Latest Reactor Antineutrino Spectrum and Boosted Dark Matter Results from PROSPECT

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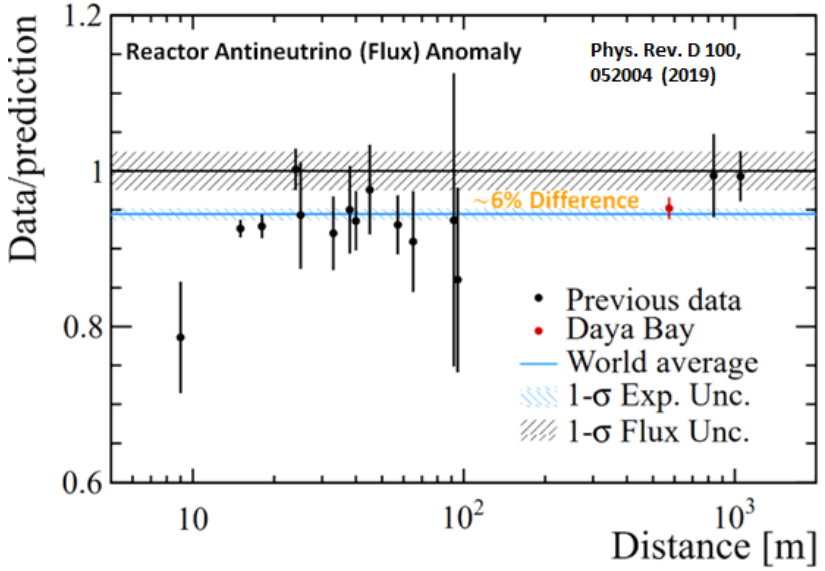
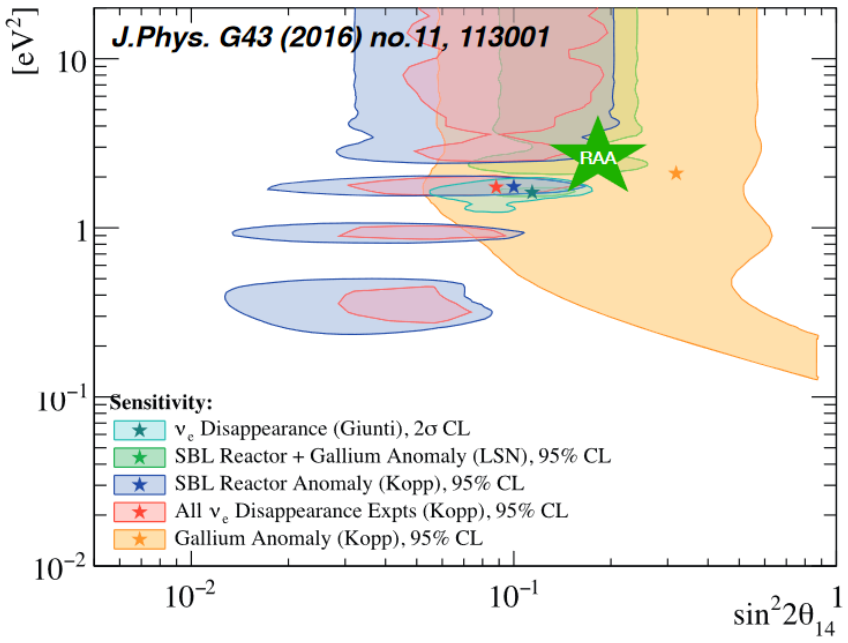
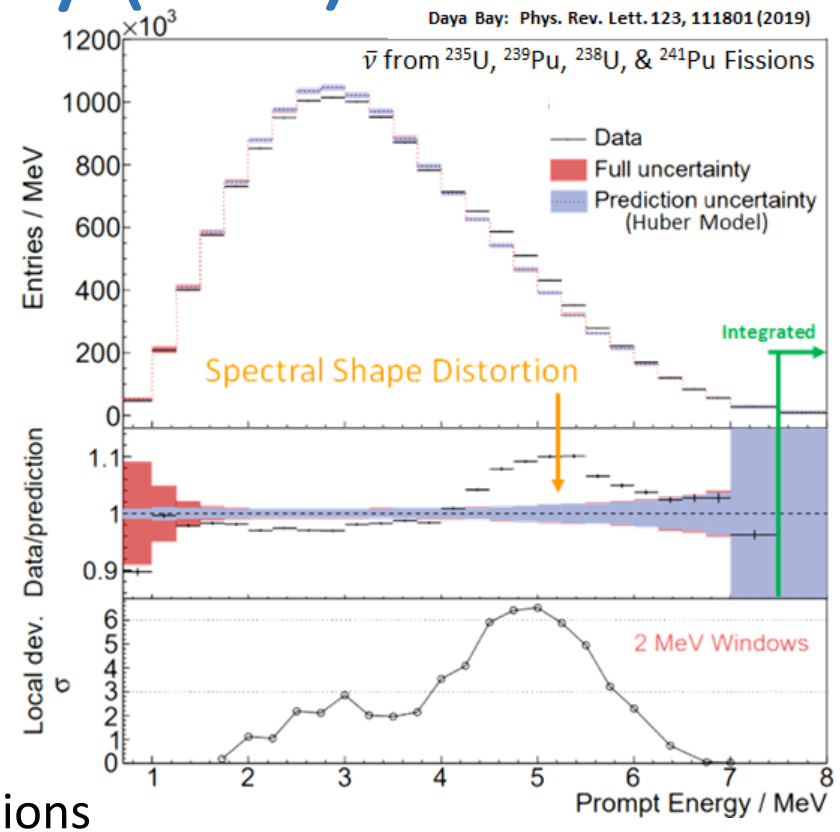
APS-DPF July Meeting 2021
Neutrinos/363

Drexel UNIVERSITY

Motivation: Reactor Antineutrino Anomaly (RAA)







- RAA: World average flux observations 6% less than theoretical predictions
  - Prediction models based on Huber+Mueller & 3-flavor neutrino oscillations
- Discrepancy may be coming from
  - Flawed/incomplete reactor modeling and nuclear data
  - Reactor $\bar{\nu}_e$ oscillation to a sterile neutrino (ν_s) over short baseline of 10-ish meters ($\Delta m^2 \approx 1$ eV scale).
- Precision Reactor Oscillation & SPECTrum Measurement (PROSPECT) Experiment:
  - Reactor-model independent search for eV-scale ν_s via $\bar{\nu}_e$-disappearance
  - Precision measurement of ^{235}U $\bar{\nu}_e$ spectrum (high statistics)

June 2021 Collaboration Meeting, 43 Collaborators

Latest Prospect Results

PROSPECT-II Physics Opportunities
arXiv:2107.03934

Joint Measurement of the ^{235}U Antineutrino Spectrum by Prospect and Stereo
arxiv:2107.03371

Joint Determination of Reactor Antineutrino Spectra from ^{235}U and ^{239}Pu Fission by Daya Bay and PROSPECT
arXiv:2106.12251

Limits on Sub-GeV Dark Matter from the PROSPECT Reactor Antineutrino Experiment
arXiv:2104.11219

Improved Short-Baseline Neutrino Oscillation Search and Energy Spectrum Measurement with the PROSPECT Experiment at HFIR
PhysRevD 103 (2021) 032001

Nonfuel Antineutrino Contributions in the High Flux Isotope Reactor
PhysRevC 101 (2020) 054605

The Radioactive Source Calibration System of the PROSPECT Reactor Antineutrino Detector
NIMA 944 (2019) 162465

Measurement of the Antineutrino Spectrum from ^{235}U Fission at HFIR with PROSPECT
PhysRevLett 122 (2019) 251801

A Low Mass Optical Grid for the PROSPECT Reactor Antineutrino Detector
JINST 14 (2019) P04014

Lithium-loaded Liquid Scintillator Production for the PROSPECT Experiment
JINST 14 (2019) P03026

PRD Editors' Suggestion

Editors' Suggestion | Open Access

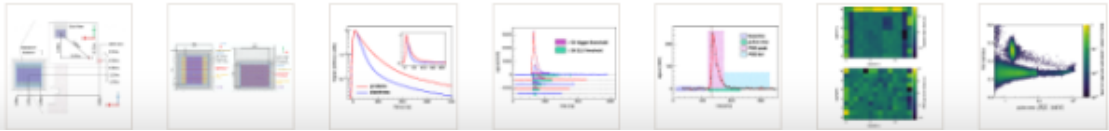
Improved short-baseline neutrino oscillation search and energy spectrum measurement with the PROSPECT experiment at HFIR

