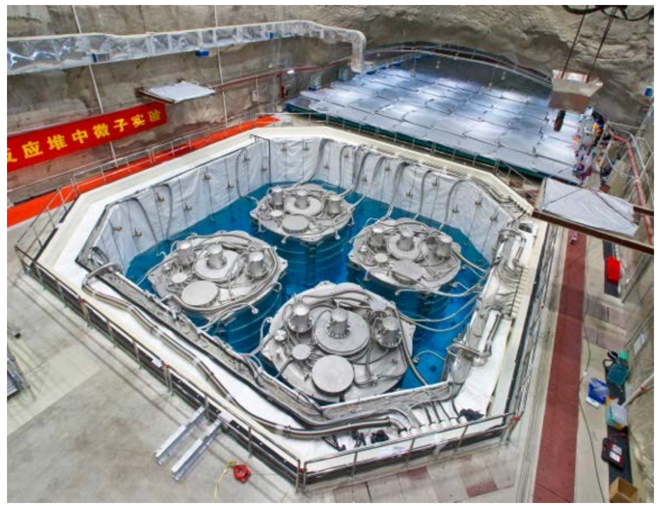
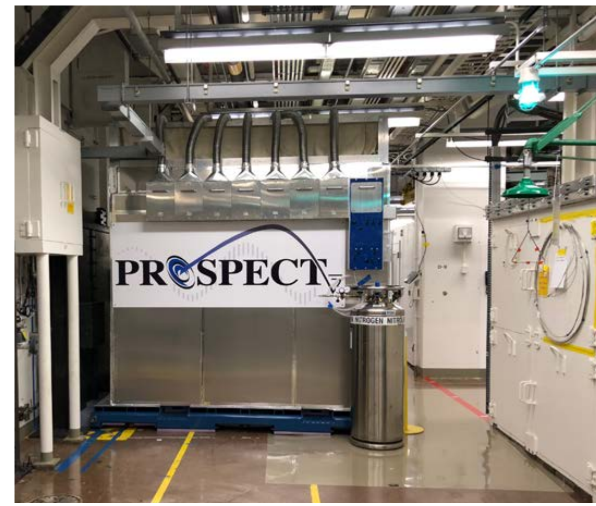
Reactor Neutrinos at Short Baselines

Recent Results and Future Prospects





Karsten M. Heeger
Yale University

August 1, 2019

Wright Laboratory

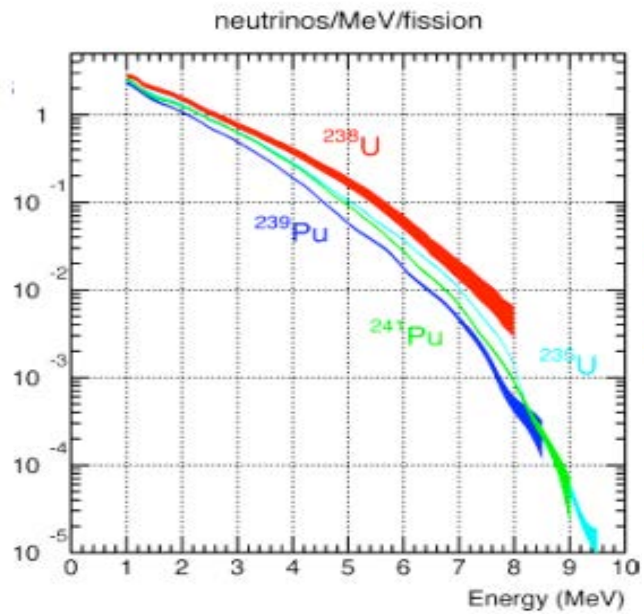
Yale

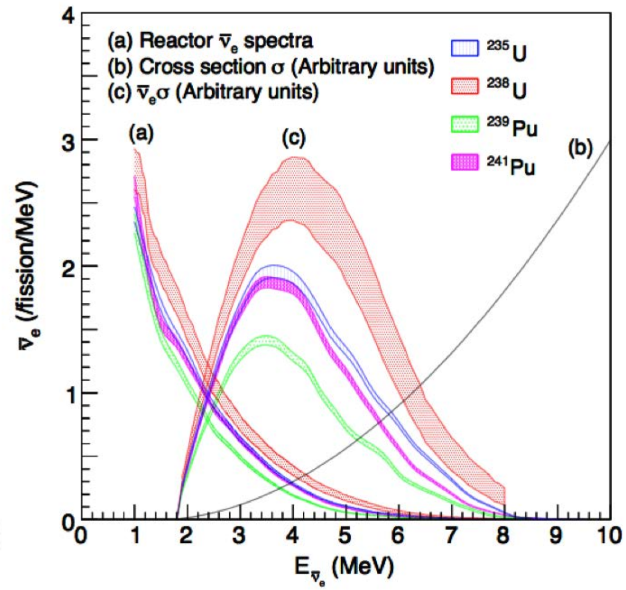
Reactor Antineutrinos

$\bar{\nu}_e$ from β-decays, pure $\bar{\nu}_e$ source

of n-rich fission products

on average ~6 beta decays until stable



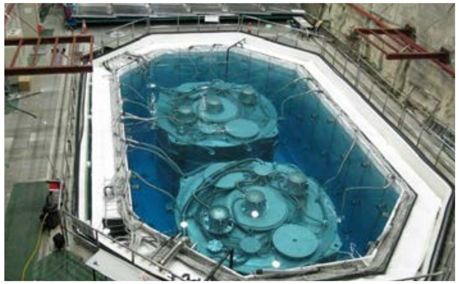


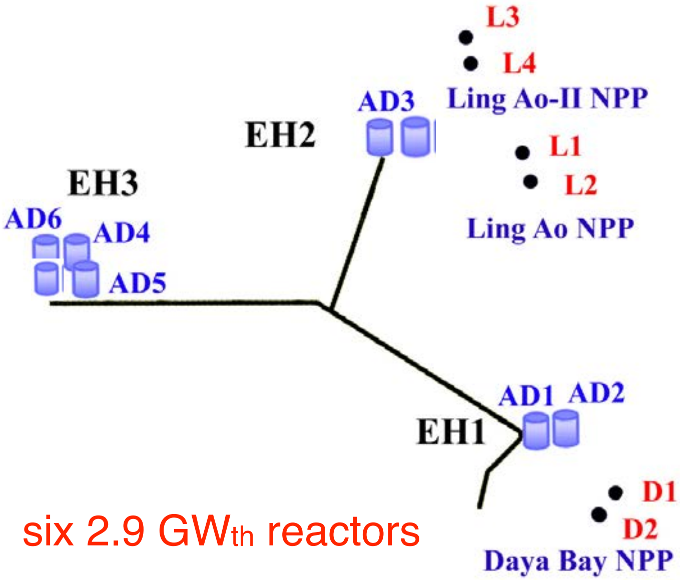
> 99.9% of $\bar{\nu}_e$ are produced by fissions in ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

mean energy of $\bar{\nu}_e$: 3.6 MeV

only disappearance experiments possible

Daya Bay Reactor Experiment



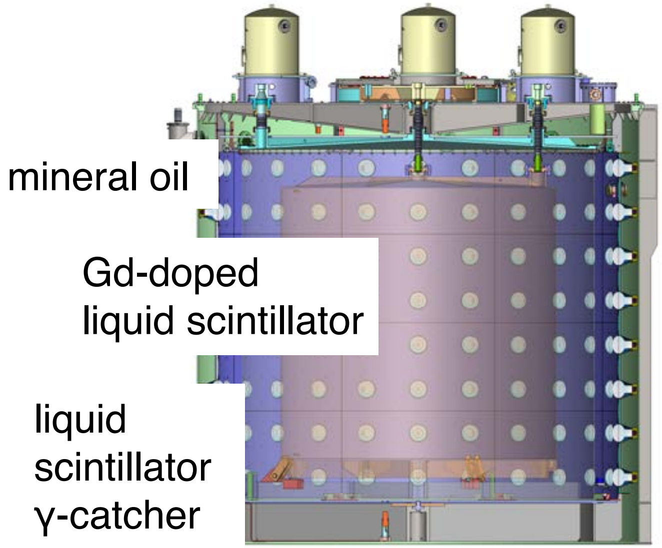


six 2.9 GW_{th} reactors

6 detectors, Dec 2011- Jul 2012

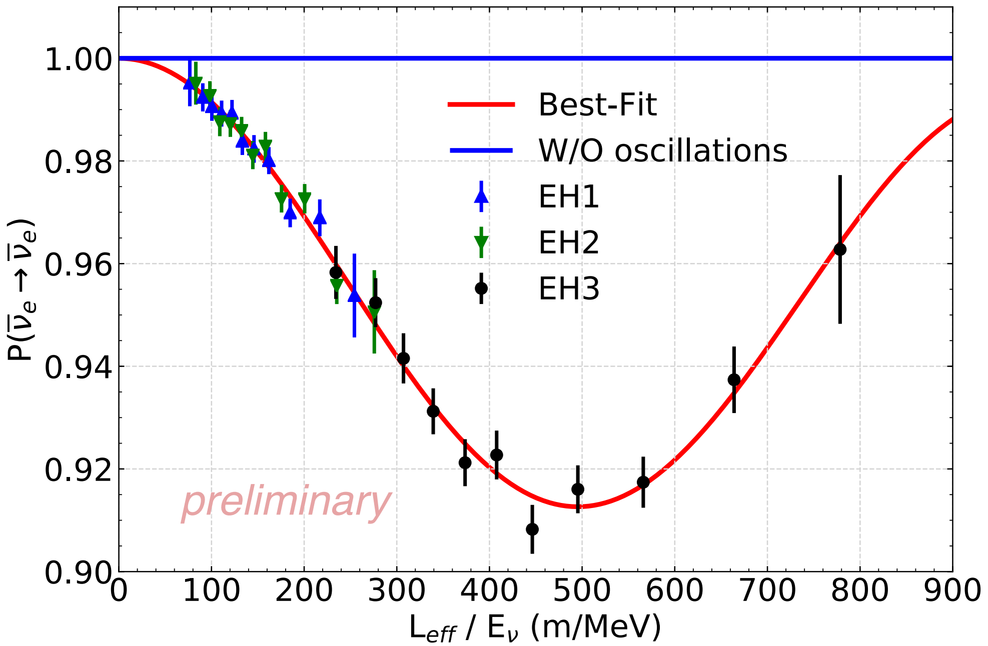
running with 8 detectors

Antineutrino Detector



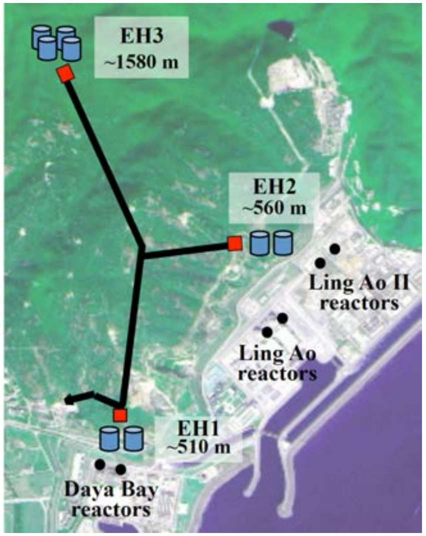
target mass: 20 ton per AD
photosensors: 192 8”-PMTs
energy resolution: $(7.5 / \sqrt{E} + 0.9)\%$

