Latest Results from the PROSPECT Reactor Antineutrino Experiment Including Limits on Sub-GeV Boosted DM

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for the PROSPECT Collaboration

ICHEP 2022

Drexel UNIVERSITY

PROSPECT

Precision Reactor Oscillation & SPECTrum Measurement (PROSPECT) Experiment

Collaboration: ~70 collaborators across 16 Institutions

Funding

Latest Publications (& Talk Outline):

Limits on Sub-GeV Dark Matter from the PROSPECT Reactor Antineutrino Experiment
PhysRevD 104 (2021) 012009

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

Joint Measurement of the ^{235}U Antineutrino Spectrum by Prospect and Stereo
PhysRevLett 128 (2022) 081802

Joint Determination of Reactor Antineutrino Spectra from ^{235}U and ^{239}Pu Fission by Daya Bay and PROSPECT
PhysRevLett 128 (2022) 081801

PROSPECT-II Physics Opportunities
arXiv:2107.03934 & arXiv:2202.12343

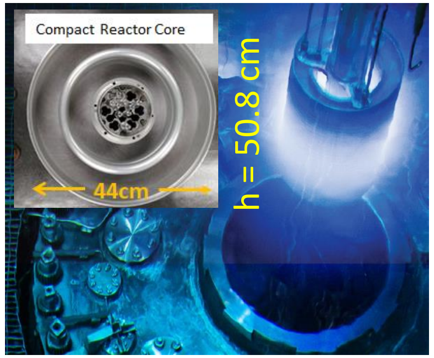
Editors' Suggestion Open Access

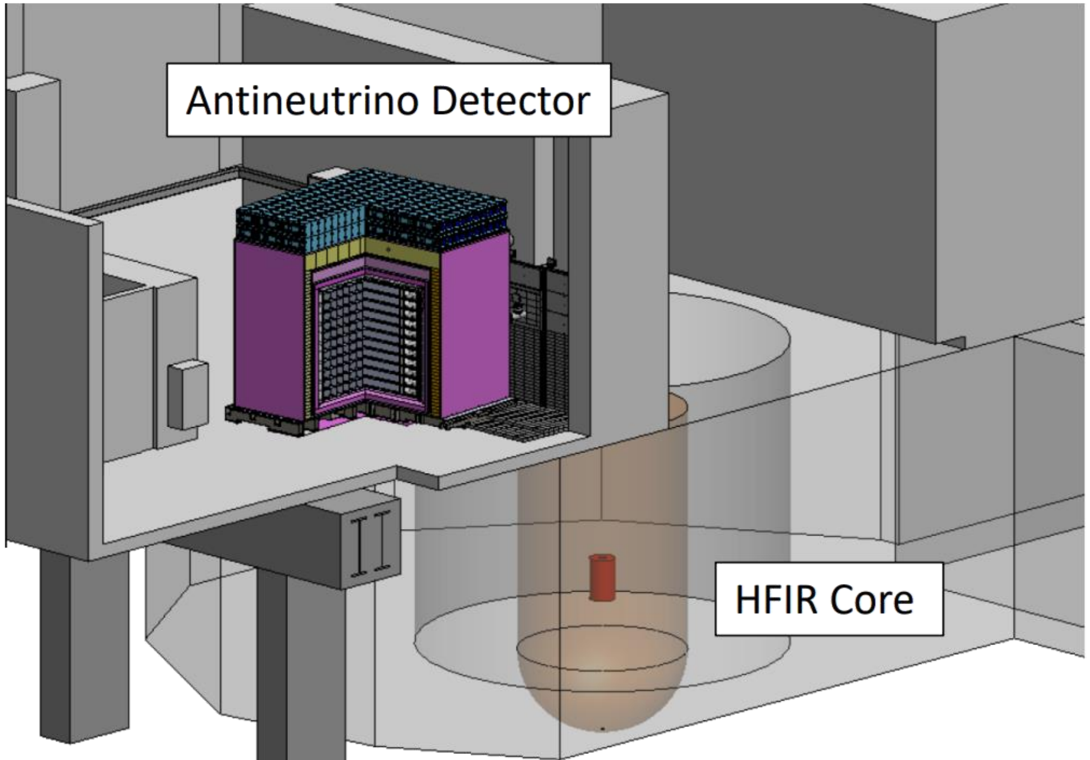
PRD Editors' Suggestion

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

PROSPECT at ORNL's HFIR





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

Detector on surface at Oak Ridge National Lab's High Flux Isotope Reactor (HFIR)

- Detect Inverse Beta Decays (IBDs) caused by reactor $\bar{\nu}_e$ neutrinos
  - Measure $\bar{\nu}_e$ spectrum from ^{235}U fissions
  - Sterile neutrino oscillation search

Challenges for a surface detector

- No overburden to shield from cosmic rays:
  - **$\sim$1 meter water equivalent (mwe)**
  - **High rate cosmic-ray induced activity (μ & n)**

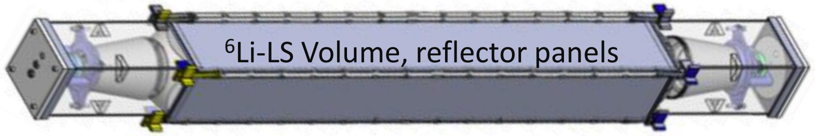
The PROSPECT Detector

~4 ton ^{6}Li-loaded liquid scintillator EJ-309 (^{6}Li-LS)

- Good Pulse Shape Discrimination (PSD) properties

14x11 segmented detector

Single Segment: 119 cm x 15 cm x 15 cm

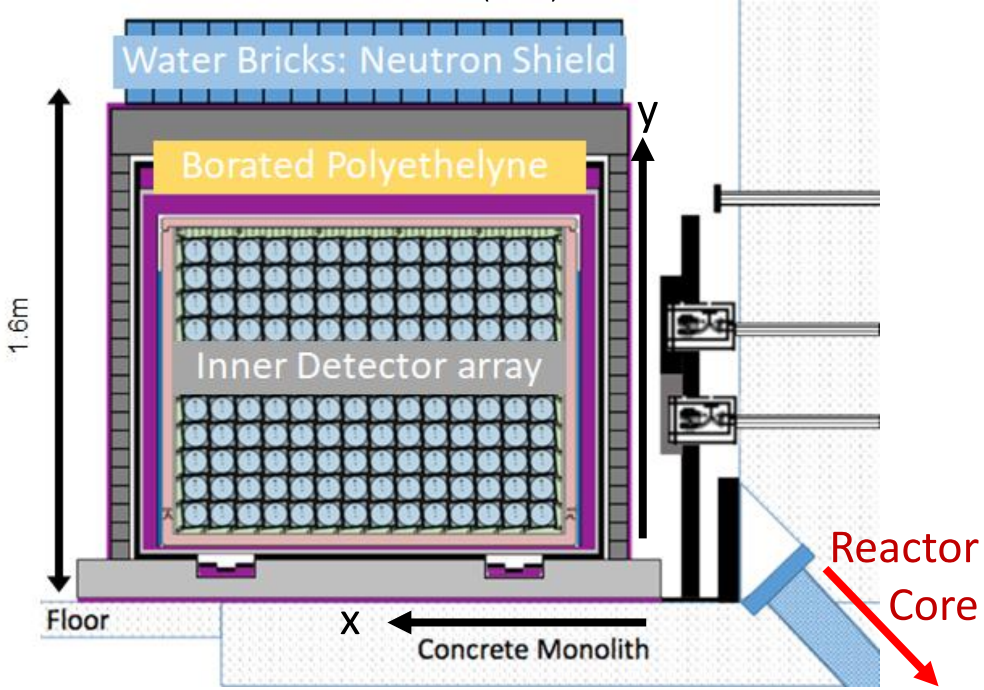


- t, Z-position reconstruction from double-ended PMT readout
- (X,Y) position reconstruction & fiducialization

Energy Resolution: ~4.5%-5% / $\sqrt{E\,[\mathrm{MeV}]}$

Enables High Resolution ^{235}U Spectrum measurements at baselines between 7 – 9 m from HFIR core

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



Pulse Shape Discrimination (PSD)

Prospect PSD $\equiv Q_{\mathrm{tail}}/Q_{\mathrm{full}}$ for PMT pulses

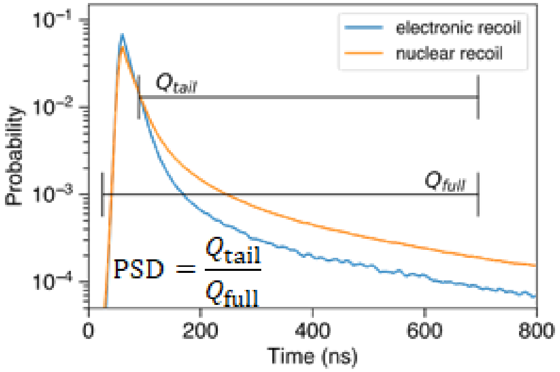
PSD from ^{6}Li-LS works as Particle ID

- Energy dependence
- ID γ-interactions, n-capture on Li (nLi), & nuclear recoil including proton recoils (for DM)
- **Enables strong background suppression**
    - Upper-right: Prompt and delayed signal coincidences differ topologically per source
    - Necessary for removal of cosmogenic fast-neutron background, reactor-induced backgrounds for IBDs.

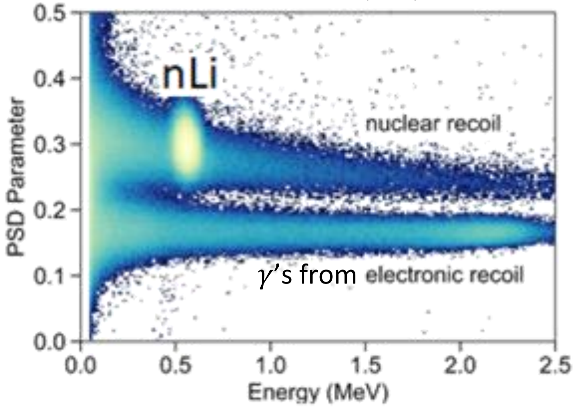
PROSPECT's segmented design and LS PSD enables the 4-ton detector able to function (& well) on surface

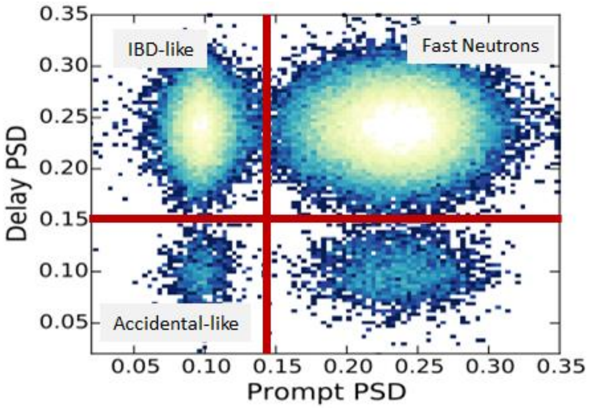
DM-search: PSD for proton recoils

- Signal contained to single segment
- $|z| < 55$ cm where PSD response is best
- Allows separation of PSD bands of proton recoils from PSD band of other nuclear recoil events.
- Bottom-right: Require PSD(E) PID agreement $\leq 2\sigma$ w/ proton recoil band



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





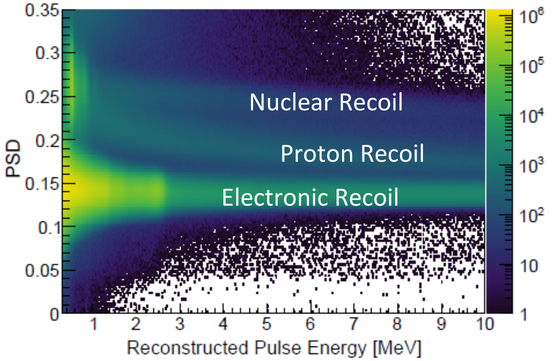


FIG. 1. Reconstructed PSD parameter values versus reconstructed energy for all single-pulse clusters in the full analysis dataset.

PhysRevD 104 (2021) 012009

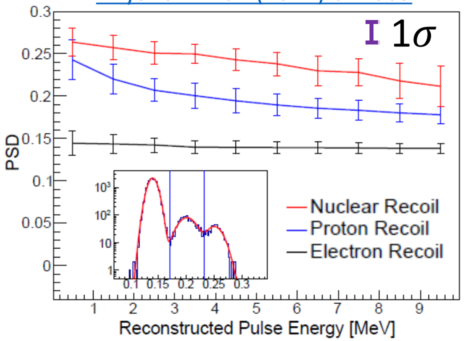


FIG. 2. Mean and 1σ standard deviation of PSD parameter distributions for three particle types as a function of energy. The inset image shows the underlying fitted distribution for the 3-4 MeV energy range, as well as blue lines representing the 2σ width of the proton band in this energy range.

Boosted Dark Matter

Dark Matter (DM) can explain cosmological/astronomical observations

DM Particles not in Standard Model (SM)

- No coupling to EM
- Interact gravitationally & through other forces (inc. non-SM forces)

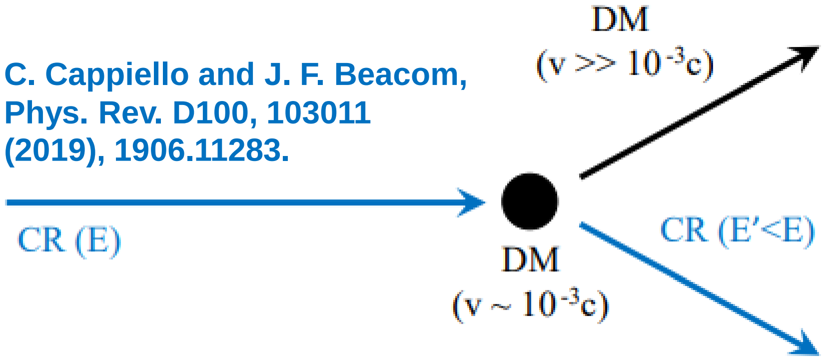
Direct detection of Light DM via recoiling nuclei

- Light DM have mass below 1 GeV
- Galactic DM must be non-relativistic so that it's still around

Boosted: Must accelerate DM to high energy via process like upscattering by Cosmic Ray (CR) collisions (**CRDM**)

- $\sigma_{\chi N} \neq 0 \rightarrow$ CR nuclei interact with DM
- DM effectively at rest
- Assumption: $\sigma_{\chi N}$ is independent of E_{DM}
- Initial DM velocity distribution washed out by CR collisions

CRDM Insensitive to DM vel. dist.



C. Cappiello and J. F. Beacom, Phys. Rev. D100, 103011 (2019), 1906.11283.

PROSPECT Boosted Dark Matter Search (CRDM)

PhysRevD 104 (2021) 012009

CRDM Source: most DM coming from Galactic Center (GC)

- For PROSPECT, varies from below horizon to 25° above
- Models: DM = Navarro-Frenk-White (NFW)
  CR = Local Interstellar Spectrum (He, p)
  - In this analysis, CR model constant over 2-week data period used

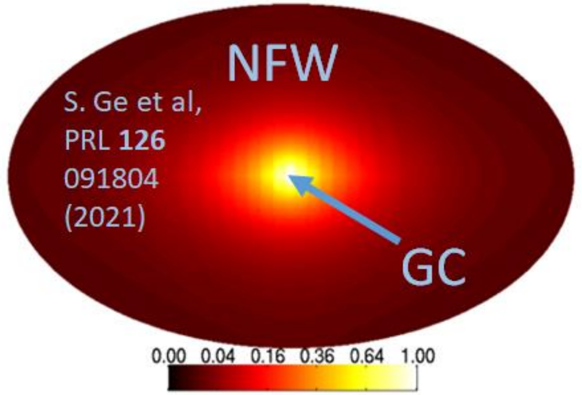
Must model atmospheric attenuation of DM due to large $\sigma_{\chi N}$ being tested

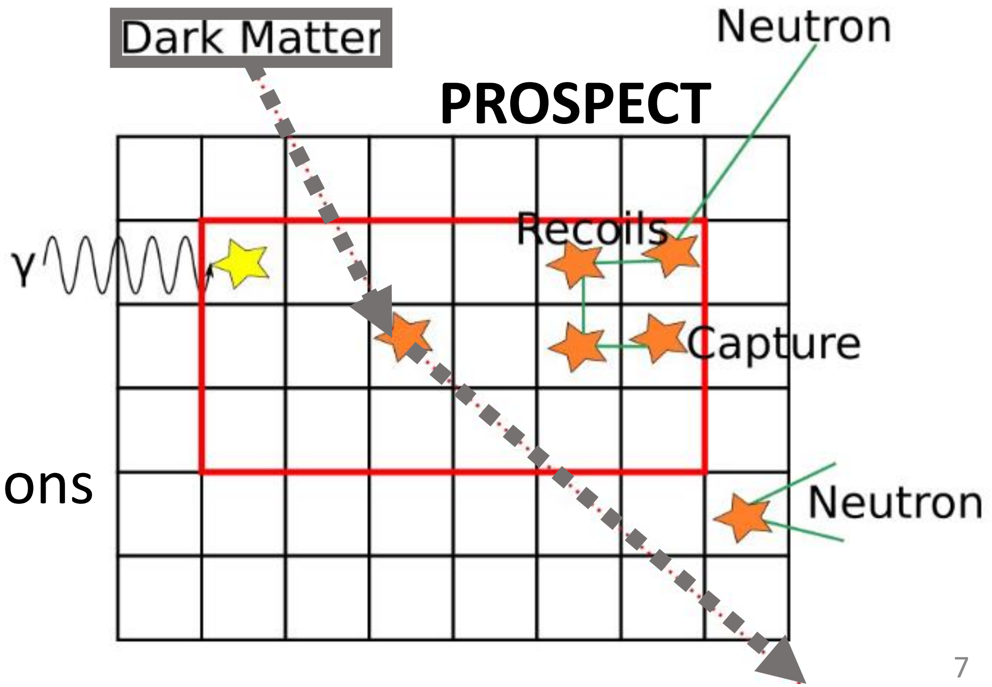
- Absorbed in Earth (below horizon)
- Multiple Scattering of DM
  - In atmosphere (even above horizon)
  - In shielding
  - Could be backscattered into space
  - Needs enough KE left for energy in recoiling nuclei to detect in PROSPECT

Direct detection via free protons recoiling from DM collisions

PROSPECT Sensitivity: 1 keV < m_χ < 1 GeV

CRDM Skypmap





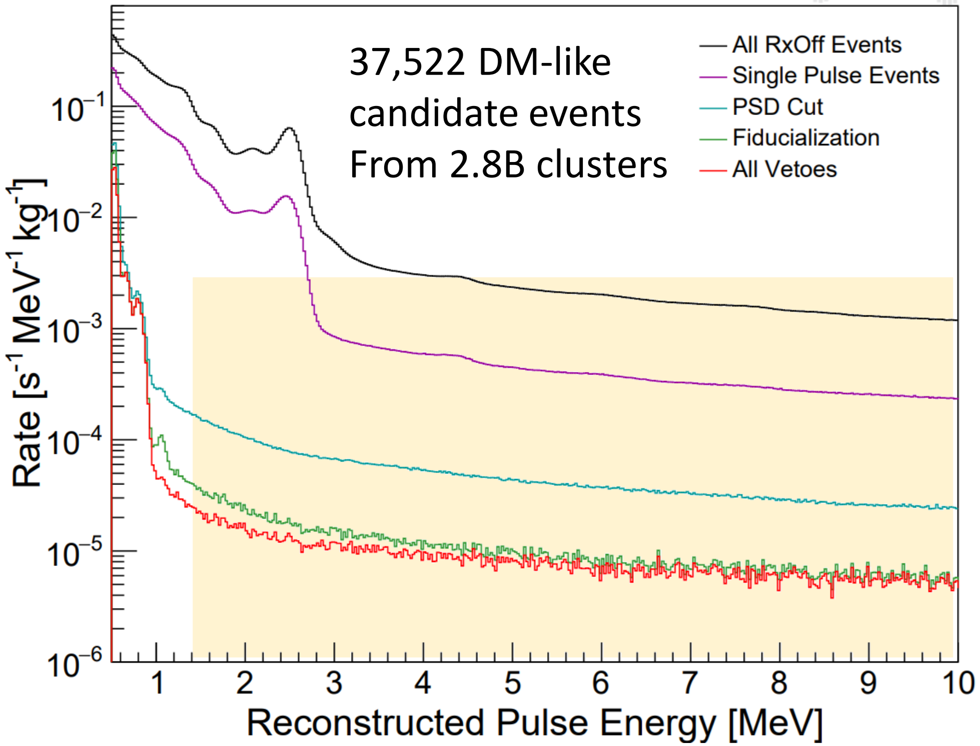
CRDM Event Selection

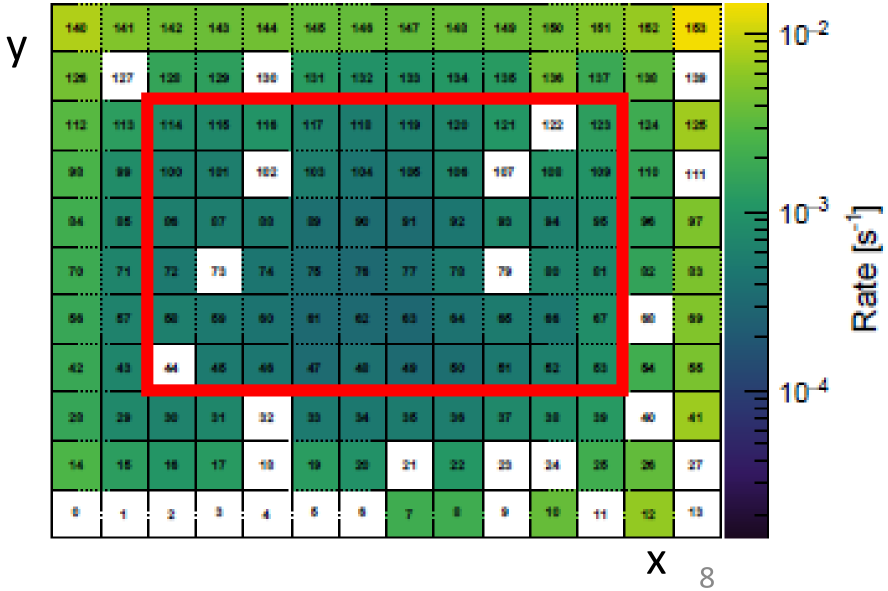
~14.6 solar days RxOff data
- March 16 – March 31, 2018

Event selection for proton recoil events
- Single Pulse (single segment)
- PSD $\leq 2\sigma$ from proton recoil PSD band
- Fiducialization:
  - Incident cosmic & secondary ns have a higher cross section, & $\therefore$ preferentially produce proton recoil signatures in edge of LS volume
  - $\rightarrow$ Remove events outside of red box, $|z| \geq 20$ cm
  - FV mass: 440 kg
- 1.5 MeV < E < 10 MeV to remove low-energy bg

Vetos (green → red)
- μ-induced: Veto events 5 μs after μ event (E > 15 MeV)
- p, n-induced: Veto events within ± 5 μs of a nuclear recoil event & Veto signals < 500 μs before an nLi capture signal
- Impact: removes bg events between 1 to ~4 MeV
- Correct rate for veto deadtime

Cuts & Vetos reduce bg by $10^{2.5} - 10^{3.5}$





CRDM Spectral Comparison

Spectral Predictions (right)

- E>2 MeV: flatness & lack of distinct spectral features
- E>1.5 MeV: spectral shape predictions are insensitive to other aspects of detector response
- Necessitates time-dependent study using total rate per hour (total counts for 1.5 - 10 MeV)
- Expect a diurnal signal in sidereal time
  - Bottom-Right: 2 km underground LXe example
- Signal (modulation) would have period of 1 sidereal day
  - 2-week data period → not much different than solar time
  - Expected High (Low) DM Flux signal for PROSPECT: 22:00 – 2:00 (10:00 – 14:00) GMST

Also consider how variations in the incident cosmic ray flux would effect modulations in the signal-like event rates

- Checked anti-FV during high, low flux periods
- Found no modulation in the cosmogenic background

Strongest predicted DM flux: Midnight – 1 AM GMST

- 37.5k candidate events

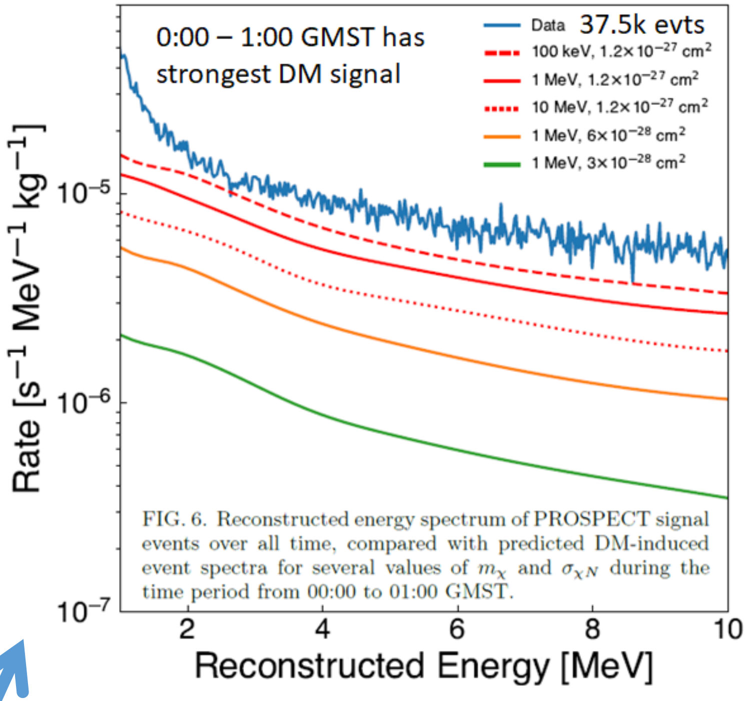


FIG. 6. Reconstructed energy spectrum of PROSPECT signal events over all time, compared with predicted DM-induced event spectra for several values of m_χ and $\sigma_{\chi N}$ during the time period from 00:00 to 01:00 GMST.

