OAK RIDGE National Laboratory

# Forthcoming Science from the PROSPECT-I Data Set

Diego Venegas Vargas

The University of Tennessee Knoxville

On behalf of the PROSPECT collaboration

July 23th – Snowmass Community Summer Study Workshop, 2022

ORNL is managed by UT-Battelle, LLC for the US Department of Energy

Community Summer Study

SNOWMASS

July 17-26 2022, Seattle

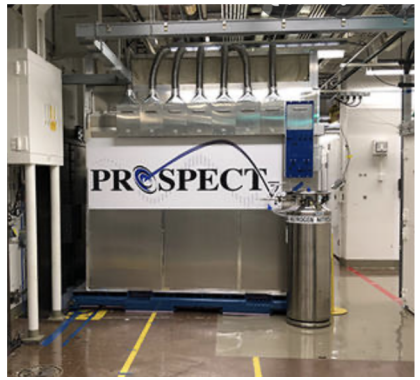
U.S. DEPARTMENT OF ENERGY

Physics Division

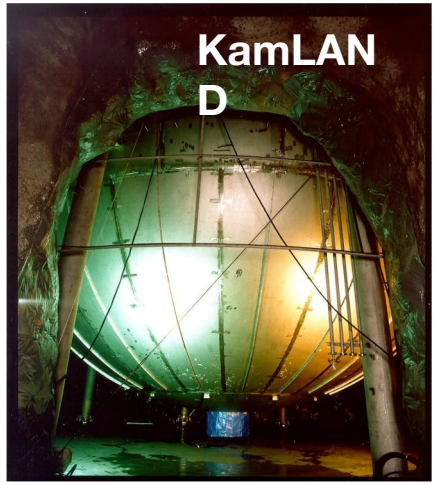
# Reactor Neutrinos

## A Tool for Discovery

**2012 - Measurement of $\theta_{13}$ with Reactor Neutrinos**

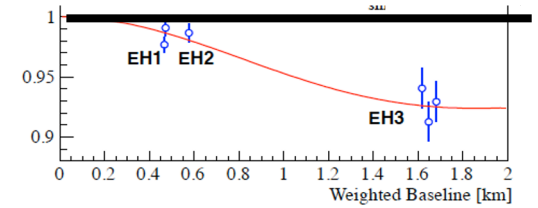


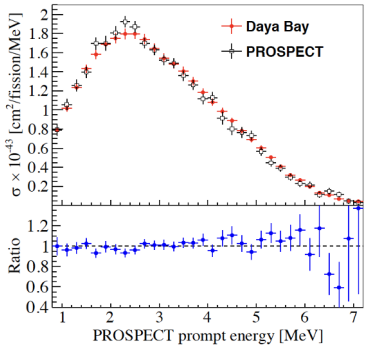

**2003 - First observation of reactor antineutrino disappearance**

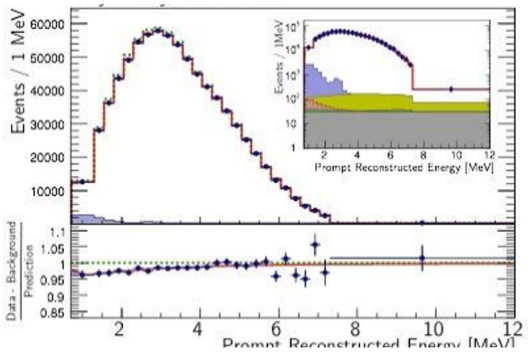


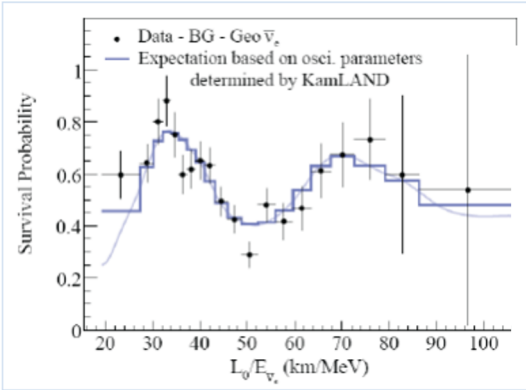

**1995 - Nobel Prize to Fred Reines at UC Irvine**

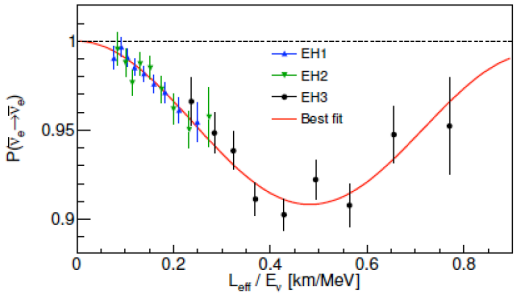
**1956 - First observation of (anti)neutrinos**



# PROSPECT Motivations and Goals

**The Flux Deficit**
Previous reactor experiments observed a 6% flux deficit when compared to reactor models.

Questions:
- Can this deficit be explained by neutrinos oscillating into an active-sterile state?
- How would one look for such oscillations?

Physics Goal 1:
- Search for short-baseline oscillations and conclusively address the sterile neutrino hypothesis as an answer to the Reactor Antineutrino Anomaly (RAA)

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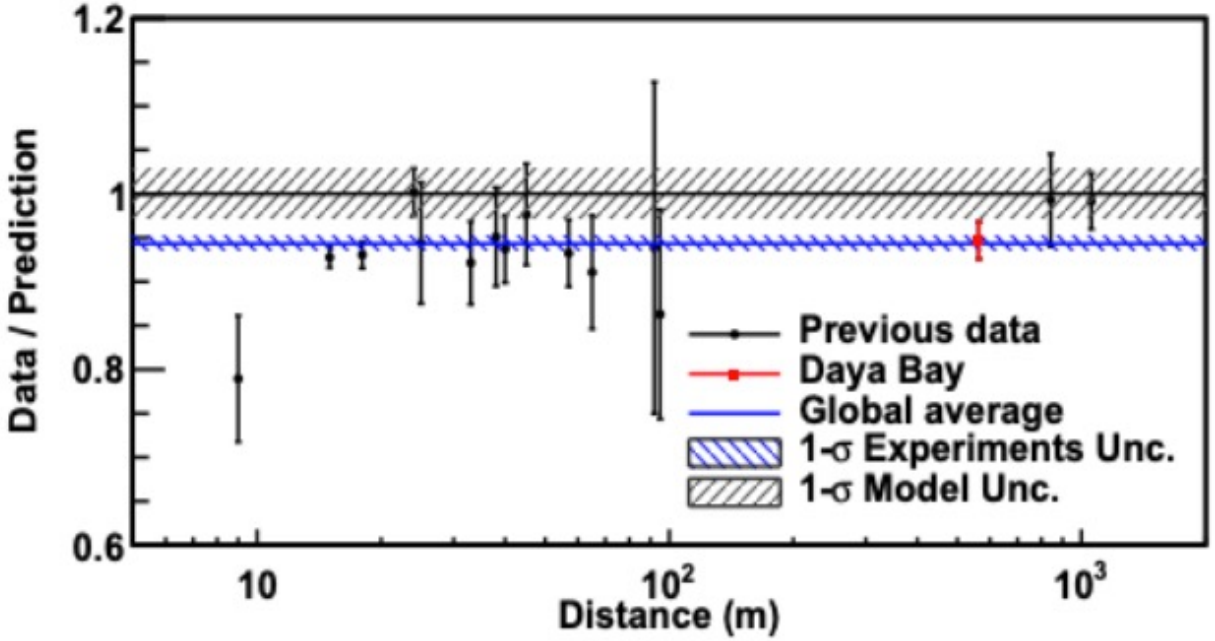



Feng Peng An et al. Measurement of the Reactor Antineutrino Flux and Spectrum at Daya Bay. Phys. Rev. Lett., 116(6):061801, 2016, 1508.04233.

# PROSPECT Motivations and Goals

**The Spectral Deviation**

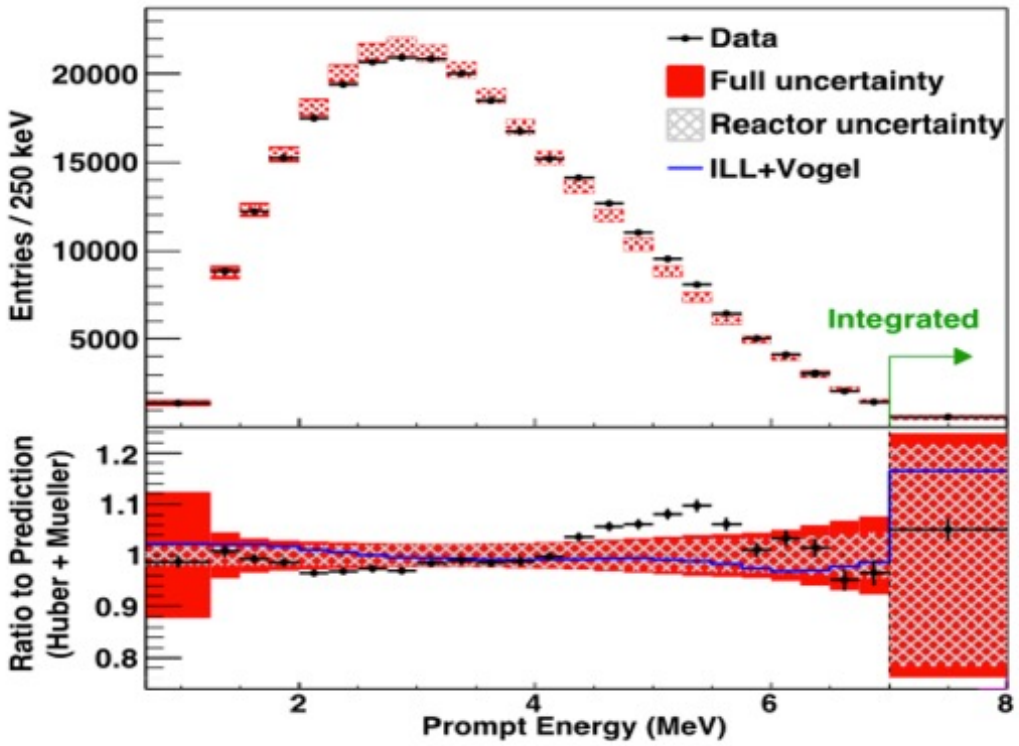
Daya Bay and other $\theta_{13}$ experiments observed bump in 4-6 MeV region, a deviation of ~10%.

Questions:

- What is the nature of this bump?
- Is it a modeling issue?
- Are the all the models wrong? Or does the problem lie with the prediction for one of the fissioning isotopes

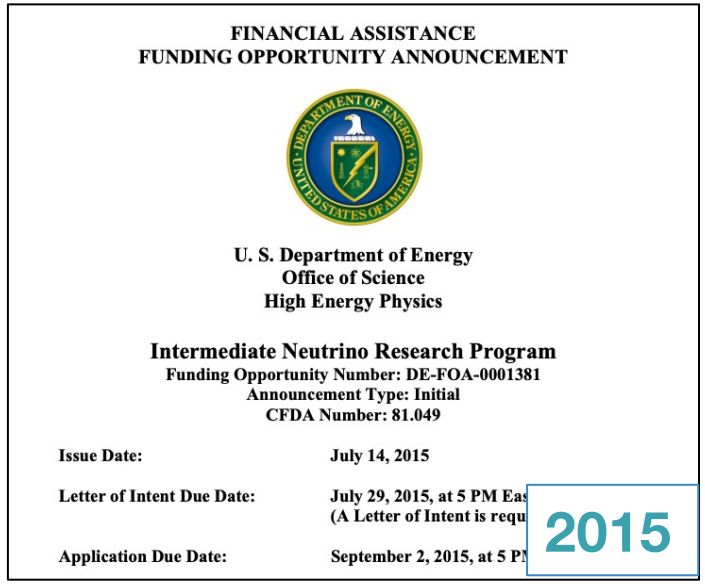
Physics Goal 2:

- To make a precise measurement of the antineutrino spectrum from a HEU reactor (mainly $^{235}U$).




Feng Peng An et al. Measurement of the Reactor Antineutrino Flux and Spectrum at Daya Bay. Phys. Rev. Lett., 116(6):061801, 2016, 1508.04233.

# PROSPECT is a successful outcome of the last Snowmass / P5 cycle

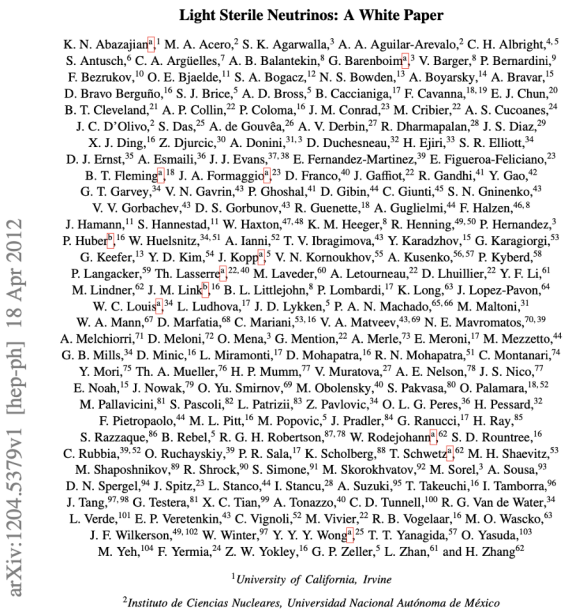



**Recommendation 4:** Maintain a program of projects of all scales, from the largest international projects to mid- and small-scale projects.

**Recommendation 6:** In addition to reaping timely science from projects, the research program should provide the flexibility to support new ideas and developments.

**Recommendation 15:** Select and perform in the short term a set of small-scale short-baseline experiments that can conclusively address experimental hints of physics beyond the three-neutrino paradigm. Some of these experiments should use liquid argon to advance the technology and build the international community for LBNF at Fermilab.