M. Andriamirado *et al.* (PROSPECT Collaboration)
Phys. Rev. D **103**, 032001 – Published 3 February 2021

Article | References | Citing Articles (1) | Supplemental Material | PDF | HTML | Export Citation

ABSTRACT

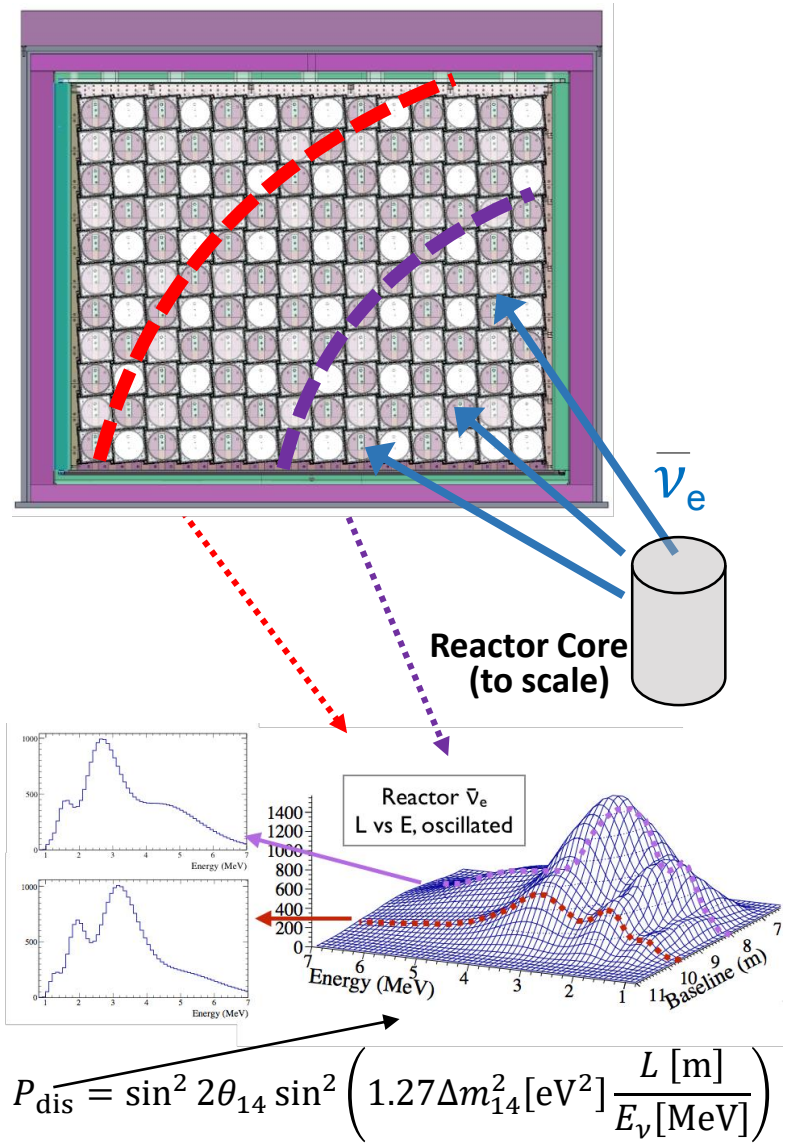
We present a detailed report on sterile neutrino oscillation and ^{235}U $\bar{\nu}_e$ energy spectrum measurement results from the PROSPECT experiment at the highly enriched High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory. In 96 calendar days of data taken at an average baseline distance 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 2.5σ 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 $\chi^2/\mathrm{d.o.f.}$ of $31/31$. PROSPECT is able to disfavor at 2.4σ confidence level the hypothesis that ^{235}U $\bar{\nu}_e$ are solely responsible for spectrum discrepancies between model and data obtained at commercial reactor cores. A data-model deviation in PROSPECT similar to that observed by commercial core experiments is preferred with respect to no observed deviation, at a 2.2σ confidence level.



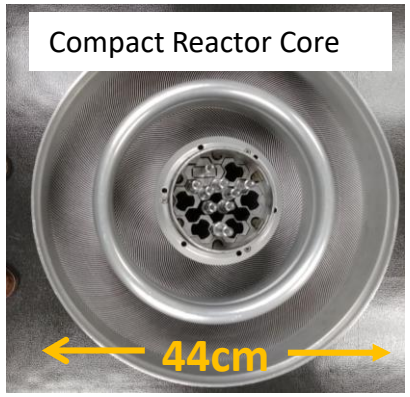
Short Baseline Measurements at Enriched ^{235}U Reactor

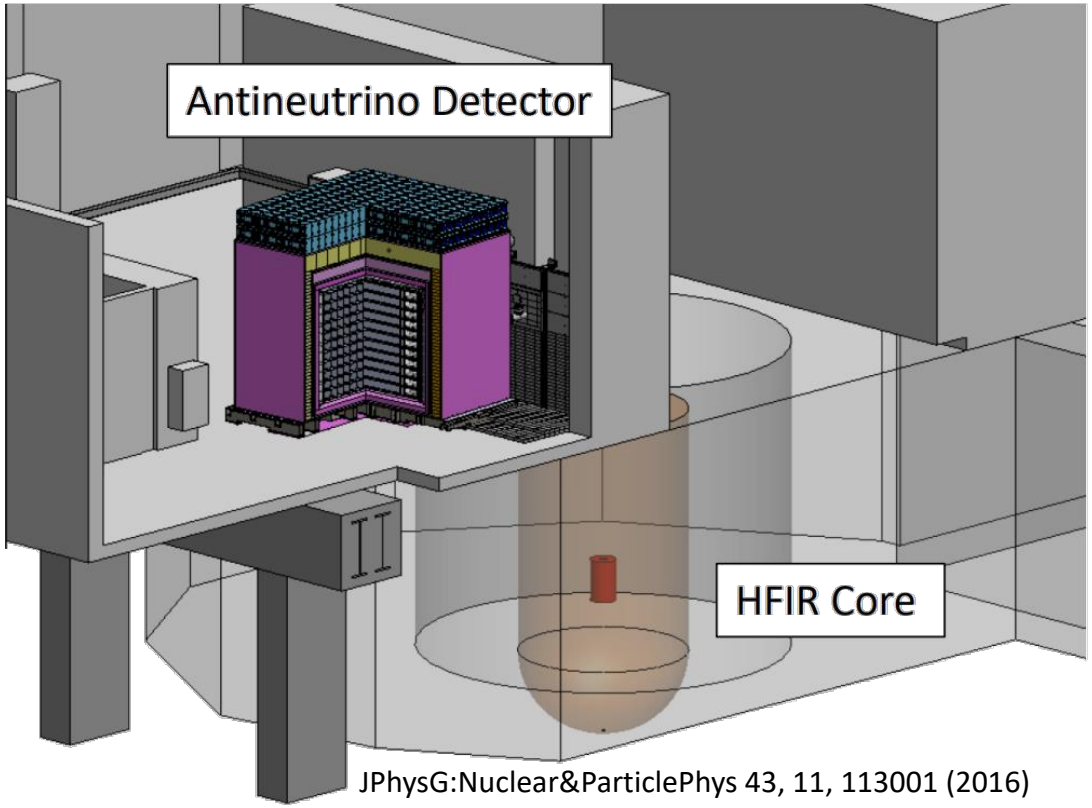
Place segmented detector close to a compact reactor core

- Compact Highly Enriched ^{235}U (HEU) fuel → $\bar{\nu}_e$ emitted by ^{235}U fissions
  - Spectral measurement
- Core compactness so oscillations do not wash out
- Need several meters of detector volume close to core w/ position reconstruction for multiple baselines (L)
- Remove reactor-model dependence on oscillations: Relative spectral-shape distortions in identical detector segments at different L



PROSPECT at ORNL's HFIR





JPhysG:Nuclear&ParticlePhys 43, 11, 113001 (2016)

High Flux Isotope Reactor (HFIR) at Oak Ridge National Lab (ORNL)

- 85 MW Reactor w/ 24 day duty cycle
- HEU fuel in a compact cylinder core
  - h = 50.8 cm, d = 44 cm
- > 99% $\bar{\nu}_e$ emitted by ^{235}U fissions

