Final Search for Short-Baseline Neutrino Oscillations with the PROSPECT-I Reactor Antineutrino Detector

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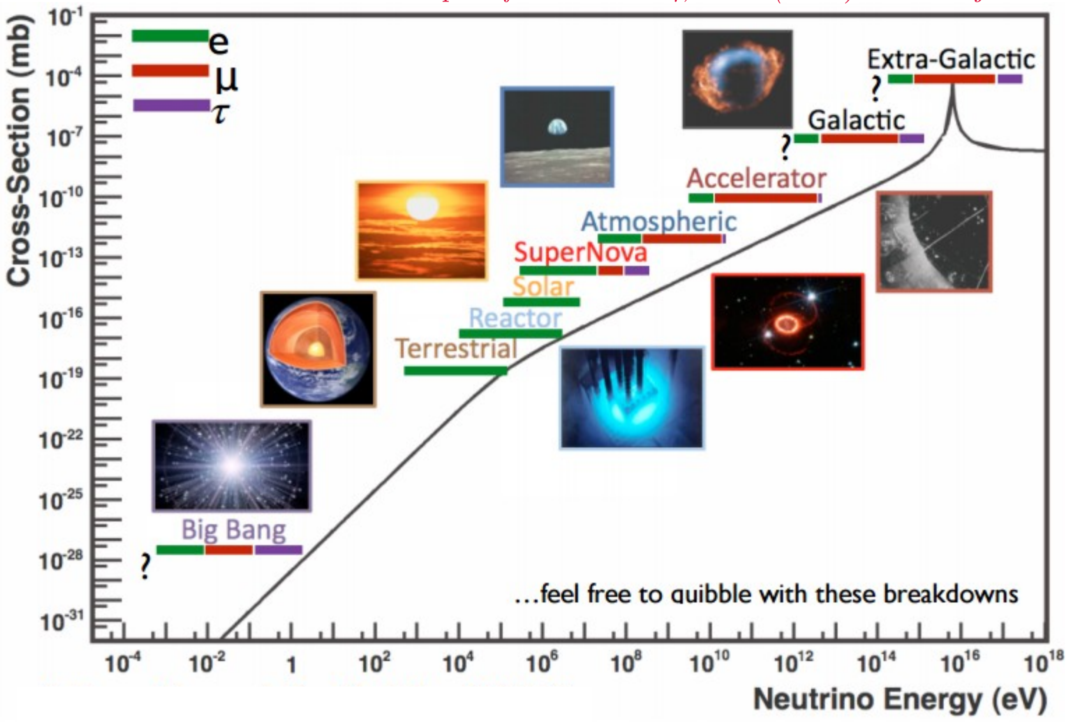
On behalf of the PROSPECT Collaboration

Neutrinos

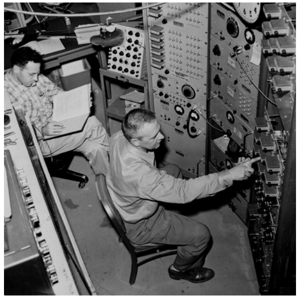
- Neutrinos are produced everywhere:
  - Different flavors as neutrinos or antineutrinos.
- Fermilab Booster Neutrino Beam produces mostly muon flavor (anti)neutrinos in the GeV regime.
  - Small contamination of electron (anti)neutrinos.
- Reactor antineutrinos:
  - MeV regime.
  - Monosource of electron antineutrinos.

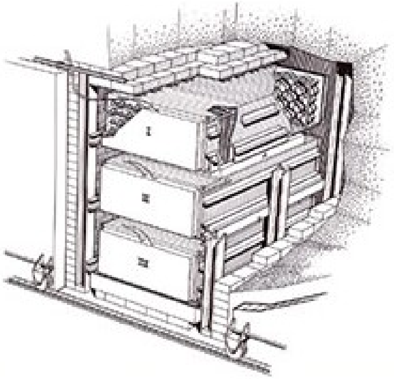
Adapted from RMP 84, 1307 (2012) B. Littlejohn



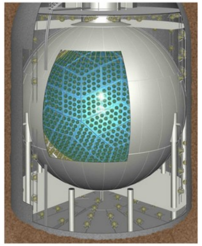
Reactor Antineutrinos Achievements

First detection of ν_e by Cowan & Reines.

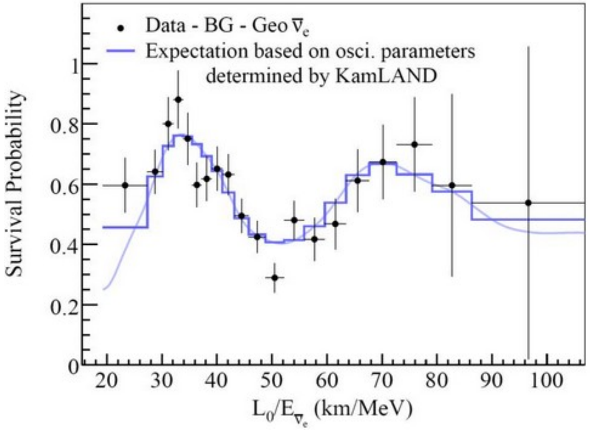




First observation of neutrino oscillation from reactor by KamLand.

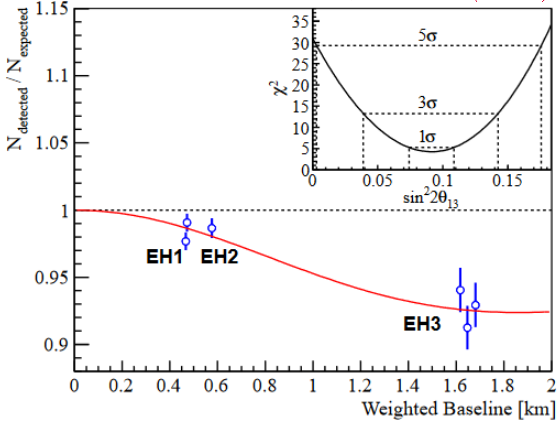


PRL 90, 021802 (2003)



Measurement of Θ_{13} by Daya Bay.

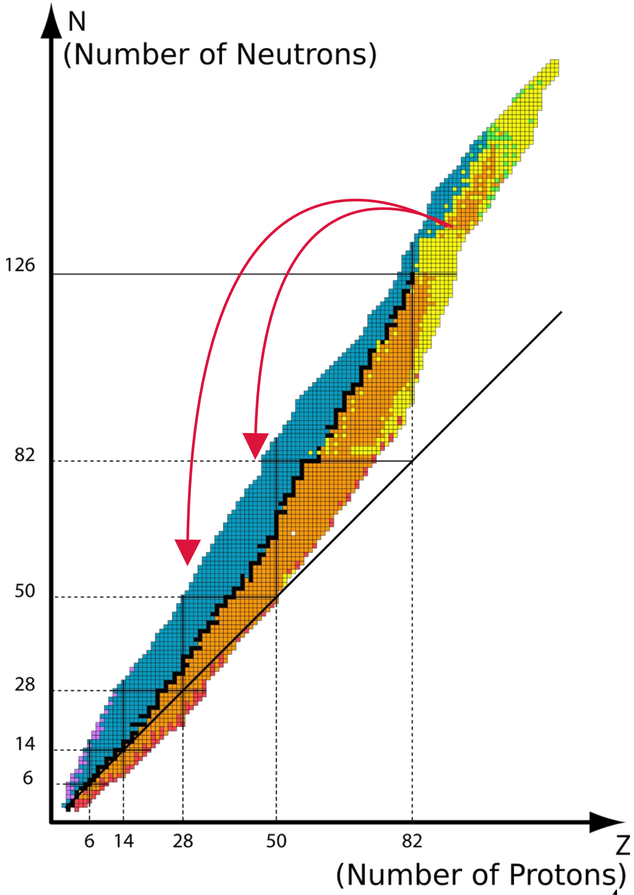
PRL 108, 171803 (2012)



Recent results are shown for precision and emphasis

Neutrinos from Reactor

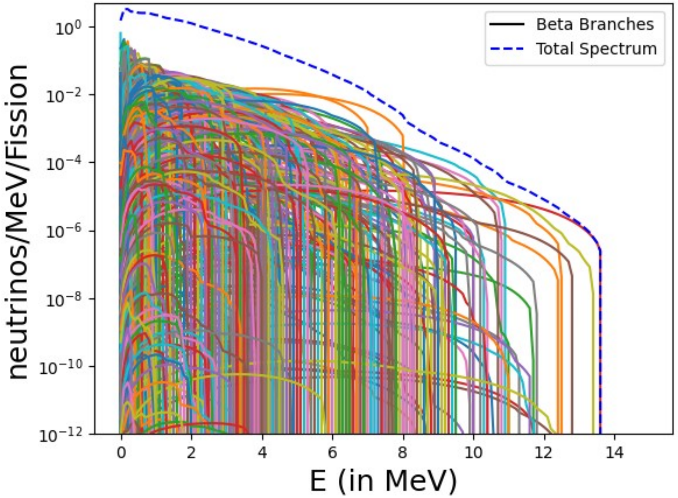
- Fission isotopes bombarded with neutrons and produces neutron-rich daugthers:
  - Beta decay of unstable produces ~6 antineutrinos/fission.
- 99% of antineutrinos in nuclear reactor are produced by fissions in ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu.
  - Highly-Enriched Uranium (HEU) only burns ^{235}U.
  - Low-Enriched Uranium (LEU) is a mixture of isotopes.



Prediction of Antineutrino Spectrum

Ab-initio/Summation:

- Summation of all β-branches of all fission products using database.
- Huge uncertainty in the database: rare isotopes/beta-branches ... *back then*



A. Irani, IIT - CONFLUX

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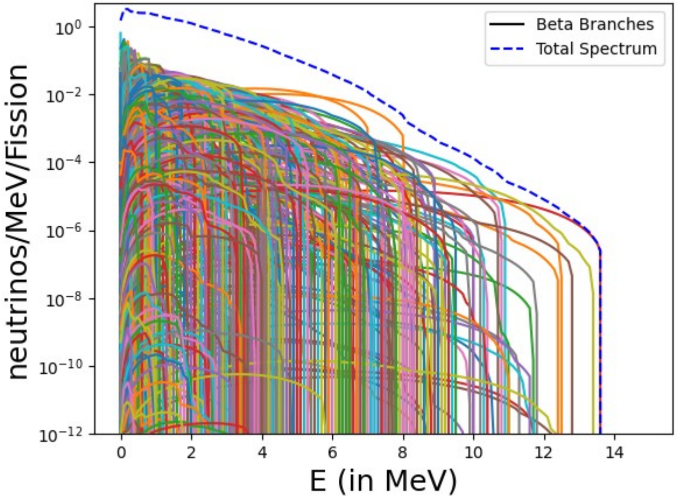
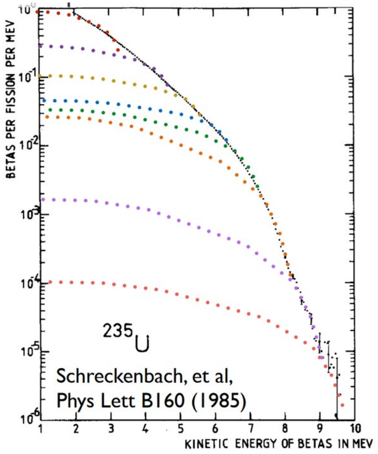


A. Irani, IIT - CONFLUX

Conversion:

- Measure beta spectra then convert into ν_e using ‘virtual beta branches’.
- Legacy dataset from the 80s.
- Claimed smaller error than ab-initio … *back then*



Reactor Antineutrino Anomaly

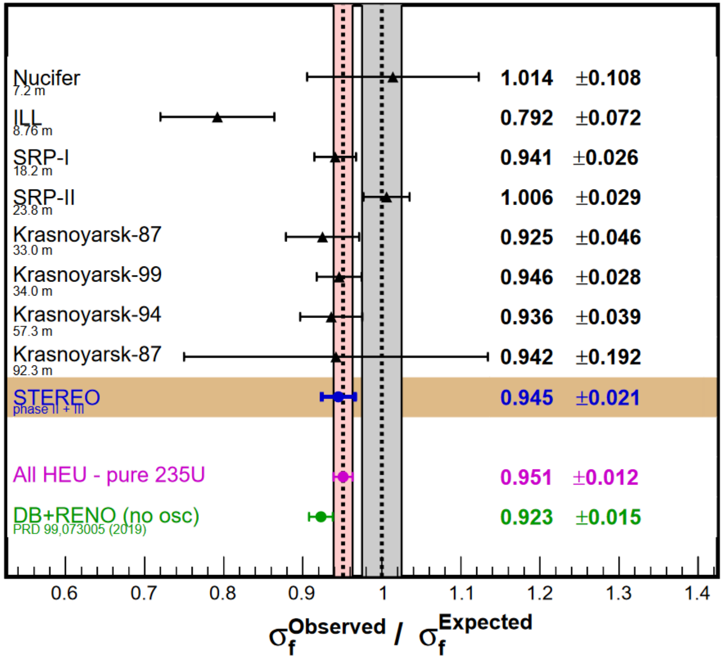
Re-evaluation of the antineutrino spectrum:

- Th. A. Mueller *et al.*, *PRC 83, 054615 (2011)*: Combine summation and conversion methods.
- Huber, *PRC 84, 024617 (2011)*: %-level correction factor in the conversion.

Huber-Mueller model is used as benchmark for all reactor experiments.

- 5.7% flux deficit: Reactor Antineutrino Anomaly.
- $\sim 3\sigma$ tension with previous experiments.

Nature 613, 257–261 (2023)

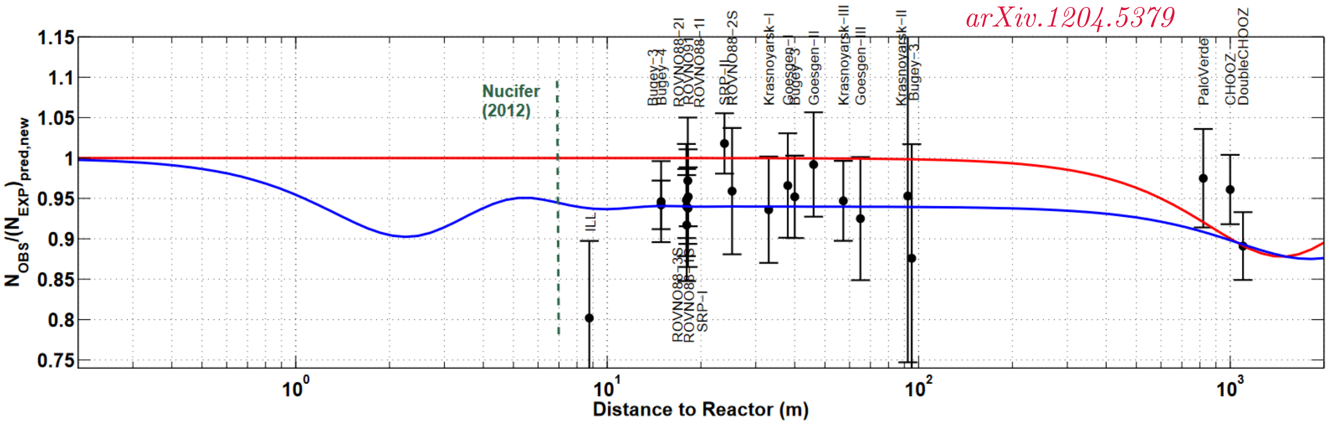


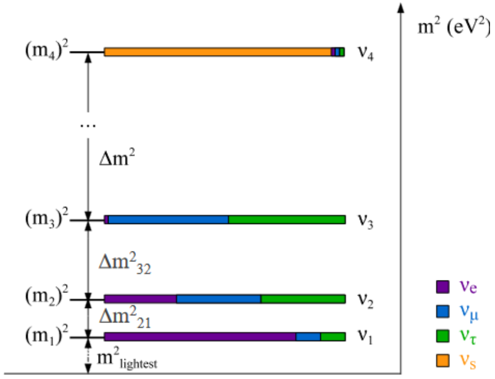
Recent results are shown for precision and emphasis

Reactor Antineutrino Anomaly

What could be the origin of this deficit?

- Miscalculation of the flux prediction?
- Could this be an eV-scale sterile neutrino oscillation at short-baseline ('3+1' model)?



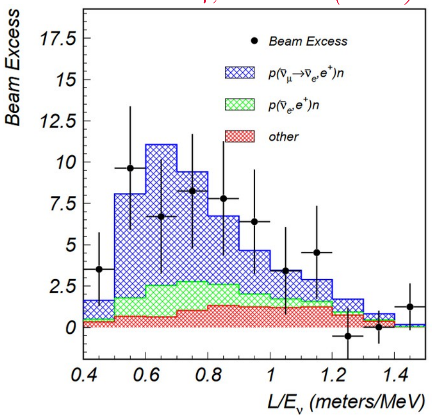


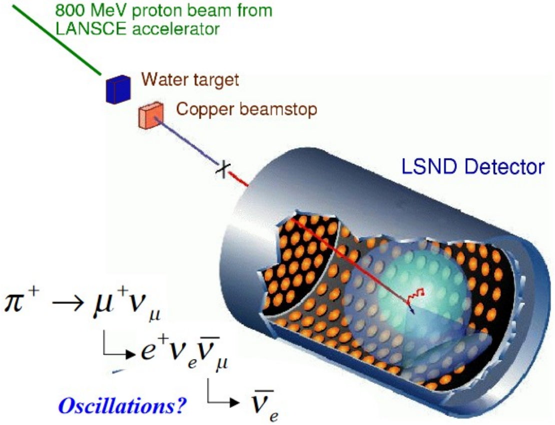
Other Sterile Neutrino Hints

LSND/MiniBooNE anomaly:

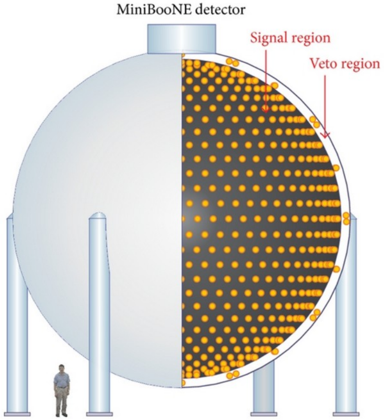
- Excess of electron (anti)neutrinos in muon (anti)neutrino beam.
  - Significant of ~6σ.
  - Also suggests 3+1 eV-scale sterile neutrino oscillations?

PRD 64, 112007 (2001)

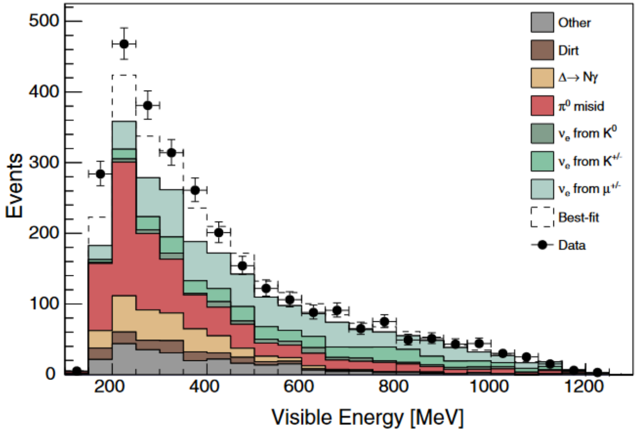




- Same L/E.
- Different energy, beam and detector systematics.
- Different event signatures, backgrounds.



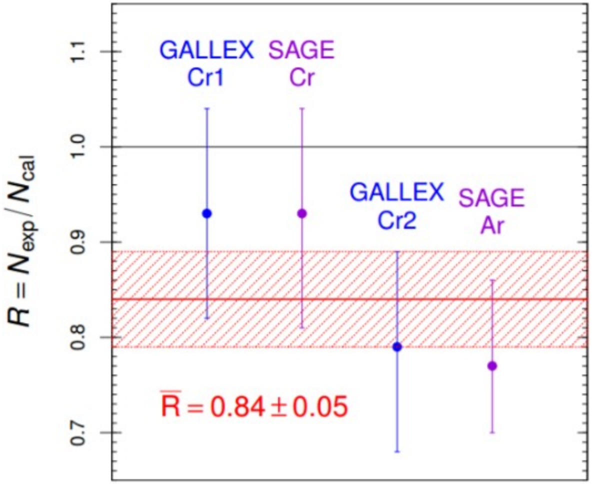
PRD 103, 052002 (2021)



Other Sterile Neutrino Hints

Gallium anomaly:

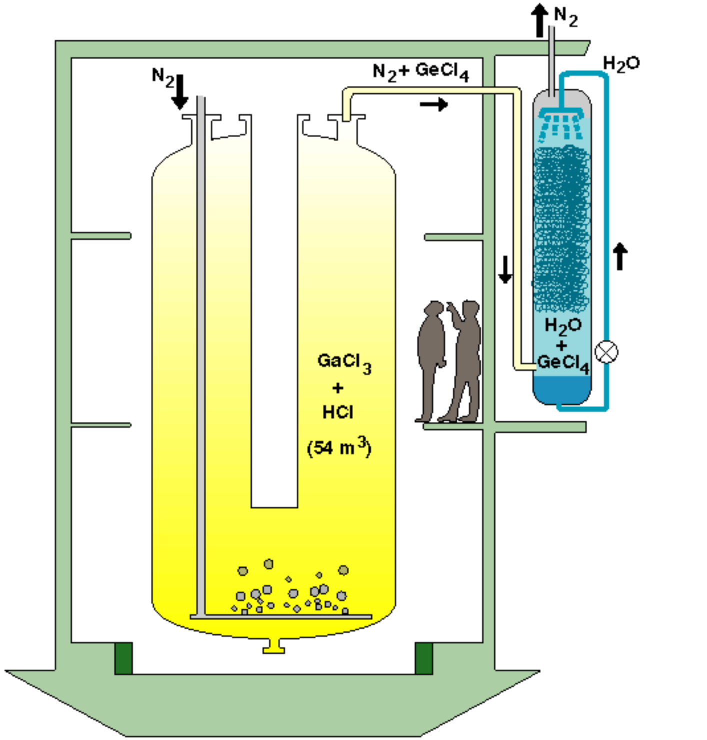
- Deficit of electron neutrinos from radioactive sources in Gallium based detectors:
  - GALLEX and SAGE experiments.
  - Also suggests 3+1 eV-scale sterile neutrino oscillations?



