PROSPECT: Precision Reactor Oscillation and SPECTrum Experiment

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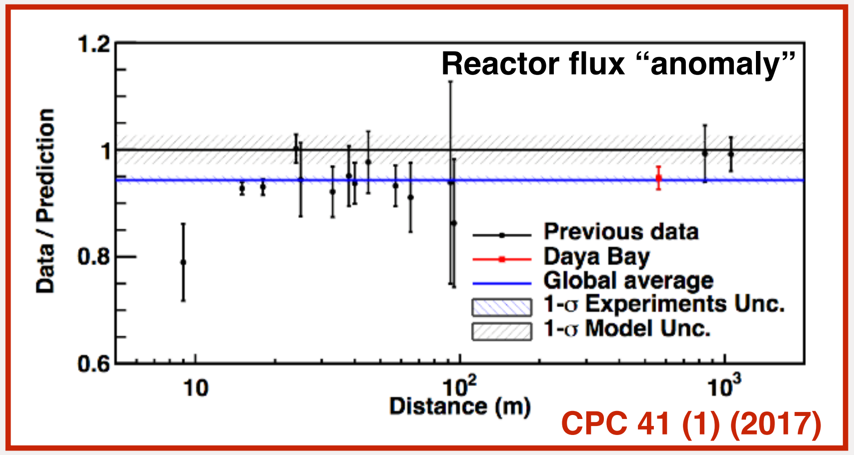
(on behalf of the PROSPECT collaboration)

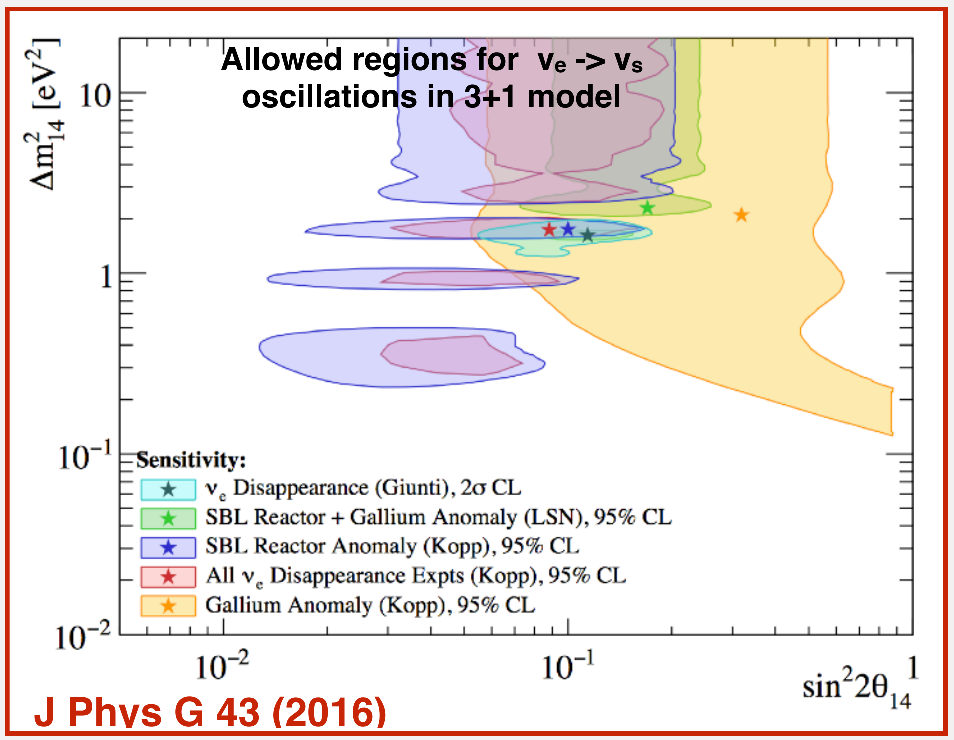
DPF 2017

Motivation

Reactor antineutrino experiments observe deficit in antineutrino rates compared to the predictions



Additional sterile neutrino could be a possible reason for the deficit

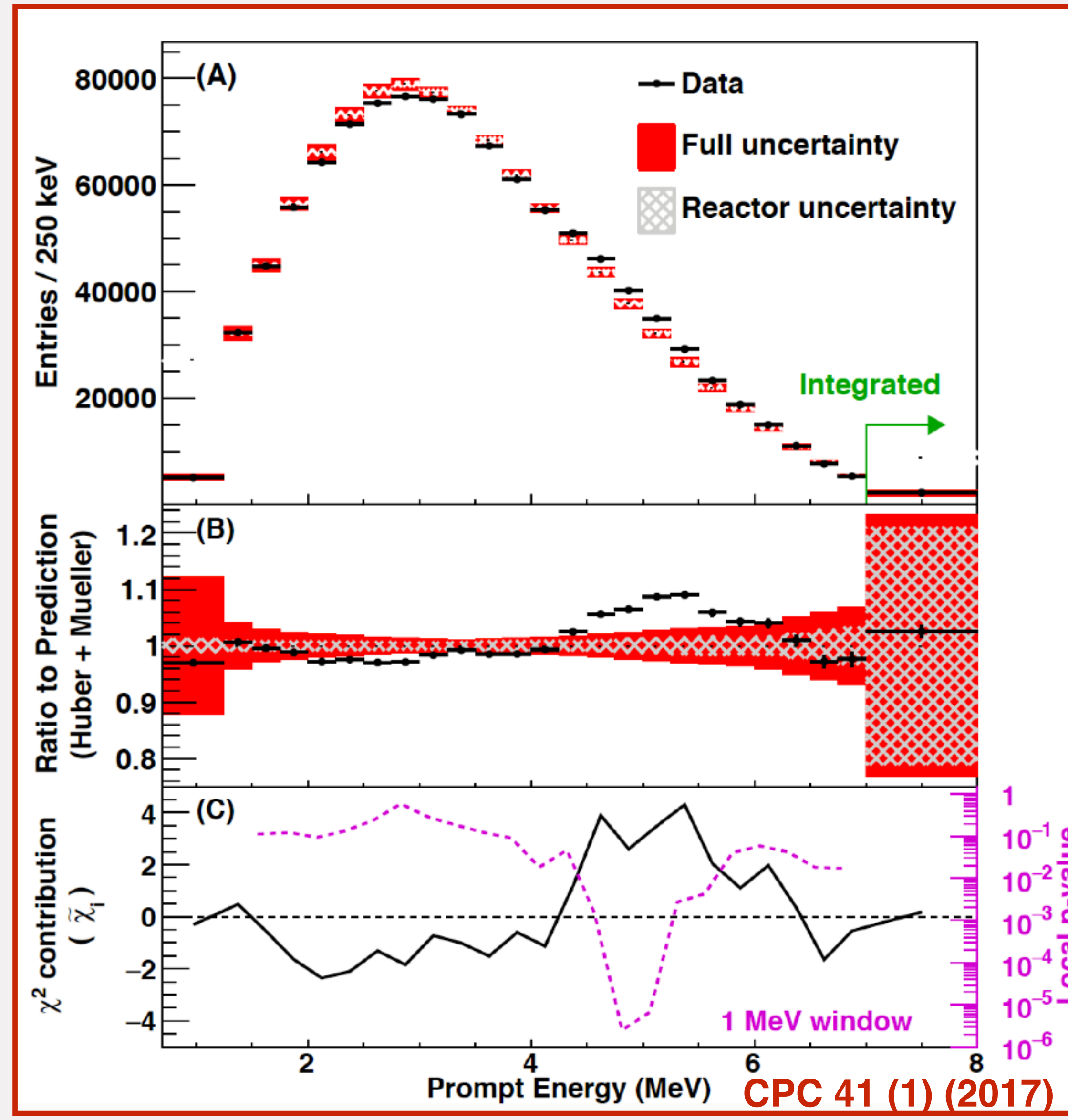


Large mass splitting -> ~Meter length oscillations

Motivates short-baseline experiment with compact source, good position resolution

Recent Θ_{13} experiments at LEU reactors observe spectral deviations

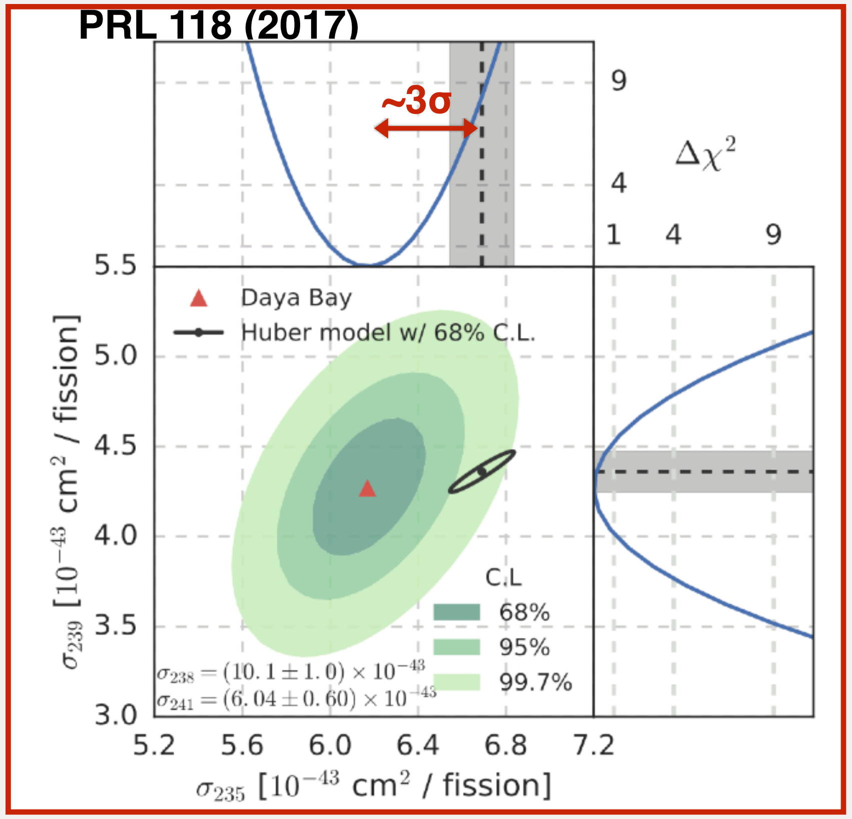
Could be a contribution from a single isotope or multiple isotopes



Motivates reactor experiment with different fuel types and good energy resolution

Recent Developements

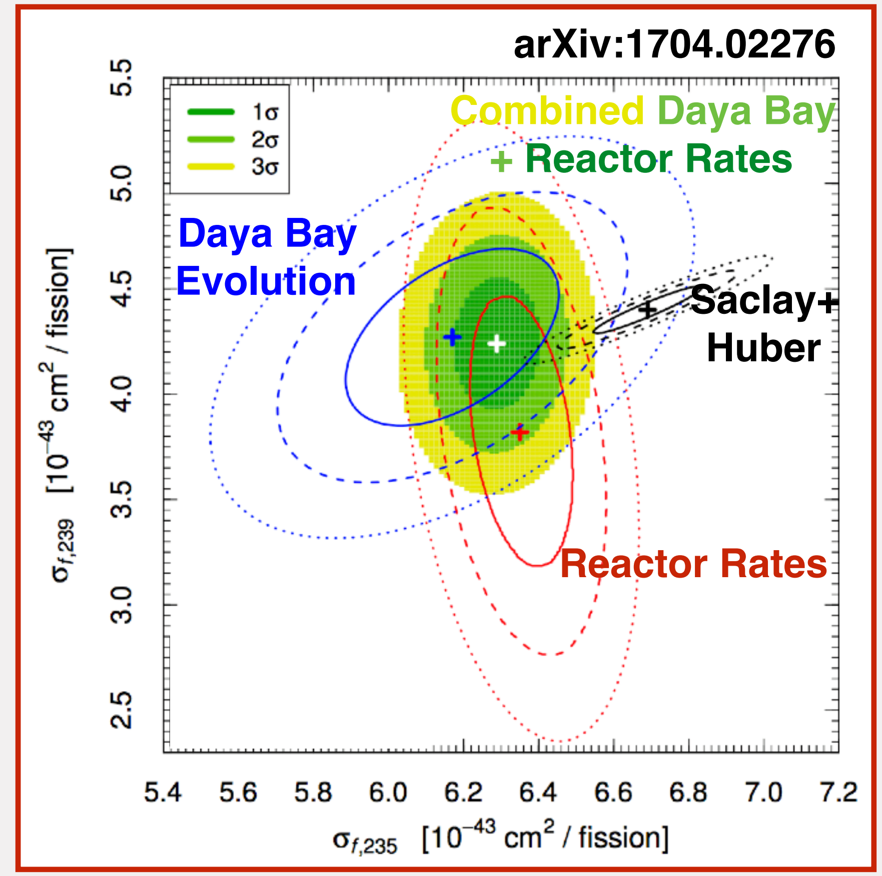
- Daya Bay has recently reported IBD yields of U235 and Pu239 using evolution of LEU reactor fuel
- Showed that reactor flux models are incorrect at least for U235



Could U235 be responsible for Reactor Antineutrino Anomaly ?

- U235 preferred to be the cause when a single isotope is assumed to be the cause for the anomaly
- No reason to assume a single isotope is the cause for anomaly

- IBD yields calculated from reactor rates (of 26 reactor antineutrino experiments) do no agree with Daya Bay measurement



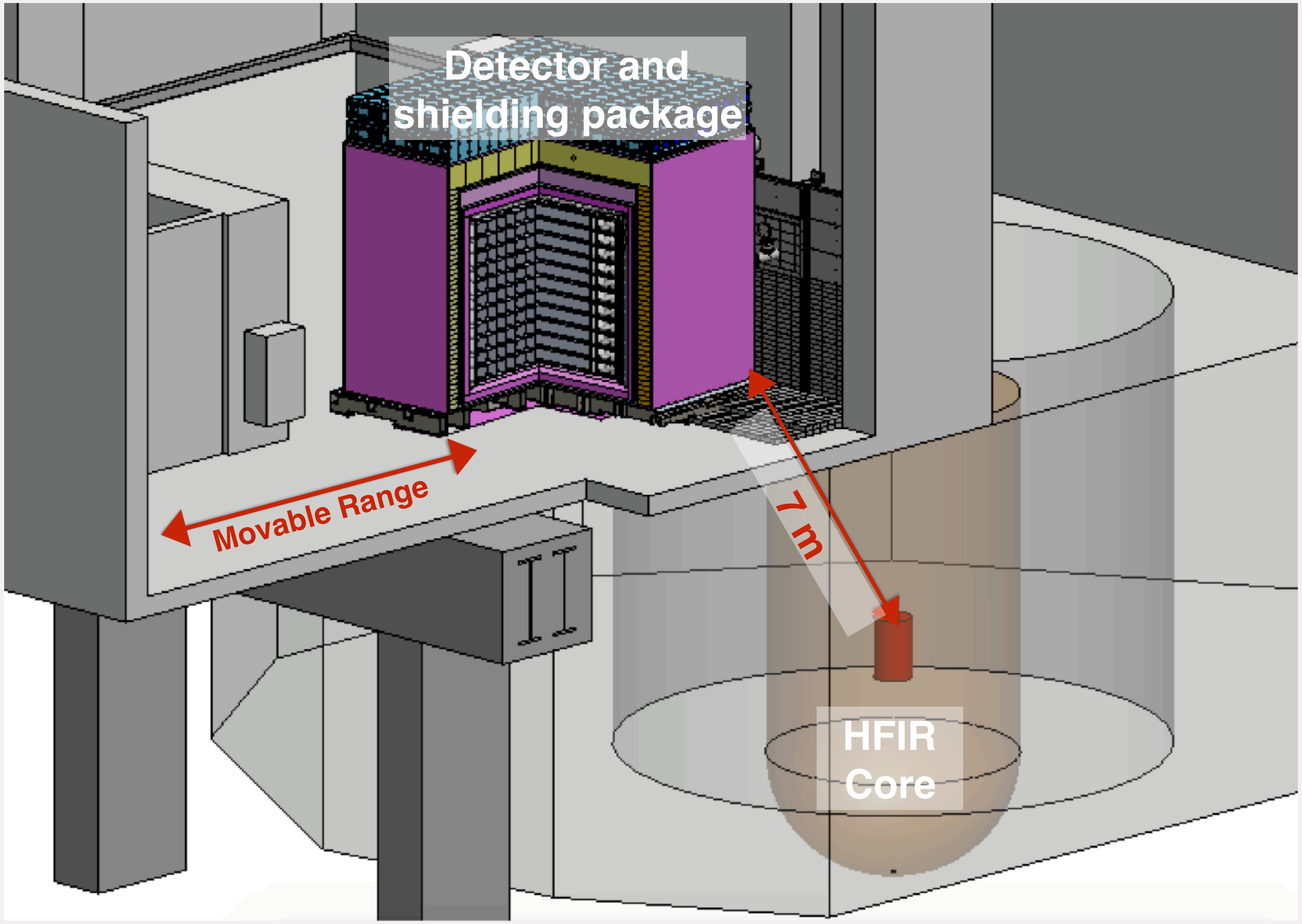
- Daya Bay results in global context creates tension in IBD yields
- Oscillation to sterile states not considered

