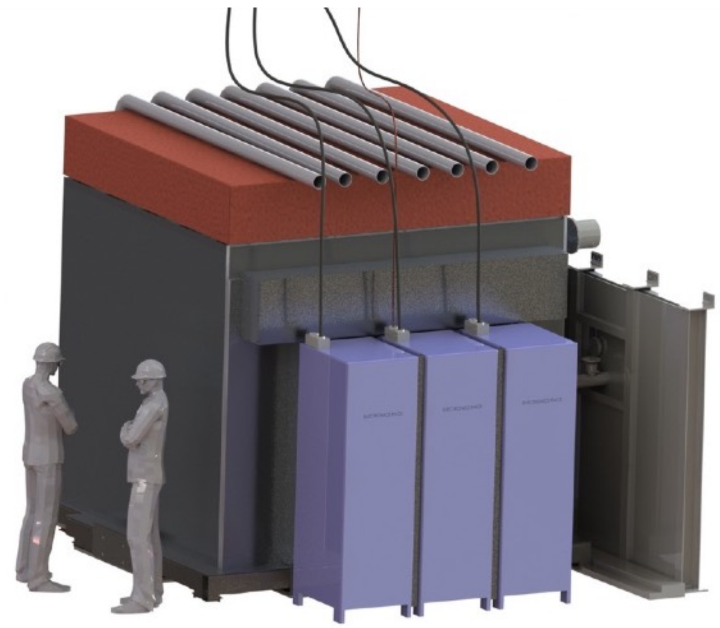
PROSPECT (Precision Reactor Oscillation and Spectrum Experiment)



Pieter Mumm

National Institute of Standards and Technology

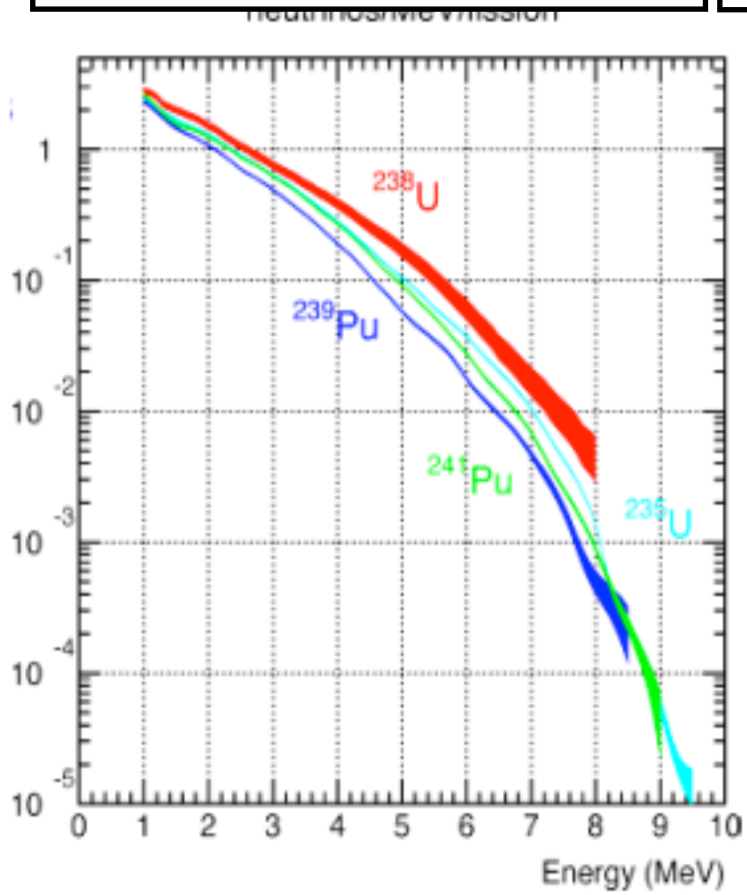
For the PROSPECT Collaboration

PROSPECT

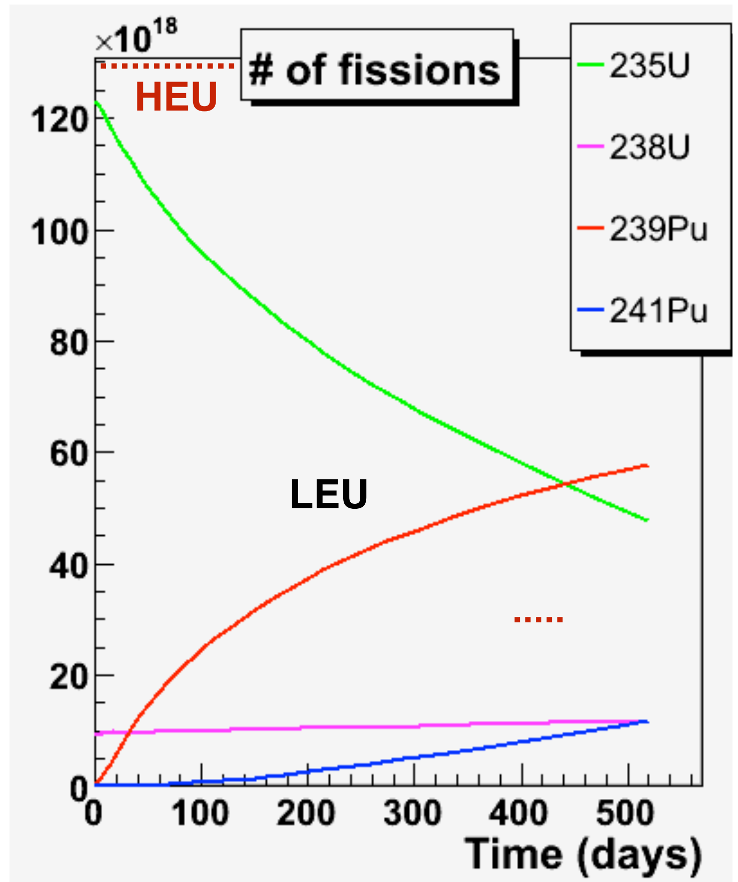
Thanks to PROSPECT collaboration for many slides

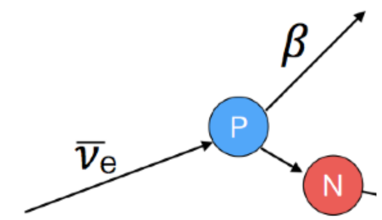
Some key points on reactor antineutrinos

parent dependent spectrum



time-dependent rate and spectrum

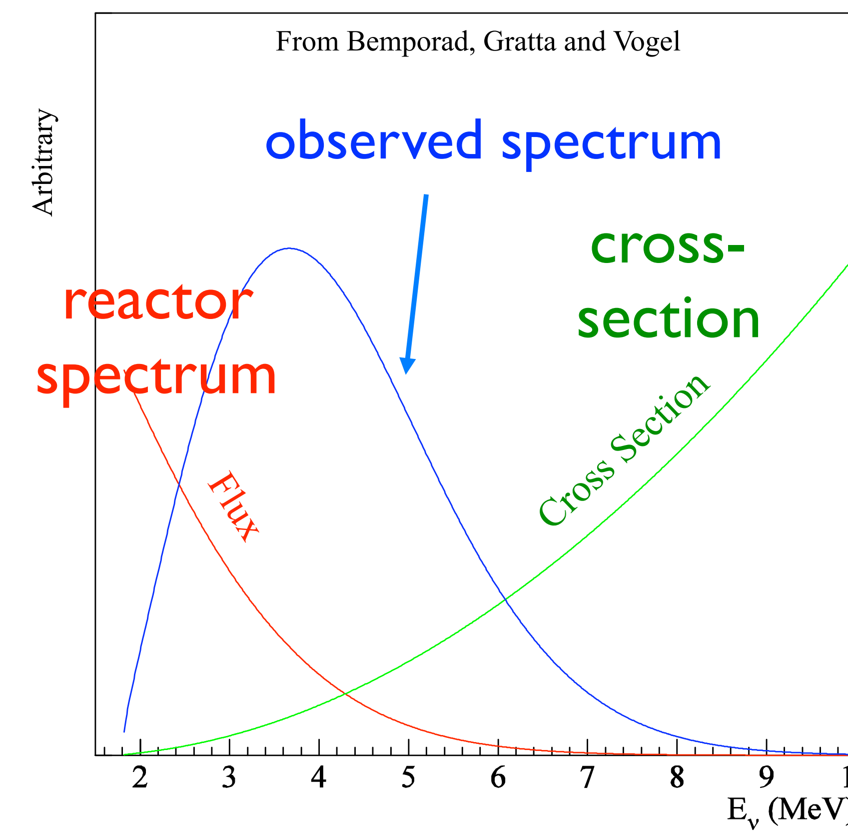




Detection

inverse beta decay

$$\overline{\nu}_e + p \rightarrow e^+ + n$$



Source: fissions in ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu
'pure'

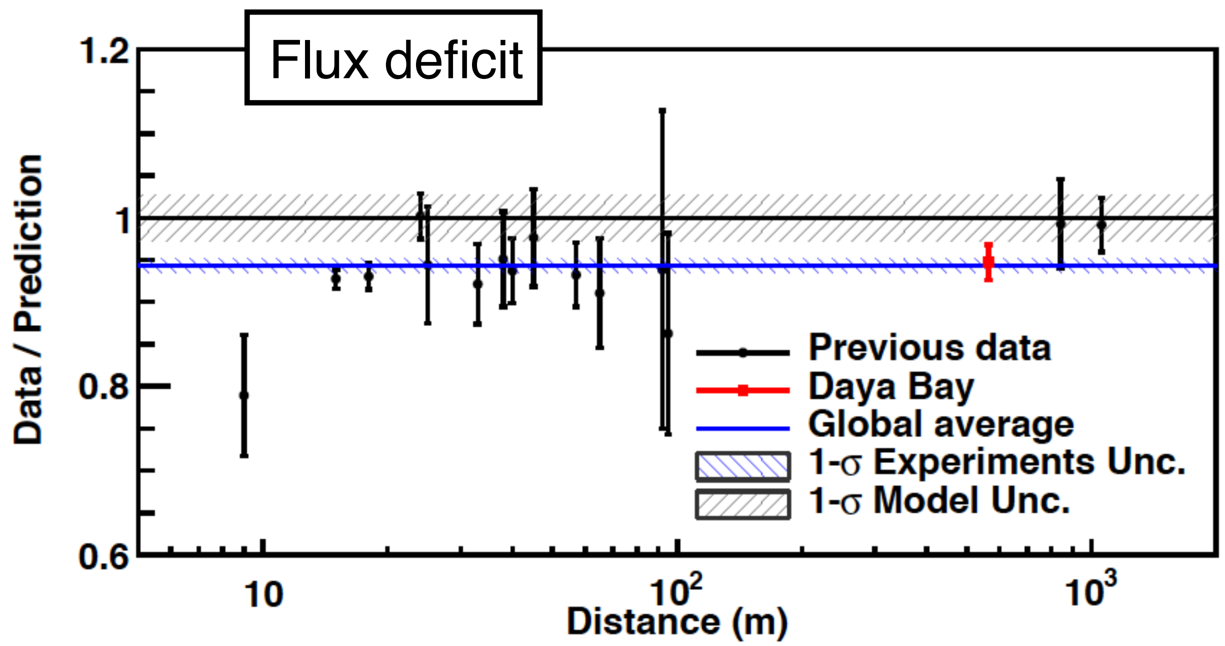
Spectrum varies between reactor types, and can be time dependent

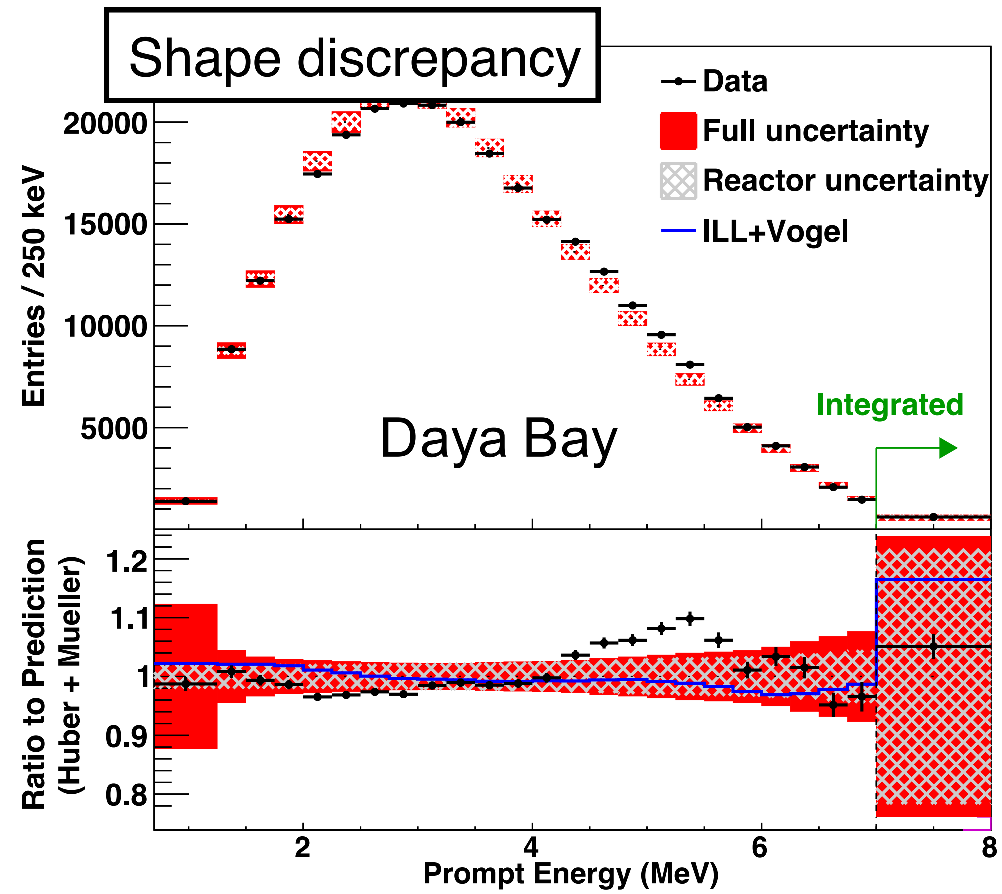
cross-section accurate to +/-0.2%

threshold: neutrinos with E < 1.8 MeV are not detected

only ~ 1.5 ν_e/fission are detected

Rate and spectrum 'anomalies'



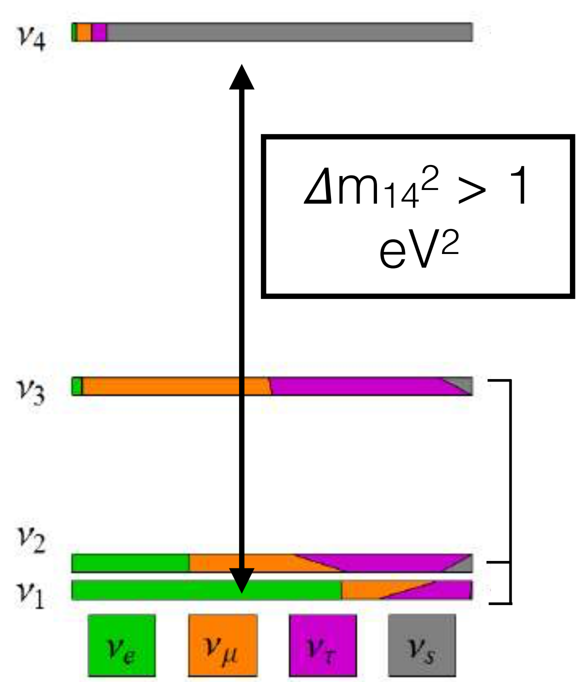


2011 dual ν_e flux predictions:
- re-analysis of 19 short-baseline expts.
- new antineutrino spectra: +3%
- neutron lifetime correction: +1%
- off-equilibrium effects: +1%

Flux deficits observed elsewhere

Sterile Neutrino:

- High frequency oscillation
- Mass splitting ~1eV²
- Baseline ~few meters

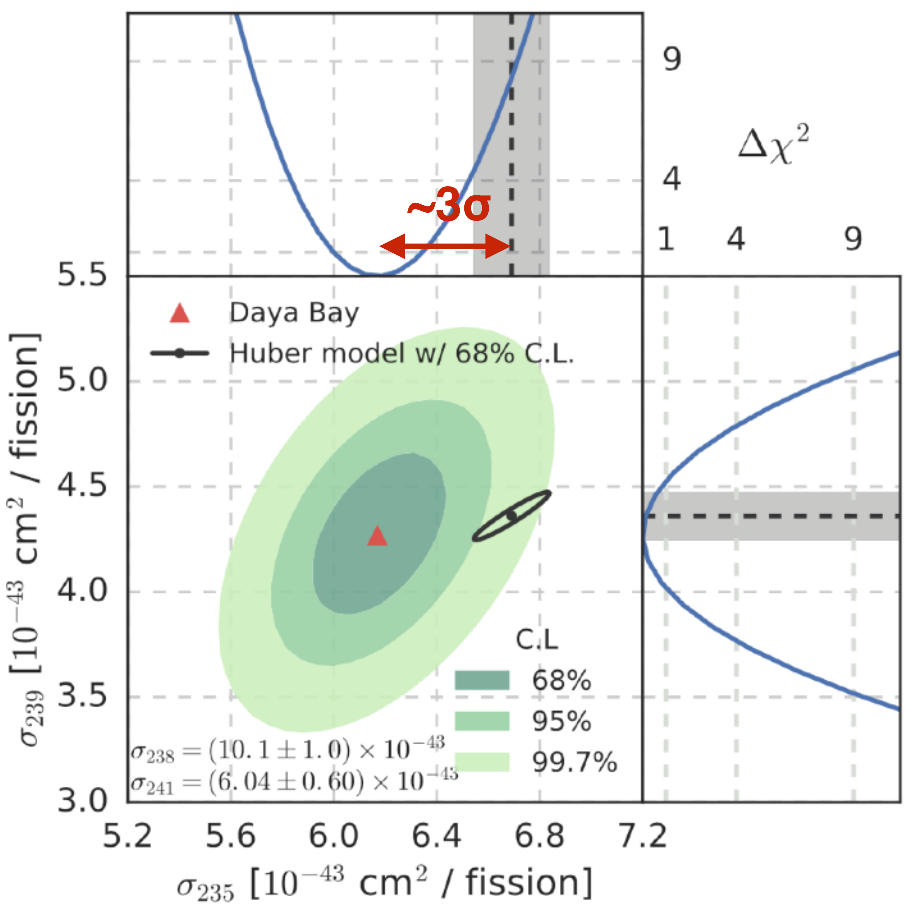


All θ_{13} experiments observe a similar spectral excess of ~10% between 5-7 MeV

Both motivate additional experiments:
- ***other reactor/fuel types***
- ***excellent energy resolution***
- ***short baseline***

Daya Bay Fuel Evolution Analysis

Daya Bay, arXiv:1704.01082v1

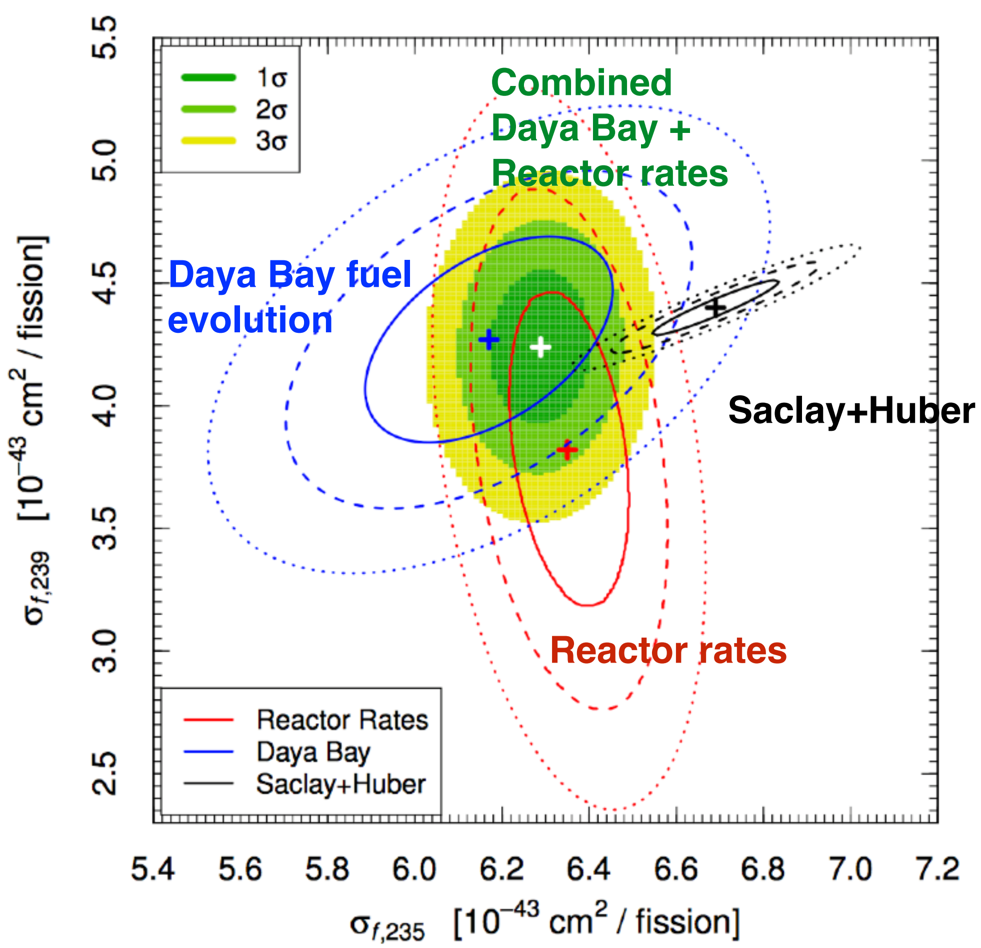


Daya Bay recently reported IBD yields of ^{235}U and ^{239}Pu using evolution of LEU reactors.

