The PROSPECT Short-Baseline Reactor Experiment

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for the PROSPECT Collaboration

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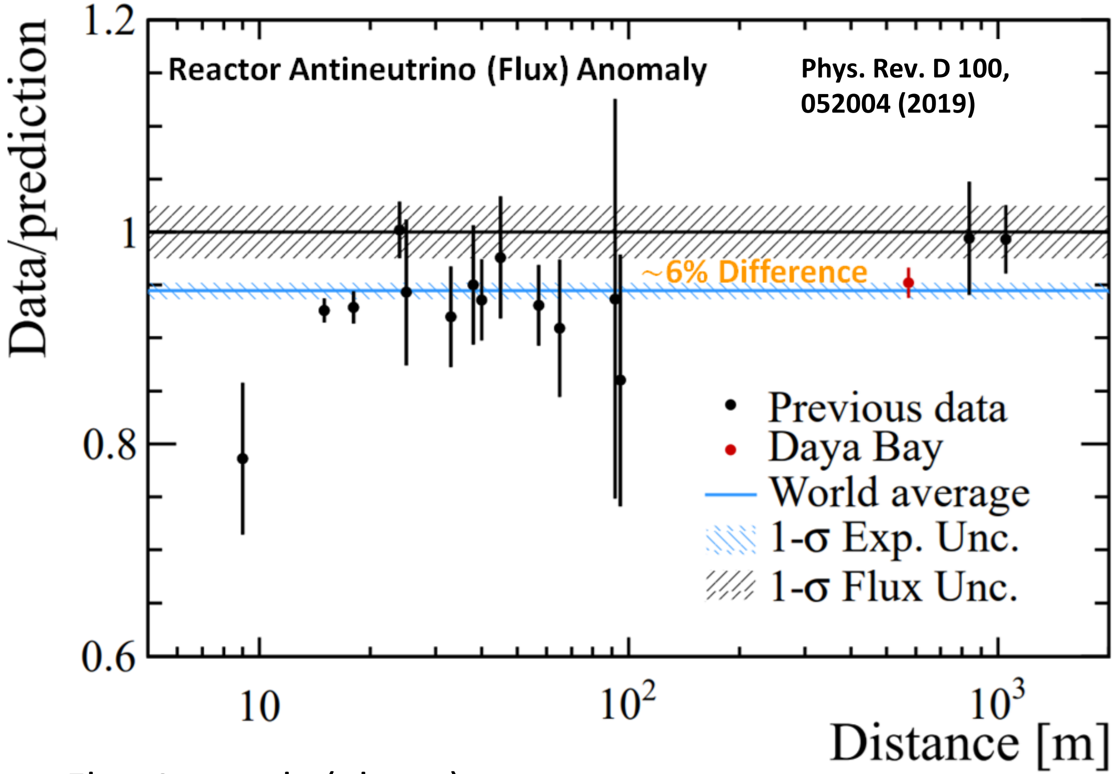
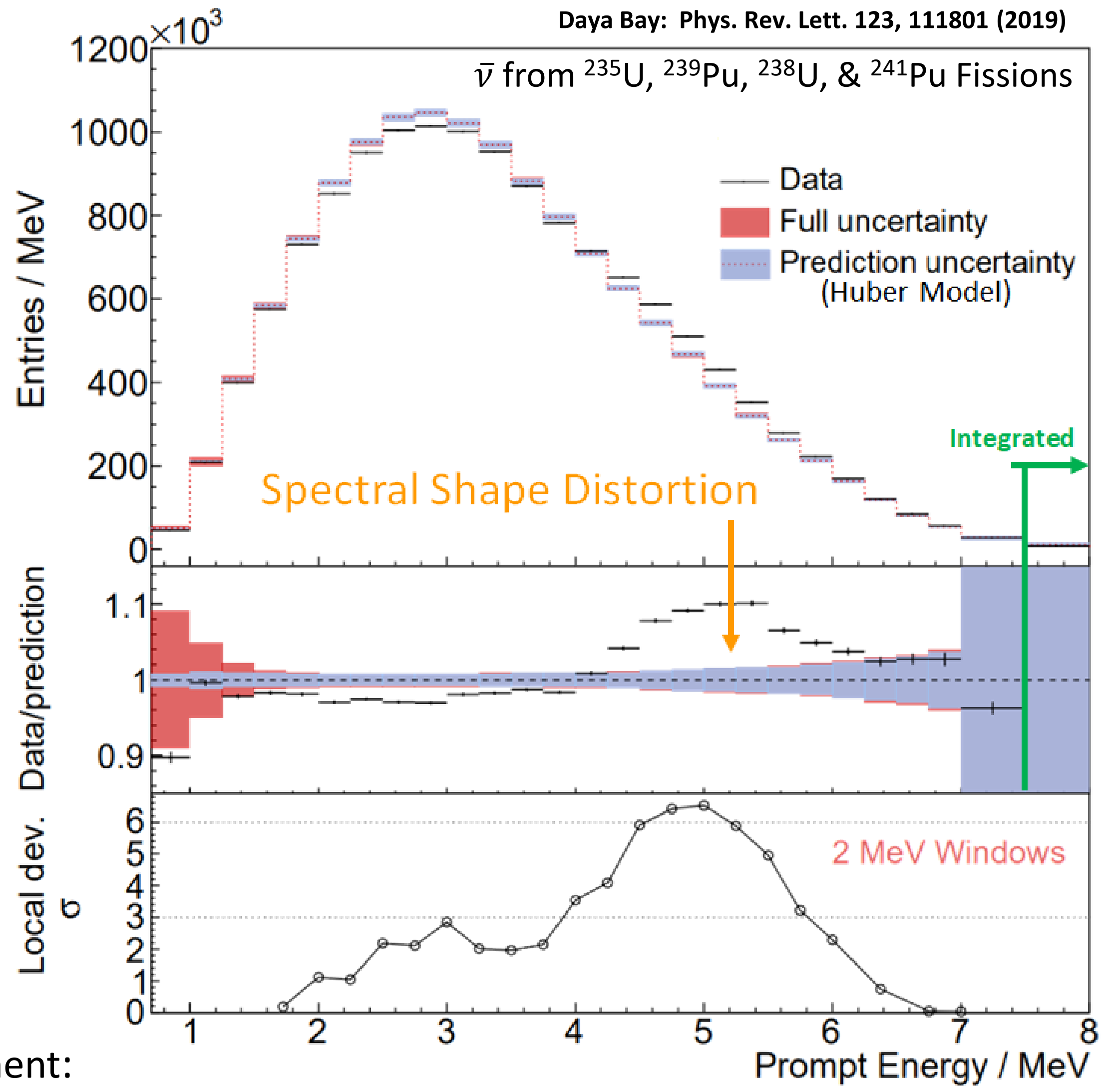
Drexel UNIVERSITY

