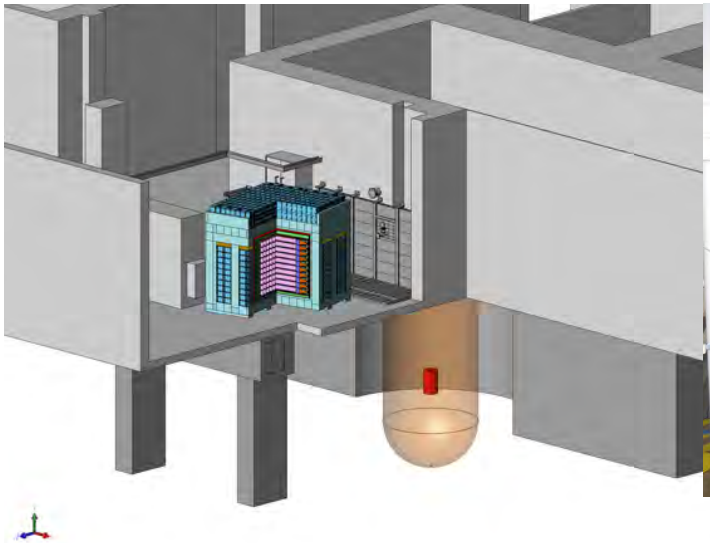
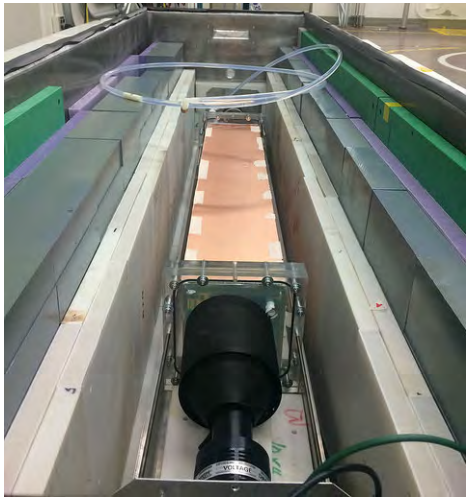
PROSPECT
A Precision Oscillation and Spectrum Experiment





Karsten M. Heeger
Yale University

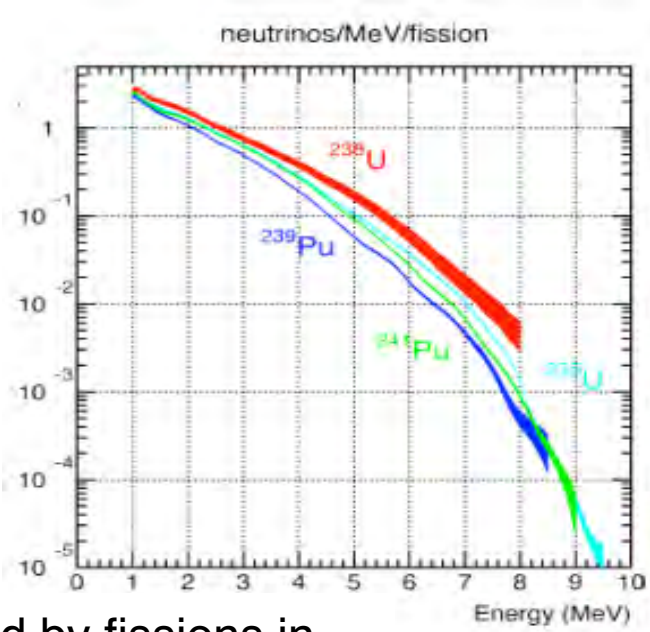
on behalf of the PROSPECT collaboration

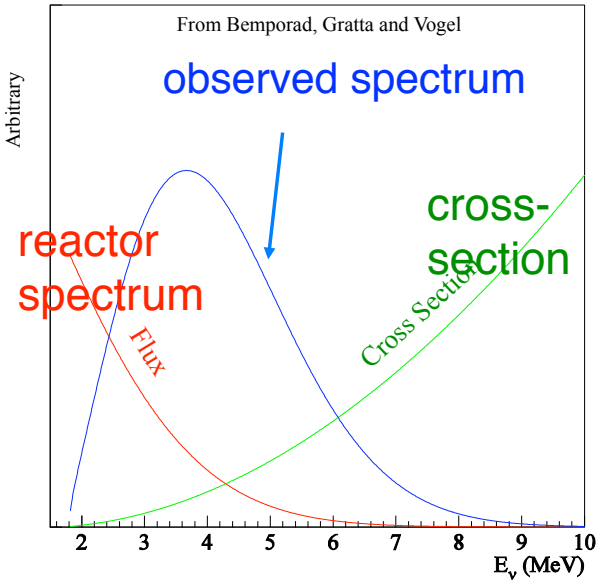
TAUP, September 10, 2015

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

$$\frac{d^2N(E,t)}{dEdt} \equiv \sum_i \frac{W_{th}(t)}{\sum_j f_j(t)e_j} f_i(t)S_i(E)c_i^{ne}(E,t) + S_{SNF}(E,t) \quad (1)$$

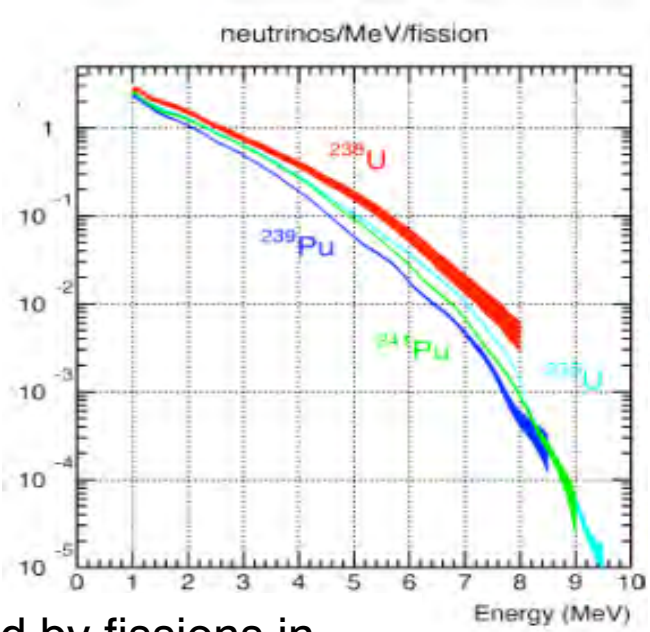
mean energy of $\bar{\nu}_e$: 3.6 MeV

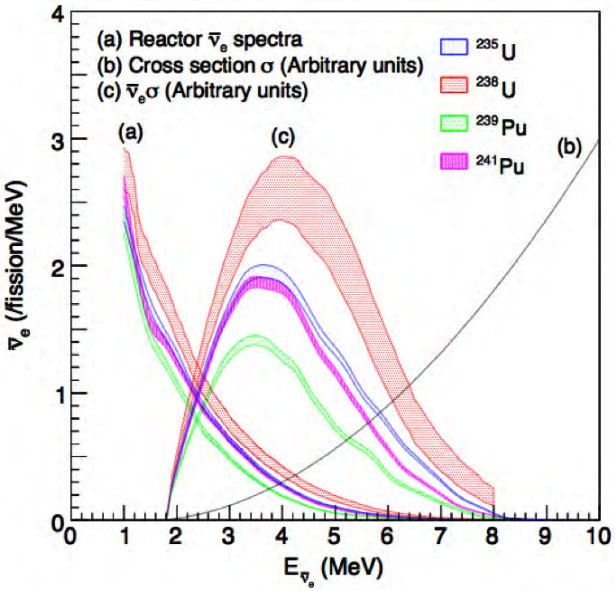
only disappearance experiments possible

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

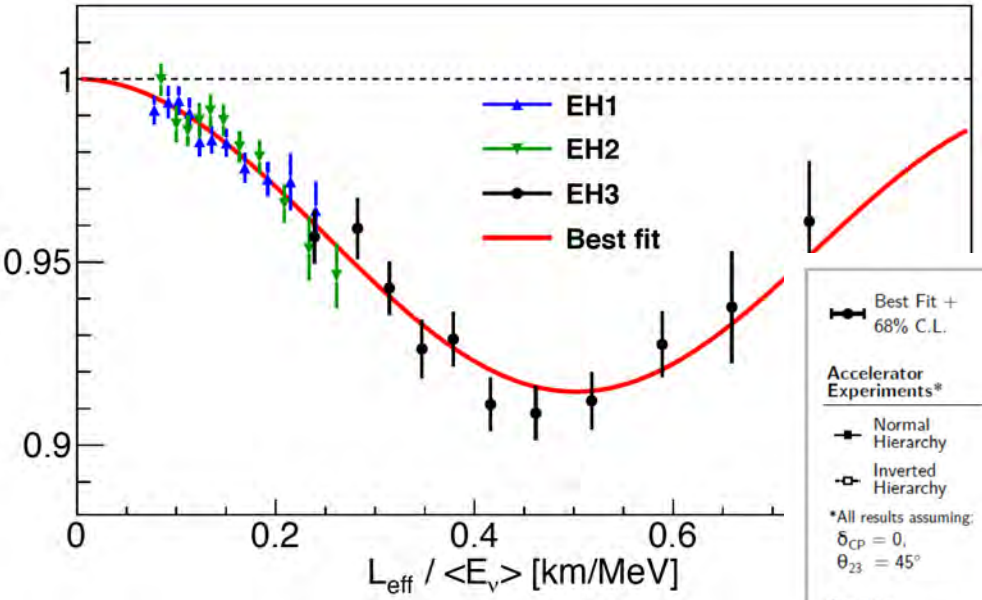
$$\frac{d^2N(E,t)}{dEdt} \equiv \sum_i \frac{W_{th}(t)}{\sum_j f_j(t)e_j} f_i(t)S_i(E)c_i^{ne}(E,t) + S_{SNF}(E,t) \quad (1)$$

