First results from

# The Precision Reactor Oscillation and Spectrum Experiment

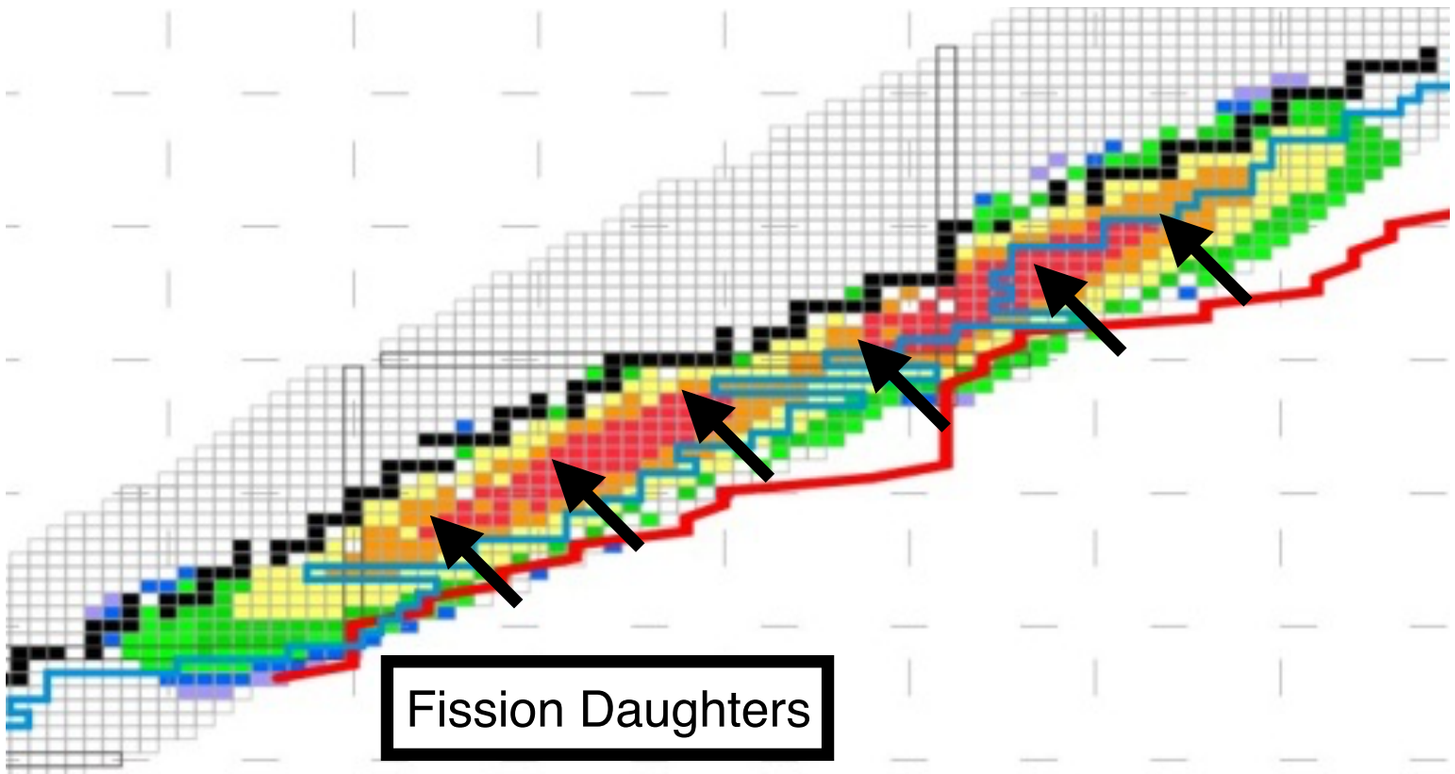
David E. Jaffe

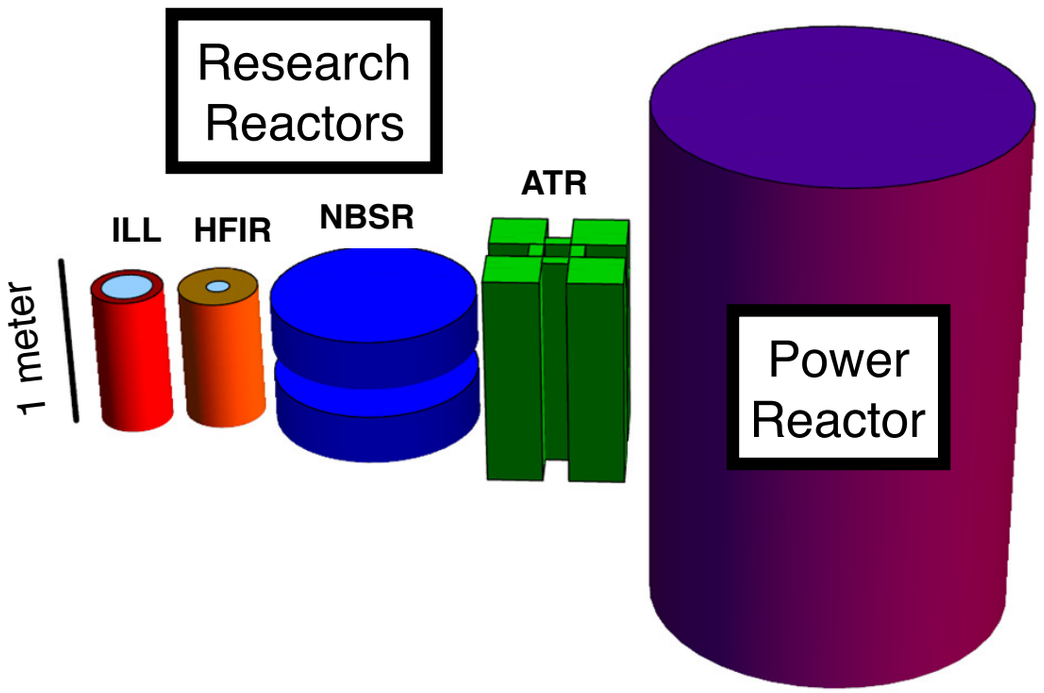
28 June 2018

# What I'm going to talk about

1. Problems:
    1. Reactor antineutrino flux and spectrum measurements do not agree with expectation
2. Experiments attempting to address the problems
    1. DANSS
    2. NEOS
    3. SOLID
    4. STEREO
    5. Daya Bay
3. The PROSPECT Experiment
    1. Goals
    2. Design
    3. First results
4. What I'll say at the end

# Reactor neutrino production



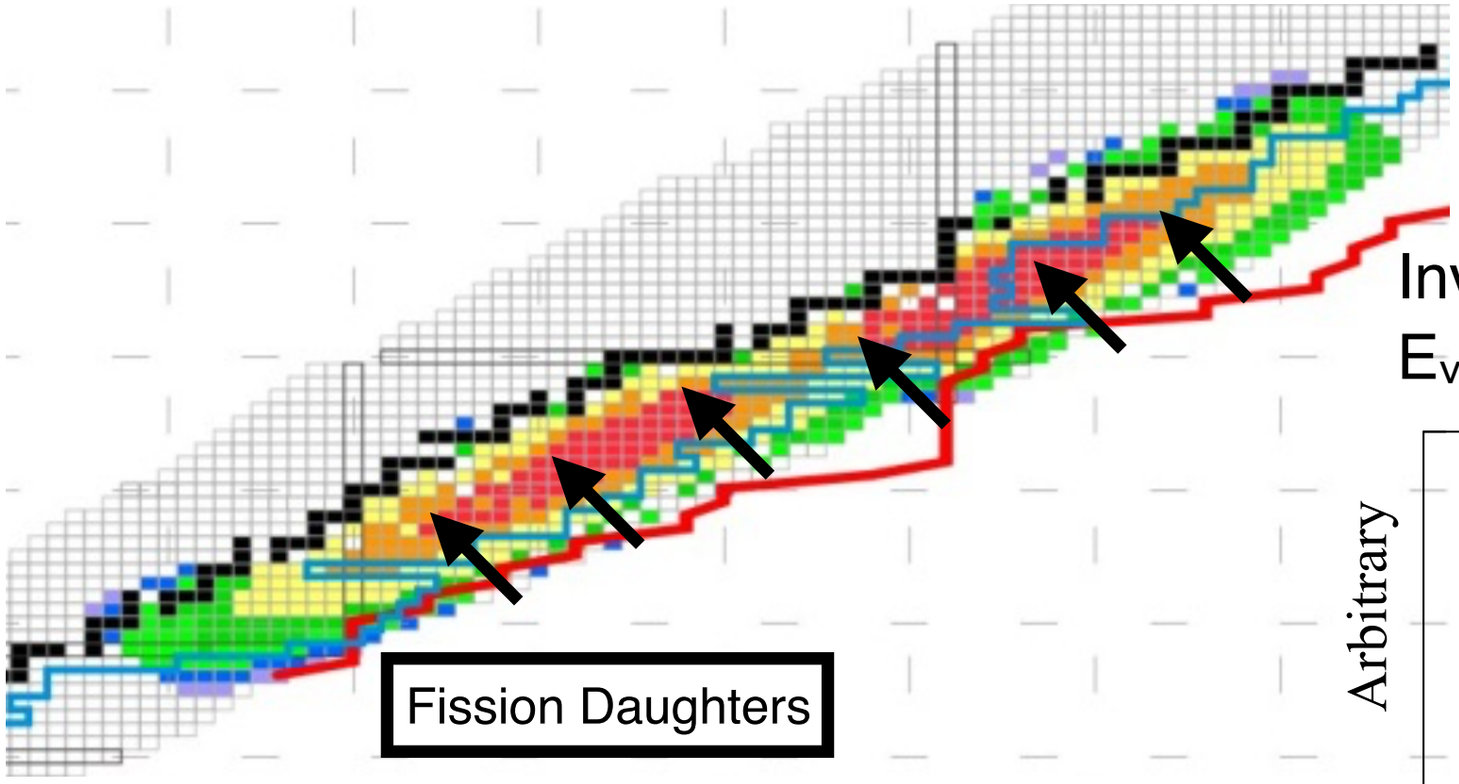

$$S(E_{\bar{\nu}}) = \sum_{i=0}^{n} \text{Decay Rate } R_i \sum_{j=0}^{m} f_{ij} \text{ Spectrum } S_{ij}(E_{\bar{\nu}})$$

Branching Fraction

- Fission of parent isotopes yield neutron-rich daughters
  - Beta decays produce ~6$\nu$/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(HEU) cores: mainly $^{235}$U

# Reactor neutrino production and detection

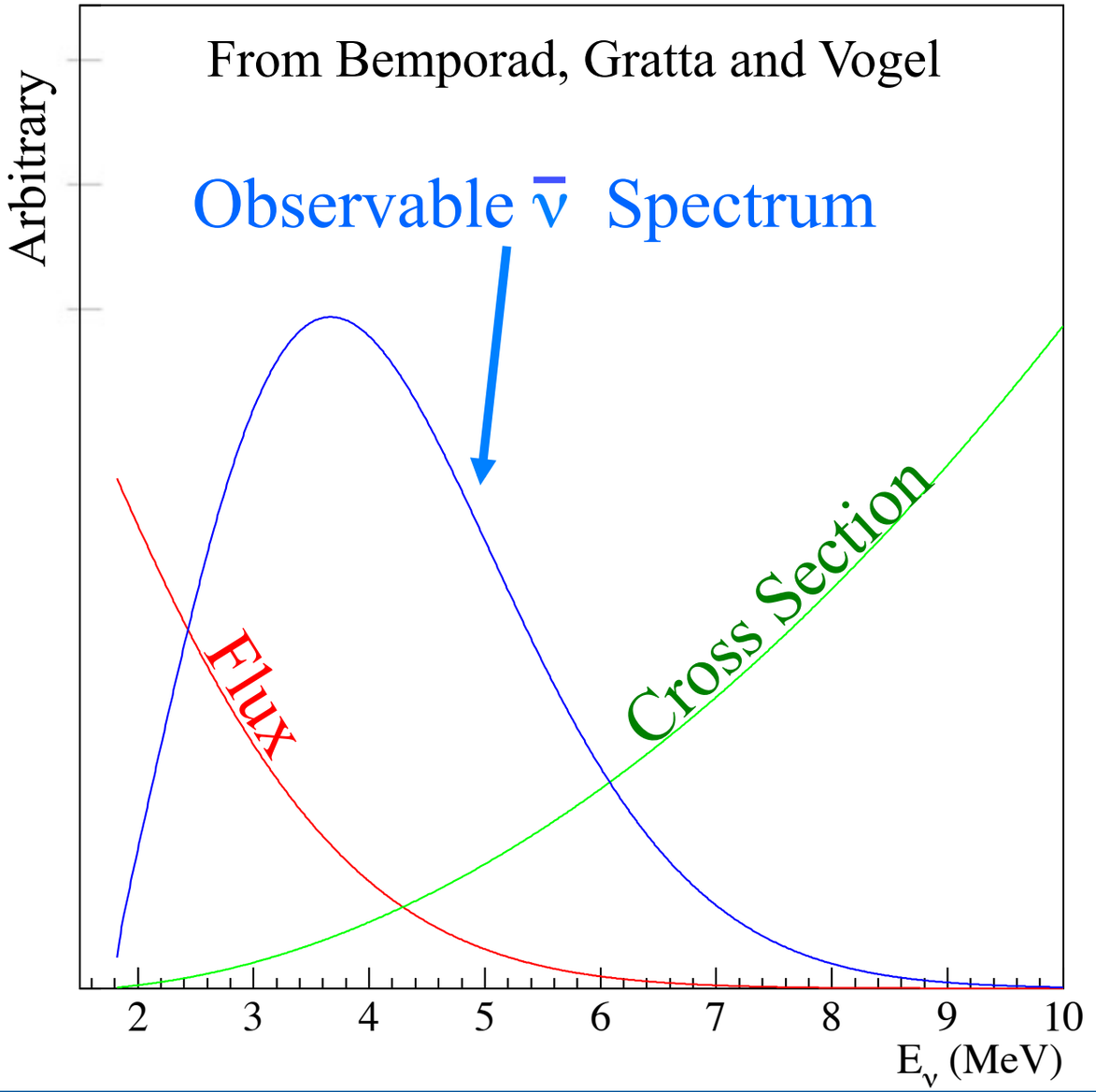



~6 $\overline{\nu}_e$ per fission

$2 \times 10^{17}$ $\overline{\nu}_e$ per $MW_{thermal}$

Inverse Beta Decay: $\overline{\nu}_e p \rightarrow e^+ n$

$E_\nu = T_{e+} + T_n + (m_n - m_p) + m_e \approx T_{e+} + 1.8\text{MeV}$




Decay Rate

Spectrum

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

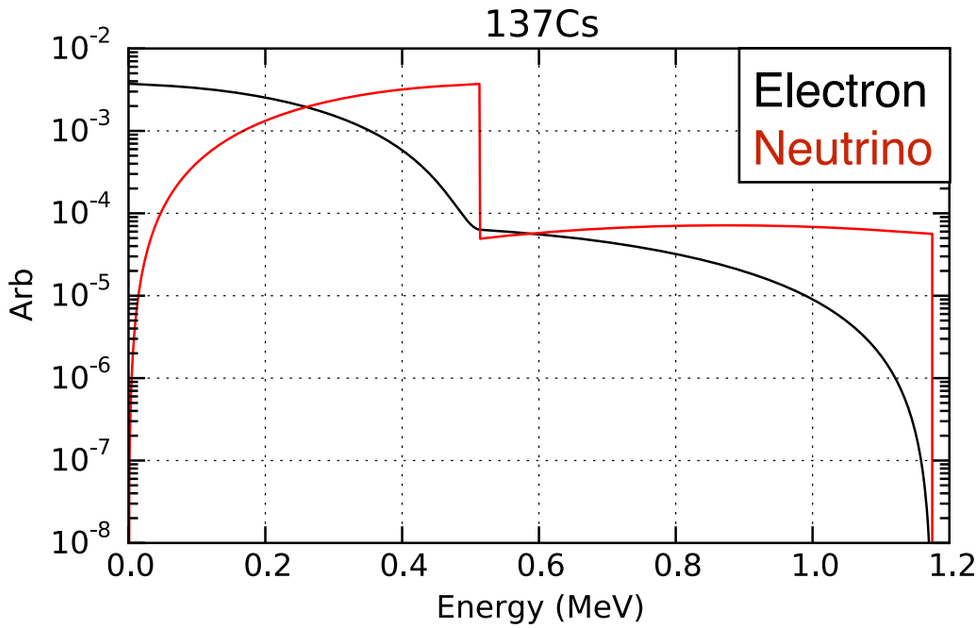
Branching Fraction

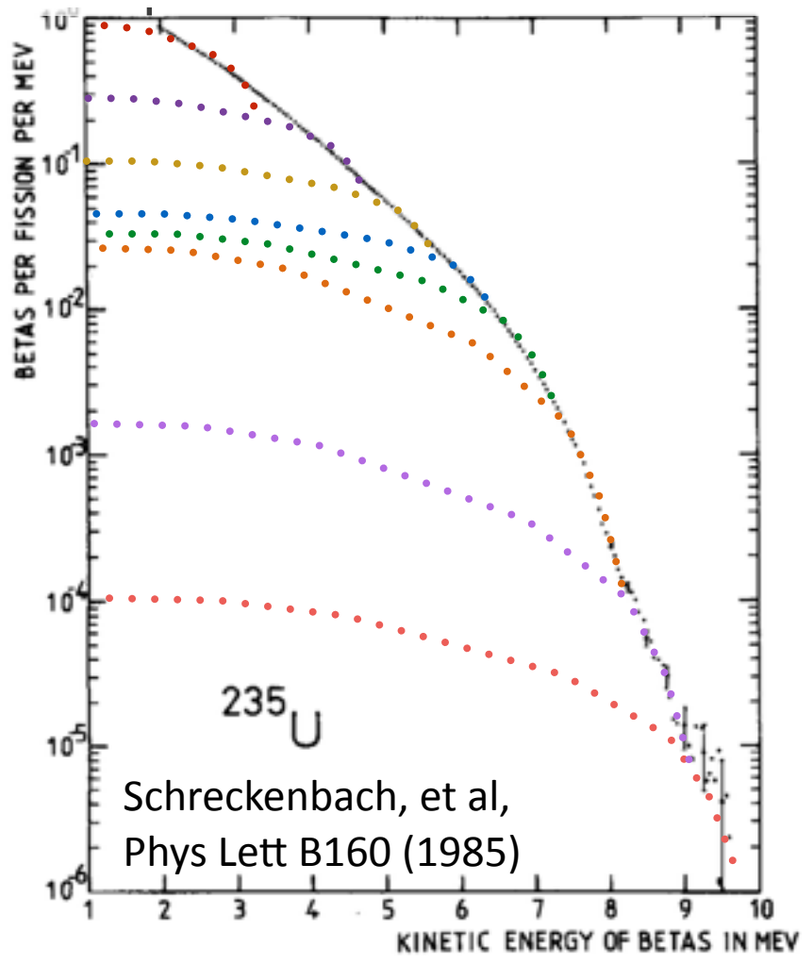
- Fission of parent isotopes yield neutron-rich daughters
  - Beta decays produce ~6$\nu$/ fission, <10MeV

# 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 and are incomplete
- ***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?



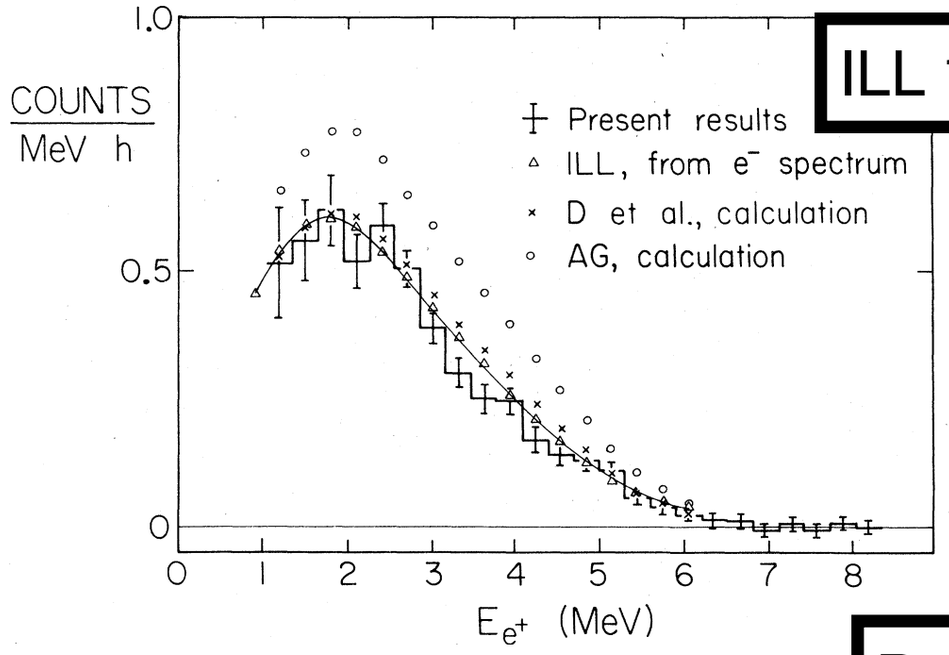




Schreckenbach, et al,
Phys Lett B160 (1985)

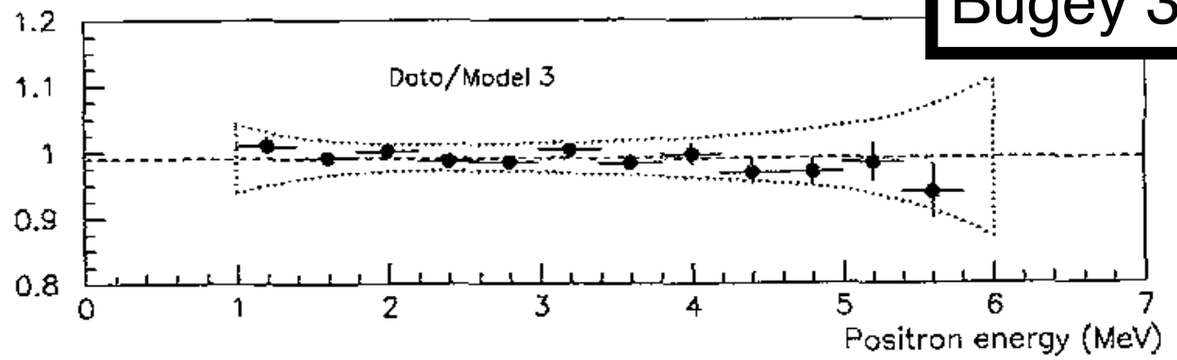
# Initial comparisons of neutrino flux and spectra measurements and predictions

- **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 or predictions
- **1990s:** Bugey PWR spectrum agrees with Beta-conversion spectra
- **1990-2000s:** Measured fluxes agree with predictions

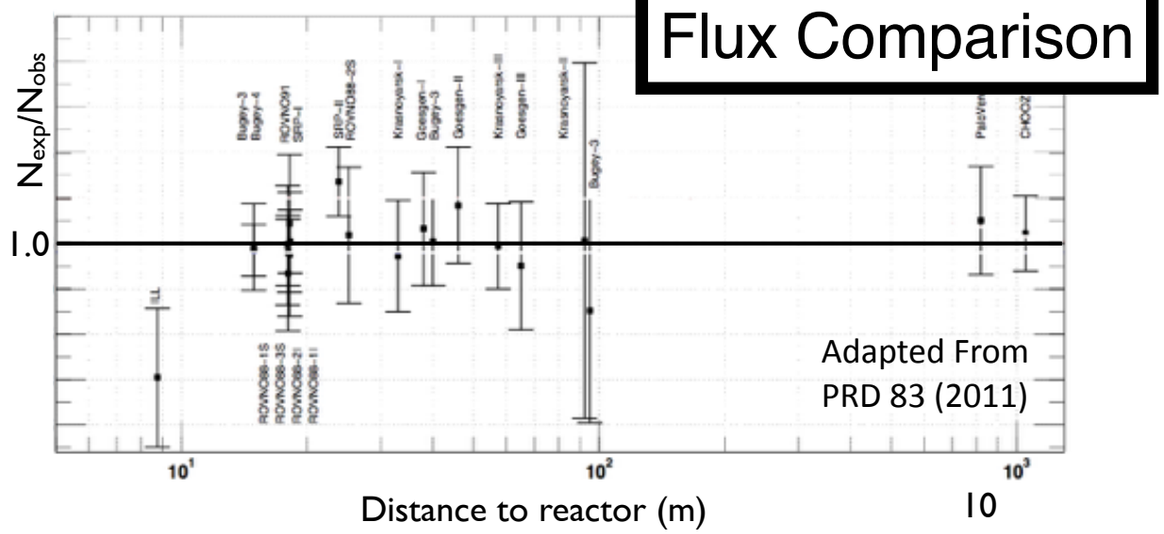
ILL 1981




Bugey 3

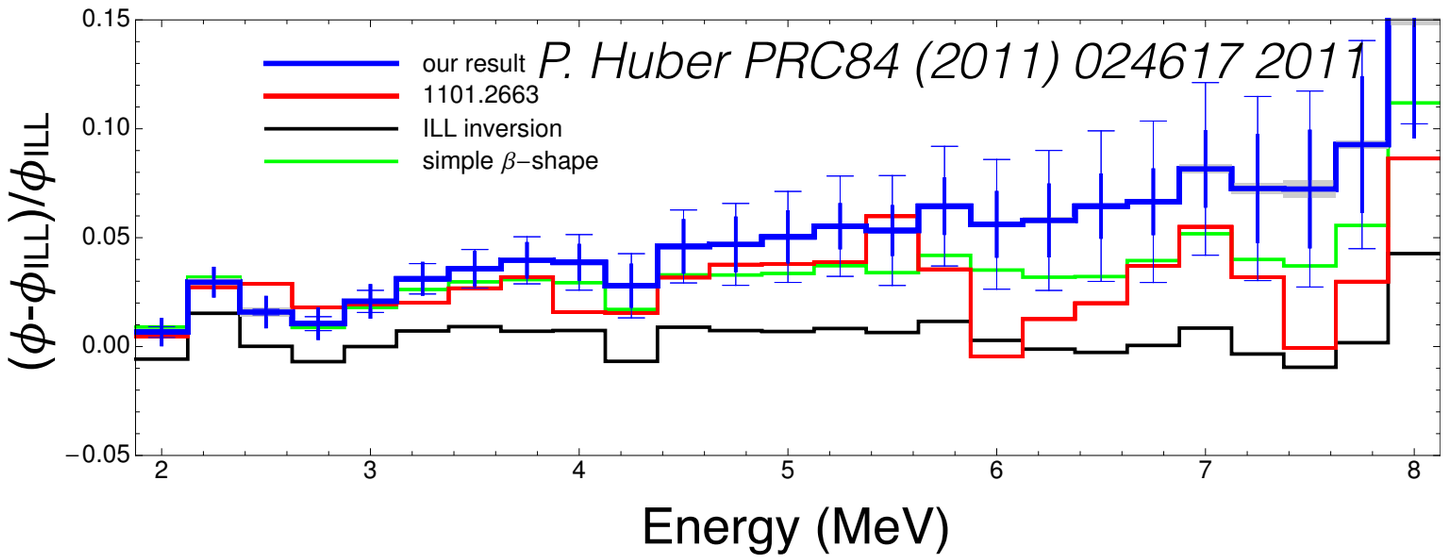


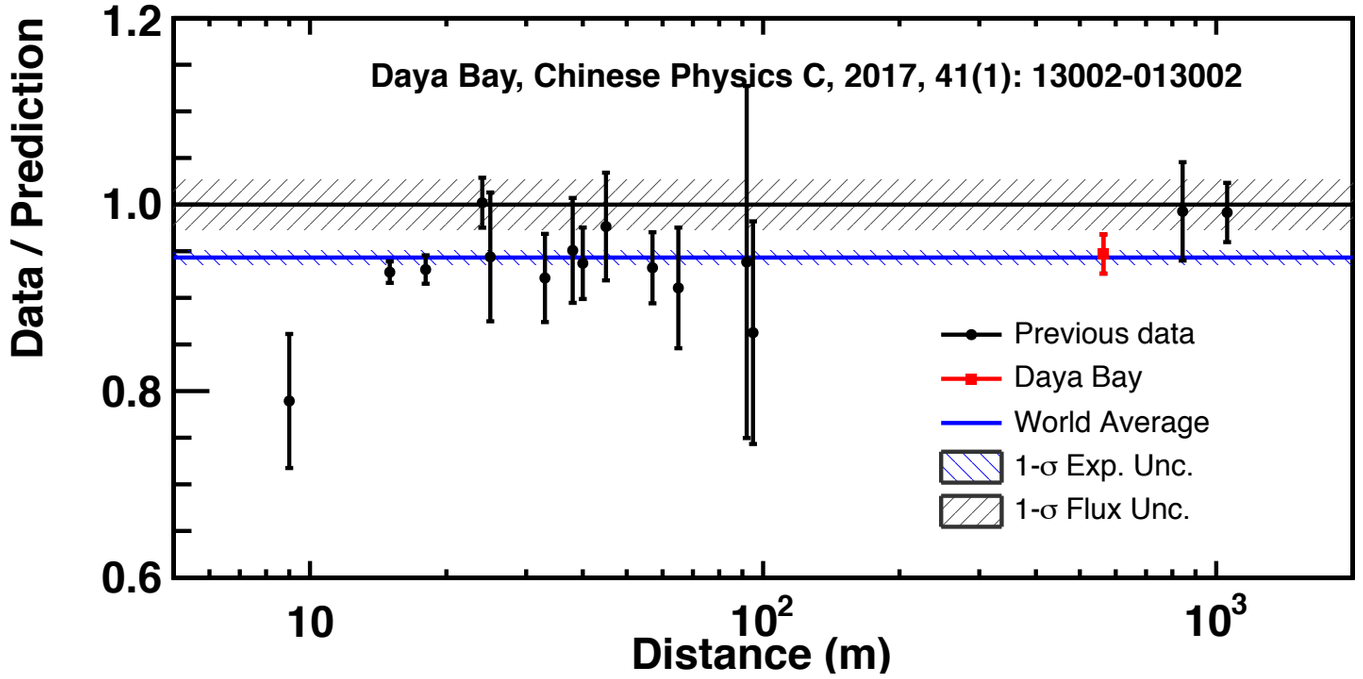

Flux Comparison



# Re-evaluation of flux prediction

- **2011:** Two beta-conversion reanalyses increase predicted flux
  - One pure conversion, one hybrid between ab-initio and conversion
  - $\sim 3\sigma$ tension with previous experiments
- **Change in Flux/Spectrum:**
  - Conversion: +3%
  - Neutron lifetime: +1%
  - Non-equilibrium isotopes: +1%



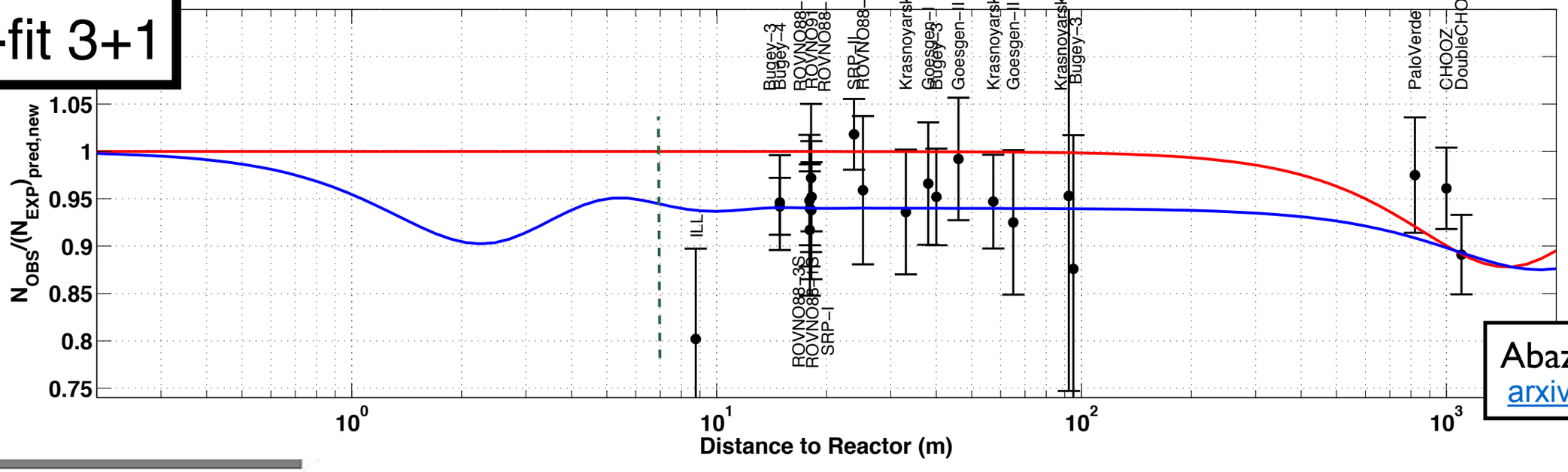




Dubbed the "Reactor Antineutrino Anomaly" = "RAA"

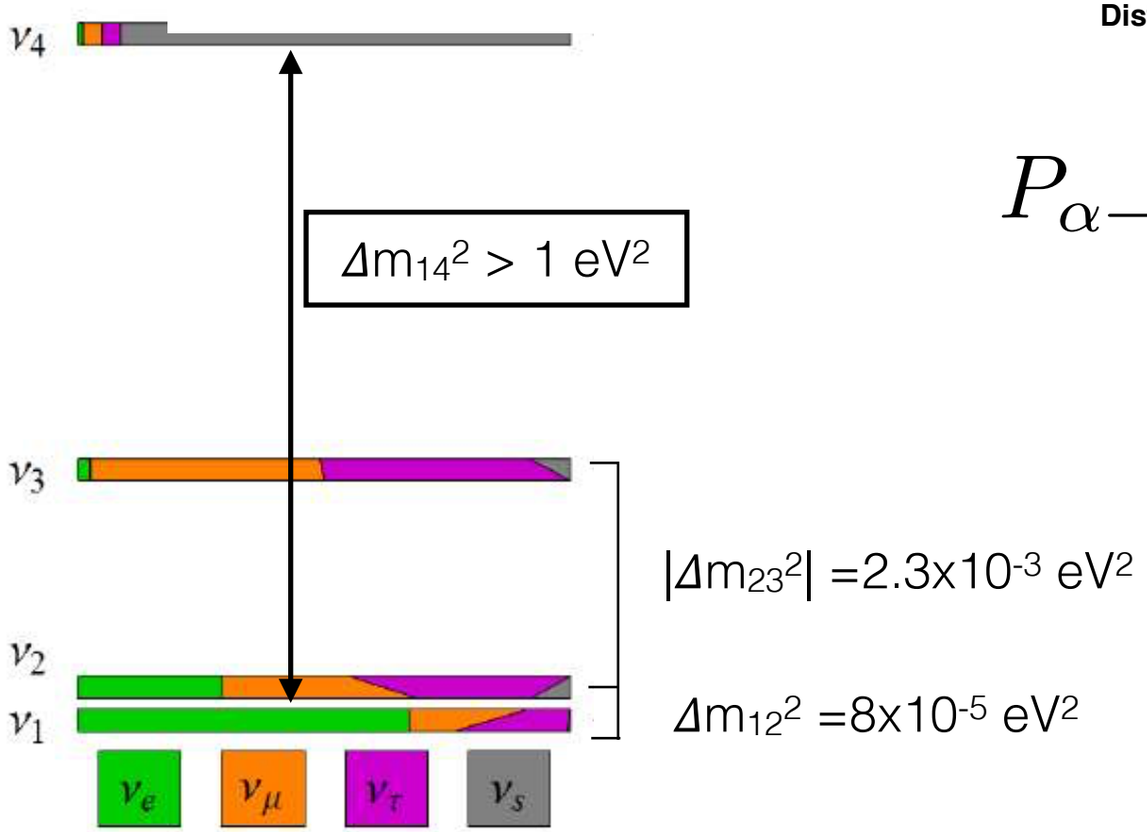
# Sterile Neutrinos??

PROSPECT

Best-fit 3+1




Abazajian et al.
arxiv:1204.5379




$$P_{\alpha\to\beta,\alpha\neq\beta} = sin^2(2\theta)sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

Two neutrino oscillation

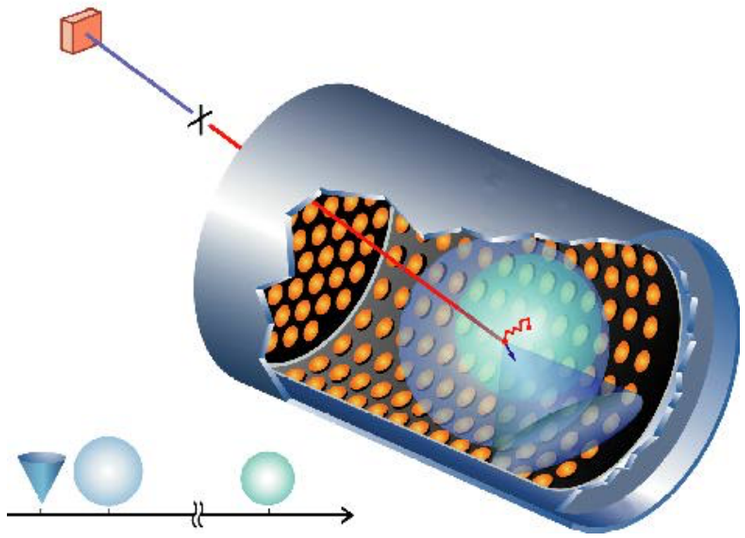
**Is flux deficit due to oscillation of active to sterile neutrinos?**

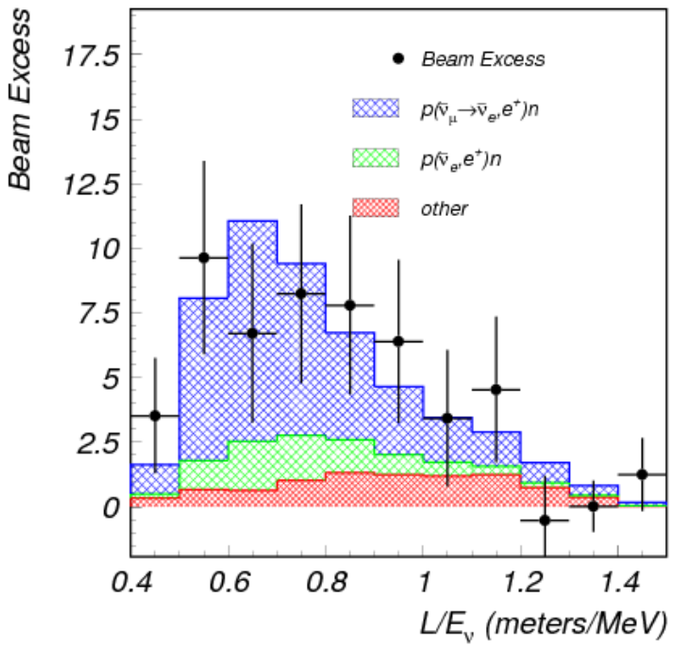
- High frequency oscillation
- Mass splitting ~1eV$^2$
- Baseline ~few meters

# Other Sterile Neutrino Hints

PROSPECT

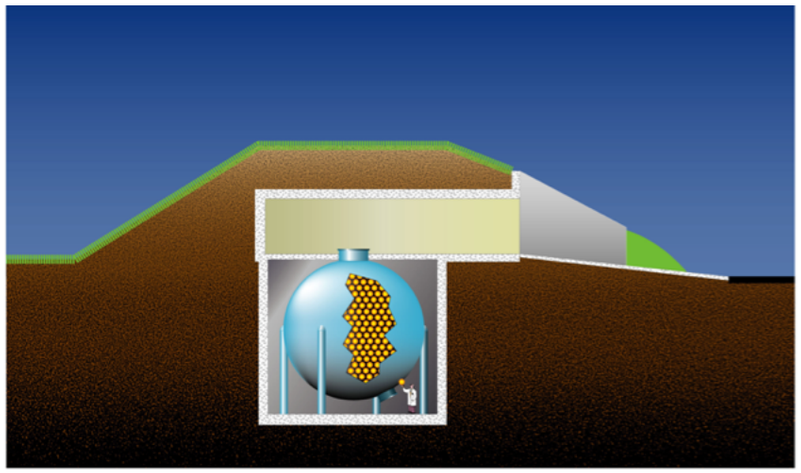
LSND
decay at rest

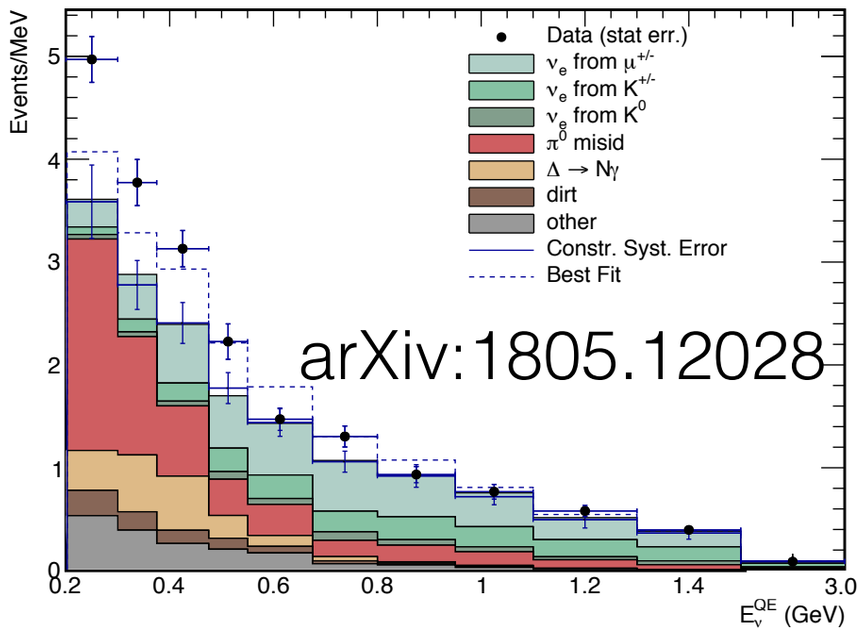





**anti-$\nu_e$ appearance**

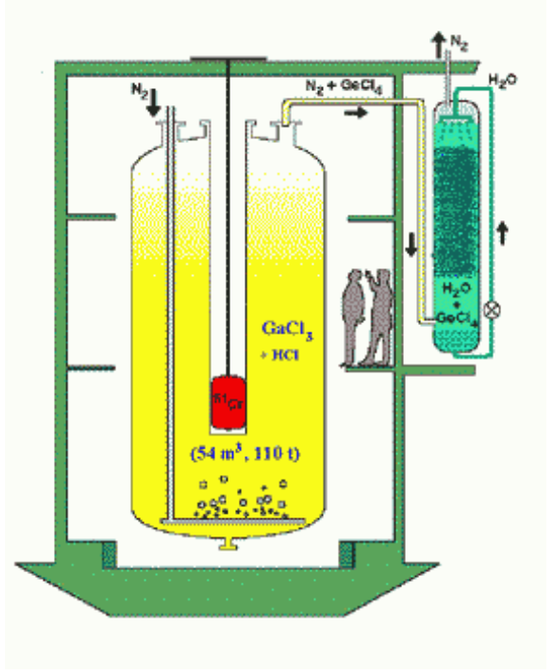
MiniBooNE
short baseline accelerator

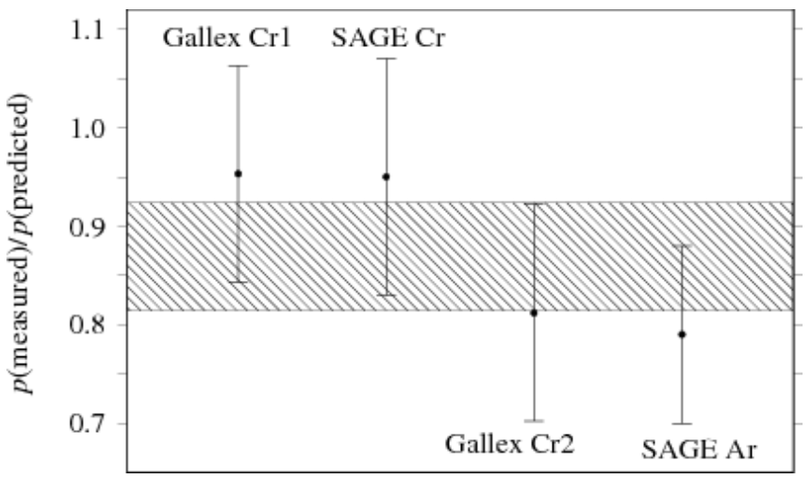





**low energy $\nu_e$ appearance**

GALLEX/SAGE
Ga source calibration



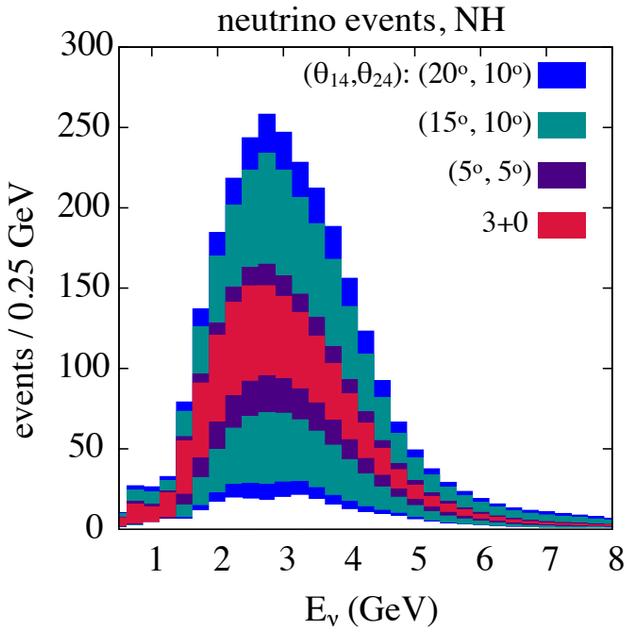



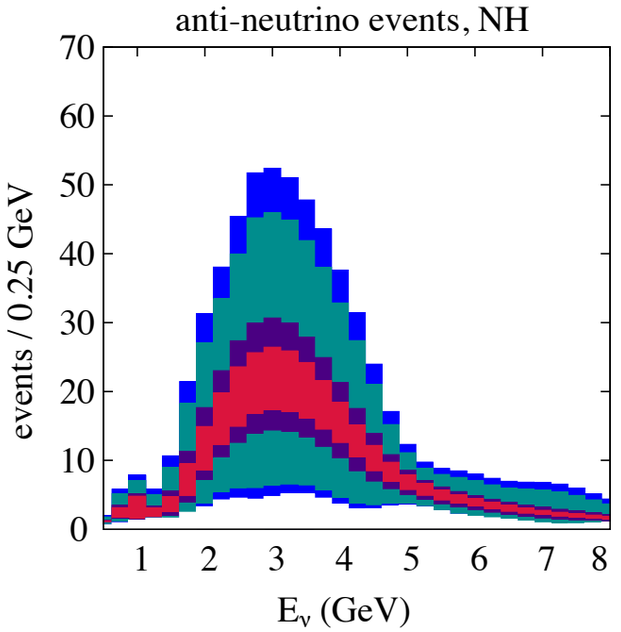

**$\nu_e$ disappearance**

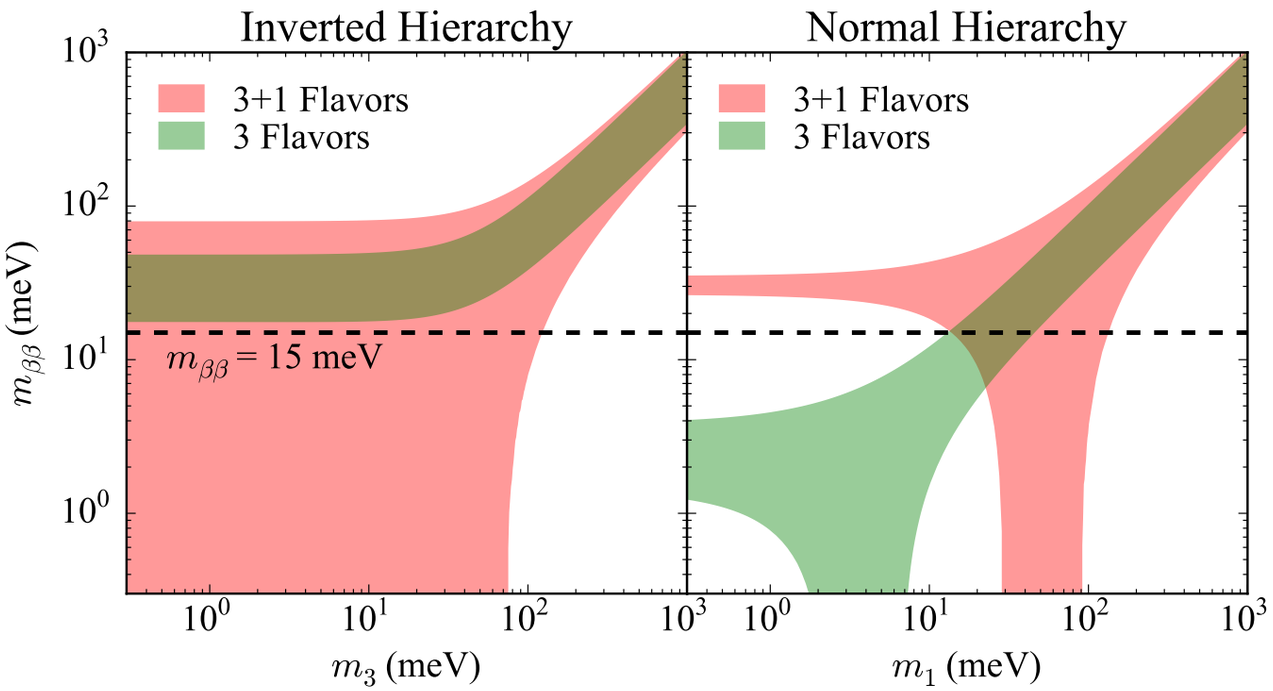
# Impact on Future Experiments

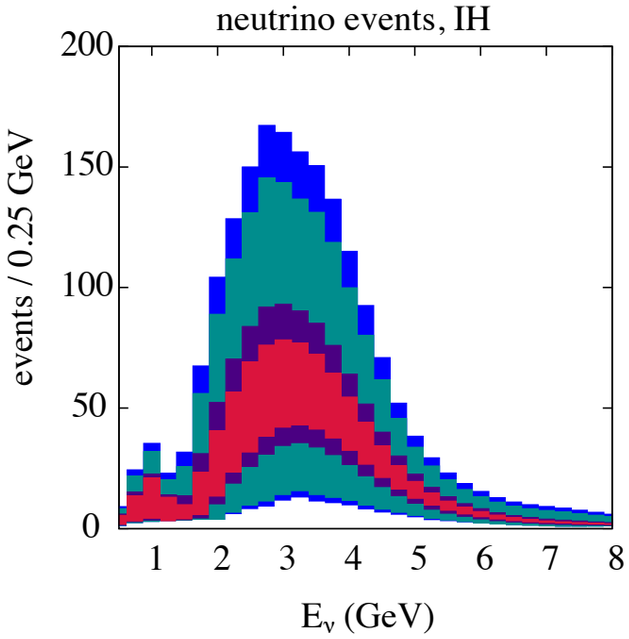
eV-scale neutrinos would impact:

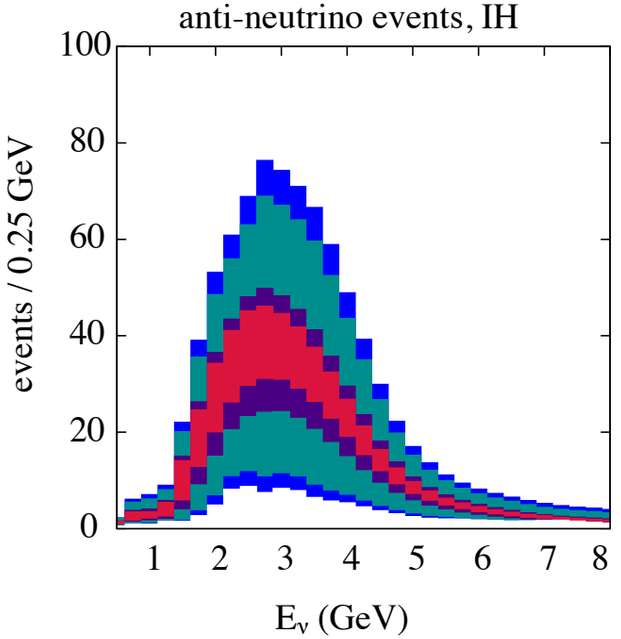
- Expected neutrino spectrum for Long-baseline oscillation searches
- Mass ordering for Double Beta Decay searches



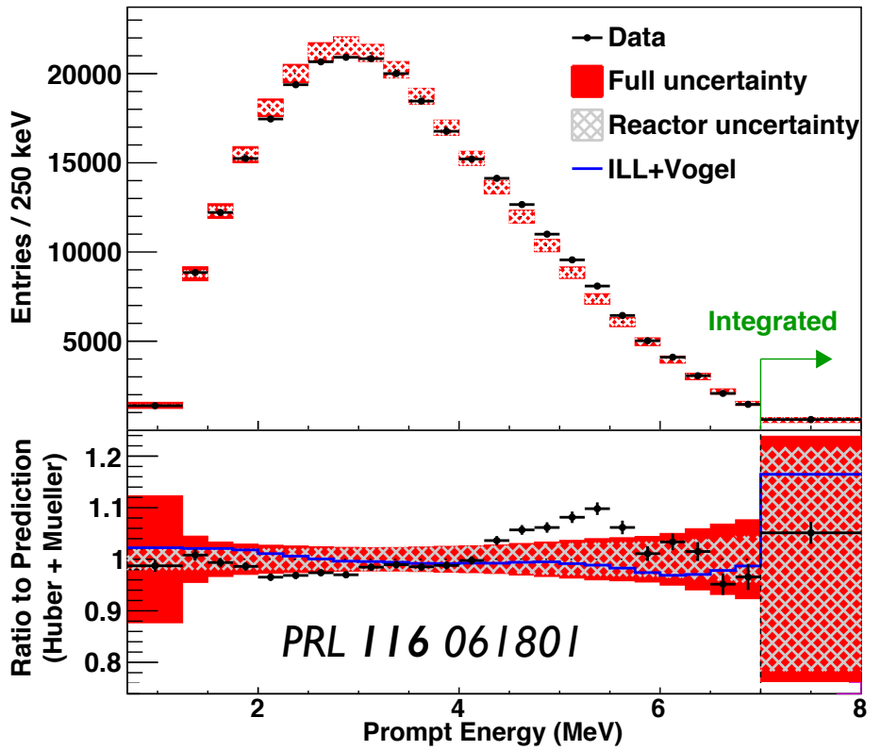



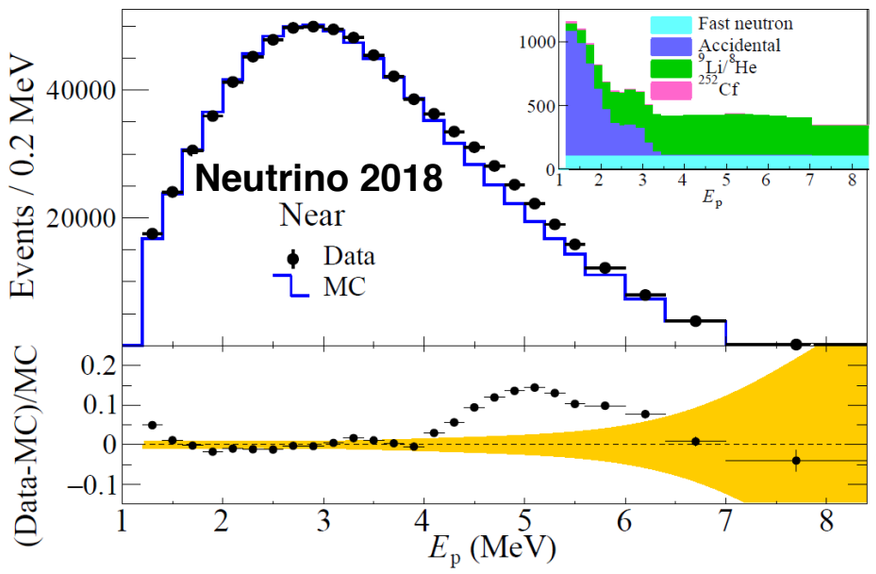

Gandhi, Kayser, Masud, Prakash
arXiv:1508.06275

# Another Anomaly: Spectral Features

## Daya Bay

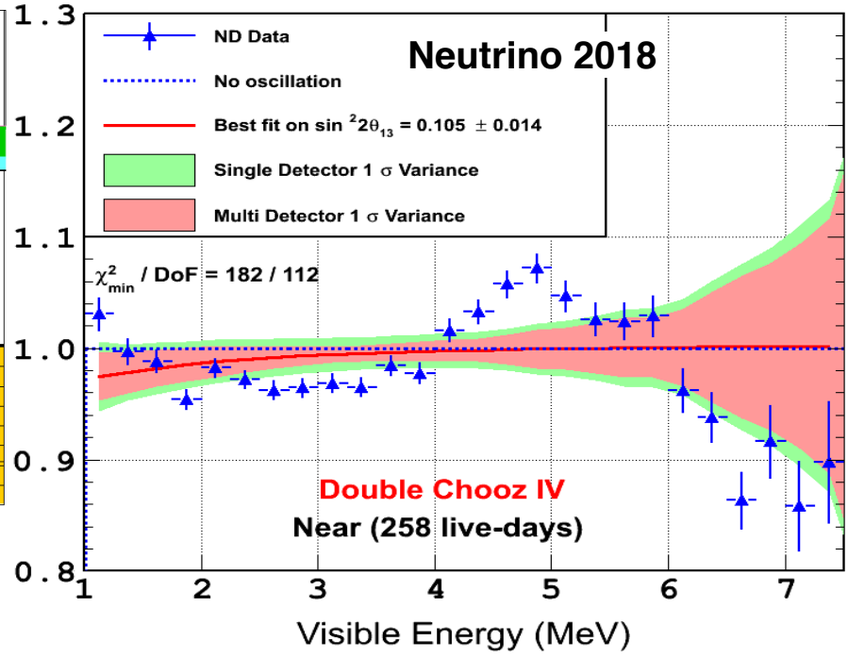



## RENO




RENO normalization differs from DYB, DC

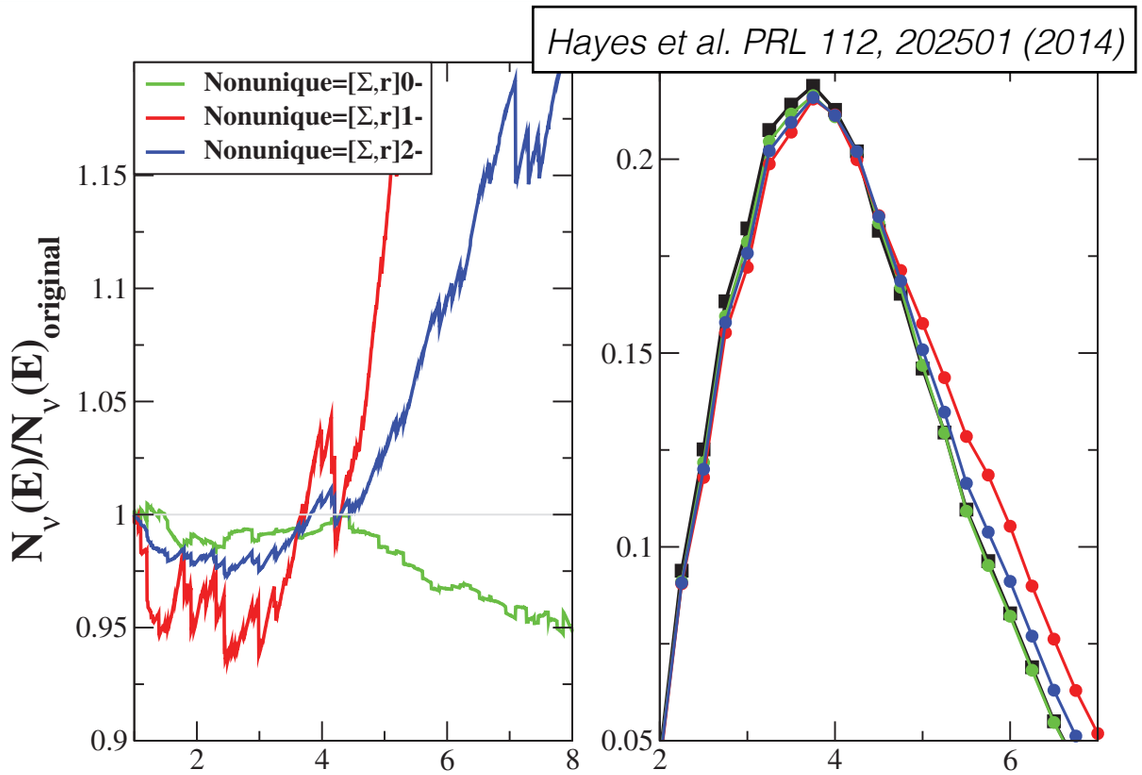
## Double Chooz

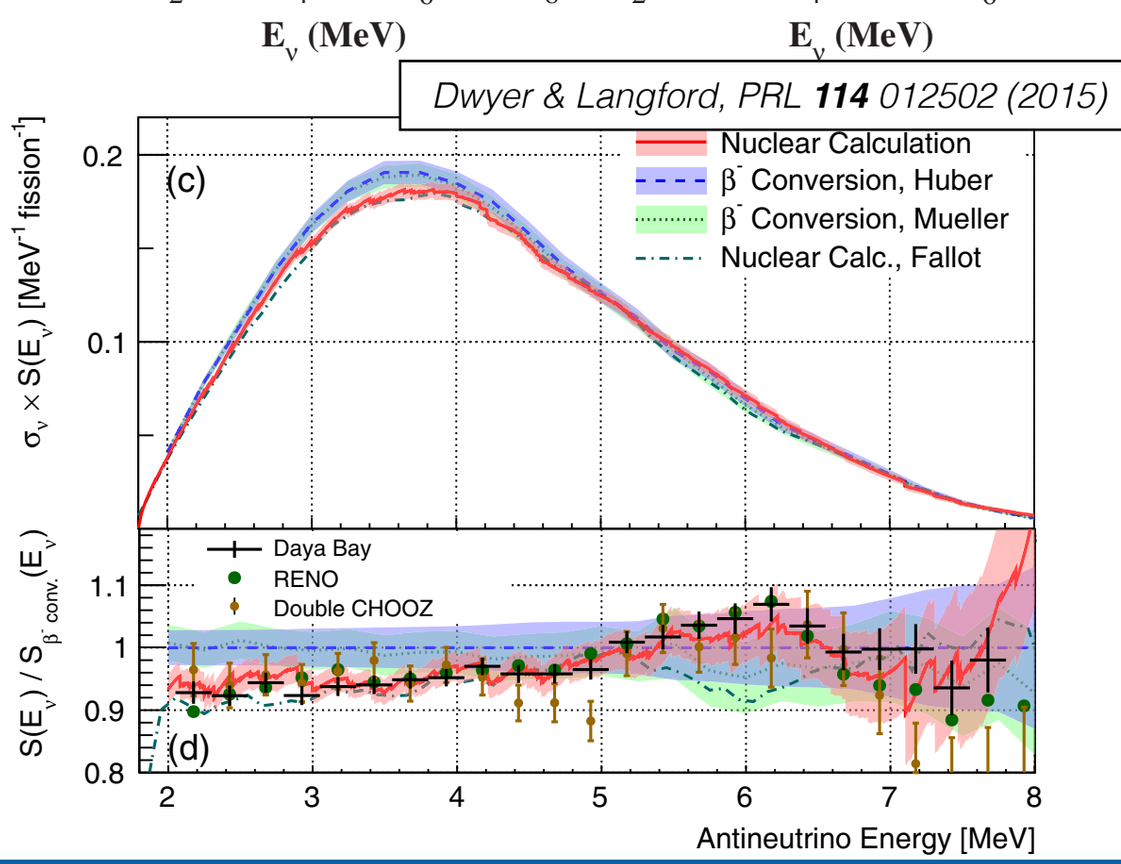



- All three $\boldsymbol{\theta}_{13}$ experiments have observed a spectral deviations, most prominently between 4-6MeV prompt energy (5-7MeV neutrino energy)
- Predictions based on beta-conversion (Huber, Mueller, Haag)
- Tracks with reactor power, observed in both Near and Far detectors
- Cannot be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

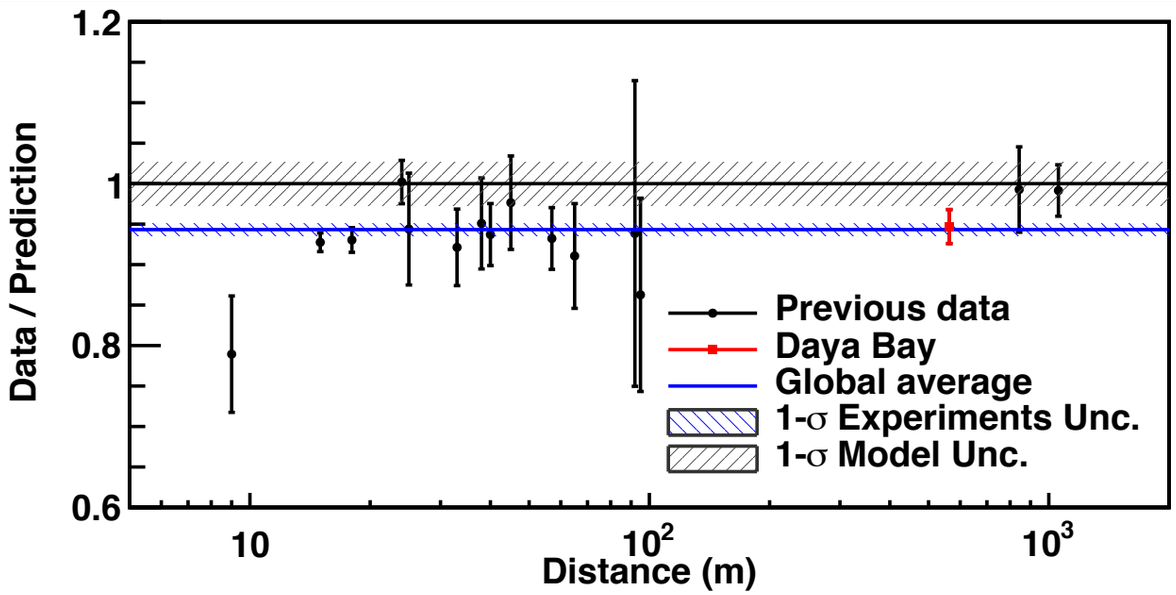
# New Anomaly: Spectral Features

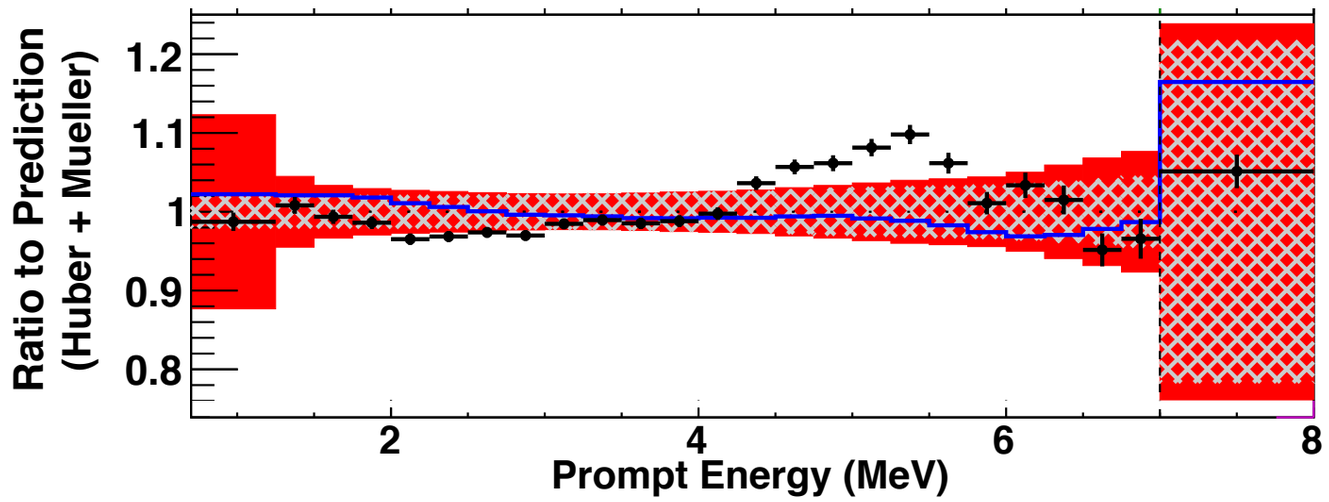
- **Beta-converted spectra could be wrong:**
  - Use Allowed shapes for all decays, known to be incorrect
  - Error in the measurements?
- Ab-initio calculation for one database seems to reproduce the feature
- **Problem:** Large uncertainties and missing data
- **Problem:** More complete database doesn't reproduce the shape Sonzogni et al., PRL**116** (2016) 132502