# Results from PROSPECT-I



**Light Sterile Neutrinos: A White Paper**


K. N. Abazajian[a],[1] M. A. Acero,[2] S. K. Agarwalla,[3] A. A. Aguilar-Arevalo,[2] C. H. Albright,[4,5] S. Antusch,[6] C. A. Argüelles,[7] A. B. Balantekin,[8] G. Barenboim[a],[3] V. Barger,[8] P. Bernardini,[9] F. Bezrukov,[10] O. E. Bjaelde,[11] S. A. Bogacz,[12] N. S. Bowden,[13] A. Boyarsky,[14] A. Bravar,[15] D. Bravo Berguño,[16] S. J. Brice,[5] A. D. Bross,[5] B. Caccianiga,[17] F. Cavanna,[18,19] E. J. Chun,[20] B. T. Cleveland,[21] A. P. Collin,[22] P. Coloma,[16] J. M. Conrad,[23] M. Cribier,[22] A. S. Cucoanes,[24] J. C. D'Olivo,[2] S. Das,[25] A. de Gouvêa,[26] A. V. Derbin,[27] R. Dharmapalan,[28] J. S. Diaz,[29] X. J. Ding,[16] Z. Djurcic,[30] A. Donini,[31,3] D. Duchesneau,[32] H. Ejiri,[33] S. R. Elliott,[34] D. J. Ernst,[35] A. Esmaili,[36] J. J. Evans,[37,38] E. Fernandez-Martinez,[39] E. Figueroa-Feliciano,[23] B. T. Fleming[a],[18] J. A. Formaggio[a],[23] D. Franco,[40] J. Gaffiot,[22] R. Gandhi,[41] Y. Gao,[42] G. T. Garvey,[34] V. N. Gavrin,[43] P. Ghoshal,[41] D. Gibin,[44] C. Giunti,[45] S. N. Gninenko,[43] V. V. Gorbachev,[43] D. S. Gorbunov,[43] R. Guenette,[18] A. Guglielmi,[44] F. Halzen,[46,8] J. Hamann,[11] S. Hannestad,[11] W. Haxton,[47,48] K. M. Heeger,[8] R. Henning,[49,50] P. Hernandez,[3] P. Huber[b],[16] W. Huelsnitz,[34,51] A. Ianni,[52] T. V. Ibragimova,[43] Y. Karadzhov,[15] G. Karagiorgi,[53] G. Keefer,[13] Y. D. Kim,[54] J. Kopp[a],[5] V. N. Kornoukhov,[55] A. Kusenko,[56,57] P. Kyberd,[58] P. Langacker,[59] Th. Lasserre[a],[22,40] M. Laveder,[60] A. Letourneau,[22] D. Lhuillier,[22] Y. F. Li,[61] M. Lindner,[62] J. M. Link[b],[16] B. L. Littlejohn,[8] P. Lombardi,[17] K. Long,[63] J. Lopez-Pavon,[64] W. C. Louis[a],[34] L. Ludhova,[17] J. D. Lykken,[5] P. A. N. Machado,[65,66] M. Maltoni,[31] W. A. Mann,[67] D. Marfatia,[68] C. Mariani,[53,16] V. A. Matveev,[43,69] N. E. Mavromatos,[70,39] A. Melchiorri,[71] D. Meloni,[72] O. Mena,[3] G. Mention,[22] A. Merle,[73] E. Meroni,[17] M. Mezzetto,[44] G. B. Mills,[34] D. Minic,[16] L. Miramonti,[17] D. Mohapatra,[16] R. N. Mohapatra,[51] C. Montanari,[74] Y. Mori,[75] Th. A. Mueller,[76] H. P. Mumm,[77] V. Muratova,[27] A. E. Nelson,[78] J. S. Nico,[77] E. Noah,[15] J. Nowak,[79] O. Yu. Smirnov,[69] M. Obolensky,[40] S. Pakvasa,[80] O. Palamara,[18,52] M. Pallavicini,[81] S. Pascoli,[82] L. Patrizii,[83] Z. Pavlovic,[34] O. L. G. Peres,[36] H. Pessard,[32] F. Pietropaolo,[44] M. L. Pitt,[16] M. Popovic,[5] J. Pradler,[84] G. Ranucci,[17] H. Ray,[85] S. Razzaque,[86] B. Rebel,[5] R. G. H. Robertson,[87,78] W. Rodejohann[a],[62] S. D. Rountree,[16] C. Rubbia,[39,52] O. Ruchayskiy,[39] P. R. Sala,[17] K. Scholberg,[88] T. Schwetz[a],[62] M. H. Shaevitz,[53] M. Shaposhnikov,[89] R. Shrock,[90] S. Simone,[91] M. Skorokhvatov,[92] M. Sorel,[3] A. Sousa,[93] D. N. Spergel,[94] J. Spitz,[23] L. Stanco,[44] I. Stancu,[28] A. Suzuki,[95] T. Takeuchi,[16] I. Tamborra,[96] J. Tang,[97,98] G. Testera,[81] X. C. Tian,[99] A. Tonazzo,[40] C. D. Tunnell,[100] R. G. Van de Water,[34] L. Verde,[101] E. P. Veretenkin,[43] C. Vignoli,[52] M. Vivier,[22] R. B. Vogelaar,[16] M. O. Wascko,[63] J. F. Wilkerson,[49,102] W. Winter,[97] Y. Y. Y. Wong[a],[25] T. T. Yanagida,[57] O. Yasuda,[103] M. Yeh,[104] F. Yermia,[24] Z. W. Yokley,[16] G. P. Zeller,[5] L. Zhan,[61] and H. Zhang[62]

[1]*University of California, Irvine*

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[3]*Instituto de Fisica Corpuscular, CSIC and Universidad de Valencia*

[4]*Northern Illinois University*

[5]*Fermi National Accelerator Laboratory*

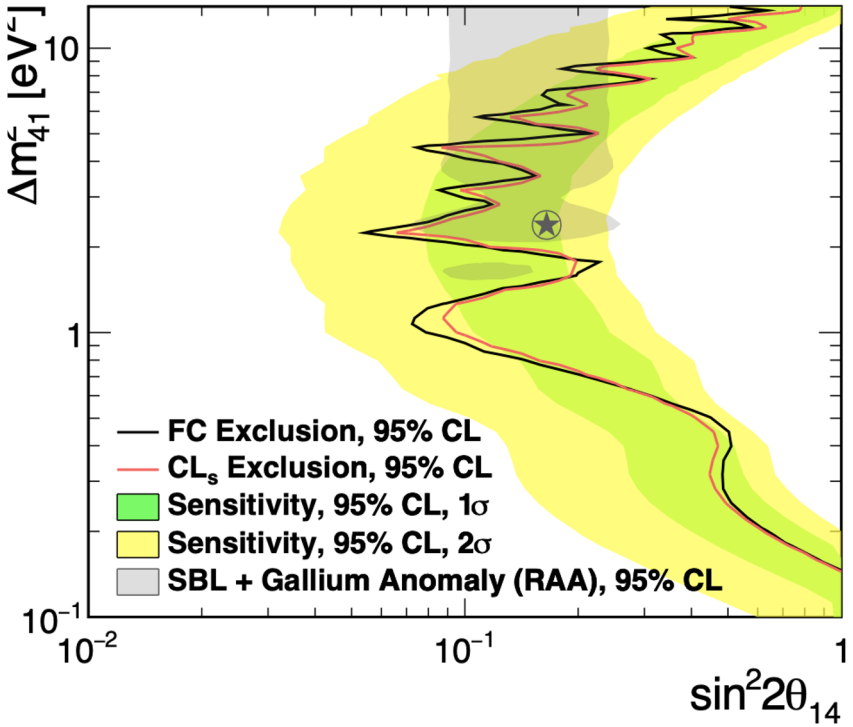
[6]*University of Basel*

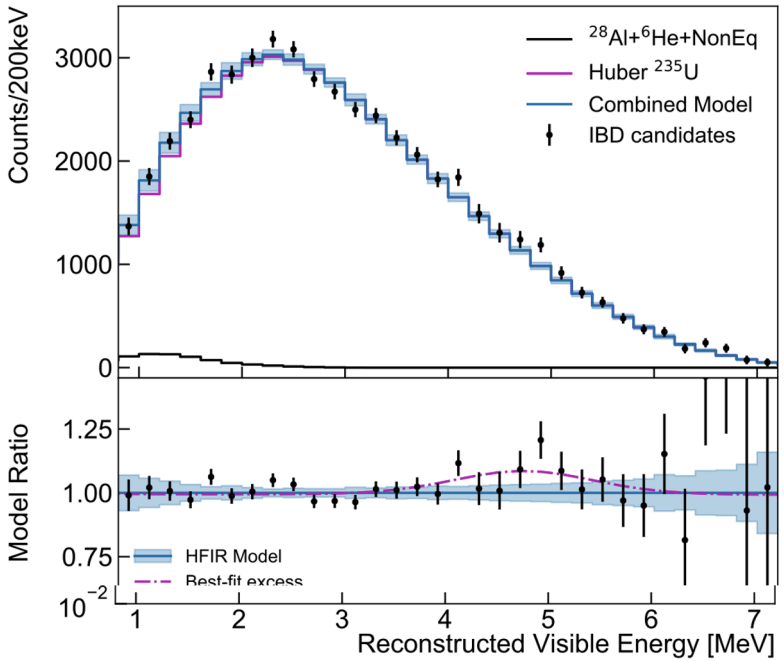


arXiv:1204.5379v1 [hep-ph] 18 Apr 2012


**2011** RAA paper & SNAC workshop, **2012** white paper motivated search for eV-scale sterile neutrinos

**2018** first physics limits from PROSPECT




- Performed direct test of the Reactor Antineutrino Anomaly, -> no signs of sterile neutrino oscillation
- Helped establish that RAA largely due to mismodeling of $^{235}$U
- Led the joint analysis with other experiments

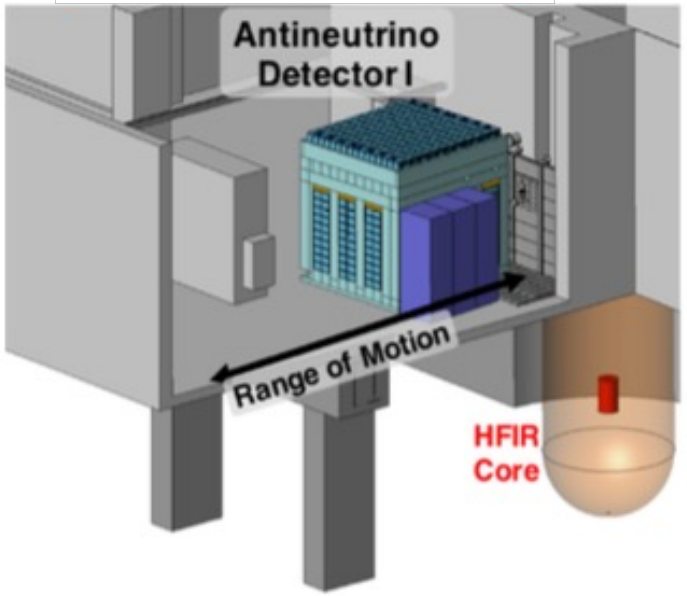
# 1. First phase of the PROSPECT Experiment

- Experiment description
- Results and highlights from P-I

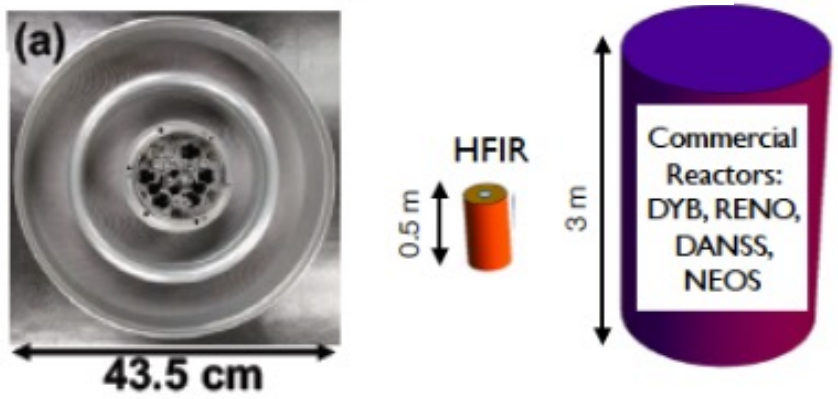
Image source: https://neutrons.ornl.gov/hfir

# PROSPECT Detector at HFIR

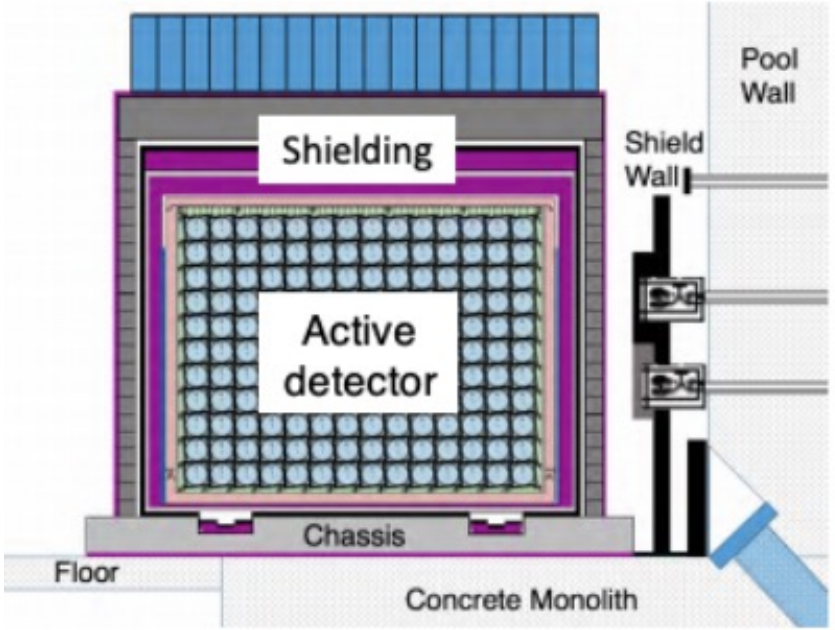
Layout of the PROSPECT experiment




- 93% 235U Fuel
- 85 MW thermal power
- Compact core
- Huge flux in the few MeV range
- ~50% duty cycle for BG measurements




Schematic of the active detector volume




14 x 11 array of 6Li doped liquid scintillator for detecting reactor antineutrinos (6.7-9.2 m from compact highly enriched uranium reactor core)

J. Ashenfelter et al. (PROSPECT), Nucl. Inst. Meth. A 922, 287(2019)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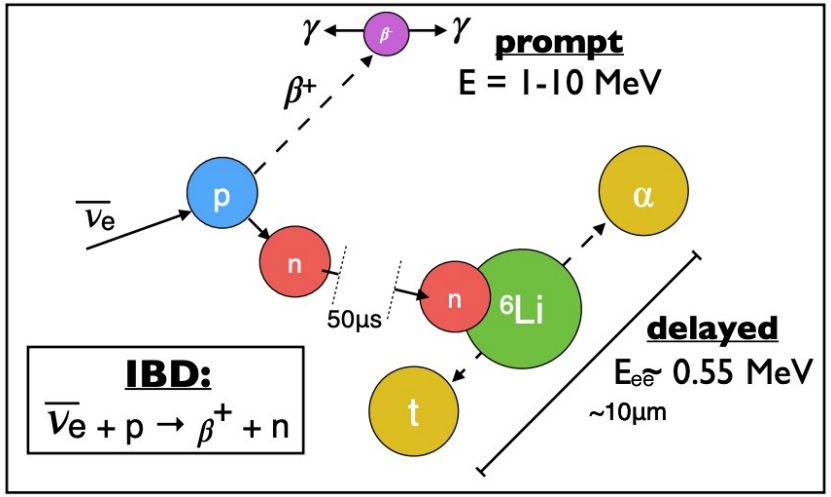
PROSPECT