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

only disappearance experiments possible

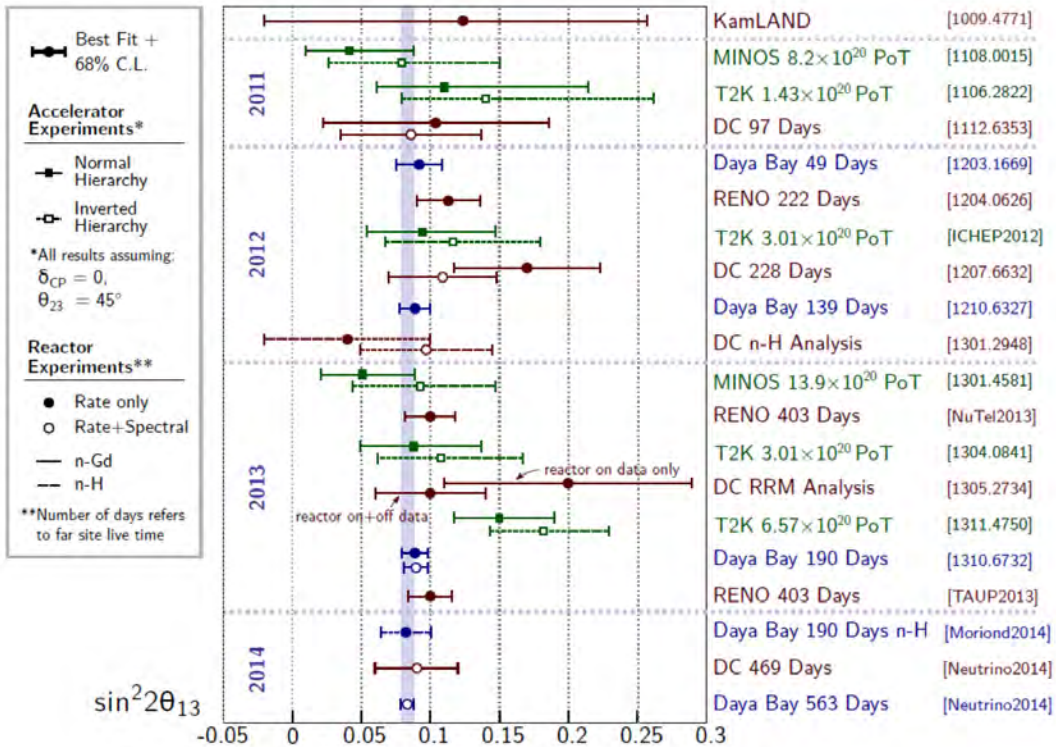
Precision Measurements with Reactor Neutrinos

Recent precision measurements with Daya Bay.



Daya Bay demonstrates L/E oscillation

Precision Measurement of θ_{13}

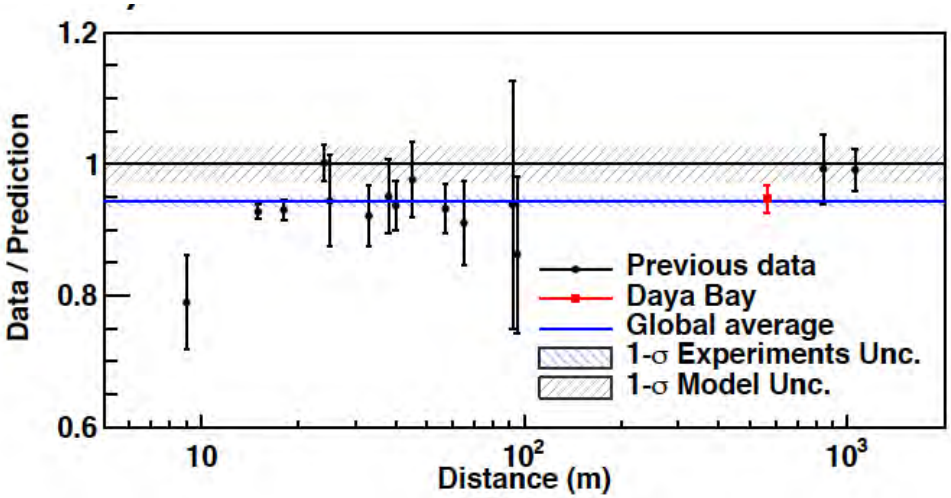


Daya Bay
Phys.Rev.Lett. 112 (2014) 061801

Reactor Flux and Spectrum "Anomalies"

Flux Deficit

Measurements compared to models

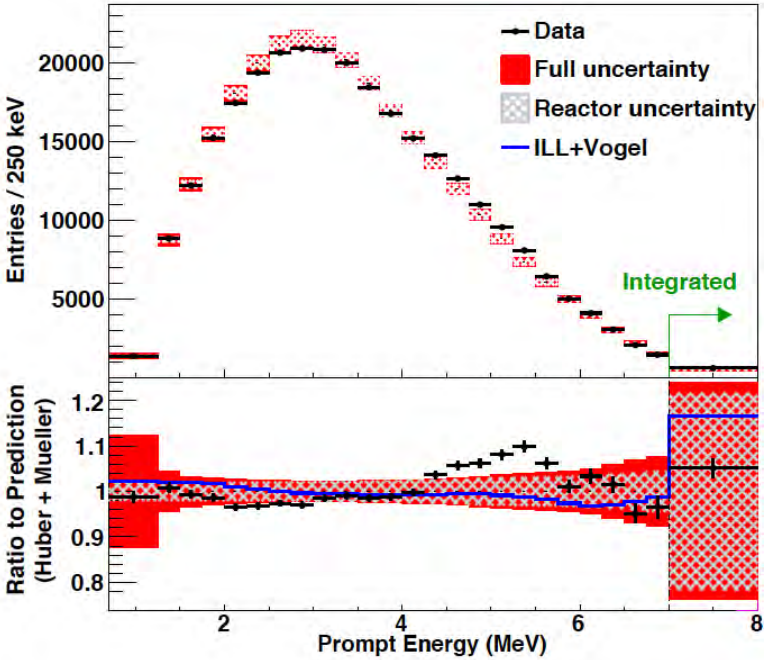


Extra neutrino oscillations or artifact of flux predictions?

More data needed to better understand these observations

Spectral Deviation

Compared to prediction

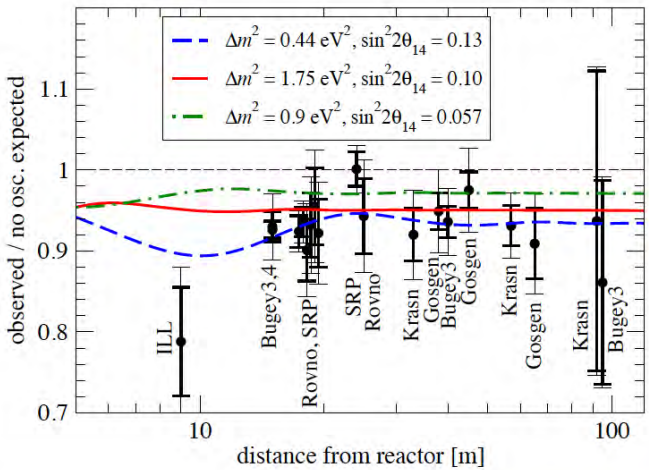


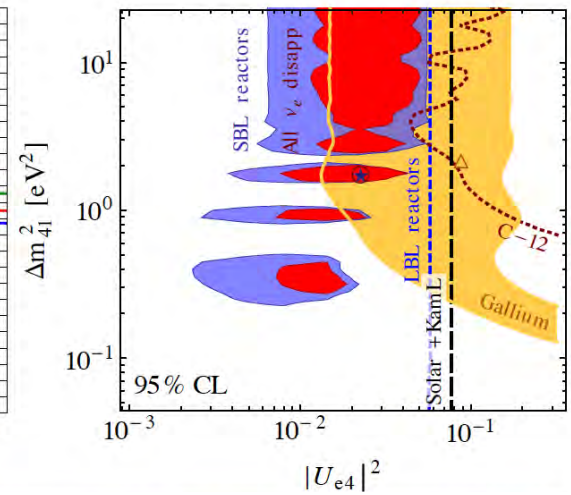
New feature in 4-6 MeV region of spectrum. Seen by Daya Bay, Double Chooz, and Reno.

