Oak Ridge National Laboratory

The University of Tennessee Knoxville

PROSPECT

eV-scale sterile neutrino searches with reactor neutrino experiment PROSPECT

Jeremy Lu

On behalf of the PROSPECT Collaboration

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

U.S. Department of Energy

PASCOS 2023

Outline

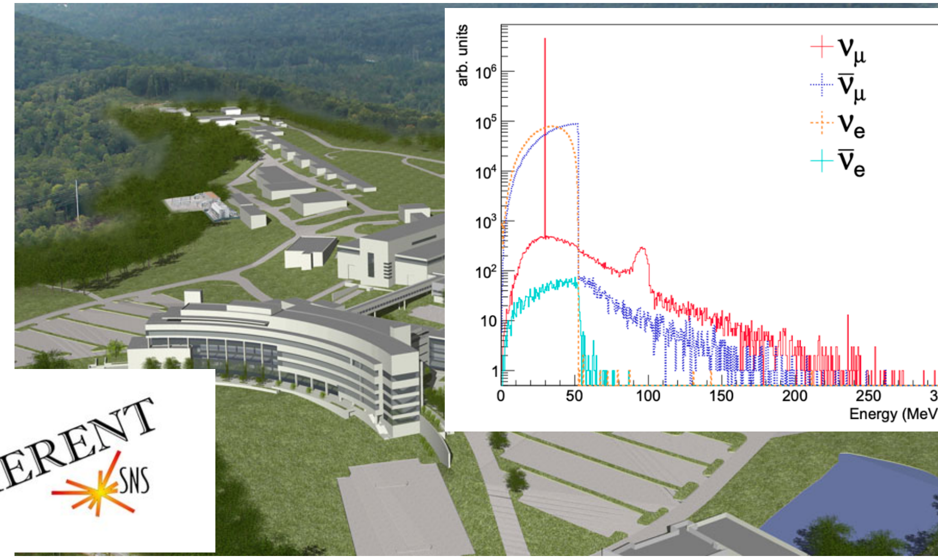
- Background context of reactor neutrino physics
- Introductions to PROSPECT experiment
- PROSPECT-II upgrades and physics goals
- Summary

ORNL's Opportunities: World Class Neutrino Sources

Spallation Neutron Source: SNS

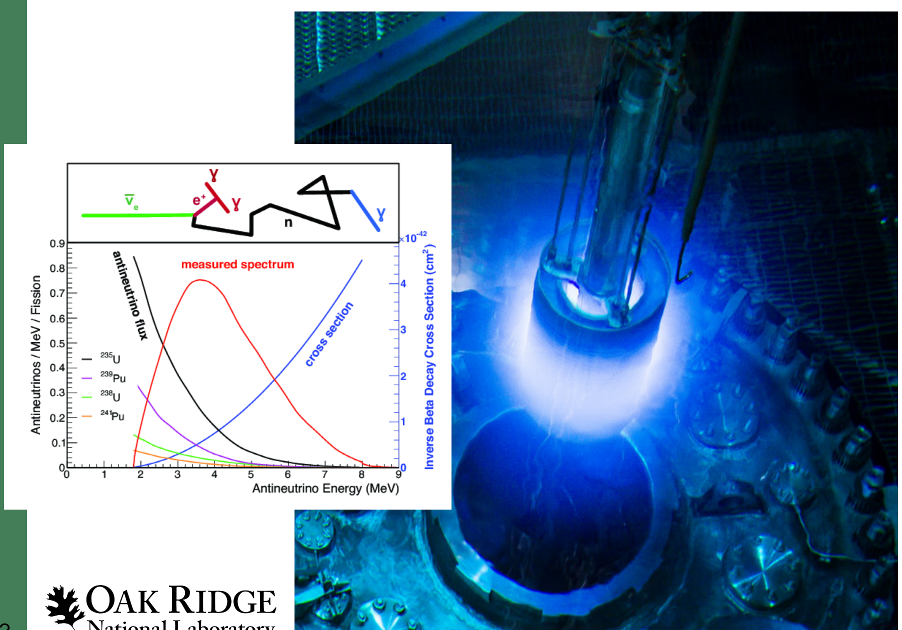
- Pulsed neutron source
- 1 GeV protons on Hg target
- 1.4 MW beam power
- 2nd target station

Phys. Rev. Lett. 129, 081801
Phys. Rev. Lett. 126, 012002



High Flux Isotope Reactor: HFIR

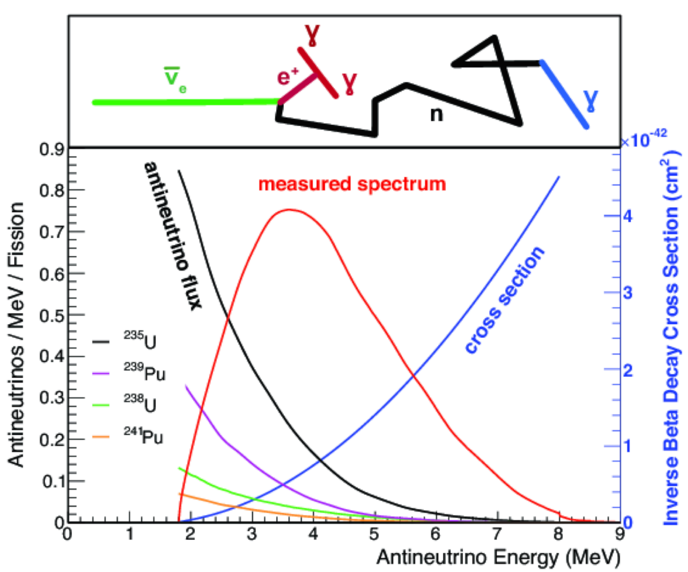
- 85 MW research reactor
- Fresh highly-enriched ^{235}U fuel
- Compact core



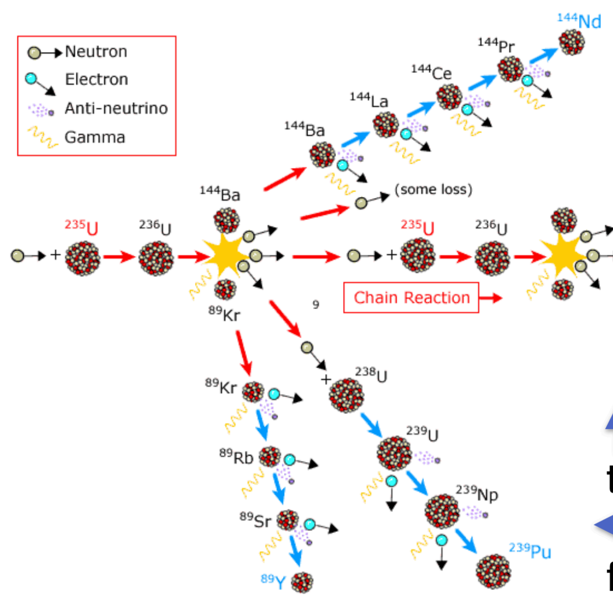
PhysRevLett 122 (2019) 251801
PhysRevLett 121 (2018) 251802

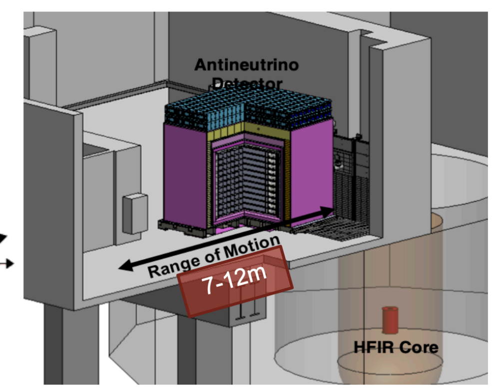
Reactors as man-made abundant neutrino source

- 85MW highly enriched 235U fuel (while in LEU 235U, 238U, 239Pu 241Pu)
- 24 days reactor-on cycle (>~99.9% neutrinos from 235U)
- Compact core (h=0.6m, d=0.4m) (great for oscillation study)
- High electron anti-neutrino flux ~2.0x10^19/sec
- Reactor-on/off cycle for background subtraction



Perfect location for PROSPECT

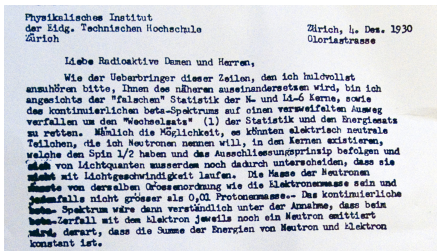




Detector location relative to reactor core

Neutrino production in fission chain (~6ν/fission)

