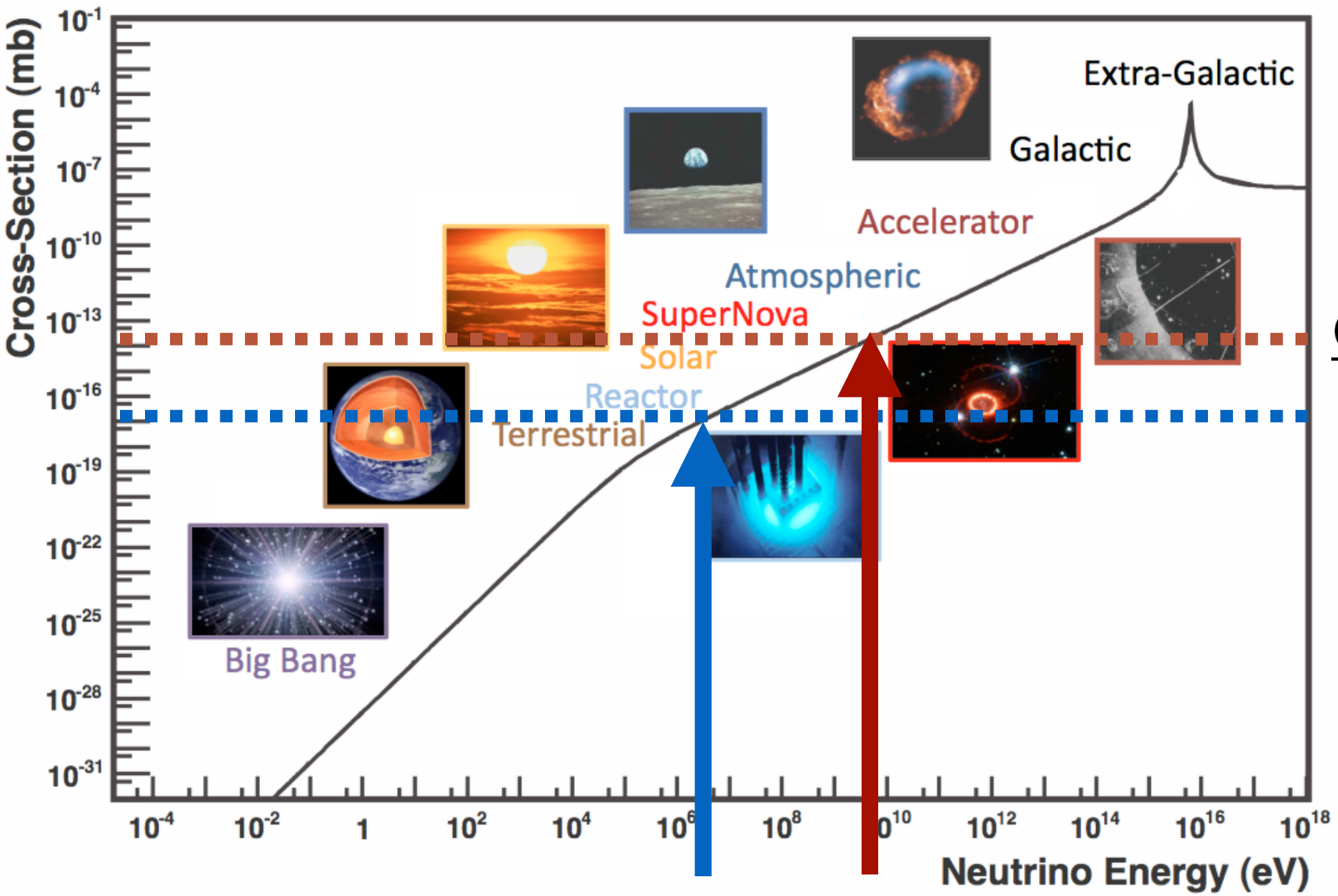
Recent Reactor $\bar{\nu}_e$ Results From the PROSPECT Experiment

April 11, 2019

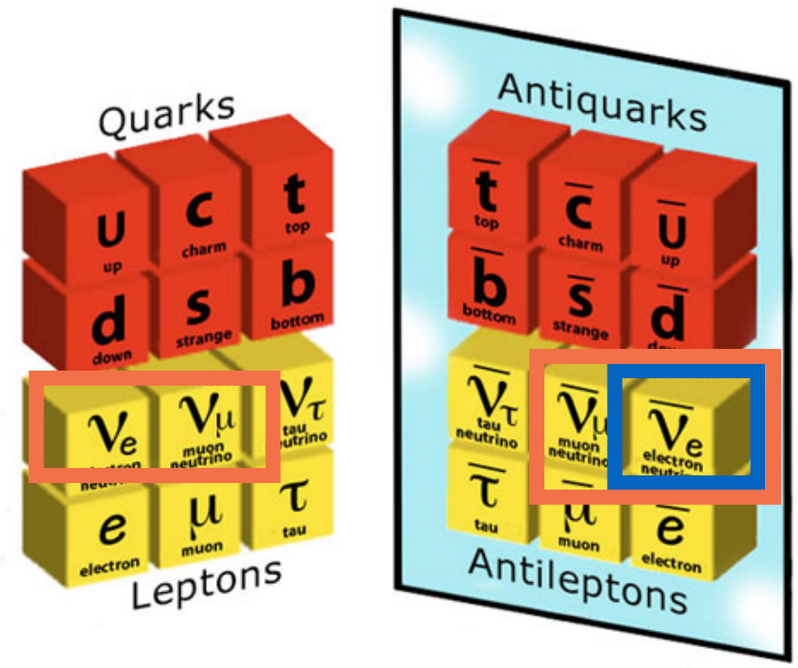
Bryce Littlejohn
Illinois Institute of Technology

Reactor Neutrinos

- 'I know Fermilab's νs; what's different about reactor νs?'



Cross-Sections: much lower!



Energy: 1-10 MeV, not 1-10 GeV

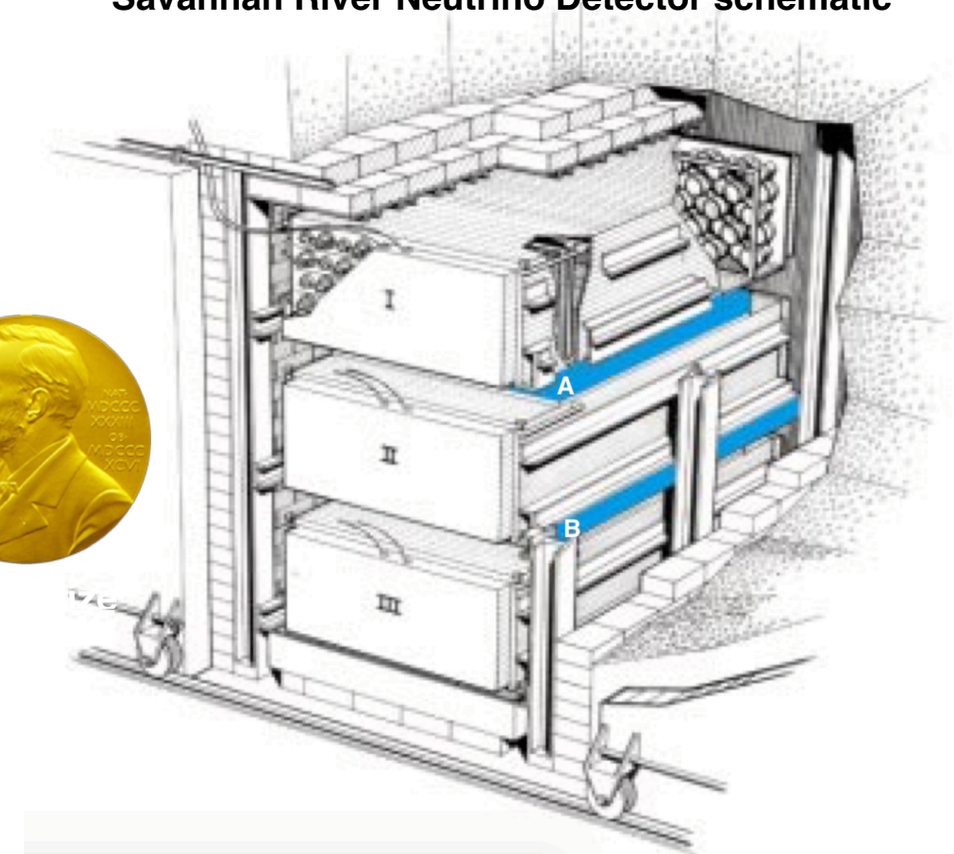
Intensity: In 1 minute, a 1GW core makes more ν than all NUMI+BNB ν produced in 2018
(yes, both DAR and DIF ν)

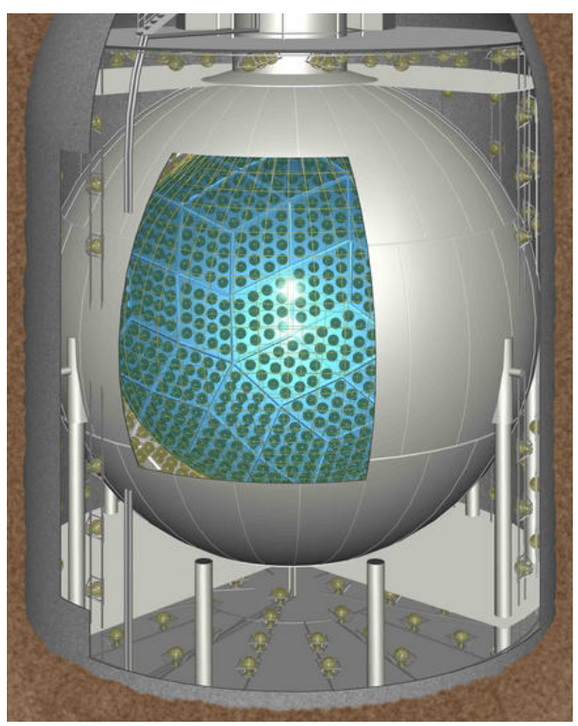
Flavor: $\bar{\nu}_e$ only, not ν_e, ν_μ, $\bar{\nu}_e$, $\bar{\nu}_\mu$

What's Been Done With Reactor Neutrinos?