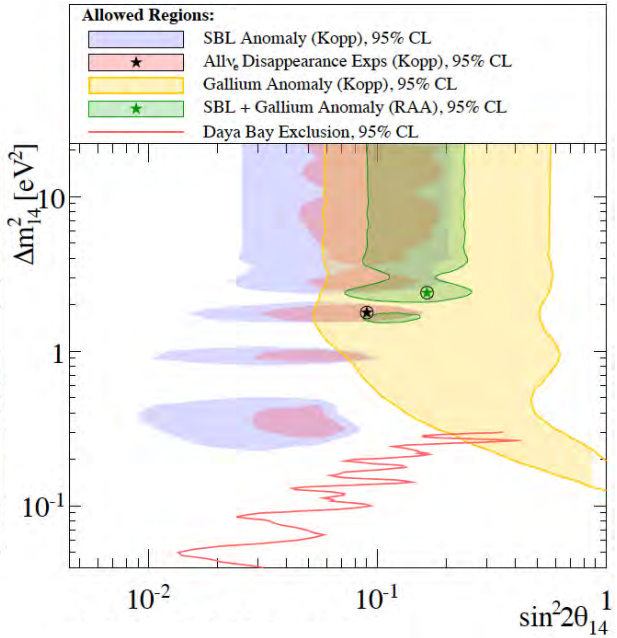
arXiv:1508.04233, Daya Bay Collaboration

$\bar{\nu}_e$ Disappearance/Exclusion Limits

Additional sterile neutrinos?
Hypothesis of 3+1 scenario





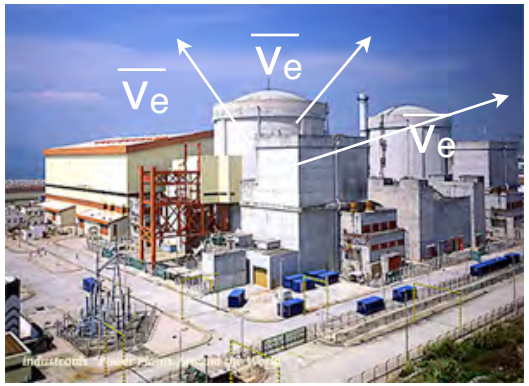


	$\sin^2 2\theta_{14}$	Δm^2_{41} [eV^2]	$\chi^2_{\rm min}$/dof (GOF)	$\Delta\chi^2_{\rm no\ osc}$/dof (CL)
SBL rates only	0.13	0.44	11.5/17 (83%)	11.4/2 (99.7%)
SBL incl. Bugey3 spect.	0.10	1.75	58.3/74 (91%)	9.0/2 (98.9%)
SBL + Gallium	0.11	1.80	64.0/78 (87%)	14.0/2 (99.9%)
global ν_e disapp.	0.09	1.78	403.3/427 (79%)	12.6/2 (99.8%)

Kopp et al, 1303.3011

Principle of Relative Measurement of $\bar{\nu}_e$ Flux

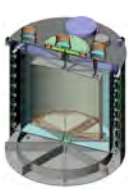
Relative measurements for precision physics



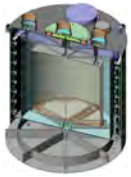
Absolute Reactor Flux
largest uncertainty in previous measurements

Relative measurement vs baseline
independent of
- flux normalization, and
- spectral shape

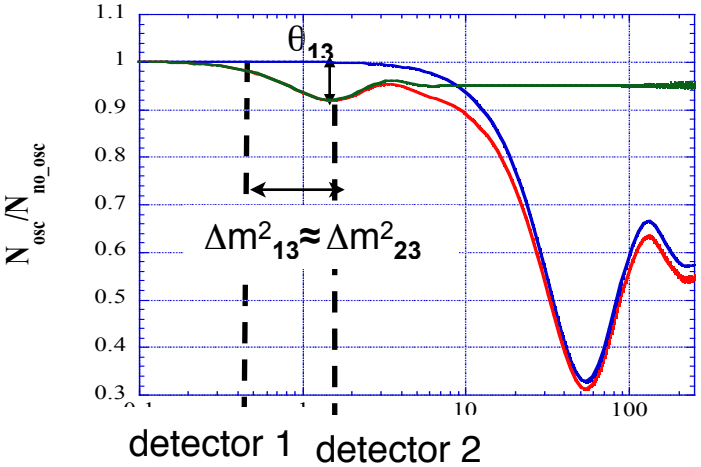
2 homogeneous detectors (e.g. Daya Bay)



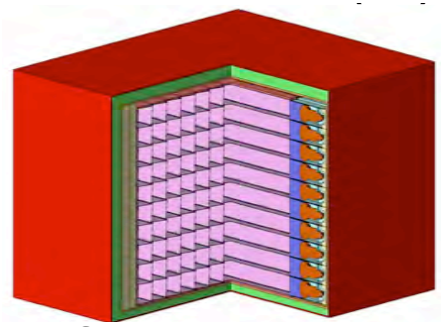
near

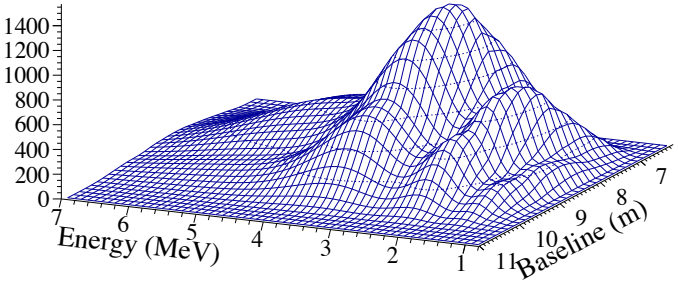


far



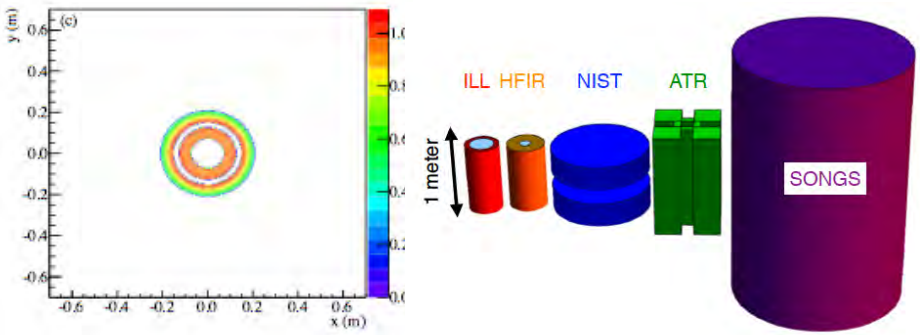
1 segmented detector (e.g. PROSPECT)





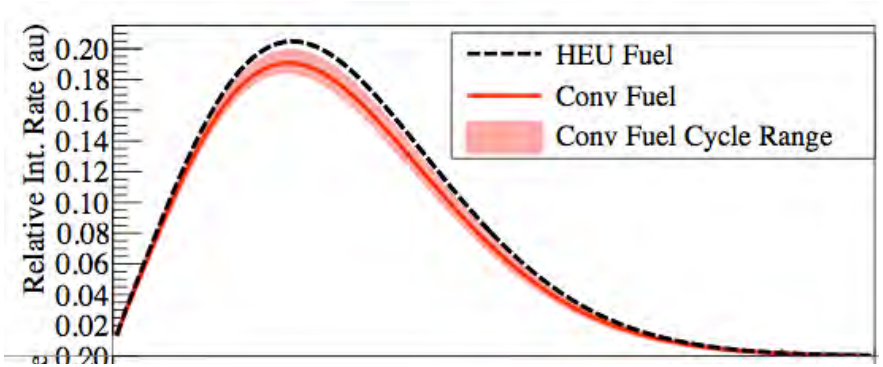
A Short-Baseline Reactor Experiment

Short Distance (<10 m) From Point Source



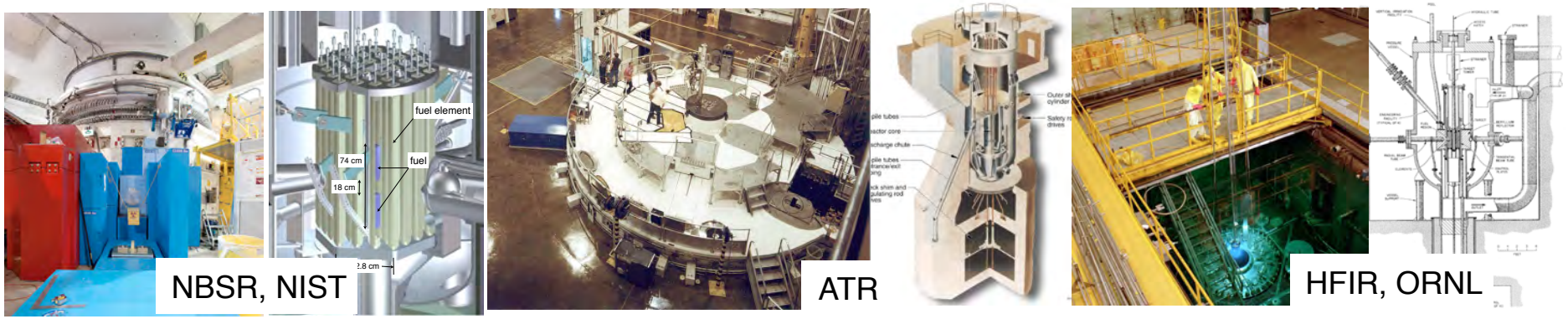
Compact core (< 1m) avoids oscillation washout

Research Reactor Spectrum



HEU core provides static spectrum of mainly ^{235}U.