S. Ge et al, PRL 126 091804 (2021)

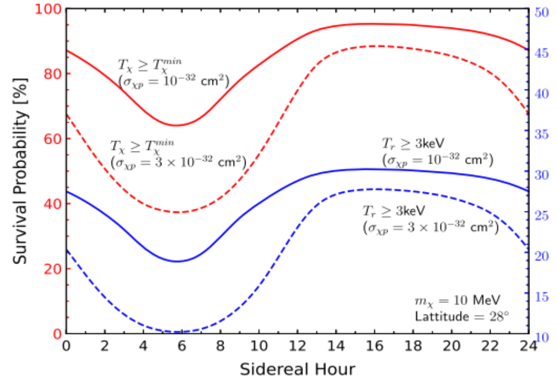
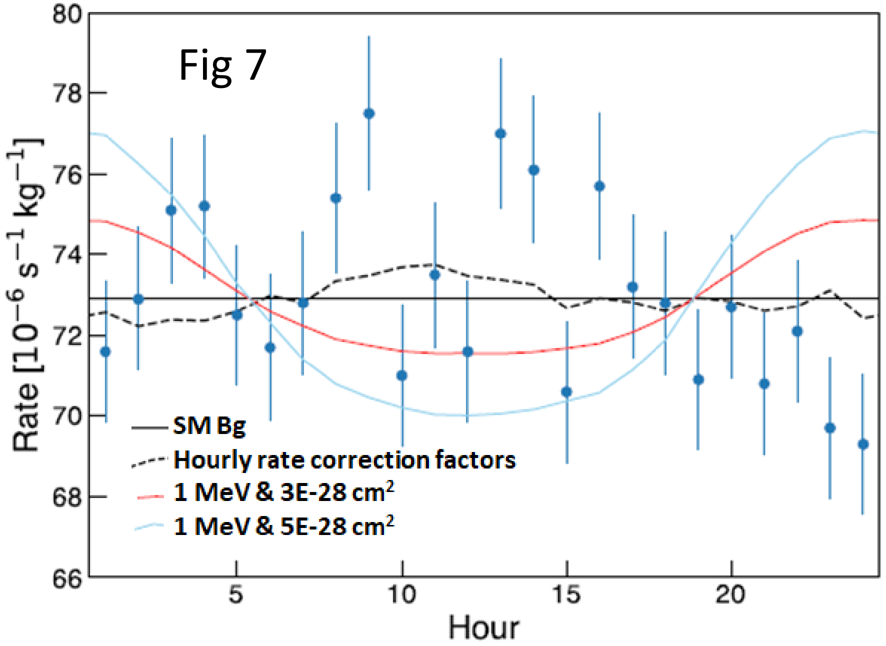


FIG. 4. The survival probability of CRDM arriving at an underground lab at latitude 28°N and a depth of 2 km vs the sidereal hour relative to the number of DM particles arriving at the Earth for two different cross sections $\sigma_{\chi p} = 1(3) \times 10^{-32}$ cm^2. The red curves correspond to the total CRDM arriving at the detector with $T_\chi \geq T_\chi^{\rm min}$, and the blue curves are those above the detector threshold ($T_r > 3$ keV for a liquid xenon detector).

PROSPECT CRDM Analysis Results

Bin data in sidereal time (right)
& search for sinusoidal modulations

- Data consistent with lack of daily modulation → **no DM signal**
- Use Gaussian CLs method to get 95% CL parameter exclusion region (bellow)



Hour 1 corresponds to 0 – 1 AM GMST.

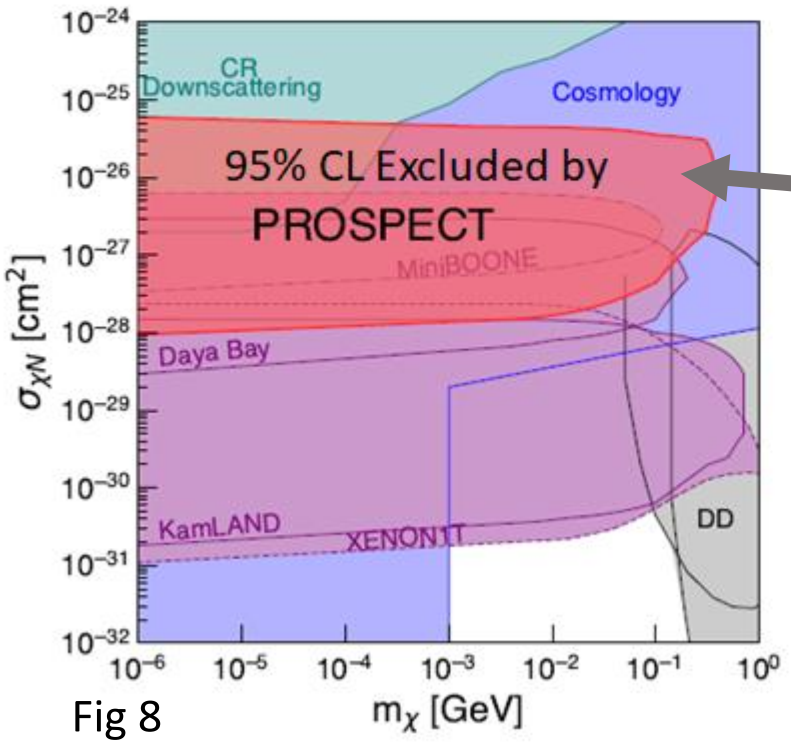


Fig 8

Upper $\sigma_{\chi N}$ region

- **First terrestrial experiment to exclude this region**
- **Complementary to cosmology observations**
- Upper bound limited by atmospheric attenuation

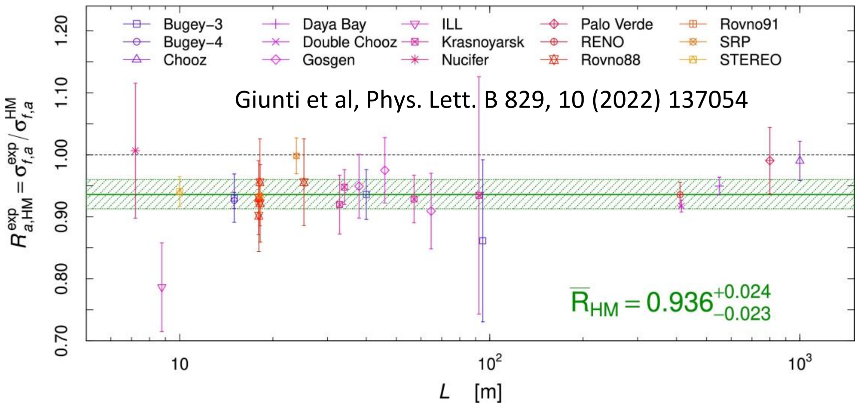
$\sigma_{\chi N}$ lower bound limited by

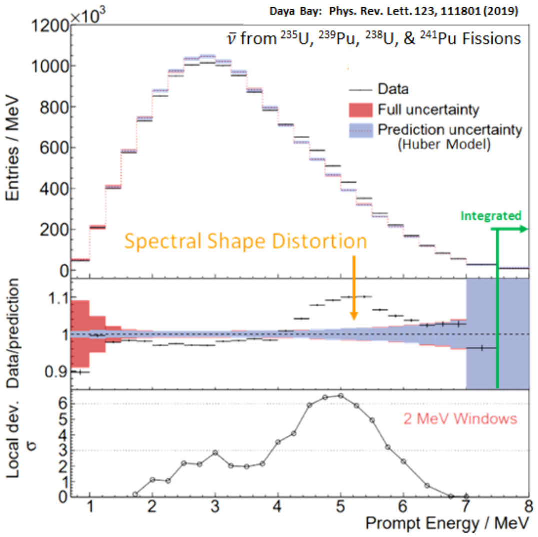
- DM flux through PROSPECT
- Background rejection
- CR & DM distribution models

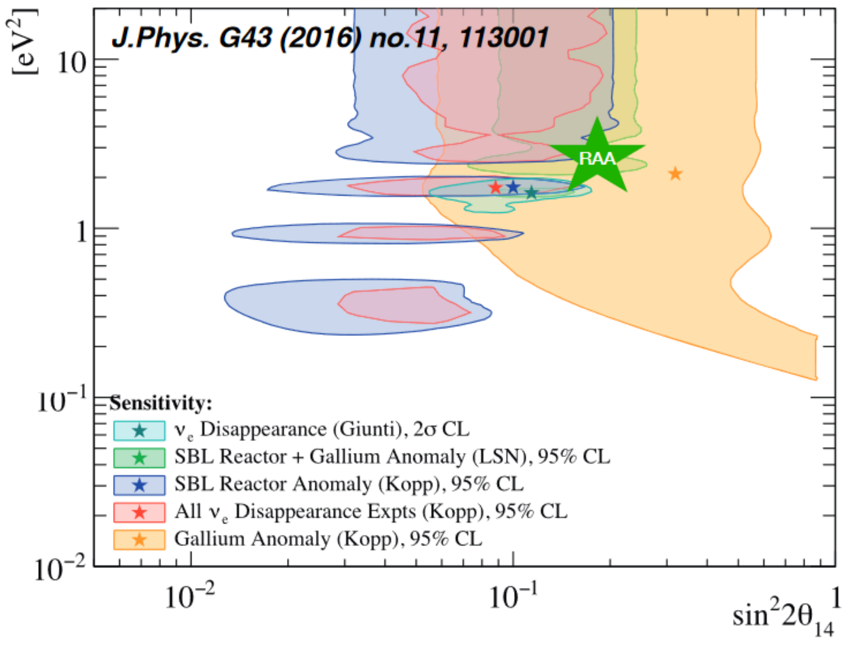
PROSPECT Studies Reactor Antineutrino Anomaly (RAA)

Motivation is RAA: World average $\bar{\nu}$-flux observations from reactors 6% less than predictions

- Based on Huber-Mueller (HM) model & 3-flavor neutrino oscillations
  - Time-varying Low Enriched Uranium (LEU) reactor composition: $\mathbf{^{235}U}$, $\mathbf{^{239}Pu}$, ^{238}U, & ^{241}Pu
- Another anomaly: spectral bump seen around 5-MeV in SBL & θ_{13}-measuring experiments.
- Discrepancies 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).



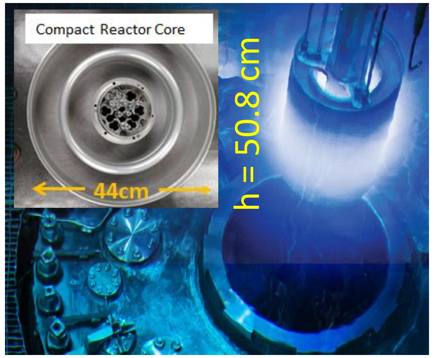


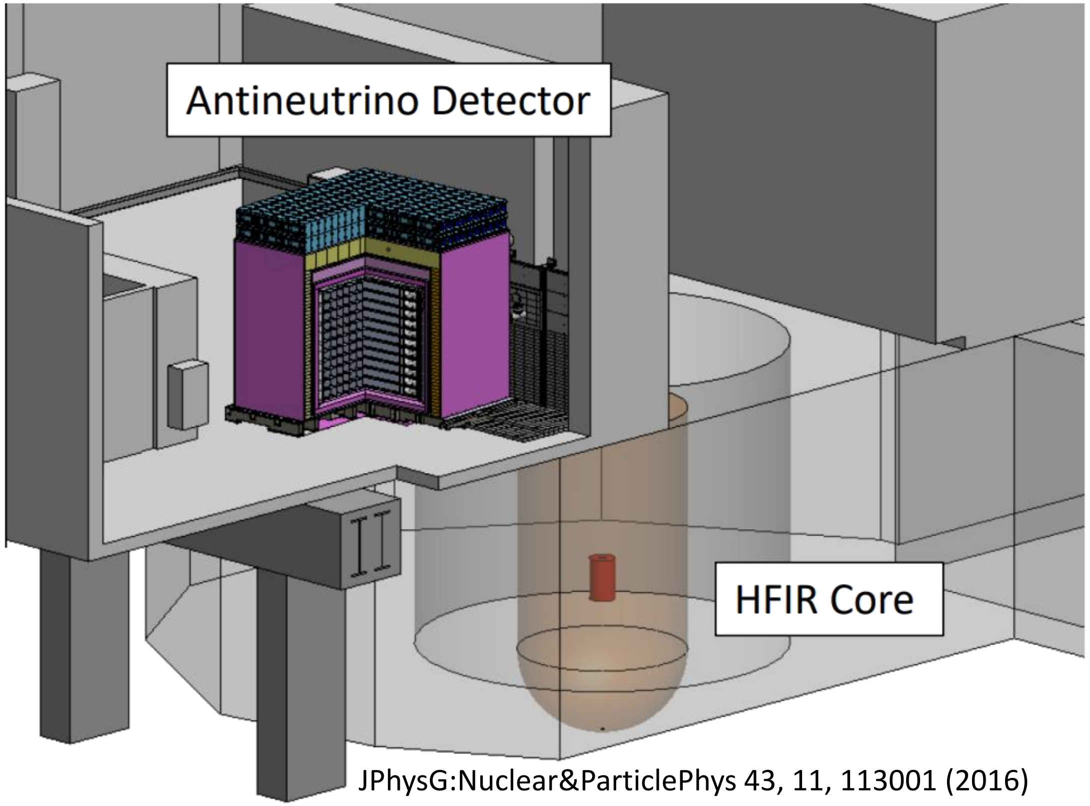


PROSPECT Experiment tests these anomalies by performing:

- Precision measurement of ^{235}U $\bar{\nu}_e$ spectrum (high statistics)
- Reactor-model independent search for eV-scale ν_s via $\bar{\nu}_e$-disappearance

PROSPECT at ORNL's HFIR (revisited)





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

High Flux Isotope Reactor at Oak Ridge National Lab

- 85 MW Reactor w/ 24 day duty cycle (On/Off)
- Compact Highly Enriched Uranium (HEU) core
  - 93% pure ^{235}U fuel
  - > 99% $\bar{\nu}_e$ emitted by ^{235}U fissions

Detector on surface near core

Challenges for IBD Analysis

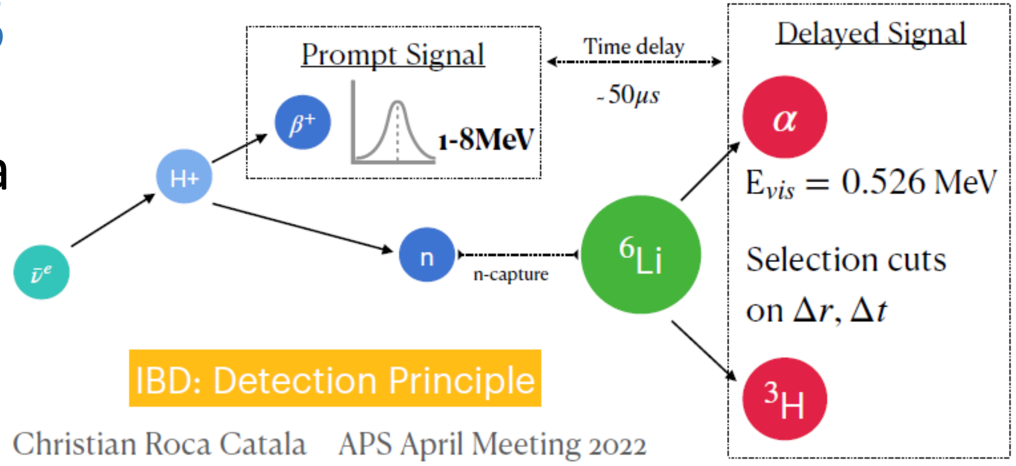
- No overburden to shield from cosmic rays:
  - **$\sim$1 meter water equivalent (mwe)**
  - **High rate cosmic-ray induced activity (μ & n)**
    - **Cosmogenic neutron flux is primary correlated background for IBDs**
- Reactor-induced accidental backgrounds

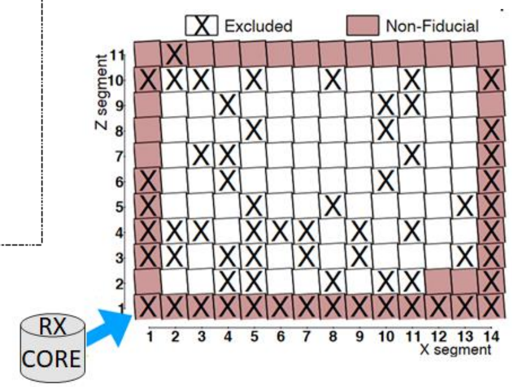
PROSPECT IBD Analysis

PhysRevD 103 (2021) 032001

Reactor $\bar{\nu}_e$ detection in PROSPECT via Inverse Beta Decay: $\bar{\nu}_e + \mathrm{p} \rightarrow \beta^+ + \mathrm{n}$

- Prompt β^+ & Delayed nLi signal
  - Tag n via PSD of n-capture on ^{6}Li
- Achieved 10^4 Background Rejection
  - Selection Cuts (Δt & Δr)
  - Exclude bad segments, employ fiducialization, & veto bg
  - Correct for veto deadtime

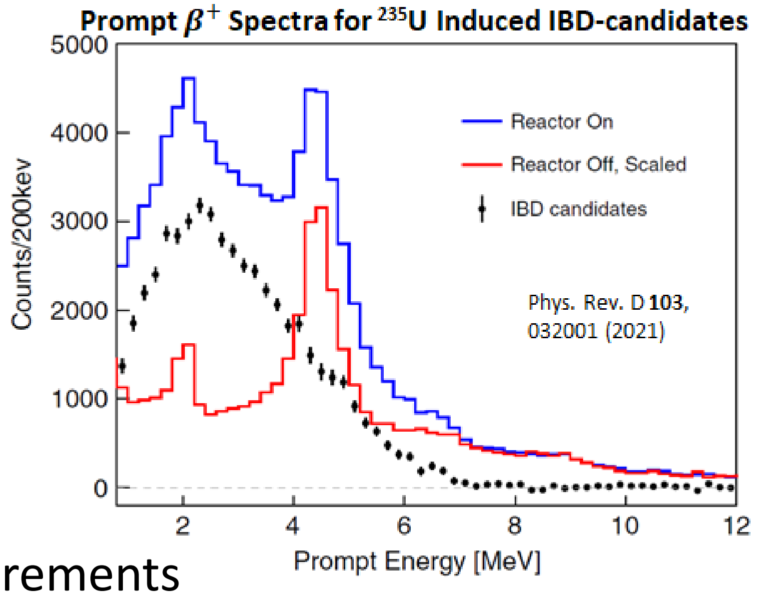


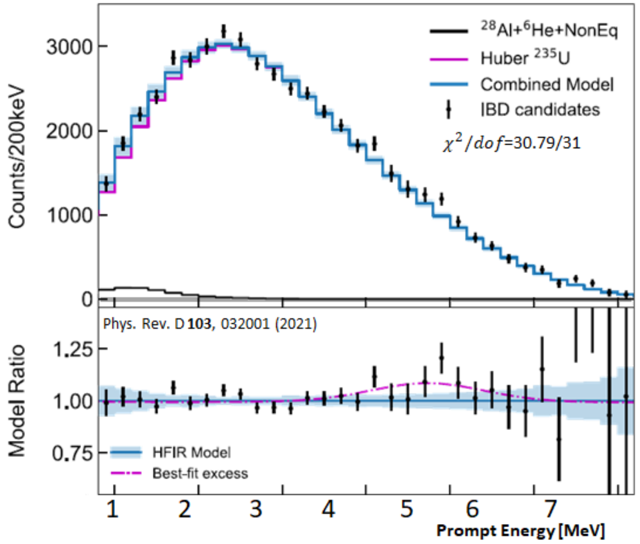


Use **RxOff** data for bg subtraction from **RxOn** data to get **prompt β^+ spectrum from IBD candidates**.

