Oak Ridge National Laboratory

ORNL Neutrino Program

Alfredo Galindo-Uribarri
Physics Division

June 18, 2024

UNAM

– LANSPA

PROSPECT Precision Oscillation and Spectrum Experiment

COHERENT SNS

LEGEND Large Enriched Germanium Experiment for Neutrinoless ββ Decay

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

U.S. DEPARTMENT OF ENERGY

DOE/HEP DOE/NP

About me:


Northwestern Passages
NU
Greenland
Iceland
Norwegian Sea
Sweden
Finland
Norway
YT
NT
Canada
Hudson Bay
AB
MB
BC
SK
NL
AECL
EACL
NB
PE
NS
WA
MT
ND
MN
SD
WI
MI
OR
ID
WY
IA
NE
IL
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North Atlantic Ocean
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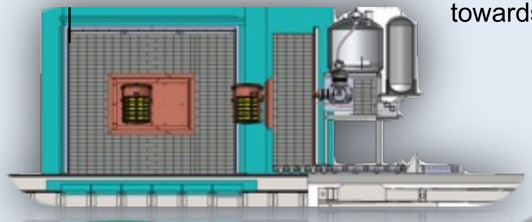
Tunisia
Morocco
Algeria
Libya
Egypt
Western Sahara
Saudi Ar
Mauritania
Mali
Niger
Chad
Sudan
Burkina Faso
Guinea

OUTLINE

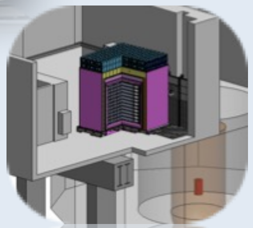
- Introduction Neutrino
  - Neutrino Sources
    - HFIR
    - SNS
- LEGEND and COHERENT
- PROSPECT I Final Results
  - Motivation
  - Spectrum
  - Oscillations

Current interests in ν science

- Experimentally determine the fundamental properties of neutrinos and their interactions with matter
- Develop the best tools and detector technologies to support neutrino research.

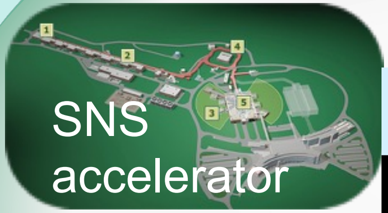


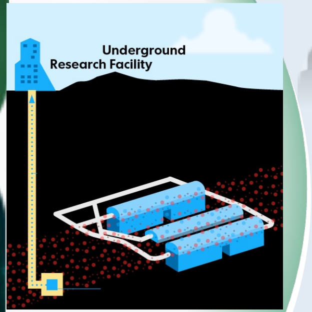
LEGEND-
towards 1 tonne ^{76}Ge experiment

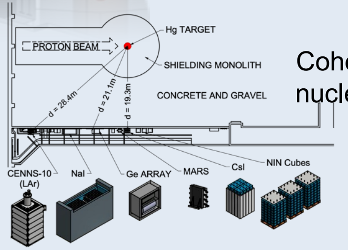


PROSPECT-
A Precision Reactor Neutrino Oscillation and Spectrum Experiment at the 85MW HFIR

Isotope Program:
Stable and Radioactive-
New capabilities

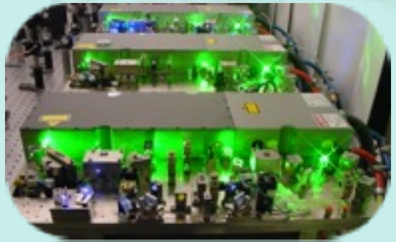






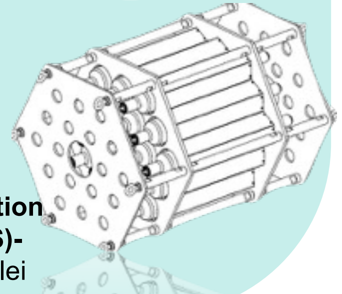
COHERENT-
Coherent elastic neutrino-nucleus scattering at SNS

Ultra Sensitive Analytical Techniques-
AMS
RIMS
NAA



Dark matter-
detectors technology

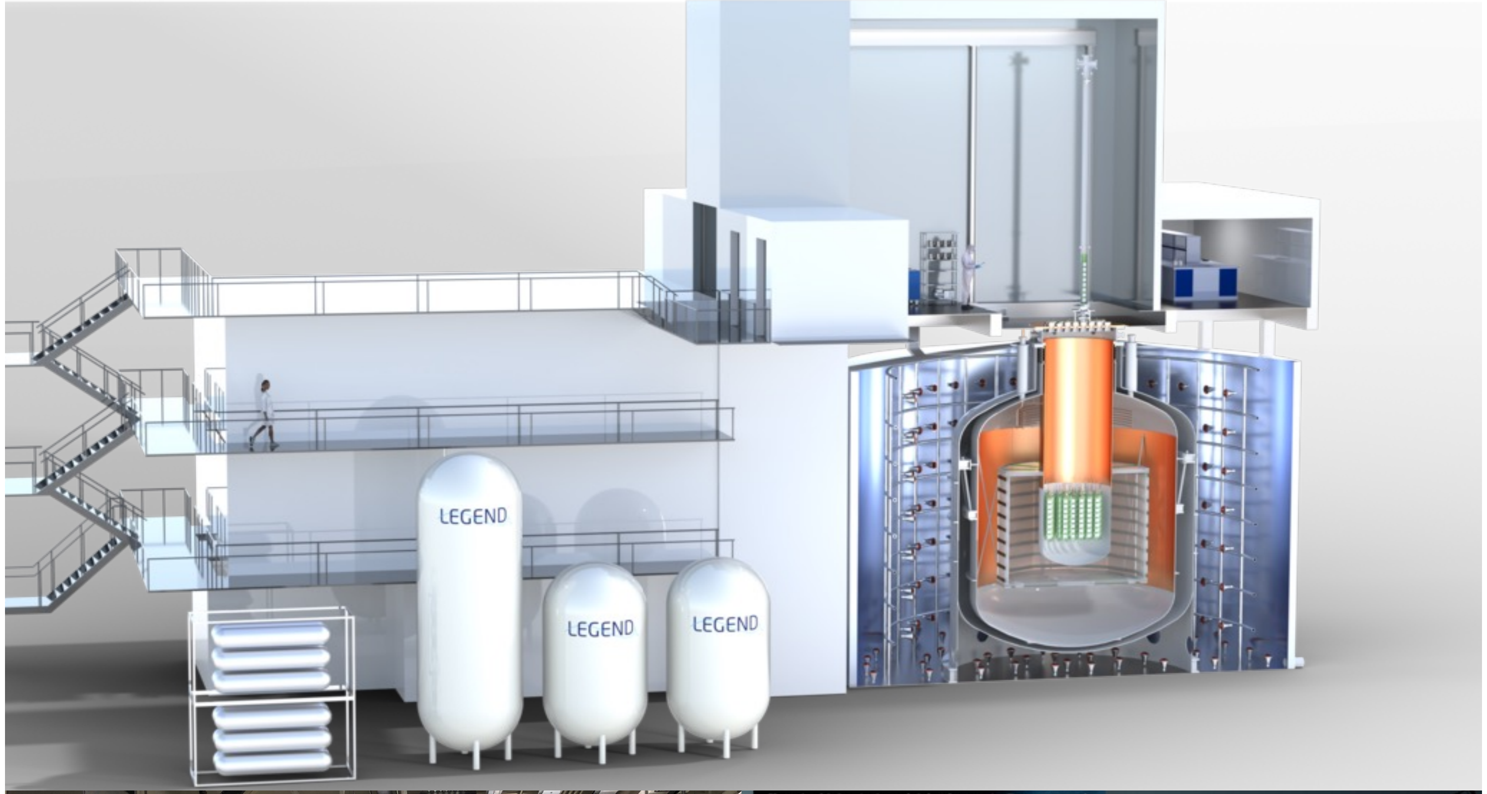
Quantum Information Science-
Machine Learning

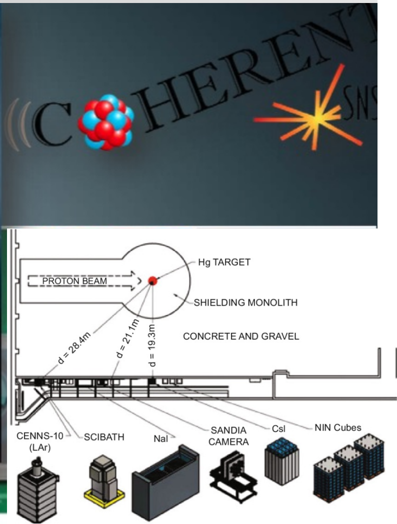


Modular Total Absorption Spectrometer (MTAS)-
β-decays of n-rich nuclei

ORNL: A hub for neutrino physics

- Oak Ridge National Laboratory (ORNL) is a multidisciplinary laboratory that presents multiple opportunities to study neutrinos.
- The diverse research portfolio includes:
  - Searches for neutrinoless double beta decay with the LEGEND experiment
  - Observation of Coherent Elastic Neutrino Nucleus Scattering (CEvNS) by the COHERENT collaboration
  - Inverse beta decay (IBD)-based antineutrino detection with the PROSPECT experiment





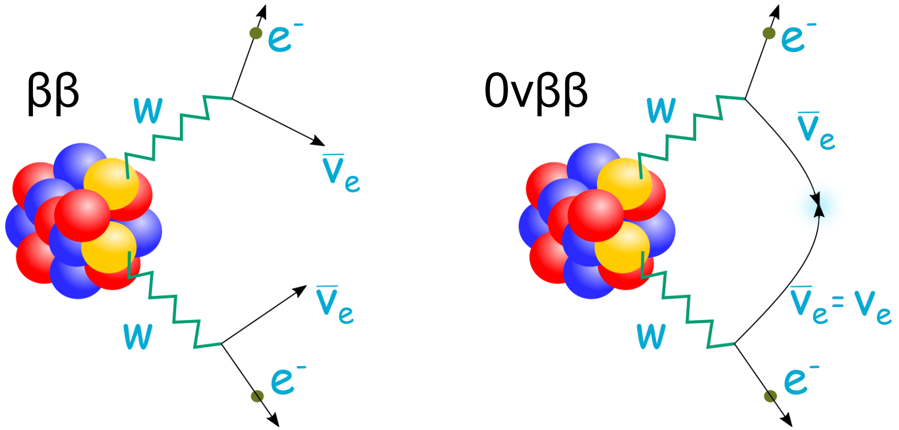
Neutrinoless double beta decay

2006

OAK RIDGE National Laboratory

Search for Neutrinoless Double Beta Decay (0νββ)

This research has been identified by recent national and international review panels as being one of the highest priorities in all of physics.

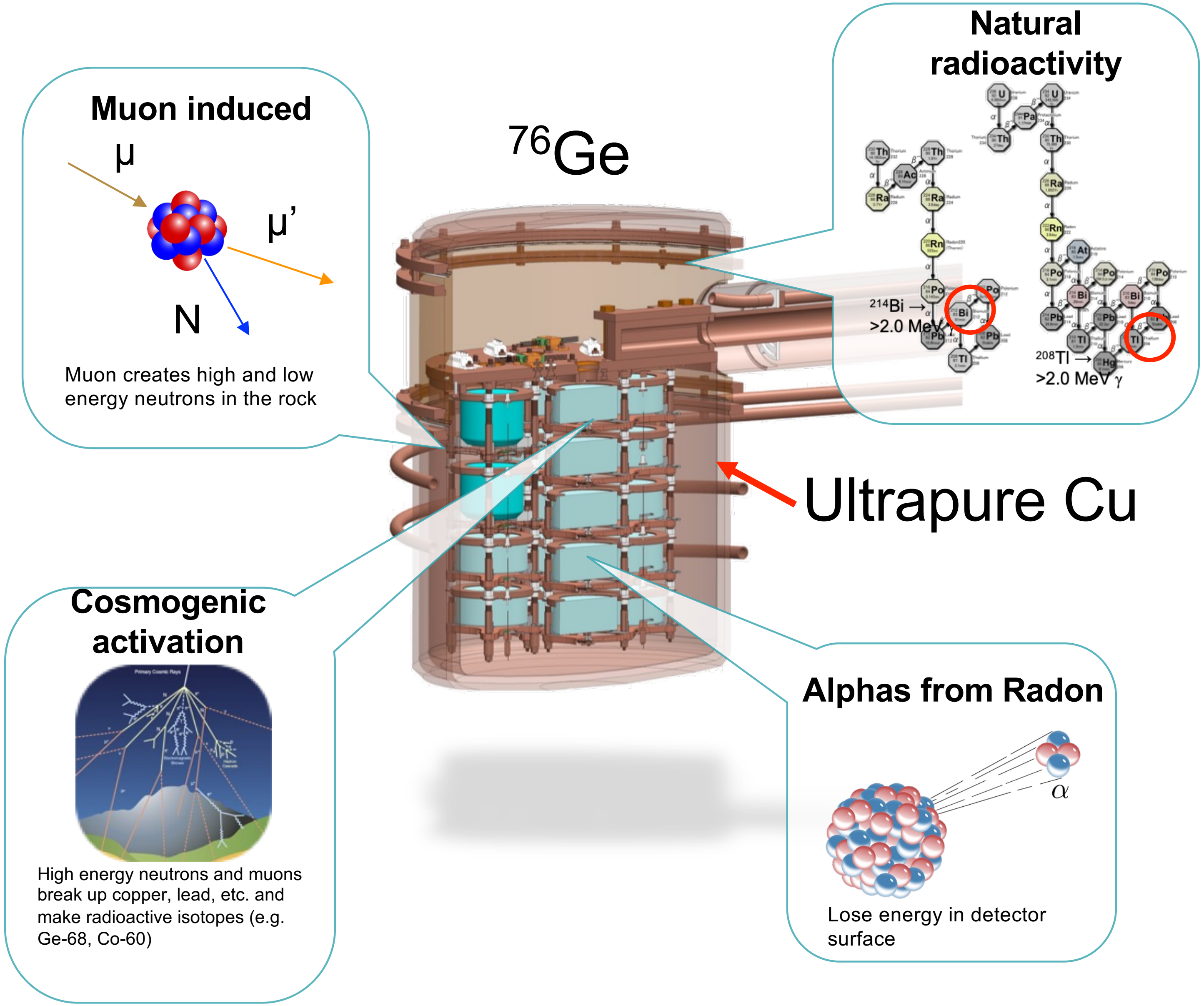


NSAC is an advisory committee that provides official advice to the Department of Energy (DOE) and the National Science Foundation (NSF) on the national program for basic nuclear science research.

- If 0νββ is observed, then
  - Lepton number is not conserved
  - The neutrino is a Majorana particle (its own anti-particle)
  - It will provide information in the absolute neutrino mass scale

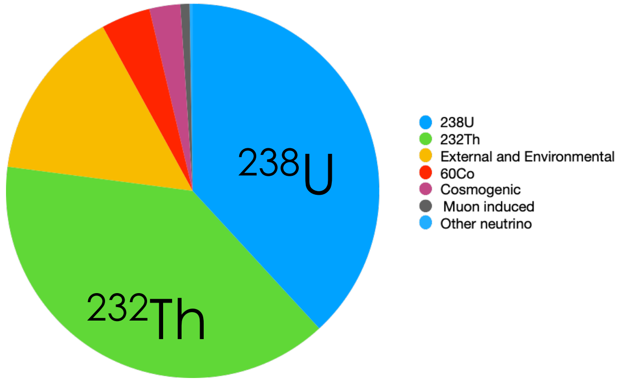
$$Sensitivity \propto \frac{1}{Background}$$

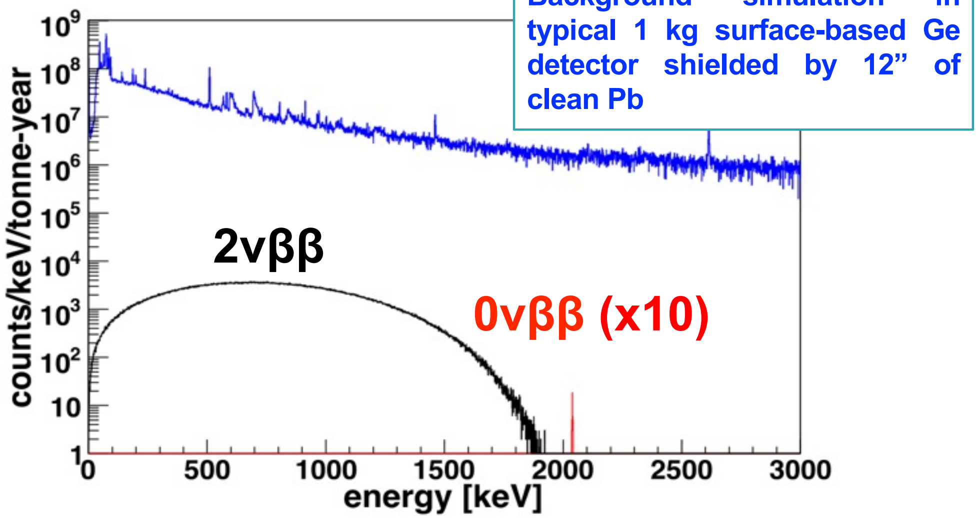
It's all about background



Radioassay of Materials in 0vbb and dark matter searches

Background contributions





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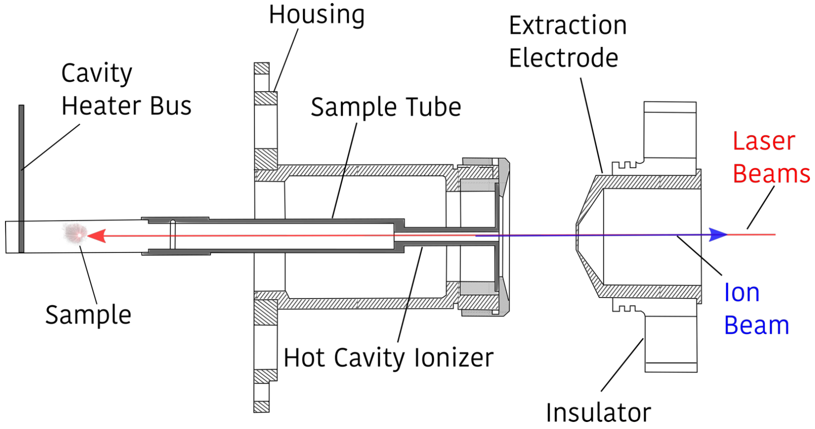
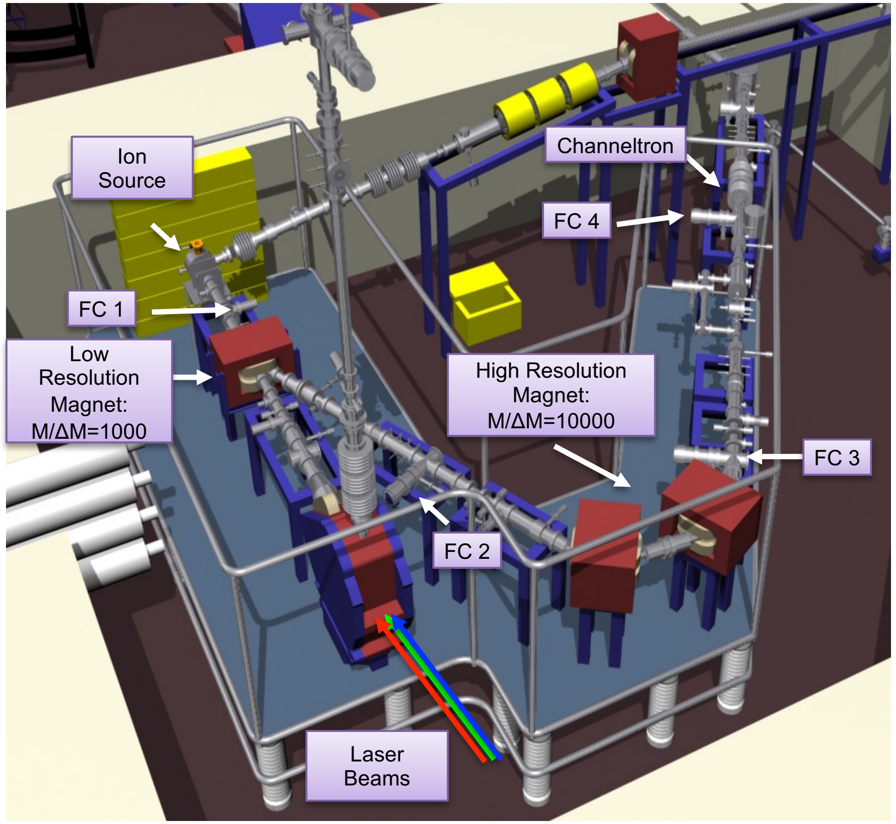
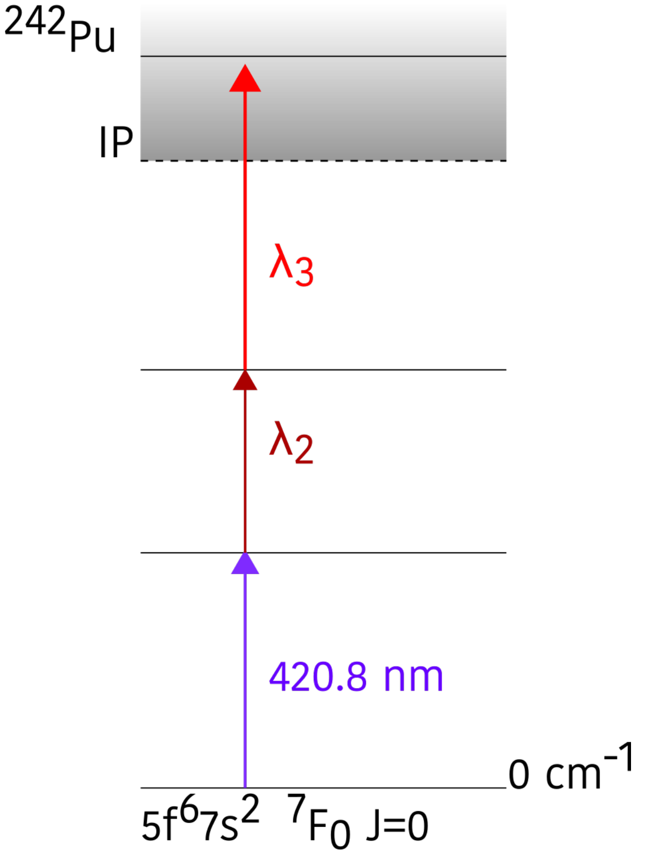
Injector for Radioactive Ion Species 2 (IRIS 2)







U Th Pu

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ORNL/UTK Students that worked in ν Physics

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Search

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Science Highlights

High efficiency laser resonance ionization of plutonium
Science Reports (Nature) 2021

A Plutonium Needle in a Haystack

New results could significantly improve resonance ionization mass spectrometry ultra-trace analysis of plutonium isotopes.

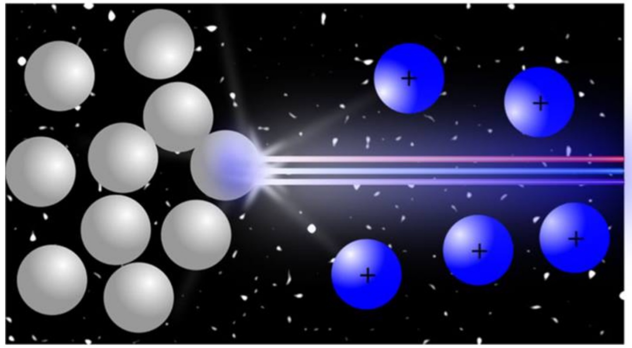


Image courtesy of Elisa Romero-Romero

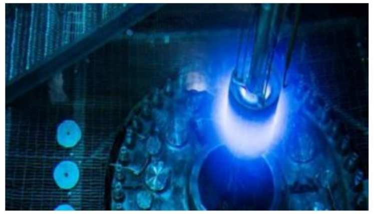
Resonance ionization mass spectrometry is a highly selective and sensitive technique for analyzing extremely small amounts of elements. It uses tunable lasers to ionize atoms of the desired elements.

DOE/NP

Elisa Romero
UNAM

Highlights

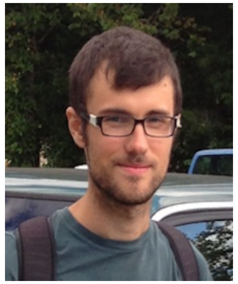
Final Measurement of the 235U Antineutrino Energy Spectrum with the PROSPECT-I Detector at HFIR
PRL 2023



PROSPECT Characterizes the Footprint of Neutrinos

Experiment at Oak Ridge National Laboratory's High Flux Isotope Reactor precisely measures the antineutrino energy spectrum.

DOE/HEP

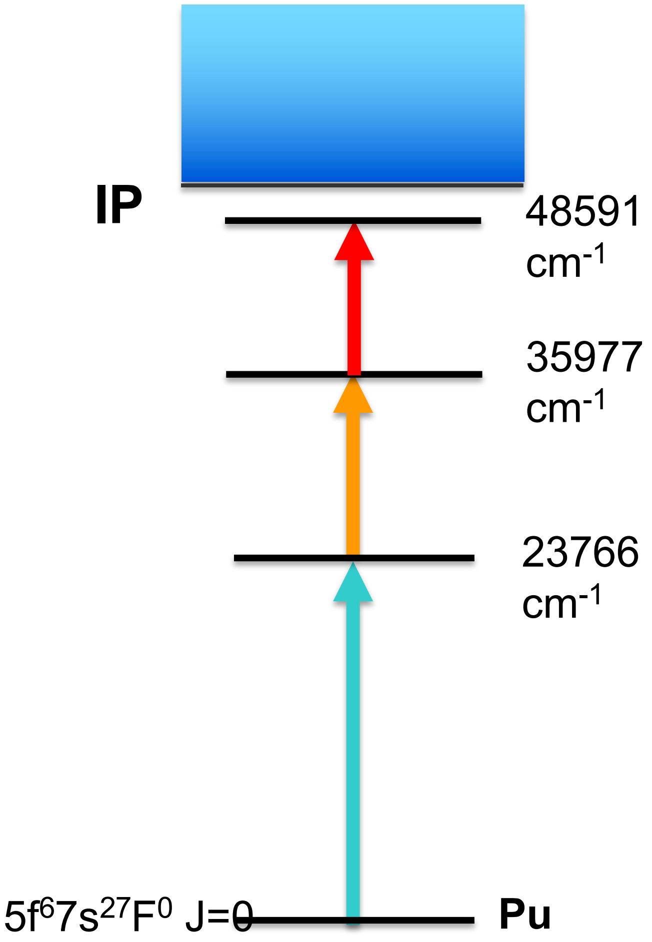


Blaine Heffron

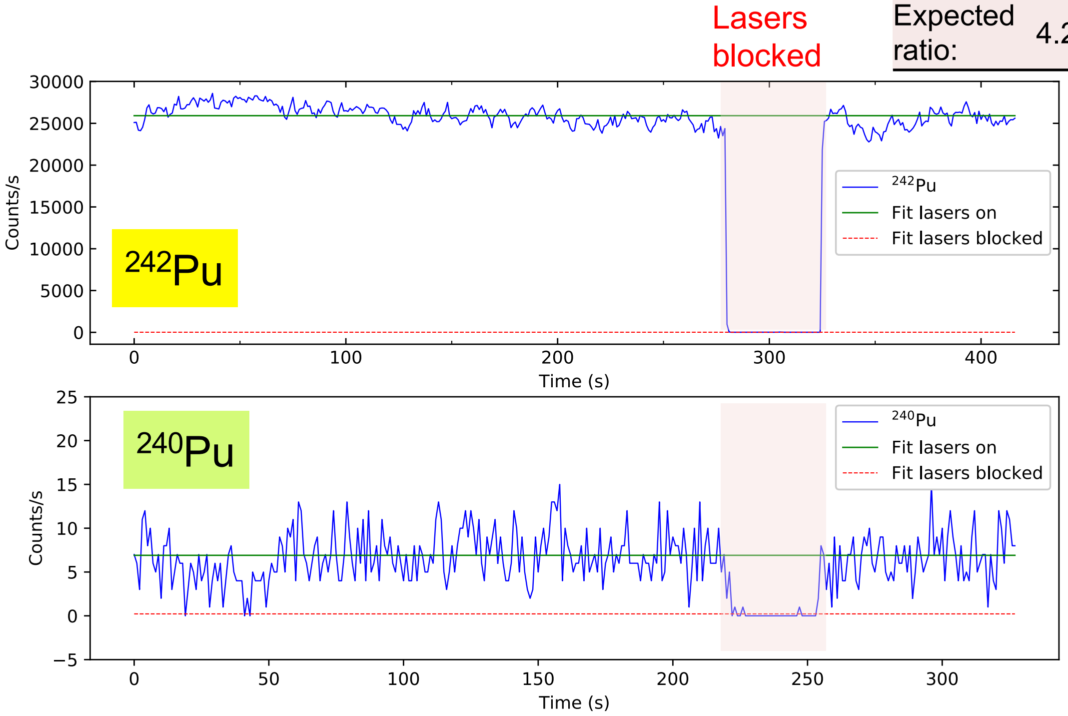
Jeremy Lu

Diego Venegas
UNAL

Sensitivity and Efficiency Measurements for ^{242}Pu



^{242}Pu diluted sample to 10 fg (10^{-14} g)



New Brunswick Laboratory
U.S. Department of Energy

Certificate of Analysis
CRM 130
Plutonium-242 Spike Assay and Isotopic Standard in Nitrate Form

Isotope	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu	^{244}Pu
Expected ratio:	4.2E-05	4.8E-05	2.0E-04	2.5E-04	1.0E+00	4.0E-06

Experimental ratio:

$$\frac{^{240}Pu_{counts}}{^{242}Pu_{counts}} = 2.4 \times 10^{-4}$$

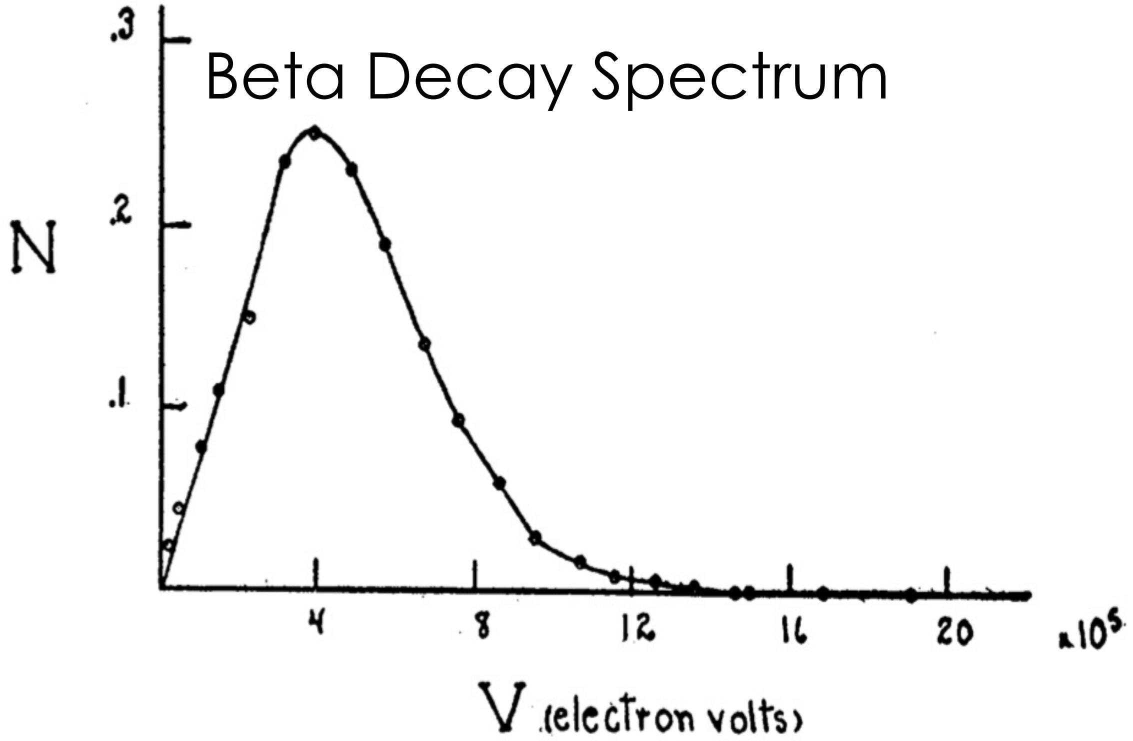
Measured efficiency = 51%

Our detection limit is 6 x 10^3 atoms!