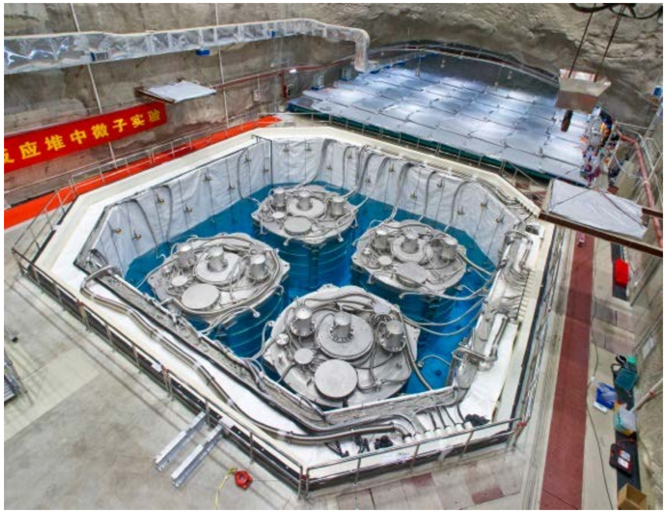
Daya Bay Neutrino Oscillation (1958 Days)



$$P_{i\rightarrow j} = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

Neutrino oscillation is energy and baseline dependent

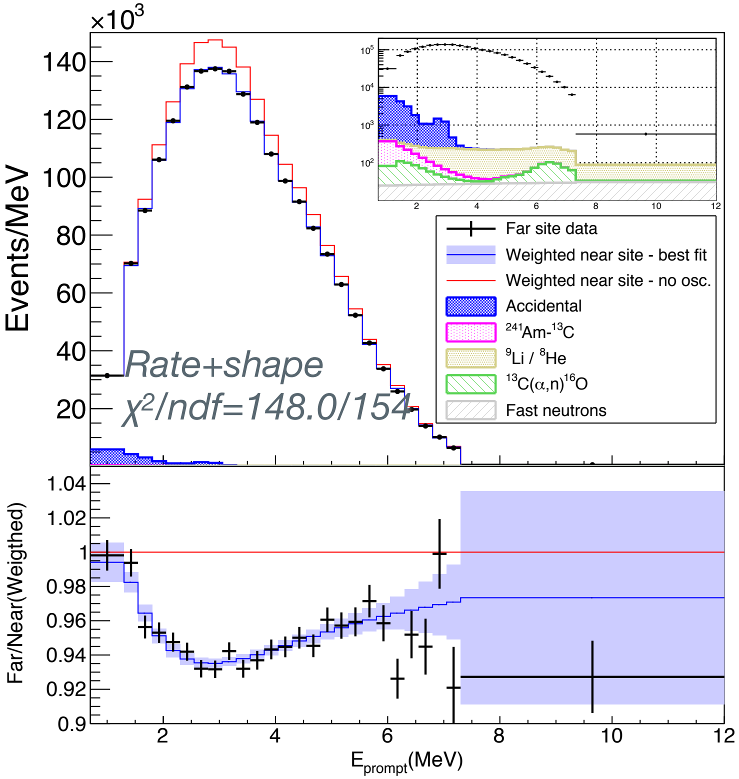


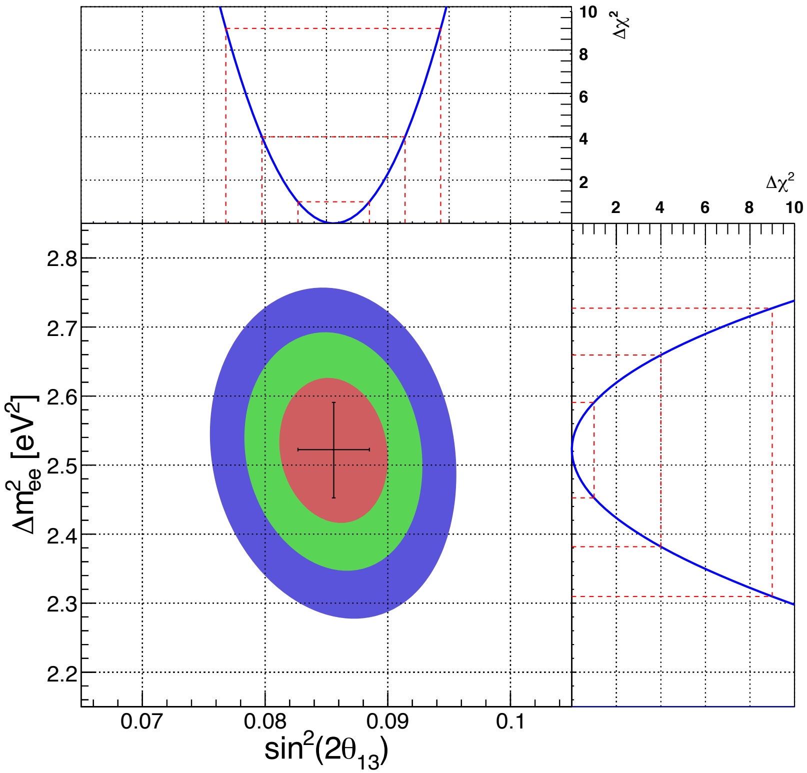


Phys. Rev D 95, 072006 (2017).
Daya Bay

Daya Bay Neutrino Oscillation (1958 Days)

nGd Analysis





Daya Bay
Phys.Rev.Lett. 121 (2018) no.24, 241805

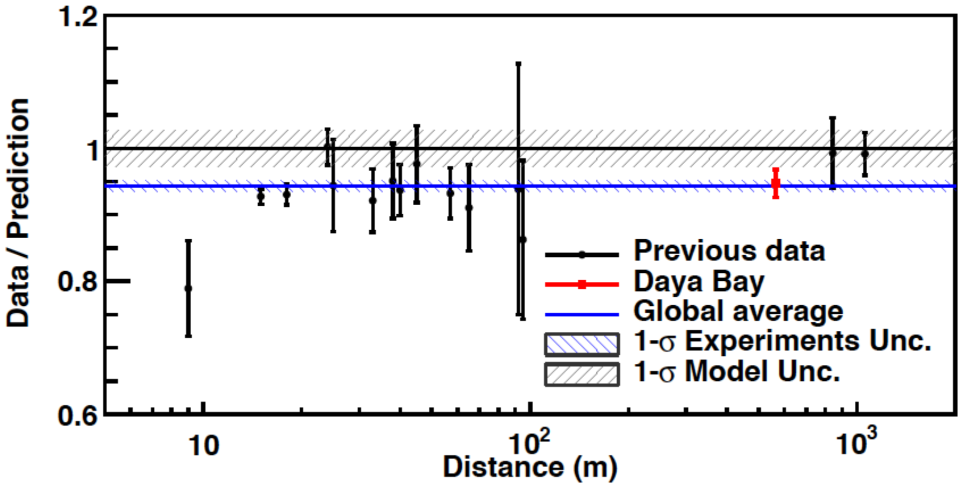
$\sin^2 2\theta_{13}$ uncertainty: 3.4%
$|\Delta m^2_{32}|$ uncertainty: 2.8%

$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$$

$$|\Delta m^2_{ee}| = (2.52 \pm 0.07) \times 10^{-3}\ \mathrm{eV}^2$$

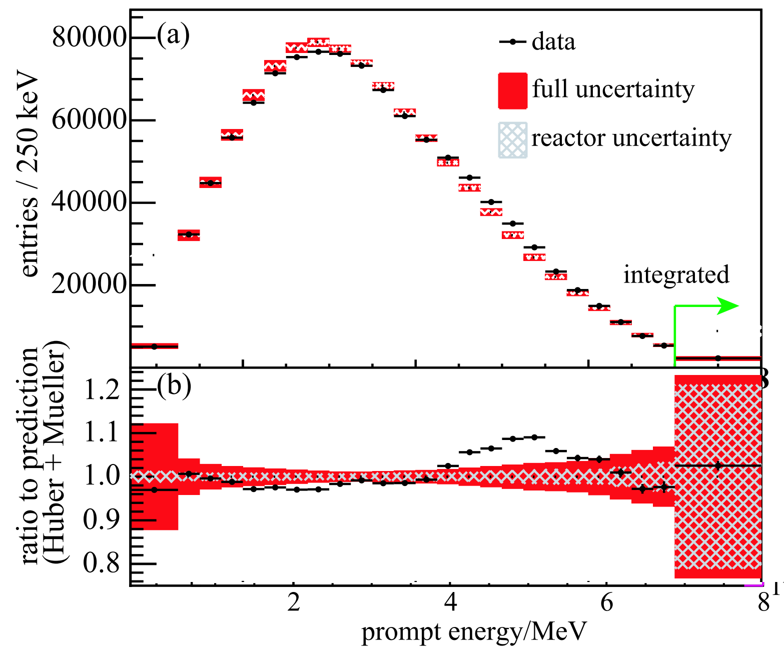
Reactor Antineutrino "Anomalies" (RAA)

Flux Deficit



Deficit due to extra (sterile) neutrino oscillations or artifact of flux predictions?

Spectral Deviation



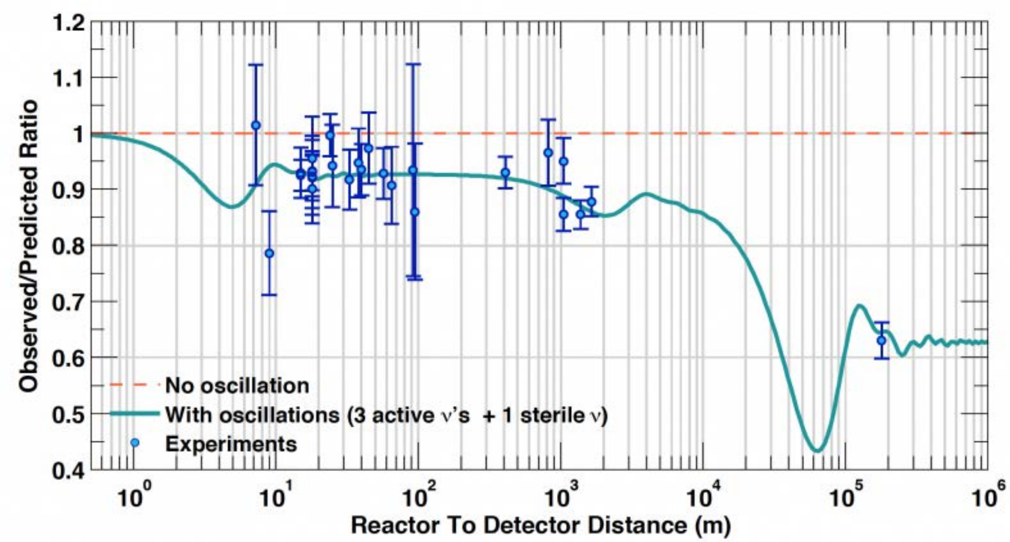
Measured spectrum does not agree with predictions.