Reactors as neutrino source in history

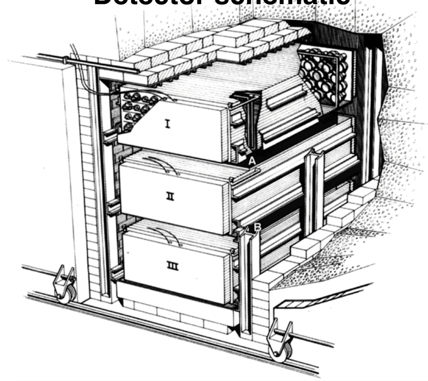

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

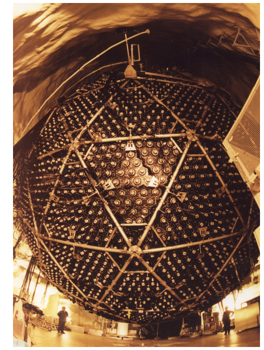
Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und [redacted] von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie [redacted] mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen [redacted] von derselben Grossenordnung wie die Elektronenmasse sein und [redacted]falls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche [redacted] Spektrum wäre dann verständlich unter der Annahme, dass beim [redacted]-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert [redacted] derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

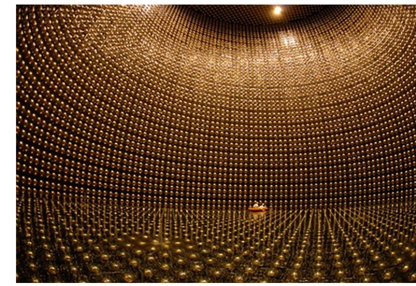
Savannah River Reactor Neutrino Detector schematic



SNO



SuperK



1930 postulation

1956 observation

2000 oscillation

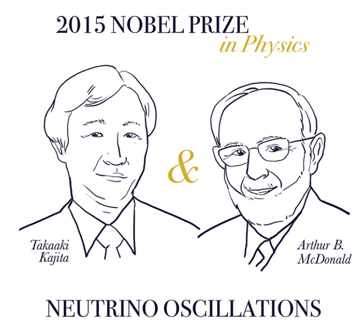
timeline

1995 Nobel Prize

2015 Nobel Prize

$$\theta_{13}, \theta_{12}, \Delta m^2_{21}$$

Fred Reines Clyde Cowan



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Motivations

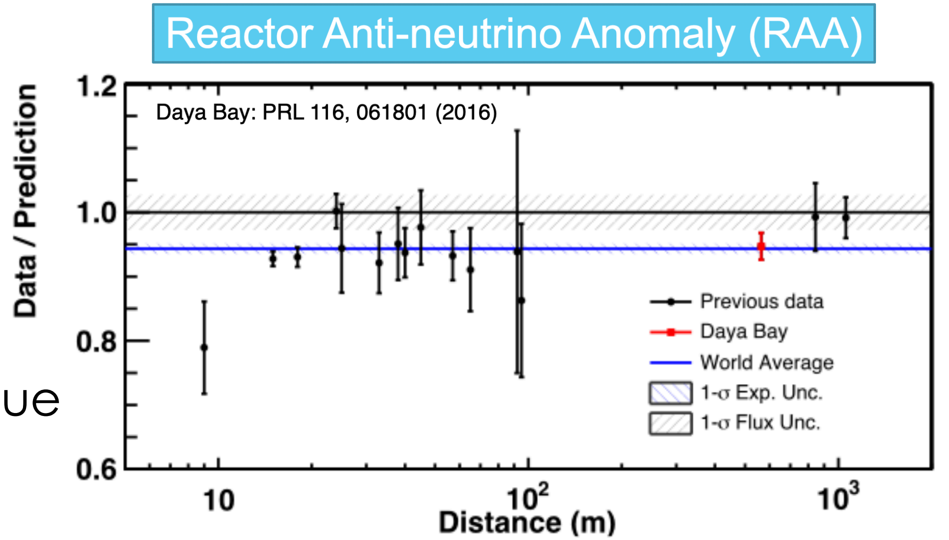
- Flux deficit of 6% from 2010's precision measurements and re-evaluated predictions (~eV-scale sterile neutrino)
- As of now it appears the RAA is likely due to miscalculations in 235U data from 1980s
- Spectral deviation centered around 5 MeV

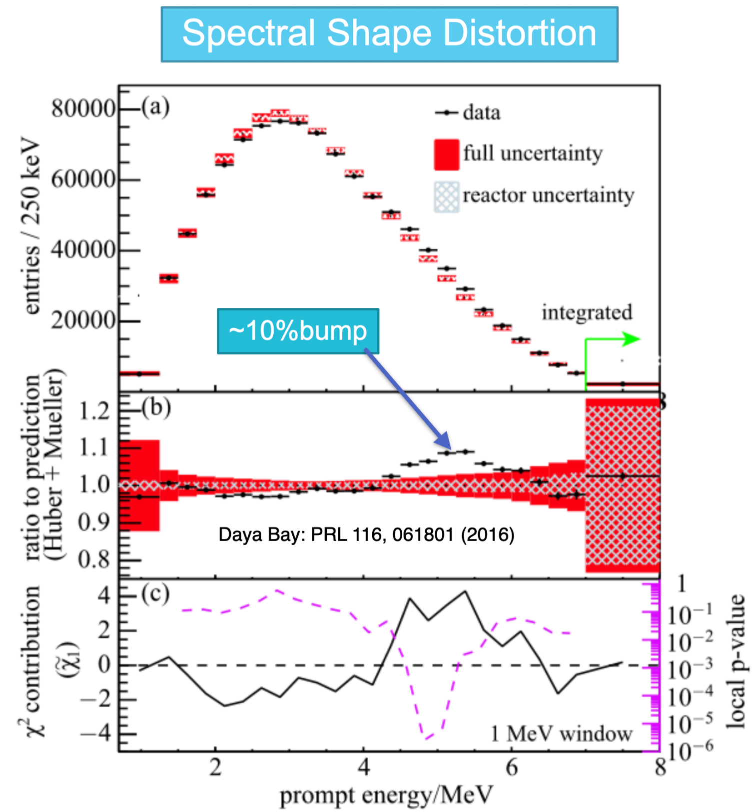
The main physics goals of PROSPECT includes:

- Reactor model-independent search for oscillations into eV-scale sterile neutrino

$$P_{dis} \sim \sin^2\theta_{14}\sin^2\left(1.27\Delta m_{41}^2(eV^2)\frac{L(m)}{E_\nu(MeV)}\right)$$

- Precise measurement of 235U anti-neutrino prompt spectrum

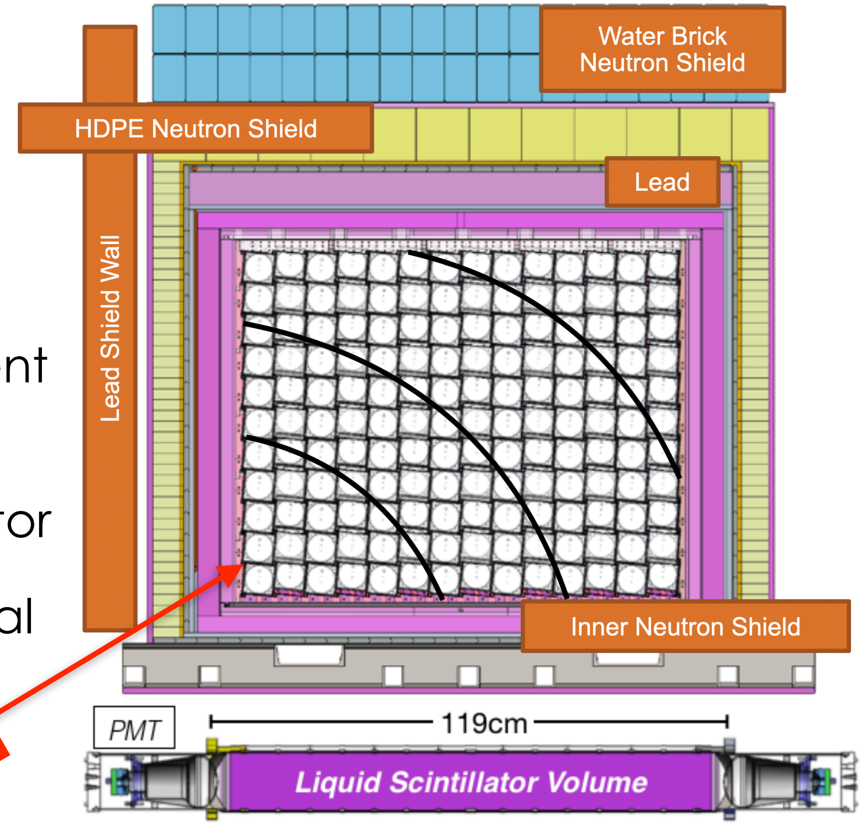




PROSPECT experiment

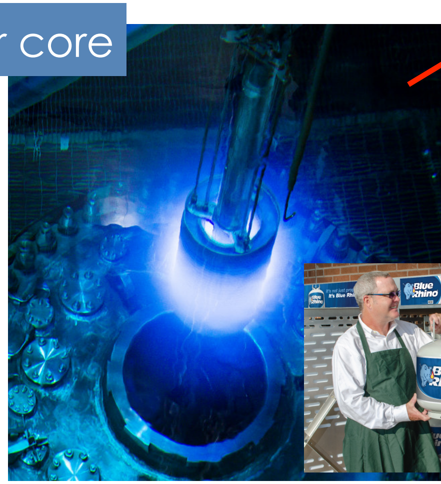
PROSPECT detector:

