

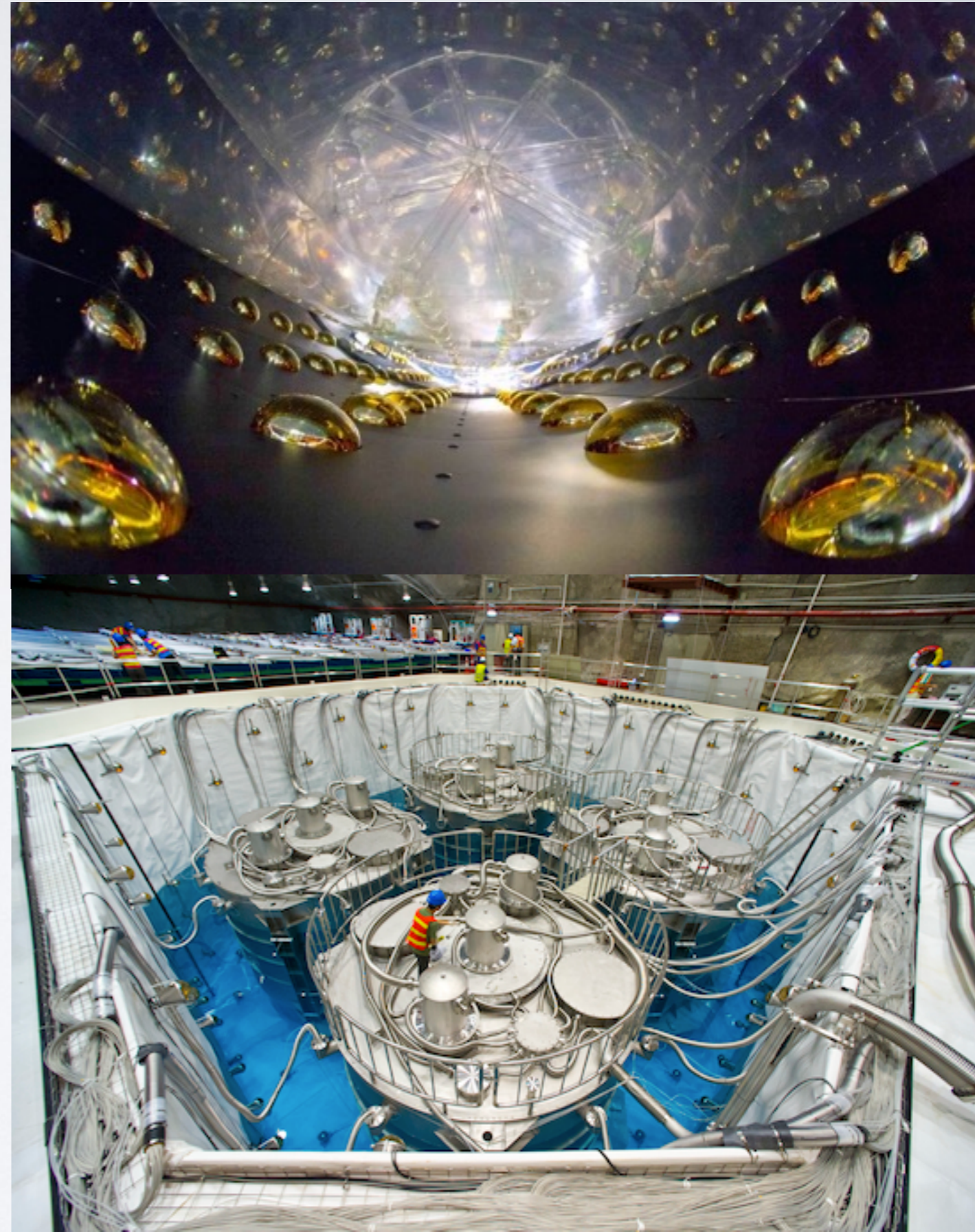
Search for a light sterile neutrino at Daya Bay

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November 18, 2014
SLAC Experimental Seminar

Outline

- Introduction
- Daya Bay experiment
- Search for a light sterile neutrino at Daya Bay
- Other recent results



Neutrino Mixing

- Neutrino flavor (weak) eigenstates and mass eigenstates are mixed

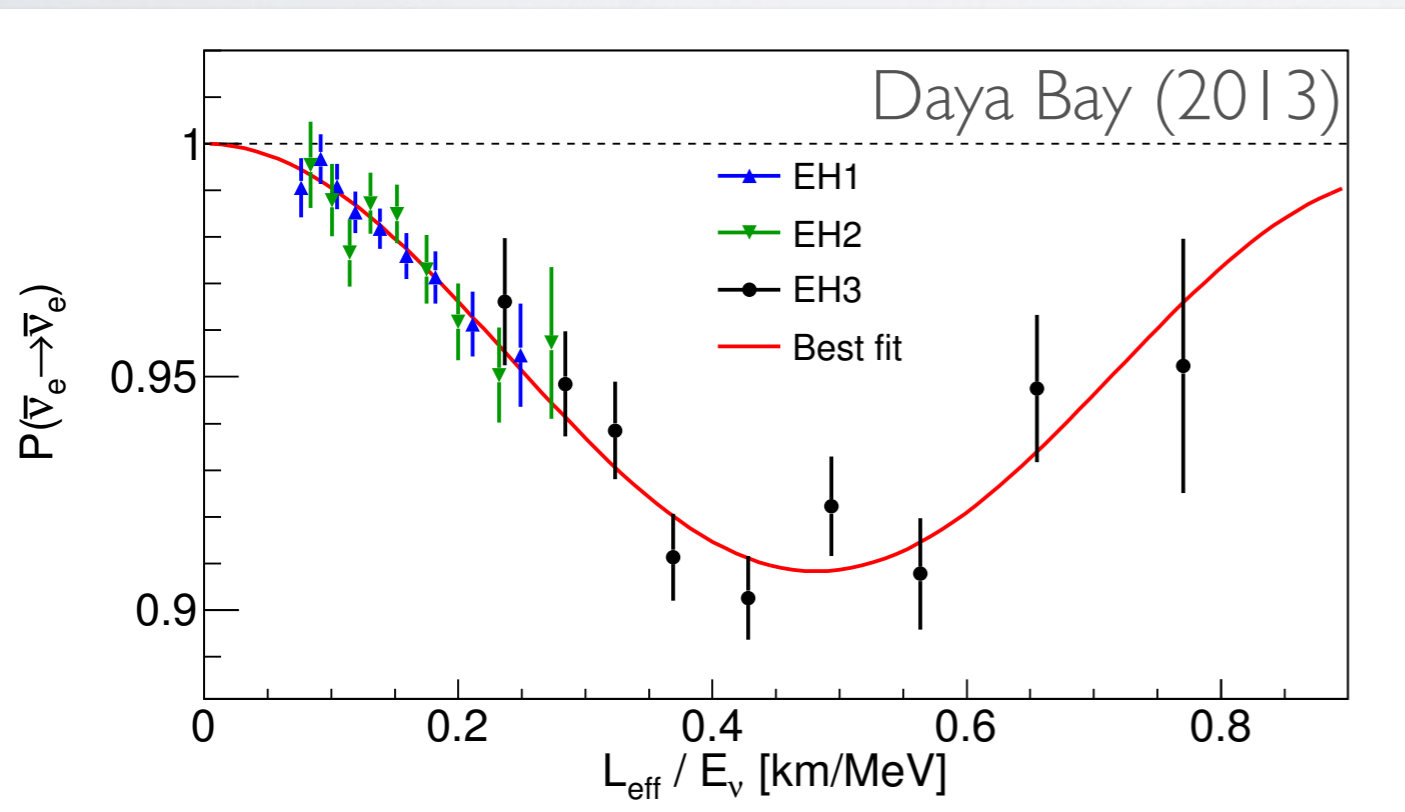
$$\text{Weak eigenstate } (\alpha = e, \mu, \tau) \quad | \nu_\alpha \rangle = \sum_i \mathbf{U}_{\alpha i} | \nu_i \rangle \quad \text{Mass eigenstate } (i = 1, 2, 3)$$

MNS mixing matrix

- Neutrinos change their flavor as they travel (neutrino oscillation)
- Natural interferometer to explore fundamental nature of neutrinos

Two neutrino case: $P(\nu_\alpha \rightarrow \nu_\beta) = | \langle \nu_\beta | \nu(t) \rangle |^2 = \sin^2 2\theta \sin^2 \left(\Delta m^2 \frac{L}{4E} \right)$

Amplitude Frequency



θ : mixing angle
 Δm^2 : mass squared difference
L : the distance traveled
E : the energy of neutrino

Neutrino Mixing

All the three angles are finally observed!

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\theta_{23} \approx 45^\circ$$

Atmospheric ν
Accelerator ν

$$\Delta m_{32}^2 \sim \Delta m_{31}^2 \sim 2.5 \times 10^{-3} \text{ eV}^2$$

$$\theta_{13} \sim 9^\circ$$

First $>5\sigma$ observation
at Daya Bay (2012)

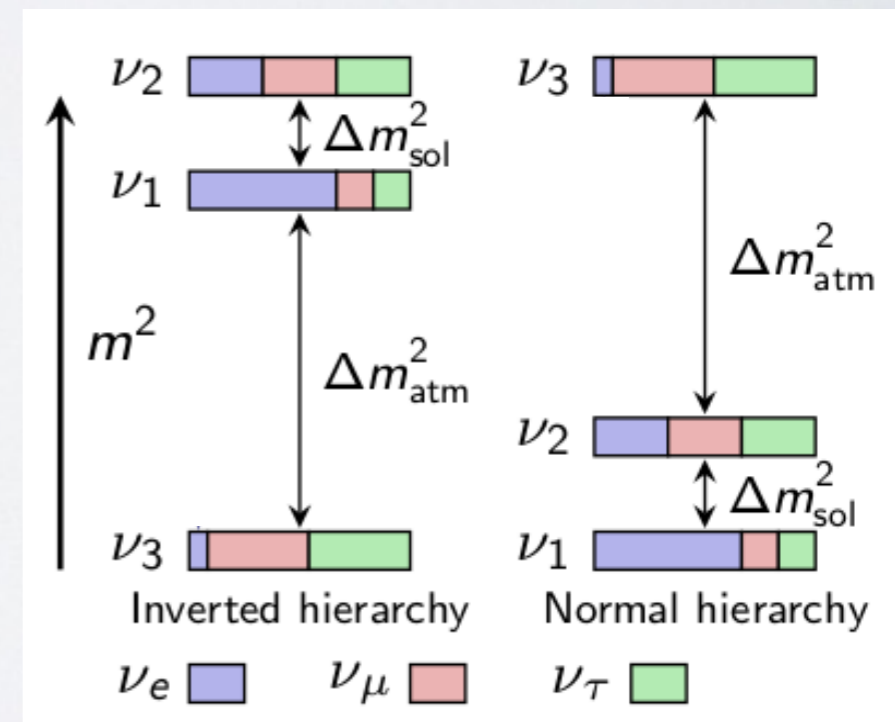
$$\theta_{12} \approx 35^\circ$$

Solar ν
Long-Baseline Reactor ν

$$\Delta m_{21}^2 \sim 7.5 \times 10^{-5} \text{ eV}^2$$

Still many open questions:

- What is the CP-violation phase, δ
- What is the absolute mass scale/ordering?
- What is the origin of neutrino mass?
- Are there any extra spices?



Sterile neutrinos

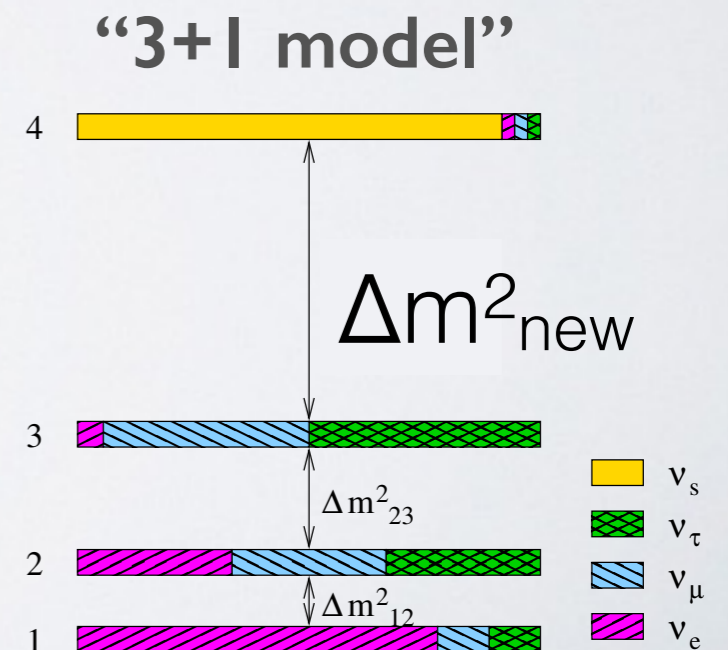
- Existence of neutrino oscillation proves neutrinos have mass
- We still don't know how to include the mass in the standard model
- Many extensions to the SM naturally include additional "species" which doesn't participate in weak interactions → **sterile neutrino**

$$- \mathcal{L} = \frac{1}{2} \begin{pmatrix} \bar{\nu}_L^0 & \bar{\nu}_L^{0c} \end{pmatrix} \begin{pmatrix} m_L & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_R^{0c} \\ \nu_R^0 \end{pmatrix} + h.c. \quad (\text{arXiv: 1204.5379})$$

- If $M_R \gg m_D$, it might explain the lightness of active neutrinos through the see-saw mechanism.
- If $M_R \sim m_D$, "light" sterile states can be mixed with active states through the mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_{s1} \\ \dots \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \dots \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} & \dots \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} & \dots \\ U_{s11} & U_{s12} & U_{s13} & U_{s14} & \dots \\ \dots & \dots & \dots & \dots & \dots \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \dots \end{pmatrix}$$

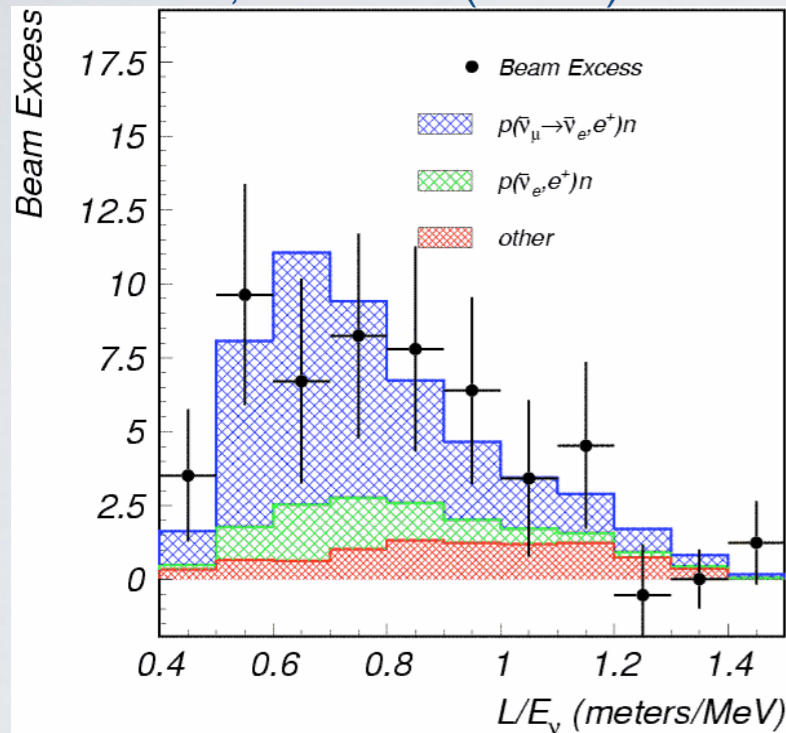
→ Create additional oscillation modes



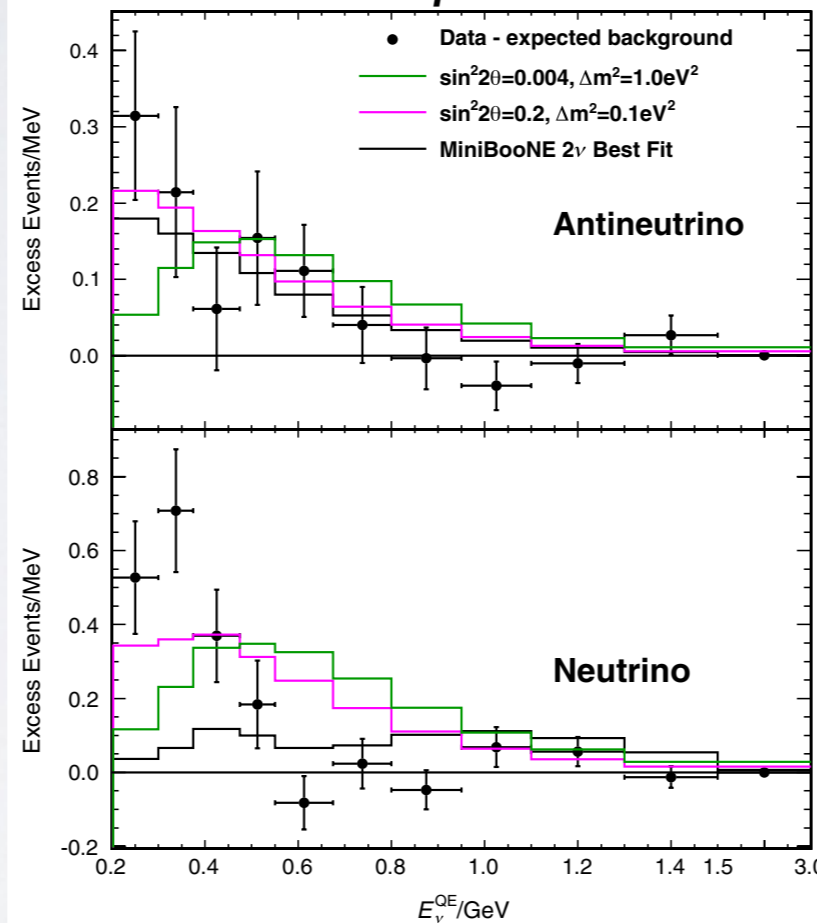
“Hint” of sterile neutrinos

- The LSND experiment observed a small excess of ν_e events in ν_μ beam
Best fit: $\Delta m^2 \sim 1 \text{ eV}^2, \sin^2 2\theta \sim 0.003$

PRD 64, 112007 (2001)



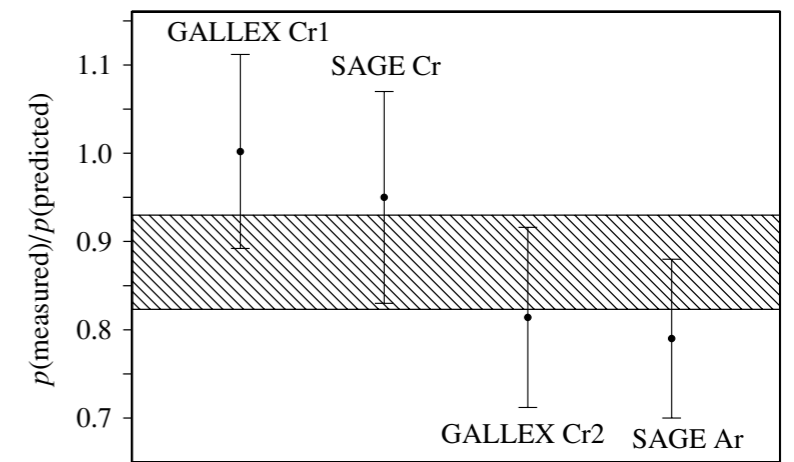
MiniBooNE $\nu_\mu \rightarrow \nu_e$ search



PRL 110, 161801 (2013)

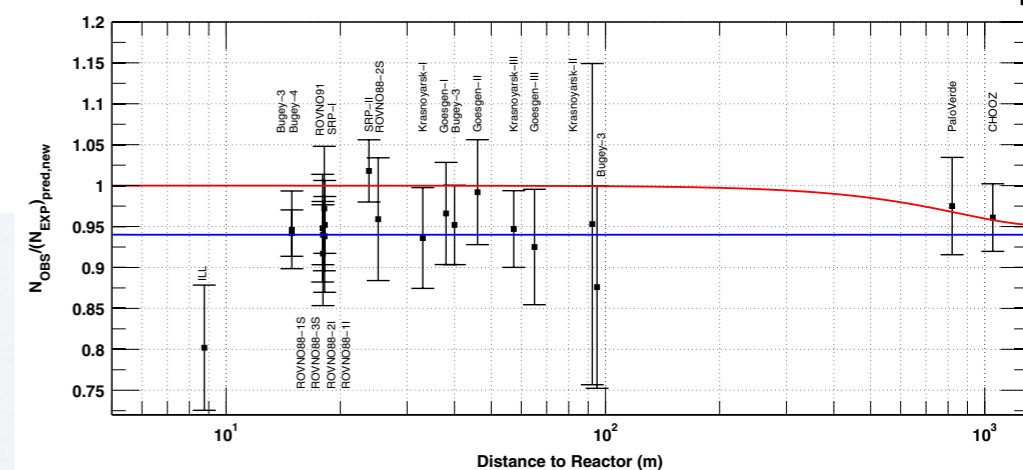
MiniBooNE see the similar size excess,
 but in different energy dependence