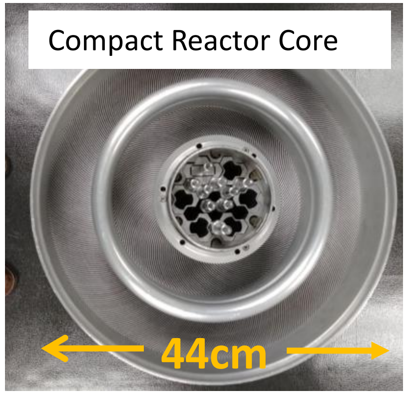
Motivation

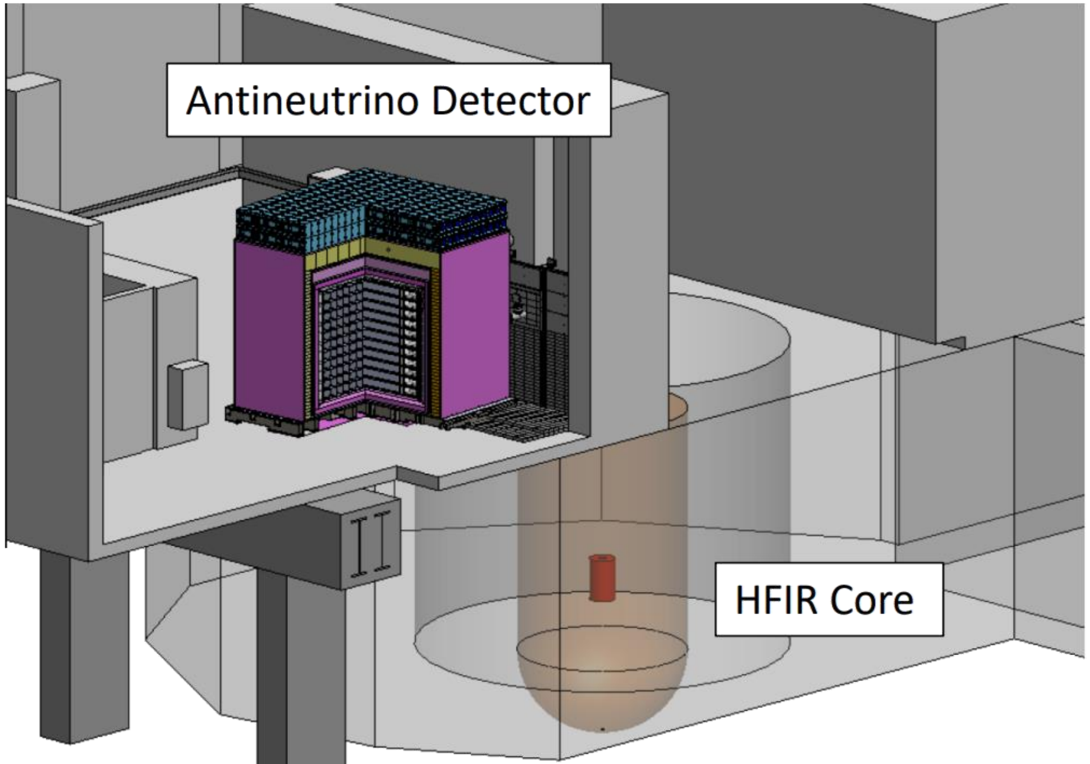




- Flux Anomaly (above)
  - 1 explanation) $\bar{\nu}_e$ oscillation to a sterile neutrino (ν_s) over short baseline of 10-ish meters ($\Delta m^2 \approx 1$ eV scale).
- Both Flux and spectral discrepancies (right) could be due to flawed/incomplete reactor modeling and nuclear data.
- Need detector near a compact reactor to see oscillations
- 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)

Short Baseline Measurements at Enriched ^{235}U Reactor





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

85 MW High Flux Isotope Reactor (HFIR)

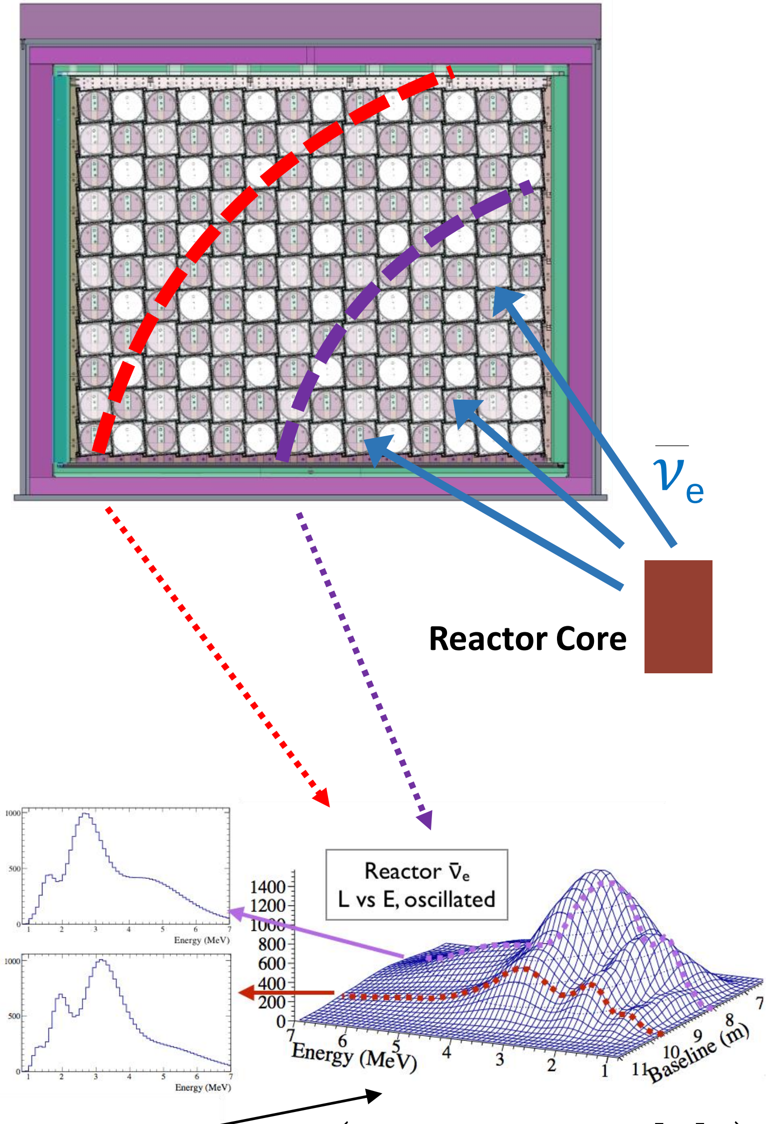
- Oak Ridge National Lab (ORNL)
- Highly Enriched ^{235}U (HEU) fuel in a compact core
- > 99% $\bar{\nu}_e$ emitted by ^{235}U fissions

Place detector close to the reactor core

- Several meters of detector volume w/ position reconstruction for multiple baselines (L)
- Remove reactor-model dependence: Look for relative spectral-shape distortions in identical detector segments at different L

Challenges

- No overburden to shield from cosmic rays: Cosmogenic neutrons from atmosphere are primary correlated background
- Reactor-induced accidental backgrounds

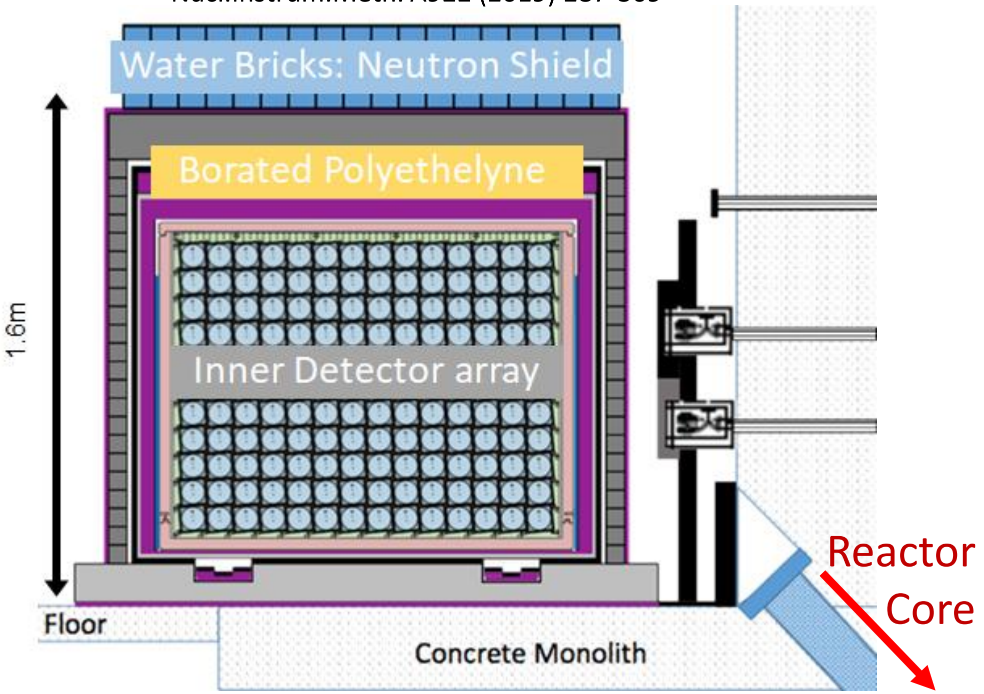


$$P_{\text{dis}} = \sin^2 2\theta_{14} \sin^2\left(1.27\Delta m^2_{14}[\text{eV}^2]\frac{L\,[\text{m}]}{E_\nu[\text{MeV}]}\right)$$