E. Romero-Romero UTK Ph.D. Thesis 2019

Oak Ridge National Laboratory

1930: Neutrino existence is postulated



Scott, F. A. Phys. Rev. 48.5 (1935): 391.

Particle properties:

- no electric charge
- spin 1/2 fermion
- massless or tiny
- Fermi's "weak" interaction

"I have done a terrible thing; I have postulated a particle that cannot be detected."

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Neutrino Physics Through the Years

Neutrino postulation

Neutrinos introduced by Pauli to save conservation laws in β decay experiments

1930

First observation of neutrino

Observation of (anti)neutrinos at Savannah Reactor through IBD with scintillator

1950

Solar Neutrino

Homestake experiment observed for the first-time solar neutrinos

1970

Oscillations (mass)

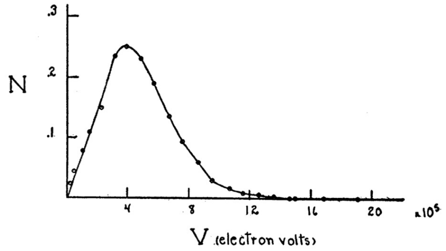
KamLAND kiloton detector at long baselines, discovery of antineutrino oscillations (mass)

2000

Mixing angle

DYB,DC,RENO use near/far detectors for precision measurement of last mixing angle

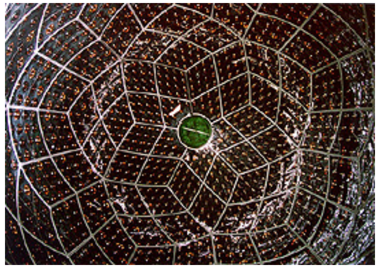
2010



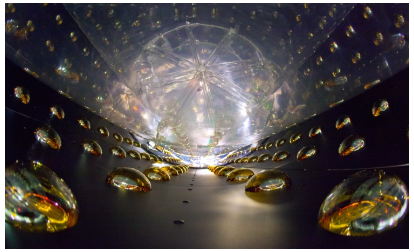
Scott, F. A. Phys. Rev. 48.5 (1935): 391.

Savannah reactor

Homestake mine

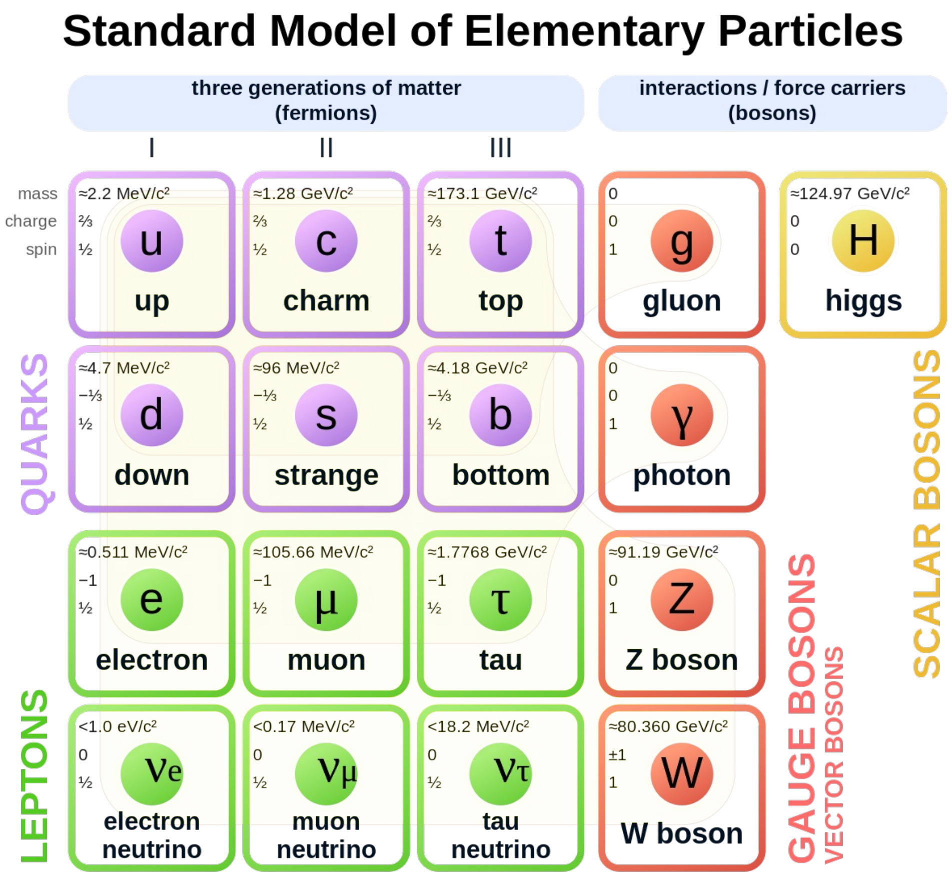


KamLAND



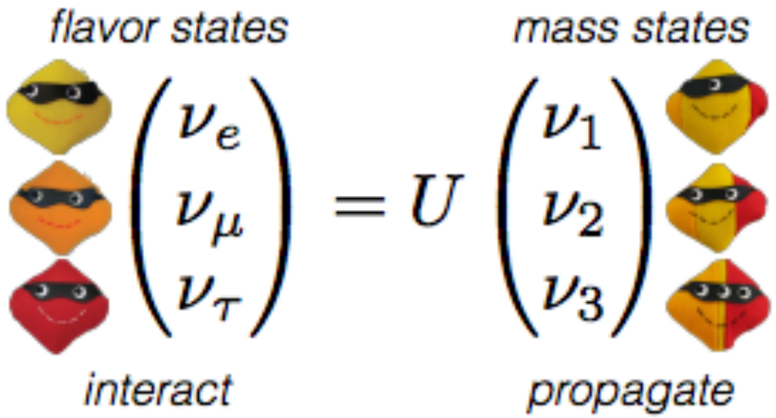
DayaBay

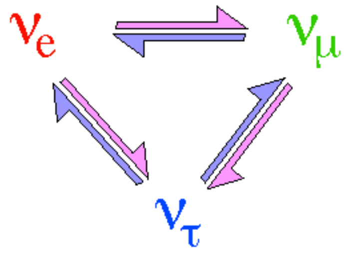
Neutrinos in the Standard Model



Current picture

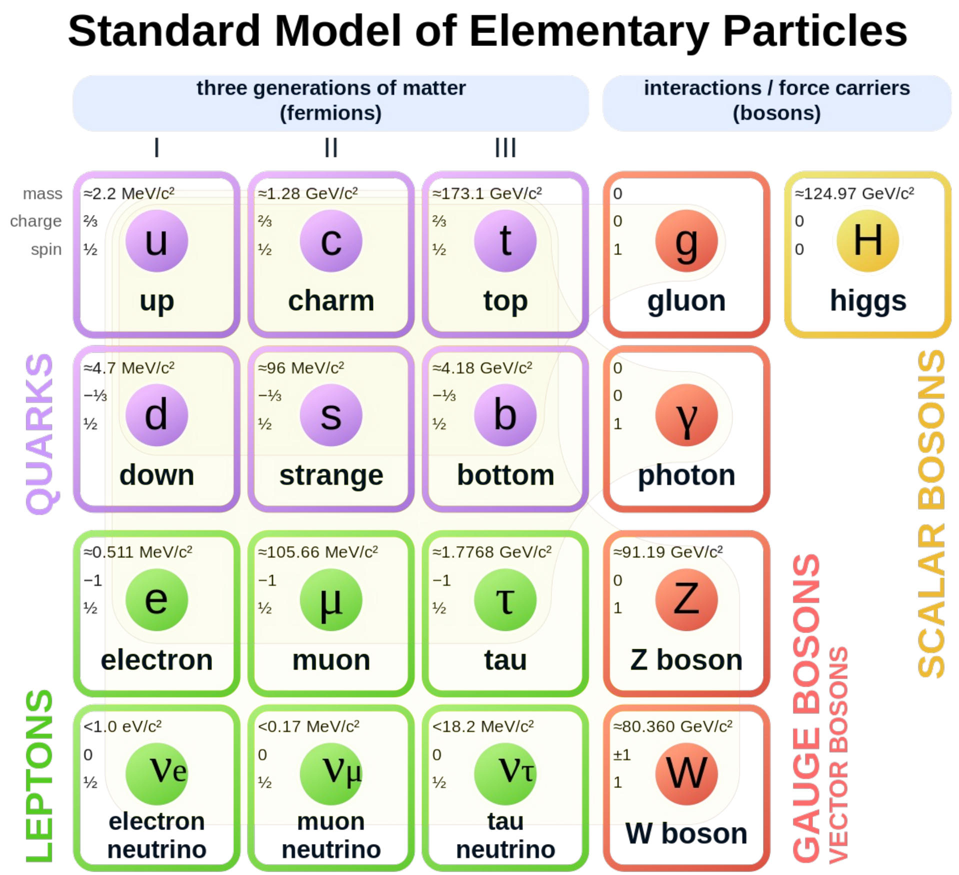
- 3 types of neutrinos corresponding to three lepton generations
- Neutrinos are massless in the SM
- Electrically neutral and weakly interacting
- Neutrino oscillations are evidence for the non-zero mass of the neutrino (BSM physics)





$$P(\alpha \to \beta) = \delta_{\alpha\beta} - 4 \sum_{j>i} U_{\alpha i} U_{\alpha j} U_{\beta i} U_{\beta j} \sin^2\left(\frac{\Delta m^2_{ij} L}{2E}\right)$$

Neutrinos in the Standard Model



Current picture

- 3 types of neutrinos corresponding to three lepton generations
- Neutrinos are massless in the SM
- Electrically neutral and weakly interacting
- Neutrino oscillations are evidence for the non-zero mass of the neutrino (BSM physics)

Current Mysteries

- What is the mass of the neutrino?
- Are neutrinos Dirac or Majorana fermions?
- What are the relative mass differences between neutrino species? (mass hierarchy)
- Are there more than 3 types of neutrinos (sterile neutrinos?)

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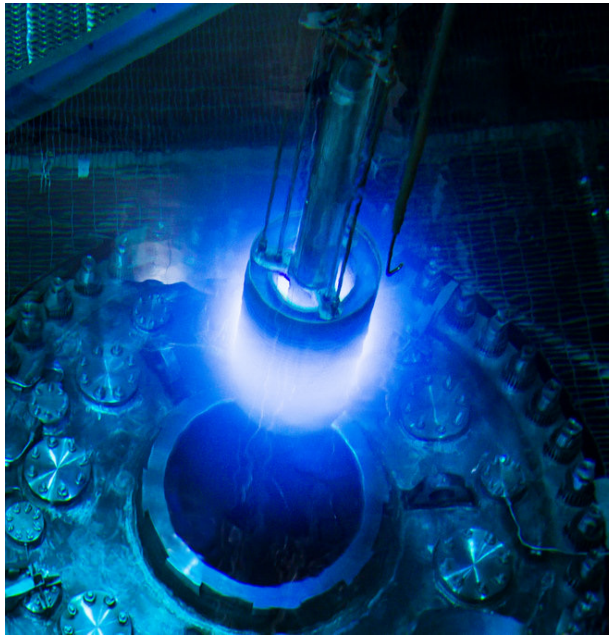
ORNL's Opportunities: World Class _Neutrino_ Sources

Spallation Neutron Source: SNS

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



High Flux Isotope Reactor: HFIR

- 85 MW research reactor
- Compact core
- Highly-enriched uranium fuel

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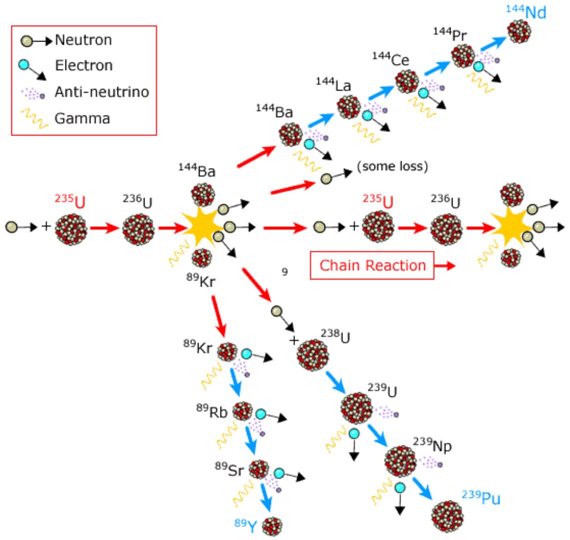
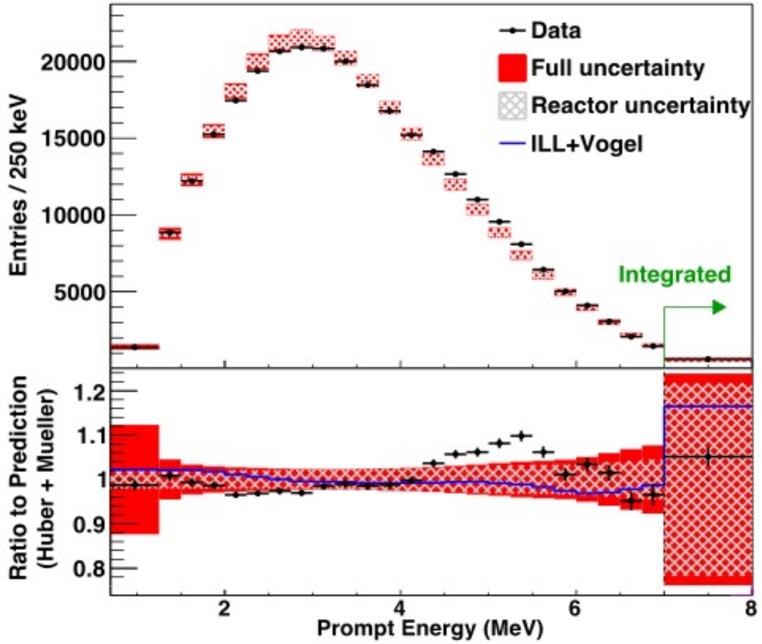
Neutrino flux origin and spectra

HFIR
Fission

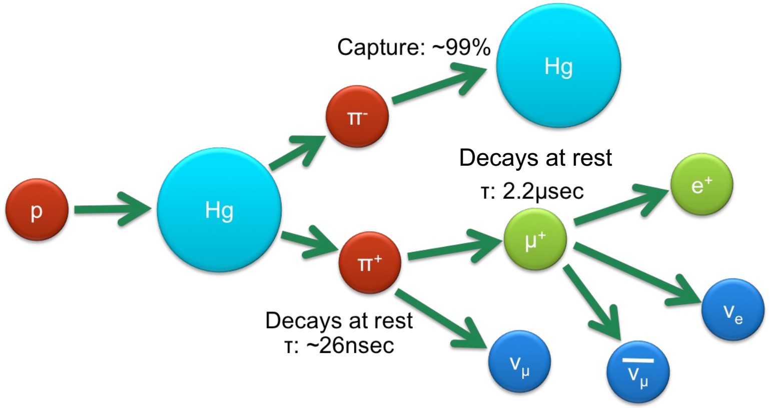


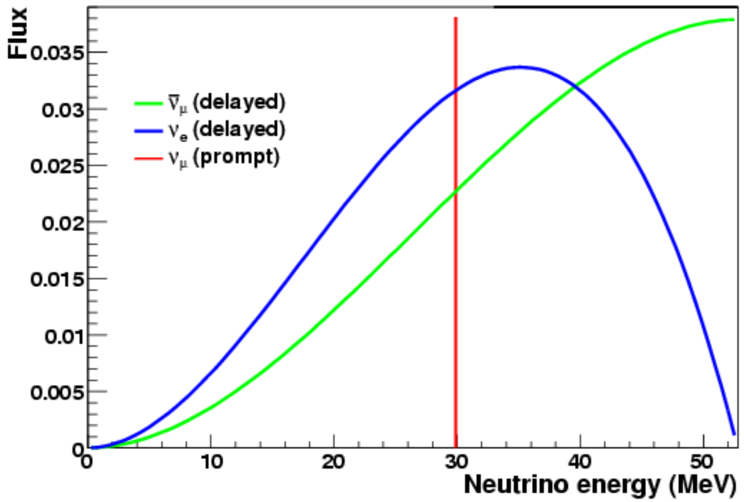


Beta decay fission fragments ($\bar{\nu}_e$)

Huge flux
Few MeV
No timing structure

SNS
Spallation

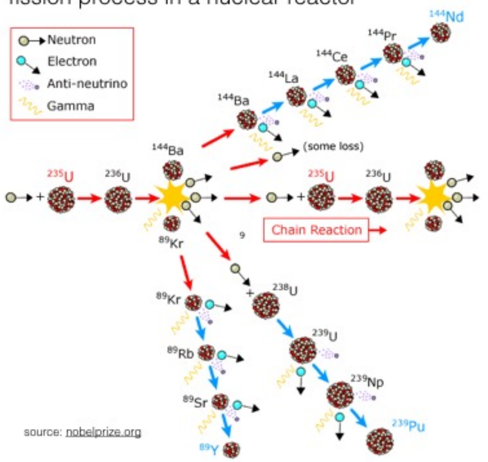


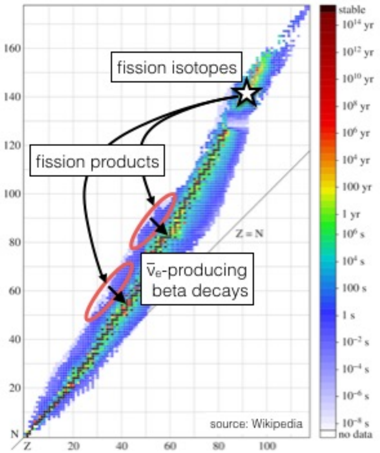


Pion-decay-at-rest neutrino source

Large Flux
Few tens-of-MeV,
Sharply-pulsed timing
Background rejection

Common Types of Interactions for Reactor Neutrinos

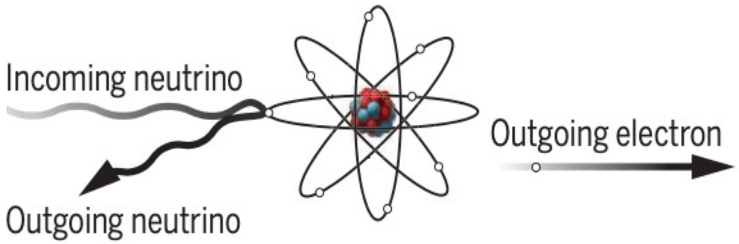




- Nuclear reactors are the most intense terrestrial sources of neutrinos
- They produce an immense flux of antineutrinos in the MeV range.
- Flavor pure, only electron antineutrinos are produced
- Allow for proximity to the source, and it is usually paid by others

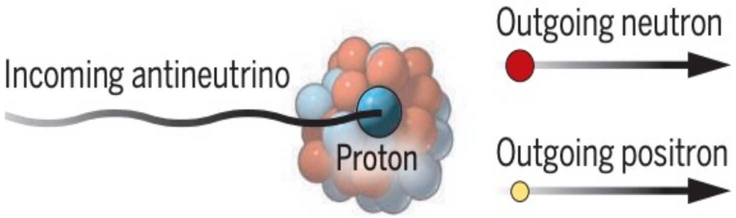
Neutrino electron elastic scattering

An incoming neutrino scatters off of an electron. It may exchange charge with the electron or it may not. In either case, a recoiling electron emerges in a direction that is very close to that of the incoming neutrino.



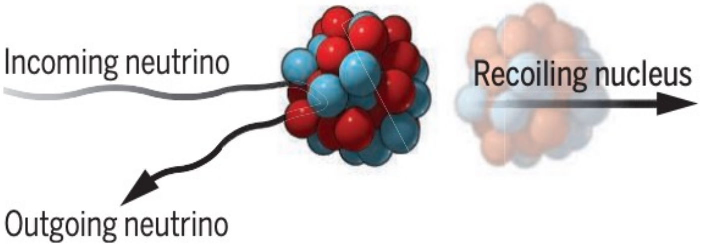
Inverse beta decay

An incoming antineutrino (neutrino) exchanges charge with a proton (neutron) in the nucleus, converting it to a neutron (proton) and becoming a positron (electron).



Coherent elastic neutrino-nucleus scattering (CEνNS)

The entire nucleus recoils as a solid body off of an incoming neutrino whose quantum wavelength is comparable to the diameter of the nucleus. No charge or internal energy is transferred to the nucleus.

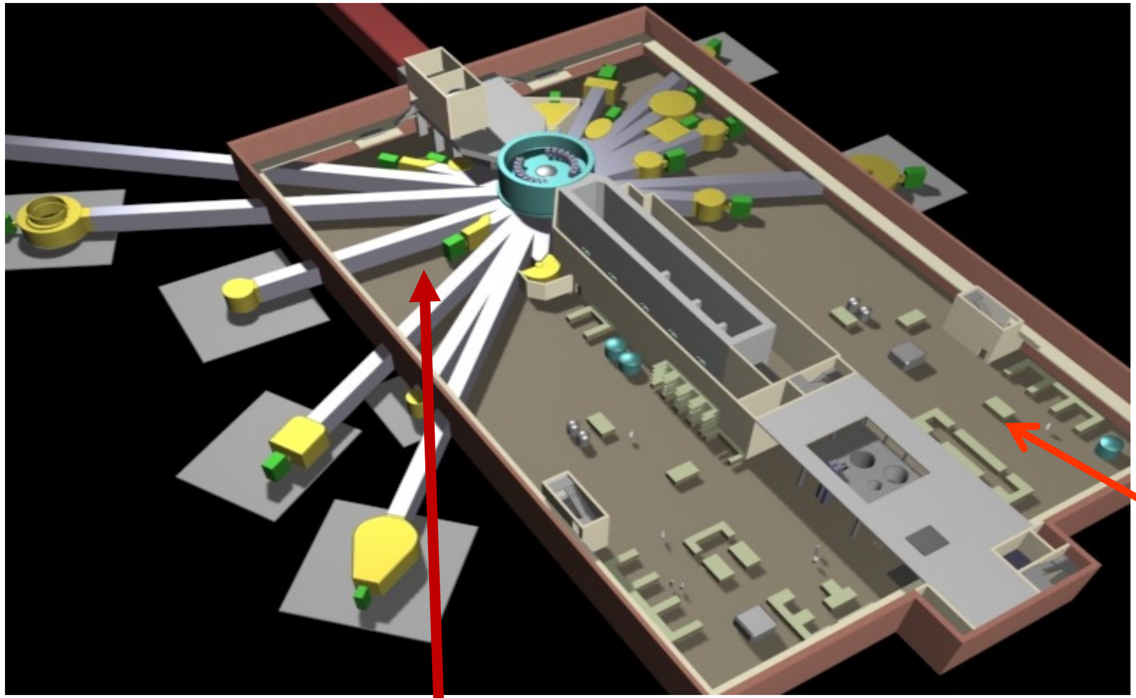


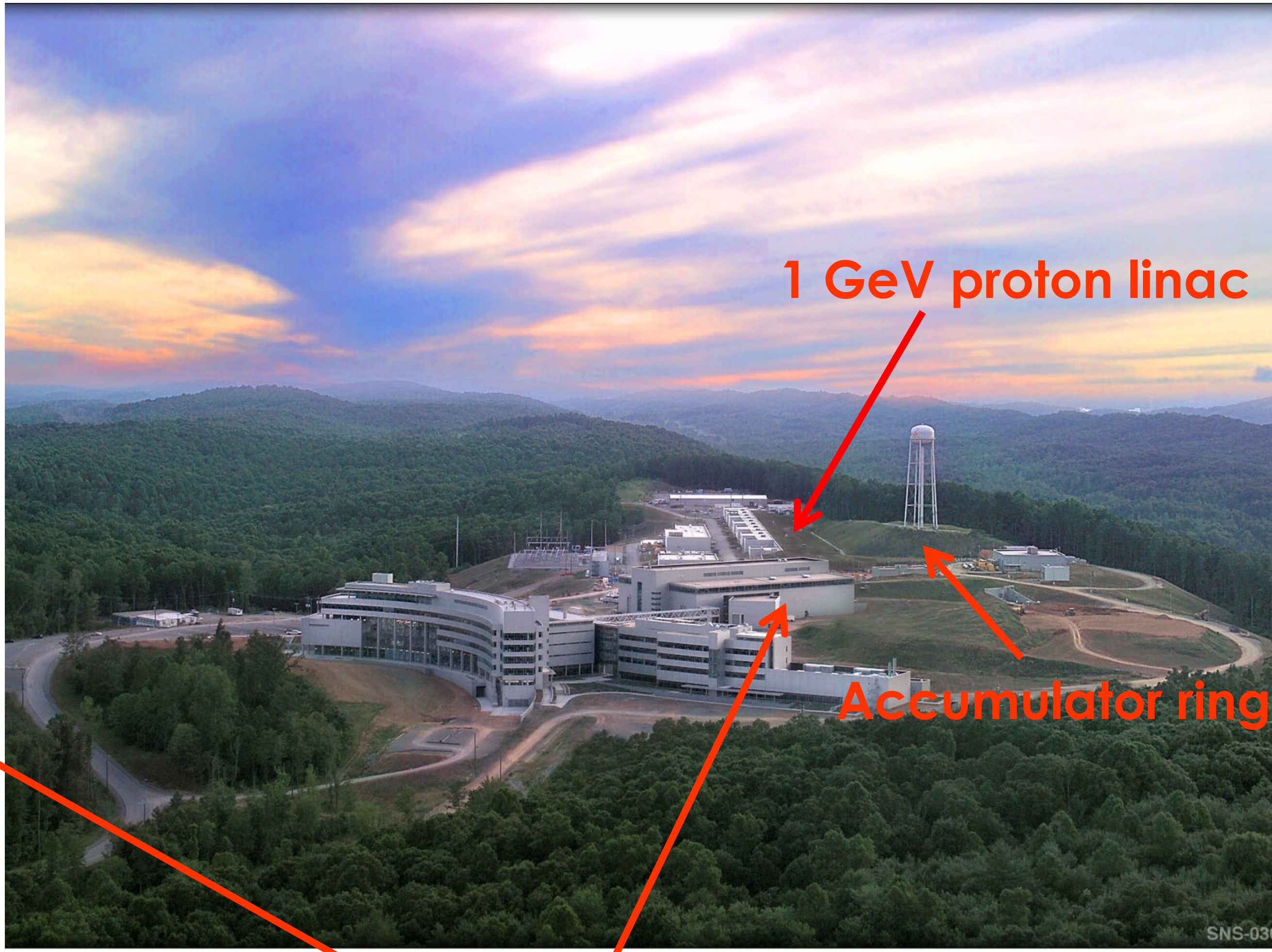
Link J M 2017 Scattering neutrinos caught in the act Science 357 1098–1099 URL https://www.science.org/doi/abs/10.1126/science.aao4050

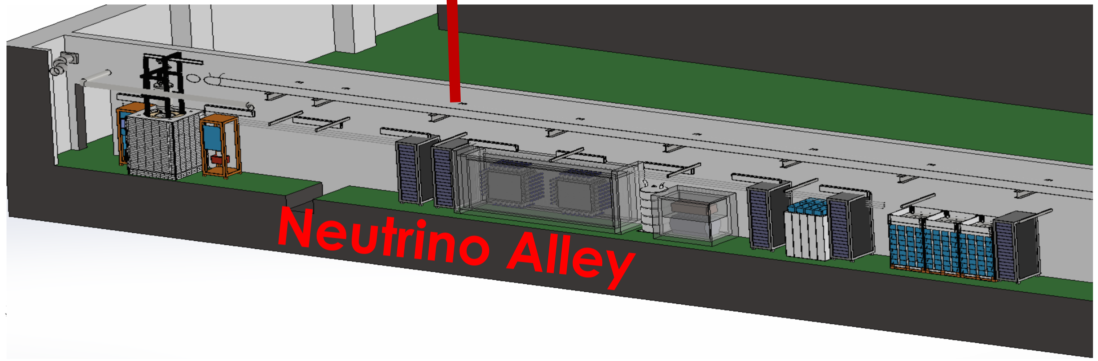
COHERENT

Neutrino Alley

After extensive BG program study we find a well protected location







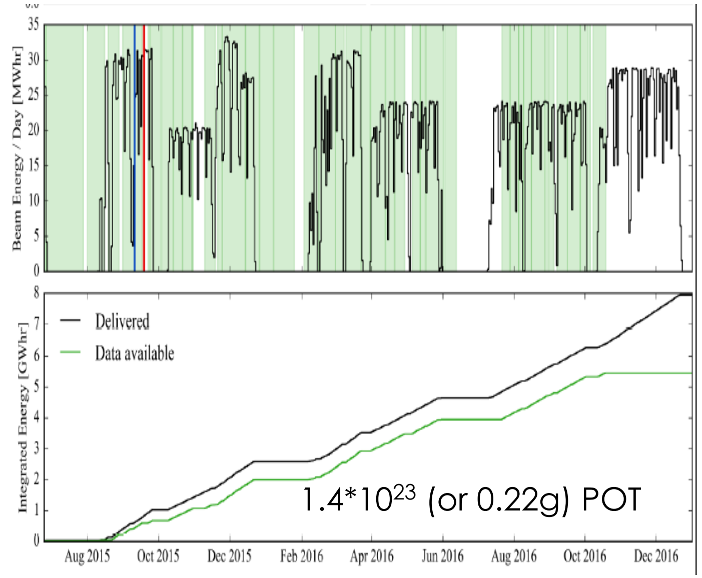
Target Building

Alley is 20-30 meters from the target. Space between target and alley is filled with steel, gravel and concrete

