Recent Reactor-Based Measurements of θ_{13}

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IceCube Particle Astrophysics Symposium

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Disclaimer

I am a member of the Daya Bay Collaboration.

Reactor Antineutrino Experiments with 1-2 km baselines are sensitive to θ_{13}

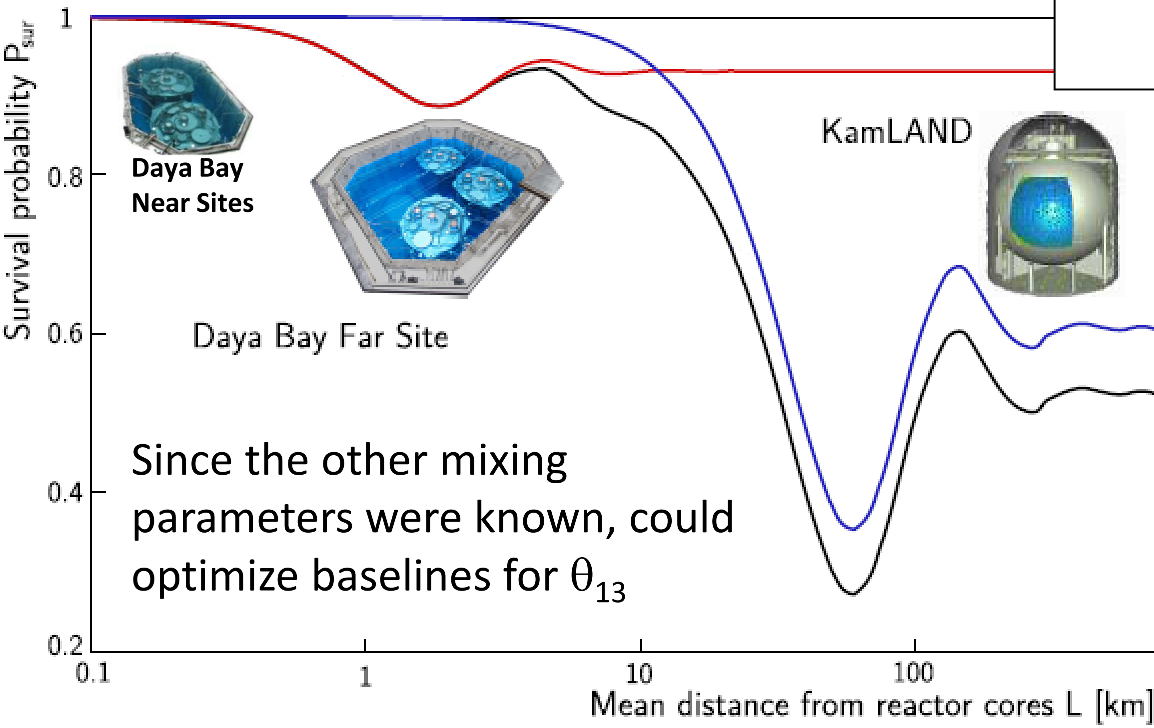
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} e^{ia_1/2}\nu_1 \\ e^{ia_2/2}\nu_2 \\ \nu_3 \end{pmatrix}$$

$c_{ij} = \cos(\theta_{ij})$;
$s_{ij} = \sin(\theta_{ij})$;

U_{MNSP} Matrix
Maki, Nakagawa, Sakata, Pontecorvo

$$P_{sur} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{32} \frac{L}{4E}\right) - \sin^2 2\theta_{12} \cos^4 2\theta_{13} \sin^2\left(\Delta m^2_{21} \frac{L}{4E}\right)$$

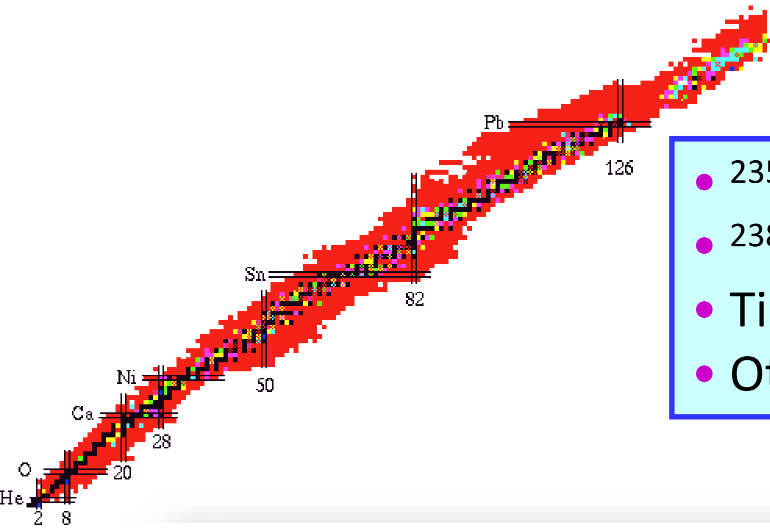
$$\Delta m^2_{32} \approx \Delta m^2_{31} \approx \Delta m^2_{atm}$$



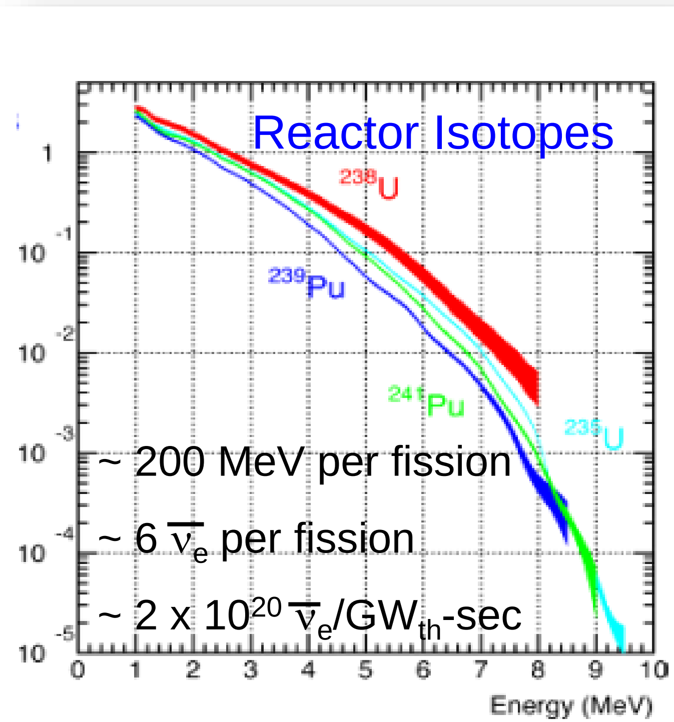
Since the other mixing parameters were known, could optimize baselines for θ_{13}

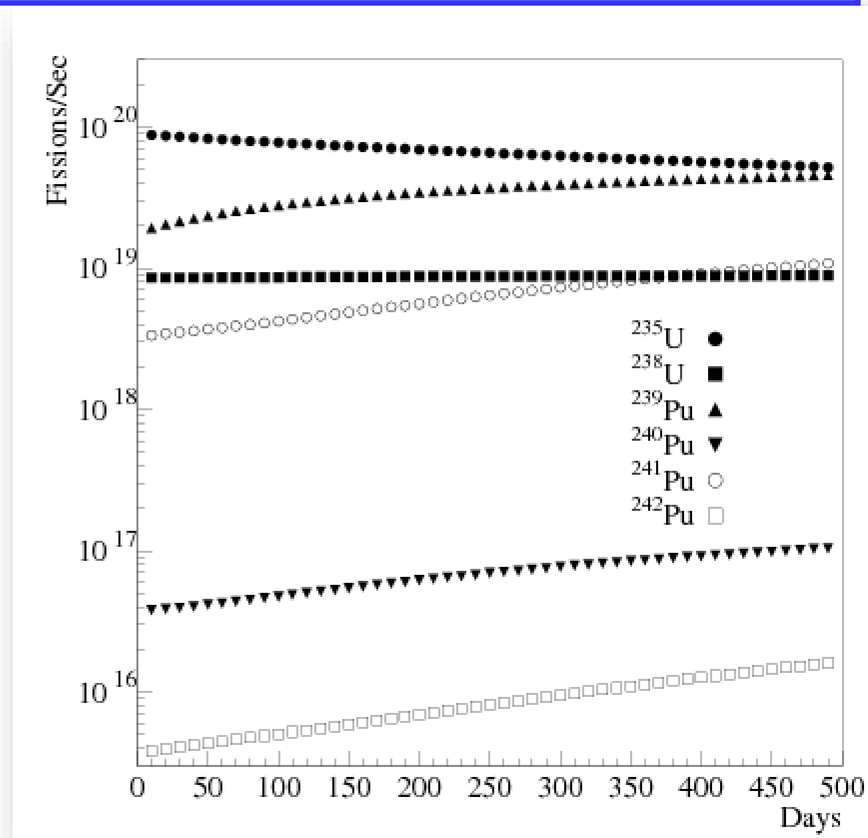
Why measure θ_{13}?
- (was) Least-known mixing angle
- Access to ν mass hierarchy
- Access to CP-violating phase δ

The Reactor Neutrino Flux and Spectrum



- ^{235}U, ^{239}Pu, ^{241}Pu from β ***measurements***
- ^{238}U calculated
- Time dependence due to fuel cycle
- Other contributions: spent fuel, nonequilibrium



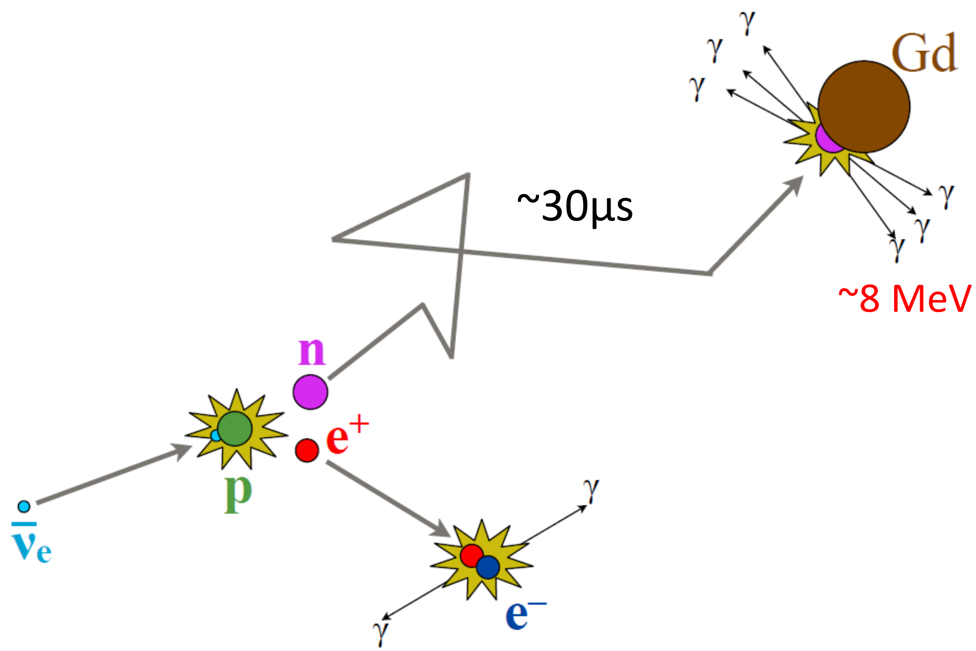


Modified from slide by R. McKeown

Inverse beta decay has a distinctive signature

Inverse β-decay (IBD):

$$\bar{\nu}_e + p \rightarrow e^+ + n$$
$$\downarrow$$
$$n + {}^{x}Gd \rightarrow {}^{x+1}Gd + \gamma$$



Prompt positron:

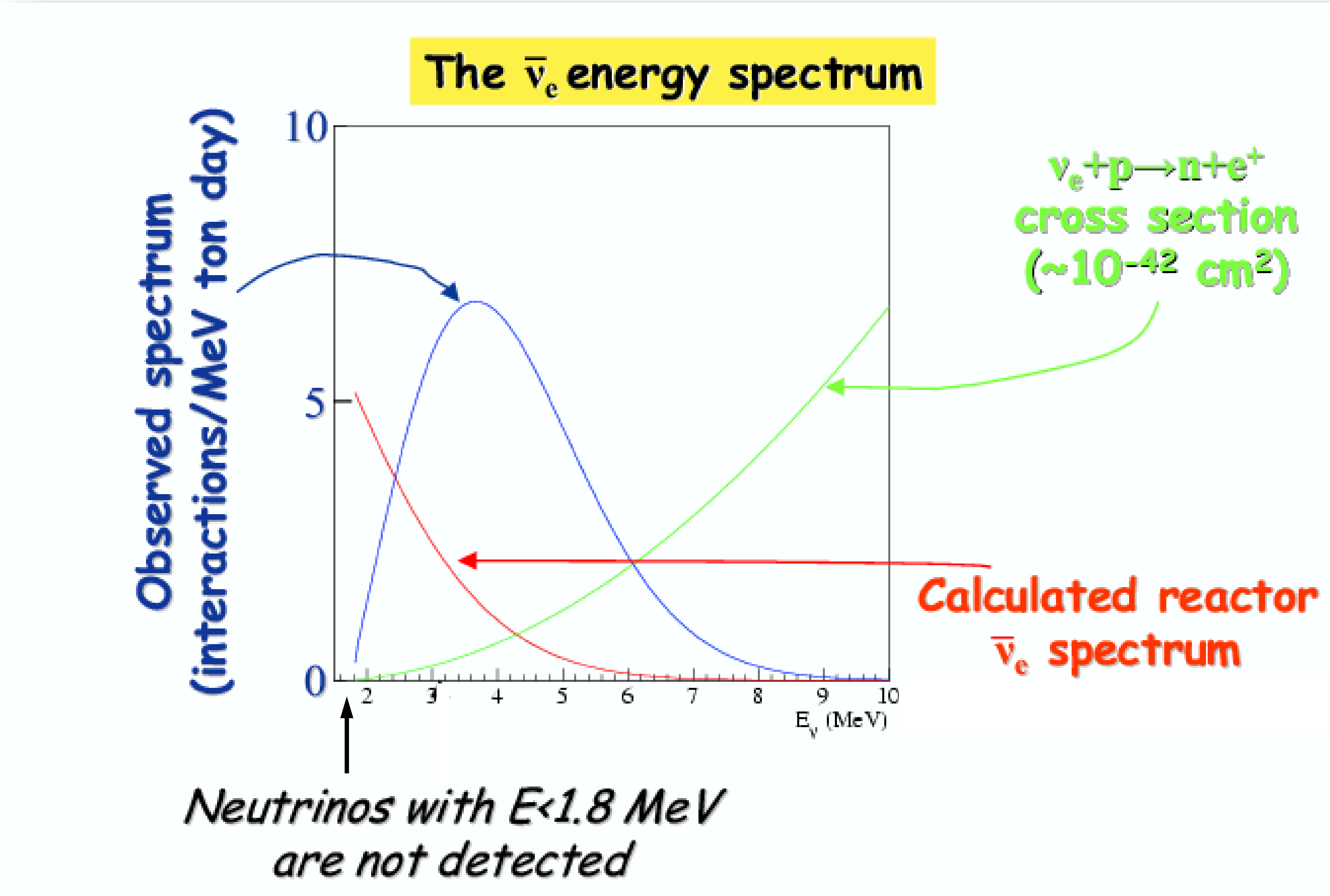
Carries antineutrino energy

$E_{e+} \approx E_{\nu} - 0.8$ MeV

Delayed neutron capture:

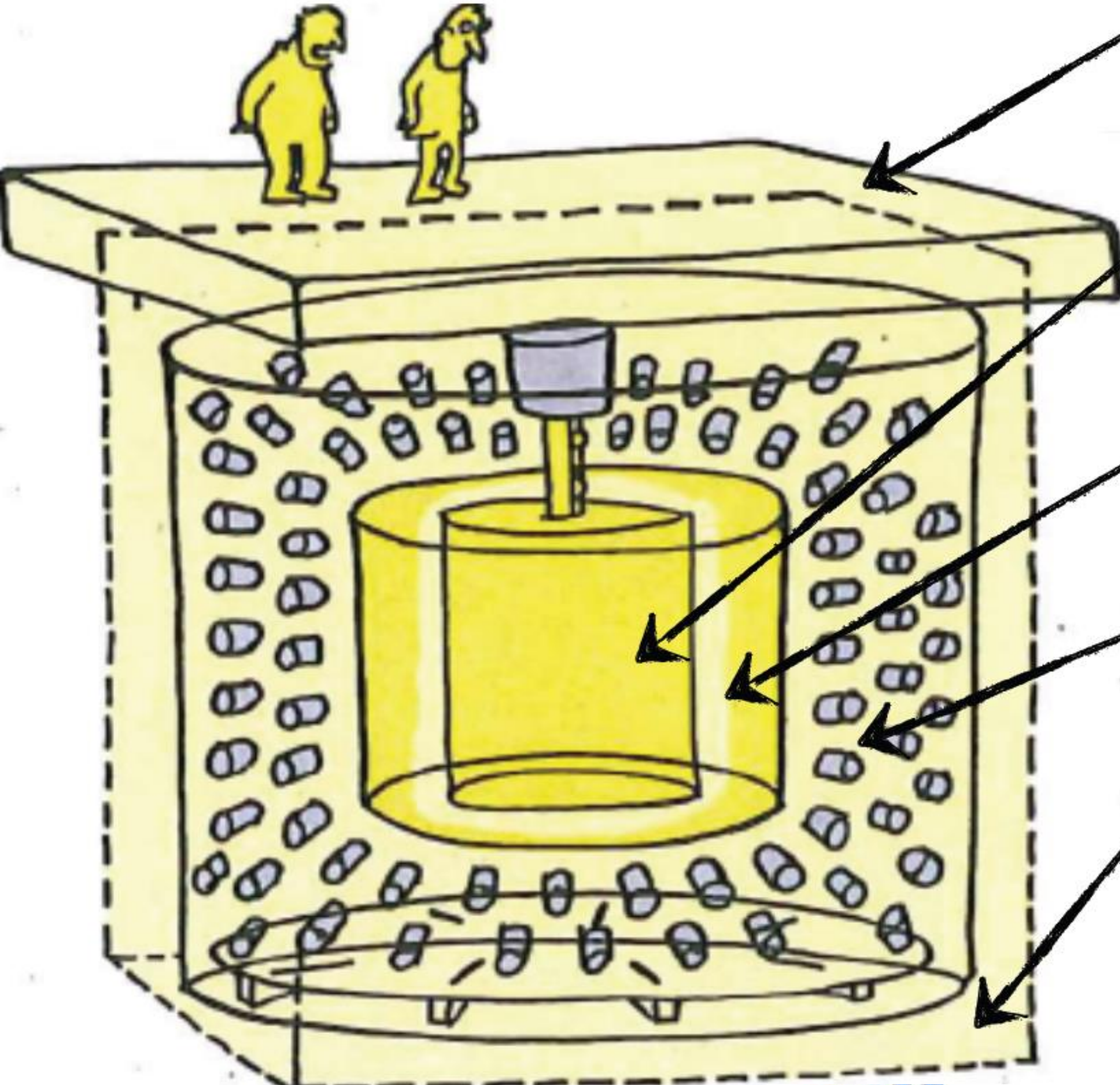
Efficiently tags antineutrino signal

Prompt + Delayed coincidence provides distinctive signature



Slide by R. McKeown

Detectors are optimized for inverse beta decay observation



Outer μ-Veto (**OV**)

ν-Target (NT)

Gd-doped Liquid-Scintillator

γ-Catcher (GC)

Liquid-Scintillator

Light Buffer

Oil (negligible scintillation)

Inner μ-Veto (**IV**)

Inert γ-Shield

15cm of steel (around all detector)

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

$$\downarrow$$

$$n + {}^{x}Gd \rightarrow {}^{x+1}Gd + \gamma$$

Anatael Cabrera (CNRS-IN2P3 & APC)

Daya Bay Experiment Site

Adjacent mountains with horizontal access provide 860 (250) m.w.e cosmic shielding.

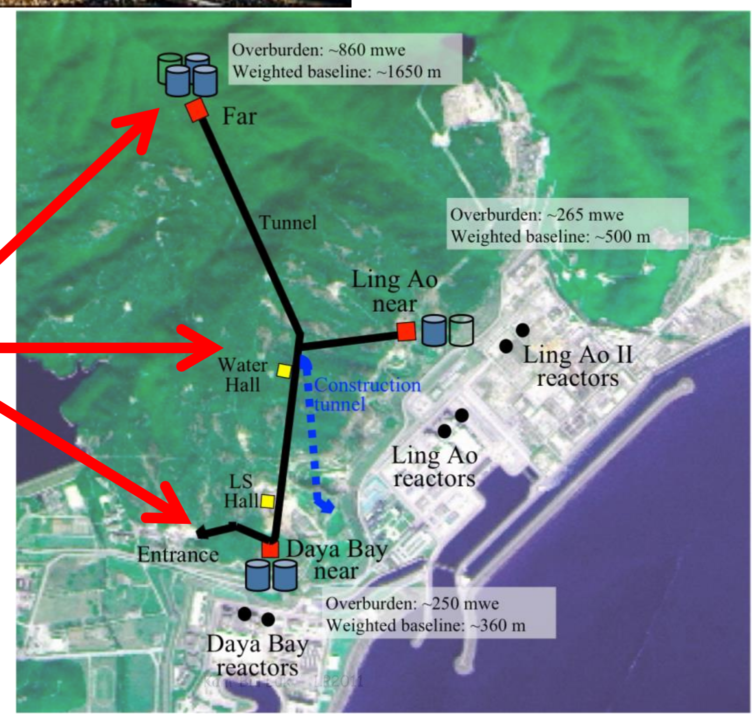
Daya Bay

Ling Ao I + II

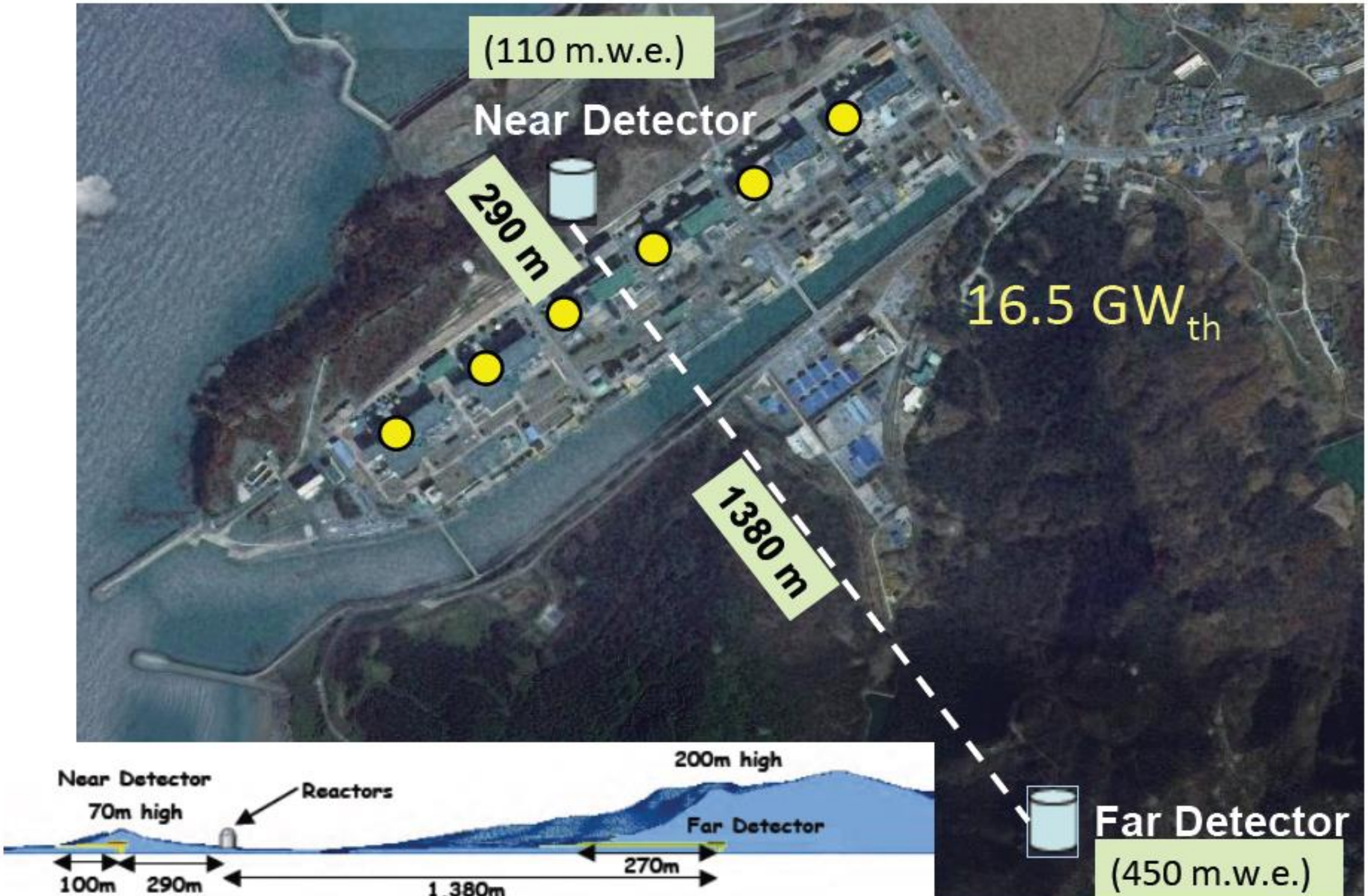
6 commercial reactor cores with 17.4 GW_{th} total power.