Right: ^{235}U Spectrum Results (PRD)

- Reference spectra for pure ^{235}U, helps disentangle LEU results w/ their mixed fuel composition
- Consistent w/ Daya Bay LEU measurements
- Disfavors no-bump scenario (2.17σ) & disfavors scenario of bump solely due to ^{235}U fissions (2.44σ)



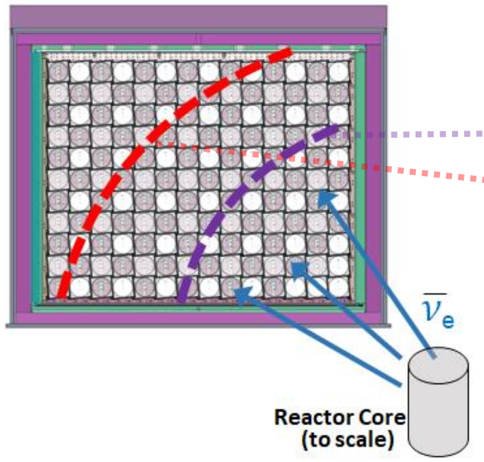


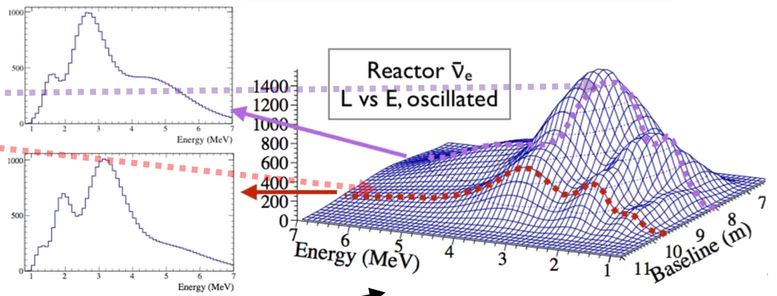
Search for $\bar{\nu}_e$ Oscillations to Sterile Neutrinos

PhysRevD 103 (2021) 032001

PROSPECT placed close to HFIR

- Compact HFIR HEU core → oscillations do not wash out
- Several meters of the segmented detector volume close to core → multiple baselines (L) to simultaneously look for $\bar{\nu}_e$ disappearance

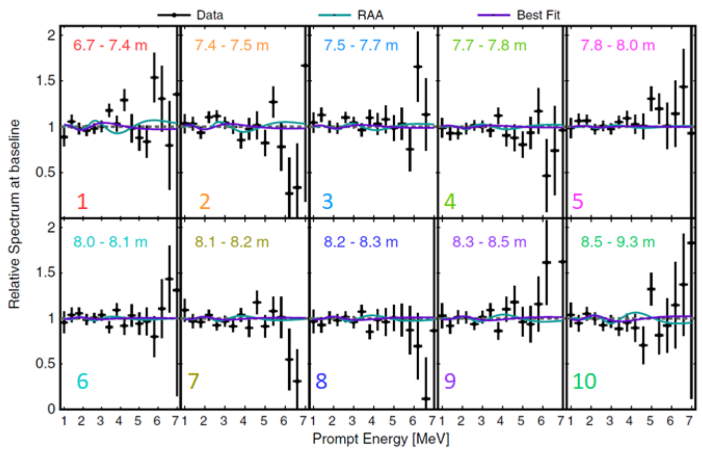




$$P_{\text{dis}} = \sin^2 2\theta_{14} \sin^2\left(1.27\Delta m_{14}^2[\text{eV}^2]\frac{L\,[\text{m}]}{E_\nu[\text{MeV}]}\right)$$

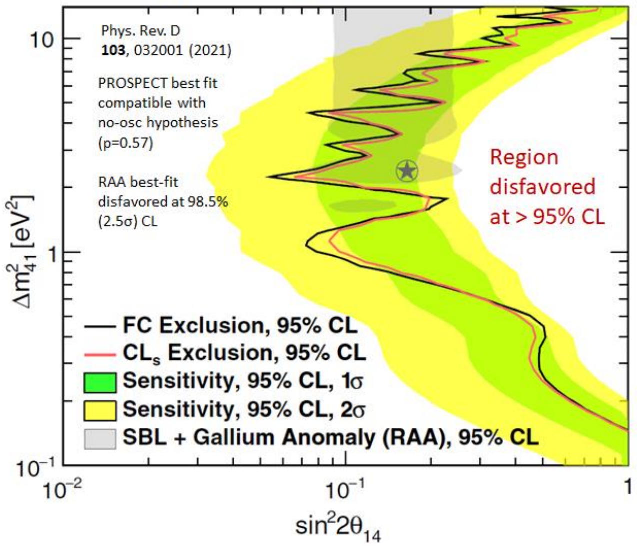
Analysis

- Remove reactor-model dependence on oscillations
  - Look for relative spectral-shape distortions in PROSPECT's identical detector segments
  - χ^2 comparison of relative spectra across 10 baselines
  - Exclusions: Gaussian CLs, Feldman-Cousins
- 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

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



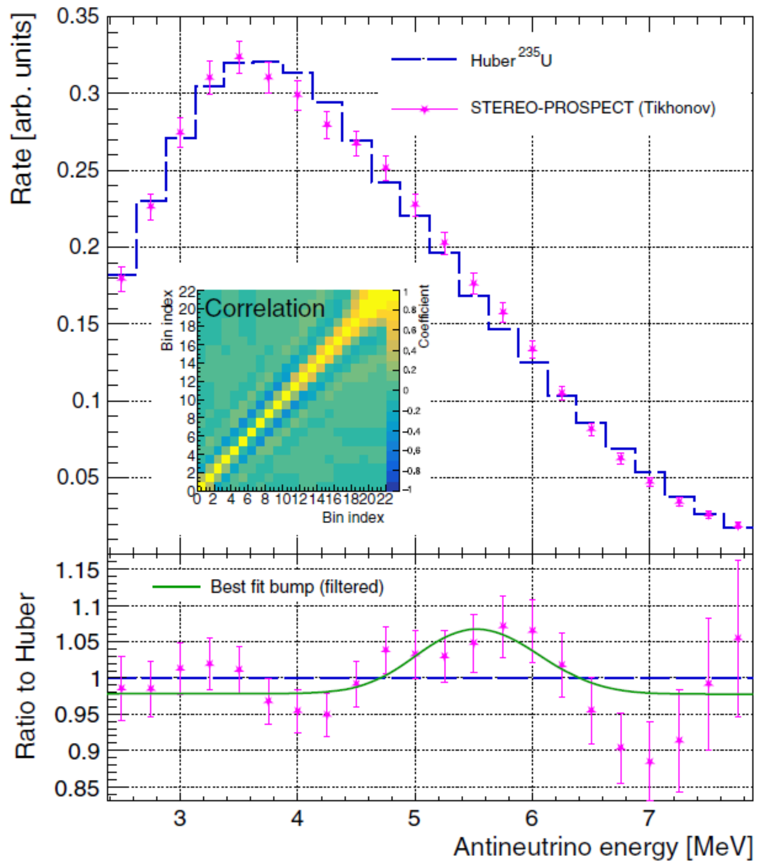
What else can we do?

- Absolute flux measurement in the works

PROSPECT Joint Spectrum Analyses with STEREO, DAYA BAY

PROSPECT + STEREO (^{235}U HEU)

PhysRevLett 128 (2022) 081802

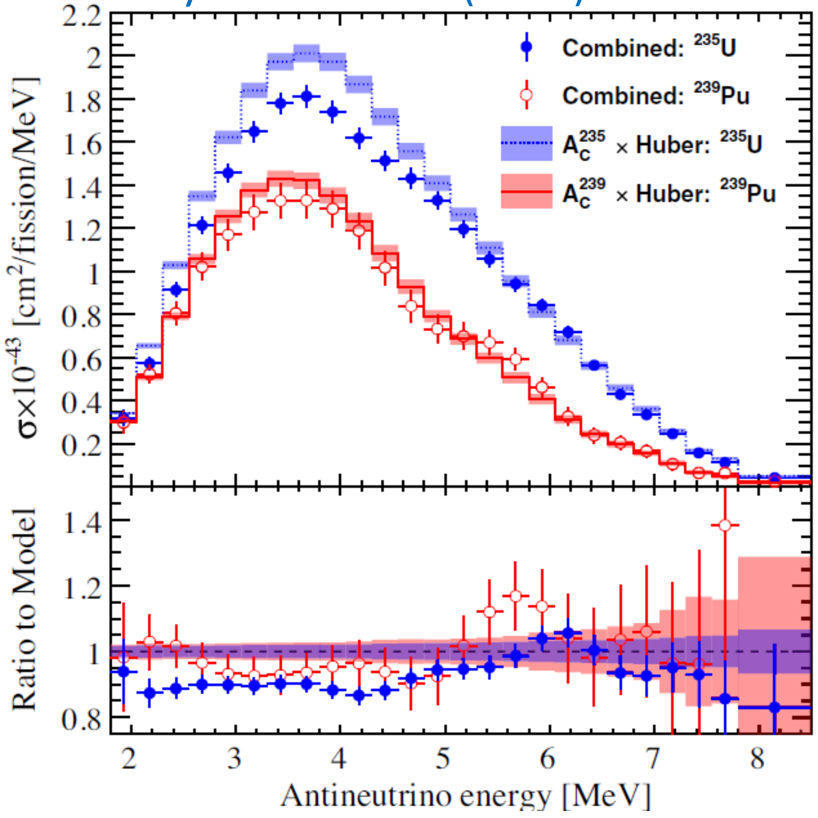


- Improved ^{235}U reference
- Bump excess at 2.4σ

- Comparison to HM in unfolded ($E_{\overline{\nu}_e}$) space
  - Verifies compatibility
- Unfolding via Tikhonov regularization, or WienerSVD
  - Improved uncertainties for ^{235}U spectral shape
  - Positive results in combining HEU/LEU experiments
- Stronger confirmation of 4-6 MeV excess (bump)

PROSPECT + Daya Bay (HEU+LEU)

PhysRevLett 128 (2022) 081801



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

Information Recovery From “Bad” Detector Segments

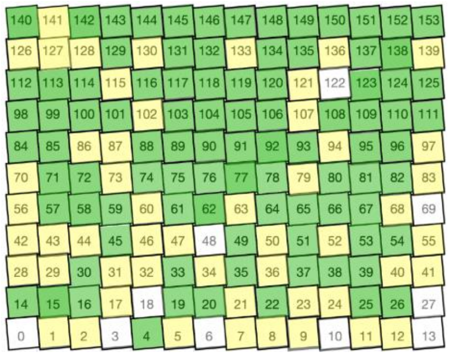
PhysRevD 103 (2021) 032001

PRD Analyses only use live segments with both PMTs operational throughout entire PROSPECT data collection.

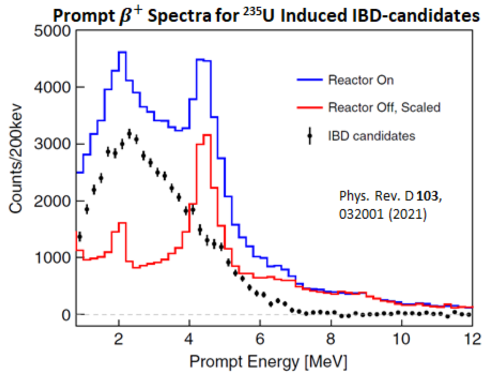
Actual # of dead segments increases with time due to LS ingress, so perform Data Splitting into periods to maximize # live segments.

- Segments with 1 good PMT still have good enough PSD info for bg suppression: recover for vetoing bgs.
- Combine periods w/ the unfolding techniques (prev. page)

Will be used in upcoming analyses:
Spectrum, Oscillation, & Absolute Flux

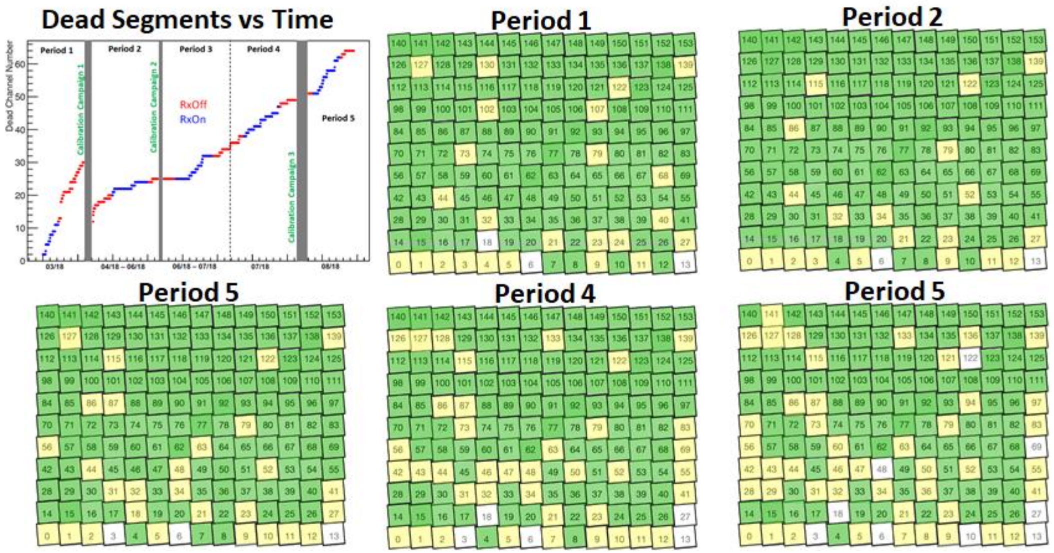


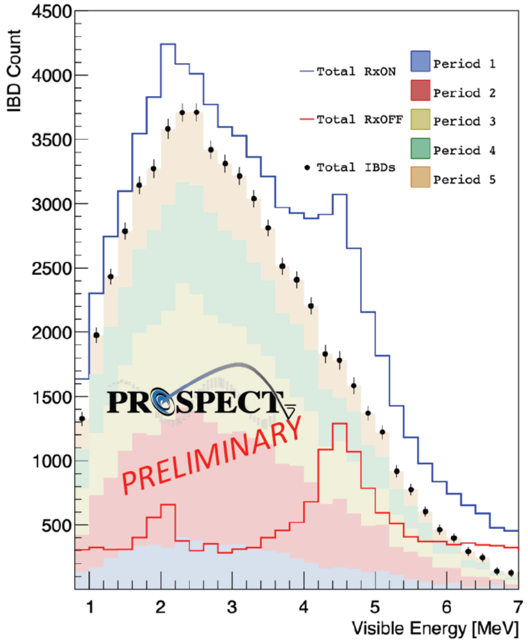
Live Single PMT Dead

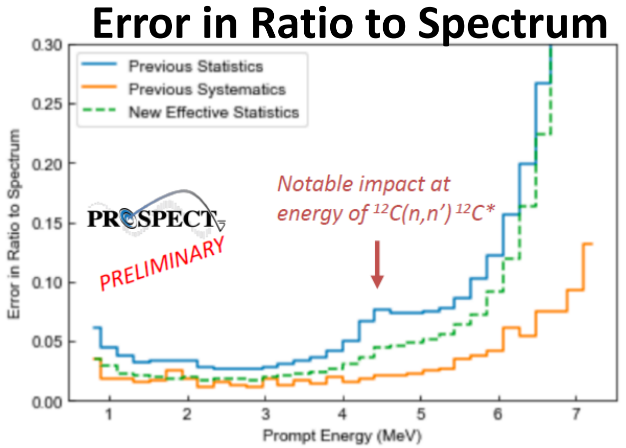


Improvements:

S:B	1.4 → 3.8	x2.7
# IBDs	~50k → ~60k	x1.2
Effective Stats	~15k → ~30k	x2.0

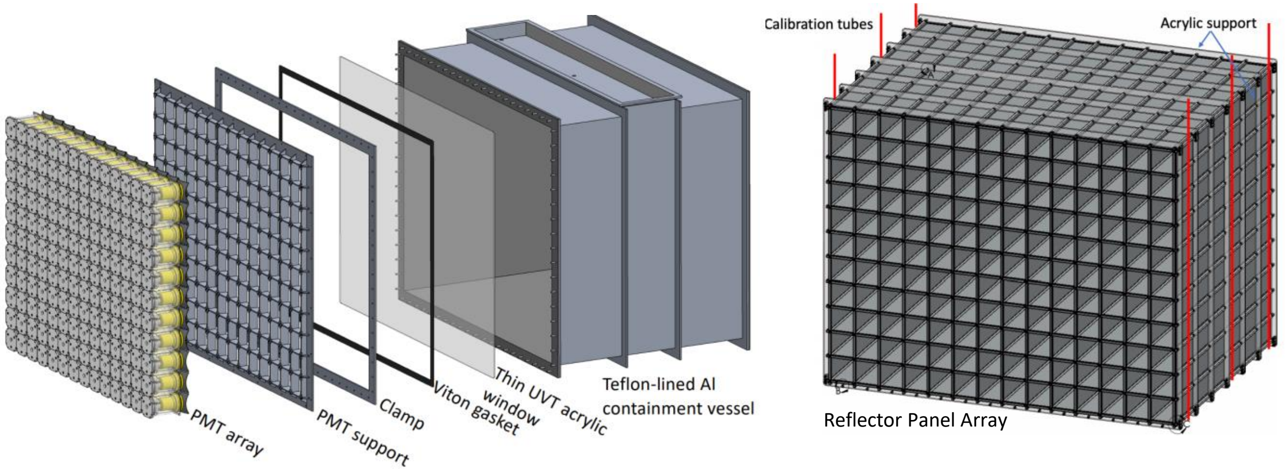






Proposed PROSPECT-II Upgrade

arXiv:2107.03934 & arXiv:2202.12343



Evolved design that addresses PROSPECT-I technical issues

- Robust: Complete separation of PMTs from LS volume
- Slight increase in detector volume
- 1 year construction period: reuse existing equipment

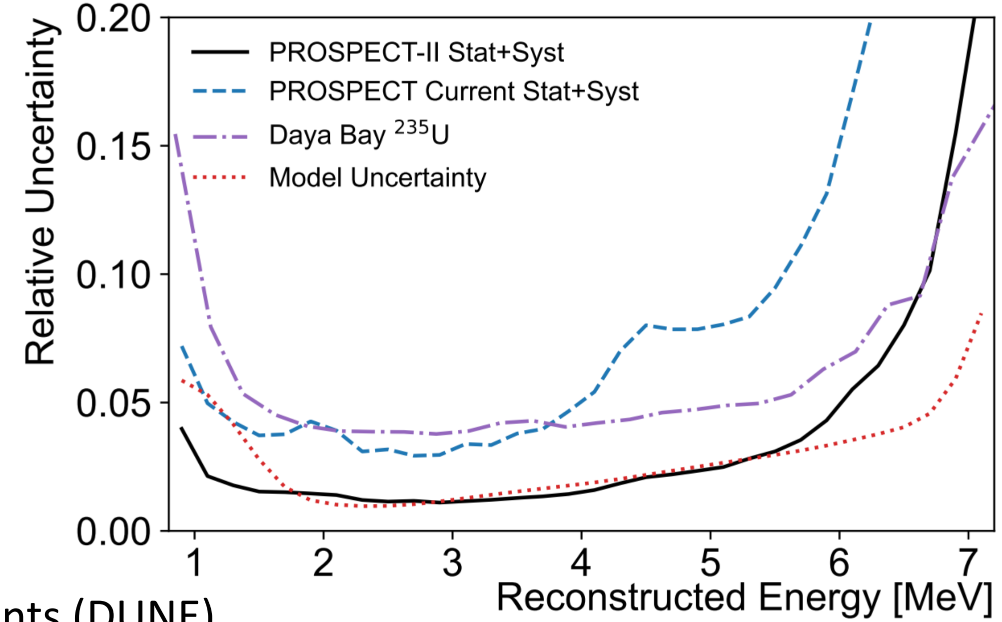
Transportable: same detector deployed at HFIR (HEU) & commercial LEU reactors (mixed fuel composition).

- Measurements with correlated detector systematics
- No detector has taken measurements at both reactor types

^{235}U spectrum uncertainty (stat+sys) reaches model precision w/ ~2 years data at HFIR

Significant improvement of isotopic yields with high statistic ^{235}U data, especially combining with other experiments or measuring both reactor types

Case	Description	Precision on σ_i (%)		
		^{235}U	^{239}Pu	^{238}U
1	Daya Bay LEU	3.7	8.2	30
2	Daya Bay LEU + P-II HEU	2.4	6.3	21.3
3	P-II LEU + P-II HEU+	1.4	3.4	15.9
4	P-II LEU + P-II HEU+, Correlated	1.4	3.0	8.7
-	Model Uncertainty [66]	2.1	2.5	11.2



Improved sterile neutrino limits will help with CP-violation measurements (DUNE)

Summary

- PROSPECT Boosted DM results:
  - Surface detector design allows for BDM analysis, sensitivity to low m_χ
  - First dedicated experimental analysis constraining sub-GeV DM by considering upscattering by CRs
  - First to exploit the diurnal sidereal modulation of the Boosted DM signal
  - Addresses regions of parameter space never before probed by terrestrial experiments
- PROSPECT reactor antineutrino measurements:
  - PRD results with ^{235}U spectrum, ν_s parameter space exclusions
  - Absolute flux measurement in the works
  - ^{235}U spectrum analysis updates:
    - Combined with other experiments
    - Updated analyses to maximize collected data from PROSPECT
  - Plans for an improved PROSPECT-II detector

Backup

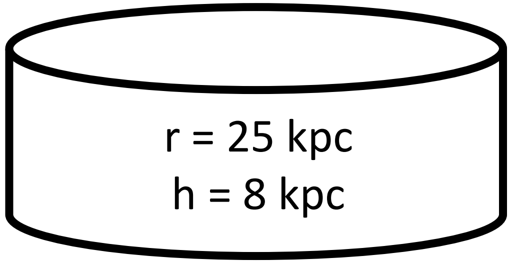
June 2021 Collaboration Meeting, 43 Collaborators

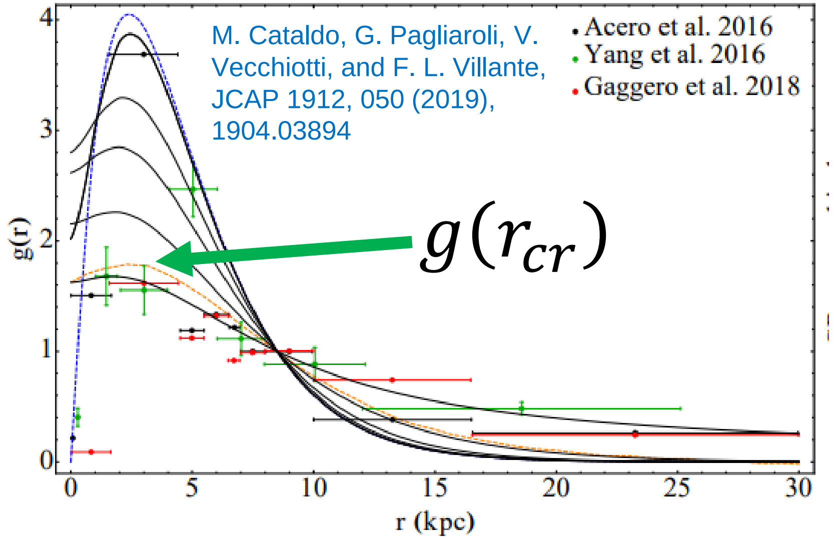
Local Interstellar Spectrum (LIS) Cosmic Ray Model

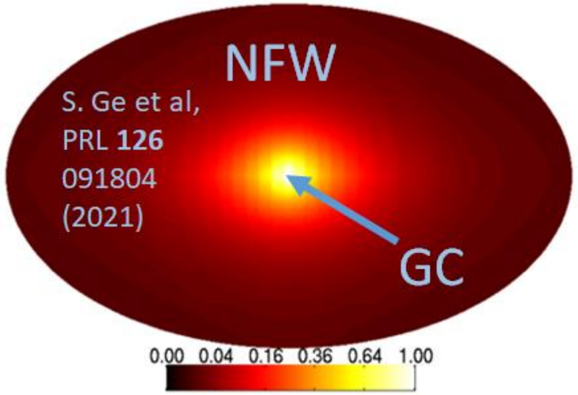
- DMs can come from anywhere in the local galactic region, may be different than CR spectrum seen at Earth (Solar B-field).
- LIS gives spectrum for H & He
  - Independent of location: γ-ray observations show LIS is similar to CR spectrum elsewhere in Milky Way
- CR Halo: galactic B-field confines CRs; approx. cylinder
- CR density (Prospect Analysis):

$$\rho_{\mathrm{CR}}(r_{cr}, z) = \rho_0\, g(r_{cr})\Theta(25 - \mathrm{r}_{\mathrm{cr}})\Theta(4 - |z|)$$

  - ρ_0: match above equal to LIS @ Earth
  - Θ is Heaviside step function
  - Assume ρ_0 is t-independent (2-week data period for analysis)
- CRDM skymap using NFW DM distribution.