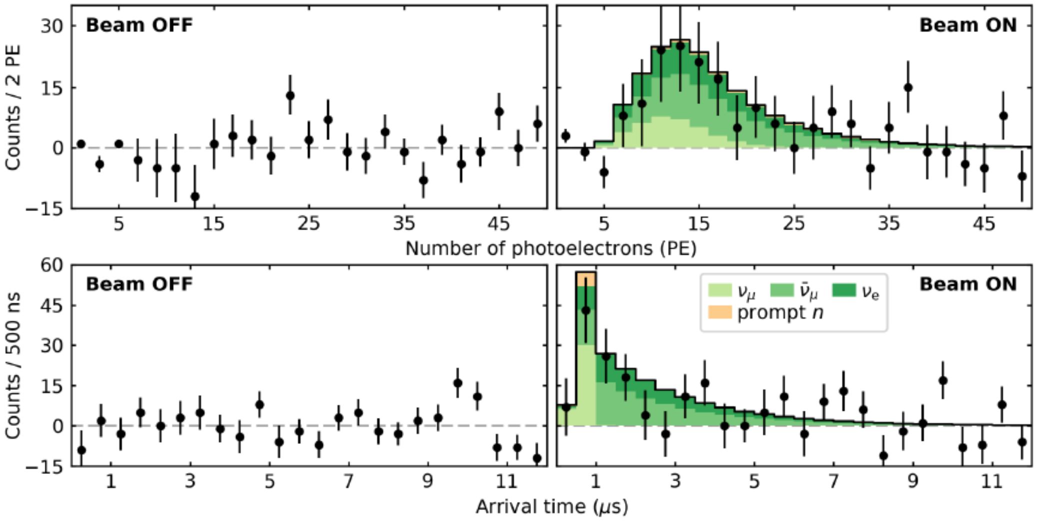
There are extra 10 mWE from above

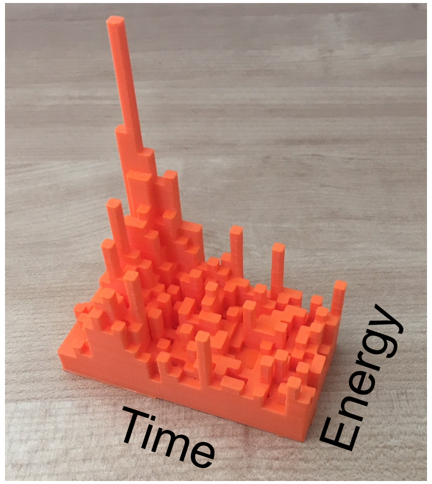
First Detection of CEvNS

Hand held neutrino detector



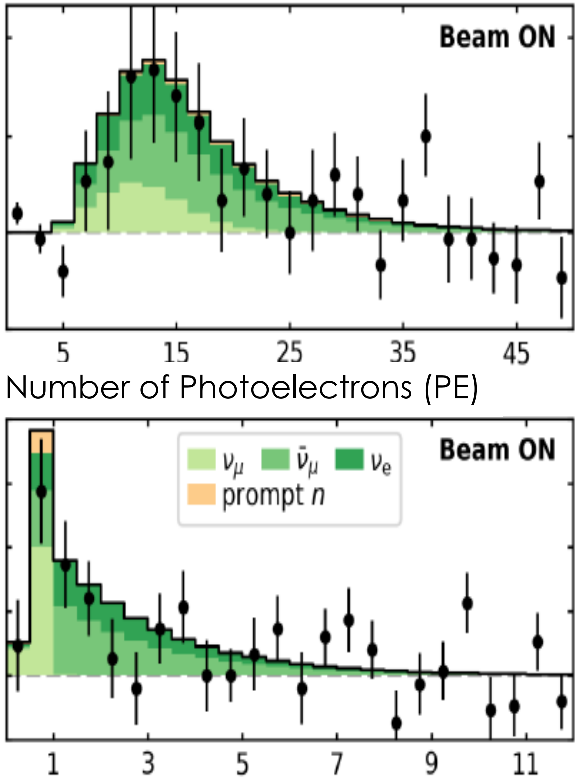
16 Month of data





Coherent Elastic Neutrino Nucleus Scattering

Akimov et al. Science
Vol 357 (6356), Sept. 2017

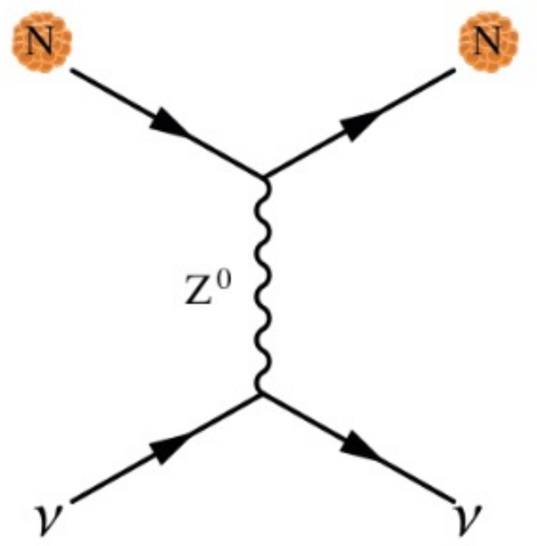


- SNS is an intense source of neutrinos from pion decay at rest (DAR)
  - π^+: ν_μ ; ν_e , $\bar{\nu}_\mu$
  - π^- decay chain mostly captured!
  - A neutrino scatters on a nucleus that recoils as a whole; **coherent** up to E_ν ~ 50 MeV, proportional to the number of neutrons.

Coherent Elastic neutrino-Nucleus Scattering (CEvNS)

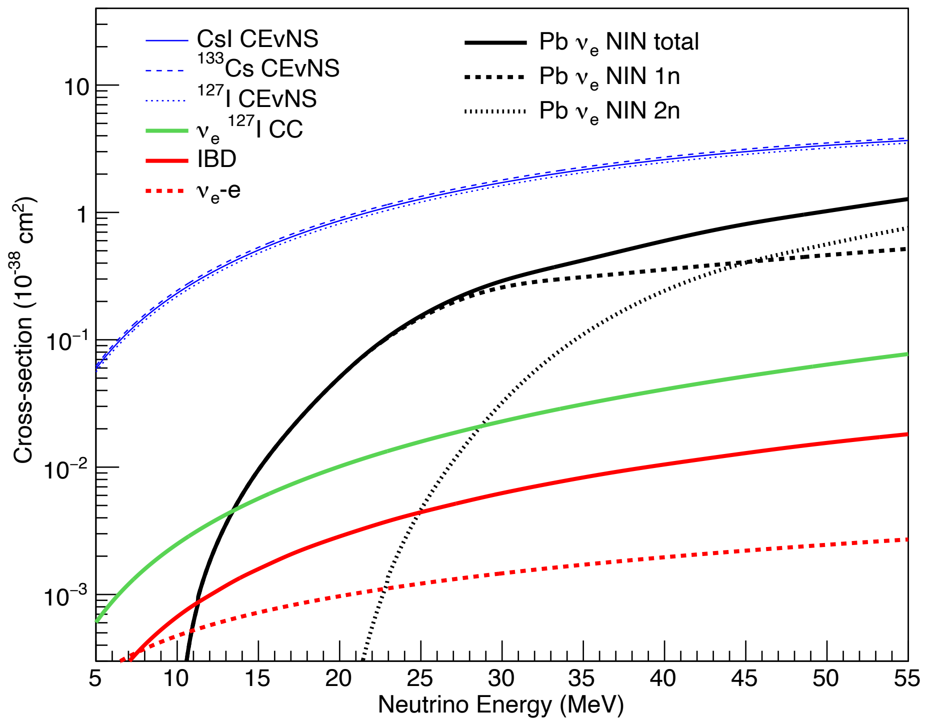
A neutrino scatters on a nucleus via exchange of a Z, and the nucleus recoils as a whole;

coherent up to $E_\nu \sim 50$ MeV



D.Z. Freedman PRD 9 (1974)
Submitted Oct 15, 1973

V.B.Kopeliovich & L.L.Frankfurt
JETP Lett. 19 (1974)
Submitted Jan 7, 1974



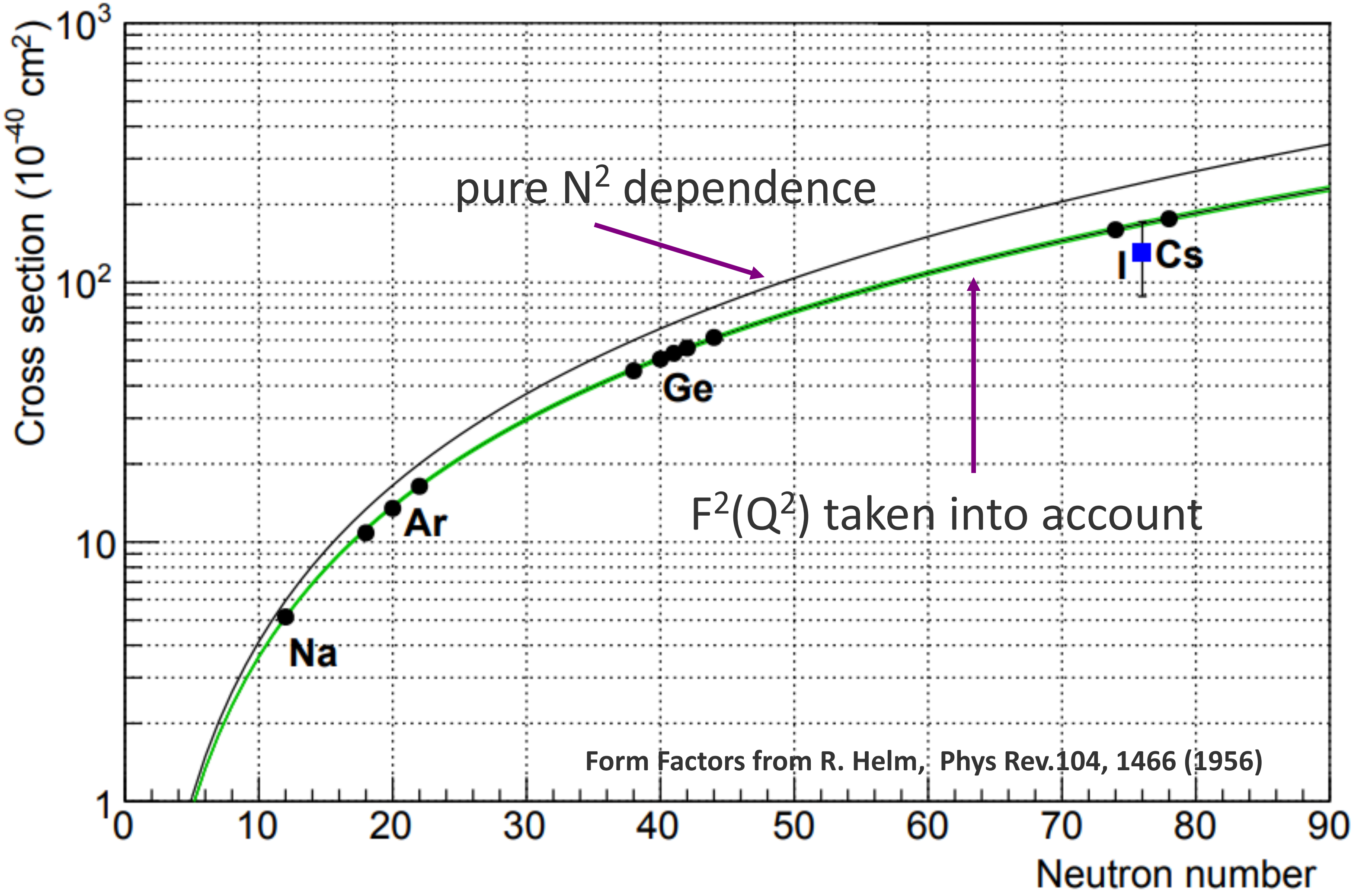
CEvNS cross-section is large!

$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2} k^2 (1+\cos\theta) \frac{(N-(1-4\sin^2\theta_W)Z)^2}{4} F^2(Q^2) \quad \boxed{\propto N^2}$$

CEvNS cross section is well calculated in the Standard Model

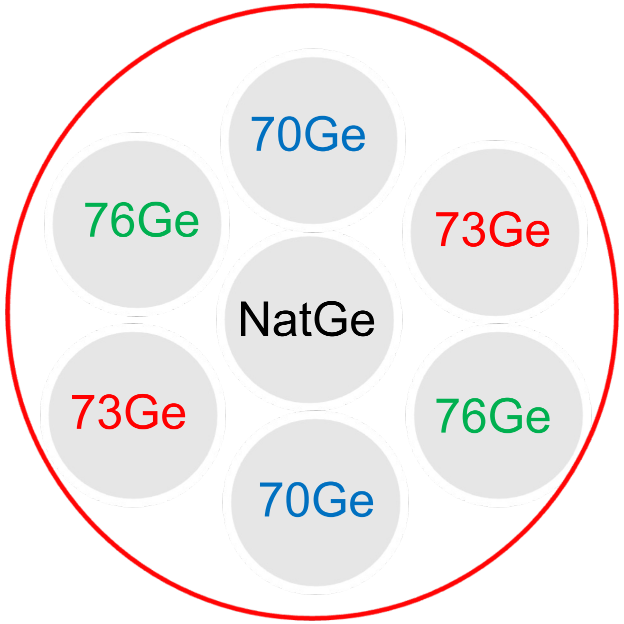
Physics Motivation - Neutron Distribution Functions

$$\frac{d\sigma}{d\Omega} \propto (N - (1 - 4\sin^2\theta_W)Z)^2 F^2(Q^2)$$

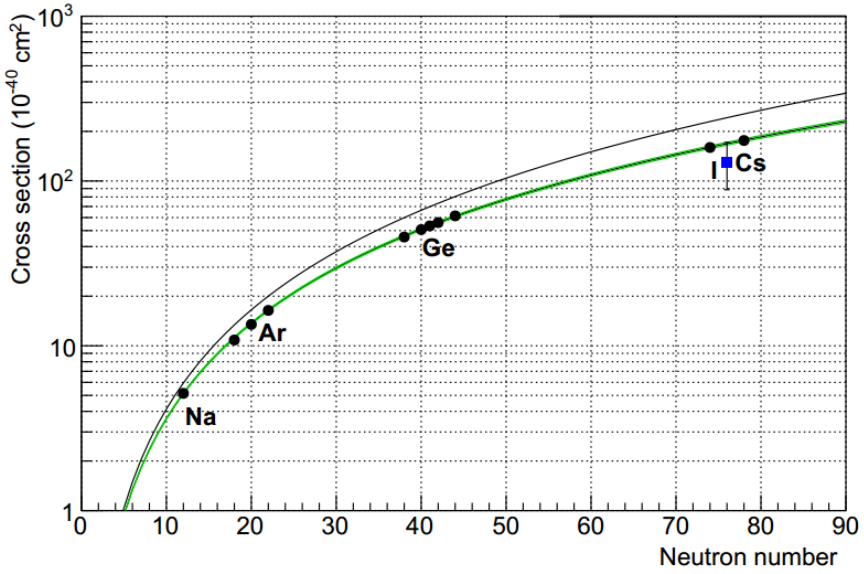


COHERENT scattering – Relative measurements

- Experiment with **identical** detectors
- **Different** isotopic composition
- Use **enriched** isotopes
- Perform **simultaneous** measurements
- **Cancelation of some systematic** errors
- Use **odd A** nuclei (Axial)



Mass	Natural Abundance	Decay Mode	Nuclear Spin
70	20.57%	STABLE	0+
72	27.45%	STABLE	0+
73	7.75%	STABLE	9/2+
74	36.50%	STABLE	0+
76	7.73%	STABLE	0+



Collaboration with CINVESTAV - Isotopically enriched detectors

- Omar Miranda
- Gonzalo Sanchez
- Laura Duque Herrera

PHYSICAL REVIEW D

covering particles, fields, gravitation, and cosmology

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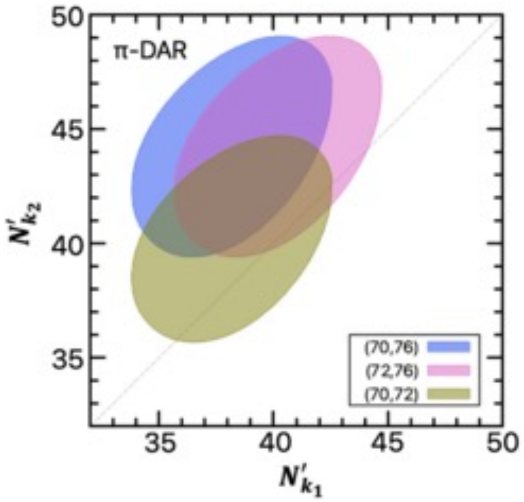
Novel approach for the study of coherent elastic neutrino-nucleus scattering

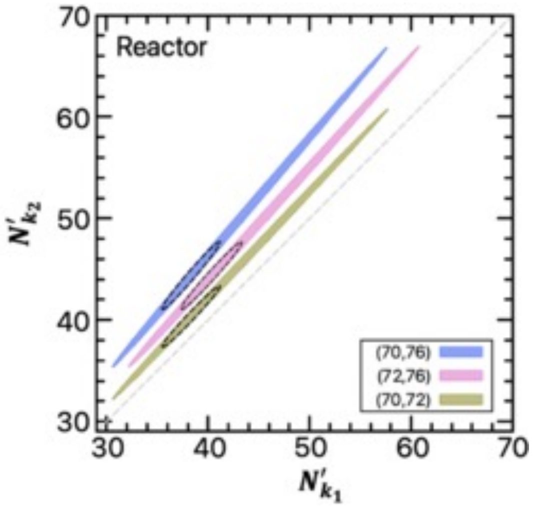
A. Galindo-Uribarri, O. G. Miranda, and G. Sanchez Garcia

Phys. Rev. D **105**, 033001 – Published 3 February 2022

More

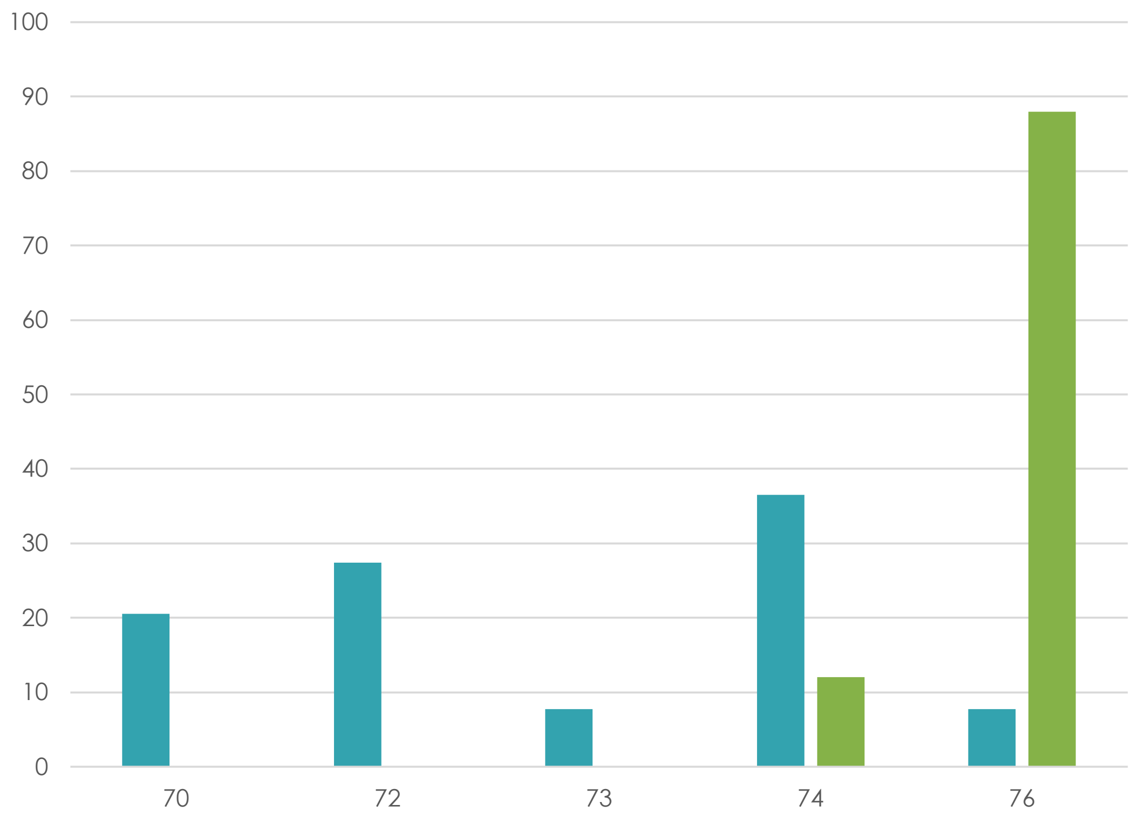
Gonzalo Sanchez





The Weizmann Award to the best doctoral theses carried out in Mexico by young researchers

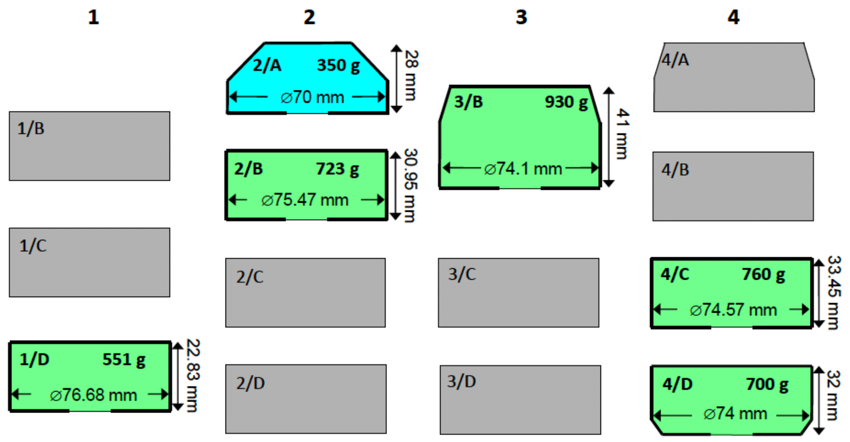
^{76}Ge Enrichment for 0νββ



70	72	73	74	76
20.57	27.45	7.75	36.50	7.73
.016	.006	.02	12.0	88.0

GERDA Depleted Ge Detectors

JINST
PUBLISHED BY IOP PUBLISHING FOR SISSA MEDIALAB
RECEIVED: *February 28, 2013*
ACCEPTED: *March 27, 2013*
PUBLISHED: *April 18, 2013*



Isotopically modified Ge detectors for GERDA: from production to operation

D. Budjáš,[i] M. Agostini,[i] L. Baudis,[l] E. Bellotti,[e,f] L. Bezrukov,[g] R. Brugnera,[j] C. Cattadori,[f] A. di Vacri,[a] R. Falkenstein,[k] A. Garfagnini,[j] S. Georgi,[d] P. Grabmayr,[k,1] A. Hegai,[k] S. Hemmer,[j] M. Hult,[c] J. Janicskó Csáthy,[i] V. Kornoukhov,[g,h] B. Lehnert,[b] A. Lubashevskiy,[d] S. Nisi,[a] G. Pivato,[j] S. Schönert,[i] M. Tarka[l] and K. von Sturm[k]

AVAILABLE

	70	72	73	74	76
Natural	20.57	27.45	7.75	36.50	7.73
Depleted	22.3	30.0	8.3	38.8	0.6
Enriched 76	.016	.006	.02	12.0	88.0

The measured characteristics and performance of the tested depleted detectors were as good as those of a reference BEGe from standard Canberra production made of natural germanium

Isotopically enriched detectors

Zinc detectors
- ^{64}Zn
- ^{68}Zn

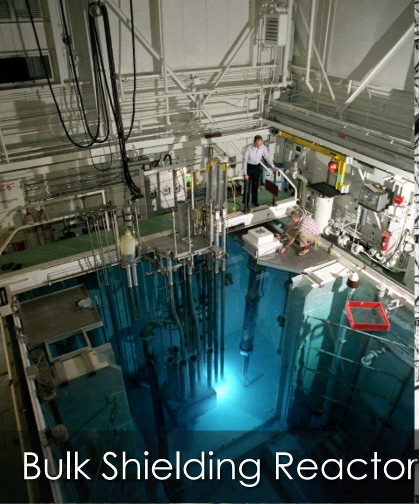
Silicon detectors
- ^{28}Si
- ^{30}Si

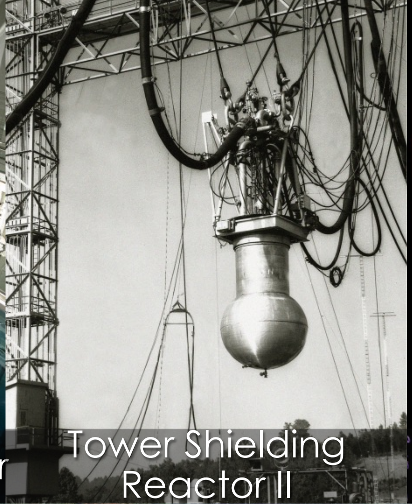
- Mass = 1 Kg each
- Run time = 1 year
- Taking data simultaneously

