a precision short baseline reactor antineutrino experiment

Karin Gilje
for the PROSPECT Collaboration

Colloquium Towards CP Violation in Neutrino Physics

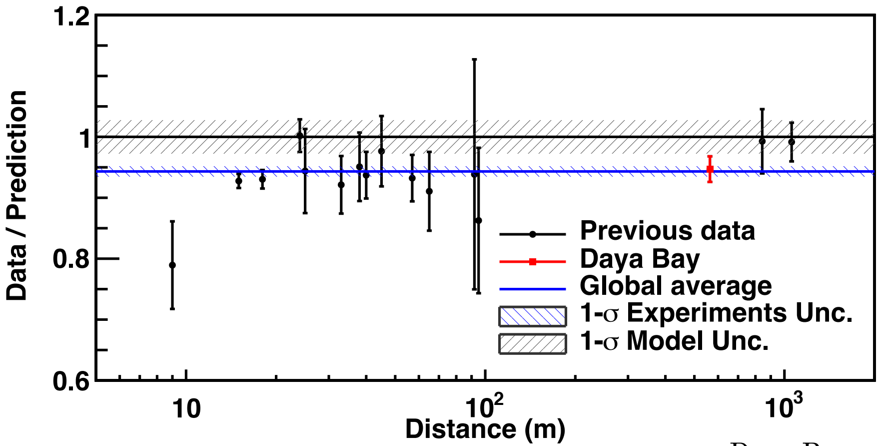
Prague

November 6, 2015

Reactor Antineutrino Anomalies

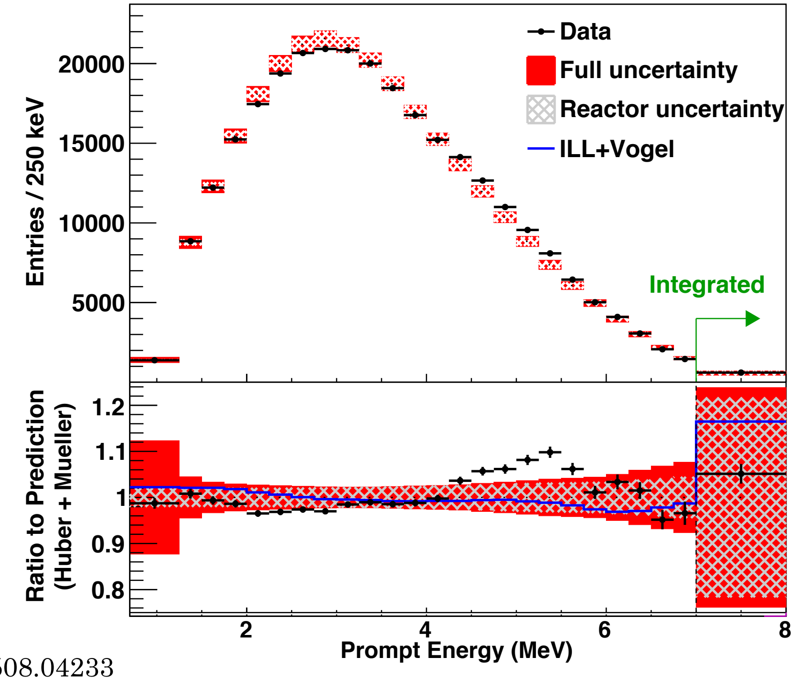
Flux Deficit

- 5% flux deficit
- Few super-short baseline experiments (<10m)



Spectral Anomaly

- Excess in events near 5 MeV



Daya Bay, arXiv:1508.04233

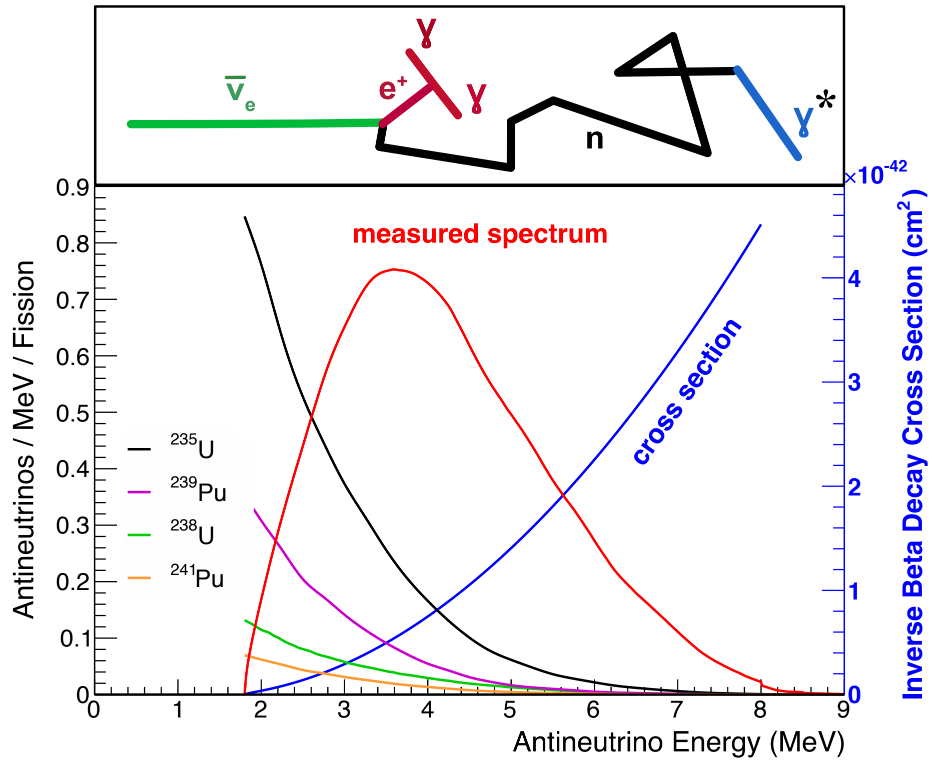
Reactor Spectrum Models

- Power reactor fuels are mixtures of U-235, U-238, Pu-239, and Pu-241.
- The total emitted spectrum is primarily an admixture of these four isotopes.
- Searches for reactor antineutrinos are typically based on inverse beta decay (IBD).

$$\bar{\nu}_e + p = e^+ + n$$

- Neutron capture can be on Gadolinium, Lithium, Hydrogen…

*Output of neutron capture depends on the target!

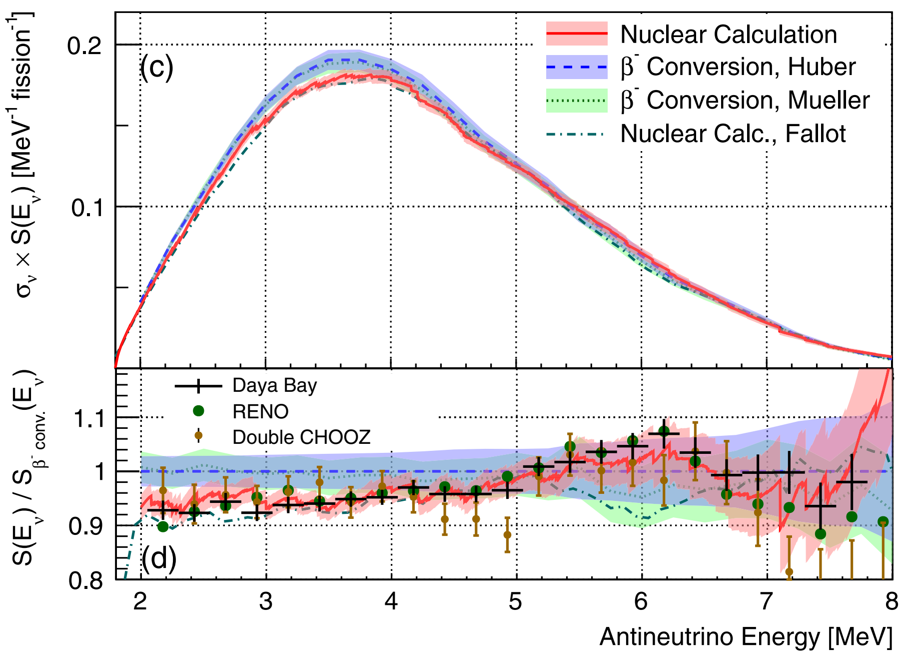


Vogel *et al*, arXiv:1503.01059v2 (2015)

Possible Solution #1

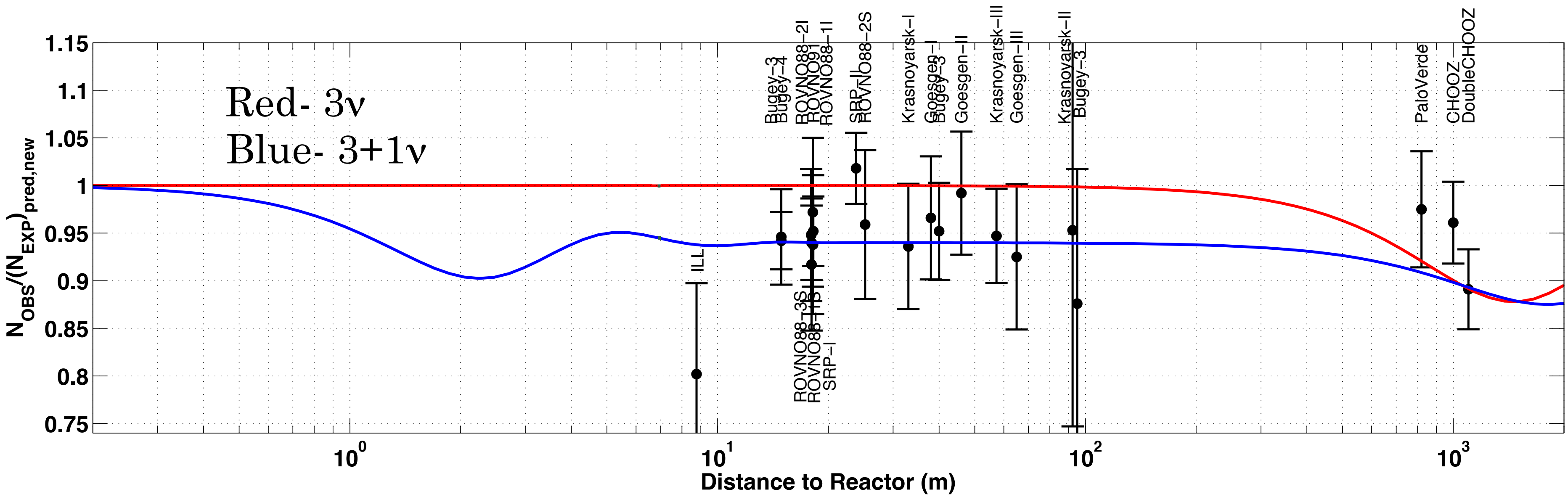
- Deficiency in inputs to Spectral Models.
  - *Ab initio* approach
    - Calculate spectrum branch-by-branch using nuclear databases.
  - Conversion approach
    - Measure beta spectrum
    - Work backwards to $\bar{\nu}_e$ spectrum
  - Both methods have uncertainties!