- 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}, θ_{12}, $|\Delta m^2_{31}|$

Savannah River Neutrino Detector schematic





KamLAND Detector

2016 Breakthrough Prize

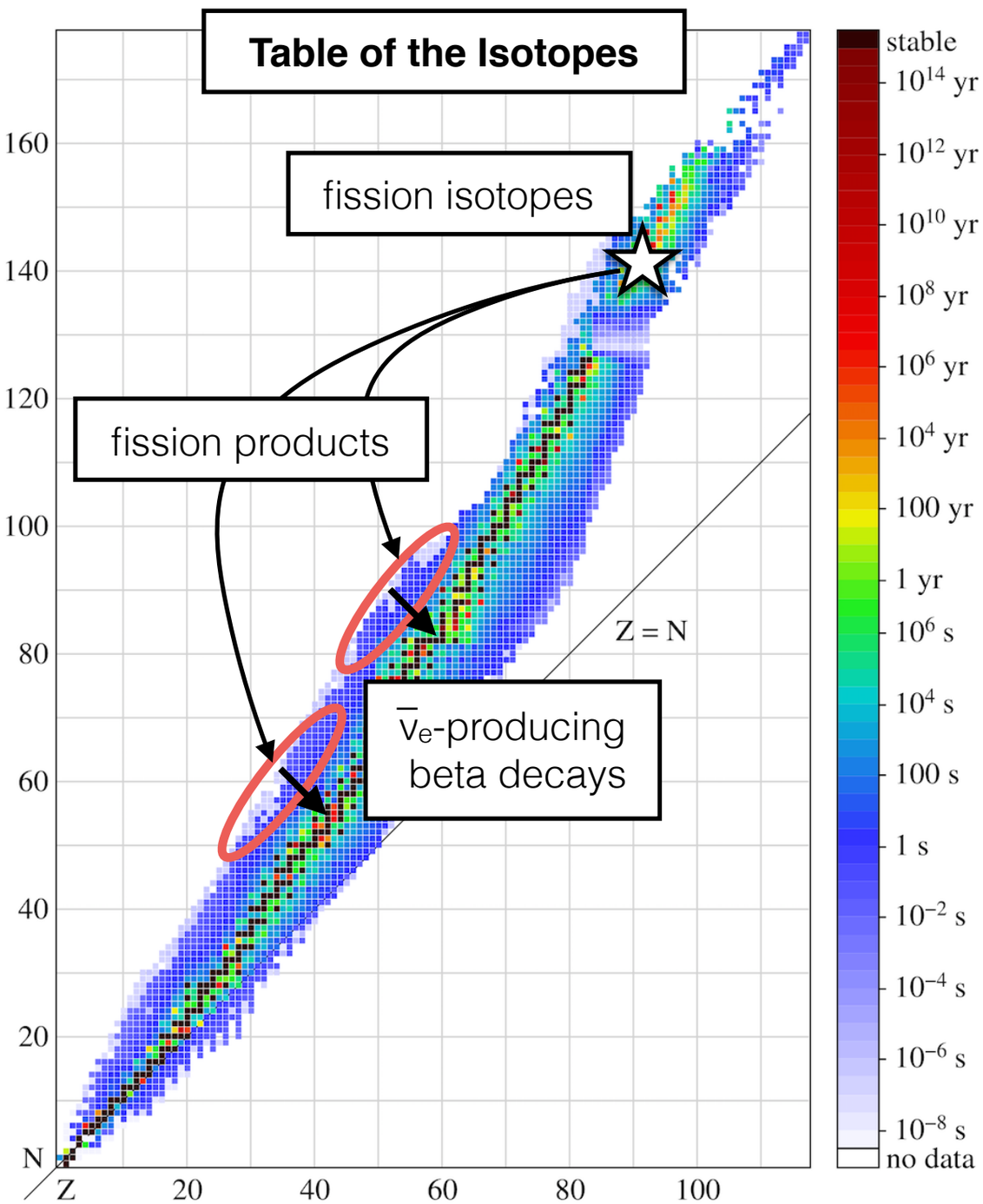
Daya Bay Far Site

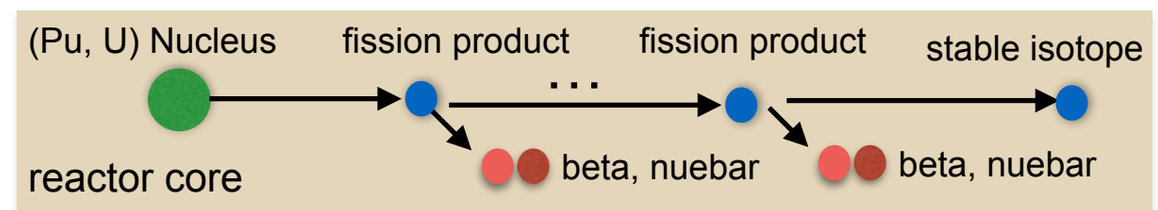
What We've Been Doing Very Recently

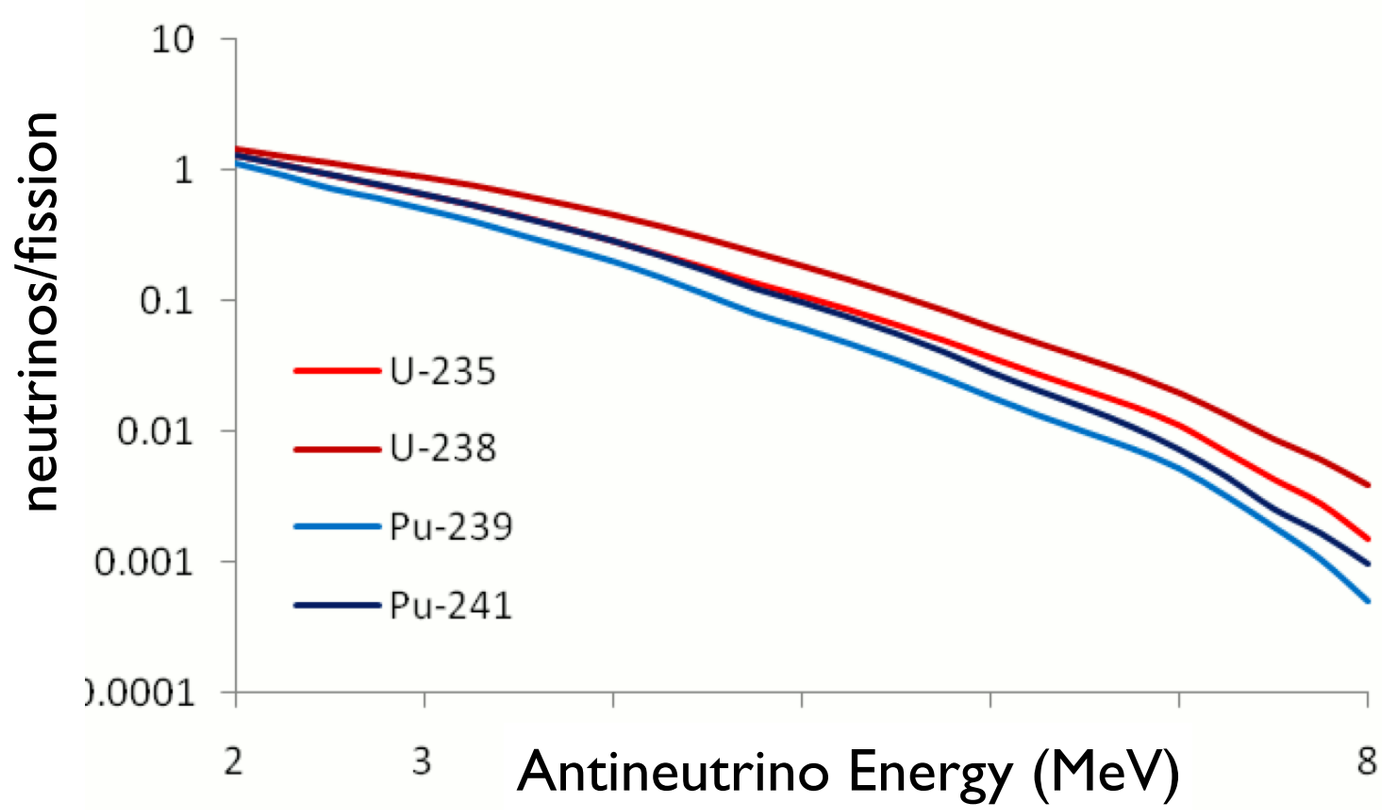
- Important questions remain that have big implications
  - Do we understand reactor neutrino fluxes?
    - Sterile neutrinos?
  - Do we understand reactor neutrino energies?
    - Bad nuclear data; implications for nuclear applications?
    - Mass hierarchy measurements at reactors?