Possible, but not definite

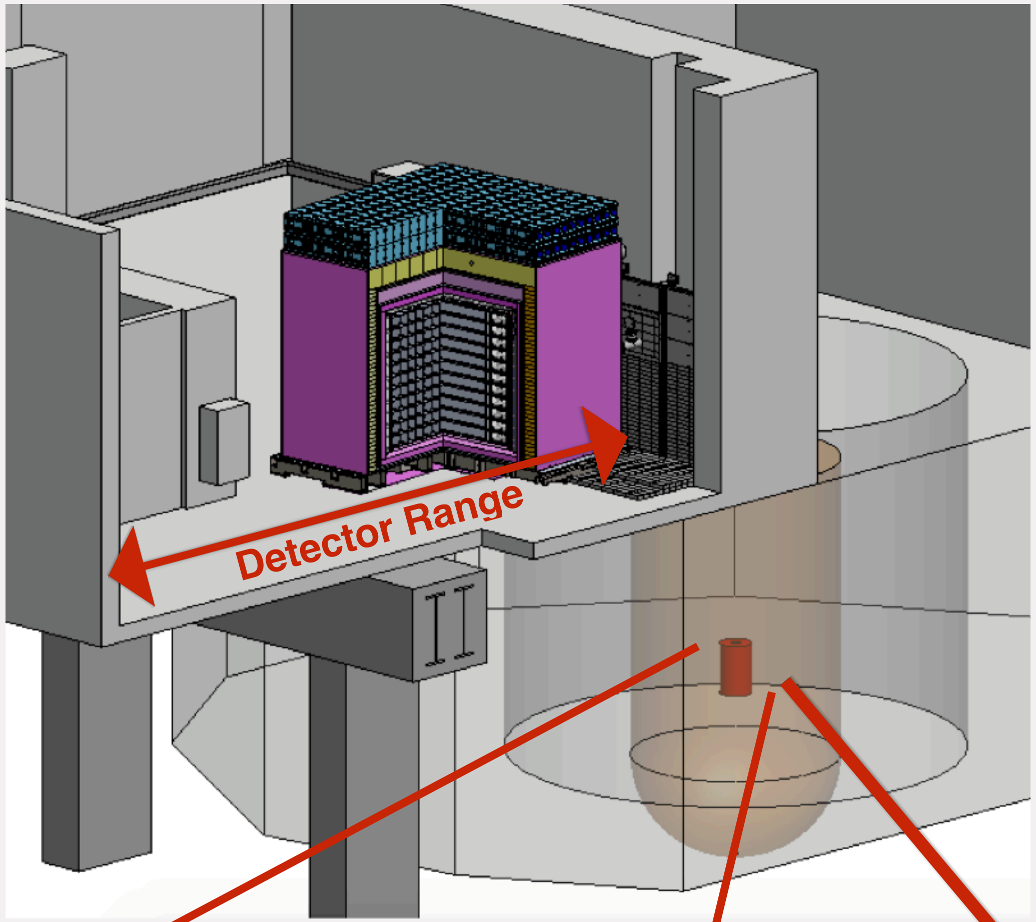
Motivates an experiment that truly probes the L/E nature of oscillations

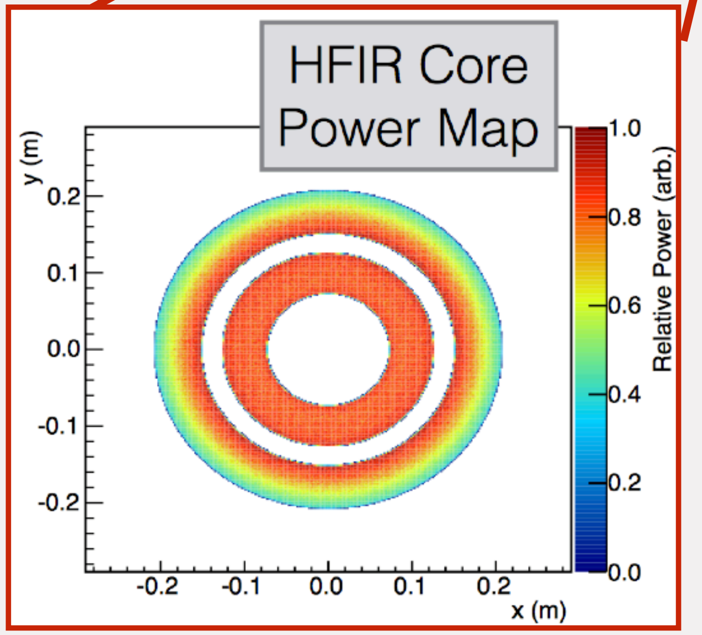
Physics Goals:

1. Precisely measure reactor ^{235}U $\bar{\nu}_e$ spectrum
2. Search for short-baseline oscillations arising from eV-scale sterile neutrinos



Antineutrino Source





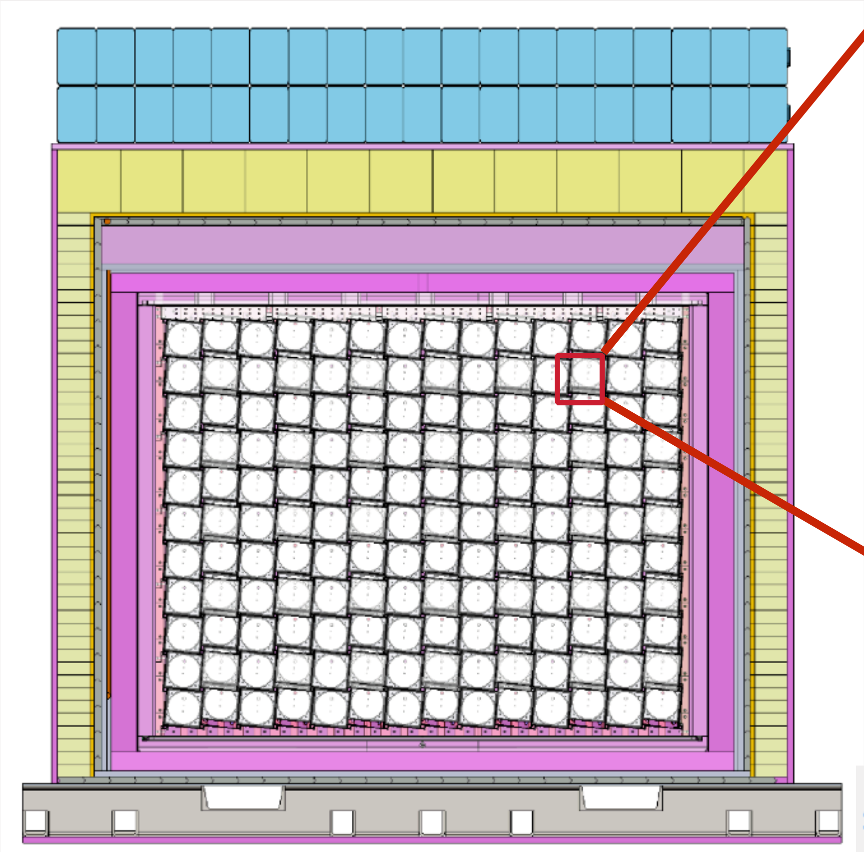
Power map of HFIR reactor core

- High Flux Isotope Reactor (**85 MW**) at ORNL
- HEU Reactor - **~93 %** U235 enrichment (**>99%** $\bar{\nu}_e$ from U235)
- Short reactor cycles (~**25 days**) - Low P239 buildup **(< 0.5%)**
- Compact core (**0.5m high, 0.4 m wide**) - No oscillation washout

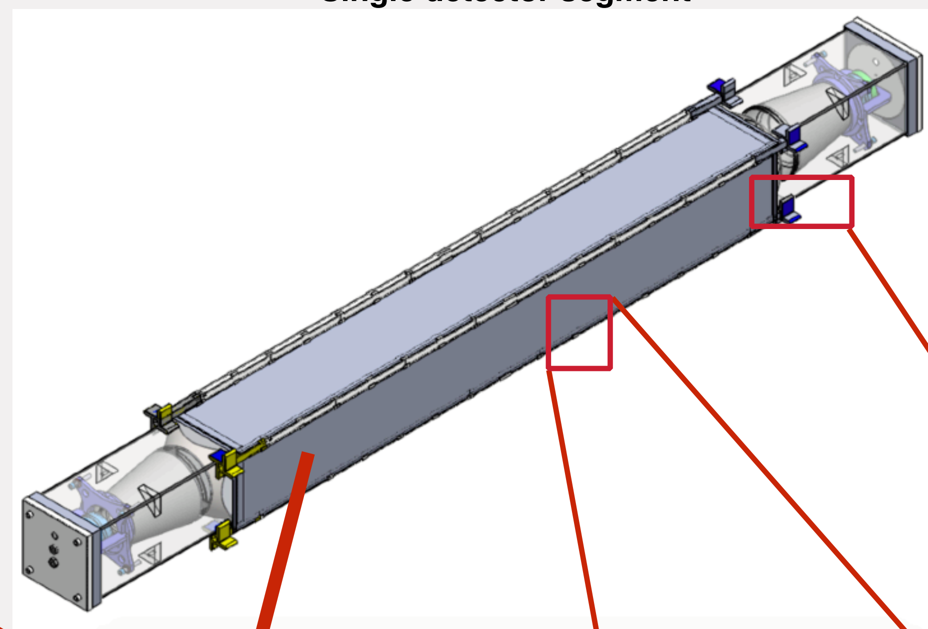
- **~47 %** up-time
- **>50%** reactor off-time - Extensive background characterization
- ~ 3 years experience of on-site operation
- 24/7 access

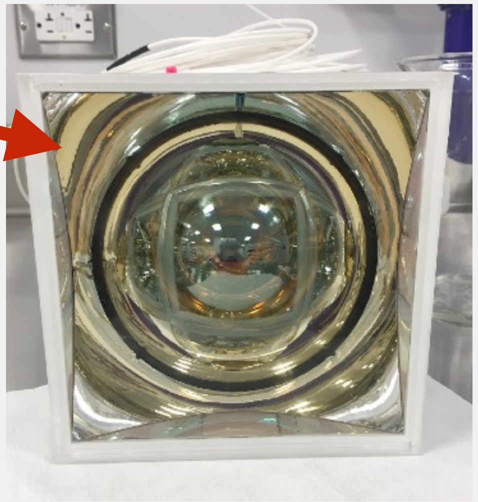
Detector Design

Cross-section of detector including the shielding package



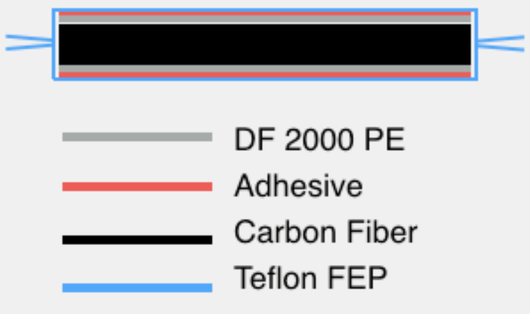
Single detector segment

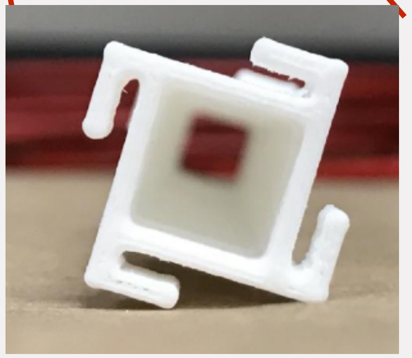




Assembled PMT housing

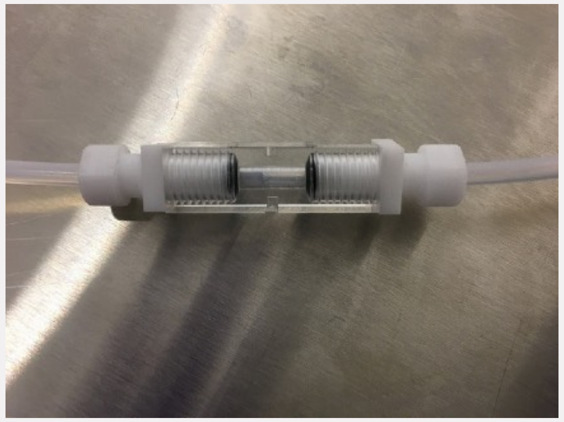
Multi-layer highly reflective, rigid low mass separators