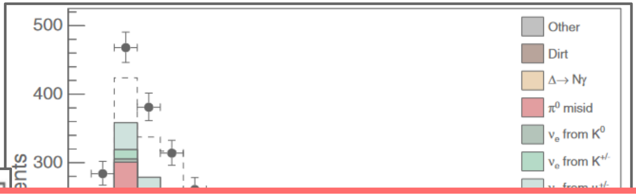
ν_e Sources:

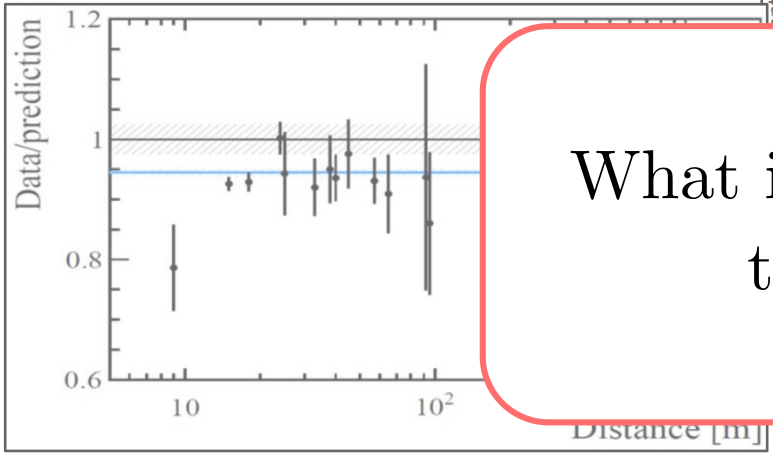
$$e^- + {}^{51}\text{Cr} \rightarrow {}^{51}\text{V} + \nu_e$$

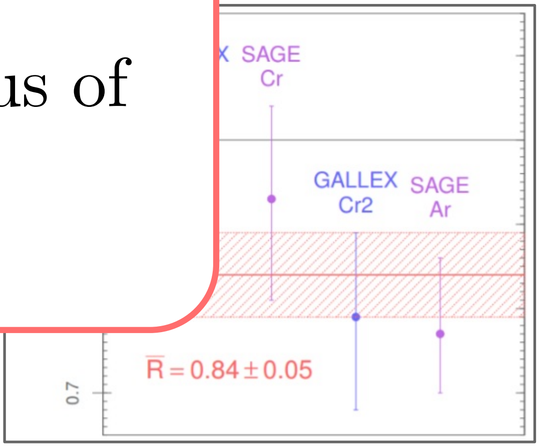
$$e^- + {}^{37}\text{Ar} \rightarrow {}^{37}\text{Cl} + \nu_e$$



Current Landscape





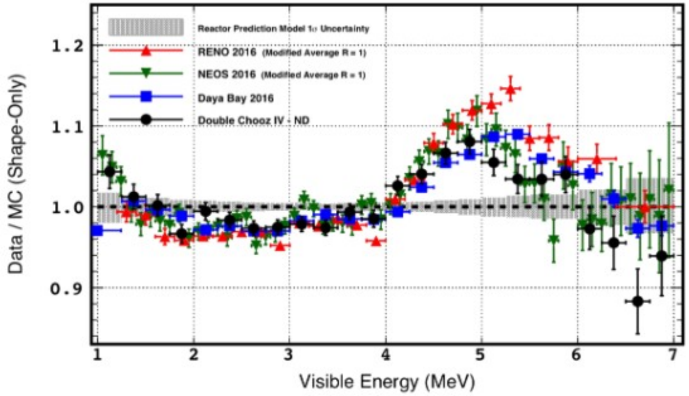


What is the current status of these anomalies?

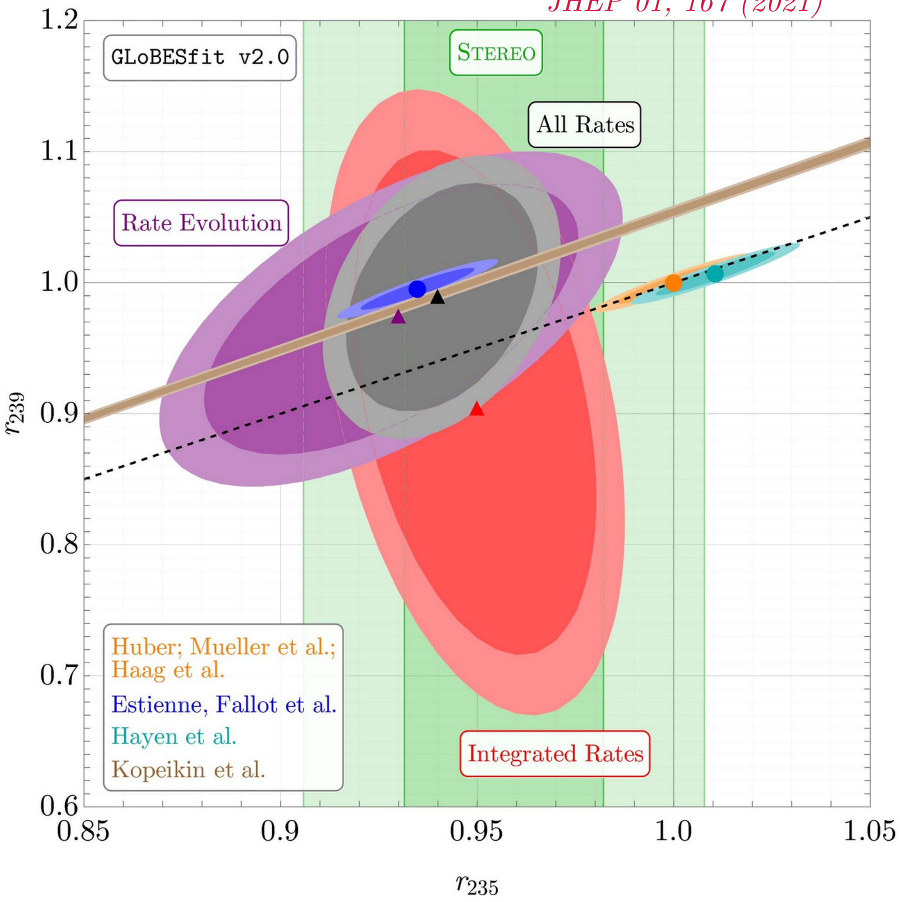
Current Landscape

The Reactor Antineutrino Anomaly is fading:

- Daya Bay fuel evolution measurement suggests over-prediction of ^{235}U flux, *PRL 118, 251801 (2017)*.
- New fission beta measurement suggests lower ^{235}U is needed *PRD 104, L071301 (2021)*
- Ab-initio prediction shows reduced deficit with improved beta data, *PRL 123, 022502 (2019)*
- Beta conversion unable to predict neutrino spectrum:
  - Distortion around 5 MeV.



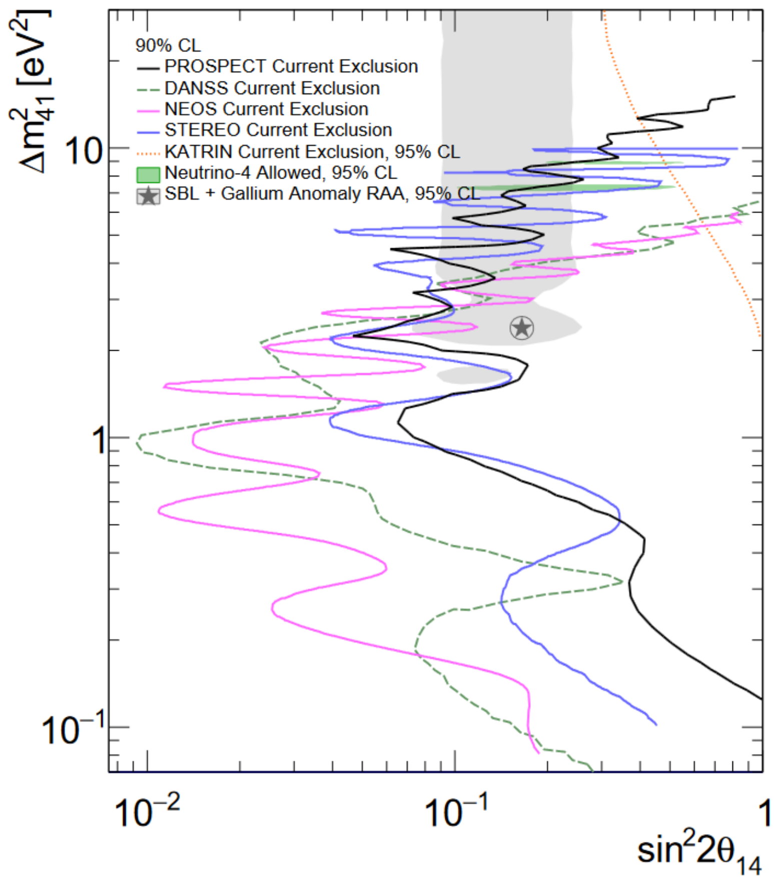
JHEP 01, 167 (2021)



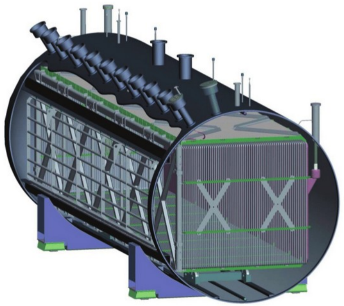
Current Landscape

The Reactor Antineutrino Anomaly is fading:

- Many SBL reactor oscillation experiments have ruled out much of ‘sterile neutrino hypothesis’ space: DANSS, NEOS, PROSPECT, STEREO.

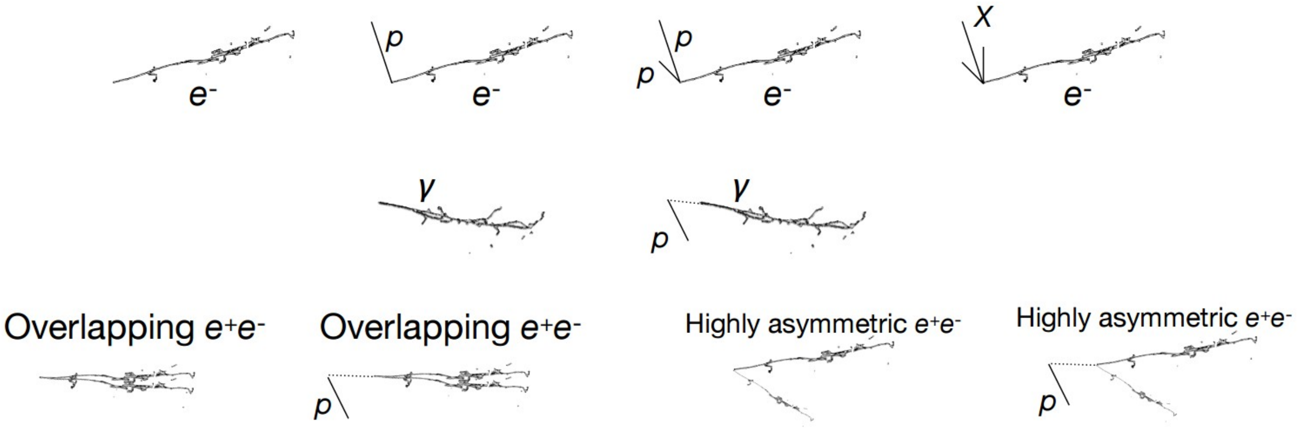


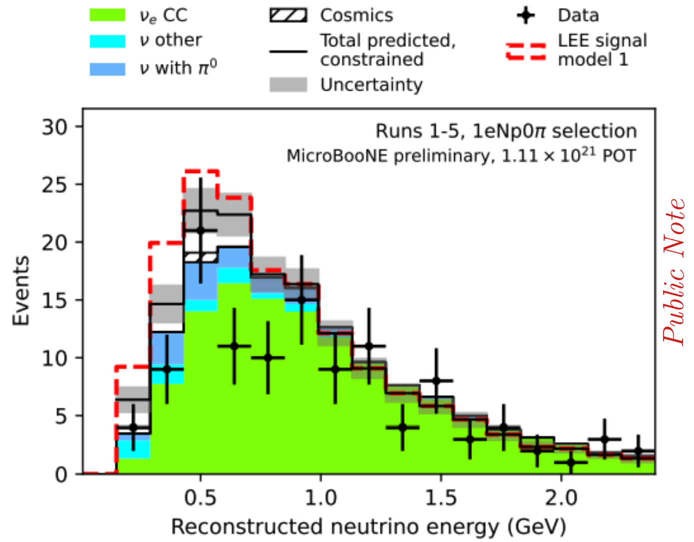
Current Landscape



The LSND/MiniBooNE anomaly is still present:

- MicroBooNE: MiniBooNE's excess doesn't seem ν_e-dominated but many potential photon and e^+e^- channels remain unexplored.
- LSND anomaly still has not been directly experimentally verified (JSNS² is working here!)

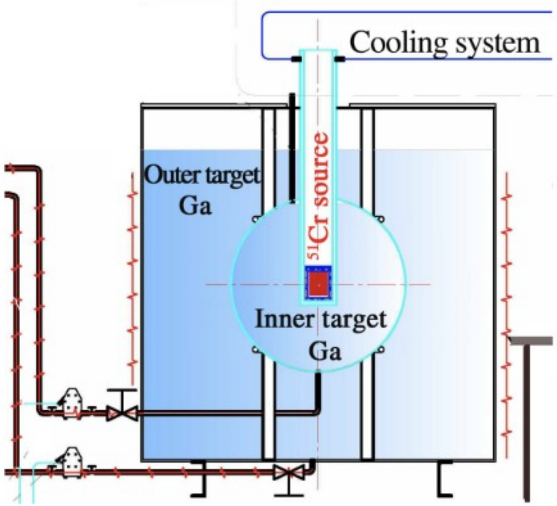


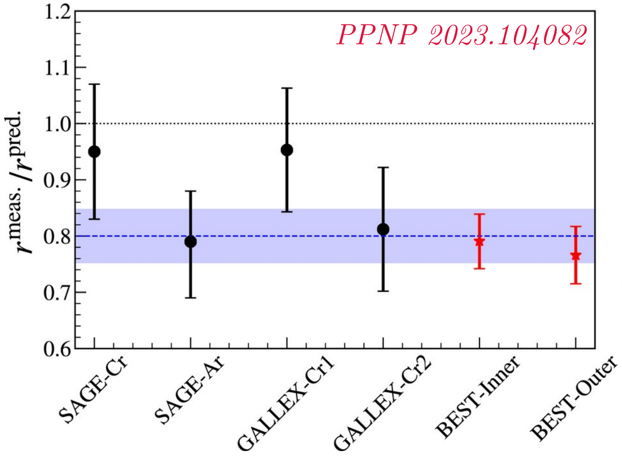


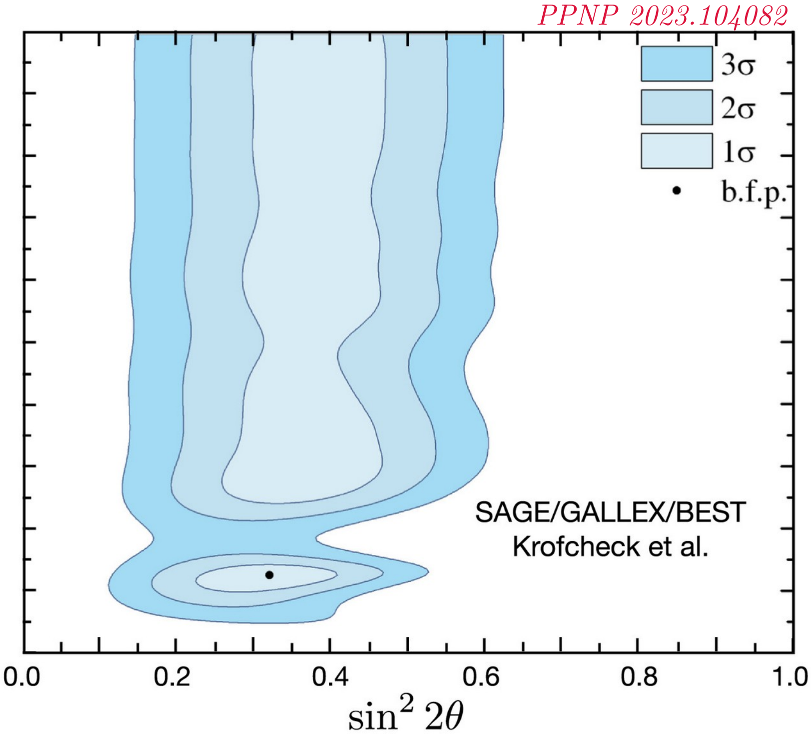
Current Landscape

The Gallium anomaly is still present:

- Strengthen by the BEST experiment:
  - Best-fit ($Sin^2(2\Theta_{14})$, Δm^2_{14}) = (0.32, 1.25) with > 4σ significance.



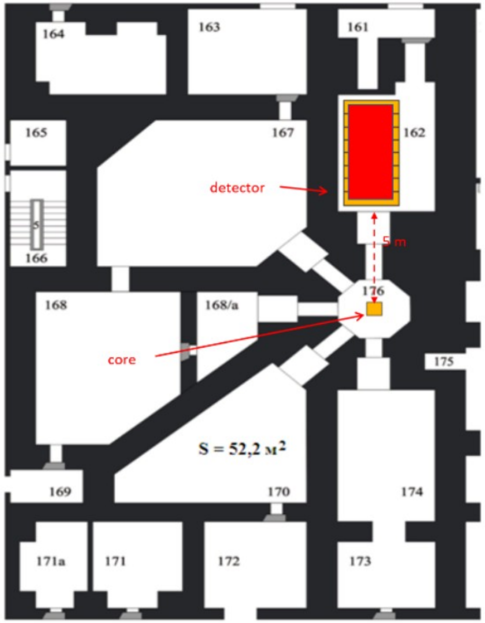




The Neutrino-4 Experiment

Reactor antineutrino experiment deployed at SM-3 Dimitrovgrad, Russia

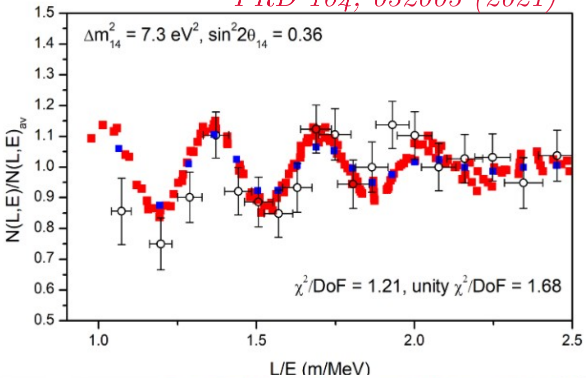
- Non-zero oscillation ($\sin^2(2\Theta_{14})$, Δm^2_{14}) = (0.36, 7.3), at ~2.9σ.
  - Consistent with the newly strengthen Gallium Anomaly.

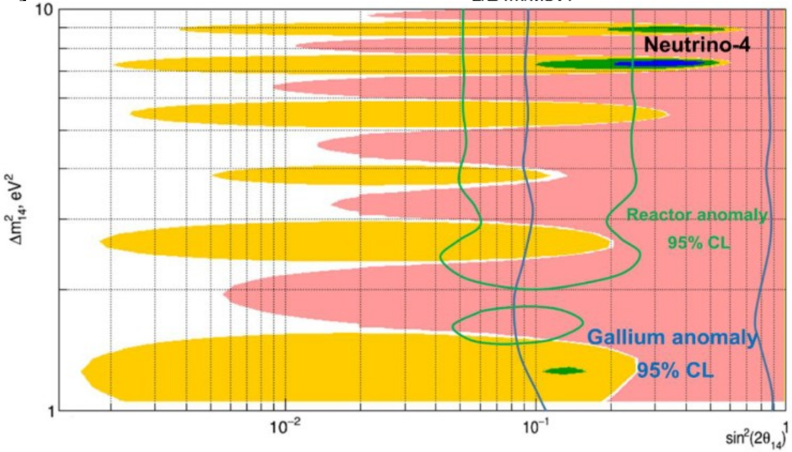


- HEU reactor operating at 90 MW.
- Movable detector L ϵ [6.4, 11.9 m] (23 cm step).

Notes on Neutrino-4 results:
- arXiv:2006.13147
- PLB 816, 136214 (2021)
- JETP Lett. 112, 452 (2020)

PRD 104, 032003 (2021)

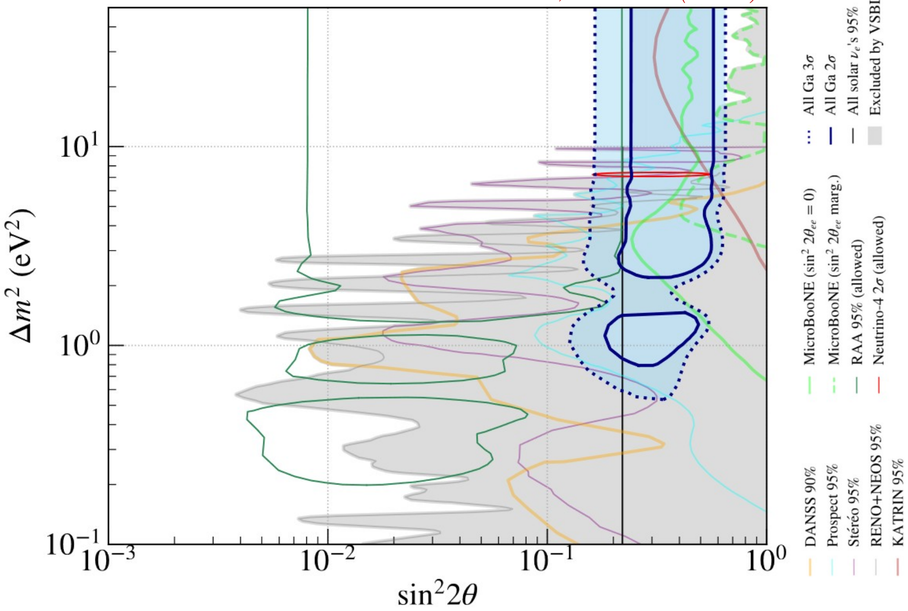




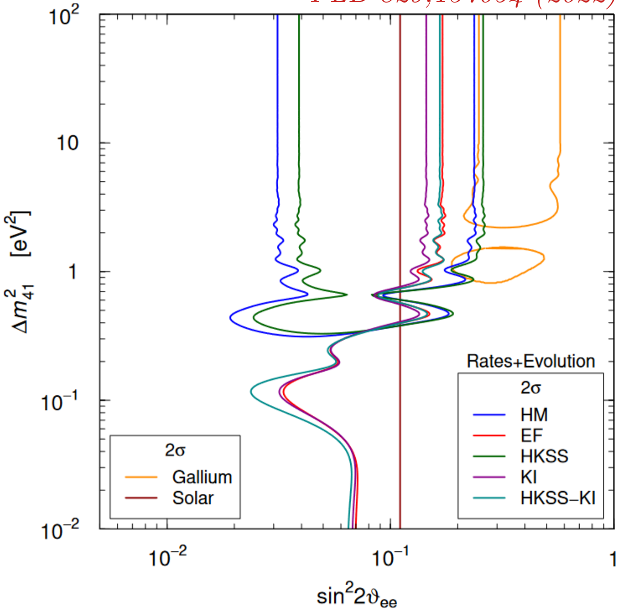
Current tension: Reactor

- The gallium anomaly and Neutrino-4 seems mostly ruled out by other SBL reactor measurements.
- If the Gallium anomaly is caused by electron-flavor disappearance, then how can the electron-flavor Reactor Anomaly be 'fading away'?