Dwyer and Langford, PRL **114** 012502 (2015)



Possible Solution #2

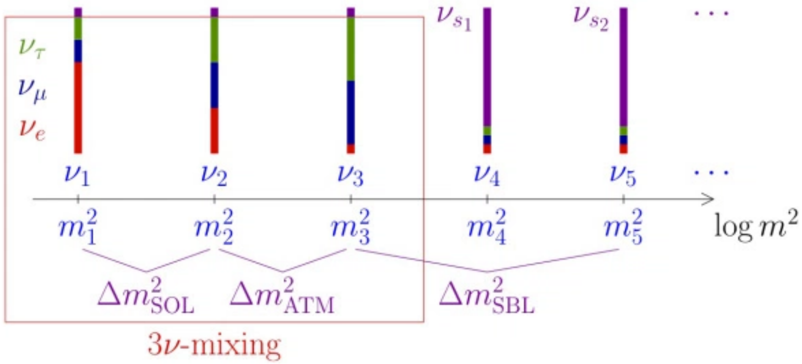
- The existence of sterile neutrinos (ν_s)
  - Can explain the visible deficit in the reactor antineutrino rate.
  - Probe only light neutrinos



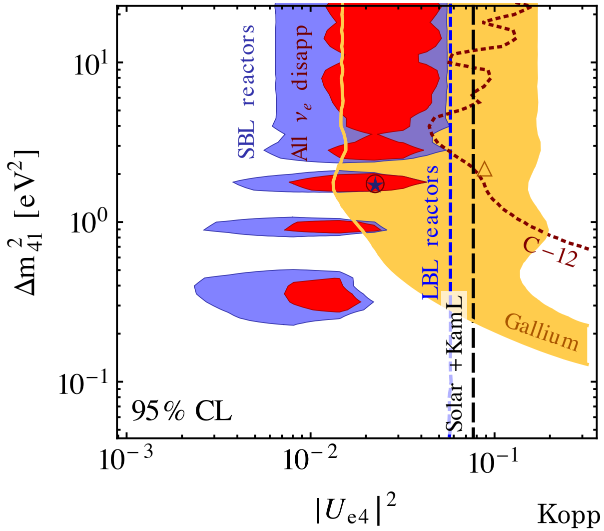
Light Sterile Neutrino Whitepaper, arXiv:1204.5379

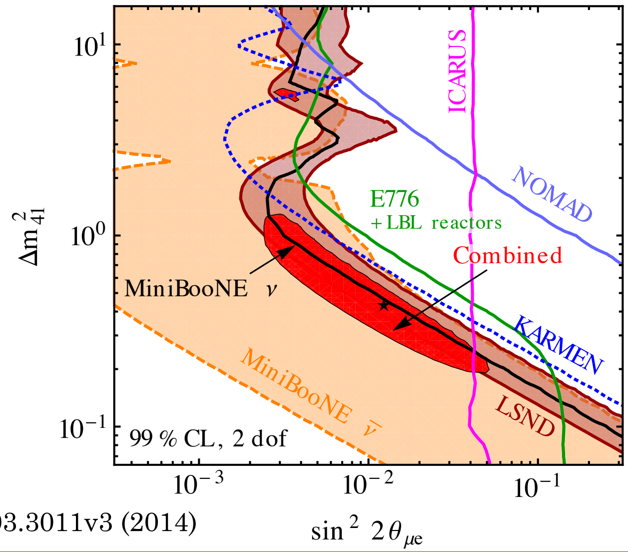
Sterile Neutrinos

- LEP tells us that there are 3 active neutrinos.
- There can be neutrinos that don't interact weakly.
- Hints of these sterile neutrinos can be seen indirectly through the reduction of expected rates. (LSND, MiniBOONE…)



Sterile Neutrino Fits: C. Giunti





Kopp *et al.* arXiv:1303.3011v3 (2014)

Why should we care about ν_s?

- NEW PHYSICS! (new particle, new neutrino flavor, beyond standard model physics)
- Sterile neutrino existence will effect our interpretation of CP violation searches.
- Oscillations to sterile neutrinos can cause interference over longer baselines.

Sterile Neutrinos and CP Violation

- There is an interesting article that addresses these issues specifically.
  - The impact of sterile neutrinos on CP measurements at long baselines, Raj Gandhi et al. arXiv: 1508.06275

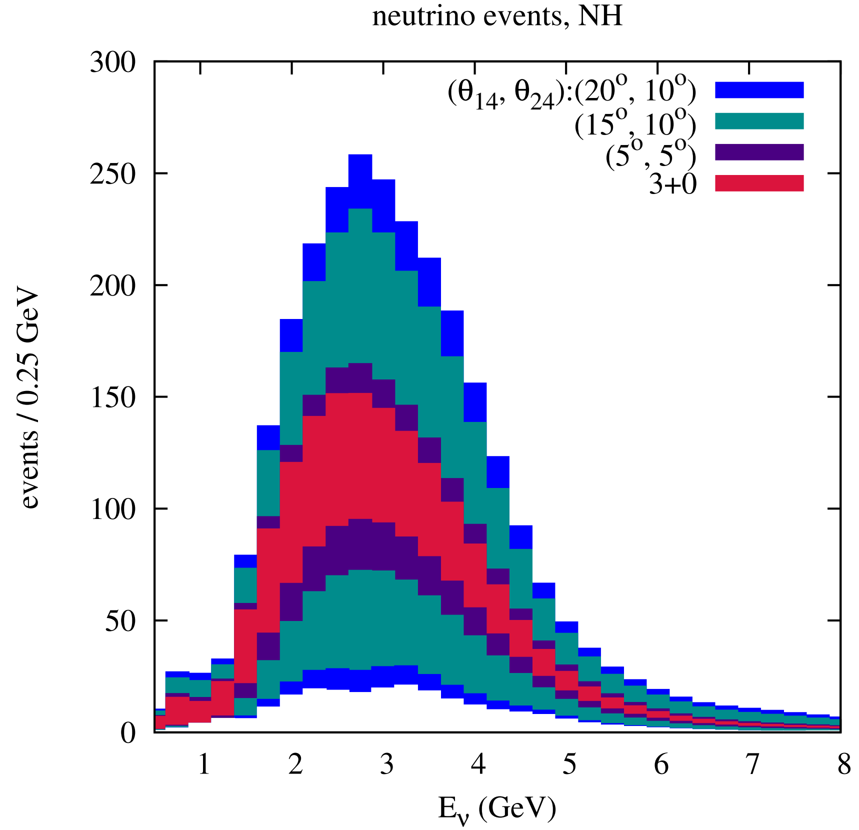
3+1 adds:

- 3 mixing angles: θ_{14}, θ_{24}, and θ_{34}
- 2 delta phase factors, δ_{34} and δ_{24}
- 3 mass splittings (approximately equal): Δm^2_{14}, Δm^2_{24}, and Δm^2_{34}

Sterile Neutrinos and CP Violation

- With three δ_{CP} phase factors, CP violation could exist in the lepton sector even if δ_{13} is zero.
- A degeneracy appears between 3+1 and 3+0 predictions of the shape and rate of events in LBL experiments. This will make interpreting δ_{CP} measurements more challenging.
- SBL measurements will provide critical and timely input to the interpretation of LBL experiments.

Assuming: $\Delta m^2 = 1\ eV^2$



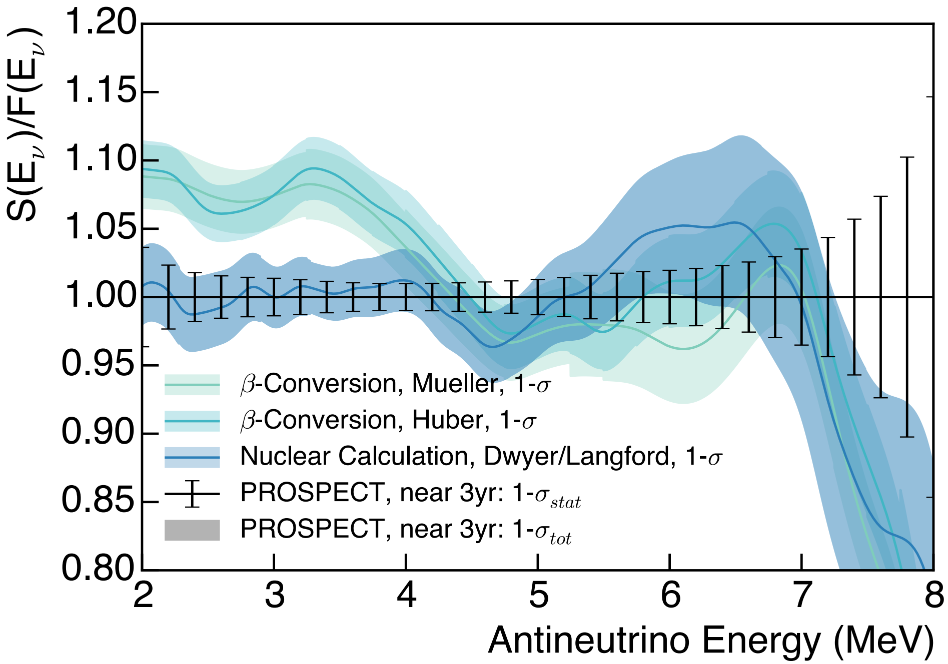
Gandhi, R. et al: arXiv1508.06275

Problem Summary

- We see a deficit in the expected reactor flux.
- We see a deviation from the expected reactor spectrum shape.
- Two possible solutions:
  - Incomplete physics model of the spectrum.
  - Sterile neutrino or other new physics.
- We need new data to resolve these issues.

PROSPECT- Precision Reactor Oscillation and Spectrum Experiment

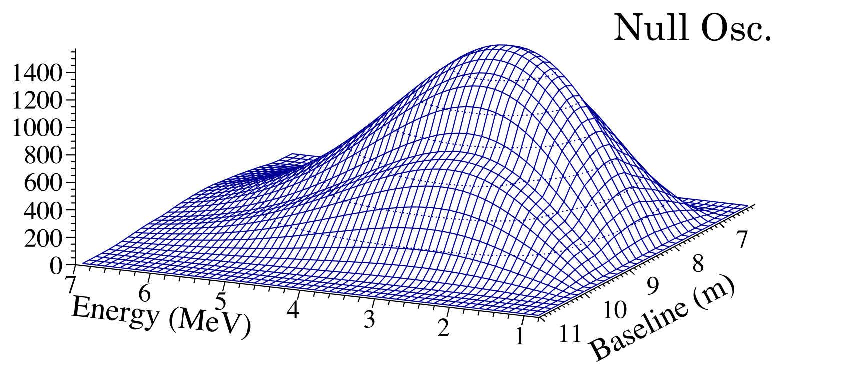
- Goal 1: A precise measurement of the U-235 spectrum.
- Goal 2: Perform a sterile neutrino search with interest in Δm^2 around 1.0 eV^2.



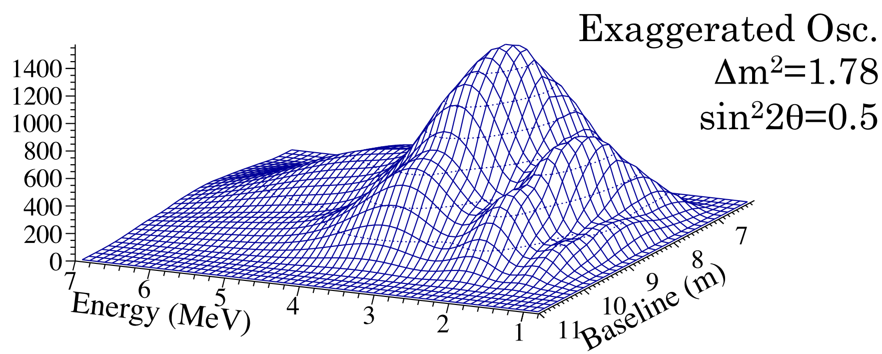
PROSPECT- Precision Reactor Oscillation and Spectrum Experiment

- Goal 1: A precise measurement of the U-235 spectrum.
- Goal 2: Perform a sterile neutrino search with interest in Δm^2 around 1.0 eV^2.