Cross-sectional view of a segment

Source capsule

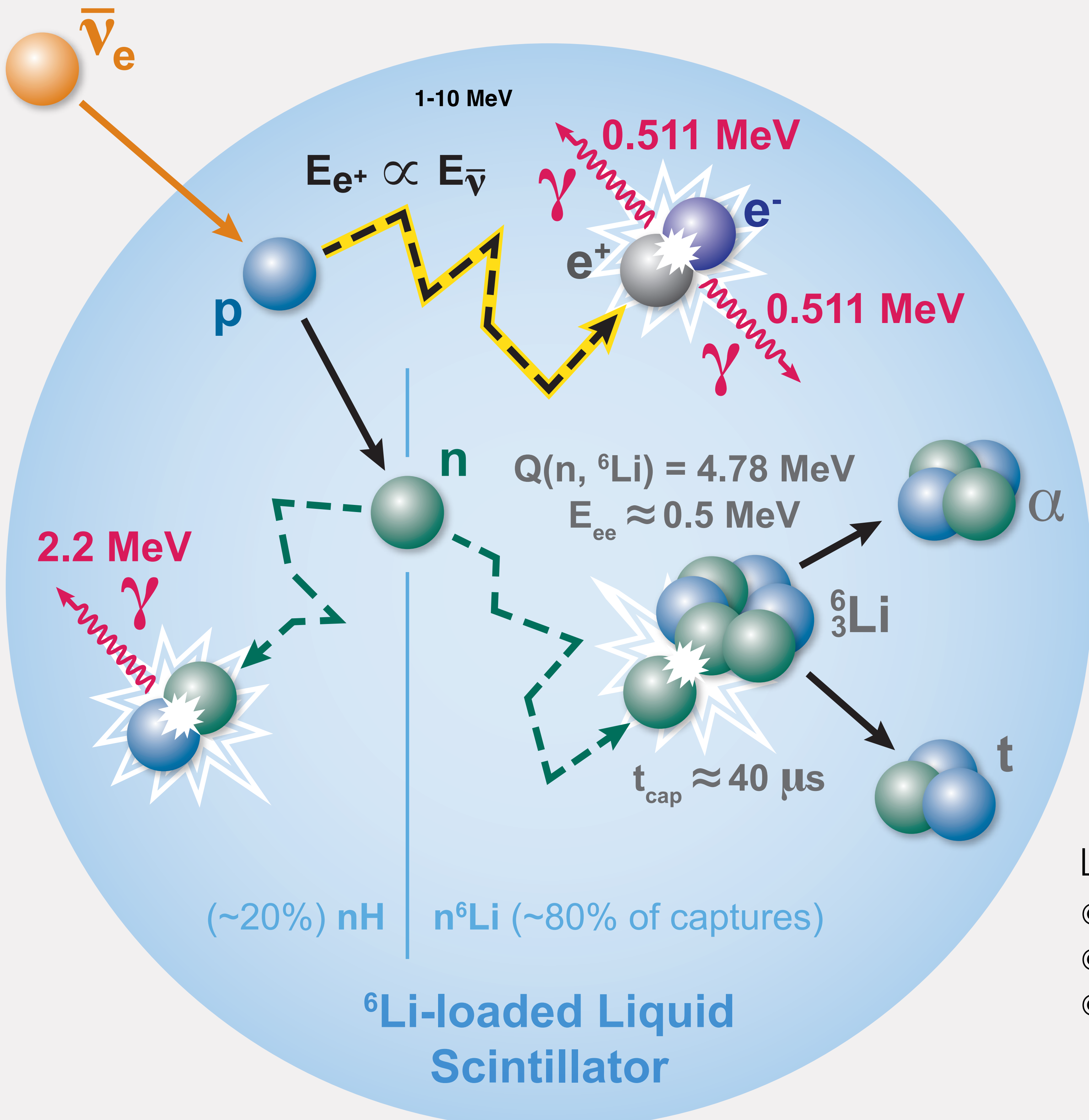


Optical diffuser

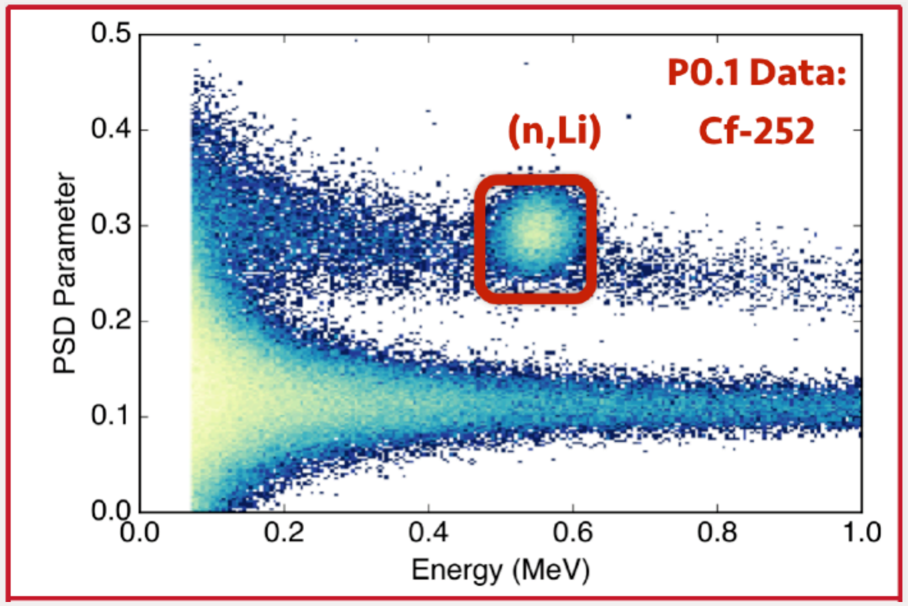
- Single volume **~4 ton** Li6-loaded liquid scintillator detector
- Optically divided into a **14x11** identical segments
- Low mass optical separators
- Each segment is a detector i.e., **154 detectors**
- Double-ended readout
- Pinwheels give *in-situ* access to optical and source calibrations

Detection Mechanism

Inverse Beta Decay as the detection mechanism



Pulse Shape allows for discrimination between gamma-like and neutron-like events



Li6-loaded EJ-309 scintillator as target:
- Excellent background rejection
- High IBD detection efficiency
- Spatial and temporal dense energy deposition

Phased Approach

P-0.1

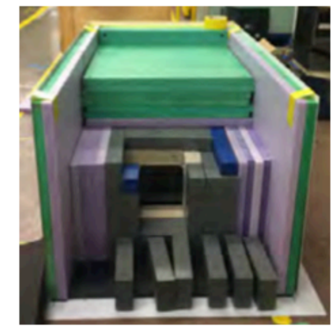
PROSPECT-0.1
Characterize LS
Aug 2014-Spring 2015

5cm length
0.1 liters
LS, ^{6}LiLS

P-2

PROSPECT-2
Background studies
Dec 2014 - Aug 2015

12.5 cm length
1.7 liters
^{6}LiLS



multi-layer shielding

P-20

PROSPECT-20
Segment characterization
Scintillator studies
Background studies
Spring/Summer 2015

1m length
23 liters
LS, ^{6}LiLS

P-50

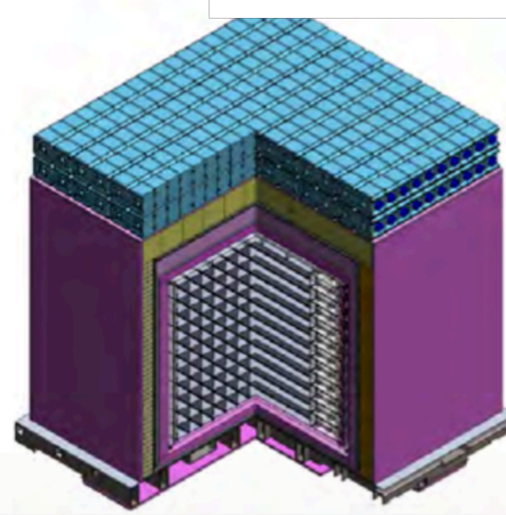
PROSPECT-50
Baseline design prototype
Early 2016

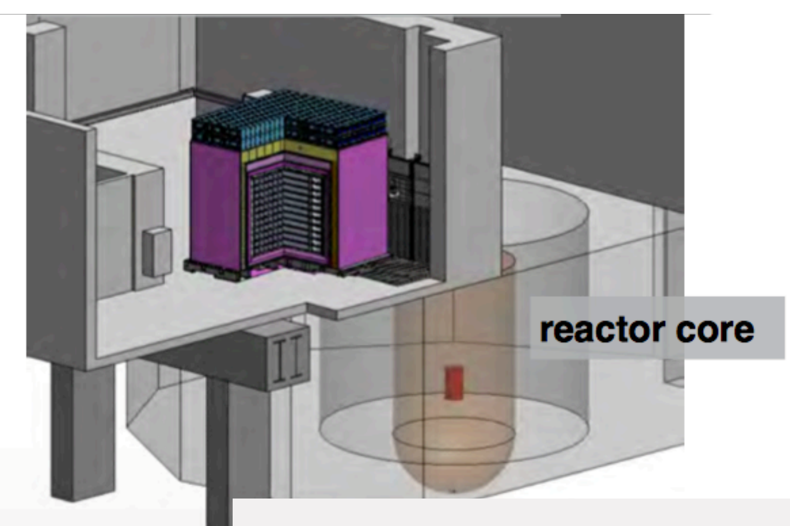
1x2 segments
1.2m length
50 liters
^{6}LiLS

PROSPECT

Late 2017

11x14 segments
1.2m length
~4.5 tons
^{6}LiLS



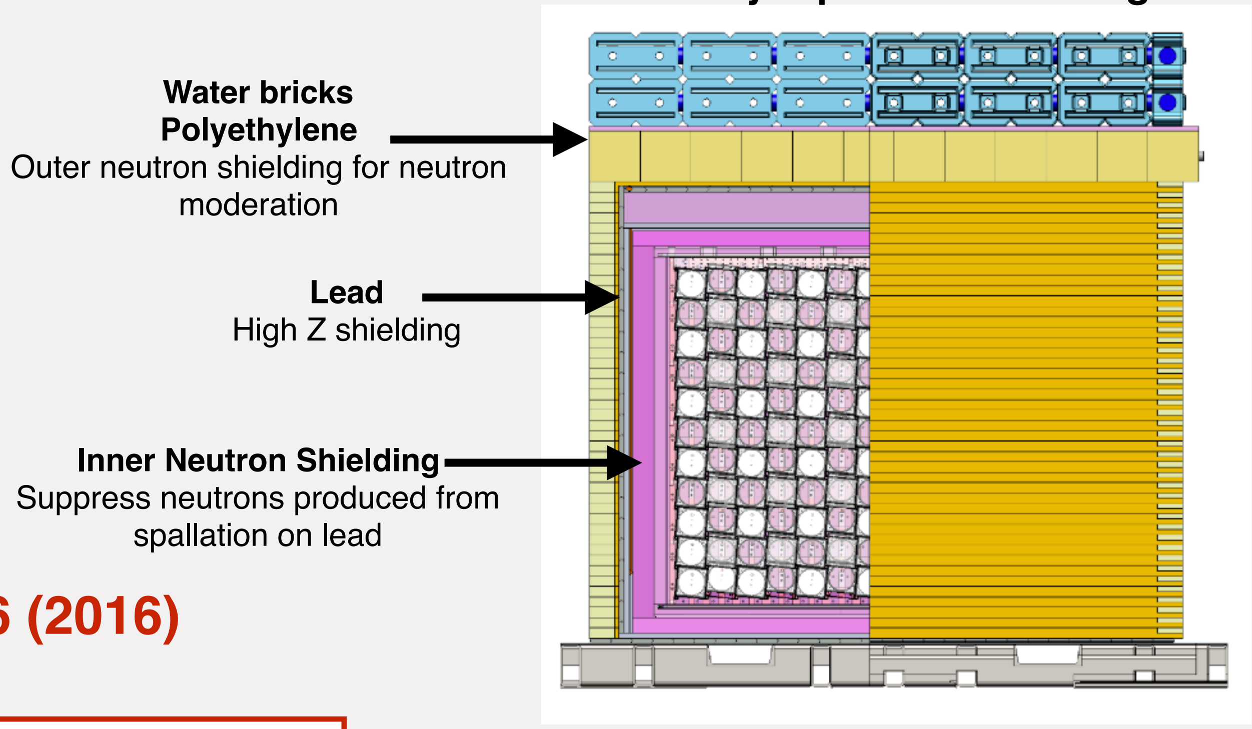


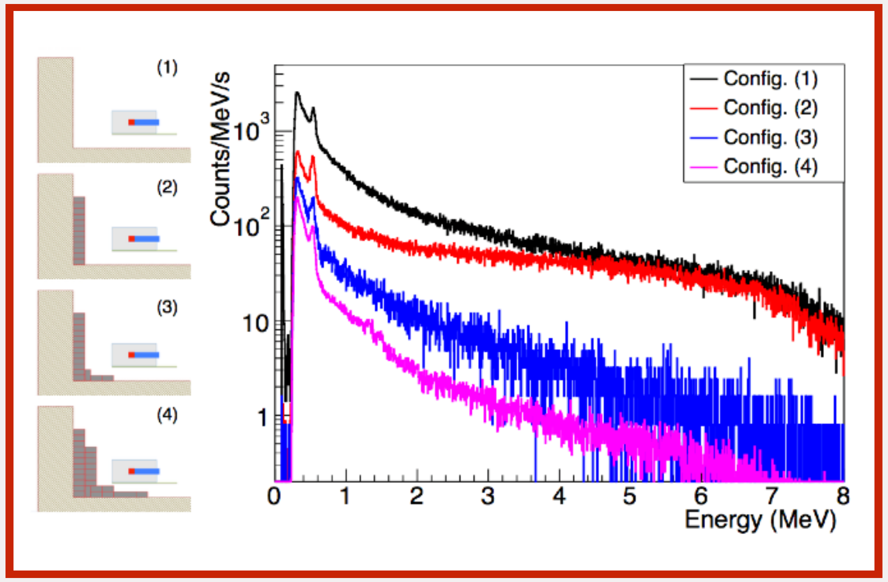
Background Characterization and Reduction

- HFIR background characterized in detail
- Both reactor related and unrelated backgrounds measured
- Lead wall designed to shield reactor related backgrounds
- Passive shield design motivated by measured backgrounds

Local shielding joining reactor wall

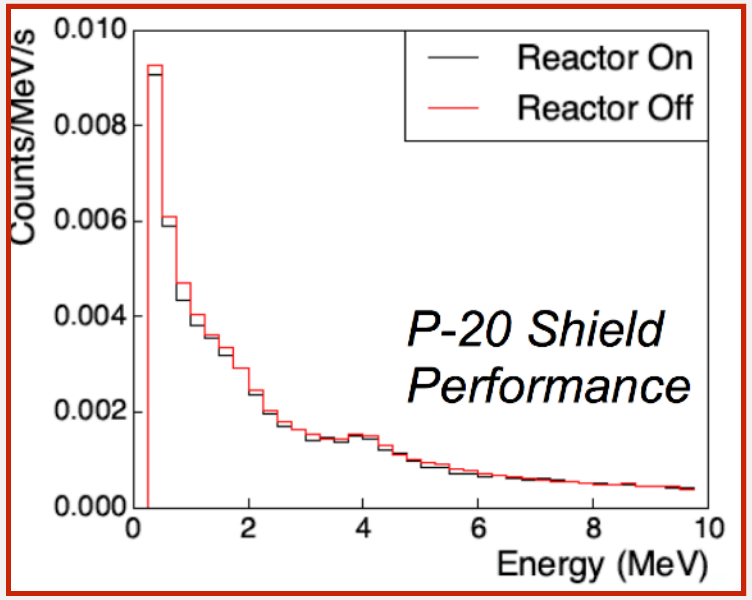
Multi-layer passive shielding





Effect of varying lead wall configuration on gammas

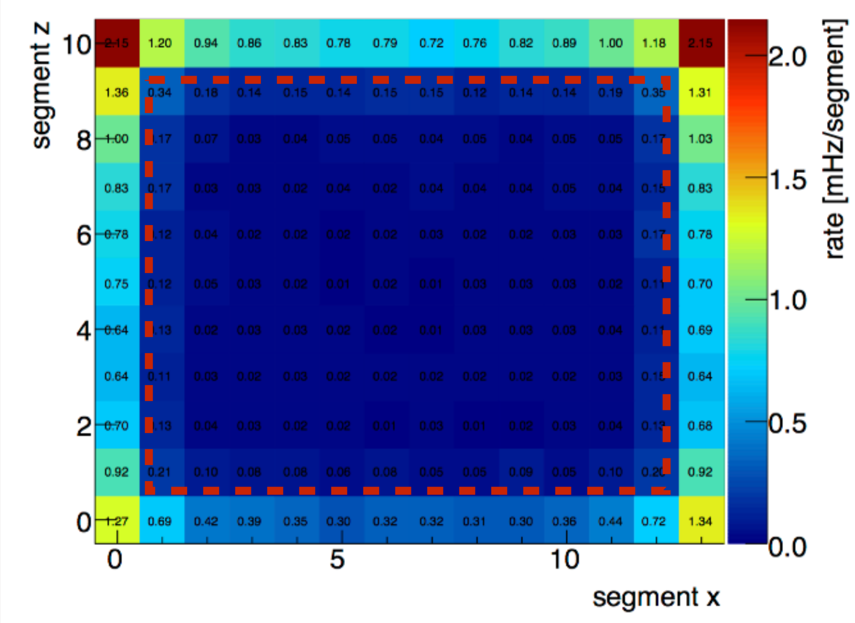
NIM A806 (2016)

