Yale

Wright Laboratory

Neutrinos
Dark Matter
Nuclear Structure
Relativistic Heavy Ions

Timing Requirements for IBD Detectors

TJ Langford
Yale University
December 15, 2015

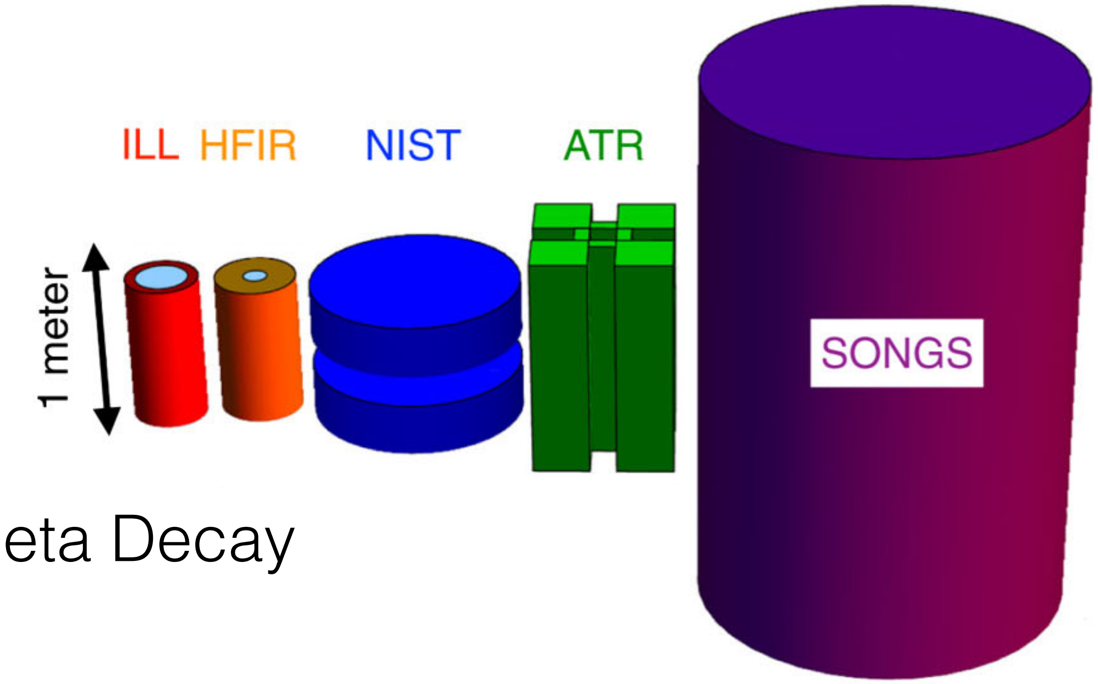
PROSPECT

Overview

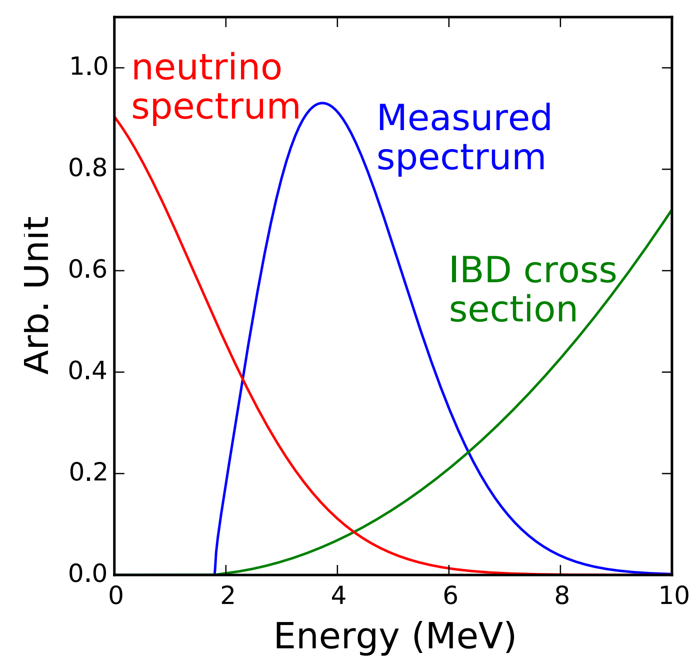
- Reactor Inverse Beta Decay with organic scintillator
- Example experiments: Daya Bay and PROSPECT
- Time Scales of IBD detection
- Application of LAPPD technology to IBD-detectors

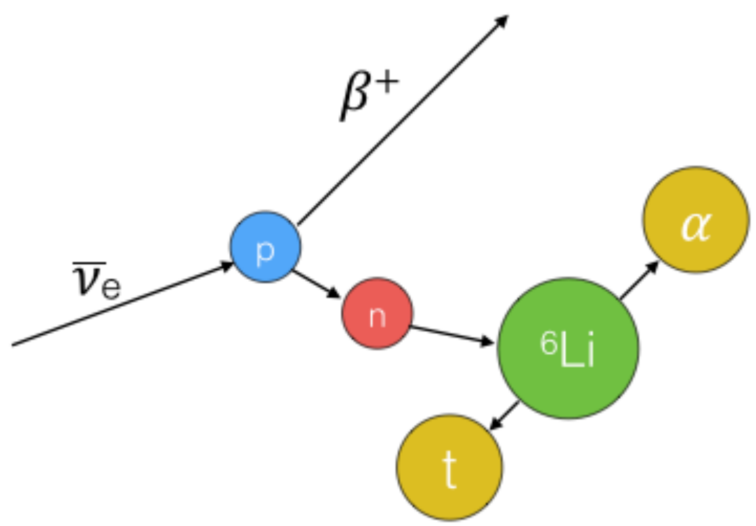
Reactor Antineutrino Detection

- **Reactors produce ~10^{20} neutrinos/s**
  - Pure source of anti-electron neutrinos
  - Compact sources available (research reactors)
  - E_ν ~ 0-12 MeV, Ideal for detection via Inverse Beta Decay
  - *Currently have anomalies that need fixing!*

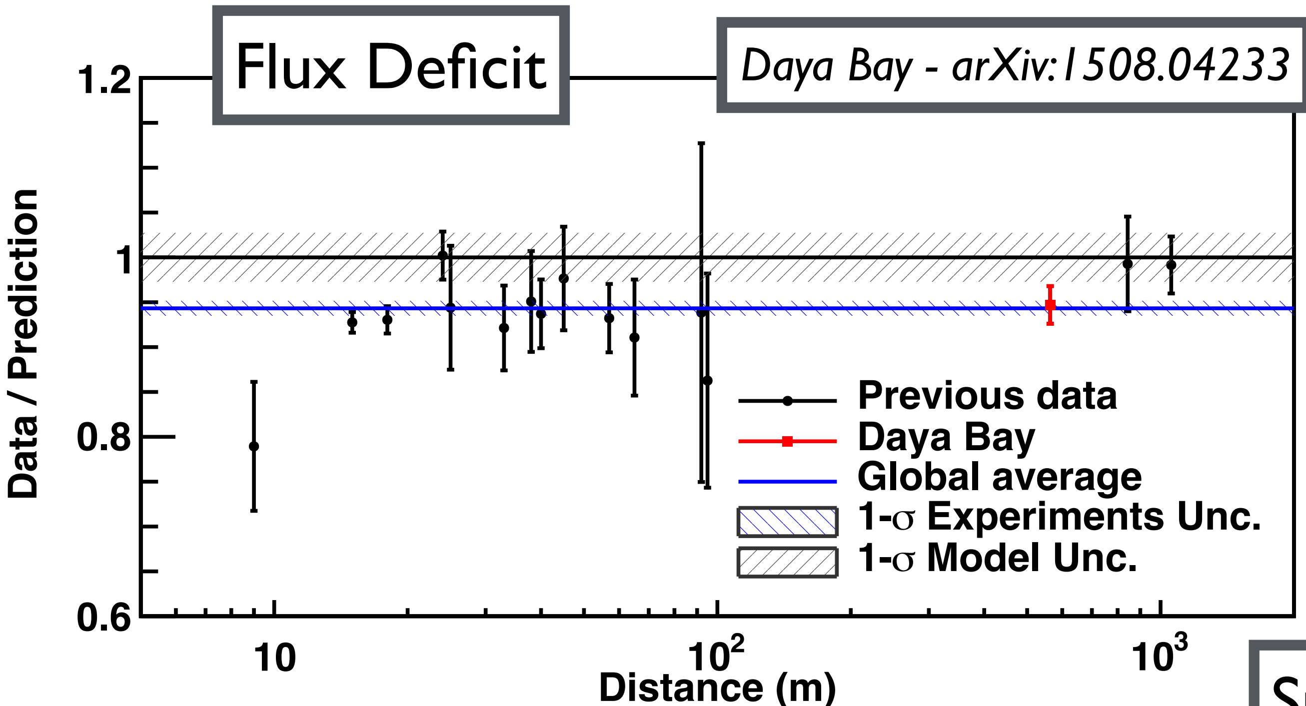


- **Liquid organic scintillator detectors**
  - Source of protons for IBD
  - Light production ~10^4 ph/MeV
  - ~420nm peak emission wavelength
  - Loaded with neutron capture agent (Gd, Li) for coincidence tagging