- the Precision Reactor Oscillation and SPECTrum Experiment
- Short baseline reactor neutrino experiment located at HFIR, ORNL
- ~4 ton ^{6}Li-loaded liquid scintillator detector
- Optically segmented into 14 x 11 identical detectors



7-9m

HFIR reactor core



- In-situ internal calibration access
- Less than ~1m w.e. overburden

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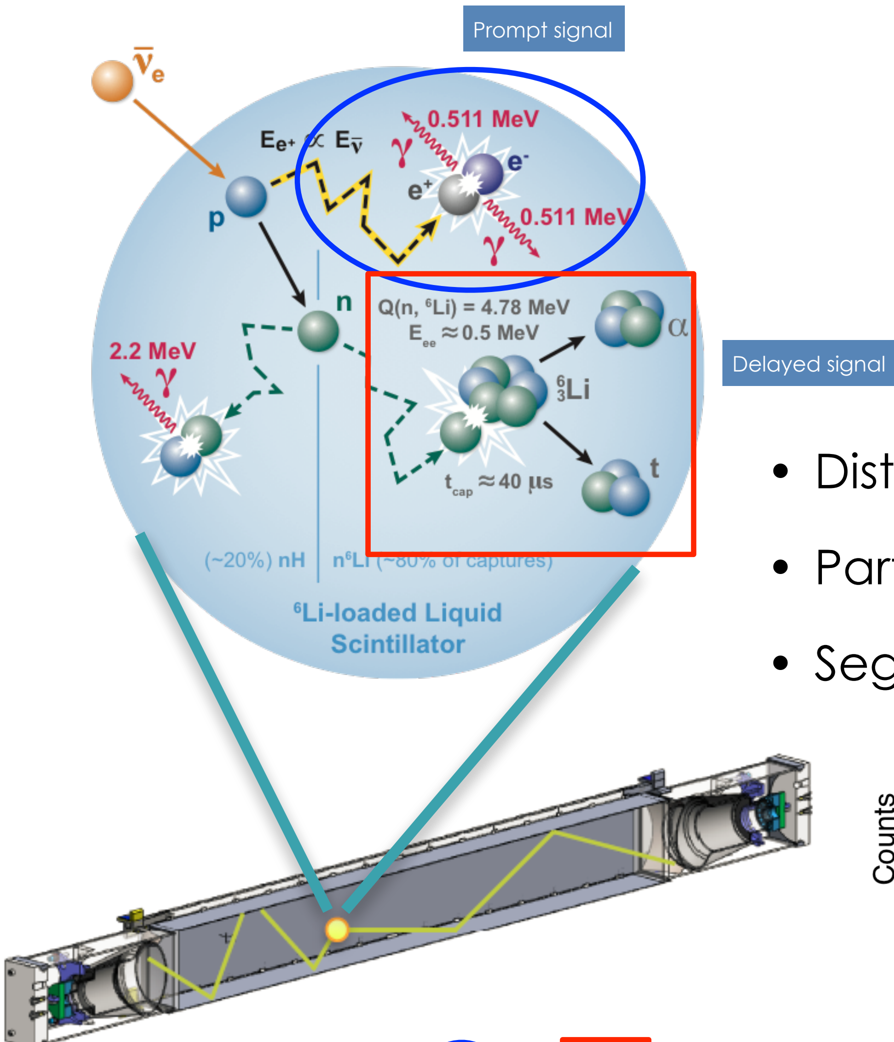
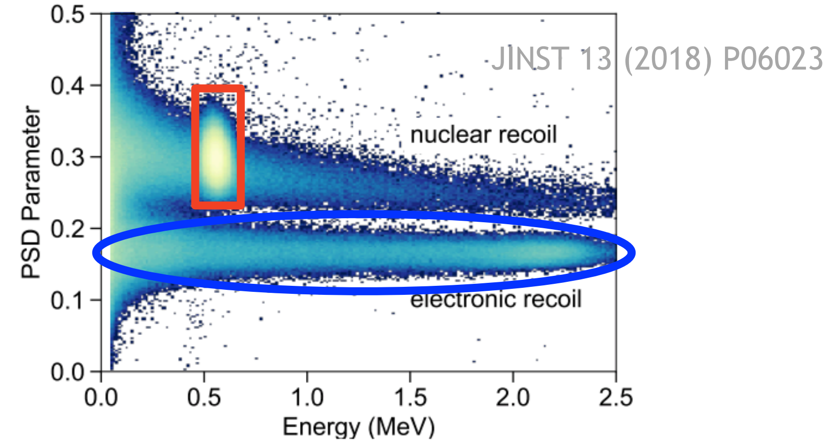
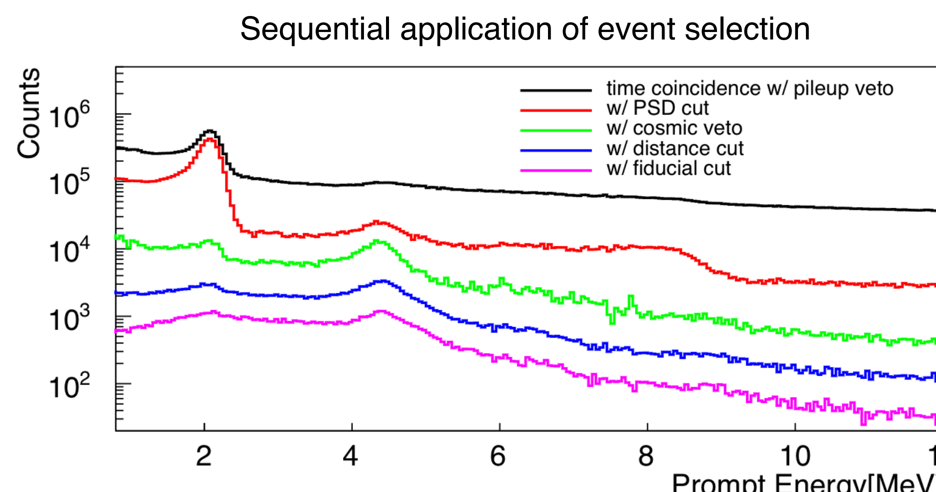
Inverse Beta Decay as neutrino signal





- Distinctive spatial/temporal correlation
- Particle ID capable LS via PSD (tail fraction)
- Segment fiducialization, veto cuts, etc



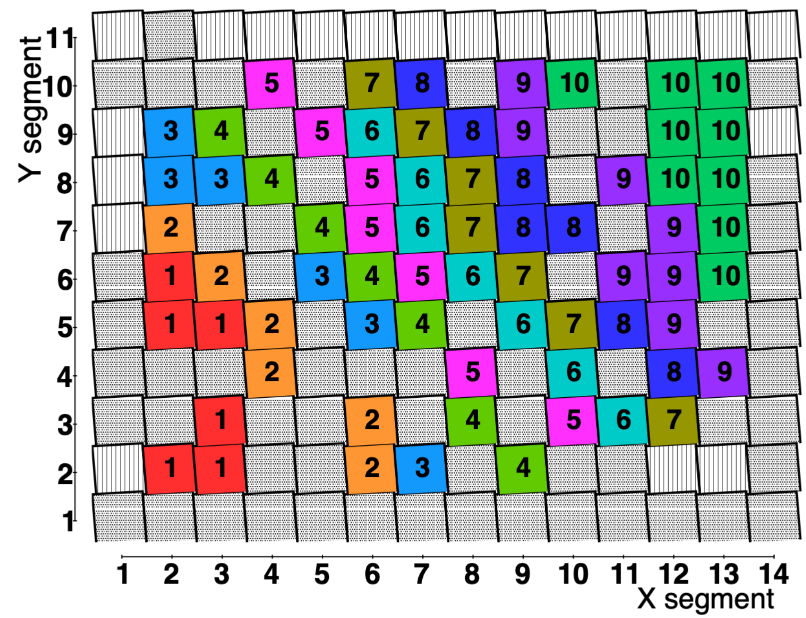
PRD103, 032001(2020)

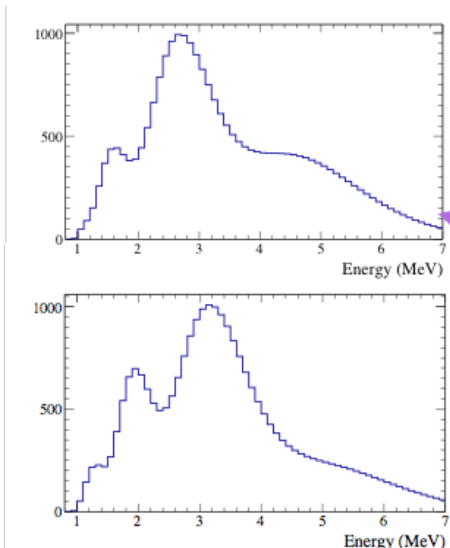
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

