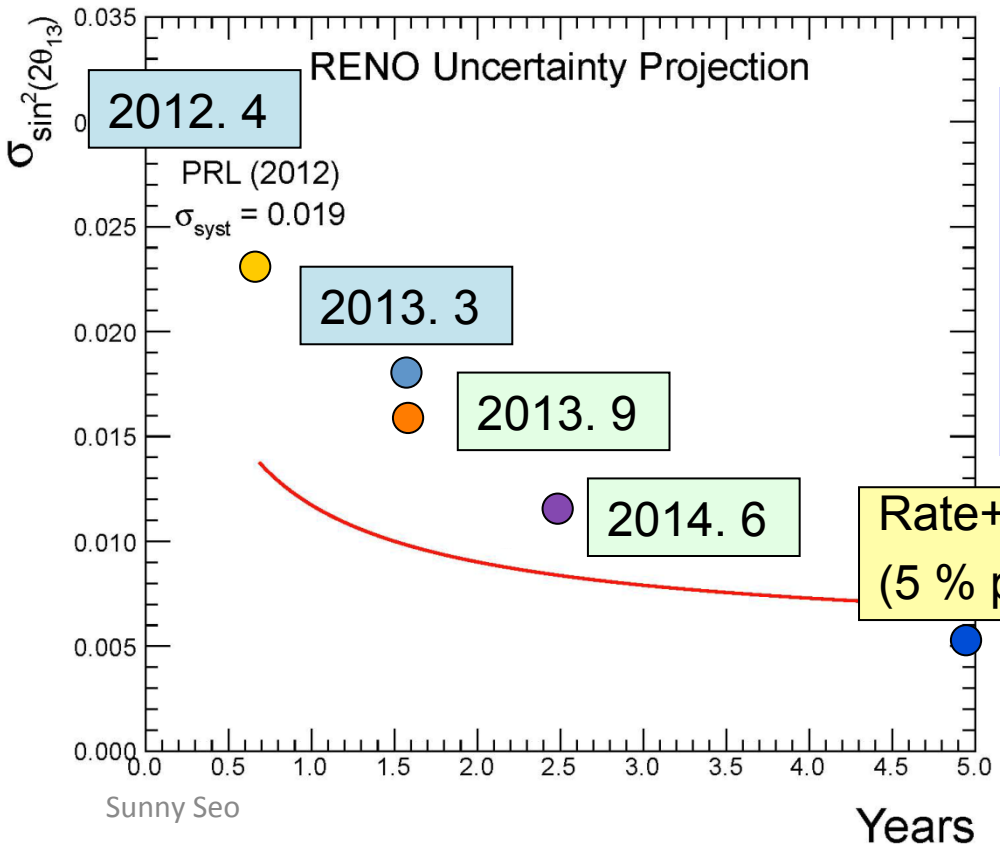
preliminary



RENO's Projected Sensitivity of θ_{13}

Singapore 2015 $\sin^2 2\theta_{13} = 0.090 \pm 0.008(stat.) \pm 0.008(syst.)$

(~800 days) 0.090 ± 0.011 (8.2 σ) (11 % precision) → ± 0.005 (18 σ) (in 3 years) (5 % precision)



- 5 years of data :