# Antineutrino Detection

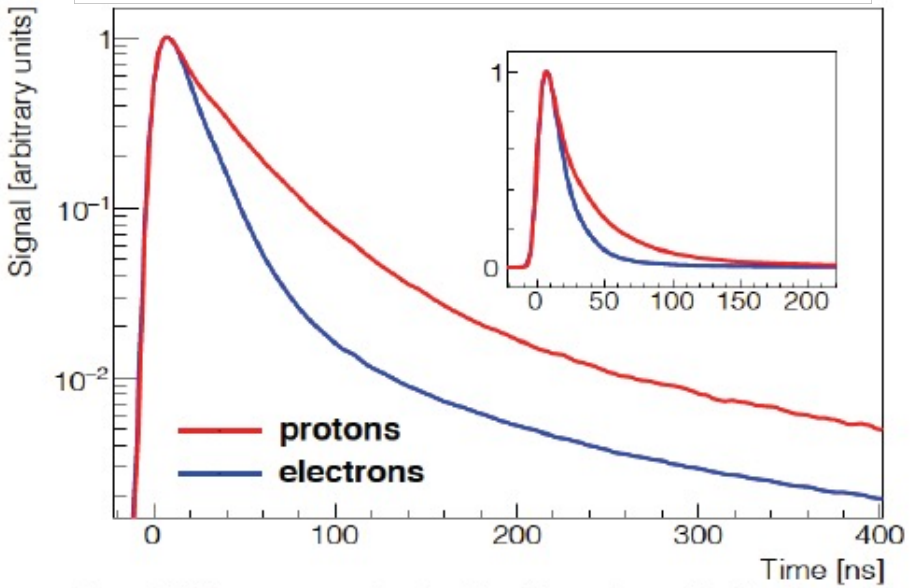
**Schematic of the IBD process**




- PROSPECT detects antineutrinos via the Inverse Beta Decay (IBD) process
- Prompt signal ($e^+$) provides a good energy estimate of incoming $\nu$
- Localized delayed (n - $^6Li$) signal

**6-LiLS with PSD Capabilities**

**- Average waveforms for electronic/nuclear type events**




- Differences in ionization density between electronic/nuclear recoil type events result in distinct pulse shapes for each event
- Prompt and delayed signal posses unique pulse shapes (different from background events)

M. Andriamirado et al. (PROSPECT Collaboration), Phys. Rev. D 103, 032001 (2021).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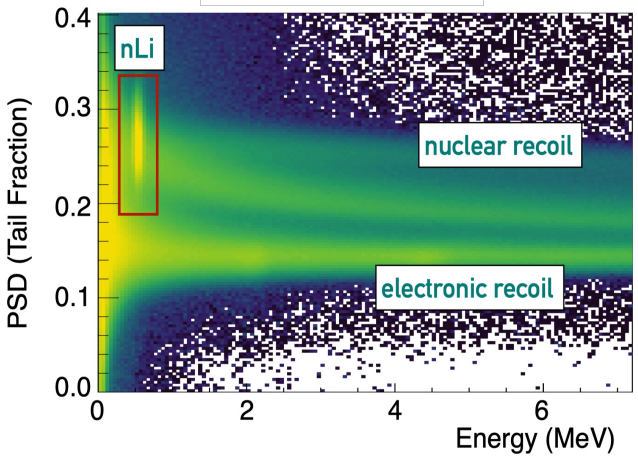
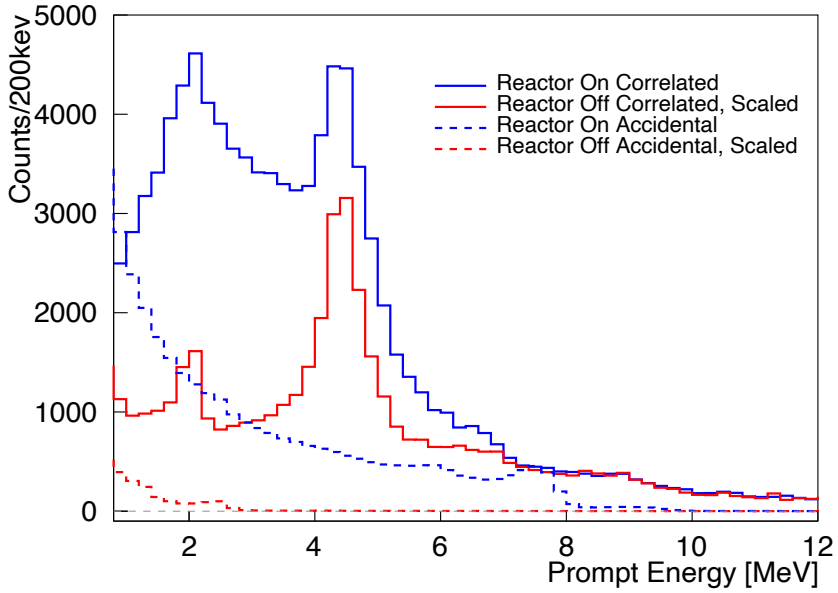
# IBD Event Selection

- **IBD Topology-based cuts**
  - Neutron Capture Region
  - Prompt PSD
  - Prompt-Delayed signal distance
  - Prompt-Delayed Timing
  - Fiducial z cut
- **Veto cuts**
  - Muon Veto Time
  - Neutron Veto Time
  - Recoil Veto time

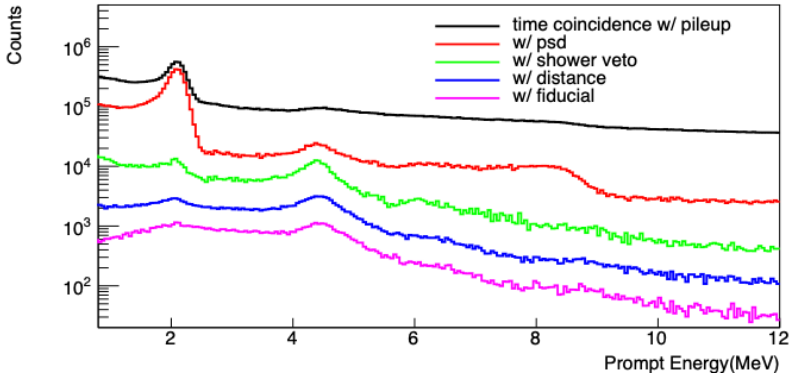
**Prompt PSD Cut**




**Measured prompt energy spectrum of correlated IBD-like candidates**




**Prompt Energy Distributions Under Different Cuts**




- Sequential application of selection cuts results in a significant reduction of background events
- These selection criteria was used for most recent results

- 95.65 reactor-on calendar days, 73.09 reactor-off
- >50,000 IBD events
- Signal to background ratio > 1

M. Andriamirado et al. (PROSPECT Collaboration), Phys. Rev. D 103, 032001 (2021).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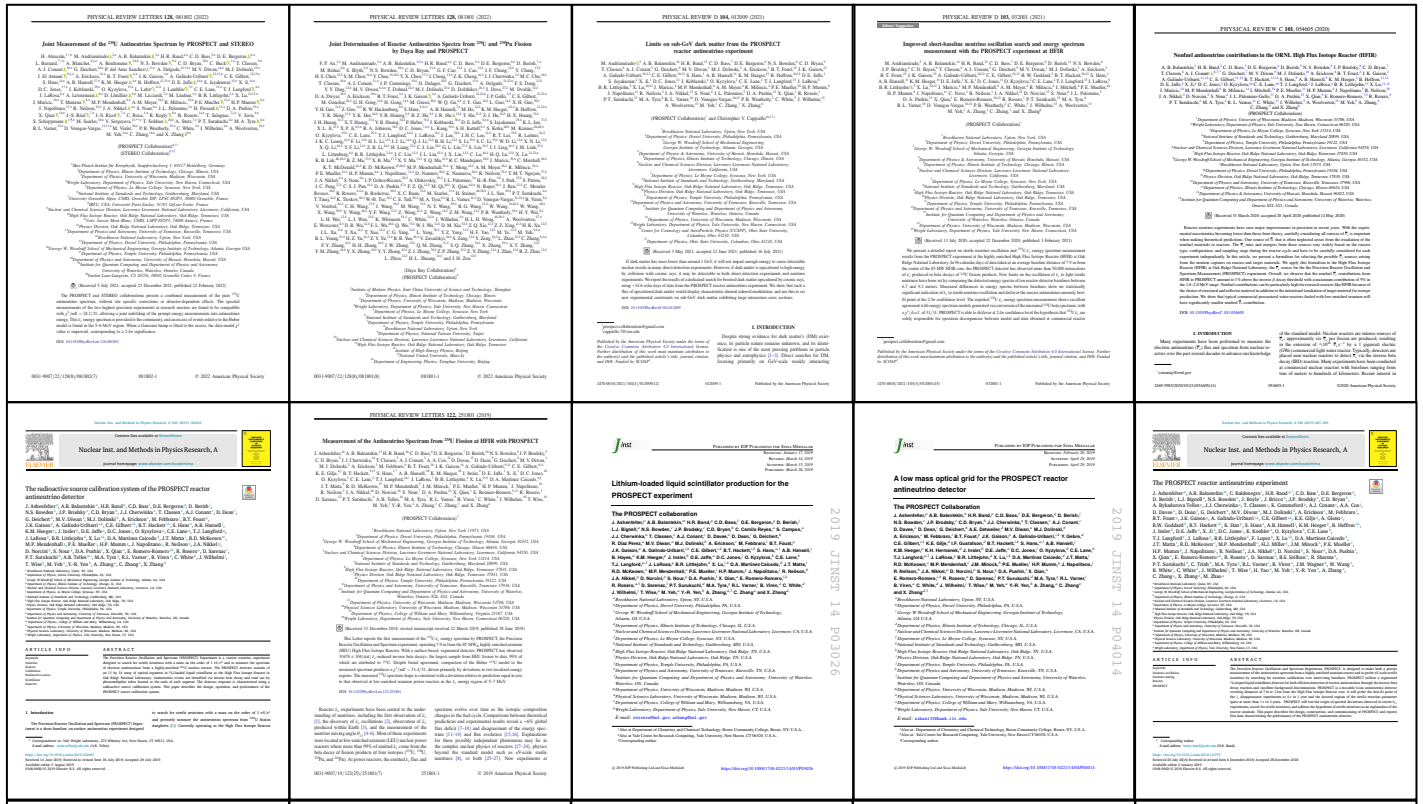
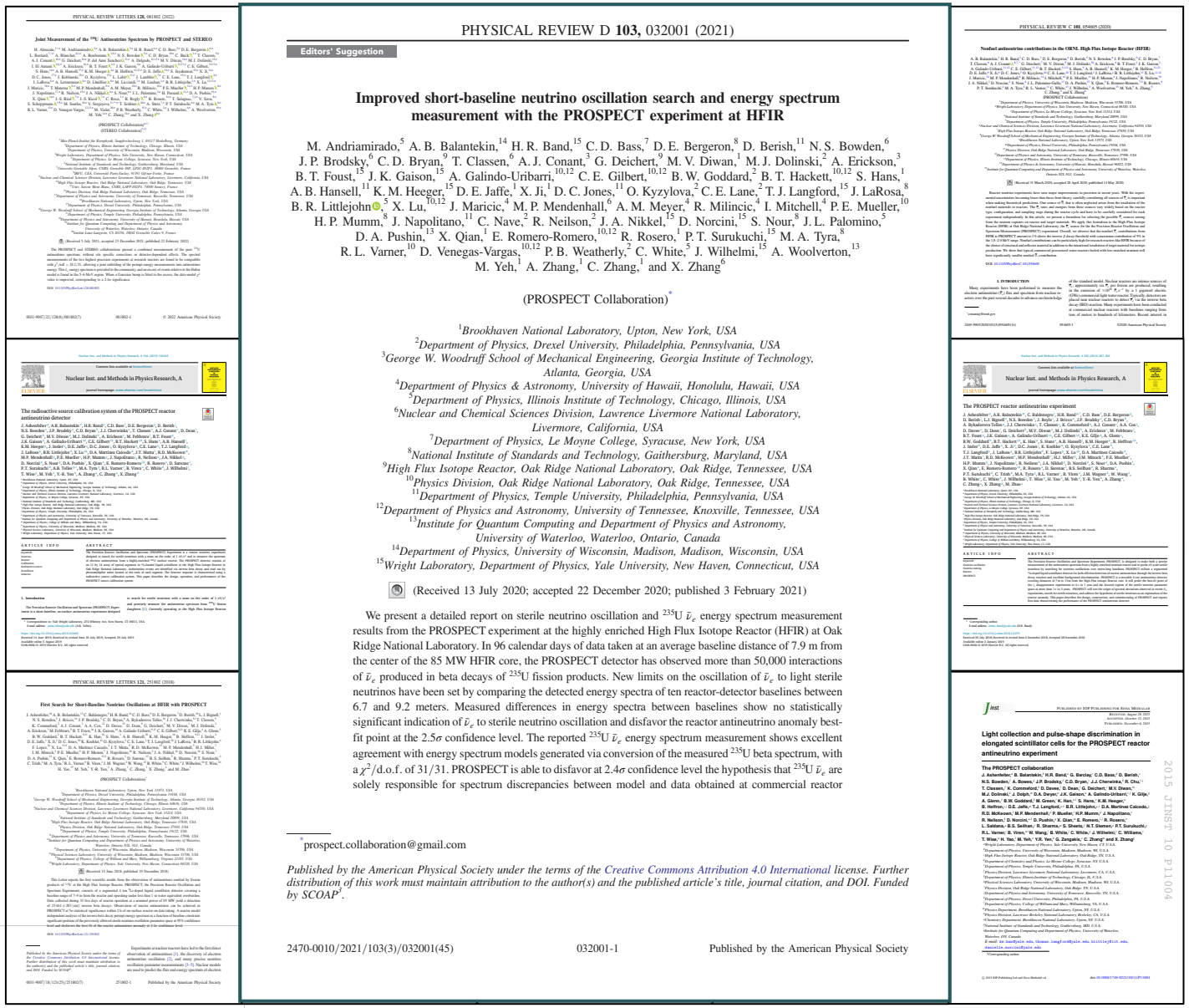
# PROSPECT-I Results and Highlights: - Publications




- After a total of ~96(~73) calendar days of Reactor-On(Off) data taking the PROSPECT experiment has produced world-class physics results which are summarized in over 15 publications.