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

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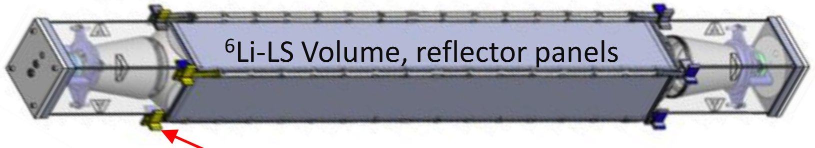
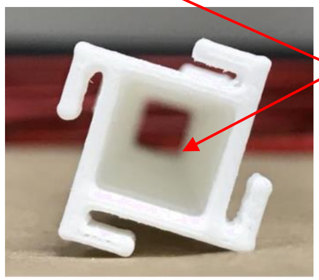
y

x

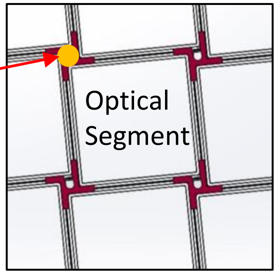
Reactor Core

Single Segment: 119 cm x 15 cm x 15 cm



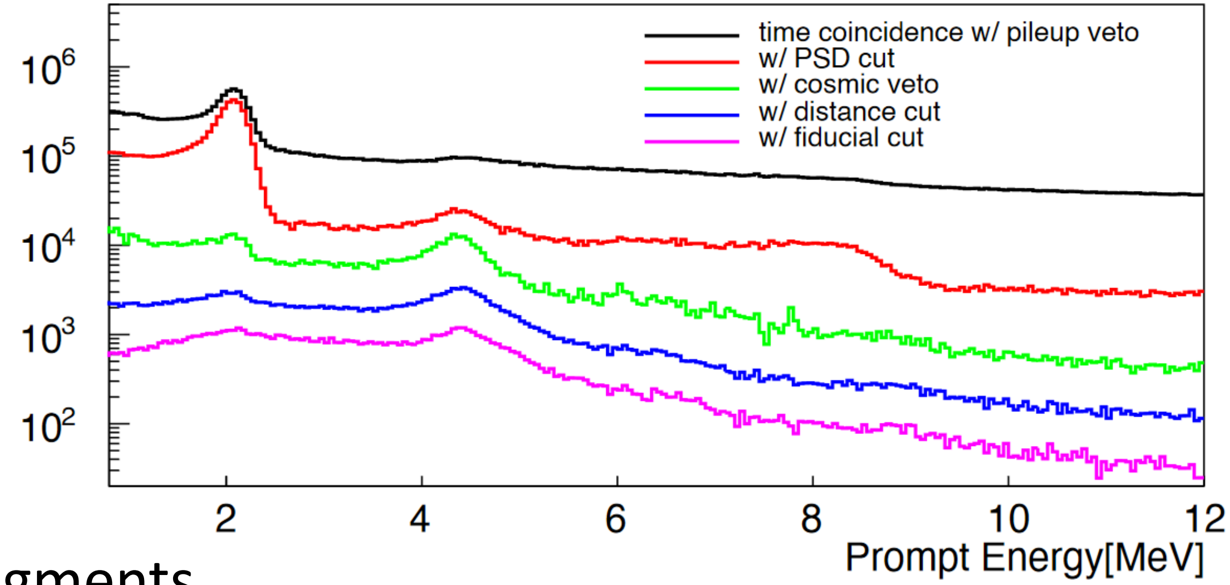


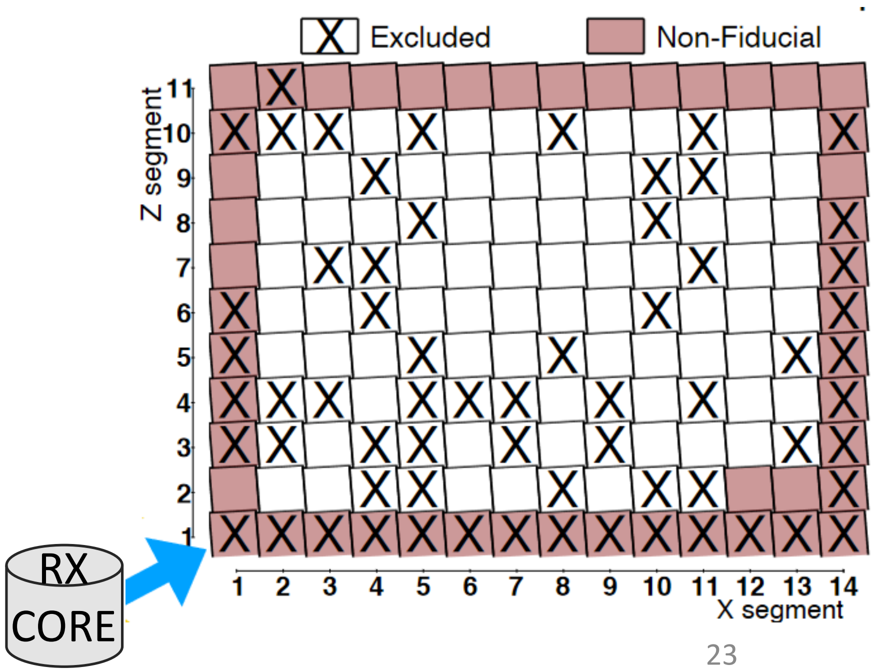
3D-printed rods w/ in-situ calibration source access



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

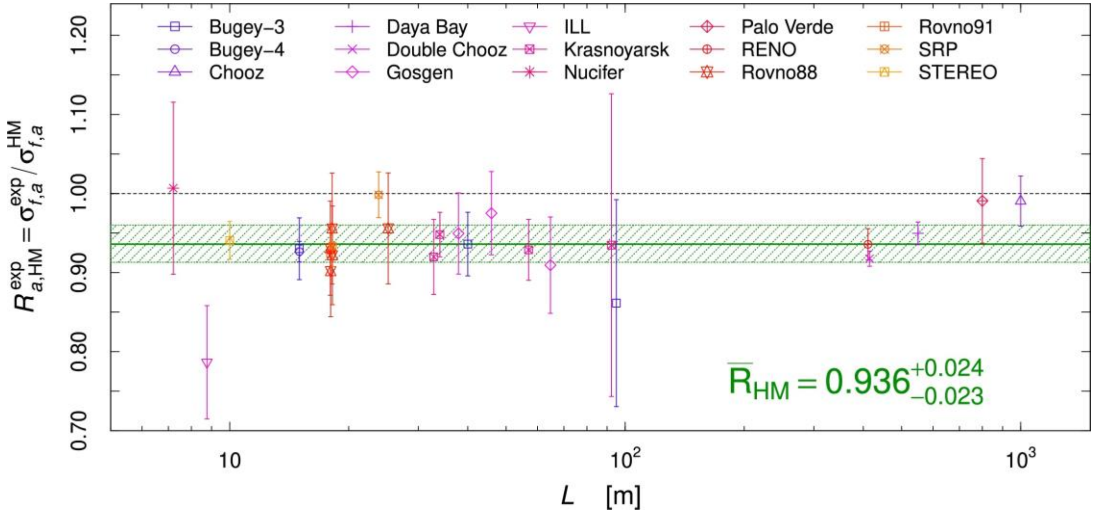


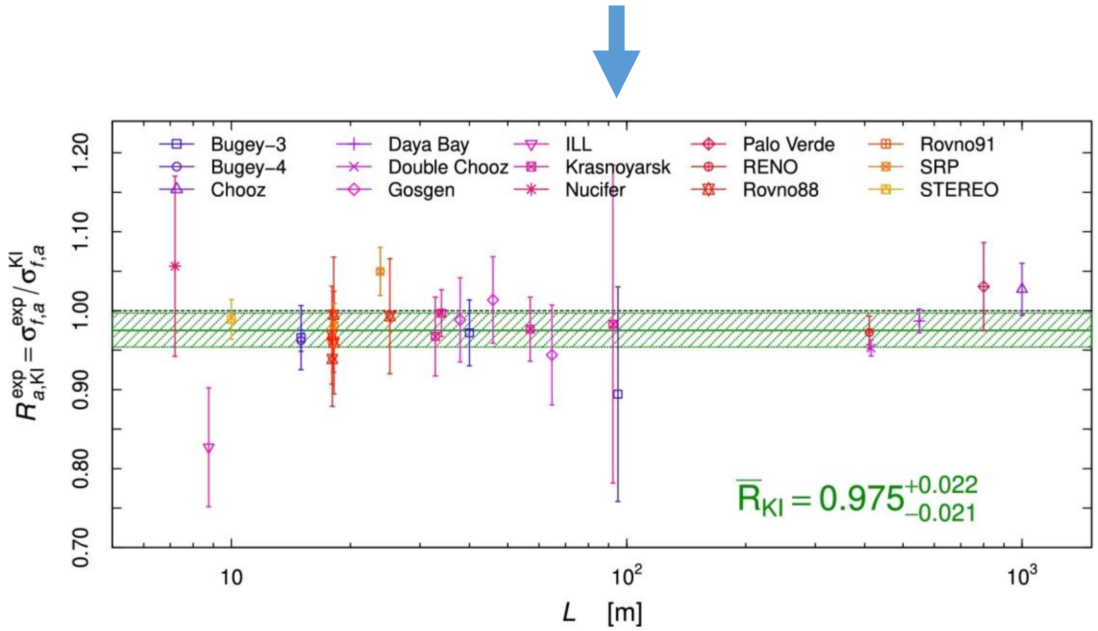


Incomplete Models Seem To Cause RAA

- RAA: World average flux observations 6% less than theoretical predictions
  - Majority of discrepancy seems to be coming from flawed, incomplete reactor modeling and nuclear data
- Prediction models based on Huber+Mueller & 3-flavor neutrino oscillations
- Updated β-spectrum measurements from U^{235} fissions & nuclear/reactor modeling remove most of the deficit
  - Kopeikin, Skorokhvatov, & Titov, Phys. Rev. D 104, L071301 (2021)
  - Berryman & Huber, JHEP 2021, 167 (2021)
  - Giunti, Li, Ternes, & Xin, Phys. Lett. B 829, 10 (2022) 137054
- No RAA at 1.1 σ to 1.5 σ depending on model

Giunti et al, Phys. Lett. B 829, 10 (2022) 137054





(c) KI model [24]: no RAA ($1.1\,\sigma$).

Skymap of CRDM

- S. Ge et al, PRL 126 091804 (2021)
- CRDM depends on both the spatial & spectral distributions of CRs & DM
  - Varies w/in galaxy
  - CR & DM concentrated @ core
    - Signal from core

- Top: NFW model
  - standard reference model for DM distribution
- Bottom: simpler cored isothermal distribution for comparison

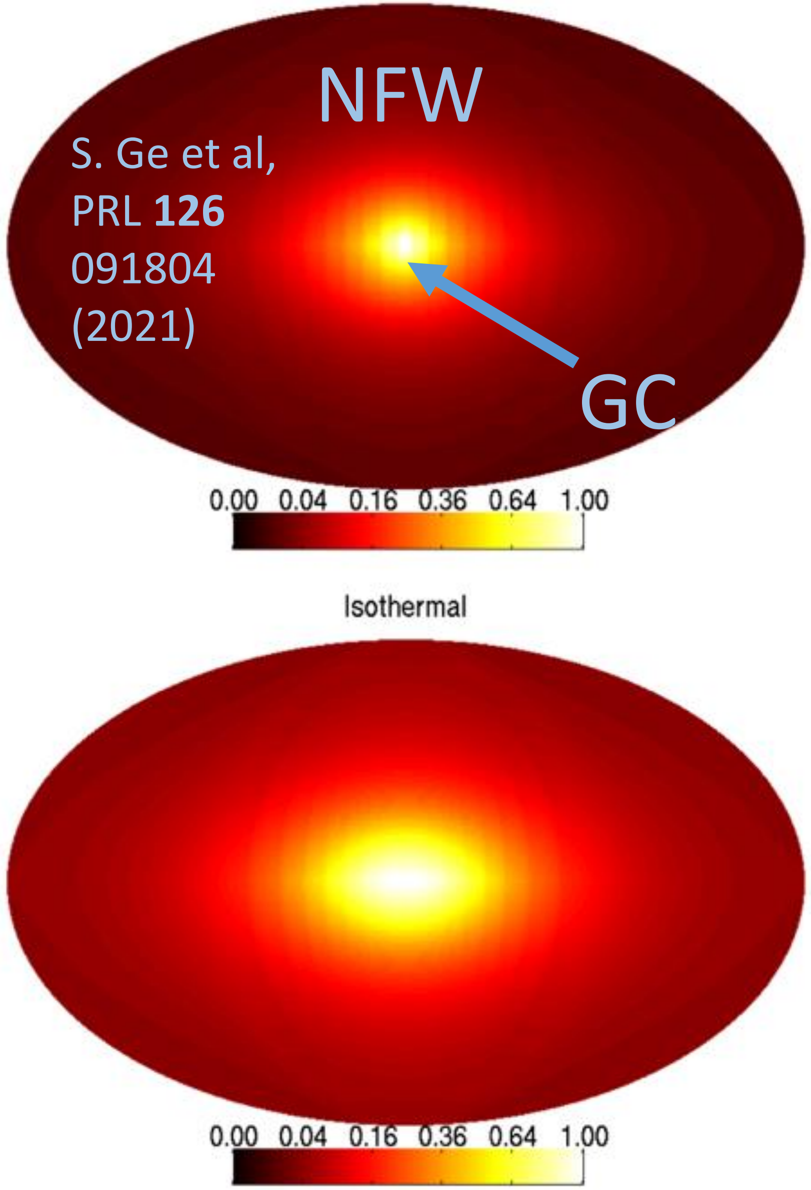


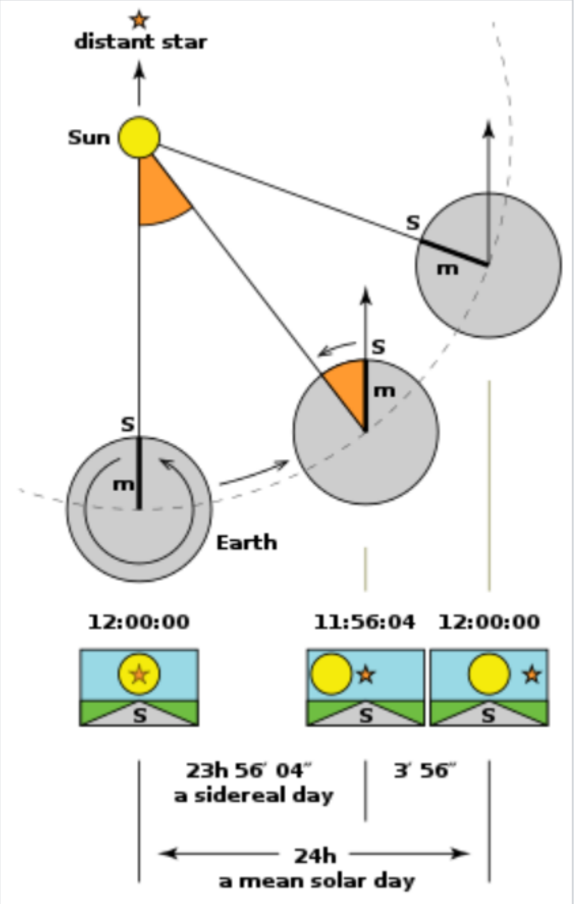
FIG. 1. Relative sky maps of CRDM fluxes in the Galactic coordinates with amplitude in the GC direction set to unity. The upper and lower panels are for the NFW and Isothermal DM density profiles, respectively.

Propagate DM to Detector through Atmosphere

- Multiple scattering of DM in atmosphere & shielding
  - Shielding: building (< 1 m water equivalent, negligable), detector shielding
  - Based on interaction cross sections $\sigma_{\chi N}$
  - Too high cross-section:
    - DM doesn't have enough energy left @ detector & get detected
    - May even be scattered back into space
  - Require incident DM above horizon (Otherwise attenuation kills 'em)
    - DM $\sigma_{\chi N}$ considered in analysis are large, so DM can attenuate in atmo, even above horizon
    - For PROSPECT location, Galactic Center varies from 25° above horizon to below
- Initial KE pulled from spectrum
- Initial direction based on Line-of-Sight integral of DM×CR density functions
- Only continue tracking particles that'll make it to detector & be detectable
- PROSPECT Sensitivity: 1 keV $< m_\chi <$ 1 GeV, search DM Energies: 25 MeV – 1 GeV

Sidereal time

- As the boosted DM density is location dependent and far away from Earth, it varies over the course of a solar day & from day to day.
  - Sources not dependent on solar cycle
  - Earth blocks sources below horizon
- Signal (modulation) would have period of 1 sidereal day (not 1 solar day).
  - There is one more sidereal day per year than solar day
  - Use diurnal sidereal time to search for signals
  - Also consider variations in the flux of incident cosmic n & μ that would effect modulations in the signal-like event rates.



Sidereal time vs solar time. **Above left**: a distant star (the small orange star) and the Sun are at culmination, on the local meridian **m**. *Centre*: only the distant star is at culmination (a mean sidereal day). *Right*: a few minutes later the Sun is on the local meridian again. A solar day is complete.

https://en.wikipedia.org/wiki/Sidereal_time

CRDM Signal

- Expected diurnal signal in sidereal time
  - Right: LXe example
  - Signal (modulation) would have period of 1 sidereal day

- Also consider variations in the flux of incident cosmic n & μ that would effect modulations in the signal-like event rates.

S. Ge et al, PRL 126 091804 (2021)

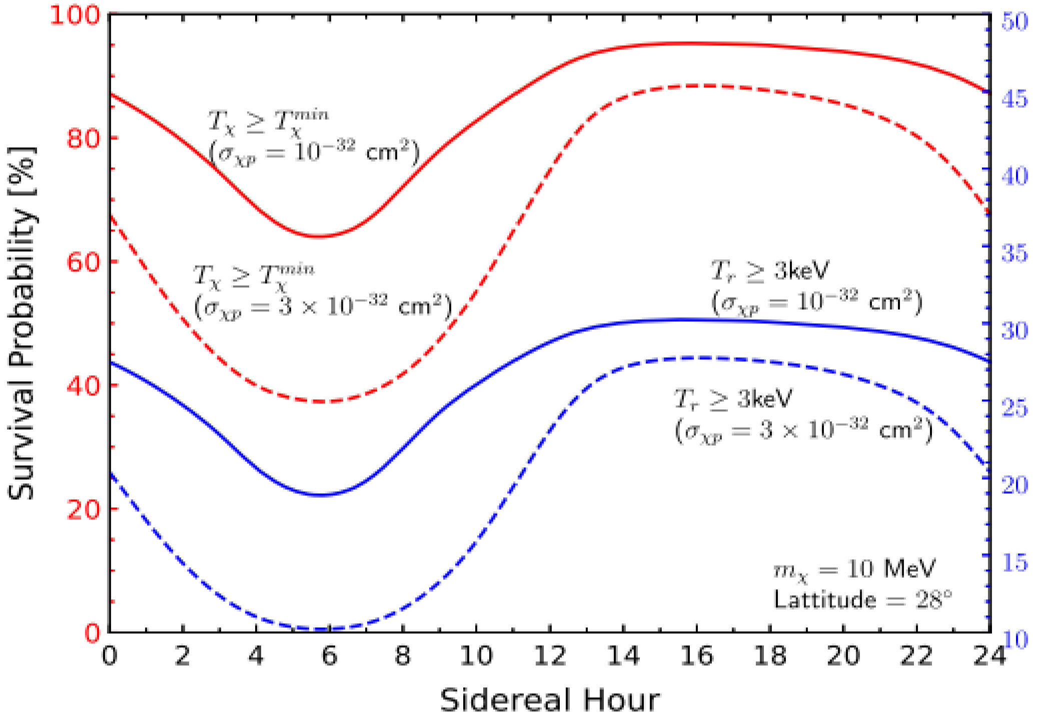
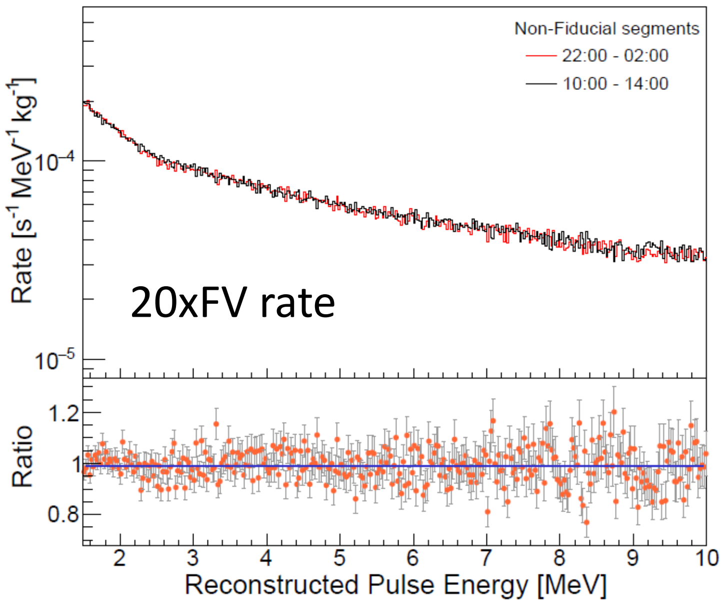


FIG. 4. The survival probability of CRDM arriving at an underground lab at latitude 28°N and a depth of 2 km vs the sidereal hour relative to the number of DM particles arriving at the Earth for two different cross sections $\sigma_{\chi p} = 1(3) \times 10^{-32}$ cm^2. The red curves correspond to the total CRDM arriving at the detector with $T_\chi \geq T_\chi^{\rm min}$, and the blue curves are those above the detector threshold ($T_r > 3$ keV for a liquid xenon detector).

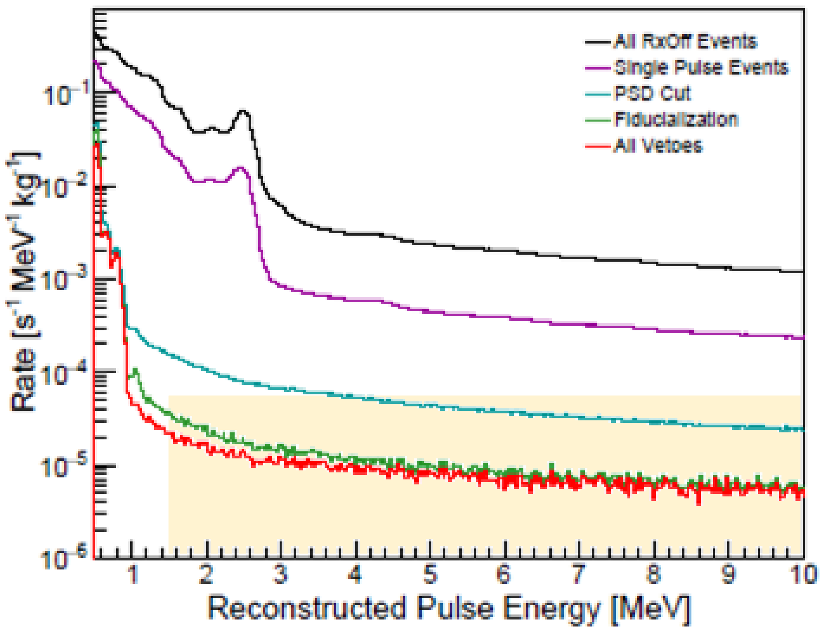
Cross-Check

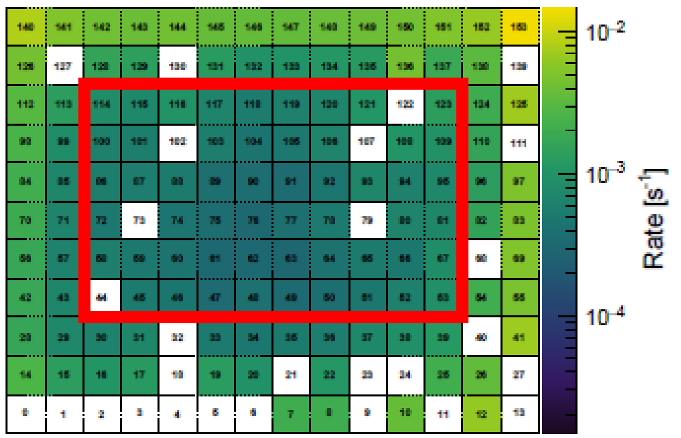
- Test for unforeseen variations in signal selection efficiency, miss-modeled cosmogenic flux variations
- Take single-pulse events in AntiFV w/ same cuts
- Check with two 4-hour long test datasets
- Ratio spectra fit with constant value (flat-line fit)
  - Best-fit 0.987±0.003 consistent with expected 0.988
- **No modulation in the cosmogenic background**



Analysis cuts leave 37,522 DM-like candidate evts

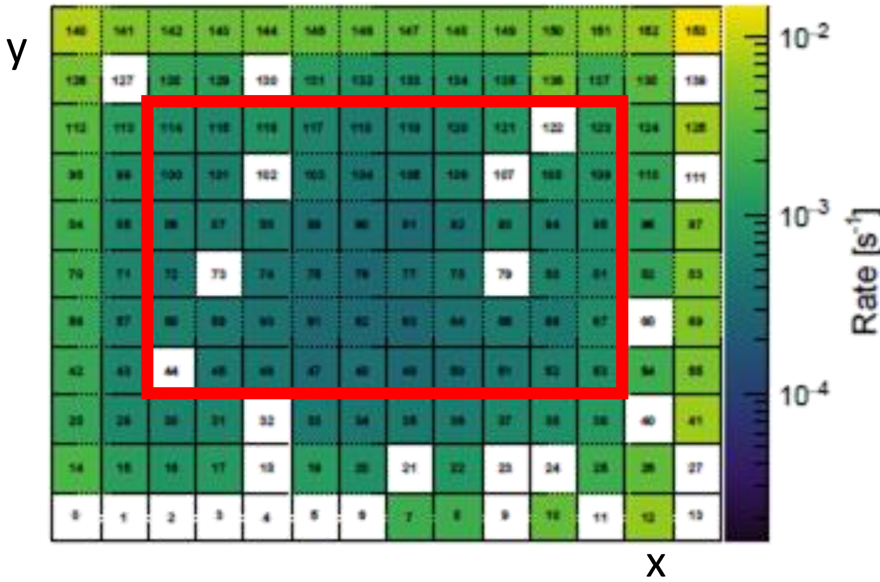
- 2σ PSD cut for given energy
- 1.5 MeV < E < 10 MeV
- Muon Cuts:
  - Since PROSPECT is a surface detector, lots of cosmic ray backgrounds
  - Fiducialization cut leaves FV of 440 kg
    - Remove events in outermost 2 layers (rows & columns)
    - $|z| \geq 20$ cm
    - 3rd-to-bottom row also removed due to high activity
  - timing coincidence:
    - veto events 5 μs after μ-like event with E > 15 MeV
    - veto events within $\pm$5 μs of a proton recoil-like event
    - Veto signals < 500 μs before an N-Li capture signal
    - Pileup cuts
    - Correct for deadtime
- Use only Reactor Off data: March 16 – March 31, 2018 (~14.6 solar days)

