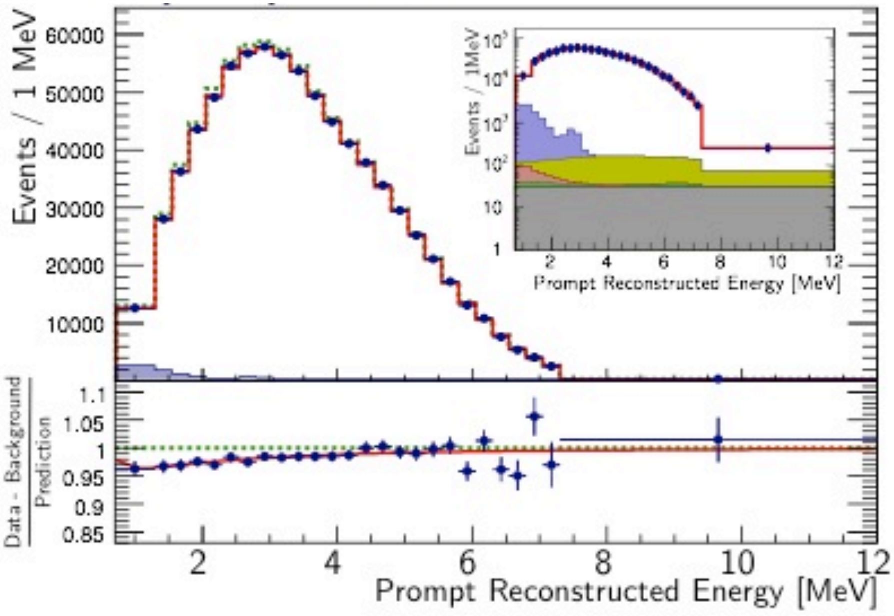
Prospects for Measuring the Reactor Neutrino Flux and Spectrum



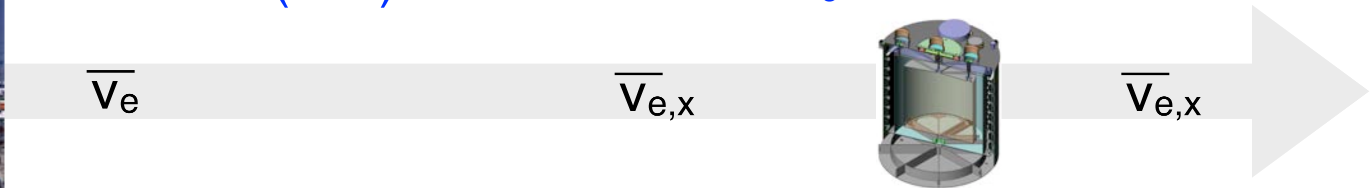
Karsten Heeger
Yale University

as a member of the Daya Bay and PROSPECT collaborations

INT, Seattle, November 8, 2013

Reactor Neutrino Oscillation Experiments

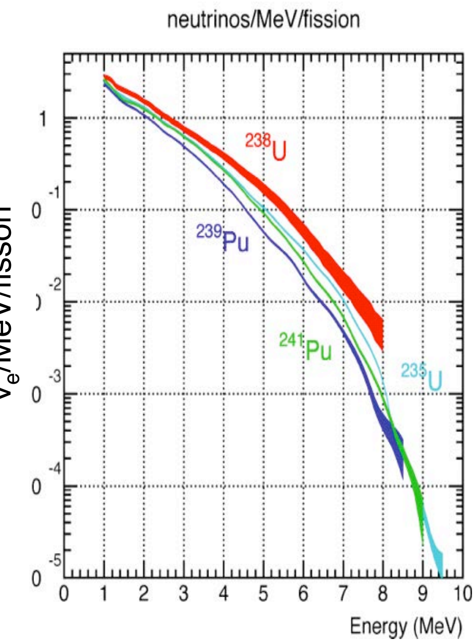
Measure (non)-1/r^2 behavior of $\overline{\nu}_e$ interaction rate



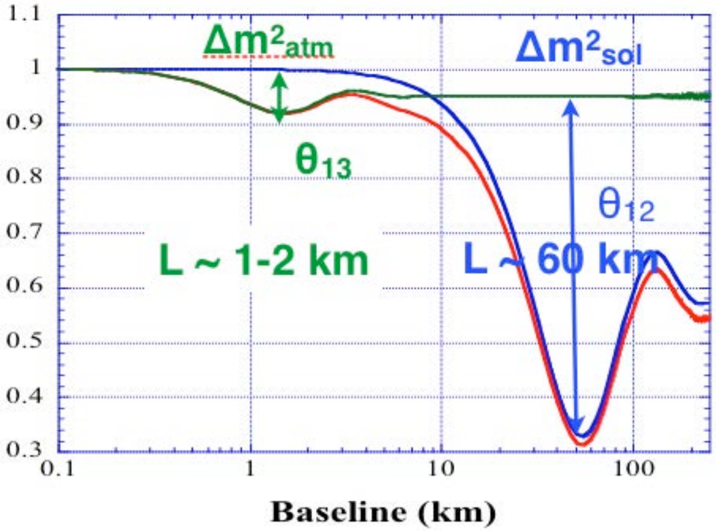
far

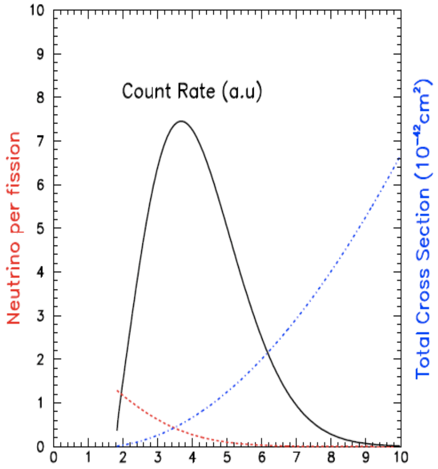
$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

L/E → Δm^2 amplitude of oscillation → θ



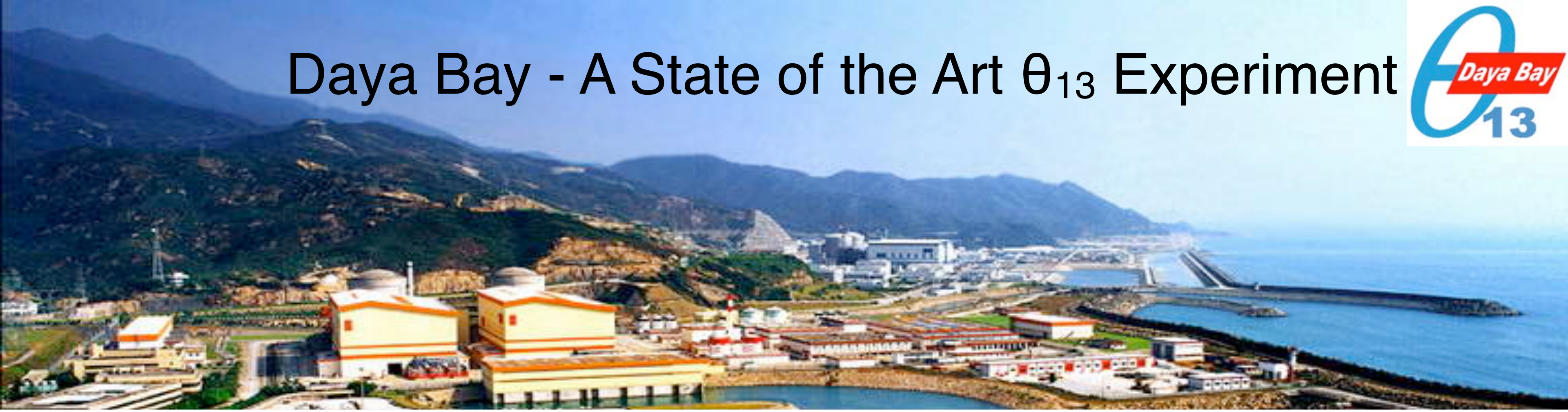
Energy (MeV)

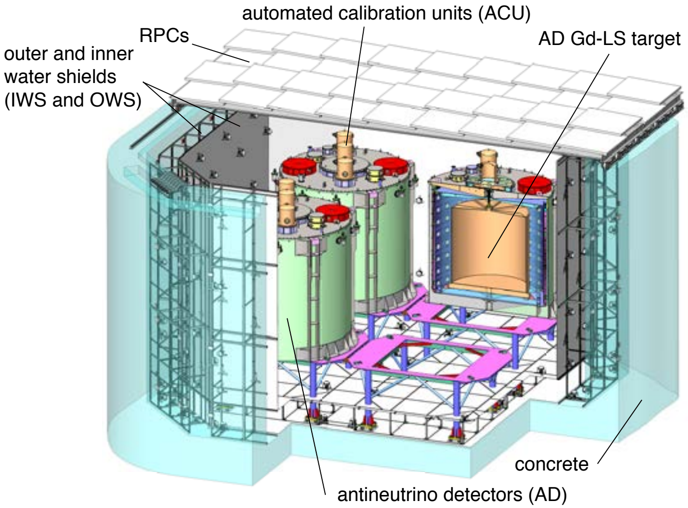




Neutrino Energy

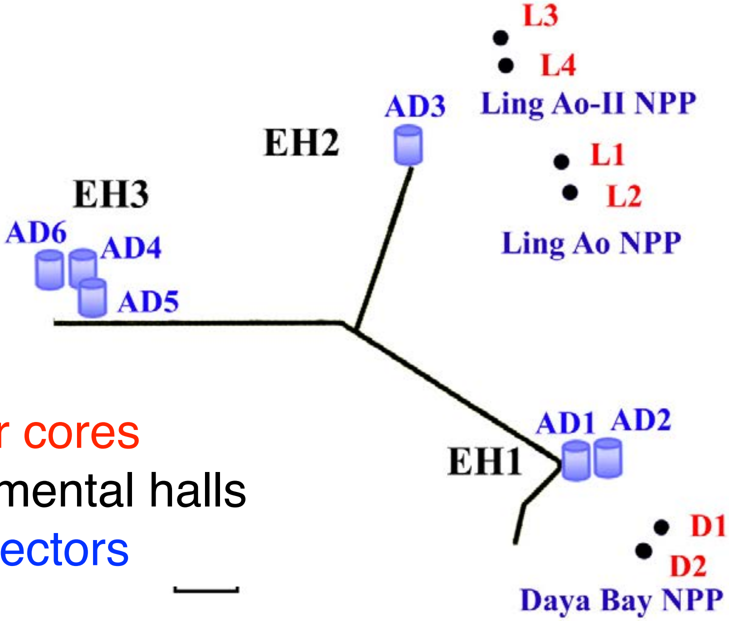
Daya Bay - A State of the Art θ_{13} Experiment





	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

Daya Bay sums data from multiple reactors

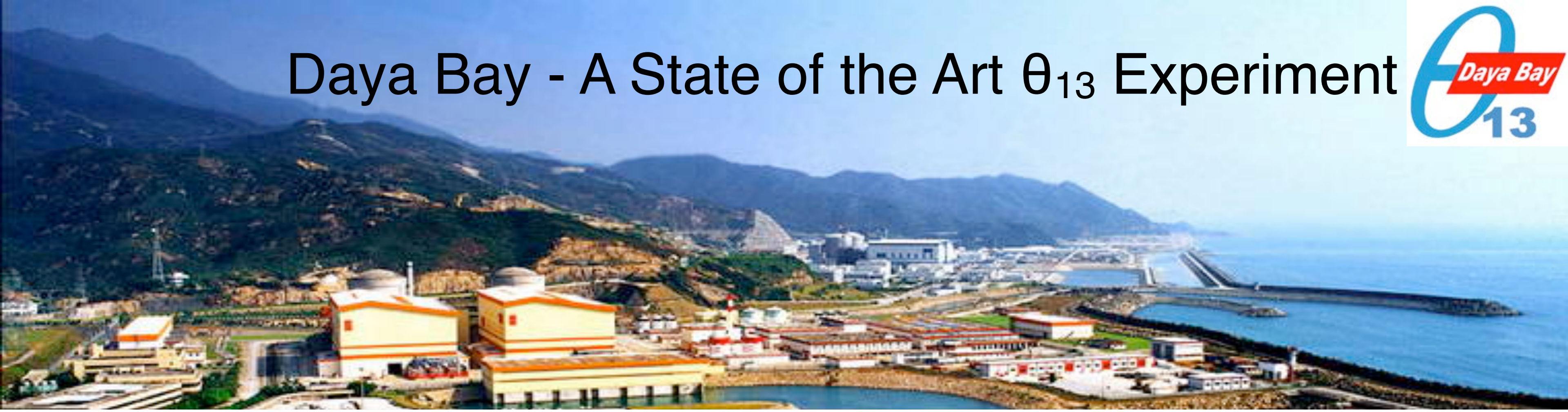


6 reactor cores

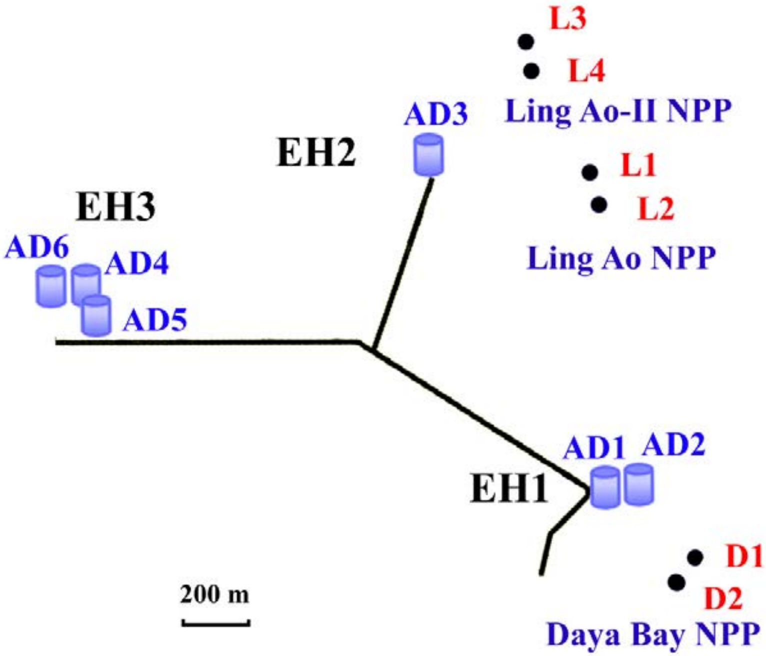
3 experimental halls

6 (8) detectors

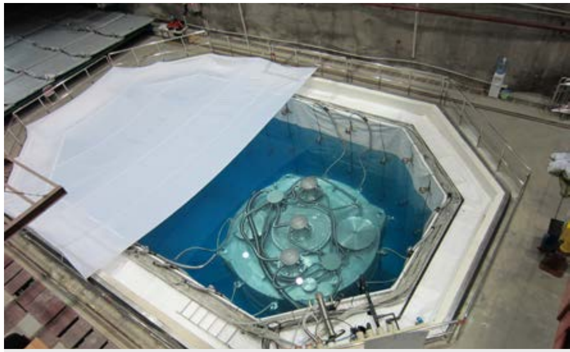
Daya Bay - A State of the Art θ_{13} Experiment



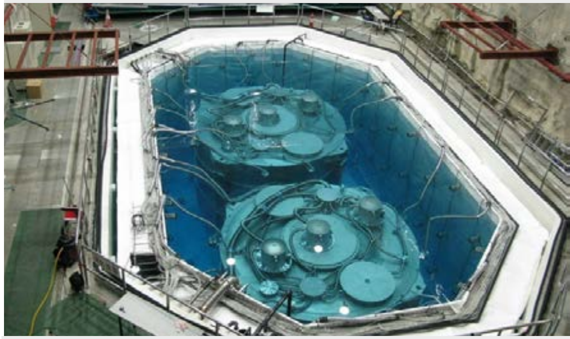
Hall 3: began 3 AD operation on Dec. 24, 2011