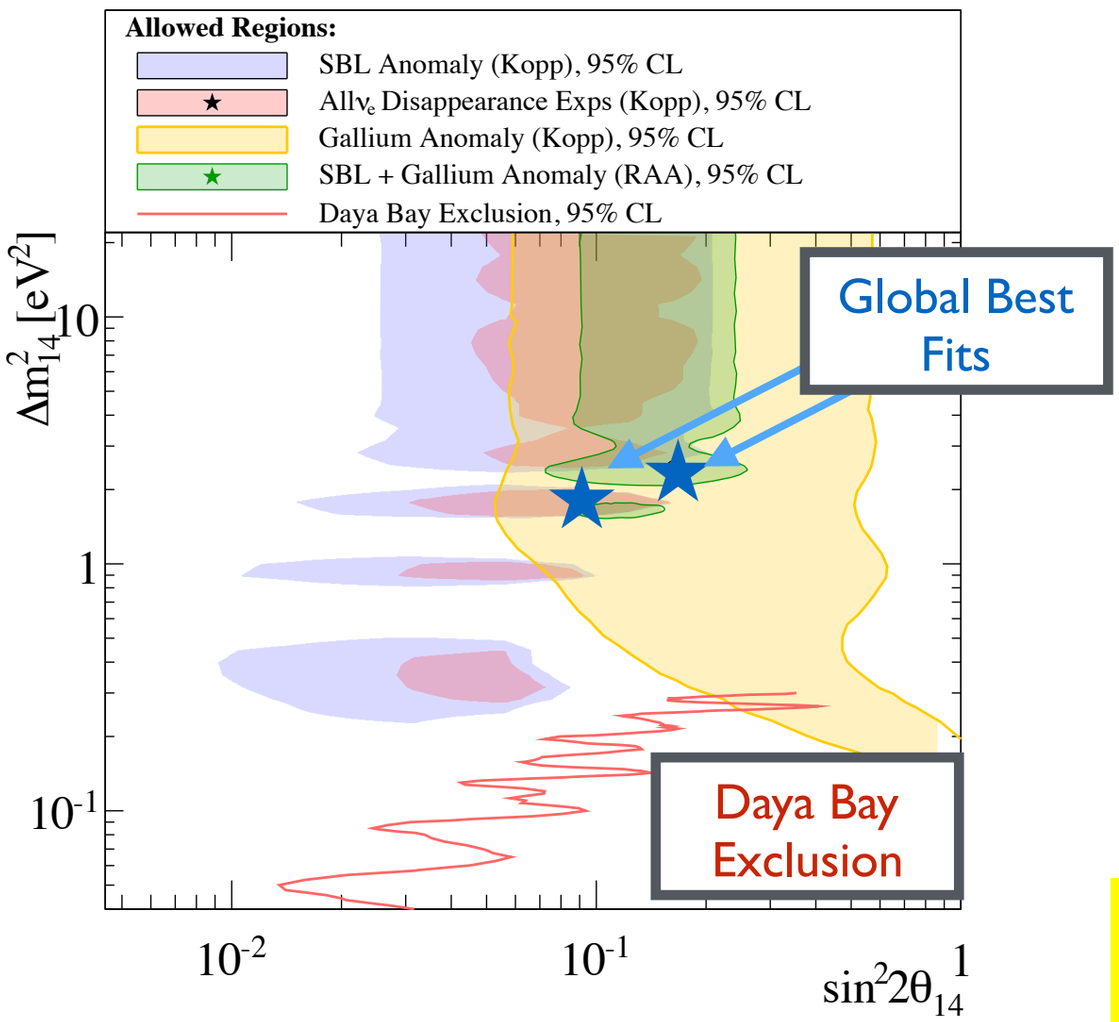


# Anomalies lead to Discoveries



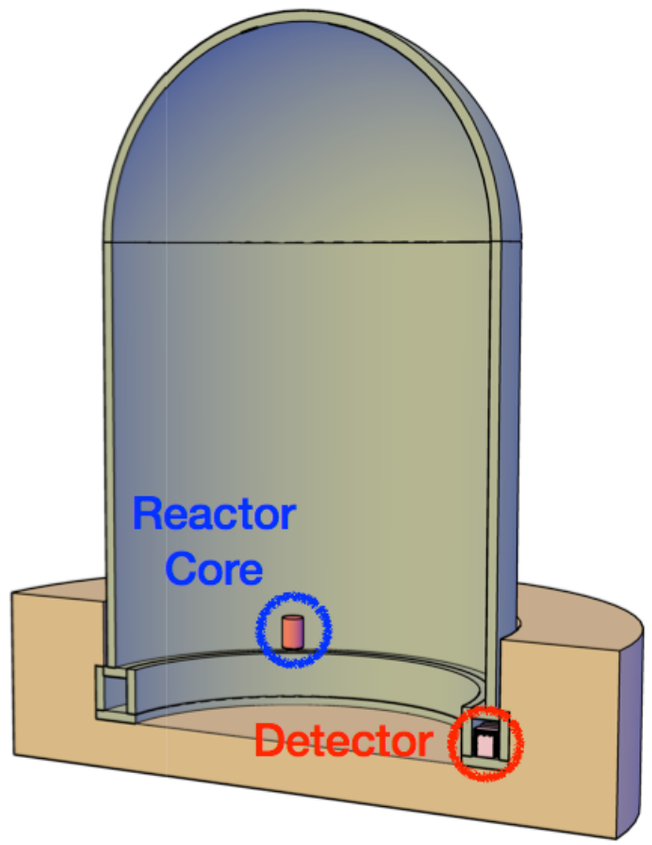

- Spectral anomaly could point were to look
  - All $\theta_{13}$ measurements at LEU power reactors
  - HEU measurement powerful crosscheck
- **We need new data**
- Existing experiments beginning to probe these questions (*Next pages*)

P.Vogel: "…it is possible, perhaps even likely, that both anomalies have their origin in standard physics." arXiv:1603.08990

# Experimental Site

- Hanbit Nuclear Power Plant in Younggwang, Korea
  - **2.8 $GW_{th}$** commercial reactor
  - Core size: 3.1 m diameter and 3.8 m height
  - Low enriched uranium fuel (4.6% $^{235}U$)
- Detector in Tendon Gallery
  - **~24 m baseline** and **~20 m.w.e overburden**

Reactor building



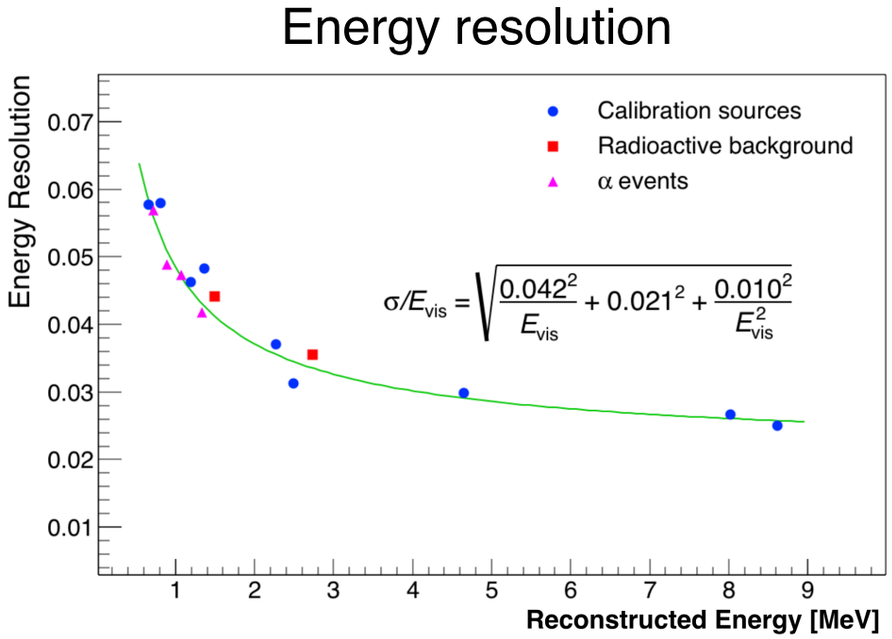

# NEOS Detector

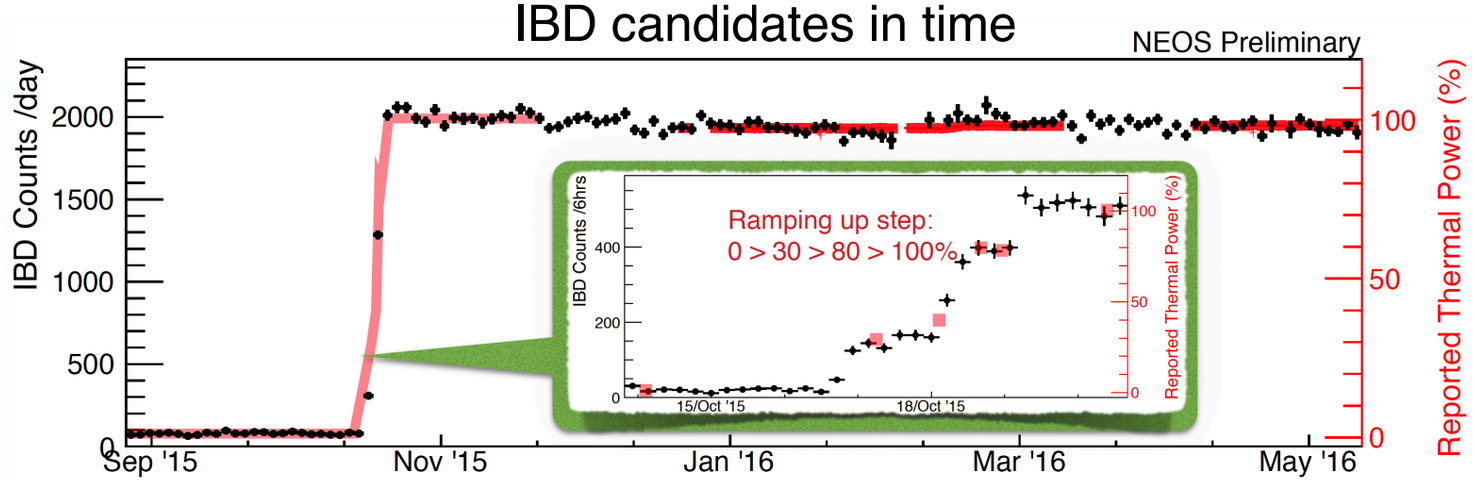
- Active target (Liquid Scintillator, LS)
  - Homogeneous, 1000 L volume
  - Inverse Beta Decay (IBD) in 0.5% Gd-loaded LS
  - Mixed LS
    - LAB- and DIN-based LS (9:1)
    - PSD is improved over LAB only.
  - Cylindrical stainless steel tank with PTFE reflector

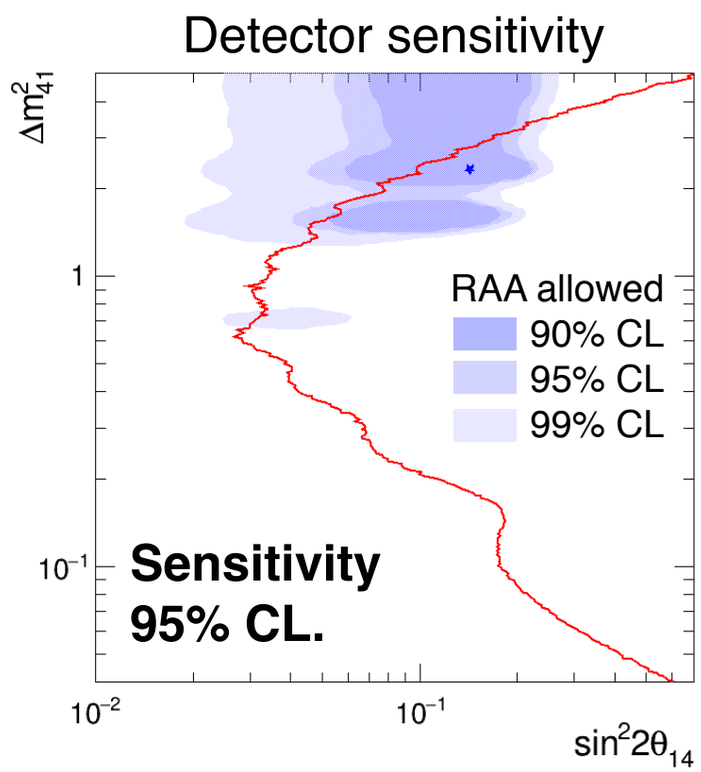
LAB: Linear Alkyl Benzene
DIN: Di-isopropylnaphthalene
PSD: Pulse Shape Discrimination

# Detector Performance and Sensitivity

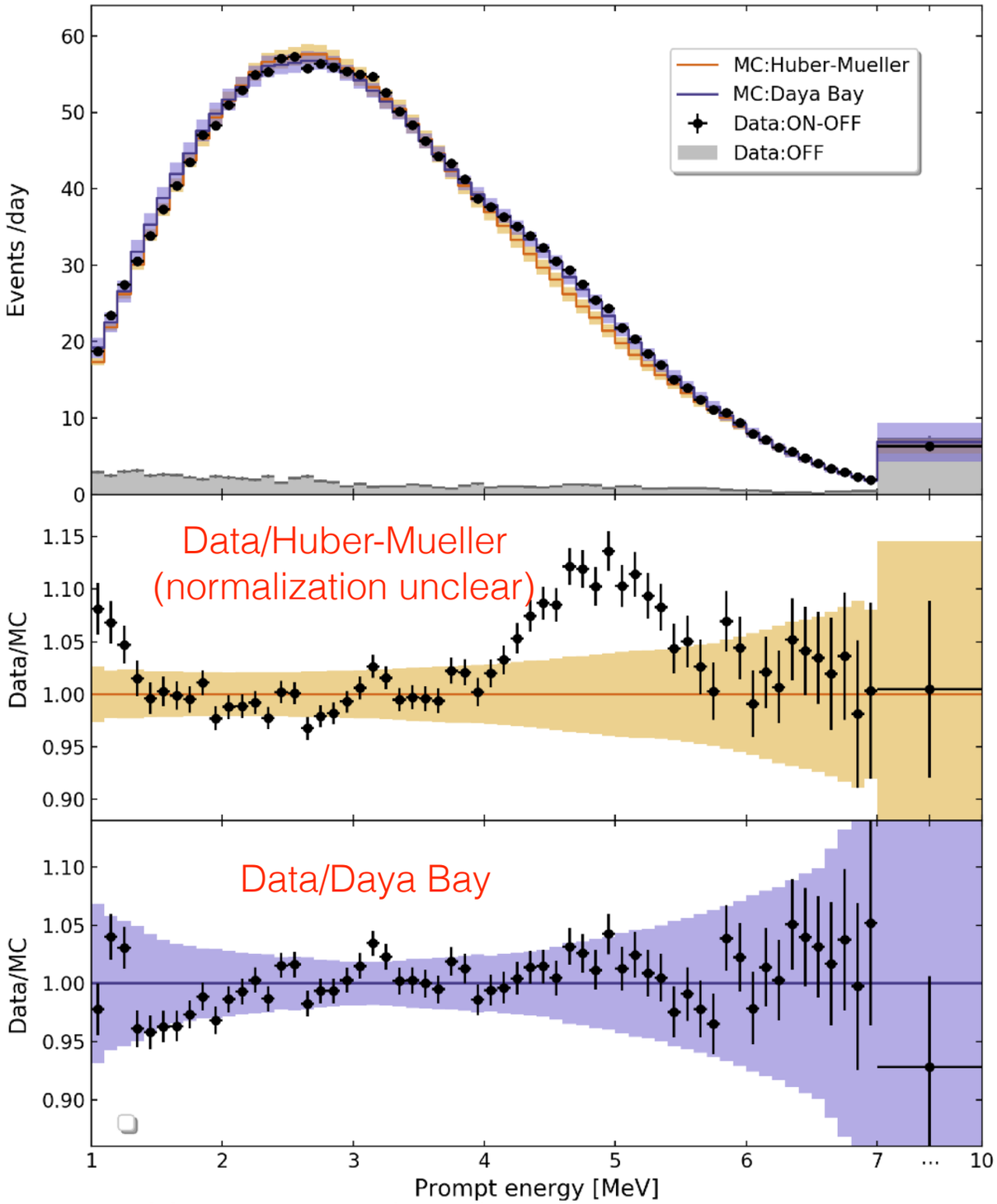
- Data taking: Aug 2015 - May 2016
  - Reactor-on period: 180 days
  - Reactor-off period: 46 days
- IBD candidates
  - Reactor-on period: 2000 IBD candidates per day
  - Reactor-off period: 80 IBD candidates per day
  - **On-off ratio: ~24**
- Ramping-up step is seen.
- **5% energy resolution** at 1 MeV
- Most sensitive range for ~eV sterile neutrinos



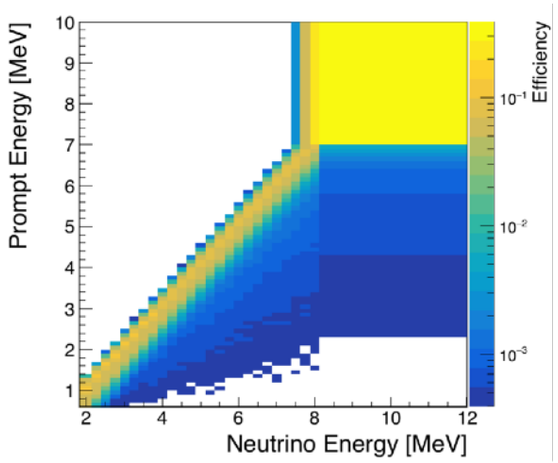



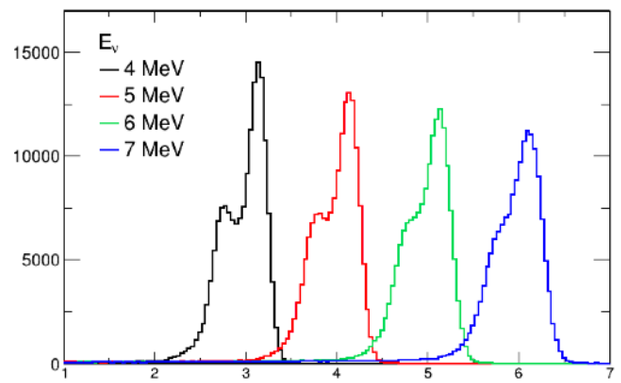
# Prompt energy spectrum




My comments in red.

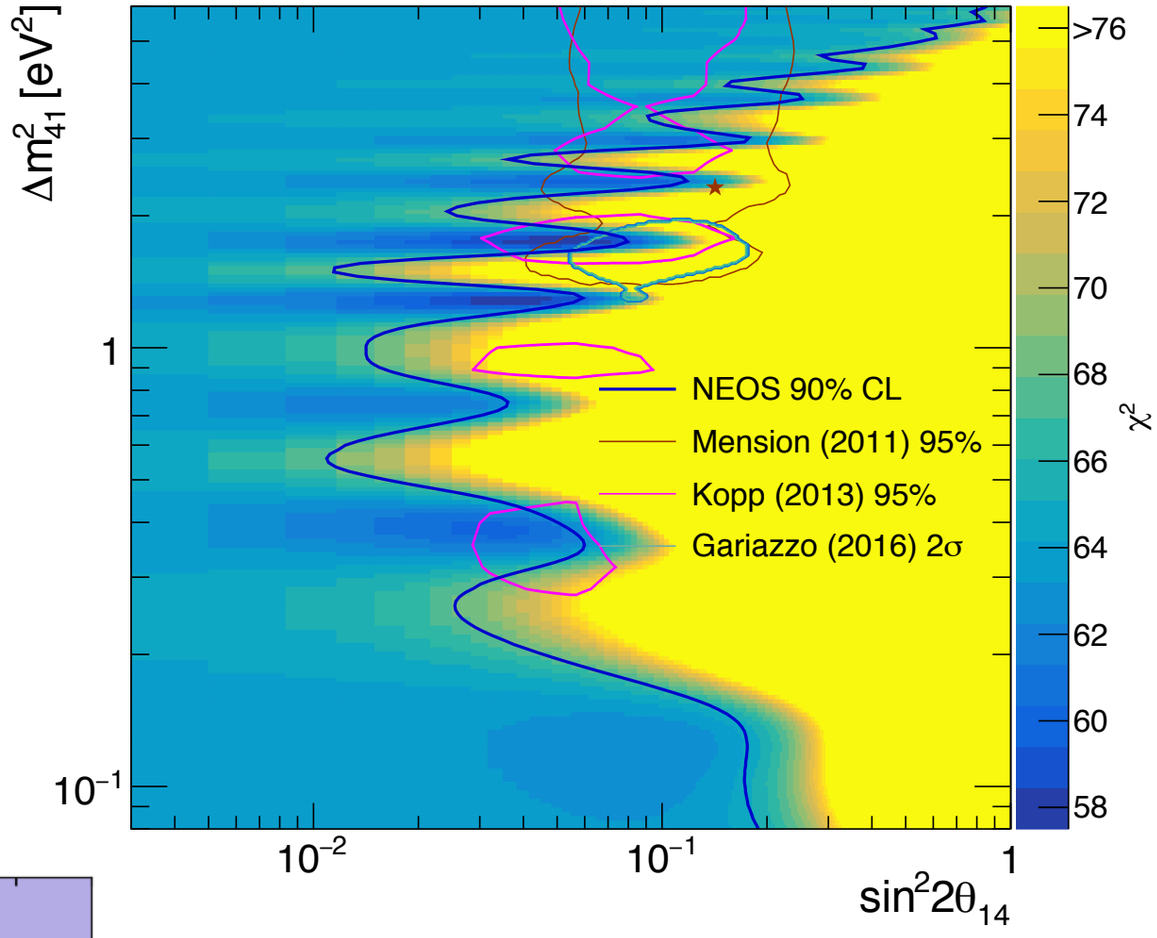
- Negligible background change between on-off periods,
- Spectral anomaly observed (vs Huber-Mueller normalization),
- Small structural fluctuations.
- Reference spectra generated using detector response matrix,
  - energy escape due to detector size

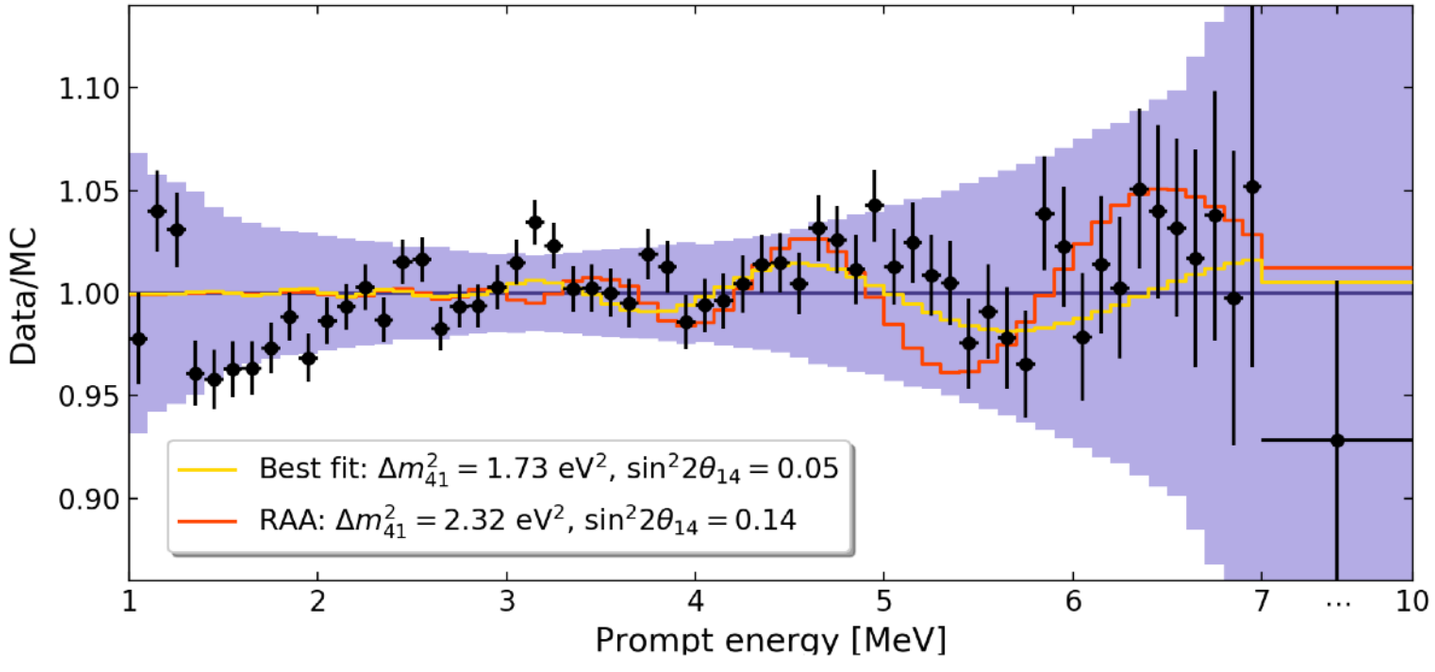


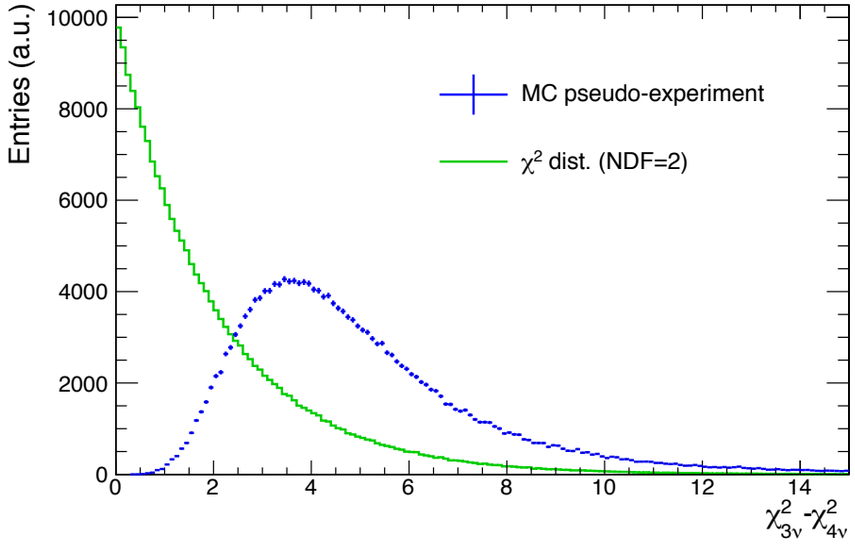



# Active-to-sterile oscillation

- Normalized with the Daya Bay shape
- Best fits at:
  (1.73 eV², 0.05), (1.30 eV², 0.04)
  with $\chi^2$(3v)-$\chi^2$(4v) = 6.5,
  p-value = 0.22
- Fine structures in reactor ν spectrum or oscillation?

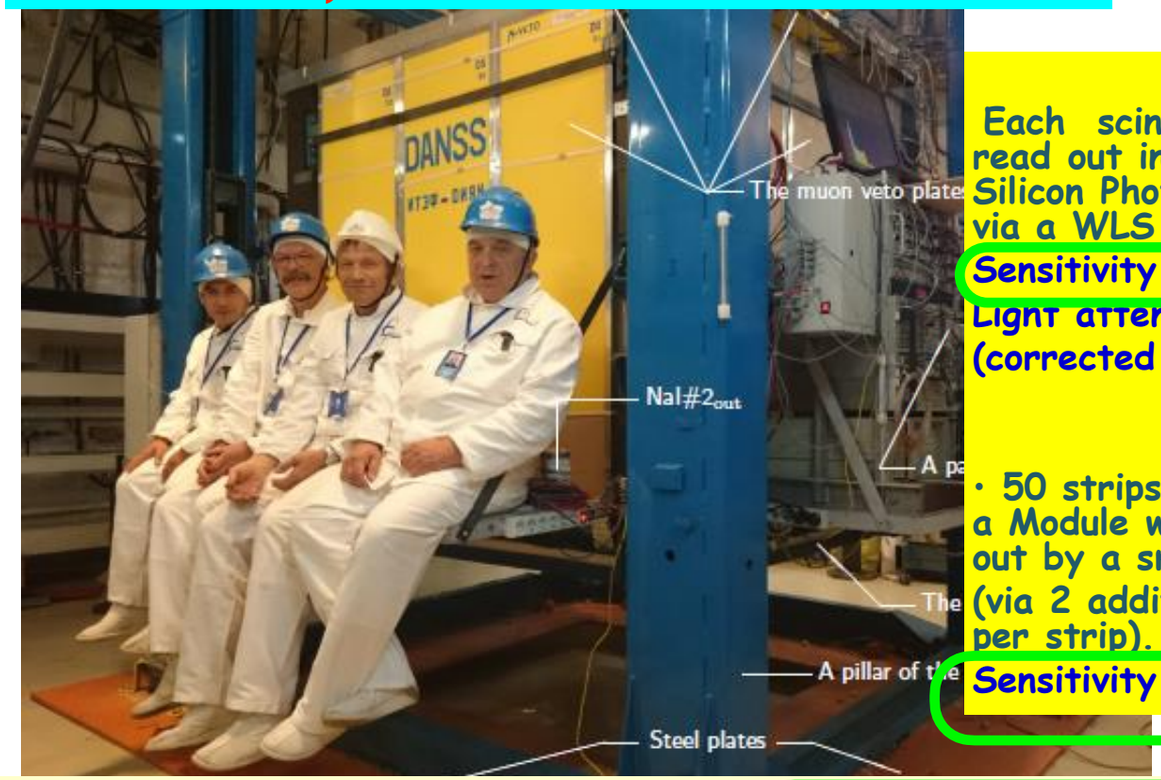


# DANSS at Kalinin Nuclear Power Plant

## M.Danilov, Moriond 24 March 2017




Each scintillator strip is read out individually by a Silicon Photo Multiplier (SiPM) via a WLS fiber.
Sensitivity is ~18 p.e./MeV
Light attenuation ~20%/m (corrected in analysis!)

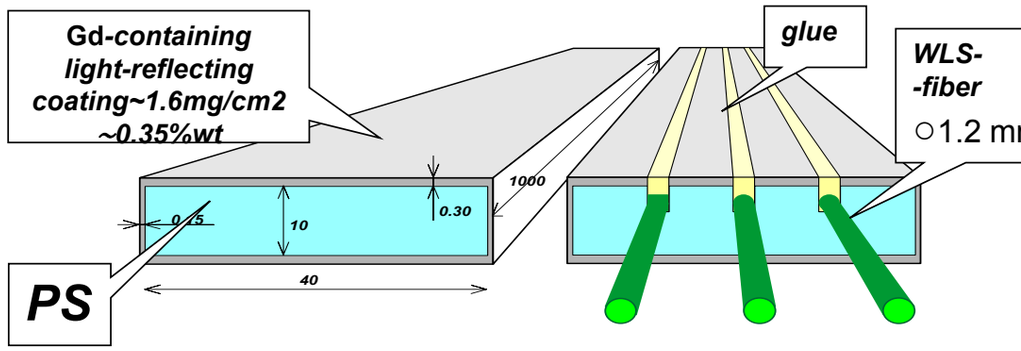
· 50 strips are combined into a Module which is also read out by a small PMT (via 2 additional WLS fibers per strip).
Sensitivity is ~20 p.e./MeV

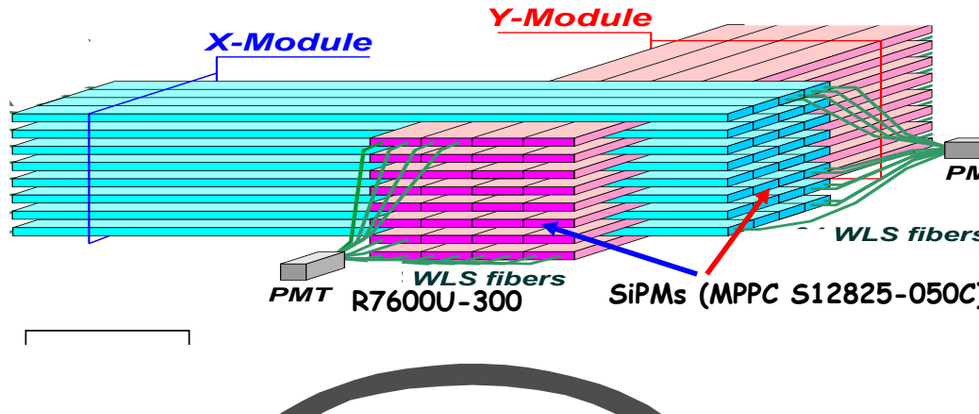
DANSS is installed on a movable platform under 3GW WWER-1000 reactor (Core:h=3.5m, ∅=3.1m) at Kalinin NPP. ~50 mwe shielding => μ flux reduction ~6! No cosmic neutrons!
Detector distance from reactor core 10.7-12.7m (center to center)
Fuel contribution at beginning and middle of campaign

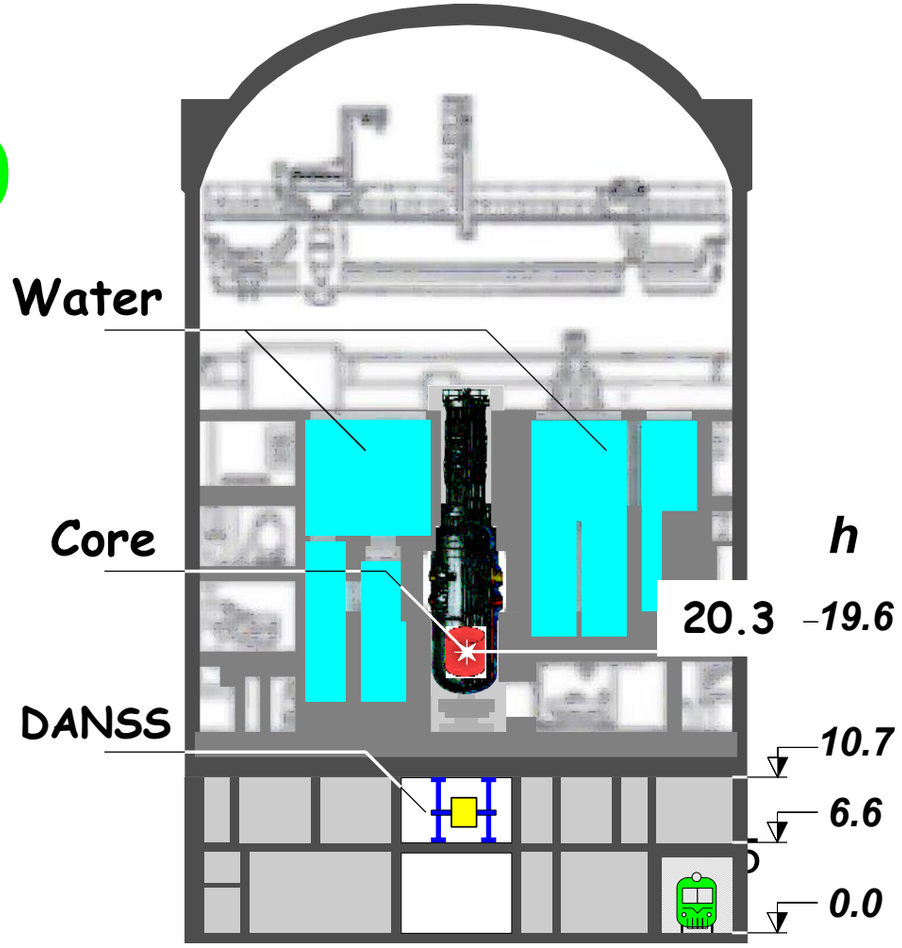
| | | |
|---|---|---|
| 235U | 69% | 58% |
| 239Pu | 21% | 30% |
| 238U | 7% | 7% |
| 241Pu | 3% | 5% |

Trigger: ΣEpmt>0.7MeV => Read 2600 wave forms (125MHz), look for correlated pairs offline.

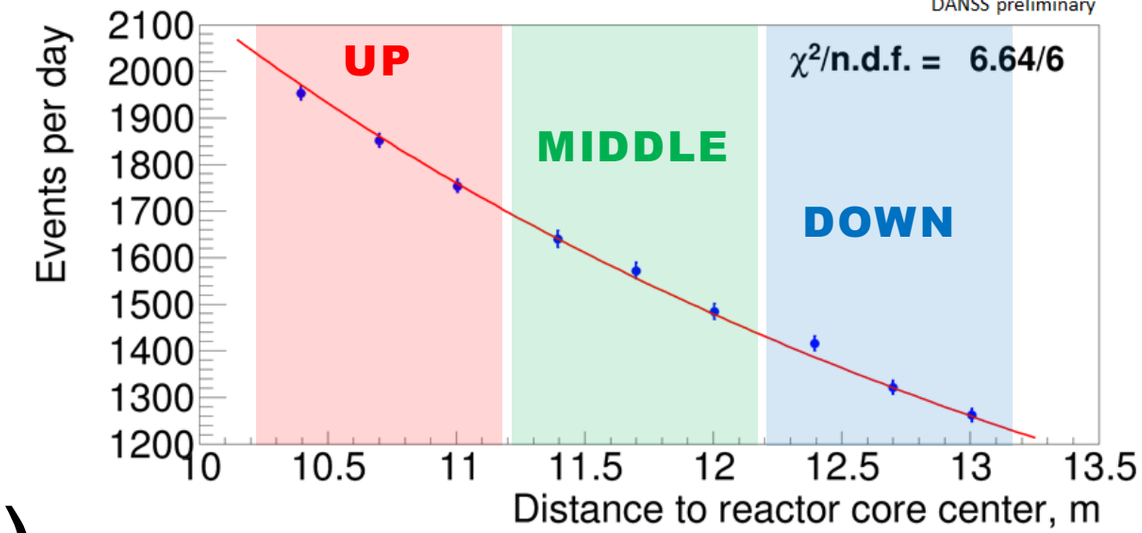
## DANSS Design



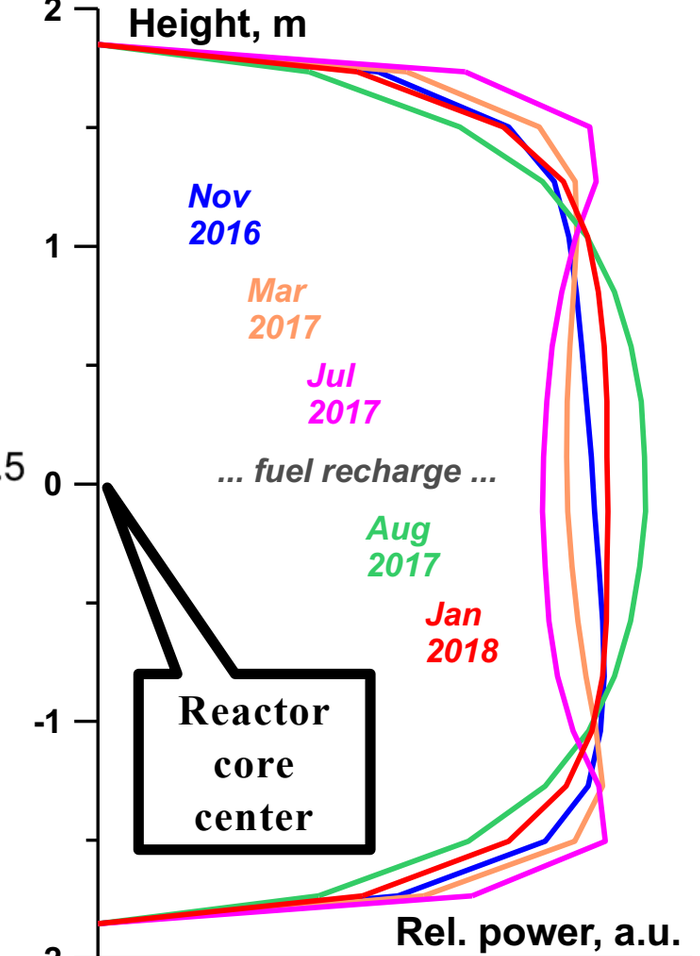
# DANSS (V.Egorov, Neutrino2018)




IBD intensity follows reasonably the $1 / L^2$ dependence.

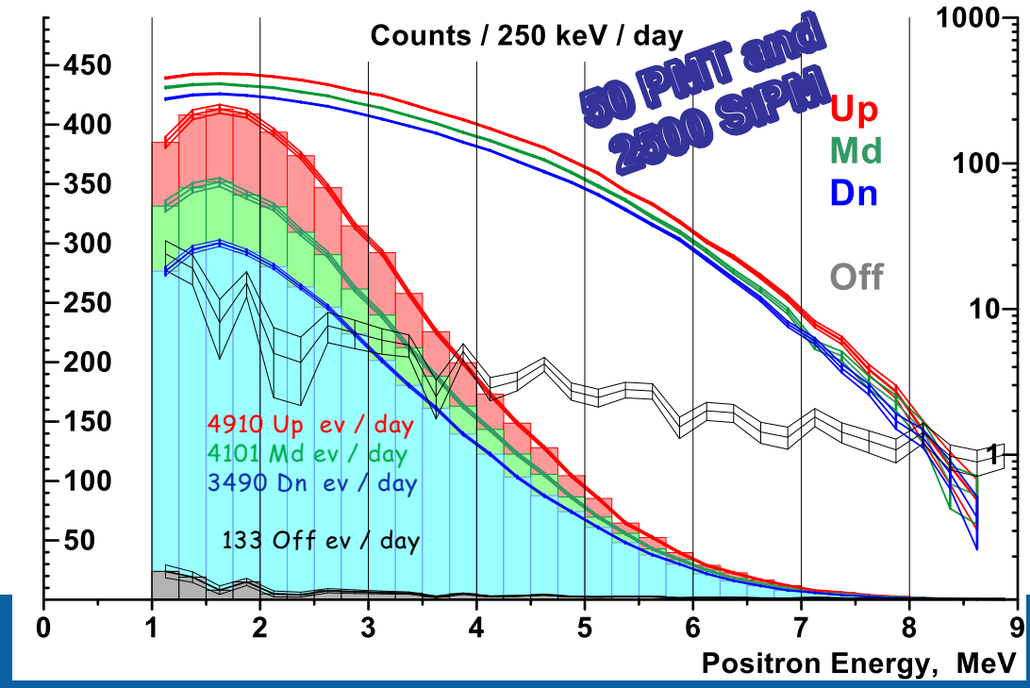
Effective distance L takes into account real spatial distribution of the detection efficiency and the reactor core burning profile (monitored permanently by the KNPP staff) .

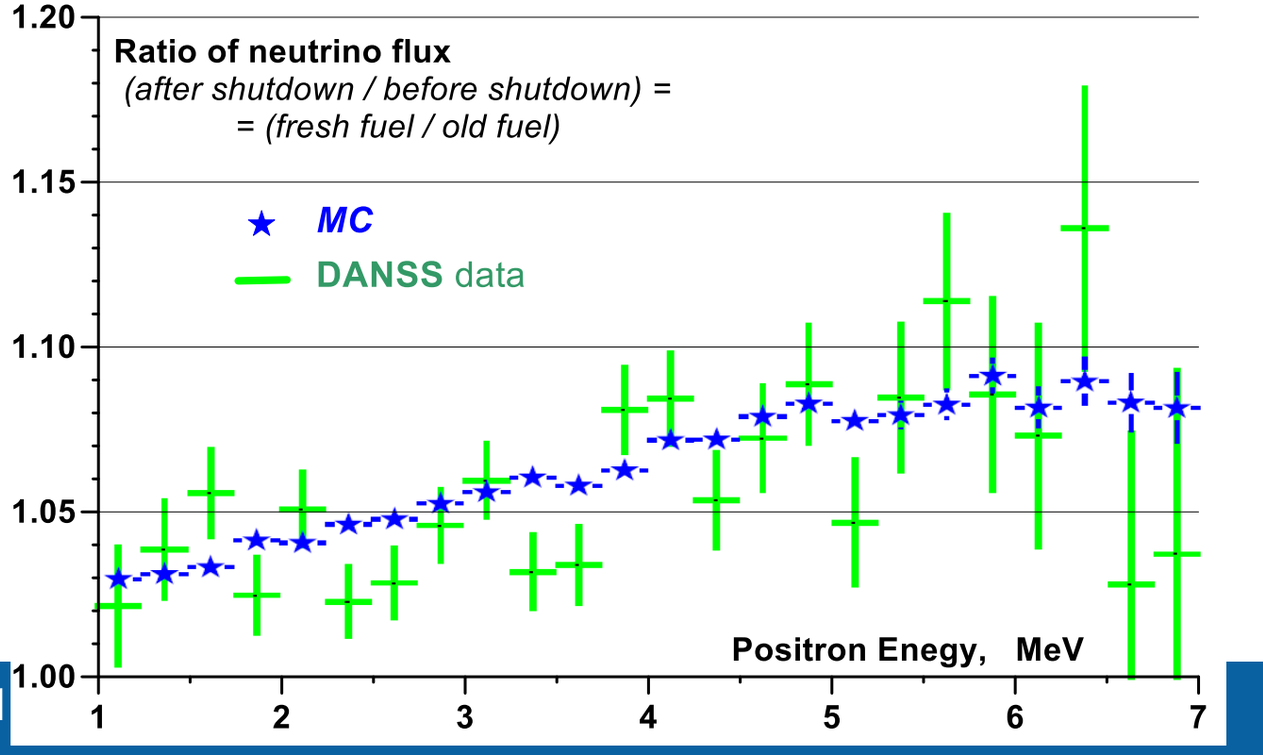
The time variation of reactor core burning profile is taken into account with a precision of 30 min and ~10 cm.



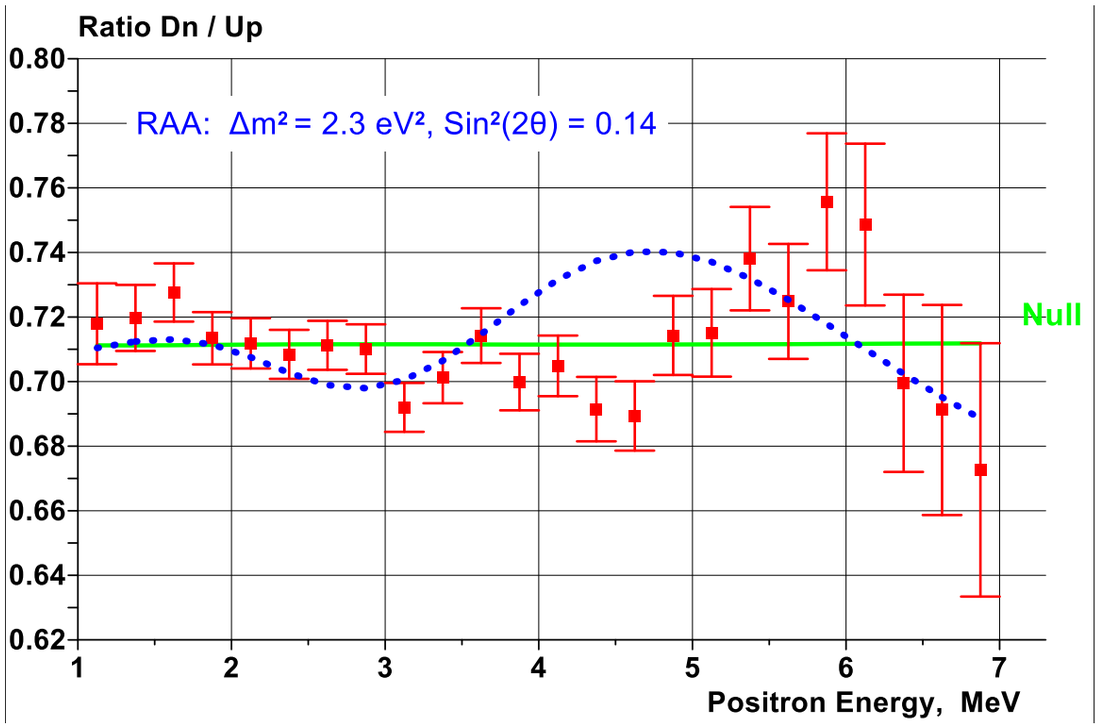

Time evolution of the core burning profile

An example of energy spectra (full segmentation)

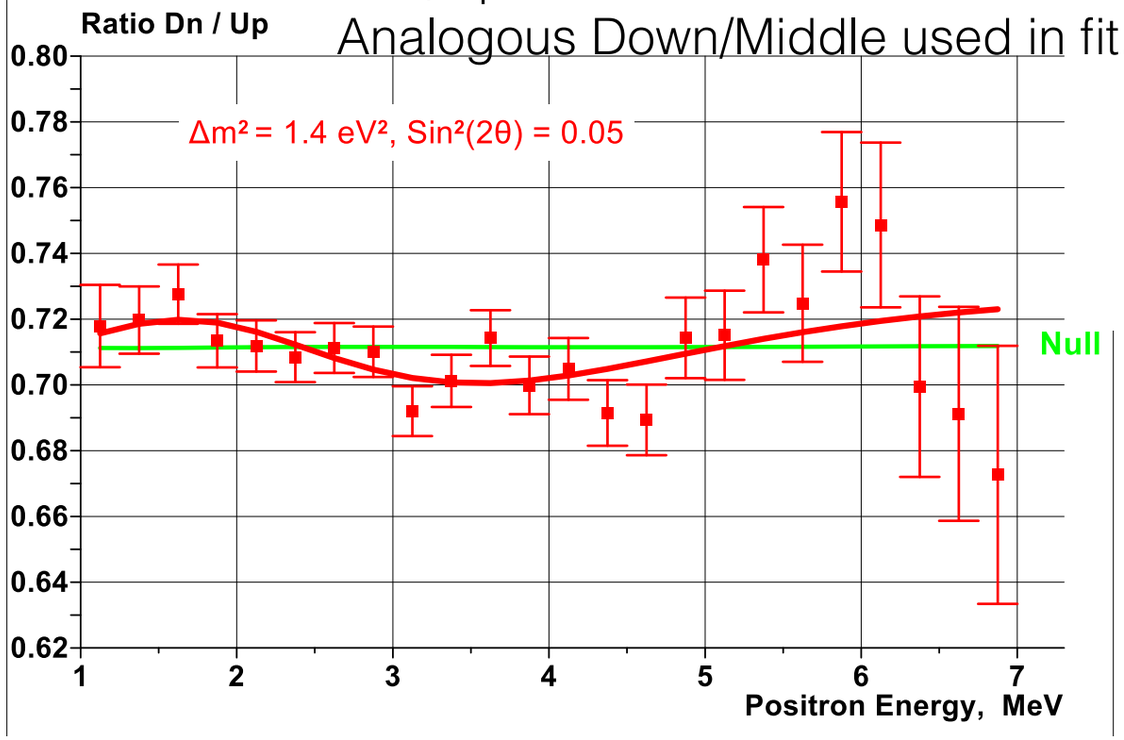


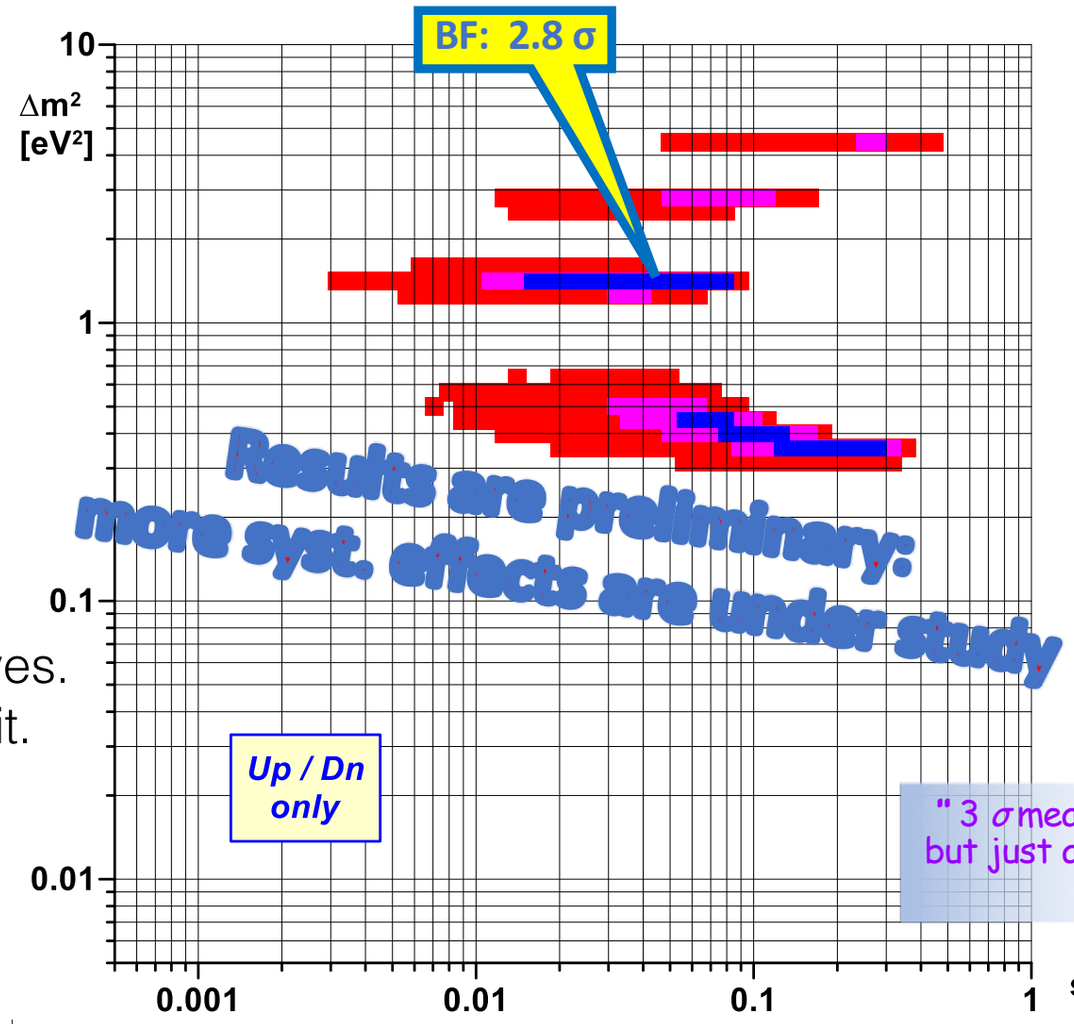
# DANSS (V.Egorov, Neutrino2018)




Down/Up with best fit and RAA curves.
Analogous Down/Middle used in fit.




## Significance of the best regions




The RAA min-chisquare point
($\Delta m^2$=2.3 eV$^2$, sin$^2$(2)=0.14)
is excluded at 5σ level.

# BR2 nuclear site

- Compact research reactor
  - ∅ 50 cm and height 90 cm
  - Fuel 93.5% $^{235}$U
  - Thermal power 50-80 MW
  - Duty cycle 150 days/year (~ 1 month cycles)
  - SoLid at baseline 6-9 m
- At ground level
  - Overburden 10 mwe
  - Muon rate: O(250 Hz)
  - Cosmogenic neutrons
  - Natural radioactivity

# SoLid Experiment

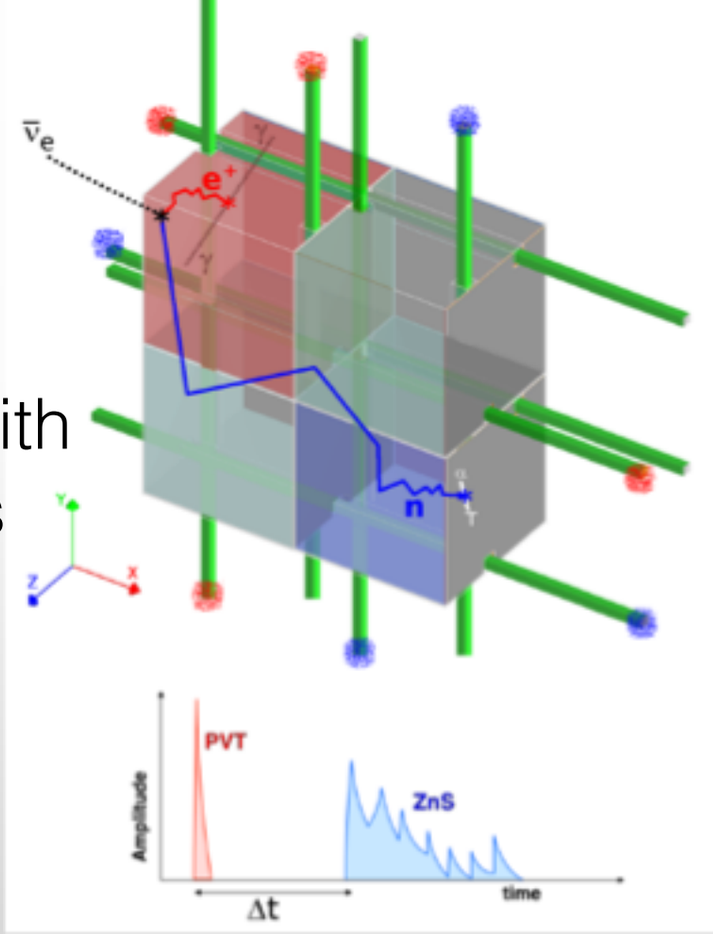
Nick van Remortel, Neutrino 2018

# SoLid detection principle

**JINST 12 (2017) no.04, P04024**
**JINST 13 (2018) no.05, P05005**

- Anti-electron-neutrinos detected through inverse beta decay (IBD) in the composite (PVT + $^{6}$LiF:ZnS) scintillator element
  $\nu_e + p \rightarrow n + e^+$ $(E_{\overline{\nu_e}} > 1.8$ MeV)
- Prompt positron signal
  - Positron energy contained in one/two PVT cubes
  - Allows precise localisation of IBD interaction
  - Provides seed for anti-neutrino energy
- Delayed neutron signal
  - Neutron captured in $^{6}$LiF:ZnS close by
    $n + {}^{6}Li \rightarrow {}^{3}H + \alpha$ + 4.78 MeV
  - Capture time O(60 μs)
- Both signals
  - Collected by WLS fibers in X and Y directions and transported to MPPC for readout
  - Discrimination (ES – NS) based on pulse shape

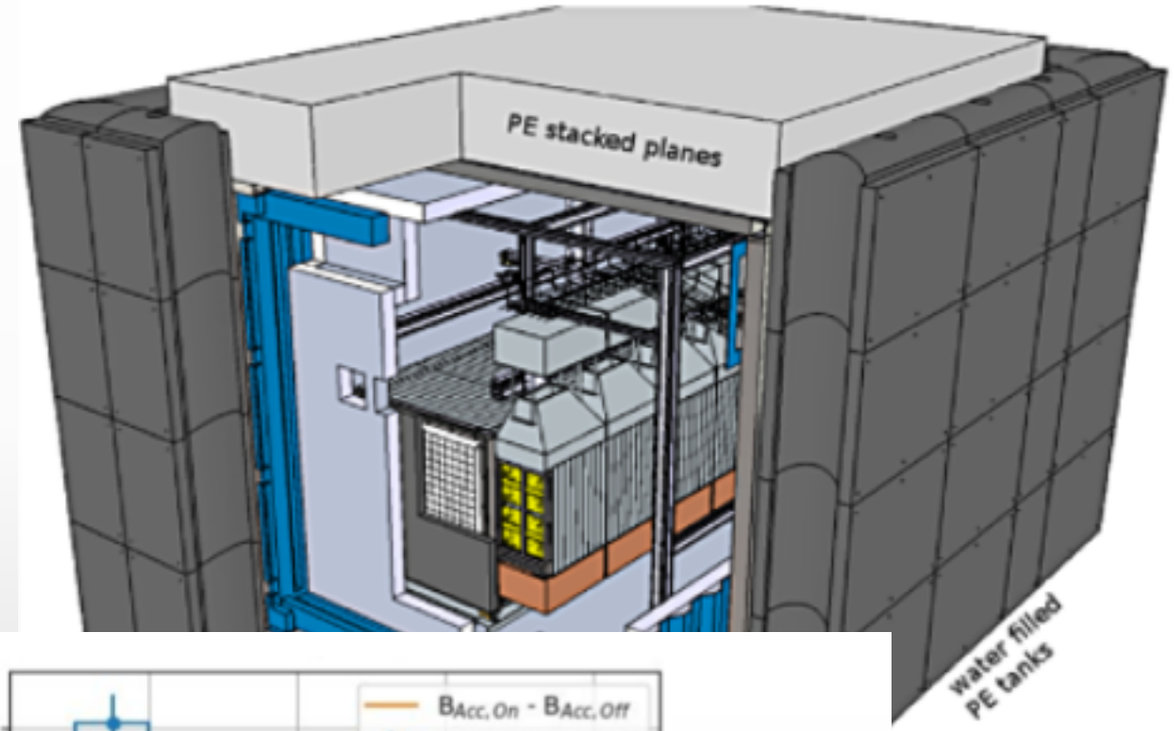
(5cm)$^3$ PVT cube with 2 $^{6}$LiF:ZnS sheets



- Container 2.4x2.6x3.8 $m^3$
  - Cooled to 10°C to reduce MPPC dark count rate (1/3)
- Shielding
  - Water enclosure 50cm thick, 3.4 m high, 28ton
  - Polyethylene ceiling 50cm thick, 6ton
  - Cadmium lining
- Automated calibration system for absolute efficiency and energy scale calibration at % level ($^{207}$Bi, $^{60}$Co, $^{137}$Cs, $^{22}$Na, AmBe, $^{252}$Cf)

→ Full G4 simulation

1.6 ton sensitive mass

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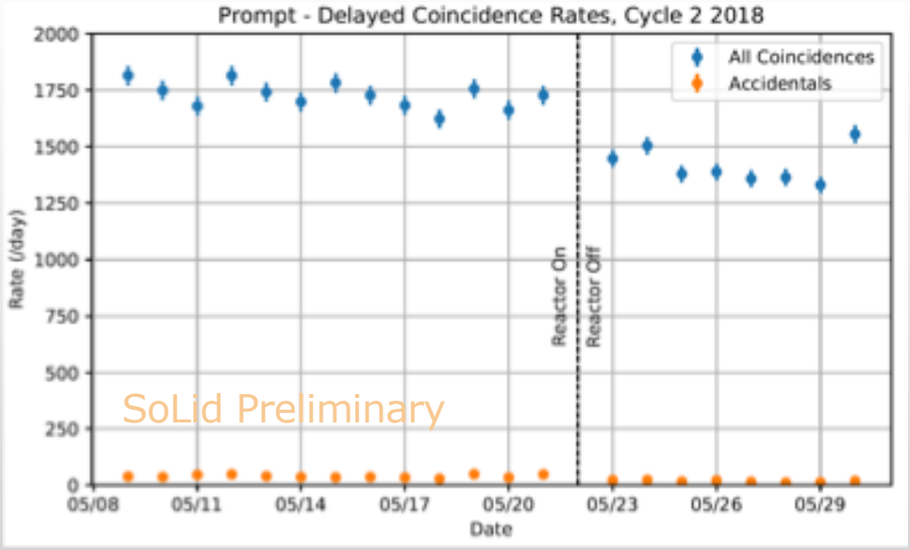
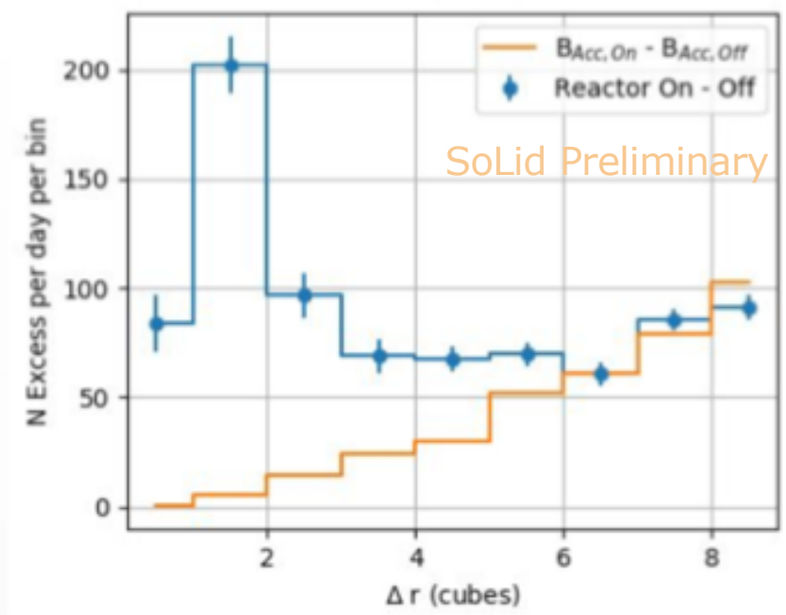
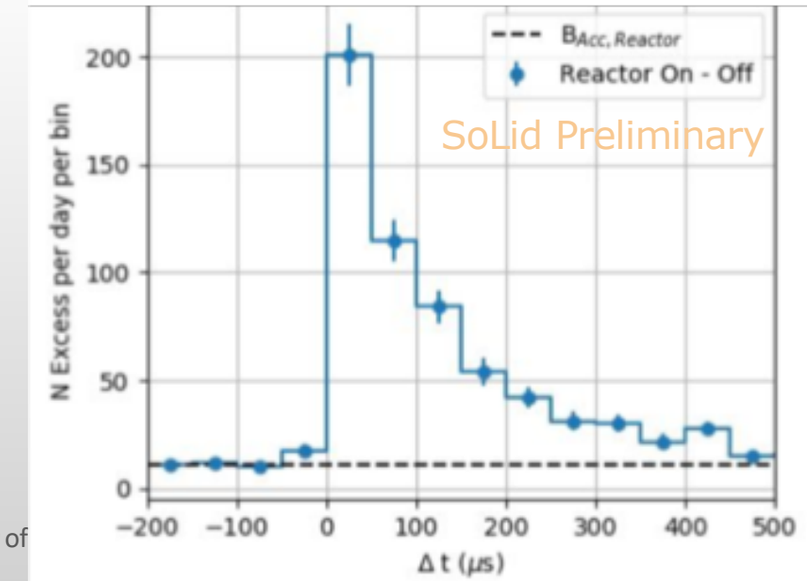
# IBD-like Events

- Preliminary rate monitoring based on:
  - Timing, Topology, Muon veto, Energy selection
- Significantly higher IBD-like rate during reactor ON
- How does it behave?
  - Spatially confined ✓
  - Time difference: consistent with thermalised n-capture ✓