Reactor Antineutrino Production

- Reactor $\bar{\nu}_e$: produced in decay of product beta branches
  - Each isotope: different branches, so different neutrino energies (slightly)

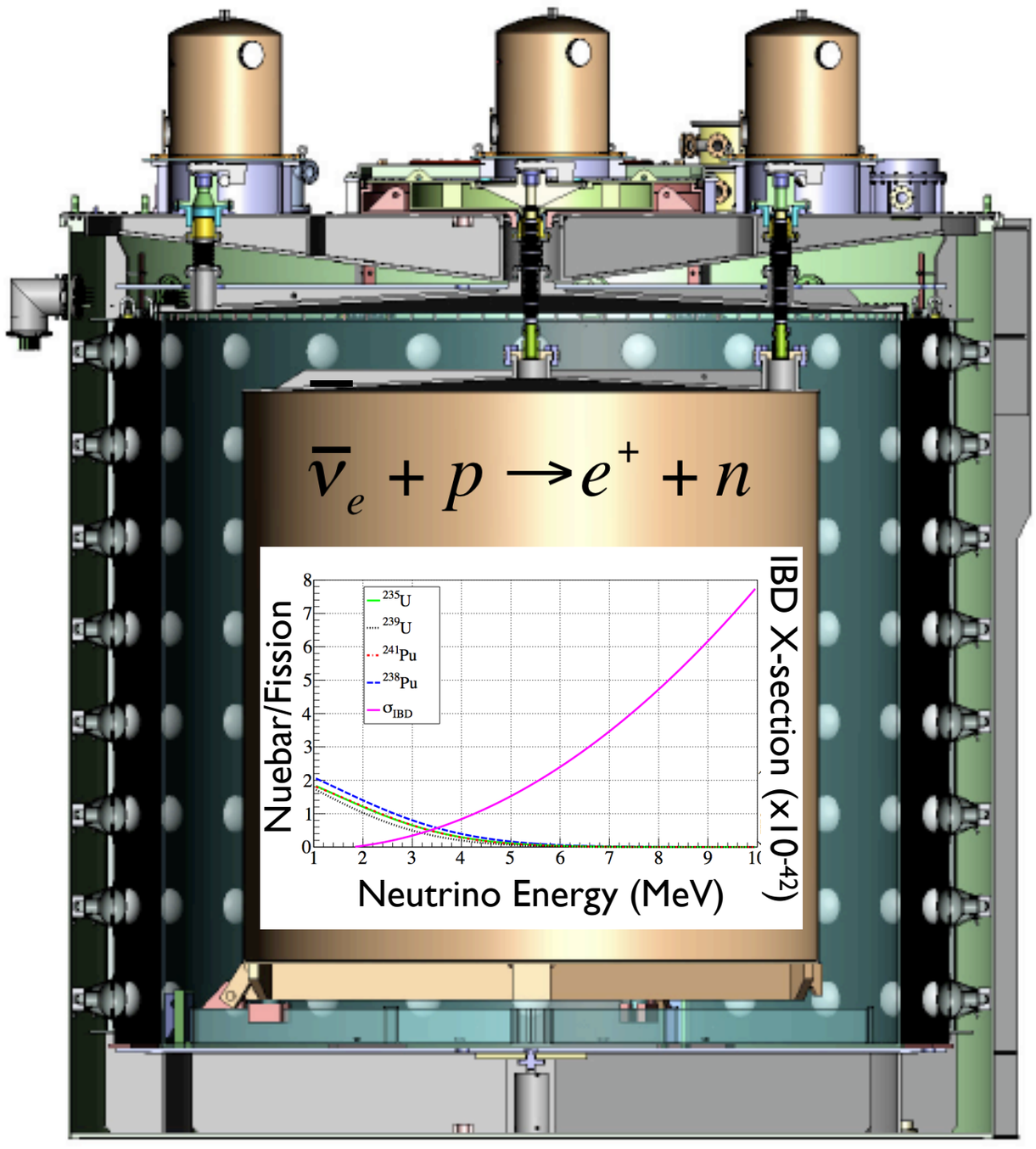




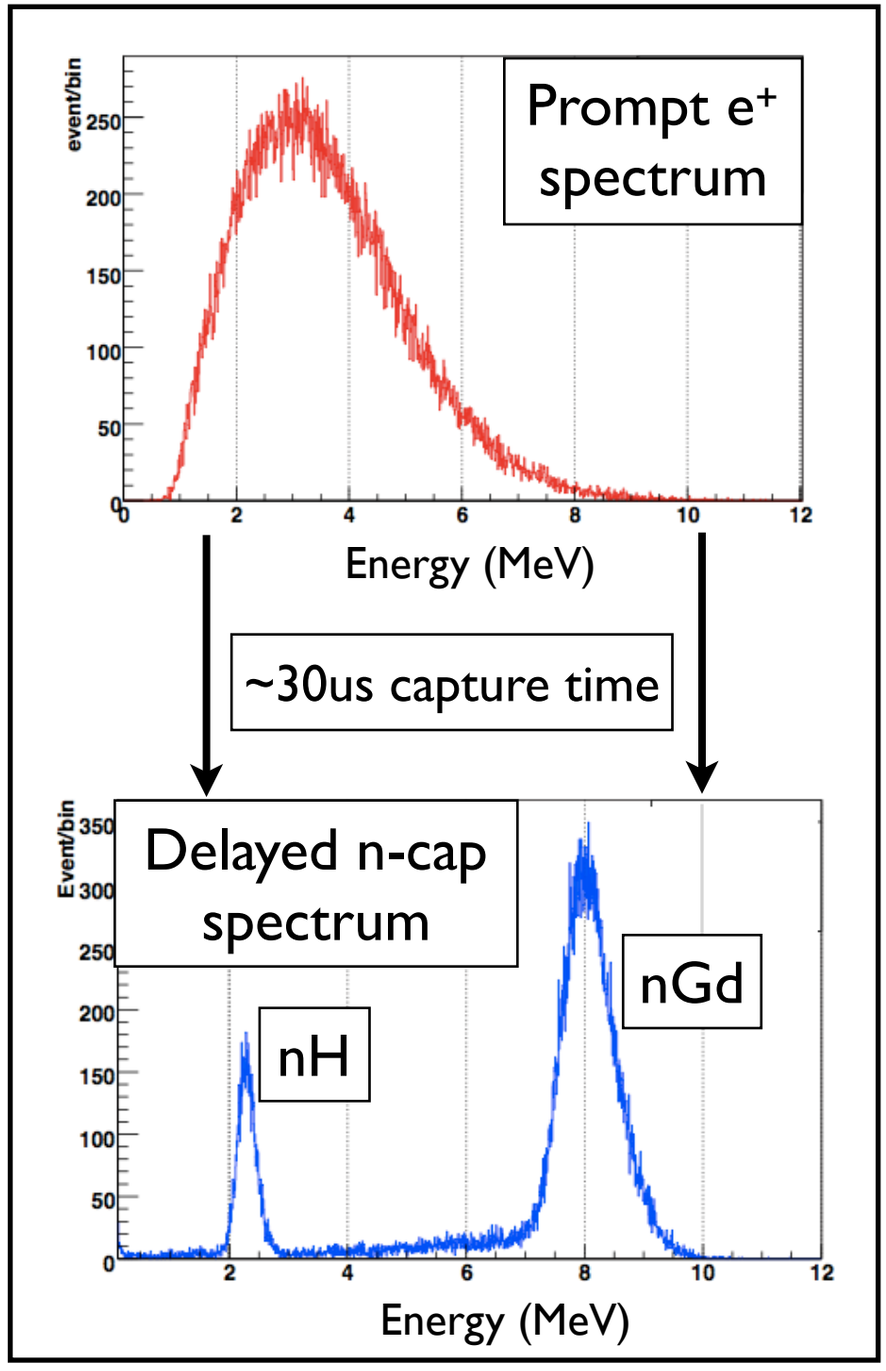


Reactor Antineutrino Detection

- Detect inverse beta decay with liquid or solid scintillator, PMTs
  - IBD e+ is direct proxy for antineutrino energy