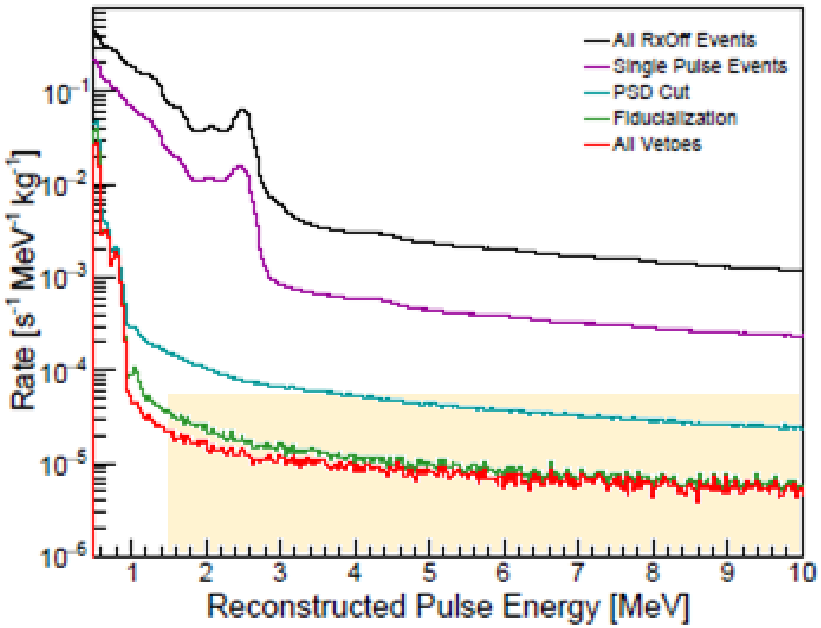


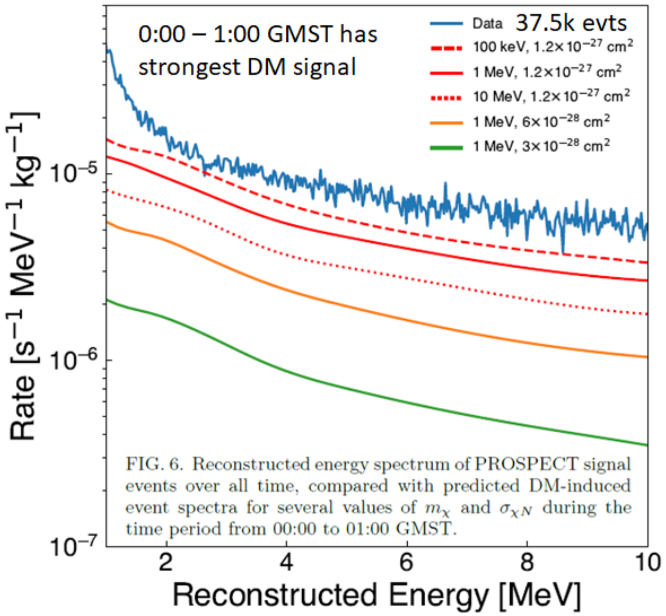


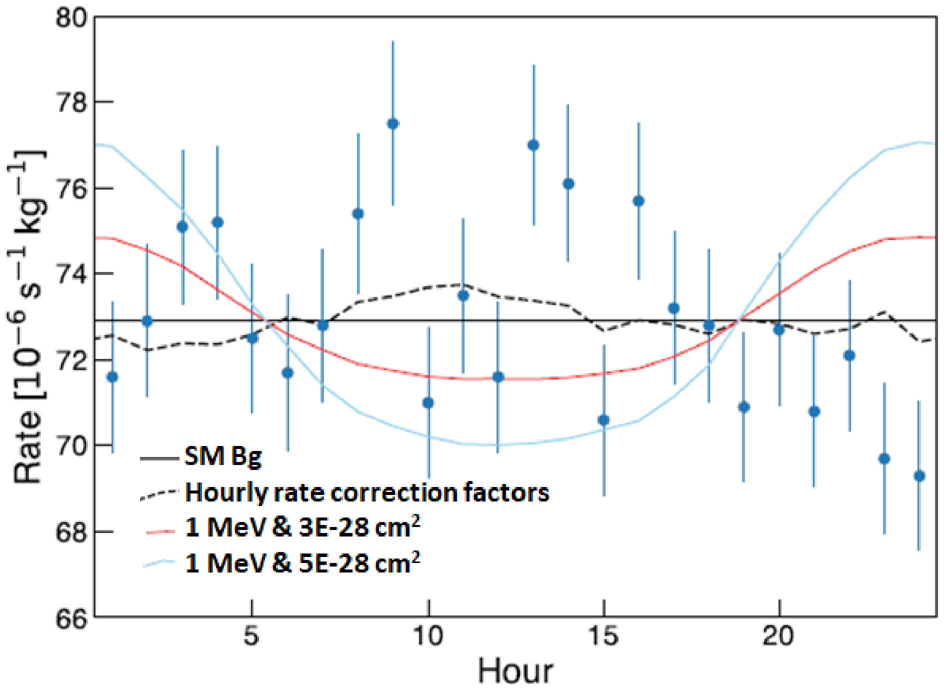
PROSPECT BDM Analysis

- PSD requirements consistent w/ proton-like recoil, remove muons
- Use only Reactor Off data: March 16 – March 31, 2018 (~14.6 solar days)
- Simulate propagation through atmosphere to detector (DM Attenuation)
  - DM must be above horizon, galactic center varies up to 25° above horizon.
- Sensitivity 1 keV < m_{DM} < 1 GeV, 25 MeV < E_{DM} < 1 GeV
- Search for diurnal sidereal time modulations









DM Search Results

- Many DM candidates (37.5k evts)
  - Probably SM bgs
- Search for signal in diurnal sidereal modulations
  - Attempt to exclude strongly-interacting DM
  - We have performed the first dedicated experimental analysis constraining sub-GeV DM by considering upscattering by CRs. This analysis, which is also the first to exploit the diurnal sidereal modulation of the boosted DM signal, addresses regions of parameter space never before probed by terrestrial experiments.
- Right: Data (blue) for proton-recoil rates & spectral predictions of DM-p collisions for $(m_\chi, \sigma_{\chi N})$ pairs

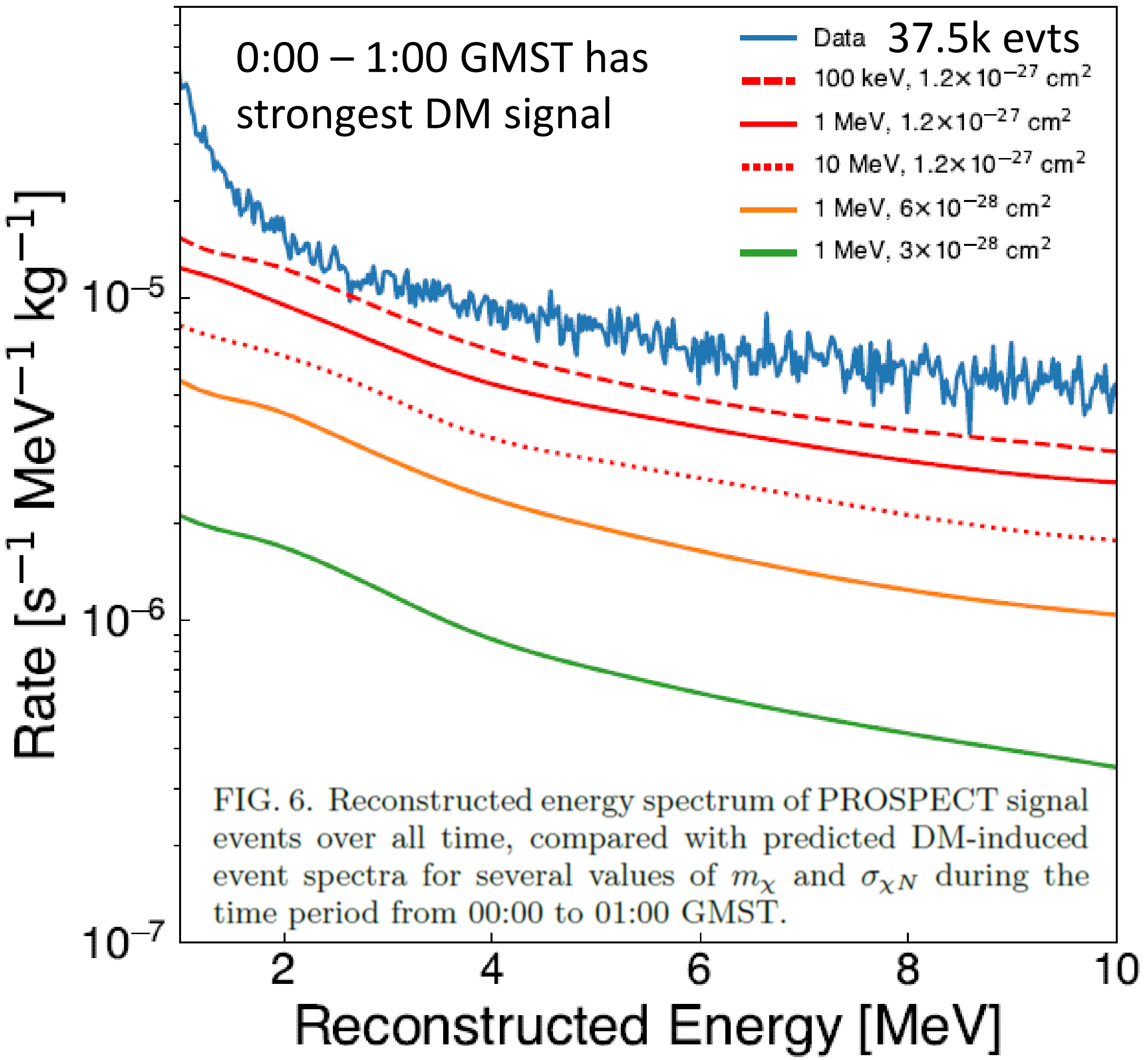


FIG. 6. Reconstructed energy spectrum of PROSPECT signal events over all time, compared with predicted DM-induced event spectra for several values of m_χ and $\sigma_{\chi N}$ during the time period from 00:00 to 01:00 GMST.

DM Search Results

- Right: Data (blue) for proton-recoil rates & spectral predictions of DM-p collisions for $(m_\chi, \sigma_{\chi N})$ pairs
- DM-induced proton recoil spectra
  - Reco energy in PROSPECT related to DM-p collision by E-dependent quenching factor
  - modeled by 'Birks9' fit
  - Predictions are for 0:00 – 1:00 GMST which has strongest DM signal
- Above 2 MeV, spectral shapes are similar
  - Bc of flatness & lack of distinct spectral features above 1.5 MeV, predictions are insensitive to other aspects of detector response.

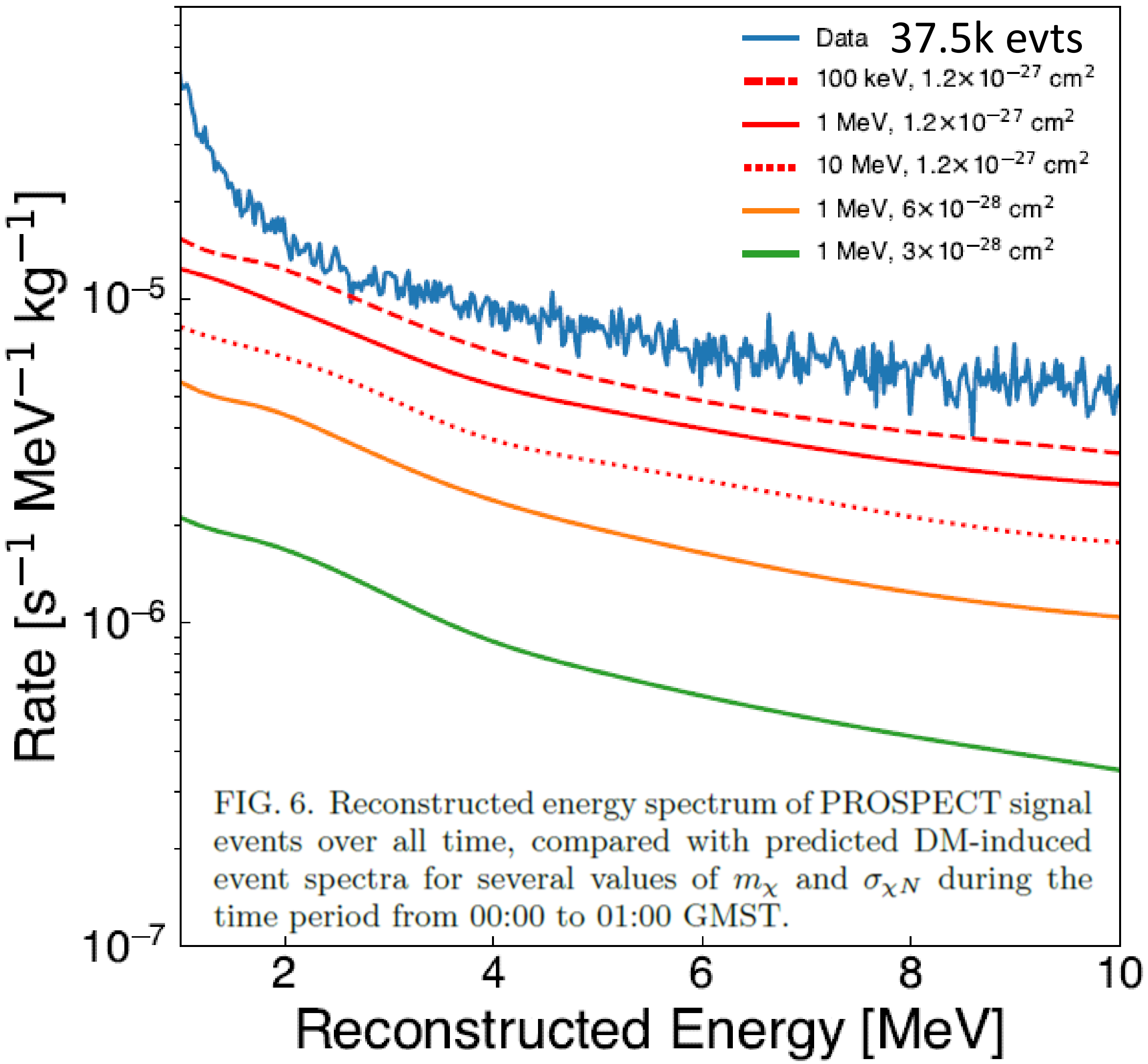


FIG. 6. Reconstructed energy spectrum of PROSPECT signal events over all time, compared with predicted DM-induced event spectra for several values of m_χ and $\sigma_{\chi N}$ during the time period from 00:00 to 01:00 GMST.

DM Time-binned Analysis: Gaussian CL$_s$

- Use Gaussian CL$_s$ method for quantitative determination for rejected $(m_\chi, \sigma_{\chi N})$ parameter space (at given confidence level)
  - Test statistic $\Delta\chi^2 = \chi^2_{DM} - \chi^2_{const}$.
  - χ^2_{const} is χ^2 from P$_0$ fit to hourly data
  - Hourly rate correction factors applied (dashed)
  - $\mathrm{CL}_s(x) = \dfrac{1+\mathrm{Erf}\left(\frac{\overline{\Delta T_1}-\Delta T(x)}{\sqrt{8|\overline{\Delta T_1}|}}\right)}{1+\mathrm{Erf}\left(\frac{\overline{\Delta T_0}-\Delta T(x)}{\sqrt{8|\overline{\Delta T_0}|}}\right)}$ where
    - $\Delta T(x) = \Delta\chi^2(x)$ is for PROSPECT's dataset
    - $\overline{\Delta T_0}$ = $\chi^2_{\mathrm{DM}}(x_{H0})$, where x_{H0} is Asimov dataset of modulation-free hypothesis
    - $\overline{\Delta T_1}$ = $-\chi^2_{const}(x_{H1})$, where x_{H1} is Asimov dataset for DM w/ $(m_\chi, \sigma_{\chi N})$
  - CL$_s$ < 0.5 are disfavored by the data at 95% confidence level
  - Right: 95% CL exclusion from PROSPECT Data

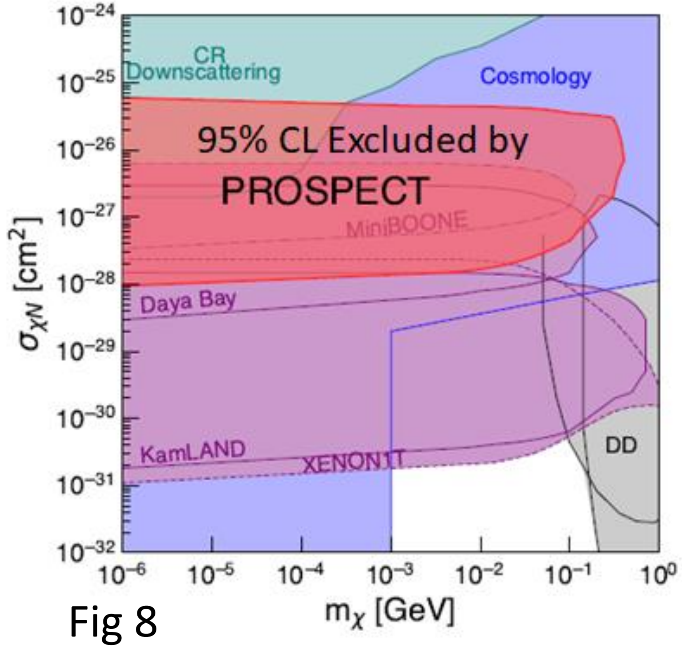
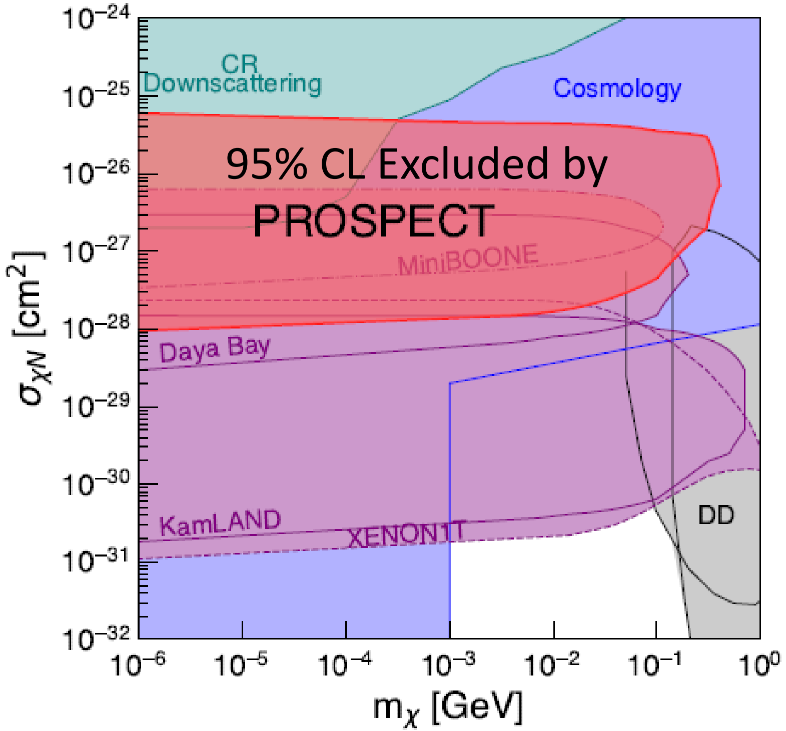


Fig 8

Discussion

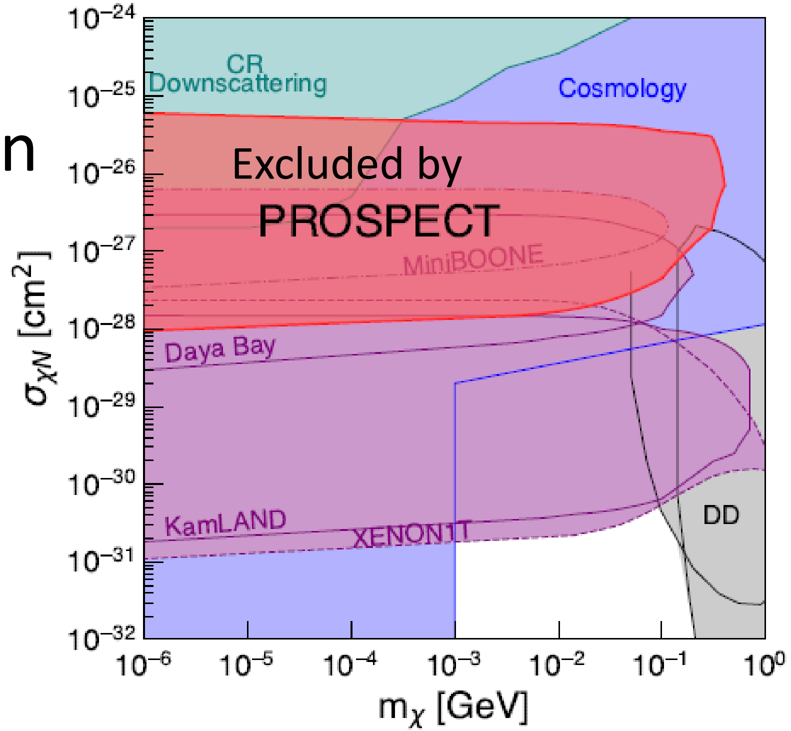
- No boosted DM signal found
- Upper excluded regions first to be excluded by terrestrial exp.
- Size of region due to background rejection and daily modulation
- No significant gain by changing E binning or ranges
- Upper $\sigma_{\chi N}$ limit defined by attenuation
  - it can't reach PROSPECT
  - Suggestion later to move PROSPECT to high elevation
  - Not much else affects it
  - More data could modestly improve it



Discussion for Lower $\sigma_{\chi N}$, sinusoidal modulation

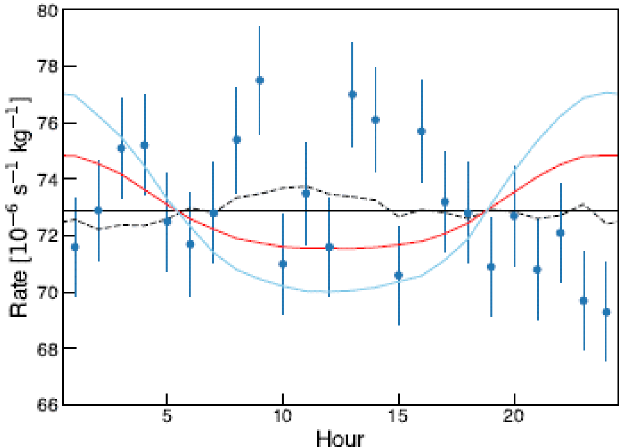
Lower $\sigma_{\chi N}$

- defined by low DM flux through detector
- Extend sensitivity w/ more data & improved bg rejection
- affected by galactic CR halo shape, varies by < 2x
- DM model compared to NFW & extremely cored model
  - changes daily modulation amplitude and low $\sigma_{\chi N}$ by O(10%)