Place detector near core

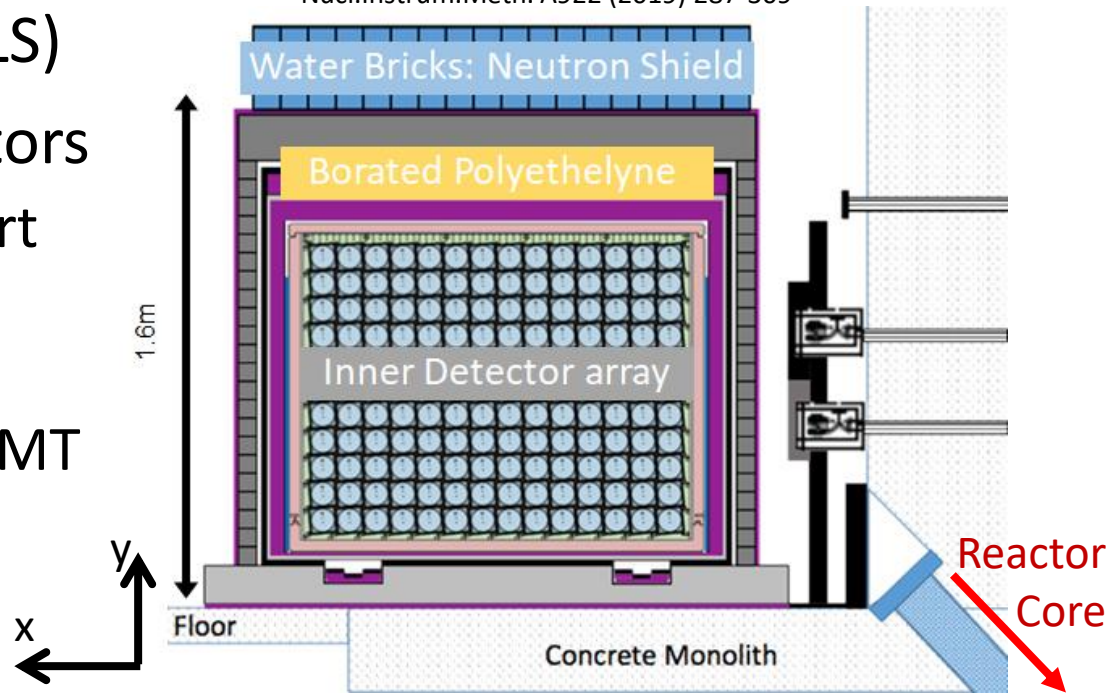
Challenges

- No overburden to shield from cosmic rays:
  - **~1 meter water equivalent (mwe)**
  - **Cosmogenic neutrons from atmosphere are primary correlated background**
- Reactor-induced accidental backgrounds

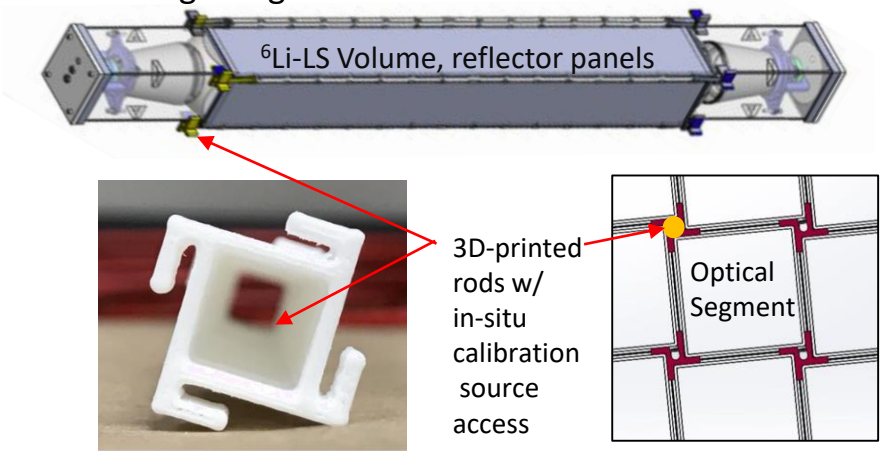
The PROSPECT Detector

- ~4 ton ^{6}Li-loaded liquid scintillator EJ-309 (^{6}Li-LS)
- Segments: optically segmented identical detectors
  - Thin reflector panels fixed by 3D-printed support rods
    - calibration source access between segments.
  - Z-position reconstruction from double-ended PMT readout
  - 14x11 array
    - (X,Y) position reconstruction & fiducialization
    - Enables baselines between 7 – 9 m
- Energy Resolution: ~4.5%-5% / $\sqrt{E[\mathrm{MeV}]}$
- Detection of reactor $\bar{\nu}_e$ in PROSPECT via Inverse Beta Decay interactions

Nucl.Instrum.Meth. A922 (2019) 287-309



Single Segment: 119 cm x 15 cm x 15 cm

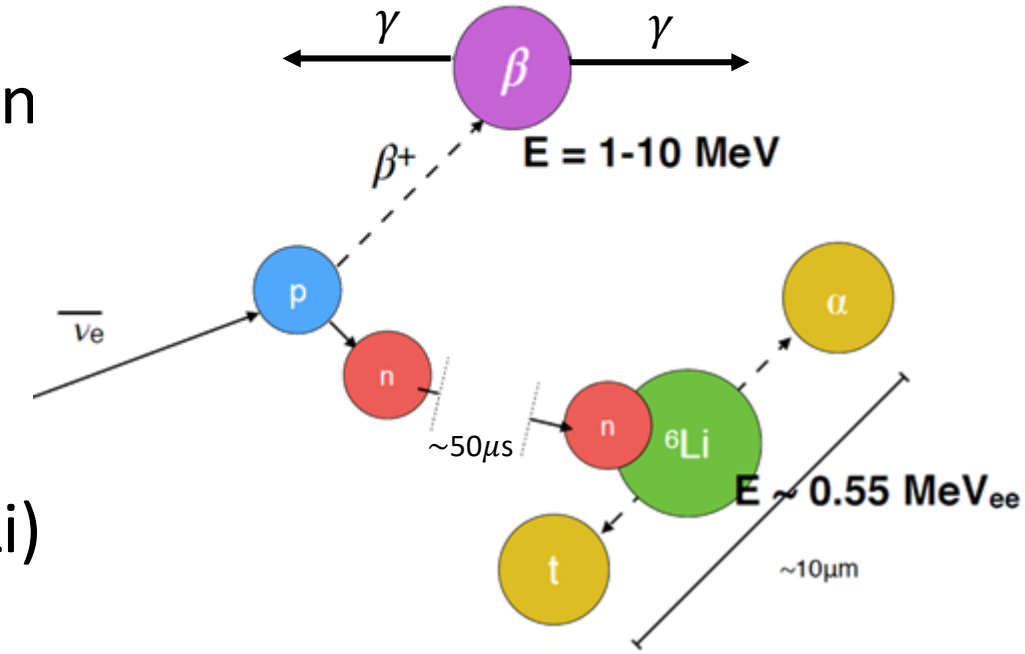


IBD interactions in PROSPECT

Coincidence signal from IBD interaction:

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

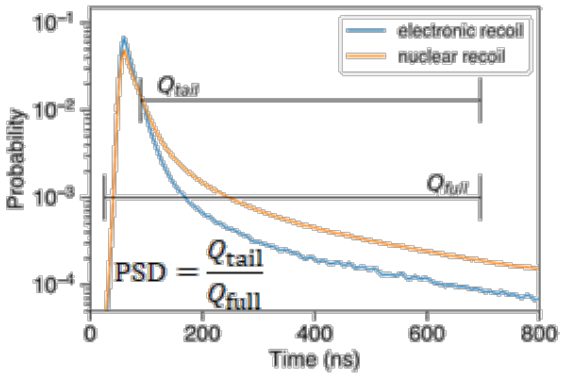
- Prompt signal: β^+ ionization & annihilation



- Delayed Signal: neutron capture on ^{6}Li (nLi)
  - E from subsequent decay localized to single segment
  - $\sim$50 μs delay between prompt and nLi
  - Tag nLi via PSD

Pulse Shape Discrimination (PSD)

- Prospect PSD $\equiv Q_{\text{tail}}/Q_{\text{full}}$
- PSD from ^{6}Li-LS works as particle ID
  - Energy dependence
  - γ-interactions, n-capture like nLi, & nuclear recoil
- PSD-correlations between prompt and delayed signals differ topologically per source
  - Coincidence Signal w/ PSD requirements enable strong background suppression
  - Necessary for removal of cosmogenic fast-neutron background, reactor-induced backgrounds.