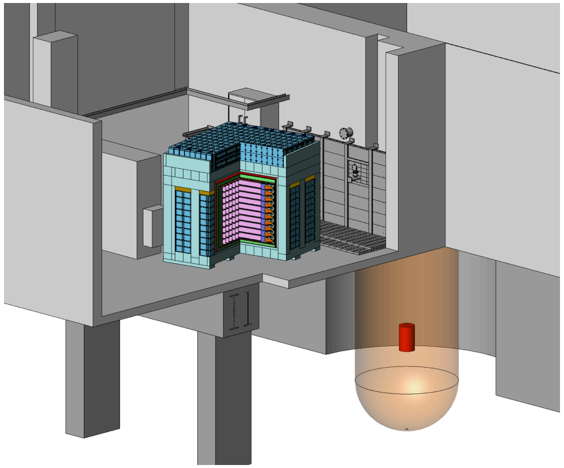
Simulated antineutrino rates



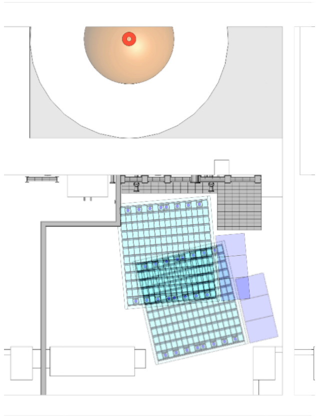
PROSPECT:
E = 1-7 MeV and L = 6-11 m



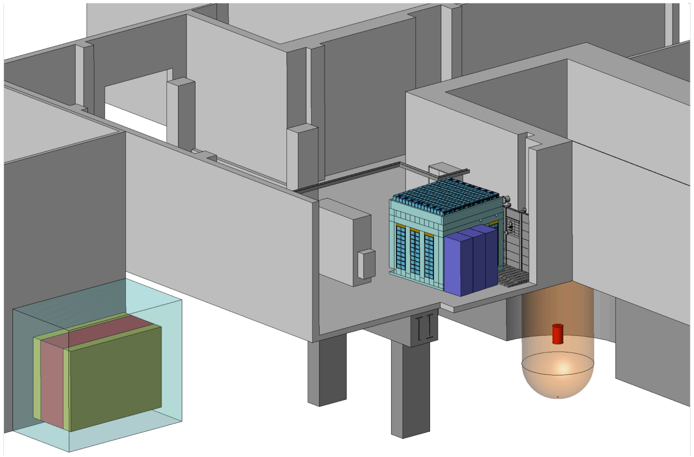
PROSPECT Design



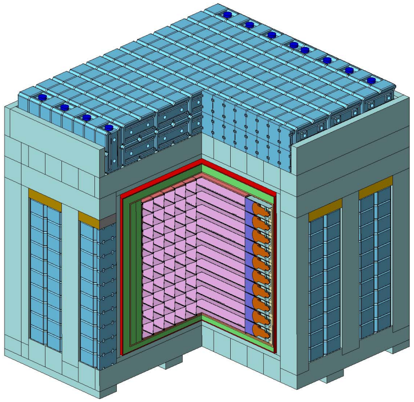
Phase I: a 3-ton detector at ~7m



Phase I: movable detector, 7-12 m coverage



Phase II: two detectors, 7-12m and 16-20m, 3-ton and 8-10-ton

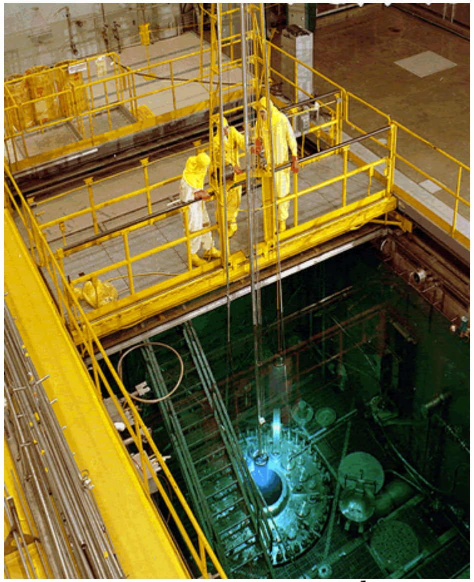


Phased Approach

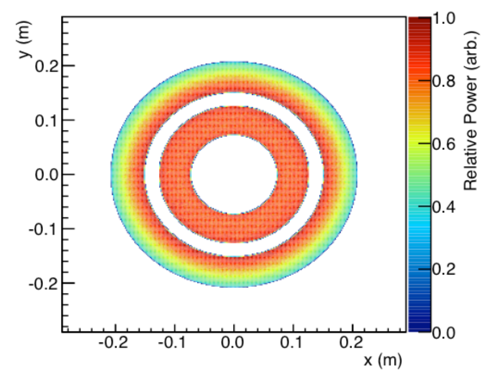
- Addresses experimental situation in a timely manner.
  - 3σ result in 1 year.
- Systematic control and increased physics reach.
- Allows flexibility in response to results from Phase I.

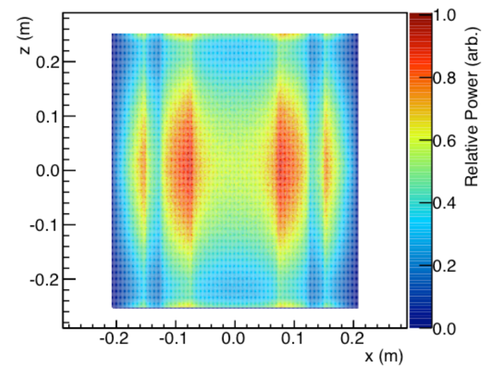
High Flux Isotope Reactor (HFIR) at ORNL

- Compact core research reactor operated at 85 MW
- Highly Enriched Uranium (HEU) Fuel-almost all fissions from U-235
- Scheduled live time: 41%
  - Allows in-depth background study.
- Worked with PROSPECT for 2 years and multiple deployments. Design developed in cooperation.
- 0.2 m radius x 0.5 m height



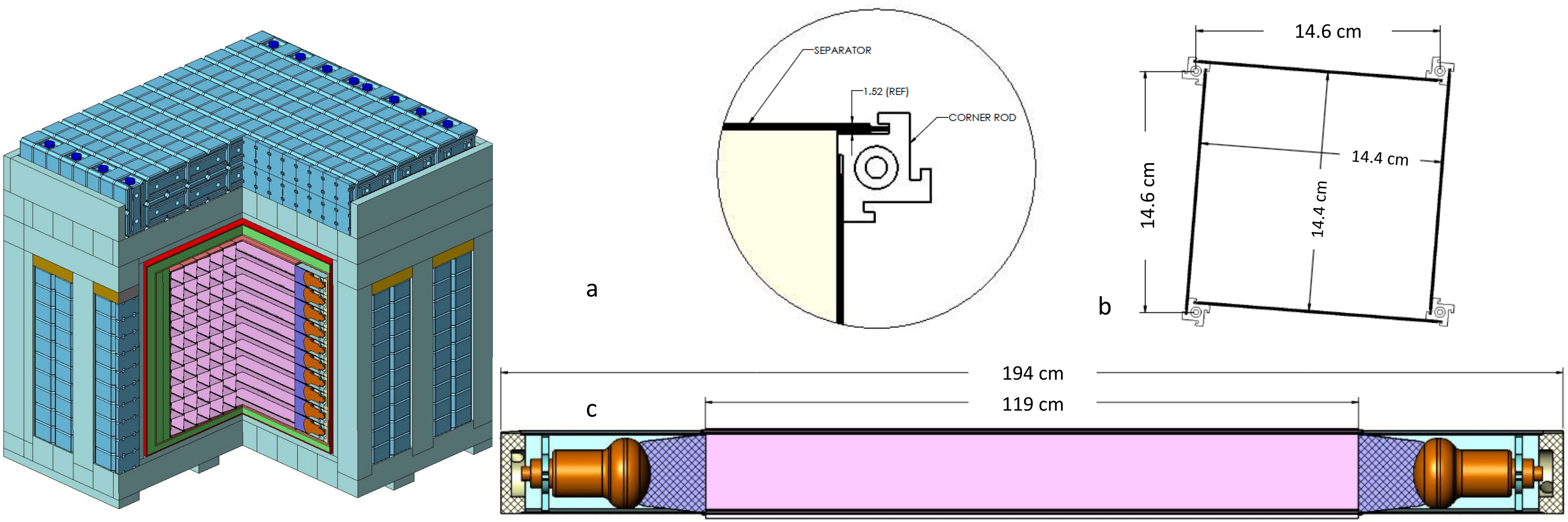
ornl.gov





Detector Construction

- Li-loaded EJ-309 liquid scintillator
- Double-ended PMT readout
- Optically separated segments with specular reflectors.
- 12x10 cells for Phase I detector
- Corner pinwheels provide support and a place for calibration
- Movable near detector



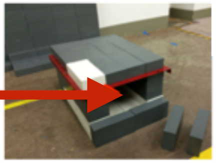
Phased Detector Development

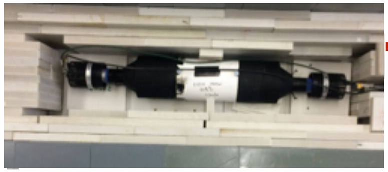
Run DAQ, Remote data-taking

See n-Li + PSD

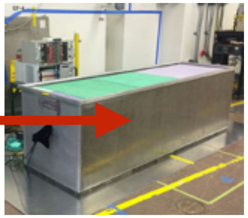
PROSPECT 0.1* Aug 2014

2 inches





5 inches



PROSPECT 2* Dec 2014- Mar 2015

Demonstrate shielded background rates

Demonstrate full timing and PE response

PROSPECT 20* Mar 2015

1 meter

PROSPECT 200 mockup

3x3x1 meter mockup at IIT

Deploy final design concepts

Observe relative segment responses

PROSPECT 60

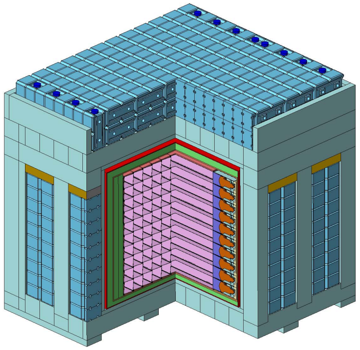
See antineutrinos

Meet physics goals

PROSPECT 400

PROSPECT 2k Phase I (3ton)

PROSPECT Phase II (**10k**)?



*Deployment complete!!!

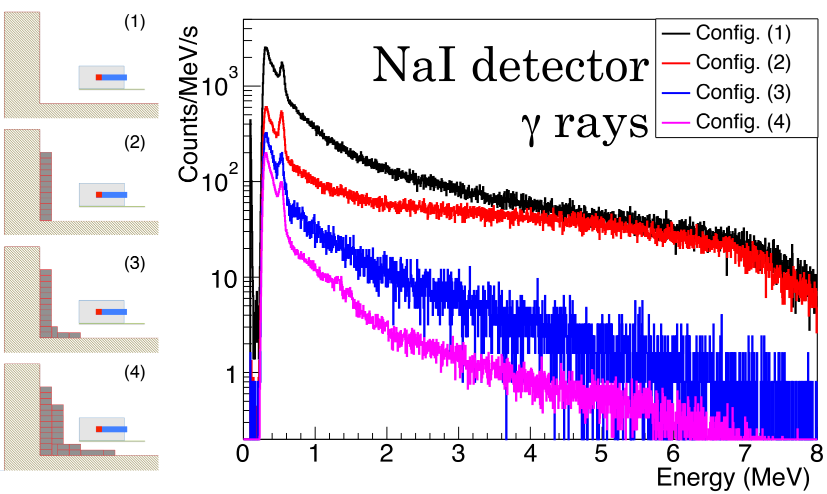
Approximate mass kg

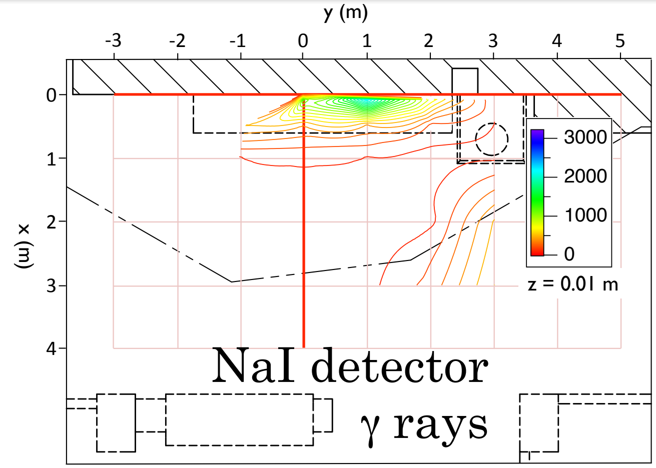
Near Surface Detection

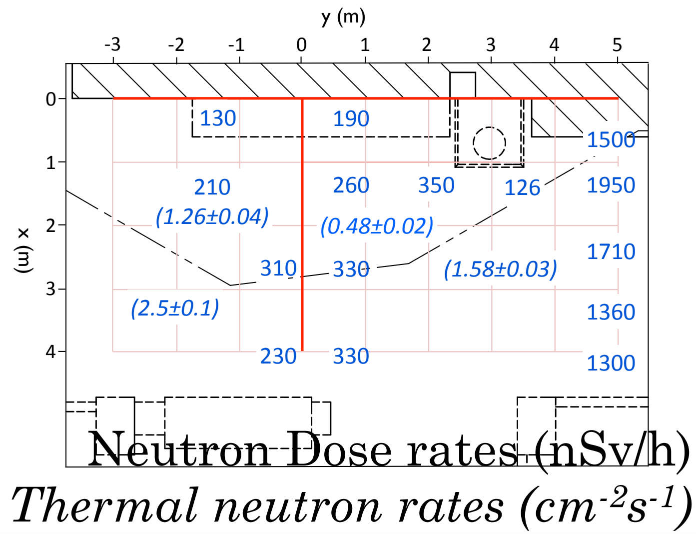
- Backgrounds
  - Cosmogenic
  - Reactor
- Reduction Techniques
  - Multi-layered shielding
  - Temporal and spatial correlation of IBD signal
  - Particle Identification from Pulse Shape Discrimination (PSD)
  - Segmentation for fiducialization and spatial coincidence of events

