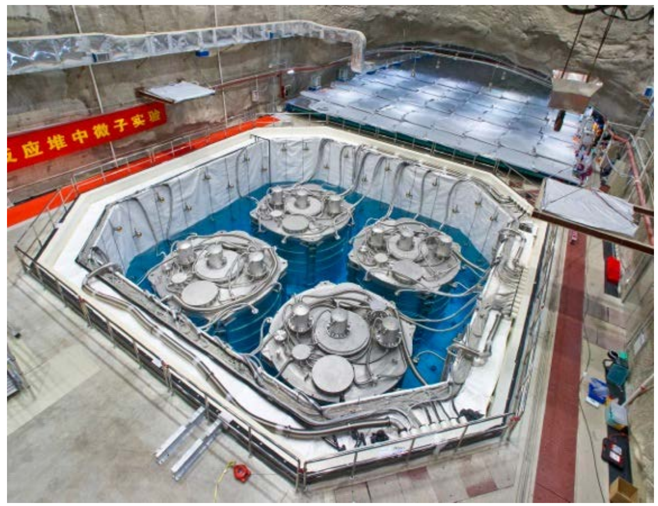
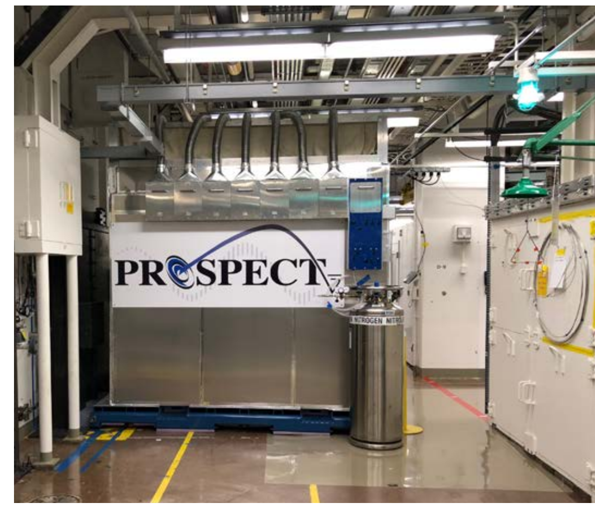
Precision Studies with Reactor Neutrinos

Understanding Flux and Spectrum





Karsten M. Heeger
Yale University

June 27, 2019

Wright Laboratory

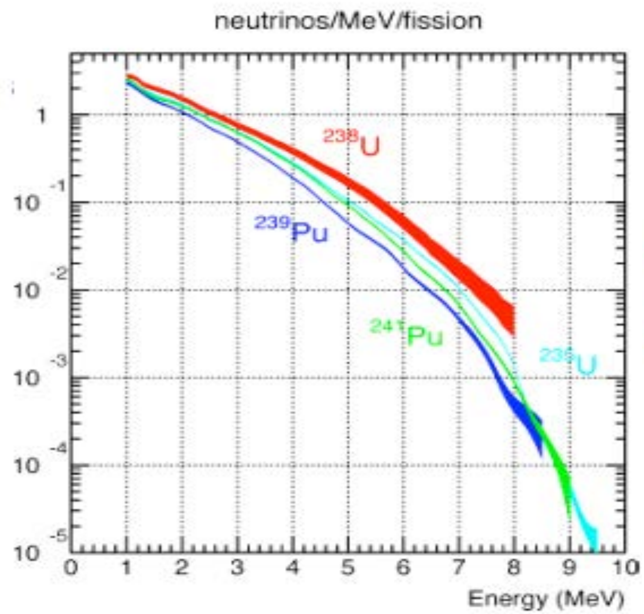
Yale

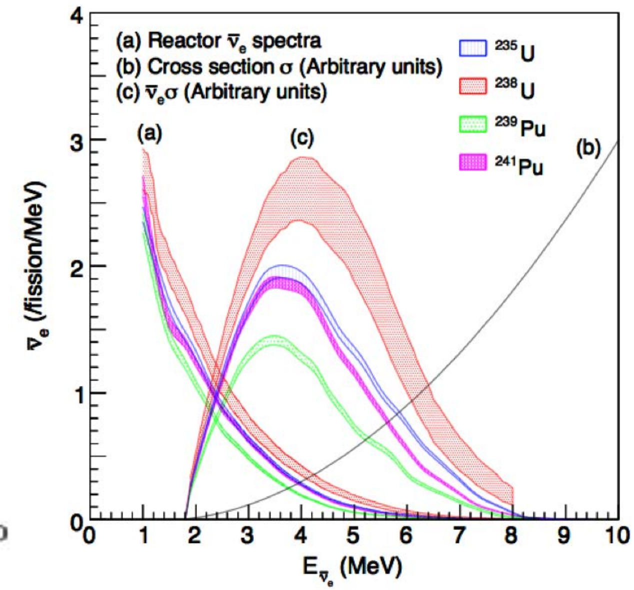
Reactor Antineutrinos

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

of n-rich fission products

on average ~6 beta decays until stable



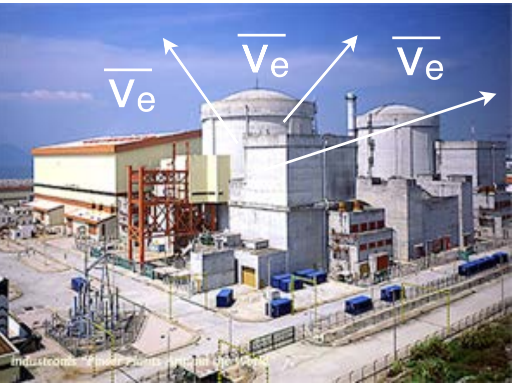


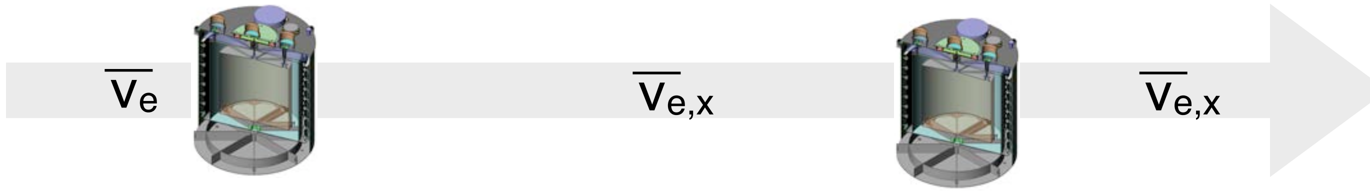
> 99.9% of $\bar{\nu}_e$ are produced by fissions in ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

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

only disappearance experiments possible

Relative Measurement of $\overline{\nu}_e$ Flux and Spectrum

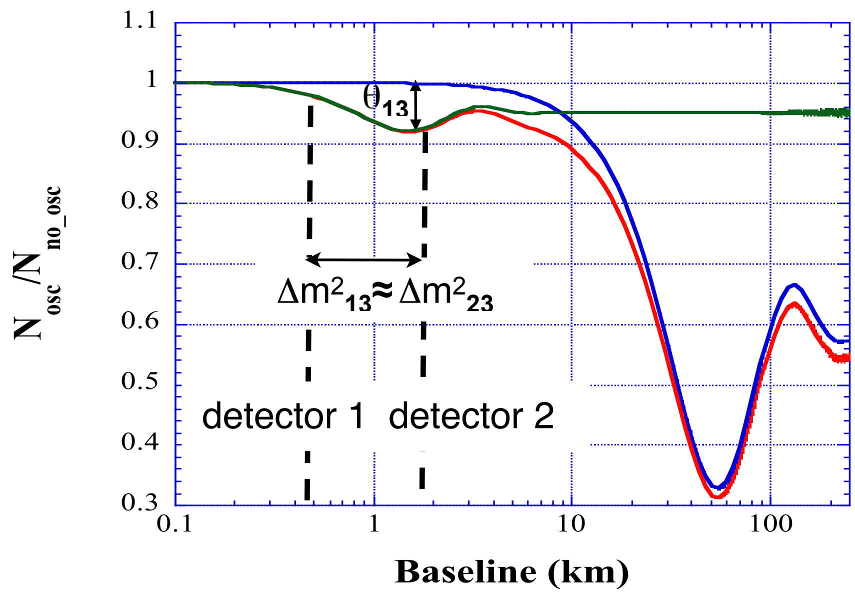




$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

Absolute Reactor Flux
Largest uncertainty in previous measurements

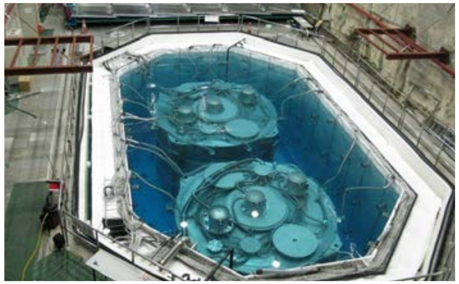
Relative Measurement
Removes absolute uncertainties!