# PROSPECT-I Results and Highlights
## - Oscillation and Spectrum



PHYSICAL REVIEW D **103,** 032001 (2021)

Editors' Suggestion

**Improved short-baseline neutrino oscillation search and energy spectrum measurement with the PROSPECT experiment at HFIR**


M. Andriamirado,[5] A. B. Balantekin,[14] H. R. Band,[15] C. D. Bass,[7] D. E. Bergeron,[8] D. Berish,[11] N. S. Bowden,[6] J. P. Brodsky,[6] C. D. Bryan,[9] T. Classen,[6] A. J. Conant,[3] G. Deichert,[9] M. V. Diwan,[1] M. J. Dolinski,[2] A. Erickson,[3] B. T. Foust,[15] J. K. Gaison,[15] A. Galindo-Uribarri,[10,12] C. E. Gilbert,[10,12] B. W. Goddard,[2] B. T. Hackett,[10,12] S. Hans,[1] A. B. Hansell,[11] K. M. Heeger,[15] D. E. Jaffe,[1] X. Ji,[1] D. C. Jones,[11] O. Kyzylova,[2] C. E. Lane,[2] T. J. Langford,[15] J. LaRosa,[8] B. R. Littlejohn,[5] X. Lu,[10,12] J. Maricic,[4] M. P. Mendenhall,[6] A. M. Meyer,[4] R. Milincic,[4] I. Mitchell,[4] P. E. Mueller,[10] H. P. Mumm,[8] J. Napolitano,[11] C. Nave,[2] R. Neilson,[2] J. A. Nikkel,[15] D. Norcini,[15] S. Nour,[8] J. L. Palomino,[5] D. A. Pushin,[13] X. Qian,[1] E. Romero-Romero,[10,12] R. Rosero,[1] P. T. Surukuchi,[15] M. A. Tyra,[8] R. L. Varner,[10] D. Venegas-Vargas,[10,12] P. B. Weatherly,[2] C. White,[5] J. Wilhelmi,[15] A. Woolverton,[13] M. Yeh,[1] A. Zhang,[1] C. Zhang,[1] and X. Zhang[6]

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[13]*Institute for Quantum Computing and Department of Physics and Astronomy, University of Waterloo, Waterloo, Ontario, Canada*
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We present a detailed report on sterile neutrino oscillation and $^{235}$U $\bar{\nu}_e$ energy spectrum measurement results from the PROSPECT experiment at the highly enriched High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory. In 96 calendar days of data taken at an average baseline distance of 7.9 m from the center of the 85 MW HFIR core, the PROSPECT detector has observed more than 50,000 interactions of $\bar{\nu}_e$ produced in beta decays of $^{235}$U fission products. New limits on the oscillation of $\bar{\nu}_e$ to light sterile neutrinos have been set by comparing the detected energy spectra of ten reactor-detector baselines between 6.7 and 9.2 meters. Measured differences in energy spectra between baselines show no statistically significant indication of $\bar{\nu}_e$ to sterile neutrino oscillation and disfavor the reactor antineutrino anomaly best-fit point at the 2.5$\sigma$ confidence level. The reported $^{235}$U $\bar{\nu}_e$ energy spectrum measurement shows excellent agreement with energy spectrum models generated via conversion of the measured $^{235}$U beta spectrum, with a $\chi^2$/d.o.f. of 31/31. PROSPECT is able to disfavor at 2.4$\sigma$ confidence level the hypothesis that $^{235}$U $\bar{\nu}_e$ are solely responsible for spectrum discrepancies between model and data obtained at commercial reactor



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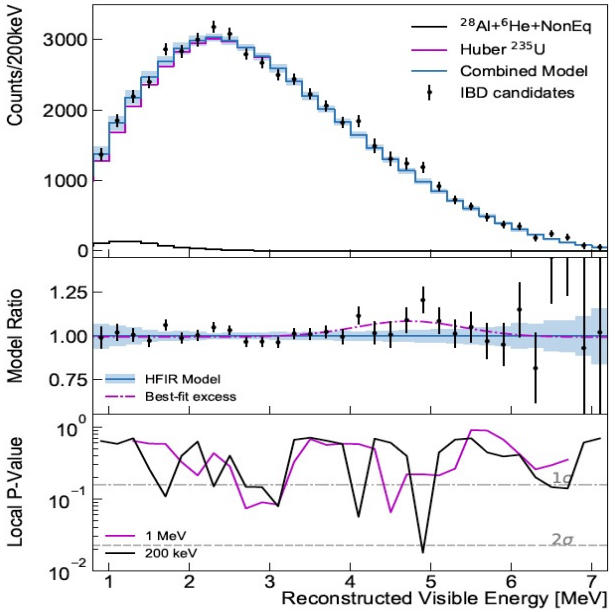
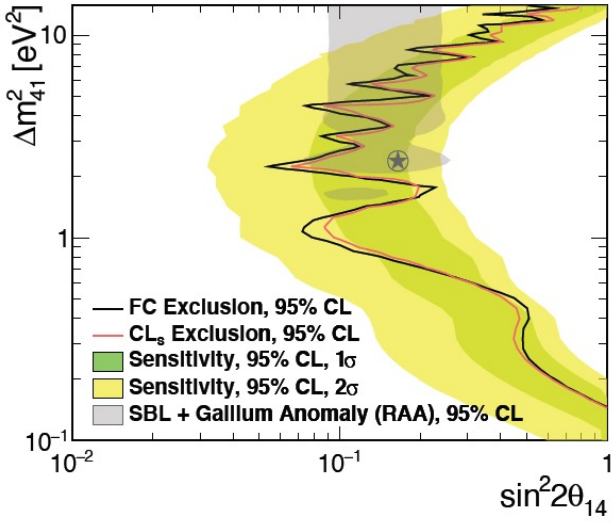
**Prompt Energy Antineutrino Spectrum**




- $\chi^2$/ndf =30.79/31 for shape-only comparison with model
- No $^{235}$U bump disfavored at 2.2σ CL
- All $^{235}$U is disfavored at 2.4σ CL

**Oscillation Exclusion Contours**




- RAA best-fit excluded: 98.5% CL
- Data is compatible with null oscillation hypothesis (p=0.57)

# PROSPECT-I Results and Highlights
## - Joint Spectrum Analyses

PHYSICAL REVIEW LETTERS **128,** 081802 (2022)

**Joint Measurement of the $^{235}$U Antineutrino Spectrum by PROSPECT and STEREO**

H. Almazán,[1,*,σ] M. Andriamirado,[2,π] A. B. Balantekin,[3,π] H. R. Band,[4,π] C. D. Bass,[5,π] D. E. Bergeron,[6,π] L. Bernard,[7,†,σ] A. Blanchet,[8,‡,σ] A. Bonhomme,[1,8,σ] N. S. Bowden,[9,π] C. D. Bryan,[10,π] C. Buck,[1,σ] T. Classen,[9,π] A. J. Conant,[10,π] G. Deichert,[10,π] P. del Amo Sanchez,[11,σ] A. Delgado,[12,13,π] M. V. Diwan,[14,π] M. J. Dolinski,[15,π] I. El Atmani,[8,§,σ] A. Erickson,[16,π] B. T. Foust,[4,π] J. K. Gaison,[4,π] A. Galindo-Uribarri,[12,13,π] C. E. Gilbert,[12,13,π] S. Hans,[14,π] A. B. Hansell,[17,π] K. M. Heeger,[4,π] B. Heffron,[12,13,π] D. E. Jaffe,[9,π] S. Jayakumar,[15,π] X. Ji,[14,π] D. C. Jones,[17,π] J. Koblanski,[18,π] O. Kyzylova,[15,π] L. Labit,[11,σ] J. Lamblin,[7,σ] C. E. Lane,[15,π] T. J. Langford,[4,π] J. LaRosa,[6,π] A. Letourneau,[8,σ] D. Lhuillier,[8,σ] M. Licciardi,[7,σ] M. Lindner,[1,σ] B. R. Littlejohn,[2,π] X. Lu,[12,13,π] J. Maricic,[18,π] T. Materna,[8,σ] M. P. Mendenhall,[9,π] A. M. Meyer,[18,π] R. Milincic,[18,π] P. E. Mueller,[12,π] H. P. Mumm,[6,π] J. Napolitano,[17,π] R. Neilson,[15,π] J. A. Nikkel,[4,π] S. Nour,[5,π] J. L. Palomino,[2,π] H. Pessard,[11,σ] D. A. Pushin,[19,π] X. Qian,[14,π] J.-S. Réal,[7,σ] J.-S. Ricol,[7,σ] C. Roca,[1,σ] R. Rogly,[8,σ] R. Rosero,[14,π] T. Salagnac,[7,‖,σ] V. Savu,[8,σ] S. Schoppmann,[1,¶,σ] M. Searles,[10,π] V. Sergeyeva,[11,**,σ] T. Soldner,[20,σ] A. Stutz,[7,σ] P. T. Surukuchi,[4,π] M. A. Tyra,[6,π] R. L. Varner,[12,π] D. Venegas-Vargas,[12,13,π] M. Vialat,[20,σ] P. B. Weatherly,[15,π] C. White,[2,π] J. Wilhelmi,[4,π] A. Woolverton,[19,π] M. Yeh,[14,π] C. Zhang,[14,π] and X. Zhang[9,π]

(PROSPECT Collaboration)[π,††]
(STEREO Collaboration)[σ,‡‡]

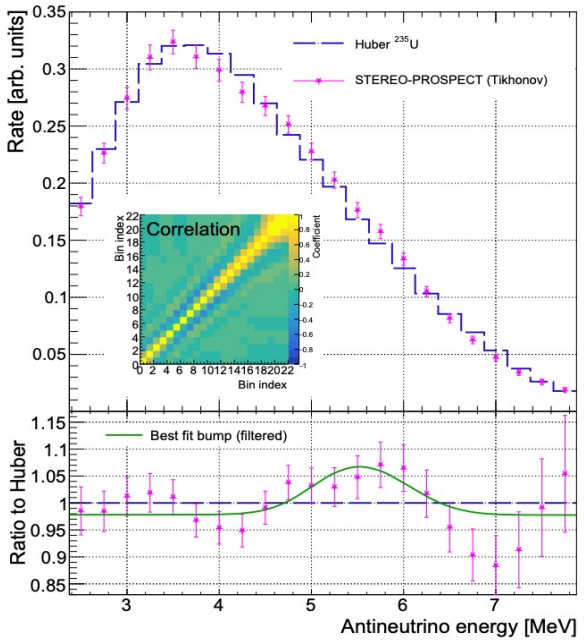
PHYSICAL REVIEW LETTERS **128,** 081801 (2022)

**Joint Determination of Reactor Antineutrino Spectra from $^{235}$U and $^{239}$Pu Fission by Daya Bay and PROSPECT**

F. P. An,[1,δ] M. Andriamirado,[2,π] A. B. Balantekin,[3,δ,π] H. R. Band,[4,π] C. D. Bass,[5,π] D. E. Bergeron,[6,π] D. Berish,[7,π] M. Bishai,[8,δ] S. Blyth,[9,δ] N. S. Bowden,[10,π] C. D. Bryan,[11,π] G. F. Cao,[12,δ] J. Cao,[12,δ] J. F. Chang,[12,δ] Y. Chang,[13,δ] H. S. Chen,[12,δ] S. M. Chen,[14,δ] Y. Chen,[15,16,δ] Y. X. Chen,[17,δ] J. Cheng,[12,δ] Z. K. Cheng,[16,δ] J. J. Cherwinka,[3,δ] M. C. Chu,[18,δ] T. Classen,[10,π] A. J. Conant,[11,π] J. P. Cummings,[19,δ] O. Dalager,[20,δ] G. Deichert,[11,π] A. Delgado,[21,22,π] F. S. Deng,[23,δ] Y. Y. Ding,[12,δ] M. V. Diwan,[8,δ,π] T. Dohnal,[24,δ] M. J. Dolinski,[25,π] D. Dolzhikov,[26,δ] J. Dove,[27,δ] M. Dvořák,[12,δ] D. A. Dwyer,[28,δ] A. Erickson,[29,π] B. T. Foust,[4,π] J. K. Gaison,[4,π] A. Galindo-Uribarri,[21,22,π] J. P. Gallo,[2,δ] C. E. Gilbert,[21,22,π] M. Gonchar,[26,δ] G. H. Gong,[14,δ] H. Gong,[14,δ] M. Grassi,[20,δ] W. Q. Gu,[8,δ] J. Y. Guo,[16,δ] L. Guo,[14,δ] X. H. Guo,[30,δ] Y. H. Guo,[31,δ] Z. Guo,[14,δ] R. W. Hackenburg,[8,δ] S. Hans,[8,δ,π,*] A. B. Hansell,[7,π] M. He,[12,δ] K. M. Heeger,[4,δ,π] B. Heffron,[21,22,π] Y. K. Heng,[12,δ] Y. K. Hor,[16,δ] Y. B. Hsiung,[9,δ] B. Z. Hu,[9,δ] J. R. Hu,[12,δ] T. Hu,[12,δ] Z. J. Hu,[16,δ] H. X. Huang,[32,δ] J. H. Huang,[12,δ] X. T. Huang,[33,δ] Y. B. Huang,[34,δ] P. Huber,[35,δ] J. Koblanski,[36,π] D. E. Jaffe,[8,δ,π] S. Jayakumar,[25,π] K. L. Jen,[37,δ] X. L. Ji,[12,δ] X. P. Ji,[8,δ,π] R. A. Johnson,[38,δ] D. C. Jones,[7,δ,π] L. Kang,[39,δ] S. H. Kettell,[8,δ] S. Kohn,[40,δ] M. Kramer,[28,40,δ] O. Kyzylova,[25,π] C. E. Lane,[25,π] T. J. Langford,[4,δ,π] J. LaRosa,[6,π] J. Lee,[28,δ] J. H. C. Lee,[41,δ] R. T. Lei,[39,δ] R. Leitner,[24,δ] J. K. C. Leung,[41,δ] F. Li,[12,δ] H. L. Li,[12,δ] J. J. Li,[14,δ] Q. J. Li,[12,δ] R. H. Li,[12,δ] S. Li,[39,δ] S. C. Li,[35,δ] W. D. Li,[12,δ] X. N. Li,[12,δ] X. Q. Li,[42,δ] Y. F. Li,[12,δ] Z. B. Li,[16,δ] H. Liang,[23,δ] C. J. Lin,[28,δ] G. L. Lin,[37,δ] S. Lin,[39,δ] J. J. Ling,[16,δ] J. M. Link,[35,δ] L. Littenberg,[8,δ] B. R. Littlejohn,[2,δ,π] J. C. Liu,[12,δ] J. L. Liu,[43,δ] J. X. Liu,[12,δ] C. Lu,[44,δ] H. Q. Lu,[12,δ] X. Lu,[21,22,π] K. B. Luk,[40,28,δ] B. Z. Ma,[33,δ] X. B. Ma,[17,δ] X. Y. Ma,[12,δ] Y. Q. Ma,[12,δ] R. C. Mandujano,[20,δ] J. Maricic,[36,π] C. Marshall,[28,δ] K. T. McDonald,[44,δ] R. D. McKeown,[45,46,δ] M. P. Mendenhall,[10,π] Y. Meng,[43,δ] A. M. Meyer,[36,π] R. Milincic,[36,π] P. E. Mueller,[21,π] H. P. Mumm,[6,π] J. Napolitano,[7,δ,π] D. Naumov,[26,δ] E. Naumova,[26,δ] R. Neilson,[25,π] T. M. T. Nguyen,[37,δ] J. A. Nikkel,[4,π] S. Nour,[6,π] J. P. Ochoa-Ricoux,[20,δ] A. Olshevskiy,[26,δ] J. L. Palomino,[2,π] H.-R. Pan,[9,δ] J. Park,[35,δ] S. Patton,[28,δ] J. C. Peng,[27,δ] C. S. J. Pun,[41,δ] D. A. Pushin,[47,π] F. Z. Qi,[12,δ] M. Qi,[48,δ] X. Qian,[8,δ,π] N. Raper,[16,δ] J. Ren,[32,δ] C. Morales Reveco,[20,δ] R. Rosero,[8,δ,π] B. Roskovec,[20,δ] X. C. Ruan,[32,δ] M. Searles,[11,π] H. Steiner,[40,28,δ] J. L. Sun,[49,δ] P. T. Surukuchi,[4,π] T. Tmej,[24,δ] K. Treskov,[26,δ] W.-H. Tse,[18,δ] C. E. Tull,[28,δ] M. A. Tyra,[6,π] R. L. Varner,[21,π] D. Venegas-Vargas,[21,22,π] B. Viren,[8,δ] V. Vorobel,[24,δ] C. H. Wang,[13,δ] J. Wang,[16,δ] M. Wang,[33,δ] N. Y. Wang,[30,δ] R. G. Wang,[12,δ] W. Wang,[16,46,δ] W. Wang,[48,δ] X. Wang,[50,δ] Y. Wang,[48,δ] Y. F. Wang,[12,δ] Z. Wang,[12,δ] Z. Wang,[14,δ] Z. M. Wang,[12,δ] P. B. Weatherly,[25,π] H. Y. Wei,[8,δ] L. H. Wei,[12,δ] L. J. Wen,[12,δ] K. Whisnant,[51,δ] C. White,[2,δ,π] J. Wilhelmi,[4,π] H. L. H. Wong,[40,28,δ] A. Woolverton,[47,π] E. Worcester,[8,δ] D. R. Wu,[12,δ] F. L. Wu,[48,δ] Q. Wu,[33,δ] W. J. Wu,[12,δ] D. M. Xia,[52,δ] Z. Q. Xie,[12,δ] Z. Z. Xing,[12,δ] H. K. Xu,[12,δ] J. L. Xu,[12,δ] T. Xu,[14,δ] T. Xue,[14,δ] C. G. Yang,[12,δ] L. Yang,[39,δ] Y. Z. Yang,[14,δ] H. F. Yao,[12,δ] M. Ye,[12,δ] M. Yeh,[8,δ,π] B. L. Young,[51,δ] H. Z. Yu,[16,δ] Z. Y. Yu,[12,δ] B. B. Yue,[16,δ] V. Zavadskyi,[26,δ] S. Zeng,[12,δ] Y. Zeng,[16,δ] L. Zhan,[12,δ] C. Zhang,[8,δ,π] F. Y. Zhang,[43,δ] H. H. Zhang,[16,δ] J. W. Zhang,[12,δ] Q. M. Zhang,[31,δ] S. Q. Zhang,[16,δ] X. Zhang,[10,π] X. T. Zhang,[12,δ] Y. M. Zhang,[16,δ] Y. X. Zhang,[49,δ] Y. Y. Zhang,[43,δ] Z. J. Zhang,[39,δ] Z. P. Zhang,[23,δ] Z. Y. Zhang,[12,δ] J. Zhao,[12,δ] R. Z. Zhao,[12,δ] L. Zhou,[12,δ] H. L. Zhuang,[12,δ] and J. H. Zou[12,δ]