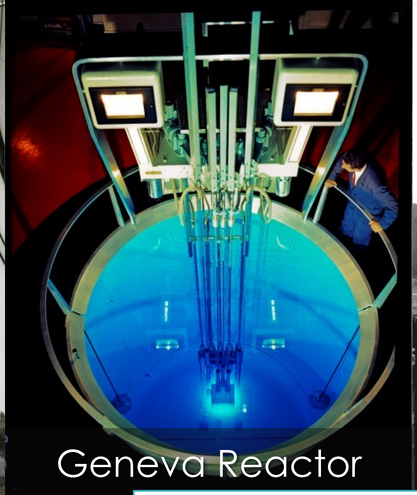
Laura Duque Herrera

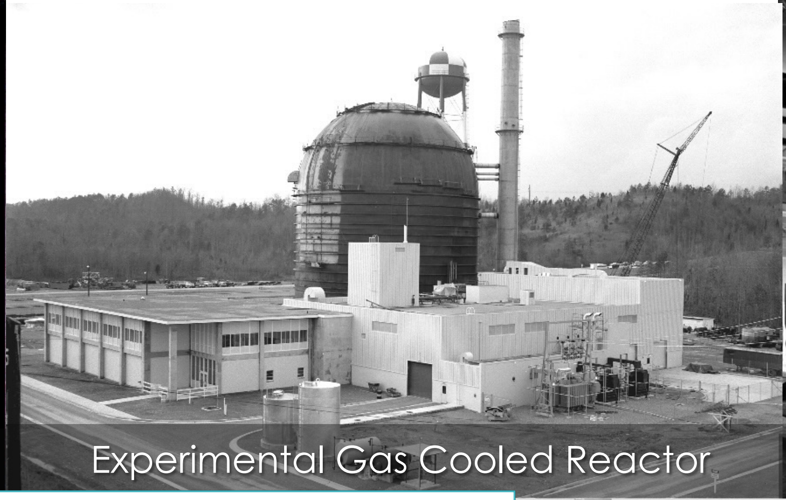
Tin detectors
- ^{112}Sn
- ^{120}Sn

Nickel detectors
- ^{58}Ni
- ^{64}Ni


Bulk Shielding Reactor


Tower Shielding Reactor II


Geneva Reactor


Experimental Gas Cooled Reactor

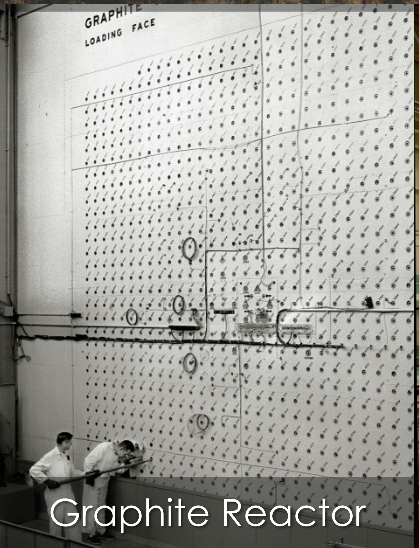

Homogeneous Reactor Test


Health Physics Research Reactor

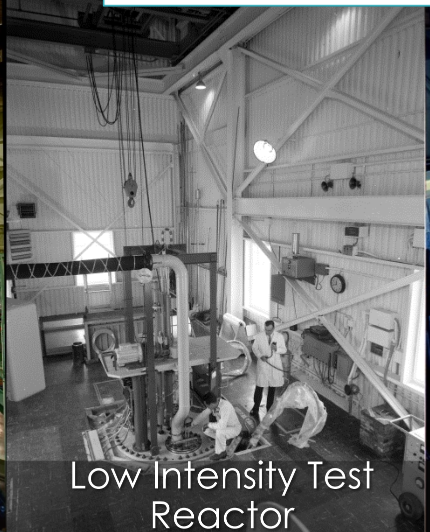
ORNL reactors

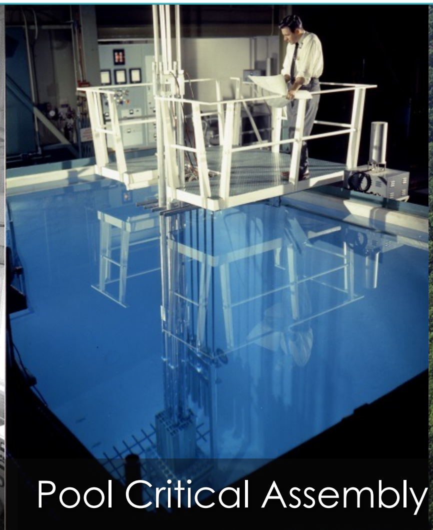
1943 - 1992


Molten Salt Reactor Experiment


Graphite Reactor

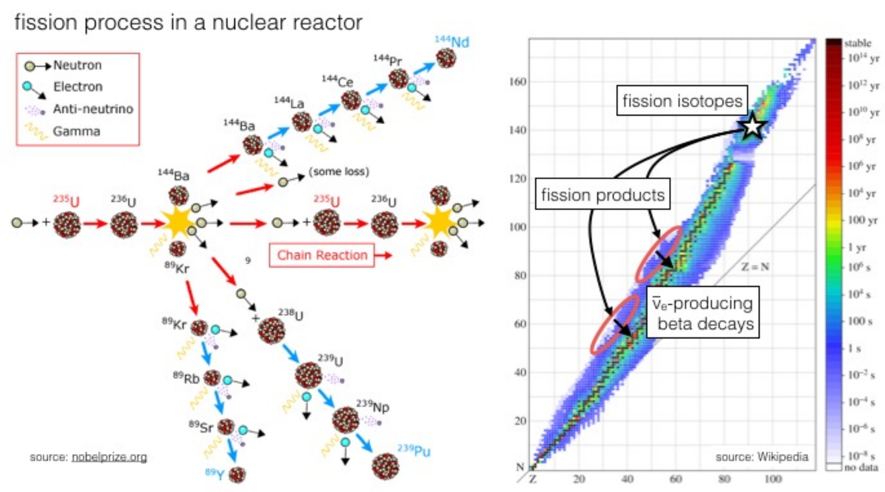

Oak Ridge Research Reactor


Low Intensity Test Reactor

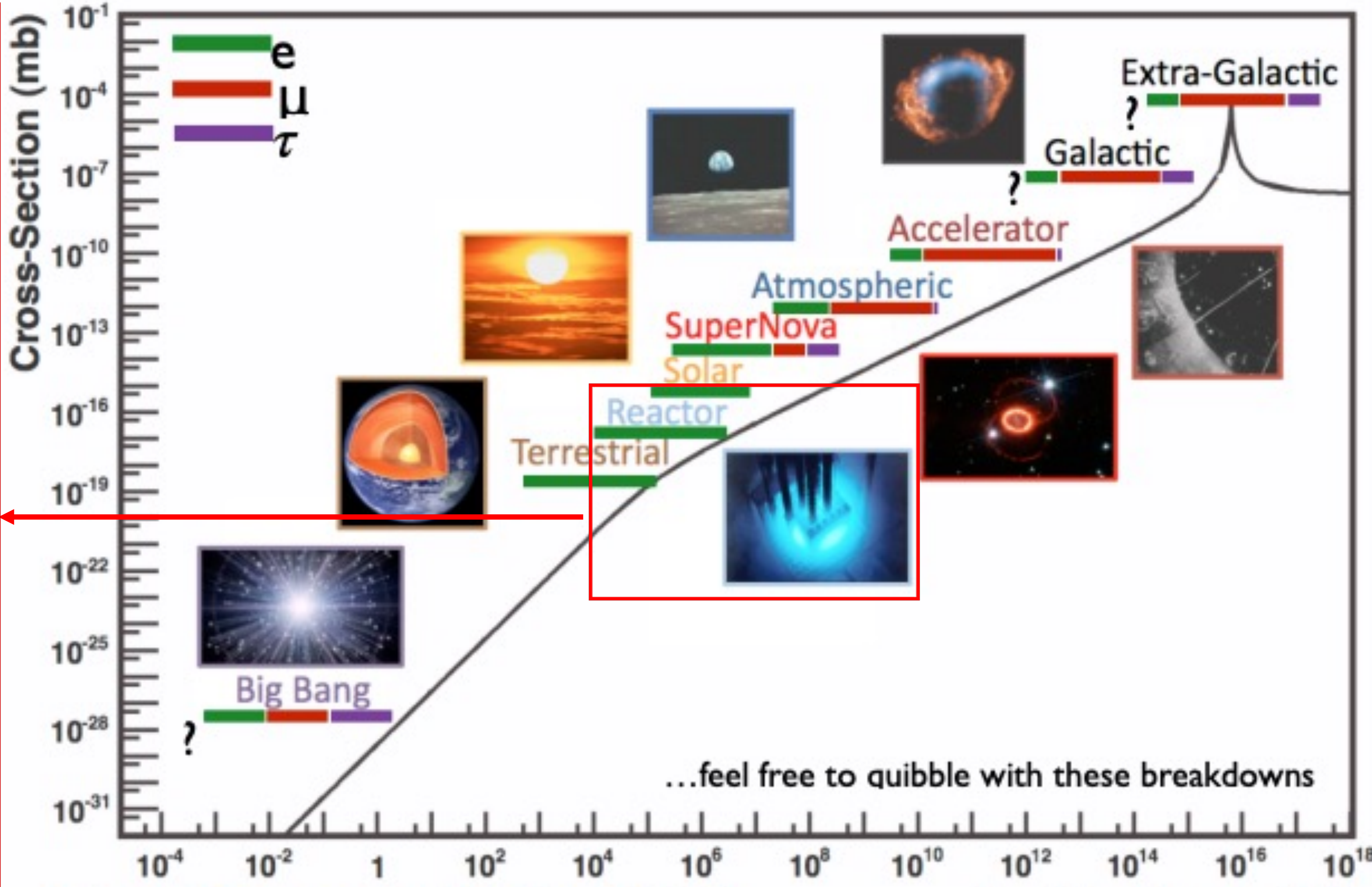

Pool Critical Assembly


Tower Shielding Reactor

Neutrino Sources: Nuclear Reactors



- Nuclear reactors are the most intense terrestrial sources of neutrinos
- They produce an immense flux of antineutrinos in the MeV range.
- Flavor pure, only electron antineutrinos are produced
- Allow for proximity to the source
- Reactor operations are usually paid by others



Zeller and Formaggio, Rev. Mod. Phys. 84 (2012)

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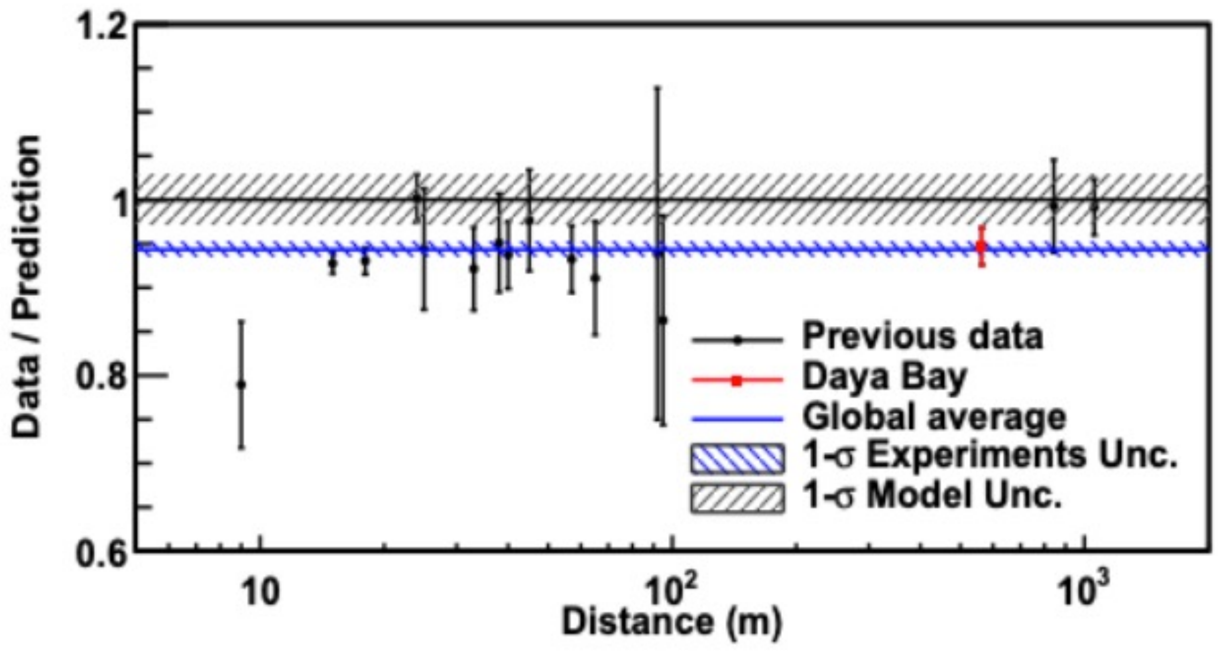
PROSPECT Motivations and Goals: Sterile Neutrinos?

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

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

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

.



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

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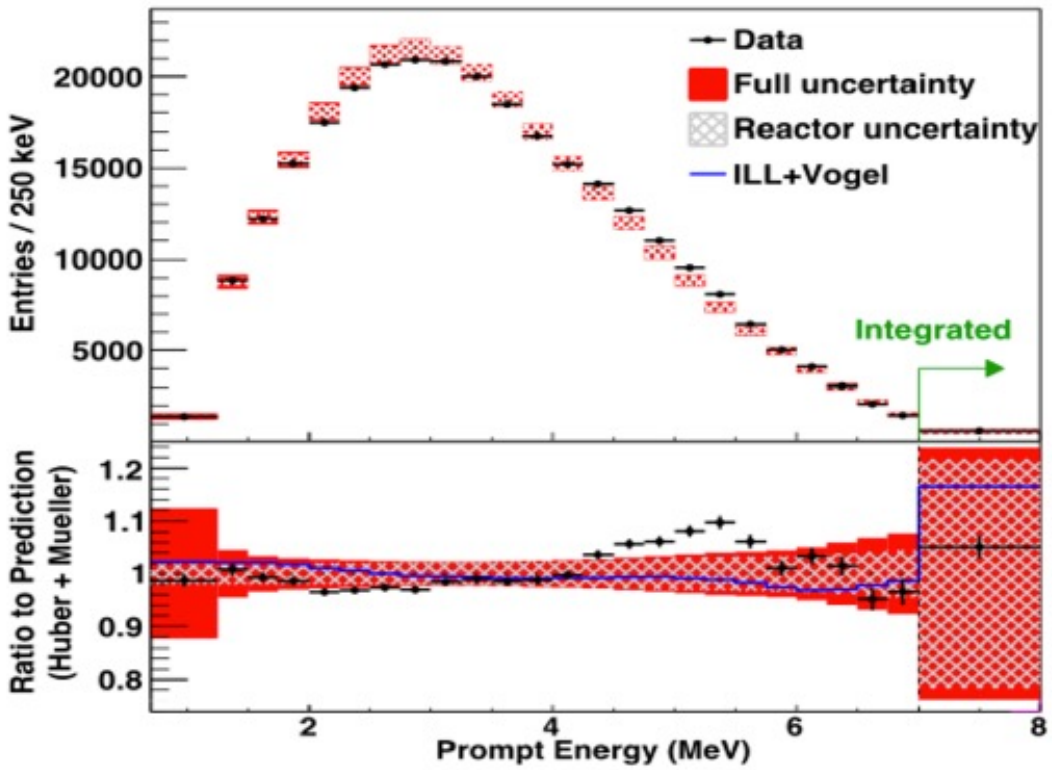
PROSPECT Motivations and Goals: Anomaly in the spectrum?

The Spectral Deviation
Daya Bay and other θ_{13} experiments observed bump in 4-6 MeV region, a deviation of ~10%.

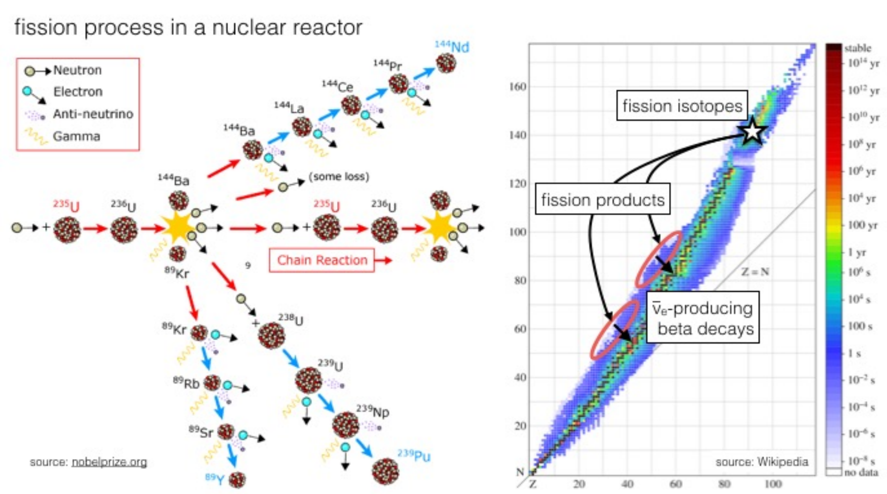
Questions:
- What is the nature of this bump?
- Is it a modeling issue?
- Are the all the models wrong? Or does the problem lie with the prediction for one of the fissioning isotopes

Physics Goal 2:
- To make a precise measurement of the antineutrino spectrum from a HEU reactor (mainly ^{235}U).



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

Neutrino Flux from Nuclear Reactors



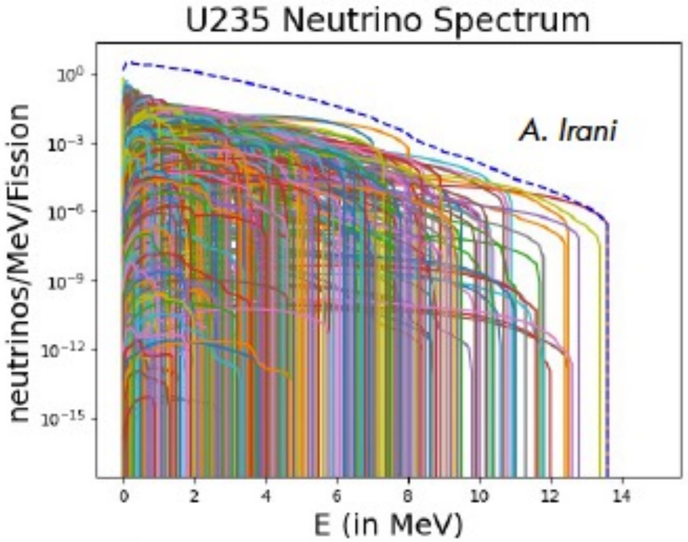
- Nuclear reactors are the most intense terrestrial sources of neutrinos
- They produce an immense flux of antineutrinos in the MeV range.
- Flavor pure, only electron antineutrinos are produced
- Allow for proximity to the source
- Reactor operations are usually paid by others

Summation method

• Summing all beta-decay contributions from all fission fragments

• Database dependent;

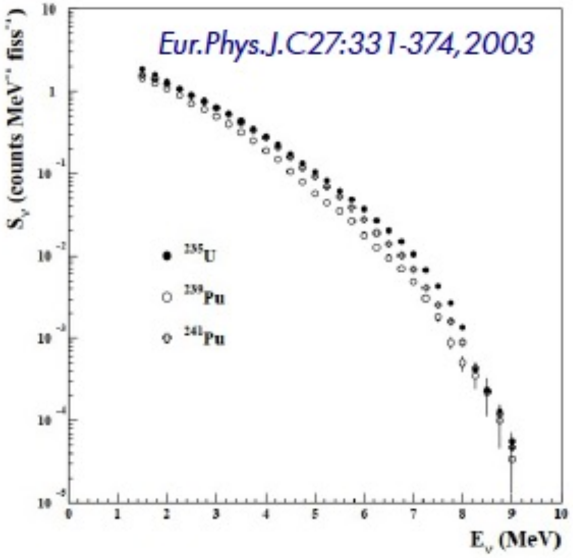
- ~1000 different beta-decaying isotopes contribute to the reacto electron antineutrino flux!



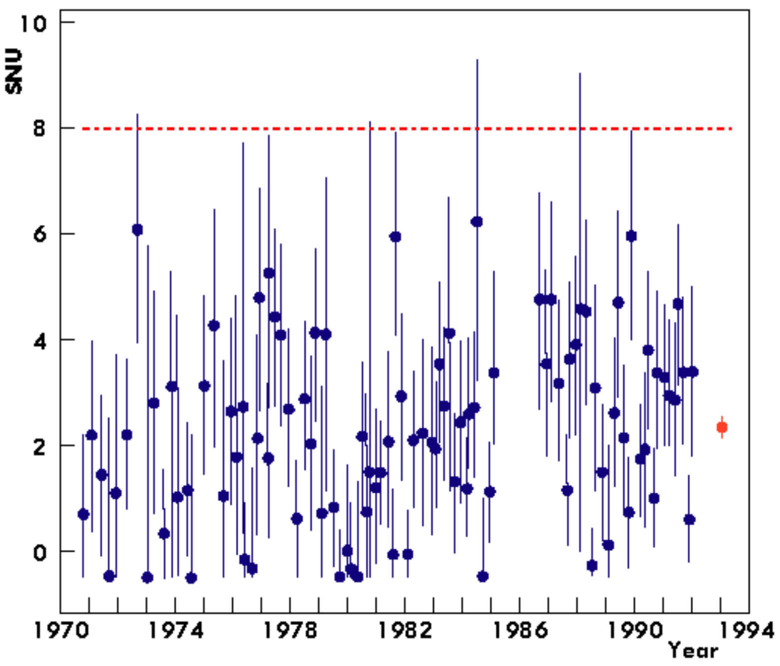
Conversion method

• Relies on measurements of integral spectra from ^{235}U, ^{239}Pu, and ^{241}Pu (e.g. from ILL and KI research reactors).

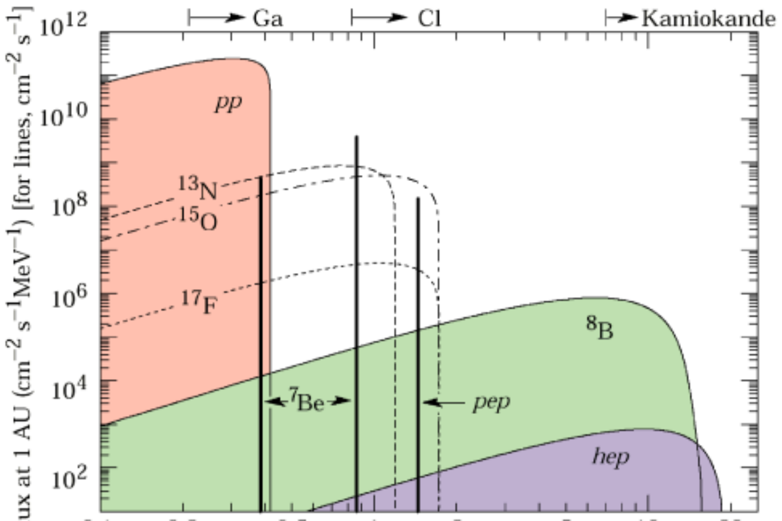
• Conversion of electron spectra to antineutrino spectra is possible but requires some nuclear physics input (e.g. forbidden transitions and finite size effects).



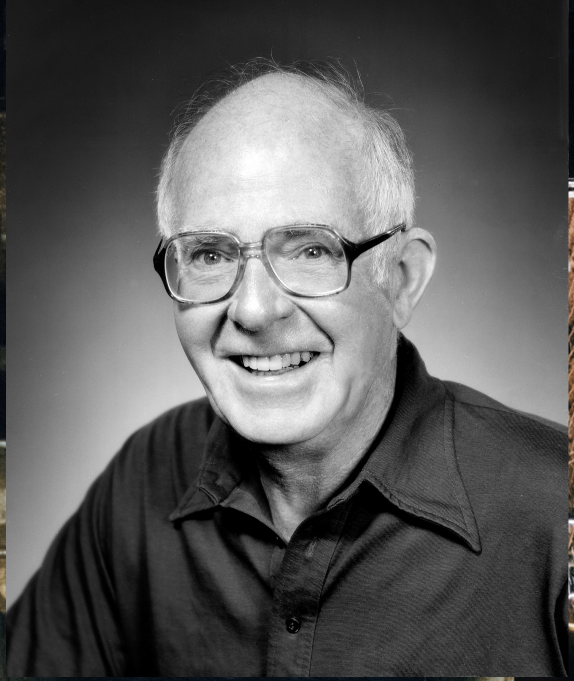
SN anomaly



10
8
6
4
2
0
SNU
1970
1974
1978
1982
1986
1990
1994
Year



Ga
Cl
Kamiokande
pp
^{13}N
^{15}O
^{17}F
^{7}Be
pep
^{8}B
hep
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}



PROSPECT Motivations and Goals: Sterile Neutrinos?

Sterile Neutrino, 3+1 Scenario

- Expanding PMNS matrix to include sterile neutrino components

- Sterile Neutrino searches become simpler at short baseline

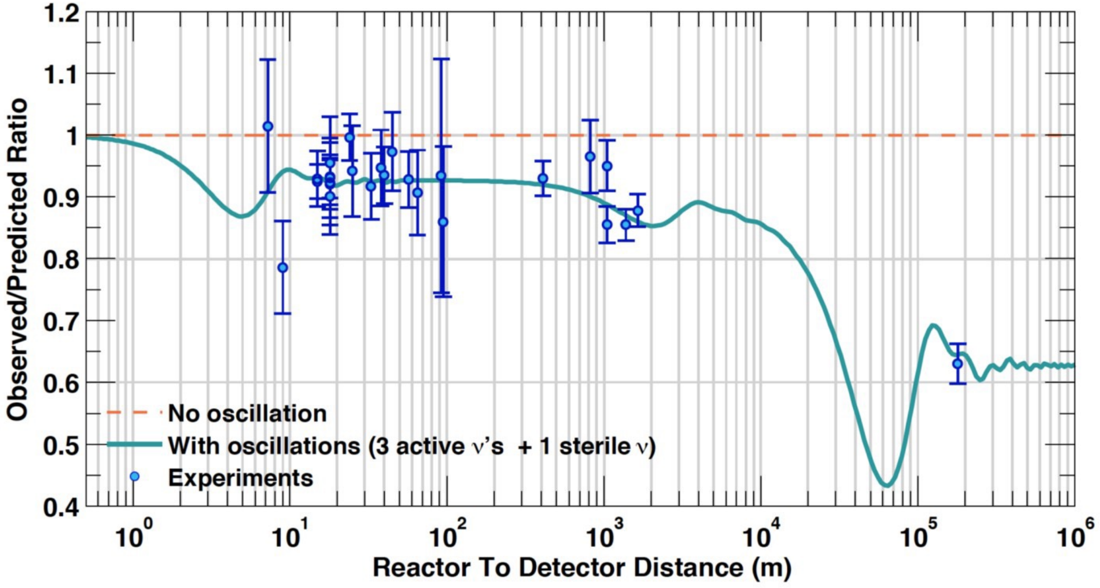
$$P(\bar{\nu}_e \longrightarrow \nu_e) = 1 - \sin^2 2\theta_{14} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

- $\text{Sin}^2(2\theta)$ modulates the oscillation amplitude

- Δm^2 is the oscillation phase

- Δm^2 assumed to be ~1eV^2

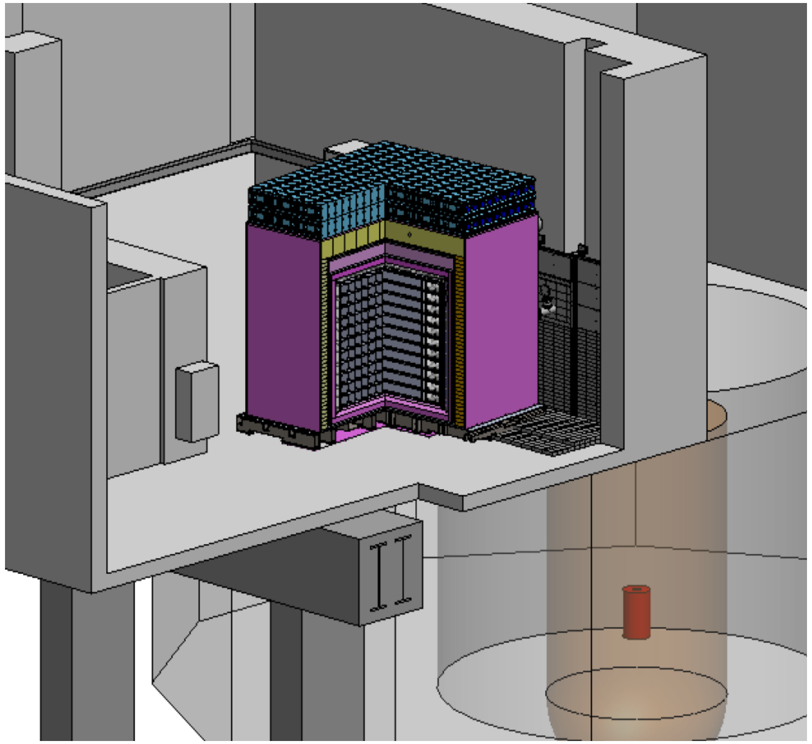
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \mu_4 \end{pmatrix}$$

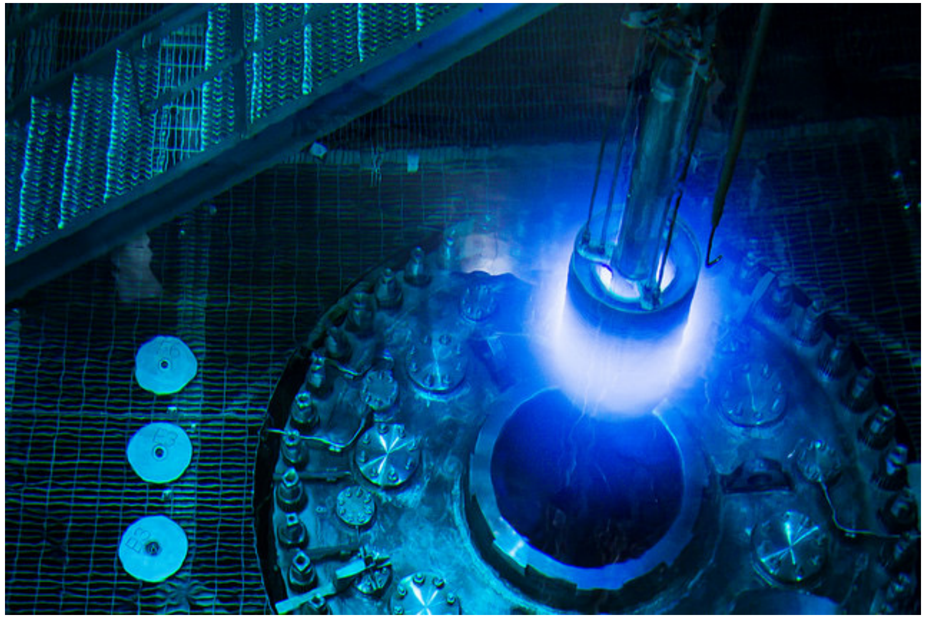


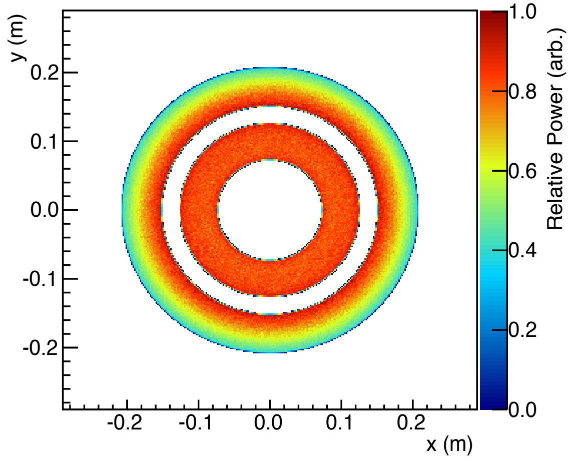
https://doi.org/10.1016/j.physrep.2021.06.002

HFIR – High Flux Isotope Reactor

- Favorable positioning, 7-12 m from the core
- Fresh core each cycle
- Fuel evolution is negligible
- Detailed core model available for simulation







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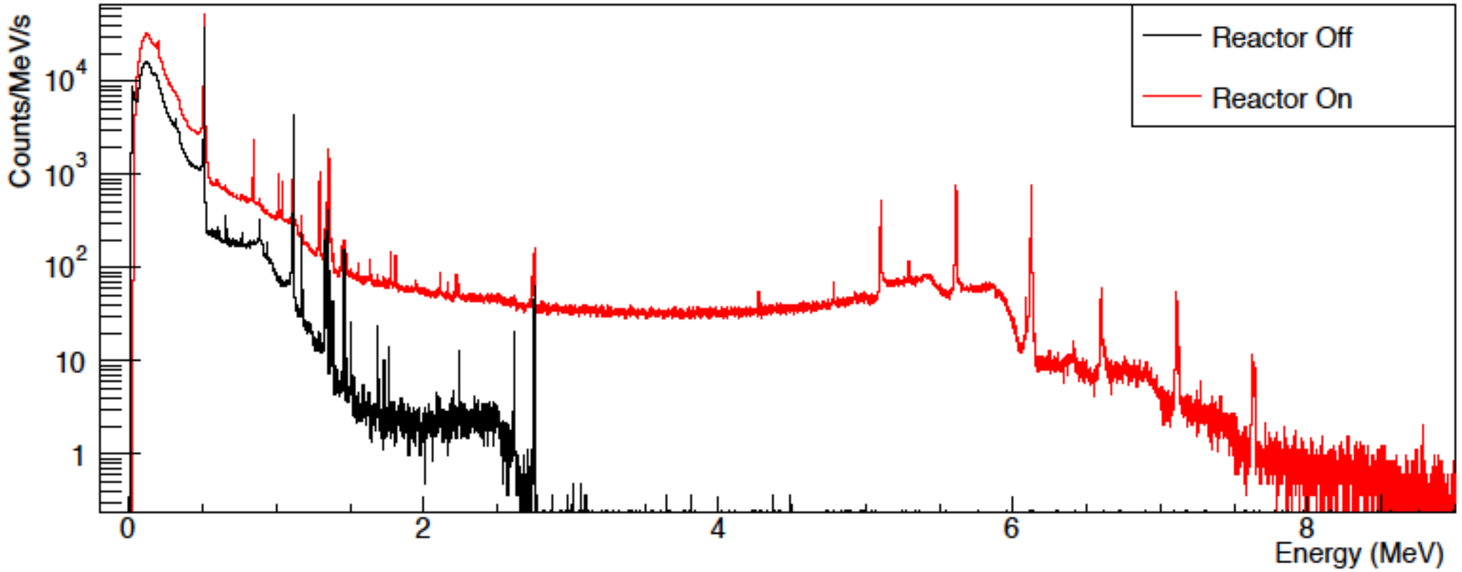
PROSPECT