Gallium anomaly



PRC 73, 045805 (2006)

Reactor antineutrino anomaly

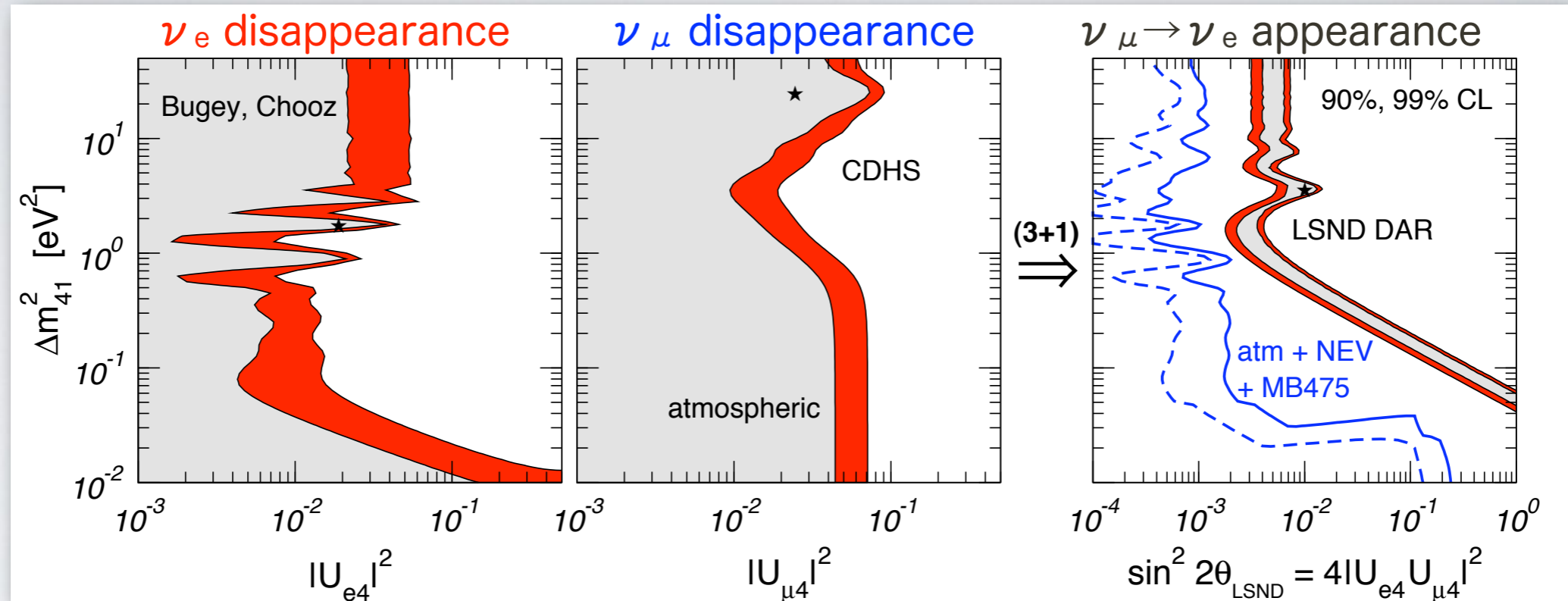


PRD 83, 073006 (2011)

Gallium and reactor antineutrino anomalies can
 also be explained by 1 eV sterile neutrinos

Situation is mixed...

- Those “hints” are in tension with other (mostly disappearance) searches.



M. Maltoni, J. Conf. Ser. **110**, 082011 (2008)

$\nu_\mu \rightarrow \nu_e$ appearance

$$P(\nu_\mu \rightarrow \nu_e) = 4|U_{e4}|^2|U_{\mu4}|^2 \sin^2 \left[1.27 \Delta m_{41}^2 \frac{L}{E} \right]$$

ν_e disappearance

$$P(\nu_e \rightarrow \nu_x) = 1 - 4|U_{e4}|^2(1 - |U_{e4}|^2) \sin^2 \left[1.27 \Delta m_{41}^2 \frac{L}{E} \right]$$

ν_μ disappearance

$$P(\nu_\mu \rightarrow \nu_x) = 1 - 4|U_{\mu4}|^2(1 - |U_{\mu4}|^2) \sin^2 \left[1.27 \Delta m_{41}^2 \frac{L}{E} \right]$$

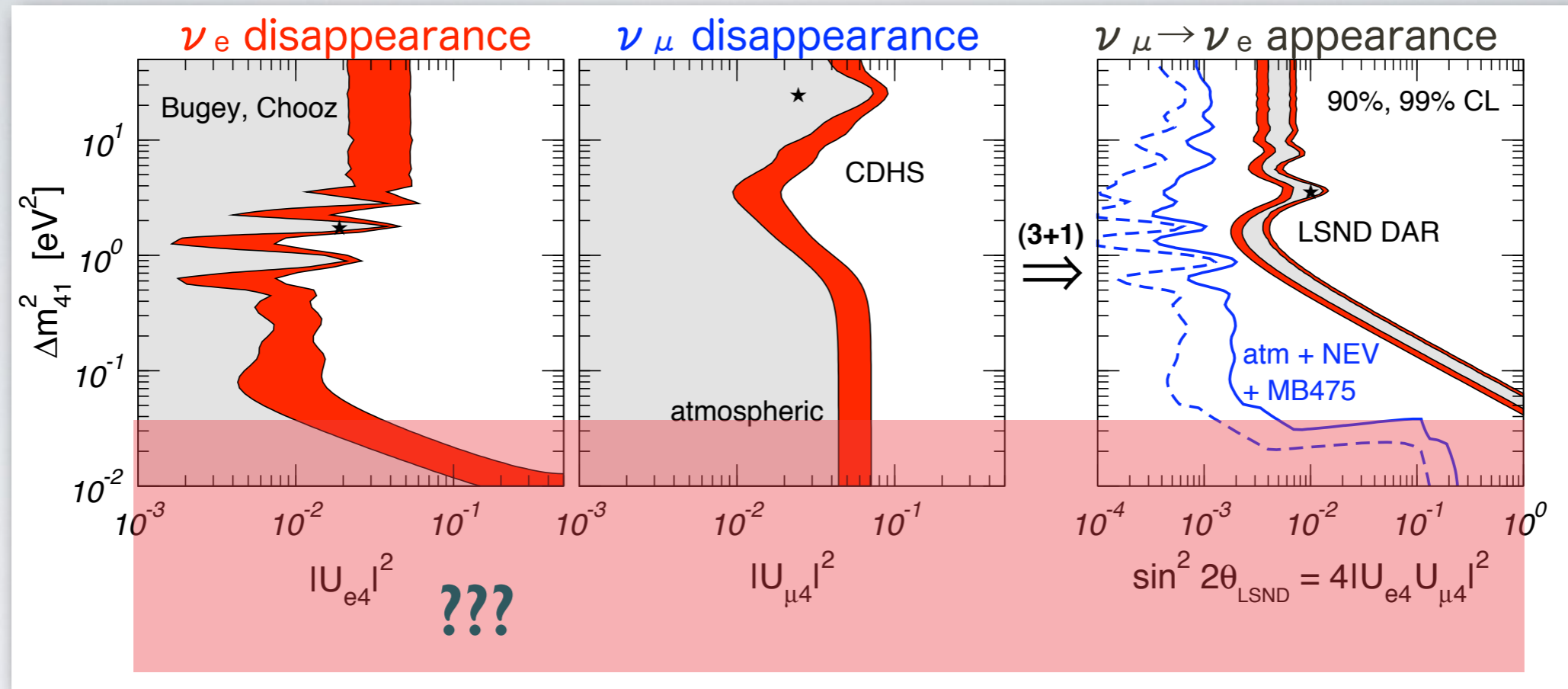
Recent results from MINOS and SciBooNE+MiniBooNE also found no signal in ν_μ disappearance channel

PRL **107**, 011802 (2011)

PRD **85**, 032007 (2012)

PRD **86**, 052009 (2012)

Lighter sterile neutrino ?



- Previous (and future) searches were largely focused on ~ 1 eV² region
- Sterile neutrino can be anywhere. What about lower mass region?
 - Not extensively searched before, especially for electron (anti-)neutrino disappearance channel.
 - sub-eV sterile neutrino might help reconcile tensions between cosmological data. [PRL 112, 051302 \(2014\)](#), [PRL 113, 051303 \(2014\)](#), etc....

We should look everywhere!

Sterile neutrino search at Daya Bay

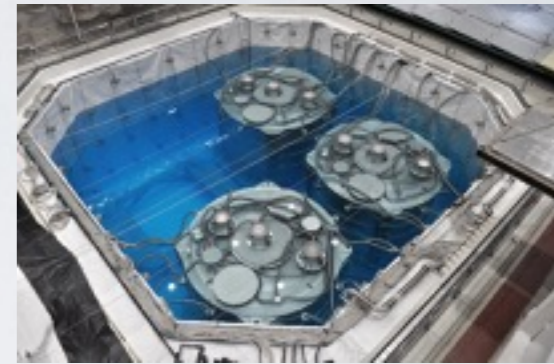
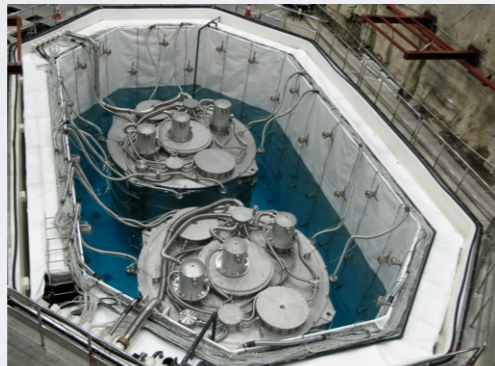
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \simeq 1 - \cos^4 \theta_{14} \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m_{ee}^2 L}{4E_\nu} \right) \leftarrow \text{Oscillation due to } \theta_{13}$$

$$- \sin^2 2\theta_{14} \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E_\nu} \right) \leftarrow \text{Additional oscillation}$$

Detector 1: L~350m

Detector 2: L~500m

Detector 3: L~1600m



$\bar{\nu}_e$

$\langle E_\nu \rangle \sim 4\text{MeV}$



Sensitive at

$$\Delta m_{41}^2 \sim 0.5 \times 10^{-2} \text{ eV}^2$$

Sensitive at

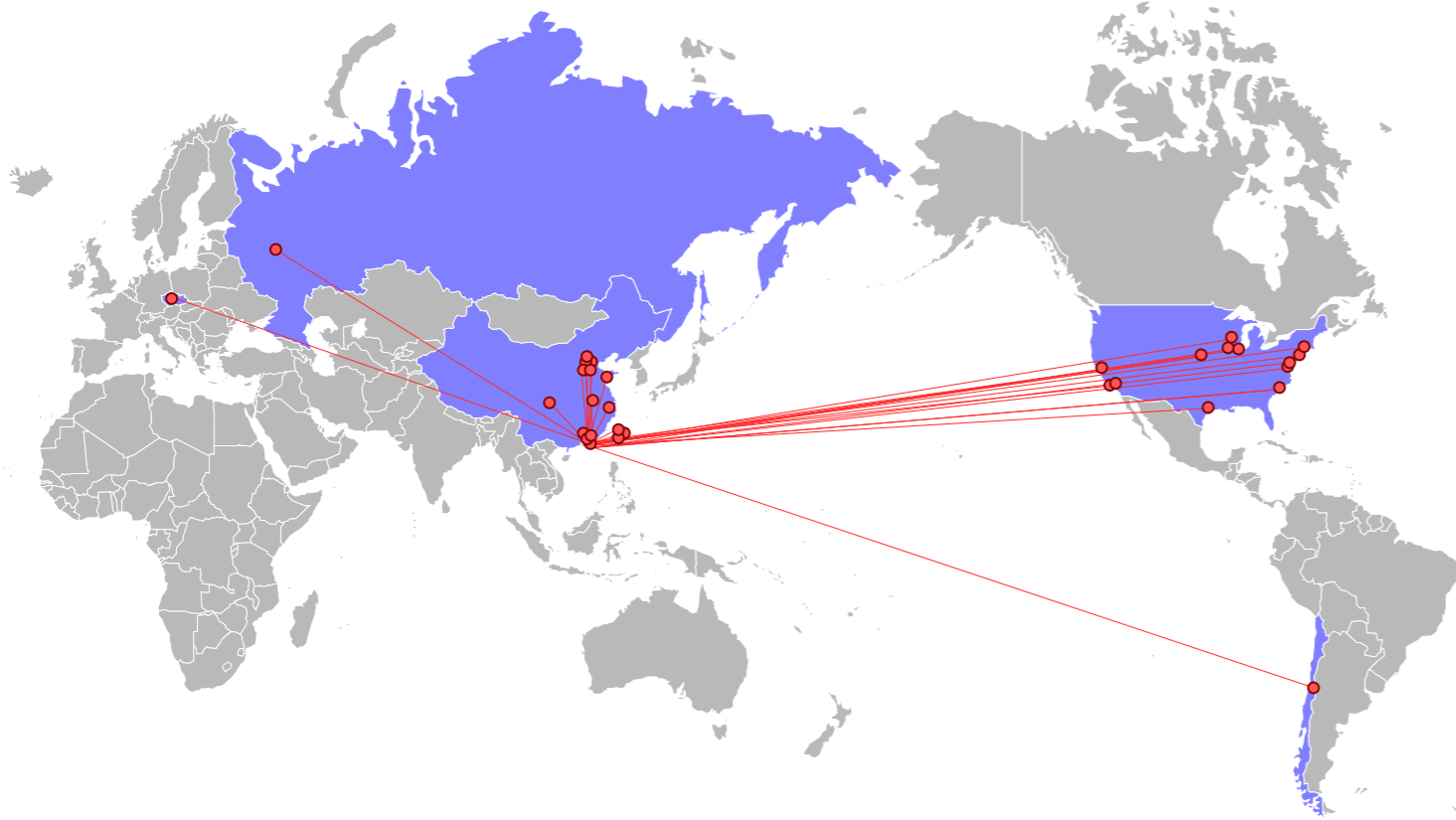
$$\Delta m_{41}^2 \sim 0.5 \times 10^{-3} \text{ eV}^2$$

Daya Bay can provide very stringent test below 0.1 eV^2 , with minimal dependence to reactor antineutrino flux prediction

Daya Bay experiment



The Daya Bay Collaboration



Asia (21)

IHEP, Beijing Normal Univ., Chengdu Univ. of Sci. and Tech., CGNPG, CIAE, Dongguan Univ. of Tech., Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiao tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Xi'an Jiaotong Univ., Zhongshan Univ., Univ. of Hong Kong, Chinese Univ. of Hong Kong, National Taiwan Univ., National Chiao Tung Univ., National United Univ.

North America (17)

BNL, LBNL, Iowa State Univ., RPI, Illinois Inst. Tech., Princeton, UC-Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, Univ. of Wisconsin, William & Mary, Virginia Tech., Univ. of Illinois-Urbana-Champaign, Siena, Temple Univ, Yale

Europe (2)

JINR, Dubna, Russia; Charles University, Czech Republic

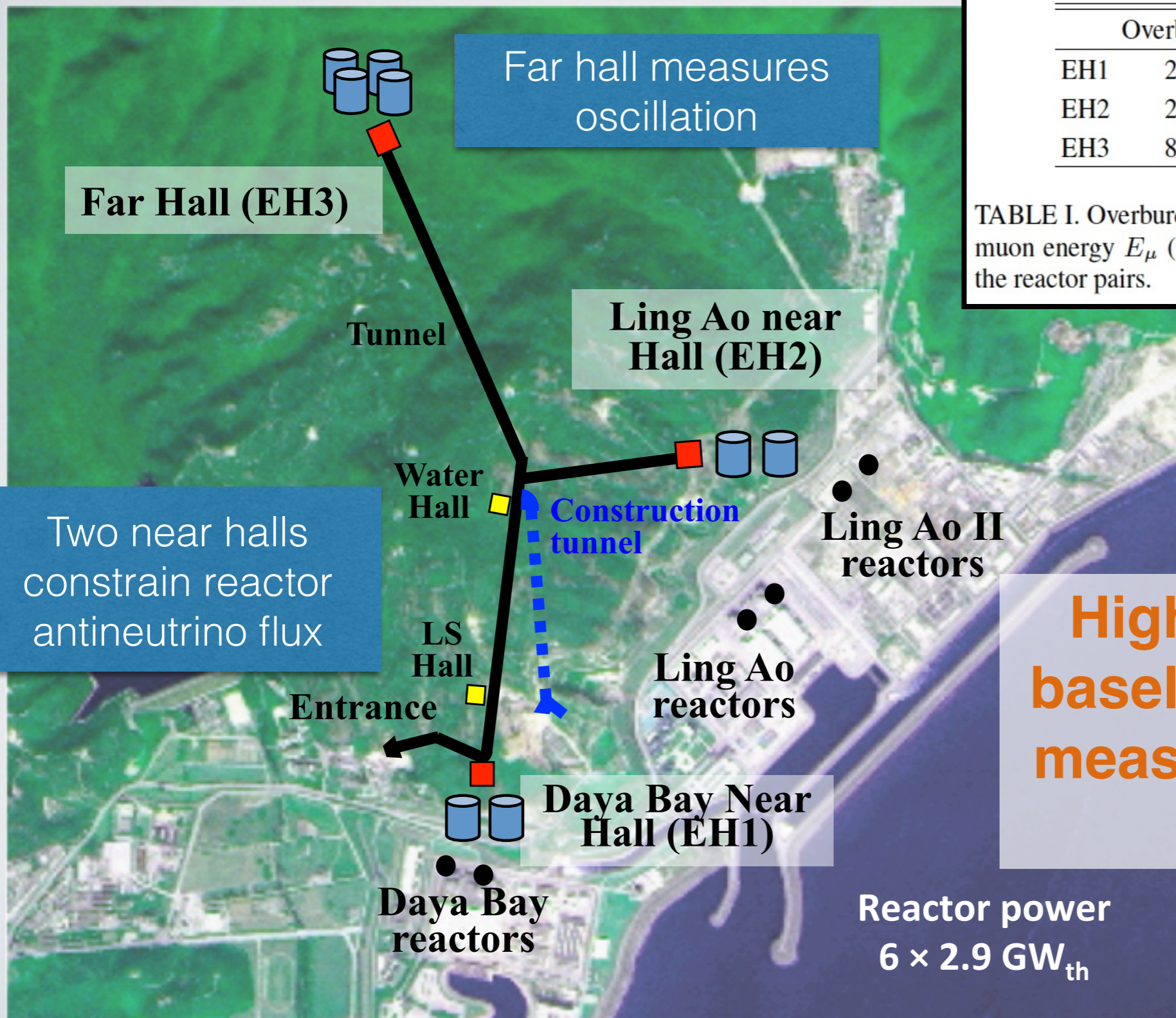
South America (1)