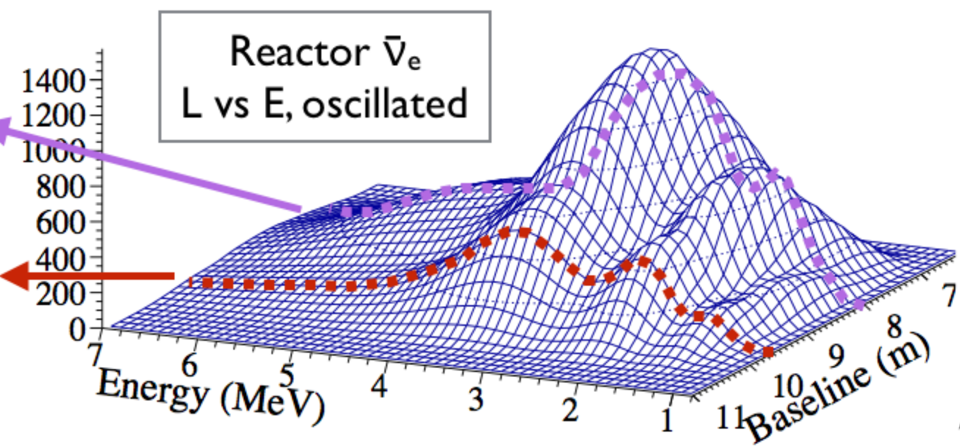
Prompt signal Delayed signal

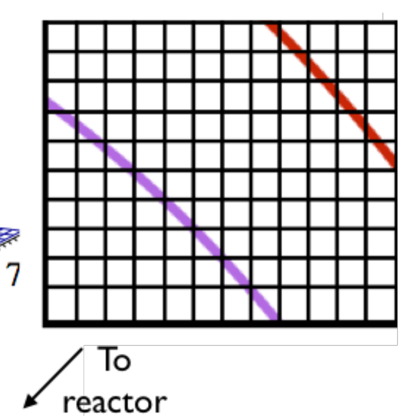
Reactor model-independent search for sterile neutrinos

- Prompt energy spectra grouped into baseline bins
- Relative spectral comparisons between data and predictions (non-oscillated, oscillated), enabling χ^2-based statistical searches sterile neutrinos









$$P_{dis} \sim \sin^2\theta_{14}\sin^2\left(1.27\Delta m_{41}^2(eV^2)\frac{L(m)}{E_\nu(MeV)}\right)$$

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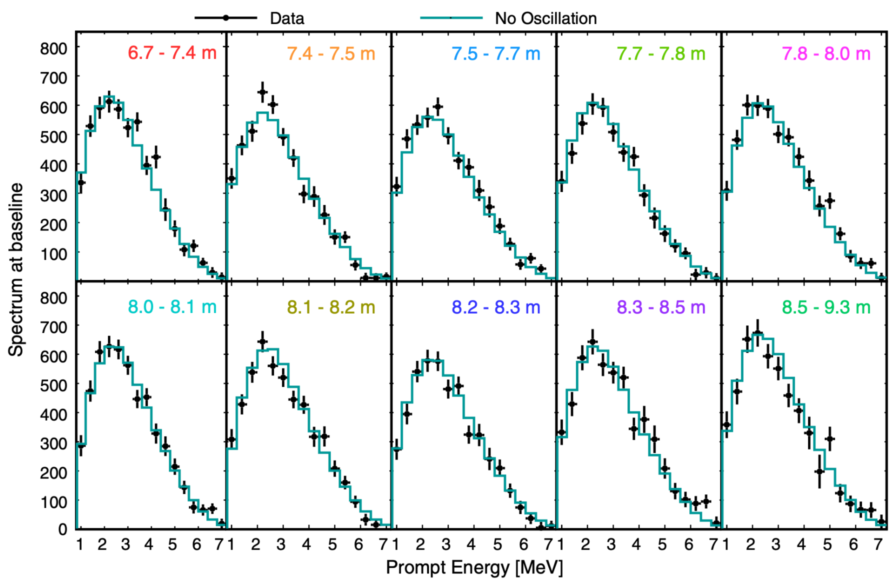
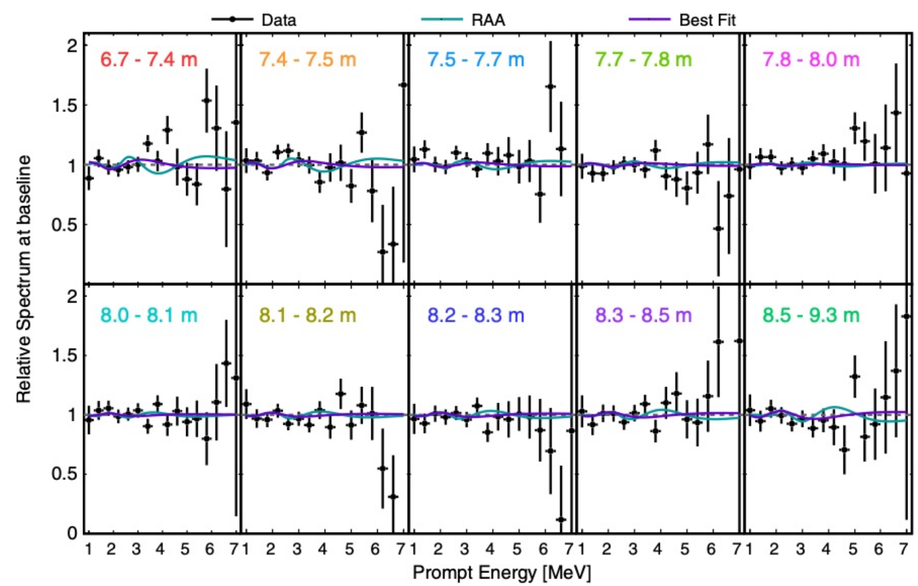
PROSPECT spectrum

- Per-baseline IBD spectra offers model-independent search for sterile neutrino oscillation

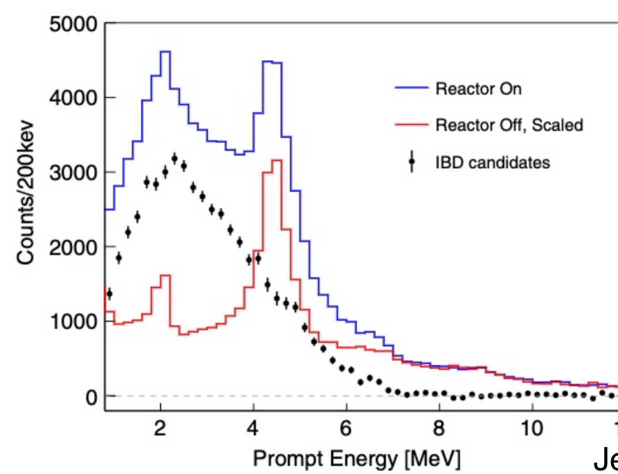
Absolute spectra



Relative spectra



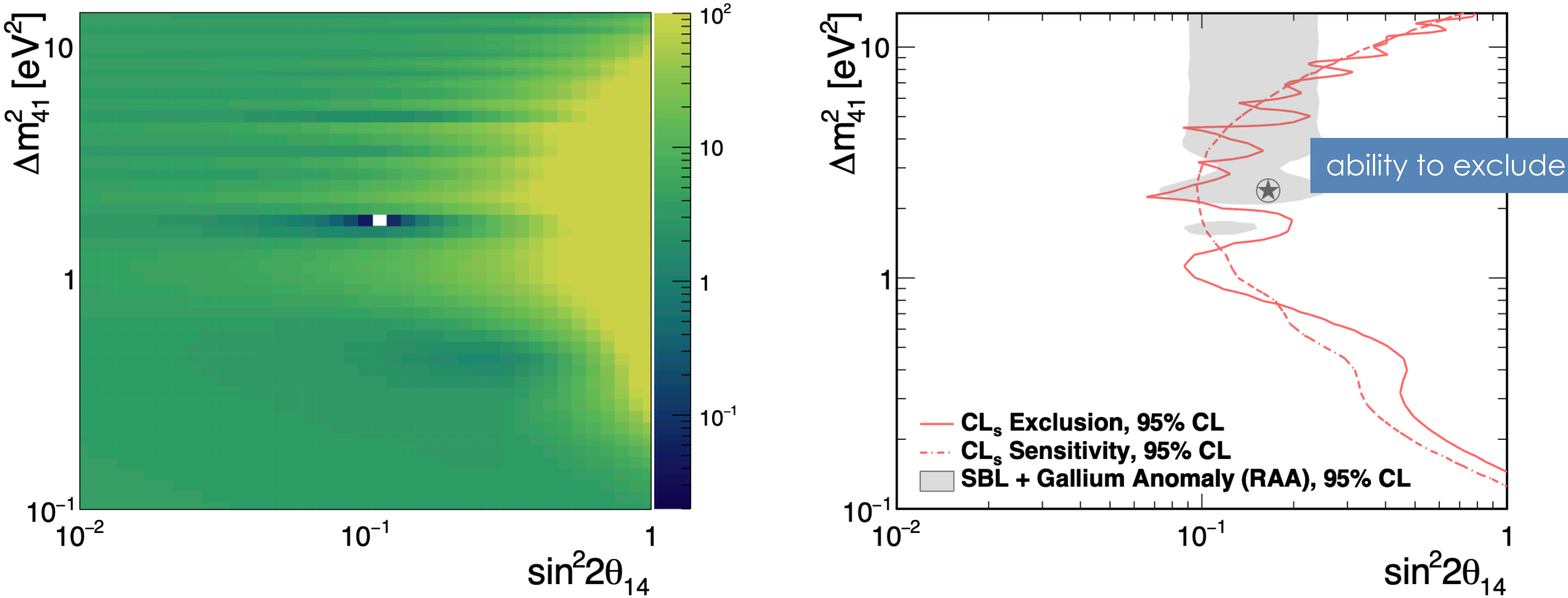
- High statistics(~50k) IBD candidates energy spectrum from ^{235}U fuel