Daya Bay, CPC 41, No. 1 (2017)

Understanding reactor flux and spectrum anomalies requires additional data

Reactor Antineutrino "Anomalies" (RAA)

Flux Deficit



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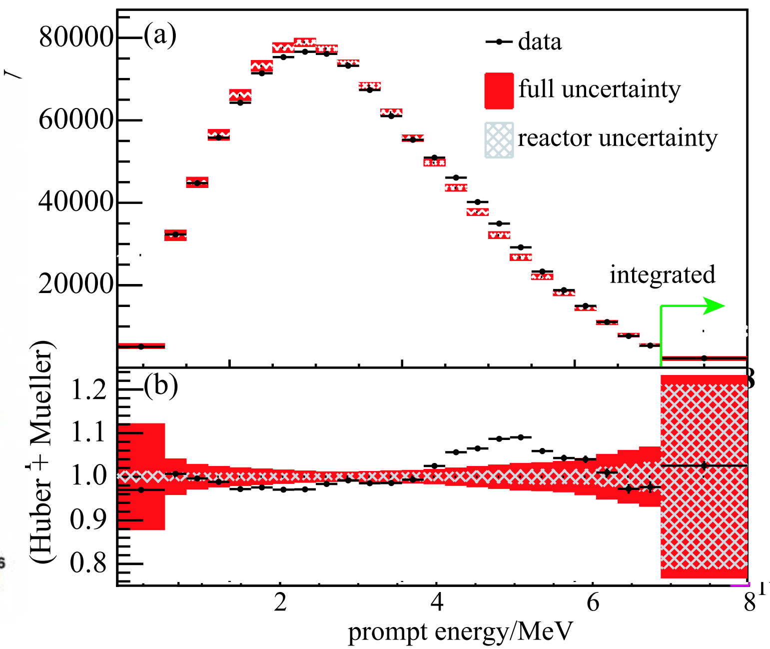


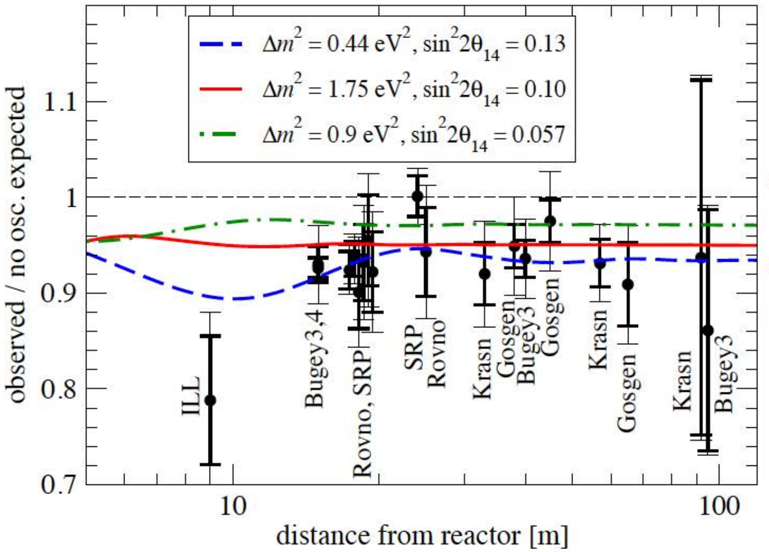
Measured spectrum does not agree with predictions.

Daya Bay, CPC 41, No. 1 (2017)

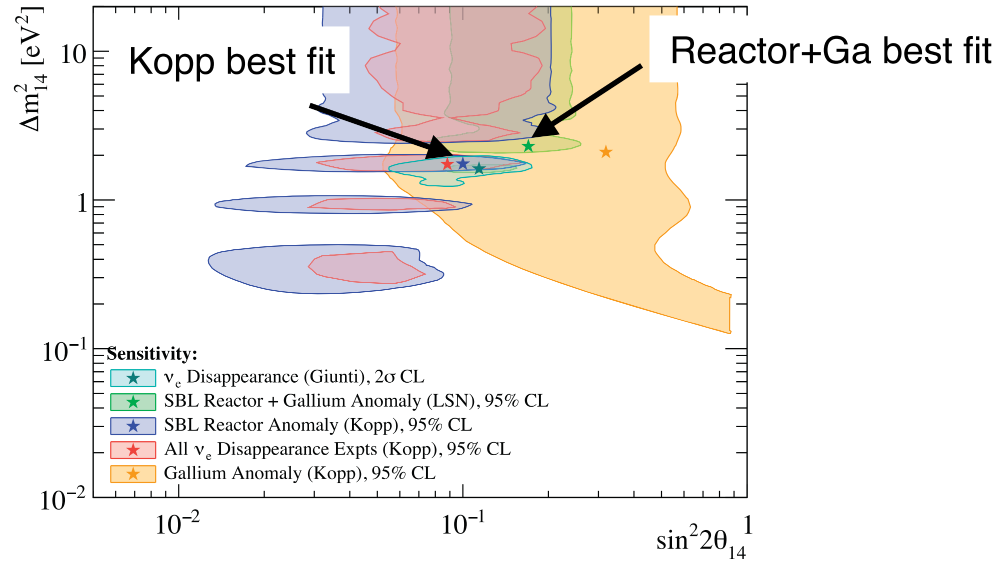
Understanding reactor flux and spectrum anomalies requires additional data

Reactor Antineutrino Flux Deficit

Reactor $\bar{\nu}_e$ flux measurements



$\bar{\nu}_e$ disappearance data



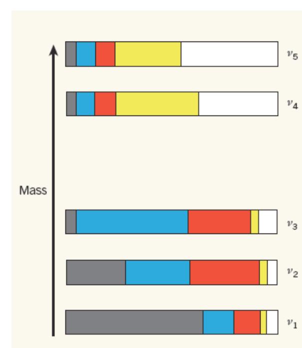
PROSPECT J. Phys. G: 43 (2016)

2011 reanalysis of the predicted reactor flux in tension with global data

Measurements of neutrino source with SAGE/Gallex also show a deficit

new oscillation signal requires:

$\Delta m^2 \sim O(1 eV^2)$ and $\sin^2 2\theta > 10^{-3}$
"sterile" neutrino states



$\Delta m^2_{new} \sim 1\ eV^2$

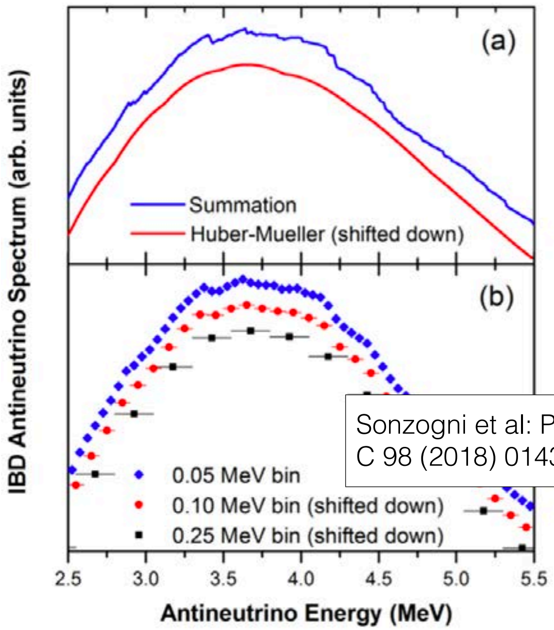
Predicting the Antineutrino Flux and Spectrum

Two major approaches

1. *Ab-initio*
   - sum the spectrum from thousands of beta branches using nuclear databases
   - databases incomplete and large uncertainties

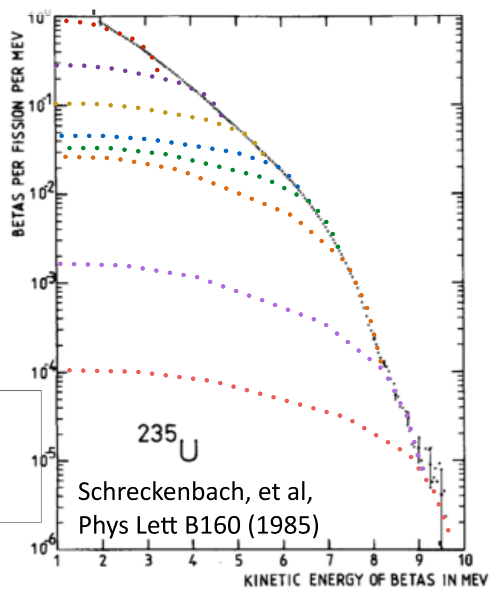
Decay Rate — Branching Fraction — Spectrum

$$S(E_{\bar{\nu}}) = \sum_{i=0}^{n} R_i \sum_{j=0}^{m} f_{ij} S_{ij}(E_{\bar{\nu}}).$$



Sonzogni et al: Phys Rev C 98 (2018) 014323

2. **Beta conversion**
   - empirical measurements of beta spectra for each isotope (foils, 1980's)
   - fit with 'virtual branches' and kinematically convert to antineutrino spectra

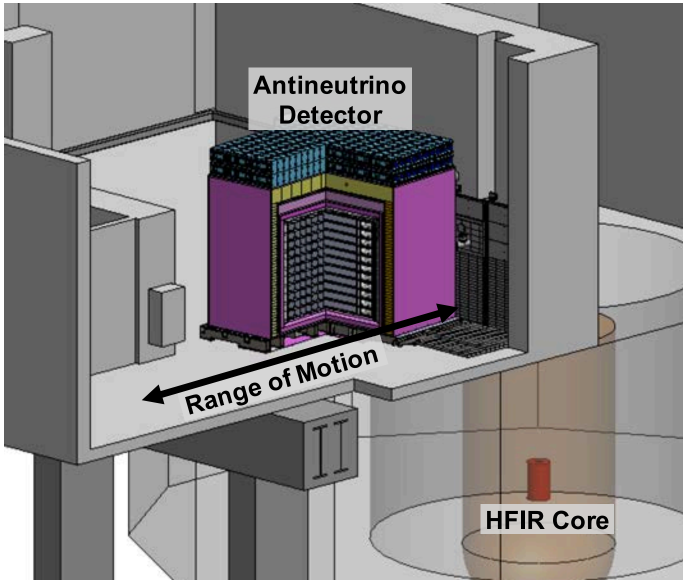


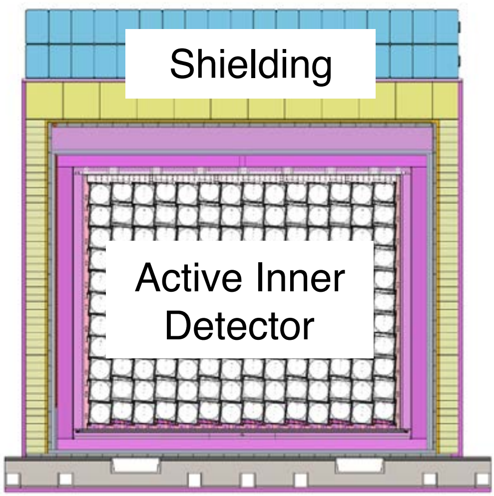
Schreckenbach, et al, Phys Lett B160 (1985)

Huber-Mueller model used as benchmark to experiment at LEU reactors: Phys. Rev. C 85, 029901 (2012) and Phys. Rev. C 83 (2011)

predicting reactor spectra is complicated, nuclear physics uncertainties

Precision Oscillation and Spectrum Experiment



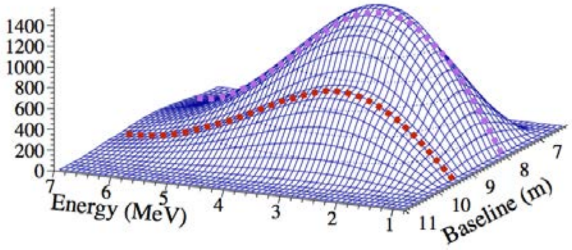


Objectives **Search for short-baseline oscillation at <10m**
Precision measurement of ^{235}U reactor $\overline{\nu}_e$ spectrum

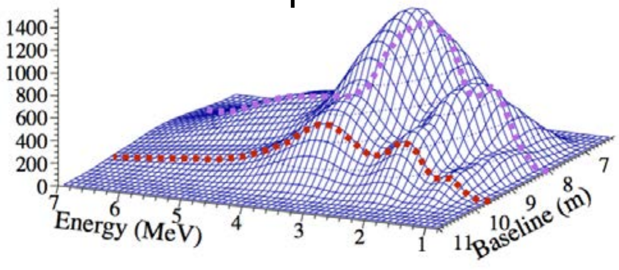
Relative Spectrum Measurement
relative measurement of L/E and spectral shape distortions