US operates high-powered research reactors



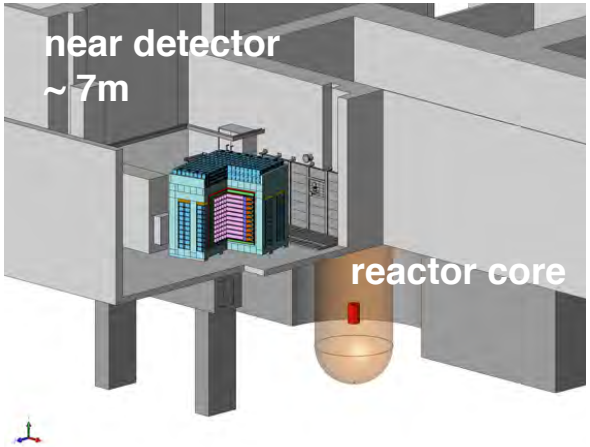
arXiv:1506.03547, PROSPECT collaboration

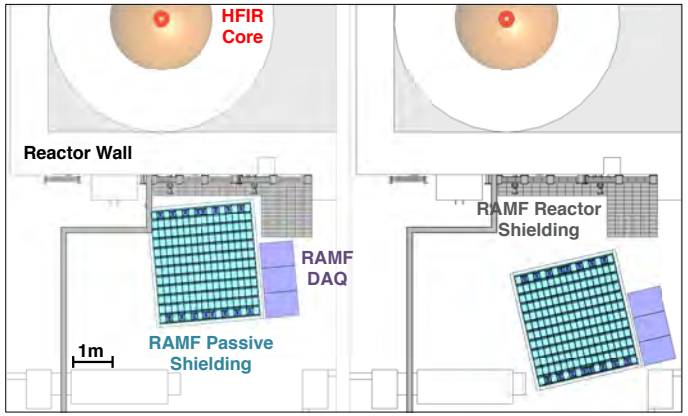
PROSPECT: Precision Oscillation and Spectrum Experiment

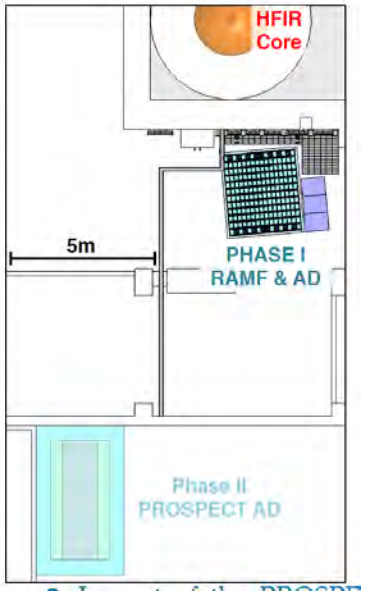
Physics Objectives

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

Phased Approach







Phase 1 - one detector, near detector: ~ 7m movable detector ~7-12 m

Phase II - two detectors, near detector: ~7-10m far detector: ~16-20m

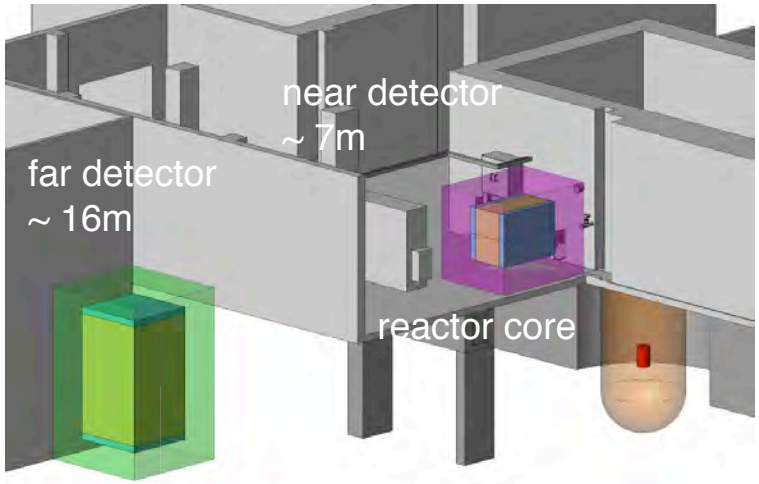
- movable detector enables systematic control, background checks, and increased physics reach
- phased approach mitigates risks

arXiv:1309.7647
PROSPECT collaboration

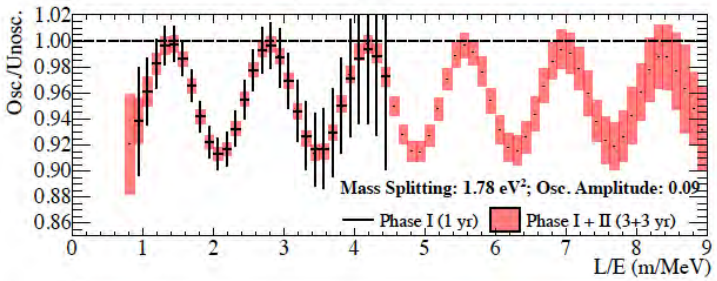
PROSPECT Physics

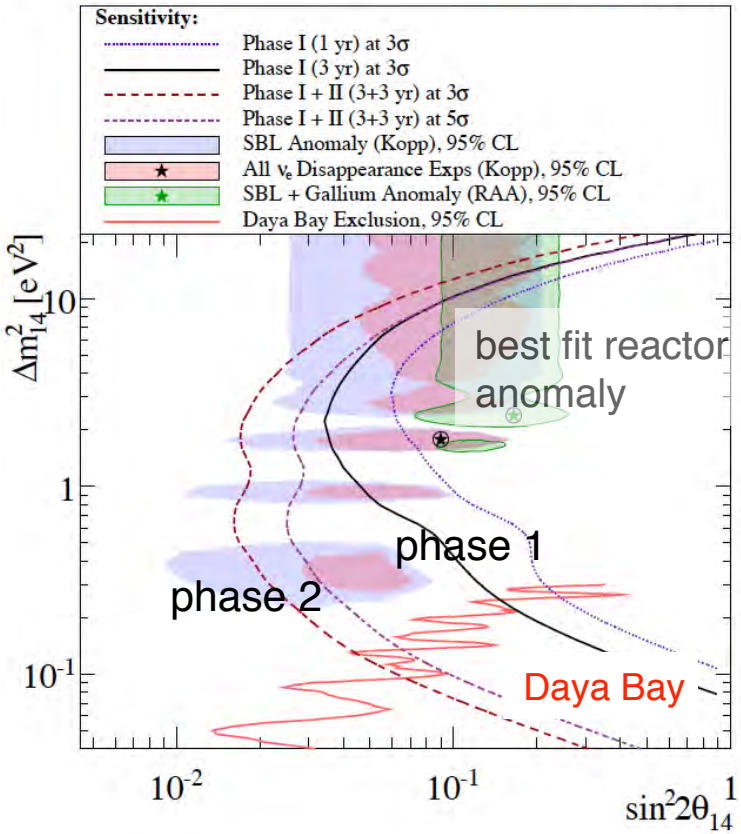
A Precision Oscillation Experiment

An experimental approach to test for oscillation of eV-scale neutrinos



Phase 1 = Near Detector Only
Phase 2 = Near + Far Detector





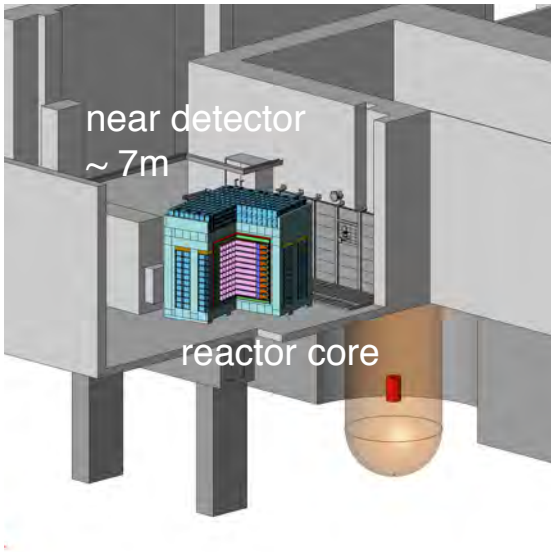
Objectives

3σ test of best fit after 1 year
3σ test of favored region after 3 years
5σ test of allowed region after 3+3 years