Example: Daya Bay Detector



Daya Bay Monte Carlo Data

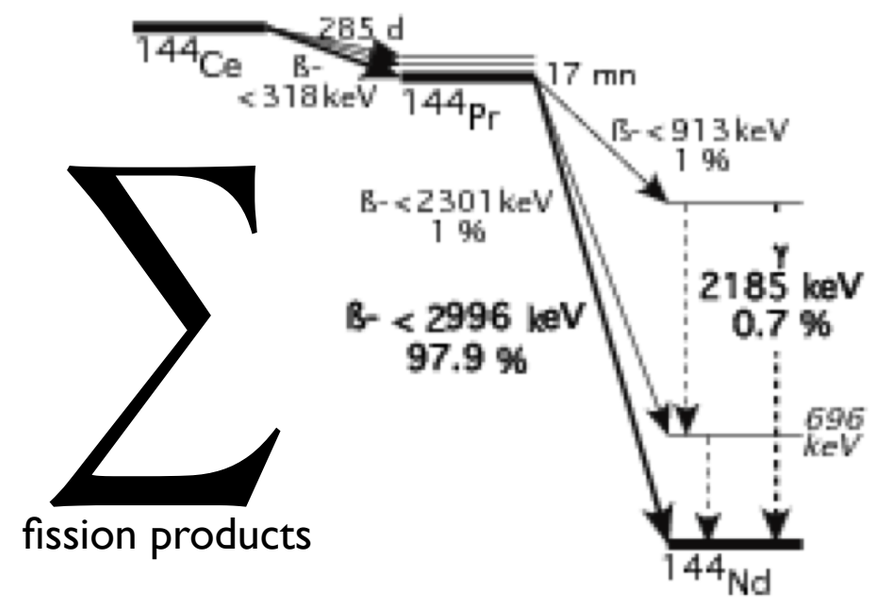
Predicting $S_i(E)$, Neutrinos Per Fission

- Two main methods:

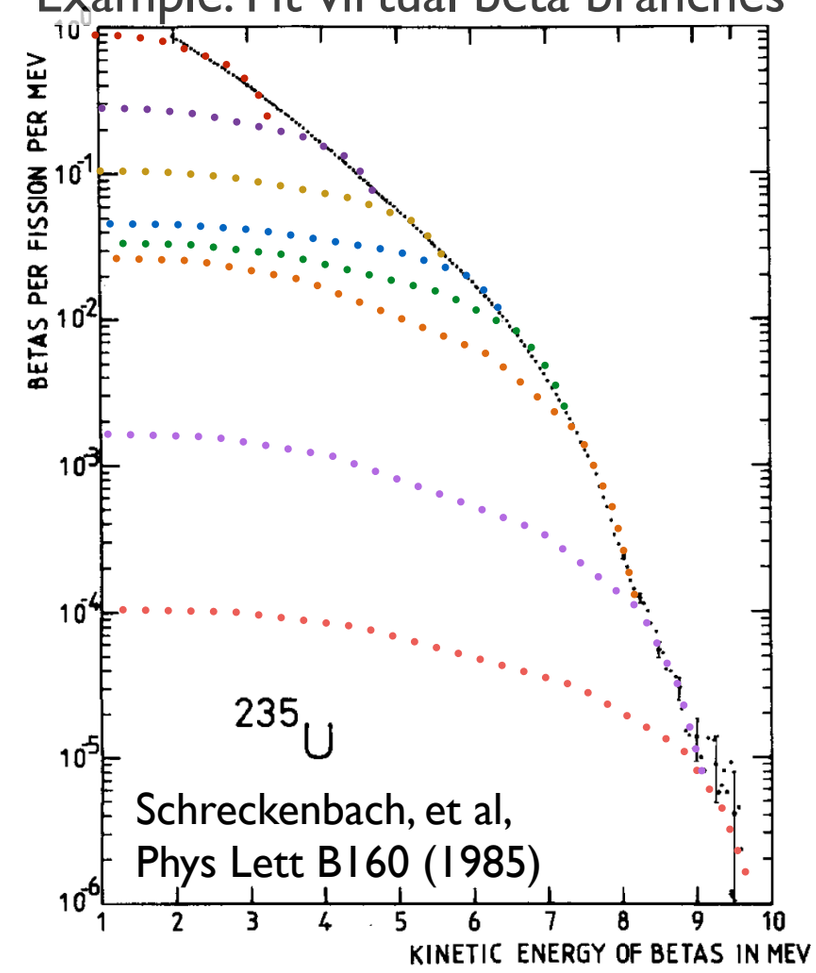
- *Ab Initio* approach:
  - Calculate spectrum branch-by-branch w/ databases: fission yields, decay schemes, …
  - **Problem:** rare isotopes / beta branches: missing, possibly incorrect info…

- Conversion approach
  - Measure beta spectra directly
  - Convert to $\overline{\nu}_e$ using 'virtual beta branches'
  - **Problem:** 'Virtual' spectra not well-defined: what forbiddenness, charge, etc. should they have?
  - 'Preferred' method: smaller error bars