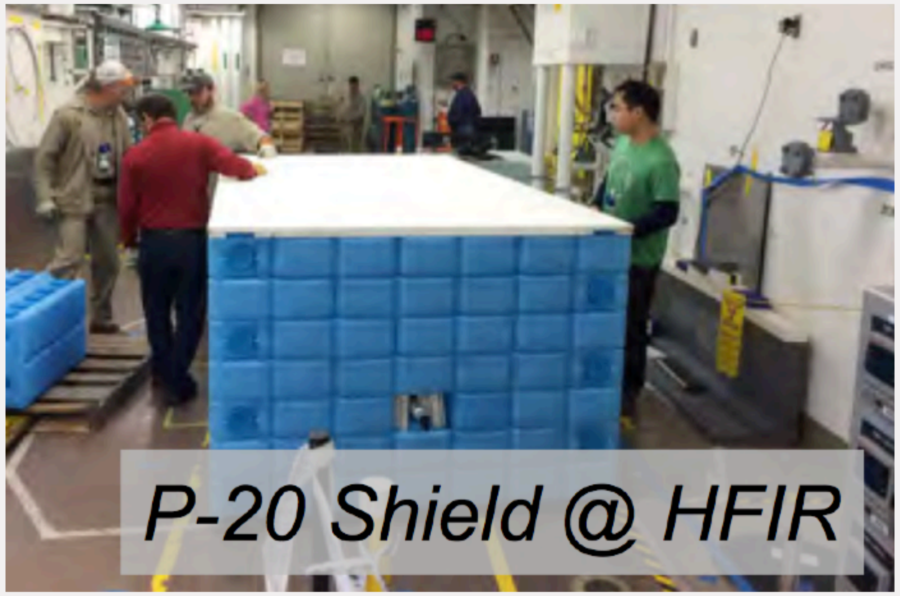


P20 shield was able to shield the reactor backgrounds effectively

Cosmic backgrounds can be calibrated out using data from reactor off time

Use outer layer of the detector as veto



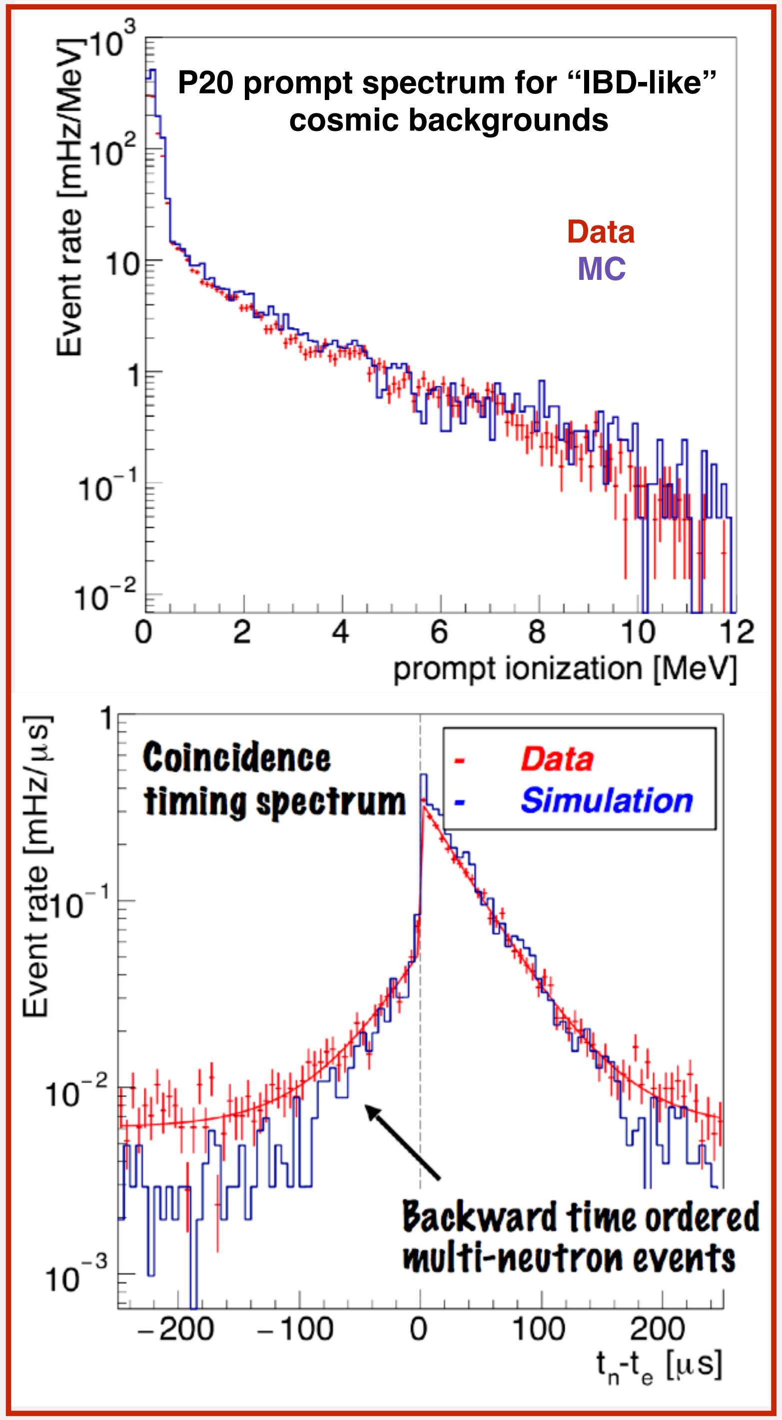


~ 25% the size of PROSPECT shielding

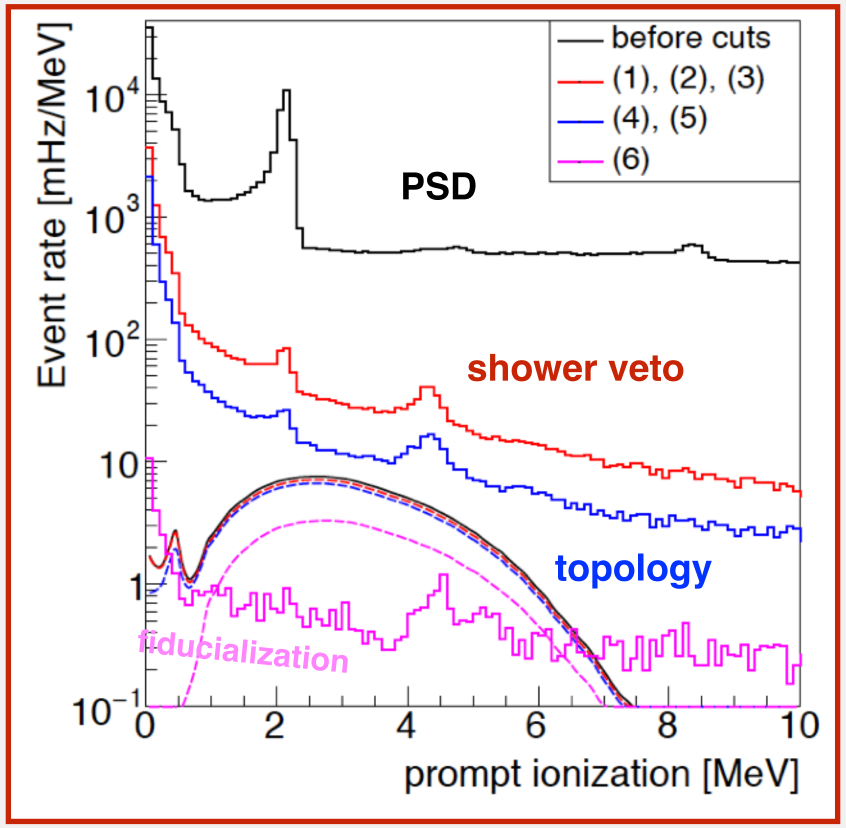
Simulation Benchmarking

- PROSPECT prototyes measured cosmic backgrounds during reactor-off periods
- PROSPECT Monte Carlo simulations agree well with the P20 data

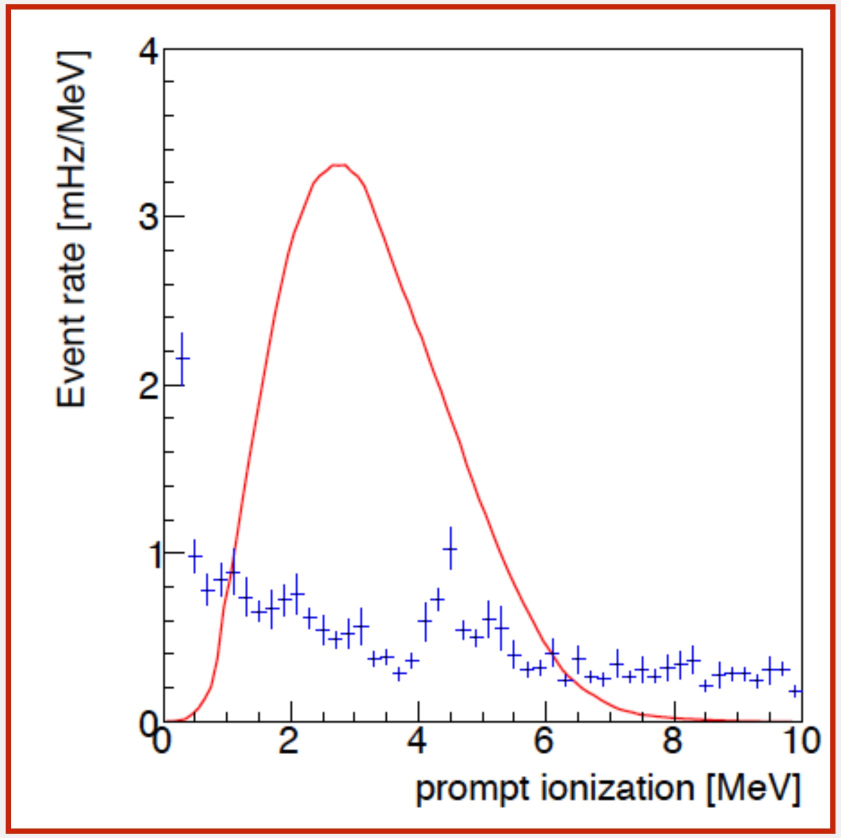
Comparison of Data with PROSPECT MC



Projected PROSPECT Signal and Backgrounds



Simulated signal (dashed) and cosmic backgrounds (solid) prompt energy spectrum through selection cuts

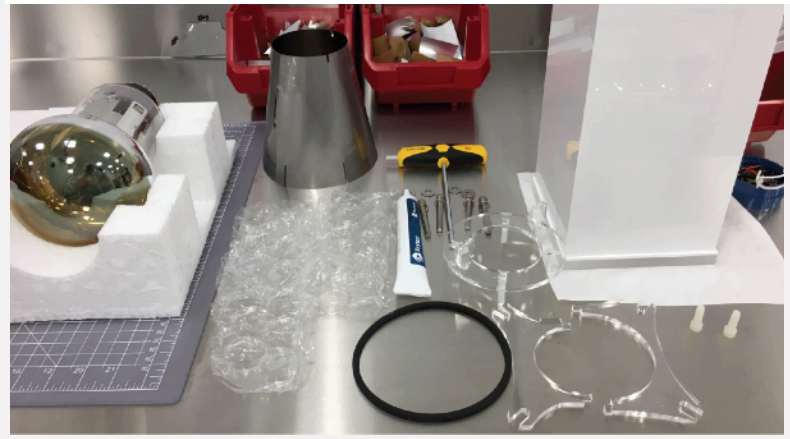


Simulated signal and cosmic backgrounds after all selection cuts

Projected S:B for PROSPECT full-size detector is better than 3:1

Ongoing Construction

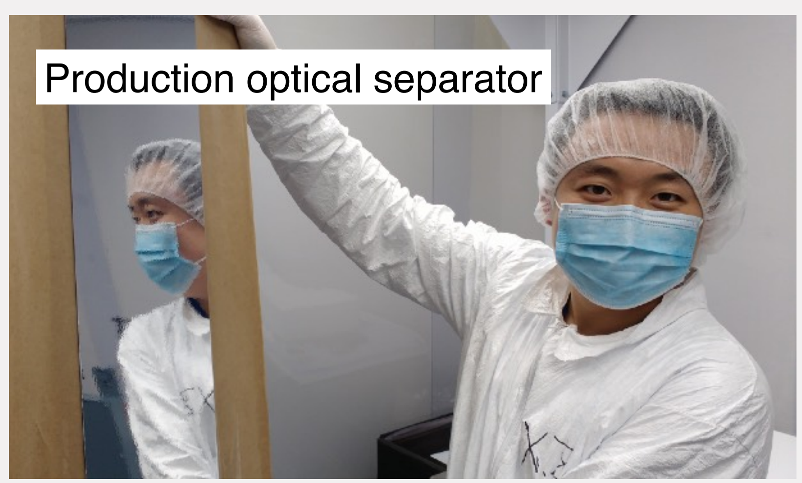
PMT burn-in and testing



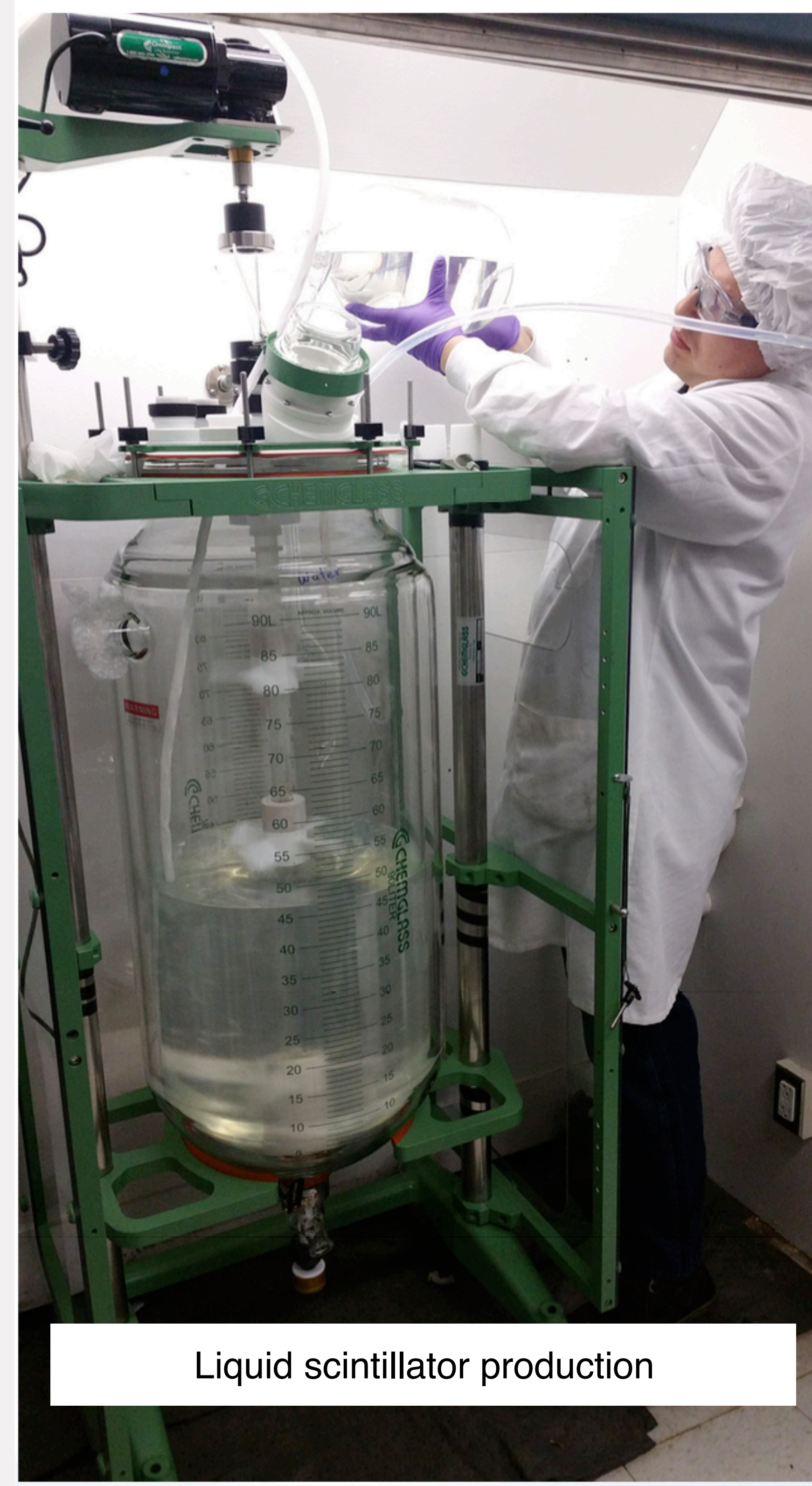
PMT module components ready for assembly