Daya Bay has multiple detectors



Hall 2: began 1 AD operation on Nov. 5, 2011

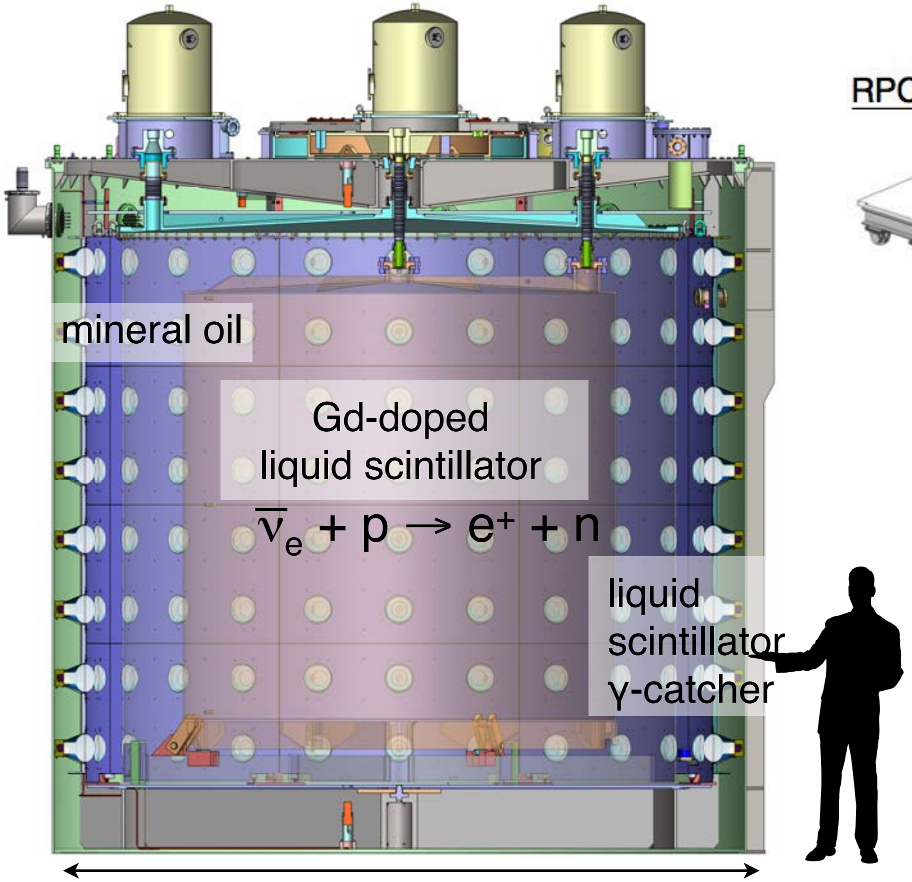


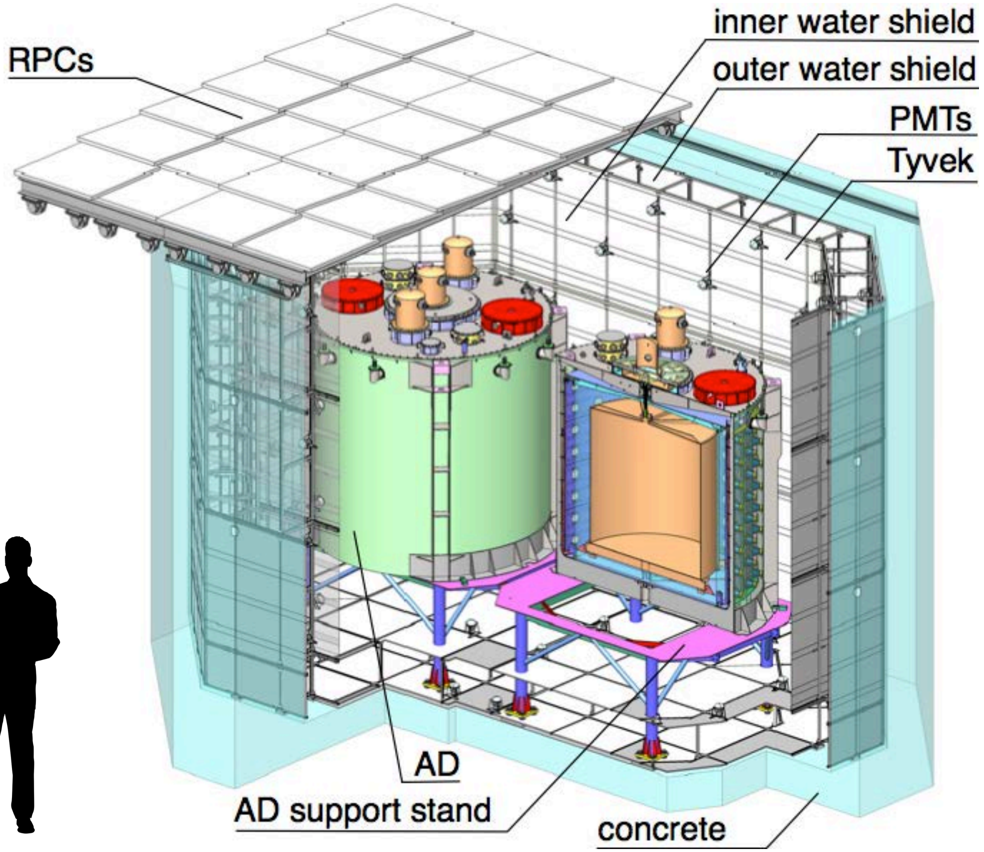
Hall 1: began 2 AD operation on Sep. 23, 2011

Daya Bay Detectors

6 “functionally identical” detectors
Gd-LS defines target volume, no position cut

Dual tagging systems: 2.5 meter water shield and RPCs





Two-zone ultrapure water Cherenkov detector

target mass: 20 ton per AD
photosensors: 192 8”-PMTs
energy resolution: (7.5 / √E + 0.9)%

multiple detectors allow comparison and cross-checks

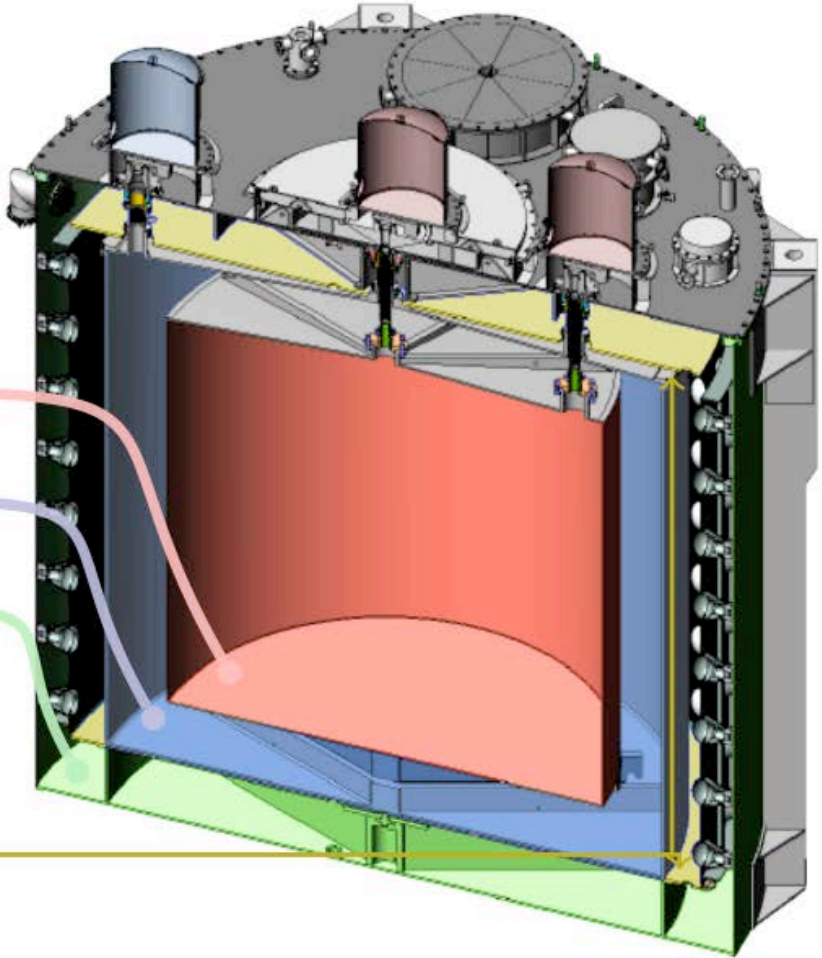
Antineutrino Detector (AD) Design

8 functionally identical detectors
reduce systematic uncertainties

	3 zone cylindrical vessels		
	Liquid	Mass	Function
Inner acrylic	Gd-doped liquid scint.	20 t	Antineutrino target
Outer acrylic	Liquid scintillator	20 t	Gamma catcher
Stainless steel	Mineral oil	40 t	Radiation shielding

192 8 inch PMTs in each detector

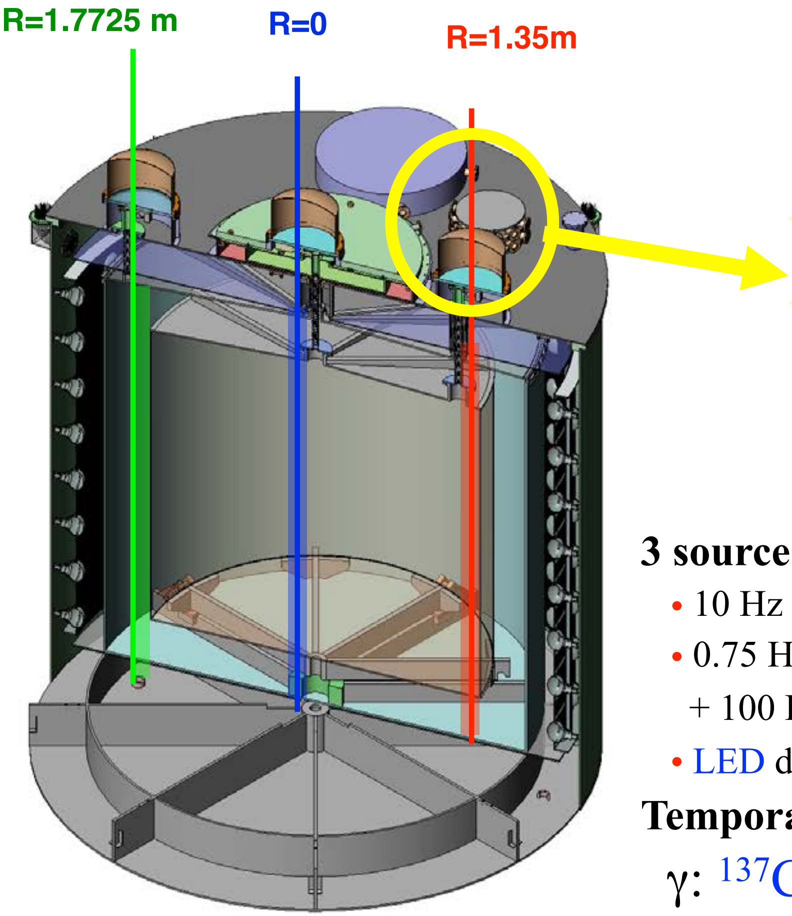
Top and bottom reflectors increase light yield
and flatten detector response



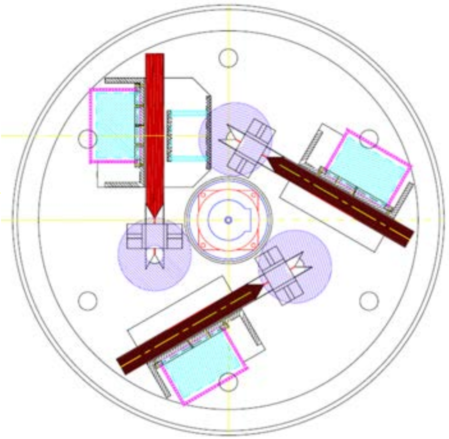
3 volumes eliminate edge effects, common to all θ_{13} experiments

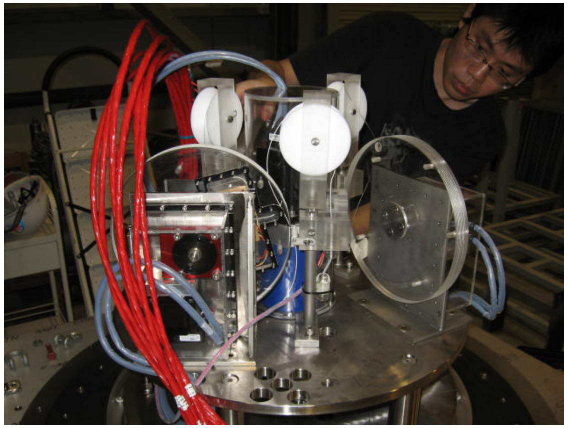
Automated Calibration System

3 Automatic calibration 'robots' (ACUs) on each detector



Top view





3 sources in each robot, including:

- 10 Hz ^{68}Ge (0 KE e^+ = 2×0.511 MeV γ's)
- 0.75 Hz ^{241}Am-^{13}C neutron source (3.5 MeV n without γ) + 100 Hz ^{60}Co gamma source (1.173+1.332 MeV γ)
- LED diffuser ball (500 Hz) for time calibration

Temporary special calibration sources:

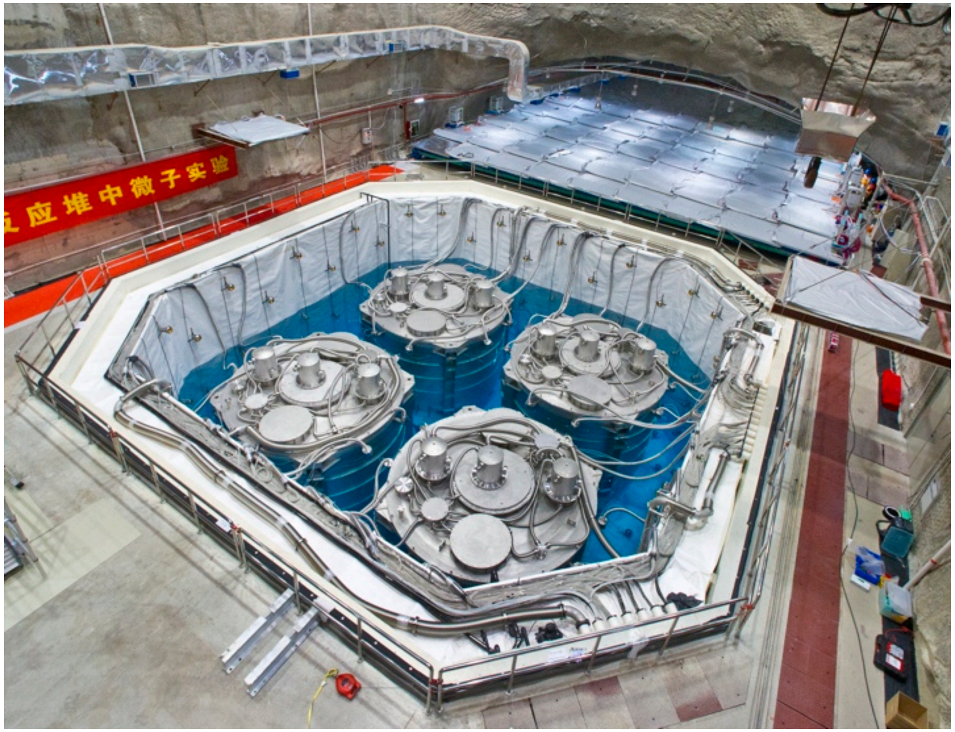
γ: ^{137}Cs (0.662 MeV), ^{54}Mn (0.835 MeV), ^{40}K (1.461 MeV)

n: ^{241}Am-^{9}Be, ^{239}Pu-^{13}C

Three axes: center, edge of target, middle of gamma catcher

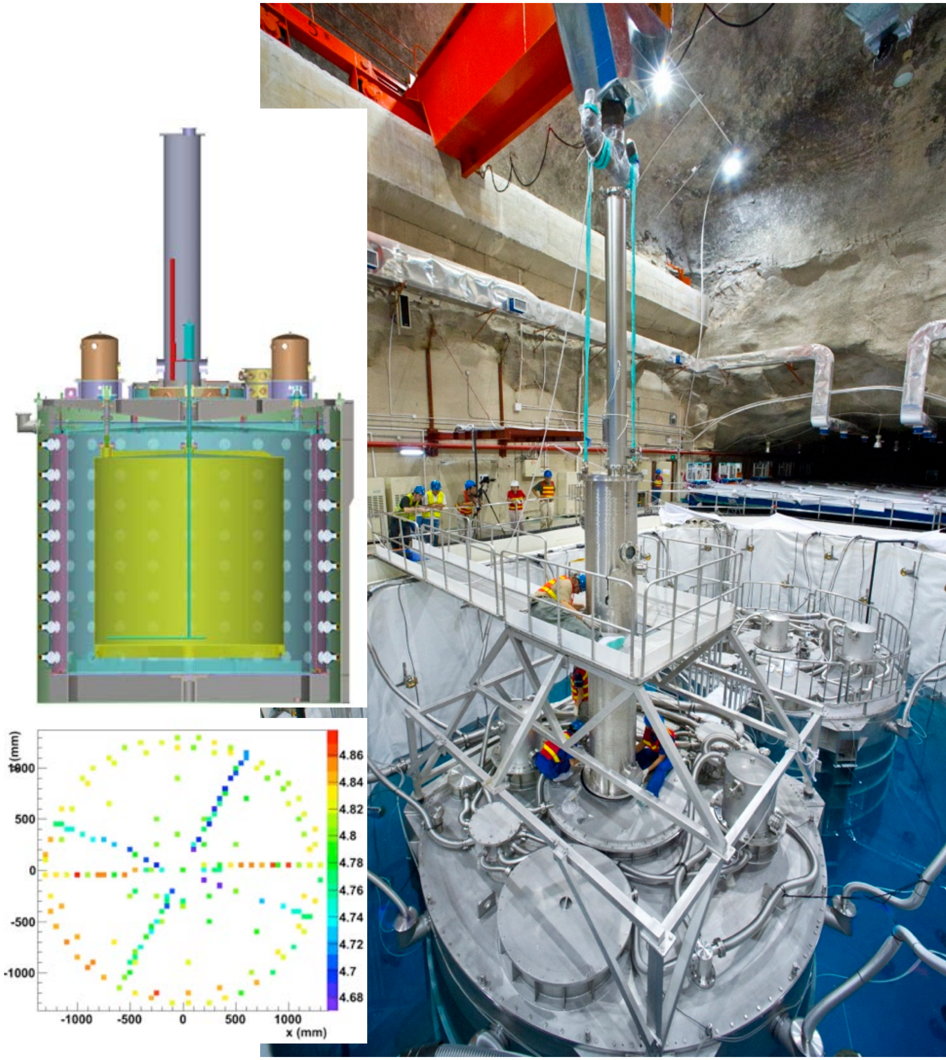
Daya Bay Fall 2012

Installation of Final Antineutrino Detectors



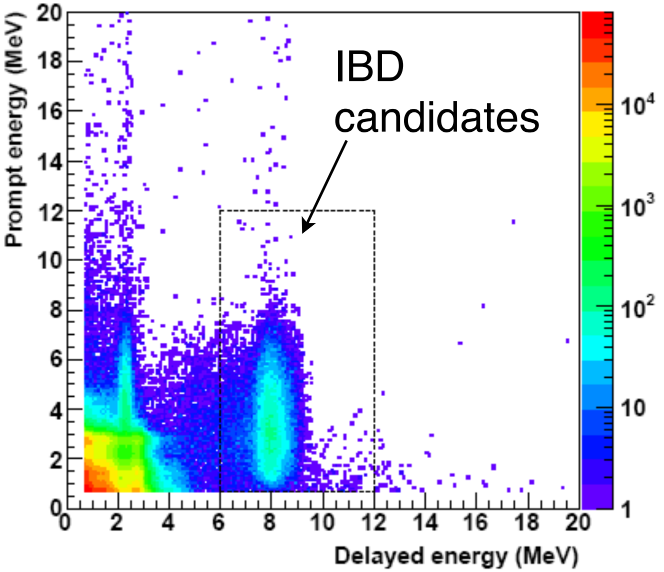
Regular, automated and special, full-volume calibration to understand detector response