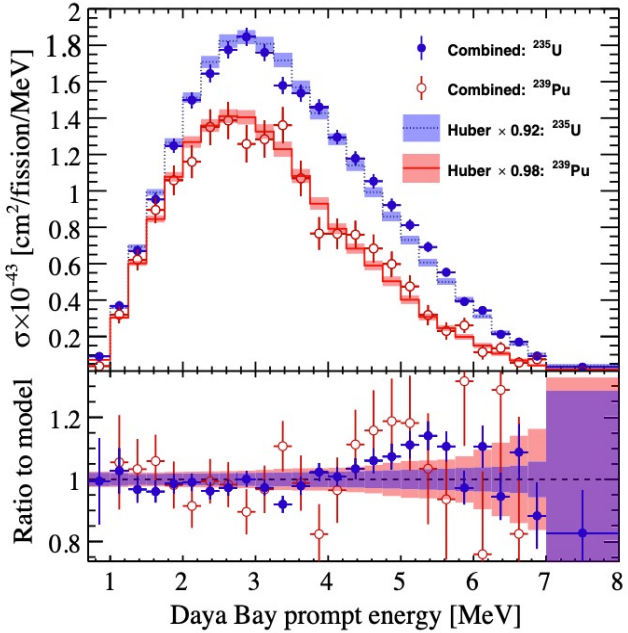
(Daya Bay Collaboration)[δ]
(PROSPECT Collaboration)[π]

**PROSPECT + STEREO**




- Improved $^{235}$U reference
- Bump excess at 2.4$\sigma$

**PROSPECT + Daya Bay**




- 3% improvement to $^{235}$U relative shape uncertainty
- ~20% Reduced degeneracy between dominant $^{235}$U and $^{239}$Pu isotopes in evolution analysis

# PROSPECT-I Results and Highlights
## - Joint Spectrum Analyses

PHYSICAL REVIEW LETTERS **128,** 081802 (2022)

**Joint Measurement of the $^{235}$U Antineutrino Spectrum by PROSPECT and STEREO**

H. Almazán,[1,*,σ] M. Andriamirado,[2,π] A. B. Balantekin,[3,π] H. R. Band,[4,π] C. D. Bass,[5,π] D. E. Bergeron,[6,π] L. Bernard,[7,†,σ] A. Blanchet,[8,‡,σ] A. Bonhomme,[1,8,σ] N. S. Bowden,[9,π] C. D. Bryan,[10,π] C. Buck,[1,σ] T. Classen,[9,π] A. J. Conant,[10,π] G. Deichert,[10,π] P. del Amo Sanchez,[11,σ] A. Delgado,[12,13,π] M. V. Diwan,[14,π] M. J. Dolinski,[15,π] I. El Atmani,[8,§,σ] A. Erickson,[16,π] B. T. Foust,[4,π] J. K. Gaison,[4,π] A. Galindo-Uribarri,[12,13,π] C. E. Gilbert,[12,13,π] S. Hans,[14,π] A. B. Hansell,[17,π] K. M. Heeger,[4,π] B. Heffron,[12,13,π] D. E. Jaffe,[9,π] S. Jayakumar,[15,π] X. Ji,[14,π] D. C. Jones,[17,π] J. Koblanski,[18,π] O. Kyzylova,[15,π] L. Labit,[11,σ] J. Lamblin,[7,σ] C. E. Lane,[15,π] T. J. Langford,[4,π] J. LaRosa,[6,π] A. Letourneau,[8,σ] D. Lhuillier,[8,σ] M. Licciardi,[7,σ] M. Lindner,[1,σ] B. R. Littlejohn,[2,π] X. Lu,[12,13,π] J. Maricic,[18,π] T. Materna,[8,σ] M. P. Mendenhall,[9,π] A. M. Meyer,[18,π] R. Milincic,[18,π] P. E. Mueller,[12,π] H. P. Mumm,[6,π] J. Napolitano,[17,π] R. Neilson,[15,π] J. A. Nikkel,[4,π] S. Nour,[5,π] J. L. Palomino,[2,π] H. Pessard,[11,σ] D. A. Pushin,[19,π] X. Qian,[14,π] J.-S. Réal,[7,σ] J.-S. Ricol,[7,σ] C. Roca,[1,σ] R. Rogly,[8,σ] R. Rosero,[14,π] T. Salagnac,[7,‖,σ] V. Savu,[8,σ] S. Schoppmann,[1,¶,σ] M. Searles,[10,π] V. Sergeyeva,[11,**,σ] T. Soldner,[20,σ] A. Stutz,[7,σ] P. T. Surukuchi,[4,π] M. A. Tyra,[6,π] R. L. Varner,[12,π] D. Venegas-Vargas,[12,13,π] M. Vialat,[20,σ] P. B. Weatherly,[15,π] C. White,[2,π] J. Wilhelmi,[4,π] A. Woolverton,[19,π] M. Yeh,[14,π] C. Zhang,[14,π] and X. Zhang[9,π]

(PROSPECT Collaboration)[π,††]
(STEREO Collaboration)[σ,‡‡]

PHYSICAL REVIEW LETTERS **128,** 081801 (2022)

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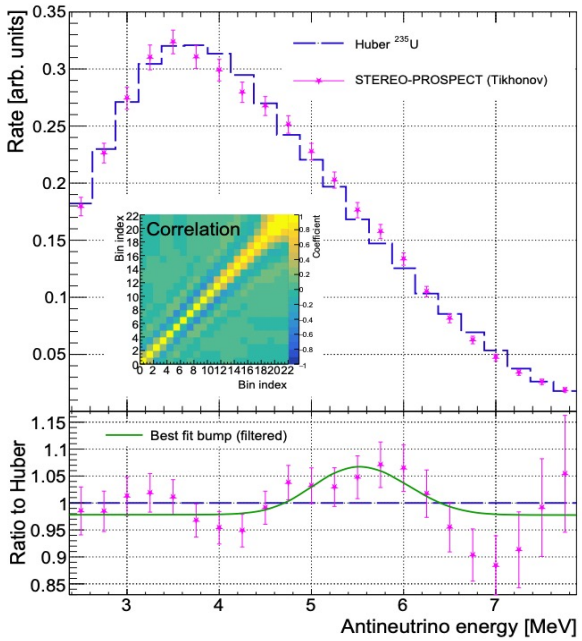
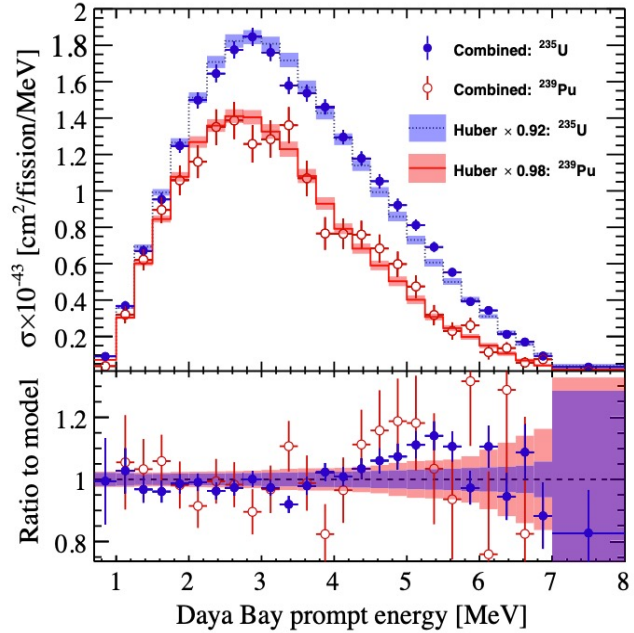
(Daya Bay Collaboration)[δ]
(PROSPECT Collaboration)[π]

**PROSPECT + STEREO**

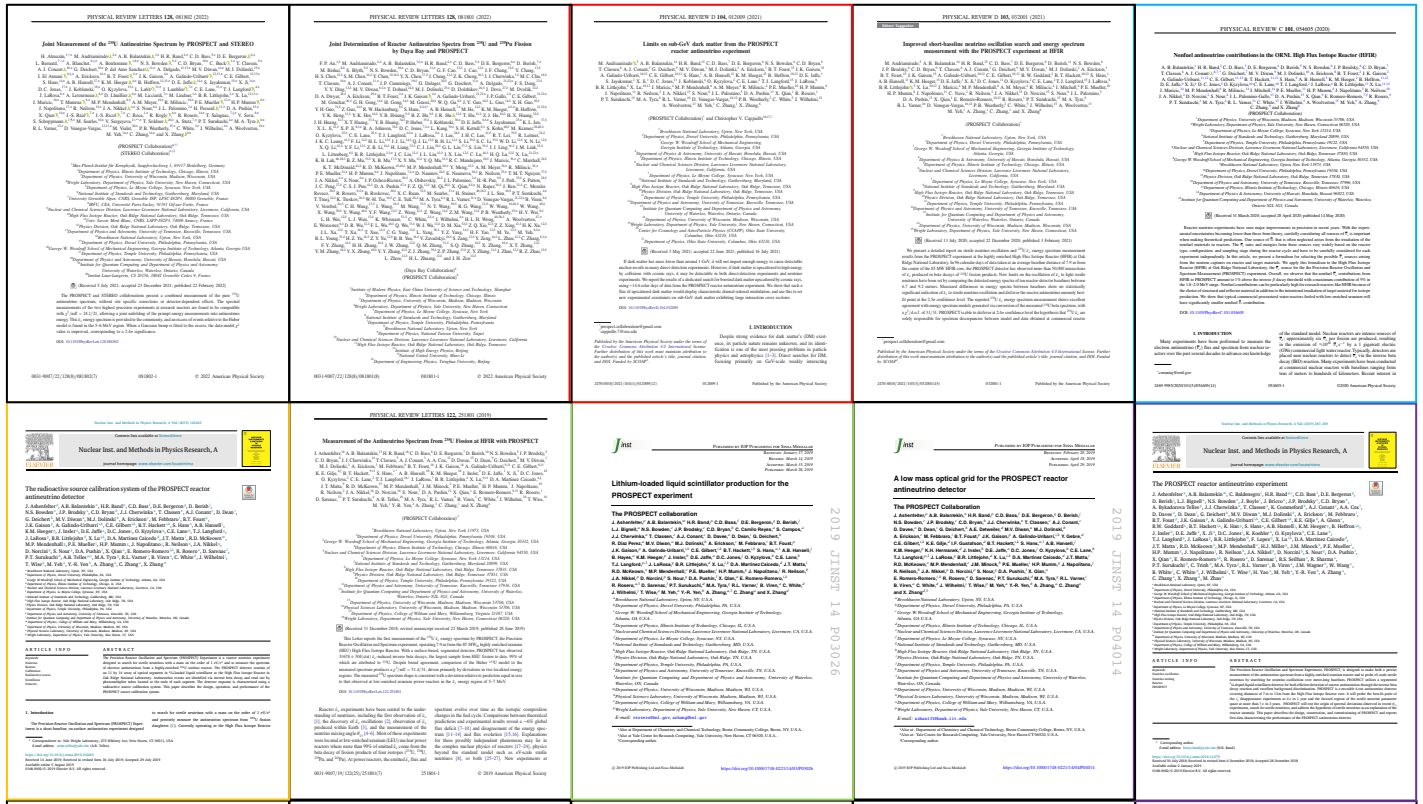



**PROSPECT + Daya Bay**




- **Stronger confirmation of excess between 4-6 MeV area**
- **Successful combination of results between HEU/HEU and HEU/LEU experiments**

