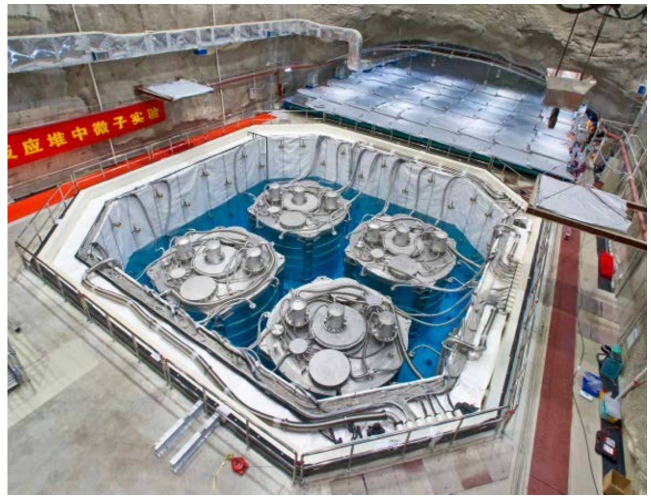
Search for New Physics with Reactor Neutrinos



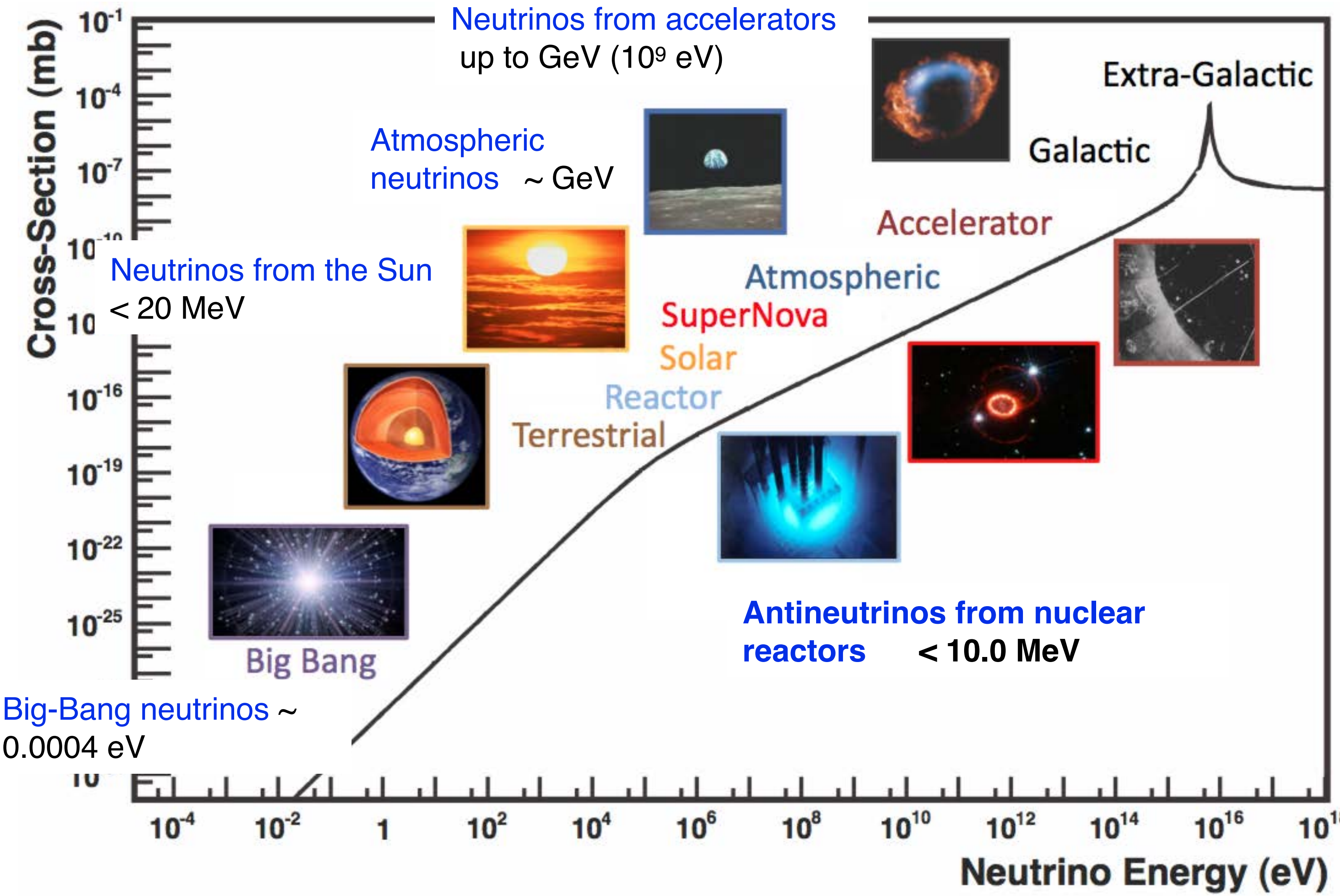
Karsten M. Heeger
Yale University

November 7, 2018

Wright Laboratory

Yale

Neutrino Sources



Neutrinos from accelerators up to GeV (10^9 eV)

Atmospheric neutrinos ~ GeV

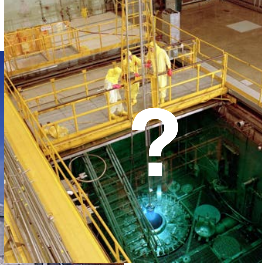
Neutrinos from the Sun < 20 MeV

Antineutrinos from nuclear reactors **< 10.0 MeV**

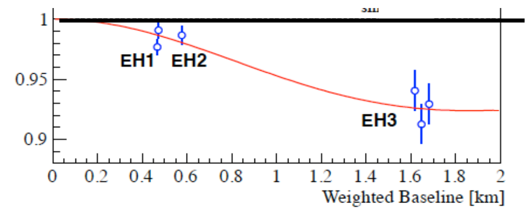
Big-Bang neutrinos ~ 0.0004 eV

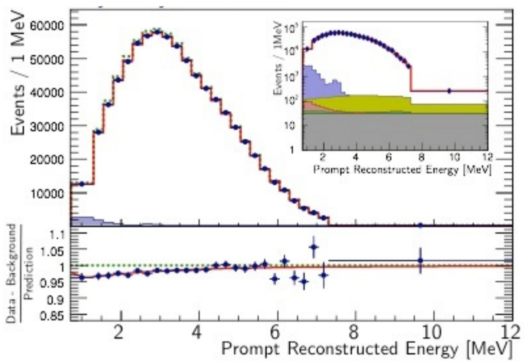
Reactor Antineutrinos

A Tool for Discovery

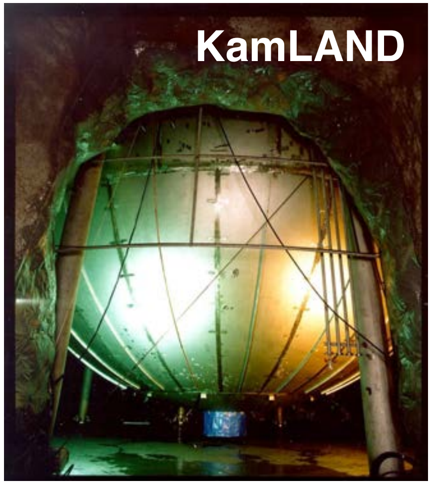


2012 - Measurement of θ_{13} with Reactor Neutrinos



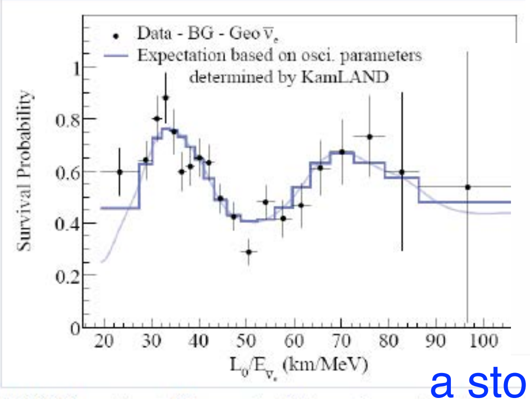


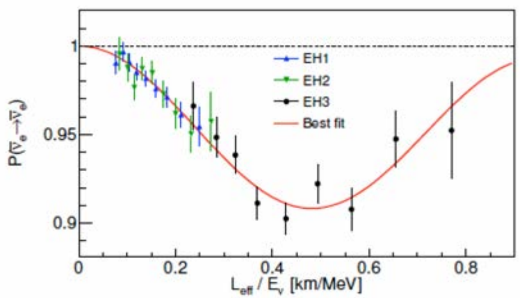
2003 - First observation of reactor antineutrino disappearance



1995 - Nobel Prize to Fred Reines at UC Irvine

1956 - First observation of (anti)neutrinos





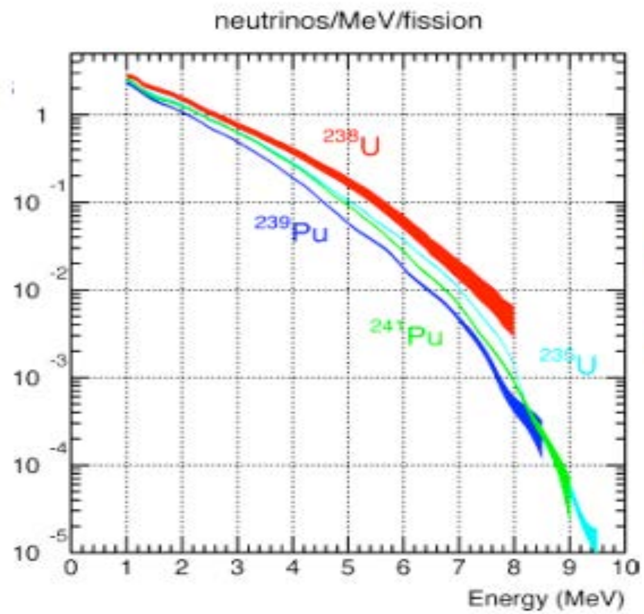
a story of varying baselines...

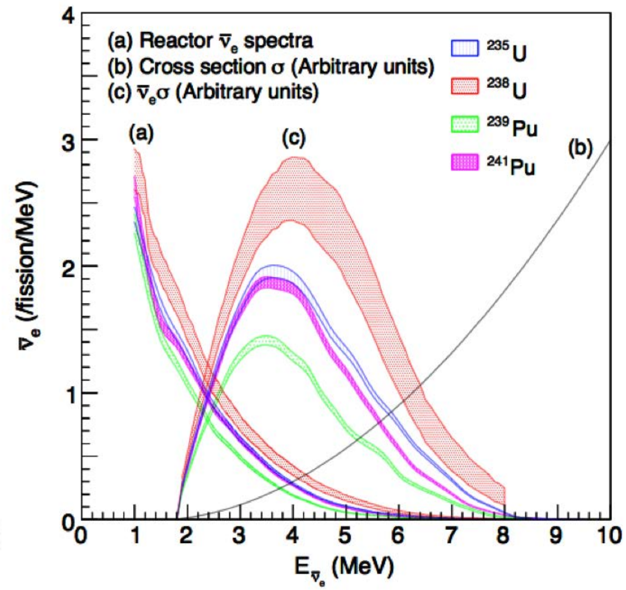
Reactor Antineutrinos

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

of n-rich fission products

on average ~6 beta decays until stable



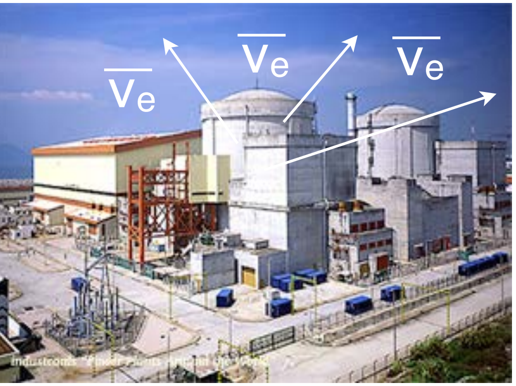


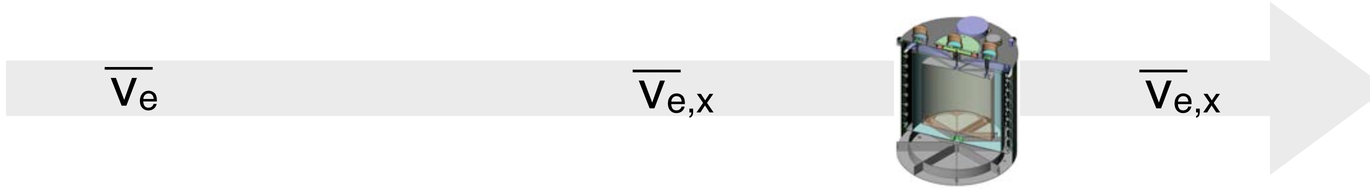
> 99.9% of $\bar{\nu}_e$ are produced by fissions in ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

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

only disappearance experiments possible

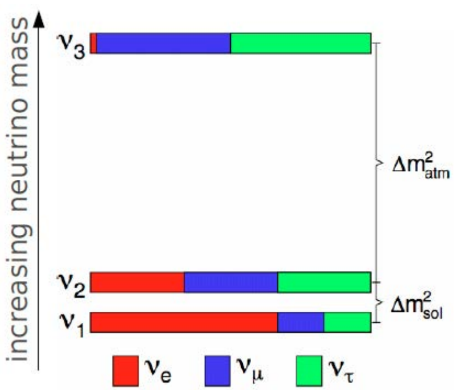
Reactor Neutrino Oscillation Experiments





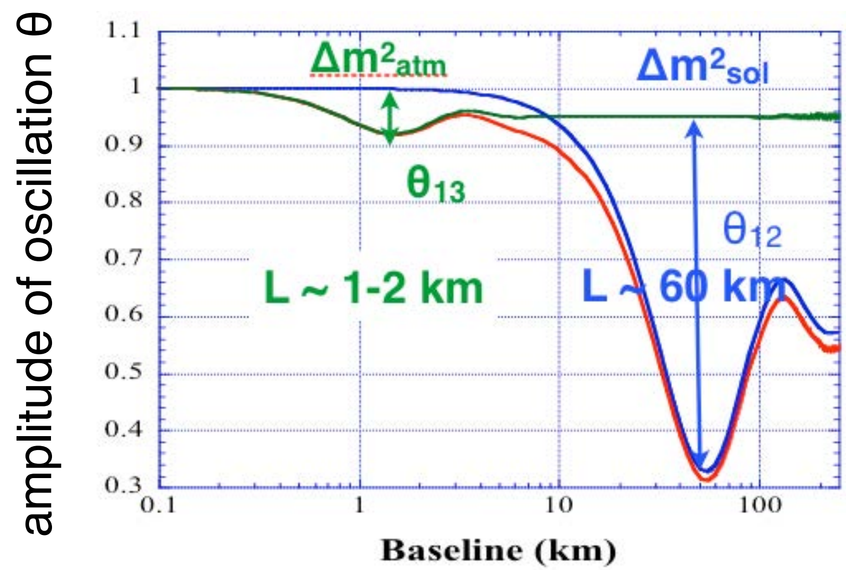
Measure (non)-1/r² behavior

for 3 active ν, two different oscillation length scales: Δm^2_{12}, Δm^2_{23}



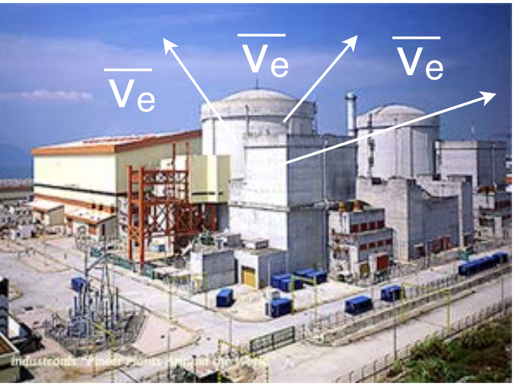
Δm^2_{23} = ~2.4×10^{-3} eV²

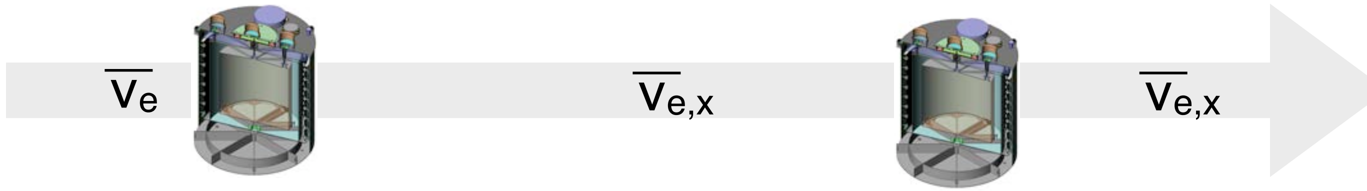
Δm^2_{12} = ~7.6×10^{-5} eV²



oscillation frequency L/E → Δm^2

Reactor Neutrino Oscillation Experiments





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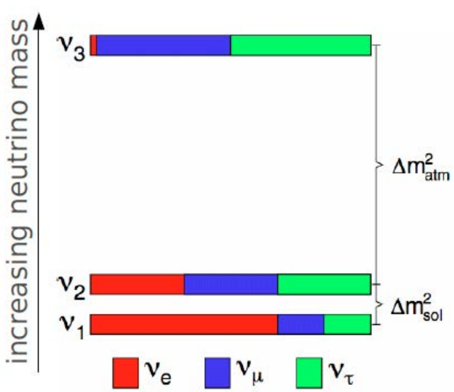