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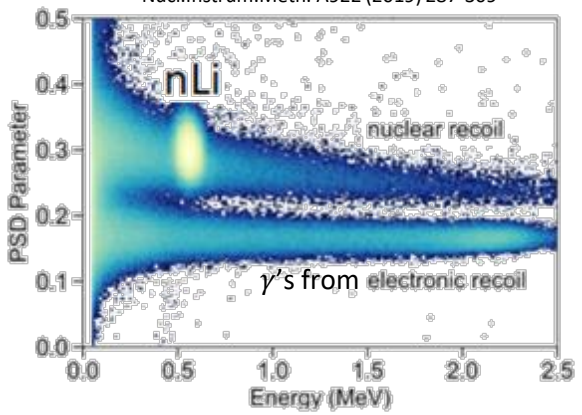
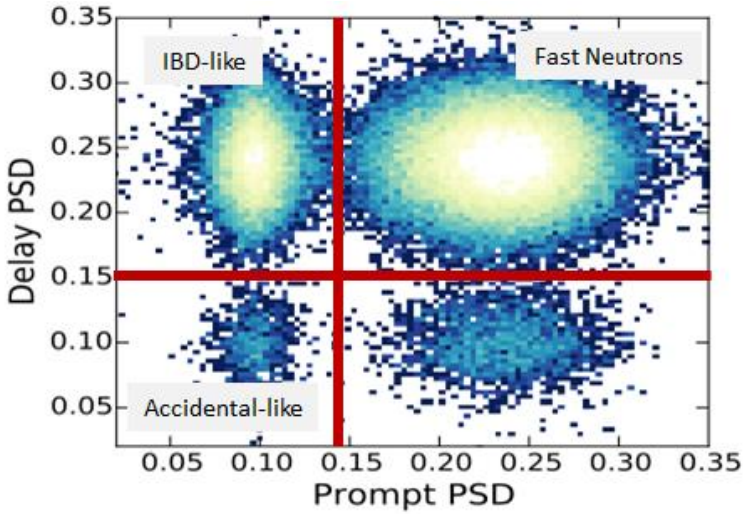
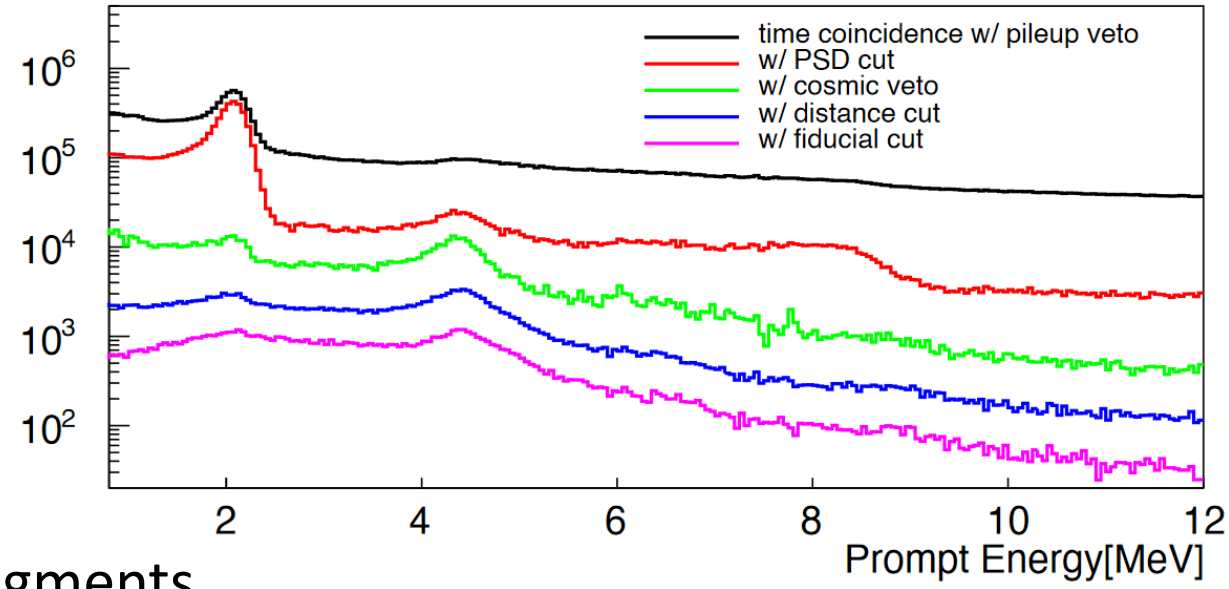
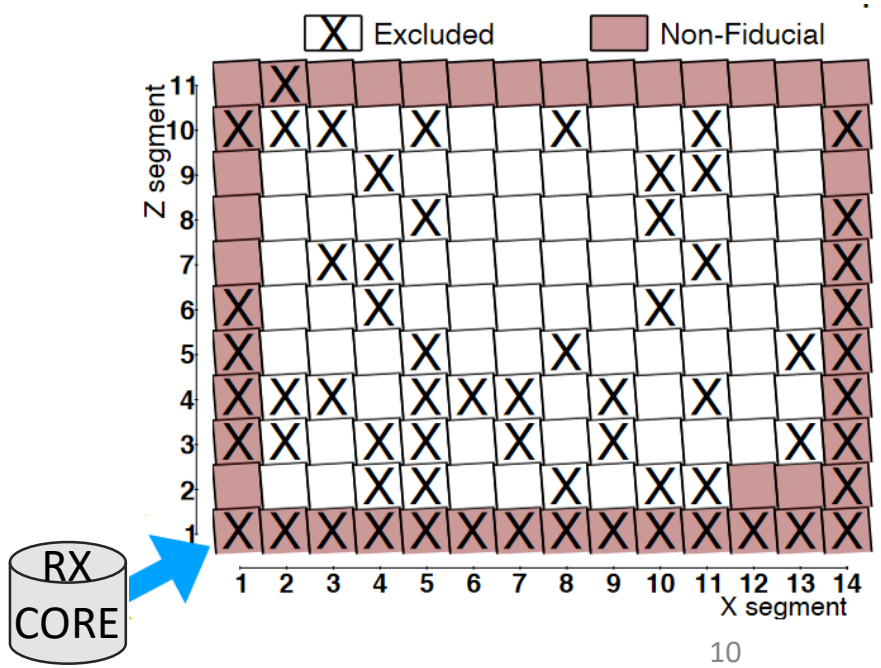




IBD selection

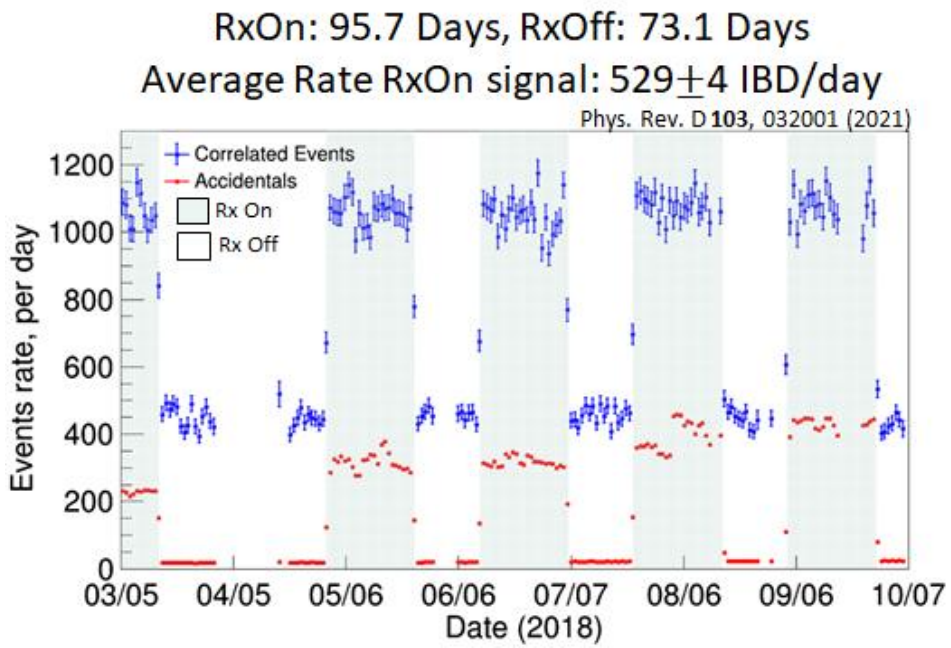
- 2σ PSD requirements for nLi & e^+
- E_{prompt} = 0.8 – 7.2 MeV
- E_{nLi} w/in 3σ of 0.526 MeV
- Spatial & temporal coincidence
  - $\Delta t \leq 120\ \mu s$ between prompt & delayed
  - Prompt-delayed event separated by $\Delta z \leq 140$ (100) mm in same (neighboring) segments
- Overburden < 1 mwe → cosmogenic backgrounds are a challenge
  - Reject n-like events coincident with cosmic μ
- Fiducialization of outer segment layers
  - Exclude candidates from 36 fiducial segments due to PMT current instabilities (X)
- 10^4 background reduction