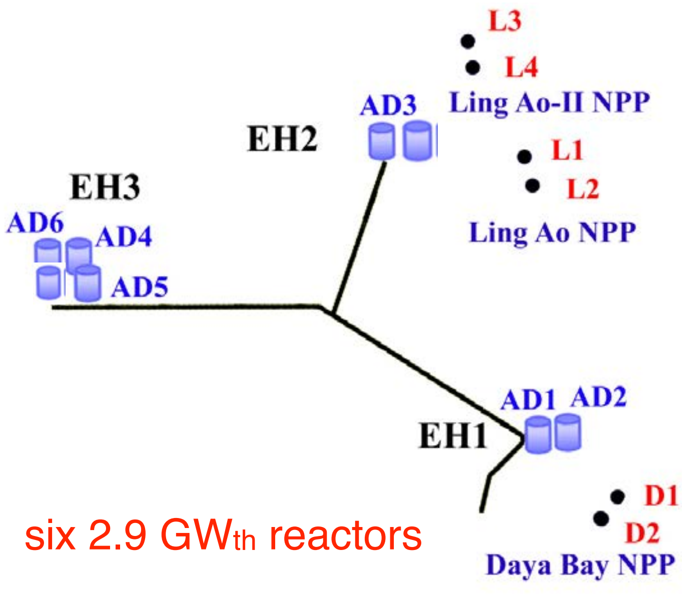


relative measurement (largely) cancels reactor systematics

Daya Bay Reactor Experiment

Experimental Hall



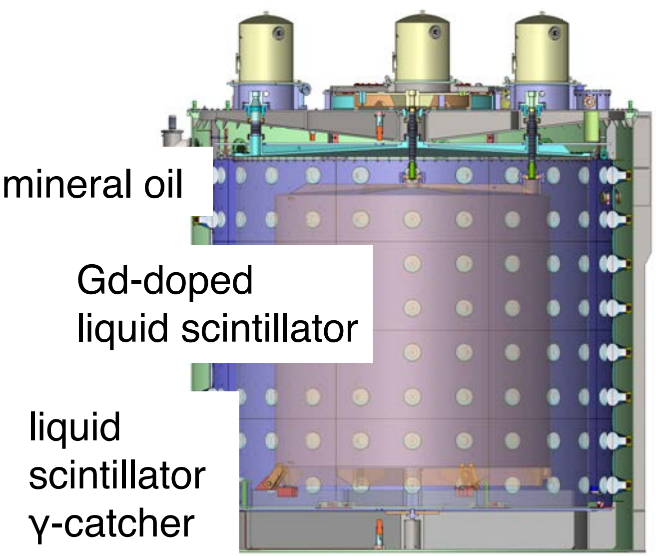


six 2.9 GW_{th} reactors

6 detectors, Dec 2011- Jul 2012

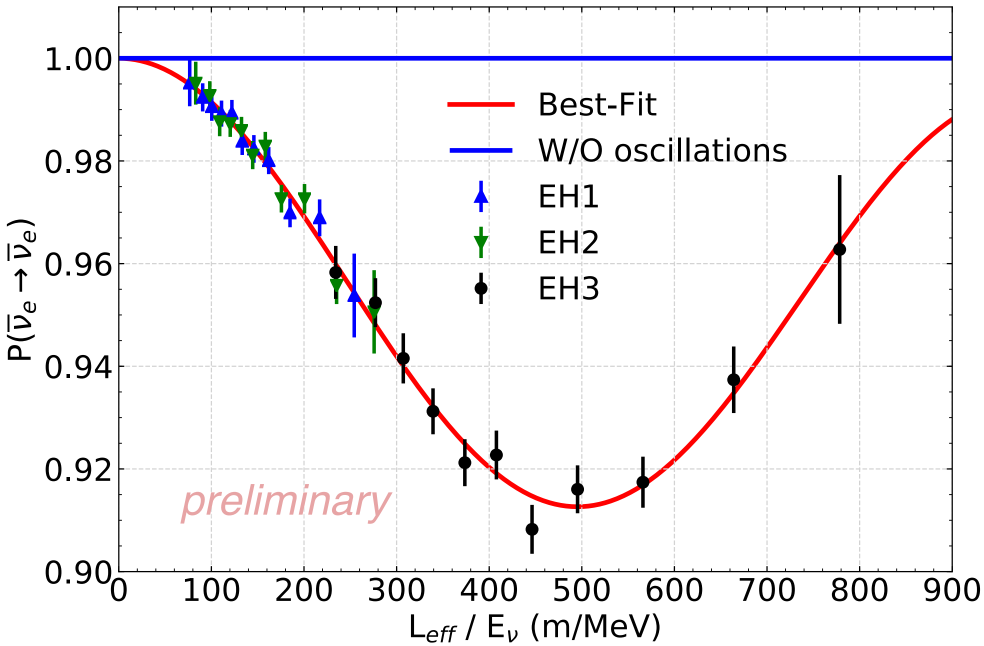
running with 8 detectors

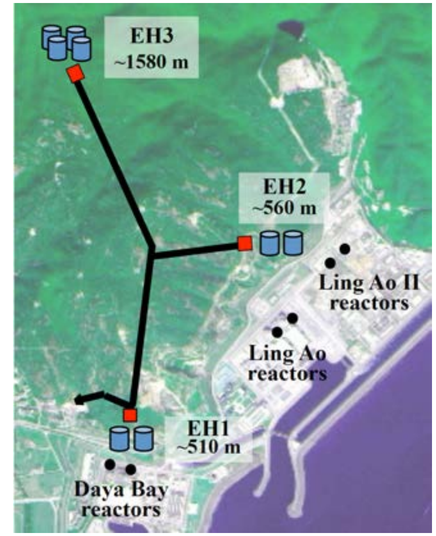
Antineutrino Detector

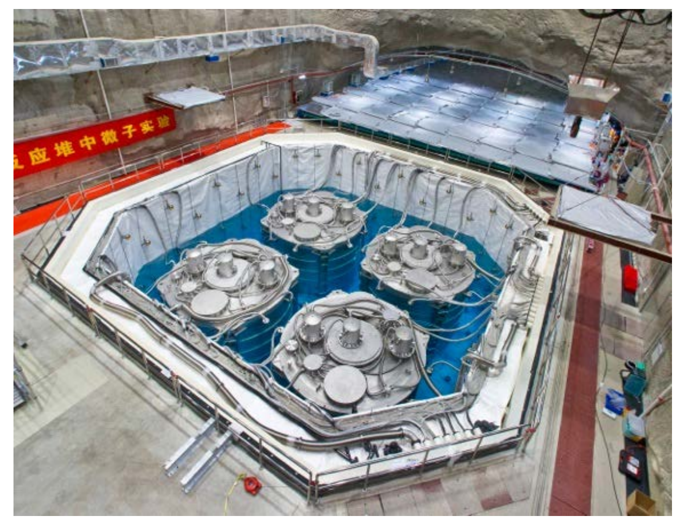


target mass: 20 ton per AD
photosensors: 192 8”-PMTs
energy resolution: $(7.5 / \sqrt{E} + 0.9)\%$

Daya Bay Neutrino Oscillation (1958 Days)







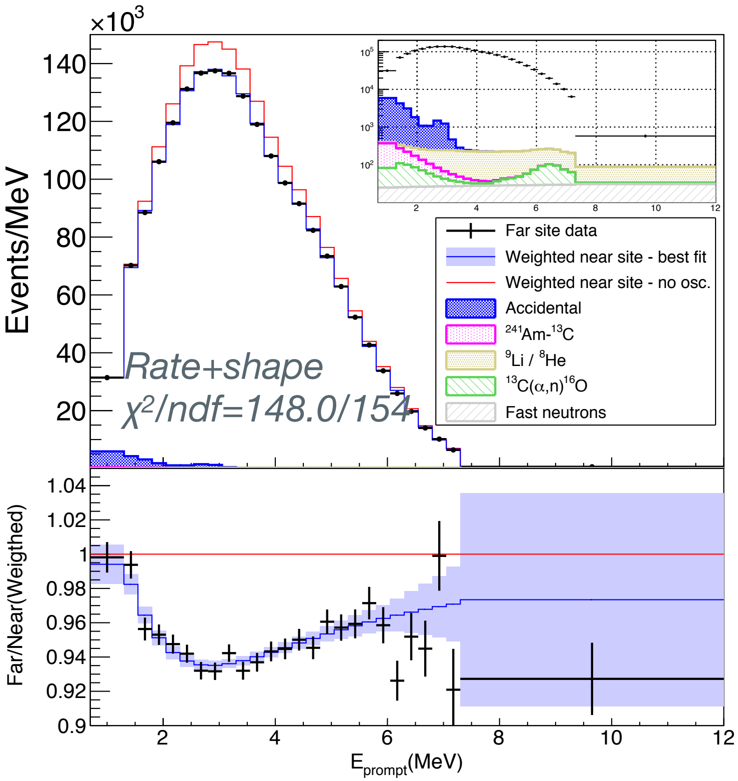
$$P_{i\rightarrow j} = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

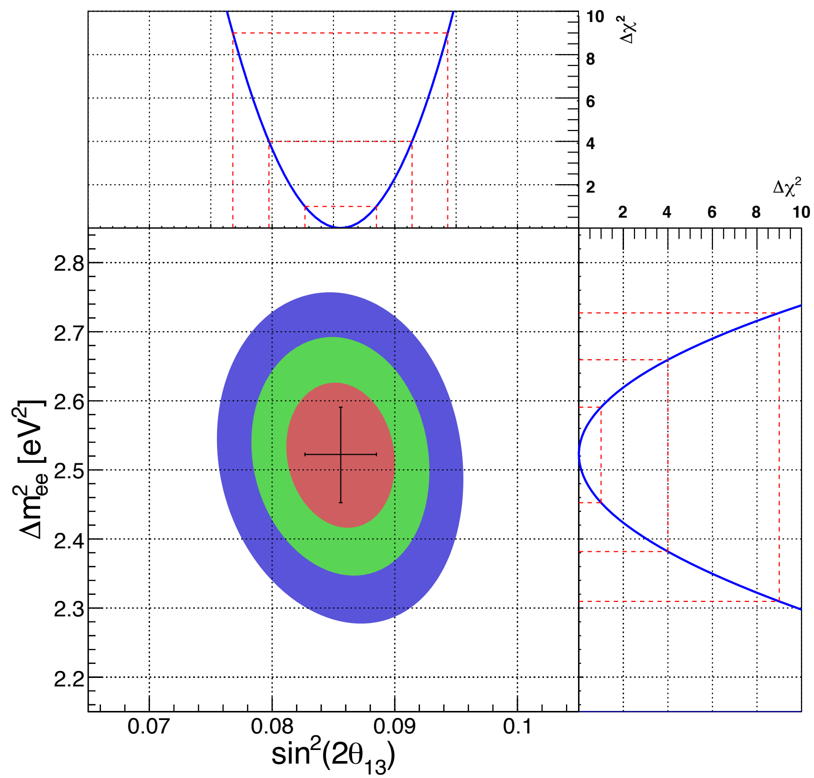
Neutrino oscillation is energy and baseline dependent

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

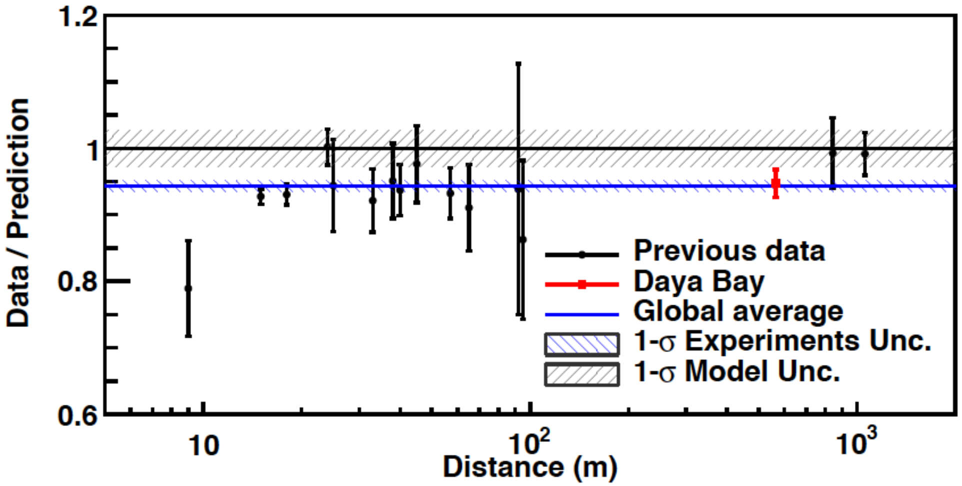
$\sin^2 2\theta_{13}$ uncertainty: 3.4%
$|\Delta m^2_{32}|$ uncertainty: 2.8%

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

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

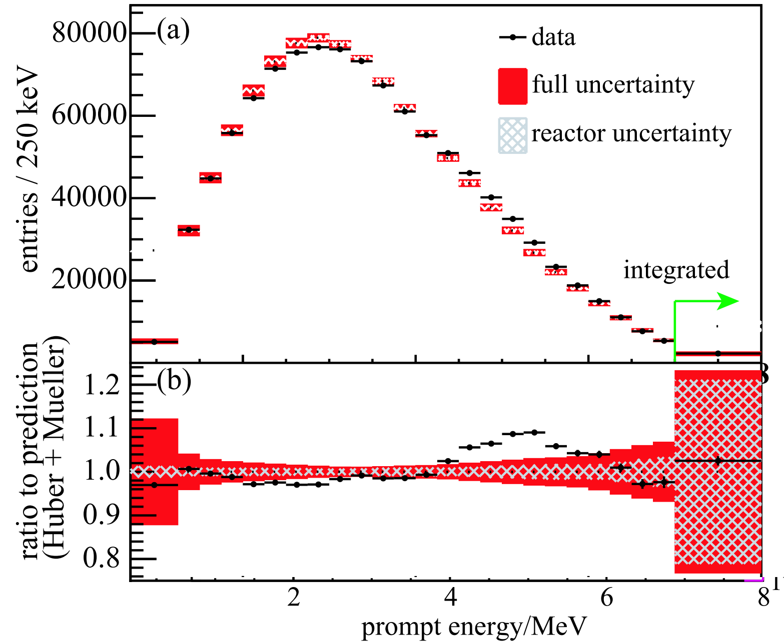
Reactor Antineutrino "Anomalies" (RAA)

Flux Deficit



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

Spectral Deviation



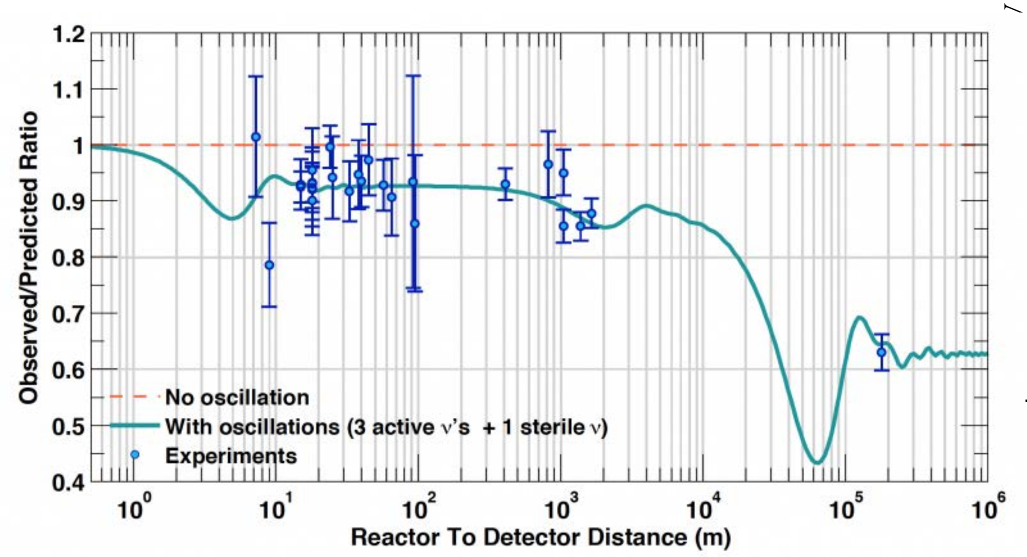
Measured spectrum does not agree with predictions.