Production PMT module

Optical separator fabrication

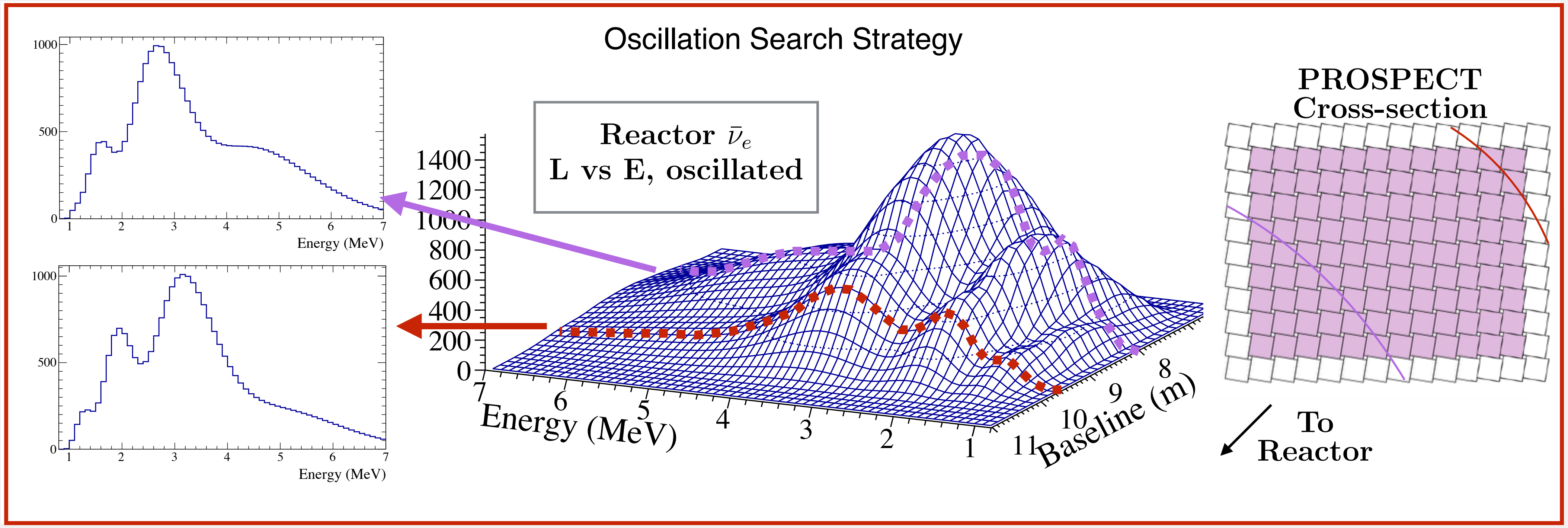


Production optical separator

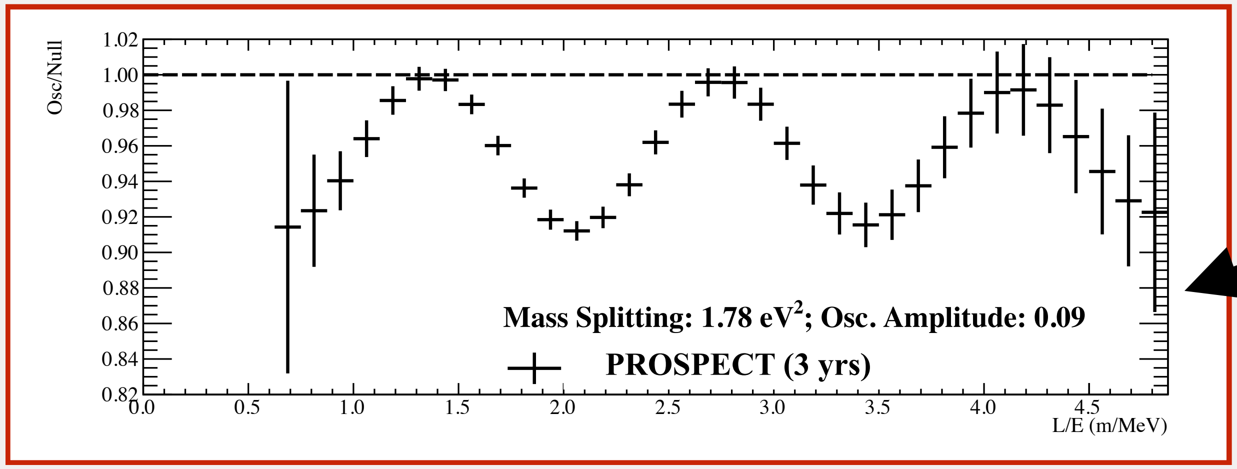


Liquid scintillator production

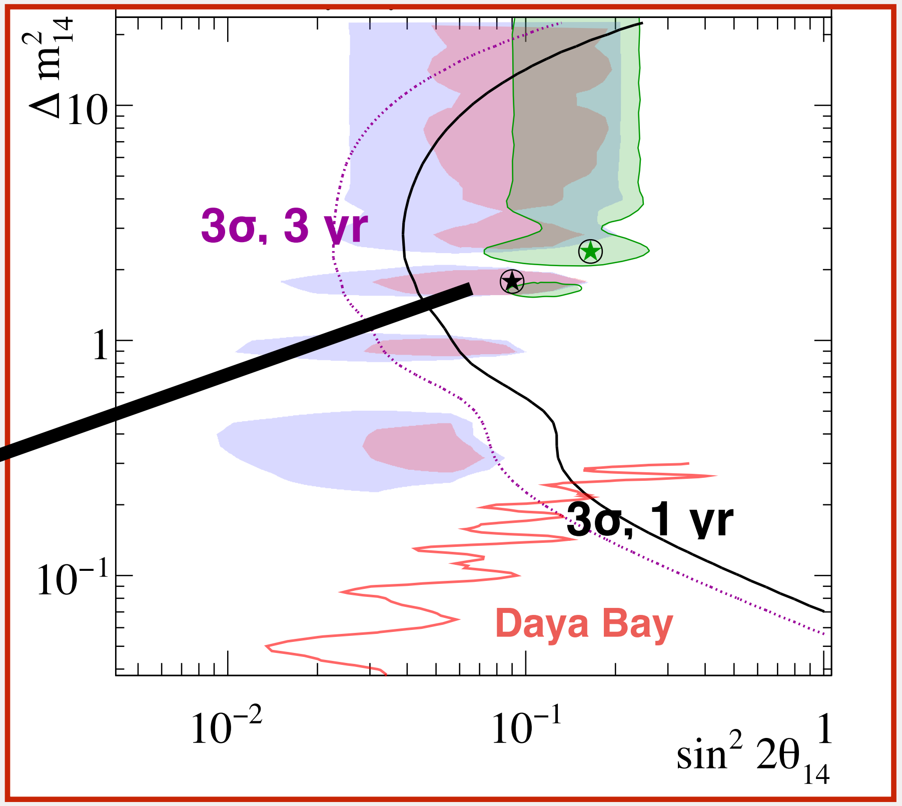
Physics: Oscillation Search



- Perform a **relative spectrum measurement** between 154 independent detectors (segments)
- Identical segments provide clear baseline-dependent spectrum
- **Independent of underlying reactor flux and spectrum models**
- Systematic effects minimized by relative search and detector movement



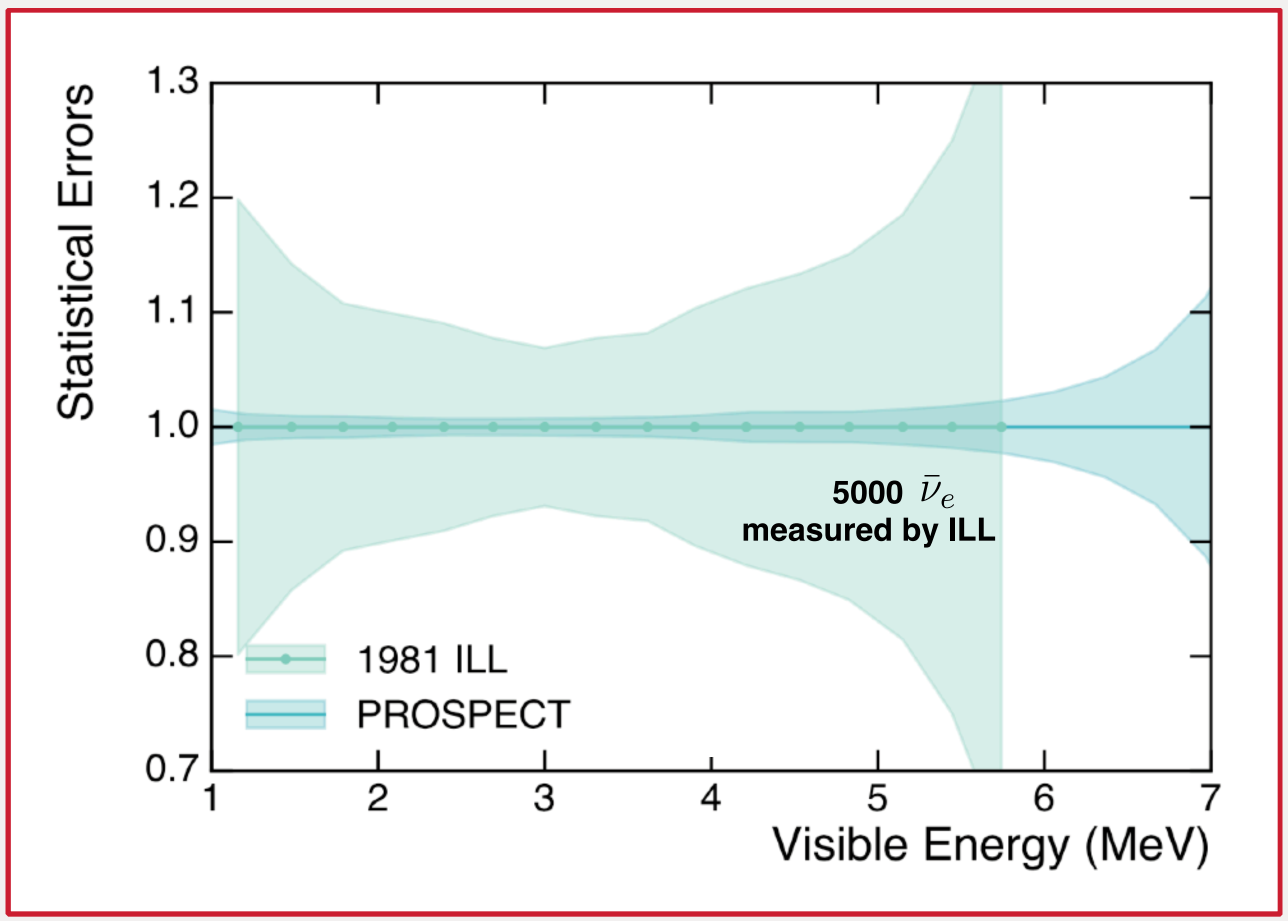
Observed neutrino rates as a function of baseline/energy



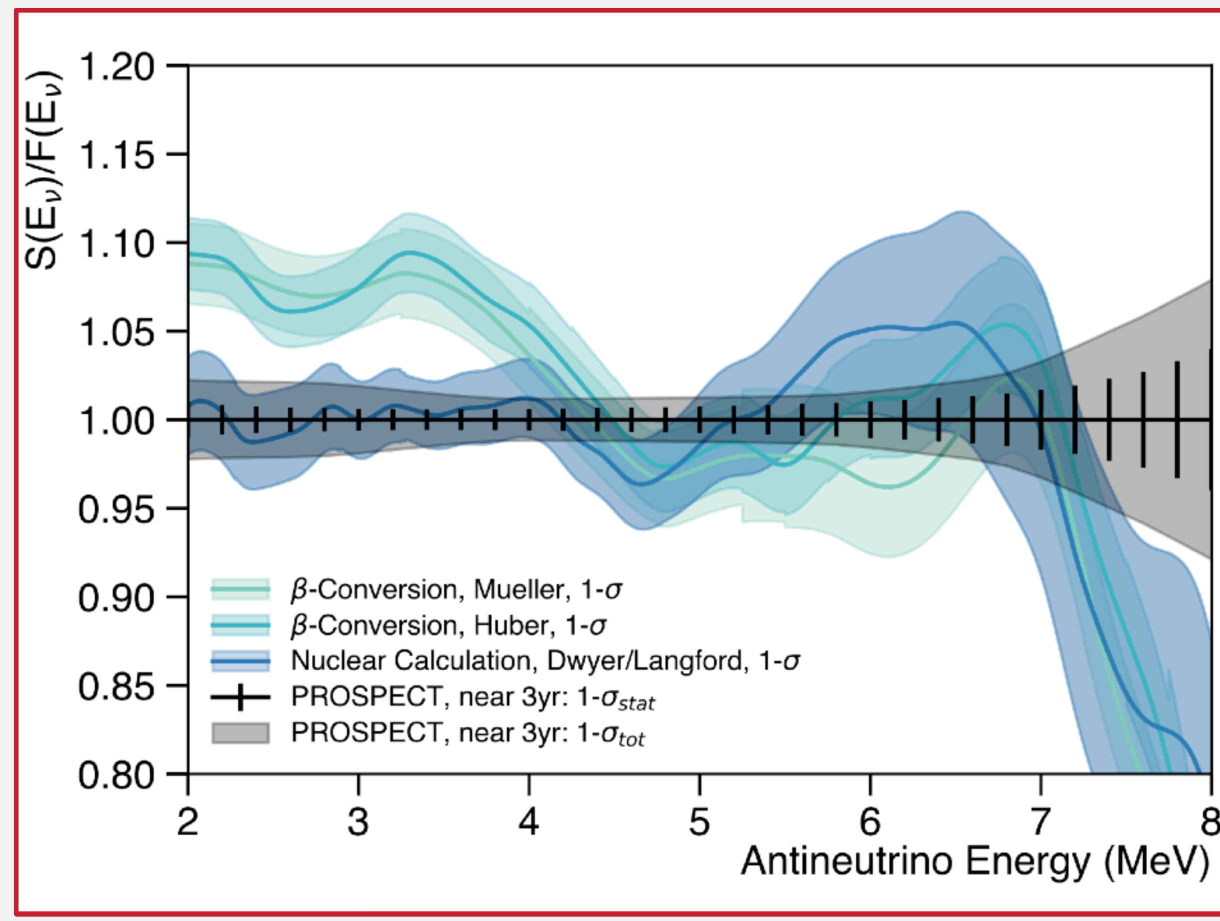
Sensitivity of PROSPECT Experiment

Physics: Spectrum Measurement

- Estimated IBD events - **160k/year**
- Expected energy resolution **4.5%/**$\sqrt{E}$
- Perform most precise ^{235}U spectrum measurement
- Compare various reactor antineutrino spectrum models
- Provide a benchmark for future reactor antineutrino experiments
- Excellent complement to existing LEU reactor measurements



Improvement in precision over ILL



Test various reactor antineutrino spectrum models

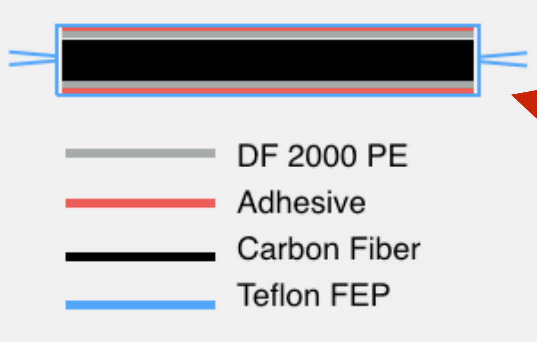
Summary

- Reactor antineutrino experiments reported anomalous rate and shape measurements
- **PROSPECT program**
    - Designed segmented LiLS detector and deployed multiple detectors at HFIR in preparation of a full-size detector deployment
    - Make precision ^{235}U spectrum measurement, complementary to LEU measurements and compare various models
    - PROSPECT will be able to cover sterile neutrino best-fit point at better than 3σ in one calendar year and favored regions at 3σ in 3 yrs
- Detector construction proceeding with full speed
- Data taking to commence later this year

