The Physics Potential of Advanced Short-Baseline Reactor Neutrino Detectors

December 12, 2019

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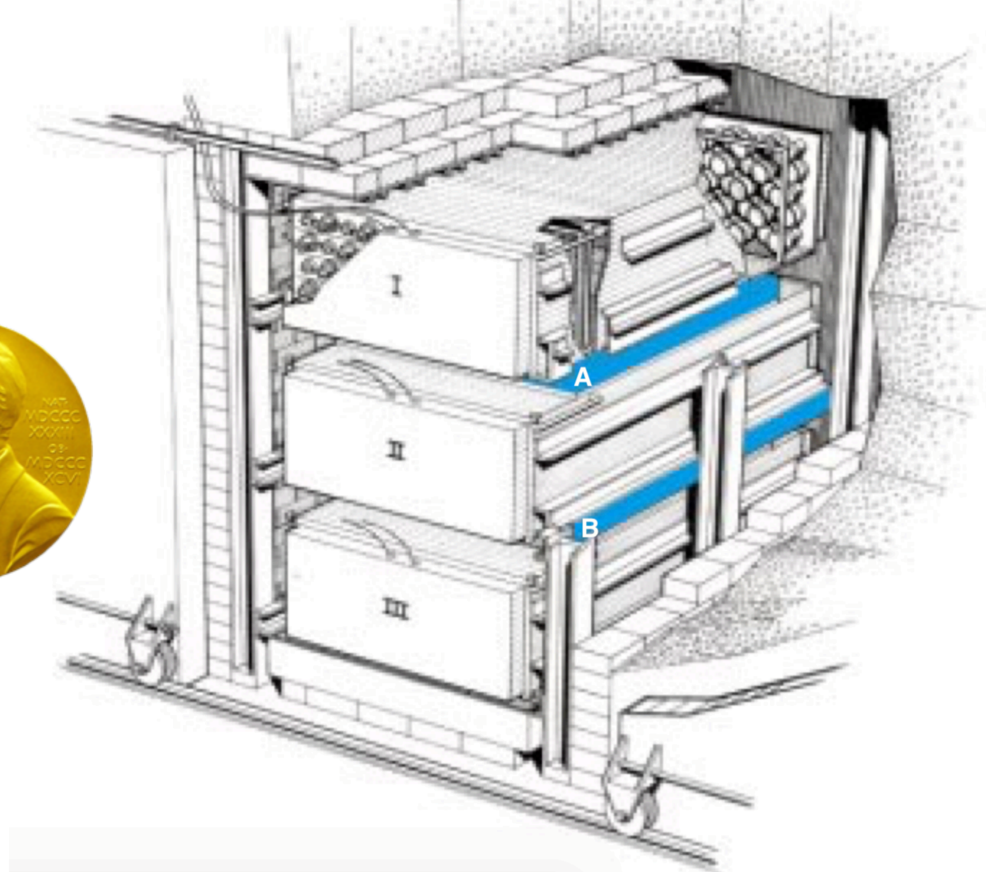
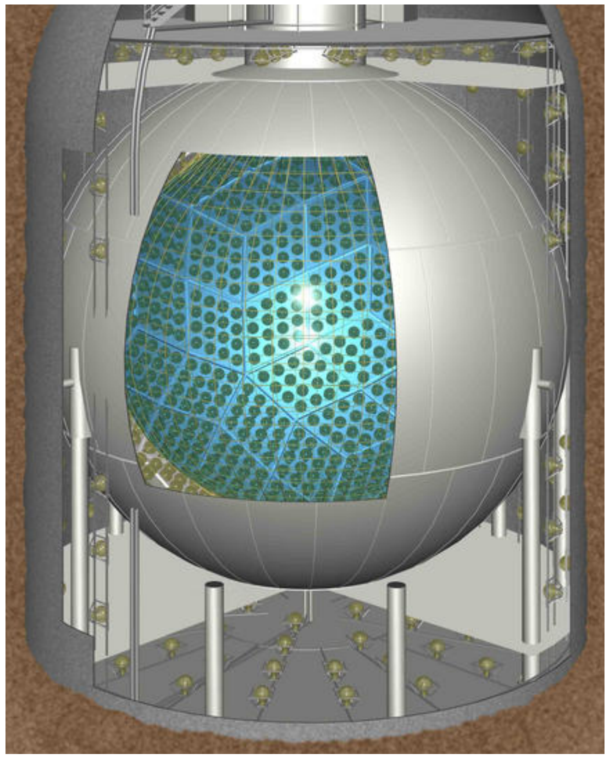
Reactor Neutrino Achievements

- Proved neutrinos' existence (1950s)
- Probed CC/NC cross-sections back when that was new and cool (50s-70s)
- More recently: proving neutrinos have mass, and measuring SM neutrino oscillation parameters
  - Leading or competitive precision for 3 of 6 SM oscillation parameters: θ_{13}, Δm^2_{21}, $|\Delta m^2_{31}|$

Savannah River Neutrino Detector schematic





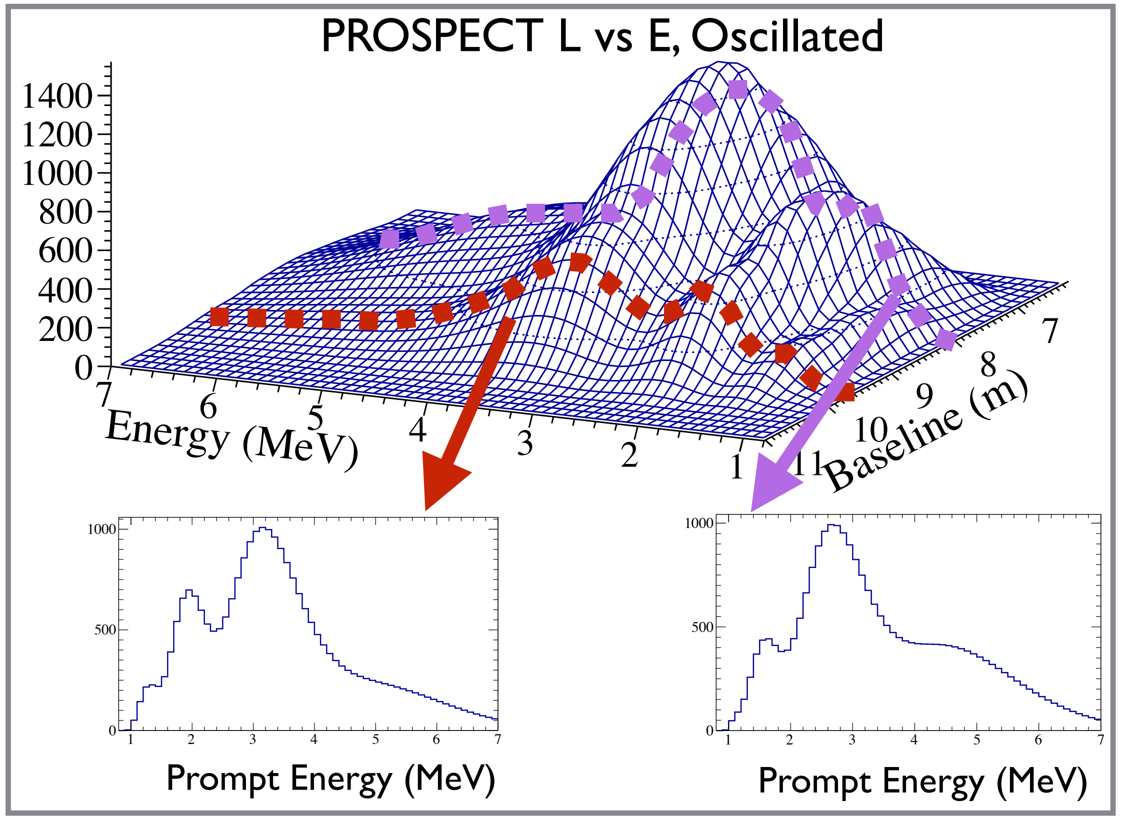
KamLAND Detector

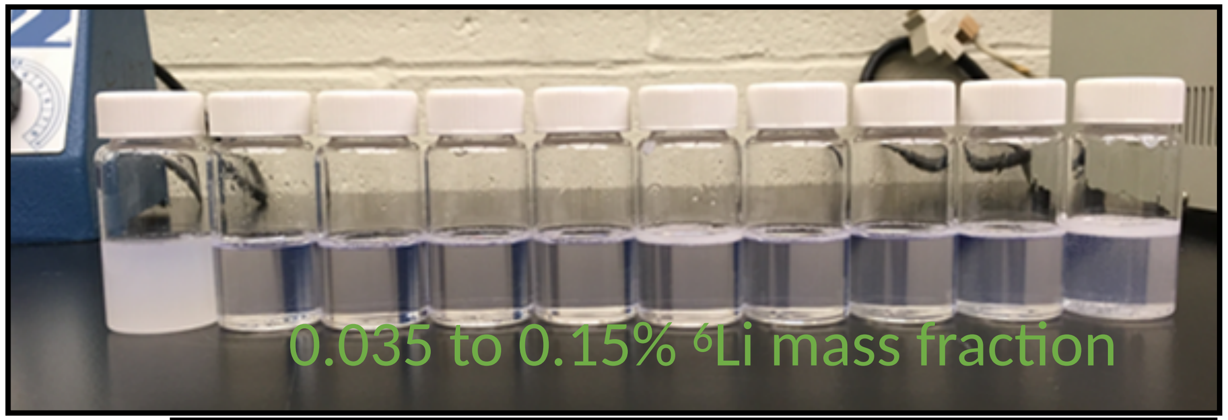
2016 Breakthrough Prize

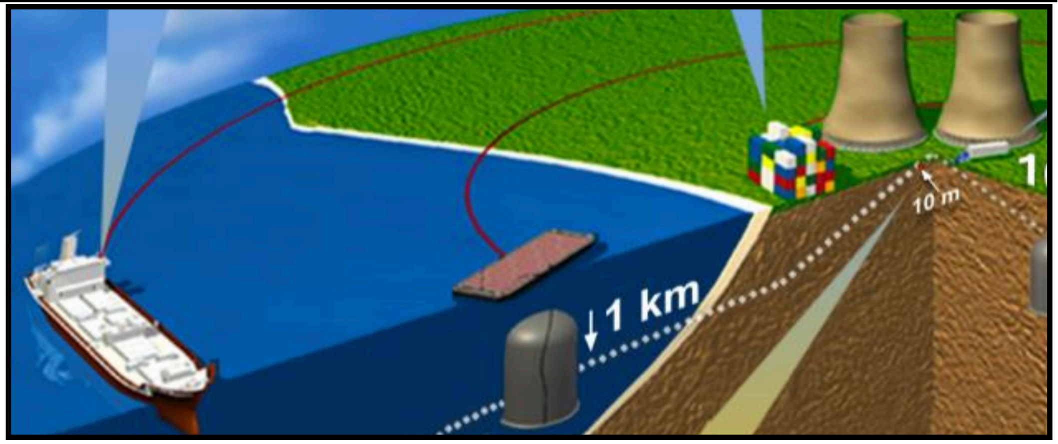
Daya Bay Far Site

Reactor Neutrinos Today at Short Baselines

- Attacking Current Science Drivers
  - Physics associated with neutrino mass: sterile neutrinos
  - Precision fluxes for pursing science drivers at reactors
- BRN-Relevant Tech Development
  - Advanced scintillator technology
  - Precision background characterization
- Applications
  - Improving nuclear data
  - Developing reactor monitoring capabilities







- Goal: overview promise of reactor neutrinos in these three areas.

Science Drivers: Sterile Neutrinos

- If there are ~eV range mass states are out there:

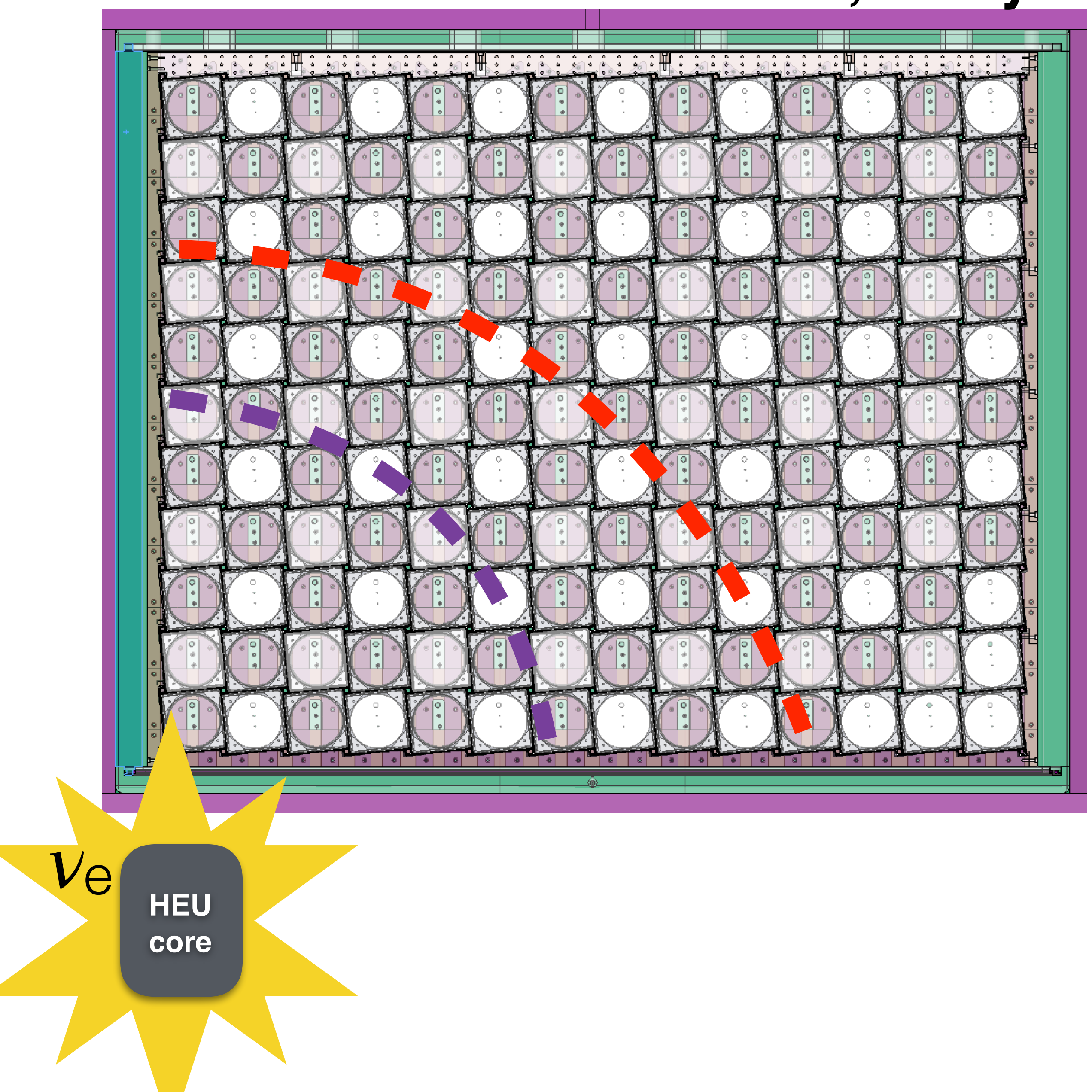
$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{bmatrix} = U \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{bmatrix}$$

- Primary science driver: probe this physics!!!
  - $U_{\mu 4}$: probed with accelerator/atmospheric ν_μ
  - $U_{\tau 4}$: probed with atmospheric/solar MSW, and accelerator NC ν_x interactions
  - $U_{\mu 4}$ and U_{e4} combo: probed with accelerator ν_μ-to-ν_e
- Reactors currently provide, and will continue to provide, the most direct and stringent limits on U_{e4}.
  - Pure U_{e4} probe is <u>even more important</u> if neutrino-related BSM physics is more complex than above: neutrino decay, hidden neutrino portal, 3+N, NSI, …

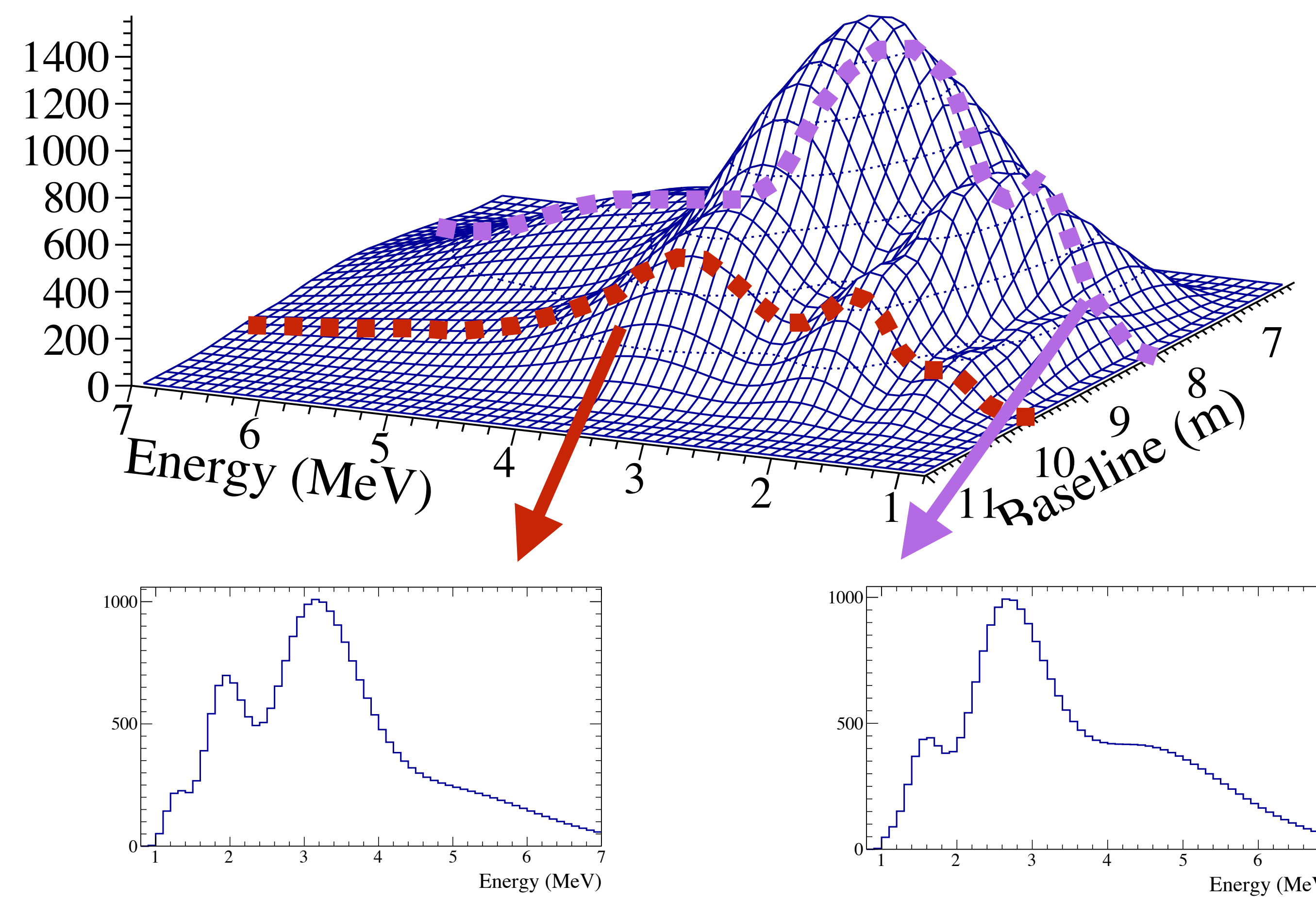
Sterile Neutrino Measurement Styles

- Measure IBD deficit from ν_e disappearance (i.e. flux anomaly)?
- *Better choice:* Directly probe L/E behavior by comparing energy spectra between different short baseline ranges