# PROSPECT-I Results and Highlights:
# - Publications




Additional results include:

- **Search for Boosted Dark Matter**
  - PhysRevD 104 (2021) 012009
- **Non-fuel reactor contributions**
  - PhysRevC 101 (2020) 054605
- **Liquid Scintillator production and characterization**
  - JINST 14 (2019) P03026
- **Calibration Method**
  - NIMA 944 ( 2019) 162465
- **Instrumentation**
  - NIMA 922 (2018) 287

# PROSPECT-I Results and Highlights
## - Professional Training

**1. Ben Foust**

**2. Jeremy Gaison**

**3. Adam Hansell**

**3. Olga Kyzylova**

**5. Xianyi Zhang**

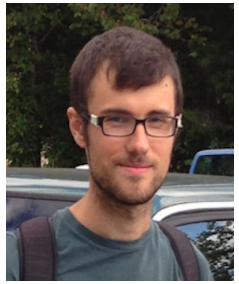
**6. Danielle Norcini**

**7. Andrew Conant**

**8. Danielle Berish**

**9. Pranava Teja Surukuchi**

**10. Blaine Heffron**



**11. Brennan Hackett**

- PROSPECT has served as a fantastic professional development and training program for young scientists.
  - 9 Ph.D. Theses
  - 2 M.S. Theses
  - Multiple Postdocs and undergraduates as well

1. **Precision Measurement of the U-235 Antineutrino Spectrum with PROSPECT and STEREO,** Ph.D. Thesis, Yale, 2022.
2. **Measurement of the Reactor Antineutrino Spectrum of U-235 by PROSPECT and Daya Bay,** Ph.D. Thesis, Yale, 2021.
3. **Characterization of Time-Varying Backgrounds in the PROSPECT Experiment,** Ph.D. Thesis, Drexel, 2021.
4. **A New Measurement of the Neutron Multiplicity Emitted in 252Cf Spontaneous Fission, Temple,** Ph.D. Thesis, Temple, 2020.
5. **Energy Scale Study for PROSPECT'S Measurement of the Antineutrino Spectrum of 235U,** Ph.D. Thesis, IIT, 2019.
6. **First Search for eV-Scale Sterile Neutrinos and Precision Measurement of the 235U Antineutrino Spectrum with the PROSPECT Experiment,** Ph.D. Thesis, Yale, 2019.
7. **Antineutrino Spectrum Characterization of the High Flux Isotope Reactor Using Neutronic Simulations,** Ph.D. Thesis, Georgia Tech, 2019.
8. **Short-Wavelength Reactor Neutrino Oscillations with the PROSPECT Experiment,** Ph.D. Thesis, Temple, 2019.
9. **Search for Sterile Neutrino Oscillations with The Prospect Experiment,** Ph.D. Thesis, IIT, 2019.
10. **Characterization of Reactor Background Radiation at HFIR for the PROSPECT Experiment,** M.S. Thesis, UTK, 2017.
11. **DANG and the Background Characterization of HFIR for PROSPECT, Brennan Hackett,** M.S. Thesis, Surrey, 2017.

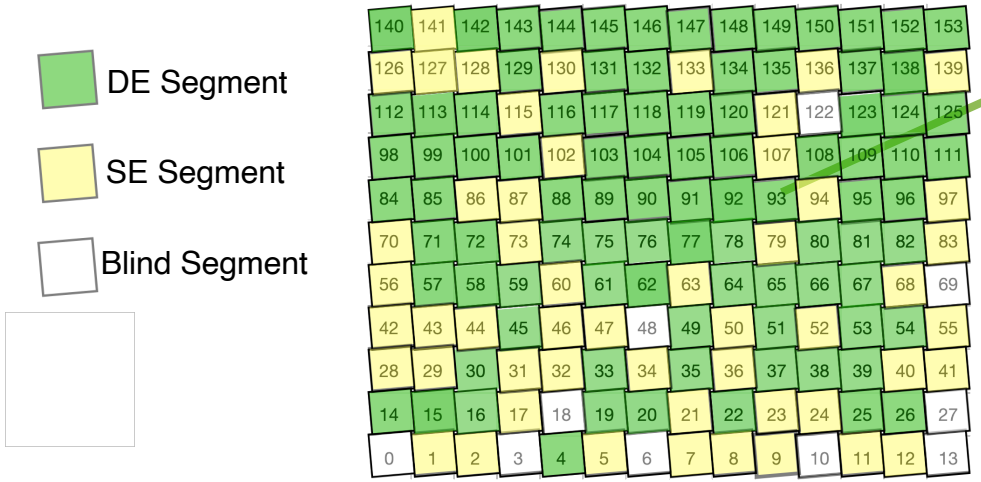
# 2. New Analysis Methods

- Motivation for a final P-I analysis
- Data Splitting
- Single Ended Event Reconstruction

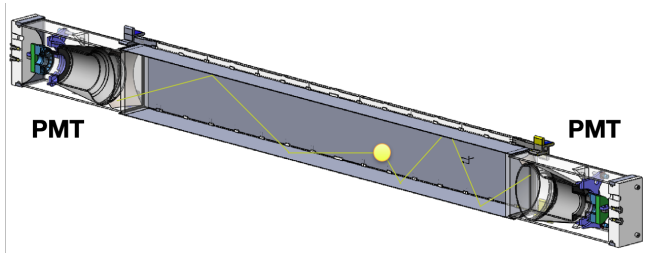
# Motivation for a final PROSPECT-I Analysis

- Previous results were impacted by the periodic loss of photo-multiplier tube bases throughout data collection.

**Detector configuration used for PRD analysis**




154 segments with two PMTs




Some segments coupled to one PMT or both switched off due to scintillator leakage into PMT housing.

- In order to improve upon previous results, two new data recovery approaches have been proposed:

Data Splitting (DS)
&
Single Ended Event Reconstruction (SEER)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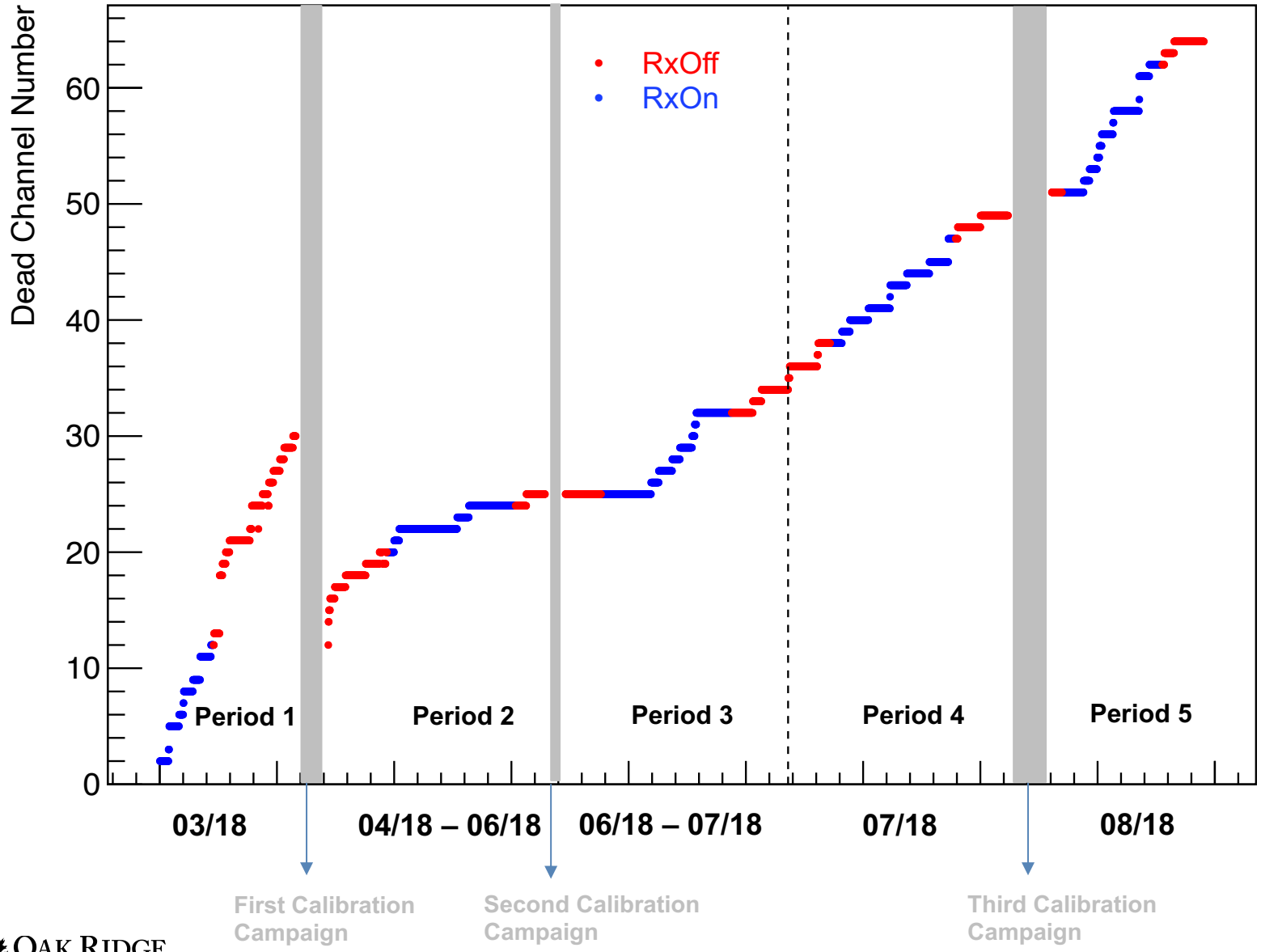
# **First Approach:** Data Splitting (DS)




## Goals

- Split PROSPECT-I data into distinct periods in order to recover statistics.
- Maximize number of live segments in each period

## Splitting Criteria

- Each period should start immediately after a new calibration campaign
- Each period must contain one full RxOn cycle
- All periods should have RxOff data before and after each corresponding RxOn cycle
  - Period 1 is an exception since there is no prior RxOff data available.
- Keep ratio of RxOff/RxOn data between 50%-70%.
  - Since there is no calibration campaign between periods 3 and 4, we used the ratio of RxOff/RxOn files to define these two (70%).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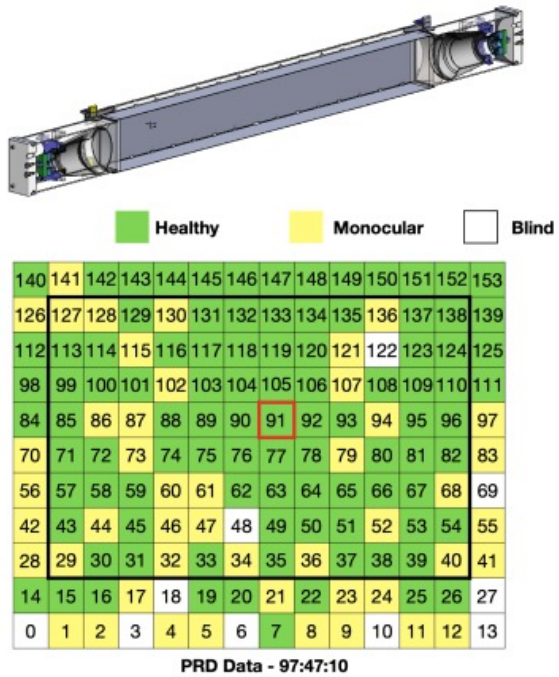
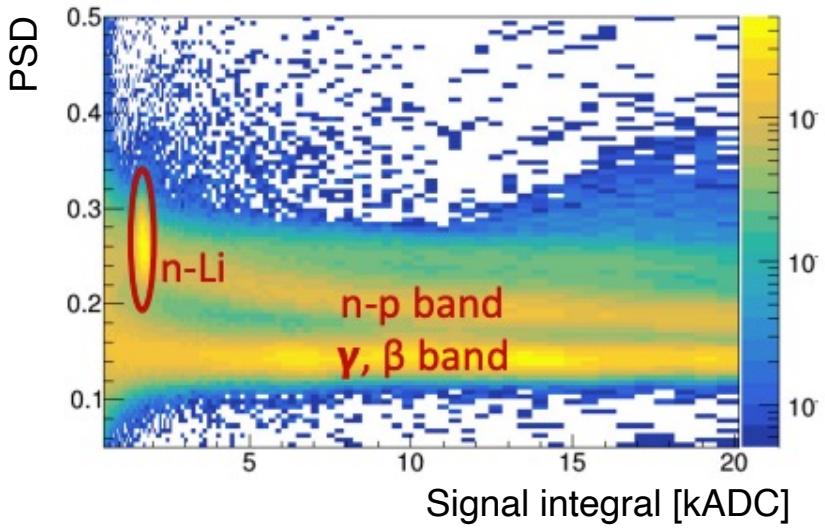
# **Second Approach:** Single Ended Event Reconstruction (SEER)

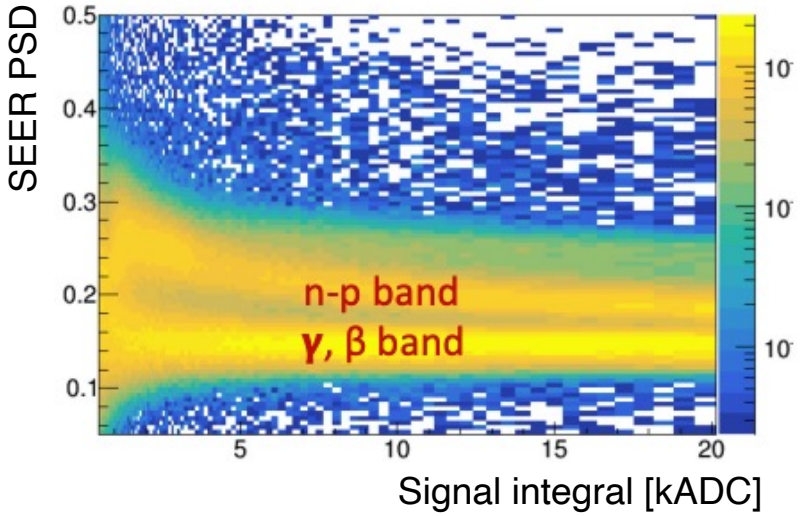
- The implementation of SEER into the existing analysis presents a great opportunity to improve our current results (statistics and S:B).
- Lacks energy and position reconstruction capabilities
- Provides a good handle on particle identification (great background suppression)