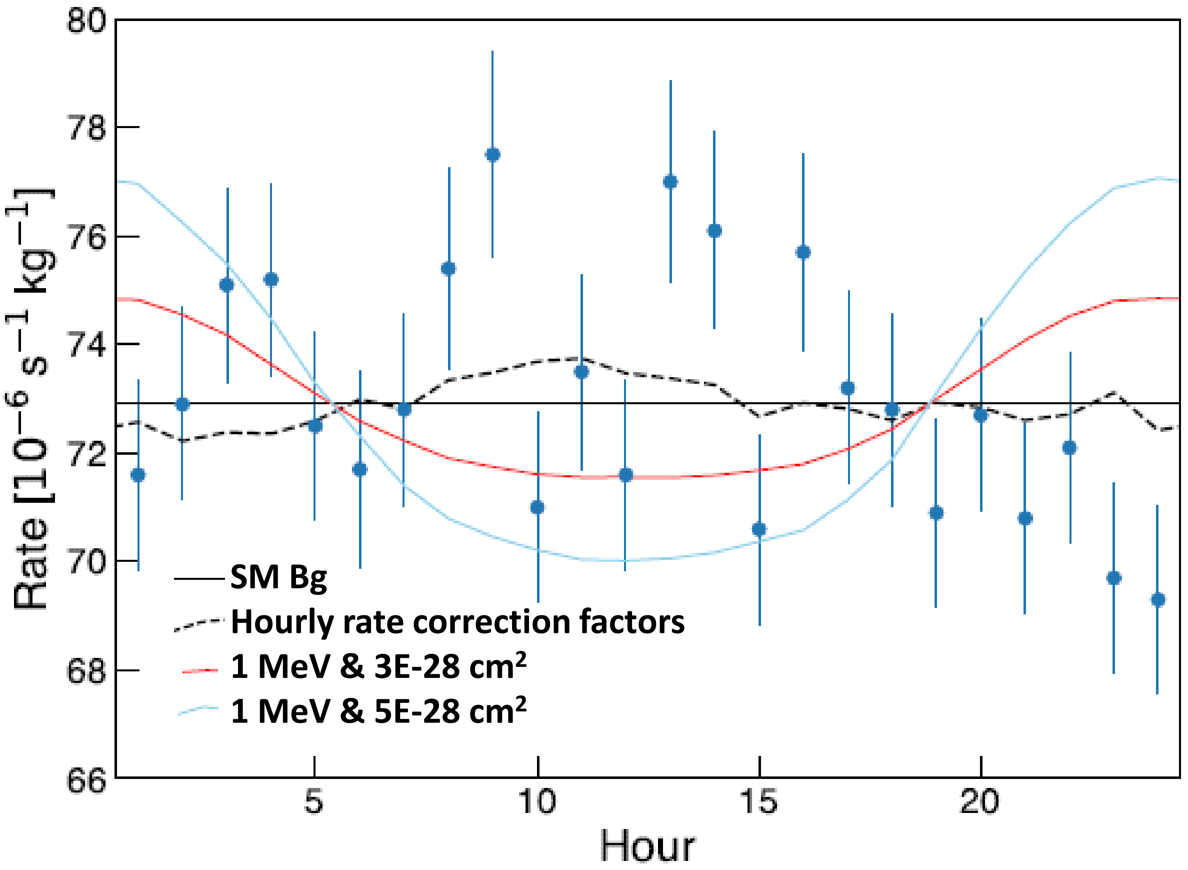
Sinusoidal modulation of hourly rate

- Consistent with lack of daily modulation



DM Time-binned Analysis

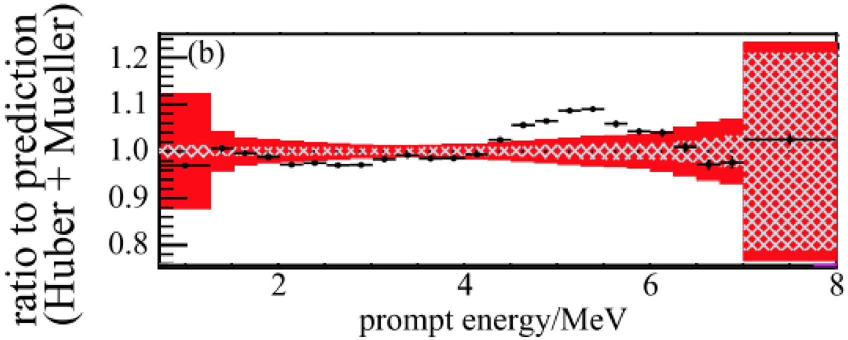
- Predictions smaller than data for most of parameter space of interest
  - Necessitates time-dependent study: total rate per hour (total counts for 1.5 - 10 MeV)
  - No visual indications of diurnal sidereal modulation



Motivation: Reactor Antineutrino Spectrum Deviations

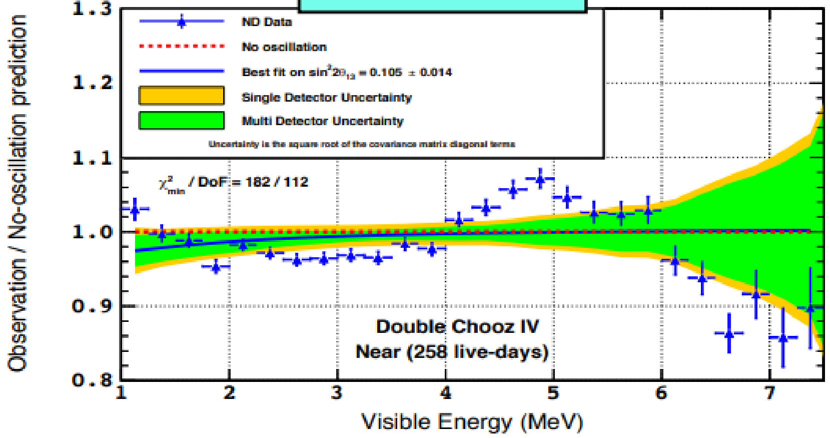
Experiments precisely measured spectrum from Low Enriched Uranium (LEU) reactors ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

Daya Bay



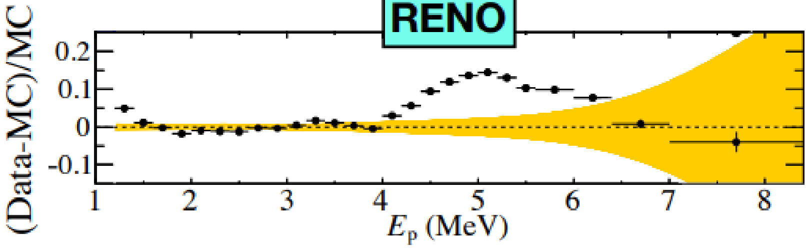
CPC Vol. 41 (1) (2017)

Double Chooz



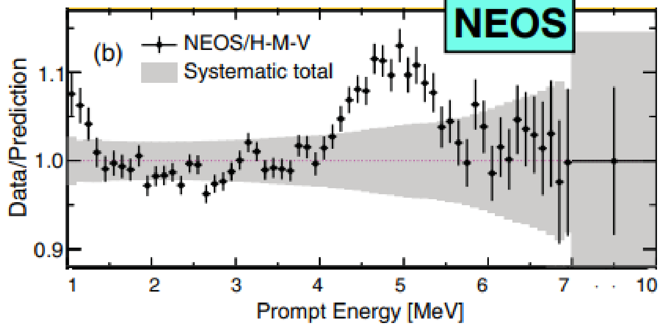
arXiv:1901.09445

RENO



PRD 98, 012002 (2018)

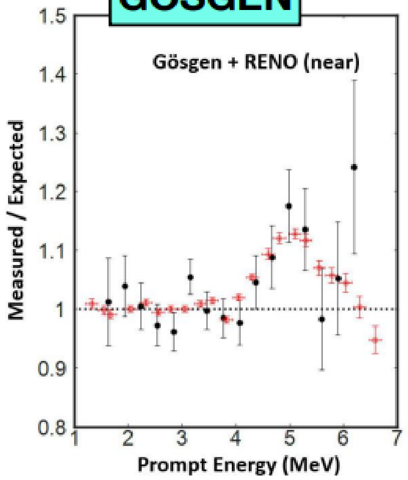
NEOS



PRL 118, 121802 (2017)

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

GOSGEN



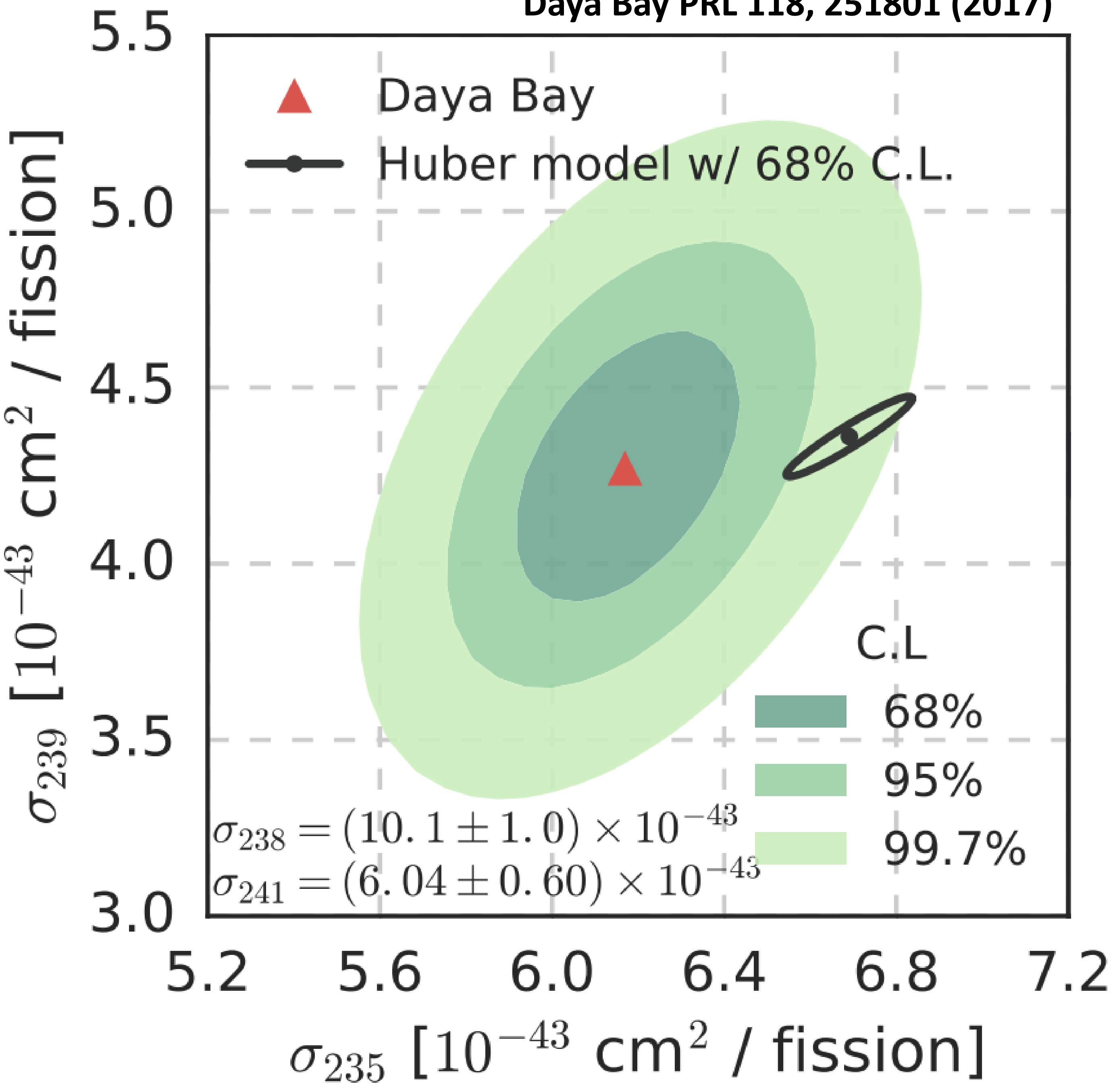
Re-evaluation (2018) of Gosgen(1980's) experiment also showed a deviation in 4-6 MeV region.

arXiv:1807.01810

Where this deviation is coming from?

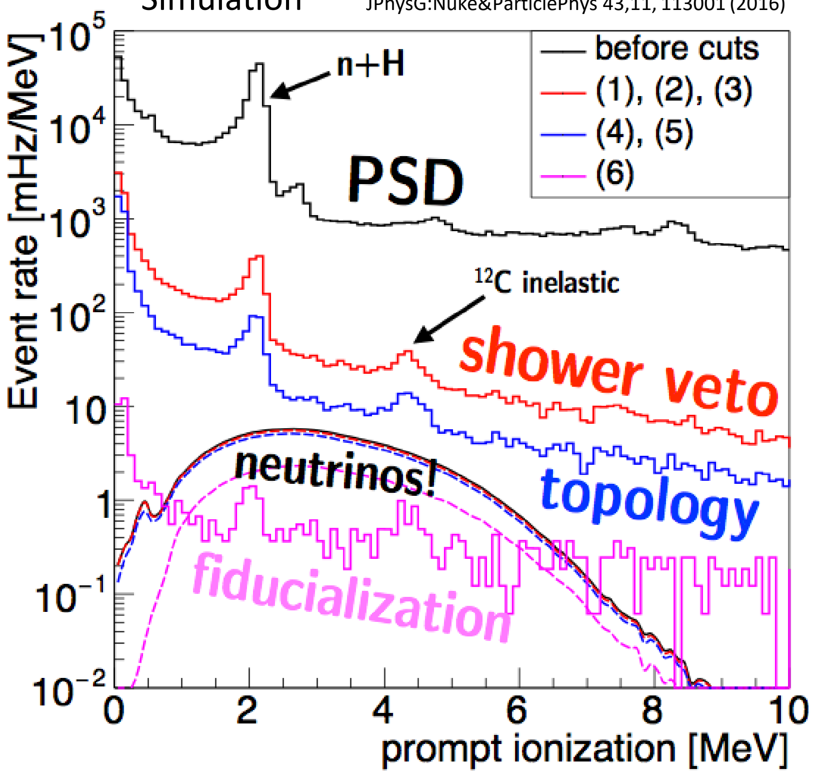
- Cannot be explained by the sterile neutrino introduced for flux deficit.
- Could be an issue with reactor models? Experiments used conventional reactors (LEU).

Daya Bay PRL 118, 251801 (2017)



Background Suppression, Removal, and Subtraction

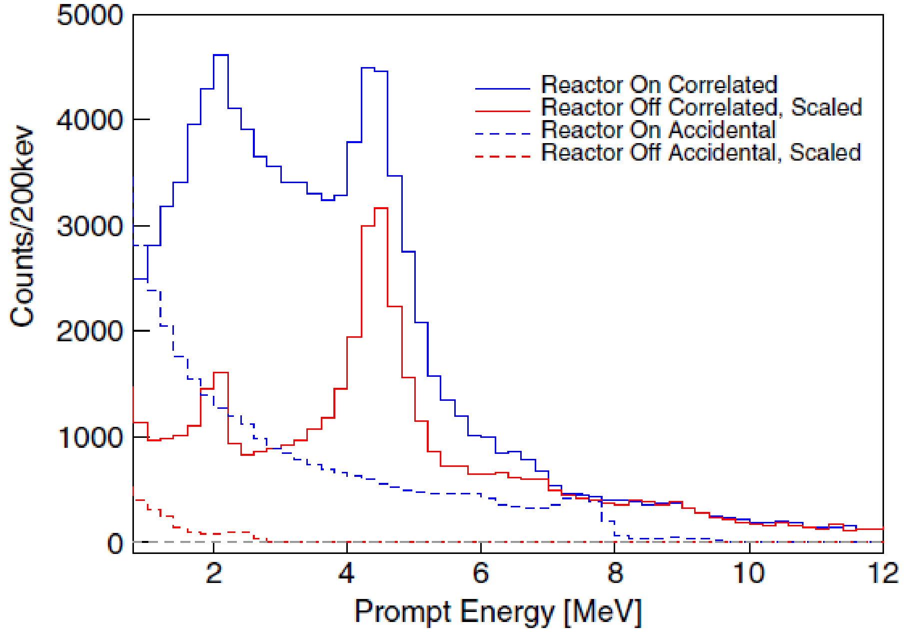
- Cuts, Vetos and Fiducialization reduce background (bg) by 10^4



- Apply correction for atmospheric pressure as it is correlated to cosmogenic backgrounds

HFIR has scheduled Rx-Off periods

- high-precision measurement of IBD-like backgrounds
  - Obtain Rate and spectral shape
- Accidentals spectra (temporally-uncorrelated events passing all other coincidence cuts)
- Used to subtract Rx-Off IBD-like background from Rx-On IBD-like sample

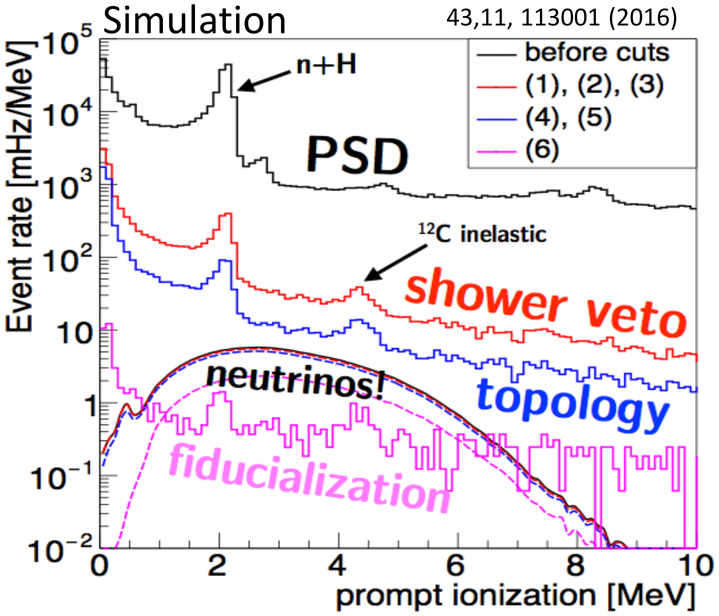


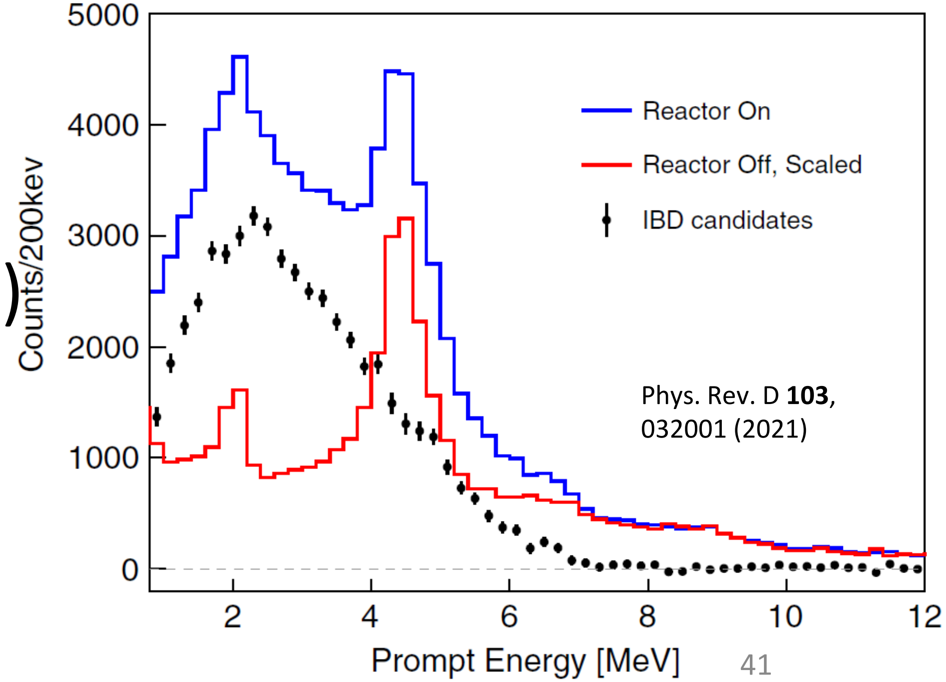
Background Suppression, Removal, and Subtraction

PROSPECT

- Overburden < 1 mwe → cosmogenic backgrounds are a challenge
- Cuts, Vetos and Fiducialization reduce background (bg) by 10^4
- Get RxOn IBD-like prompt event spectra (bottom, blue) by subtracting accidentals spectra (temporally-uncorrelated events passing all other coincidence cuts)
- Use HFIR's scheduled Rx-Off periods
  - high-precision measurement of IBD-like background spectra
  - Obtain Rate, spectral shape (bottom, red)
- Final Rx IBD Prompt Candidates Spectrum (bottom)
  - Blue - red

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

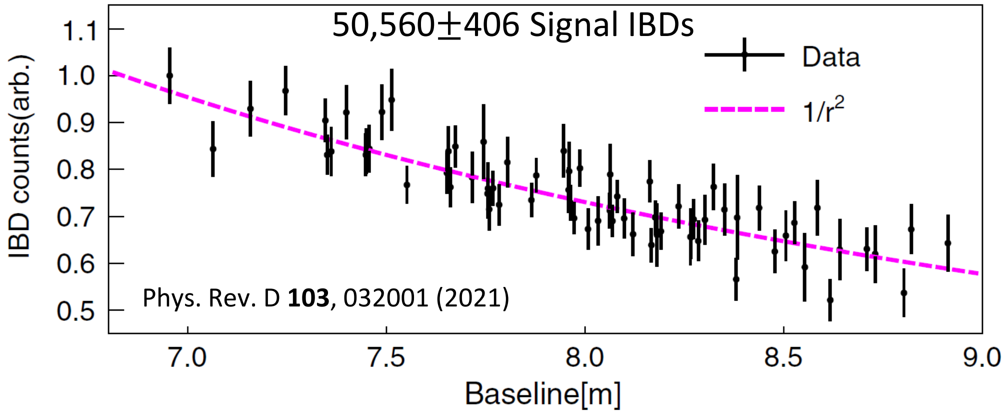




Phys. Rev. D **103**, 032001 (2021)

Prospect Data and r^{-2} IBD Signal

- Reactor IBD signal:
  - Rate per fiducial segment.
  - Consistent with $1/r^2$ behavior



Before spectral shape relative-zation

After spectral shape relative-zation

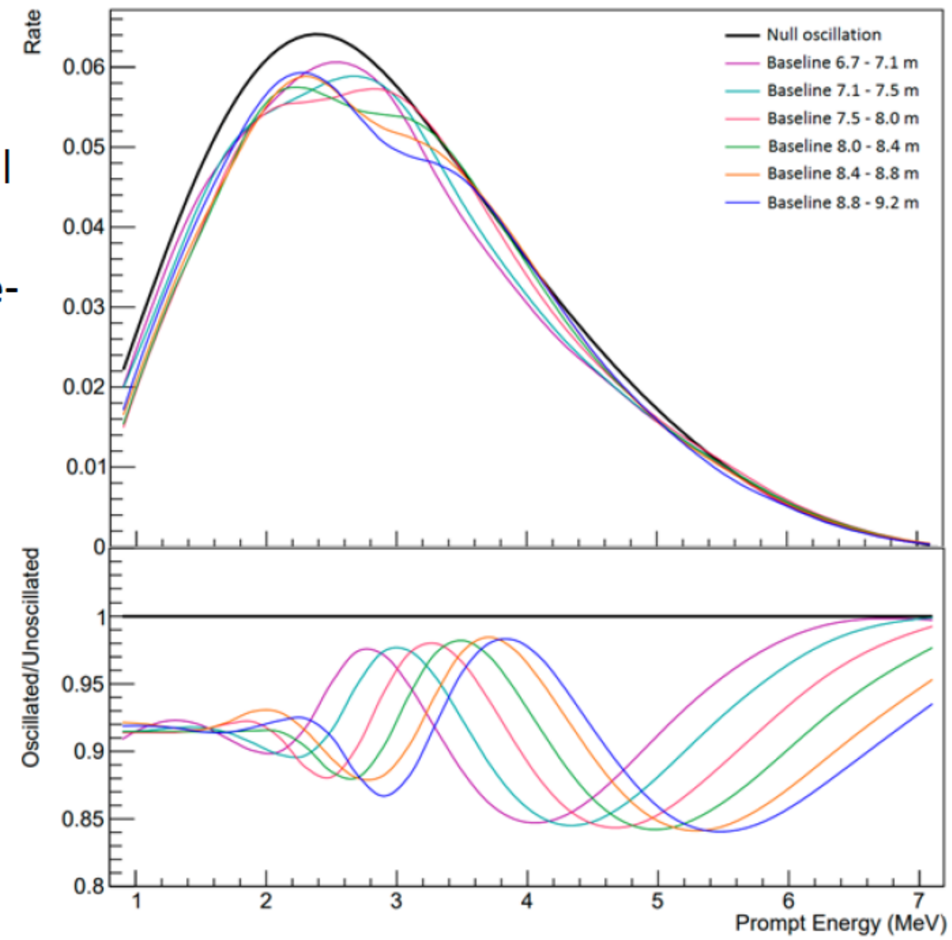


TABLE III. Statistics of selected IBD candidates and accidental/cosmogenic backgrounds. Errors, where included, represent statistical uncertainties in the relevant signal and background datasets.