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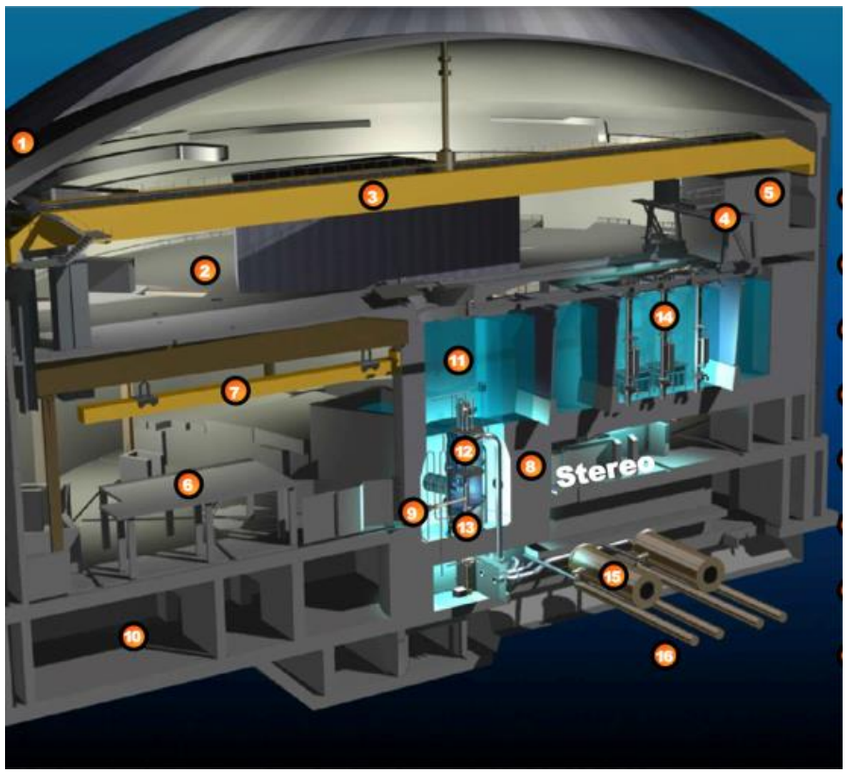
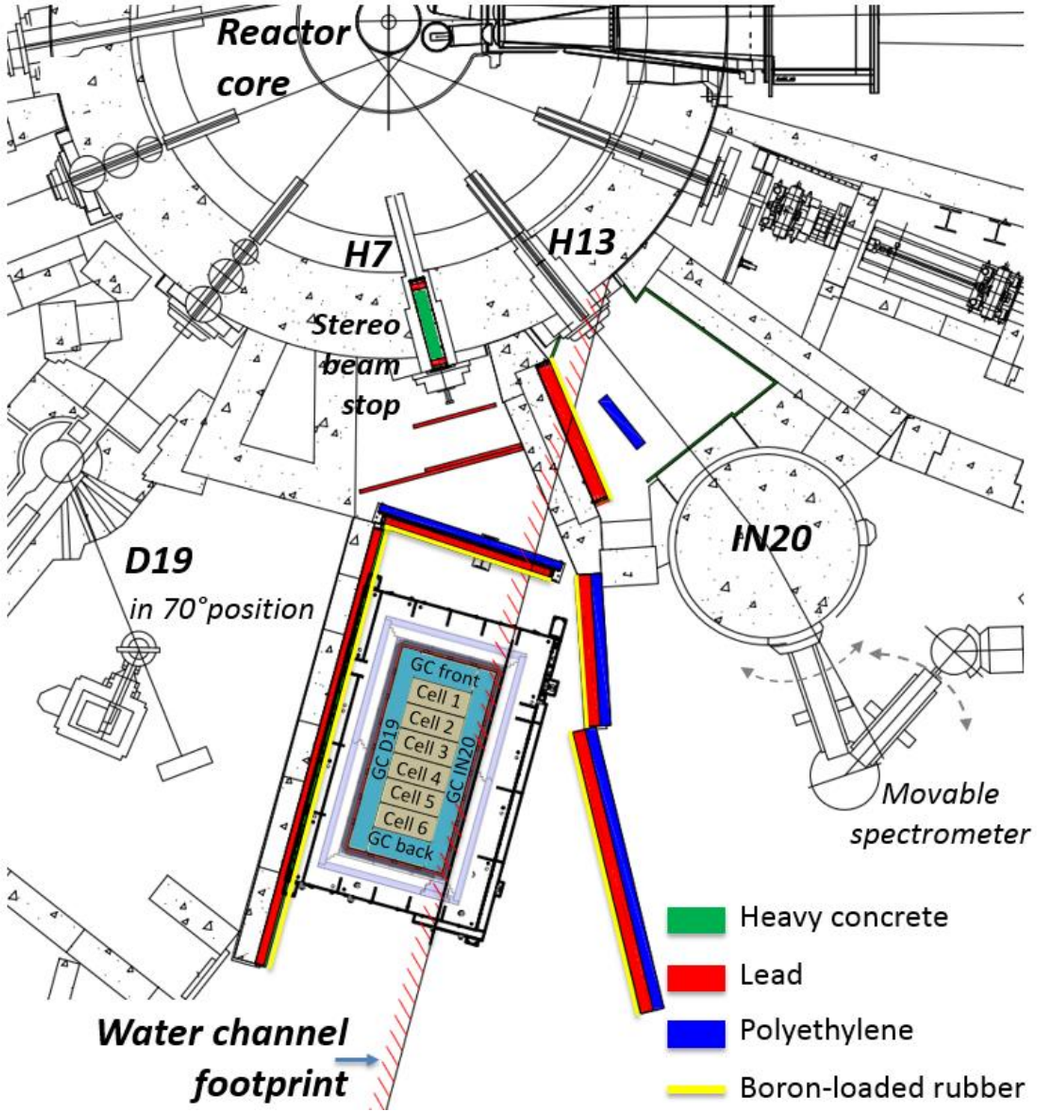
# ILL site STEREO Experiment

- 58 MW research reactor
- $10^{19}$ $s^{-1}$ $\bar{\nu}_e$ flux
- Highly enriched fuel: $^{235}U$ (93%)
- 3-4 cycles of 50 days per year
- compact core Ø40 cm x 80 cm
- [9–11] m from core




But :

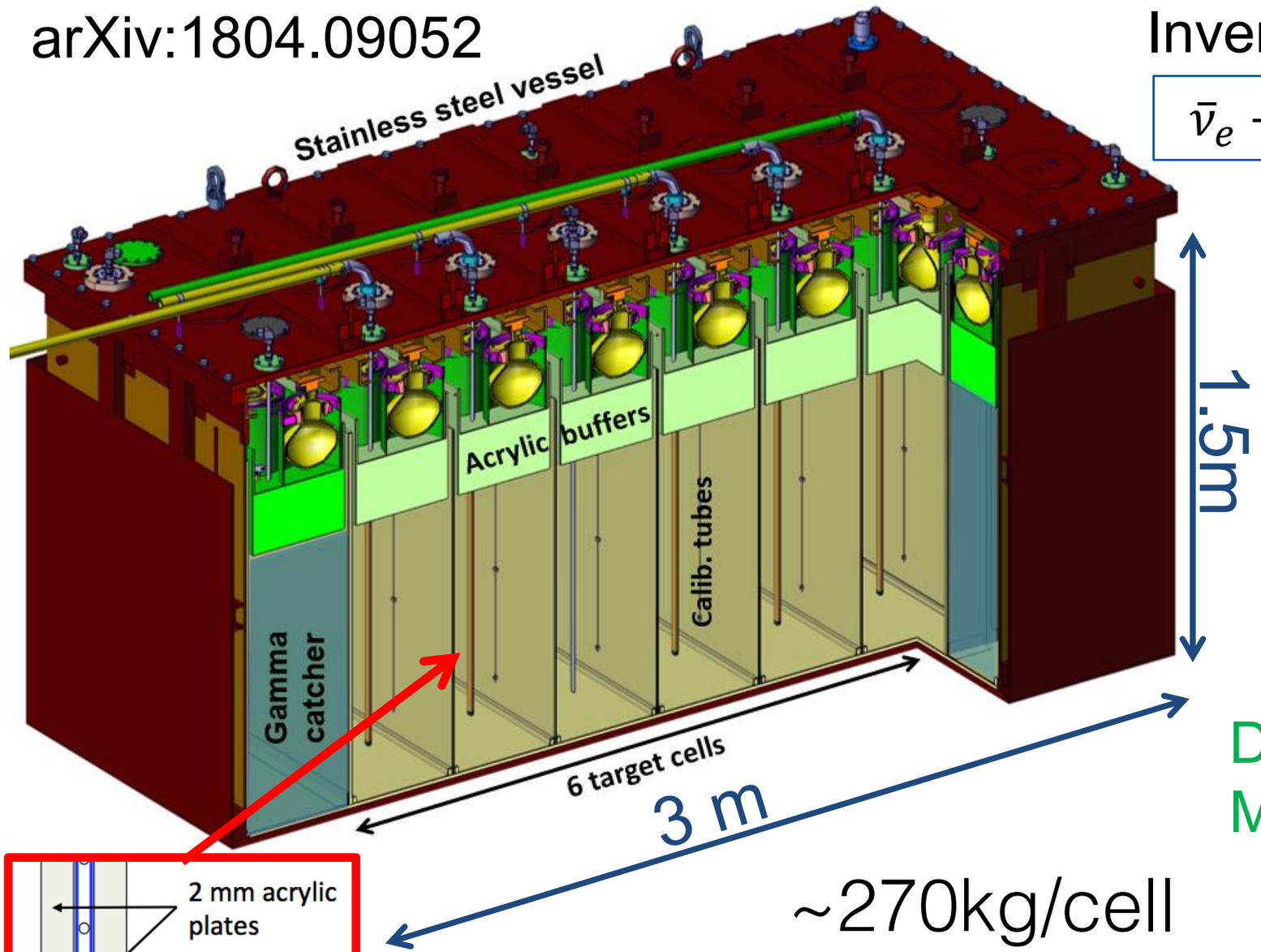
- Shallow depth (cosmics)
- $\gamma$ and neutron background due to experimental lines

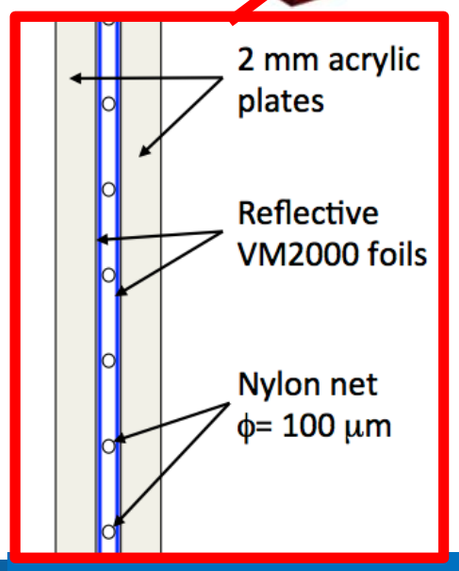


# The STEREO detector



arXiv:1804.09052

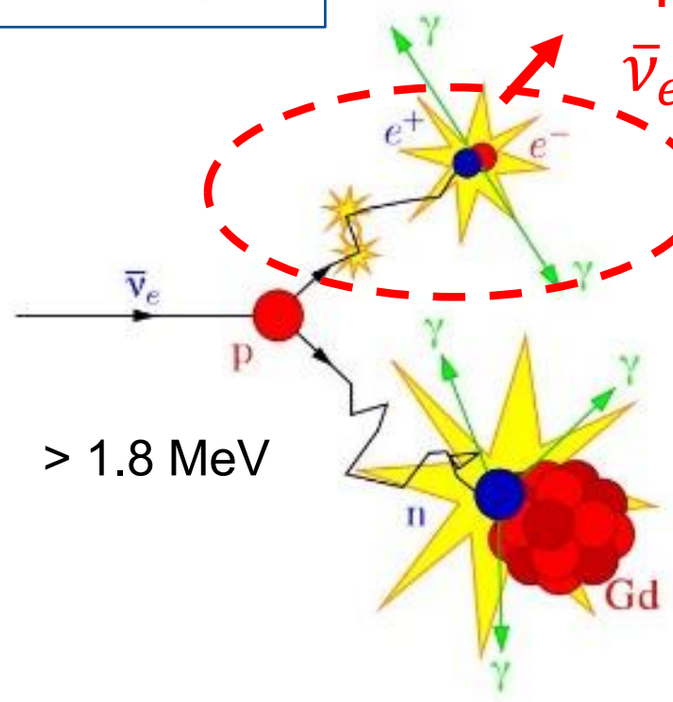



~270kg/cell

## Invert Beta Decay

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




Delayed signal
Mean neutron capture time 16 μs

### Target

6 cells filled with
Gd-loaded liquid scintillator
4 top PMTs per cell

### Gamma-catcher

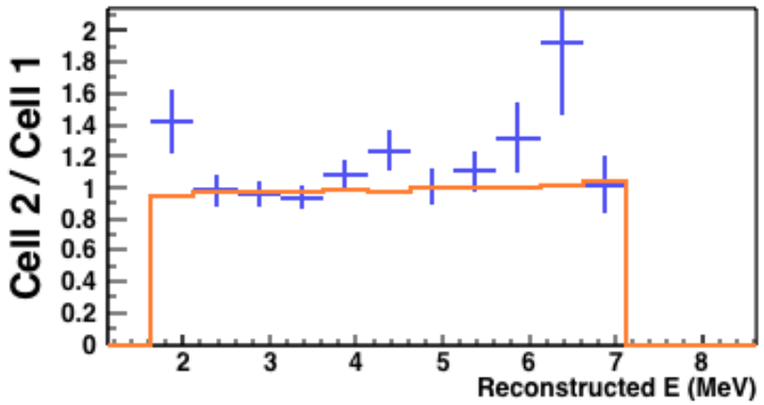
Outer-crown to detect γ's escaping from the Target + active shielding

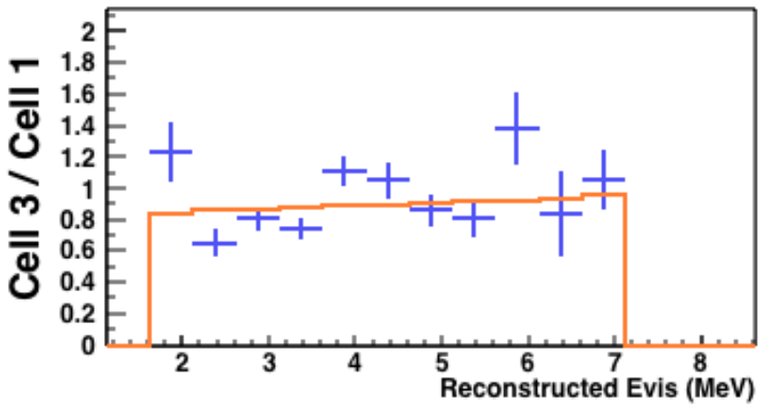
24 PMTs

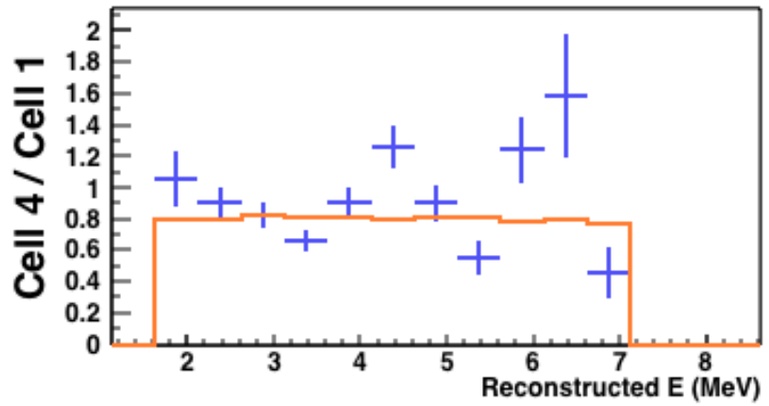
# Phase-I results

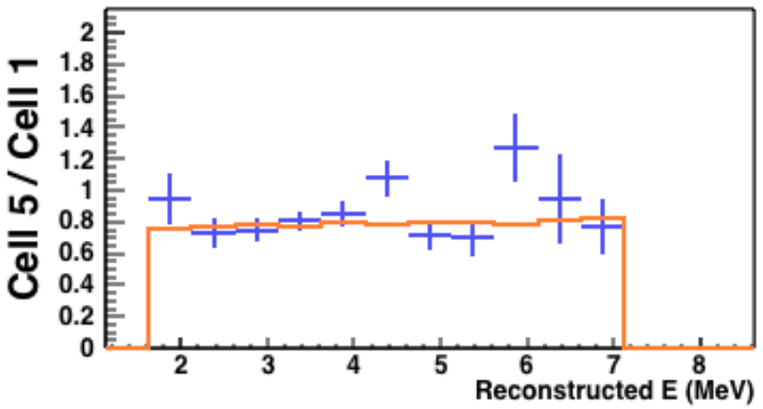
66 days ON data

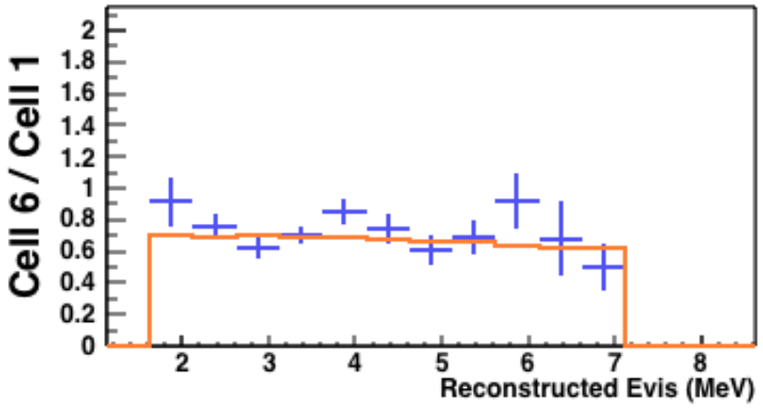
Spectral shape ratios of cell N to cell 1



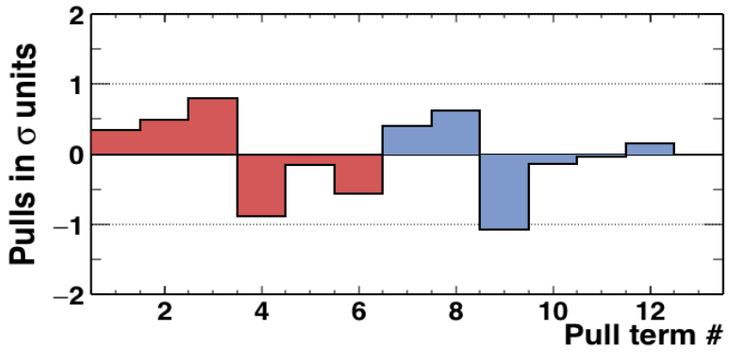



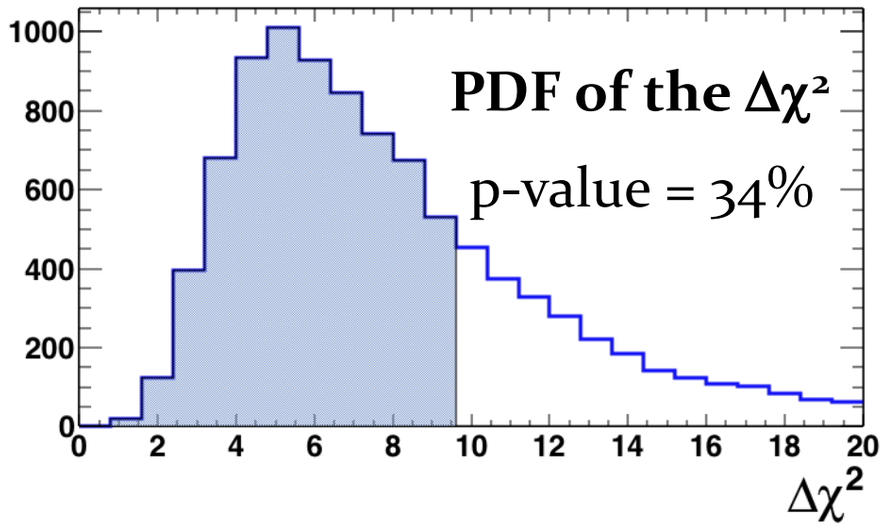




**+ Measured ratios**

**- Non oscillated predictions**

**Minimized pull terms stay within ~±1σ**



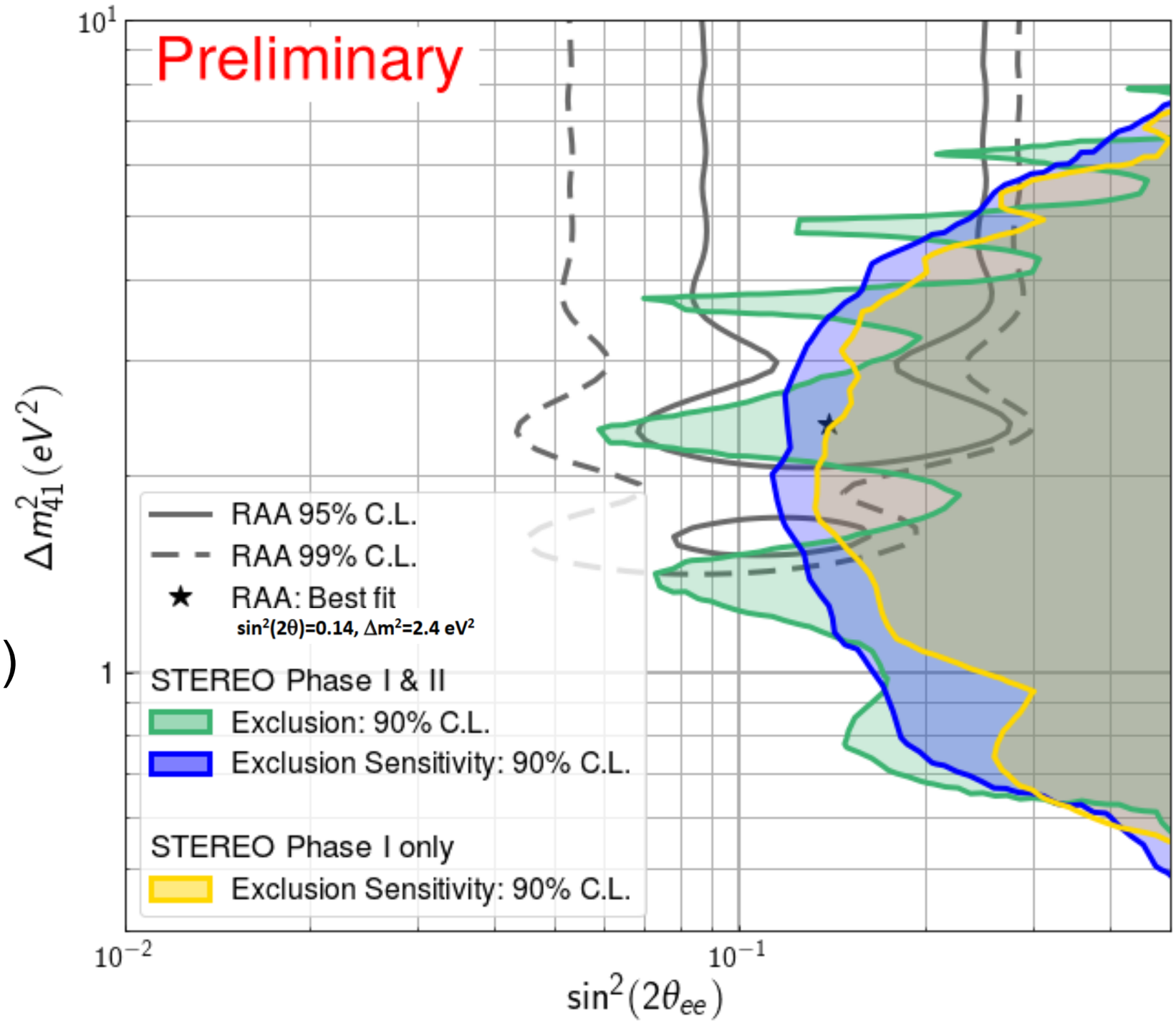




**→ The nul oscillation hypothesis not rejected**

# New preliminary result



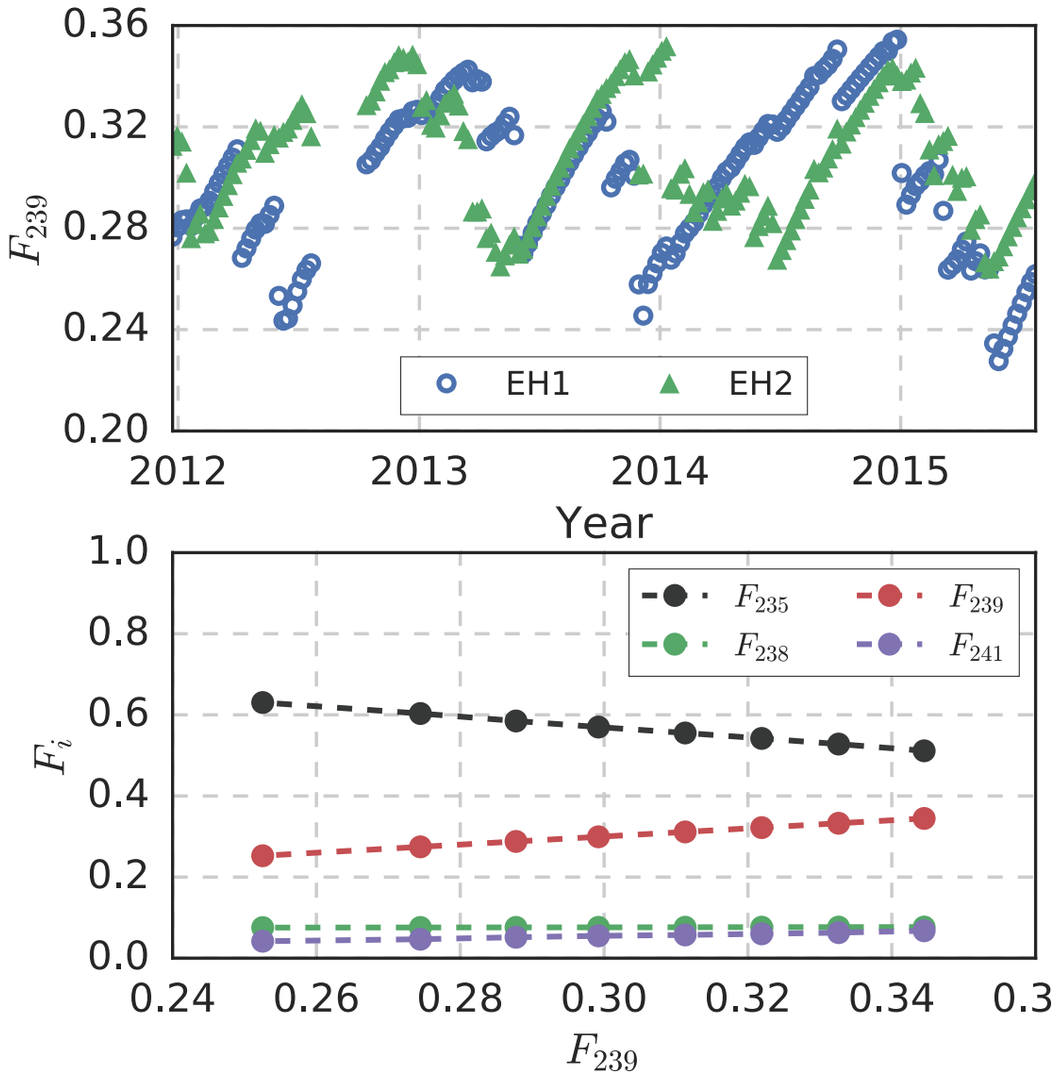
- Phase-I + phase-II (66 + 47 days)
- Two measurements treated as fully independent (detector maintenance between the two phases.)

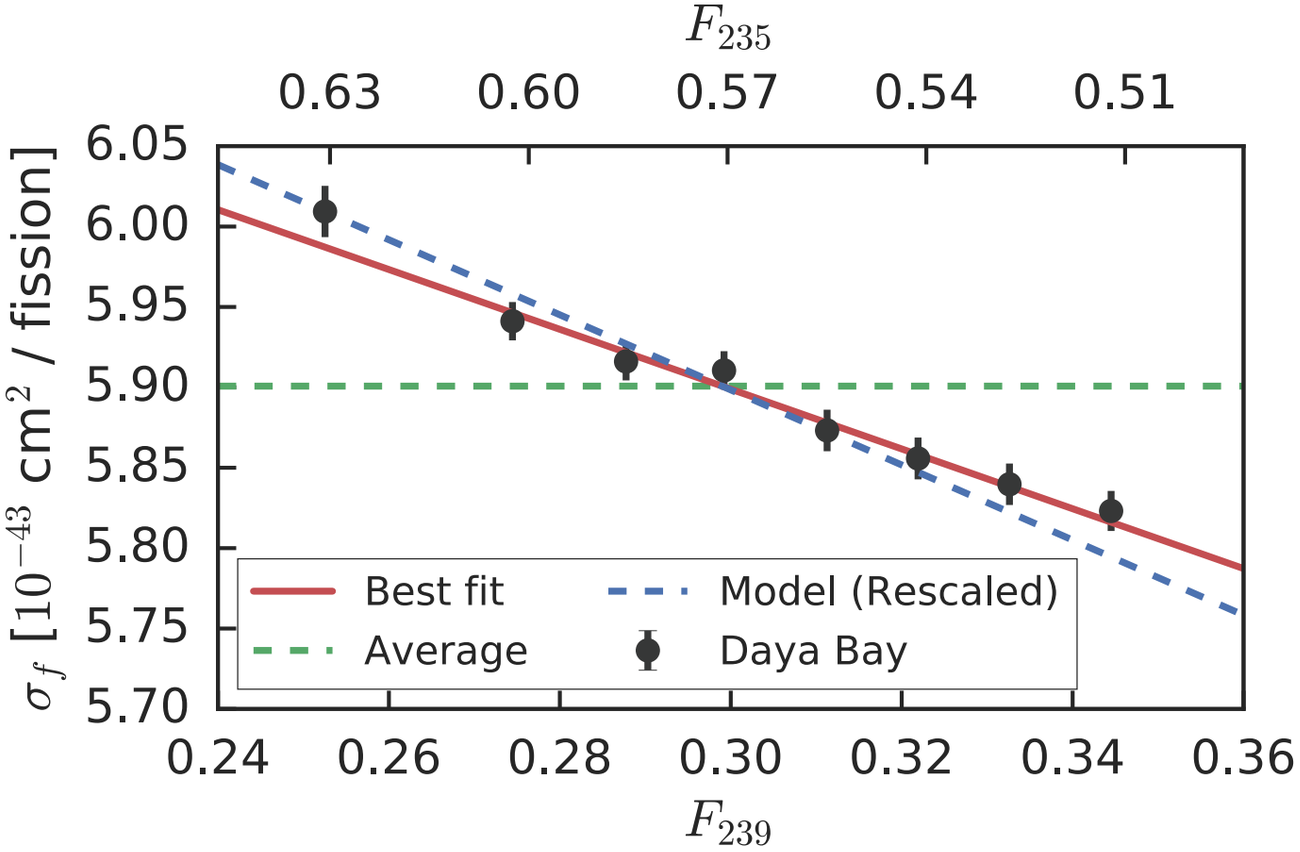



**→ Best fit value of the RAA rejected at 98% C.L.**

# Evolution of the Reactor Antineutrino Flux and Spectrum at Daya Bay

PRL**118** (2017) 251801




| RAA cause | $\Delta\chi^2$/ndf | p-value |
|---|---|---|
| $^{235}$U | 0.17/1 | 0.68 |
| $^{239}$Pu | 10.0/1 | 0.00016 |
| All isotopes | 7.9/1 | 0.0049 |

Observed correlation between antineutrino flux and reactor fuel composition with 2.2M IBD in Daya Bay near detectors favors $^{235}$U as cause of Reactor Antineutrino Anomaly(RAA)

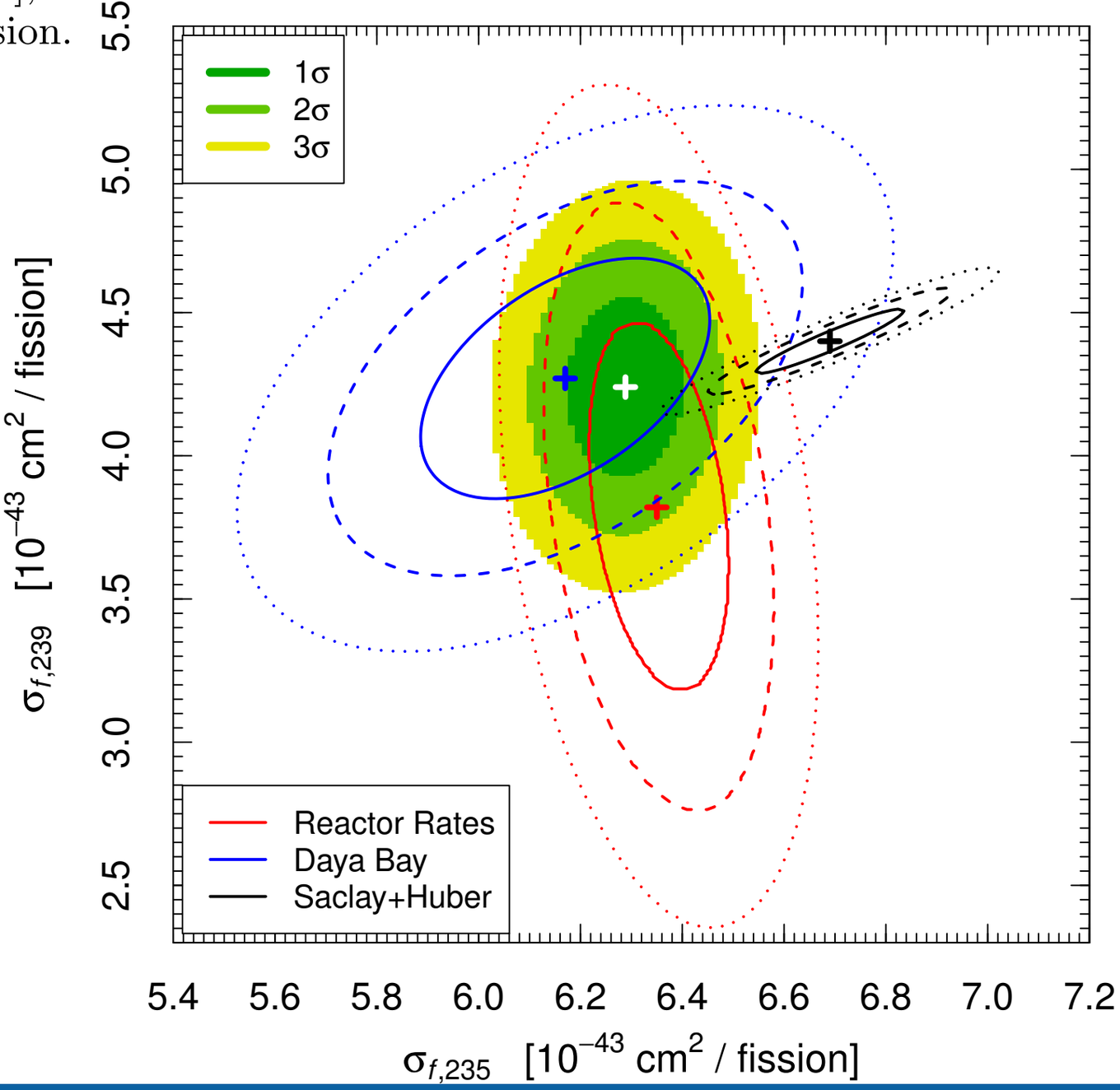
| | SH | Reactor Rates | Daya Bay | Combined | |
|---|---|---|---|---|---|
| $\sigma_{f,235}$ | $6.69 \pm 0.14$ | $6.35 \pm 0.09$ | $6.17 \pm 0.17$ | $6.29 \pm 0.08$ | $2.5\sigma$ |
| $\sigma_{f,239}$ | $4.40 \pm 0.11$ | $3.82 \pm 0.43$ | $4.27 \pm 0.26$ | $4.24 \pm 0.21$ | $0.7\sigma$ |

TABLE I. Comparison of the theoretical Saclay+Huber (SH) values of the cross sections per fission $\sigma_{f,235}$ and $\sigma_{f,239}$ with those obtained from the fit of the reactor rates, from the Daya Bay data [5], and from the combined fit. The units are $10^{-43}\,\mathrm{cm}^2$/fission.

## Improved Determination of the $^{235}$U and $^{239}$Pu Reactor Antineutrino Cross Sections per Fission

arXiv:1704.02276, C.Giunti

Combined results of measured flux at LEU & HEU reactors with Daya Bay results



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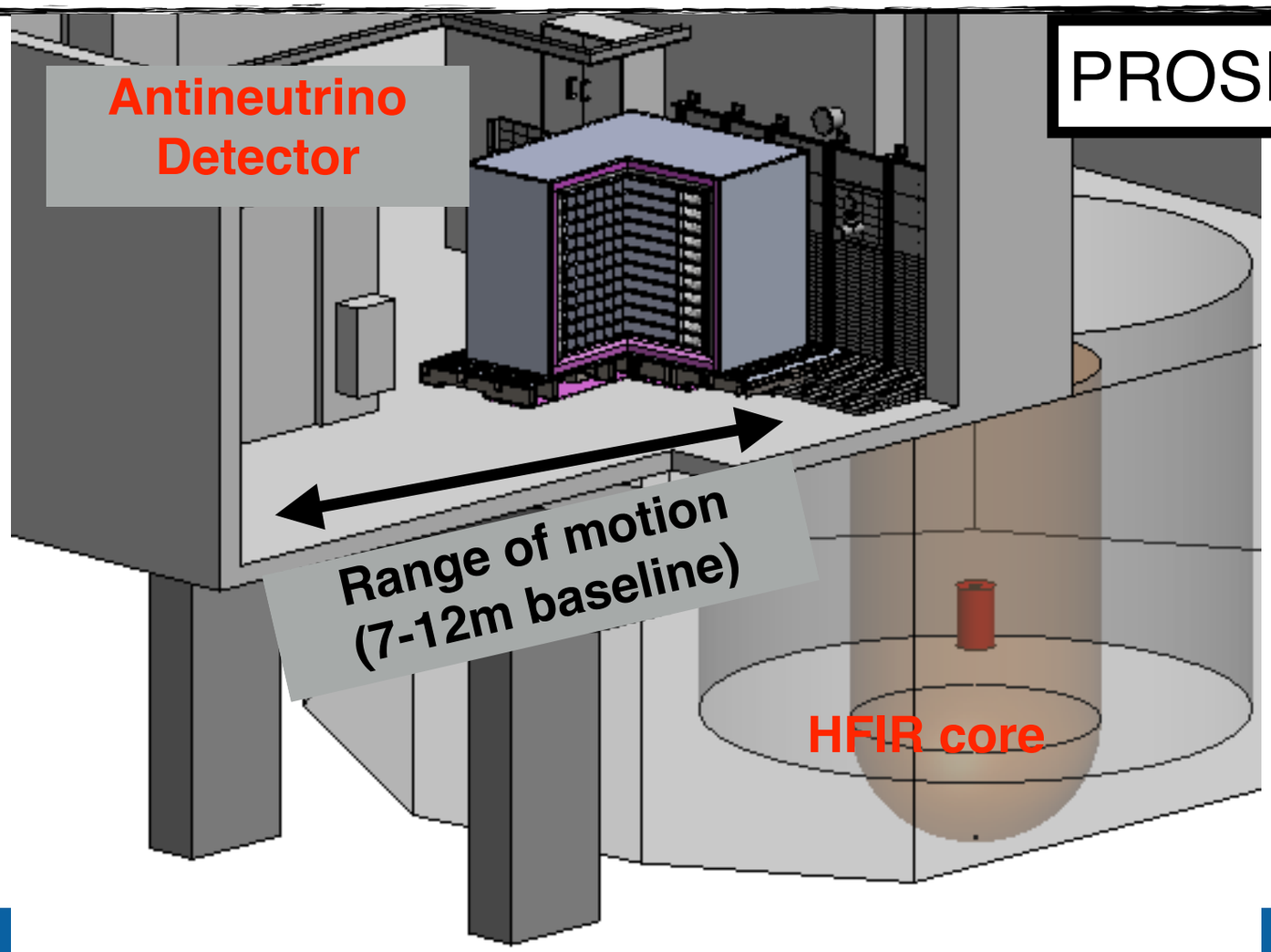
# The Precision Reactor Oscillation and Spectrum Experiment

# Phased Experimental Plan

## Physics Goals:

- Reactor-model-independent search for neutrino oscillations into eV-scale sterile states.
  - Distortions in energy spectrum that vary with baseline
- Precision measurement of the $^{235}$U antineutrino spectrum with the best energy resolution to date.




PROSPECT at HFIR

## Experimental Strategy:

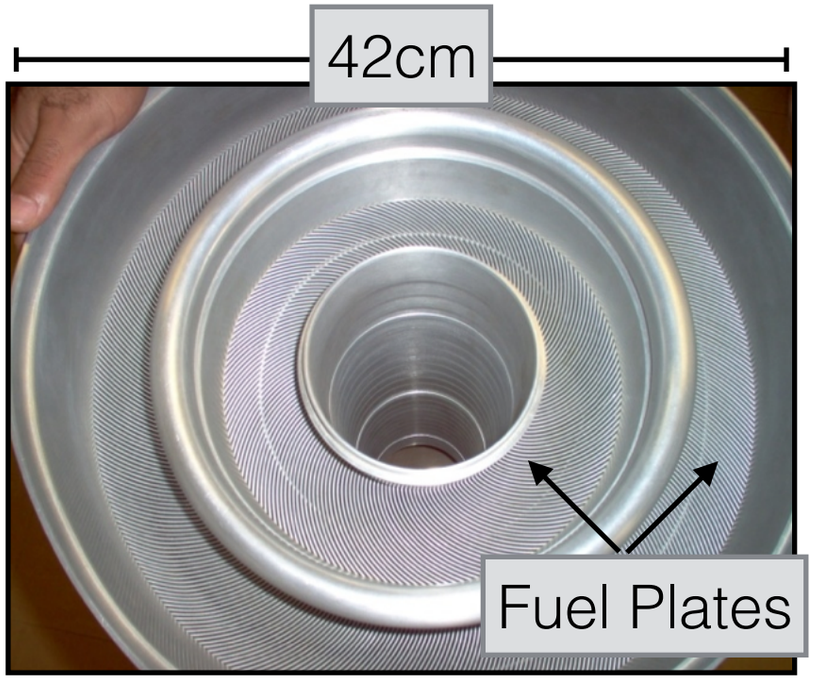
- Sterile neutrino search, cover best fit region at $4\sigma$ in 1 year
- World-leading $^{235}$U spectrum with 100k events/year

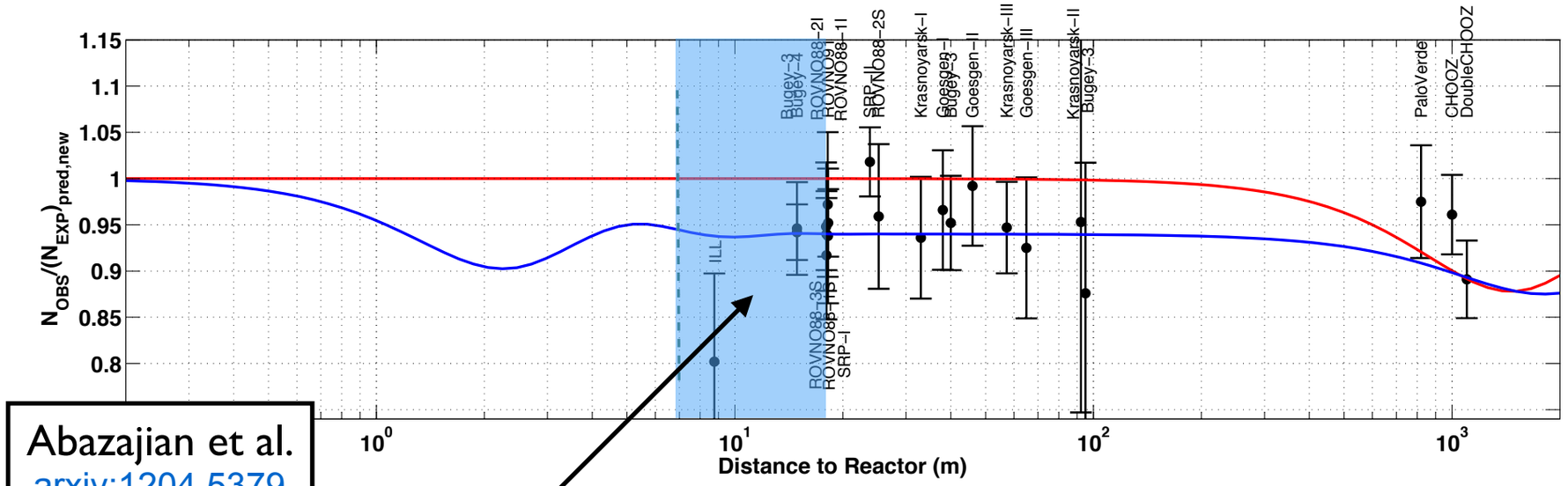
## Challenges:

- Minimal overburden, cosmogenic backgrounds
- Reactor-related backgrounds

# High Flux Isotope Reactor

- High Flux Isotope Reactor (HFIR) at Oak Ridge National Lab
- 85MW HEU (>99% of $\overline{\nu}_e$ flux from $^{235}$U fission) compact-core reactor, 42% uptime
- PROSPECT activity for past 3 yrs
- Backgrounds well characterized
- Unique location for a short baseline experiment

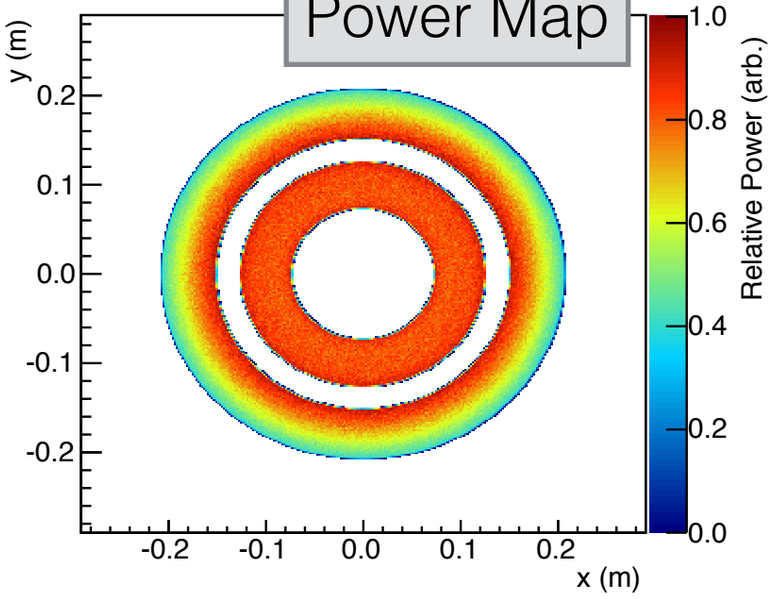



Abazajian et al.
arxiv:1204.5379

HFIR Baselines

HFIR Core Power Map

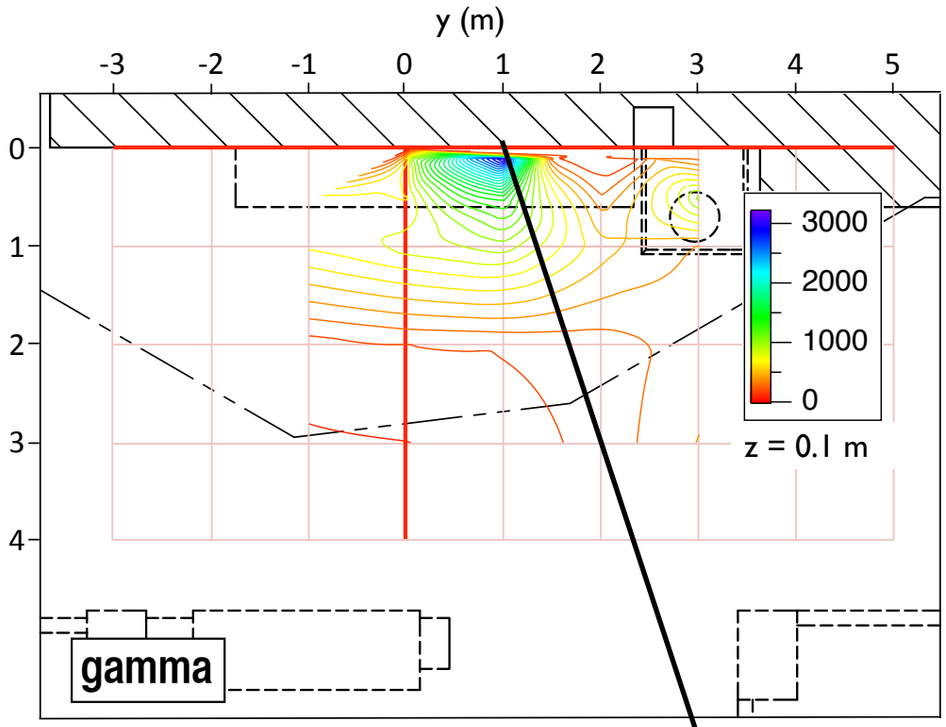


# Surface Neutrino Detection

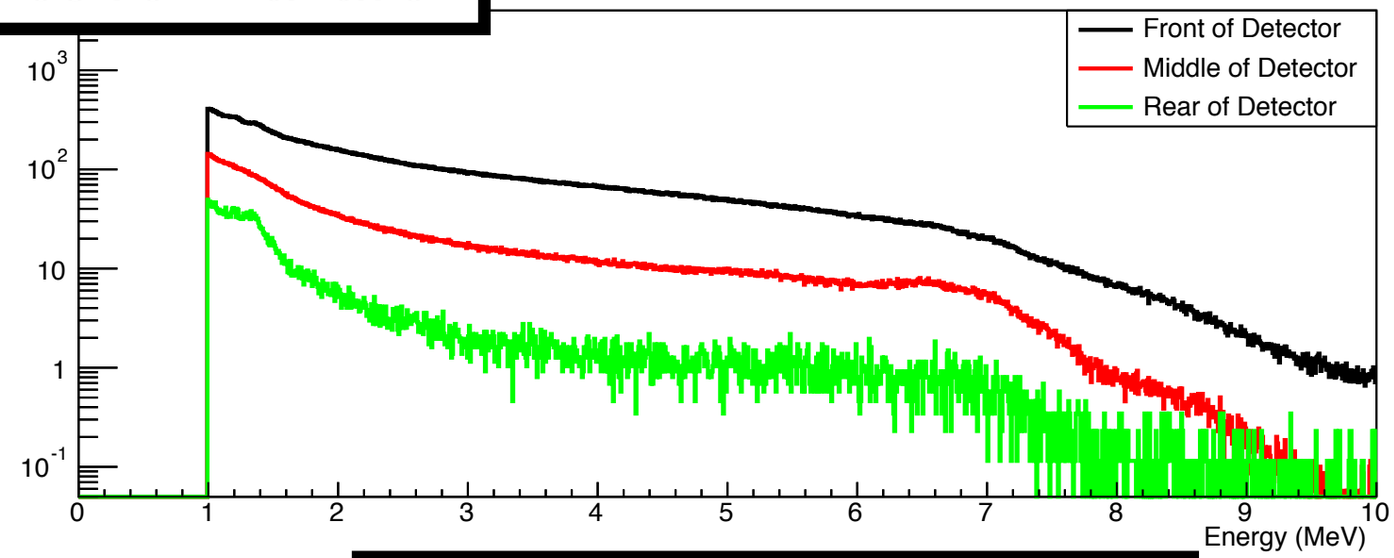
**Must be very close to research reactor**

- Reactor-related backgrounds (gammas and thermal n)
- Detector will have to operate at the surface (or close to it) so cosmic-ray backgrounds are problematic

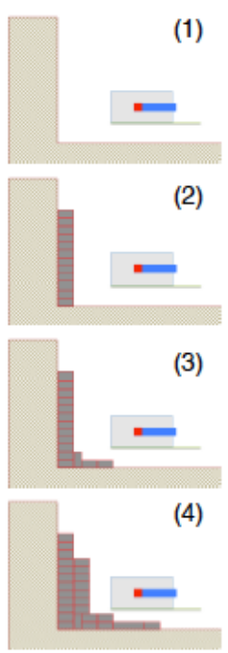
# Reactor Backgrounds

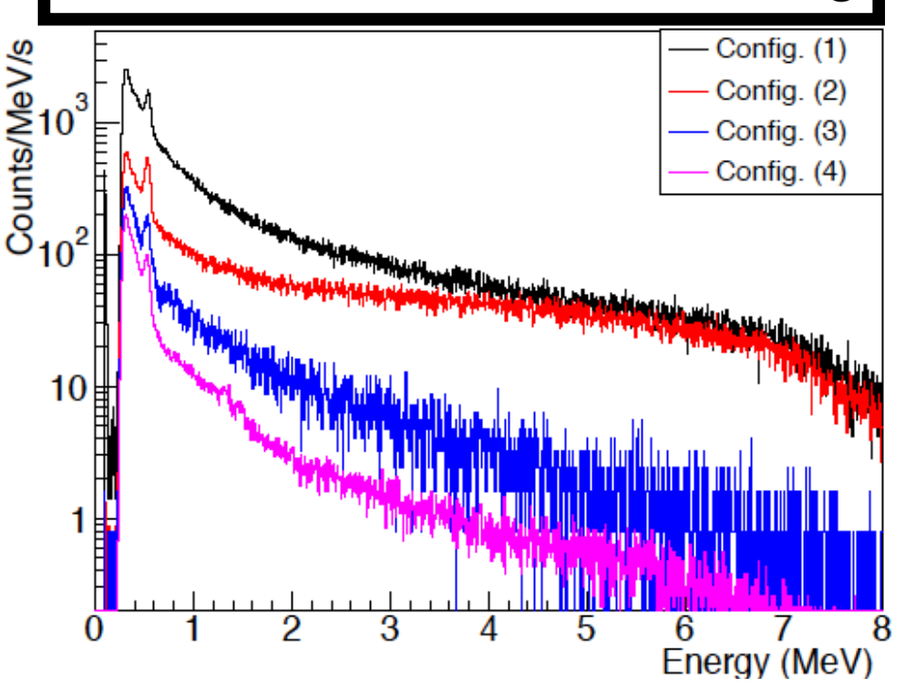



## Position Variation



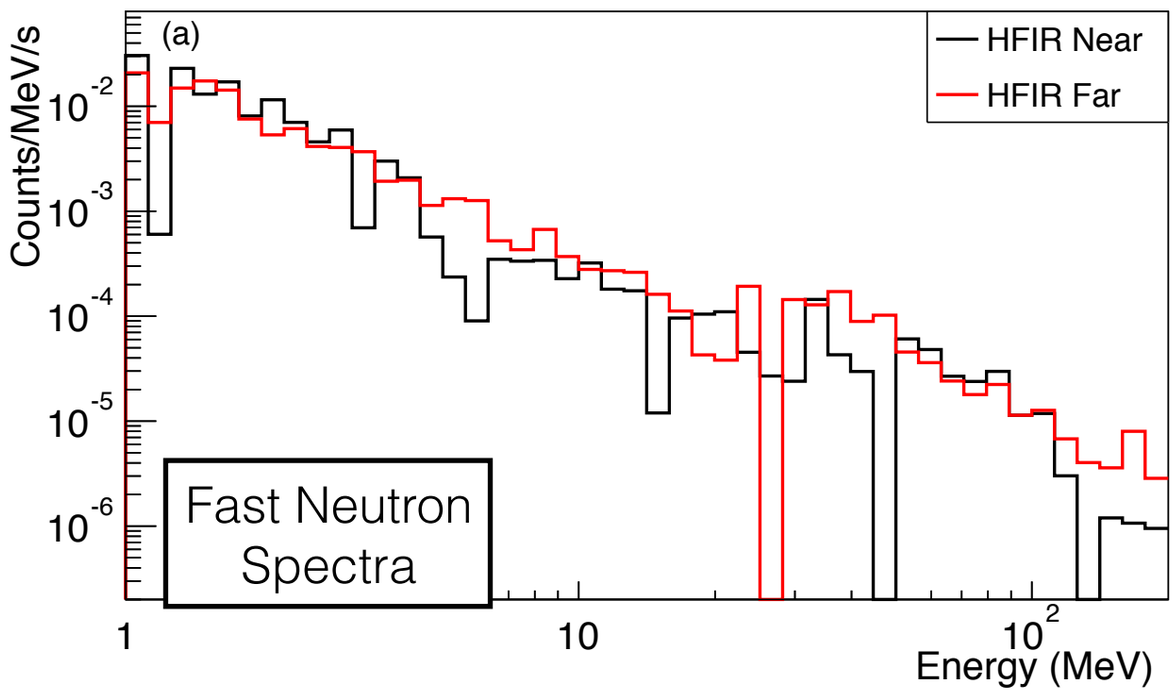

## Rate Variation with Shielding

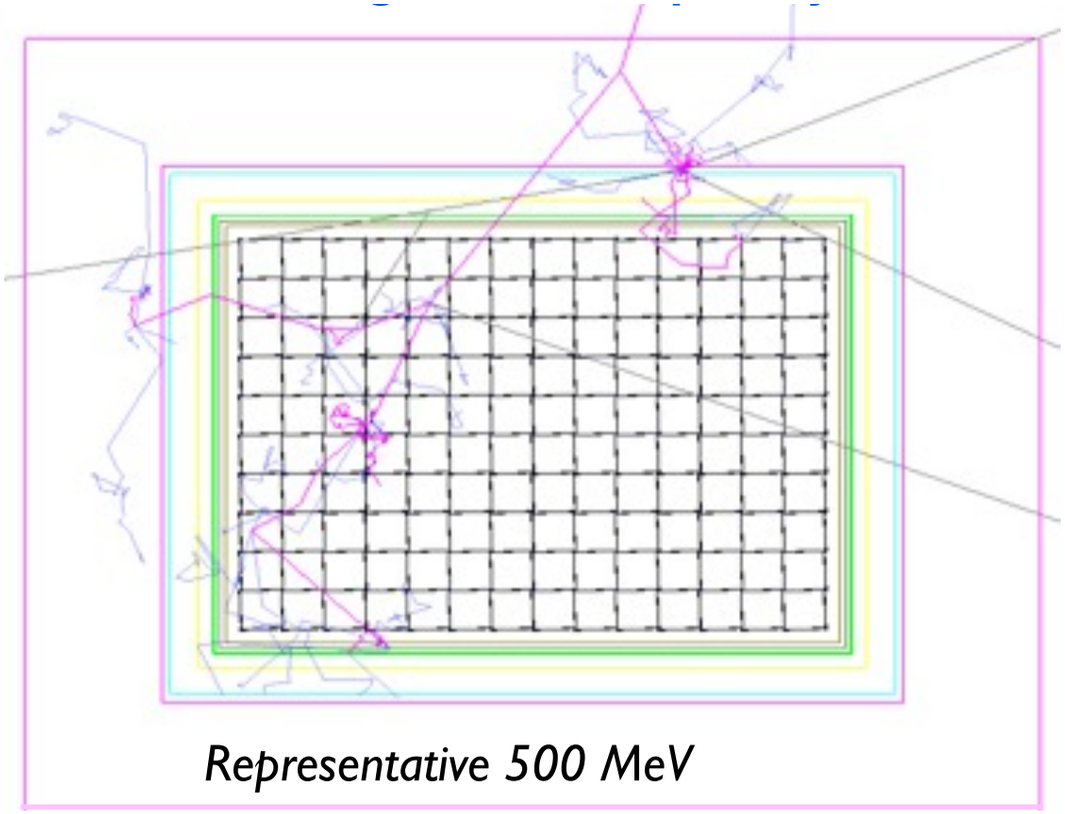



Targeted shielding effectively reduced gamma backgrounds

# Cosmogenic Backgrounds



*Representative 500 MeV*

FaNS-1 at HFIR

- <10MeV neutrons are effectively shielded
- >100MeV neutrons create showers of particles and many secondary neutrons
- IBD-like backgrounds stem mainly from fast neutron interactions

***Suppress fast neutron background with shielding, detector segmentation and particle identification***

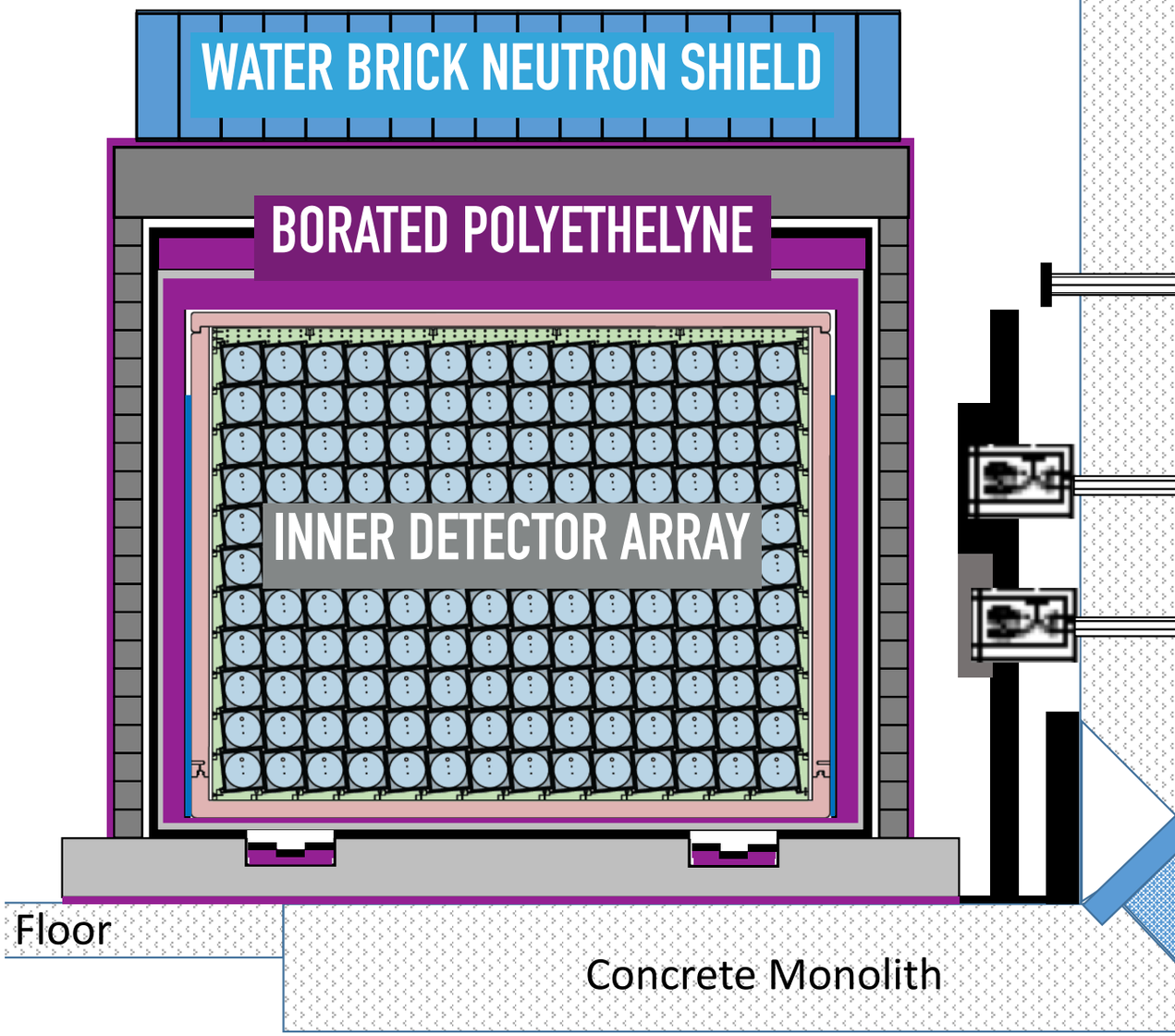
# Surface Neutrino Detection

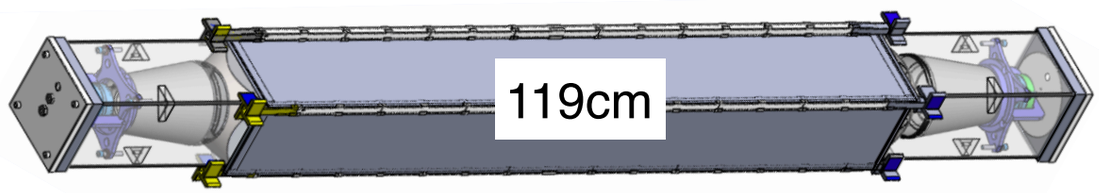
**Three-pronged effort to address these backgrounds:**

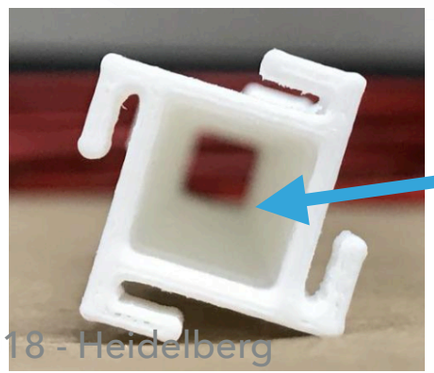
1. New detector design
2. New liquid scintillator
3. New shielding design