Catholic Univ. of Chile



~230 collaborators

Experimental layout

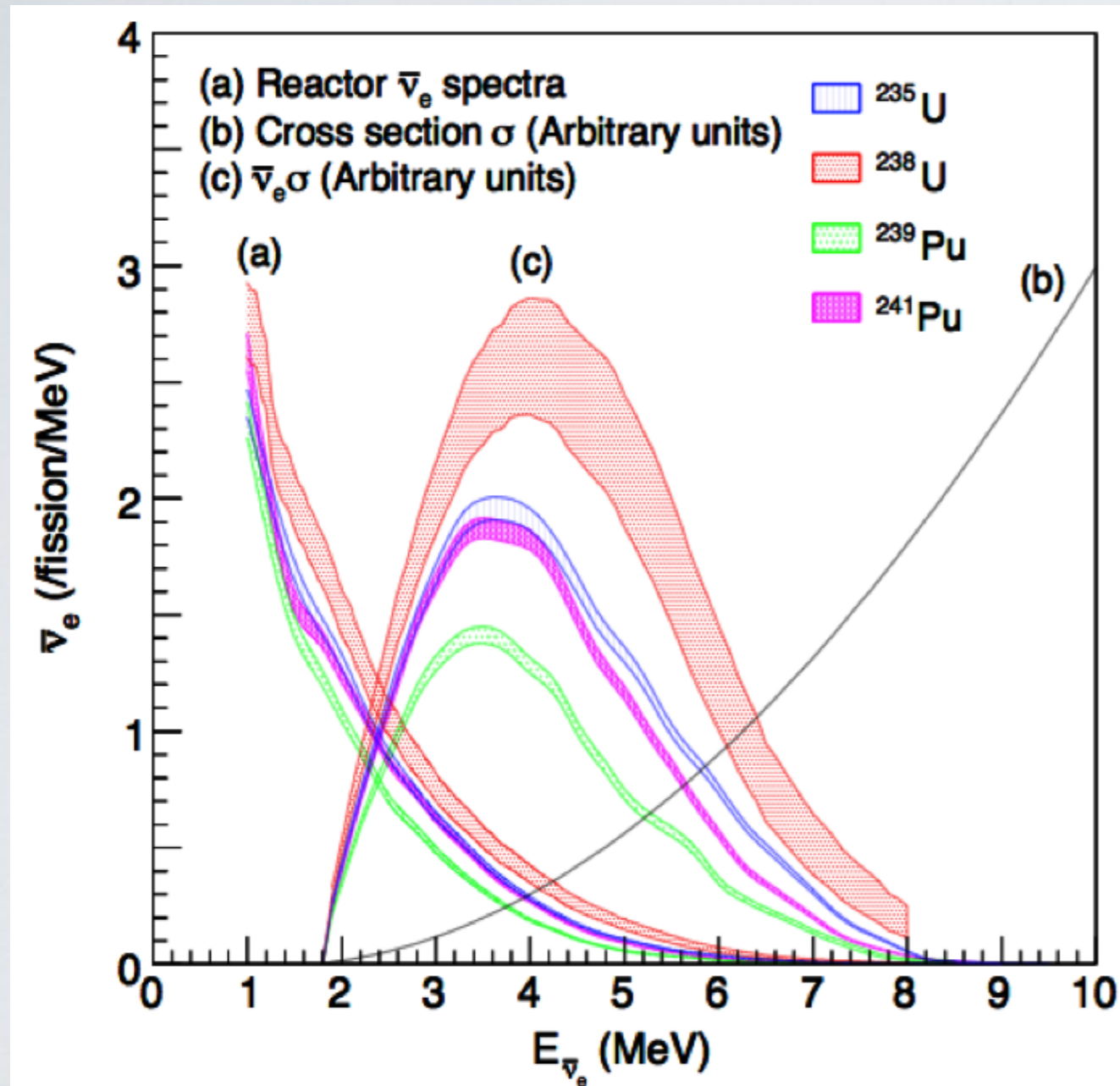


	Overburden	R_μ	E_μ	D1,2	L1,2	L3,4
EH1	250	1.27	57	364	857	1307
EH2	265	0.95	58	1348	480	528
EH3	860	0.056	137	1912	1540	1548

TABLE I. Overburden (m.w.e), muon rate R_μ (Hz/m²), and average muon energy E_μ (GeV) of the three EHs, and the distances (m) to the reactor pairs.

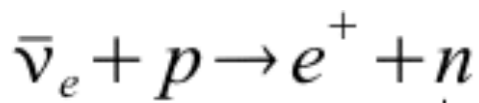
High-statistics, multi-baseline (350m - 2000m) measurement of reactor antineutrinos

Reactor Antineutrinos

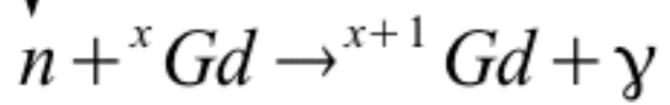


- Most powerful man-made source of antineutrinos, and it's free
- Nuclear fission release:
 - 6 antineutrinos/fission
 - Typically $\sim 10^{20}$ fissions/ GW_{th}
- Detected through inverse beta decay
- Broad spectrum with mean energy of ~ 4 MeV

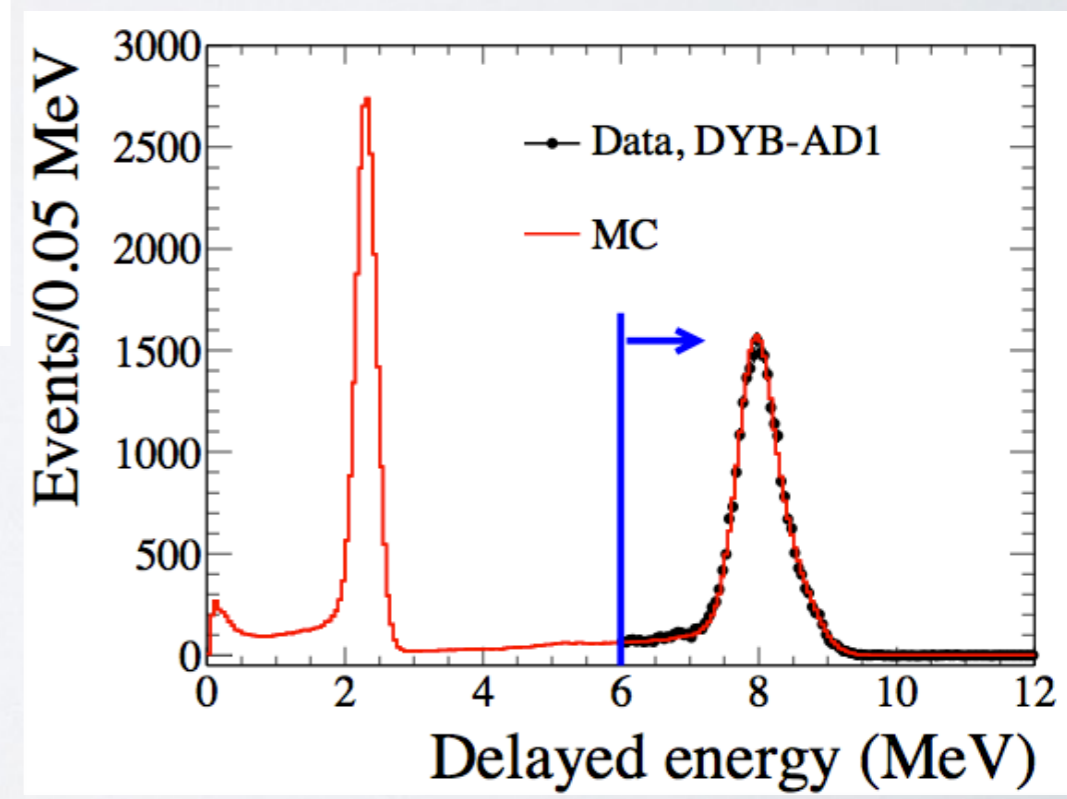
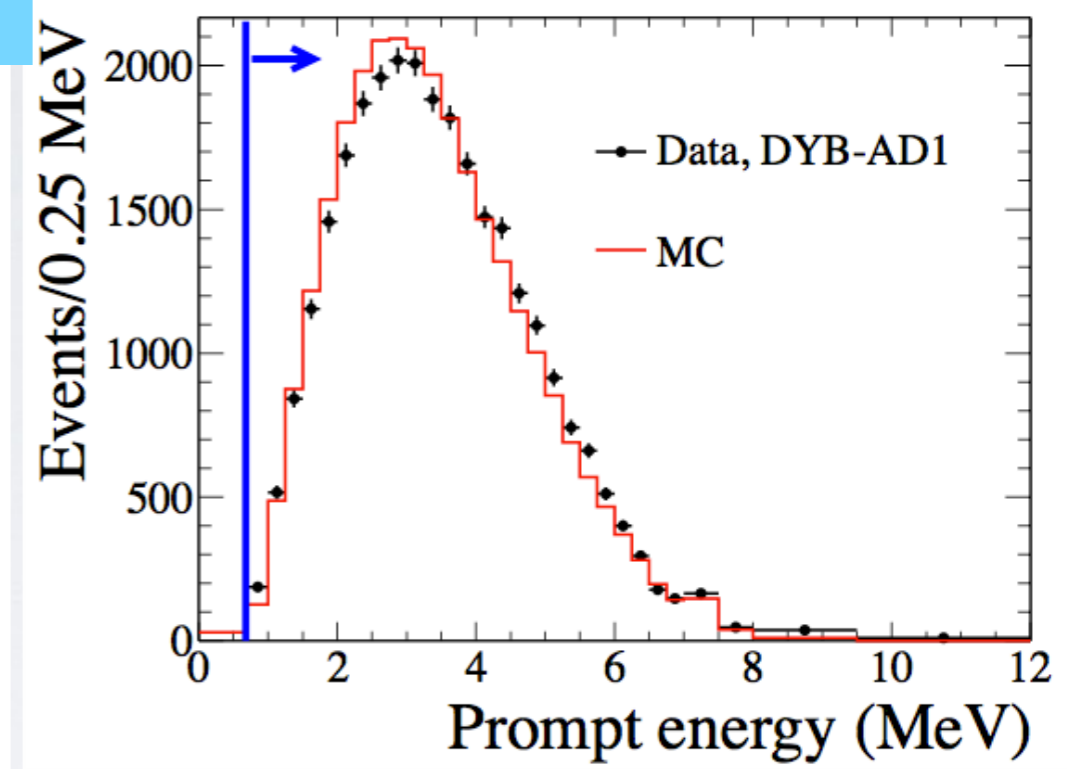
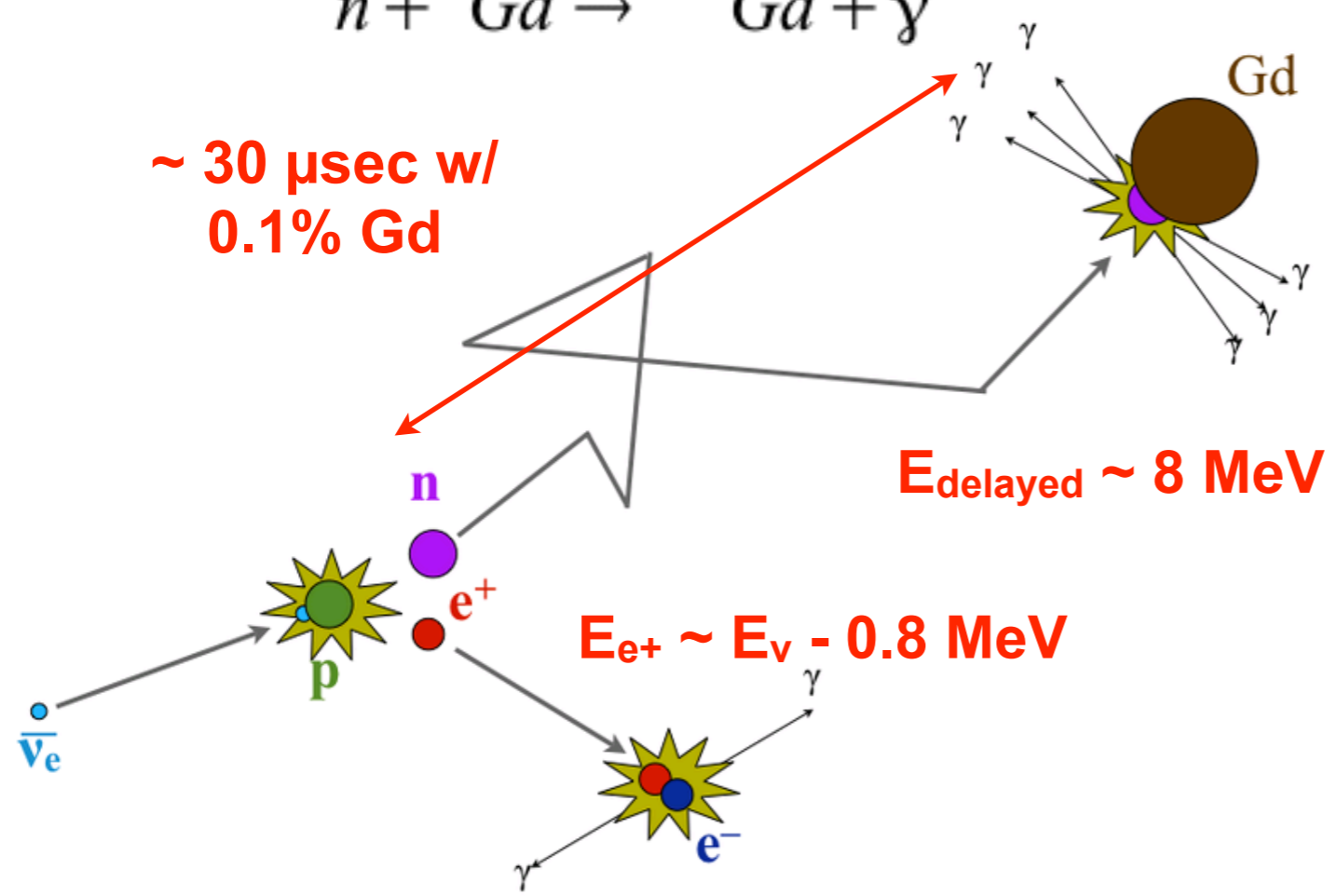
Antineutrino Detection Method



Antineutrinos are detected via inverse beta decay reaction



~ 30 μsec w/
0.1% Gd



Prompt + Delayed coincidence

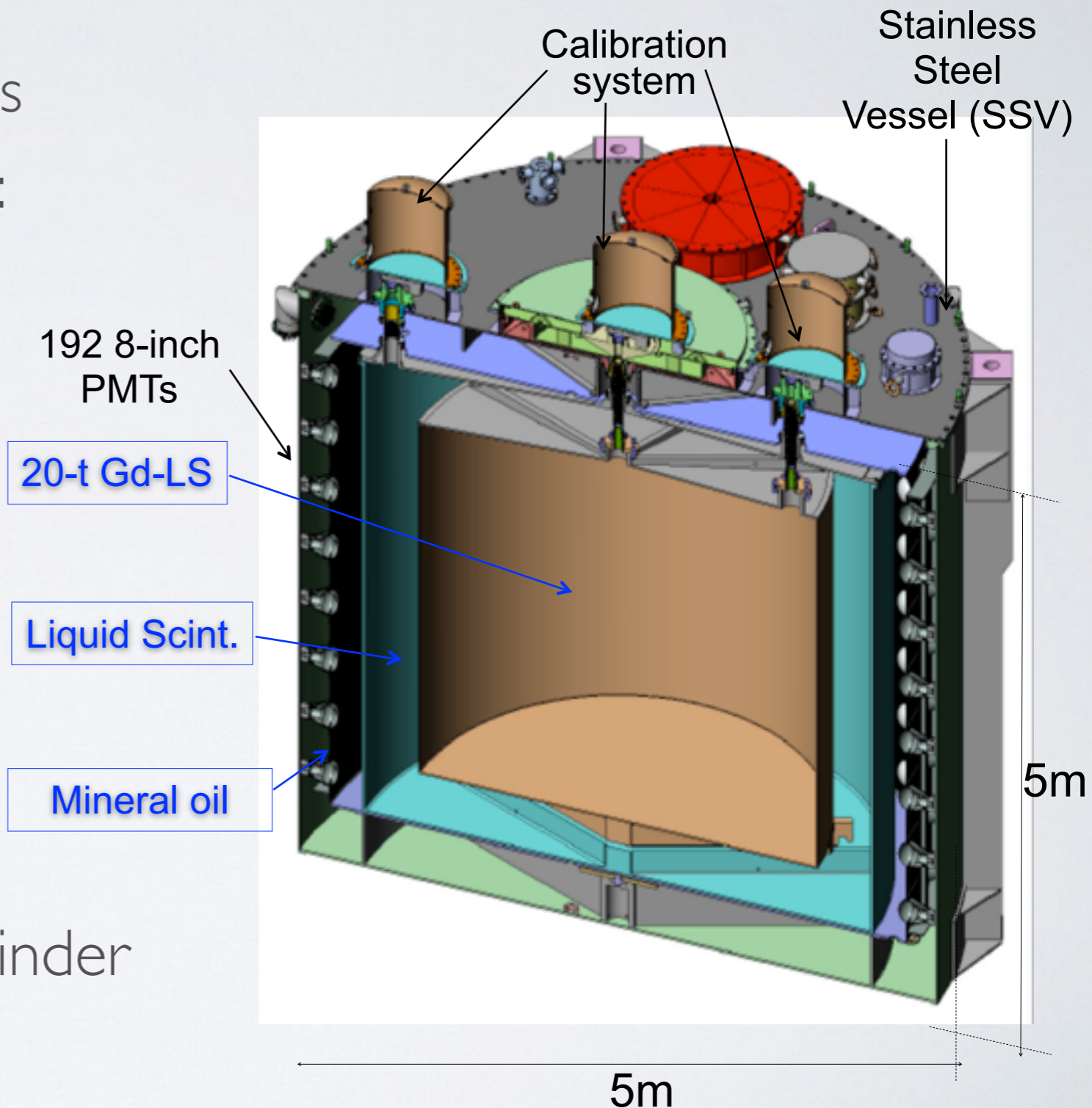
- Prompt positron: carries antineutrino energy
- Delayed neutron capture: efficiently tag antineutrino signal

Antineutrino Detector

- 8 functionally identical detectors
- Three-zone cylindrical modules:

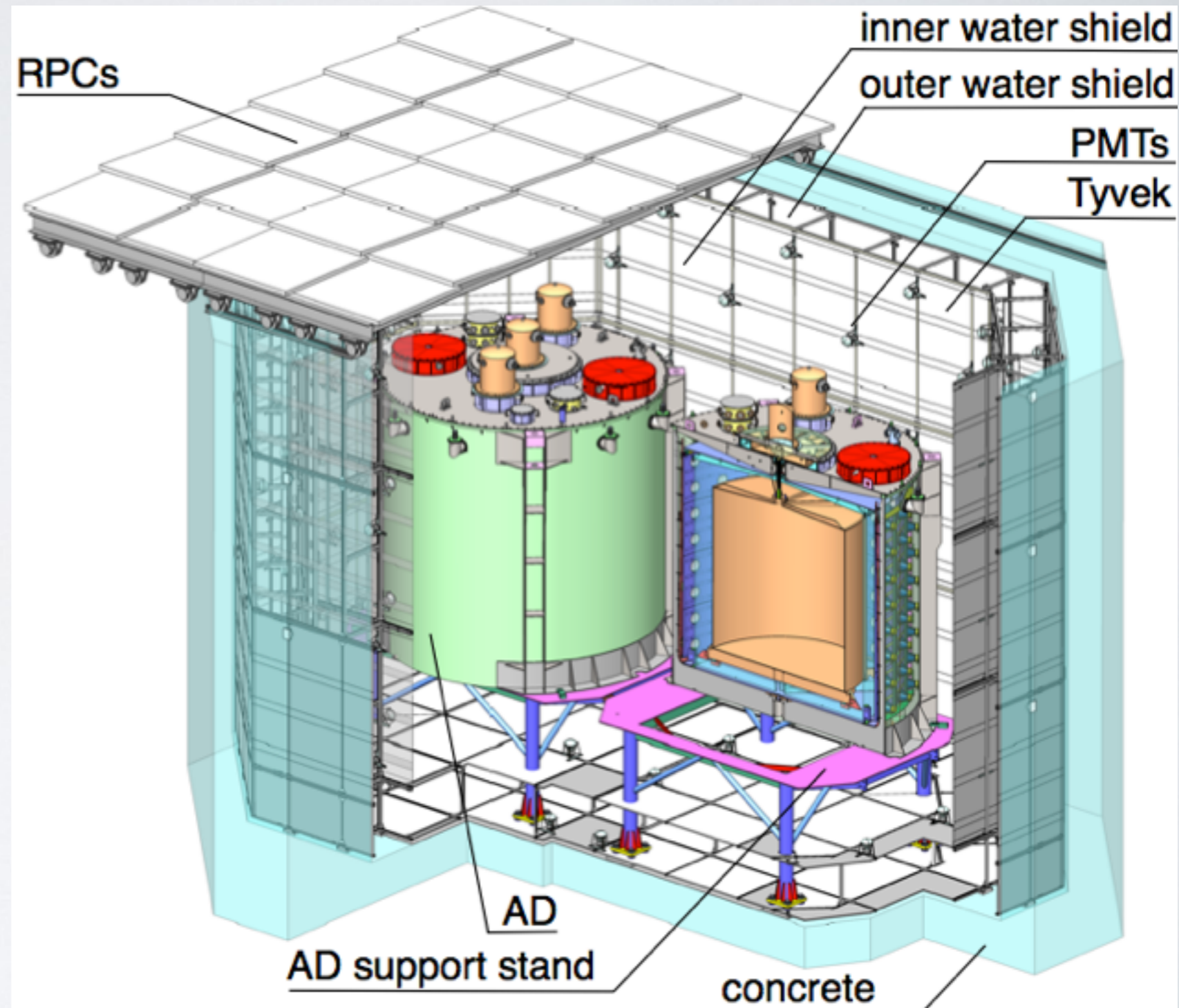
Zone	Mass	Liquid	Purpose
Inner acrylic vessel	20 t	Gd-doped liquid scintillator	Anti-neutrino target
Outer acrylic vessel	22 t	Liquid scintillator	Gamma catcher (from target zone)
Stainless steel vessel	40 t	Mineral Oil	Radiation shielding

- Reflectors at top/bottom of cylinder are used to increase light yield.