**DEER PSD Distribution**




**SEER PSD Distribution**





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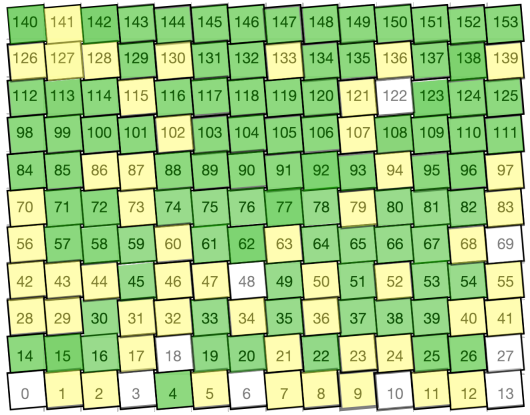
# Detector Configuration for Each Period

**Detector Configuration Used for Previous Analysis**

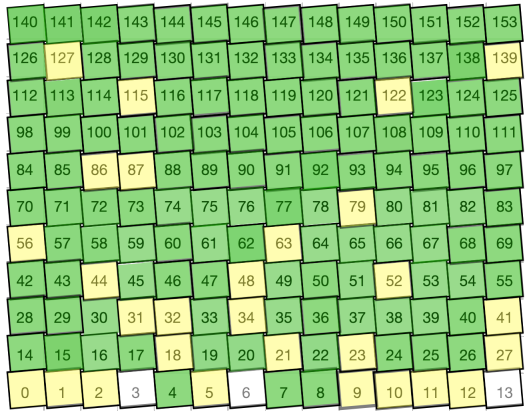


- Previous analysis did not make use of single ended segments.
- This new method takes full advantage of all the data collected by the PROSPECT detector

**Period 1**

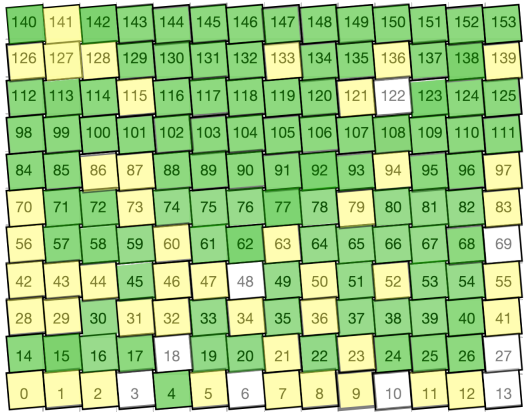
**Period 2**

**Period 3**



**Period 4**

**Period 5**



DE Segment

SE Segment

Blind Segment



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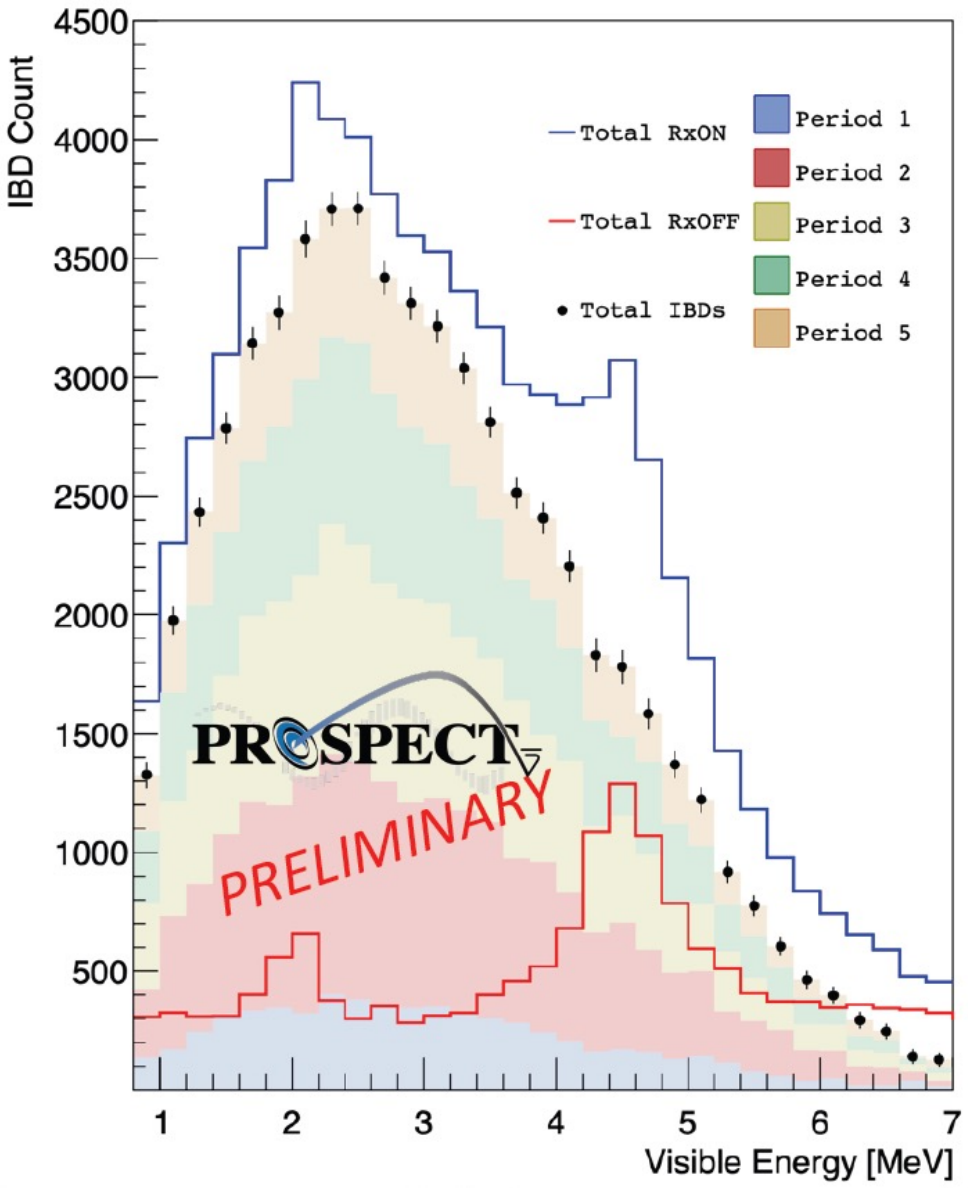
# Combined DS+SEER Analysis Results and Summary

- First implementation of new DS+SEER optimized provided the following improvements:
  - IBD counts ~**(x1.2)**
  - IBD effective counts ~**(x2)**
  - Signal to cosmogenic background (S/CB) ~**(x2.8)**
  - Signal to accidental background (S/AB) ~**(x2.4)**
- **This new analysis is expected to have a big impact on both spectrum and sterile neutrino oscillation results!**

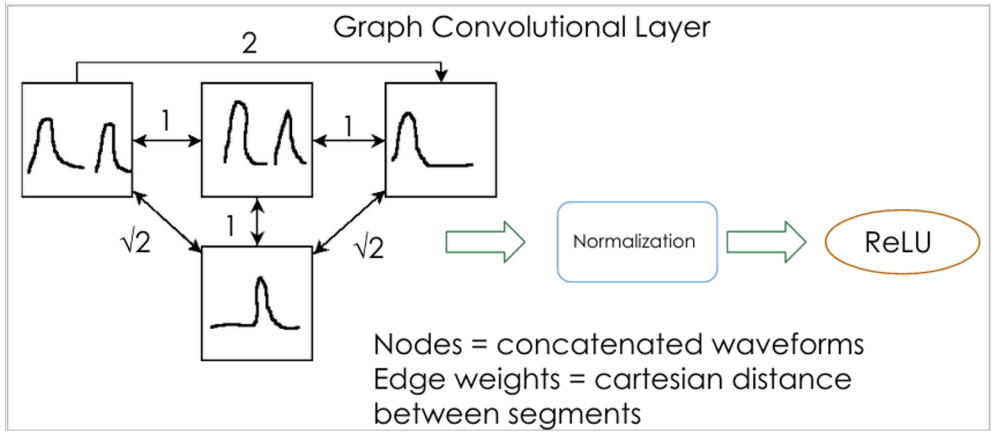


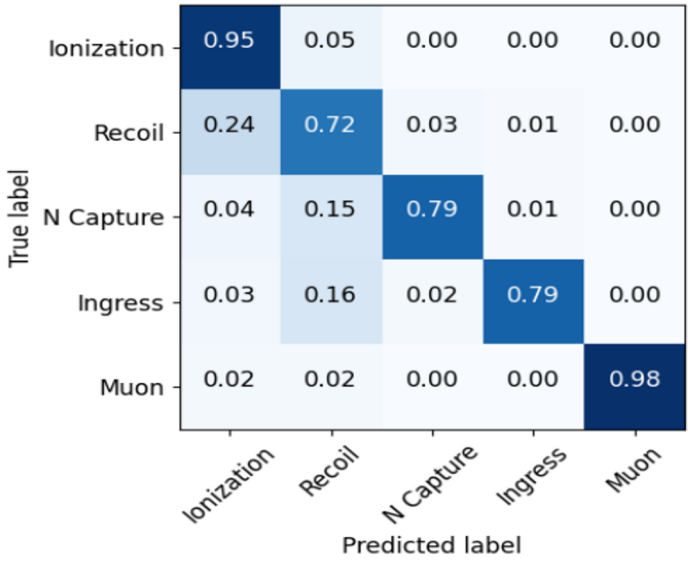
# 3. New Opportunities with the PROSPECT-I Data

- Machine Learning Analysis
- Absolute Flux Measurement
- Multi-period Oscillation analysis
- Multi-period Spectrum analysis

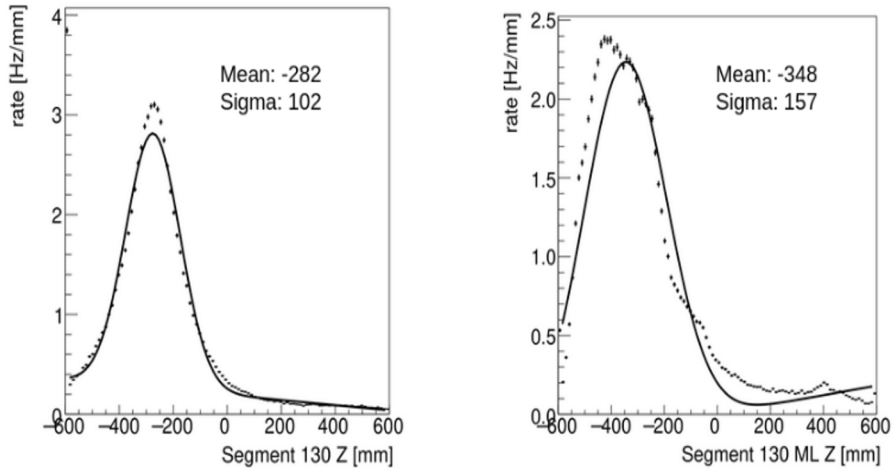
# Machine Learning Efforts

- Neural networks have been used to improve single ended event reconstruction
- Truth table which shows the classifier performance, with most difficulty arising from misidentifying recoil events as ionizations
- Overall, the SE Z reconstruction error is on the order of 60 mm which is roughly three times larger than the dual ended error.




Classifier for event selection using graph neural networks




SE Z prediction model using sparse convolutional neural networks

- Left: dual ended calibration source position reconstruction (fit + data)
- Right: ML SE reconstruction (fit + data)

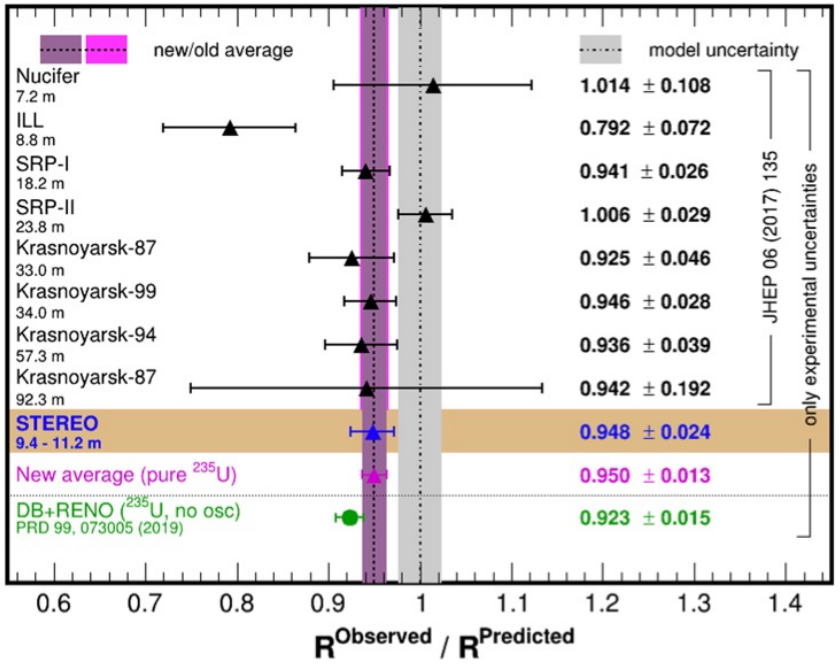
# Motivation for an Absolute Flux Analysis

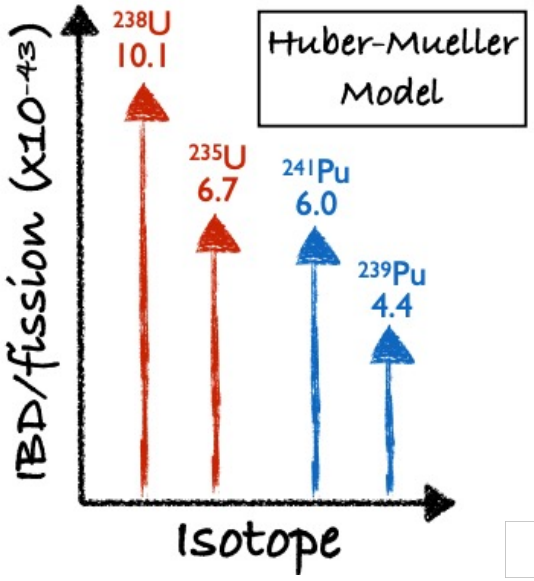
*Phys. Rev. Lett. 125, 201801 (2020)*

- Previous results for measured and predicted do not agree: Observed flux deficit
  - Are reactor neutrinos oscillating to sterile neutrinos?
  - Are the flux predictions overestimated?