Background Study

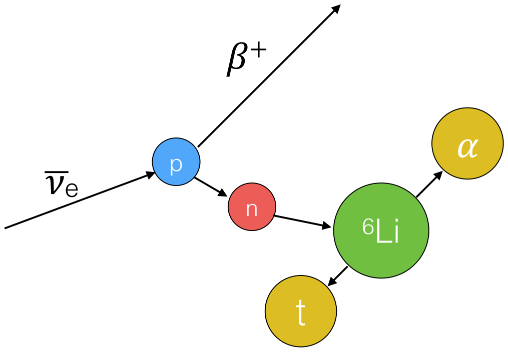
- Researched three HEU reactor sites (HFIR, ATR, NIST)
- Characterized rate and distribution of source backgrounds and cosmogenics
- HFIR chosen for schedule and logistics
- Publication of survey at arXiv: 1506.03547





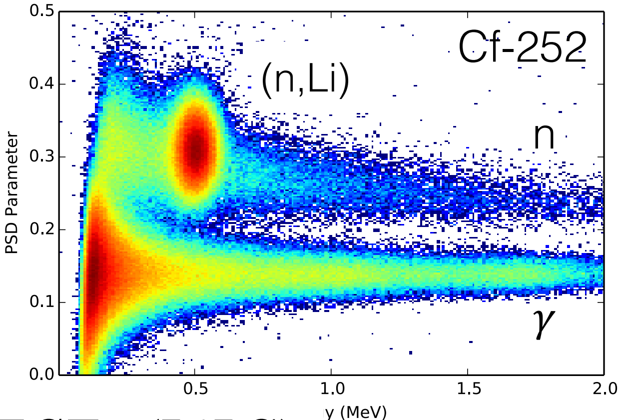


Using Pulse Shape Discrimination to Reduce Backgrounds



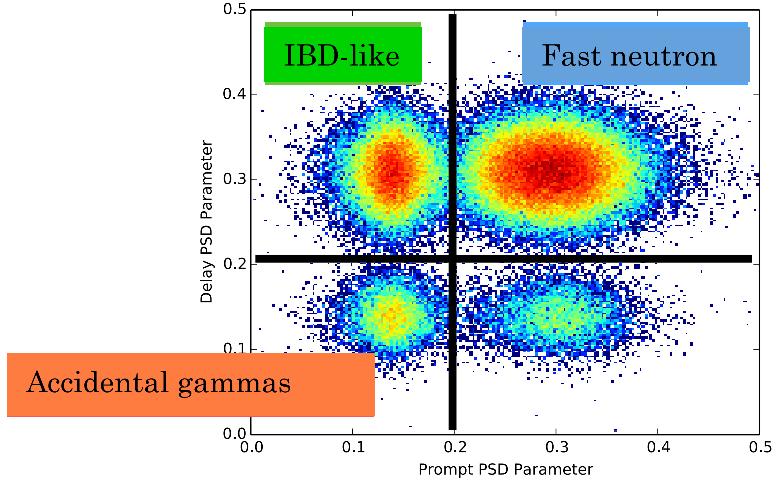
Prompt signal: 1-10 MeV positron annihilation

Delay signal: 0.6 MeV capture on ^{6}Li



PSD signatures	
Signal	IBD event: γ-like prompt, n-like delay
Background	Fast neutron: n-like prompt, n-like delay
	Accidental gamma: γ-like prompt, γ-like delay

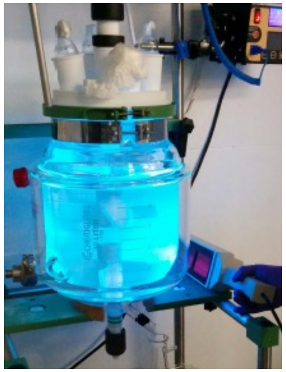
PROSPECT2 (LiLS) arXiv:1309.7647

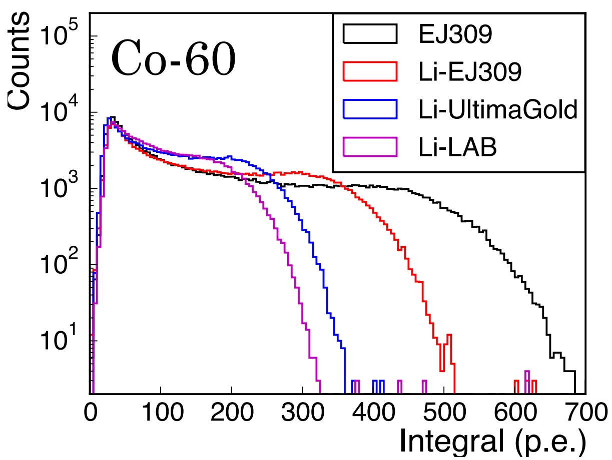


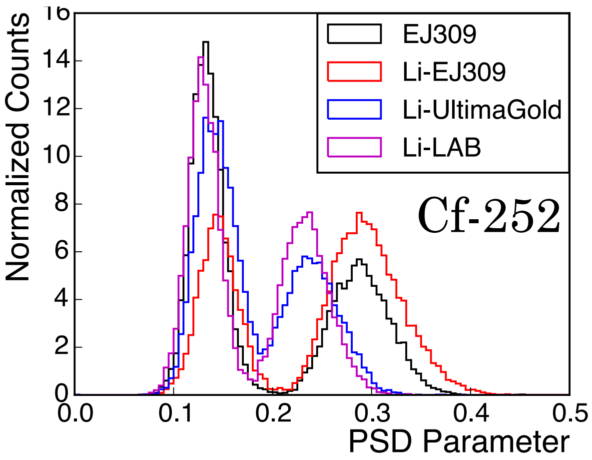
Liquid Scintillator Development

Scintillator Specifications

- We developed three different formulae of LiLS
- Li-loaded EJ-309 performed best of all, down-selected on this formula
- 8200ph/MeV, high PSD figure of merit
- Large batches have been produced for testing in realistic geometries (more two slides from now)







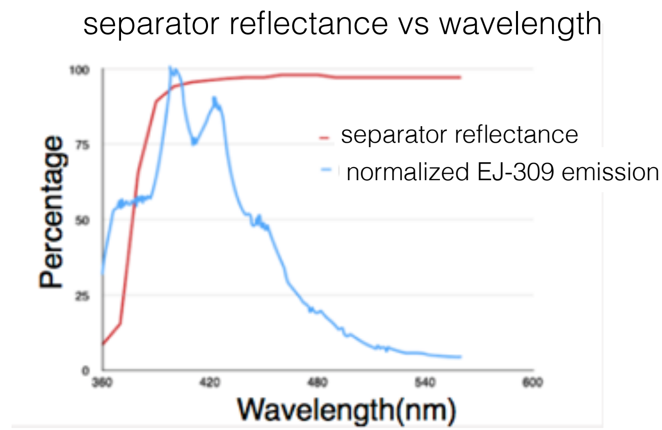
Segmentation Design

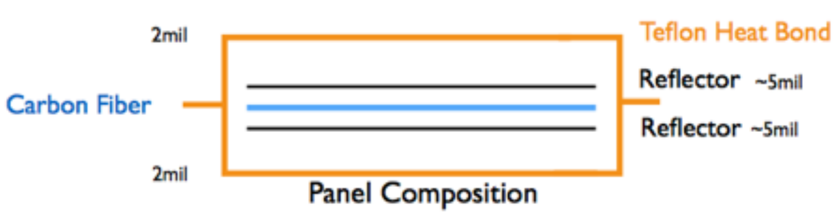
Compatibility:

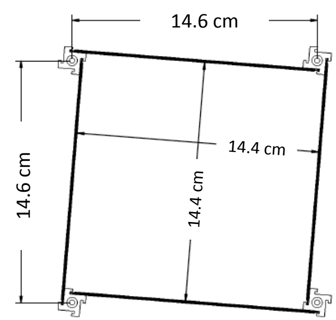
- Extensive material compatibility testing required to ensure long-term LS performance
- Focus on materials proven in recent experiments (PTFE, acrylic, polypropylene, …)
- Long-term mechanical stability verified

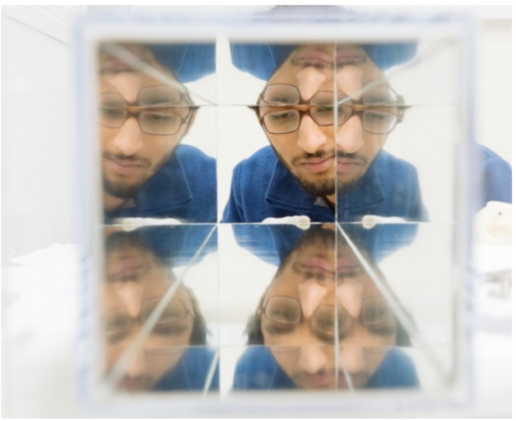
Separators:

- Physics goals demand low inactive mass, high reflectivity and long-term compatibility
- Developed multi-layer system meeting all requirements
- Fabrication procedures for full-scale system under validation
- <2% inactive mass