6(8) Antineutrino Detectors (ADs) give 120(160) tons total target mass.

Via GPS and modern theodolites, relative detector positions are known to 3 cm.

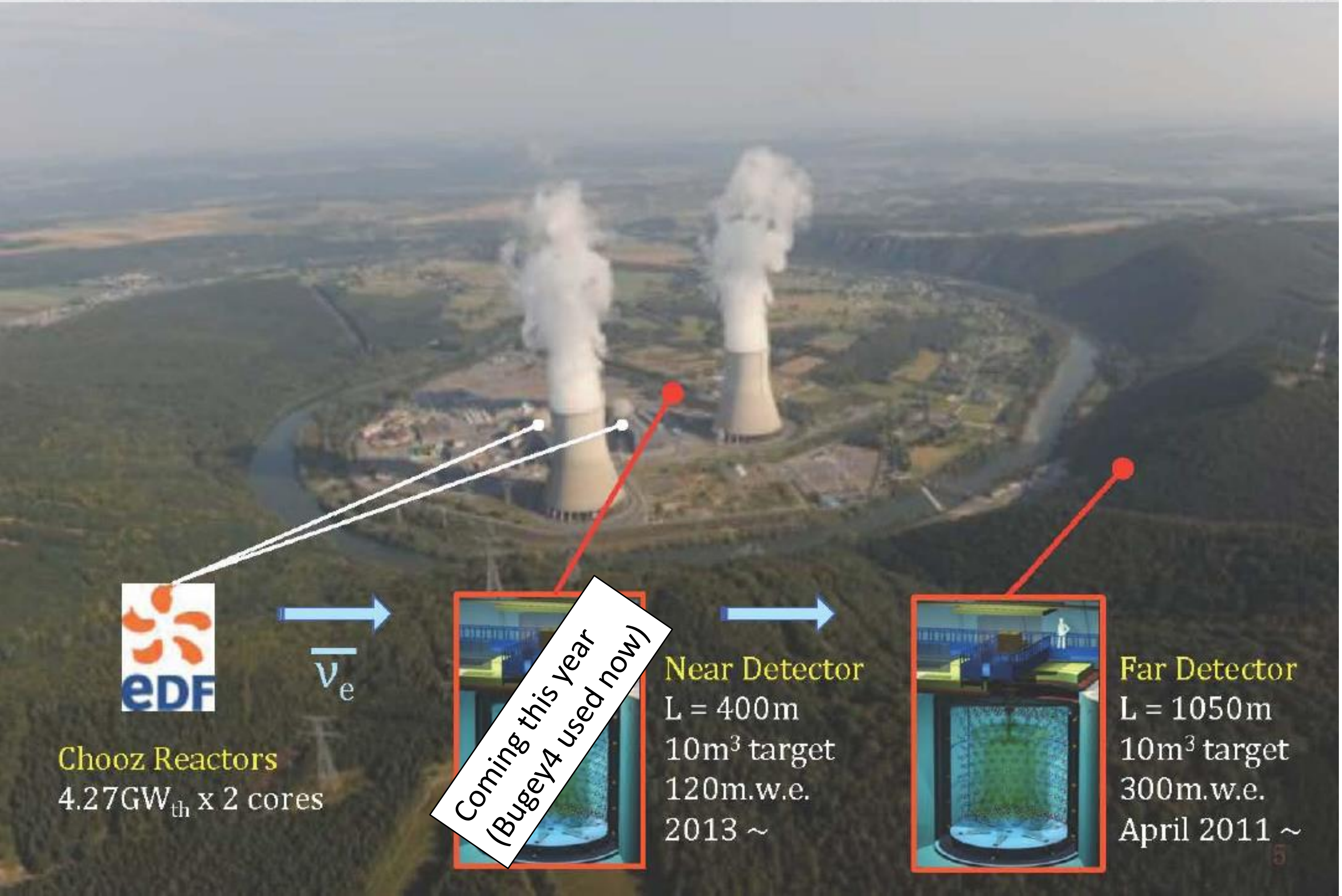


RENO Experimental Setup



Seon-Hee Seo

Double Chooz experiment



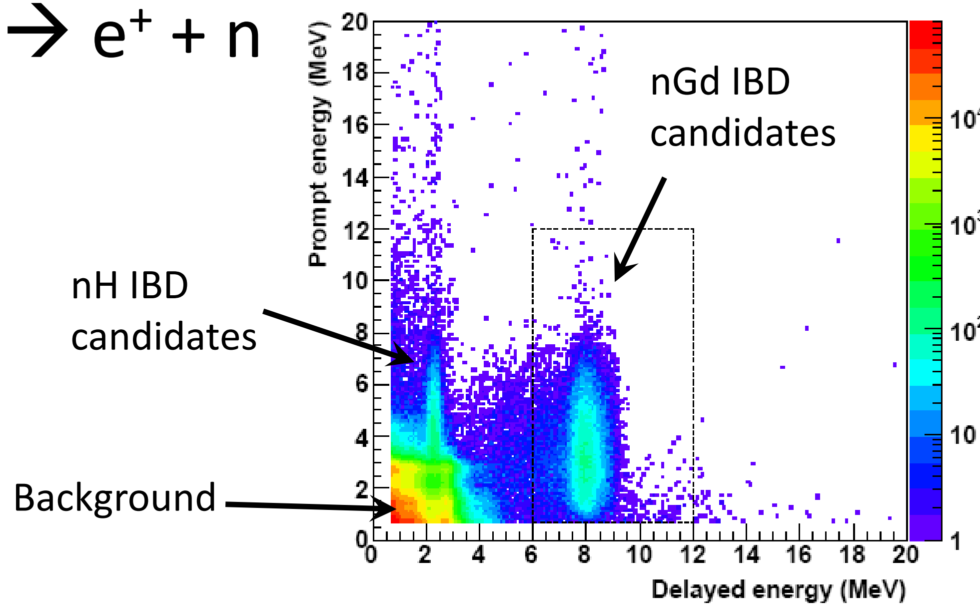
Antineutrino (IBD) Selection

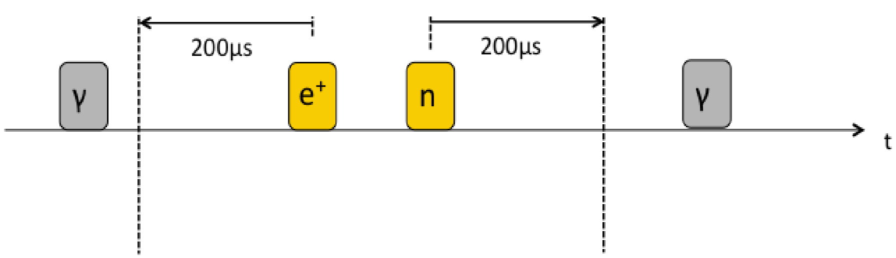
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

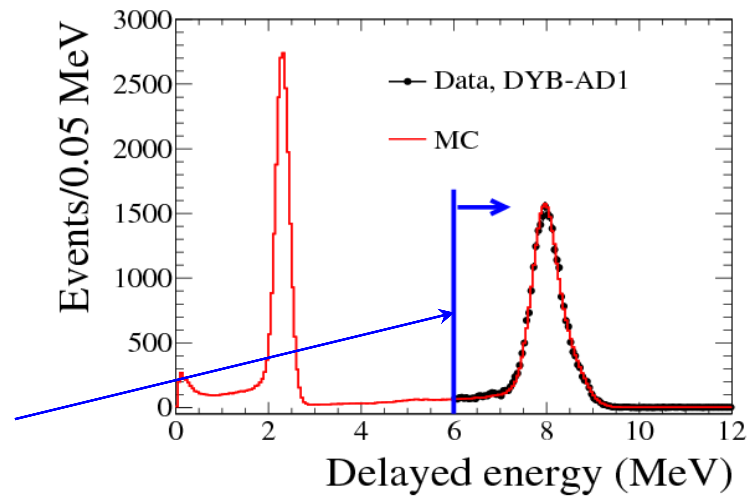
Prompt + Delayed Selection (DayaBay)

- Reject Flashing Photomultiplier Events
- Prompt Positron: 0.7 MeV < E_p < 12 MeV
- Delayed Neutron: 6.0 MeV < E_d < 12 MeV
- Capture time: 1 μs < Δt < 200 μs
- Muon Veto:
  - Pool Muon (12 PMTs): Reject 0.6 ms
  - AD Muon (>20 MeV): Reject 1 ms
  - AD Shower Muon (>2.5GeV): Reject 1 s
- Multiplicity:

No other signal > 0.7 MeV in -200 μs to 200 μs of IBD.







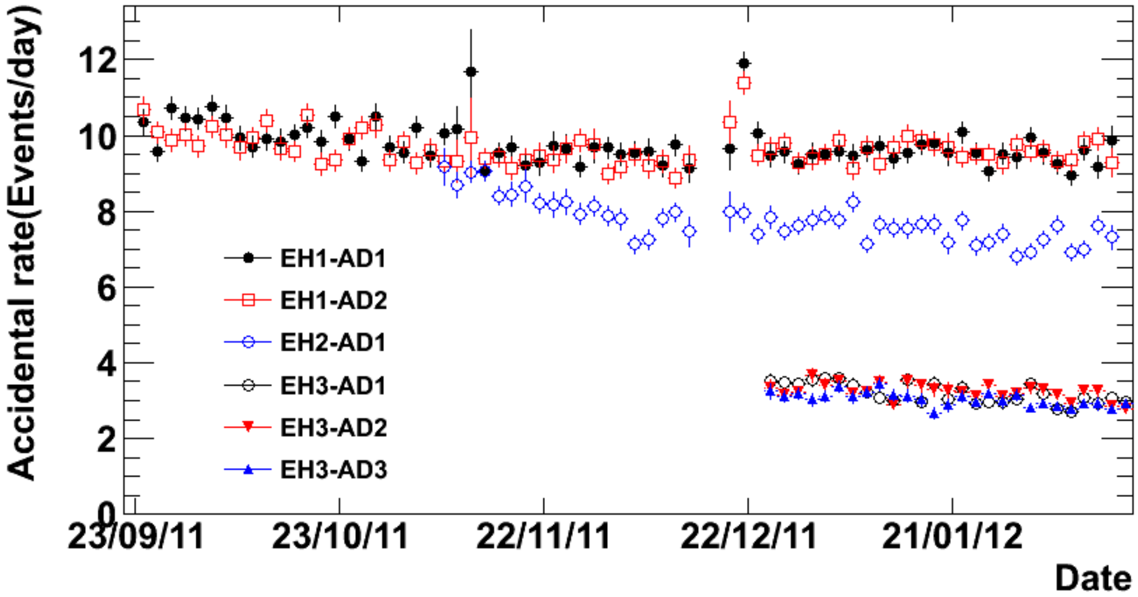
Uncertainty in relative E_d efficiency (0.12%) between detectors is largest detector systematic.

Background: Accidentals

Accidentals: Two uncorrelated events ‘accidentally’ passing the cuts and mimic IBD event.

Rate and spectrum can be accurately predicted from singles data.

Multiple analyses/methods estimate consistent rates.