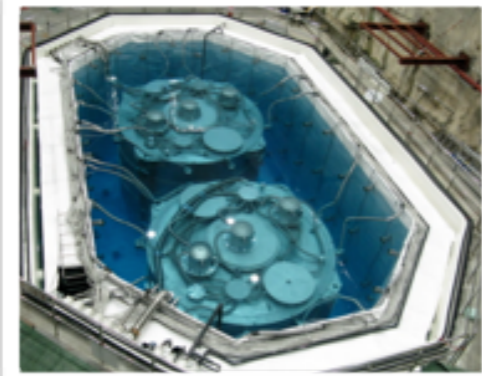
Muon Tagging System

- 2.5 meter thick two-section water shield
 - Cherenkov detector to tag cosmic ray muons.
 - Shield for neutrons and gammas from surrounding materials.
- RPC
 - Covers water pool to provide further muon tagging.



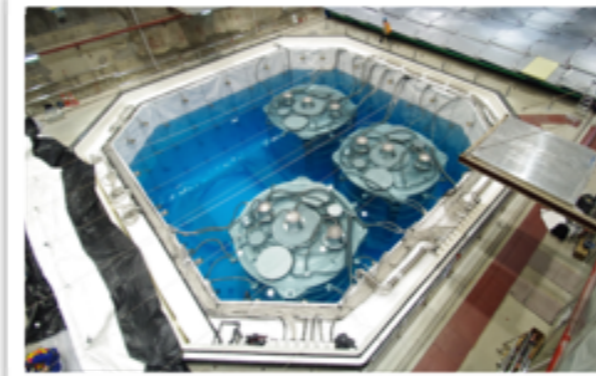
Timeline of Detector Installation

EH1



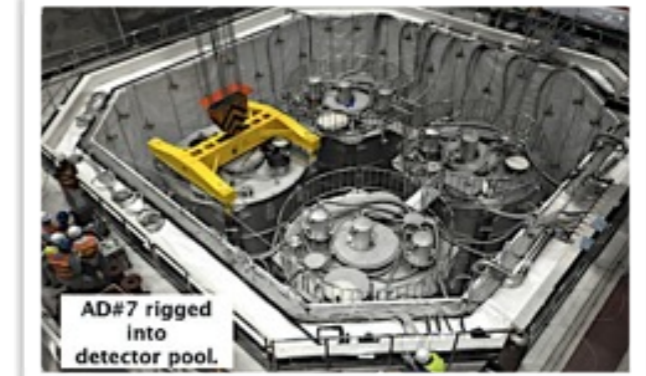
Aug. 2011

EH3



Dec. 2011

EH3



Aug. 2012

6-AD Data Taking

2011/12 - 2012/07

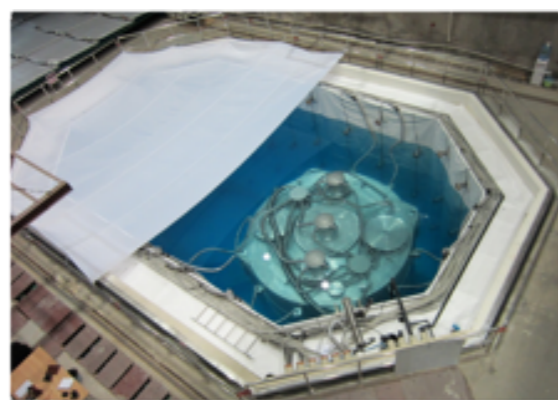
8-AD Data Taking

2012/10 - now

Apr. 2011

YN joined LBNL

Nov. 2011



EH2

Aug. 2012



EH2

Data from full 6-AD period (Dec 2011 - Jul 2012) was used for this analysis

Characterizing Detector Response

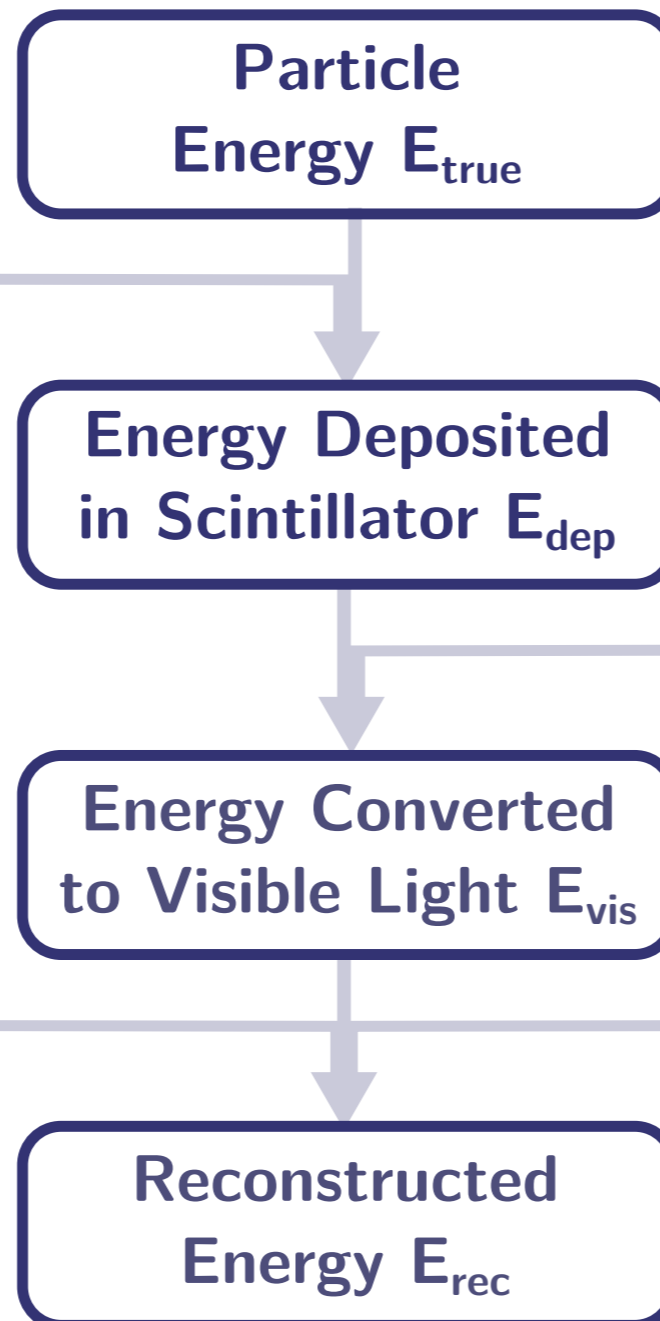
Energy Losses in Acrylic

Acrylic vessels non-scintillating

- Induce shape distortion
- Correction from MC

Energy Resolution

- Light production
- Light collection
- PMT/electronics response



Two major sources
of non-linearity.
Difficult to decouple !



1: Scintillator Response

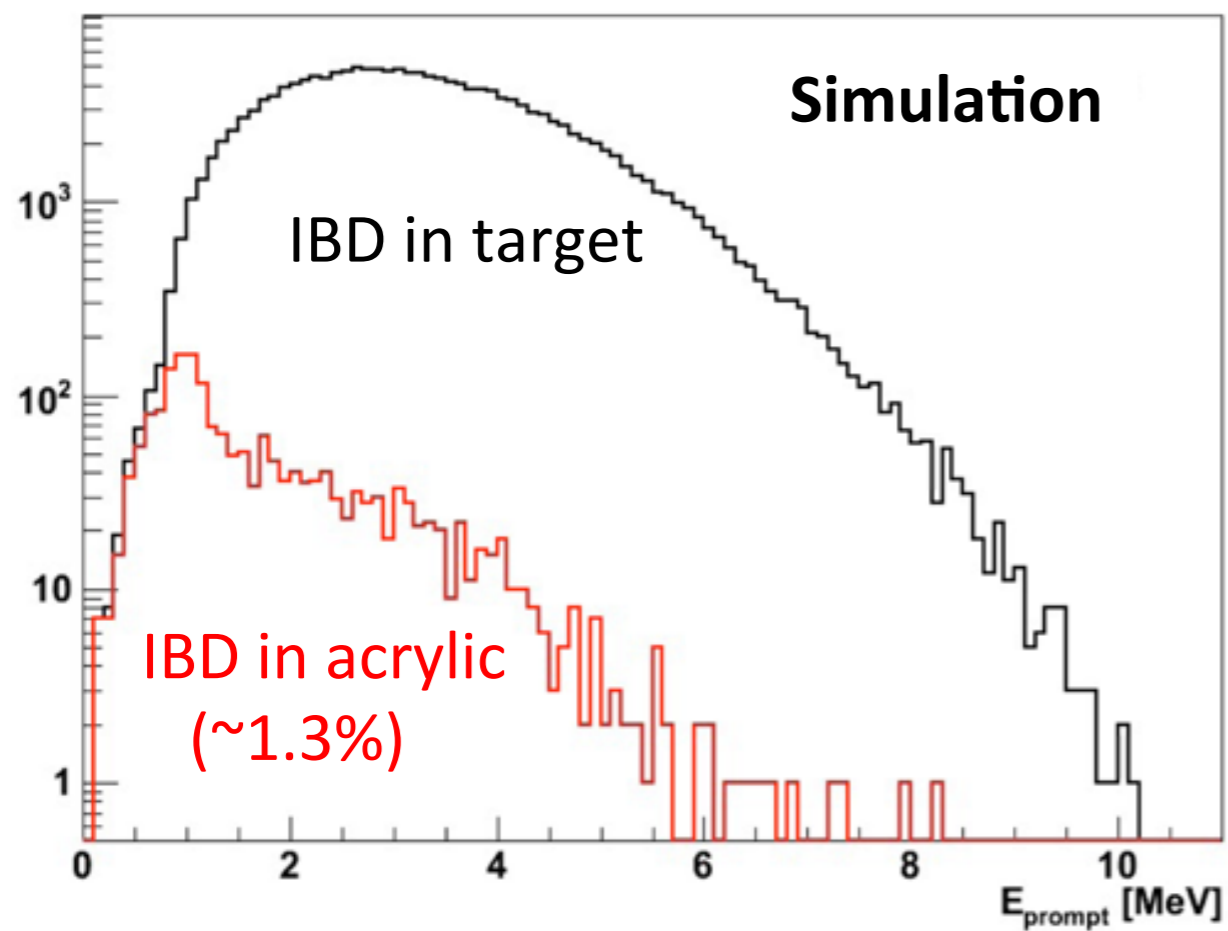
- Quenching effects
- Cherenkov radiation

2: Readout Electronics

- Charge collection efficiency decreases with visible light

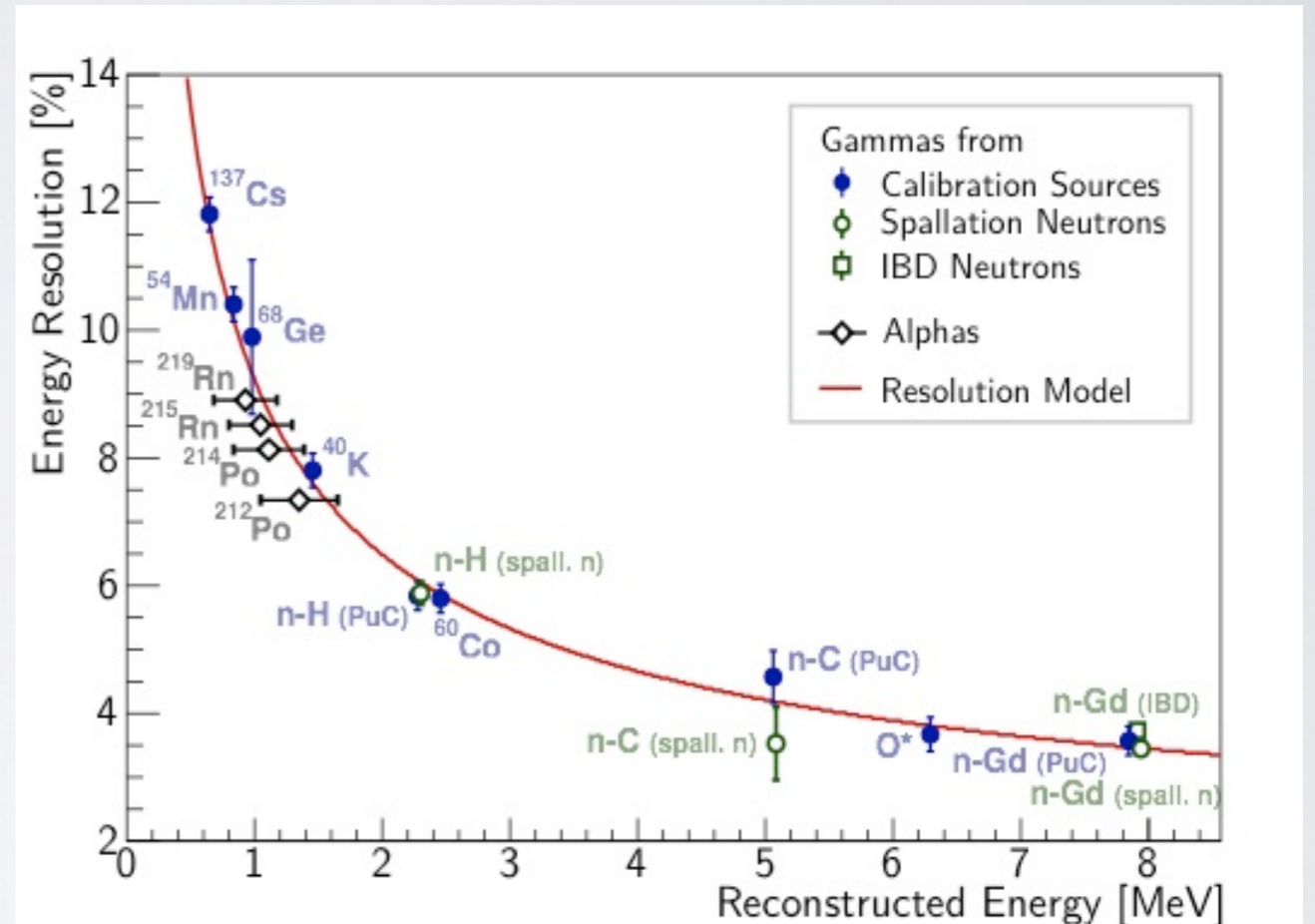
Acrylic Vessel / Energy Resolution

Energy loss in the acrylic vessel distorts spectrum



Modeled using MC simulation

Energy resolution



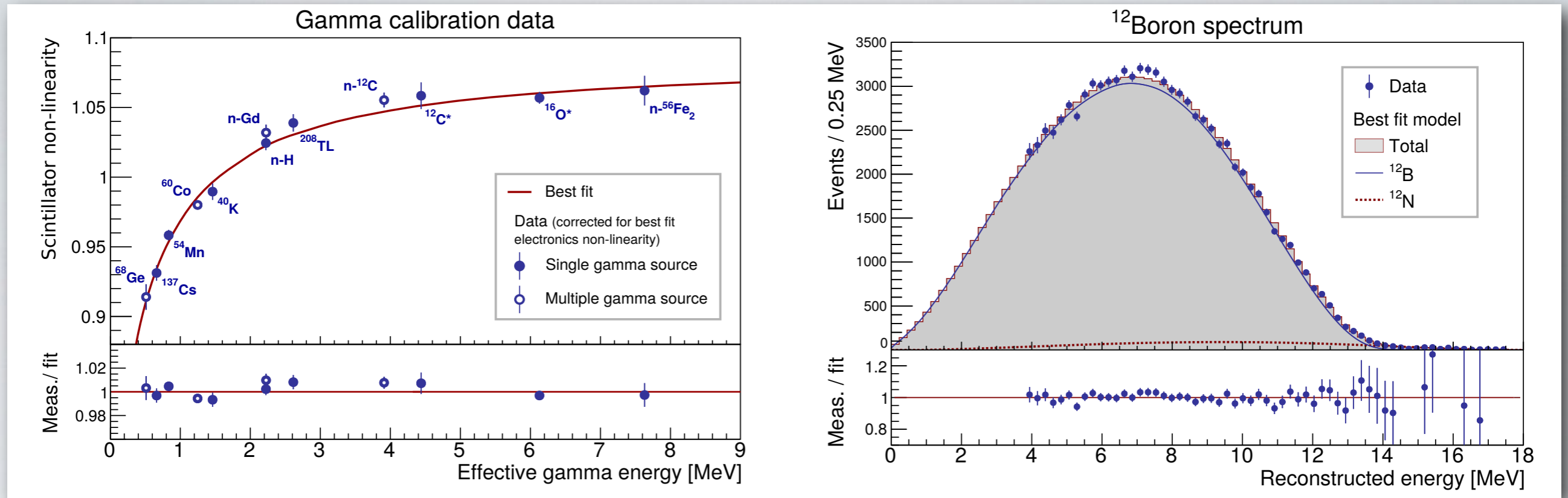
Contributions from:

- a : Spacial/temp. resolution (E)
- b : Photon statistics (E)
- c : Dark noise (const:)

$$\frac{\sigma_E}{E} = \sqrt{a^2 + \frac{b^2}{E} + \frac{c^2}{E^2}}$$

Calibrated primarily using mono-energetic gamma sources

Constraining Non-Linearity Parameters



Full detector calibration data

1. Monoenergetic gamma lines from various sources
 - Radioactive calibration sources, employed regularly: ^{68}Ge , ^{60}Co , ^{241}Am - ^{13}C and during special calibration periods: ^{137}Cs , ^{54}Mn , ^{40}K , ^{241}Am - ^9Be , Pu - ^{13}C
 - Singles and correlated spectra in regular physics runs (^{40}K , ^{208}Tl , n capture on H)
2. Continuous spectrum from ^{12}B produced by muon spallation inside the scintillator