PROSPECT Physics

A Precision Spectrum Experiment

A precision measurement to address spectral unknowns



Phase 1 = Near Detector Only

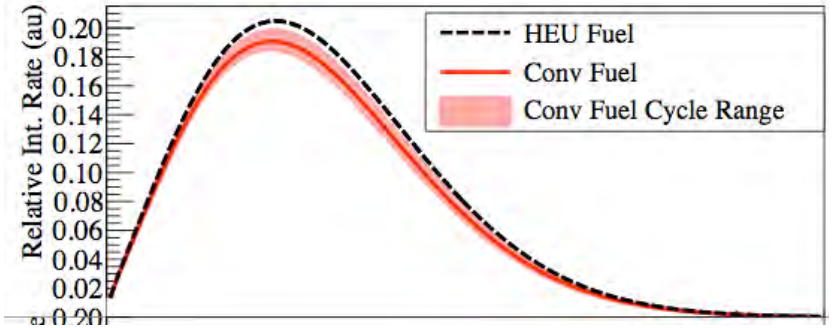
Objectives

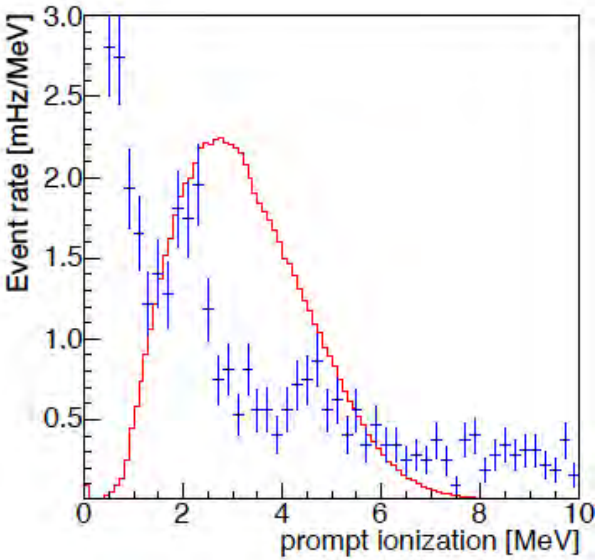
Measurement of ^{235}U spectrum

Compare different reactor models

Compare different reactor cores

Measurement of HEU (^{235}U) spectrum



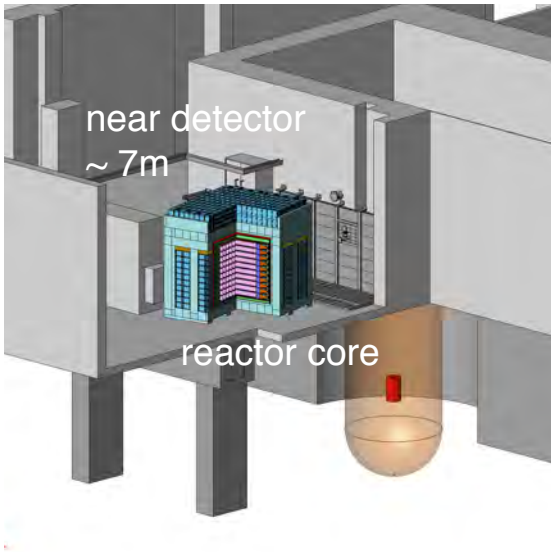


between 2-6 MeV:
average stat. precision < 1.5%, systematics < 2%

PROSPECT Physics

A Precision Spectrum Experiment

A precision measurement to address spectral unknowns



Phase 1 = Near Detector Only

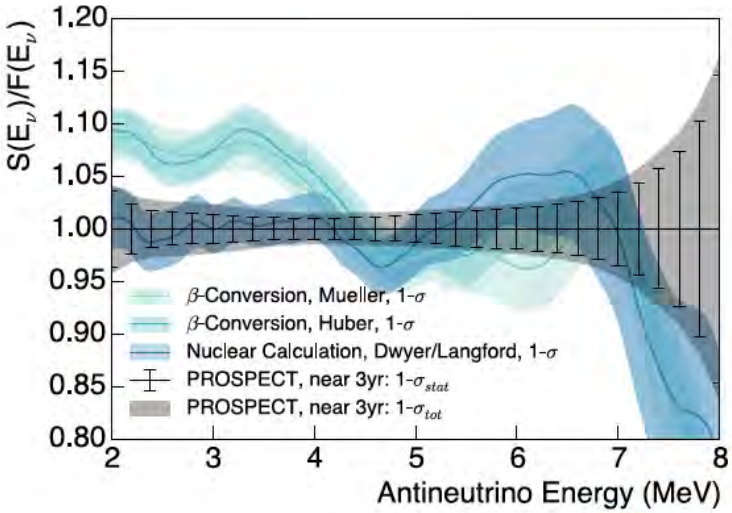
Objectives

Measurement of ^{235}U spectrum

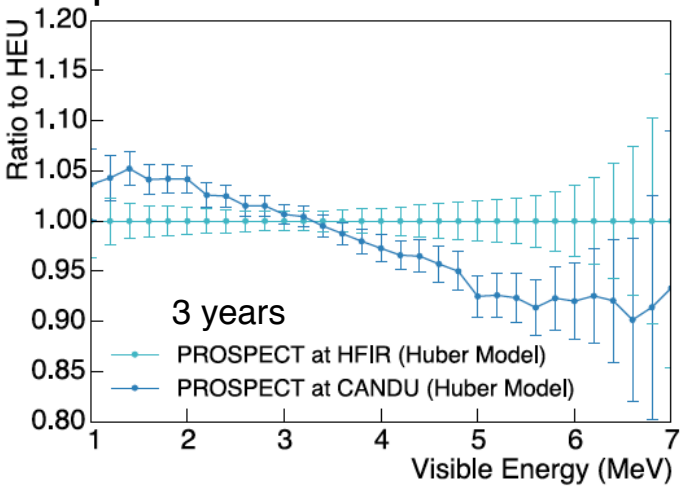
Compare different reactor models

Compare different reactor cores

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

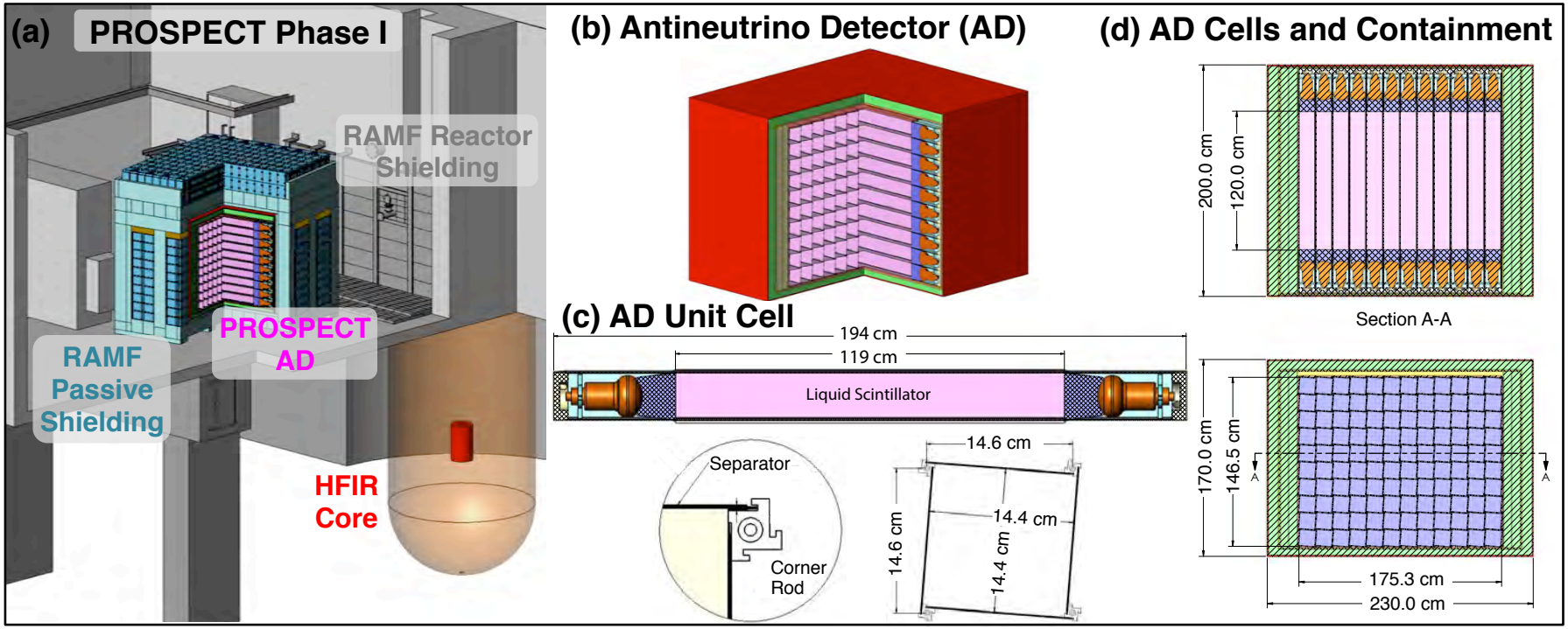


Comparison of reactor cores



PROSPECT Phase I Detector System

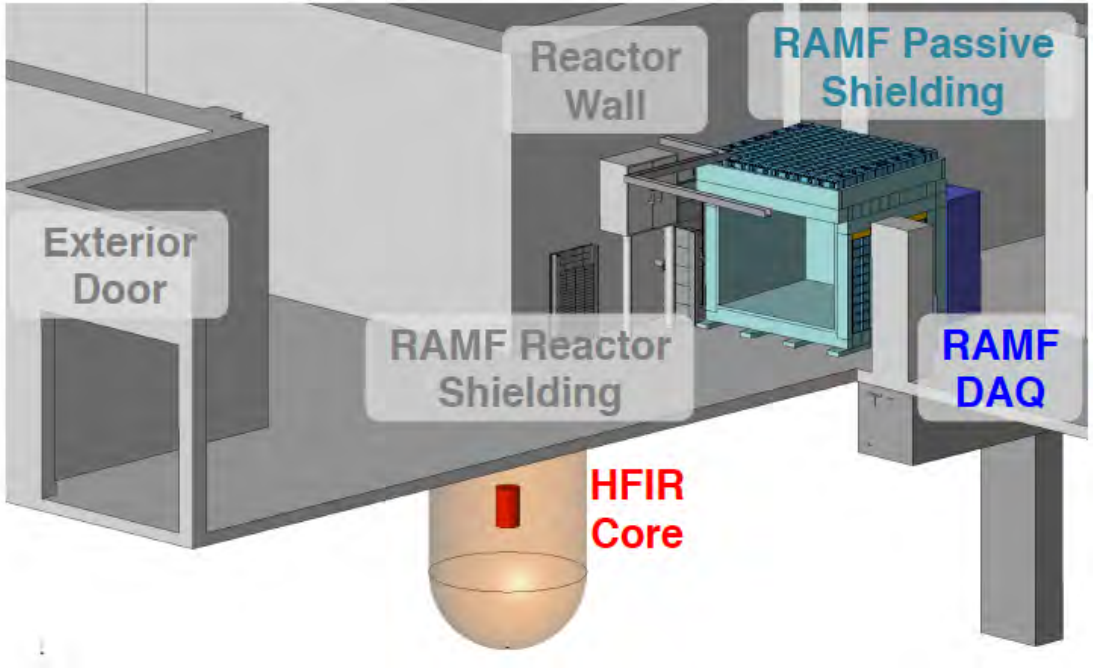