Example: Ce-144 Decay Scheme



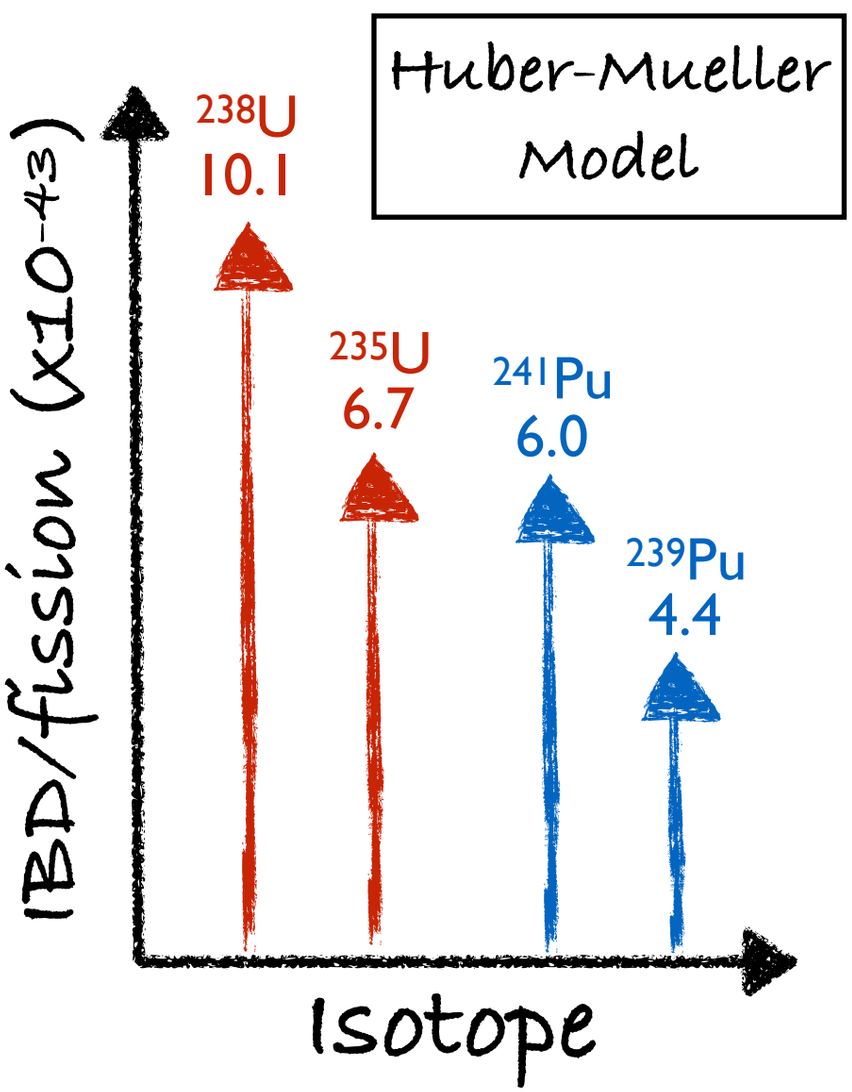
Example: Fit virtual beta branches



Reactor Antineutrino Flux

Reactor Flux Predictions

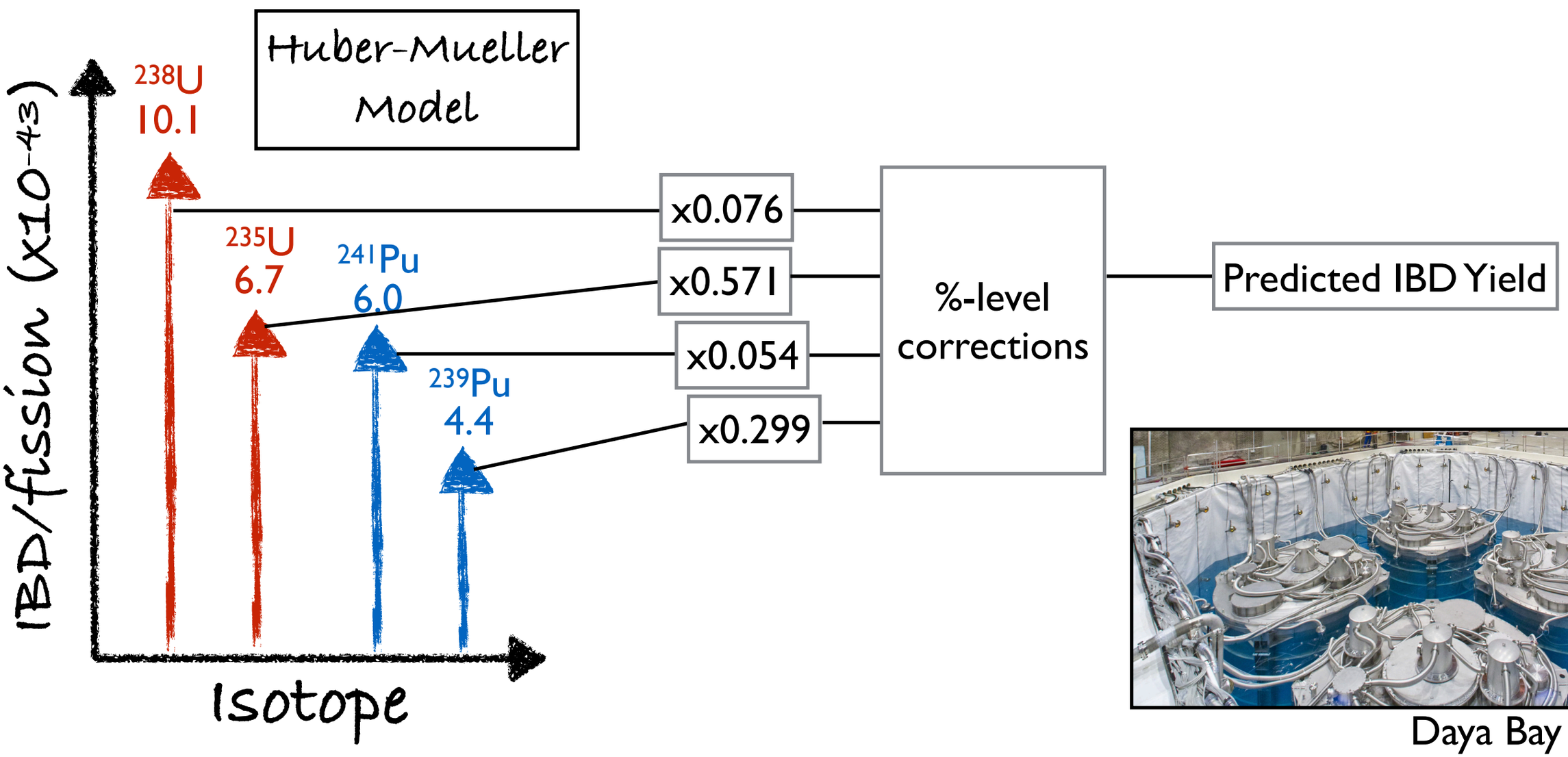
- Three isotopes' $\bar{\nu}_e$ flux predictions re-formulated in 2011
  - *Ab initio* ^{238}U prediction re-done at same time (fast fission)
  - 'flux' often cited as IBD per fission, or 'IBD yield': flux * IBD cross-section



Mueller, *et al*, Phys. Rev. C83 (2011)
Mention, *et al*, Phys. Rev. D83 (2011)
Huber, Phys. Rev. C84 (2011)

Reactor IBD Yield Measurements

- Three isotopes' $\bar{\nu}_e$ flux predictions re-formulated in 2011
- To predict one experiment's yield: multiply each isotope's IBD yield by its fission fraction, correct, sum, and you're done.

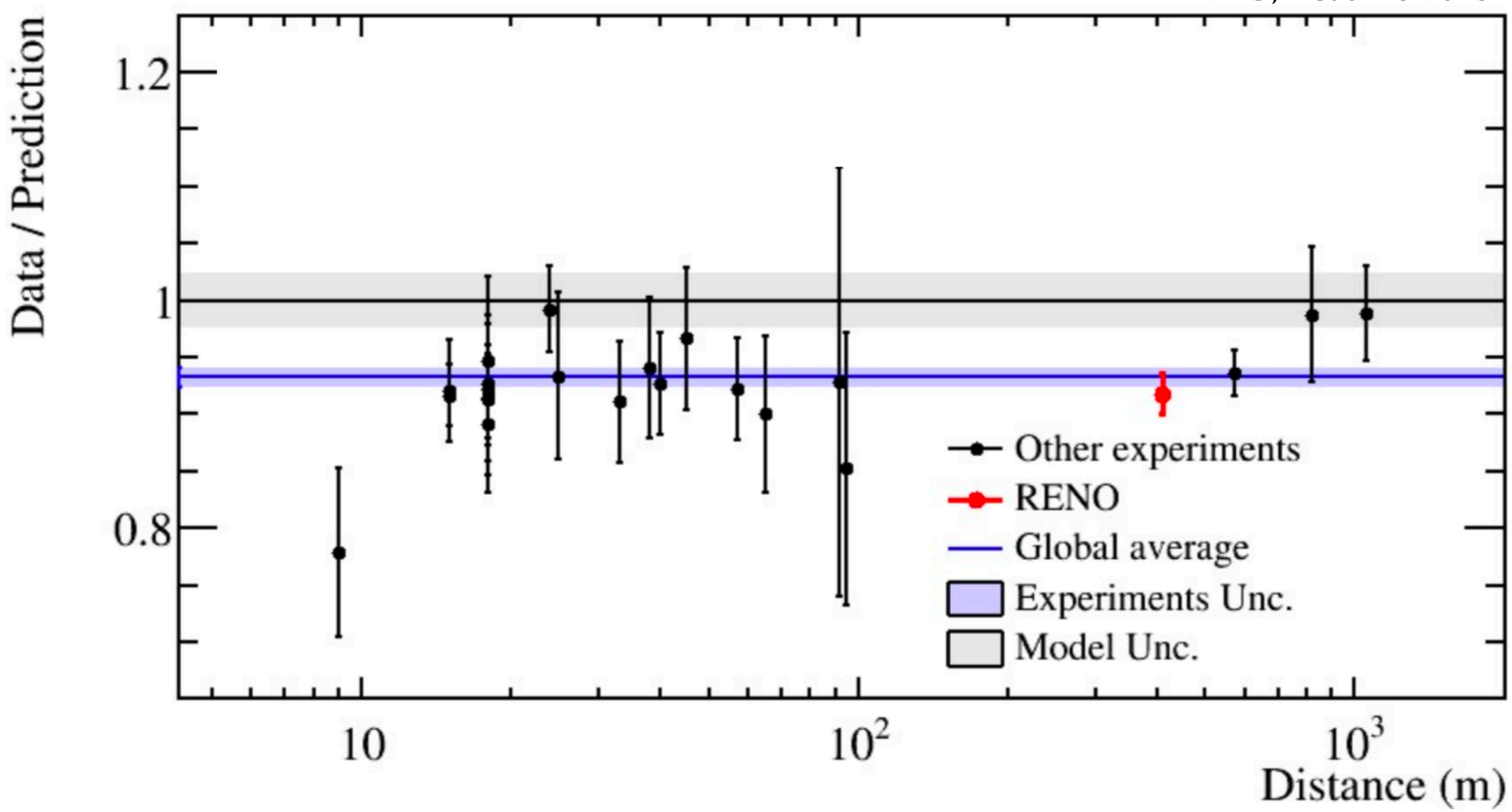


Daya Bay

Reactor Antineutrino Flux Anomaly

- Bad news: these flux predictions don't match the data.
- New precise measurements also do not match predictions: Daya Bay (1.5%), RENO (2%), Double Chooz (~1%?)
- WHY the deficit??

RENO, Neutrino 2018

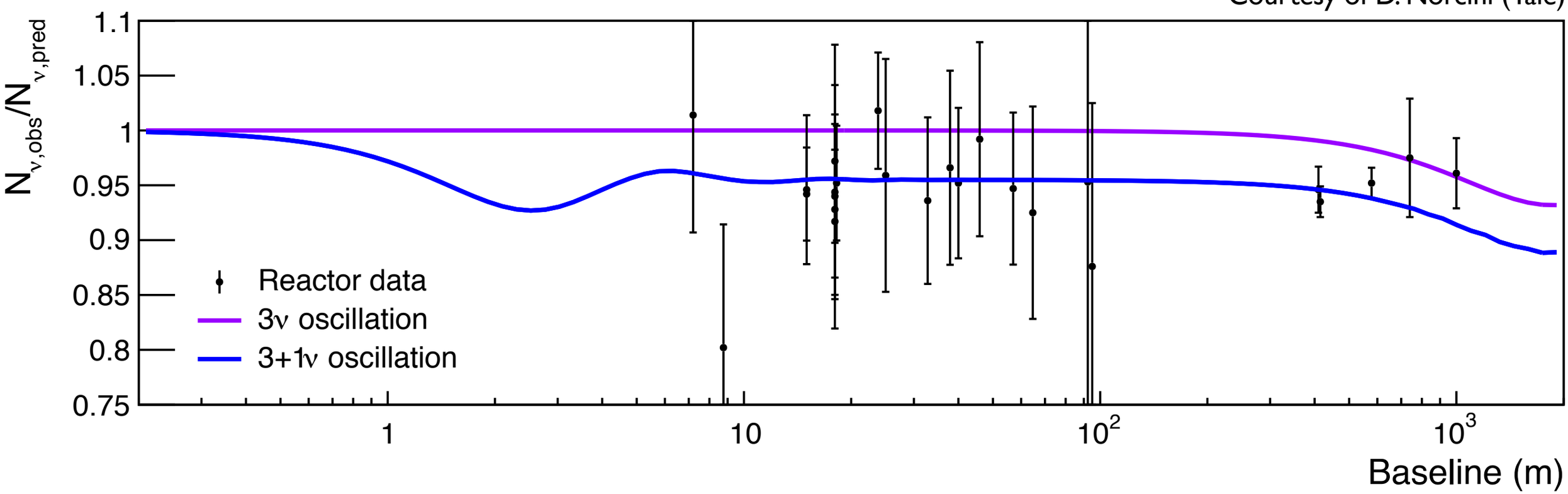


Sterile Neutrino Oscillations

- Hypothesis 1: Some $\bar{\nu}_e$ oscillated to unobservable types
  - This hypothesis indicates a deficit that is <u>baseline-dependent</u>
  - Oscillation must max out at small baselines: large (~eV) mass splitting
  - Only measured averaged disappearance at longer baselines; need a better signature.