Standalone measurements

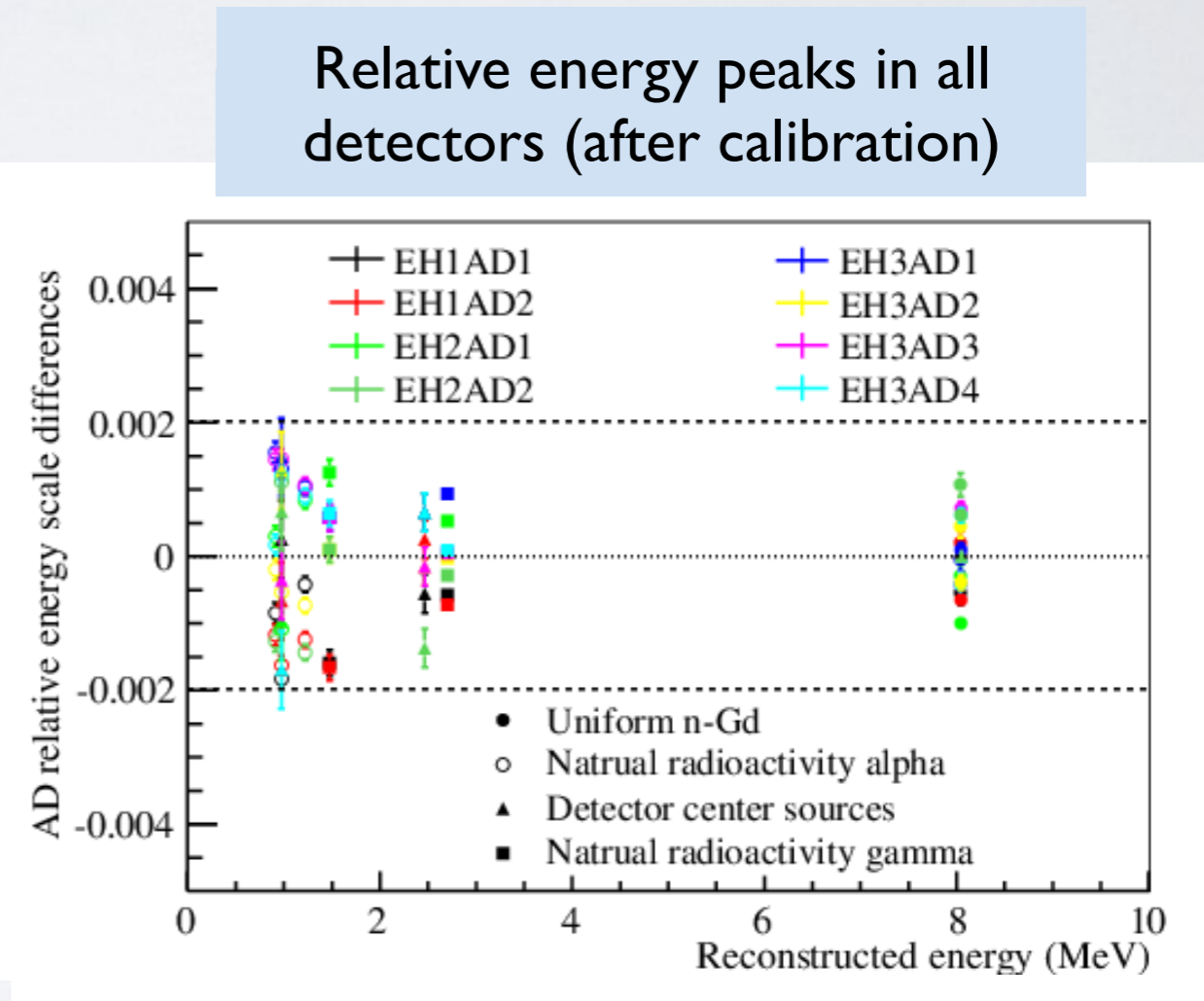
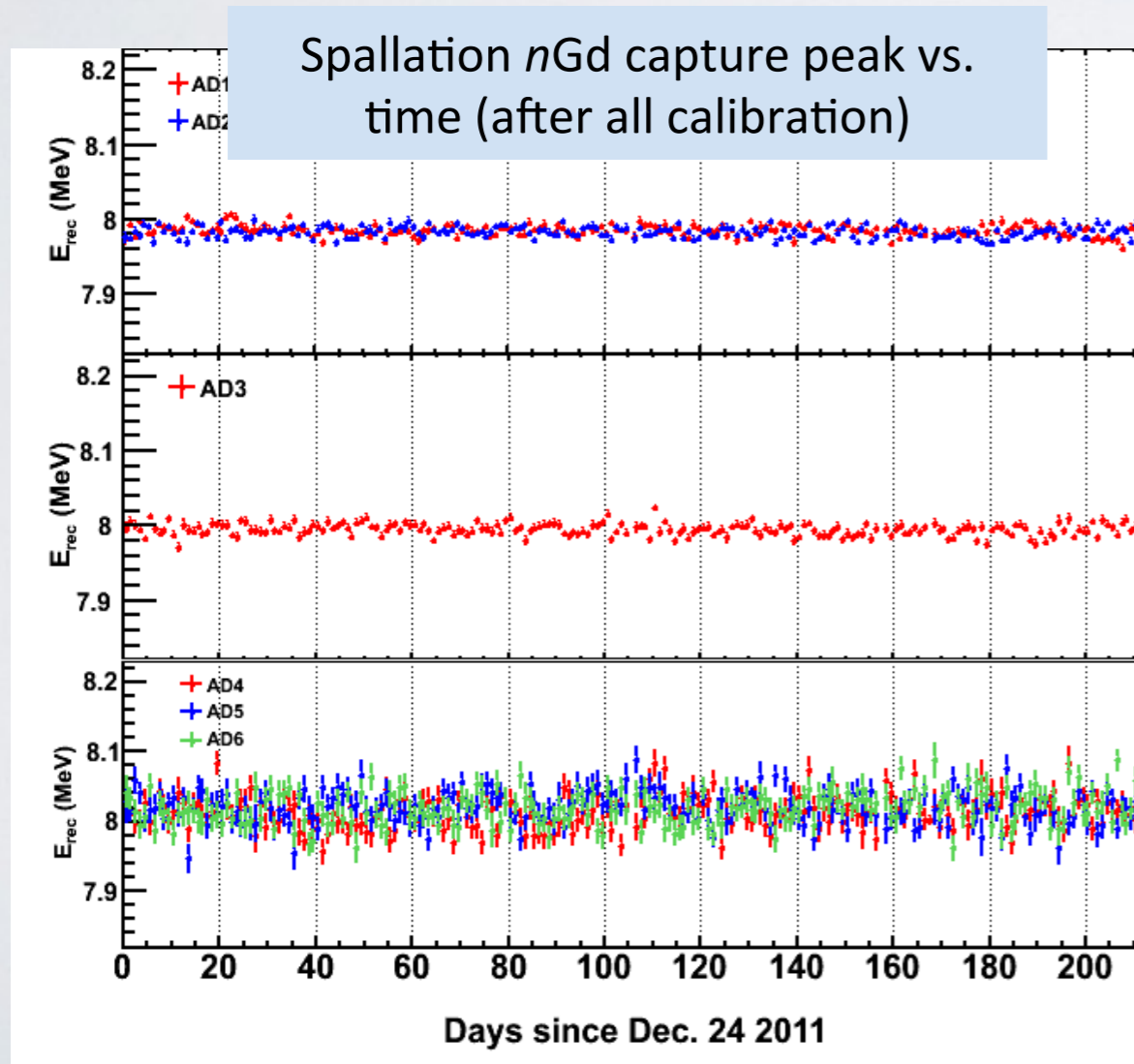
- Scintillator quenching measurements using neutron beams and Compton e^-
- Calibration of readout electronics with flash ADC

Relative Energy Scale

Crucial ingredient: Consistent energy response for all ADs

Careful calibration with in-situ data and calibration sources:

- Energy response stable to 0.1% in all detectors
- Total relative uncertainty of $<0.2\%$ between detectors



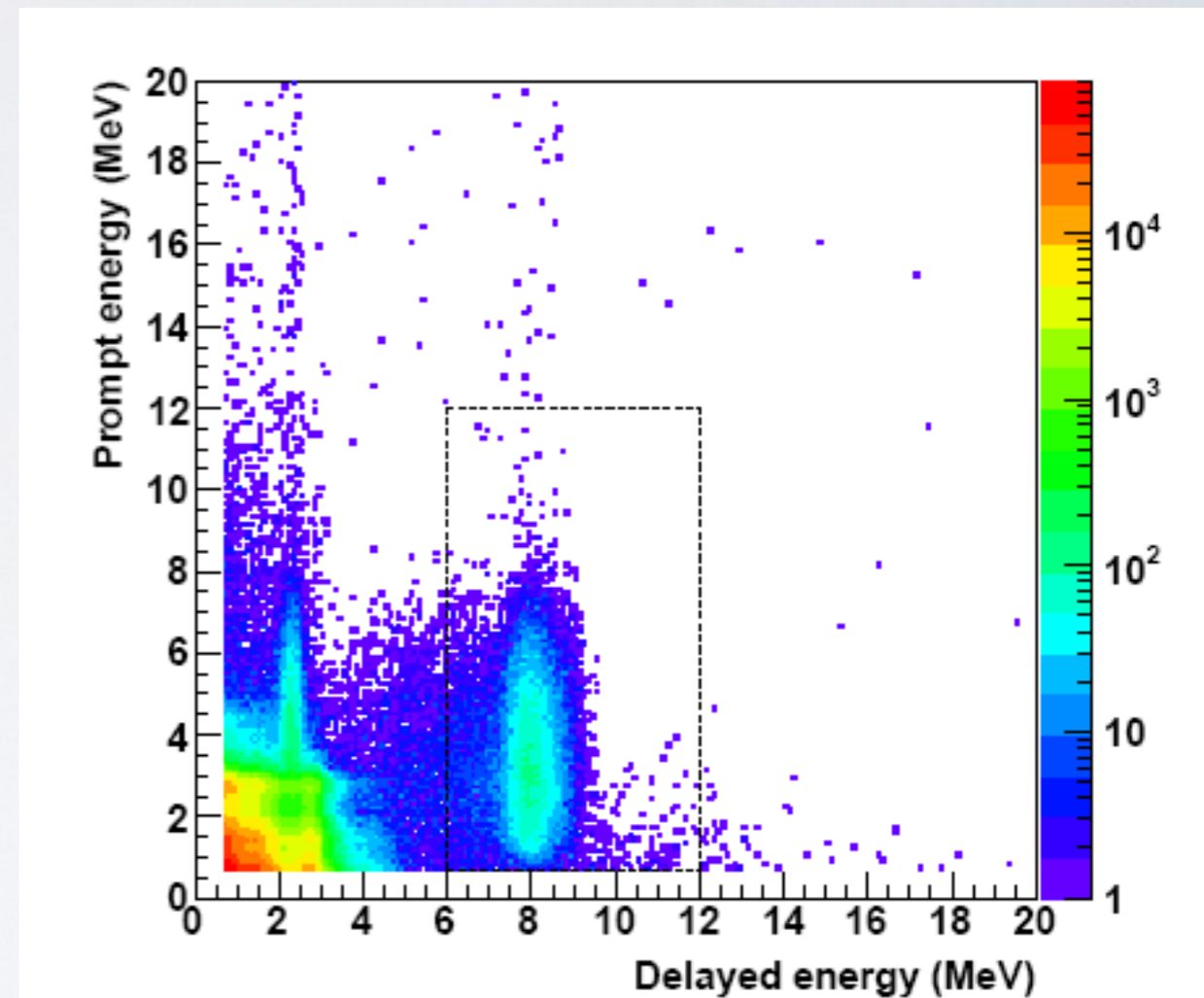
Search for sterile neutrinos



Antineutrino candidate selection

- Reject spontaneous PMT light emission (“flashers”)
- Prompt positron energy: $0.7 < E_p < 12 \text{ MeV}$
- Delayed neutron energy: $6 < E_d < 12 \text{ MeV}$
- Neutron capture time: $1 < \Delta t < 200 \text{ } \mu\text{sec}$
- Muon veto
 - Water pool muon: reject 0.6ms
 - AD muon (>3000 photoelectrons) : reject 1.4ms
 - AD shower muon ($>3 \times 10^5$ p.e.): reject 0.4 sec
- Multiplicity cut: only select isolated pairs

Selection identical to the oscillation parameter measurement



Signal and Background Summary

	EH1 (Near)		EH2 (Near)		EH3 (Far)	
	AD1	AD2	AD3	AD4	AD5	AD6
Antineutrino candidates	101290	102519	92912	13964	13894	13731
DAQ live time (day)	191.001		189.645		189.779	
Efficiency	0.7957	0.7927	0.8282	0.9577	0.9568	0.9566
Accidentals (/day/AD)*	9.54±0.03	9.36±0.03	7.44±0.02	2.96±0.01	2.92±0.01	2.87±0.01
Fast neutron (/day/AD)*	0.92±0.46		0.62±0.31		0.04±0.02	
⁸He/⁹Li (/day/AD)*	2.40±0.86		1.20±0.63		0.22±0.06	
Am-C corr. (/day/AD)*			0.26±0.12			
¹³C(α, n)¹⁶O (/day/AD)*	0.08±0.04	0.07±0.04	0.05±0.03	0.04±0.02	0.04±0.02	0.04±0.02
IBD rate (/day/AD)*	653.30 ± 2.31	664.15 ± 2.33	581.97 ± 2.07	73.31 ± 0.66	73.03 ± 0.66	72.20 ± 0.66

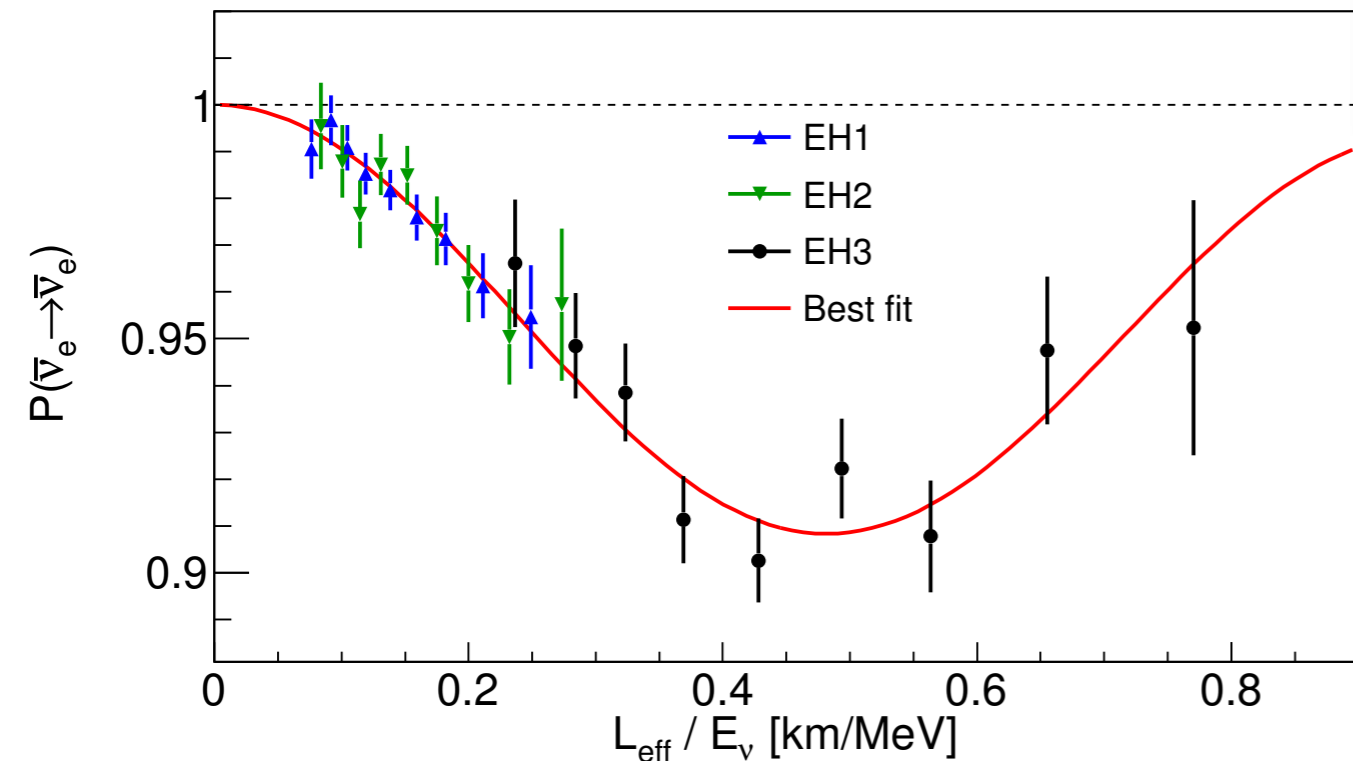
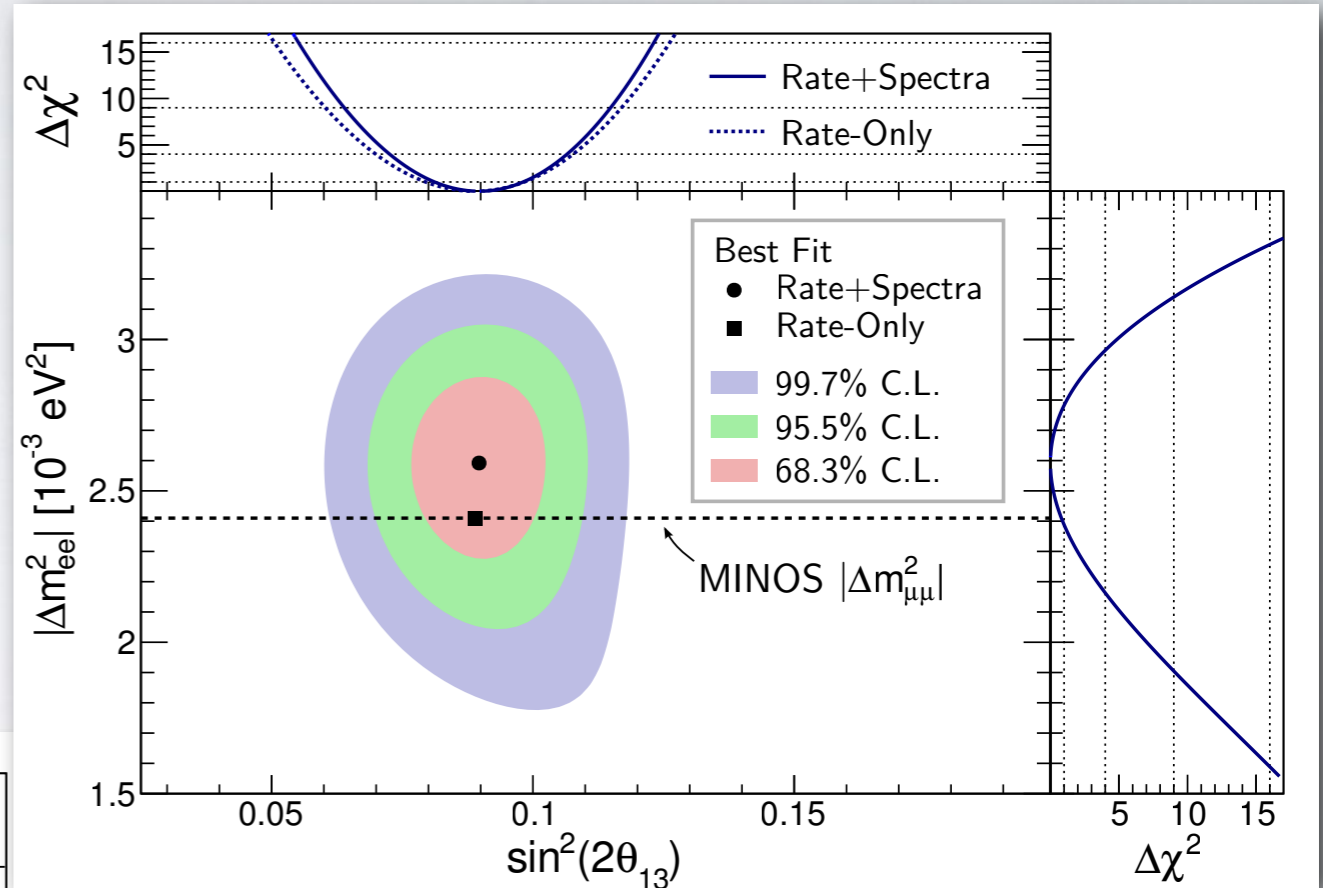
* Corrected for the efficiency of the muon veto and multiplicity cuts

More than 300k antineutrino interactions

- Consistent rates for side-by-side detectors

Spectral analysis 2013

- High precision measurement of $\sin^2 2\theta_{13}$ and Δm_{ee}^2 ($\sim \Delta m_{32}^2 \sim \Delta m_{31}^2$) with spectral analysis
- First direct measurement of Δm_{ee}^2