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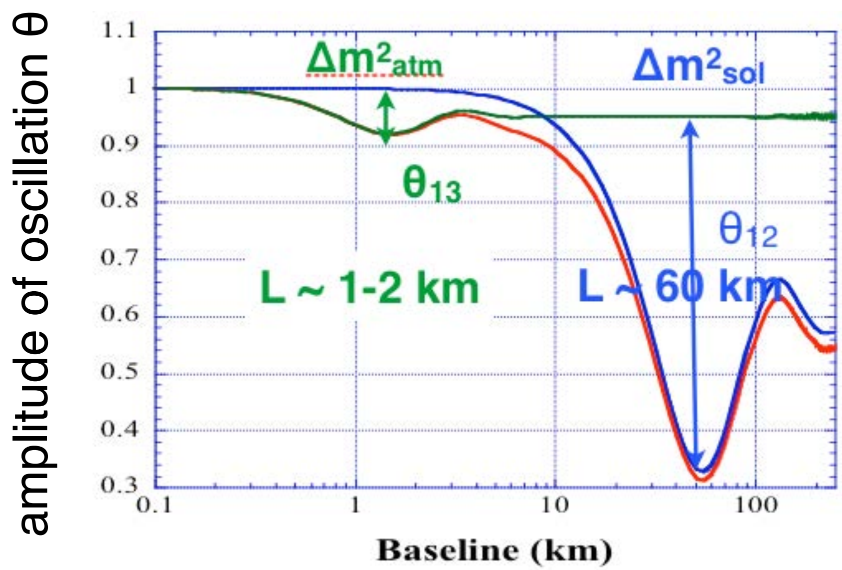
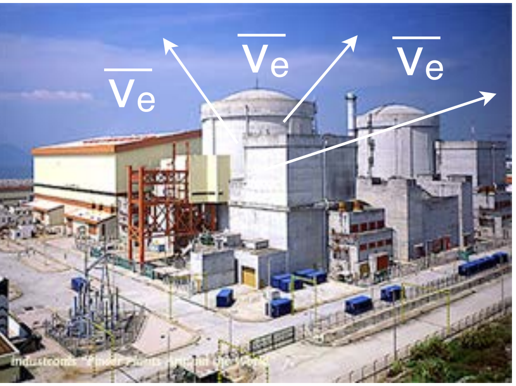
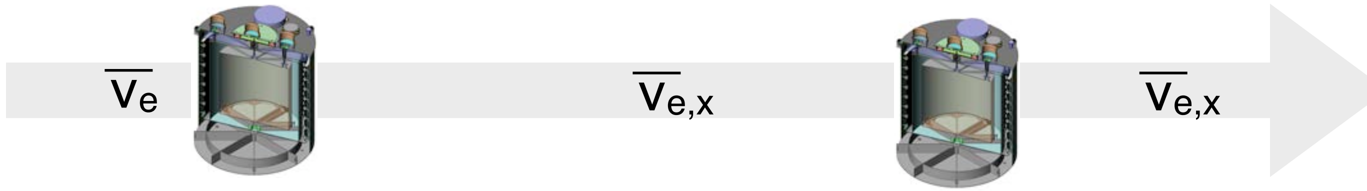


oscillation frequency L/E → Δm^2

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

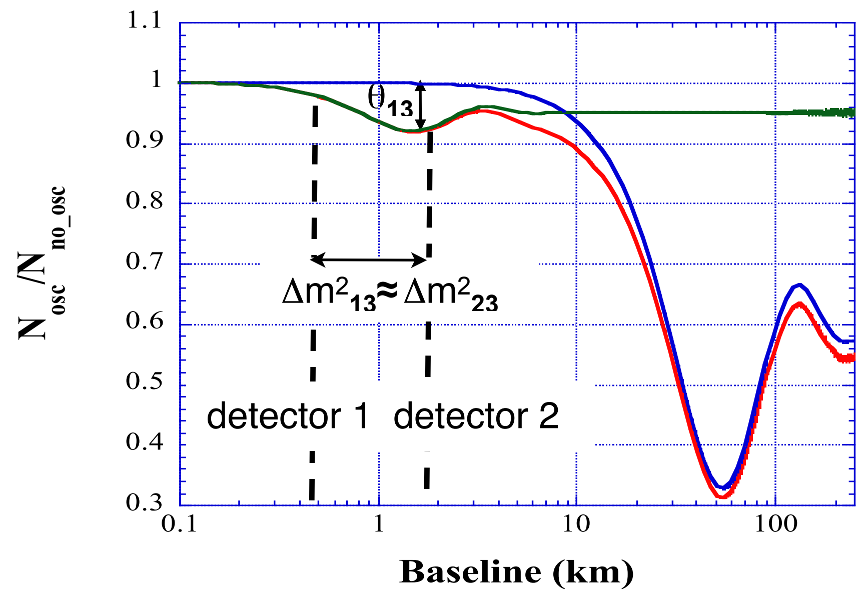




$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

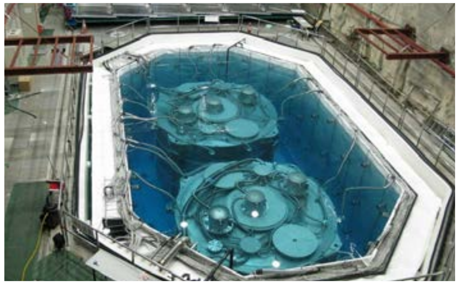
Absolute Reactor Flux
Largest uncertainty in previous measurements

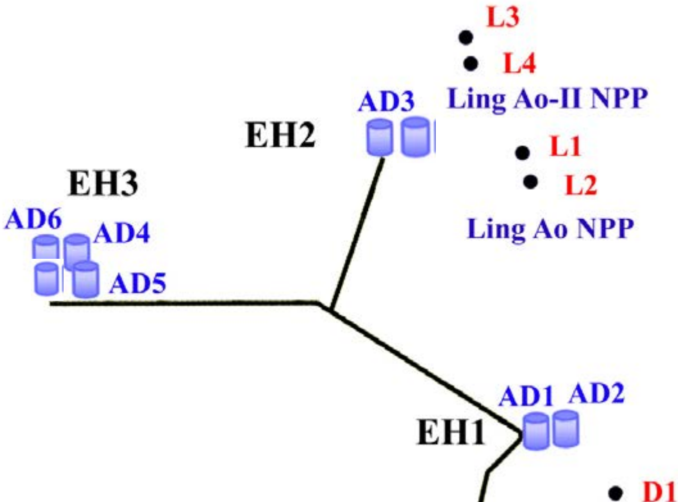
Relative Measurement
Removes absolute uncertainties!



relative measurement (largely) cancels reactor systematics

Daya Bay Reactor Experiment



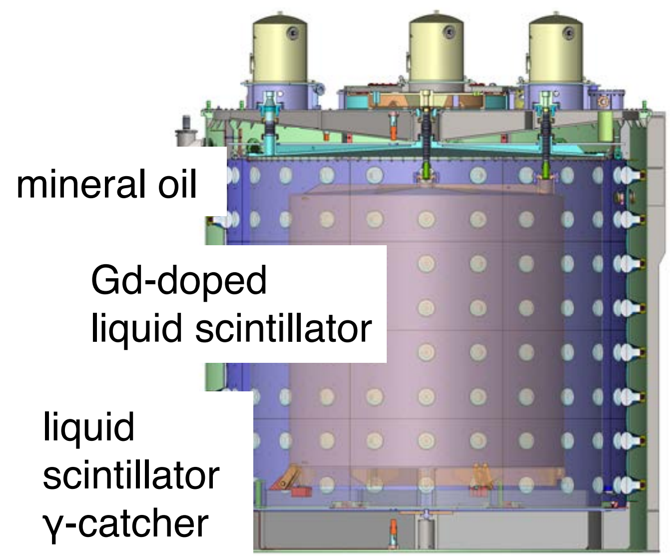


six 2.9 GW_{th} reactors

6 detectors, Dec 2011- Jul 2012

now running with 8 detectors

Antineutrino Detector

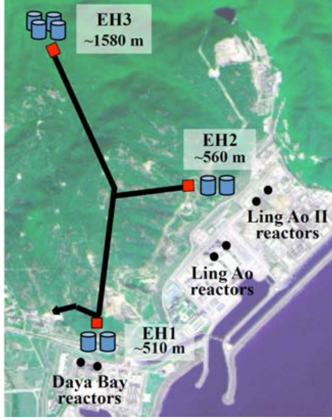


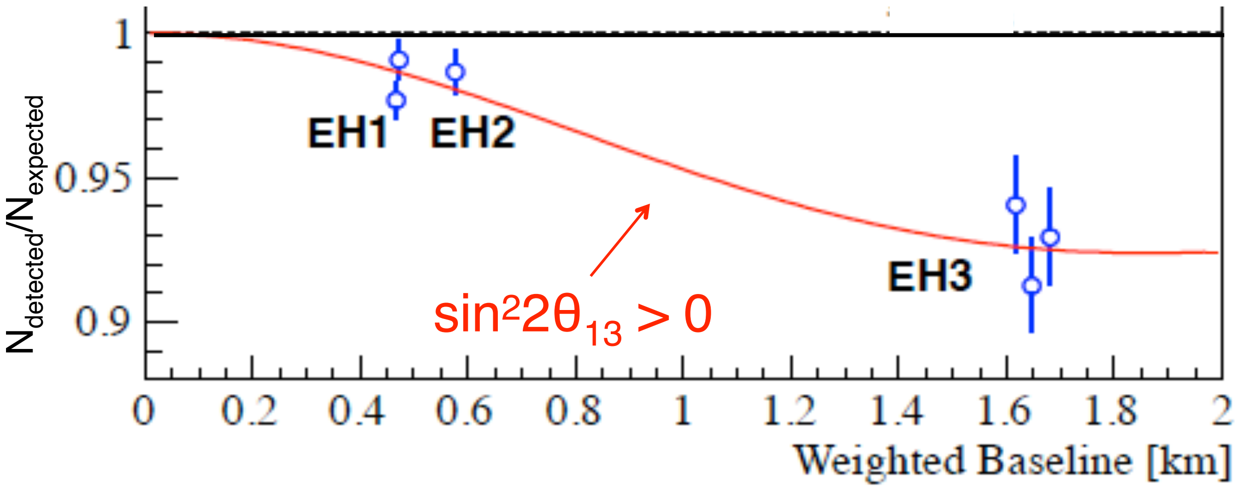
target mass: 20 ton per AD
photosensors: 192 8”-PMTs
energy resolution: $(7.5 / \sqrt{E} + 0.9)\%$

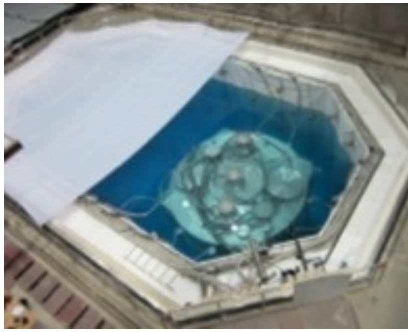

应堆中微子实验

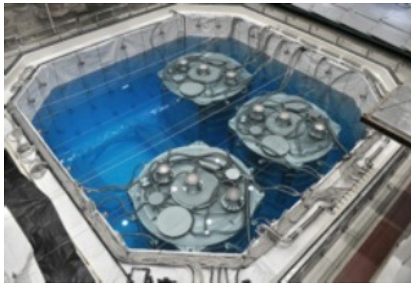
Observation of $\overline{\nu}_e$ Disappearance

Based on 55 days of data with 6 ADs, discovered disappearance of reactor $\overline{\nu}_e$ at short baseline. [PRL **108**, 171803]









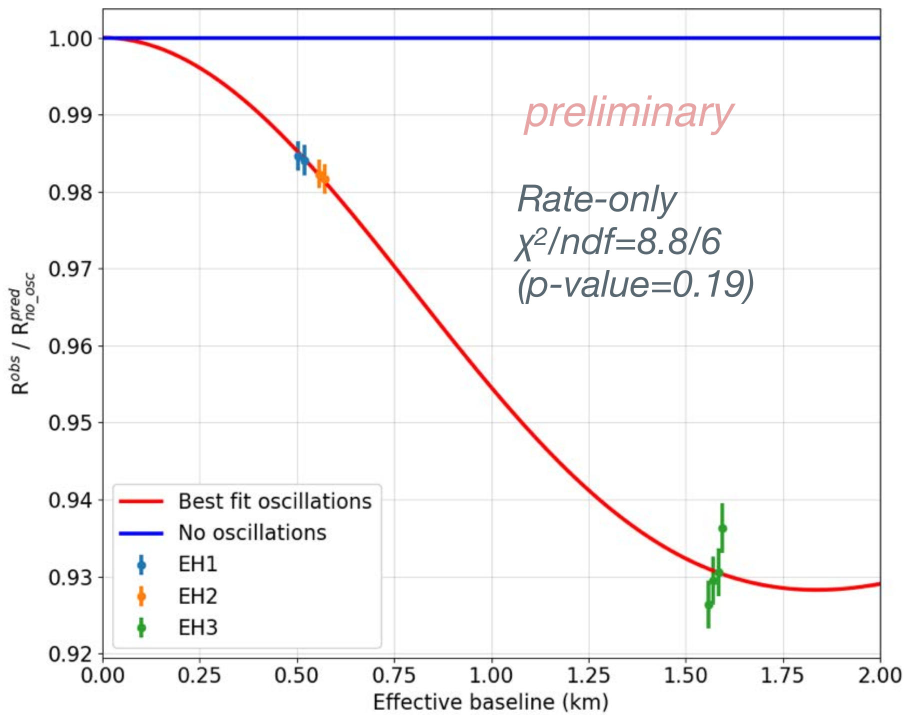
Obtained the most precise value of θ_{13}:

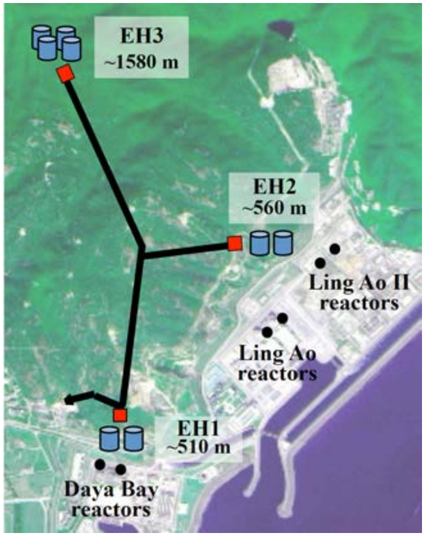
$\sin^2 2\theta_{13} = 0.089 \pm 0.010 \pm 0.005$ [CPC **37**, 011001]

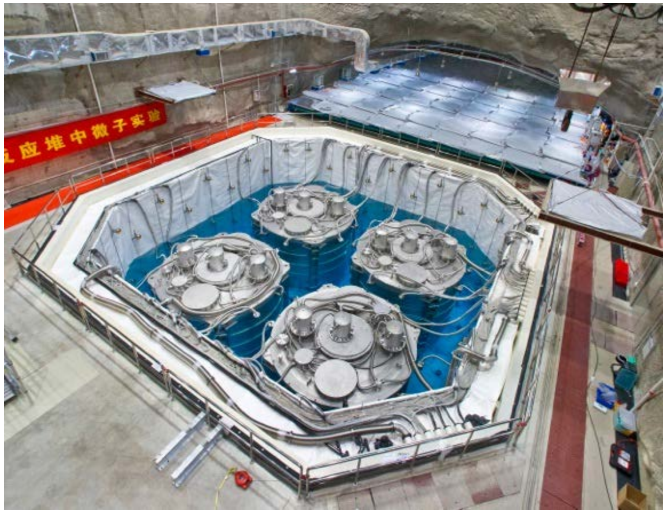
2012 *- One of Science's breakthroughs of year*
2015 *- Breakthrough Prize in Fundamental Physics*

Daya Bay Neutrino Oscillation (1958 Days)

- See a clear rate and shape distortion that fits well to the 3-neutrino hypothesis:

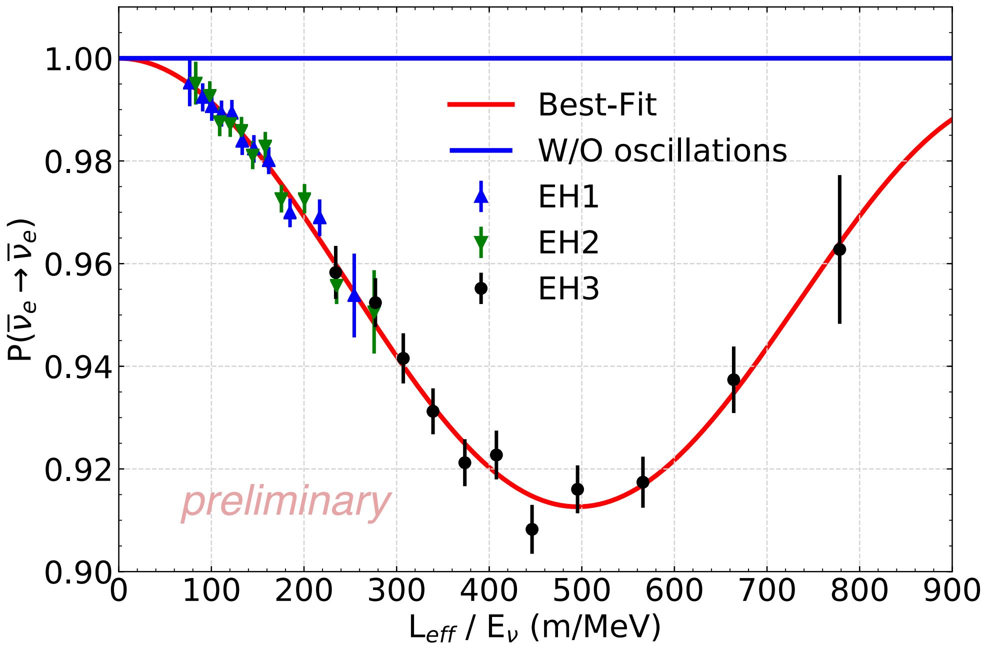


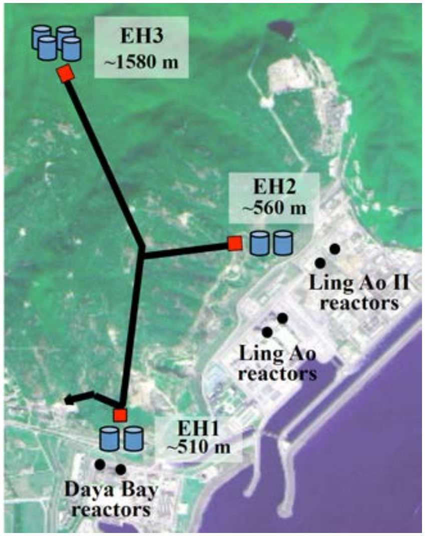


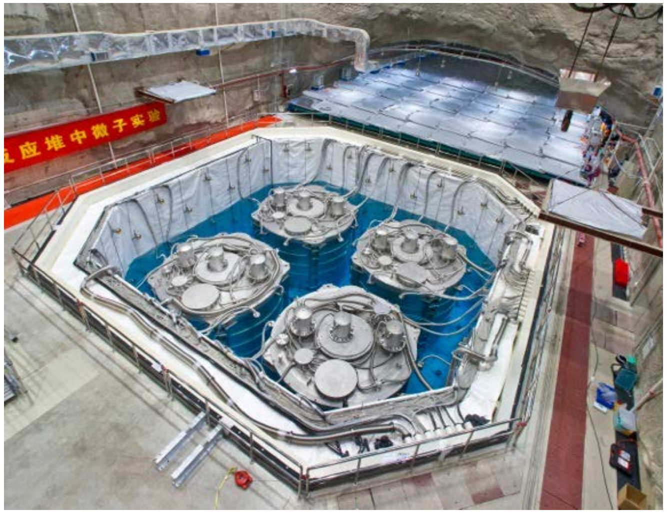


Nothing abnormal found with two far ADs whose rates deviate from best-fit

Daya Bay Neutrino Oscillation (1958 Days)