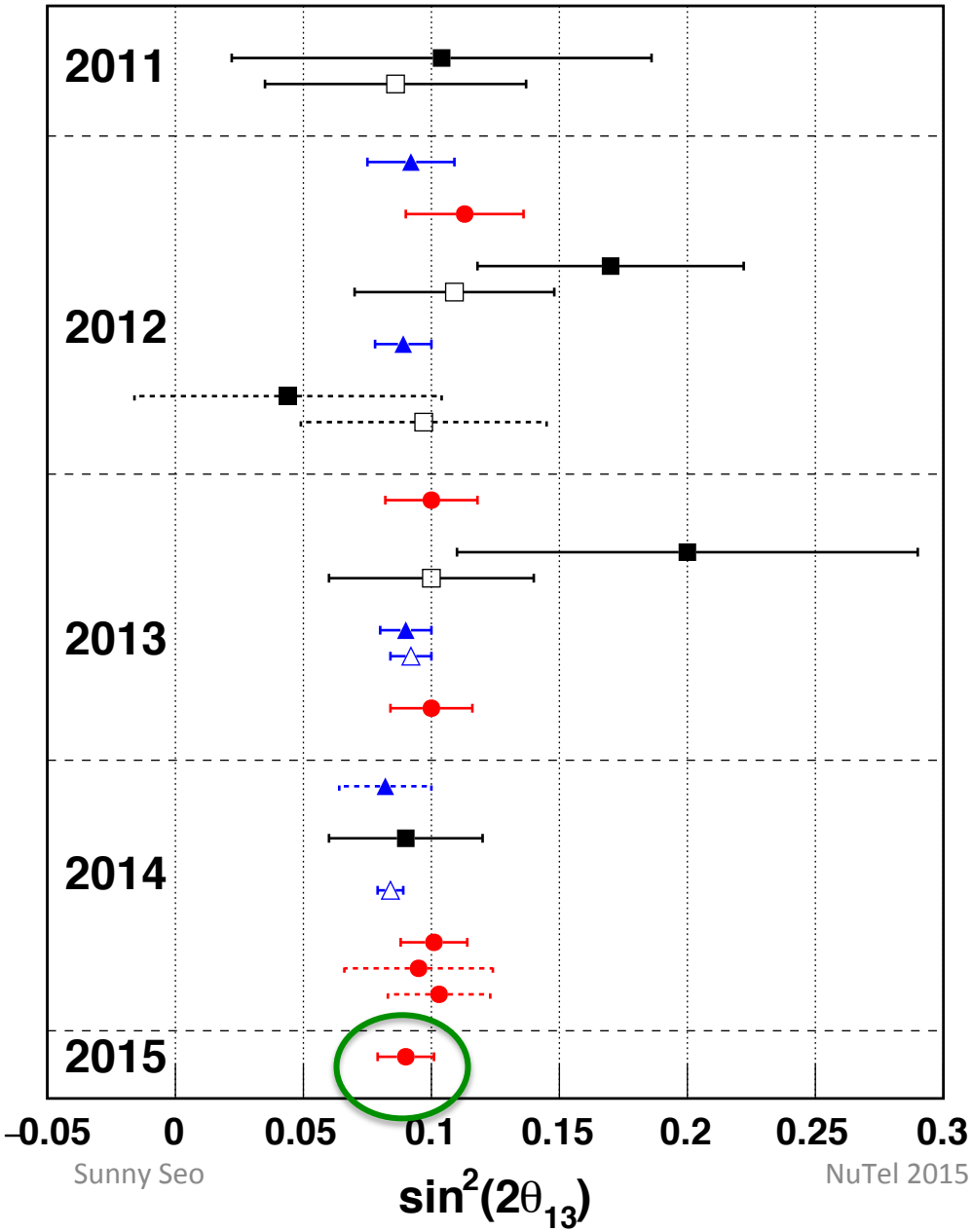
(1) Rate-only: ±7%

- stat. error : ±0.008 → ±0.005

- syst. error : ±0.010 → ±0.005

(2) Rate+shape: ±5%

A Brief History of θ_{13} from Reactor Experiments



DC: 97 days R+S	[1112.6353]
DB: 49 days	[1203.1669]
RENO: 222 days	[1204.0626]
DC: 228 days R+S	[1207.6632]
DB: 139 days	[1210.6327]
DC: n-H R+S	[1301.2948]
RENO: 403 days	[NuTel2013]
DC: RRM analysis **R+S**	[1305.2734]
DB: 190 days **R+S**	[1310.6732]
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]
384 days n-H	[NOW 2014]
RENO: 795 days	**[Singapore 2015]**

Summary

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

- New measurement of θ_{13} by rate-only analysis

$$\sin^2 2\theta_{13} = 0.090 \pm 0.008(\text{stat}) \pm 0.008(\text{syst})$$ (preliminary)

- Shape analysis for Δm^2 is being finalized… (Stay tuned !!)