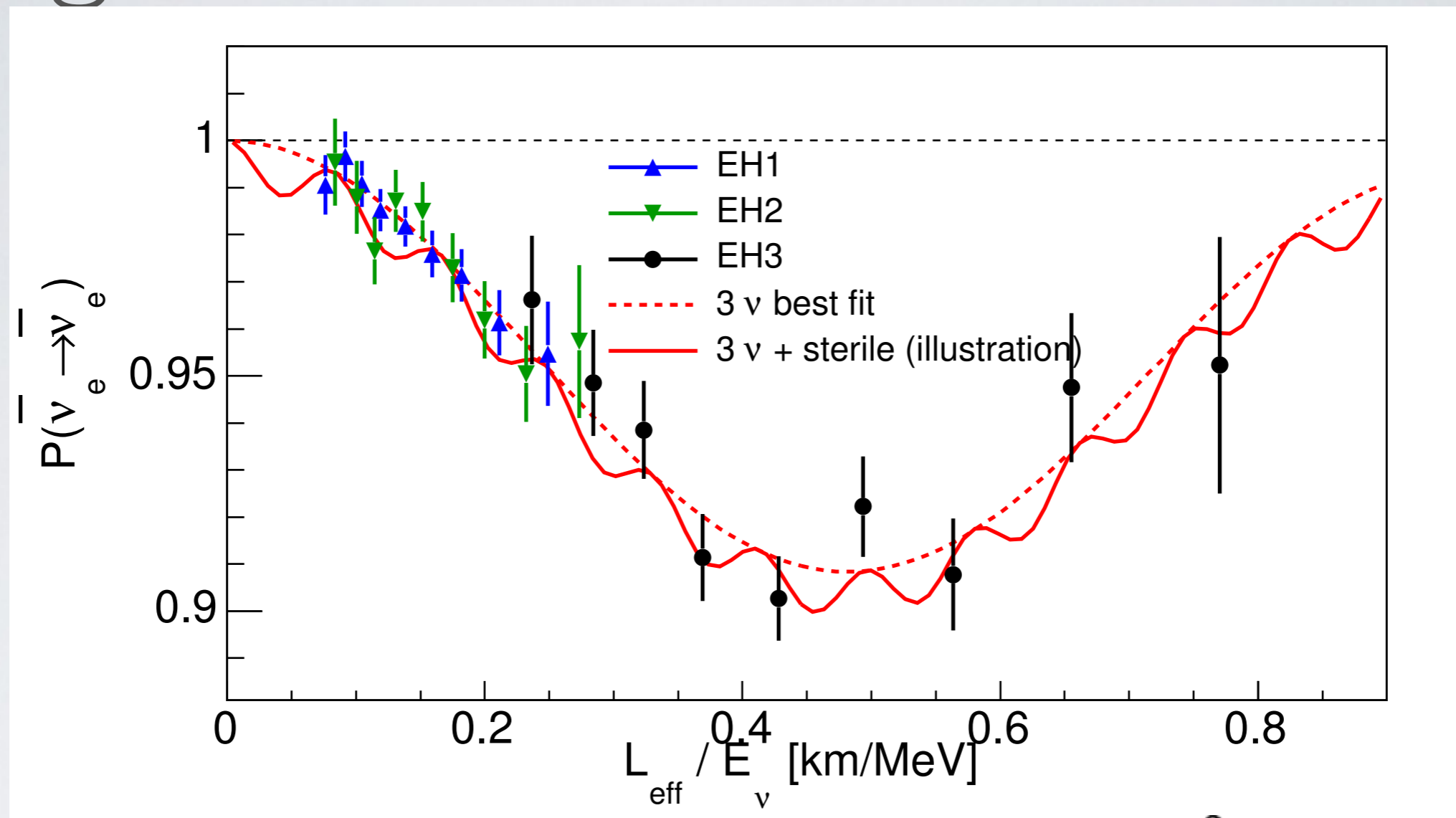
$$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$$

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

PRL 112, 061801 (2014)

Use the same data set to search for sterile neutrinos

Signature of sterile neutrinos



$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \simeq 1 - \cos^4 \theta_{14} \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m_{ee}^2 L}{4E_\nu} \right) - \sin^2 2\theta_{14} \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E_\nu} \right)$$

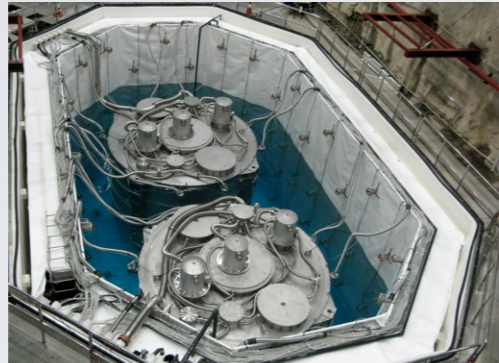
- Signature of sterile neutrino would appear as additional spectral distortion and overall rate deficit

Signature of sterile neutrinos

EH1: L~350m

EH2: L~500m

EH3: L~1600m



$\bar{\nu}_e$

$\langle E_\nu \rangle \sim 4\text{MeV}$



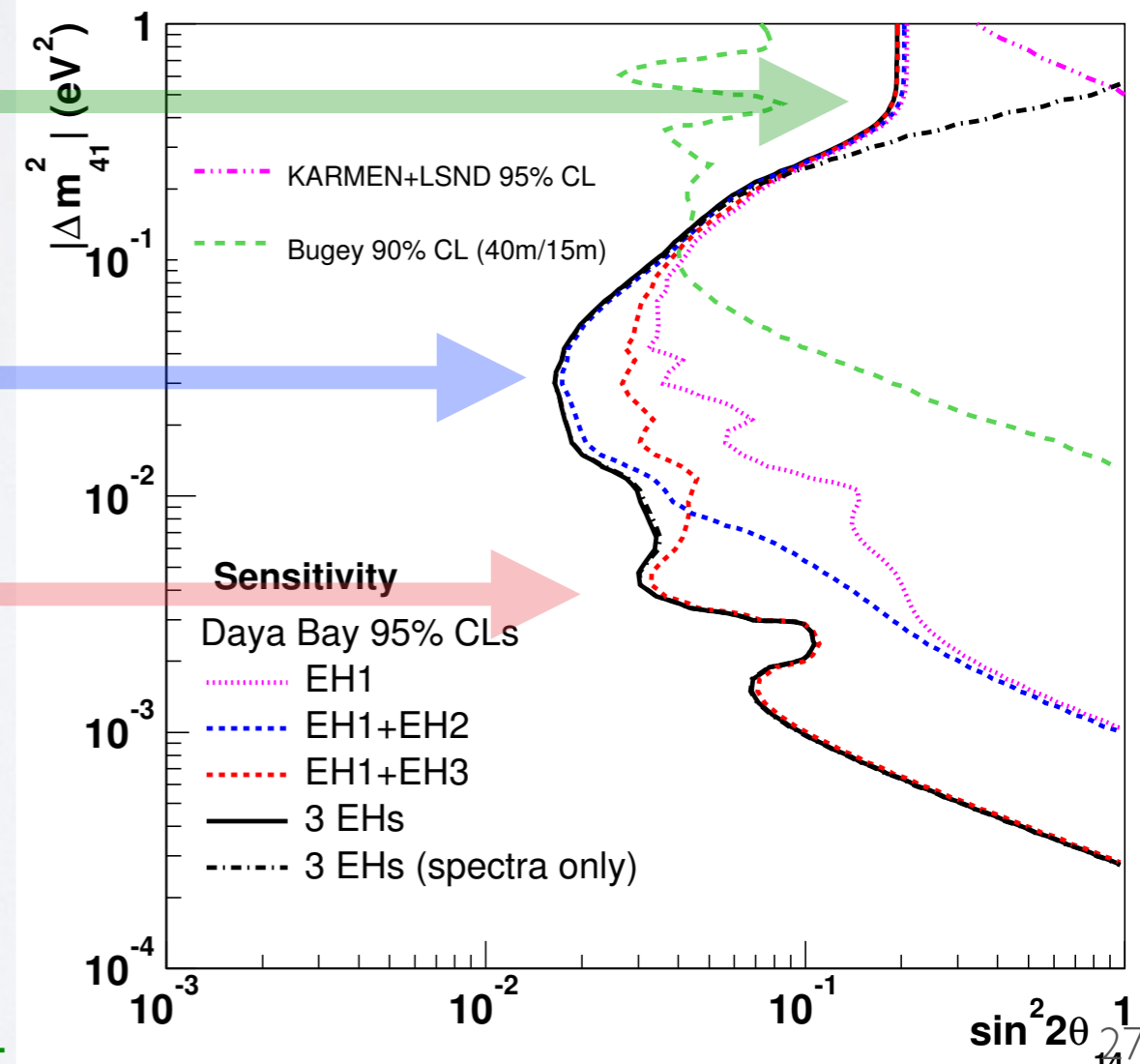
Global rate deficit

One oscillation cycle at $L=150\text{m}$
Relative EH2/EH1 comparison

One oscillation cycle at $L=1300\text{m}$
Relative EH3/EH1 comparison

Probing largely unexplored region at $\Delta m^2_{41} < 0.1 \text{ eV}^2$

Independent to absolute flux prediction



Analysis Methods

Multiple independent analyses

- **Fit to reactor flux model**
 - Utilize all information available
 - Possible bias due to reactor antineutrino flux model
- **Pure relative rate+shape comparison (*Focus in this talk*)**
 - Lose sensitivity at high Δm^2 region
 - Independent of reactor antineutrino flux model

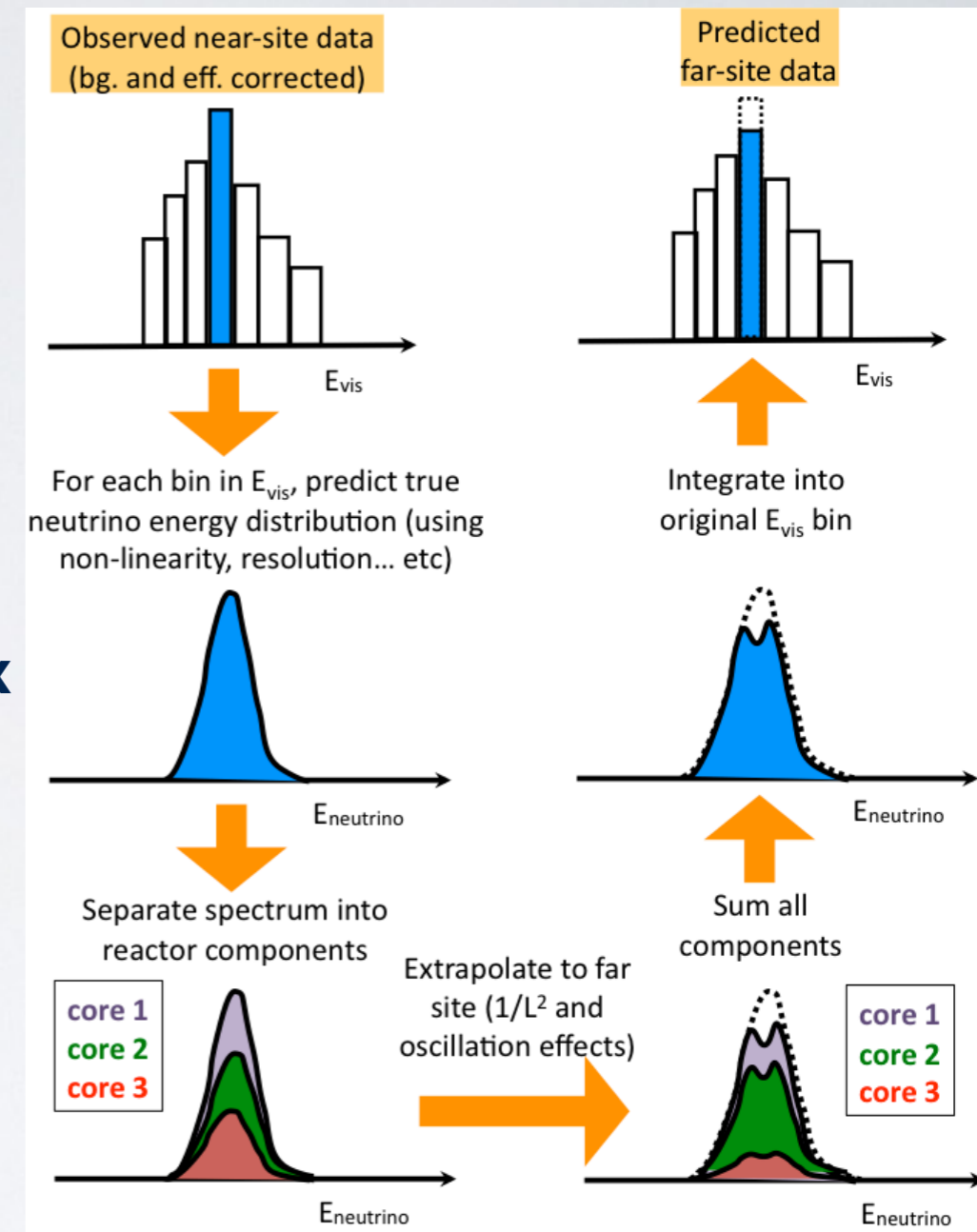
Pure relative rate+shape analysis

- Use near site observed spectra to predict far site spectra
 - Based on our knowledge of reactor power profile, experimental geometry, and detector response

Visible to true energy unfolding matrix

$$F_i^{pred} = N_i^{obs} \sum_j^{energy} M_{ij} \frac{\sum_k^{cores} P(E_j, L_k^{far}) \phi_{jk} / (L_k^{far})^2}{\sum_k^{cores} P(E_j, L_k^{near}) \phi_{jk} / (L_k^{near})^2}$$

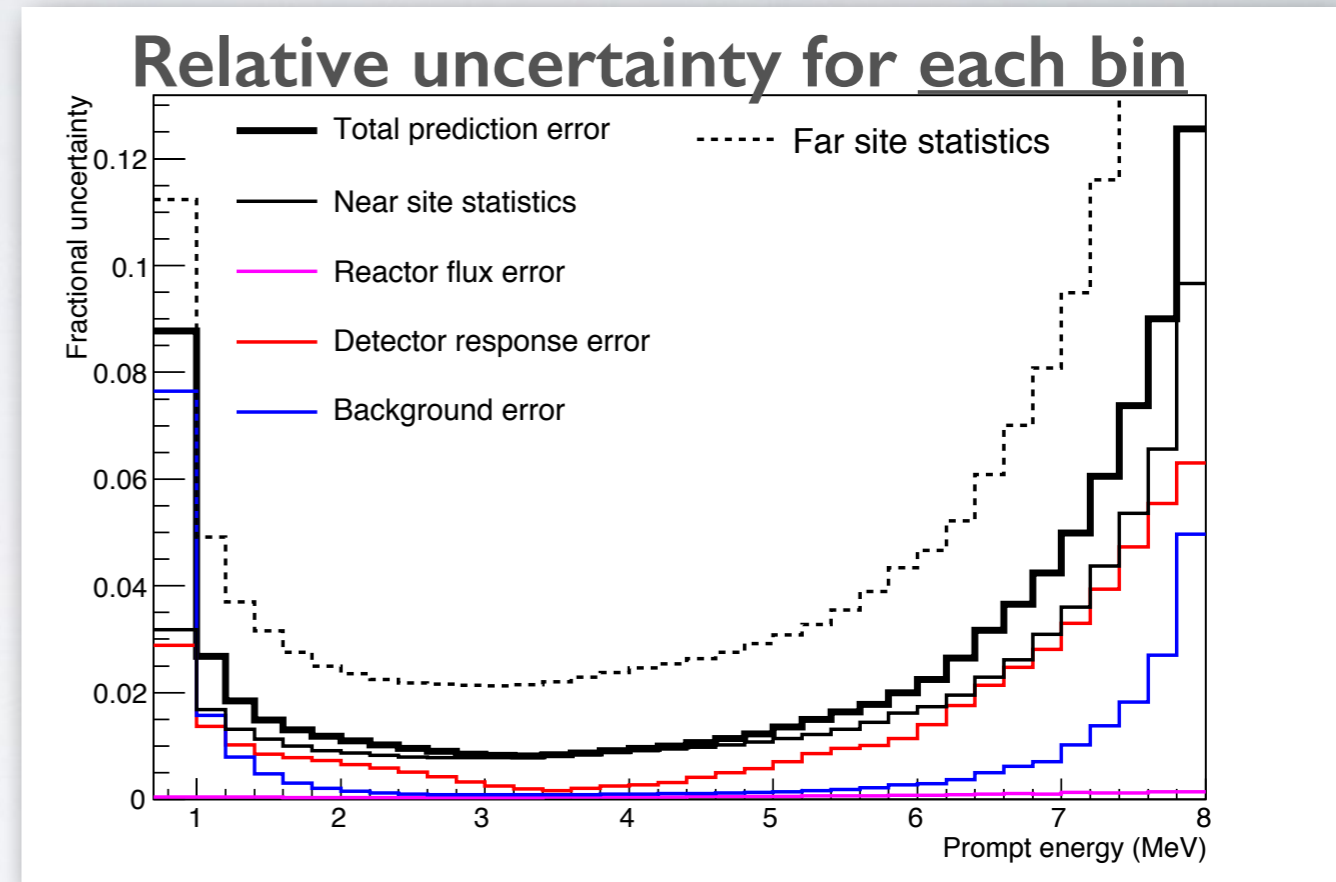
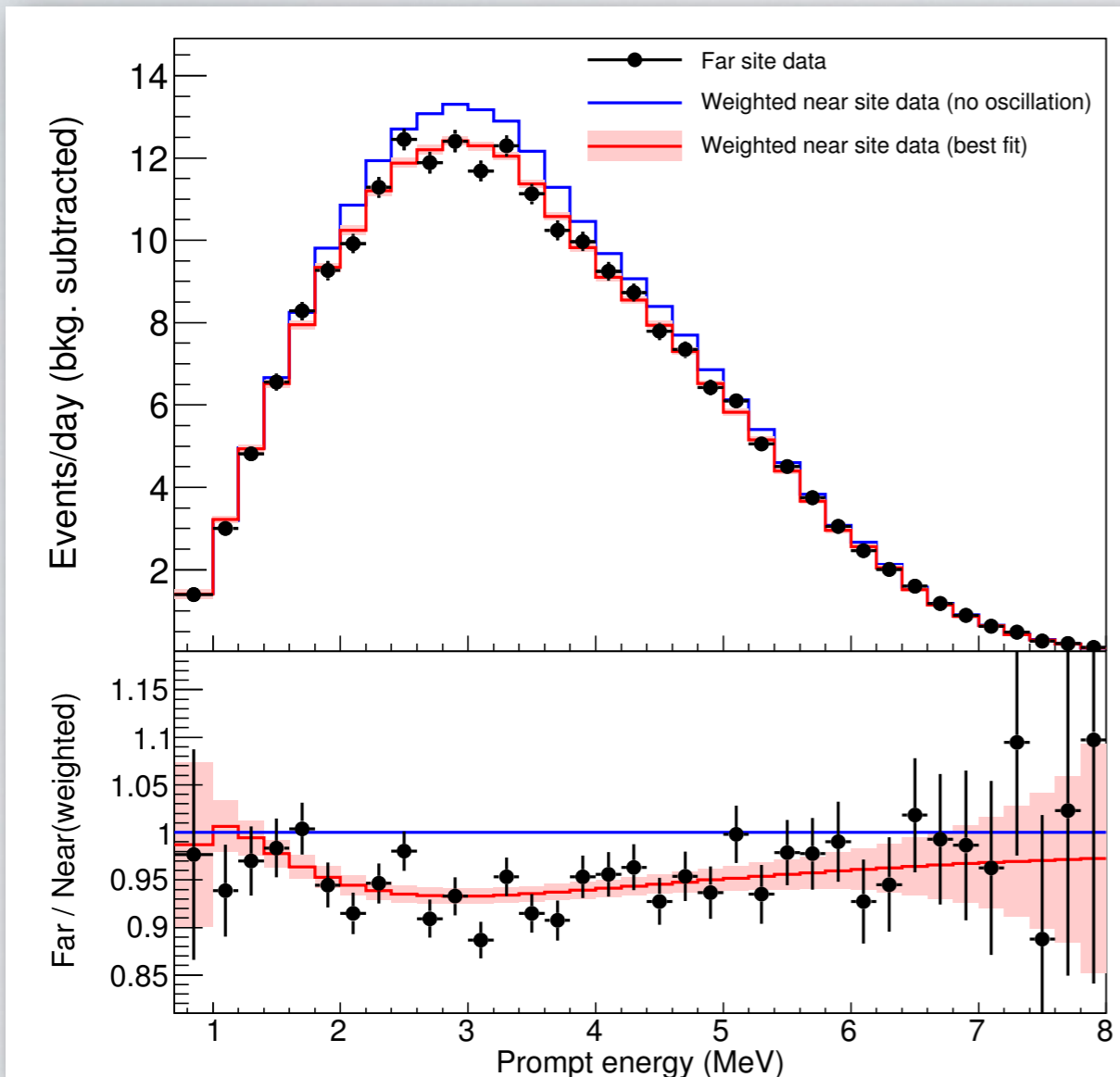
Far site prediction \leftarrow F_i^{pred} \leftarrow N_i^{obs} \leftarrow Near site data \leftarrow $\sum_j^{energy} M_{ij}$ \leftarrow Oscillation probability \leftarrow $\frac{\sum_k^{cores} P(E_j, L_k^{far}) \phi_{jk} / (L_k^{far})^2}{\sum_k^{cores} P(E_j, L_k^{near}) \phi_{jk} / (L_k^{near})^2}$ \leftarrow Flux from each core