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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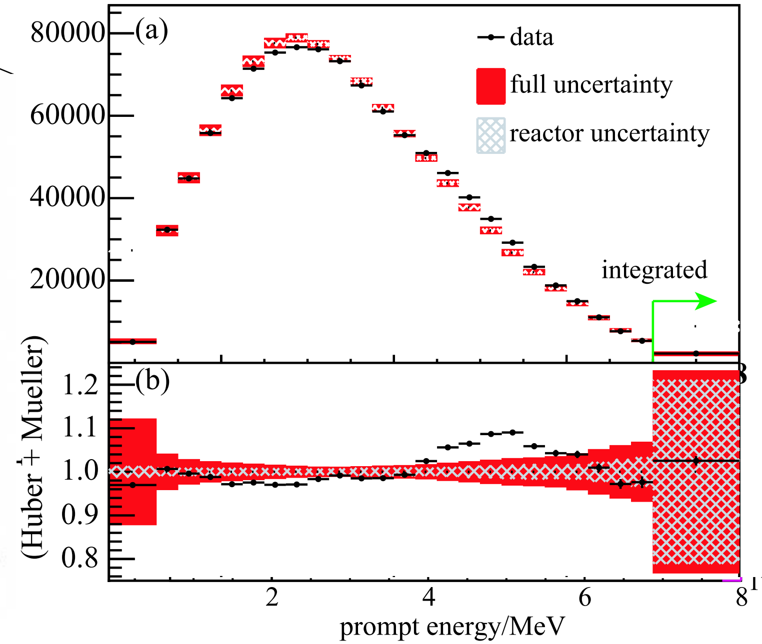
Spectral Deviation



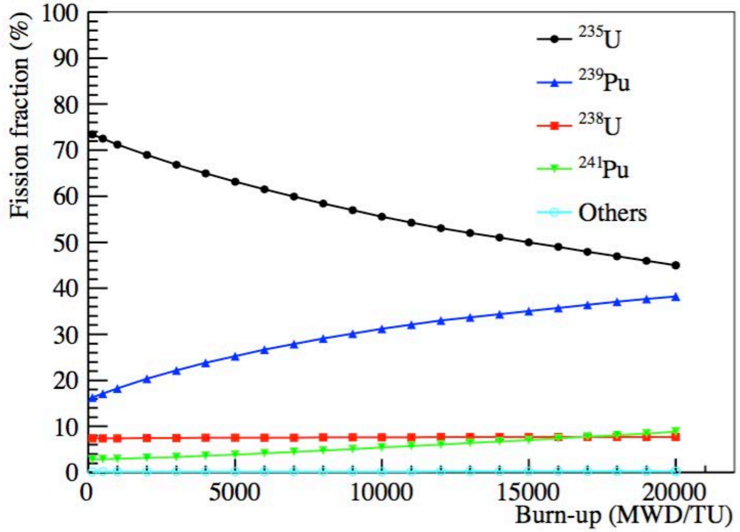
Measured spectrum does not agree with predictions.

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

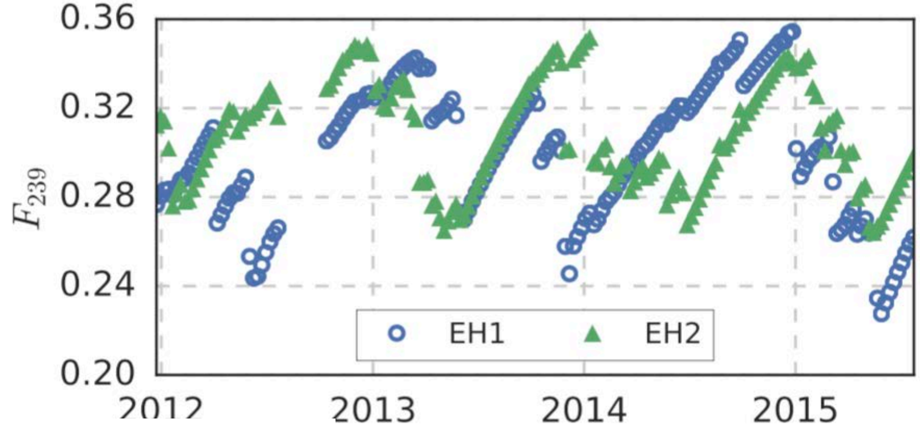
Understanding reactor flux and spectrum anomalies requires additional data

$\overline{\nu}_e$ Fluxes and Fuel Content

Isotopes in PWR Reactor: ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

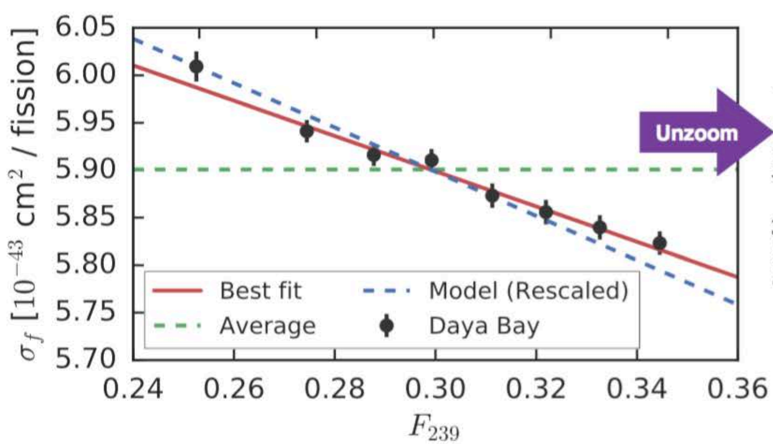


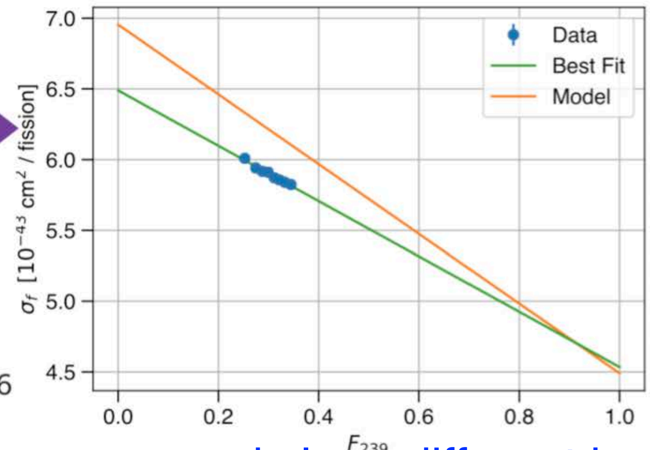
Daya Bay, Chin. Phys. C 41(1) (2017)



combine periods of common fission fractions

Daya Bay, PRL 118 (2017)





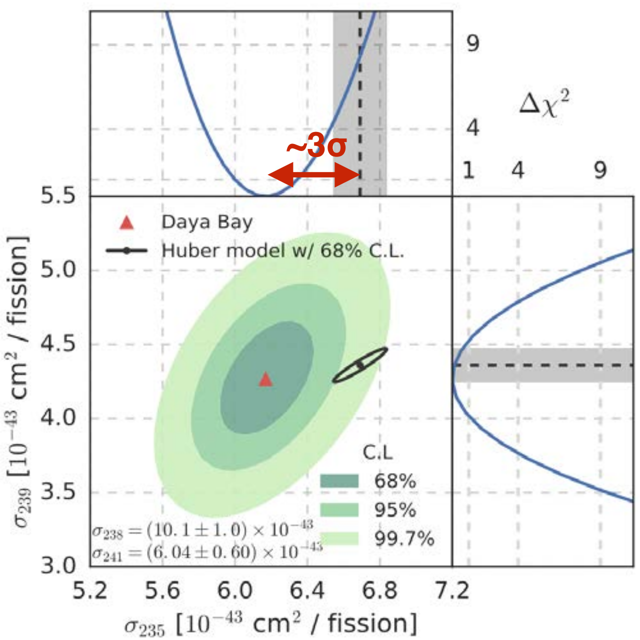
lower ^{235}U?

flux changes with fission fractions, measured slope different by 2.6σ

Fuel Evolution and $\overline{\nu}_e$ Fluxes

Daya Bay Fuel Evolution Analysis

Daya Bay, PRL 118 251801 (2017)

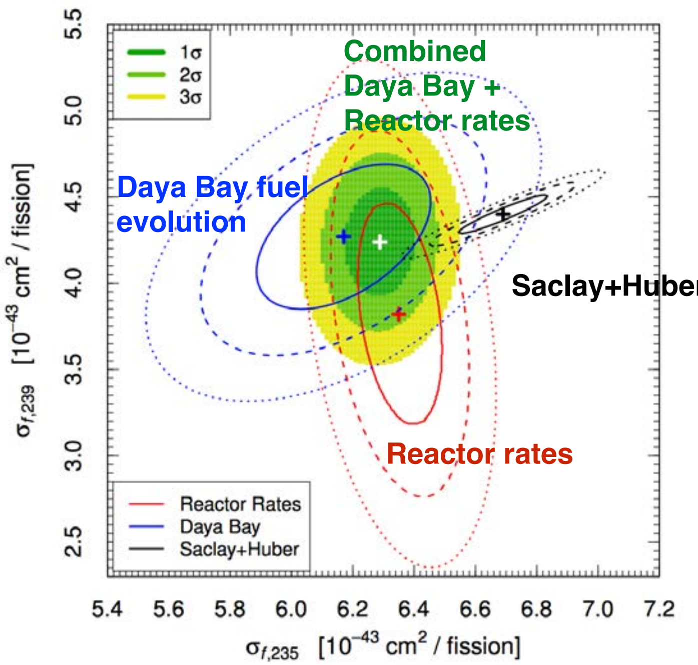


Daya Bay reported IBD yields of ^{235}U and ^{239}Pu using evolution of LEU reactors.
Fitted ^{235}U lower than model.

Analysis of Daya Bay with Fuel Burnup
Hayes et al, Phys.Rev.Lett. 120 (2018) no.2, 022503

Improved Determination of Fluxes

Giunti et al, Phys.Rev. D96 (2017) no.3, 033005

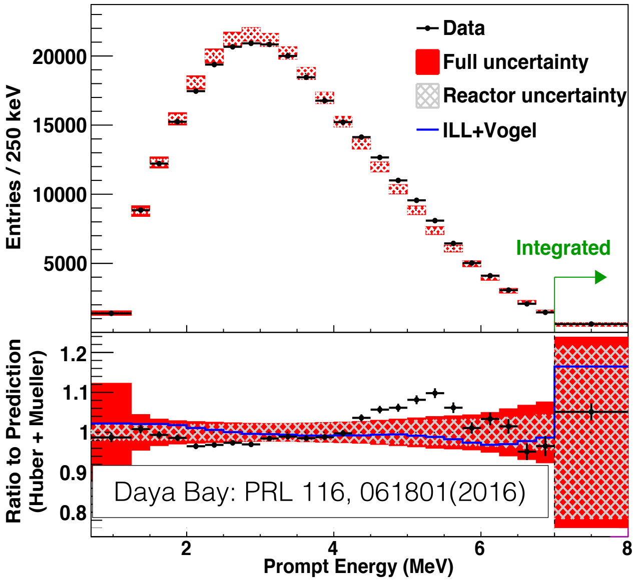


IBD yields calculated from reactor rates (of 26 reactor experiments) do not agree with Daya Bay measurement.

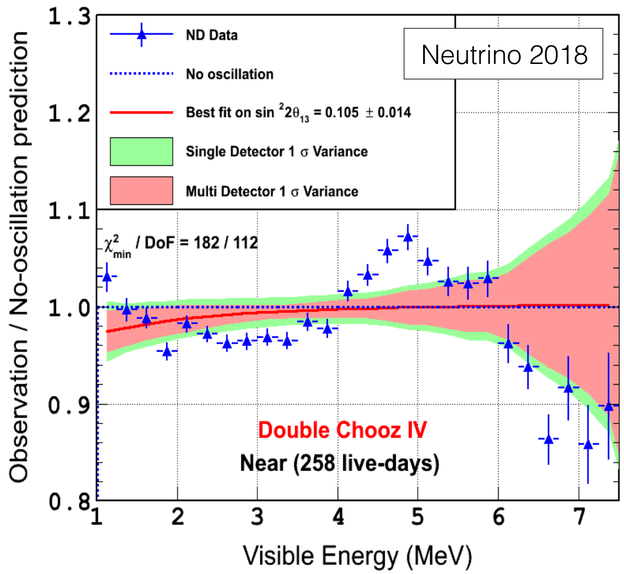
“not enough information to use the antineutrino flux changes to rule out the possible existence of sterile neutrinos”

Spectral Deviation θ_{13} in Experiments

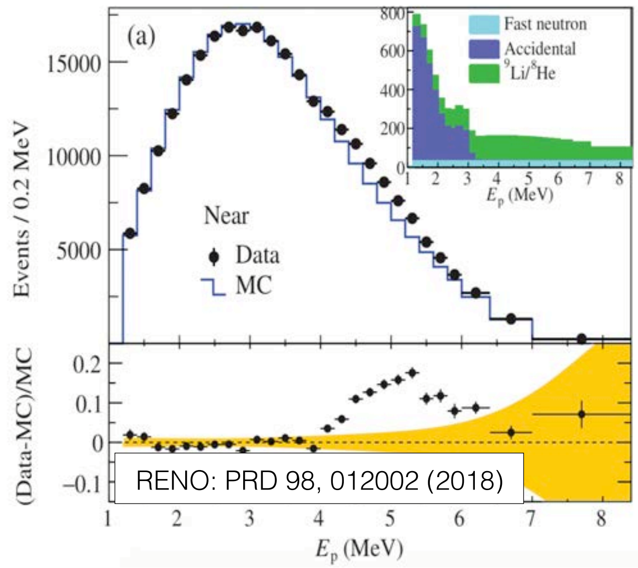
Daya Bay



Double Chooz



RENO



all Θ_{13} experiments observe deviations throughout the spectrum, prominent excess 4-6 MeV prompt energy (5-7 MeV neutrino energy)

cannot be explained by a sterile neutrino

tracks with reactor power (LEU power), appears in near and far detectors

Most likely an issue with nuclear models - one, some, all isotopes?