Antineutrino Detector



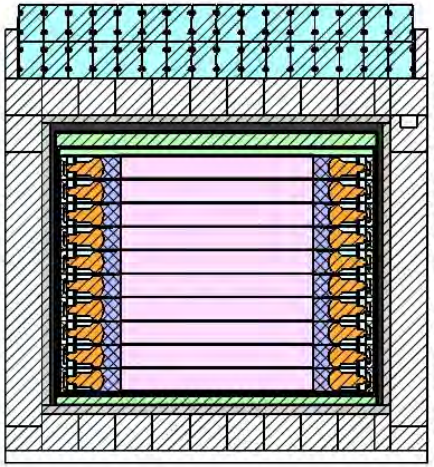
- 3000L of ^{6}Li liquid scintillator
- 120 scintillator loaded cells, ~15x15x120cm
- double ended PMT readout, light guides, <4-5%/√E resolutions
- thin optical separators, minimal dead material
- containment vessel, filled in place

PROSPECT Shielding

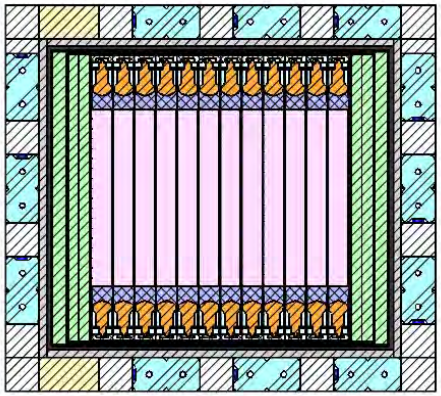
Reactor Antineutrino Measurement Facility (RAMF) at HFIR



Layered Shielding side view



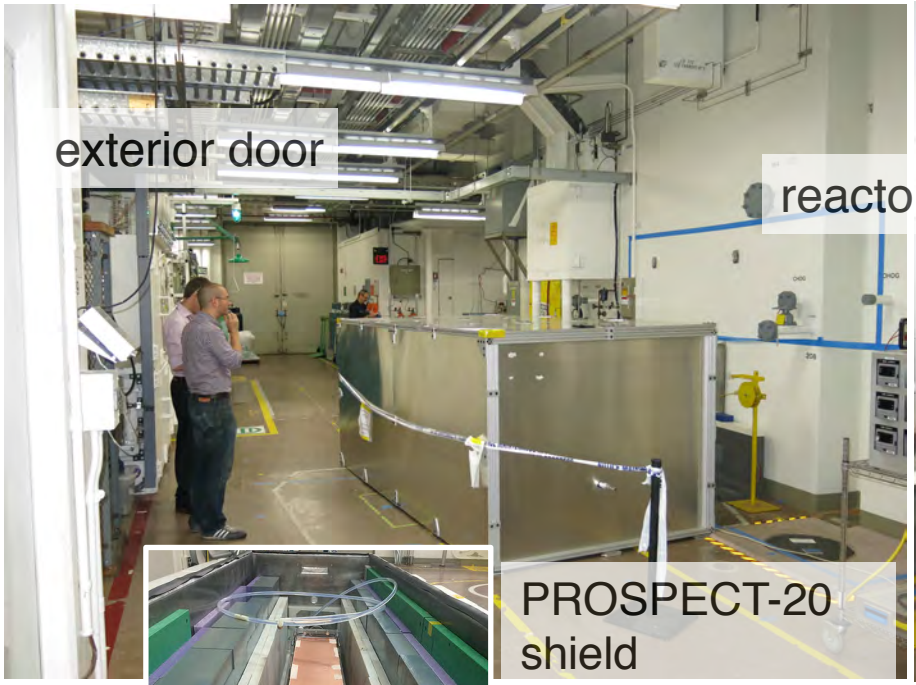
top view

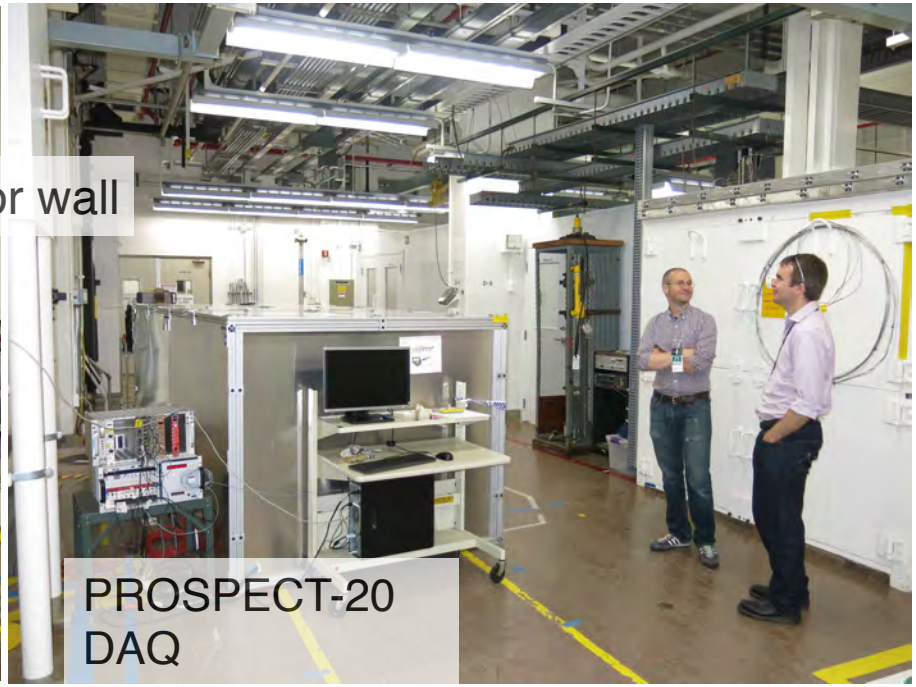


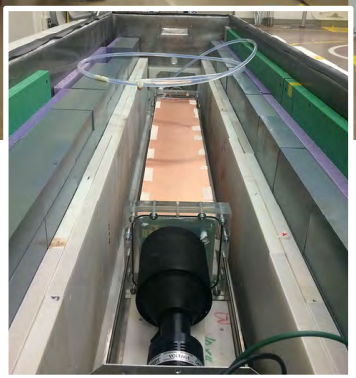
- local shielding next to reactor wall
- multi-layer passive shield around detector
- general purpose digitizing electronics and DAQ
- general utilities
- easy access

PROSPECT Experimental Location

PROSPECT-20 Detector at HFIR





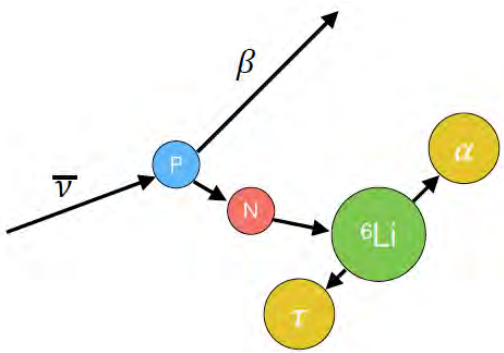


PROSPECT-20
test detector
inside shield

- established on-site operation
- easy access 24/7
- door to outside
- space for near and far detector