Category	Reactor-On	Reactor-Off
Calendar days	95.65	73.09
Live days	82.25	65.16
IBD candidates	115852	30568
Accidental backgrounds	28358 ± 18	1309 ± 4
Correlated candidates	87494 ± 341	29258 ± 175
Rate per calendar day	915 ± 4	400 ± 2
Cosmogenic backgrounds	36934 ± 221	N/A
Total IBD signal	50560 ± 406	N/A
Rate per calendar day	529 ± 4	N/A

Osc 1

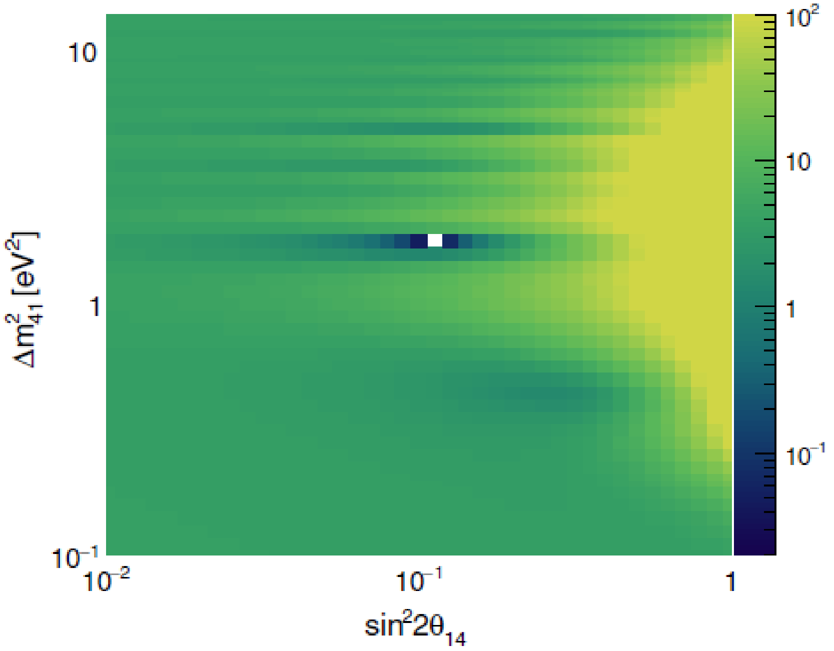


FIG. 44. The value of $\Delta\chi^2$ obtained for each $(\sin^2 2\theta_{14}, \Delta m^2_{41})$ grid point, relative to the best-fit point (white square) at $(0.11, 1.78\ \mathrm{eV}^2)$. The χ^2 definition is provided in Eq. (11). The white spot corresponds to the location of the best-fit point ($\Delta\chi^2 = 0$).

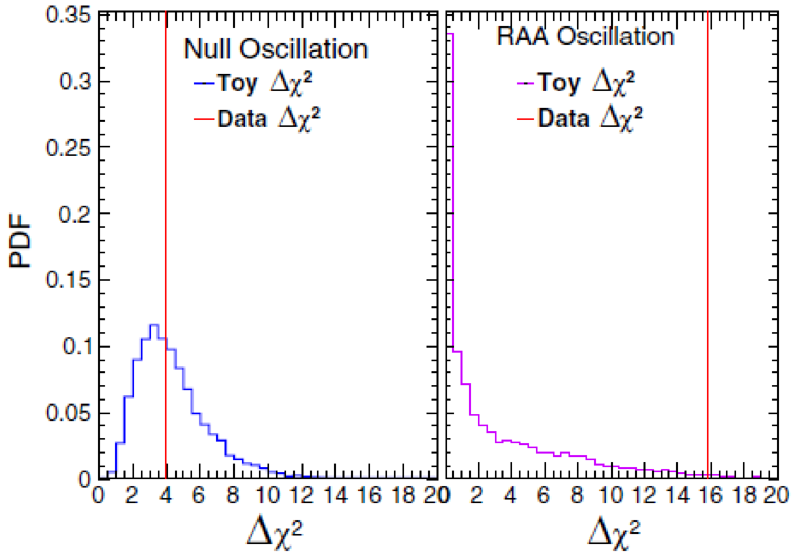


FIG. 46. Distributions of $\Delta\chi^2$ for toy MC datasets generated for the null oscillation (left, blue) and RAA best-fit point (right, magenta); $\Delta\chi^2$ are calculated between true and best-fit grid points individually for each toy. Red vertical lines indicate the observed $\Delta\chi^2$ value from PROSPECT's data. The observed value sits in the middle (higher end) of the distribution for the null (RAA) grid point, indicating good (poor) compatibility of the data with representative toy datasets from that grid point.

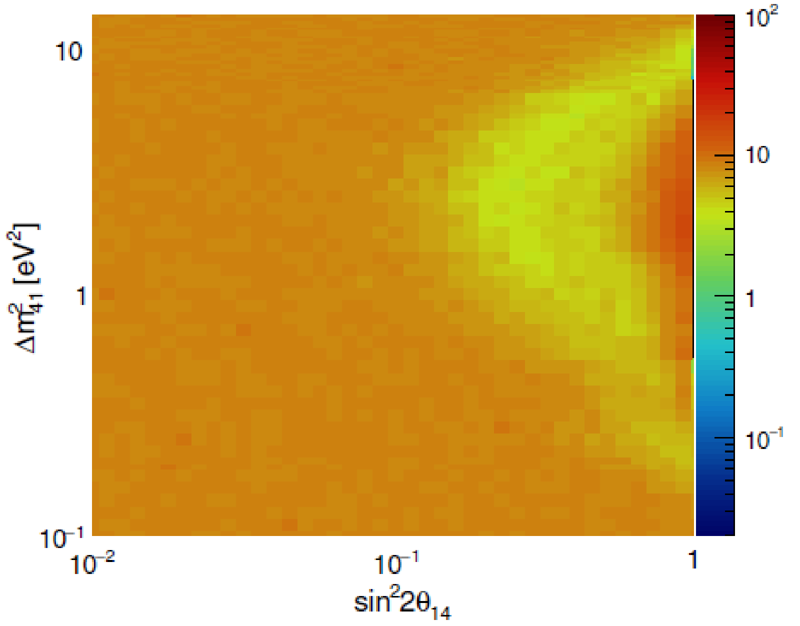


FIG. 47. Map of critical $\Delta\chi^2$ values indicating 95% confidence level incompatibility with that grid point's predicted oscillatory behavior; generated using the Feldman-Cousins (FC) frequentist approach. For reference, the incorrect assumption of an χ^2 distribution with 2 degrees of freedom yields a flat map with $\Delta\chi^2 = 5.99$.

OSC V_{tot}

- Diagonal (statistical) is dominant
- Largest Sys impact: relative normalization uncert. impacting low Δm^2 values

TABLE IV. Summary of systematic uncertainties taken into account in the oscillation systematic covariance matrix V_{sys}. Where applicable, nominal parameter values are provided. References to relevant sections where uncertainties are described are also given.

Parameter	Section	Nominal value	Uncertainty	Correlations
Absolute background normalization	VI B, VI D	···	1.0%	Correlated between energies and baselines
Absolute n-H peak normalization	VI D	···	3.0%	Correlated between energies and baselines
Relative signal normalization	V C	···	5%	Correlated between energies
Baseline uncertainty	II	···	10 cm	Correlated between energies and baselines
First-order Birks constant	IV B	0.132 MeV/cm	0.004 MeV/cm	Correlated between baselines
Second-order Birks constant	IV B	0.023 MeV/cm	0.004 MeV/cm	Correlated between baselines
Cherenkov contribution	IV B	37%	2%	Correlated between baselines
Absolute energy scale	IV B	···	0.6%	Correlated between baselines
Absolute photostatistics resolution	IV C	···	5%	Correlated between baselines
Absolute energy leakage	IV D	···	8 keV	Correlated between baselines
Absolute energy threshold	IV B, III G		5 keV	Correlated between baselines
Relative energy scale	III H, IV B	···	0.6%	Uncorrelated between baselines
Relative photostatistics resolution	III H, IV C	···	5%	Uncorrelated between baselines
Relative energy leakage	IV D	···	8 keV	Uncorrelated between baselines
Relative energy threshold	IV B, III G	···	5 keV	Uncorrelated between baselines
Reflector panel thickness	IV B	1.18 mm	0.03 mm	Uncorrelated between baselines

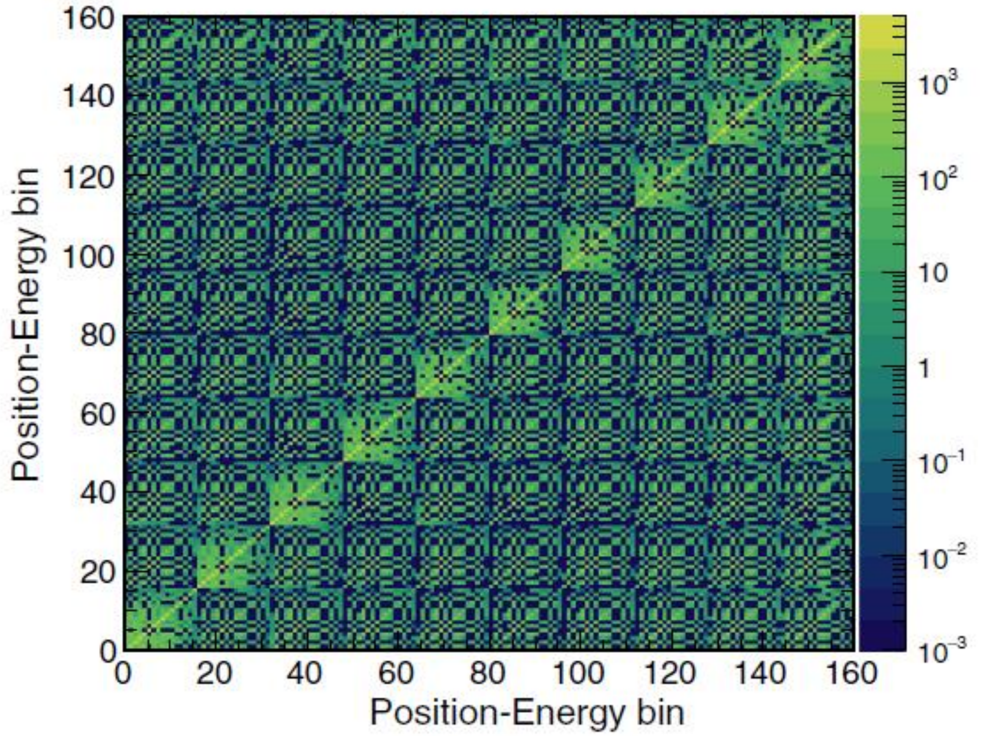


FIG. 43. Total uncertainty covariance matrix for the energy-baseline bins used for the PROSPECT oscillation analysis. Full covariance matrix elements are computed by multiplying reduced covariance matrix elements by the relevant measured signal rates $M_i \cdot M_j$. Submatrices of common baseline are visible within these covariance matrices, with baselines increasing with increasing i and j.

^{235}U Spectral Analysis

TABLE V. Descriptions and values of the individual uncertainties combined to produce the final covariance matrix.

Parameter	Section	Uncertainty	Description
Background normalization	VI B, VI D	1%	Accounts for variation between reactor-off periods
n-H peak	VI D	3%	Accounts for uncertainty on background subtraction in the n-H peak region
Detector nonlinearity	IV B	0.004	Uncertainty for Birks nonlinearity in energy deposition
Cherenkov vontribution	IV B	2%	Uncertainty on Cherenkov contributions to collected photons
Energy scale	IV B	0.6%	Uncertainty on linear energy scale
Energy resolution	IV C	5%	Uncertainty in photostatistics contribution to energy-dependent resolution
Energy loss	IV D	8 keV	Uncertainty in energy lost by escaping 511 keV γ rays
^{28}Al activation	IX A	100%	Uncertainty in the amount of ^{28}Al contributing to the spectrum
Nonequilibrium correction	IX A	100%	Uncertainty in extrapolating $\bar{\nu}_e$ contribution from long-lived fission daughters
Panel thickness	IV B	0.03 mm	Uncertainty in mass of the panels separating segments
Z fiducial cut	V C	25 mm	Uncertainty in the position of events near the edge of the fiducial volume
Energy threshold	IV B, III G	5 keV	Uncertainty in the segment-by-segment energy threshold cut

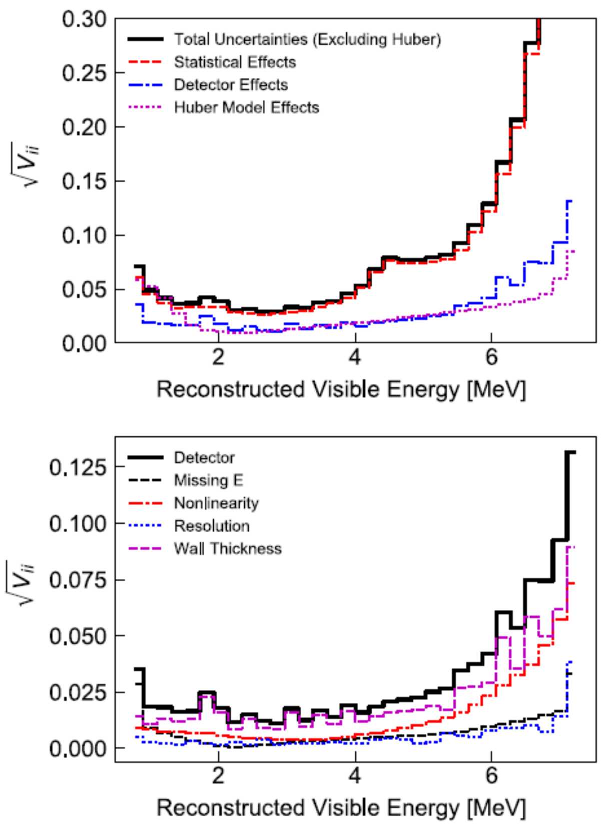


FIG. 50. Uncertainties for the PROSPECT ^{235}U $\bar{\nu}_e$ spectrum measurement, represented by the square root of the uncertainty covariance matrix diagonal elements. Top: Comparison of the three categories of uncertainties: statistics, detector, and model. Bottom: Comparison of the individual contributions to the detector uncertainty.

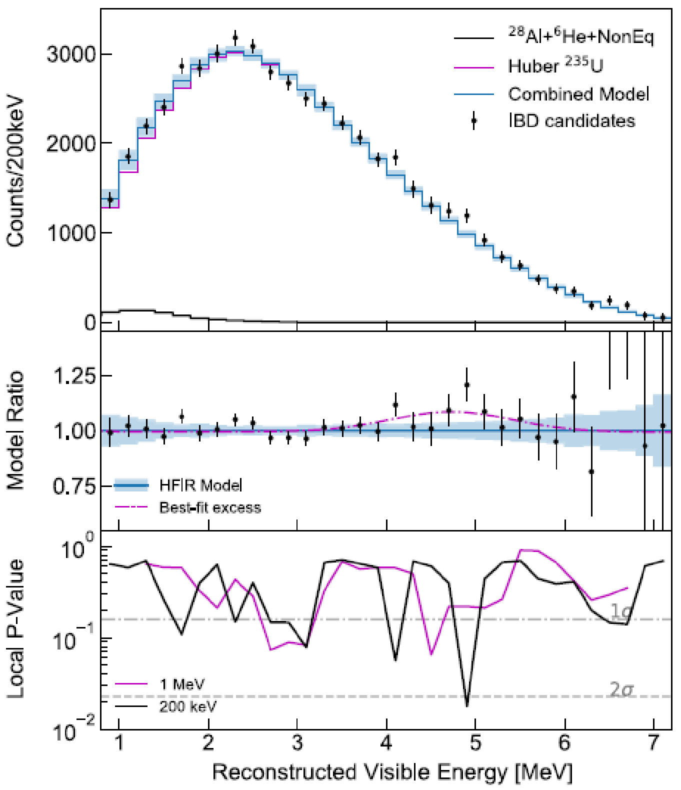


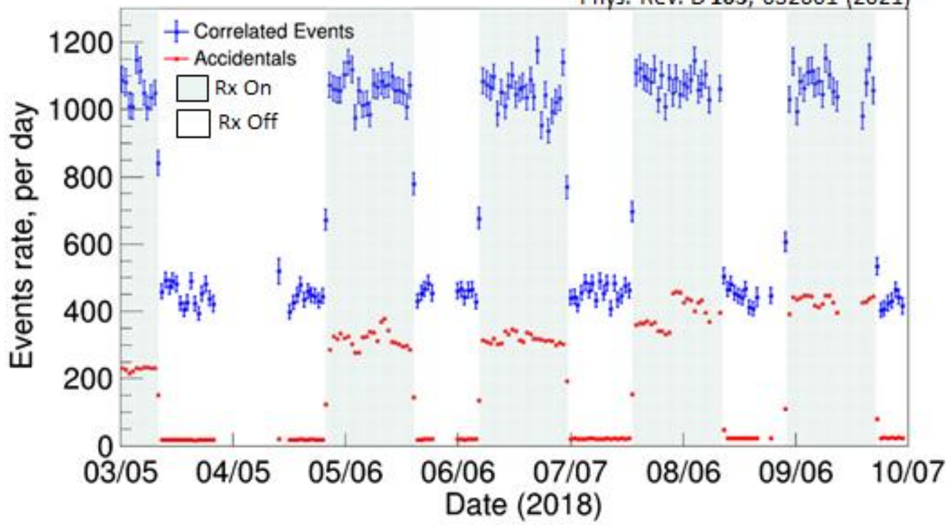
FIG. 51. Top: Comparison of the ^{235}U model to the measured PROSPECT E_{rec} spectrum. Middle: Ratio of the measurement to the HFIR prediction based on the Huber model. Bottom: The local p value from 1 MeV- and 200 keV-wide sliding windows, quantifying any local deviations from the model prediction. Error bars on data points represent statistical uncertainties, while error bands on the model represent systematic uncertainty contributions as represented in Fig. 50.

Prospect Data and IBD Signal

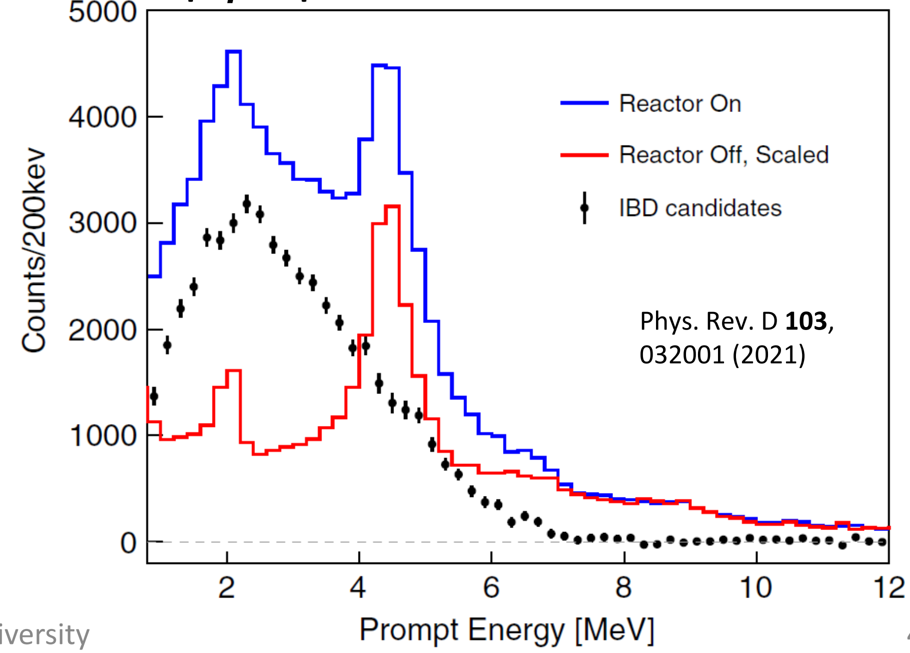
PROSPECT

- 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 (1.78) for cosmogenic (accidental coincidence) backgrounds
- Bottom: Prompt β^+ Spectra for ^{235}U Induced IBD-candidates
  - Final Rx IBD Prompt Candidates Spectrum (black)
    - Subtract: RxOn (Blue) – RxOff (red)

RxOn: 95.7 Days, RxOff: 73.1 Days
Average Rate RxOn signal: 529±4 IBD/day

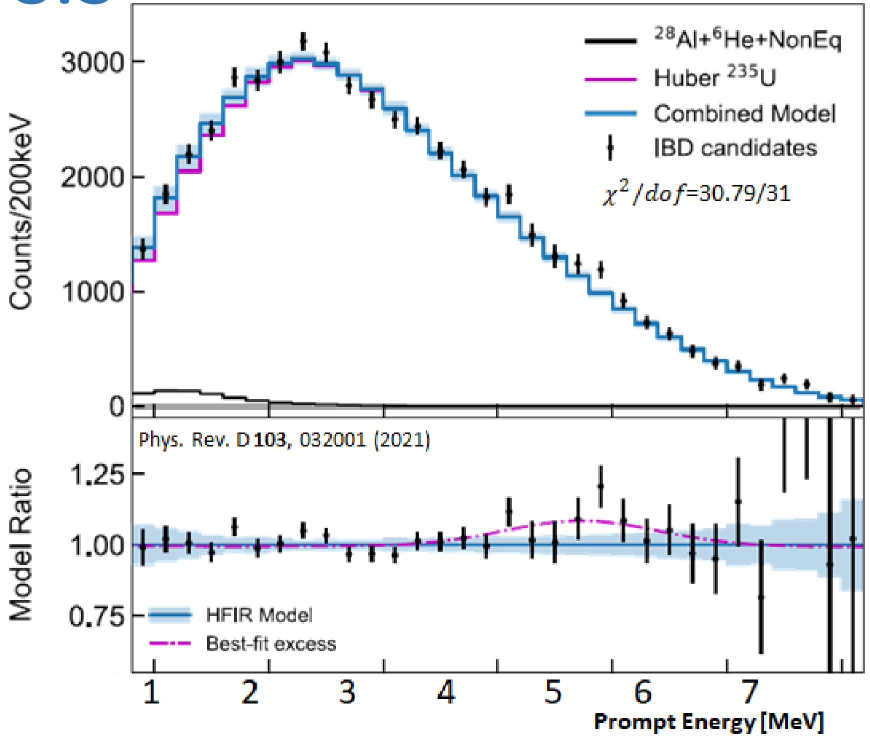


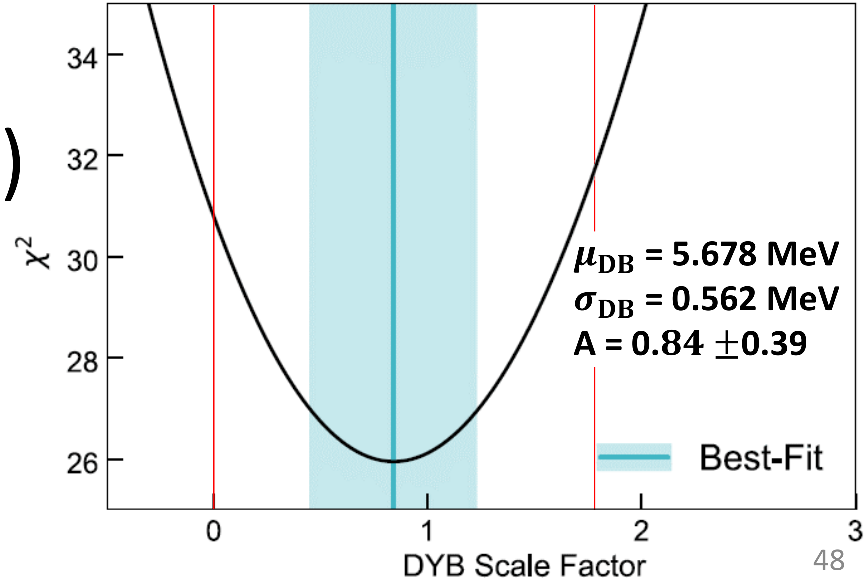
Prompt β^+ Spectra for ^{235}U Induced IBD-candidates