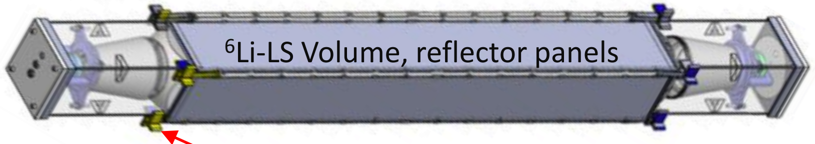
The PROSPECT Detector

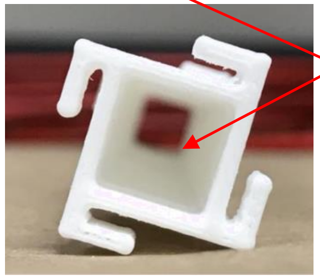
- ~4 ton ^{6}Li-loaded liquid scintillator EJ-309 (^{6}Li-LS)
- 14x11 optically segmented identical detectors (segments)
  - Enables (X,Y) position reconstruction, event topology ID, and fiducialization using outer segments.
  - Thin reflector panels fixed by 3D-printed support rods
- Each segment has double-ended PMT readout
  - PMT timing differences give Z-position reconstruction
- Support rods enable calibration source access throughout detector volume (between segments).
- Detector volume 7-9 m from core
  - covers short baselines
- Energy Resolution: ~4.5%-5% / $\sqrt{E[\mathrm{MeV}]}$
- Overburden: ~1 mwe
- Detection of reactor $\bar{\nu}_e$ in PROSPECT via Inverse Beta Decay (IBD) interactions

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

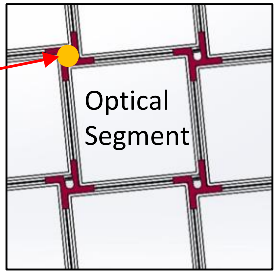


Single Segment: 119 cm x 15 cm x 15 cm





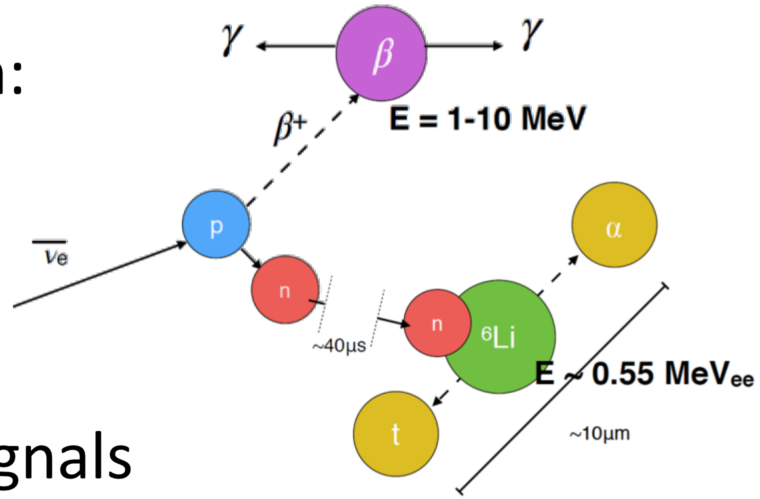
3D-printed rods w/ in-situ calibration source access

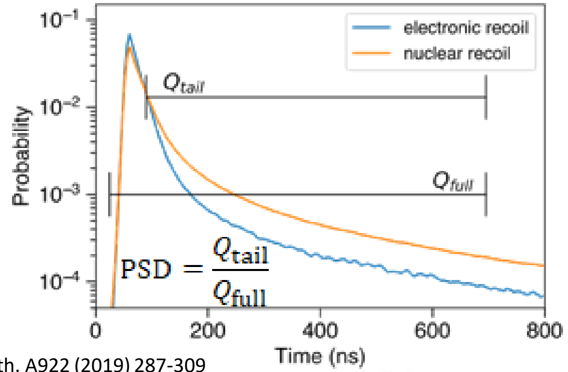


IBD interactions in PROSPECT

IBD interaction:

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





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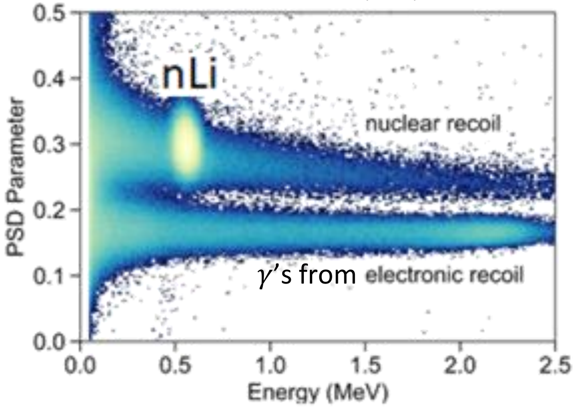
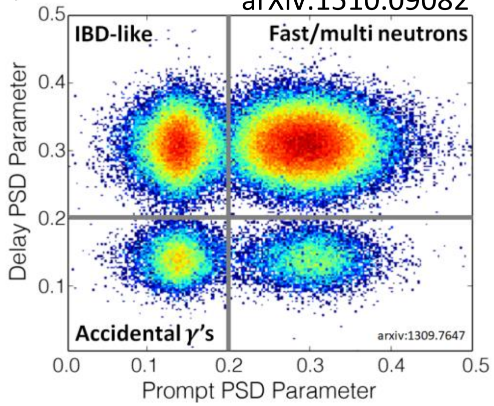


arXiv:1510.09082



Coincidence signals

- Prompt signal
  - Ionization and annihilation of positron (β^+)
  - $E_{deposit}$ between 1-10 MeV
- Delayed Signal
  - nLi: neutron capture on ^{6}Li
  - subsequent decay $E_{deposit}$ ~0.55 MeV electron equivalent
  - nLi decay highly localized to single segment
  - $\sim 40\ \mu s$ delay between prompt and nLi
  - gives neutron tagging

