PROSPECTs for Sterile Neutrino Searches at Reactors

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(on behalf of the PROSPECT collaboration)

Nu HoRIzons VII

Overview

- Reactor neutrinos and antineutrino flux/spectrum predictions
- Reactor anomalies
- Global efforts addressing anomalies
- PROSPECT experiment

Reactors as Neutrino Sources

Neutrinos are prolific source of neutrinos

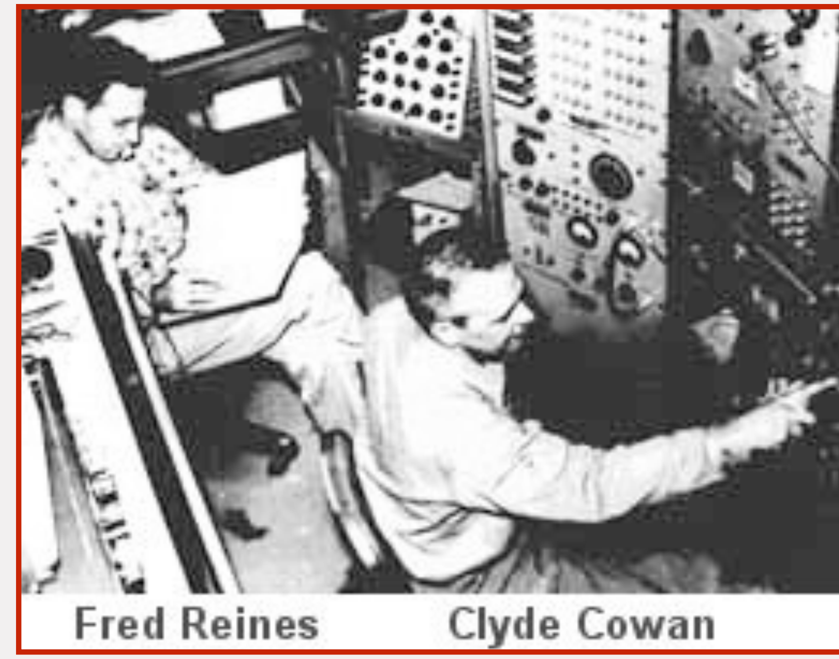
~10^{21} neutrinos per GWth per second

Reactor played crucial role in neutrino history

Discovery

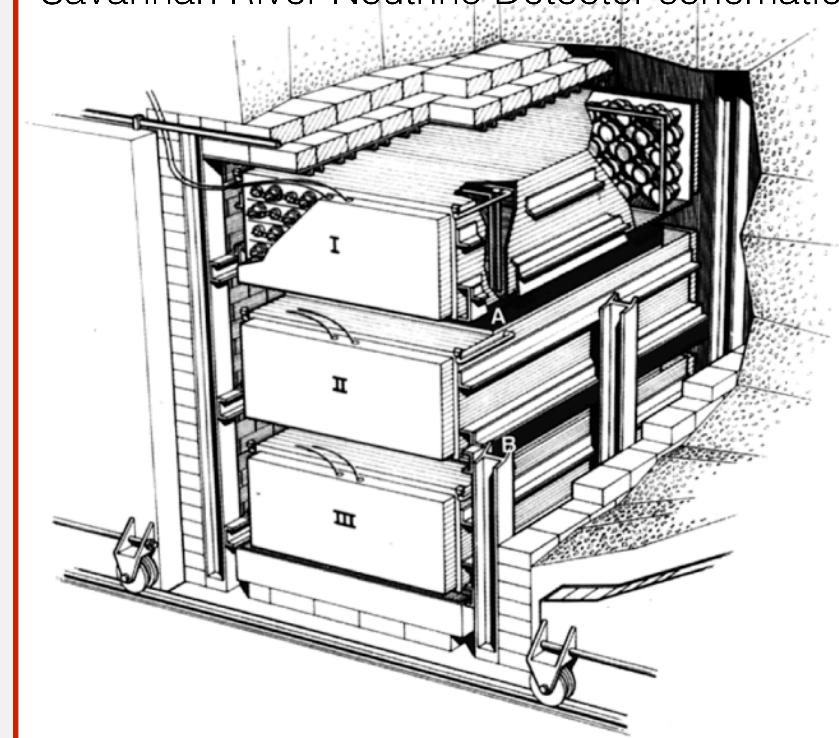
Cross-section measurements

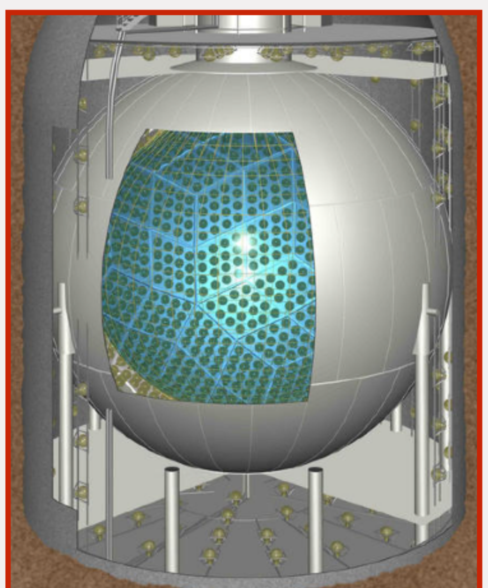
Multiple mixing angle measurements



2016 Breakthrough prize

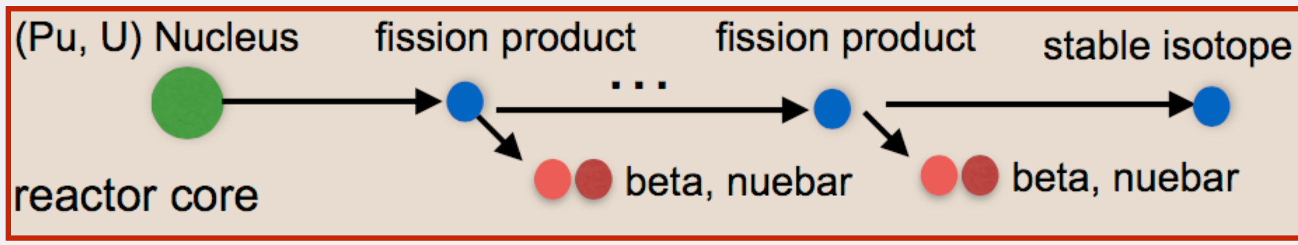
Savannah River Neutrino Detector schematic

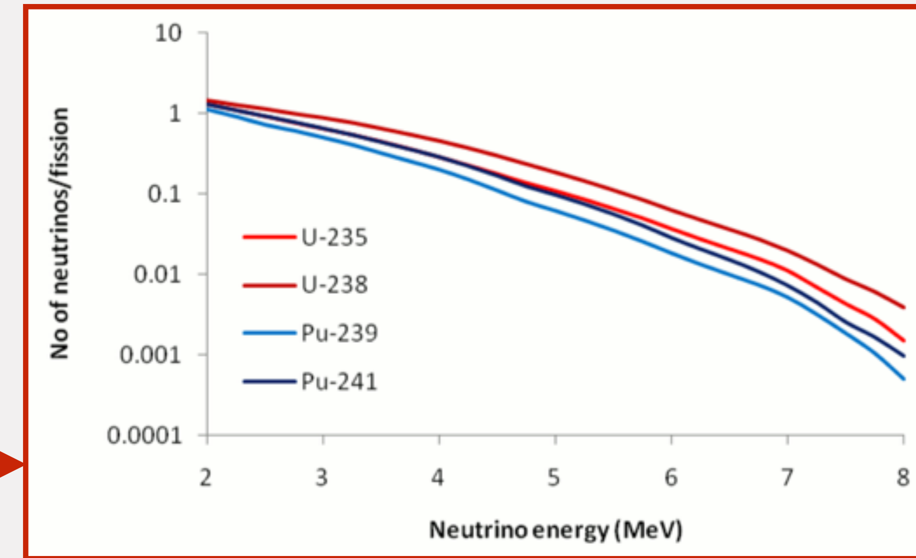


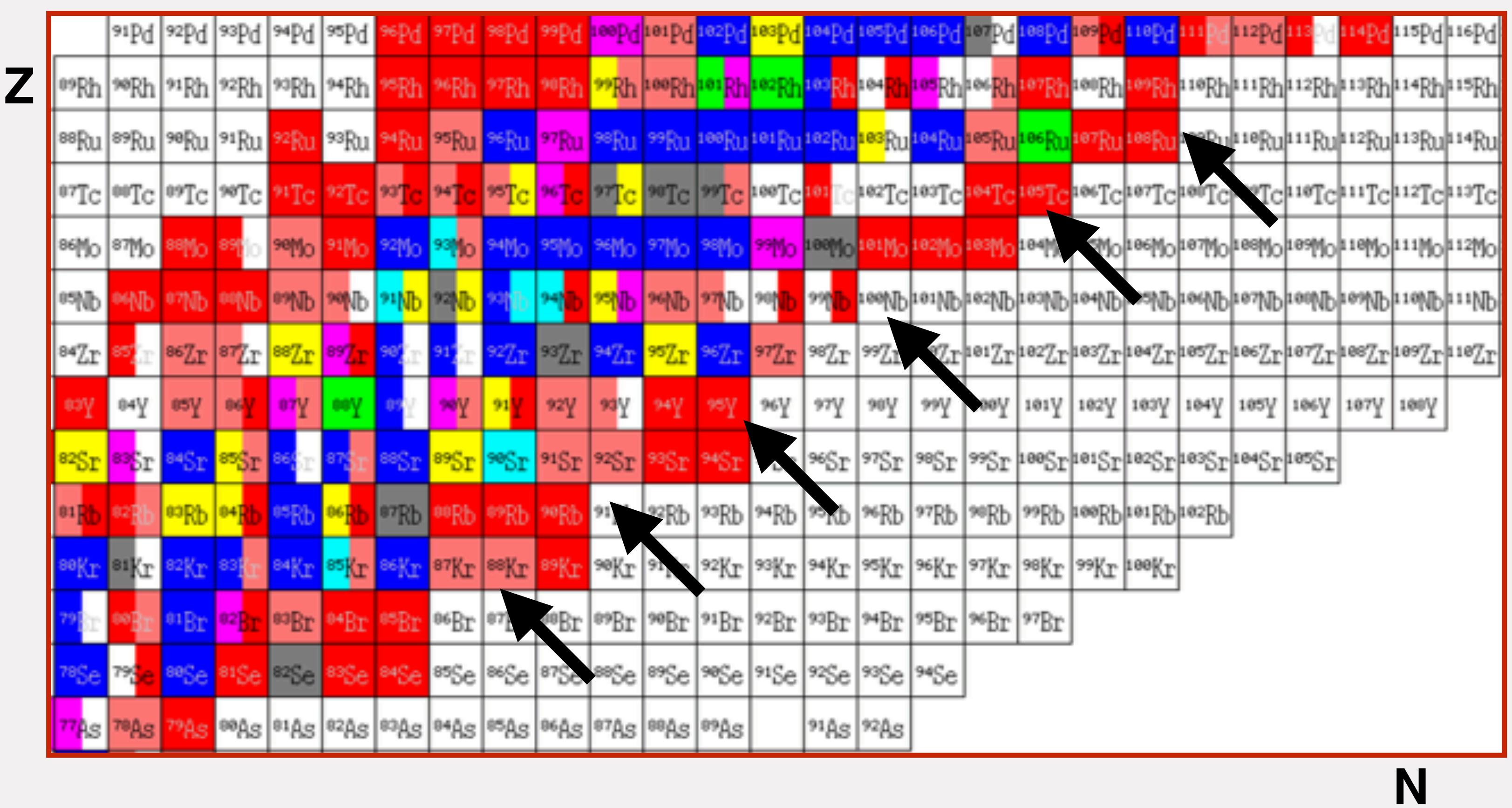


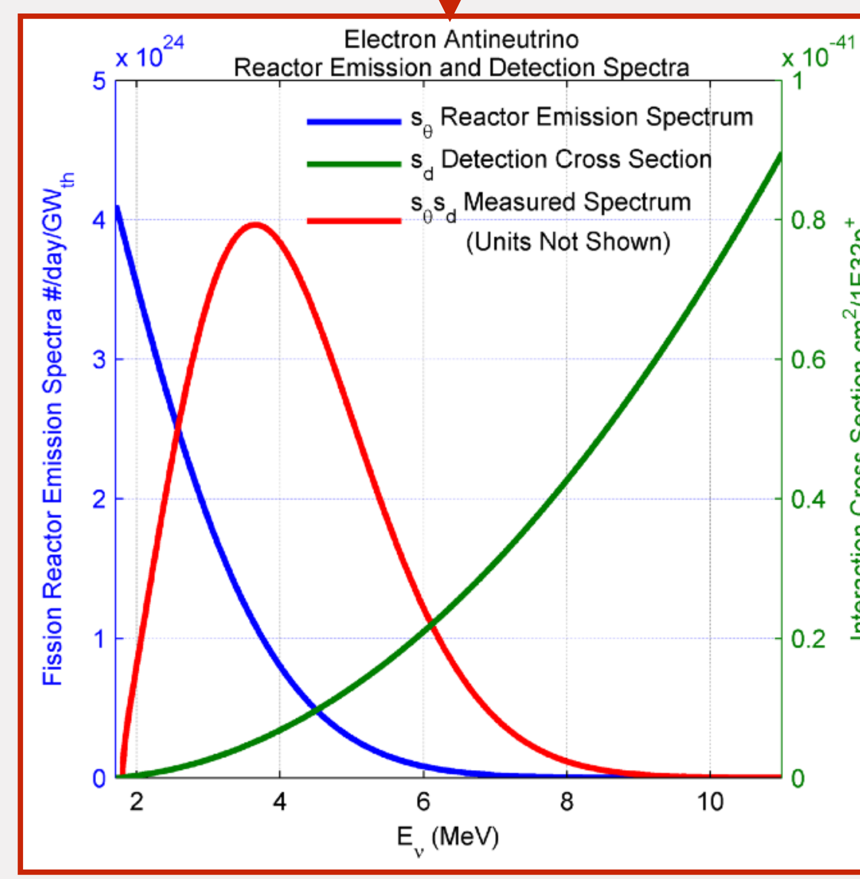
Neutrinos from Reactors

- Four main fission isotopes: ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu
- Fission of fuel in reactor produces neutron rich daughters
- Neutron rich daughters beta decay and produces $\overline{\nu}_e$
- ~6 $\overline{\nu}_e$/fission based on fission isotope





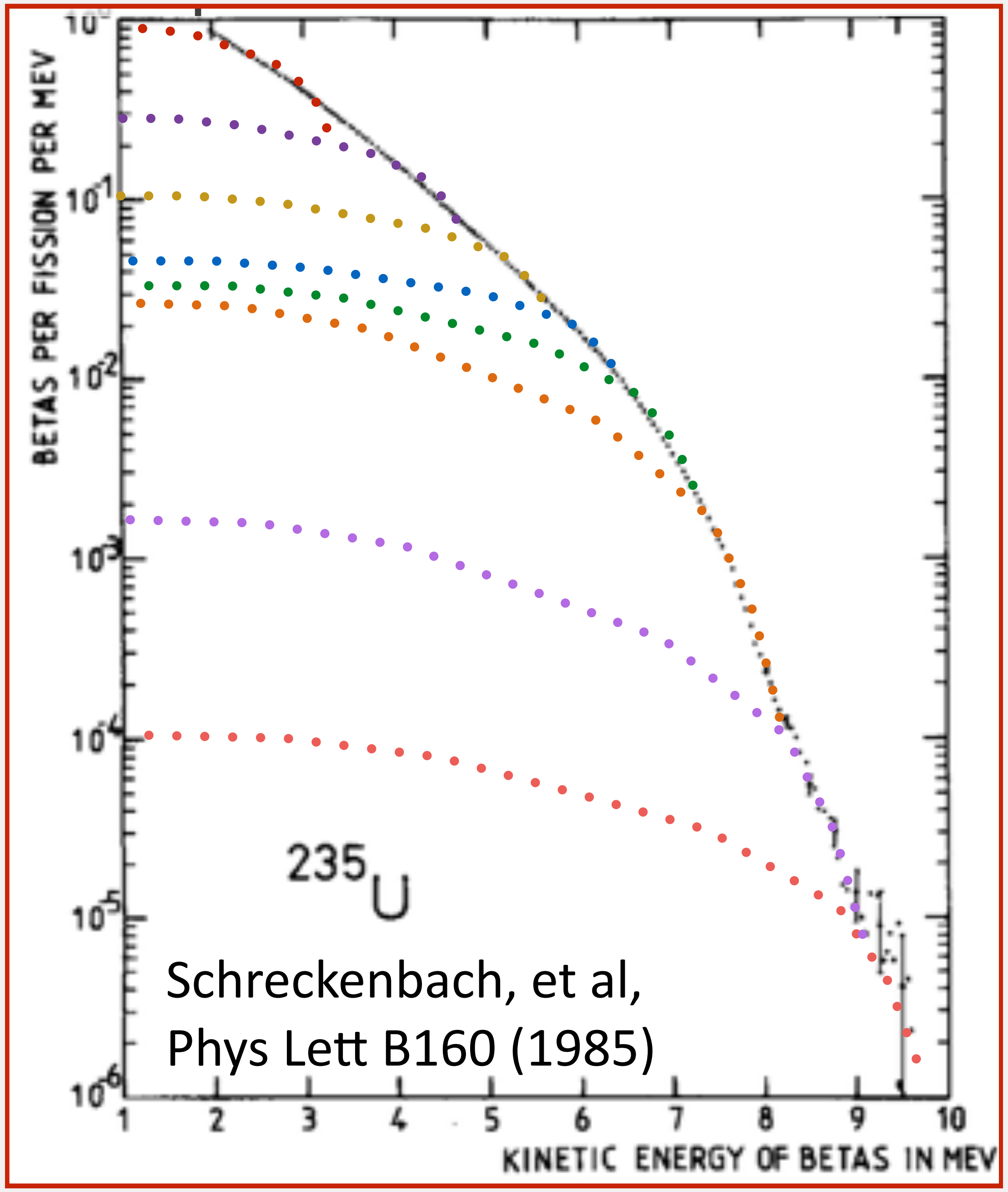




Estimating Neutrino Flux and Spectrum

$$S(E_\nu) = \frac{W_{th}}{\Sigma_i (f_i/F) e_i} \Sigma_i \frac{f_i}{F} \left(\frac{dN_i}{dE_\nu} \right)$$

Conversion Approach



***ab initio* approach**

- Use existing databases and sum the spectra from all the beta decay branches
- Databases are incomplete and uncertainties are big

Conversion method

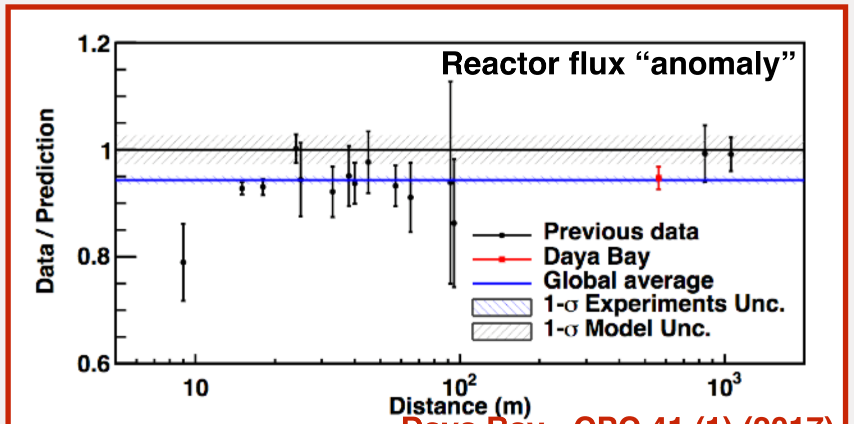
- Measure beta spectrum and fit it to virtual branches to convert to neutrino spectrum
- Assumptions impact the output i.e., forbidenness, weak magnetism and finite size corrections etc.

Hybrid Approach

- *ab initio* for available data and use virtual beta branches for the rest

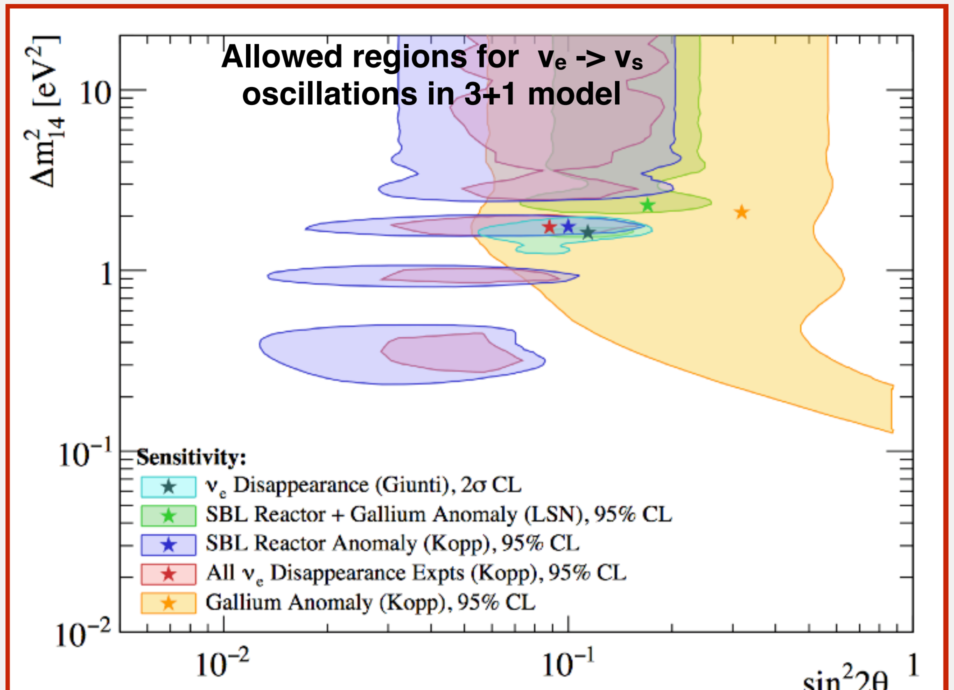
Anomalies

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



Daya Bay - CPC 41 (1) (2017)

Additional sterile neutrino could be a possible reason for the deficit



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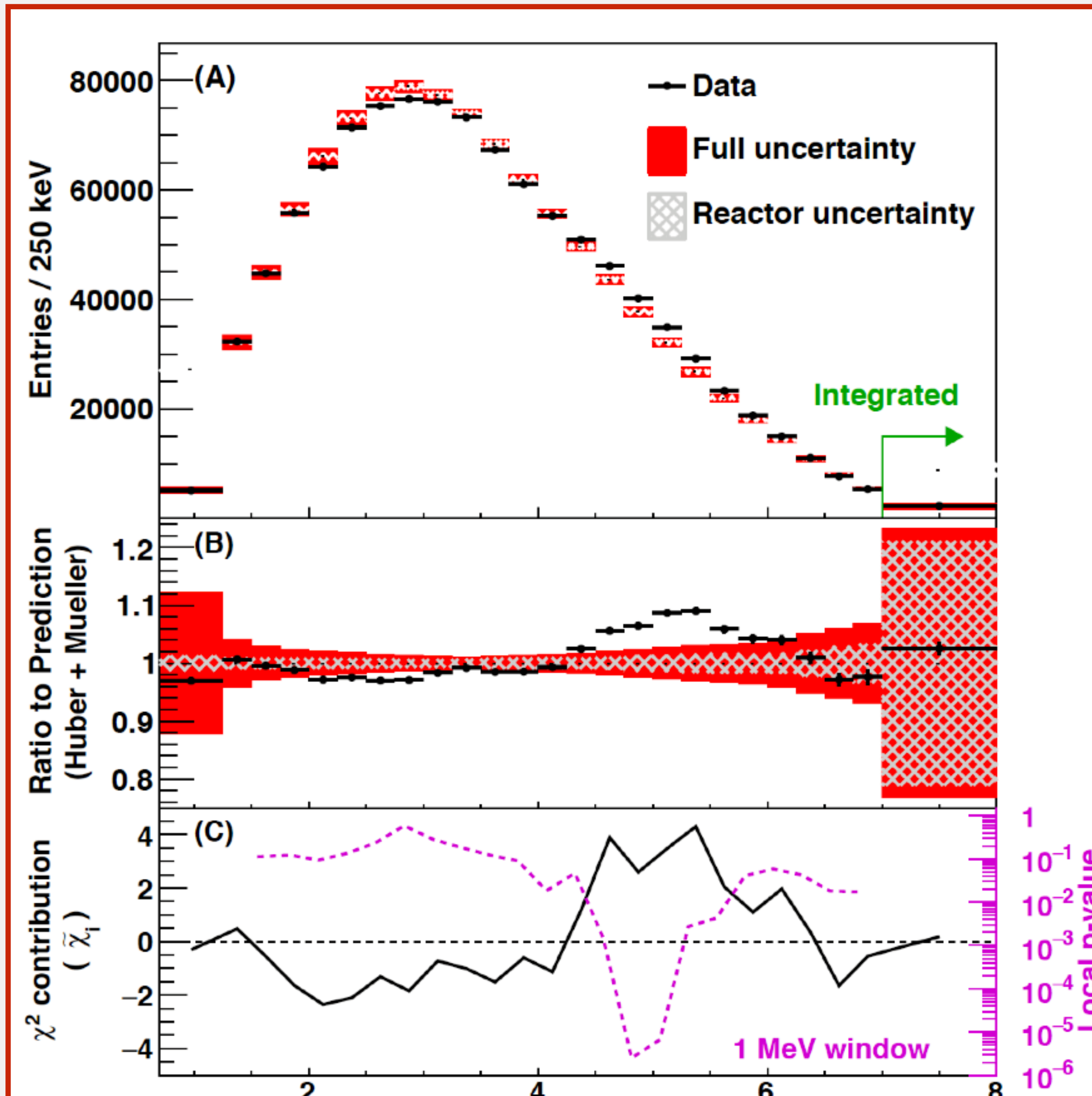
Large mass splitting -> ~Meter length oscillations

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

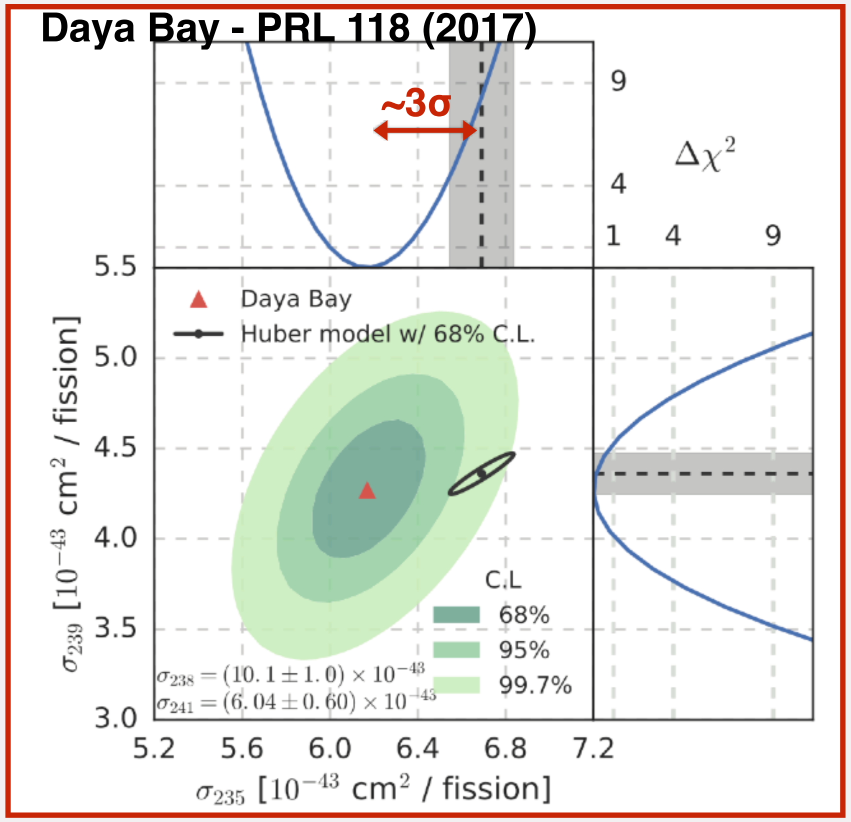


Daya Bay - CPC 41 (1) (2017)

Motivates reactor experiment with different fuel types and good energy resolution

More Discrepancies

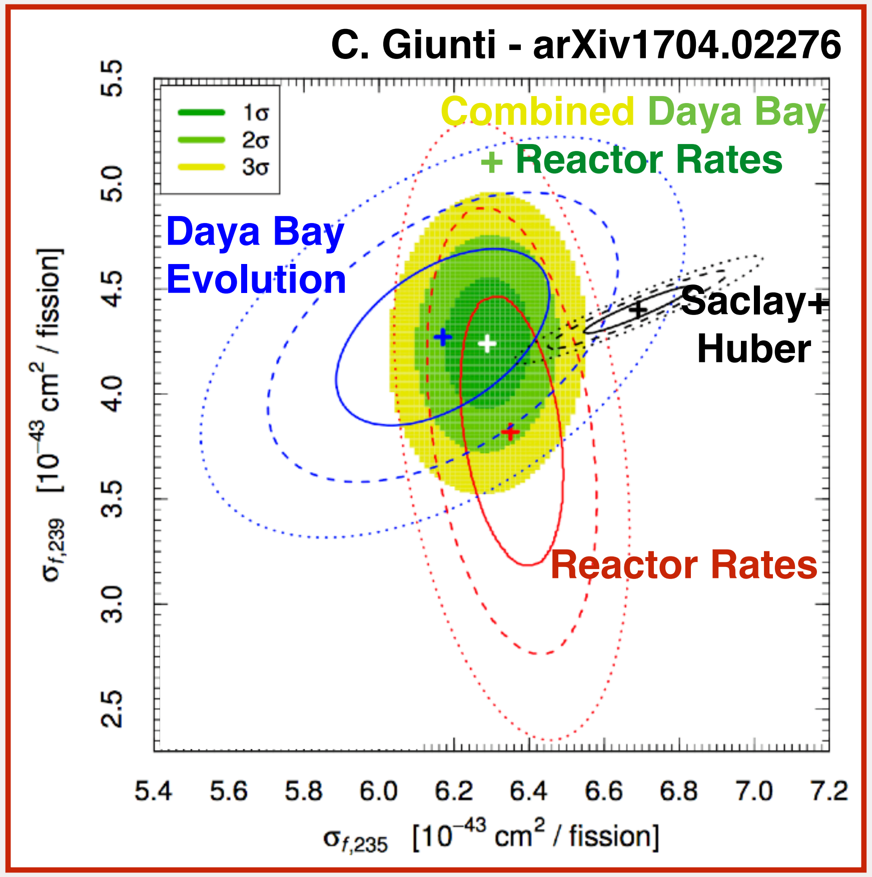
- Daya Bay has recently reported IBD yields of U235 and Pu239 using evolution of LEU reactor fuel
- Showed that reactor flux models are incorrect at least for U235



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 not agree with Daya Bay measurement



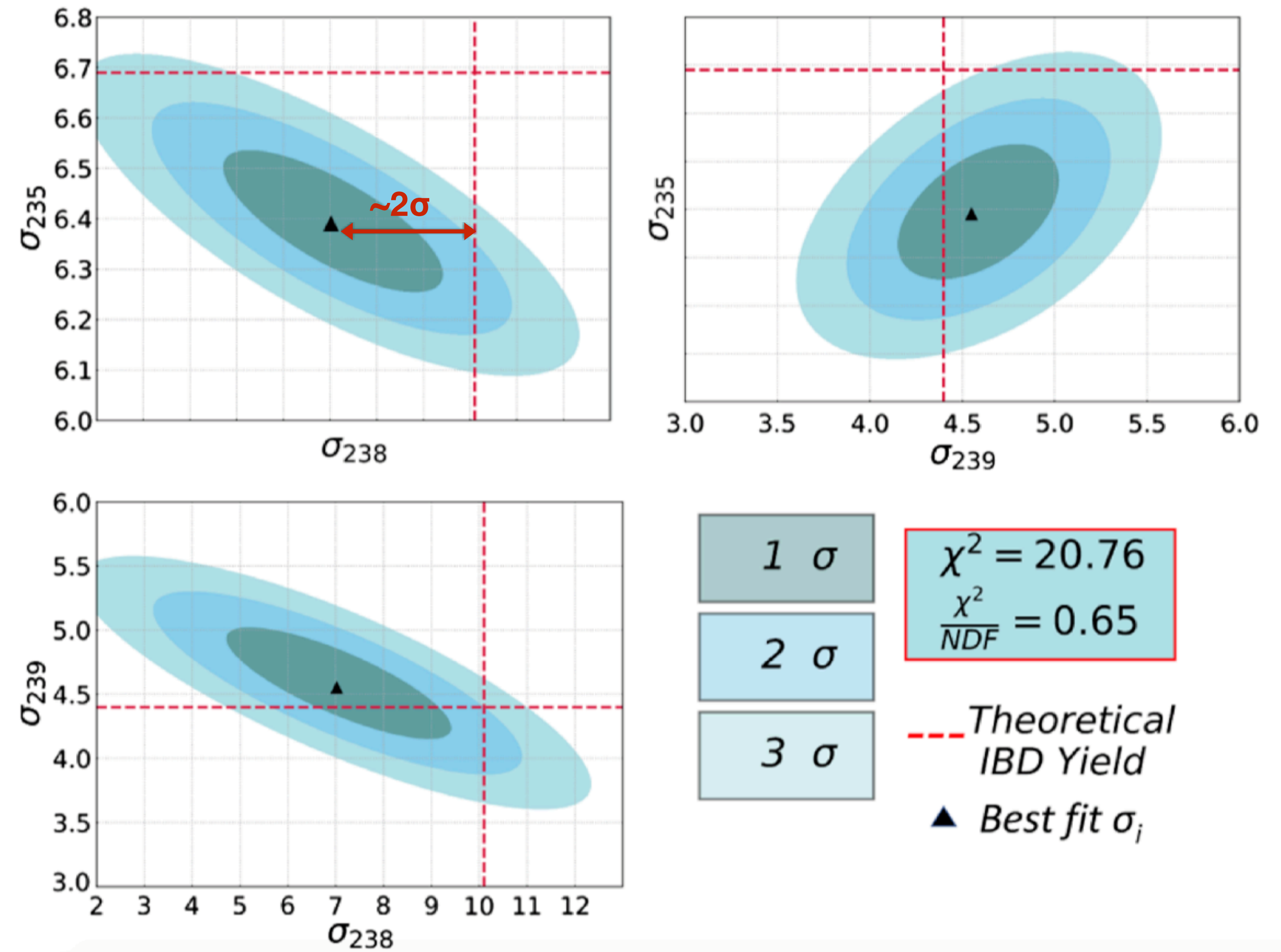
- Daya Bay results in global context creates tension in IBD yields
- Oscillation to sterile states not considered

Possible, but not definite

Further Perspective

$$\chi^2 = \sum_{a,b}\left(\sigma_{f,a} - \sum_i F_{i,a}\sigma_i\right)\mathrm{V}^{-1}_{ab}\left(\sigma_{f,b} - \sum_i F_{i,b}\sigma_i\right) + \frac{(\sigma_1^{th} - \sigma_1)^2}{V_{\mathrm{ext},11}}.$$

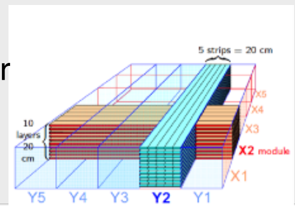
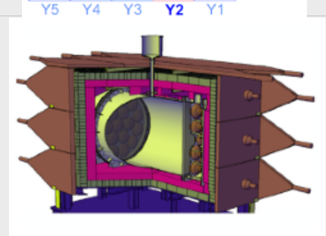
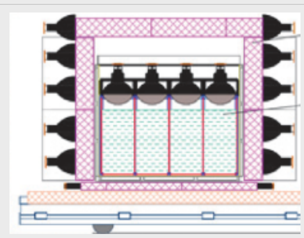
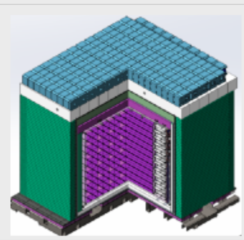
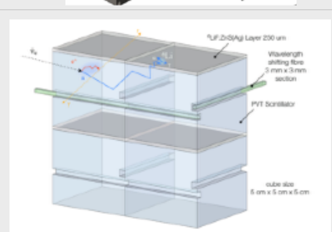
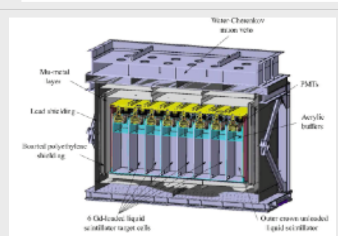
- A combination fit with Daya Bay evolution data and global reactor rate data with only constraints on the ^{241}Pu was generated
- ^{238}U IBD yield obtained is ~2σ away from prediction
- Possible reasons for this discrepancy:
    - Sterile neutrinos + Wrong ^{235}U or ^{239}Pu flux estimates
    - Wrong ^{238}U and ^{235}U and/or ^{239}Pu flux estimates
    - Incorrect experimental IBD yields



Y. Gebre, B. R. Littlejohn, P. T. Surukuchi, PRD 97, 013003

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

Global Efforts

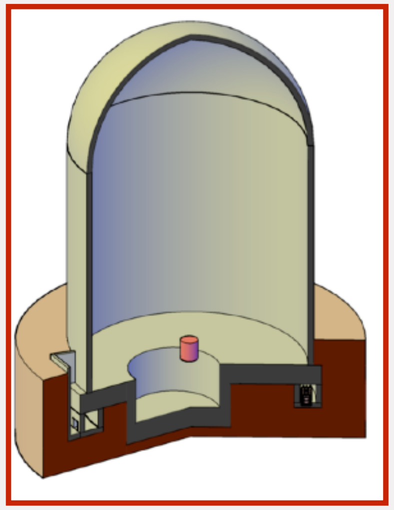
Experiment	Reactor/Fuel	Baseline (m)	Mobility	Detection Material	Segmentation	Readout	Energy Resolution	PID	Status
DANSS Kalinin nuclear reactor (Russia) 	3000 MWth LEU	10.7-12.7	Yes	PS+Gd Sheets	2D, 5mm	WLS fibers + SiPM and PMT	25%/√E	Topology	Collecting data
NEOS Hanbit nuclear power complex (Korea) 	2800 MWth LEU	~24	No	GdLS	-	PMT Double-ended	5% @ 1MeV	Recoil PSD	Phase-1 complete
Neutrino-4 SM-3 reactor (Russia) 	100 MWth HEU	6-12	Yes	GdLS	2D, 10 cm	PMT Single-ended	Not available	Topology	Phase-1 complete
PROSPECT High Flux Isotope Reactor (USA) 	**85 MWth HEU**	**7-12**	**Yes**	**^{6}LiLS**	**2D, 14.6 cm**	**PMT Double-ended**	**4.5%/√E**	**Topology + recoil and capture PSD**	**Commissioning and installation in progress**
Soliδ BR2 research reactor (Belgium) 	40-80 MWth HEU	6-9	No	PVT cubes+ ^{6}Li:ZnS(Ag) sheets	3D, 5 cm	WLS fibers + SiPM	20%/√E	Topology + capture PSD	Collecting data
STEREO ILL research reactor (France) 	58 MWth HEU	9-11	No	GdLS	2D, 25 cm	PMT Single-ended	12% @ 2 MeV	Recoil PSD	Collecting data

Some values from Mauro Mezzetto, neutrino 2016

DANSS and NEOS performed oscillation analysis

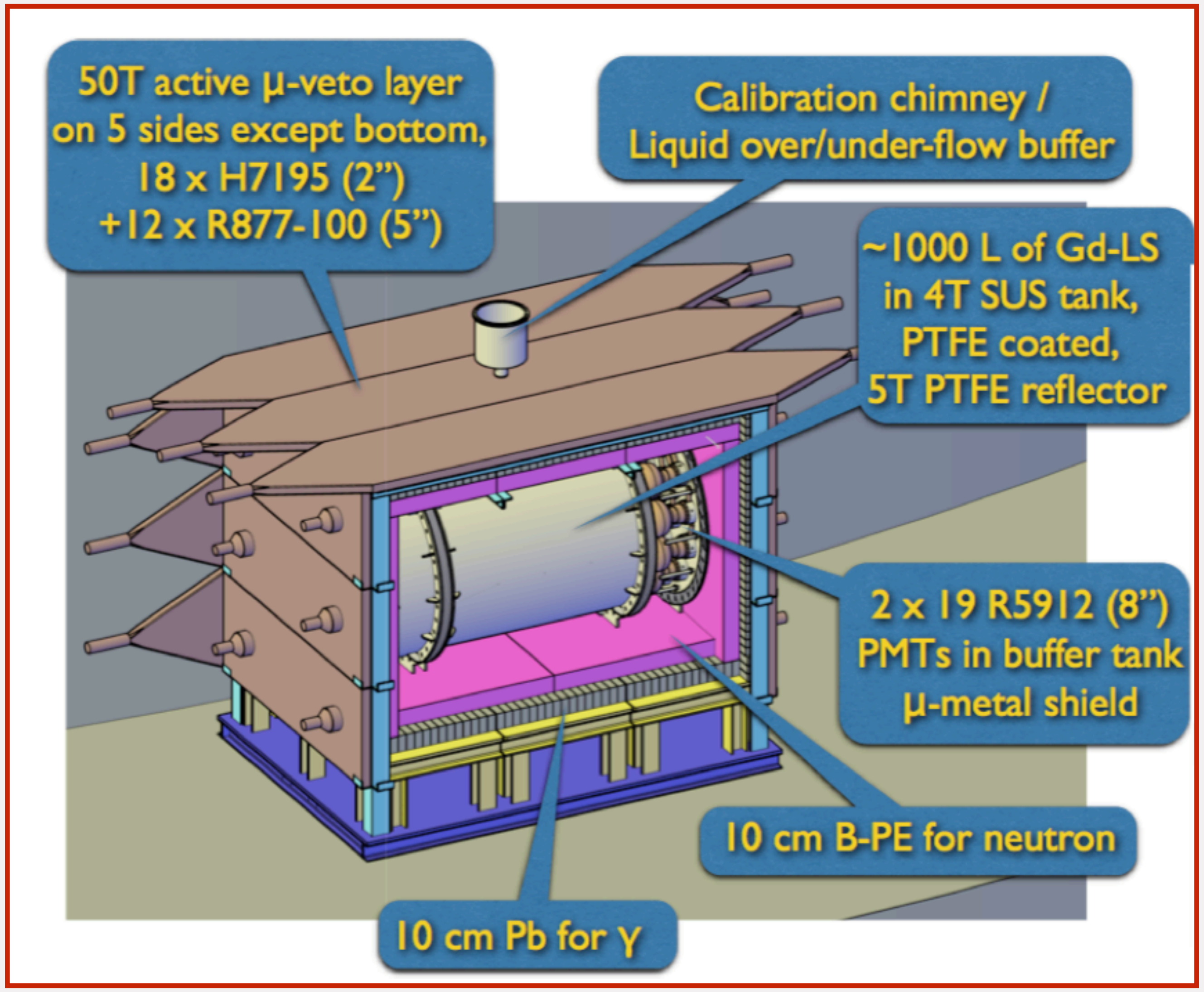
PROSPECT

NEOS - Experimental Setup



Experiment Location

- **2.8 GWth** LEU reactor
- **3.1 m diameter x 3.7 m height**
- Detector **24 m** away
- ~20 mwe overburden



Detector Characteristics:

LS:

- **1008 L single** volume tank
- **LAB+UG-F (9:1) with 0.5% Gd**
- 38 x 8" PMTs in mineral oil buffer

Shielding:

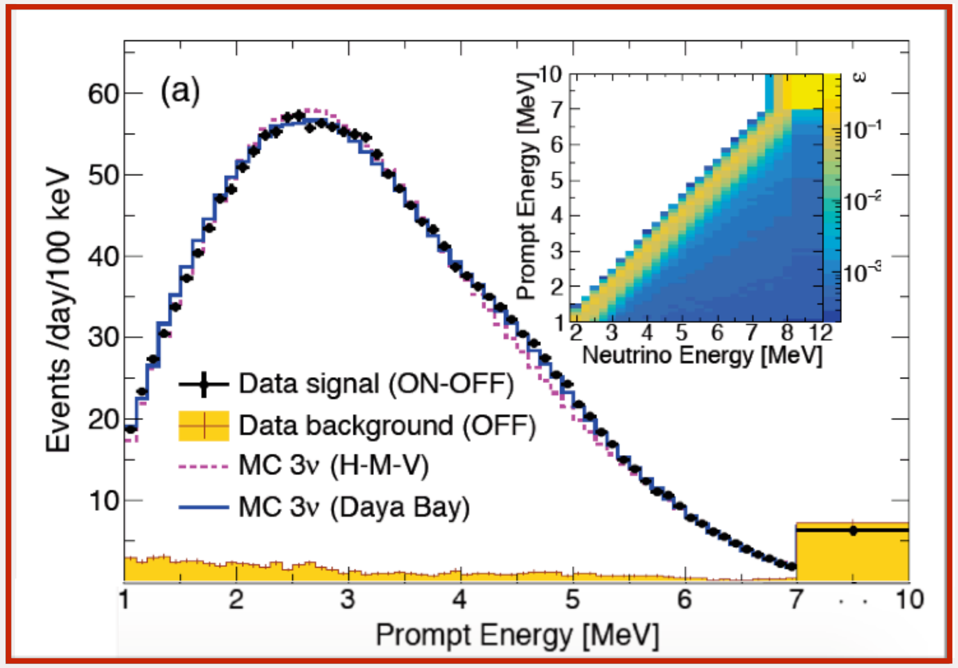
- Passive - 10 cm BPE and 10 cm Pb
- Active - 50T muon veto on 5 sides
- Chimney for source calibration
- **Resolution = 5 % @ 1 MeV**

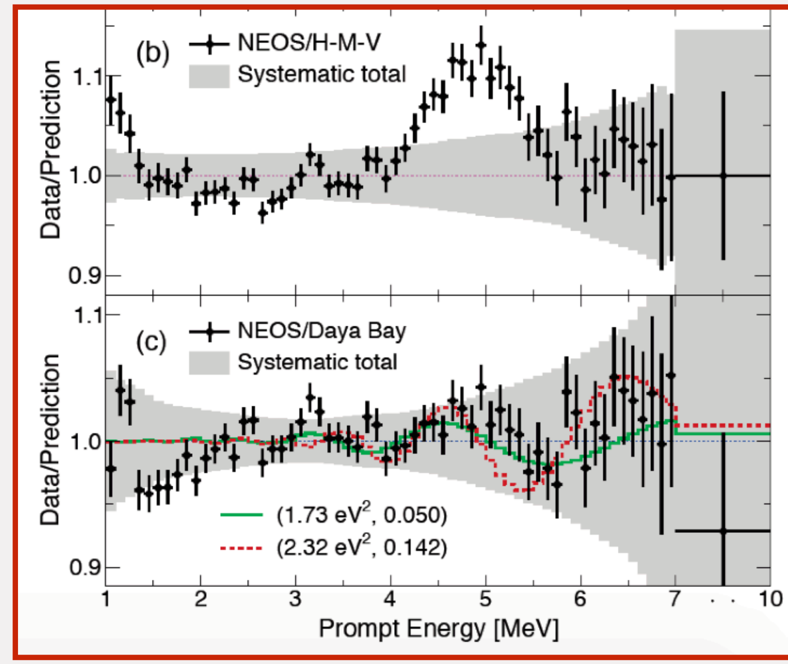
Data:

- 180 days reactor on and 46 reactor off
- 1976.7±3.4(85.1±1.4) reactor on(off) IBDs/day
- **S:B = ~23**

NEOS - Results

- 5 MeV bump seen at this short baseline
- **Relative comparison between NEOS and modified Daya Bay near spectrum**
- Normalization and covariance matrices unclear
- No strong evidence for oscillations

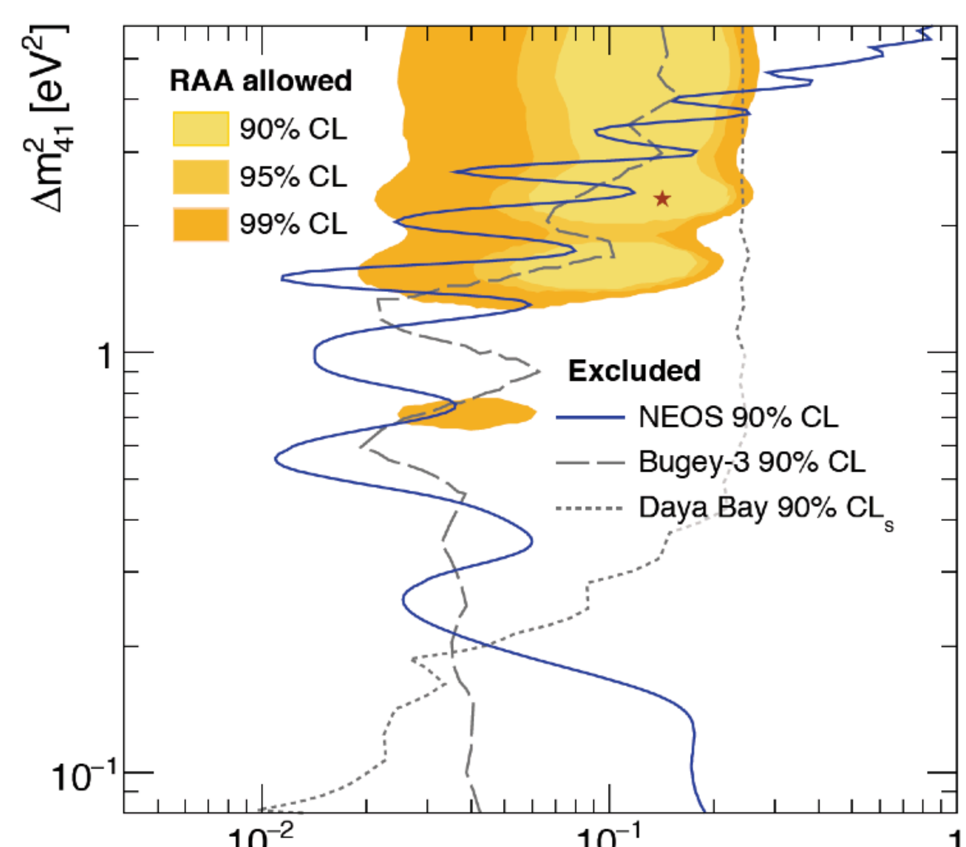




Take DYB quoted unfolded covariance matrices
Convolve with detector response matrix
Add stats and detector syst

Daya Bay unfolded spectrum modified to account for different fission fractions. Detector response applied to it.

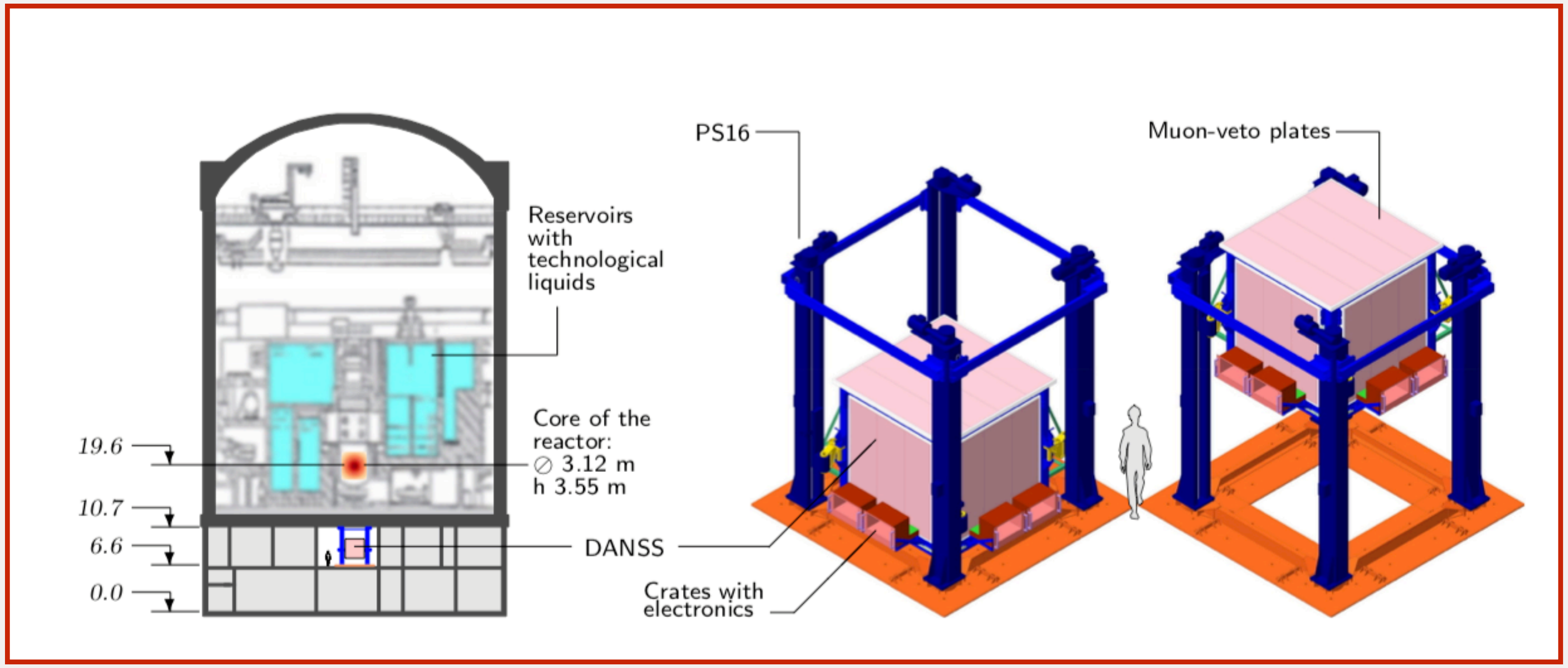
$$\chi^2 = \sum_{i=1}^{N}\sum_{j=1}^{N}\left(M_i - \frac{t_{\rm on}}{t_{\rm off}}B_i - T_i\right)\boxed{V_{ij}^{-1}}\left(M_j - \frac{t_{\rm on}}{t_{\rm off}}B_j - \boxed{T_j}\right), \quad (3)$$



Phys. Rev. Lett. 118. 121802 (2017)

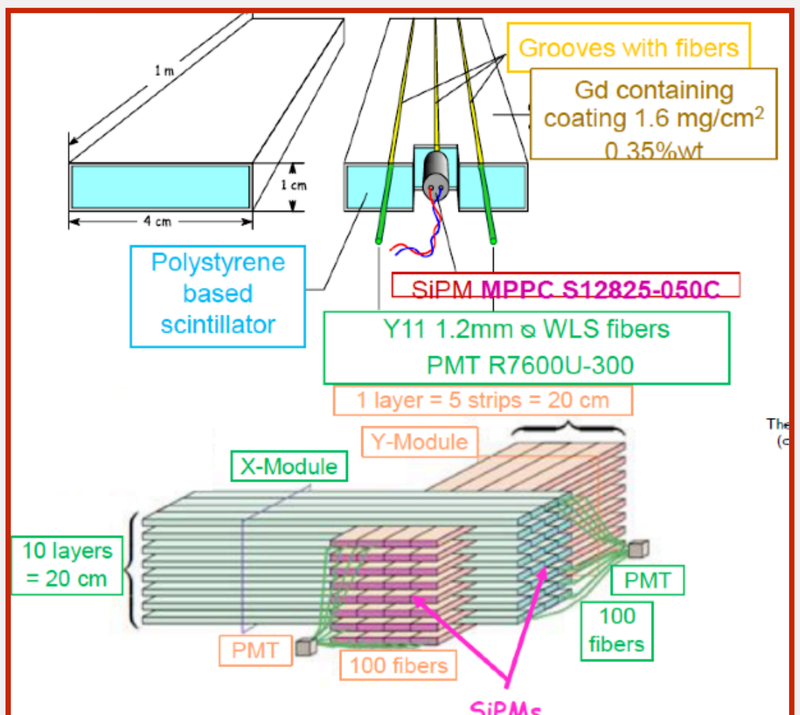
- Plan to restart taking data for a longer period
- Observe fuel evolution over 500 days
- Different range of fission fractions from Daya Bay

DANSS - Experimental Setup



Experiment Location

- 3 GWth LEU reactor
- **3.1 m diameter x 3.7 m height**
- Detector **10.7-12.7 m** away
- ~50 mwe overburden



Detector Characteristics:

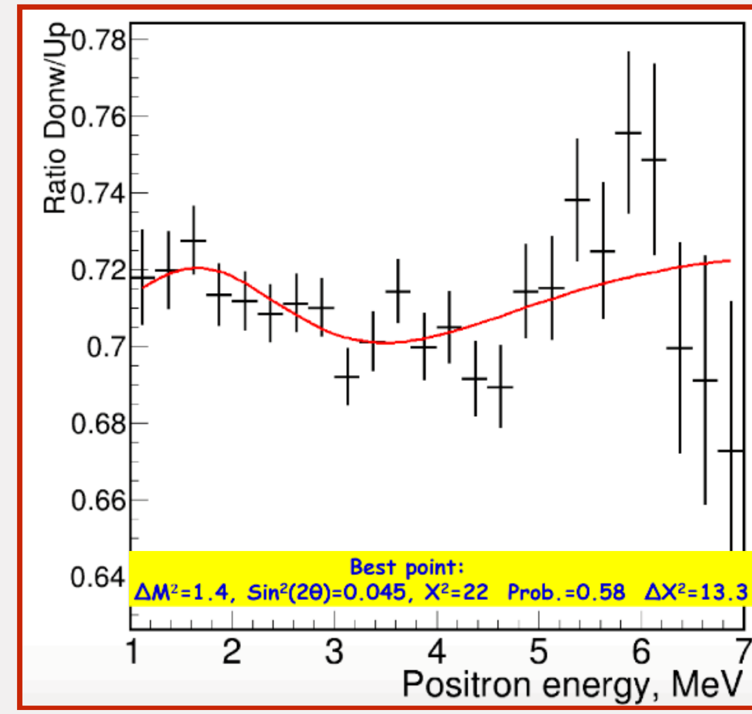
- Movable detector
- 2500 polystyrene-based scintilllator strips
- **Gd coating with 0.35% by weight**
- 3 WLS fibers: 1 fiber readout by SiPM side fibers bunched and read out by PMT

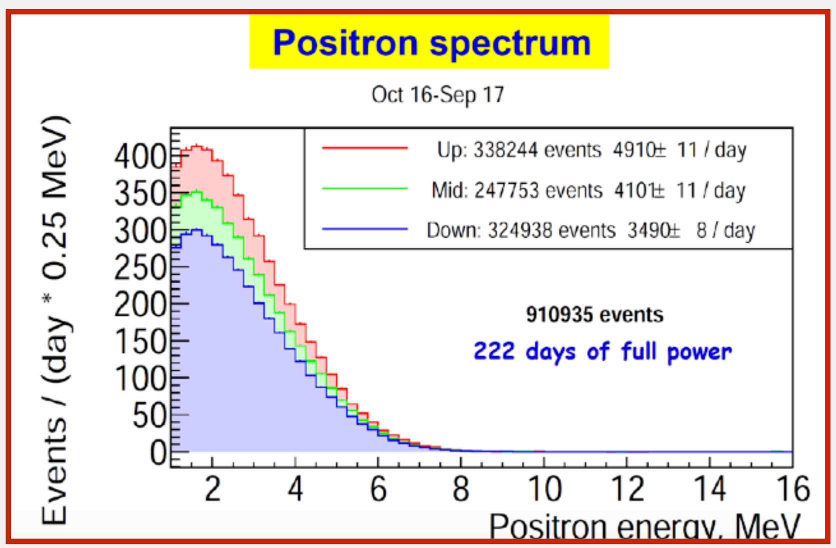
Shielding:

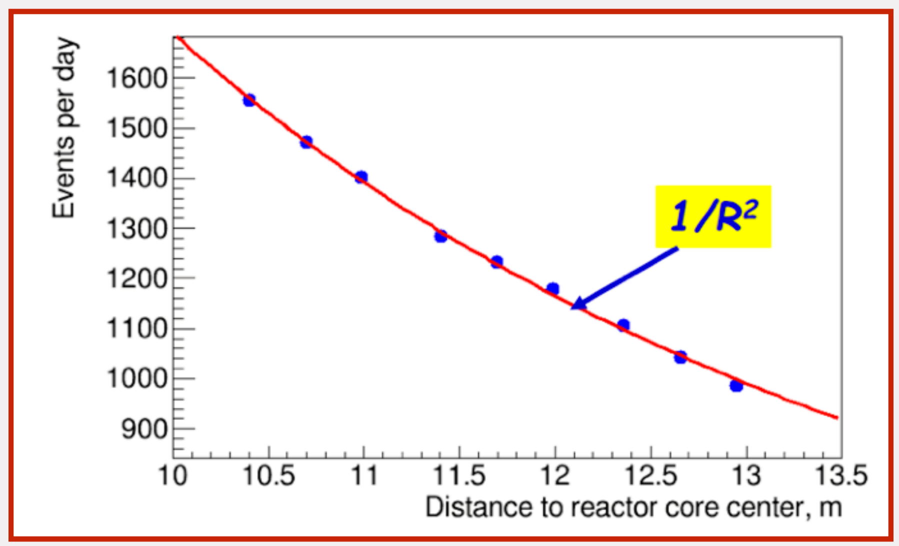
- Passive - 5 cm electrolytic copper, 8 cm BPE, 5 cm Pb, and 8 cm BPE
- Active - Muon veto on 5 sides
- **Resolution = 25 %**

DANSS - Data

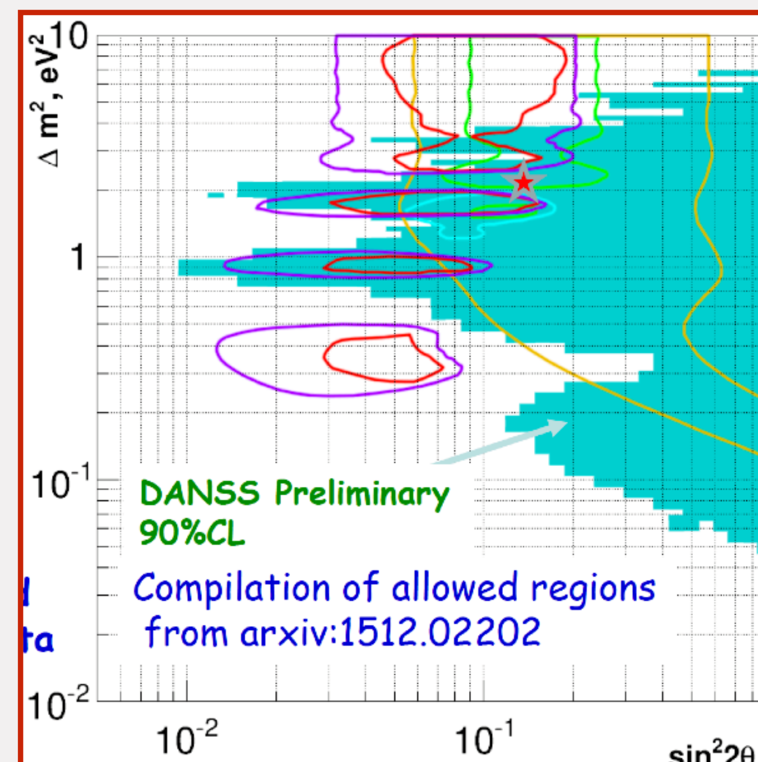
- Data collected for 222 days
- **~5000 events/day** in fiducial volume at the closest position
- 3 baselines at 3 positions
- $1/R^2$ dependence observed
- For oscillation analysis, ratio of spectrum at 10.7(up) m to 12.7m(down) fit to oscillation model
- Used gaussian CLs method for fitting
- Unclear on the systematics taken into account
- Best-fit points excluded at 90% CL







Exclusion Curve



- Plan to continue data taking
- Perform better calibration and systematic studies
- Use Feldman-Cousins method

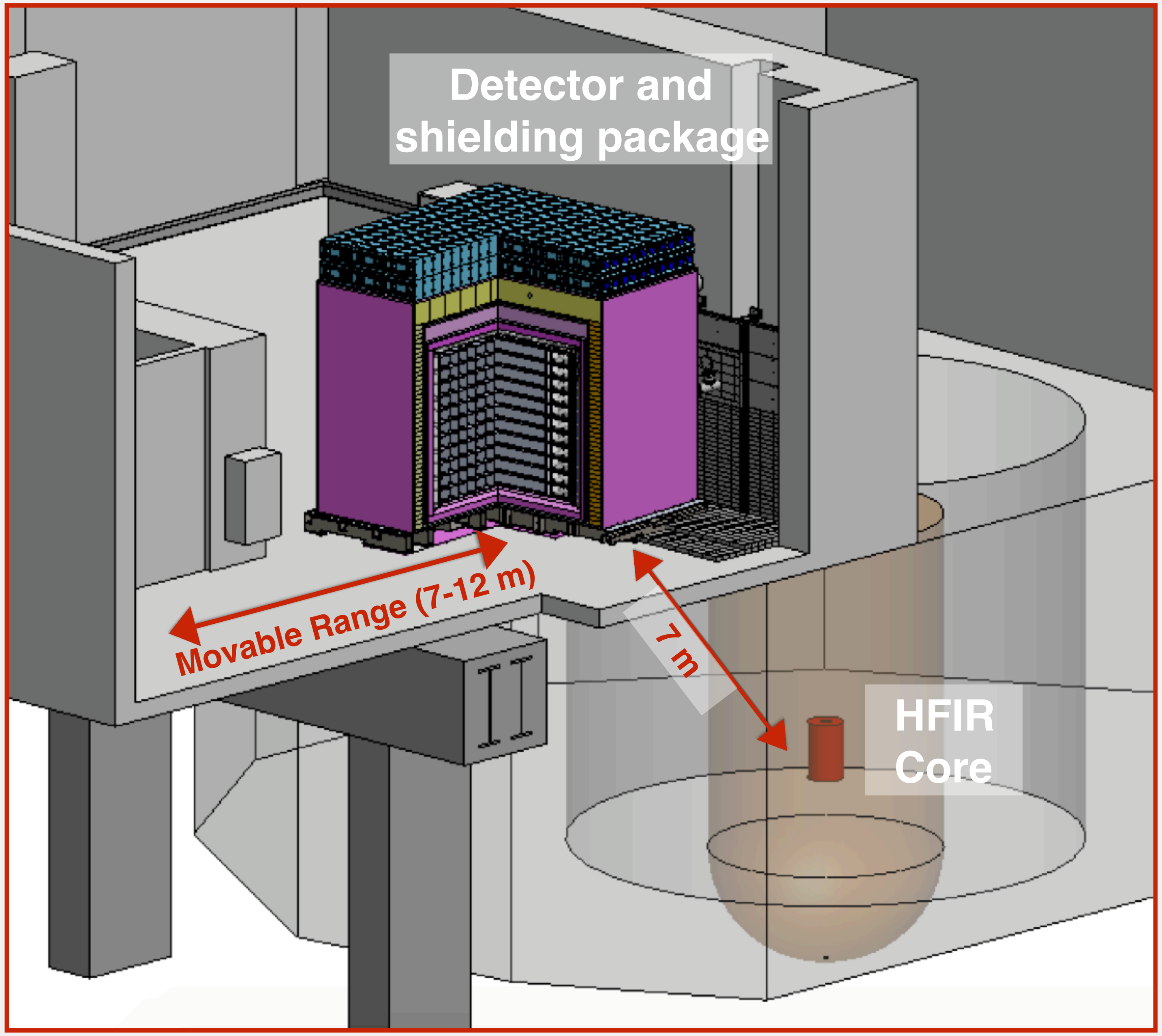
Danilov at Solvay Workshop

PROSPECT Experiment

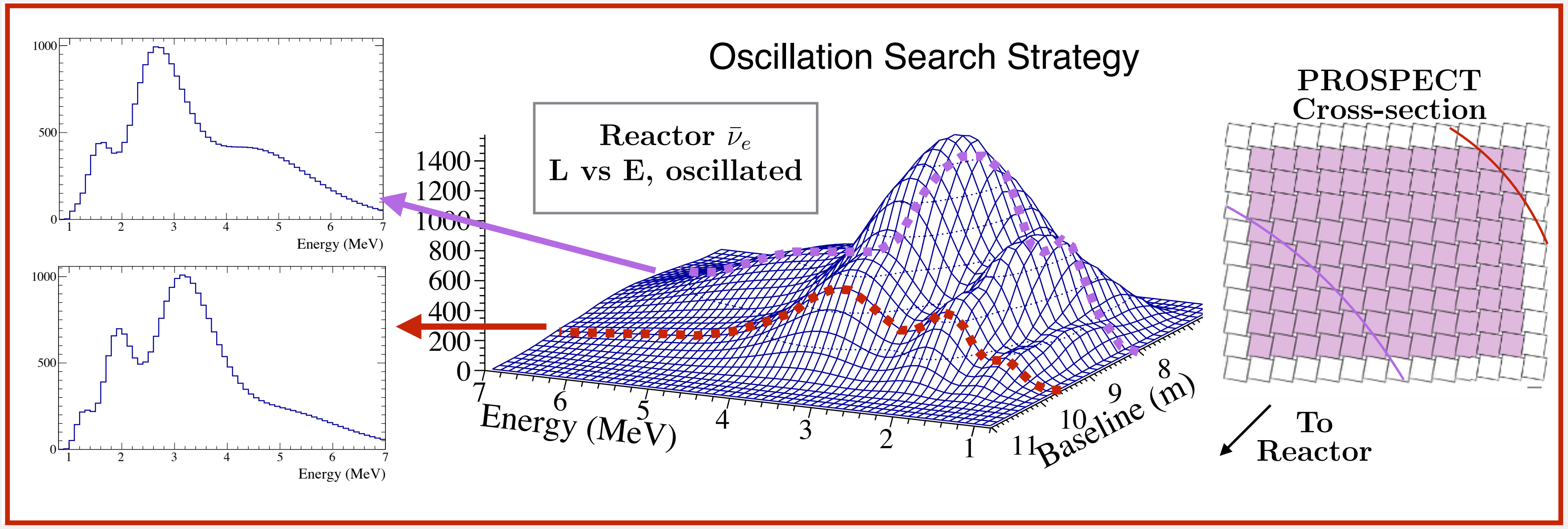
PROSPECT Experiment

Physics Goals:

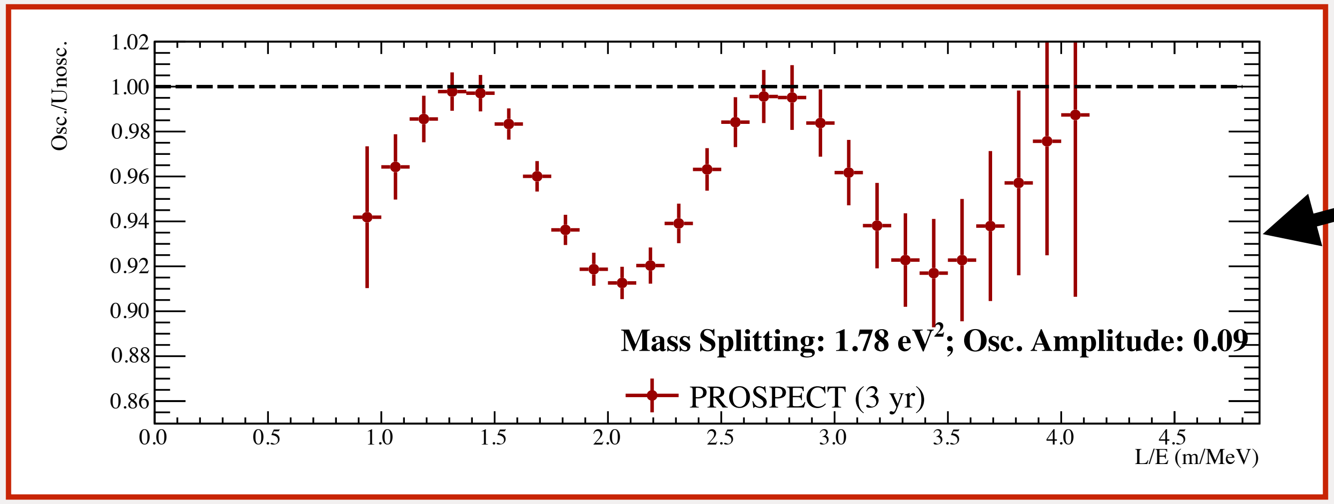
1. Precisely measure reactor ^{235}U $\bar{\nu}_e$ spectrum
2. Search for short-baseline oscillations arising from eV-scale sterile neutrinos



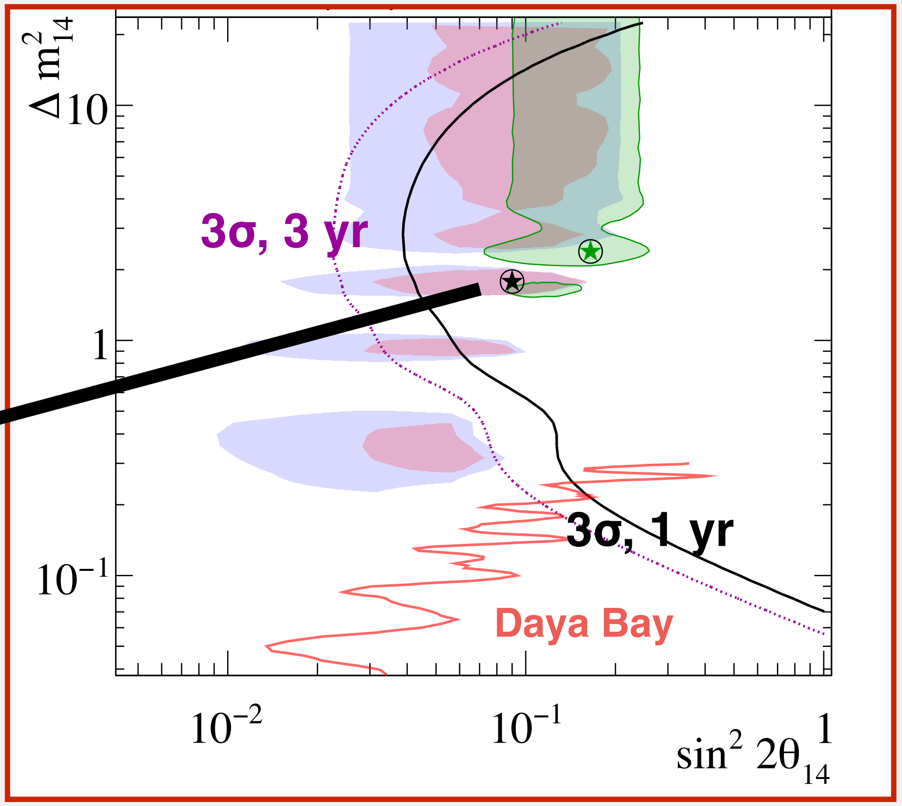
Oscillation Search



- 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



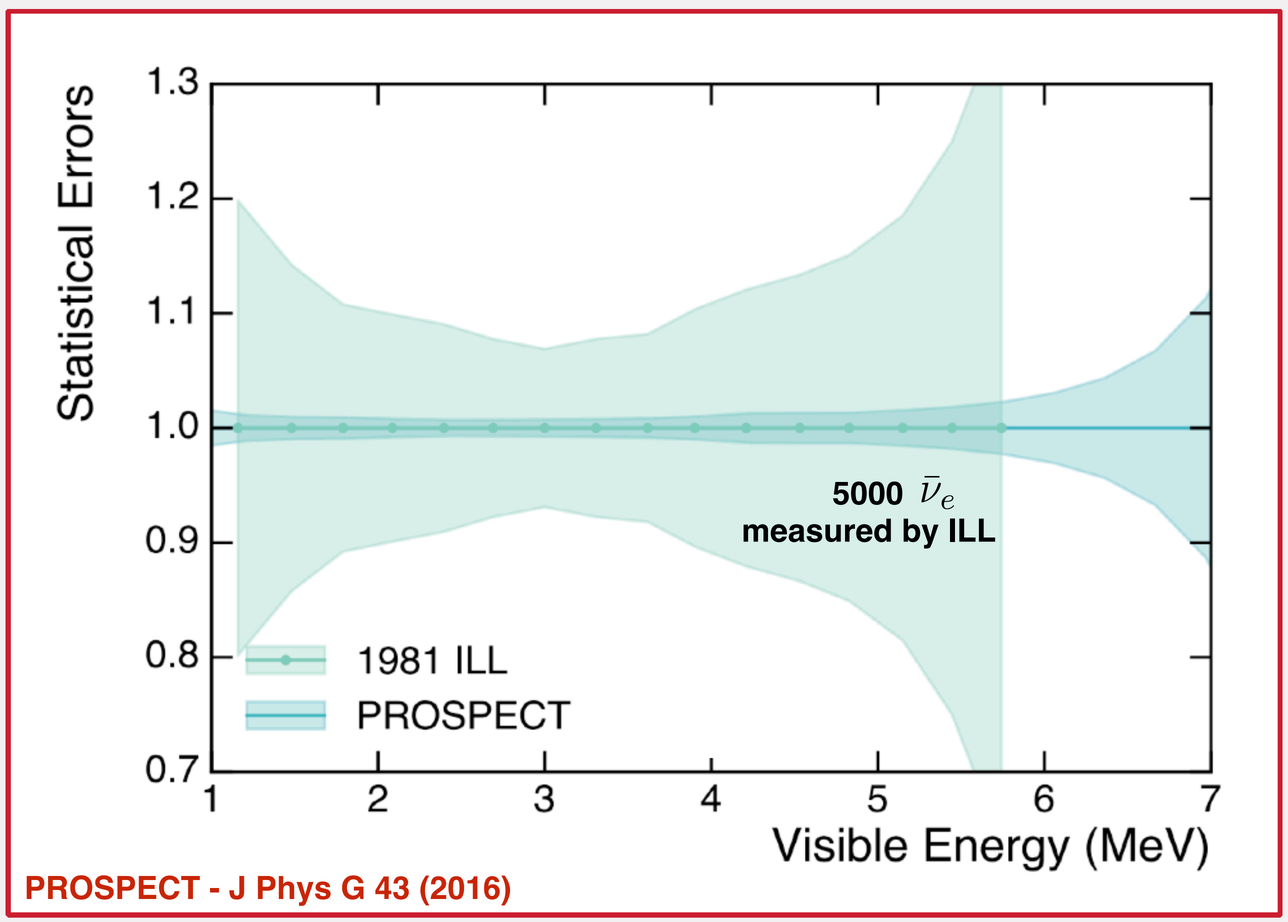
Oscillated neutrino rates as a function of L and E



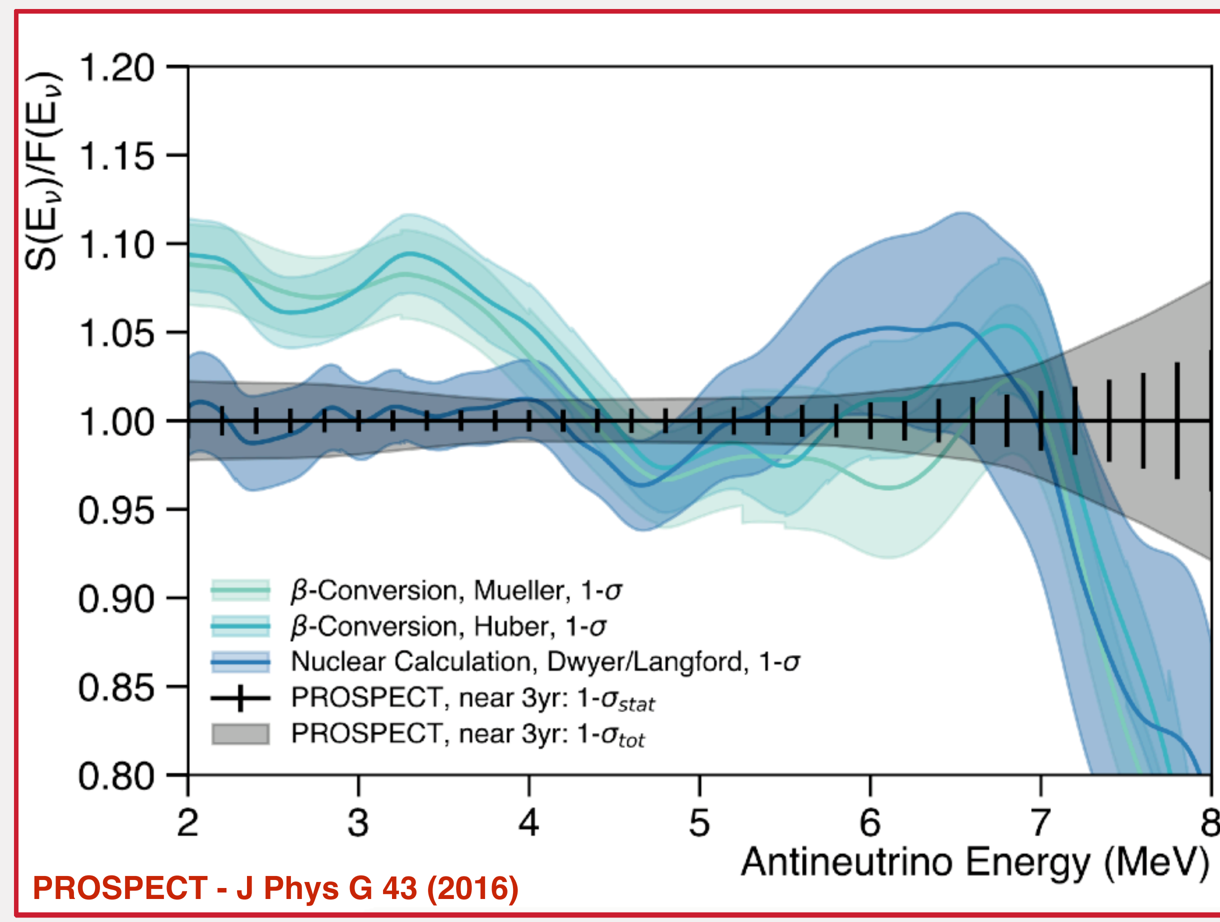
Sensitivity of PROSPECT Experiment

Spectrum Measurement

- Estimated IBD events - **160k/year**
- 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



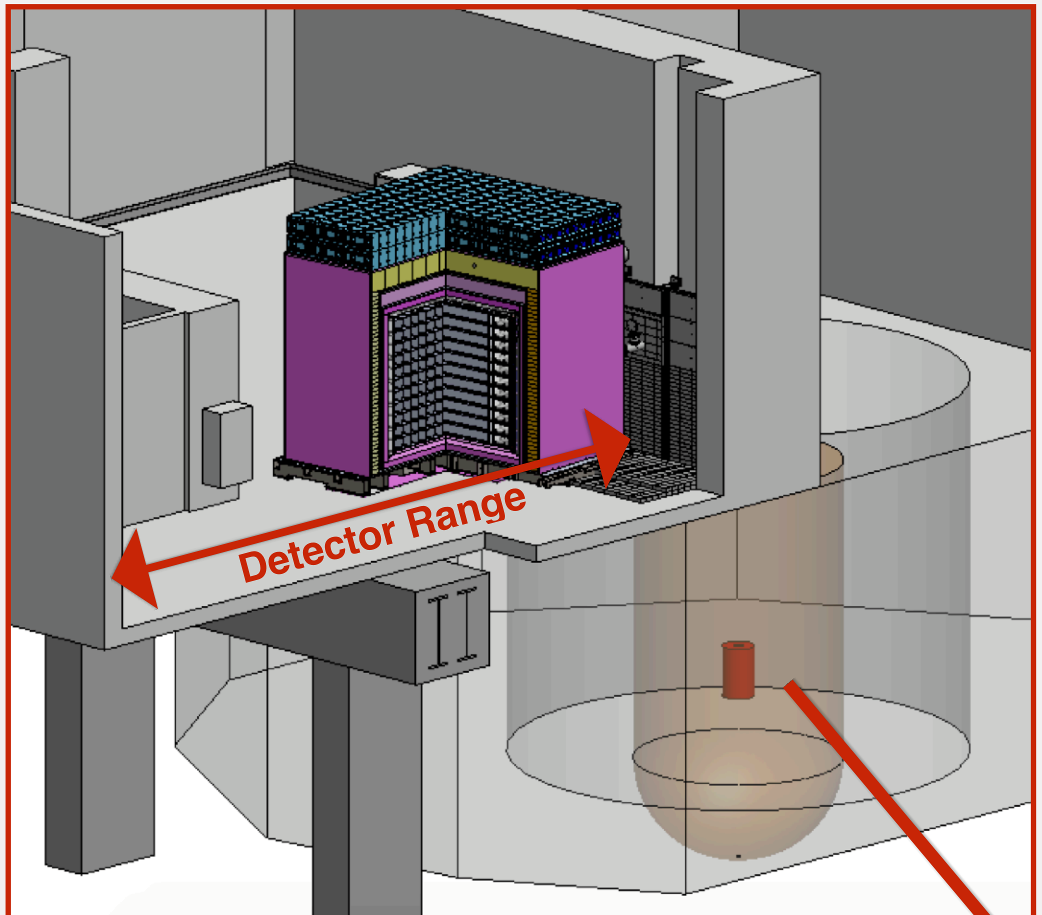
Improvement in precision over ILL



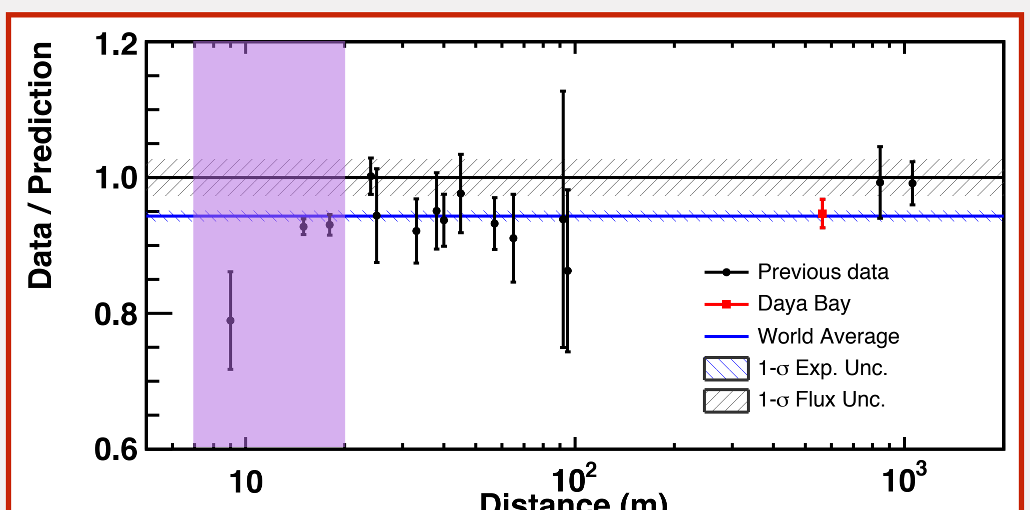
Test various reactor antineutrino spectrum models

Antineutrino Source

- High Flux Isotope Reactor (**85 MW**) at ORNL
- HEU Reactor - **~93 %** ^{235}U enrichment (**>99%** $\bar{\nu}_e$ from ^{235}U)
- Short reactor cycles (~**25 days**) - Low P239 buildup **(< 0.5%)**
- Compact core (**0.5m high, 0.4 m wide**) - No oscillation washout



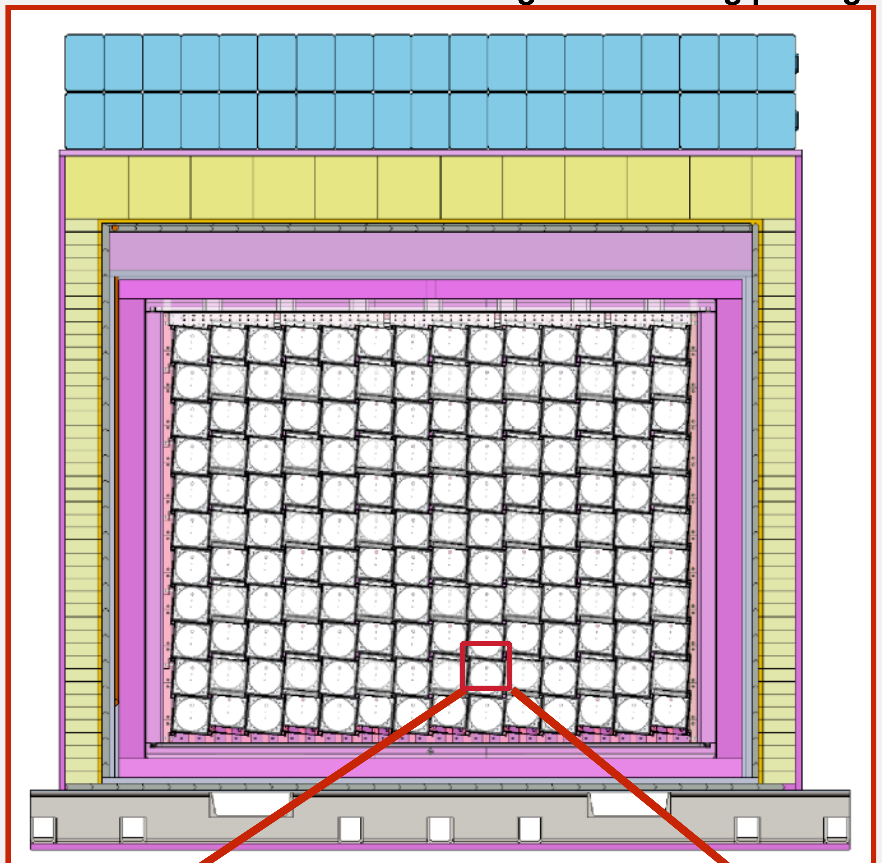
- **~47 %** up-time
- **>50%** reactor off-time - Extensive background characterization
- ~ 3 years experience of on-site operation
- Easy 24/7 access



Baseline coverage of the PROSPECT detector

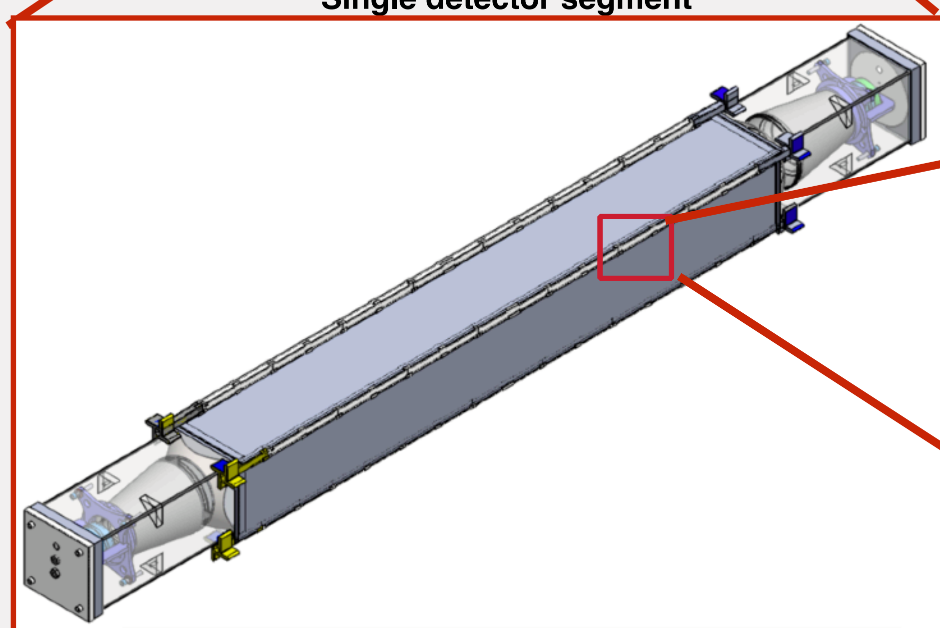
Detector Design

Cross-section of detector including the shielding package

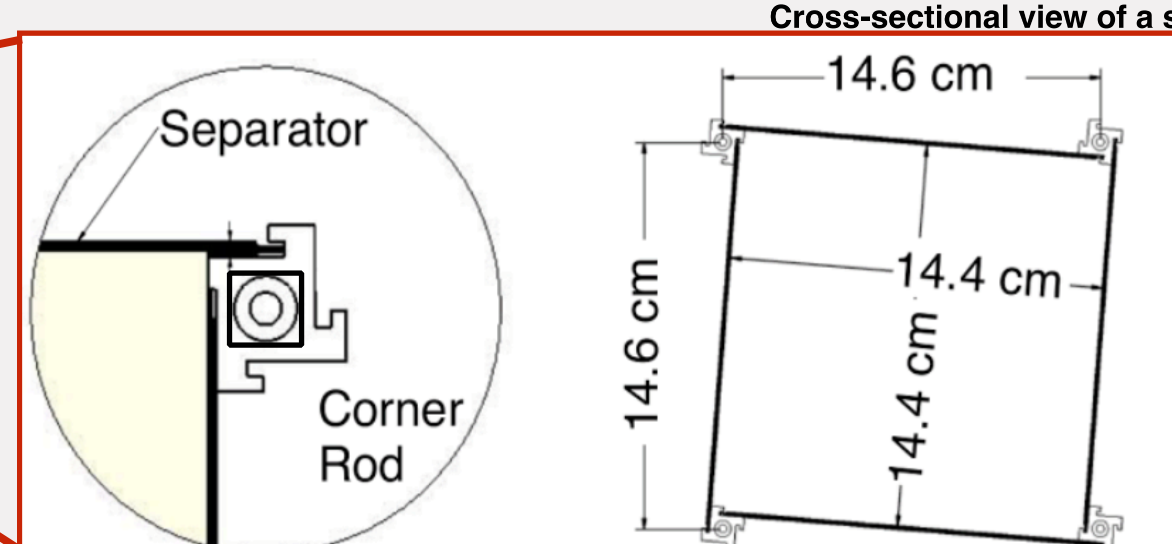


- Single volume **~4 ton** Li6-loaded liquid scintillator detector
- Optically divided into a **11x14** identical segments
- Each segment is a detector i.e., **154 detectors**
- Low mass optical separators
- Minimum dead material
- Double-ended readout
- *in-situ* calibration access

Single detector segment



Cross-sectional view of a segment

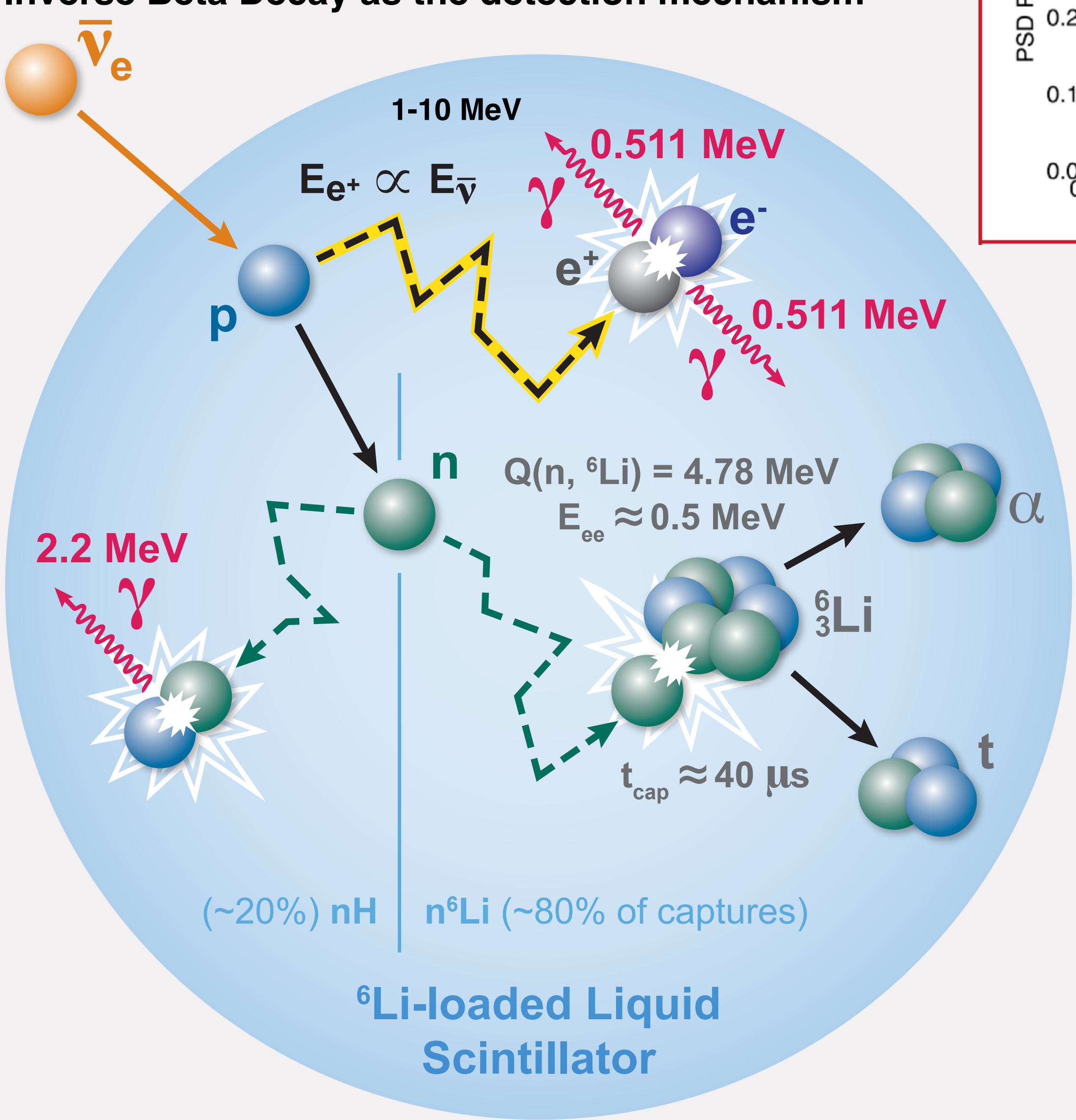


Detection Mechanism

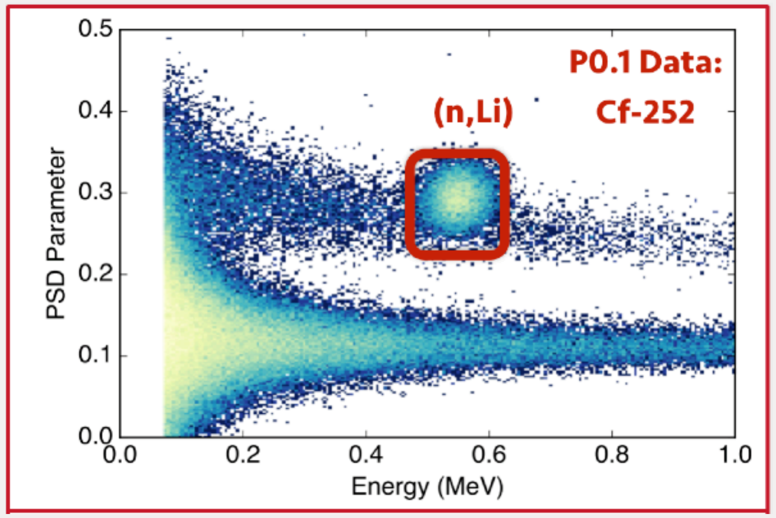
Li6-loaded EJ-309 scintillator as target:

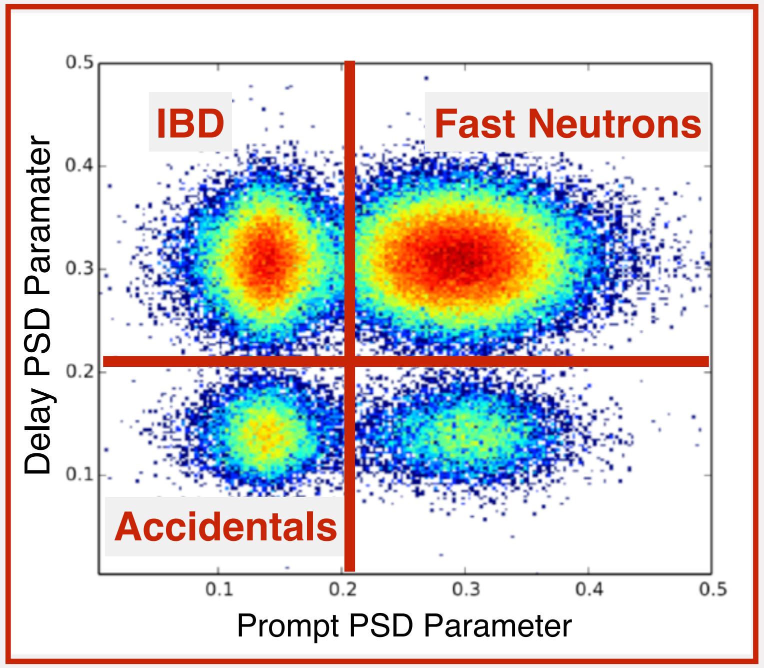
- Excellent background rejection
- High IBD detection efficiency
- Spatial and temporal dense energy deposition

Inverse Beta Decay as the detection mechanism



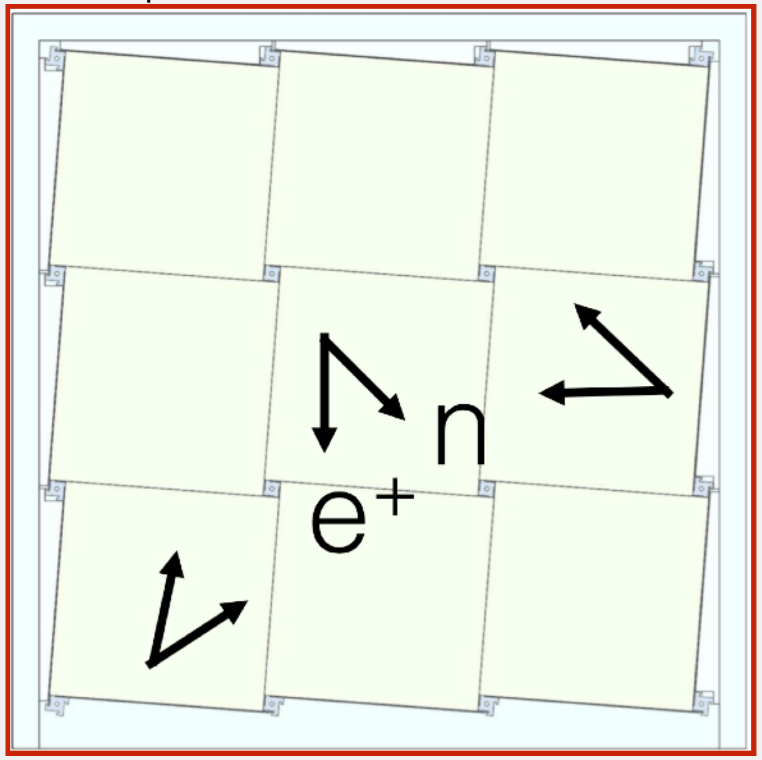
Pulse Shape allows for discrimination between gamma-like and neutron-like events





Comparison of coincidences

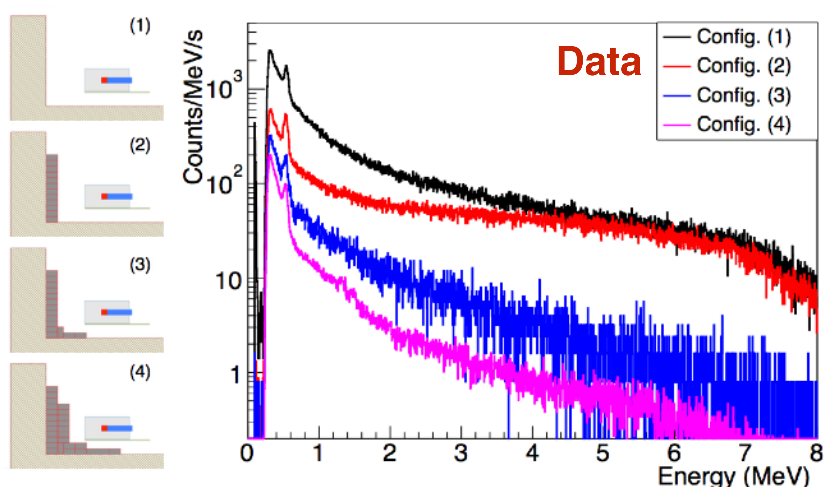
Spatial coincidence of IBD events



Segmentation allows for background rejection

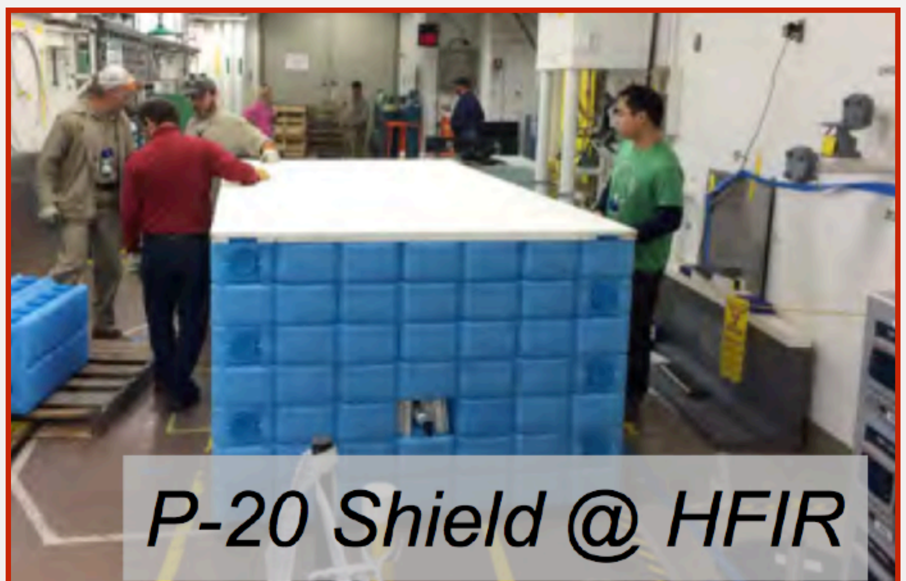
Background Characterization and Reduction

- 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

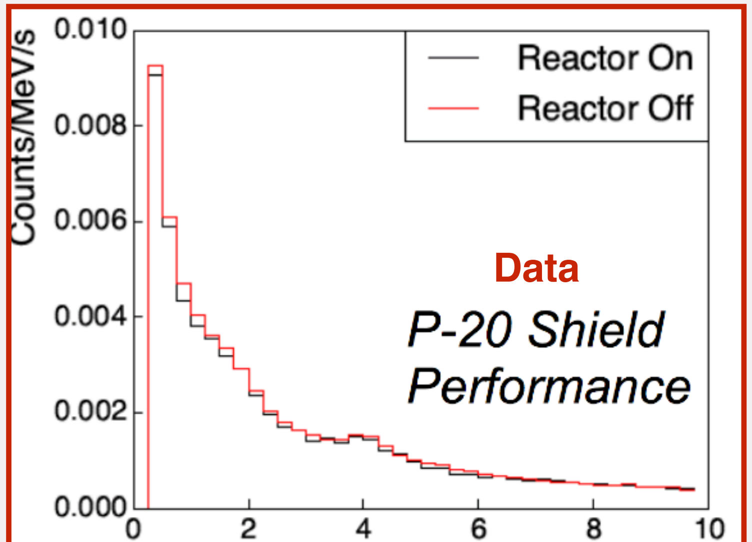


NIM A 806 (2016) 401

Effect of varying lead wall configuration on gammas



~ 25% the size of PROSPECT shielding



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P20 shield was able to shield the reactor backgrounds effectively

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

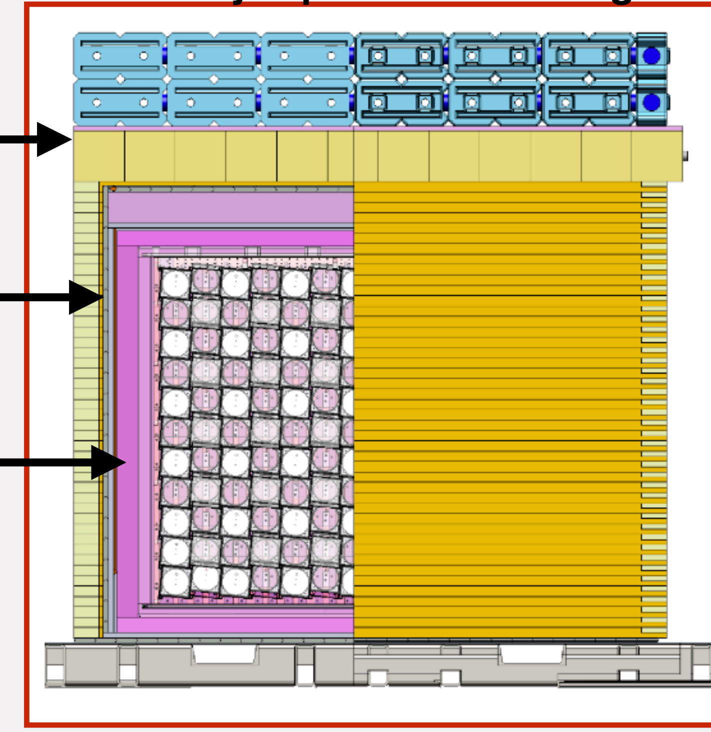
Local shielding joining reactor wall

Multi-layer passive shielding

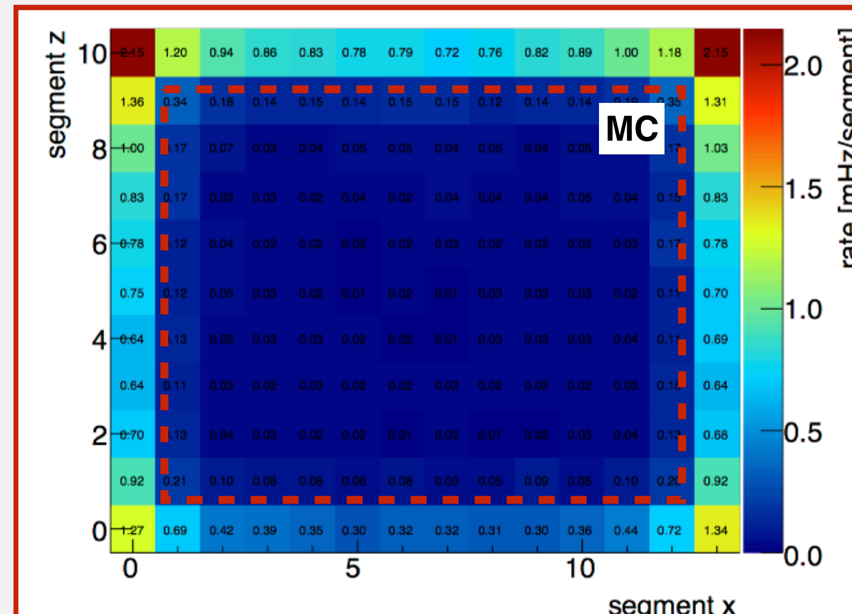
Water bricks
Polyethylene
Outer neutron shielding for neutron moderation

Lead
High Z shielding

Inner Neutron Shielding
Suppress neutrons produced from spallation on lead



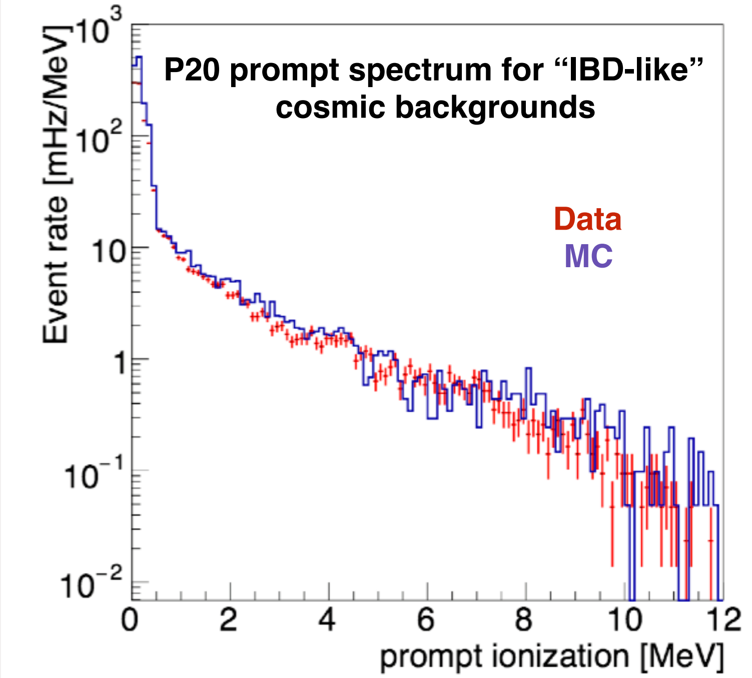
Use outer layer of the detector as veto

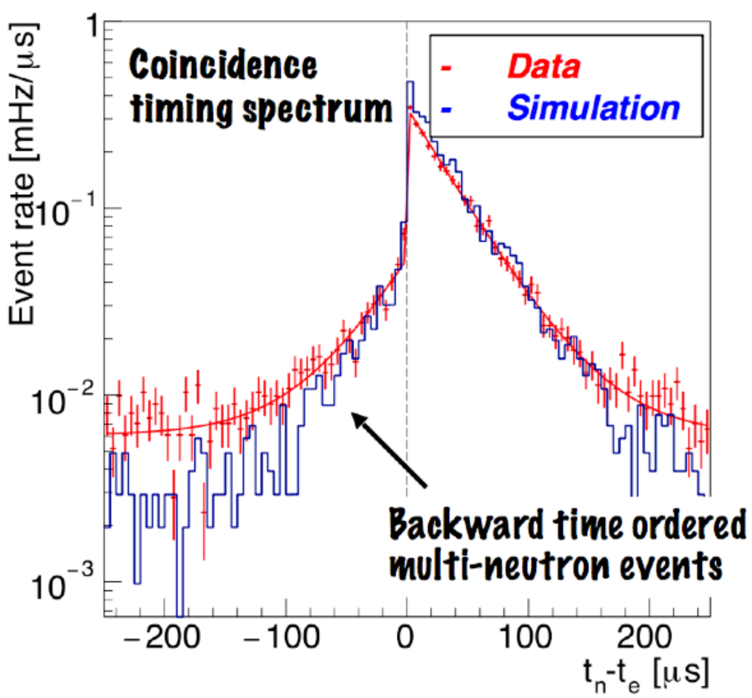


Simulation Benchmarking

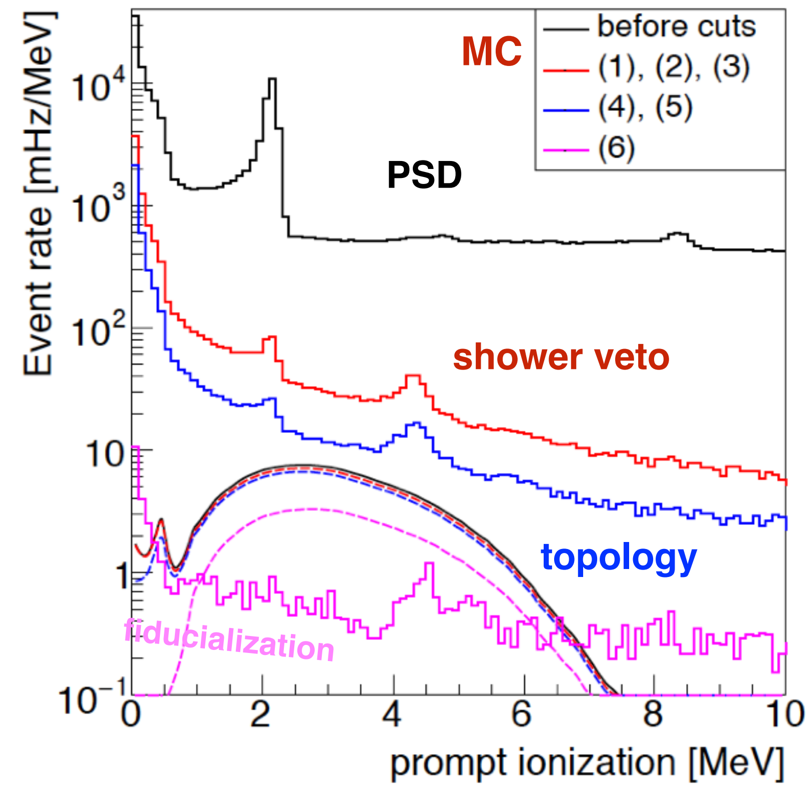
- P20 measured cosmic backgrounds during reactor-off periods
- PROSPECT Monte Carlo simulations agree well with the P20 data

Comparison of Data with PROSPECT MC

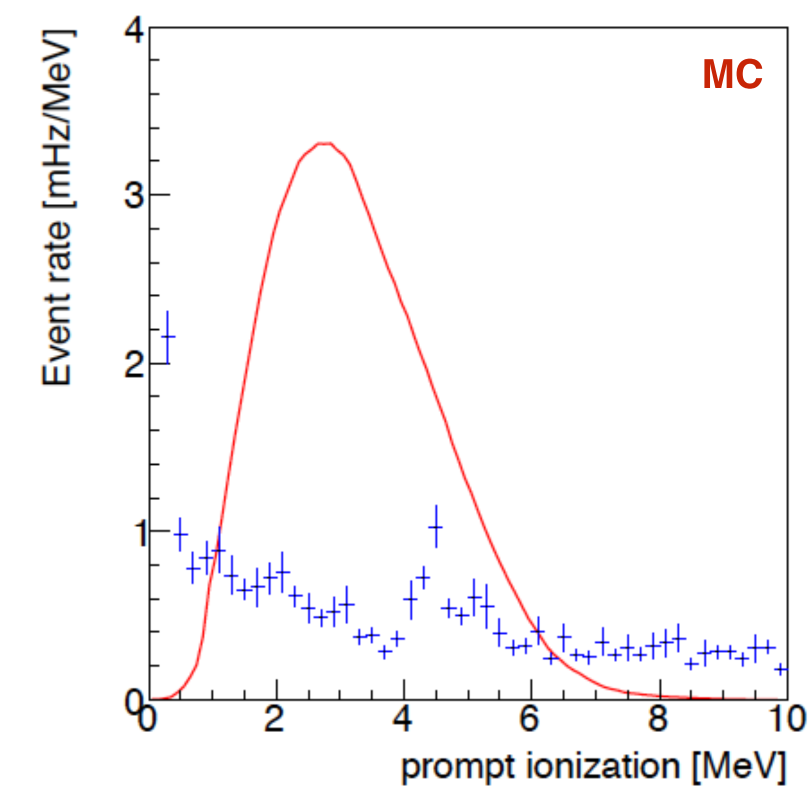




Projected PROSPECT Signal and Backgrounds



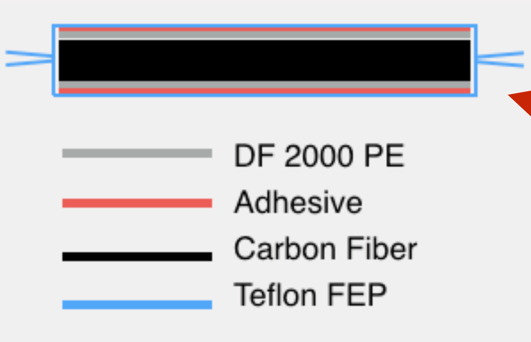
Simulated signal (dashed) and cosmic backgrounds (solid) prompt energy spectrum through selection cuts



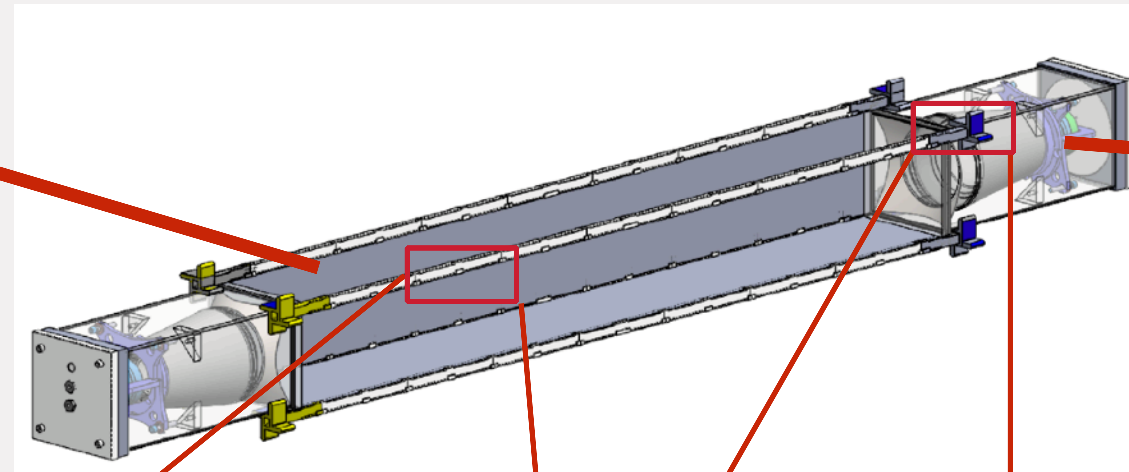
Simulated signal and cosmic backgrounds after all selection cuts