Full Volume Calibration



Antineutrino Candidates (Inverse Beta Decay)

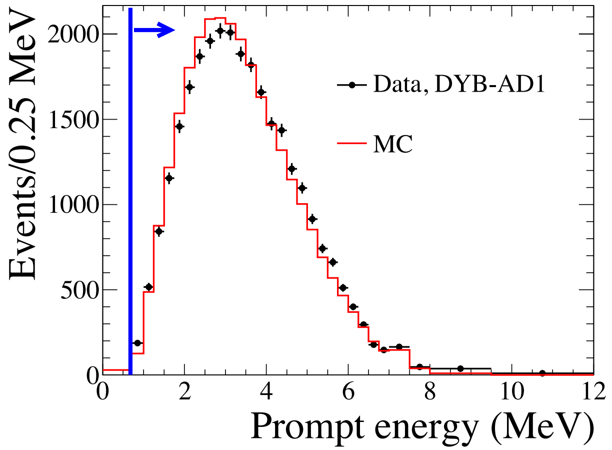
Prompt + Delayed Selection



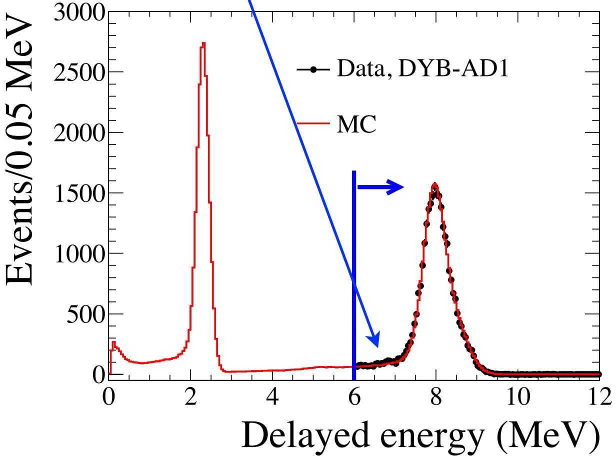
$$\overline{\nu}_e + p \rightarrow e^+ + n$$

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

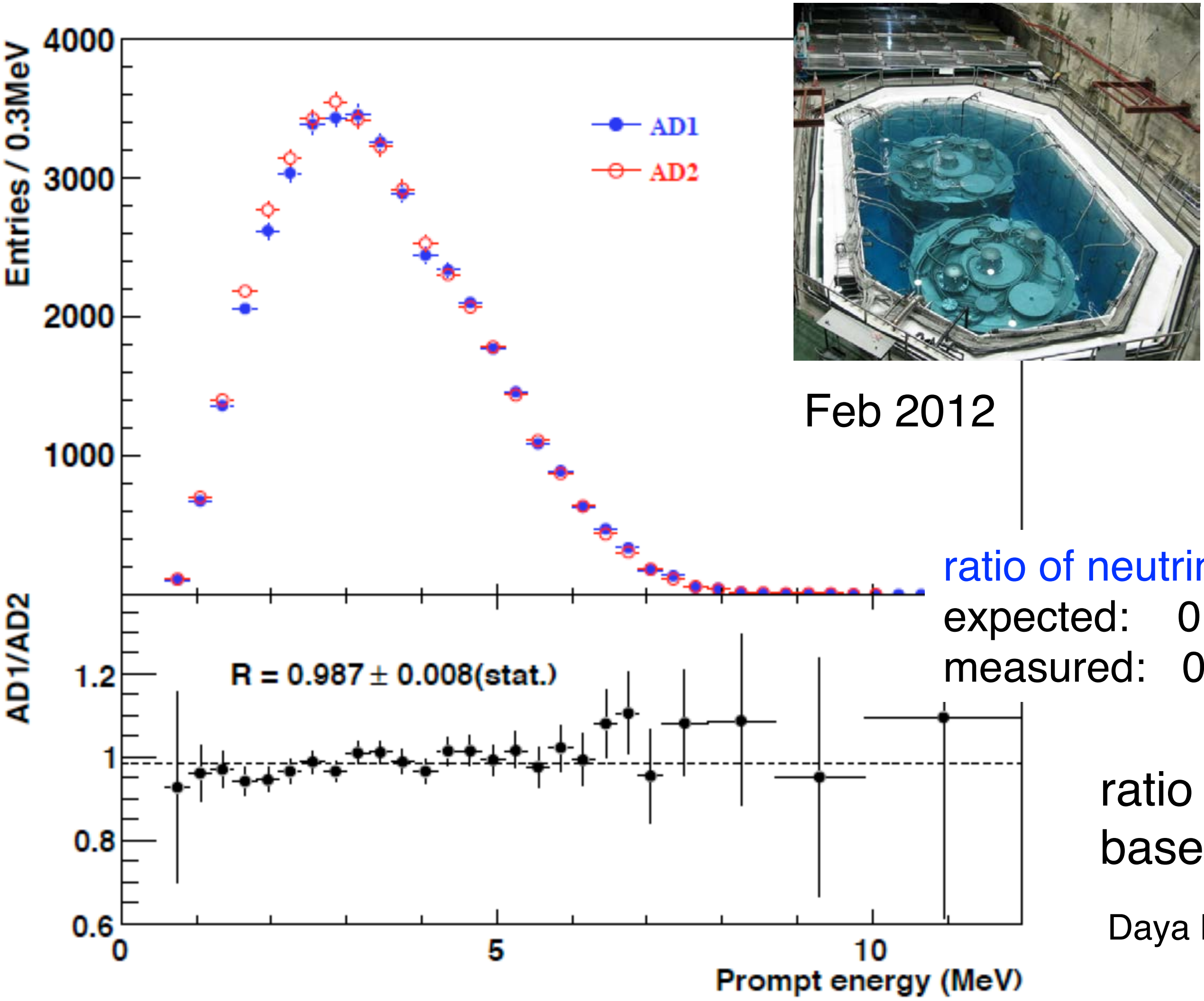
Prompt Energy Signal



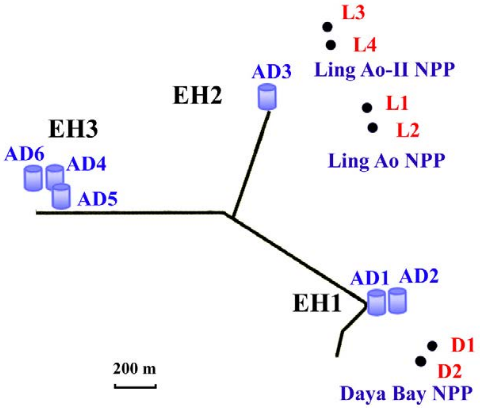
Delayed Energy Signal



Side-by-Side Comparison in Near Hall



Feb 2012



ratio of neutrino events in AD1 and AD2

expected: 0.981

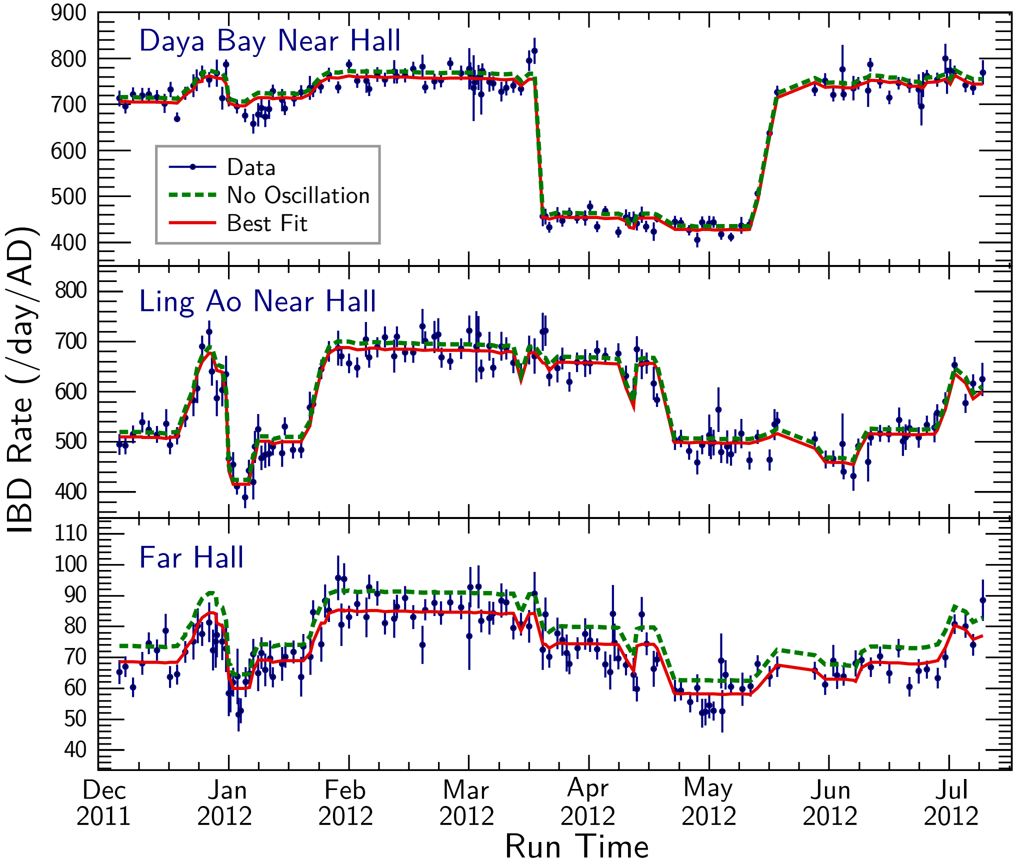
measured: 0.987± 0.008 (stat) ± 0.003

ratio is not 1 because of baseline difference

Daya Bay, arXiv:1202:6181 (2012)

Highest statistics in near-site spectra in EH1

Measuring Antineutrino Rate vs Time

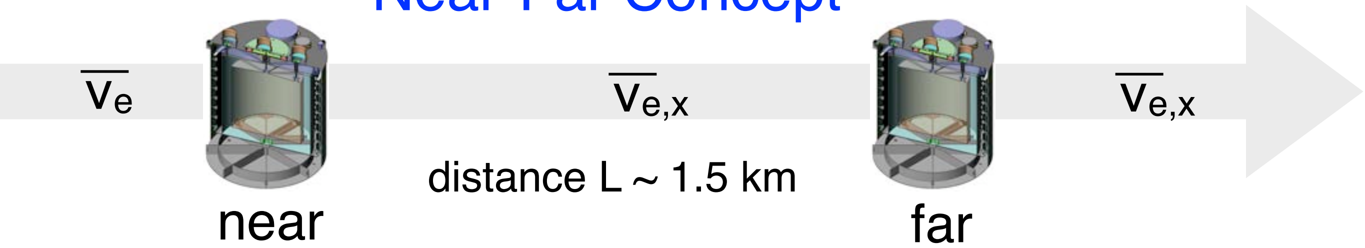


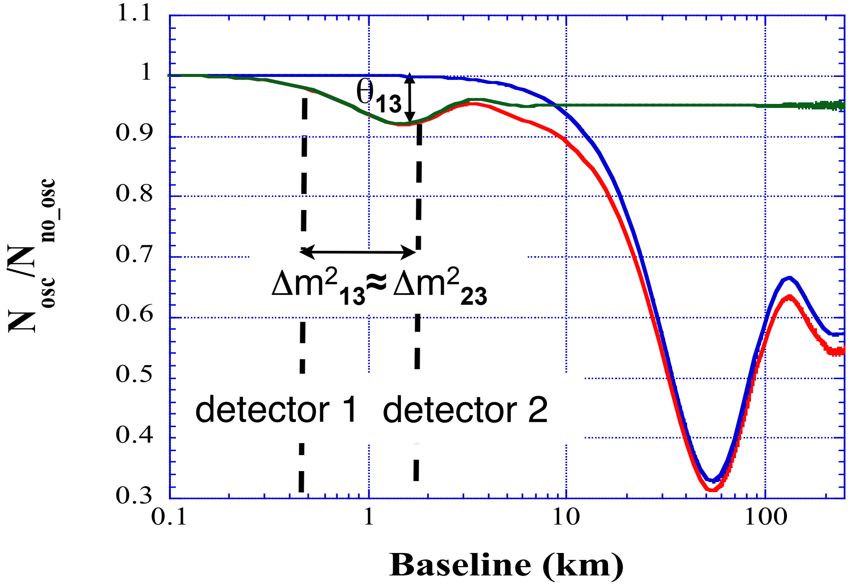
Detected rate strongly correlated with reactor flux expectations

- Predicted Rate assumes no oscillation
- Absolute normalization determined by fit to data
- Normalization within a few percent of expectations

Measuring θ_{13} with Reactor Experiments

Near-Far Concept





Absolute Reactor Flux
Largest uncertainty in previous measurements

Relative Measurement
Removes absolute uncertainties!