PRL 128, 232501 (2022)



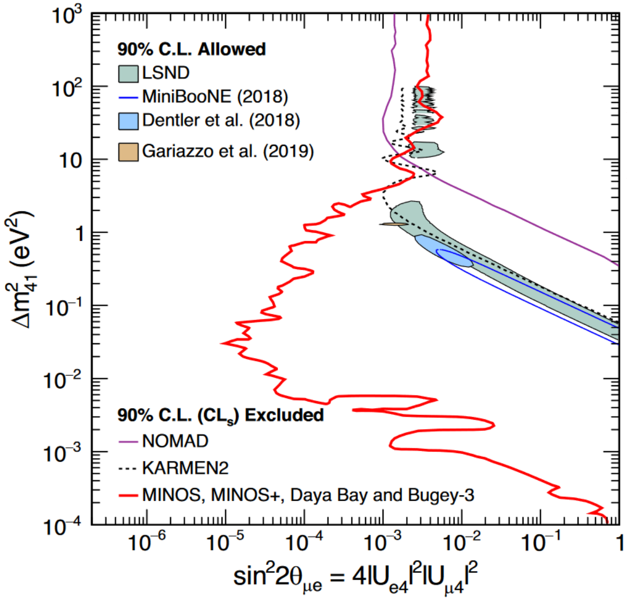
PLB 829,137054 (2022)



Current tension: Accelerator

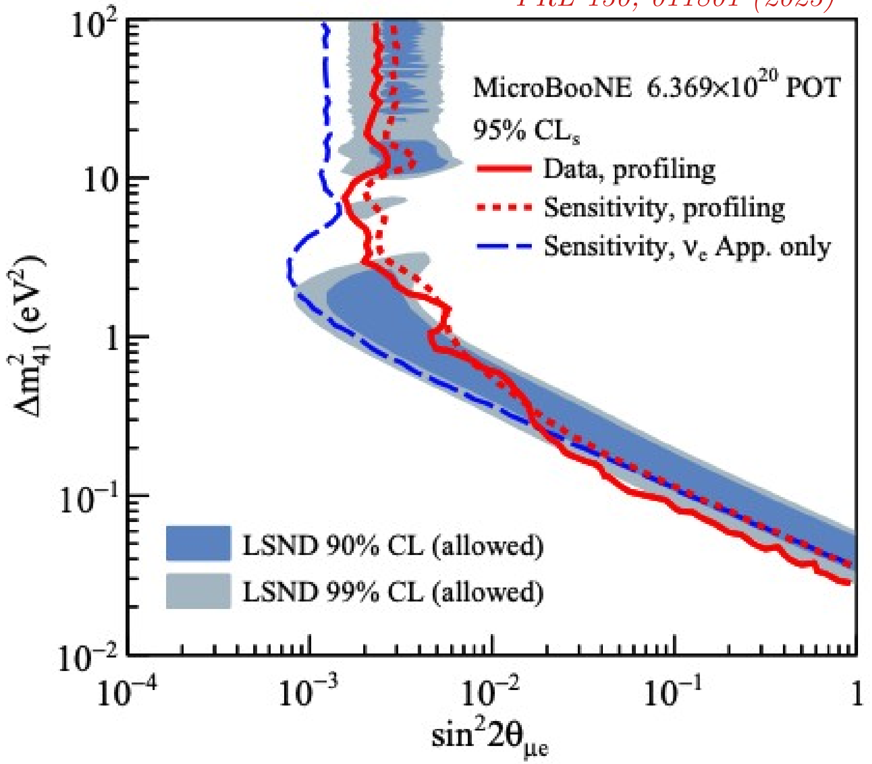
LSND/MiniBooNE anomaly:

- No excess seen by the MicroBooNE experiment.
- For a 3+1 model, combined mu- and e-flavor disappearance searches rule out the suggested mu-e oscillation space.

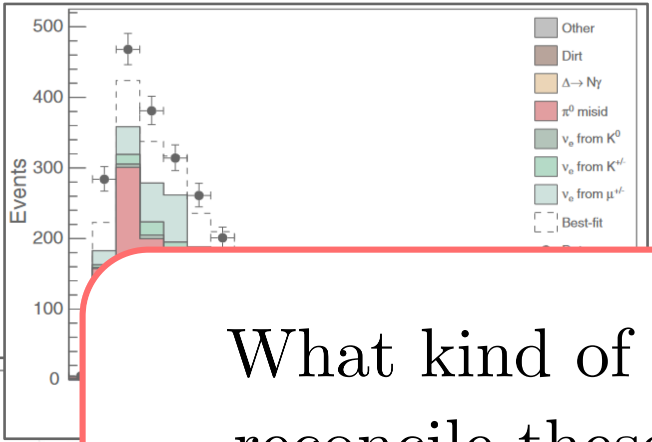


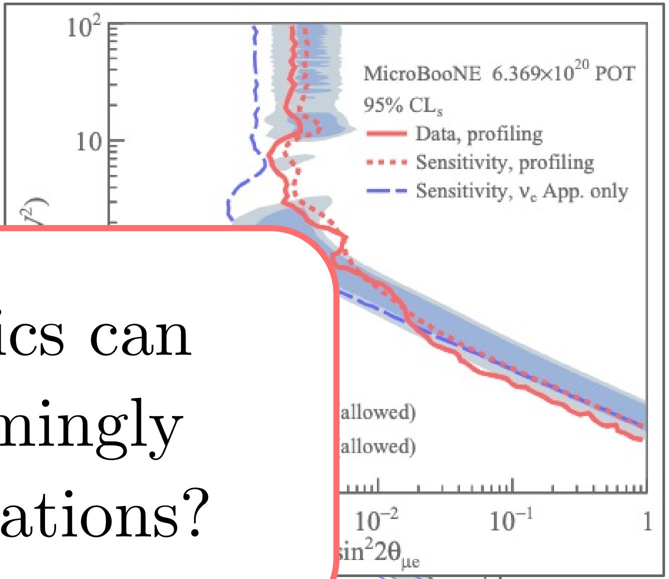
PRL 125, 071801 (2020)

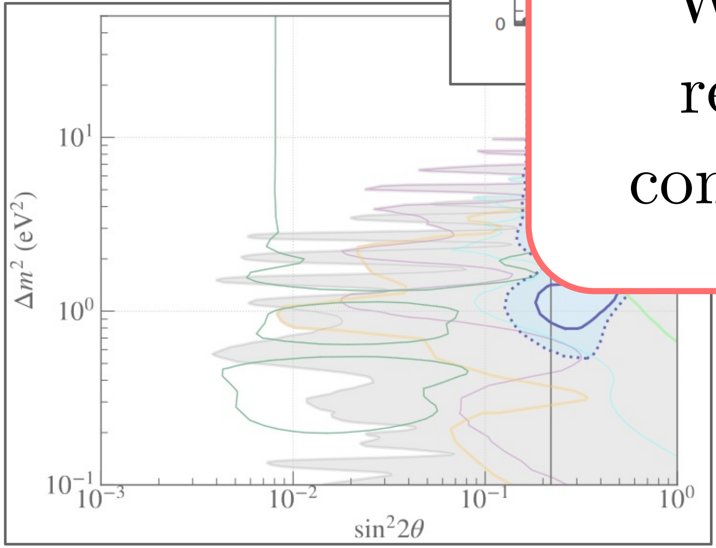
PRL 130, 011801 (2023)

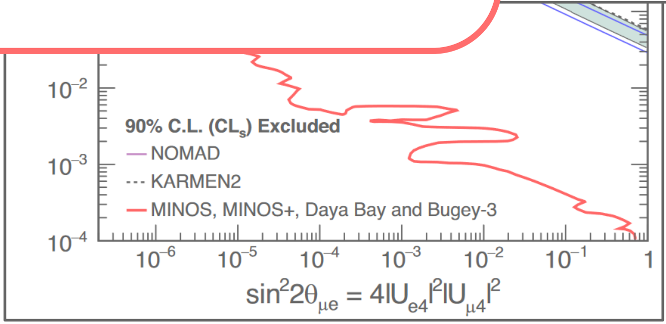


Current tension - Summary





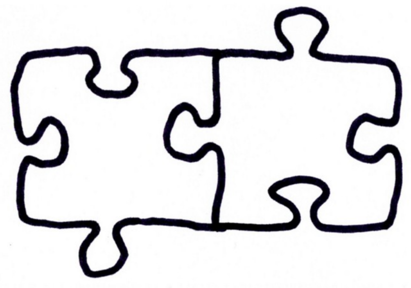


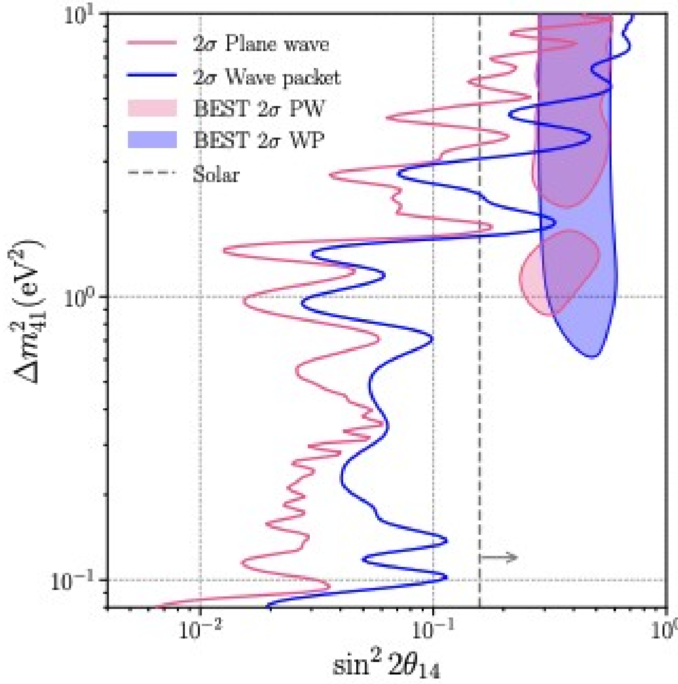


What kind of physics can reconcile these seemingly contradictory observations?

Going Forward

- Vanilla 3+1 – oscillation from a single additional sterile neutrino – cannot be the full solution.
- Around/after Snowmass 2022, the community has gravitated towards more diverse, potentially interlocking explanations:
  - 3+1 ... plus more: decoherence, decays, NSI, etc.
  - Neutrino couplings to hidden sector particles
  - Conventional explanations
  - Some combination!





PRD 107, 036004 (2023)

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Going Forward

1 - Short-Baseline Neutrino

- Direct MiniBooNE test.
- Access to rich hidden sector in > GeV beam.
- Two-beam osc capabilities.

2 - DUNE

- Highest ν/BSM flux.
- High beam energy.
- PRISM ND concept.

3 - IceCube

- Probe non-standard matter effects.
- Very high energy ν's also accessible

All experiments can contribute to the resolution of the puzzle.

6 - JSNS²

- Direct LSND test.
- Access to rich 'lowmass' hidden sector.
- Probe LFV models.

5 - Reactor

- Pure e-flavor.
- Low (MeV) ν energies.
- Pure probe of vacuum oscillations.

4 - Sources

- Direct Gallium Anomaly Test.
- Pure e-flavor.
- Lowest ν energy.

B. Littlejohn: summarizing Snowmass22 NF02 Report and Whitepaper.

The Precision Reactor Oscillation and SPECTrum Experiment

Experimental layout

Scientific goals:

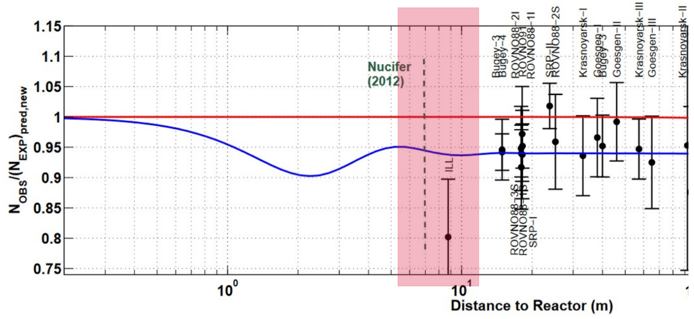
- Search for sterile neutrino oscillations,
- Precise measurement of the ^{235}U antineutrino spectrum.

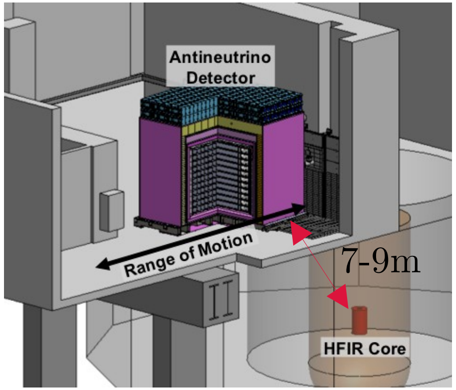
Strategy:

- Deployment at HFIR facility, Oak Ridge, TN.
- Proximity of the reactor, baseline < 10 m.
- High statistics for precision measurement.

Challenges:

- Minimal overburden.
- Backgrounds: cosmogenic fast neutrons and reactor gammas.



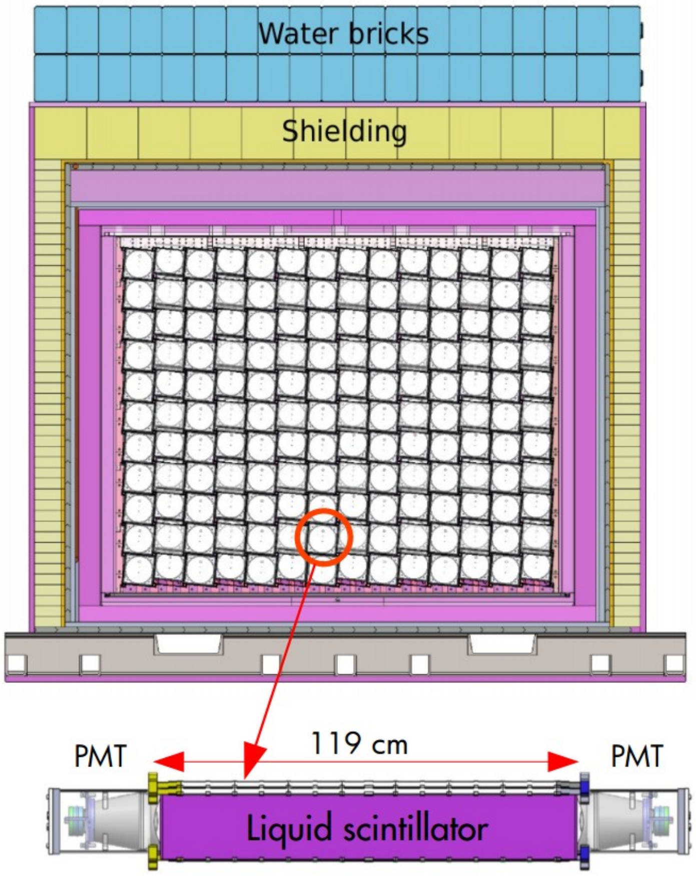


High Flux Isotope Reactor (HFIR)

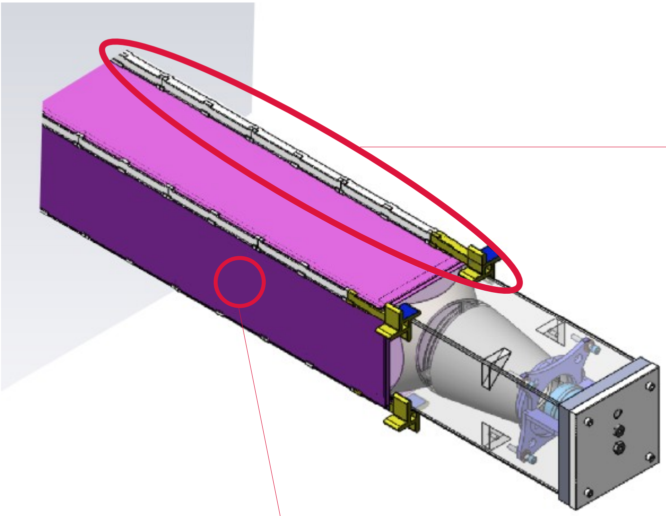
- 85 MW Highly-Enriched Uranium reactor
  - $> 99\%$ of ν from ^{235}U.
- 24-day cycles:
  - 46% Reactor on
  - 54% Reactor off
  - No isotopic evolution.
- Compact cylindrical core: 0.2m radius, 0.5m height
  - Ideal to probe high frequency oscillation.

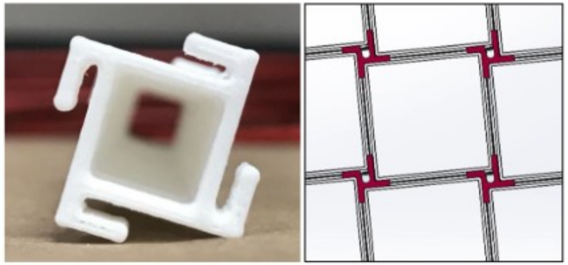
PROSPECT Detector

- Deployed at the vicinity 7-9m of HFIR reactor.
- Detector is filled with 4-tons of ^{6}Li-doped liquid scintillator
- Grid of 11x14 (154) optically separated segments:
  - Relative measurement for neutrino oscillations.
  - Fiducialization.
  - Topology cut.
- 3D position reconstruction (X,Y,Z) from double-ended PMT readout.

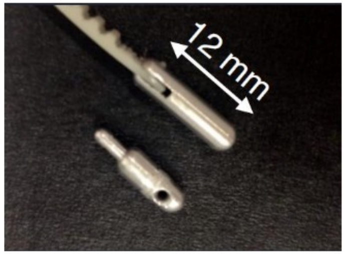


PROSPECT Detector Component

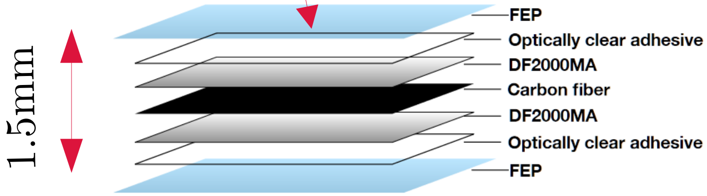




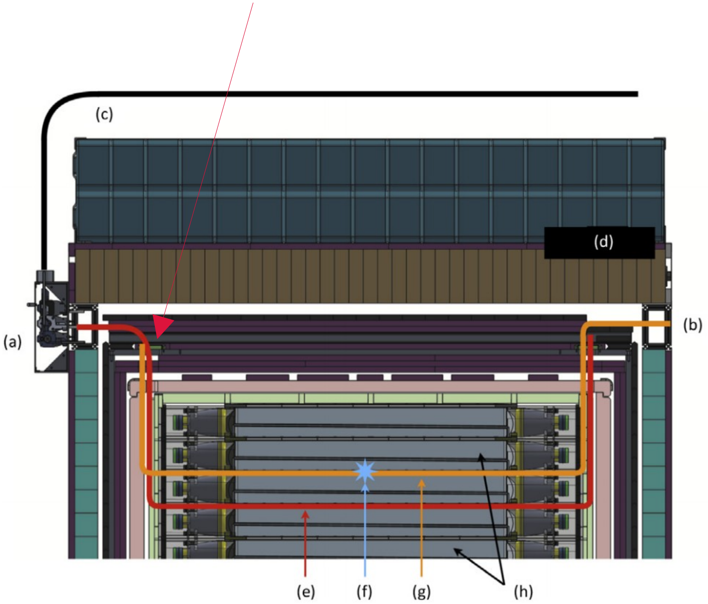
Held together by 3D-printed support hollow rods.



Calibration source capsule



Segments are thin reflector panels.