Reactor flux model found to be incorrect for ^{235}U.

Improved Determination of Fluxes

Giunti et al, arXiv:1704.02276



IBD yields calculated from reactor rates (of 26 reactor experiments) in tension with Daya Bay measurement.

Composite models: arXiv:1708.01133

Analysis of Daya Bay with Fuel Burnup

Hayes et al, arXiv:1707.07728

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

Precision Reactor Oscillation and Spectrum Experiment

Physics Objectives:

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

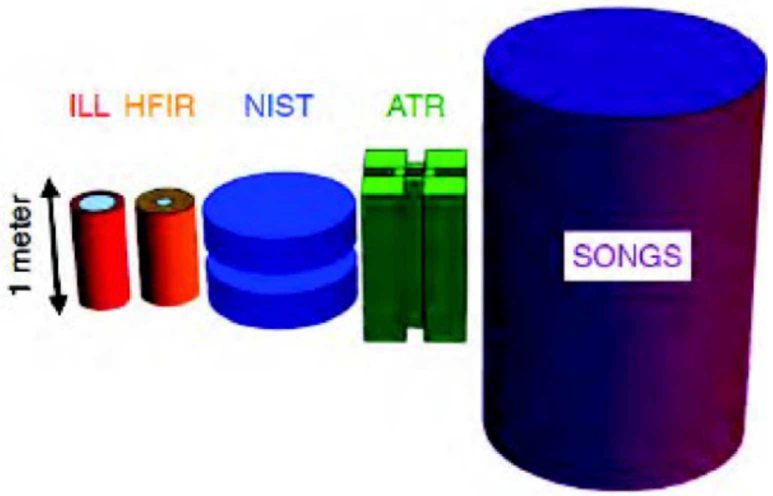
PROSPECT whitepaper, arXiv:1309.7647

PROSPECT Physics Program, J. Phys. G, 43 113001; arXiv:1512.02202

High Flux Isotope Reactor (HFIR) at ORNL

Highest power density in the hemisphere (2 MW/l)
Water cooled at 15,000 gpm

"Point Source" vs Extended Core

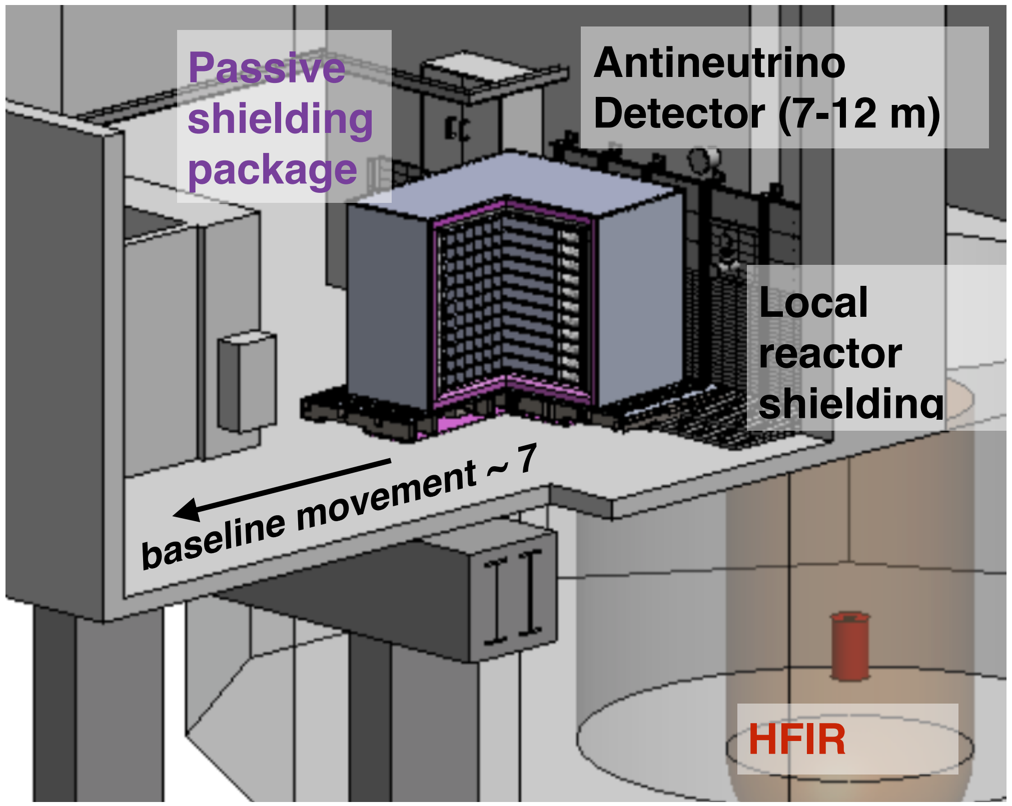


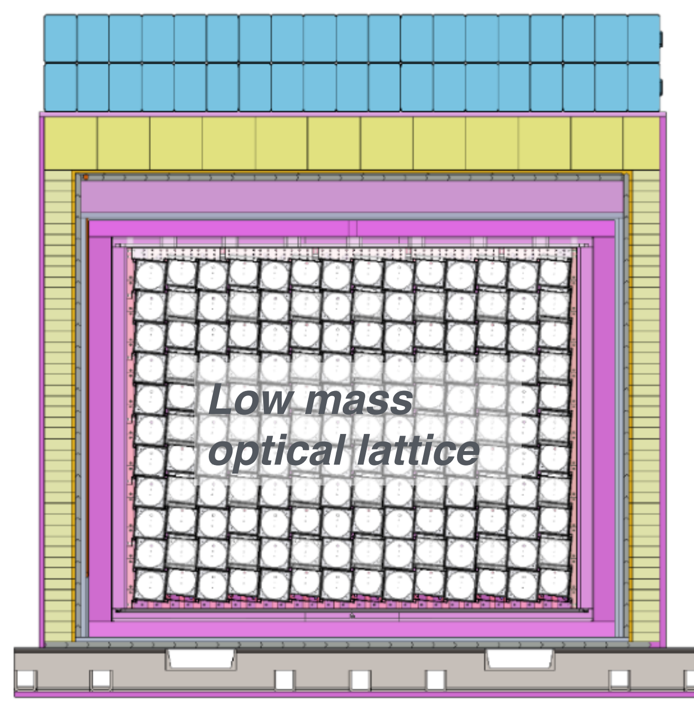
HFIR research reactor

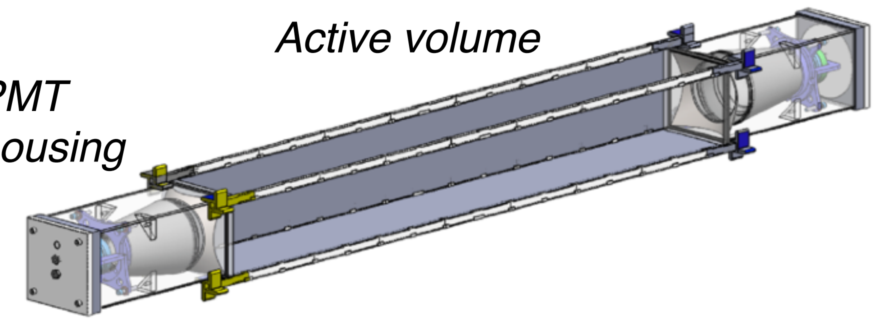
- **Compact core (~1m) and 85 MW, HEU (~93% ^{235}U) Fuel**
- Reactor off periods ~ 60% (key for background characterization)
- Backgrounds well characterized
- Detailed MCNP core model available
- Onsite PROSPECT activity last 4 years.

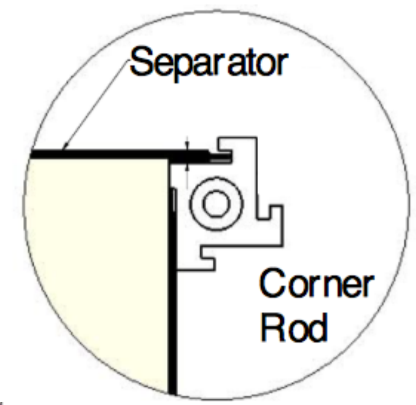
Experimental Parameters for a Reactor Antineutrino Experiment at Very Short Baselines
K.M. Heeger, B.R. Littlejohn, H.P. Mumm, M.N. Tobin., Phys.Rev. D87 (2013) 073008

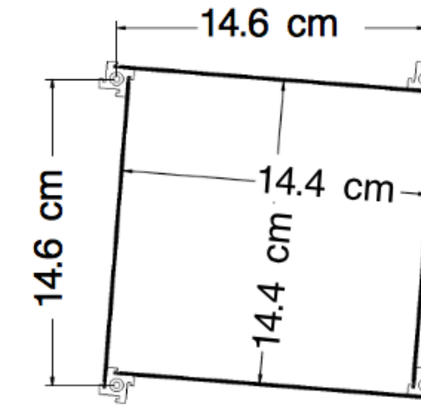
PROSPECT Antineutrino detector

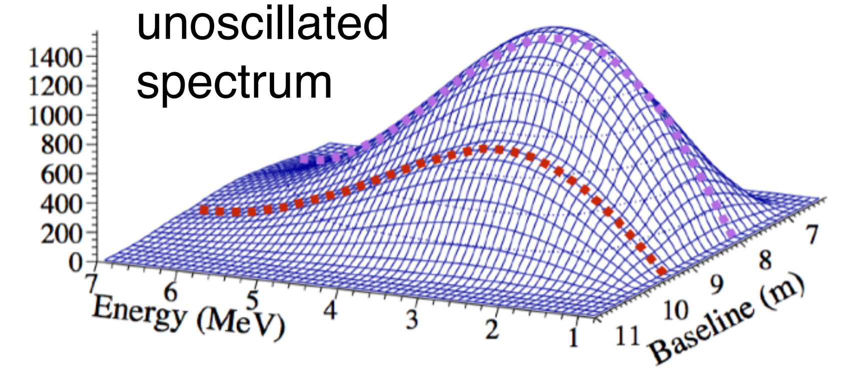


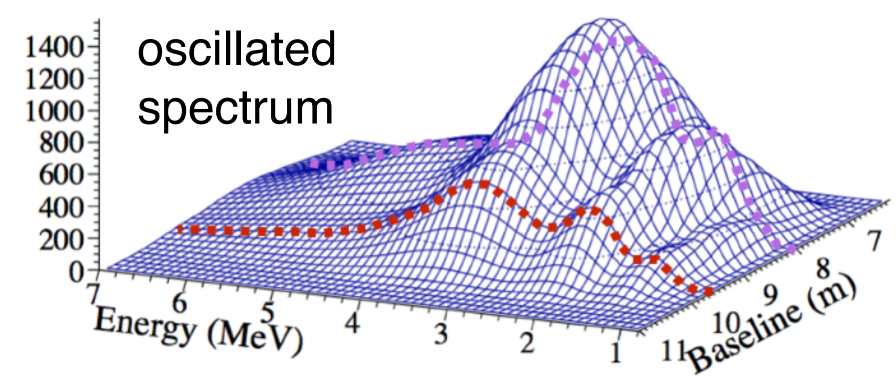








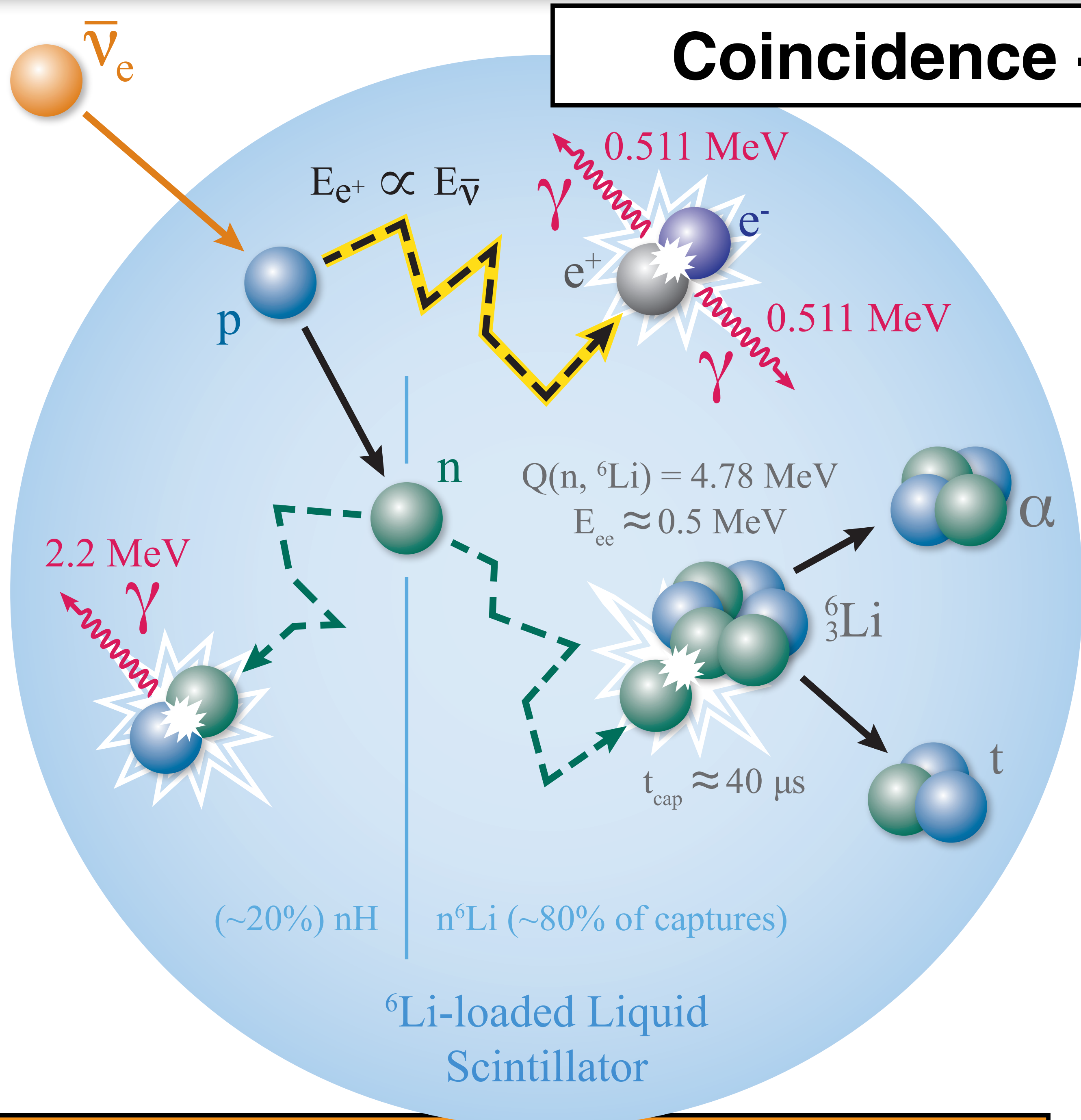




- Single 4,000 L ^{6}Li-loaded liquid scintillator (3,000 L fiducial volume)
- 11 x 14 (154) array of optically separated segments
- Very low mass separators
- Double ended PMT readout, light concentrators -> good light collection and energy response ~4.5-5%√E energy resolution
- Corner rods allow for full *in situ* calibration access
- **150k detected neutrinos per year, ~900/day. S:B ~ 3:1**