PROSPECT Event Detection

Event Identification

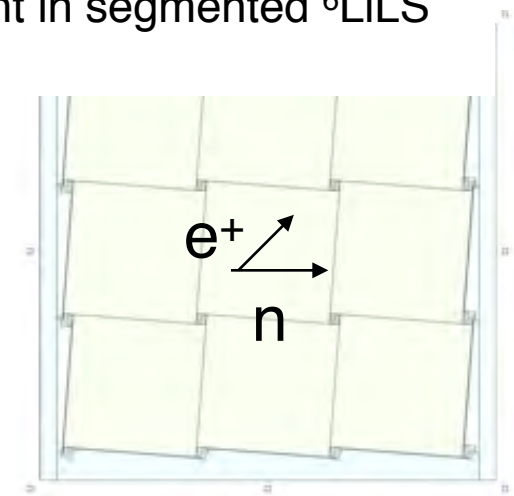


Prompt signal: 1-10 MeV positron from inverse beta decay (IBD)

Delay signal: ~0.5 MeV signal from neutron capture on ^{6}Li

40μs delayed n capture

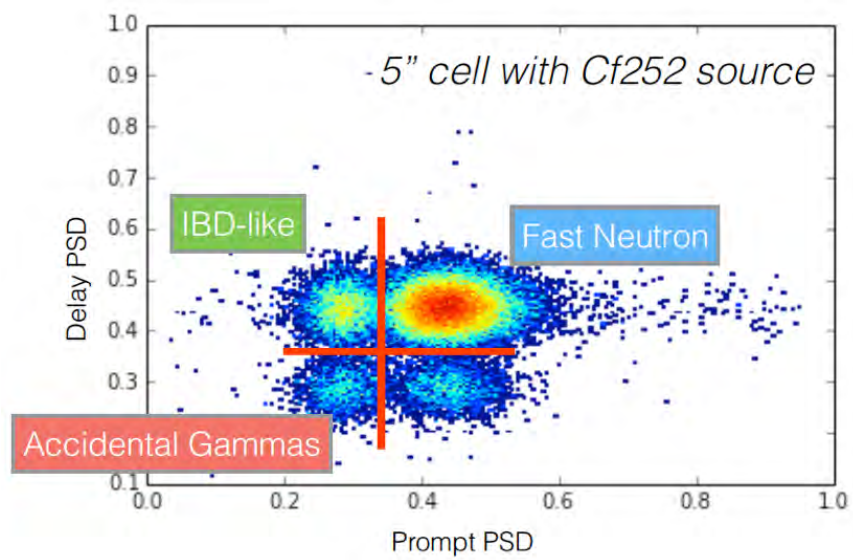
IBD event in segmented ^{6}LiLS detector



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

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

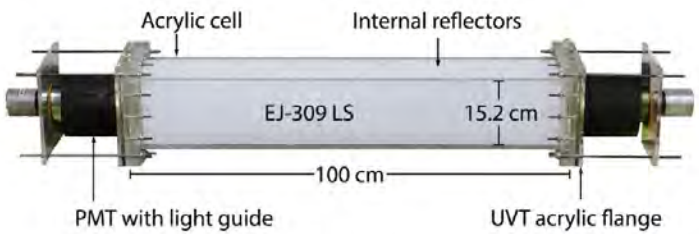
accidental gamma
γ-like prompt, γ-like delay



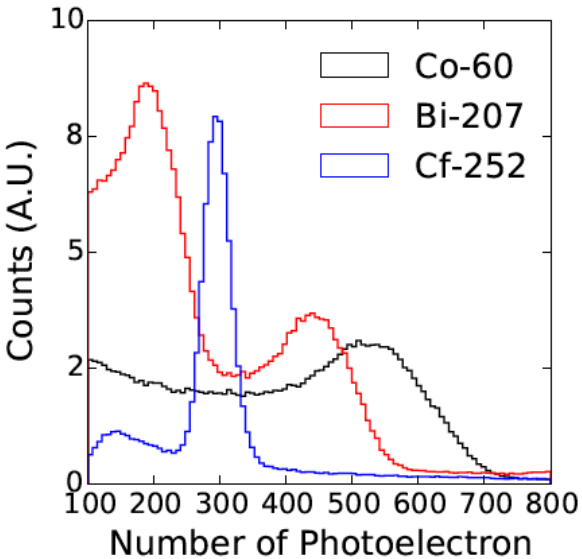
Background reduction is key challenge

PROSPECT Scintillator Target

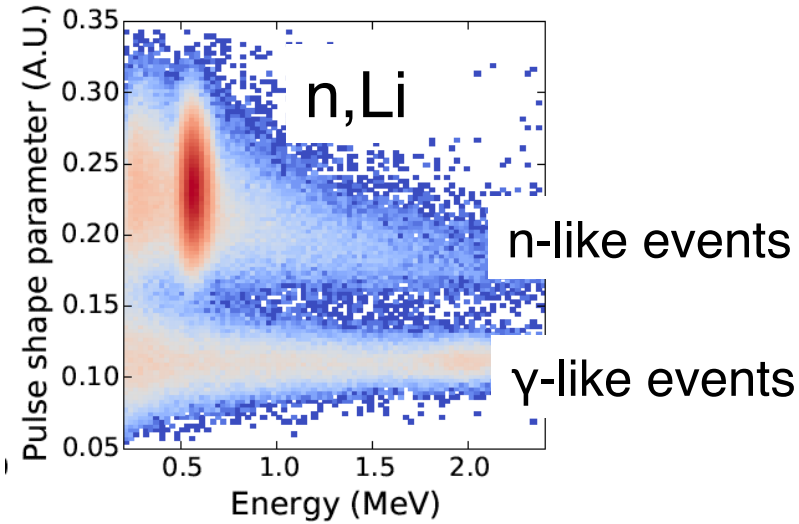
Prototype Detectors
PROSPECT-20 w/ LiLS and Unloaded LS



Light Yield/ PE Spectra



Pulse Shape Discrimination



PSD performance for Cf-252.

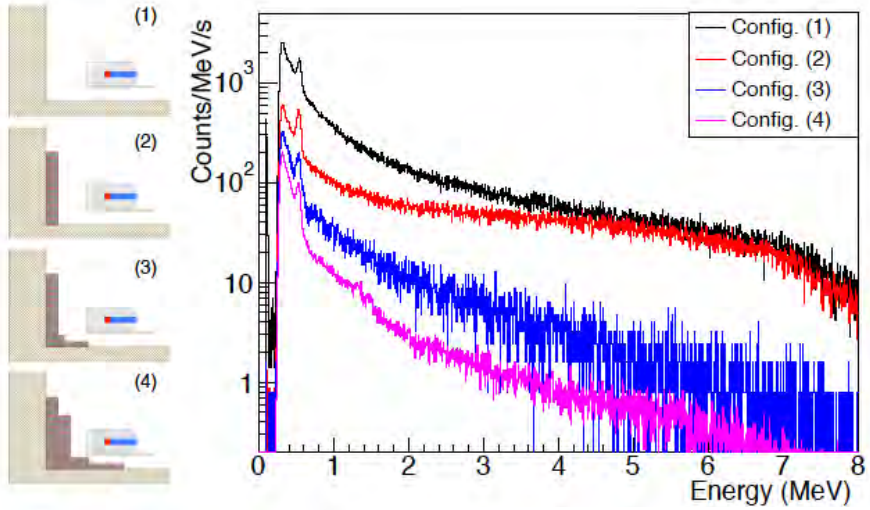
- Compton edge of ^{60}Co and ^{217}Bi γ-rays and the quenched (n, Li) capture peak from ^{252}Cf neutrons
- light collection: 522±16 PE/MeV

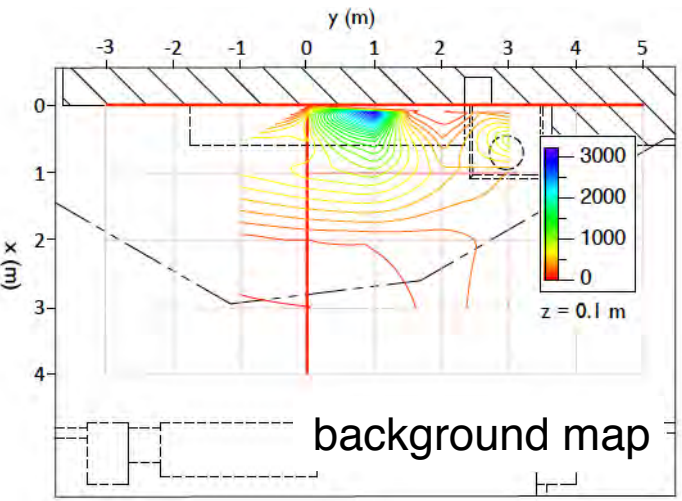
unloaded LS studies described in arXiv:1508.06575, PROSPECT collaboration