Reactor gamma background

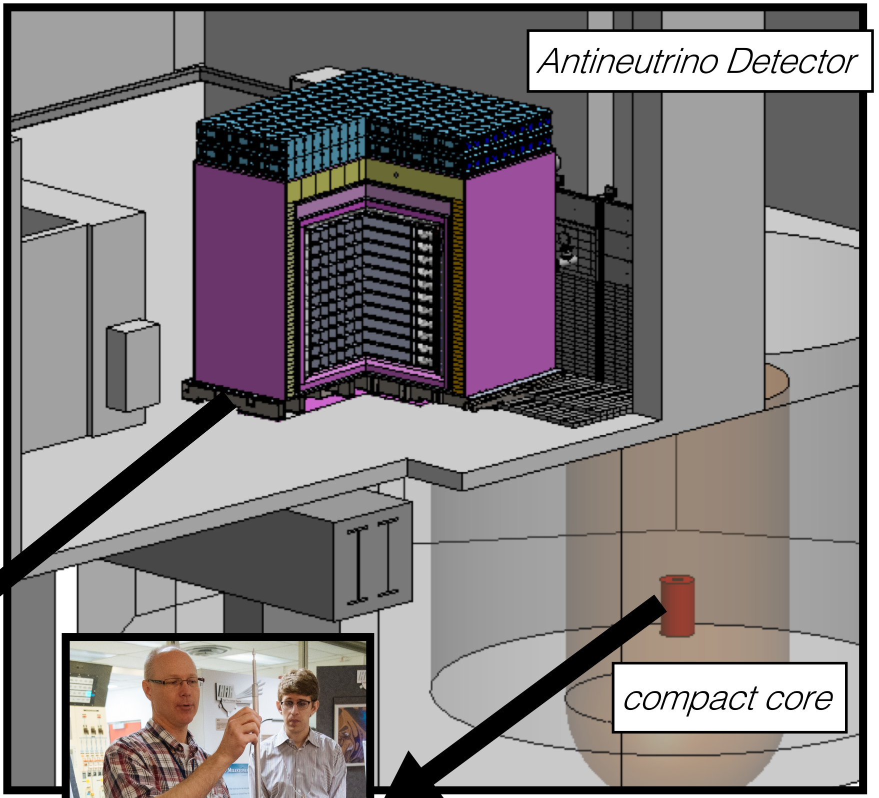
- Characterize the background radiation fields encountered at HFIR,
- Understand the sources of those backgrounds
- Develop background mitigation strategies appropriate for low-background experiments

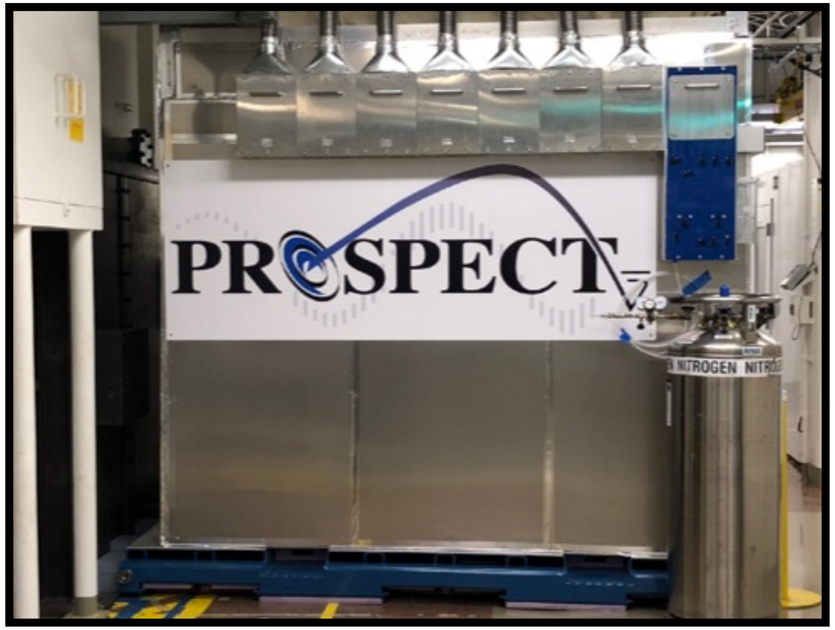
Example HPGe gamma-ray spectra taken with Reactor on and off

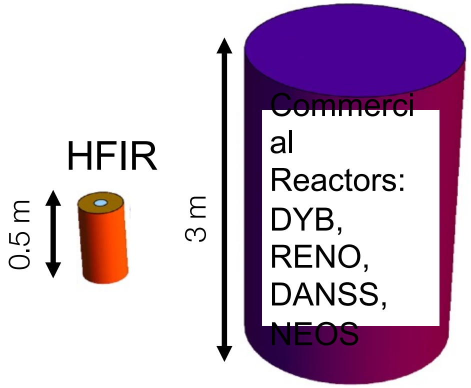


The PROSPECT Experiment

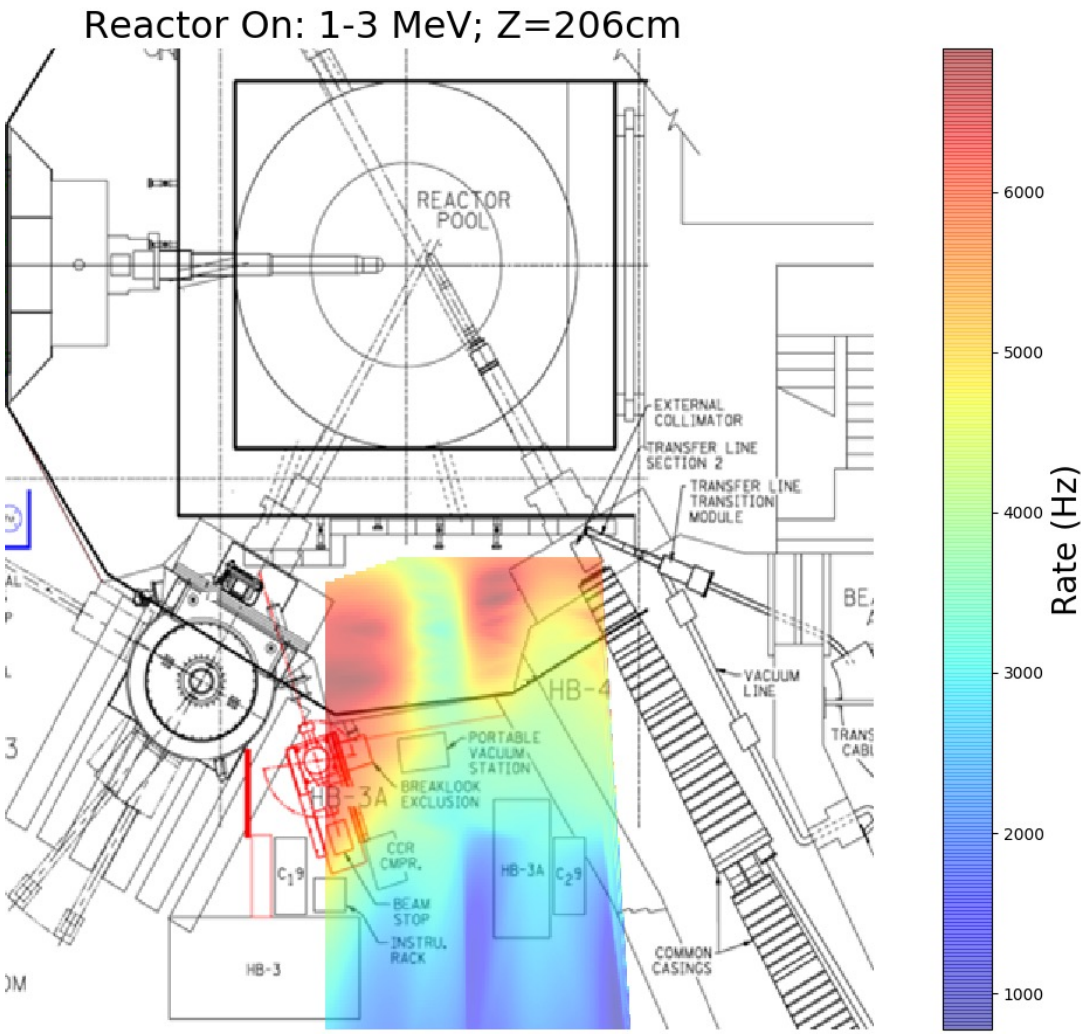
- A 4-ton ^{6}Li-doped segmented liquid scintillator detector at the HFIR research reactor
  - US-based: Oak Ridge Lab (Tennessee)
  - Very short baseline: 6.7-9.2 meters
  - Compact core (<50cm dimensions) with 50% duty cycle.
  - IBD data taken from 2018-2019

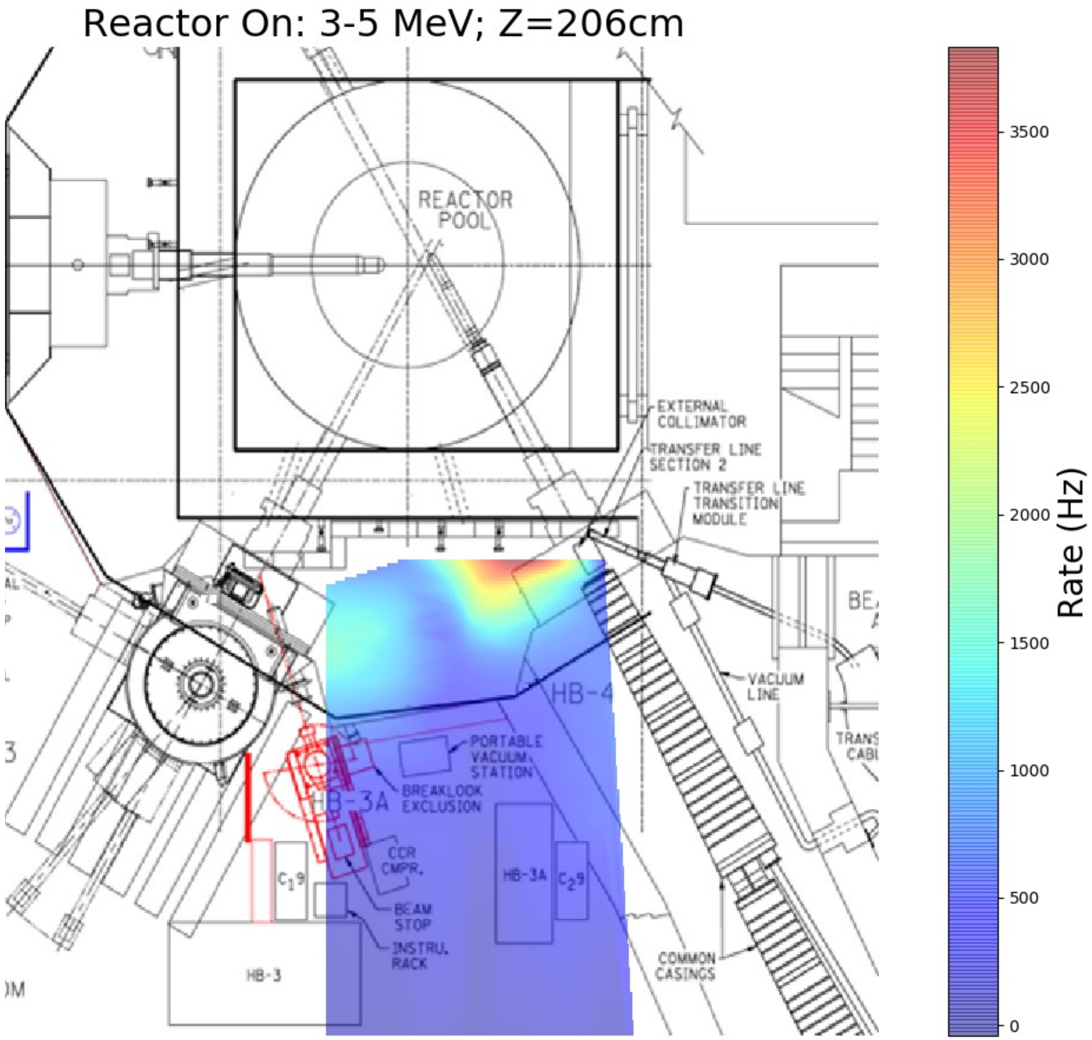






Backgrounds – Spatial Variance





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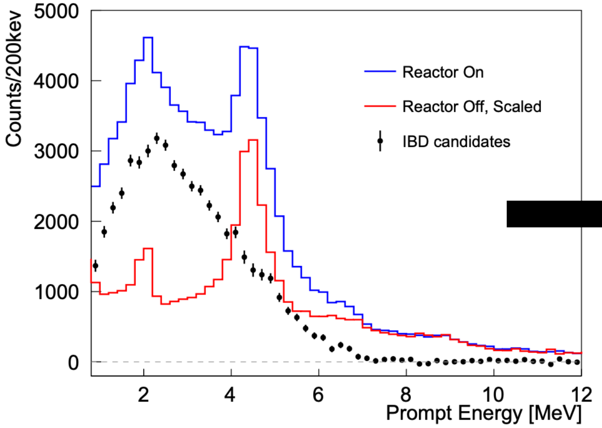
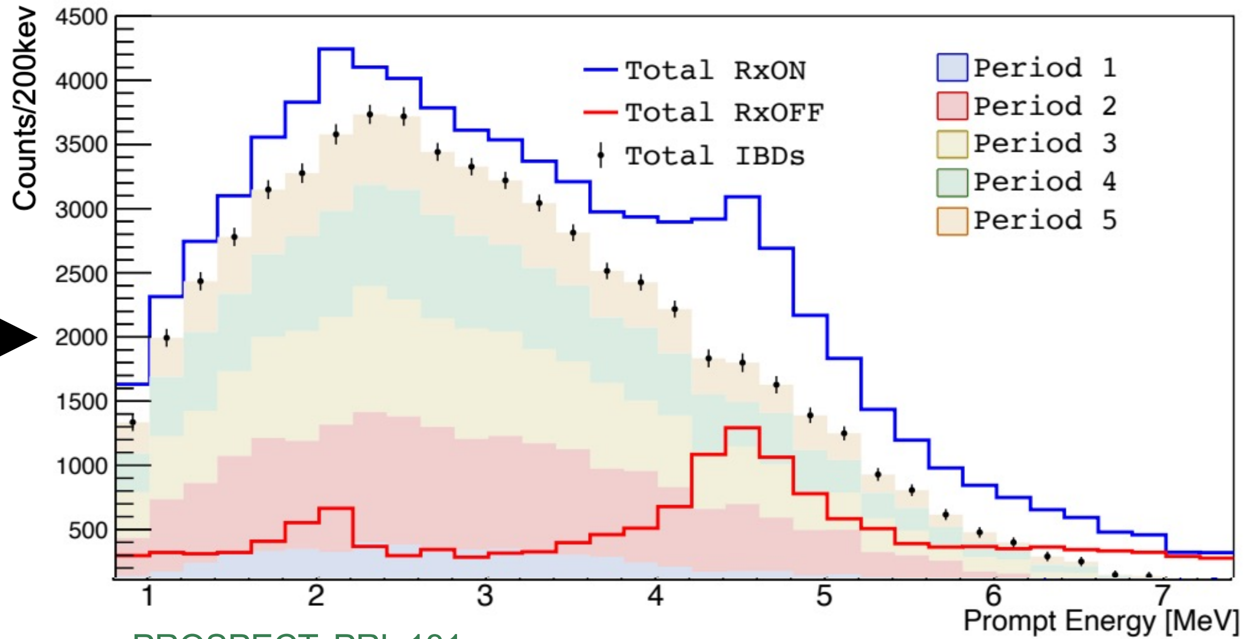
PROSPECT Final IBD Selection

Improved PROSPECT's IBD selection in light of gradual PMT failures (62 of 398 PMTs)

- Split dataset into 5 periods: 1 reactor cycle per period.
- Used segments with 1 functioning PMT to veto cosmic neutron backgrounds
- Ratio of signal to cosmic background increases from 1.4 to 3.9, and IBD counts increase by 20%. Total statistical power is more than doubled.



PROSPECT, PRD 103 (2021)



PROSPECT, PRL 131 (2023)

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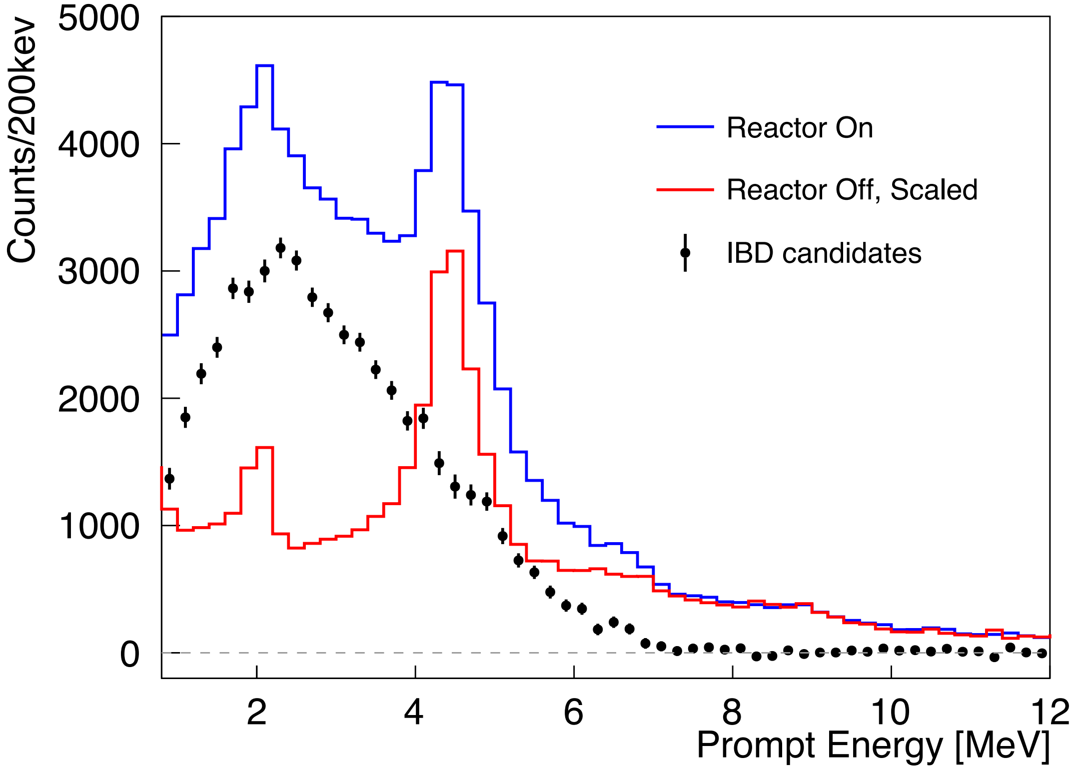
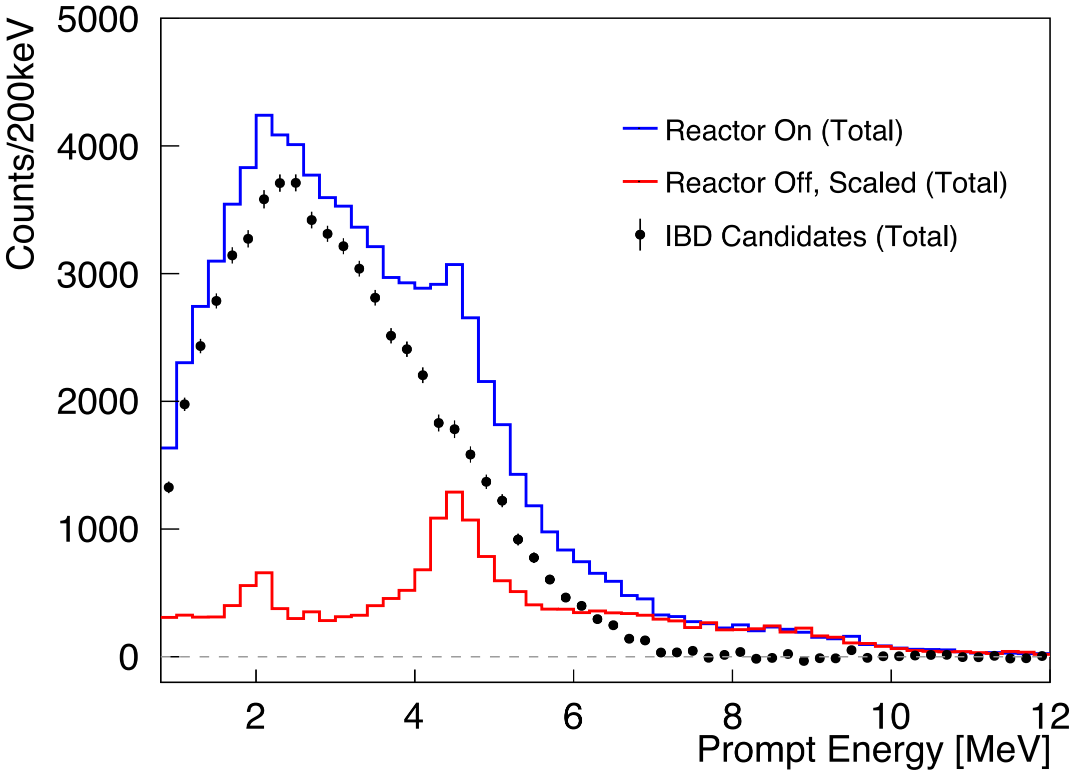
Multi-Period Spectrum Analysis

Previous PROSPECT Analysis	New Multi-Period Analysis





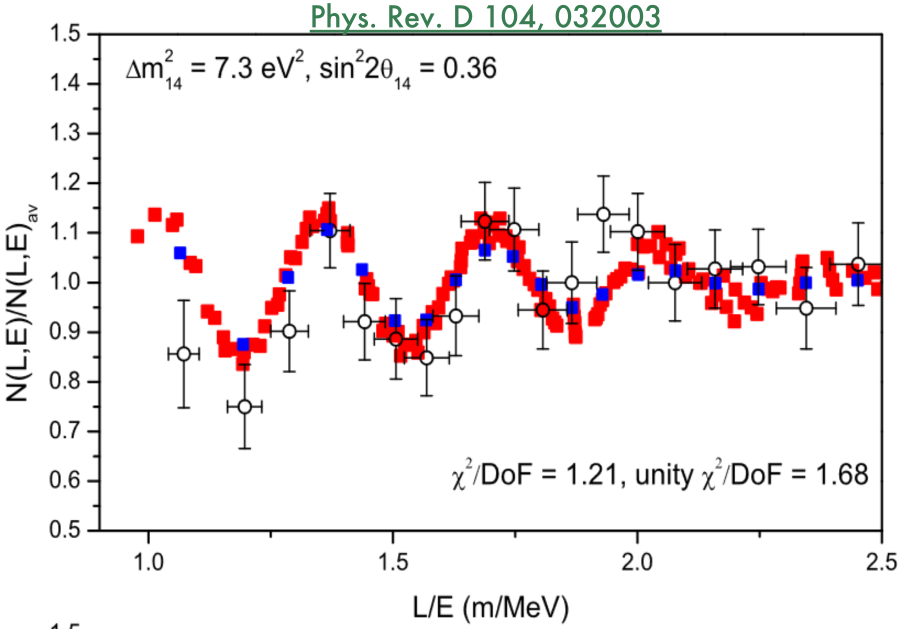
Great background reduction provided by new analysis

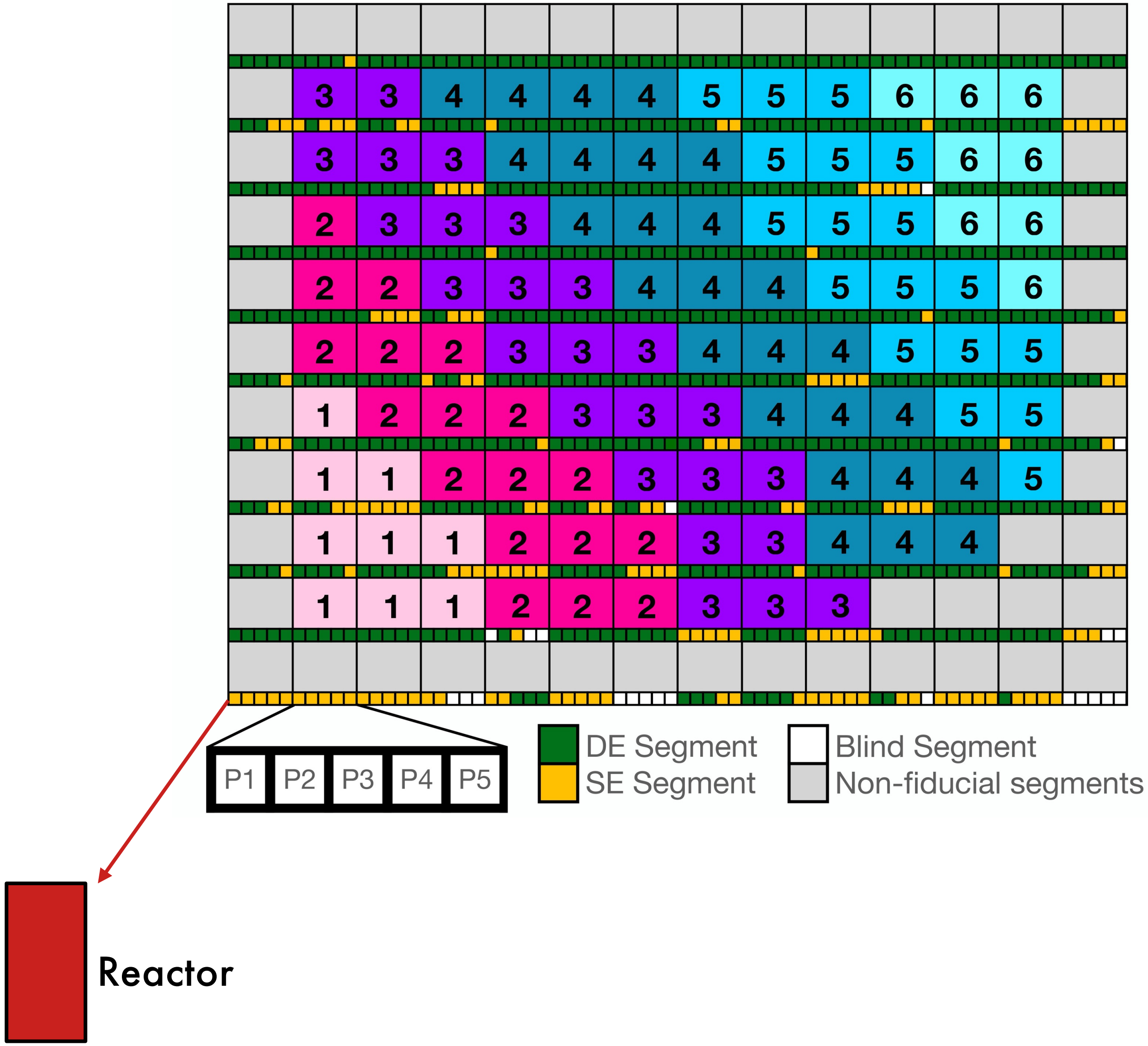
- Implementation of new DS+SEER optimized provided the following improvements:
  - IBD counts ~**60k (x1.2)**
  - IBD effective counts ~**30k (x2)**
  - Signal to cosmogenic background (S/CB) **~3.9(x2.8)**
  - Signal to accidental background (S/AB) **~4.3(x2.4)**

New Multi-Period Oscillation Analysis

- Previous oscillation measurement was statistics-limited. Increase in effective statistics (x2) will improve current sensitivity
- Recent results from the Neutrino-4 collaboration reported a non-zero sterile neutrino oscillation

Phys. Rev. D 104, 032003

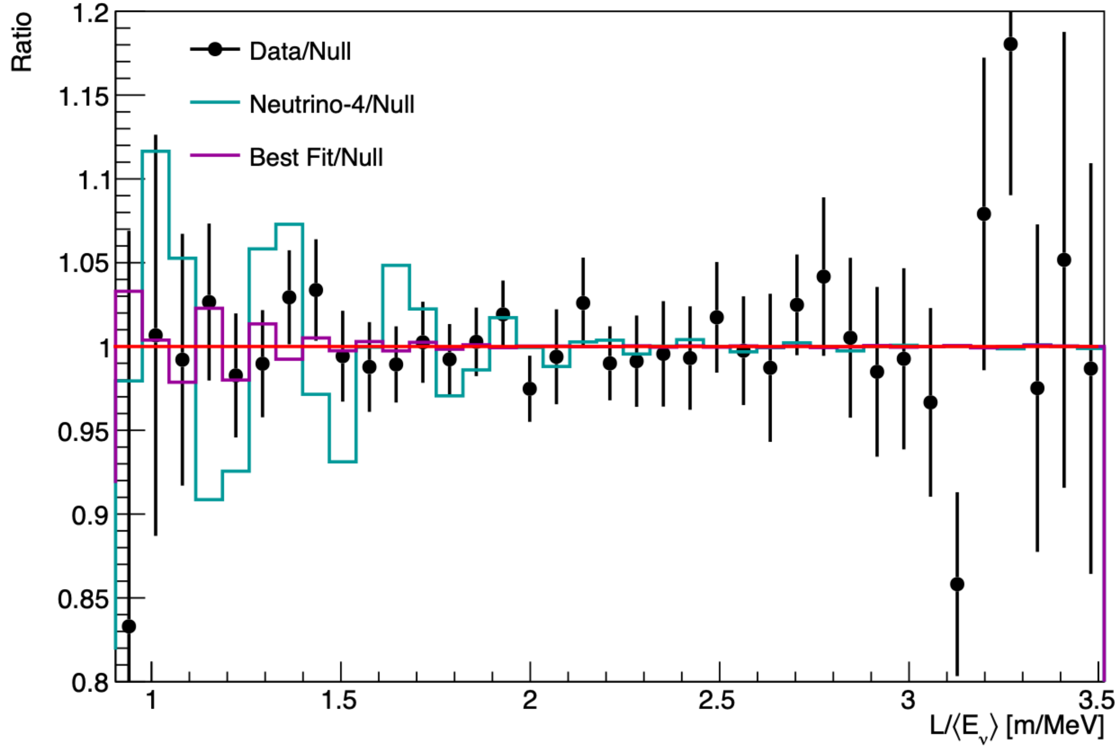




PROSPECT Final Osc: Probing L/E

- Qualitatively examined PROSPECT's IBD dataset in bins of L/Eν
- No obvious oscillatory features are visible in the ratio of L/Eν spectra between data and the null-oscillation prediction
  - One would expect to see substantial features in the presence of oscillations matching the Neutrino-4 best fit point.