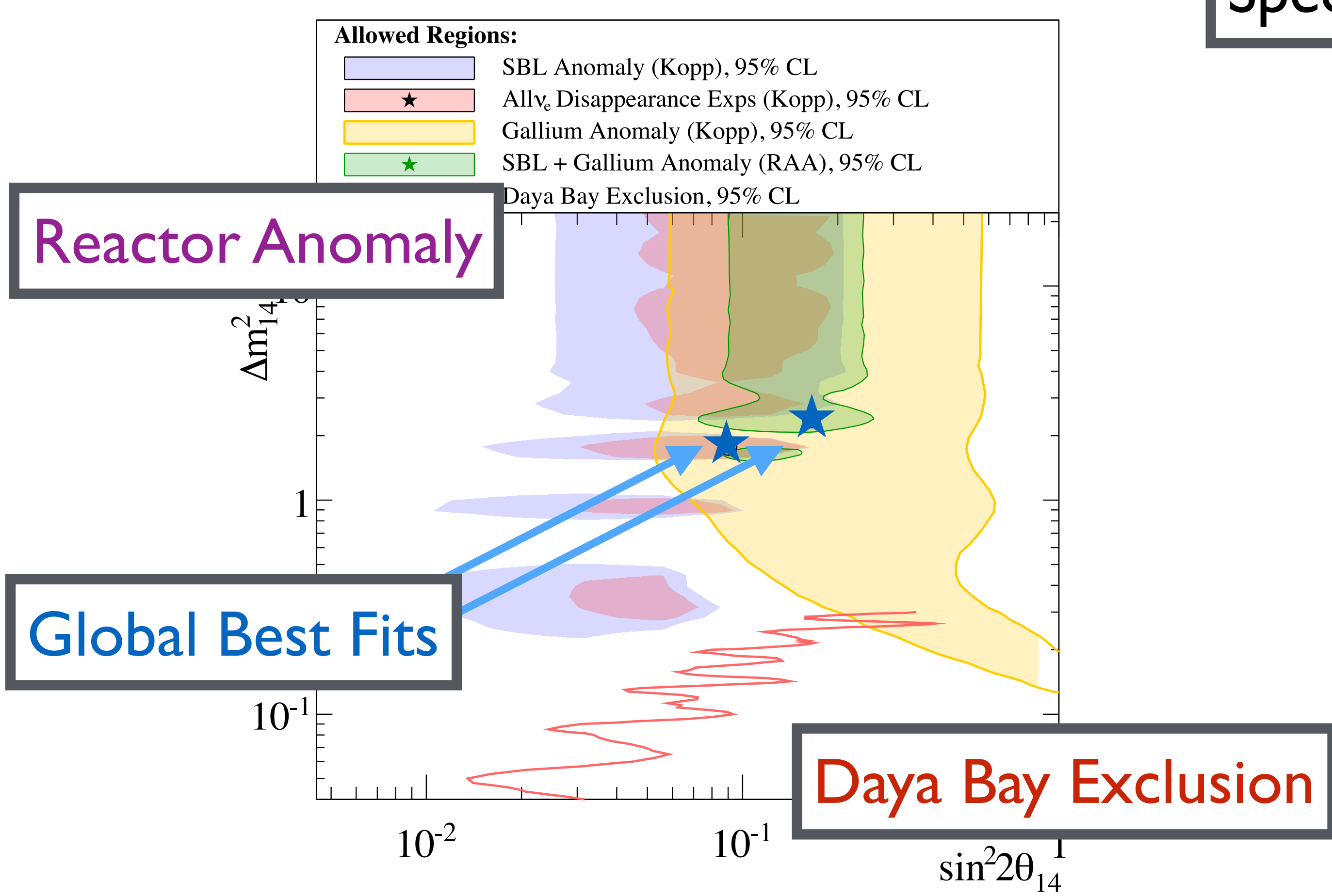


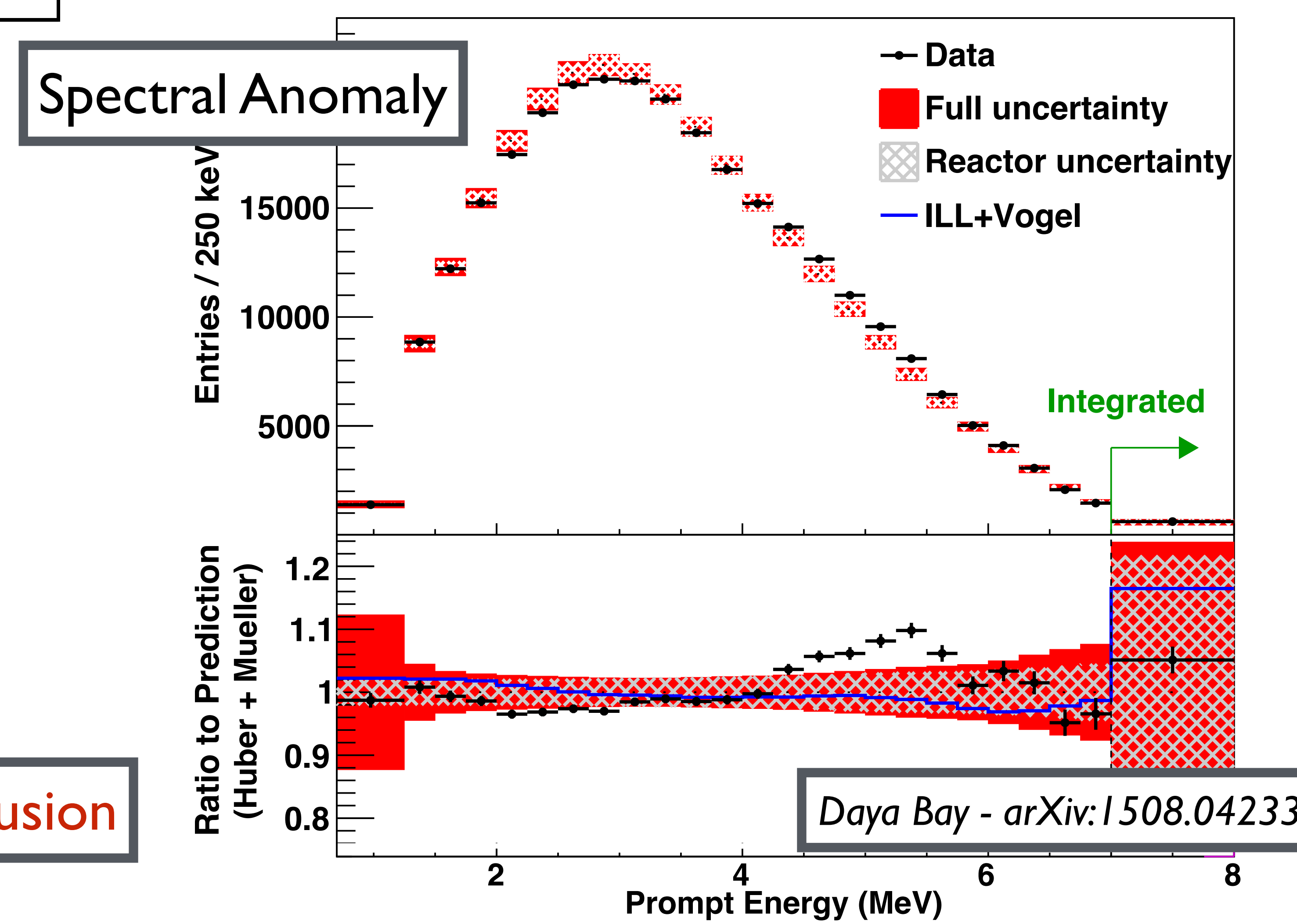
Reactor Anti-Neutrino Anomalies



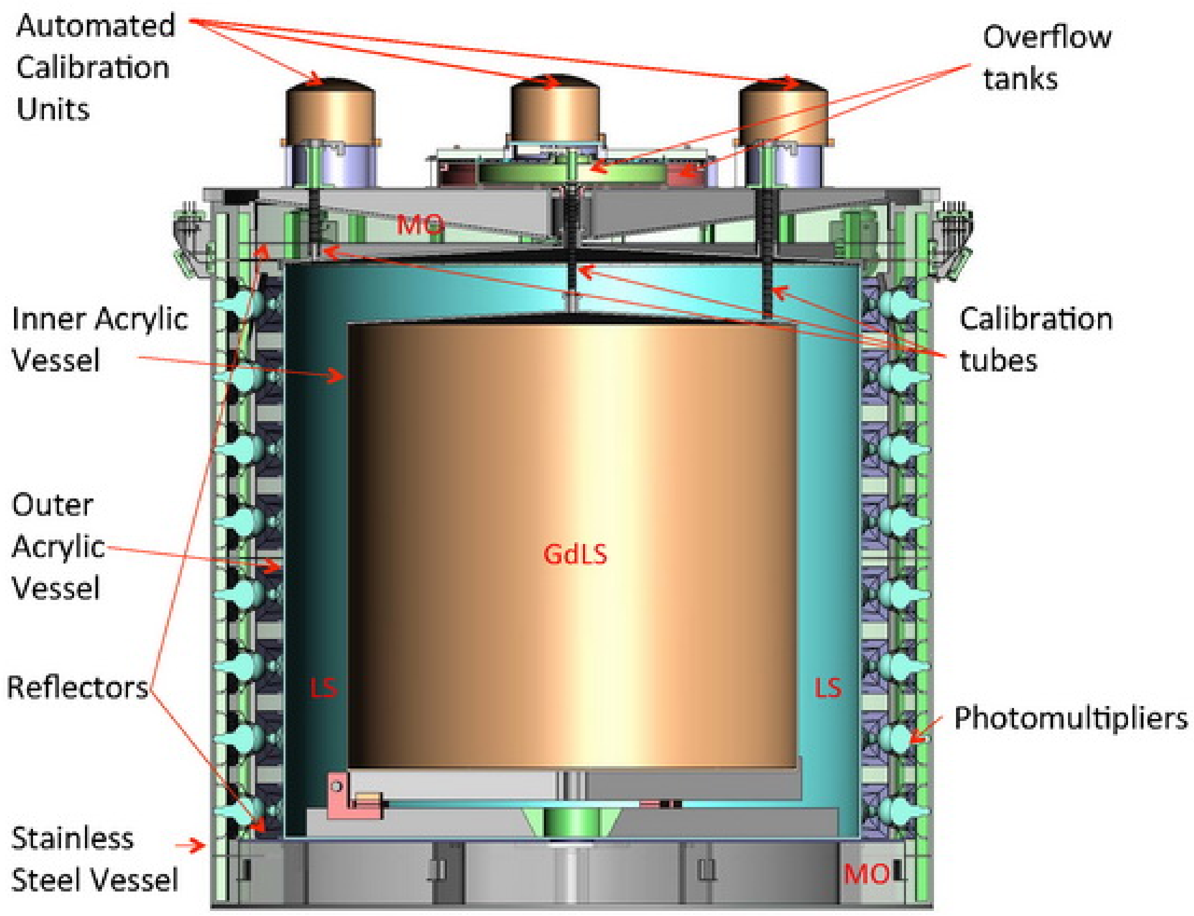
Recent anomalous results in the measured flux and spectrum exist

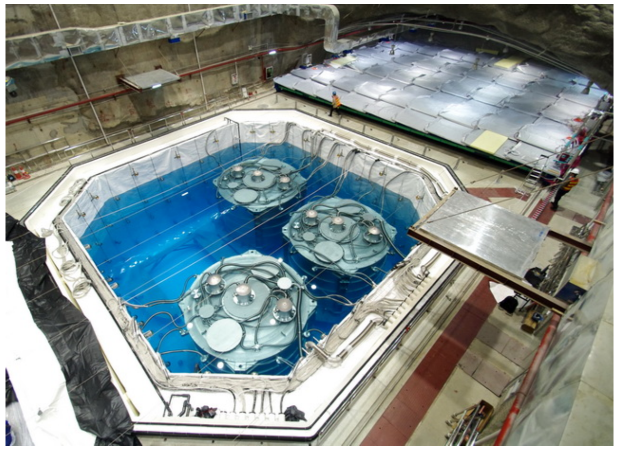
- 5% flux deficit
- Bump: 10% local spectral deviation
- **Indication of new physics?**

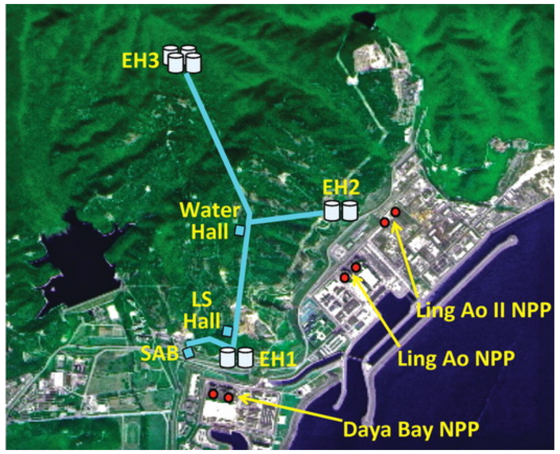




Daya Bay



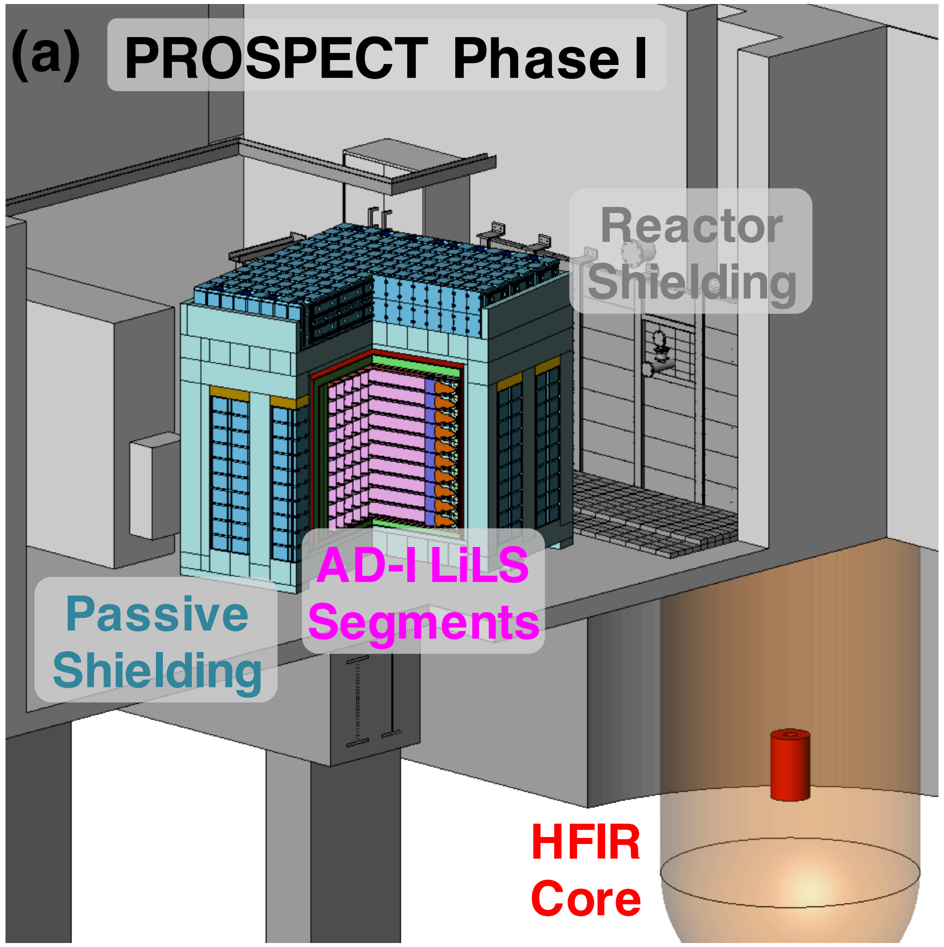


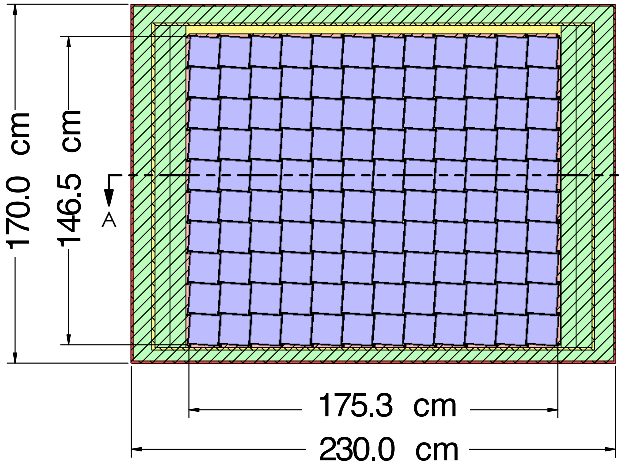


- Large single volume detectors
- 192 PMTs, detect few PE each
- Far from reactor, ~point detector

F.P. An et al. 1508.03943

PROSPECT





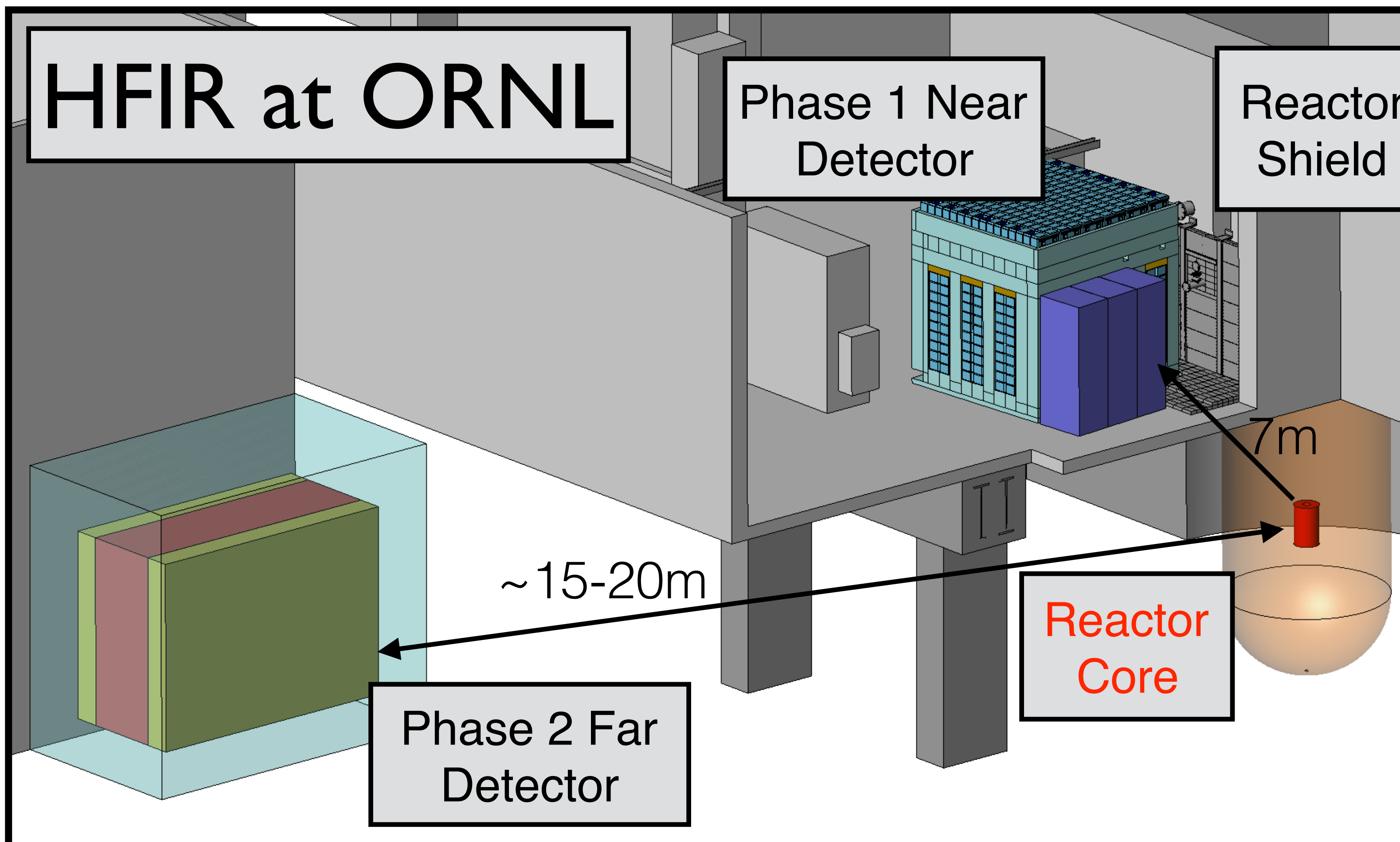
- Compact, segmented detector
- Two PMTs detect 1000s of PE each
- Near reactor, 15cm position resolution