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

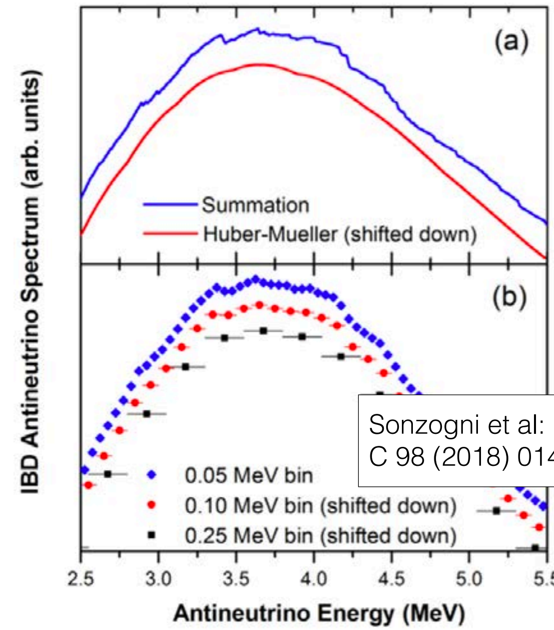
Decay Rate — Branching Fraction — Spectrum

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

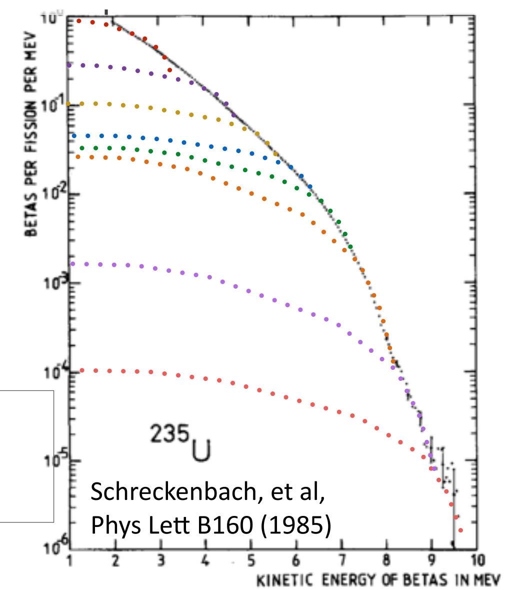
2. **Beta conversion**
   - empirical measurements of beta spectra for each isotope (foils, 1980's)
   - fit with 'virtual branches' and kinematically convert to antineutrino spectra

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

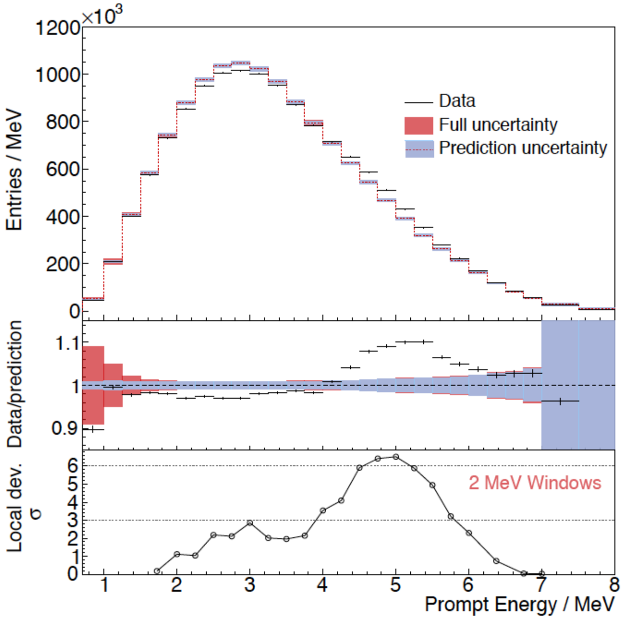


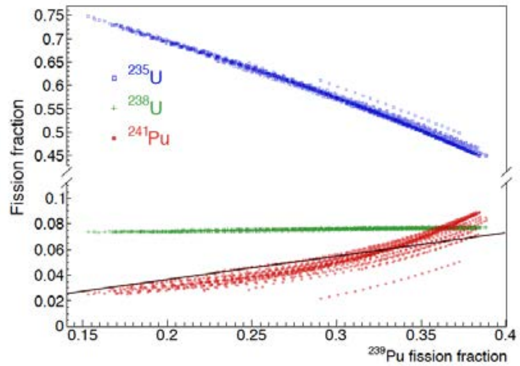
Sonzogni et al: Phys Rev C 98 (2018) 014323

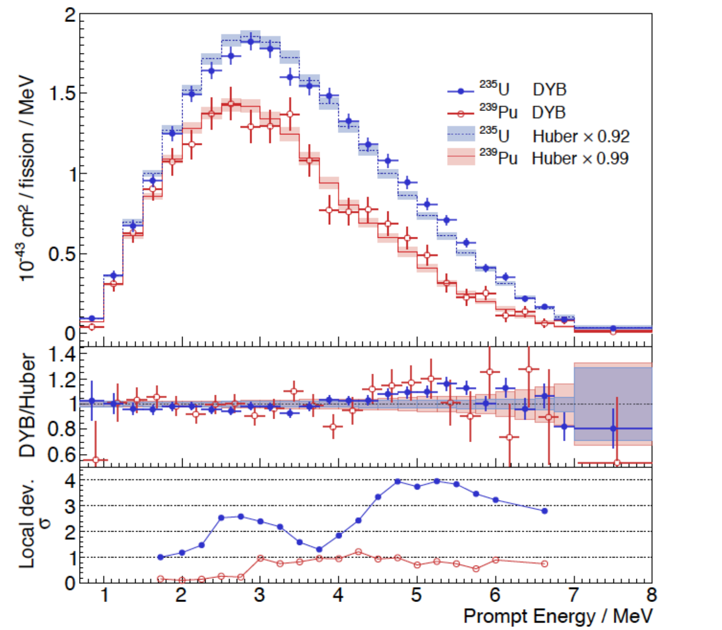


Measured Spectra from ^{235}U and ^{239}U

Latest from Daya Bay, arXiv:1904.07812







3.5 million IBD candidates in 1958 days

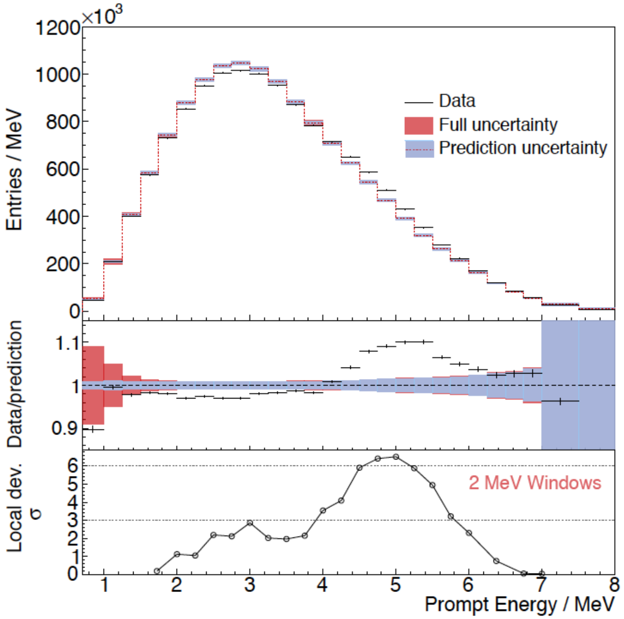
Individual spectra of the two dominant isotopes, ^{235}U and ^{239}Pu, are extracted using the evolution

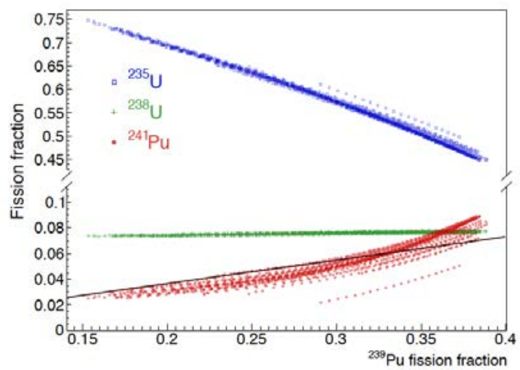
Shape of prompt energy spectrum disagrees with the prediction of the Huber-Mueller model at 5.3σ

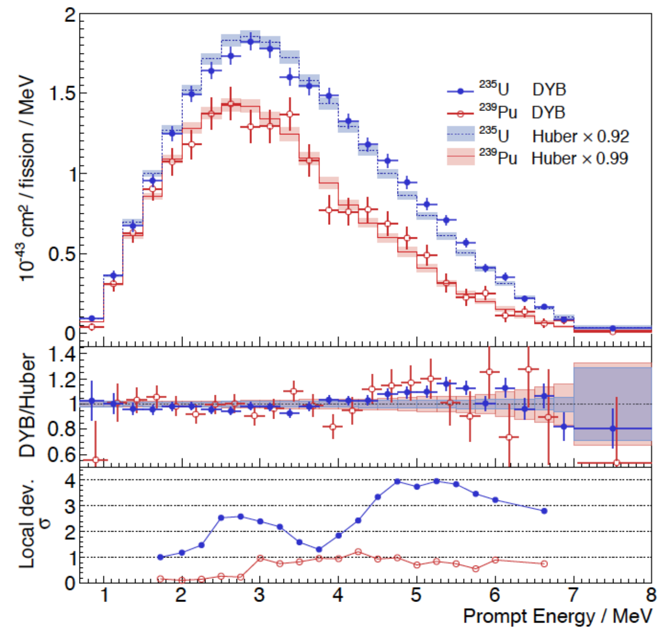
In 4–6 MeV, a 7% (9%) excess for the ^{235}U (^{239}Pu) compared with the normalized Huber-Mueller model prediction.

Measured Spectra from ^{235}U and ^{239}U

Latest from Daya Bay, arXiv:1904.07812



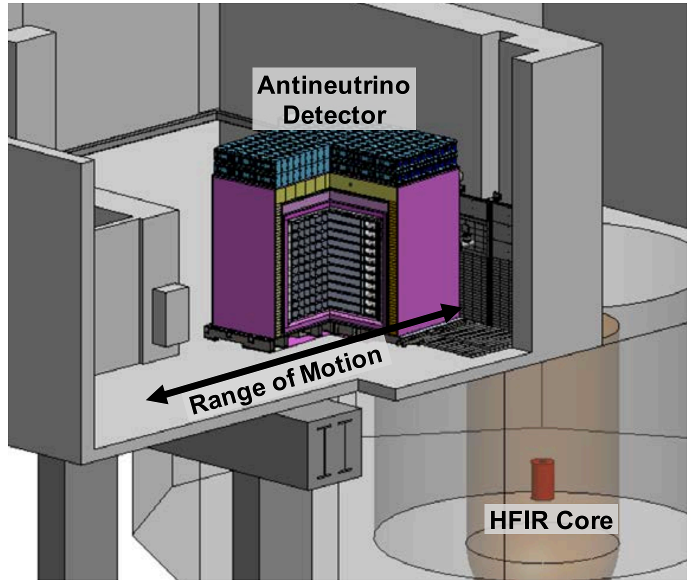


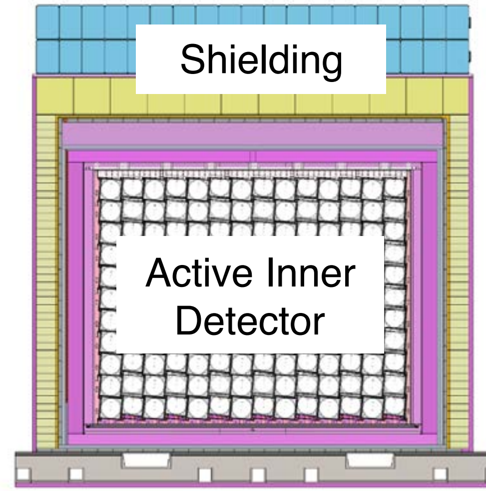


Comparison of the measured and predicted ^{235}U and ^{239}Pu IBD yields prefers an incorrect prediction of the ^{235}U flux as the primary source of the reactor antineutrino rate anomaly.

Discrepancy in the comparison of spectrum shape for ^{235}U suggests incorrect spectral shape prediction for the ^{235}U spectrum.