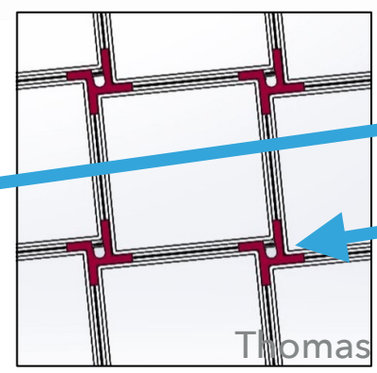
# PROSPECT DETECTOR DESIGN

- 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**



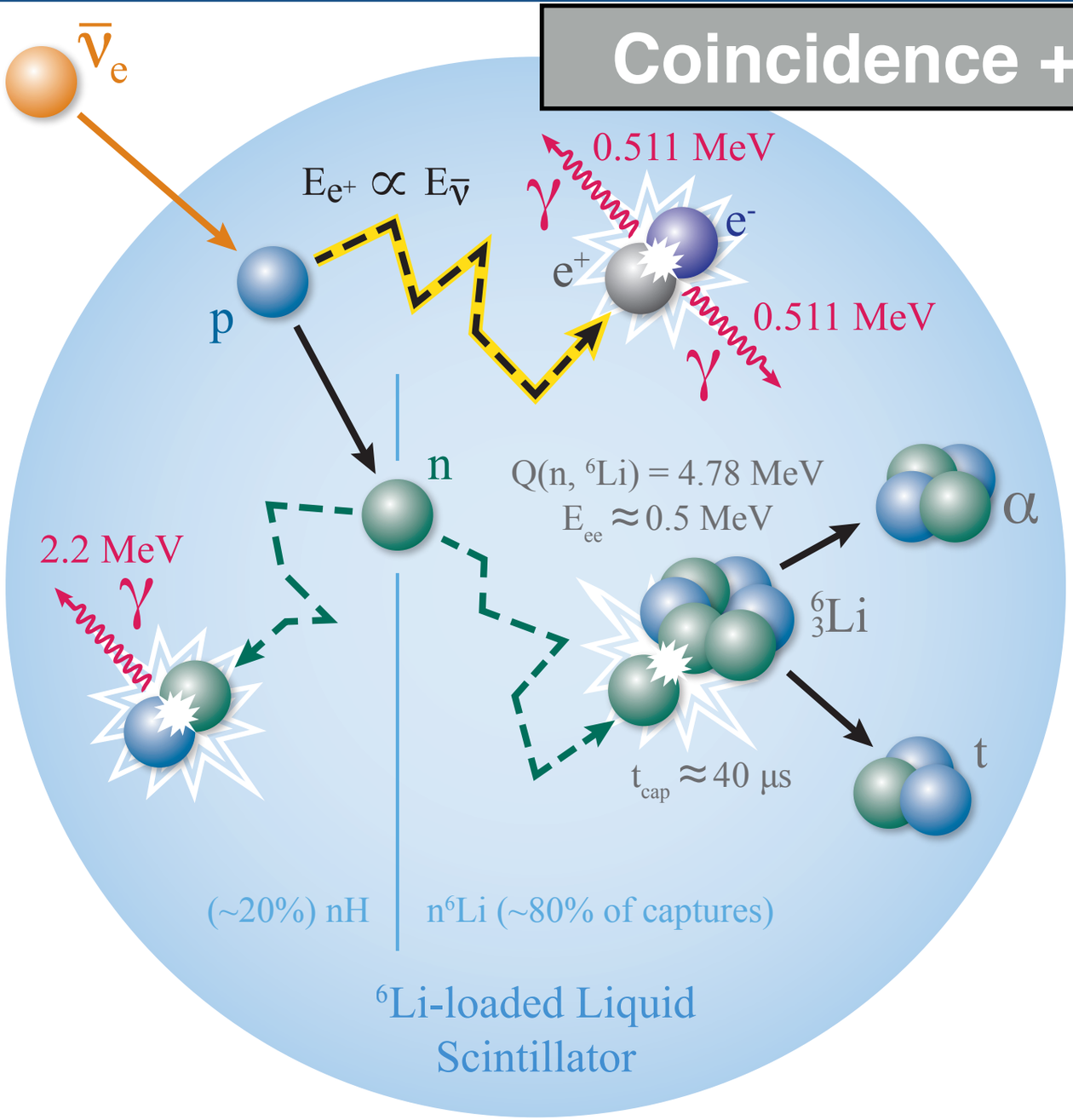





TILTED ARRAY FOR CALIBRATION ACCESS

# IBD Detection with $^6$LiLS

## Coincidence + PSD to reject of backgrounds

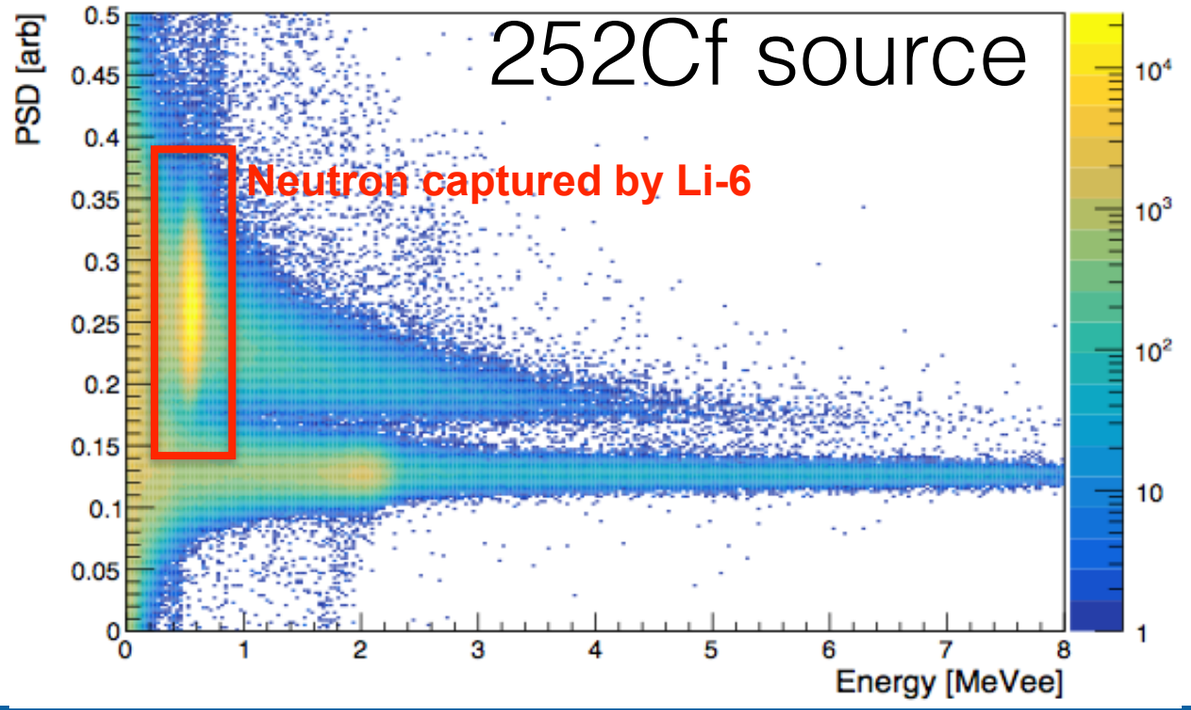



**Pulse-shape Discrimination (PSD) Signatures**

**Inverse Beta Decay**
$\gamma$-like prompt, n-like delay

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

**Accidental Gammas**
~~$\gamma$-like prompt, $\gamma$-like delay~~




**Event Coincidence Signature:**
e-like prompt signal, followed by a ~50$\mu$s delayed neutron capture

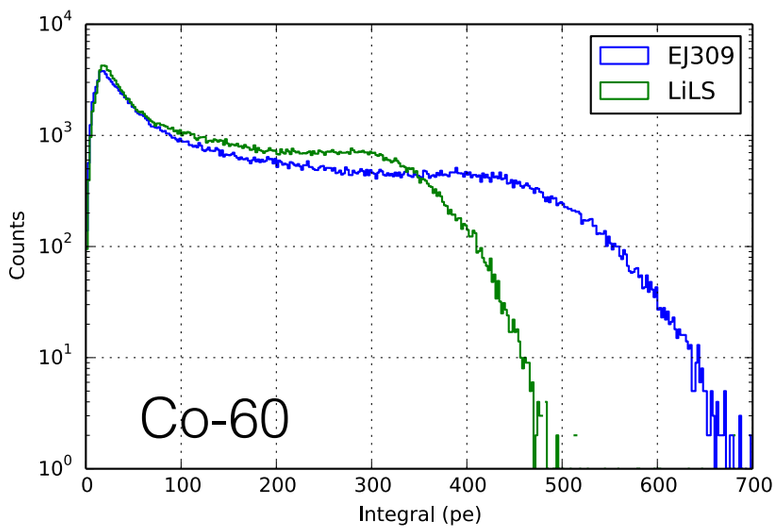
# $^{6}$Li-loaded Liquid Scintillator

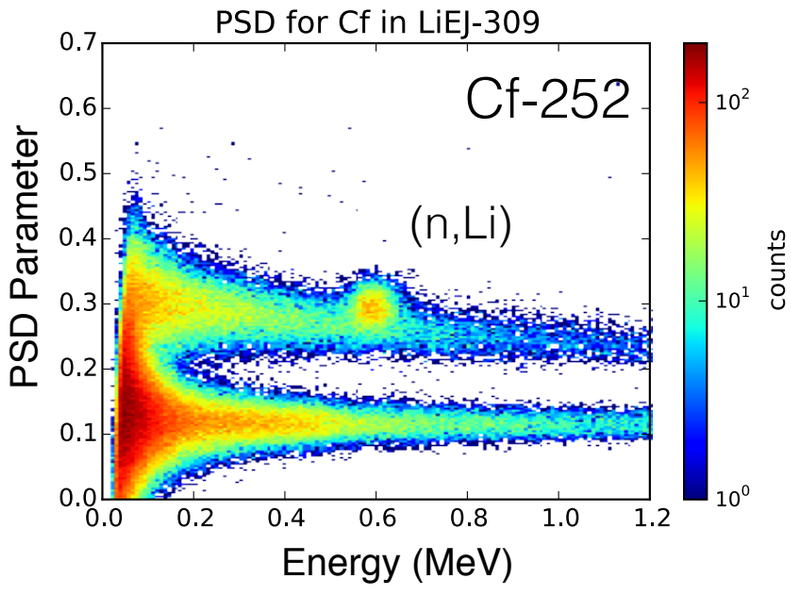
**LiLS Requirements:**

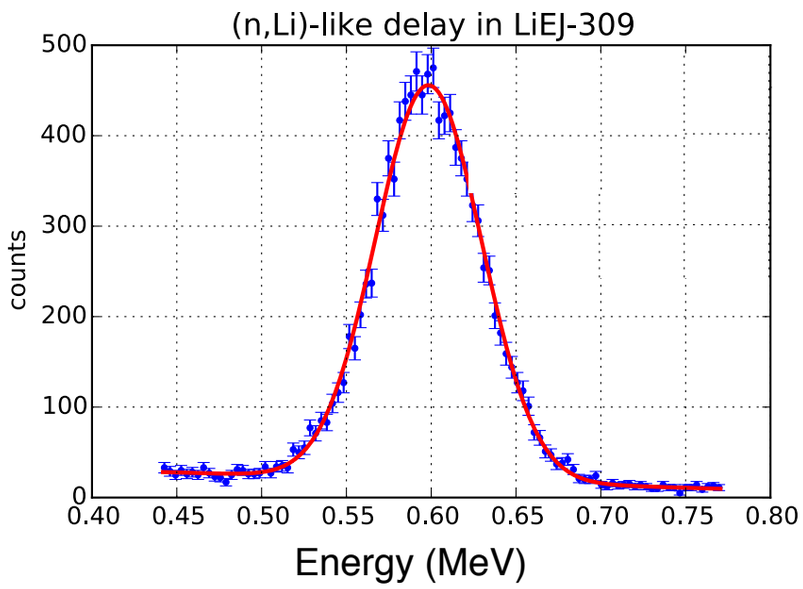
- High light yield (>6000ph/MeV) for energy resolution
- Excellent pulse-shape discrimination (PSD)
- Non-toxic, high flashpoint
- Stable and affordable

**LiLS based on EJ-309 meets all requirements**

- 8200ph/MeV, excellent PSD
- **Safe to operate at a reactor**
- 95% $^{6}$Li enrichment, 0.1% by mass



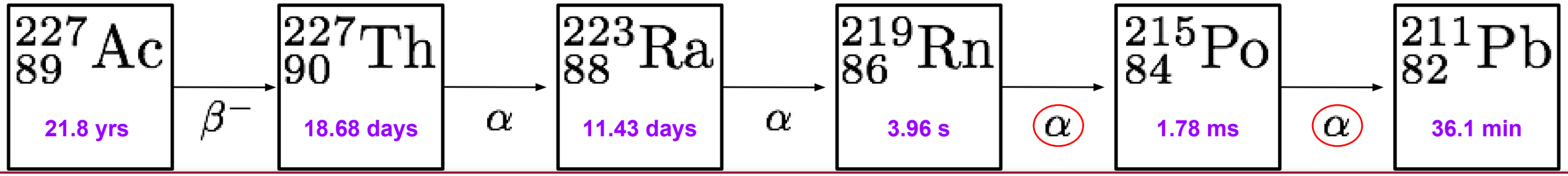




**developed novel LiLS with excellent light yield, PSD, and neutron capture capabilities**

# $^{227}$Ac spike of $^{6}$LiLS

note: not full U-235 decay chain




- **α,α** coincidence $^{219}$Rn→$^{215}$Po→$^{211}$Pb (RnPo) provides localized, nearly mono-energetic deposits
- If $^{227}$Ac uniformly dissolved in $^{6}$LiLS, then relative RnPo rate per cell gives the relative mass per cell: Essential for oscillation measurement
- R&D at BNL determined no significant $^{227}$Ac adsorption on detector materials
- ~0.8 Bq $^{227}$Ac added to ~4500 L total $^{6}$LiLS

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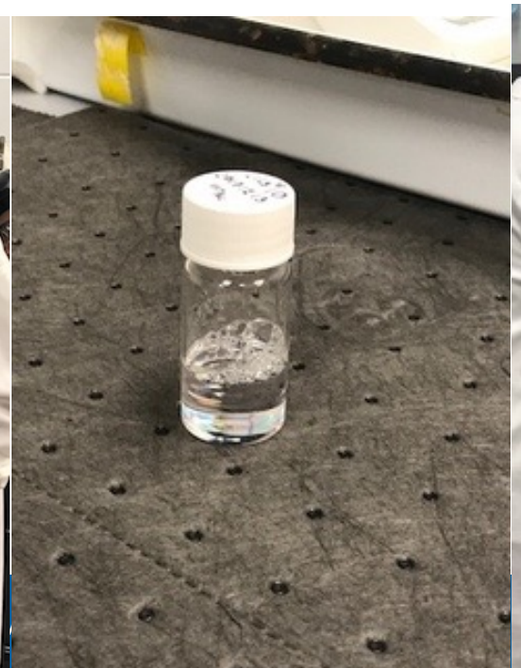
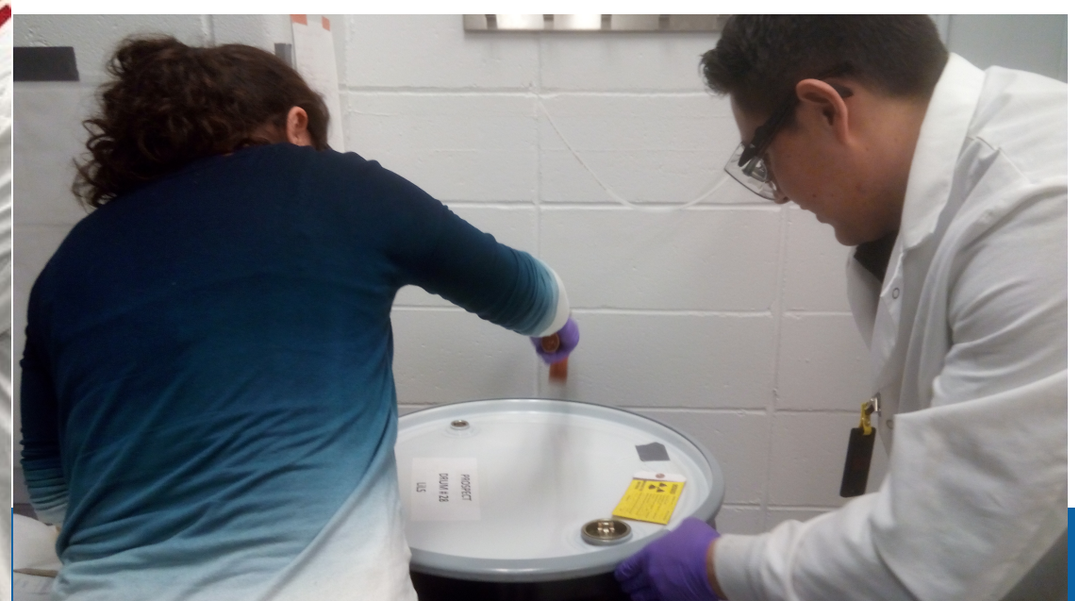
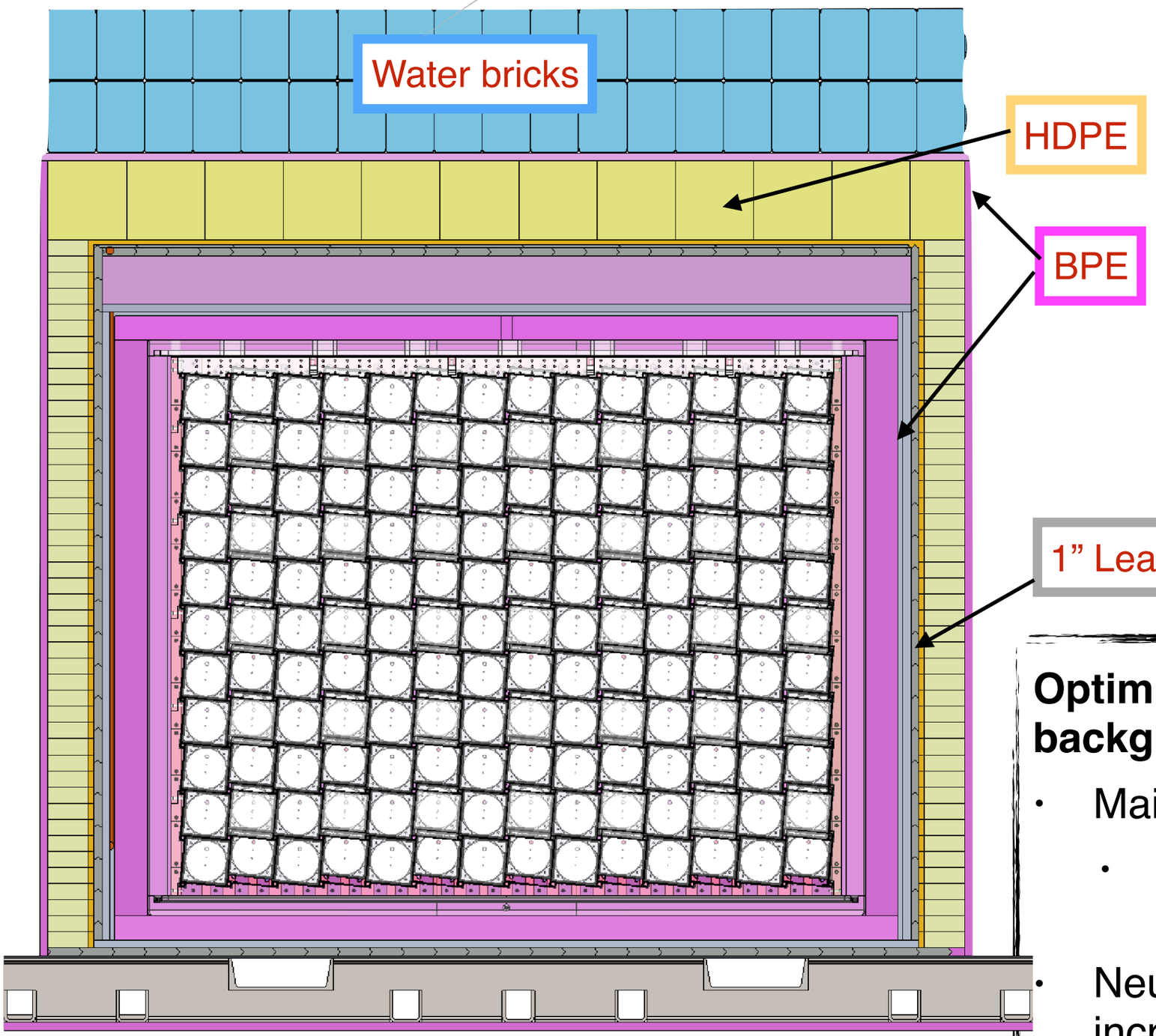
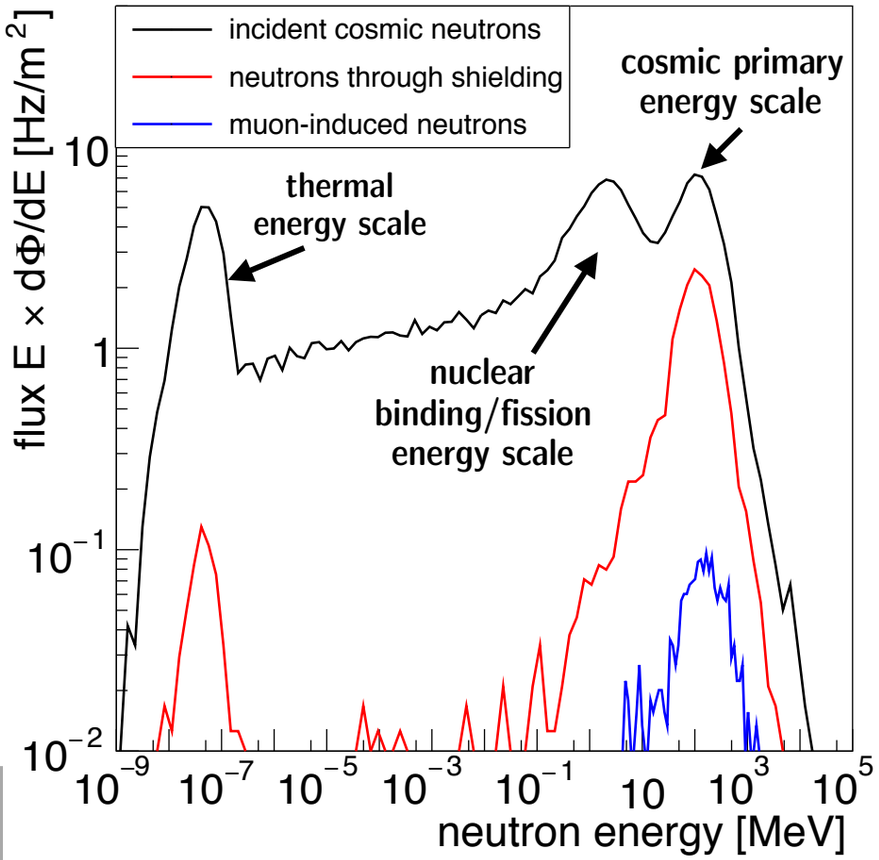
TEMPLE UNIVERSITY





# Novel Shielding Design



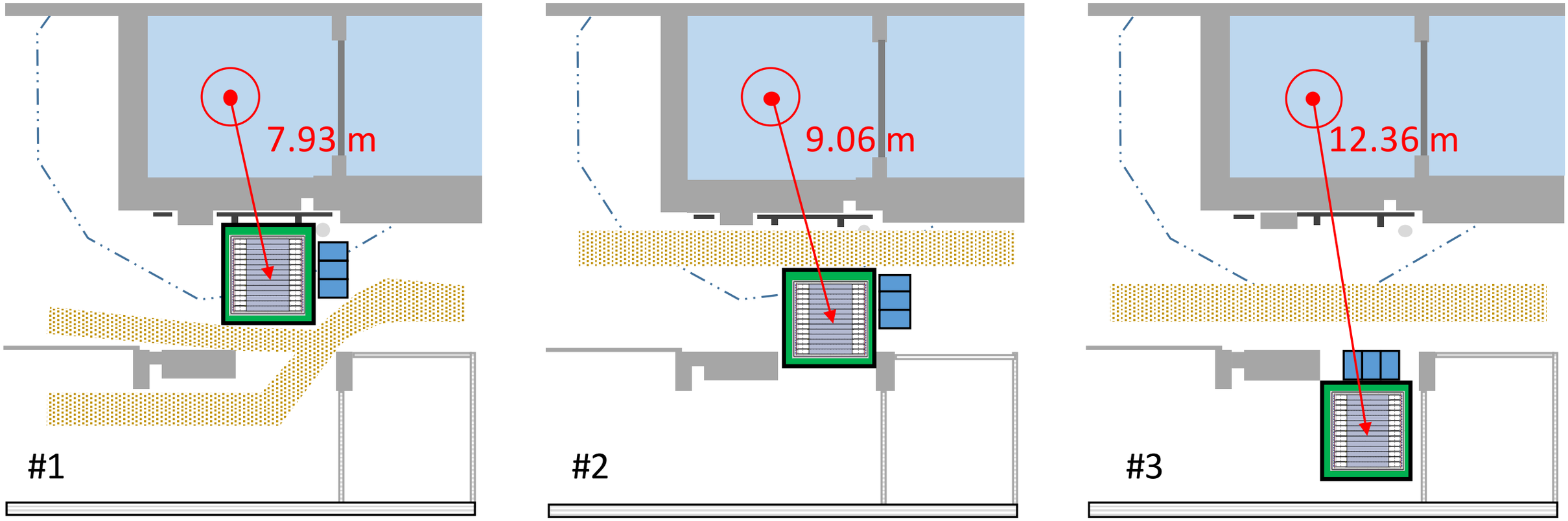




**Optimize space, weight, and total background suppression**

- Main problem is ~100MeV neutrons
  - create majority of IBD-like backgrounds (gamma-like prompt, neutron capture)
- Neutron spallation on high-Z shielding increases backgrounds
- *Need neutron shielding inside lead shielding*

# Possible Baselines

The detector is on a movable platform




Current position

Movement must respect existing walls and allow for standard walkway access, maintaining detector orientation, but can allow the electronics racks to be relocated.

# CONSTRUCTION & INSTALLATION

OCTOBER 25, 2017
YALE WRIGHT LABORATORY

ASSEMBLY BEGAN
NOVEMBER 1, 2017
PARTIALLY ASSEMBLED ROW

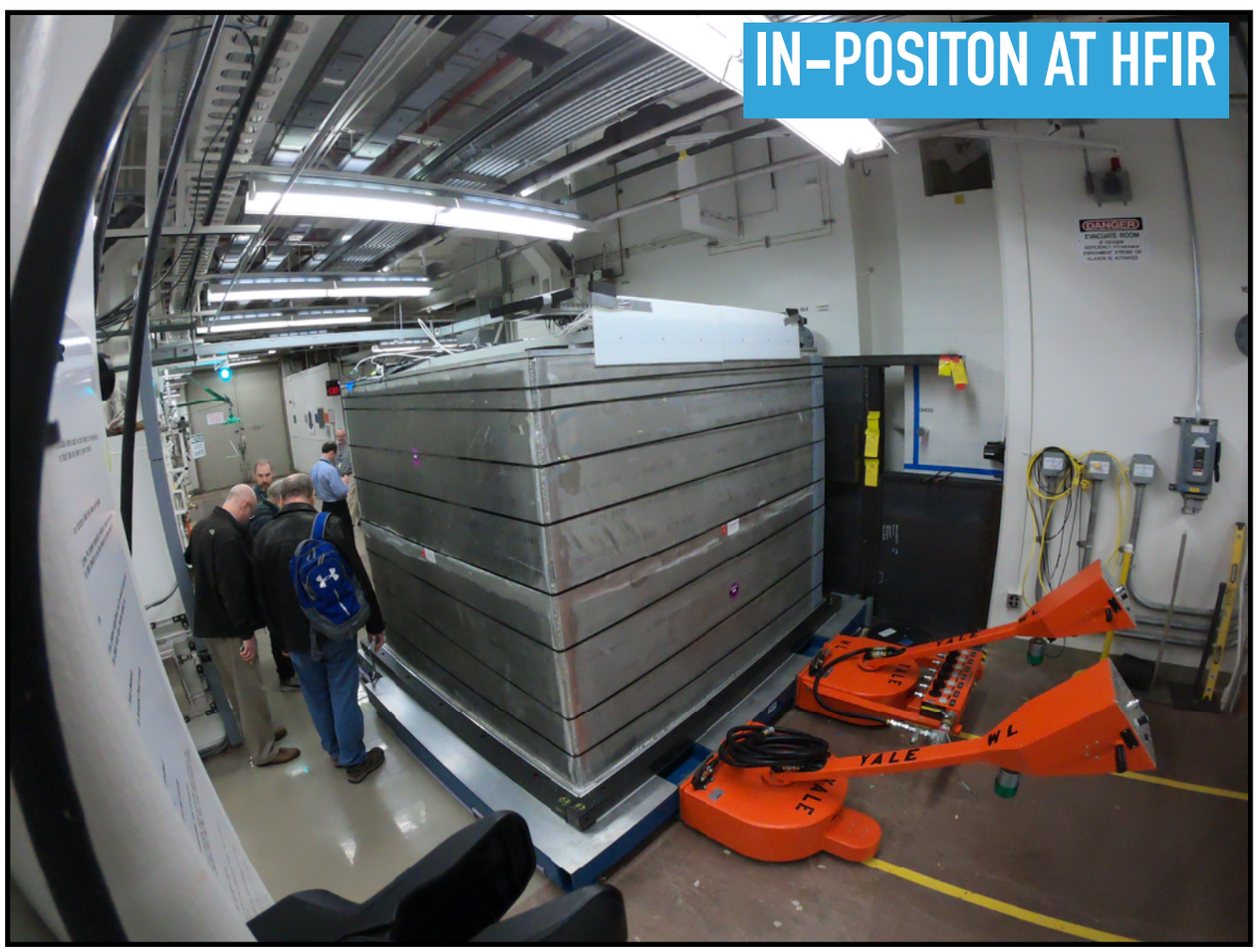
# ASSEMBLY OF FIRST ROW

NOVEMBER 1, 2017
YALE WRIGHT LAB

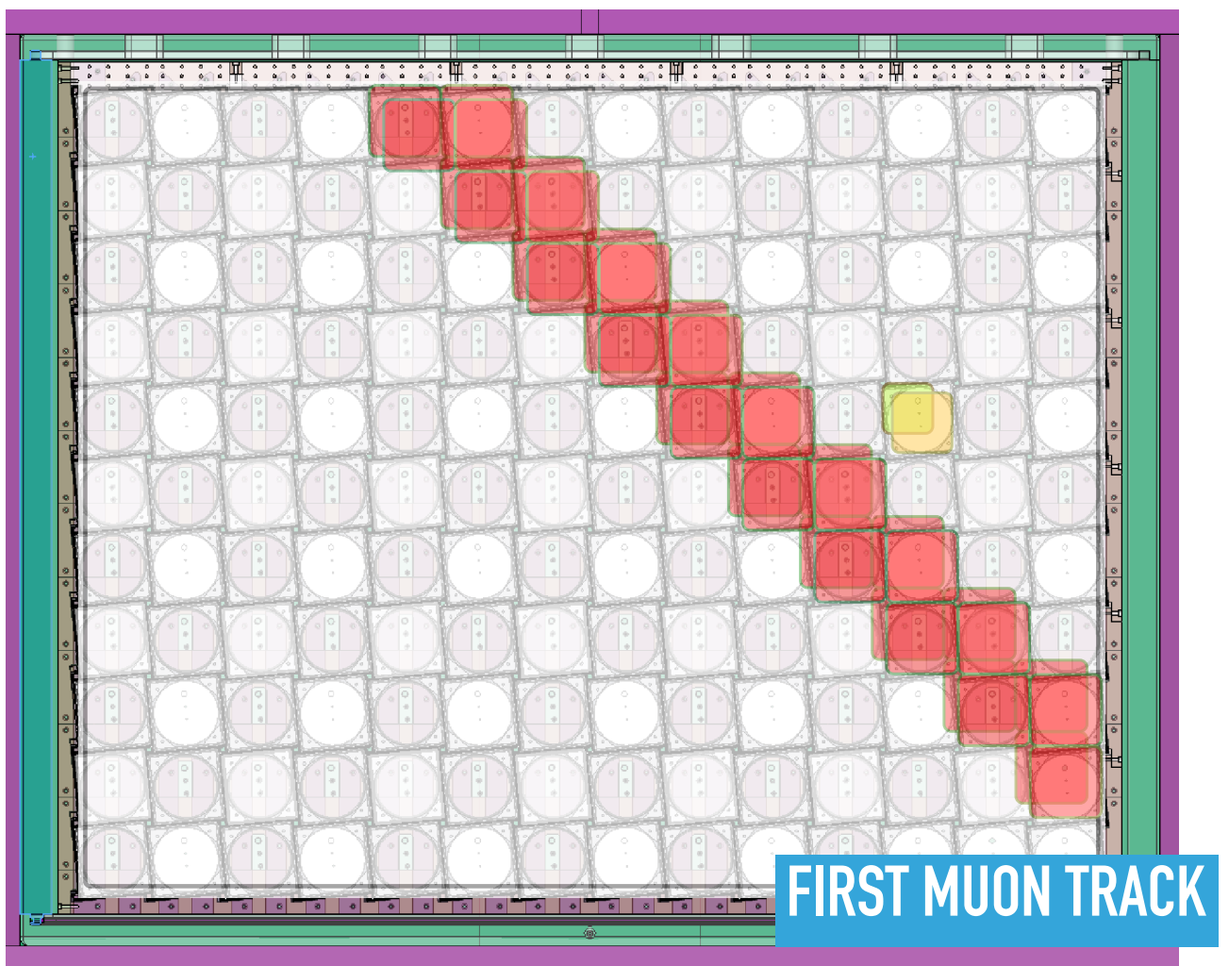
# NOVEMBER 17, 2017
# FINAL ROW INSTALLATION

# DEC, 2017 – JAN 2018
# DRY COMMISSIONING AT YALE

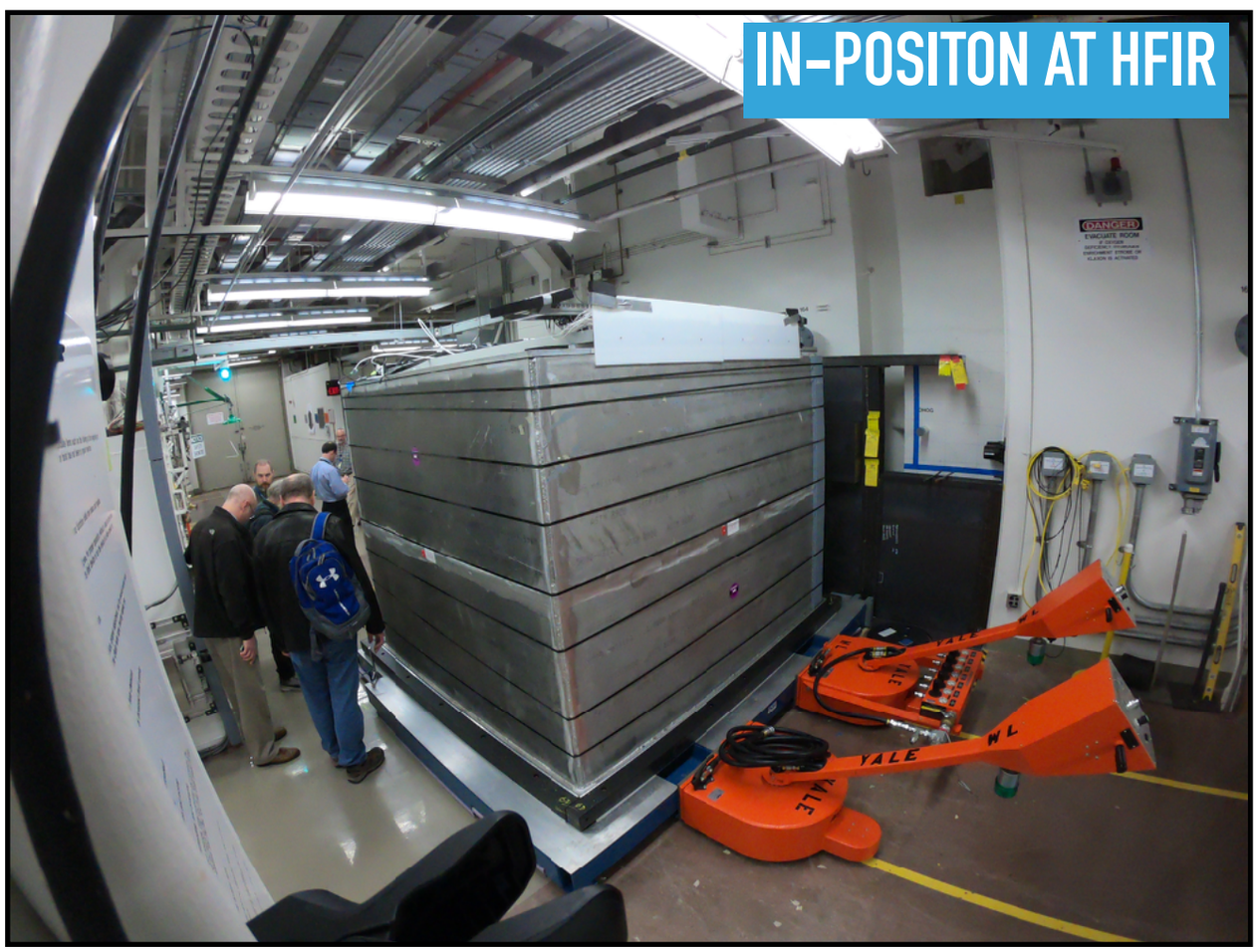
FEBRUARY 2018
ARRIVAL AT ORNL


IN-POSITON AT HFIR
DANGER
YALE

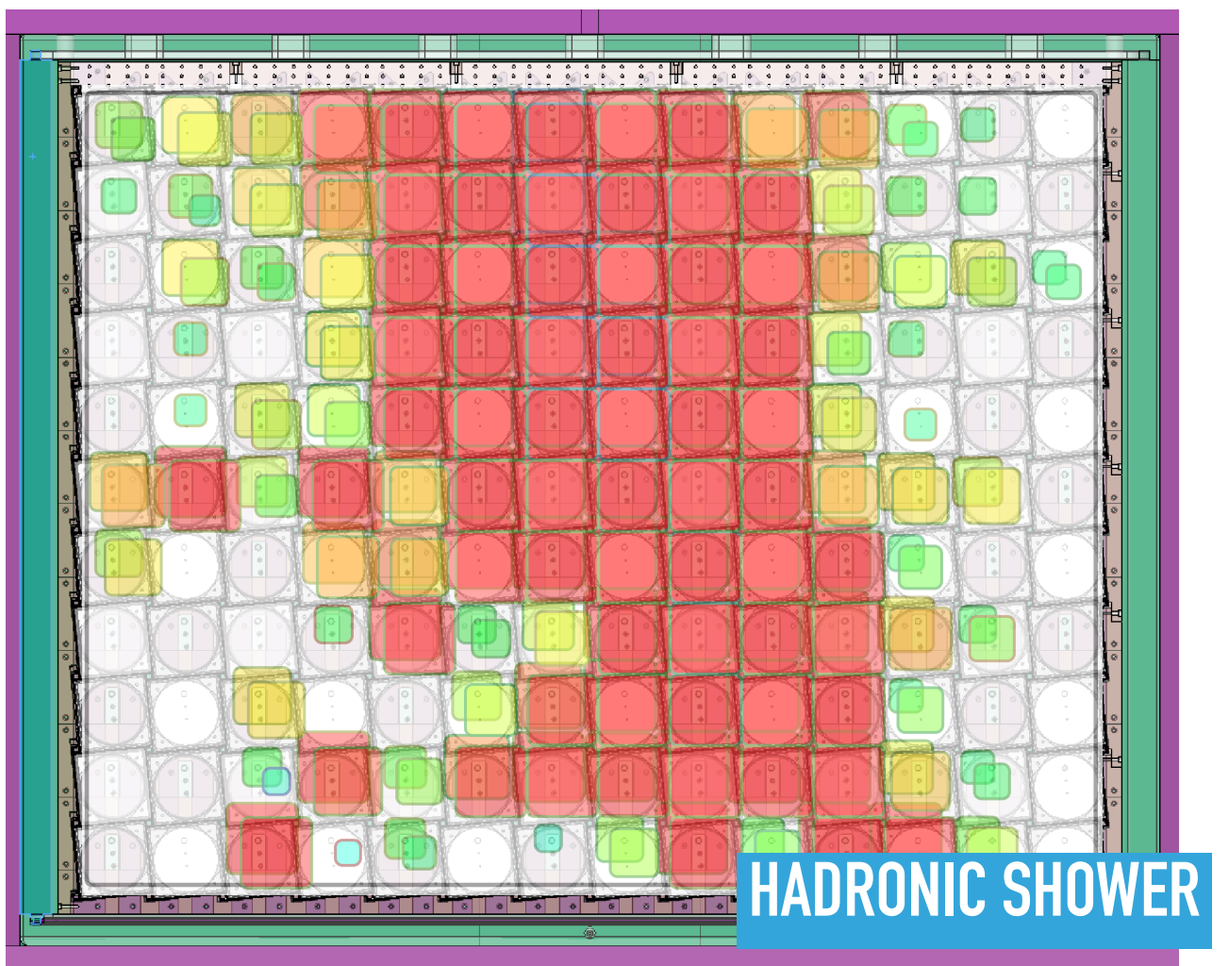
ZIPU 132501 8
22T8
TARE
DANGER
NOMINAL CAPACITY
4 BAR
FILLING THE MIXING TANK


FIRST MUON TRACK

FEBRUARY 2018
ARRIVAL AT ORNL

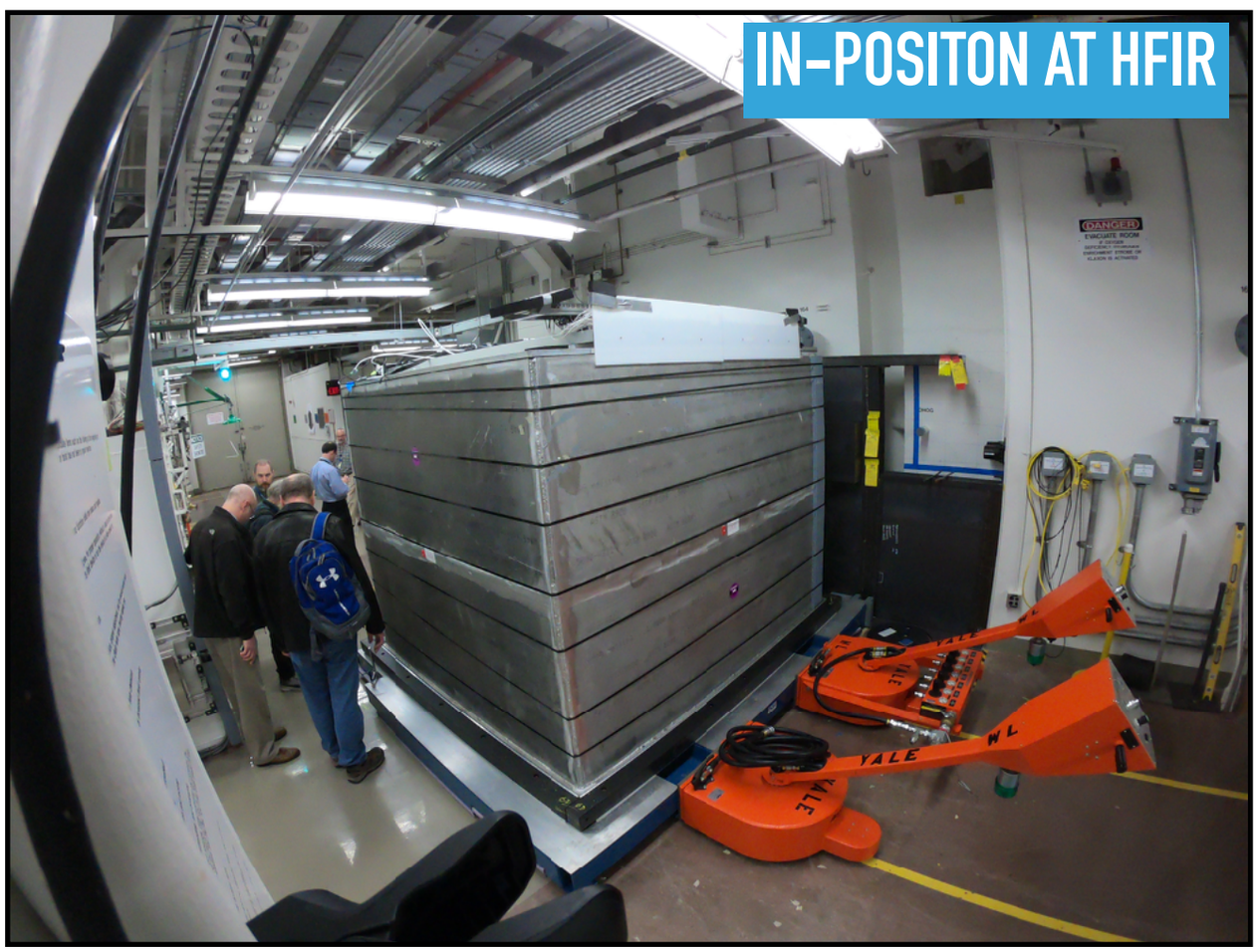

IN-POSITON AT HFIR
DANGER
YALE

ZIPU 1325018
22T6
TARE
DANGER
NOMINAL CAPACITY
4 BAR
FILLING THE MIXING TANK

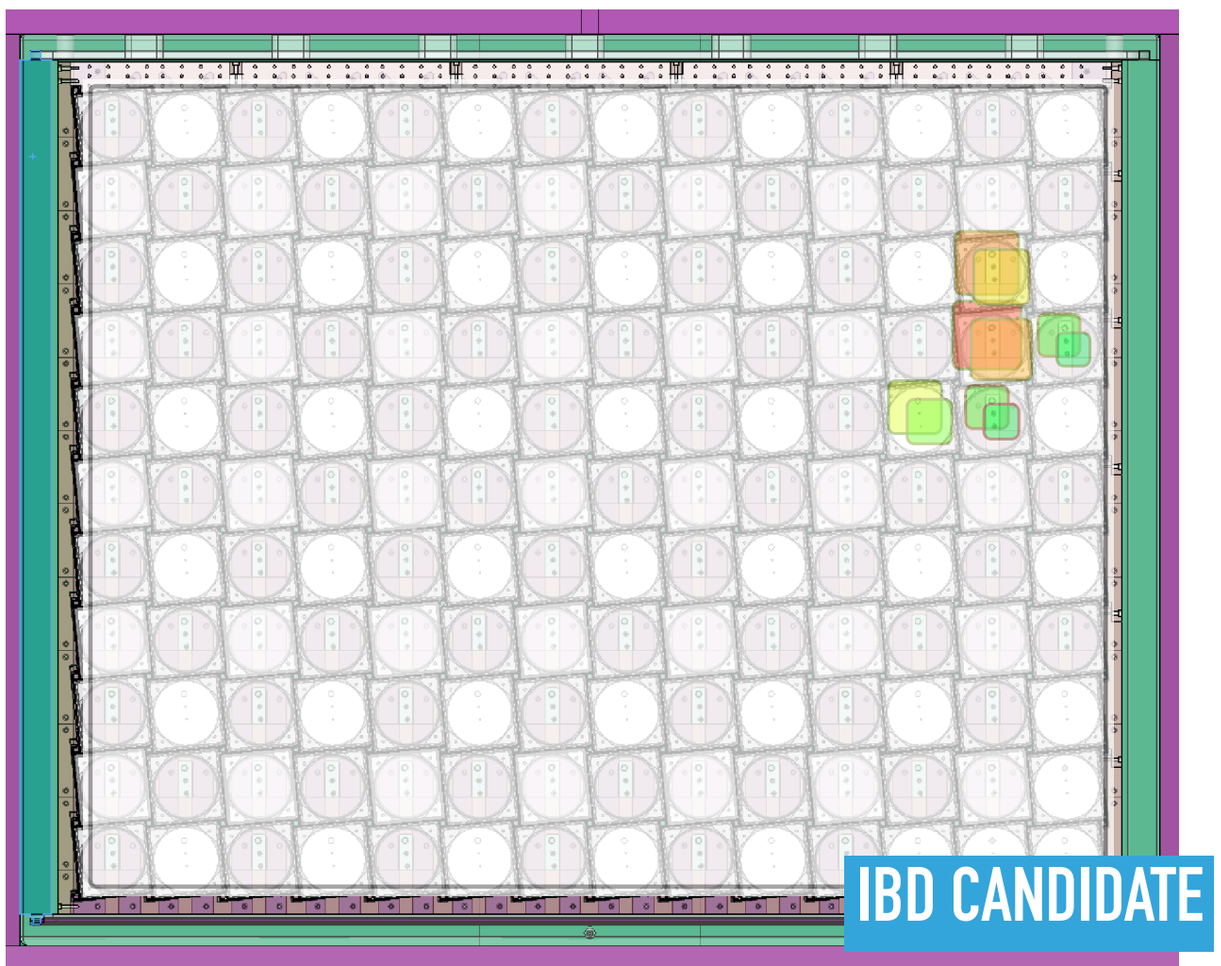

HADRONIC SHOWER

# FEBRUARY 2018 ARRIVAL AT ORNL

# IN-POSITON AT HFIR



# FILLING THE MIXING TANK

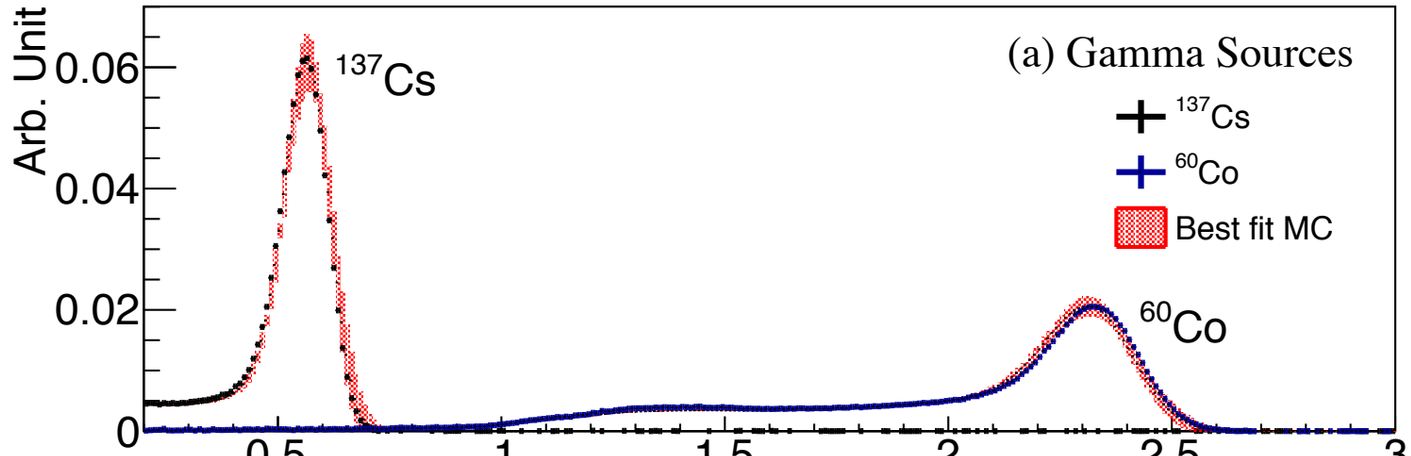


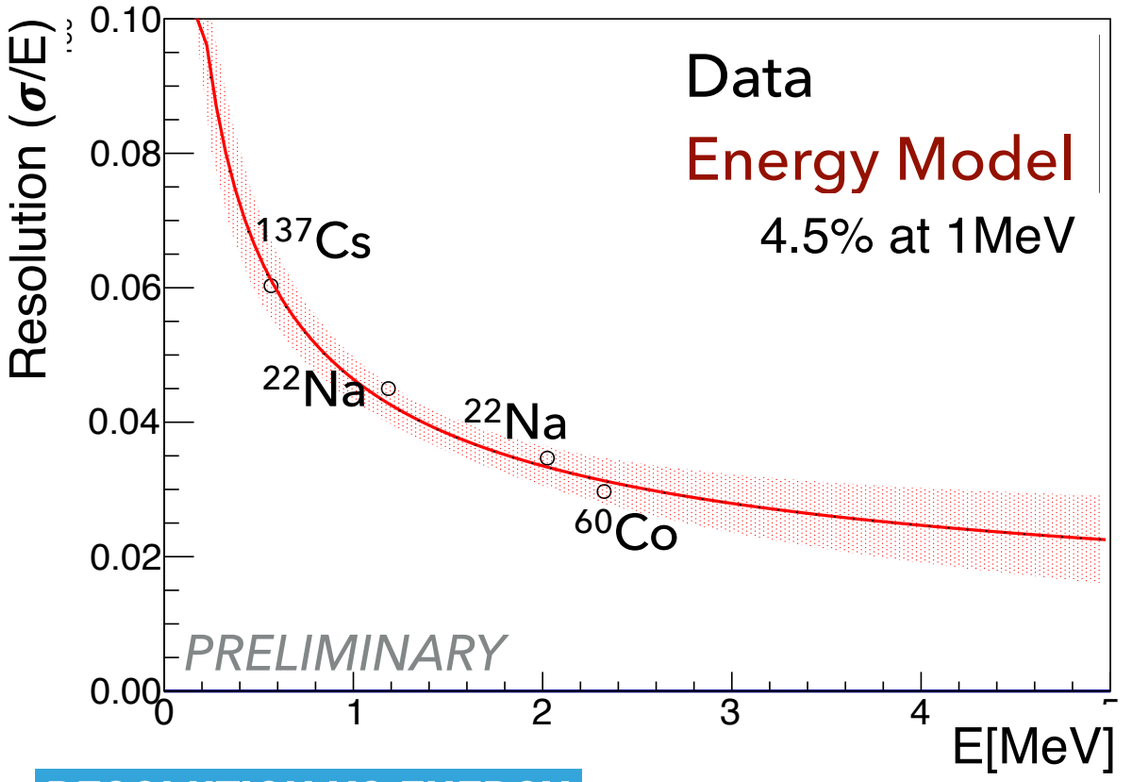
# IBD CANDIDATE

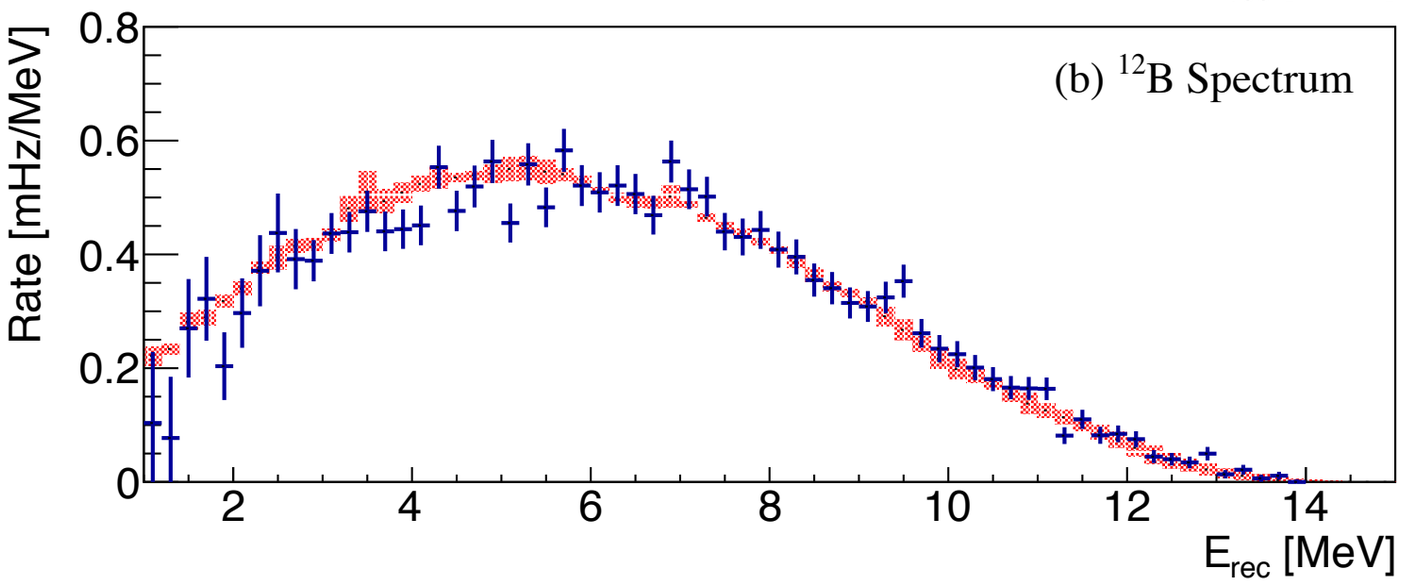
# PERFORMANCE & RESULTS

# Energy reconstruction

- Gamma sources ($^{137}$Cs, $^{60}$Co) 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**



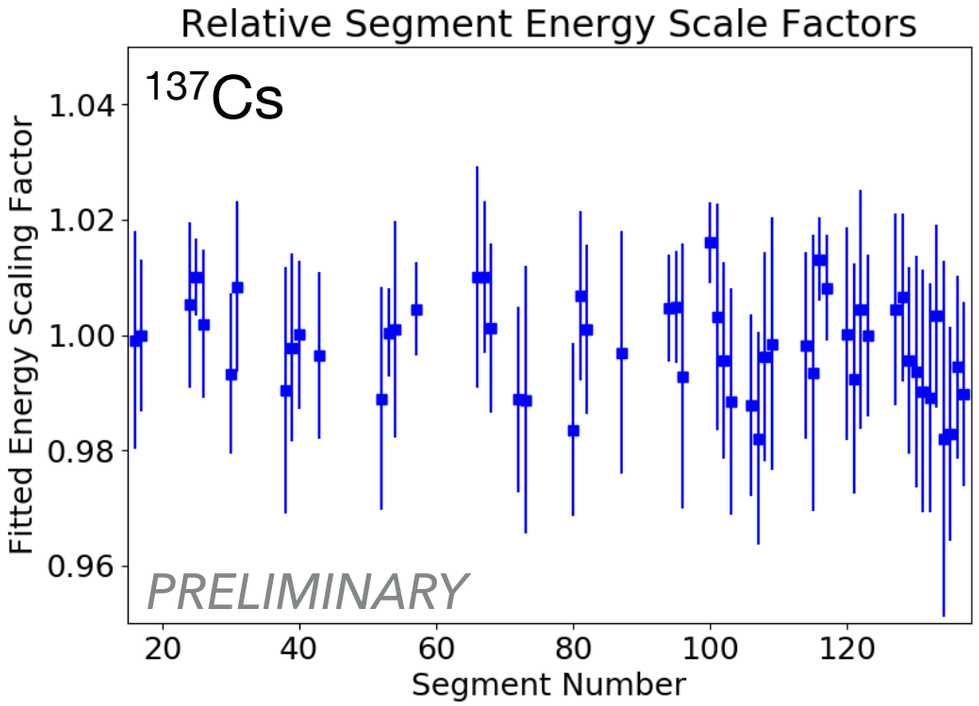



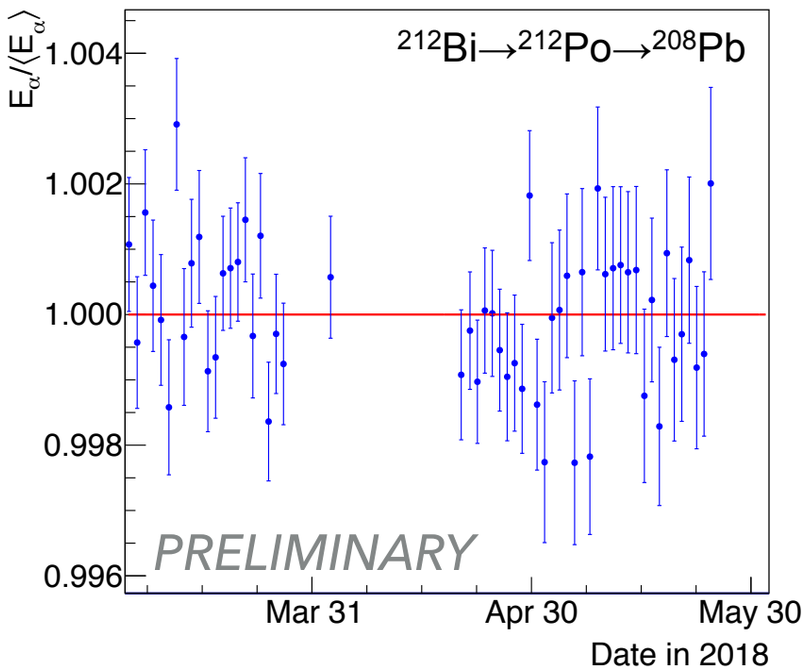

RESOLUTION VS ENERGY

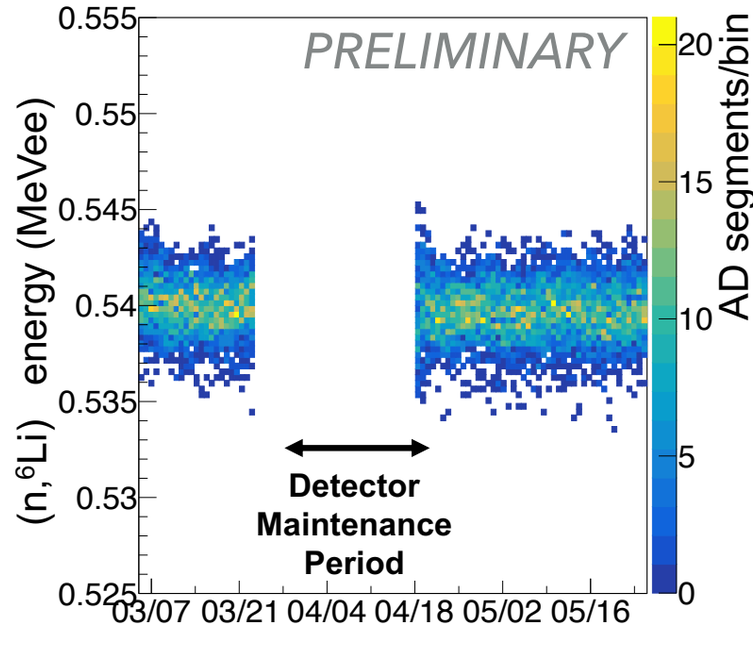


E[MeV]

# Detector uniformity



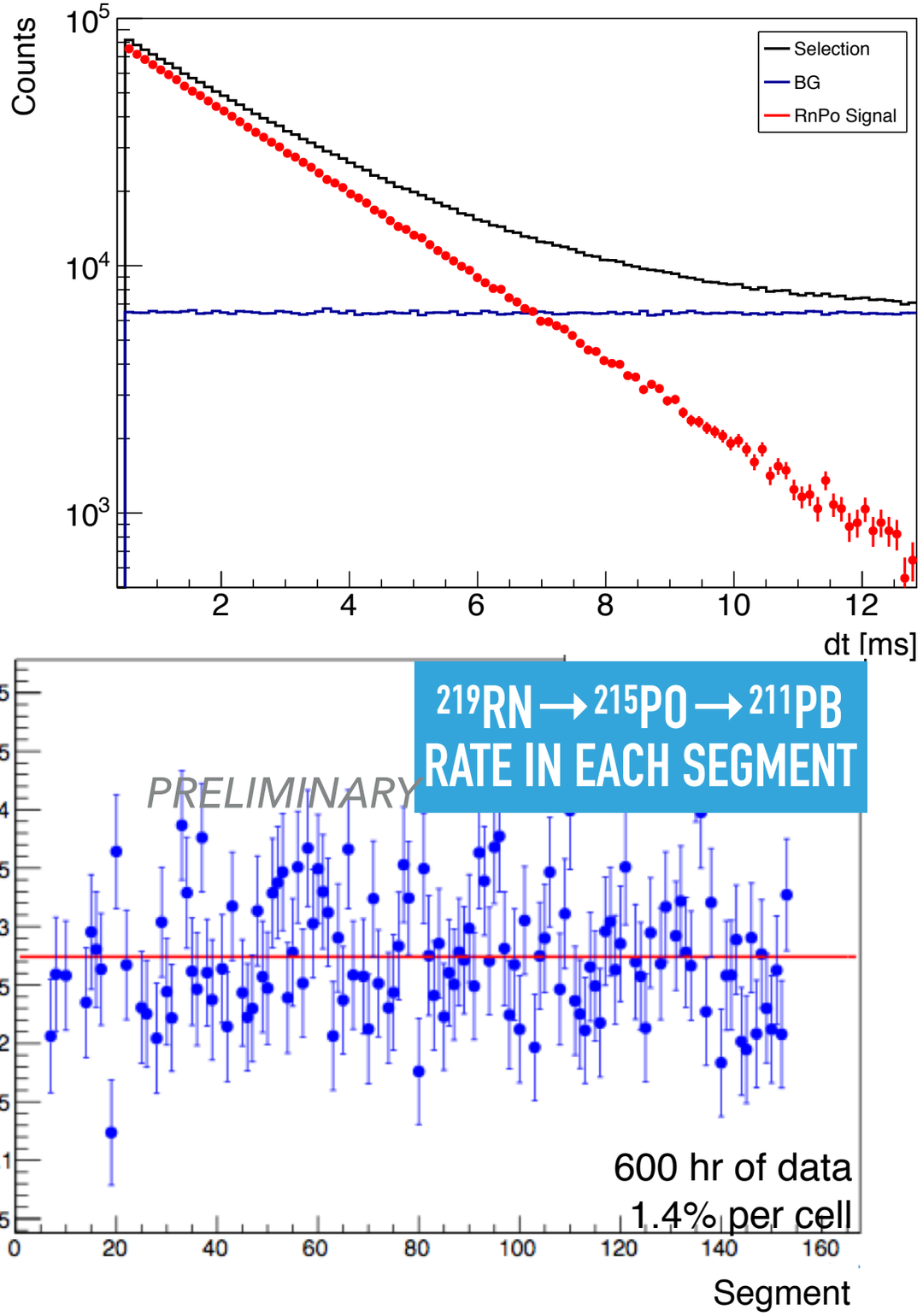



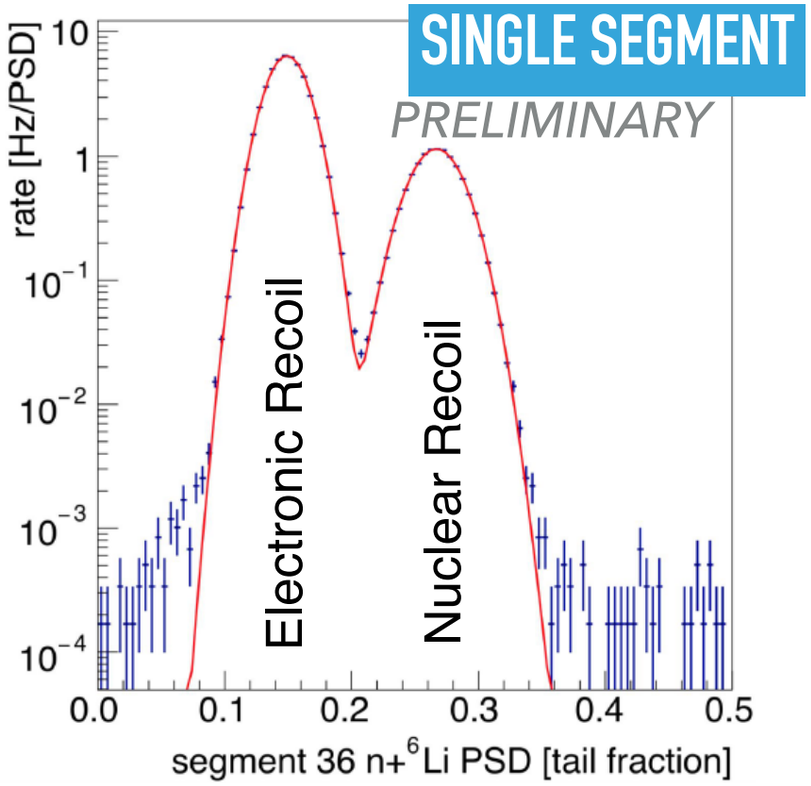

- **Calibration Source Deployment:**
  - 35 calibration source tubes throughout detector to map energy response
  - Segment to segment uniformity ~1%
  - $^{252}$Cf source to study neutron capture efficiency
- **Intrinsic radioactive sources**
  - Track uniformity over time with distributed internal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

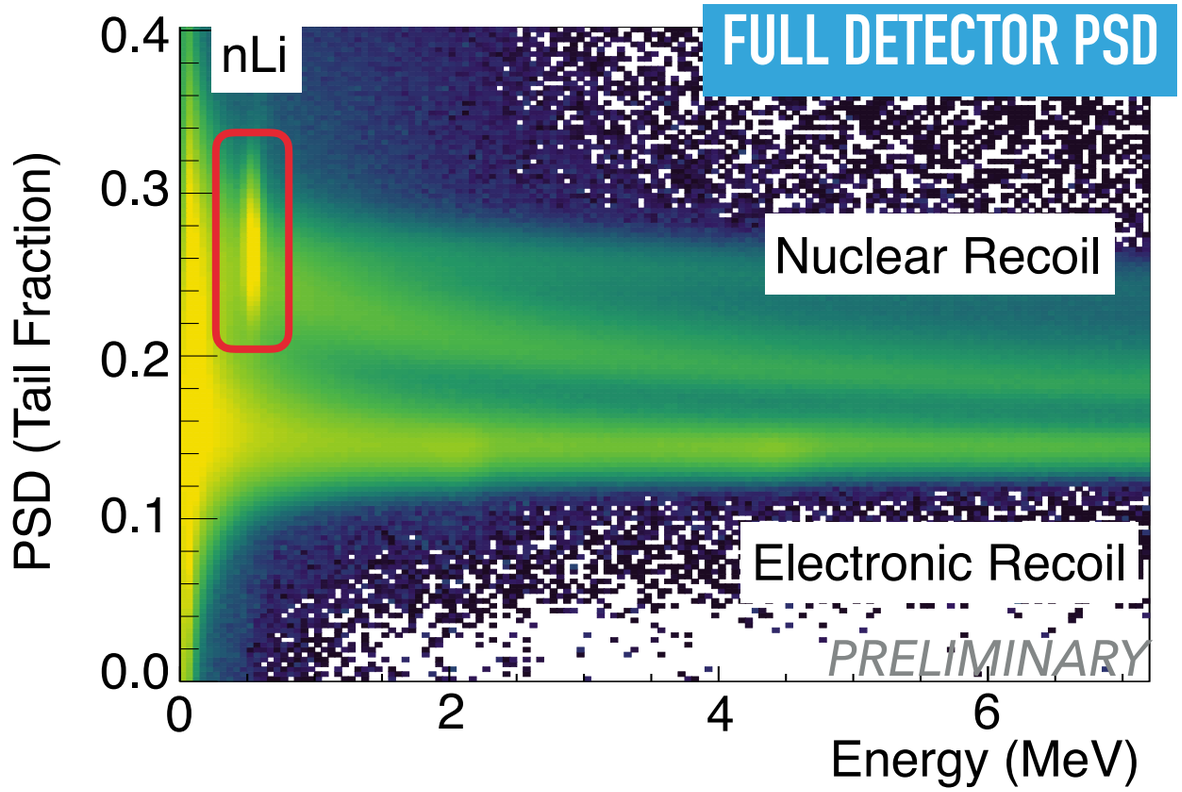
# Segment volume measurement

- 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, 1.78ms half-life, efficient selection straightforward,
- Measured absolute z-position resolution of < 5cm
- Direct measurement of relative target mass in each segment