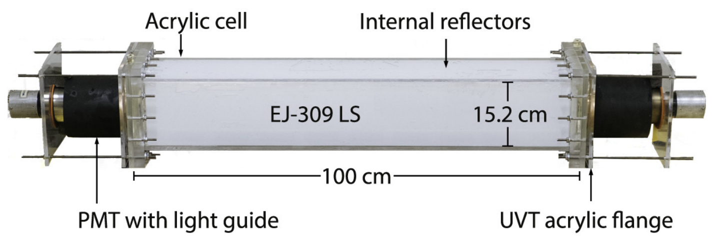


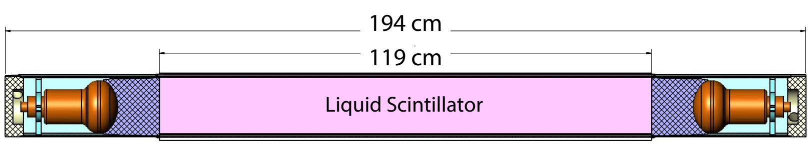
Segment Response

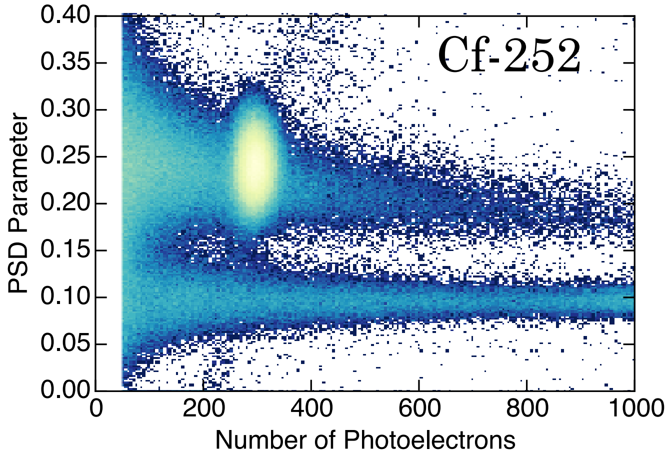
arXiv: 1508.06575

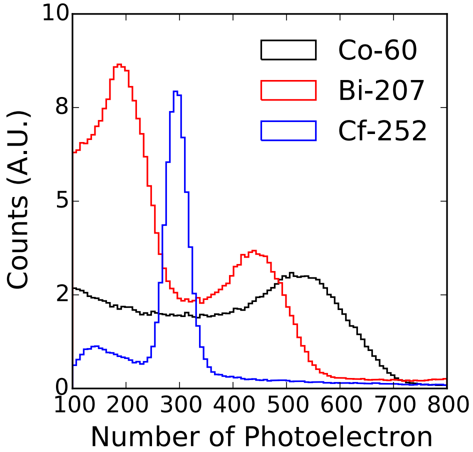
PROSPECT20 at Yale:

- Full size cell with realistic geometry and internal reflectors
- Optimize light collection and PSD
- 530 PE/MeV, Figure of Merit 1.4 at (n,Li) capture peak
- PSD at (n,Li) capture peak has 99.99% rejection of γ and 99% acceptance of neutron events



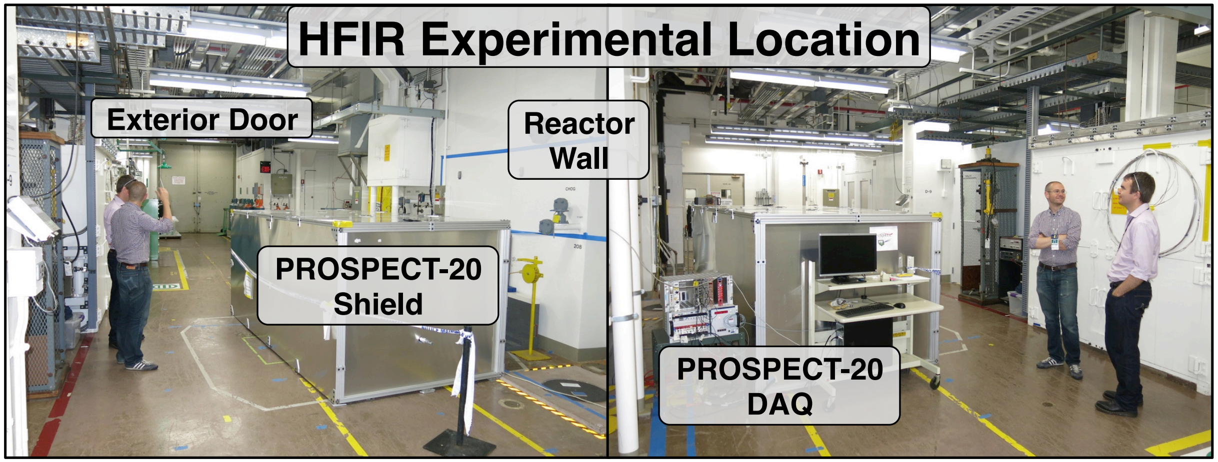


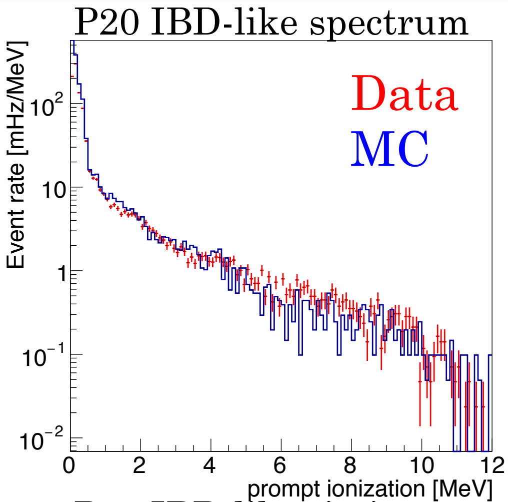


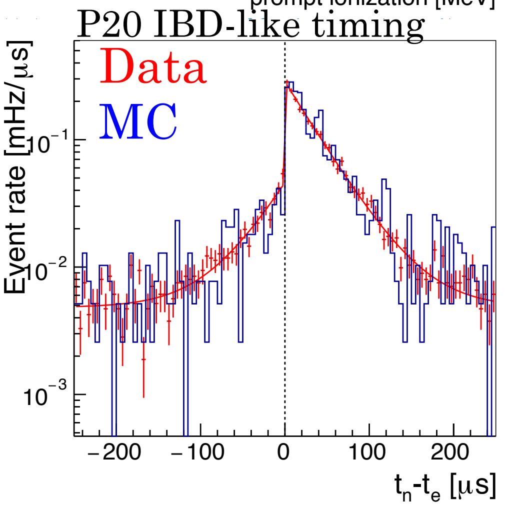


ILLINOIS INSTITUTE OF TECHNOLOGY

Data/MC Validation at HFIR



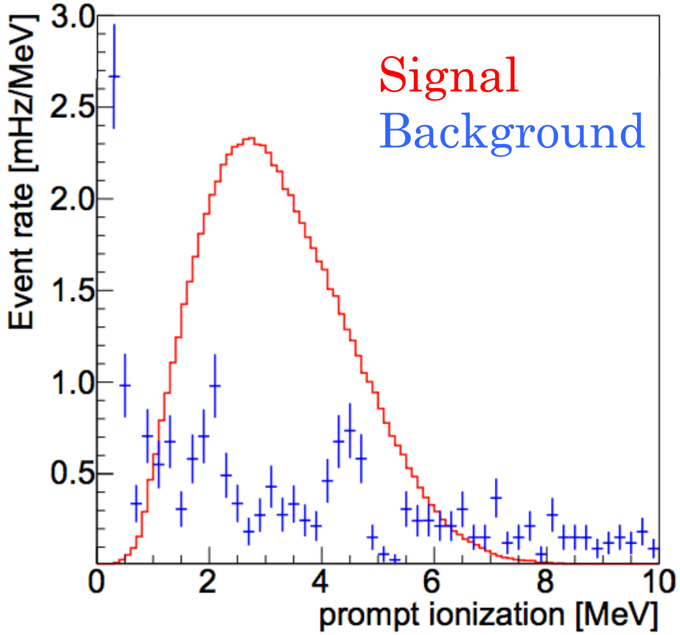


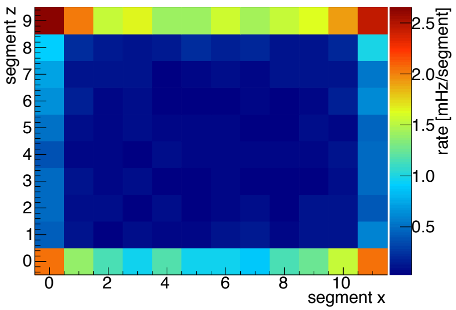


- Background Mitigation
  - Benchmark MC against prototypes
  - Allows extrapolation to full detector
  - 4 months of operation (2 reactor cycles) with >99% uptime
  - no change in IBD-like backgrounds with reactor status

Simulation

- Detector response
  - Feeds into sensitivity calculation
  - Feeds into understanding of detector precision
- Design
  - Optimize shielding
  - Light Transport
  - And more…
- Cut Development
  - PSD, timing, spatial, fiducialized volume …