Daya Bay makes **relative** oscillation measurement

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

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

far/near $\overline{\nu}_e$ ratio target mass distances efficiency oscillation deficit

Reactor Experiments - Current Results

From Discovery to Precision Measurements

2012 Daya Bay 5.2σ measurement of non-zero θ_{13}

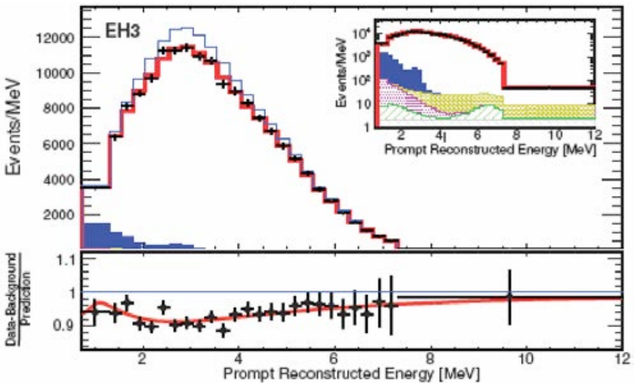
PRL 108:171803 (2012)

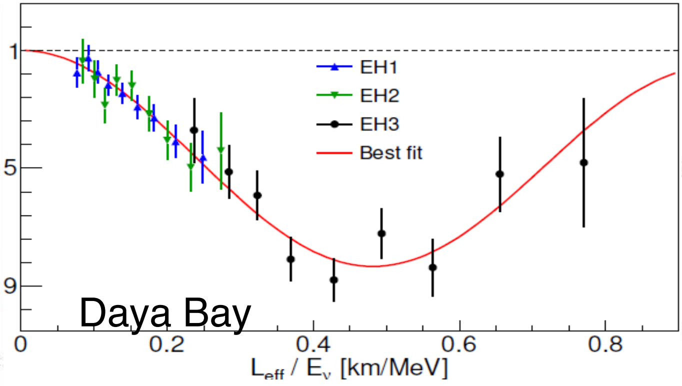
Daya Bay 7.7σ Improved measurement

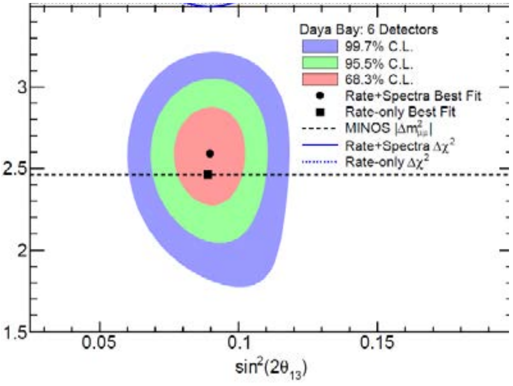
CP**C37**:011001 (2013)

consistent results from Double Chooz and RENO

2013





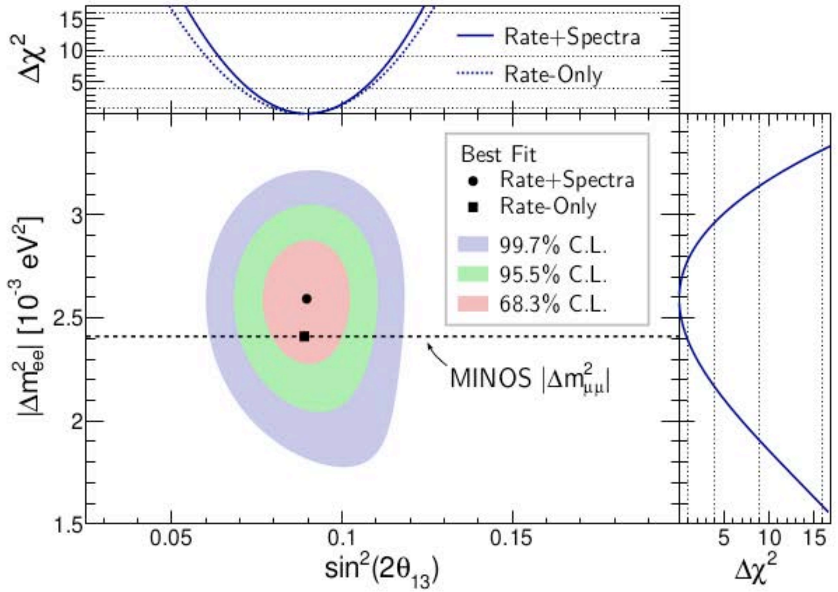


Most precise $\sin^2 2\theta_{13}$ measurement (10%)

First Δm^2_{ee} measurement (`atmospheric' Δm^2 from ν_e agrees with ν_μ from MINOS, consistent with 3-ν model)

Rate+Spectra Oscillation Analysis

Relative oscillation analysis between near and far detectors



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

$$|\Delta m^2_{ee}| = 2.59^{+0.19}_{-0.20} \cdot 10^{-3}\,\mathrm{eV}^2$$

$$\chi^2/N_{\mathrm{DoF}} = 162.7/153$$

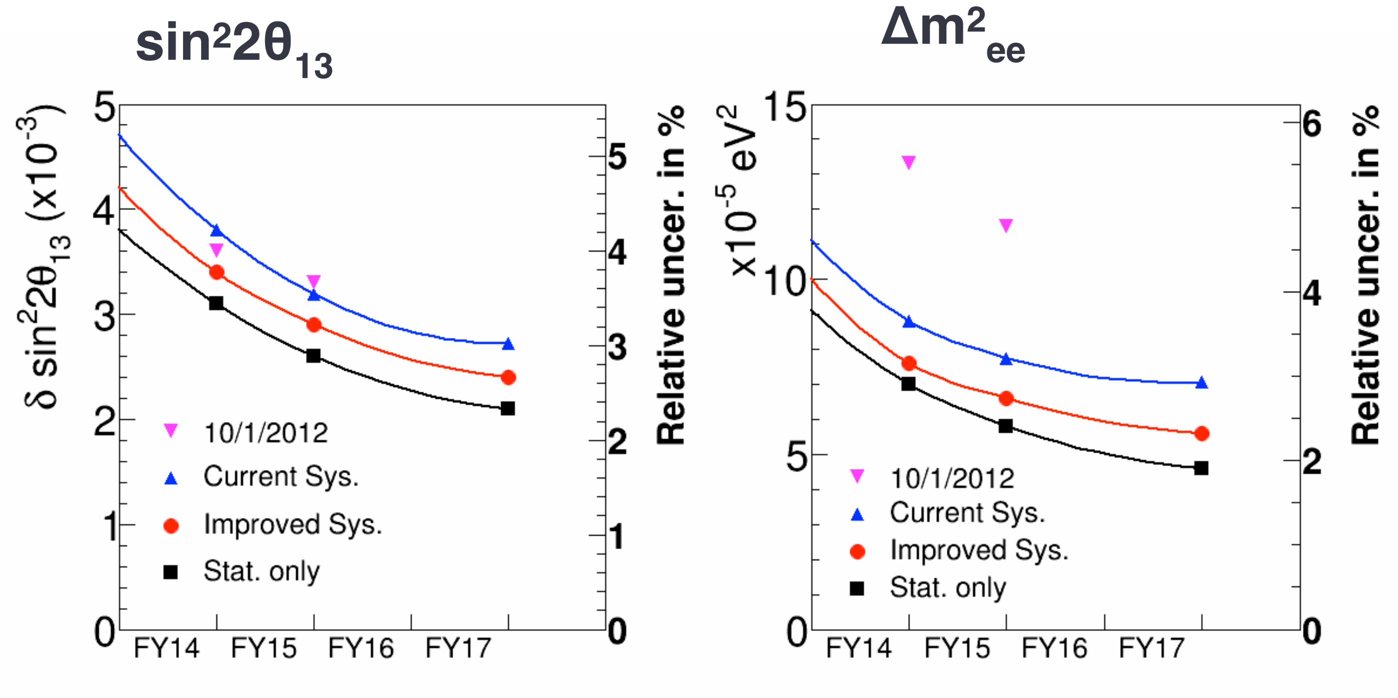
Strong confirmation of oscillation-interpretation of observed $\bar{\nu}_e$ deficit

	Normal MH Δm^2_{32} $[10^{-3}\mathrm{eV}^2]$	Inverted MH Δm^2_{32} $[10^{-3}\mathrm{eV}^2]$
From Daya Bay Δm^2_{ee}	$2.54^{+0.19}_{-0.20}$	$-2.64^{+0.19}_{-0.20}$
From MINOS $\Delta m^2_{\mu\mu}$	$2.37^{+0.09}_{-0.09}$	$-2.41^{+0.11}_{-0.09}$

A. Radovic, DPF2013

Daya Bay - Sensitivity Projections

Precision Measurements



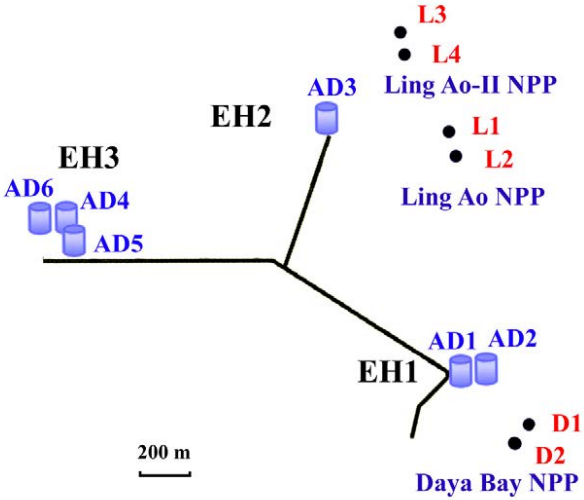
Combination of n-Gd and n-H with anticipated systematics improvements ($\sin^2 2\theta_{13}$ =0.09, Δm^2_{ee} =2.41e-3 eV^2)

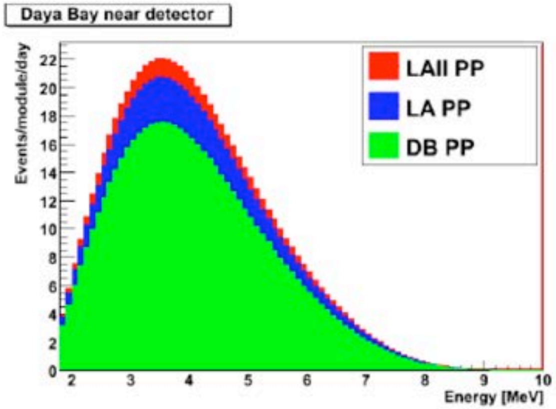
Reactor experiments will provide most precise measurement of $\sin^2 2\theta_{13}$ for the foreseeable future.

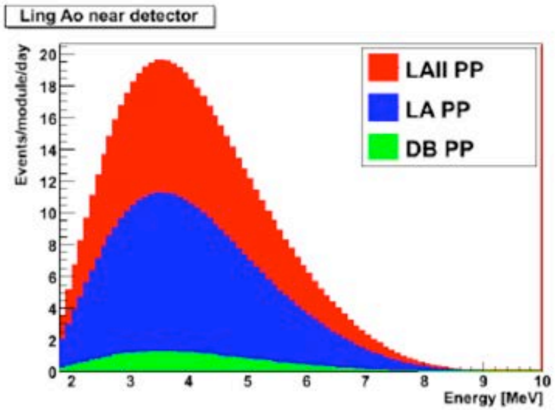
Towards Absolute Spectrum and Flux

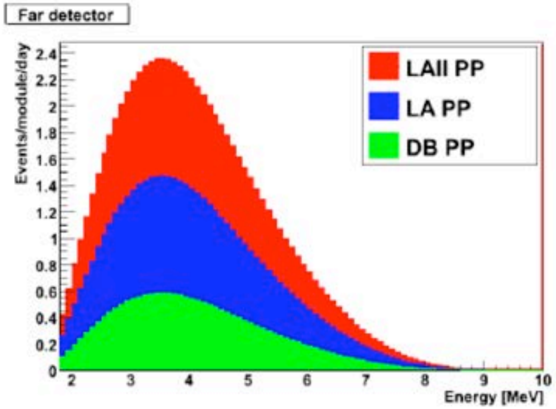
Multiple Reactor Cores

Oscillation of different reactors mixed together in one detector. From measurement, we don't know which IBD event is from which reactor









C. Lewis

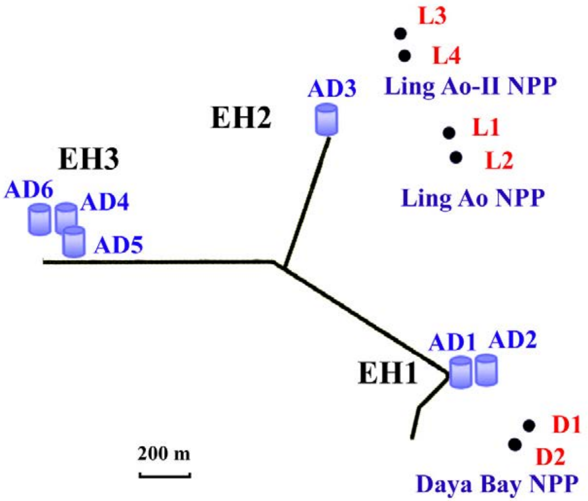
now have full set of 8 detectors operations

Daya Bay can compare spectra between detectors and experimental halls

Towards Absolute Spectrum and Flux

Multiple Reactor Cores

Oscillation of different reactors mixed together in one detector. From measurement, we don't know which IBD event is from which reactor



Combine 3 ADs antineutrino spectrum together:

$$S_{combined}(E_\nu) = \sum_{d=1}^{3} S_d(E_\nu) / M_d$$

Obtain normalized reactor antineutrino spectrum: oscillation, proton number, total fission number Ftotal

$$S_{Norm}(E_\nu) = \frac{S_{combined}(E_\nu)}{P_{sur\_eff}(E_\nu) \cdot N_p} \Big/ F_{total}$$

Where Ftotal is from all 6 reactors contributions to 3 ADs:

$$F_{total} = \sum_d \sum_r \frac{1}{4\pi L_r^2} \cdot \frac{W_r^d}{\sum_i \alpha_{ir}^d \cdot e_i}$$

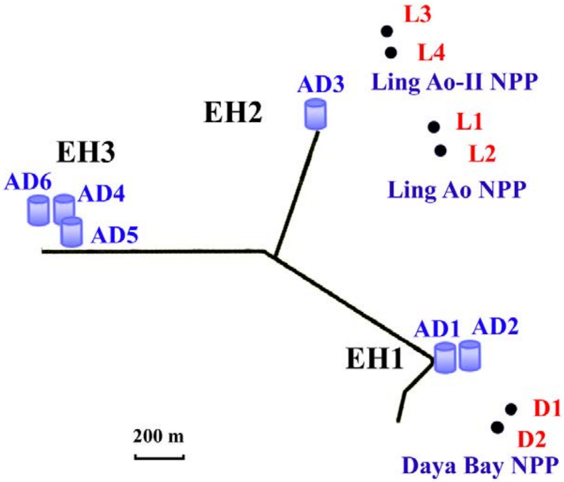
index:
d day
r reactor
i isotope

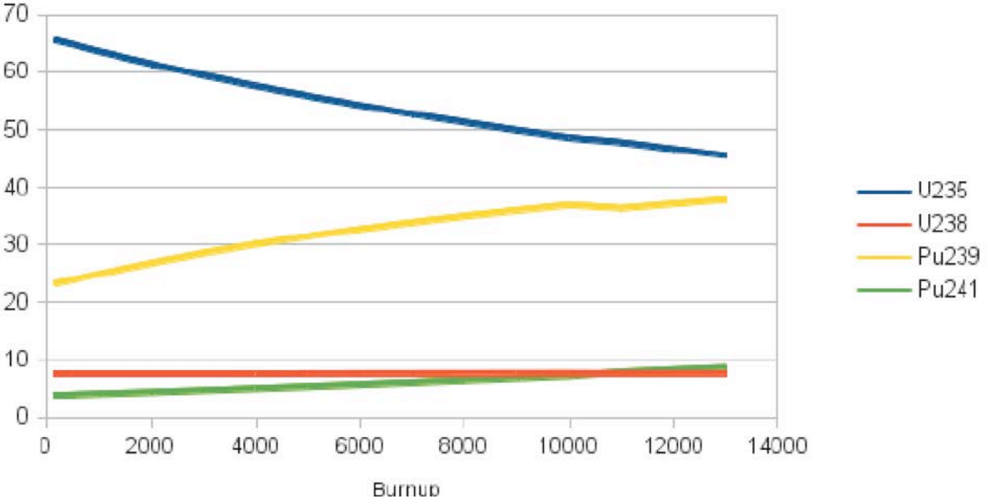
Daya Bay

Summed spectrum is an averaged, effective spectrum

Towards Absolute Spectrum

Fuel Evolution of Multiple Reactor Cores

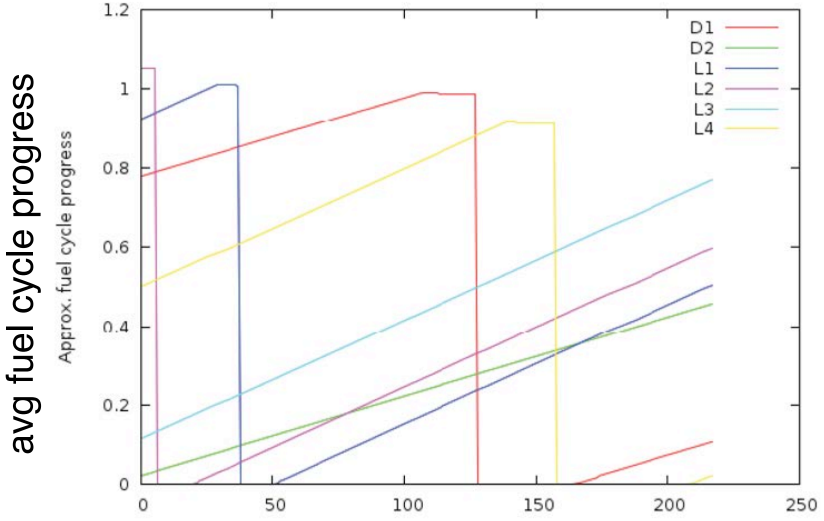




Antineutrino detectors in EH1 get ~ 80% of IBDs from D1 and D2

D1 and D2 have 18 month fuel cycles

Twice per fuel cycle one of these cores will be off for ~month.

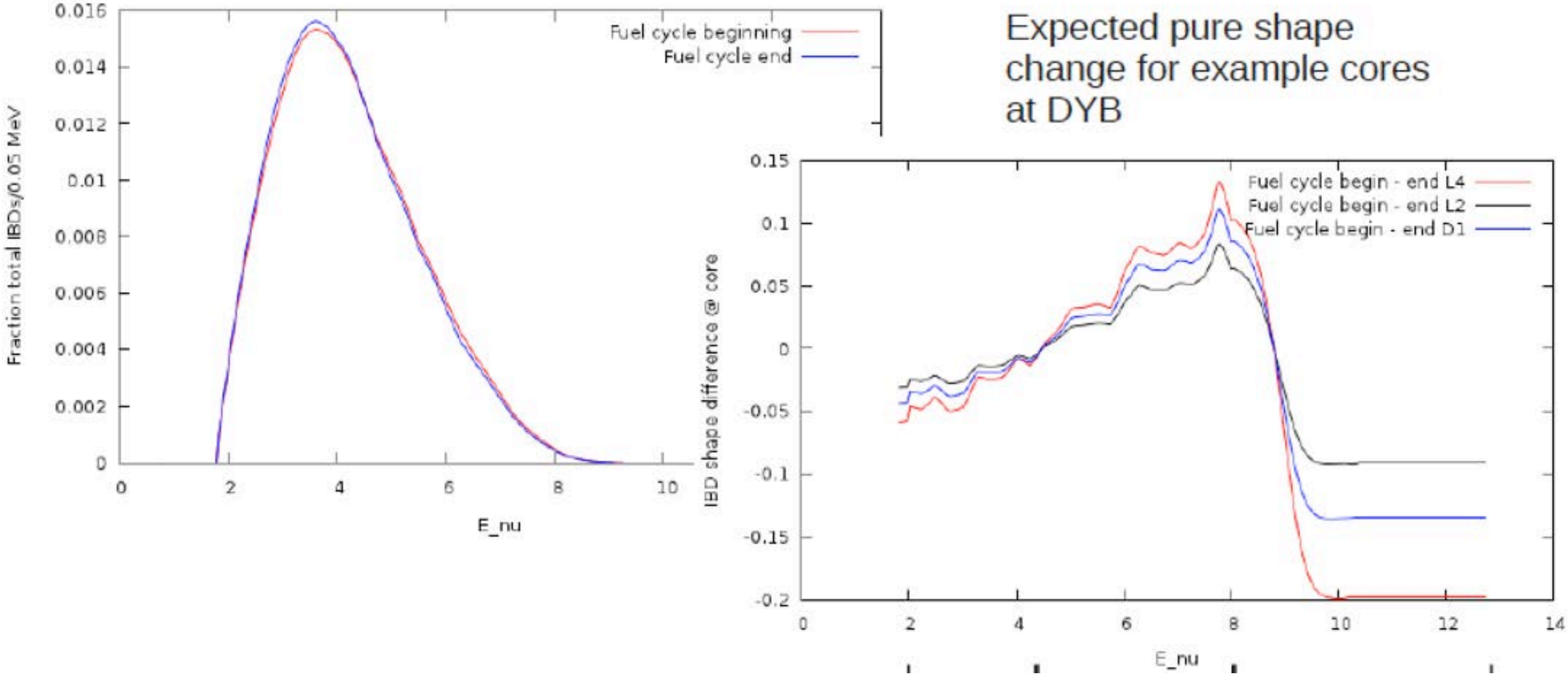


C. Lewis

Towards Absolute Spectrum

Fuel Evolution of Reactor Core

- For a single core, IBDs shift to lower energy bins as fuel evolves



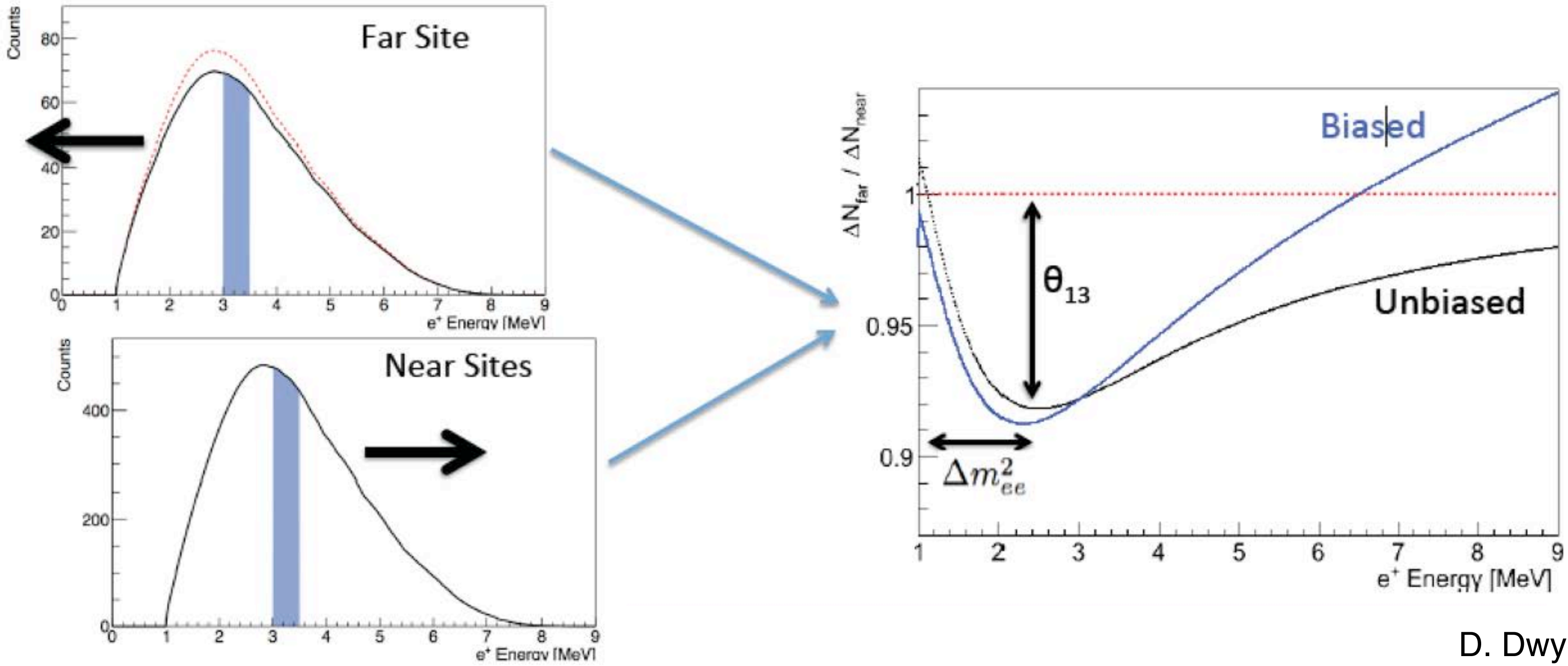
Expected pure shape change for example cores at DYB

C. Lewis

Summing data from different times adds different spectral changes from multi-reactor experiment.

Energy Response and Scale

Understanding energy scale is important for both oscillation analysis and spectral measurement

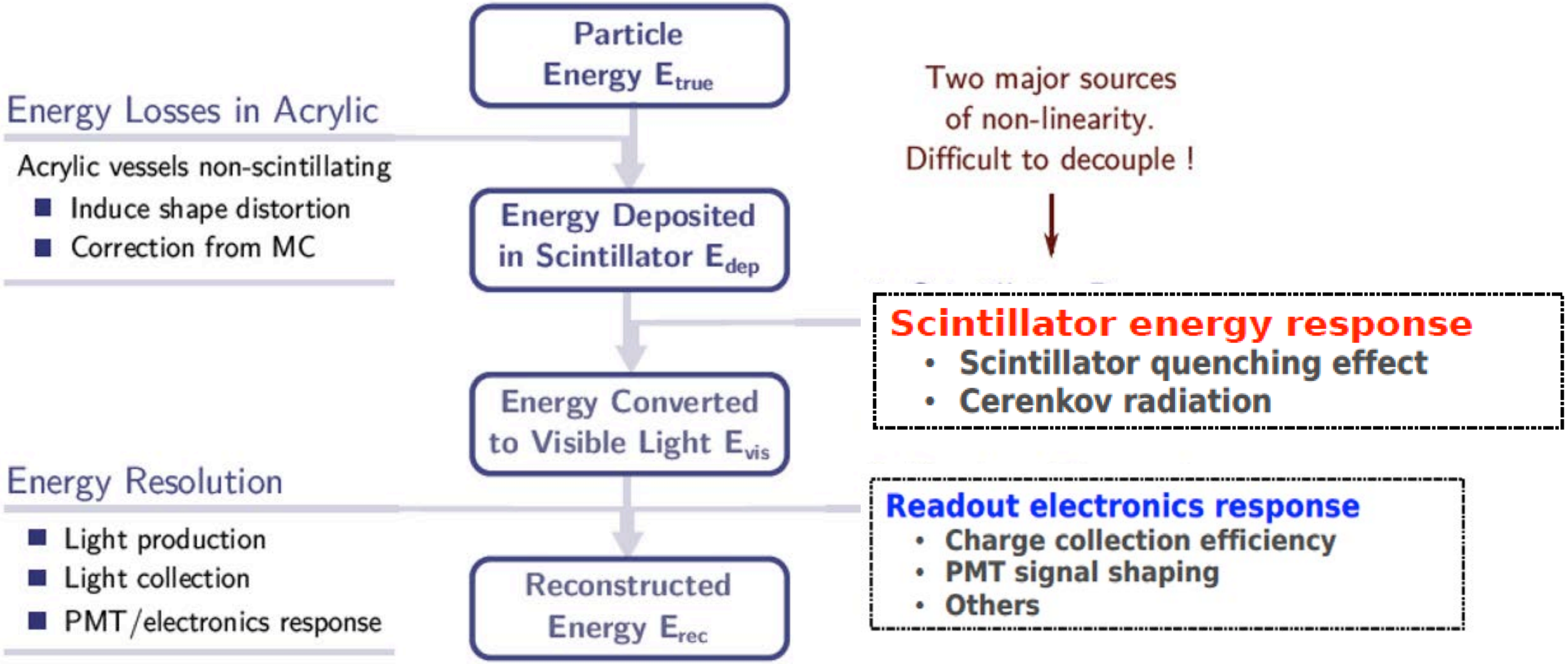


D. Dwyer

Requires detailed translation between true and detected antineutrino energy.

Energy Response

Measurement of the absolute spectrum requires understanding the energy response -> Model maps true energy E_{true} to reconstructed kinetic energy E_{rec}



Particle Energy E_{true}

Energy Deposited in Scintillator E_{dep}

Energy Converted to Visible Light E_{vis}

Reconstructed Energy E_{rec}

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 !

Scintillator energy response

- Scintillator quenching effect
- Cerenkov radiation

Readout electronics response

- Charge collection efficiency
- PMT signal shaping
- Others

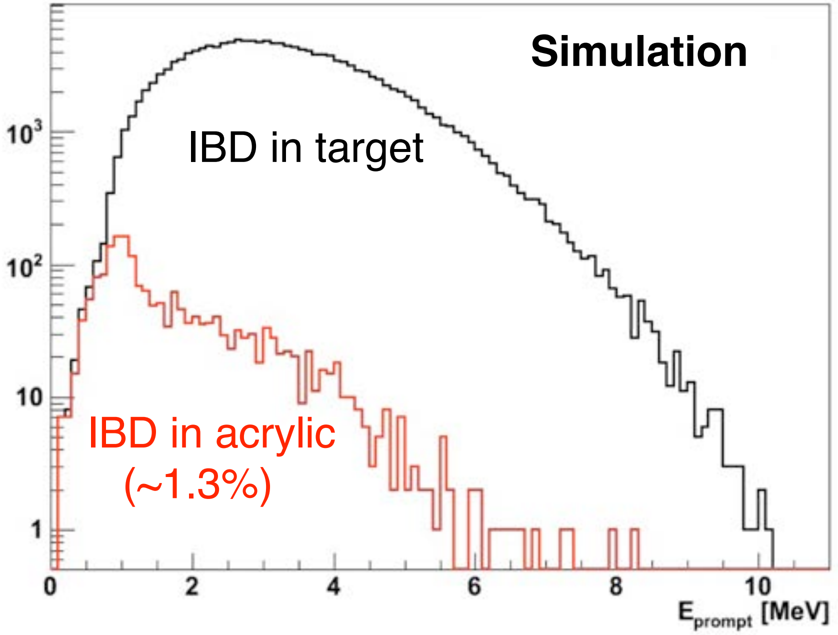
Minimal impact on relative oscillation measurement, crucial for measurement of absolute reactor spectra

Detector Response: Acrylic Vessels

Energy loss in acrylic causes small distortion of energy spectrum

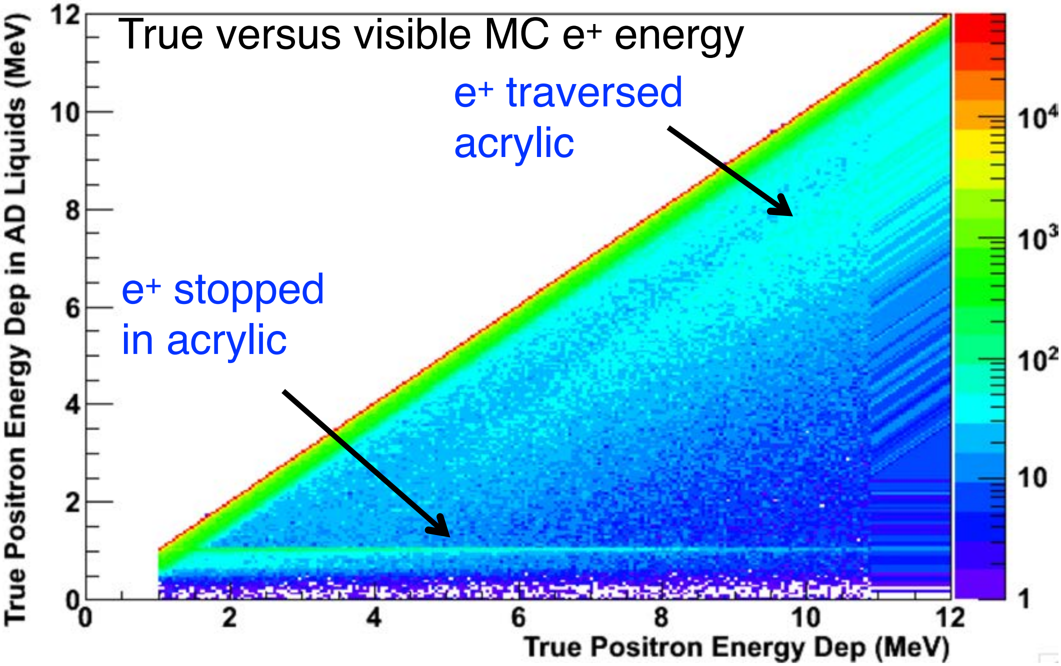
If antineutrino interacts in or near acrylic vessel, a portion of the kinetic energy of inverse beta positrons will not be detected

Annihilation gammas with longer range can also deposit energy in the vessels


Simulation

IBD in target

IBD in acrylic (~1.3%)


True versus visible MC e+ energy

e+ traversed acrylic

e+ stopped in acrylic

Generated 2D distortion matrix from MC to correct predicted positron energy spectrum

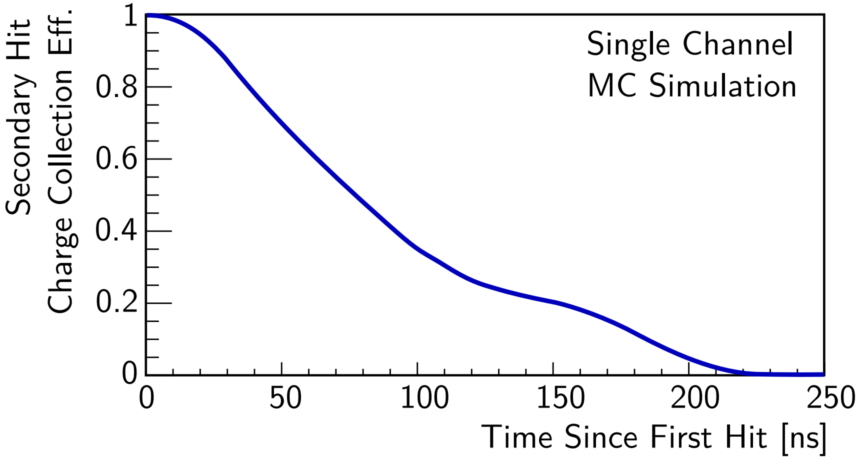
Uncertainties from varying acrylic vessel thicknesses and MC statistics incorporated into analysis.

Electronics Non-Linearity Model

PMT readout electronics introduces additional biases

Electronics does not fully capture late secondary hits

- Slow scintillation component missed at high energies
- Charge collection efficiency decreases with visible light



- Effective model as a function of total visible energy
- 2 empirical parameterizations: exponential and quadratic
- Total effective non-linearity f from both scintillation and electronics effects:

$$f = \frac{E_{\mathrm{rec}}}{E_{\mathrm{true}}} = \frac{E_{\mathrm{rec}}}{E_{\mathrm{vis}}} \cdot \frac{E_{\mathrm{vis}}}{E_{\mathrm{true}}}$$

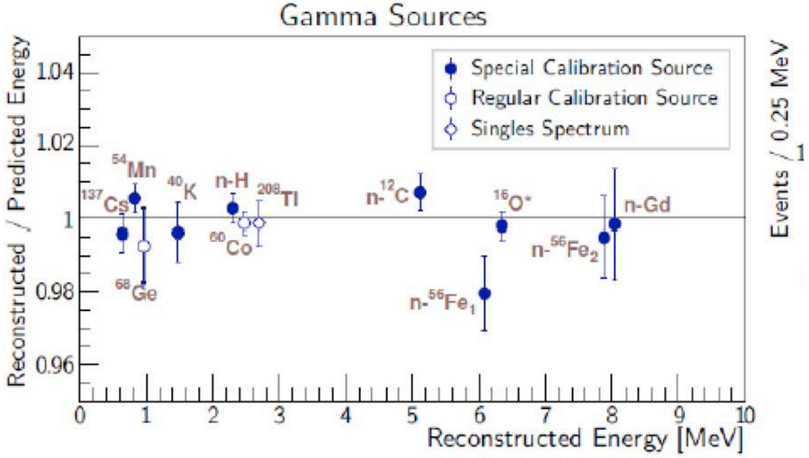
$\boxed{1}$ Electronics non-linearity

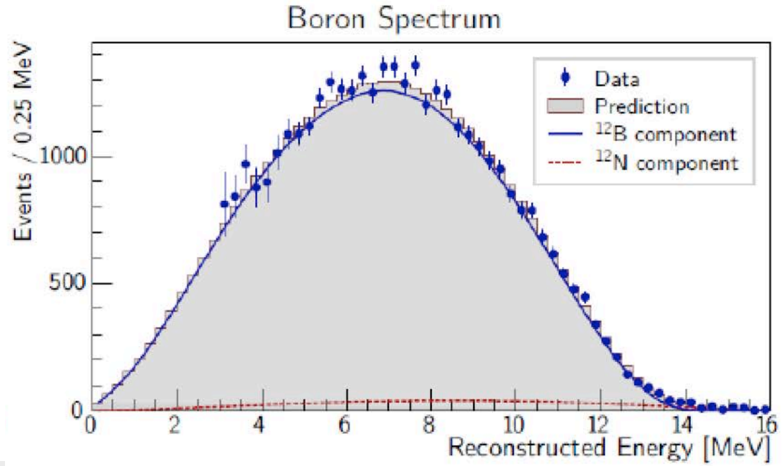
$\boxed{2}$ Scintillator non-linearity

Energy Response Model

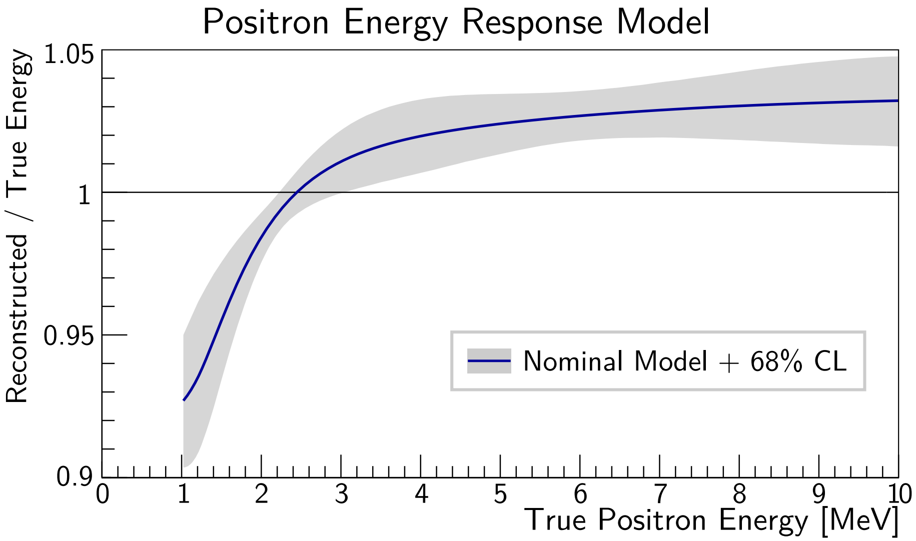
Constraints

Use calibration gamma sources and continuous ^{12}B spectrum to constrain energy model parameters





Positron Energy Response



multiple models are constructed with different data and parameter constraints

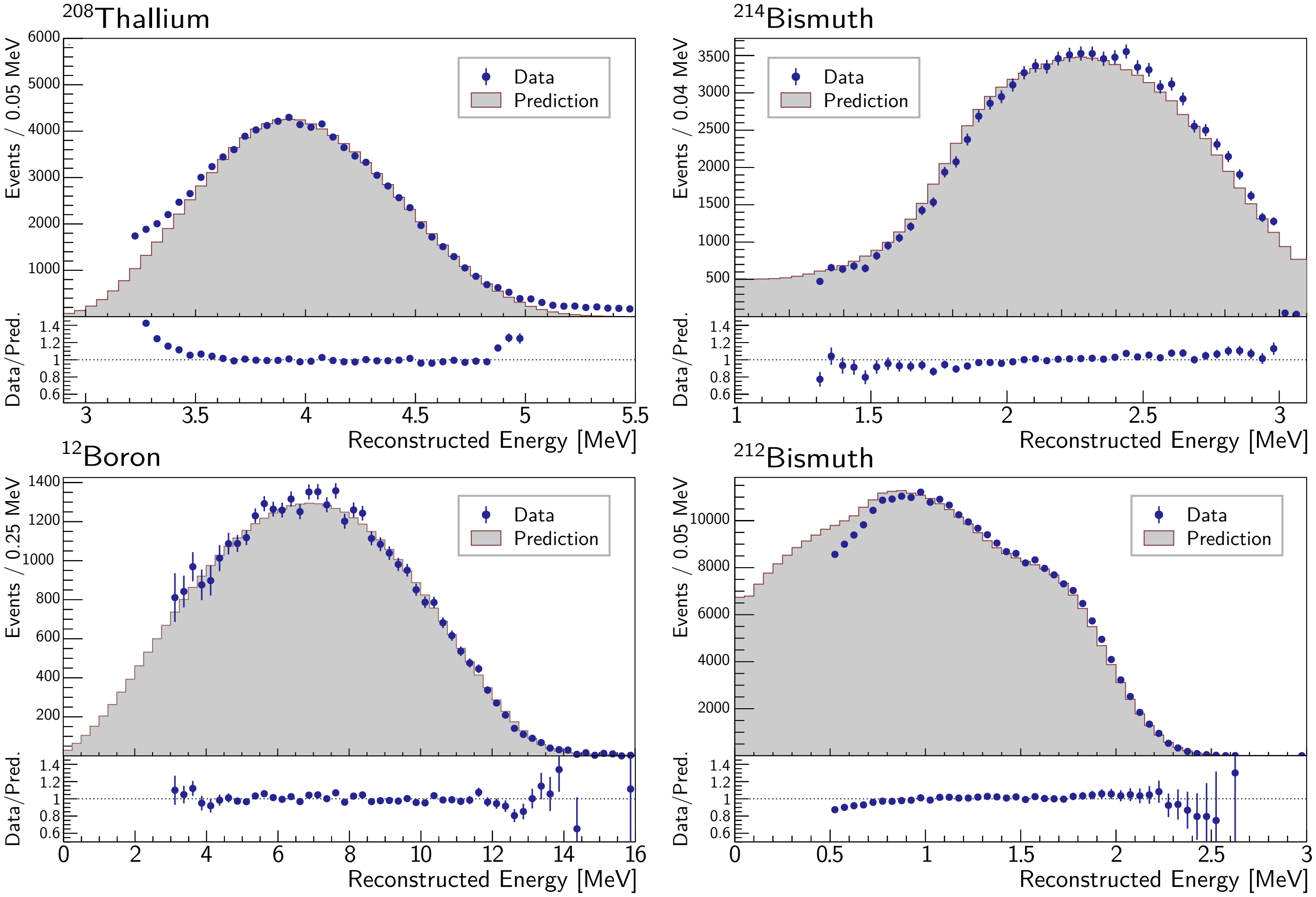
conservatively combine 5 minimal correlated energy models

Detector response to gamma and e- used to predict response to e+

Gamma + Beta Spectra

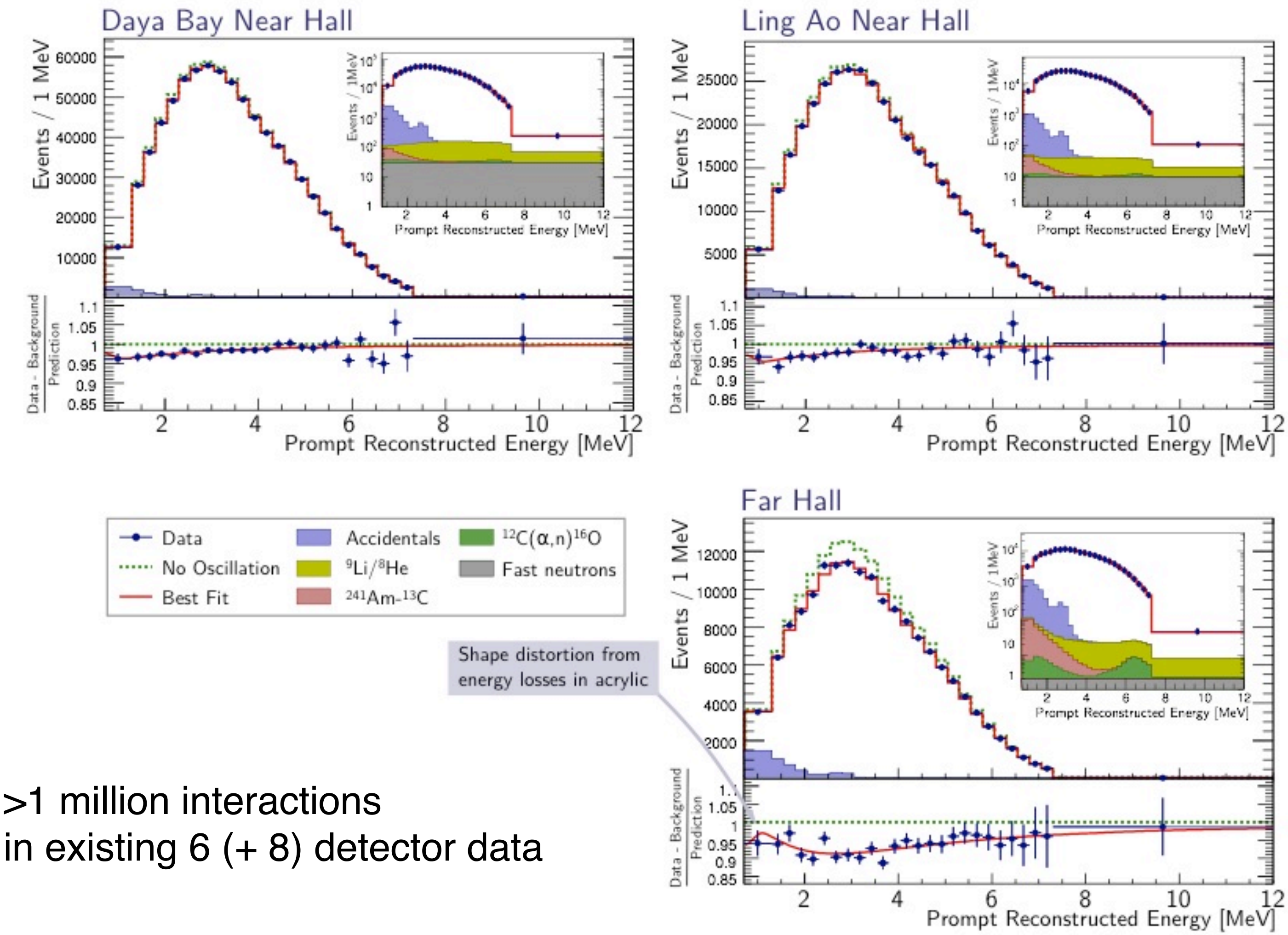
Additional spectra from ^{212}Bi, ^{214}Bi and ^{208}Tl decays

- Sizable theoretical uncertainties from 1st forbidden non-unique beta decays
- ^{212}Bi, ^{214}Bi and ^{208}Tl spectra only utilized to cross-check results



Absolute Spectral Shape

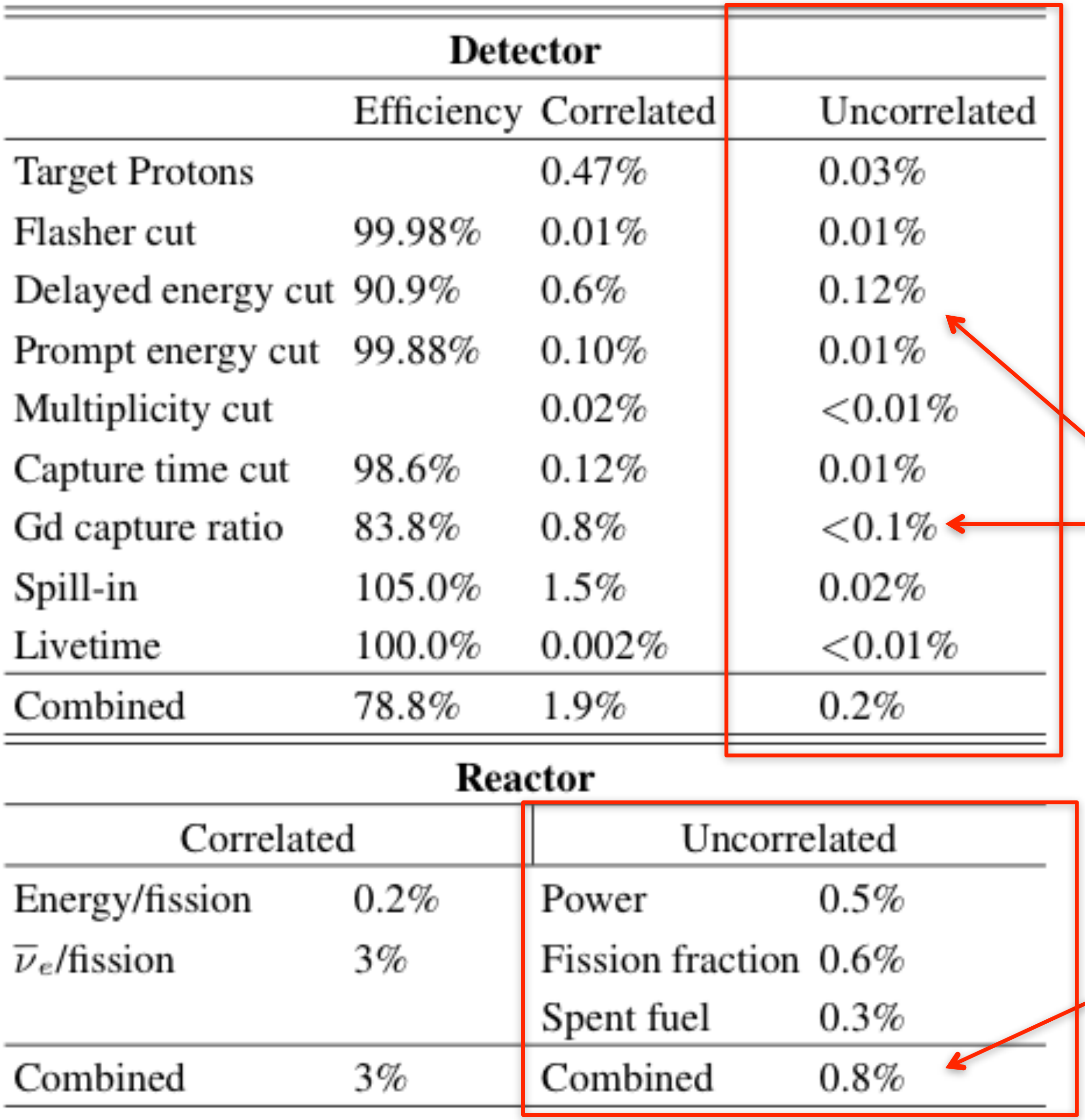
Measurement of absolute antineutrino spectrum strongly dependent on detector energy model



Shape distortion from energy losses in acrylic

>1 million interactions
in existing 6 (+ 8) detector data

Uncertainty Summary - Relative



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%

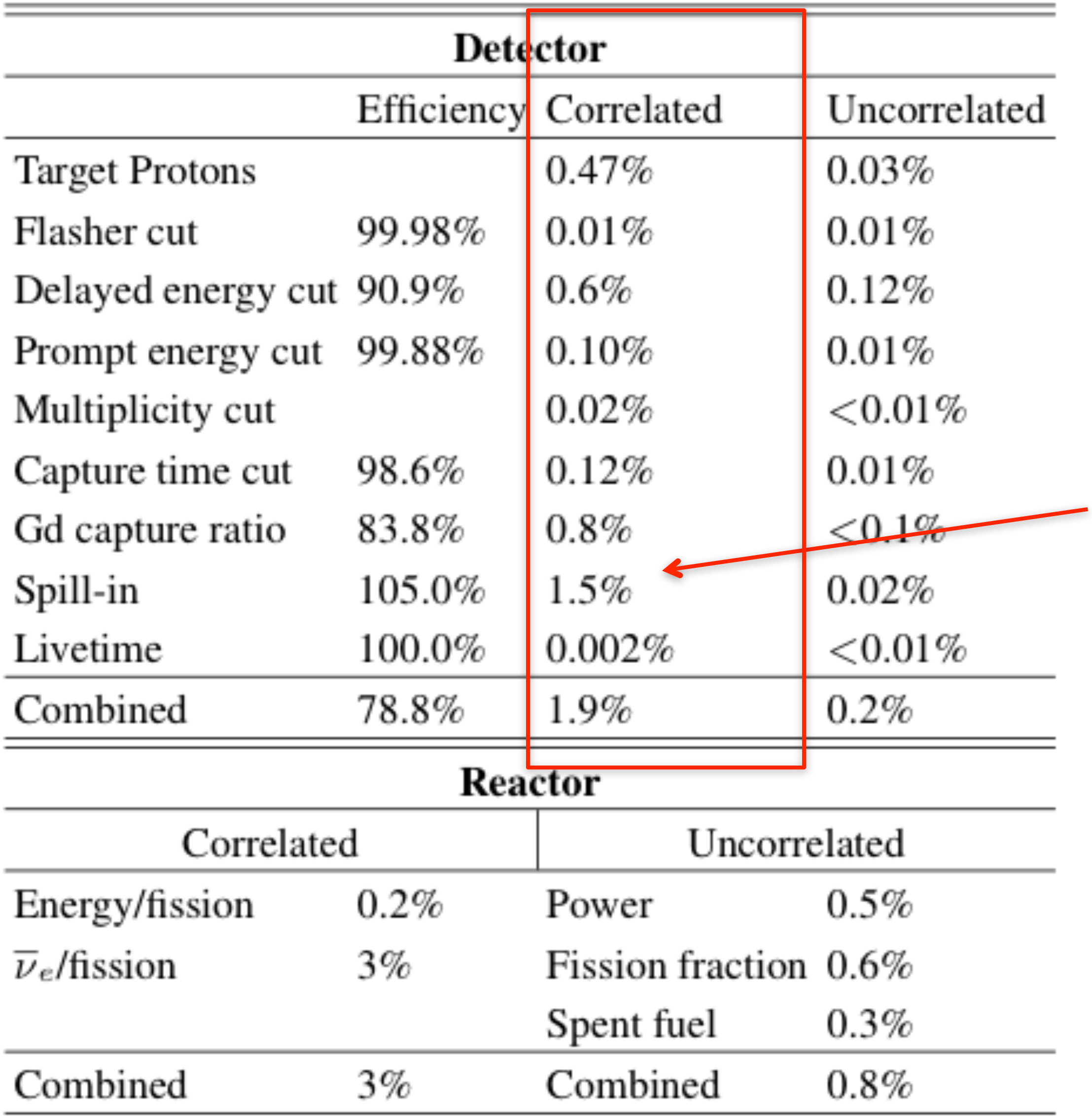
Reactor			
Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
$\overline{\nu}_e$/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%

For near/far oscillation, only uncorrelated uncertainties are used.

Daya Bay still statistics limited. Largest systematics are smaller than far site statistics (~0.5%)

Influence of uncorrelated reactor systematics reduced by far vs. near measurement.

Uncertainty Summary - Absolute



Detector

	Efficiency	Correlated	Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
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Reactor

Correlated		Uncorrelated	
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$\overline{\nu}_e$/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%

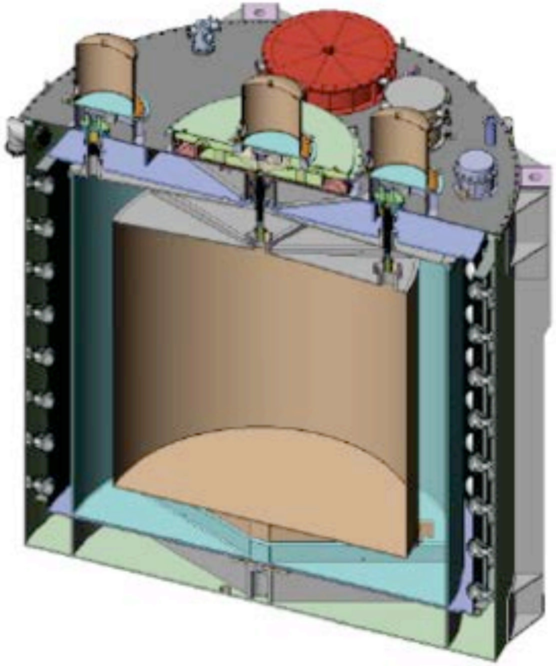
Absolute flux measurement depends on the absolute detector efficiencies and uncertainties/

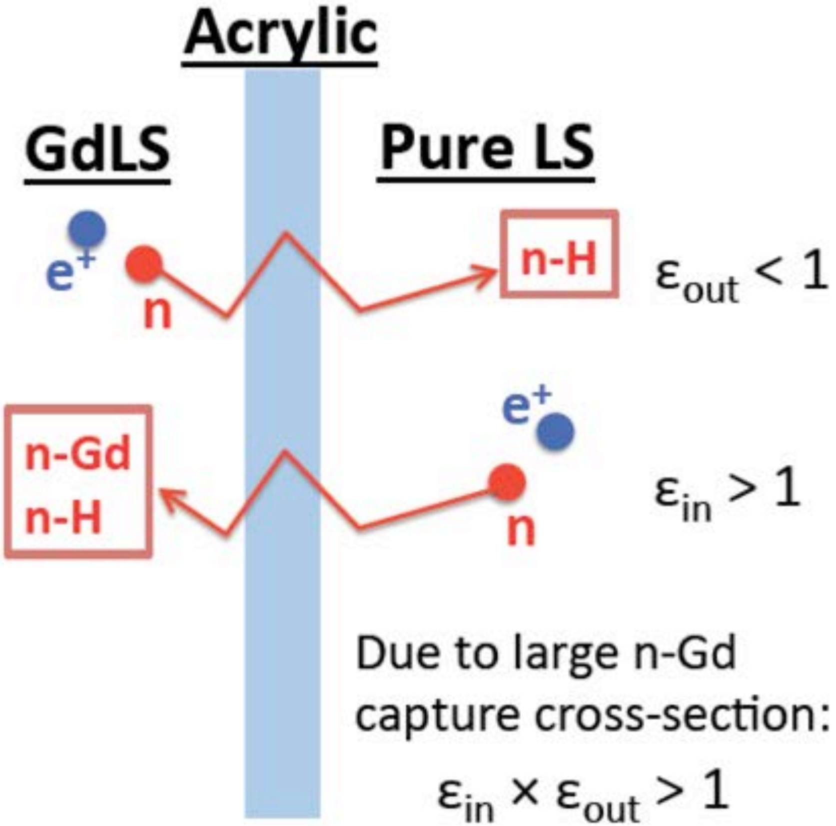
Dominated by spill-in/spill-out of neutrons.

Influence of uncorrelated reactor
systematics reduced by
far vs. near measurement.

Neutron Spill-in/Spill-Out

Some neutrons traverse acyrlic, changing absolute detector efficiency





Acrylic

GdLS

Pure LS

e^+ n → n-H $\varepsilon_{out} < 1$

n-Gd
n-H ← n e^+ $\varepsilon_{in} > 1$

Due to large n-Gd capture cross-section:

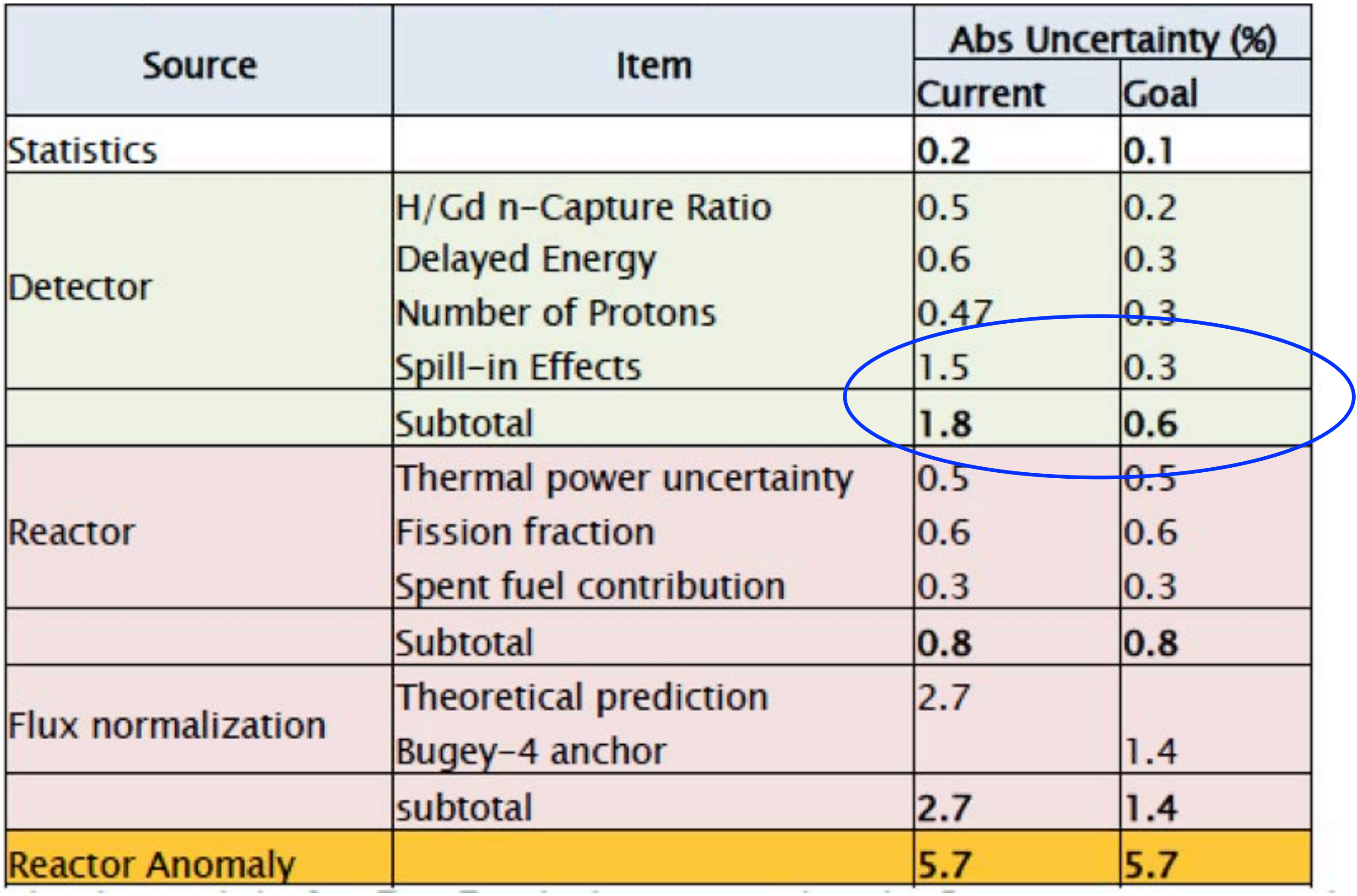
$$\varepsilon_{in} \times \varepsilon_{out} > 1$$

Combined effect ≈ 105% ± 1.5%

Difficult to address with data; heavily reliant on simulation

Daya Bay - Projected Uncertainties

Absolute Uncertainties

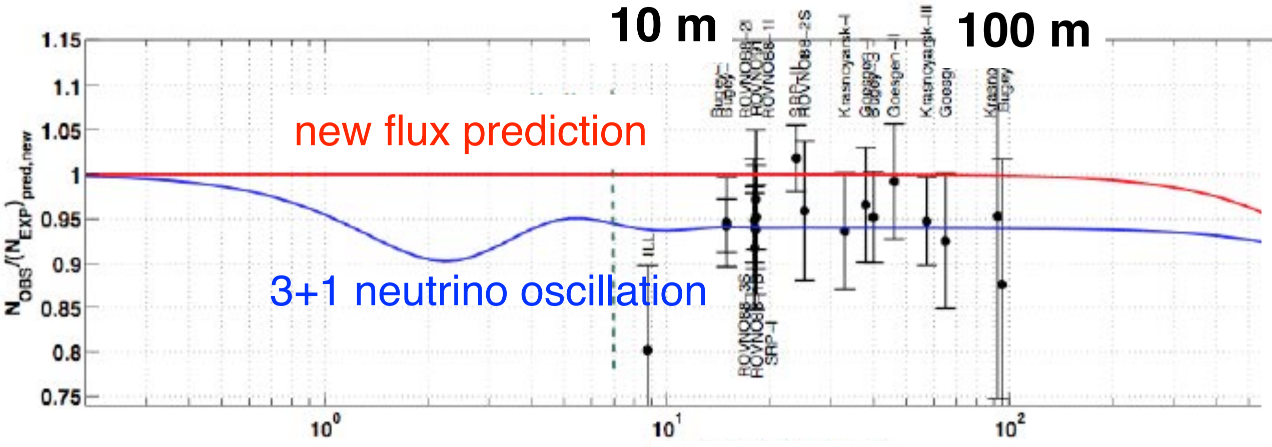


Source	Item	Abs Uncertainty (%)	
		Current	Goal
Statistics		**0.2**	**0.1**
Detector	H/Gd n-Capture Ratio	0.5	0.2
	Delayed Energy	0.6	0.3
	Number of Protons	0.47	0.3
	Spill-in Effects	1.5	0.3
	Subtotal	**1.8**	**0.6**
Reactor	Thermal power uncertainty	0.5	0.5
	Fission fraction	0.6	0.6
	Spent fuel contribution	0.3	0.3
	Subtotal	**0.8**	**0.8**
Flux normalization	Theoretical prediction	2.7	
	Bugey-4 anchor		1.4
	subtotal	**2.7**	**1.4**
Reactor Anomaly		**5.7**	**5.7**

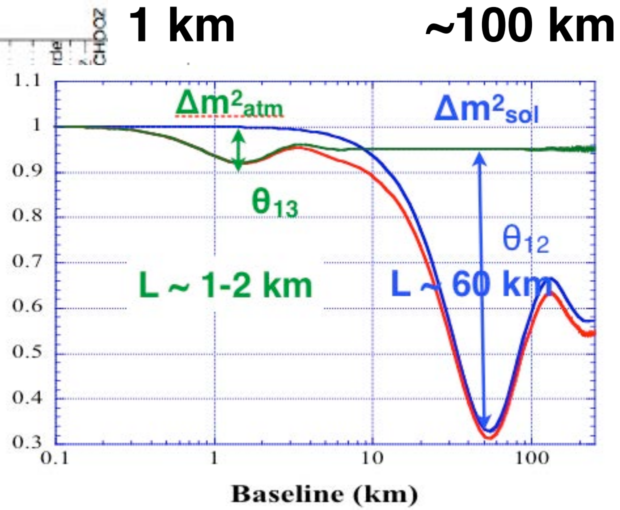
Daya Bay

Short-Baseline Reactor Experiments

Baselines



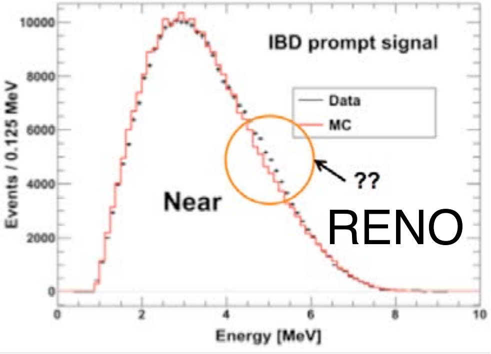
adapted from Schwetz, Neutrino2012



Reactor Anomaly

apparent deficit in observed reactor flux

Reactor Spectra



One of several anomalies

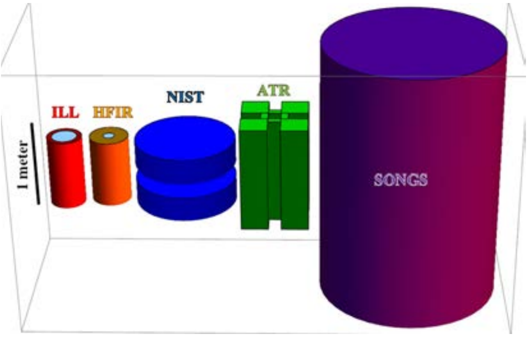
LSND ($\bar{\nu}_e$ appearance)
MiniBoone (ν_e appearance)
Ga anomaly
N_{eff} in cosmology
Reactor anomaly ($\bar{\nu}_e$ disappearance)

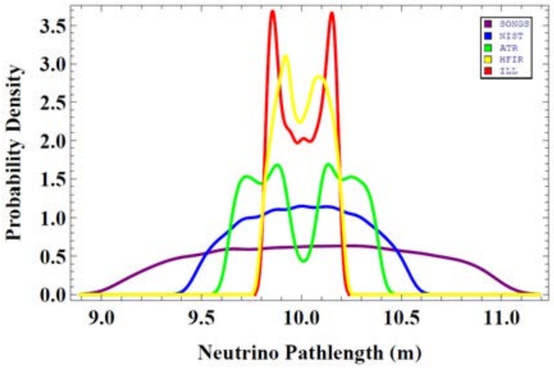
Do we understand reactor flux predictions and spectrum?