# Pulse shape discrimination performance

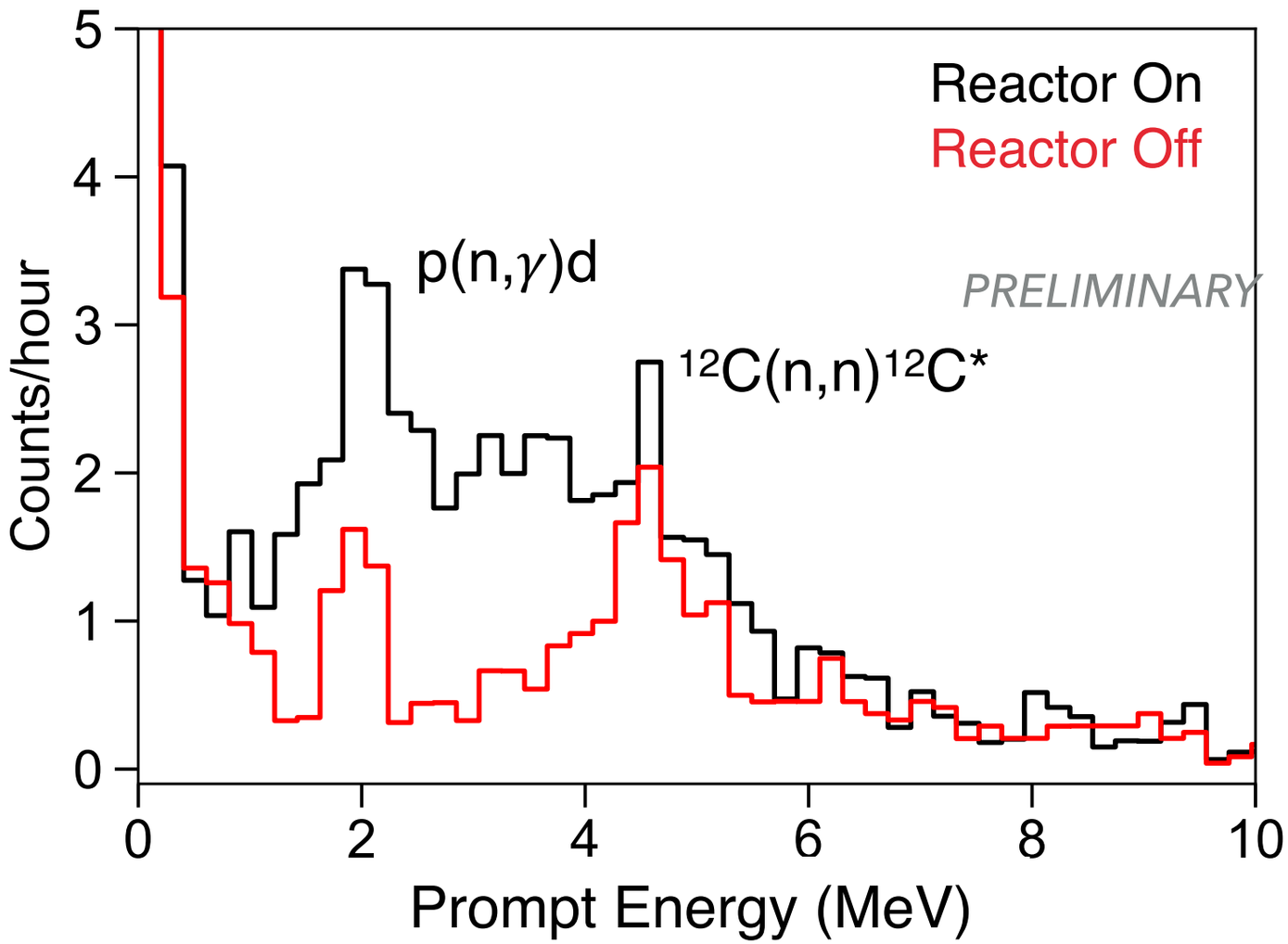



- Excellent particle ID of gamma interactions, neutron captures, and nuclear recoils
- Dominant backgrounds: Cosmogenic fast neutrons, reactor-related gamma rays, reactor thermal neutrons
  - Vast majority identified and rejected by PSD for Prompt and Delayed signals
- **Tag IBDs with high efficiency 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 5$\sigma$ detection at earth's surface: < 4hrs**

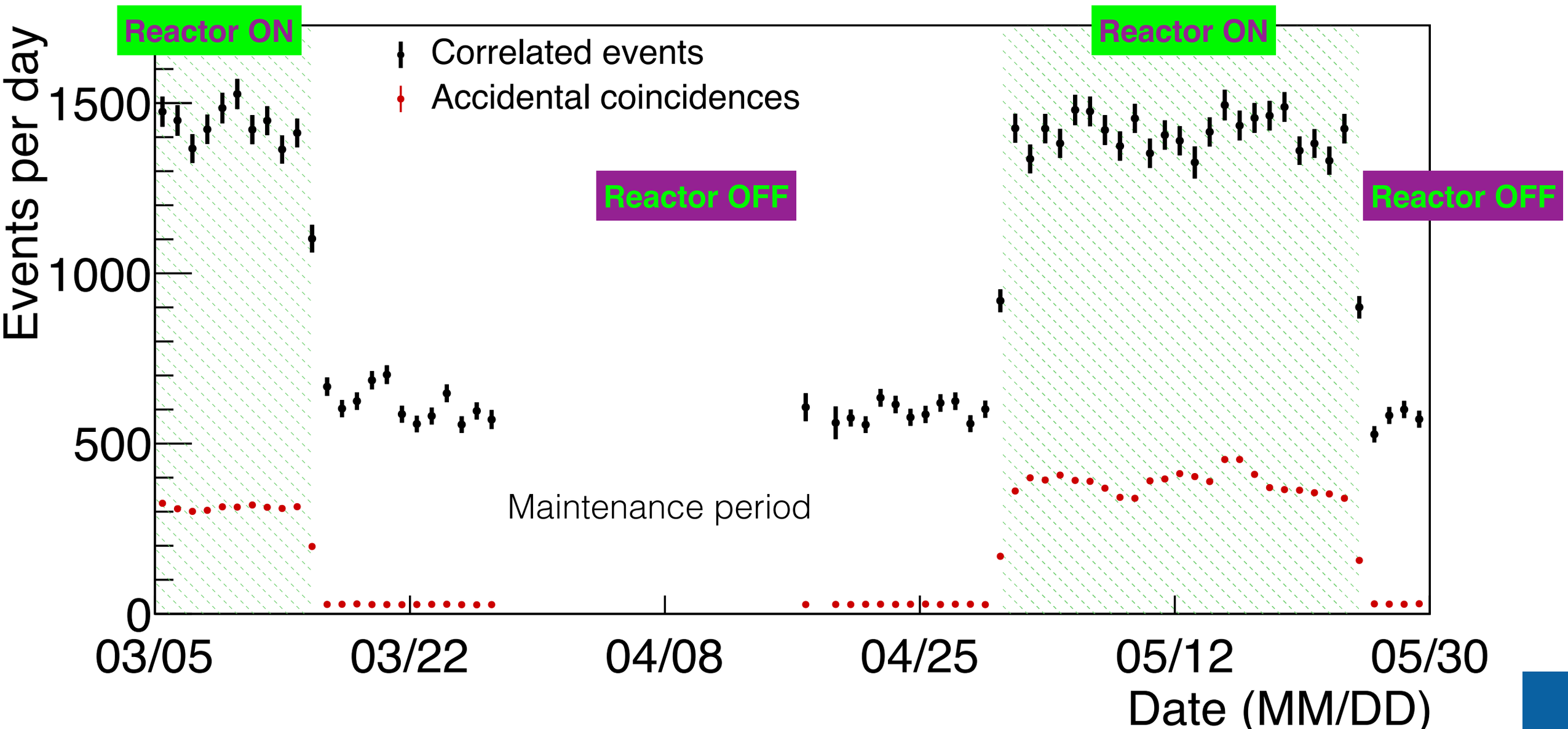



***PROSPECT is measuring the $^{235}U$ antineutrino spectrum***

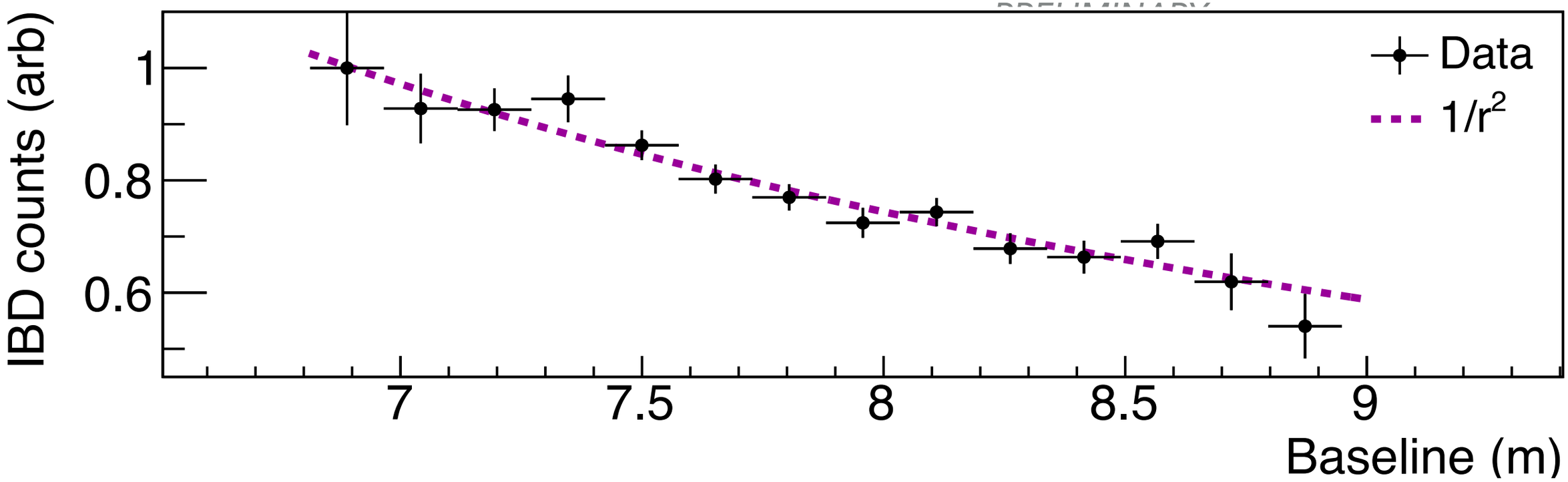
# First analysis data set (arXiv: 1806.02784)

- 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



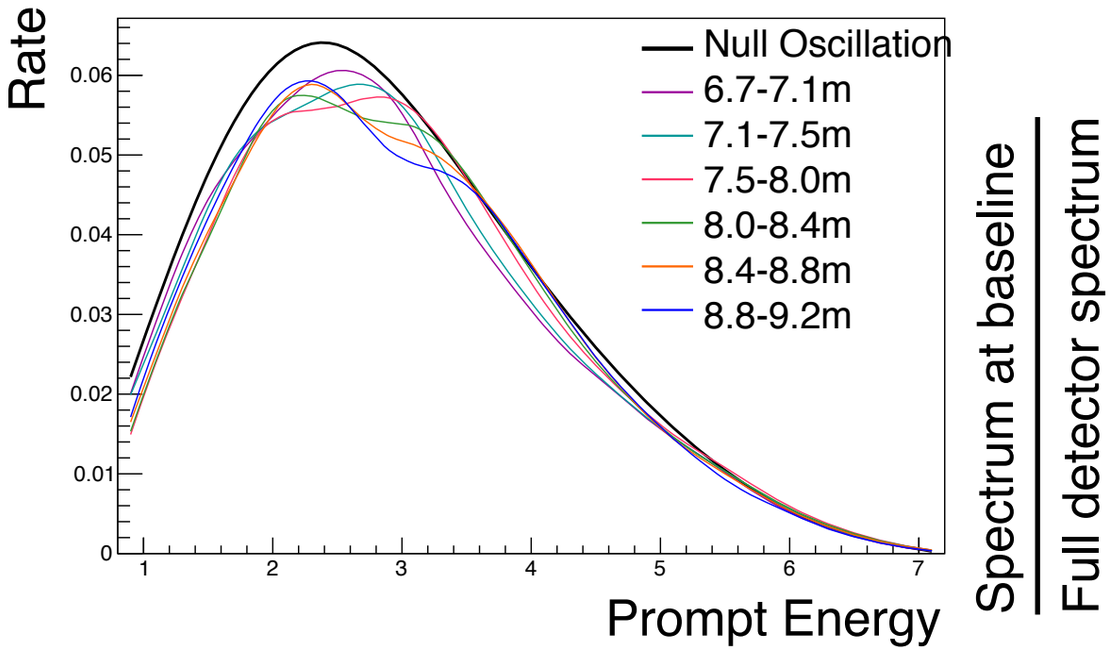
# Neutrino Rate vs baseline



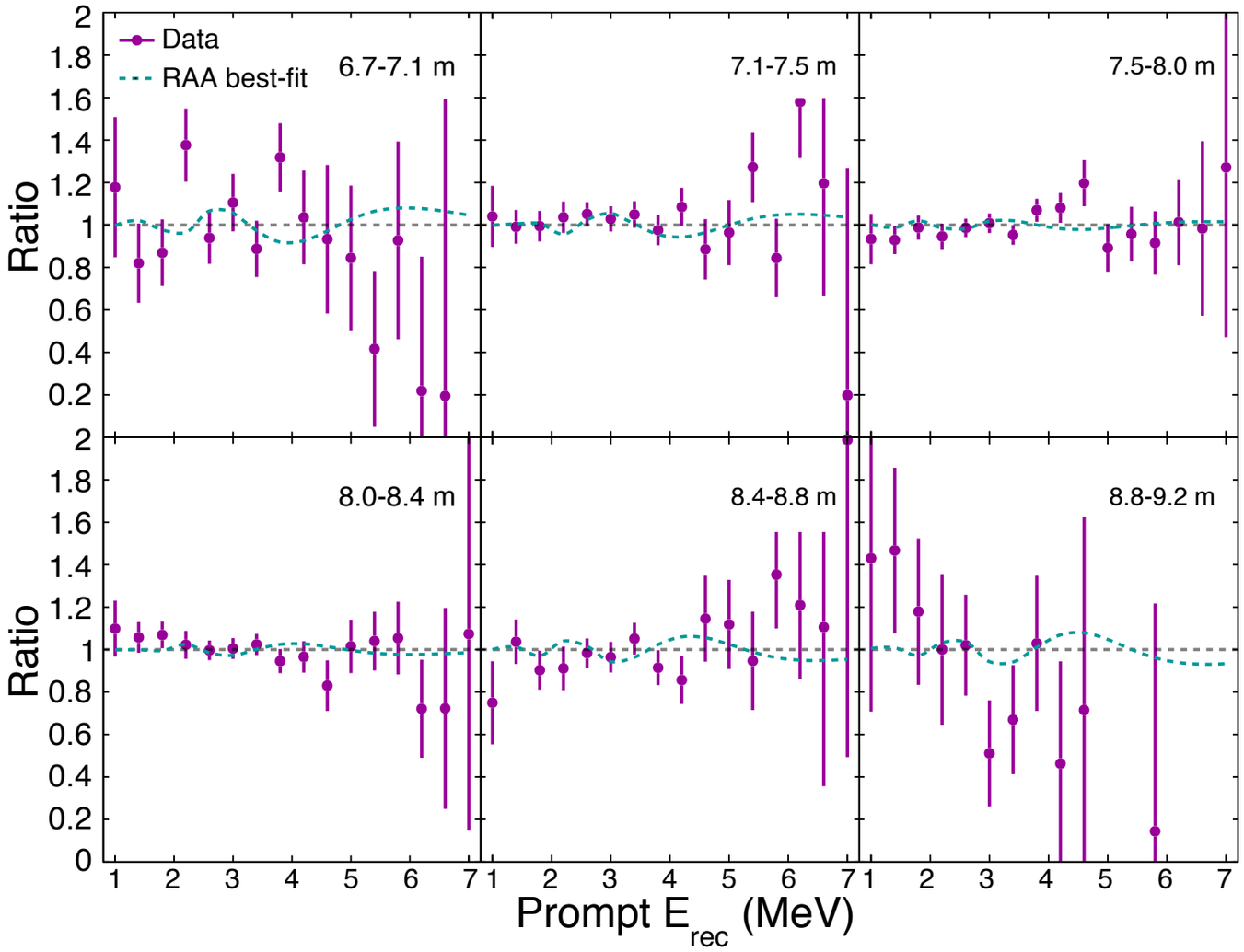

- Bin events from 108 fiducial segments into 14 baseline bins
- *40% flux decrease from front of detector to back*
- **Observation of $1/r^2$ behavior throughout detector volume**

# Neutrino Spectrum vs baseline

**BASELINE-DEPENDENT OSCILLATION ILLUSTRATION**



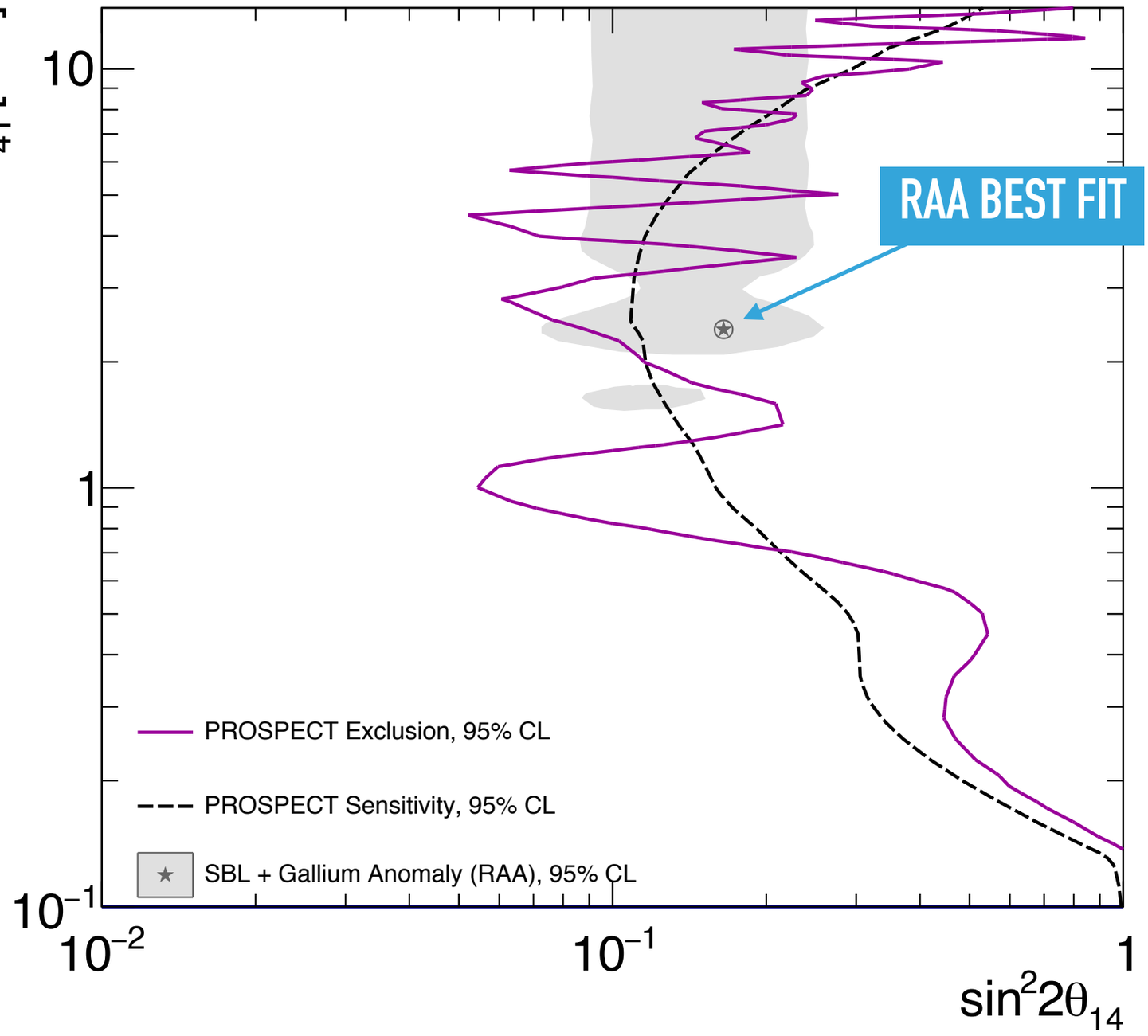

Spectrum at baseline / Full detector spectrum




- 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, independent of reactor model**

# Oscillation search results

- Feldman-Cousins based confidence intervals for oscillation search
- Covariance matrices captures all uncertainties and energy/baseline correlations
- Critical $\chi^2$ 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*



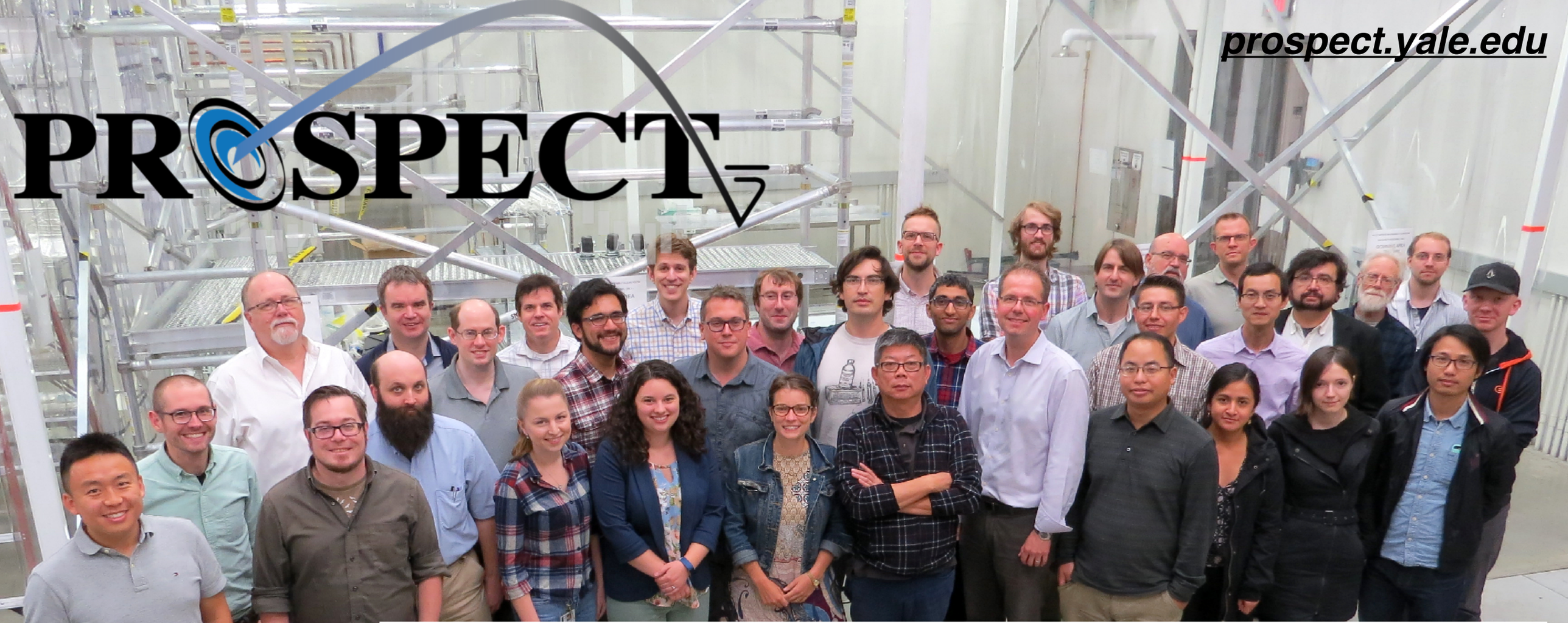

**Disfavors RAA best-fit point at >95% (2.3$\sigma$)**

# Conclusion and outlook

- PROSPECT started taking data on March 6, 2018
- Detector performing well. Background rejection and energy resolution consistent with expectation.
- Observed antineutrinos from HFIR with good signal/background.
- **Observed an energy spectrum of antineutrinos at the Earth's surface (1mwe overburden) with 24 hours of data**
- **Working towards a high-statistics $^{235}$U spectrum measurement**
- Opportunity for detailed understanding of cosmogenic backgrounds
- **First oscillation analysis on 33 days of reactor-on data disfavors the RAA best-fit at 2.3$\sigma$ (arXiv: 1806.02784)**
- **Sterile neutrinos are increasingly disfavored as an explanation of reactor anomalies based on the results of PROSPECT and other reactor neutrino experiments.**

# PROSPECT

prospect.yale.edu



**BNL collaborators:**

L.J.Bignell, M.V.Diwan, S.Hans, D.Jaffe, X.Ji, X.Qian, R.Rosero, R.Sharma, B.Viren, M.Yeh, A.Zhang, C.Zhang, M.Zhao


**Funding provided by:**

HEISING-SIMONS FOUNDATION

U.S. DEPARTMENT OF ENERGY

GRFP NSF GRADUATE RESEARCH FELLOWSHIP PROGRAM


**14 Institutions, 70 collaborators**

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Drexel

UNIVERSITY OF WATERLOO

W&M

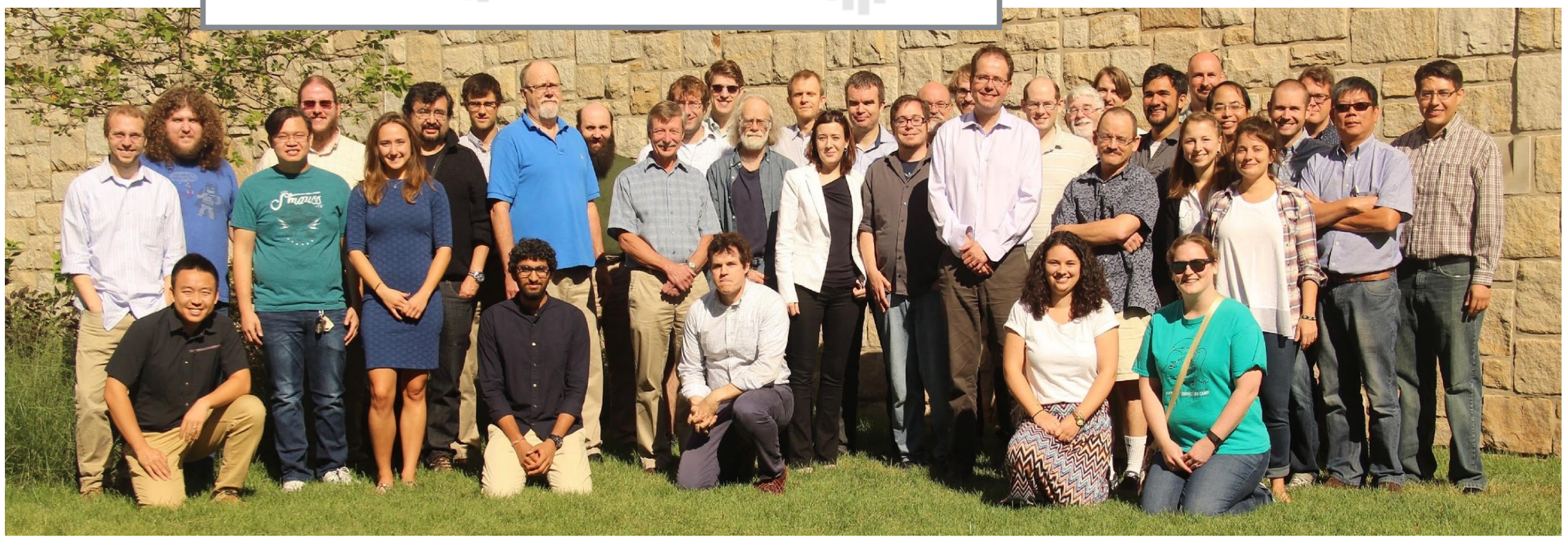
Lawrence Livermore National Laboratory

OAK RIDGE National Laboratory

Yale

# EXTRAS

# PROSPECT

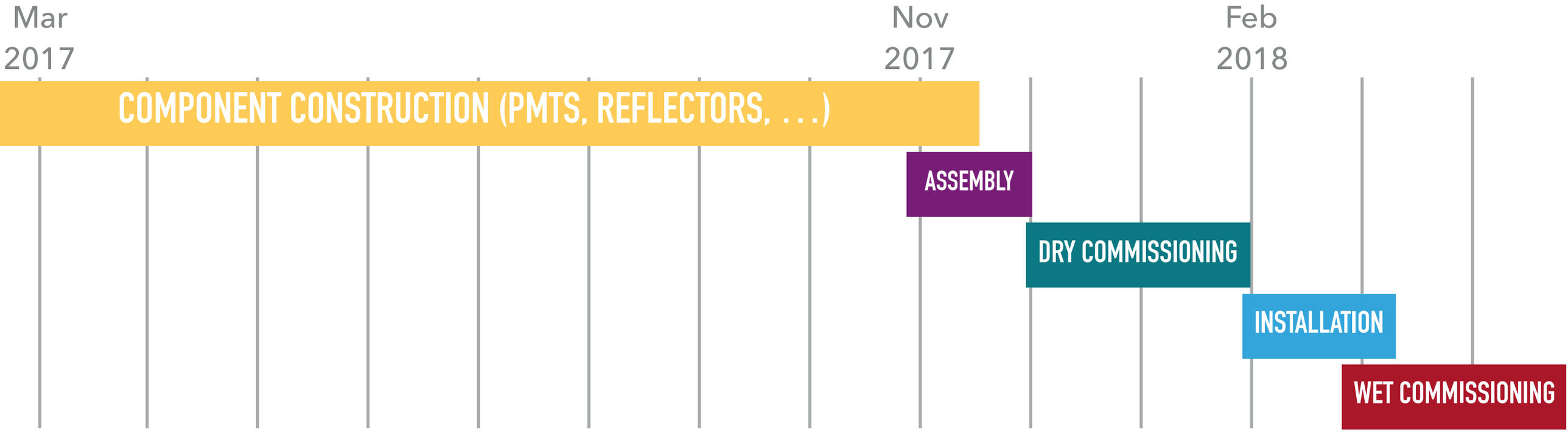


Lawrence Livermore National Laboratory · NIST · Brookhaven National Laboratory · Oak Ridge National Laboratory · Le Moyne College · University of Waterloo · Drexel University · Illinois Institute of Technology · University of Wisconsin–Madison · Georgia Tech · UT · Yale · W&M

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

http://prospect.yale.edu

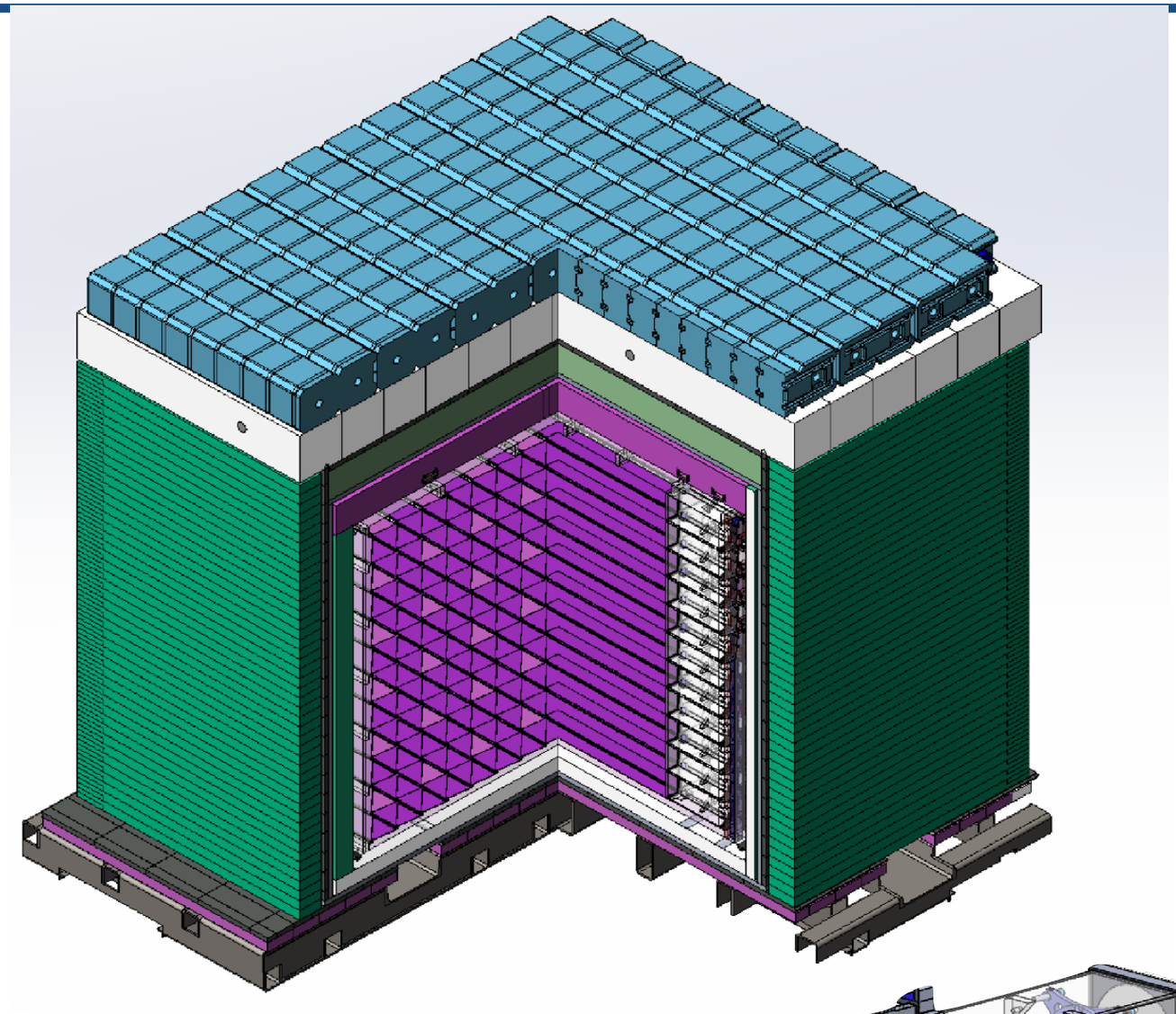
# DETECTOR CONSTRUCTION



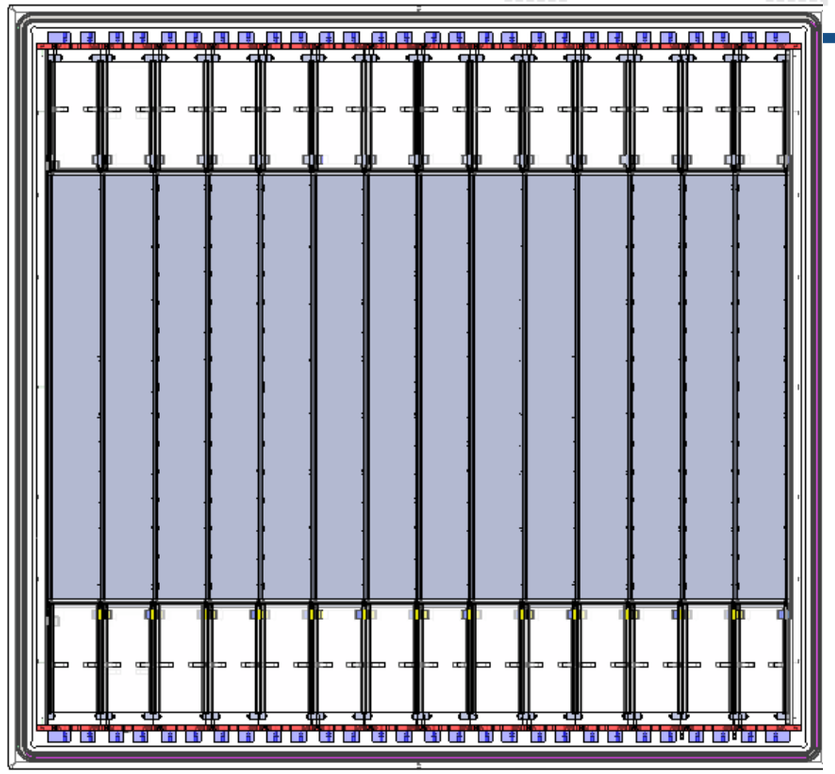

- Component construction ran for 1 year (Nov 2016 - Nov 2017)
- First of 308 PMT modules assembled March 2017
- Inner detector assembly ~3weeks (1 layer/day)
- Dry commissioning at Yale Wright Lab to integrate DAQ and HV
- Ship to Oak Ridge National Lab on January 31, 2018
- Installation (filling and shielding construction ~2months)
- Wet commissioning March, 2018

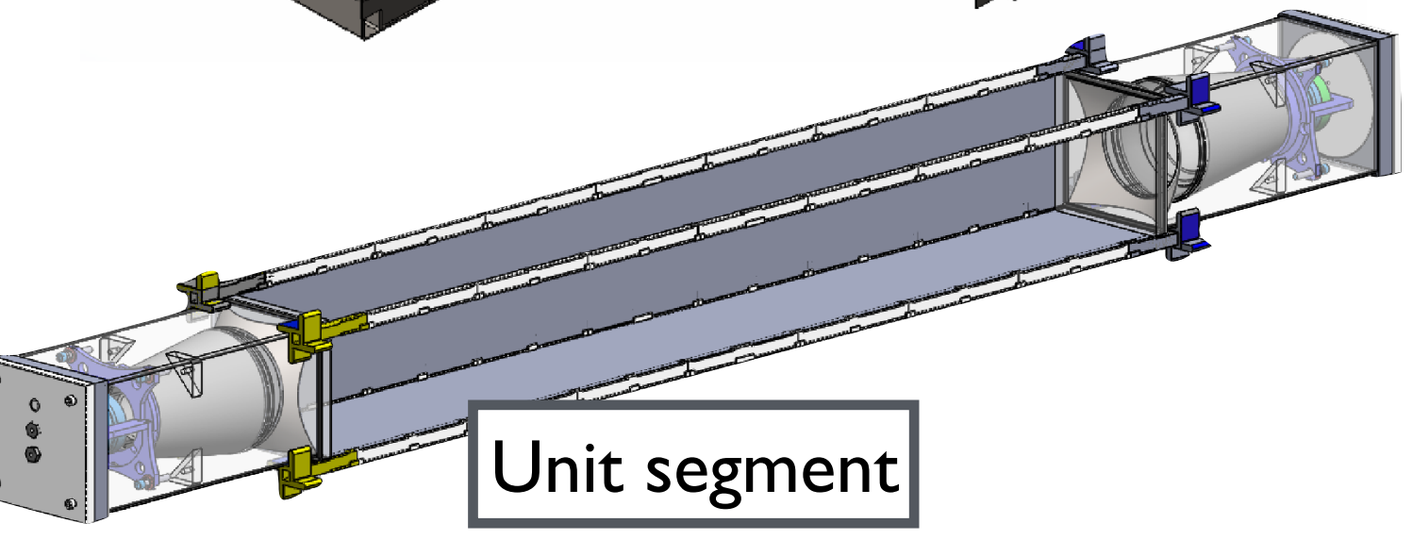
# Segmented Mobile Antineutrino Detector

PROSPECT $\bar{\nu}$



PMTs

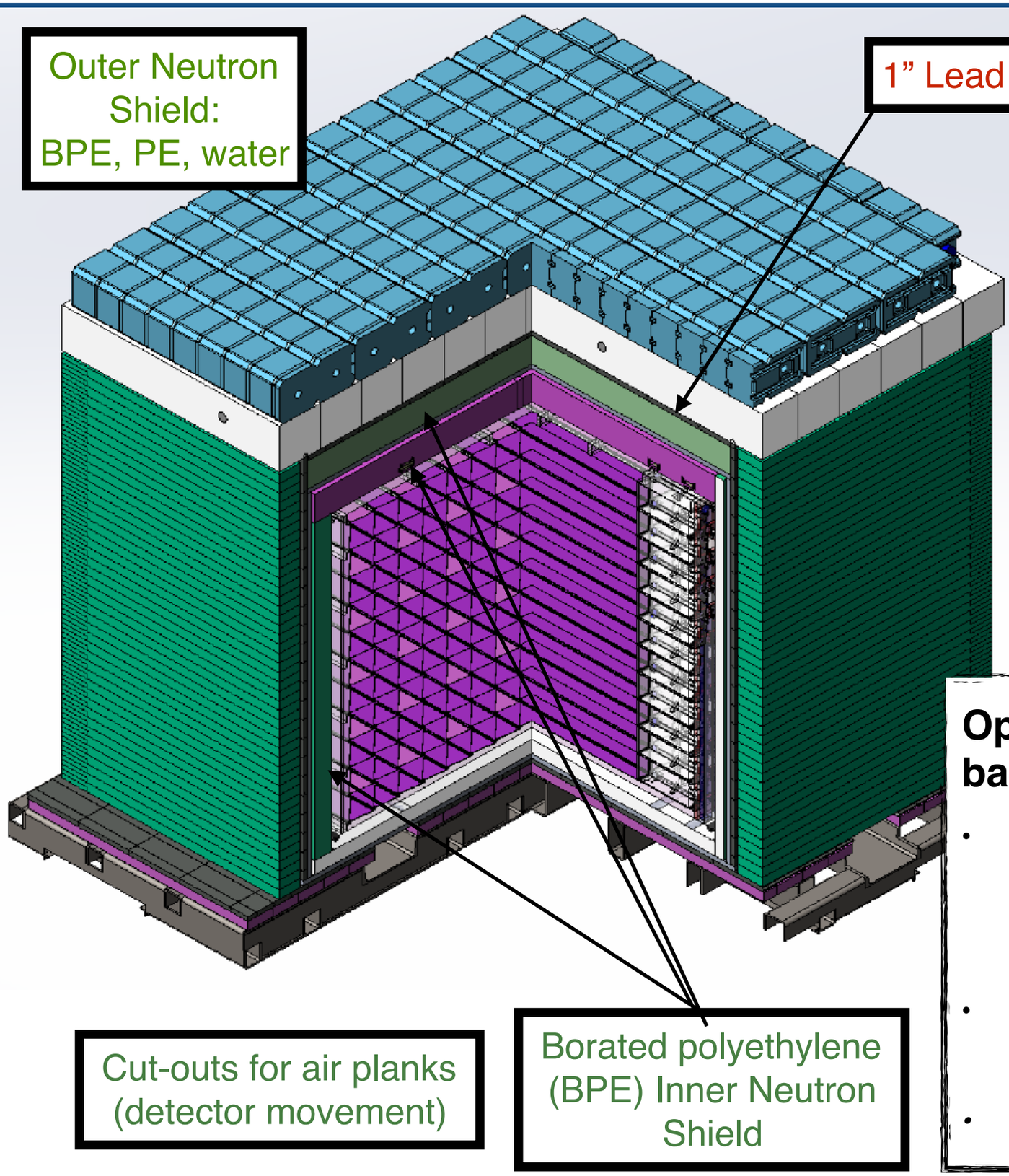


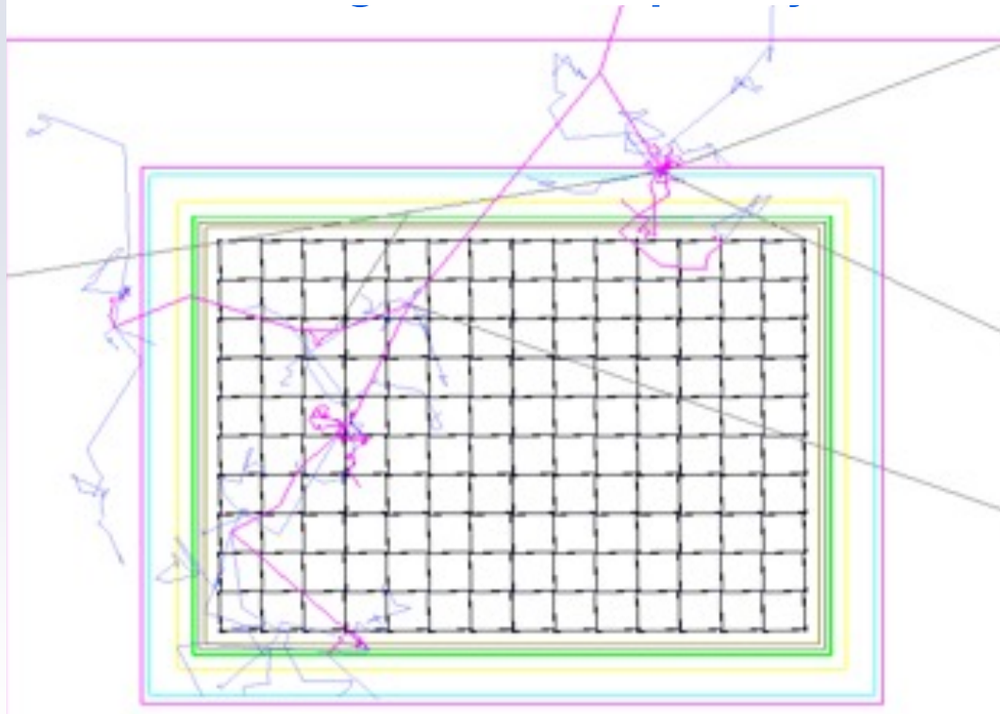


Unit segment

- 4ton lithium-loaded liquid scintillator ($^6$LiLS) antineutrino detector
- 11x14 optical segments
  - 15x15x120cm$^3$, ~25 liters each
  - **Identify multiple particle interactions, reject showers**
- Double-ended PMT readout
- Access for calibration sources between cells

# Novel Shielding Design



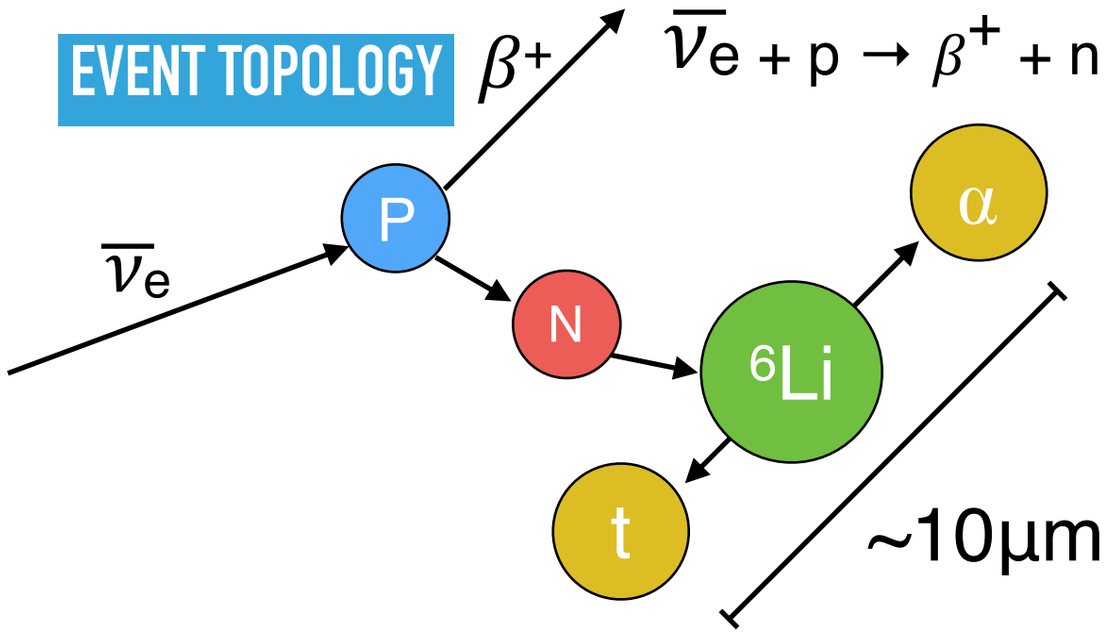



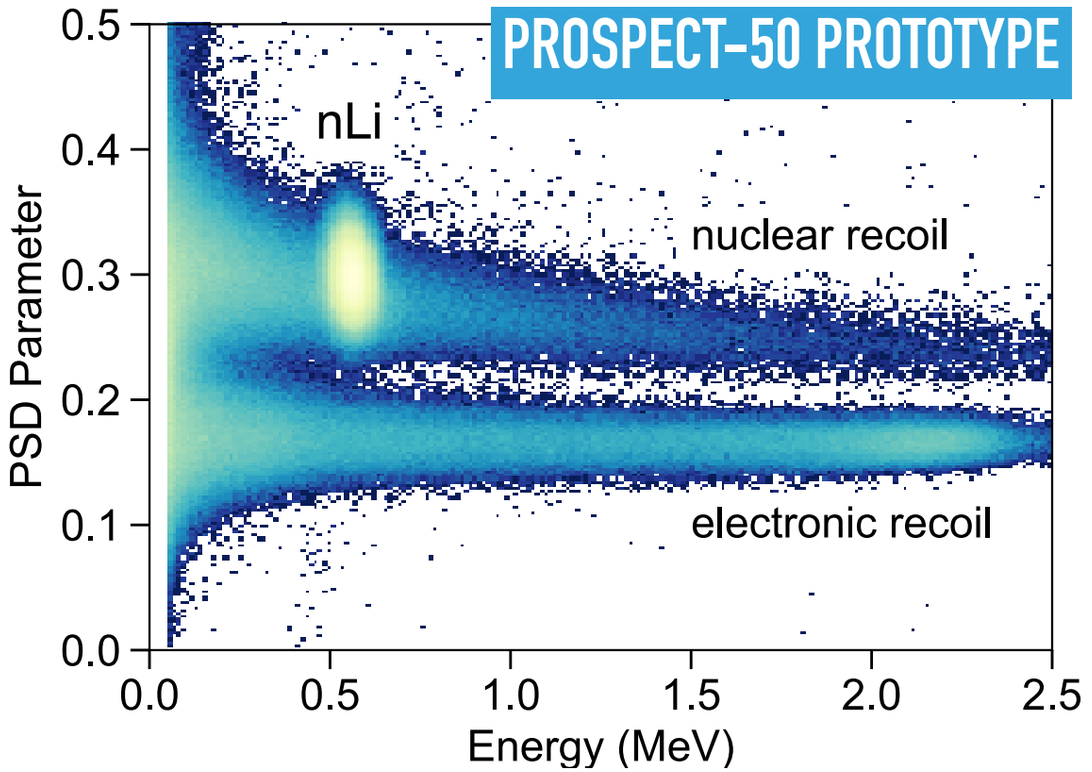
*Representative 500MeV Neutron Primary*

**Optimize space, weight, and total background suppression**

- Main problem is ~100MeV neutrons
  - create majority of IBD-like backgrounds (gamma-like prompt, neutron capture)
- Neutron spallation on high-Z shielding increases backgrounds
- *Need neutron shielding inside lead shielding*

# $^6$LI LOADED LIQUID SCINTILLATOR



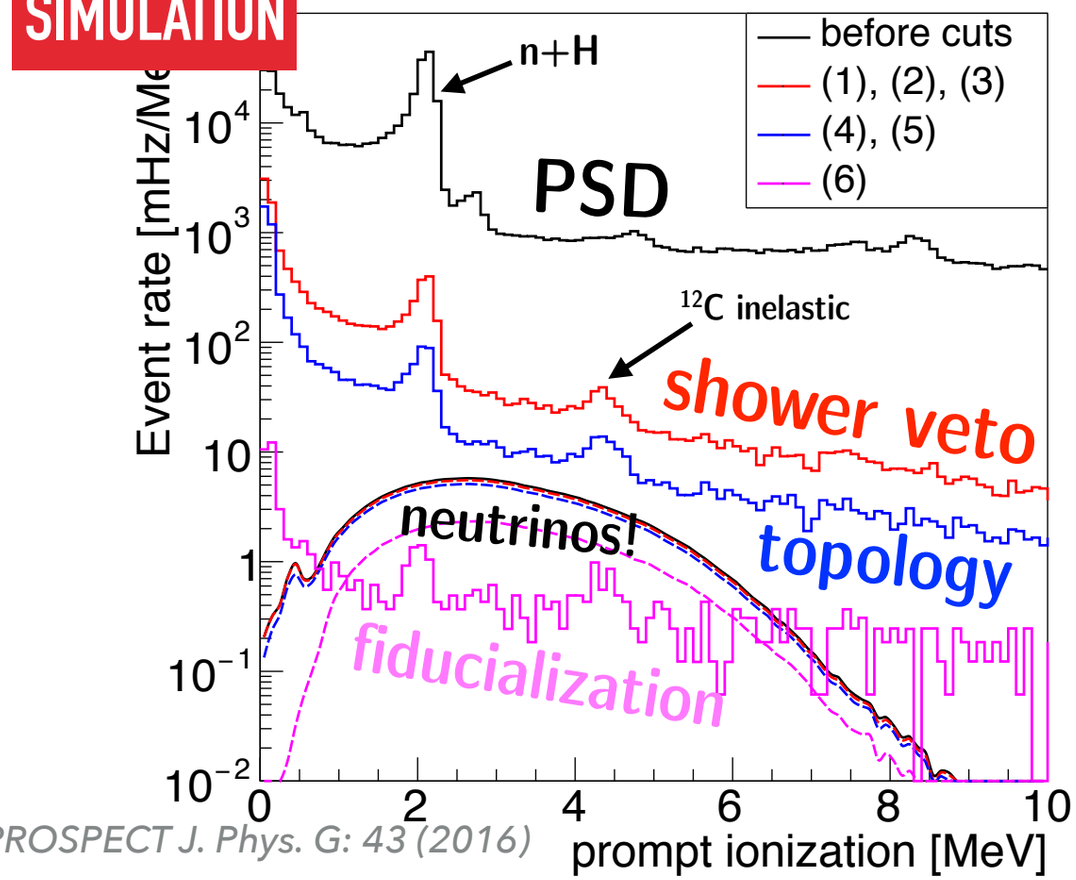




- Compact, segmented detector needs a capture agent that is highly localized
  - Minimize position dependent efficiency variation
  - Distance between prompt/delay to reject accidental backgrounds
- High light yield (8200ph/MeV) for energy resolution
- Particle ID through pulse-shape discrimination (PSD)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

*PROSPECT* [ARXIV:1805.09245](ARXIV:1805.09245)

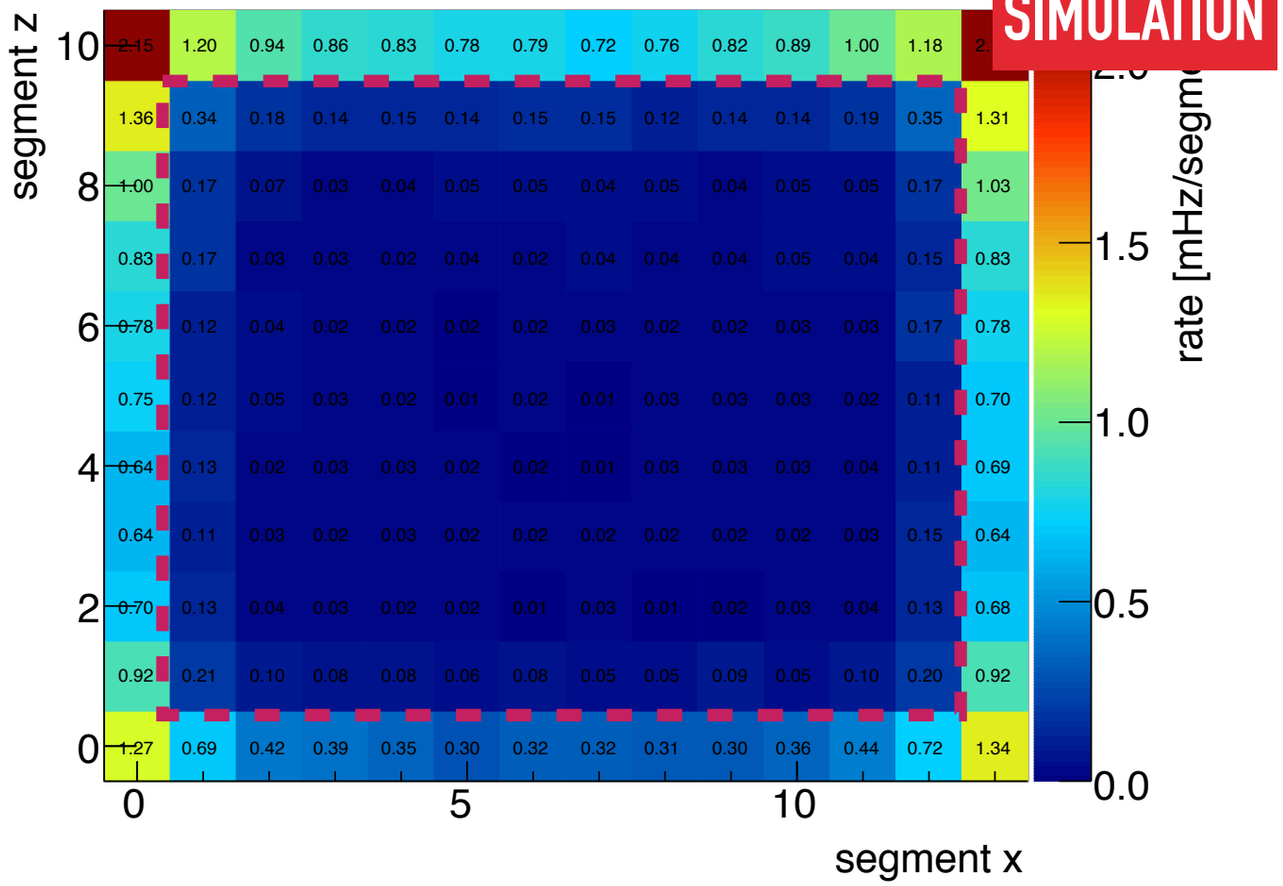
# ACTIVE BACKGROUND SUPPRESSION

SIMULATION



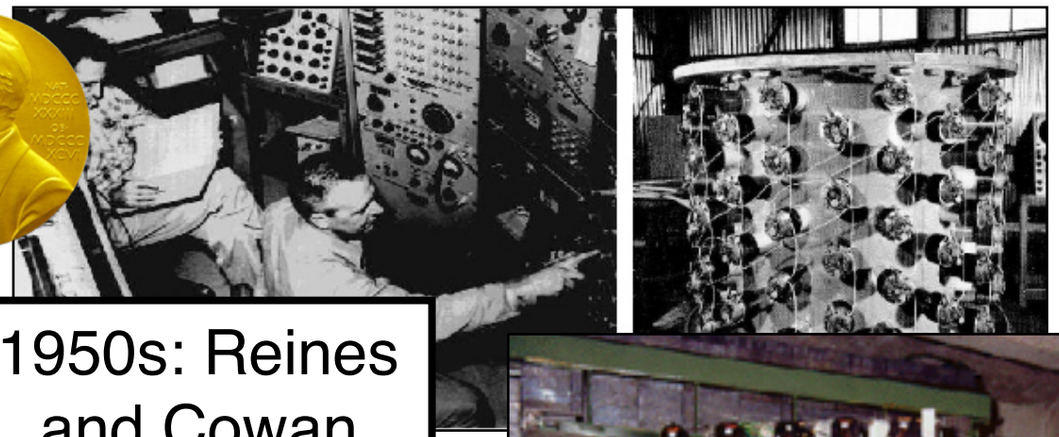

*PROSPECT J. Phys. G: 43 (2016)*

SIMULATION




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

# Reactors: Tools for discovery



1950s: Reines and Cowan

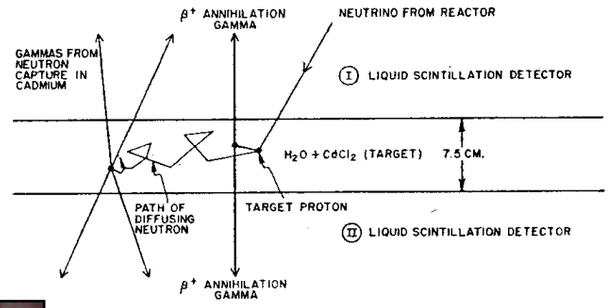
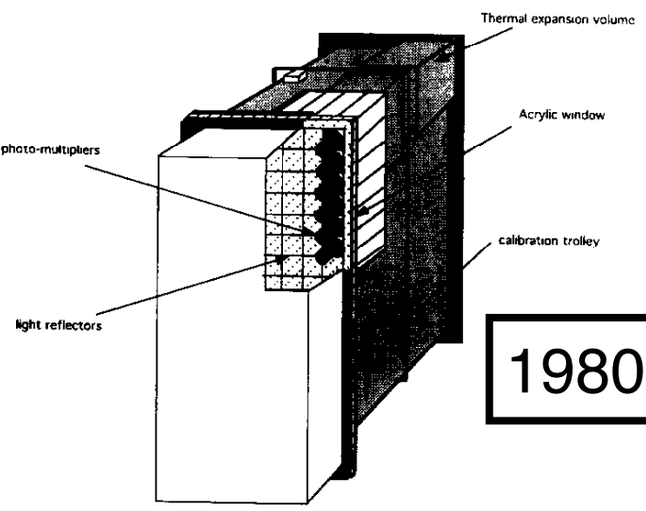
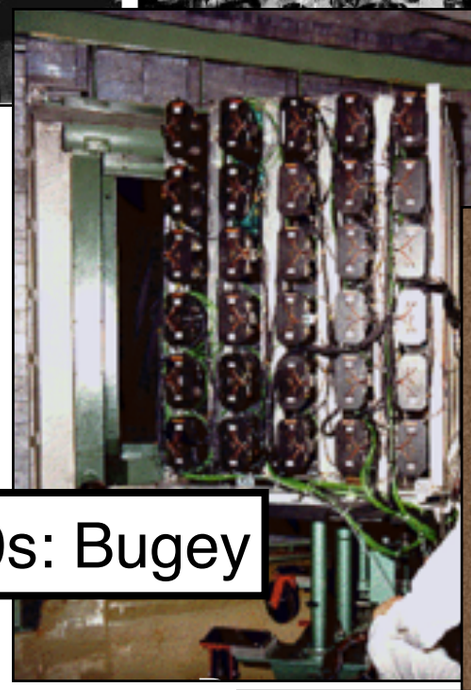
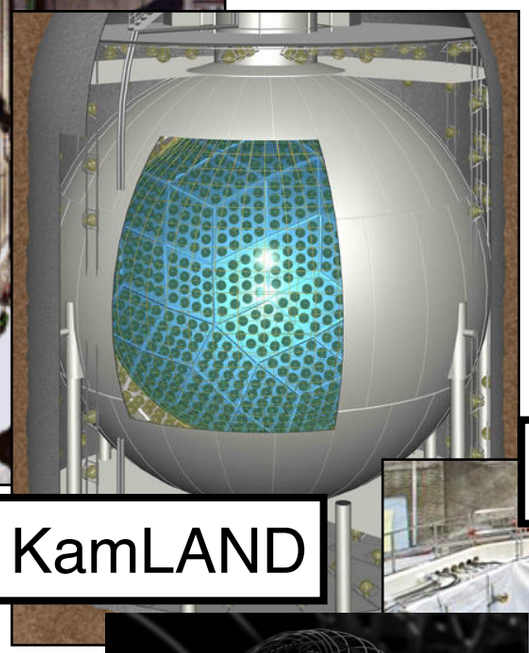