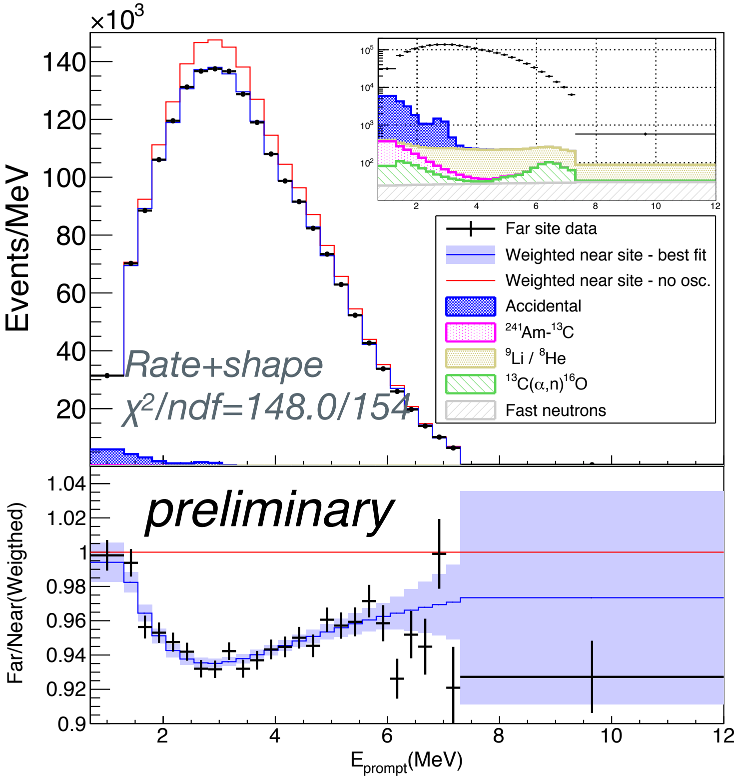
$$P_{i \rightarrow j} = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

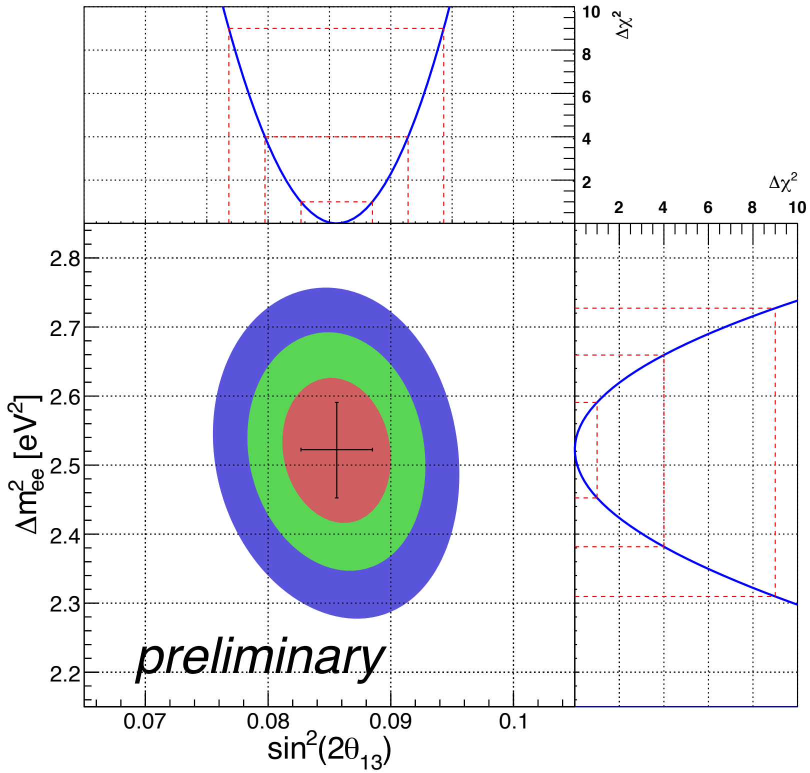
Neutrino oscillation is energy and baseline dependent

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

Daya Bay Neutrino Oscillation (1958 Days)

nGd Analysis





$\sin^2 2\theta_{13}$ uncertainty: 3.4%

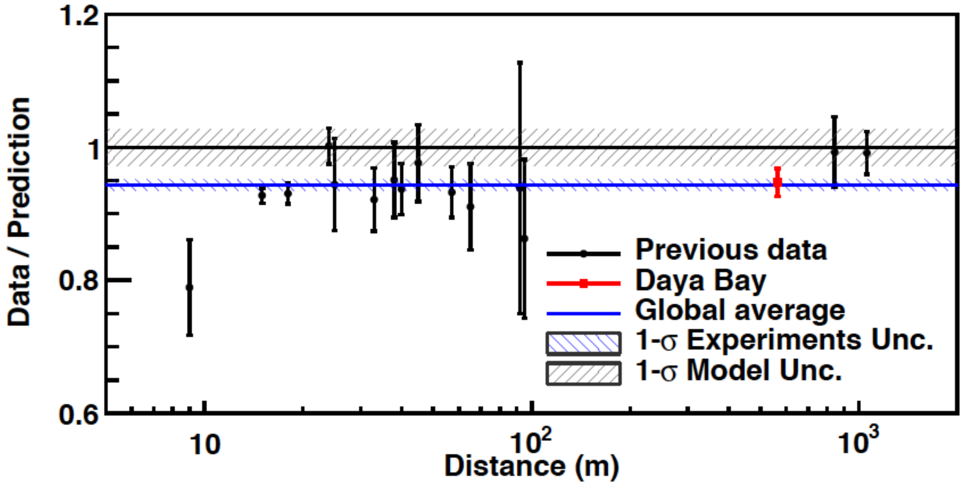
$|\Delta m^2_{32}|$ uncertainty: 2.8%

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

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

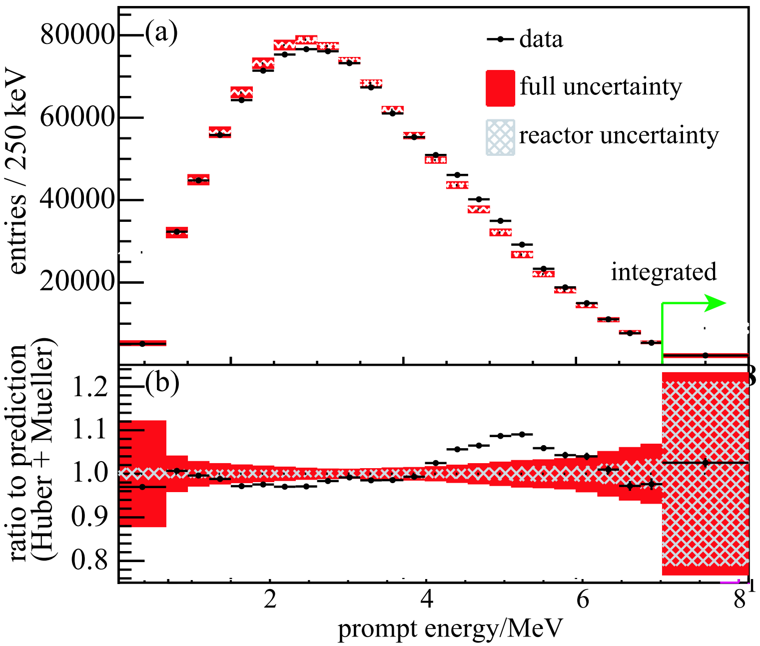
Reactor Antineutrino “Anomalies” (RAA)

Flux Deficit



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

Spectral Deviation



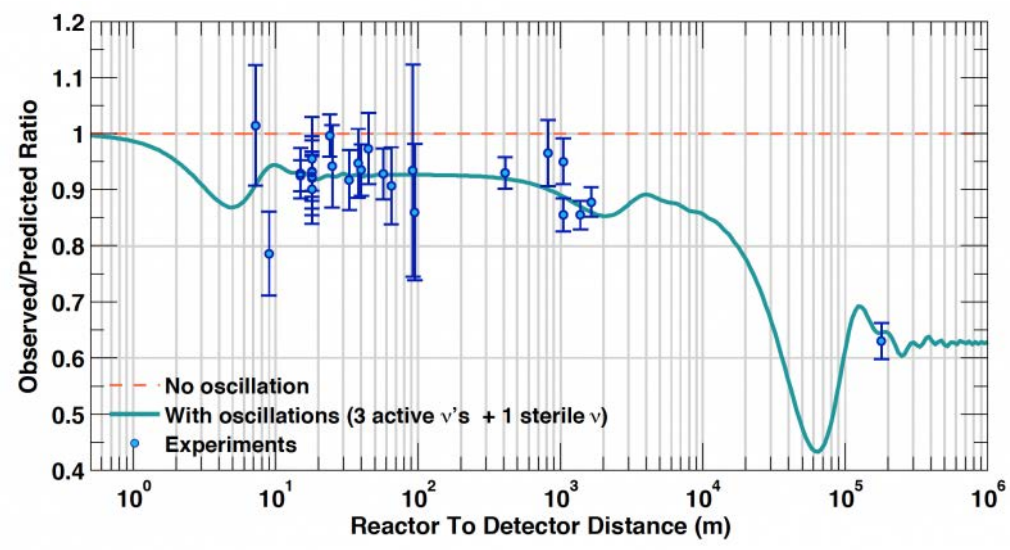
Measured spectrum does not agree with predictions.

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

Understanding reactor flux and spectrum anomalies requires additional data

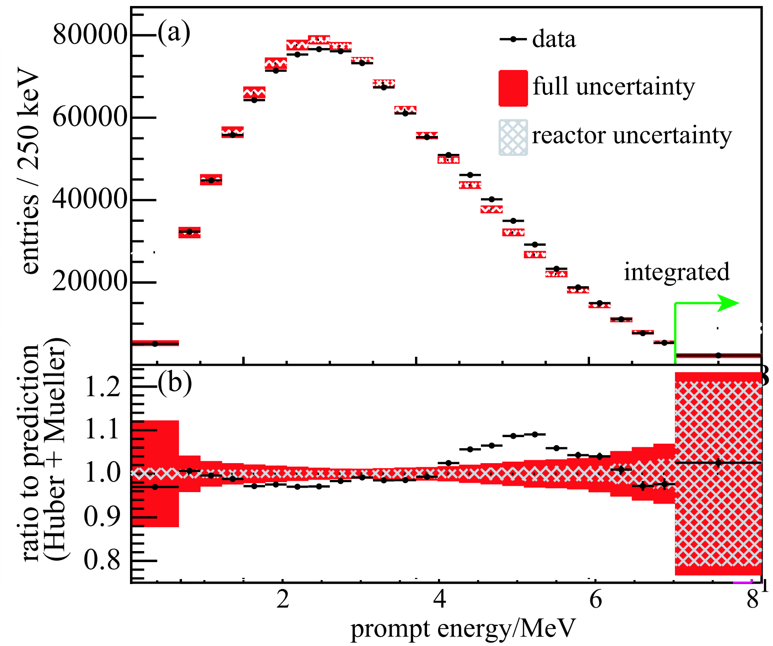
Reactor Antineutrino “Anomalies” (RAA)

Flux Deficit



Phys. Rev. D 83, 073006 (2011)

Spectral Deviation



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

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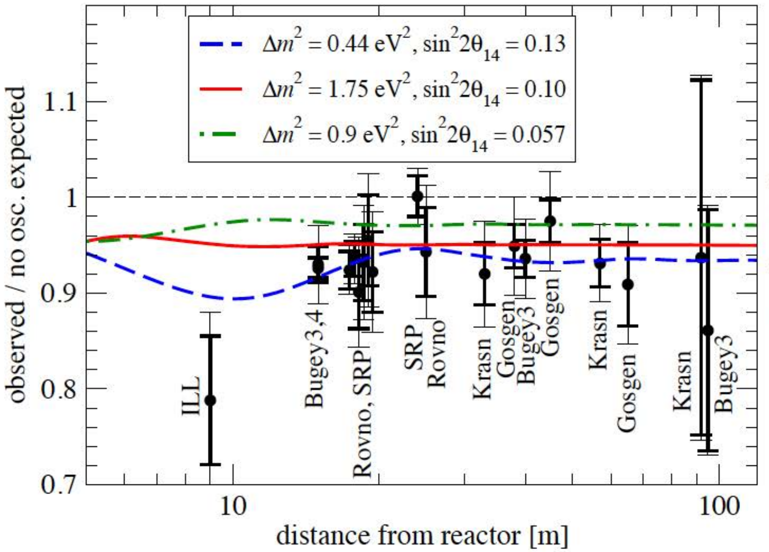
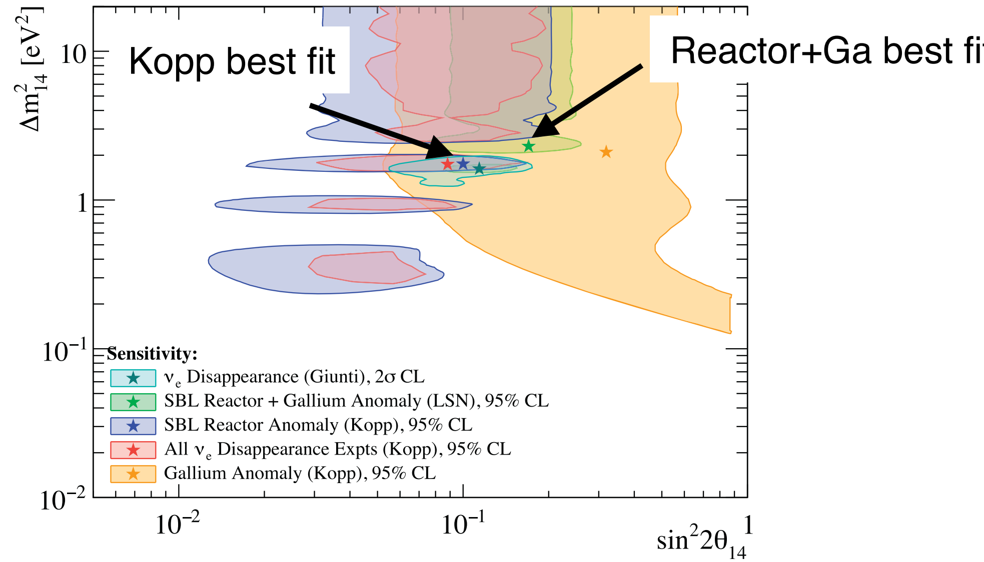
Reactor Antineutrino Flux Deficit

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



$\overline{\nu}_e$ disappearance data



PROSPECT J. Phys. G: 43 (2016)

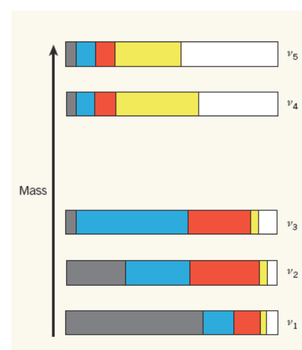
2011 reanalysis of the predicted reactor flux in tension with global data

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

new oscillation signal requires:

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

"sterile" neutrino states



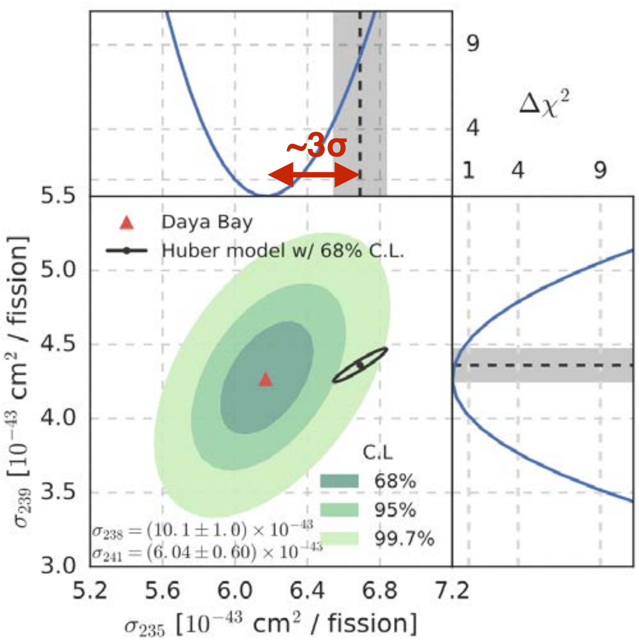
$\Delta m^2_{new} \sim 1\ eV^2$

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

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

Daya Bay Fuel Evolution Analysis

Daya Bay, PRL 118 251801 (2017)



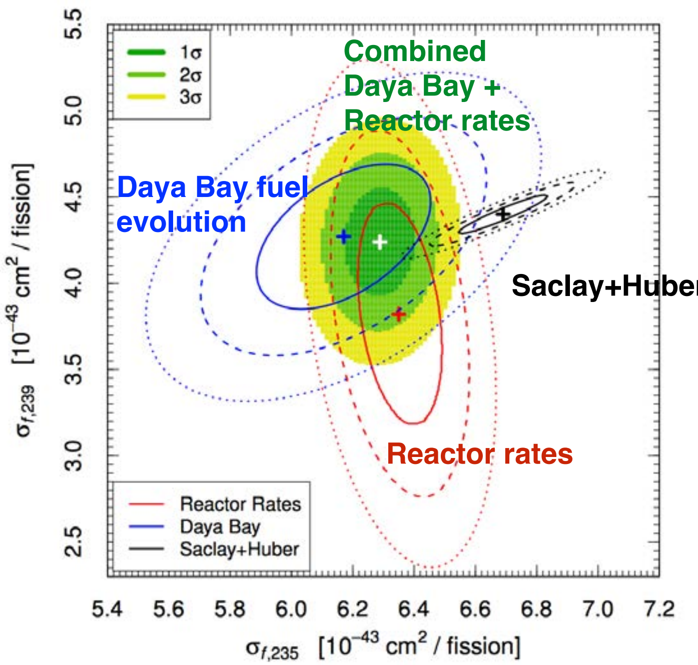
Daya Bay reported IBD yields of ^{235}U and ^{239}Pu using evolution of LEU reactors. Reactor flux model found to be incorrect for ^{235}U.