All correlated reactor and detector systematics cancel to the first order

Pure relative rate+shape analysis

Result of 3-ν fit

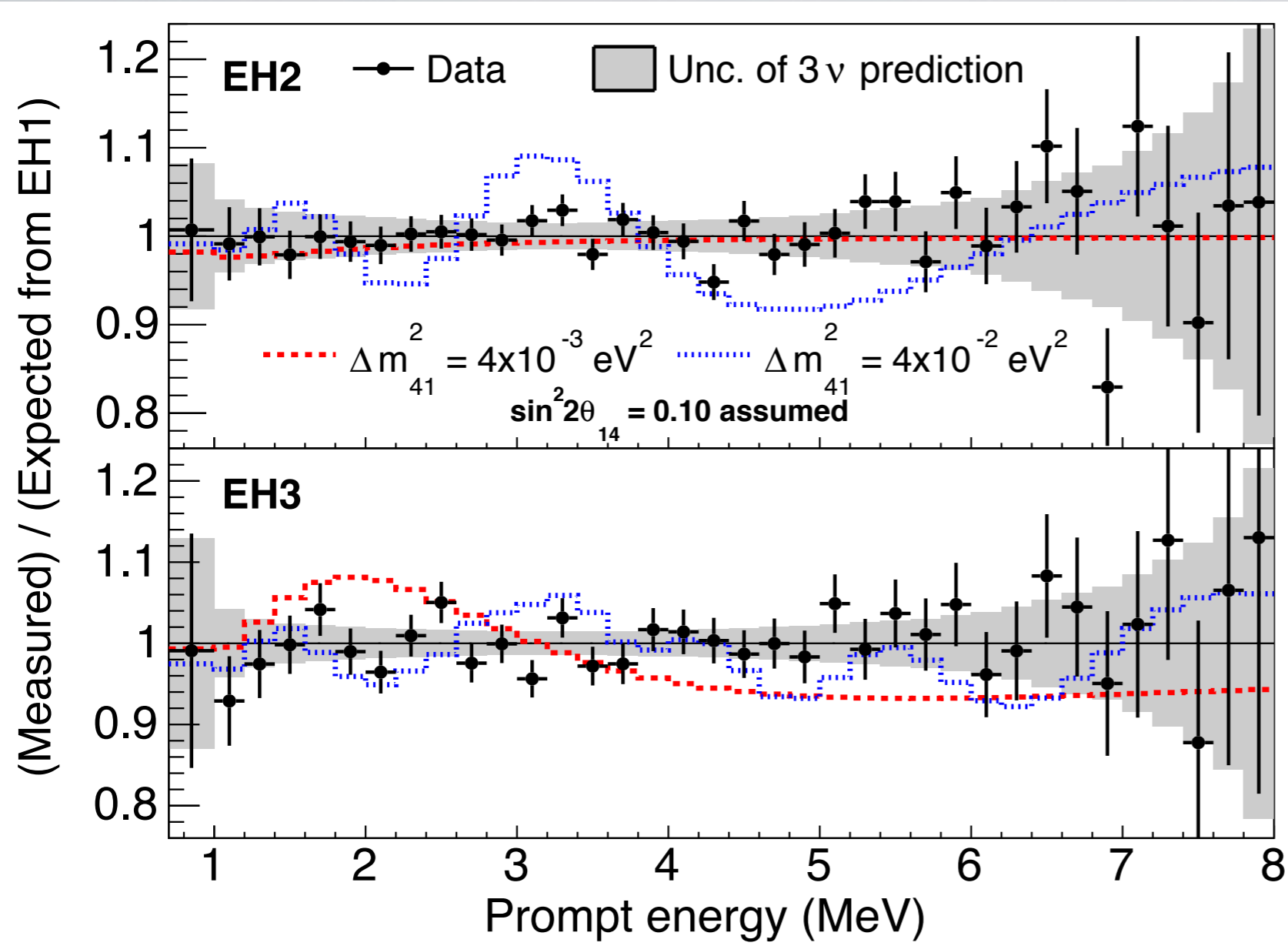


$$\chi^2 = (F_j^{obs} - F_j^{pred})(V_{ij})^{-1}(F_i^{obs} - F_i^{pred})$$

- Utilize covariance matrices to handle all the systematic uncertainties.

Expanded to 3+1 (sterile) ν fit

Testing sterile neutrino signal



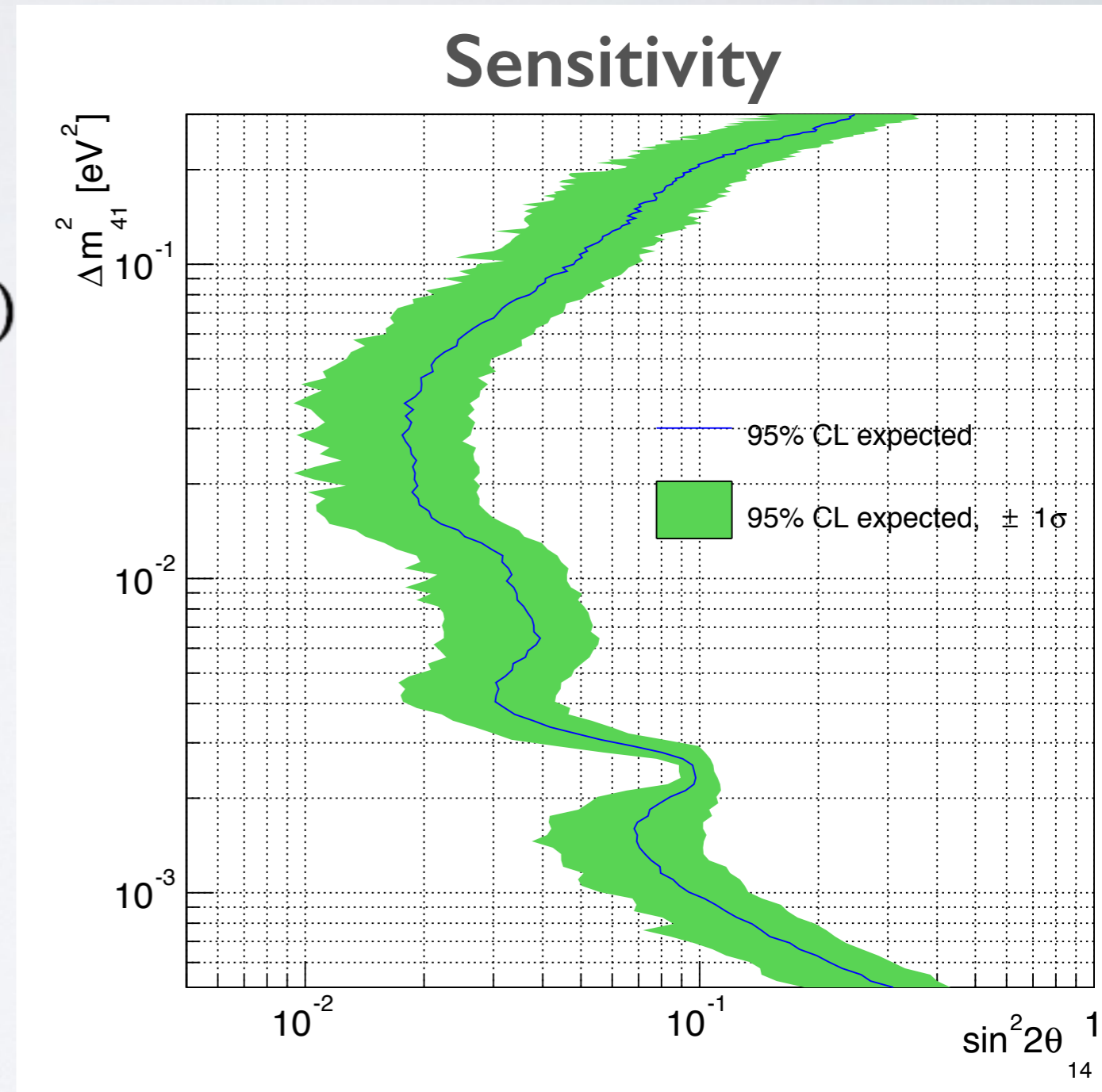
- Compare EH2/EH1 and EH3/EH1
- $\Delta\chi^2 = \chi^2(3\nu) - \chi^2(3+1\nu) = 3.8$
- p-value = 0.74 (estimated by toy MC)
- No significant signal observed.

Limits to the sterile neutrino mixing



Feldman-Cousins Method

- Oscillation signal is tested by evaluating
$$\Delta\chi^2(\Delta m_{41}^2, \sin^2 2\theta_{14}) = \chi^2(\Delta m_{41}^2, \sin^2 2\theta_{14}) - \chi^2(\text{best})$$
- Value of $\Delta\chi^2$ corresponds to a certain confidence level is statistically determined by a large set of toy MC samples (Feldman-Cousin's (F-C) approach)
- Achieved world best sensitivity at at $\Delta m_{41}^2 < 0.1 \text{ eV}^2$



CLs Method

- Implemented an alternate method of setting limits with “CLs” method
- Two-hypothesis test between the 3ν standard model (H_0) and $3+1$ model (H_1)

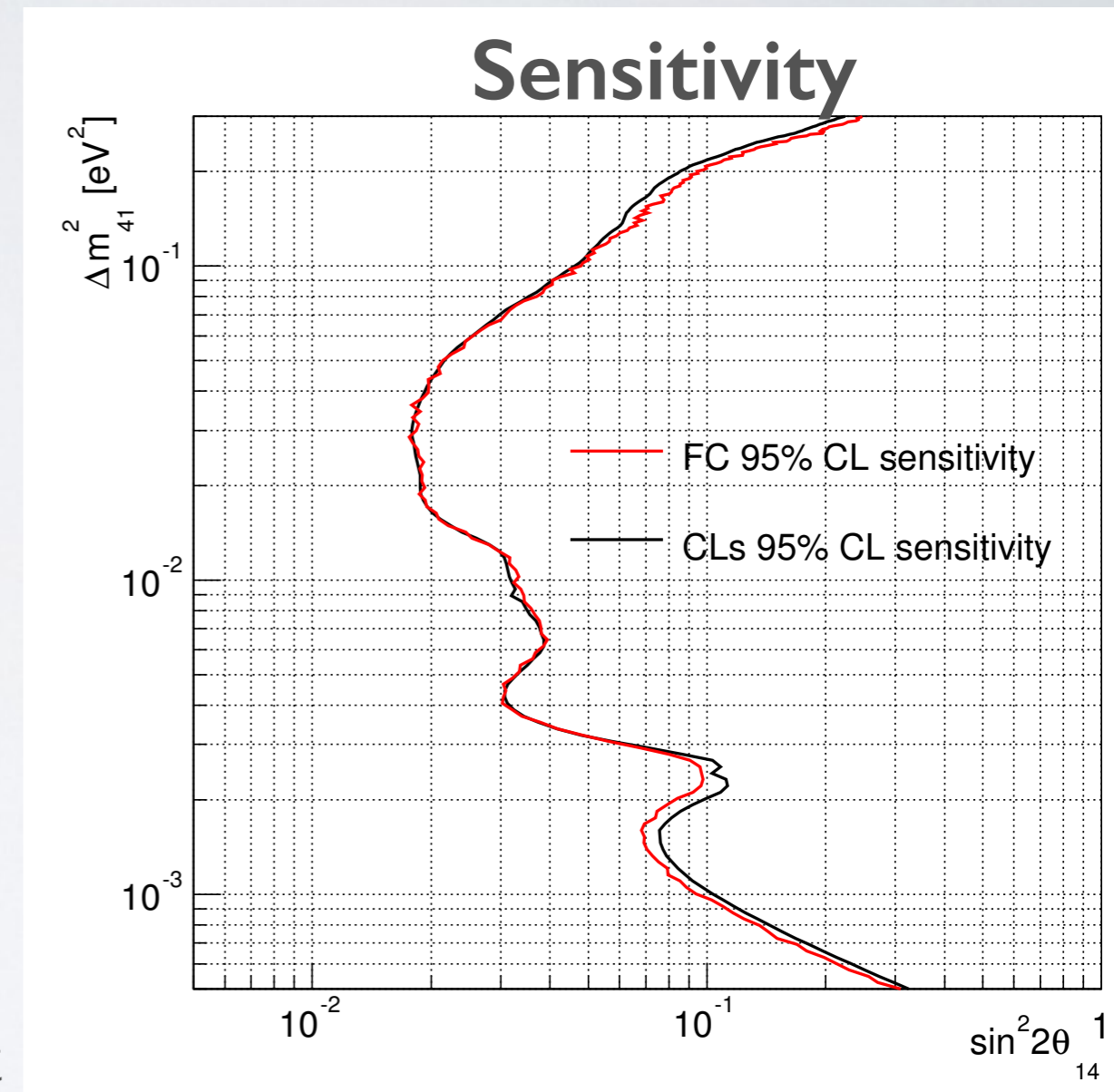
$$\Delta\chi^2 = \chi^2((3+1)\nu) - \chi^2(3\nu)$$

Evaluate p-values for the two hypotheses: p_0 and p_1 .

- Determine CLs as:

$$CLs = \frac{1 - p_1}{1 - p_0}$$

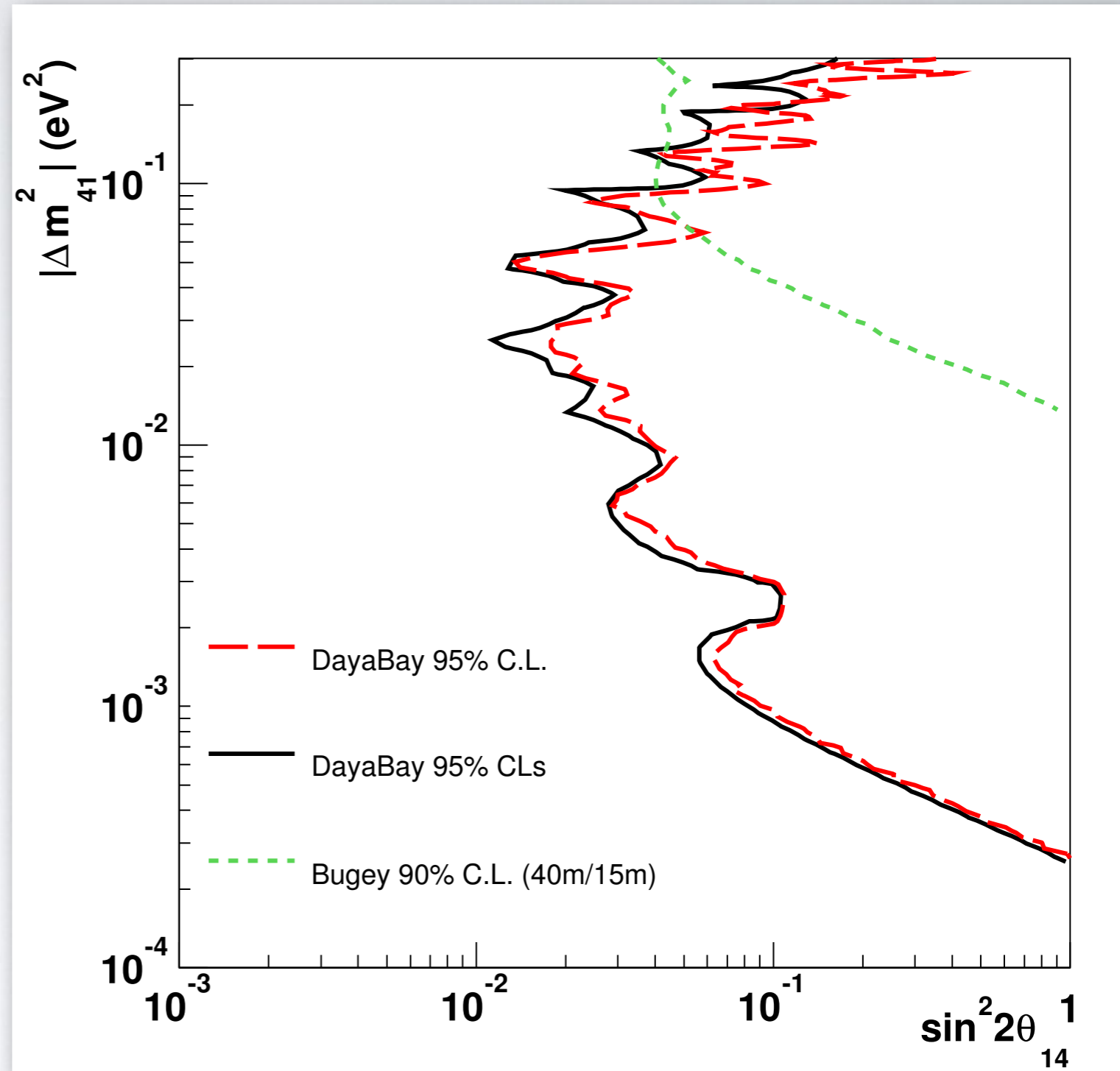
- Compared to FC method, stable and fast, but cannot be used for parameter estimation.
- Two methods show very similar sensitivity



Technical implementation in
arXiv: 1407.5052

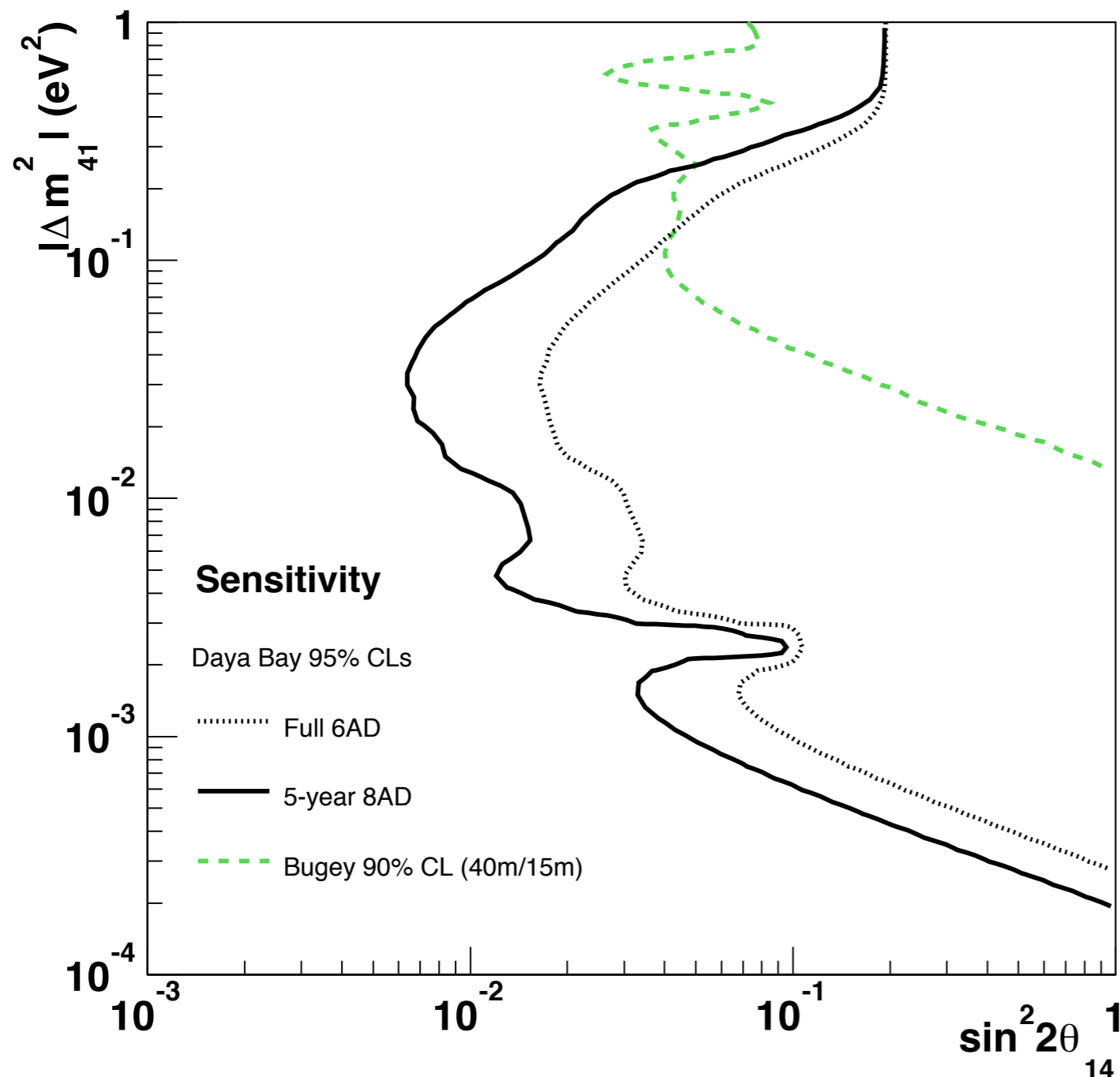
Observed limit

- The most stringent limit at $\Delta m^2_{41} < 0.1 \text{ eV}^2$
- All analysis methods produced consistent results.



Result published in
Phys. Rev. Lett. **113**, 141802 (2014)

Future sensitivity



- Current sensitivity is limited by statistics
- Expect more than a factor two improvements with 5 years of data taking.