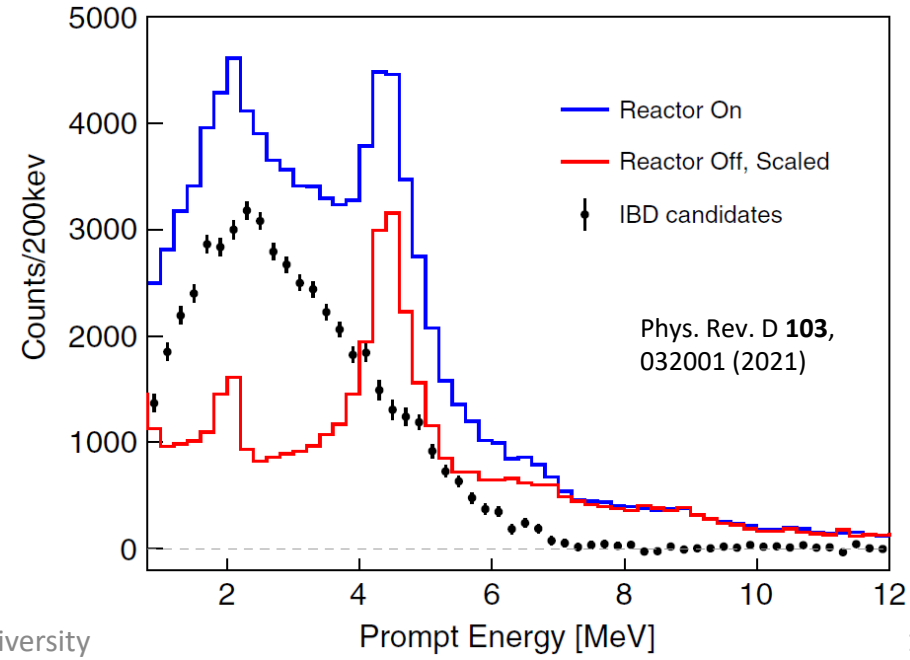




Prospect Data and IBD Signal

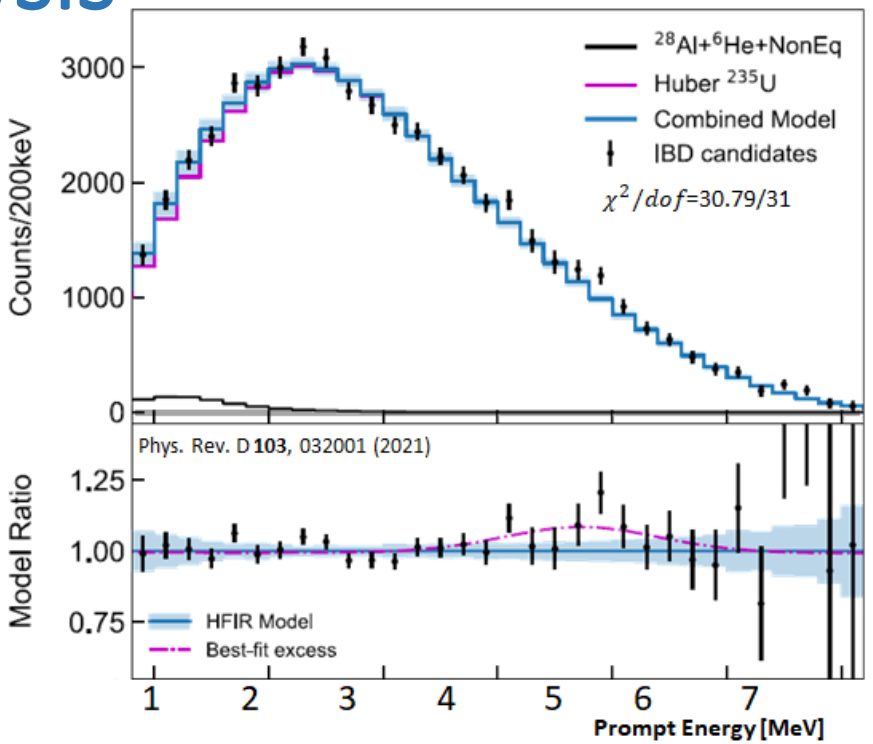
- Reactor (Rx) On/Off data periods
- Use HFIR's scheduled Rx-Off periods
  - High-precision measurement of IBD-like background rate, spectral shape
- S/B = 1.37 for cosmogenic backgrounds
- S/B = 1.78 for accidental coincidence
- Bottom: Prompt β^+ Spectra for ^{235}U Induced IBD-candidates
  - Final Rx IBD Prompt Candidates Spectrum (black)
    - Subtract: RxOn (Blue) – RxOff (red)

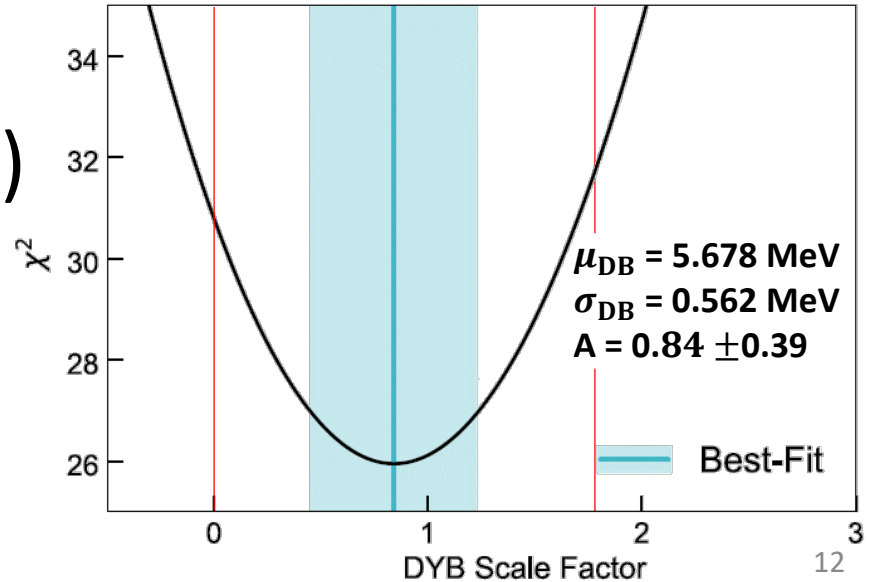




^{235}U $\bar{\nu}_e$ Spectral Measurement Analysis

- Spectral shape-only comparison using Gaussian amplitude (A) fit
  - Added to Huber ^{235}U model
  - Fix μ & σ to Daya Bay result (A=1), vary A
  - Roll through PROSPECT response, compare
- PROSPECT consistent w/ Daya Bay (A = 1)
- Huber ^{235}U (A = 0) disfavored at 2.17σ
- ^{235}U solely responsible for bump (A = 1.78) disfavored at 2.44σ