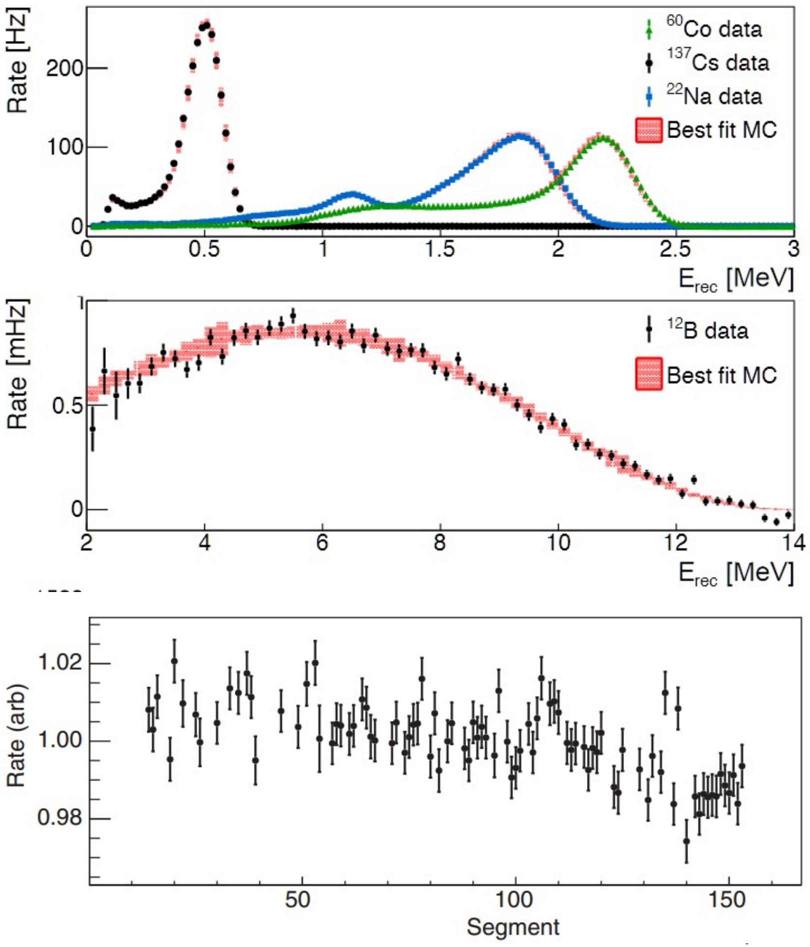
Detector Performance

Radioactive sources deployed throughout the detector for calibration:

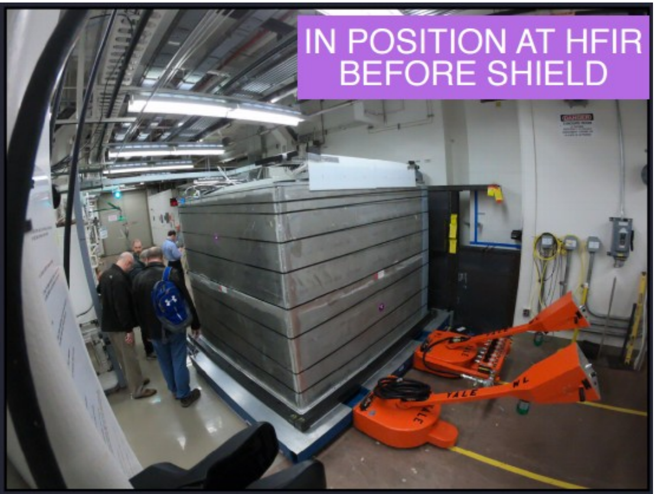
- Gammas sources (^{137}Cs, ^{60}Co, ^{22}Na) for single segment response measurement.
- ^{12}B for β-energy scale calibration.

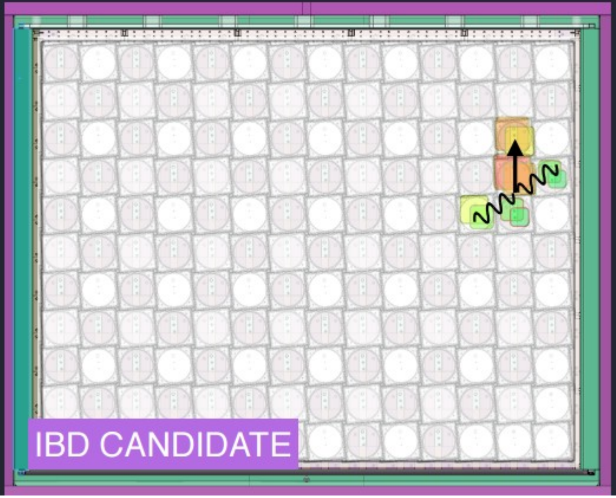
^{227}Ac dissolved in liquid scintillator:

- ^{219}Rn-^{215}Po (α-α) provides a proxy for relative mass per cell measurement, 2.2% variation.
- Crucial for neutrino oscillation

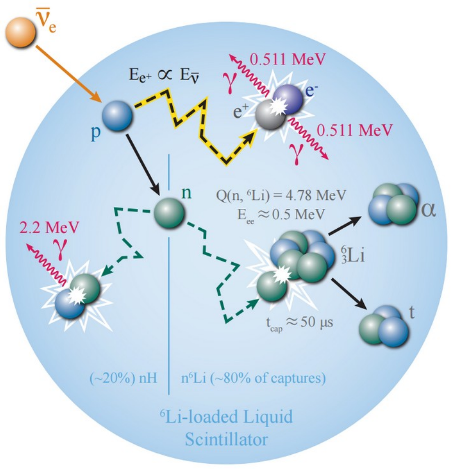


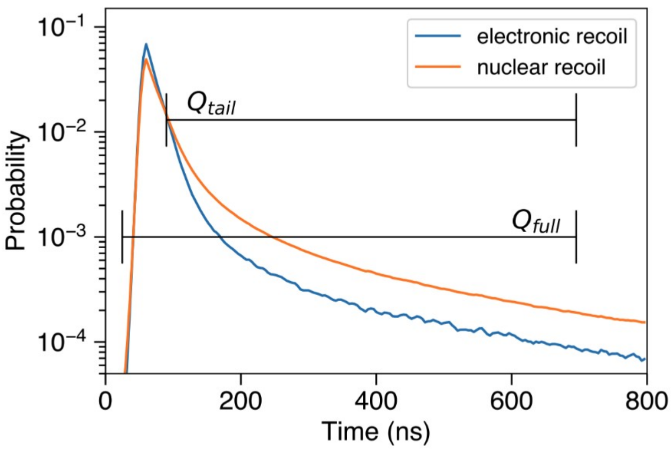
PROSPECT Installation

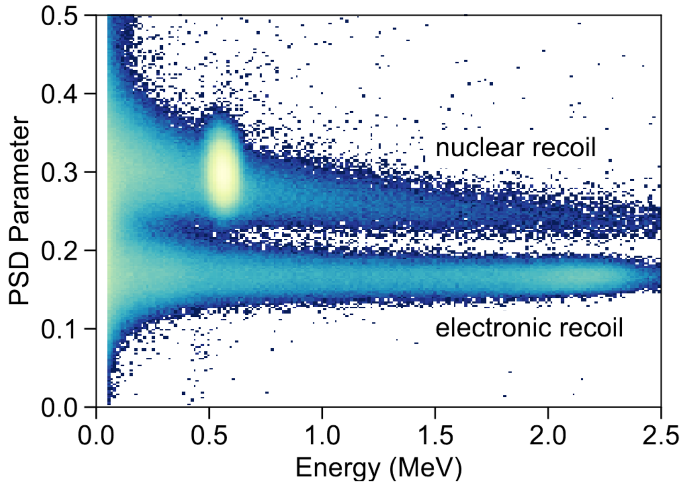




Antineutrino detection







- Positron annihilates promptly and gives an estimate of the ν_e energy.
- Delayed neutron capture on 6Li tags IBD events.
- Correlated coincident signals!!

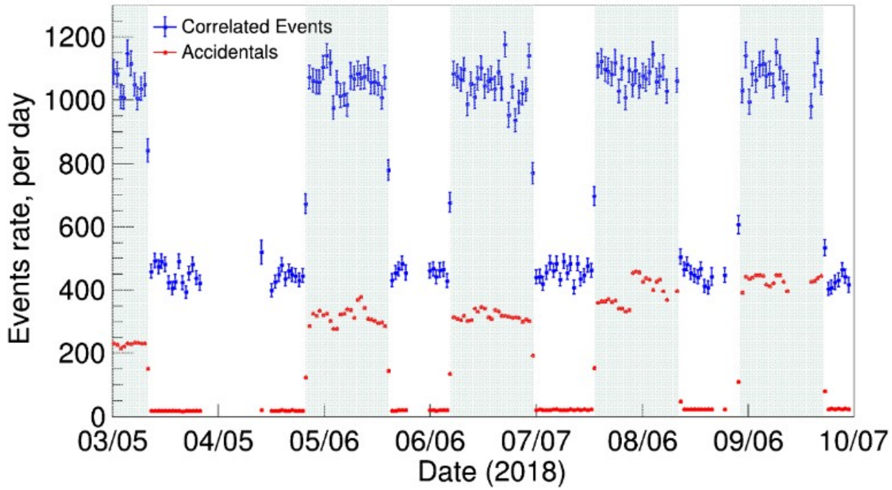
- Developed ⁶LiLS with capabilities to distinguish particles through scintillation timing profile.
- Electronic recoil emit light faster than nuclear recoil.

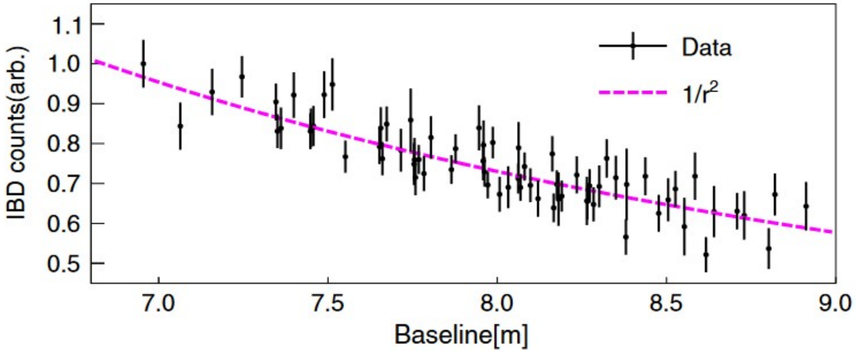
- Pulse Shape Discrimination quantifies the scintillation shape, Qtail/Qfull.
- PSD adds powerful information to identify IBD and reject backgrounds.

Data

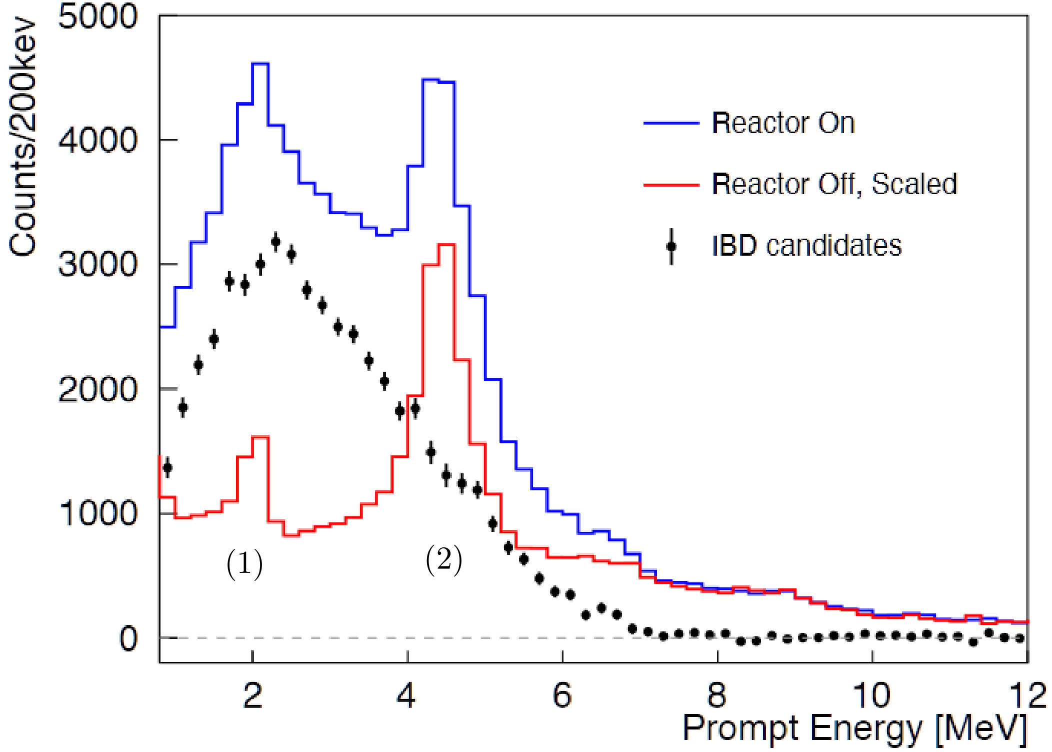
PROSPECT detector took data from March 5 to October 6, 2018

- 105 days reactor-on.
- 78 days reactor-off.
- 8 days of calibration.
- Discard candidates from 36 fiducial segments experiencing PMT current instabilities.
- Average of 529 IBD per day.
- IBD rate follow $1/r^2$ distribution.





IBD Signal and Background



Reactor Off Background:

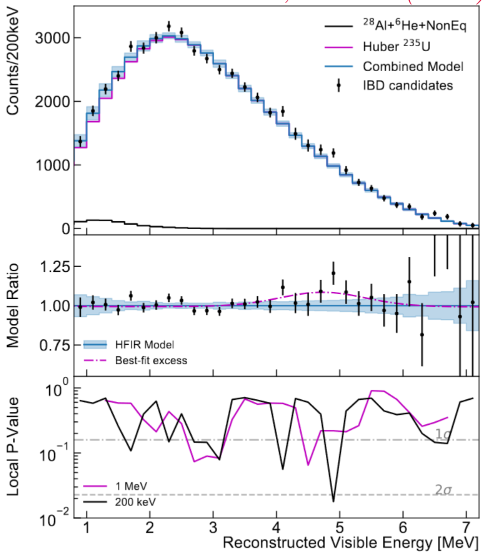
1) Multi-neutron events, $^{1}H(n,\gamma)^{2}H$ peak at 2 MeV.

2) Fast neutron events, $^{12}C(n,n')^{12}C^{*}$ peak at 4.5 MeV from the first excited state of ^{12}C:
   - Outgoing n' can leak into the neighboring segments.

Results and Highlights

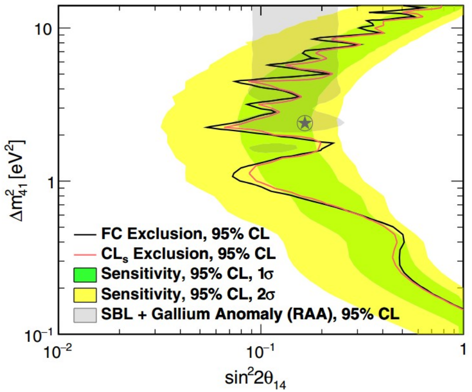
Small experiment with successful run and outsized physics impact.

PRD 103, 032001 (2021)



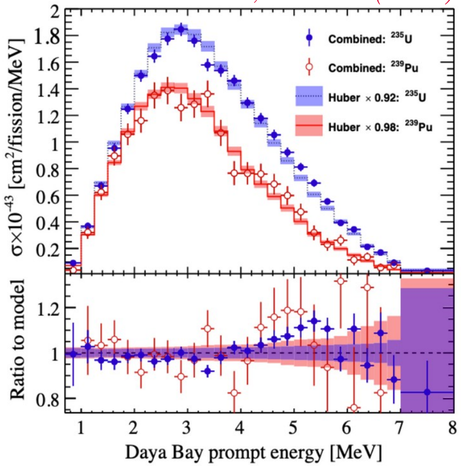
Best precision measurement of ^{235}U spectrum.

PRL 121, 251802 (2018)
PRD 103, 032001 (2021)



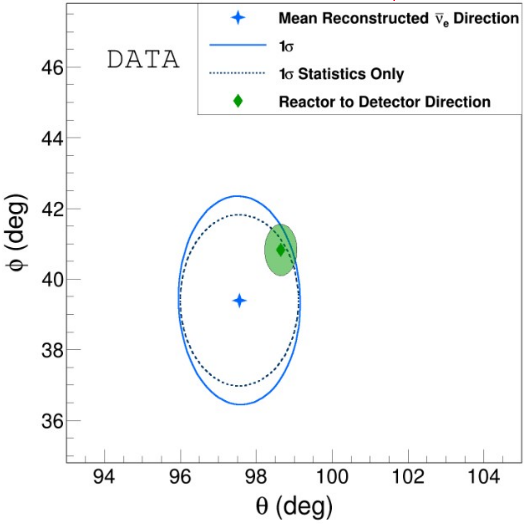
World leading sterile neutrino exclusions.

PRL 128, 081801 (2022)
PRL 128, 081802 (2022)



Joint analysis constraining production from multiple isotopes.

arXiv:2406.08359

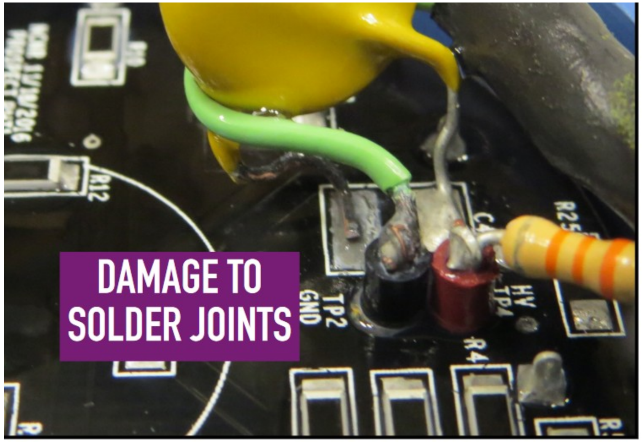


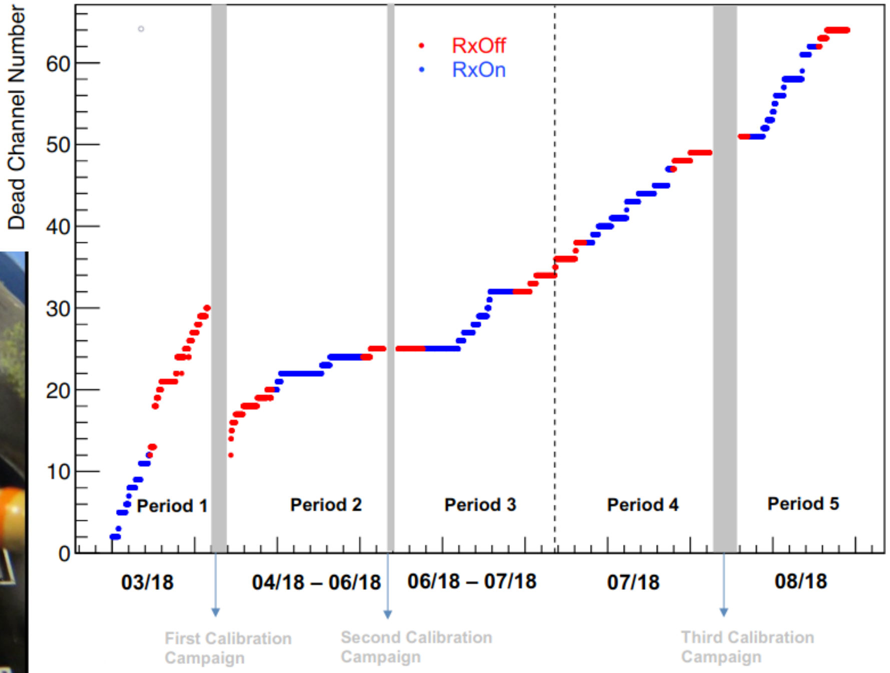
Application demonstration, Precise reconstruction of the mean neutrino direction from a compact nuclear reactor.

Joint analysis with the final PROSPECT, STEREO, and DYB data is underway, stay tuned!!

What's new in the final PROSPECT-I analyses

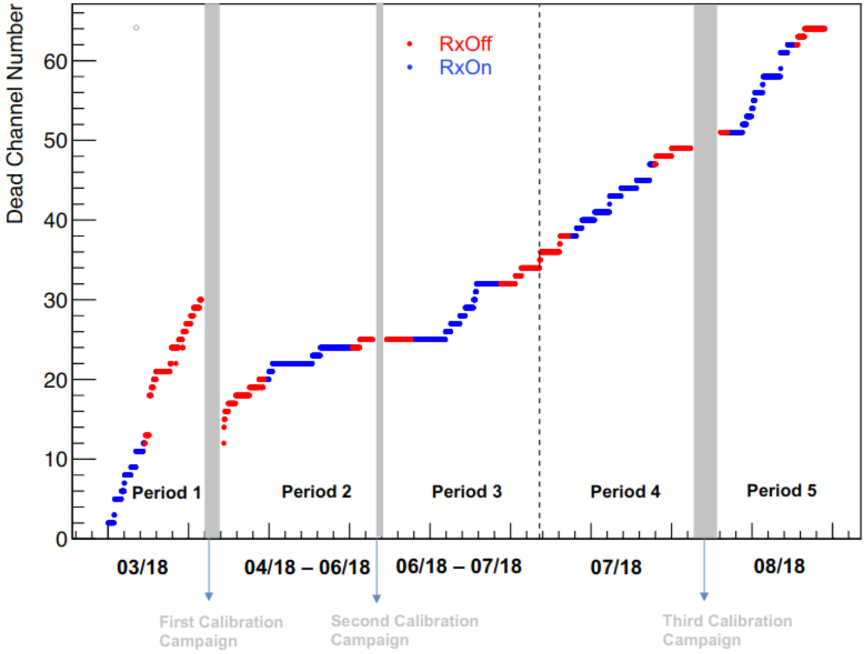
- Over the course of operation, a number of PMTs displayed current instabilities:
  - LiLS ingressed into the PMT housing, and interacted with the PMT circuitry.
  - ~20% of the total segment turned off at the end.
- Maximize the PROSPECT-I data set:
  - Data splitting (DS),
  - Single-Ended Event Reconstruction (SEER).





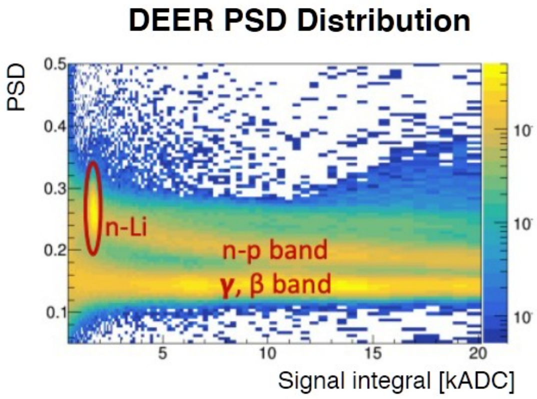
Dataset Optimization: Data Splitting

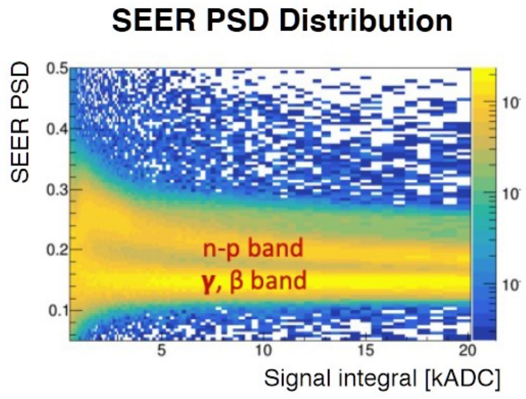
- Split the dataset into distinct periods:
  - Maximize number of live segments in each period.
- Splitting criteria:
  - Each period must contain one full RxOn cycle.
  - Each period should start immediately after a new calibration campaign.
  - All periods should have RxOff data before and after each corresponding RxOn cycle.