	EH1-AD1	EH1-AD2	EH2-AD1	EH3-AD1	EH3-AD2	EH3-AD3
Accidental rate(/day)	9.73±0.10	9.61±0.10	7.55±0.05	3.05±0.04	3.04±0.04	2.93±0.03
BG/Signal	1.5%	1.4%	1.2%	3.9%	3.9%	3.9%

Background: Fast neutrons

Correlated events mimic IBD events

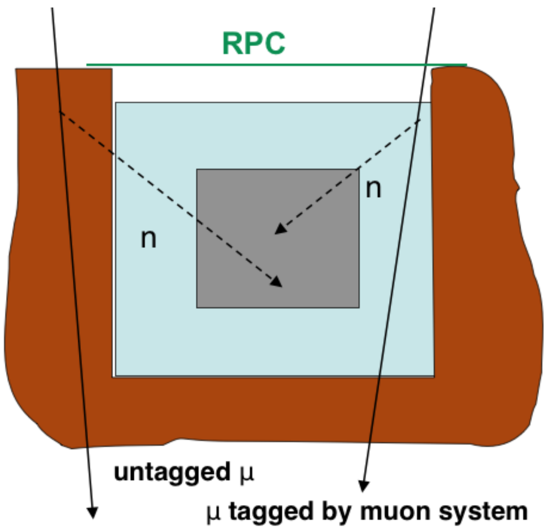
Fast Neutrons

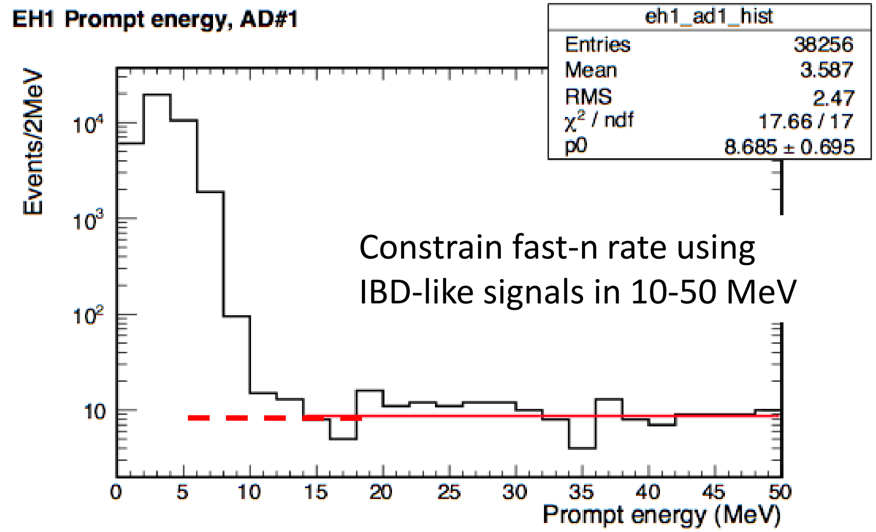
Energetic neutrons produced by cosmic rays (inside and outside of muon veto system)

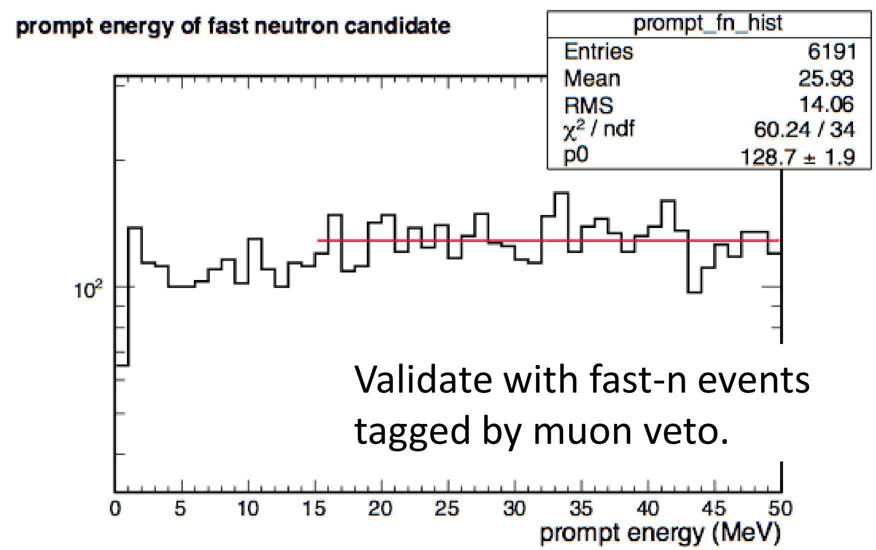
Mimics antineutrino (IBD) signal

Prompt: Neutron collides/stops in target

Delayed: Neutron captures on Gd







Analysis muon veto cuts control BG/Signal: 0.06% (0.1%) of far (near) signal.

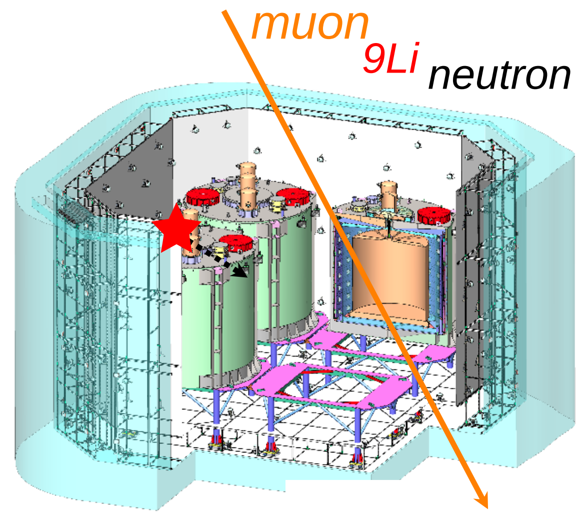
Background: Li/He decay

Correlated events mimic IBD events

- prompt: β-decay
- delayed: neutron capture

$$^{9}\mathrm{Li} \rightarrow {}^{9}\mathrm{Be} + e^{-} + \bar{\nu}_e$$

$$\hookrightarrow n + 2\alpha$$



Generated by cosmic rays, long-lived

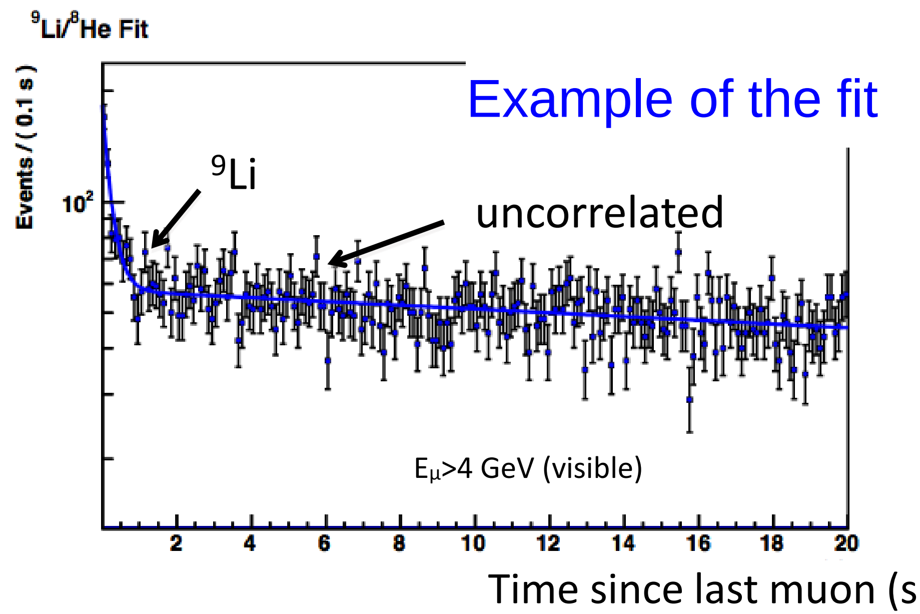
^{9}Li: $\tau_{1/2}$ = 178 ms, Q = 13. 6 MeV

^{8}He: $\tau_{1/2}$ = 119 ms, Q = 10.6 MeV

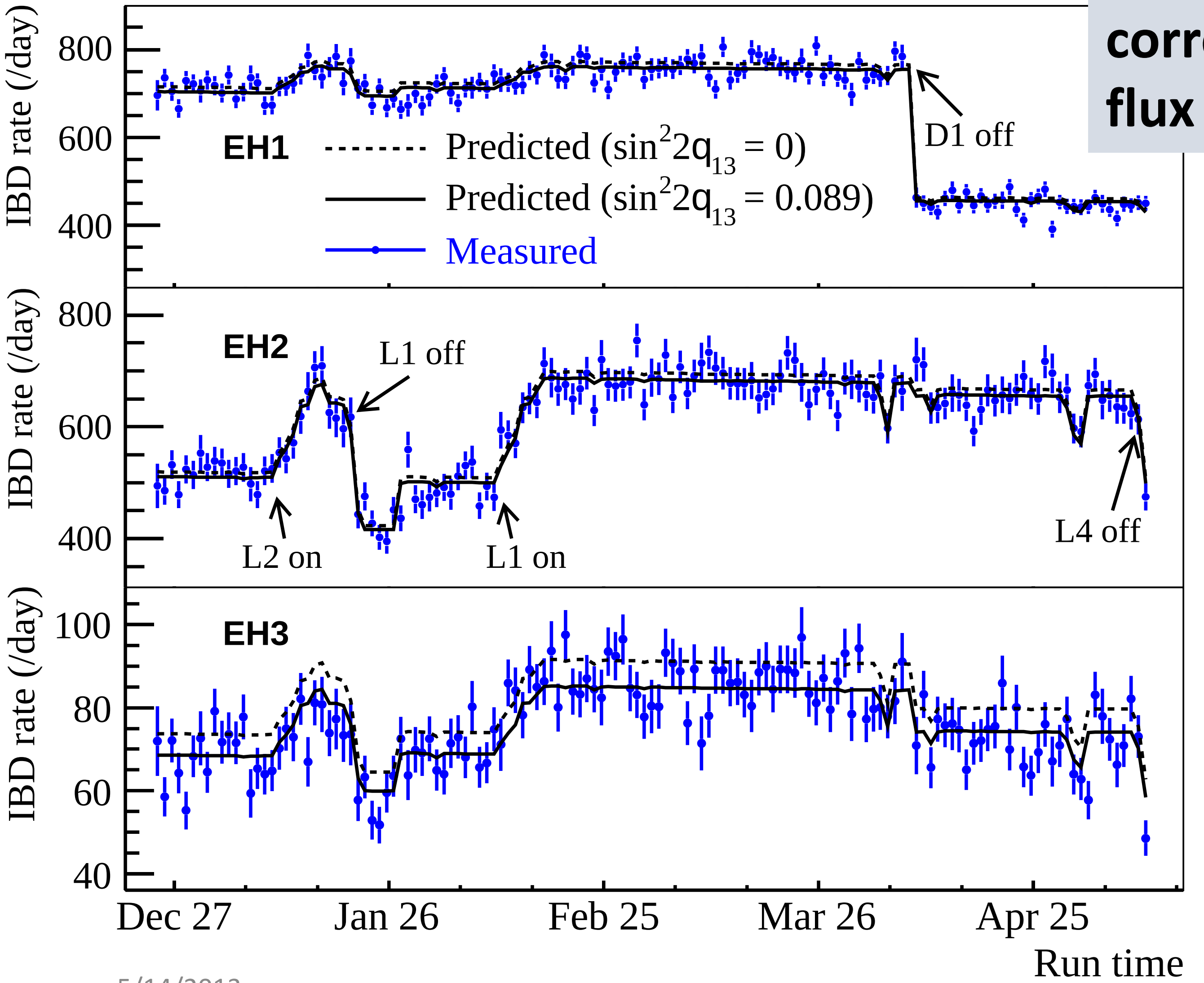
^{9}Li/^{8}He, Br(n) = 48% /12%, **^{9}Li dominant**

fit with known decay times for ^{8}He/^{9}Li

Analysis muon veto cuts control B/S to ~0.3% (0.4%) of far (near) signal.