^{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

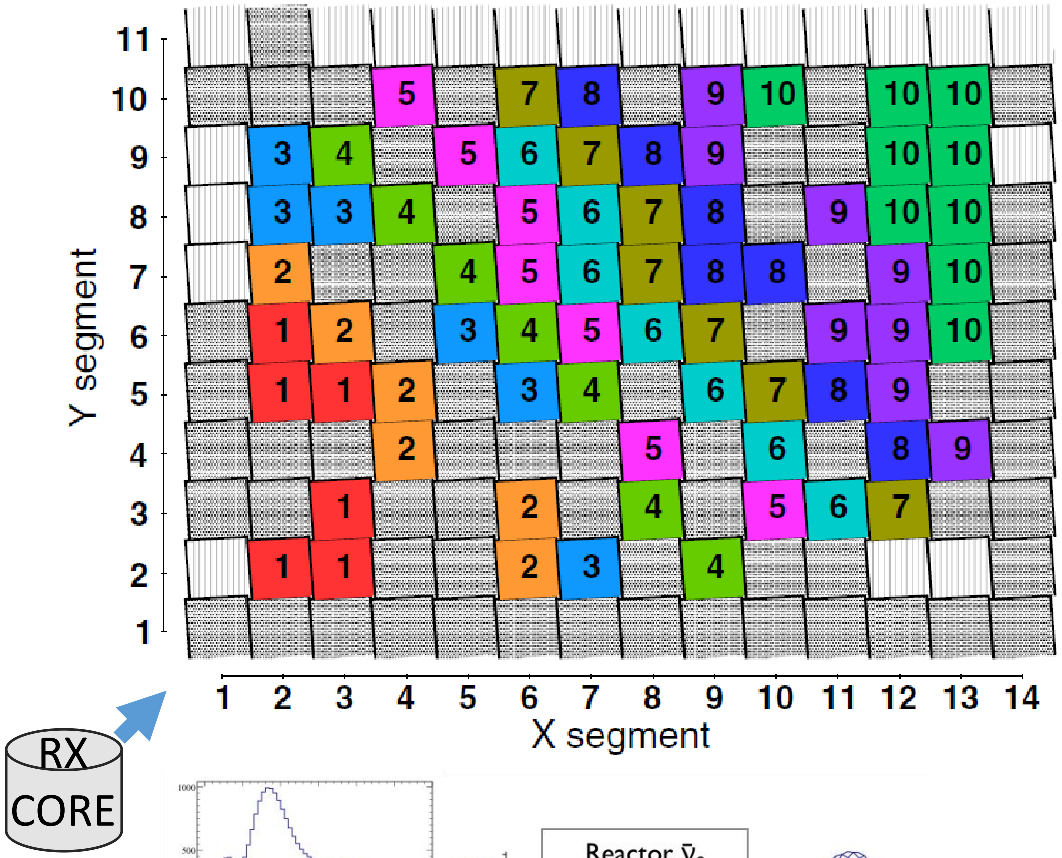


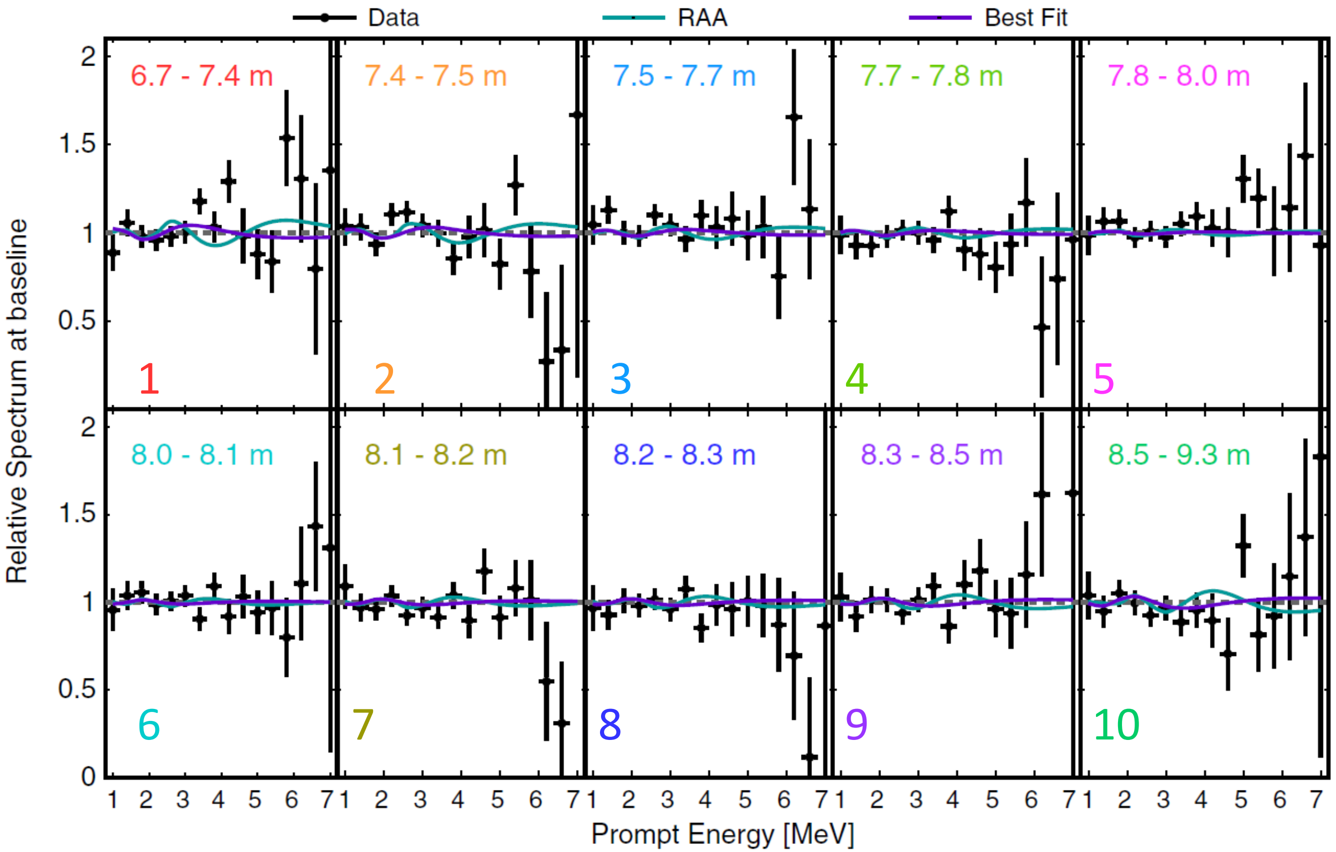


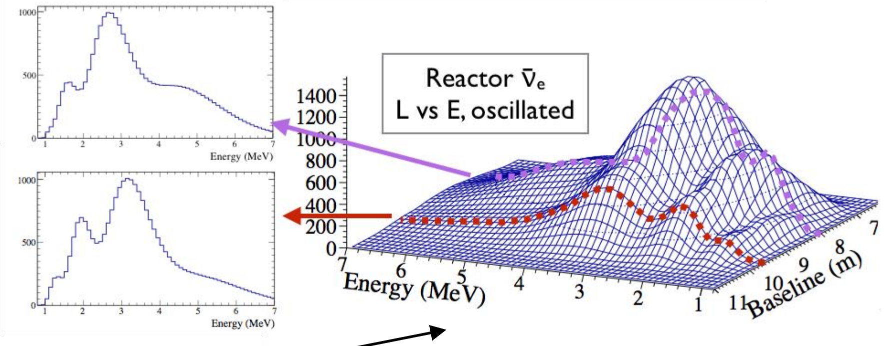
Search for Sterile Neutrino Oscillations in IBD Spectrum

PROSPECT

Phys. Rev. D **103**, 032001 (2021)







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

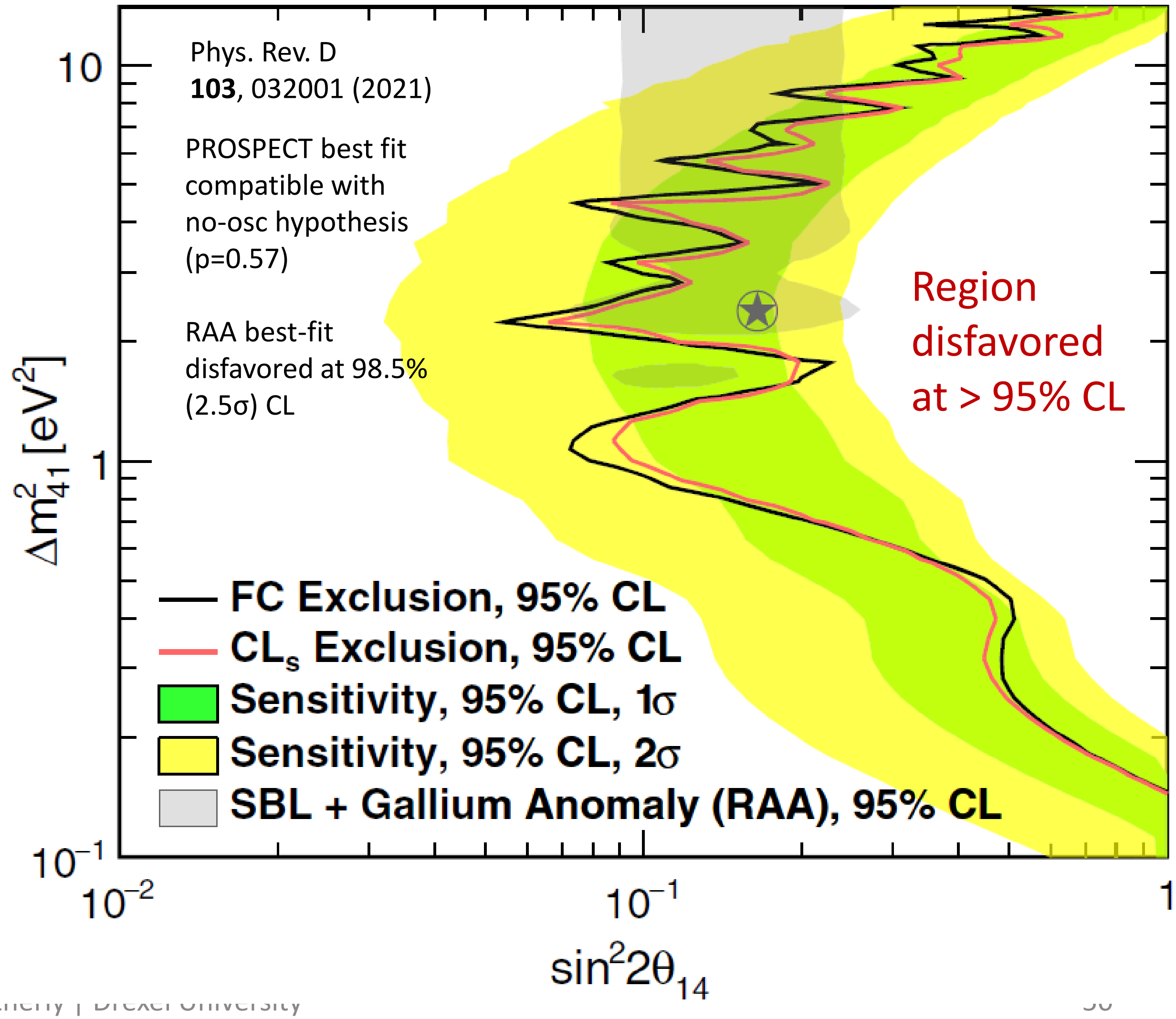
- 10 baselines with different oscillated spectra
- Ratio comparisons to full detector spectrum
- No obvious deviations from no-oscillation (flat) scenario

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

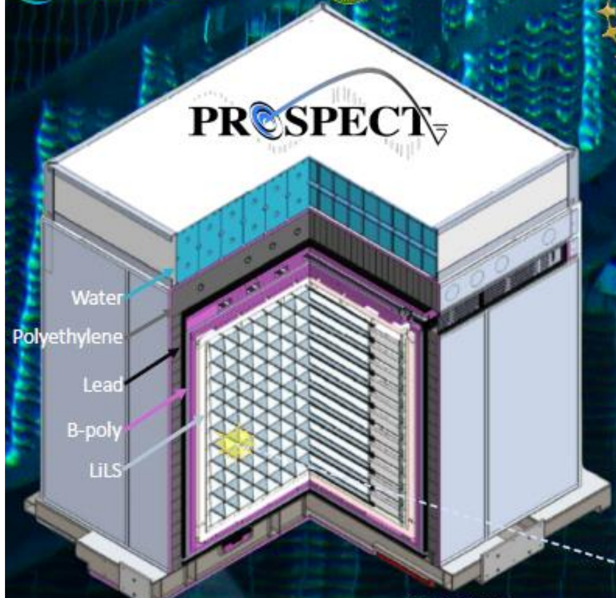
$(\Delta m^2_{41}, \sin^2(2\theta_{14}))$= (1.78 eV2 , 0.11)



Absolute Reactor Antineutrino Flux Measurement with PROSPECT-I data

Neutrino 2022

Paige Kunkle
On behalf of the PROSPECT Collaboration



Detector design

The Precision Oscillation and Spectrum Experiment (PROSPECT) is an above-ground, near-field **segmented** reactor neutrino detector.

- 4 tons ^{6}Li-doped liquid scintillator (LiLS)
- Double PMT readout with light concentrators
- ~8 m baseline to High Flux Isotope Reactor (HFIR) core at ORNL

The **inverse beta decay (IBD) process** is used to detect $\bar{\nu}_e$'s that interact inside the fiducial volume.

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

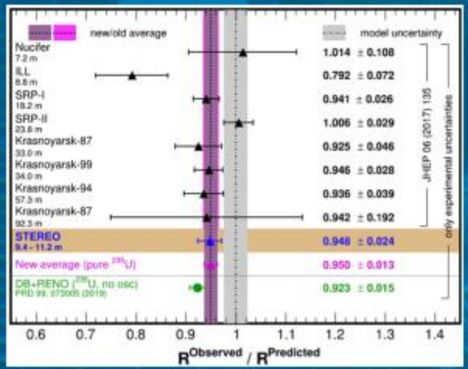
Due to high statistics and strong background rejection, **uncertainties are dominated by the systematics.**

$\bar{\nu}_e$

~8 m

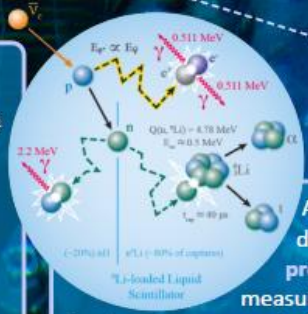
Motivation

Measured antineutrino yields by various experiments show a consistent **deficit** relative to their corresponding Huber model flux predictions.[1]



Flux predictions could be flawed and **overestimated**, or neutrinos could be oscillating to a **sterile** state.

An **updated and more precise** absolute reactor flux **measurement** by PROSPECT relative to current flux predictions can probe these anomalies.



Procedure

After a 7 month run PROSPECT-I demonstrated **world-leading precision** in a ^{235}U spectrum measurement.[2] These capabilities imply a measurement of **absolute** ^{235}U IBD event yield using PROSPECT-I data is feasible.

Theoretical predictions can use detected IBD rate and other components to compute the time-dependent $\bar{\nu}_e$ **flux in HFIR's core** at time t in terms of neutrinos per unit energy:[3]

$$\frac{d\phi(E_\nu, t)}{dE_\nu} = \frac{W_{th}(t)}{\bar{E}(t)} \sum_{i=1}^{4} f_i(t) s_i(E_\nu) + s_{nf}(E_\nu, t)$$

Contributing factors include **thermal power** output of reactor core, **fission fraction** and $\bar{\nu}_e$ **flux** from fission isotope i, and **average energy release per fission.**

Components

Knowledge of **reactor power** is limited to HFIR's power measurement systems and estimated to be known to 2.14%.

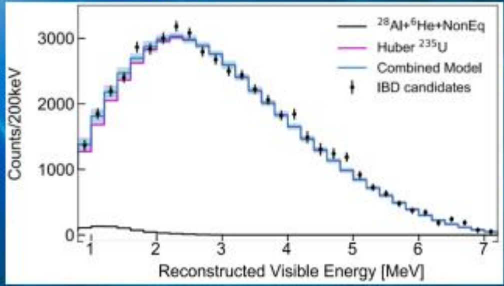
Uncertainty in **statistics** is known to 1.6% through calibration and simulation of components including the fiducial volume cut and spill-in/spill-out.

Backgrounds from **accidental gammas** and **cosmogenic neutrons** are suppressed by PROSPECT's coincidence cuts and can yield ~1% uncertainty.

Combustion measurements from commercial labs can be used to benchmark the **number of target protons** in the LiLS for neutrinos from the HFIR HEU core to interact with. They are quoted to <1%.

Measurement Goals

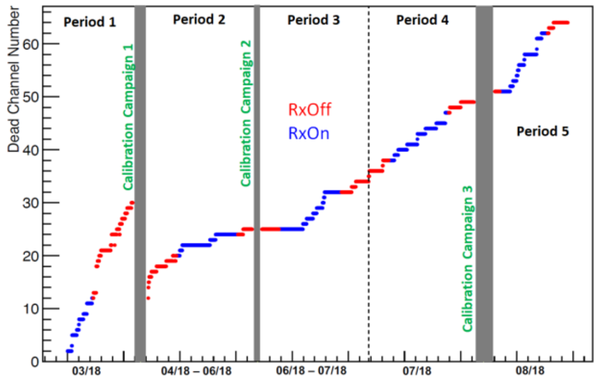
Combining all components indicates the **IBD detection efficiency** can be known to 1.4%. Integrating over all neutrinos at all energies makes a **3% absolute flux measurement** attainable.



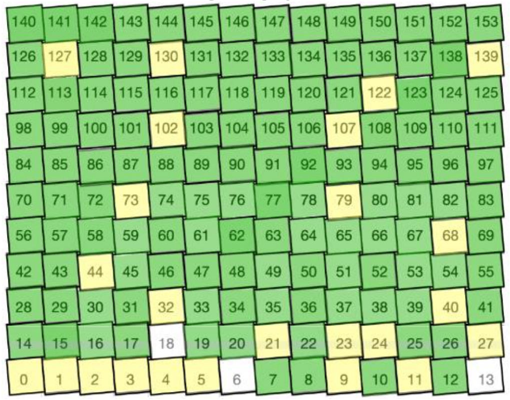
Performing an absolute reactor neutrino flux will also demonstrate **how well an above-ground detector can monitor the power of a research reactor**, for which there is no other comparable data set.

[1] H. Almazán *et al.* (STEREO Collaboration). Phys. Rev. Lett. 125, 201801 (2020).
[2] M. Andriamirado *et al.* (PROSPECT Collaboration). Phys. Rev. D 103, 032001 (2021).
[3] Mueller T *et al.* Phys. Rev. C 83, 054615 (2011).

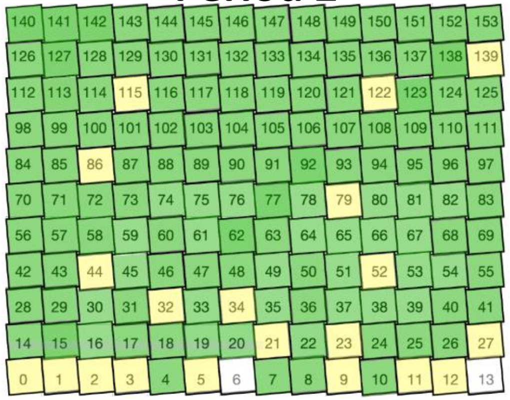
Dead Segments vs Time



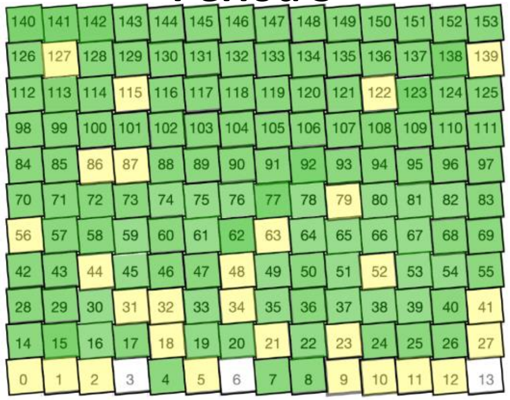
Period 1



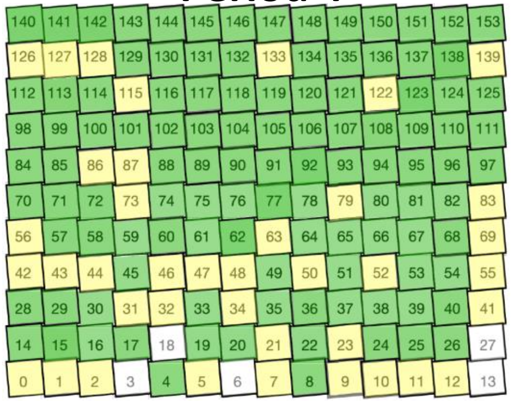
Period 2



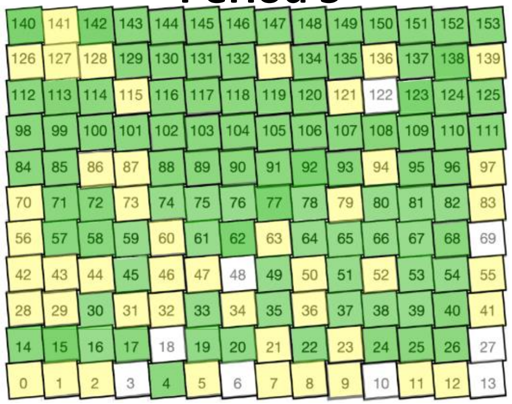
Period 5



Period 4



Period 5



Preliminary	IBD Effective	IBD Effective/ calendar day	Total IBD counts	Total IBD counts/ calendar day	S/CB (Total)	S/AB (Total)
Previously Published PROSPECT Results	15312	160	50560	529	1.37	1.78
Data Splitting	23325	244	64130	670	2.29	1.73
SEER	24285	254	47860	501	3.63	3.88
Data Splitting + SEER	31823	336	60653	632	3.89	4.32

- First implementation of new DS+SEER optimized provided the following improvements:
  - IBD counts ~**20%**
  - 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!**

Things to include

- Simplify detector discussion
- “Classical” Results from PRD for Spectra &
- Combined results: Prospect + Stereo & PROSPECT + DB (introduces Tikhonov Regularization & WienerSVD). WSVD framework very useful for…
- DEER+SEER+DataSplitting
  - WSVD: Generate Prompt Toy MCs, Unfold T MCs, Model Comparison, minimize Wiener Filter F from $S' = R^{-1} \cdot M \cdot F = S$, where S is the unfolded data, M is the visible data M and S is the true data.
- Update current-ish sterile motivation for prospect later in talk to motivate P-II upgrade (2 slides: 1 for update to RAA & DUNE-CP, and one for Detector Update)

	Latest results from DEAP-3600	Joseph McLaughlin	Bologna, Italy	14:30 - 14:50
15:00	DarkSide-20k and the Future Liquid Argon Dark Matter Program	Yi Wang	Bologna, Italy	14:50 - 15:10
	Status of the XENONnT dark matter experiment	Pietro Di Gangi	Bologna, Italy	15:10 - 15:30
	The LUX-ZEPLIN (LZ) experiment	Amy Cottle	Bologna, Italy	15:30 - 15:50
16:00	Recent progress and plan of PandaX experiment	Qing Lin	Bologna, Italy	15:50 - 16:10
	Dark matter search to the limits: the DARWIN experiment	Carla Macolino	Bologna, Italy	16:10 - 16:30
17:00	Searching for dark matter with the PICO bubble chambers	Eric Vazquez-Jauregui	Bologna, Italy	17:00 - 17:20
	Latest Results from the PROSPECT Reactor Antineutrino Experiment including Limits on Sub-GeV Boosted Dark Matter	Pierce Weatherly		
	Xenon-1T excess as a possible signal of a sub-GeV hidden sector dark matter	Michael Klasen	Bologna, Italy	17:40 - 18:00
18:00	MIGDAL: Towards an unambiguous observation of the Migdal effect in nuclear scattering	Ioannis Katsioulas	Bologna, Italy	18:00 - 18:20
	Dark Matter Data Center	Heerak Banerjee	Bologna, Italy	18:20 - 18:40