Ashenfelter et al. 1512.02202

PROSPECT Experimental Plan

Physics Goals:

- Search for short baseline ν_e oscillations using detector segmentation
  - Distortions in energy spectrum that vary with baseline
- Measure ^{235}U antineutrino spectrum to illuminate the "Bump"



Experimental Strategy:

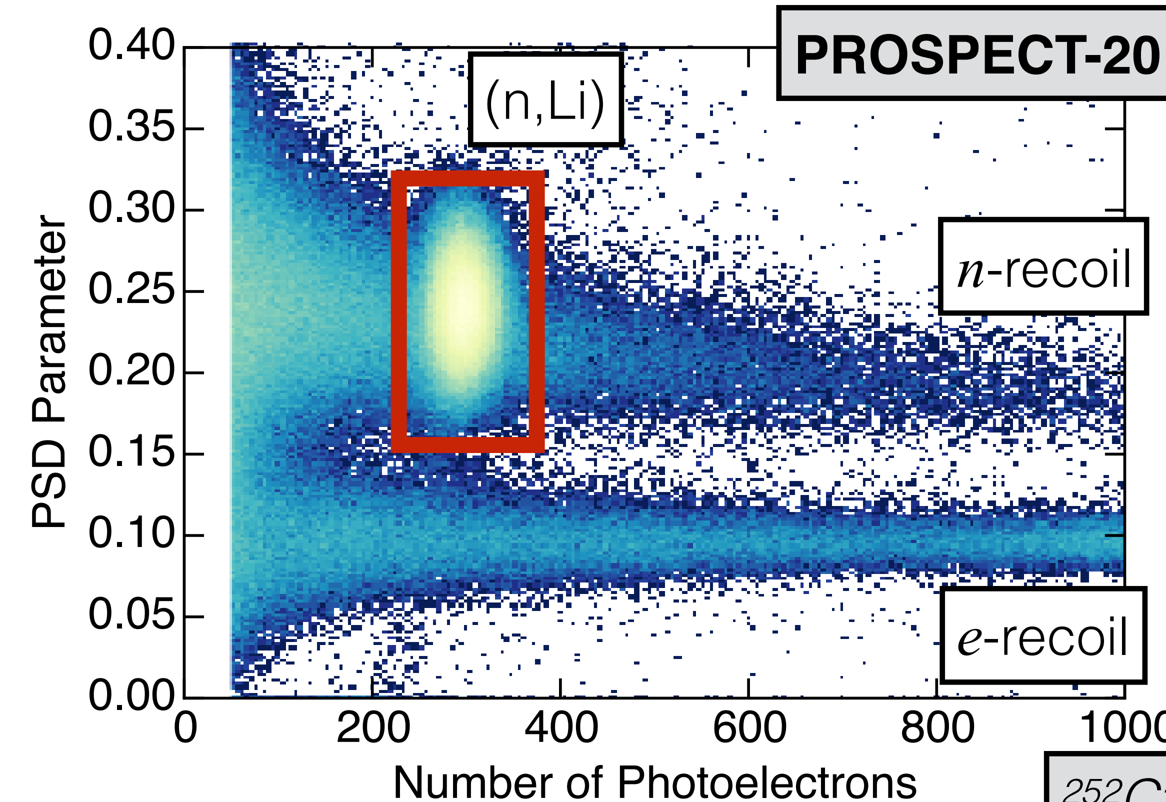
- **Phase 1:**
  - Sterile neutrino search, cover best fit region at 3σ in 1 year
  - Measure ^{235}U spectrum with 100k events/year
- **Phase 2:** World-leading short baseline sensitivity

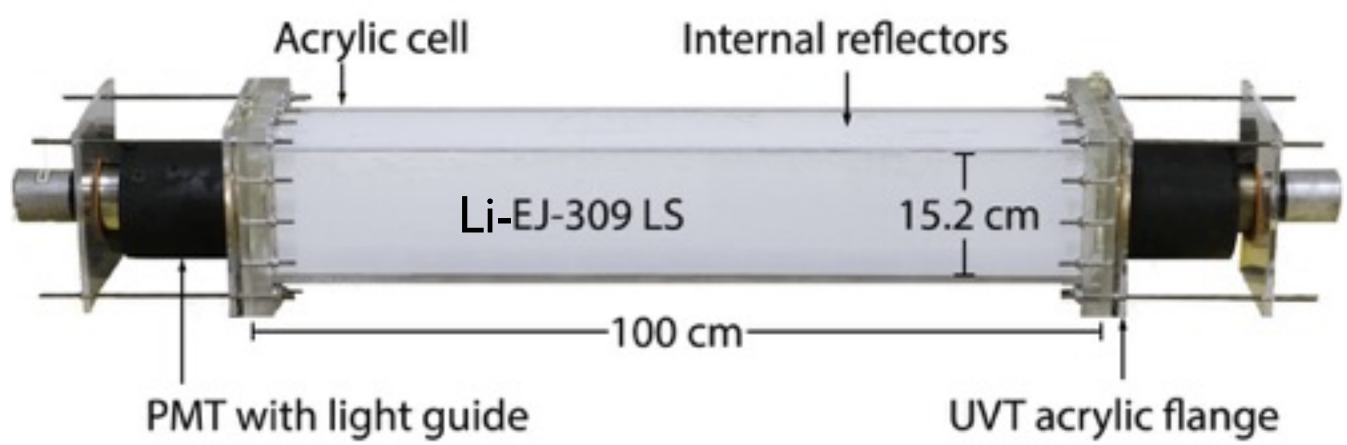
Challenges:

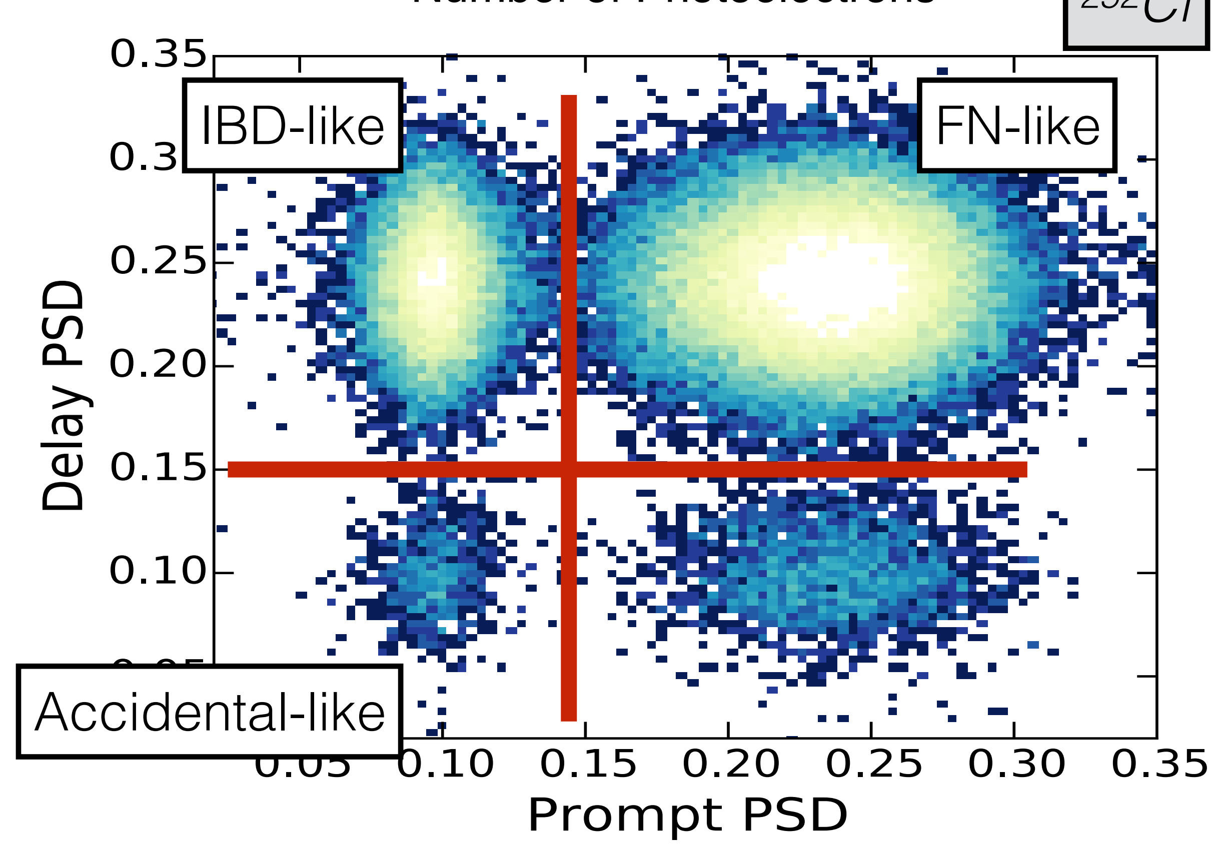
- Minimal overburden, cosmogenic backgrounds
- Reactor-related backgrounds
  - High energy ($\lesssim$10MeV) gammas

PROSPECT IBD Detection

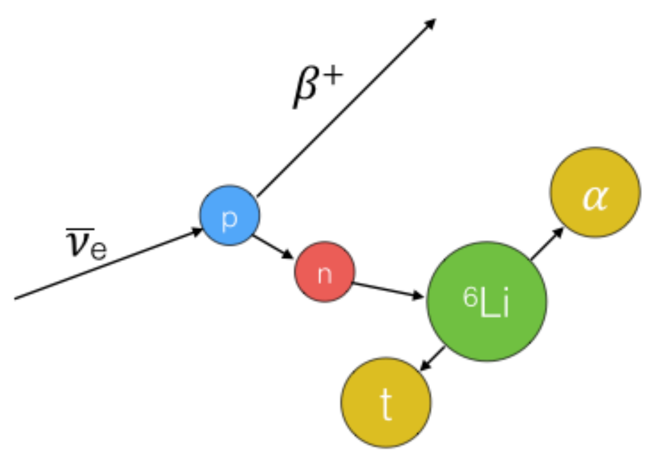
- Segmented detector, >500pe/MeV in two PMTs
- Coincidence of β^+ and neutron capture
- Pulse shape discrimination on prompt and delay events
    - Separates IBD-like events from backgrounds
- (n,^{6}Li) capture is localized, consistent light output







prompt signal: 1-10 MeV positron from inverse beta decay
delay signal: 0.6 MeV signal from neutron capture on ^{6}Li; 40μs delayed



IBD Time Scales

From short to long

PMT SPE width: ~3ns

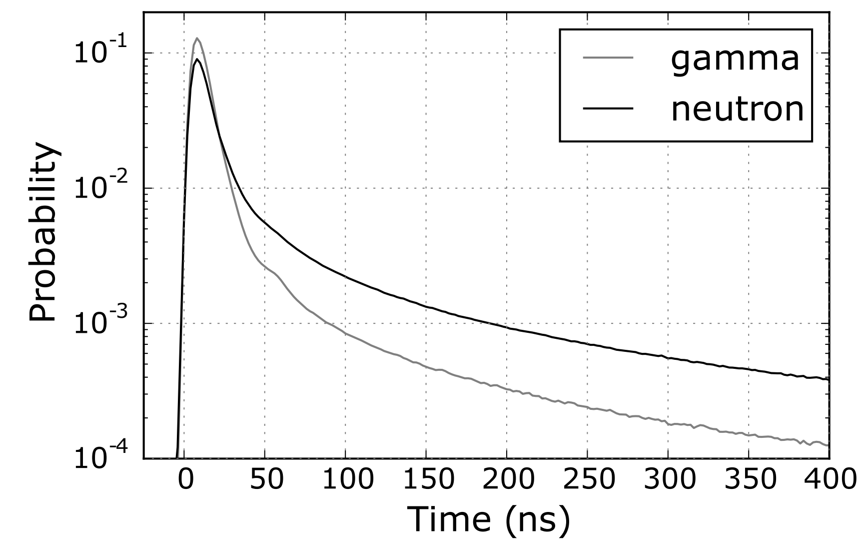
Scintillation time: ~3.5ns fast component, 100ns slow component (EJ-309)

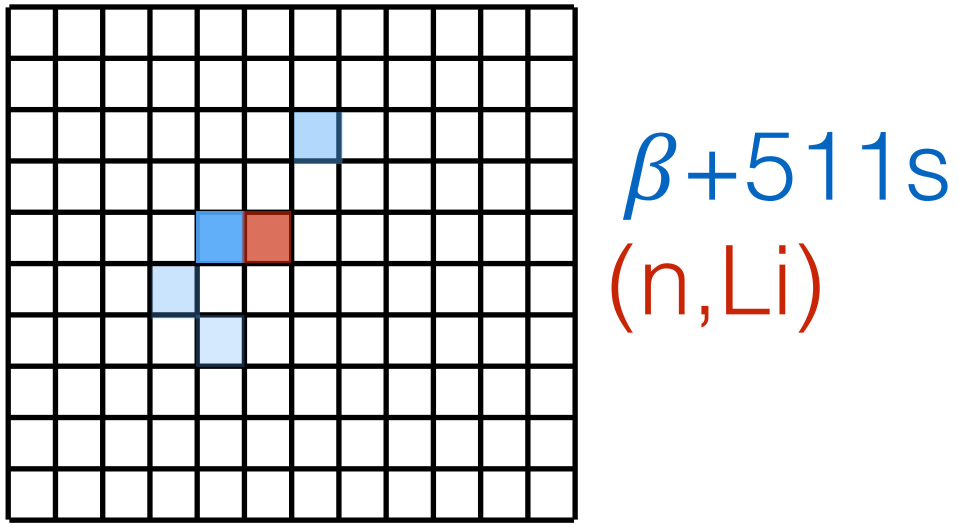
Positron annihilation gamma interaction time: <4ns