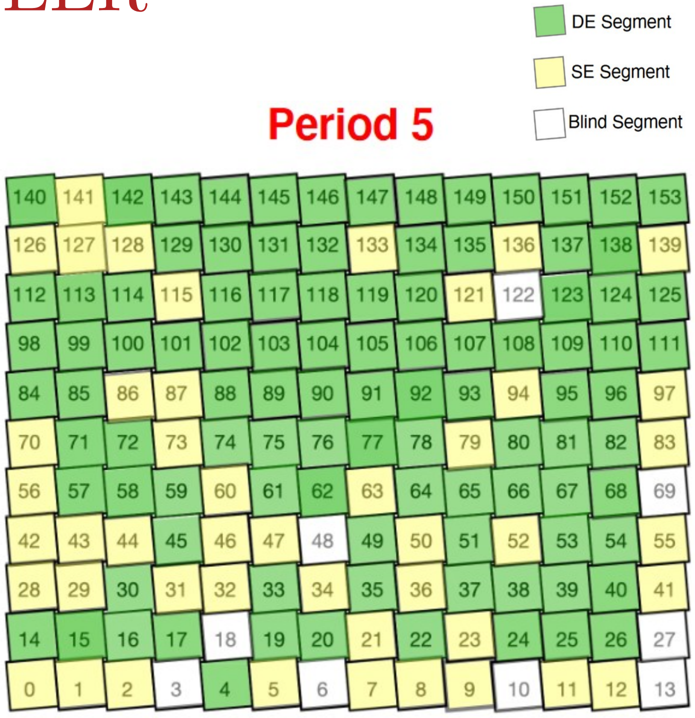


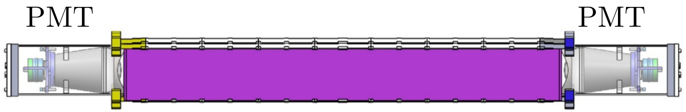
Dataset Optimization: SEER

- Only one PMT experience current instabilities for some segments (SE-segments):
  - Lack of energy and z-position reconstruction capabilities.
- Provides a good handle for background suppression:
  - PSD reconstruction from SE-segments is still good.



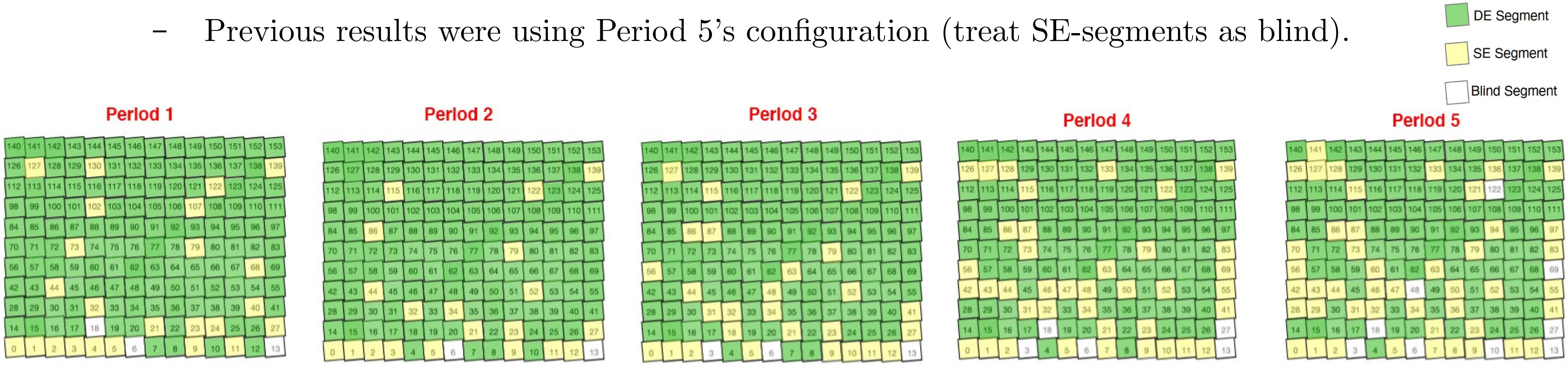




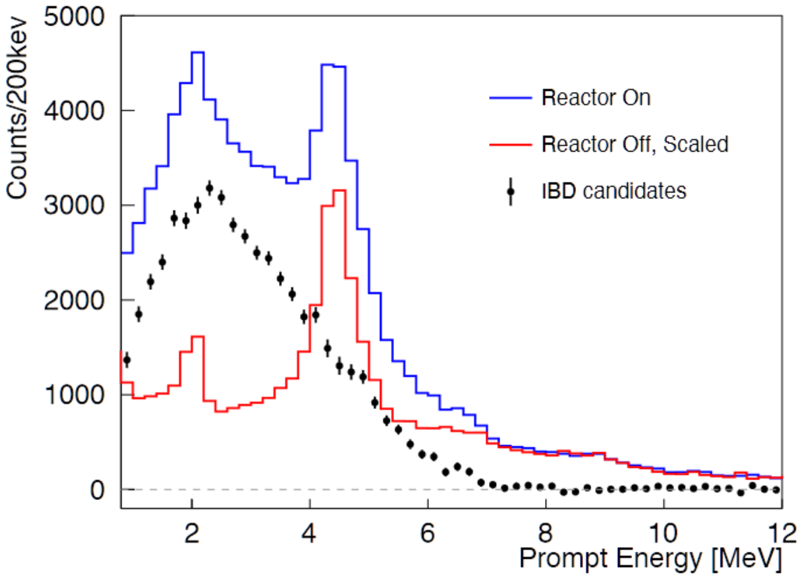


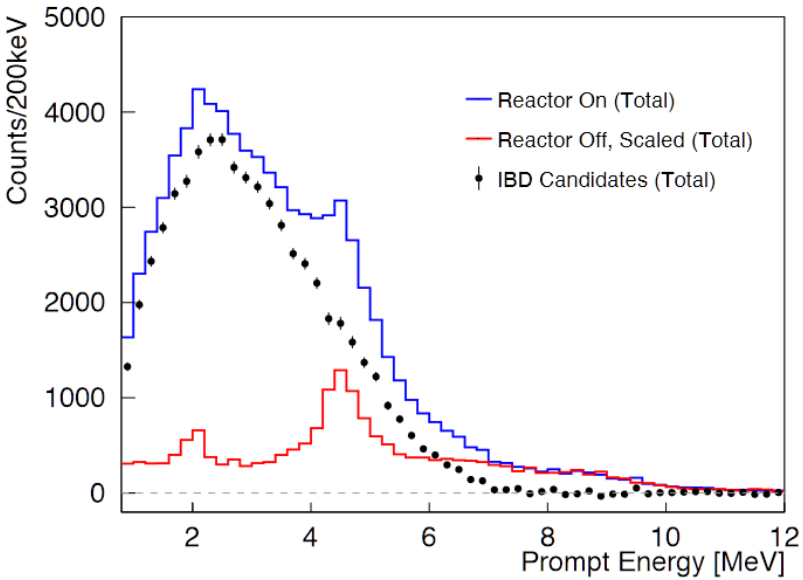
Detector configuration

- Previous analysis did not make use of single-ended segments:
  - This new method uses all the data collected by the PROSPECT-I detector.
- 5 detector configurations with their own response:
  - Each period is an independent measurement with correlated systematics.
  - Previous results were using Period 5's configuration (treat SE-segments as blind).



Final Optimized Dataset





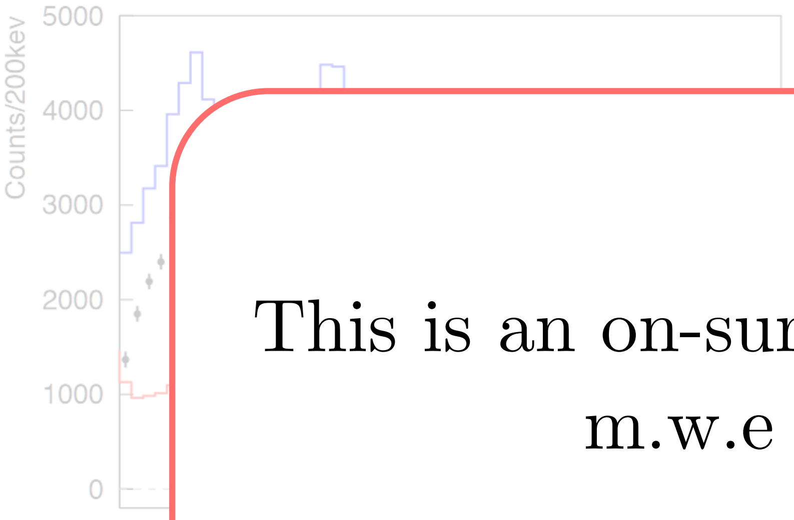
Previous analysis, Phys. Rev. D 103, 032001, using only DE-segments.

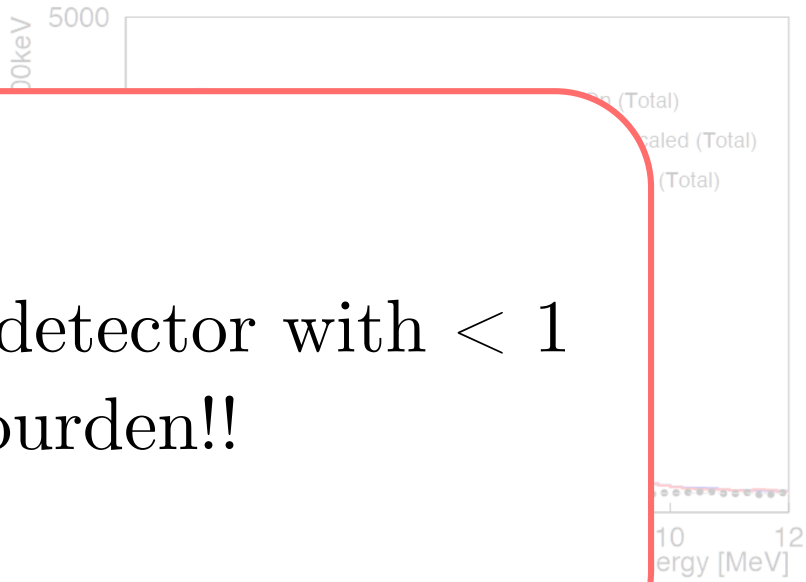
- 50,560 IBD signal.
- 1.37 S/B ratio.

Current analysis, arXiv:2406.10408 using DS&SEER.

- 61,029 IBD signal.
- 3.90 S/B ratio.

Final Optimized Dataset





This is an on-surface detector with < 1 m.w.e overburden!!

Previous
using only DE-segments.

- 50,560 IBD signal.
- 1.37 S/B ratio.

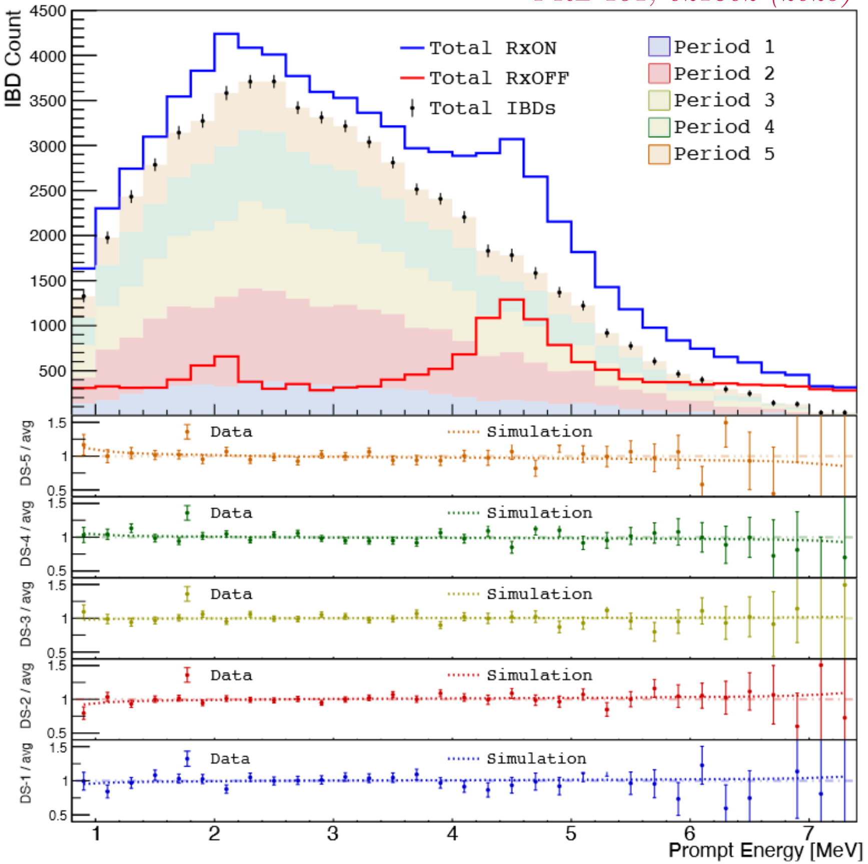
0408 using DS&SEER.

- 61,029 IBD signal.
- 3.90 S/B ratio.

New ^{235}U Antineutrino Prompt Spectrum Measurement

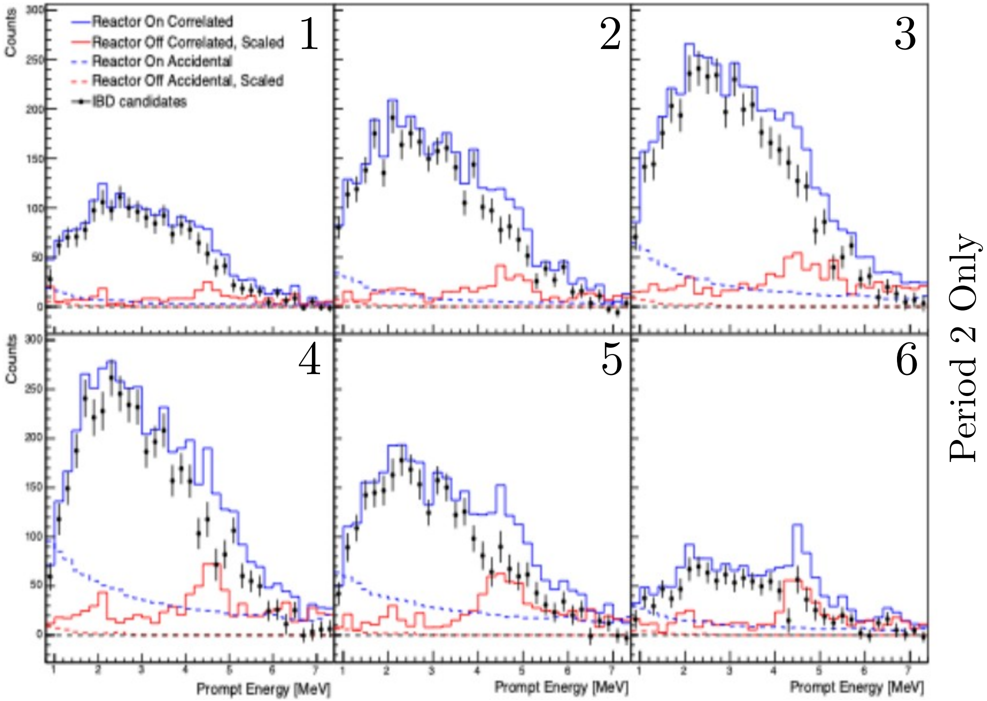
- Combine segments' spectra into one.
  - Same treatment for period.
- Produced a final antineutrino prompt spectrum measurement with the new dataset.
  - Spectra are compatible to each other.
    - Minimimal impact from segment status of each period.
    - Minor impact from difference in detector response.

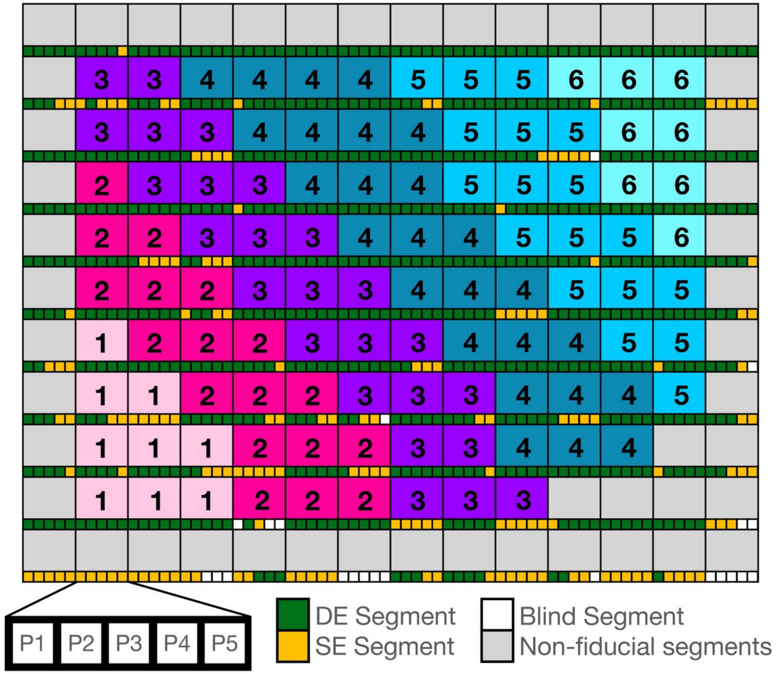
PRL 131, 021802 (2023)



Oscillation Analysis Strategy

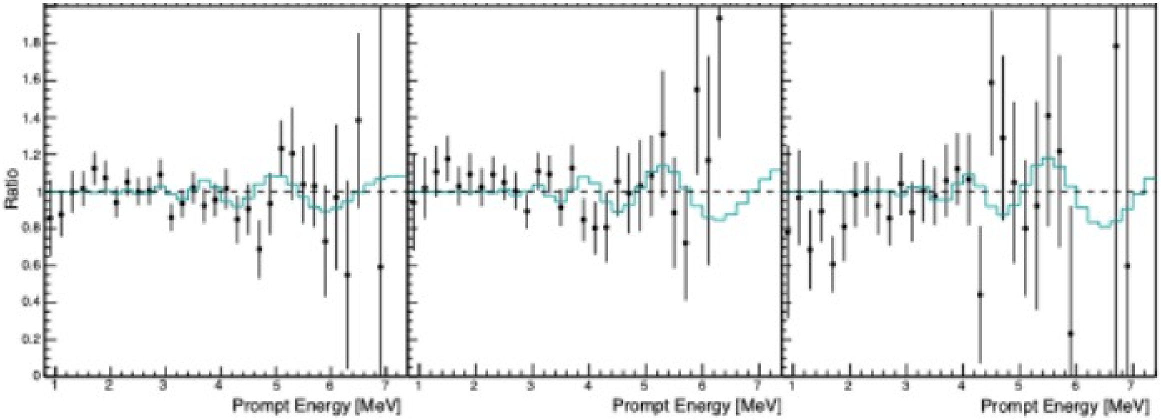
- Combine spectra from segments into baseline.
  - 6 baseline bins x 33 energy bins x 5 periods.



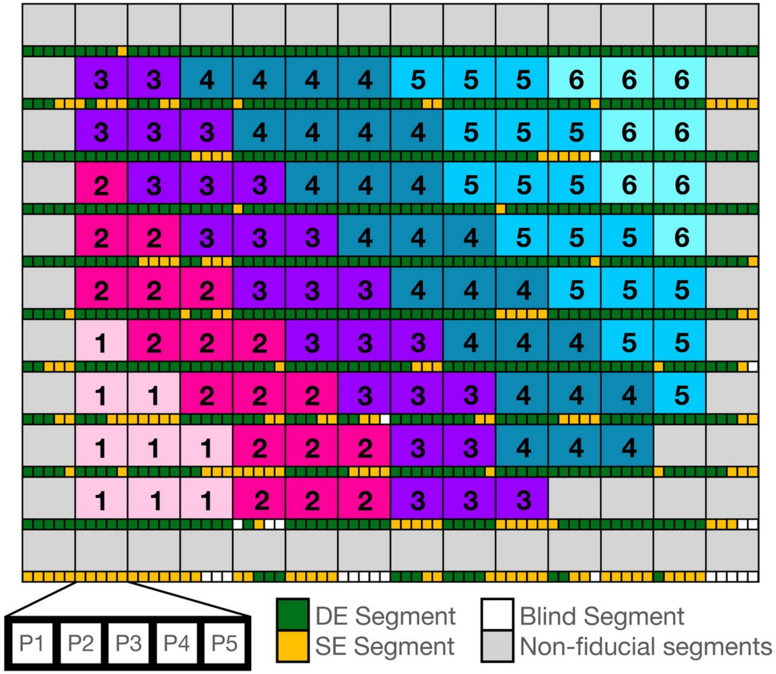


Oscillation Analysis Strategy

- Combine spectra from segments into baseline.
  - 6 baseline bins x 33 energy bins x 5 periods.
- Search for spectral distortion by comparing each baseline to the detector integrated average (flux independent).

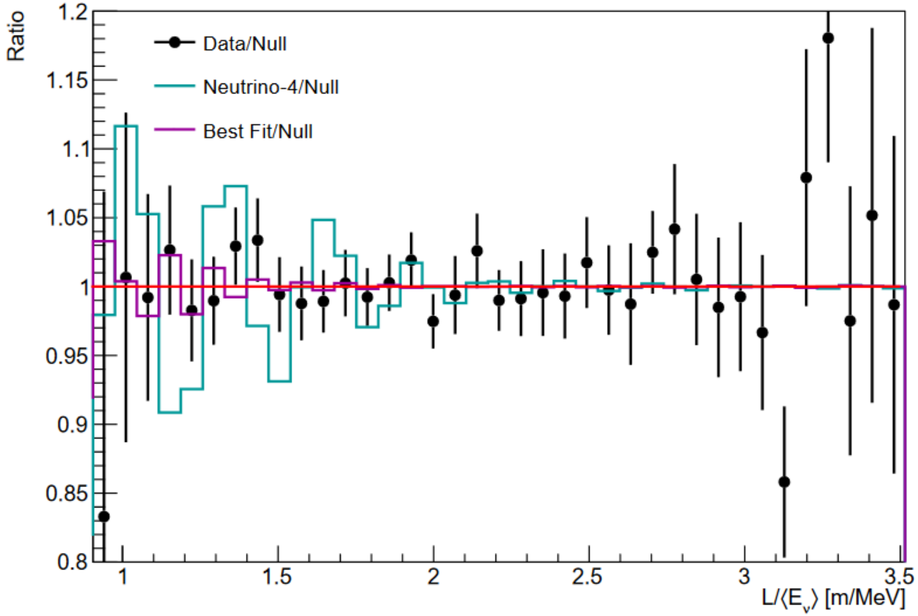


Subset of period 2



Data Visualization

- Challenging to visualize the final data set in the full analysis binning configuration.
- Summarize the data in L/<E_ν> format.
- No obvious sign of oscillation in the measured dataset.