Fig. 1. Schematic diagram of neutrino detector

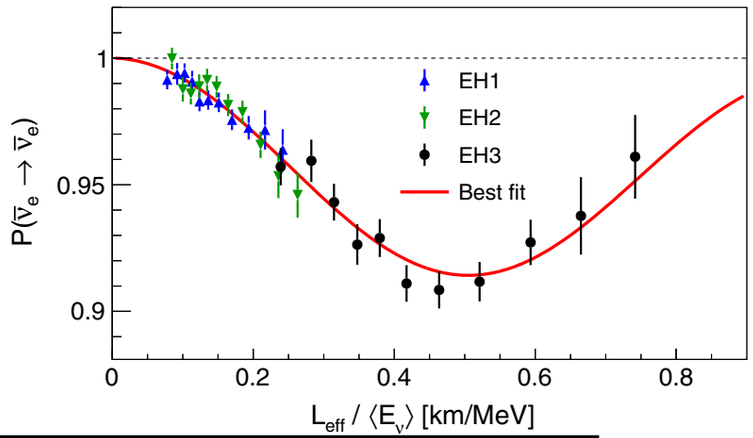


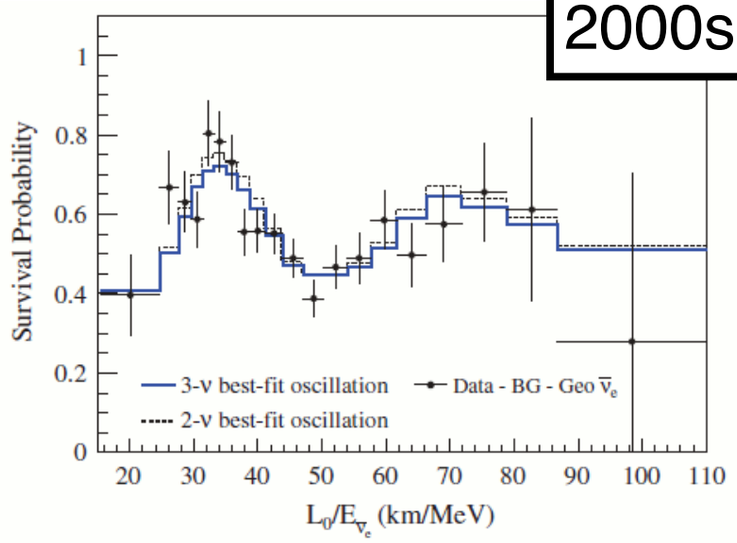
1980s: Bugey



2000s: KamLAND



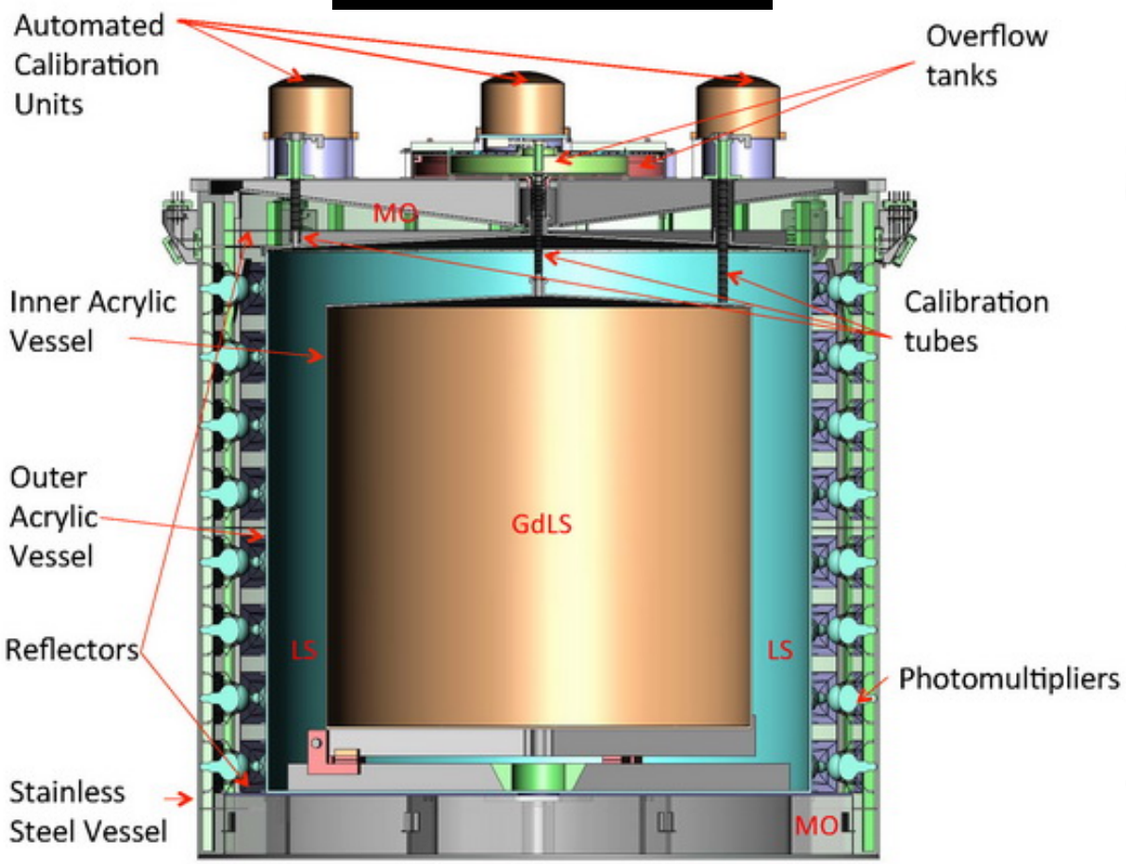

2010s: Daya Bay - $\theta_{13}$

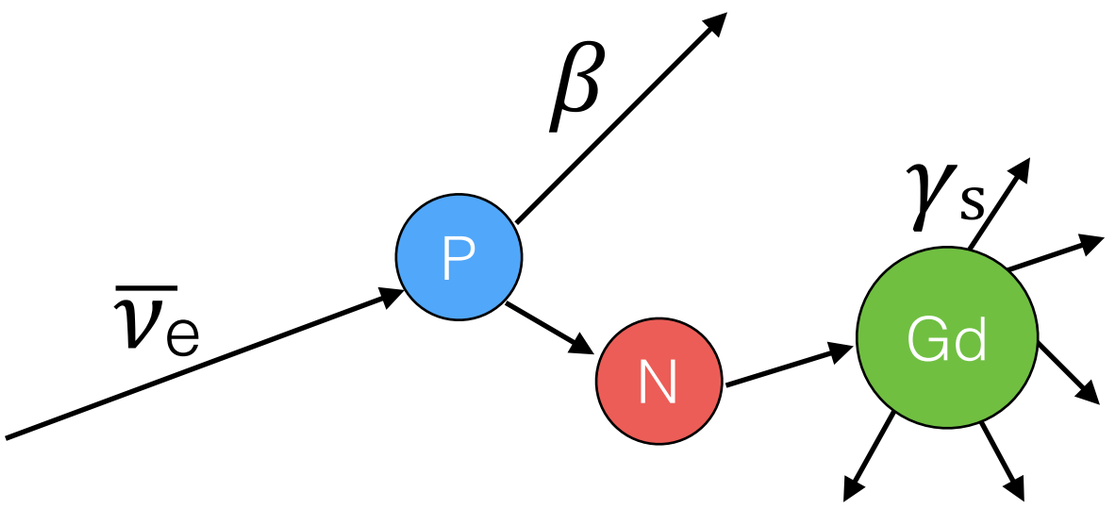


2018: PROSPECT

# Detecting Reactor Neutrinos

## Daya Bay



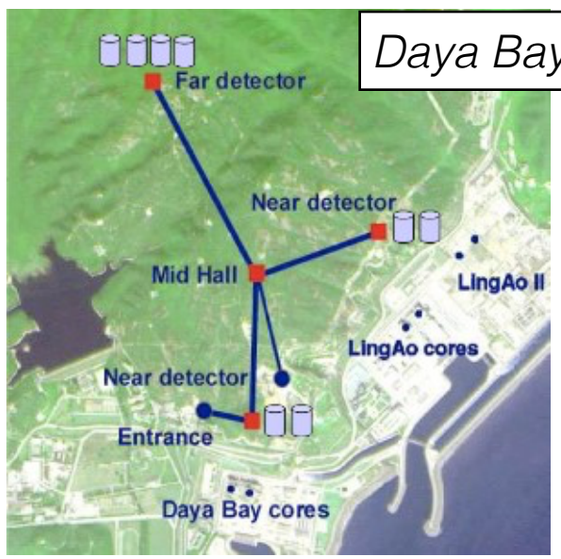

**Inverse Beta Decay: $\bar{\nu}_e p \rightarrow e^+ n$**

- 0.1%Gd-Loaded Organic liquid scintillator (GdLS) surrounded by photomultiplier tubes
- Neutrinos interact with free protons
- $E_\nu = T_{e+} + T_n + (m_n - m_p) + m_e \approx T_{e+} + 1.8\text{MeV}$
- Neutrino energy threshold of 1.8 MeV, producing signal of ~1MeV
- Capture resulting neutron as a tag of IBD interaction (typically Gd)
- Time-correlated signals, separated by ~10s $\mu$s

# Precision Reactor Neutrino Physics

Kilometer baseline $\theta_{13}$ precision experiments: Daya Bay, Double Chooz, RENO

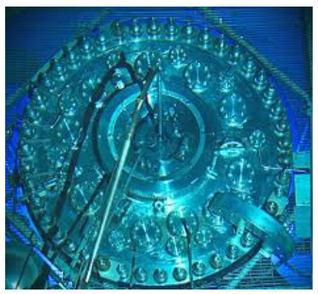
*Daya Bay antineutrino detectors*




*Daya Bay site*

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - sin^2(2\theta) sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

*survival probability*



*reactor core*

fraction anti-$\nu_e$

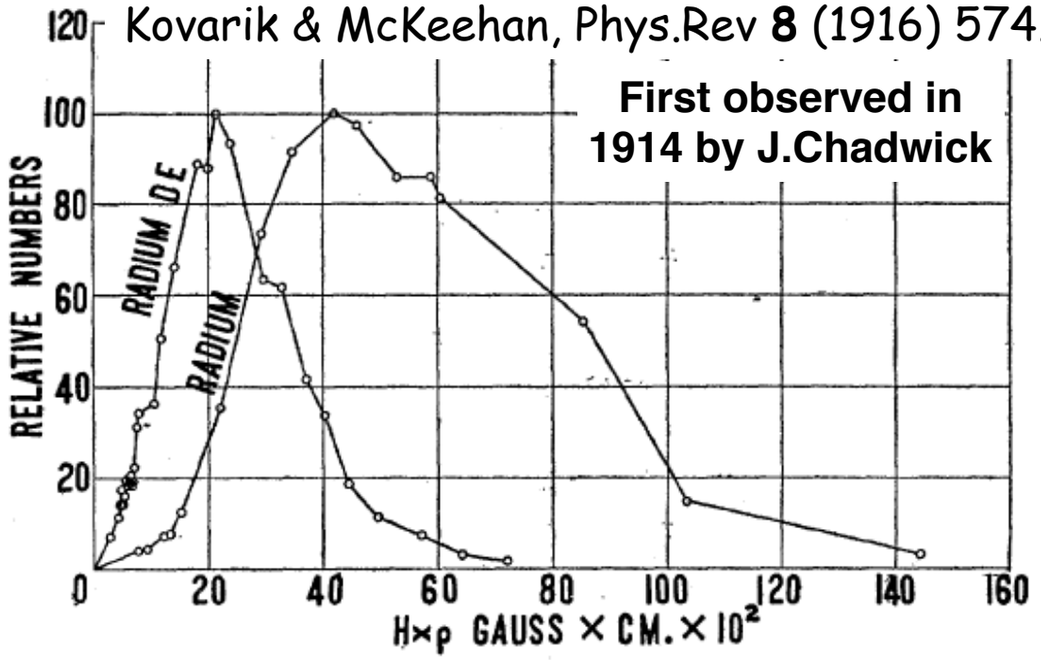
detect inverse beta decay:
anti-$\nu_e$ + p → $e^+$ + n

*near detector*

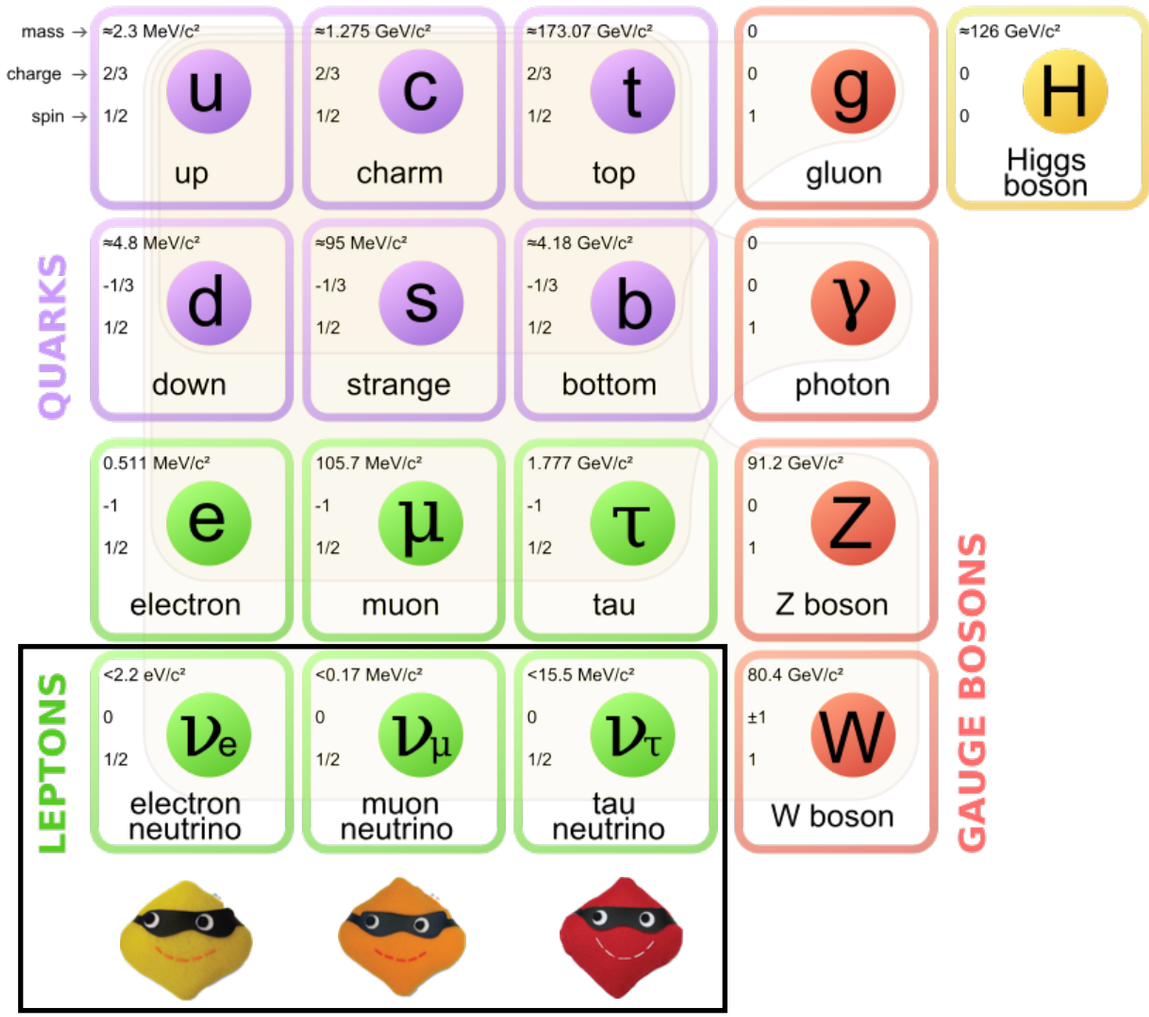
*far detector*

Relative measurements reduce dependence on predictions of reactor properties

# Neutrinos in the Standard Model




*Pauli(1930): "I have hit upon a desperate remedy to save…the law of conservation of energy."*




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

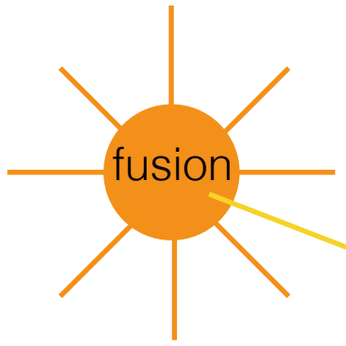
## Detection of the Free Neutrino: a Confirmation

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

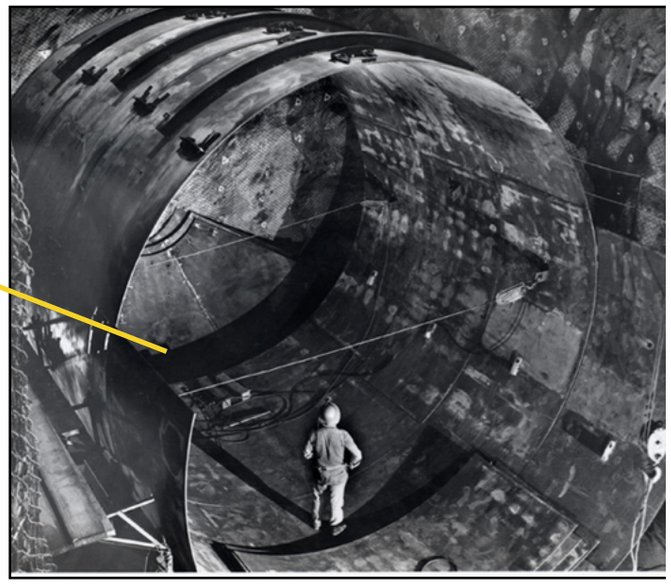
- Neutrinos were added to the SM to address the beta-decay "anomaly"
- *Successfully detected ~40 years later at the Savannah River Reactor*

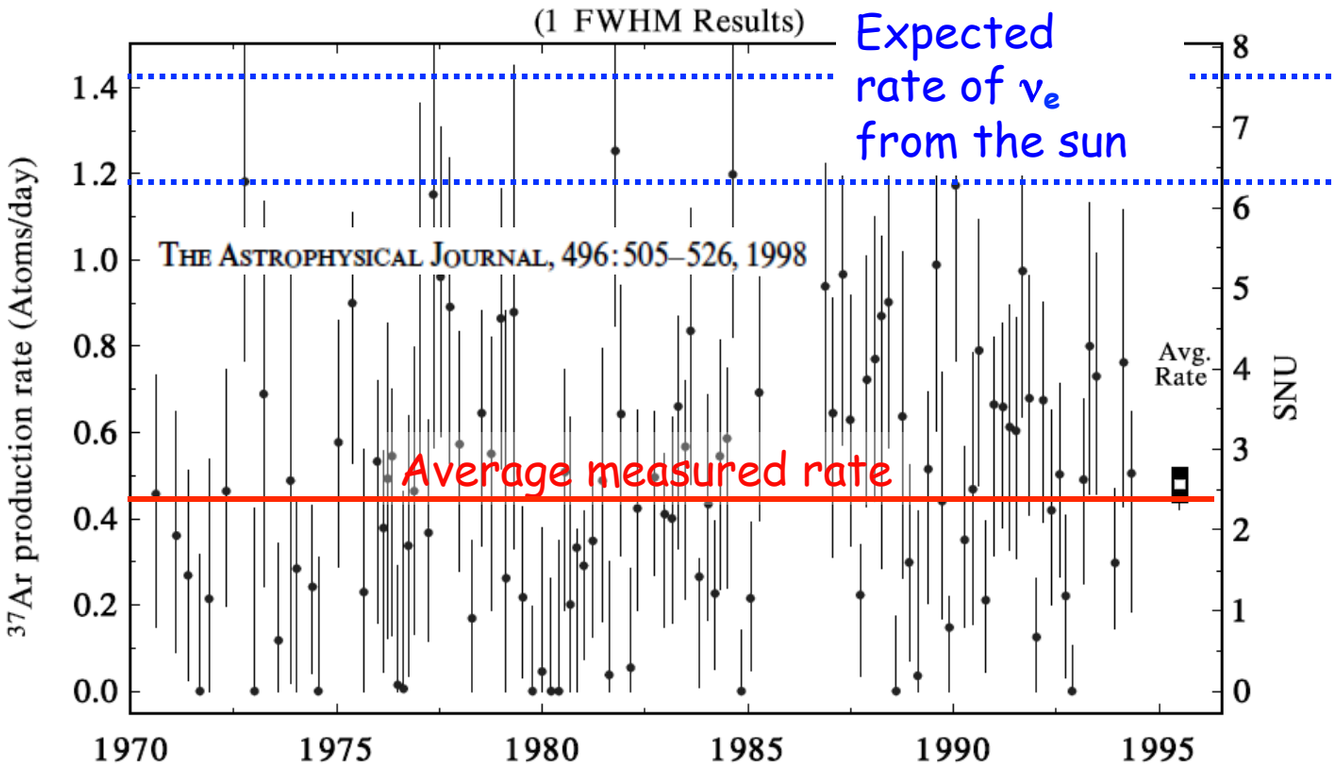
# Neutrino Anomalies…

## solar neutrino anomaly

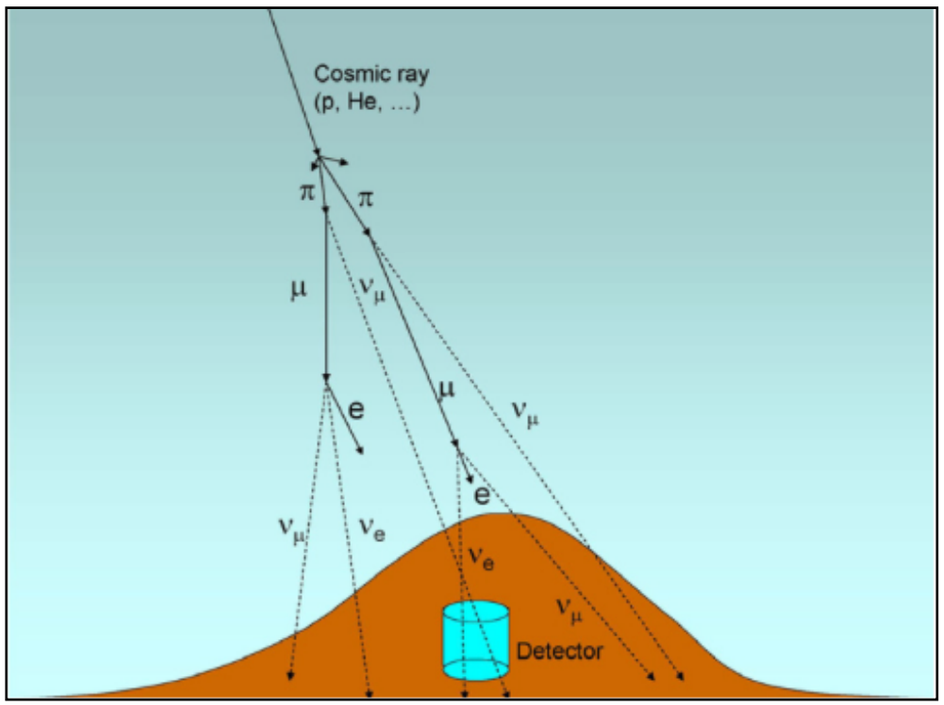


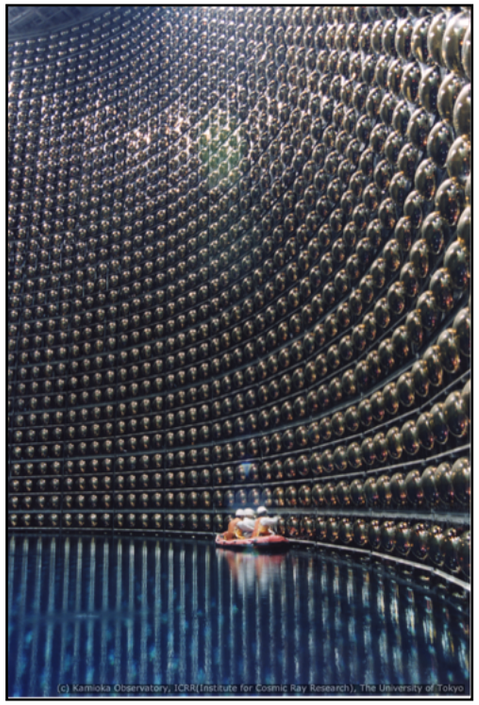

$\nu_e$

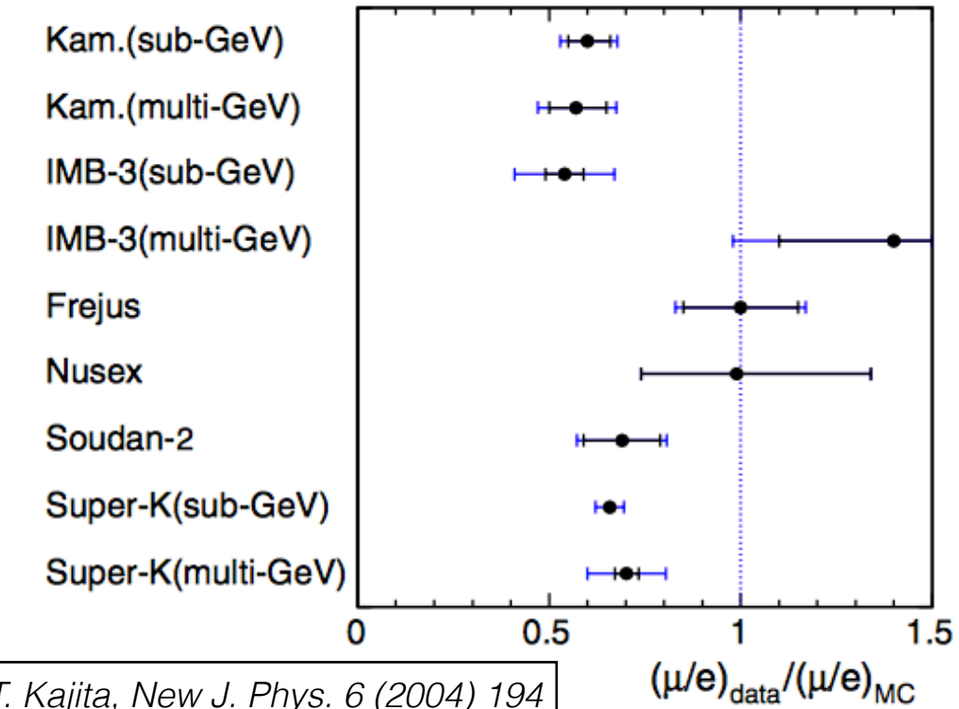





## atmospheric neutrino anomaly



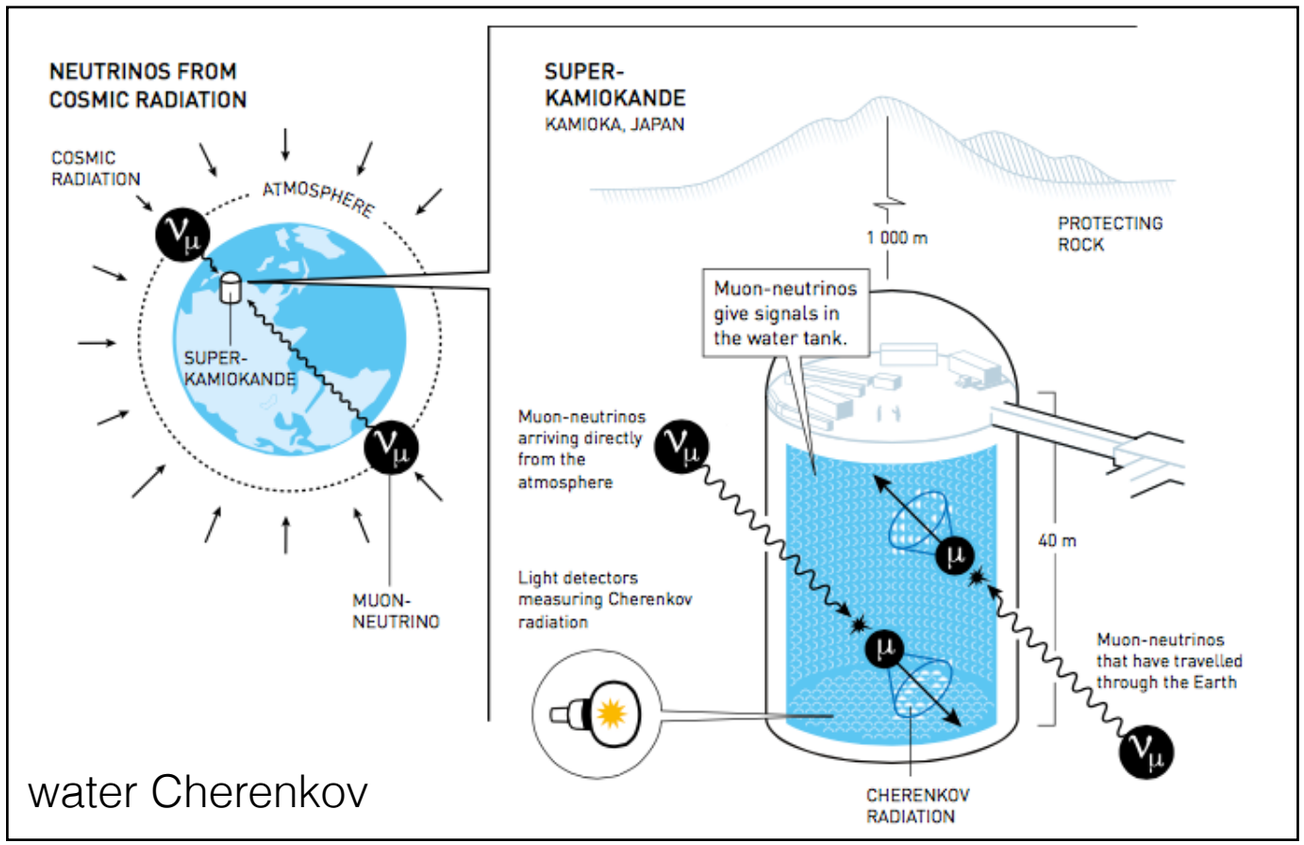





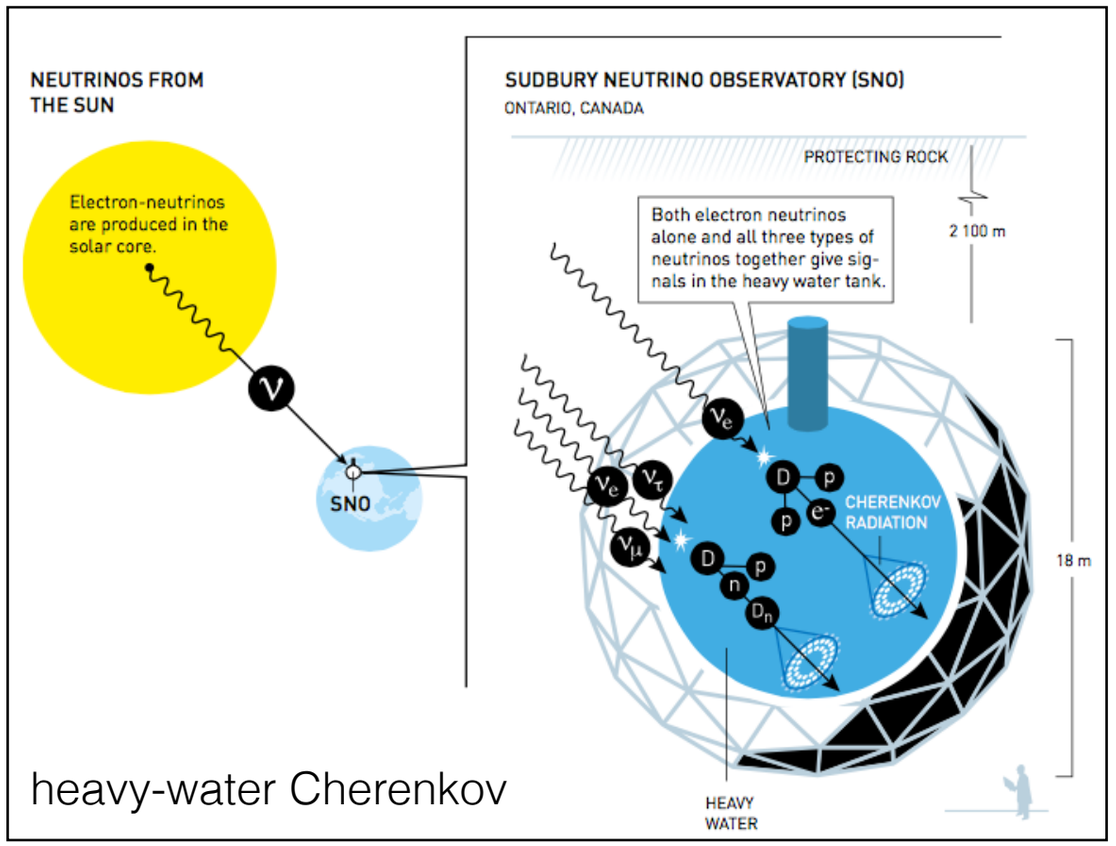

*T. Kajita, New J. Phys. 6 (2004) 194*

# … Lead to Discoveries

*Super-Kamiokande 1998: solved atmospheric anomaly*




*SNO 2001: solved solar anomaly*



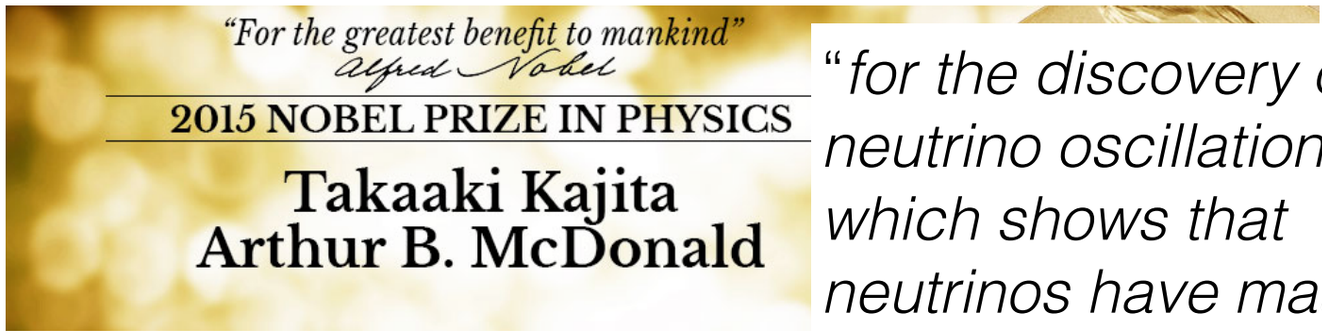

**$\nu_\mu \rightarrow \nu_\tau$ oscillation through the earth**

**sum of all $\nu$ matched solar prediction**

**The Nobel Prize in Physics 2002**

Raymond Davis Jr., Masatoshi Koshiba, Riccardo Giacconi

"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

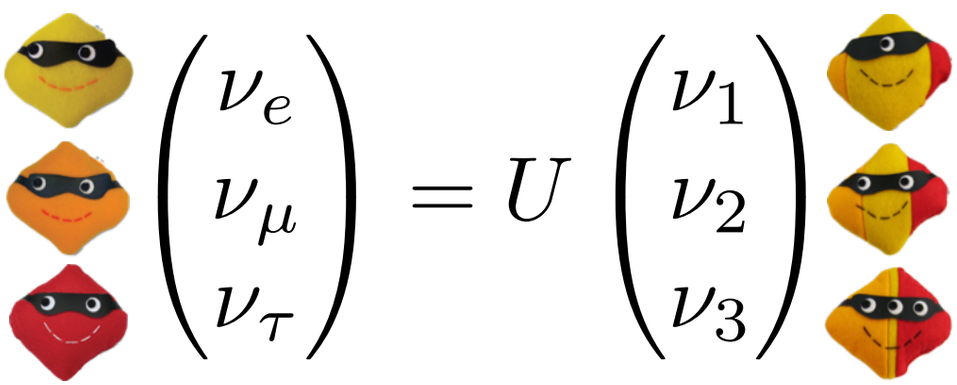



"*for the discovery of neutrino oscillations which shows that neutrinos have mass*"

# Neutrino Oscillations

Neutrinos undergo oscillations between flavor and mass states, implying they are massive (although very light) particles.

*flavor states* *mass states*



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \quad where\ U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\nu 1} & U_{\nu 2} & U_{\nu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

*production* *propagate* *PMNS mixing matrix*

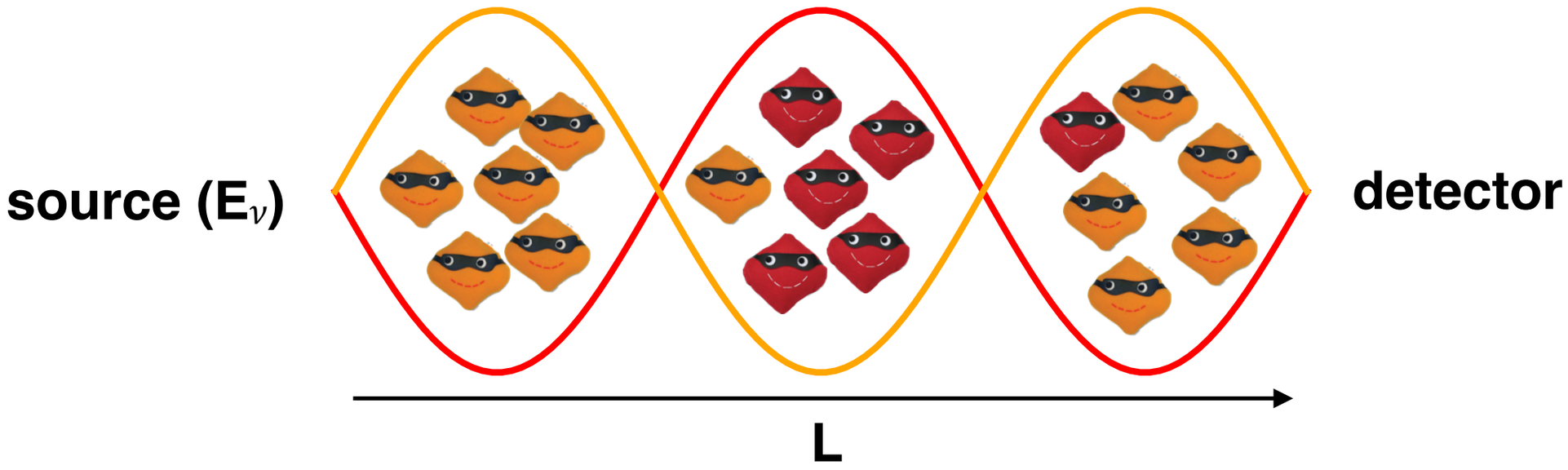
*atmospheric/accelerator* *reactor* *solar*

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & -0 & 1 \end{pmatrix}$$

$$where\ c_{ij} = cos(\theta_{ij})$$
$$s_{ij} = sin(\theta_{ij})$$
$$\delta = CP\ phase$$

# Ex: Two Neutrino Oscillation

$$P_{\alpha\to\beta,\alpha\neq\beta} = sin^2(2\theta)sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right) \quad where \;\; \alpha,\beta = \nu_e,\nu_\mu,\nu_\tau$$

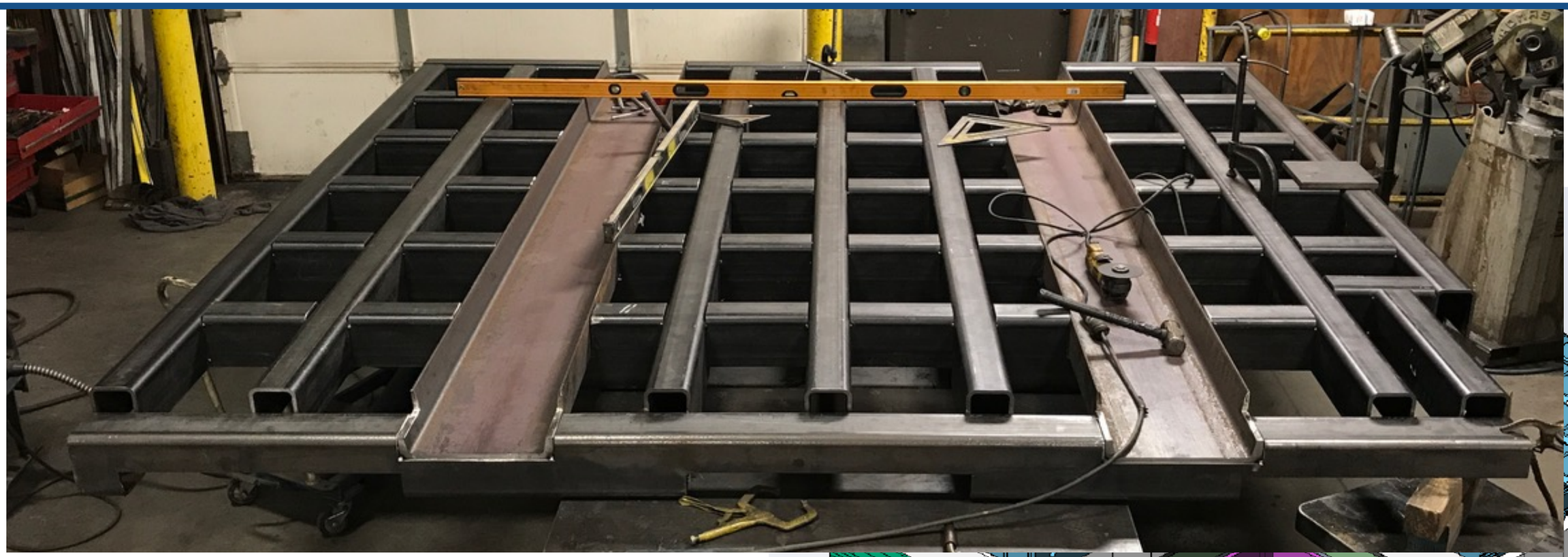


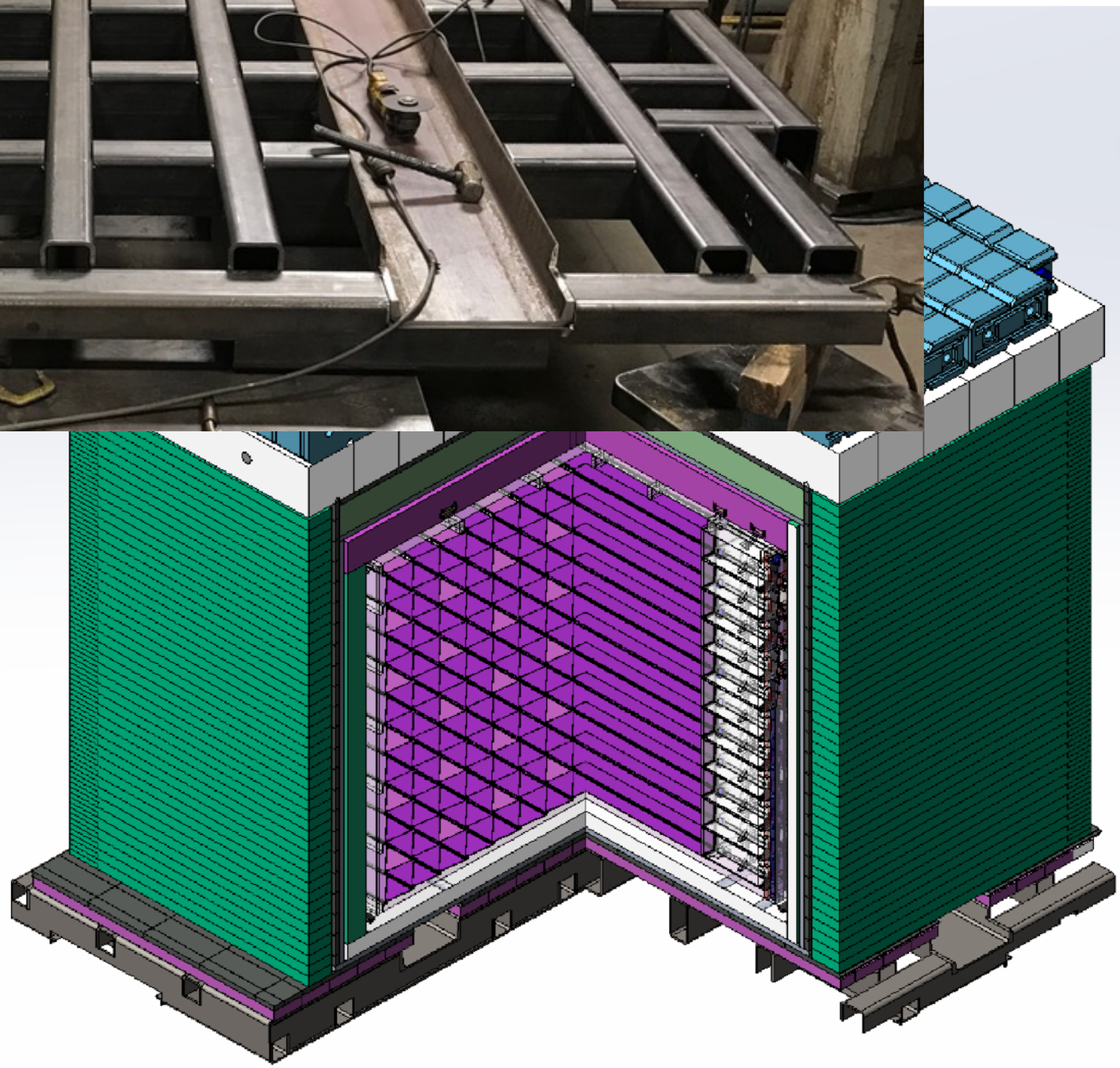

Parameters $\theta$ (mixing angle - amplitude) and $\Delta m^2$ (mass splitting - frequency) are defined by nature. We can target specific $\Delta m^2$ measurements by designing our experiments to have a certain L/E.

# Outline

- ~~Neutrinos in the Standard Model~~
- Reactor neutrinos and new anomalies
- **PROSPECT**: The Precision Reactor Oscillation and Spectrum Experiment
- Current efforts

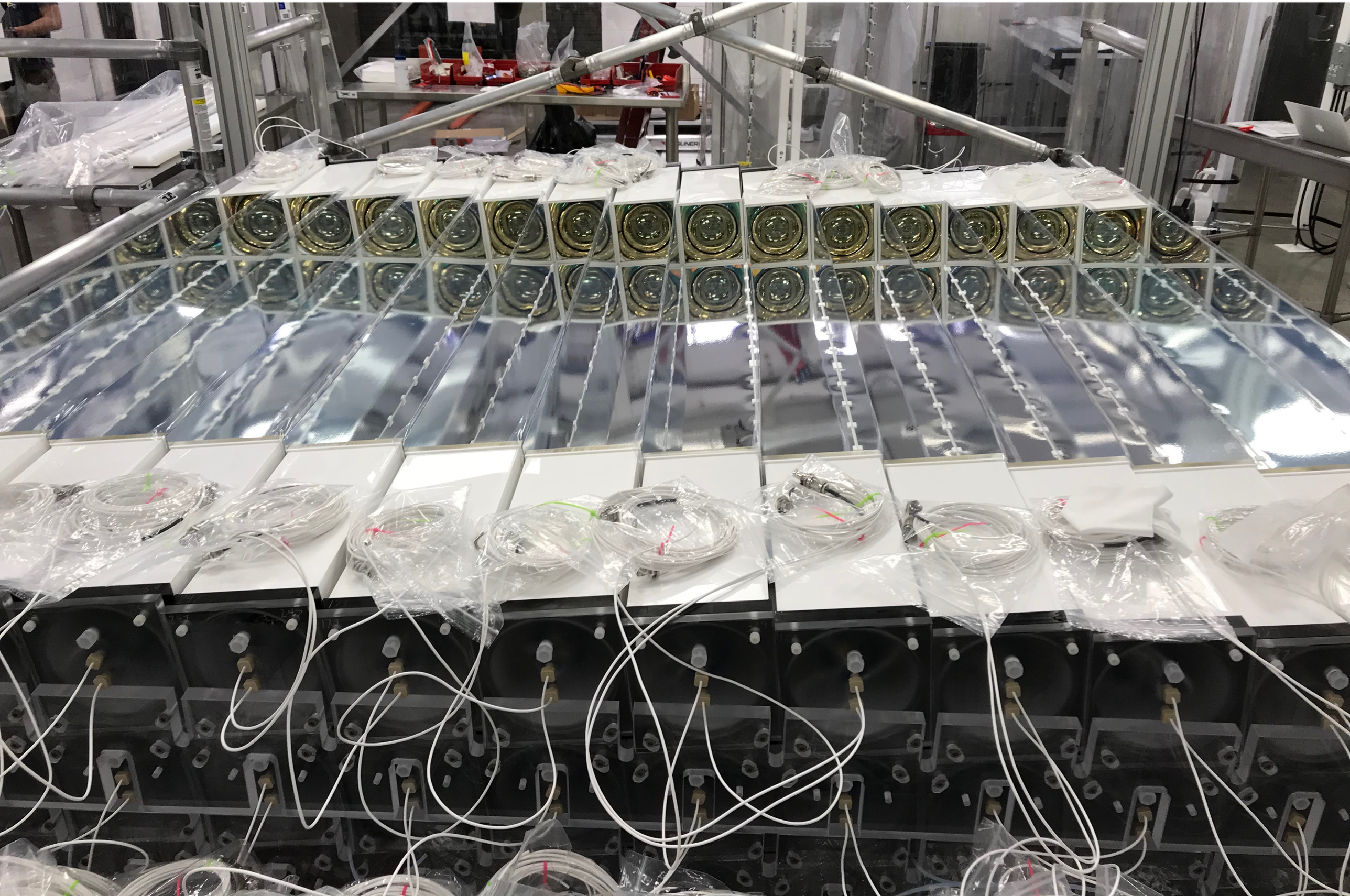
# Novel Shielding Design





Cut-outs for air planks (detector movement)

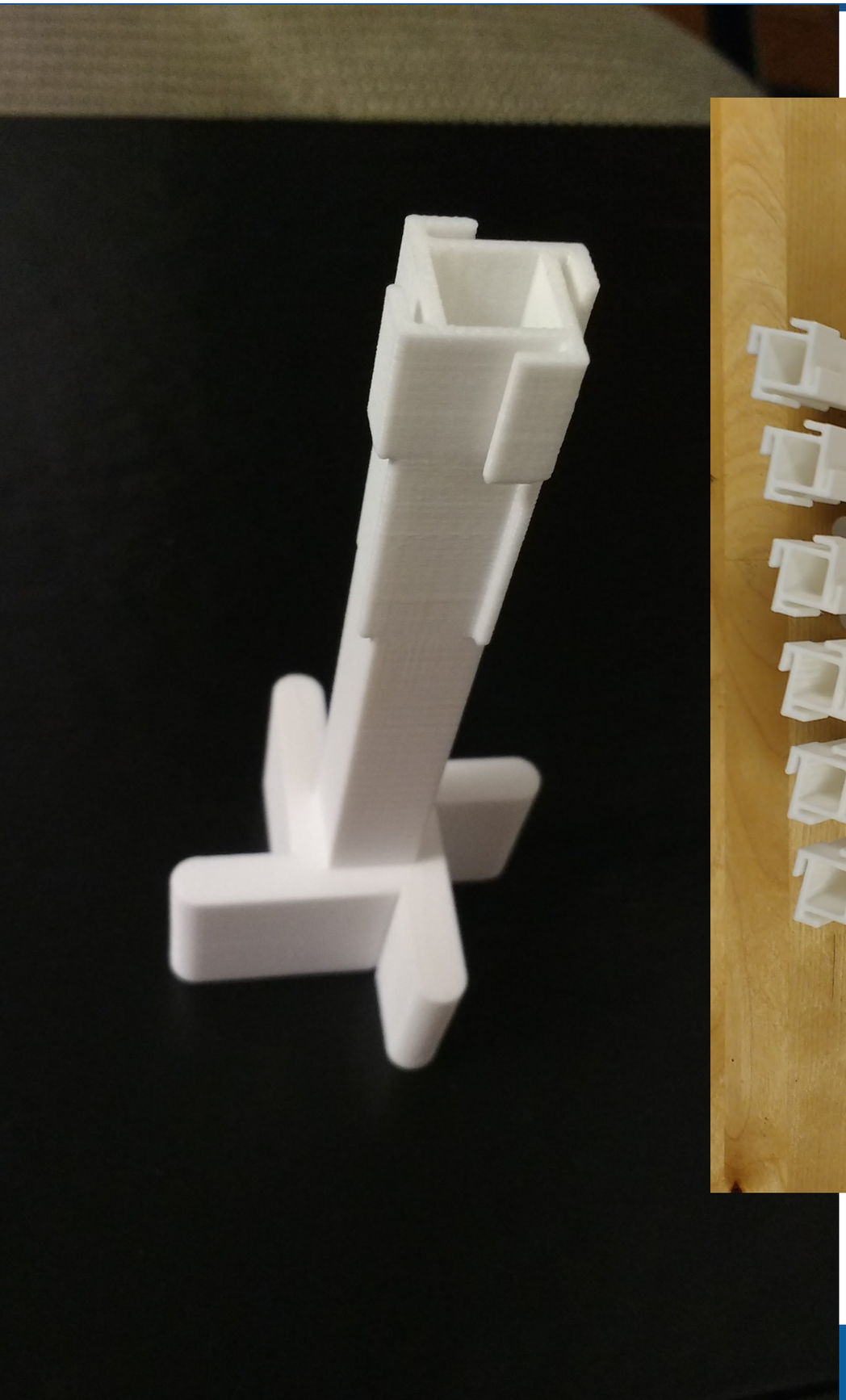
# AD assembly



# AD assembly

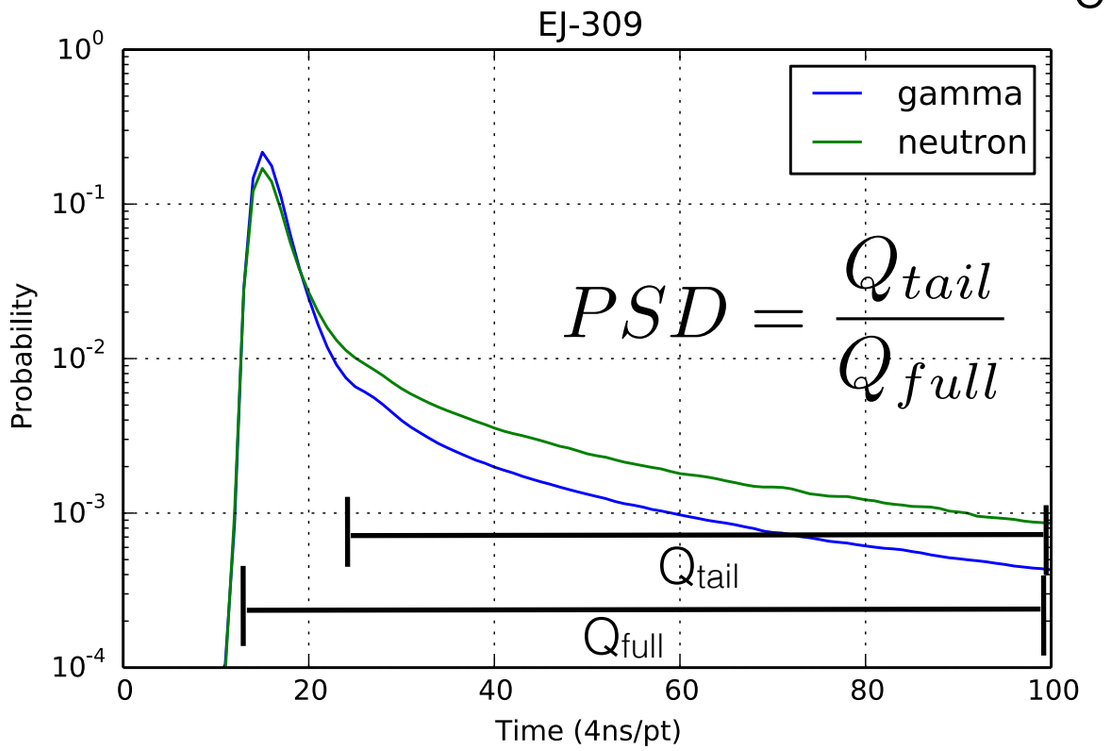
# AD assembly

# Reflectors and pinwheels

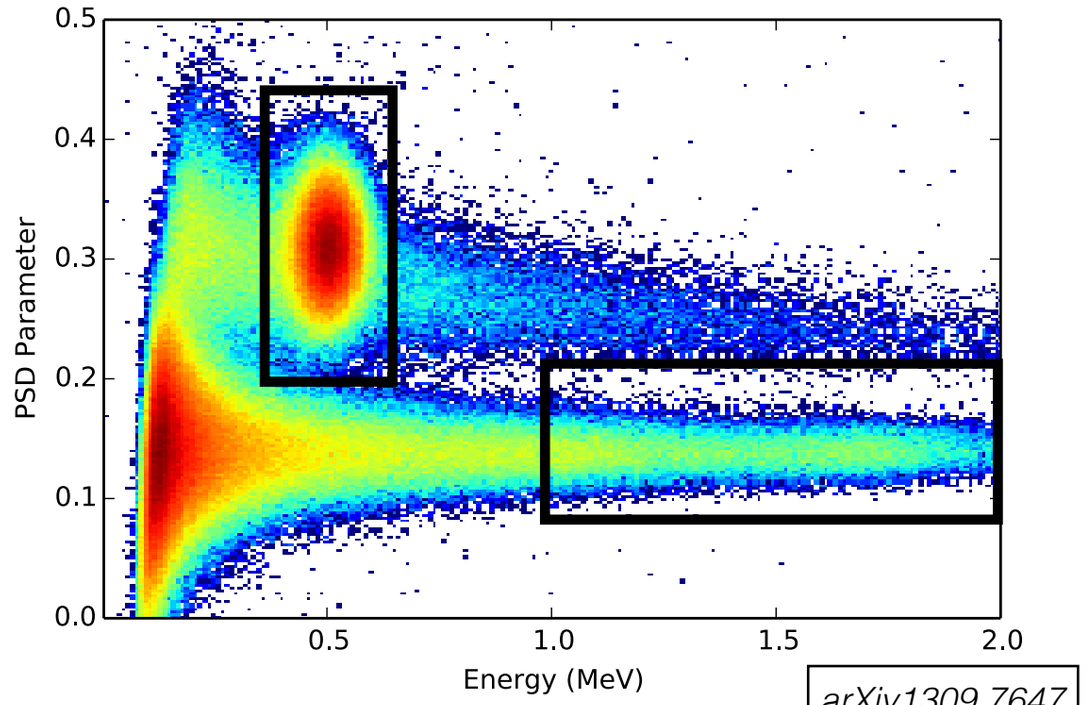


# Pulse Shape Discrimination

Can take advantage of how different particles deposit energy in scintillator using pulse-shape discrimination (PSD). Gives particle identification information.




energy+PSD cuts for prompt and delay signals



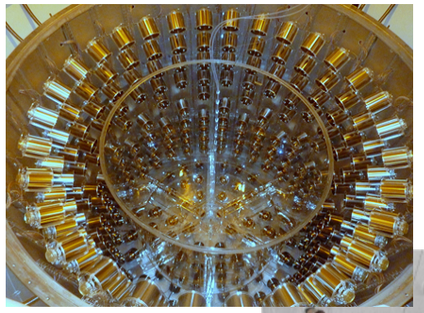

*arXiv1309.7647*

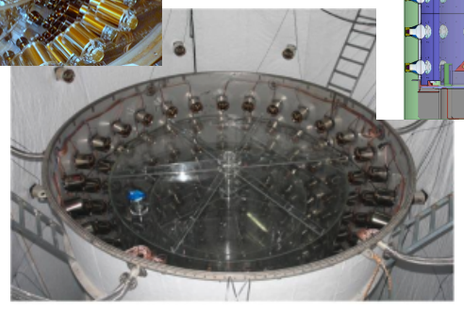
PROSPECT-2 (LiLS)

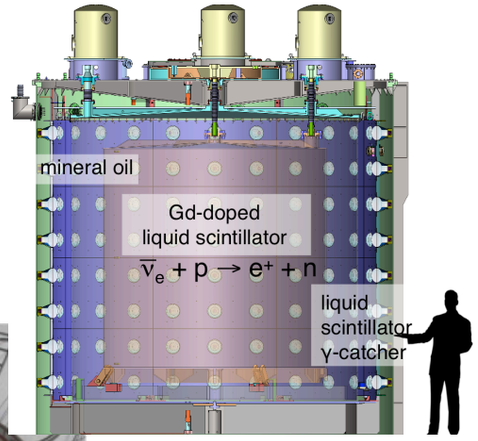
particle classification: light particles = “gamma-like”, heavy charged = “neutron-like”

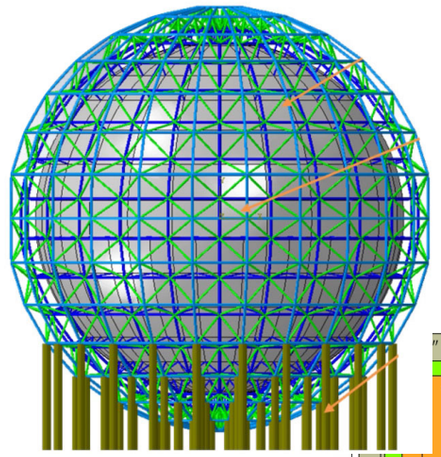
# Baselines Probe Different Parameters

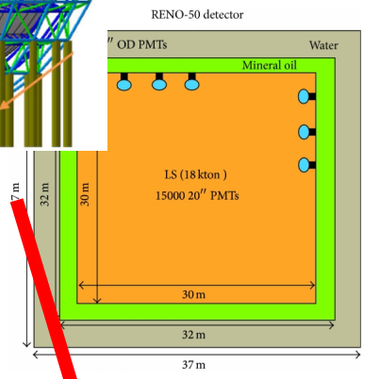
PROSPECT

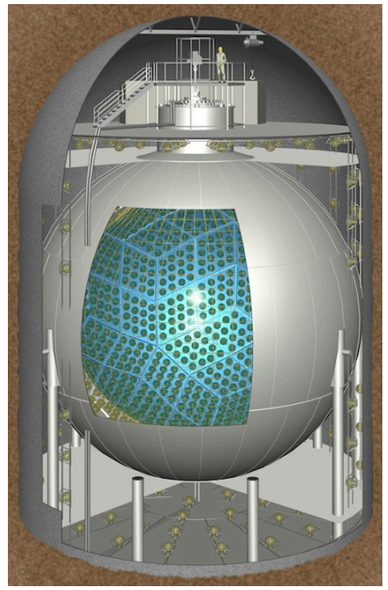


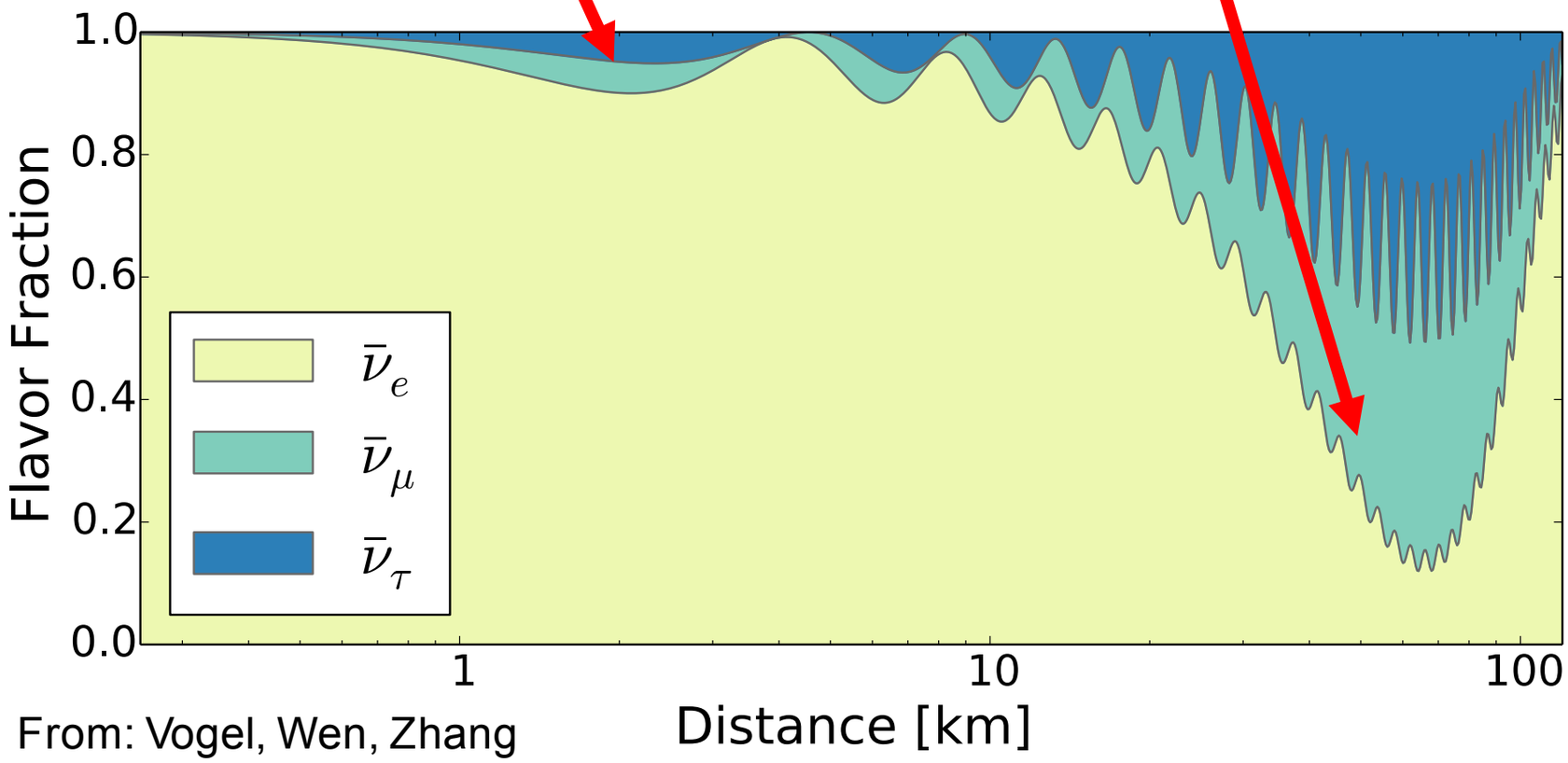




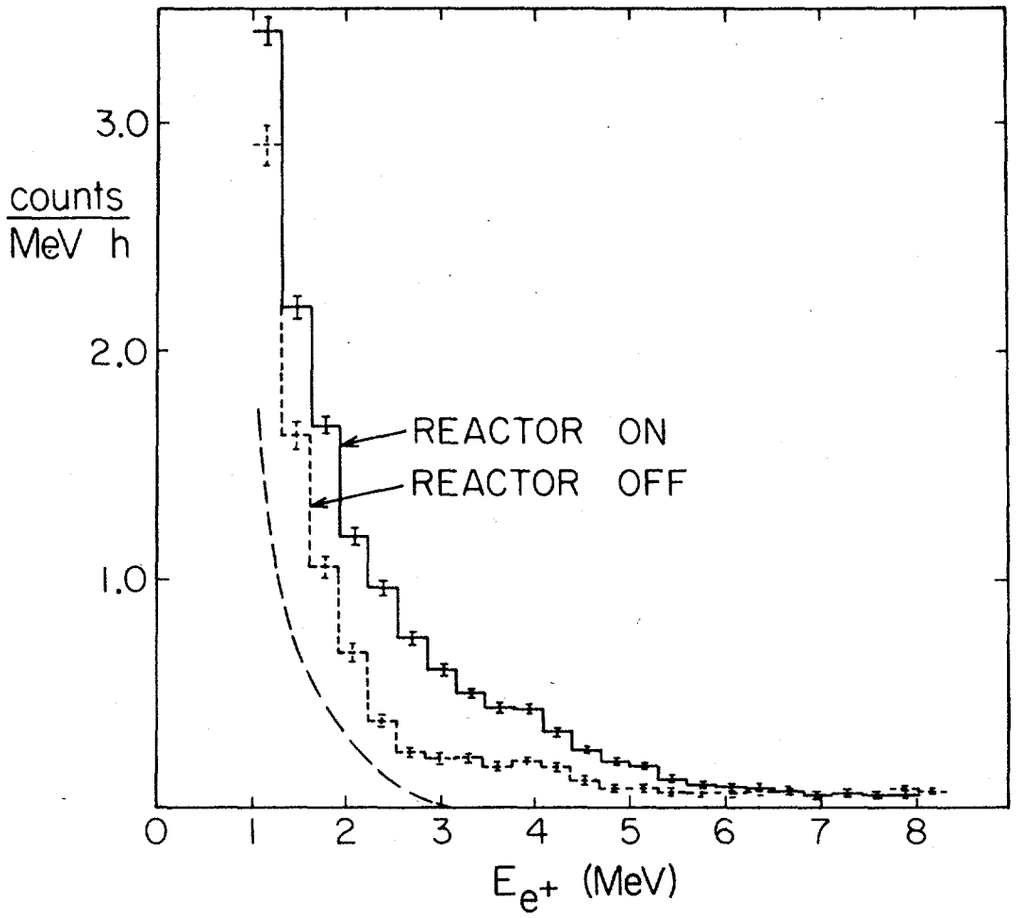


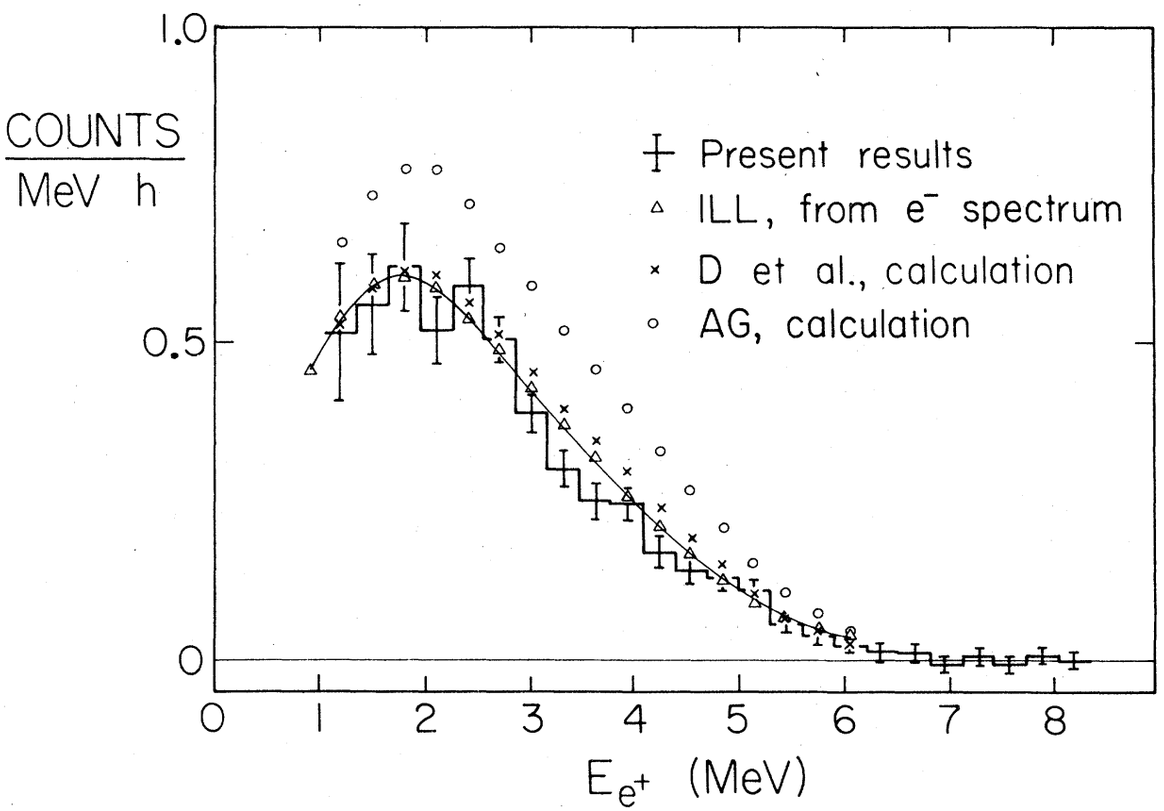





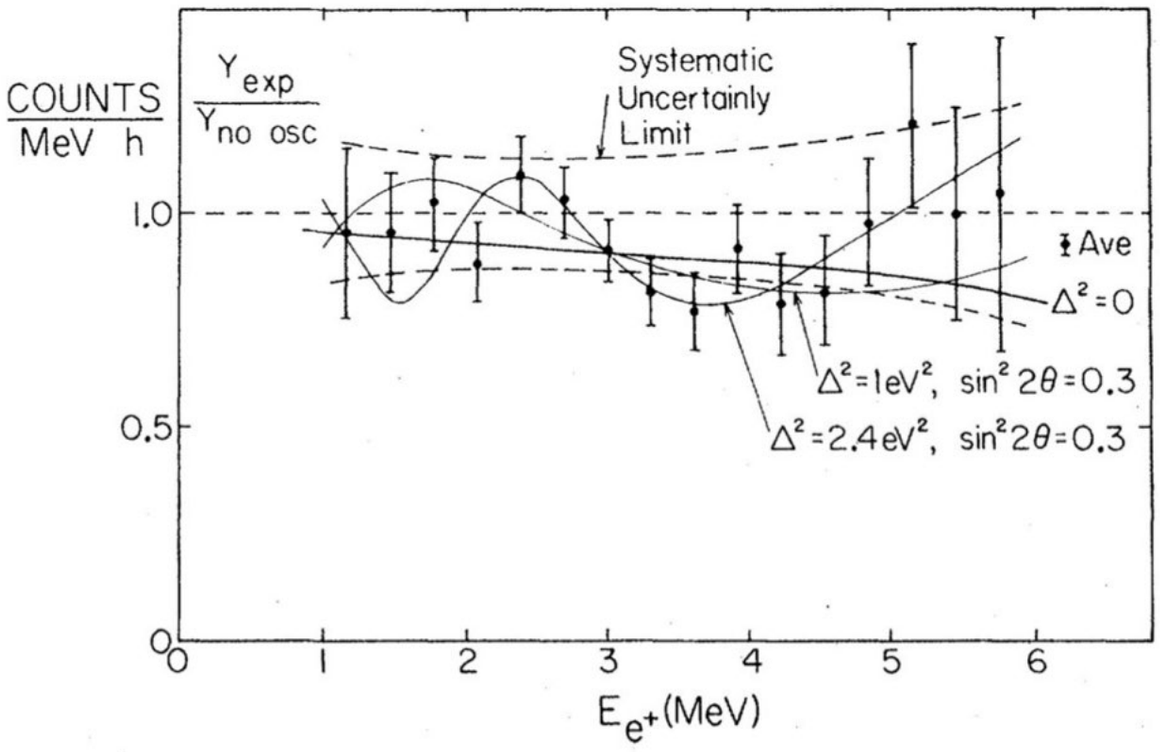

From: Vogel, Wen, Zhang

# ILL $^{235}$U Spectrum Measurement



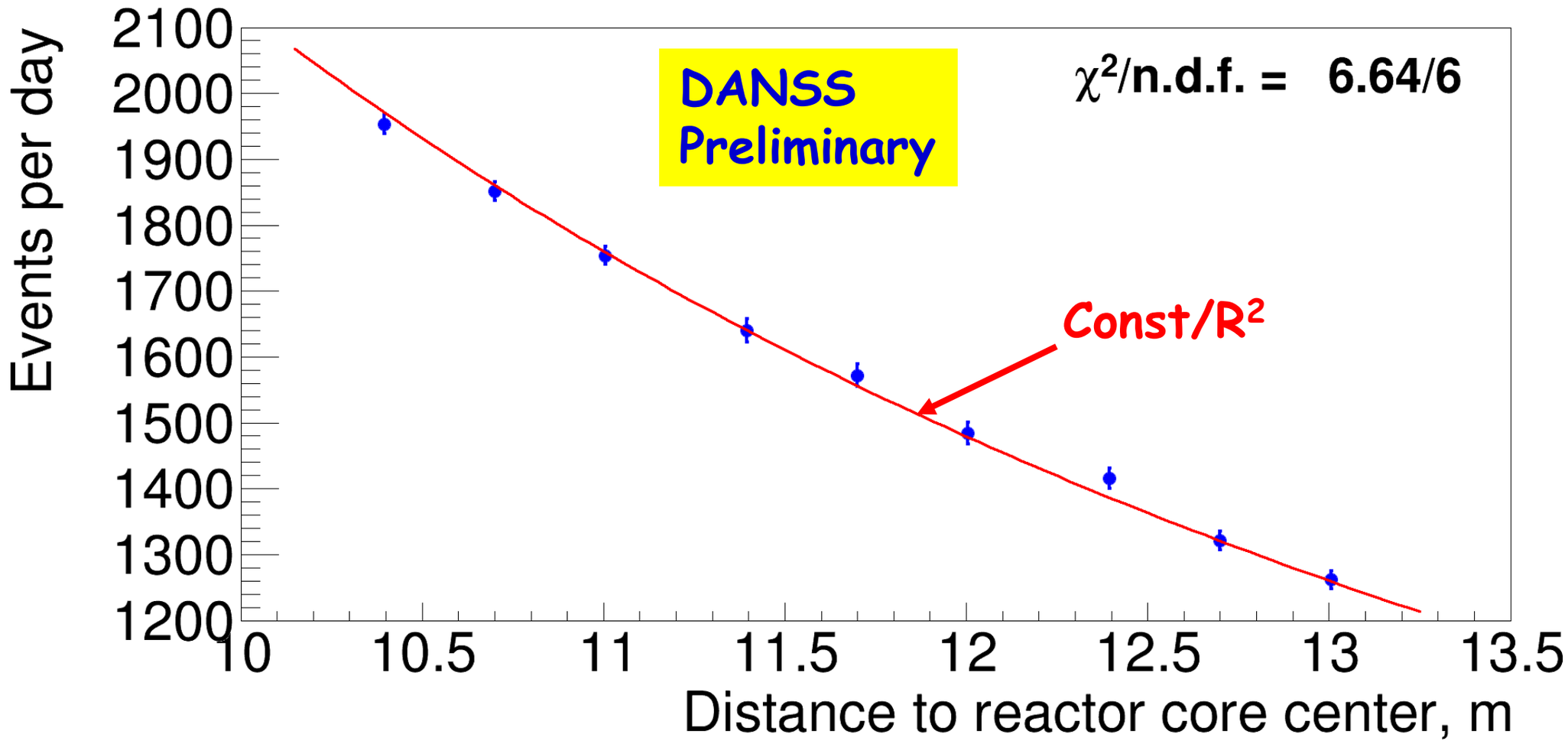




- **1981:** Only published measurement of $^{235}$U spectrum at ILL reactor in France with S/B ~ 1
- ±20% uncertainties, unable to constrain reactor models
- Fewer than 5000 neutrino events detected