Antineutrino Rate vs. Time

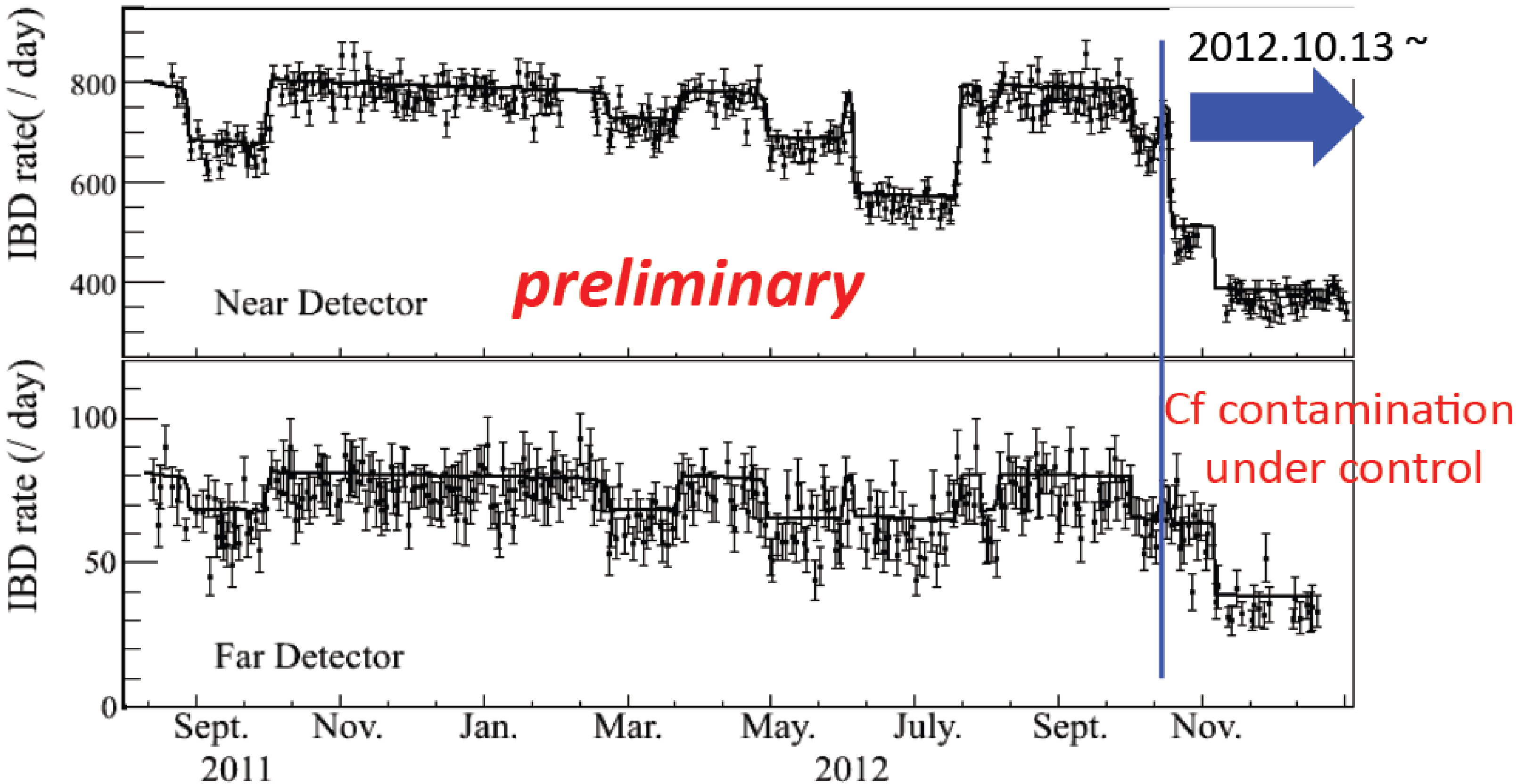


Detected rate strongly correlated with reactor flux expectations.

Predicted Rate:

- Normalization is determined by data fit.
- Absolute normalization is within a few percent of expectations.

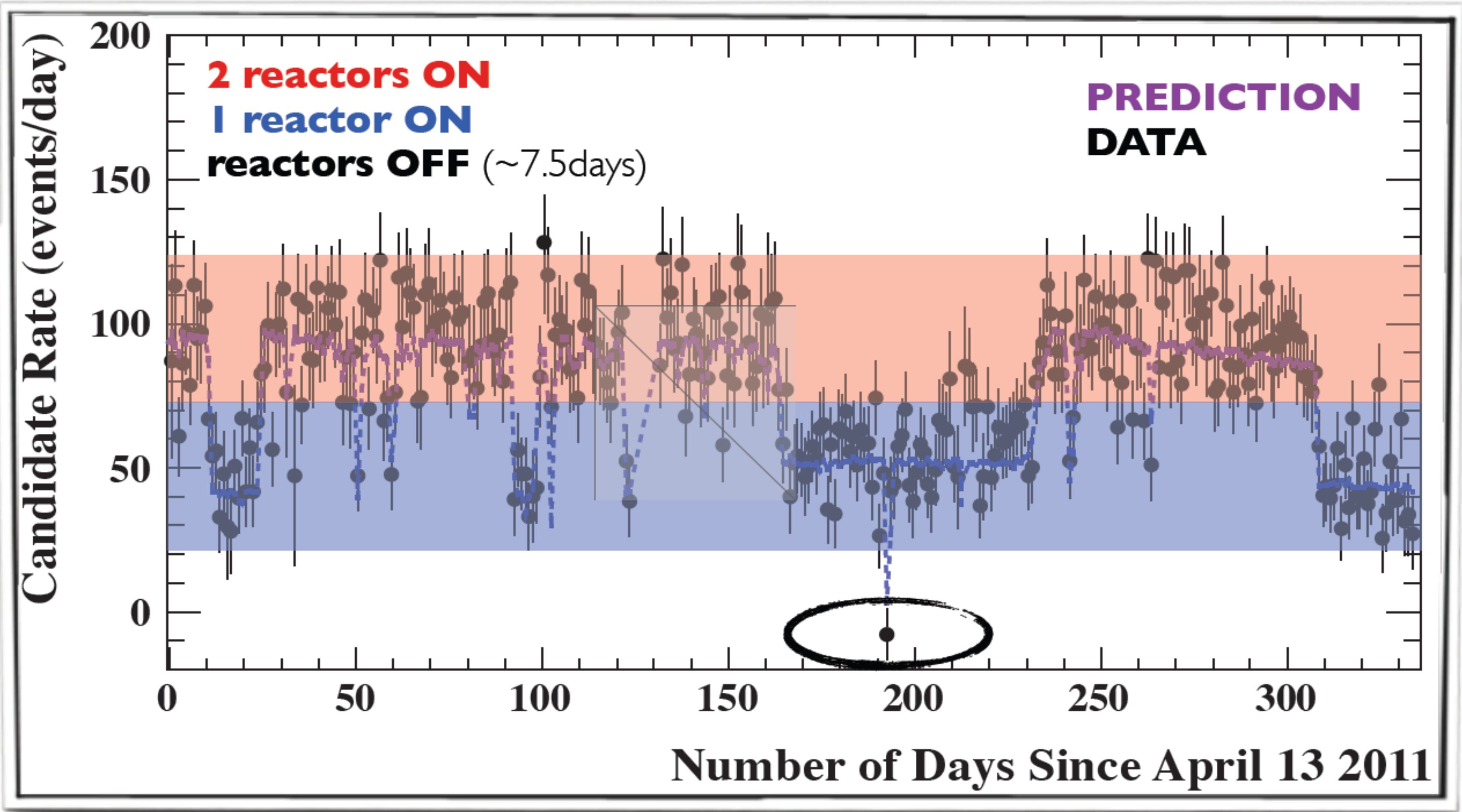
Observed Daily IBD Rate



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

Seon-Hee Seo

observed vs expected rate…



next: plot observed vs expected IBD rate per day

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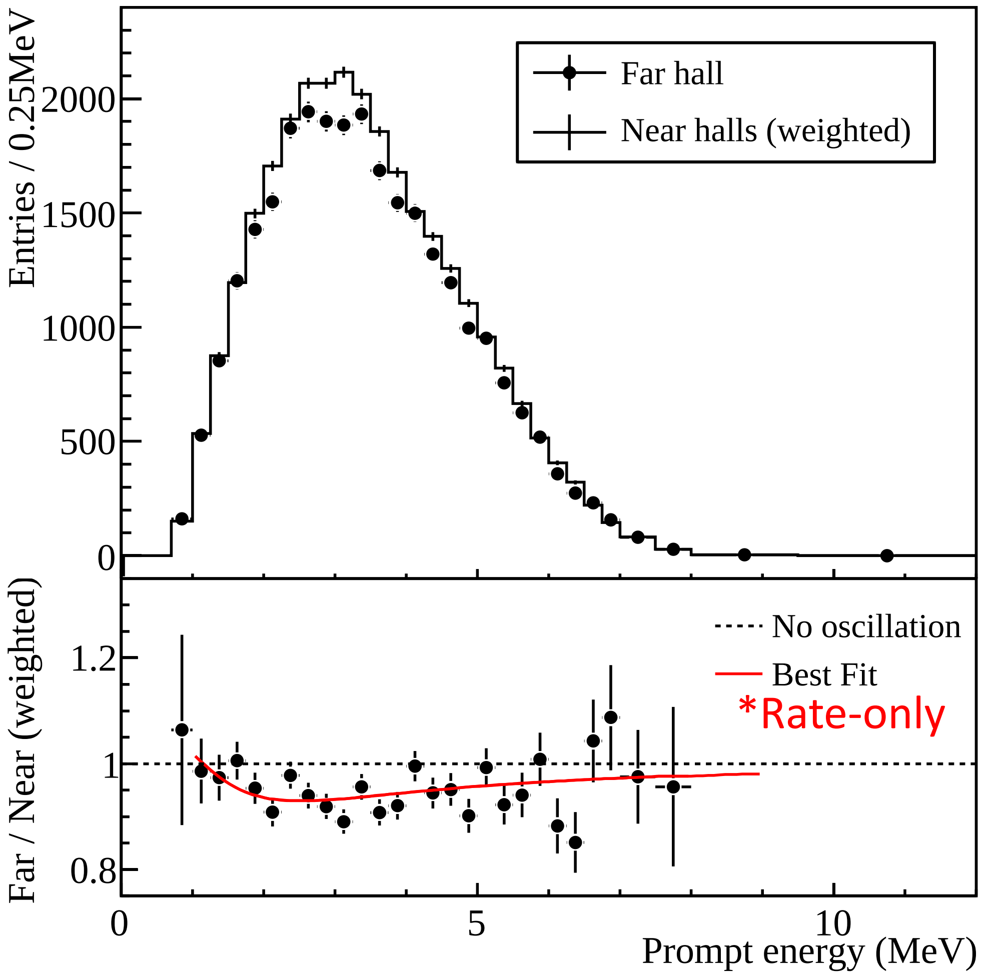
Far vs. Near Comparison

Compare the far/near measured rates and spectra



$$R = \frac{Far_{measured}}{Far_{expected}} = \frac{M_4 + M_5 + M_6}{\sum_{i=4}^{6}(\alpha_i(M_1 + M_2) + \beta_i M_3)}$$

M_n are the measured rates in each detector. Weights α_i,β_i are determined from baselines and reactor fluxes.

R = 0.944 ± 0.007 (stat) ± 0.003 (syst)

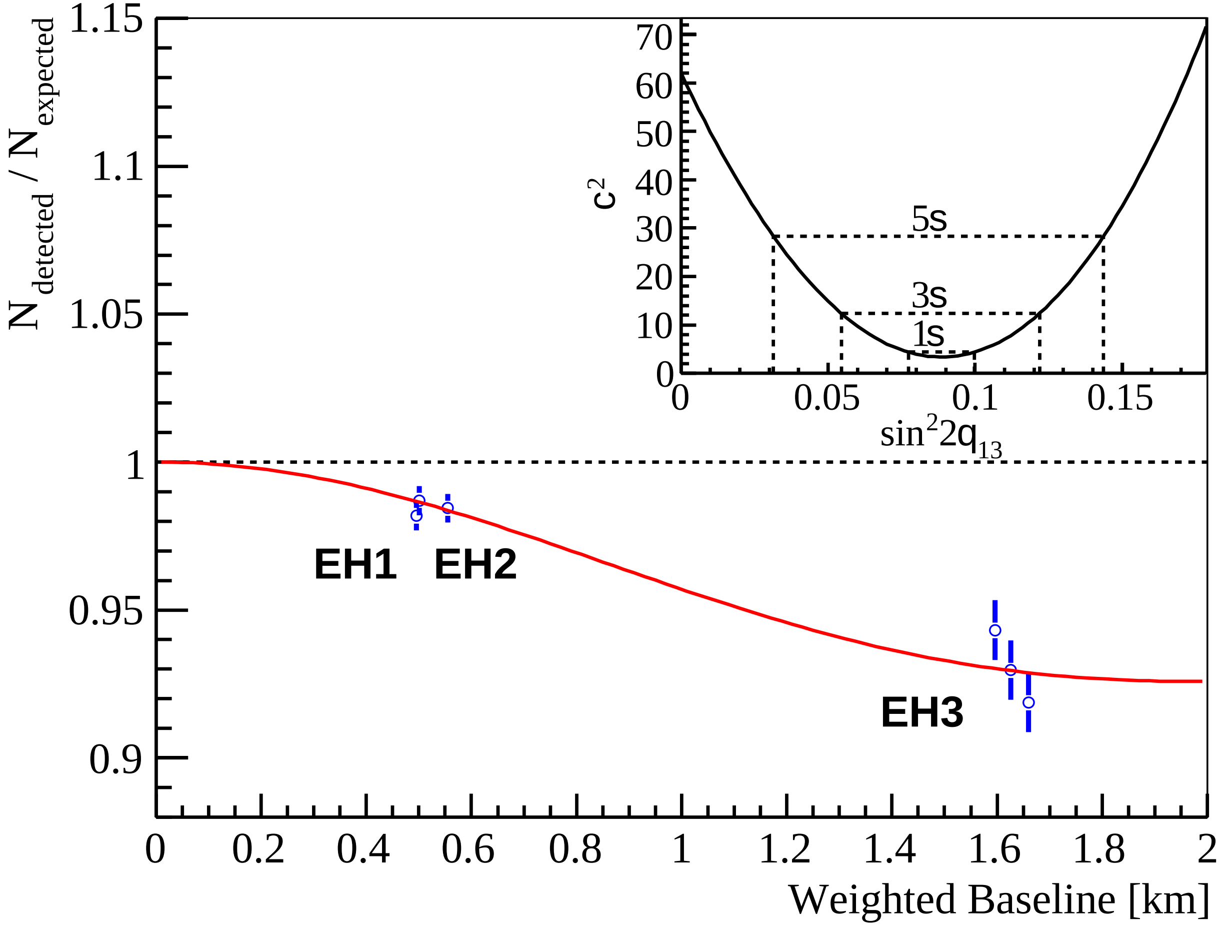
Clear observation of far site deficit.

Spectral distortion consistent with oscillation.*

* Caveat: Spectral systematics not fully studied; θ_{13} value from shape analysis is not recommended.

Rate Analysis

Estimate θ_{13} using measured rates in each detector.



Uses standard χ^2 approach.

Far vs. near relative measurement.
[Absolute rate is not constrained.]

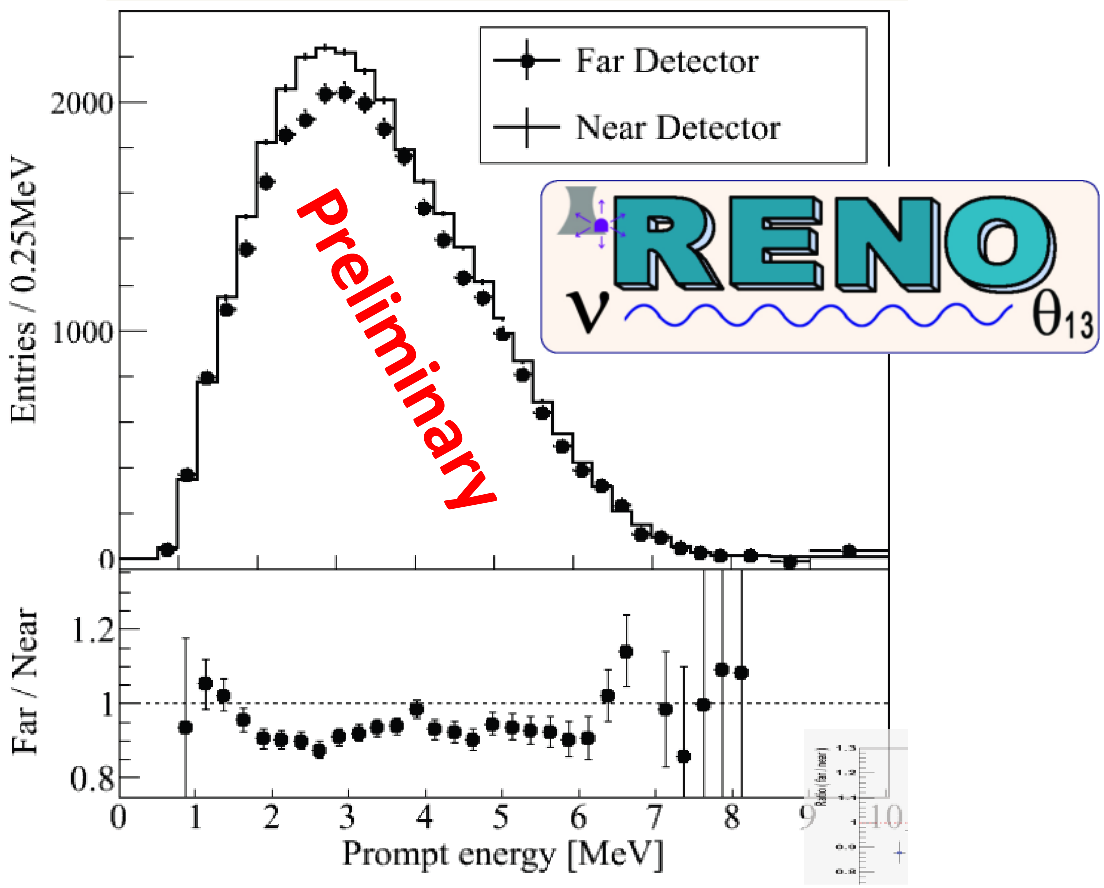
Consistent results obtained by independent analyses, different reactor flux models.

Most precise measurement of $\sin^2 2\theta_{13}$ to date.

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

Recent θ_{13} Results

RENO, NuTel2013

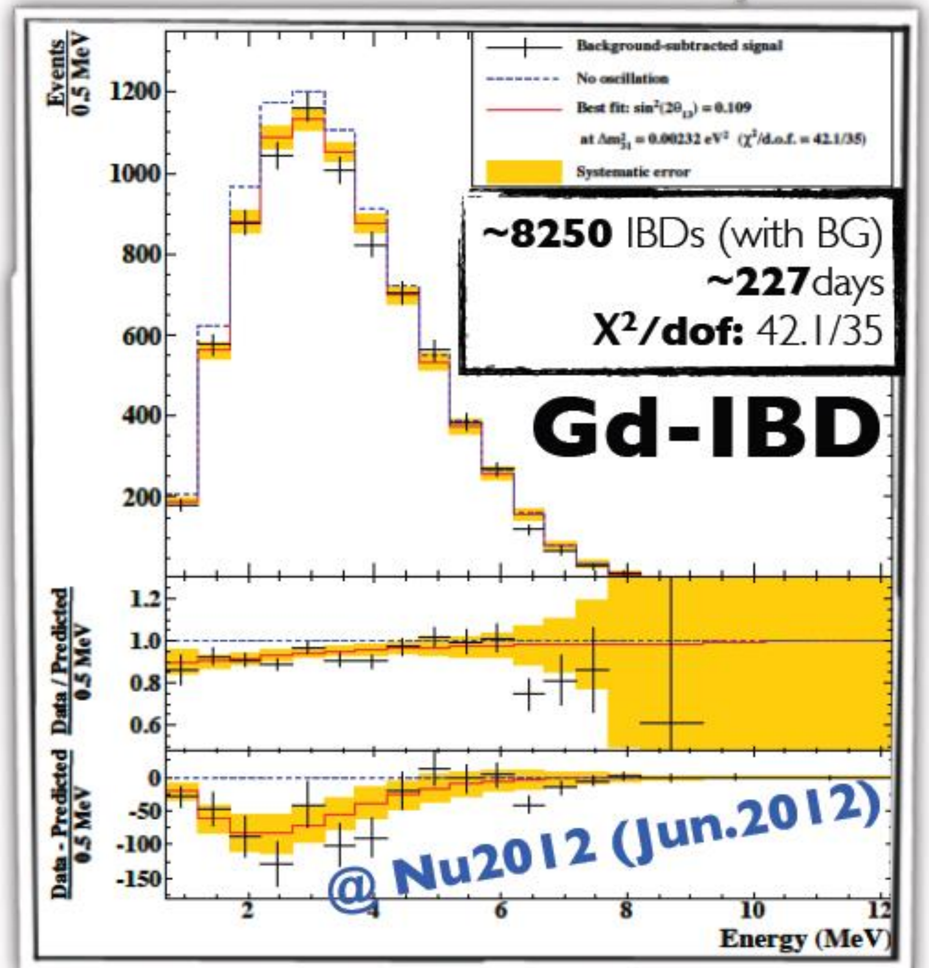


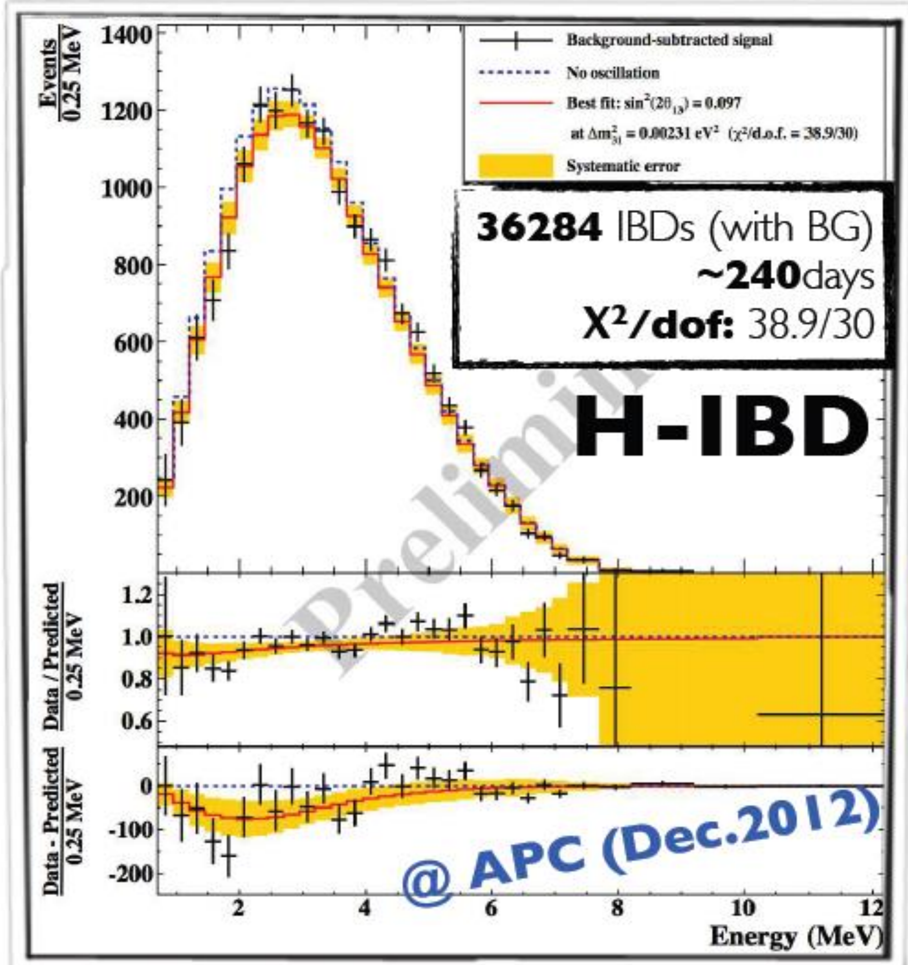
R = 0.929 ± 0.006 (stat) ± 0.009 (syst)

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

Seon-Hee Seo

two independent measurements of θ_{13}...