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



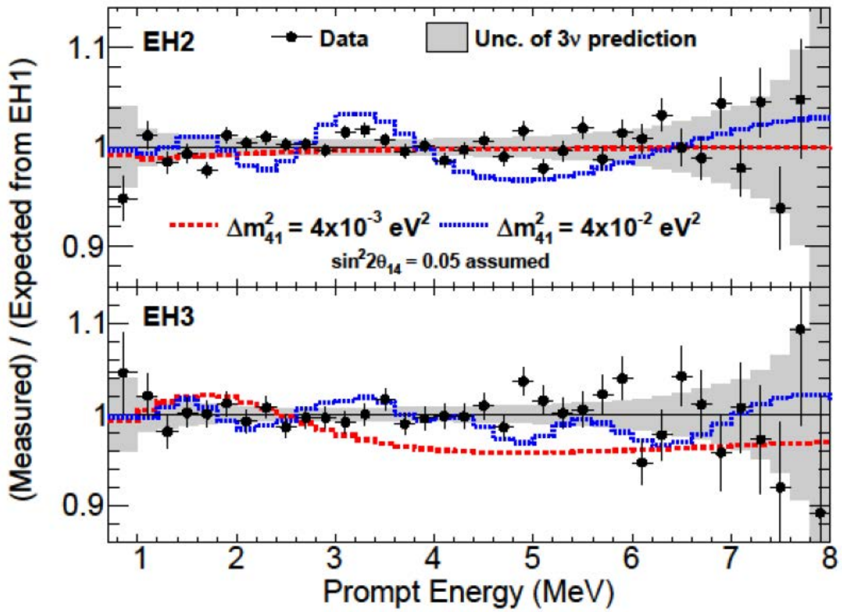
IBD yields calculated from reactor rates (of 26 reactor experiments) do not agree with Daya Bay measurement.

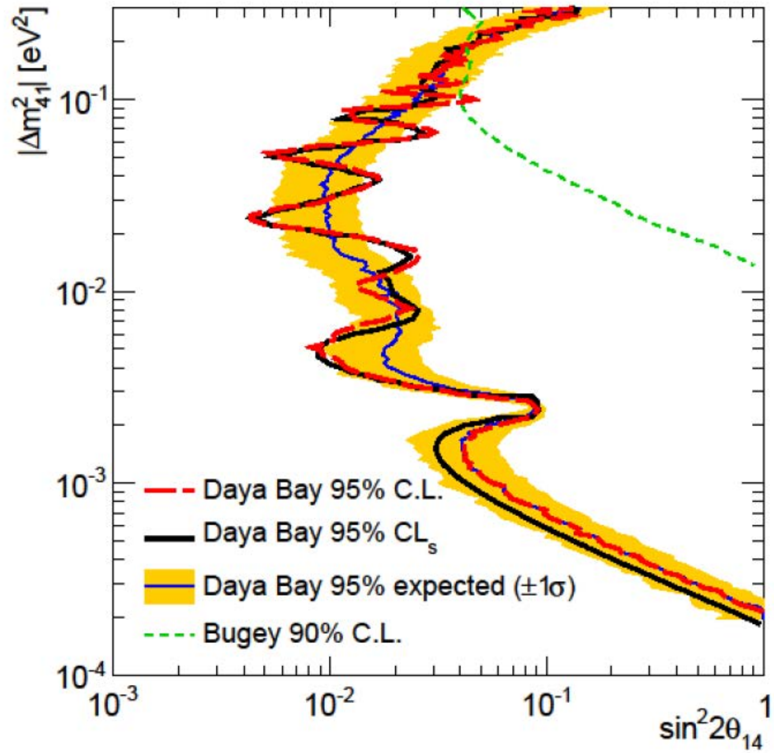
"not enough information to use the antineutrino flux changes to rule out the possible existence of sterile neutrinos"

Sterile Neutrino Search: Daya Bay

$$P_{ee} \approx 1 - \cos^4\theta_{14}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{ee}L}{4E}\right) - \sin^2 2\theta_{14}\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right)$$

sterile neutrinos would appear as additional spectral distortion and overall rate deficit



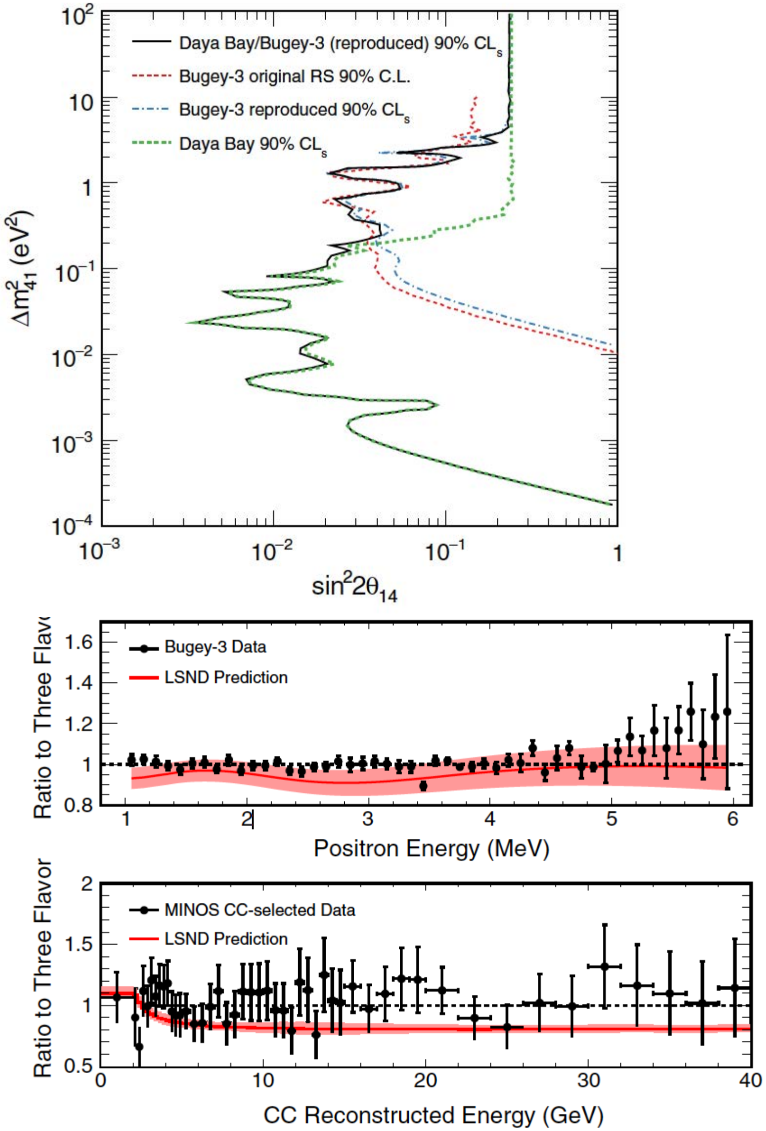


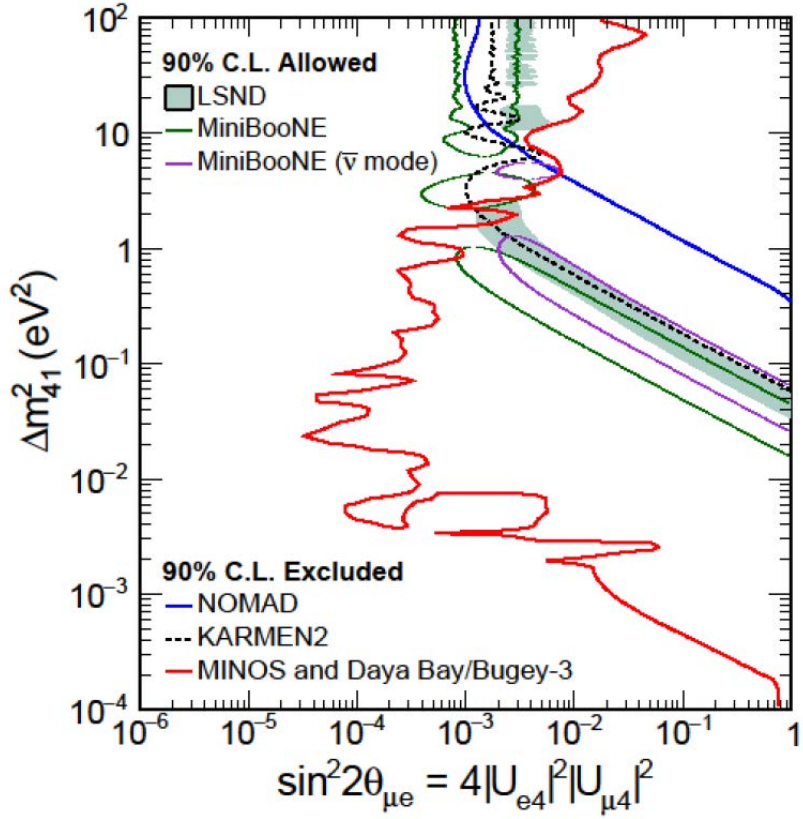
No hint of light sterile neutrino

Most stringent limit for $\Delta m^2_{41} < 0.1$ eV^2

Phys. Rev. Lett. 117, 151802 (2016)

Sterile Neutrino Search: Daya Bay+Minos+Bugey





Combined $\bar{\nu}_e$ disappearance of Daya Bay and Bugey with ν_μ disappearance of MINOS

Excluded parameter space allowed by MiniBooNE & LSND for $\Delta m^2_{41} < 0.8$ eV^2

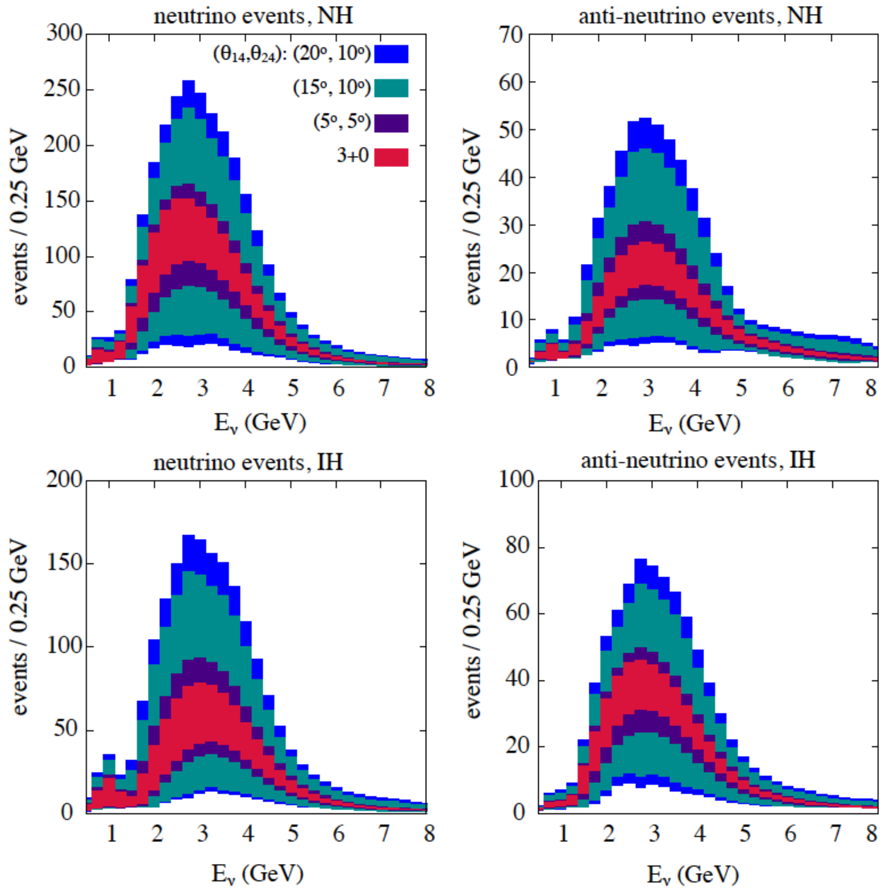
Phys. Rev. Lett. 117 (2016) no.15, 151801

Steriles and Future Neutrino Program

Discovery of eV-scale sterile neutrinos would be a paradigm change for particle physics.

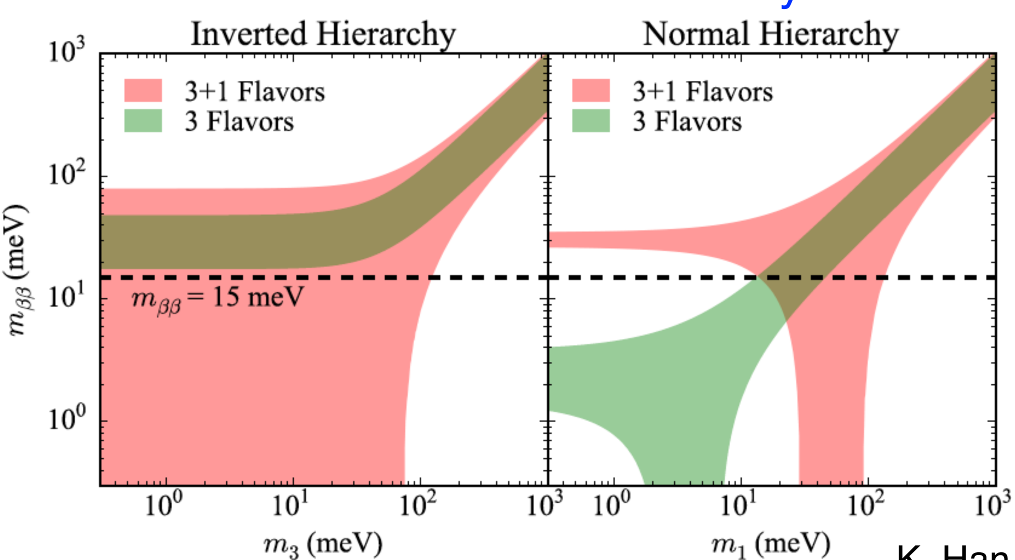
- Expected neutrino spectrum and sensitivity to CP violation for long-baseline neutrino program
- Effective neutrino mass measured by $0\nu\beta\beta$

DUNE



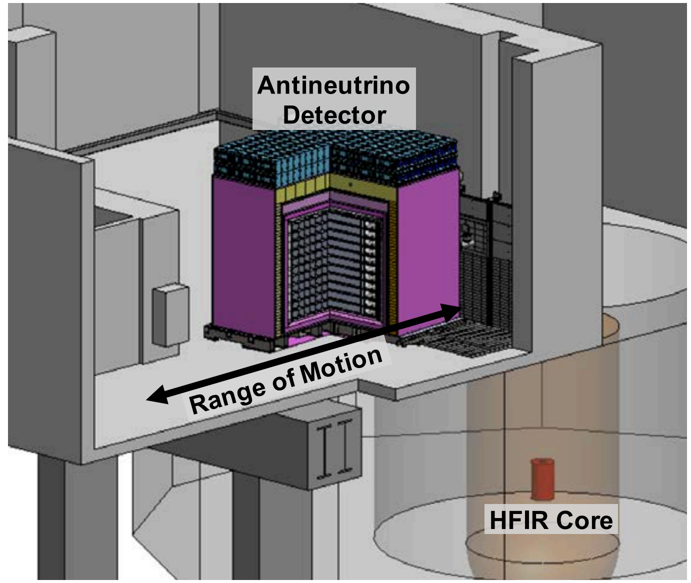
Gandhi, Kayser, Masud, Prakash arXiv: 1508.06275

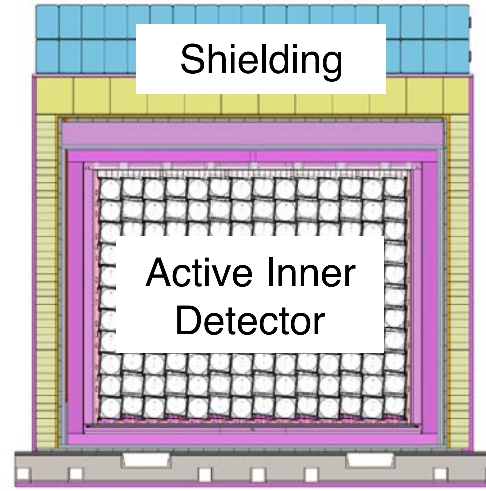
Neutrinoless Double Beta Decay



K. Han

Precision Oscillation and Spectrum Experiment

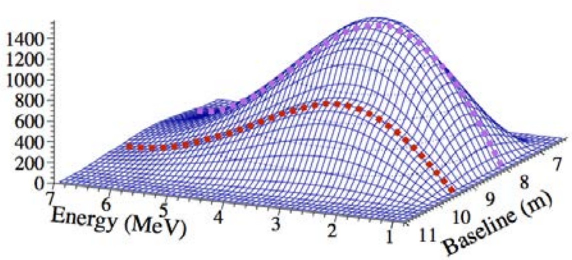




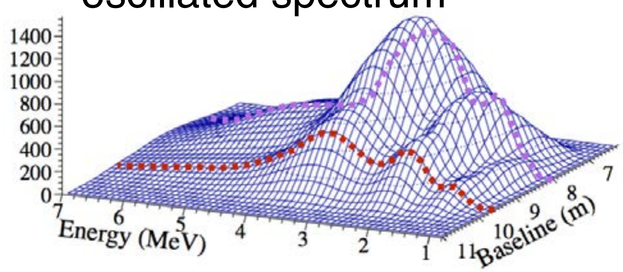
Objectives **Search for short-baseline oscillation at <10m**
Precision measurement of ^{235}U reactor $\overline{\nu}_e$ spectrum