IBD detection with ^{6}Li Liquid Scintillator

Coincidence + PSD to reject of backgrounds

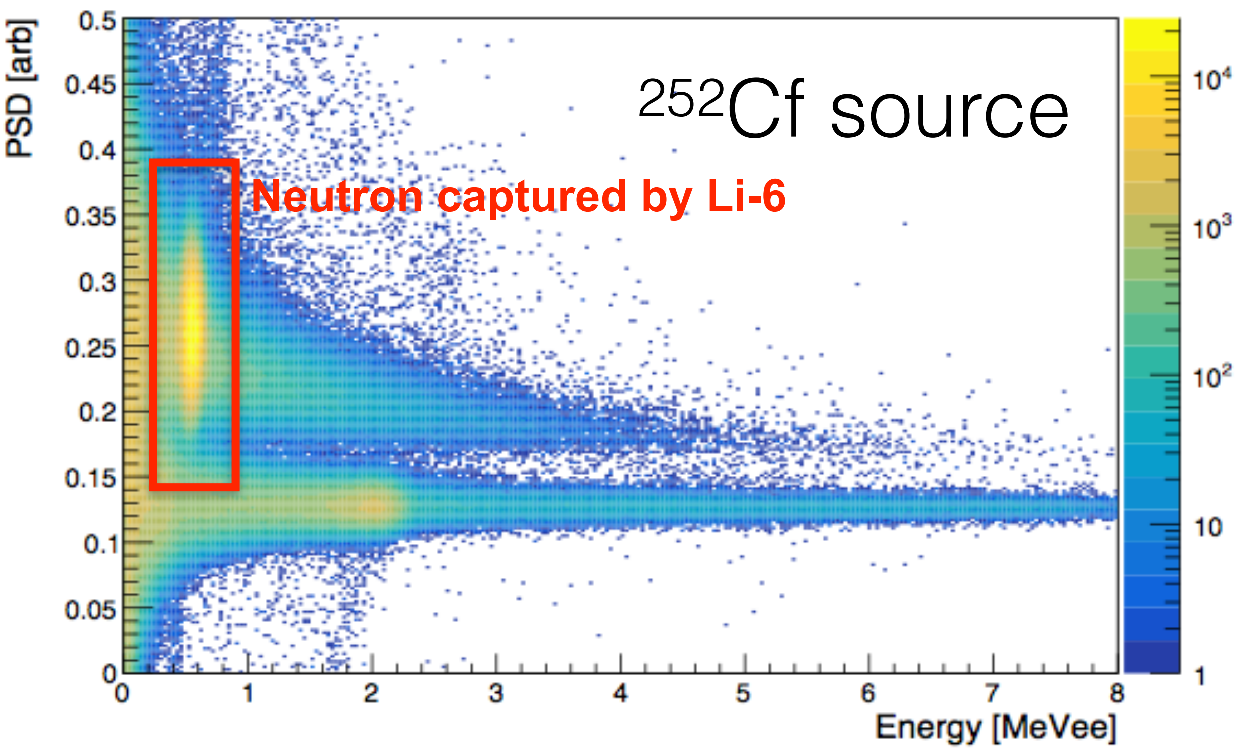


Pulse-shape Discrimination (PSD) Signatures

Inverse Beta Decay
γ-like prompt, n-like delay

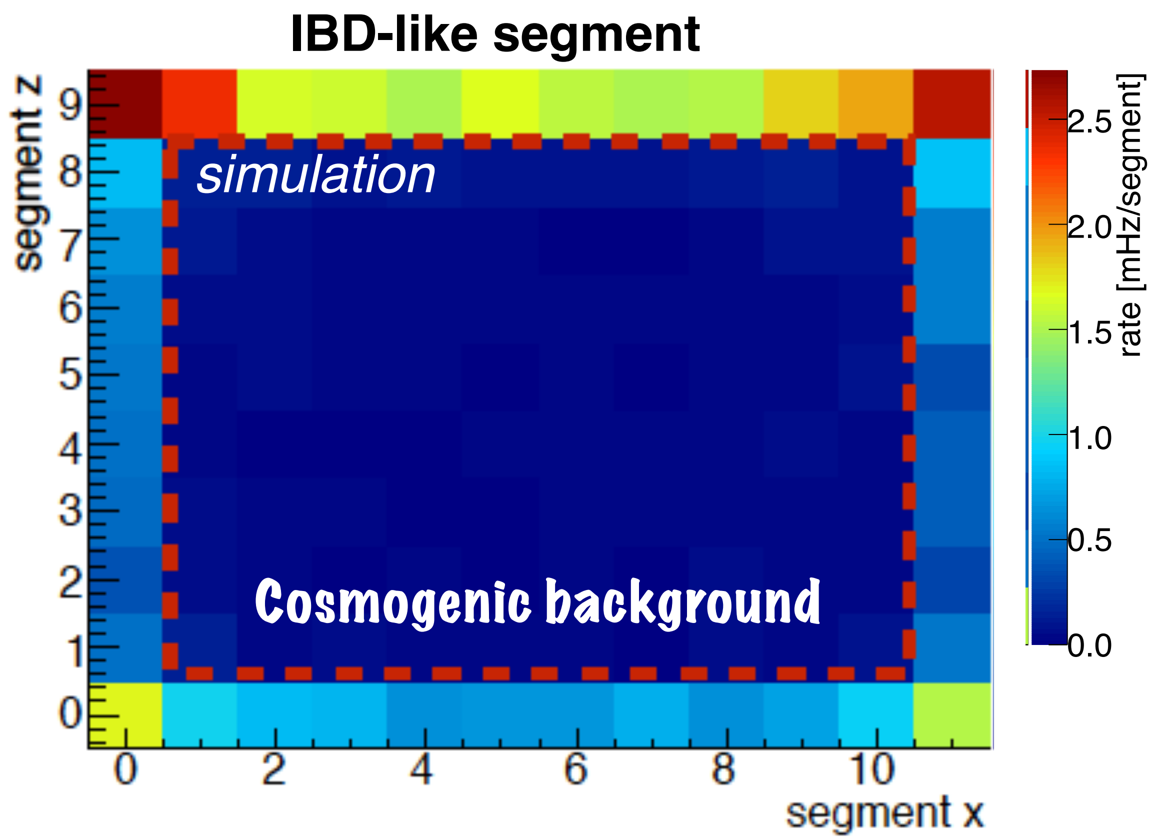
Fast Neutron
~~n-like prompt, n-like delay~~

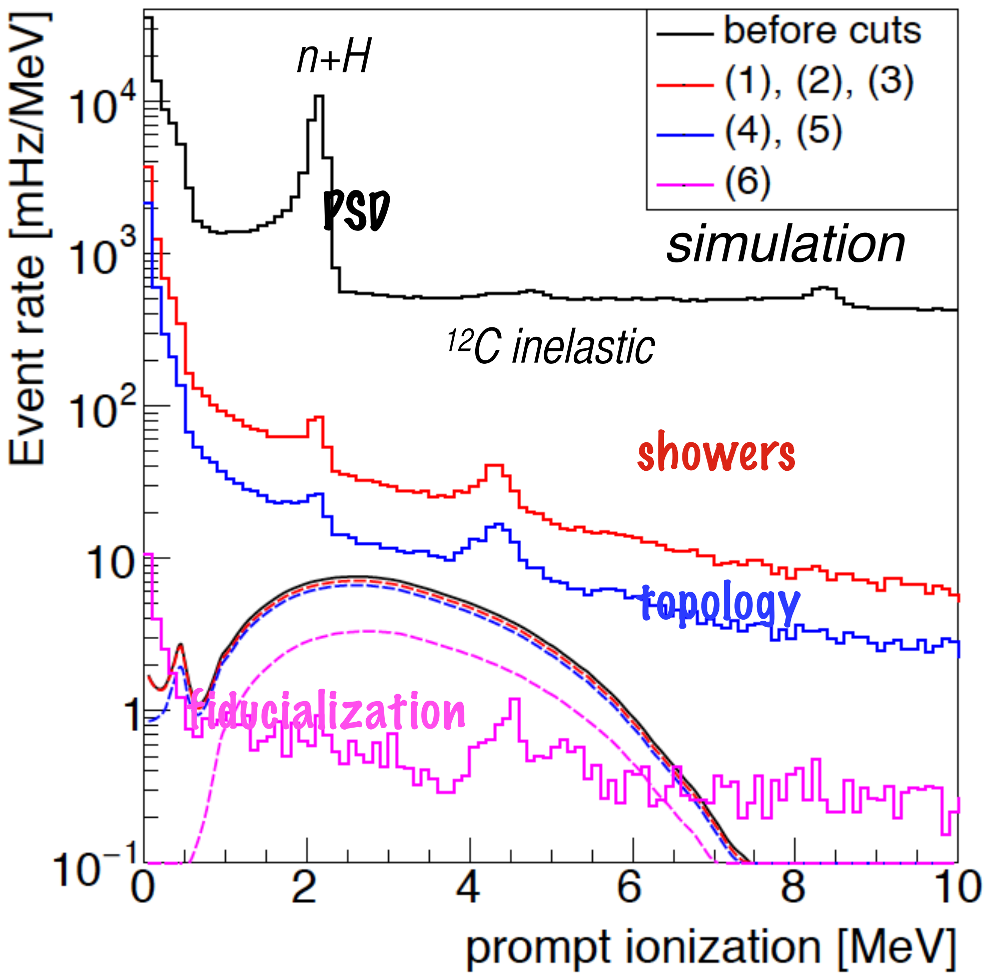
Accidental Gammas
~~γ-like prompt, γ-like delay~~



Event Coincidence Signature:
e-like prompt signal, followed by a ~50μs delayed neutron capture

Fiducialization, PSD, and topology





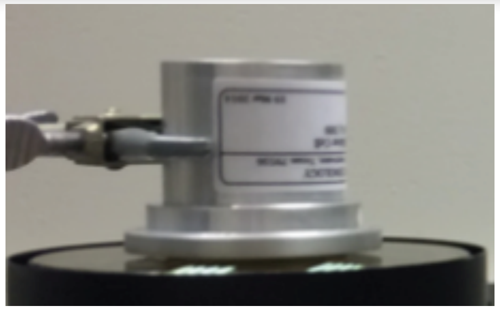
No single cut isolates IBD events, yet sequence of cuts leveraging spatial and timing characteristics of an IBD *yields > 3 orders of magnitude background suppression and an expected signal to background of > 3:1.*

Series of cuts:
- PSD
- Timing
- Spatial topology
- Fiducialization

Rate and shape of residual IBD-like background can be measured during multiple interlaced reactor-off periods.