PROSPECT: One Detector, Many L



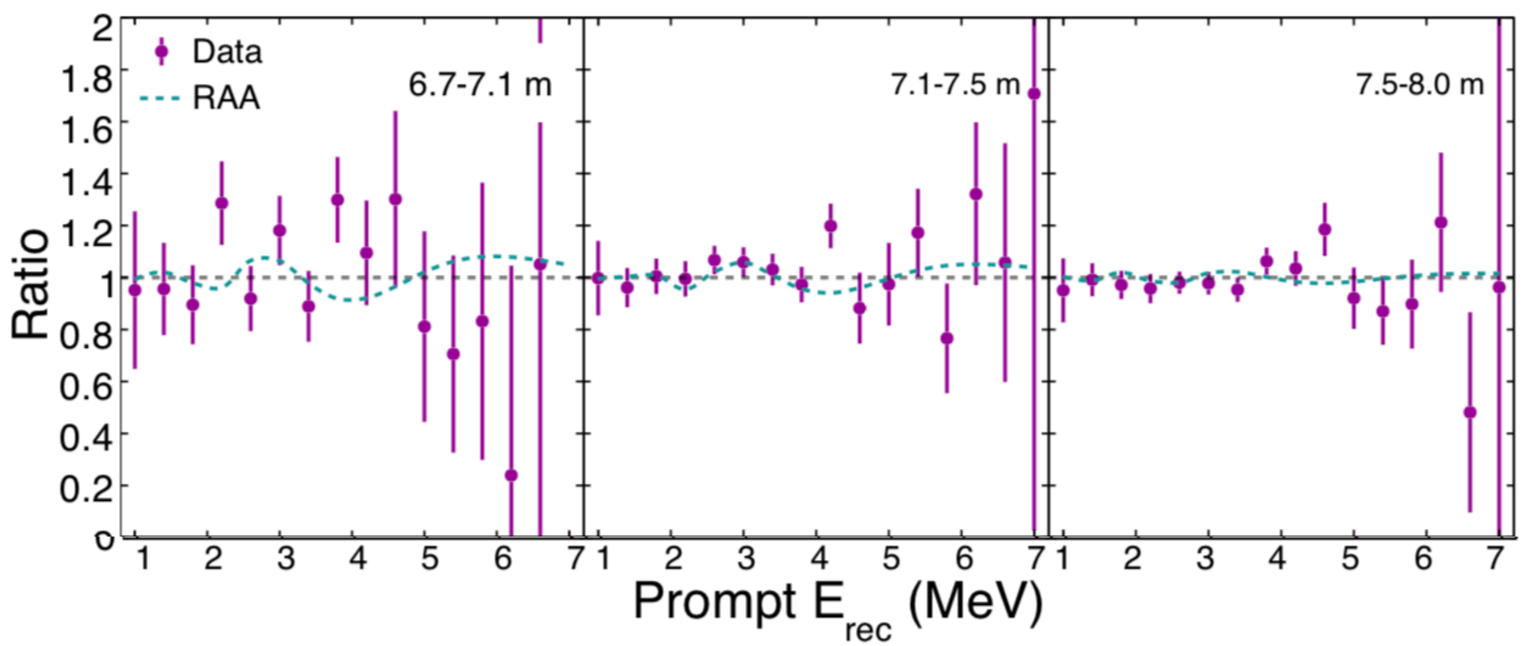
PROSPECT L vs E, oscillated



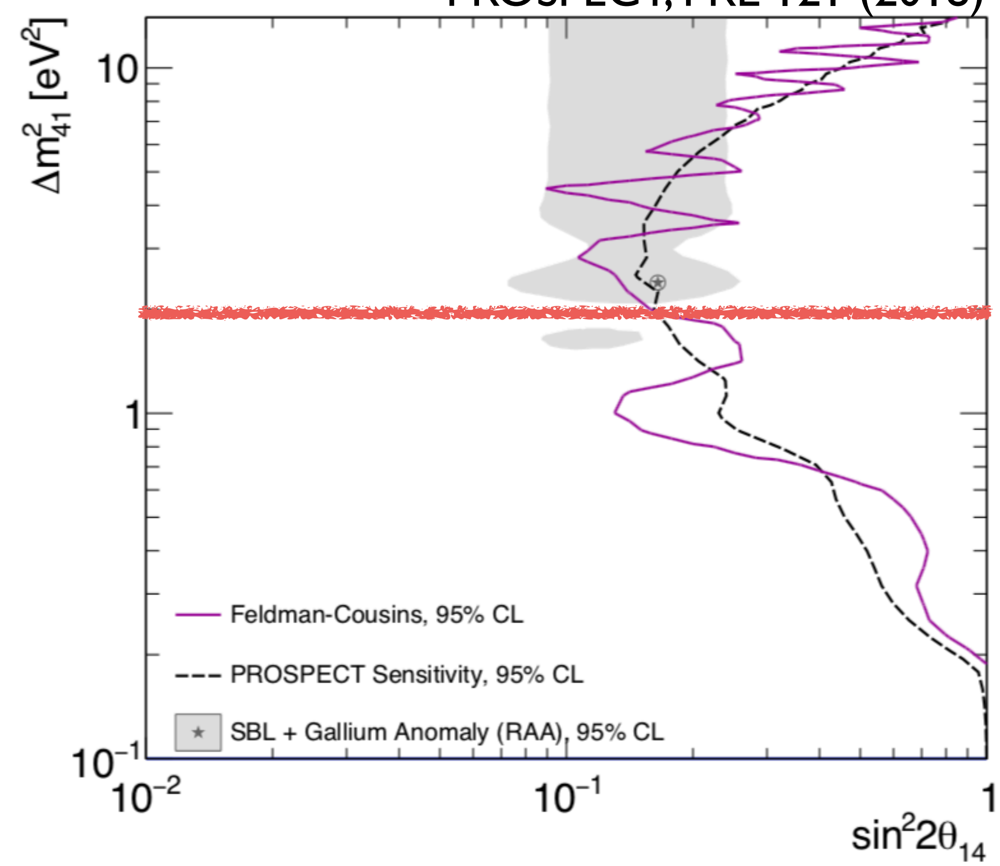
$$sin^2(2\theta)sin^2(1.27\Delta m^2\frac{L}{E_\nu})$$

Recent Sterile Oscillation Results

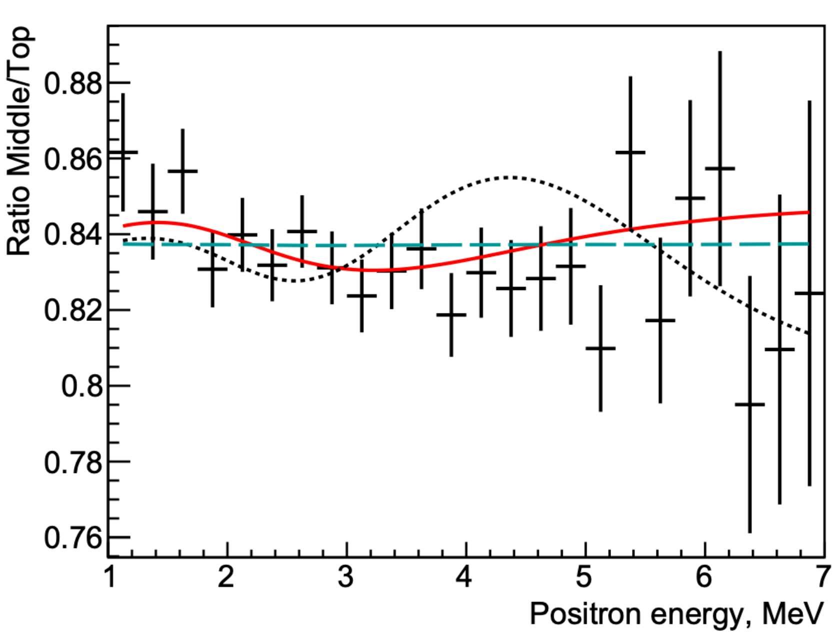
- Above ~few eV: compact HEU cores
  - PROSPECT and STEREO

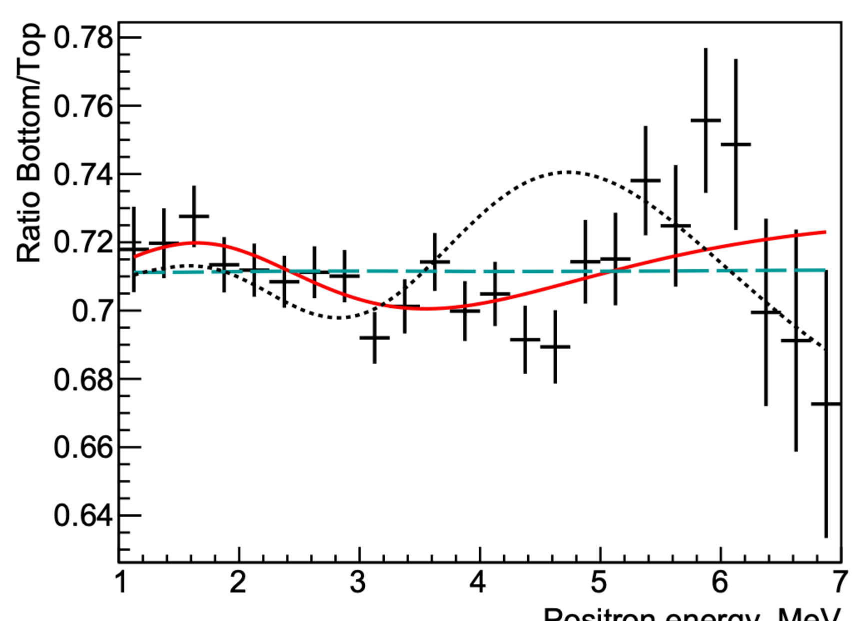


PROSPECT, PRL 121 (2018)

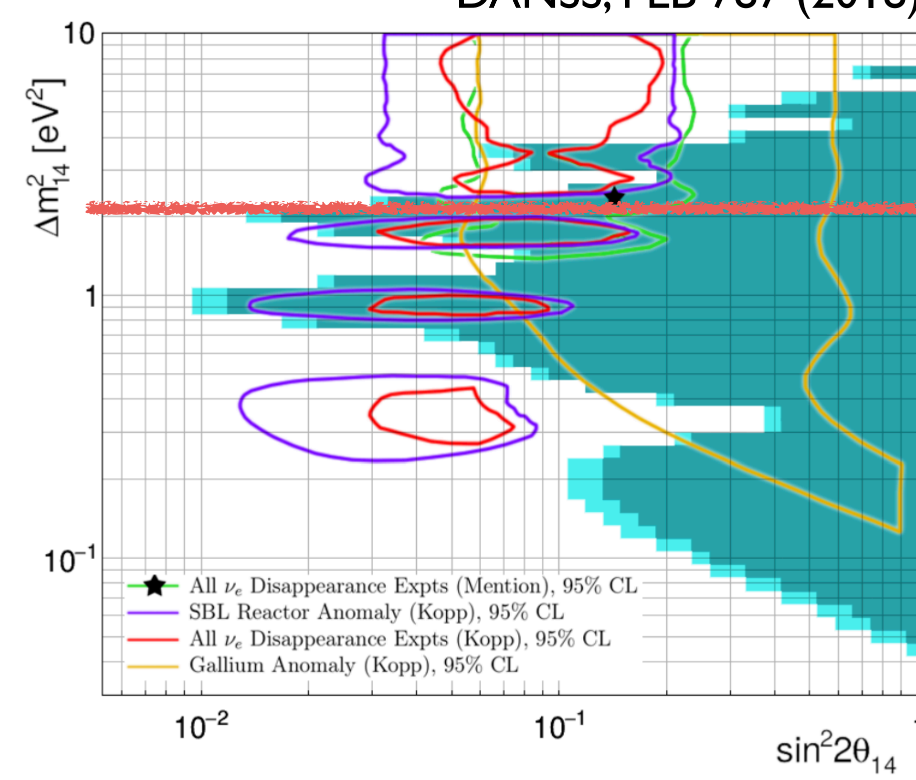


- Below ~few eV: commercial LEU cores
  - DANSS and NEOS



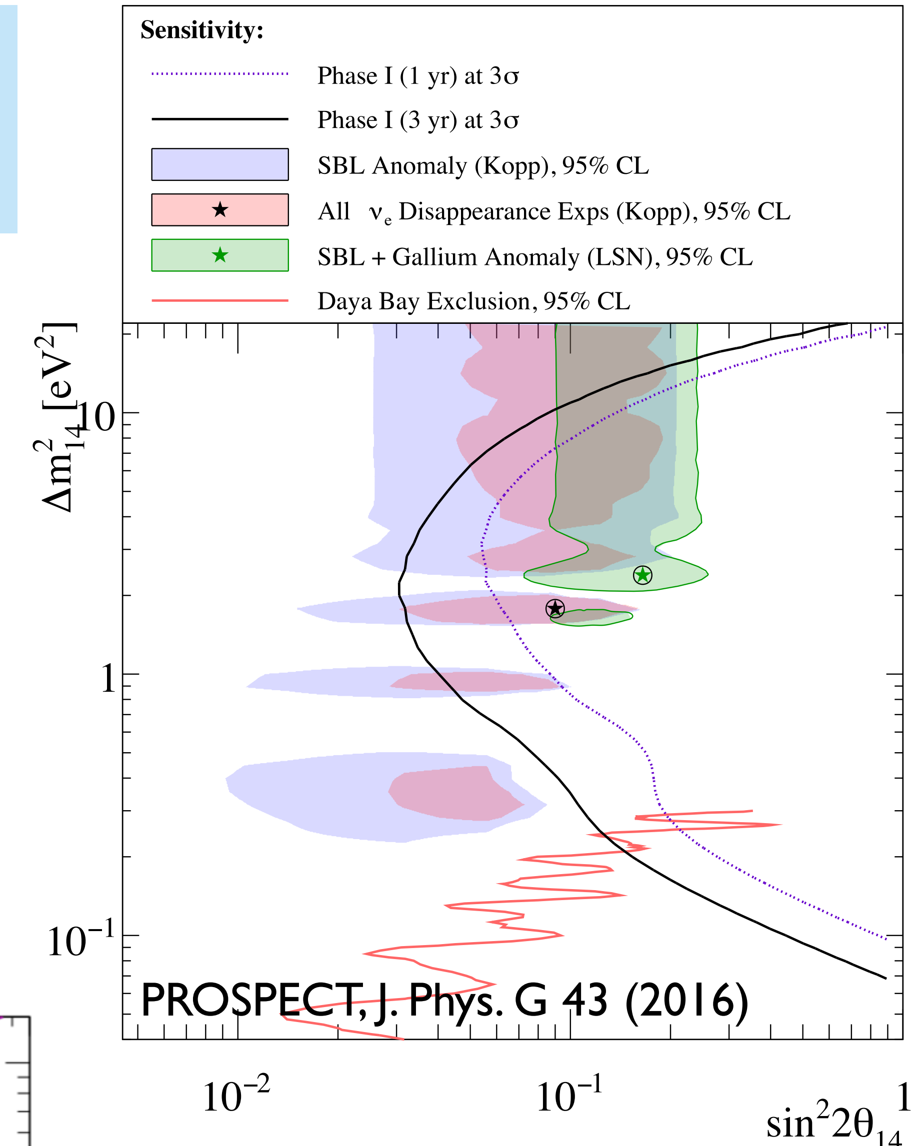


DANSS, PLB 787 (2018)

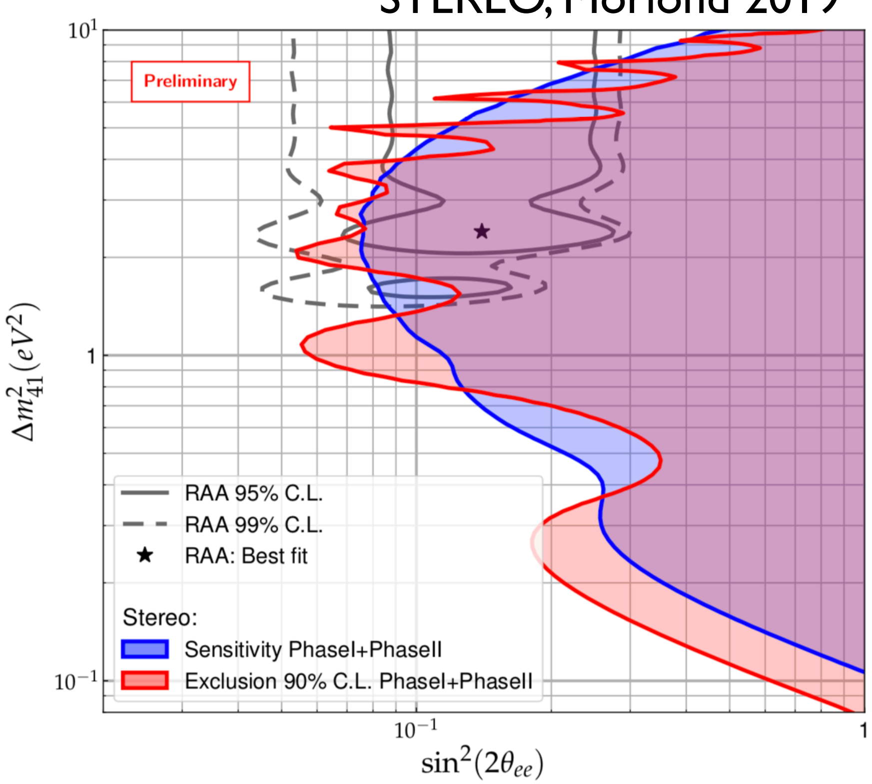


US-Based Avenues For Improvement

- To improve in > eV range, more statistics needed from compact-core reactors
  - Also joint STEREO-PROSPECT analysis
- To improve in < eV range:
  - PROSPECT deployments at LEU and HEU with same detector
  - Joint PROSPECT-Daya Bay analysis (NEOS-style near-far ratio comparison)



STEREO, Moriond 2019



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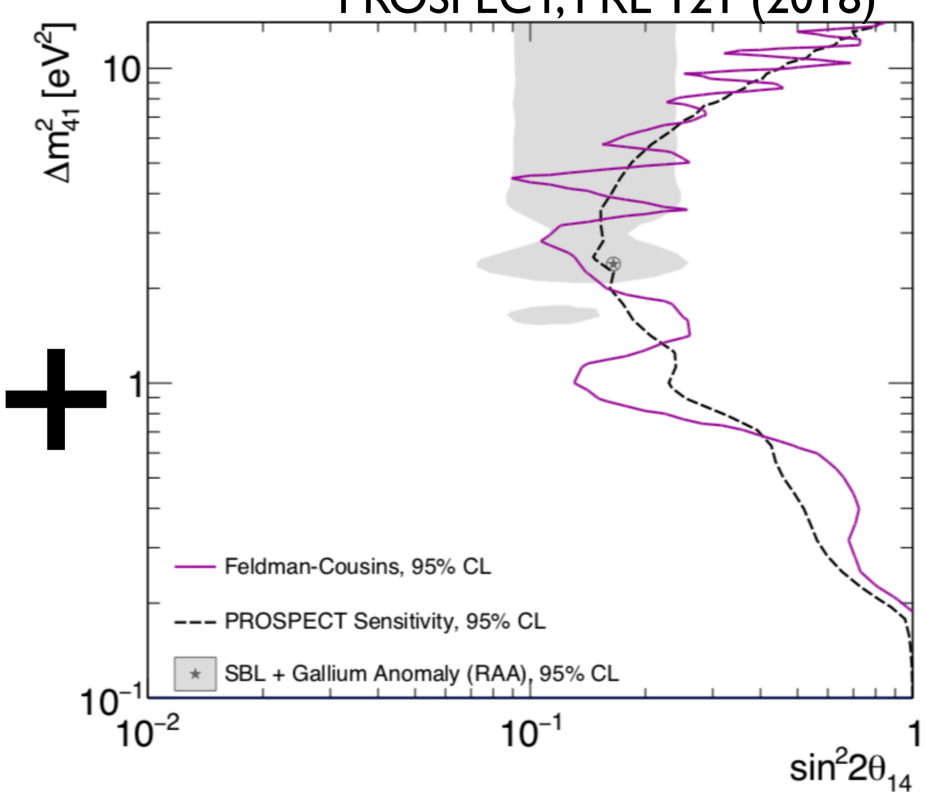
PROSPECT, PRL 121 (2018)



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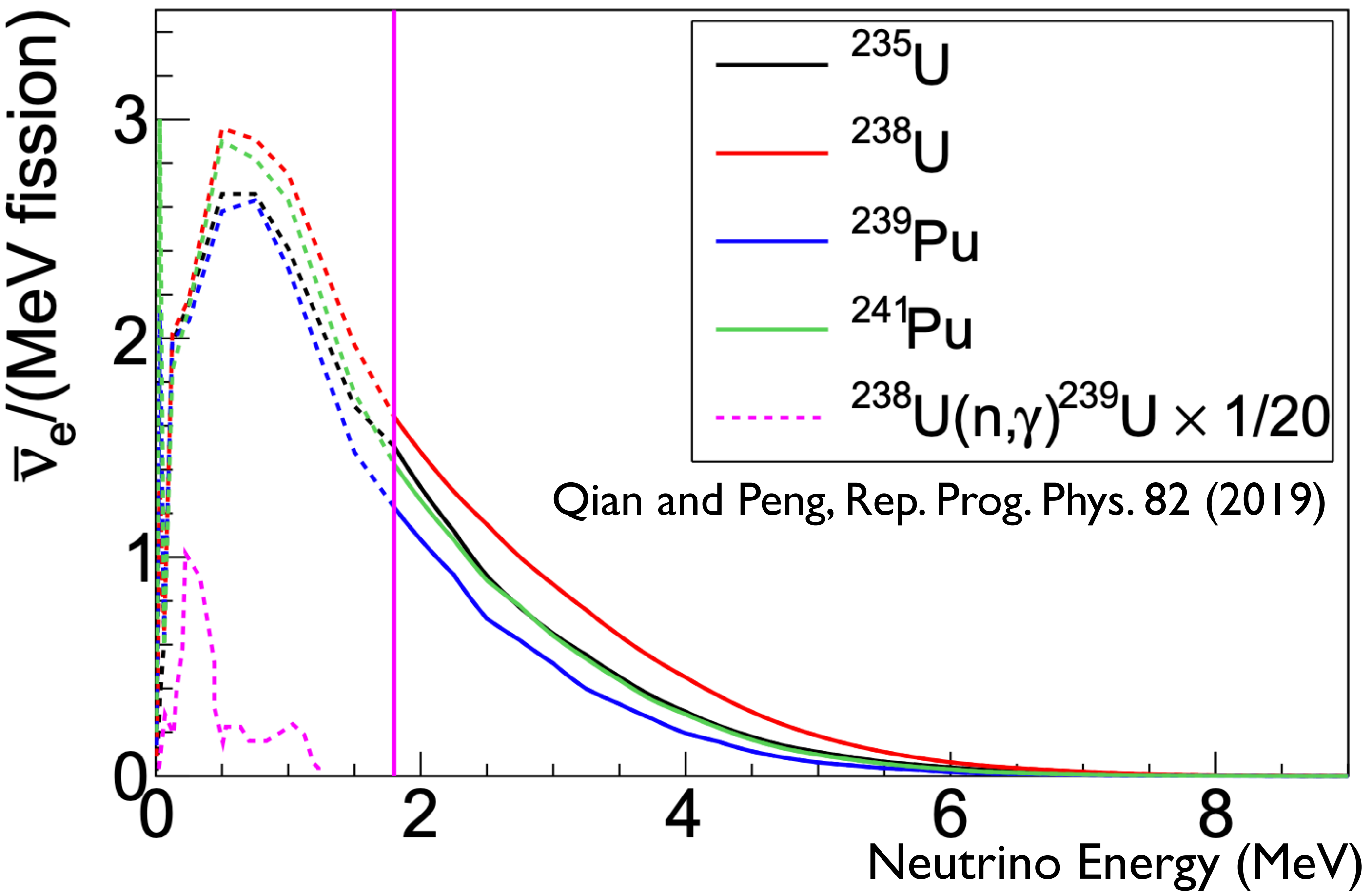
Improvement from
- Wider range of baselines
- Higher statistics

Science Drivers: Reactor Production

- What ν_e fluxes and spectra are made by each fission isotope?