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

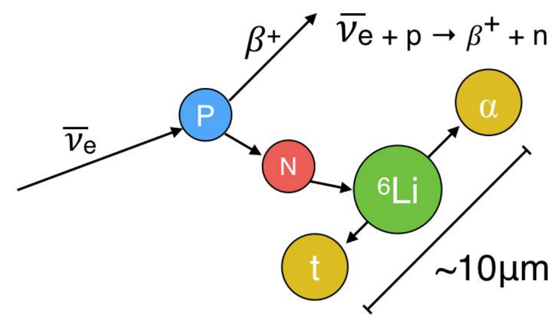
unoscillated spectrum



oscillated spectrum



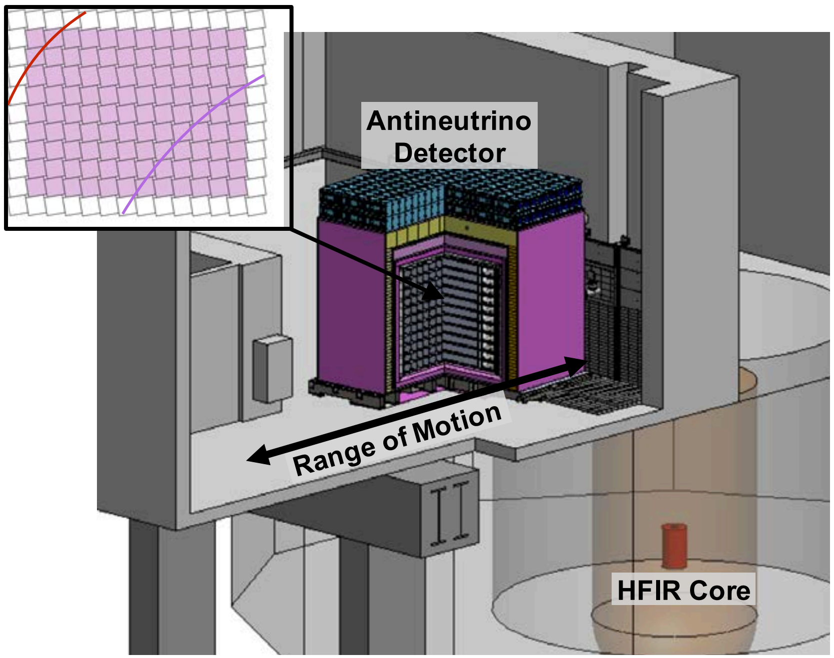
Segmented, ^{6}Li-loaded Detector

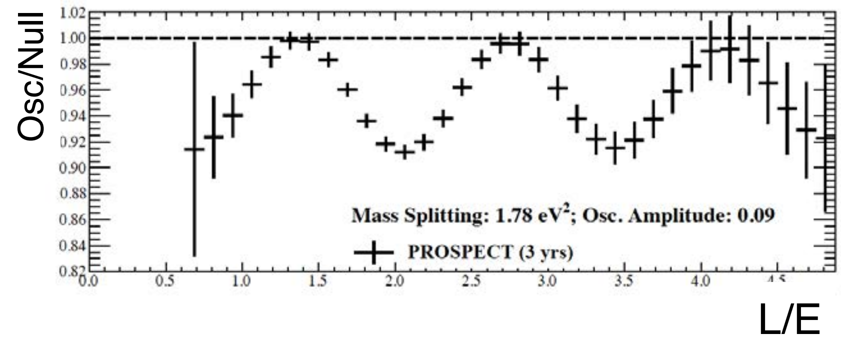


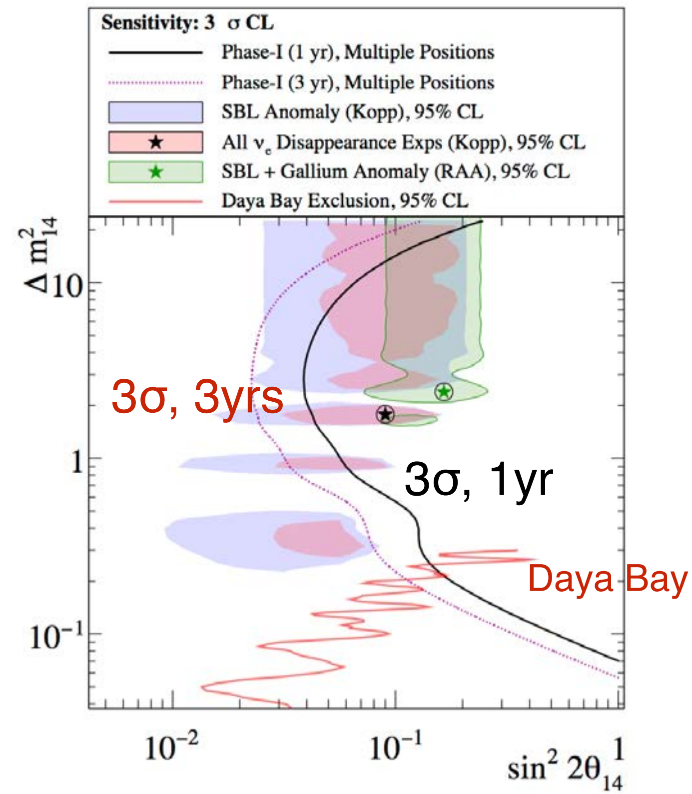
PROSPECT Physics

A Precision Oscillation Experiment

Model-independent test of oscillation of eV-scale neutrinos







Objectives

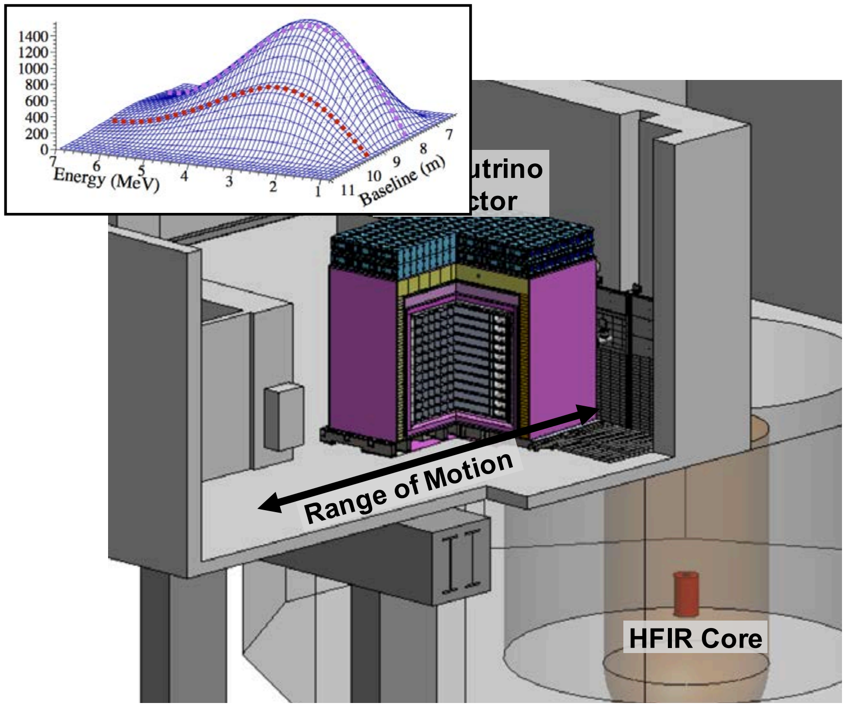
4σ test of best fit after 1 year

$>3\sigma$ test of favored region after 3 years

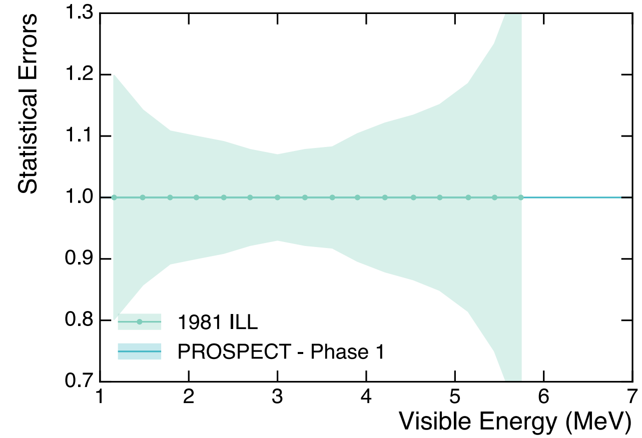
PROSPECT Physics

A Precision Spectrum Experiment

A precision measurement of spectrum



Improvement on ILL

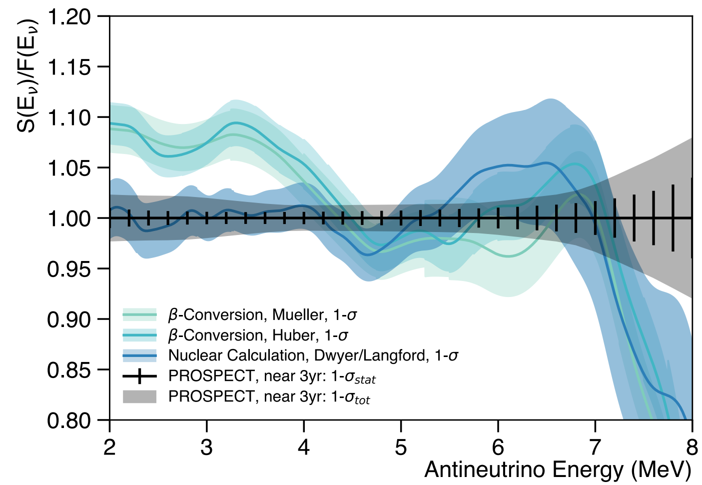


~100k events per year

~4.5%/√E

1981 ILL: ~5000 events

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

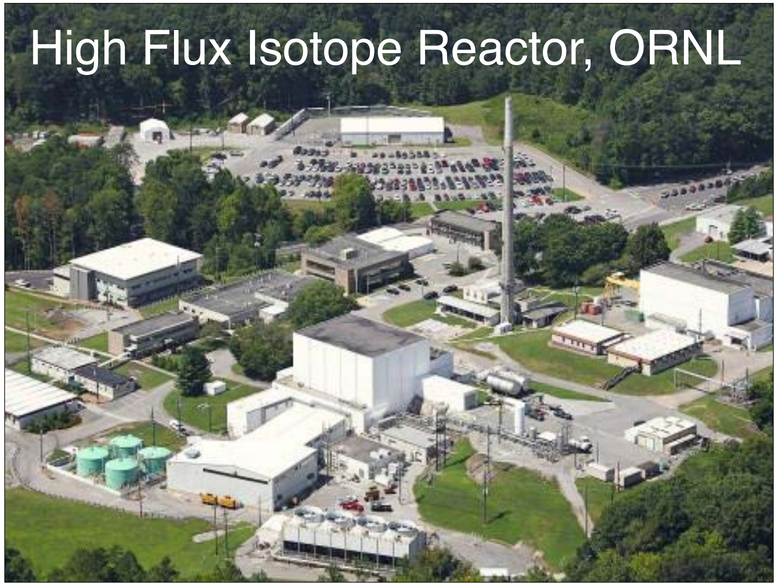


Objectives

Measurement of ^{235}U spectrum

Compare different reactor models

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 will have to operate 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**

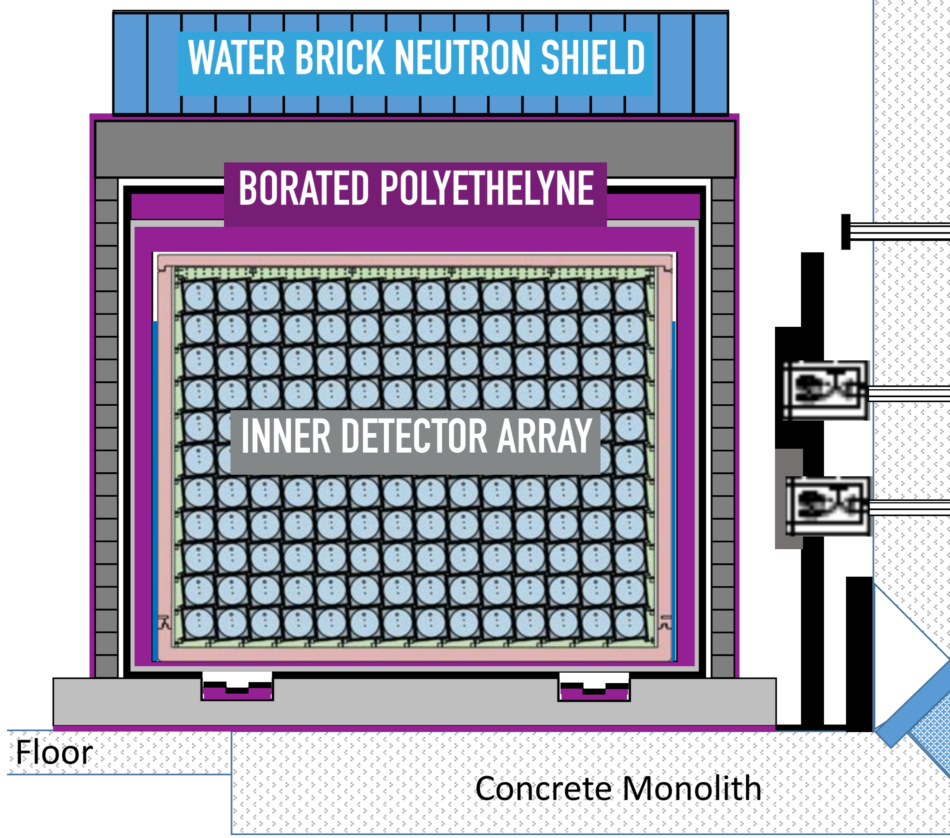
Very low mass separators (1.5 mm thick)

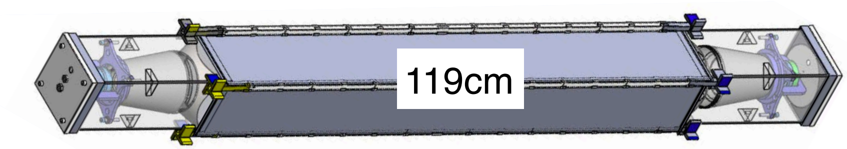
- Corner support rods allow for full *in situ* calibration access

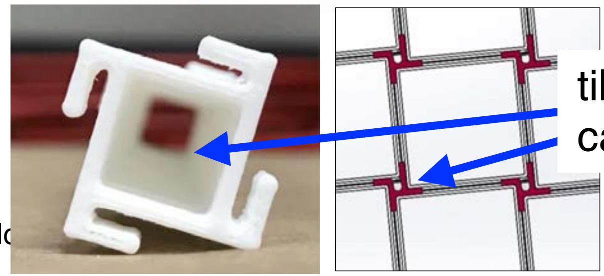
Double ended PMT readout, with light concentrators

- good light collection and energy response ~4.5-5%√E energy resolution
- full X,Y,Z event reconstruction

Optimized shielding to reduce cosmogenic backgrounds



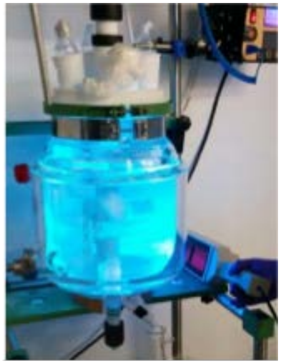




tilted array for calibration access

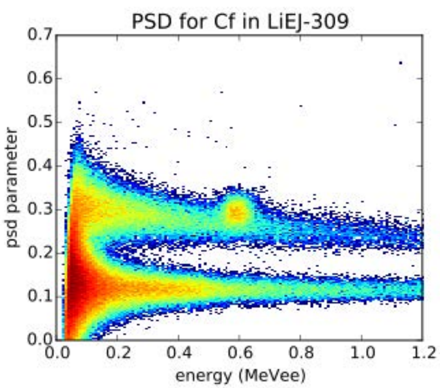
Inner Detector Components

^{6}Li Loaded Liquid Scintillator



Developed non-toxic, non-flammable formulation based on EJ-309

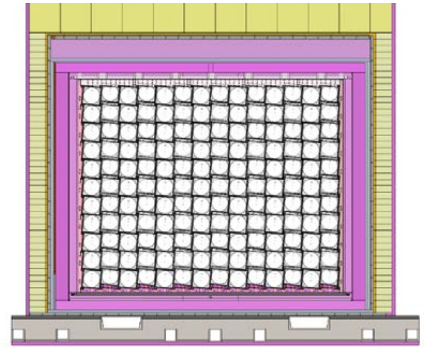
Light Yield
- EJ-309 base: 11500 ph/MeV
- LiLS: 8200 ph/MeV



Excellent PSD performance for neutron capture & heavy recoils

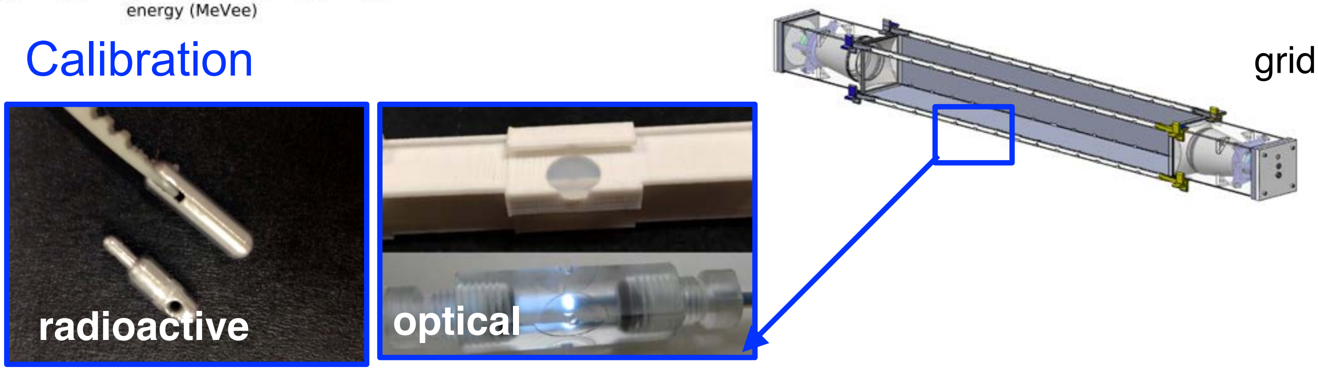
0.1% ^{6}Li loading

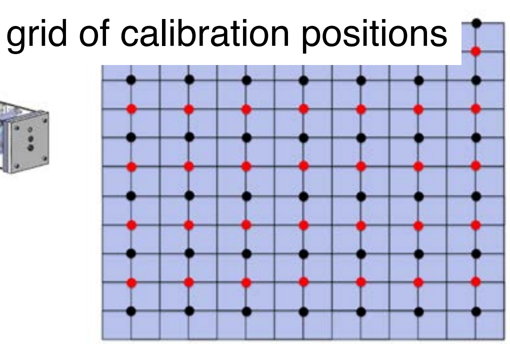
Low mass optical separators



High reflectivity, high-rigidity, low mass reflector system developed

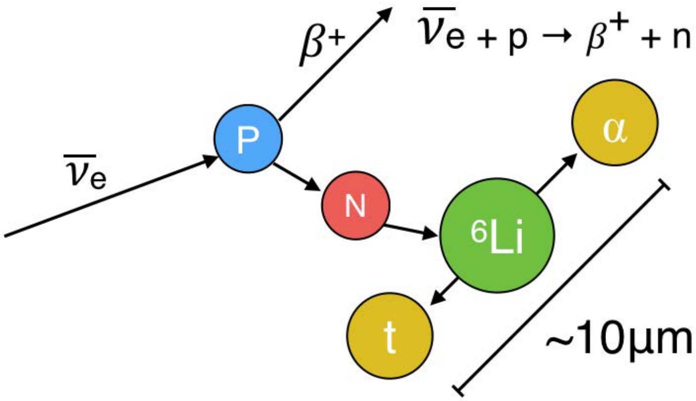
Calibration





Antineutrino Event Identification with ^{6}Li

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

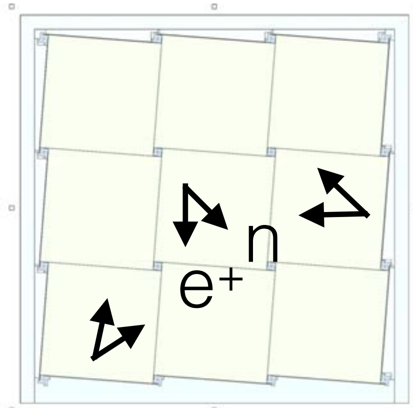
accidental gamma
γ-like prompt, γ-like delay