PROSPECT collaboration, PRD**103**, 032001(2020)

PROSPECT oscillation results

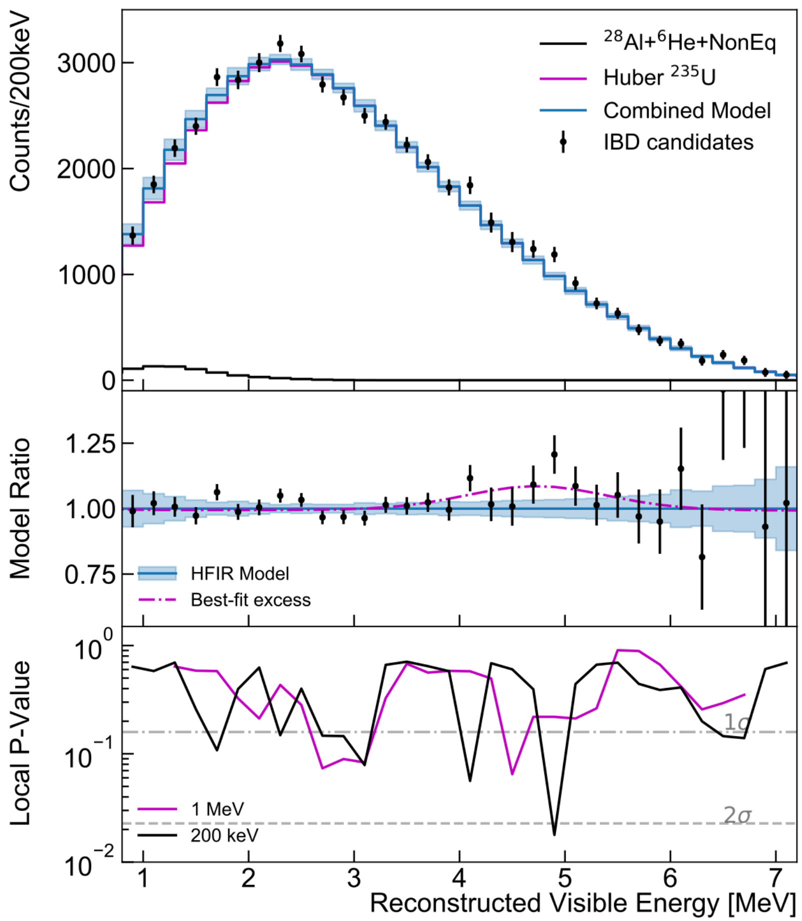
- $\Delta\chi^2$ map relative to the best fit point to generate exclusion curves (Gaussian CL/Feldman-Cousins frequentist approach)
- Ability to address RAA at 2.5σ confidence level

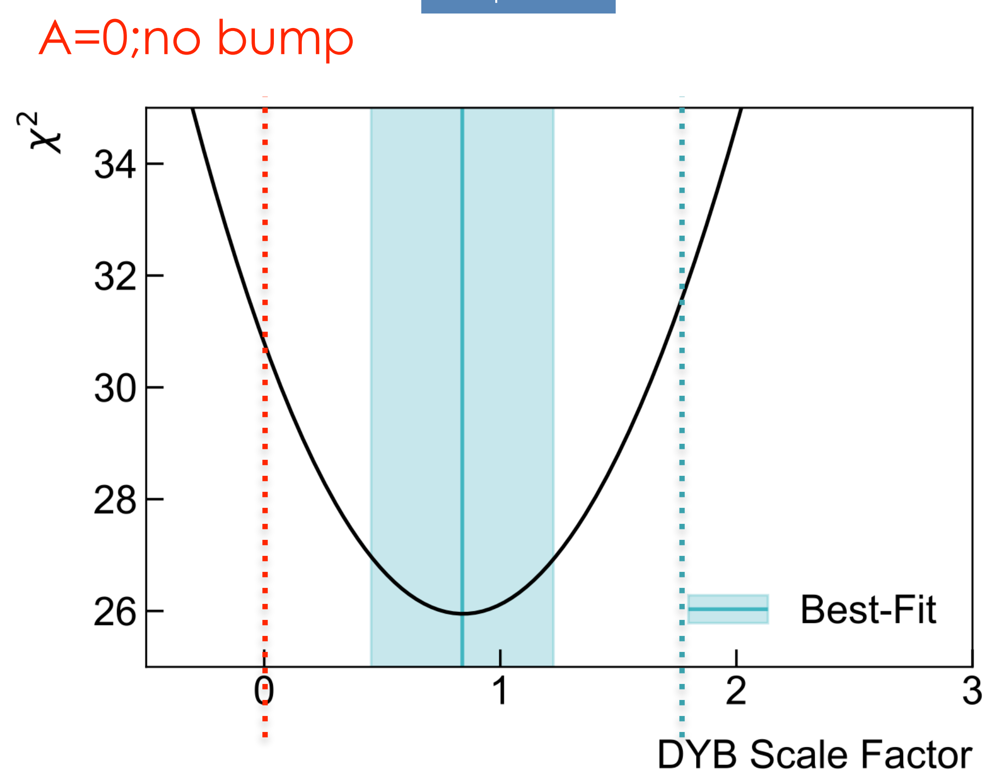


PROSPECT collaboration, PRD**103**, 032001(2020)

PROSPECT spectrum results

- High precision 235U spectrum (over 50,000 IBDs detected)
- The isotopic origin of the spectral bump; disfavors no bump at 2.2σ and 235U solely responsible for LEU bumps at 2.4σ



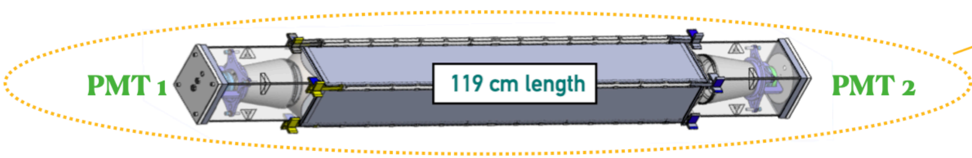


PROSPECT collaboration, PRD**103**, 032001(2020)

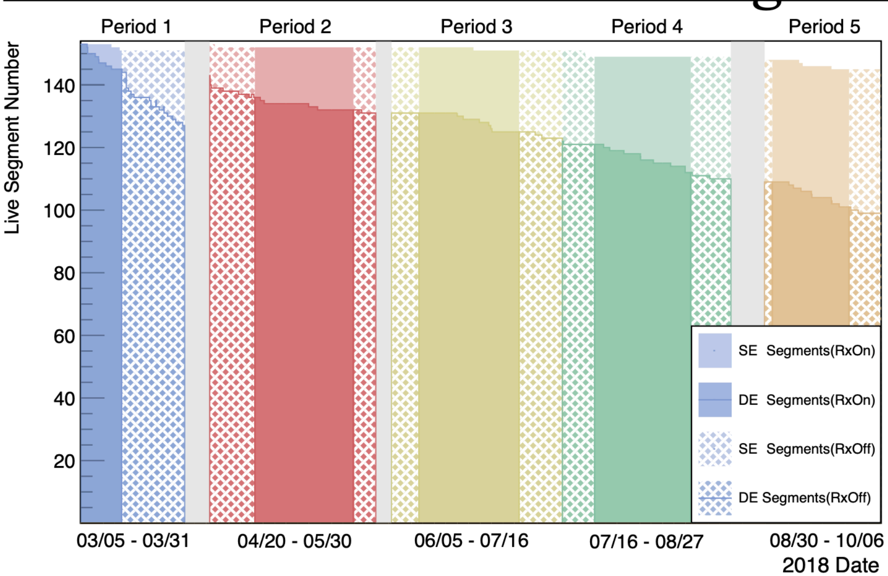
Final PROSPECT spectrum results

- Final spectrum (arXiv:2212.10669) analysis on the same dataset using multi-period + usage of single ended dead segments analysis approach (accepted for publication on PRL)
- ~20% increase of detected IBD counts ~50,000 to 60,000 ; double effective statistics (background-free IBD counts), signal to background ration increased to 3.8 from 1.4