rate+shape analysis→ clear θ_{13} E/L pattern & BG constrains

DC-II(Gd): $\sin^2(2\theta_{13})=0.109\pm0.04$ $[0.030^{stat}\pm0.025^{syst}]$

DC-II(H): $\sin^2(2\theta_{13})=0.097\pm0.05$ $[0.034^{stat}\pm0.034^{syst}]$

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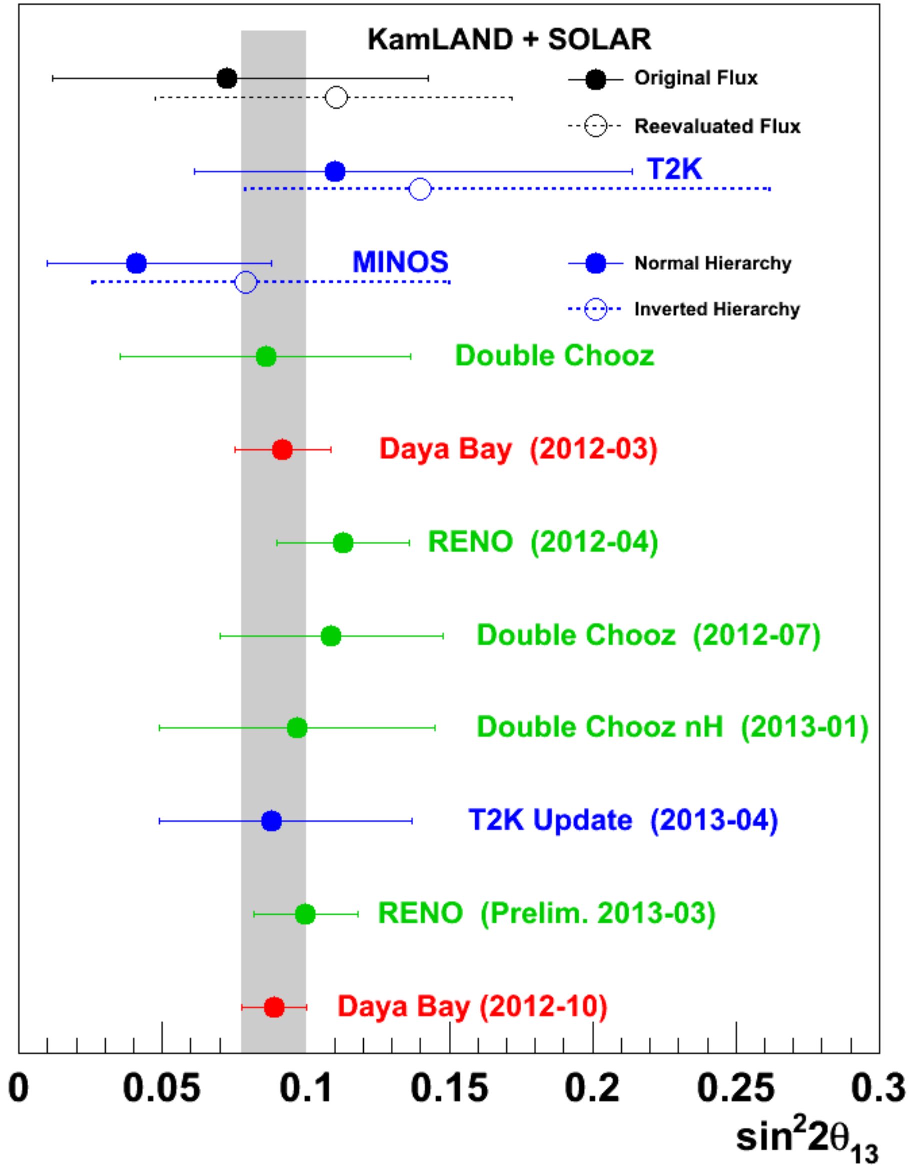
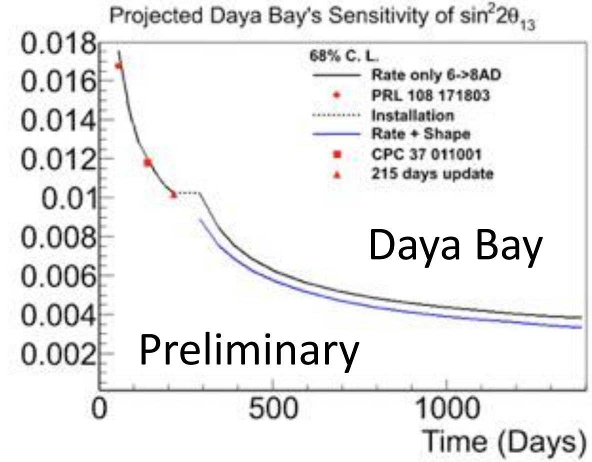
Current θ_{13} Landscape

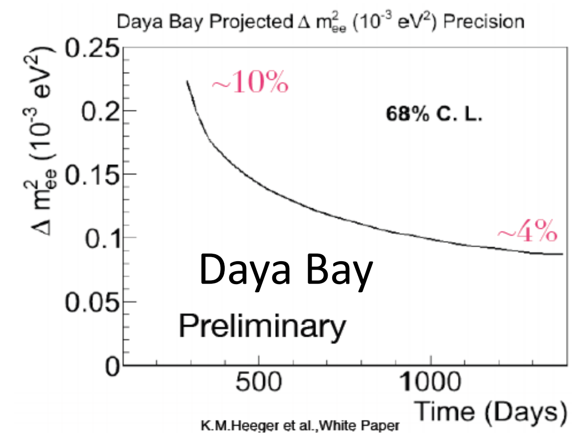


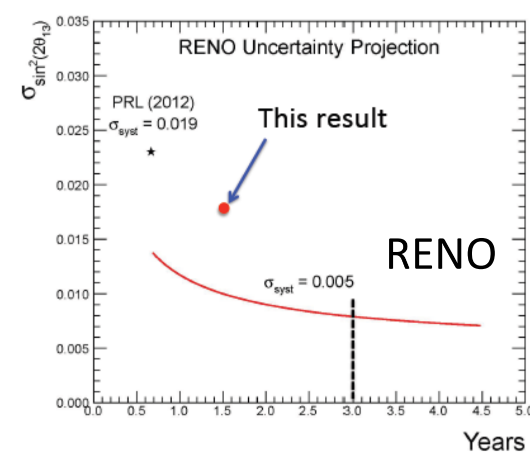
Slide by R. McKeown

Summary of Ongoing work

- Daya Bay
  - Running with 8 detectors since October 2012
  - Working on Rate + Shape analysis for θ_{13}
  - Expected precision on $\sin^2 2\theta_{13}$ of ~0.004 (prelim.)
  - Independent determination of Δm^2 (~10%→~4%)
  - Neutrino flux prediction & absolute measurement
  - Neutrino flux spectral shape measurement
- RENO
  - Rate + Shape analysis
  - Reduce systematic uncertainty on $\sin^2 2\theta_{13}$ to < 0.01
  - Goal: total uncertainty <0.011 after 3 years
- Double Chooz
  - Near detector (systematics 2.2% → 0.6%)
  - Improving all analyses
  - Expected precision on $\sin^2 2\theta_{13}$ of 0.01



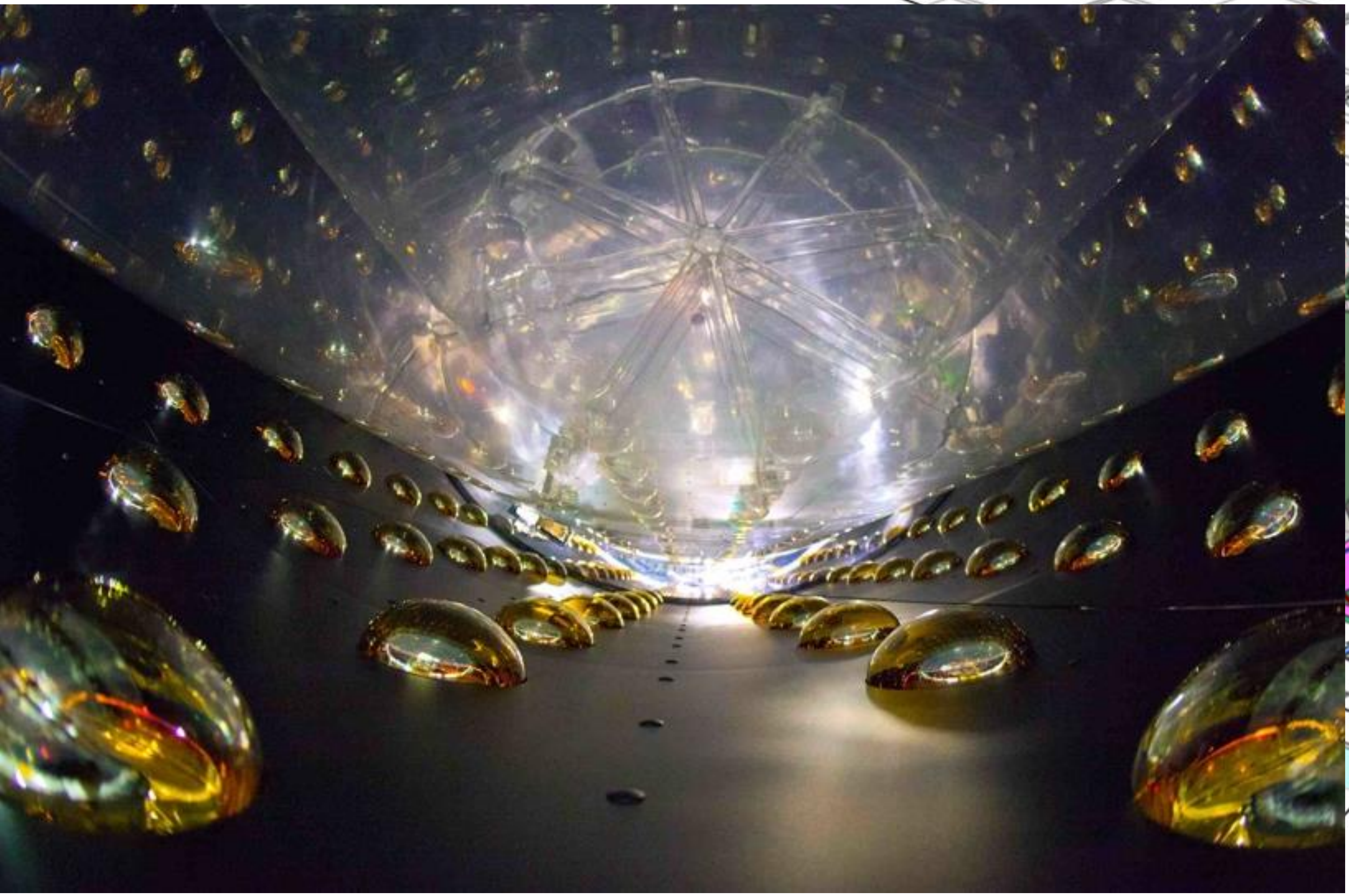




Thanks and
Stay Tuned!