Background reduction is key challenge

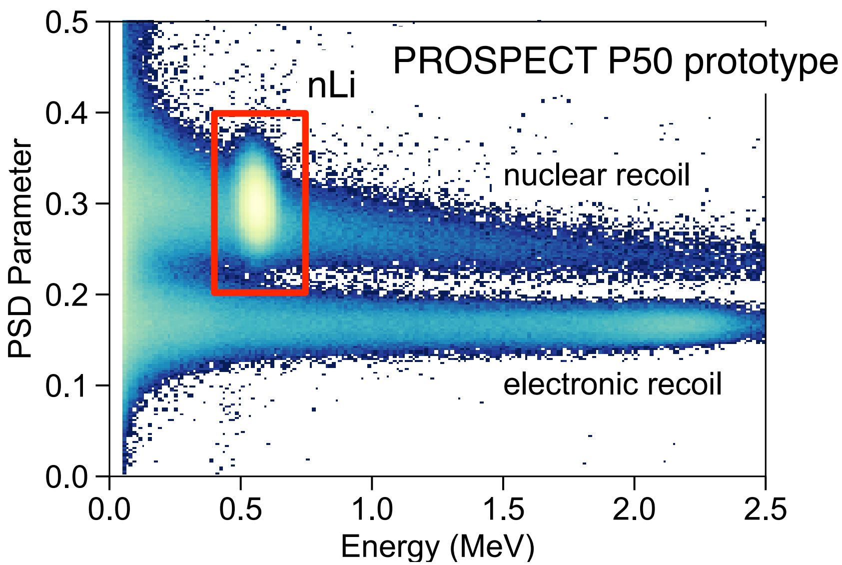
Background Reduction

detector design & fiducialization

IBD event in segmented ^{6}LiLS detector



Pulse Shape Discrimination



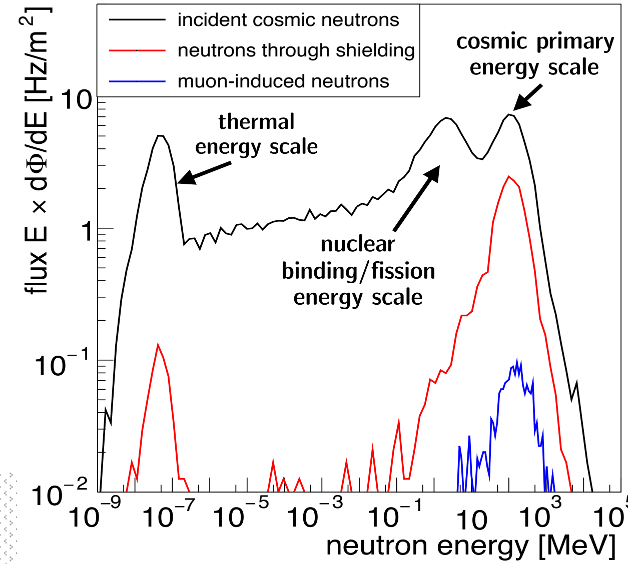
PROSPECT,arXiv:1805.09245

Backgrounds & Shield Design

On-site Measurements

Characterize background field at HFIR, develop localized shielding

PROSPECT, Nucl. Instrum. Meth. A806 (2016) 401–419



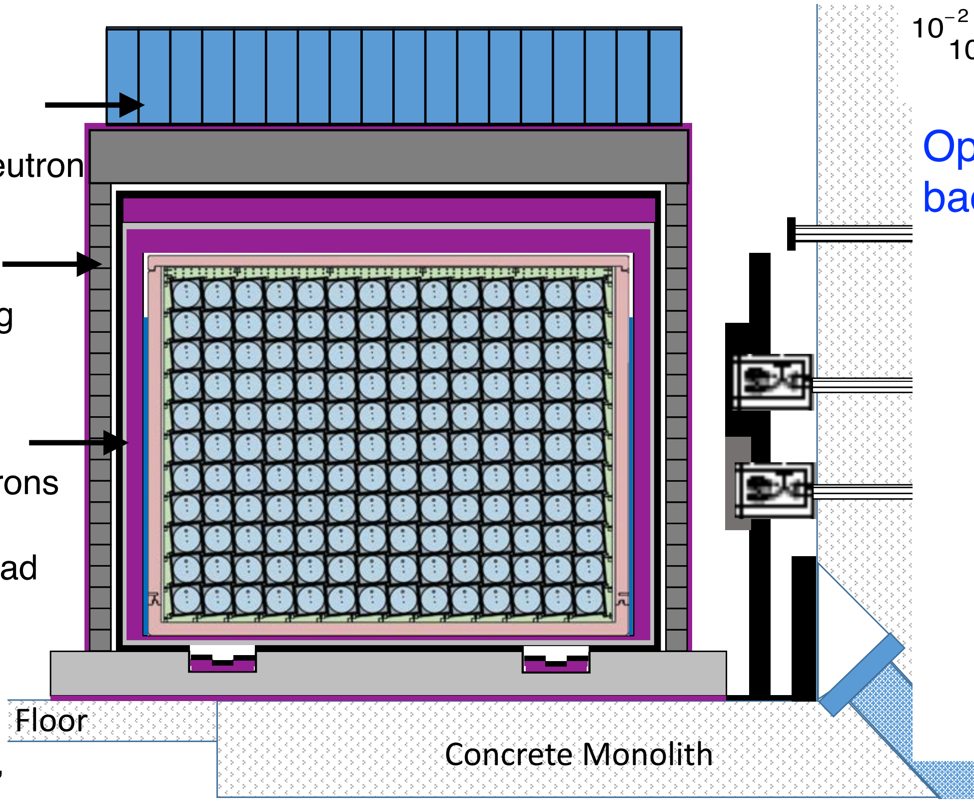
PROSPECT Shielding

local shielding next to reactor wall
multi-layer passive shield:
water bricks, HDPE, borated HDPE, lead

Water bricks
Polyethylene
Outer neutron shielding for neutron moderation

Lead
High Z shielding

Inner Neutron Shielding
Suppress neutrons produced from spallation on lead



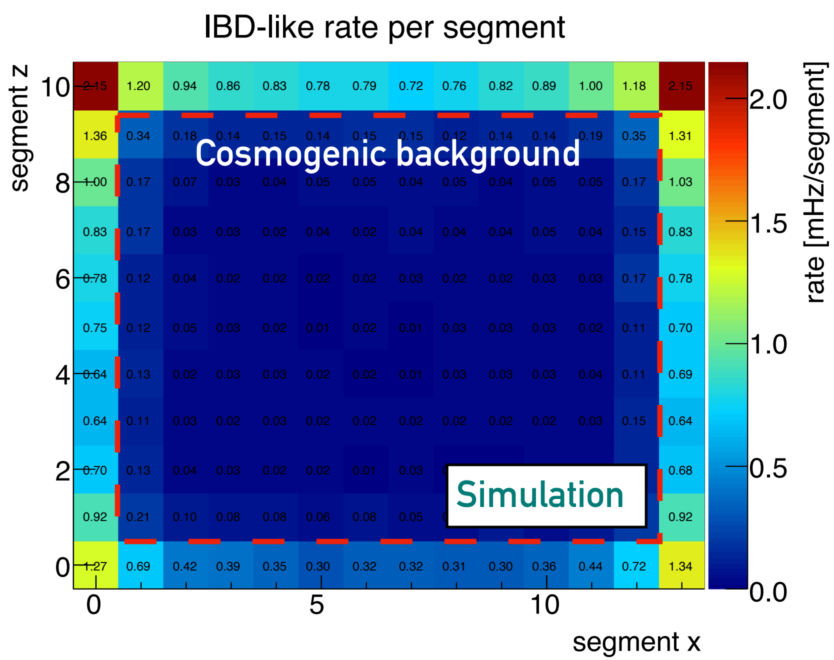
Optimize space, weight, and total background suppression

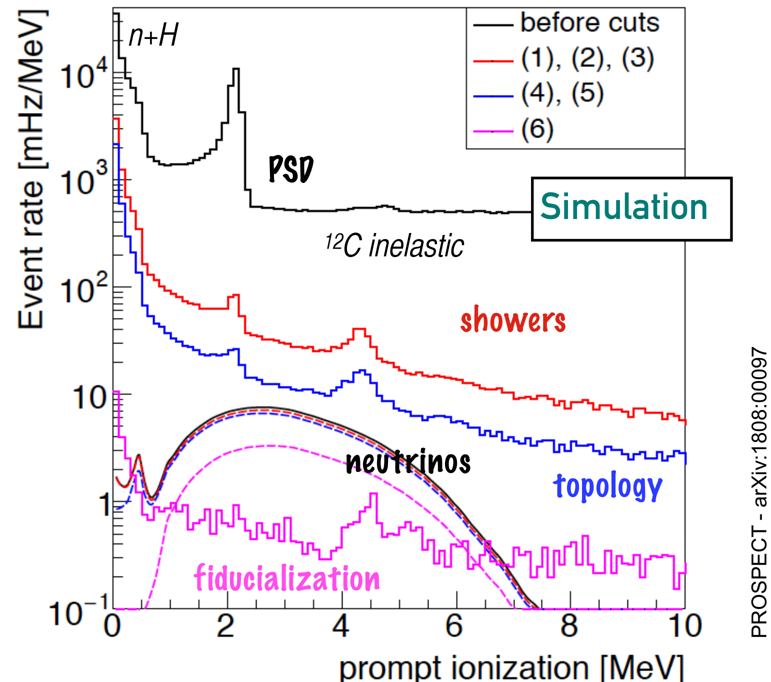
Main problem is ~100MeV neutrons, create majority of IBD-like backgrounds (gamma-like prompt, neutron capture)

Neutron spallation on high-Z shielding increases backgrounds

Need neutron shielding inside lead shielding

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

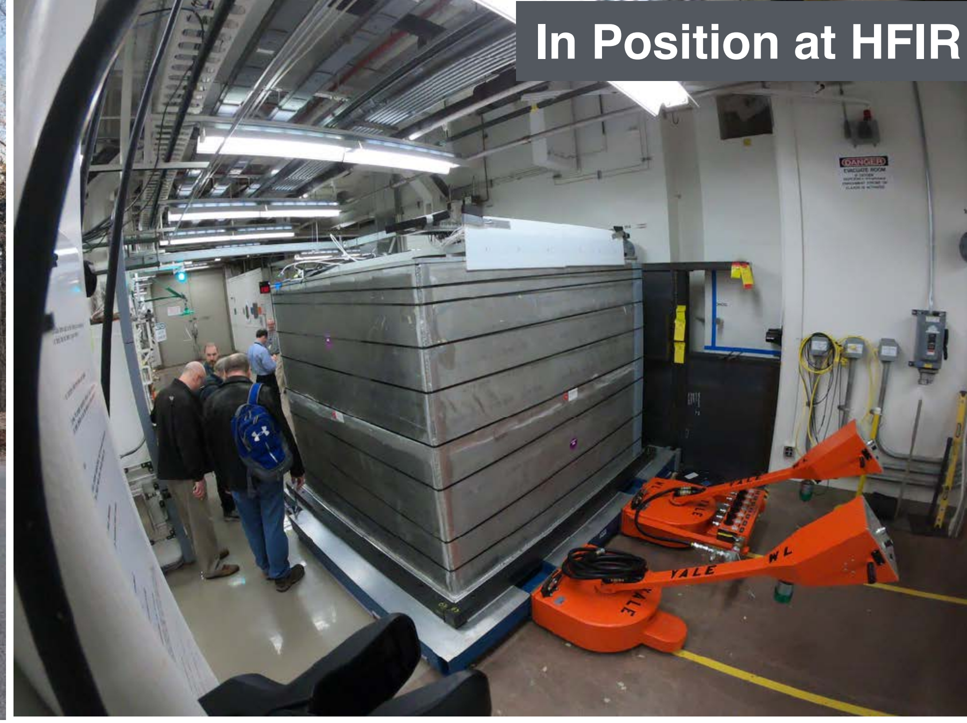
Final Row Installation
November 17, 2017