Pulse Shape Discrimination (PSD) from ^{6}Li-LS works as particle ID

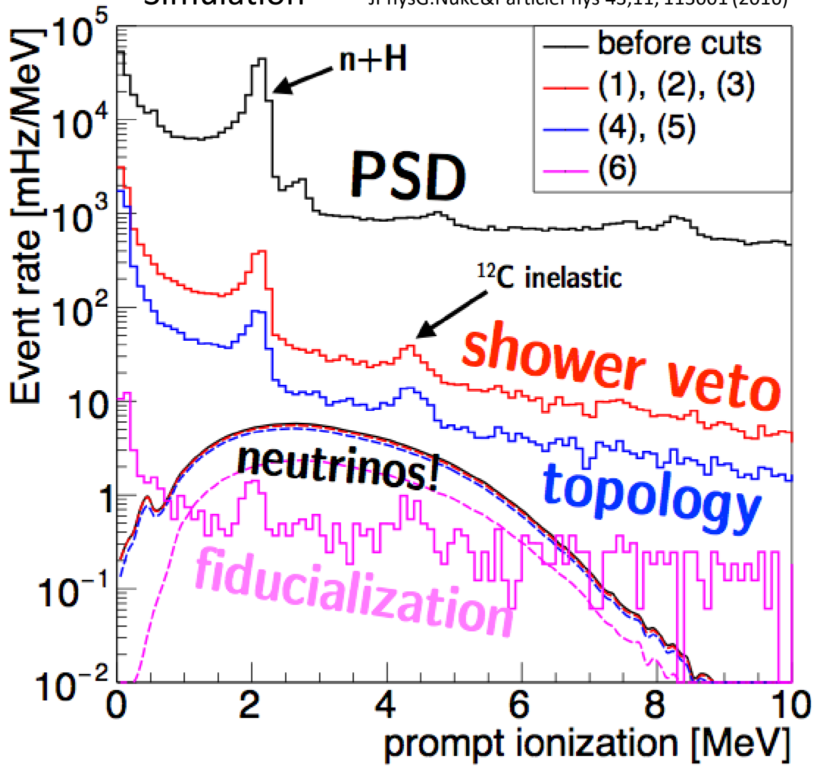
- Distinguish between γ-interactions, n-capture like nLi, & nuclear recoil
- PSD-correlations between prompt and delayed signals

Coincidence Signal w/ PSD requirements enable strong background suppression

- Necessary for removal of cosmogenic fast-neutron background, reactor-induced γ-rays, reactor thermal neutrons

Background Suppression, Removal, and Subtraction

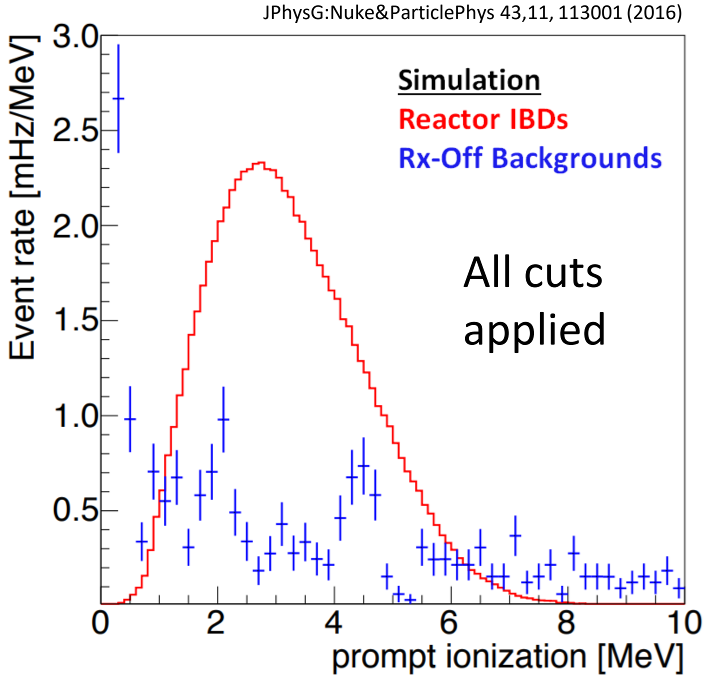
- Cuts, Vetos and Fiducialization reduce background (bg) by 10^4



- Apply correction for atmospheric pressure as it is correlated to cosmogenic backgrounds
- PROSPECT talks this session for updated background studies:
  - J20.00001 Cosmogenic Fast neutron bg (C. Nave)
  - J20.00002 Cosmic ray bg (J. Minock)
  - J20.00003 Optimized IBD selection for bg reduction (X. Lu)

Rx-Off periods

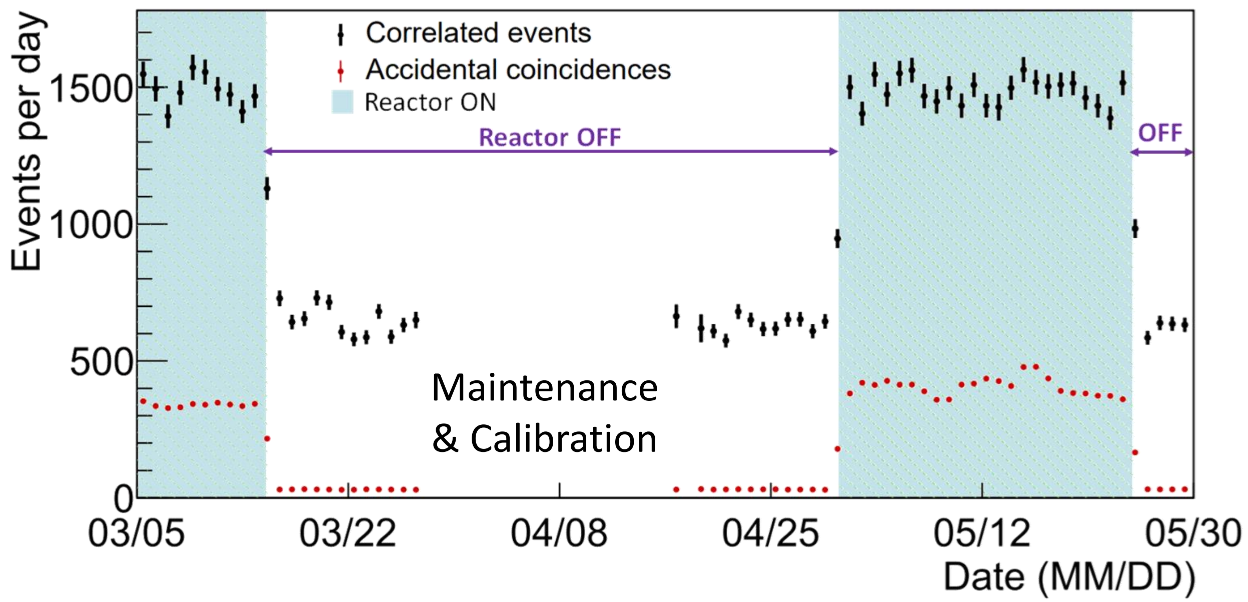
- high-precision measurement of IBD-like backgrounds
  - Obtain Rate and spectral shape
- Used to subtract Rx-Off IBD-like background from Rx-On IBD-like sample
- Below: MC simulation of IBD-like samples Rx-On & Rx-Off Bgs (Cosmics, etc)



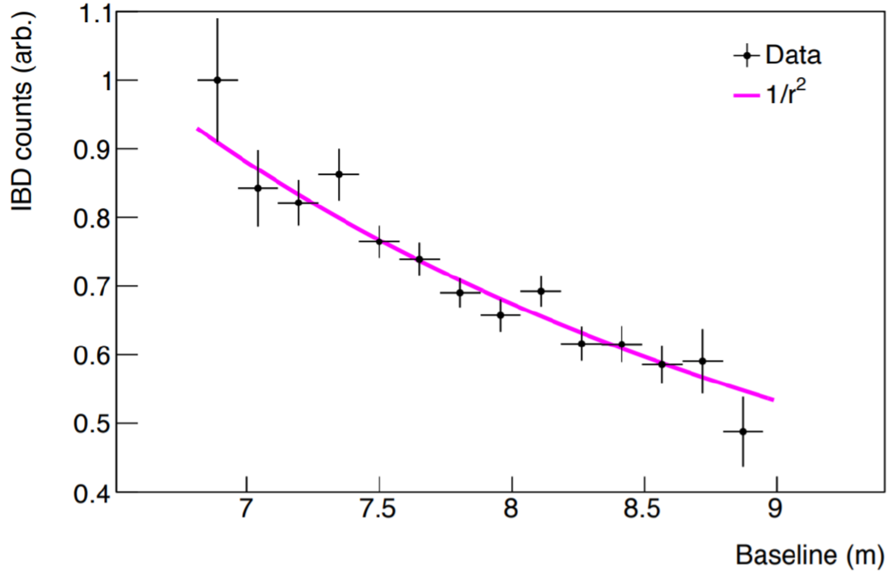
Prospect Data and IBD Signal

- Top: Reactor (Rx) On/Off data periods
  - 33 (28) days of reactor on (off)
- BG-Subtraction gives:
  - S/B = 1.32 for correlated backgrounds
  - 24,461 IBDs (E_{prompt}=0.8 – 7.2 MeV)
  - Average rate Rx-On signal: 771 IBD/day
  - Best demonstrated S:B for on-surface reactor experiments
- Reactor IBD signal (bottom):
  - Relative flux over 14 baseline bins.
  - 40% drop from near to far corner of detector
  - Consistent with $1/r^2$ behavior