- A P-I absolute flux measurement with a target precision of about 2% would be dominated by systematic uncertainties.
  - Reactor power
  - Proton Density
  - IBD detection efficiency

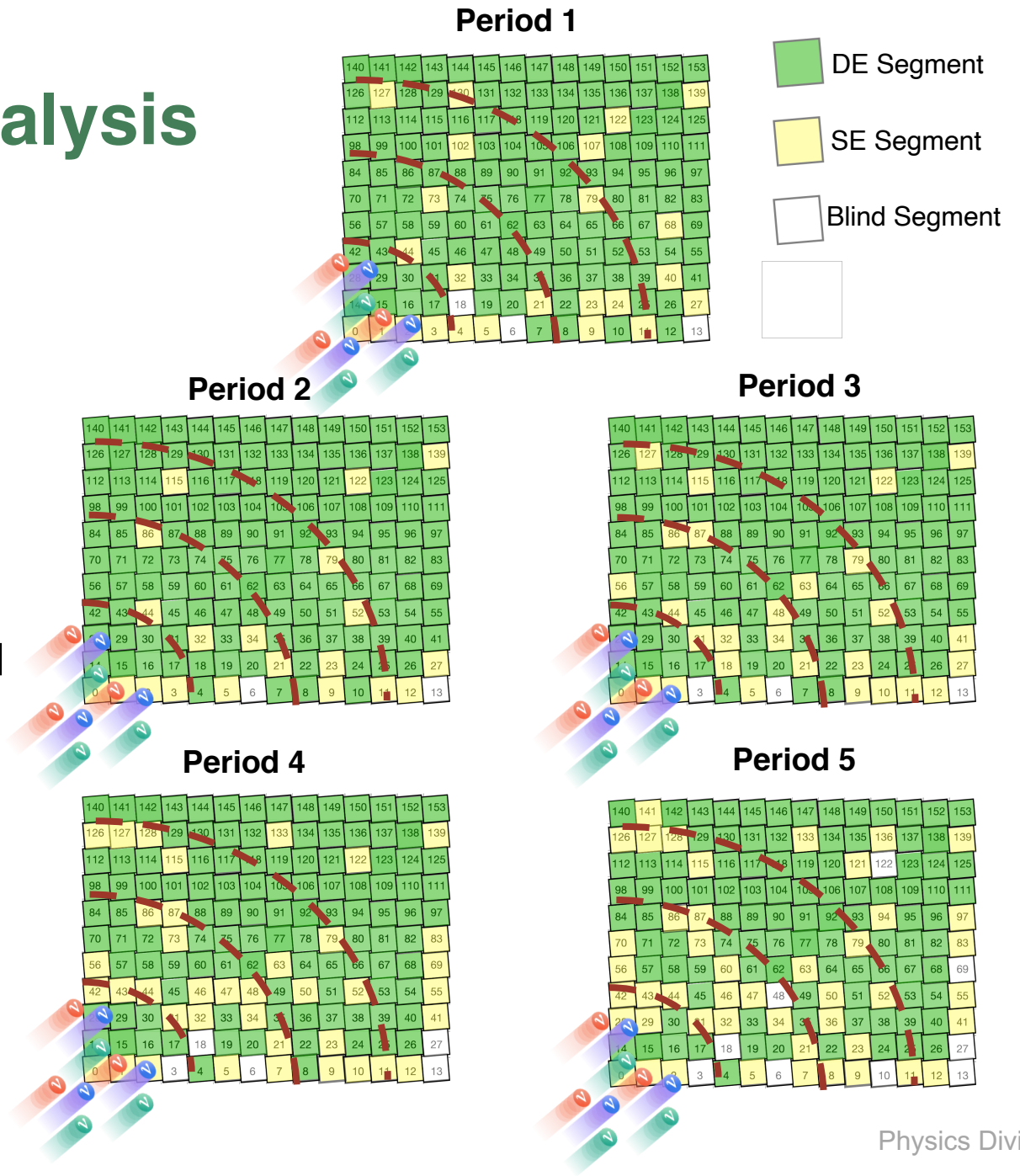
- Applications:
  - Updated and more precise measurement relative to flux predictions
  - Reactor antineutrino anomaly and sterile neutrino oscillation
  - Reactor power monitoring for verification and safeguards



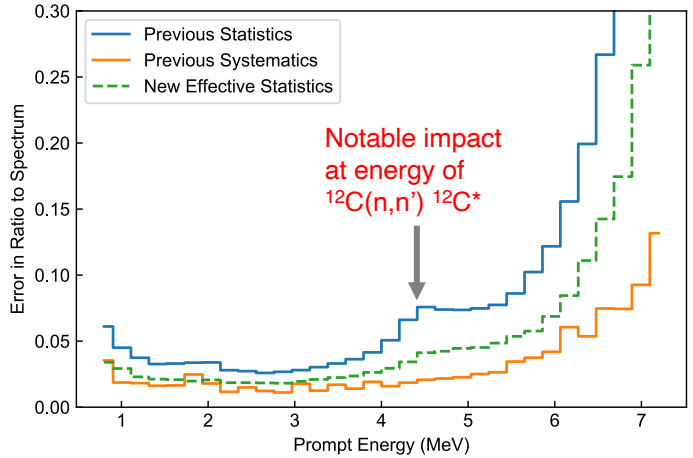
# Multi-Period Oscillation Analysis

- Previous oscillation measurement was statistics-limited. Increase in effective statistics (x2) will improve current sensitivity
- Multi-period analysis allows for the use of additional baseline bins which result in a sensitivity gain.
- A new framework capable of producing a joint oscillation analysis for each data period is being developed
  - Future joint-oscillation analysis with other reactor experiments

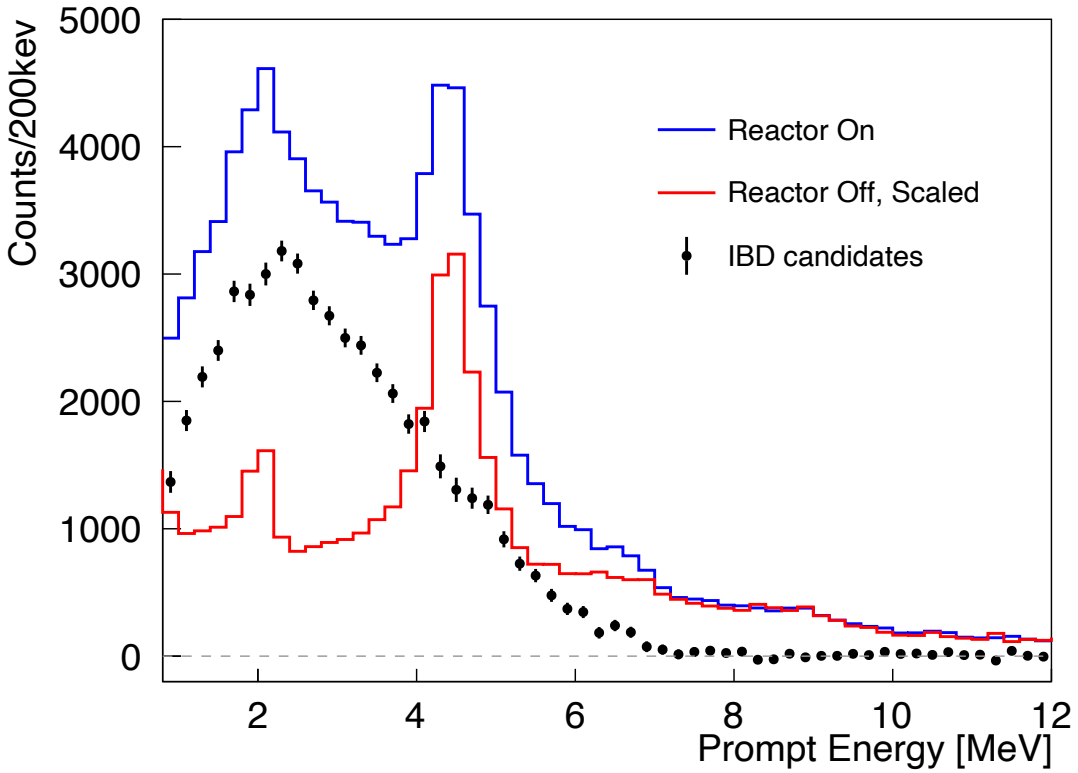


# Multi-Period Spectrum Analysis

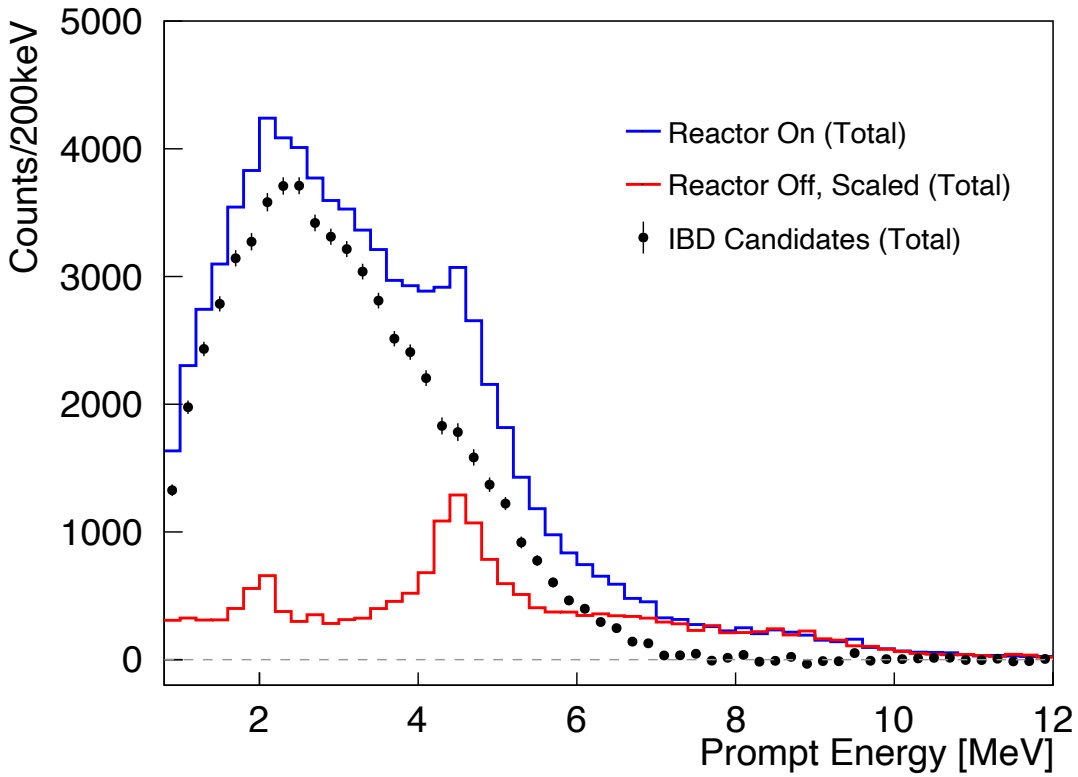
Great background reduction provided by new analysis




## Previous PROSPECT Analysis

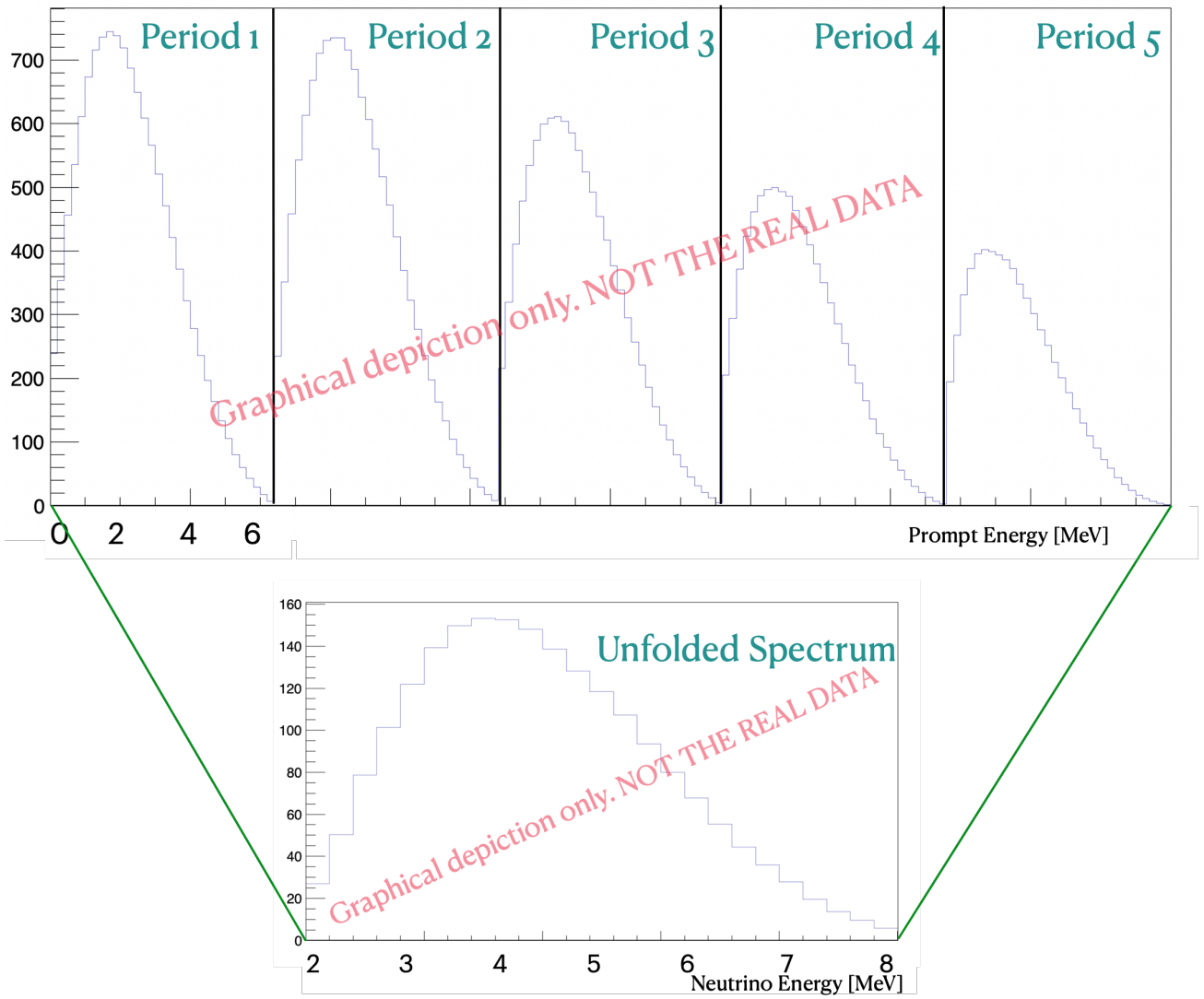



## New DS+SEER Multi-Period Analysis



# Multi-Period Spectrum Analysis

- The implementation of a period-by-period analysis allows for the treatment of each period as an independent experiment.
- Following the work done during the joint spectrum analysis, a new unfolding framework has been developed to jointly unfold the prompt spectrum from each period into one final antineutrino energy spectrum
- This new framework paves the way for multi-experiment and multi-reactor experiments



# Summary and Conclusions

- PROSPECT-I data still presents a fantastic opportunity to obtain world-class physics results.
- Increase in effective statistics caused by new DS+SEER analysis will have a significant impact on new efforts such as spectrum and oscillation measurements
- Multi-period analysis motivated the development of frameworks that will facilitate joint studies between different reactor-based experiments

Learn about PROSPECT-II
on the next talk by Felicia Sutanto

prospect.yale.edu