- First result on n-H IBD analysis

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

- $\sin^2(2\theta_{13})$ to 5% accuracy within 3 years

→ will provide the first glimpse of δ_{CP}. If accelerator results are combined.

- Sterile neutrino search analysis is on-going.

Good News

- **$ 2 M grant** from Samsung was awarded to **RENO-50 R&D** for 3 years.

This grant will be used for R&D of

① Liquid scintillator purification.

② High QE PMT performance to reach 3% resolution.

→ RENO-50 needs you !

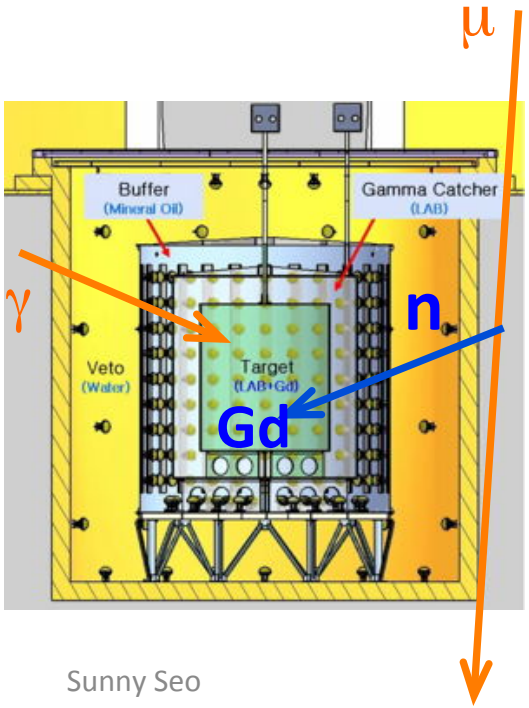
❖ **See RENO-50 Poster by Dr. Hyunkwan Seo.**

Backup slides

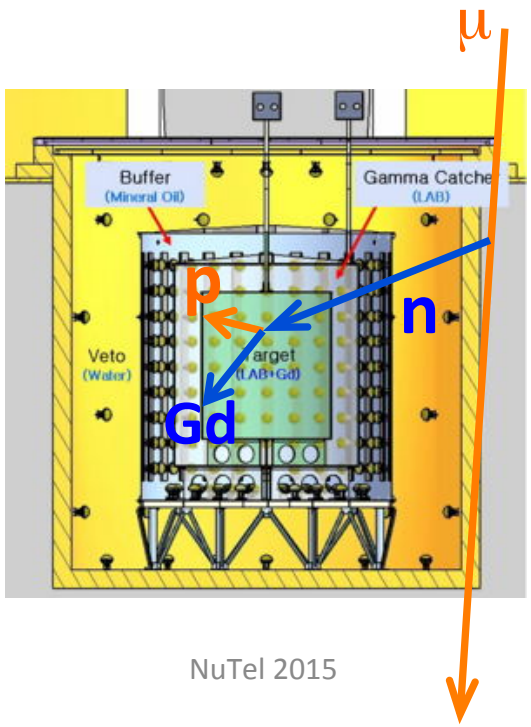
Backgrounds

- Accidental coincidence between prompt and delayed signals
- 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