arxiv:2406.10408 June 17, 2024



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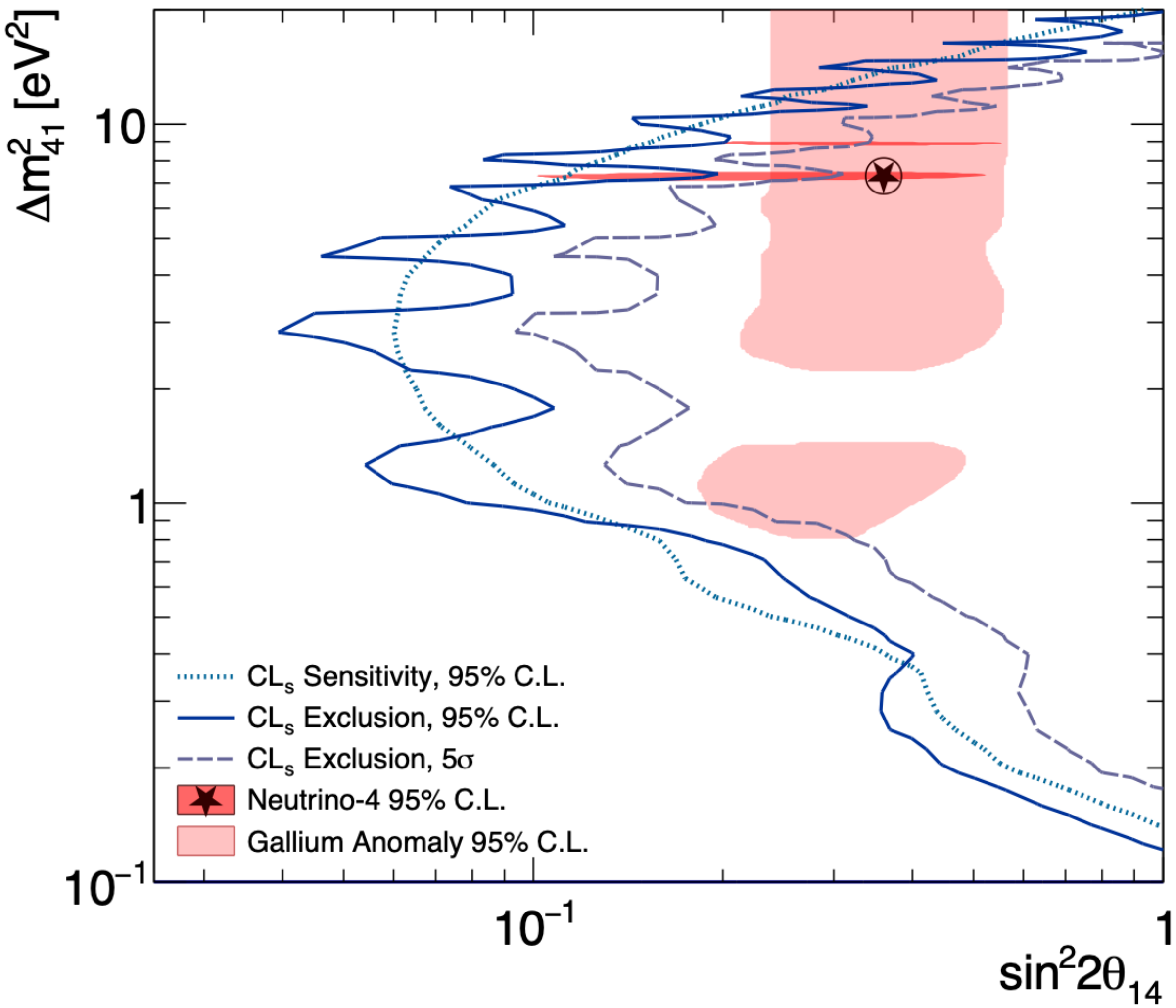
- PROSPECT provides new world-leading limits on sterile neutrino oscillations
  - New regions of high-Δm^2 space are excluded at >95% CL, including all space below 10 eV^2 suggested by the Gallium Anomaly
  - Neutrino-4 best-fit point is ruled out at >5σ CL



PROSPECT, Neutrino 2024, arXiv[2406.TBD]

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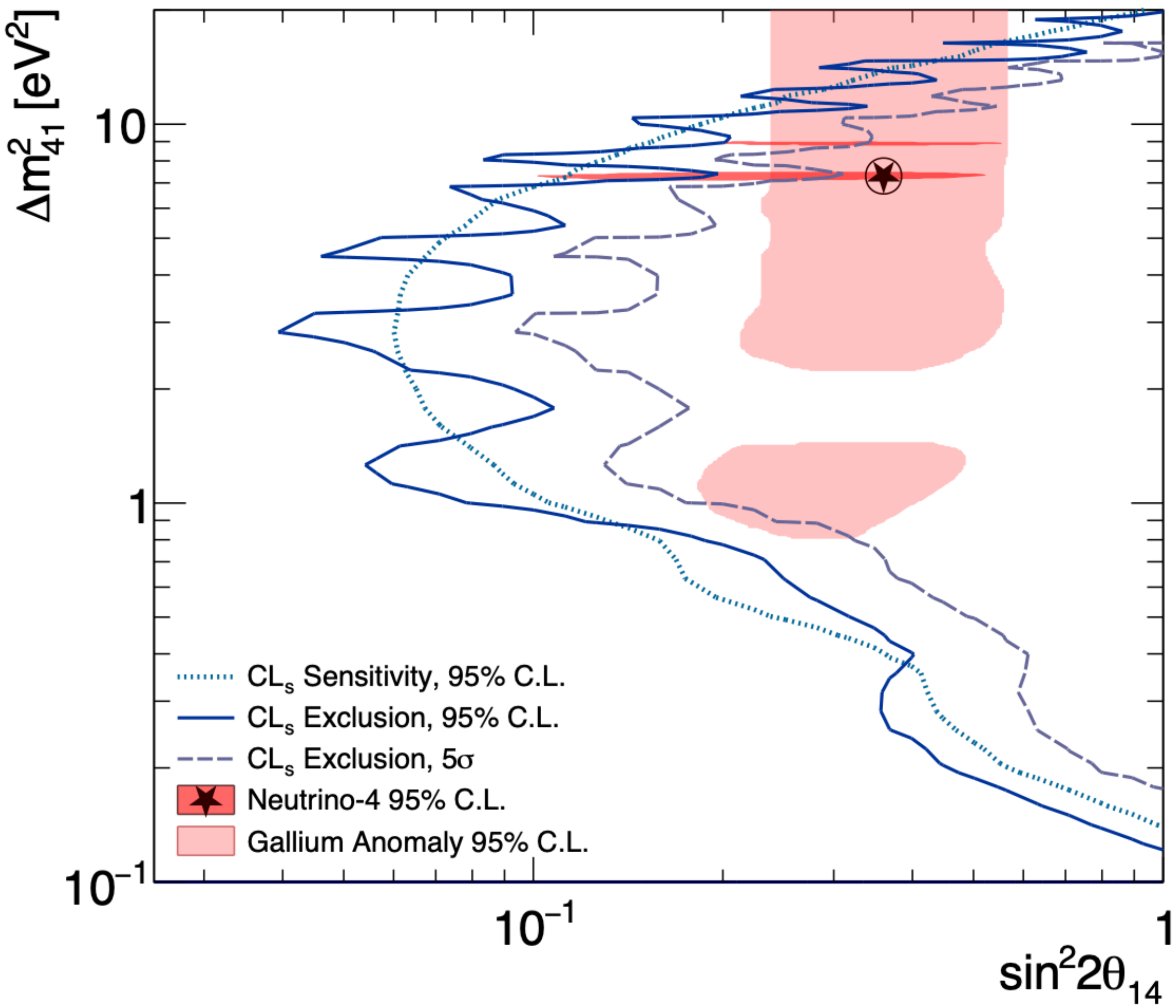
Phase space for 3+1 sterile neutrino oscillations excluded by the final PROSPECT-I dataset

New PROSPECT data set is compatible with an absence of sterile neutrino oscillations.

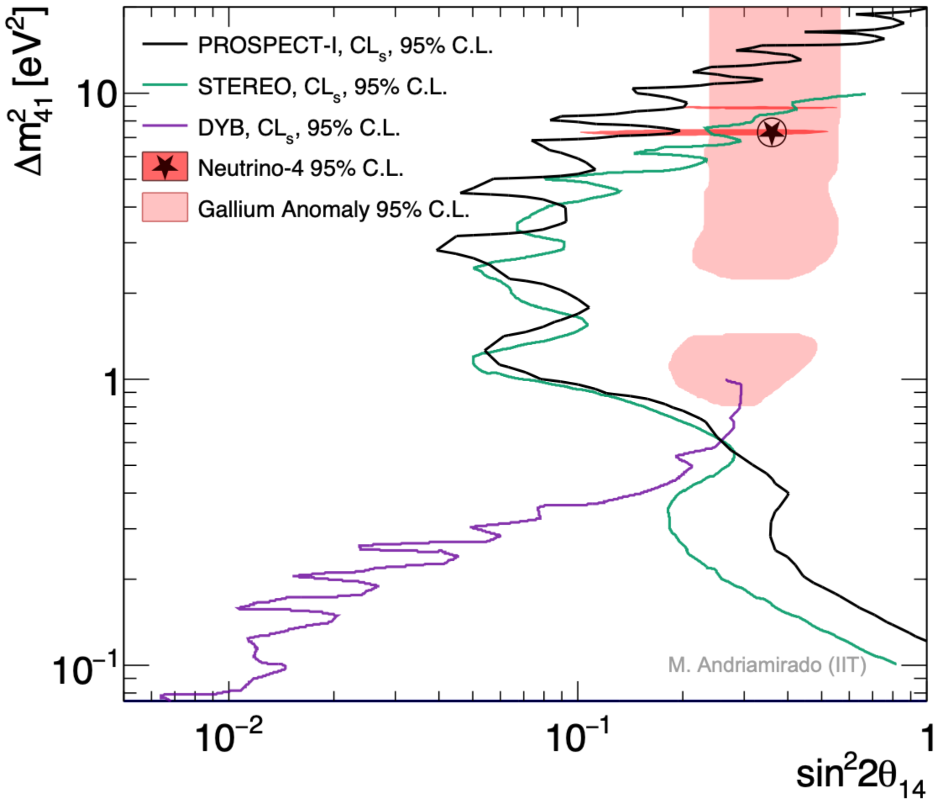
Best-fit point of the Neutrino-4 reactor experiment's claimed observation of short-baseline oscillation is ruled out at more than 5σ.

Excluded all phase space for Δm2 below 10 eV2 suggested by the recently strengthened Gallium anomaly



DPS Joint Oscillation Analysis

- A combination of Daya Bay, PROSPECT, and STEREO datasets offers new benefits for sterile oscillation searches
  - PROSPECT and STEREO datasets have comparable statistical power
  - Daya Bay's LEU-based ^{235}U spectrum measurement is directly comparable to HEU STEREO and PROSPECT measurements
  - Additional sterile sensitivity unlocked by comparison of long (Daya Bay) and short (STEREO, PROSPECT) baseline energy spectra (a la NEOS/RENO)



- Analysis work started between three collaborations in late 2023. Stay tuned!

HFIR Neutrino Laboratory

Workshop on Neutrino Science and Applications at HFIR

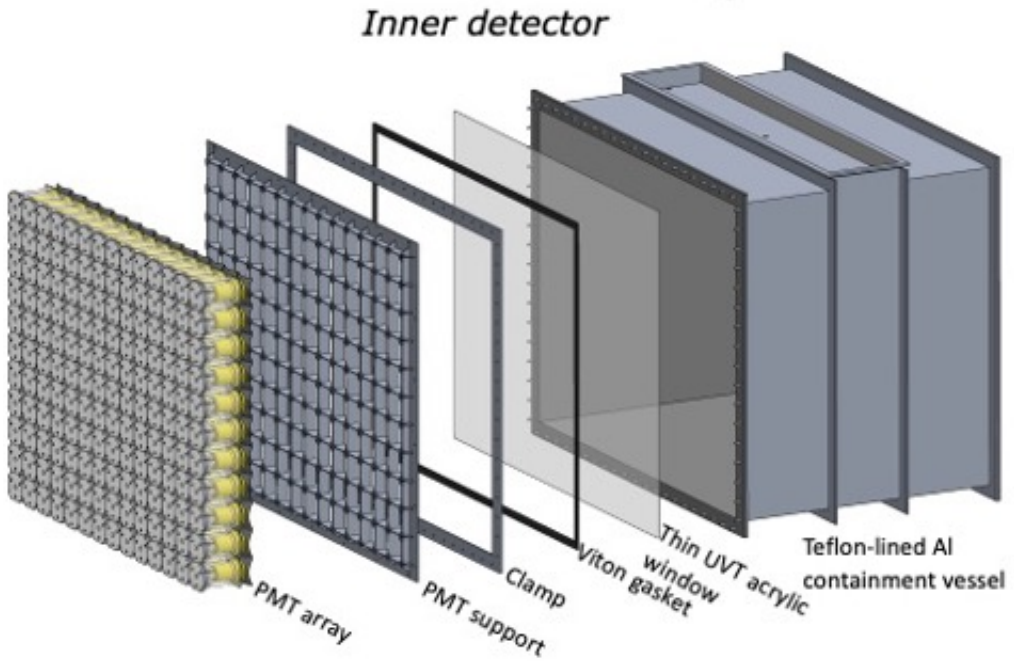
22–24 Apr 2024
Building 8600- SNS

- Currently exploring community interest in HFIR as a multi-use particle physics lab
- Workshop attended by IBD, Reactor-CEvNS, Detector R&D, QIS folks
- Forming an experiment interest group, steering committee in 2024
- Existing and future facilities at ORNL (HFIR, SNS, STS) make it the hub for low-energy neutrino physics in the USA.

Next Step: PROSPECT-II

- Goal: Match initial performance (maintain similar pitch, similar scintillator characteristics) while improving stability
- Remove PMTs from active volume
  - Eliminates main PROSPECT-1 fail
- Improve environmental control/isolation
  - Fewer materials in contact with LiLS
  - Improved cover gas system
  - Active cooling
- Enable emptying/refilling
  - Allows movement to multiple sites (HEU, LEU, DAR source, beam dump) unlocking a diverse potential long-term physics program

PROSPECT II



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"Local" Students and Postdocs that worked in PROSPECT-I

+ more than 35 from collaboration institutions


Ran Chu UTK


Brennan Hackett UTK


Elisa Romero UTK


Rosa Luz Peinado Sonora

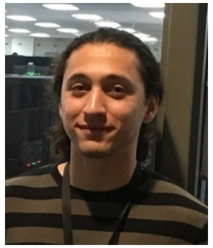

Andrea Delgado Texas A&M


Adriana Ghiozzi UC Berkeley


Sabrina Cheng MIT


Brandon White PD-ORNL 13


James Matta PD-ORNL 17


Alex Guirado Sonora


Alan Garcia UTEP


Diego Vargas Wesleylan

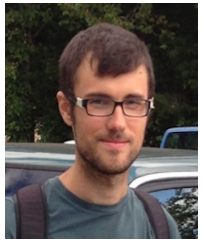

Ivan Corona UAEM

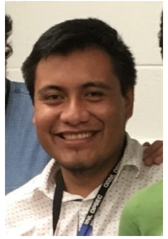

Corey Gilbert UTK


Xiaobin Lu UTK


Cristian Baldenegro Sonora


Omar Garcia CINVESTAV

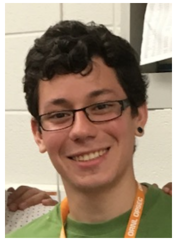

Blaine Heffron UTK


Noel Cruz UNAM

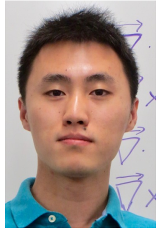

Jack Boyle Surrey


Travis Stockinger UTK


Biswas Sharma UTK


Felix Pastrana Colombia


David Murphy UCD


Shiyu Fan UTK

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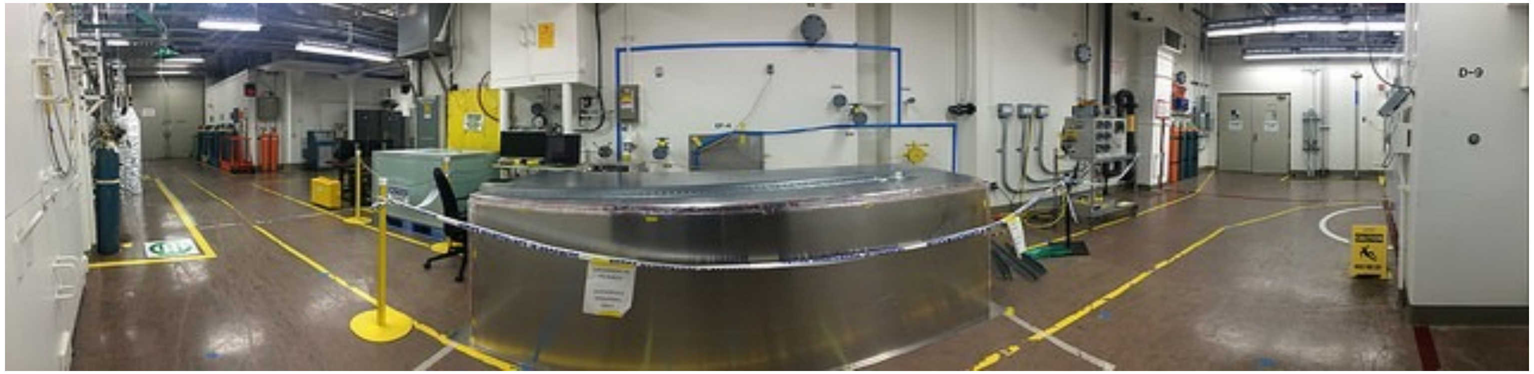
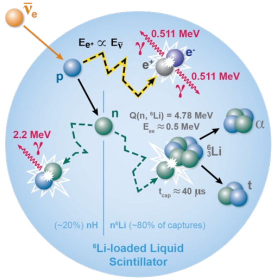
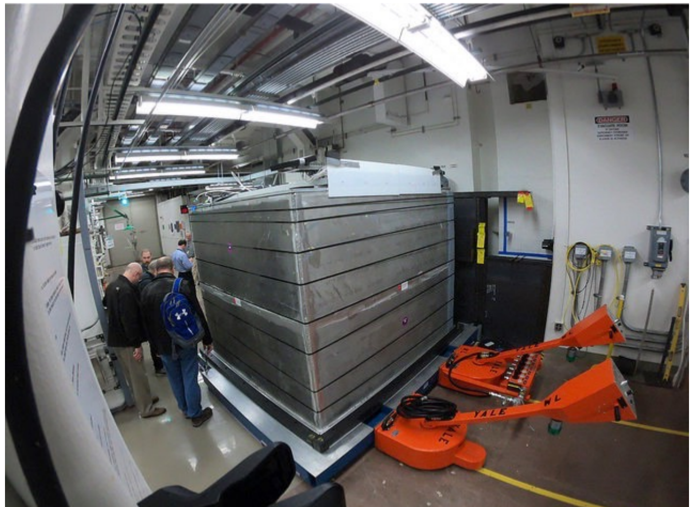
Visit to the Graphite Reactor Summer interns 2024



PROSPECT

A Precision Oscillation and Spectrum Experiment





In Memoriam Dr. Salvador Galindo-Uribarri

Salvador Galindo Uribarri.

Difusión científica, historia de la ciencia y apoyo de científicos jóvenes.

Review

The Unsettled Number: Hubble's Tension

Jorge L. Cervantes-Cota, Salvador Galindo-Uribarri and George F. Smoot

Special Issue

Universe: Feature Papers 2023 – Cosmology

Edited by
Dr. Kazuharu Bamba

Co-author on 3 articles
with NL George Smooth

Infamous "co-author"

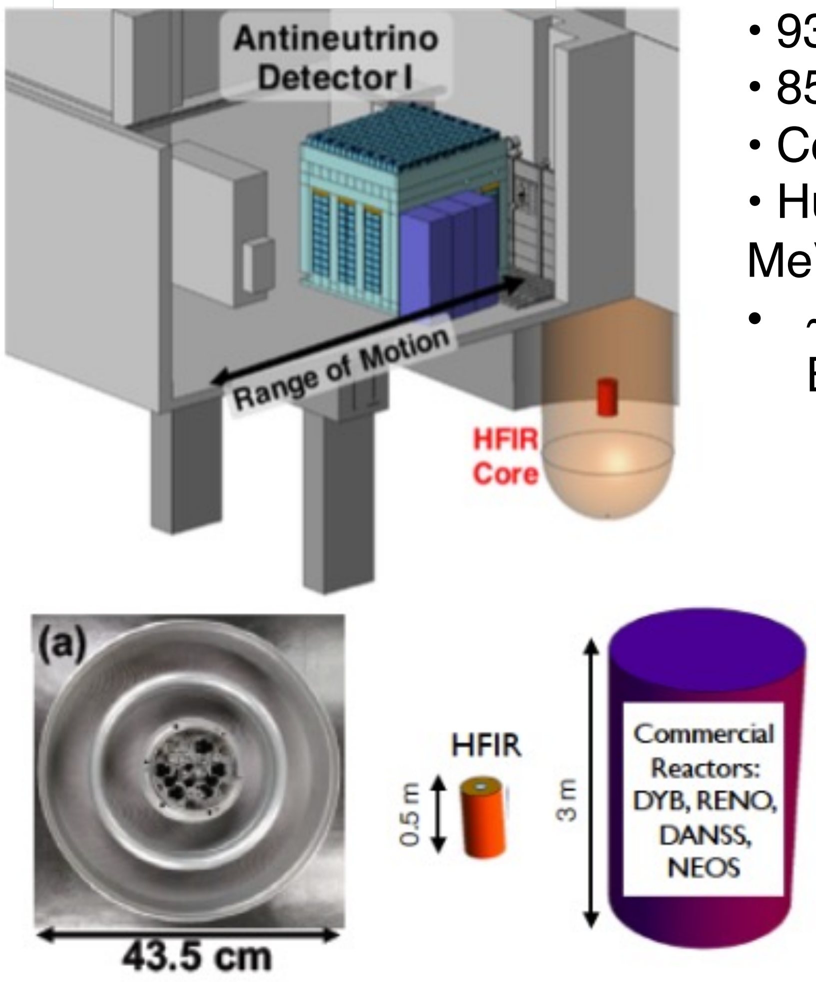
OAK RIDGE National Laboratory

ORNL provides strong support for Neutrino Program

PROSPECT Collaboration with ORNL personnel at HFIR

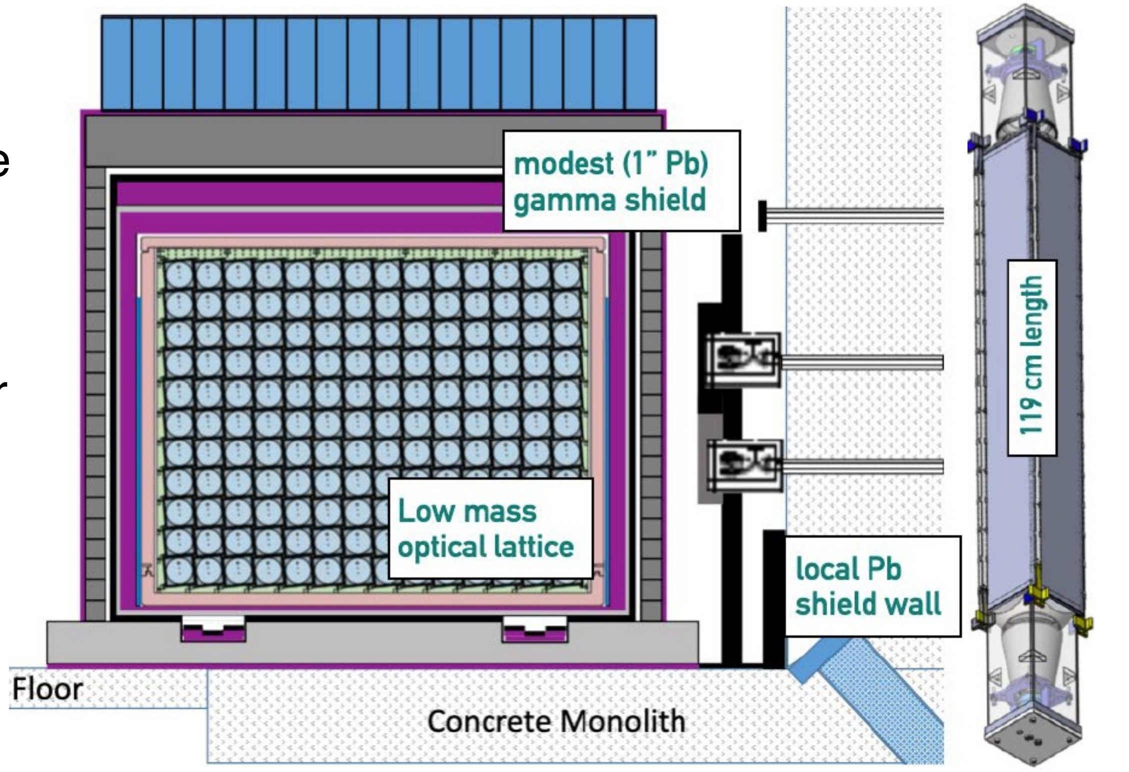
PROSPECT Detector at HFIR

Layout of the PROSPECT experiment



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

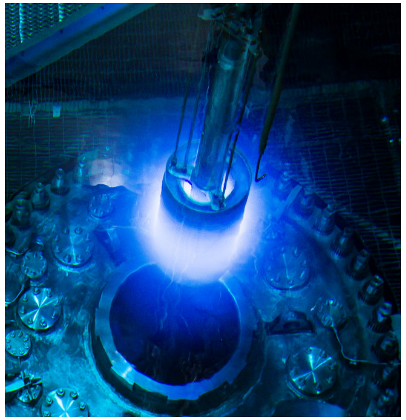
Schematic of the active detector volume

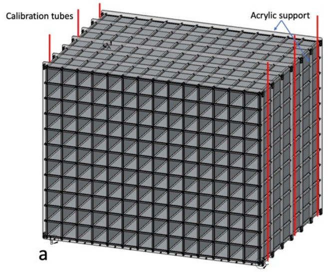


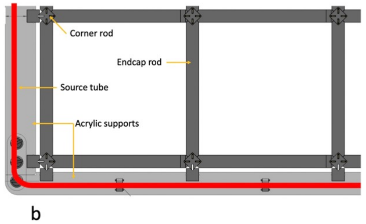
14 x 11 array of 6Li doped liquid scintillator for detecting reactor antineutrinos (6.7-9.2 m from compact highly enriched uranium reactor core)

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

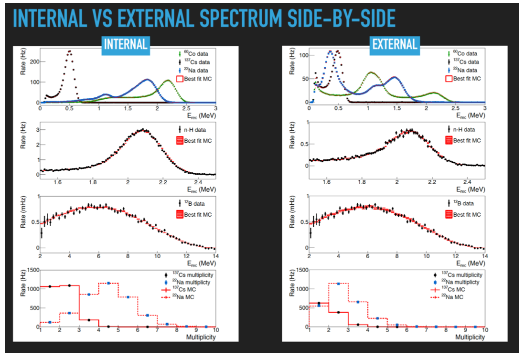
PROSPECT II Physics Opportunities

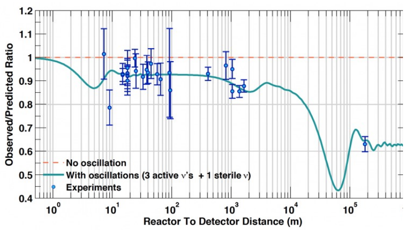


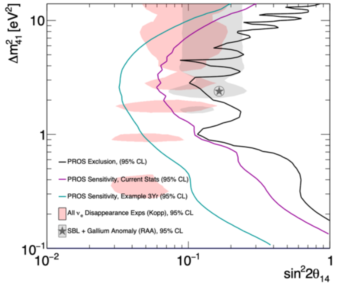




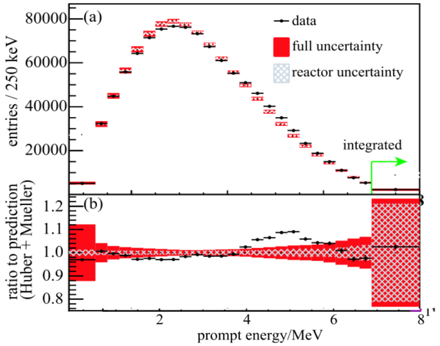
P-II New Design
P-II External Calibration







Deficit due to extra (sterile) neutrino oscillations or artifact of flux predictions?



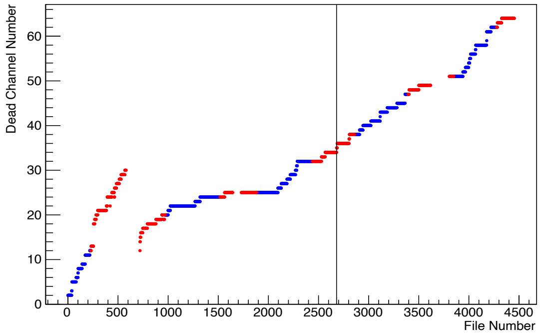
Spectral Deviation

Measured spectrum does not agree with predictions.

Understanding reactor flux and spectrum anomalies requires additional data

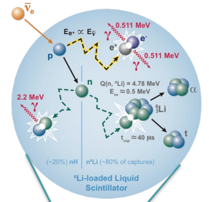
P-I Final Analysis

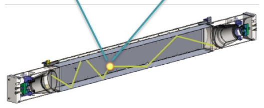
Gain 52% of IBD effective counts over what was published in the PRD



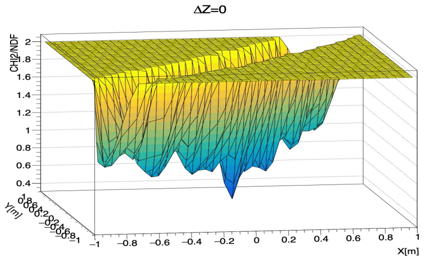
Ongoing projects applying ML to PROSPECT (NN various configs.)

- Single-ended event and z-position
- Positron discrimination to improve IBD
- Reconstruction/classification of antineutrino events (energy spectrum and origin of interaction). Participation in neutrino meetings.