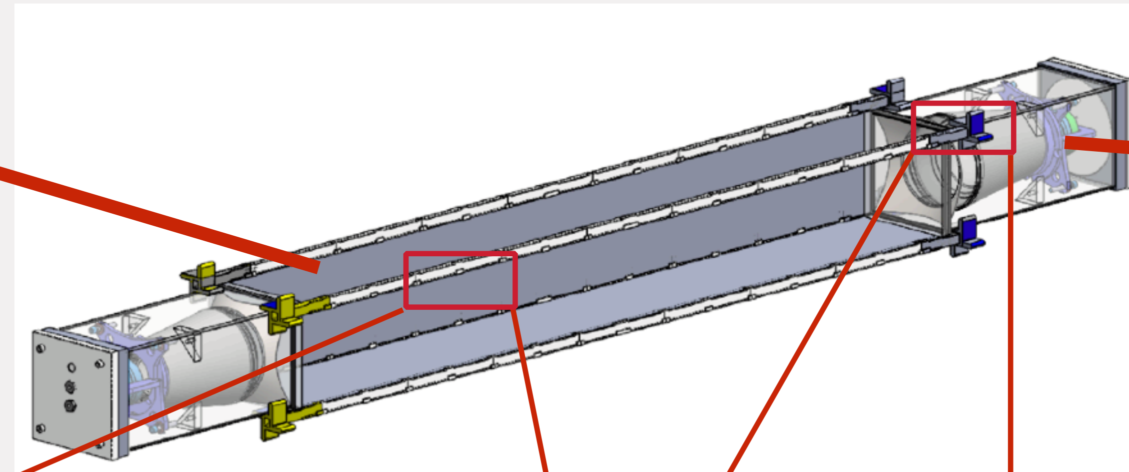
Thank you

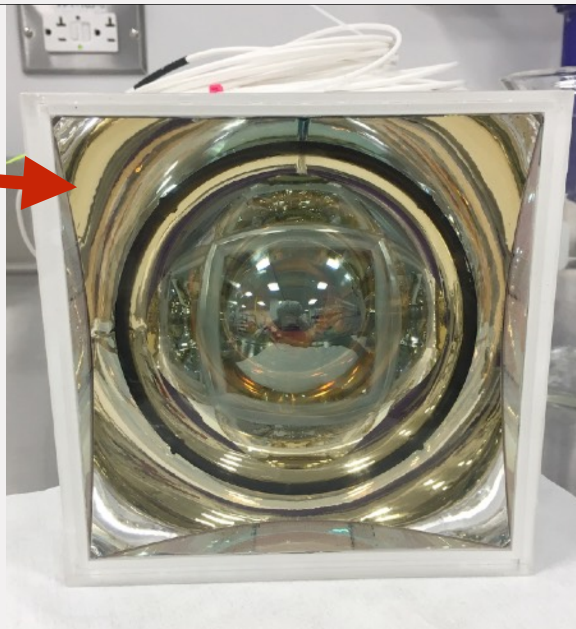
arXiv:1309.7647
Nucl. Instru. Meth. Phys. Res. A 806 (2016) 401
Journal of Phys. G 43 (2016) 11
JINST 10 (2015) P11004

Detector Development

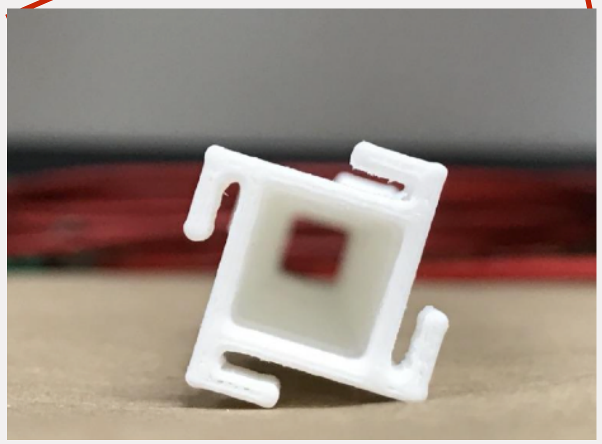


Multi-layer highly reflective, rigid low mass separators





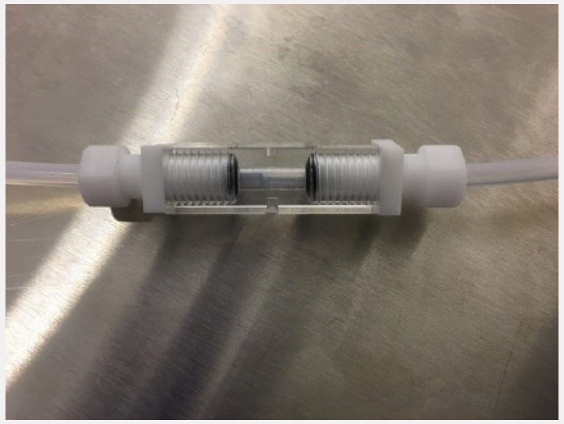
Assembled PMT housings



3D printed pinwheel to join optical separators and support the optical lattice

- All material inside the detector are tested for chemical compatibility with the liquid scintillator
- LS shows long term stable performance
- Multiple prototypes validated the design of the various detector components

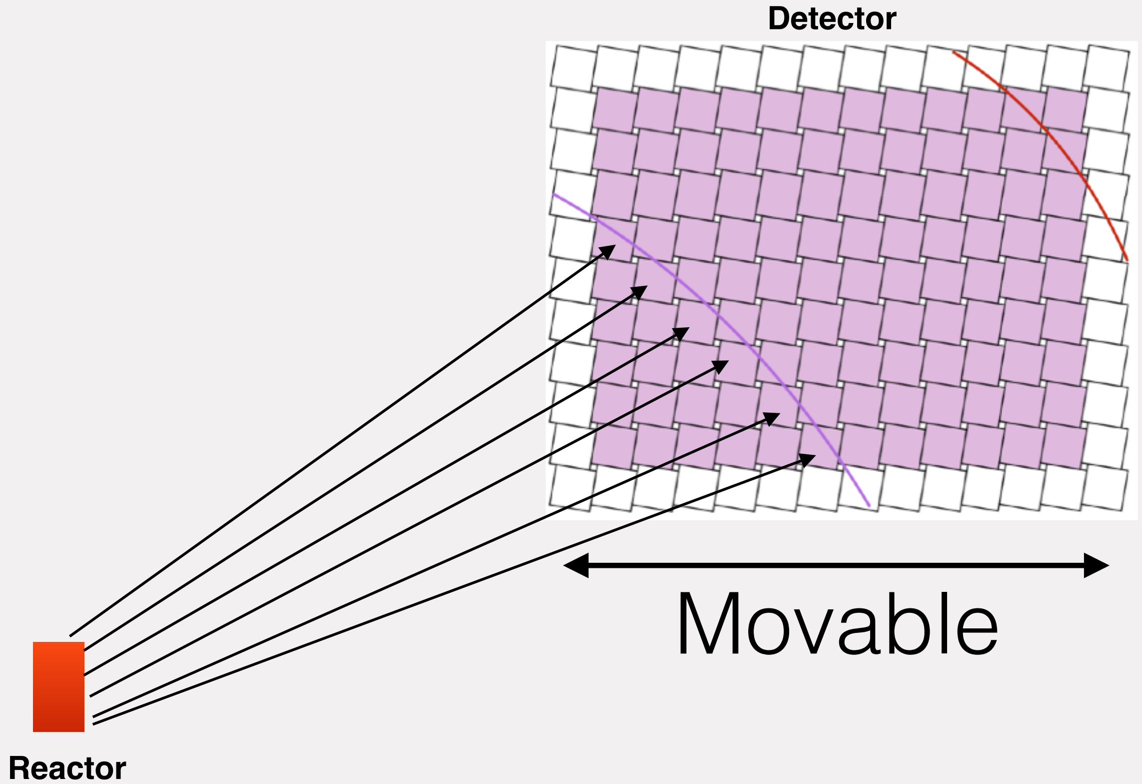
Source capsule

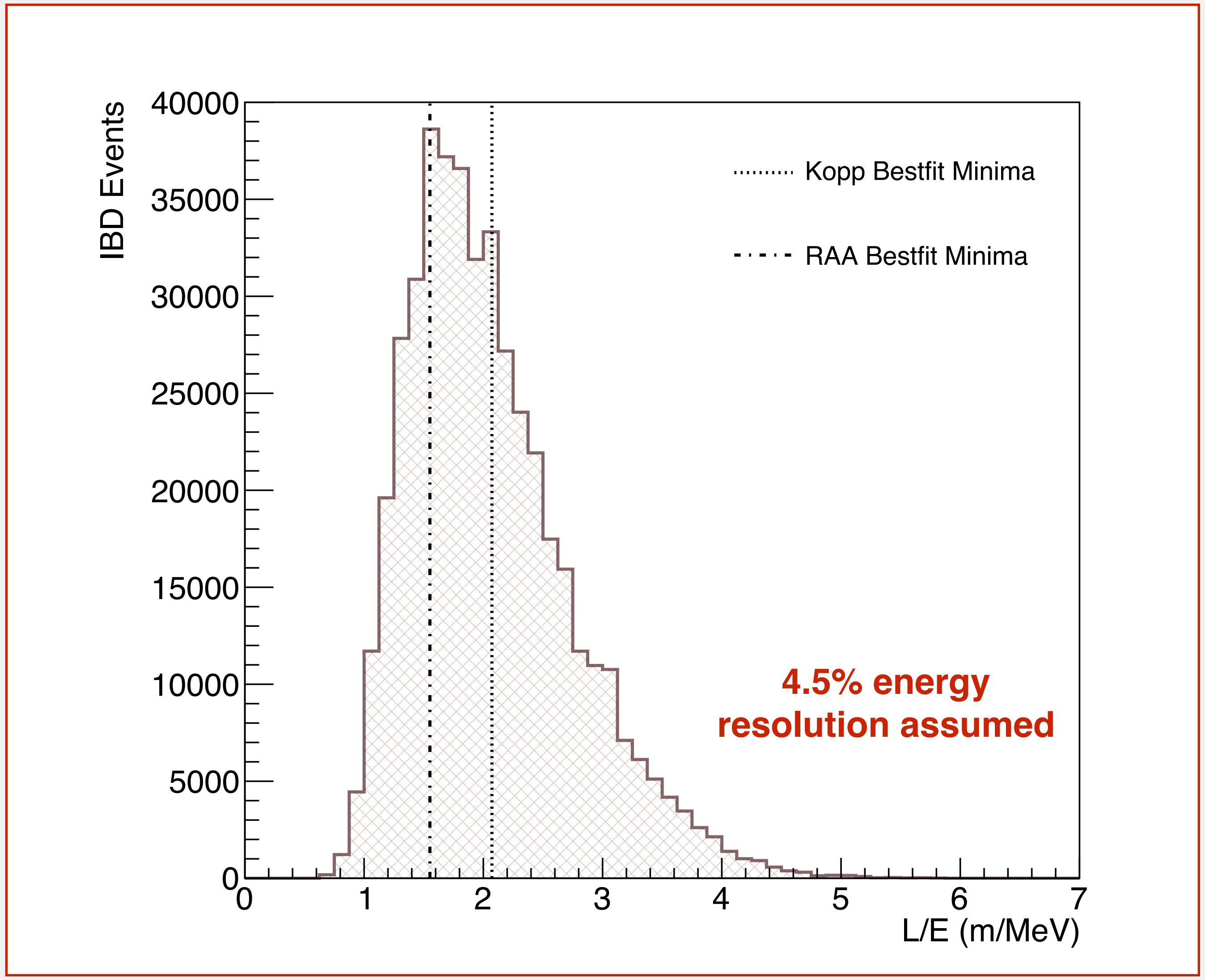


Optical diffuser

Pinwheels give *in-situ* access to optical and source calibrations

Anticipated L/E Coverage

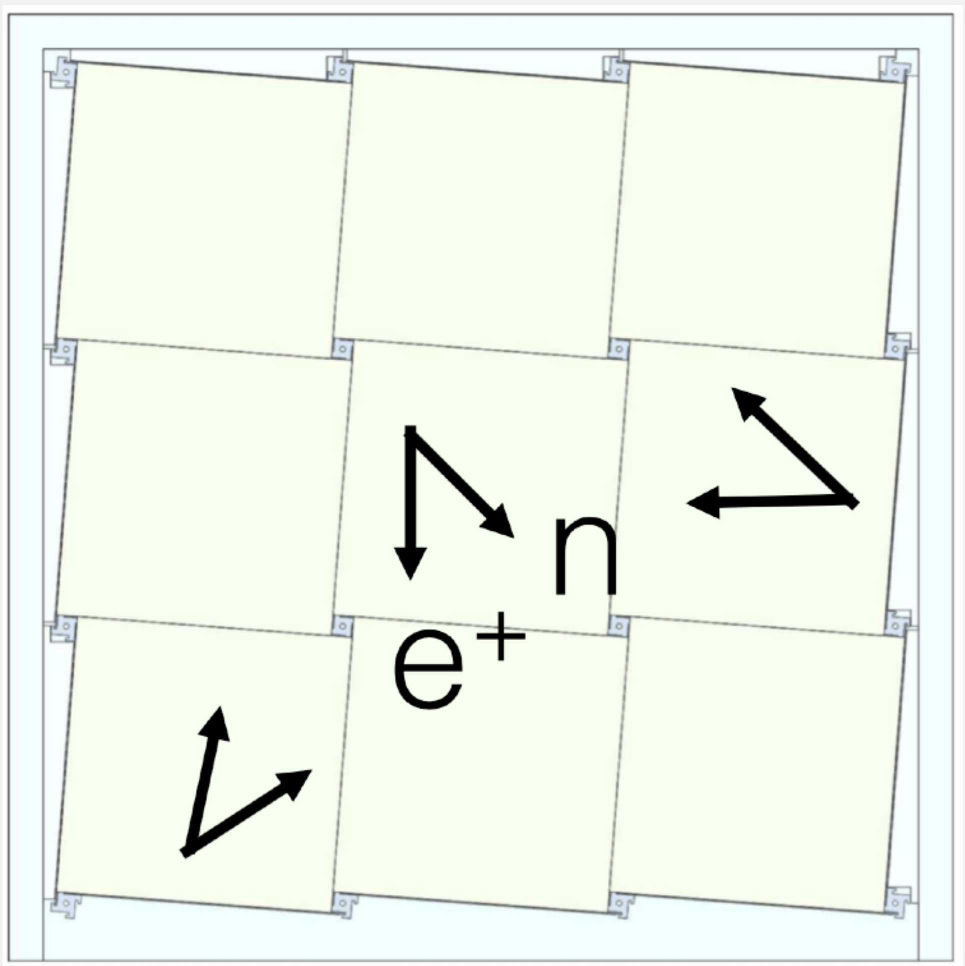




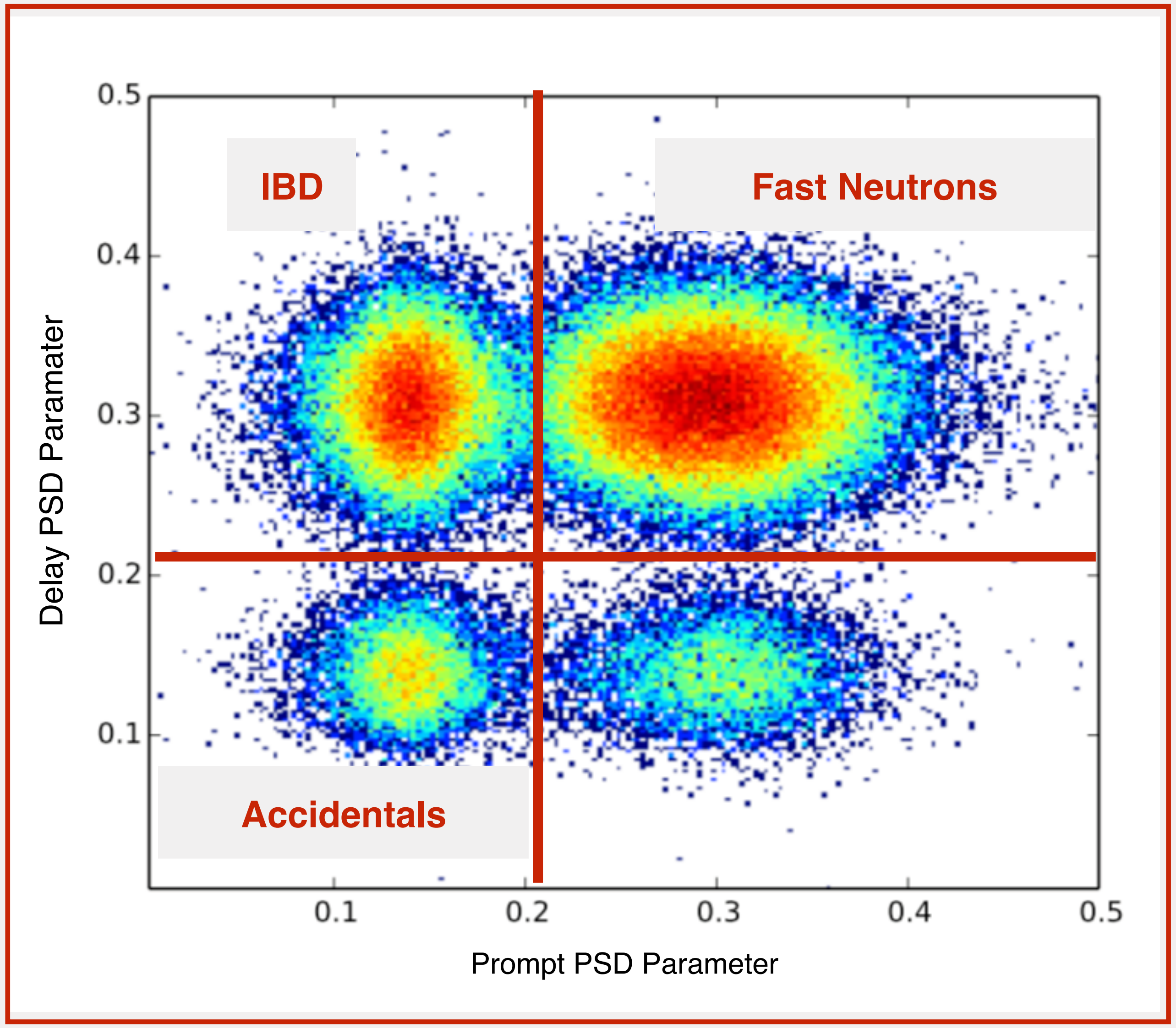
- Each segment covers multiple L/E bins
- Conversely, each L/E bin is covered by multiple segments
- Systematic biases (both correlated and uncorrelated) reduced
- Movement of the detector => varied contribution to L/E bins from each segment