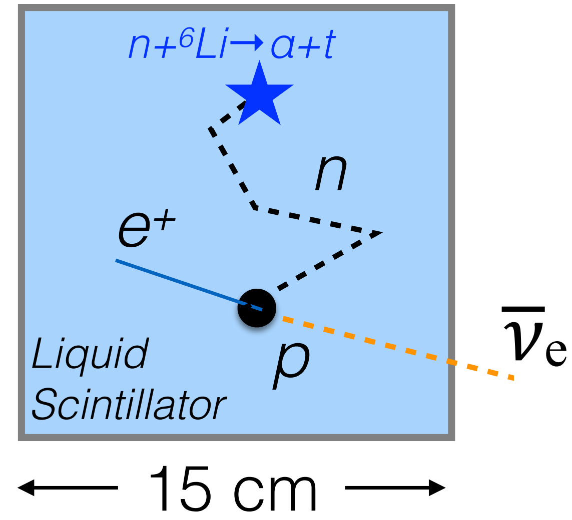
Optical photon transport time: ~5-10ns

Fast neutron interaction time: 50ns

Neutron capture coincidence: ~30-40μs lifetime

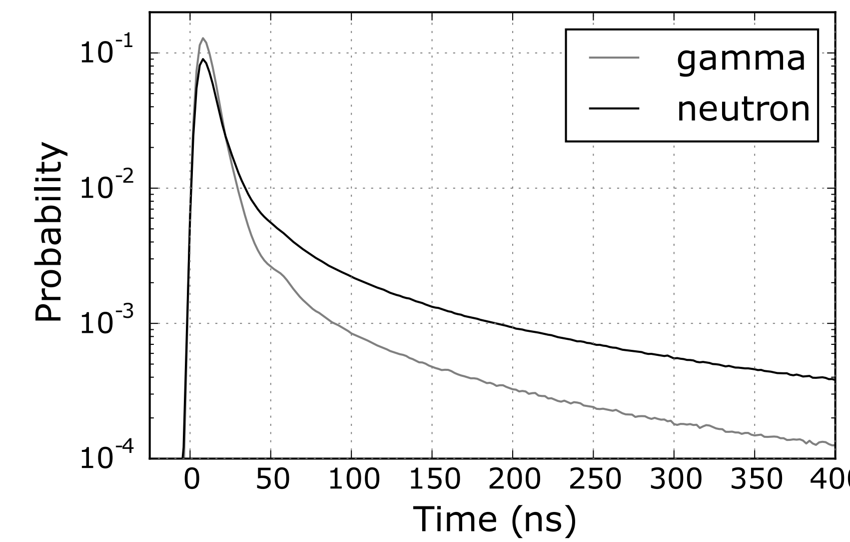






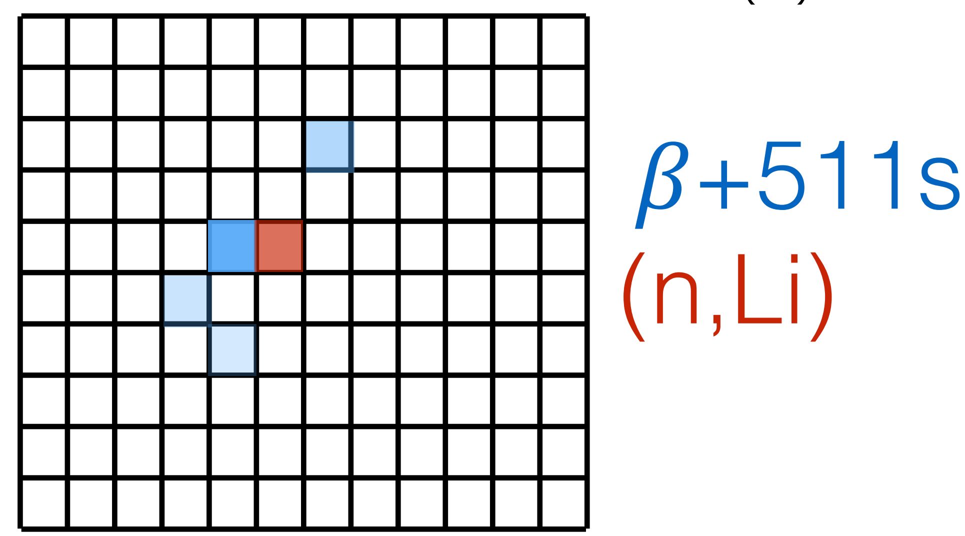
IBD Time Scales

From short to long



PMT SPE width: ~3ns

Scintillation time: ~3.5ns fast component, 100ns slow component (EJ-309)

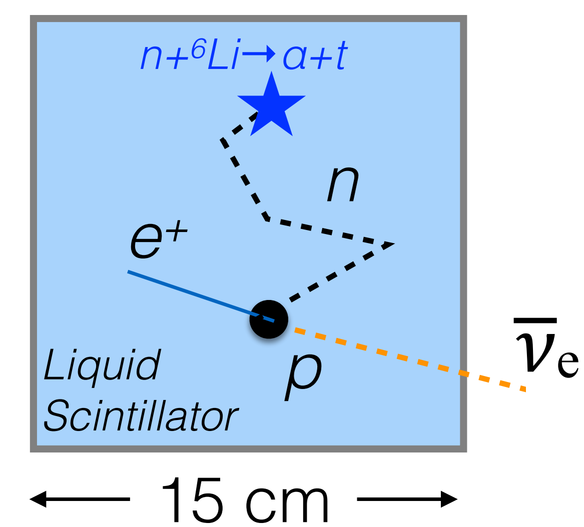


Positron annihilation gamma interaction time: <4ns

Optical photon transport time: ~5-10ns

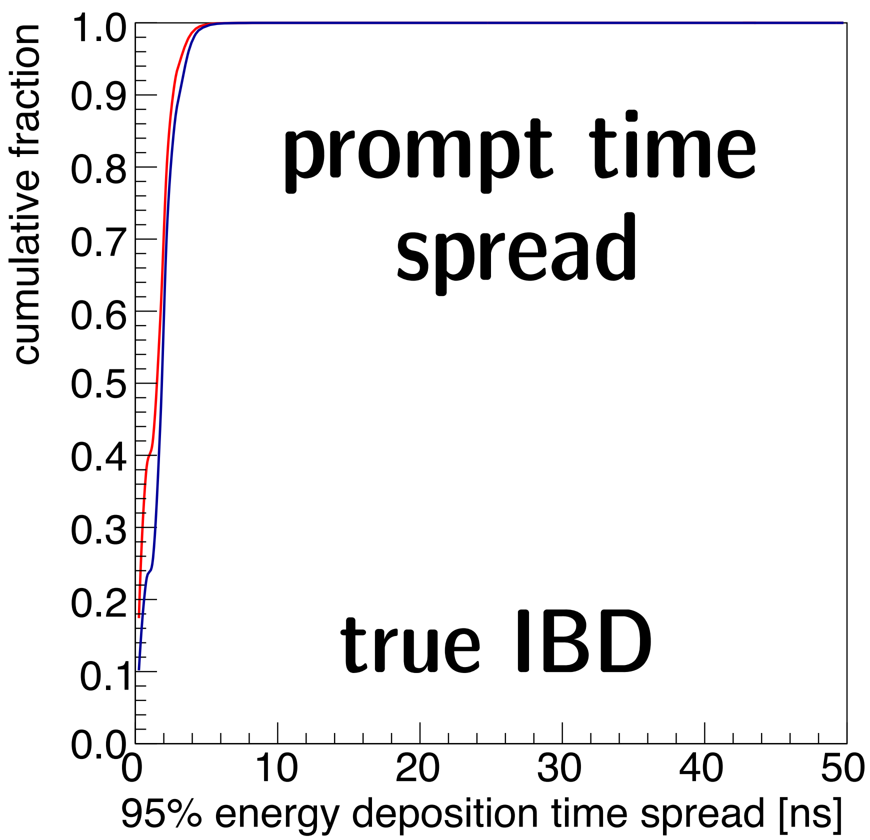
Fast neutron interaction time: 50ns

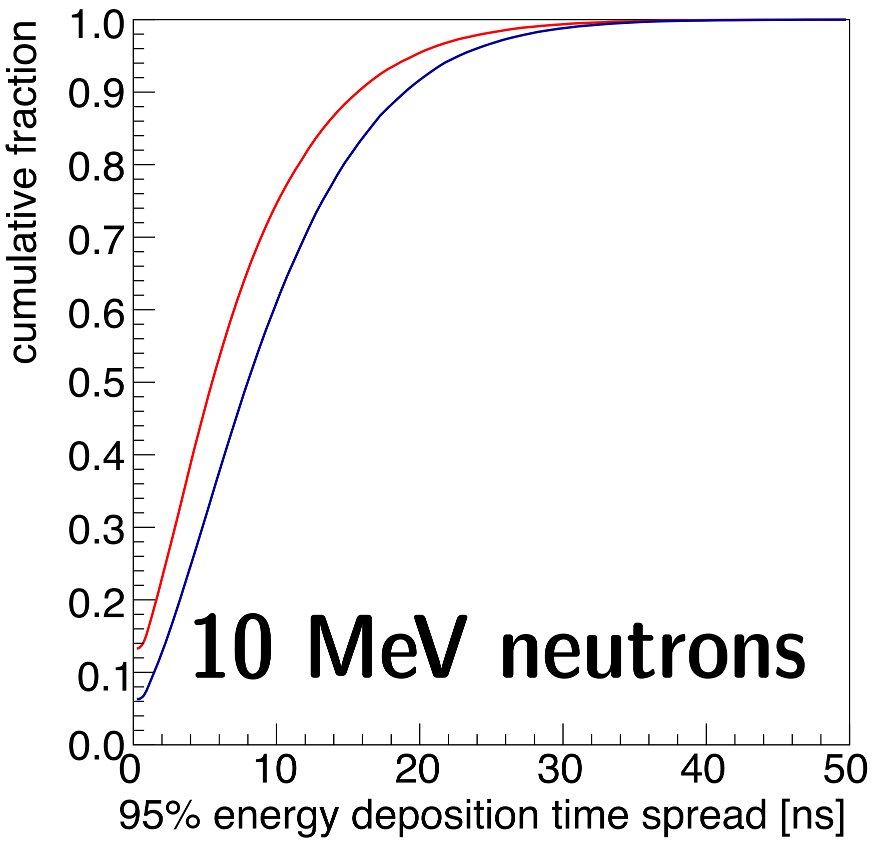
Neutron capture coincidence: ~30-40μs lifetime



IBDs vs Fast Neutrons

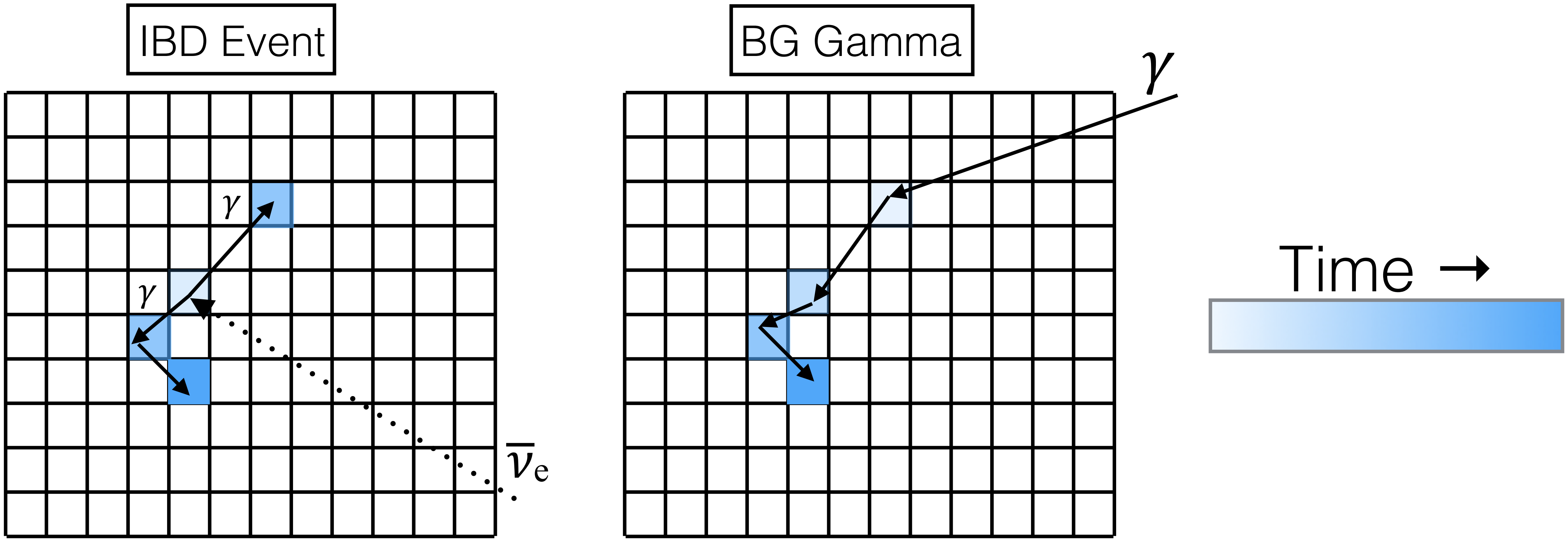
M. Mendenhall AAP2015





- IBD positron and 511s interact in < 4ns
- Fast neutrons take much longer to interact
- Can separate via fine segmentation, or from *fast timing*

IBDs vs BG Gamma



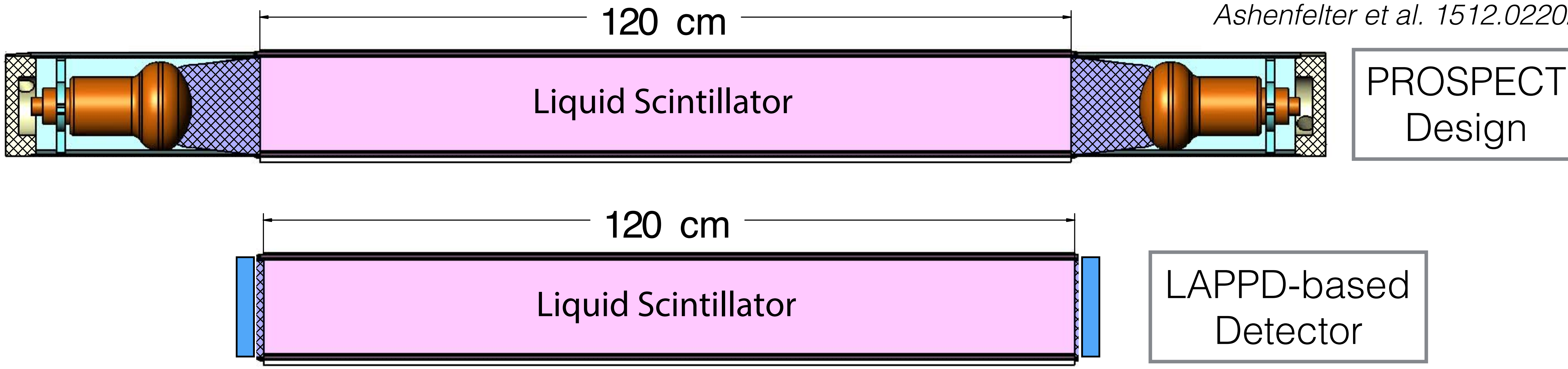
- IBD positron and 511s interact in < 4ns
  - 511s after IBD, point back in time to single origin
- High-energy gammas scatter sequentially, separated by ~ns
- Could be separated via fine segmentation or *fast timing*