Search for Sterile Neutrino Oscillations in IBD Spectrum

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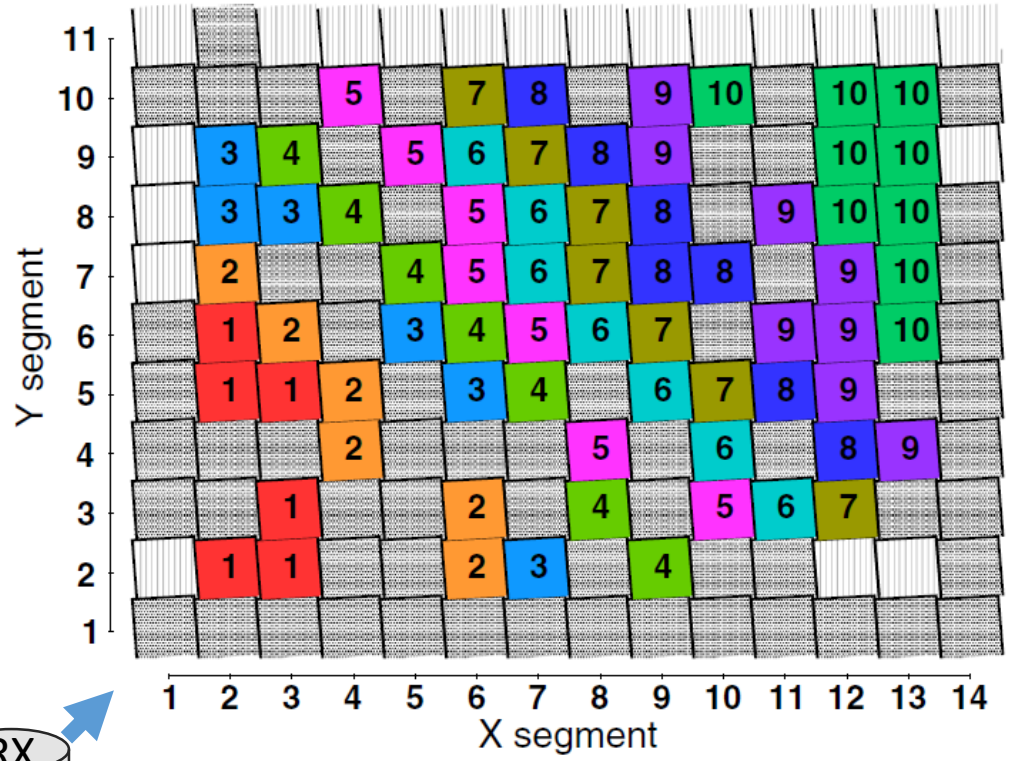
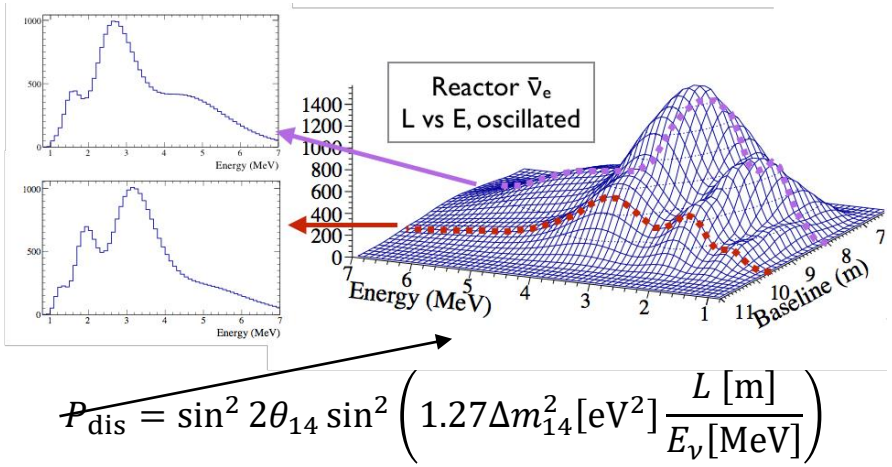
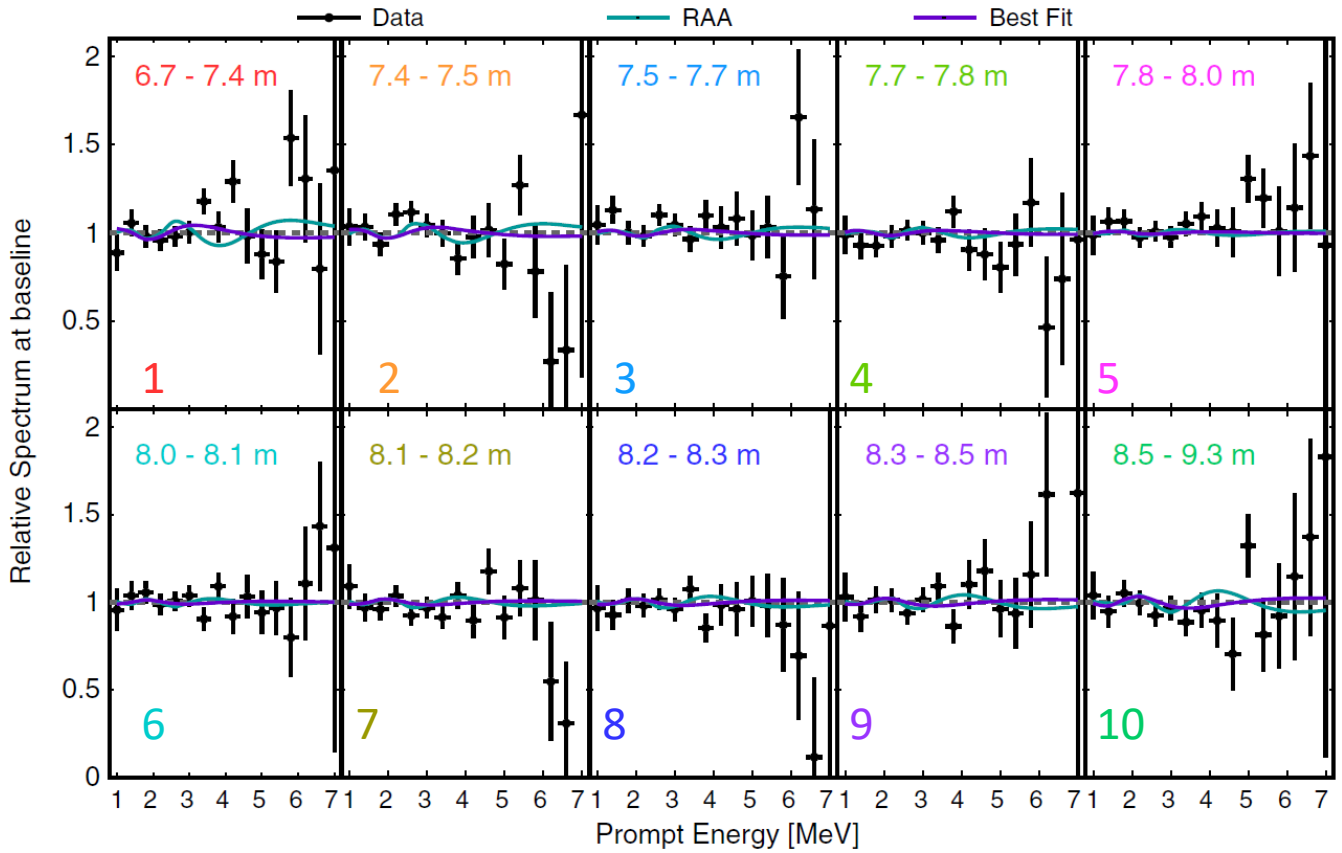




$$P_{\text{dis}} = \sin^2 2\theta_{14} \sin^2\left(1.27\Delta m^2_{14}[\text{eV}^2]\frac{L\ [\text{m}]}{E_\nu[\text{MeV}]}\right)$$



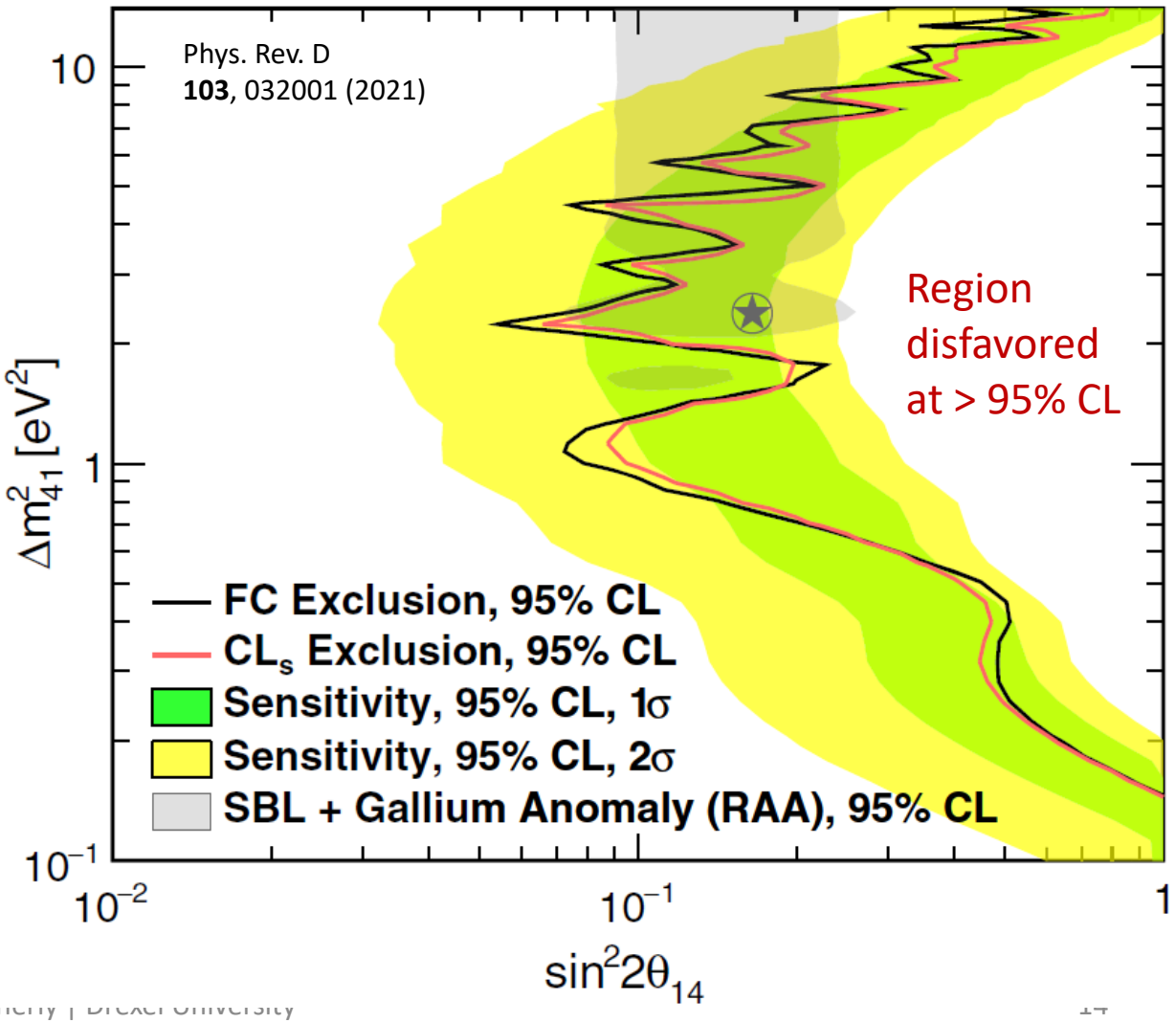
- 10 baselines with different oscillated spectra
- Ratio comparisons to full detector spectrum
- No obvious deviations from no-oscillation (flat) scenario