PROSPECT Backgrounds

Background Measurements at HFIR

varying reactor shields



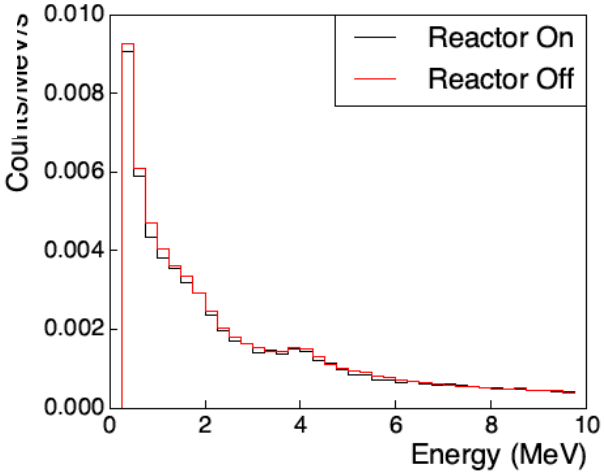


background map

IBD-like events for reactor-on and off

reactor generated backgrounds are minimal

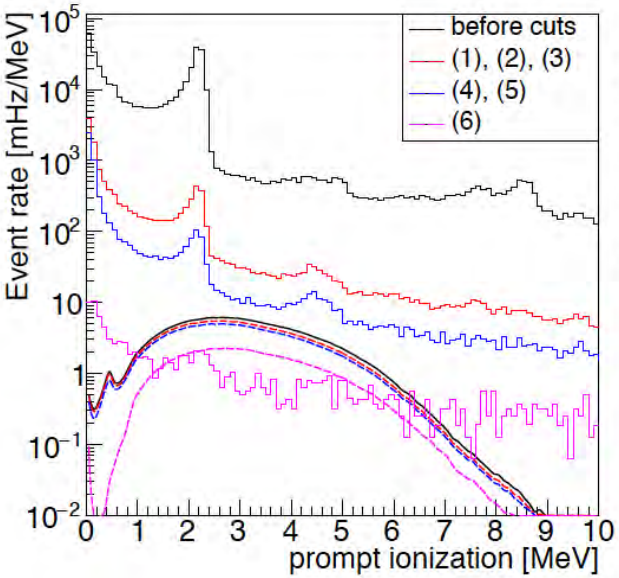
IBD-like backgrounds are cosmogenic



arXiv:1506.03547, PROSPECT collaboration

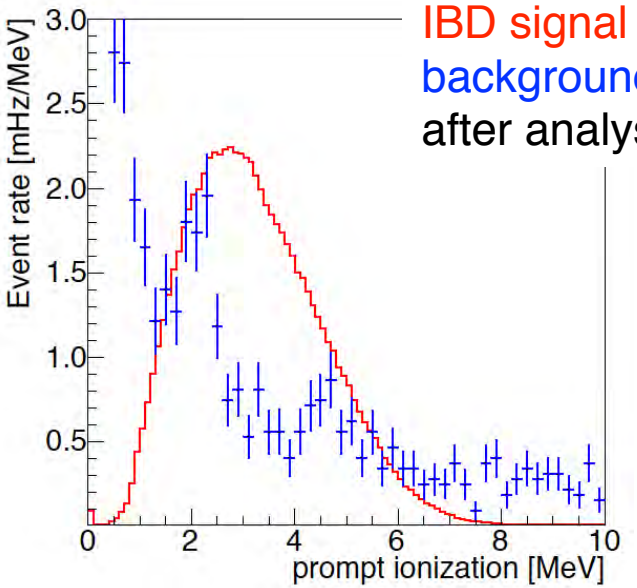
PROSPECT Signal & Background

Simulated Signal and Background Spectra



Signal (dashed) and background (solid) prompt spectra are shown through selection cuts

Cuts	IBD signal	Cosmic BG
PSD	1680	1.7e6
Time (1, 2, 3)	1500	3.2e4
Spatial (4, 5)	1360	9500
Fiducial (6)	610	390



IBD signal
backgrounds
after analysis cuts

S/B better than 1:1 is predicted.

Rate and shape of the residual IBD-like background can be measured with high precision during reactor off periods.

Phased PROSPECT Detectors

PROSPECT 0.1
Aug. 2014

5cm
0.1 liter
LS cell

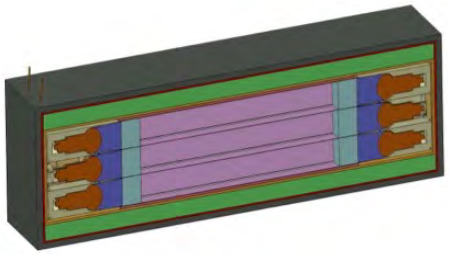
PROSPECT 2
Dec. '14/Jan. '15

12.5cm
2 liter
LS cell

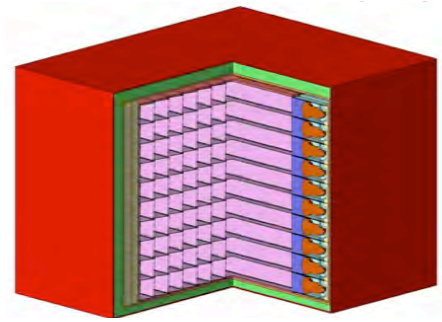
PROSPECT 20
Early 2015

1m
20 liter
^{6}LiLS cell

PROSPECT N×20



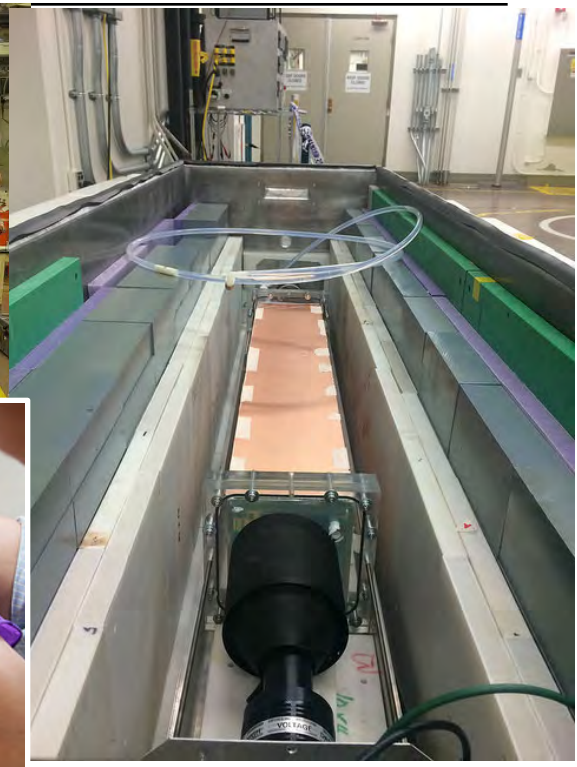
N×20 liter
LS segments

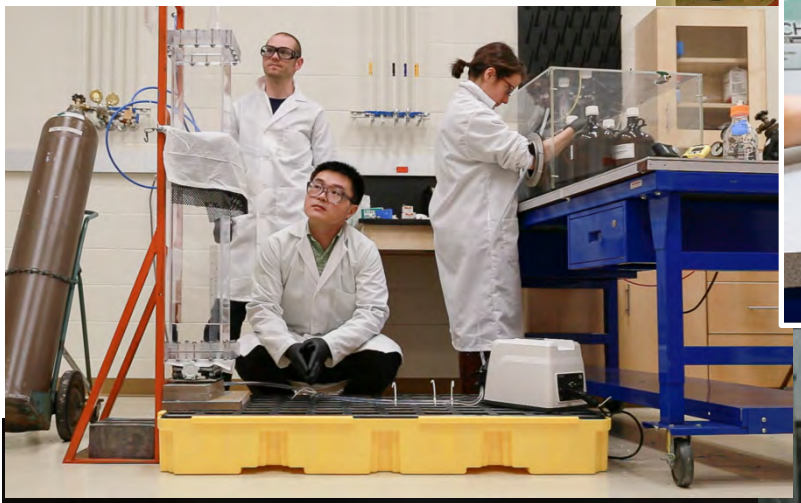


PROSPECT 2ton
Late 2016*

*** Technically driven schedule**

PROSPECT R&D and Technical Activities





prospect.yale.edu

PROSPECT Collaboration

site of experiment
High Flux Isotope Reactor, Oak Ridge National Laboratory

prospect.yale.edu

Brookhaven National Laboratory
Drexel University
Illinois Institute of Technology
Lawrence Livermore National Laboratory
Le Moyne College
National Institute of Standards and Technology
Oak Ridge National Laboratory
Temple University
University of Tennessee
University of Waterloo
University of Wisconsin
College of William and Mary
Yale University

63 collaborators
13 institutions
3 national laboratories

Summary

- New data are needed to address the existing reactor anomalies.
- PROSPECT will
  - Probe favored region of eV-scale sterile neutrinos at 3σ with 3 years of data.
  - Measure ^{235}U ν_e spectrum, address spectral deviation, and provide new constraints on $\bar{\nu}$ reactor antineutrino models complementary to current and future LEU measurements.
- PROSPECT has developed LiLS detectors that can mitigate reactor- and cosmogenic related backgrounds.
- Multiple detectors have been deployed at HFIR in preparation for full-size detector.
- Completed R&D for technical verification and to mitigate technical, cost, and schedule risks. Ready to proceed with detailed design and construction.
- Data taking in 2017 with first physics results in 2018 possible.

prospect.yale.edu