Precision Oscillation and Spectrum Experiment





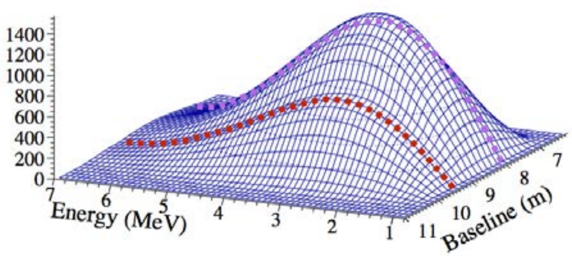
Objectives **Search for short-baseline oscillation at <10m**

Precision measurement of ^{235}U reactor $\overline{\nu}_e$ spectrum

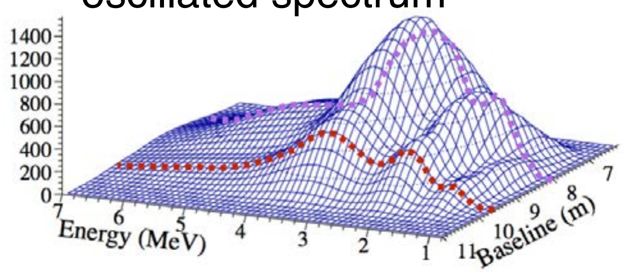
Relative Spectrum Measurement

relative measurement of L/E and spectral shape distortions

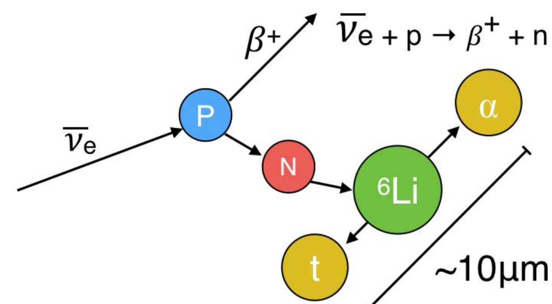
unoscillated spectrum



oscillated spectrum



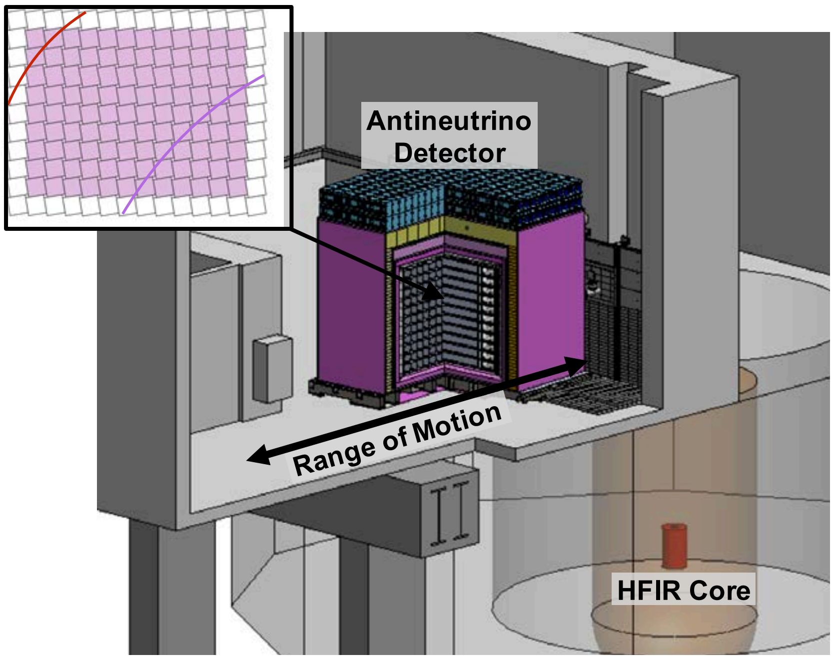
Segmented, ^{6}Li-loaded Detector

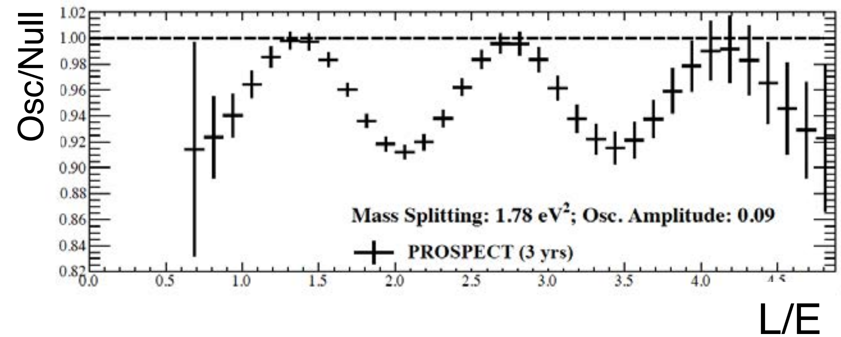


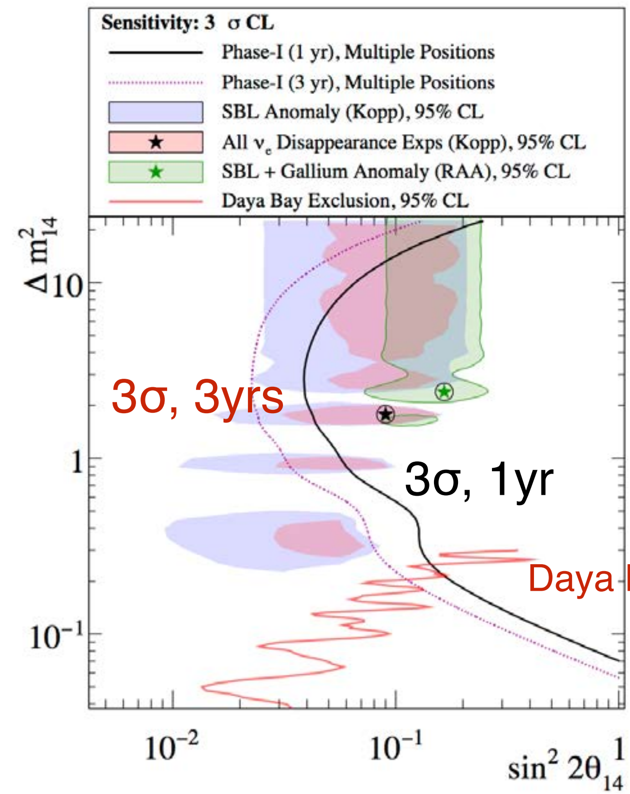
PROSPECT Physics

A Precision Oscillation Experiment

Model-independent test of oscillation of eV-scale neutrinos







Objectives

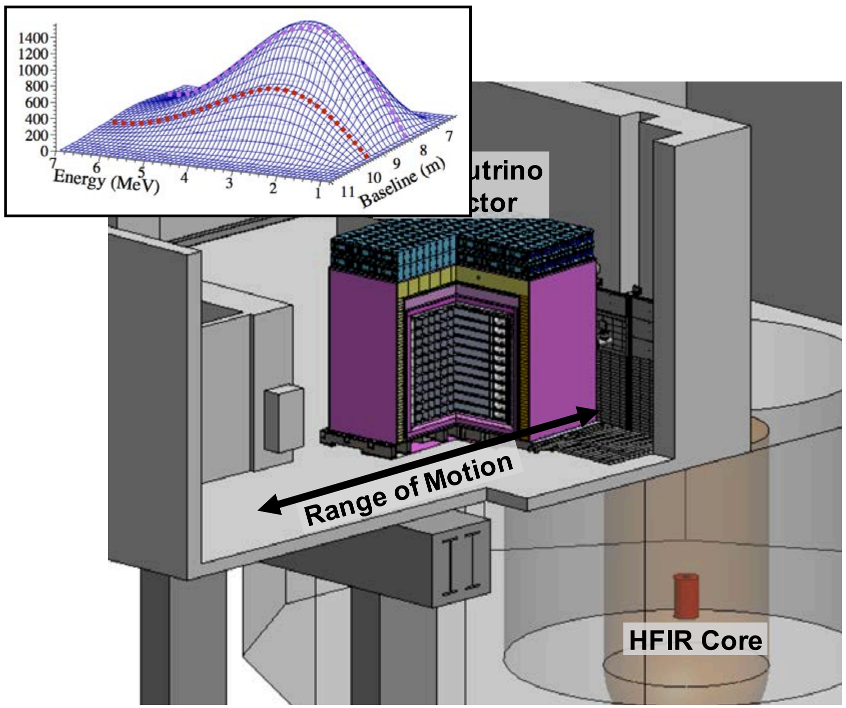
4σ test of best fit after 1 year

>3σ test of favored region after 3 years

PROSPECT Physics

A Precision Spectrum Experiment

A precision measurement of spectrum

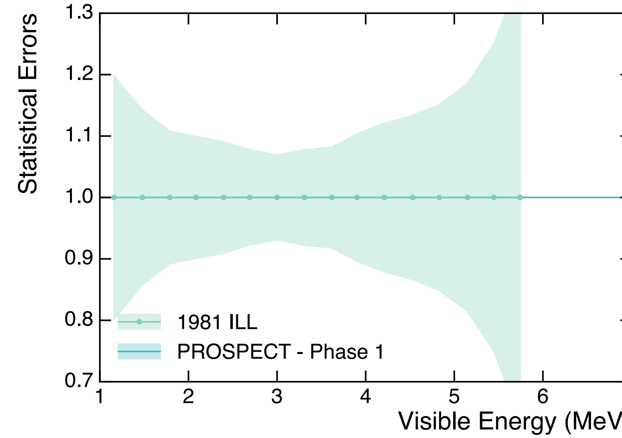


Objectives

Measurement of ^{235}U spectrum

Compare different reactor models

Improvement on ILL

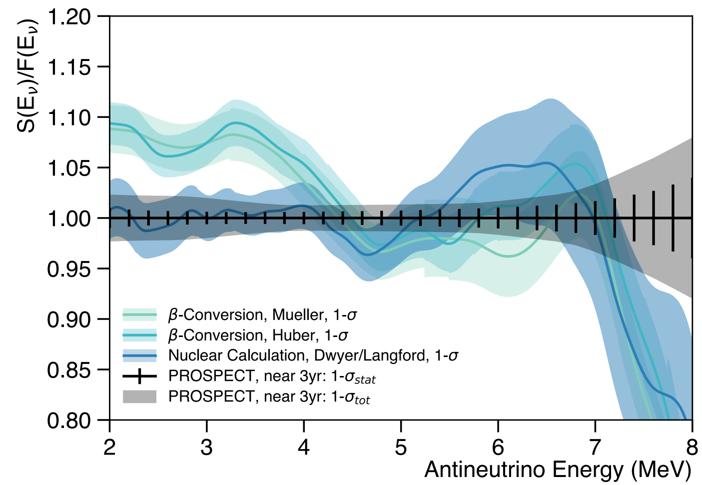


~100k events per year

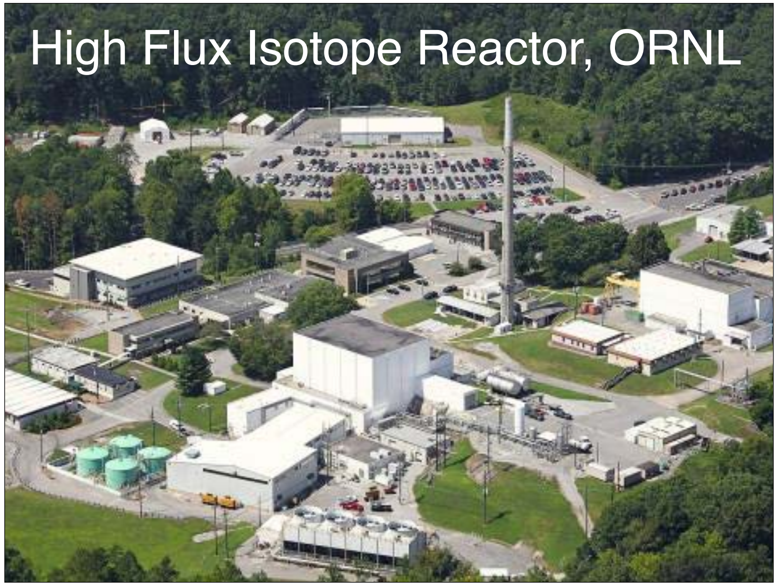
~4.5%/√E

1981 ILL: ~5000 events

Testing models of $^{235}U\ \overline{\nu}_e$ 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

Surface Neutrino Detection

Very close to research reactor

Reactor-related backgrounds (gammas and thermal n)

Detector operates at the surface (or close to it) so cosmic-ray backgrounds are problematic

Three-pronged approach to backgrounds:

- **New detector design**
- **New liquid scintillator**
- **New shielding design**

PROSPECT Detector Design

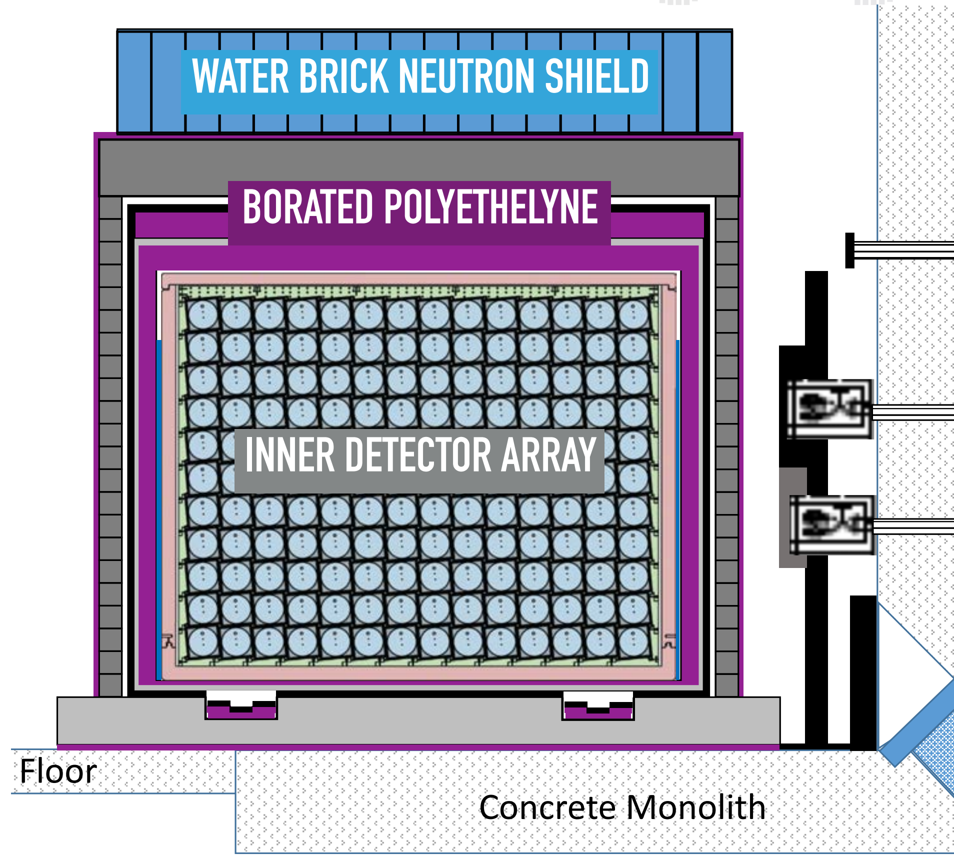
Single 4,000 L **^{6}Li-loaded liquid scintillator** (3,000 L fiducial volume)