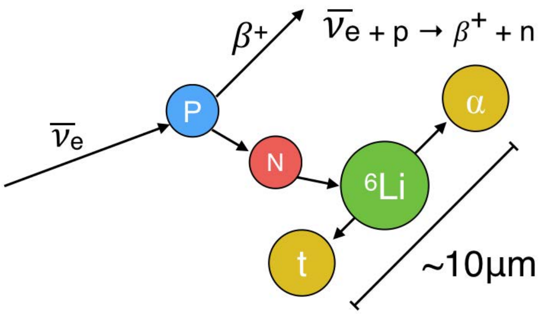
Segmented, ^{6}Li-loaded Detector

unoscillated spectrum

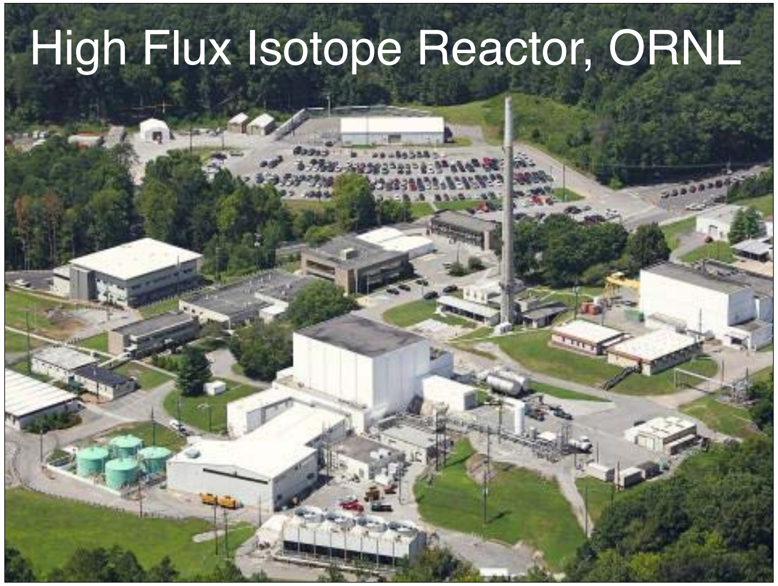


oscillated spectrum





Experimental Site



Reactor Core

Power: 85 MW
Core shape: cylindrical
Size: h=0.5m r=0.2m
Duty-cycle: 46%, 7 cycles/yr, 24 days
Fuel: HEU (^{235}U)

compact reactor core,
detector near surface,
little overburden

highly-enriched (HEU): >99% of $\overline{\nu}_e$ flux from ^{235}U fission

PROSPECT Detector Design

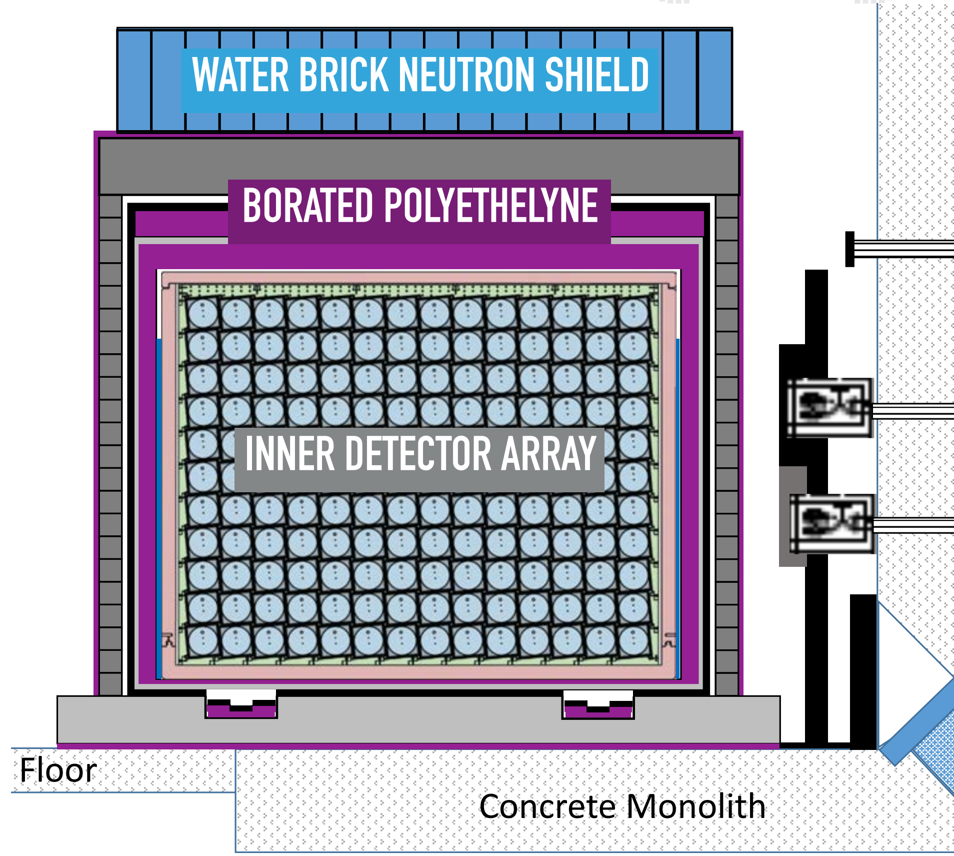
Single 4,000 L **^{6}Li-loaded liquid scintillator** (3,000 L fiducial volume)

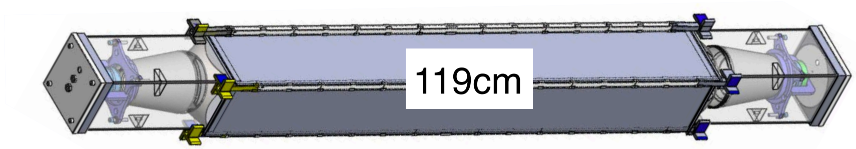
11 x 14 (154) **array of optically separated segments**

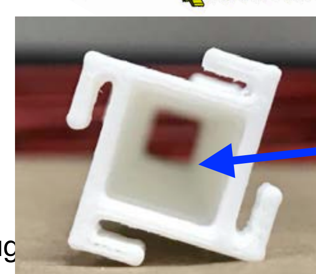
Very low mass separators (1.5 mm thick)
- Corner support rods allow for full *in situ* calibration access

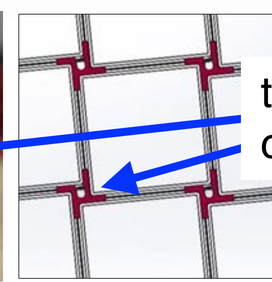
Double ended PMT readout, with light concentrators
- good light collection and energy response
- ~5%√E energy resolution
- full X,Y,Z event reconstruction

Optimized shielding to reduce cosmogenic backgrounds





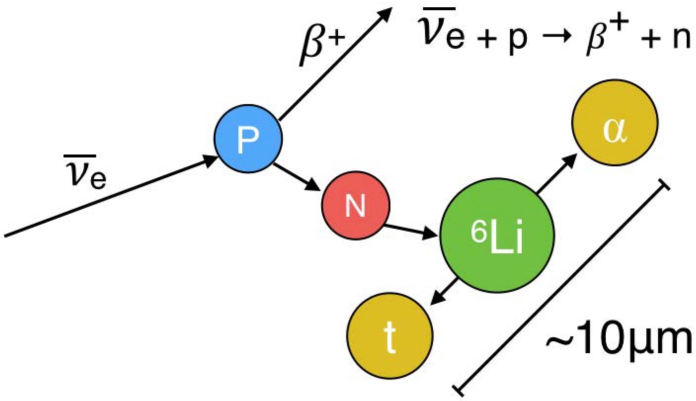




tilted array for calibration access

Antineutrino Event Identification with ^{6}Li

Inverse Beta Decay

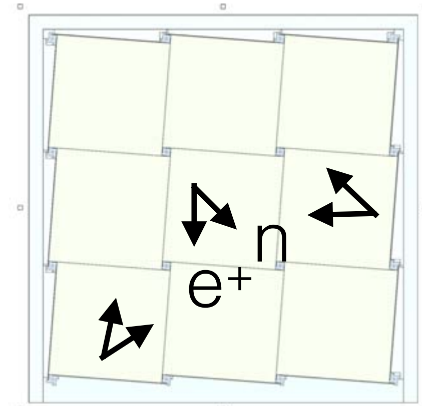


40μs delayed n capture

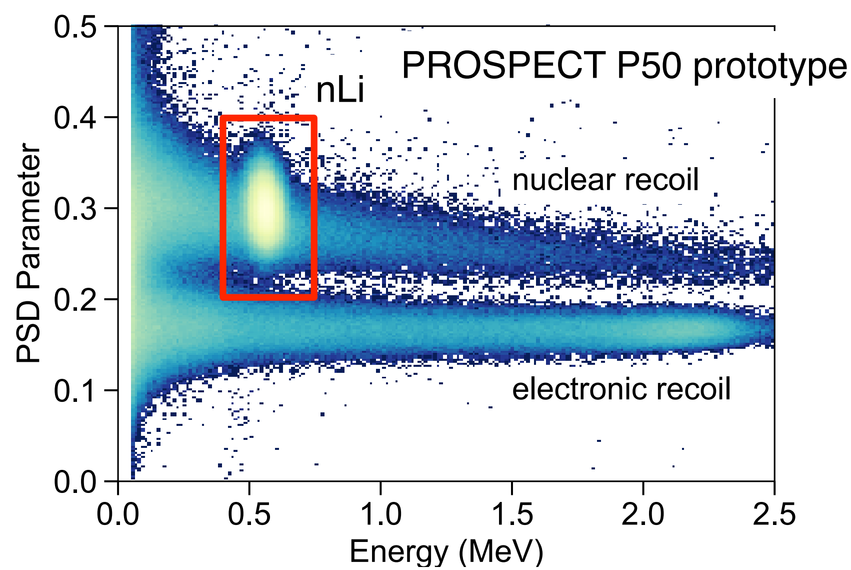
Background Reduction

detector design & fiducialization

IBD event in segmented ^{6}LiLS detector



Pulse Shape Discrimination



signal — inverse beta decay (IBD)
γ-like prompt, n-like delay

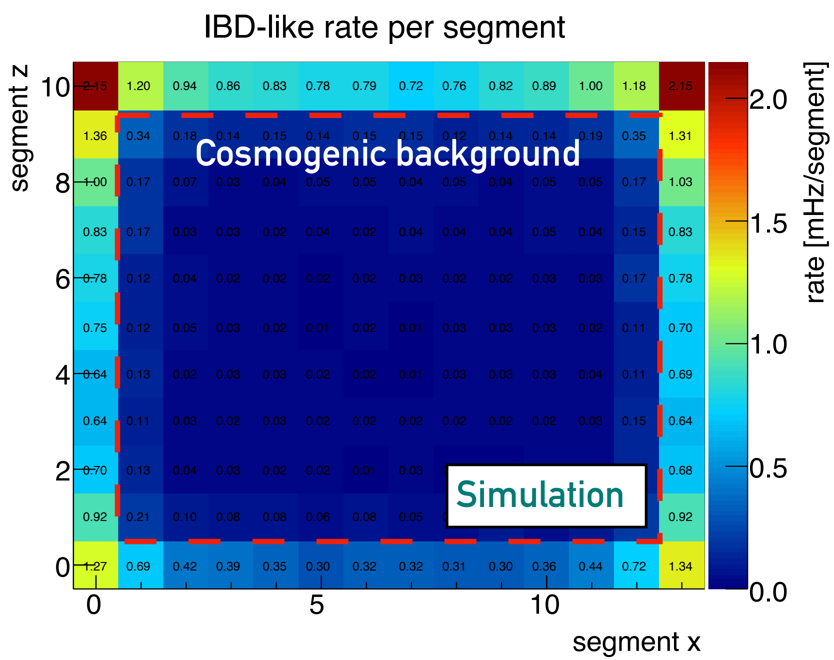
backgrounds — fast neutron
n-like prompt, n-like delay

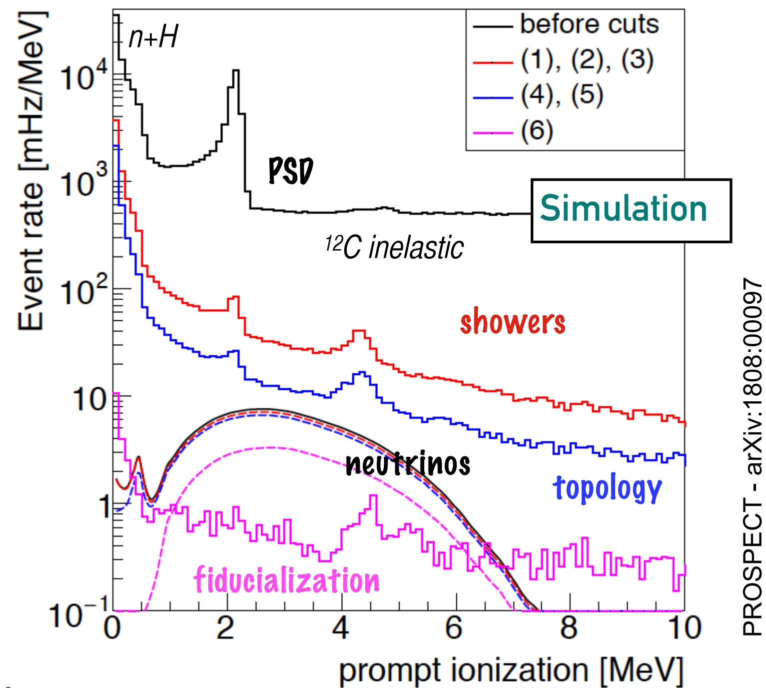
accidental gamma
γ-like prompt, γ-like delay

Background reduction is key challenge

PROSPECT,arXiv:1805.09245

Background Rejection





Detector design further optimized for background rejection

A sequence of cuts leveraging spatial and timing characteristics of an IBD *yields > 10^4 background suppression and signal to background of > 1:1.*

Rate and shape of residual IBD-like background can be measured during multiple interlaced reactor-off periods.