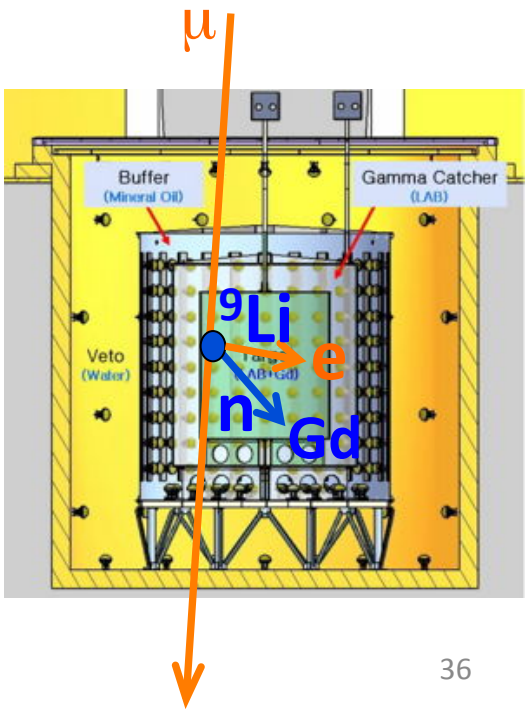
Accidentals



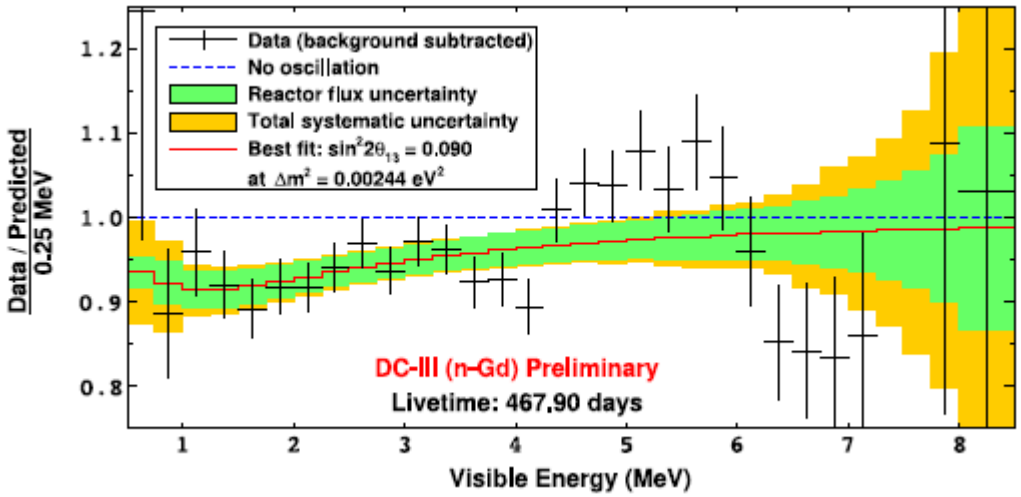
Fast neutrons



^{9}Li/^{8}He β-n followers

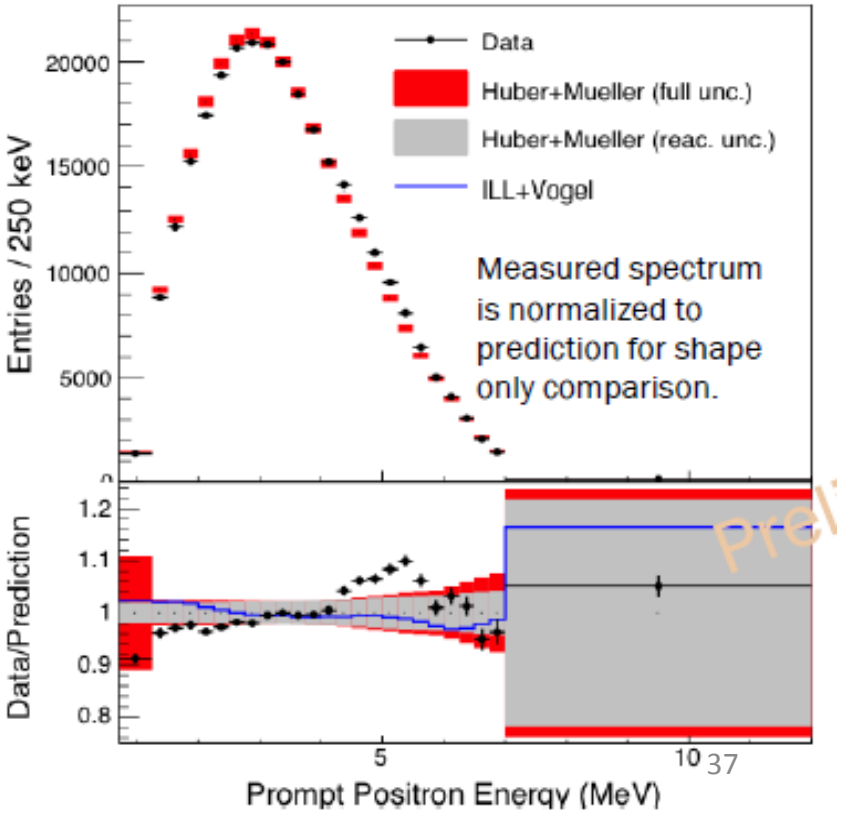