Backup

Daya Bay near site layout



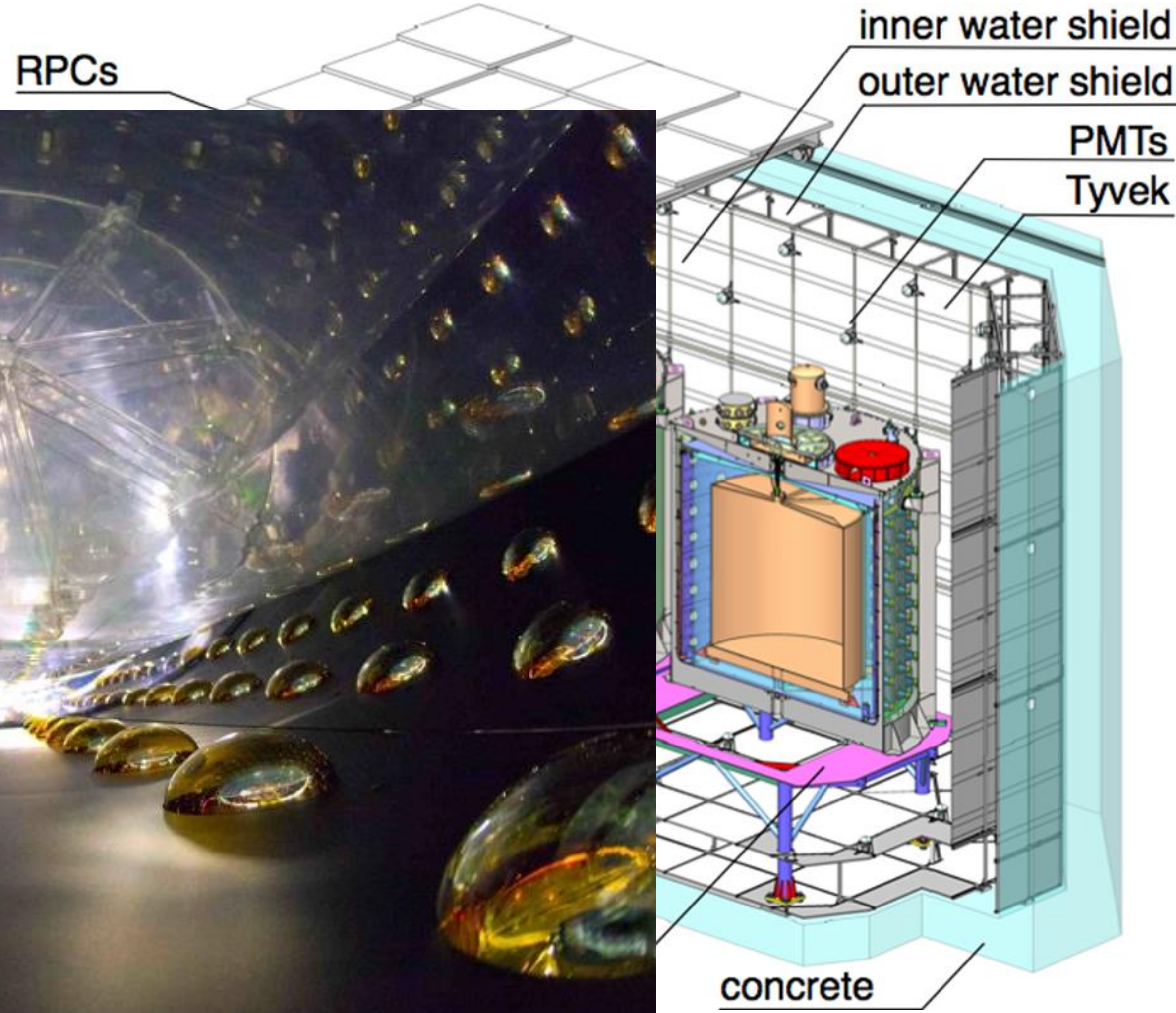
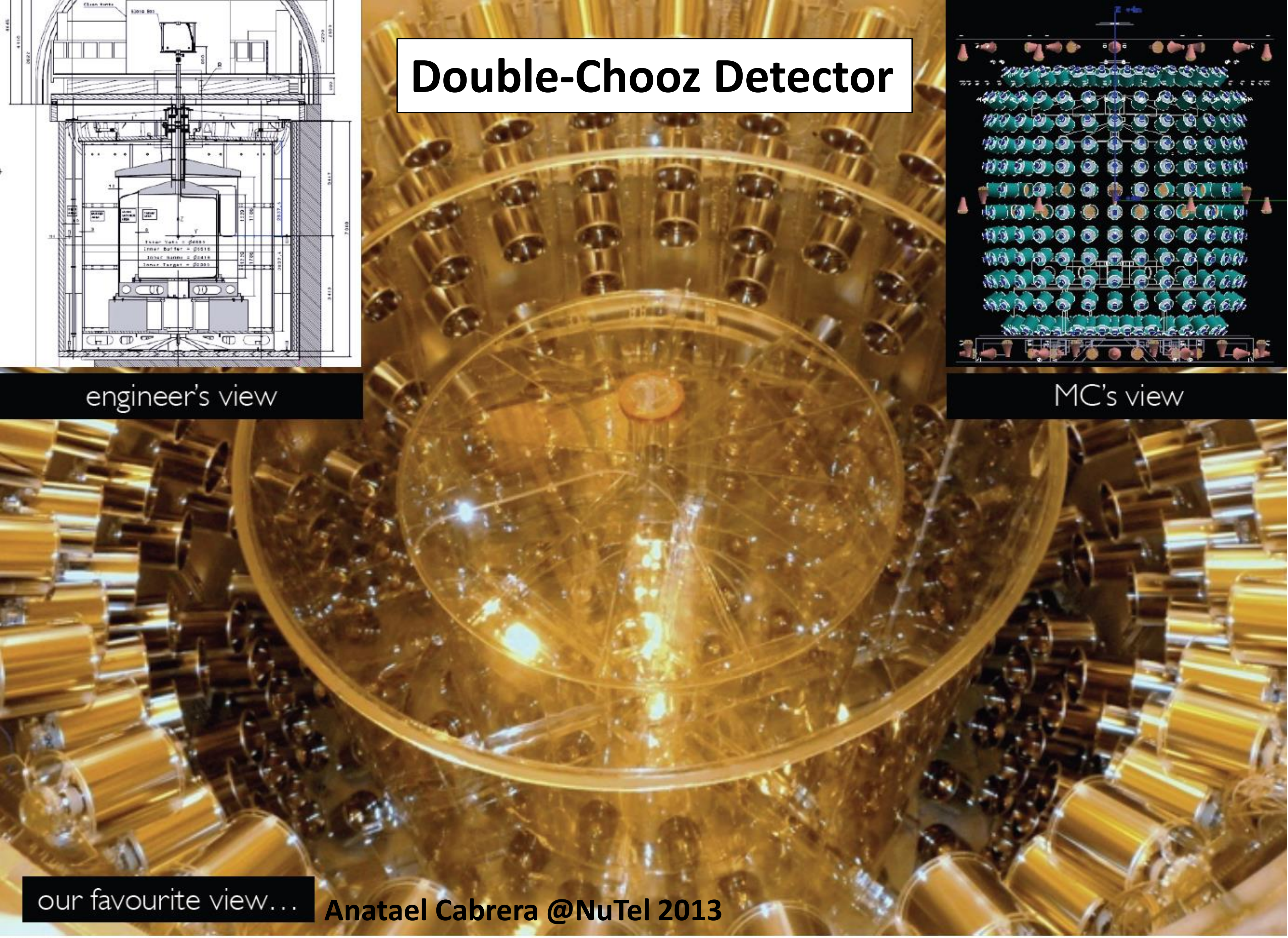


Photo by Roy Kaltschmidt

Double-Chooz Detector



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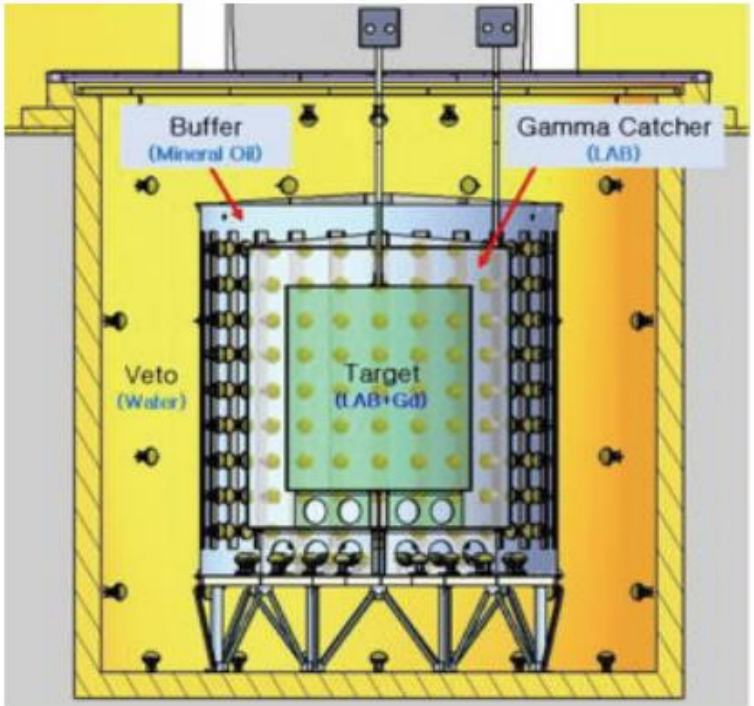
RENO Detector



- 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

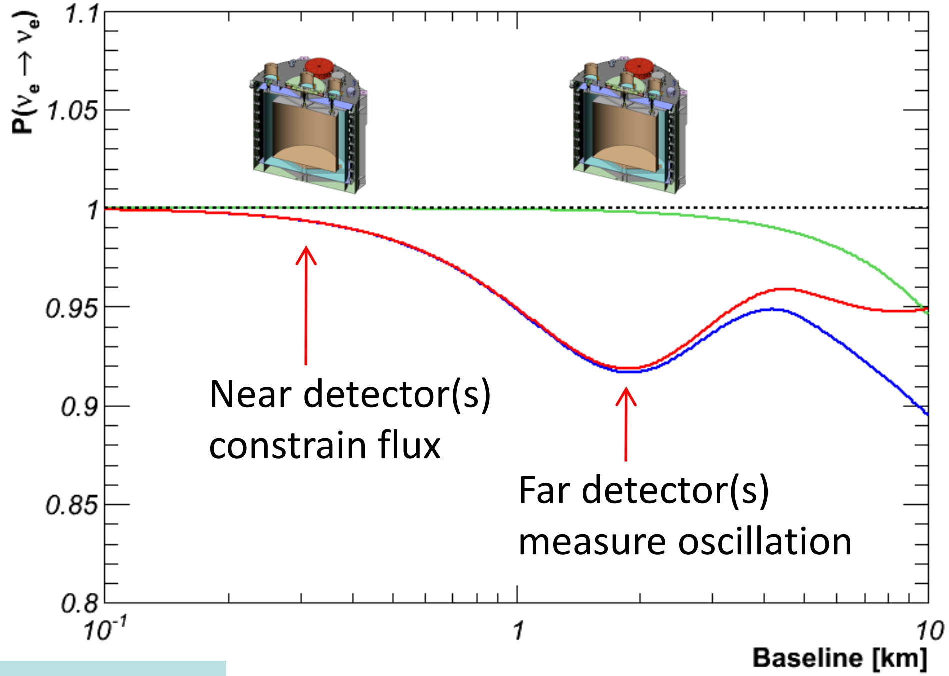
Seon-Hee Seo

Near/far measurements reduce systematic uncertainties

Absolute Reactor Flux:
Largest uncertainty in previous measurements

Relative Measurement:
Multiple detectors removes absolute uncertainty

First proposed by L. A. Mikaelyan and V.V. Sinev, Phys. Atomic Nucl. 63 1002 (2000)



Far/Near ν_e Ratio

Distances from reactor

Oscillation deficit

$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left[\frac{P_{sur}(E, L_f)}{P_{sur}(E, L_n)}\right]$$

Detector Target Mass

Detector efficiency

Data Set Summary

> 200k antineutrino interactions!

	AD1	AD2	AD3	AD4	AD5	AD6
Antineutrino candidates	69121	69714	66473	9788	9669	9452
DAQ live time (day)	127.5470		127.3763	126.2646		
Efficiency	0.8015	0.7986	0.8364	0.9555	0.9552	0.9547
Accidentals (/day)	9.73±0.10	9.61±0.10	7.55±0.08	3.05±0.04	3.04±0.04	2.93±0.03
Fast neutron (/day)	0.77±0.24	0.77±0.24	0.58±0.33	0.05±0.02	0.05±0.02	0.05±0.02
^{8}He/^{9}Li (/day)	2.9±1.5		2.0±1.1	0.22±0.12		
Am-C corr. (/day)	0.2±0.2					
^{13}C(α, n)^{16}O (/day)	0.08±0.04	0.07±0.04	0.05±0.03	0.04±0.02	0.04±0.02	0.04±0.02
Antineutrino rate (/day)	**662.47 ±3.00**	**670.87 ±3.01**	**613.53 ±2.69**	**77.57 ±0.85**	**76.62 ±0.85**	**74.97 ±0.84**

Consistent rates for side-by-side detectors

Uncertainty currently dominated by statistics

Systematic Uncertainties

	Detector		
	Efficiency	Correlated	Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	90.9%	0.6%	0.12%
Prompt energy cut	99.88%	0.10%	0.01%
Multiplicity cut		0.02%	<0.01%
Capture time cut	98.6%	0.12%	0.01%
Gd capture ratio	83.8%	0.8%	<0.1%
Spill-in	105.0%	1.5%	0.02%
Livetime	100.0%	0.002%	<0.01%
Combined	**78.8%**	**1.9%**	**0.2%**

Reactor			
Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
IBD/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	**Combined**	**0.8%**

A consistent picture of θ_{13}

$R = 0.944 \pm 0.007$ (stat) ± 0.003 (syst)
$\sin^2 2\theta_{13} = 0.089 \pm 0.010$ (stat) ± 0.005 (syst)

(preliminary)
2x statistics of PRL, improved BG, calib
$R = 0.929 \pm 0.006$ (stat) ± 0.009 (syst)
$\sin^2 2\theta_{13} = 0.100 \pm 0.010$ (stat) ± 0.015 (syst)

Energy-dependent fit, including shape
$\sin^2 2\theta_{13} = 0.109 \pm 0.04$ (total)