# $\bar{\nu}$ counting rate dependence on distance from reactor core

Detector was split into 3 sections along z (~30cm each)
Each section has 3 positions – up, middle, down
Normalization (efficiency) for central section is a fit parameter
Differences in efficiency of central and 2 other sections are also fit parameters




***Perfect agreement with 1/R$^2$ dependence***

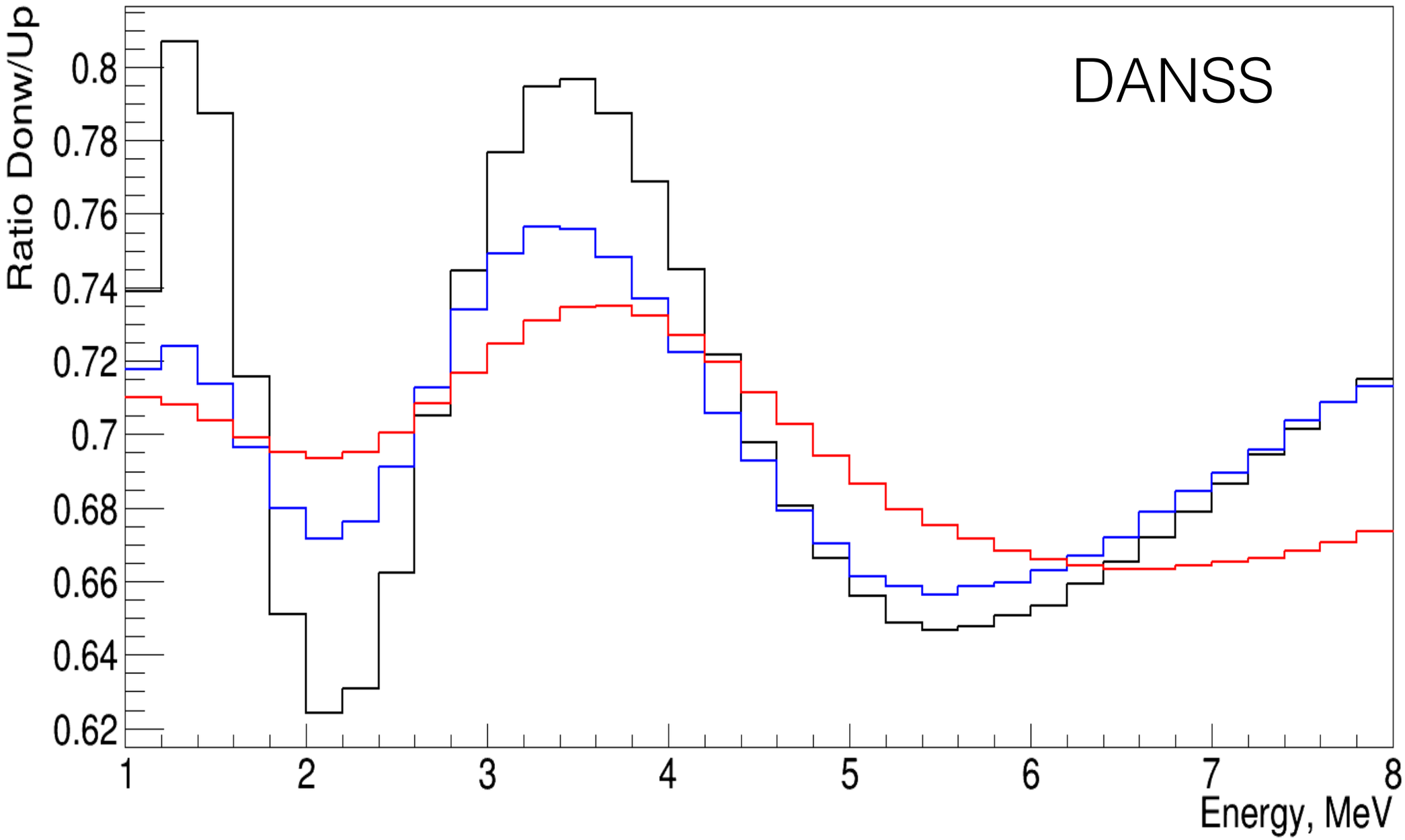
# Smearing due to reactor core size and energy resolution

$\sin^2 2\theta = 0.14$, $\Delta m^2 = 2$ eV$^2$

Ideal case

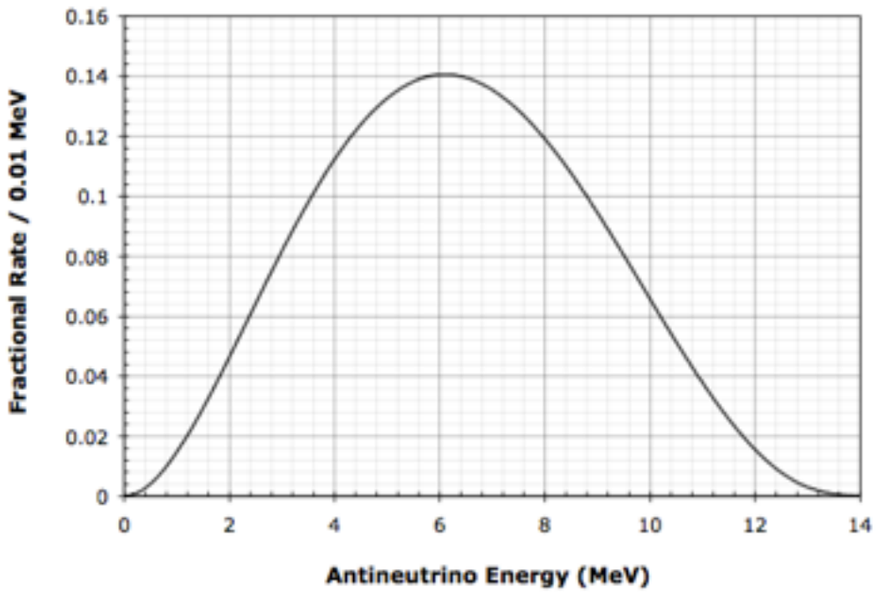
Reactor size

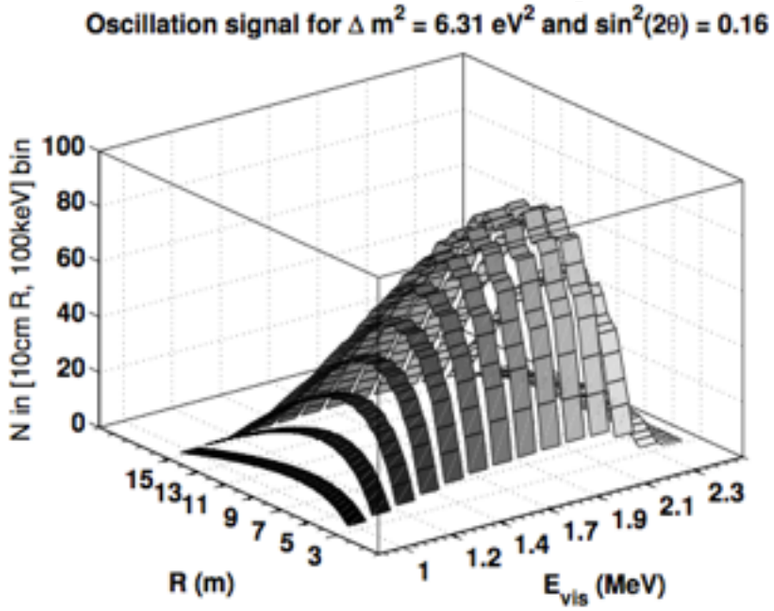
Reactor size+Energy resolution

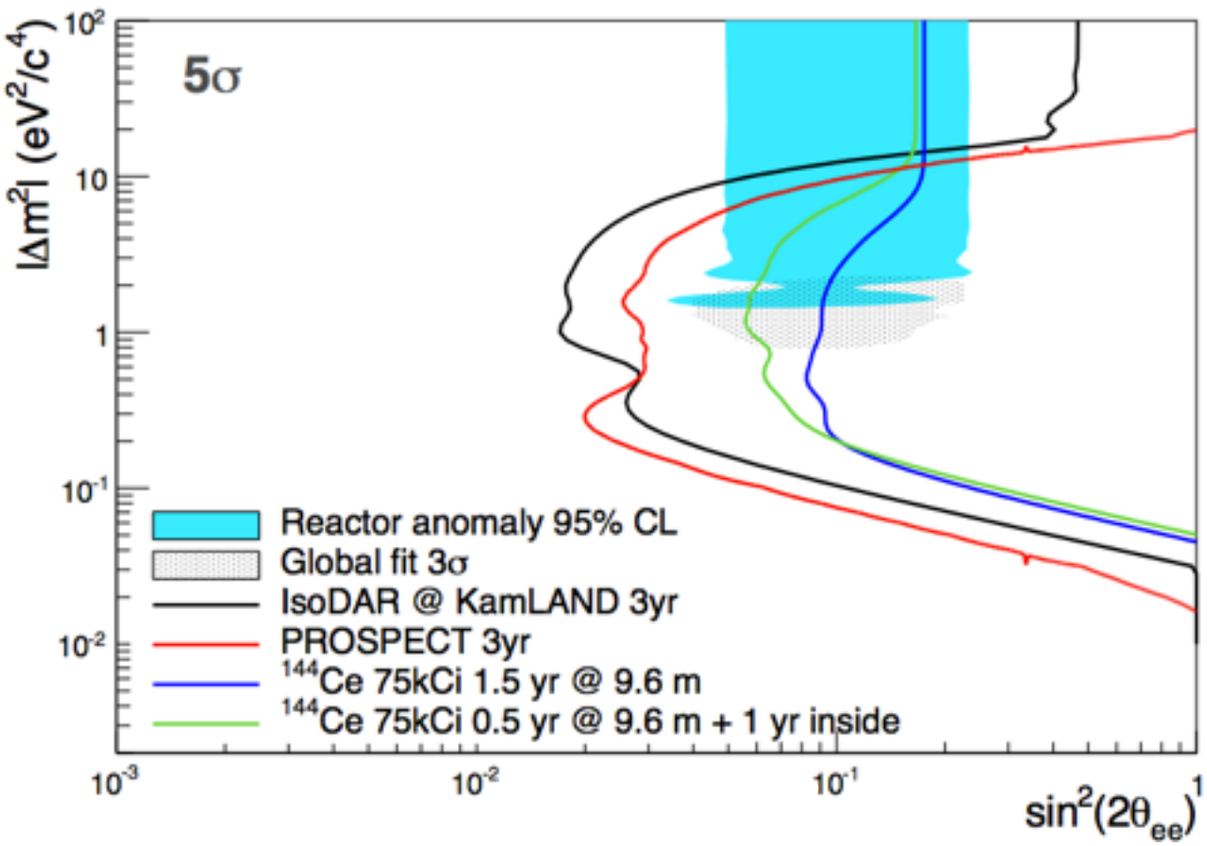


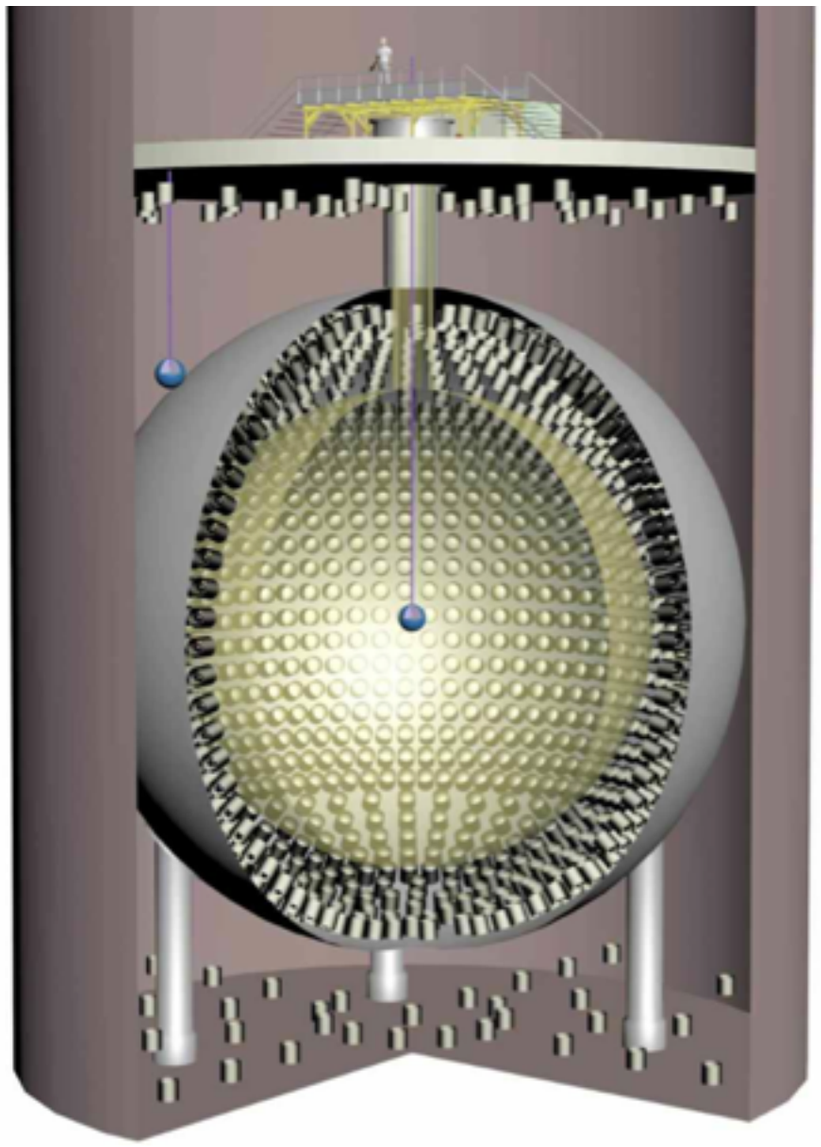
# Competing Efforts

- CeLAND and SOX: Radioactive source experiments: quick-ish CANCELLED
- IsoDAR: Accelerator-produced beta decay source: longer timescale



arXiv:1312.0896

arXiv:1307.2949

arXiv:1304.7721

# SBL Reactor Context

- PROSPECT: designed to provide a precision measurement for BOTH key physics goals
  - Moveable segmented detectors give best mapping of oscillation space
  - Design enables higher energy resolution other efforts
- PROSPECT has the experience, development, and infrastructure in place for the world's pre-eminent SBL reactor effort.

**A** (biased) overview of global efforts — Good : Not Good

| | Effort | Dopant | Good X-Res | Good E-Res | L Range (meters) | Fuel | Exposure, MW*ton | Move-able? | Running at intended reactor? |
|---|---|---|---|---|---|---|---|---|---|
| US | **PROSPECT** | **Li** | **Yes** | **Yes** | **6.5-20** | **HEU** | **185** | **Yes** | **Yes** |
| | NuLat | Li/B | Yes | Yes | TBD | TBD | TBD | Yes | No |
| EU | Nucifer | Gd | No | Yes | 7 | HEU | 56 | No | Yes |
| | STEREO | Gd | Yes | Yes | 9-11 | HEU | 100 | No | Yes |
| | SoLid | Li | Yes | No | 6-8 | HEU | 155 | No | Yes |
| Russia | DANSS | Gd | Yes | No | 9.7-12 | LEU | 2700 | Yes | Yes |
| | Neutrino4 | Gd | Yes | No | 6-12 | HEU | 150 | Yes | Yes |
| Asia | NEO | Li/Gd | No | Yes | 20-ish | LEU | 30 | No | No |

**Improved measurement of the reactor antineutrino flux and spectrum at Daya Bay** *

In this subsection, we express the measurement in two model-independent ways: the IBD yield per nuclear fission ($\sigma_{\rm f}$), and the IBD yield per GW$_{th}$ per day ($Y$).

$\sigma_{\rm f}$ for each AD is determined by solving the following equation:

$$M_d = \sum_{r=1}^{6} \frac{N_r^{\rm f}}{4\pi L_{dr}^2} \sigma_{\rm f}^d N_d^{\rm T} P_{\rm sur}^{dr} \epsilon_d^D, \tag{12}$$

where $N_r^{\rm f}$ is the predicted number of fissions from the $r$th reactor core, which is calculated based on $W_r$ (average thermal power of $r$th core), $f_r^{\rm iso}$ (average fission fraction of $r$th core for each isotope) and $E^{\rm iso}$ (mean energy release per fission for each isotope), integrated over the live time of the detector:

$$N_r^{\rm f} = \int \frac{W_r}{\sum_{\rm iso=1}^{4} f_r^{\rm iso} E^{\rm iso}} {\rm d}t. \tag{13}$$

$L_{dr}$ is the distance between the $d$th detector and the $r$th reactor core. $N_d^{\rm T}$ is the total number of target protons in the GdLS of each AD. The total detection efficiency, $\epsilon_d^D$, is different for each AD because of different effects of muon veto and multiplicity cuts on each AD. $P_{\rm sur}^{dr}$ is the survival probability given an AD-core pair, calculated using the best-fit value of $\sin^2 2\theta_{13}$ from the rate-only analysis described in the previous subsection. Due to the relatively large size of $\theta_{13}$, even at the near sites there are on average about 1.5% rate deficits, as shown in Fig. 15. The values of $\sigma_{\rm f}^d$ for all ADs, from Eq. (12), are summarized in Table 9. Similar to the normalization $R$, the uncertainty in $\sigma_{\rm f}^d$ (summarized in Table 9 as $\sigma_{\rm exp}$) is dominated by the correlated detection uncertainty $\sigma_D$.

Theoretically, $\sigma_{\rm f}$ represents the IBD cross section convolved with the reactor antineutrino spectra from all fission isotopes, and integrated over energy:

$$\sigma_{\rm f} = \sum_{\rm iso=1}^{4} f_{\rm iso} \int S_{\rm iso}(E_\nu)\sigma(E_\nu){\rm d}E_\nu. \tag{14}$$

Given a reactor model that predicts the antineutrino spectrum $S_{\rm iso}(E_\nu)$ for each of the four main fission isotopes $^{235}$U, $^{238}$U, $^{239}$Pu and $^{241}$Pu, and the fission fractions $f_{\rm iso}$ determined by NPP operations and simulations, $\sigma_{\rm f}$ can be theoretically calculated and compared with the model-independent measurement. The

arXiv:1704.01082

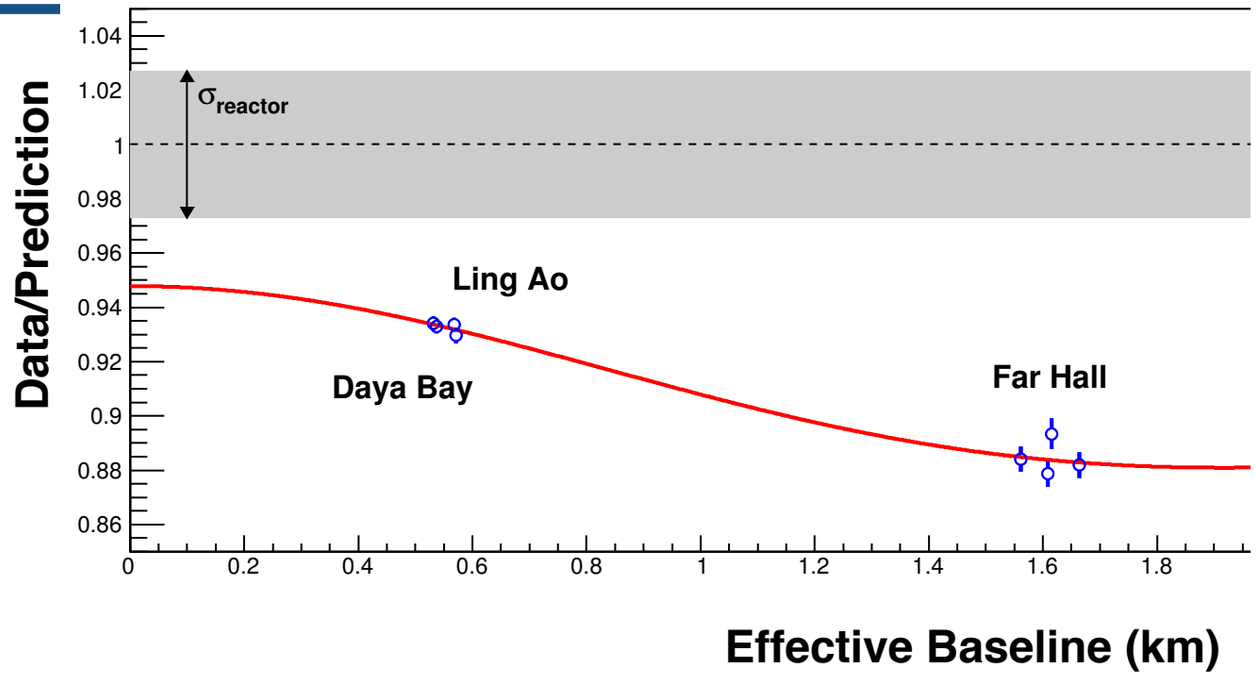
**Evolution of the Reactor Antineutrino Flux and Spectrum at Daya Bay**

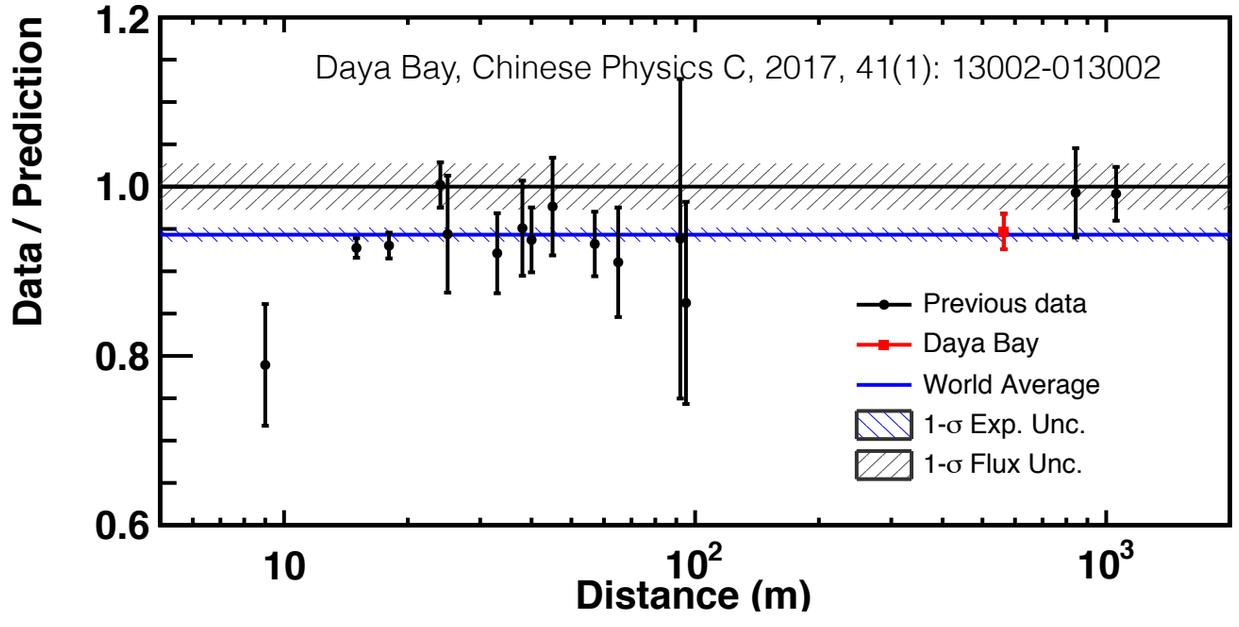
The evolution of Daya Bay's IBD yield pictured in Fig. 2 was also used to measure the individual IBD yields of $^{235}$U and $^{239}$Pu. For each $F_{239}$ bin $a$ in Fig. 2, the measured IBD yield can be described as

$$\sigma_f^a = \sum_i F_i^a \sigma_i, \tag{5}$$

where $F_i^a$ are the effective fission fractions for each isotope, and $\sigma_i$ is the IBD yield from that isotope. Measurements from

# Flux Deficit at Daya Bav

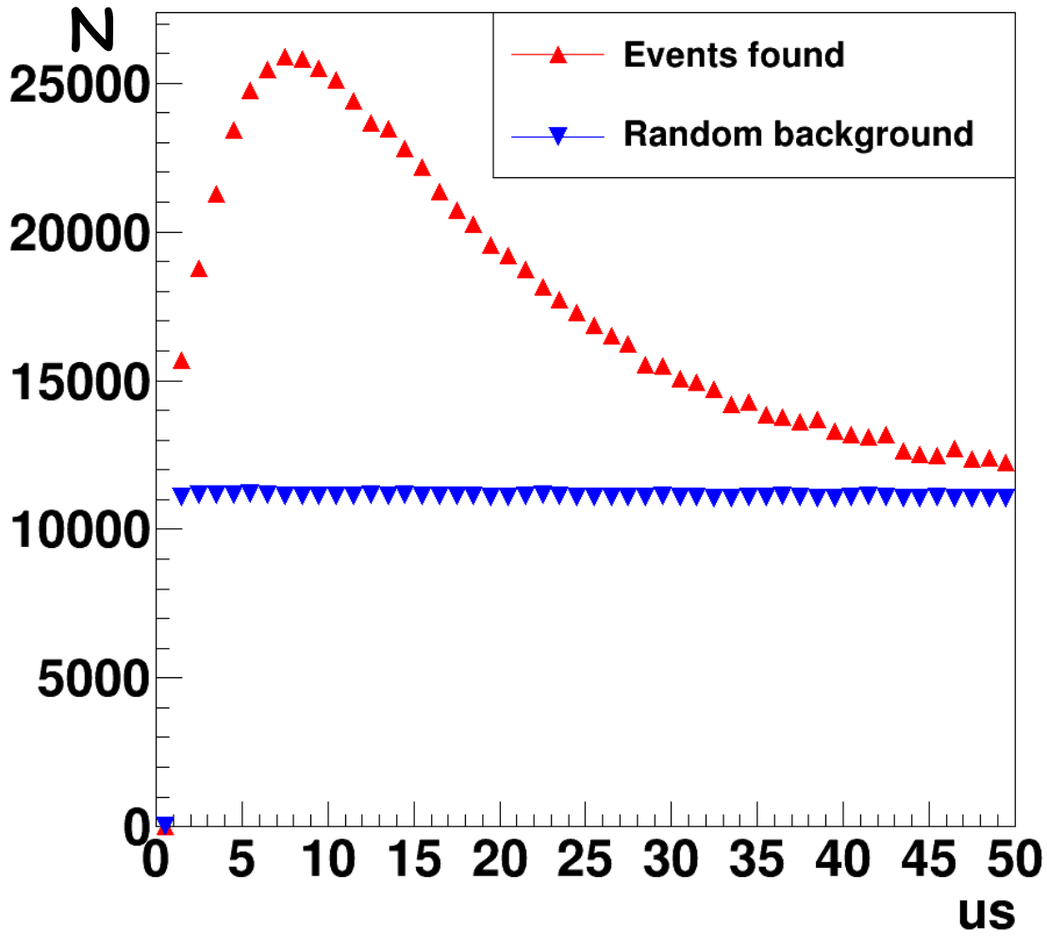


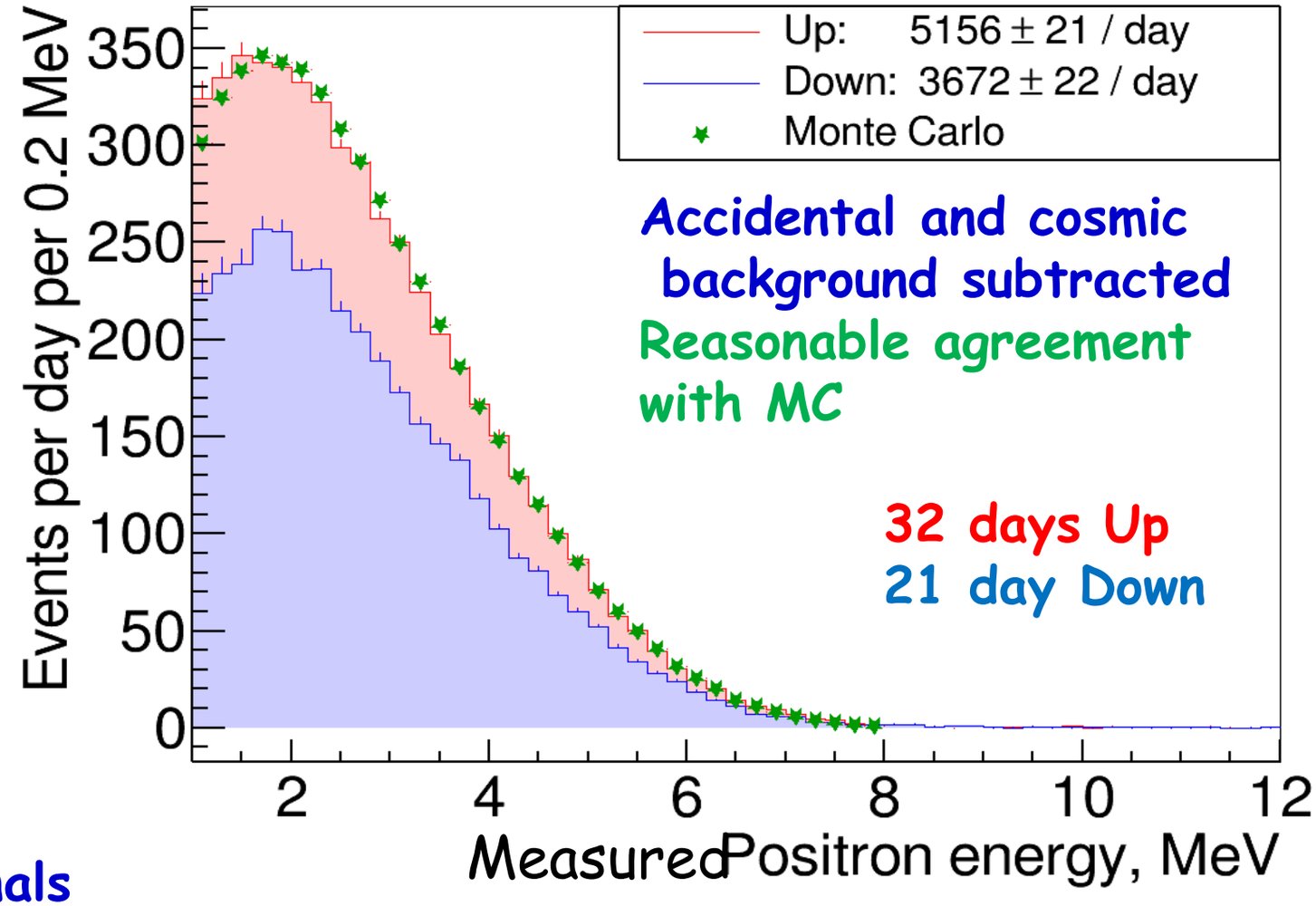
**Blind analysis of absolute flux agrees with old prediction**

***Unlikely to be due to experimental bias***

**Selection:** Ee+>1MeV, En>3MeV, 2μs<ΔT<50μs, no cosmic Veto, e+ not in outer 4cm, no additional signals, periods with 100% reactor power, middle detector position not yet used. **Cuts not yet optimized**




Time between prompt and delayed signals




Accidental and cosmic background subtracted

Reasonable agreement with MC

32 days Up

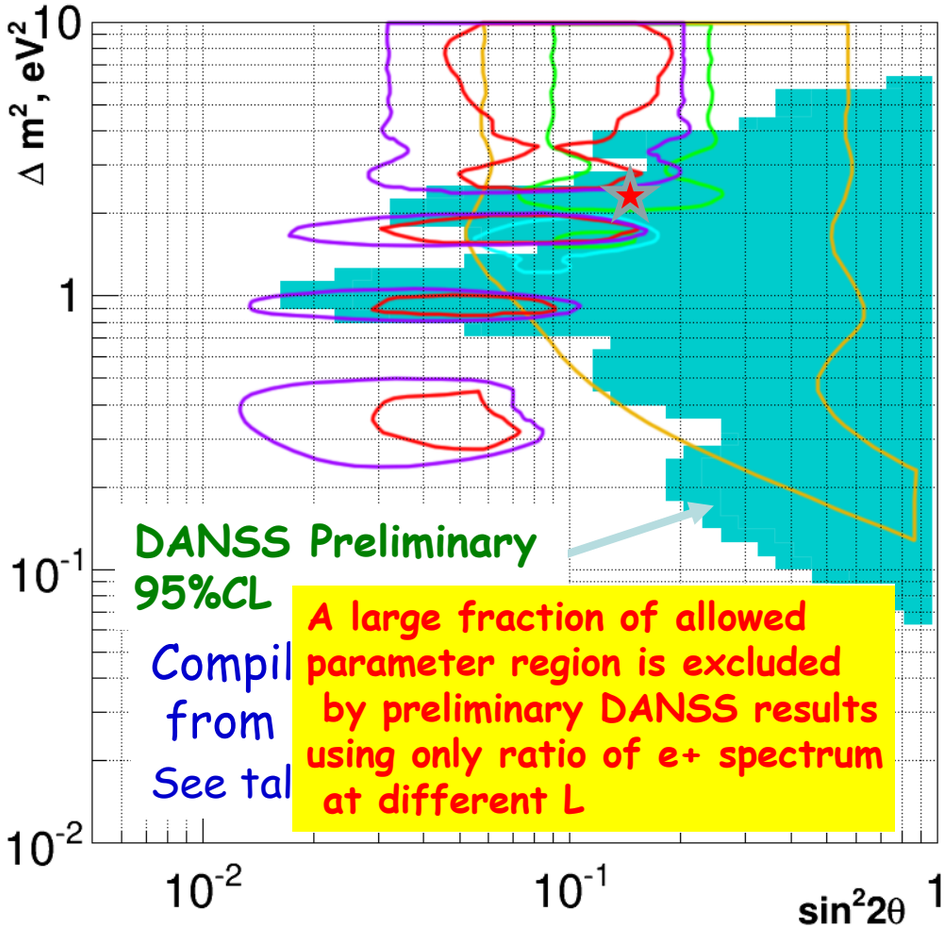
21 day Down

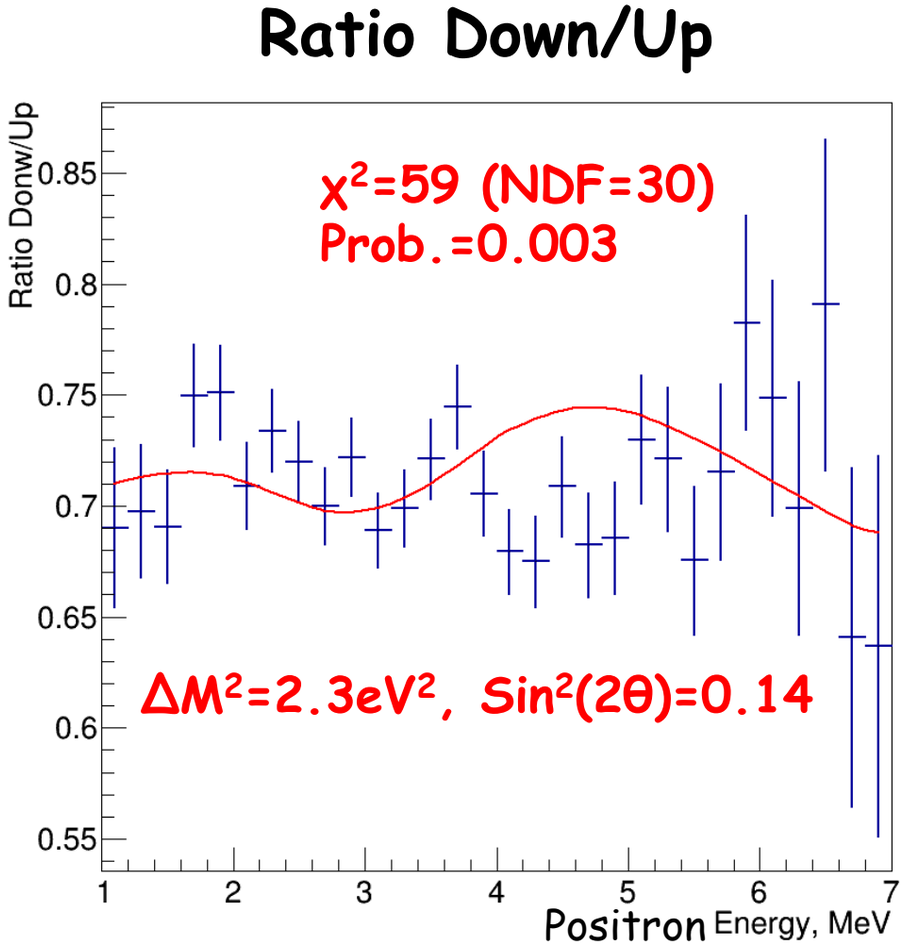
- Accidental background is comparable to signal but subtracted **exactly**
- Only ~25% of accidental background is caused by reactor
- Half of accidental background is below Ee+<2MeV
- Cosmic background is estimated from events with μ in detector and no VETO signal and from reactor off data. **It is only 2.5% in Up position.**
- **About 5000 neutrino events/day is detected in fiducial volume of 78%**

# Data Analysis

For every $\Delta M^2$ and $Sin^2(2\theta)$ $e^+$ spectrum was calculated for Up and Down detector positions taking into account reactor core size and detector energy response including tails (obtained from cosmics calibration and GEANT-4 MC simulation identical to data analysis)

Reactor burning profile was provided by NPP
Theoretical neutrino spectrum was taken from Huber and Mueller
Ratio of Down/Up spectra was calculated and compared with experiment
(independent on ν spectrum, detector efficiency, and many other problems!)



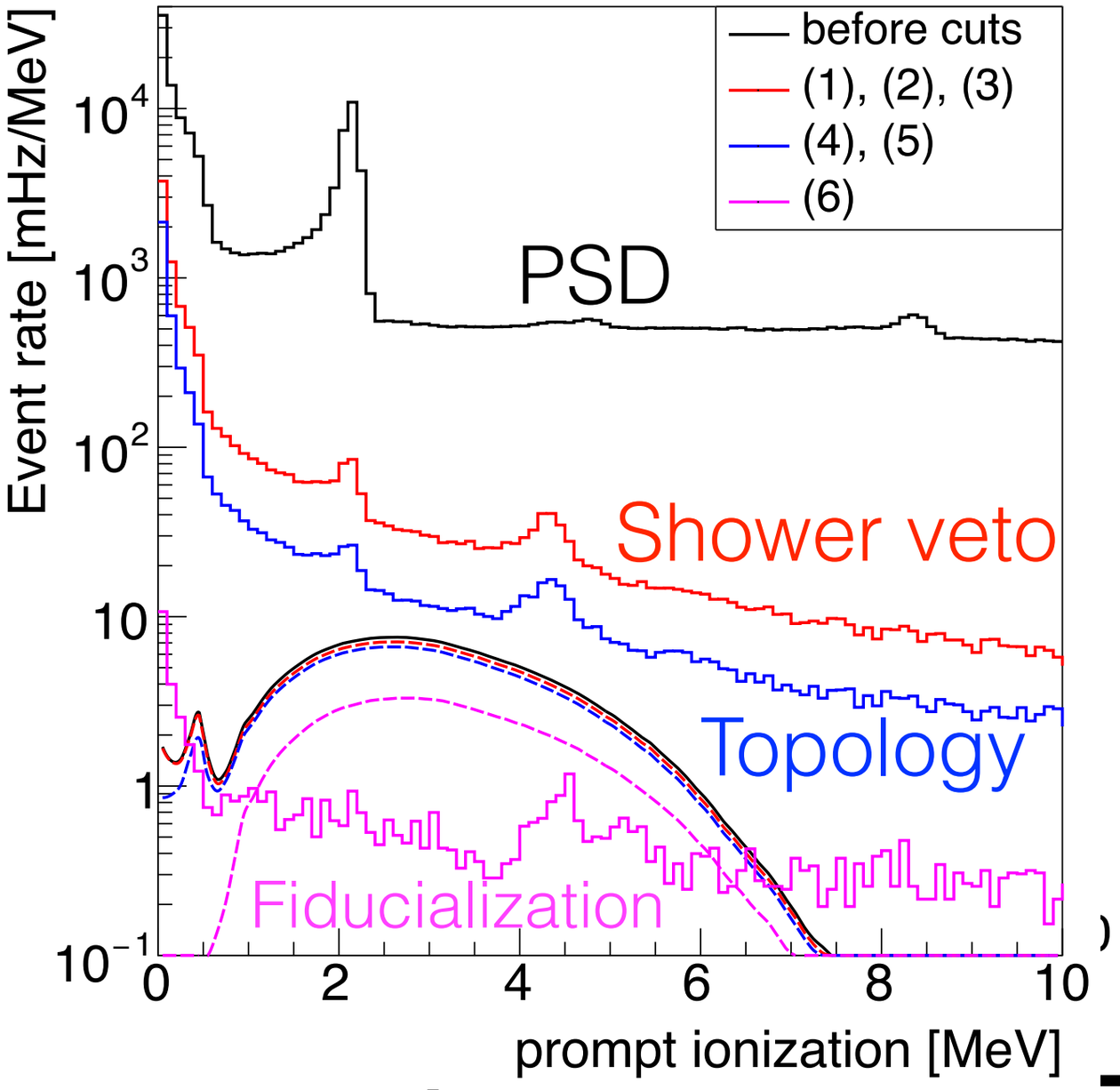



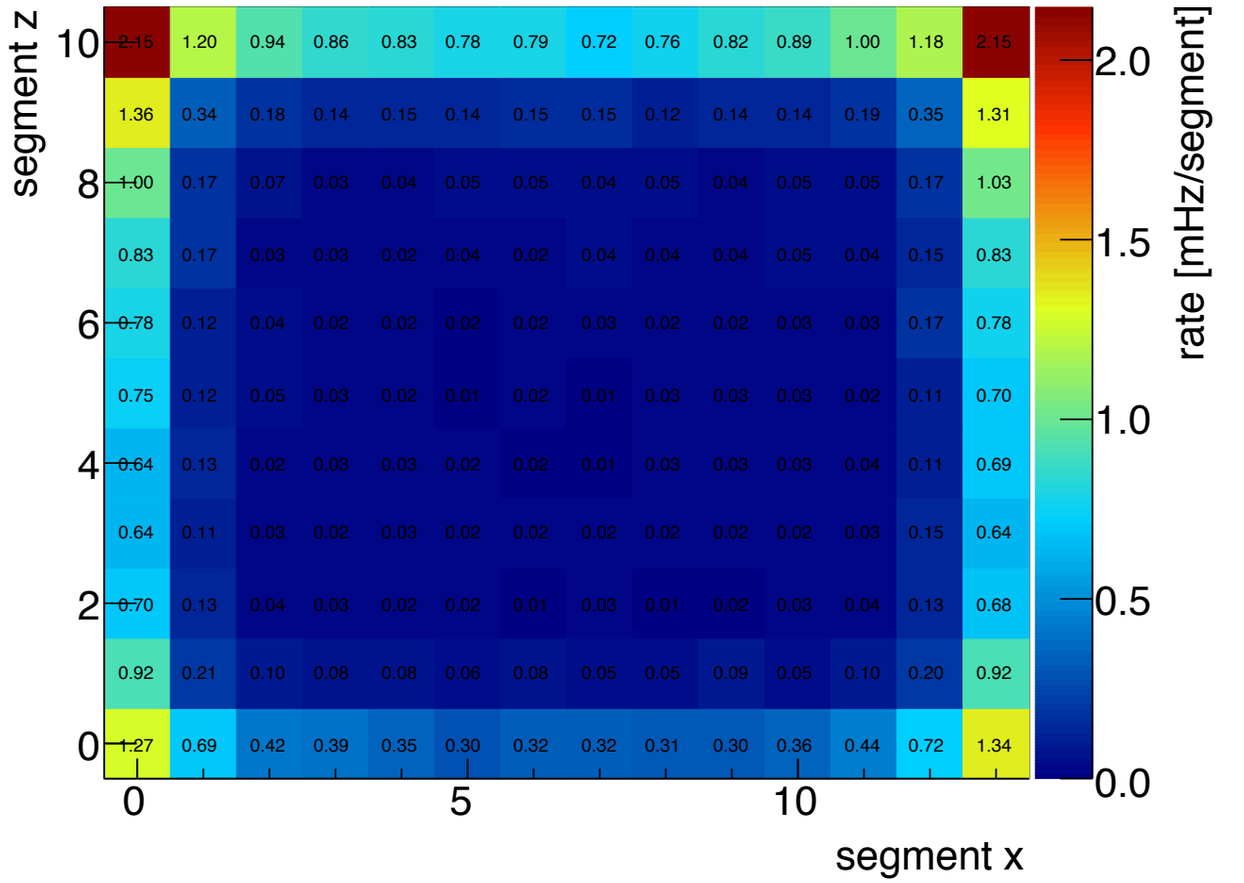

Fit with constant:
$\chi^2$=32
Prob.=0.39

Most plausible parameter set is excluded

# BG Rejection via Detector Design

## Neutron coincident events




**Background reduction steps:**

- Efficient PSD and neutron tagging
- Identification of multiple particle interactions
- **Fiducialization**

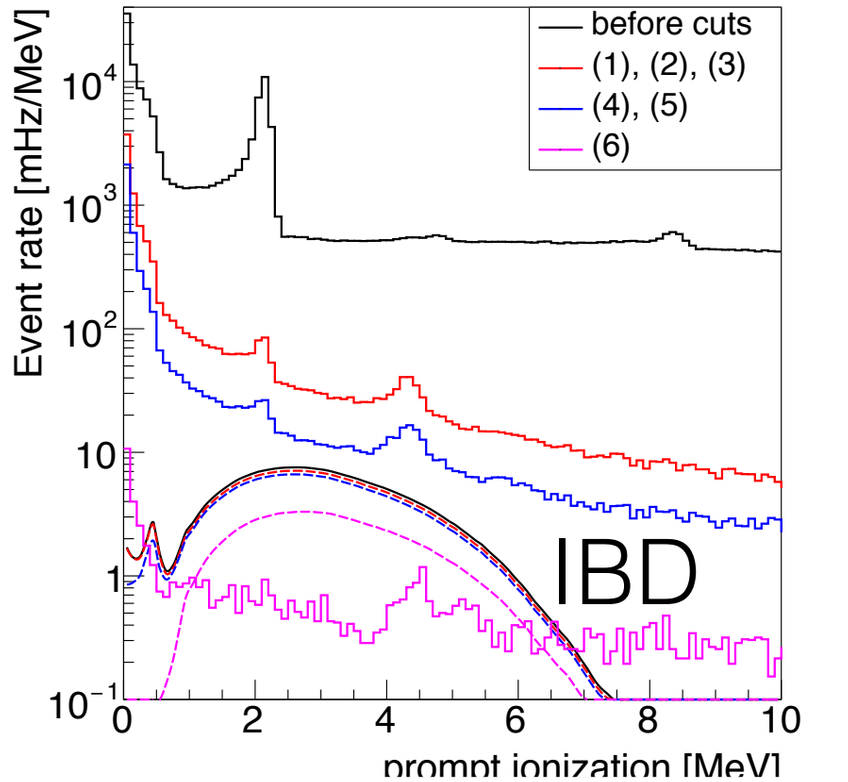
*Active suppression of >3 orders of magnitude*

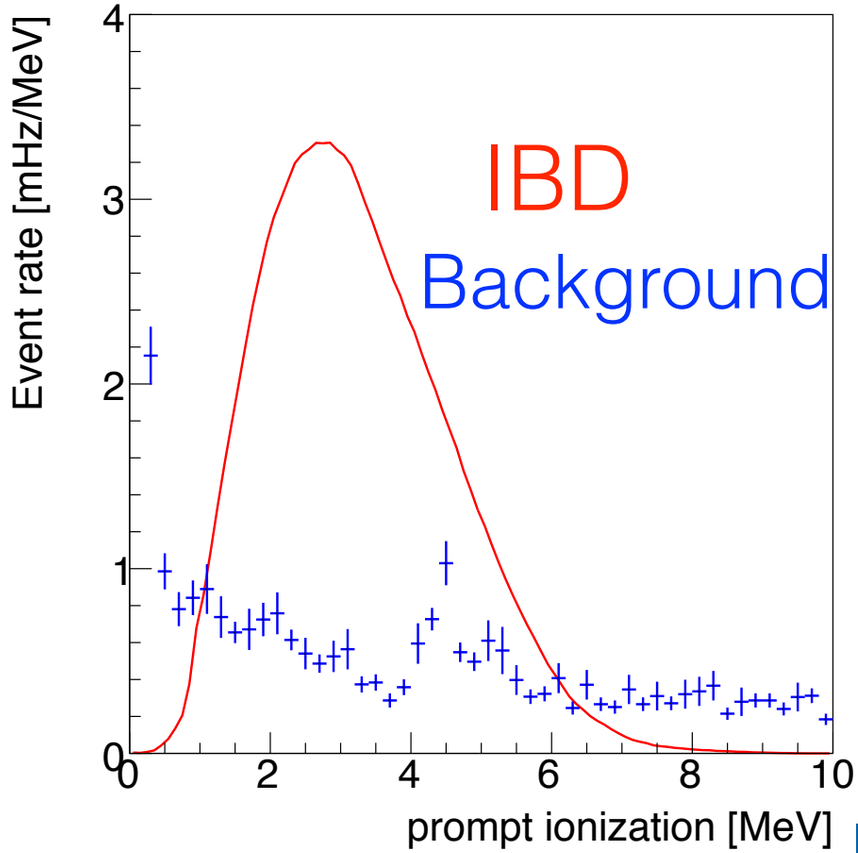
# PROSPECT Signal and Background

- Signal (dashed) and background (solid) prompt spectra are shown through selection cuts
- S/B of about 3/1 is predicted
- Rate and shape of the residual IBD-like background can be measured with high precision during reactor off periods.