Oscillation Analysis Strategy

- Use Chisquare test to quantitatively assess the parameter fitting the dataset:
  - Combined Neyman-Pearson to minimize bias from low statistics bins, *NIMA 961, P163677 (2020)*.
- Remove reactor model dependency with 'relative spectral ratio' analysis approach illustrated 2 slides back :
  - Correlated statistical uncertainty.

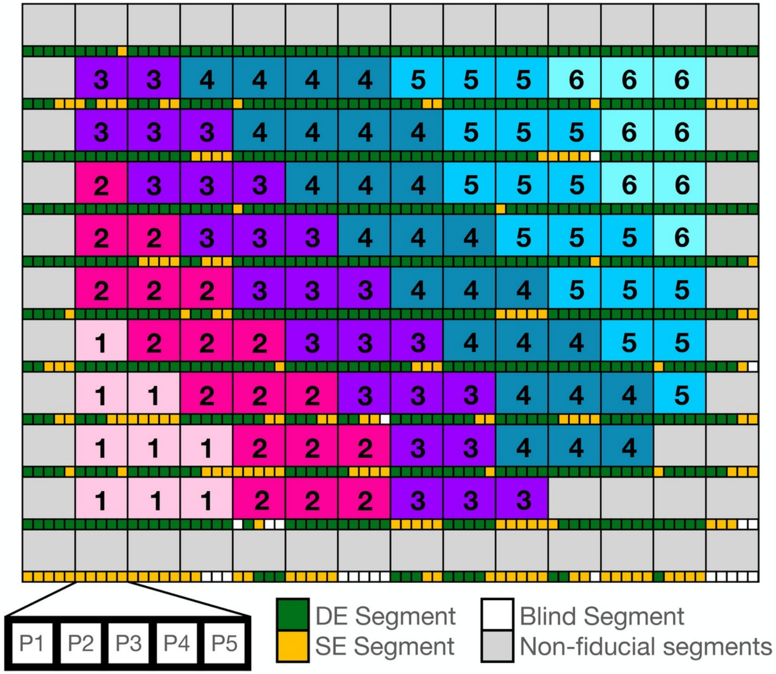
$$\chi^2_{min}(\sin^2 2\theta, \Delta m^2) = \Delta^T V_{Tot}^{-1} \Delta$$

V: Stat + Sys uncertainty

$$\Delta_{l,e} = O_{l,e} - O_e \frac{P_{l,e}}{P_e}$$

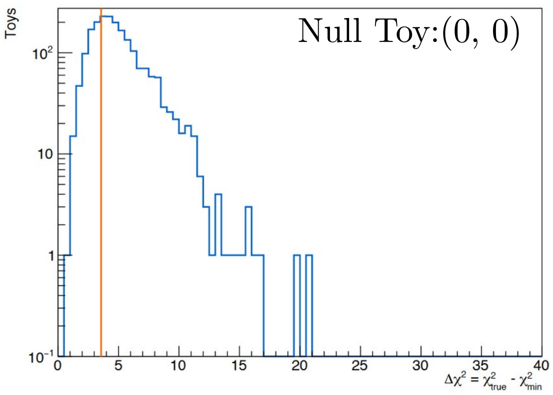
$O_{l,e}$: Observed

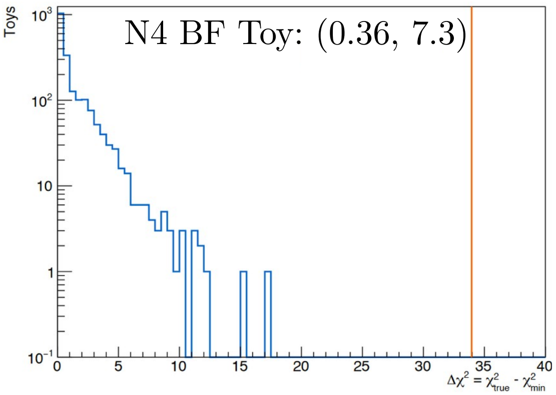
$P_{l,e}$: Prediction

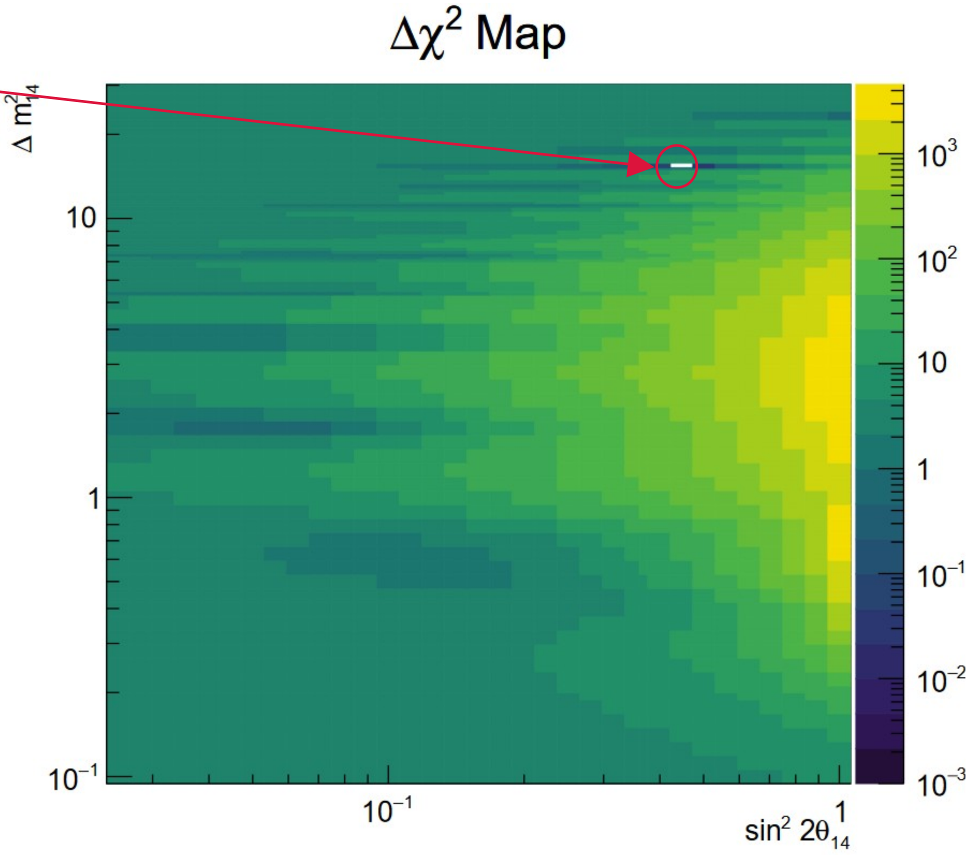


Results

- Best-fit point($\sin^2 2\theta$, Δm^2) = (0.42, 15.2).
  - $\Delta\chi^2$ of 3.56 wrt to the null hypothesis.
- Frequentist tests performed at a few key grid points:
  - Data is highly consistent with null-oscillation toys (p=0.73).
  - Toys at Neutrino-4 best-fit point provide $\Delta\chi^2$ far below that observed in the data.

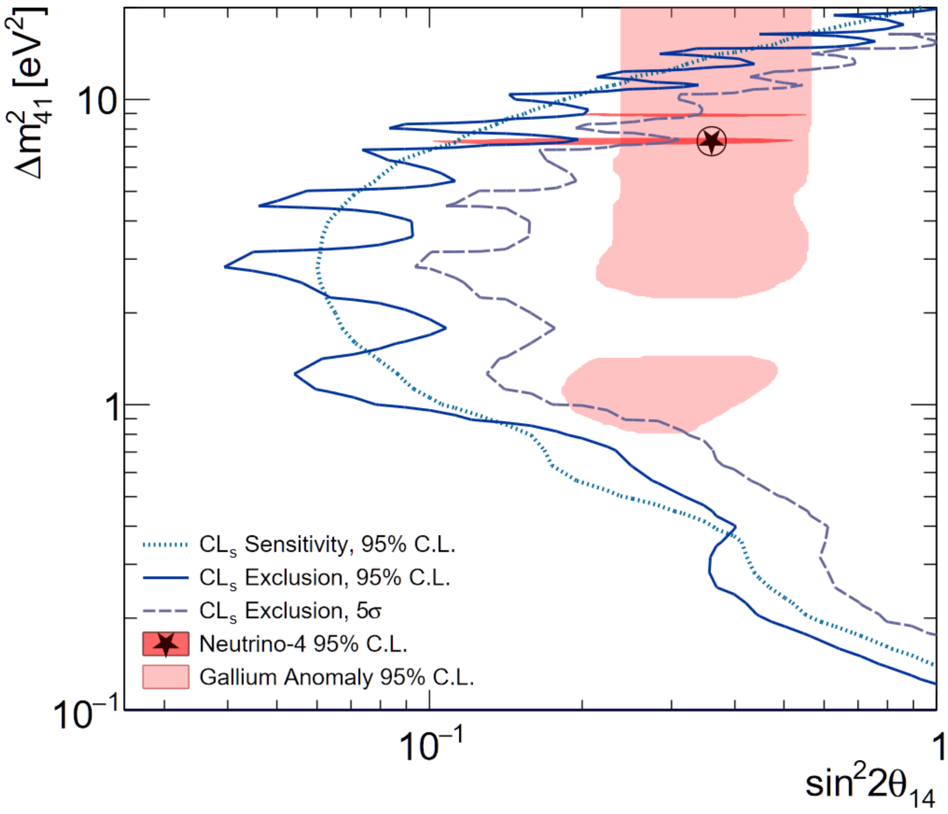






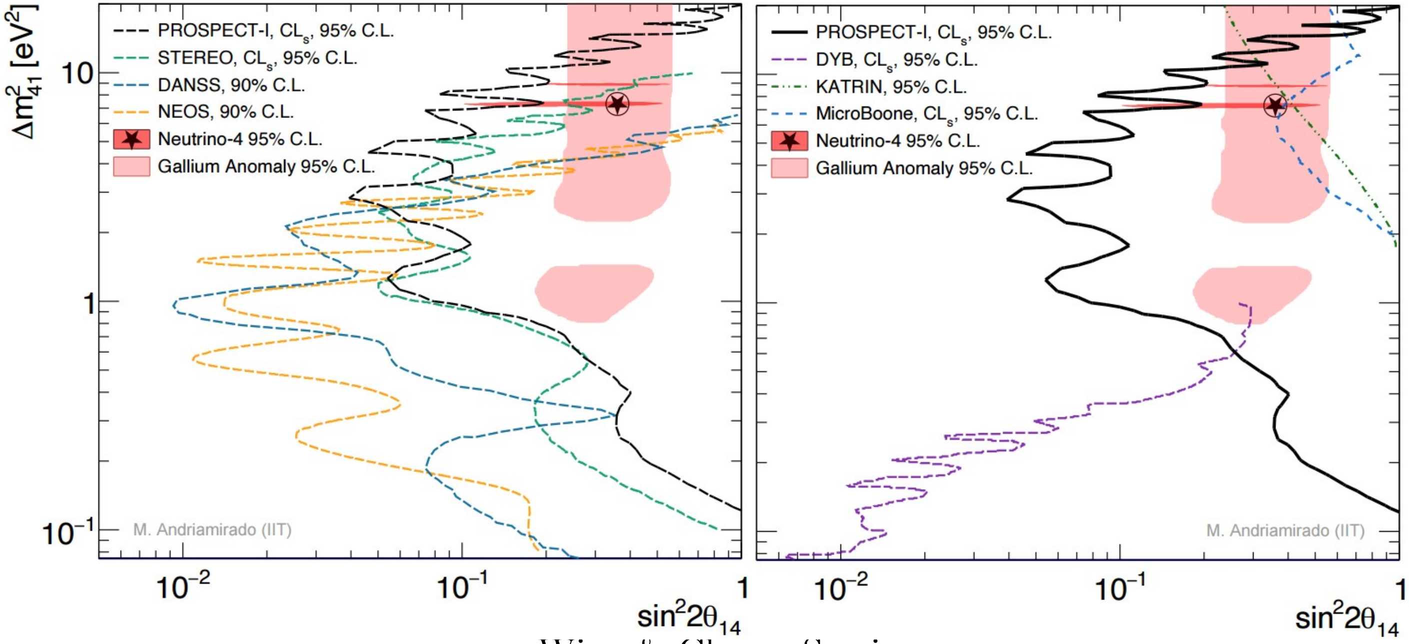
Results: Exclusion Region

- Given the compatibility of the data with null hypothesis, we use the Gaussian CLs method to draw an exclusion contour.
- Claimed observation of short-baseline oscillation from the Neutrino-4 experiment is ruled out at more than 5σ.
- Exclude all phase-space for Δm^2 below 10 eV^2 suggested by the recently strengthened Gallium Anomaly at 95% CL.



Global Context

- New PROSPECT limits lead short-baseline reactor efforts for most Δm^2 values above 3 eV^2.
- Reactor-based Θ_{14} limits are much stronger than other experiment sectors over most of the pictured phase space

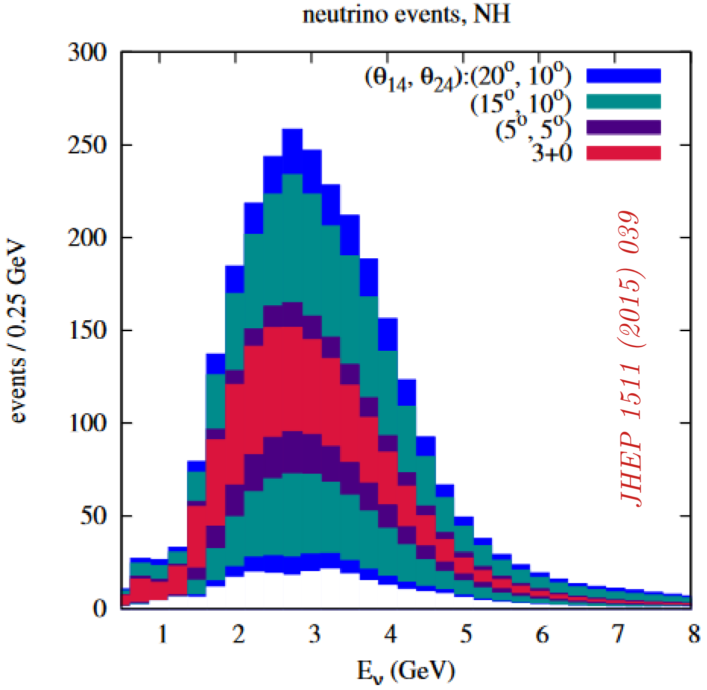


PROSPECT-II Motivations: Anomaly Resolution

- What's next ?
- Reactor experiments play central piece in an integrated global effort to understand the remaining anomalies: LSND/MiniBooNE and Gallium Anomaly.
  - Pure source of MeV electron antineutrino disappearance.
- Upgrade from few reactor antineutrino experiments: TAO, Neutrino-4+, and **PROSEPCT-II**.
  - PROSPECT-II will be the only US-based reactor antineutrino experiment.
  - Do we want to rely on Neutrino-4+ to be the only next-gen SBL effort probing higher Δm^2 regions?

Other PROSPECT-II Motivations

- SBL ν_e disappearance would also impacts LBL oscillation signatures, like DUNE!:
  - Independent experiments constraining Θ_{14} and $\Theta_{24} \leq 5°$ will extinguish potential parameter degeneracies for DUNE, JHEP 1511 (2015) 039.
- Precise measurement of the ^{235}U spectrum to determine the isotopic dependence of the bump.
- Measurement of the ^{235}U flux to increase the reliability of the global flux picture.
- Benefits of a IBD re-deployable detector:
  - Application demonstrations: Reactor monitoring, and nuclear non-proliferation.
  - BSM searches at reactor and non-reactor sources (SNS).

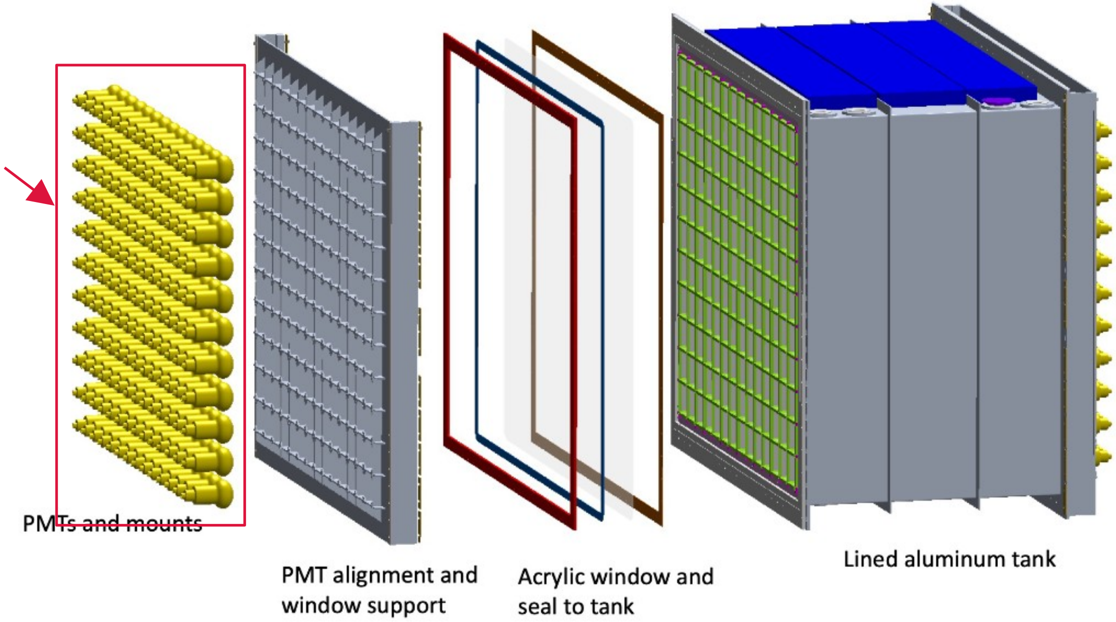


PROSPECT-II Detector

Improving stability and performance of the detector to achieve these goals.

Avoid PMT exposure to the liquid scintillator:

- Separate PMTs from LiLS.



PROSPECT-II Detector

Match the initial P-I Physics goals while improving stability and performance of the detector.

Avoid PMT exposure to the liquid scintillator:

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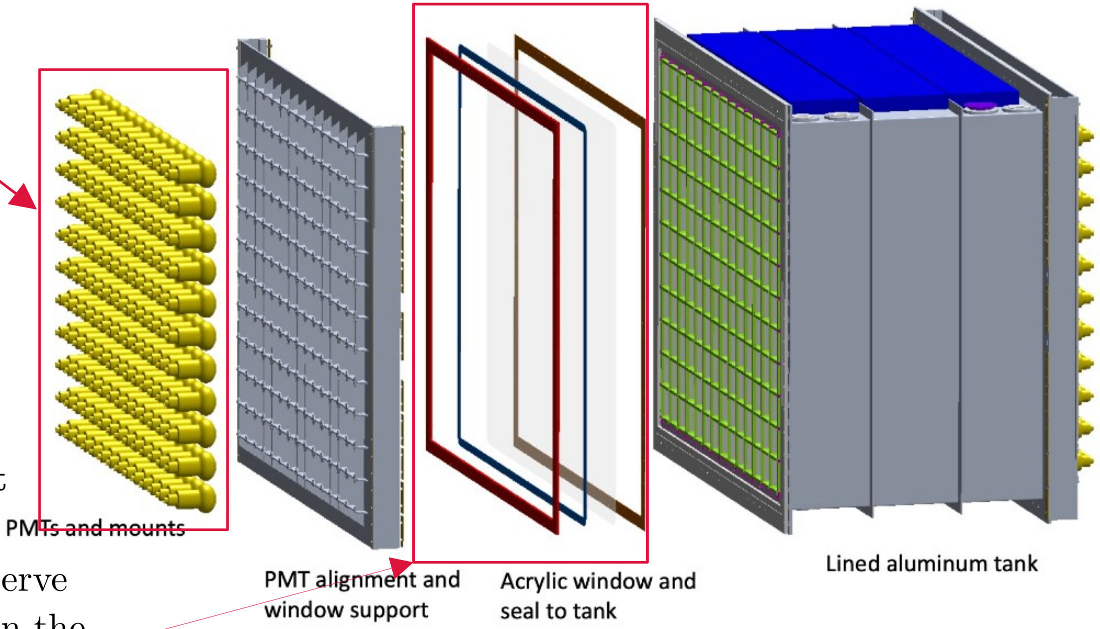

Minimize the LiLS contact with other materials:

- Thin UVT acrylic windows serve as the optical interface between the PMTs and LiLS.
- Double-layer seal design.

PROSPECT-II Detector

Match the initial P-I Physics goals while improving stability and performance of the detector.