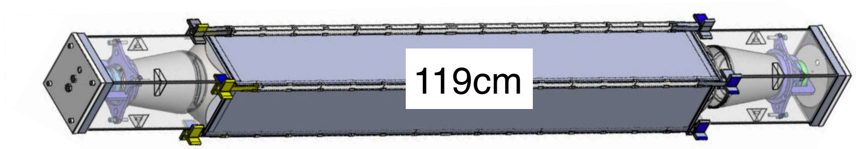
11 x 14 (154) **array of optically separated segments**

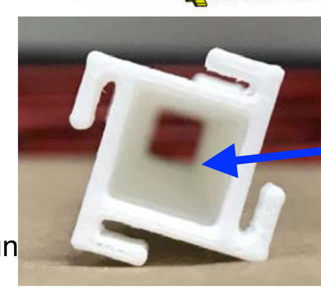
Very low mass separators (1.5 mm thick)
- Corner support rods allow for full *in situ* calibration access

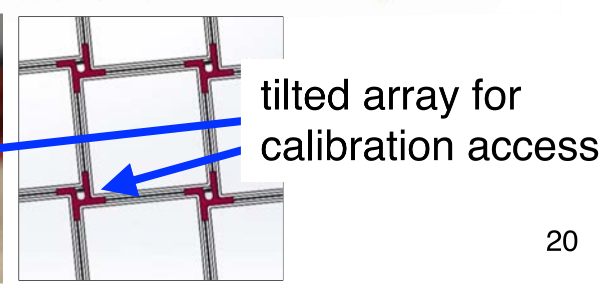
Double ended PMT readout, with light concentrators
- good light collection and energy response
- ~5%√E energy resolution
- full X,Y,Z event reconstruction

Optimized shielding to reduce cosmogenic backgrounds



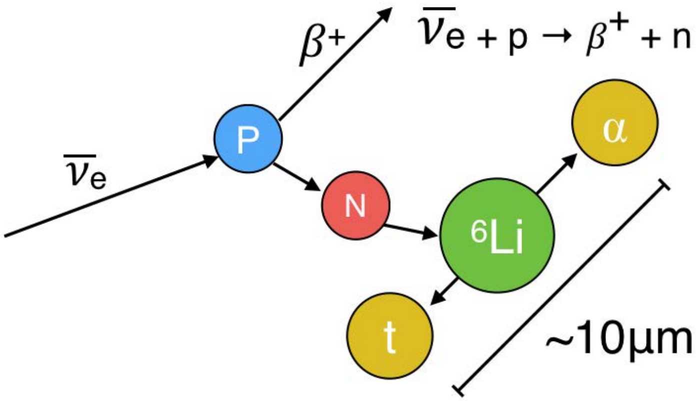






Antineutrino Event Identification with ^6Li

Inverse Beta Decay



40μs delayed n capture

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

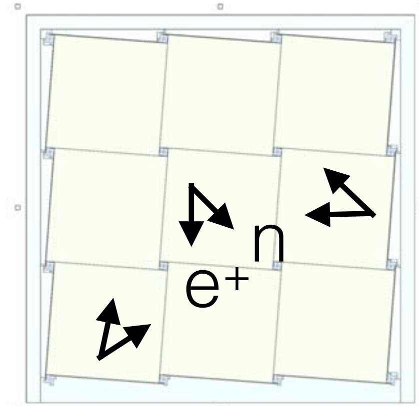
backgrounds — fast neutron
n-like prompt, n-like delay

accidental gamma
γ-like prompt, γ-like delay

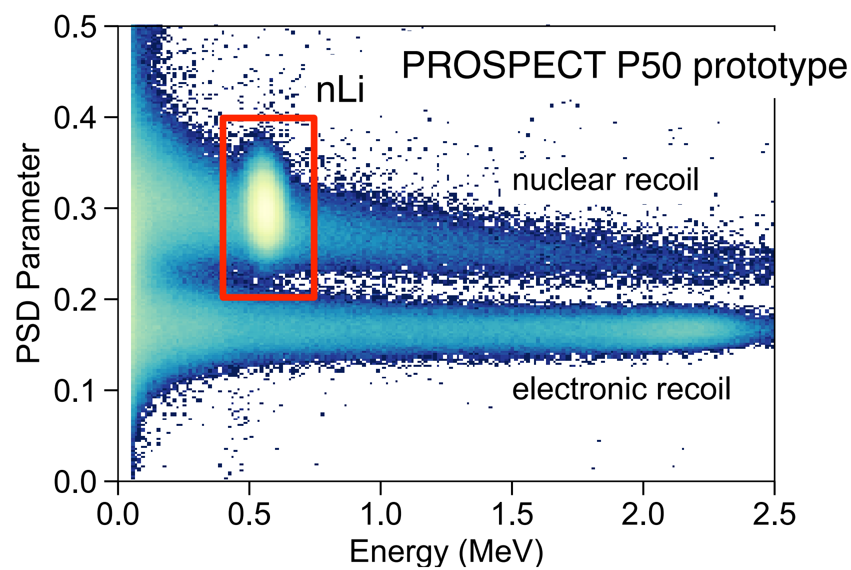
Background Reduction

detector design & fiducialization

IBD event in segmented ^{6}LiLS detector



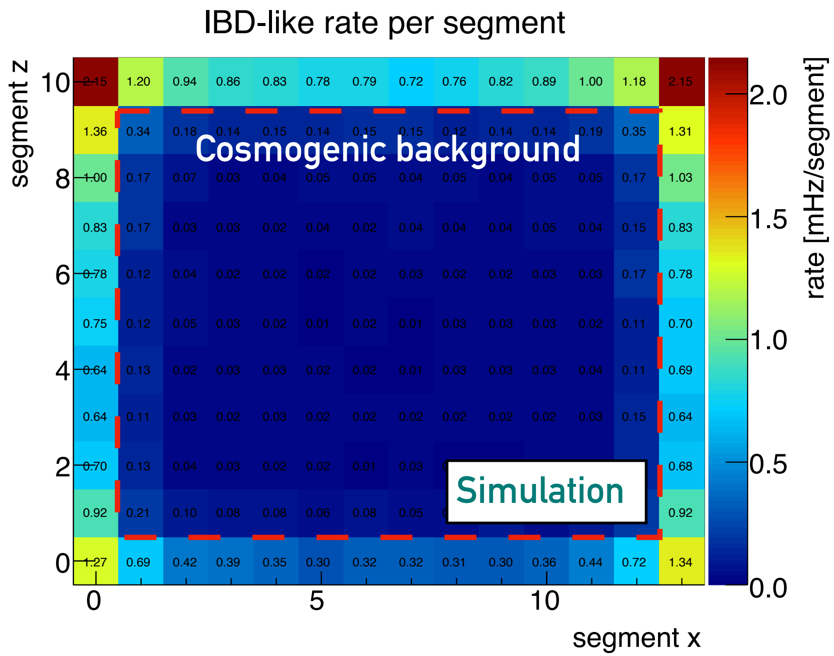
Pulse Shape Discrimination

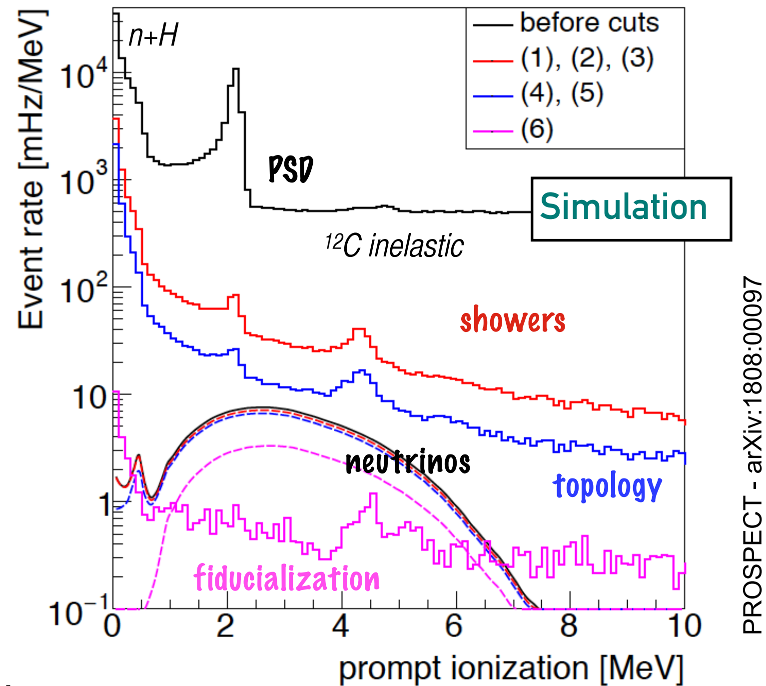


Background reduction is key challenge

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 of First Row
November 1, 2017

[Assembly in 30s (video)]