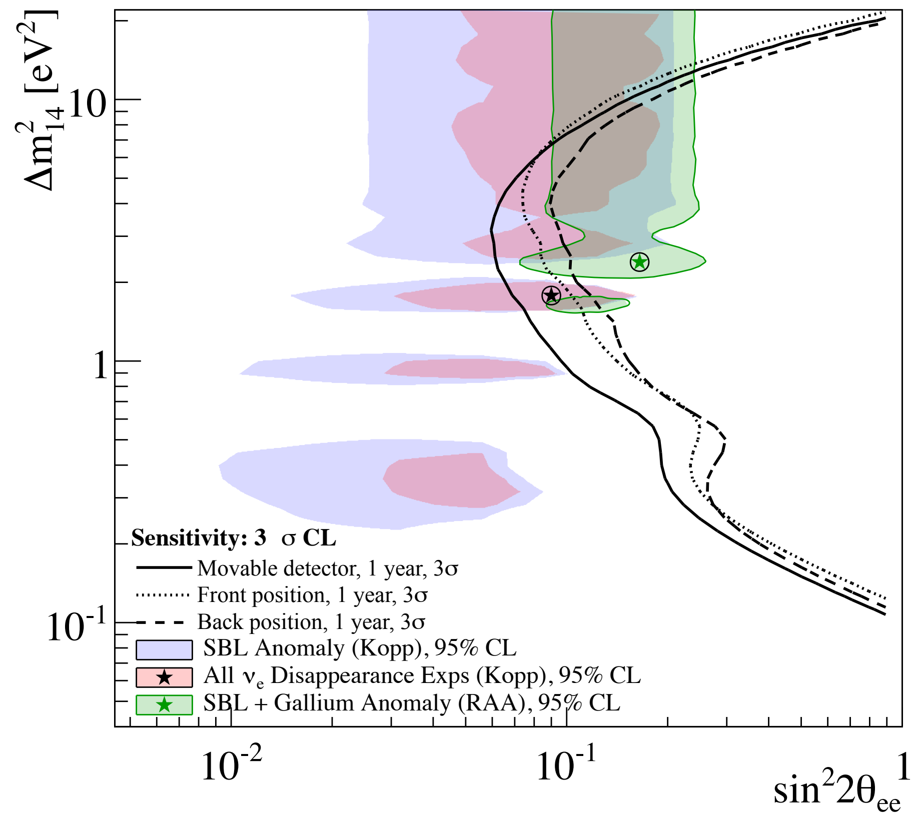




cosmogenic IBD-like backgrounds

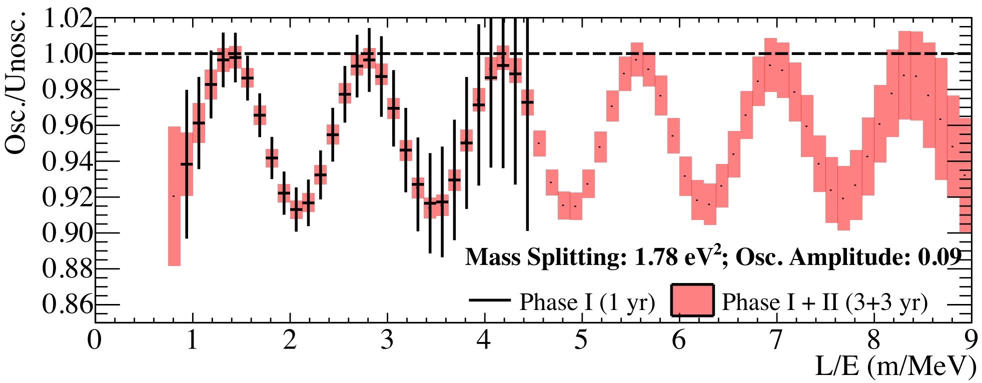
Movable Phase I

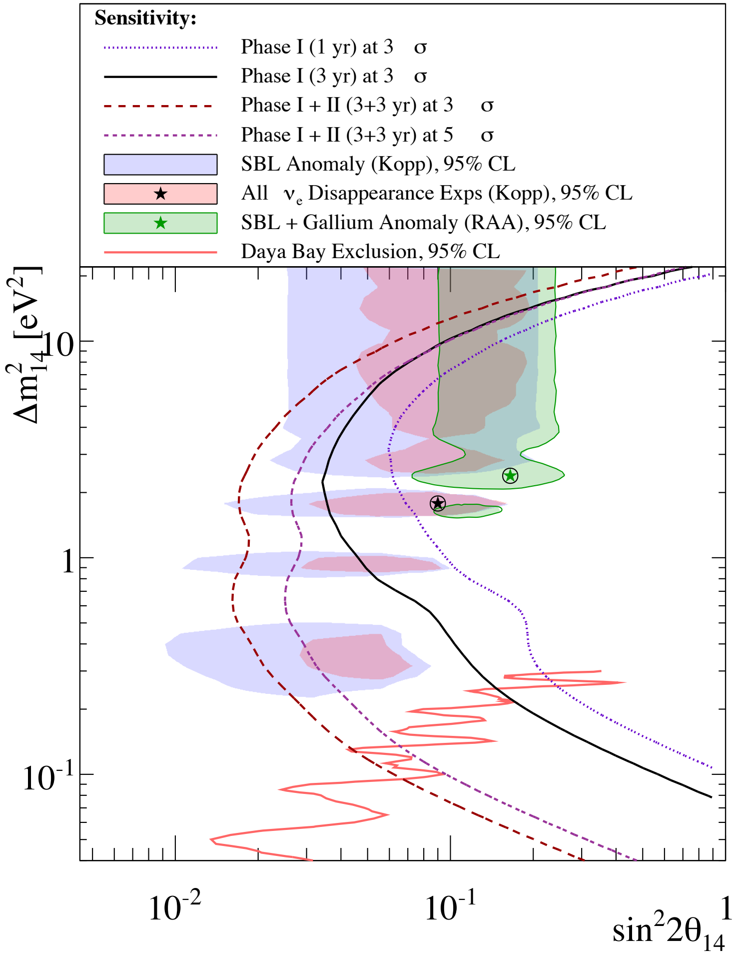
- Provides greater physics reach through increased L/E range
  - 1 year at one position will NOT cover the Kopp best fit parameters at 3σ, but 1 year at mixed positions will!
- More systematic crosschecks



Sterile Neutrino Search

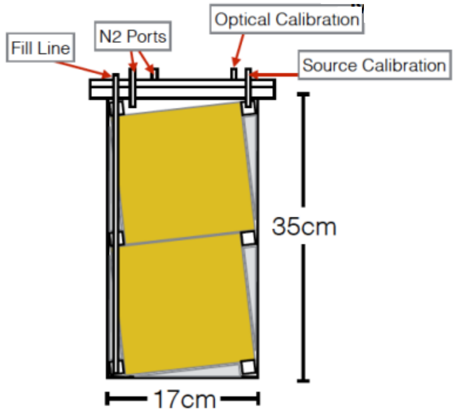
- Relative measurement – no absolute spectrum dependence
- Using two Phase I positions in 1 year
- Using three Phase I positions in 3 years
- Assumptions:
  - 4.5%/√E energy resolution
  - 15cm position resolution
  - 1.4:1 front position signal to background based on MC simulation in forward position
  - 42% fiducial volume efficiency based on MC simulation
  - 41% reactor uptime
- Expected IBD rate: ~1000/day

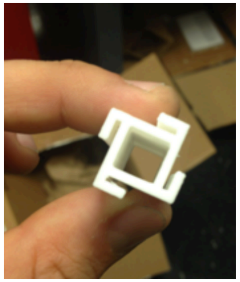


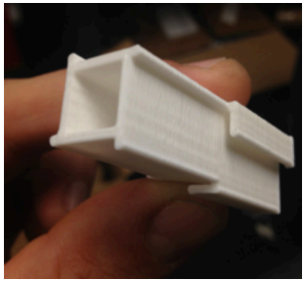


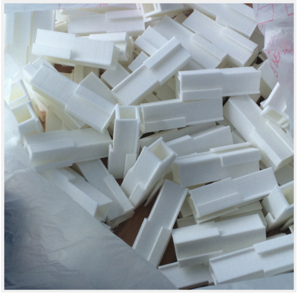
Next Steps

- PROSPECT60
  - A multi cell arrangement to test the final design
  - Background mitigation
- PROSPECT200 (ongoing)
  - Validation of internal structure (Pinwheel rods, support structure, reflector size)
  - Mechanical stress testing
- PROSPECT400
  - Potential working 4x4 arrangement
  - Considering installation at HFIR
  - Deployment depends on funding profile









Closing Statements- Physics

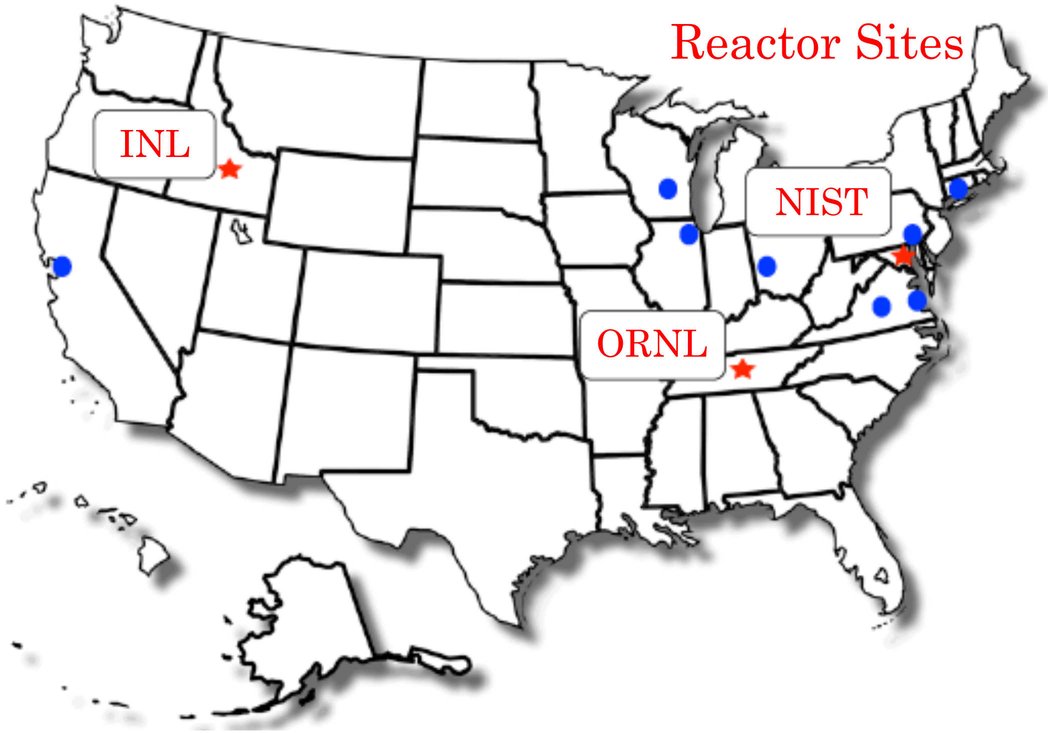
- Measurement of U-235 spectrum will provide new constraints on reactor antineutrino models, complementary to current and future LEU measurements.
- PROSPECT Phase I+II will provide the best sensitivity to eV scale sterile neutrinos.
  - Within 1 year of Phase I, we will have 3σ coverage over the Kopp global best fit for the anomalous parameter space.
  - With 3 years of Phase I and 3 years of Phase II, we will have 5σ coverage over the Kopp global fit parameter space.
- Movable detector increases physics sensitivity and allows systematic cross checks.
- Data taking with Phase I within 1 year after funding approved.

Conclusions- Protypes

- Several Prototypes have been constructed.
  - Testing detection concepts and detector structure.
    - Demonstrated full cell capabilities.
  - Testing at HFIR and validation of design.
  - Adequate performance and background reducible.
- Three Papers available now!
  - P20 Prototype at Yale. arXiv: 1508.06575
  - Backgrounds at HFIR, ATR, and NIST. arXiv: 1506.03547
  - Whitepaper. arXiv: 1309.7647

The PROSPECT Collaboration

Website: **http://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

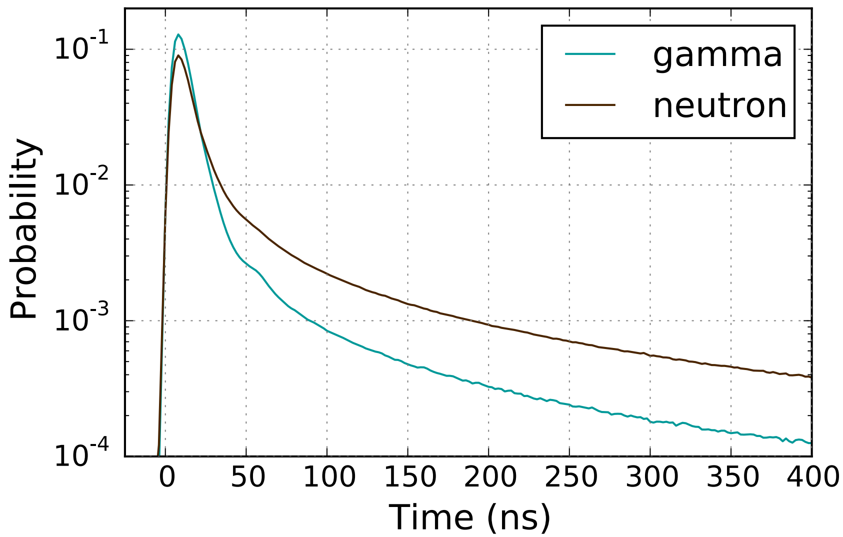
BACKUPS

Pulse Shape Discrimination (PSD)

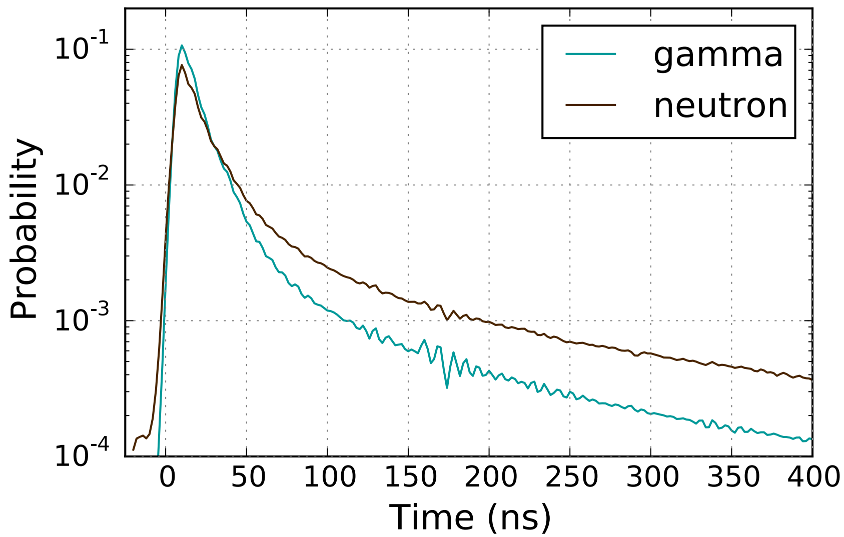
arXiv: 1508.06575

- A method of Particle Identification based on the scintillation decay times.
- Can retain good PSD performance with large cells.
- Use a figure of merit to quantify the PSD power.