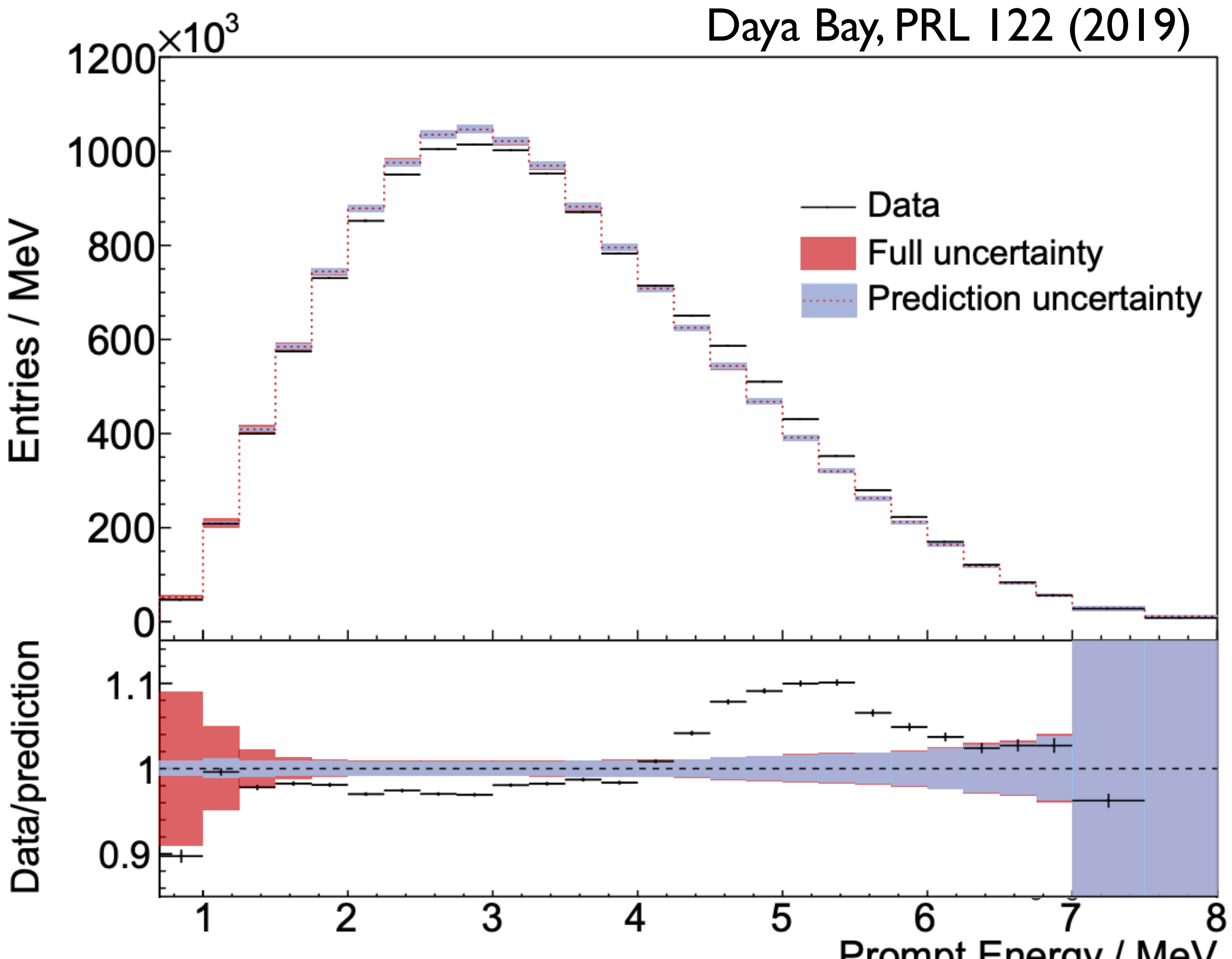


- Q: What does this have to do with neutrino science drivers?
- A: Better flux knowledge = better neutrino/BSM physics
  - Example: reactor-based coherent neutrino scattering
  - Example: reactor mass hierarchy measurements at reactors
- Note: Also very valuable in nuclear data / applications contexts

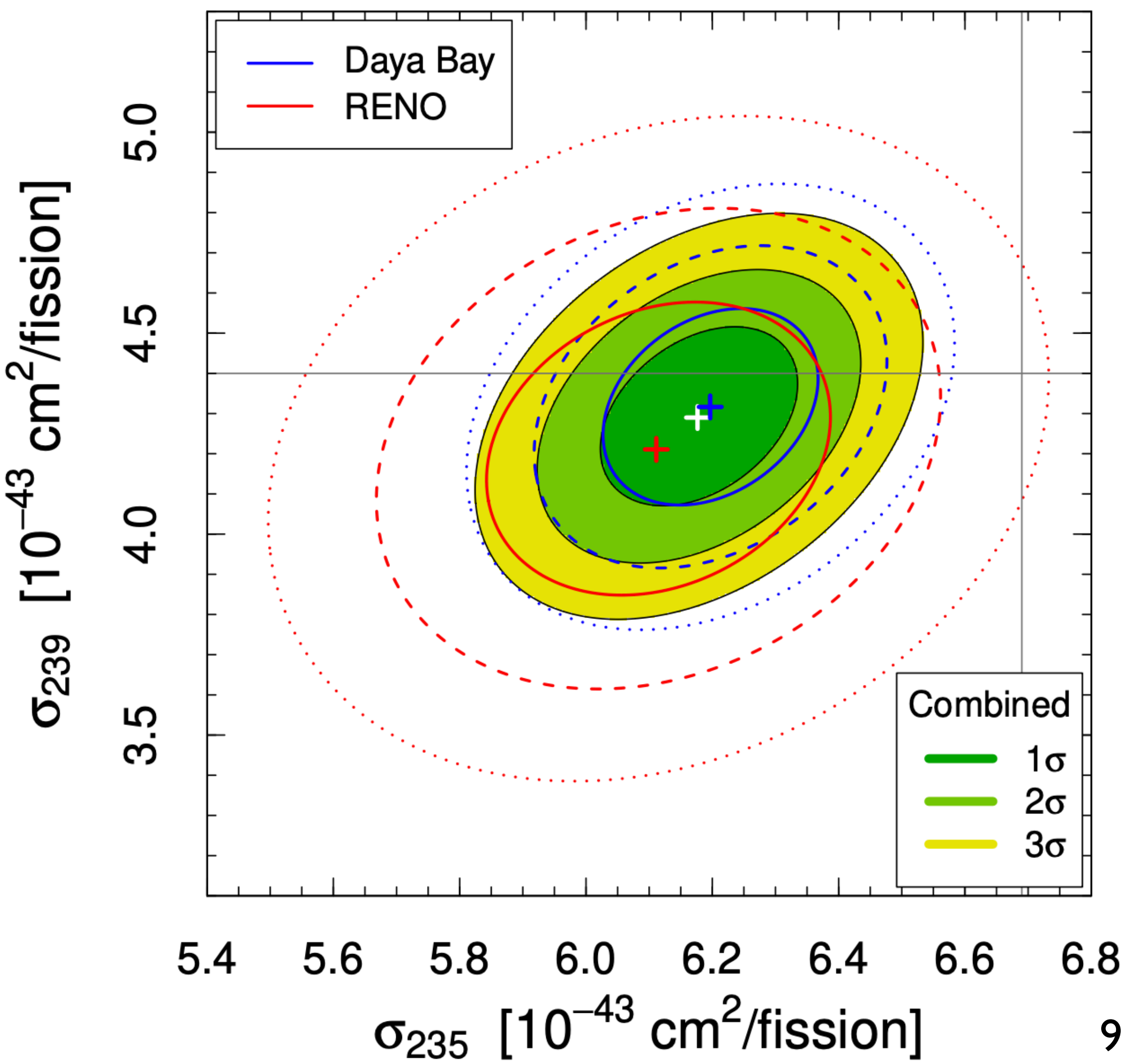
Reactor Neutrino Production

- It's remarkable *HOW MUCH* we've learned in the past 10 years
  - In 2009, 'state-of-the-art' was a Vogel parameterization from the 1980s.
- Now:
  - Flux: for ^{235}U and ^{239}Pu, direct measurements rival claimed model precision
  - Spectrum: LEU spectrum per-bin statistical uncertainties are now <%-level

Daya Bay, PRL 122 (2019)



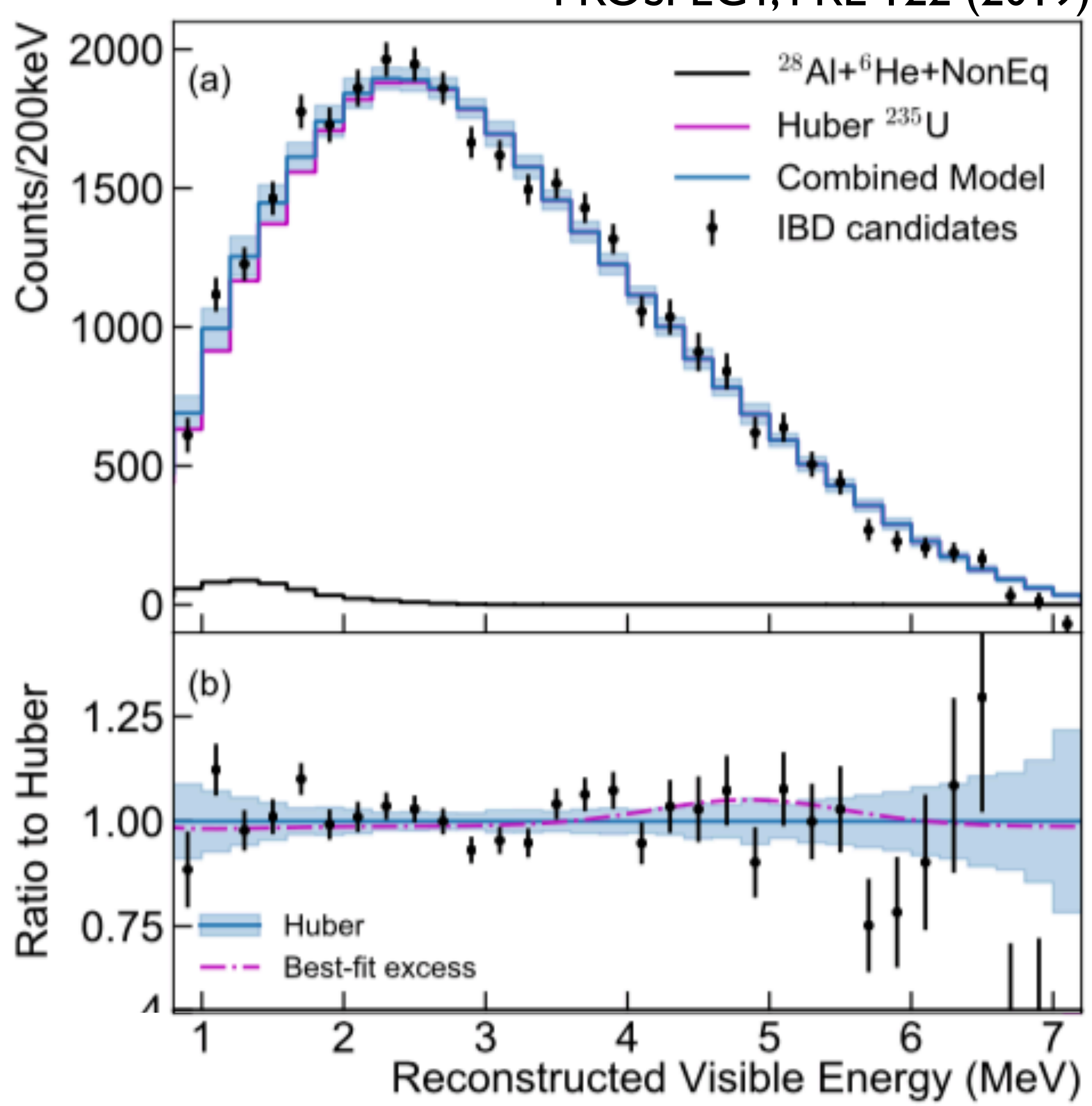
Giunti, Li, Littlejohn, Surukuchi, PRD 99 (2019)

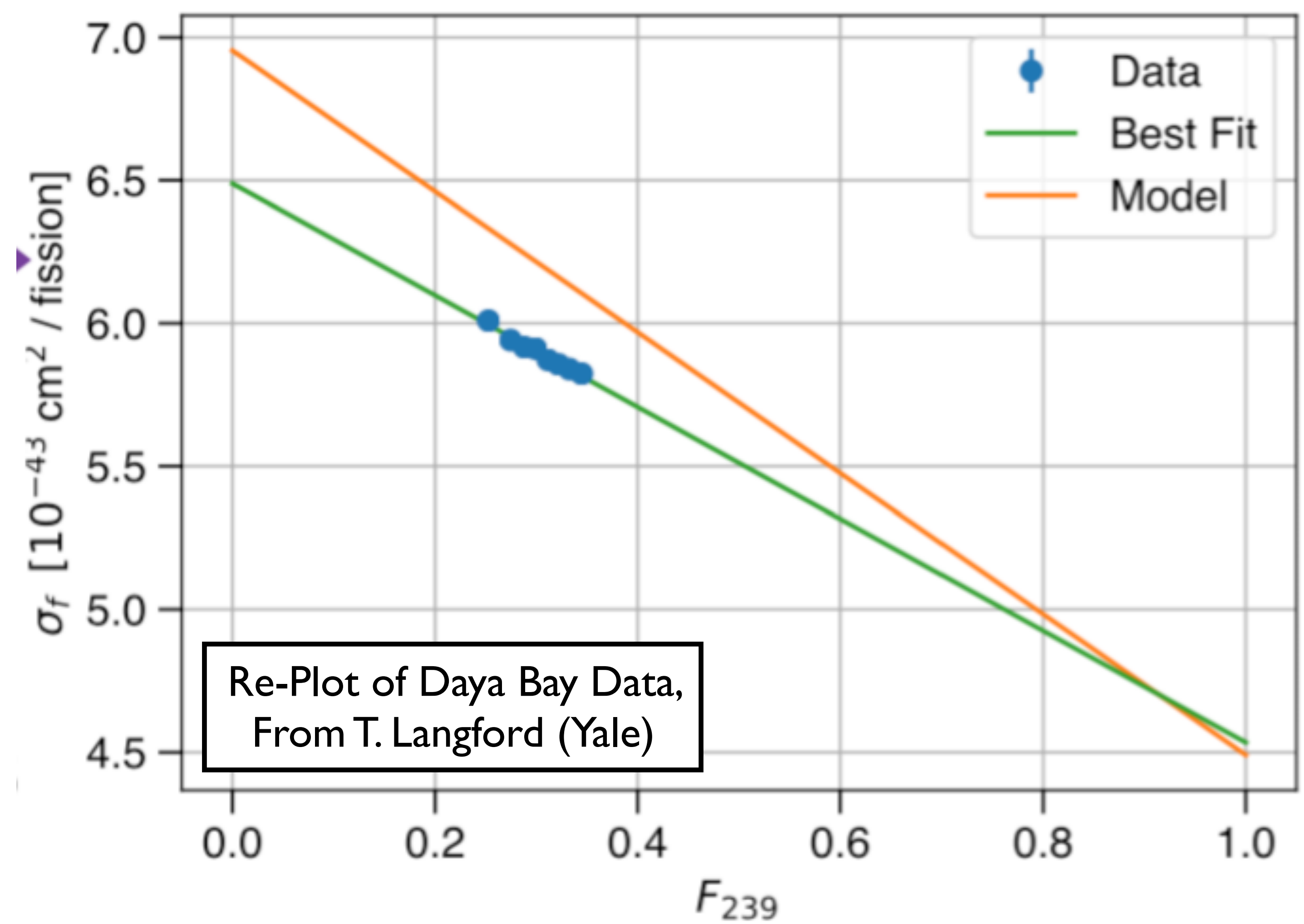


Tough Flux Questions Remain

- We are still far from a complete accurate picture, however.
  - Have no theoretical model that accurately predicts fluxes and spectra
  - Still don't know exactly WHAT exactly is incorrectly predicted
    - Only 235? 239 and 238 too? Same Q for flux AND spectrum
  - Just beginning to get hints on these questions from PROSPECT, DYB, others.

PROSPECT, PRL 122 (2019)

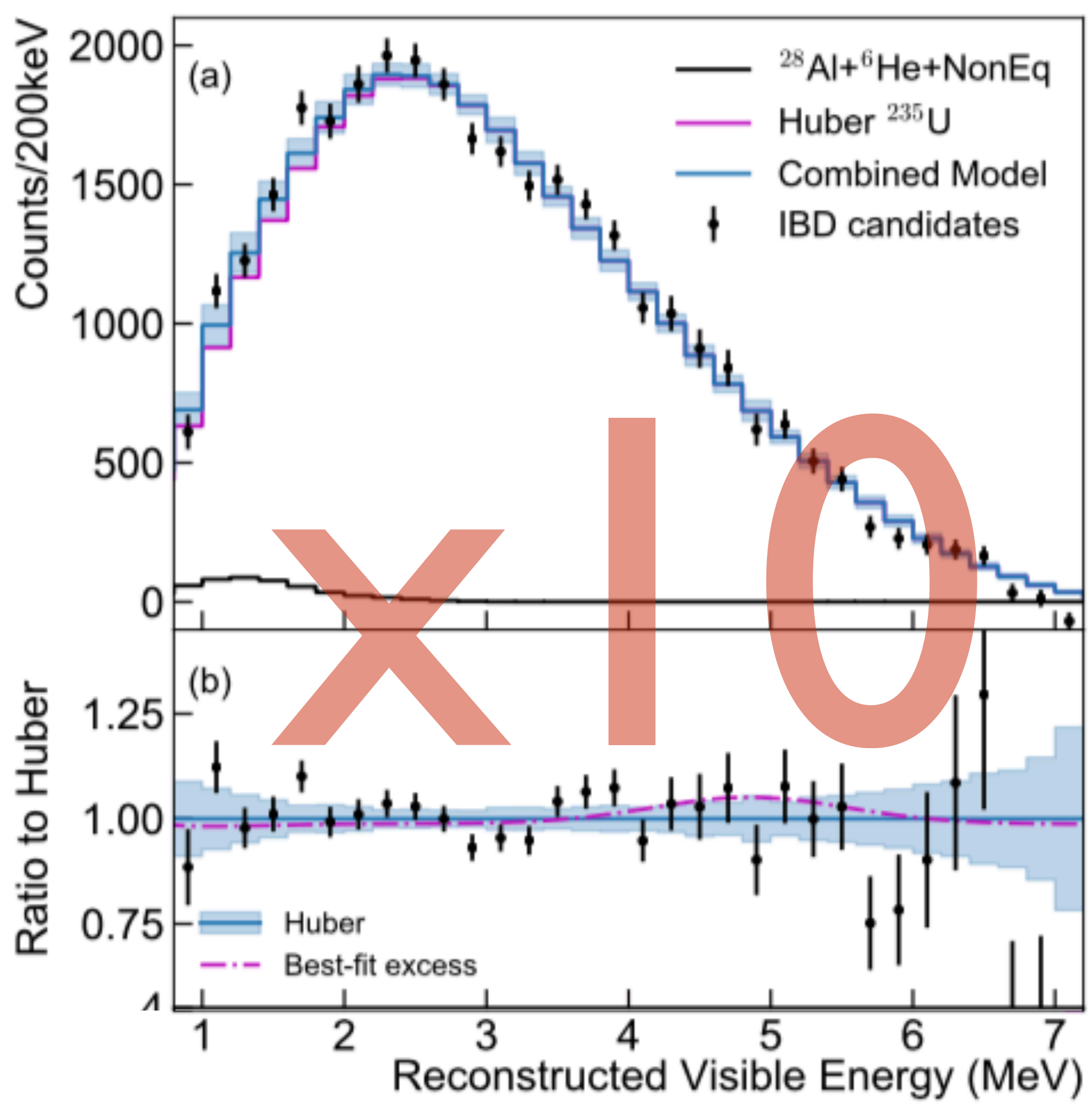


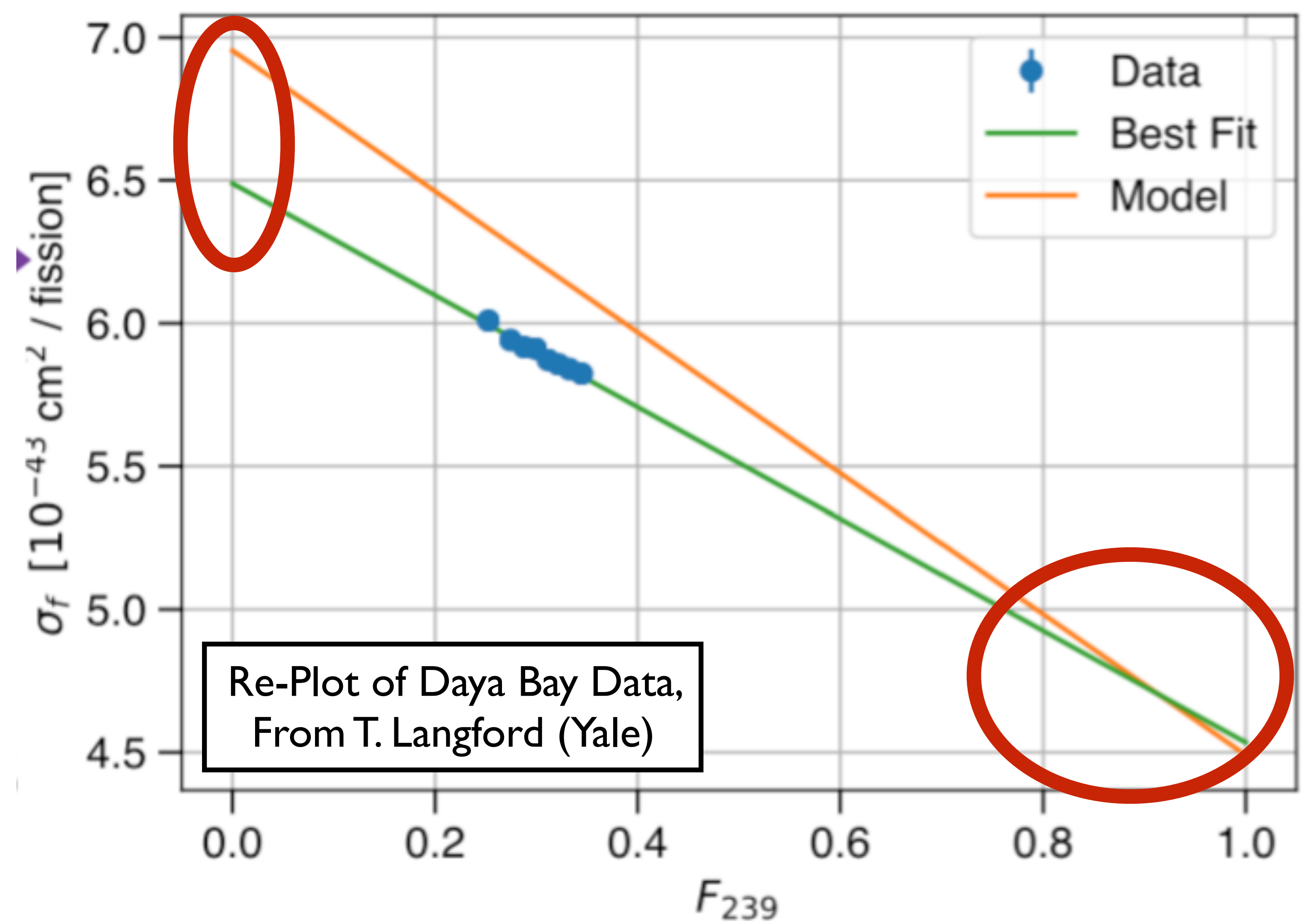


Re-Plot of Daya Bay Data, From T. Langford (Yale)