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

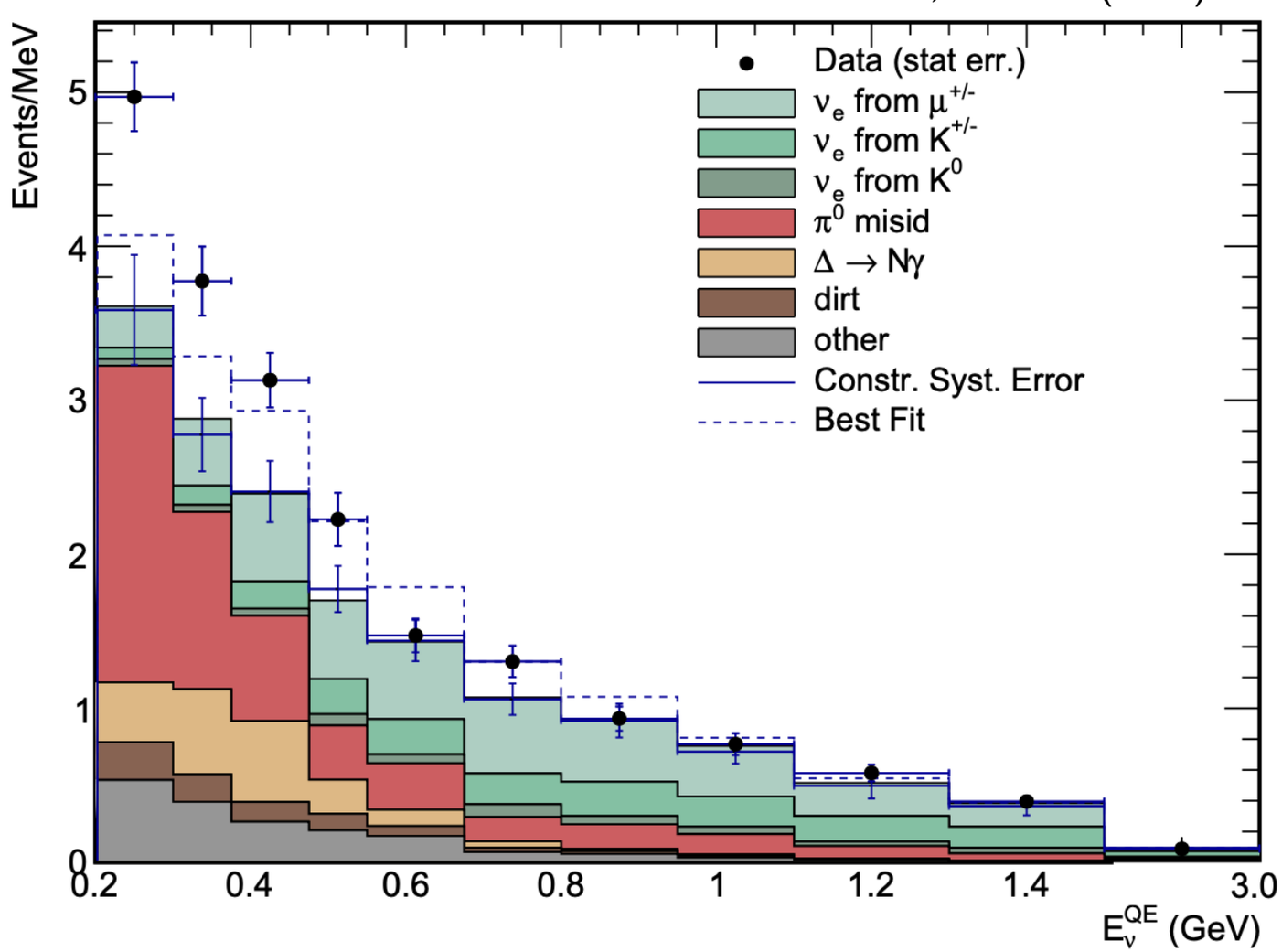
Courtesy of D. Norcini (Yale)

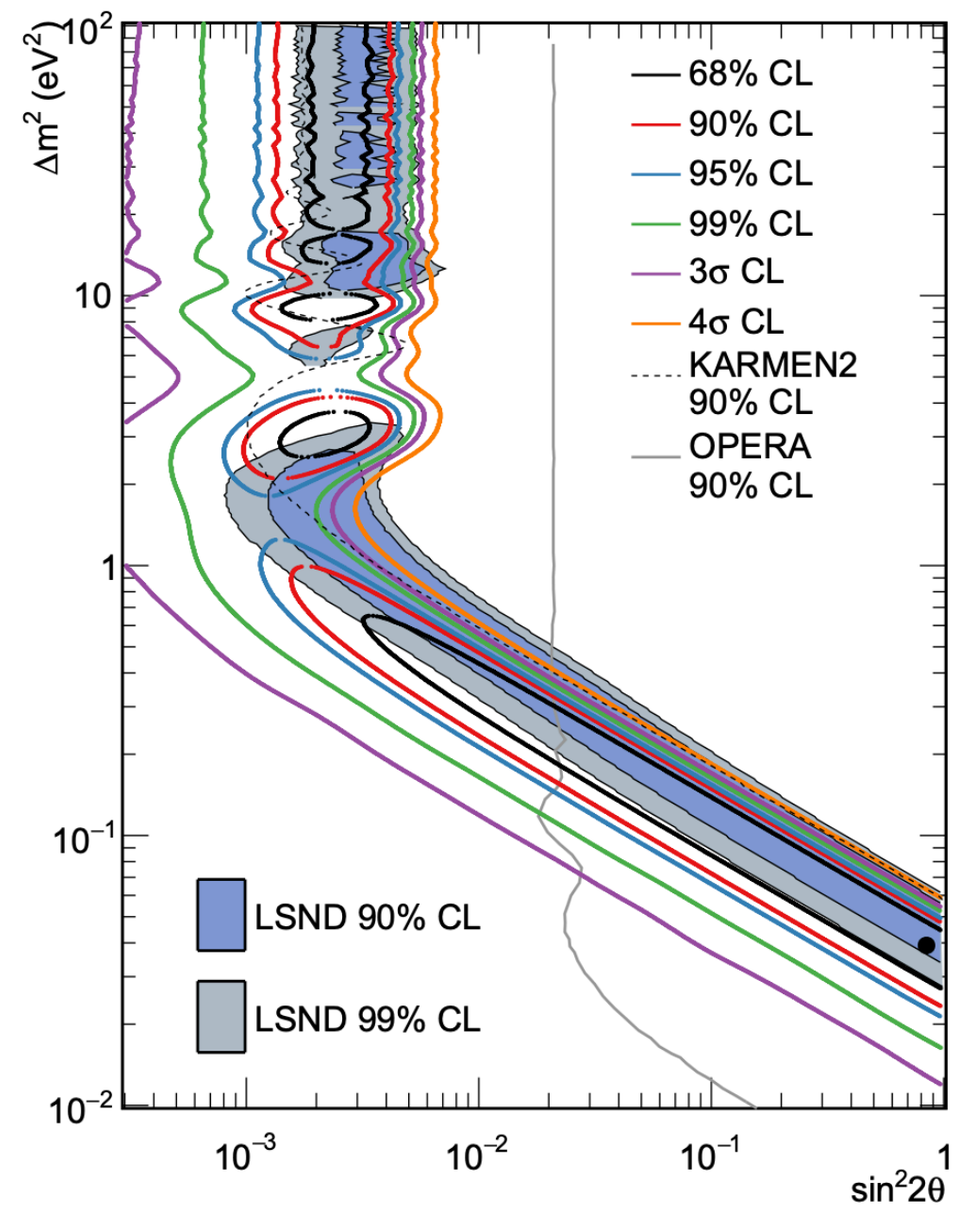


Sterile Neutrino Oscillations

- Hypothesis 1: Some $\bar{\nu}_e$ oscillated to unobservable types
  - Note other experimental hints that point towards the idea of sterile-active neutrino couplings: LSND, MiniBooNE $\nu_\mu \rightarrow \nu_e$
  - Note: reactor and accelerator results probe ~different active-sterile mixing parameters