LAPPDs for IBDs

- Improve ability to resolve individual particle interactions
  - **IBD** → ≥3 interactions separated by ns, common origin in time
  - **Gammas** → many interactions separated by ns, with distinct ordering of interactions
  - **Fast Neutrons** → multiple interactions separated by ≥10ns, also distinct ordering
- *Potentially separate multiple interactions within one segment*
- Advanced particle ID based upon spacial/timing profile of emitted light?
- Enable use of faster scintillators to improve particle tagging

Side Benefits of LAPPDs

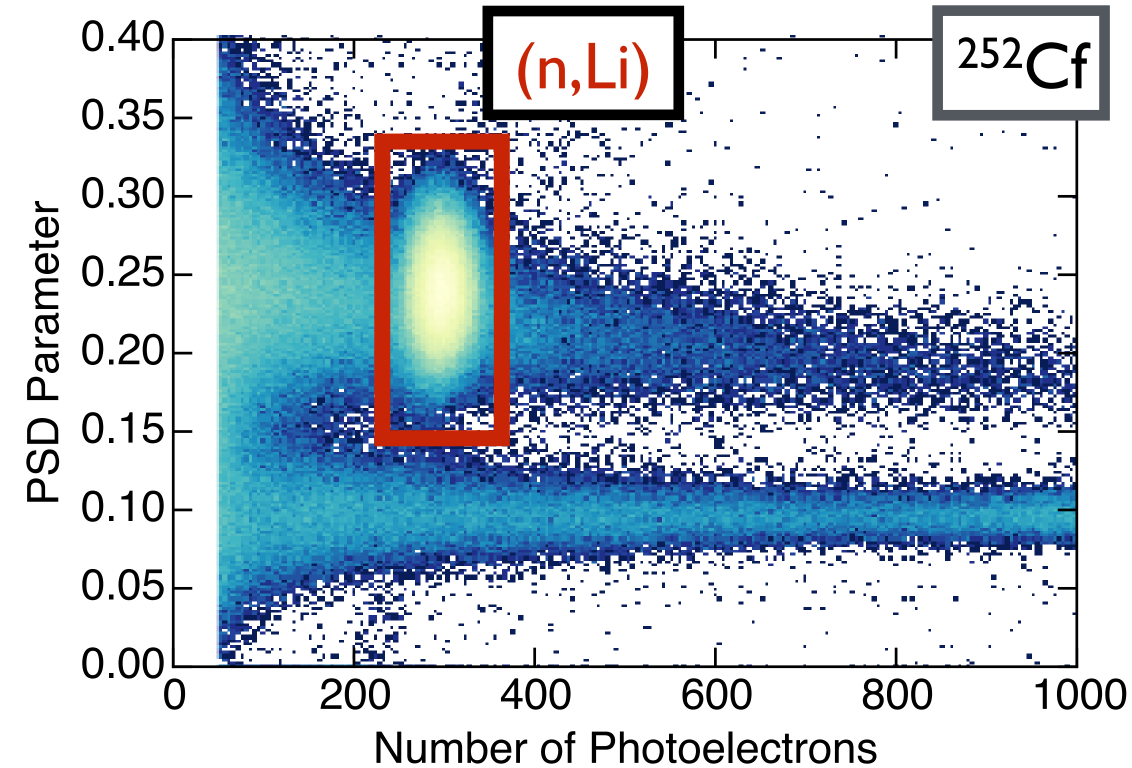
Ashenfelter et al. 1512.02202



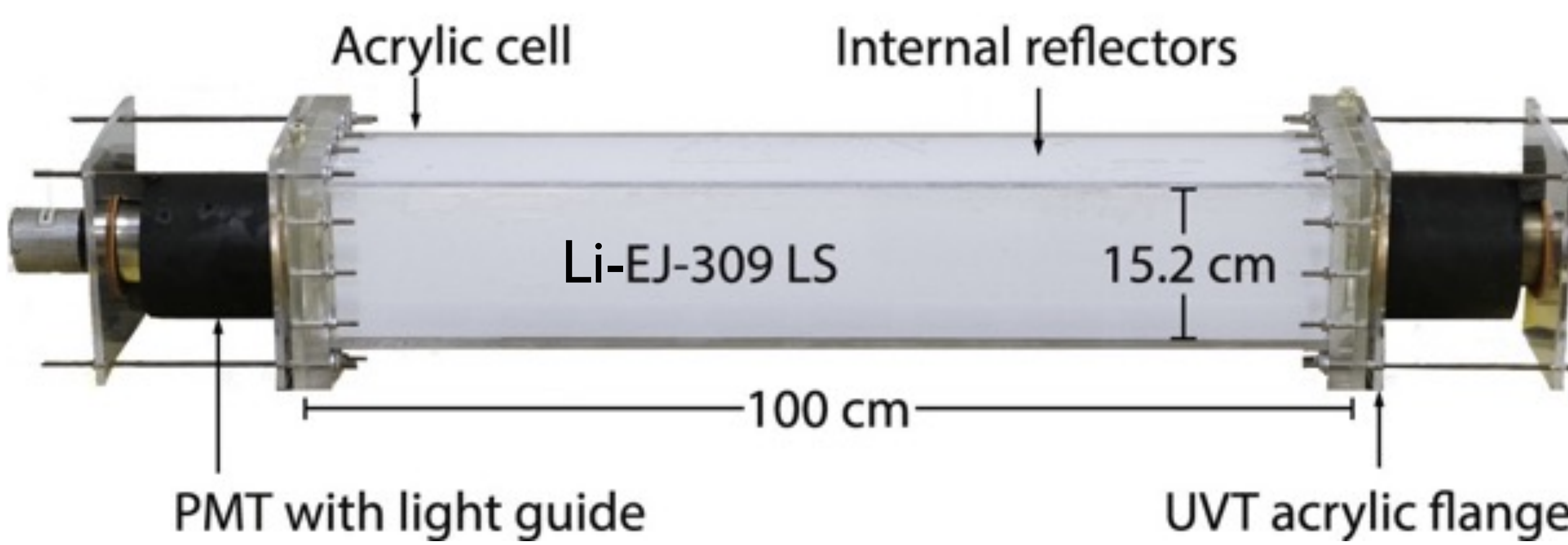
- Compact packaging decreases dead volume inside detector shielding package
  - **PROSPECT**: 1.2m active length with ~0.5m PMT dead volume
  - Improves efficiency of shielding material for small detectors
- Flat face simplifies coupling to LS cells without light guides
- Square cross-section improves coverage of LS cells without efficiency loss

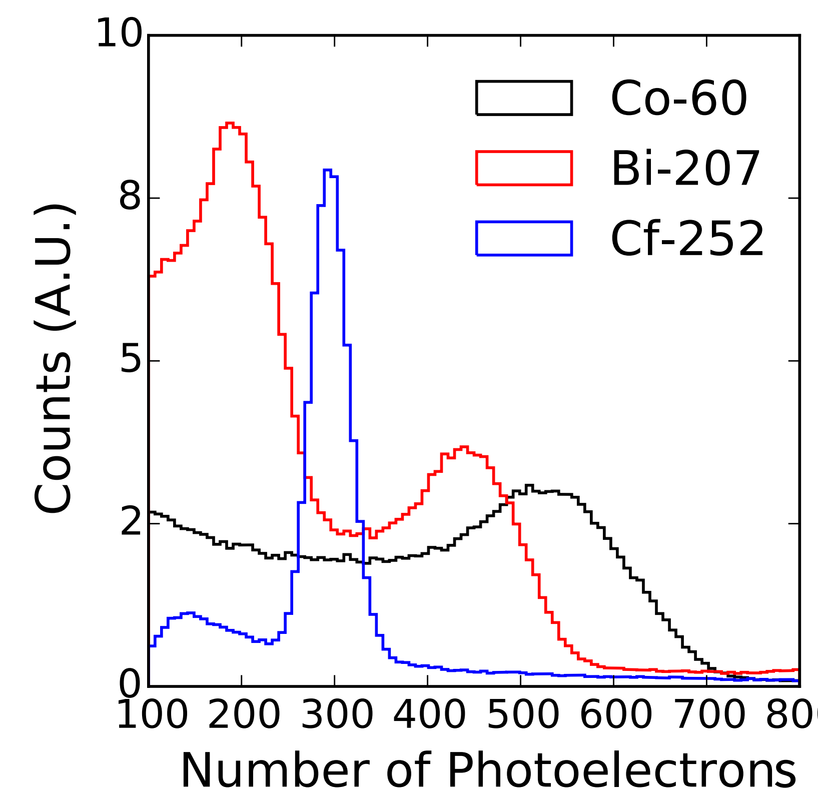
Test Platform at Yale

- **PROSPECT-20**
  - **Stand-alone** 23L test cell of ^{6}Li-loaded LS
  - 15x15x100cm^3 detector
  - *Square cross-section*
- Measured Light collection: 530PE/MeV
  - **4.5%@1MeV energy resolution**
- Measured PSD Figure of Merit: 1.4 at (n,Li) capture
  - **>99.9% background rejection**
- **6" LAPPDs easily coupled to P20**



LS Cross-sec area: 220cm^2
Photocathode: 95cm^2
> 50% coverage





PROSPECT-20 Paper arXiv:1508.06575

Summary

- New reactor-based inverse beta decay experiments are probing anomalies.
    - **Could lead to beyond the SM physics (ν_s)**
- Surface-based experiments with challenging background environments
- Backgrounds have complicated time structure that is difficult to measure with PMTs
- LAPPDs offer superior timing in a compact form-factor
    - Provide new ability to eliminate backgrounds based on timing profiles
    - Increase light collection efficiency, decrease shielding, simplify detector design
- A platform exists at Yale that is perfect for testing LAPPDs for IBD detectors

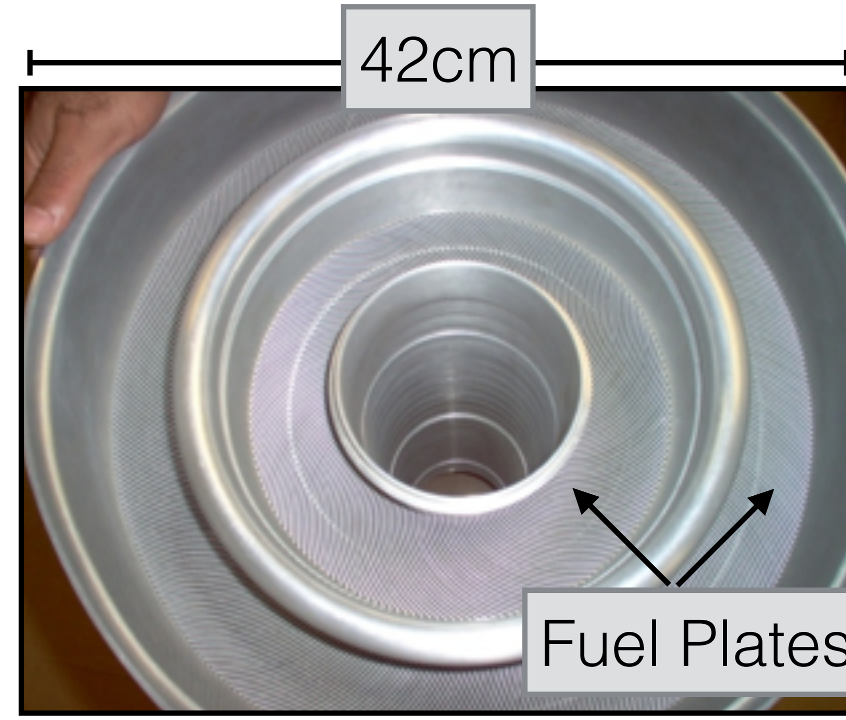
Publications: arXiv: 1512.02202, 1506.03547, 1508.06575

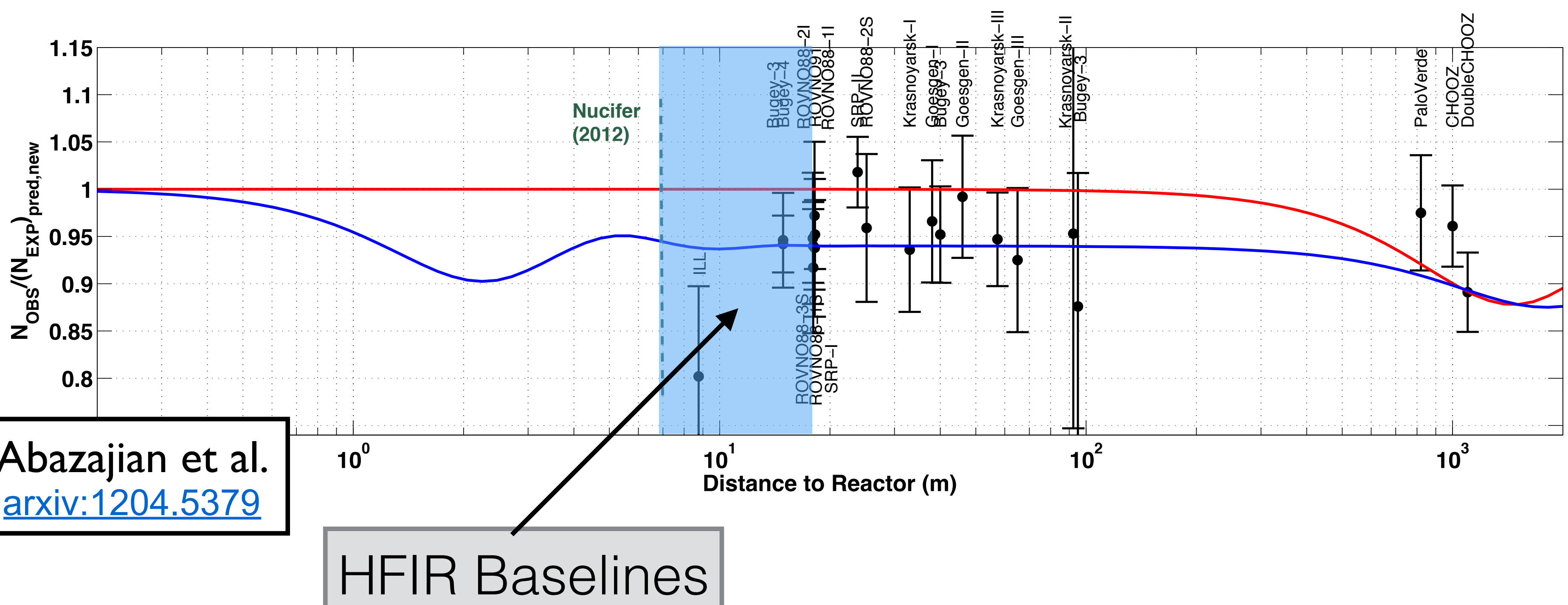
http://prospect.yale.edu

Backup Slides

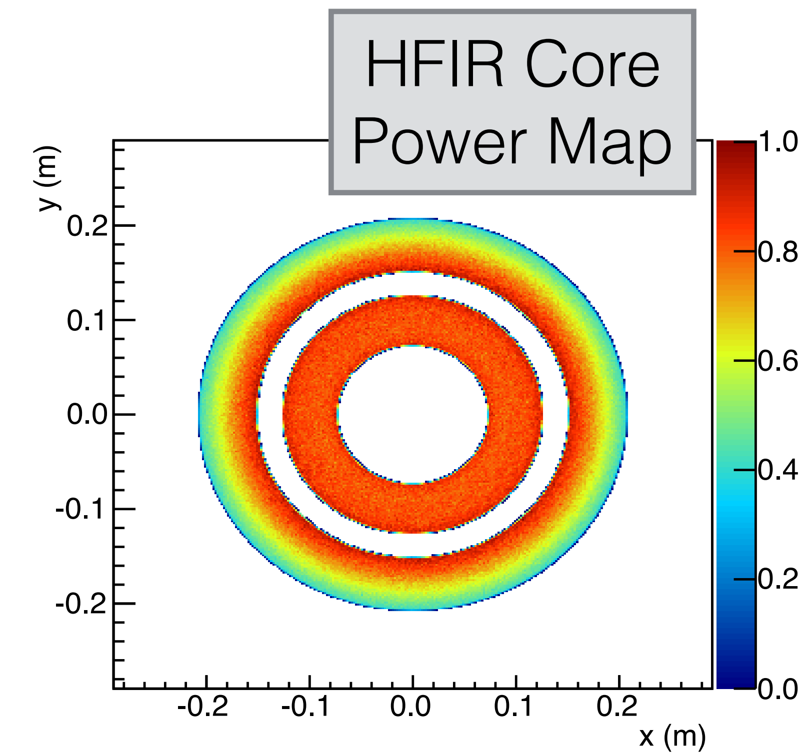
HFIR Research Reactor

- High Flux Isotope Reactor at Oak Ridge National Lab
- 85MW HEU compact-core reactor, 42% uptime
- PROSPECT activity for past 2 yrs
- Backgrounds fully characterized (arXiv:1506.03547)
- Unique location for a short baseline experiment