Combine:

- PSD
- Shower veto
- Event topology
- Fiducialization

Assembly in 30s (video)

Assembly of First Row
November 1, 2017

Wright Laboratory

Final Row Installation
November 17, 2017

Wright Laboratory

First Oscillation Analysis Data Set

33 days of Reactor On

28 days of Reactor Off

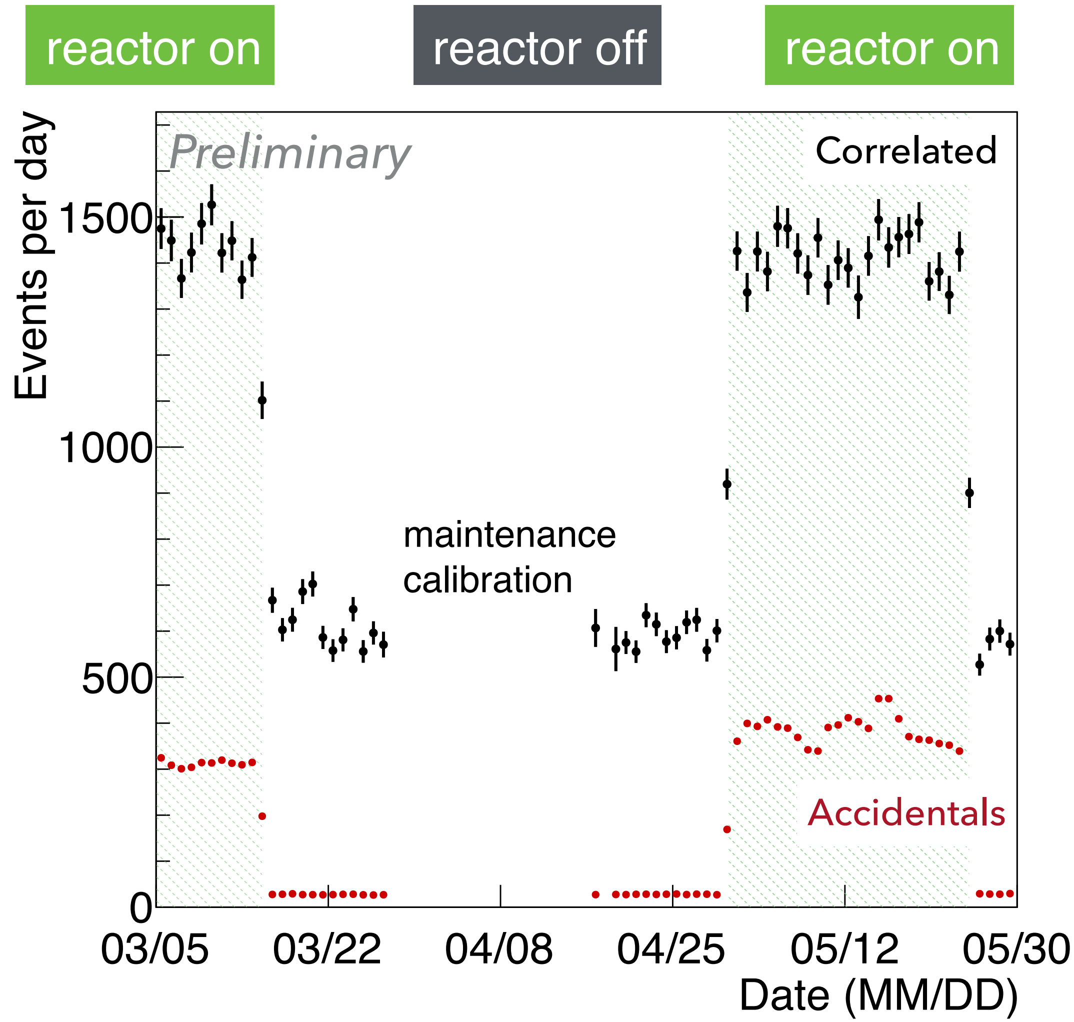
Correlated S/B = 1.36

Accidental S/B = 2.25

24,608 IBDs detected

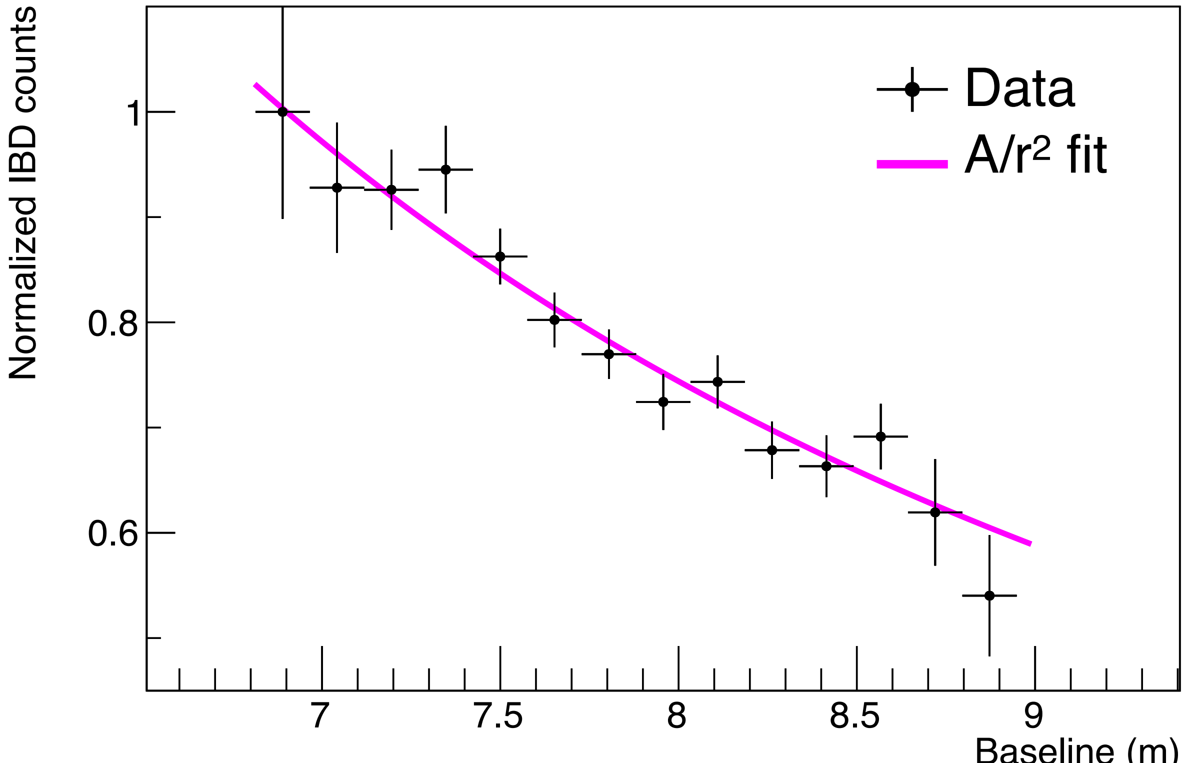
Average of ~750 IBDs/day

IBD event selection defined and frozen on 3 days of data



Phys.Rev.Lett. 121 (2018) no.25, 251802
PROSPECT Collaboration

Neutrino Rate vs Baseline



Phys.Rev.Lett. 121 (2018) no.25, 251802
PROSPECT Collaboration

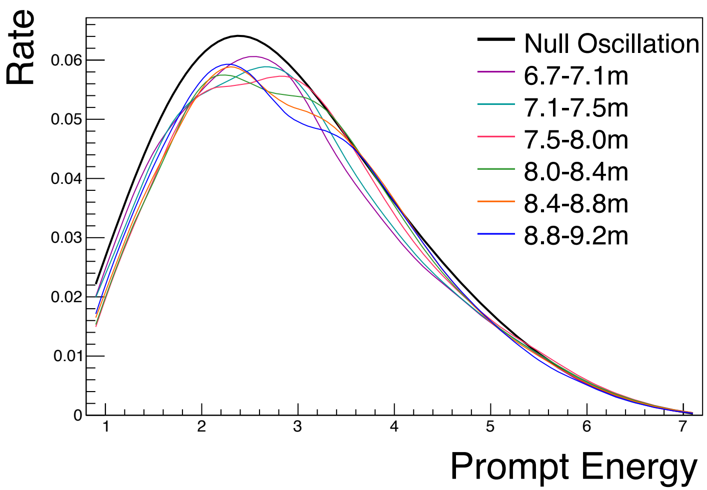
Observation of $1/r^2$ behavior throughout detector volume

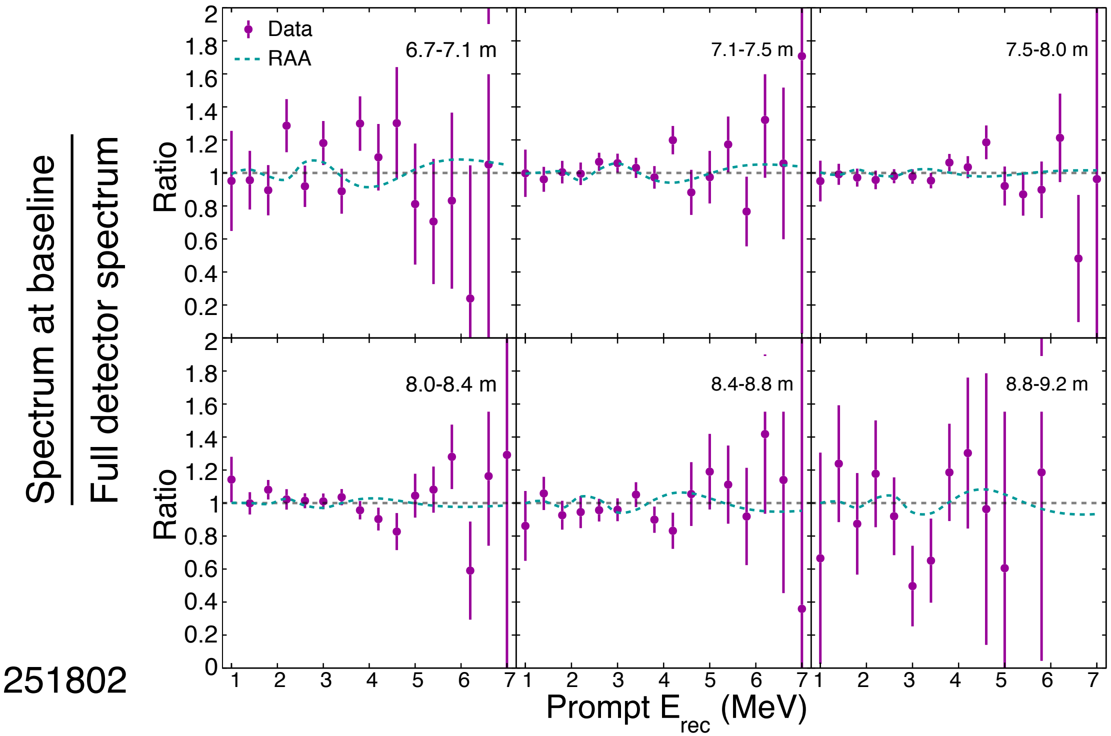
Bin events from 108 fiducial segments into 14 baseline bins