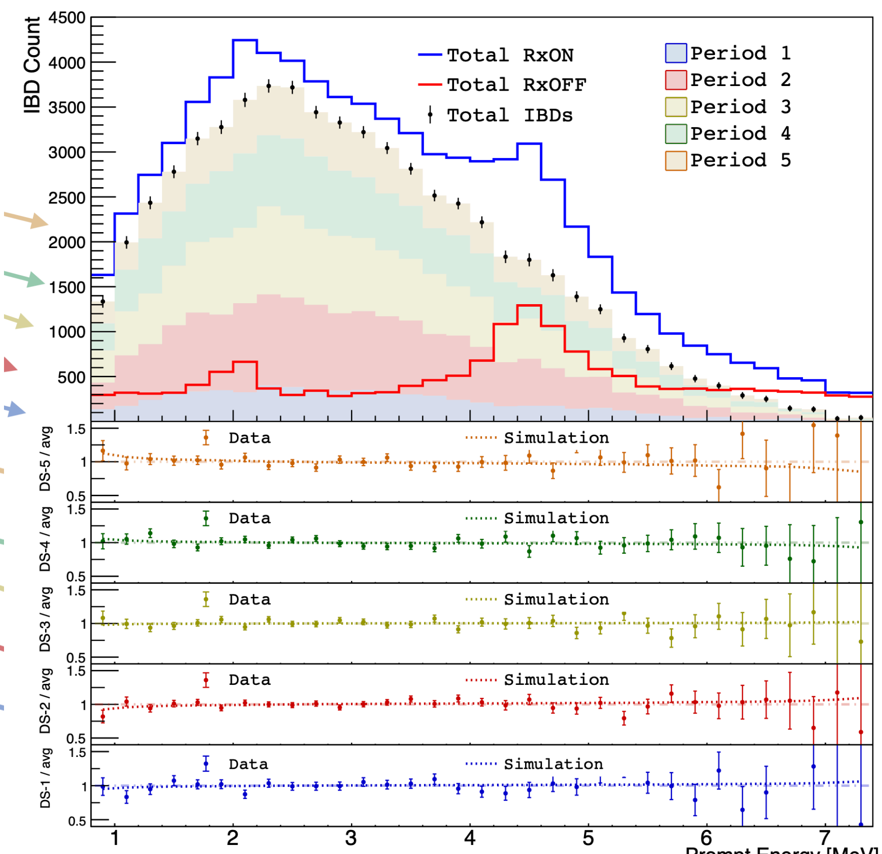
arXiv:2212.10669



Evolution of SEER vs DEER segments!

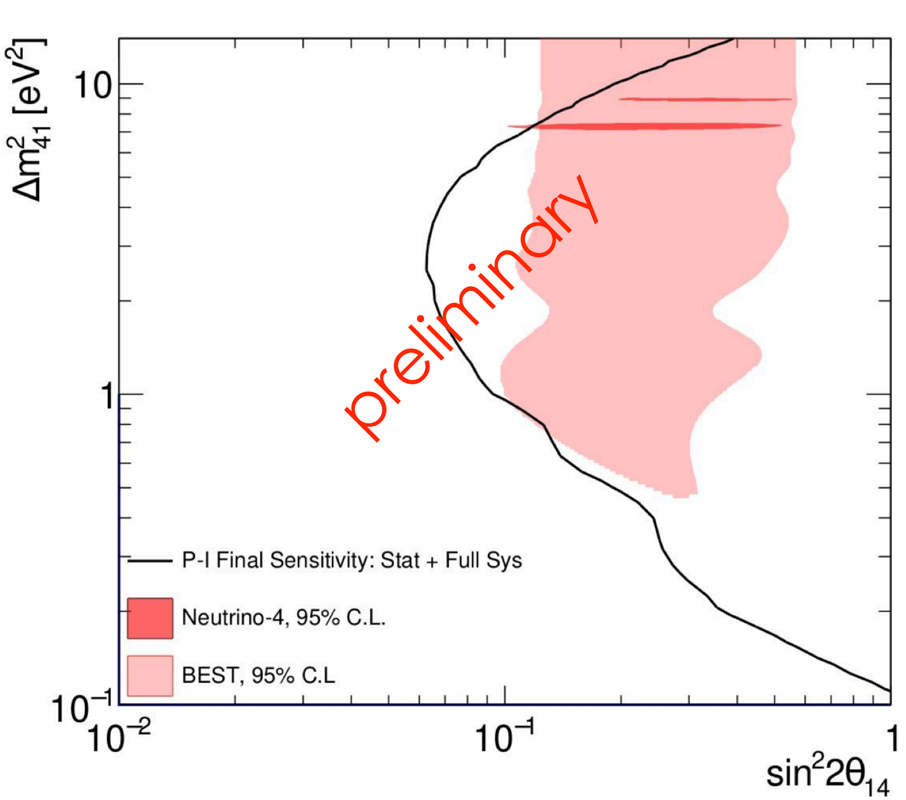


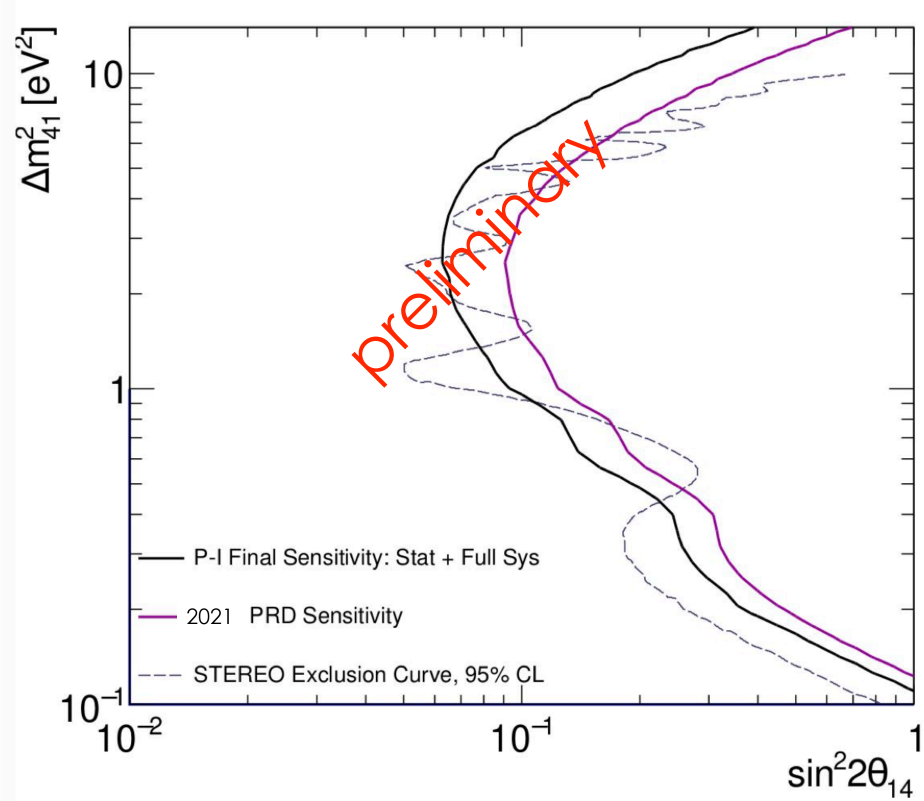
arXiv: 2212.10669v2 (2023)



Preliminary final PROSPECT oscillation results

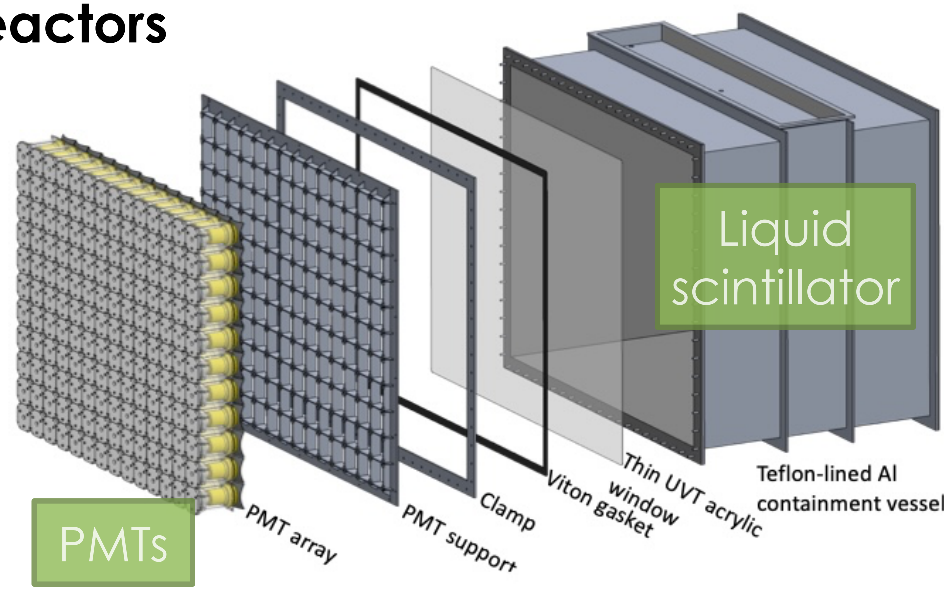
- Oscillation (ongoing, but soon) analysis benefits from the same improved dataset
- Great improvement in high mass-splitting, address Neutrino-4[Phys. Rev. D 104, 032003] claimed sterile neutrino observation/BEST allowed regions[Phys. Rev. Lett. 128, 232501] (reaffirming gallium anomaly)