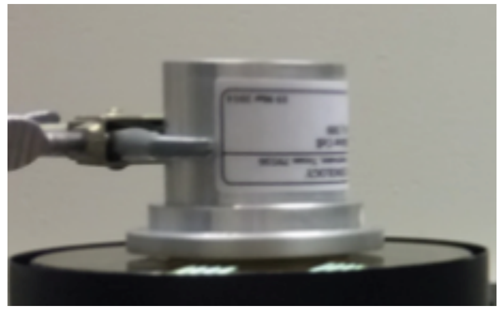


Abazajian et al.
arxiv:1204.5379



Phased Detector Development

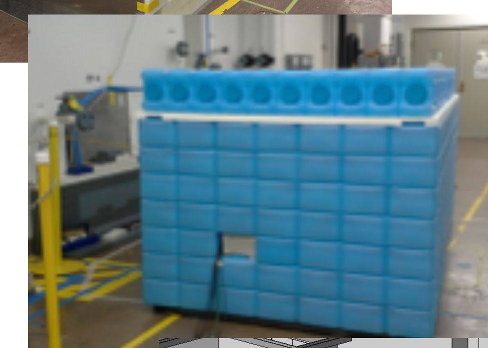
PROSPECT-0.1
Aug 2014
Spring 2015



5cm
0.1liter
LS cell

PROSPECT-2
Dec 2014
Feb 2015

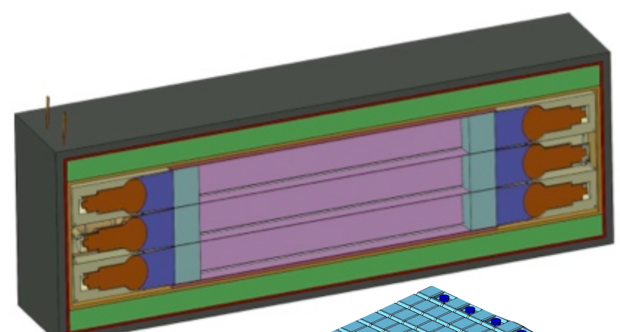
12.5cm
1.7 liter
LS cell



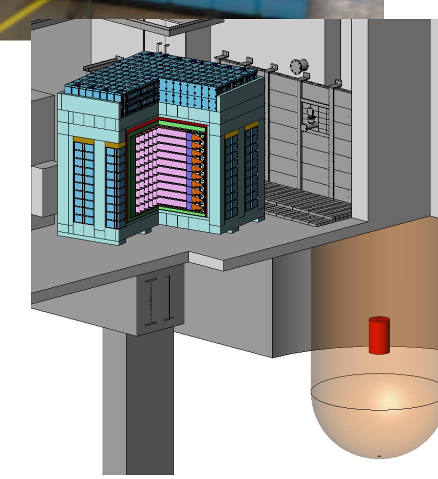
PROSPECT-20
March 2015

1m
23 liter
LS cell

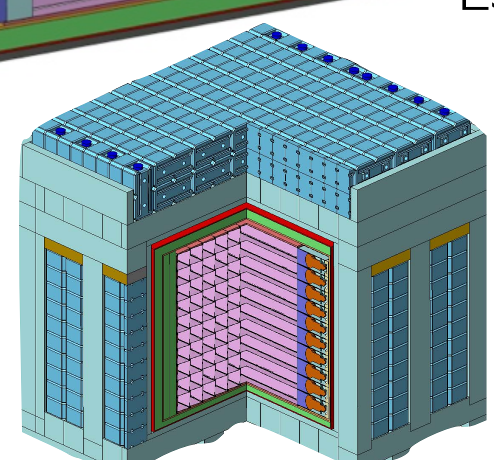
PROSPECT-Nx30
Early 2016*



1.19m long
Nx30 liter
LS segments



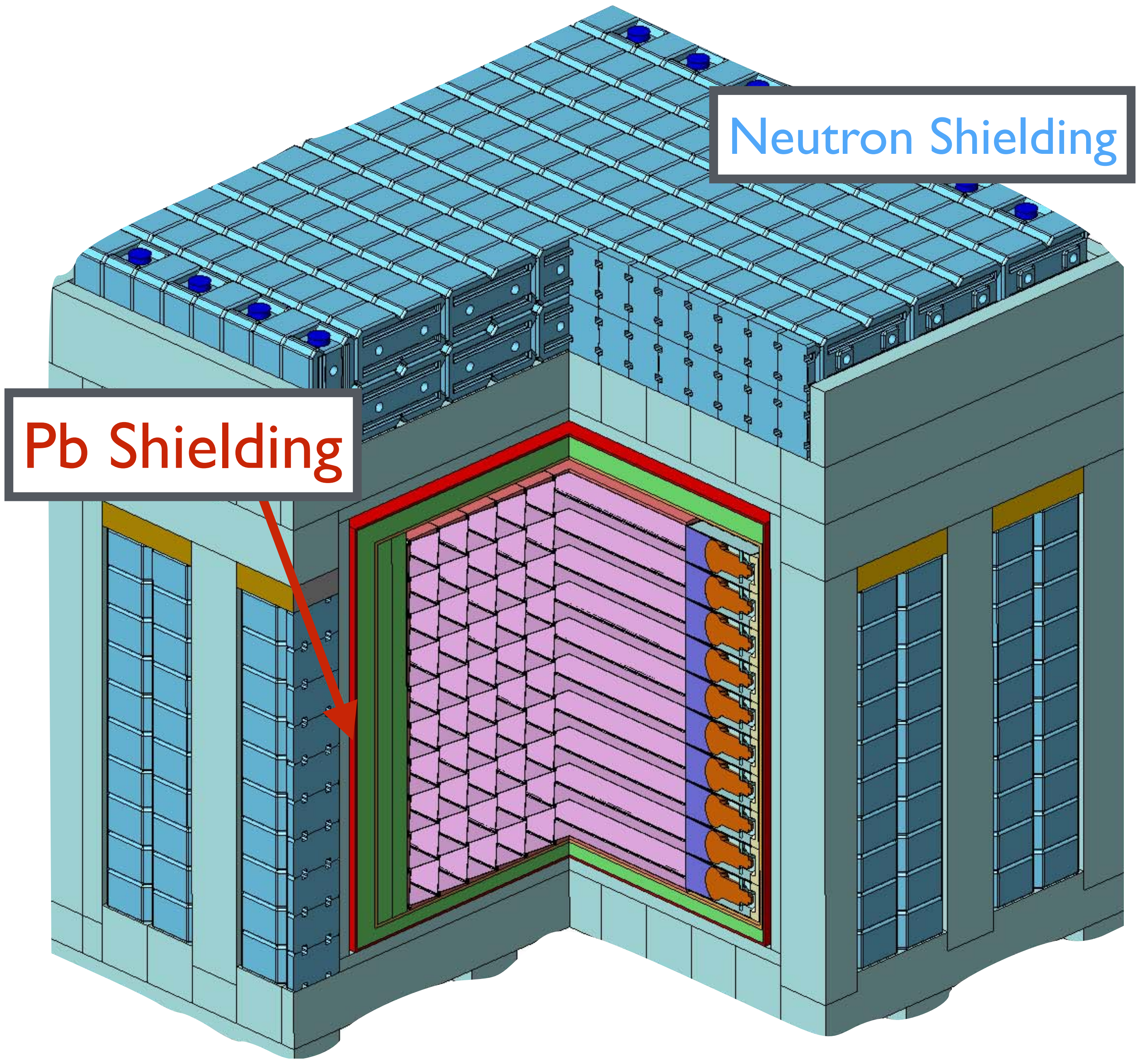
PROSPECT
Phase I
Late 2016*

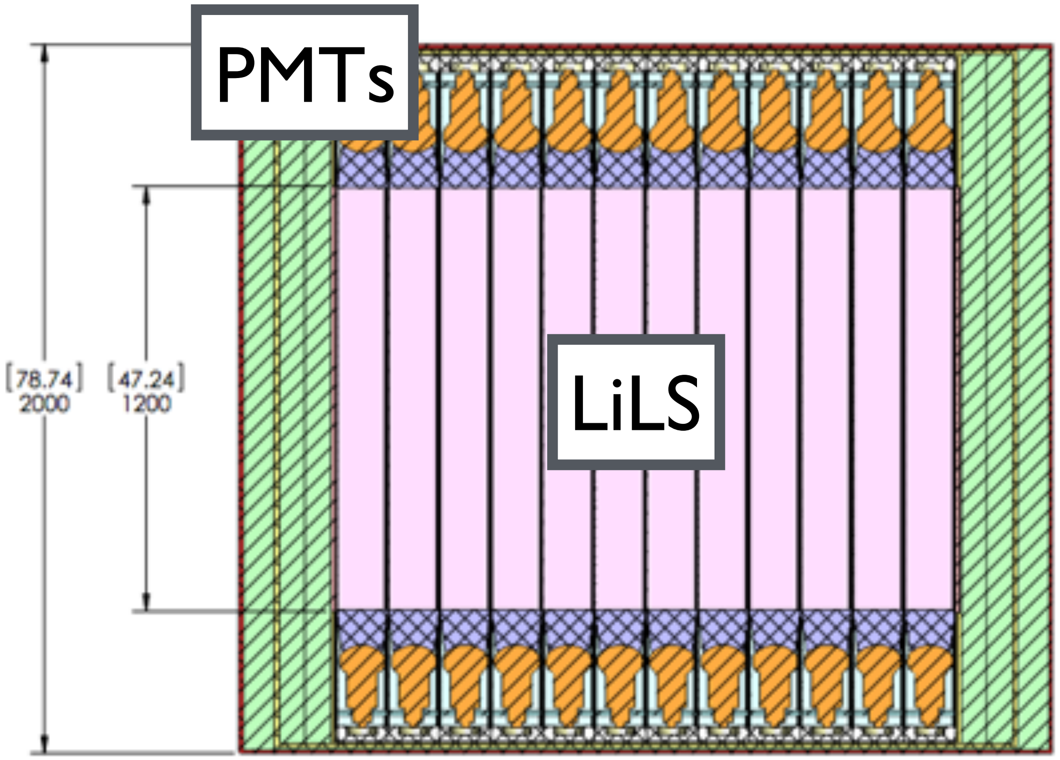


120x30 liter
LS segments
15x15x119cm

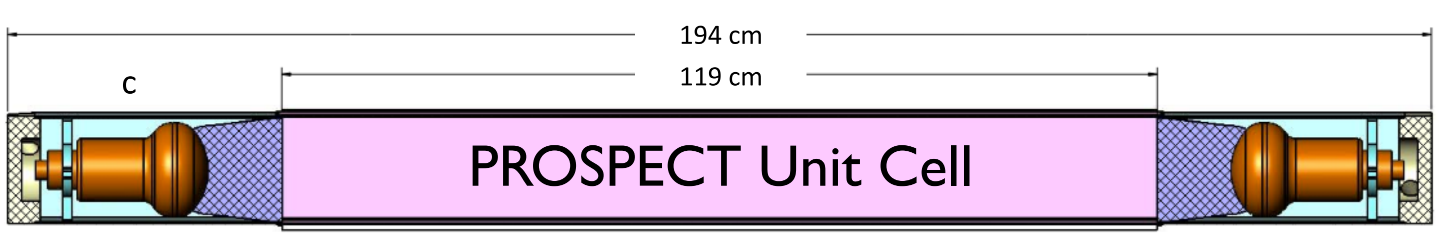
*technically driven schedule

Segmented Antineutrino Detector



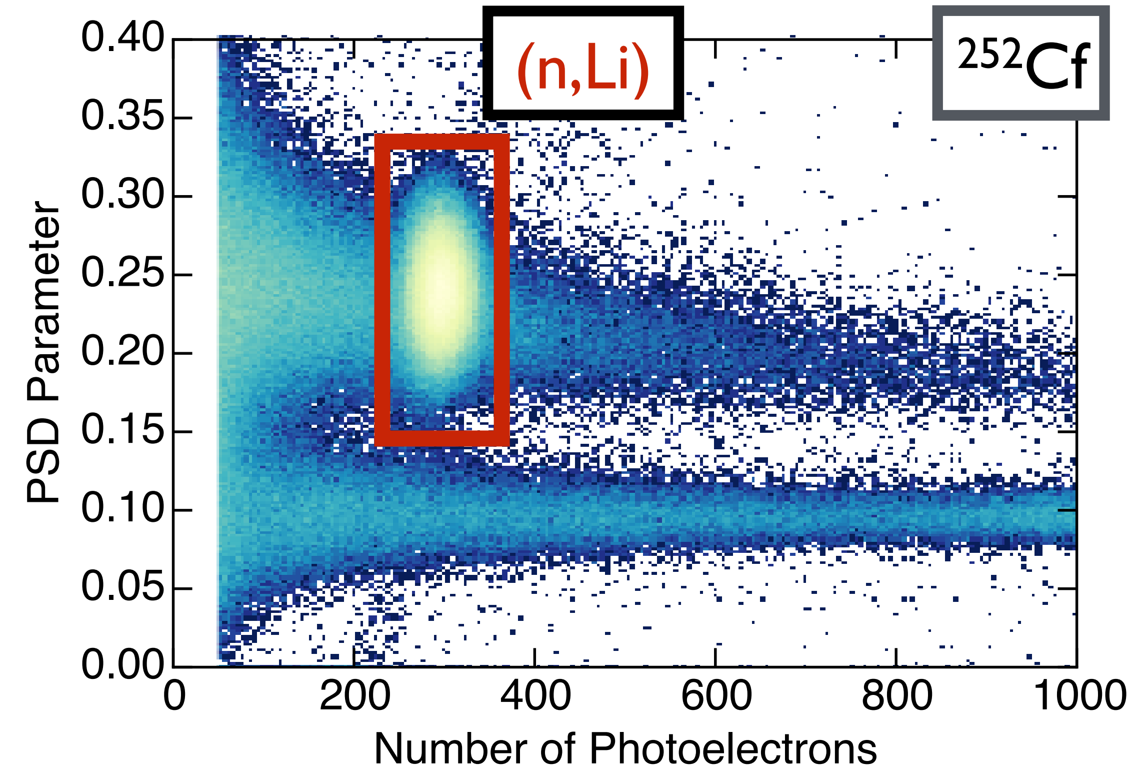


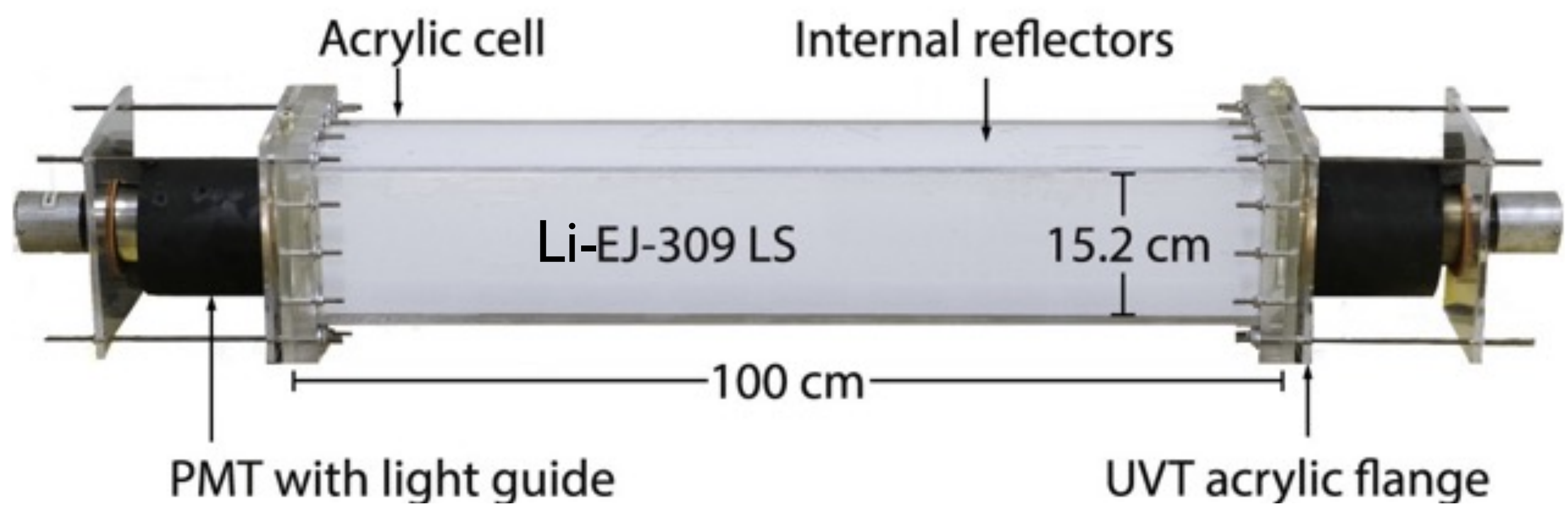
- 3ton LiLS detector
- 120 optical segments
  - 119x15x15cm^3 each
- Double-ended PMT readout
- Access for calibration sources between every cell
- Shielding package designed for surface backgrounds

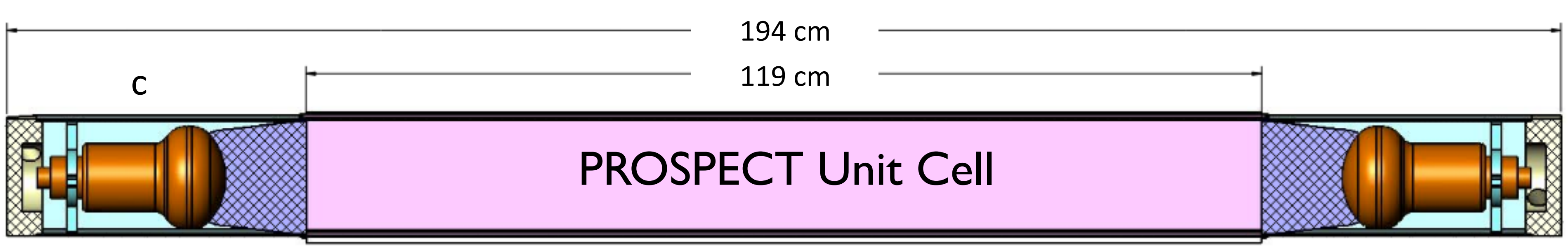


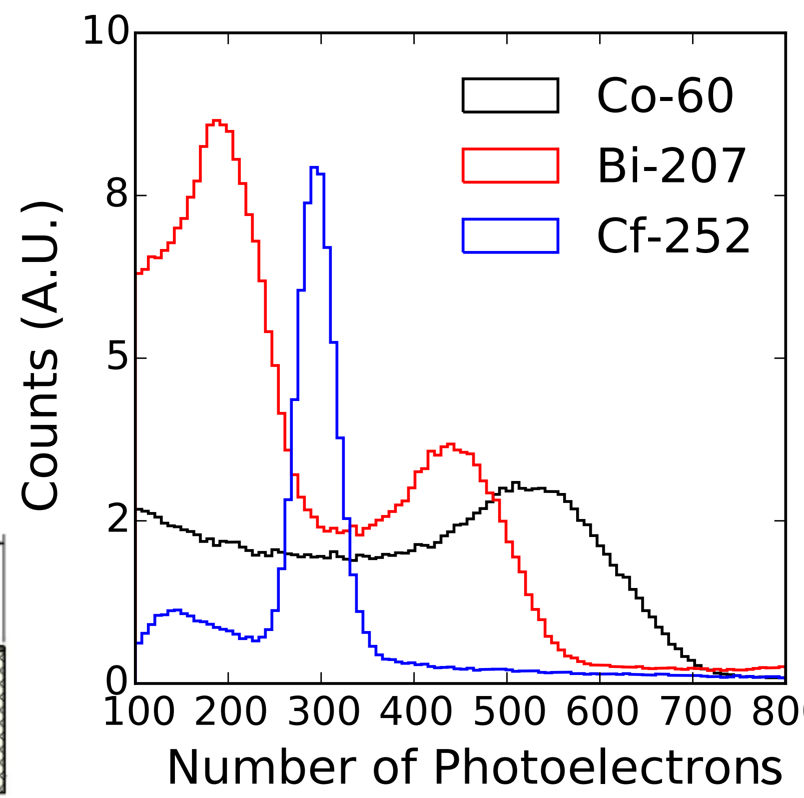
Full-scale Test Detector

- **PROSPECT-20**
  - 23L test cell of 6Li-loaded Liquid Scintillator
  - 15x15x100cm^3 detector
- Measured Light collection: 530PE/MeV
  - **4.5%@1MeV energy resolution**
- Measured PSD Figure of Merit: 1.4 at (n,Li) capture
  - **>99.9% background rejection**
- Double-ended readout
  - uniform light collection and position reconstruction