Wright Laboratory

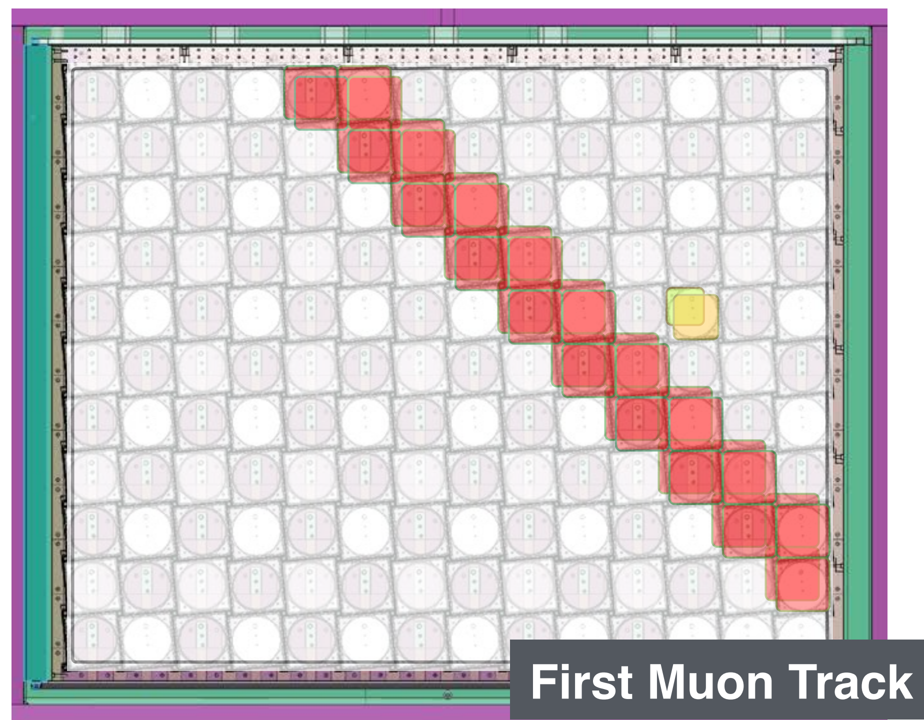
Dry Commissioning
Dec 2017 - Jan 2018

Wright Laboratory

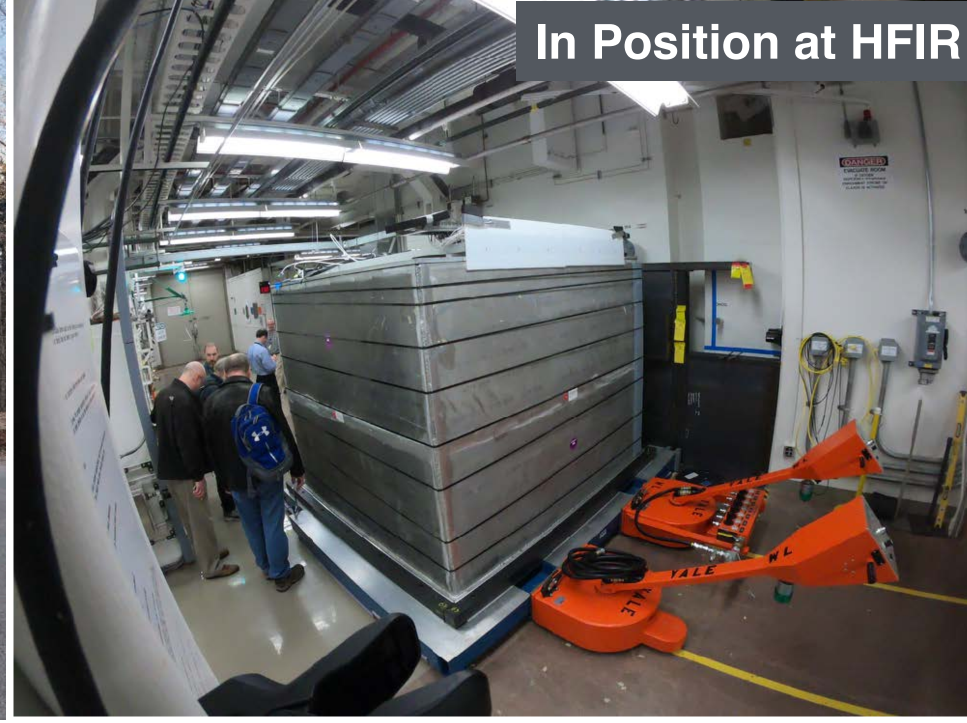

February 2018
Arrival at ORNL


In Position at HFIR


Filling from Mixing Tank


First Muon Track

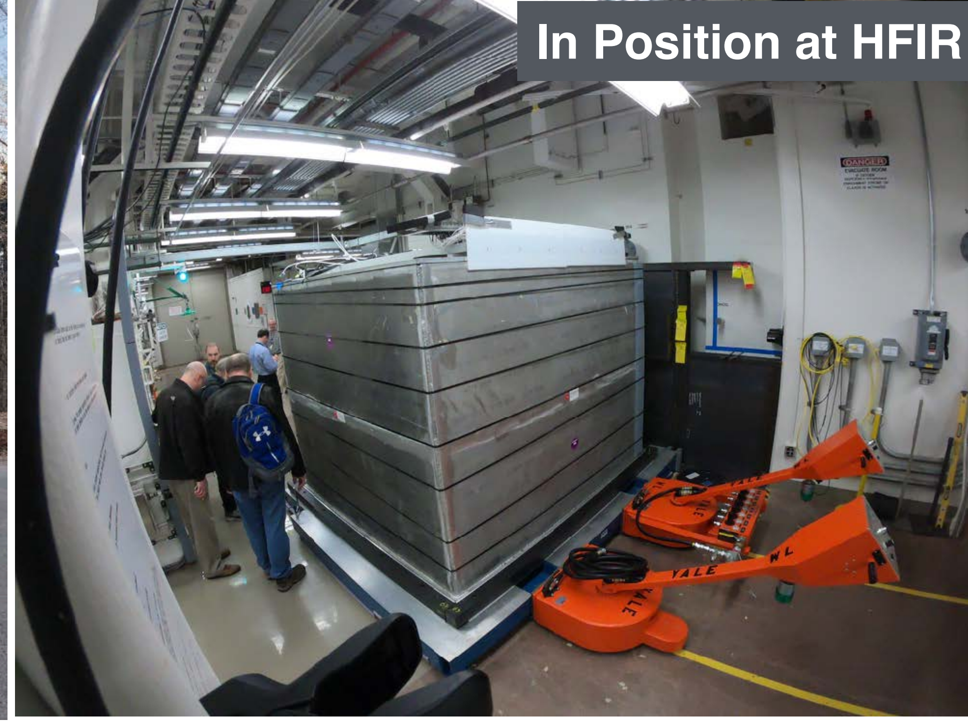

February 2018
Arrival at ORNL


In Position at HFIR
YALE

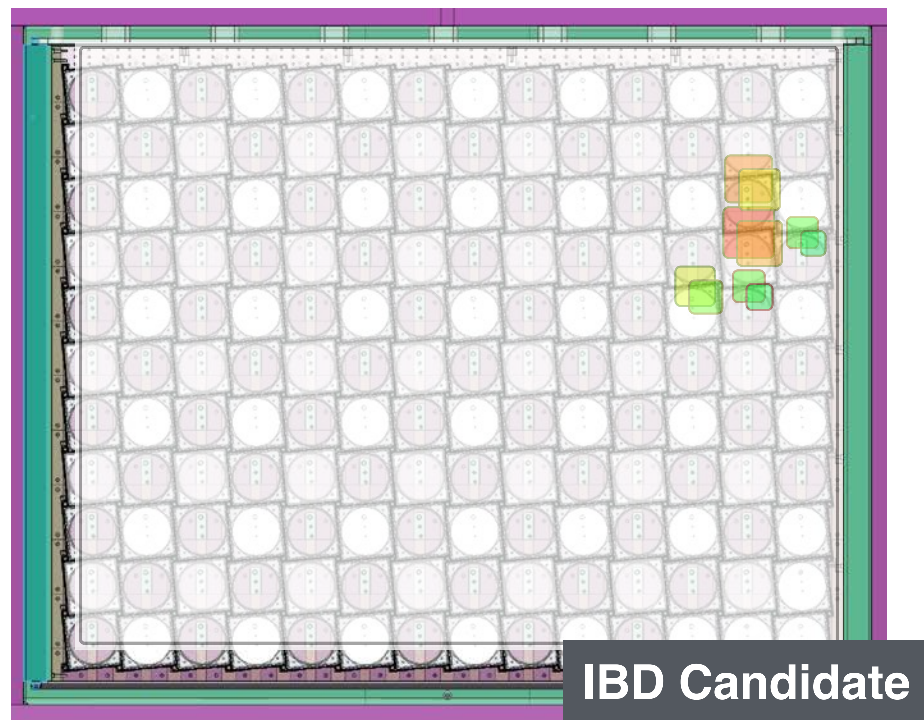

Filling from Mixing Tank
DANGER


Hadronic Shower


February 2018
Arrival at ORNL


In Position at HFIR

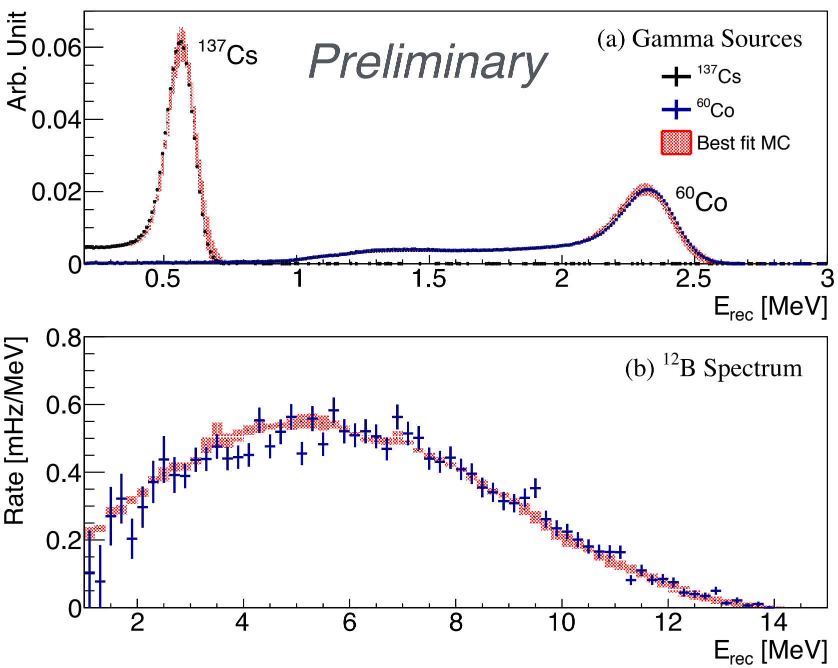

Filling from Mixing Tank


IBD Candidate

Energy Reconstruction

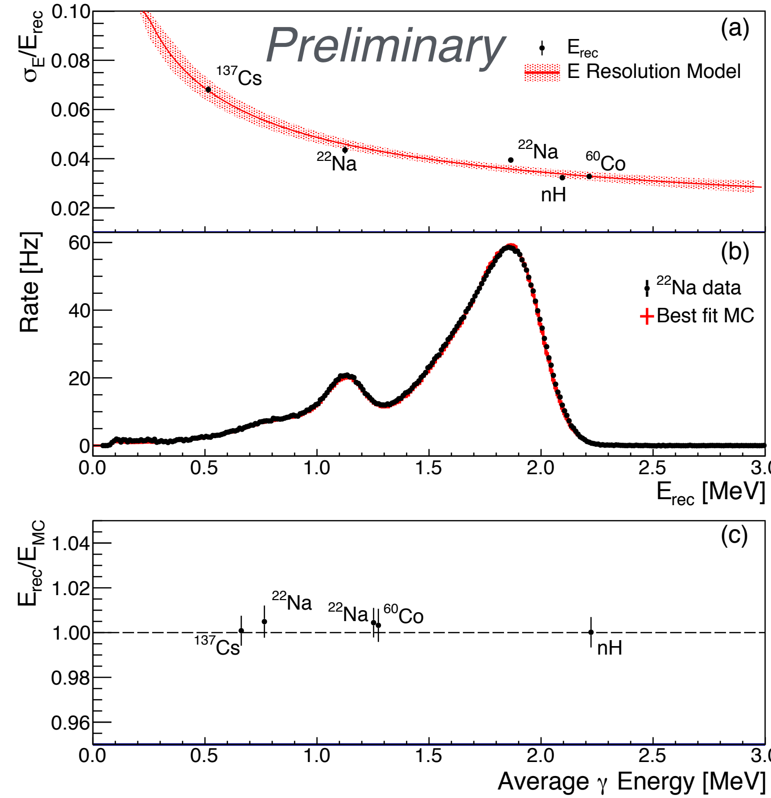
Gamma sources (**^{137}Cs, ^{60}Co, ^{22}Na**) deployed throughout detector, measure single segment response

Fast-neutron tagged ^{12}B: High-energy beta spectrum calibration



PROSPECT,arXiv:1806.02784

Resolution and Reconstruction



E[MeV]

MC/data for calibration peaks agrees to better than 1σ

Full-detector E_{rec} within ±1% of E_{true}

High light collection: 795±15 PE/MeV

First 24hrs of Detector Operation

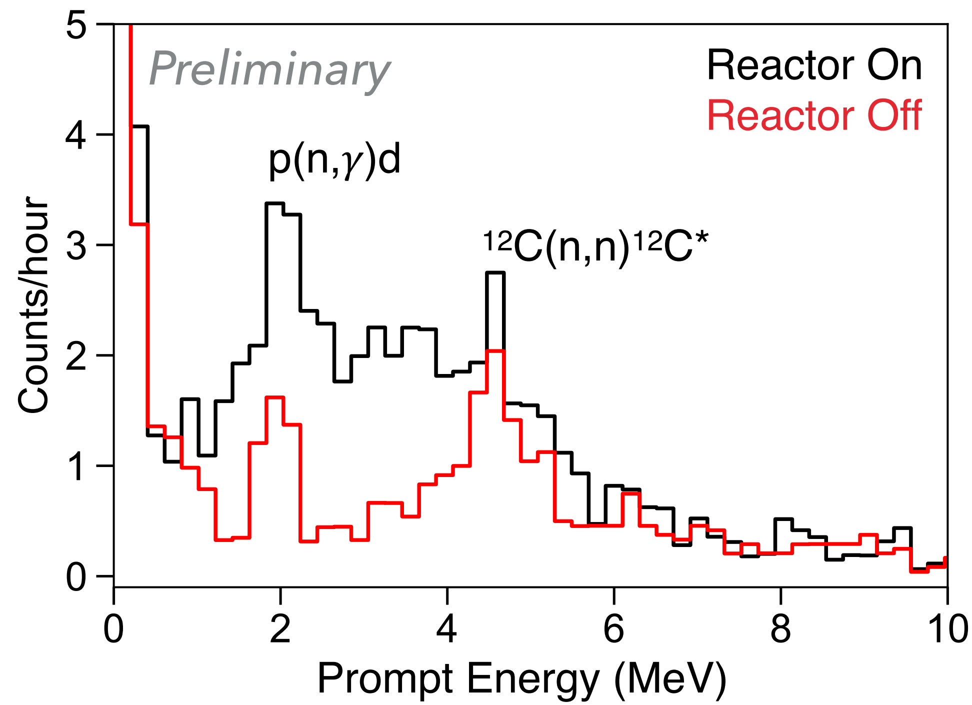
March 5, 2018: Fully assembled detector began operation

Reactor On: 1254±30 correlated events between [.8, 7.2MeV]

Reactor Off: 614±20 correlated events (first off day March 16)

Clear peaks in background from neutron interactions with H and ^{12}C

Time to 5σ detection at earth's surface: ~2hrs



PROSPECT measuring ^{235}U antineutrino spectrum

First Analysis Data Set

33 days of Reactor On

28 days of Reactor Off

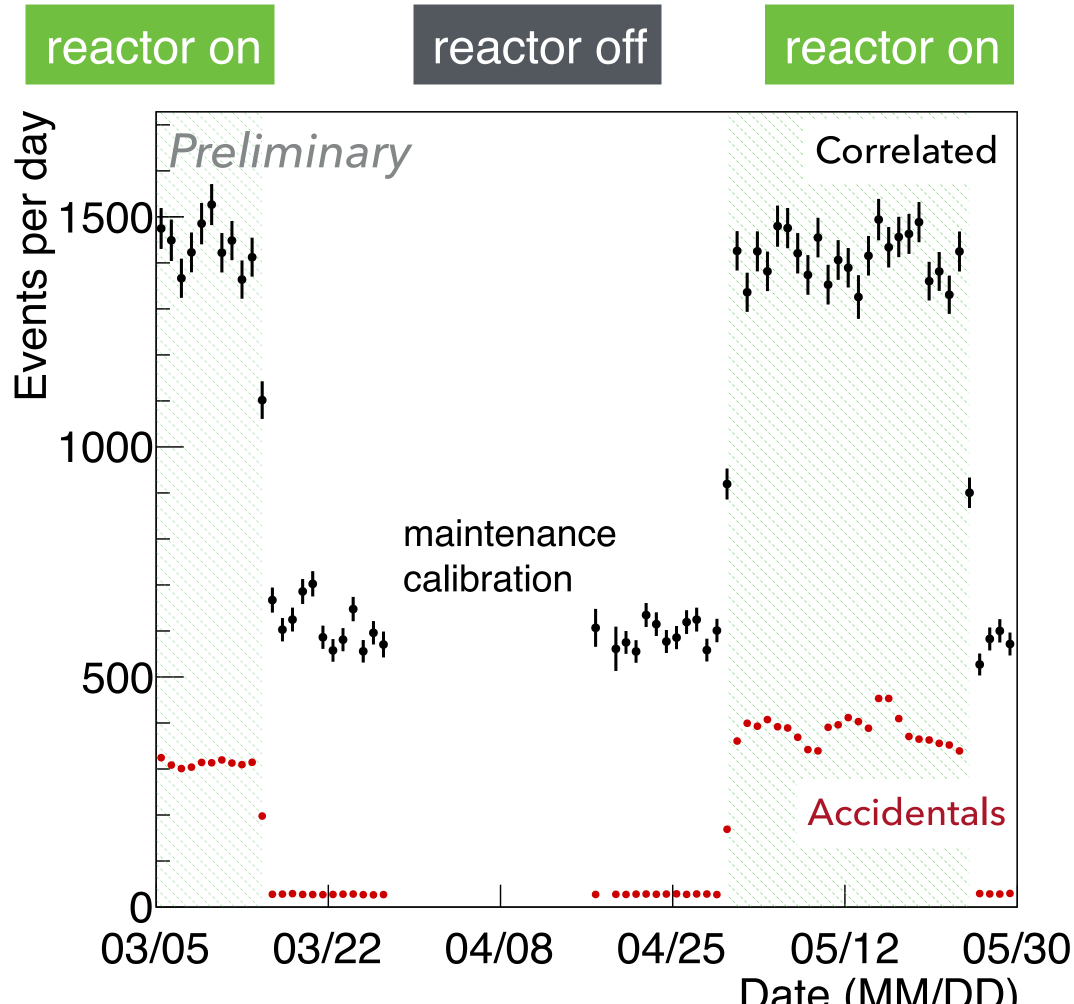
Correlated S/B = 1.36

Accidental S/B = 2.25

24,608 IBDs detected

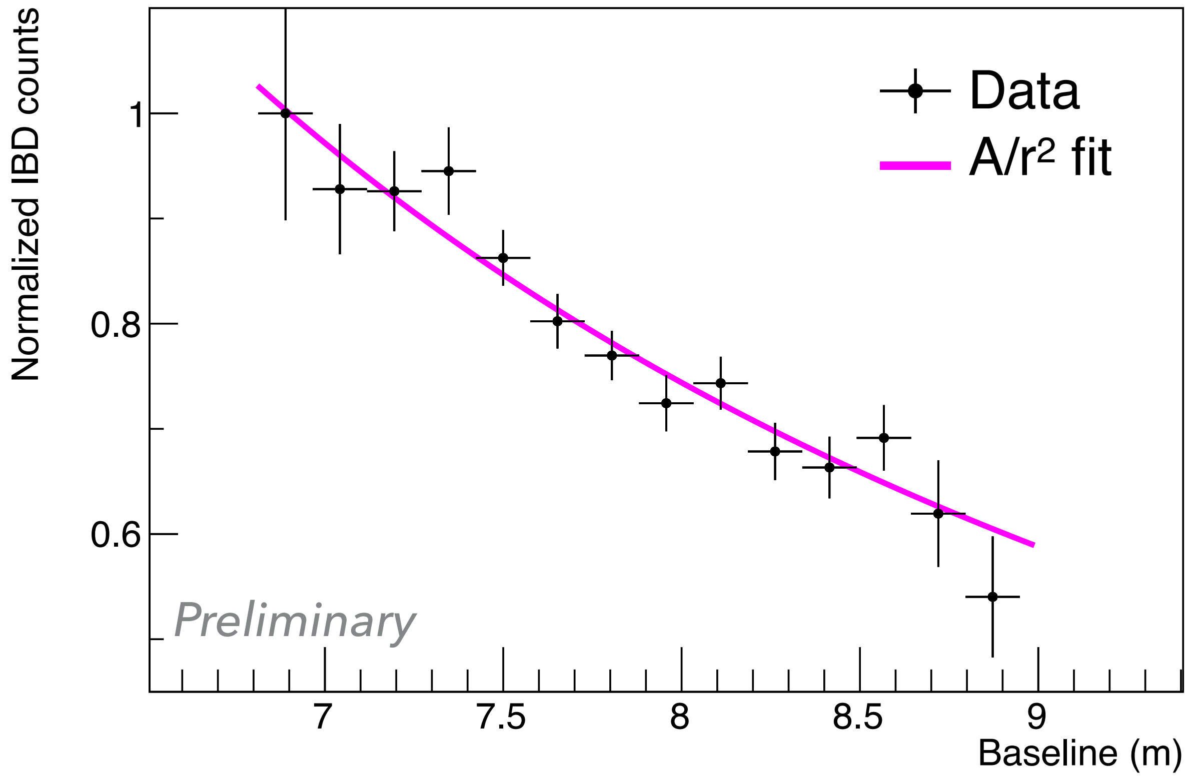
Average of ~750 IBDs/day

IBD event selection defined and frozen on 3 days of data



PROSPECT,arXiv:1806.02784

Neutrino Rate vs Baseline



PROSPECT,arXiv:1806.02784

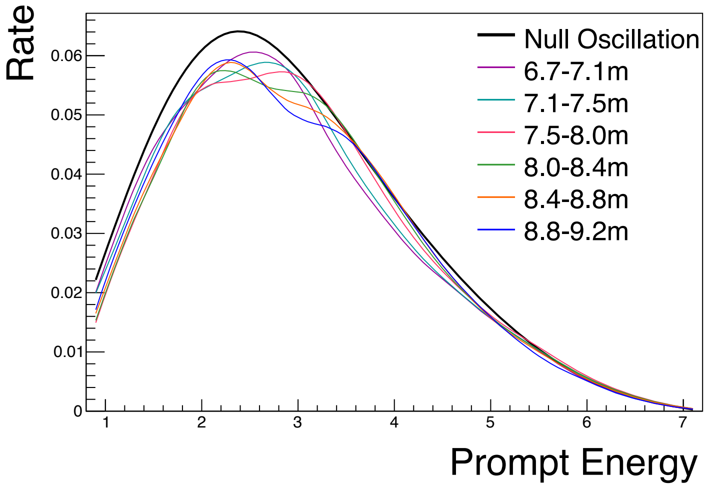
Observation of $1/r^2$ behavior throughout detector volume