PROSPECT0.1



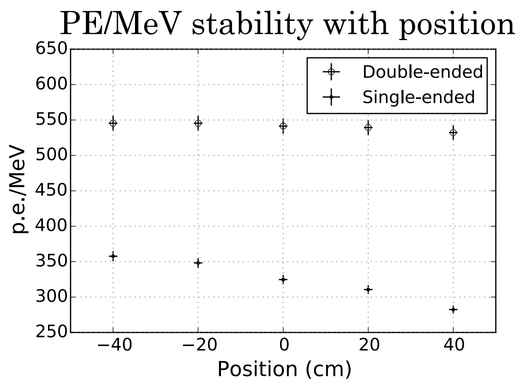
PROSPECT20

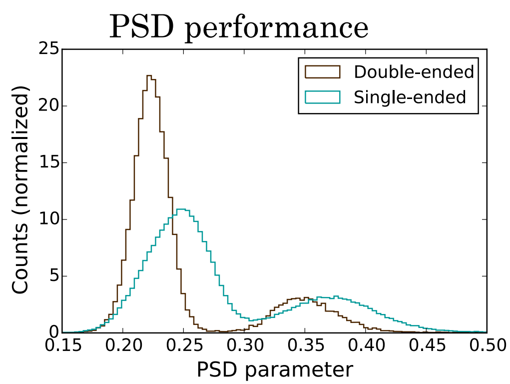


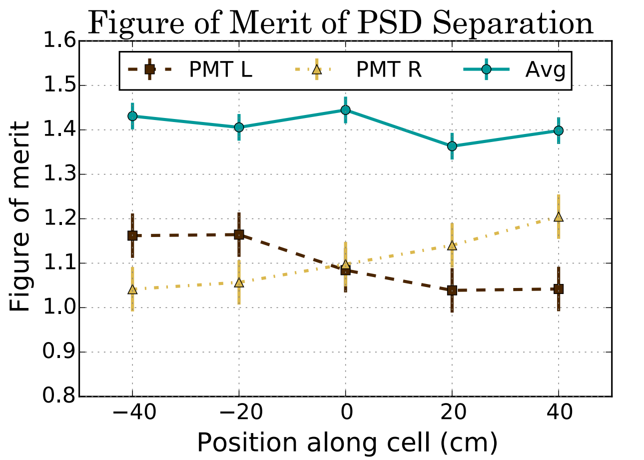
Double-Ended Readout

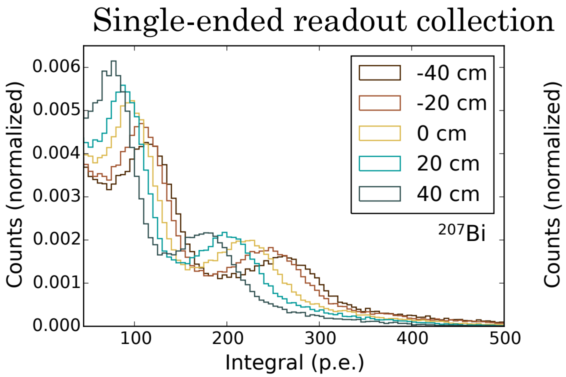
arXiv: 1508.06575

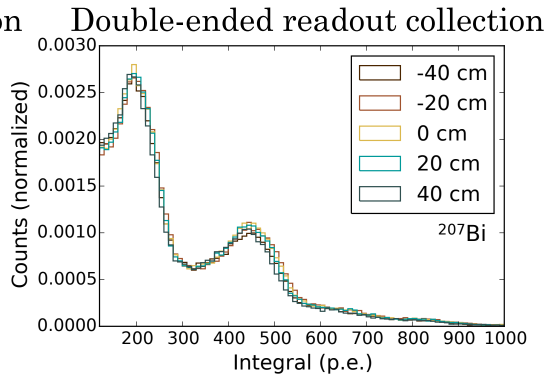
- Allows for uniform collection
- Enhances PSD separation
- Increases position resolution

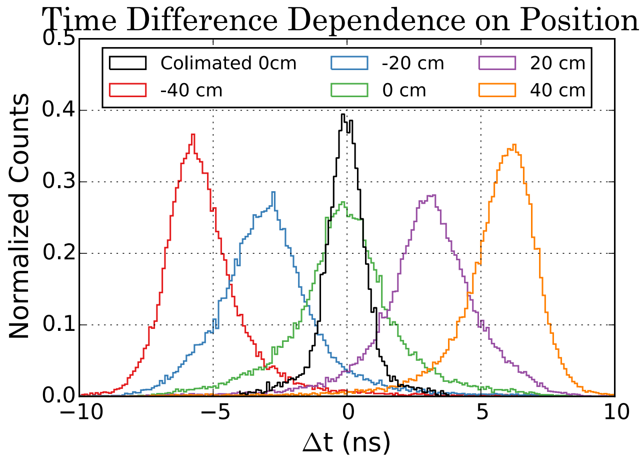










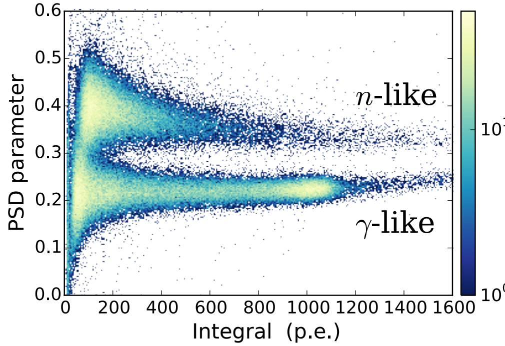


Segment Response

arXiv: 1508.06575

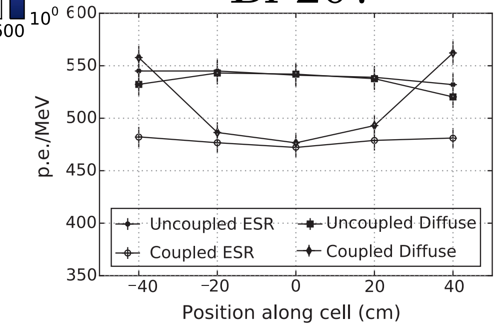
PROSPECT20 at Yale (EJ-309):

- Optimize light collection and PSD
- 527 ± 10 photons/MeV
- PSD at (n,Li) capture peak has 99.99% rejection of γ and 99% acceptance of neutron events
- Reached target light collection with realistic geometry