Phys. Rev. Lett. 121, 251802 (2018)

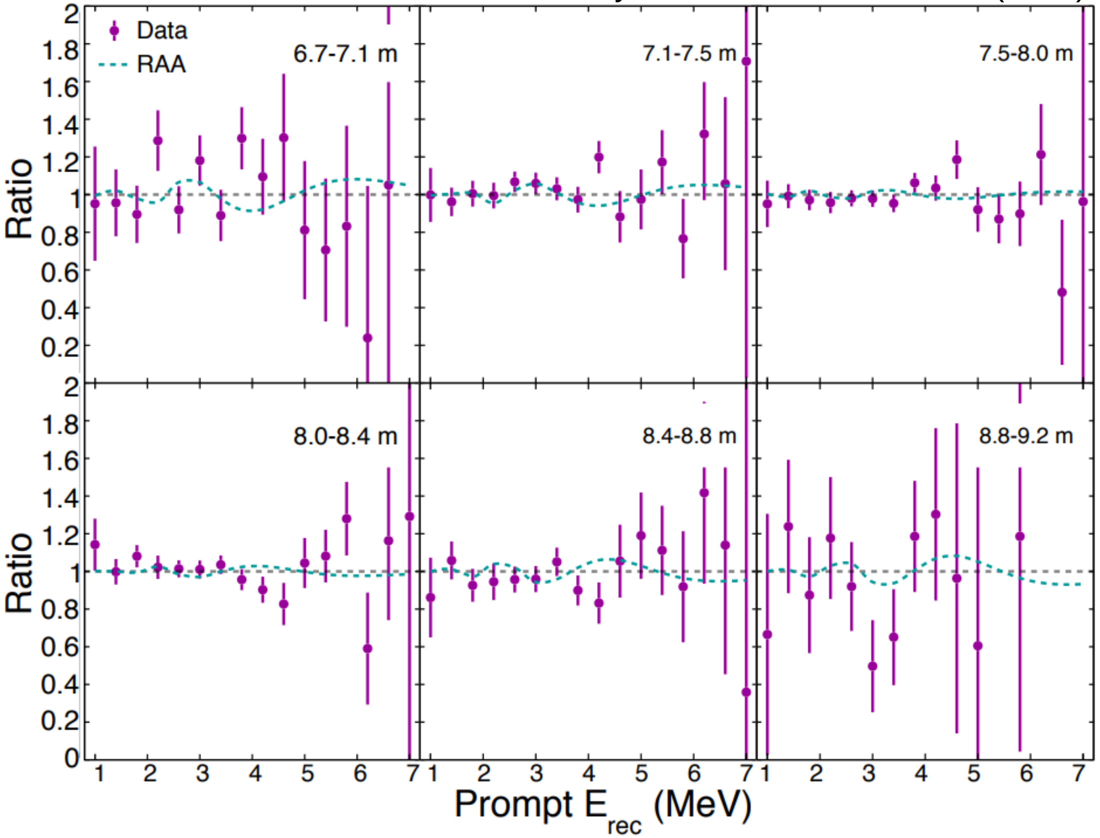


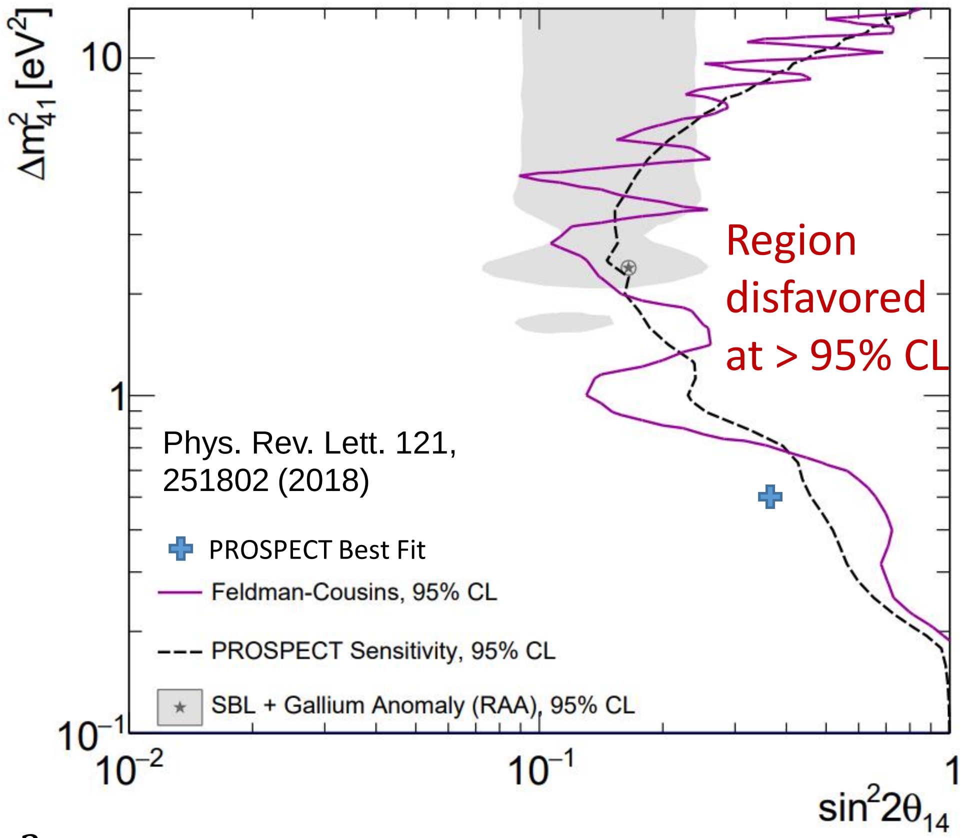
PROSPECT, PRL, 121, 251802



Search for Sterile Neutrino Oscillations in IBD Spectrum

Phys. Rev. Lett. 121, 251802 (2018)