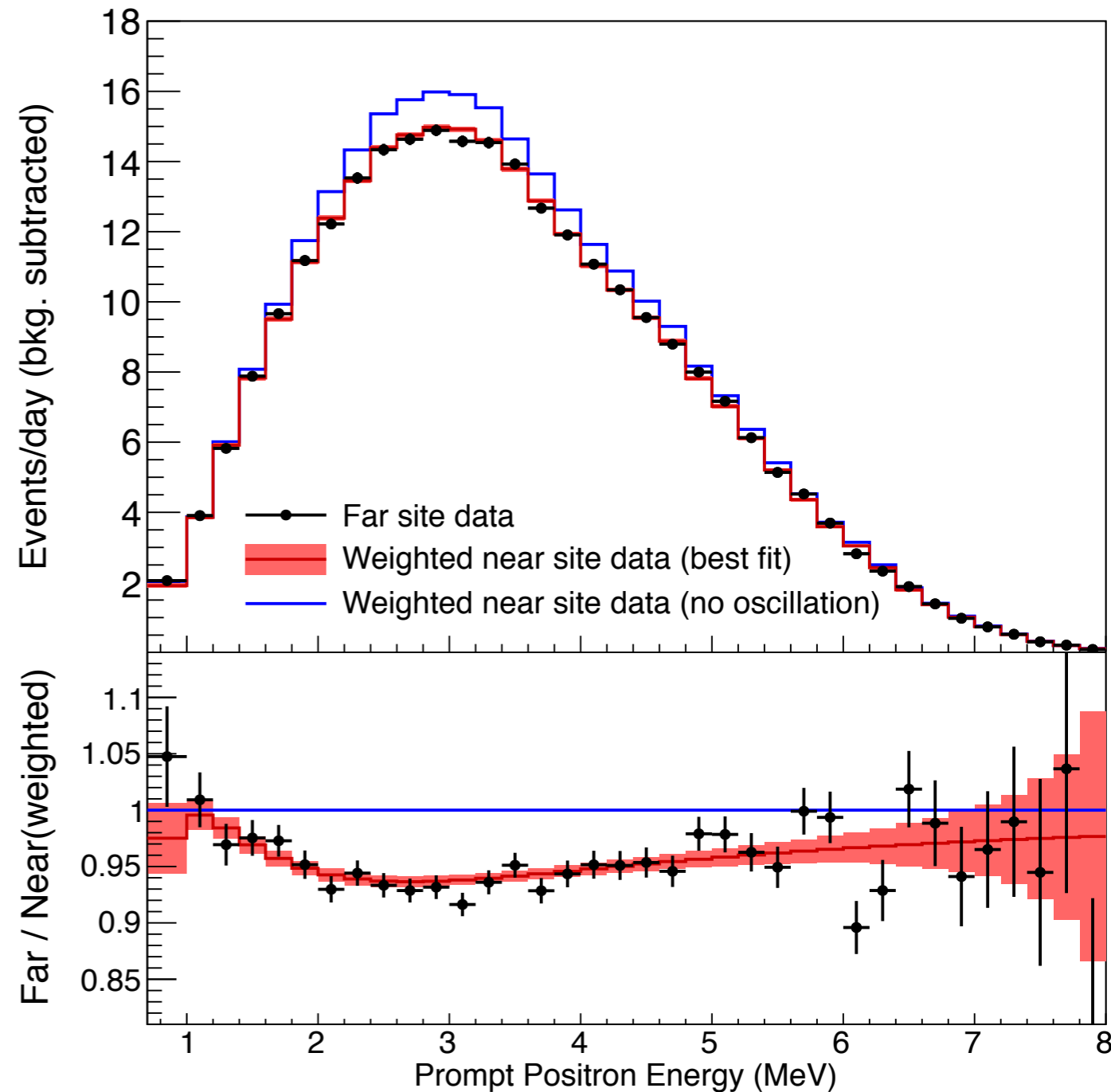
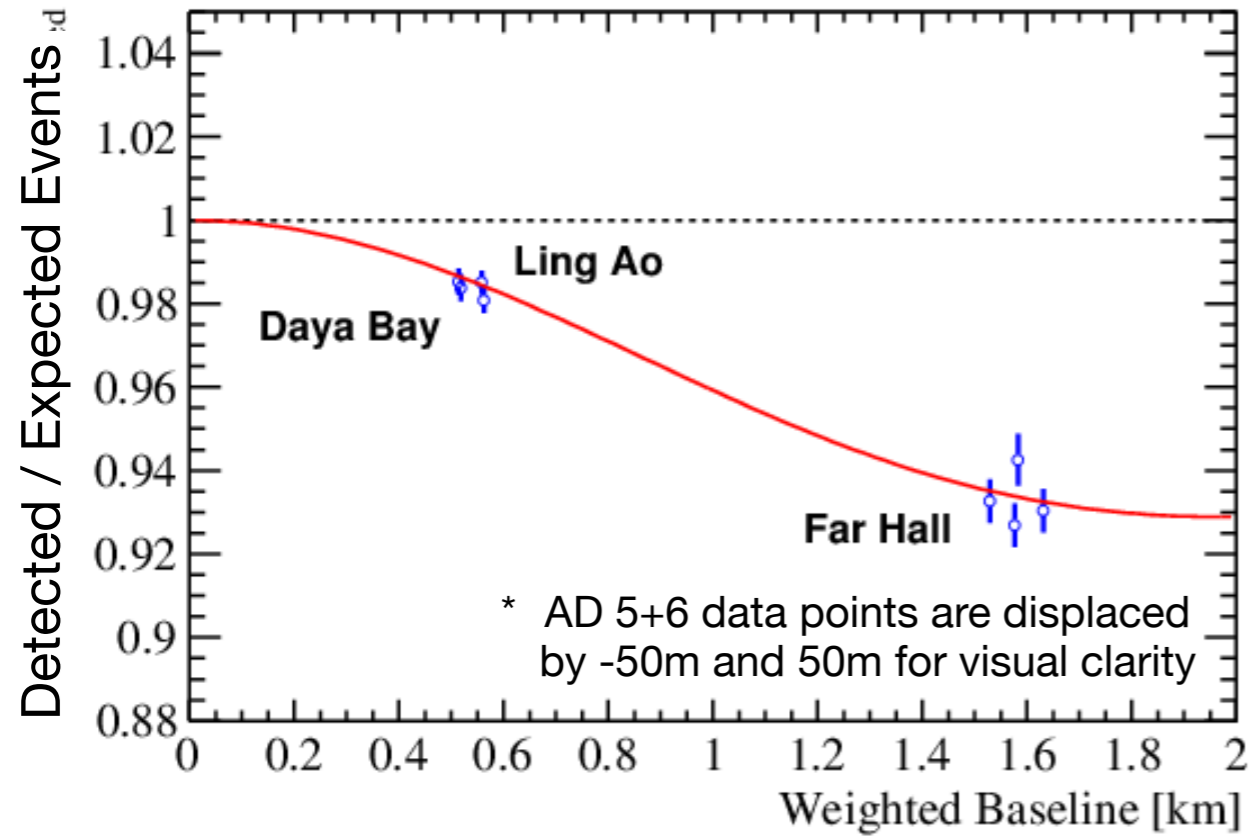
Other recent results

Oscillation parameter measurement with higher statistics

Oscillation parameter measurement with n-H capture sample

Absolute reactor antineutrino flux and spectrum measurement

Improved oscillation parameter measurement



- Improved spectral analysis with 621 days of data
- Observed data highly consistent with oscillation interpretation

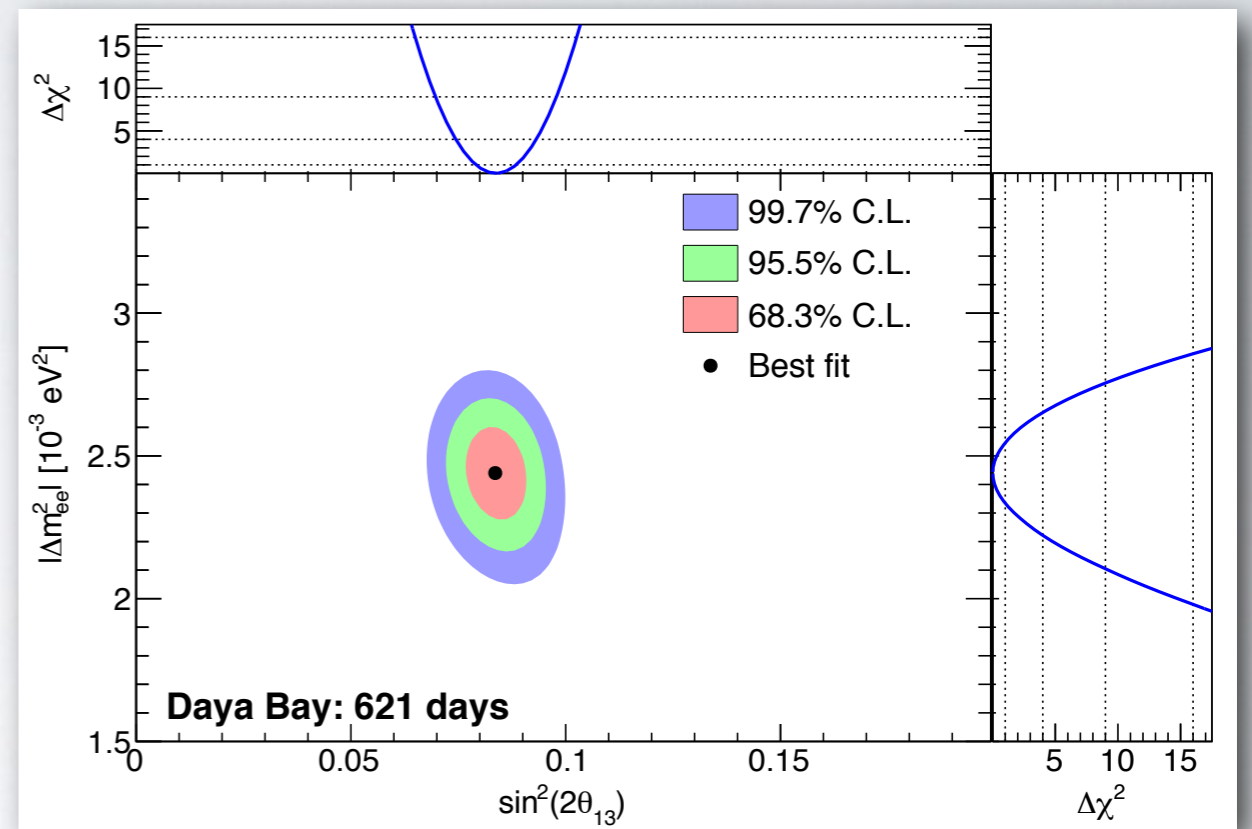
Improved oscillation parameter measurement

$$\sin^2 2\theta_{13} = 0.084_{-0.005}^{+0.005}$$

$$|\Delta m_{ee}^2| = 2.44_{-0.11}^{+0.10} \times 10^{-3} \text{eV}^2$$

$$\chi^2/NDF = 134.7/146$$

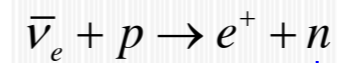
- The most precise measurement of $\sin^2 2\theta_{13}$
 - Precision better than 6%
- The most precise measurement of Δm_{ee}^2 in electron antineutrino disappearance channel
 - Consistent with muon neutrino disappearance results
 - Comparable precision.



	Normal MH Δm_{32}^2 [10^{-3}eV^2]	Inverted MH Δm_{32}^2 [10^{-3}eV^2]
From Daya Bay Δm_{ee}^2	$2.39_{-0.11}^{+0.10}$	$-2.49_{-0.11}^{+0.10}$
From MINOS $\Delta m_{\mu\mu}^2$	$2.37_{-0.09}^{+0.09}$	$-2.41_{-0.09}^{+0.11}$

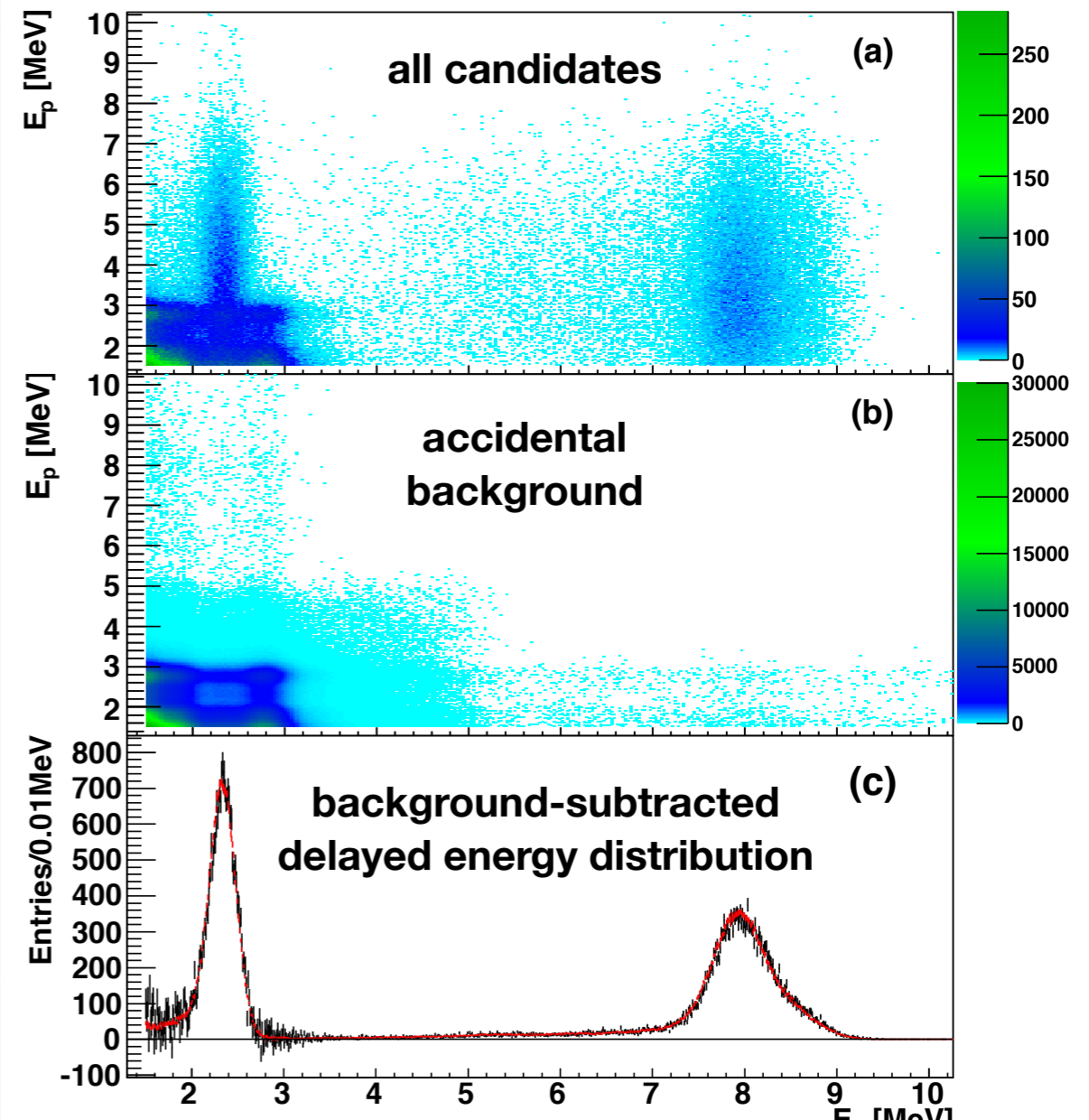
Independent $\sin^2 2\theta_{13}$ measurement with H-capture sample

- Advantage:
 - Higher statistics: 15% in Gd-LS region and 100% in LS region.
 - Different systematic uncertainty from Gd analysis
- Challenge:
 - Larger accidental backgrounds
- Strategy:
 - Raise prompt energy cut: $E_p > 1.5$ MeV
 - Require prompt-delayed distance $\Delta R < 0.5$ m



2.2 MeV 200 μs

8MeV 30 μs

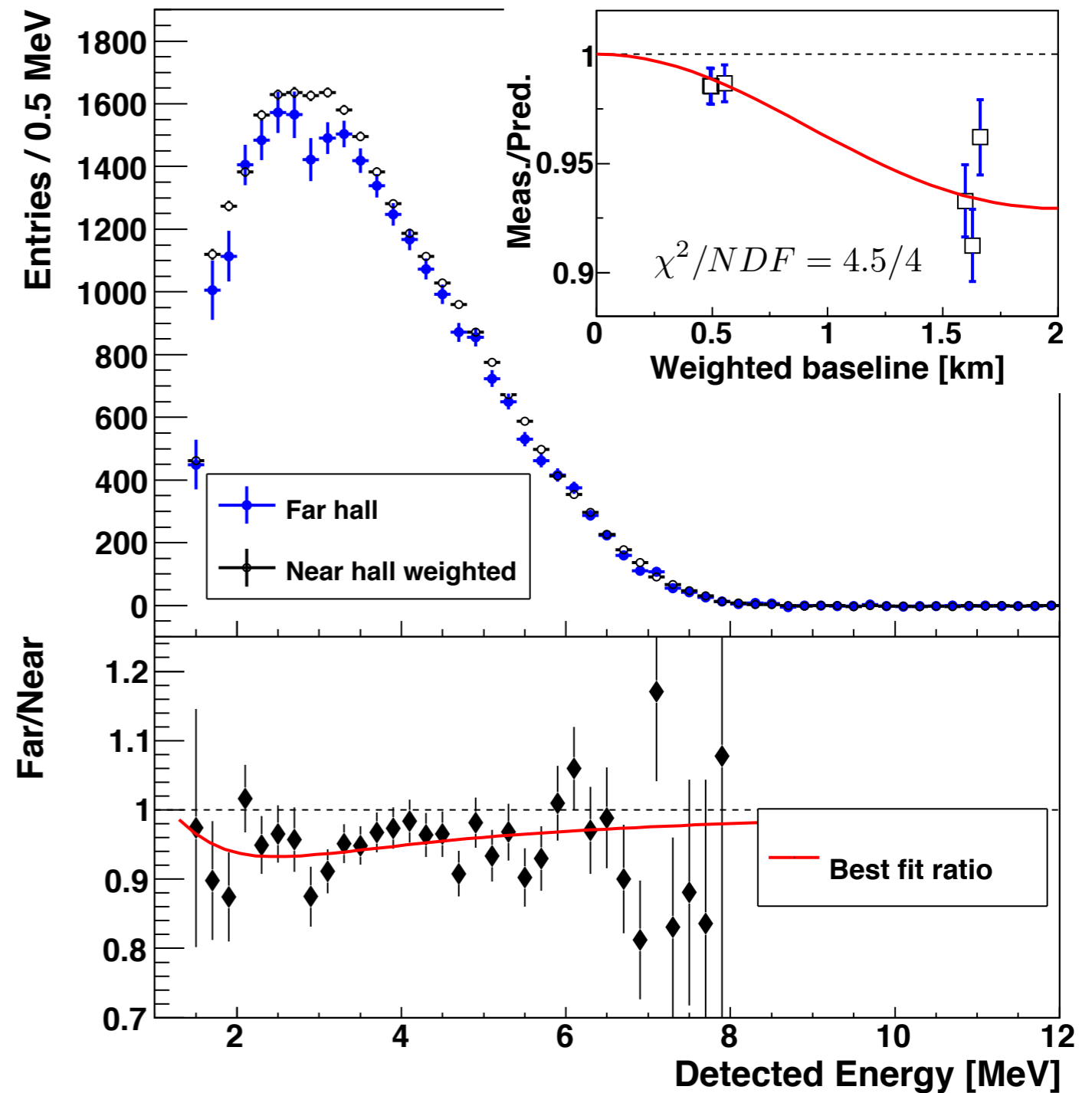


nH analysis results

- Data from 6-AD period (217 days) are used
- Observed significant rate deficit at far site. Rate analysis measured:

$$\sin^2 2\theta_{13} = 0.083 \pm 0.018$$

- Independent and consistent results of nGd analysis
- Spectrum analysis in progress



Result published in Phys. Rev. D **90**, 071101 (2014)

Many more results are on the way

Daya Bay will continue data taking until 2017

- Measurement of oscillation parameters with even higher statistics
- Search for sterile neutrino with higher statistics
- Search for new physical phenomena beyond the SM
- Study of cosmic muon and its products
- etc..

Summary

- Daya Bay searched for a light sterile neutrino by looking for relative spectral distortion between the detectors
- No significant signal found, setting the most stringent limit at $10^{-3} \text{ eV}^2 < \Delta m_{41}^2 < 0.1 \text{ eV}^2$, which was largely unexplored before.
- Result published in Phys. Rev. Lett. **113**, 141802 (2014)
- Stay tuned for many more results from Daya Bay!