Phased detector development

PROSPECT-0.1
Aug 2014
Spring 2015



5cm
0.1liter
LS cell

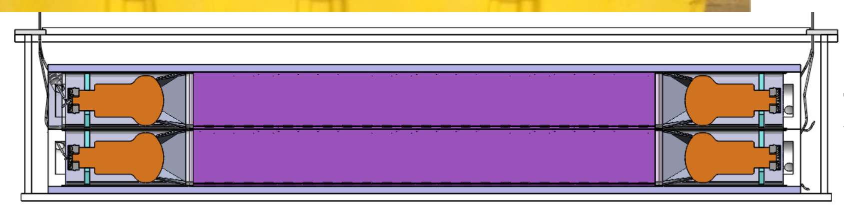
PROSPECT-2
Dec 2014
Feb 2015

12.5cm
1.7 liter
LS cell

PROSPECT-20
March 2015

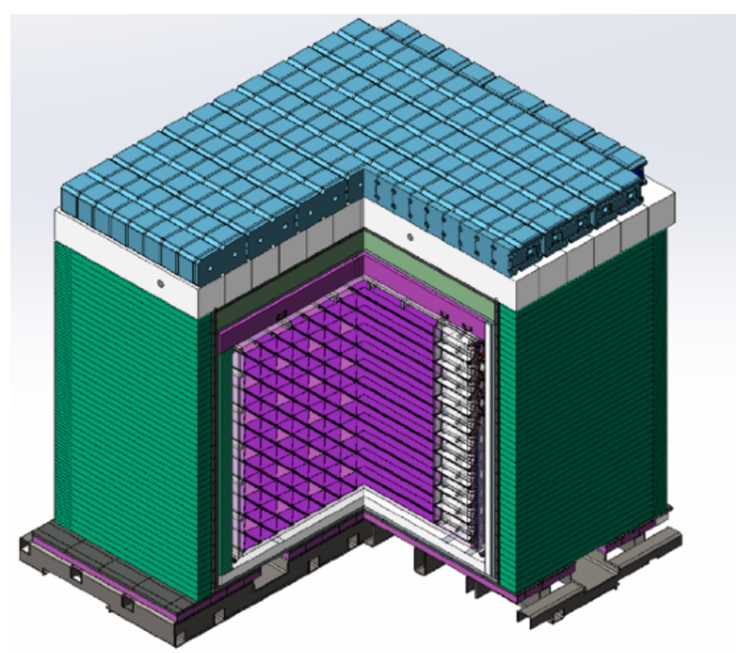
1m
23 liter
LS cell

PROSPECT-50
February 2016 - present

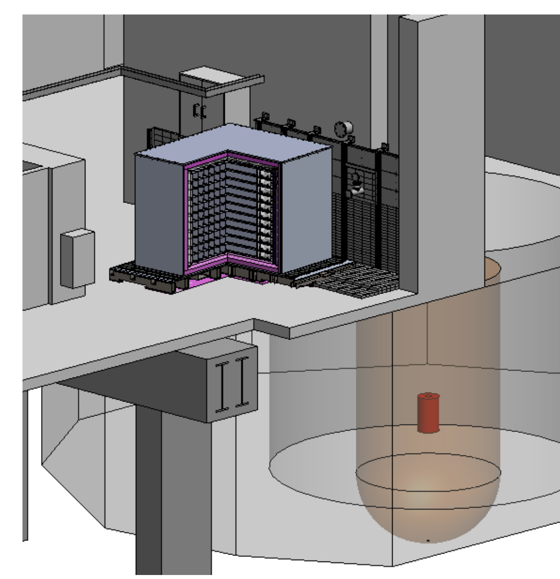


1.2m
2x25 liter
LS segments

PROSPECT
2017*



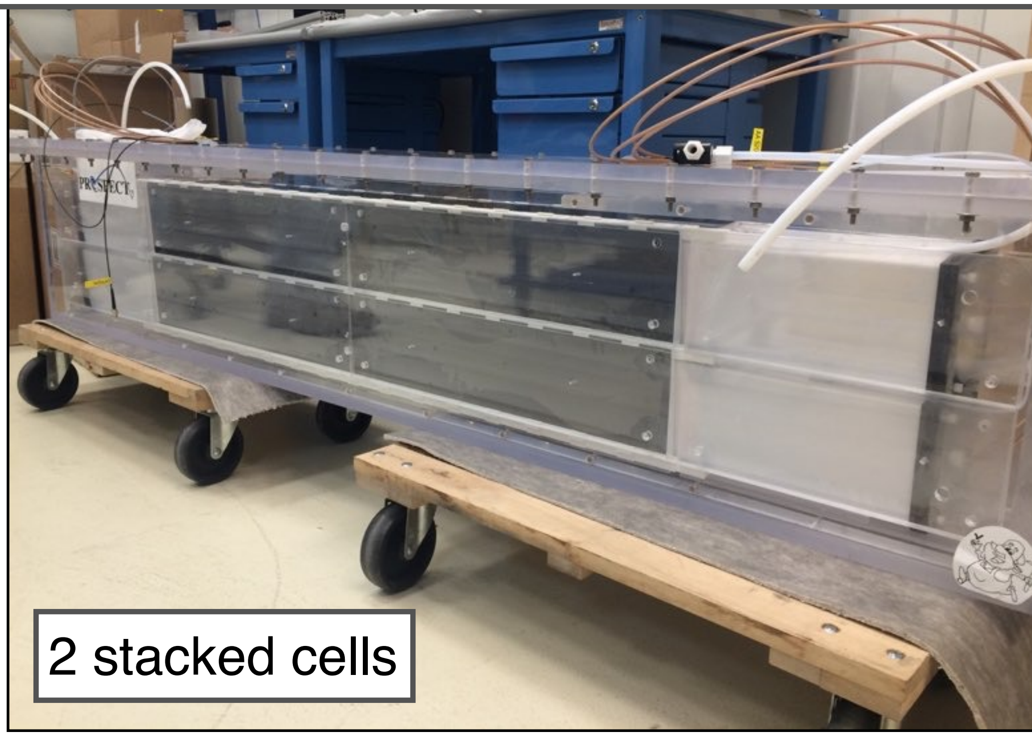
154x25 liter
LS segments
15x15x120cm

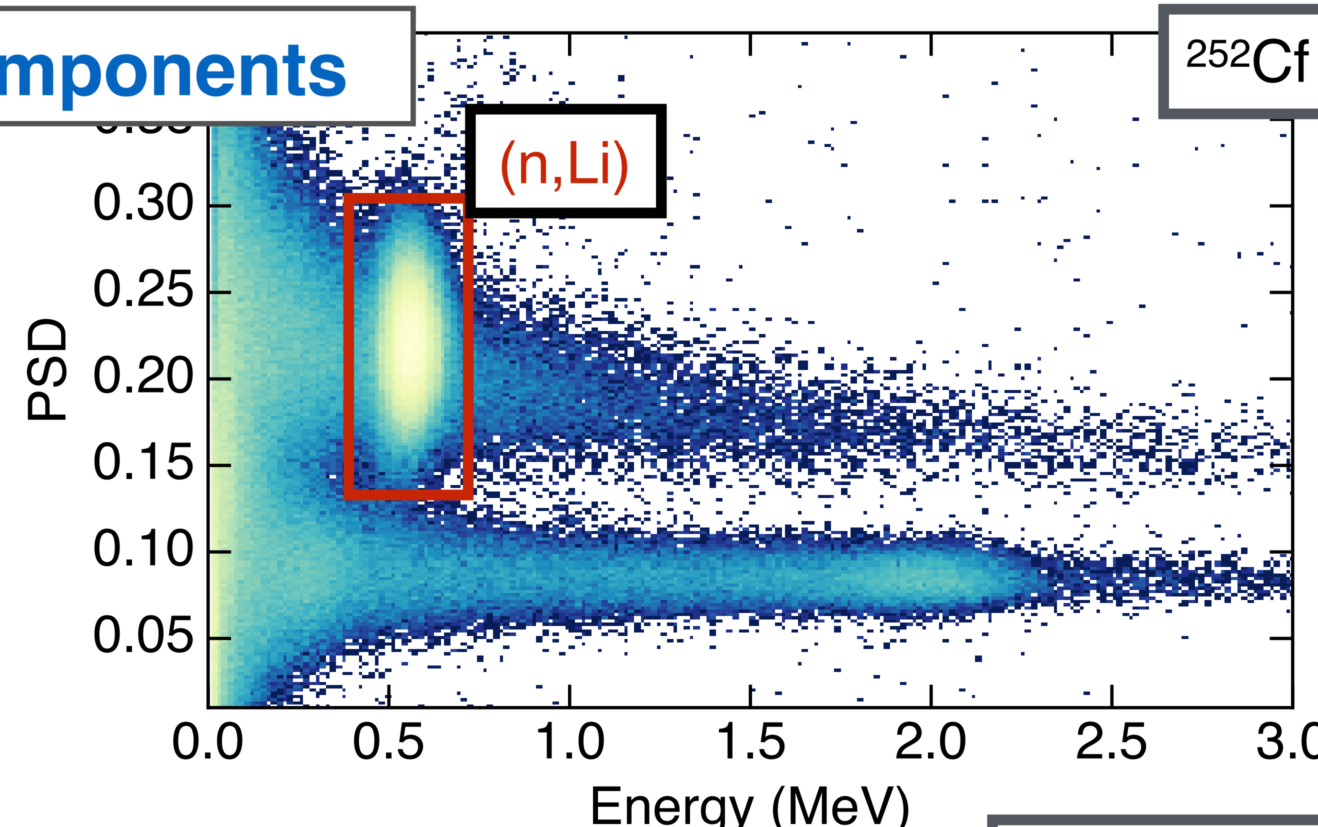


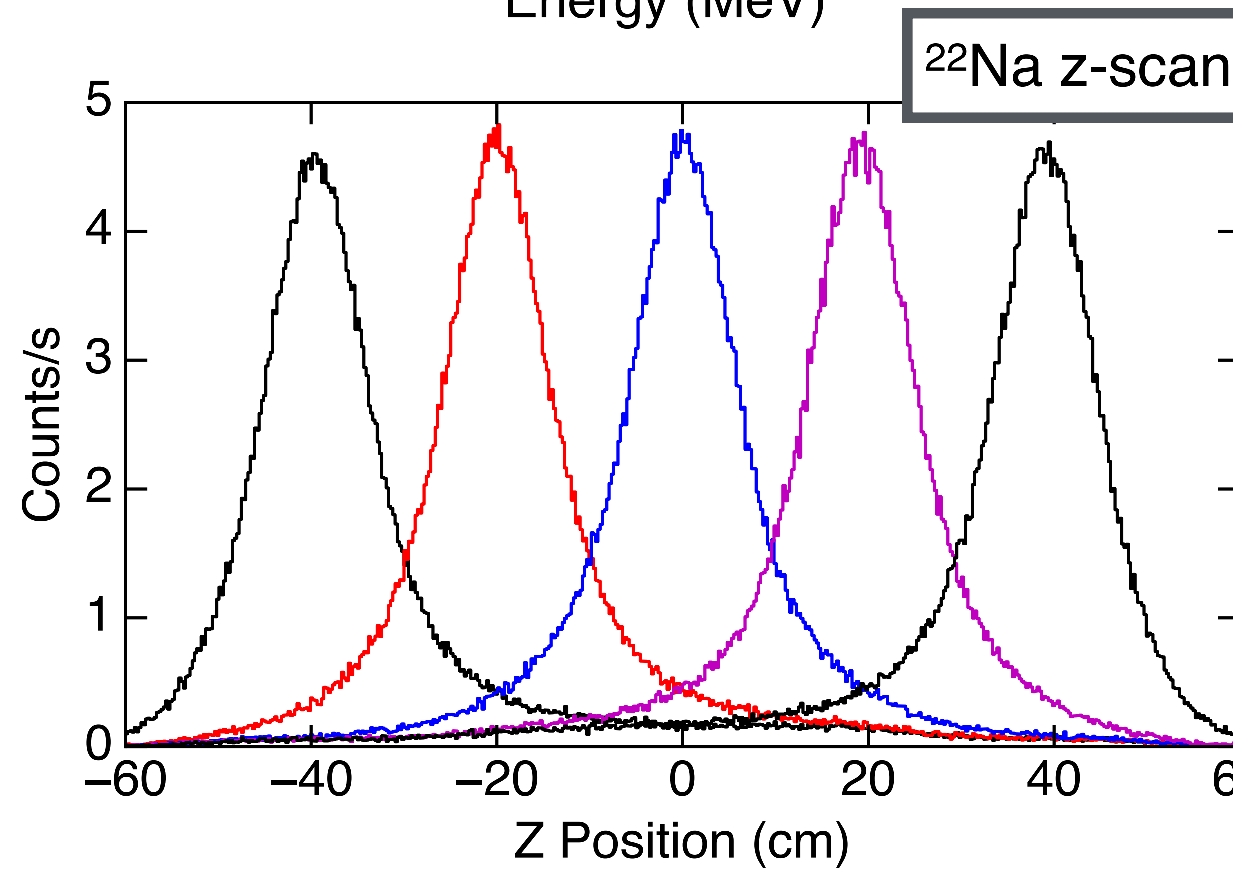
*under assembly

Prototyping: PROSPECT-50 currently operating

50 l ^{6}LiLs, double cell, production components



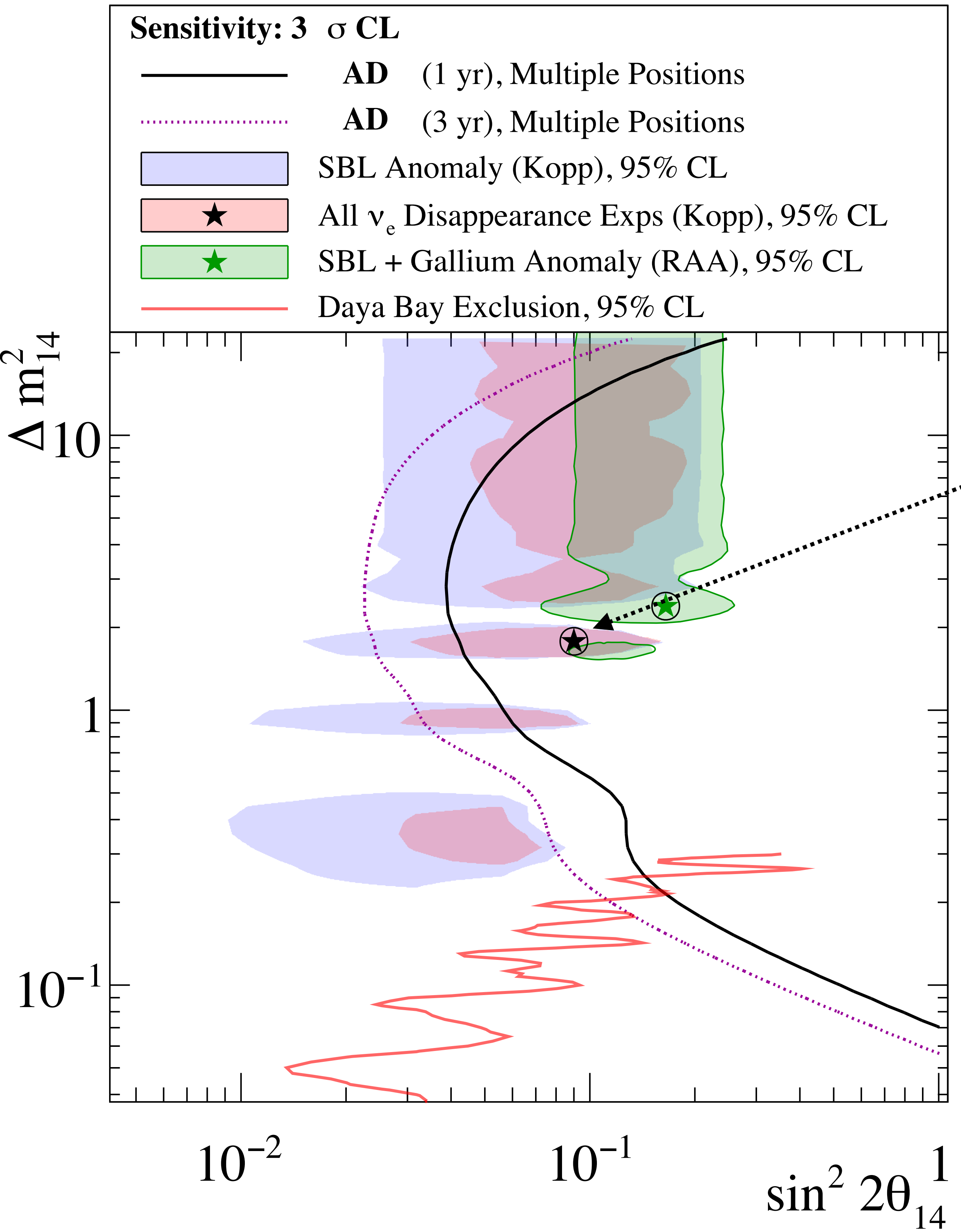


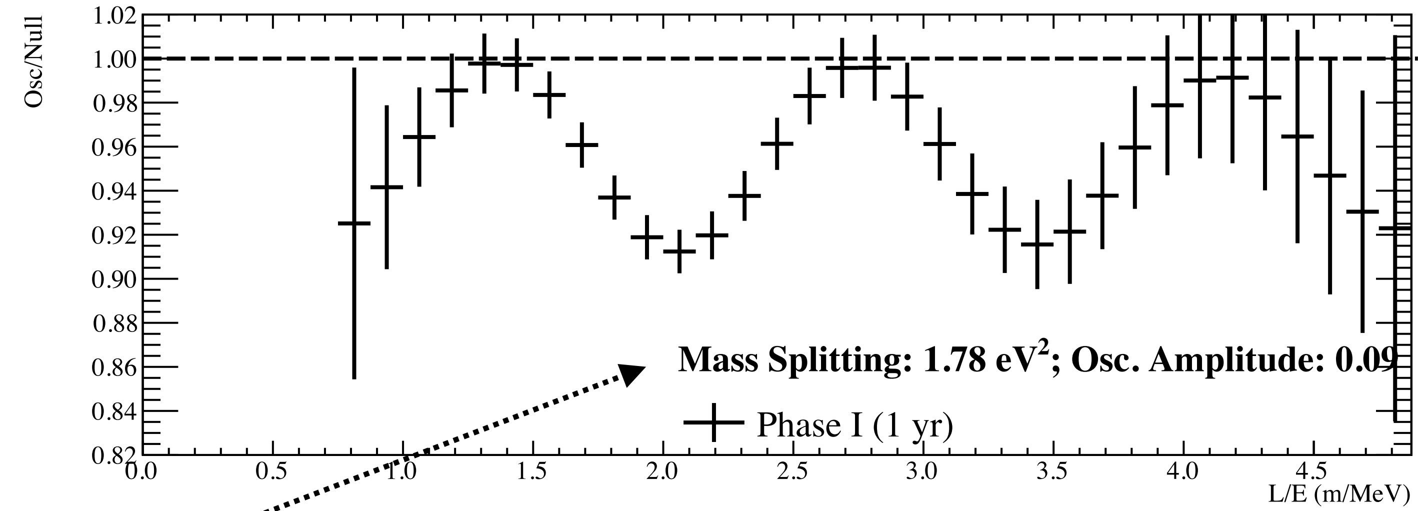


- Nearly continuous operation since March 2016
- Dual cell, all production components
- Measured light collection with ^{6}LiLS: >550PE/MeV
  - **5% energy resolution at 1MeV**
- Measured PSD Figure of Merit: 1.25 at (n,Li) capture
- Double-ended readout
  - Position reconstruction along cell length

Actinium doping, see Berish CH.00009 later this session.

Short Baseline Oscillation Search

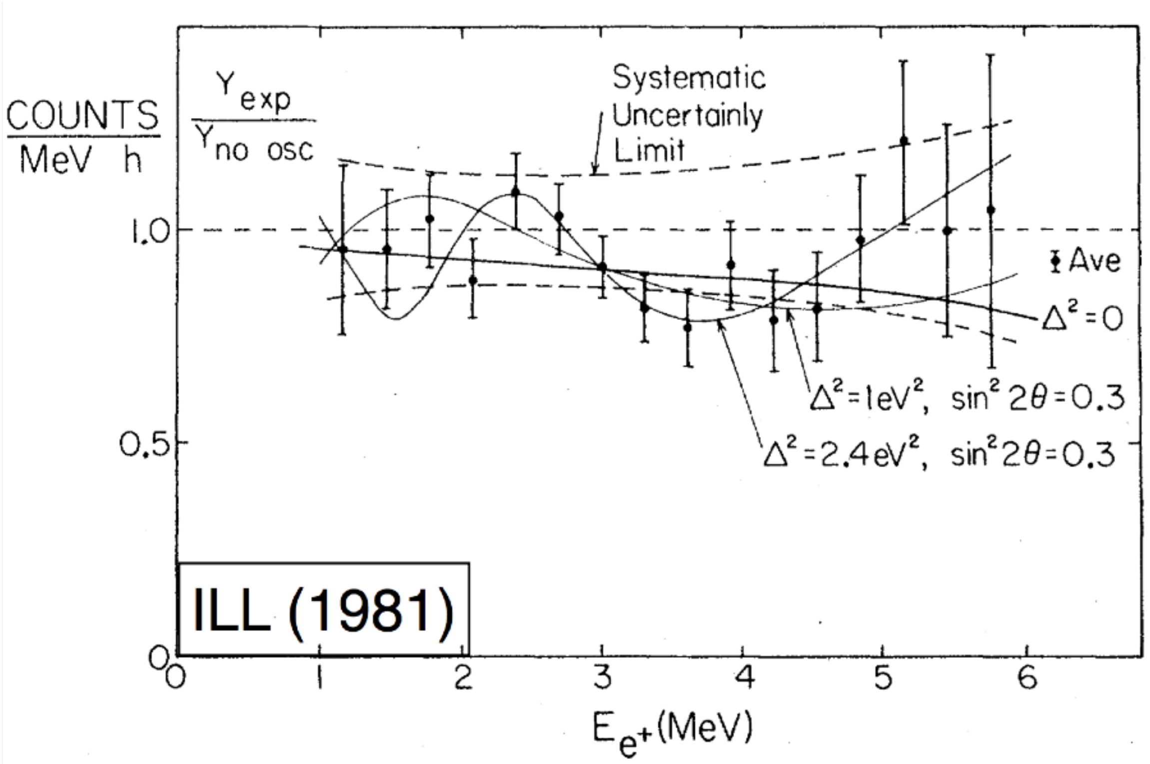


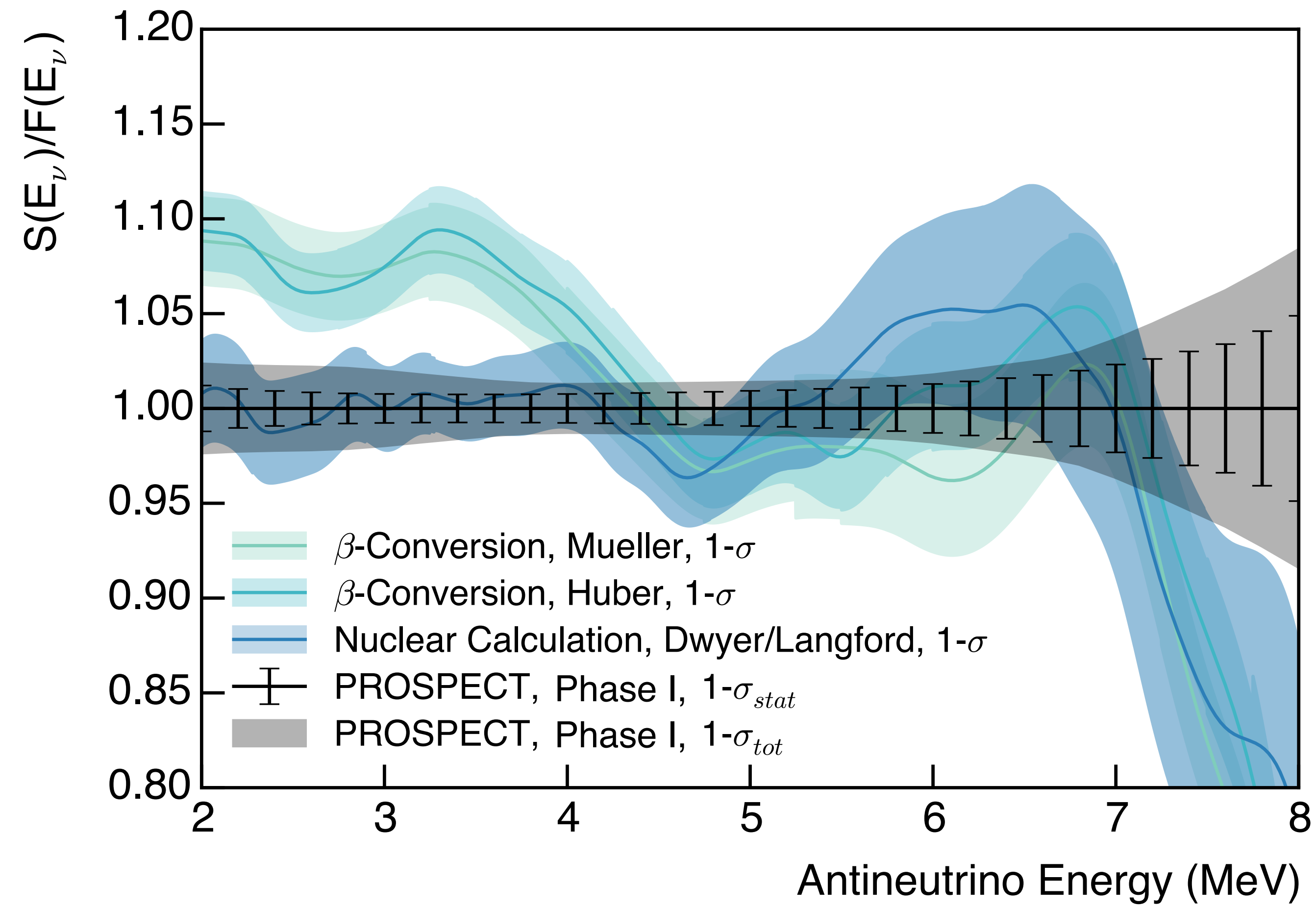


- Segmented detector designed for oscillation search
  - Each cell is a separate "detector"
  - Oscillatory L/E between segments limits uncertainties from reactor
- *True oscillometry needed for confirmation of sterile neutrinos*
- **Probe best-fit region at >3σ in 1 year**

^{235}U Spectrum Measurement

PROSPECT





Only existing HEU measurement is from ILL in 1981 (5k events total)

- Best energy resolution of any reactor neutrino experiment (4.5%@1MeV)
- **Precision will surpass spectral model uncertainties**
  - Directly test reactor neutrino models
  - Produce a benchmark spectrum for future reactor experiments

Assembly progress

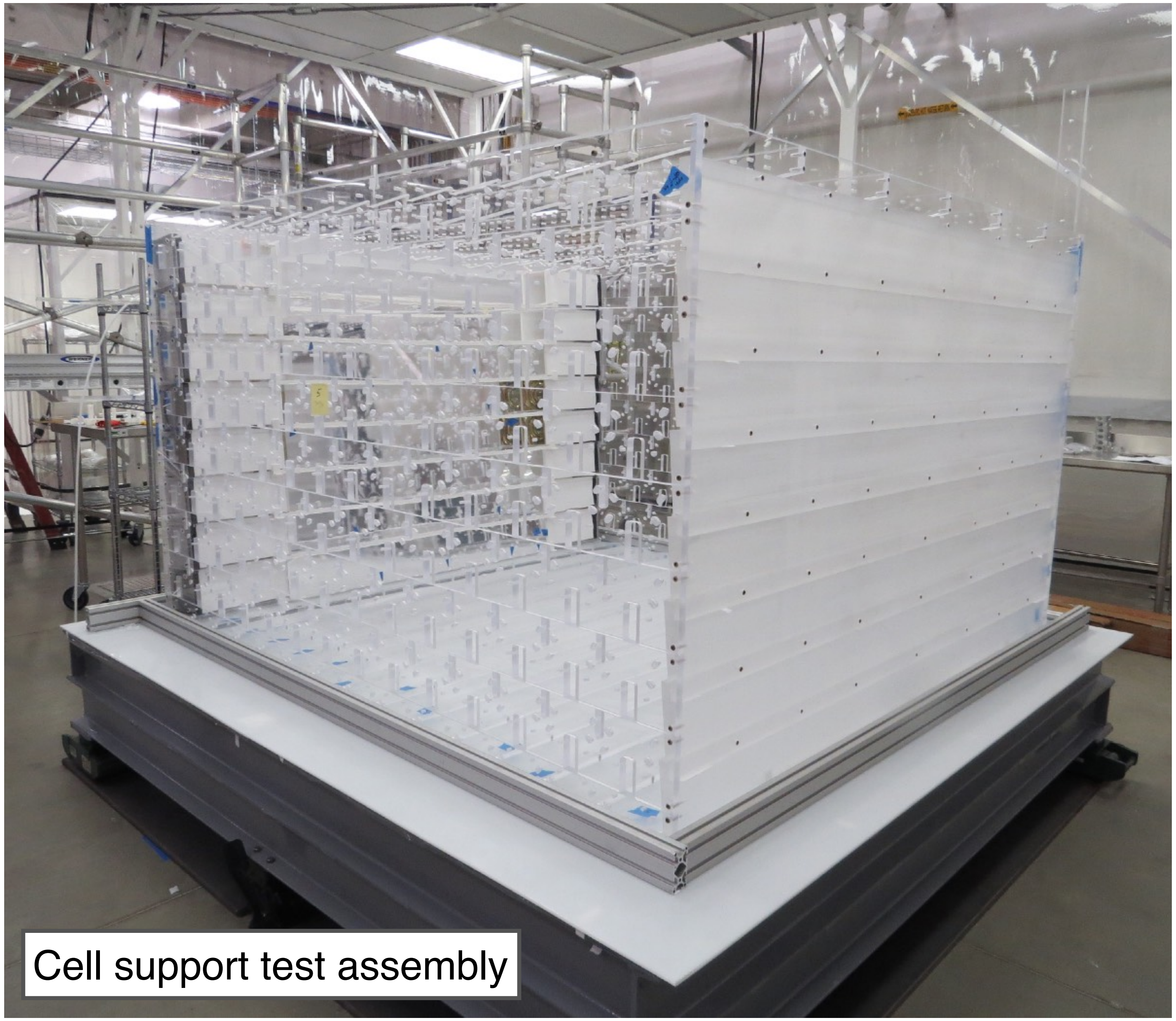
Production PMT housings

PMT dark box testing

Wright Laboratory

Assembly progress

Electronics testing



Cell support test assembly

Summary and Outlook

The reactor flux and spectrum shape anomalies remain unresolved after new TAS data and recent θ_{13} experiments

Many complementary experiments online or coming online soon. Precision data in the next couple of years. PROSPECT will be most sensitive and comprehensive short-baseline reactor experiment within this group.