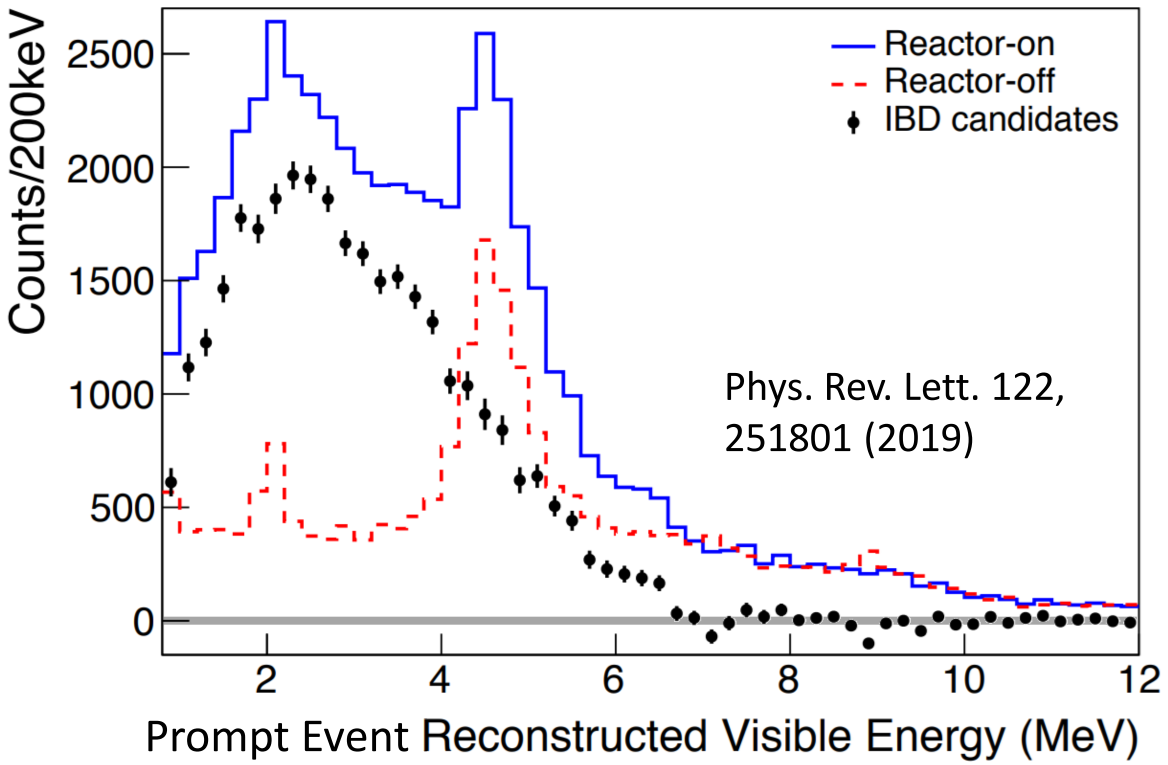


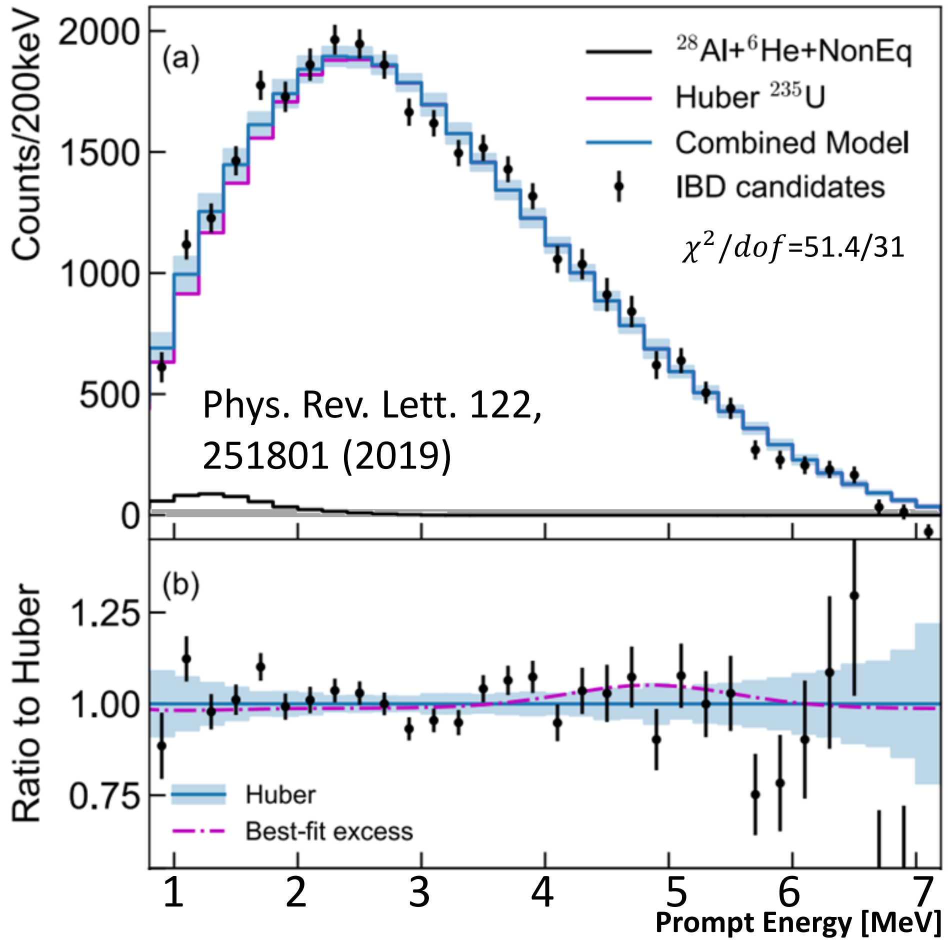


- Compare ratio of 6 different baselines to the full-detector spectrum
  - Ratio search independent of reactor models
- No oscillations → Flat ratio across every baseline
- Prediction of oscillations to ν_s for RAA best-fit parameters plotted in blue

- χ^2 comparison of measured spectra to prediction in all six baselines
  - Feldman-Cousins approach for confidence intervals
  - PROSPECT best fit has little incompatibility with no-osc
- RAA best-fit disfavored by PROSPECT > 95% (2.2σ) CL

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





Background-subtracted prompt spectra

- 40.3 (37.8) days Rx-On (Rx-Off)
- 31678±304(stat) IBD events detected over bg
- S/B = 1.7

- Top: Spectral shape-only comparison → broad agreement, though large χ^2/dof (statistically limited measurement)
- Bottom: Ad-hoc model (Gaussian + Huber ^{235}U) for distortion
  - Gaussian describing distortion at E_ν = (5-7) MeV
  - Gaussian norm (n) fit to prompt spectra: best fit n = 0.69±0.53
  - Consistent with both Huber ^{235}U Model & Daya Bay distortion (n=1)
  - ^{235}U solely responsible for bump disfavored at 2.1σ (n = 1.78)

Current and Future Status

- Prospect has detected reactor $\bar{\nu}_e$-induced IBDs
  - On-surface antineutrino detector w/ minimal overburden
  - large cosmogenic background removal using a ^{6}Li-LS loaded segmented detector and PSD.
- Segmented design and relative spectral comparisons at multiple baselines enable reactor model-independent study
- 33 days Rx-On data disfavors sterile neutrino RAA best fit point by 2.2σ
- First ^{235}U spectrum measurement with 40.3 days Rx-On data shows consistency with Huber in central energy region; statistics limited measurement.
  - Highest published stats measurement of pure ^{235}U $\bar{\nu}_e$ spectrum to date
- Paper for updates to both analyses under preparation with much more statistics/livetime
  - 96 days Rx-On data total (~56 new days additional data, ~2x IBD statistics)
  - Improvements on analysis, understanding backgrounds, re-optimized (tighter) cuts
- Current Prospect experimental phase finished taking data.
  - Upgrade in the works
  - Proposal to deploy upgrade at HFIR in 2021 for multi-year run

Backup

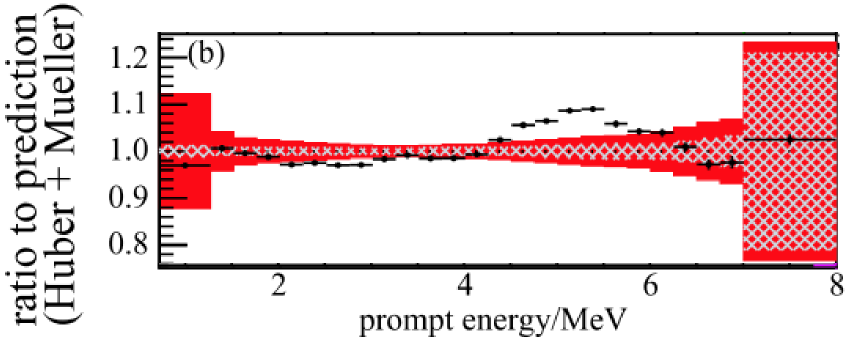
Abstract

- PROSPECT is a reactor antineutrino experiment whose primary goals are to probe short-baseline oscillations and perform a precise measurement of the U-235 reactor antineutrino spectrum. The PROSPECT detector has collected data at the High Flux Isotope Reactor (HFIR) at the Oak Ridge National Laboratory, with the active volume covering a baseline range of 7-9m. To operate in this environment with tight space constraints, limited overburden and the possibility of reactor-correlated backgrounds, the PROSPECT AD incorporates design features that provide excellent background rejection. These include segmentation and the use of Li-6 doped liquid scintillator with good pulse-shape discrimination properties. In this presentation, we will describe the performance of the PROSPECT detector and the results obtained to date including the detection of reactor antineutrinos with essentially no overburden, the first oscillation exclusion determined by the experiment, and the highest statistics U-235 reactor antineutrino energy spectrum reported to date, The current status and plans for future improvements to the experiment will also be described.