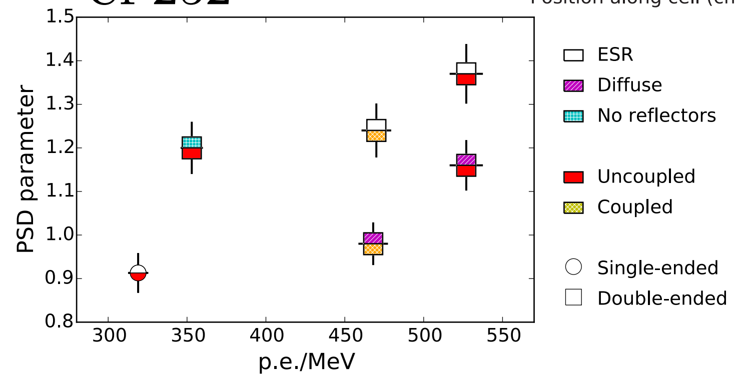


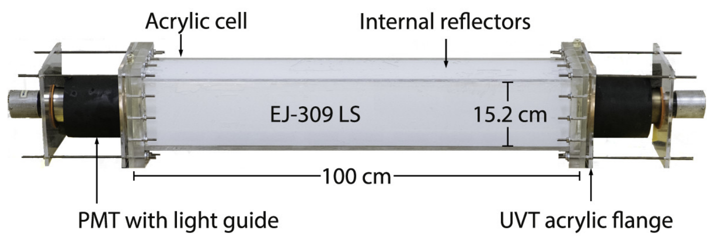
Cf-252

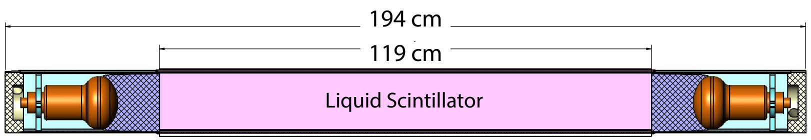
Bi-207



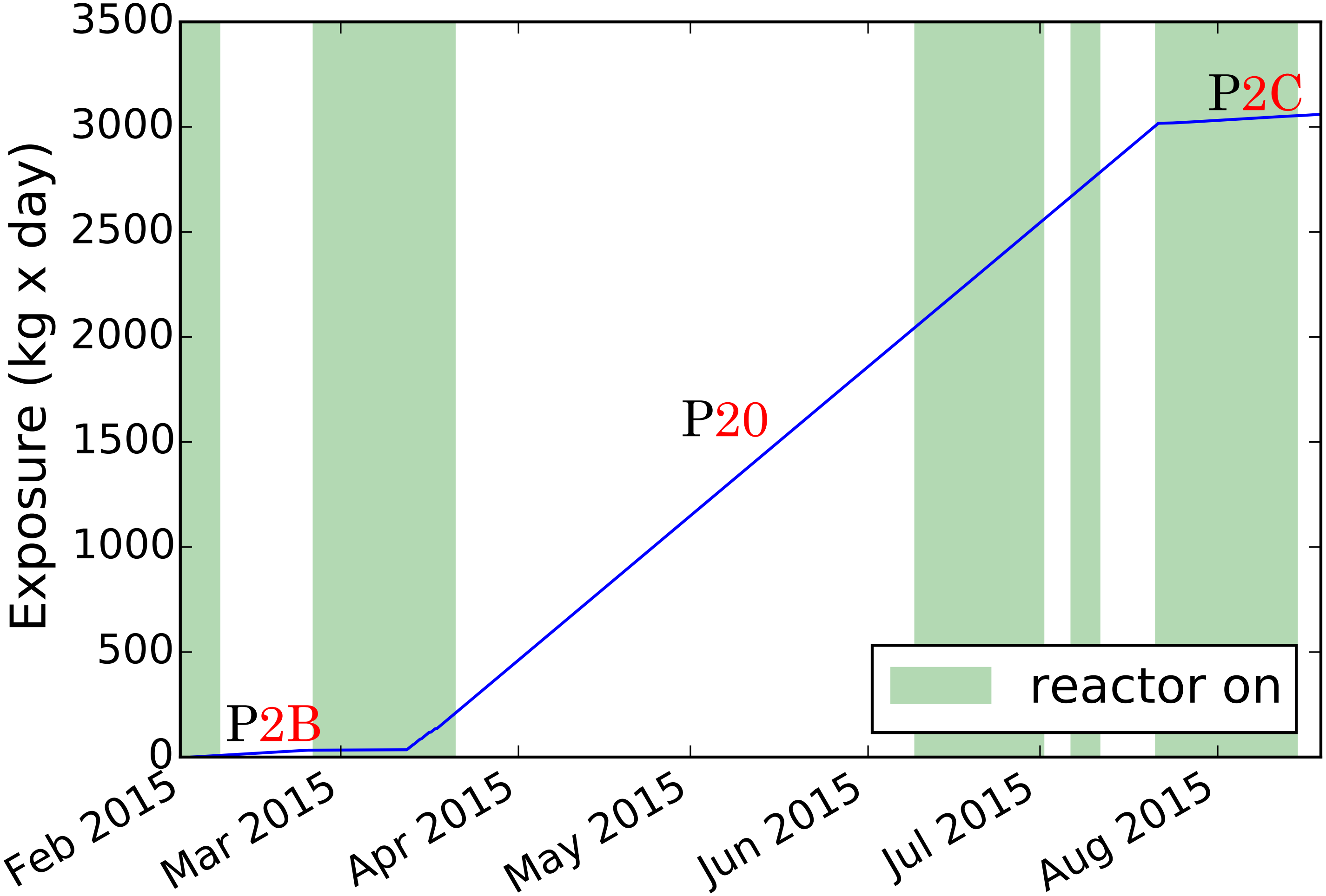
Cf-252





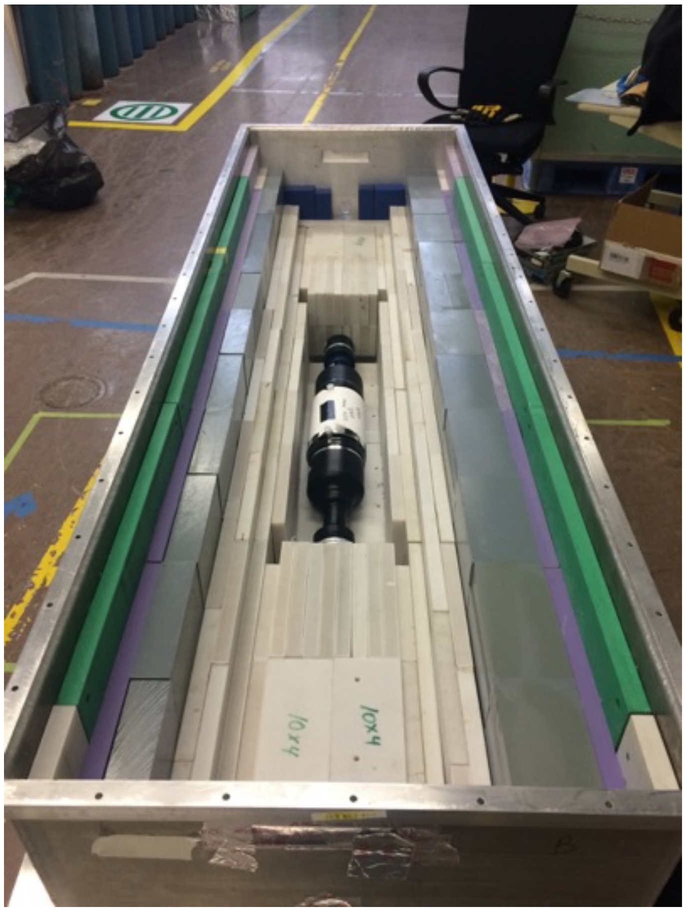


PROSPECT exposure at HFIR



PROSPECT-2 at HFIR

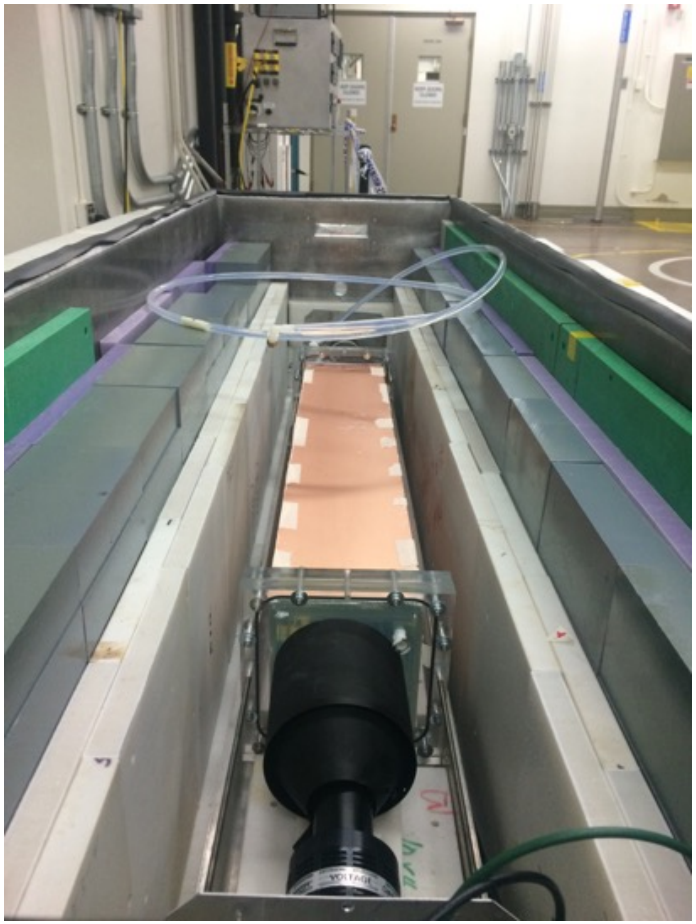
D. Norcini, DPF 2015



Detector geometry: 1.7L cylinder
Scintillator: Li-loaded EJ-309
PMTs: 5” flat ET9823
Shielding: poly, Pb, Bpoly
Reflectors: diffuse Gore
DAQ: CAEN 1720 (12bit)
Purpose: background reduction method

PROSPECT-20 at HFIR

D. Norcini, DPF 2015



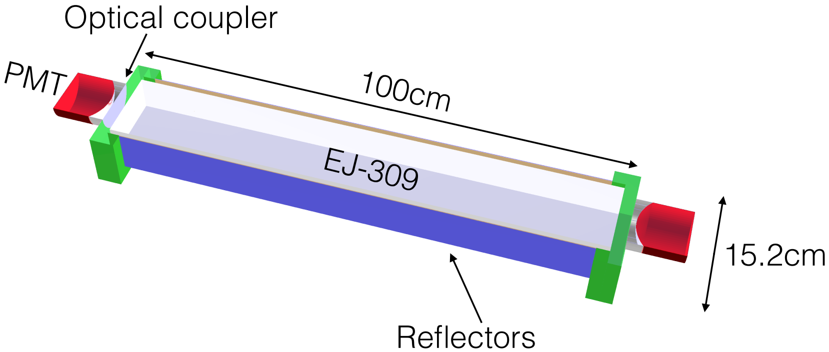
Detector geometry: 23L 1-meter rectangle
Scintillator: Li-loaded EJ-309
PMTs: 5” flat ET9823
Shielding: poly, Pb, Bpoly, water bricks
Reflectors: 3M SolarMirror
DAQ: CAEN 1720 (12bit)
Purpose: Operate full PROSPECT segment

PROSPECT-20 at Yale

D. Norcini, DPF 2015

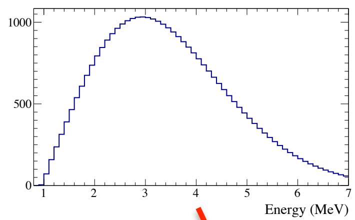
Optics optimization studies:
- Reflector type
- Reflector coupling
- PMT read-out
- Compare to simulation

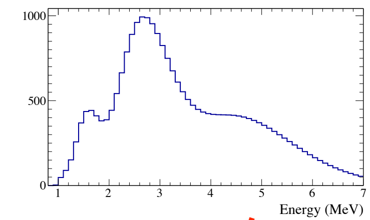
Soon to come:
- Optical coupler geometries
- Li-loaded EJ-309



Detector geometry: 23L 1-meter rectangle
Scintillator: EJ-309
PMT(s): 5” spherical Hamamatsu R6594
Shielding: Pb
Reflectors: variable
DAQ: CAEN 1730 (14bit)
Purpose: optimize optics of full segment

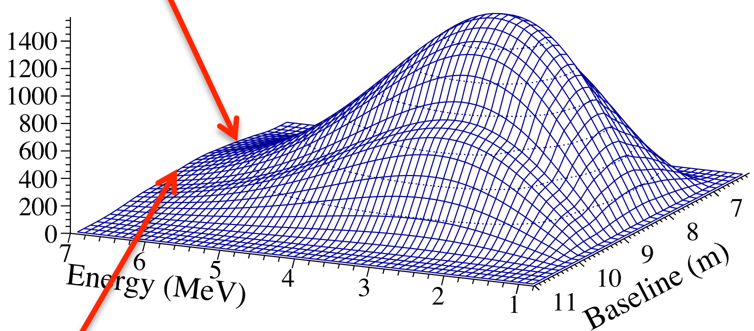
Calculating the Sensitivity

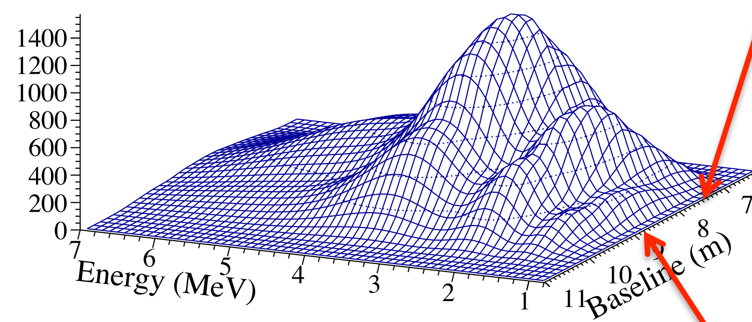


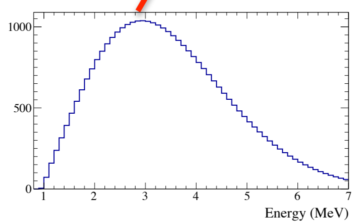


Null Oscillation Spectrum

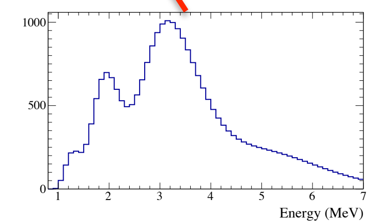
Exaggerated Oscillation Spectrum







We calculate the χ^2 for each pair of Δm^2 and $\sin^2 2\theta$ that we are interested in.



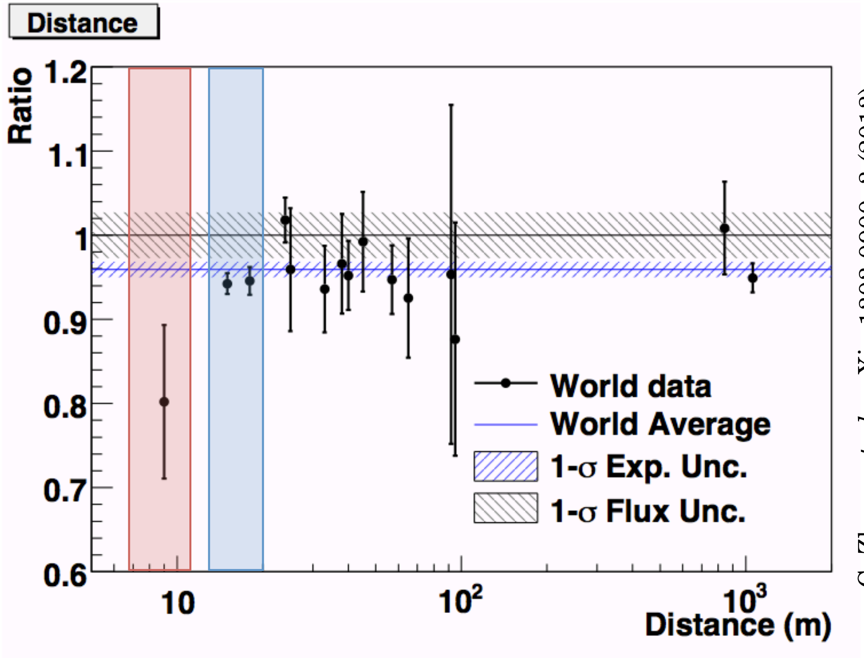
Comparison to Other Experiments

	Effort	Dopant	Good X-Res	Good E-Res	L Range (meters)	Fuel	Exposure, MW*ton	Move-able?	Running at intended reactor?
US	**PROSPECT**	**Li**	**Yes**	**Yes**	**6.5-20**	**HEU**	**185**	**Yes**	**Yes**
	NuLat	Li/B	Yes	Yes	TBD	TBD	TBD	Yes	No
EU	Nucifer	Gd	No	Yes	7	HEU	56	No	Yes
	STEREO	Gd	Yes	Yes	9-11	HEU	100	No	Yes
	SoLid	Li	Yes	No	6-8	HEU	155	No	Yes
Russia	DANSS	Gd	Yes	No	9.7-12	LEU	2700	Yes	Yes
	Neutrino4	Gd	Yes	No	6-12	HEU	150	Yes	Yes
Asia	Hanaro	Li/Gd	No	Yes	20-ish	LEU	30	No	No

B. Littlejohn Fermilab Intesity Frontier Seminar 2015

PROSPECT

- Goal 1: A precise measurement of the HFIR (High Flux Isotope Reactor) spectrum.
- Goal 2: Perform a sterile neutrino search with interest in Δm^2 around 1.0 eV^2.



C. Zhang *et al.* arXiv:1303.0900v3 (2013)

PROSPECT Phase I baseline
PROSPECT Phase II baseline