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

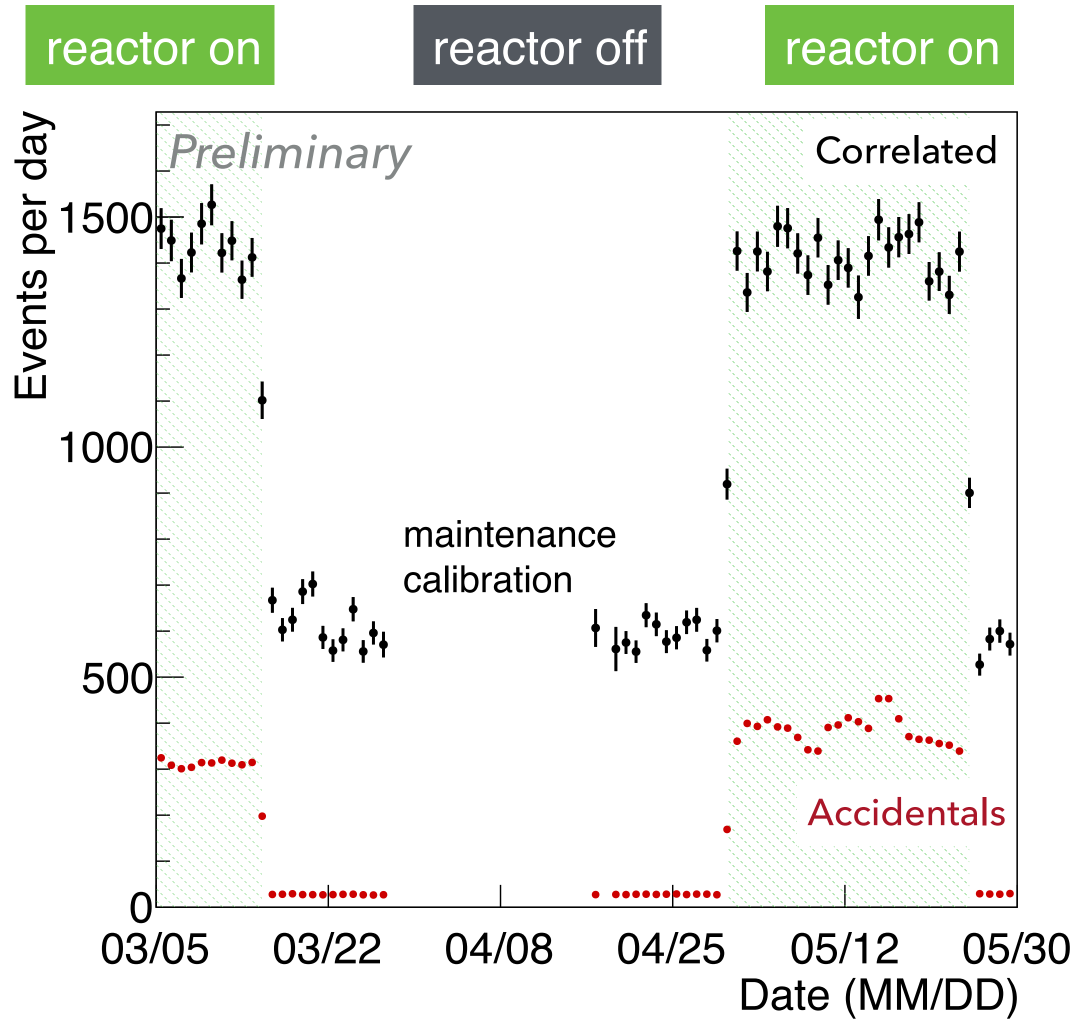
Correlated S/B = 1.36

Accidental S/B = 2.25

24,608 IBDs detected

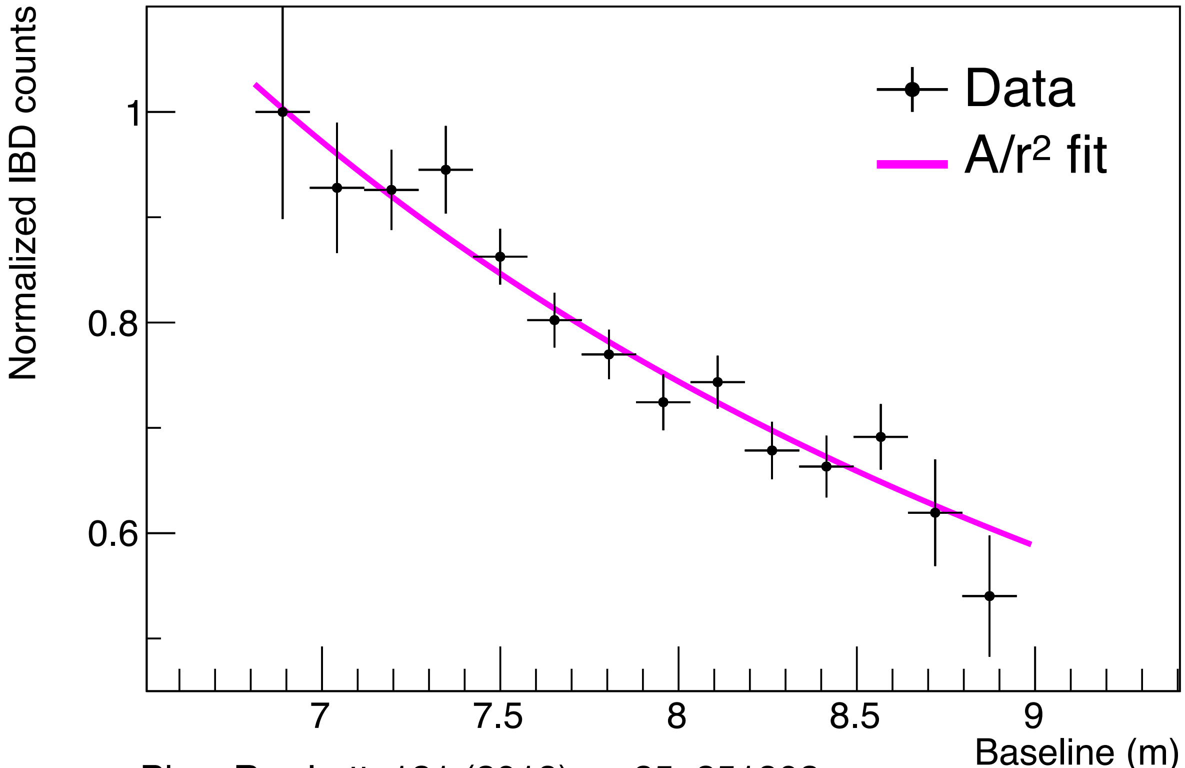
Average of ~750 IBDs/day

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



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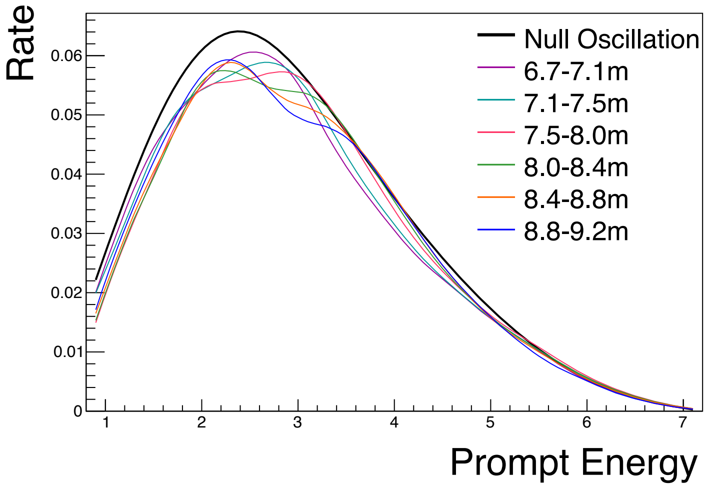
Observation of $1/r^2$ behavior throughout detector volume

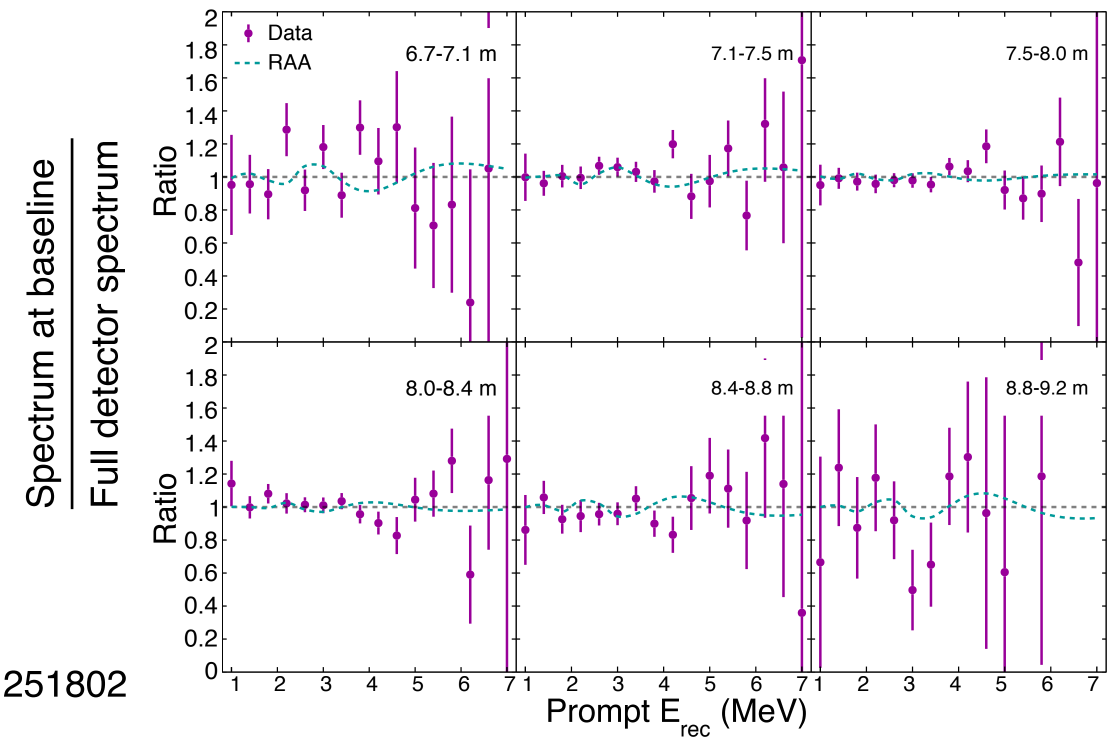
Bin events from 108 fiducial segments into 14 baseline bins

40% flux decrease from front of detector to back

Neutrino Spectrum vs Baseline

Spectral Distortion vs Baseline





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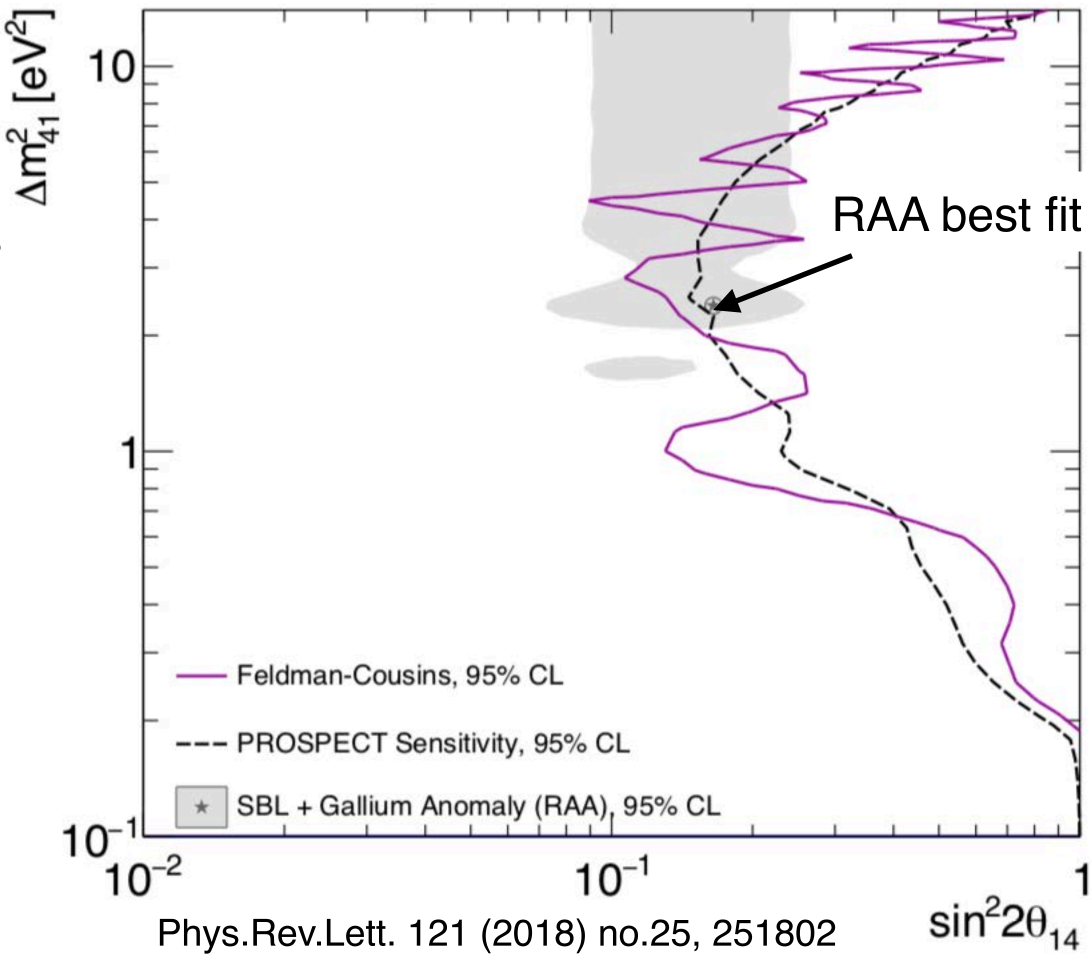
Compare spectra from 6 baselines to measured full-detector spectrum

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**



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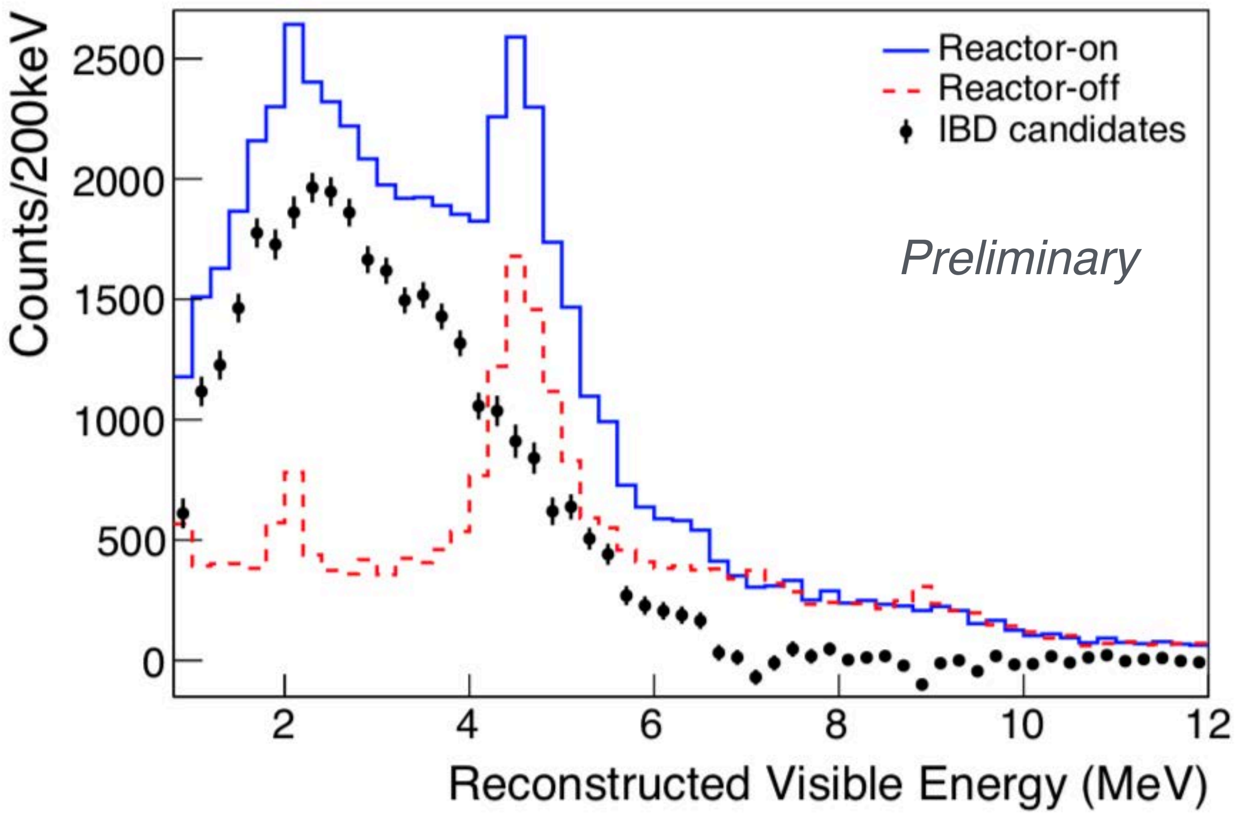
Disfavors RAA best-fit point at >95% CL (2.2σ)