40% flux decrease from front of detector to back

Neutrino Spectrum vs Baseline

Spectral Distortion vs Baseline





Phys.Rev.Lett. 121 (2018) no.25, 251802
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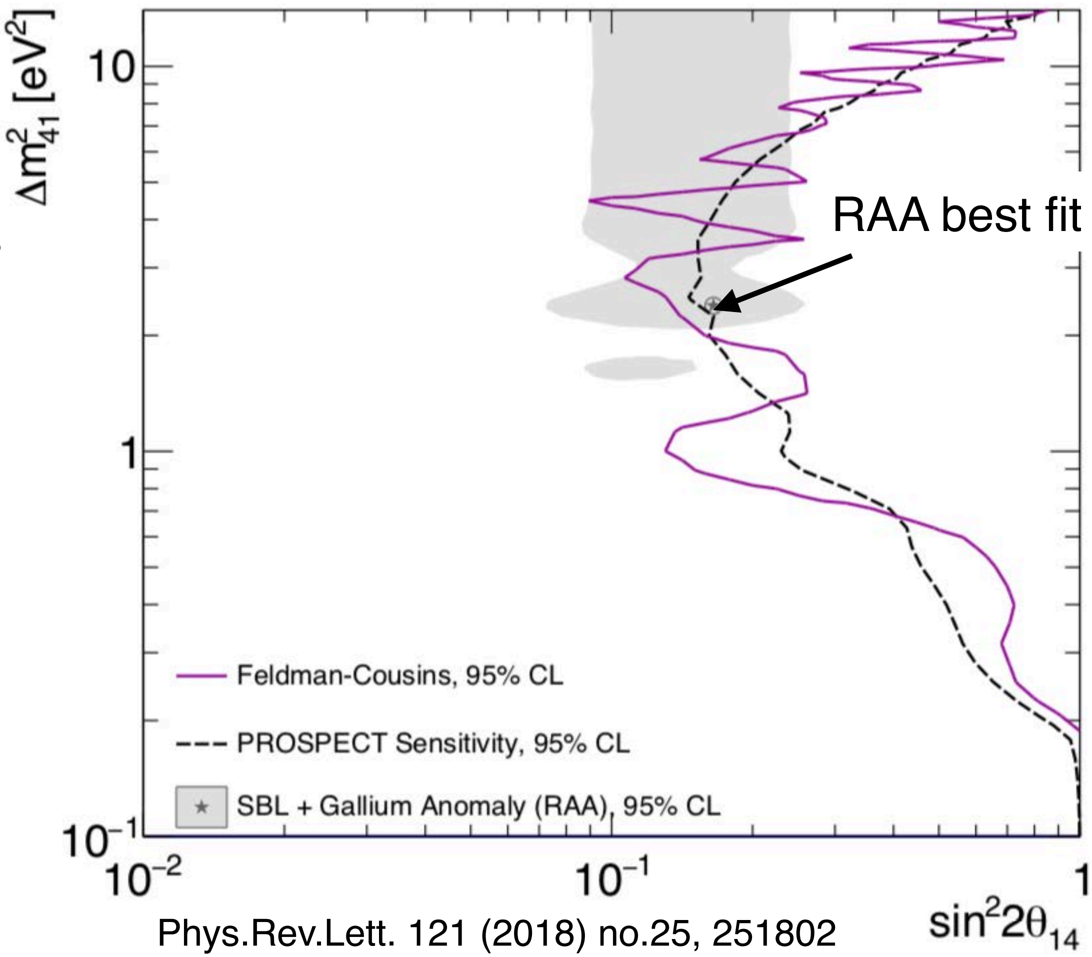
Compare spectra from 6 baselines to measured full-detector spectrum

Null-oscillation would yield a flat ratio for all baselines

Direct ratio search for oscillations, reactor model independent

Oscillation Search Results

- Feldman-Cousins based confidence intervals for oscillation search
- Covariance matrices captures all uncertainties and energy/ baseline correlations
- Critical χ^2 map generated from toy MC using full covariance matrix
- 95% exclusion curve based on 33 days Reactor On operation
- **Direct test of the Reactor Antineutrino Anomaly**



Phys.Rev.Lett. 121 (2018) no.25, 251802
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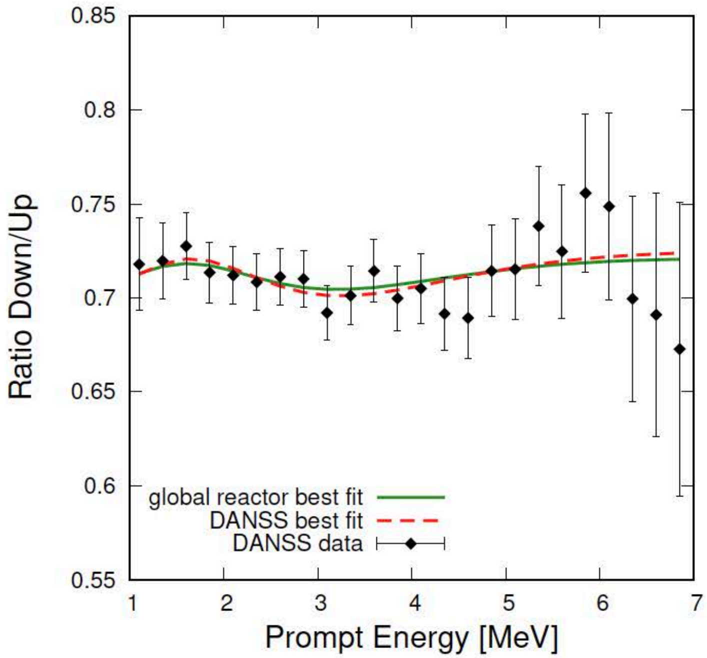
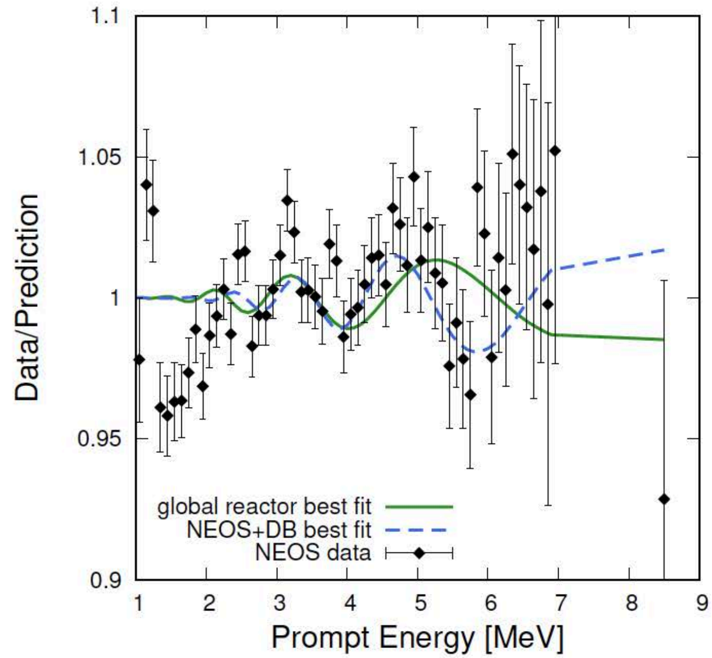
Disfavors RAA best-fit point at >95% CL (2.2σ)

DANSS, NEOS





DANSS: relative spectra @ detector locations with $L = 10.7$ and 12.7 m

NEOS: spectrum at $L = 24$ m, relative to prediction based on Daya Bay near detector spectrum

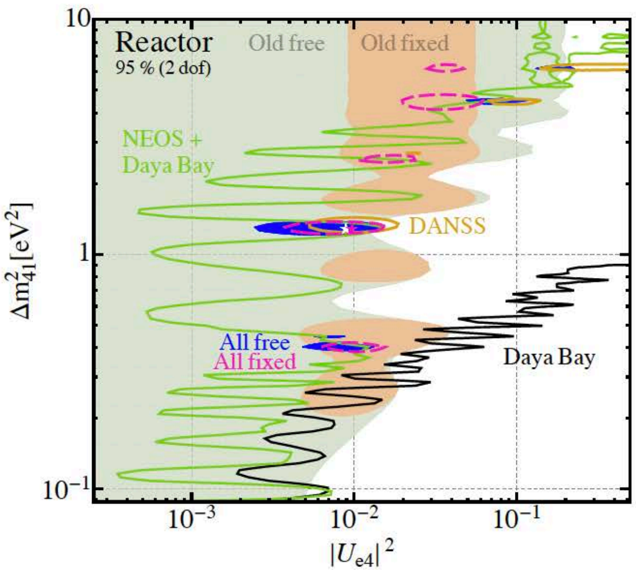
T. Schwetz

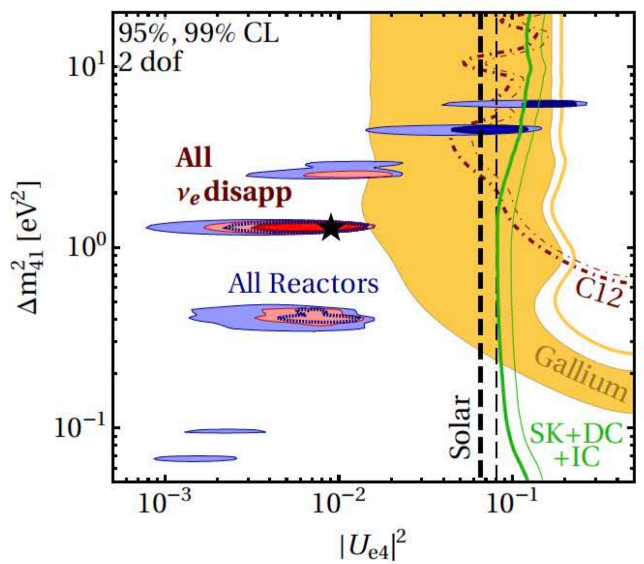
Note: Discovery requires unambiguous experimental signature
No published experiment has claimed an oscillation signal

Combined $\overline{\nu}_e$ Disappearance Analysis

Analysis	Δm^2_{41} [eV^2]	$\|U^2_{e4}\|$	χ^2_{min}/dof	$\Delta\chi^2$(no-osc)	significance
DANSS+NEOS	1.3	0.00964	74.4/(84 − 2)	13.6	3.3σ
all reactor (flux-free)	1.3	0.00887	185.8/(233 − 5)	11.5	2.9σ
all reactor (flux-fixed)	1.3	0.00964	196.0/(233 − 3)	15.5	3.5σ
$\overset{(-)}{\nu}_e$ disap. (flux-free)	1.3	0.00901	542.9/(594 − 8)	13.4	3.2σ
$\overset{(-)}{\nu}_e$ disap. (flux-fixed)	1.3	0.0102	552.8/(594 − 6)	17.5	3.8σ