The 5 MeV Excess Seen at Double-Chooz and Daya Bay

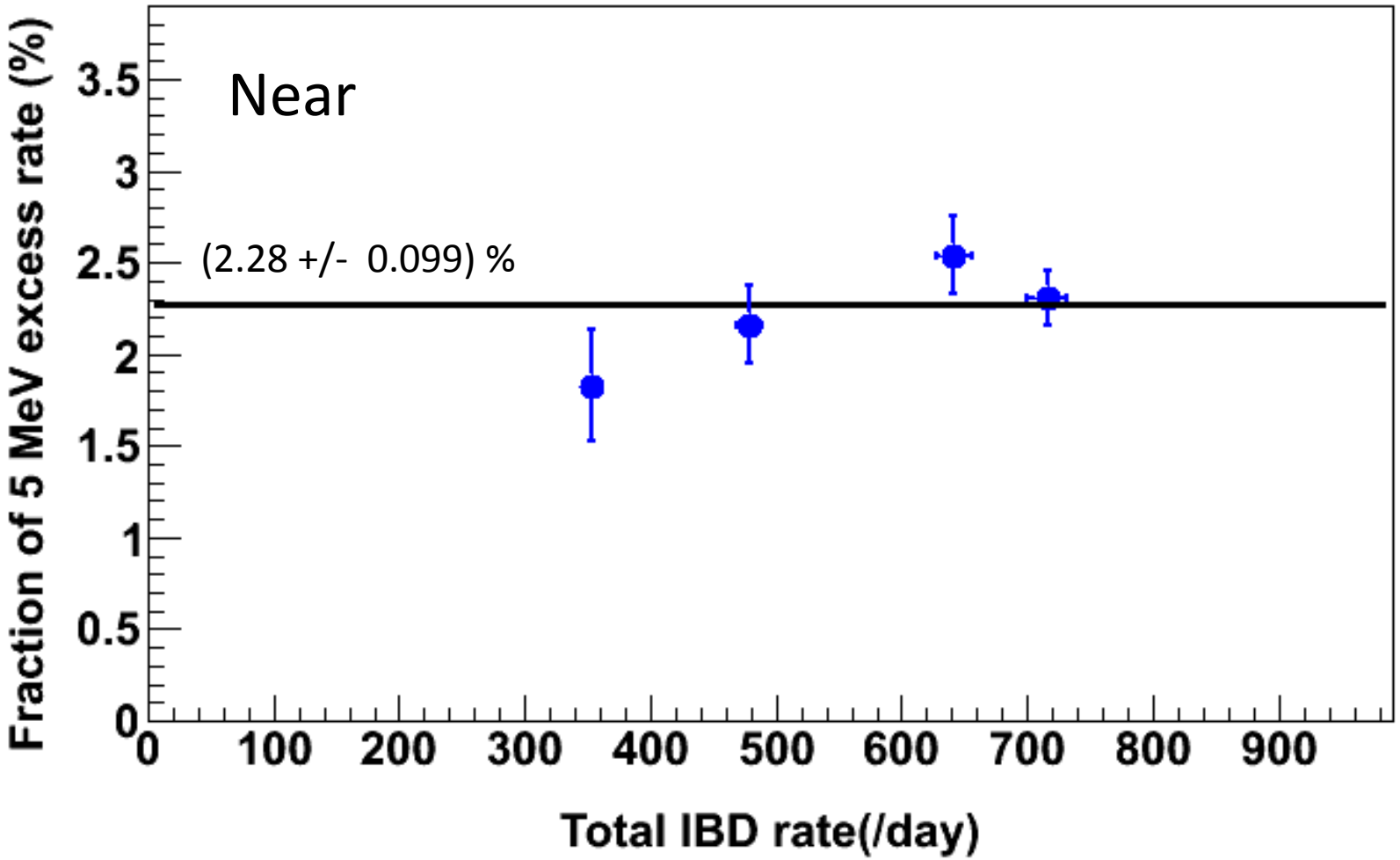


Double-Chooz, Neutrino 2014

Daya Bay, ICHEP 2014