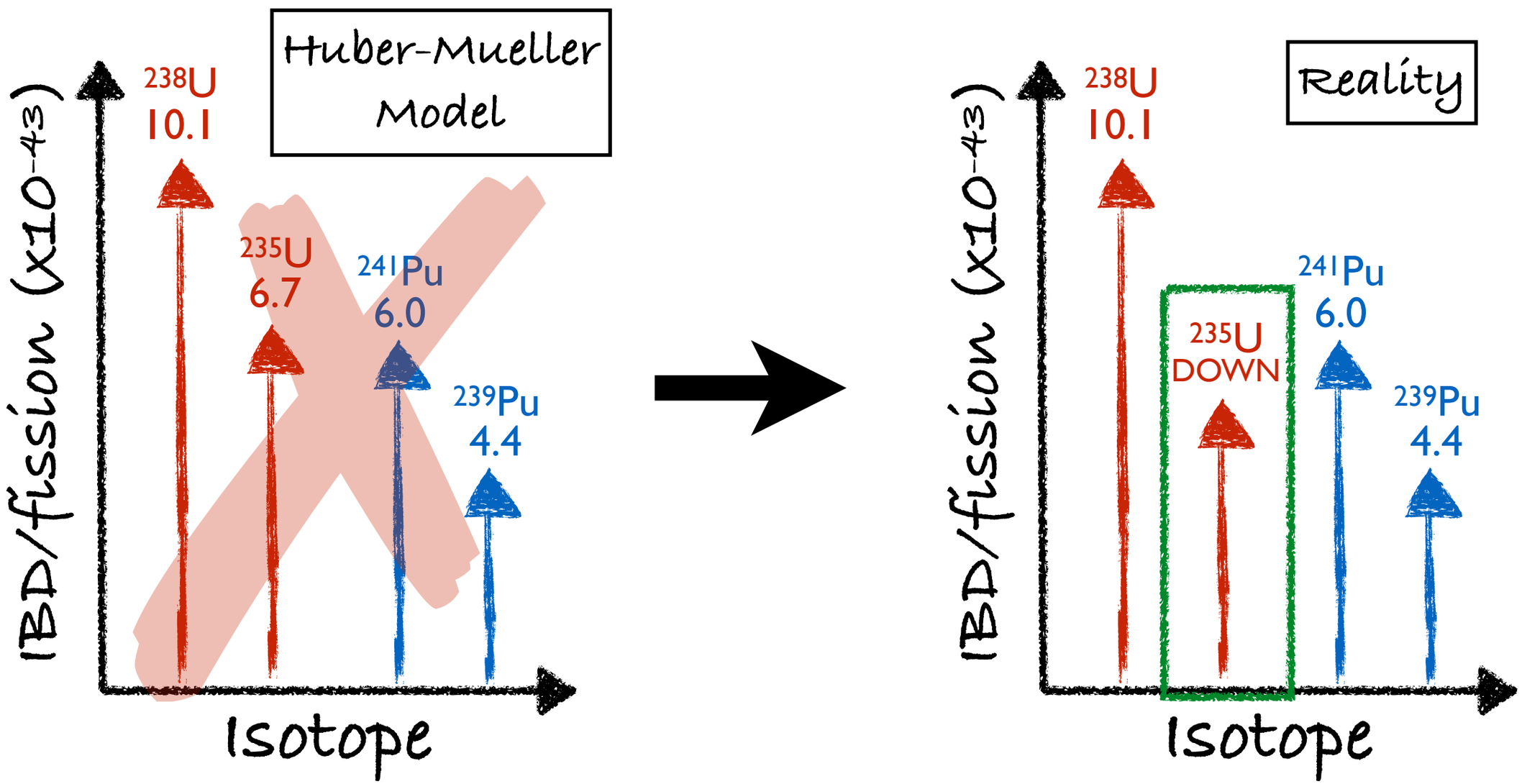
MiniBooNE, PRL 121 (2018)





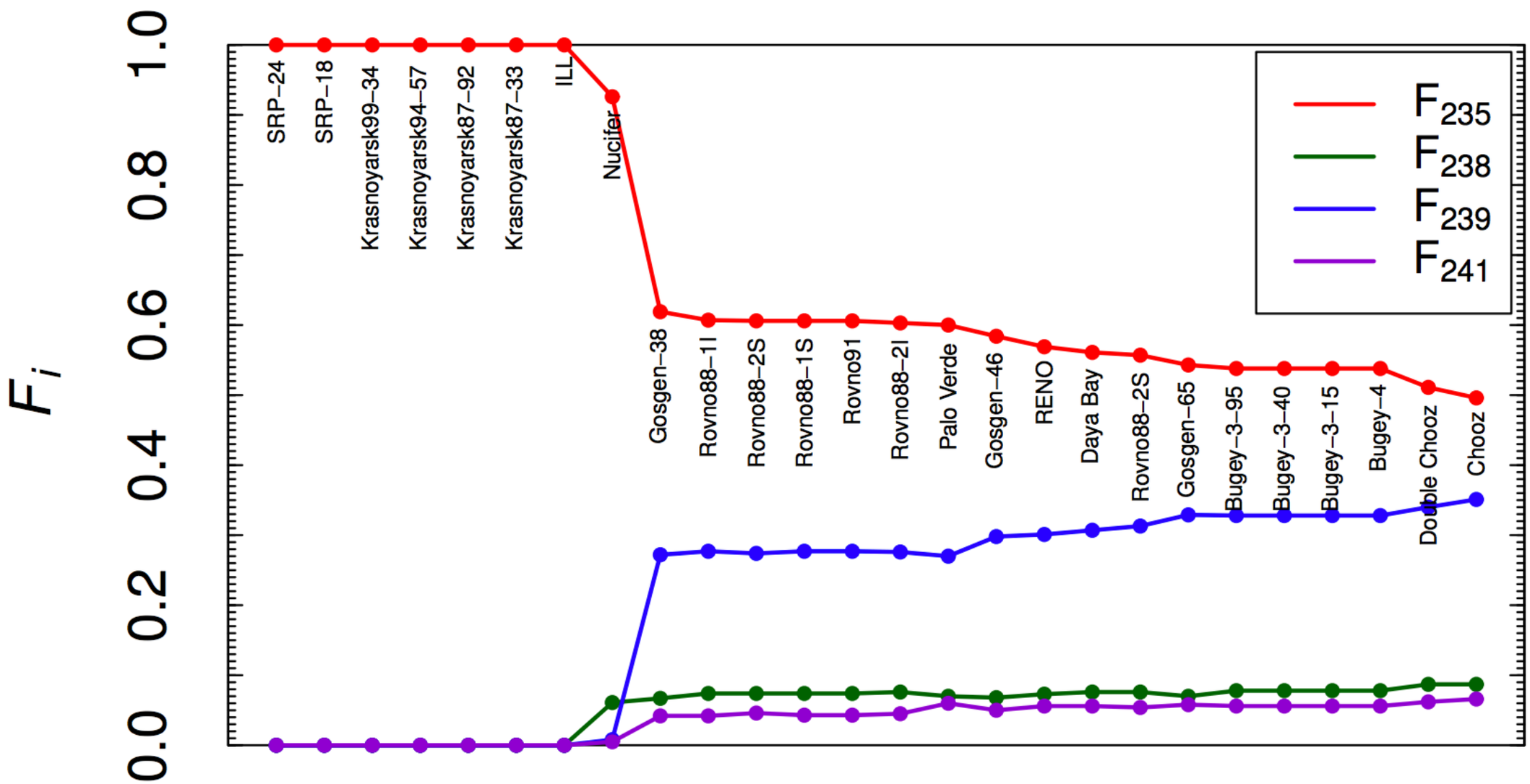
Bad Flux Predictions

- Hypothesis 2: Something is wrong with the flux predictions
- Could be just one isotope; could be all isotopes.
  - Recent Daya Bay results appear to suggest this hypothesis