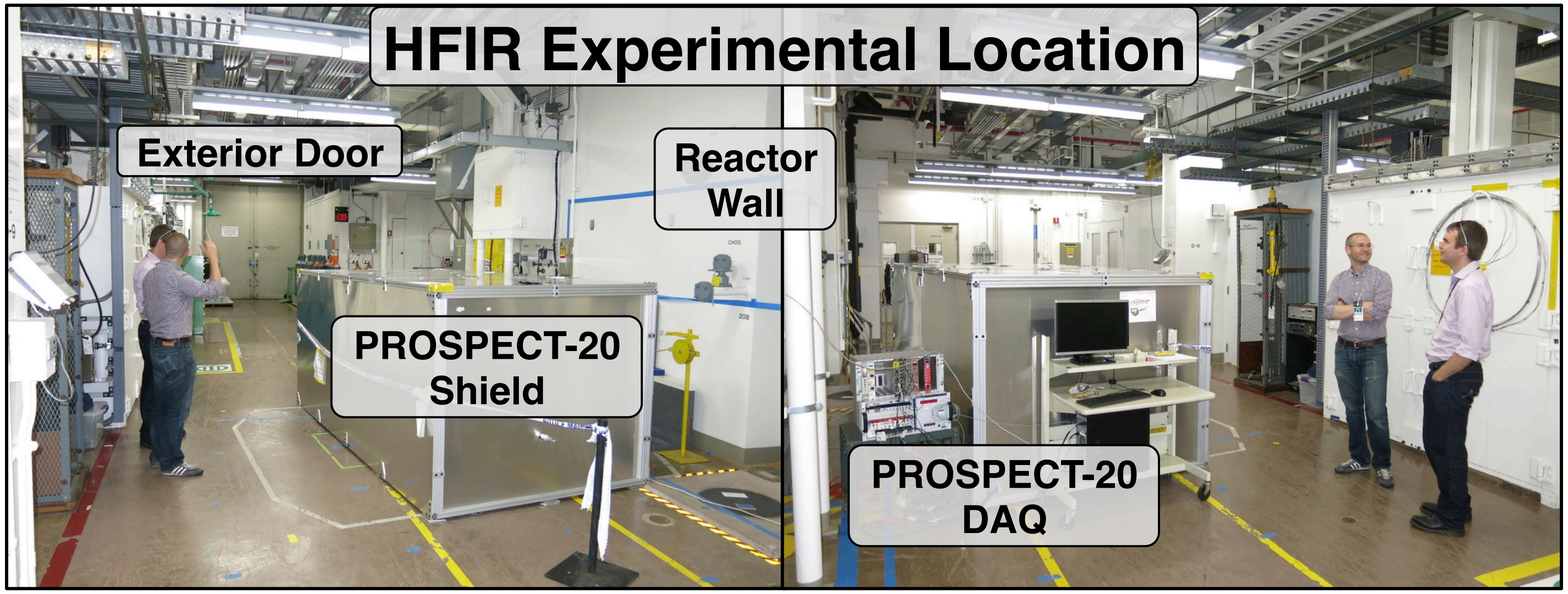


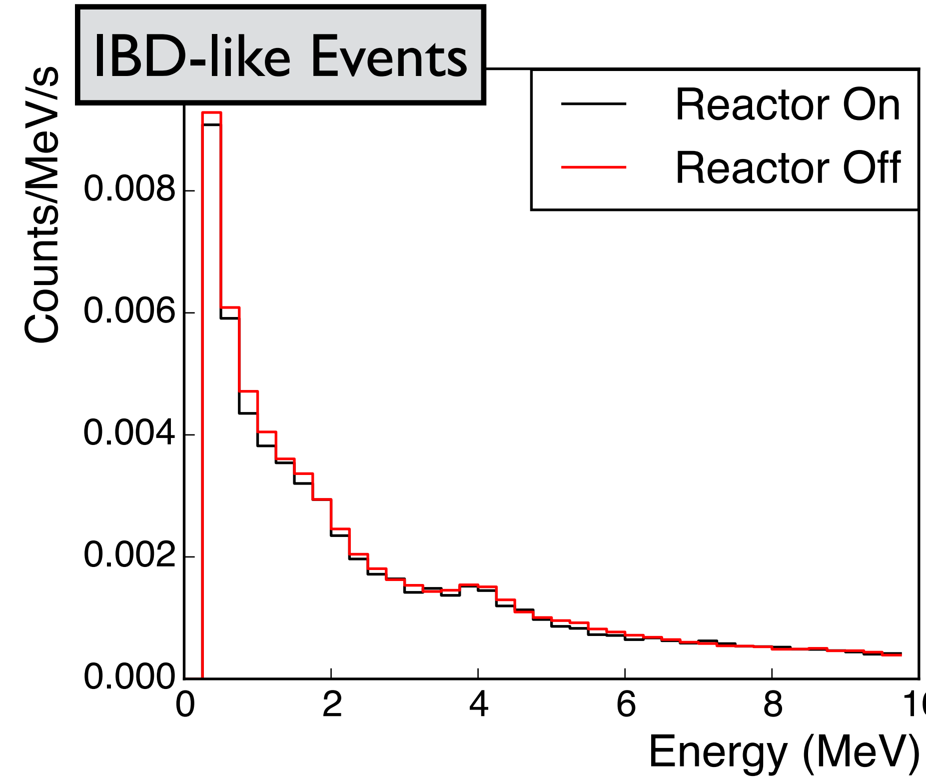




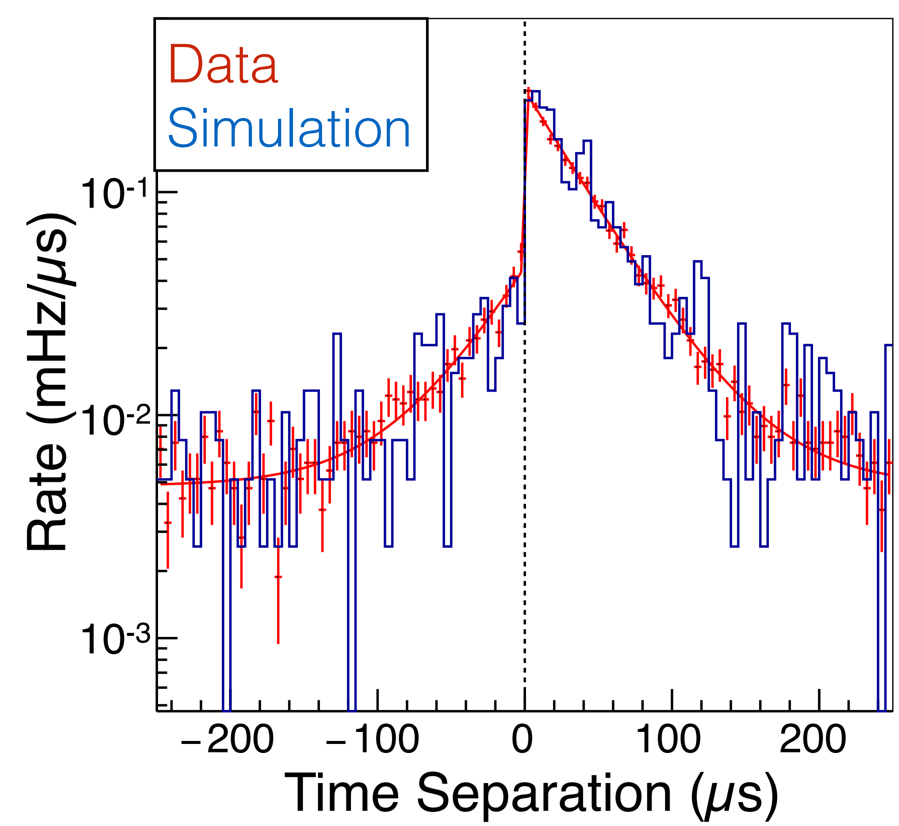
PROSPECT-20 Paper arXiv:1508.06575

Operation of PROSPECT-20 at HFIR

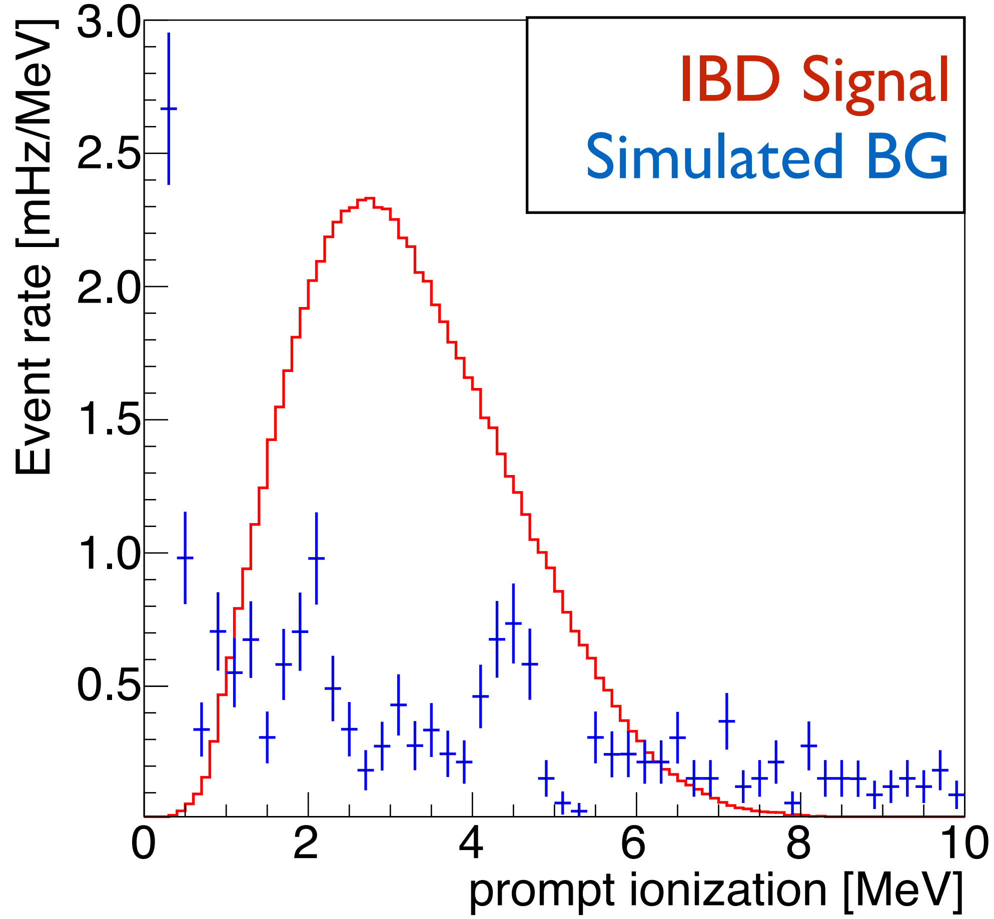


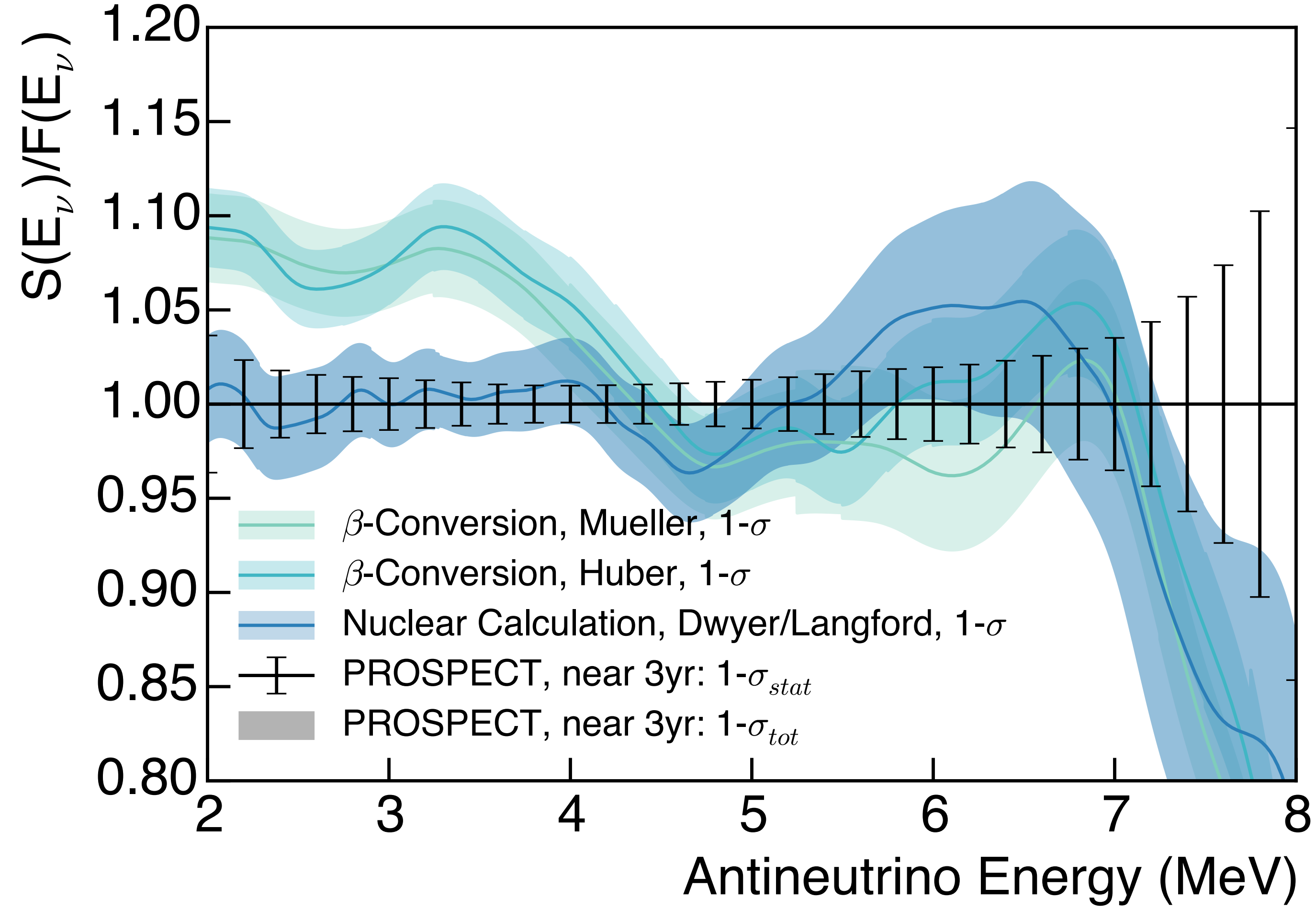


- Operated for four months at HFIR
  - Two HFIR cycles
- Shielding package roughly 25% mass of full shield
- Reactor-related backgrounds mitigated
  - Targeted local shielding
  - Active background rejection with LiLS
- **Validation of background simulations for full PROSPECT detector**