Detection Mechanism

Spatial coincidence of IBD events



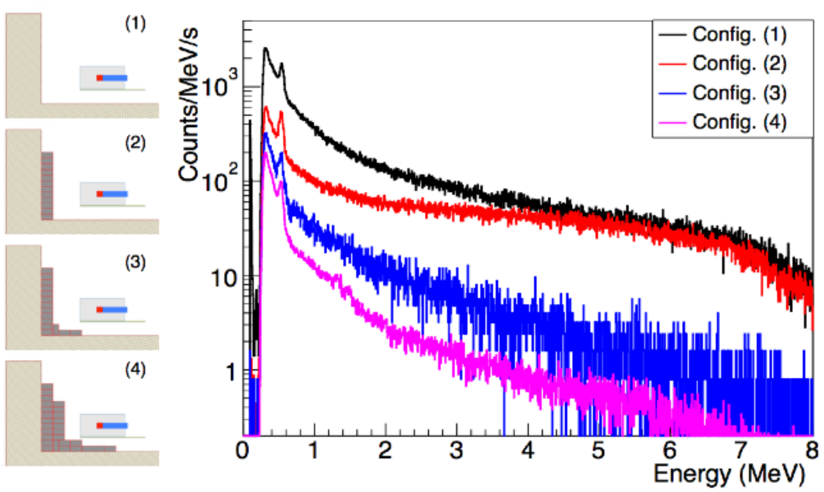
Segmentation allows for background rejection



Comparison of coincidences

Background Characterization and Reduction

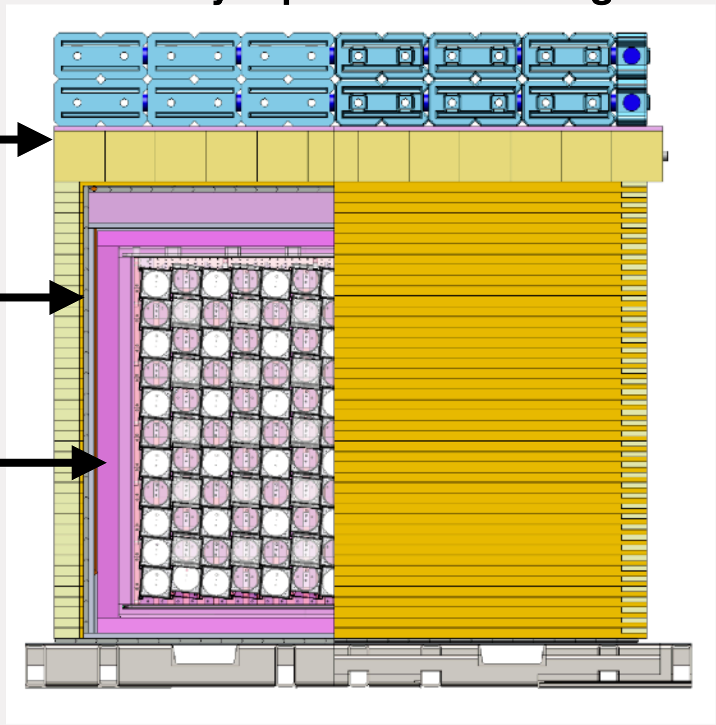
- HFIR background characterized in detail
- Both reactor related and uncorrelated backgrounds measured
- Lead wall designed to shield reactor related backgrounds
- Passive shield design motivated by measured backgrounds



Effect of varying lead wall configuration on gammas

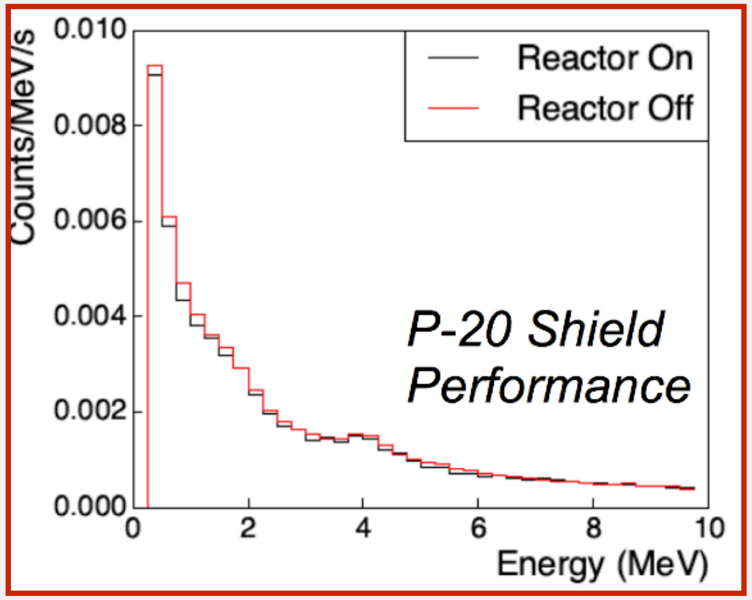
Local shielding joining reactor wall

Multi-layer passive shielding



NIM A806 (2016)

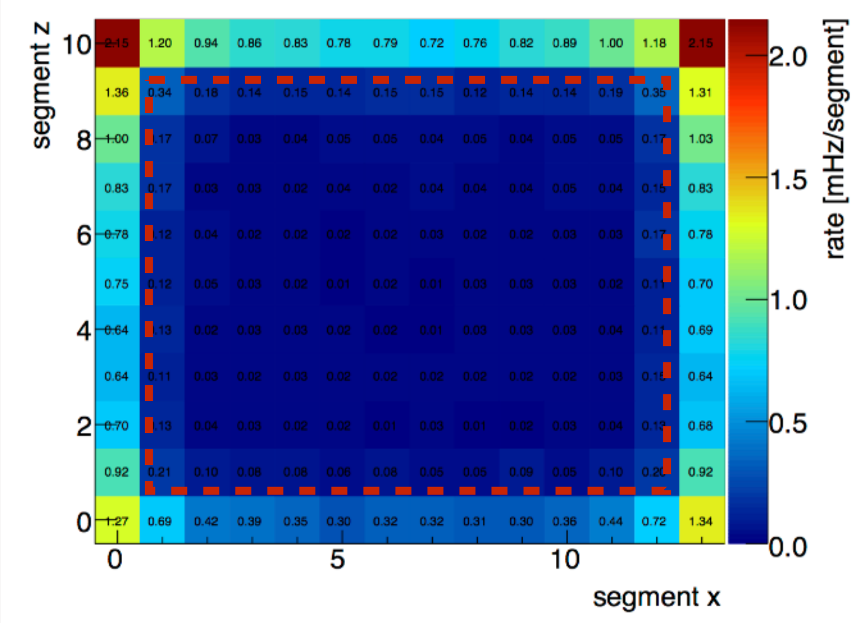
~ 25% the size of PROSPECT shielding



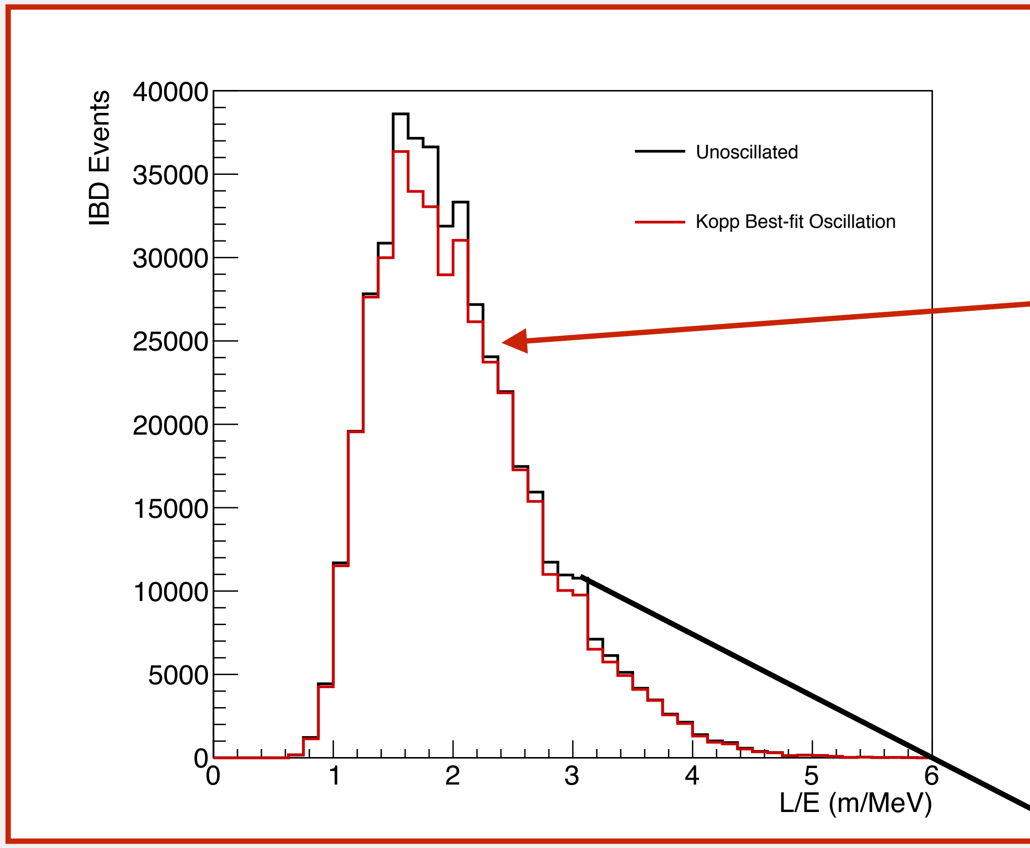
P20 shield was able to shield the reactor backgrounds effectively

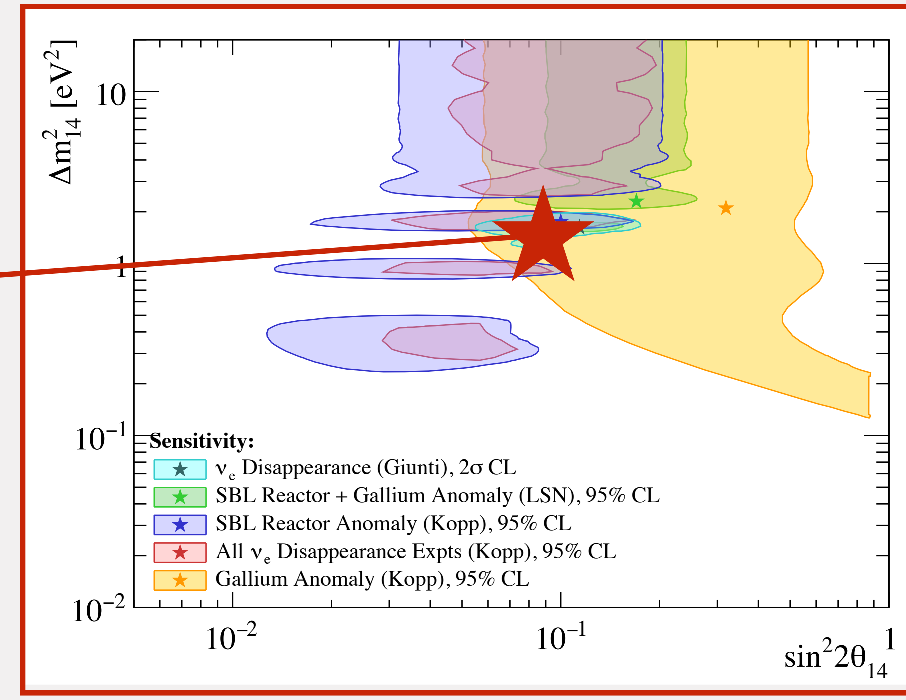
Cosmic backgrounds can be calibrated out using data from reactor off time