US-Based Avenues For Improvement

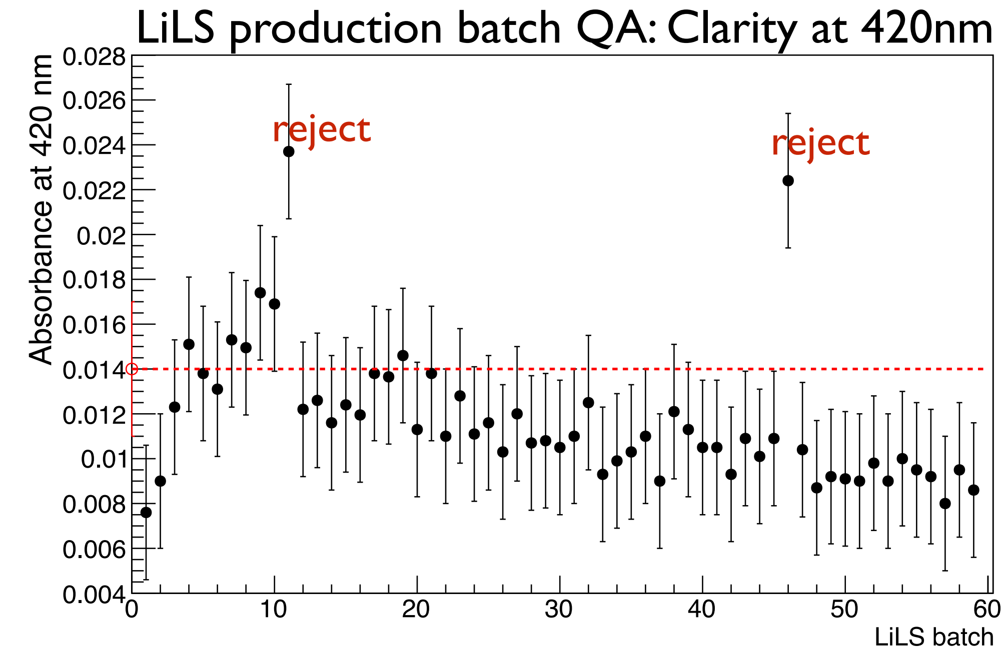
- More statistics needed at varied reactor types
  - Particularly reactors that are ^{235}U-burning, and Pu-burning (Future VTR at INL)
  - Ideally make systematics-correlated using a single mobile detector
- Also need joint analyses between diverse datasets

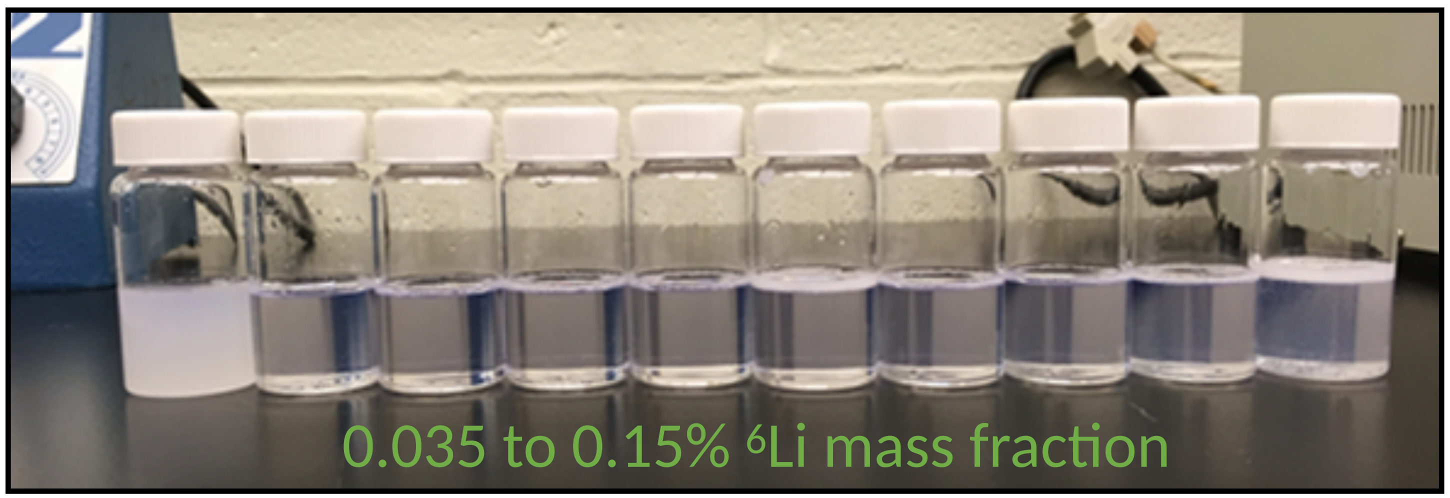


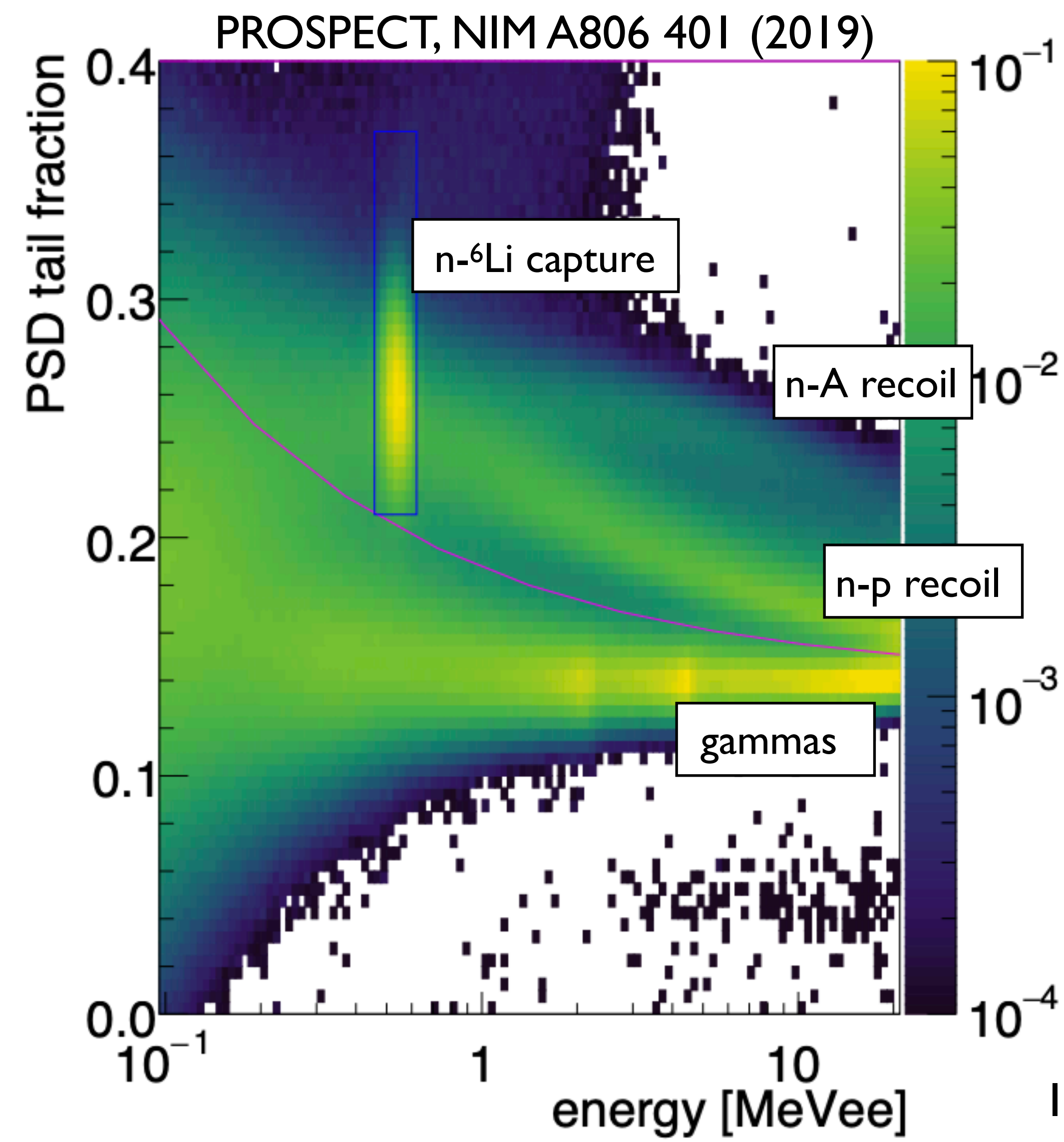


Reactor Neutrinos Today: BRN Tech

- Covered in other talks, but briefly:
  - Organic liquid scintillator R&D
    - PROSPECT has made and characterized new optically clear, PSD-capable, lithium-doped liquid scintillator
    - H. P. Mumm, CPAD 2019 Talk on Sunday





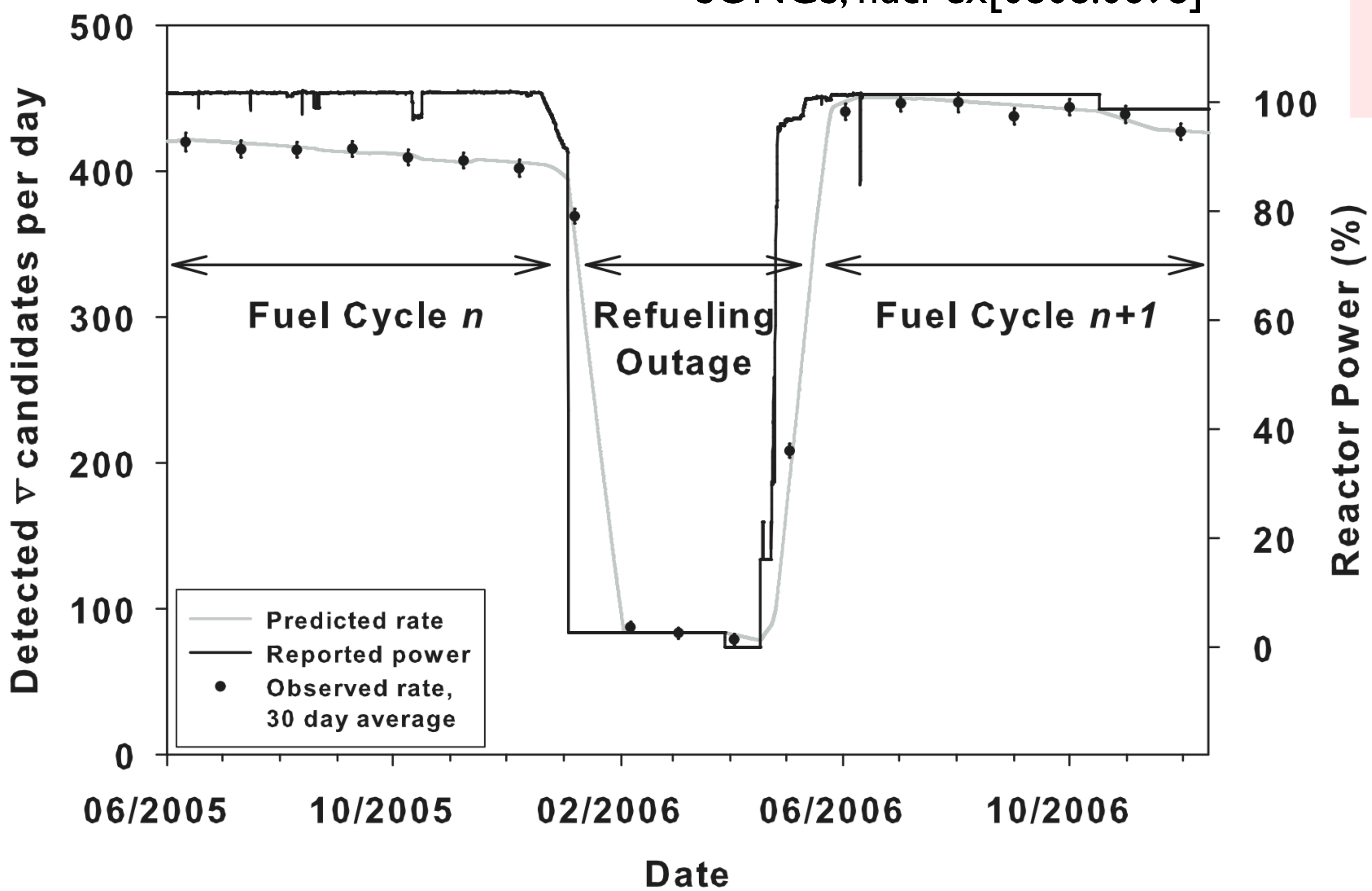


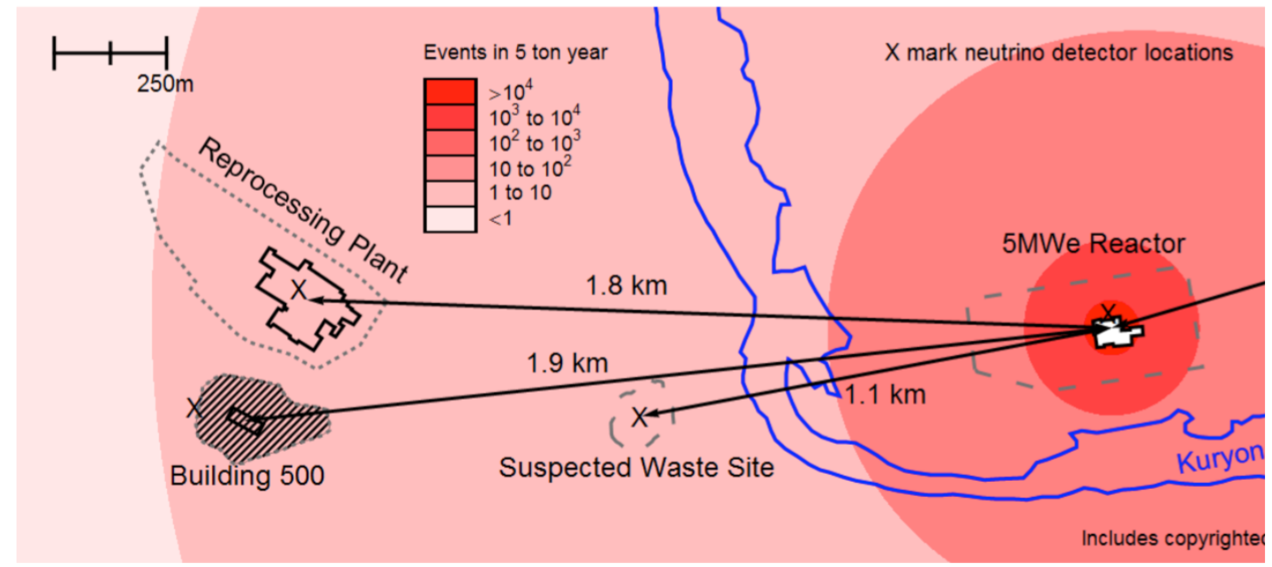
- Precision background characterizations
  - PROSPECT technology enables unique precision measurements of neutrons from many sources
  - X. Zhang, CPAD 2019 Talk on Tuesday

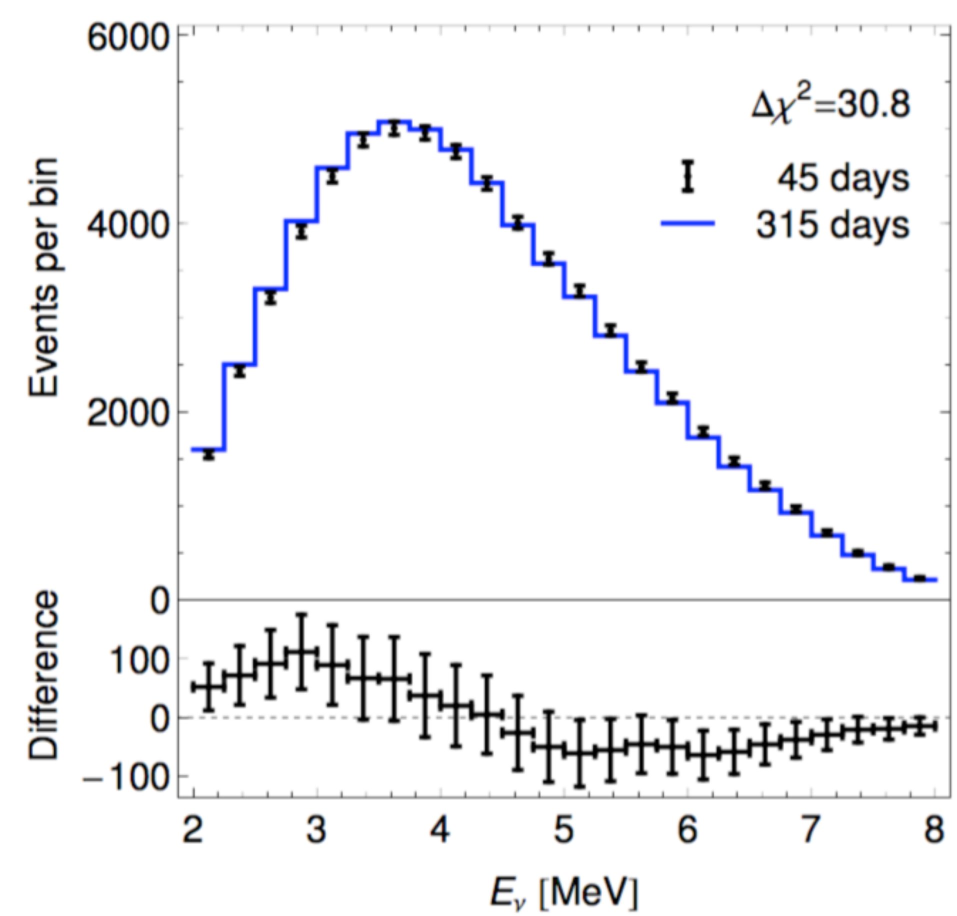
Reactor Neutrinos Today: Applications

- Reactor monitoring for applications and non-proliferation
  - Ex-situ stable daily thermal power measurements for advanced reactor designs
  - Monitoring fuel plutonium content using measured IBD energy spectrum

SONGS, nucl-ex[0808.0698]

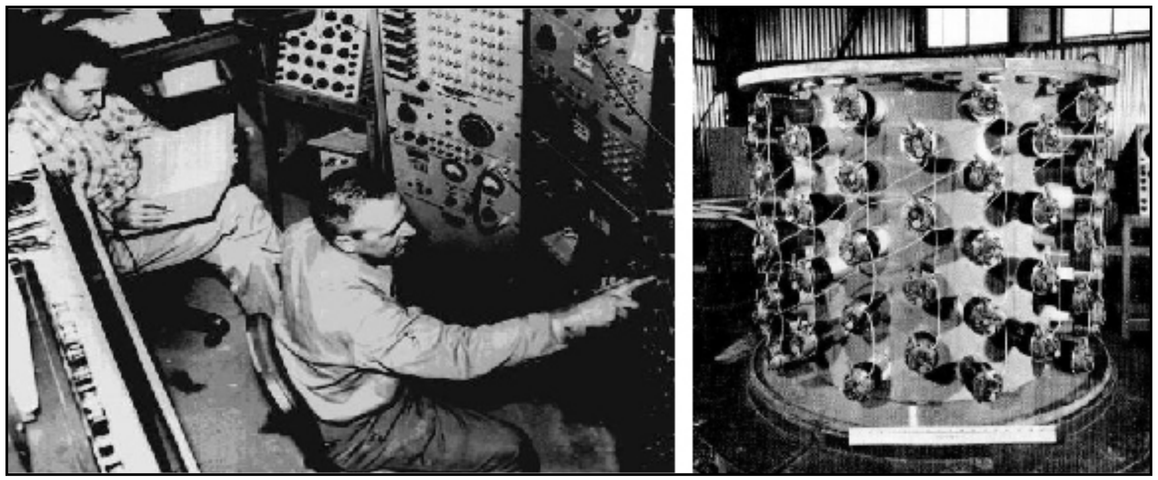




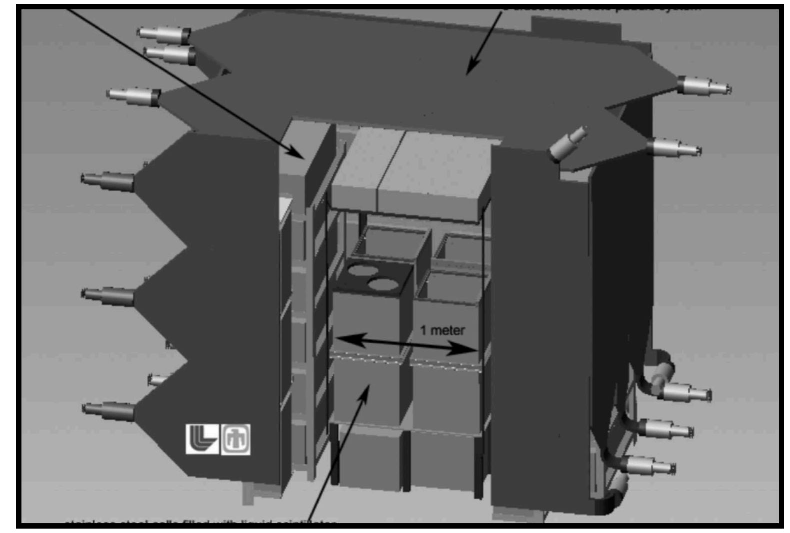


Reactor Neutrino Monitoring Advances

- Last few decades have brought major advances in realized tech:

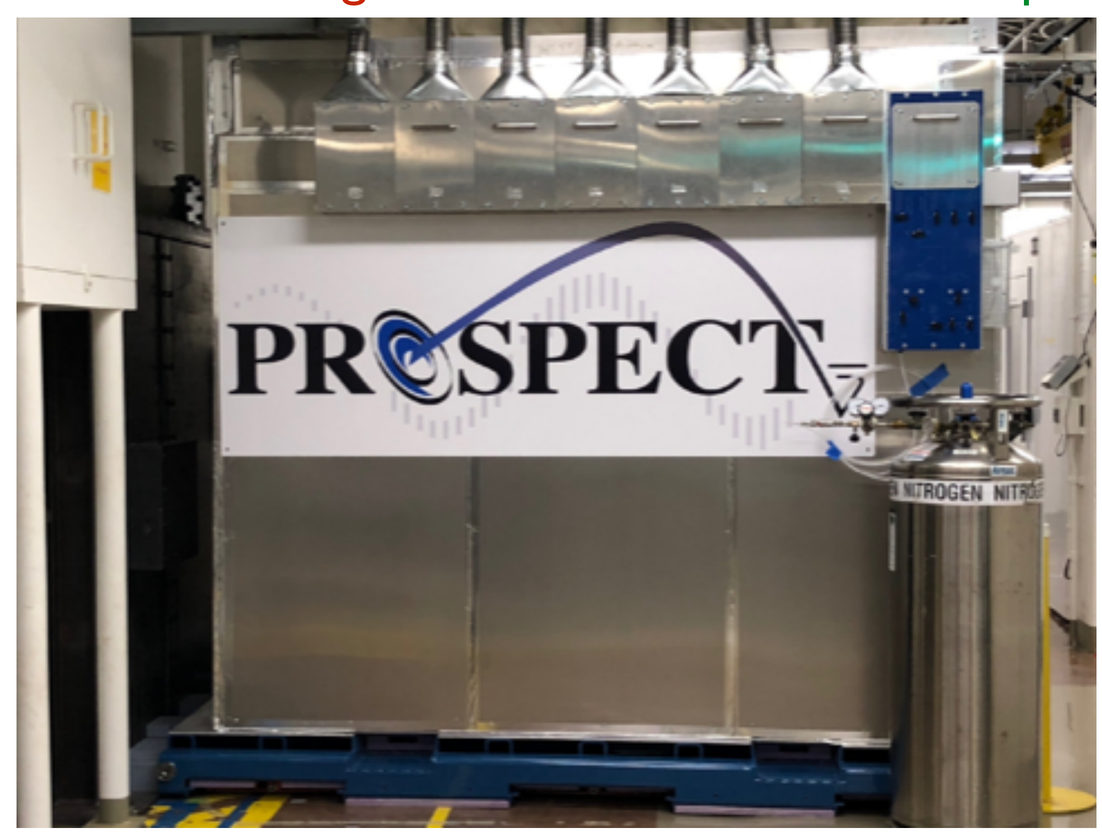


<u>1950s</u>: First Detection; ~1000 counts in 1 month;
5 background counts per 1 antineutrino count (S:B 1:5)



<u>2000s</u>: SONGS: ~230 counts per day, 25:1 S:B, but must be underground. 'semi-safe' detector liquid

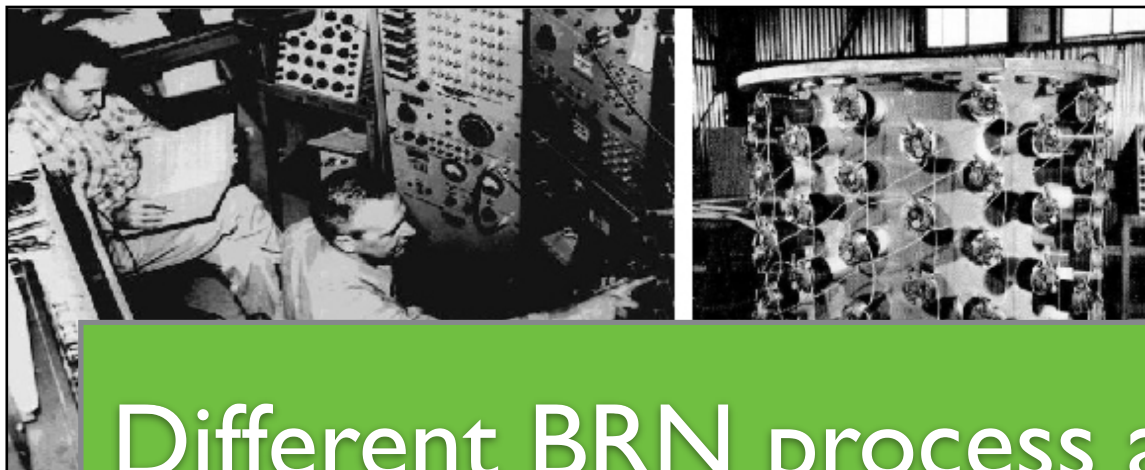
<u>1980s</u>: Bugey: ~1000 counts per day, S:B 10:1, but only underground. flammable/corrosive solvent detector liquids

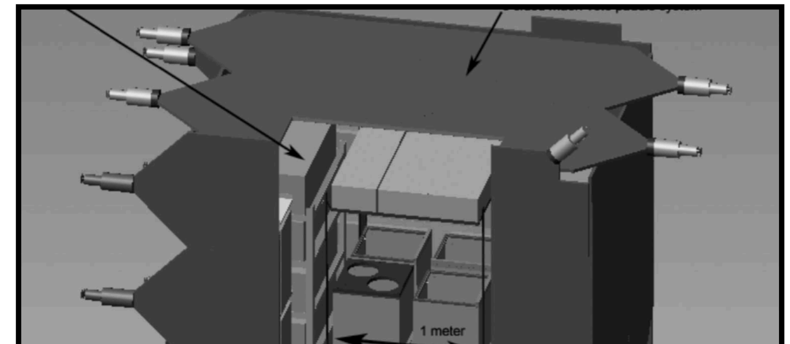


<u>NOW</u>: PROSPECT detector: ~750/day from only 80MW reactor, S:B 1:1 on surface, 'safe' plug-n-play detector

Reactor Neutrino Monitoring Advances

- Last few decades have brought major advances in realized tech:





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Different BRN process also currently being performed to understand/define the benefits of antineutrino-based reactor monitoring technology

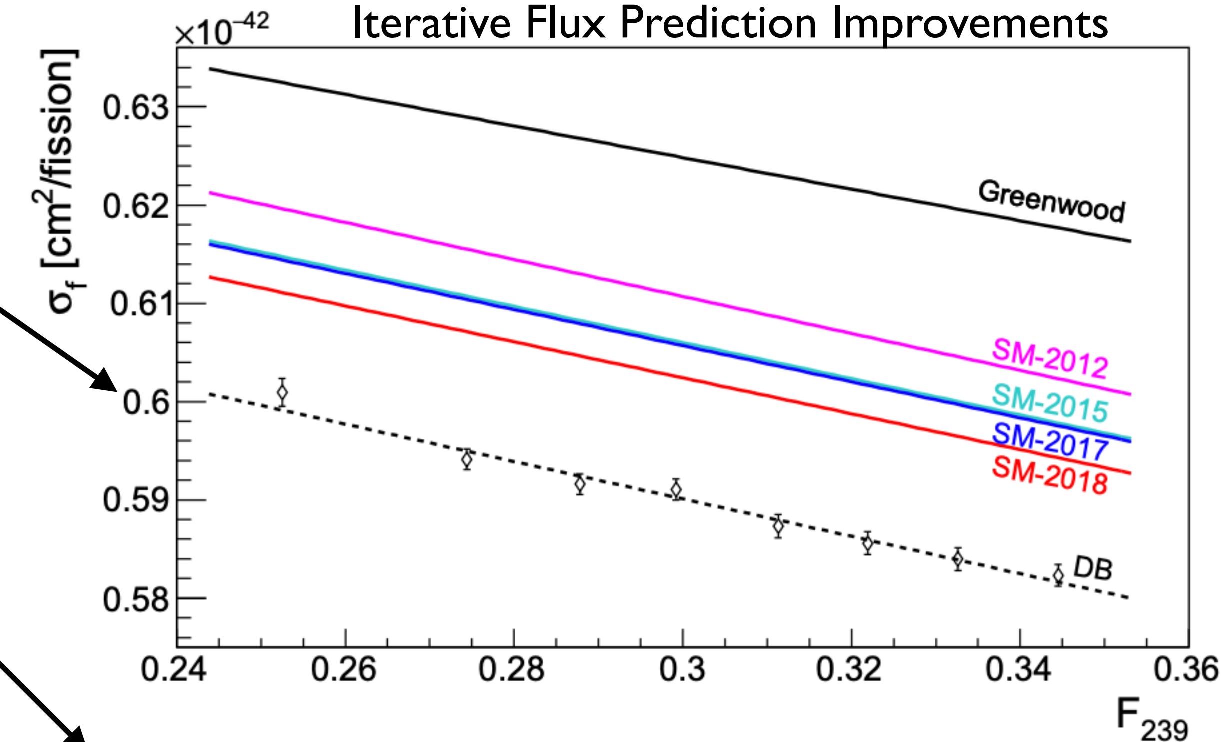
1980s: Bugey: ~1000 counts per day, S:B 10:1, but only underground. flammable/corrosive solvent detector liquids

NOW: PROSPECT detector: ~750/day from only 80MW reactor, S:B 1:1 on surface, 'safe' plug-n-play detector

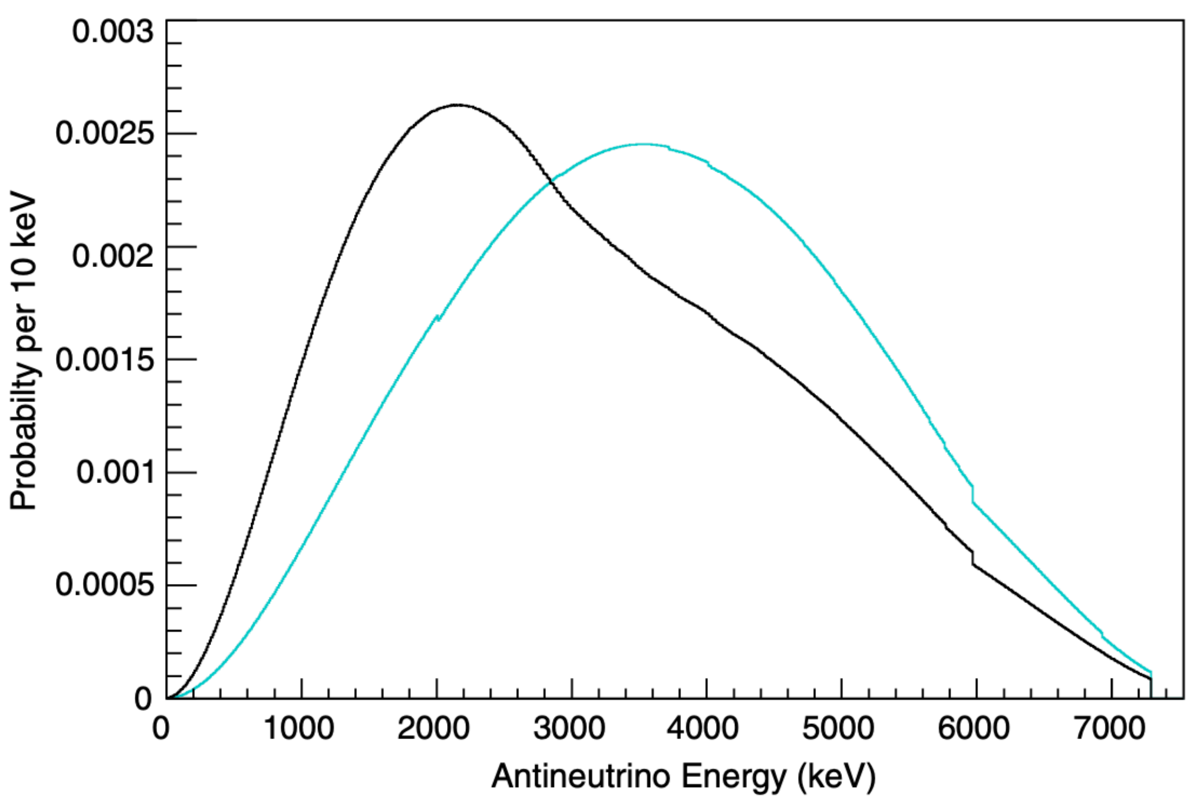
Reactor Neutrinos Today: Applications

- Reactor neutrino measurements have been a major motivator in efforts to improve nuclear data and databases
  - Can more complete nuclear data 'solve' reactor antineutrino flux and spectrum, anomalies?
  - More handles from more measurements at different reactor types

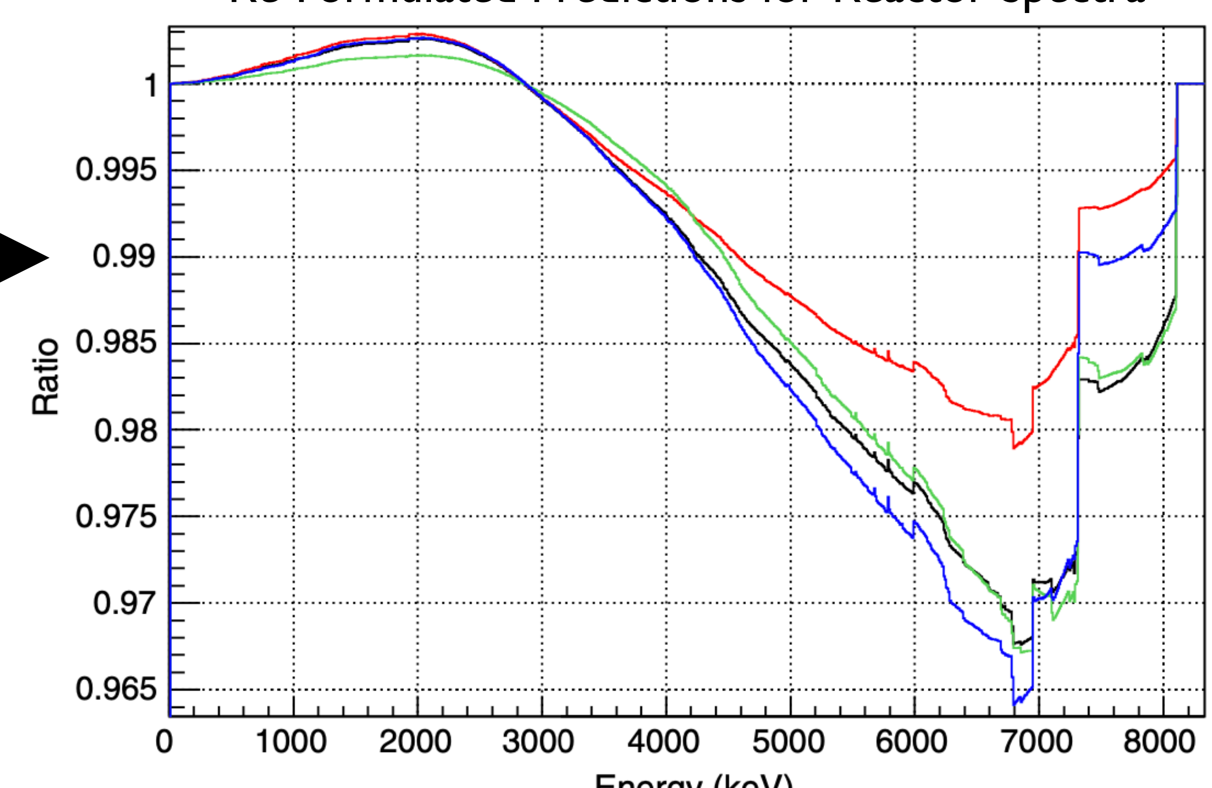
Iterative Flux Prediction Improvements



Re-Measured Nuclear Structure For Cs-142



Re-Formulated Predictions for Reactor Spectra



Conclusion

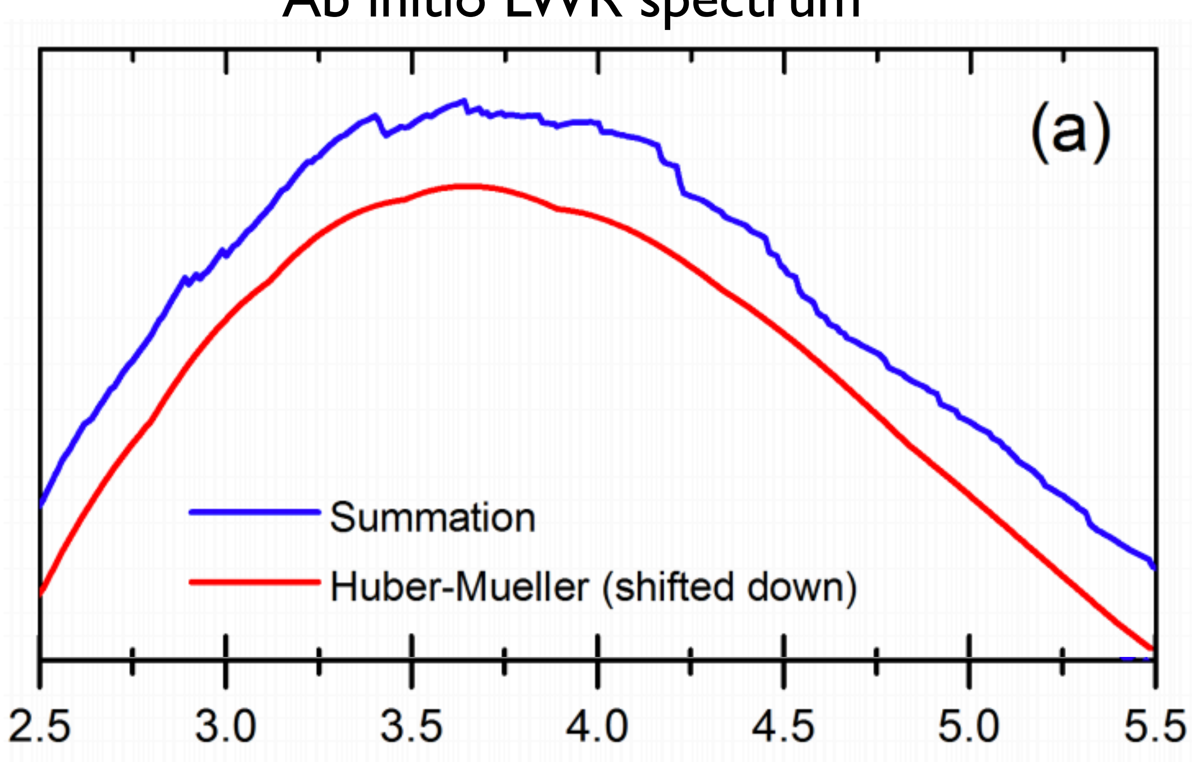
- Advanced short-baseline reactor antineutrino detectors can play a three-pronged role in US science advancement
  - Improve world-leading limits on the sterile oscillation parameter U_{e4}, and untangle reactor antineutrino flux and spectrum anomalies with complimentary data from multiple reactor types.
  - Develop organic scintillator technology and detection techniques broadly valuable for measuring neutrinos and other relevant backgrounds
  - Bridge fundamental and applied physics: use neutrino data to improve nuclear data, and to demonstrate new reactor monitoring technologies
- These efforts can build on recent accomplishments by the PROSPECT experiment
  - First-ever on-surface demonstration of high-signal, low-background reactor antineutrino detection
  - First PRL publications on sterile neutrino and ^{235}U antineutrino energy spectrum results

Backup Slides

Fine Structure: A Problem For JUNO?

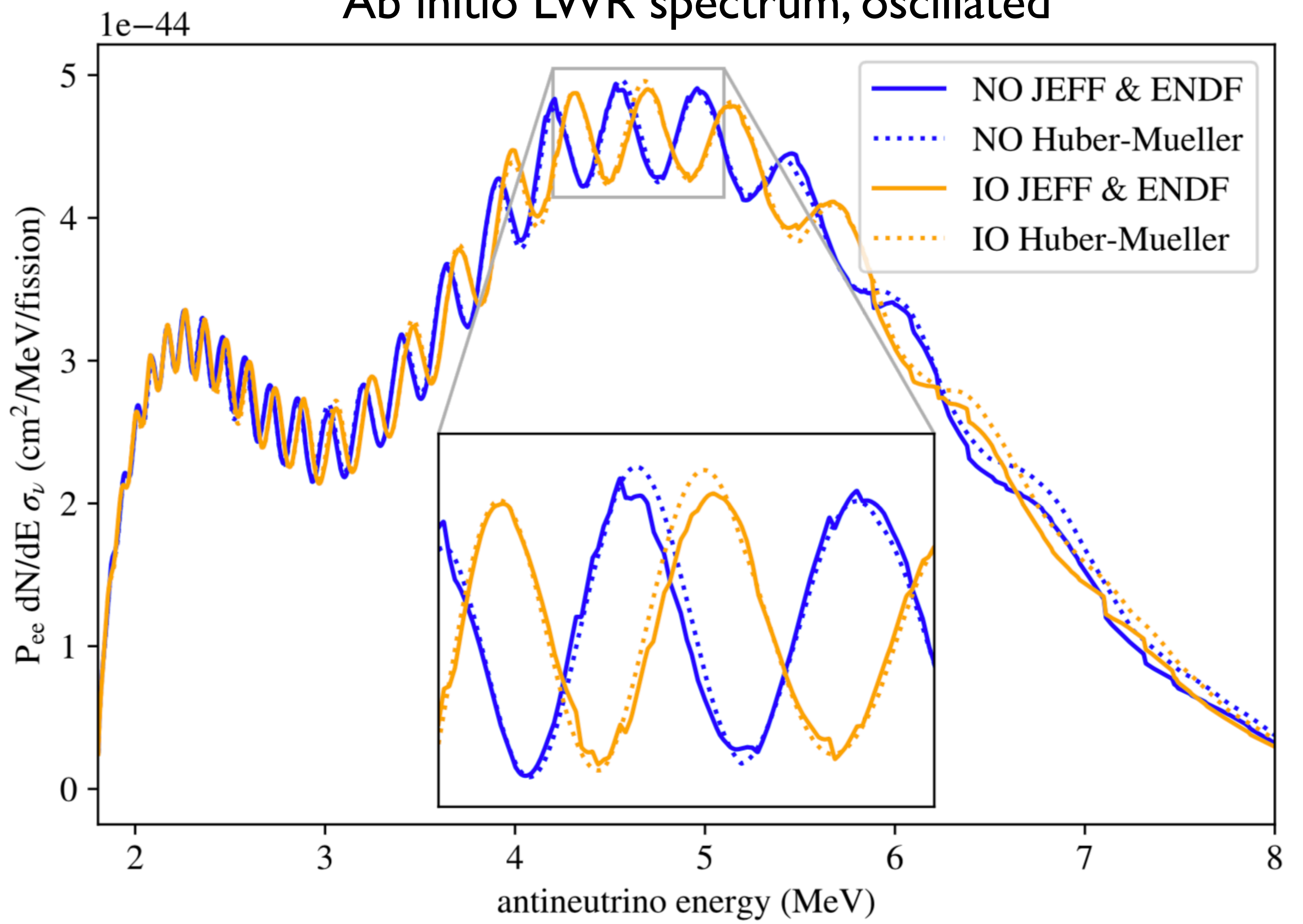
- **Another ill-defined aspect of spectrum: fine structure**
  - Arises from endpoints of individual beta branches in aggregate spectrum
  - Do fine structure wiggles obscure wiggle frequency from oscillations, and thus mass hierarchy measurements at reactors?