Motivation: Reactor Antineutrino Spectrum Deviations

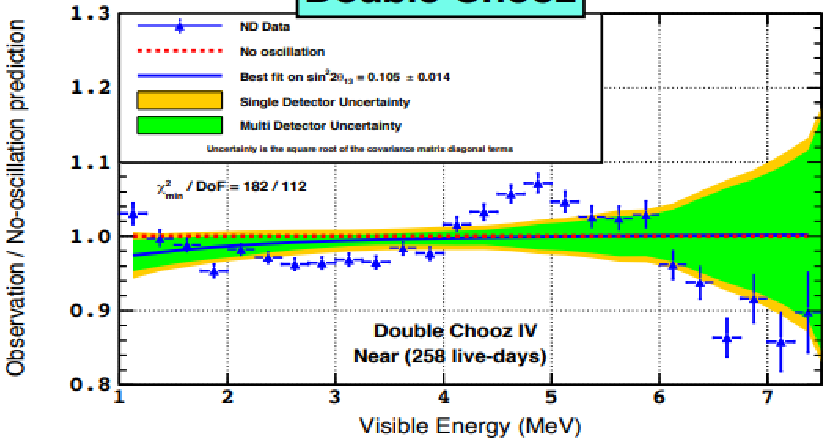
Experiments precisely measured spectrum from Low Enriched Uranium (LEU) reactors ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

Daya Bay



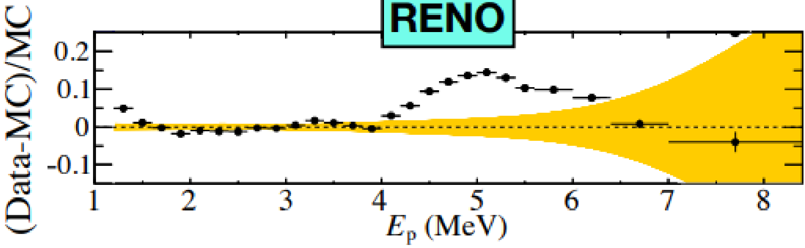
CPC Vol. 41 (1) (2017)

Double Chooz



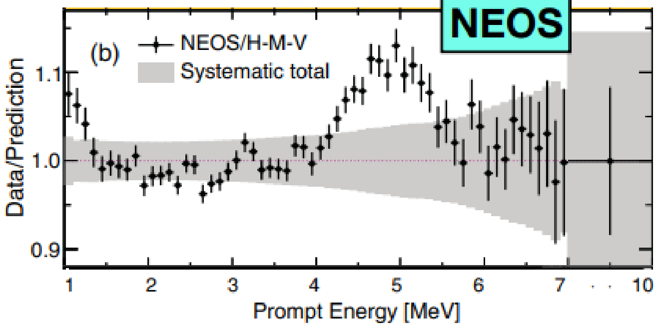
arXiv:1901.09445

RENO



PRD 98, 012002 (2018)

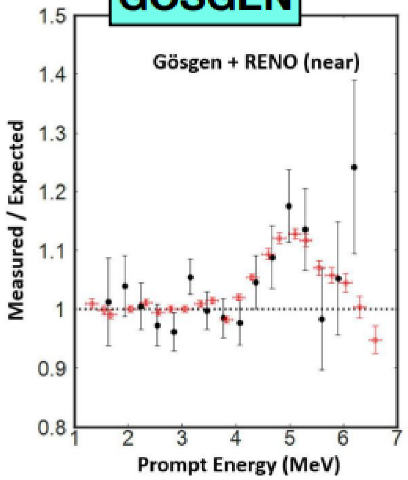
NEOS



PRL 118, 121802 (2017)

Distortion in 4-6 MeV prompt energy, not only on theta13 experiments.

GOSGEN



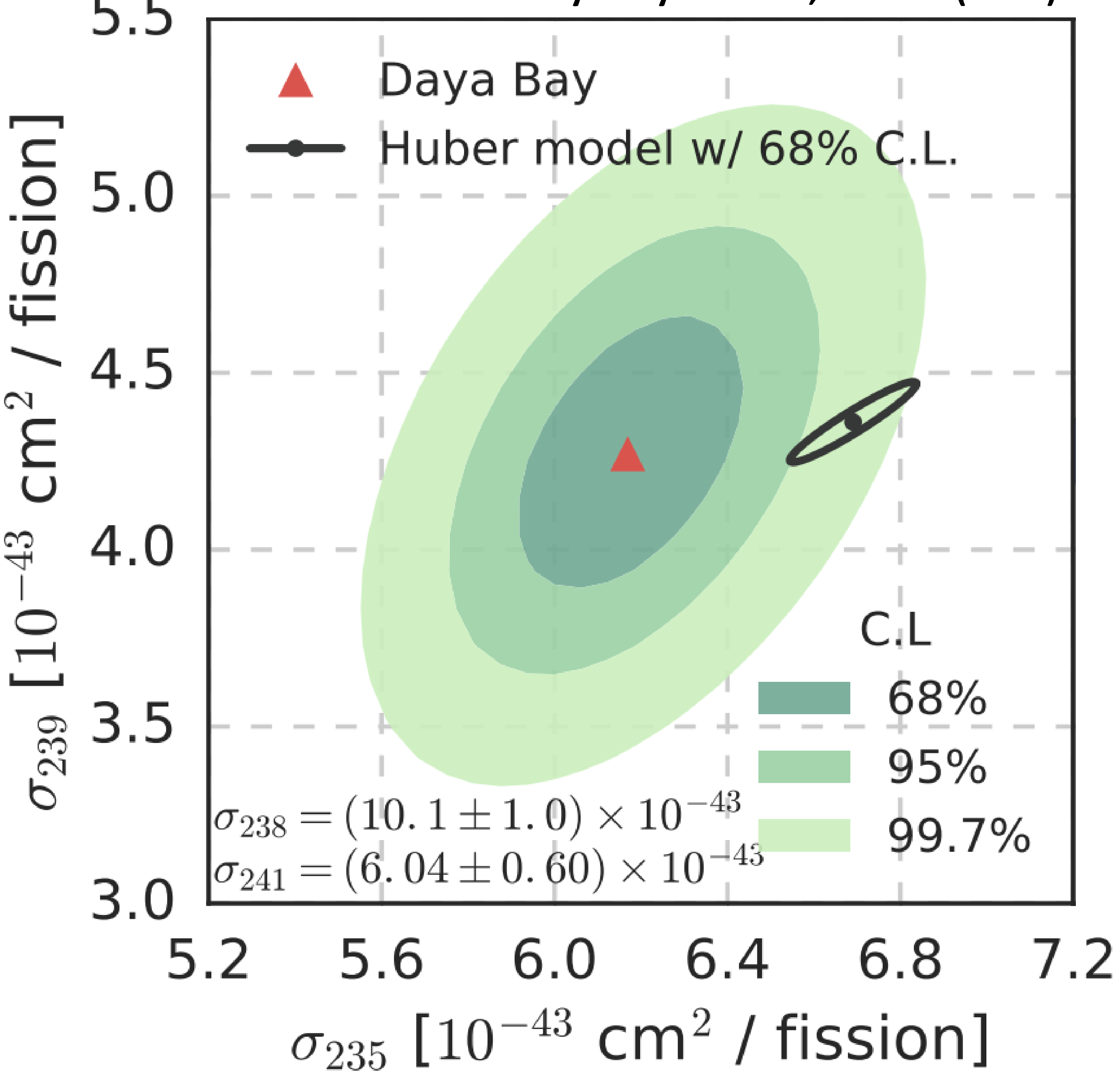
Re-evaluation (2018) of Gosgen(1980's) experiment also showed a deviation in 4-6 MeV region.

arXiv:1807.01810

Where this deviation is coming from?