Sterile Neutrino Oscillations in IBD Spectrum Analysis

- χ^2 comparison of the 10 baseline spectra ratios
  - $\chi^2(\Delta m^2_{41}, \sin^2 2\theta_{14}) = \Delta^T V_{tot}^{-1} \Delta$
  - Δ is vector of spectral bin data for all L
  - Uncert. Cov. Matrix $V_{tot} = V_{sys} + V_{stat}$
- Gaussian CLs & Feldman-Cousins approach for confidence regions
- PROSPECT best fit compatible with no-osc hypothesis (p=0.57)
- RAA best-fit disfavored by PROSPECT at 98.5% (2.5σ) CL
- Statistics limited measurement

Best-fit χ^2/NDoF 119.3/142

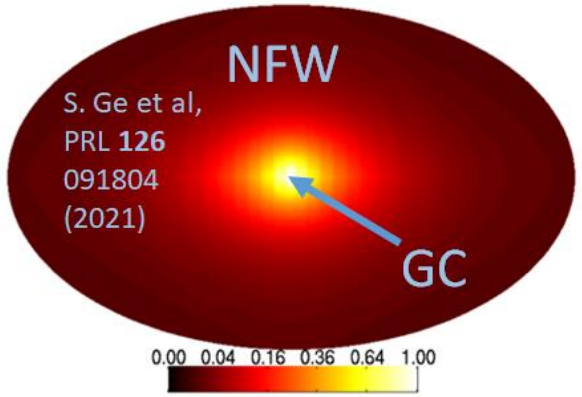
$(\Delta m^2_{41}, \sin^2(2\theta_{14}))$= (1.78 eV2 , 0.11)



Bonus: Boosted Dark Matter Search (CRDM)

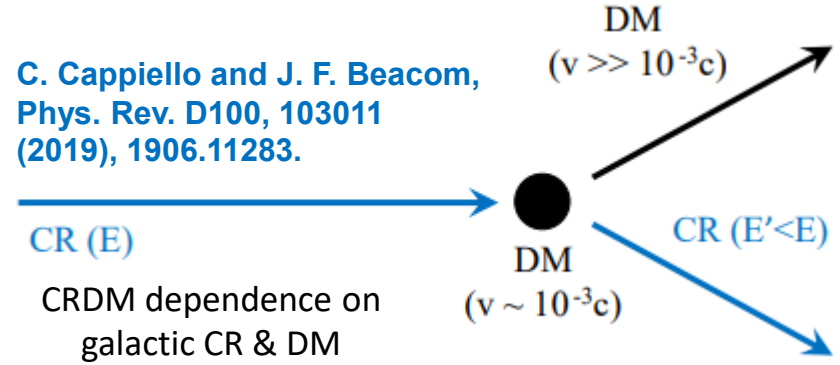
Limits on Sub-GeV Dark Matter from the PROSPECT Reactor Antineutrino Experiment arXiv:2104.11219

- CRDM: Cosmic Ray (CR) upscattering via collisions of light DM (< 1 GeV)
- Galactic center is signal source

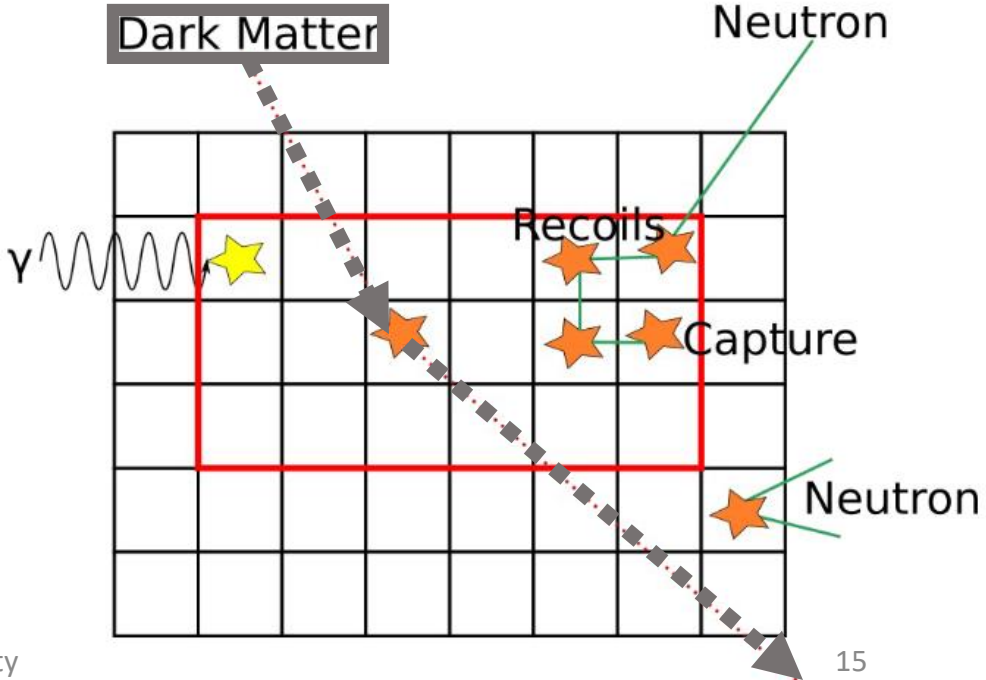


- Model atmospheric attenuation of DM due to large $\sigma_{\chi N}$
- Direct detection: free protons recoiling from DM collisions in PROSPECT

Cosmic Ray DM Upscattering
Insensitive to DM vel. dist.