Ab initio LWR spectrum



Sonzogni et al, PRC 98 (2018)

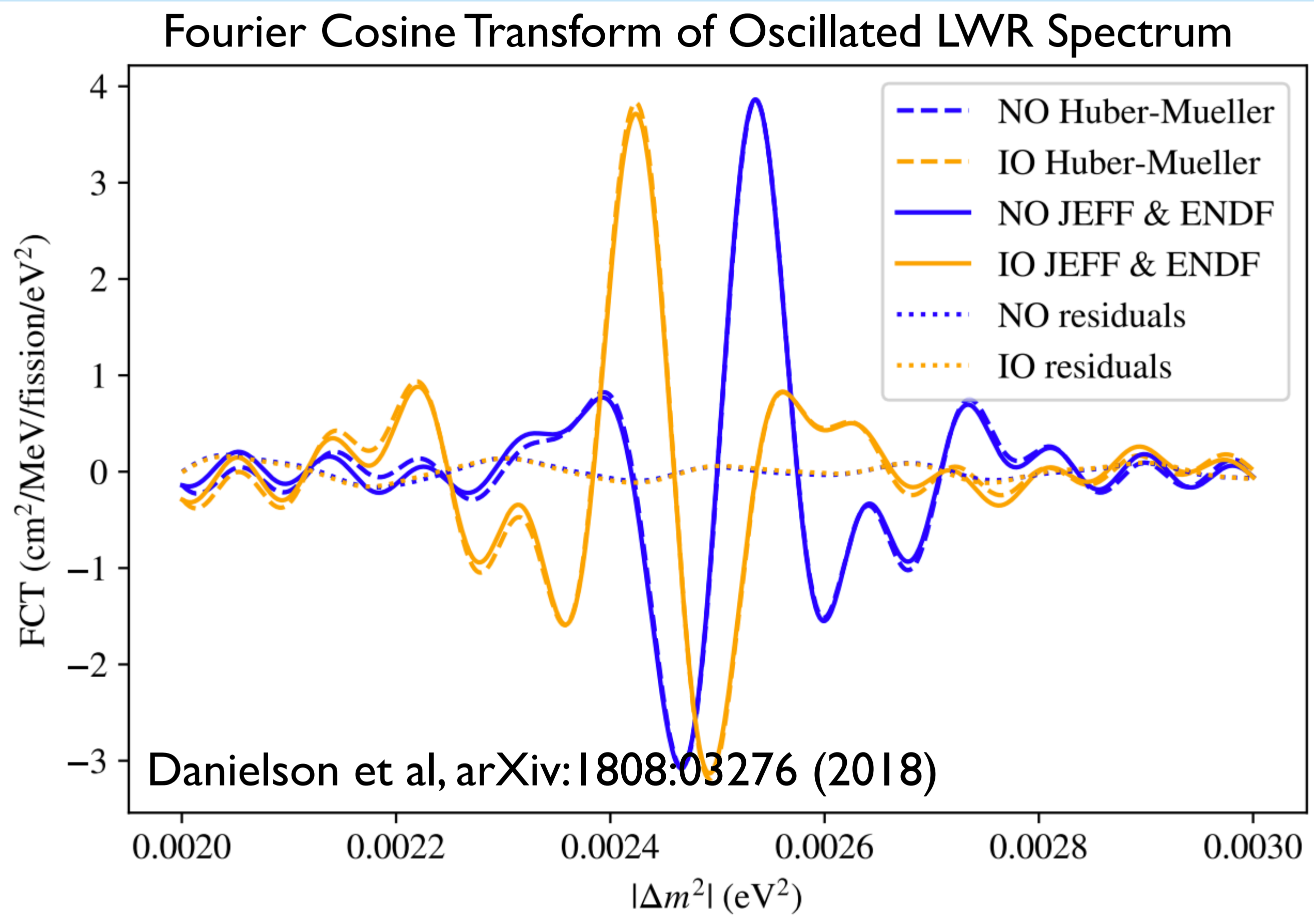
Ab initio LWR spectrum, oscillated



Danielson et al, arXiv:1808:03276 (2018)

Fine Structure: A Problem For JUNO?

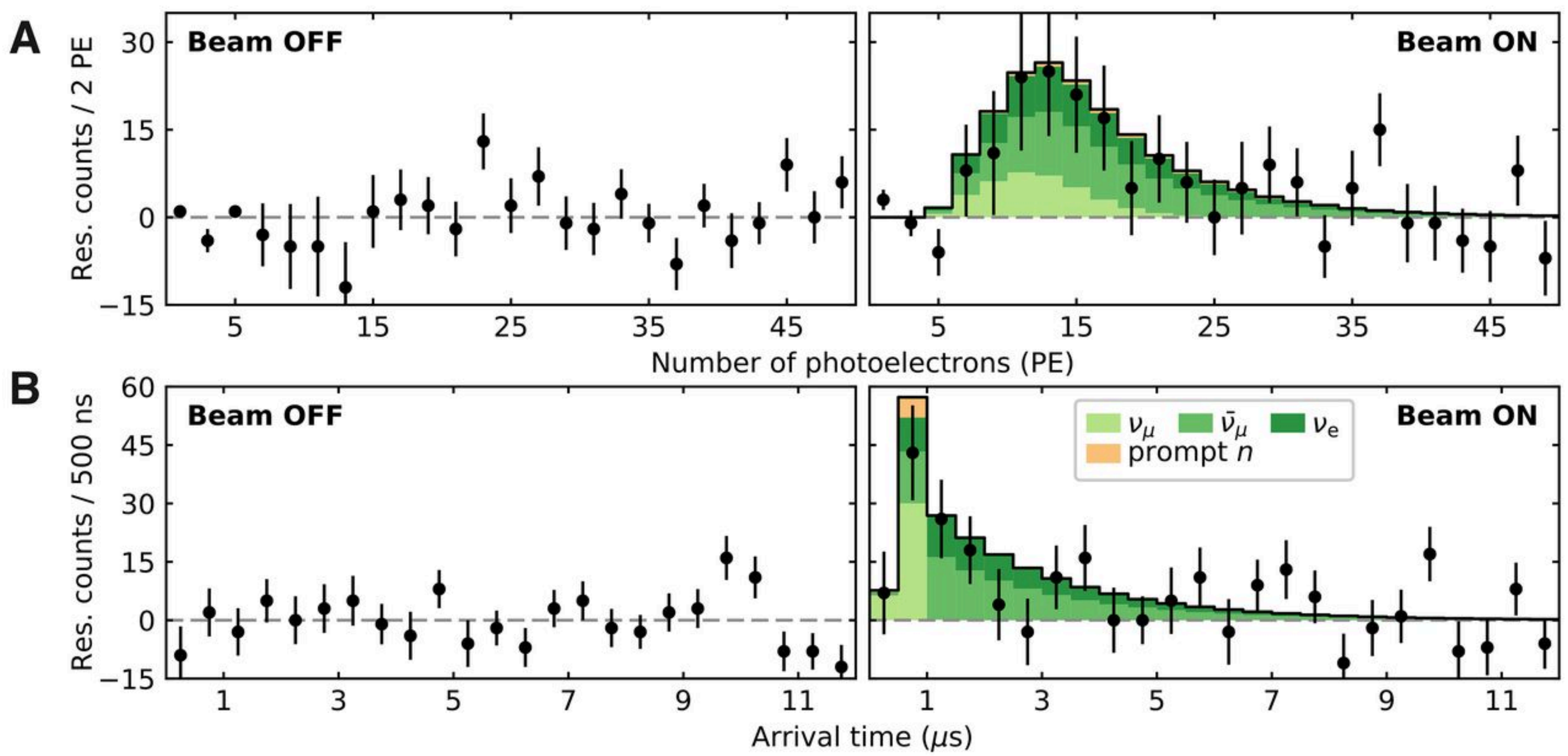
- Nuclear theorists: fine structure features are too small to affect the mass hierarchy measurement.
  - Demonstrated using a Fourier decomposition approach
- Some discussion appears to continue in community?
  - 'Fourier decomposition not used by JUNO…'
  - 'One specific energy range matters for hierarchy; what's fine structure like there?'



- Some discussion of dedicated fine structure measurements
  - Need a high-resolution detector (better than JUNO)
  - Need a high-statistics measurement (ideally much more than JUNO)
  - DYB and PROSPECT could provide some info on fine structure; optimized, dedicated detector would more precisely nail down fine structure

IBD-CEvNS Complementarity

- CEvNS is predicted by standard model with high precision
  - Precision absolute measurements of CEvNS = ability to probe BSM physics!
- Ultimate limitation for CEvNS BSM-testing with reactors: the antineutrino flux
  - As we know, we cannot trust reactor flux and spectrum predictions
  - Solution: relative measurements WRT IBD measurements
  - SM likely also predicts CEvNS-IBD ratio with high precision
- So for sake of CEvNS, let's squeeze every last improvement out of absolute IBD yield and spectrum measurements!!



PROSPECT Experiment Overview

Scientific Goals

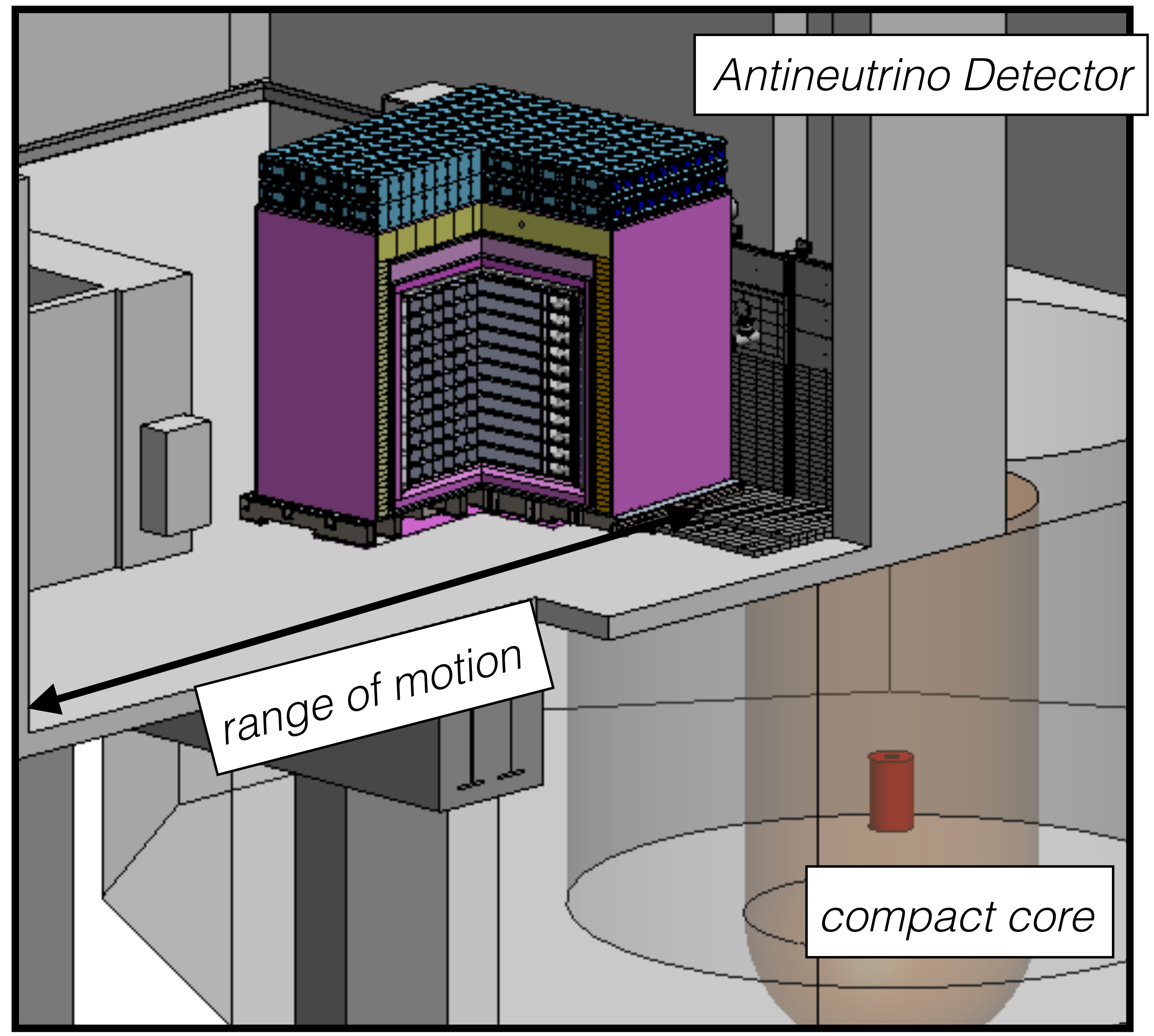
1. model independent search for eV-scale sterile neutrinos at short baselines
2. measure ^{235}U-only antineutrino spectrum to address spectral deviations

Close proximity to reactor (< 10m)

- search for sterile oscillations throughout the detector (segmented)
- high statistics for precision spectrum
- possible at research reactors, allows us to isolate a single isotope ^{235}U

Challenges at HFIR near-surface site

- backgrounds: cosmogenic fast neutrons and reactor gammas
- limited space: compact calorimeter
- current detector technology not well-matched for this environment



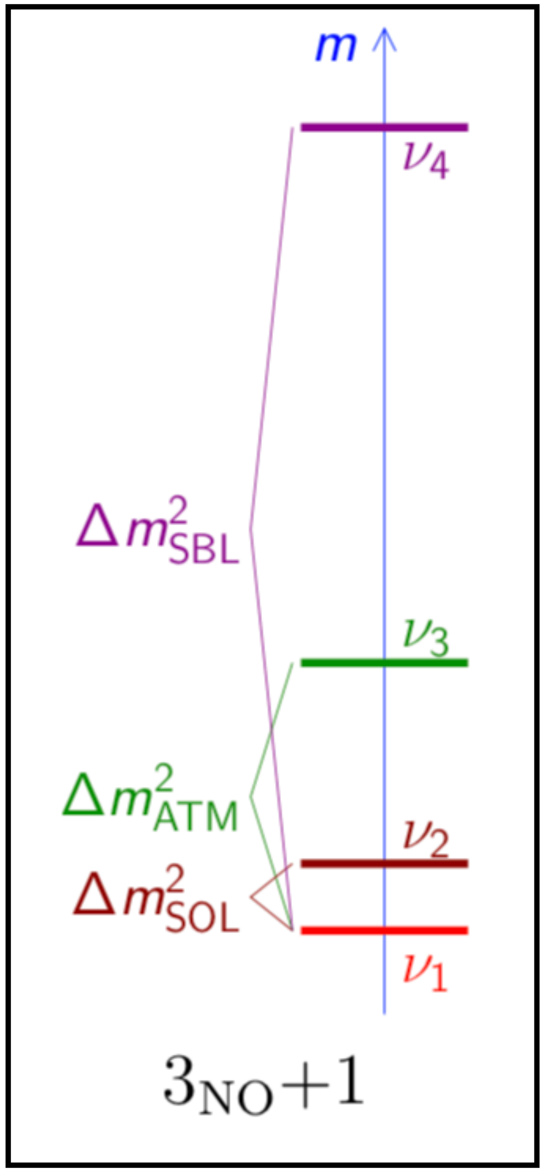
@ High Flux Isotope Reactor (HFIR), Oak Ridge National Laboratory

Active-Sterile Osc Formalism

Giunti and Lasserre, hep-ph[1901.08330]

- With 1 additional (sterile) neutrino, new PMNS matrix:

$$U = \begin{pmatrix} c_{12}c_{13}c_{14} & s_{12}c_{13}c_{14} & c_{14}s_{13}e^{-i\delta_{13}} & s_{14}e^{-i\delta_{14}} \\ \cdots & \cdots & c_{13}c_{24}s_{23} - s_{13}s_{14}s_{24}e^{i(\delta_{14}-\delta_{13})} & c_{14}s_{24} \\ \cdots & \cdots & \cdots & c_{14}c_{24}s_{34}e^{-i\delta_{34}} \end{pmatrix}$$



- Short-baseline oscillation looks like this:

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} = \left| \delta_{\alpha\beta} - \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \right|,$$

where $\Delta m^2_{41} = \Delta m^2_{\text{SBL}}$, and

$$\sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 \left| \delta_{\alpha\beta} - |U_{\beta 4}|^2 \right|.$$

- For numu, nue experiments:

$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu 4}|^2 = \sin^2 2\vartheta_{14} \sin^2 \vartheta_{24}$$ LSND/mB/uB

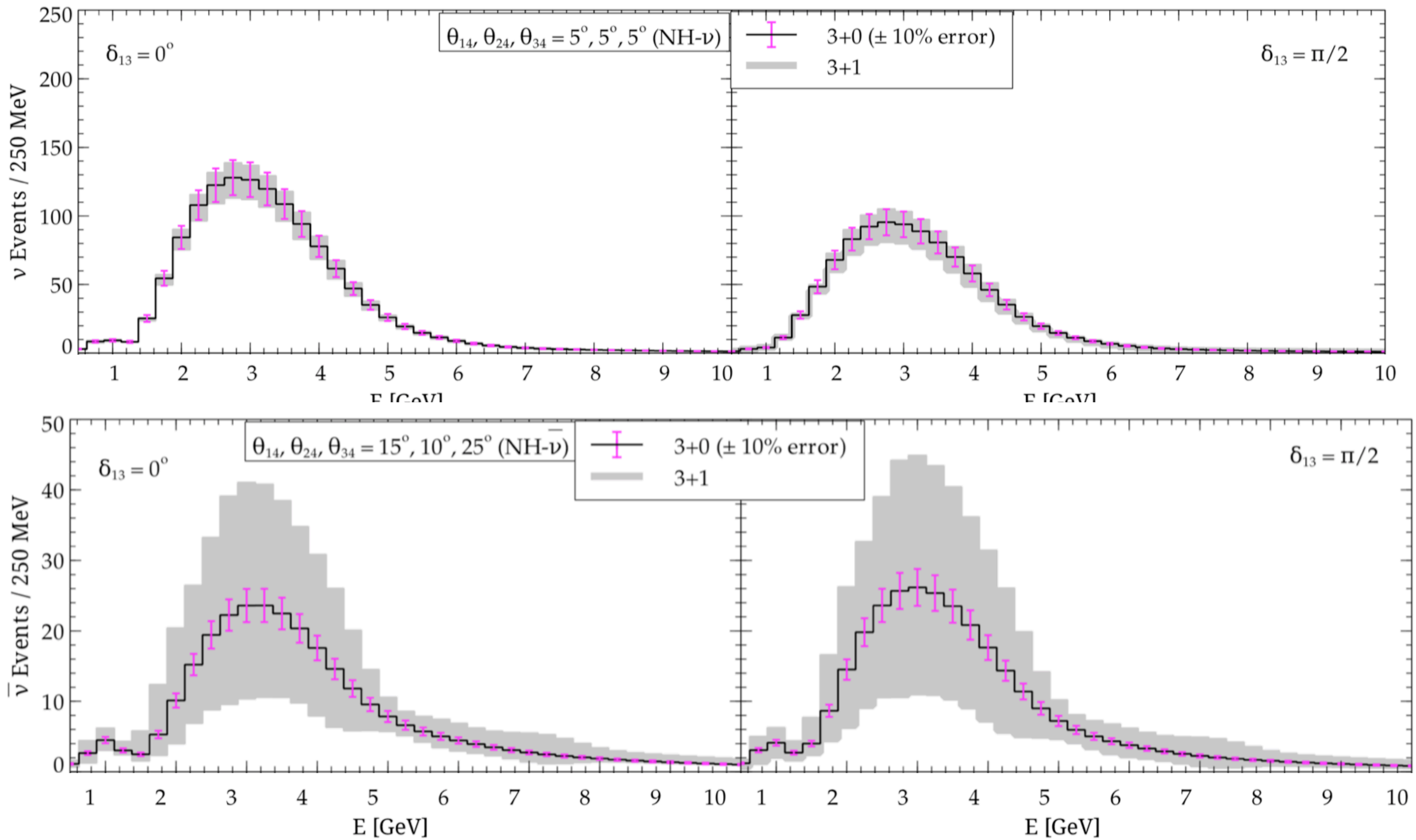
$$\sin^2 2\vartheta_{ee} = 4|U_{e4}|^2 \left(1 - |U_{e4}|^2\right) = \sin^2 2\vartheta_{14}$$ PROSPECT / short-baseline reactor

$$\sin^2 2\vartheta_{\mu\mu} = 4|U_{\mu 4}|^2 \left(1 - |U_{\mu 4}|^2\right) = \sin^2 2\vartheta_{24} \cos^2 \vartheta_{14} + \sin^2 2\vartheta_{14} \sin^4 \vartheta_{24} \simeq \sin^2 2\vartheta_{24}$$ MINOS+

Active-Sterile Osc and LBL CP-Violation

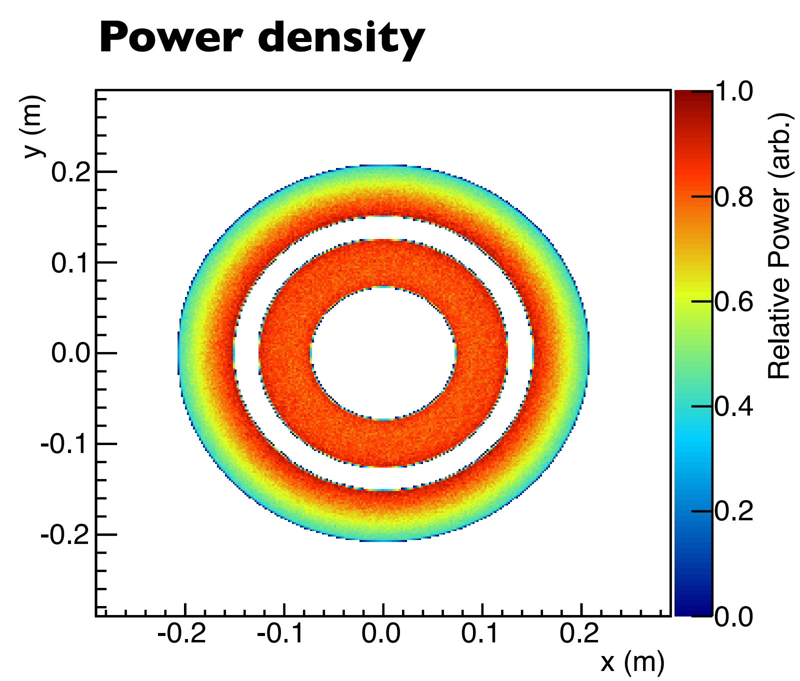
- To avoid obscuring LBL CP-violation interpretation, would be best to have O(5%) constraints on $\sin^2 2\theta_{x4}$