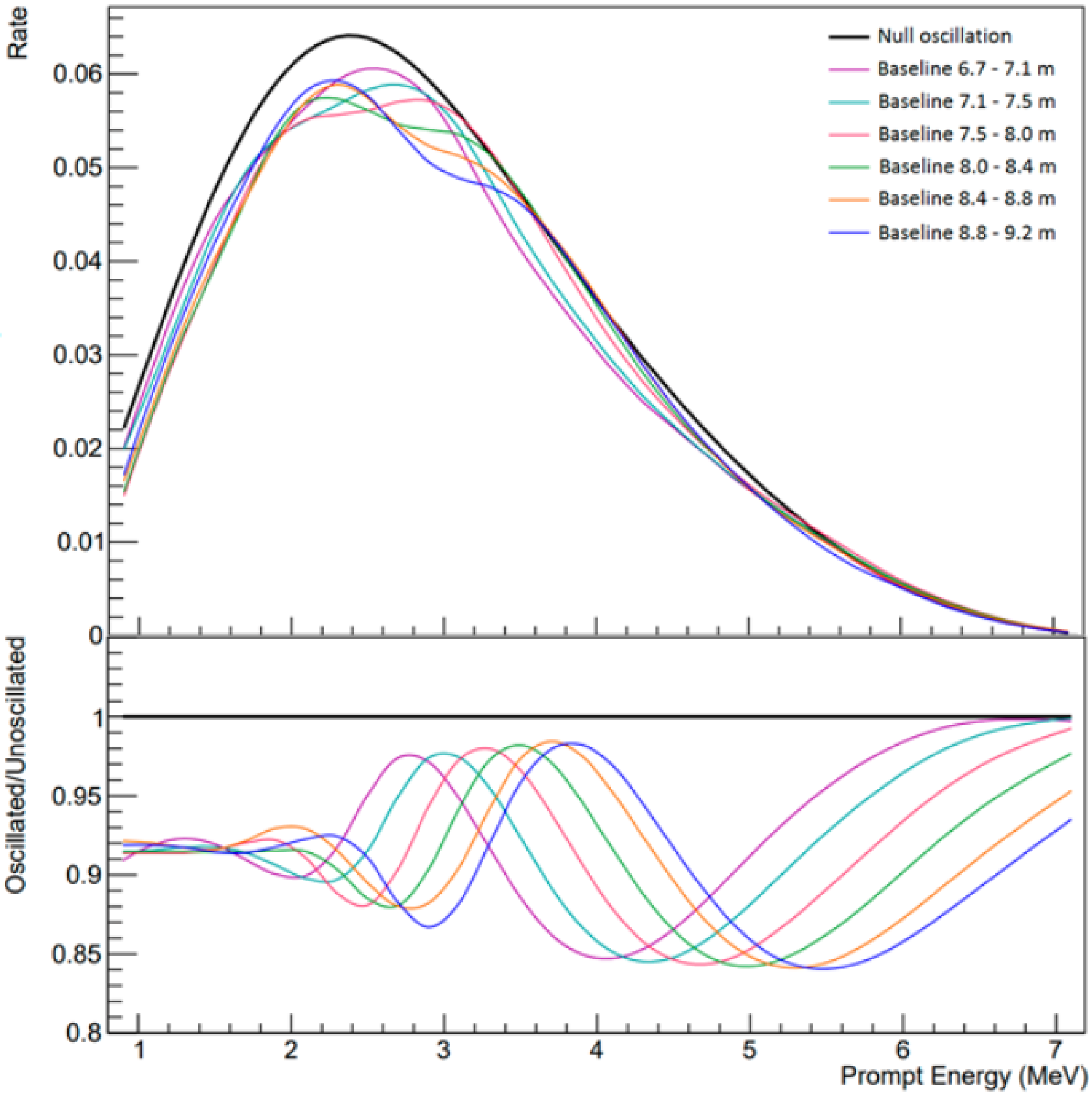
- Cannot be explained by the sterile neutrino introduced for flux deficit.
- Could be an issue with reactor models? Experiments used conventional reactors (LEU).

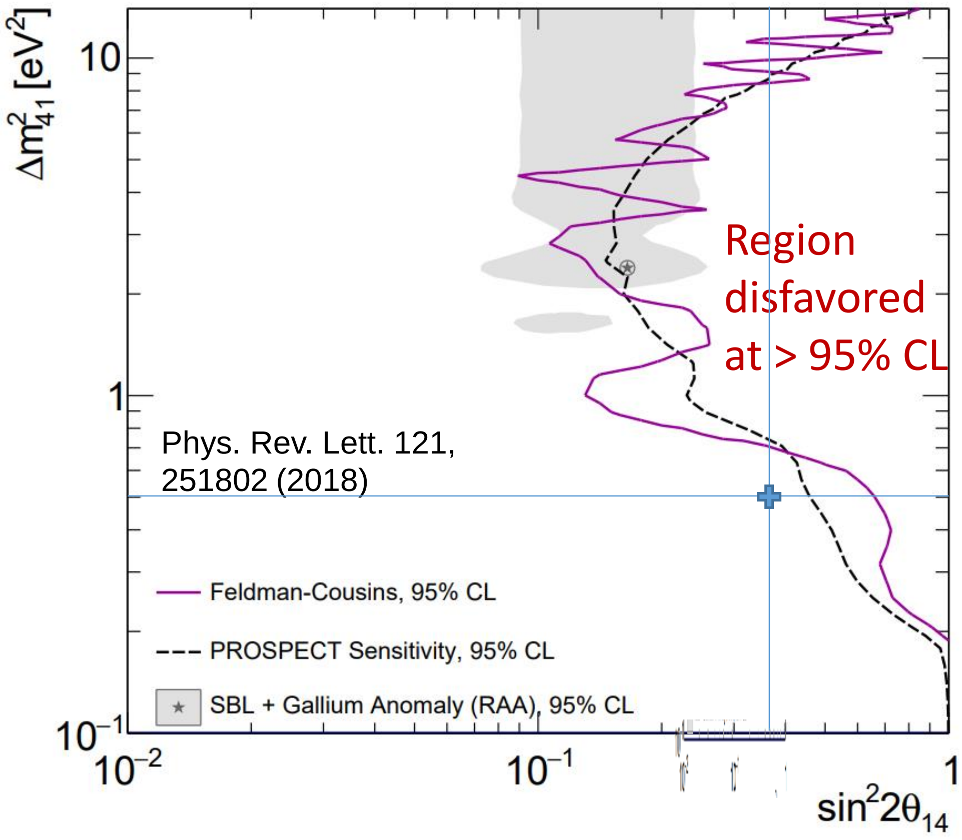
Daya Bay PRL 118, 251801 (2017)



Before spectral shape relative-zation

After spectral shape relative-zation





Δm^2_{41} [eV^2]
10
1
10^{-1}
10^{-2}
10^{-1}
1
$\sin^2 2\theta_{14}$
Region disfavored at > 95% CL
Phys. Rev. Lett. 121, 251802 (2018)
Feldman-Cousins, 95% CL
PROSPECT Sensitivity, 95% CL
SBL + Gallium Anomaly (RAA), 95% CL