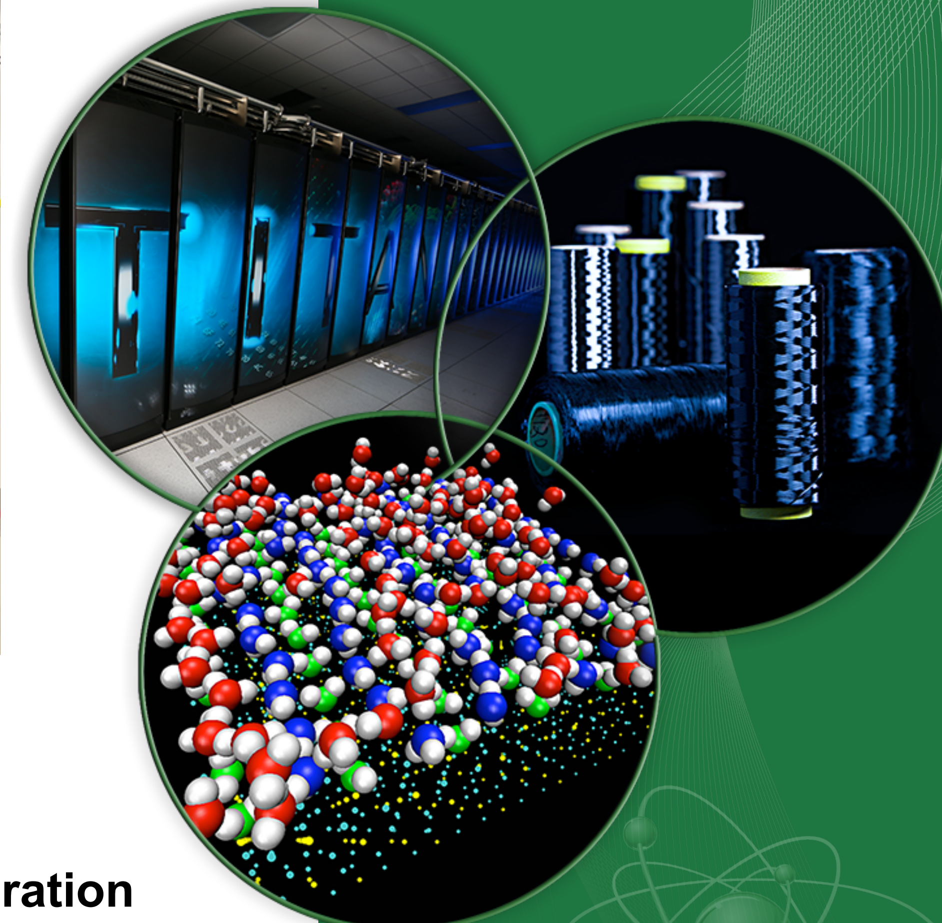
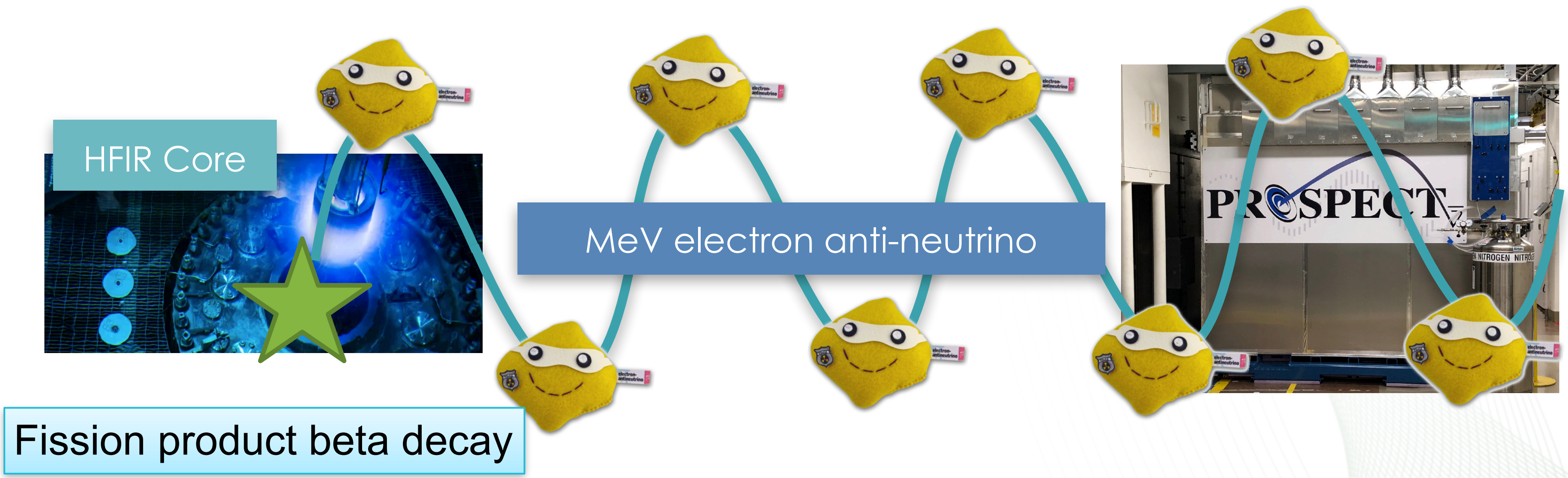


Jeremy Lu
On behalf of the PROSPECT collaboration

@NNPSS, July 18, 2019

Oak Ridge National Laboratory

The Precision Reactor Oscillation and SPECTrum Experiment



This Just In

2019 Director's S&T Award

INBOX × Important × Personal

Shared Monday, Jul 15, 1:14 PM

Good morning,

I am pleased to inform you that the PROSPECT collaboration has been selected for a 2019 Director's Science and Technology Award for the ***First Above Ground Detection of Reactor Antineutrinos by the PROSPECT Experiment***.

The S&T Awards acknowledge, celebrate and reward significant S&T accomplishments by Lawrence Livermore National Laboratory staff and their collaborators. The accomplishments honored by this award are those that have had a significant impact on the Laboratory by advancing scientific knowledge relevant to a core competency or mission, and/or those that represent a significant scientific breakthrough recognized both within the Laboratory and externally.

Team science is at the heart of how we approach advancement of science and technology and deliver on our mission challenges. In this award, we are particularly proud to recognize the entire PROSPECT collaboration: BNL, Drexel University, Georgia Institute of Technology, University of Hawaii, Illinois Institute of Technology, LLNL, Le Moyne College, NIST, ORNL, Temple University, University of Tennessee, University of Waterloo, University of Wisconsin, College of William and Mary, and Yale University.

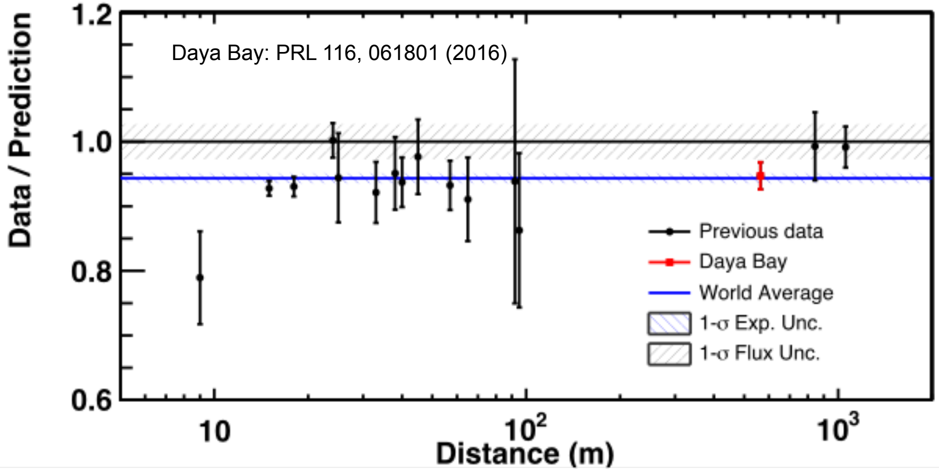
Congratulations!
Patricia K. Falcone
Deputy Director for Science and Technology
Lawrence Livermore National Laboratory

Congrats to the collaboration - this is the highest level award given at LLNL, to roughly 4 groups per year

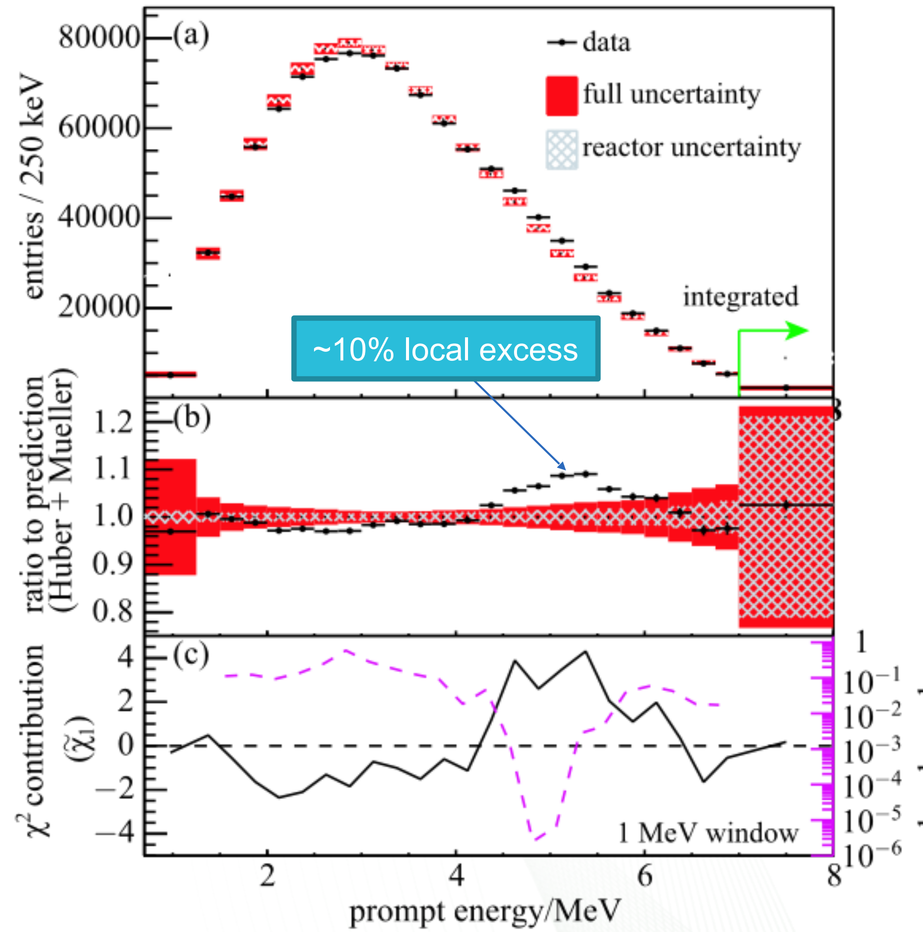
🎉 1 🍾 1

Motivation("Two clouds" in reactor neutrino physics)

Reactor Antineutrino Anomaly (RAA)



Spectral Shape Distortion



PROSPECT physics goals:

➢ Model-independent search for oscillations into eV-scale sterile neutrino

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

➢ Precise measurement of ^{235}U anti-neutrino spectrum

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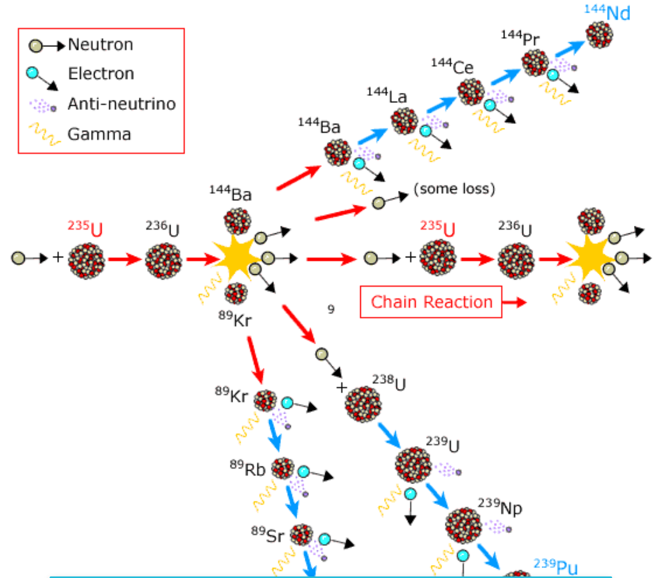
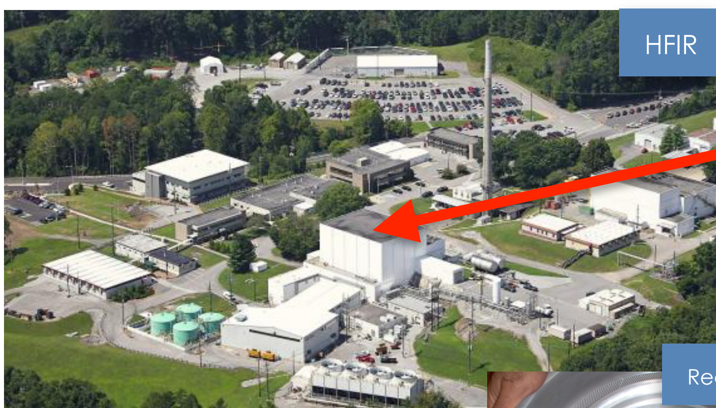
PROSPECT at HFIR

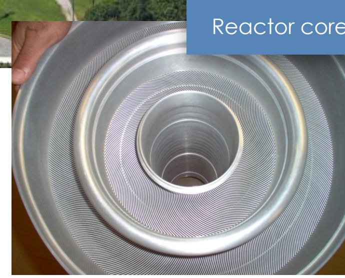
- High Flux Isotope Reactor (HFIR)
  - 85 MW research reactor
  - ~93% enriched ^{235}U fuel
  - >99% of anti-neutrinos emitted by ^{235}U fissions
  - Compact Core (h=0.6m d=0.4m)
  - close access
  - ~24 days reactor-on cycle
    - No ^{239}Pu buildup(<0.5%)

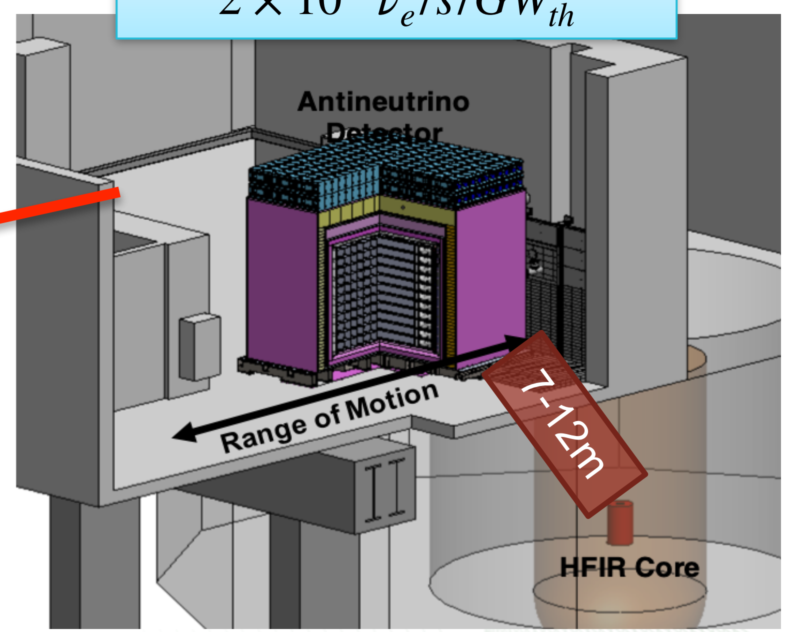


~ 6 anti-neutrino/fission

$$2 \times 10^{20} \bar{\nu}_e / s / GW_{th}$$



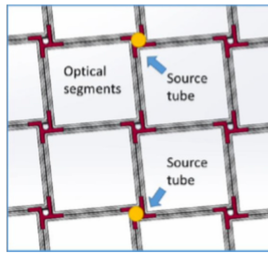


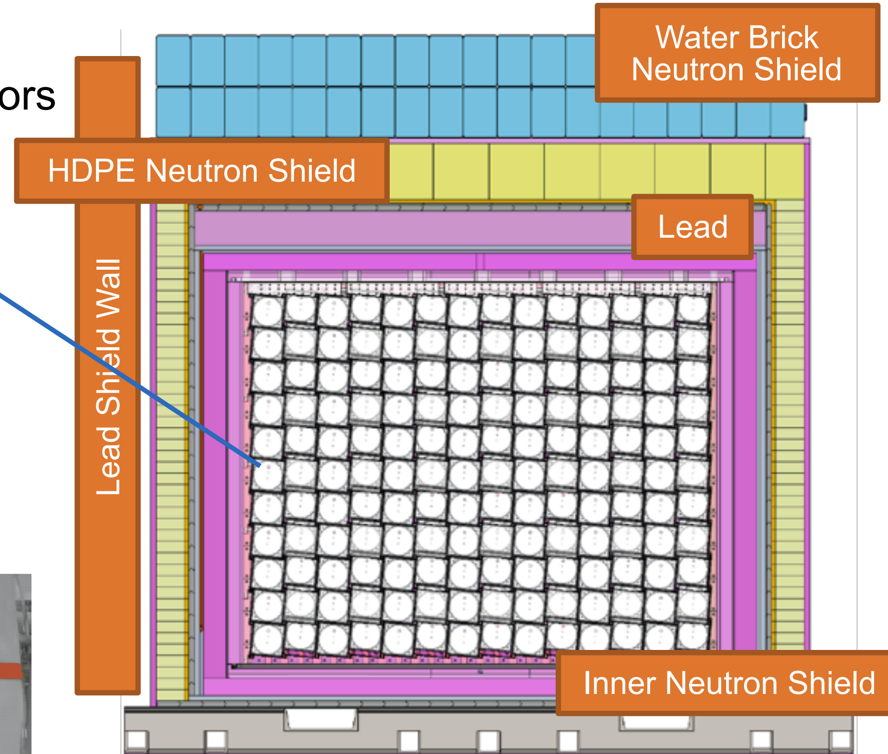


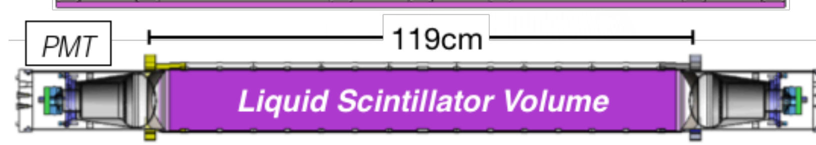
$$P_{dis} \simeq \sin^2 2\theta_{14} \sin^2\left(1.27\Delta m^2_{14}(\text{eV}^2)\frac{L(\text{m})}{E_\nu(\text{MeV})}\right)$$

Detector Overview

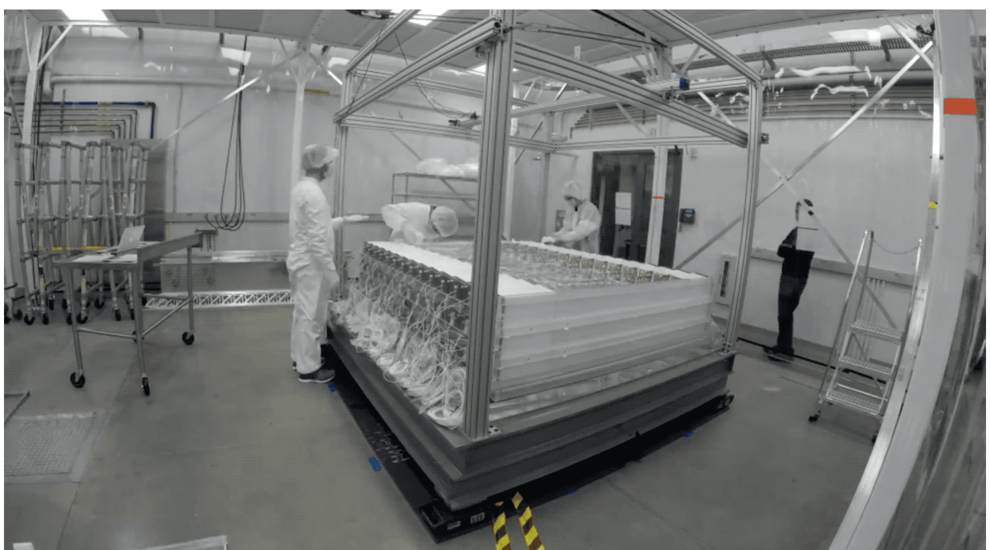
- ~4 ton ^{6}Li-loaded liquid scintillator detector
- Optically segmented into 14x11 identical detectors
- Double ended PMT readout
- Low mass separator
- Access for in-situ calibration
- energy resolution ~4.5% at 1 MeV
- ~100k anti-neutrinos detected/year, S:B ~ 3:1







Big Challenge : background suppression

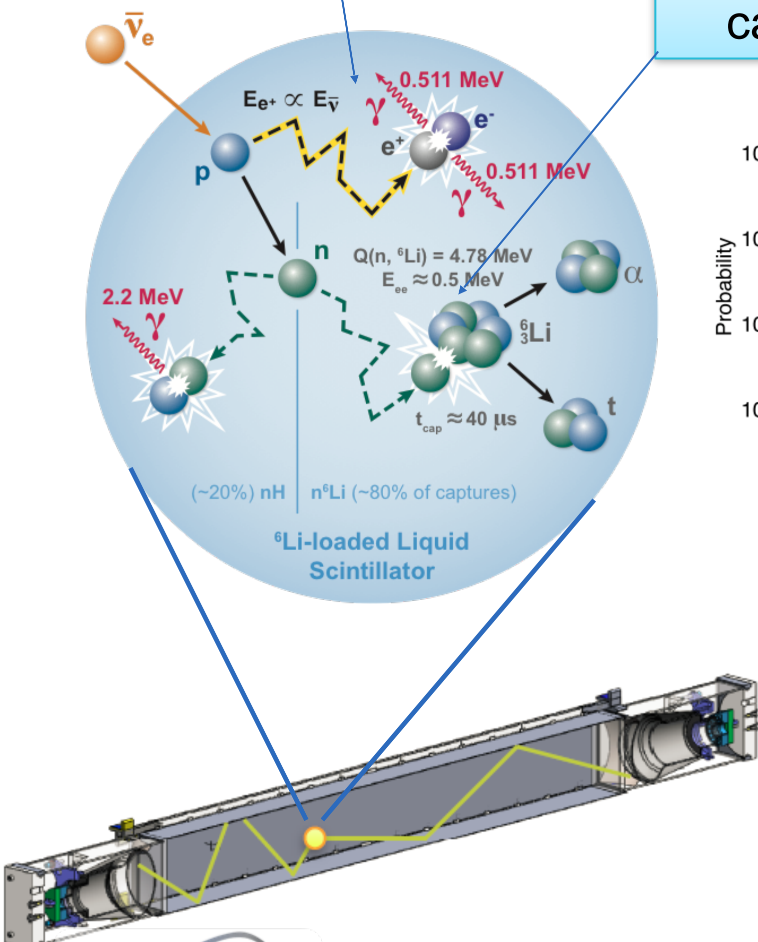


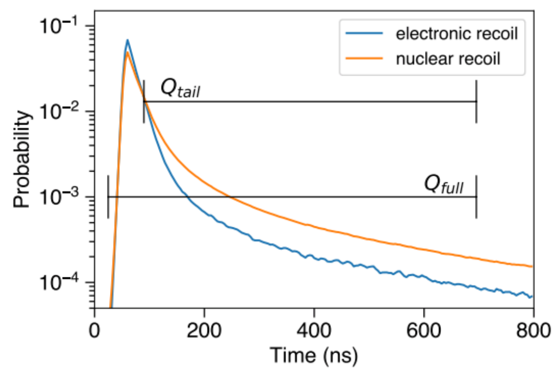
Inverse Beta Decay

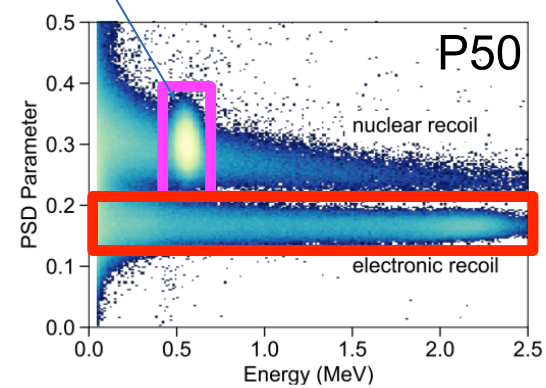
$$\bar{\nu}_e + p \rightarrow n + e^+$$

➢ Prompt signal: 1-10 MeV positron energy deposition

➢ Delayed signal: ~0.5 MeV from neutron capture on ^{6}Li







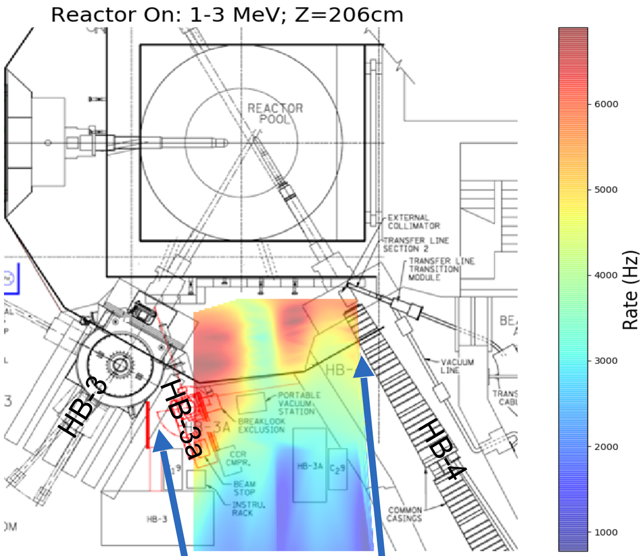
Pulse Shape Discrimination (PSD)

Customized EJ-309-based ^{6}LiLS gives excellent PSD performance

- background suppression and IBD pair event identification.
- - Background anti-neutrino - accidentals

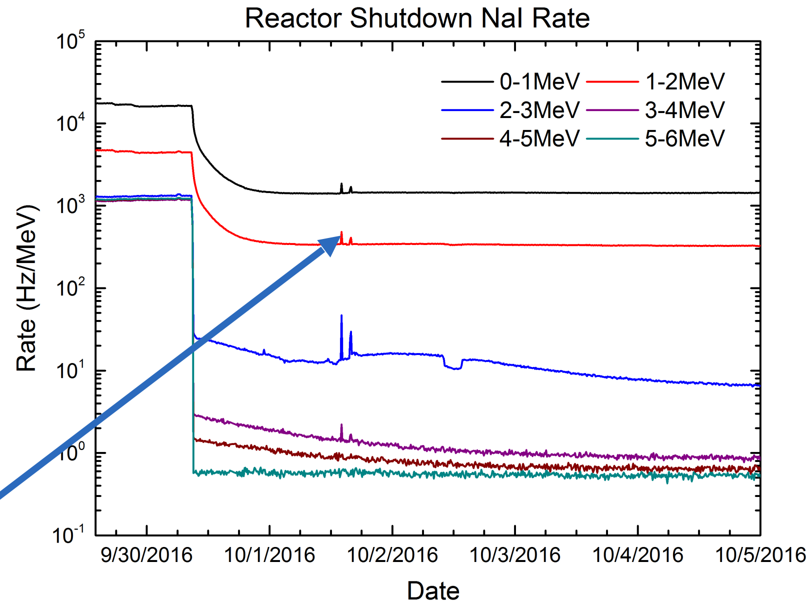
PROSPECT arXiv:1805.09245

Background Characterization



DANG

Figure 3.3: DANG: Detector Array for Neutron and Gamma detection.



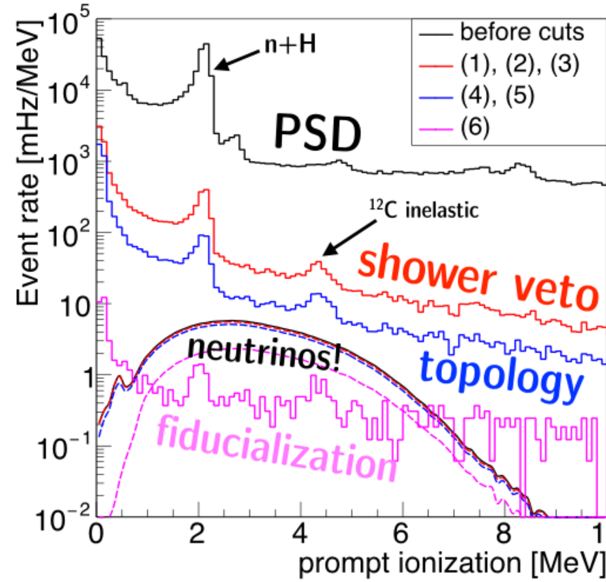
Identify hotspots from beamline underneath.

Sensitive to reactor operation such as fuel removal.

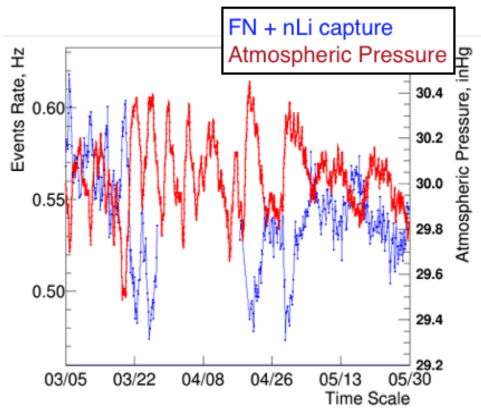
Blaine Heffron & Brennan Hackett Master's Thesis, UTK

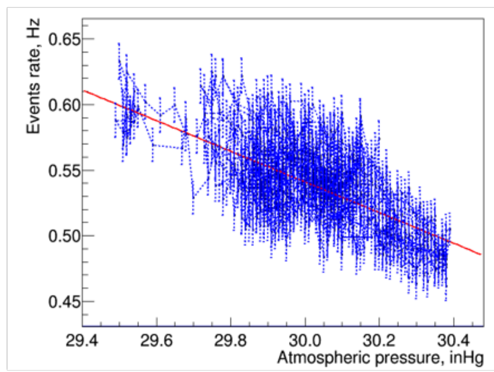
Cosmogenic Background

PROSPECT J. Phys. G: 43 (2016)

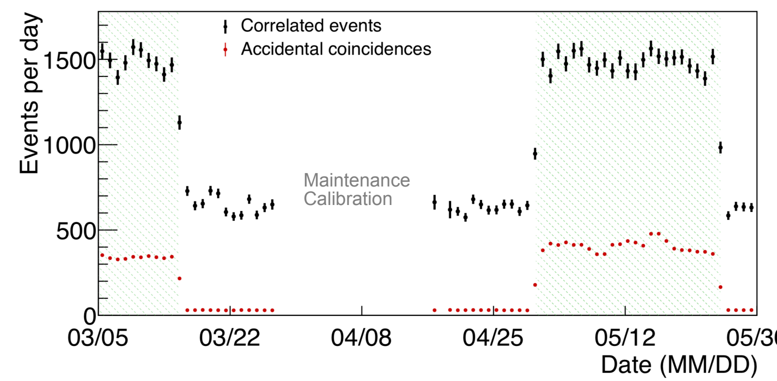


With PSD technique, shower veto, event topology and fiducialization, background noise can be greatly suppressed by order of magnitude of 4.





- Correlation between cosmogenic background and atmospheric pressure.
- Correct background subtraction for reactor-on.



33 days of reactor on
28 days of reactor off
Average of 750 IBD/day

10.1103/PhysRevLett.121.251802

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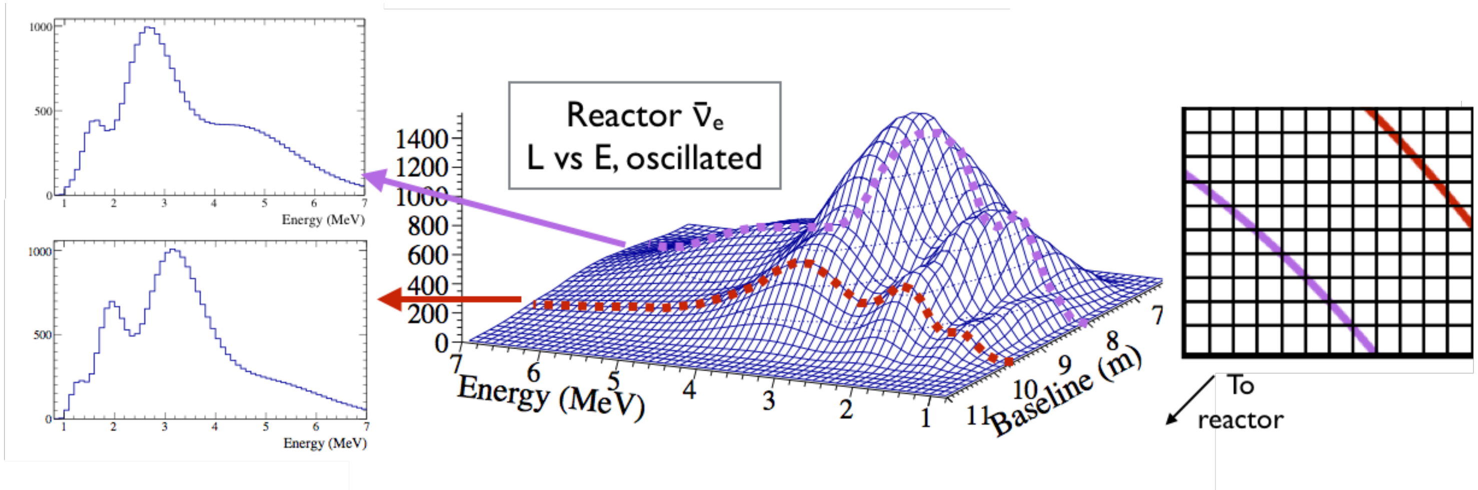
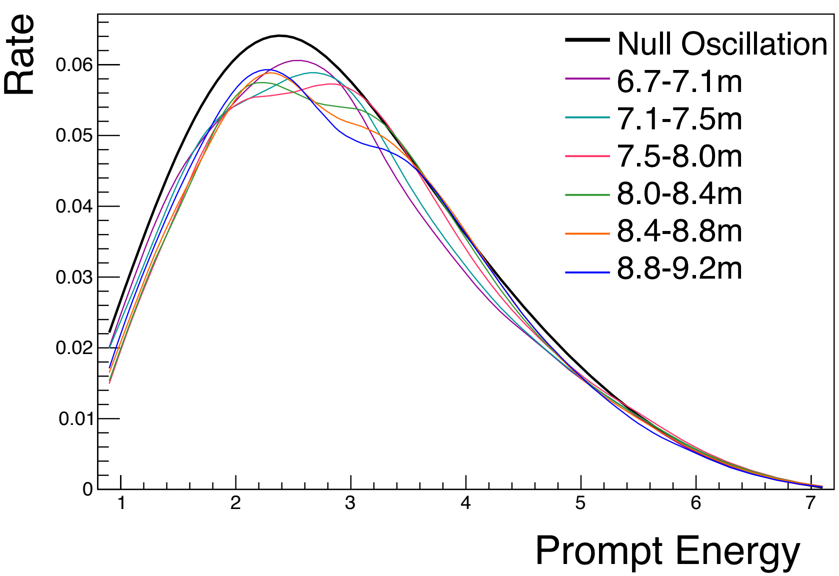
Segmentation technique

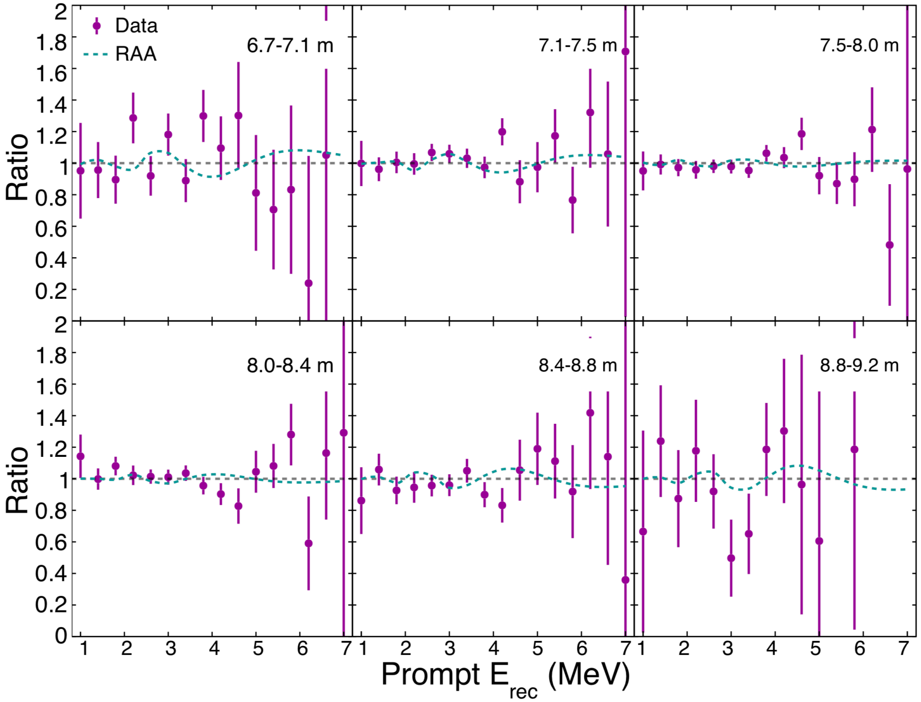


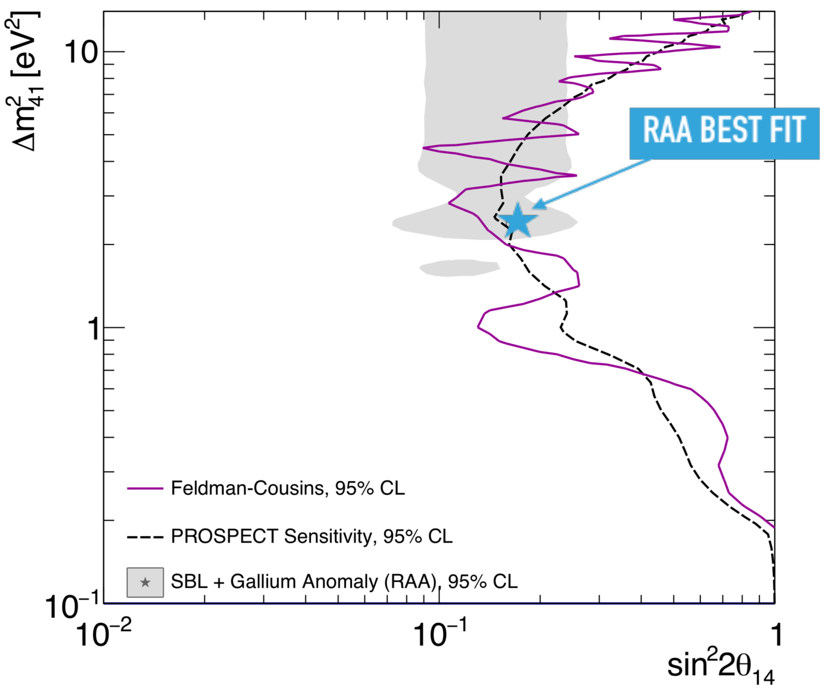


- Spectra relative difference due to additional sterile neutrino oscillation.
- Model-independent study with relative ratio of the spectra in each baseline to the baseline-integrated spectrum.

Oscillation Results

Disfavors reactor antineutrino anomaly best fit point at >95% (2.3σ)





- χ^2 test for each point $(\Delta m^2, \sin^2 2\theta_{14})$ in parameter space to get exclusion curve.

- Feldman Cousins method
- Covariance matrix for each uncertainty

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10.1103/PhysRevLett.121.251802

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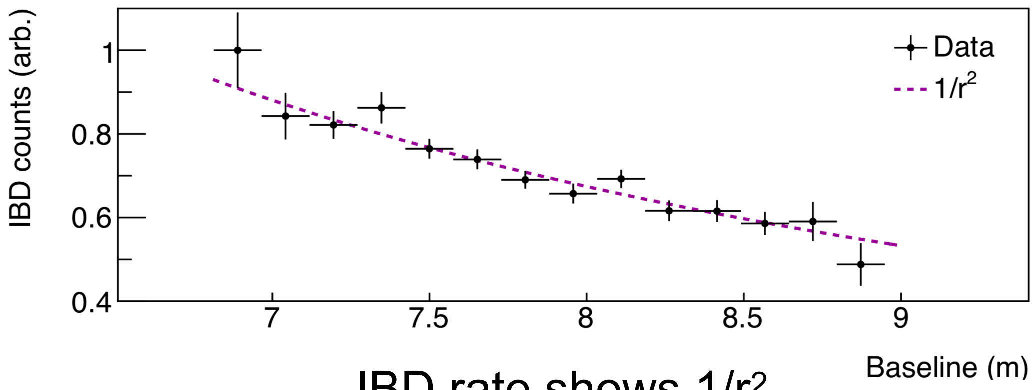
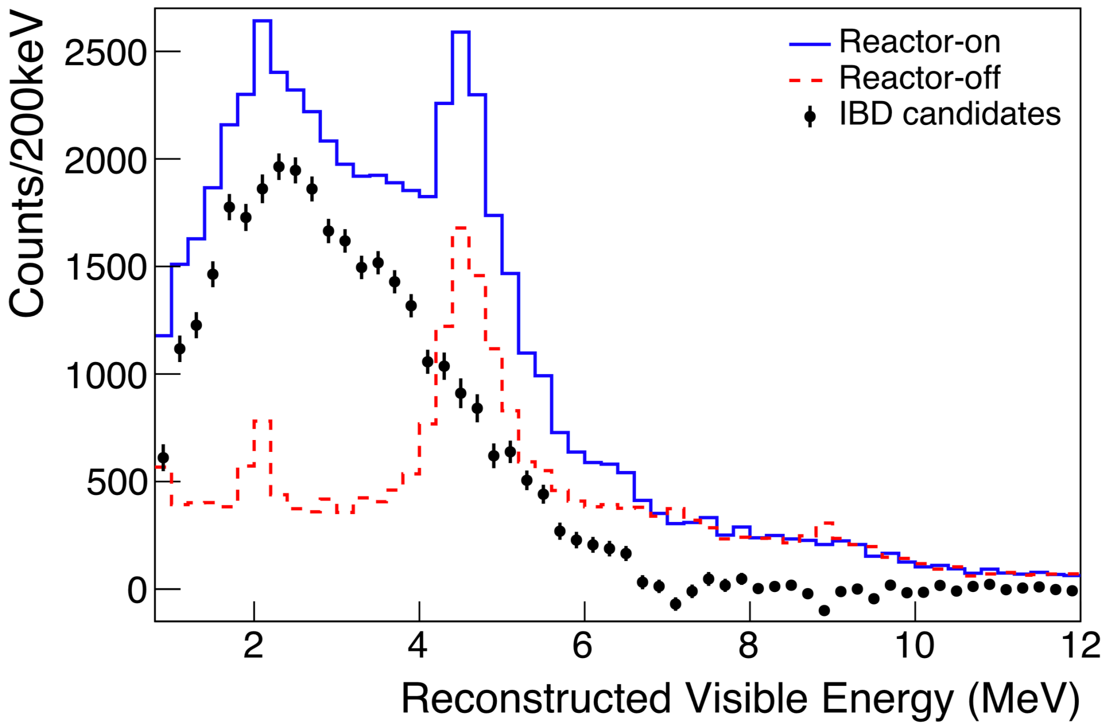
Spectrum Results

40.3 exposure-day Reactor-On
37.8 exposure-day Reactor-Off



IBD rate shows $1/r^2$

10.1103/PhysRevLett.121.251802



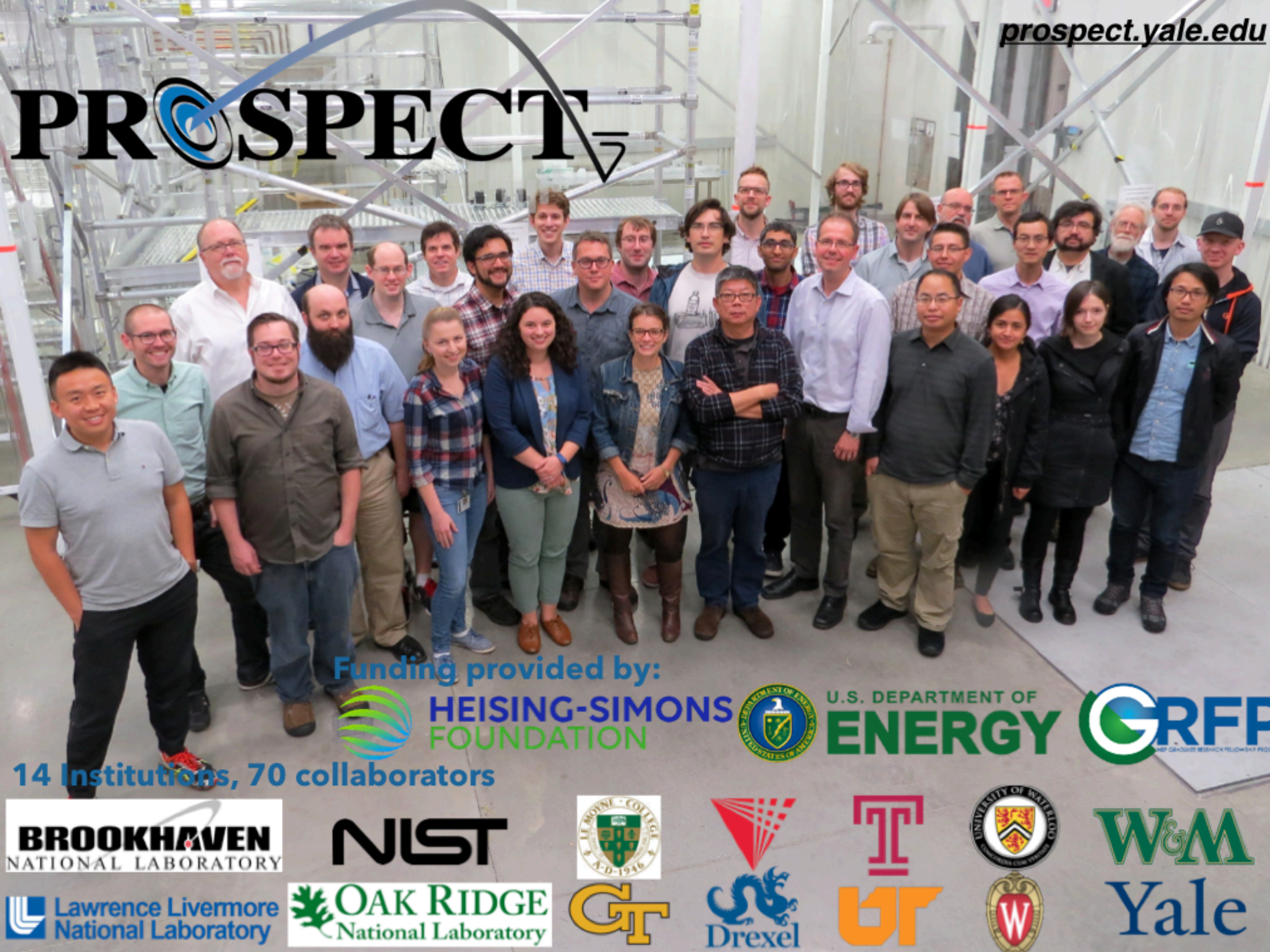
IBD events =
ReactorOn - ReactorOff

^{235}U being the solo cause of observed LEU spectral distortion is disfavored at 2.1σ

10.1103/PhysRevLett.122.251801

Conclusion

- World-leading&powerful on-surface anti-neutrino detector has been installed at HFIR. IBD is used to detect anti-neutrinos.
- Having minimal overburden, backgrounds are thoroughly examined.
- First oscillation analysis disfavors RAA best-fit at 2.3σ based on 33 days reactor-on data.
- First high-statistics measurement of ^{235}U IBD spectrum is reported.
- The detector is performing well and working towards high-statistics ^{235}U spectrum measurement.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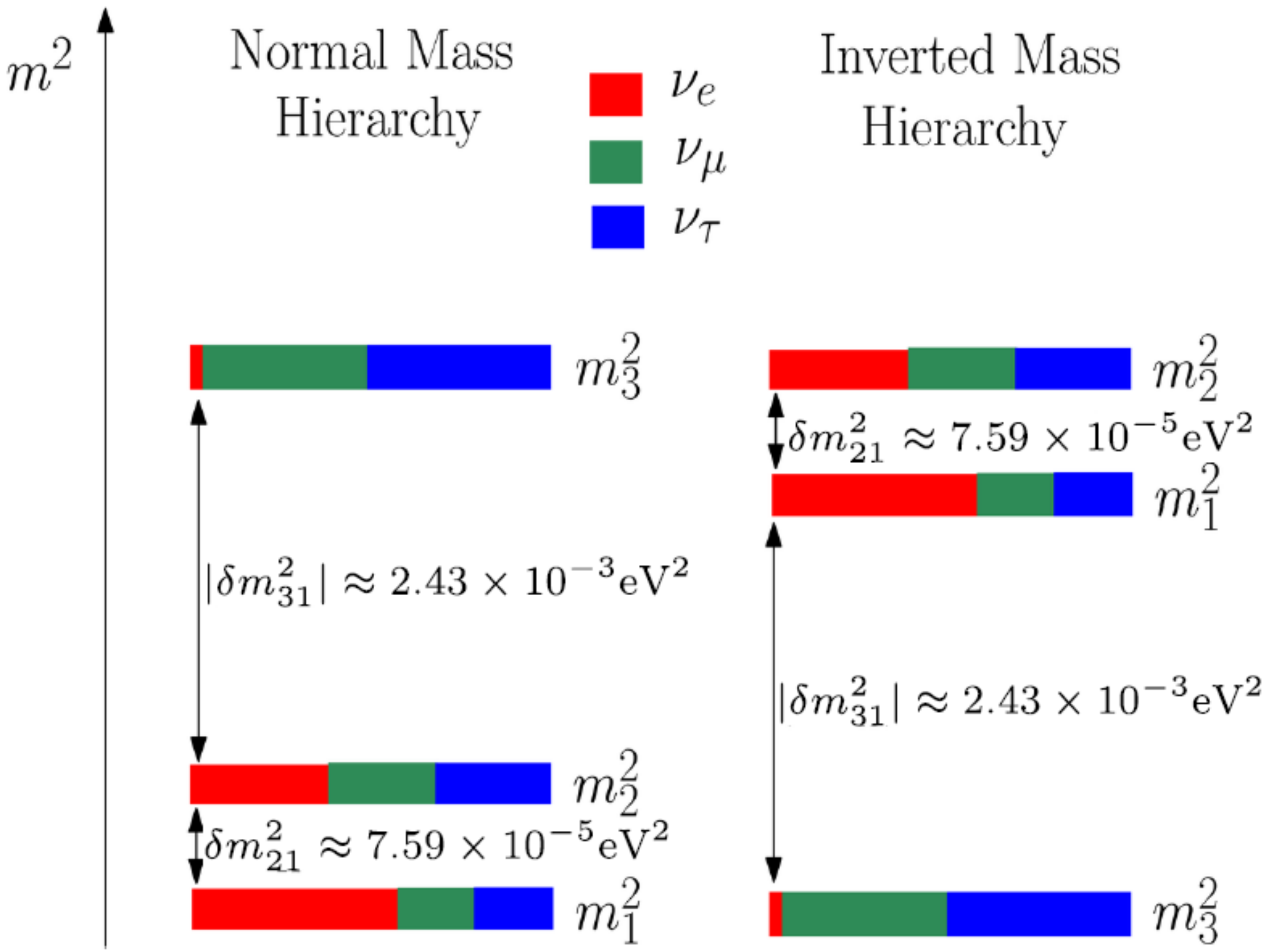
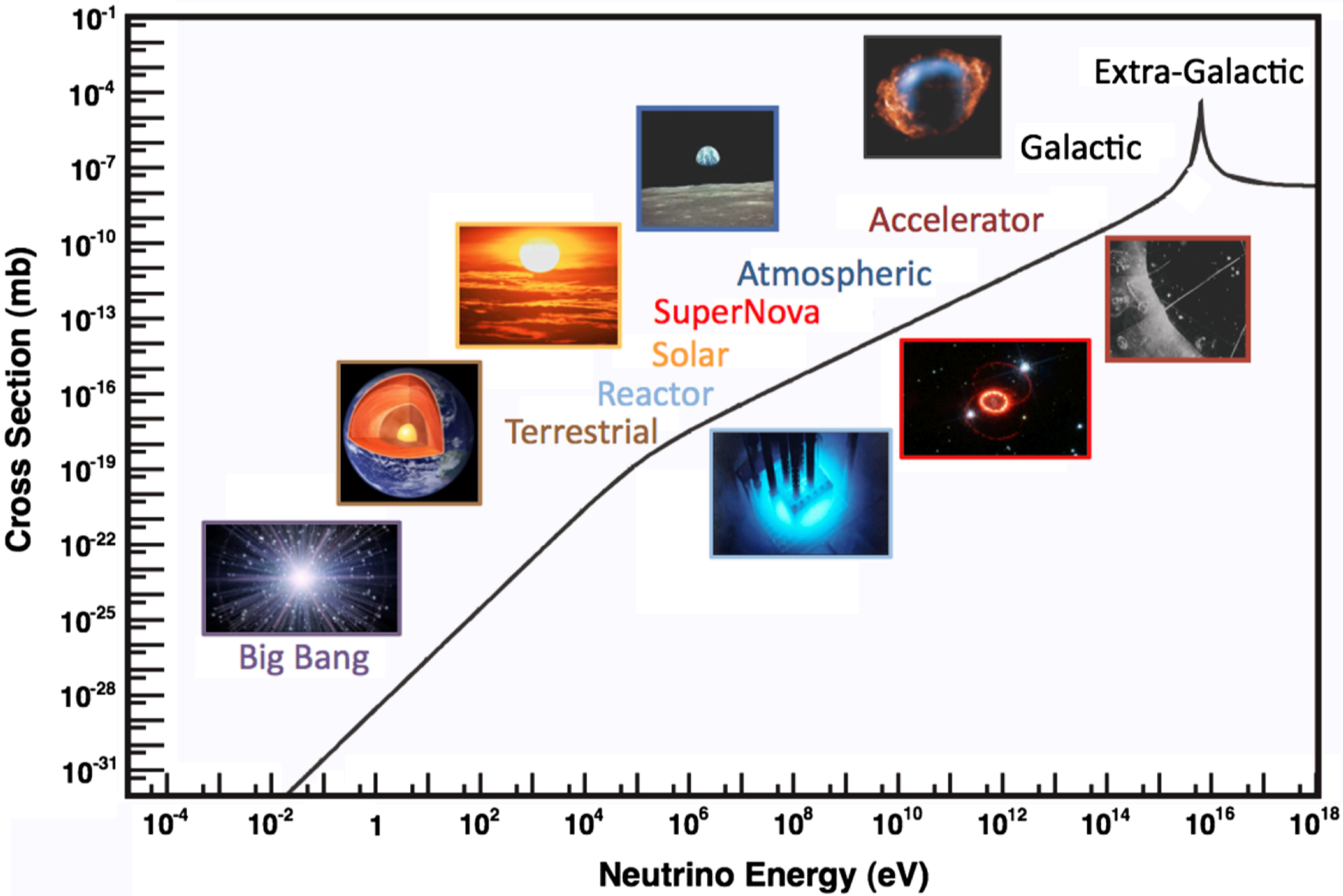
PROSPECT
Funding provided by:
HEISING-SIMONS FOUNDATION
U.S. DEPARTMENT OF ENERGY
GRFP
14 Institutions, 70 collaborators
BROOKHAVEN NATIONAL LABORATORY
NIST
W&M
Lawrence Livermore National Laboratory
OAK RIDGE National Laboratory
Drexel
Yale

Backup slides



Backup slides



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Backup slides

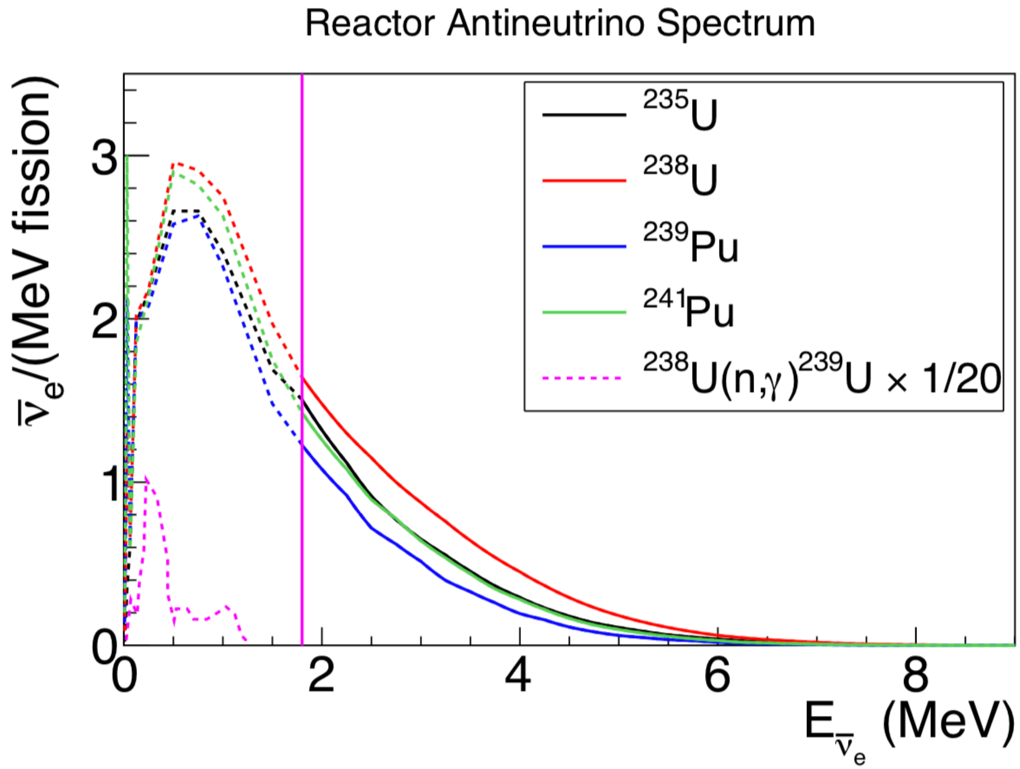


Figure 1. The $\bar{\nu}_e$ energy spectra for ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu fissions. Above the inverse beta decay (IBD) threshold (marked by the vertical line), spectra from Ref. [46, 47] are shown. Below the IBD threshold, spectra are plotted based on Table II of Ref. [48]. Fine structures at the end points of various decay branches cannot be seen, given the coarse binning. In addition, we show the antineutrino spectrum produced by neutron capture on ^{238}U (taken from Ref. [49]), which is normalized properly relative to the ^{238}U fission and scaled down by a factor of 20 for the display.

Backup slides

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

Propagation and interference [edit]

Since $|\nu_i\rangle$ are mass eigenstates, their propagation can be described by plane wave solutions of the form

$$|\nu_i(t)\rangle = e^{-i\left(E_i t - \vec{p}_i \cdot \vec{x}\right)} |\nu_i(0)\rangle ,$$

where

- quantities are expressed in natural units $(c = 1, \hbar = 1)$
- E_i is the energy of the mass-eigenstate i,
- t is the time from the start of the propagation,
- $\vec{p}_i$ is the three-dimensional momentum,
- $\vec{x}$ is the current position of the particle relative to its starting position

In the ultrarelativistic limit, $|\vec{p}_i| = p_i \gg m_i$, we can approximate the energy as

$$E_i = \sqrt{p_i^2 + m_i^2} \simeq p_i + \frac{m_i^2}{2p_i} \approx E + \frac{m_i^2}{2E},$$

where *E* is the total energy of the particle.

This limit applies to all practical (currently observed) neutrinos, since their masses are less than 1 eV and their energies are at least 1 MeV, so the Lorentz factor, γ, is greater than
factors, the wavefunction becomes:

$$|\nu_i(L)\rangle = e^{-i\frac{m_i^2 L}{2E}} |\nu_i(0)\rangle .$$

Eigenstates with different masses propagate with different frequencies. The heavier ones oscillate faster compared to the lighter ones. Since the mass eigenstates are combination corresponding flavor components of each mass eigenstate. Constructive interference causes it to be possible to observe a neutrino created with a given flavor to change its flavor c as having flavor *β* is

$$P_{\alpha\to\beta} = |\langle \nu_\beta(L) | \nu_\alpha \rangle|^2 = \left| \sum_i U_{\alpha i}^* U_{\beta i} e^{-i\frac{m_i^2 L}{2E}} \right|^2 .$$

This is more conveniently written as

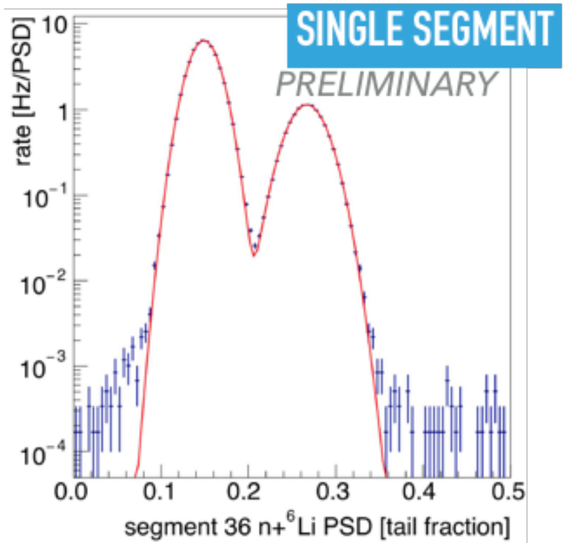
$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*\right) \sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right) + 2\sum_{i>j} \mathrm{Im}\left(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*\right) \sin\left(\frac{\Delta m_{ij}^2 L}{2E}\right),$$

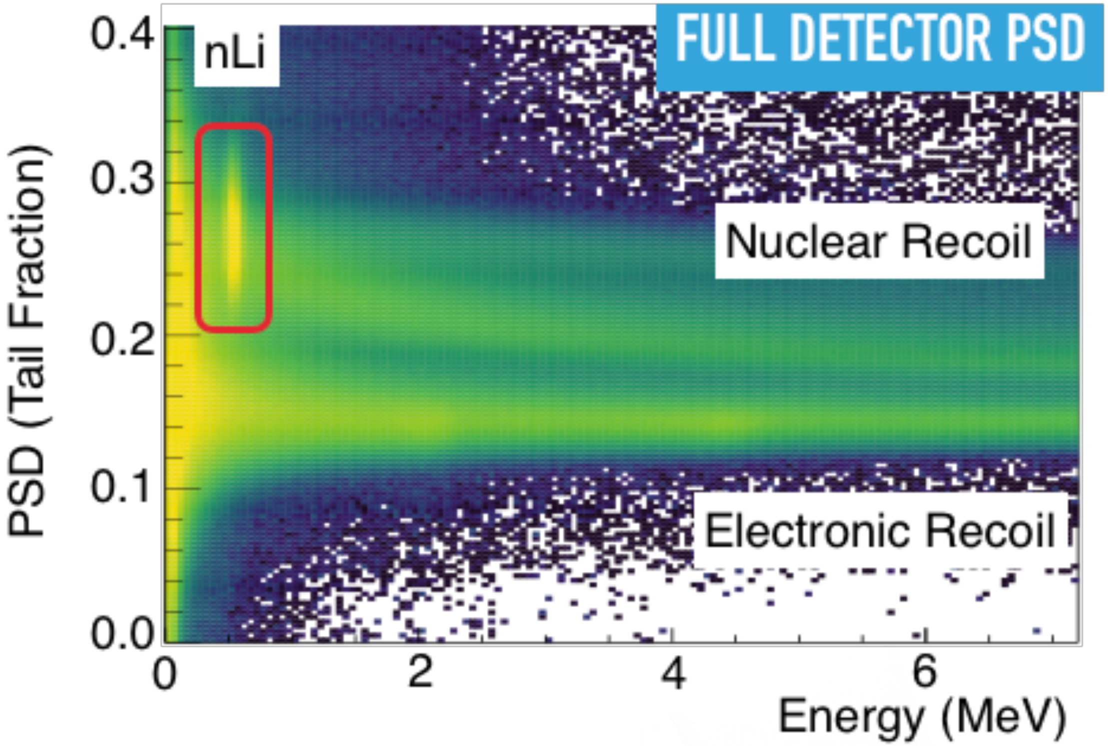
where $\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$. The phase that is responsible for oscillation is often written as (with *c* and $\hbar$ restored)

$$\frac{\Delta m^2\, c^3\, L}{4\hbar E} = \frac{\mathrm{GeV\,fm}}{4\hbar c} \times \frac{\Delta m^2}{\mathrm{eV}^2} \frac{L}{\mathrm{km}} \frac{\mathrm{GeV}}{E} \approx 1.27 \times \frac{\Delta m^2}{\mathrm{eV}^2} \frac{L}{\mathrm{km}} \frac{\mathrm{GeV}}{E},$$

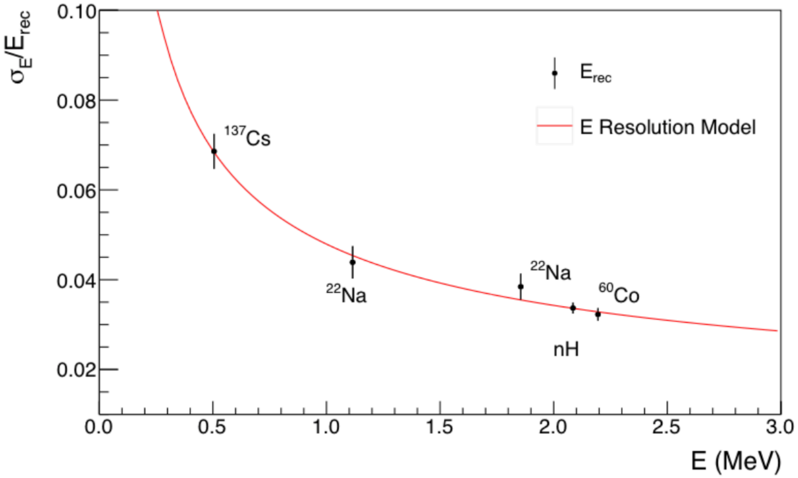
where 1.27 is unitless. In this form, it is convenient to plug in the oscillation parameters since:

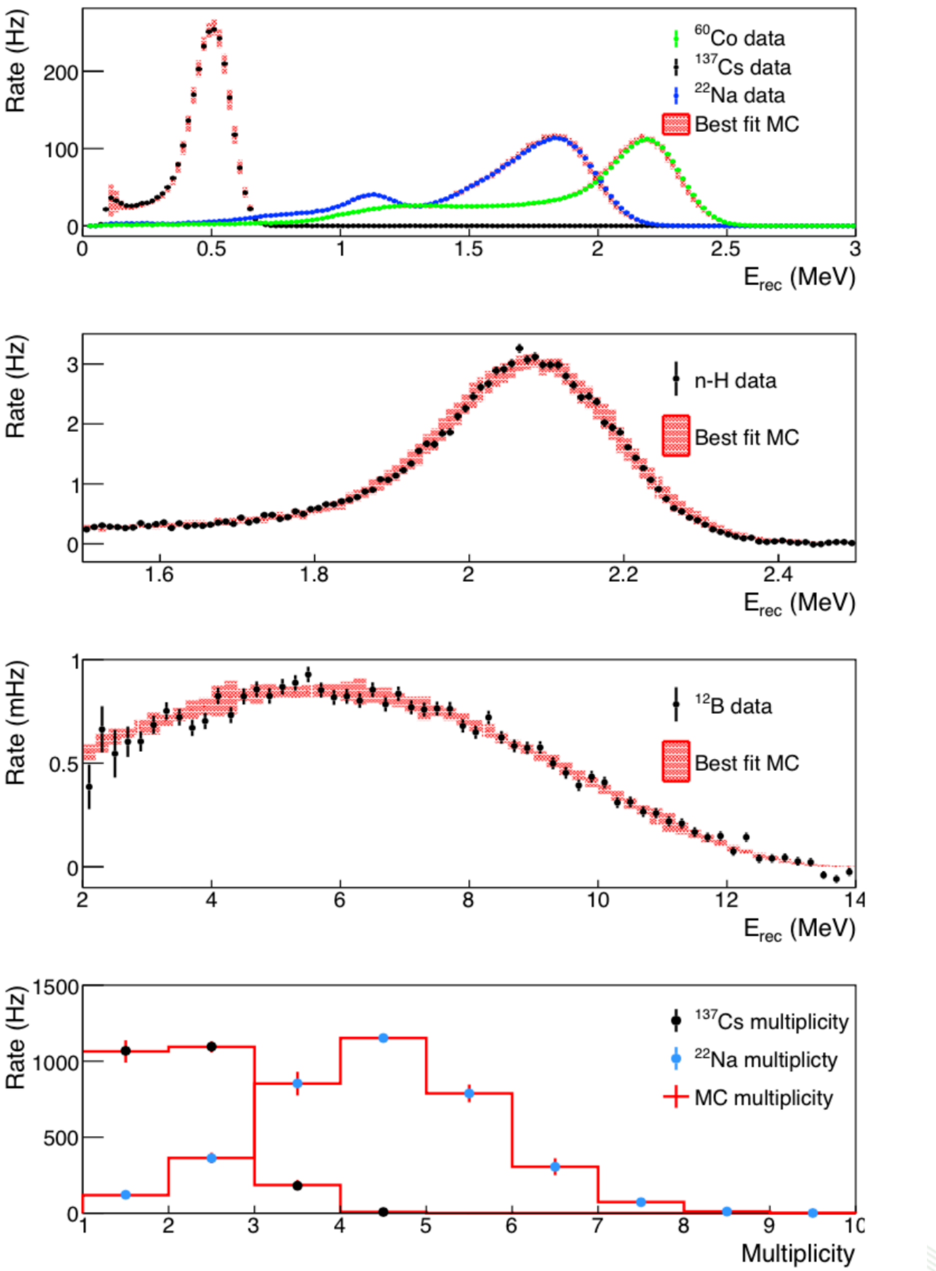
PSD performance





Energy Calibration





Bump Study

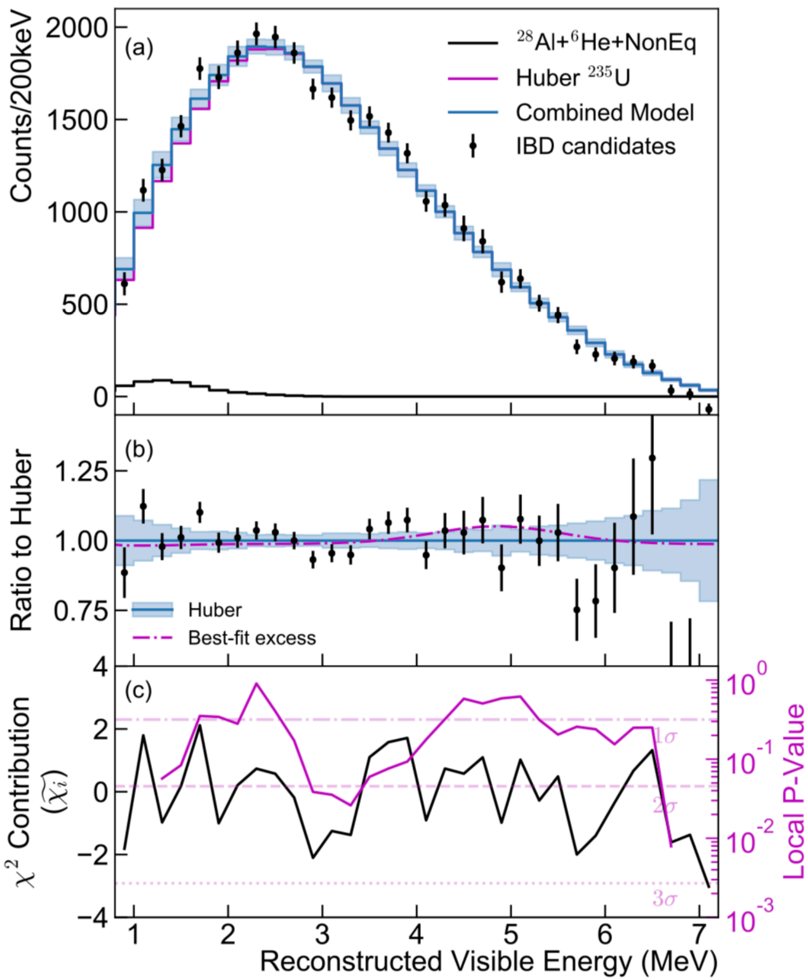


FIG. 5. (a): The measured prompt energy spectrum of inverse beta decay events compared to prediction based on the Huber ^{235}U model combined with contributions from ^{28}Al, ^{6}He, and non-equilibrium isotopes in the core. The error bars include only statistical uncertainties, while the shaded band includes detector and model uncertainties. (b): Ratio to the Huber model of the measured data and the best-fit distortion representing the spectral discrepancy observed by experiments at LEU reactors. (c): The χ^2 contribution from each bin and the local p-value of a 1 MeV-wide sliding energy window.