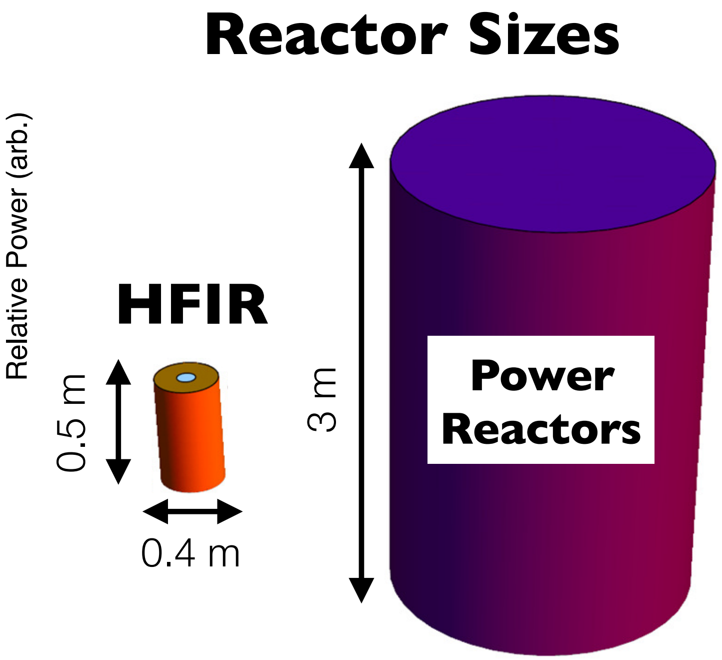
Dutta, Gandhi, Kayser, Masud, and Prakash, JHEP 2016:122
B. Kayser, 2016 PITT PACC SBN Workshop

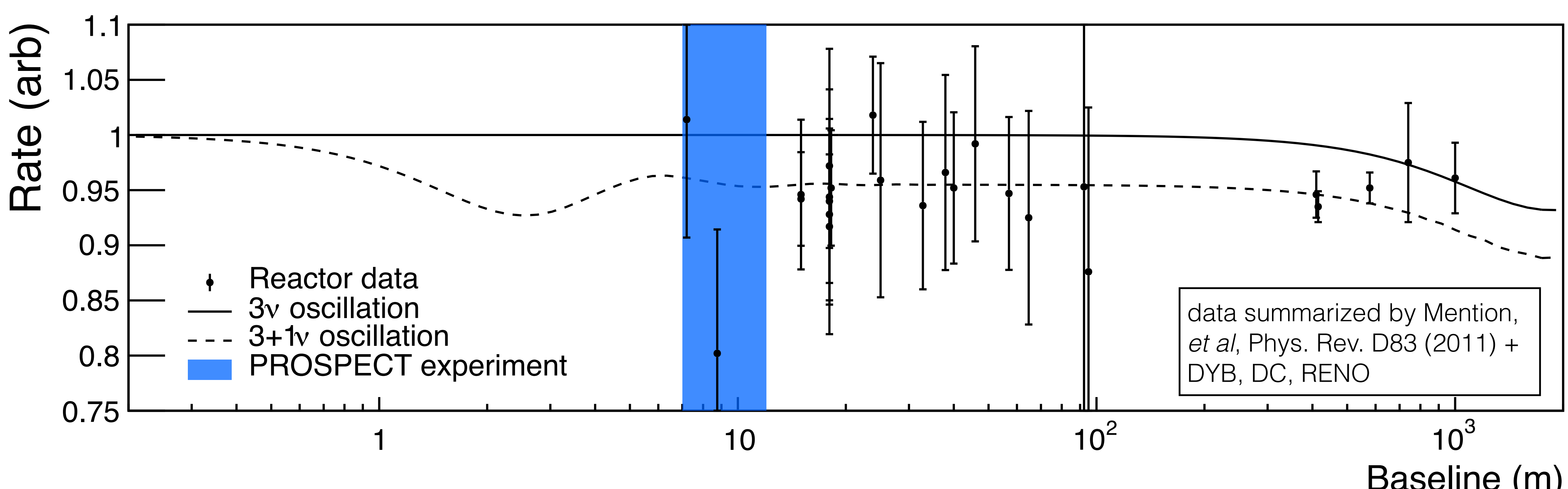


High Flux Isotope Reactor (HFIR)

- 85MW highly enriched uranium reactor
- >99% of ν from ^{235}U, ~no isotopic evolution
- 24-day cycles, 46% RxOn; RxOff: measure background
- Compact cylindrical core: 0.2m radius, 1m height
- Baselines 7-12m within mobile detector

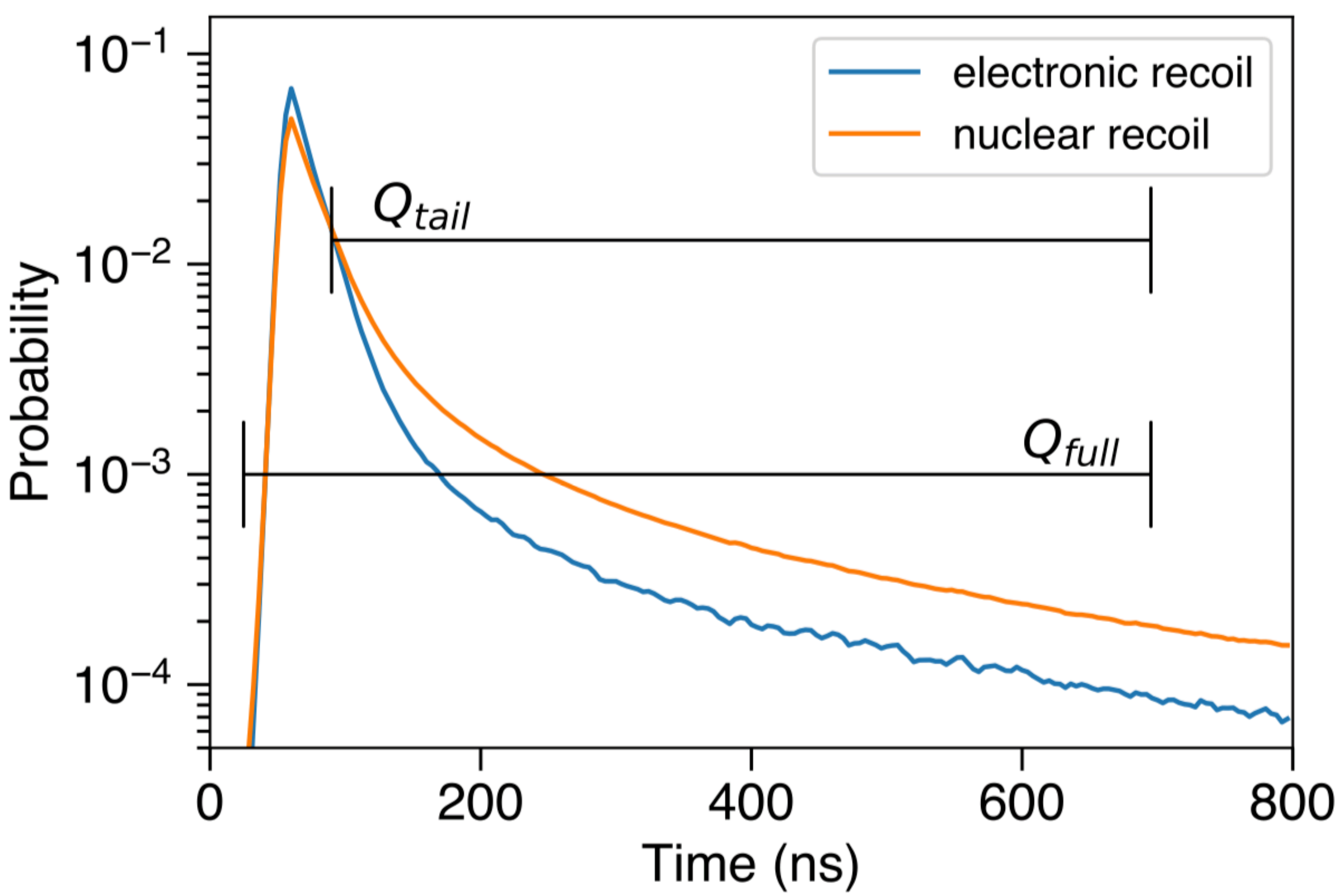




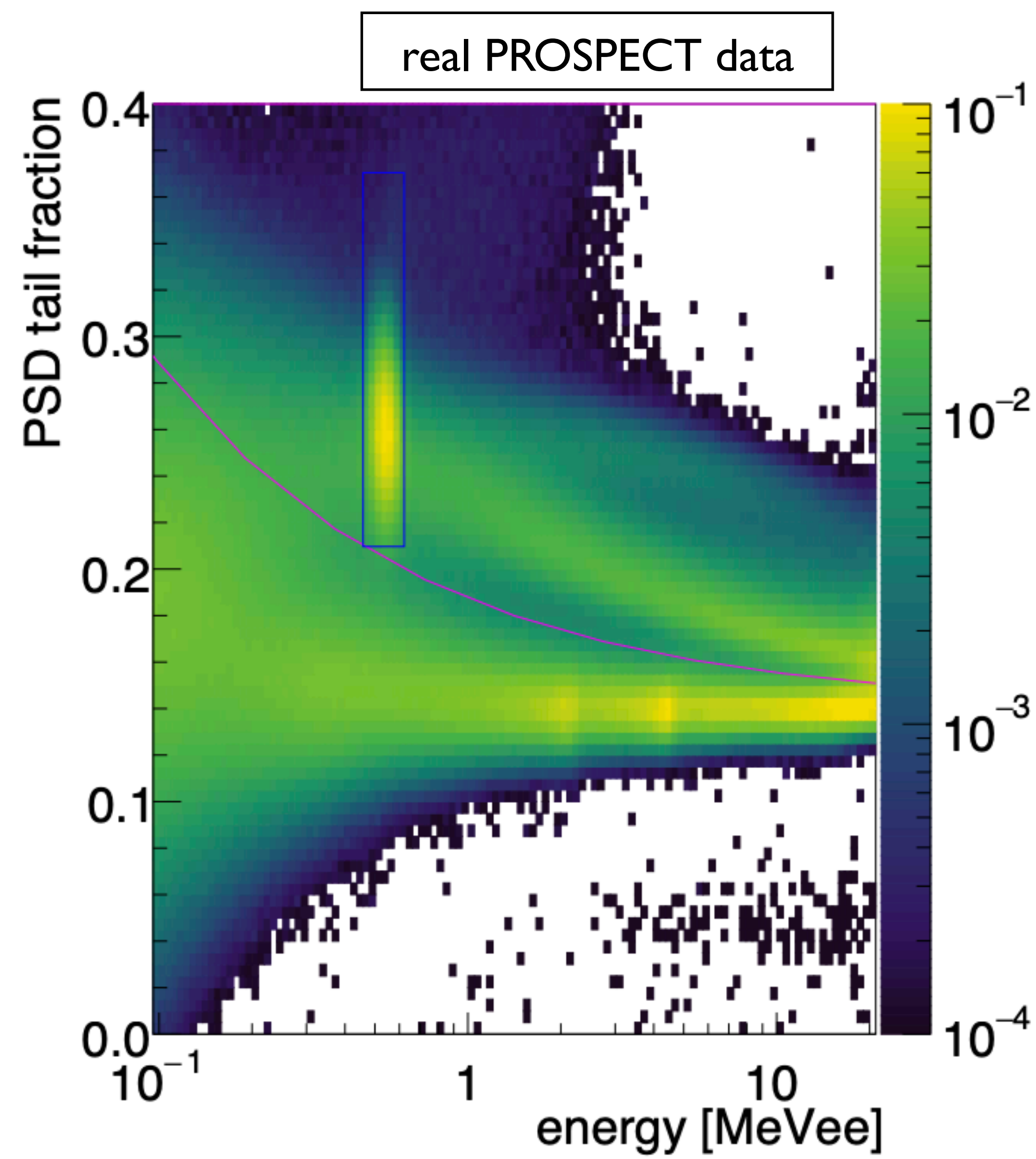


Pulse-Shape Discriminating ^{6}LiLS

- Developed ^{6}LiLS with capabilities to distinguish particles through their scintillation timing profile (ionization density).
- PSD adds powerful information to identify IBD and reject backgrounds
- A multi-year R&D effort to optimize PSD, geometry, optics, etc.



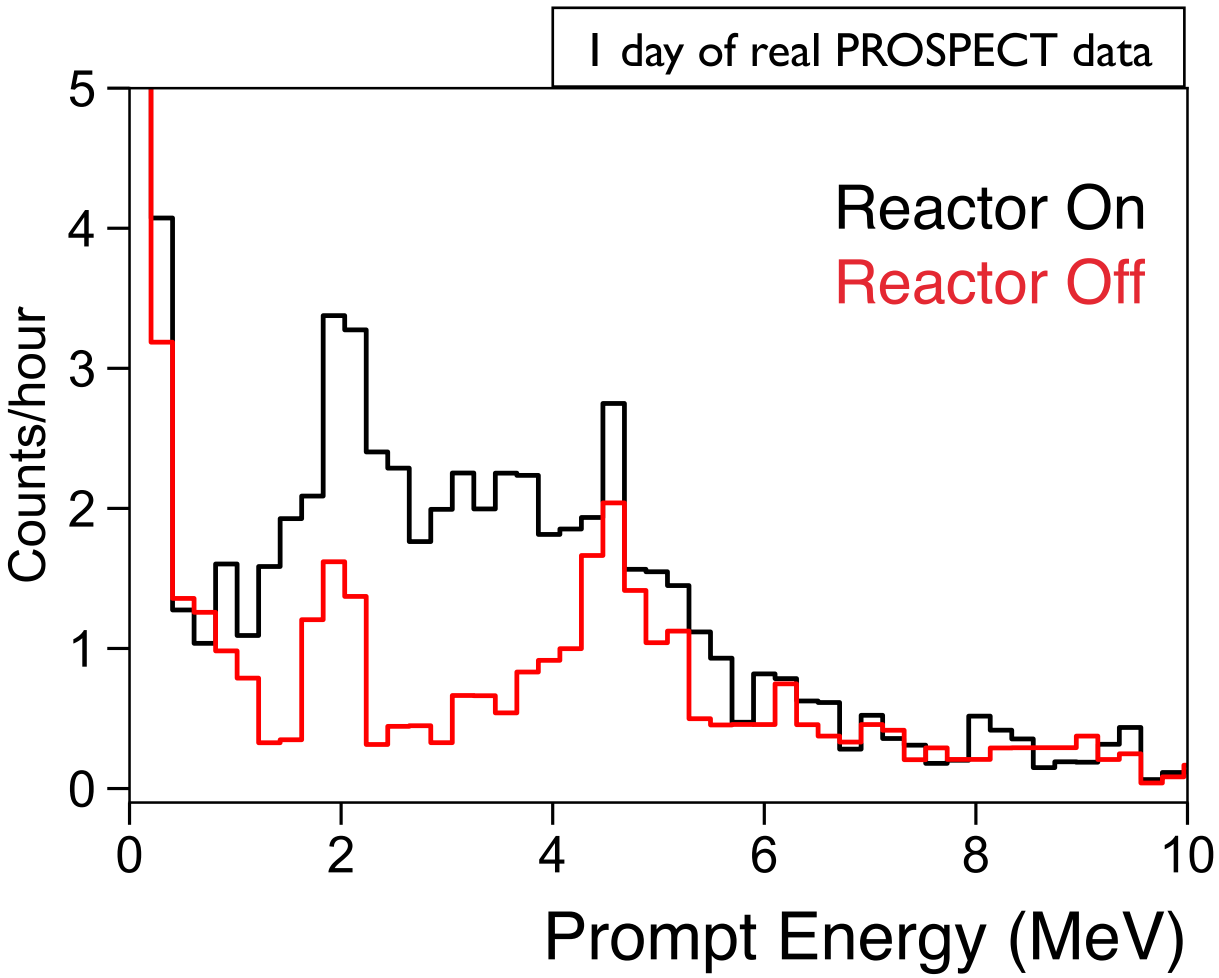
PSD = Qtail/Qfull

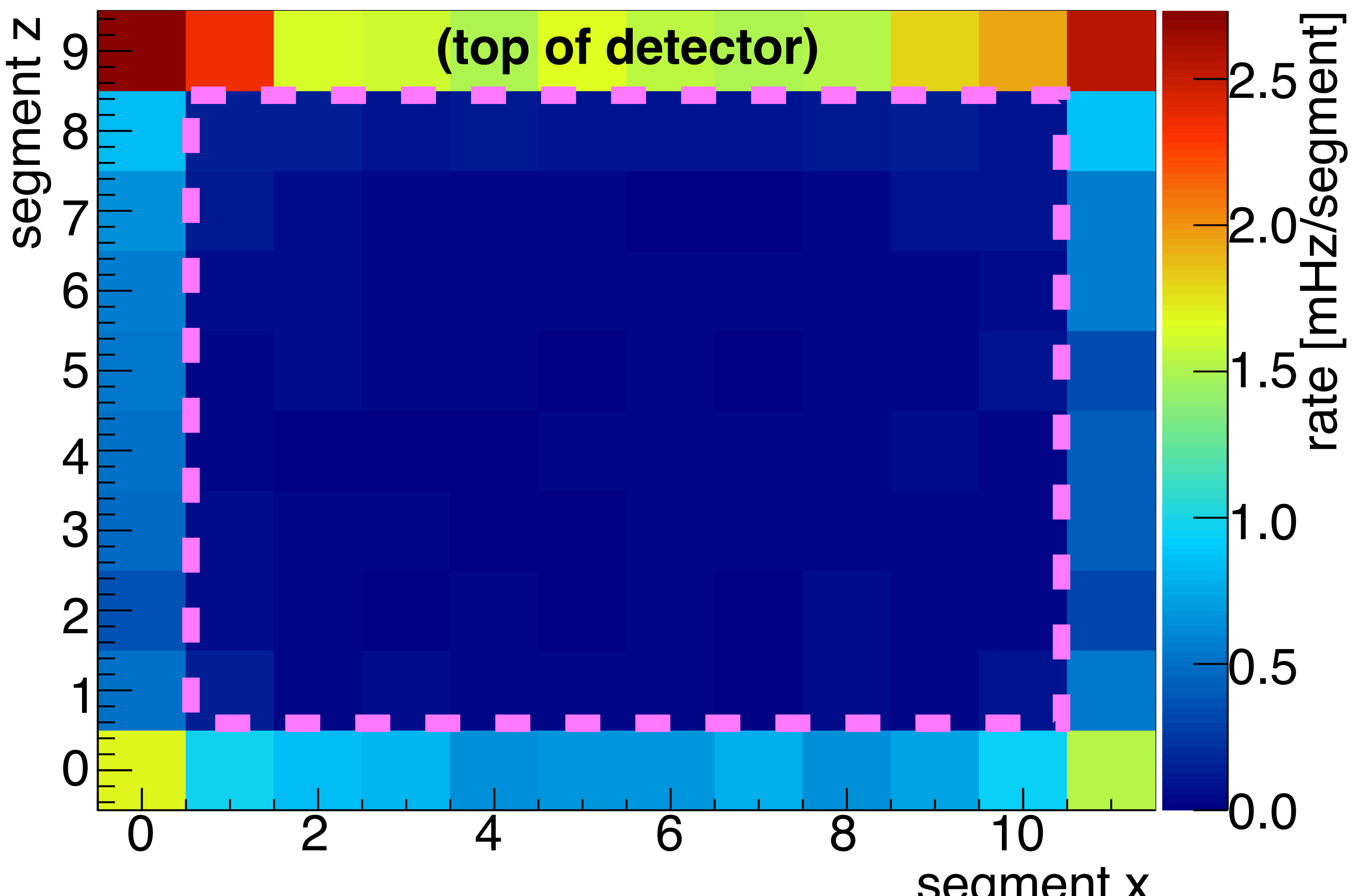


PROSPECT, NIM A806 401 (2019)

Combatting Backgrounds On-Surface

- Near-surface backgrounds: cosmogenic fast neutrons, reactor gammas
- Combination of segmentation, ^{6}Li liquid scintillator, particle ID powerful
- **PSD**, **shower veto**, **topology**, and **fiducialization** cuts provide >10^4 active background suppression (signal:background > 1)