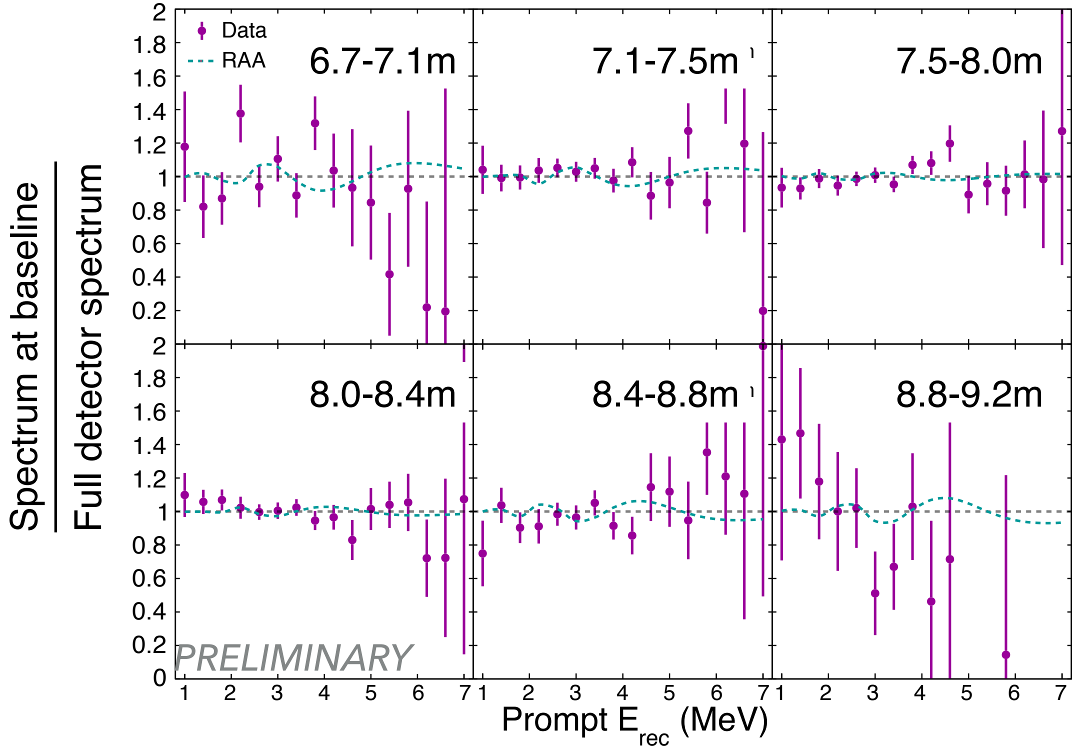
Bin events from 108 fiducial segments into 14 baseline bins

40% flux decrease from front of detector to back

Neutrino Spectrum vs Baseline

Spectral Distortion vs Baseline





PROSPECT,arXiv:1806.02784

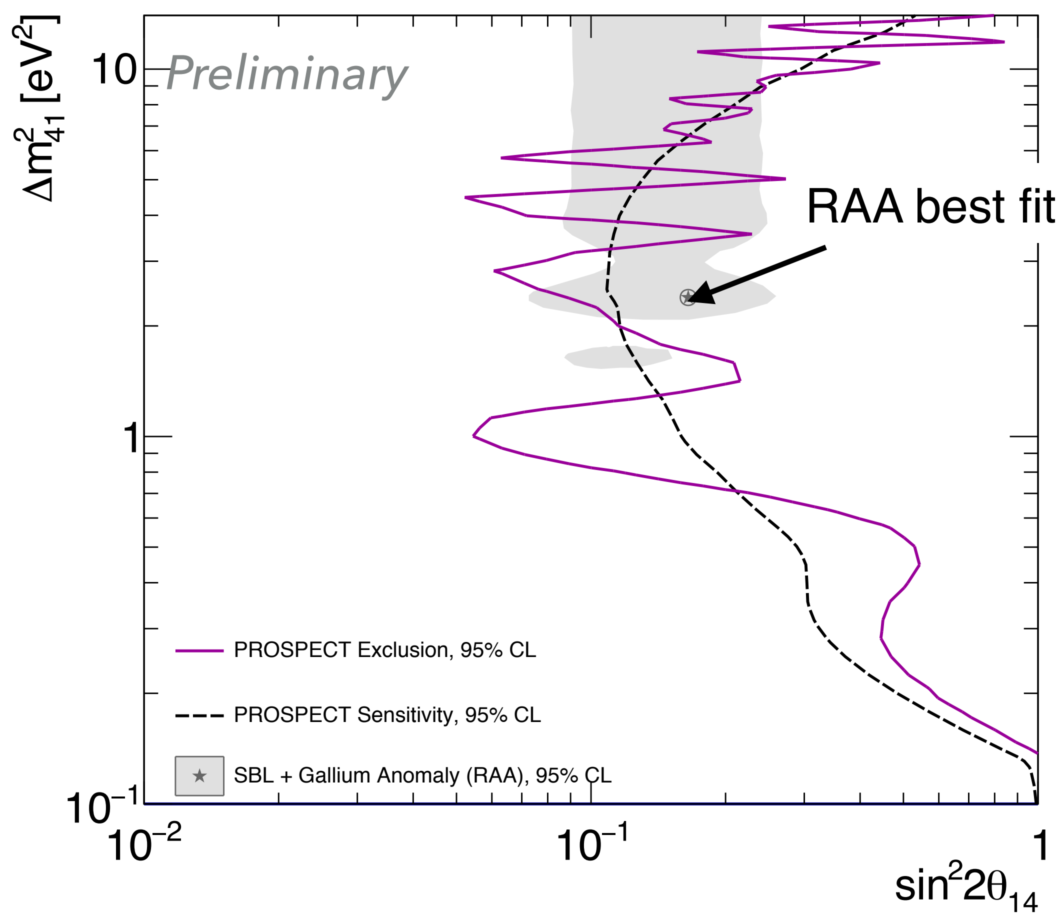
Compare spectra from 6 baselines to measured full-detector spectrum

Null-oscillation would yield a flat ratio for all baselines

Direct ratio search for oscillations, reactor model independent

Oscillation Search Results

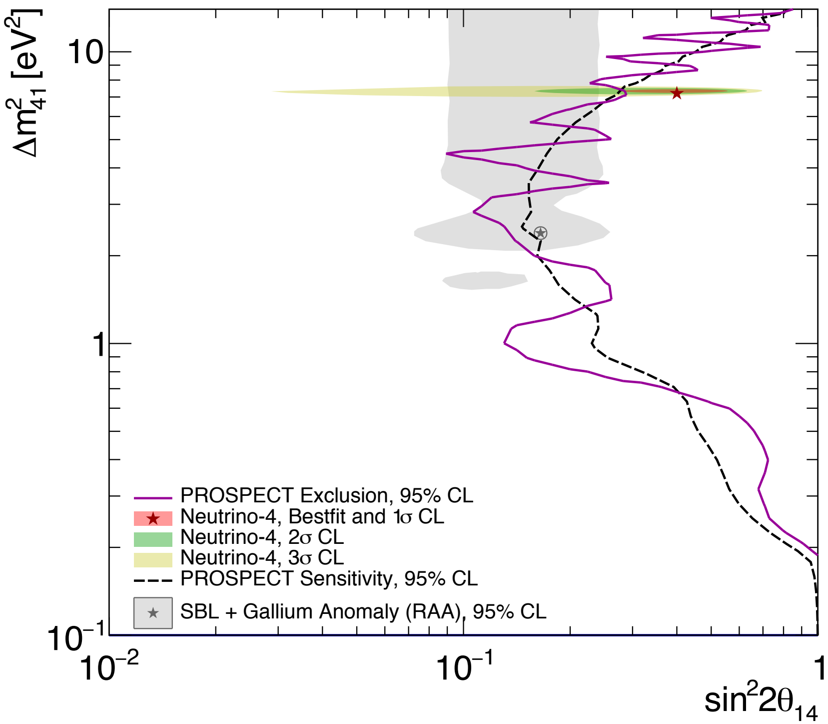
- Feldman-Cousins based confidence intervals for oscillation search
- Covariance matrices captures all uncertainties and energy/baseline correlations
- Critical χ^2 map generated from toy MC using full covariance matrix
- 95% exclusion curve based on 33 days Reactor On operation
- **Direct test of the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



PROSPECT,arXiv:1806.02784

Disfavors RAA best-fit point at >95% CL (2.3σ)

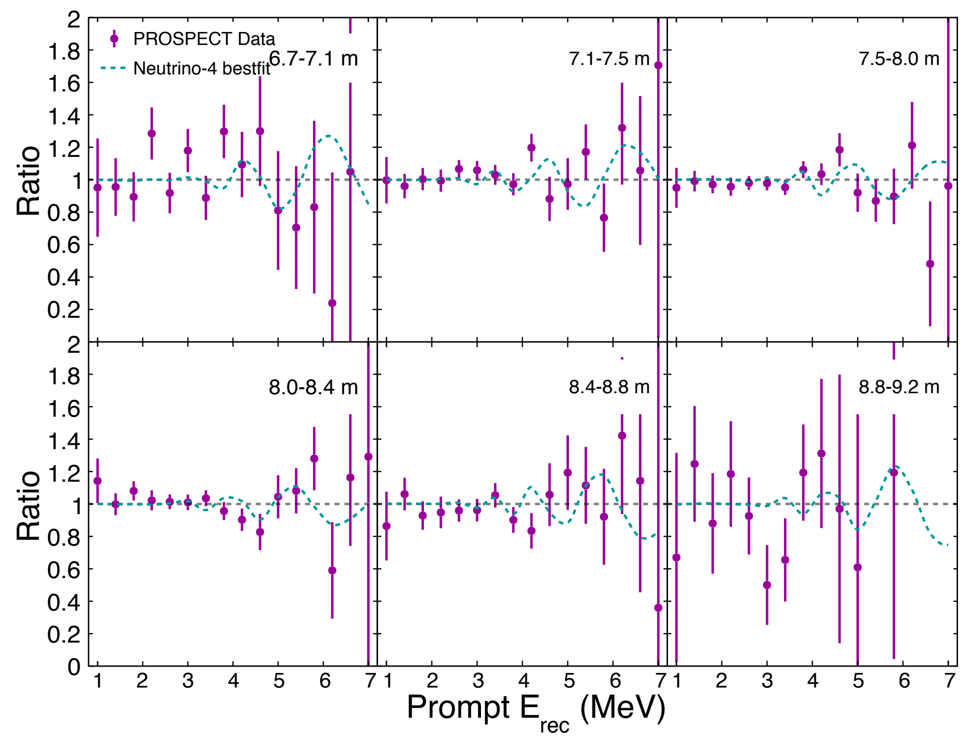
PROSPECT and Neutrino-4



Neutrino-4, arXiv:1809.10561

“The first observation of effect of oscillation in Neutrino-4 experiment on search for sterile neutrino”

PROSPECT already excludes Neutrino-4 best-fit point and 1σ region at 95%CL



Compare PROSPECT 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

Conclusion and Outlook

PROSPECT started taking data on March 6, 2018

Detector performing well. Background rejection and energy resolution meet expectation and MC.

Observed antineutrinos from HFIR with good signal/background. Observed an energy spectrum of antineutrinos at the Earth's surface with 24 hours of data. **World-leading signal-to-background for a surface-based detector (<1 mwe overburden)**

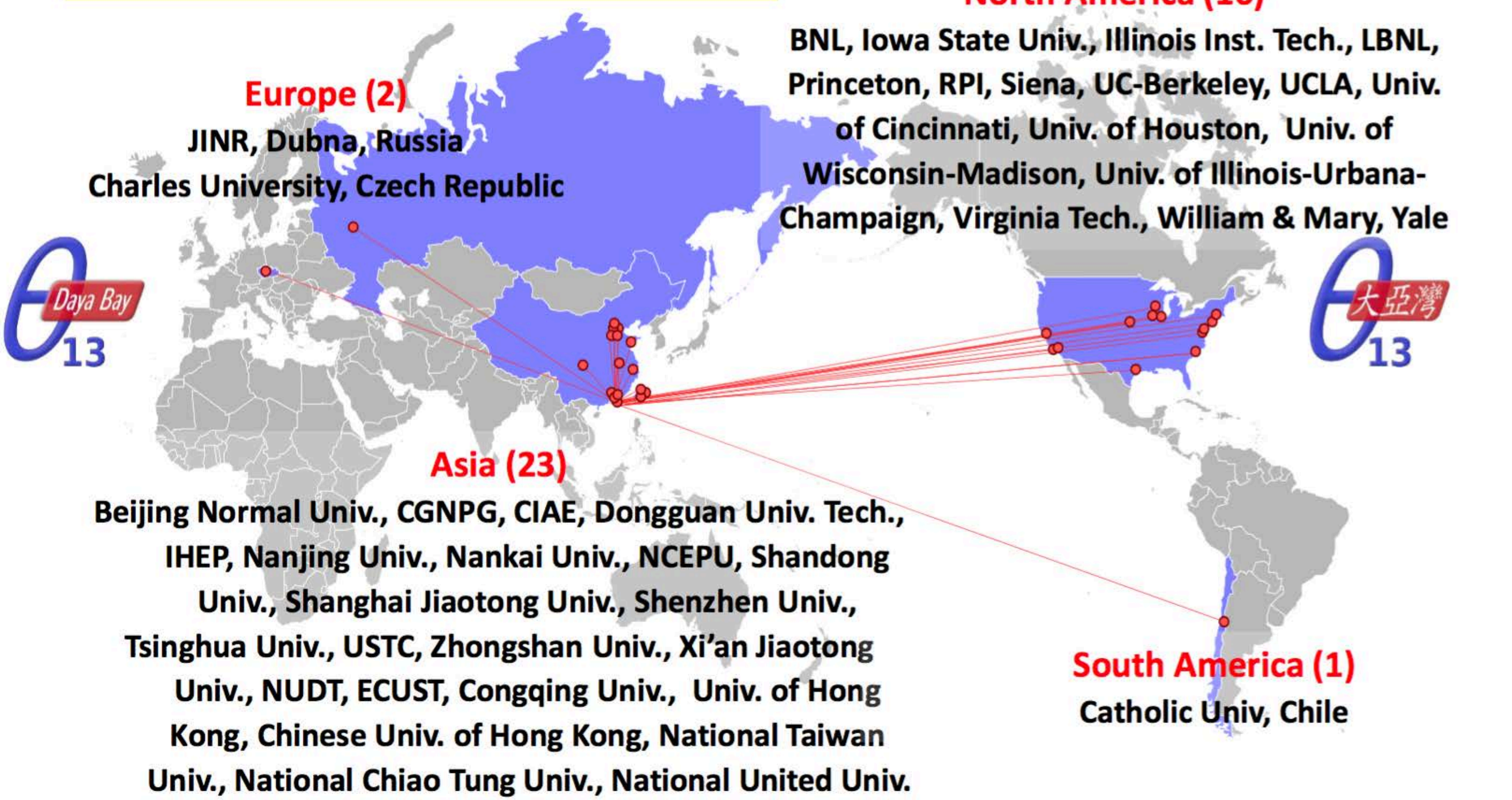
We report first high-statistics measurement of an antineutrino spectrum from a HEU reactor. Current measurement is statistics limited and will improve as we collect more data.

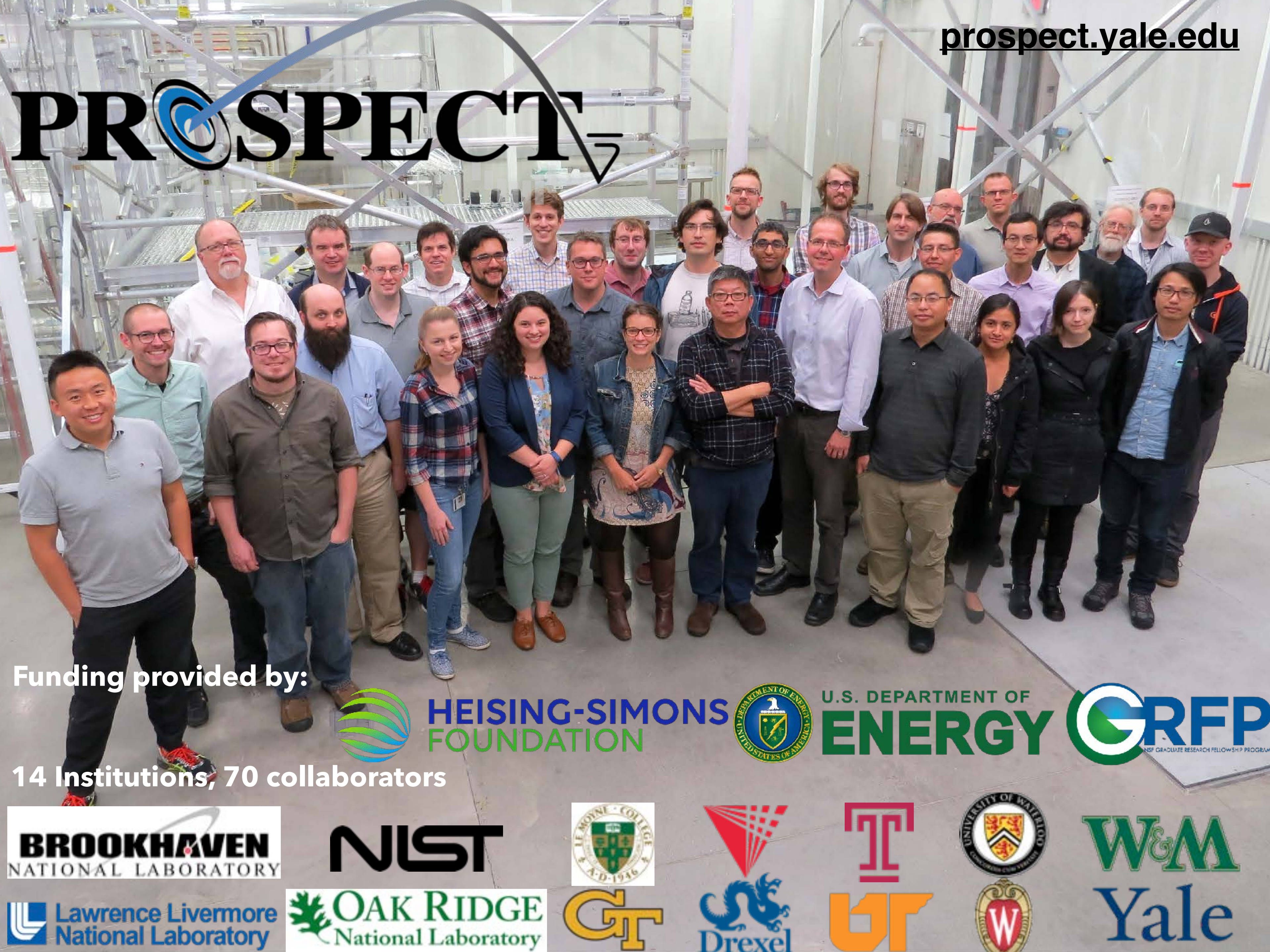
First oscillation analysis on 33 days of reactor-on data disfavors the RAA best-fit at 2.3σ (arXiv: 1806.02784)

Based on results of PROSPECT and other experiments sterile neutrinos are increasingly disfavored

Daya Bay Collaboration

203 collaborators from 42 institutions:

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U.S. DEPARTMENT OF ENERGY
GRFP
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14 Institutions, 70 collaborators
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Lawrence Livermore National Laboratory
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