Measurement of ^{235}U Spectrum

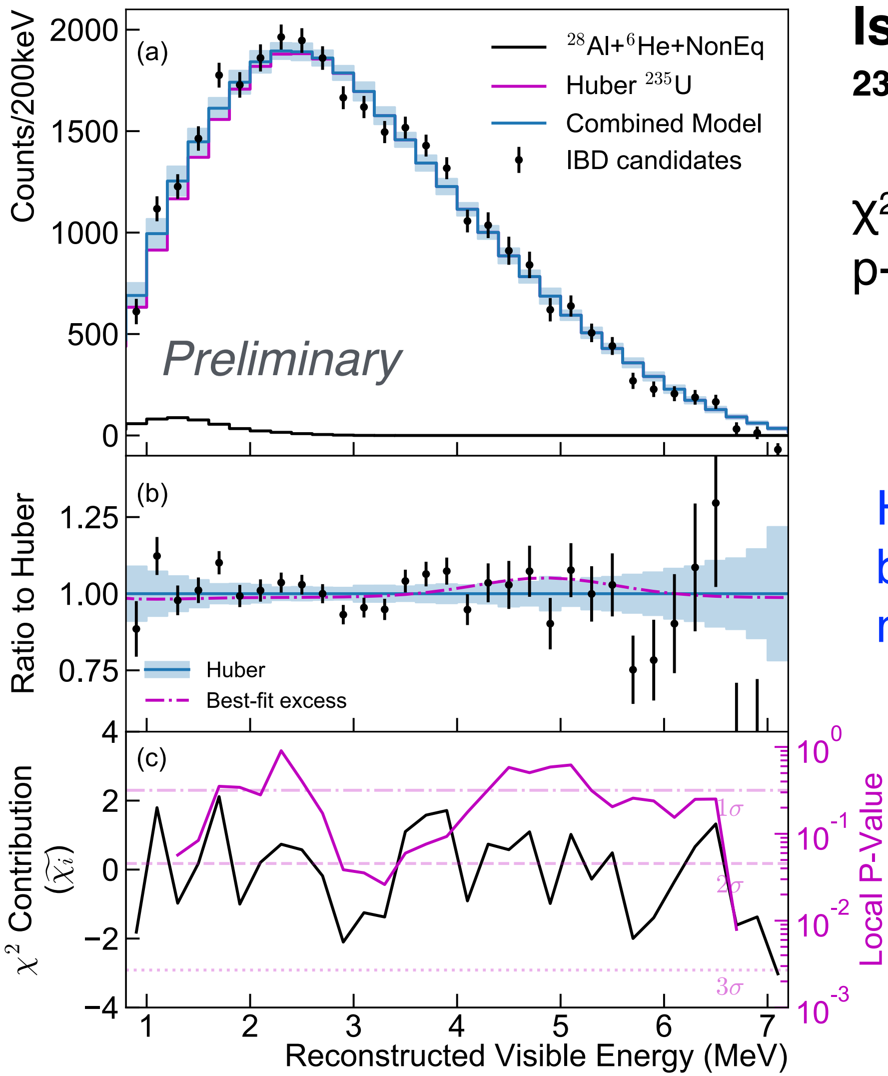
Prompt Energy Spectrum



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?

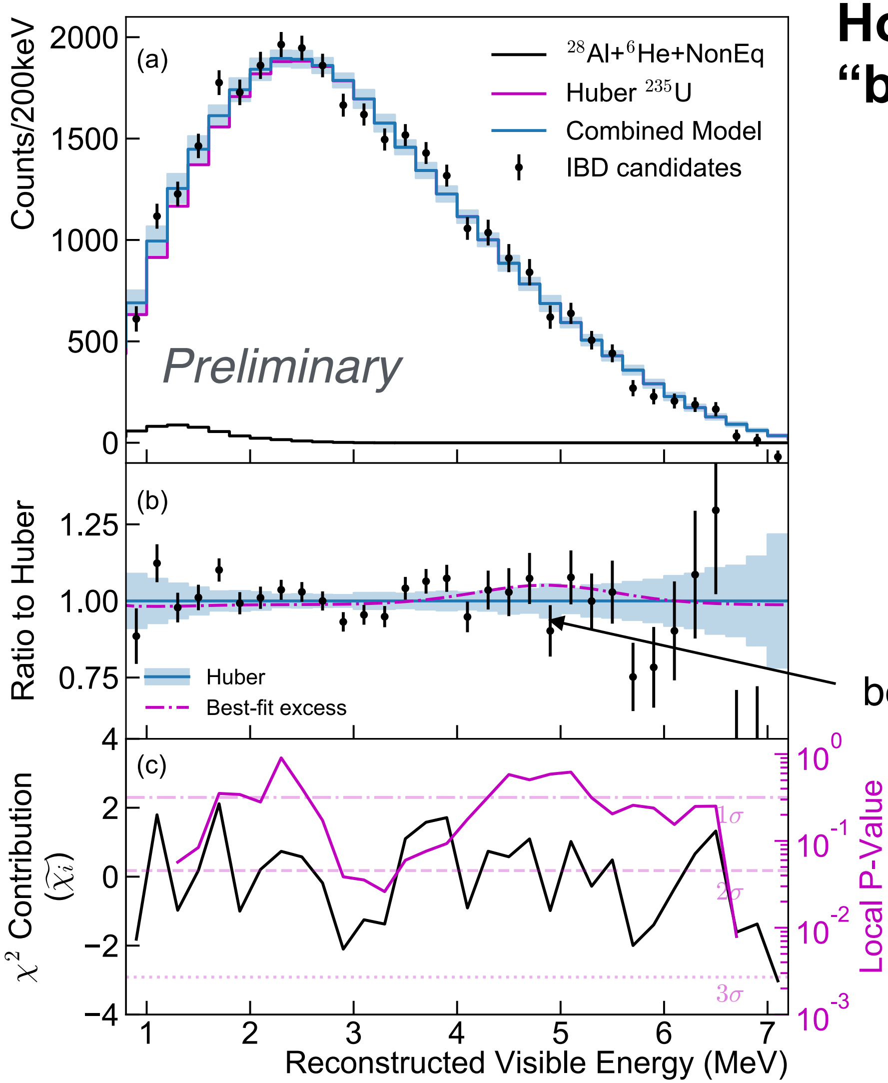
χ^2/ndf = 52.1/31
p-value = 0.01

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.

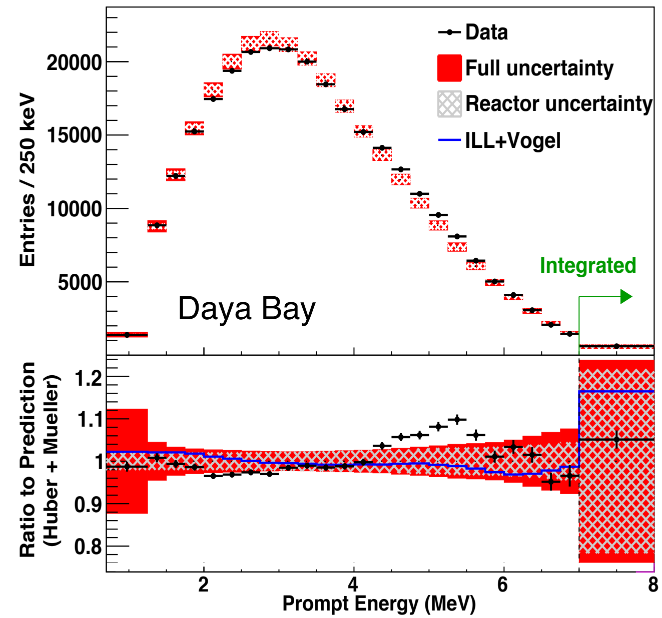
Statistics limited measurement.

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**.

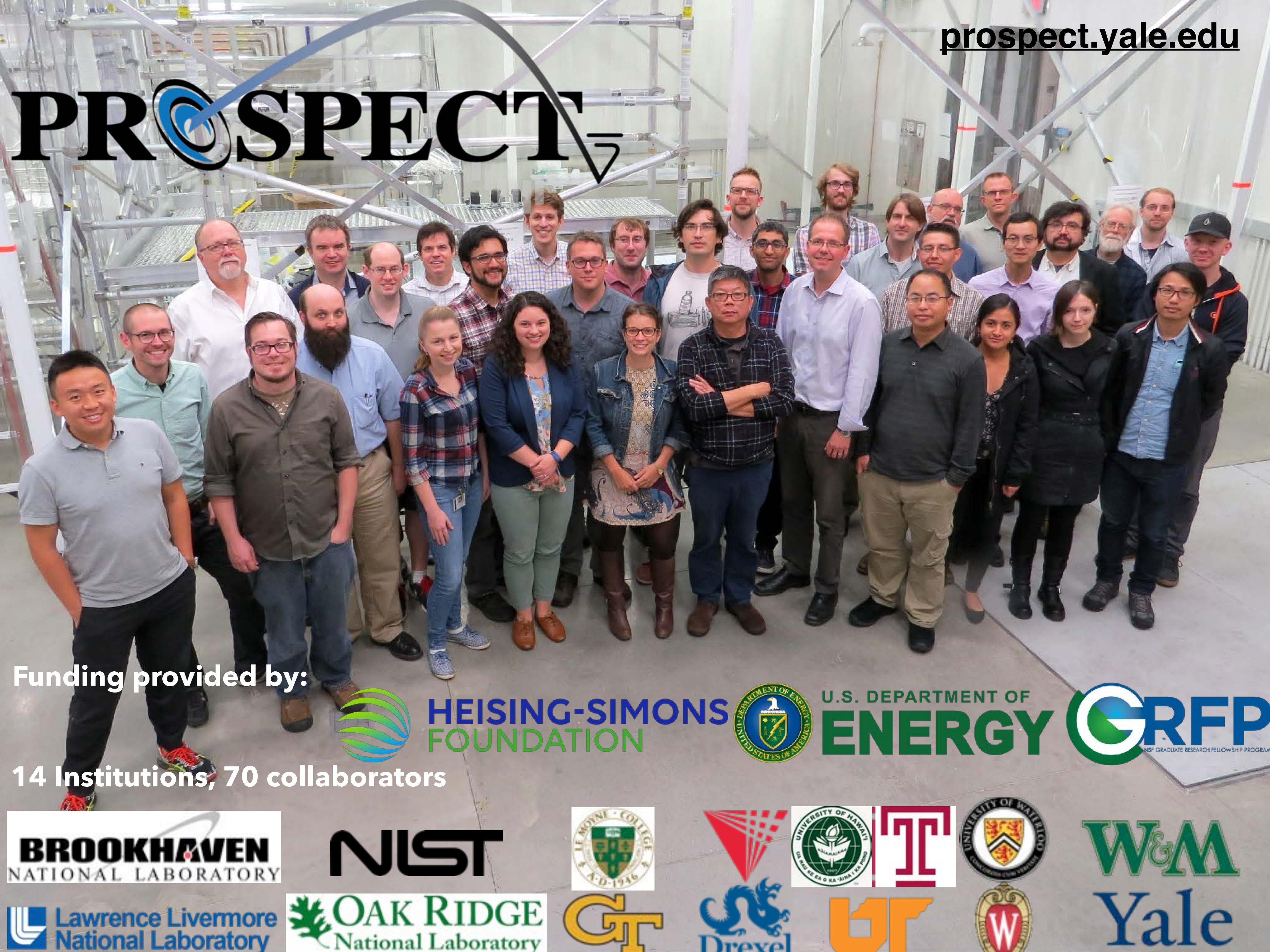
With a surface-based detector, PROSPECT has made a modern measurement of ^{235}U antineutrino spectrum from HEU reactor. Statistics limits conclusion on spectral deviation in ^{235}U.

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, Daya Bay, and other experiments sterile neutrinos are increasingly disfavored.

Have started joint analysis between Daya Bay and PROSPECT.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14 Institutions, 70 collaborators
BROOKHAVEN NATIONAL LABORATORY
NIST
Lawrence Livermore National Laboratory
OAK RIDGE National Laboratory
W&M
Yale

Daya Bay Collaboration

203 collaborators from 42 institutions: