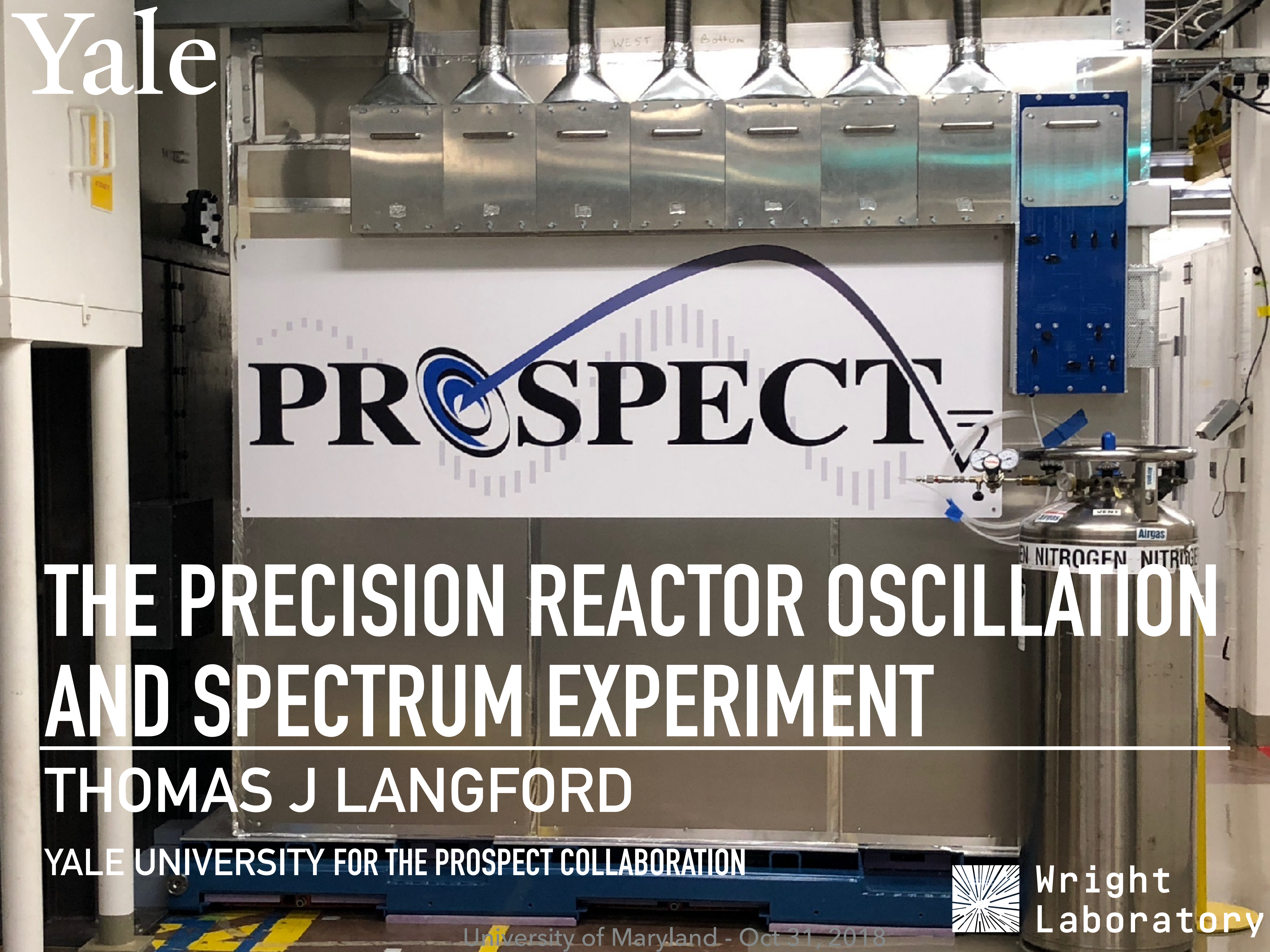


Yale

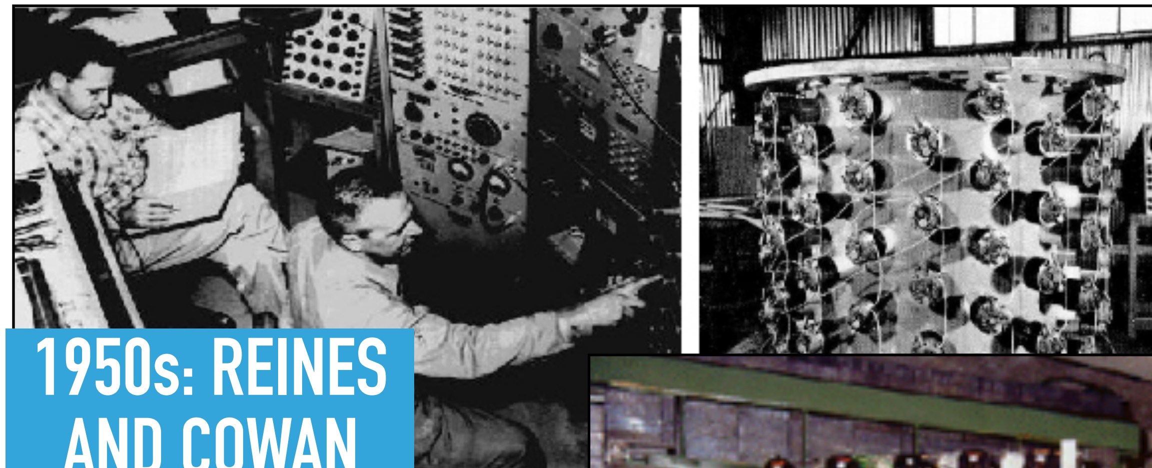
THE PRECISION REACTOR OSCILLATION AND SPECTRUM EXPERIMENT

THOMAS J LANGFORD

YALE UNIVERSITY FOR THE PROSPECT COLLABORATION

Wright Laboratory

REACTORS: TOOLS FOR DISCOVERY

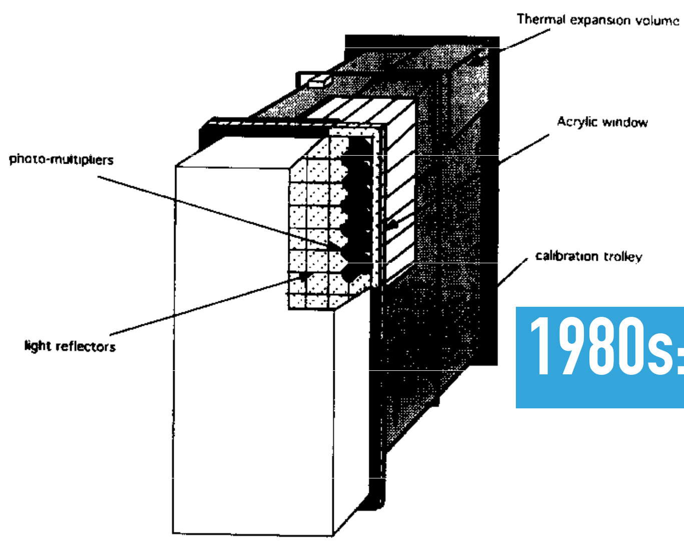


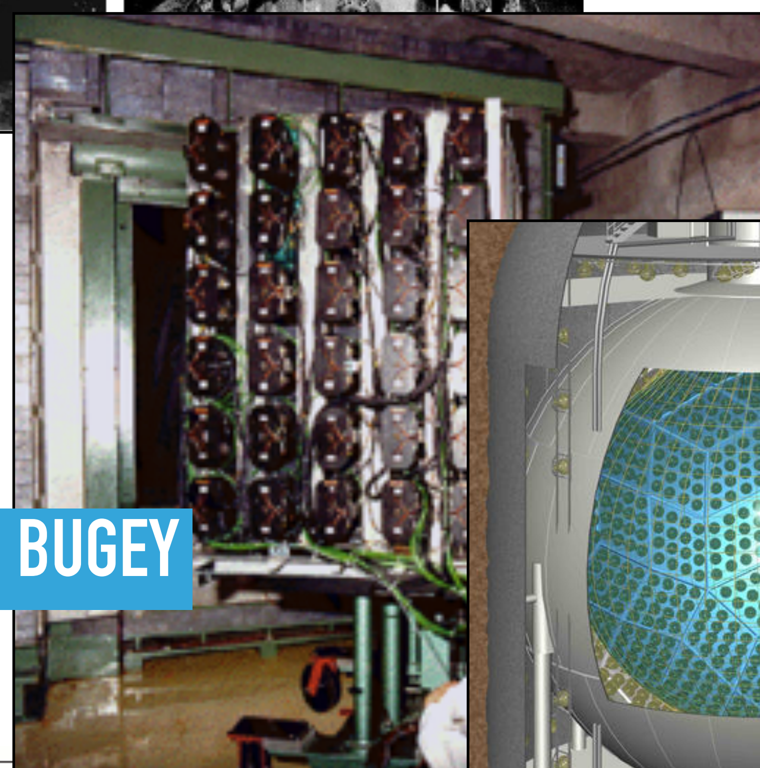
1950s: REINES AND COWAN

20 July 1956, Volume 124, Number 3212 **SCIENCE**

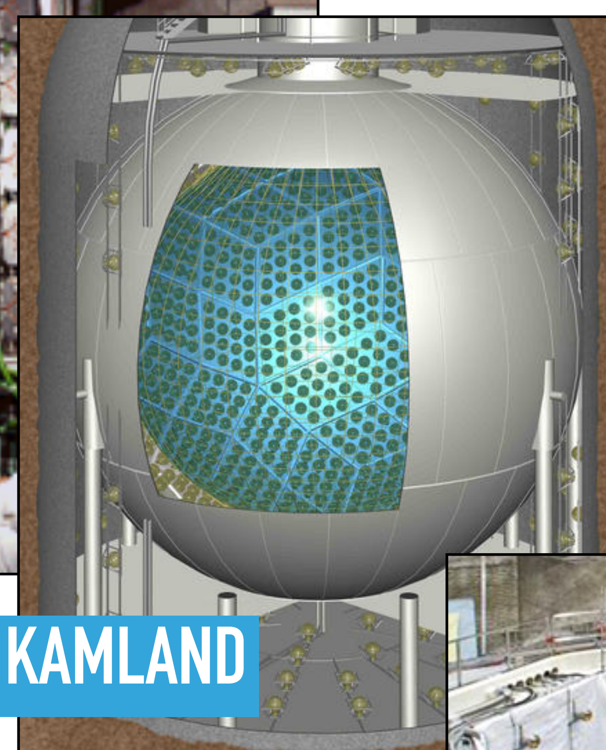
Detection of the Free Neutrino: a Confirmation

C. L. Cowan, Jr., F. Reines, F. B. Harrison, H. W. Kruse, A. D. McGuire

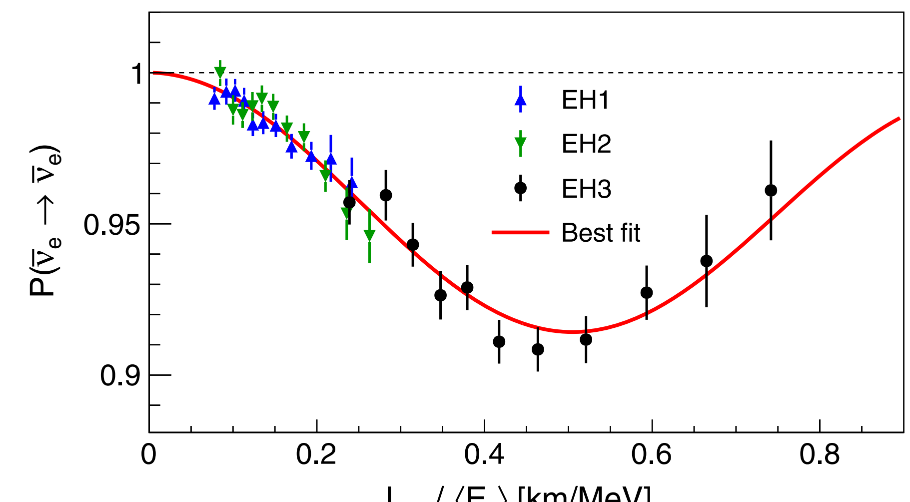


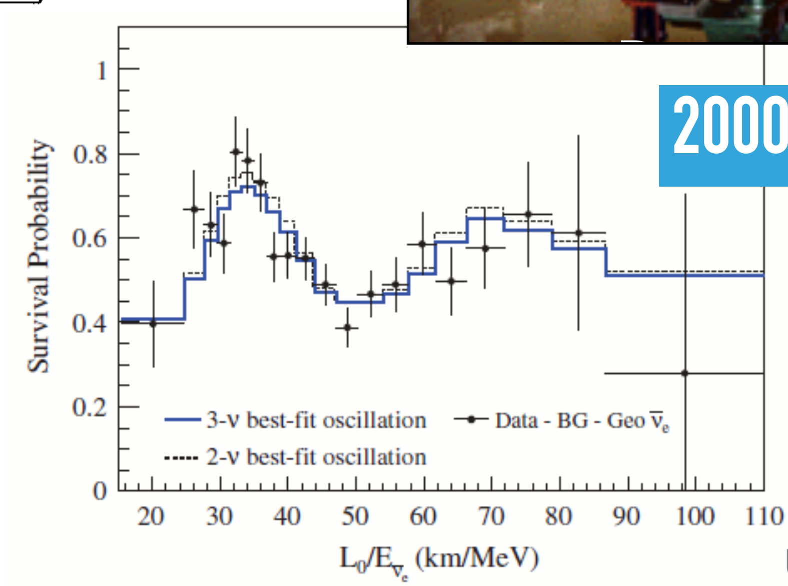


1980s: BUGEY



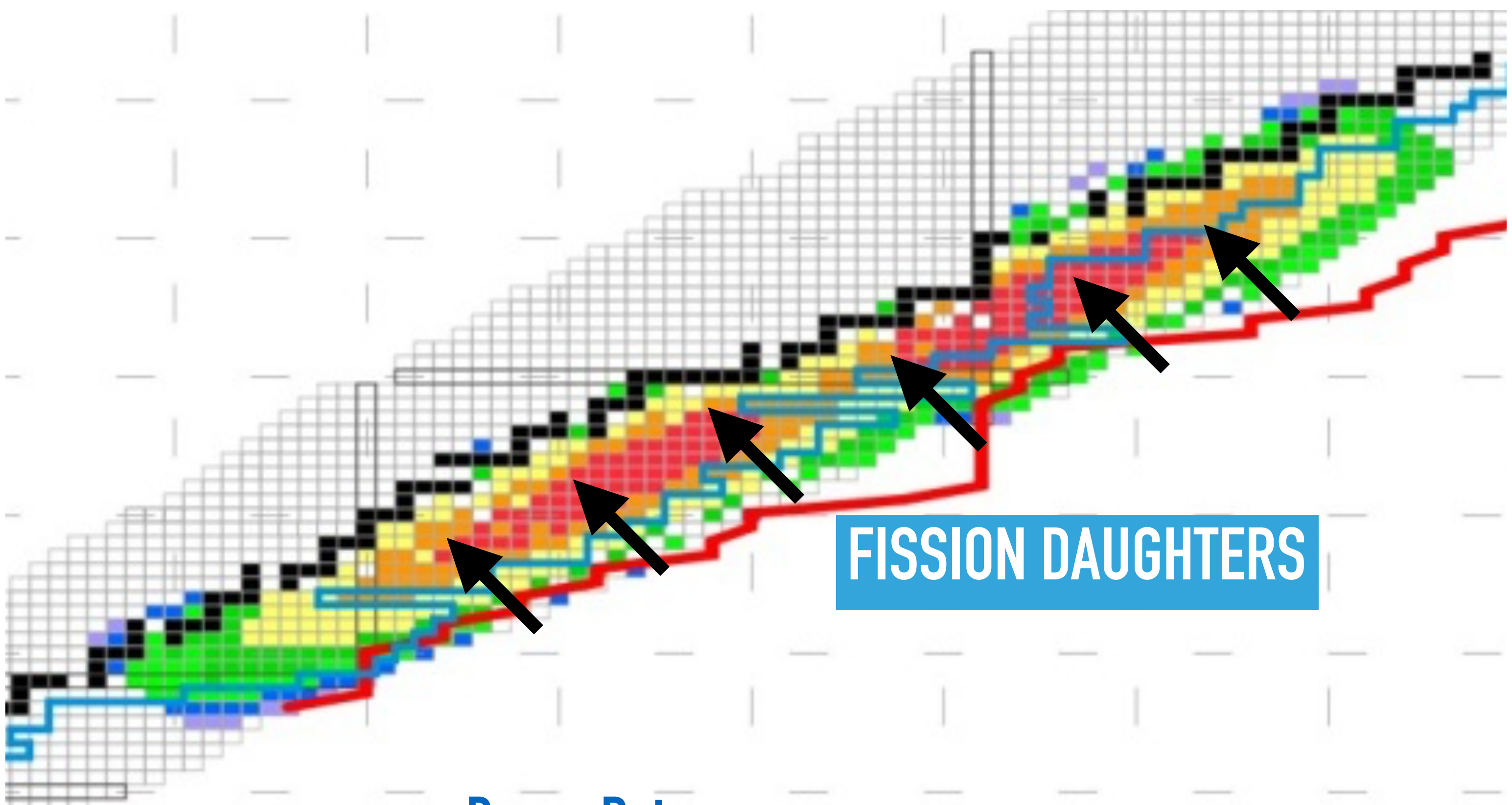
2000s: KAMLAND

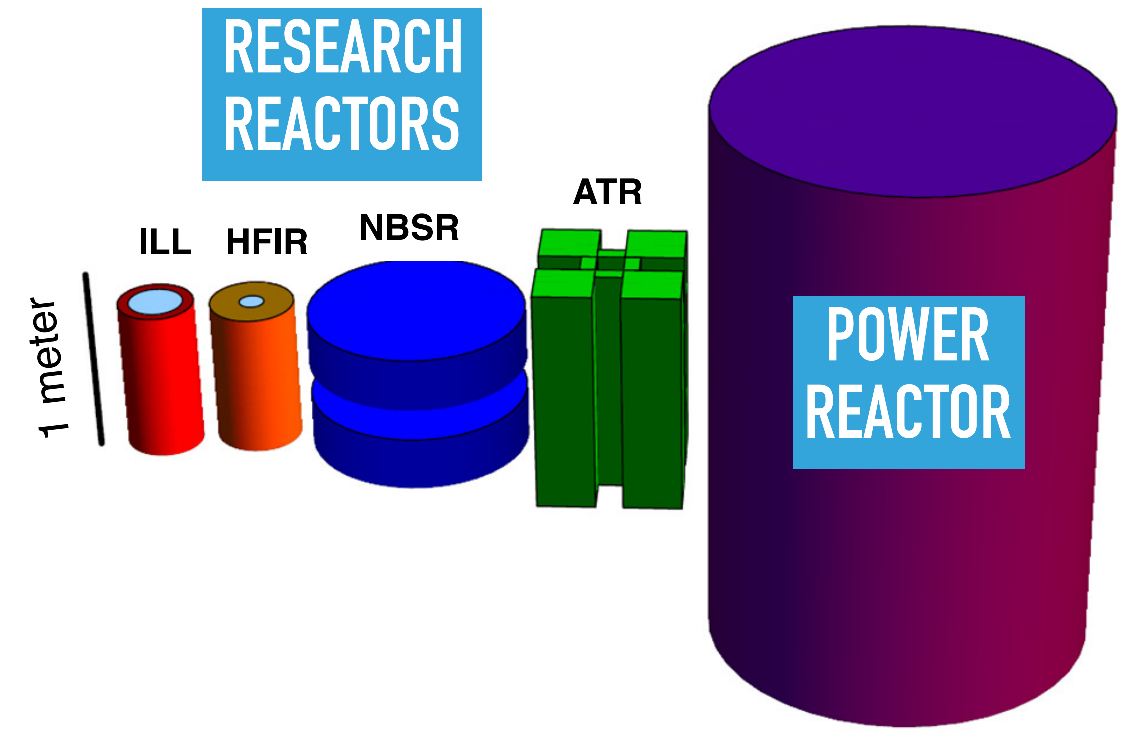




2010s: DAYA BAY – θ_{13}

REACTOR NEUTRINO PRODUCTION





Decay Rate (R_i), Spectrum ($S_{ij}(E_{\bar{\nu}})$), Branching Fraction (f_{ij}):

$$S(E_{\bar{\nu}}) = \sum_{i=0}^{n} R_i \sum_{j=0}^{m} f_{ij} S_{ij}(E_{\bar{\nu}})$$

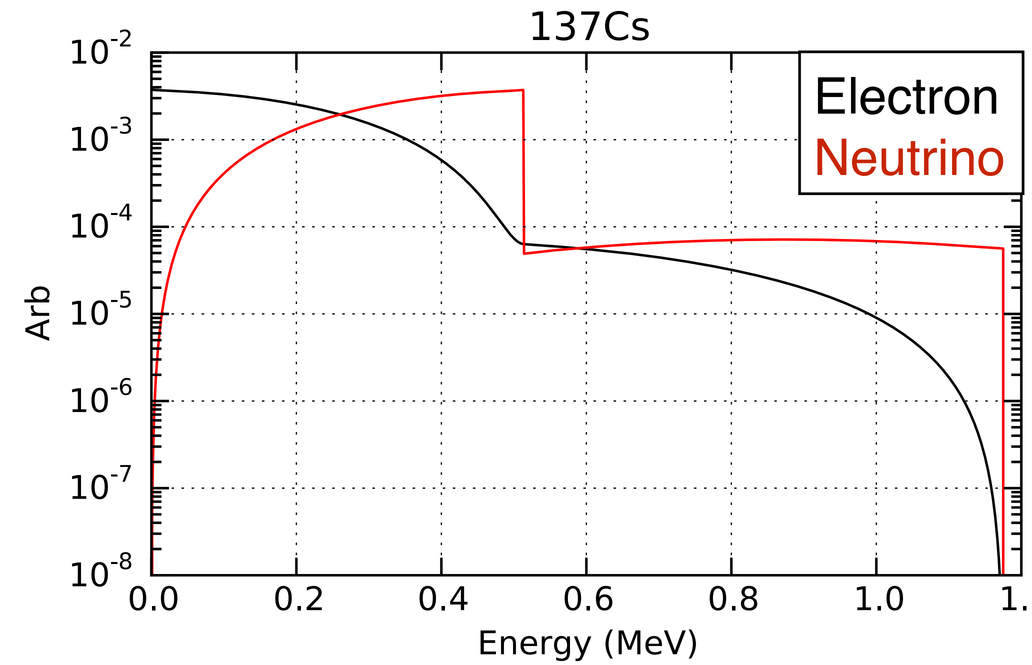
- Fission of parent isotopes yield neutron-rich daughters
- Beta decays produce ~6ν/fission, <10MeV

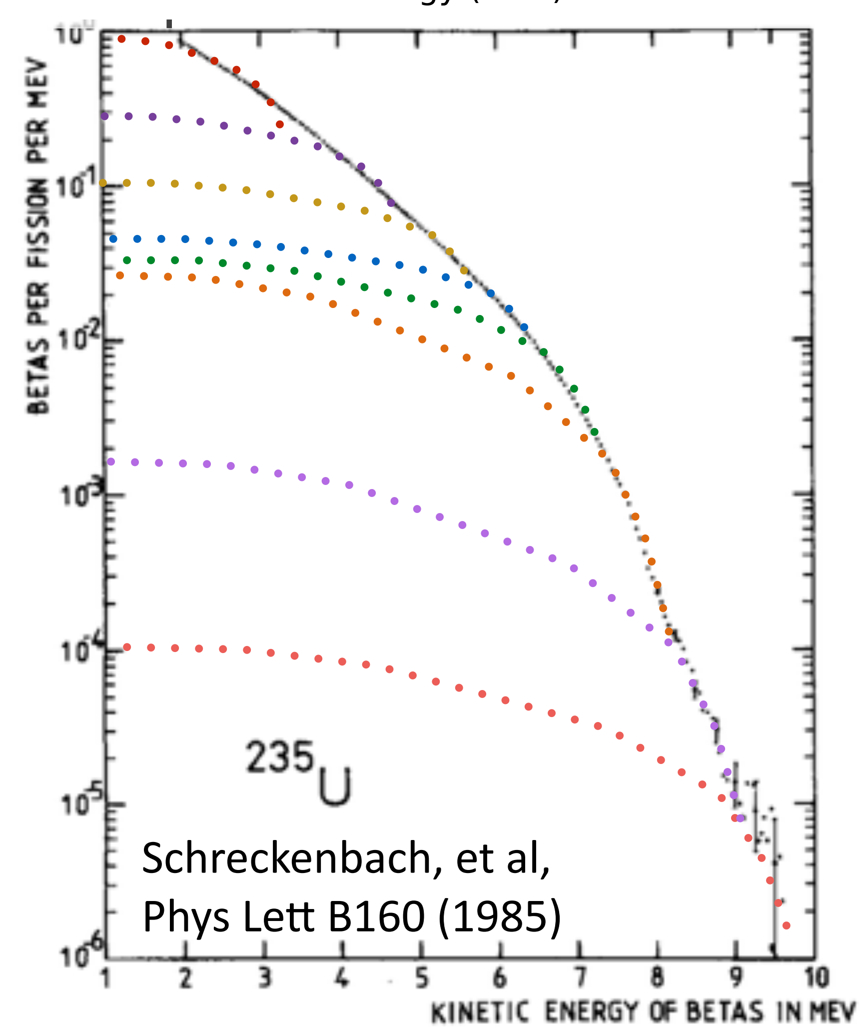
- Power plants have low-enriched uranium (LEU) cores
  - Mixture of ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu
- Research Reactors have highly-enriched cores only ^{235}U

PREDICTING NEUTRINO FLUX/SPECTRA

Two main approaches:

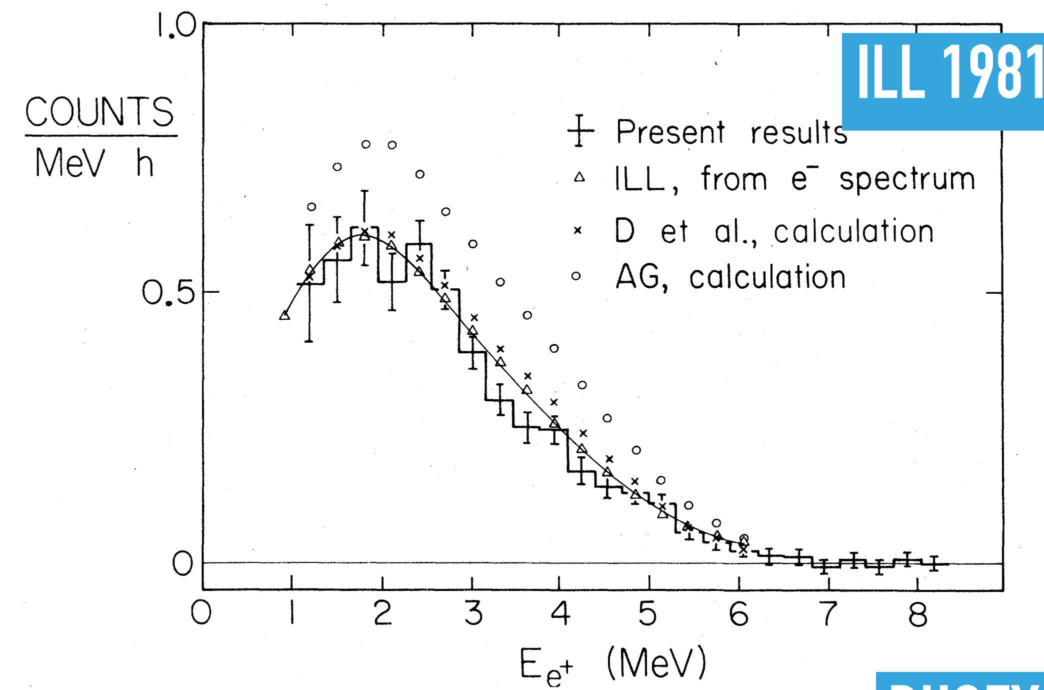
- ***Ab-initio***
  - Calculate individual beta-decay spectra for 1000s of isotopes from database info
  - Sum according to cumulative yields
  - **Problem:** databases have huge uncertainties
- ***Beta-conversion***
  - Measure cumulative beta spectra from fission parents
  - Use virtual beta-branches to convert into neutrino spectra
  - **Problem:** can virtual branches capture all relevant physics?

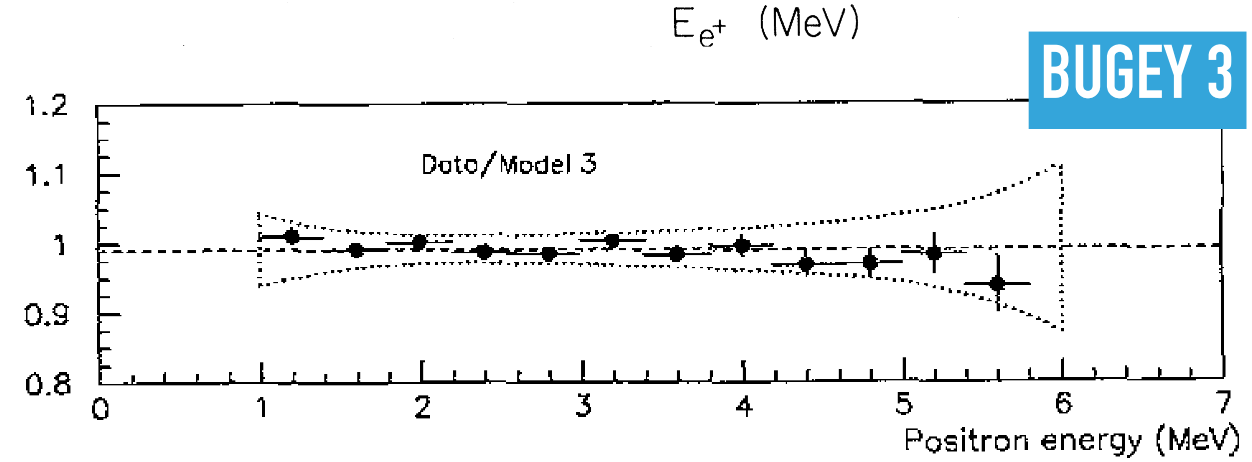


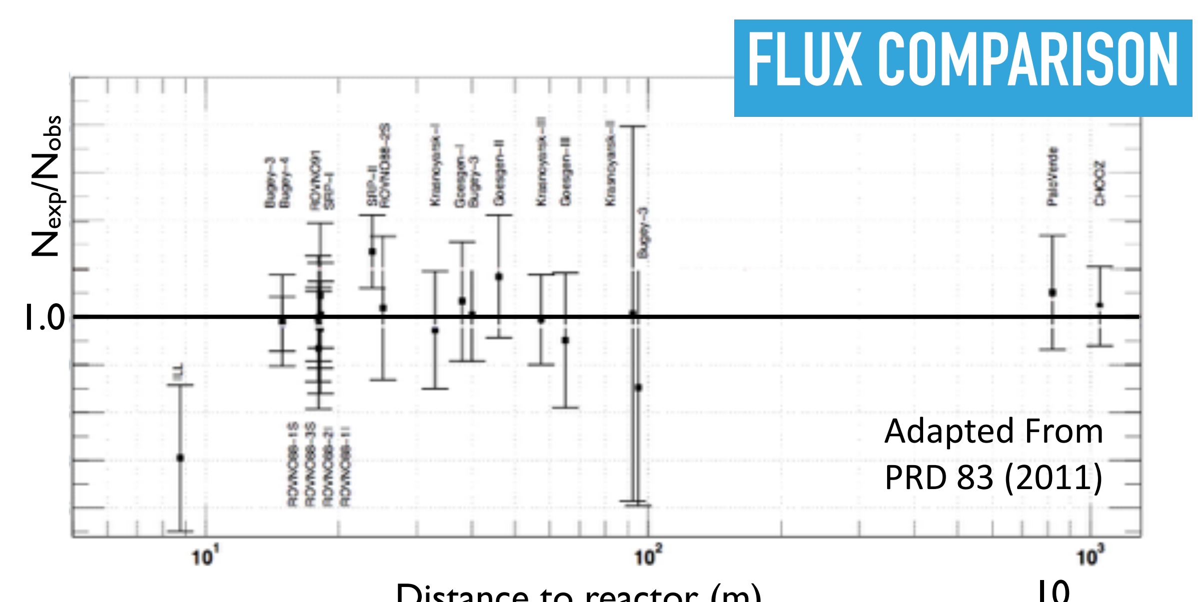


PREDICTING NEUTRINO FLUX/SPECTRA

- **Early 1980s:** Measurement of ^{235}U spectrum at Institut Laue–Langevin (ILL)
    - Agrees with ab-initio calculations
    - <5000 neutrinos detected, 20% uncertainties
- **Mid 1980s:** Beta-conversion measurements at ILL, reduce systematics improve uncertainties on predictions
- **1990s:** Bugey PWR spectrum agrees with Beta-conversion spectra
- **1990-2000s:** Measured fluxes agree with predictions

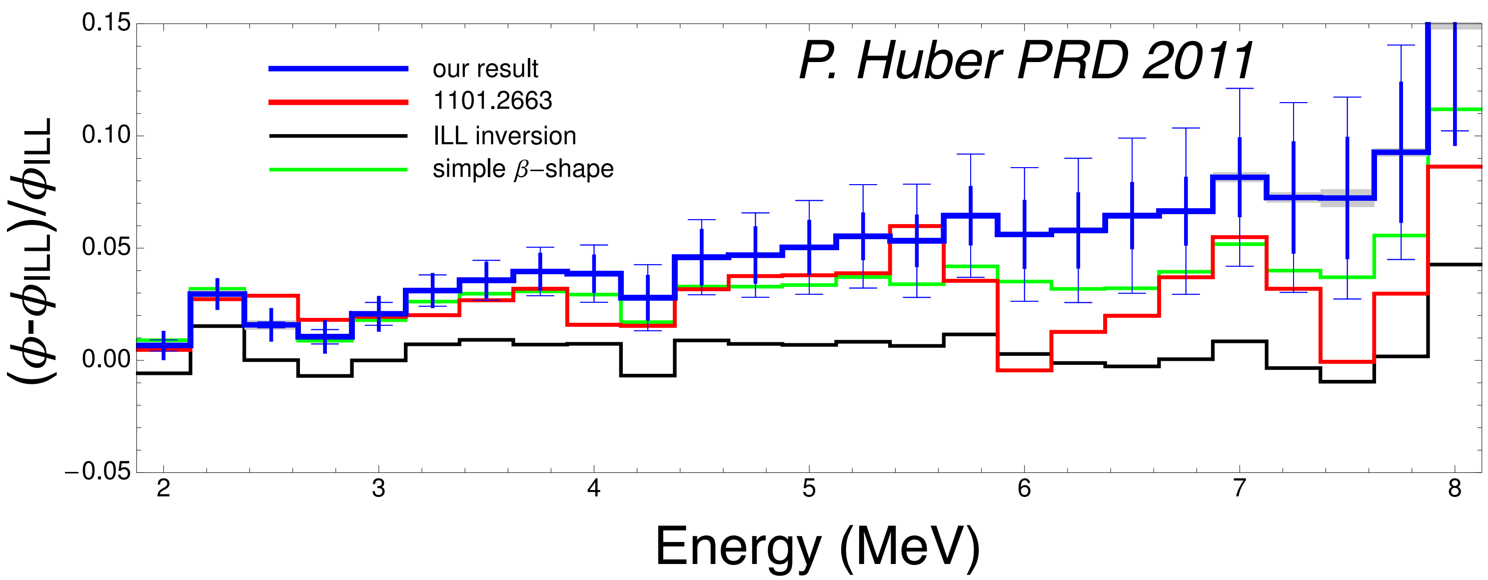


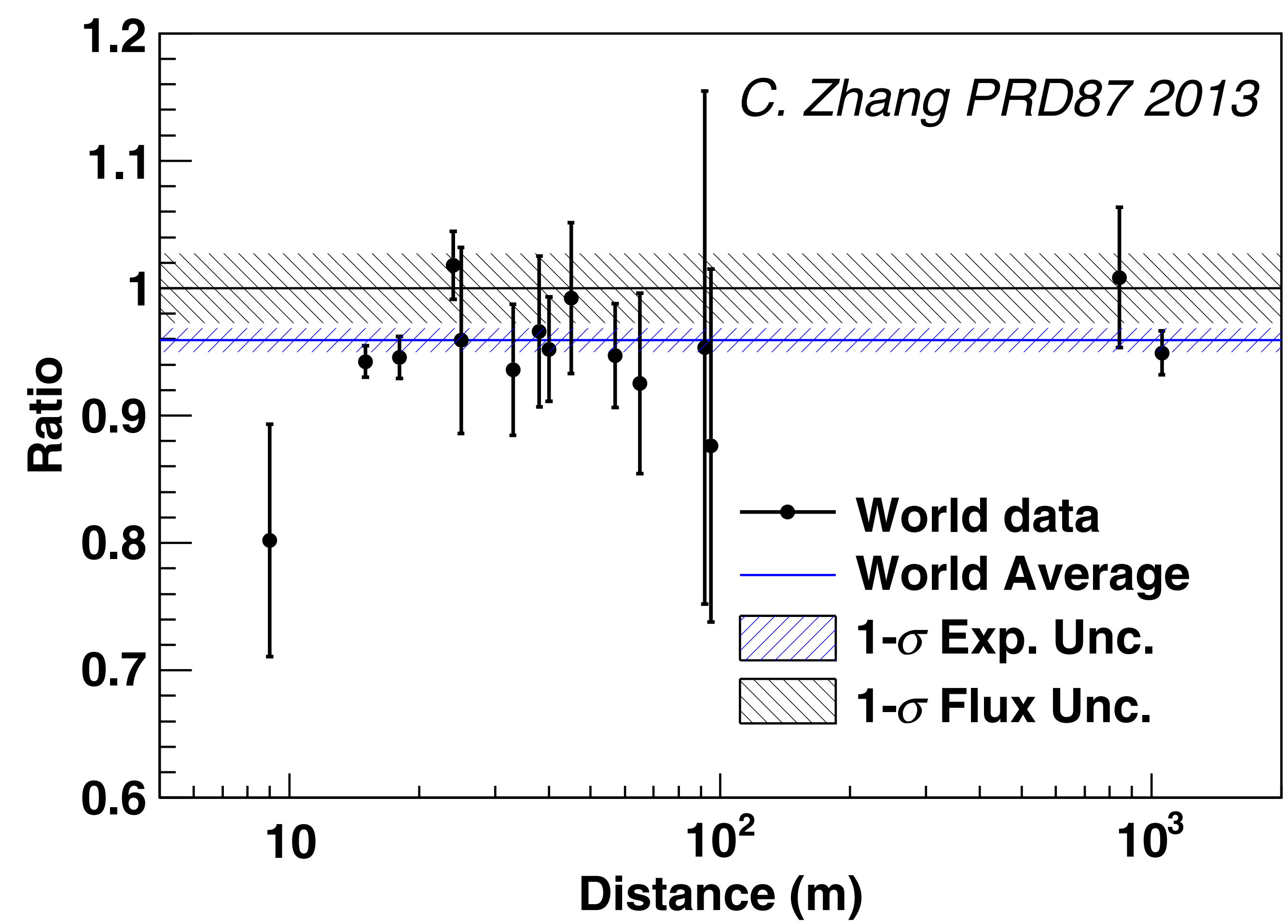




RECENT EVENTS: PROBLEMS EMERGE

- **2011:** Two beta-conversion reanalyses increase predicted flux
  - One pure conversion, one hybrid between *ab-initio* and conversion
  - 3σ tension with previous experiments
- **Change in Flux/Spectrum:**
  - Conversion: +3%
  - Neutron lifetime: +1%
  - Non-equilibrium isotopes: +1%
- **Could be bias from non-blind analyses?**





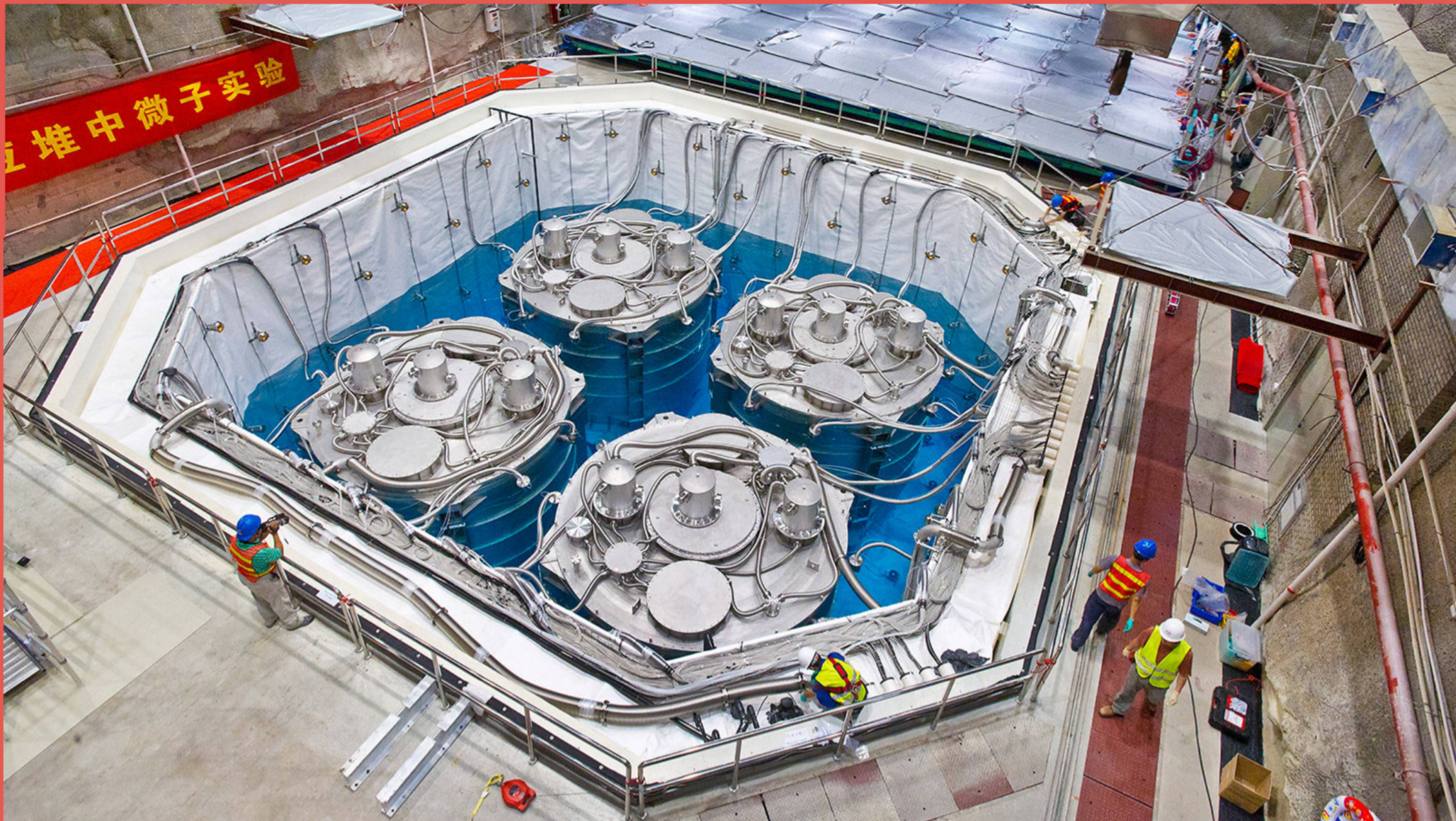


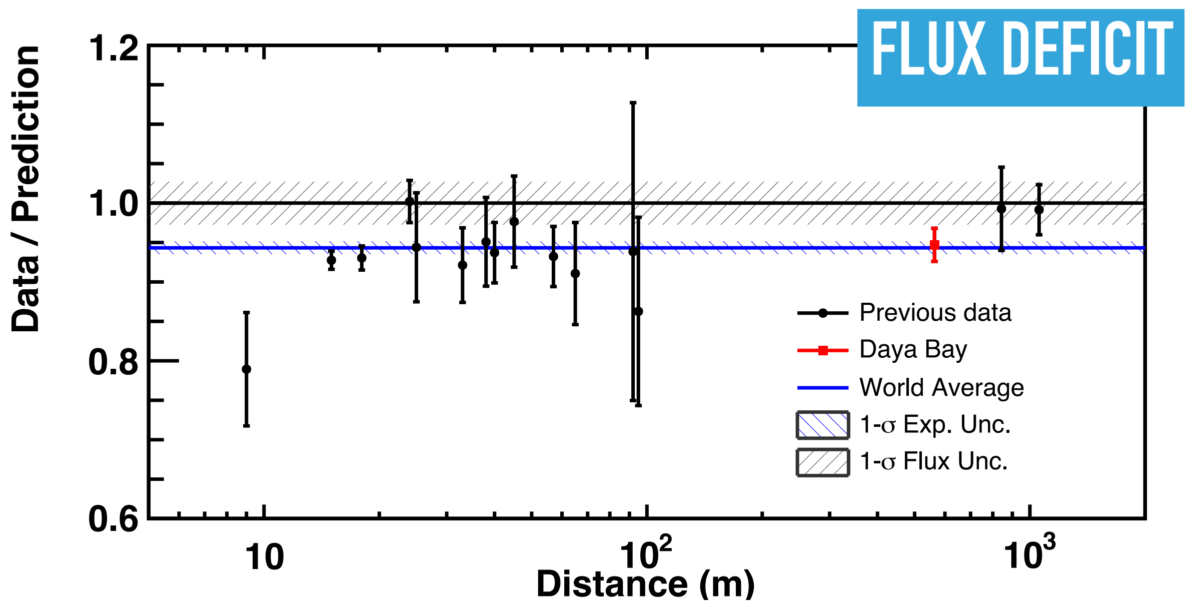
Photo courtesy of Brookhaven National Laboratory

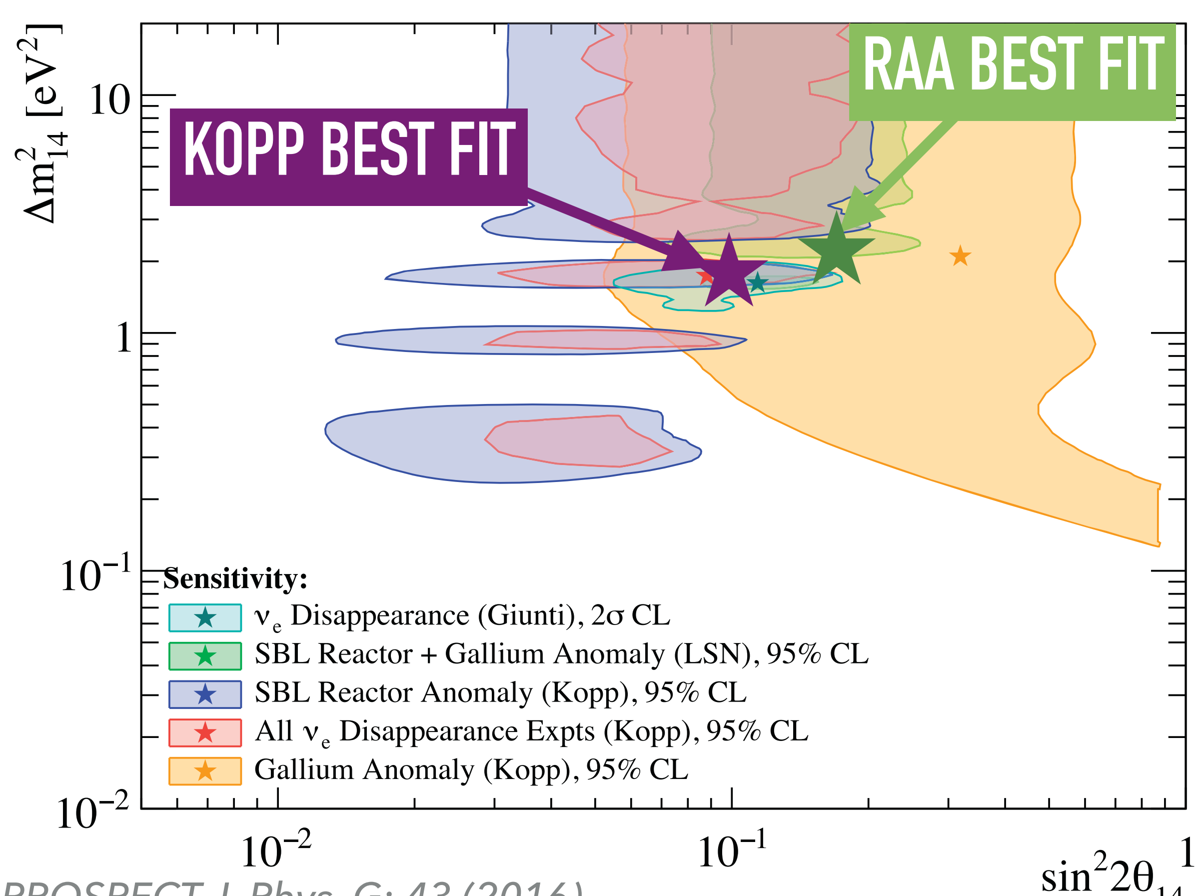
Daya Bay discovers a mismatch

02/12/16 | By Kathryn Jepsen

The latest measurements from the Daya Bay neutrino experiment in China don't align with predictions from nuclear theory.

REACTOR ANTINEUTRINO FLUX DEFICIT



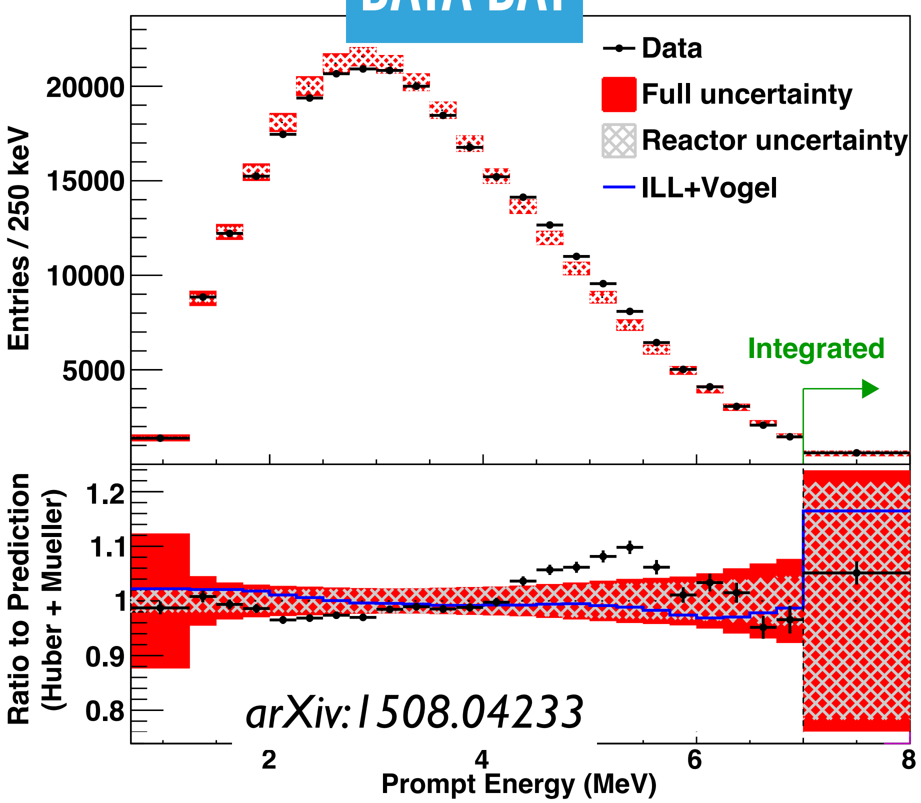


PROSPECT J. Phys. G: 43 (2016)

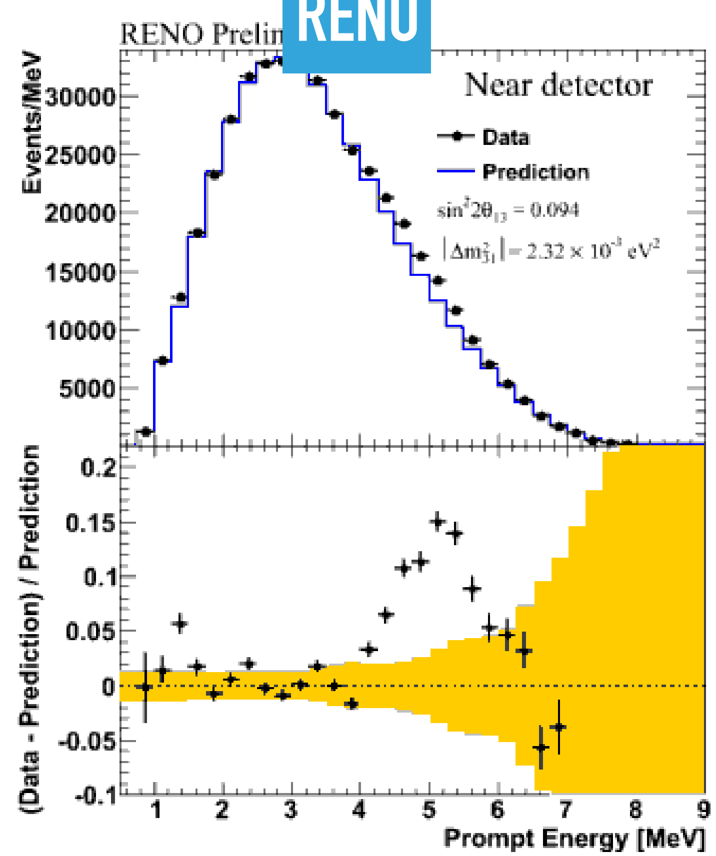
- Daya Bay's blinded analysis measures a flux consistent with old world-average
  - *Not a bias effect*
- 1eV sterile neutrino hypothesized
- **New *reactor* data needed to directly address the RAA**
  - Very short-baseline (<10m)
  - Compact research reactor to prevent washing out oscillation

θ_{13} DATA FURTHER QUESTIONS REACTOR MODELS

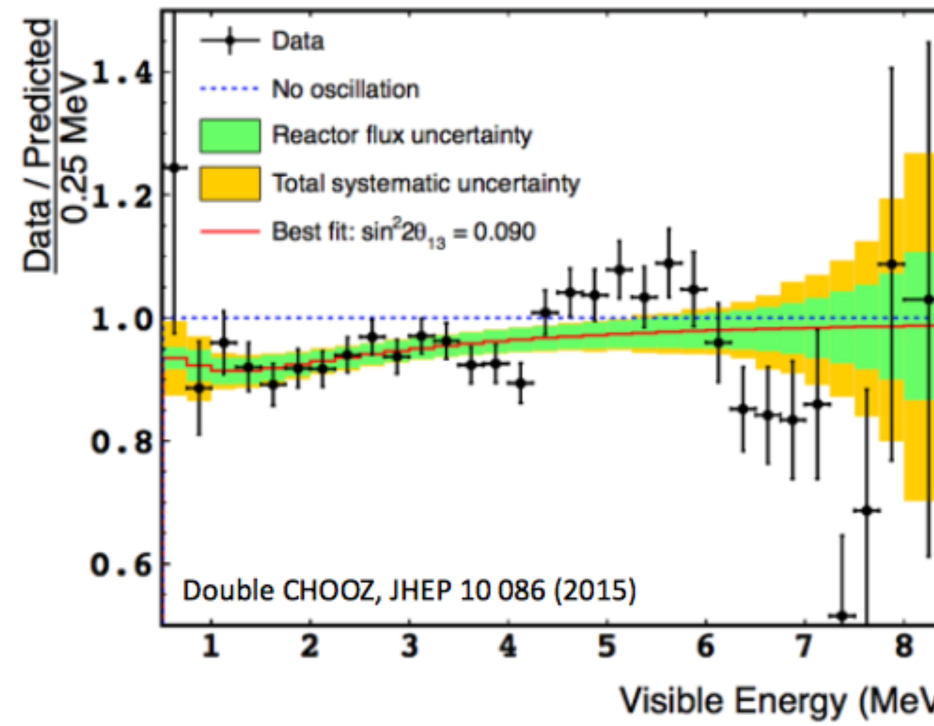
DAYA BAY



RENO



DOUBLE CHOOZ



- All three θ_{13} experiments have observed a spectral deviation between 4-6MeV prompt energy (5-7MeV neutrino energy)
- Predictions based on beta-conversion (Huber, Mueller, Haag)
- Tracks with reactor power, observed in both Near and Far detectors
- Cannot be explained by known detector effects

PARTICLE PHYSICS OR NUCLEAR PHYSICS?

- The era of precision neutrino physics has opened new questions about our understanding of neutrino physics
  - **Reactor Flux Deficit:** Sterile neutrinos or bad flux predictions?
  - **Reactor Spectral Deviation:** Inherent problem with beta-conversion or subtle nuclear physics for one isotope?
- New *reactor* data is required to sort out these questions
  - Very short baseline (< 10m) direct search for neutrino oscillations
  - Different type of reactor to disentangle isotopic nature of spectral deviation

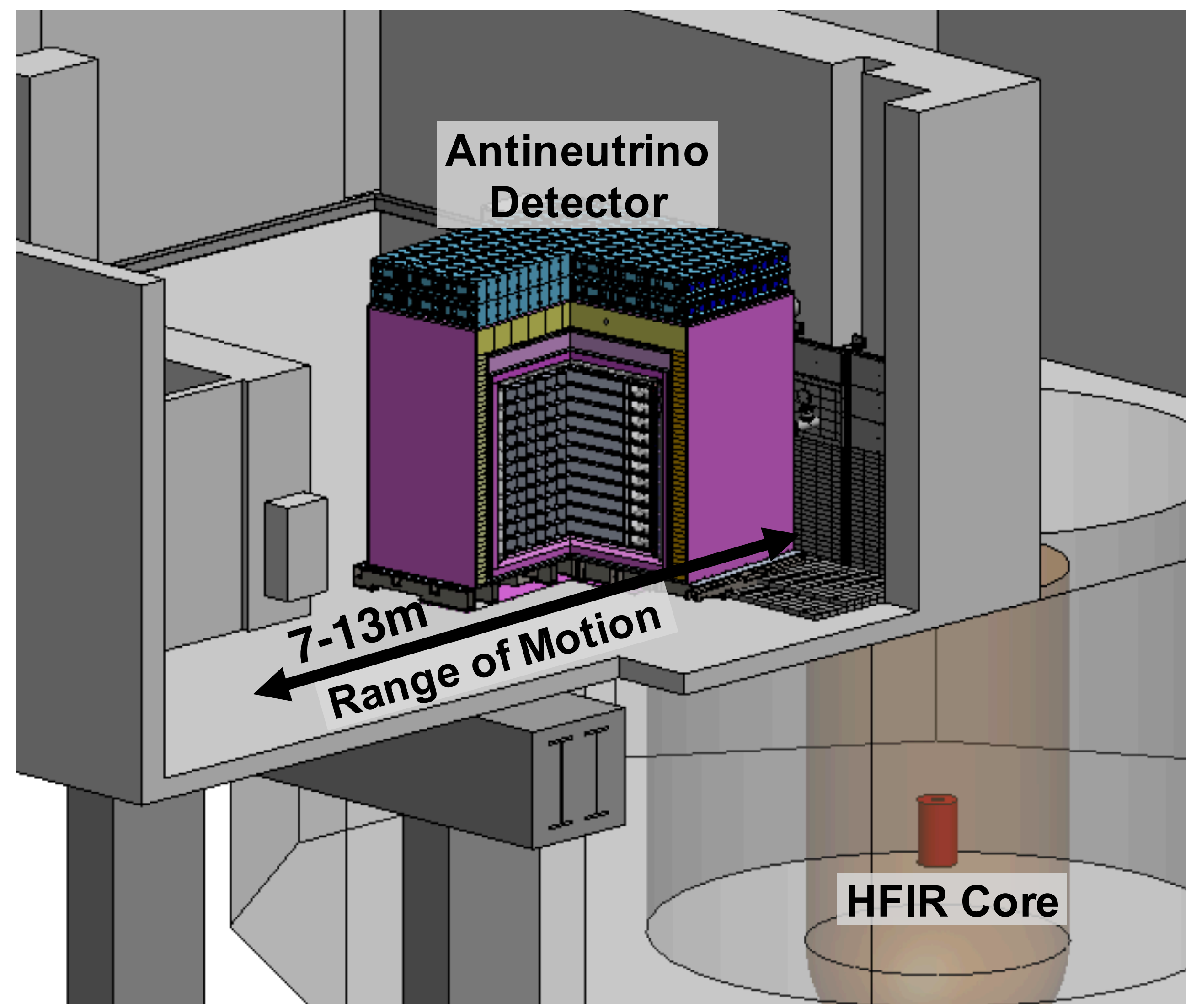
PROSPECT

THE PRECISION REACTOR OSCILLATION AND SPECTRUM EXPERIMENT

PRECISION REACTOR OSCILLATION AND SPECTRUM EXPERIMENT

1. SEARCH FOR SHORT-BASELINE OSCILLATIONS FROM STERILE NEUTRINOS INDEPENDENT FROM REACTOR MODEL INPUTS
2. MEASURE ^{235}U ENERGY SPECTRUM TO RESOLVE THE SPECTRAL ANOMALY

- **Experimental Strategy:**
  - Measure spectrum at a range of baselines (7-9m in closest position)
  - Reactor-model independent search for oscillations throughout the detector
  - High-statistics, high-resolution ^{235}U neutrino energy spectrum
- **Challenges:**
  - Minimal overburden (<1mwe)
  - High-background environment



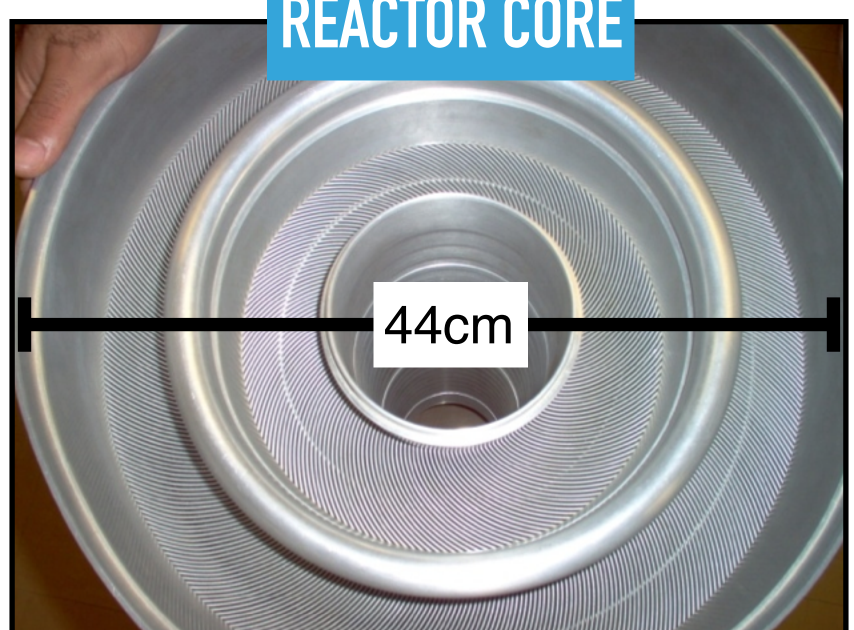
THE HIGH FLUX ISOTOPE REACTOR AT OAK RIDGE

- 85MW highly enriched uranium reactor
  - >99% ^{235}U fissions, effectively no isotopic evolution
- Compact core (44cm diameter, 51cm tall)
- 24 day cycles, 46% reactor up time
- **Detailed study of surface cosmogenic backgrounds with UMD/NIST FaNS**

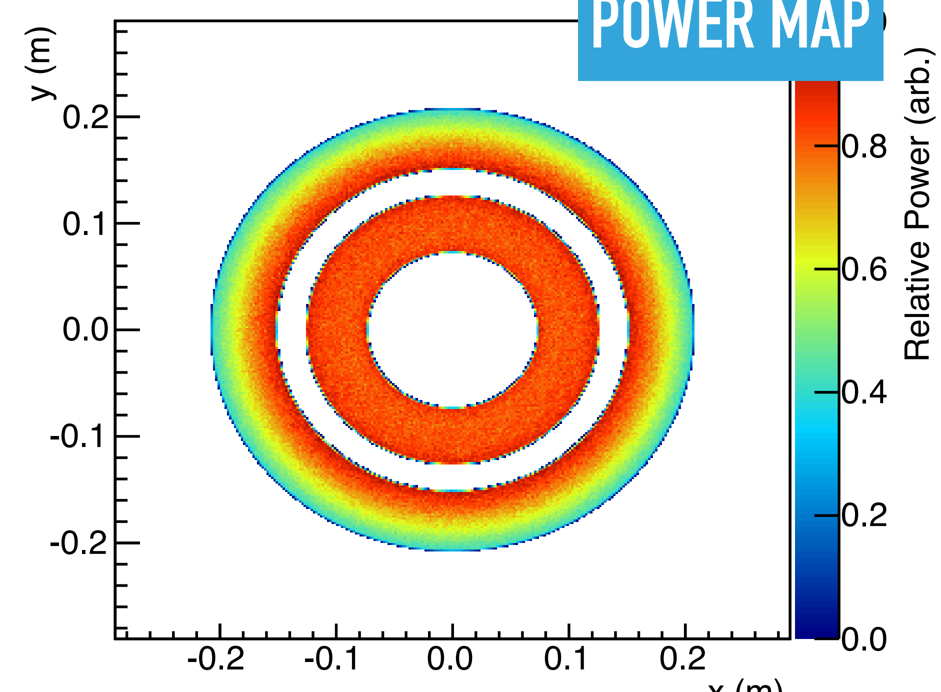
HFIR SITE

CORE REPLACEMENT

REACTOR CORE

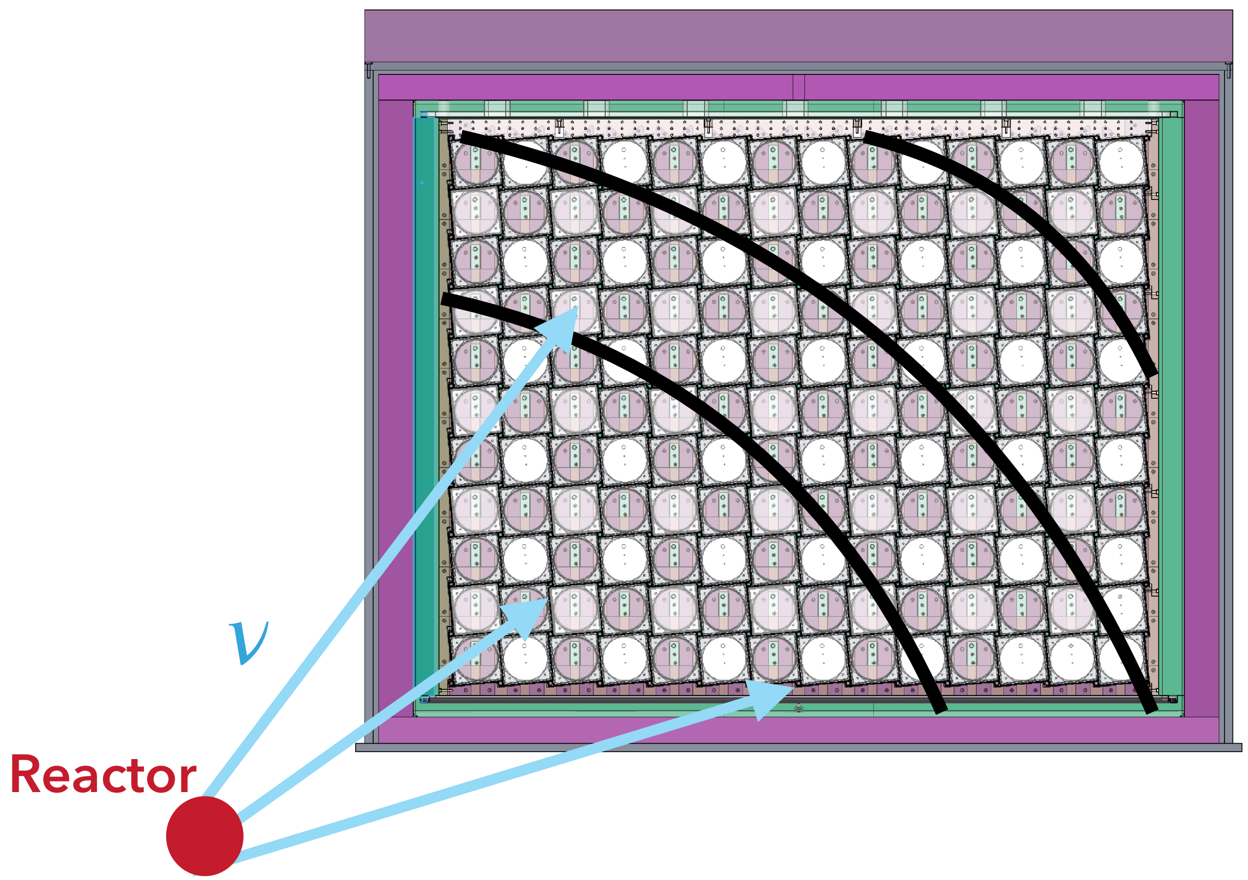


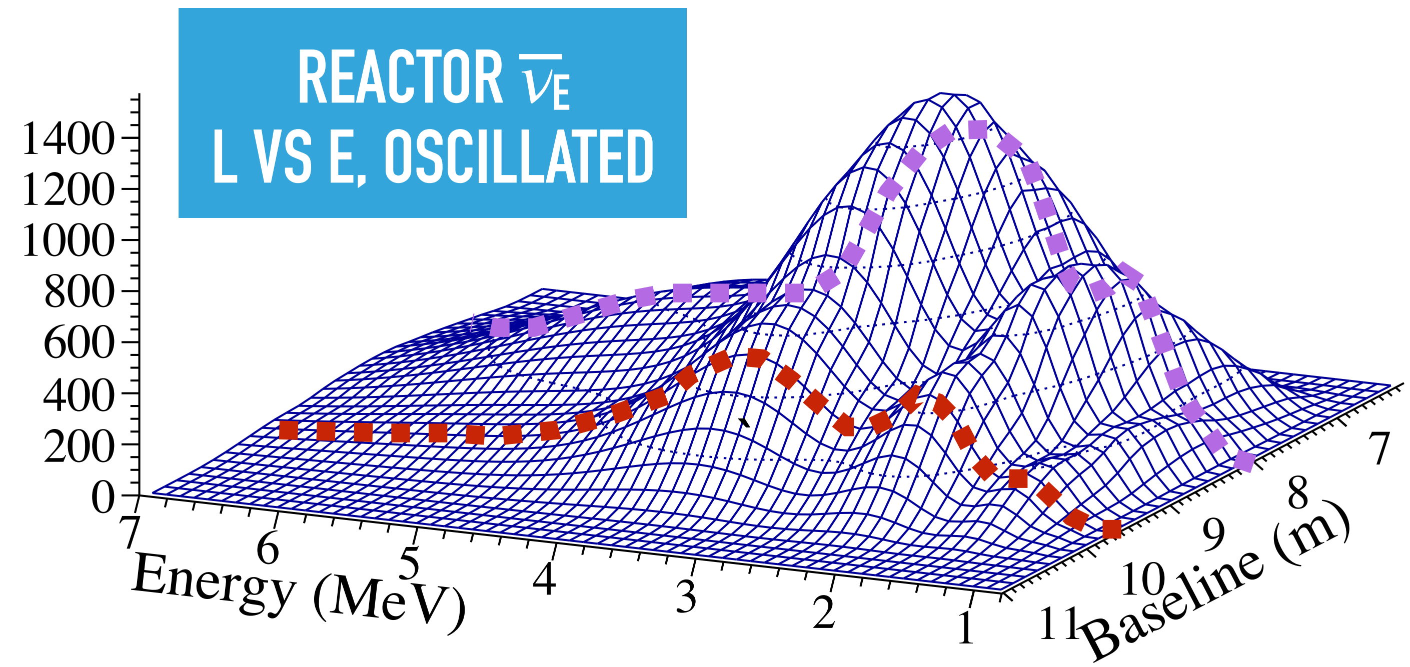
POWER MAP



OSCILLATIONS AT PROSPECT

$$P_{a\to b} \sim sin^2(2\theta_{ab})sin^2\left(1.27\frac{\Delta m_{ab}L}{E}\right)$$

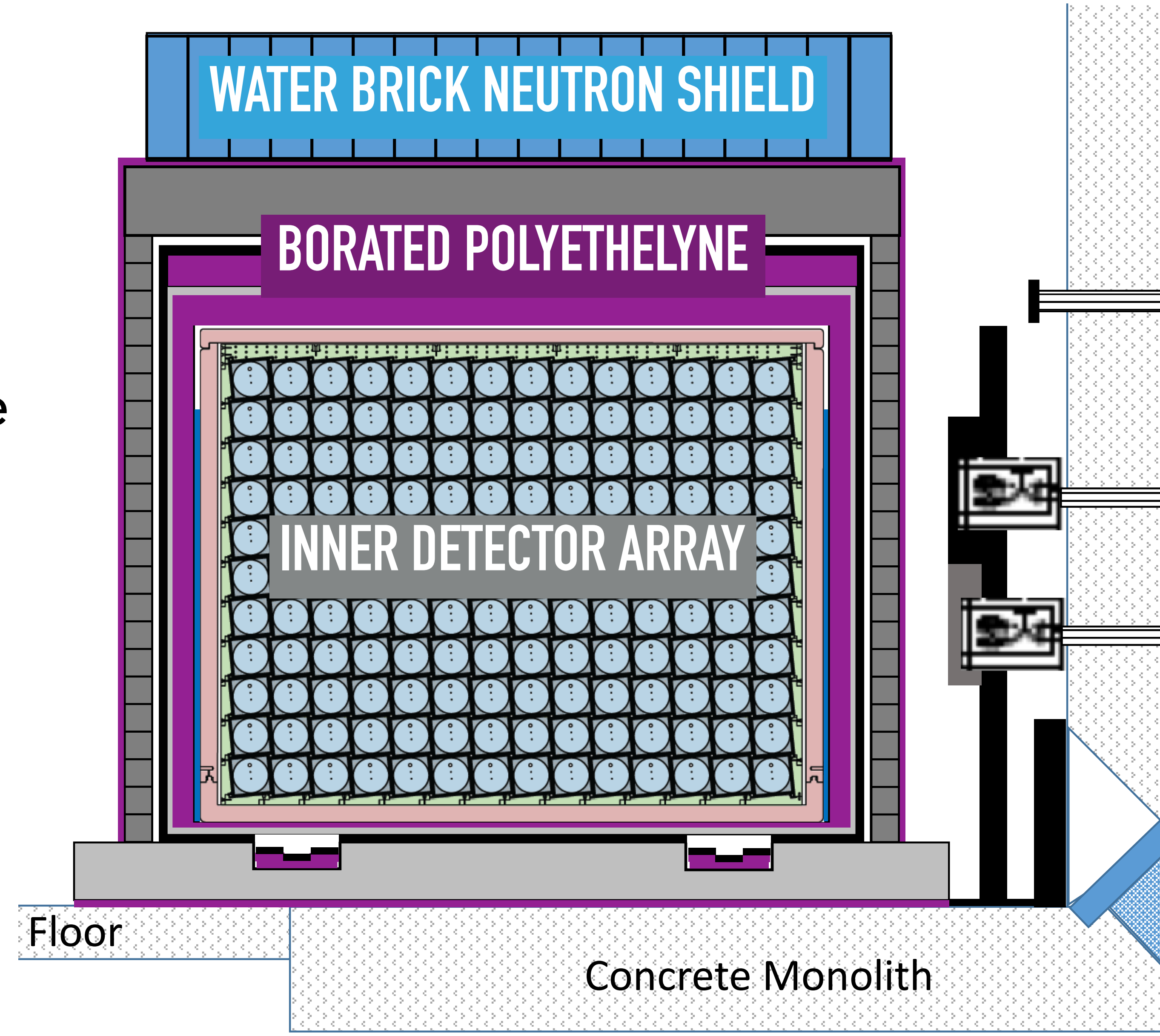


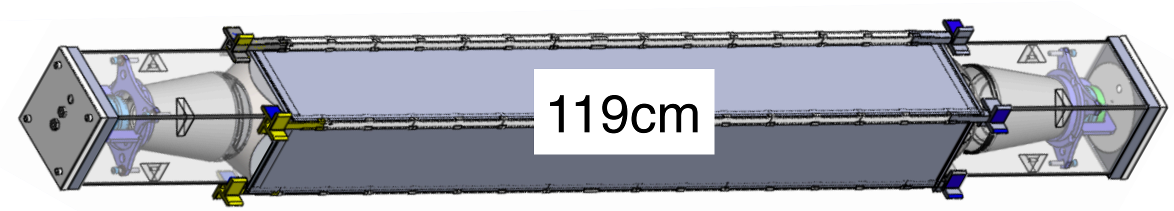


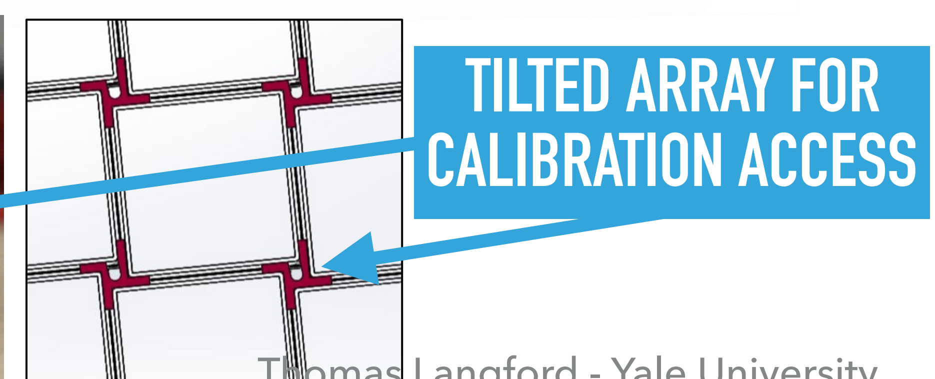
- Neutrino oscillations modify the neutrino spectrum as a function of baseline
- Segmentation provides coverage of a range of baselines without moving
- Measure neutrino spectrum for each baseline and compare shape to the detected full-volume
- ***Reactor model-independent search for sterile neutrinos***

PROSPECT DETECTOR DESIGN

- 154 segments, 119cm x 15cm x 15cm
  - ~25liters per segment, total mass: 4ton
- Thin (1.5mm) reflector panels held in place by 3D-printed support rods
- **Segmentation enables:**
  1. Calibration access throughout volume
  2. Position reconstruction (X, Y)
  3. Event topology ID
  4. Fiducialization
- Double ended PMT readout for full (X,Y,Z) position reconstruction
- **Optimized shielding to reduce cosmogenic backgrounds**

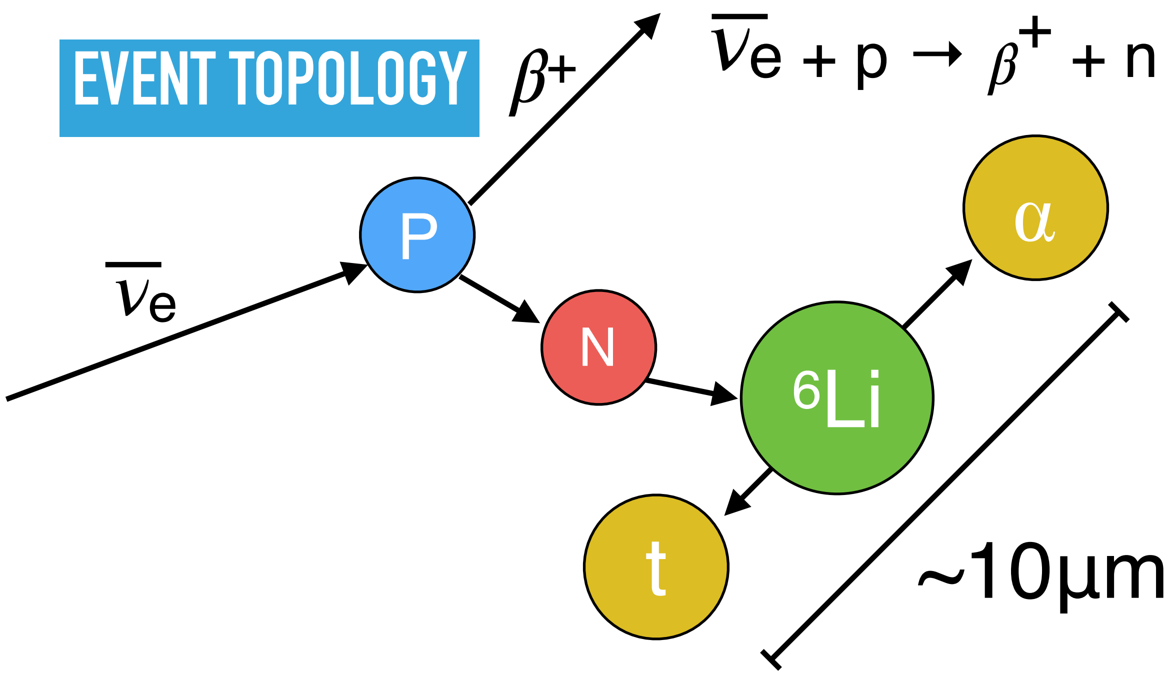


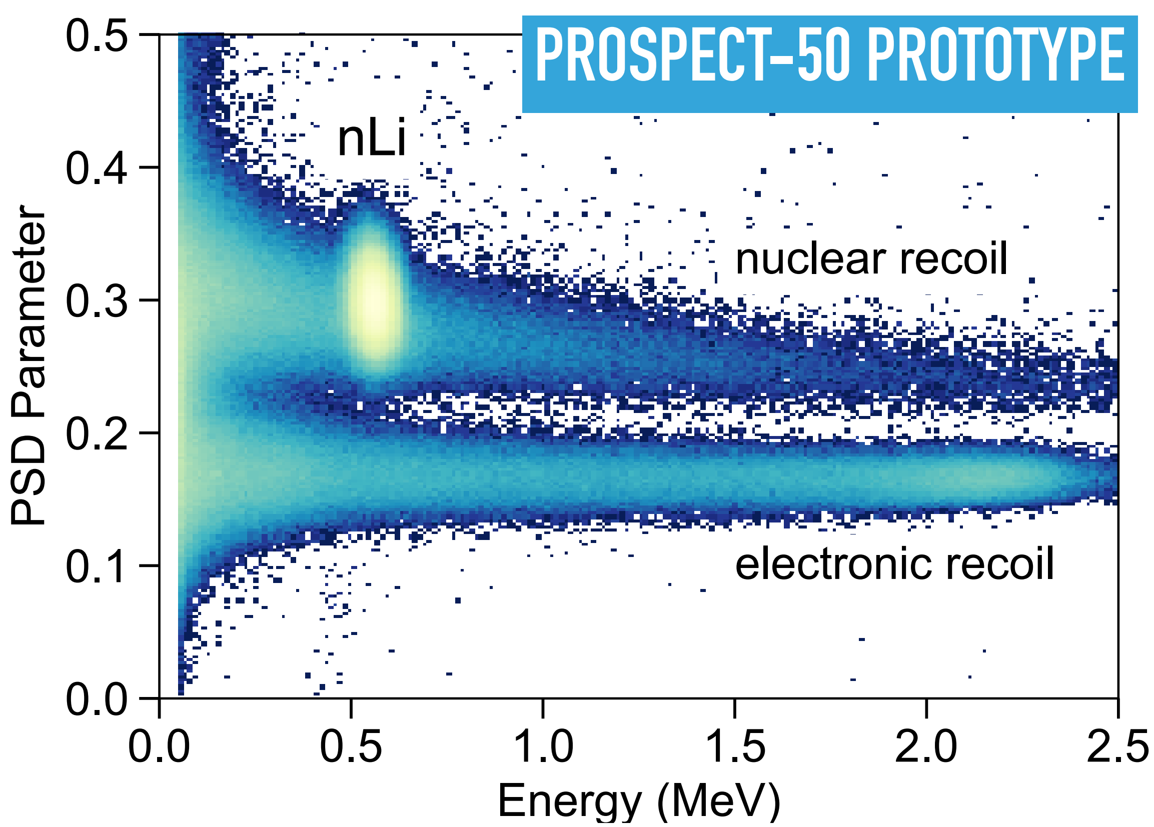




^{6}LI LOADED LIQUID SCINTILLATOR

EVENT TOPOLOGY

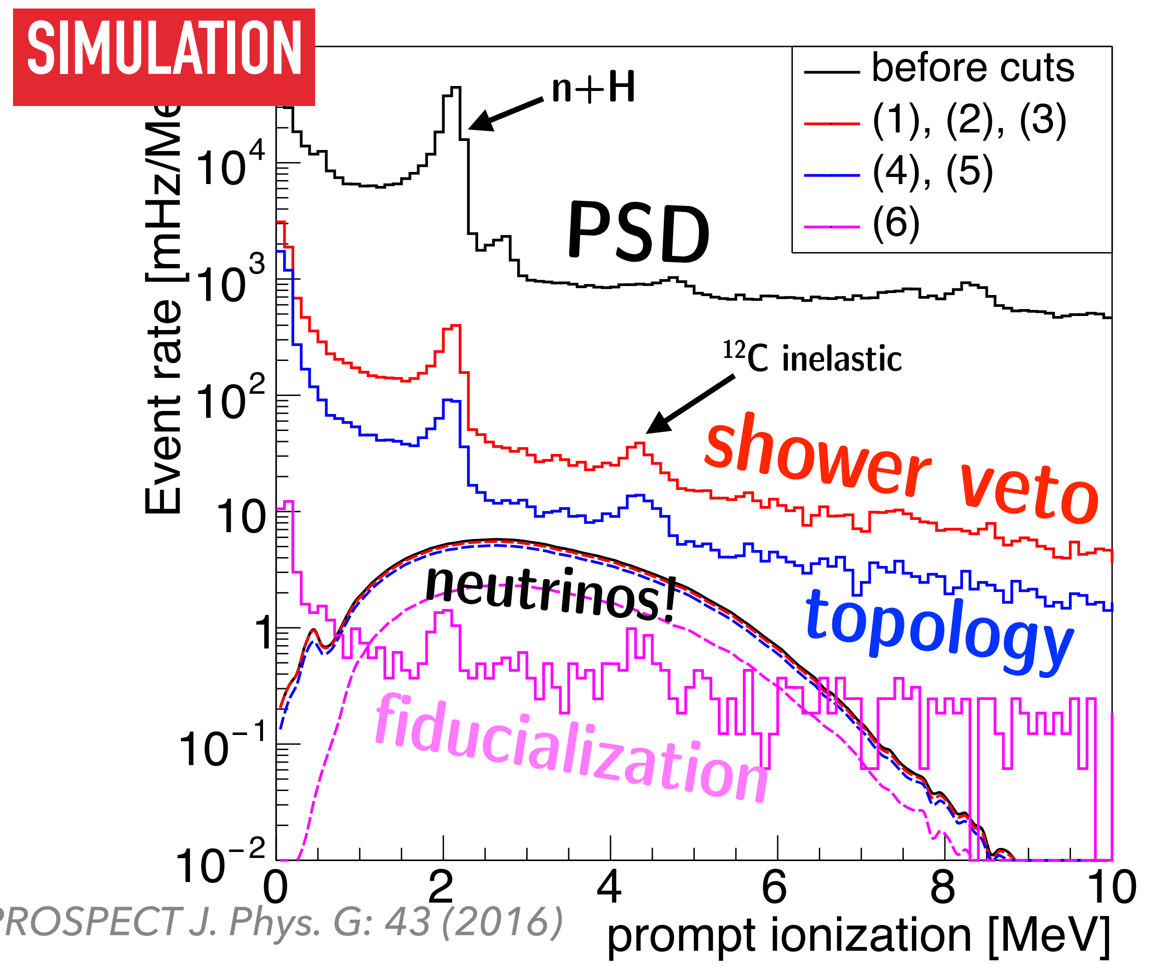




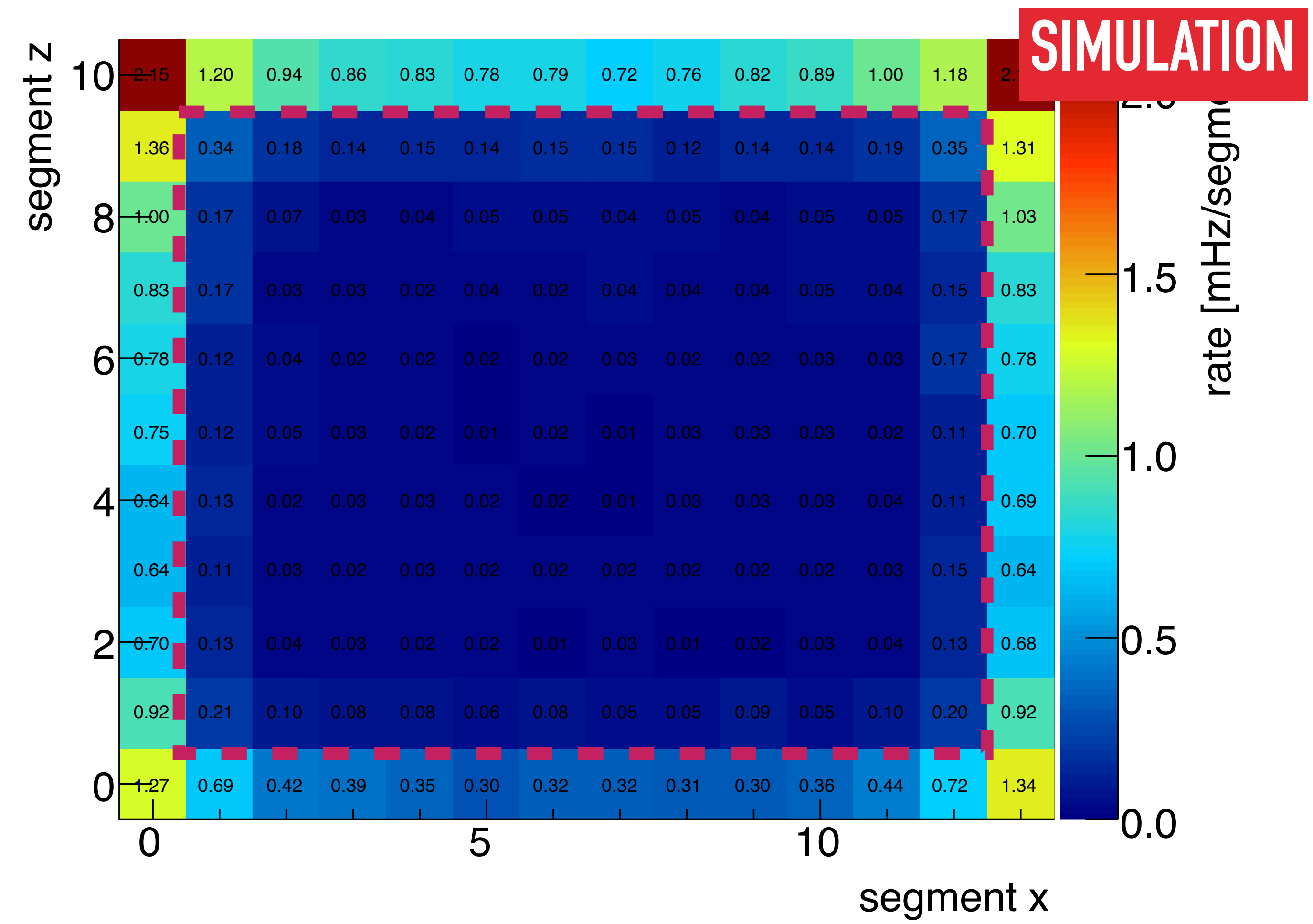
- Compact, segmented detector needs a capture agent that is highly localized
  - Minimize position dependent efficiency variation
  - Distance between prompt/delay to reject accidental backgrounds
- High light yield (8200ph/MeV) for energy resolution
- Particle ID through pulse-shape discrimination (PSD)
- **Custom developed ^{6}LiLS based on EJ-309, meets all requirements**

PROSPECT ARXIV:1805.09245

ACTIVE BACKGROUND SUPPRESSION



PROSPECT J. Phys. G: 43 (2016)



- Optimized detector design for background ID and suppression
- Combine PSD, shower veto, event topology, and fiducialization
- **Yields >10^4 active suppression of background**

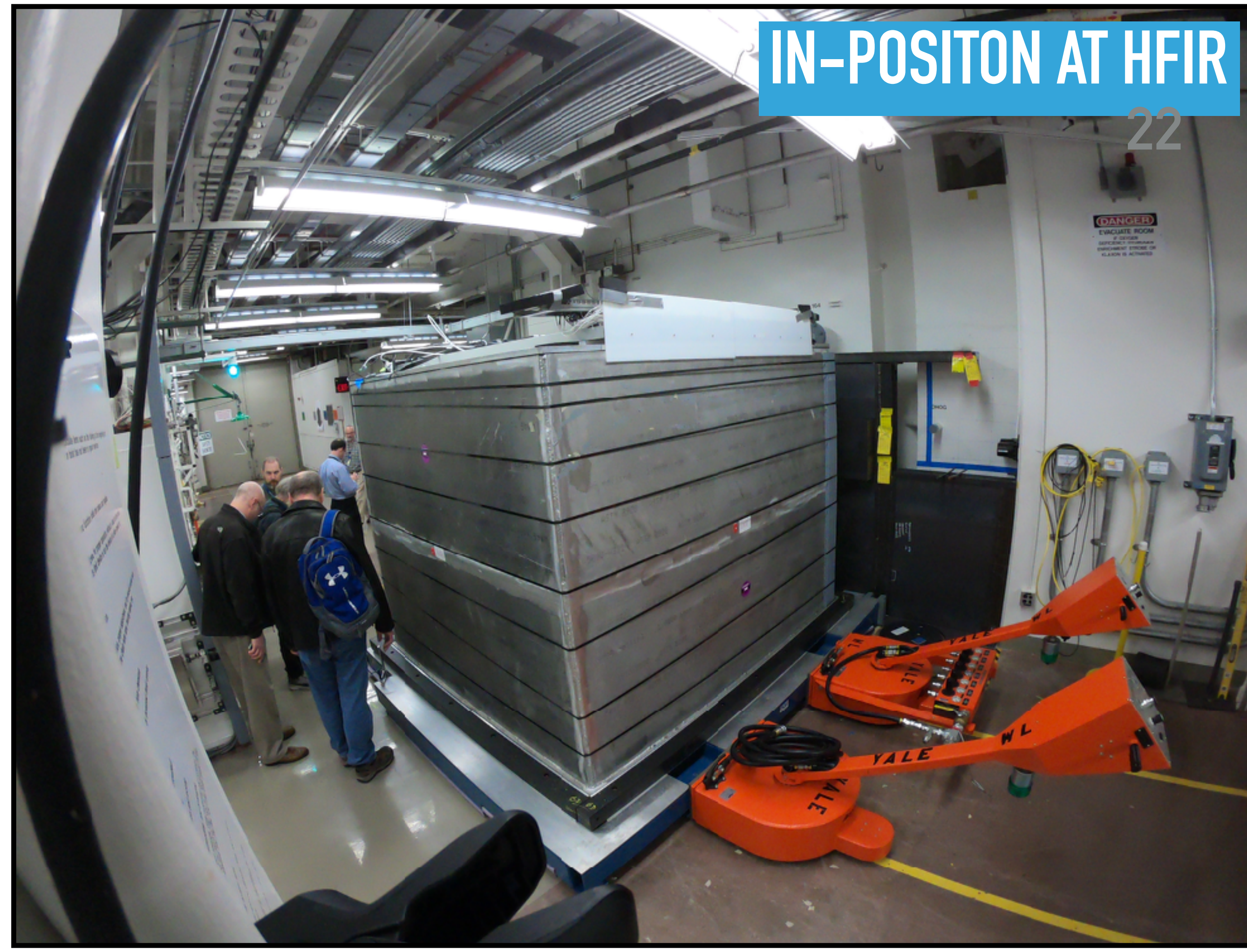
CONSTRUCTION & INSTALLATION


Assembly in 30s (video)
ASSEMBLY OF FIRST ROW
NOVEMBER 1, 2017
YALE WRIGHT LAB

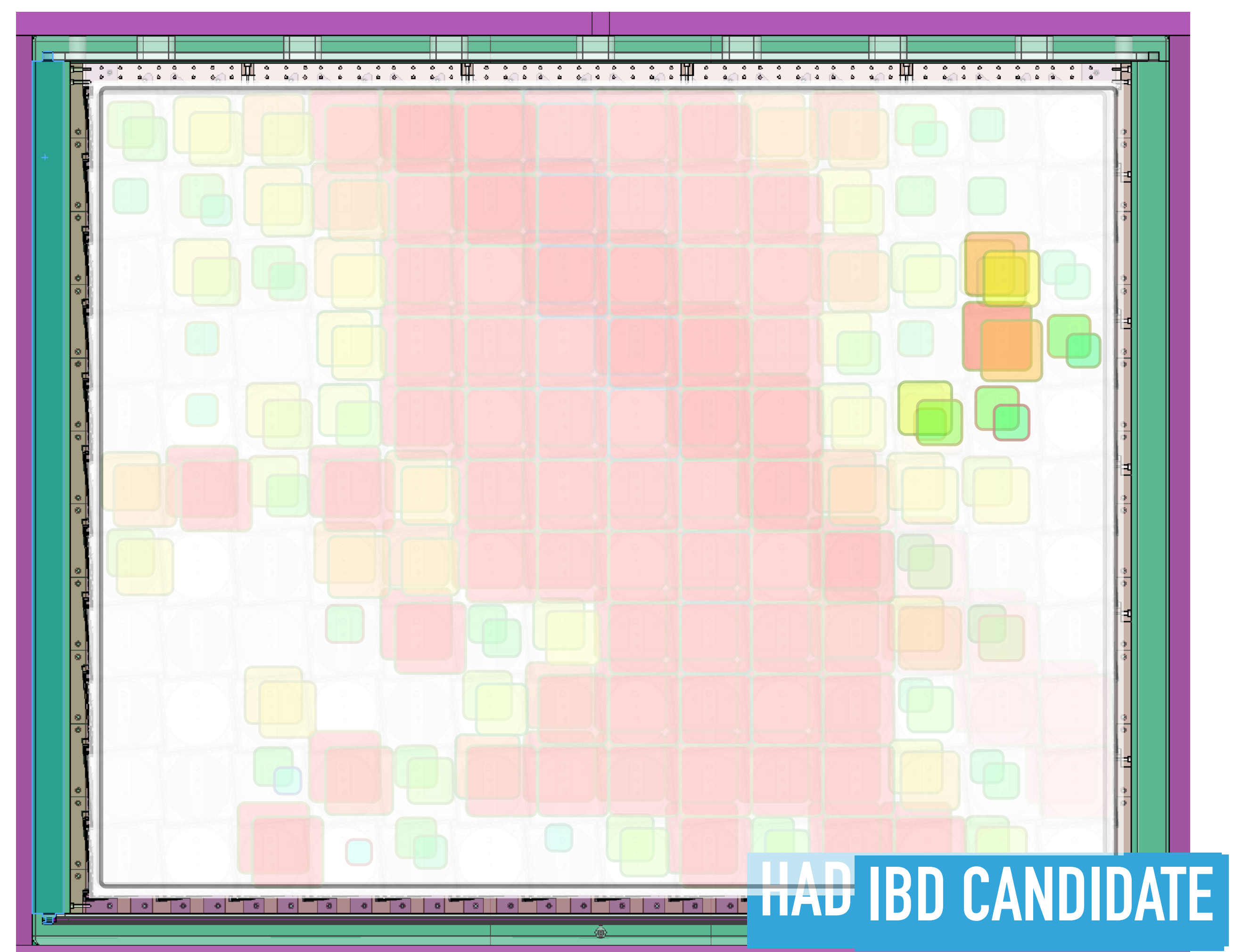

NOVEMBER 17, 2017
FINAL ROW INSTALLATION

DEC, 2017 – JAN 2018
DRY COMMISSIONING AT YALE


FEBRUARY 2018
ARRIVAL AT ORNL


IN-POSITON AT HFIR

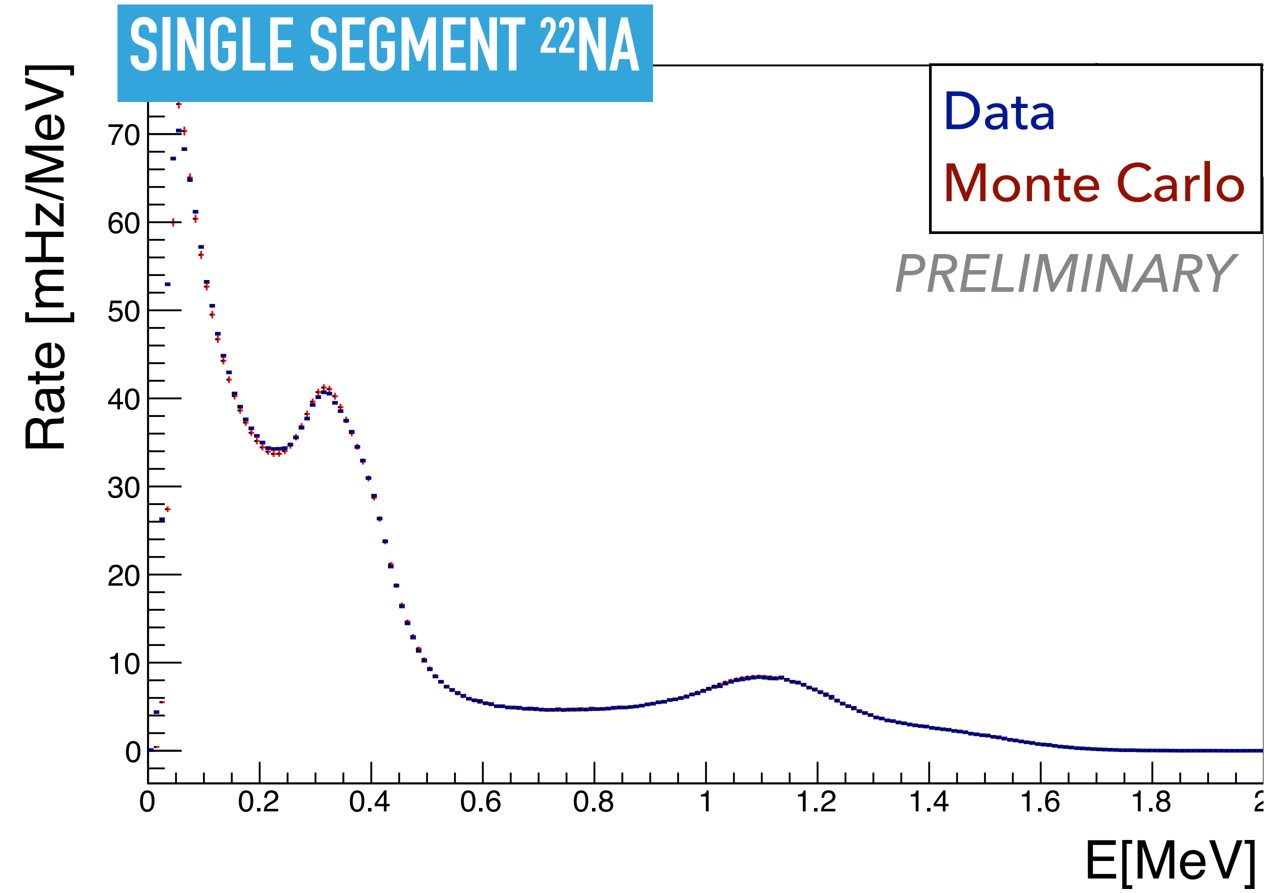

FILLING FROM MIXING TANK

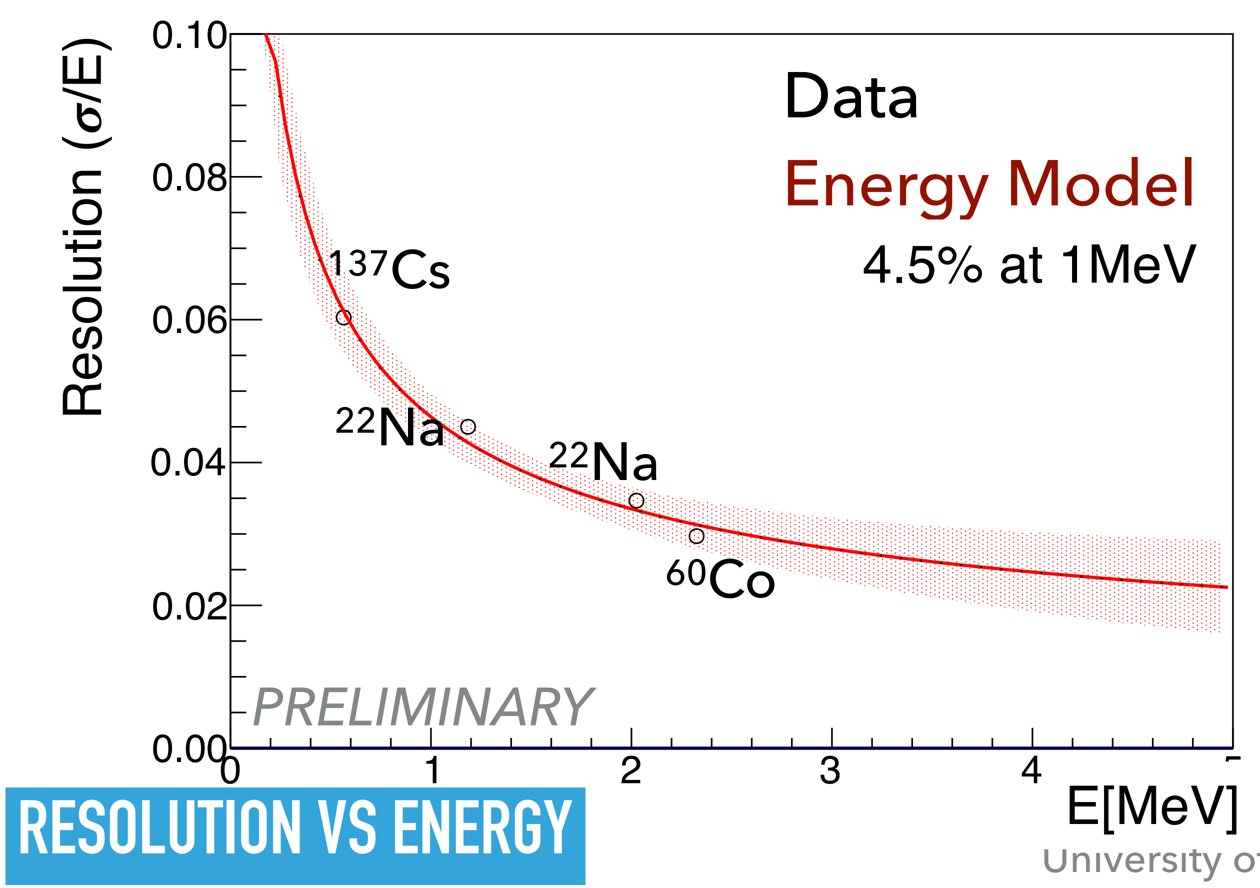

HAD IBD CANDIDATE

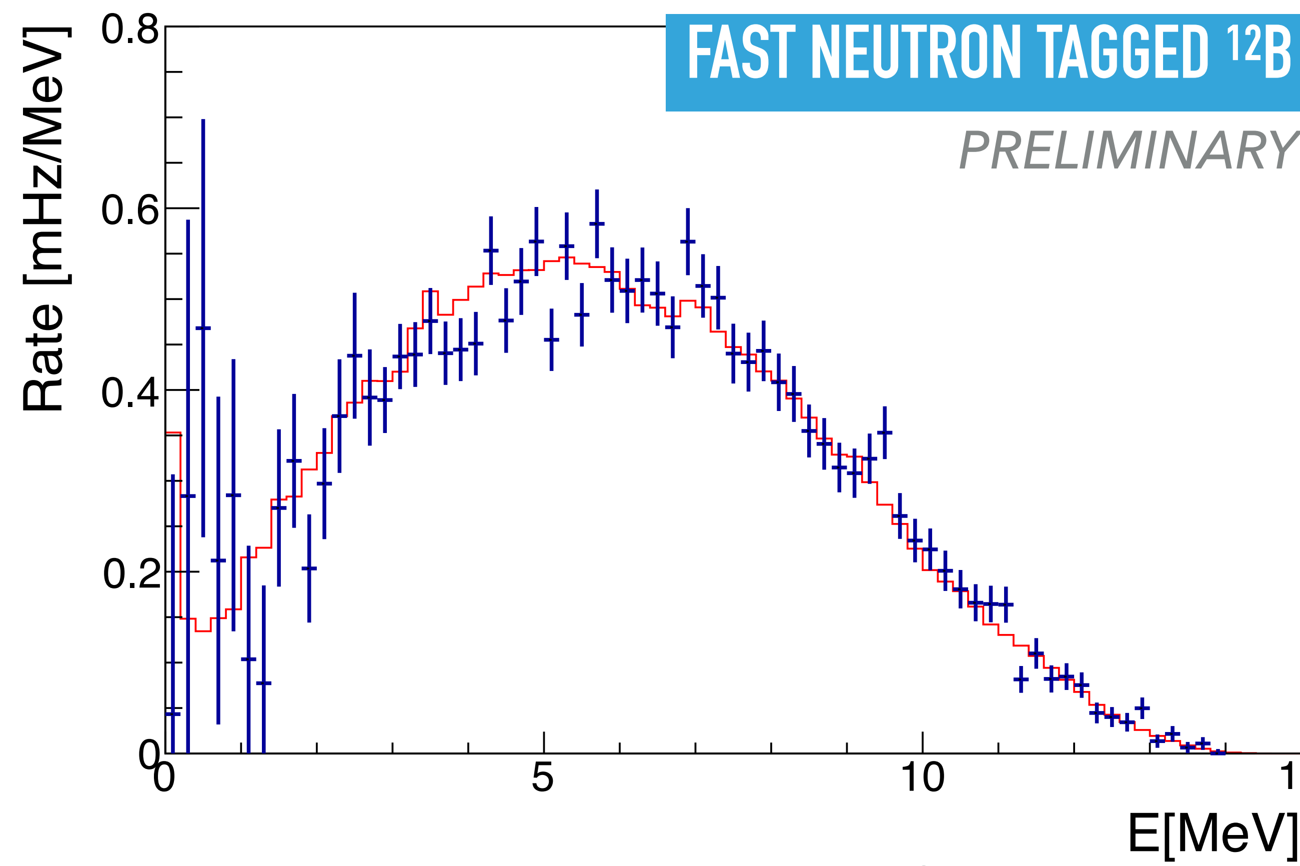
DETECTOR CHARACTERIZATION

ENERGY RECONSTRUCTION

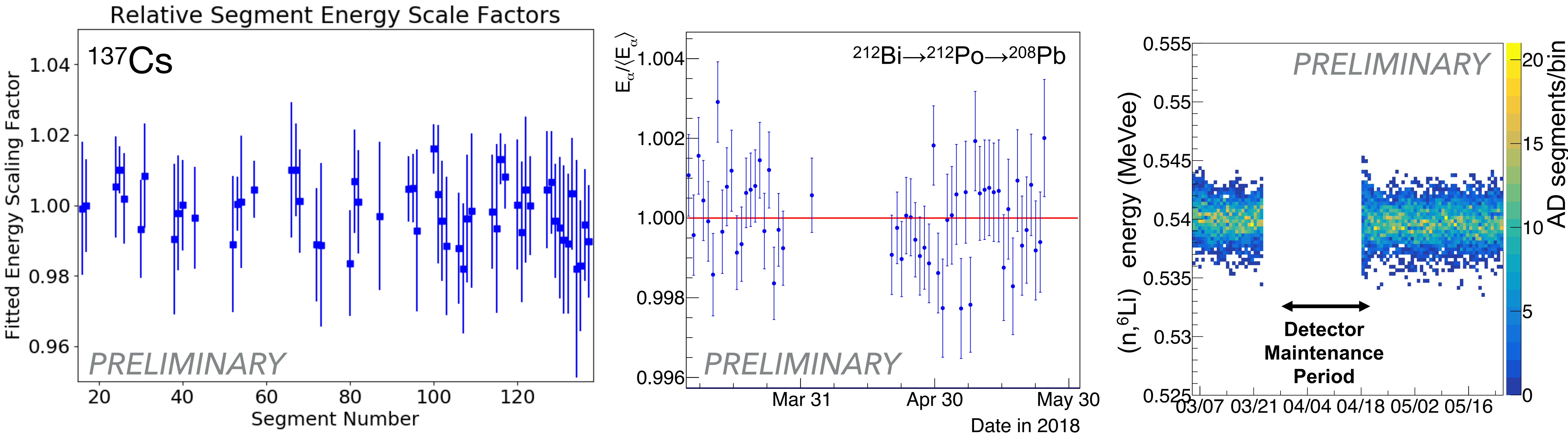
- Sources deployed throughout detector, measure single segment response
- Fast-neutron tagged ^{12}B
  - High-energy beta spectrum calibration
- Full-detector E_{rec} within 1% of E_{true}
- **High light collection: 795±15 PE/MeV**







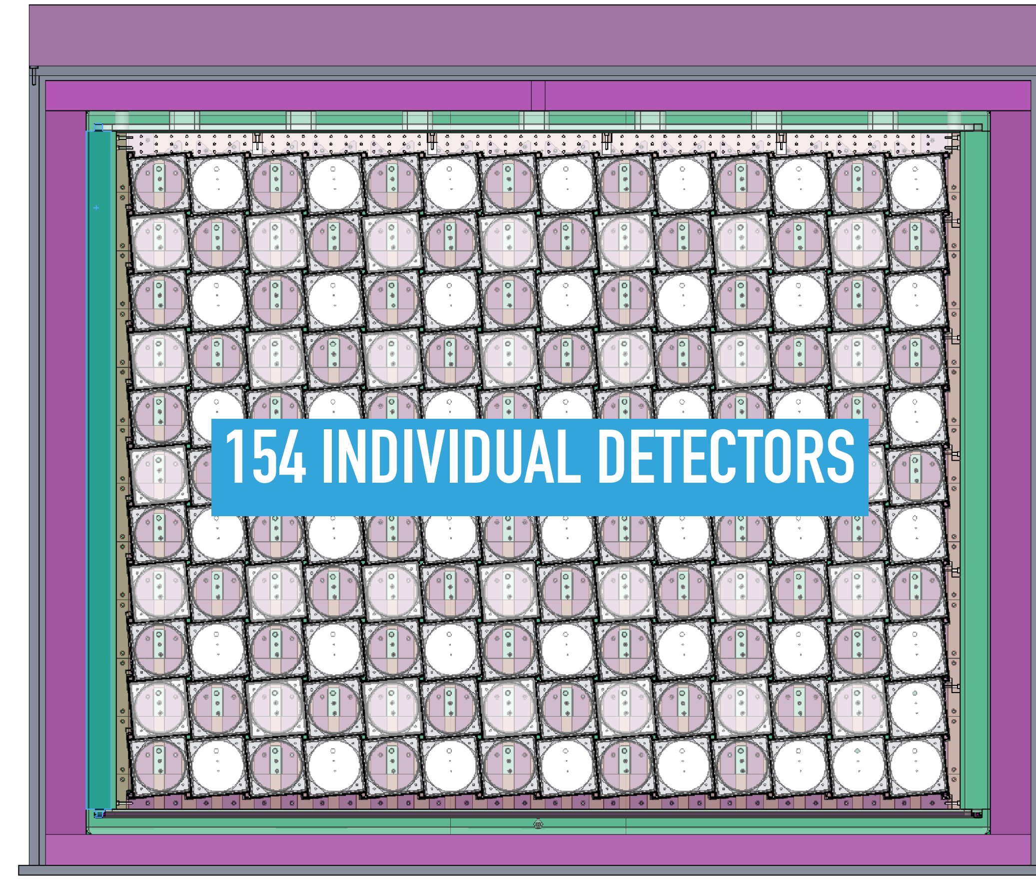
DETECTOR UNIFORMITY

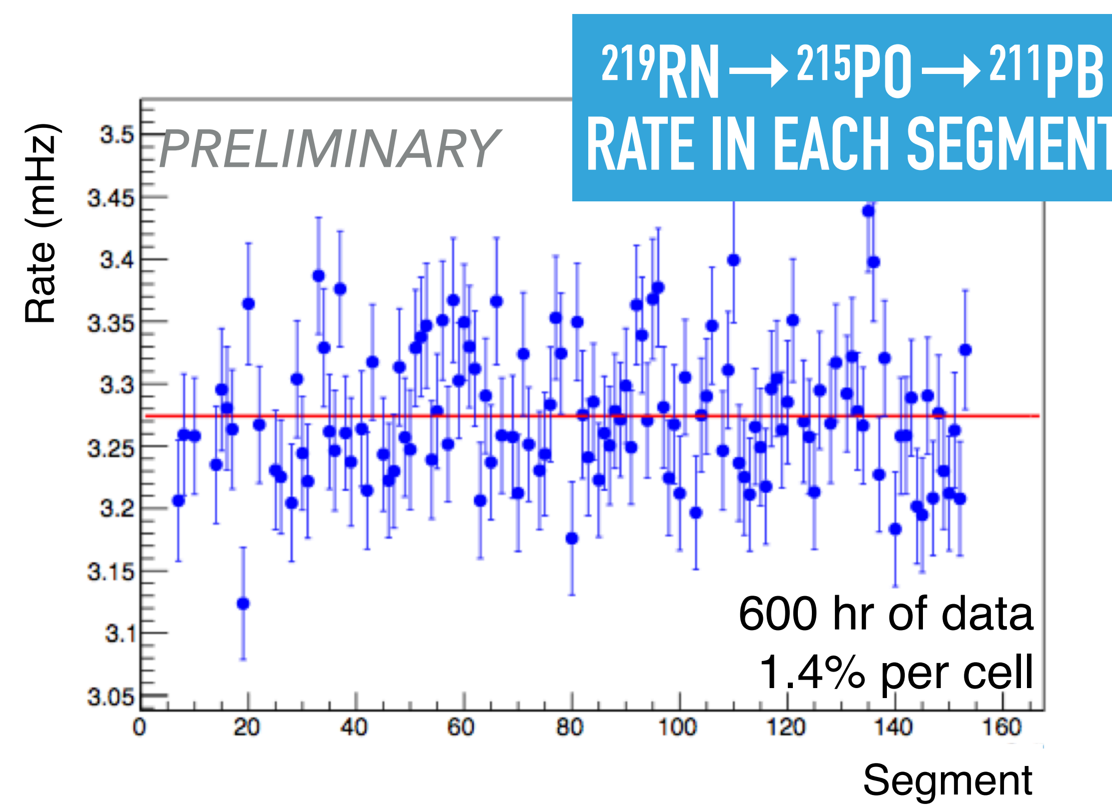


- **Calibration Source Deployment:**
  - 35 calibration source tubes throughout detector to map energy response
  - Segment to segment uniformity ~1%
  - ^{252}Cf source to study neutron capture efficiency
- **Intrinsic radioactive sources**
  - Track uniformity over time with distributed internal single-segment sources:
  - Alpha lines from ^{212}Bi→ ^{212}Po→^{208}Pb decays, nLi capture peak
  - Reconstructed energy stability over time < 1%

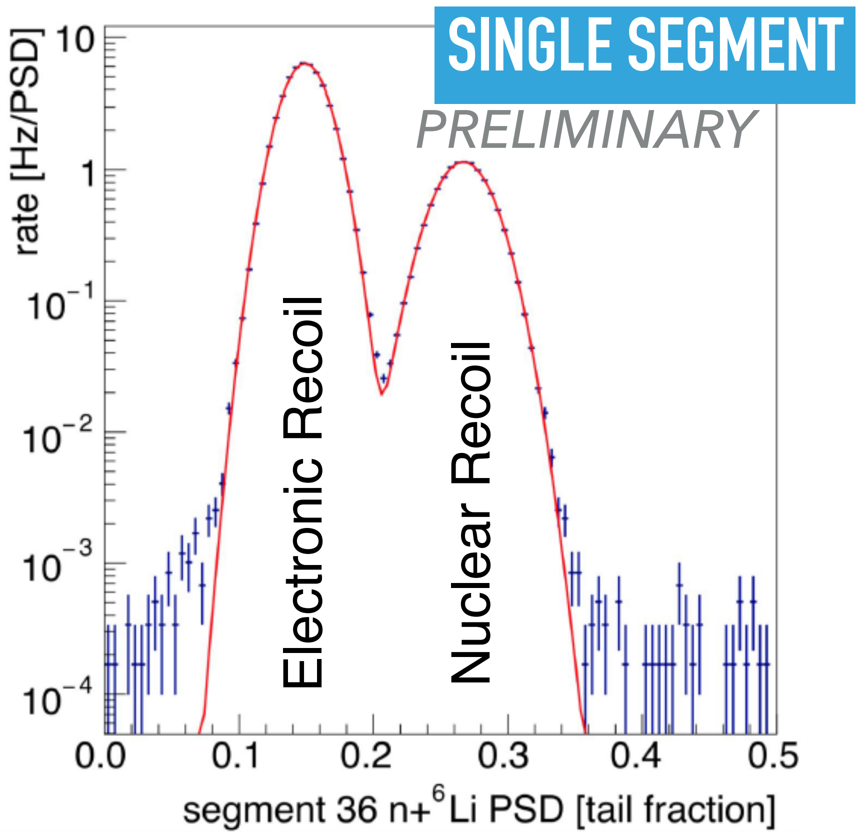
SEGMENT VOLUME MEASUREMENT

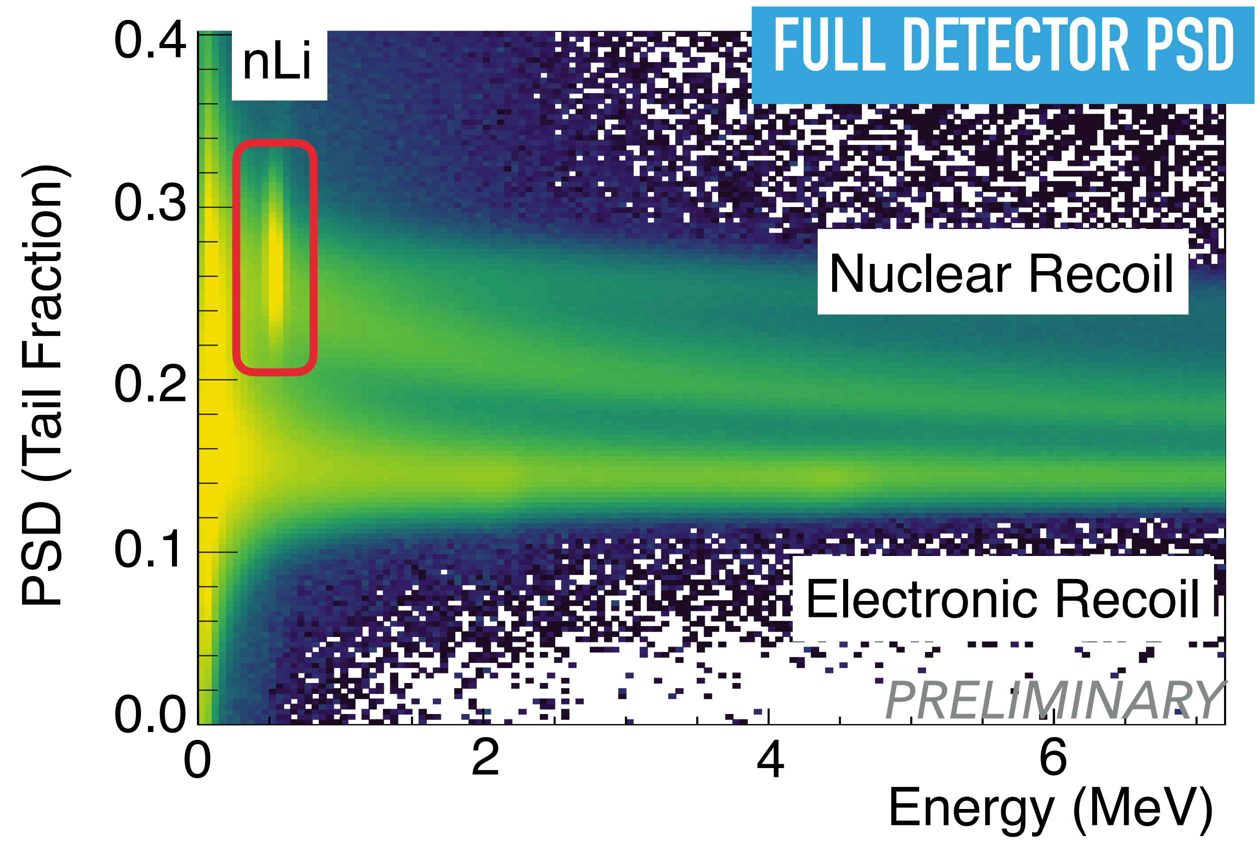
- Survey during construction: < 1% variation
- Relative mass vital for oscillation search
- ^{227}Ac added to LS prior to filling
- Double alpha decay (^{219}Rn→^{215}Po→^{211}Pb), highly localized, easy to ID, 1.78ms lifetime
- Measured absolute z-position resolution of < 5cm
- Direct measurement of relative target mass in each segment





PULSE SHAPE DISCRIMINATION PERFORMANCE

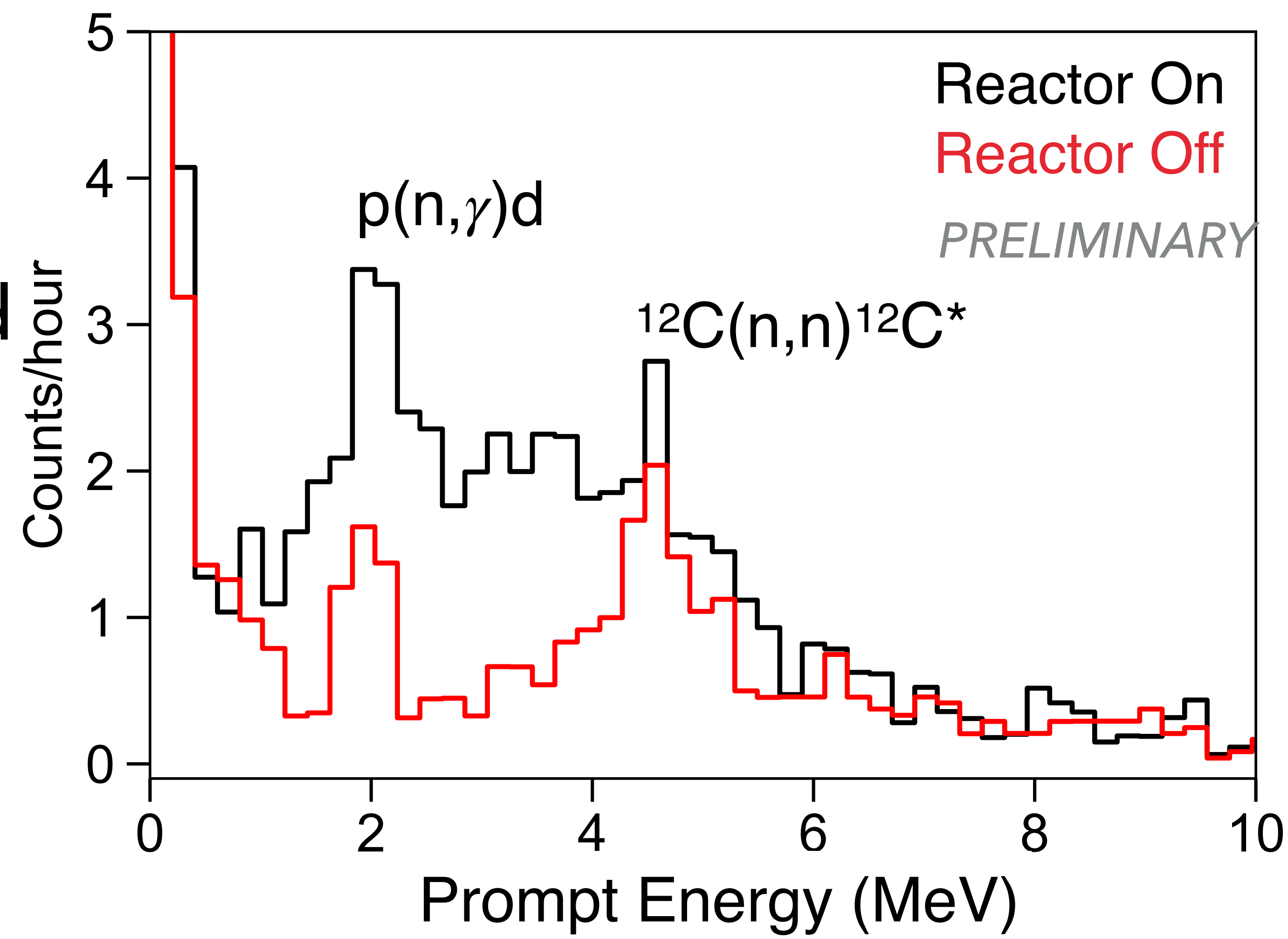




- Excellent particle ID of gamma interactions, neutron captures, and nuclear recoils
- Dominant backgrounds: Cosmogenic fast neutrons, reactor-related gamma rays, reactor thermal neutrons
  - Vast majority identified and rejected by PSD for Prompt and Delayed signals
- **Tag IBDs with high efficiency and high purity**

FIRST 24HOURS OF DETECTOR OPERATION

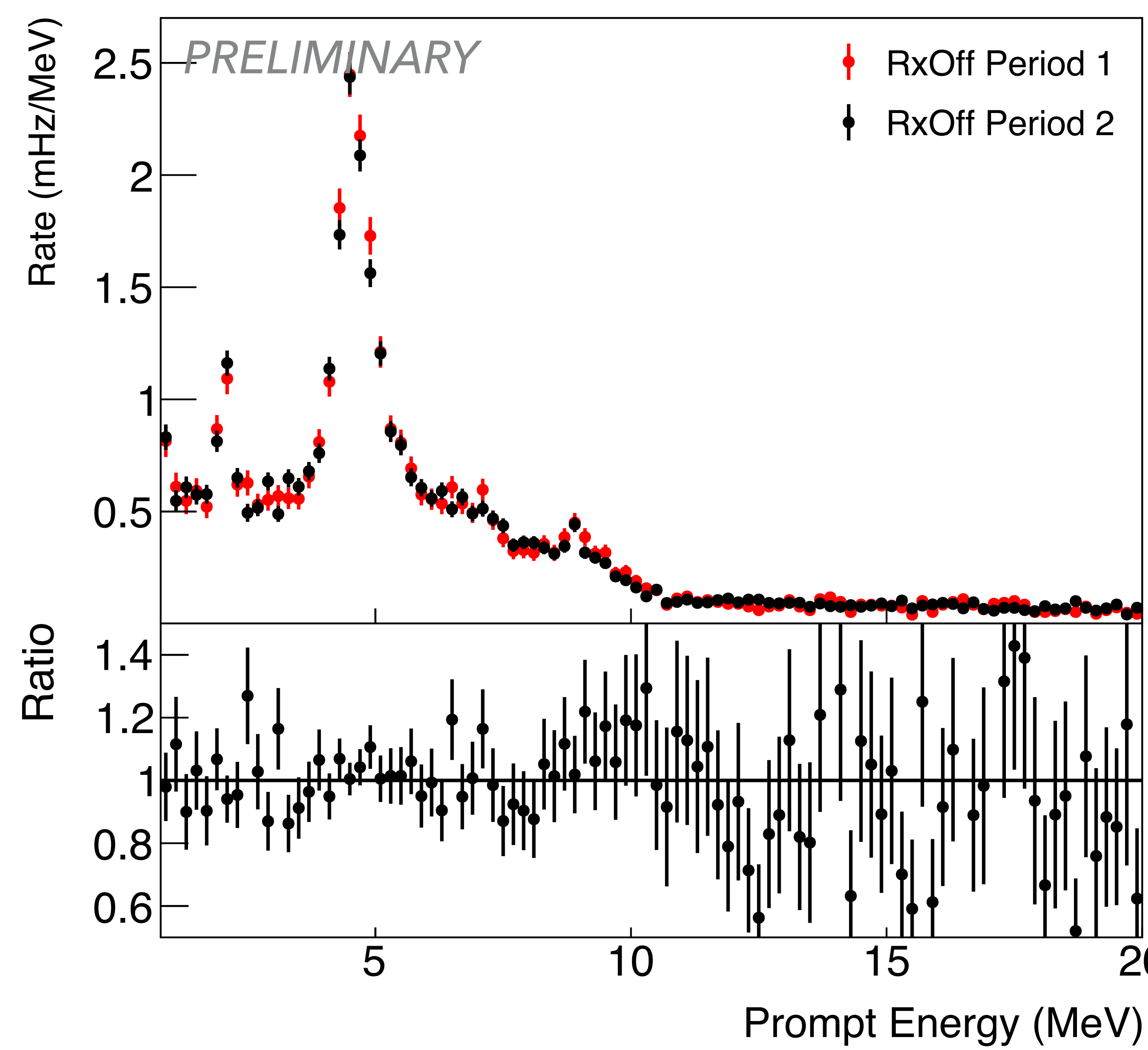
- **March 5, 2018:** Fully assembled detector began operation
- **Reactor On:** 1254±30 correlated events between [.8, 7.2MeV]
- **Reactor Off:** 614±20 correlated events (first off day March 16)
    - Clear peaks in background from neutron interactions with H and ^{12}C
- Time to 5σ detection at earth's surface: < 4hrs



PROSPECT is measuring the ^{235}U antineutrino spectrum

BACKGROUND STABILITY

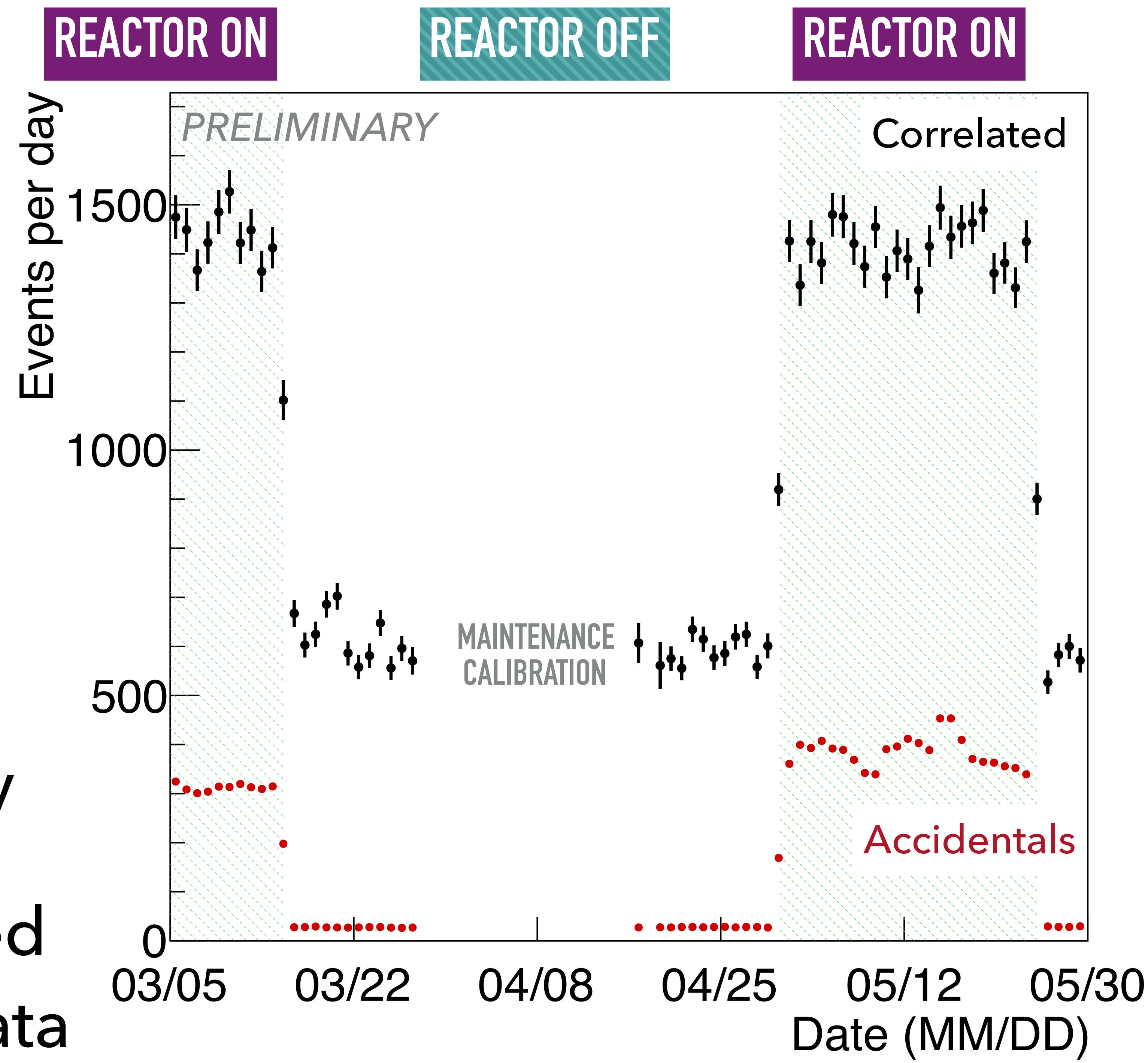
- Surface-based detector with minimal overburden
- Backgrounds are known to vary with atmospheric conditions
- Reactor Off data is split into two periods
  - Consistent rate and spectrum is observed
  - Vital cross-check for backgrounds subtraction



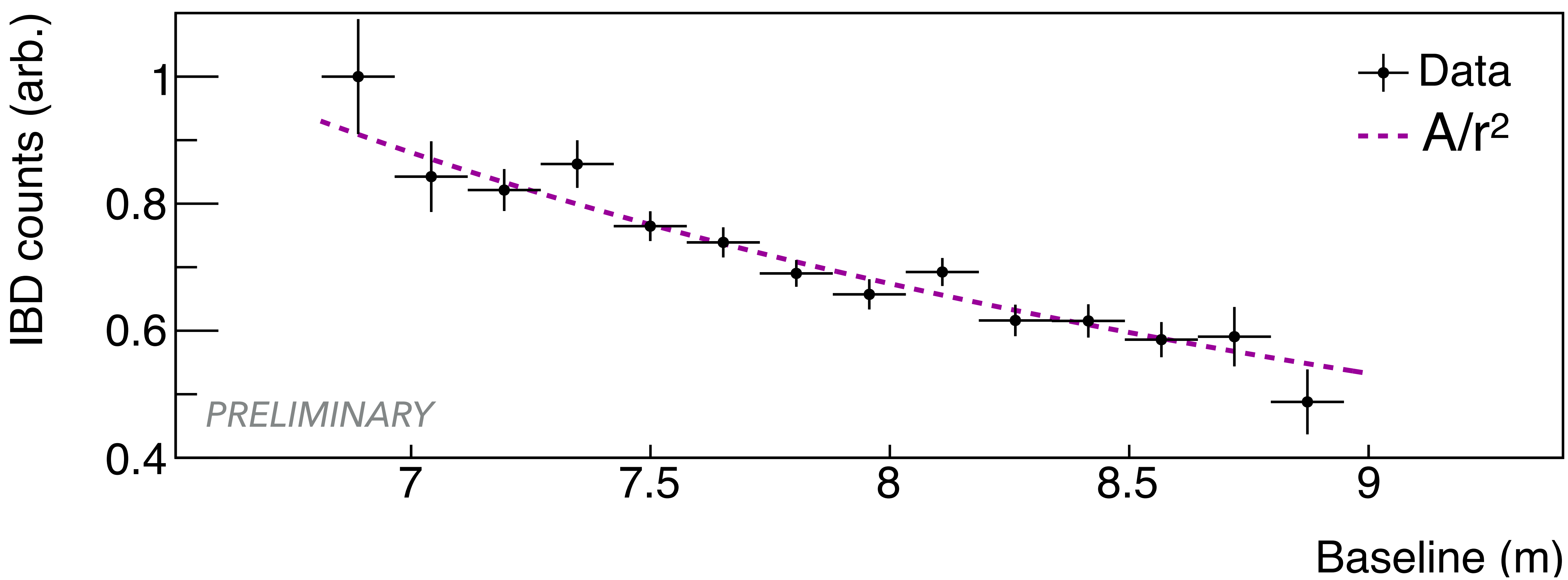
SEARCH FOR STERILE NEUTRINOS

OSCILLATION DATA SET (ARXIV: 1806.02784)

- 33 days of Reactor On
- 28 days of Reactor Off
- Correlated S/B = 1.36
- Accidental S/B = 2.25
- **24,608 IBDs detected**
- Average of ~750 IBDs/day
- IBD event selection defined and frozen on 3 days of data



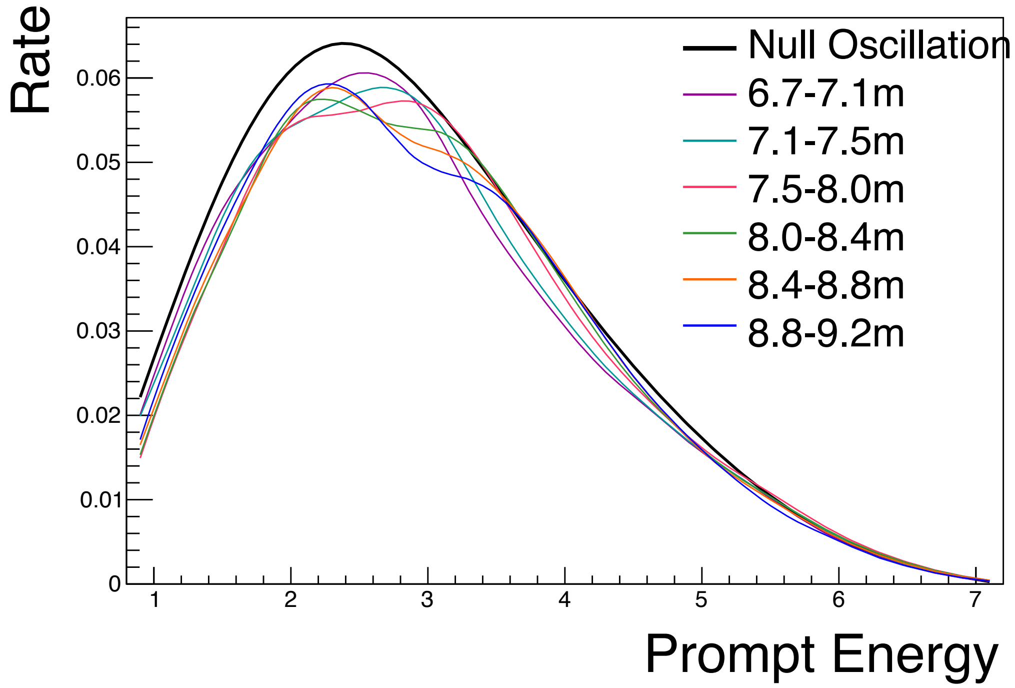
NEUTRINO RATE VS BASELINE

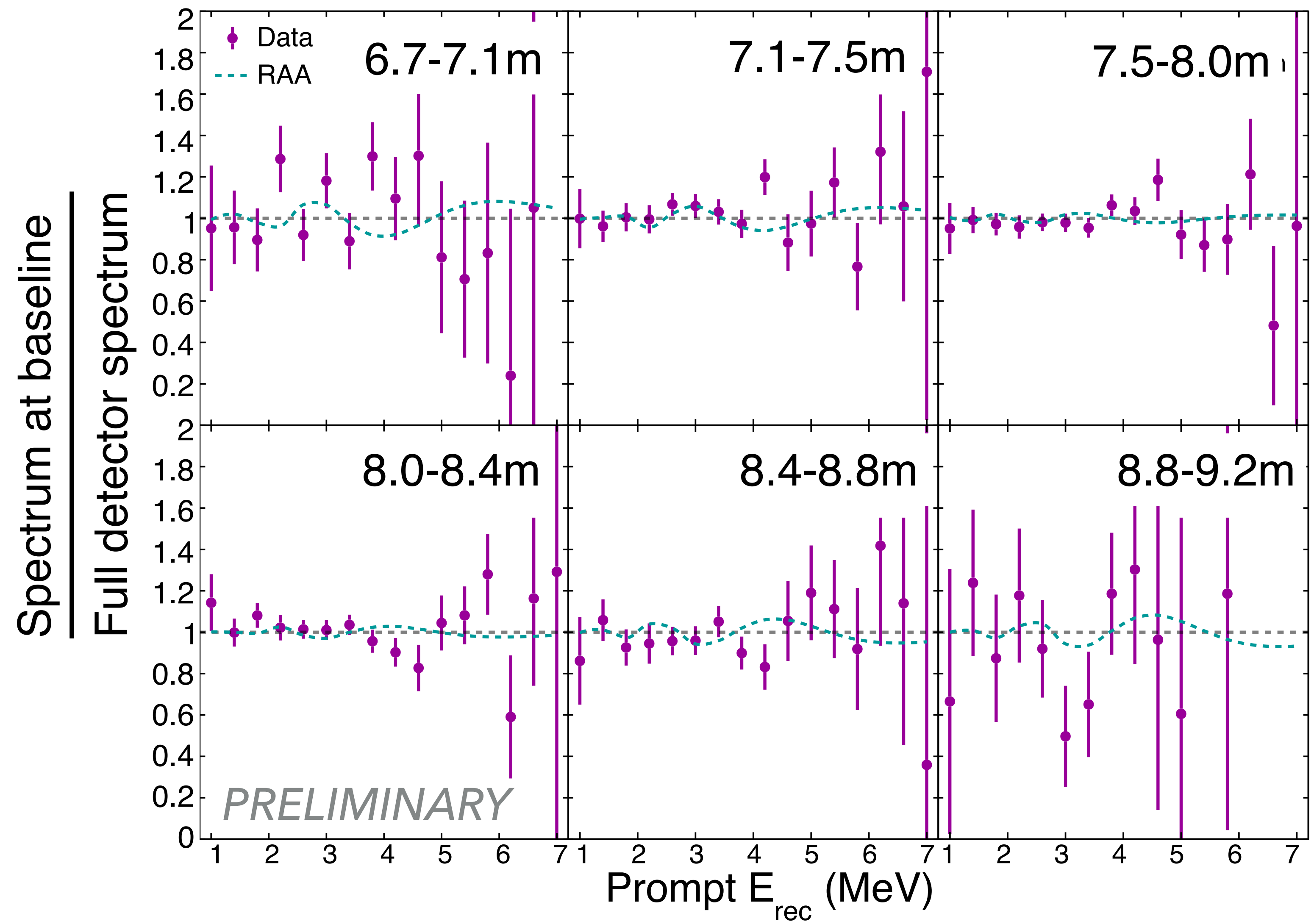


- **Observation of $1/r^2$ behavior throughout detector volume**
- Bin events from 108 fiducial segments into 14 baseline bins
- *40% flux decrease from front of detector to back*

NEUTRINO SPECTRUM VS BASELINE

BASELINE-DEPENDENT OSCILLATION ILLUSTRATION

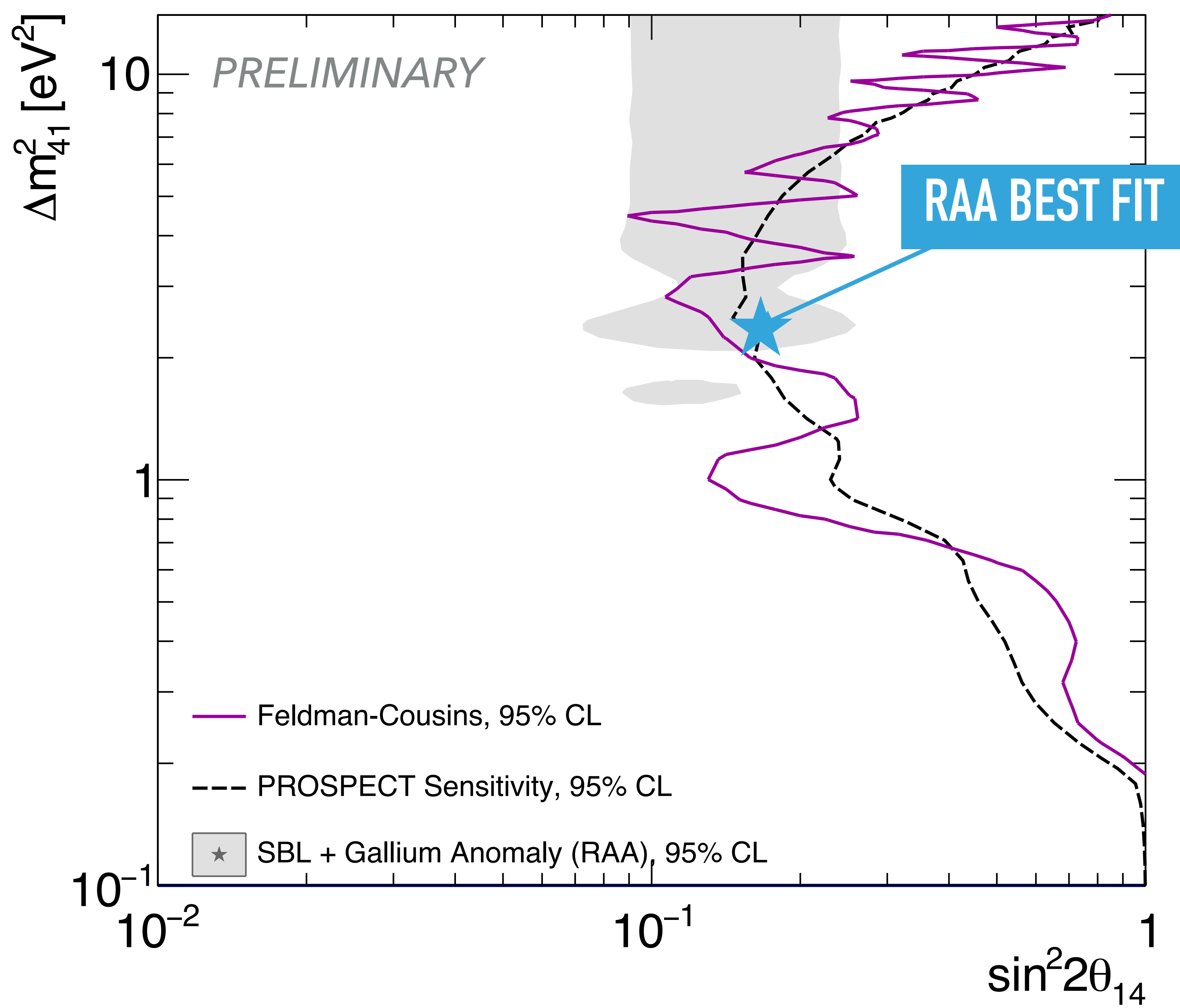




- Compare spectra from 6 baselines to measured full-detector spectrum
- Null-oscillation would yield a flat ratio for all baselines
- **Direct ratio search for oscillations, reactor model independent**

OSCILLATION SEARCH RESULTS

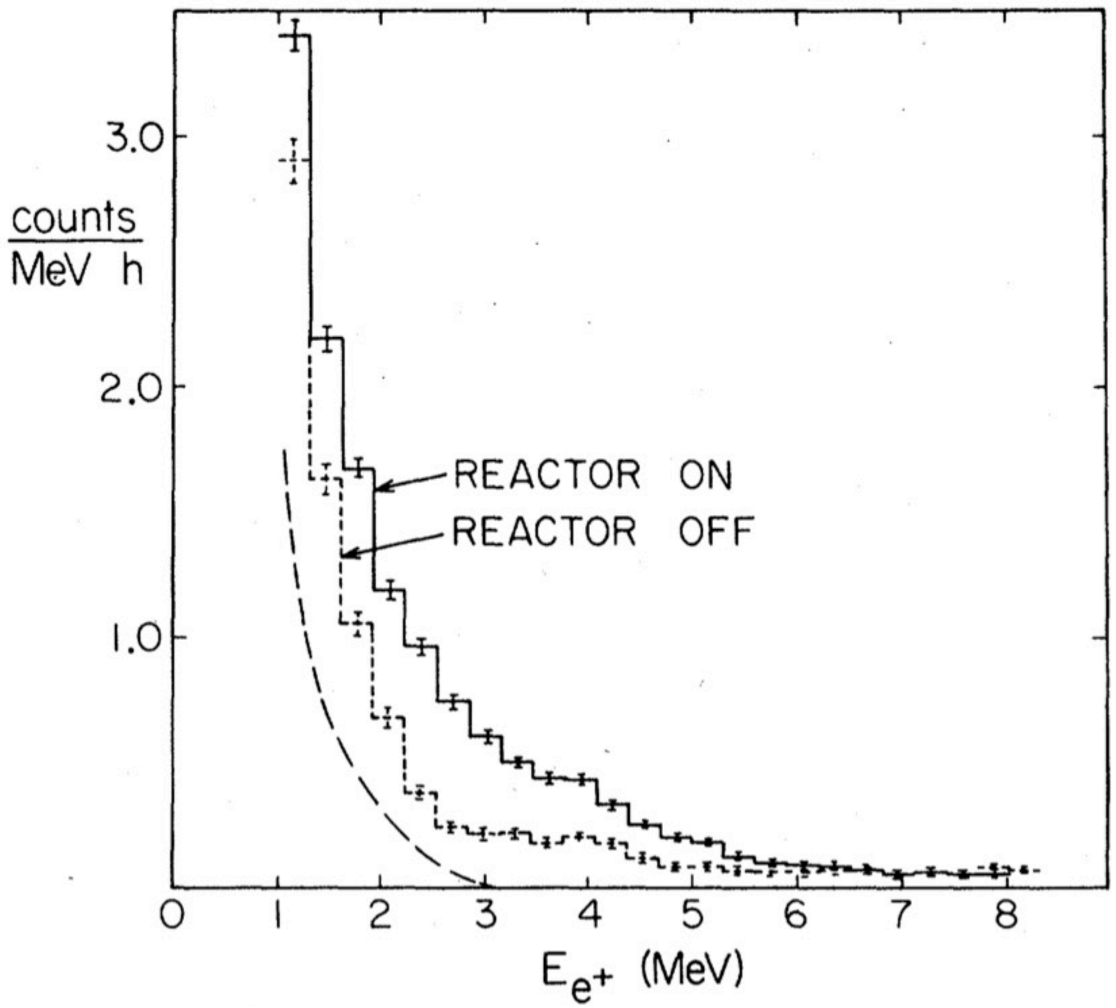
- Feldman-Cousins based confidence intervals for oscillation search
- Covariance matrices captures all uncertainties and energy/baseline correlations
- Critical χ^2 map generated from toy MC using full covariance matrix
- 95% exclusion curve based on 33 days Reactor On operation
- *Direct test of the Reactor Antineutrino Anomaly*

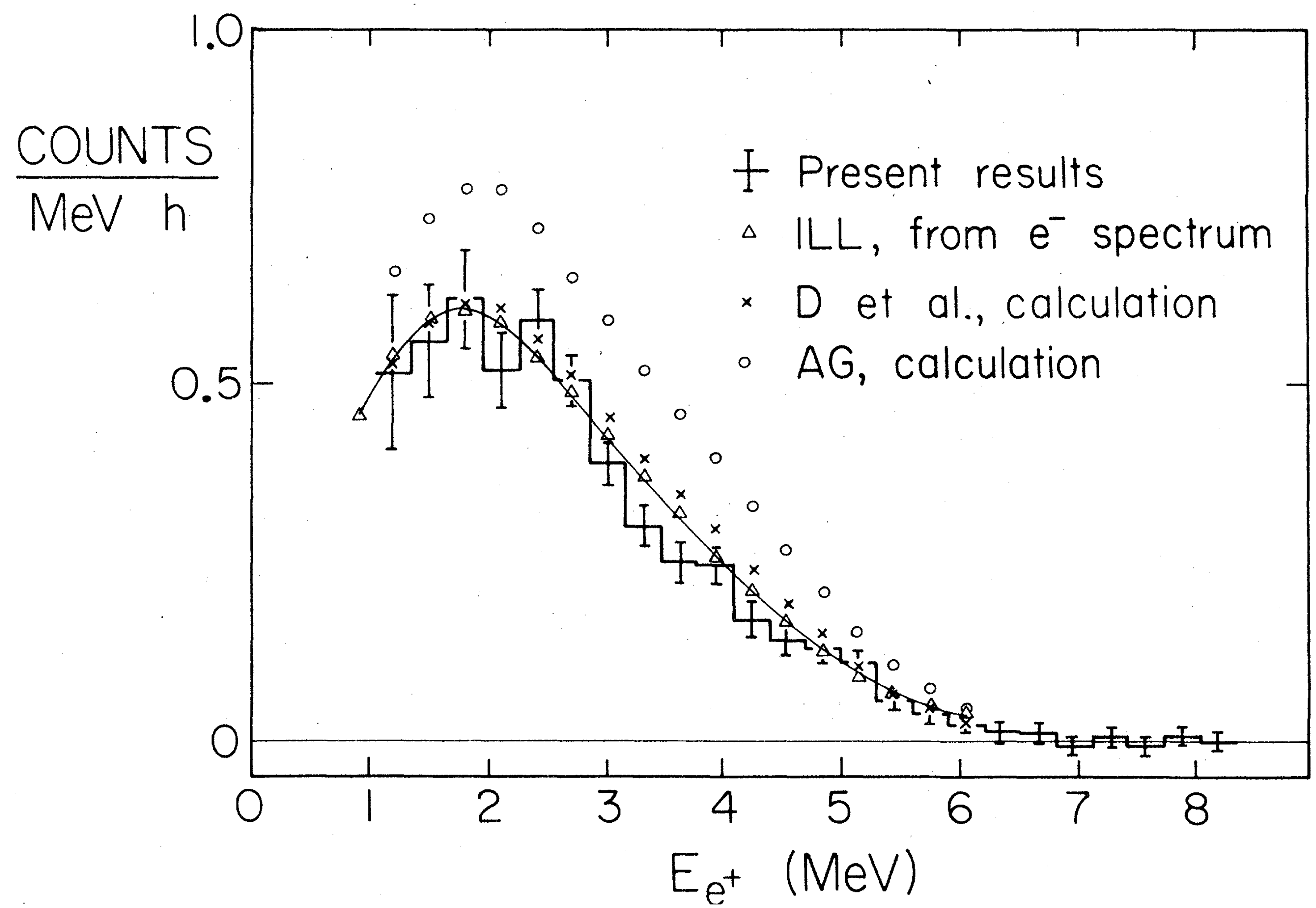


Disfavors RAA best-fit point at >95% (2.3σ)

MEASUREMENT OF THE ^{235}U SPECTRUM

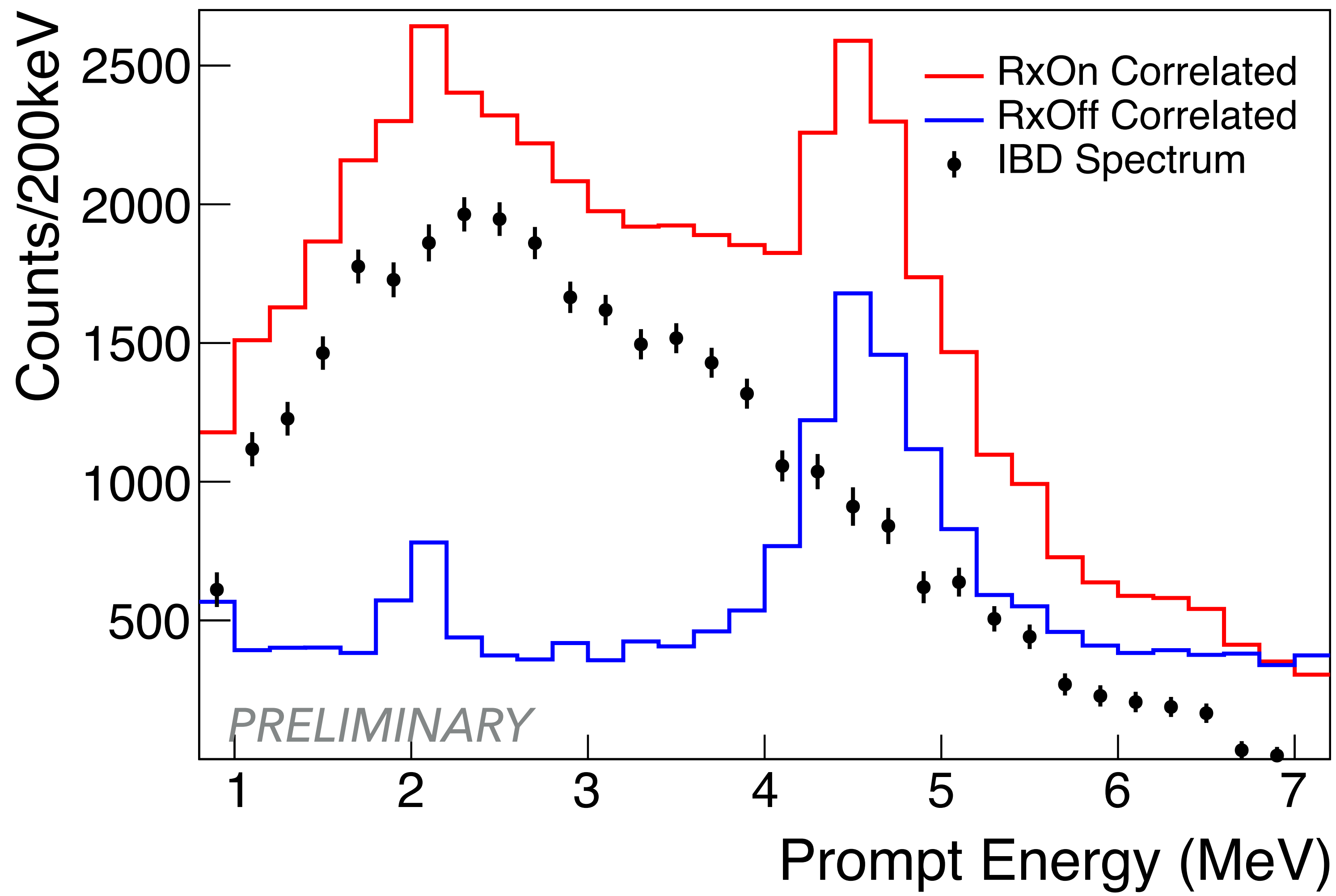
ILL ^{235}U SPECTRAL MEASUREMENT





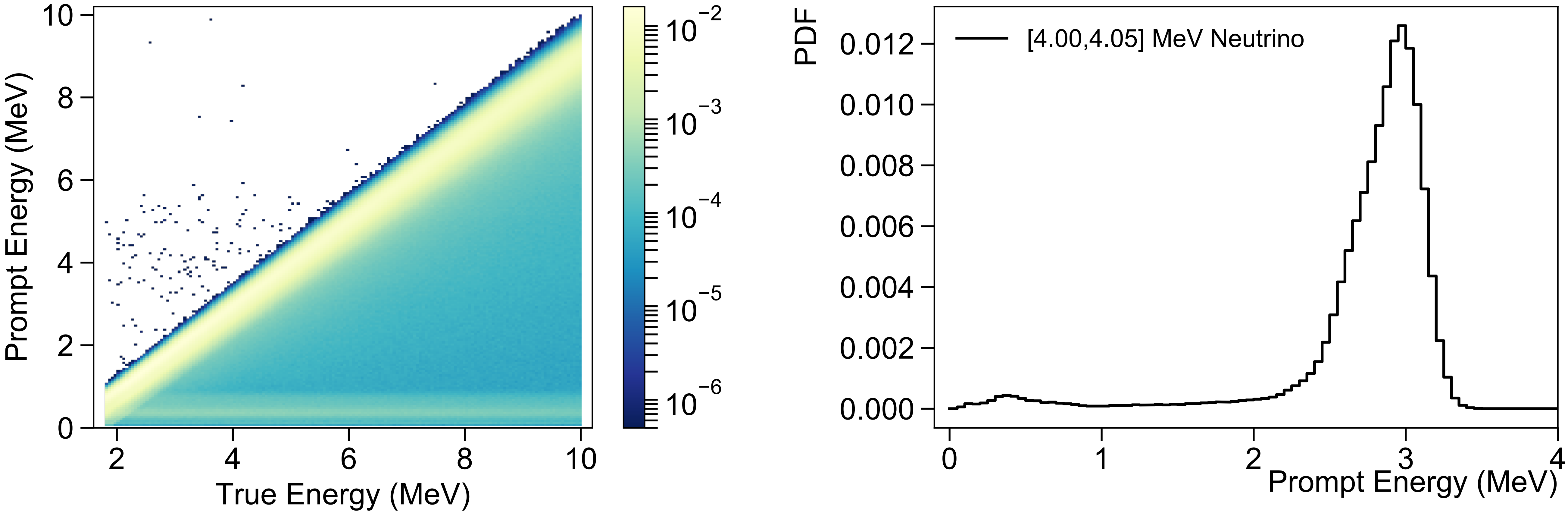
- Only existing measurement of ^{235}U, from 1981
- ~35 IBDs/day detected, total of 5000 IBDs in full data

MEASURED SPECTRUM



- 40.2 days reactor-on, 37.8 days reactor-off exposure
- ~31,000 IBDs detected, >700 IBDs/live-day
- Signal-to-background = 1.7 with no overburden!
- X6 more statistics than ILL in about half the exposure time

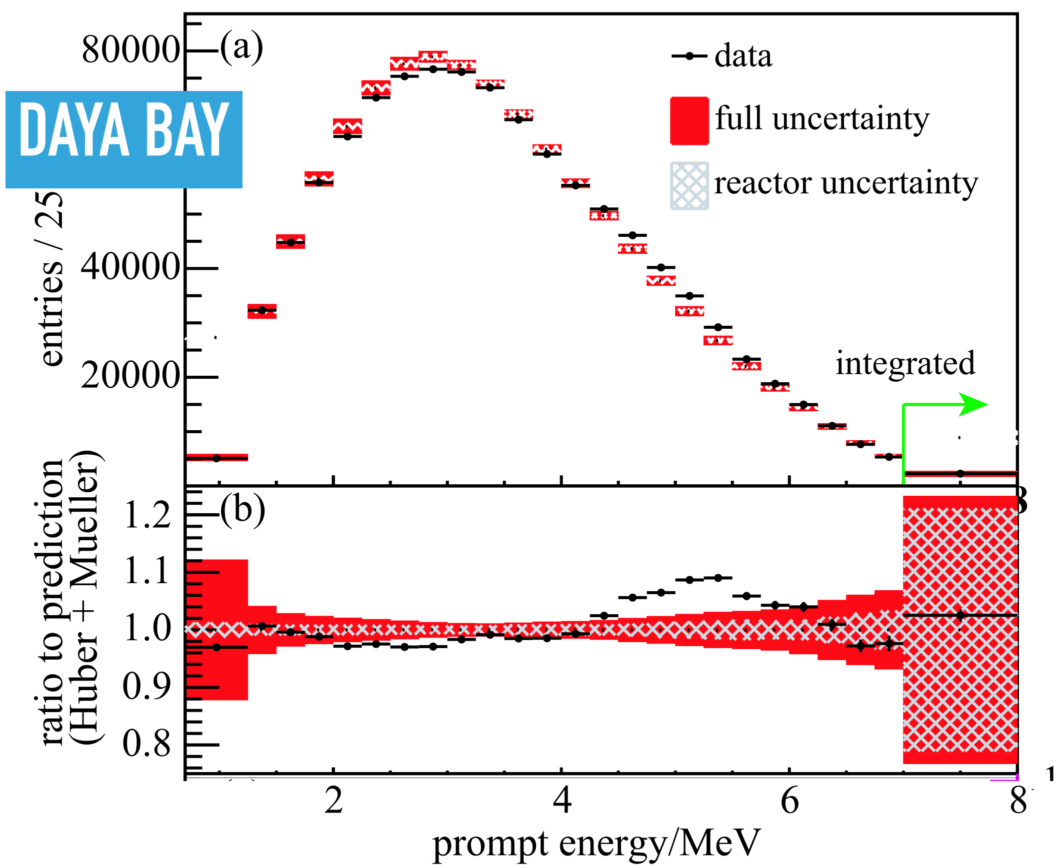
DETECTOR RESPONSE



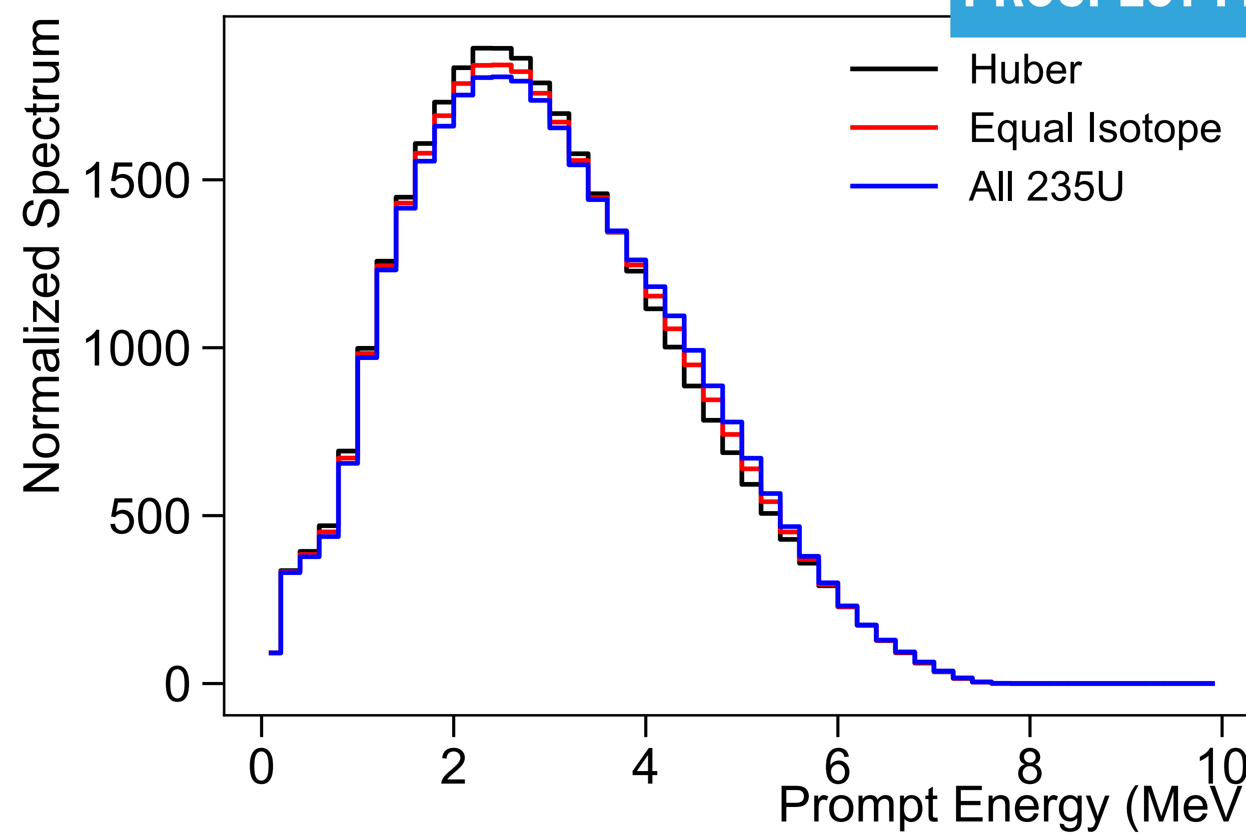
- Segmented detectors have much more complicated response than large monolithic detectors
- Detailed Monte Carlo model of the detector incorporates all known characteristics
- Covariance matrices built through variation of parameters in MC, used for comparison between measured spectrum and model predictions

BUMP-ORIGIN HYPOTHESES

DAYA BAY



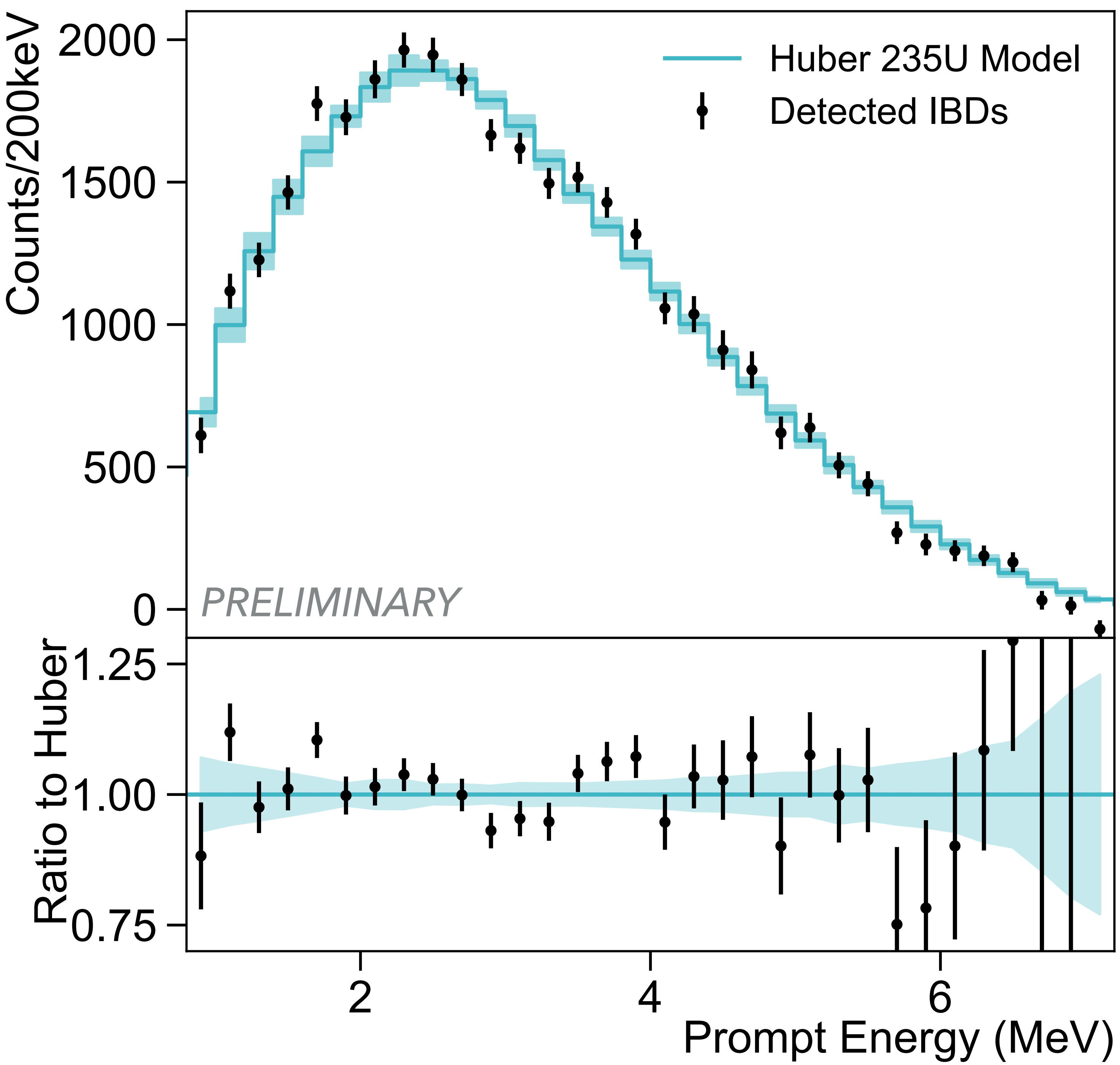
PROSPECT MODELS



Use the Daya Bay ratio to Huber/Mueller model to modify Huber ^{235}U spectrum

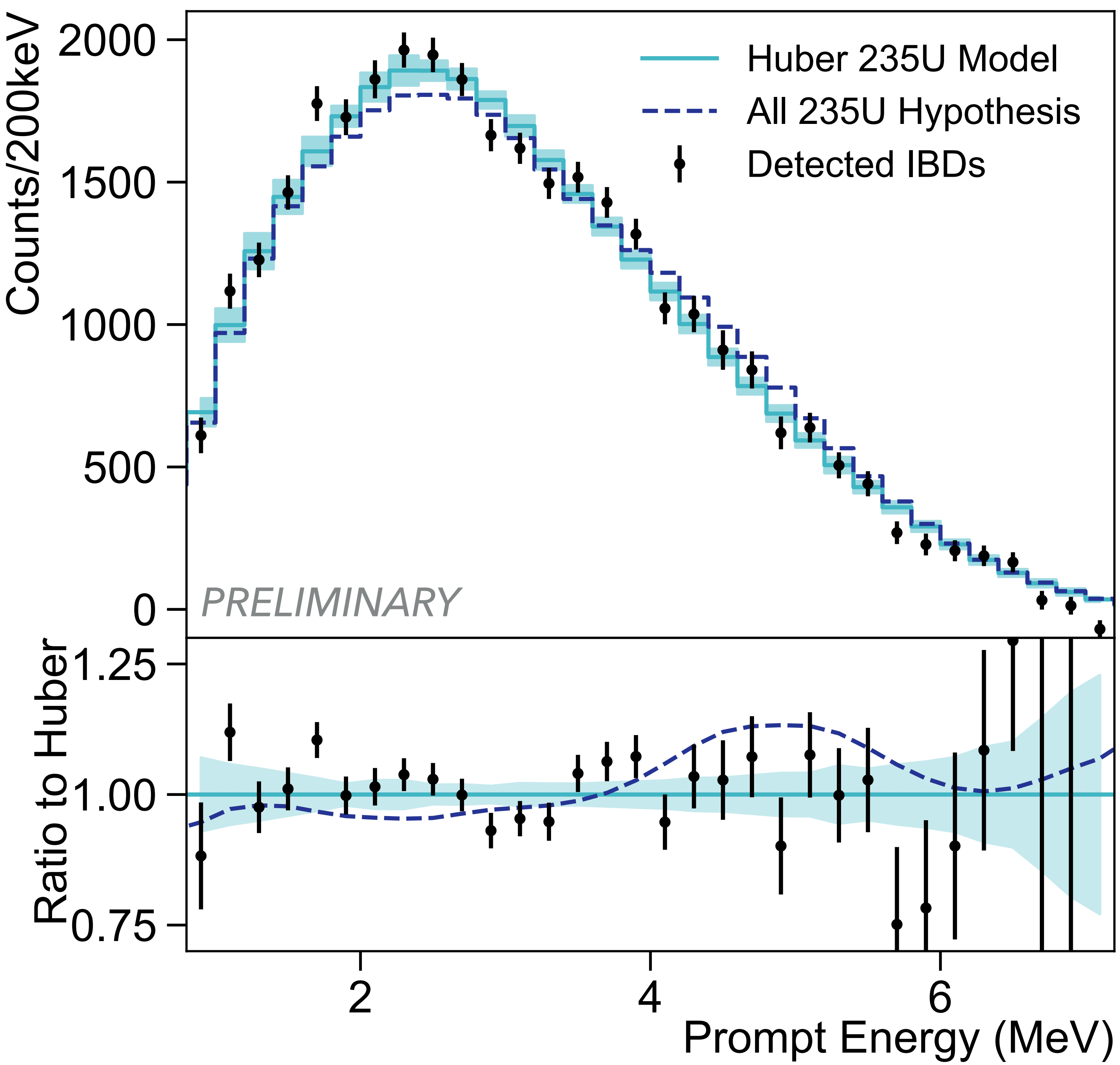
- **Hypothesis 1:** Deviation contained in other isotopes (Huber ^{235}U is correct)
- **Hypothesis 2:** Deviation shared equally by 4 parent isotopes
- **Hypothesis 3:** All deviation from ^{235}U (maximal change to Huber ^{235}U)

COMPARISON TO MODELS



- Is PROSPECT consistent with Huber ^{235}U model?
  - $\chi 2/ndf = 52.7/31$
  - Not great, but "standard" comparison

COMPARISON TO MODELS



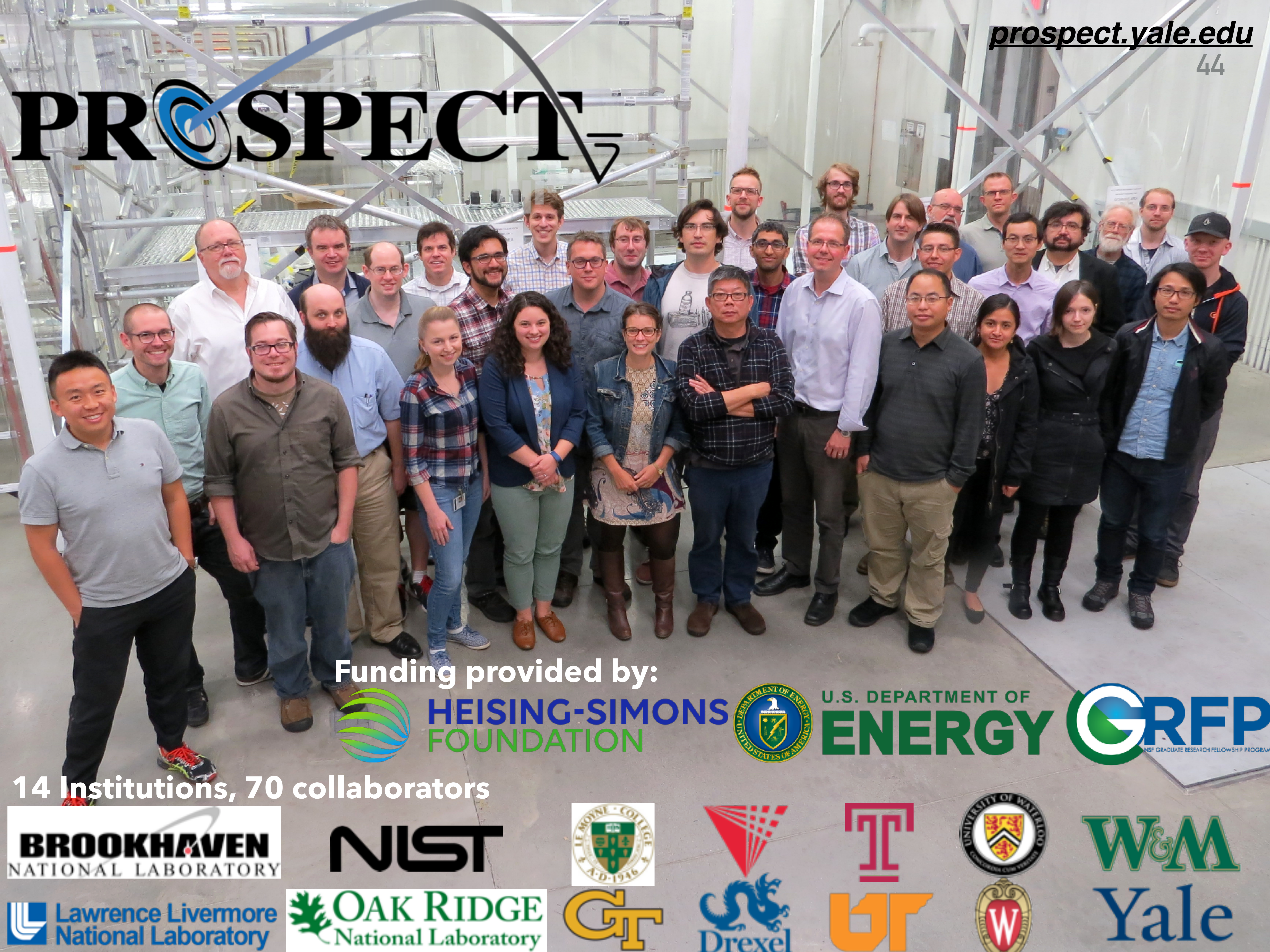
- Is PROSPECT consistent with Huber ^{235}U model?
  - $\chi2$/ndf = 52.7/31
  - Not great, but "standard" comparison
- Frequentist comparison to ad-hoc models:
  1. No strong preference between Huber and Equal Isotope
  2. **Disfavor All 235U hypothesis at 3σ**

SPECTRAL INTERPRETATION

- Our measured ^{235}U spectrum cannot fully explain the Daya Bay, Double Chooz, and RENO spectral deviations
    - Implies that some fraction of the bump must come from other fissioning isotopes
- We do not yet have the sensitivity to discriminate between the unmodified Huber model and the Equal Isotope Hypothesis
- ***Statistics limited result, stay tuned for more!***

CONCLUSION AND OUTLOOK

- PROSPECT started collecting data on March 6, 2018
- **World-leading signal-to-background achieved for surface-based detector**
- **First oscillation analysis on 33 days of reactor-on data disfavors the RAA best-fit at 2.3σ (arXiv: 1806.02784)**
- **First high-statistics measurement of the 235U IBD spectrum disfavors "All 235U" hypothesis at 3σ**
- ***Statistics limited, and continuing to collect data***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14 Institutions, 70 collaborators
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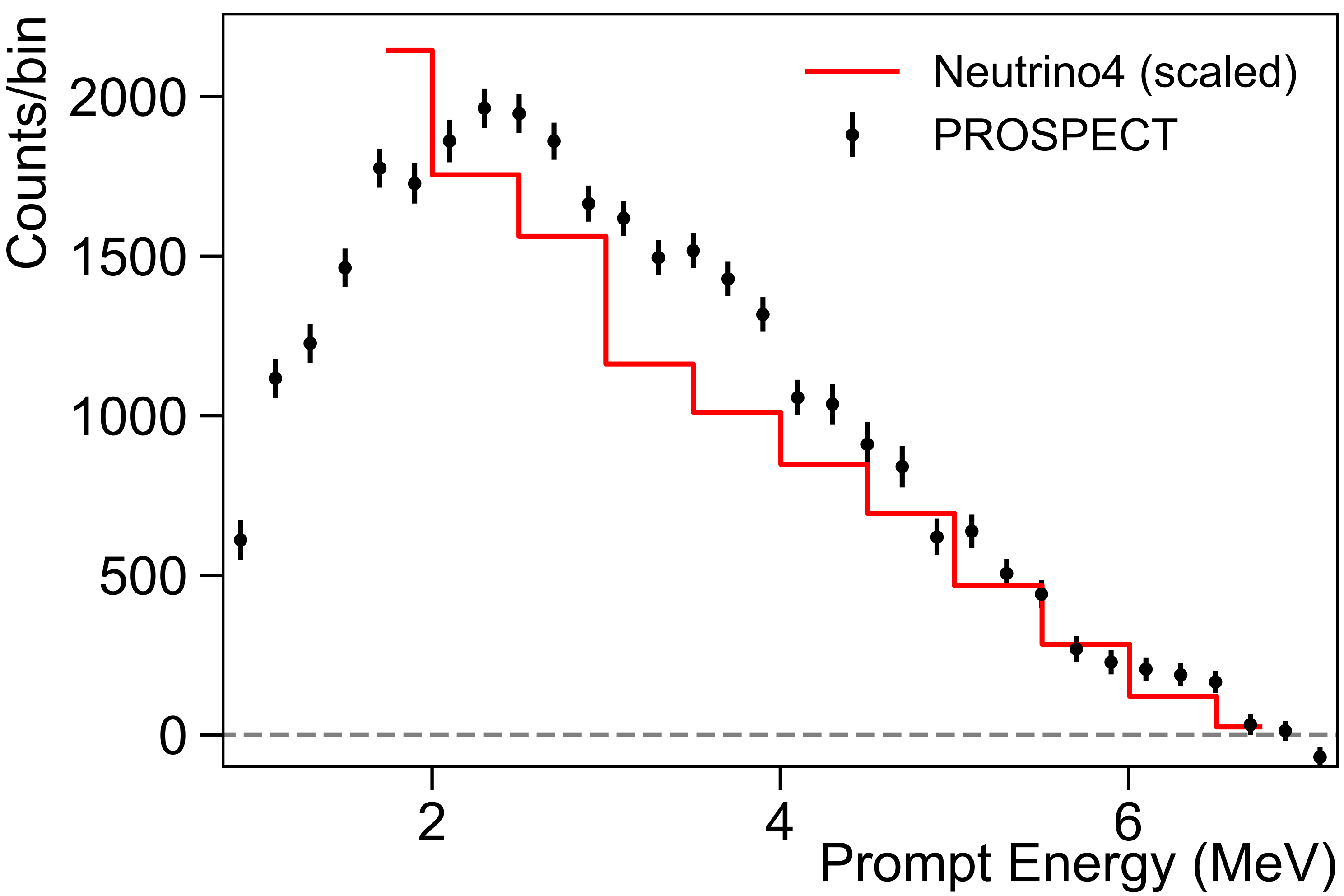
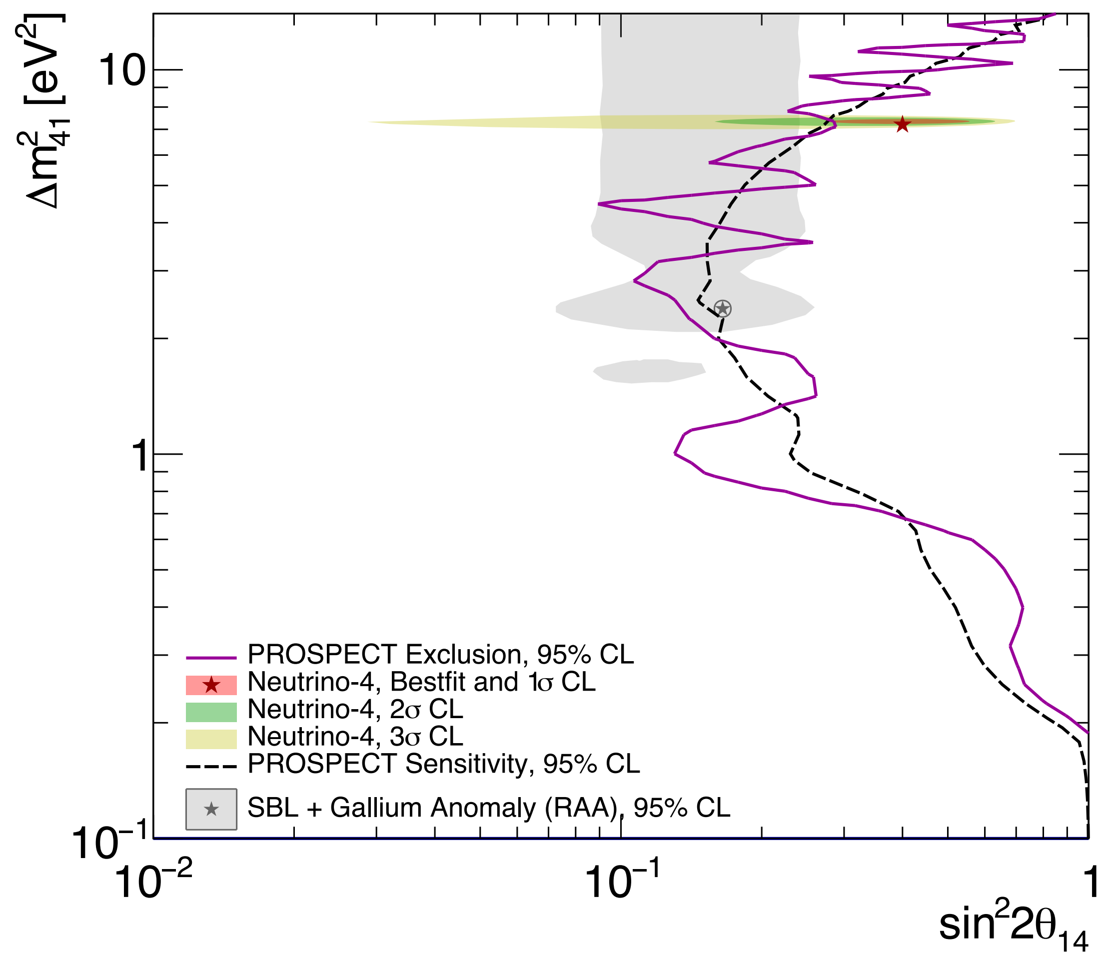
NIST
LE MOYNE COLLEGE A·D·1946
Lawrence Livermore National Laboratory
OAK RIDGE National Laboratory
Drexel
W&M
Yale

BACKUP SLIDES

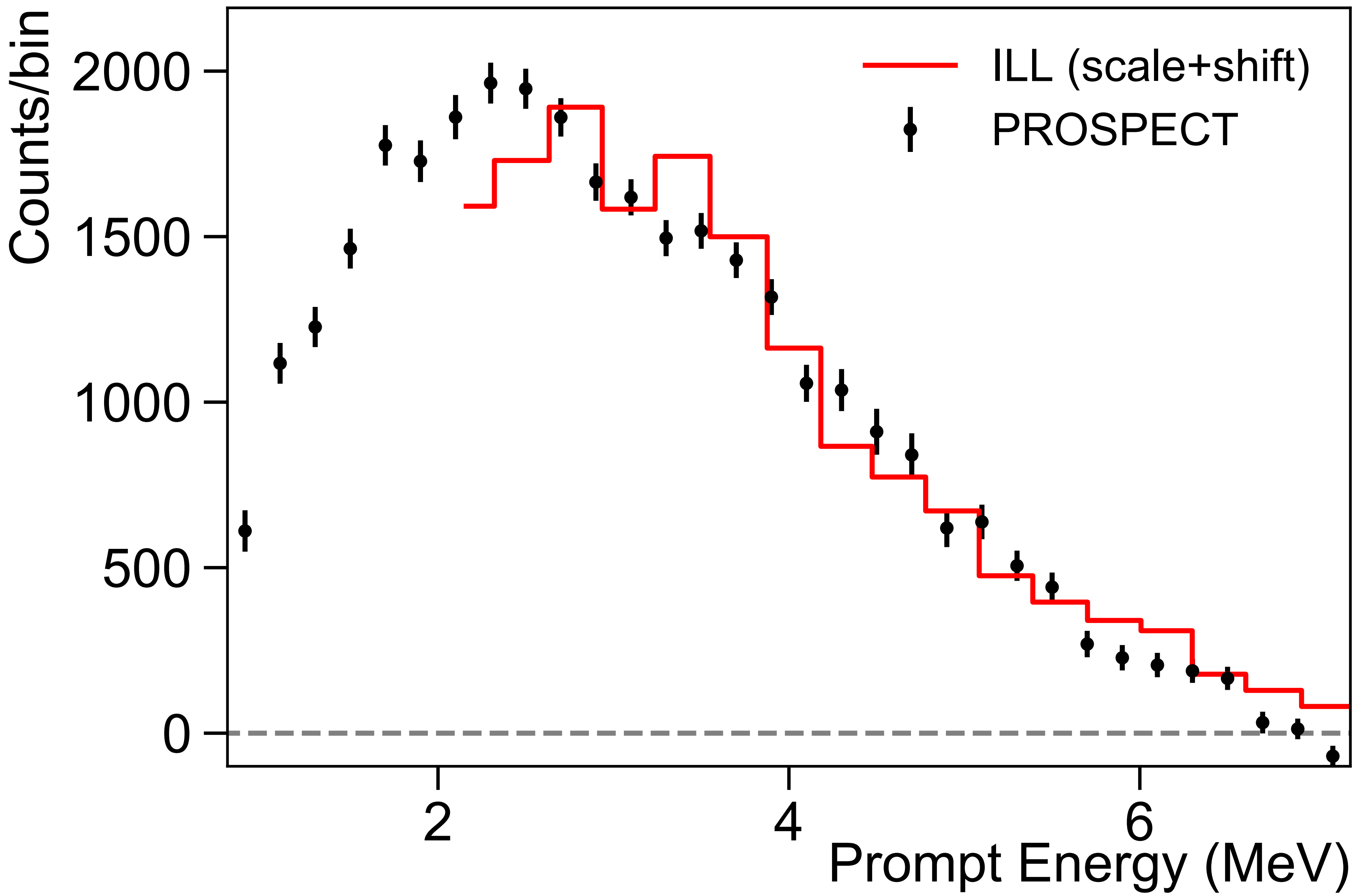
NEUTRINO-4 COMPARISON





- PROSPECT excludes Neutrino-4's best-fit region at >95% CL
- Their spectral shape does not match their MC expectations and is not understood

ILL COMPARISON



ILL COMPARISON

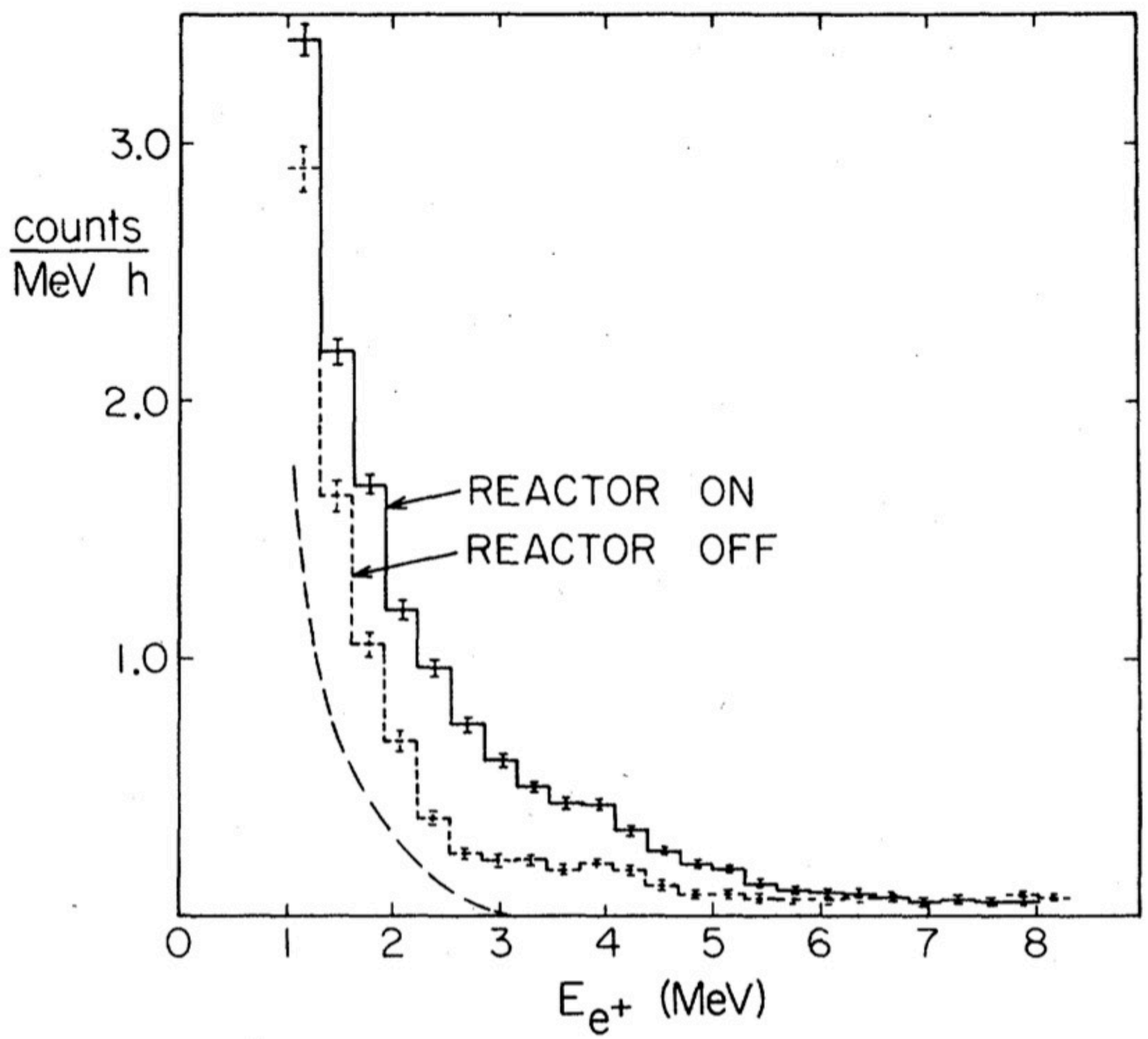
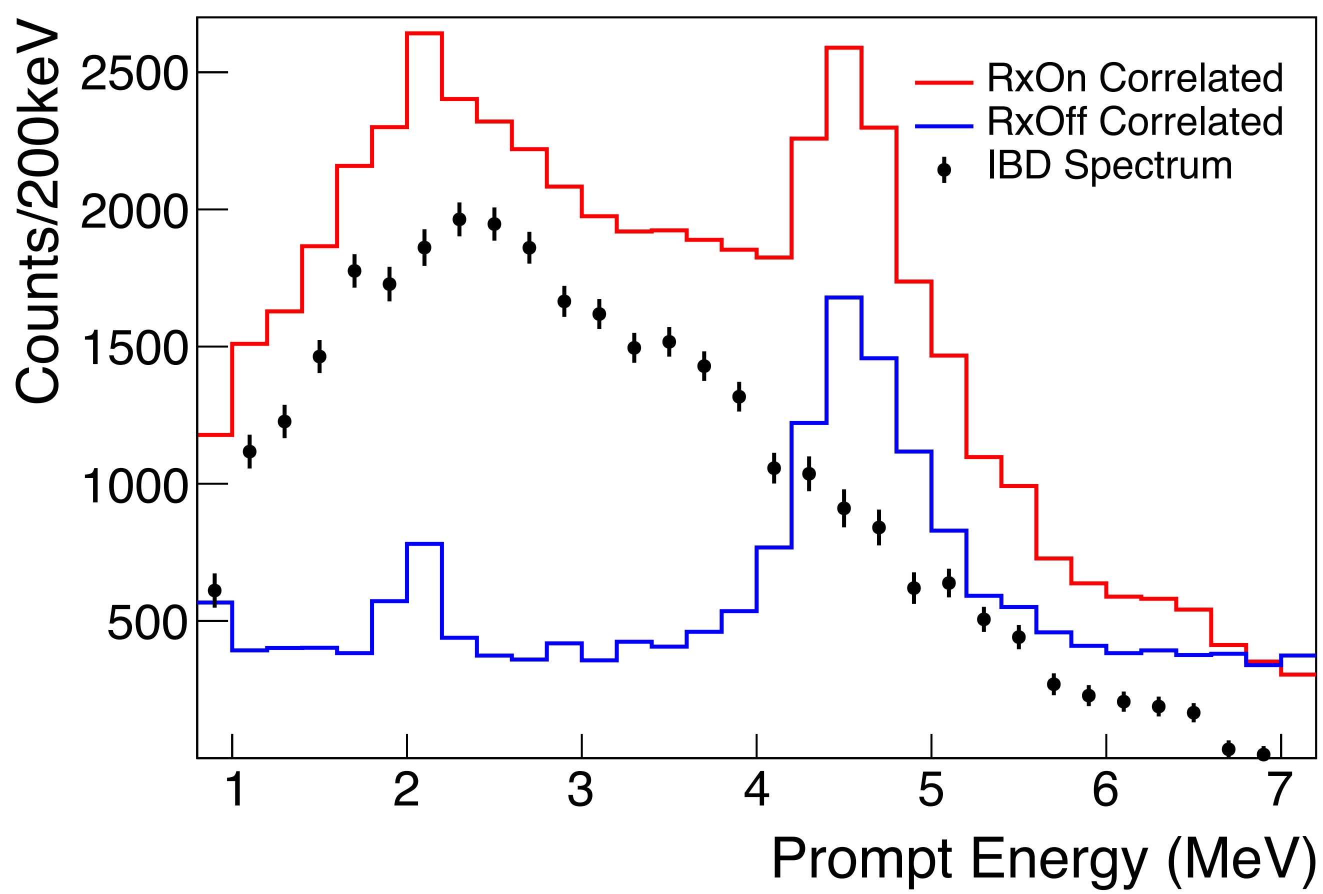
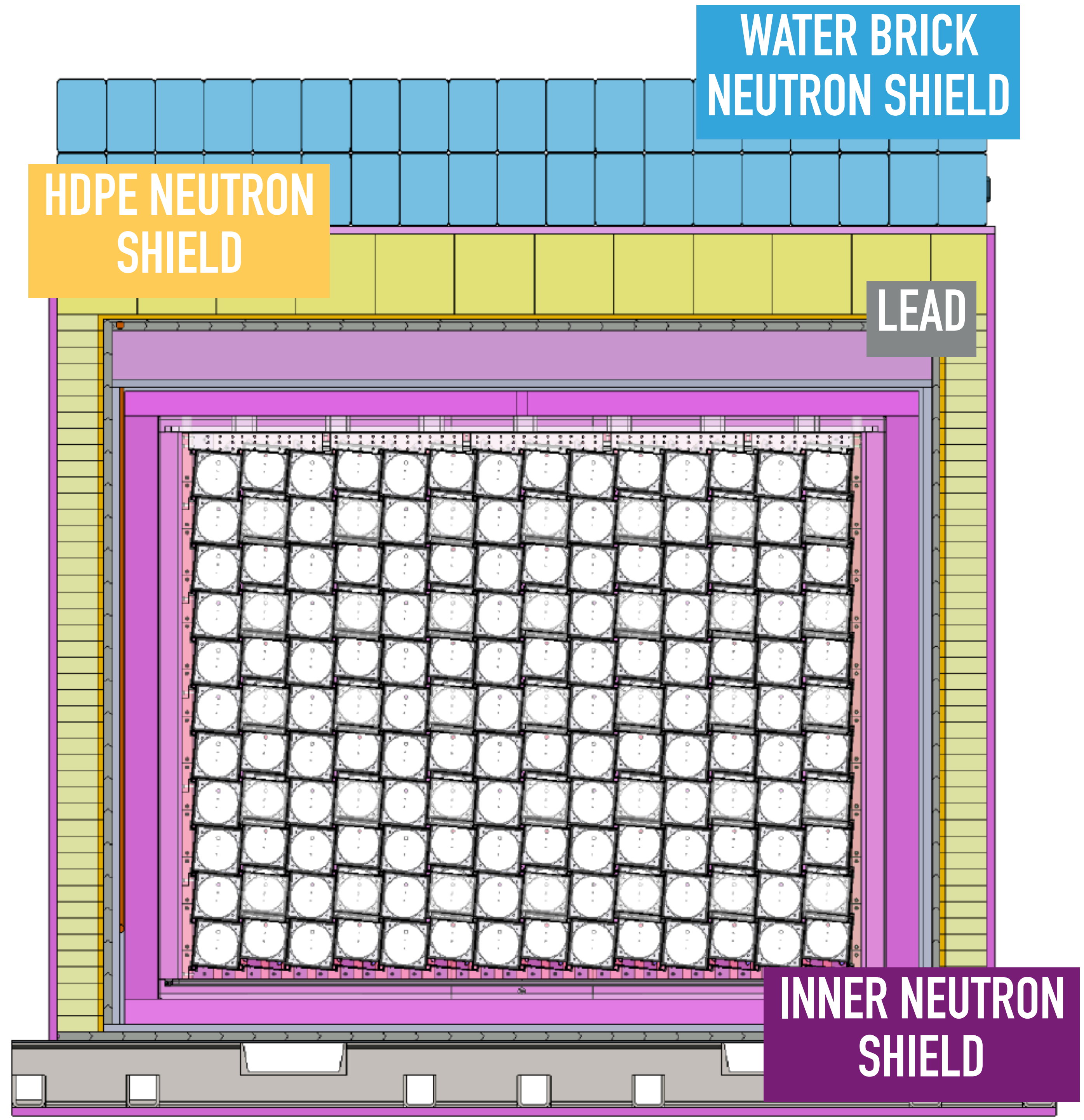


FIG. 11. Positron energy spectra for reactor on (3088.7 h live time) and reactor off (1181.8 h live time). The accidental background is shown as a dashed line.

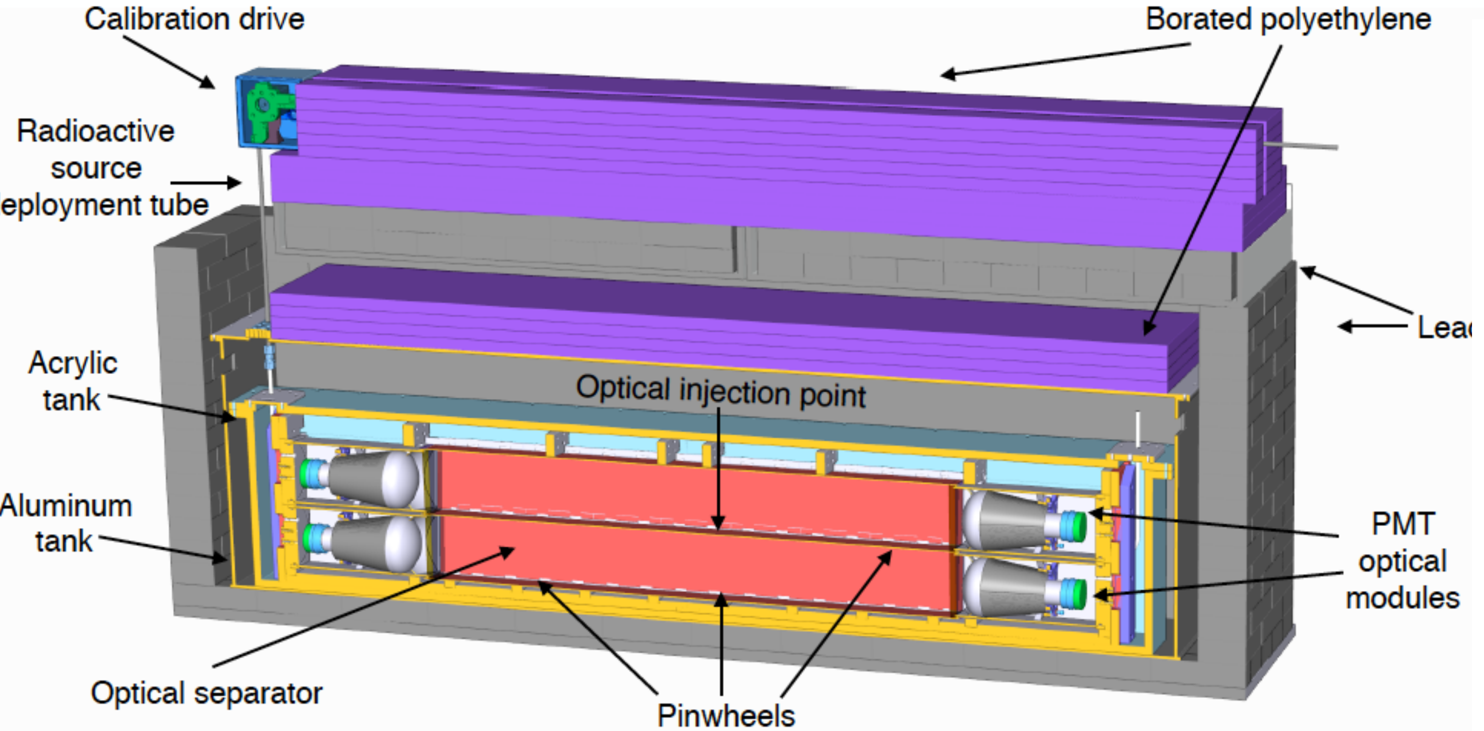


OPTIMIZED SHIELDING DESIGN

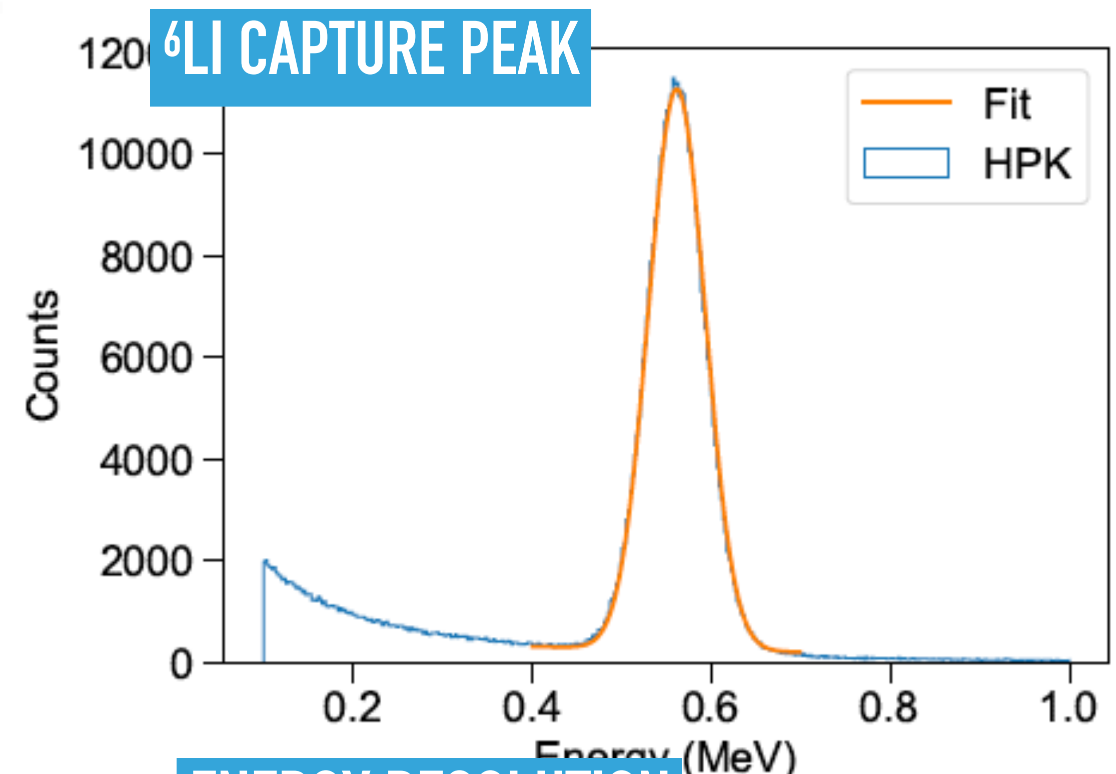
- Minimal overburden to shield PROSPECT from cosmic rays
- Designed an optimized shielding package
  - Reduce cosmic-ray fast neutron and reactor gamma backgrounds
  - Compact to fit in existing experimental hall, floor-loading limits



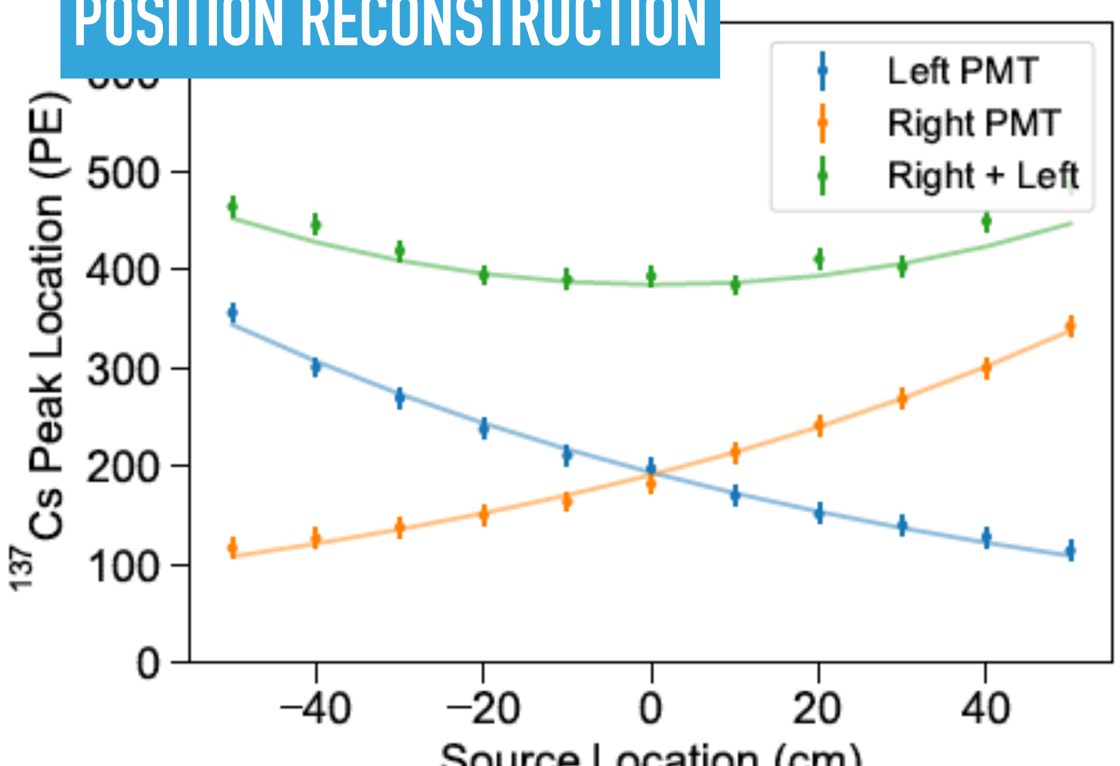
PROSPECT-50 PROTOTYPE PERFORMANCE (ARXIV:1805.09245)



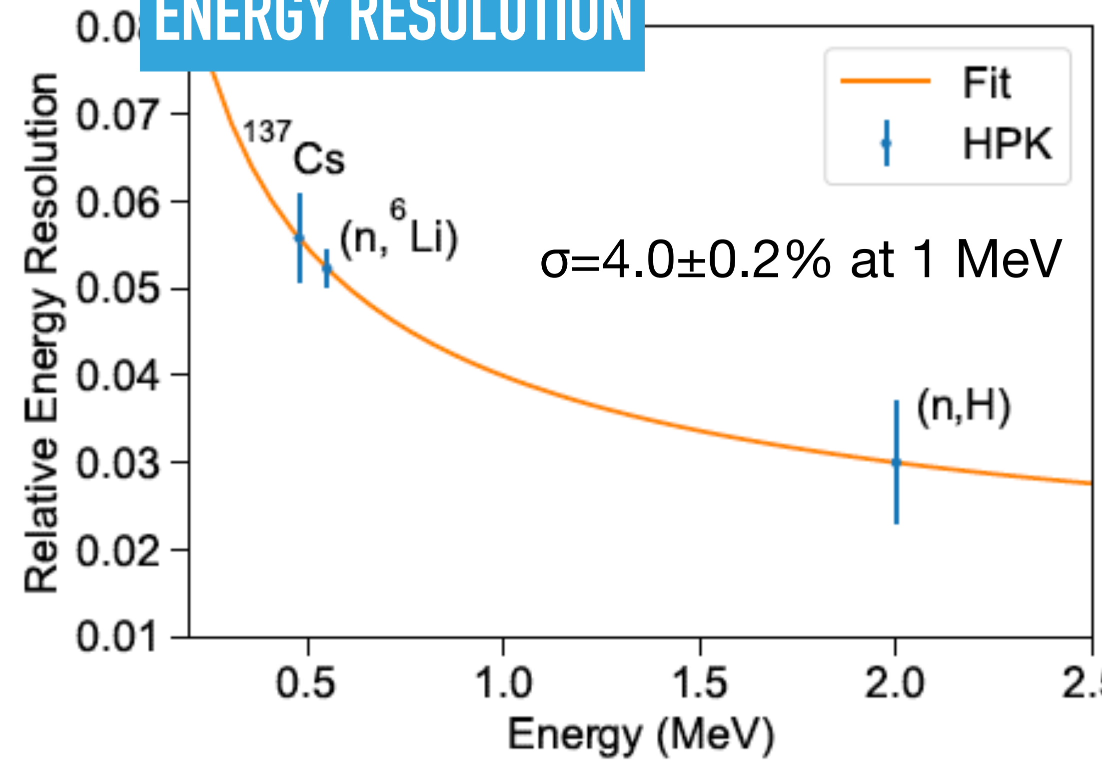
^{6}LI CAPTURE PEAK



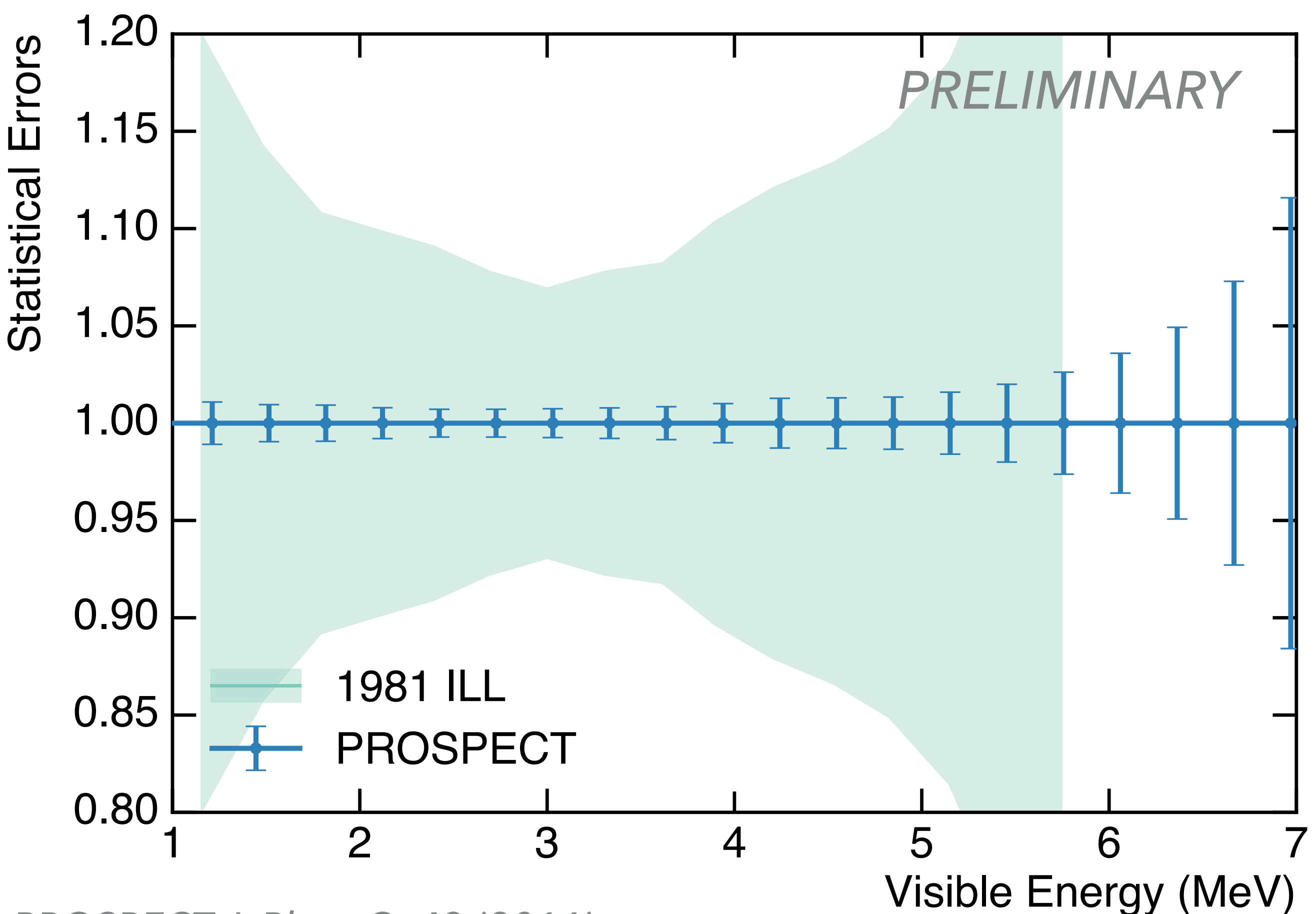
POSITION RECONSTRUCTION



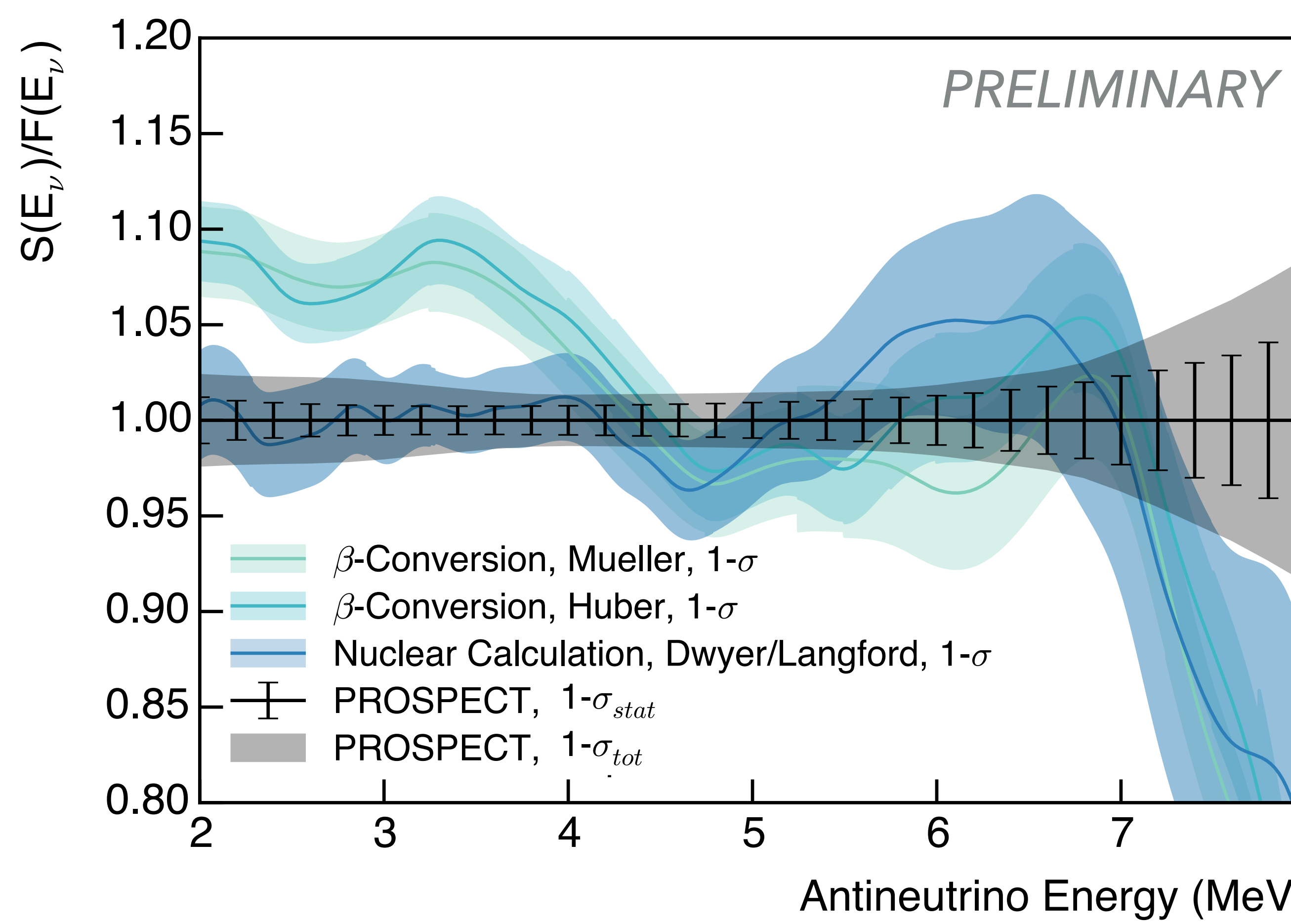
ENERGY RESOLUTION



^{235}U SPECTRAL MEASUREMENT

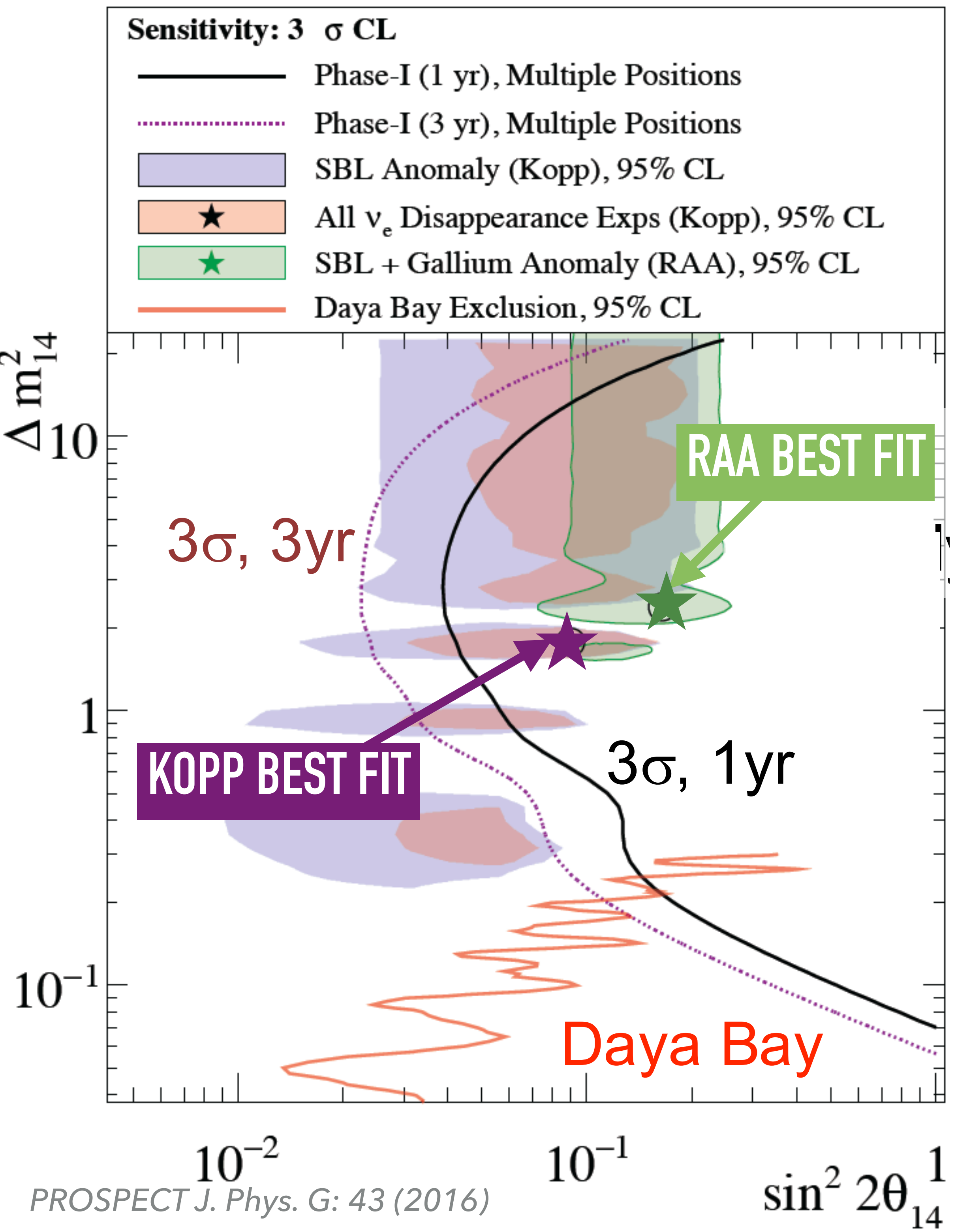


PROSPECT J. Phys. G: 43 (2016)



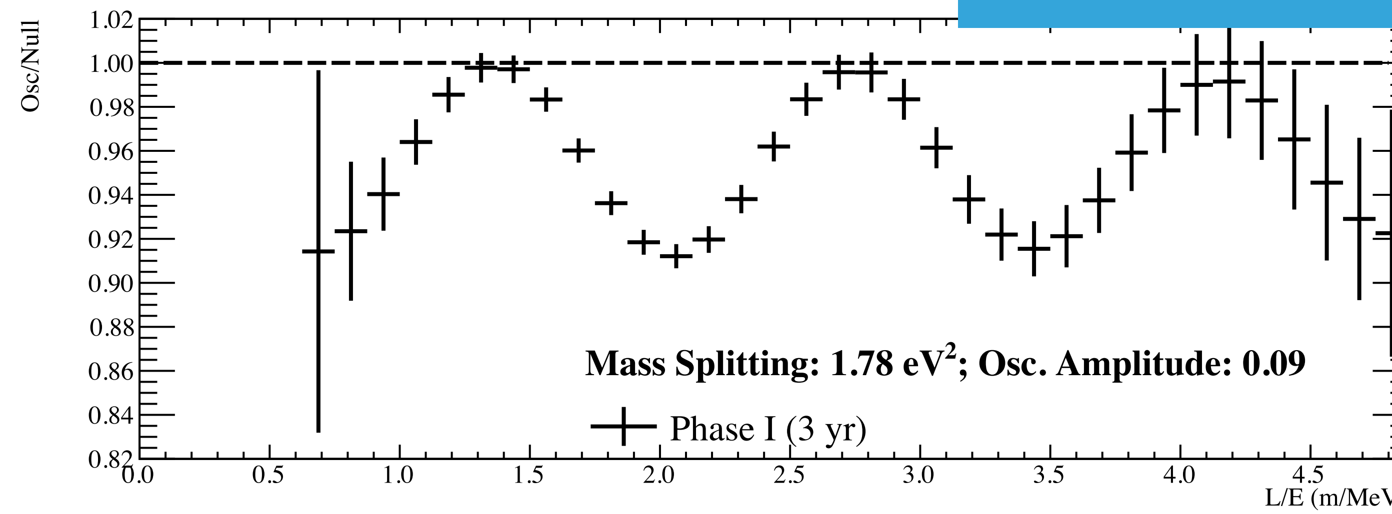
- 750 detected neutrinos per day
- Excellent energy resolution (4.5% at 1MeV)
- Directly test reactor neutrino models with a benchmark spectrum for future experiments

STERILE NEUTRINO SENSITIVITY



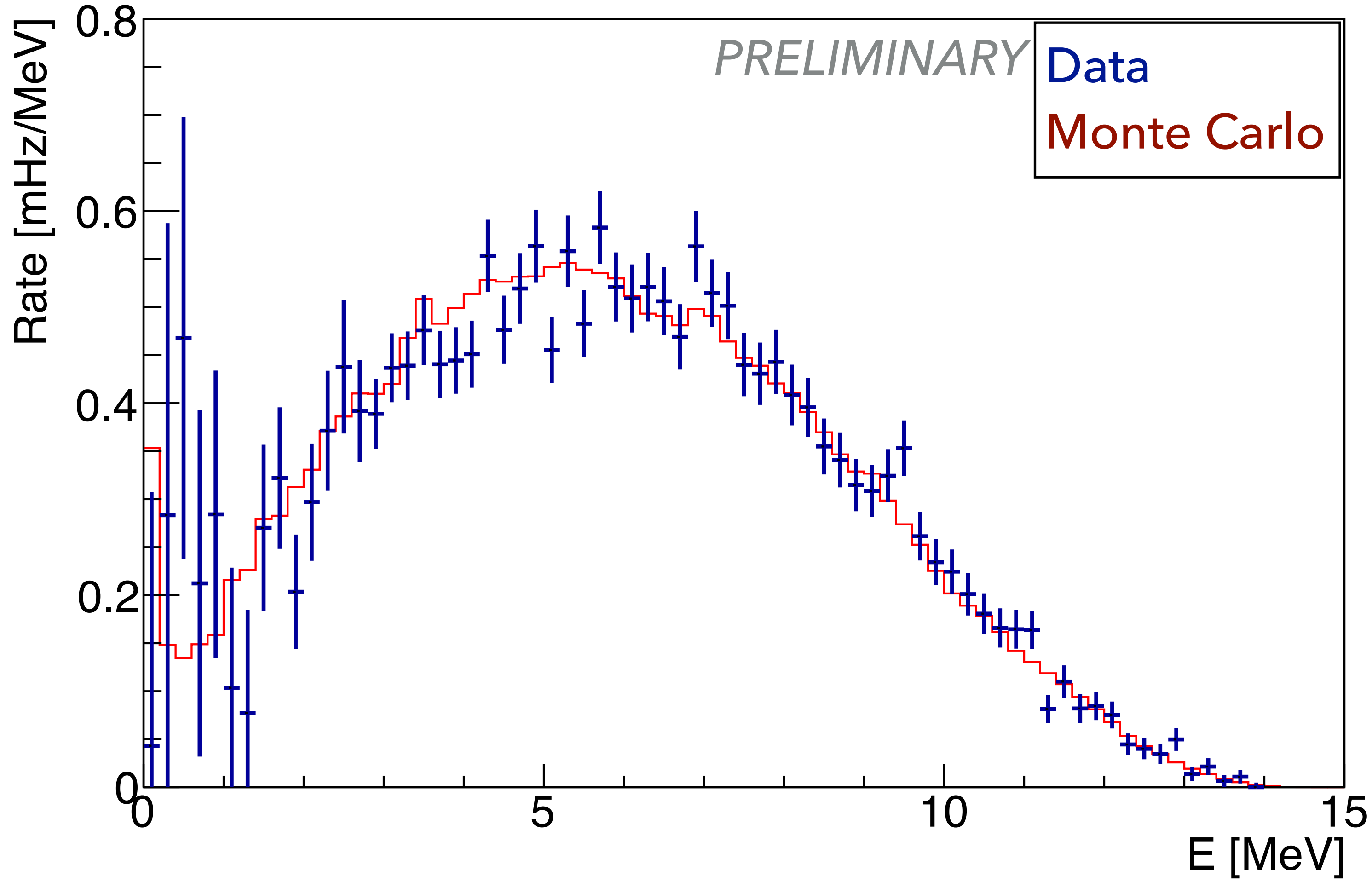
PROSPECT J. Phys. G: 43 (2016)

KOPP OSCILLATION



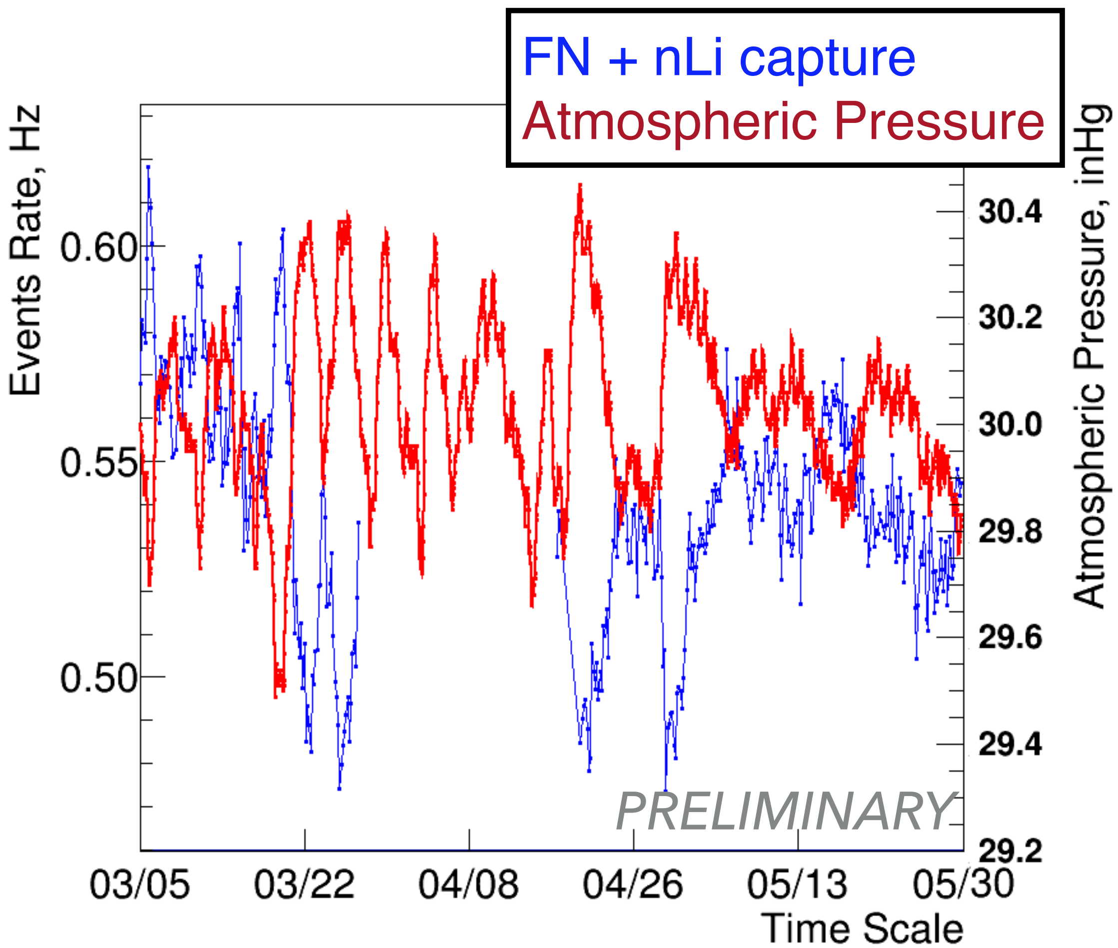
- Segmented detector designed for oscillation search
  - Each cell is a separate "detector"
  - Oscillatory L/E between segments
  - Independent from reactor models
- True oscillometry needed for confirmation of sterile neutrinos
- Probe best-fit point at 4σ in 1 year

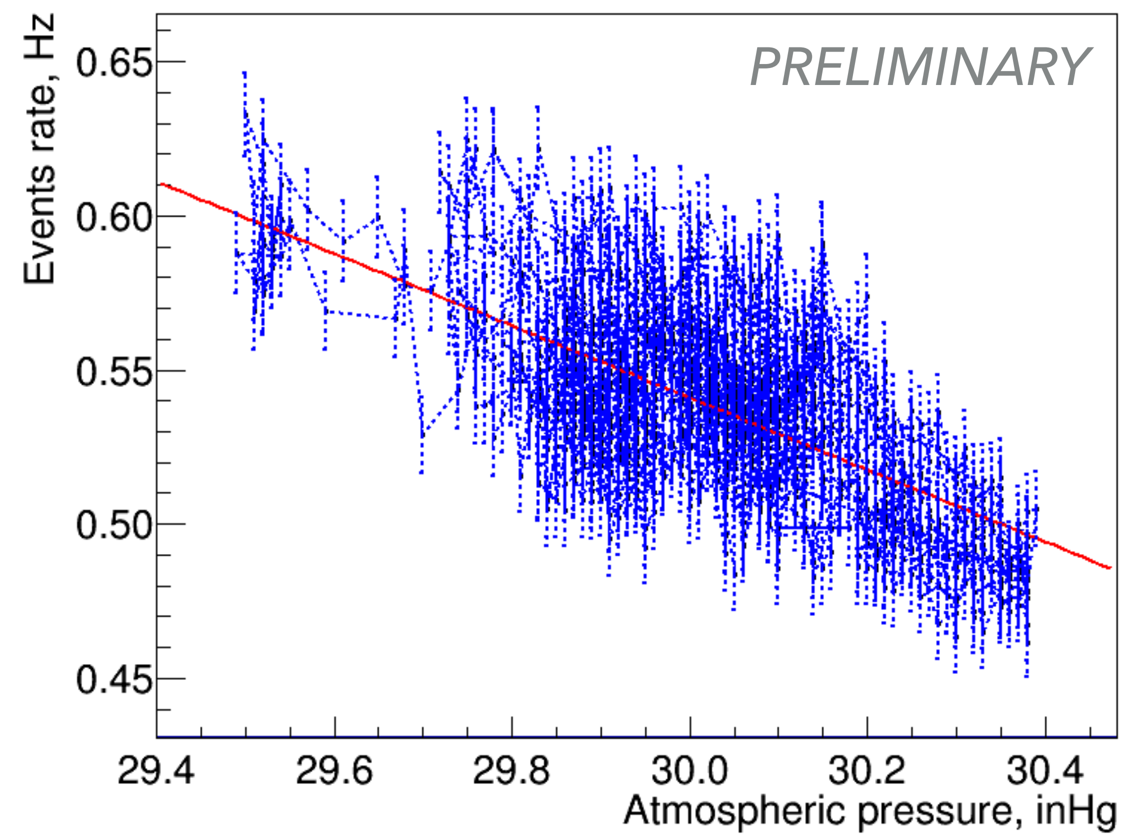
FAST NEUTRON PRODUCED ^{12}B



- Tag fast-neutron recoil events, search for ^{12}B decays within 15cm
- Minimal overburden yields good statistics, ~450/day
- Excellent high-energy beta calibration spectrum

TIME DEPENDENCE OF COSMOGENIC BACKGROUNDS





See NEUTRINO2018 PROSPECT Posters

- Correlation between cosmogenic backgrounds and atmospheric pressure
- Measure correlation during reactor off time, and use it to correct background subtraction during reactor on