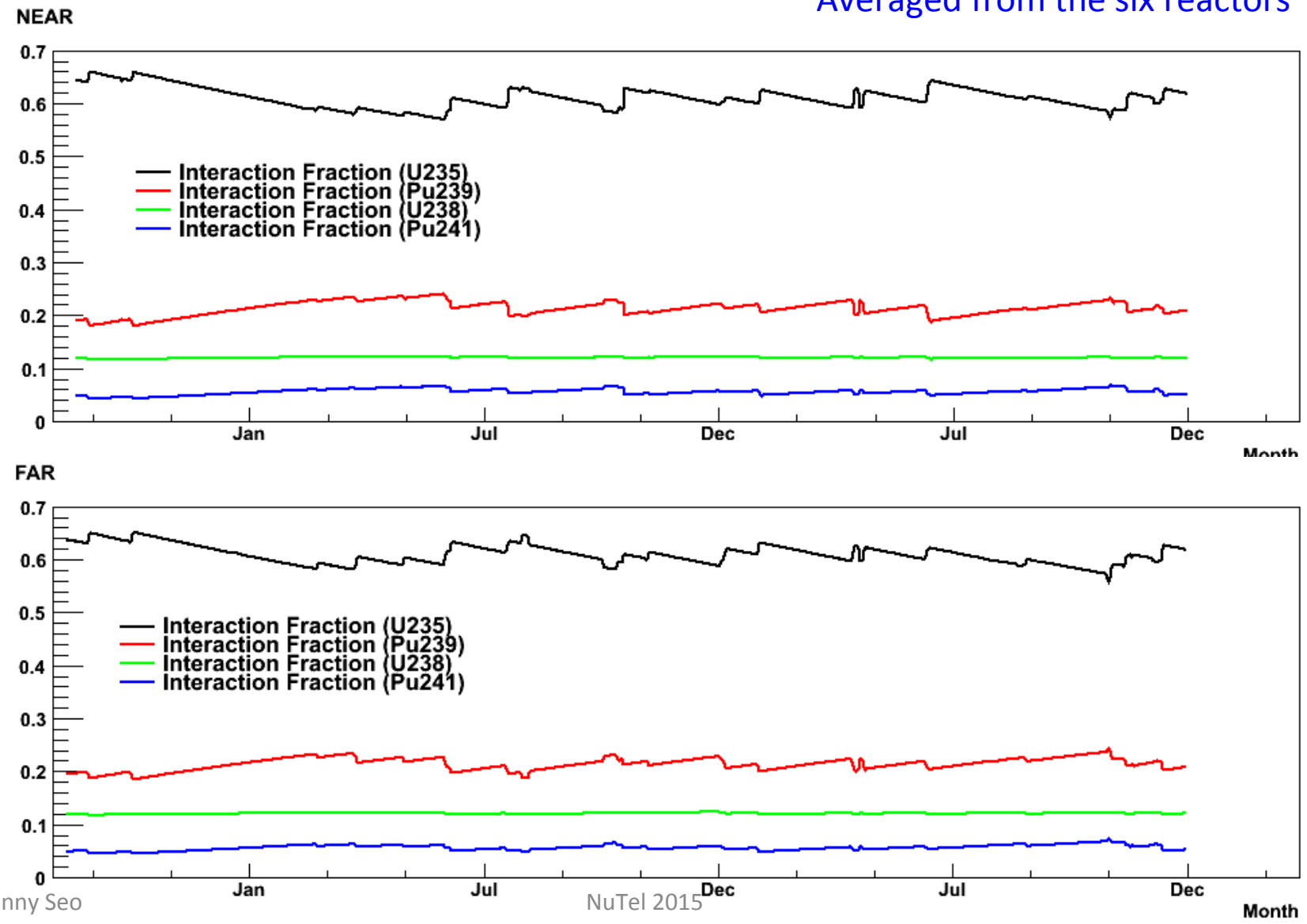


Constant Fraction of 5 MeV Excess vs. IBD Rate

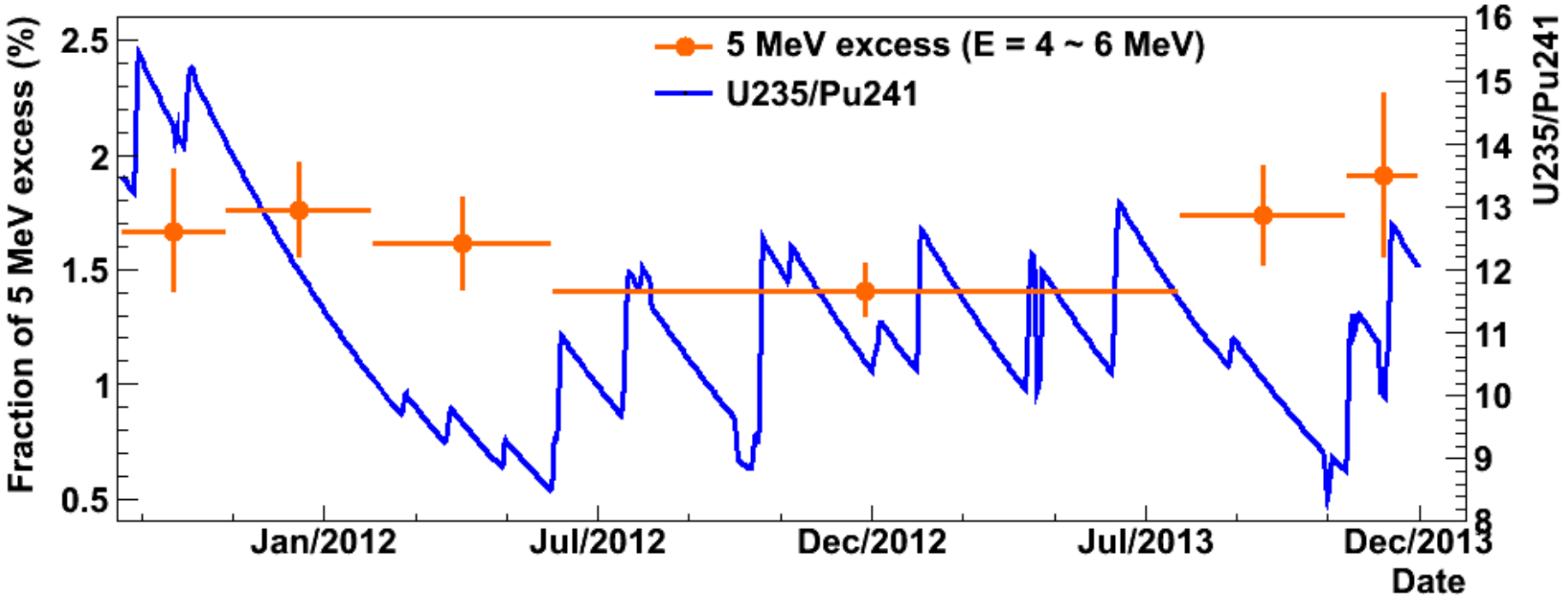


Interacting Reactor Isotope Fraction