Dentler et al., 1803.10661





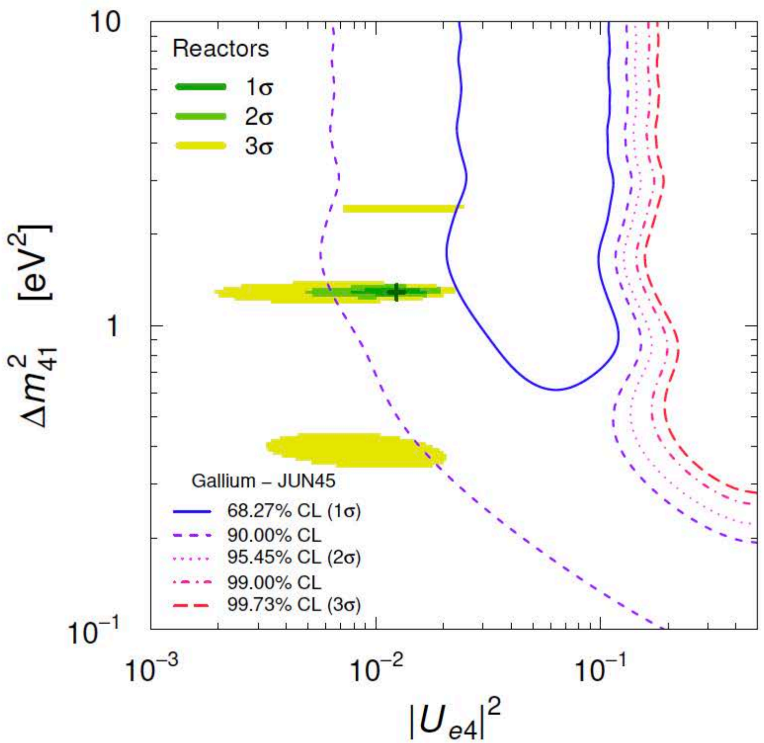
~3σ hint for sterile neutrino oscillations, independent of reactor flux calculations!

T. Schwetz

Update on Ga Anomaly

- improved shell-model cross section calculations
- significance decreases $3.0\sigma \rightarrow 2.3\sigma$
- smaller mixing angles, consistent with DANSS/NEOS spectral distortions

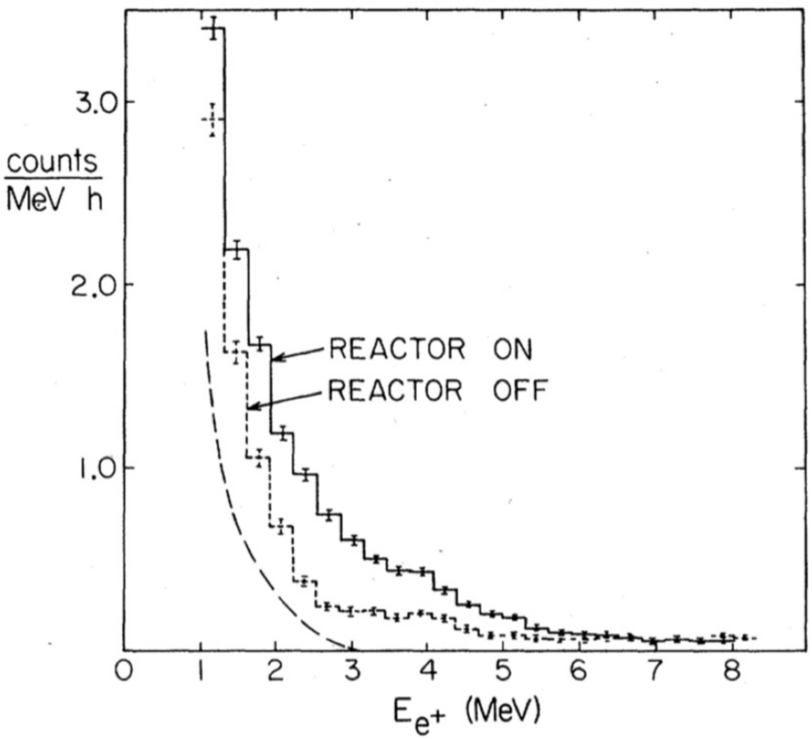
Kostensalo, Suhonen, Giunti, Srivastava, 1906.10980

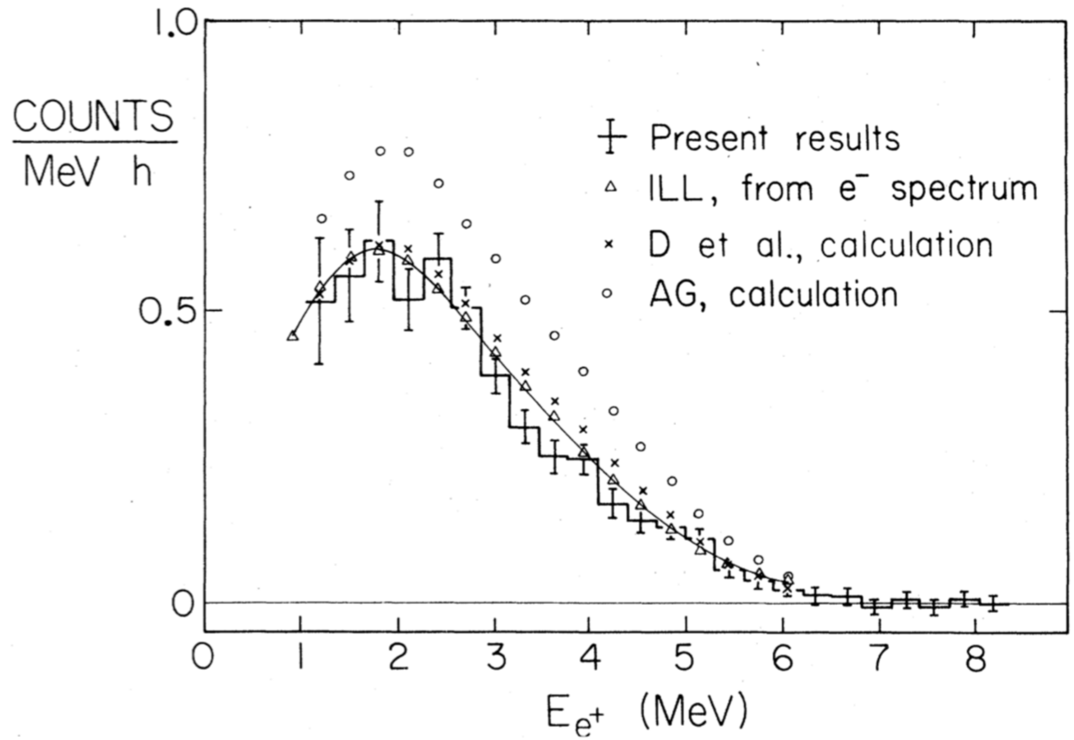


T. Schwetz

^{235}U Antineutrino Spectrum

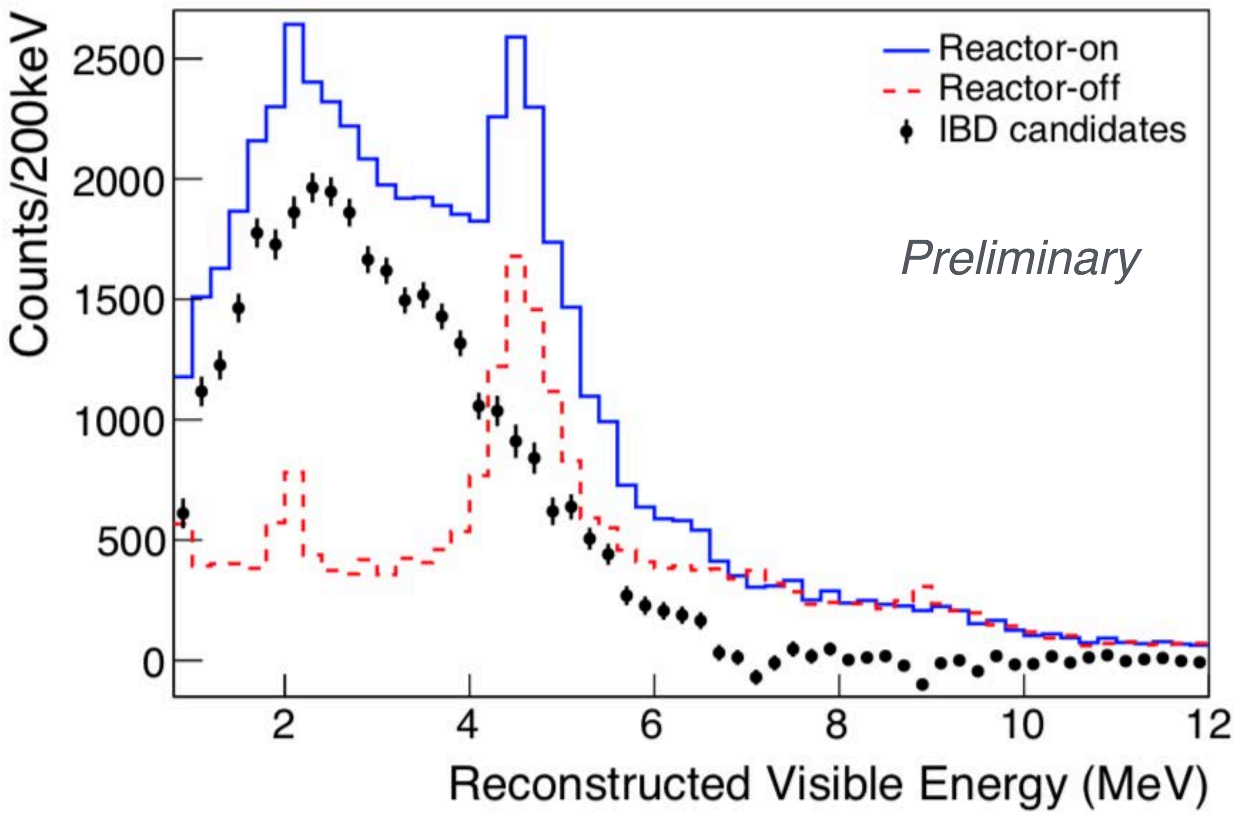
only existing measurement from 1981 ILL experiment, 5000 events





Measurement of ^{235}U Spectrum

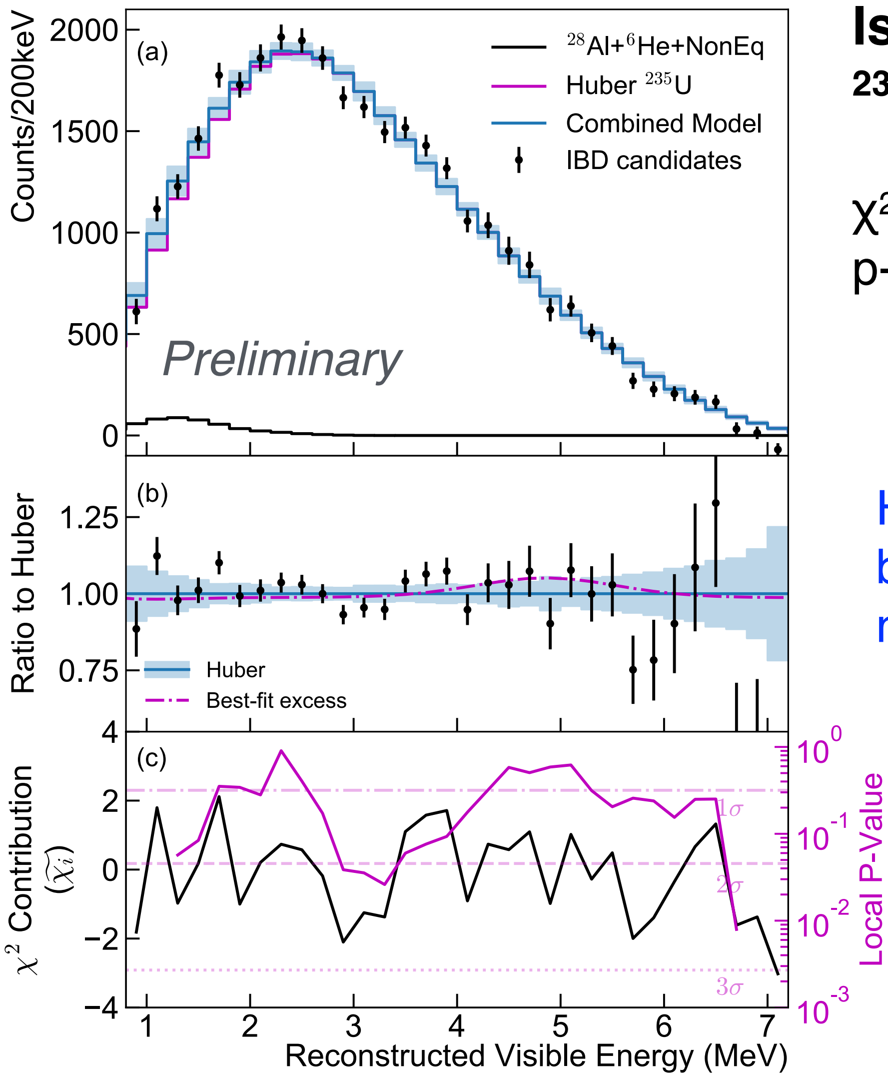
Prompt Energy Spectrum



40.2 days of reactor-on exposure, 37.8 days of reactor-off exposure
~ 31,000 IBD candidate events (reactor-off candidate events scaled to match exposure)

measured spectrum with good S/B at surface 1.7/1 (0.8-7.2 MeV)
~ 6x greater statistics than ILL (1981)