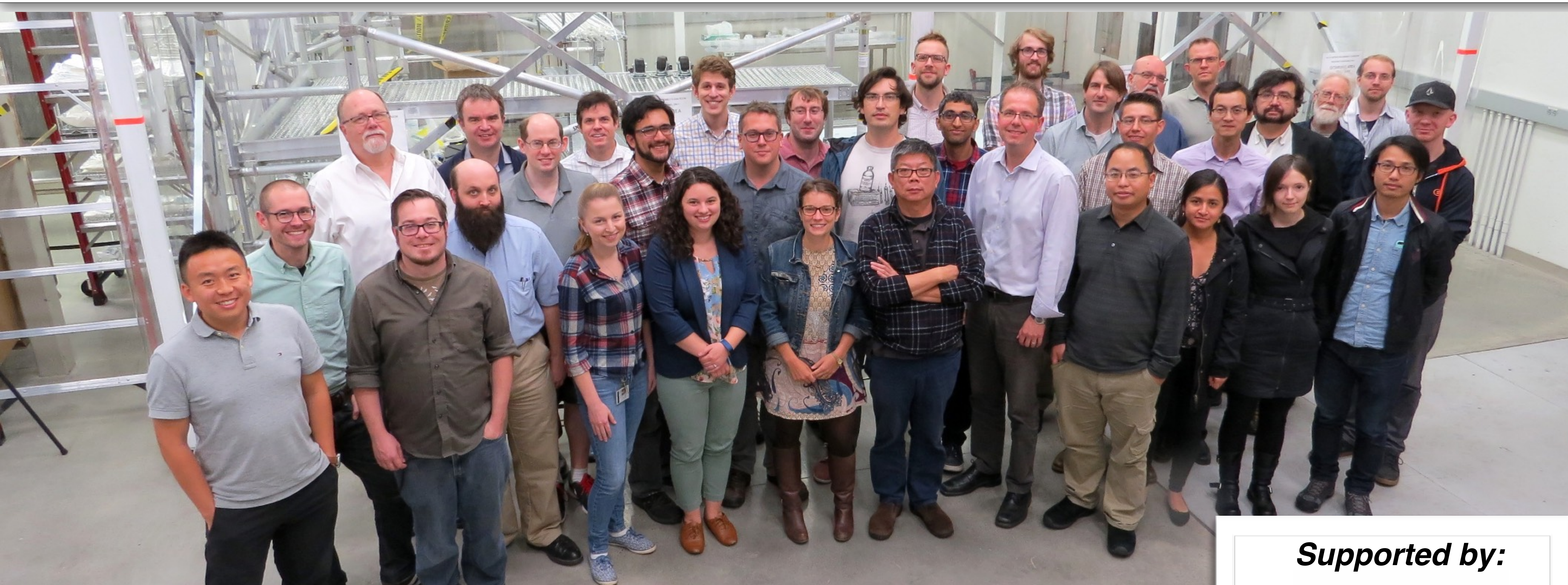
PROSPECT specifically will:

- **Measure the ^{235}U spectrum with the highest precision to date; complementary to LEU experiments**
- **Perform a model-independent sterile oscillation search, covering the current best fit at > 4σ within three years.**

All performance metrics have been demonstrated, nearing completion of detector assembly, early data in 2018.

http://prospect.yale.edu

PROSPECT



NIST
BROOKHAVEN NATIONAL LABORATORY
Lawrence Livermore National Laboratory
Oak Ridge National Laboratory
Illinois Institute of Technology
W&M
Yale
Drexel
Le Moyne College A·D·1946
University of Waterloo Concordia cum Veritate
GT

4 national laboratories
10 universities
68 collaborators

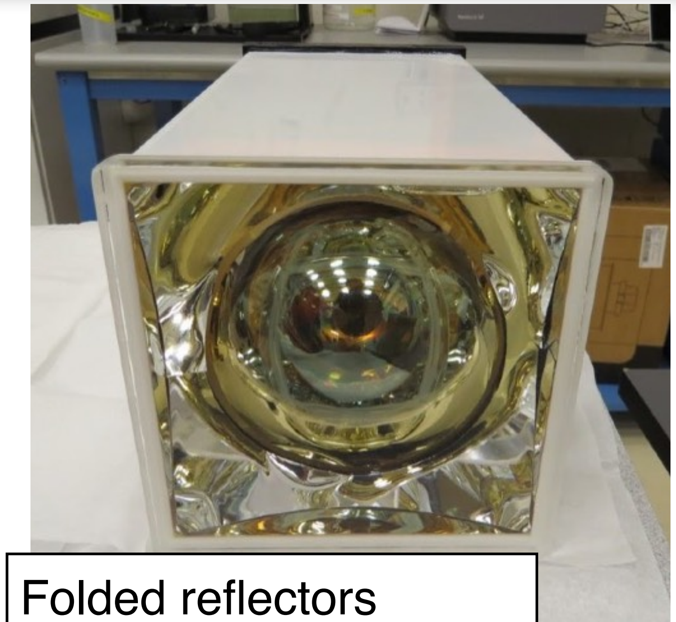
Publications:
arXiv:1309.7647,
NIM A806 (2016) 401,
JINST 10 (2015) P11004,
Journal of Phys. G 43 (2016) 11

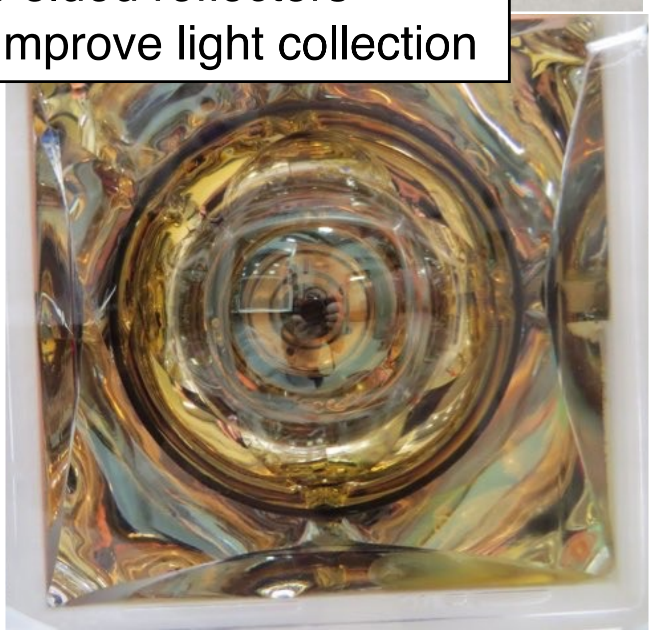
Supported by:

Heising-Simons Foundation
Department of Energy United States of America

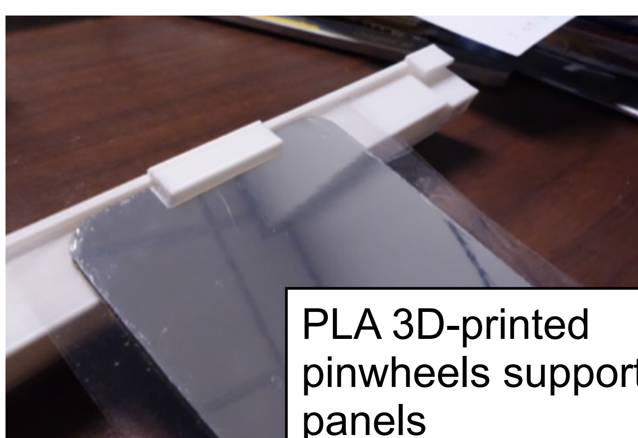
Backup

PROSPECT design



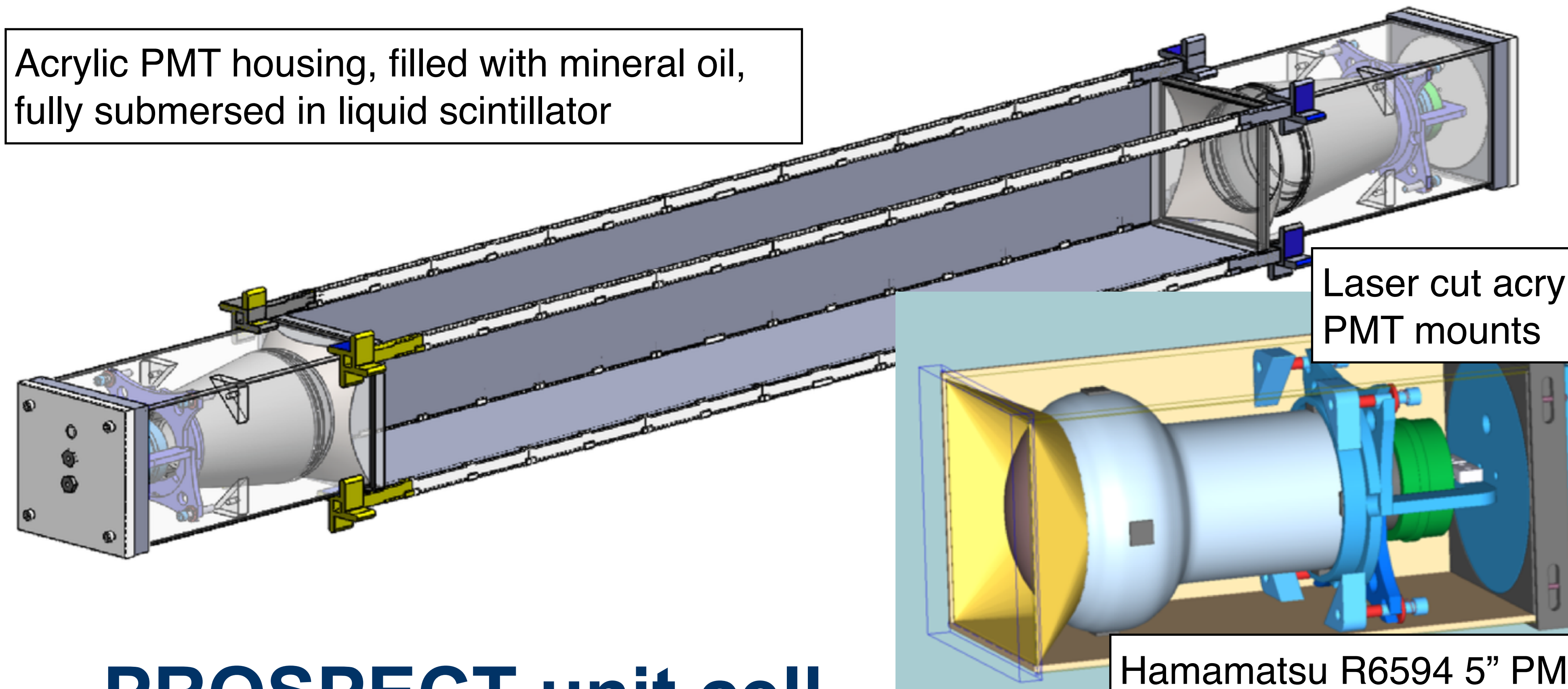


Folded reflectors improve light collection



PLA 3D-printed pinwheels support panels

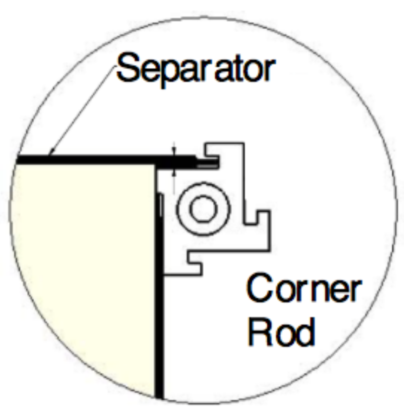
Acrylic PMT housing, filled with mineral oil, fully submersed in liquid scintillator

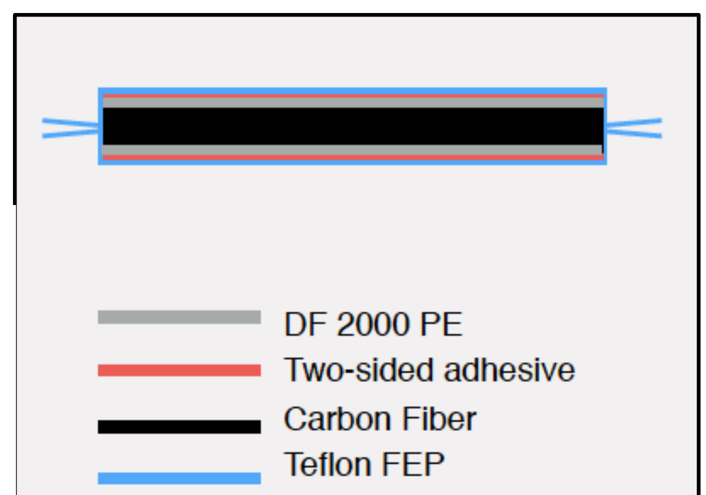


Laser cut acrylic PMT mounts

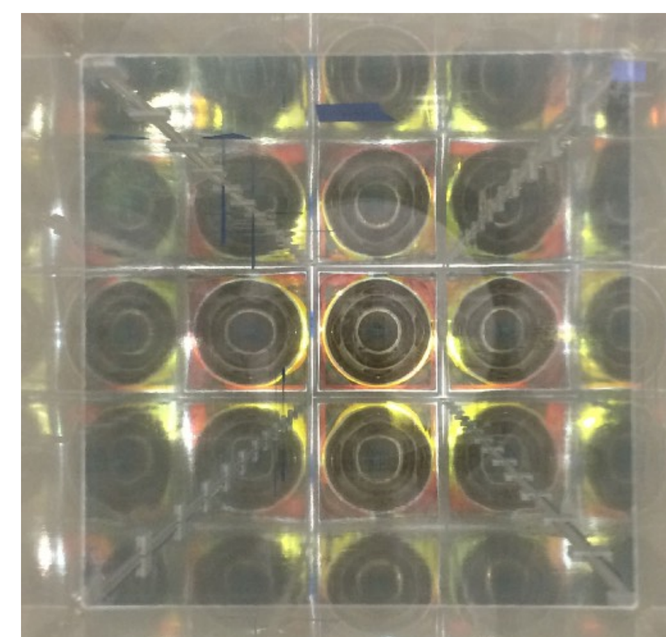
Hamamatsu R6594 5” PMT (outer layer 5” ET PMTs)

PROSPECT unit cell

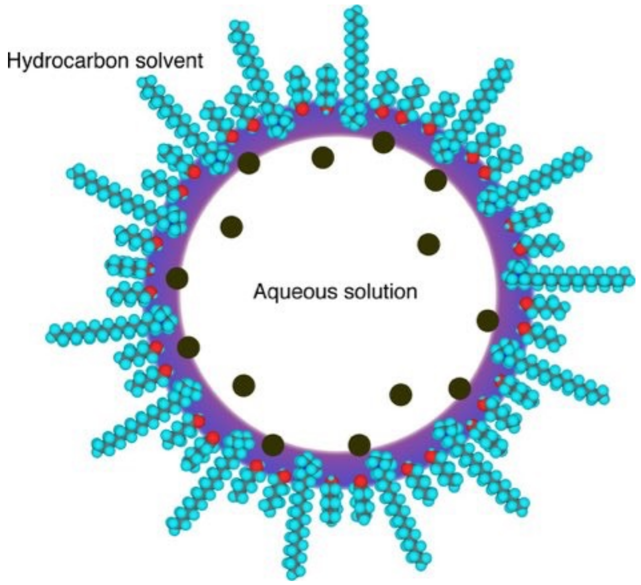




High reflectivity, high rigidity, low mass reflector system developed



Lithium-6 Loaded Liquid Scintillator

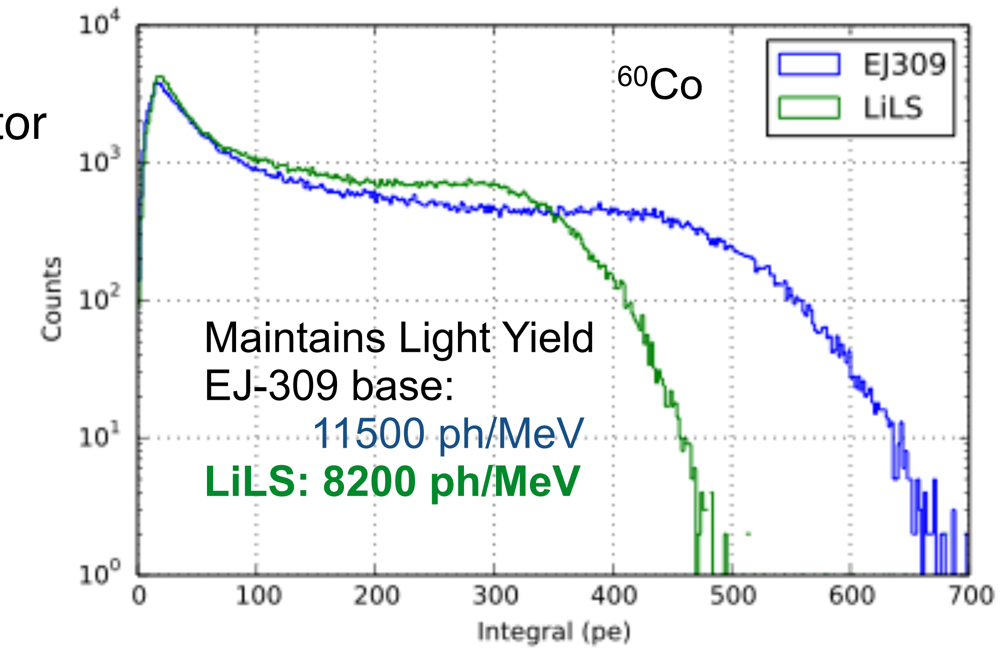


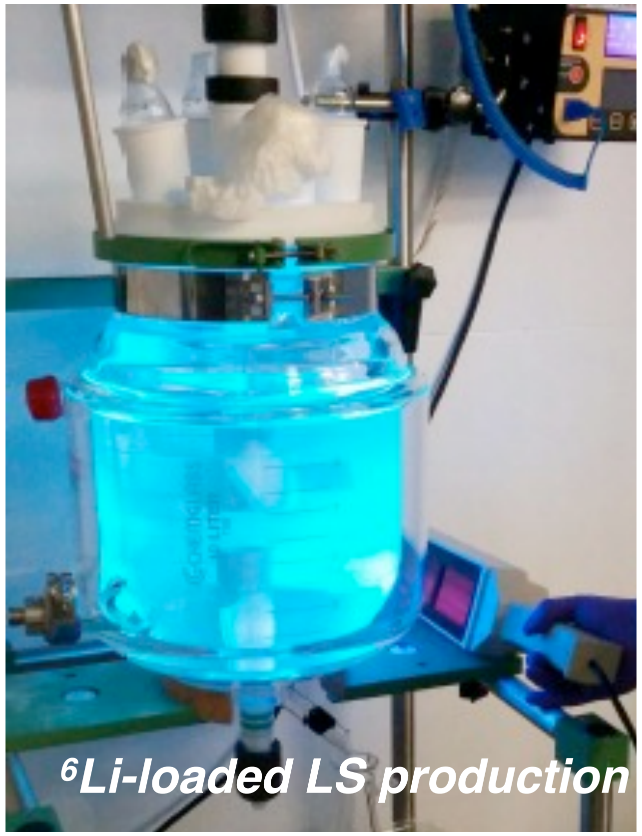
^{6}Li loading via Reverse Micelles:

- Surfactants added to base liquid scintillator
- Dynamically stable
- relatively high loading possible > 0.1%
- tolerable reduction in light yield
- tolerable reduction of PSD performance

Aqueous phase: 10 M enriched (95%) LiCl

- enriched Li_2CO_3 disolved in HCl
- Purified via anion exchange resin



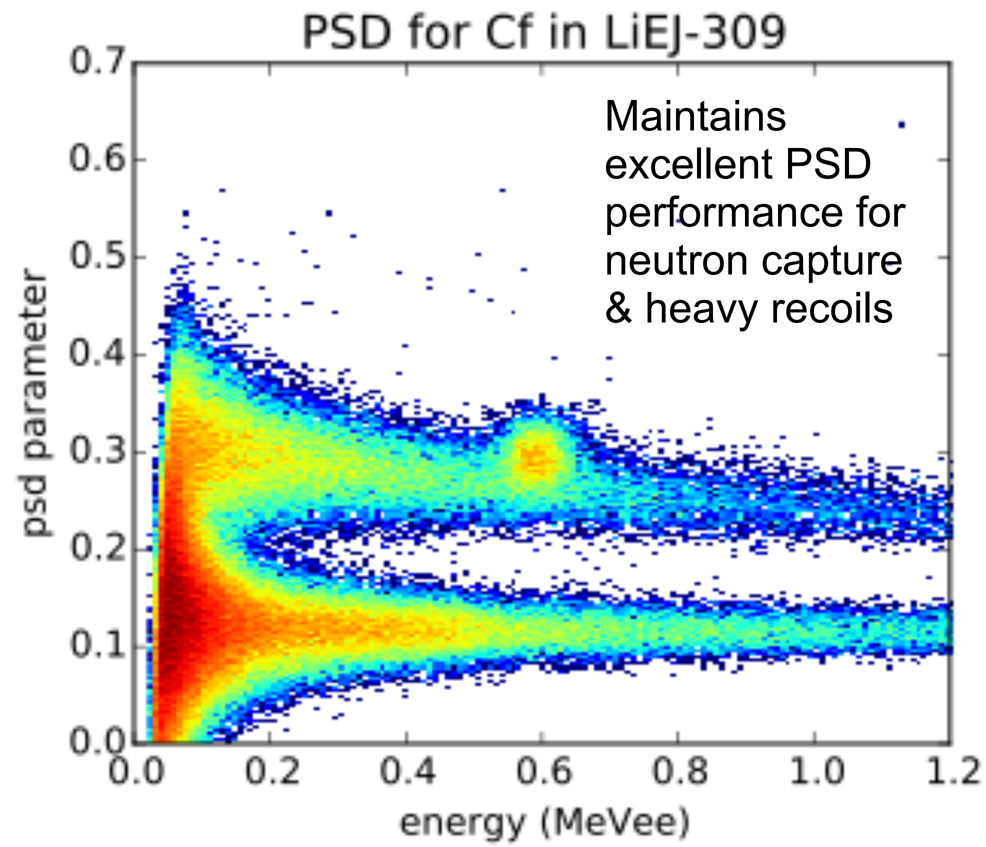


Safe, affordable:
Several non-toxic, non-flammable formulations based on EJ-309, LAB, Ultima Gold tested