Moving on

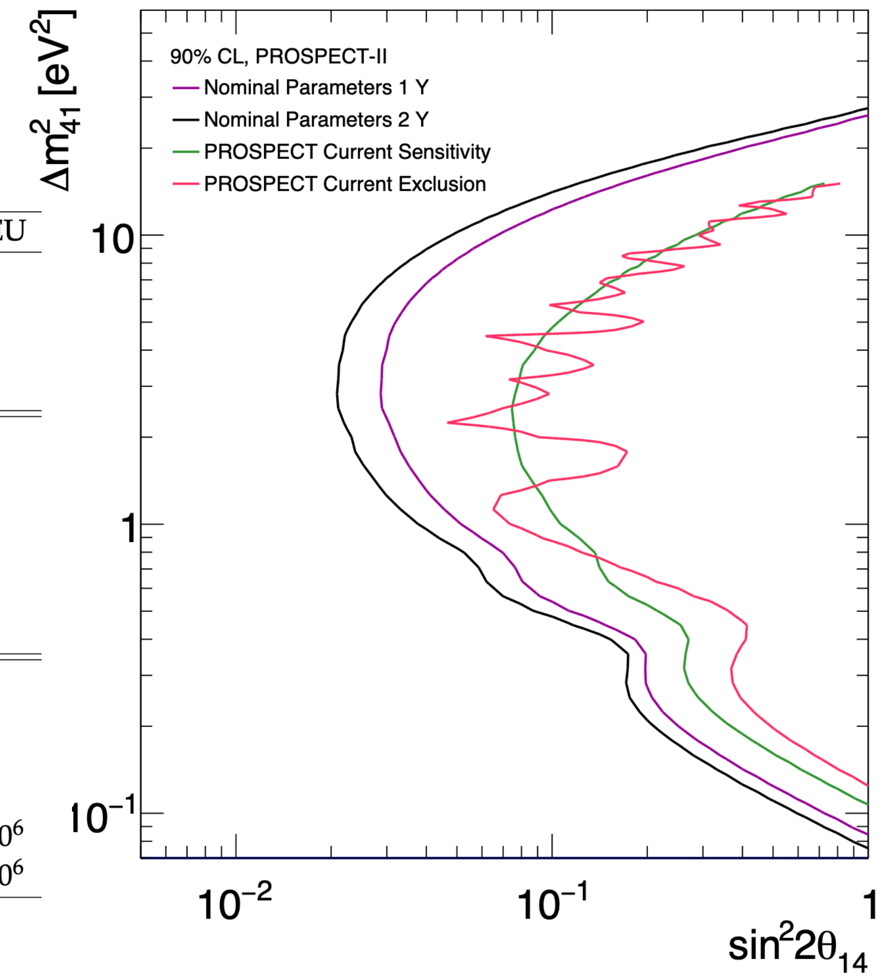
- Preparing for an upgraded version, PROSPECT-II detector to further expand the physics
  - **Movement of PMTs outside the scintillator volume (~25% longer segments)**
  - **Increased active detector volume by ~20%**
  - **Reduction of material in contact with LS**
  - **adjust calibration scheme**
  - **redeployment to LEU power reactors**



PROSPECT-II physics projections

- Estimated x6 more IBD statistics and x10 more effective statistics, with improved signal to background ratio 4.3 from 1.4
- Much better sensitivities compared to published PROSPECT-I results

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



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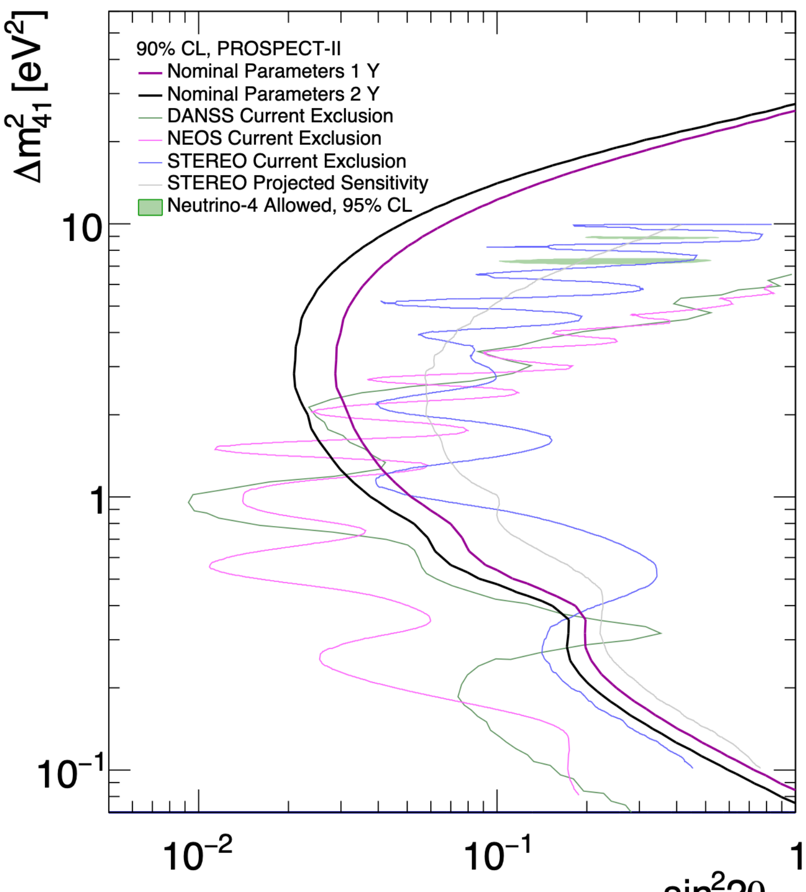
arXiv:2107.03934

PROSPECT-II sterile neutrino sensitivities

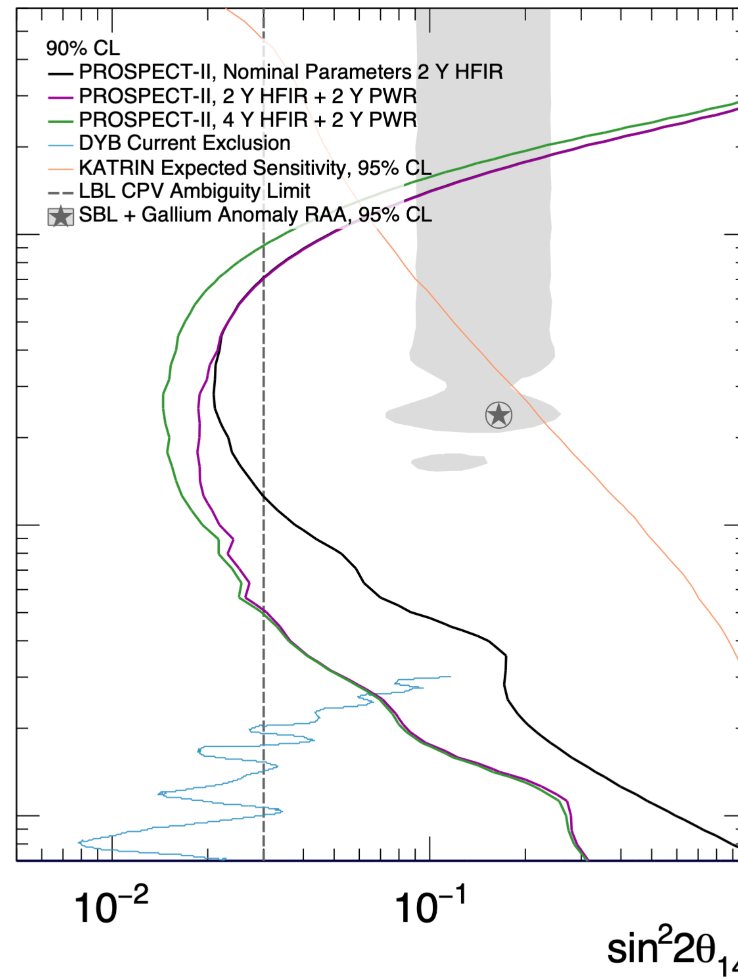
- Competitive coverage in high mass-splitting among short-baseline reactor experiments

Phys. Rev. Lett. 113, 141802

- Coverage of the parameter space gap between Daya Bay and projected KATRIN experiment Phys. Rev. Lett. 126 091803



arXiv:2107.03934



Summary

- Introduced the short-baseline reactor neutrino PROSPECT experiment
- Described the method for model-independent searches for sterile neutrino at eV scale
- Described the PROSPECT-II detector upgrades and expanded sensitivity in sterile neutrino space
- Discussed the PROSPECT sterile neutrino search in the global context
- Ongoing absolute flux analysis & joint analysis with STEREO and Daya Bay
- Sub-GeV dark matter constraints