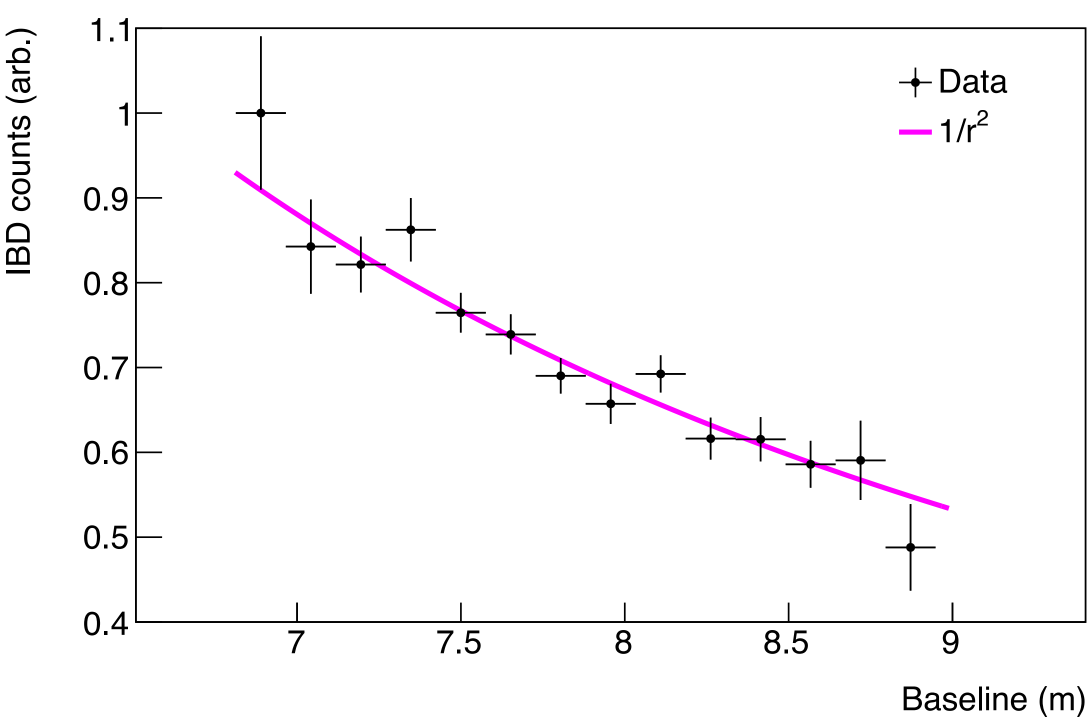


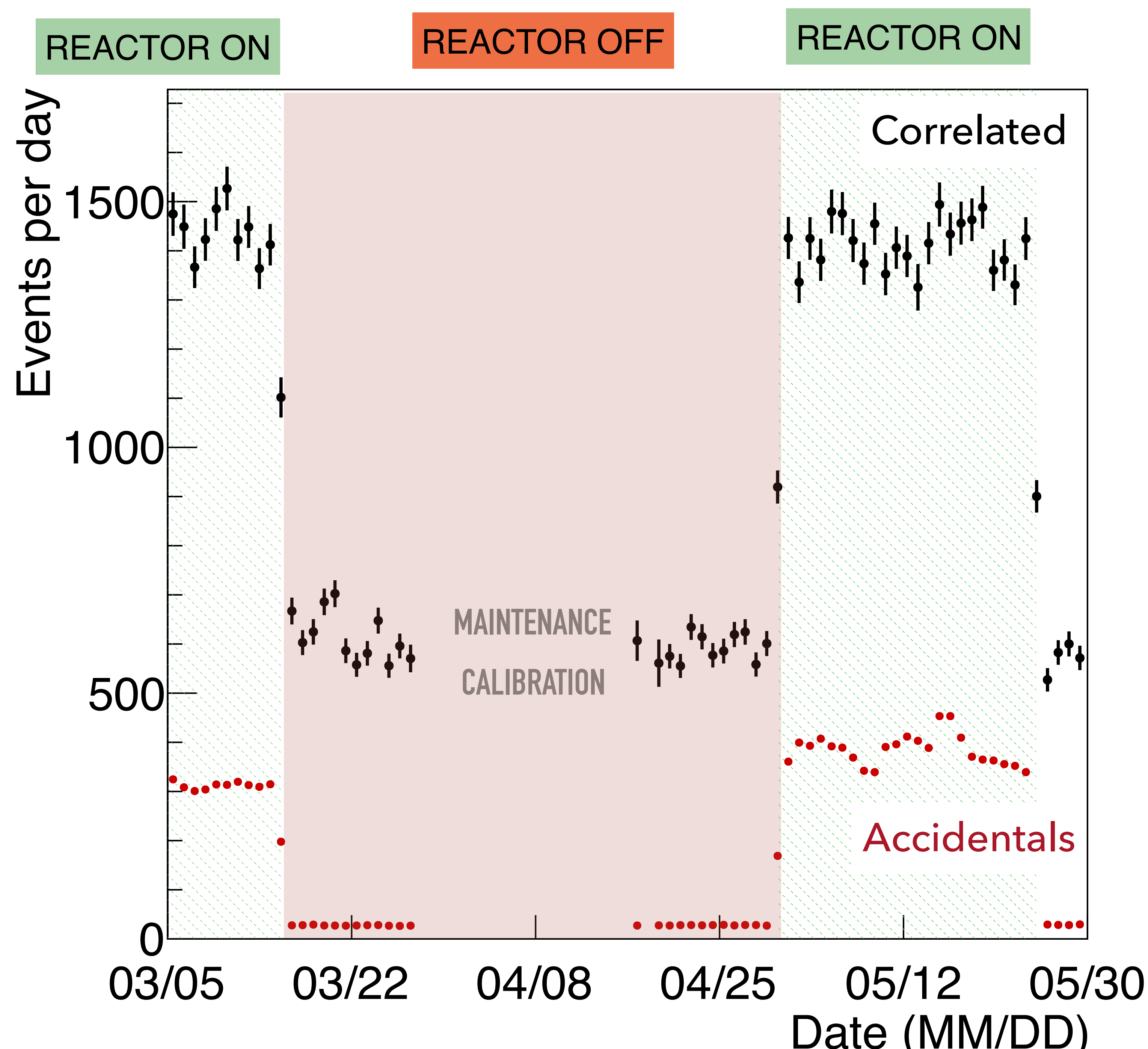
PROSPECT, NIM A806 401 (2019)

PROSPECT, J. Phys. G 43 (2016)

Review: Sterile Oscillation Dataset

- 33 days of Reactor On
- 28 days of Reactor Off
- From 0.8-7.2 MeV prompt:
  - ~25,000 IBD interactions
  - average of ~770 IBDs/day
  - **correlated S:B = 1.32**
  - **accidental S:B = 2.20**
  - IBD selection defined and frozen on 3 days of data
- Segment-to-segment 1/r² drop-off clearly visible



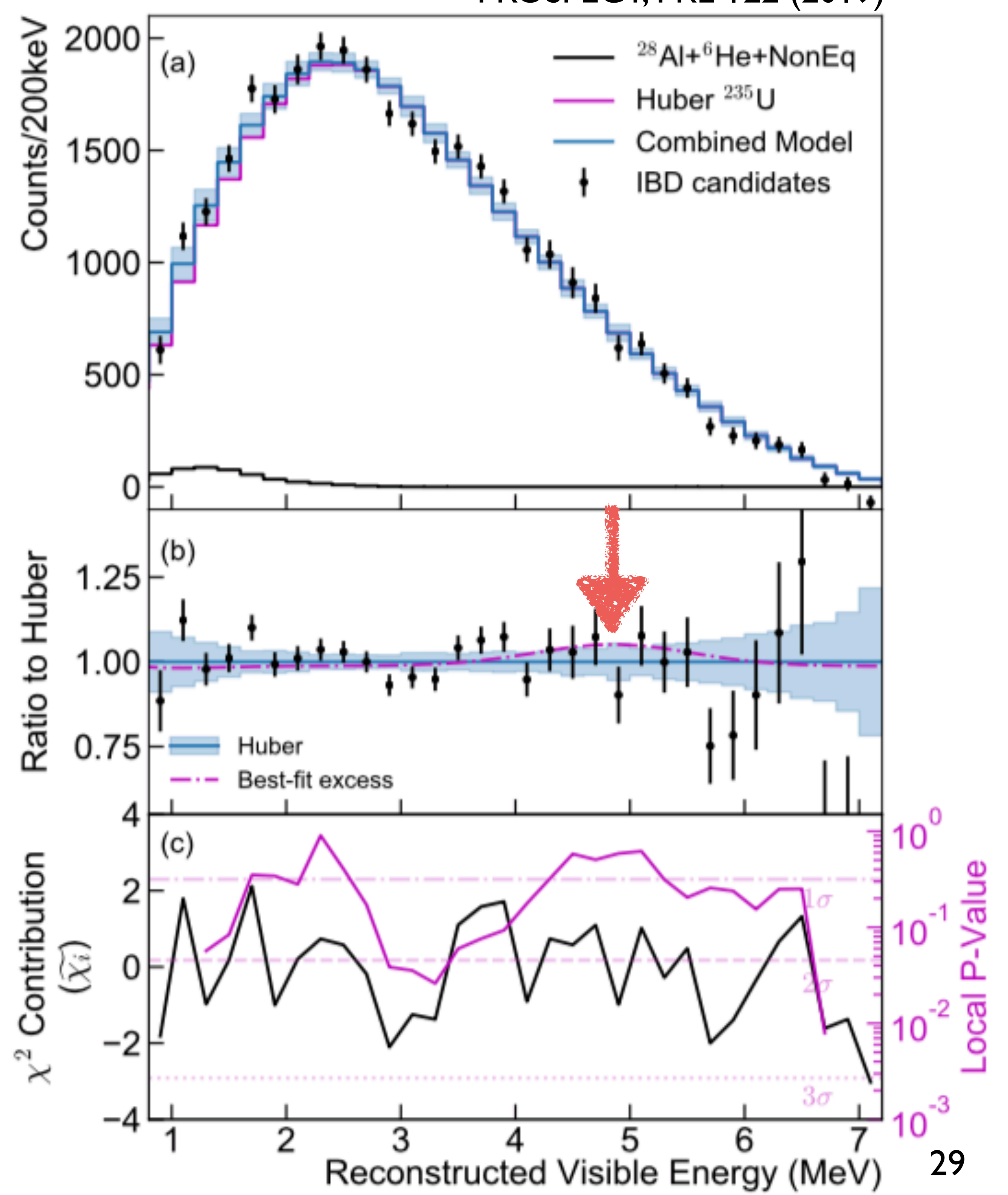


PROSPECT, PRL 121 (2018)

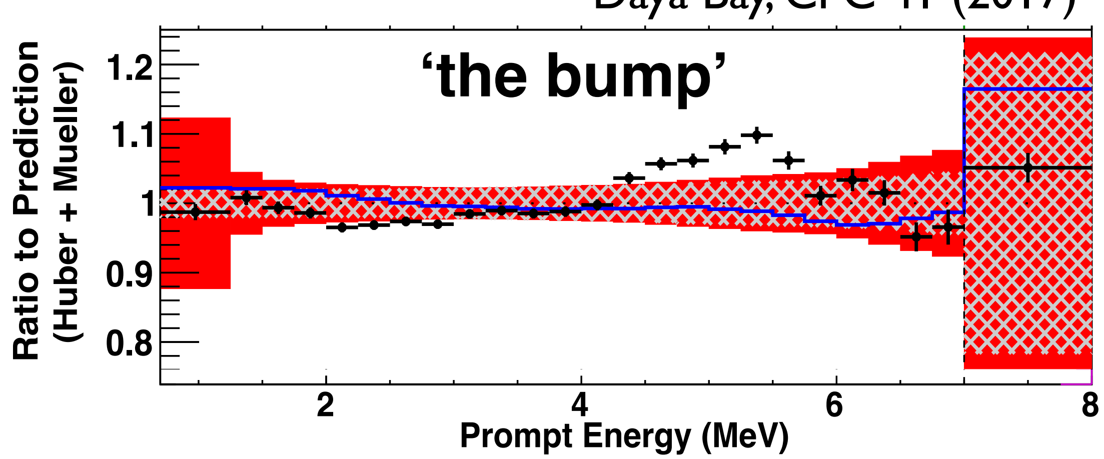
PROSPECT ^{235}U Spectrum Result

- Background-subtracted ^{235}U spectrum result
- How does PROSPECT compare to 'bump' in LEU θ_{13} experiments?
  - PROSPECT relative bump size WRT to Daya Bay: 69% ± 53%
  - ~consistent with 'no bump' (0%) and 'DYB-sized bump' (100%)
  - 'Big bump' (178%) if ^{235}U is the sole bump contributor
    - Disfavored at 2.1σ

PROSPECT, PRL 122 (2019)



Daya Bay, CPC 41 (2017)



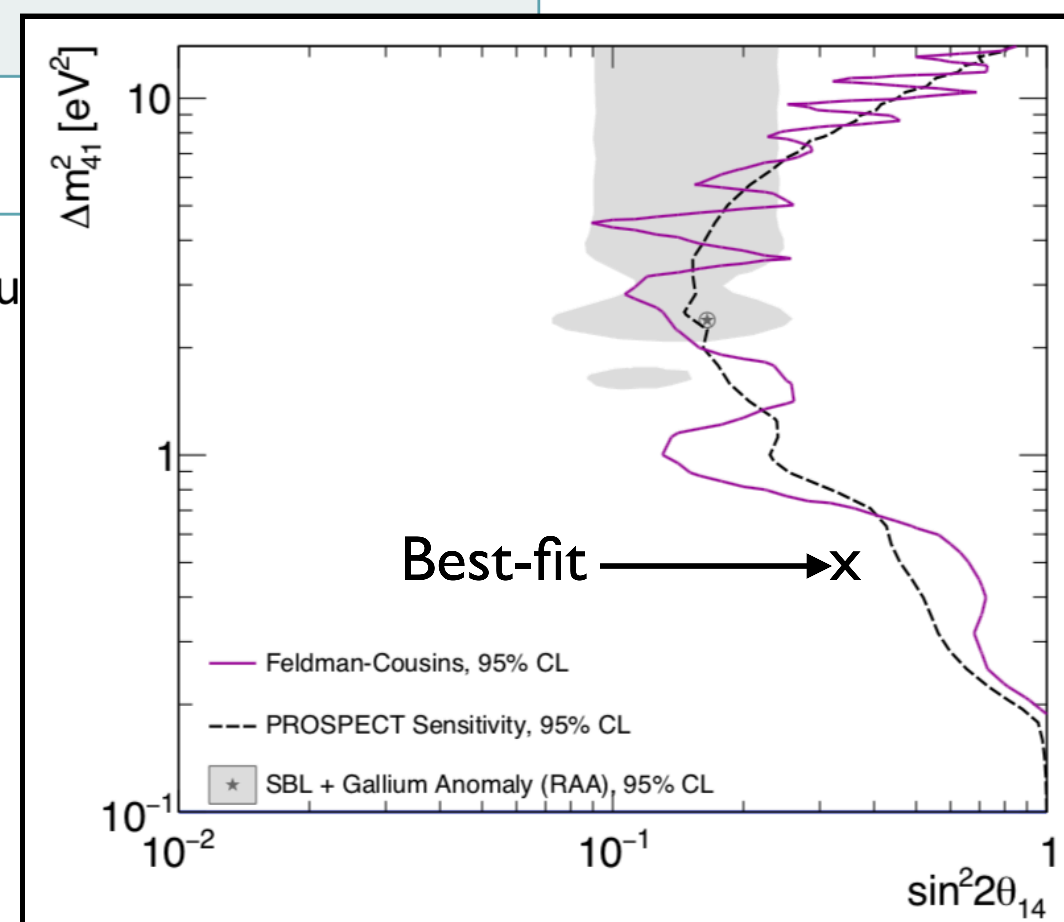
Neutrino-4

Feldman-Cousins Approach

- ❑ Standard (incorrect) method does not handle boundary features such as bounded nature of $sin^2 2\theta$ (0,1) or cases when oscillation frequency approaches energy bin size. Feldman-Cousins method solves those problems
- ❑ Comparing p-values for Feldman-Cousins and standard (incorrect) methods:

P-values	3ν-oscillation hypothesis	RAA sterile ν oscillation hypothesis
Feldman-Cousins	0.58	0.013
Standard (incorrect) confidence intervals assignment	0.14	0.005

- ❑ If standard (incorrect) confidence levels used instead of Feldman-Cou
  - We say 3ν is less compatible with data than it actually is
- ❑ Illustrates an importance of using Feldman-Cousins



Neutrino-4

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...ile ν oscillation

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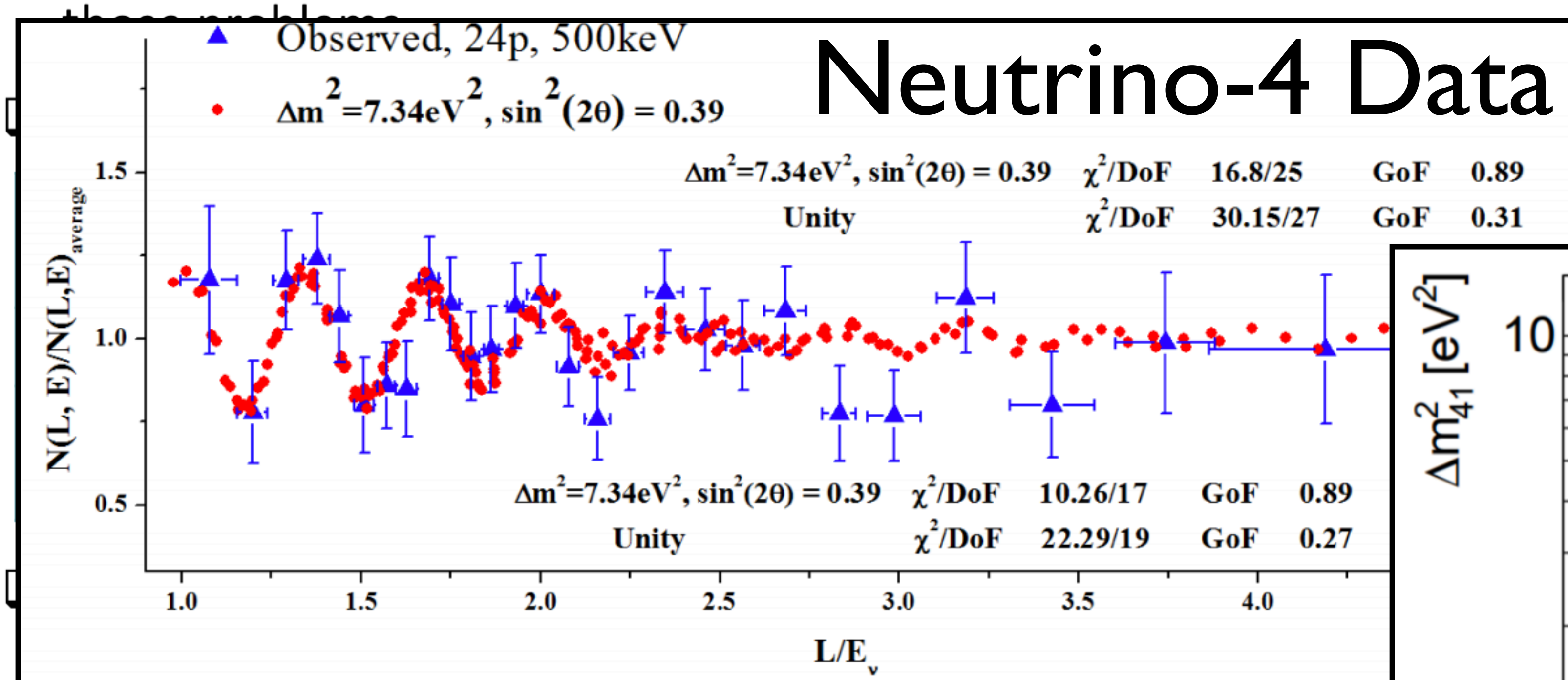

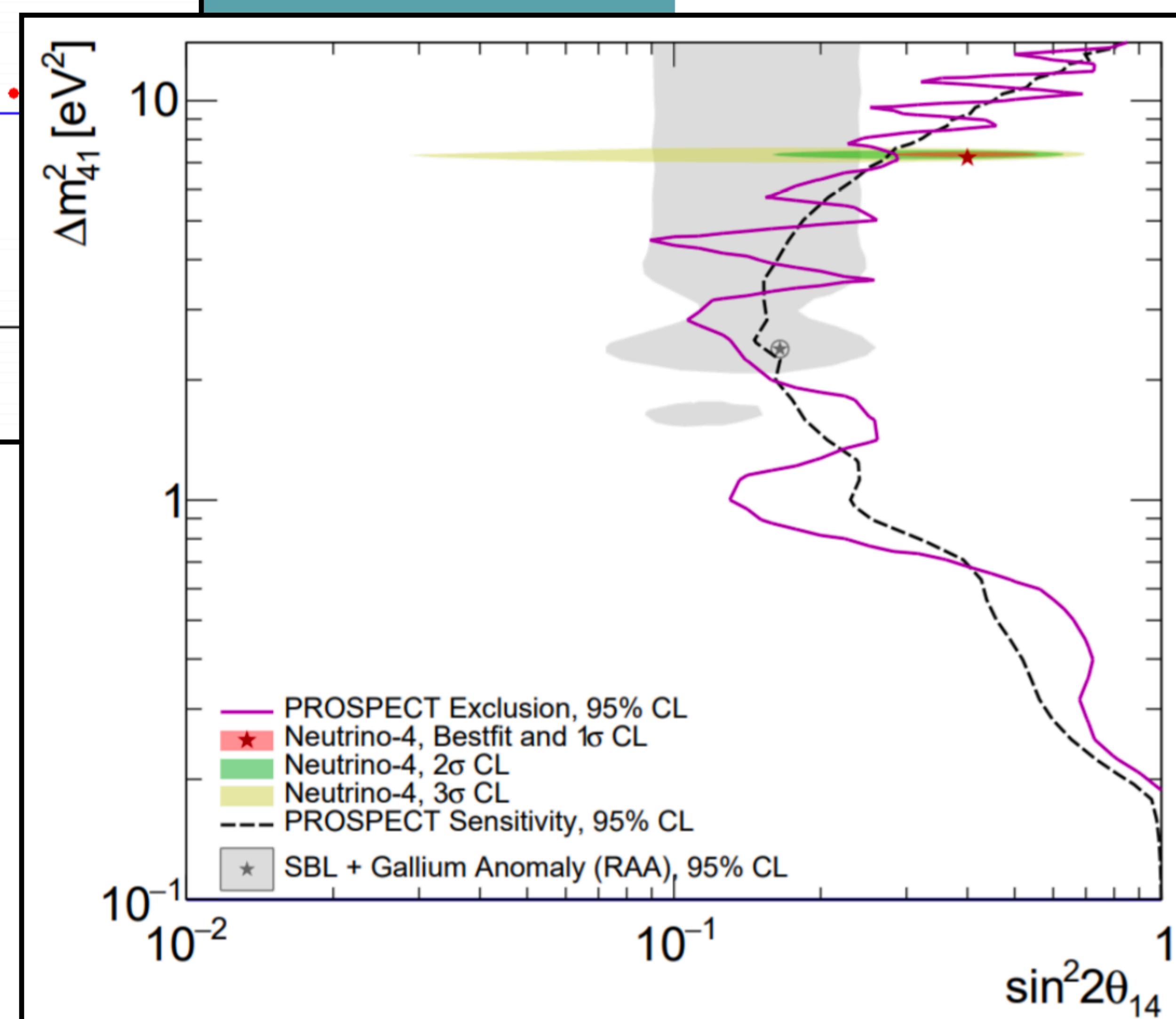

- Illustrates an importance of using Feldman-Cousins