Use outer layer of the detector as veto

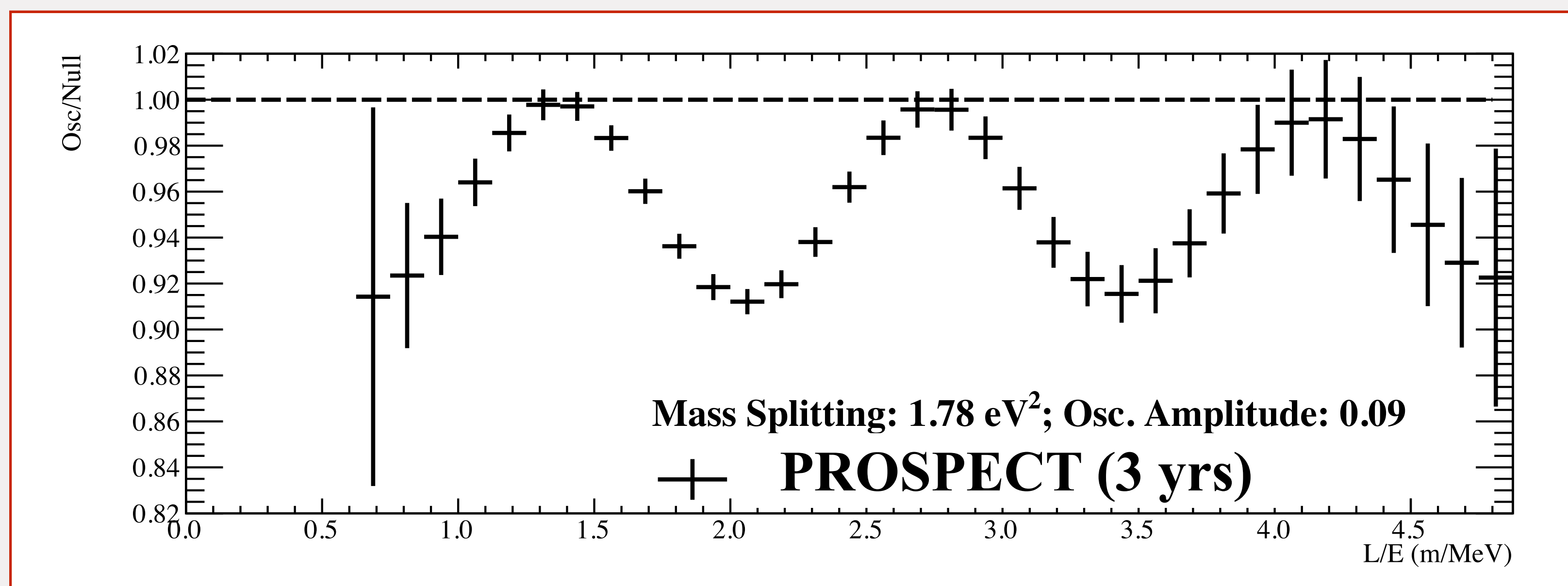


L/E Signature

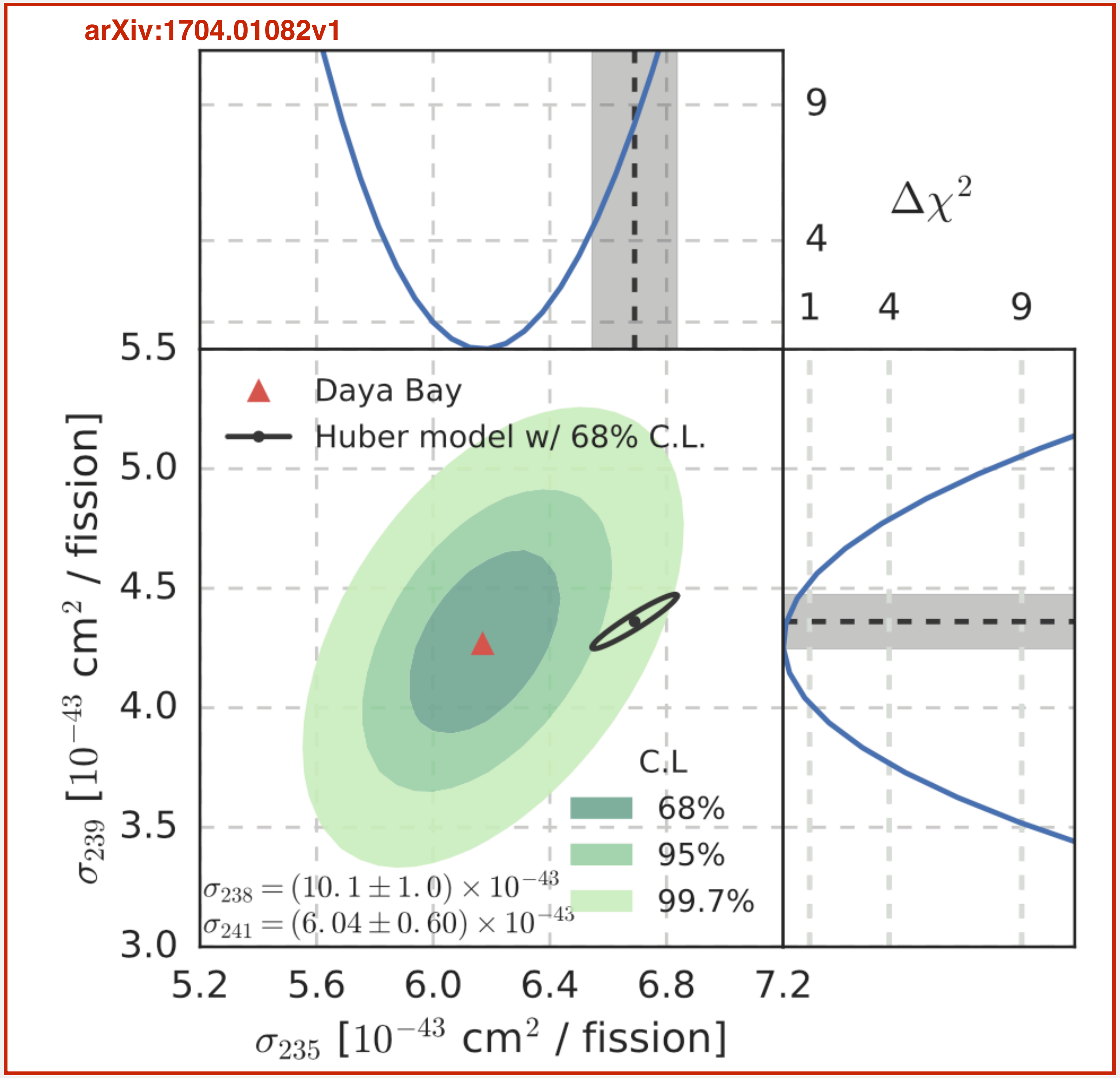




- L/E distribution shows variation between oscillated and unoscillated cases
- The ratio of oscillated vs unoscillated rates manifests as a sinusoidal curve as a function of L/E in presence of neutrino oscillations
- PROSPECT will cover a wide L/E range corresponding to multiple oscillation cycles



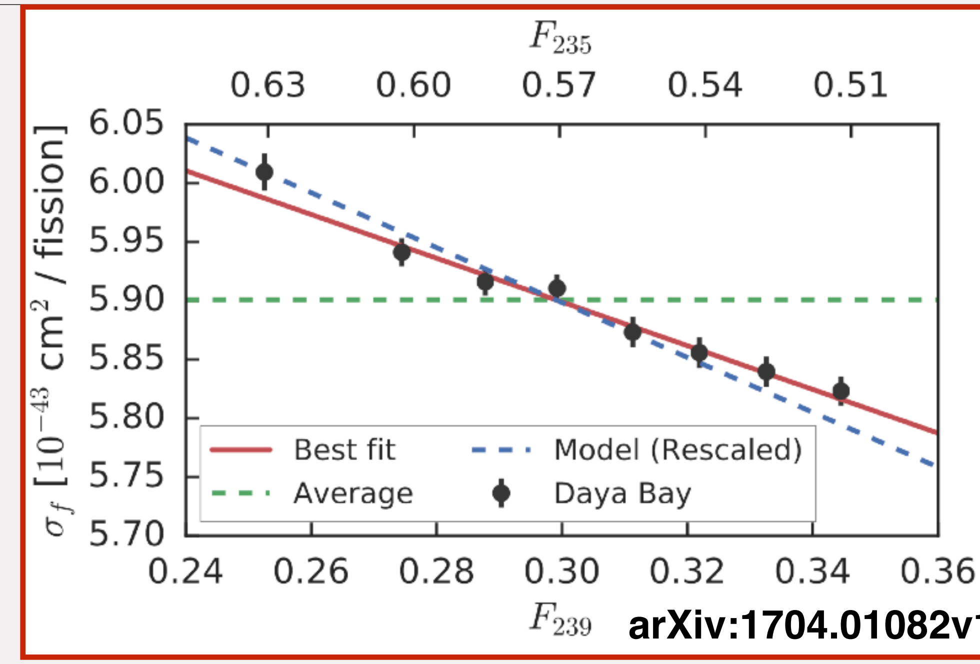
U235 Cause For Reactor Flux Anomaly ?



- Daya Bay has recently reported IBD yields of U235 and Pu239
- U235 shows a deficit of ~8% compared to predictions
- Is reactor flux anomaly only from U235 ?
- Daya Bay data seems to indicate that the anomaly is only from U235
- A pure U235 flux measurement would give conclusive evidence

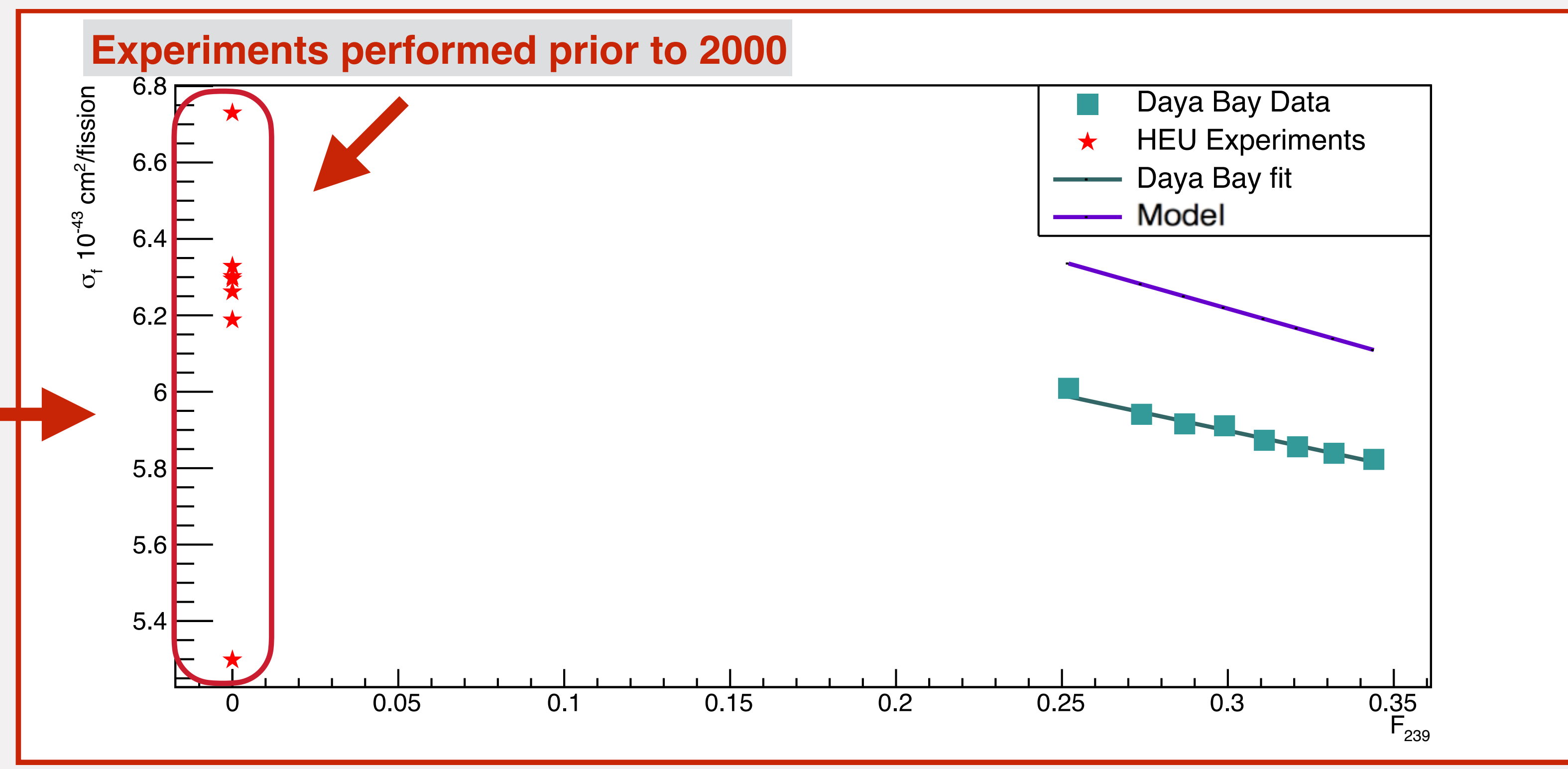
Flux Measurement at HEU

- Daya Bay has also shown flux/IBD yield evolution as a function of Pu239/ U235 fission fractions.
- Their results are incompatible with Huber-Mueller model both in total flux (normalization) and rate of change of flux with changing fission fractions (slope)
- Flux measurement at a HEU core would provide not only U235 flux but could also provide better constrain on Pu 239 flux



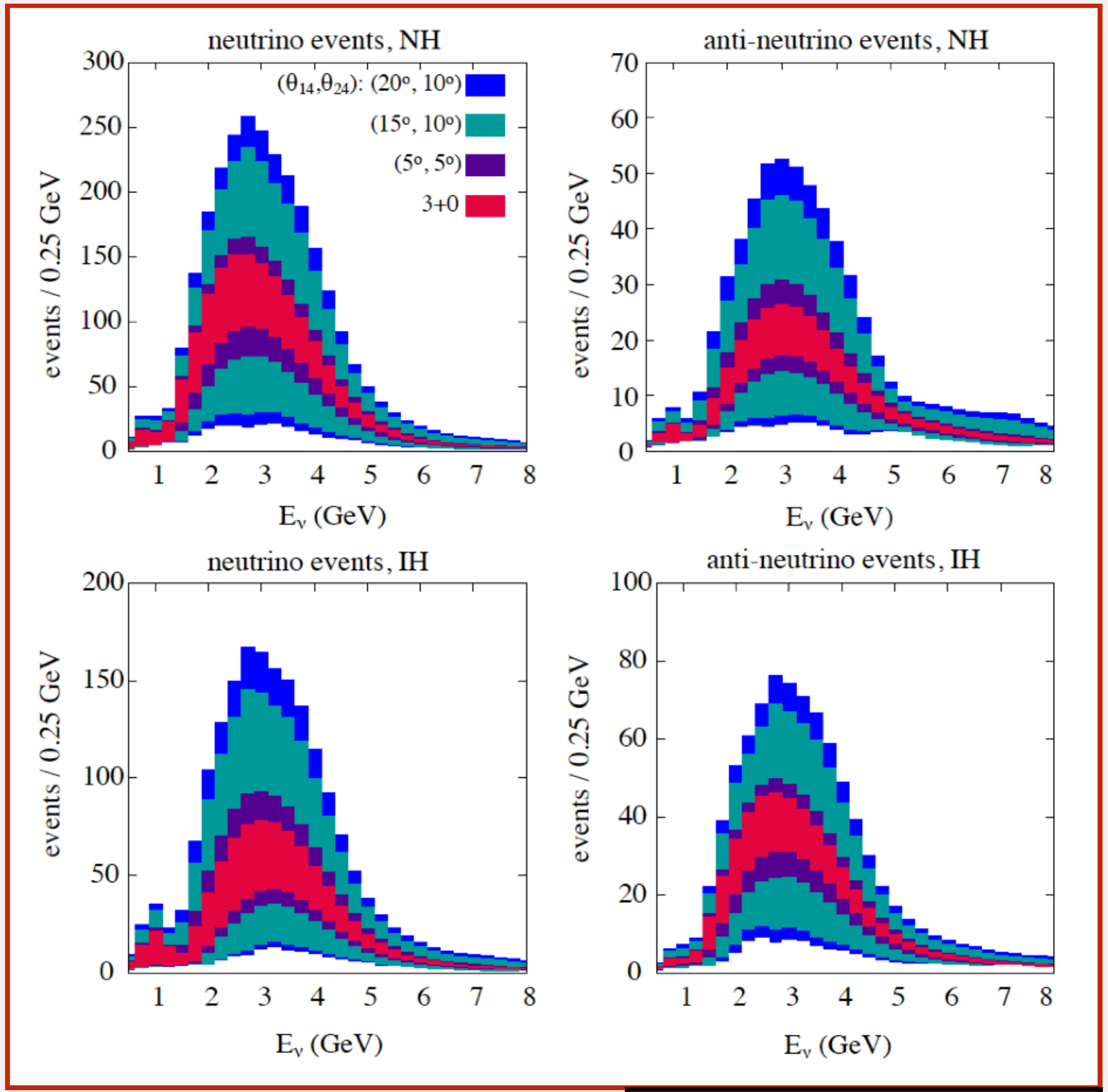
a	Experiment	f^a_{235}	f^a_{238}	f^a_{239}	f^a_{241}	$R^{exp}_{a,SH}$
1	Bugey-4	0.538	0.078	0.328	0.056	0.932
2	Rovno91	0.606	0.074	0.277	0.043	0.930
3	Rovno88-1I	0.607	0.074	0.277	0.042	0.907
4	Rovno88-2I	0.603	0.076	0.276	0.045	0.938
5	Rovno88-1S	0.606	0.074	0.277	0.043	0.962
6	Rovno88-2S	0.557	0.076	0.313	0.054	0.949
7	Rovno88-2S	0.606	0.074	0.274	0.046	0.928
8	Bugey-3-15	0.538	0.078	0.328	0.056	0.936
9	Bugey-3-40	0.538	0.078	0.328	0.056	0.942
10	Bugey-3-95	0.538	0.078	0.328	0.056	0.867
11	Gosgen-38	0.619	0.067	0.272	0.042	0.955
12	Gosgen-46	0.584	0.068	0.298	0.050	0.981
13	Gosgen-65	0.543	0.070	0.329	0.058	0.915
14	ILL	1	0	0	0	0.792
15	Krasnoyarsk87-33	1	0	0	0	0.925
16	Krasnoyarsk87-92	1	0	0	0	0.942
17	Krasnoyarsk94-57	1	0	0	0	0.936
18	Krasnoyarsk99-34	1	0	0	0	0.946
19	SRP-18	1	0	0	0	0.941
20	SRP-24	1	0	0	0	1.006
21	Nucifer	0.926	0.061	0.008	0.005	1.014
22	Chooz	0.496	0.087	0.351	0.066	0.996
23	Palo Verde	0.600	0.070	0.270	0.060	0.997
24	Daya Bay	0.561	0.076	0.307	0.056	0.946
25	RENO	0.569	0.073	0.301	0.056	0.946
26	Double Chooz	0.511	0.087	0.340	0.062	0.935

arXiv:1702.04139v1



Implications

1. Existence of sterile neutrinos have far-reaching implications on particle physics and cosmology
2. Sterile neutrinos lead to complications in interpretation of CP-violation searches
3. Sterile neutrinos will alter the effective neutrino majorana mass



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Low mass separators