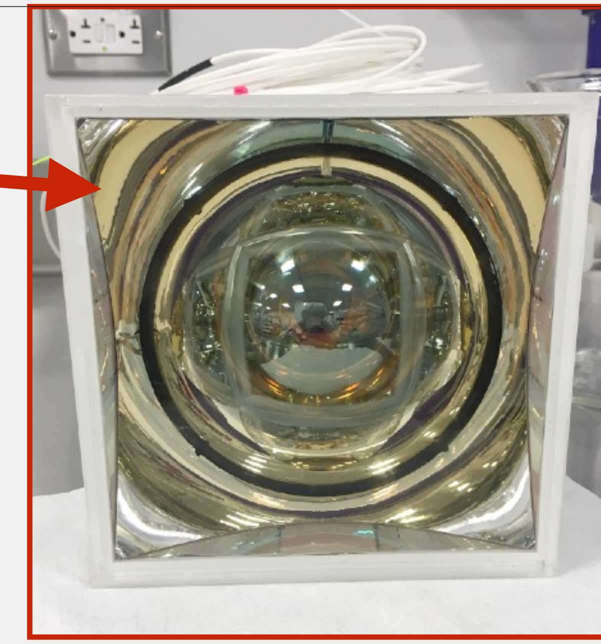
Projected S:B for PROSPECT full-size detector is better than 3:1

Detector Development

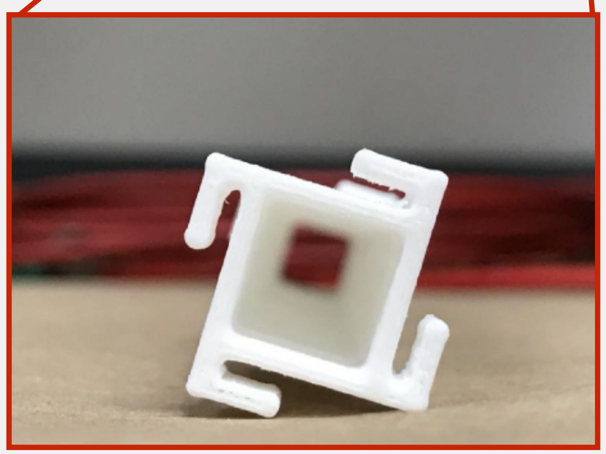


Multi-layer highly reflective, rigid low mass reflectors





Assembled PMT housings



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

Prototype source capsule

Prototype optical diffuser

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

- 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

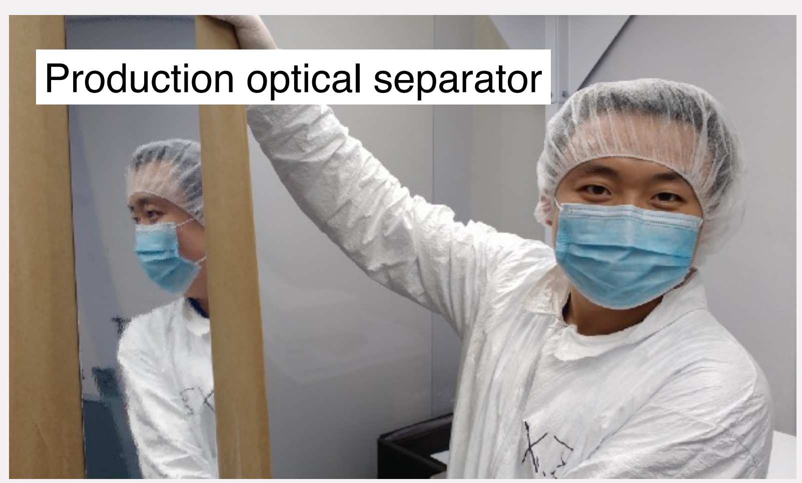
Subcomponent Construction

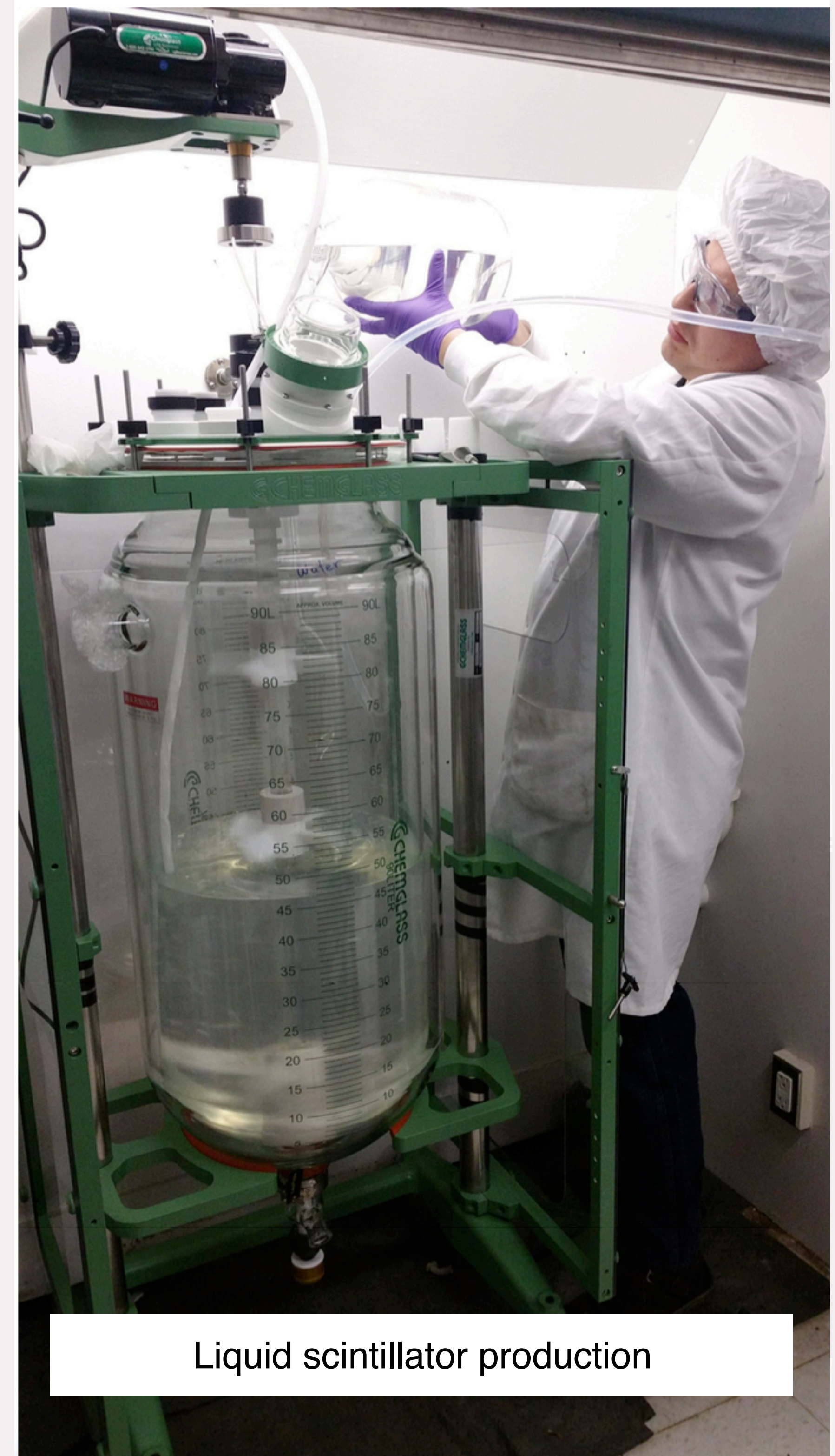

Optical separator fabrication


PMT module components ready for assembly

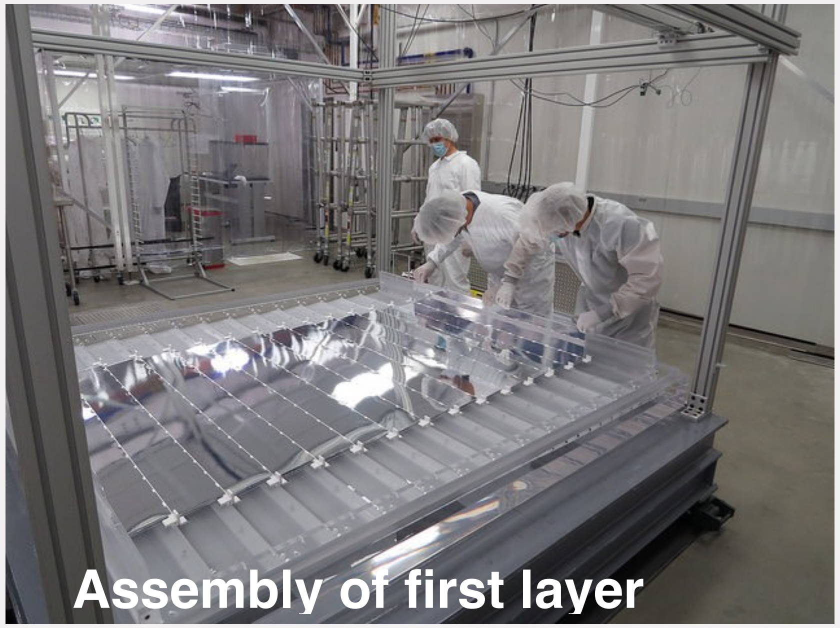

PMT testing

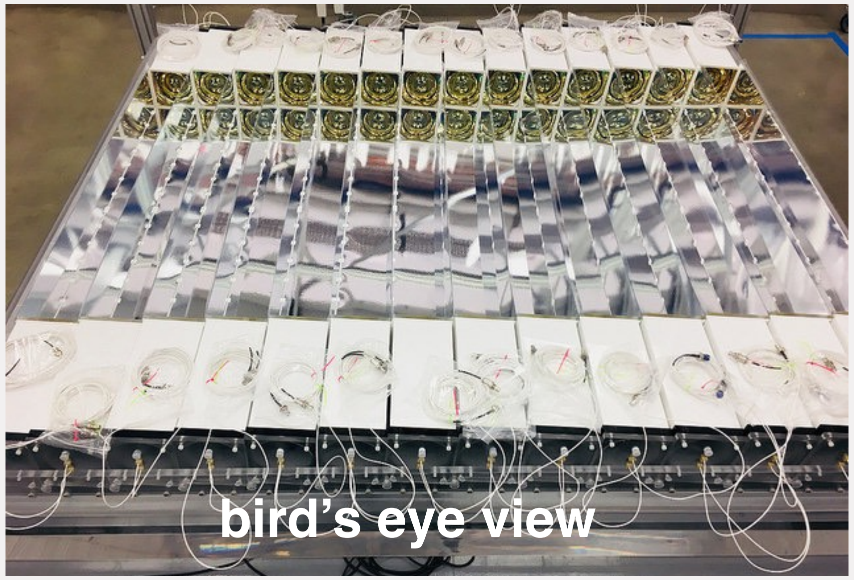

First PMT module

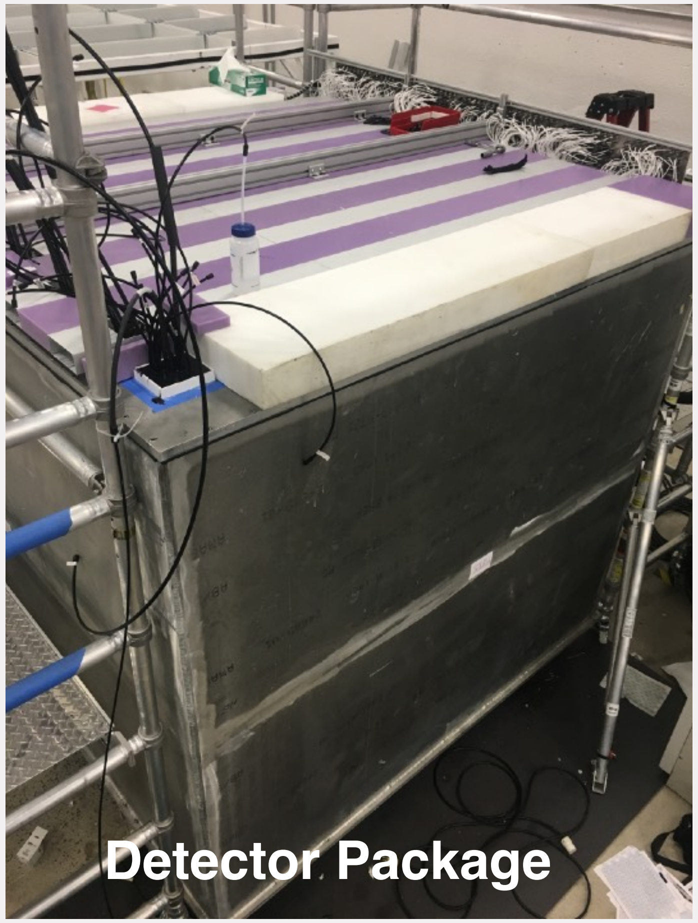

Production optical separator


Liquid scintillator production

Assembly and Installation





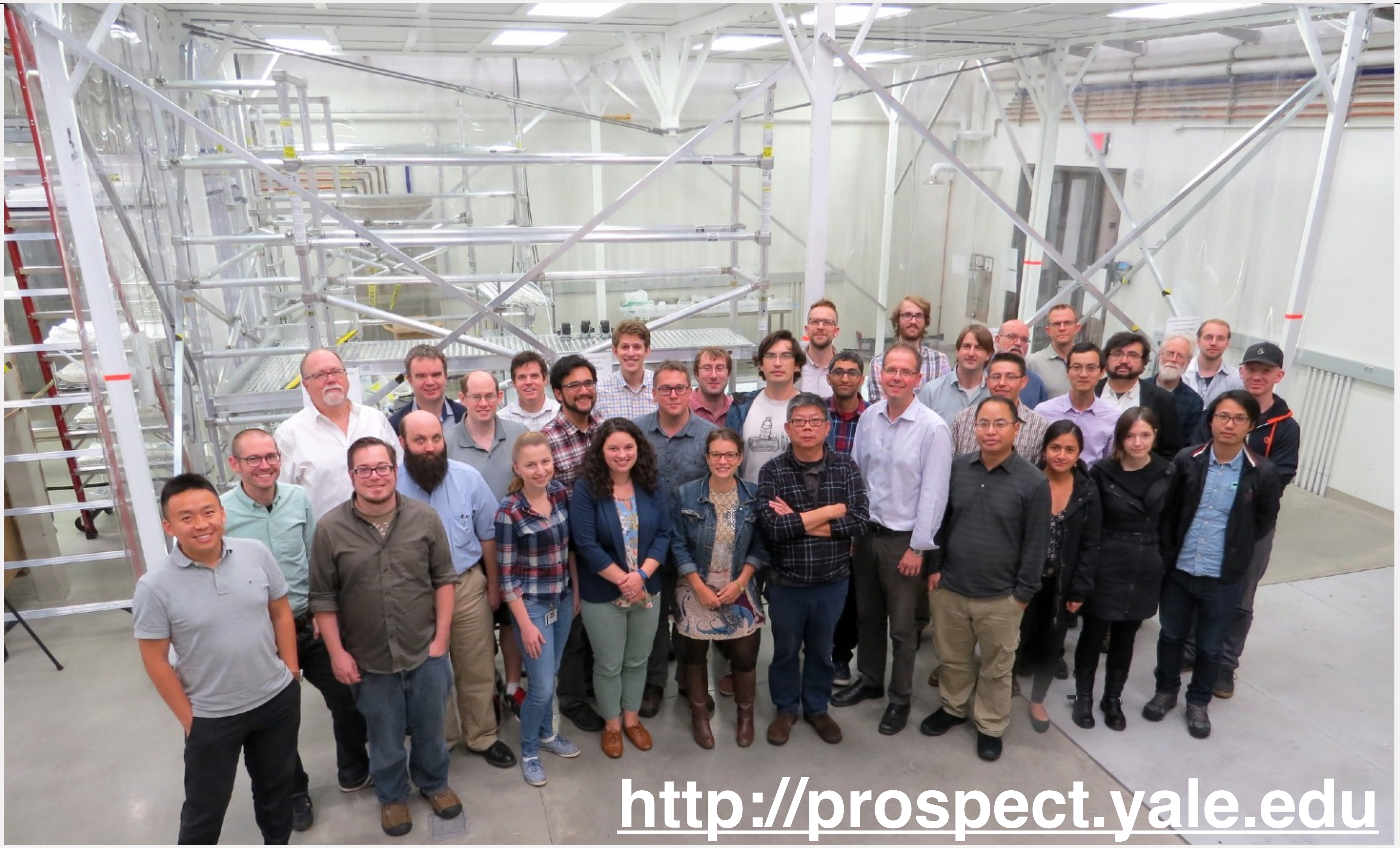


Assembly video

Summary

- Reactor antineutrino experiments reported anomalous rate and shape measurements
- New precision reactor measurement with ability to search L/E signature of oscillations needed
- **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 4σ in one calendar year and favored regions at 3σ in 3 yrs
- Detector construction finished, installation and commissioning in progress
- Data taking to commence soon

Thank you



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