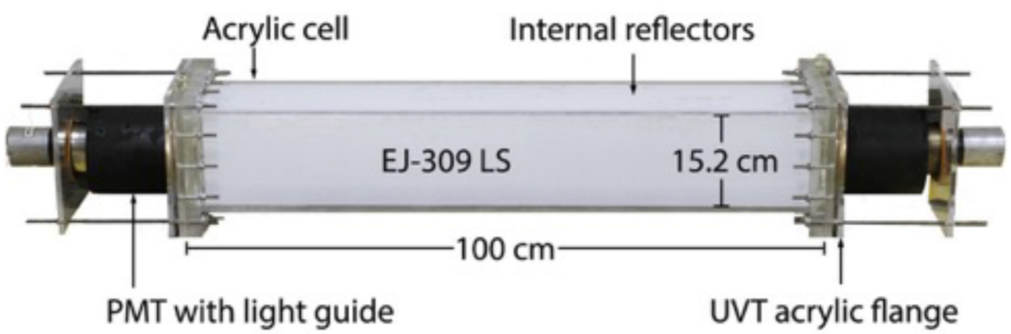
EJ-309 selected as baseline
Diisopropylnaphthalene (DIPN) base
Non-ionic surfactant

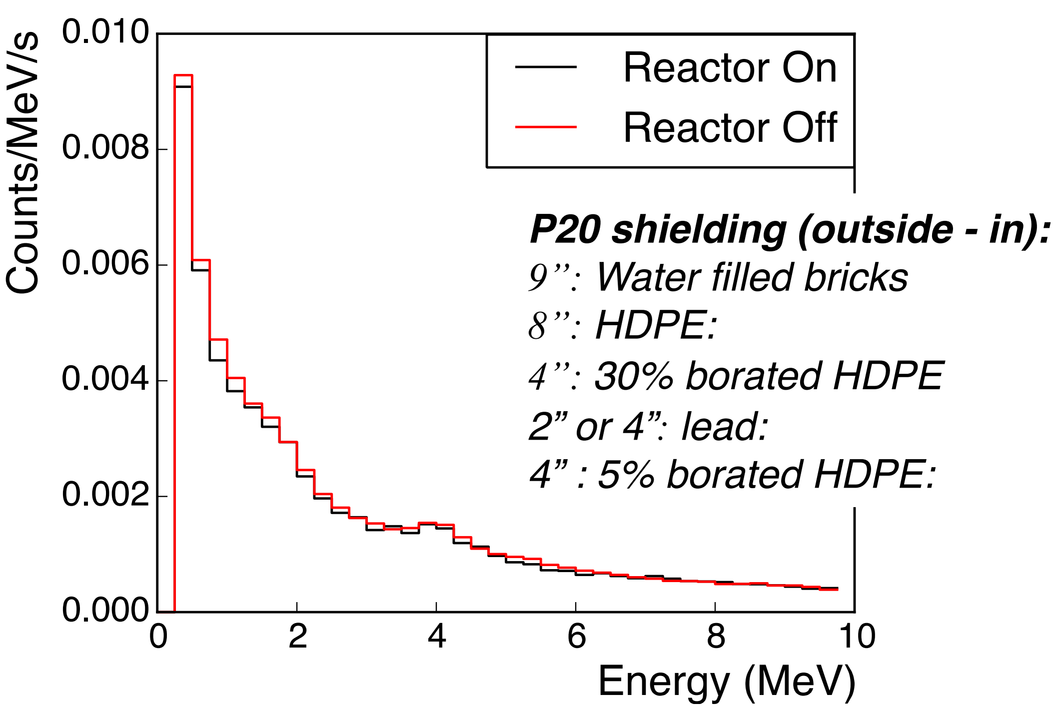
Pure samples of LS have stable performance over year timescales

Extensive material compatibility program; production materials validated

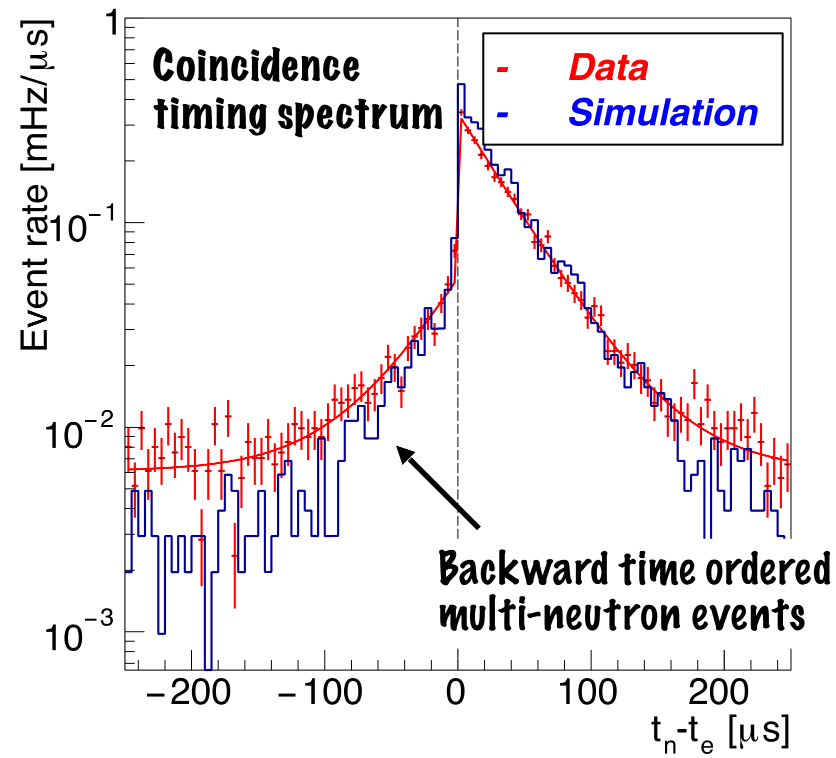


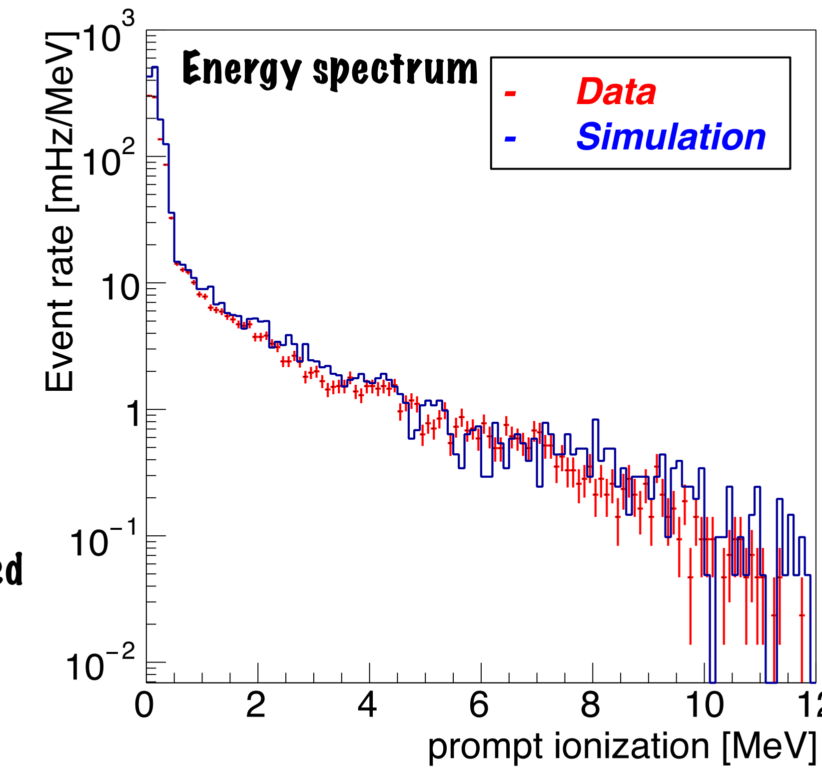
PROSPECT-20: *in situ* validation of background models





Inverse Beta Decay-like neutron coincident events

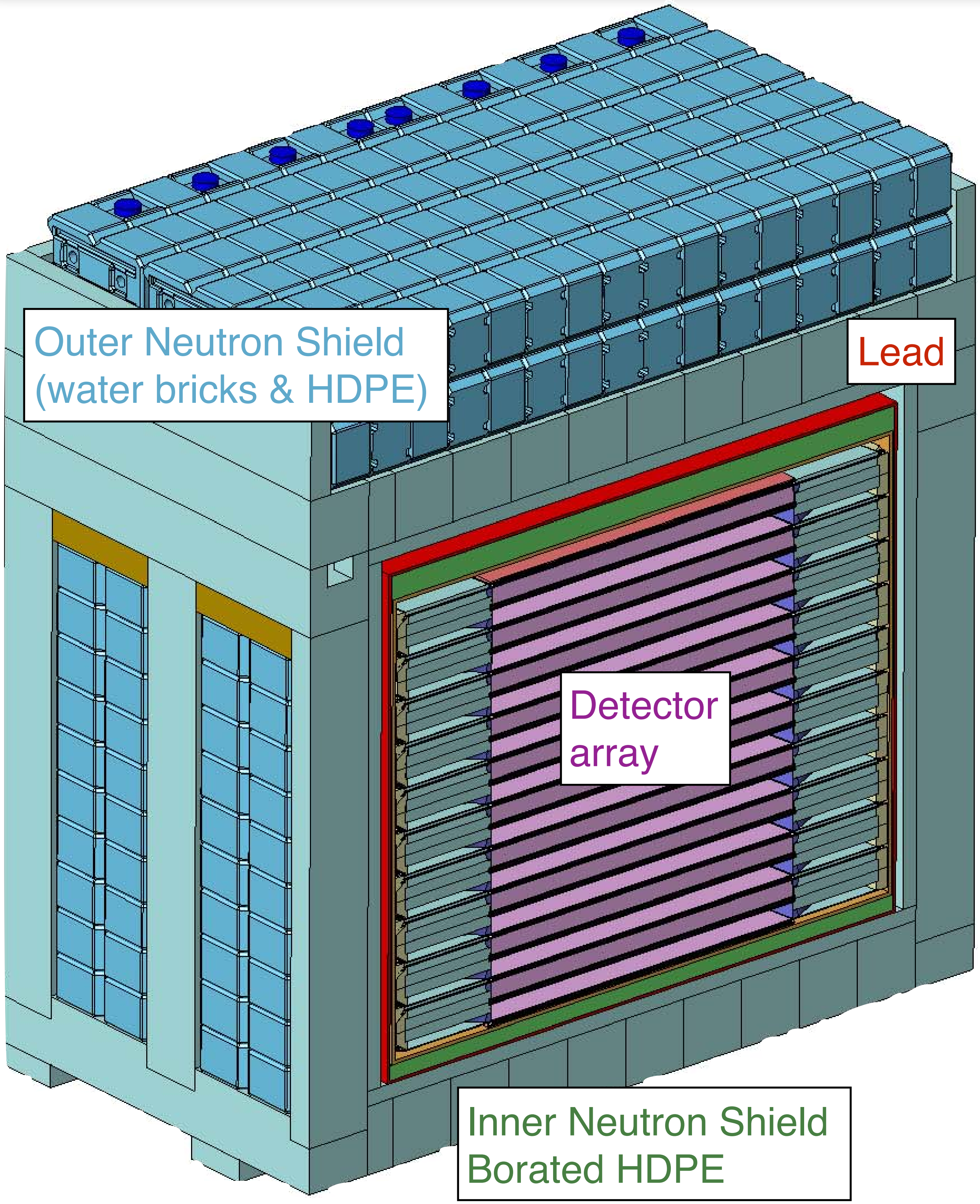


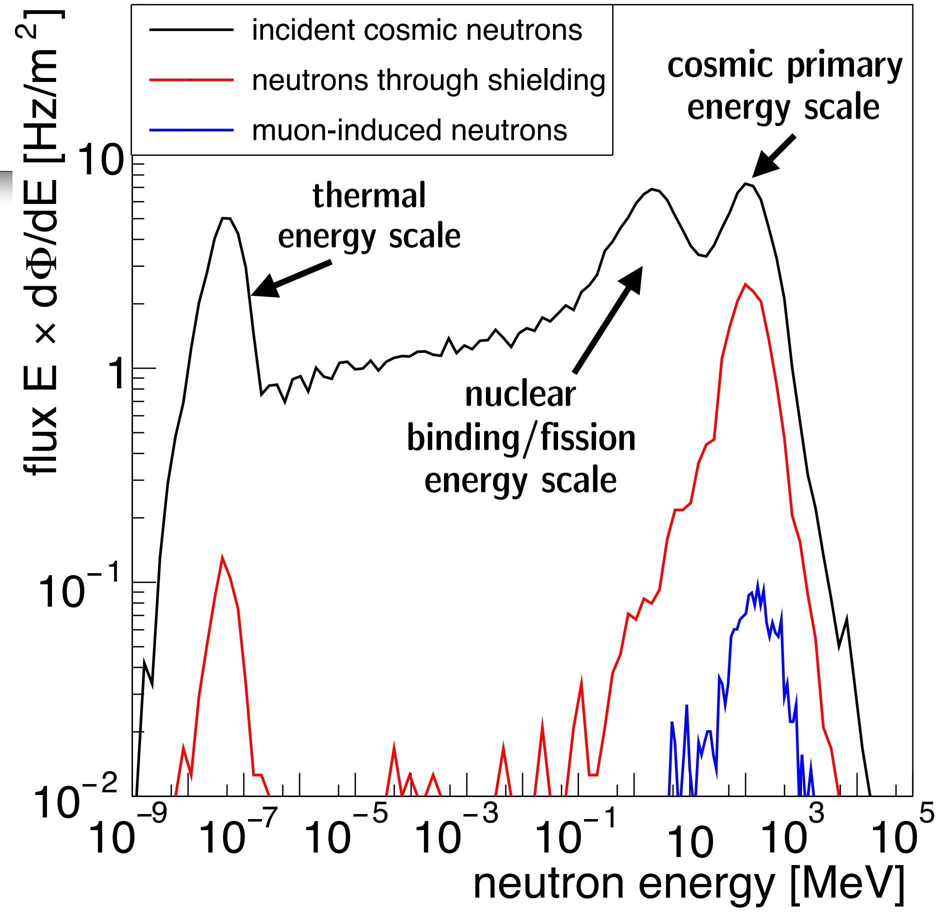


Background models validated in situ by a series of prototypes in both laboratory and reactor settings

- **Shielding package roughly 25% of full PROSPECT shielding**
- **Operated 4 months at HIFR (two reactor on cycles)**
- **Monte Carlo performs well (with minimal adjustments to overburden and capture time) - validates full PROSPECT simulation**
- **Control of Reactor-correlated backgrounds**

PROSPECT shielding

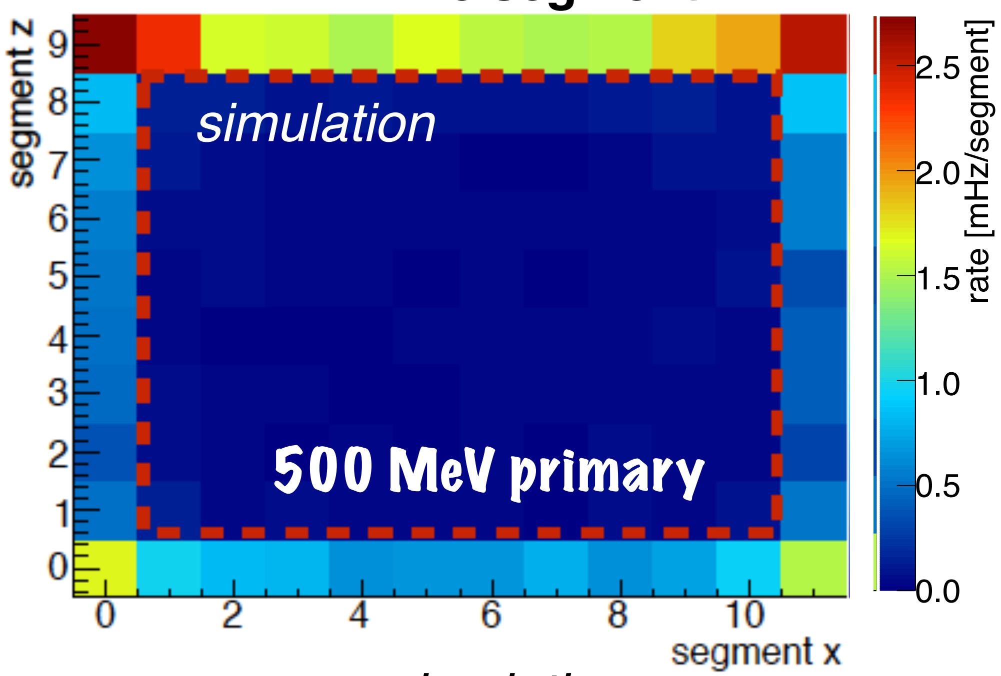




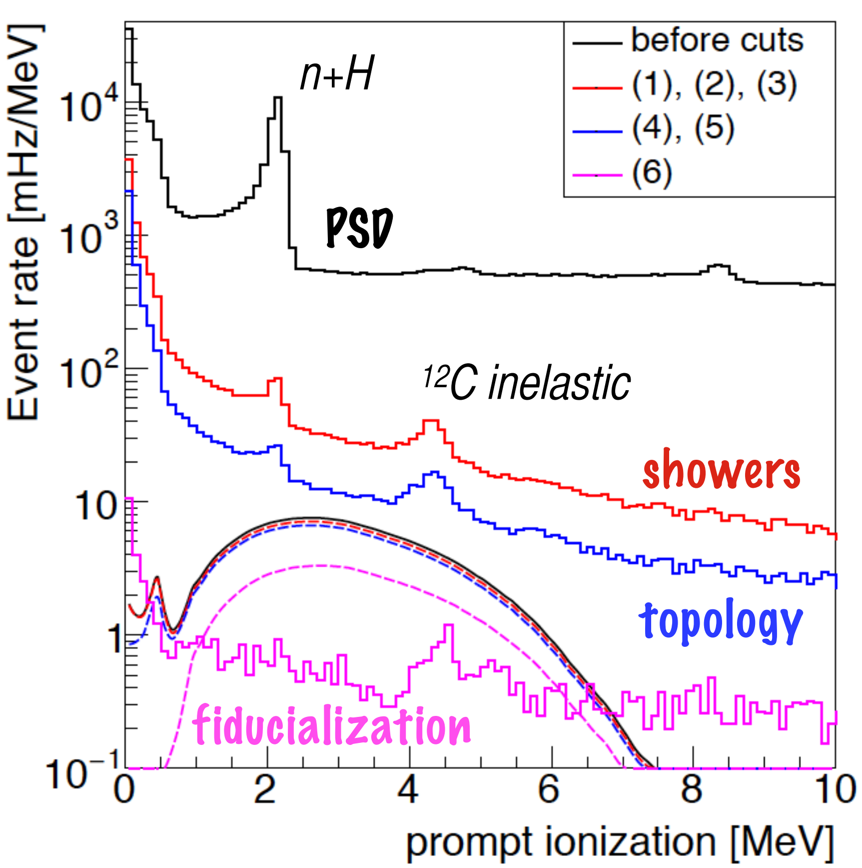
- <10s MeV neutrons removed by feasible shielding.
- Remaining IBD-like background events are primarily generated by >100 MeV cosmogenic neutrons
- Must be concerned with the production of secondaries
- Motivates a layered approach
- But optimized by tight weight and space constraints

Inner detector: 30,000 lbs, total movable package: 76,000 lbs

Fiducialization, PSD, and topology (Full PROSPECT)



simulation



Studies of Pulse Shape Discrimination (PSD) and topology suggest excellent signal to background and lessons for other detectors

Spatial topology:

- prompt and delayed signals proximate;
- multiple cell hits in the prompt signal must be compact (e.g. rejecting extended minimum ionizing tracks)
- events occurring outside the inner fiducial volume are vetoed (partial energy deposition reduces BG rejection).