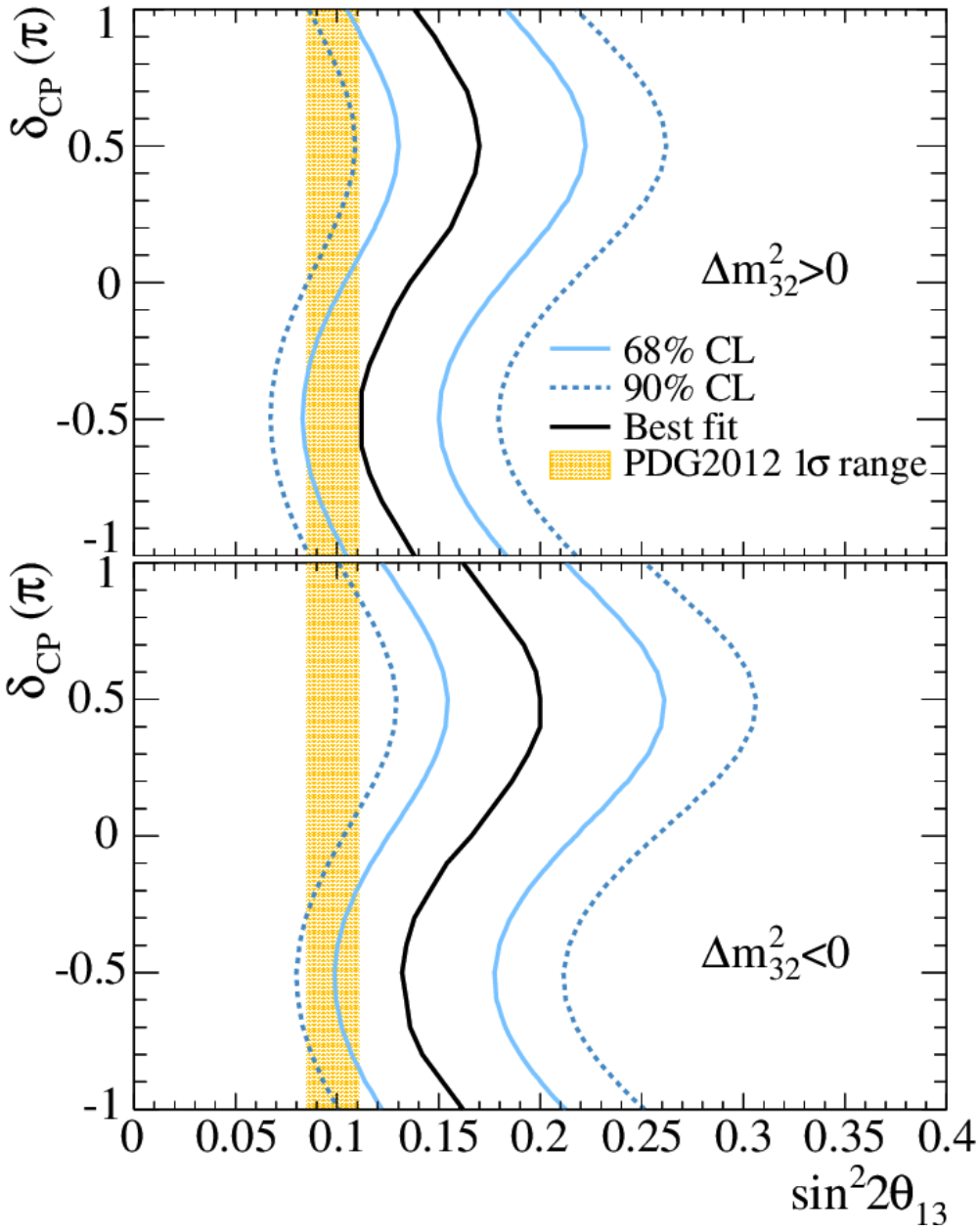
Averaged from the six reactors



Fraction of 5 MeV Excess vs. Isotope Fraction (U235/Pt241)



θ_{13} from Reactor and Accelerator Experiments



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

Best overlap is for Normal hierarchy & $\delta_{CP} = -\pi/2$

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