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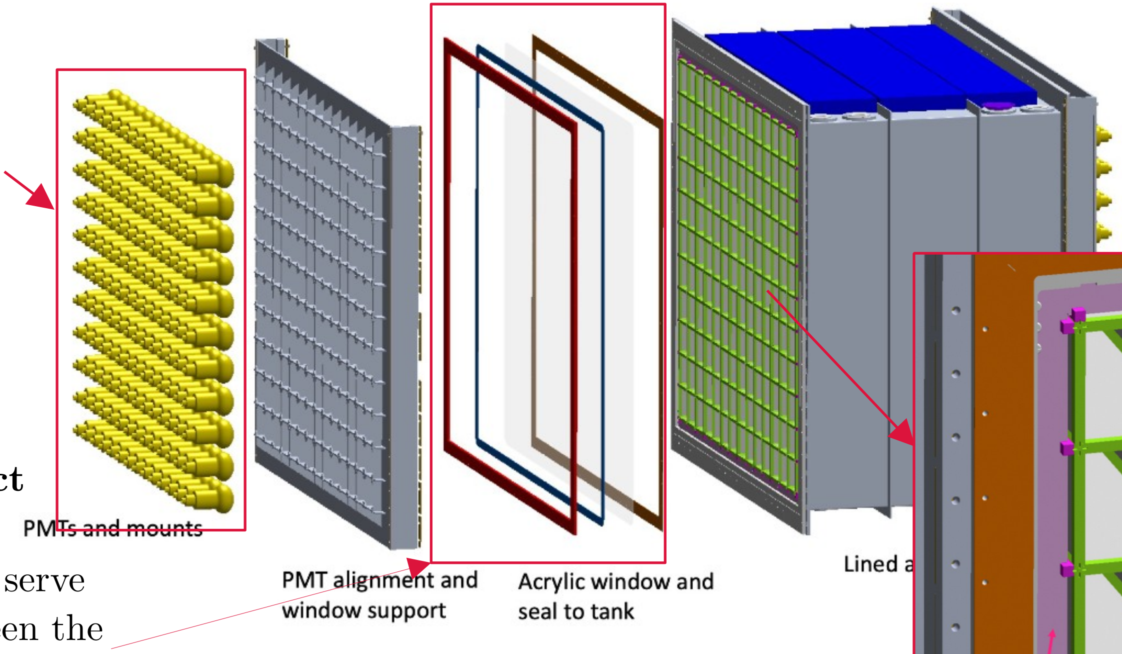
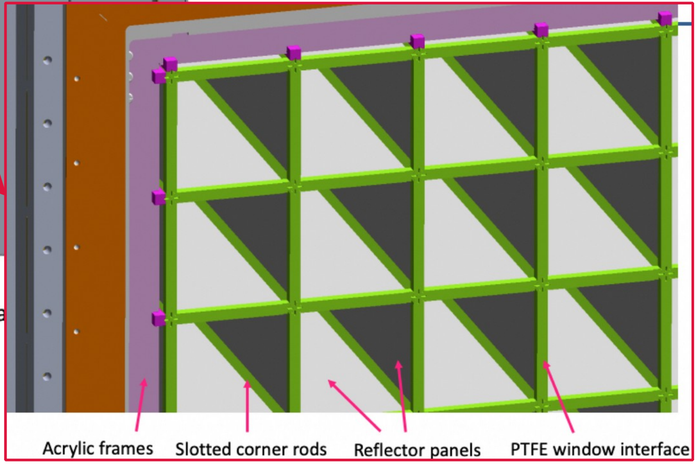


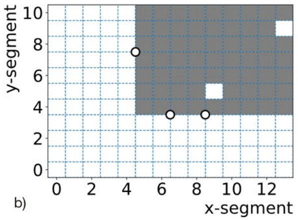


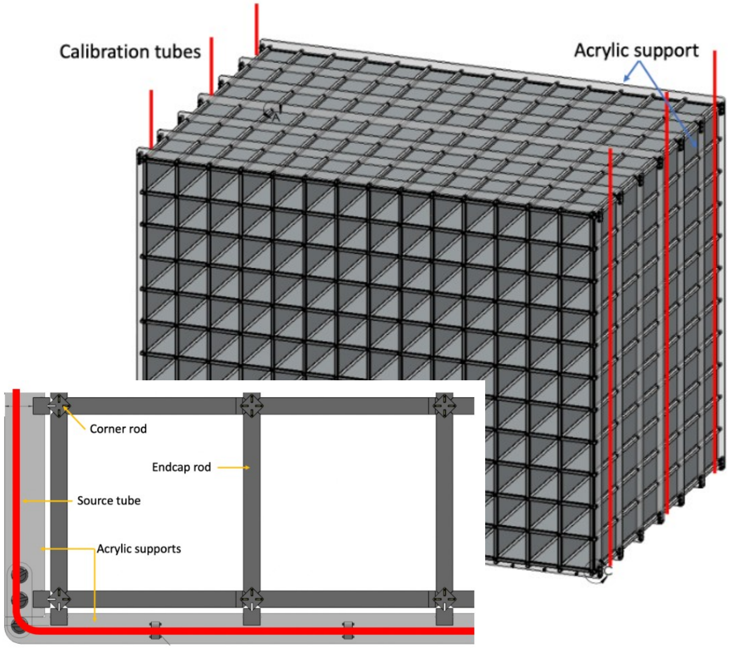
- Similar design to P-I without internal holes.
- External calibration.

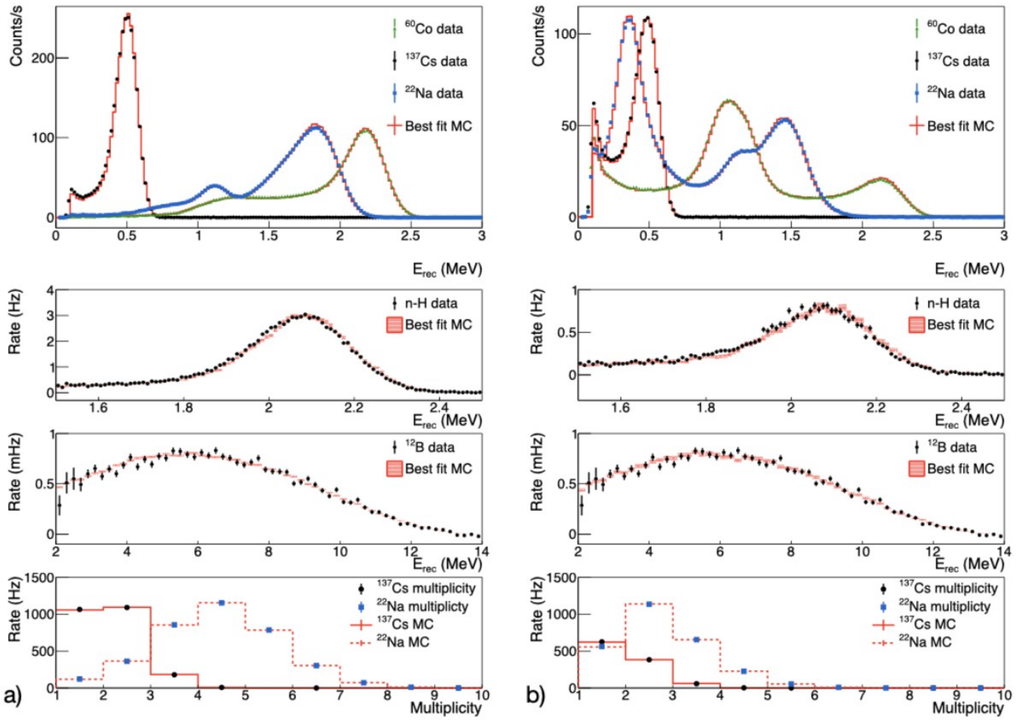
JINST 18 (2023) 06, P06010

PROSPECT-II R&D Retiring Risks

- External calibration source tubes along the perimeter of the segment array.
- Use PROSPECT-I data to simulate “external-like” source deployment.
- Performance of external calibration is comparable to internal calibration







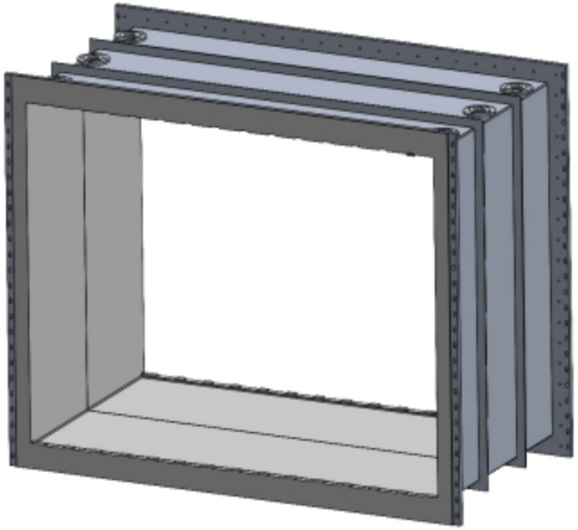
JINST 18 (2023) 06, P06010

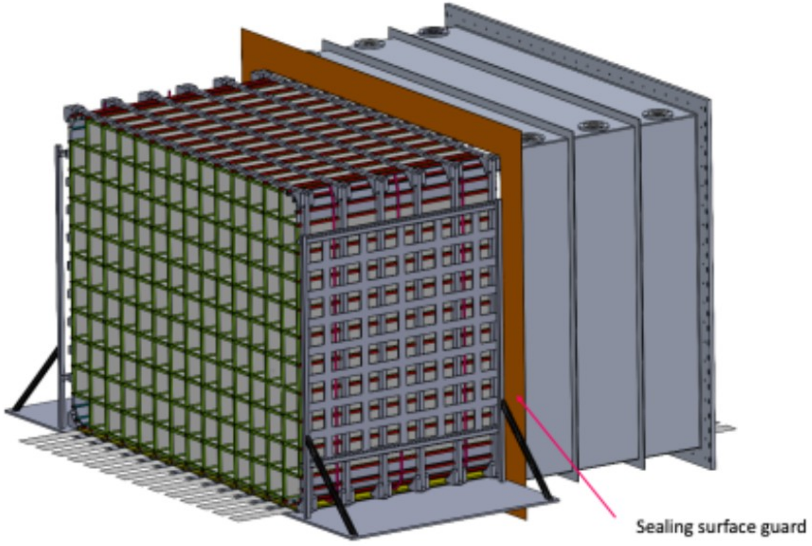
PROSPECT-II R&D Milestones

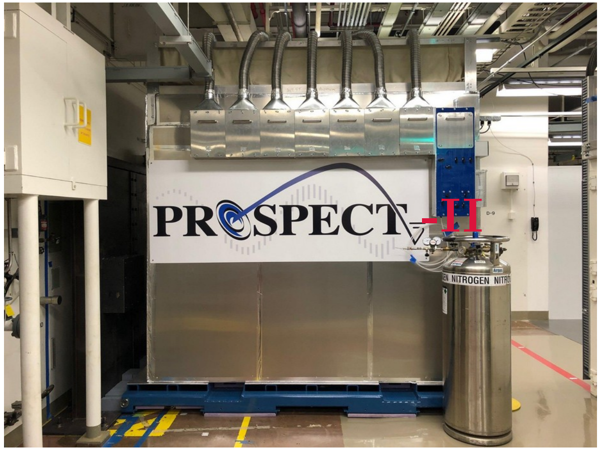
Stage 1 (Current):
- Design and build the inner containment vessel.
- Engineering Test: full fill with complete liquid control/ monitoring systems.

Stage 2:
- Build optical grid and PMT support structure, and other systems.
- Mechanically integrate the full PROSPECT-II detector package.
- Small prototype LiLS test.

Stage 3:
- Procure large batch of production LiLS.
- Fill the detector.







PROSPECT-II Deployment

Deployment at an HEU and LEU reactors:

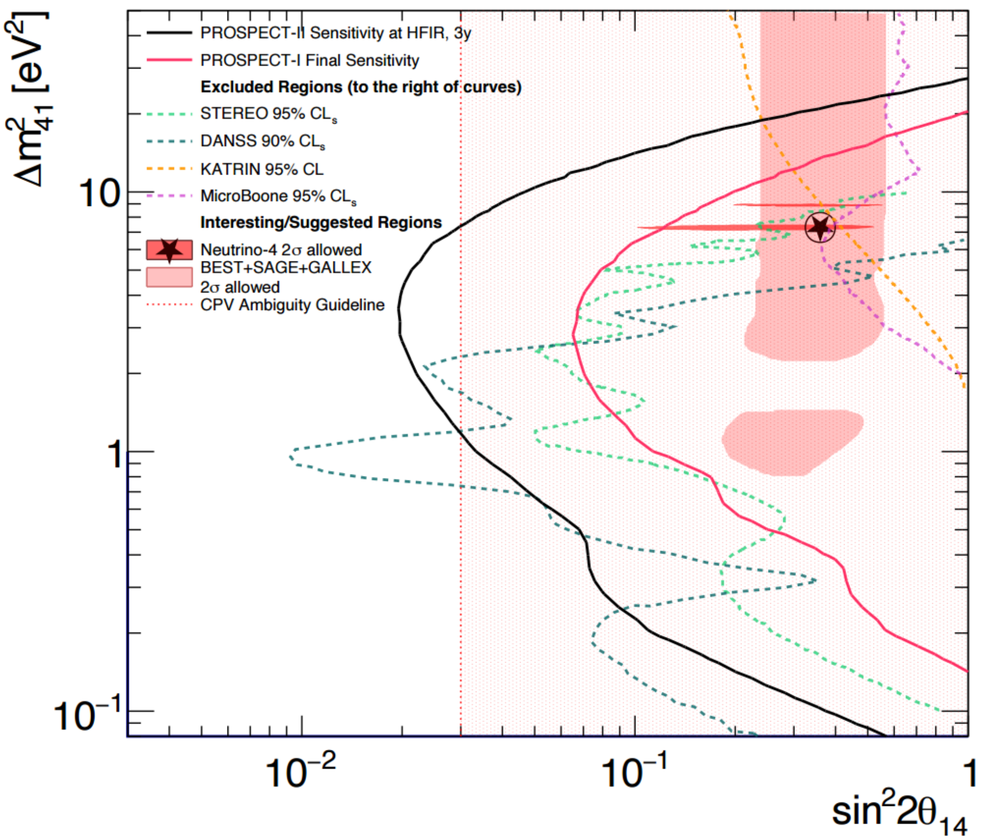
- Increase in IBD statistics: Order of magnitude larger than P-II at HFIR

Parameter		P1	P2 at HFIR	P2 at LEU
Reactor	Power (MW_{th})	85		3000
	Cylinder Size (d×h, m^2)	0.4 × 0.5		3 × 3
	Fuel	HEU		LEU
	Cycle Length	24 d		1.5 y
Detector	Segmentation	11×14	11×14	
	Segment Area (cm^2)	14.5 × 14.5	14.5 × 14.5	
	Segment Length (m)	1.17	1.45	
	Target Mass (ton)	∼4.0	4.8	
	Light collection (PE/MeV)	∼380	500	
	Detection Efficiency	∼40%	40%	
Exposure	Average Baseline (m)	7.9	7.9	25
	Reactor-On Days (d)	105	336	548
	Reactor-Off Days (d)	78	360	61
	Signal:Background	1.4	4.3	19.3
	IBD Statistics (N_{IBD})	50560	3.74×10^5	2.72×10^6
	Effective Statistics (N_{eff})	15195	2.08×10^5	1.79×10^6

JPG 49, 070501 (2022)

PROSPECT-II Projected Sensitivity

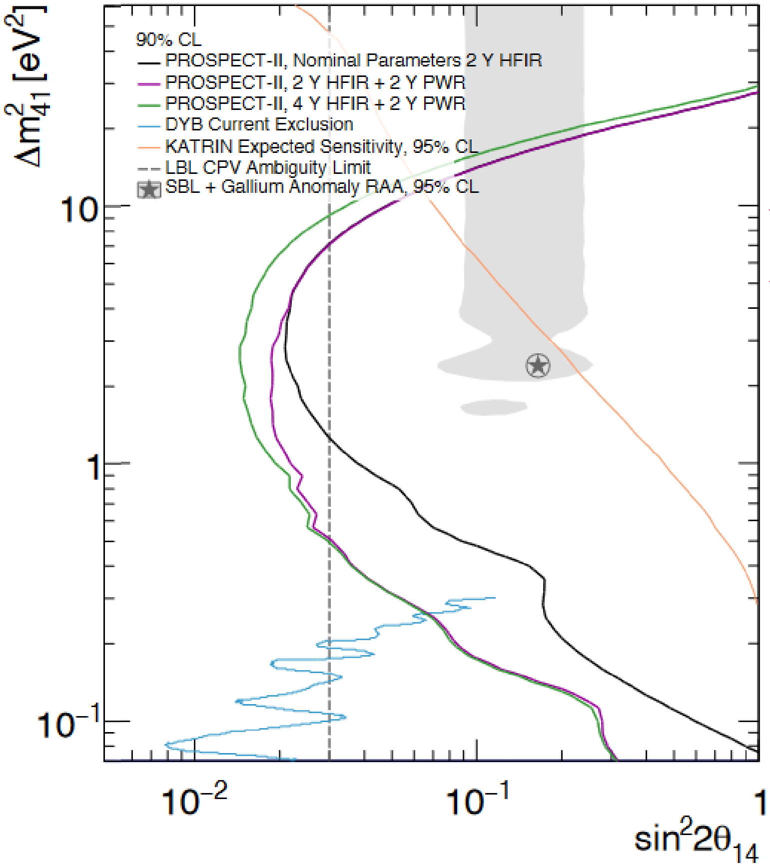
- Deployment at HFIR will address the remaining interesting oscillation phase space.
  - Address Neutrino-4 allowed sterile neutrino observation at high mass splitting.
  - Cover the Gallium Anomaly below ~15 eV^2.
  - Constraint the mixing angle Θ_{14} in between 1-10 eV^2 for the long baseline CP violation interpretation.
  - Unmatched performance below 20 eV^2 compared to accelerator based experiment.
  - P-II exceed P-I sensitivity by a factor of 3-5.
- **Flux**: measure ^{235}U flux from HFIR to <2%.



PROSPECT-II Broadened Physics Scope

Combined analysis from HEU and LEU deployments enhances PROSPECT-II physics goals:

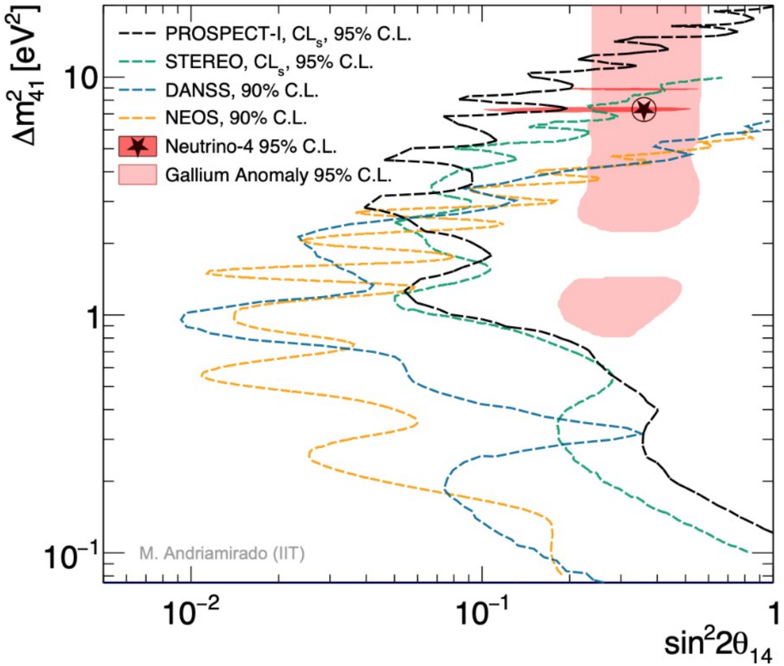
- Oscillation sensitivity extended to lower Δm^2 from longer baseline
- Spectrum measurement at different reactor gives powerful probe of spectral isotopic dependence.
- Flux measurements at both reactors yield unambiguous measurement of the isotopic antineutrino yield.



JPG 49, 070501 (2022)

Summary

- We have set world-leading limits on sterile neutrino oscillations with the final PROSPECT-I dataset.:
  - Neutrino-4 BF ruled out at $> 5\sigma$.
  - Gallium Anomaly allowed $\Delta m^2 < 10$ eV^2 rule out at 95% C.L.
  - Leads global SBL electron-flavor disappearance limits over most of the 3-10 eV^2 phase space.
- A diversity of approaches is required to unravel today's complex SBL anomaly space:
  - The reactor sector, and PROSPECT-II have a unique role to play in a complimentary global program.



- The collaboration is in the first step of a three-phase program towards the deployment of an upgraded PROSPECT-II detector.

PROSPECT

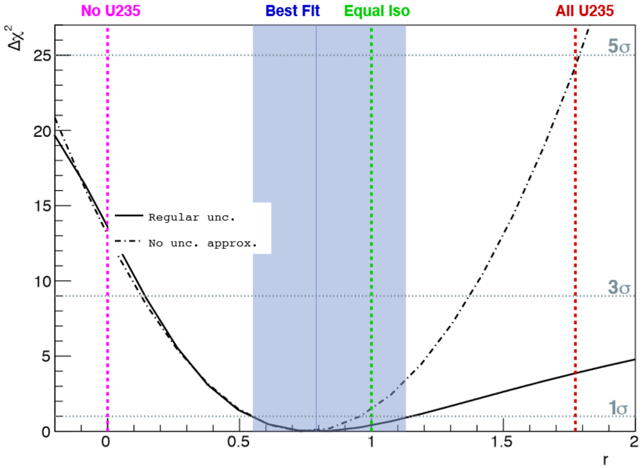
ILLINOIS INSTITUTE OF TECHNOLOGY

THANK YOU!!!!