Timing:

- delayed capture must occur within 100 μs of the prompt ionization (set by ~40 μs neutron capture time)
- multiple hits in the prompt cluster must occur within 5 ns (reject slower-moving neutron recoil events)
- events must be isolated from other neutron recoils or captures in a ±250 μs window, (reject multi-neutron spallation showers)

No single cut isolates IBD events, yet sequence of cuts leveraging spatial and timing characteristics of an IBD *yields > 3 orders of magnitude background suppression and an expected signal to background of > 1:1.*

Rate and shape of residual IBD-like background can be measured during multiple interlaced reactor-off periods.

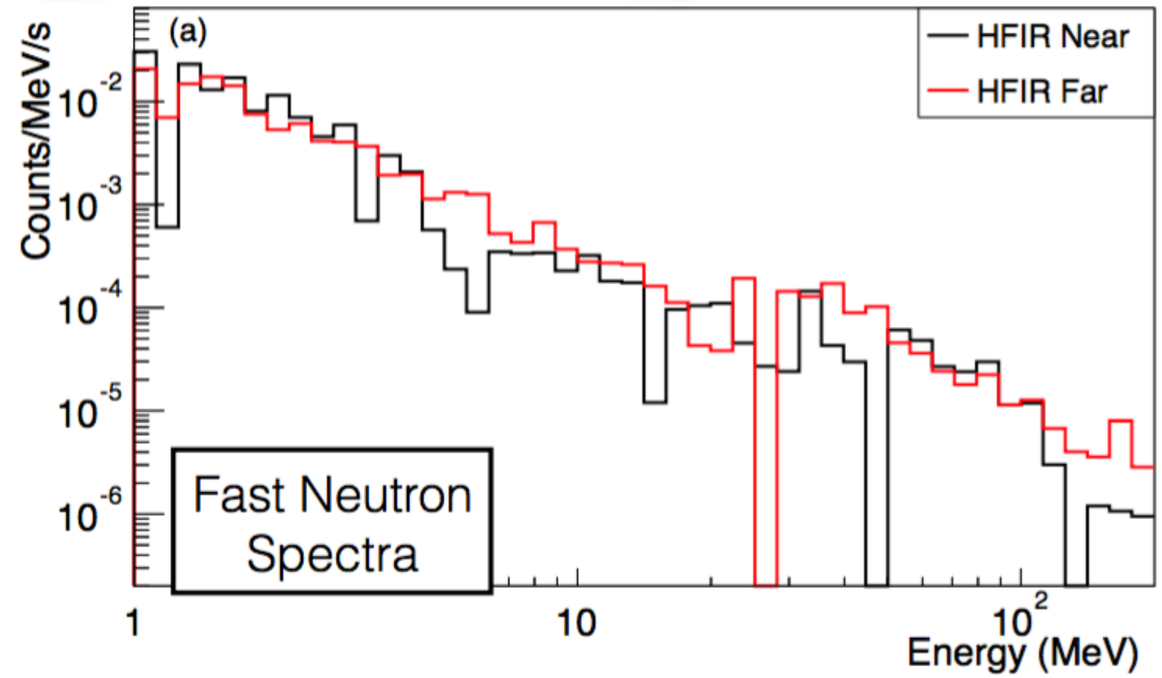
Background Characterization

- Minimal overburden: cosmogenic backgrounds
- Close proximity to reactor and other systems
- Background control challenging

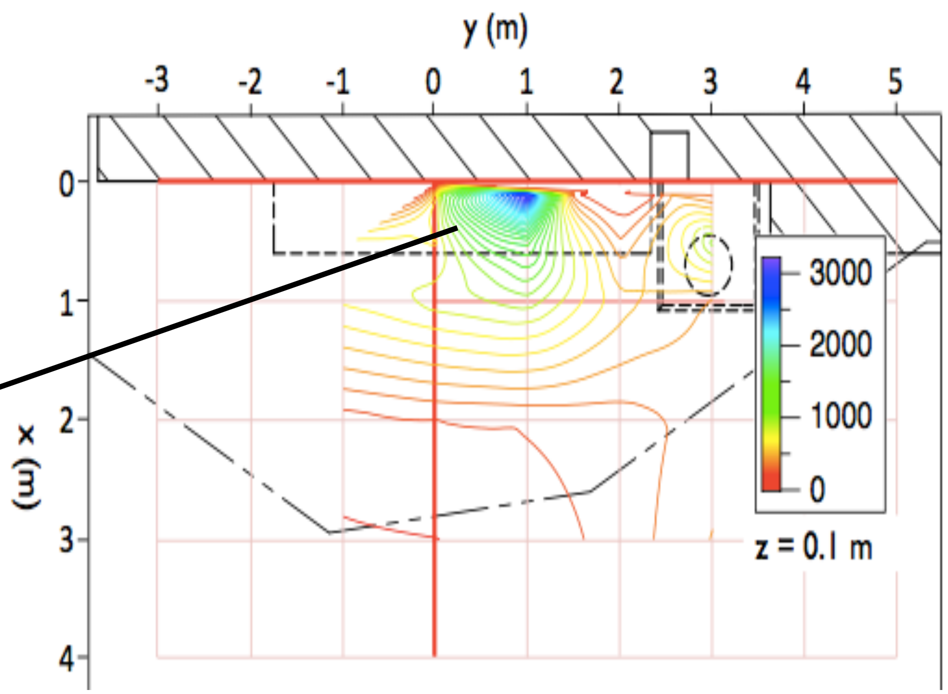
Gamma, Thermal and Fast Neutron, Muons

Extensive measurement campaigns (*ongoing*):

- Characterize background fields at HFIR
- Emphasized importance of localized shielding of penetrations, pipes, etc

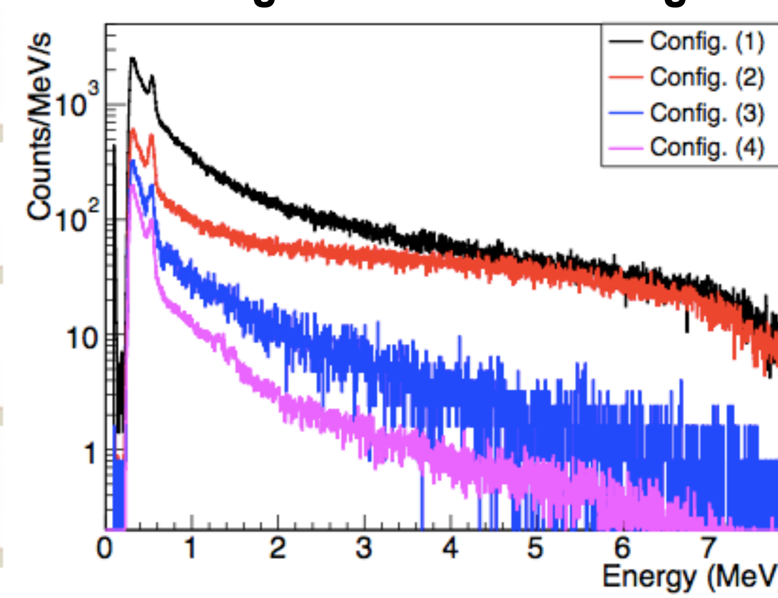


Hots spots from beam penetrations to core



γ-ray intensity variations

Targeted local Shielding

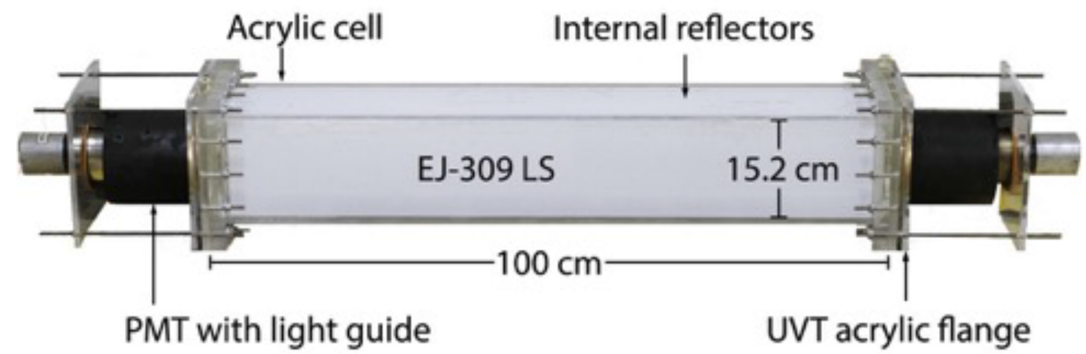


Nucl. Instrum. Meth. A806 (2016) 401–419, arXiv:1506.03547, PROSPECT Collaboration

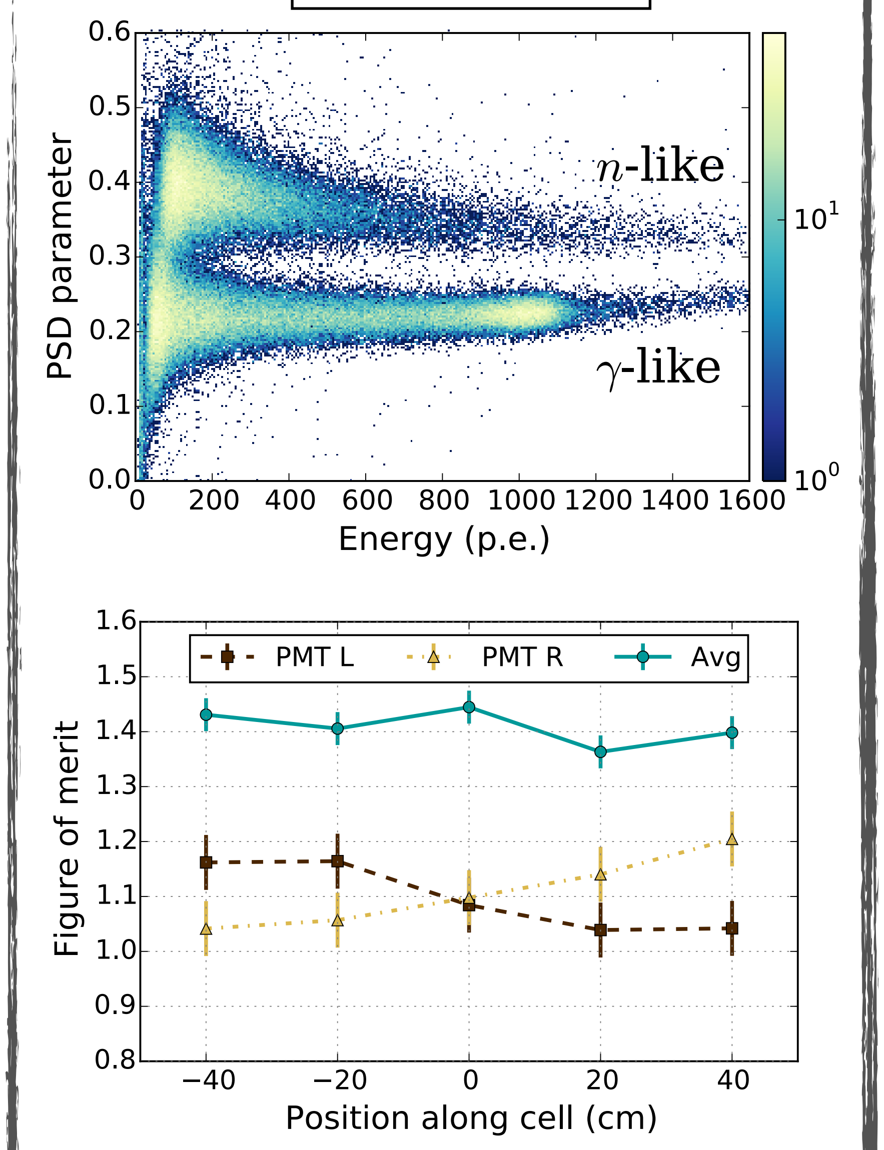
PROSPECT-20: validation performance

Representative aspect ratio & ability to reconfigure:

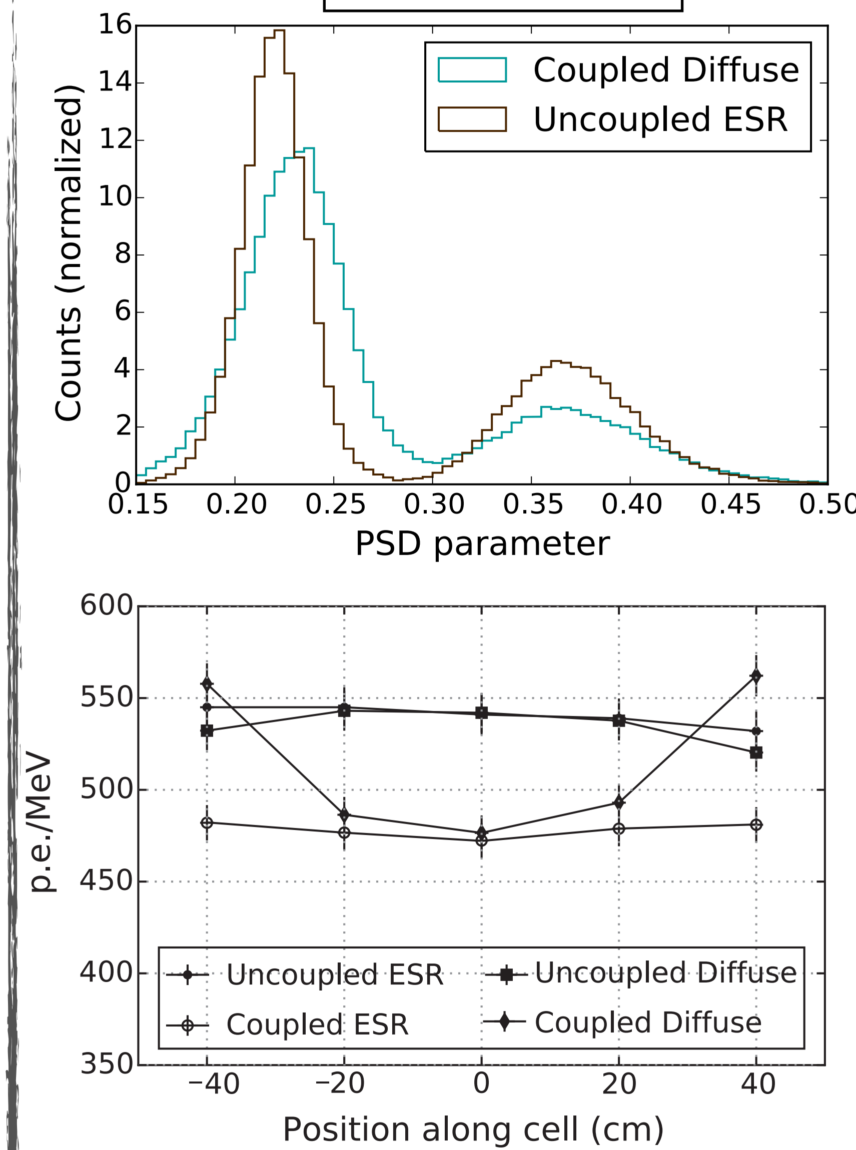
- Internal vs external reflectors, reflector coupling (TIR or not)
- Test light collection, PSD performance in an elongated geometry