Prompt Energy Spectrum



Is PROSPECT consistent with Huber ^{235}U model for HFIR HEU reactor?

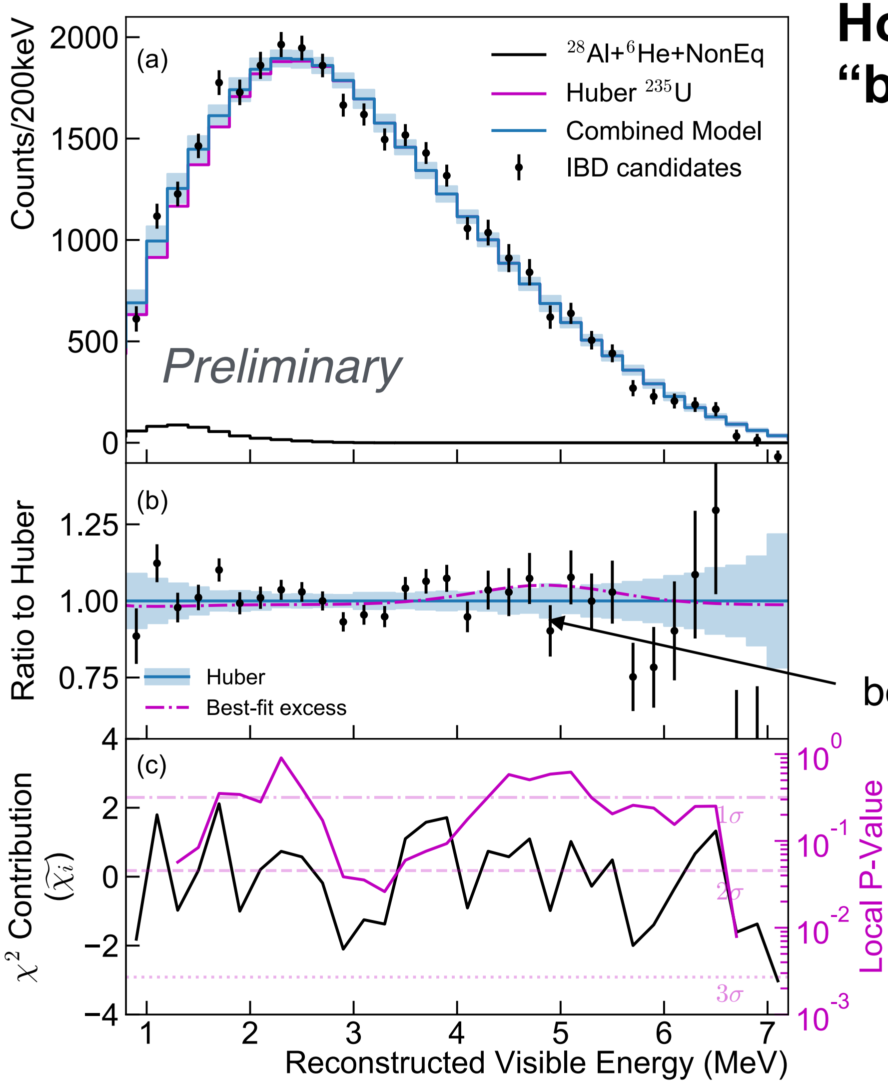
χ^2/ndf = 52.1/31
p-value = 0.01

Huber model broadly agrees with spectrum but exhibits large χ^2/ndf with respect to measured spectrum, not a good fit.

Deviations mostly in two energy regions.

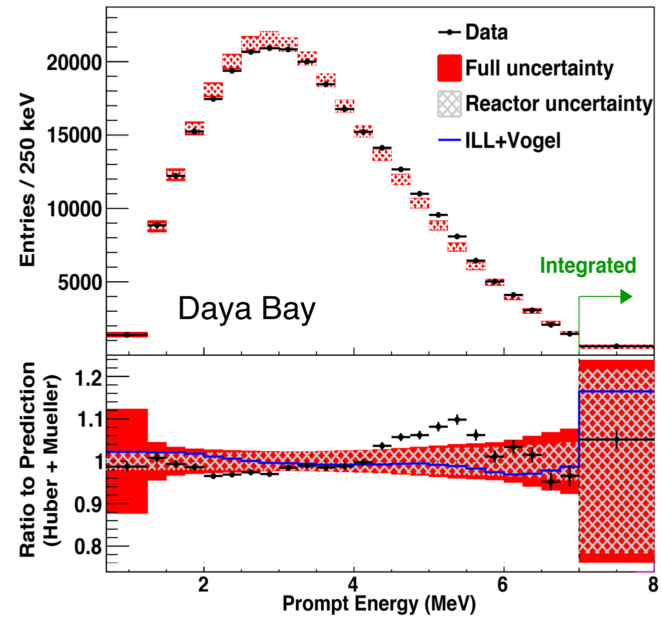
Statistics limited measurement.

Prompt Energy Spectrum



best-fit excess

How does PROSPECT compare to "bump" in θ_{13} experiments?



Shape of measured ^{235}U spectrum not inconsistent with the deviation relative to prediction observed at LEU reactors.

Summary

Daya Bay has made a high-precision measurement of the prompt energy spectrum from PWR reactor. Suggests **incorrect prediction of the ^{235}U flux as the primary source of the reactor antineutrino rate anomaly**.

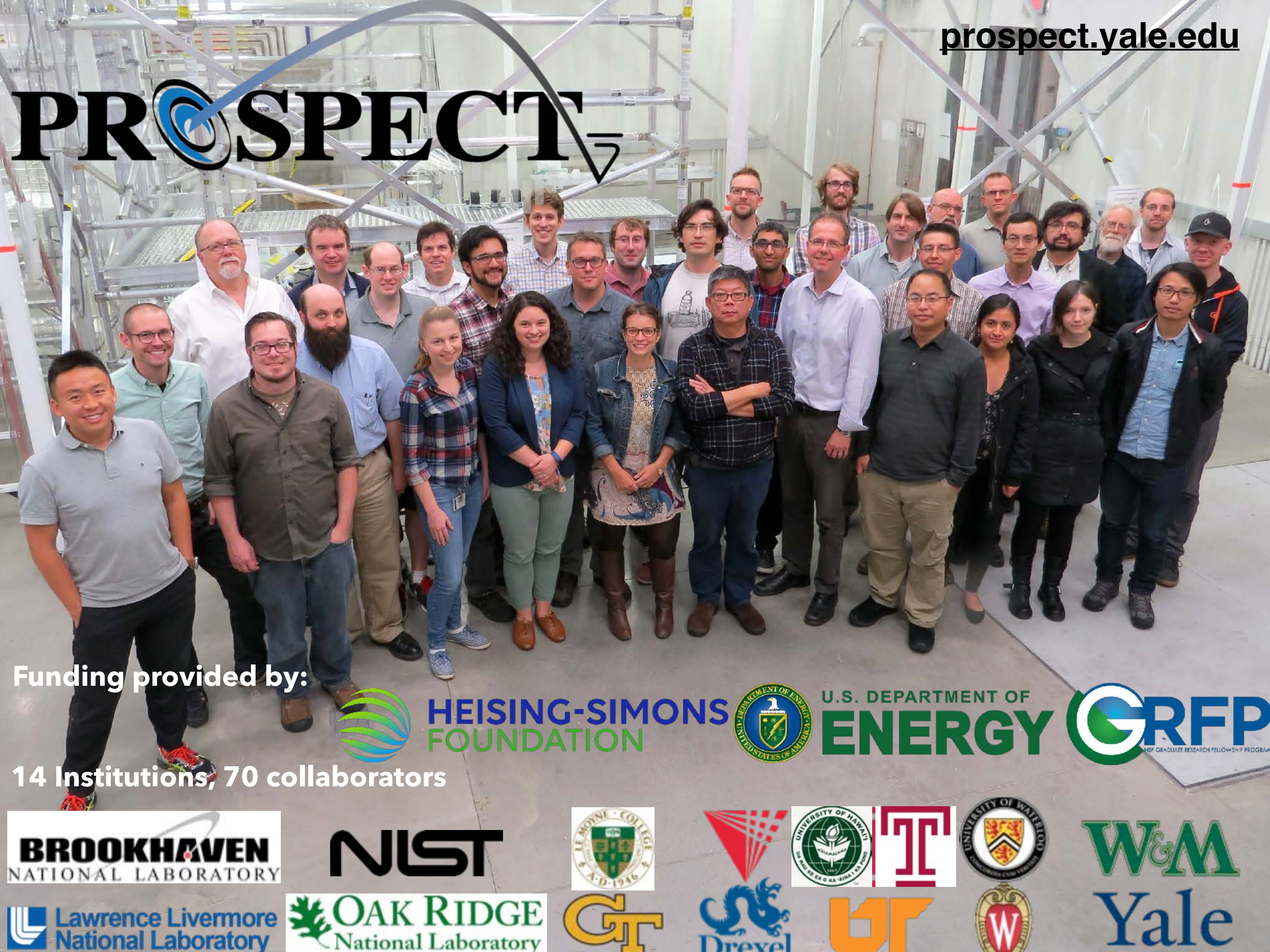
With a surface-based detector, PROSPECT has made a modern measurement of ^{235}U antineutrino spectrum from HEU reactor. Statistics limits conclusion on spectral deviation in ^{235}U.

PROSPECT has world-leading signal-to-background for a surface-based detector (<1 mwe overburden). Observed antineutrinos from HFIR with good signal/background.

PROSPECT First oscillation analysis on 33 days of reactor-on data disfavors the RAA best-fit at 2.2σ (based on model-independent measurement).

Based on results from PROSPECT and Daya Bay sterile neutrinos are increasingly disfavored. Global fits still allow sterile neutrinos.

Need more statistics! Have started joint analysis between Daya Bay and PROSPECT.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PROSPECT
Funding provided by:
HEISING-SIMONS FOUNDATION
U.S. DEPARTMENT OF ENERGY
GRFP
NSF GRADUATE RESEARCH FELLOWSHIP PROGRAM
14 Institutions, 70 collaborators
BROOKHAVEN NATIONAL LABORATORY
NIST
Lawrence Livermore National Laboratory
OAK RIDGE National Laboratory
W&M
Yale