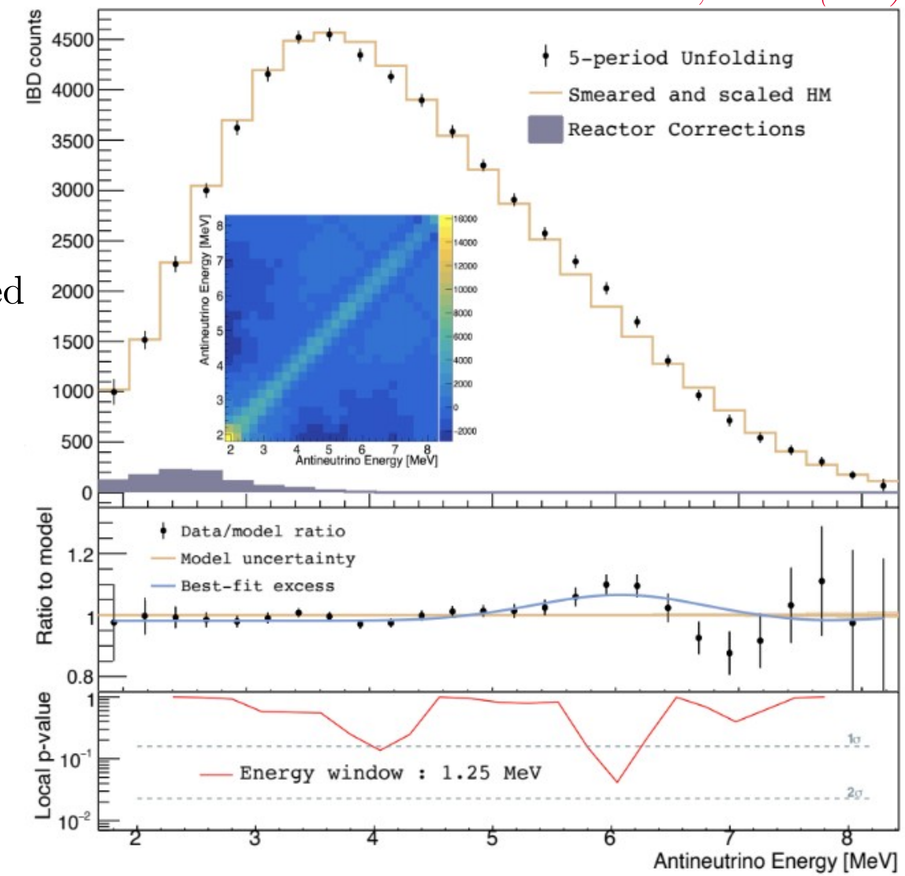
Backup Slides

New ^{235}U Antineutrino Spectrum Measurement

- Produced the final antineutrino spectrum measurement:
  - Still observed a distortion around 6 MeV.
- New constraints on the isotopic nature of data-model disagreement
  - ^{235}U is the sole contributor to the bump disfavored at 2.2σ.
  - No contribution from ^{235}U disfavored at 3.2σ.

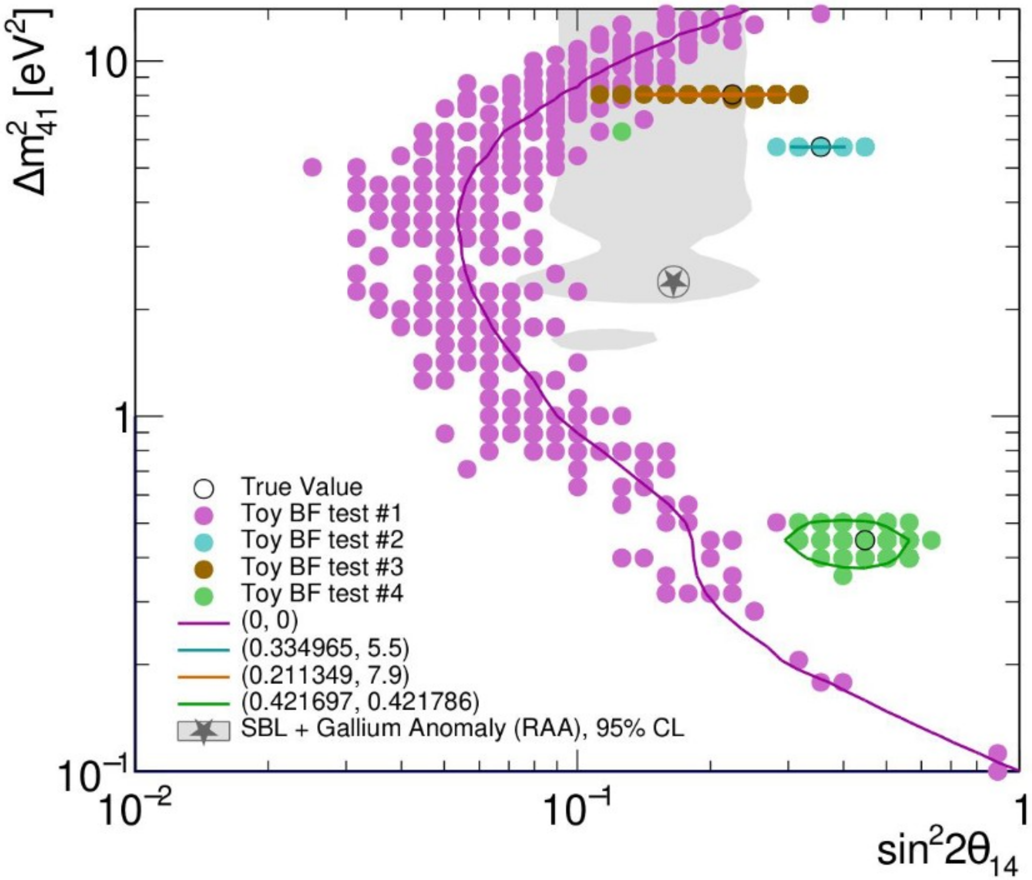


PRL 131, 021802 (2023)



Toy validation

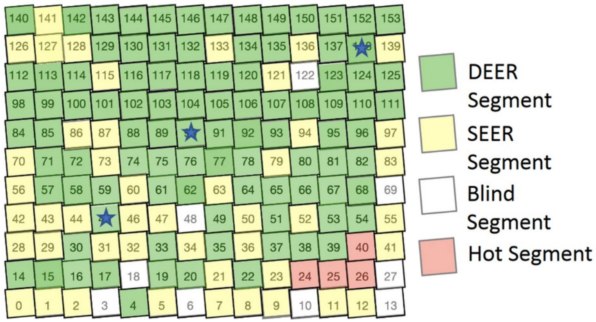
- Toys generated with statistical fluctuation.
- BF point of the null toys are spread across the dm2:
  - Small fluctuation in the null prediction corresponds to a non-zero oscillation.
- BF point of the oscillated toys are within the allowed region:
  - Contains the true point.



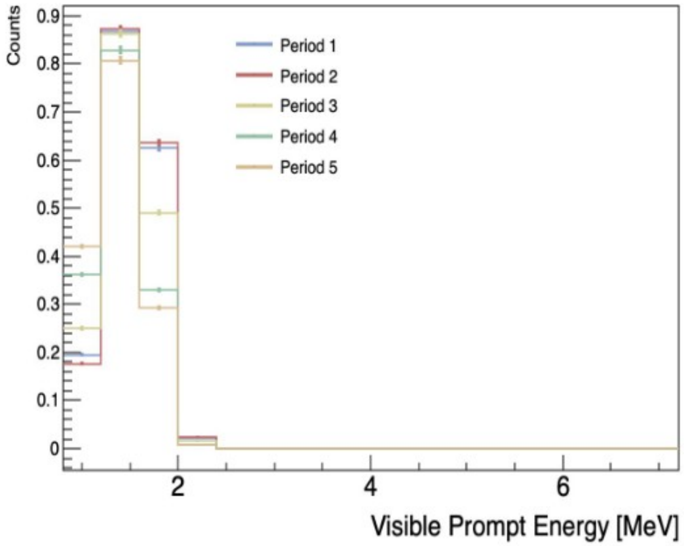
Response Matrix

- Reponse of segment 45 across different period:
- Degradation of the response as neighboring segments are turning off.
  - Leaking prominent at low and high energy.

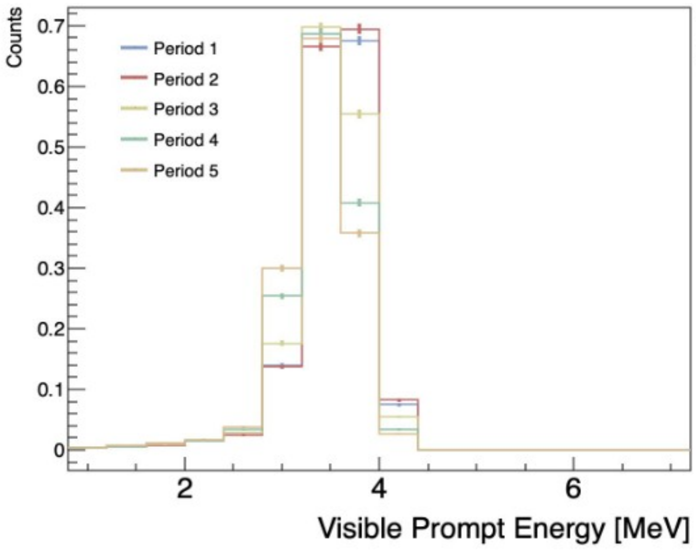
Period 5



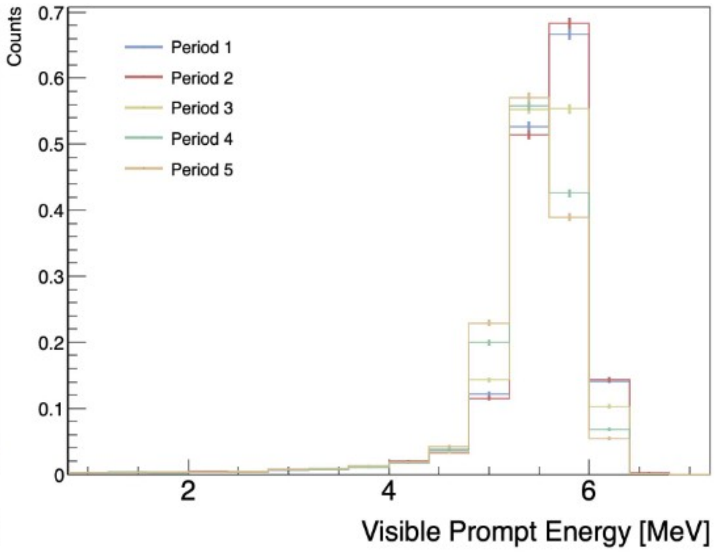
True Antinuetrino Energy [2.5-3]MeV



True Antinuetrino Energy [4.5-5]MeV

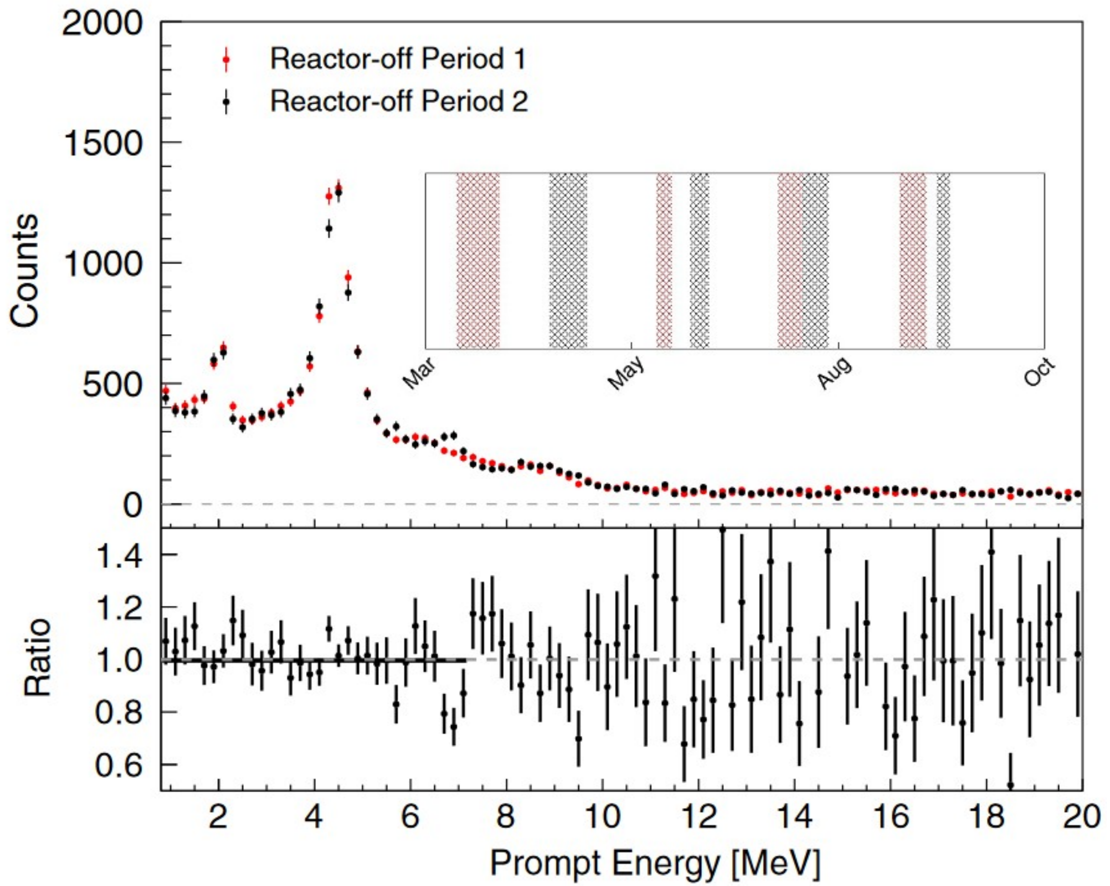


True Antinuetrino Energy [6.5-7]MeV

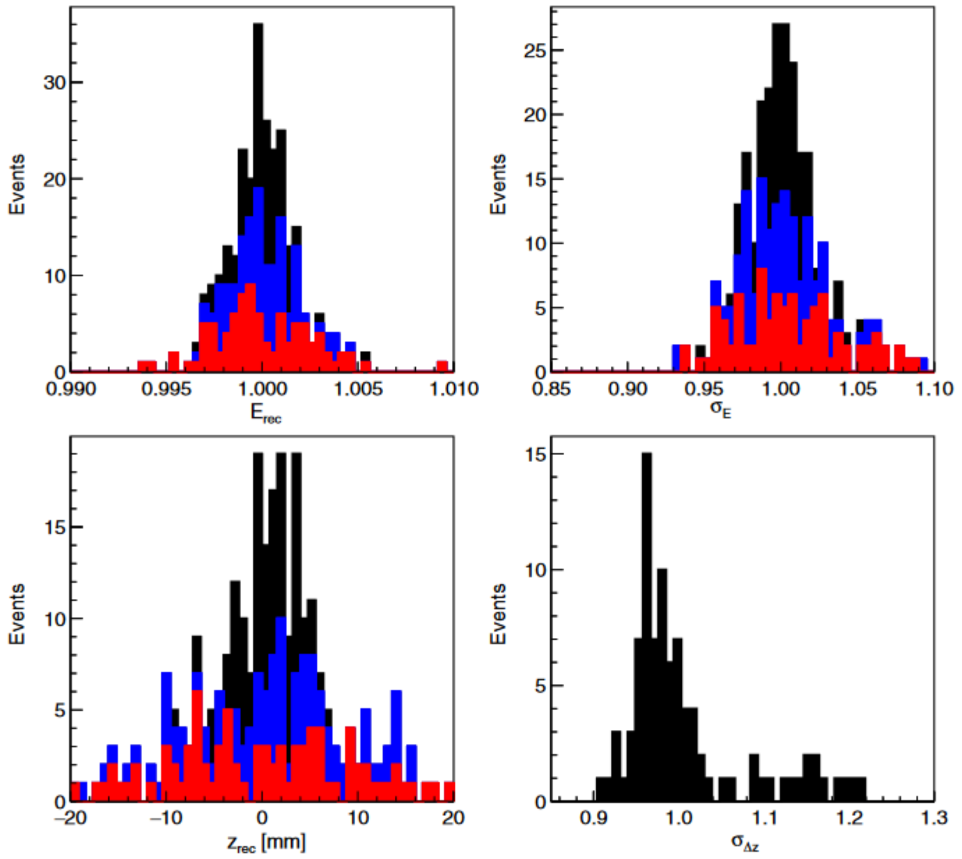


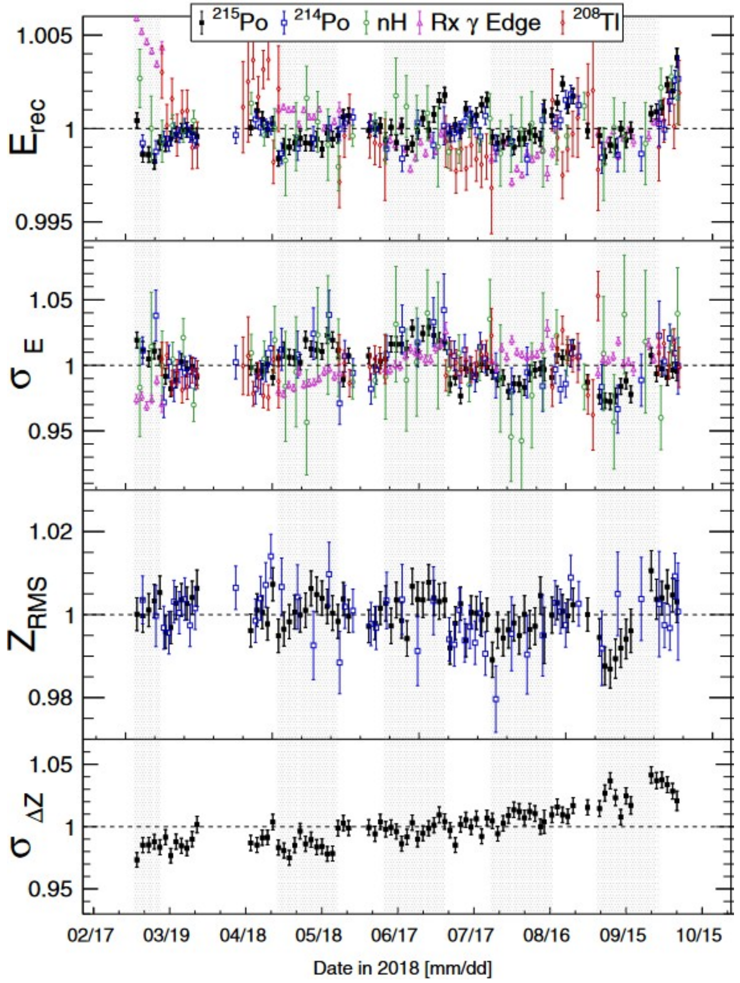
Background Stability

- Cosmogenic backgrounds vary with atmosphere conditions.
- Check the consistency between RxOff backgrounds:
  - Consistent rate and spectrum observed.

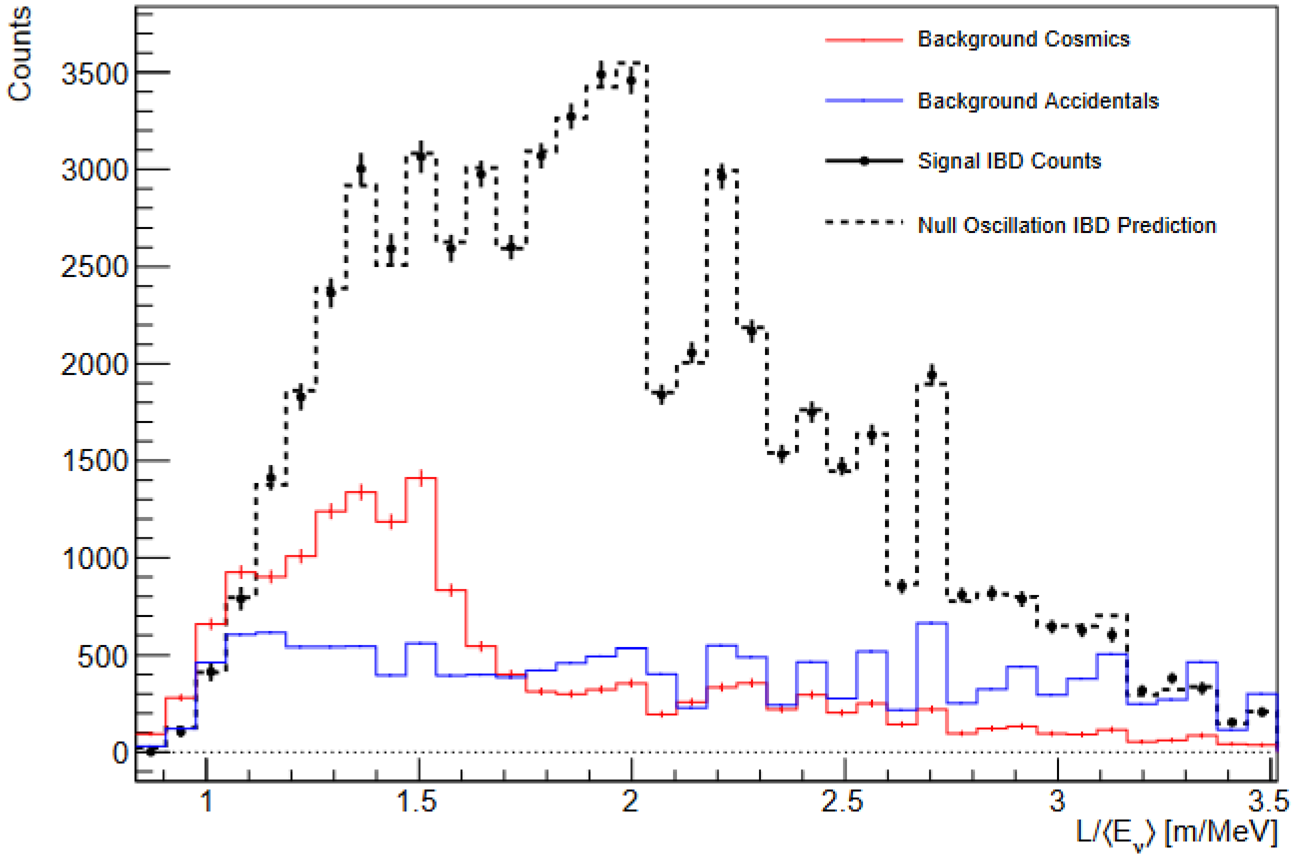


Pulse Stabilities





Absolute L/E



Counts
3500
3000
2500
2000
1500
1000
500
0
1
1.5
2
2.5
3
3.5
L/⟨E$_\nu$⟩ [m/MeV]
Background Cosmics
Background Accidentals
Signal IBD Counts
Null Oscillation IBD Prediction

Absolute L/E

Case	Description	Precision on σ_i (%)				
		^{235}U	^{238}U	^{239}Pu	^{240}Pu	^{241}Pu
-	Existing Global Data	1.3	26.4	25.2	-	42.6
1	HEU + LEU	1.6	11.1	4.6	-	10.5
3	HEU + LEU + RG-MOX	1.6	9.7	2.2	-	3.4
2	HEU + LEU + WG-MOX	1.6	9.9	2.5	-	3.6
4	HEU + LEU + Fast	1.6	10.9	4.6	27.2	10.3
5	**All**	**1.6**	**9.5**	**2.1**	**23.6**	**3.3**
6	All, Uncorrelated	1.5	14.3	2.1	36.2	4.2
-	Model Uncertainty [66]	2.1	8.2	2.5	-	2.2

Energy Smearing of N-4