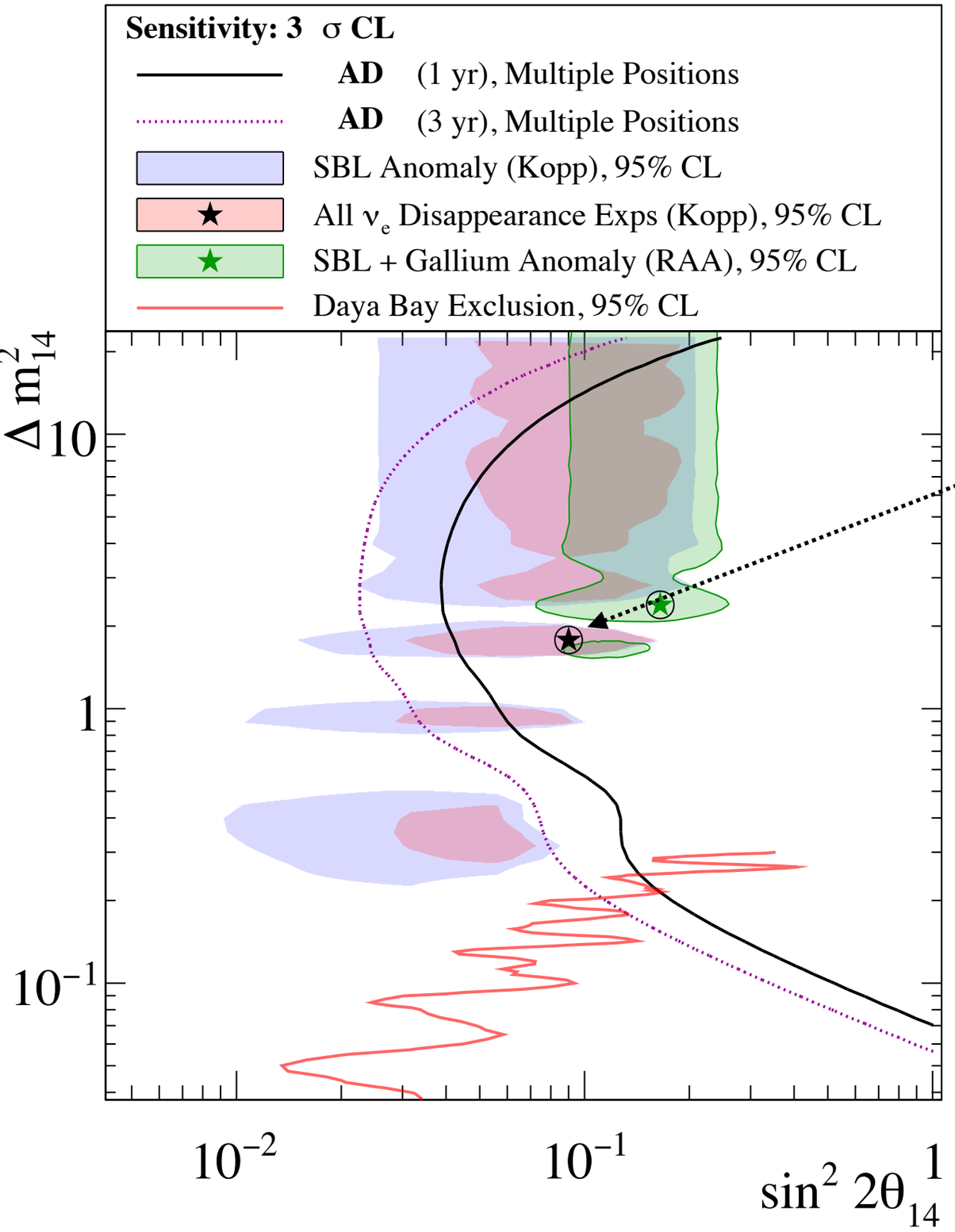
| Cuts | IBD/day | Cosmic/ |
|---|---|---|
| PSD | 2153 | 60300 |
| Shower veto(1-3) | 2016 | 18900 |
| Topology(4-5) | 1881 | 7363 |
| Fiducial(6) | 939 | 294 |

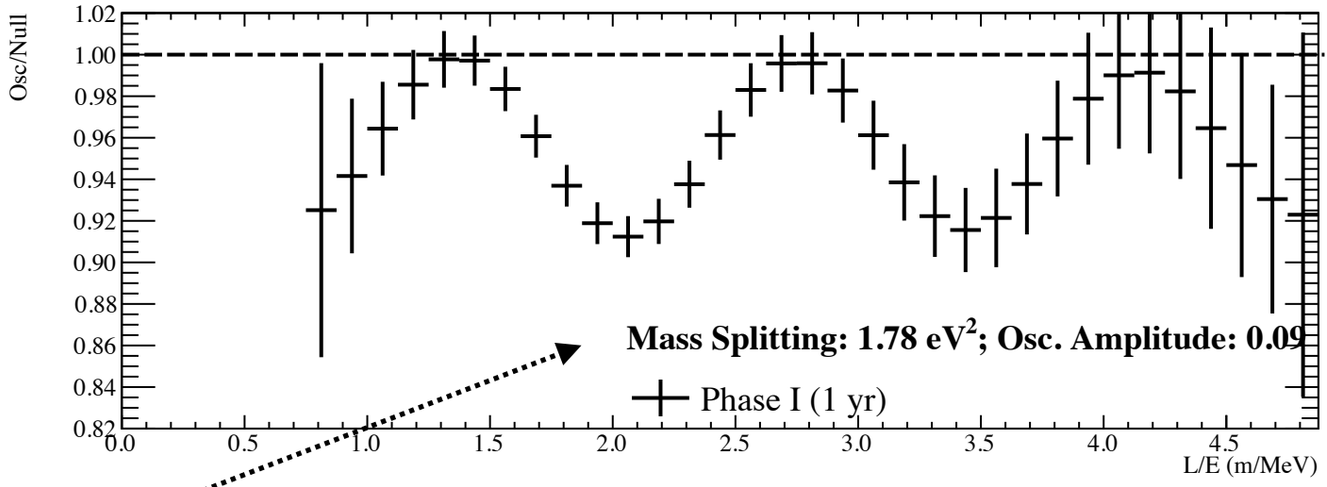
Simulated event rates ($0.8 \leq E \leq 7.2$ MeV) after applying background rejection cuts



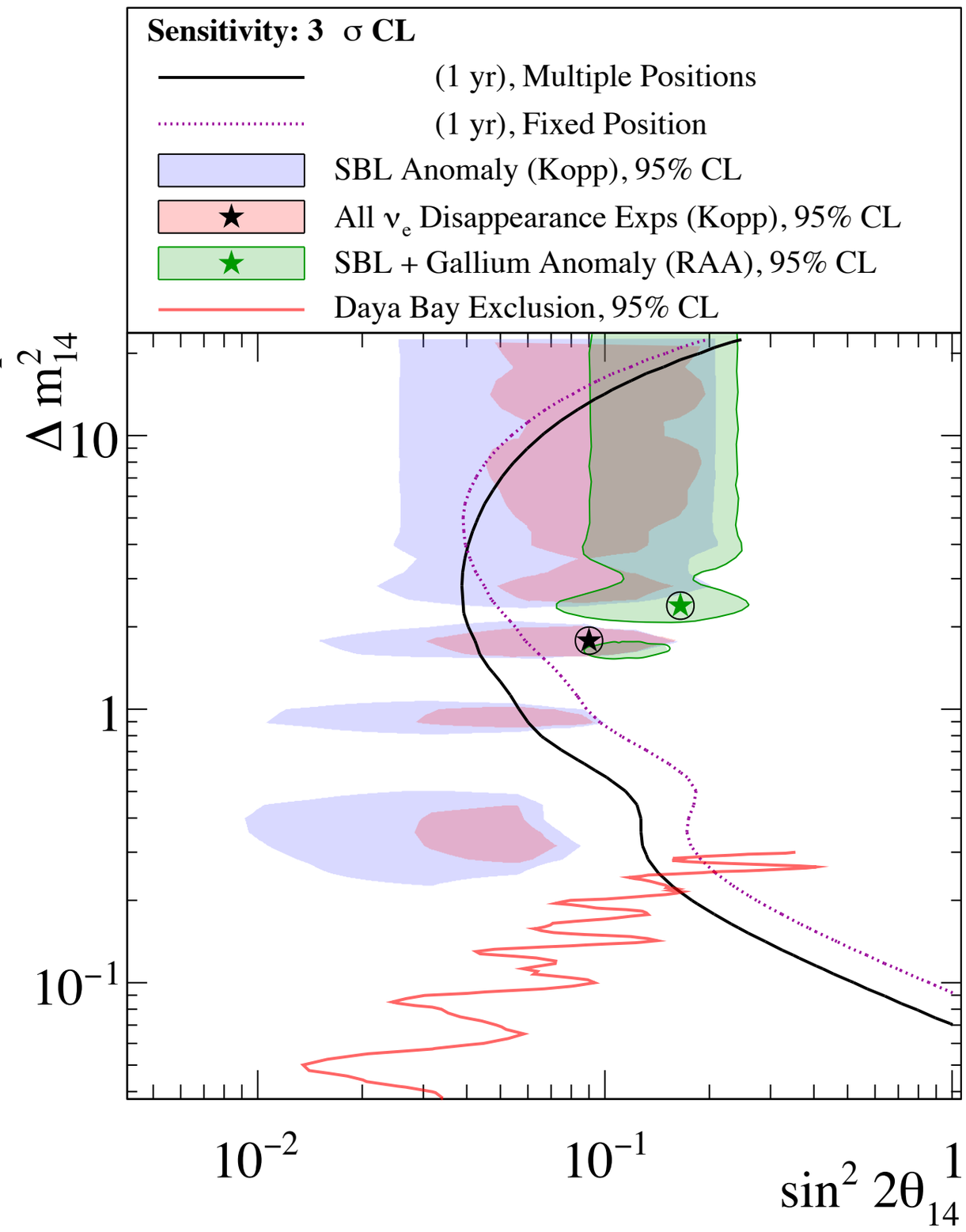
# Short Baseline Oscillation Search

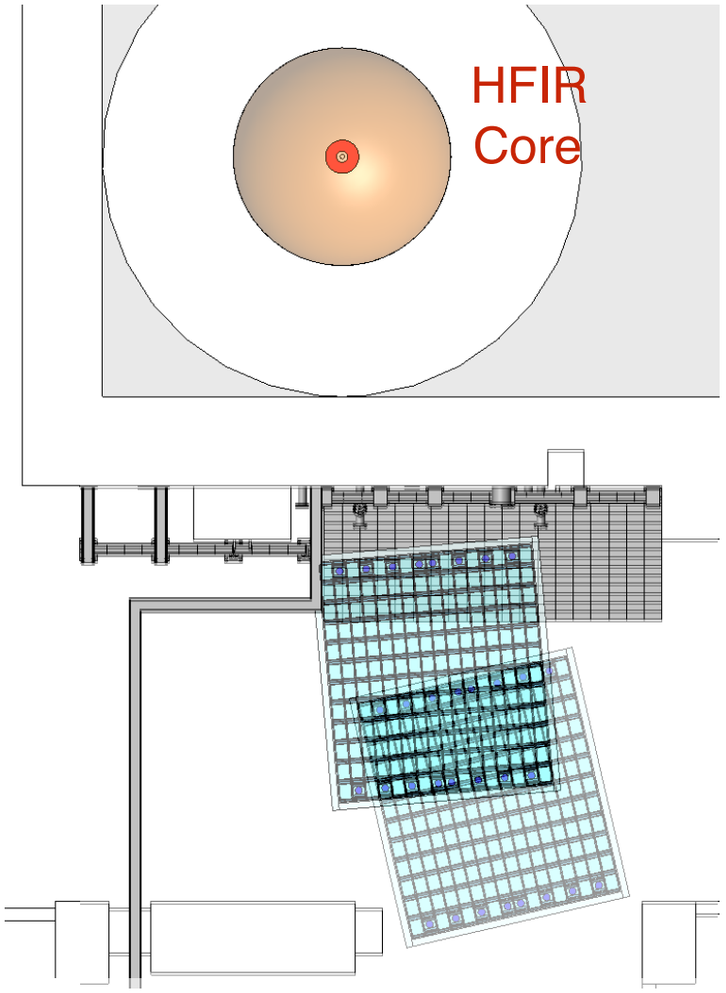



- Segmented detector designed for oscillation search
  - Each cell is a separate "detector"
  - Oscillatory L/E between segments limits uncertainties from reactor
- *True oscillometry needed for confirmation of sterile neutrinos*
- **Probe best-fit region at >3$\sigma$ in 1 year**

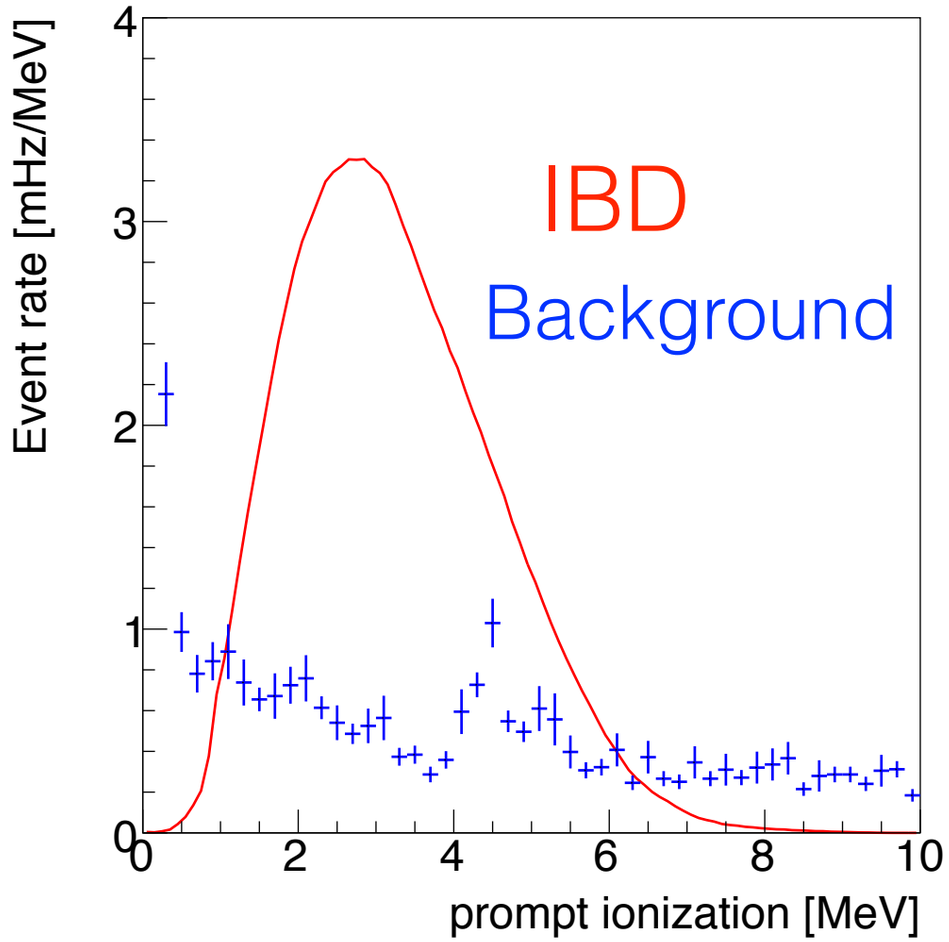
# A Movable Detector

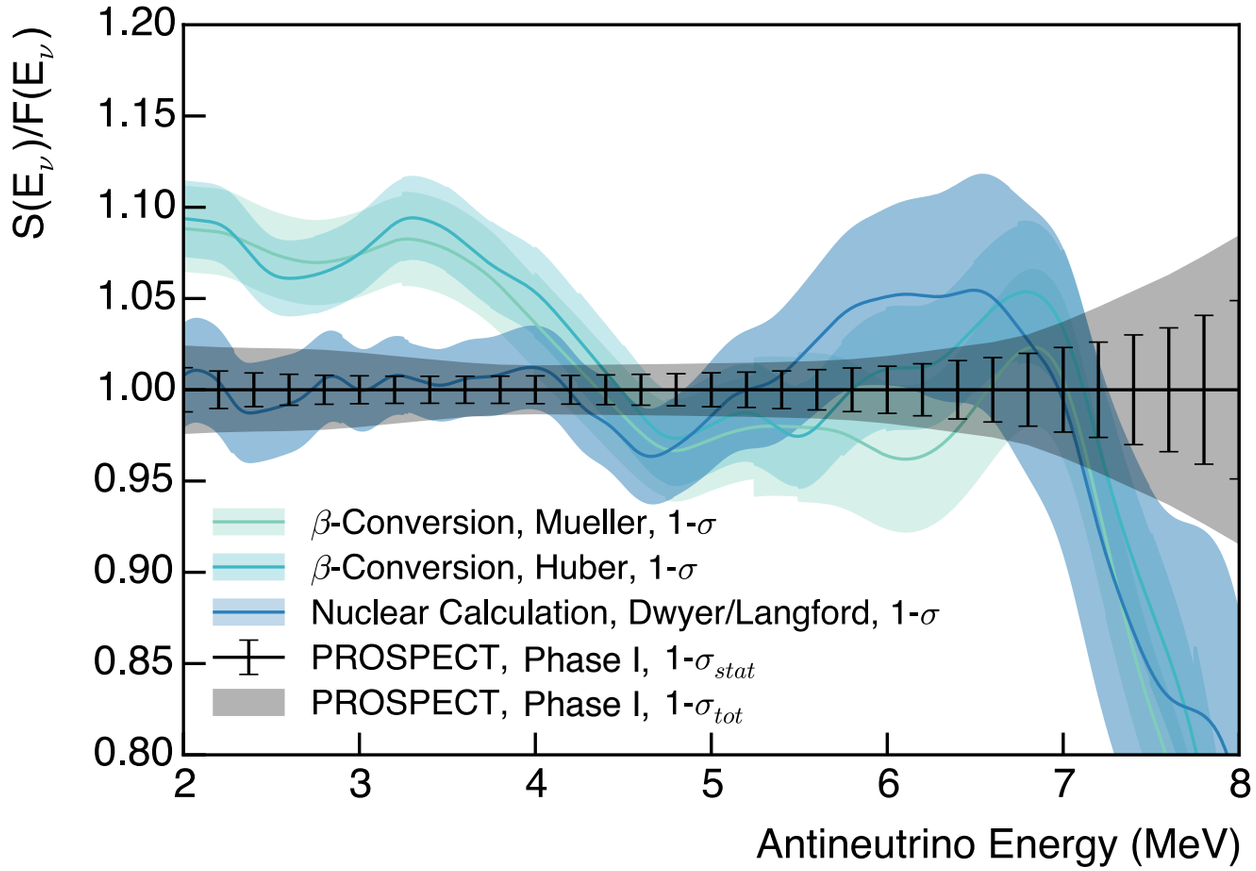



- AD is designed to translate to span 7m - 12 m baselines
- Improves the sensitivity from <3$\sigma$ to greater than 4$\sigma$
- Provides powerful systematics check

# $^{235}$U Spectrum Measurement

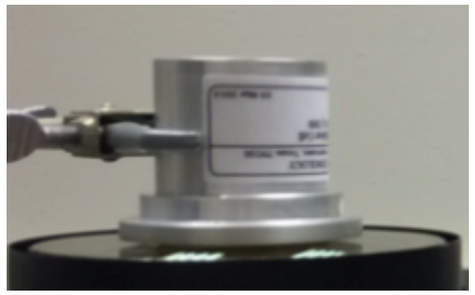



- ~900 inverse beta decays detected per day, 150k/year
- Best energy resolution of any reactor neutrino experiment (4.5%@1MeV)
- **Phase-1 precision will surpass spectral model uncertainties**
  - Directly test reactor neutrino models
  - Produce a benchmark spectrum for future reactor experiments

# Phased Detector Development

**PROSPECT-0.1**
Aug 2014
Spring 2015

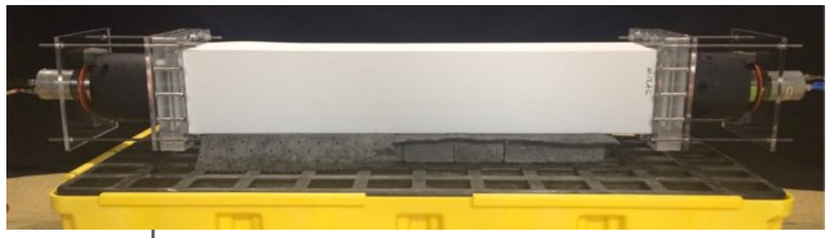


5cm
0.1liter
LS cell

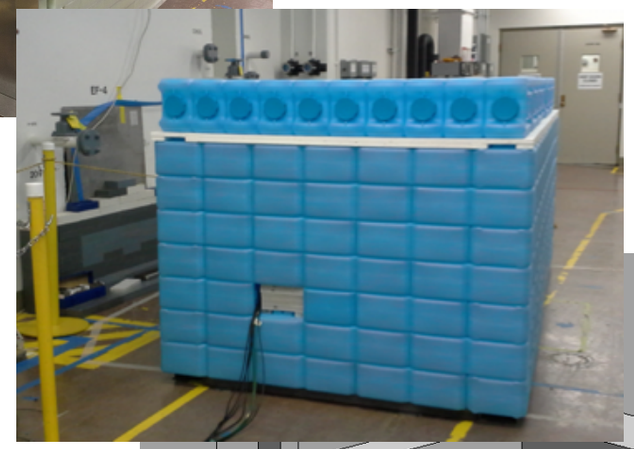
**PROSPECT-2**
Dec 2014
Feb 2015

12.5cm
1.7 liter
LS cell

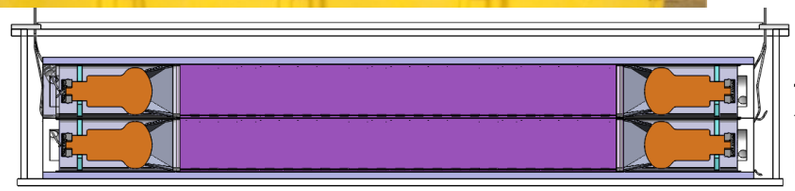
**PROSPECT-20**
March 2015



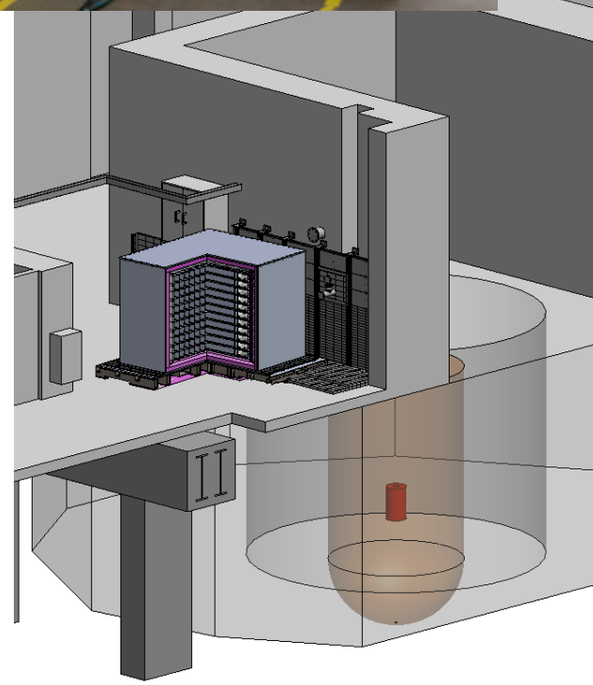
1m
23 liter
LS cell



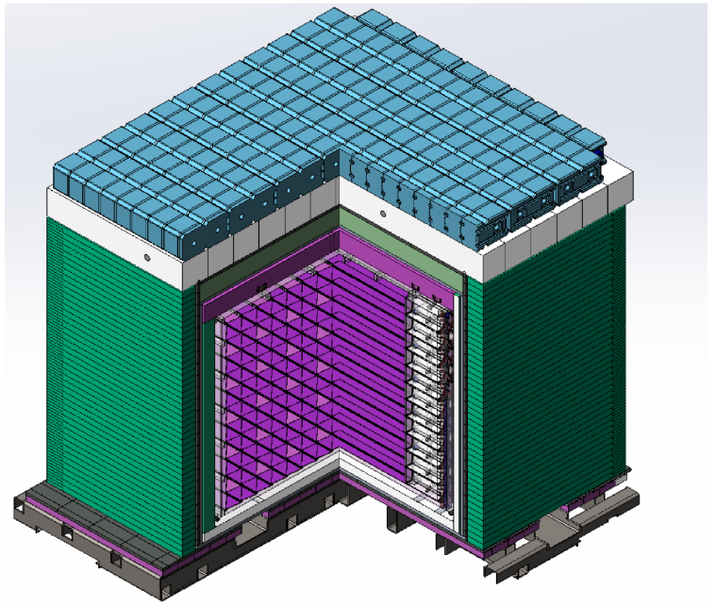
**PROSPECT-50**
February 2016



1.2m
2x25 liter
LS segments



**PROSPECT**
**Phase I**
2017*

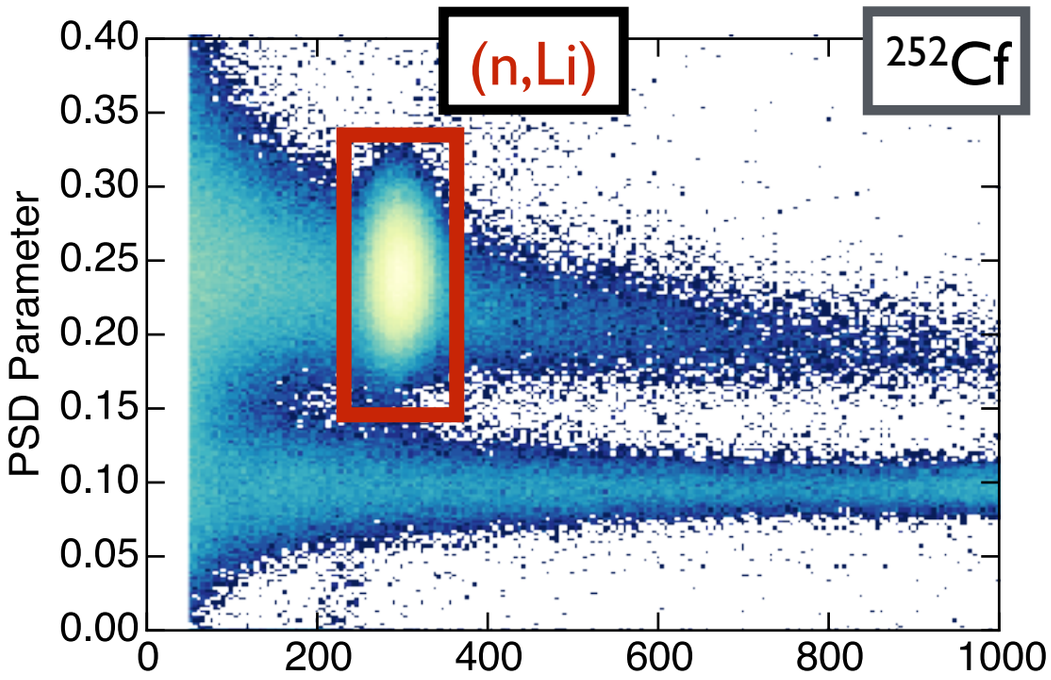


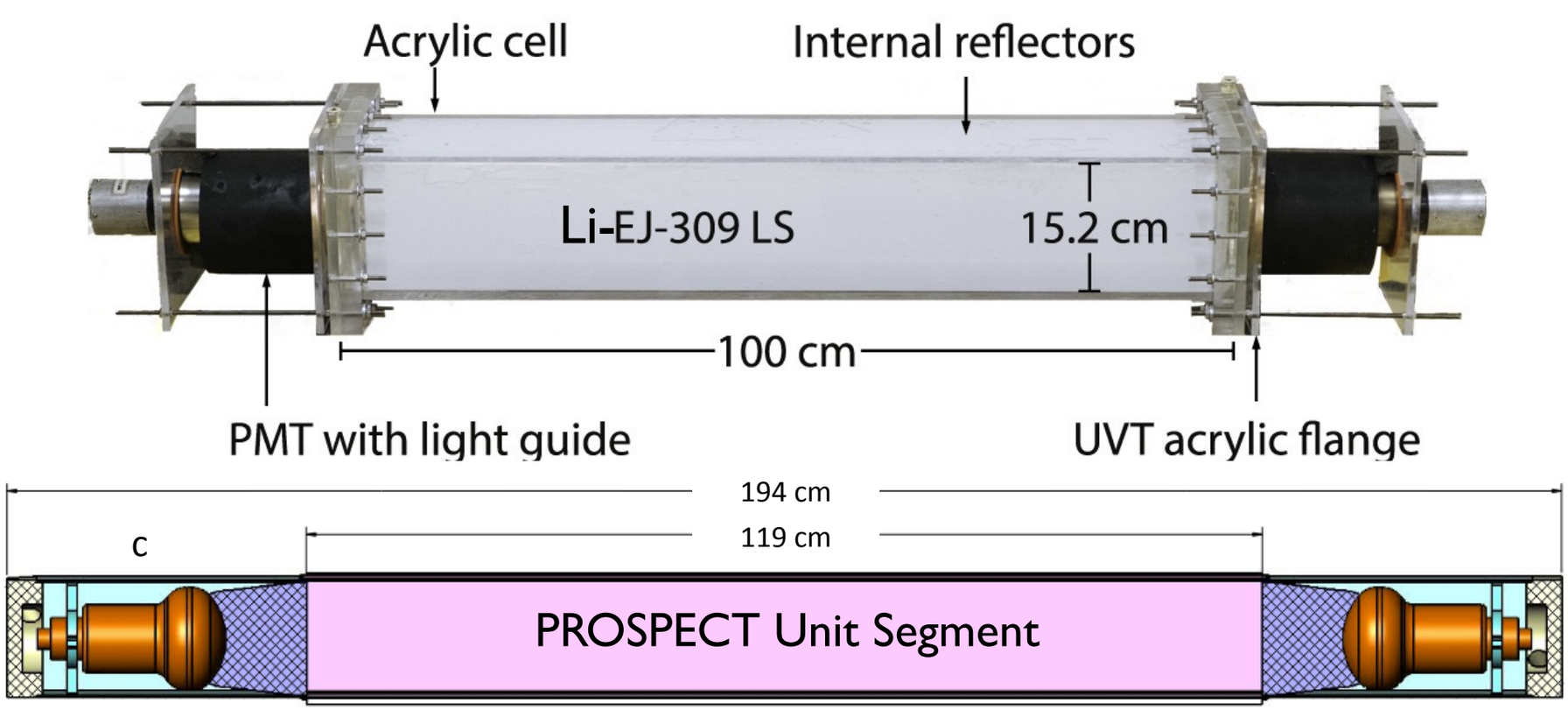
154x25 liter
LS segments
15x15x120cm

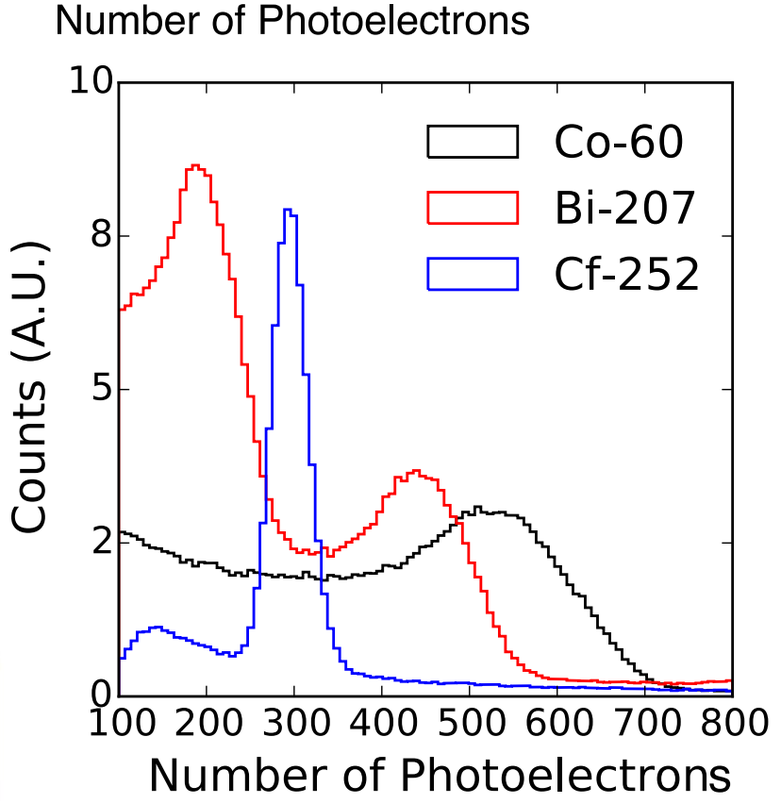
*under assembly

# 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

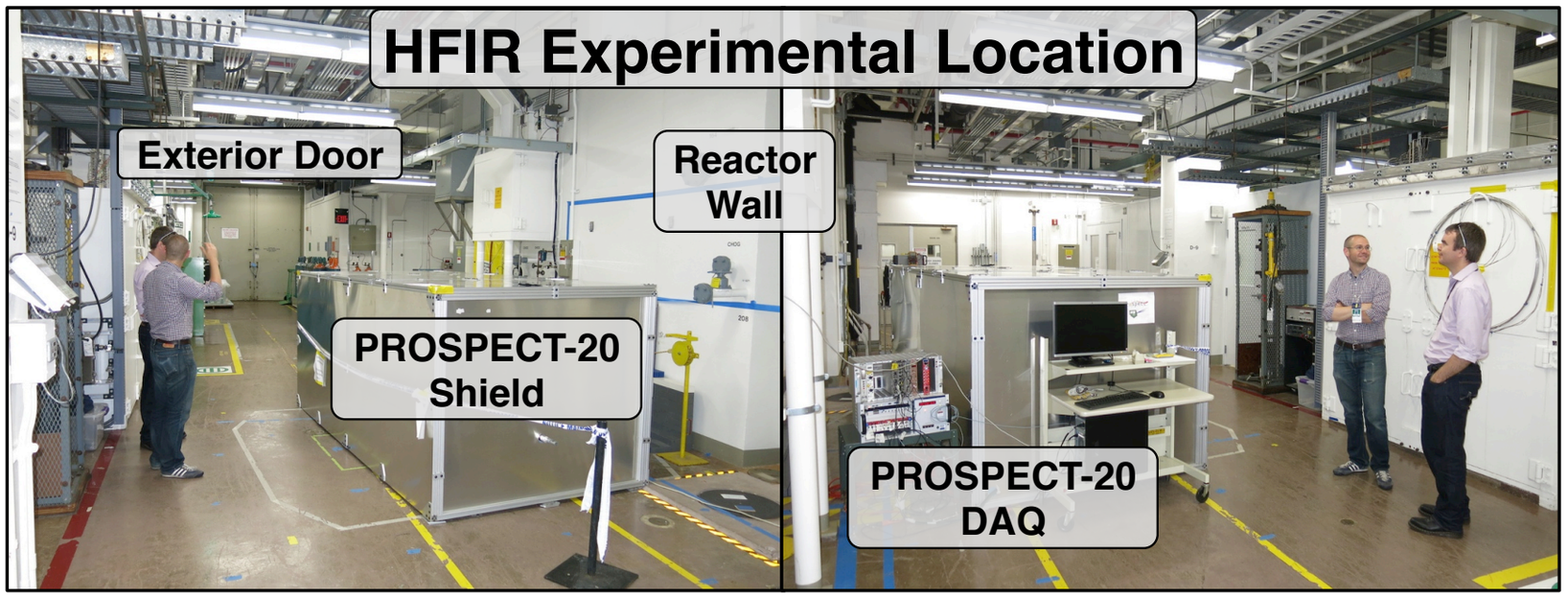


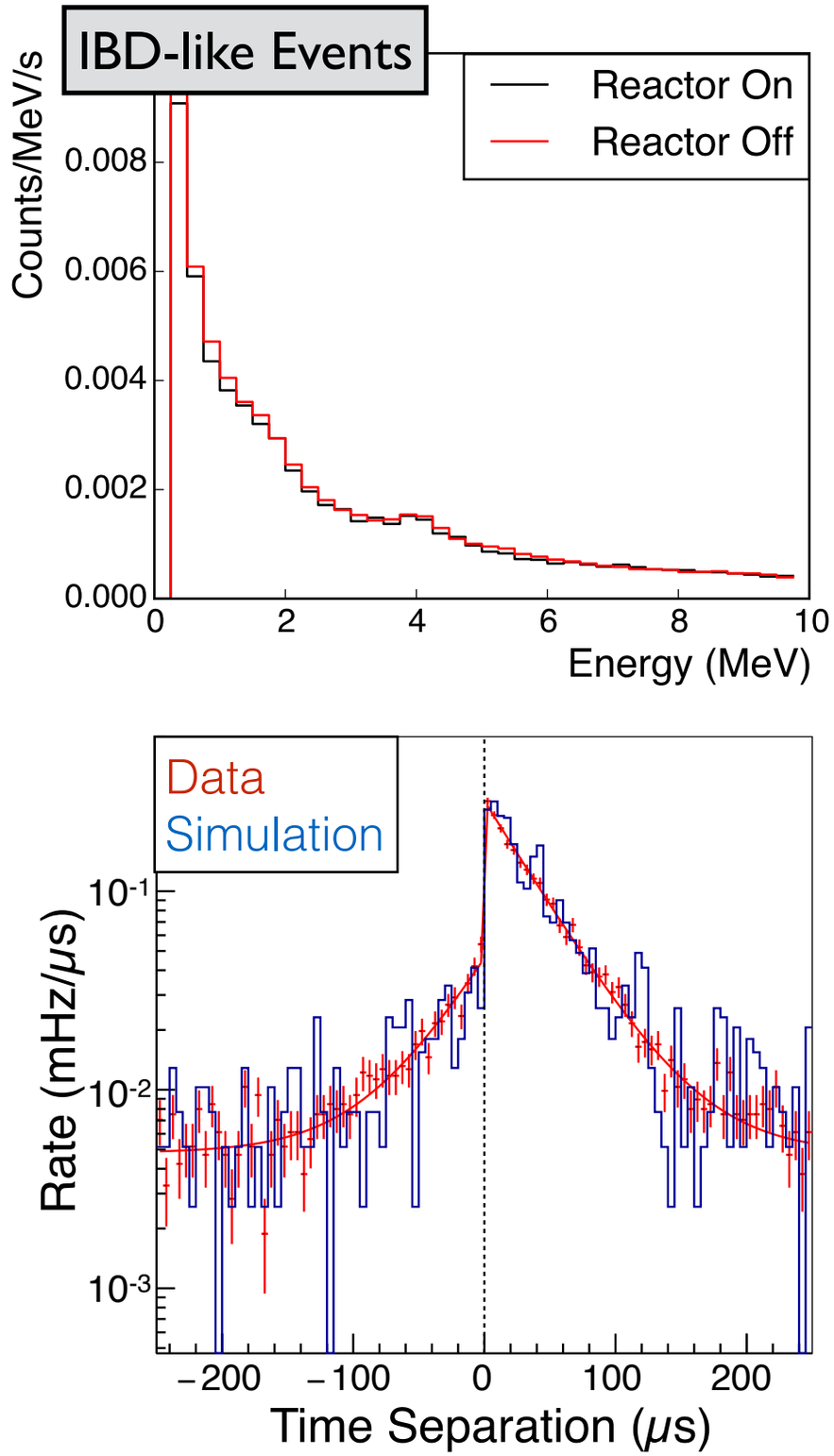




*PROSPECT-20 Paper arXiv:1508.06575*

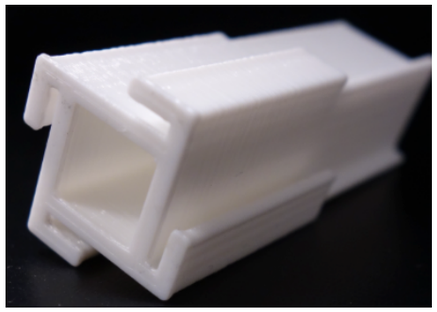
# PROSPECT-20 at HFIR

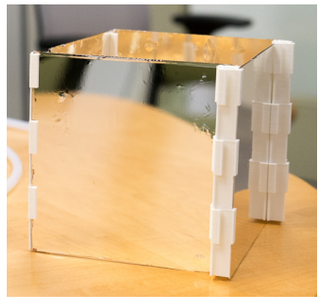


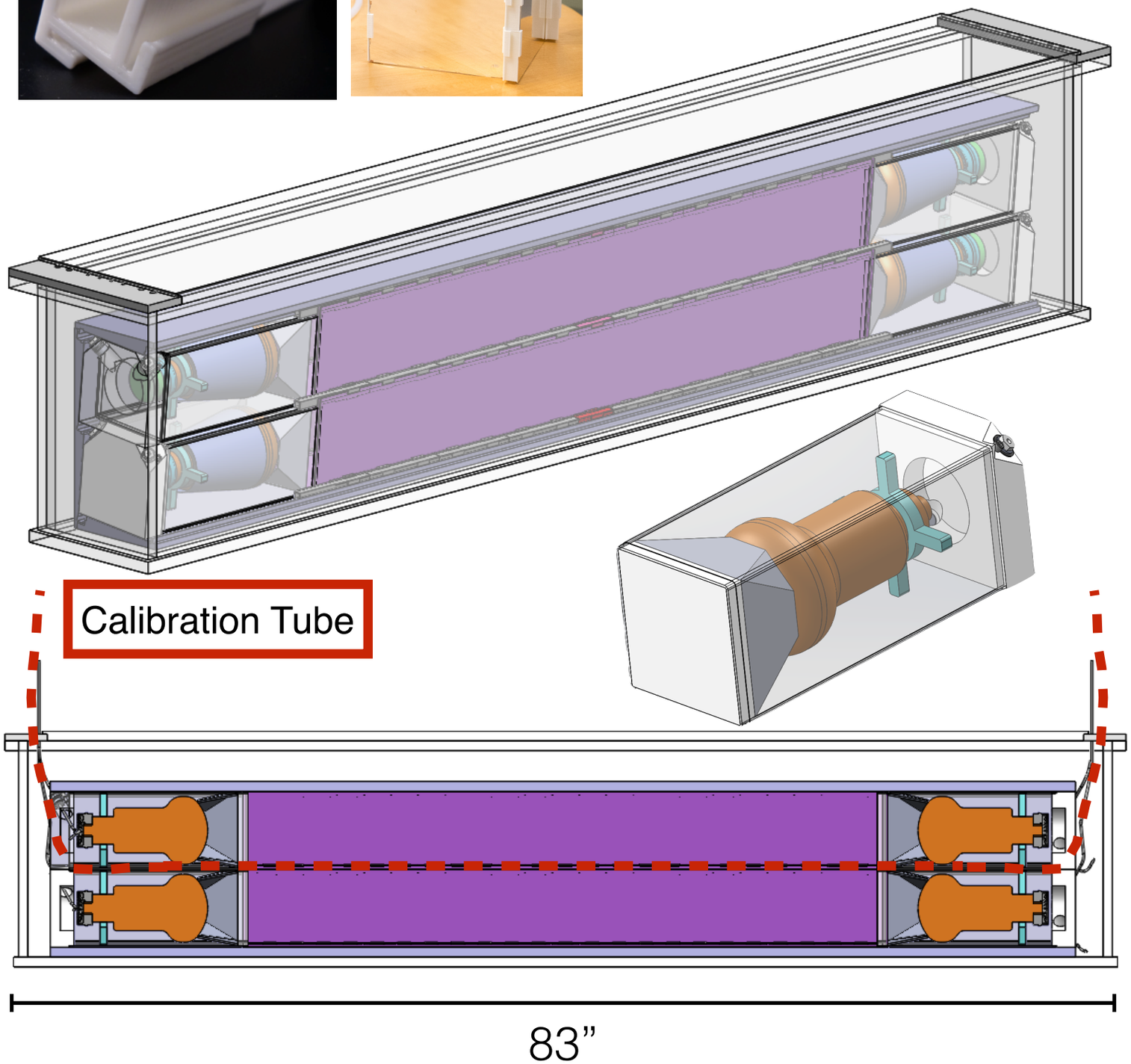




- Operated for four months at HFIR
  - Two HFIR cycles
- Shielding package roughly 25% mass of full shield
- Reactor-related backgrounds mitigated
  - Targeted local shielding
  - Active background rejection with LiLS
- **Validation of background simulations for full PROSPECT detector**

# PROSPECT-50 Demonstrator







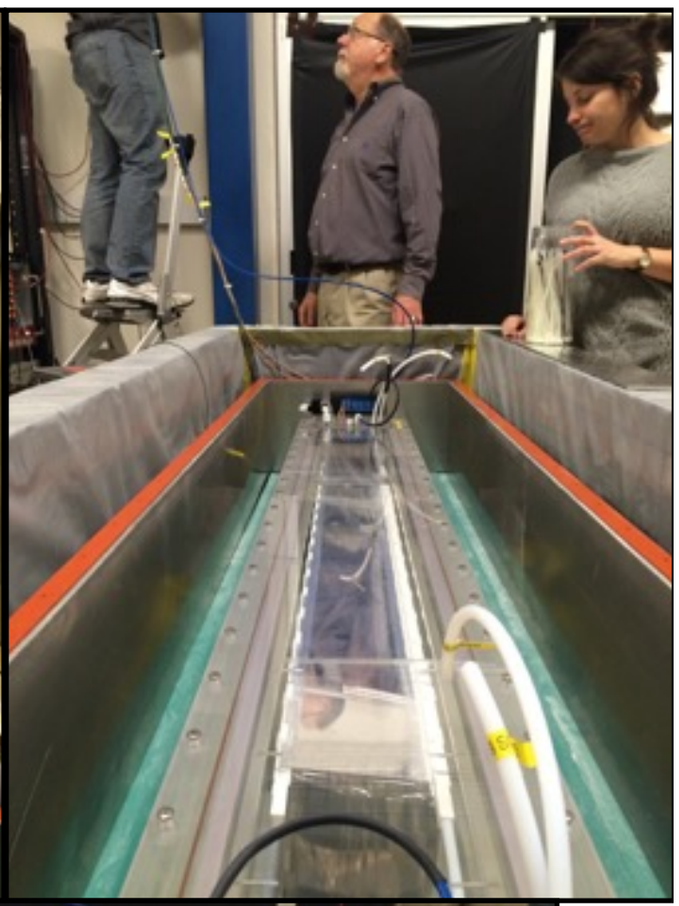

**PROSPECT-50:**

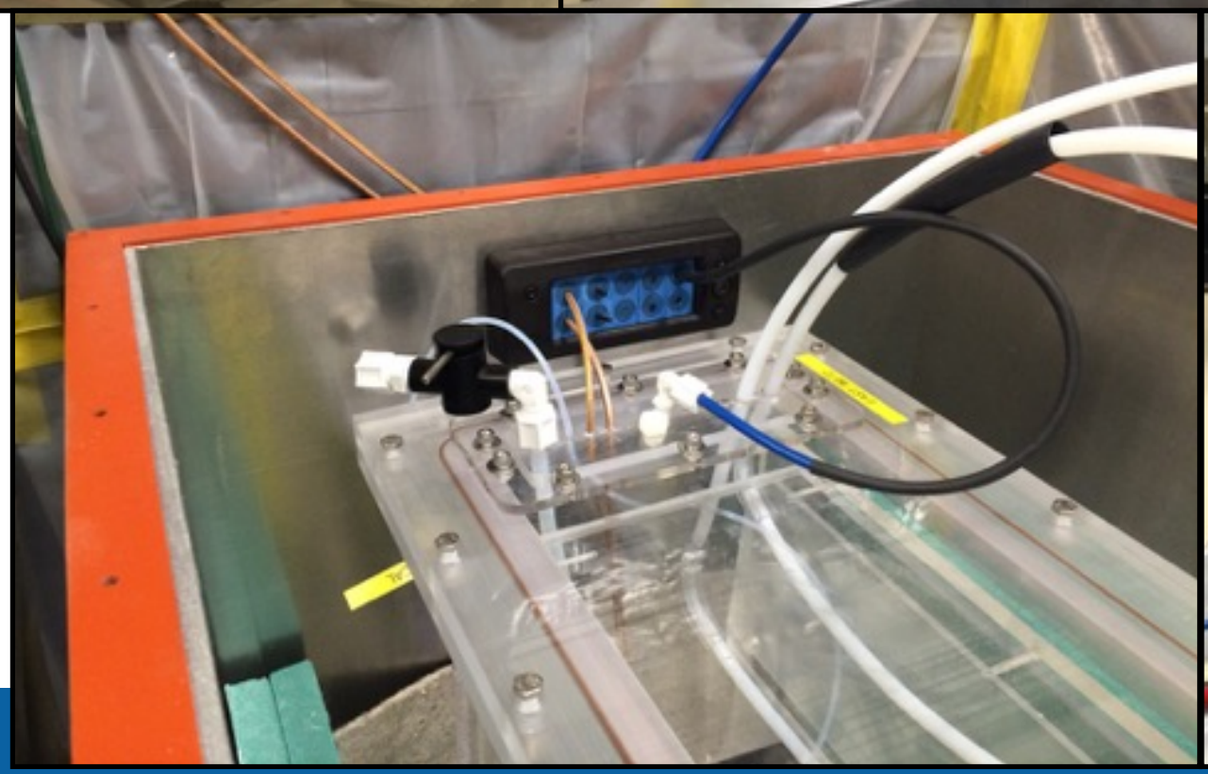
- 50 liters of $^{6}$LiLS
- Two PROSPECT segments

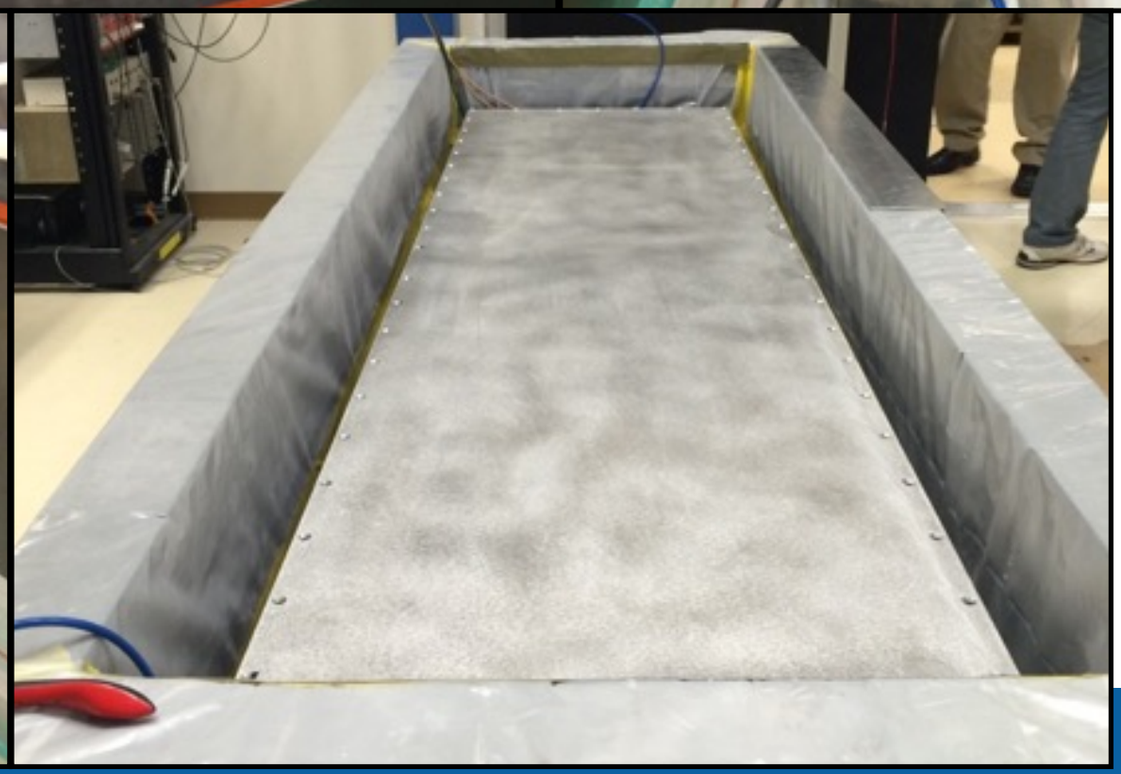
**Test platform of each subsystem**

- Thin-walled reflector panels
- PMT enclosures
- Filling system and procedure
- Calibration system
  - LED optical
  - Source capsules
- Cell-to-cell variation

# PROSPECT-50 Installation

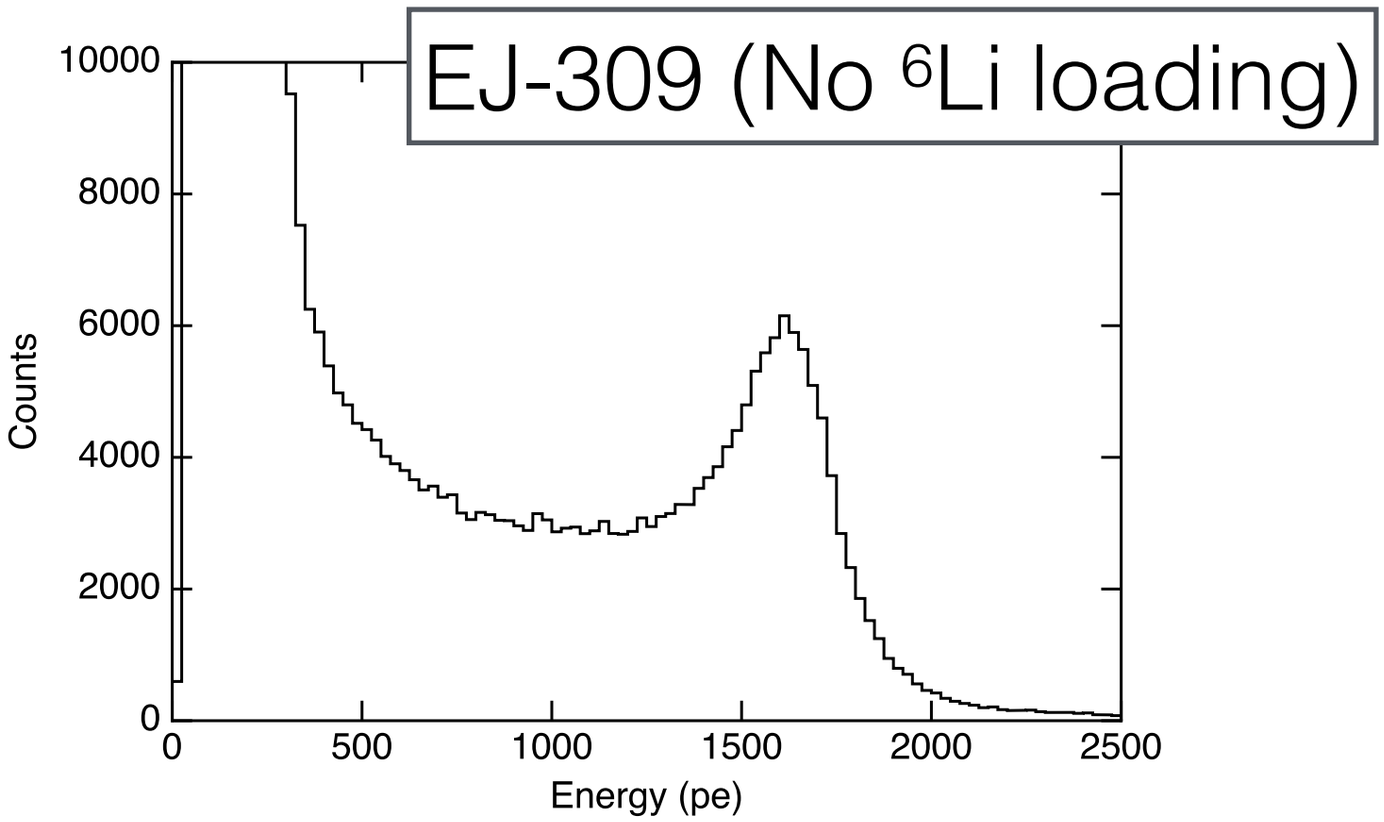


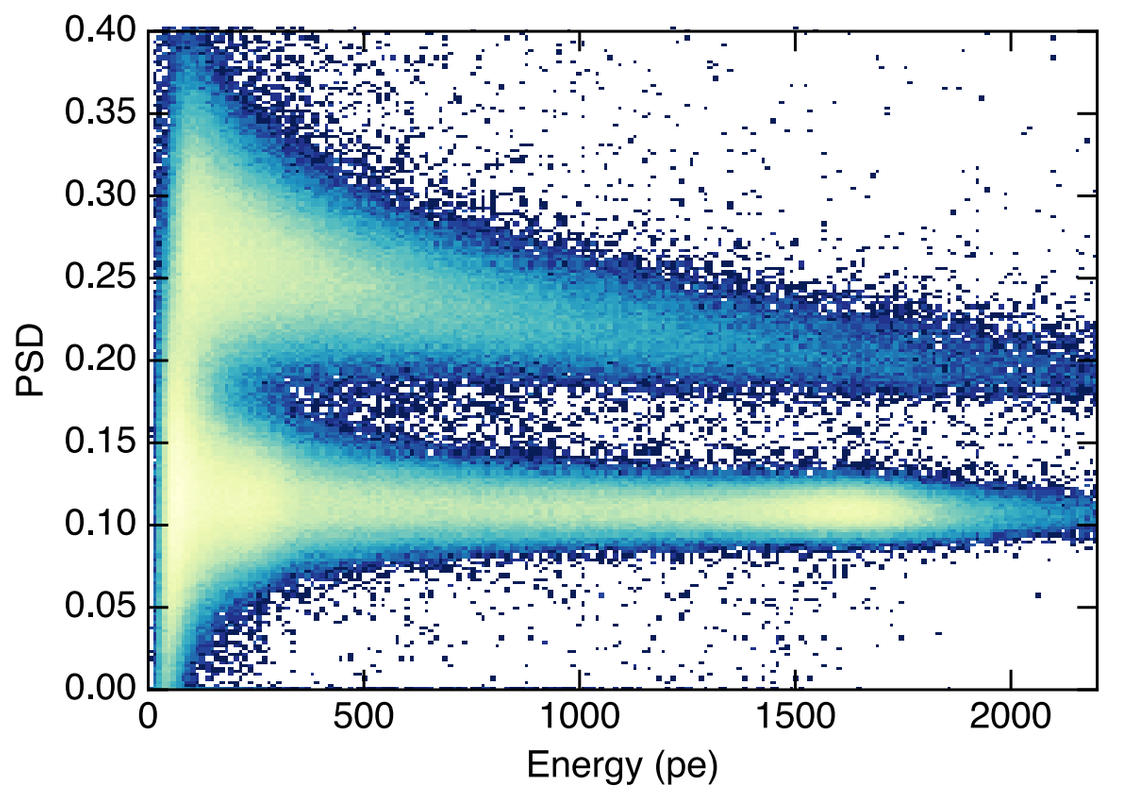




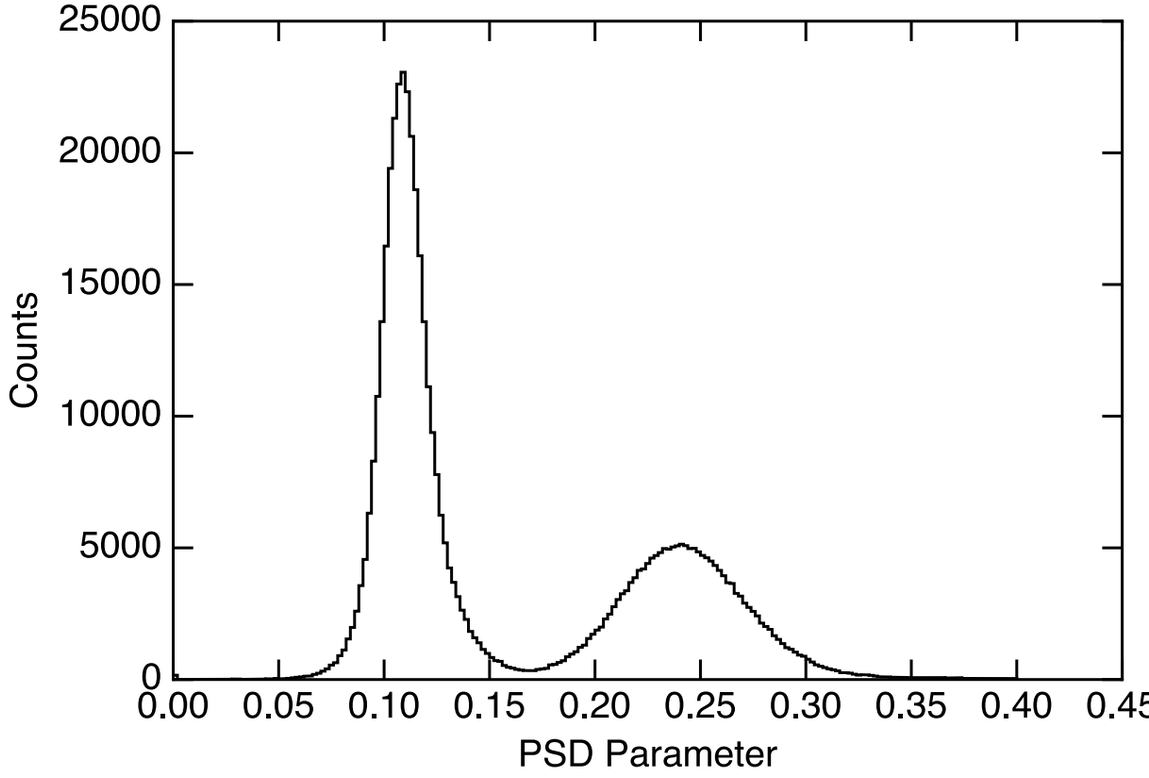
# Cf-252 Neutron Data

PROSPECT-50




- Source 30cm above, uniform illumination
- Fitted nH peak: 1615pe (2.0MeV)
- Light Collection 807pe/MeV, same as Bi
- *Excellent PSD performance*



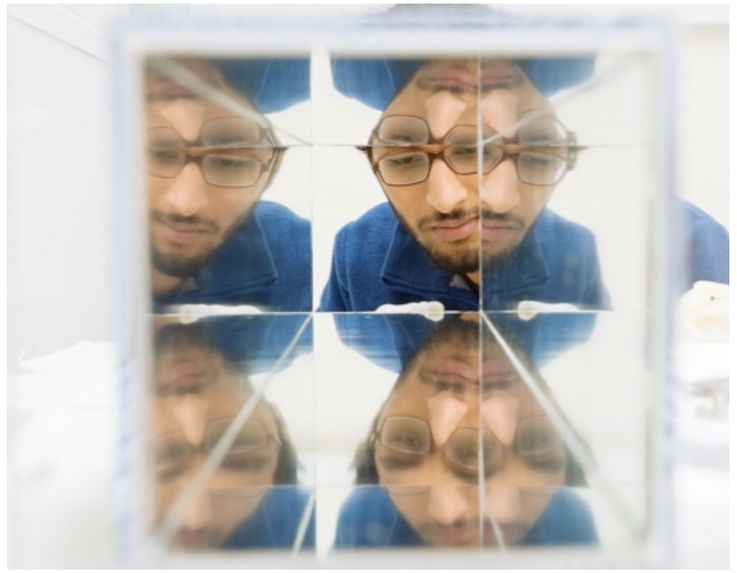
# Low-mass optical separators

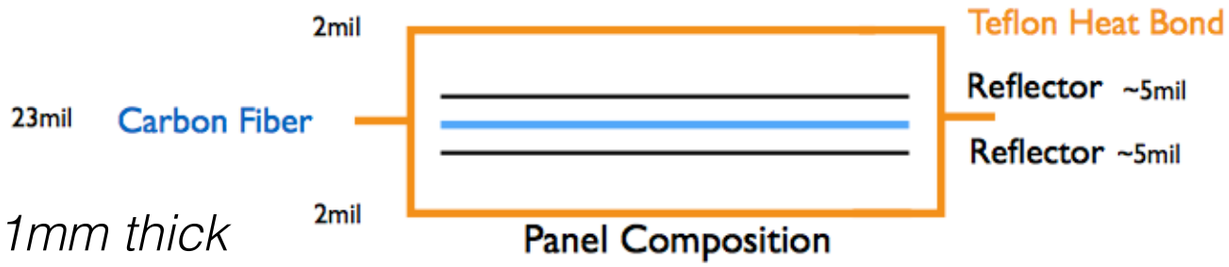
**Compatibility:**

- extensive material compatibility testing required to ensure long-term LS performance
- focus on materials proven in recent experiments - PTFE, acrylic, polypropylene, …
- long-term mechanical stability verified

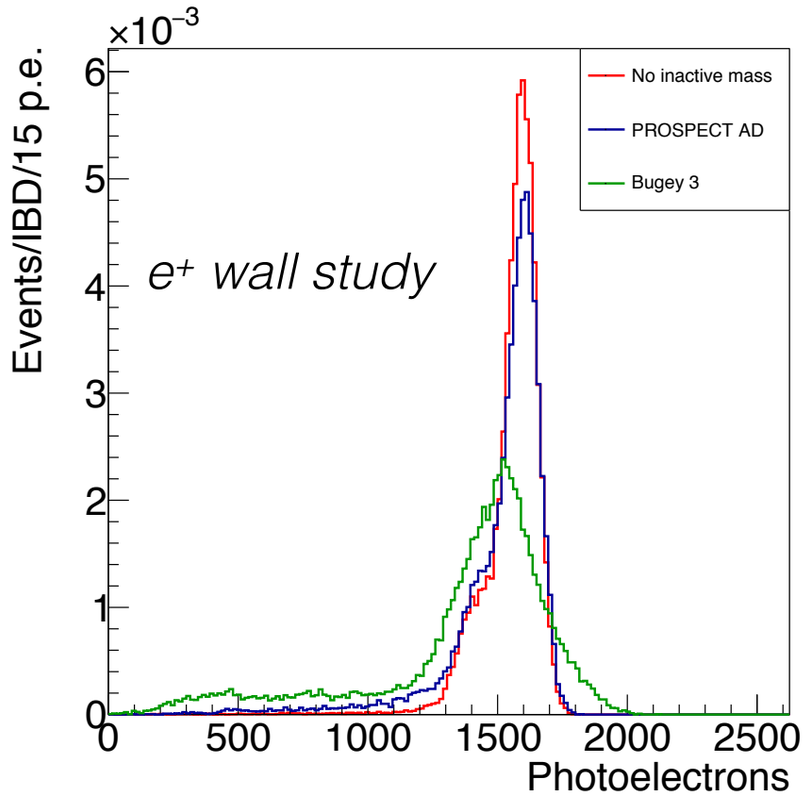
**Separators:**

- physics goals demand low inactive mass, high reflectivity, and long-term compatibility
- developed multi-layer system meeting all requirements
- fabrication procedures for full-scale system under validation





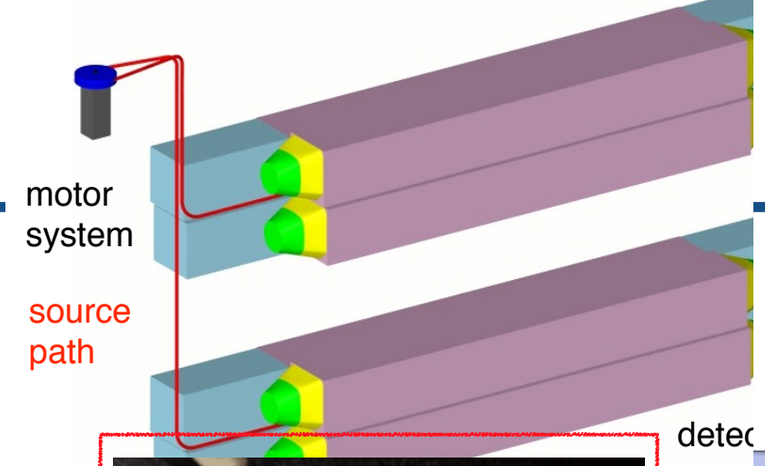

*1mm thick*

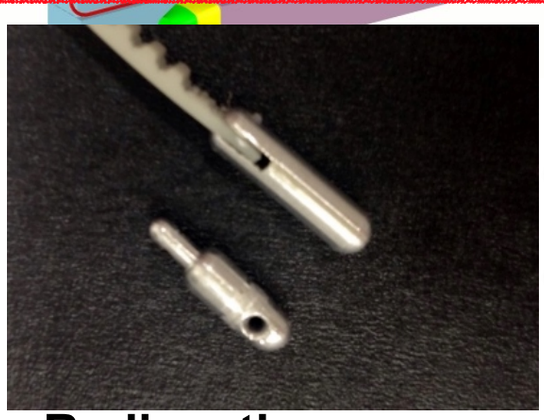



**produced robust low-mass separators from LS-compatible materials**

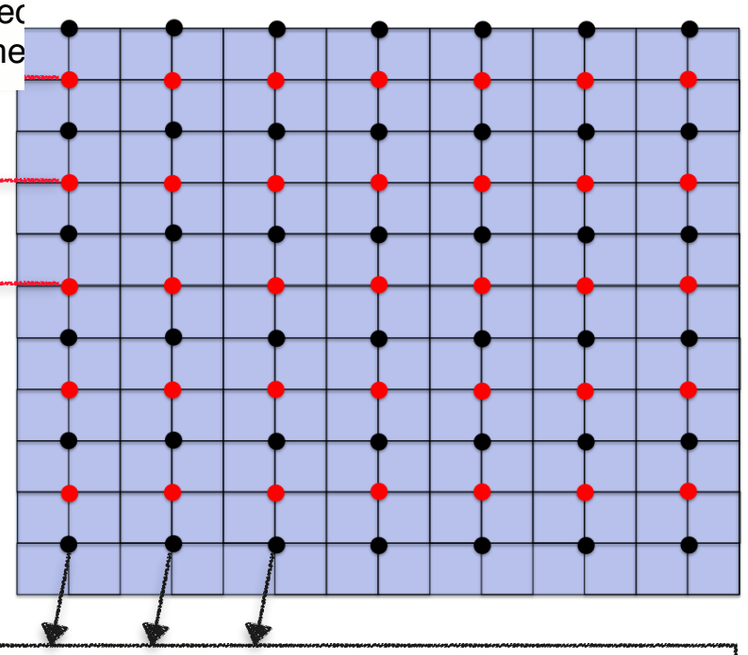
# Calibration

- The calibration sources are transported through teflon guide tubes.
- The calibration tubes are inside the 3-D printed rods.
- Almost every segment is adjacent to a radioactive calibration source and an optical calibration source.

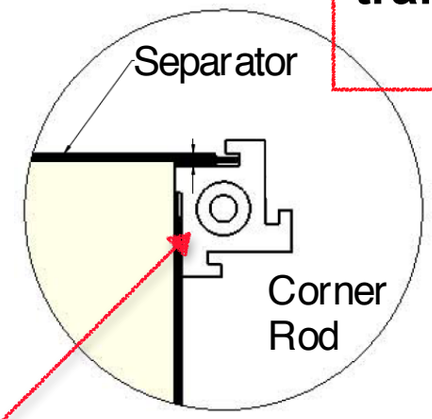


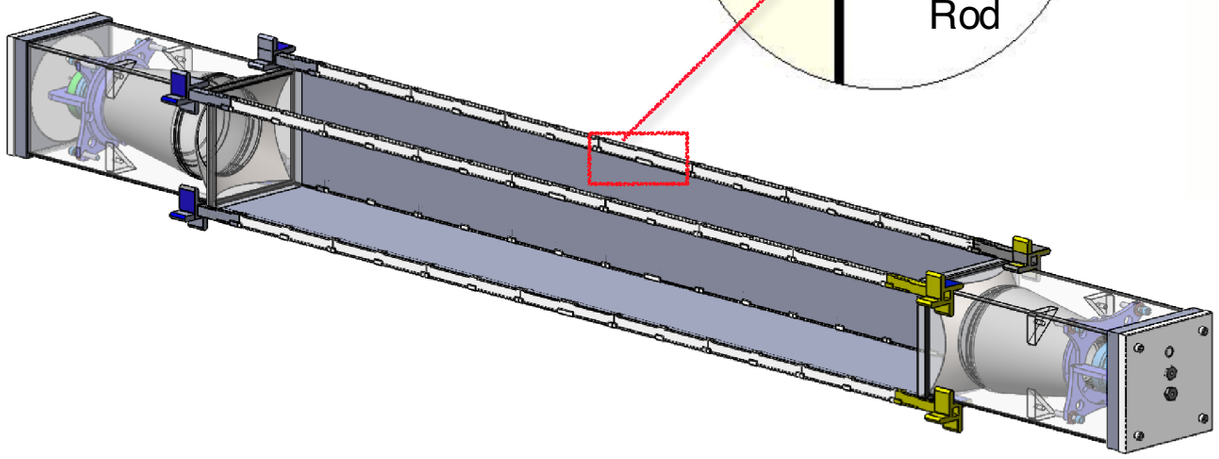



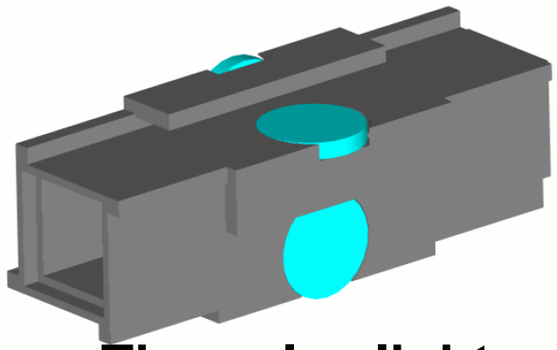
**Radioactive source transported by timing belt.**

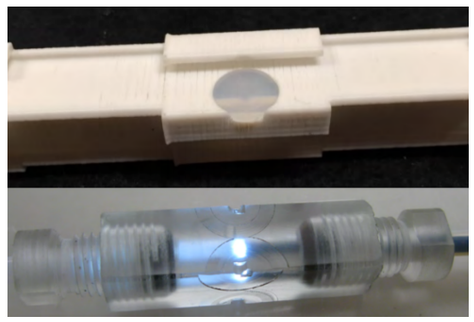


**Calibration tube**





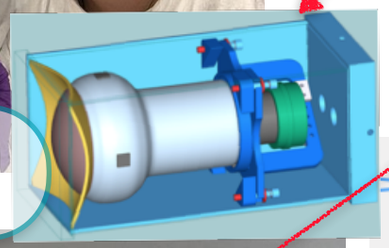


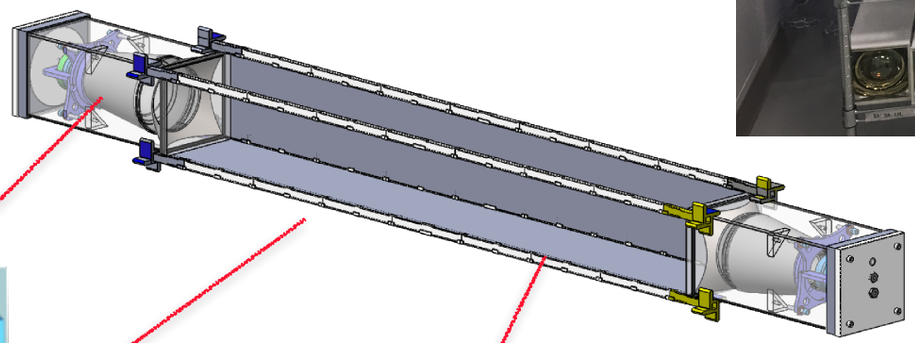
**The pulse light source for optical calibration**

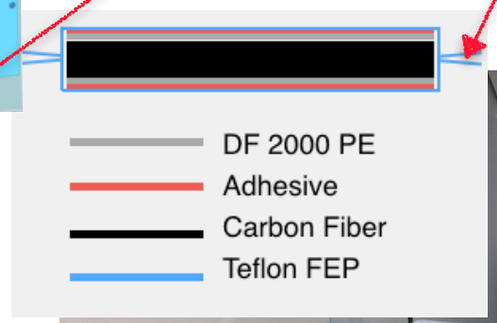
# Detector Construction

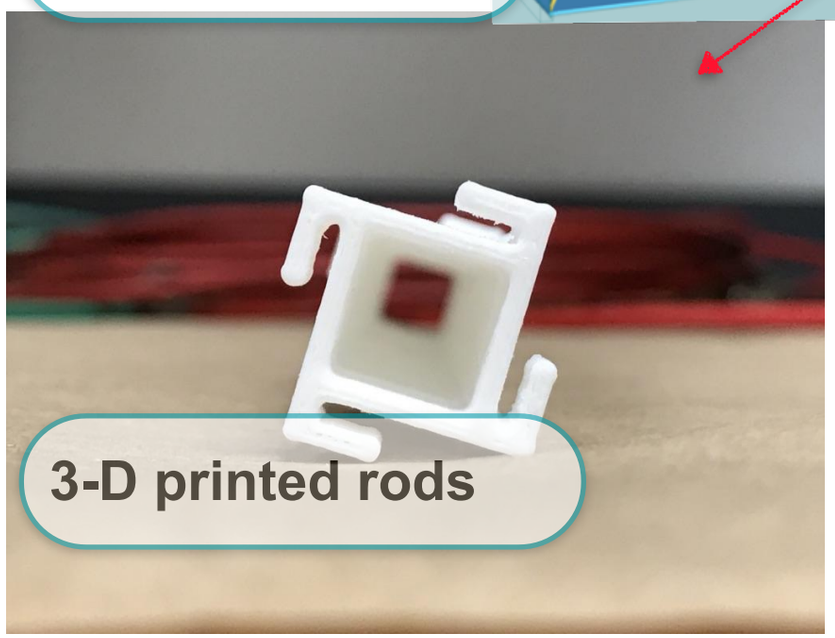
- The fabrication of PROSPECT AD-1 is ongoing.
- Goal is to deploy AD-1 at HFIR in Winter 2017

PMT housing







3-D printed rods

Multilayer reflector laminating

Making LiLS