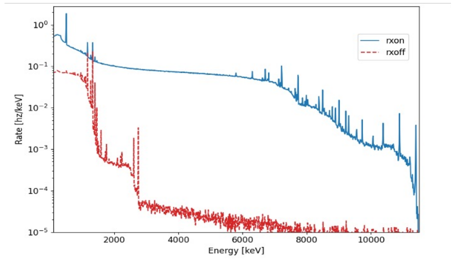


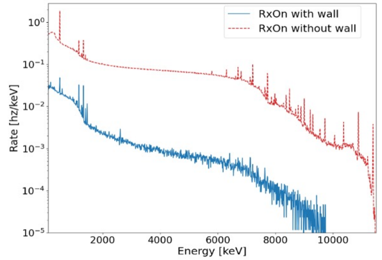


Directionality and sensitivity to core position



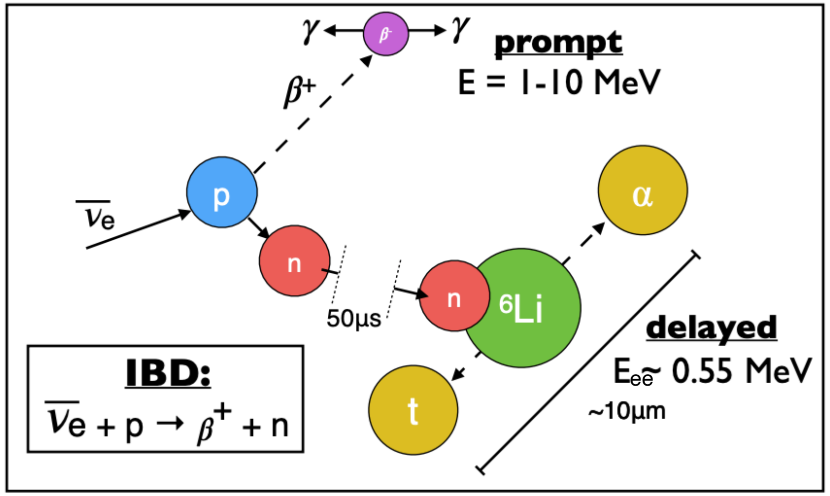
High-Res Directional Background Studies at HFIR





Antineutrino Detection Principle

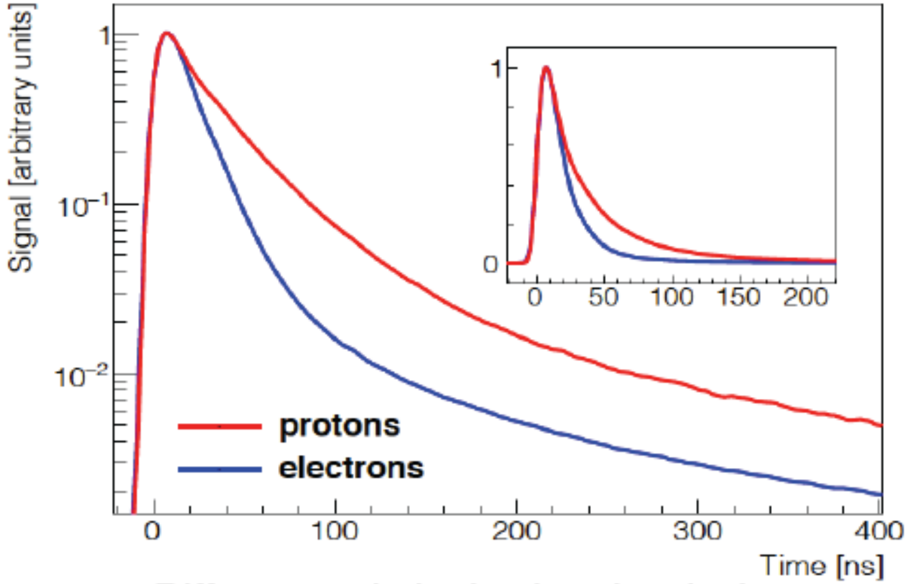
Schematic of the IBD process



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

6-LiLS with PSD Capabilities

- Average waveforms for electronic/nuclear type events



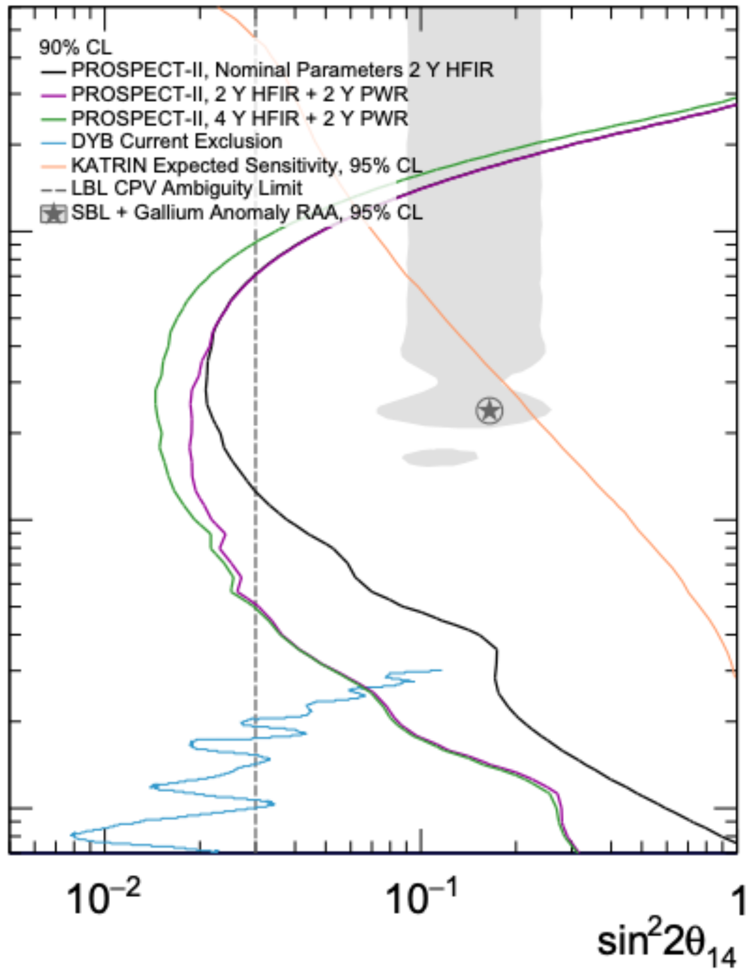
- Differences in ionization density between electronic/nuclear recoil type events result in distinct pulse shapes for each event
- Prompt and delayed signal posses unique pulse shapes (different from background events)

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

PROSPECT-II Physics Highlights

- HEU campaign:
  - Close out remaining BEST and Neutrino-4 suggested space below 20 eV^2
  - Pin down e-flavor disappearance to few-% level at <10 eV^2 , benefitting anomaly and long-baseline CPV interpretations
- Subsequent LEU campaign:
  - First correlated probe of HEU/LEU types
  - Delivers more precise isotopic ν_e flux/ spectrum information, broadly benefiting reactor-CEvNS, nuclear data/applications, …

J Phys G 49 (2022)



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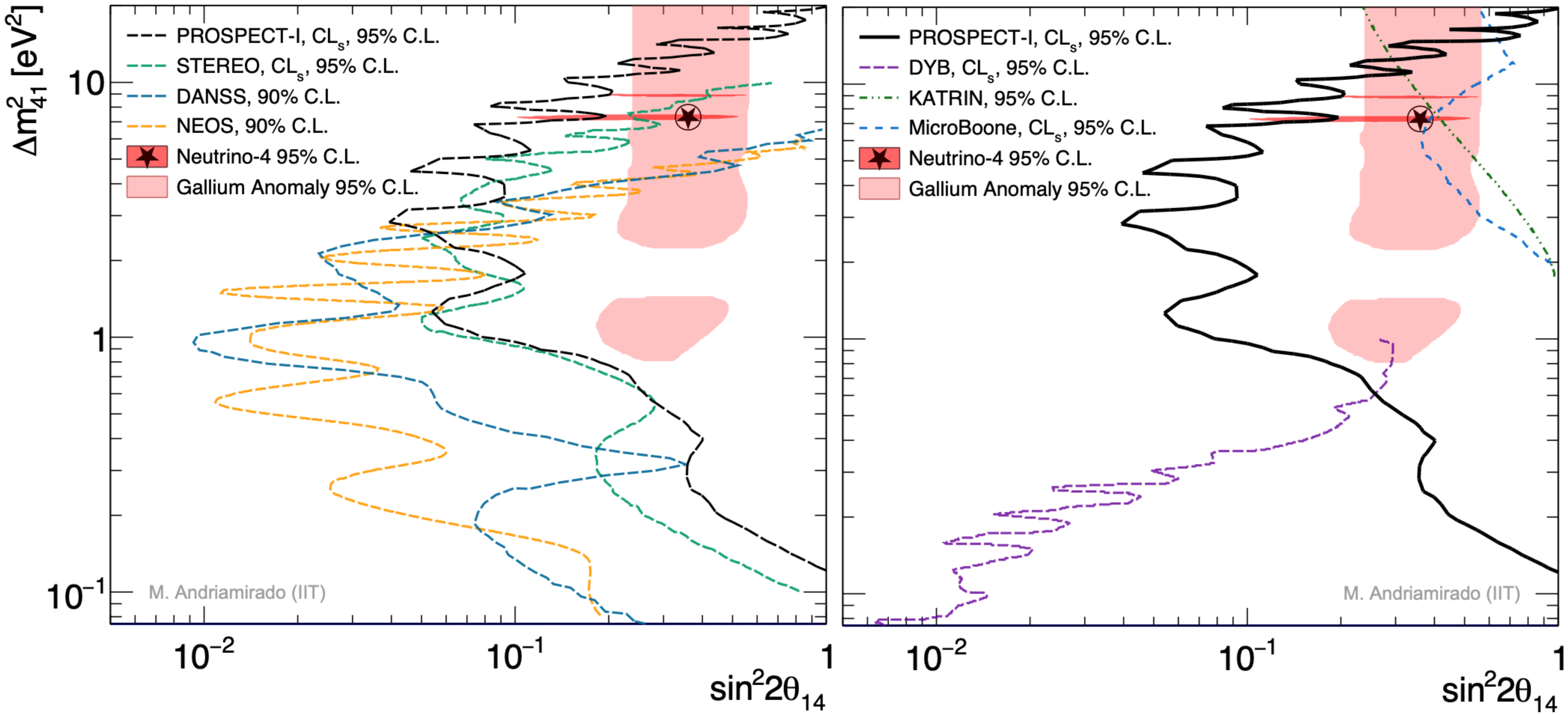
- New PROSPECT limits lead short-baseline reactor efforts for most Δm^2 values above 3 eV^2
- Reactor-based θ_{14} limits are much stronger than other experiment sectors over most of the pictured phase space.



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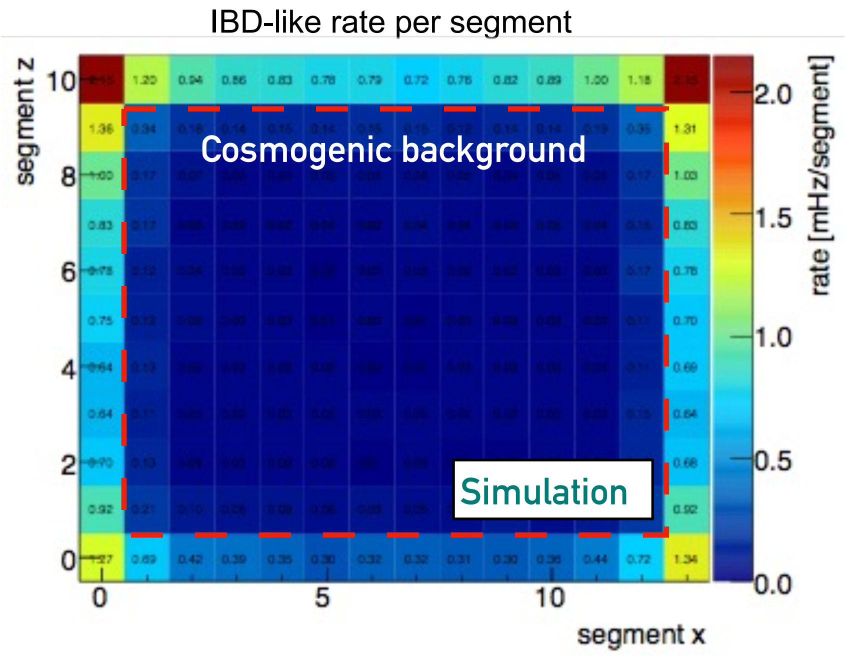
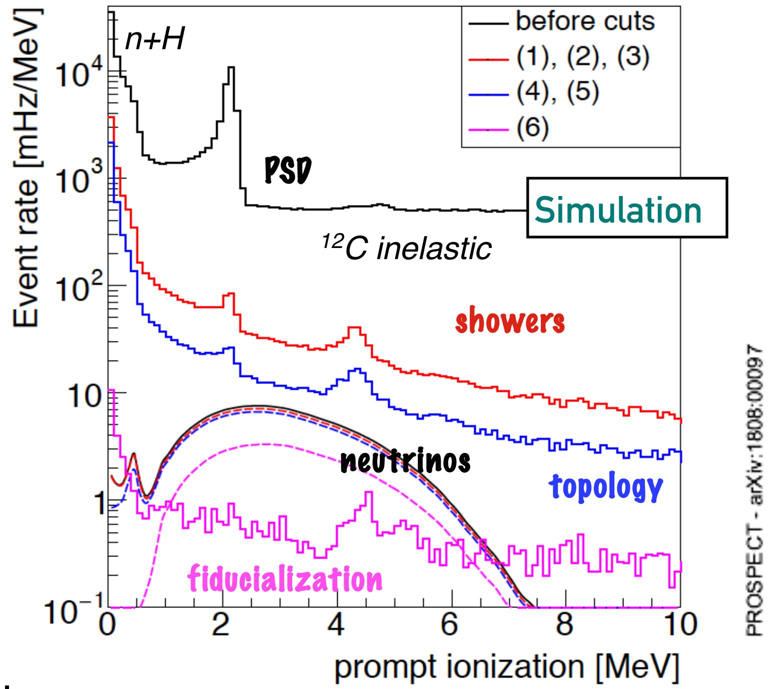
Background Rejection





Detector design further optimized for background rejection

A sequence of cuts leveraging spatial and timing characteristics of an IBD *yields* *> 10^4 background suppression and signal to background of > 1:1.*

Rate and shape of residual IBD-like background can be measured during multiple interlaced reactor-off periods.

Combine:

- PSD
- Shower veto
- Event topology
- Fiducialization

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Where are we going in the next 5 years and beyond?

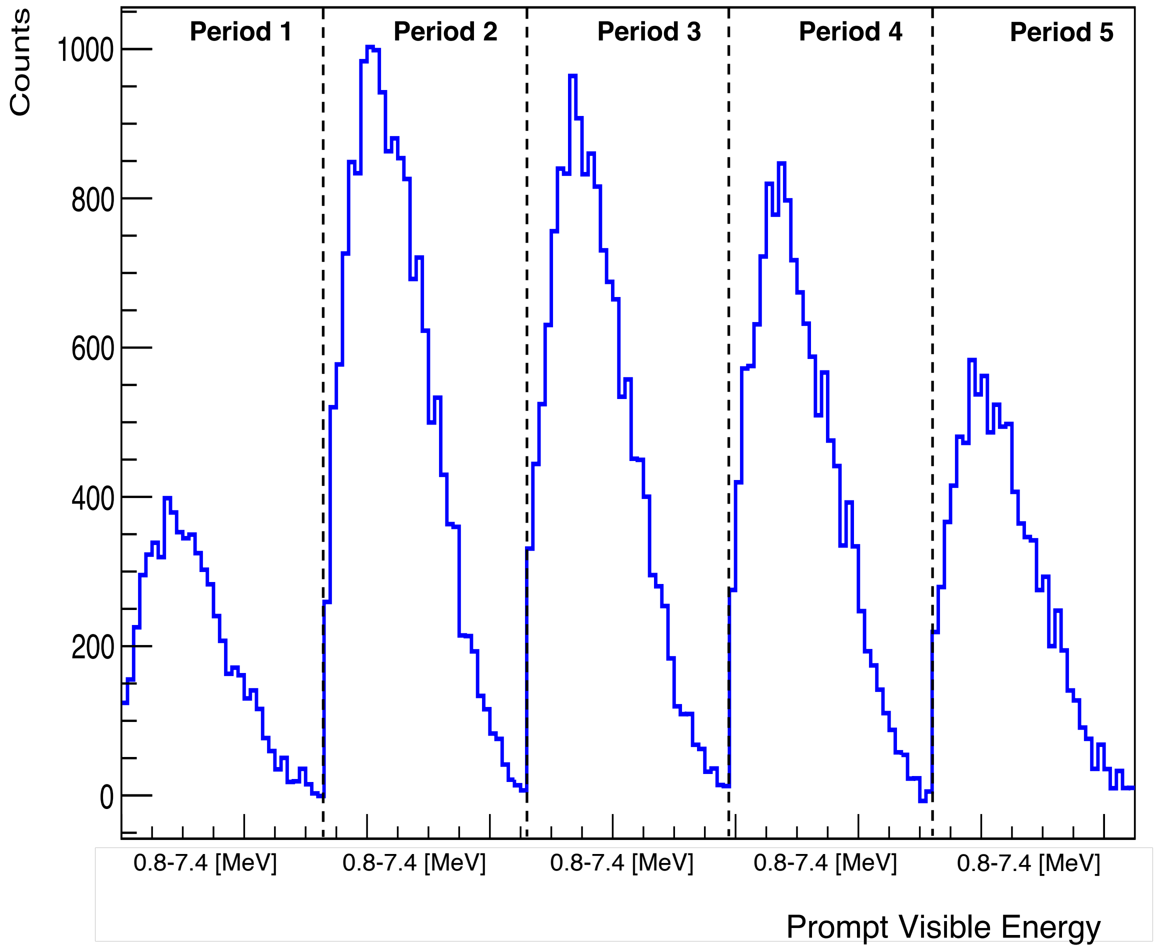
- Neutrinoless Double Beta Decay
  - LEGEND1000
  - Beyond LEGEND?
- Direct Neutrino Measurements at HFIR and SNS
  - COHERENT at SNS
  - PROSPECT at HFIR
  - Dedicated Neutrino Laboratory at STS Facility

3. New Opportunities with the PROSPECT-I Data

- Multi-period Spectrum analysis
- Multi-period Oscillation analysis

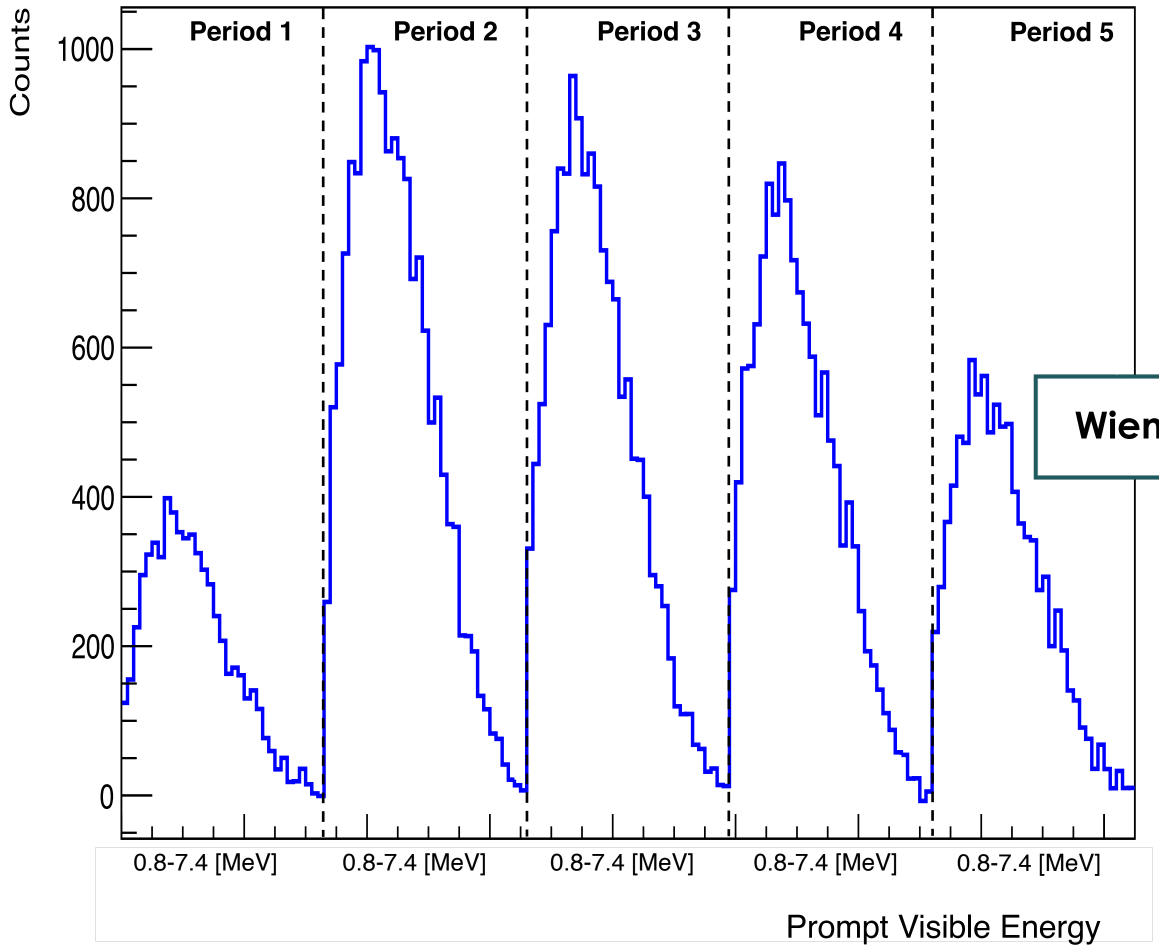
Multi-Period Spectrum Analysis: Unfolded Spectrum

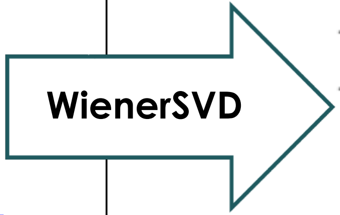
PROSPECT

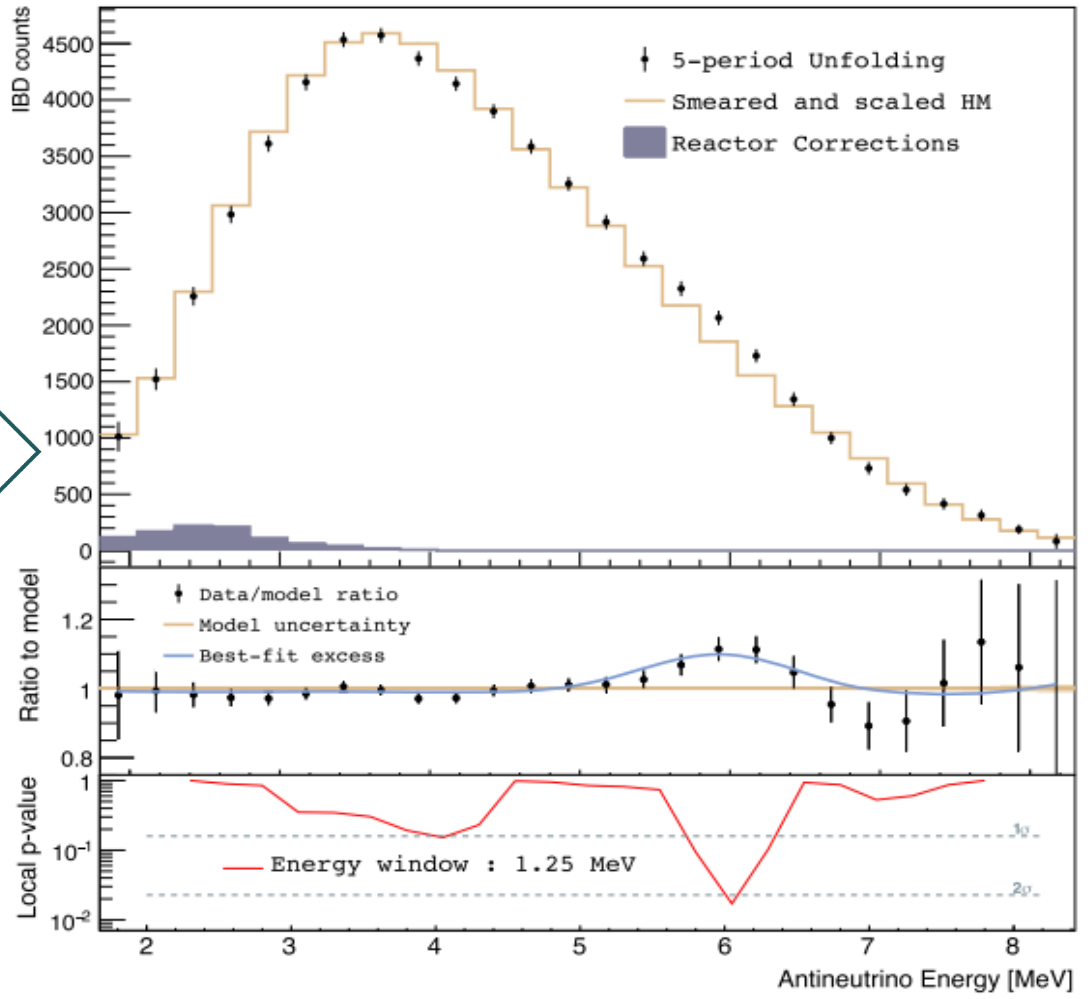


- The implementation of a period-by-period analysis allows for the treatment of each period as an independent experiment.
- New unfolding framework has been developed to jointly unfold the prompt spectrum from each period into one final antineutrino energy spectrum

Multi-Period Spectrum Analysis: Results







Phys. Rev. Lett. 131, 021802 (2023)

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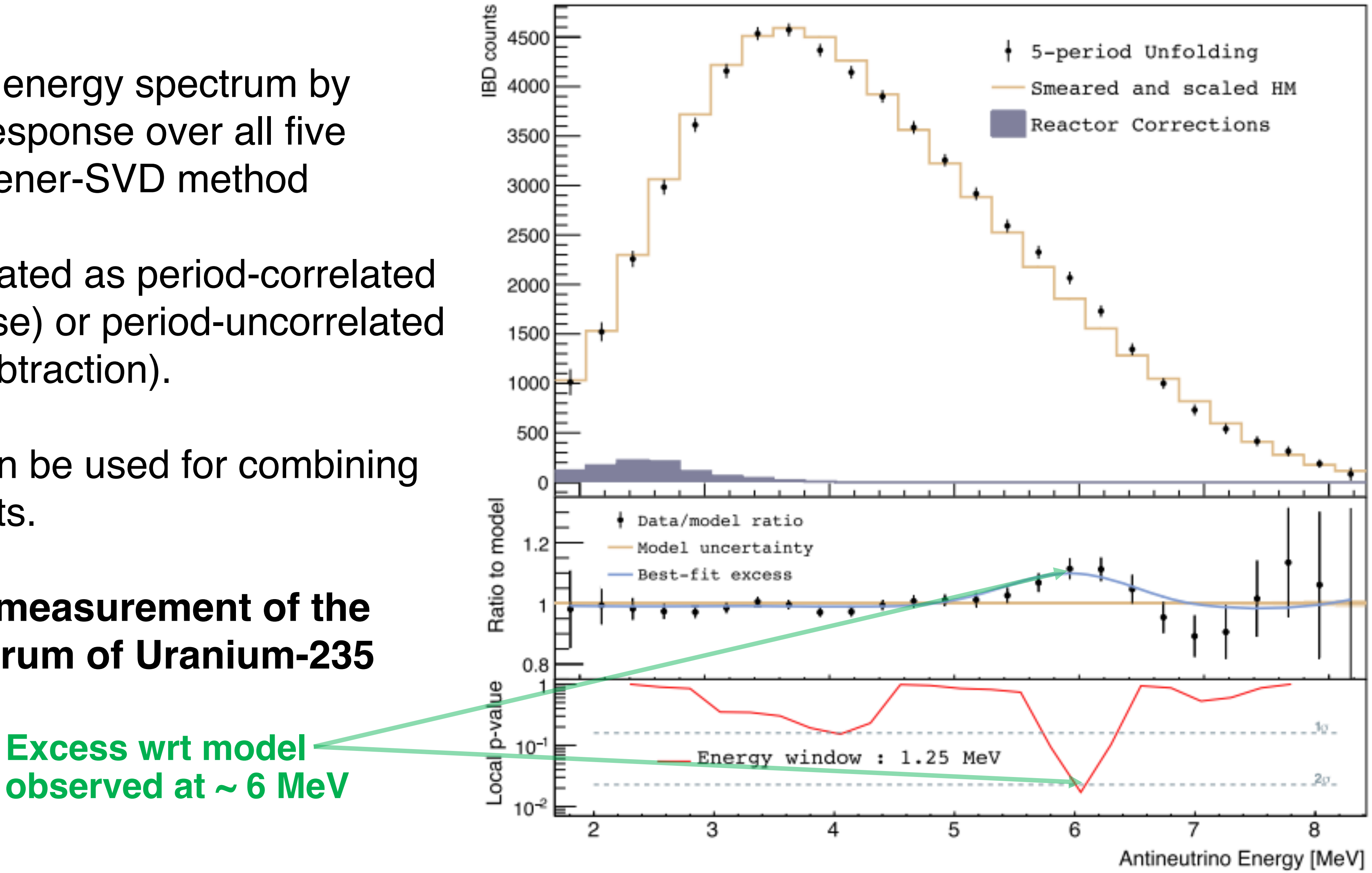
Multi-Period Spectrum Analysis: Unfolded Spectrum

- Obtain antineutrino energy spectrum by inverting detector response over all five periods with the Wiener-SVD method
- Systematics are treated as period-correlated (e.g energy response) or period-uncorrelated (e.g background subtraction).
- Same technique can be used for combining different experiments.
- **The most precise measurement of the antineutrino spectrum of Uranium-235**

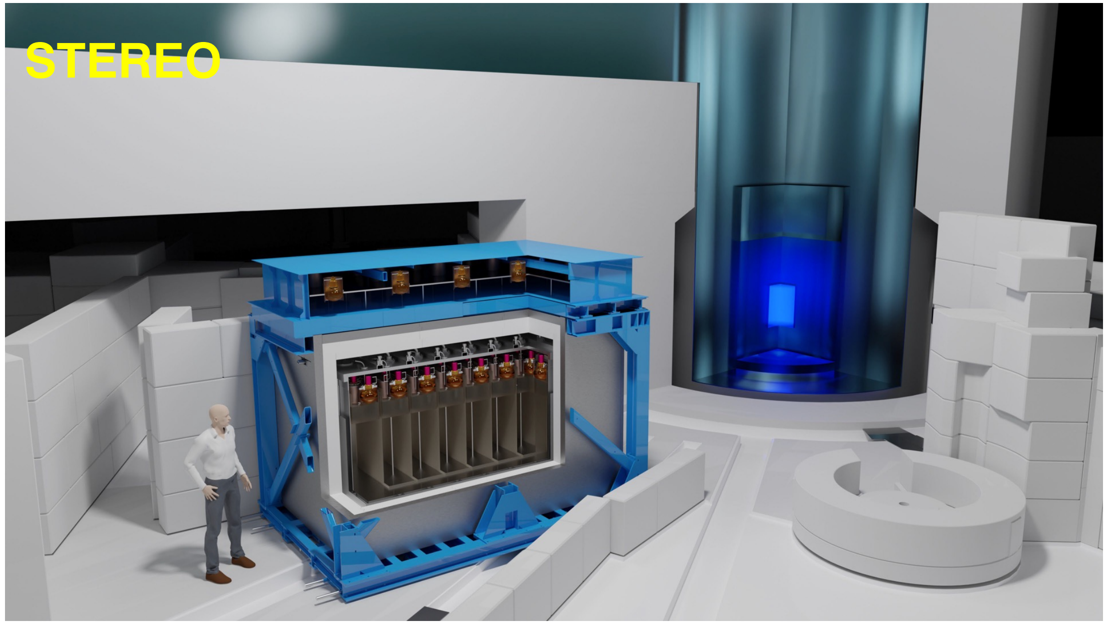


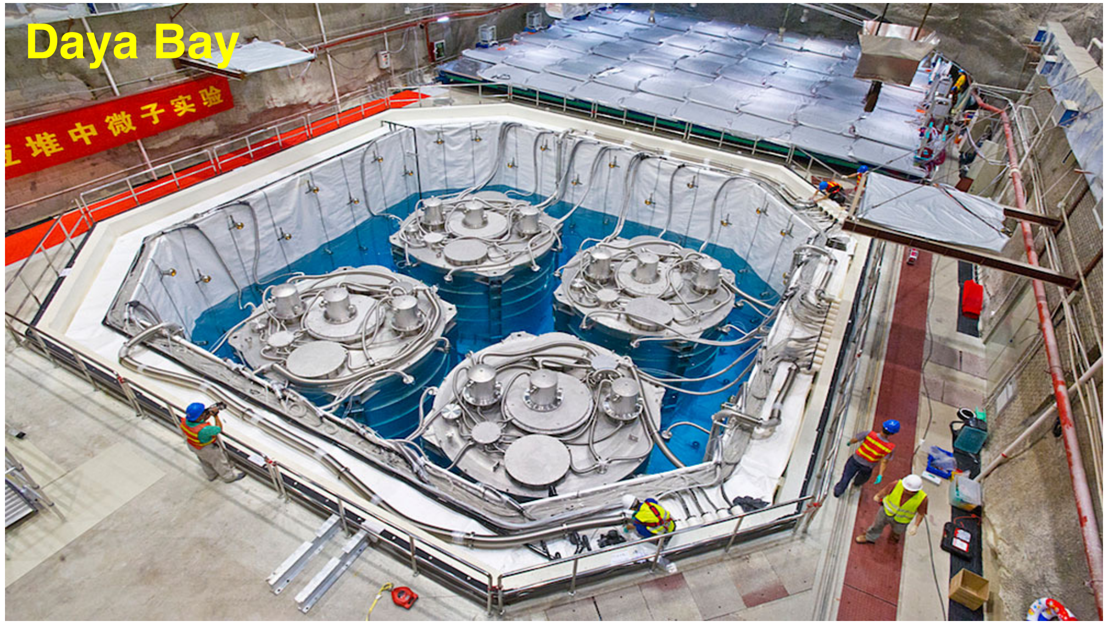
Phys. Rev. Lett. 131, 021802 (2023)

Joint Oscillation Analysis

- Motivated by previous joint analyses, and by the development of a multi-period analysis framework we propose a joint-oscillation analysis between Daya Bay, STEREO and PROSPECT.