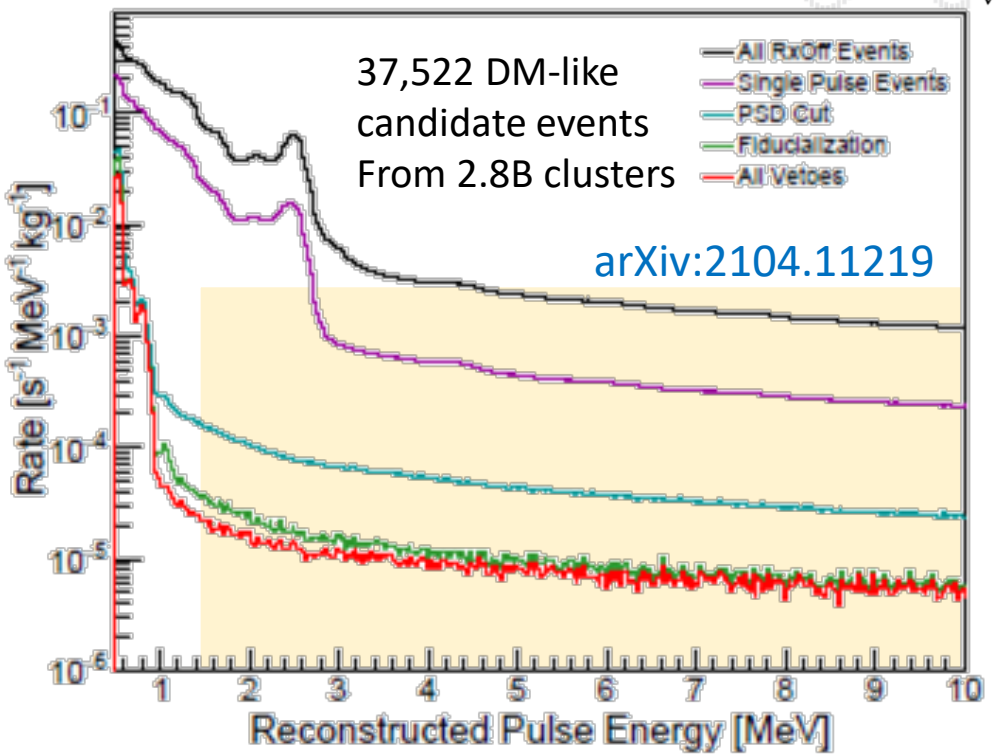


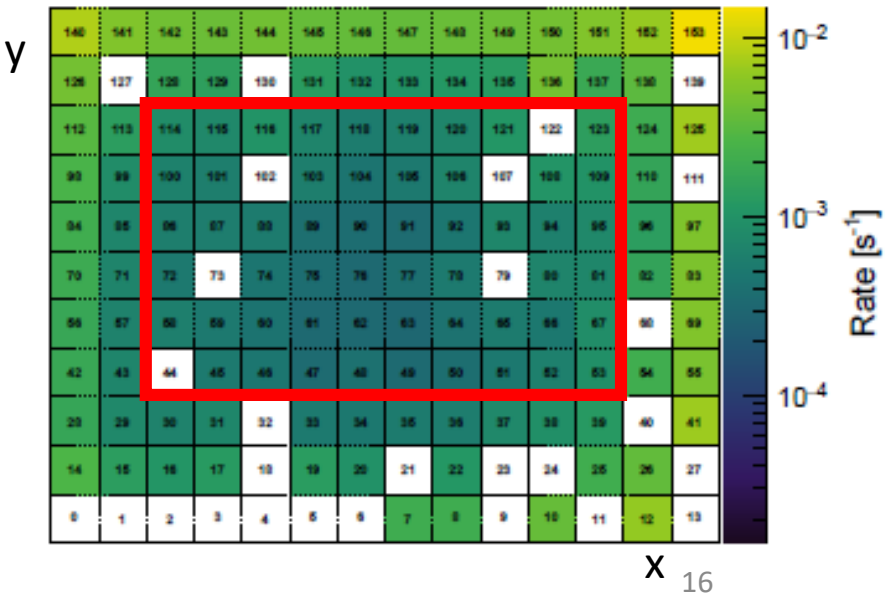
CRDM dependence on galactic CR & DM distributions



Boosted Dark Matter Analysis

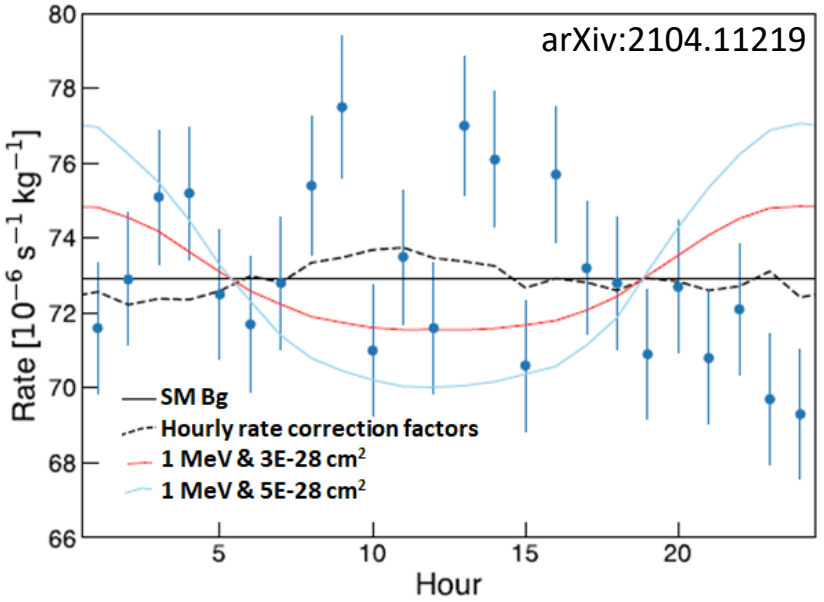
- ~14.6 solar days RxOff data
  - March 16 – March 31, 2018
- Signal: proton recoil-like events
  - Single Pulse (single segment)
  - 1.5 MeV < E < 10 MeV
  - Pulse PSD $\leq 2\sigma$ of proton recoil-like PSD band
- Fiducialization cuts leaves FV of 440 kg
  - Segments outside of red box removed
  - $|z| \geq 20$ cm removed
- Vetos:
  - μ-induced: veto events 5 μs after μ-like event with E > 15 MeV
  - p, n-induced: veto events within ± 5 μs of a proton recoil-like event
  - n-induced: Veto signals < 500 μs before an nLi capture signal
  - Pileup cuts
  - Correct for veto deadtime

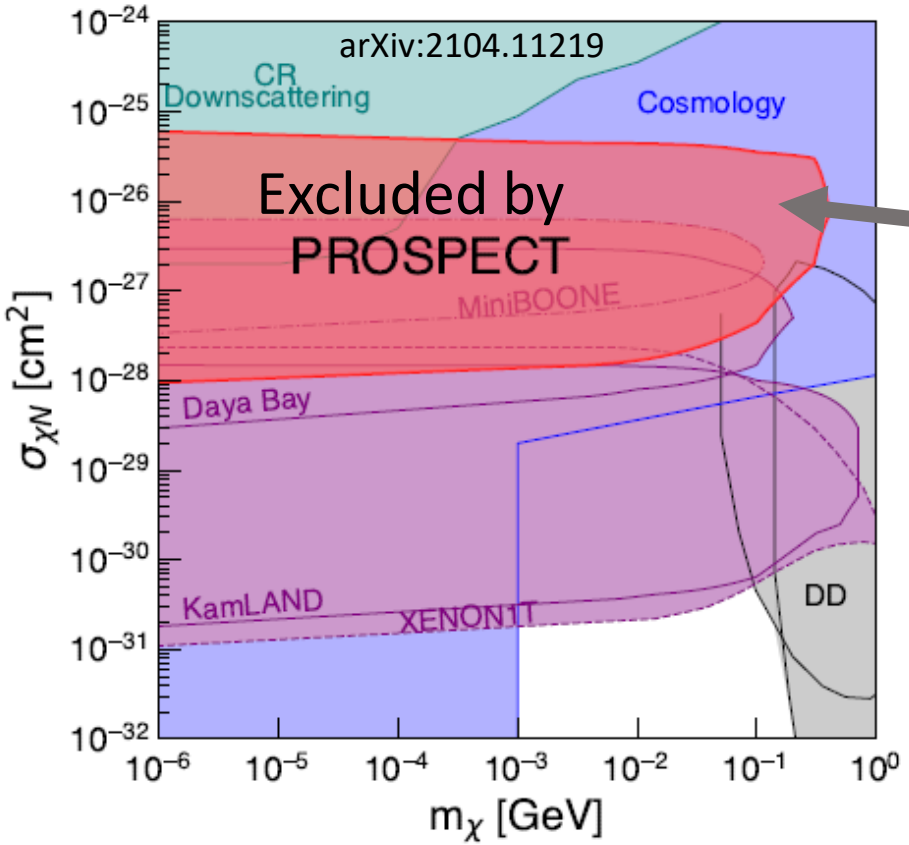




PROSPECT BDM Analysis Results

- Bin data in diurnal sidereal time (right) & search for sinusoidal modulations
  - Data consistent with lack of daily modulation, no DM signal
  - Use Gaussian CLs method to get parameter exclusion region





- Upper $\sigma_{\chi N}$ region
  - **First terrestrial experiment to exclude**
  - **Complementary to cosmology observations**
  - Upper bound limited by atmospheric attenuation
- $\sigma_{\chi N}$ lower bound limited by
  - DM flux through PROSPECT
  - Background rejection
  - CR & DM distribution models

Thank You! Questions?

Other PROSPECT talks in this session

- Reactor Position Reconstruction Study with PROSPECT
  Neutrinos/381 Diego Camilo Venegas-Vargas & Rosa Luz Zamora Peinado
- Joint Isotope-Dependent Analysis of the Daya Bay and PROSPECT Reactor Antineutrino Spectra
  Neutrinos/258 Jeremy Gaison
- A Joint Analysis of the PROSPECT and STEREO 235U Antineutrino Spectra
  Neutrinos/370 Benjamin Foust
- Physics Opportunities with a PROSPECT Upgrade
  Neutrinos/364 Rachel Carr