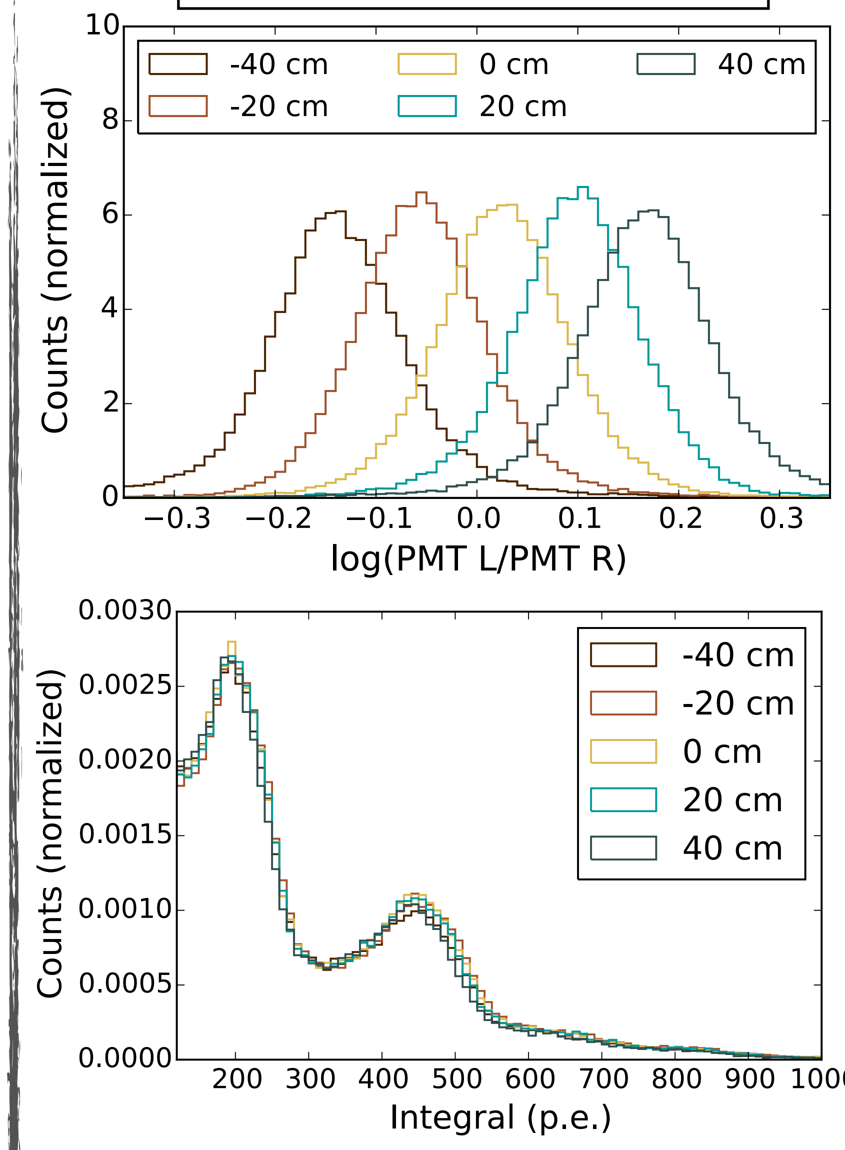
PSD by PMT



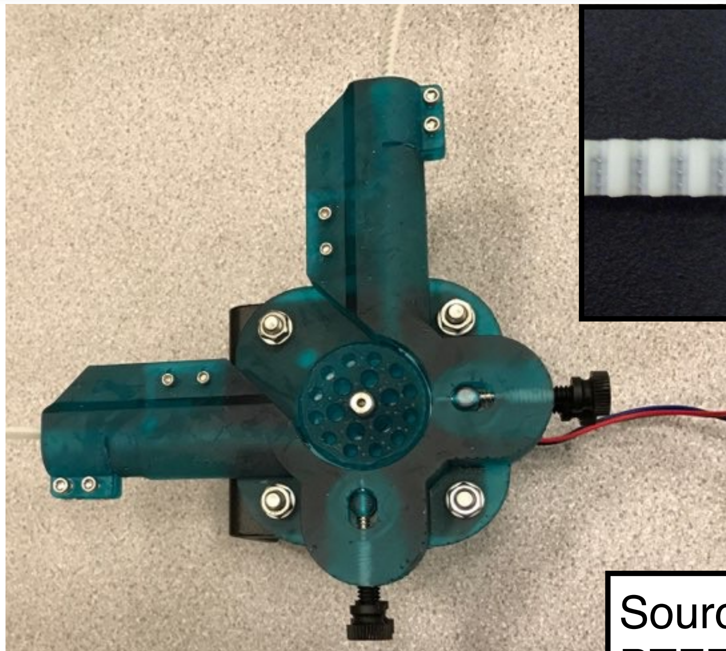
PSD along axis

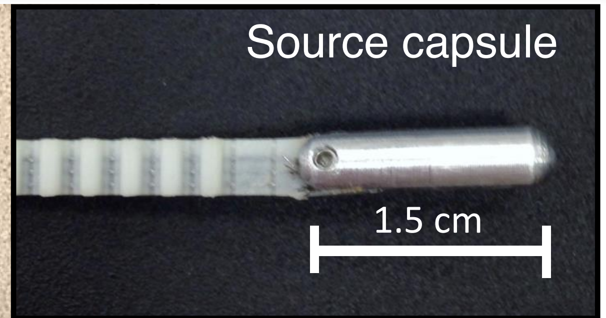


Reconstruction along axis

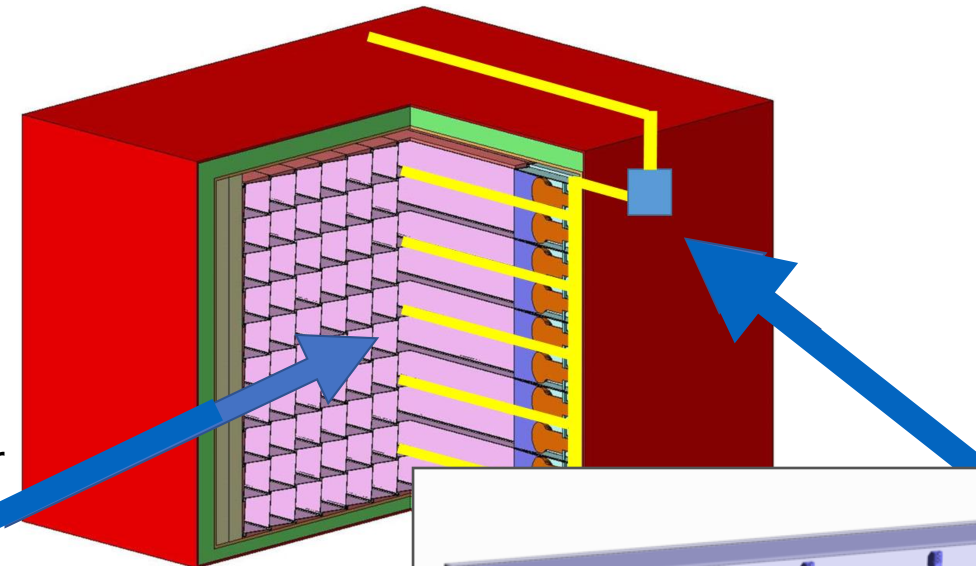


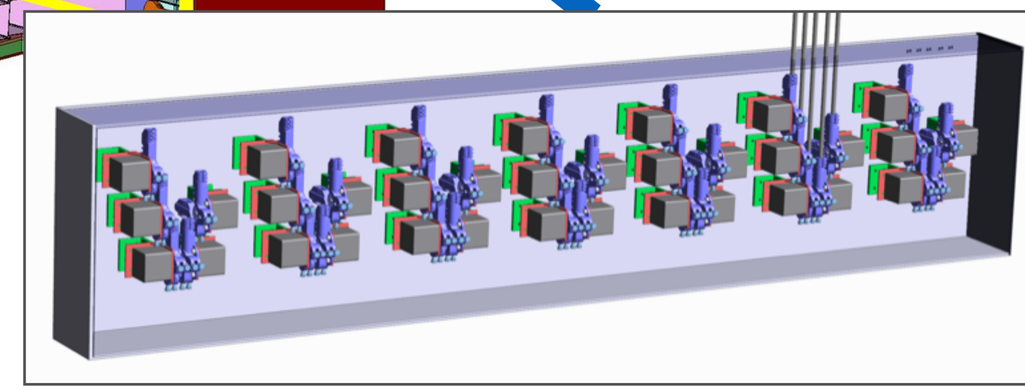
Calibration system



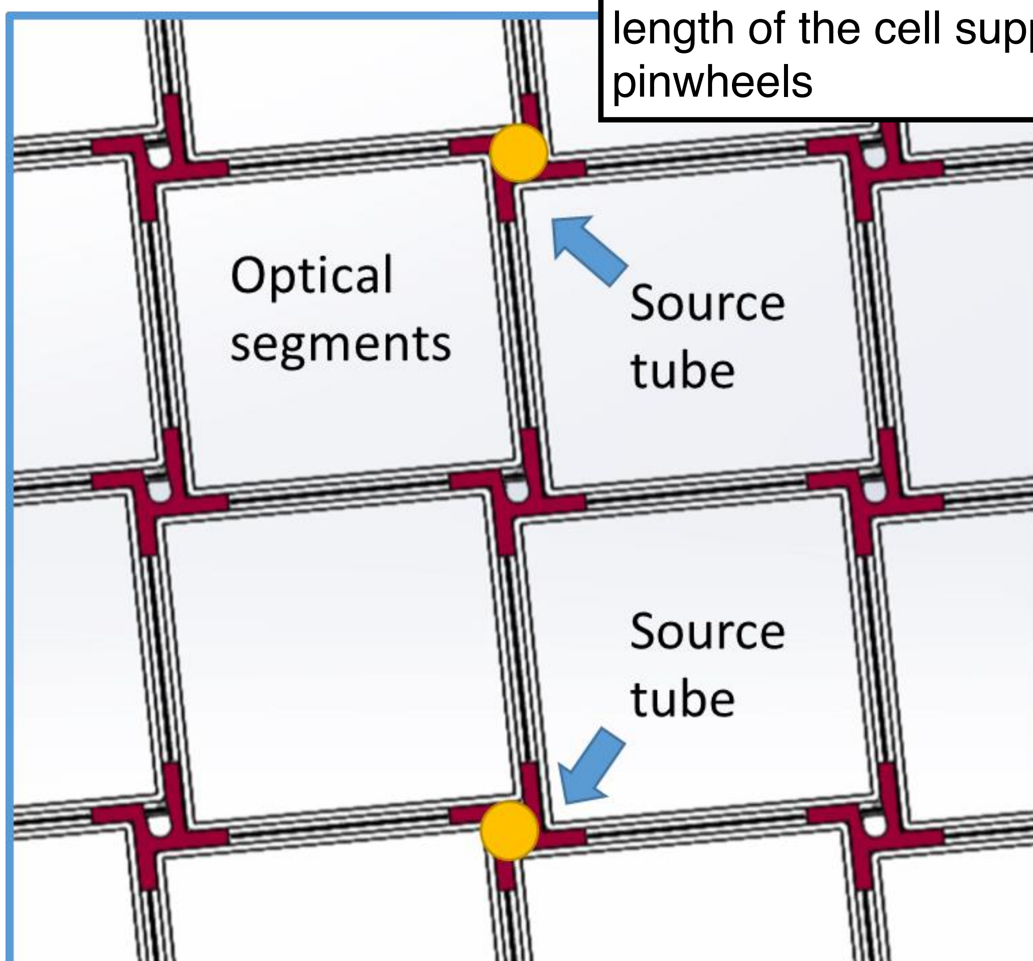


3D printed belt drive system reproducibly positions sources to ~mm





Sources positioned along PTFE tubes running the length of the cell support pinwheels



Each cell within 2 cells of a source tube

encapsulated gamma sources

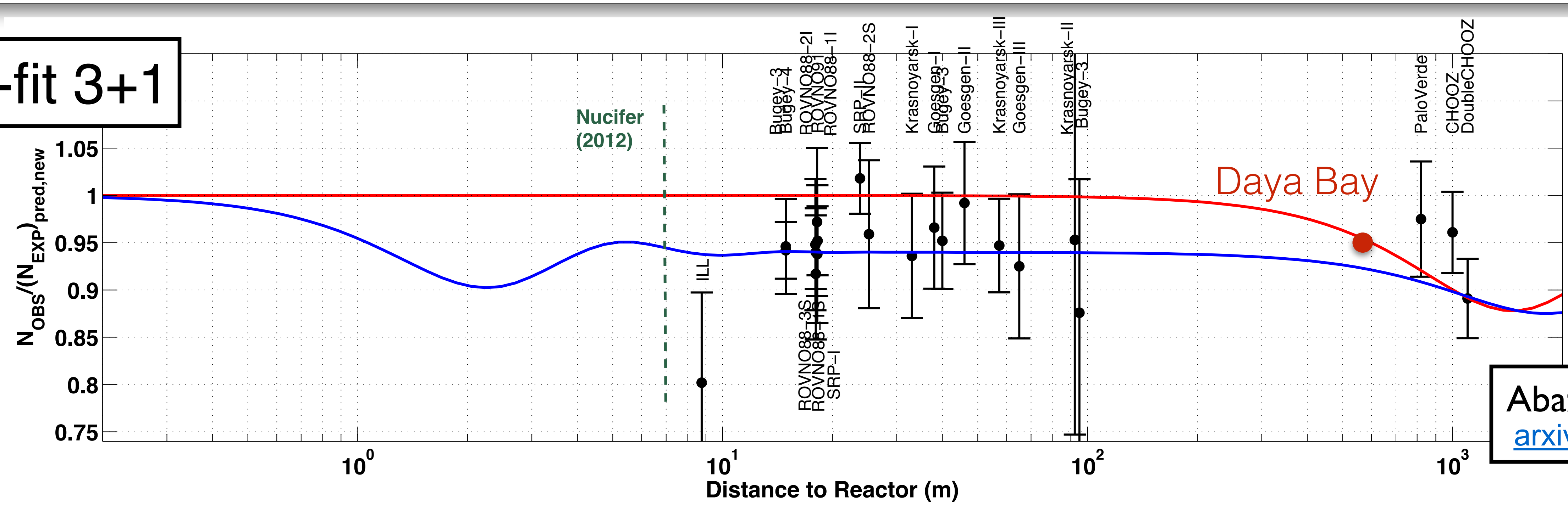
- LiLS linearity/response
- energy scale

Neutron sources

- neutron detection efficiency
- PSD studies

Rate anomaly

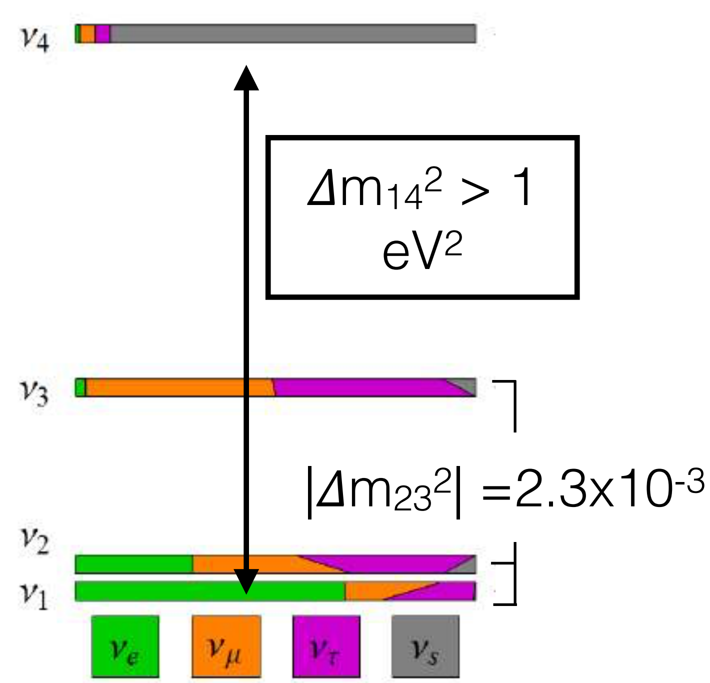
Best-fit 3+1



Abazajian et al.
arxiv:1204.5379

2011 dual ν_e flux predictions:
- re-analysis of 19 short-baseline expts.
- new antineutrino spectra: +3%
- neutron lifetime correction: +1%
- off-equilibrium effects: +1%

Error budget dominated by flux prediction



If not a bias effect, what is it?

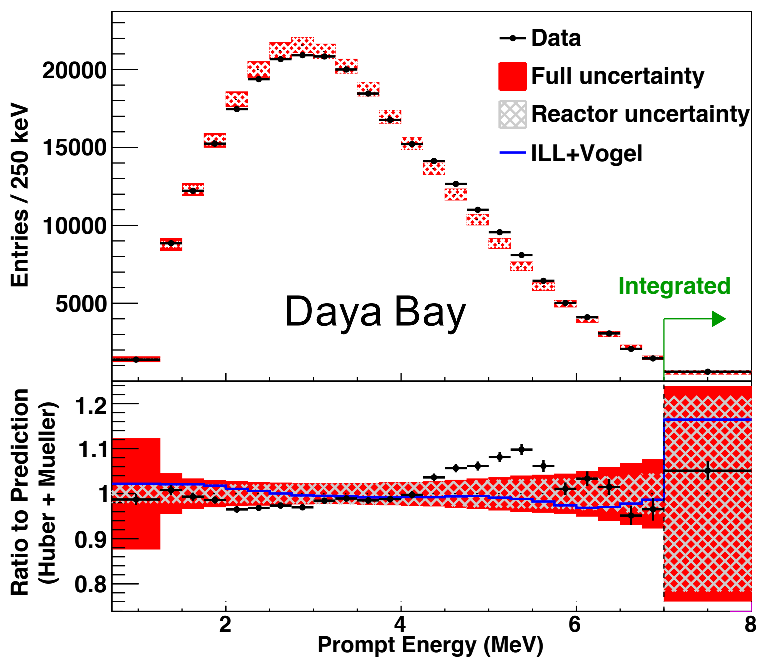
- Problem with prediction?
- Detector effect that isn't understood?
- *New physics?*

Sterile Neutrino:

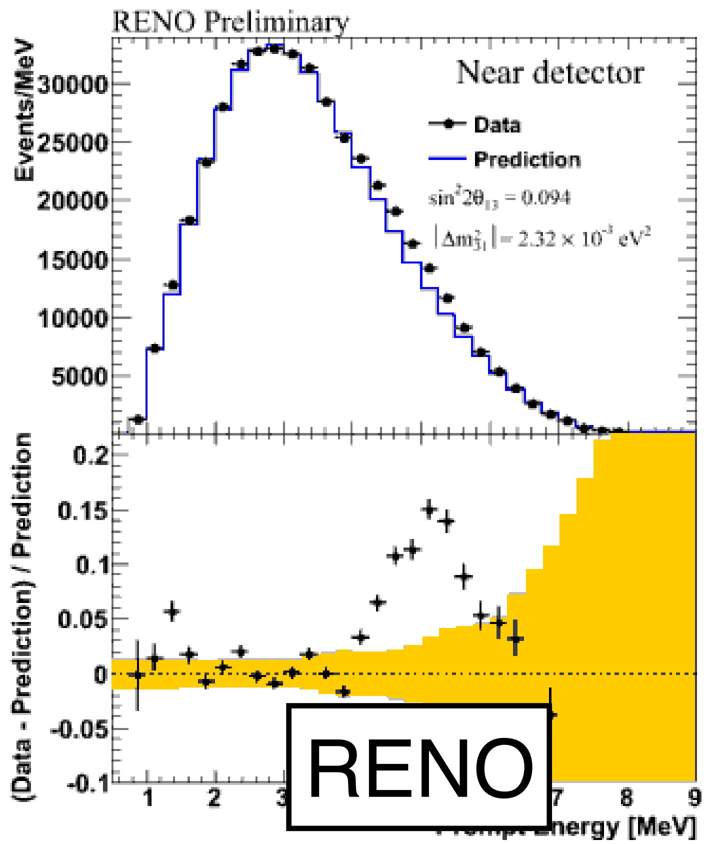
- High frequency oscillation
- Mass splitting ~1eV^2
- Baseline ~few meters

Spectral Anomoly

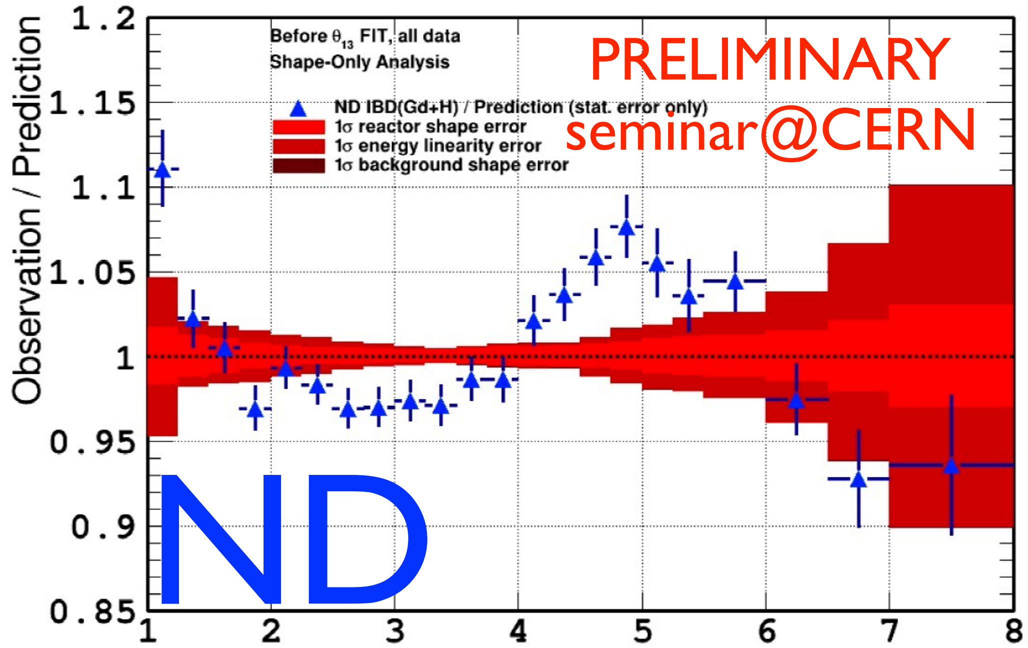
Unexpected 'bump' in *power* reactor (LEU) spectrum



Daya Bay



RENO



Double Chooz

Predictions based on beta-conversion (Huber, Mueller, Haag)

Matches all characteristics of IBD events

Excess tracks with reactor power (i.e. reactor source), Observed at all baselines

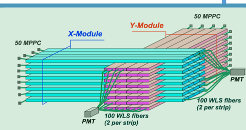
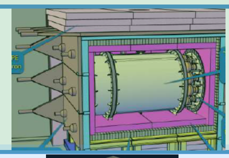
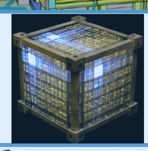
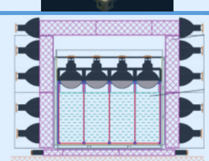
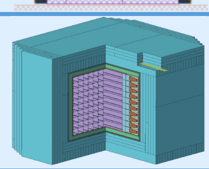
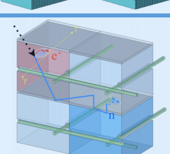
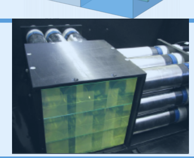
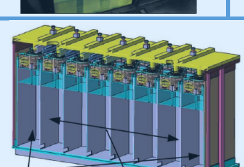
Motivates additional experiments with other reactor/fuel types, and excellent energy resolution

Focusing on Reactor anomalies

Considerable international interest:

Diverse techniques (background suppression, detection technology, location)

Overlapping sensitivities

Experiment	Reactor Power/Fuel	Overburden (mwe)	Detection Material	Segmentation	Optical Readout	Particle ID Capability
DANSS (Russia) 	3000 MW LEU fuel	~50	Inhomogeneous PS & Gd sheets	2D, ~5mm	WLS fibers.	Topology only
NEOS (South Korea) 	2800 MW LEU fuel	~20	Homogeneous Gd-doped LS	none	Direct double ended PMT	recoil PSD only
nuLat (USA) 	40 MW ^{235}U fuel	few	Homogeneous ^{6}Li doped PS	Quasi-3D, 5cm, 3-axis Opt. Latt	Direct PMT	Topology, recoil & capture PSD
Neutrino4 (Russia) 	100 MW ^{235}U fuel	~10	Homogeneous Gd-doped LS	2D, ~10cm	Direct single ended PMT	Topology only
PROSPECT (USA) 	85 MW ^{235}U fuel	few	Homogeneous ^{6}Li-doped LS	2D, 15cm	Direct double ended PMT	Topology, recoil & capture PSD
SoLid (UK Fr Bel US) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm multiplex	WLS fibers	topology, capture PSD
Chandler (USA) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm, 2-axis Opt. Latt	Direct PMT/ WLS Scint.	topology, capture PSD
Stereo (France) 	57 MW ^{235}U fuel	~15	Homogeneous Gd-doped LS	1D, 25cm	Direct single ended PMT	recoil PSD

From N. Bowden, Neutrino 2016