Experiments at Very Short Baseline

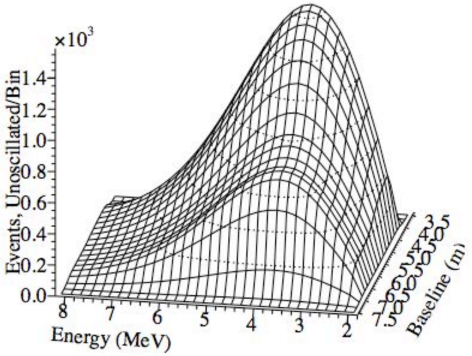
A “point source”

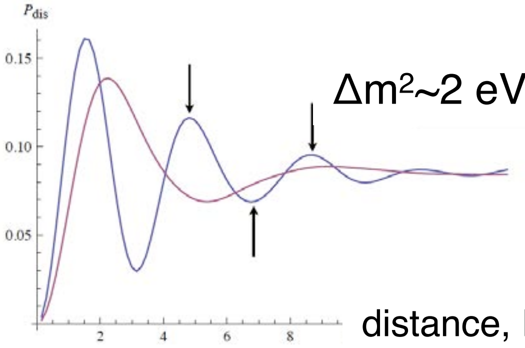
Minimum baseline spread





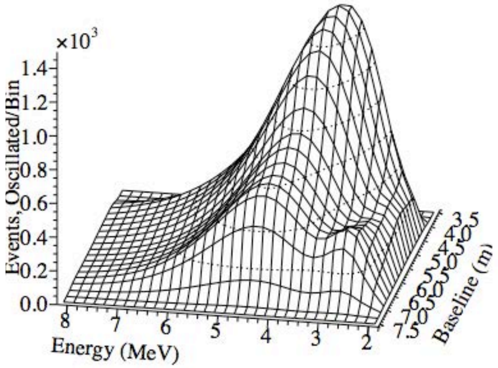
$\overline{\nu}_e$ Oscillation





Δm²~2 eV²

distance, R



~O(10)m

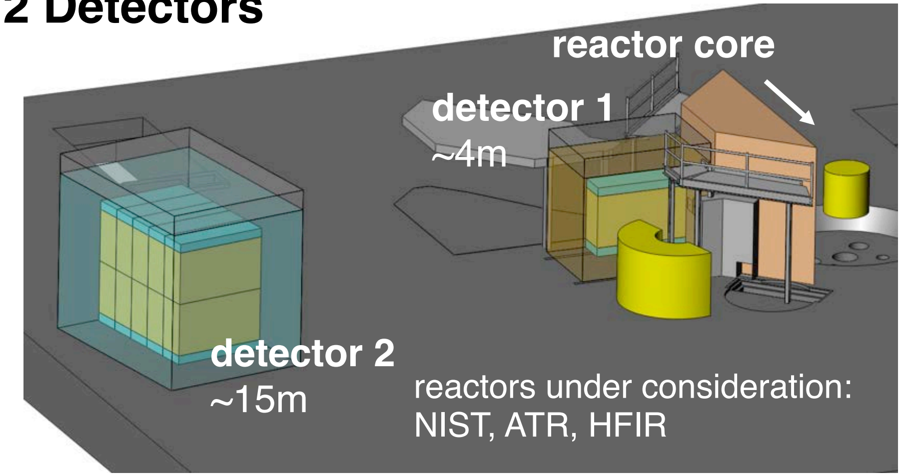
Measure un-oscillated spectrum if you don’t see oscillations

Short-Baseline Reactor Experiment

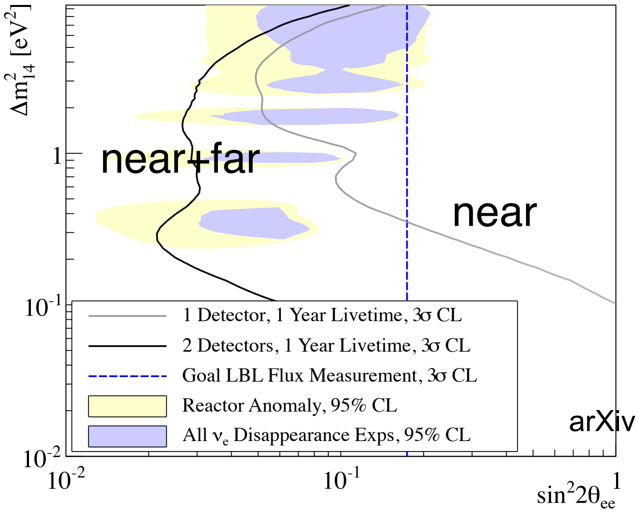
PROSPECT - A US-Based Short Baseline Experiment

A Precision Reactor Neutrino Oscillation and Spectrum Experiment

2 Detectors

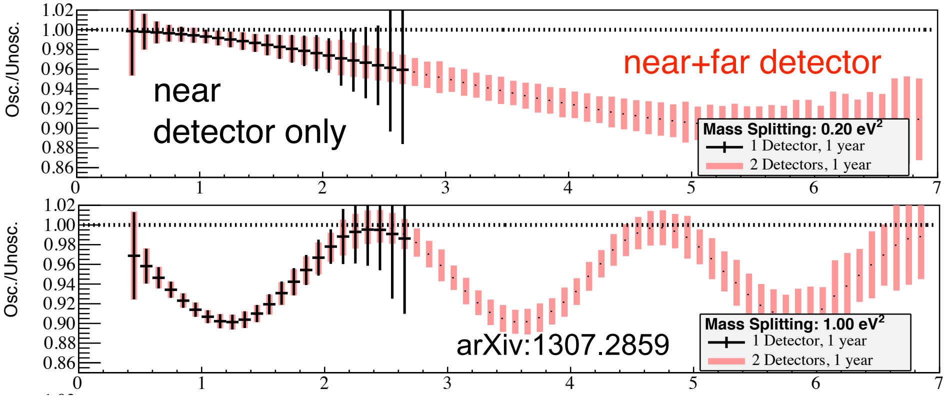


Scientific Reach



arXiv:1307.2859

Map out L/E Oscillations



arXiv:1307.2859

Phased Approach

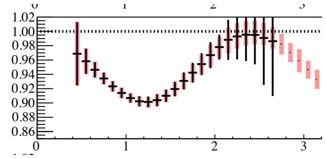
phase 1- near detector

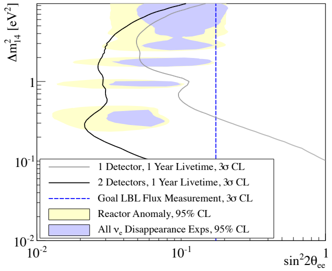
phase 2 - near + far detectors

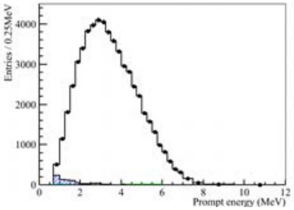
3σ in 1 year

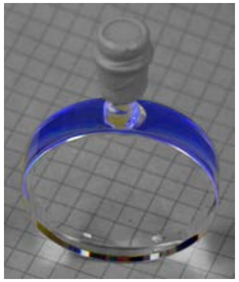
5σ in 3 years

Short-Baseline Reactor Experiment - Objectives









Primary Physics Objectives

Definitive short-baseline oscillation search with high sensitivity

Test of the oscillation region suggested by reactor anomaly and $\overline{\nu}_e$ disappearance channel (3 years of run time can exclude virtually all the implied oscillation region at 5σ)

Precision measurement of reactor $\overline{\nu}_e$ spectrum for physics and safeguards

Secondary Physics and Applied Goals

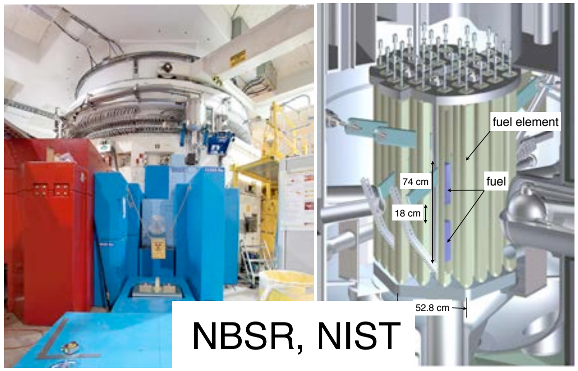
^{6}Li doped scintillator development

Segmented antineutrino detectors for near-surface operation; develop antineutrino-based reactor monitoring technology for safeguards

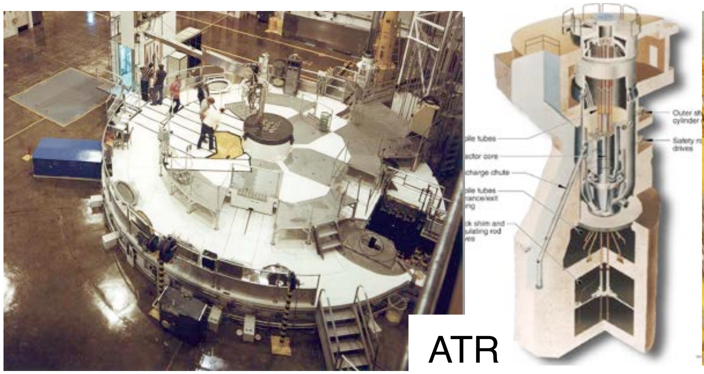
Possible first measurement of antineutrinos from spent fuel

US Research Reactors

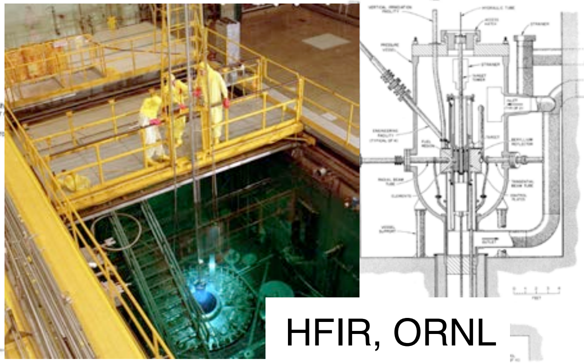
US Operates High-Powered Research Reactors



NBSR, NIST



ATR

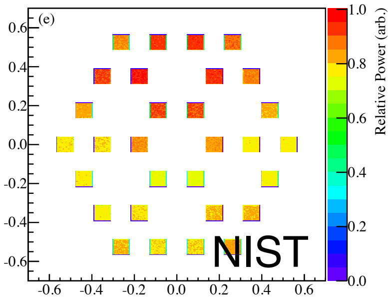


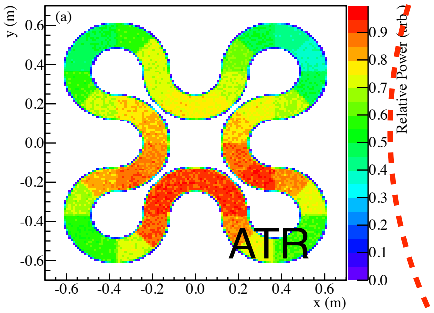
HFIR, ORNL

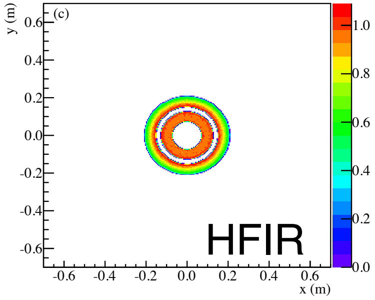
Site	Power (MW_{th})	Duty Cycle	Near Detector		Far Detector	
			Baseline (m)	Avg. Flux	Baseline (m)	Avg. Flux
NIST	20	68%	3.9	1.0	15.5	1.0
HFIR	85	41%	6.7	0.96	18	1.93
ATR	120	68%	9.5	1.31	18.5	4.30

commercial core

Reactor Cores

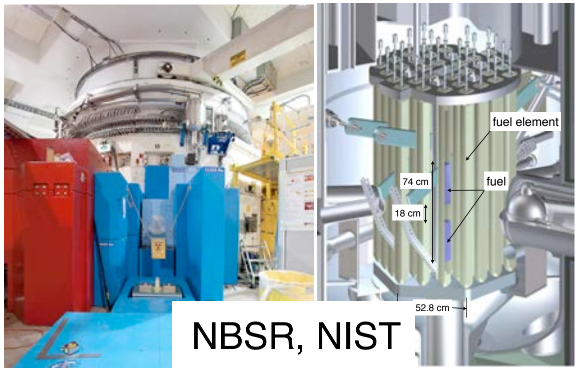




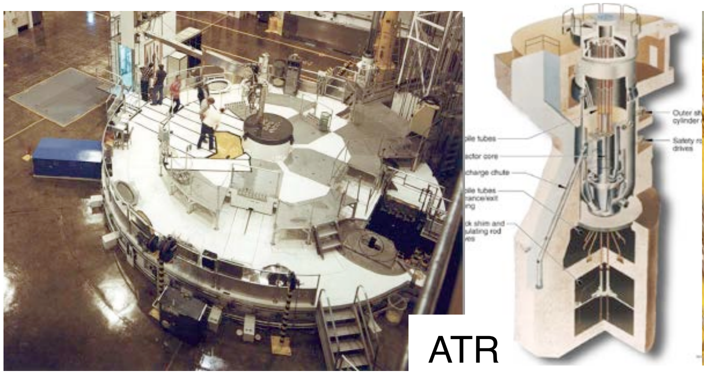


US Research Reactors

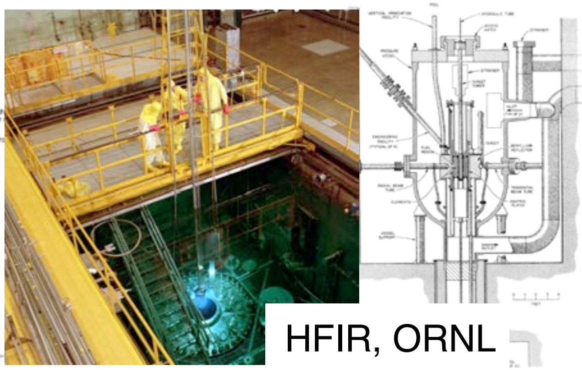
US Operates High-Powered Research Reactors



NBSR, NIST

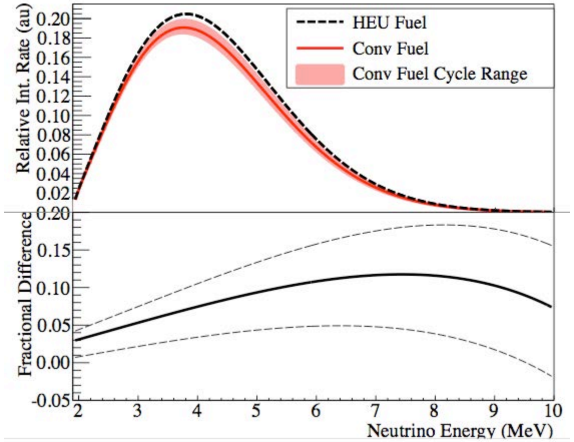


ATR



HFIR, ORNL

HEU Reactor Fuel

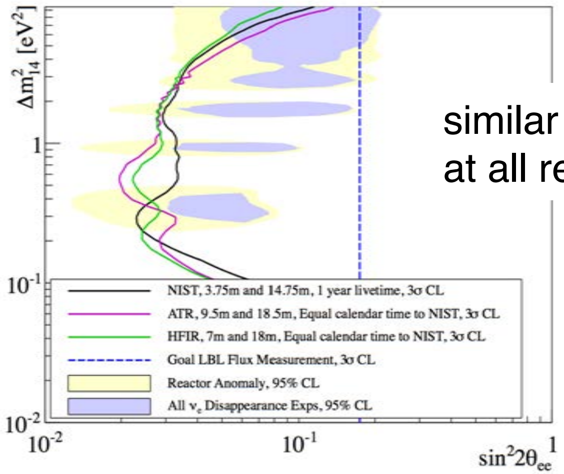


HEU, no time variation

Reactor off periods for background studies

Ability to reconfigure/run for extended periods

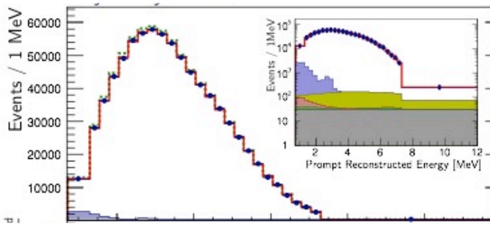
Sensitivity



similar scientific reach at all reactor sites

Opportunities for R&D, backup options for detector deployment

Absolute Spectral Shape and Flux



Reactor θ_{13} Experiments

- highest statistics
- requires removal oscillation effect from measured spectrum or simultaneous fit to oscillation
- remove fuel evolution of multiple reactor cores to extract “effective generic reactor spectrum”
- will add data point to absolute flux measurement at baseline of *O*(1km)

Short-Baseline Experiments

- potential measurement without oscillation effect
- measures HEU spectrum
- likely better simulation of reactor cores during fuel cycle
- oscillation search based on relative measurement in segmented detector, absolute flux measurement very difficult

Common Challenges

- calibration is important (edge effects, relative calibration between detector segments in short-baseline experiment)
- requires excellent understanding of energy response model
- requires translation from detected antineutrino energy to true energy

Summary

Reactor neutrinos are a tool for discovery. Reactors are flavor pure sources of $\overline{\nu}_e$

Current reactor experiments **(L~1-2km)** provide precision data on $\boldsymbol{\theta_{13}}$ and oscillations measurements. Unprecedented statistics on reactor spectra. Will provide **next benchmark in measurement of absolute spectral shape and flux.**

Short-baseline **(L~10m)** measurements offer opportunities for **definitive short-baseline oscillation search** and studies of the **reactor spectrum** at a research reactor. Different reactor antineutrino source, environment, and systematics. Segmented detector needed for background rejection, poses new challenges for spectral measurement.

Improved calculations and **assessment of spectral uncertainties** important for comparison of data and predictions.

Thanks to Daya Bay and PROSPECT collaborations and many colleagues for their input and discussions.

End