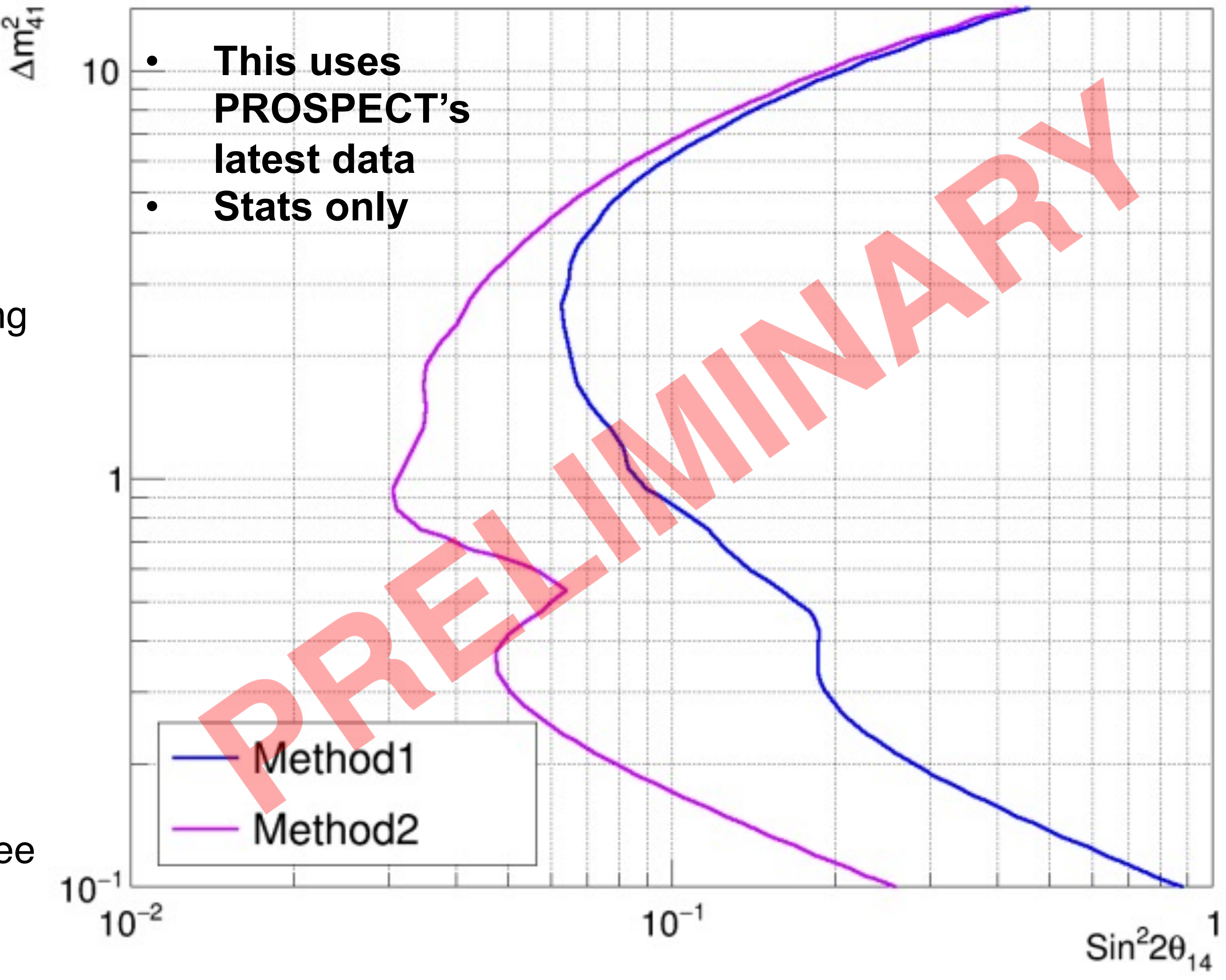
- PROSPECT:
  - Short baseline (7-9m) HEU-based reactor antineutrino experiment
- STEREO:
  - Short baseline (9-11m) HEU-based reactor antineutrino experiment
- Daya Bay:
  - Long baseline (~2km) LEU-based reactor antineutrino experiment



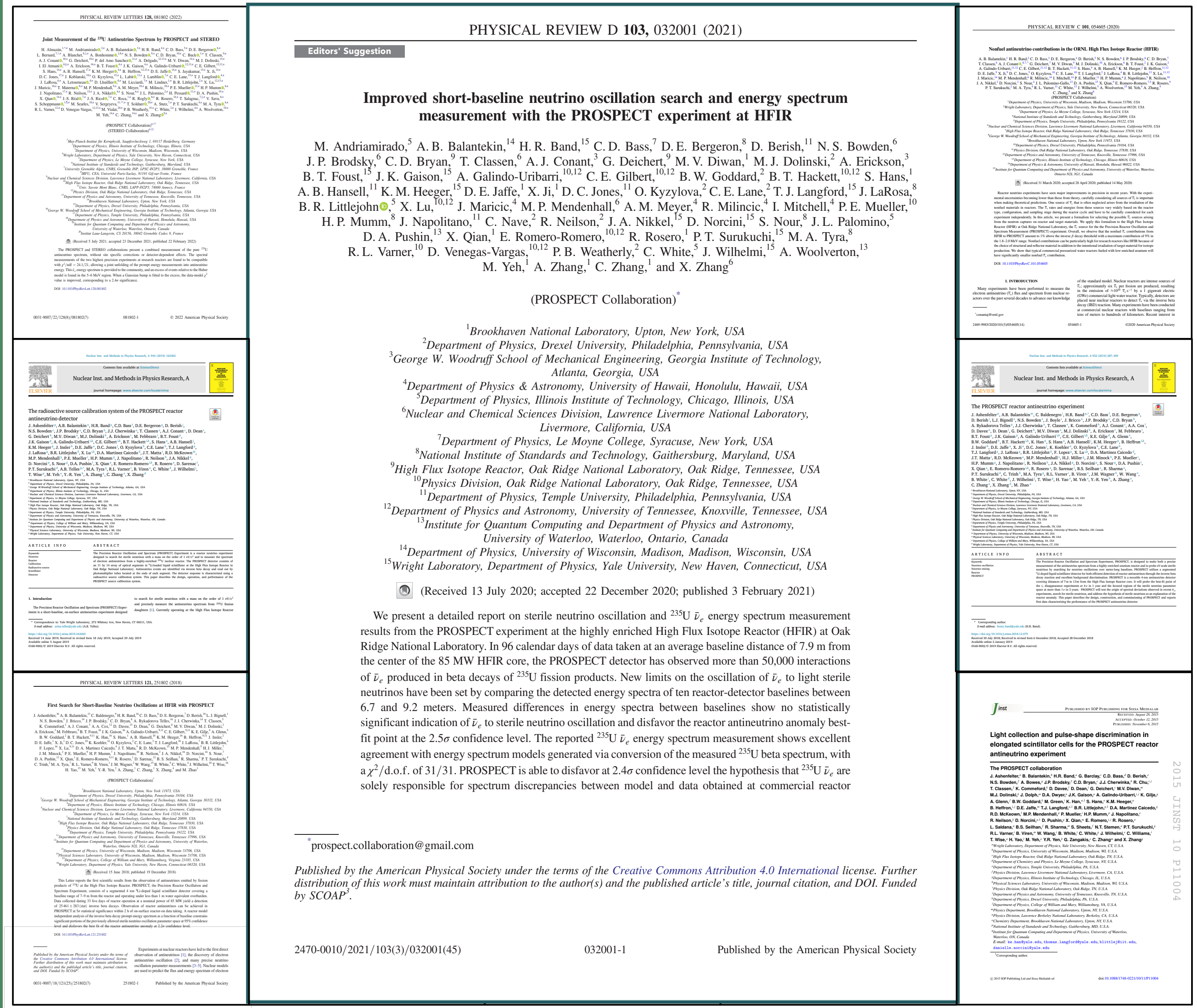


Joint Oscillation Analysis

- The combination of inputs from all three experiments provides improved sensitivity to different regions of Δm^2_{14}
- $\Delta m^2 < 10^{-3}\ eV^2$:
  - The oscillation period in the baseline is too long to observe. The three experiments have no sensitivity
- $\Delta m^2 \in [10^{-3}, 10^{-1}]\ eV^2$:
  - The result will be dominated by the Daya Bay experiment for its kilometer-long baseline
- $\Delta m^2 \in [10^{-1}, 10]\ eV^2$:
  - The result will be dominated by the STEREO and PROSPECT experiments.
- $\Delta m^2 > 10\ eV^2$
  - Survival probability is consistent across all three experiments



PROSPECT-I Previous Results-2021
- Oscillation and Spectrum


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

Editors' Suggestion

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

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

(PROSPECT Collaboration)*

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[15]Wright Laboratory, Department of Physics, Yale University, New Haven, Connecticut, USA

(Received 13 July 2020; accepted 22 December 2020; published 3 February 2021)

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

*prospect.collaboration@gmail.com

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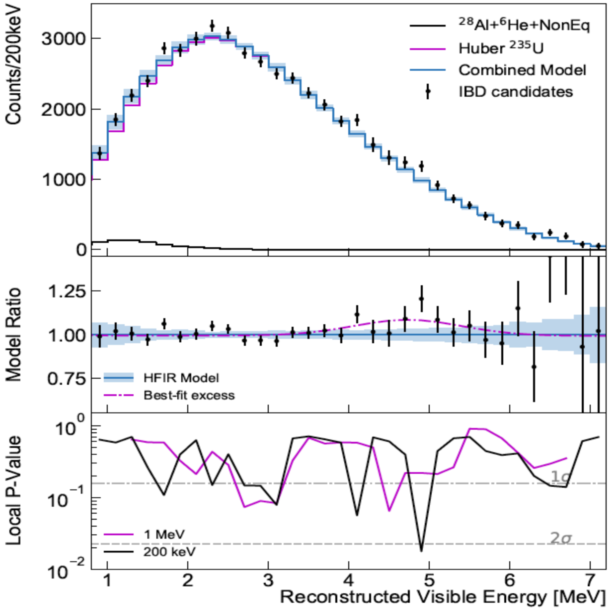
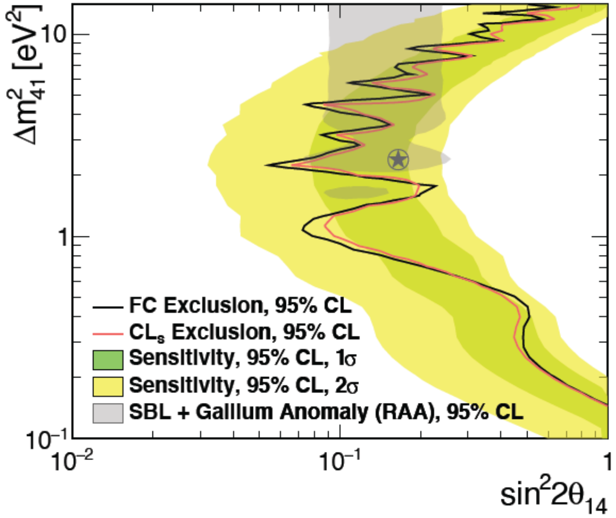
2470-0010/2021/103(3)/032001(45) 032001-1 Published by the American Physical Society

Prompt Energy Antineutrino Spectrum



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

Oscillation Exclusion Contours



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

PROSPECT - Motivation

Spectral Shape as a Function of Energy and Baseline

- Possibility of sterile neutrino oscillation as an explanation of observed electron antineutrino deficits
- Reactor-model independent search for sterile neutrinos at the eV-scale

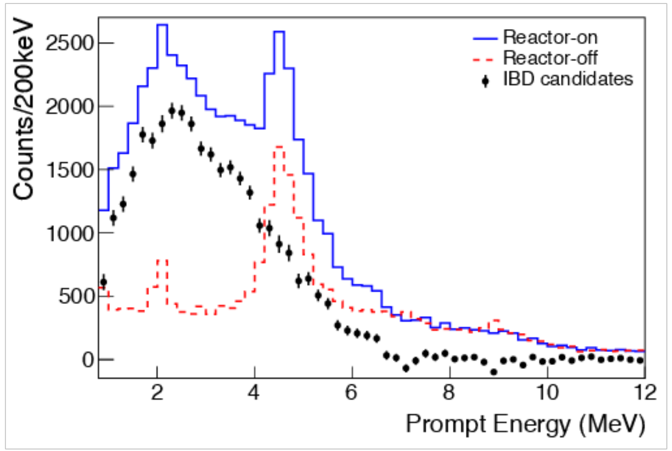
Precision Measurement of Reactor Spectrum

- Anomalies in spectral shape at ~ 5-6 MeV
- Provide complementary measurement of 235U (fuel evolution)

Safeguards - a Passive Standoff Capability

PROSPECT - Motivation

- Started taking data in March 2018
  - ✓ Detection of neutrinos at surface (HFIR)
  - ✓ First oscillation analysis (PRL) – published
  - ✓ First spectrum analysis (submitted to PRL)
- Updated oscillation + spectrum results
- Joint analysis with other experiments



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PROSPECT science results

Limits on Sub-GeV Dark Matter from the PROSPECT Reactor Antineutrino Experiment
M. Andriamirado et al. (PROSPECT Collaboration) submitted to PRD
arXiv:2104.11219

Improved Short-Baseline Neutrino Oscillation Search and Energy Spectrum Measurement with the PROSPECT Experiment at HFIR
M. Andriamirado et al. (PROSPECT Collaboration) PRD **103 (2021)** 032001 19

Nonfuel Antineutrino Contributions in the High Flux Isotope Reactor
A.B. Balantekin et al. (PROSPECT Collaboration) PRC 101 (2020) 054605 1

The Radioactive Source Calibration System of the PROSPECT Reactor Antineutrino Detector
J. Ashenfelter et al. (PROSPECT Collaboration) NIMA 944 (2019) 162465 3

Measurement of the Antineutrino Spectrum from 235U Fission at HFIR with PROSPECT
J. Ashenfelter et al. (PROSPECT Collaboration) PRL 122 (2019) 251801 26

A Low Mass Optical Grid for the PROSPECT Reactor Antineutrino Detector
J. Ashenfelter et al. (PROSPECT Collaboration) JINST 14 (2019) P04014 7

Lithium-loaded Liquid Scintillator Production for the PROSPECT Experiment
J. Ashenfelter et al. (PROSPECT Collaboration) JINST 14 (2019) P03026 14

The PROSPECT Reactor Antineutrino Experiment
J. Ashenfelter et al. (PROSPECT Collaboration) NIMA 922 (2018) 287 42

First search for short-baseline neutrino oscillations at HFIR with PROSPECT
J. Ashenfelter et al. (PROSPECT Collaboration) PRL 121 (2018) 251802 118

Performance of a segmented 6Li-loaded liquid scintillator detector for the PROSPECT experiment
J. Ashenfelter et al. (PROSPECT Collaboration) JINST 13 (2018) P06023 19

The PROSPECT physics program
J Ashenfelter et al. (PROSPECT Collaboration) Journal of Physics G: Nuclear and Particle Physics 43 (2016)113001 87

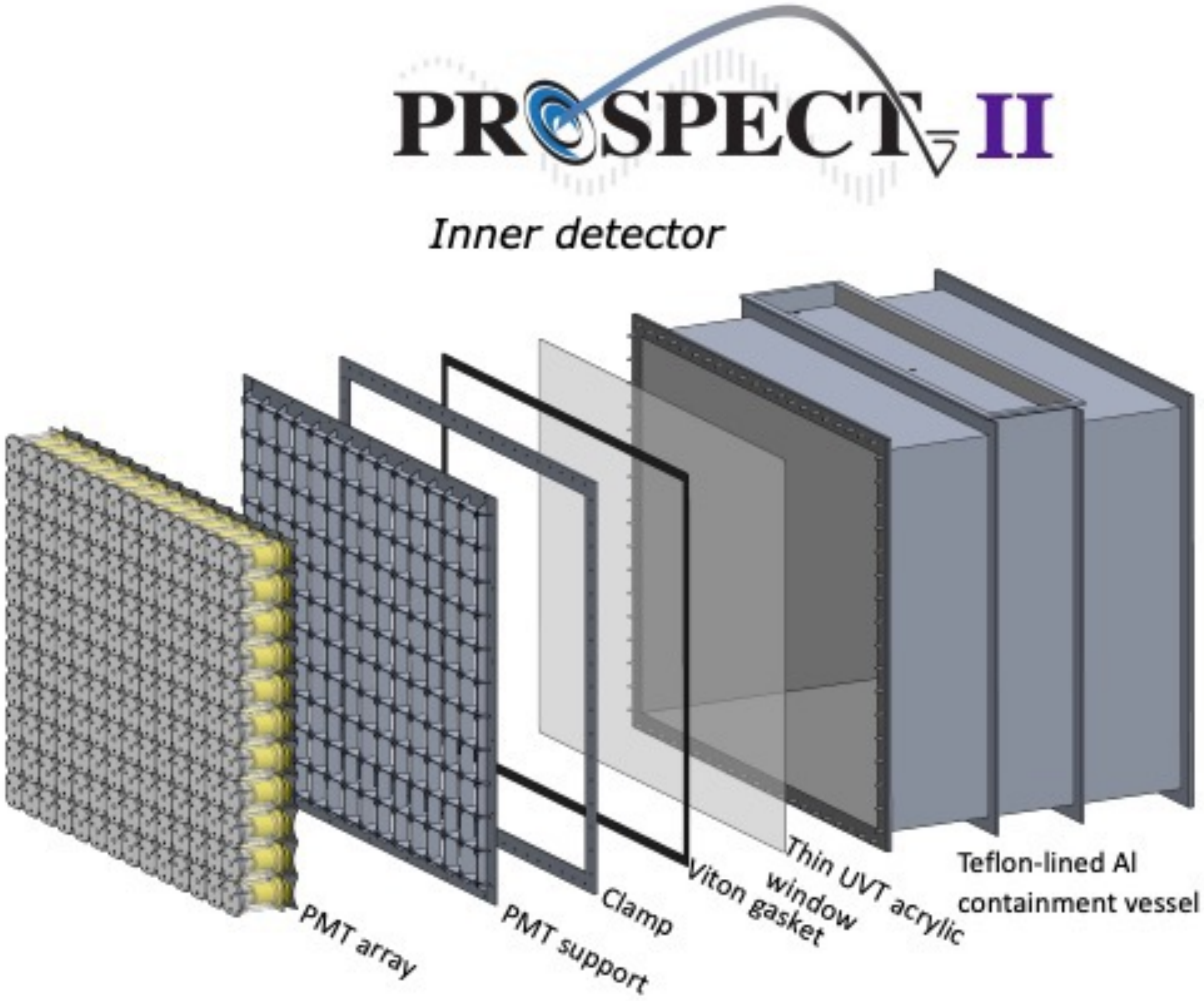
Background radiation measurements at high power research reactors
J. Ashenfelter et al. (PROSPECT Collaboration) NIMA 806 (2016) 401 29

Light collection and pulse-shape discrimination in elongated scintillator cells for the PROSPECT reactor antineutrino experiment
J. Ashenfelter et al. (PROSPECT Collaboration) JINST 10 (2015) P11004 20

~10 Papers on the works (ORNL lead writing role in 4)

Next Phase of PROSPECT

- Retains successful elements of PROSPECT-I: **segmented ^{6}Li-doped liquid scintillator with minimal shielding, located 7-9m from HEU core of HFIR** (+ possible LEU site)
- **Moves PMTs out of liquid scintillator volume**
- **Uses external calibration system** instead of calibration tubes inside active volume
- **Increases signal collection capacity** with 25% longer segments, 20% increased ^{6}Li fraction, longer data-taking period



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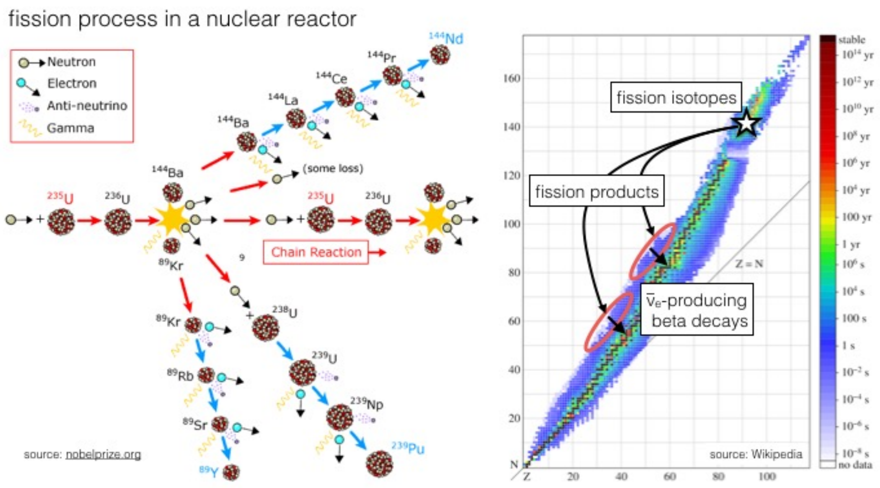
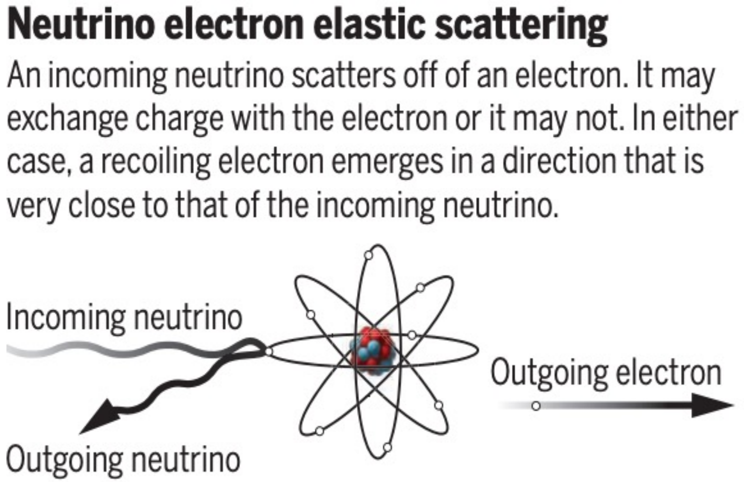
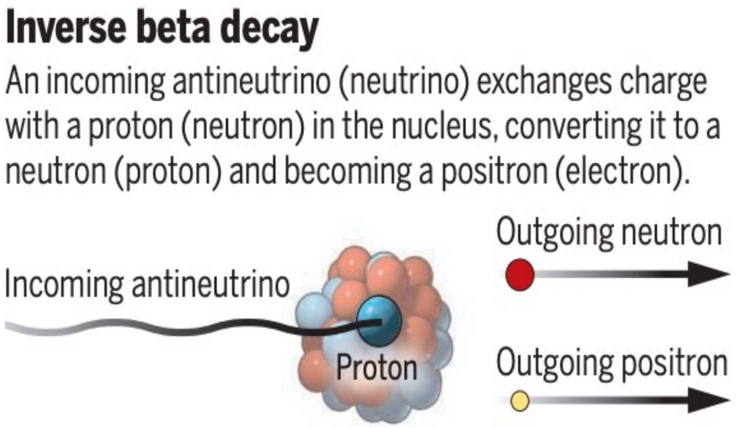
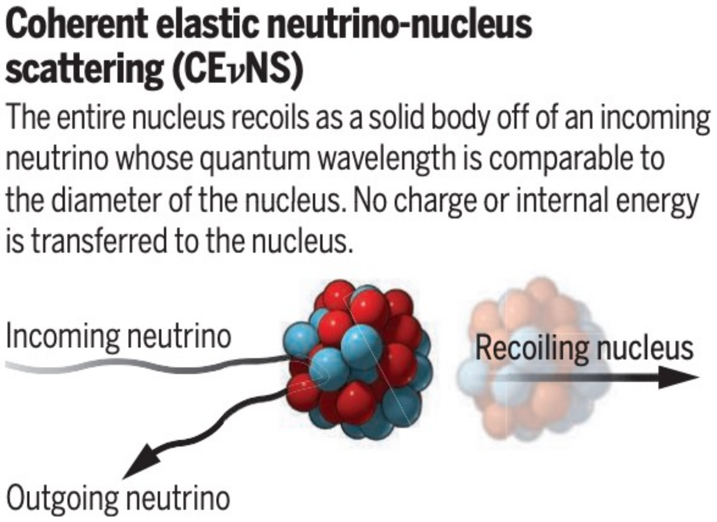
Common Types of Interactions for Reactor Neutrinos



- Nuclear reactors are the most intense terrestrial sources of neutrinos
- They produce an immense flux of antineutrinos in the MeV range.
- Flavor pure, only electron antineutrinos are produced
- Allow for proximity to the source, and it is usually paid by others







Link J M 2017 Scattering neutrinos caught in the act Science 357 1098–1099 URL https://www.science.org/doi/abs/10.1126/science.aao4050

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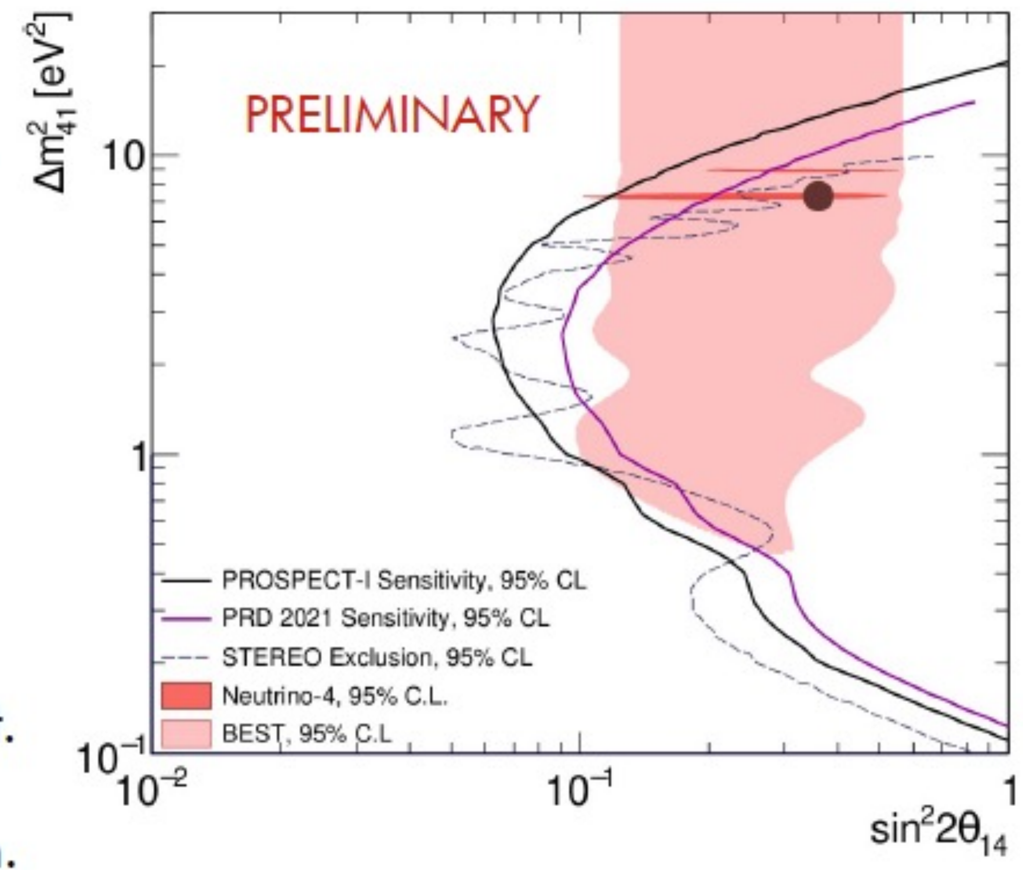
- Last step of the analysis, expect results to be published soon.
- Substantial improvement at high mass-splitting:
  - Address N-4 non-zero sterile neutrino oscillation observation
  - Cover BEST experiment allowed regions
  - Complement STEREO's latest result.
- Aim for a Phys. Rev. Letters publication.



- Several appearance and disappearance experiments observed anomalous results
- eV-scale sterile neutrinos invoked as a solution to the anomalies
- Experiments very diverse; different sources and detector technologies
- Several experiments already exclude regions of parameters space
- Need to invoke more complicated models if anomalies persist

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