PHYSICAL REVIEW D 104, 012009 (2021)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Thank you!
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HEISING-SIMONS FOUNDATION
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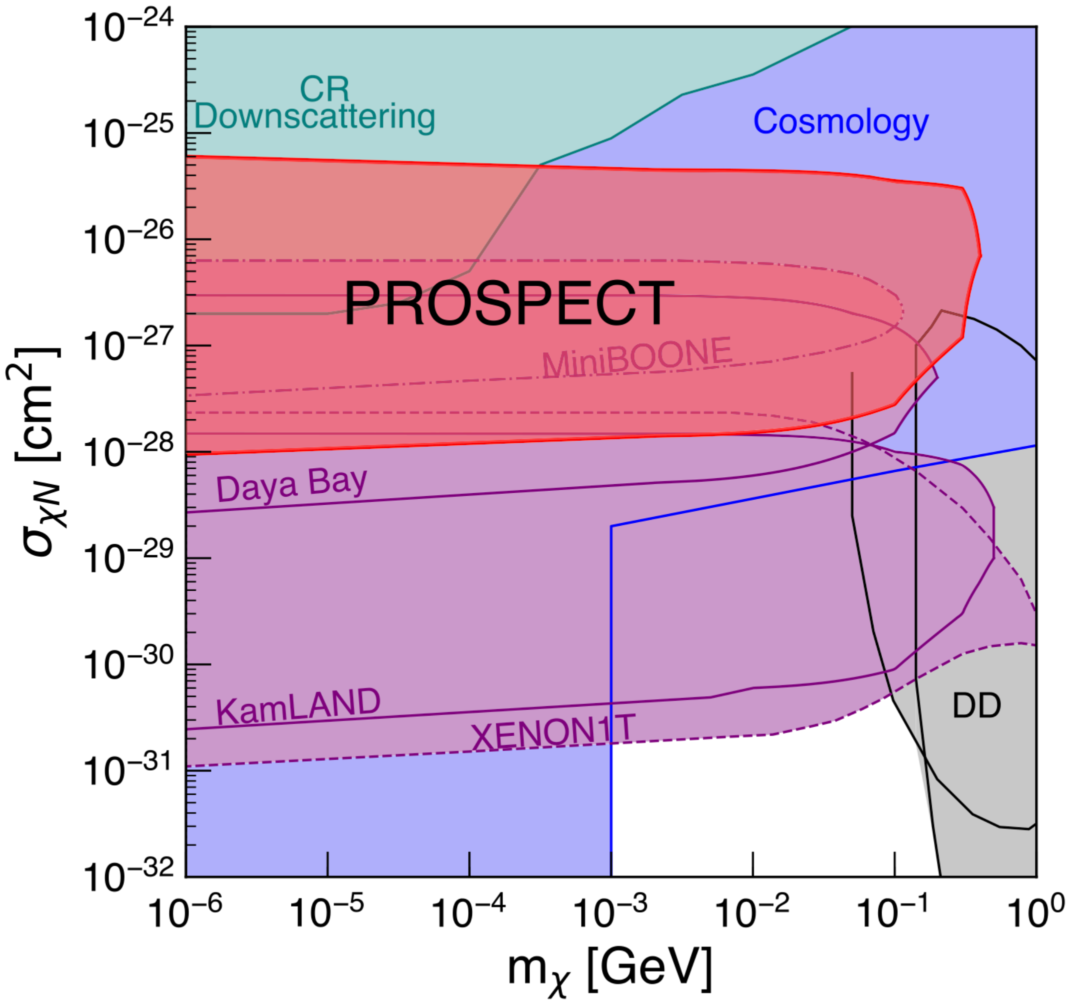
GRFP
14 Institutions, 70 collaborators
BROOKHAVEN NATIONAL LABORATORY
NIST
Lawrence Livermore National Laboratory
OAK RIDGE National Laboratory
Drexel
W&M
Yale

Backup slides

Limits on sub-GeV dark matter from the PROSPECT reactor antineutrino experiment

PHYSICAL REVIEW D 104, 012009 (2021)



- isolated proton recoil signatures within 440 kg of target liquid scintillator
- identified 37522 candidate interactions of energetic dark matter upscattered by cosmic rays
- do not exhibit any statistically significant degree of diurnal sidereal modulation

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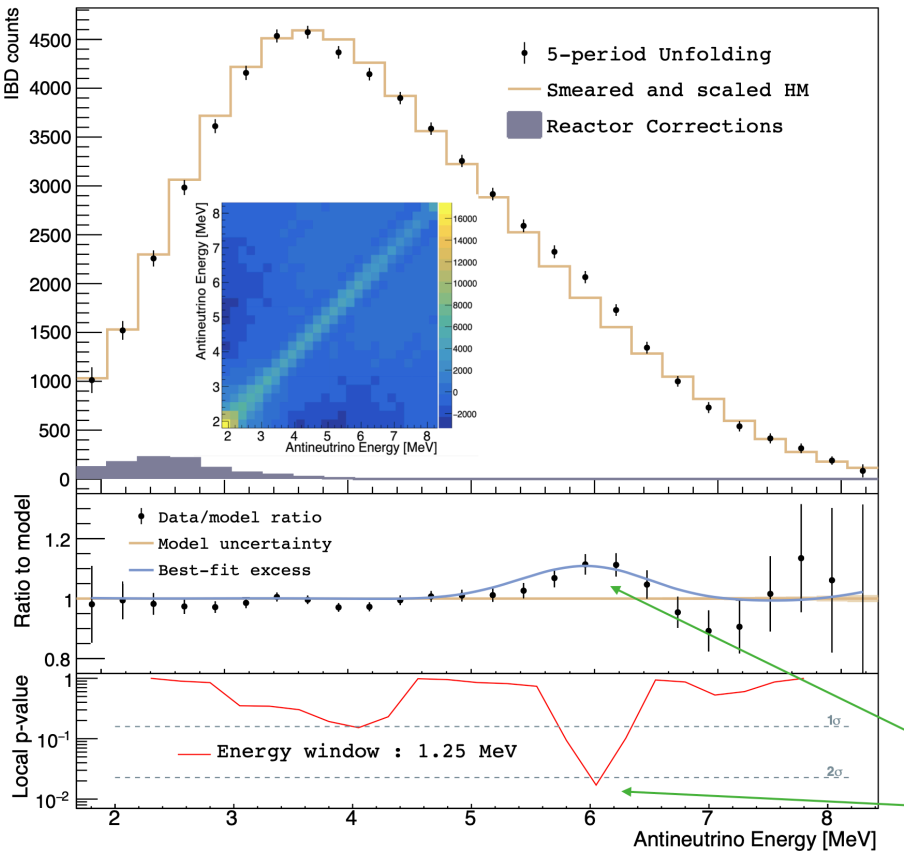
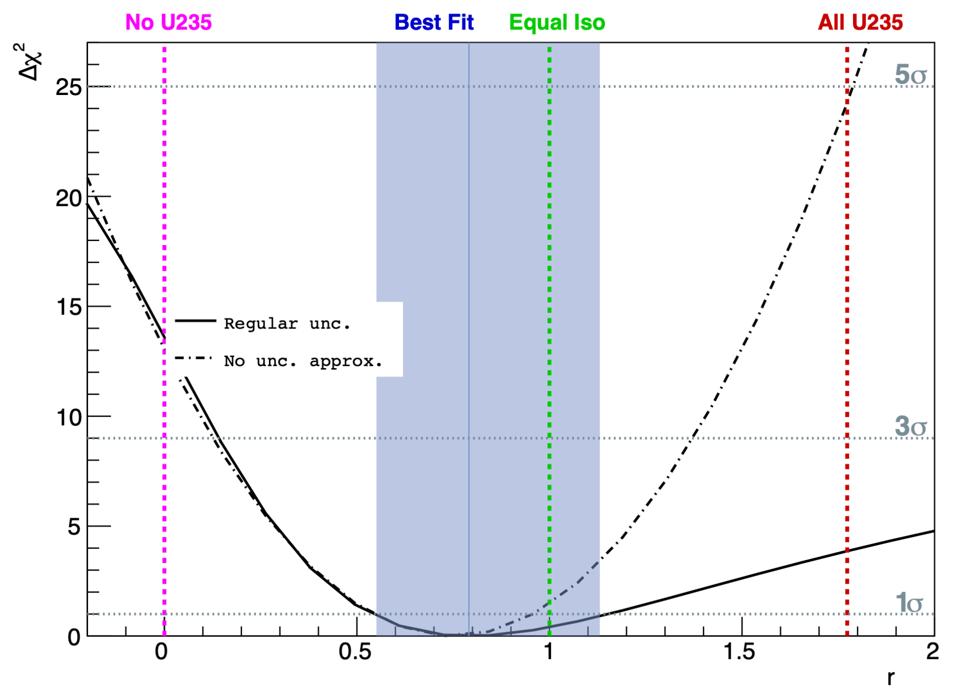
Backup slides

Final PROSPECT spectrum analysis



Ratio of PROSPECT bump amplitude to Daya-Bay bump



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Backup slides

As a by-product of the spallation, charged and neutral pions are also produced. About 99% of π^- produced are captured within the thick and dense mercury target, while the majority of π^+ stop and decay at rest with a lifetime of 26 ns according to Eq. 4. The majority of μ^+ also stop inside the target and decay at rest, but with a longer lifetime of 2.2 μs according to Eq. 5. This produces three distinct neutrino flavours, prompt ν_μ, and delayed ν_e and $\bar{\nu}_\mu$, with the kinetically well-defined energy spectra as shown in Fig. 5.

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \tag{4}$$

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e \tag{5}$$