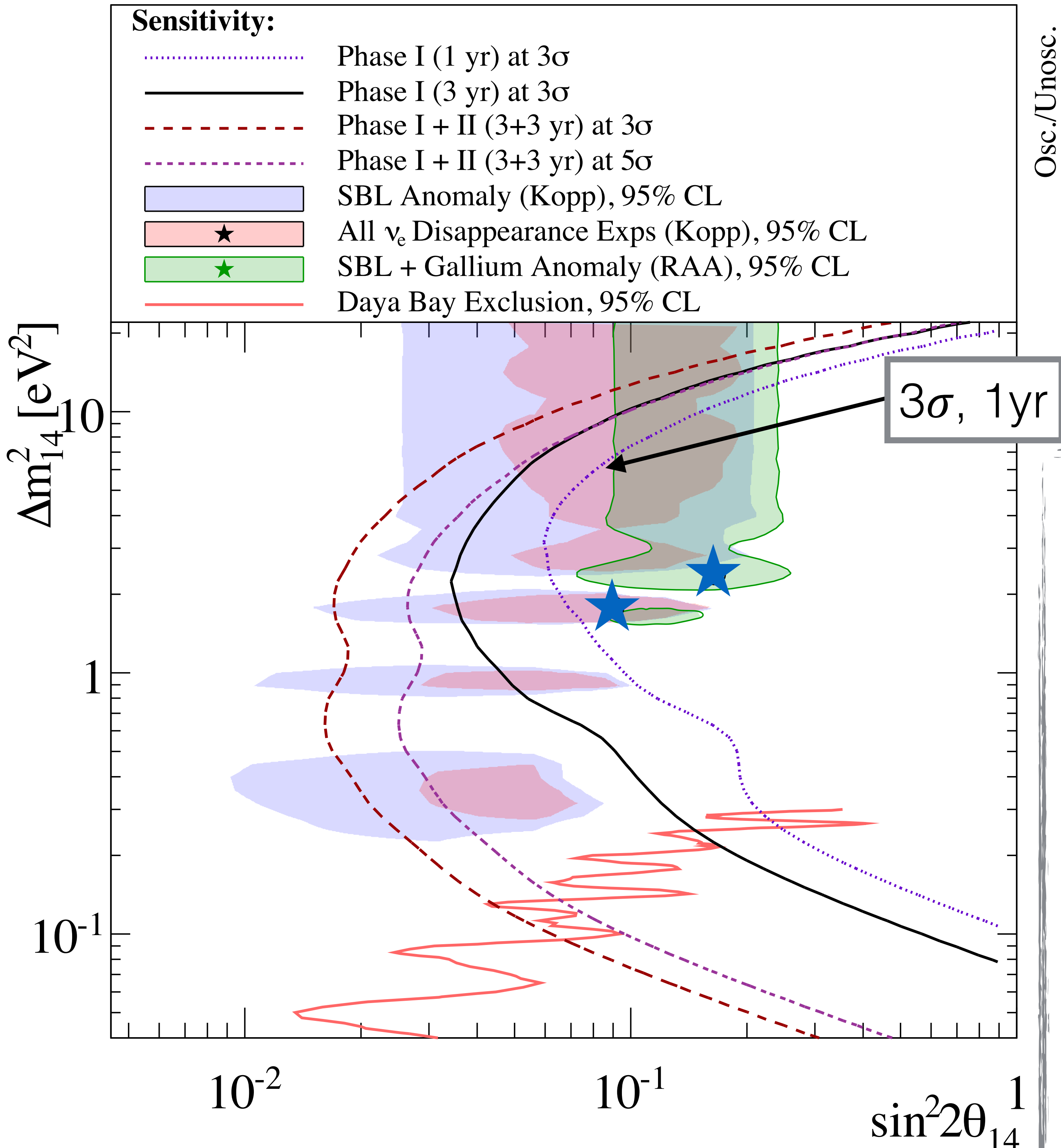
^{235}U Spectrum Measurement

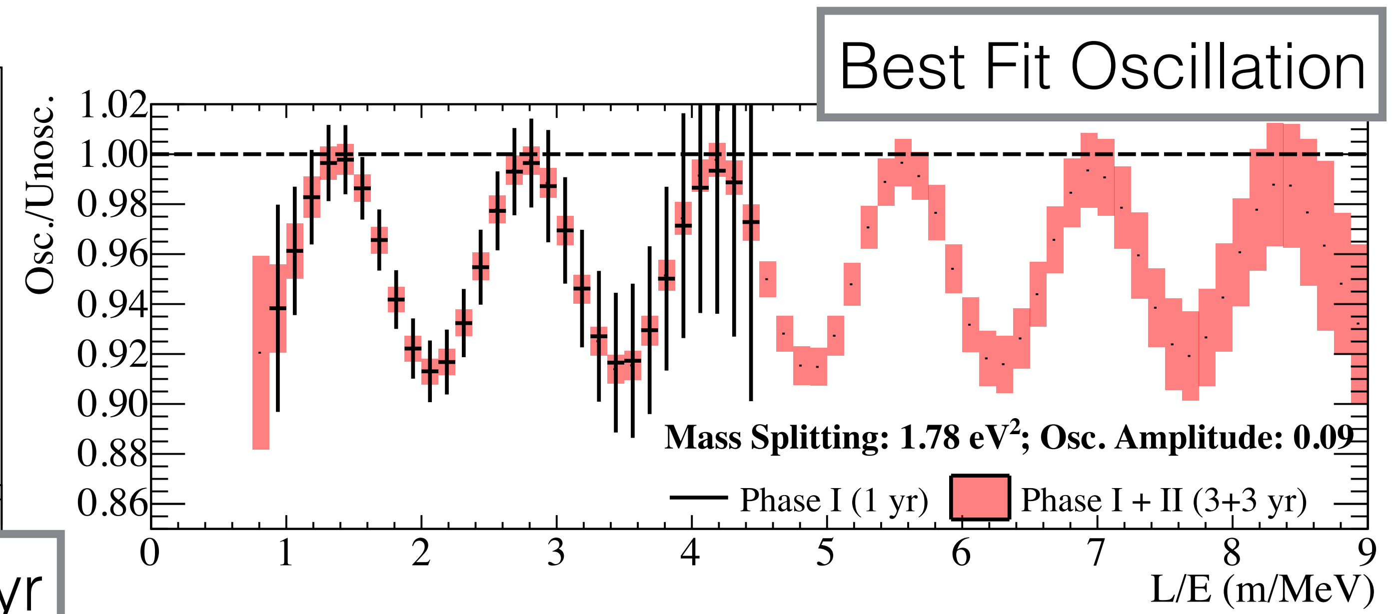




- Simulated Signal/Background > 1, validated by PROSPECT-20 at HFIR
- ~1000 inverse beta decays detected per day, 100k/year
- Best energy resolution of any reactor neutrino experiment (4.5%@1MeV)
- **Phase-1 precision will surpass spectral model uncertainties**
  - Directly test reactor neutrino models
  - Produce a benchmark spectrum for future reactor experiments

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**