Bad Flux Predictions

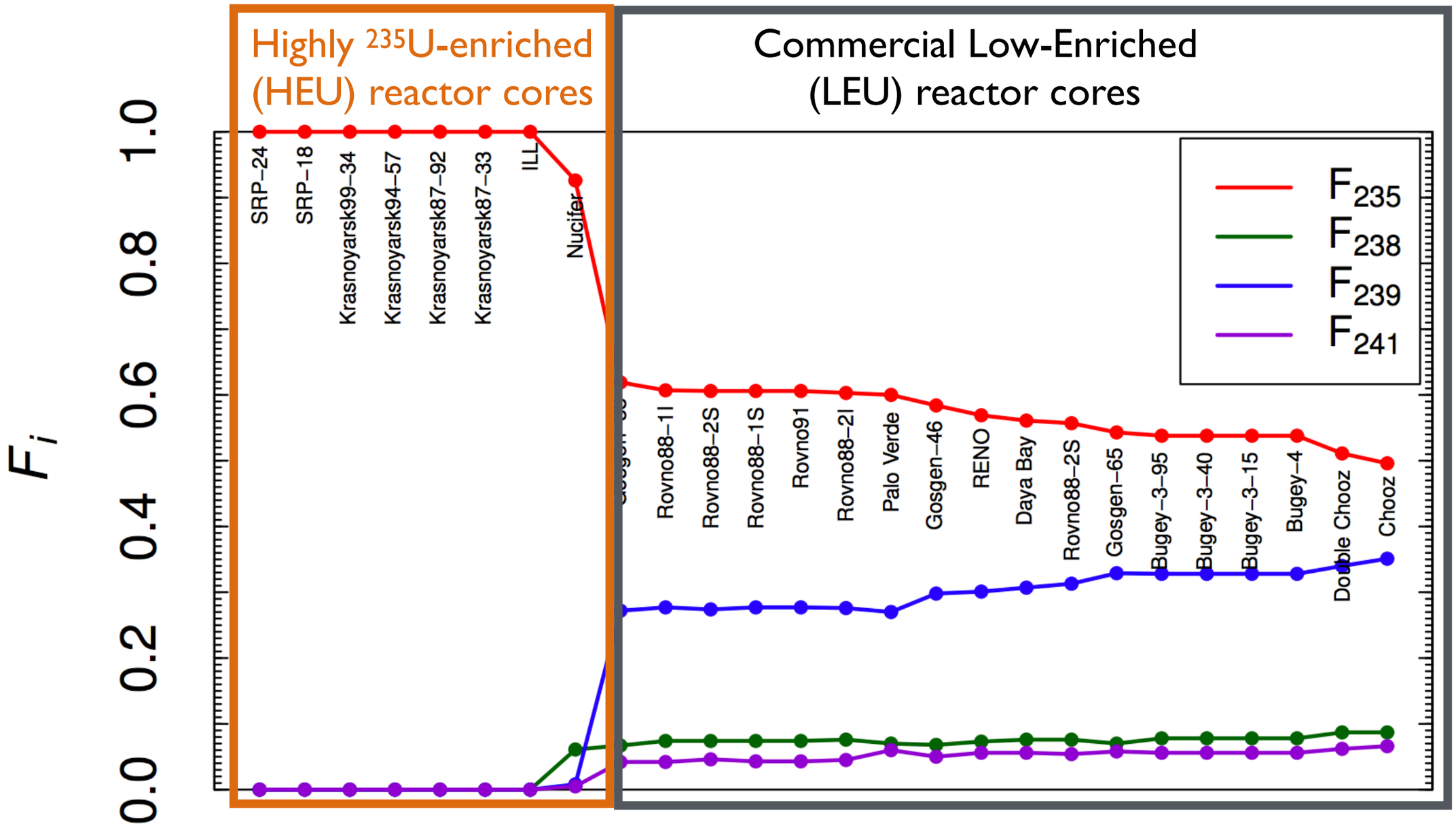
- Hypothesis 2: Something is wrong with the flux predictions
  - This hypothesis indicates a deficit that <u>could be</u> fuel-content-dependent
  - All isotopes have ~same $\langle E_\nu \rangle$, so oscillations can't cause a similar dependence.



Giunti, et al, JHEP 10:143 (2017)

Bad Flux Predictions

- Hypothesis 2: Something is wrong with the flux predictions
  - This hypothesis indicates a deficit that *could be* fuel-content-dependent
  - All isotopes have ~same $\langle E_\nu \rangle$, so oscillations can't cause a similar dependence.



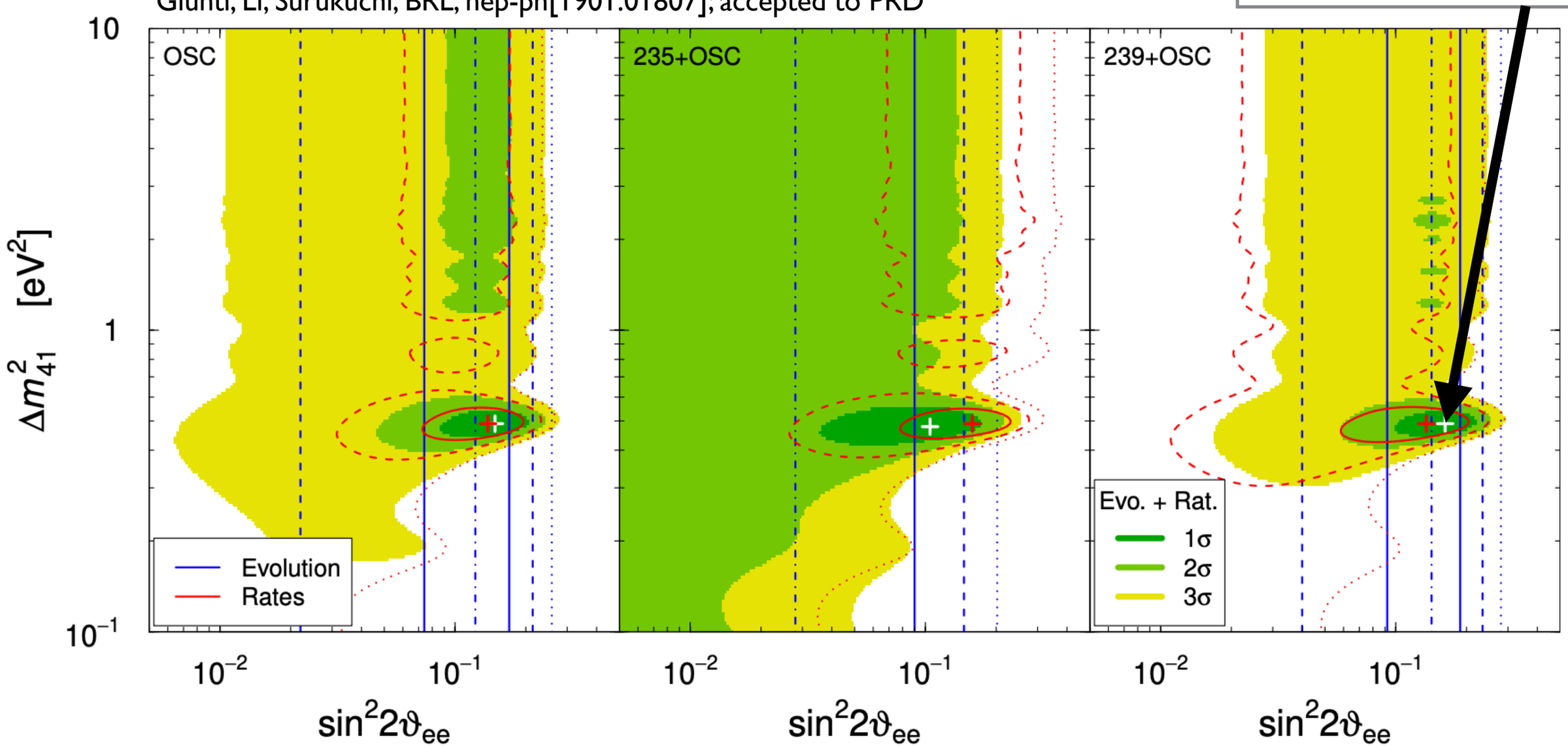
Giunti, et al, JHEP 10:143 (2017)

Combine The Two Hypotheses

- Note: you can have BOTH hypotheses be true
  - Global fits say this actually gives the <u>best</u> fit to existing flux measurements.

Overall best-fit comes from allowing osc <u>and</u> bad ^{239}Pu predictions

Giunti, Li, Surukuchi, BRL, hep-ph[1901.01807]; accepted to PRD

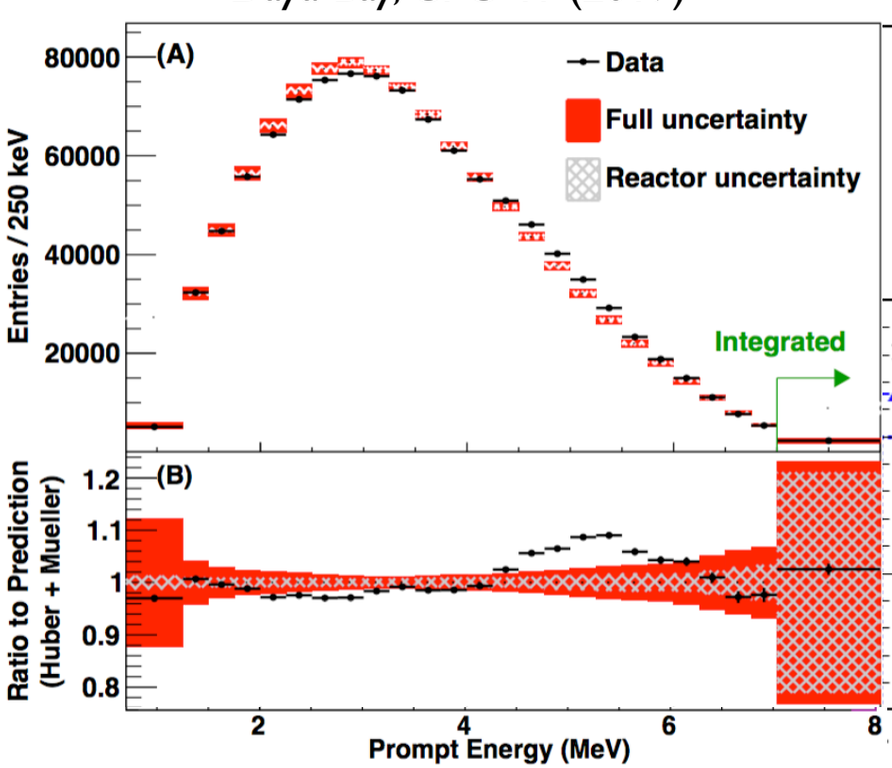


Reactor Antineutrino Spectrum

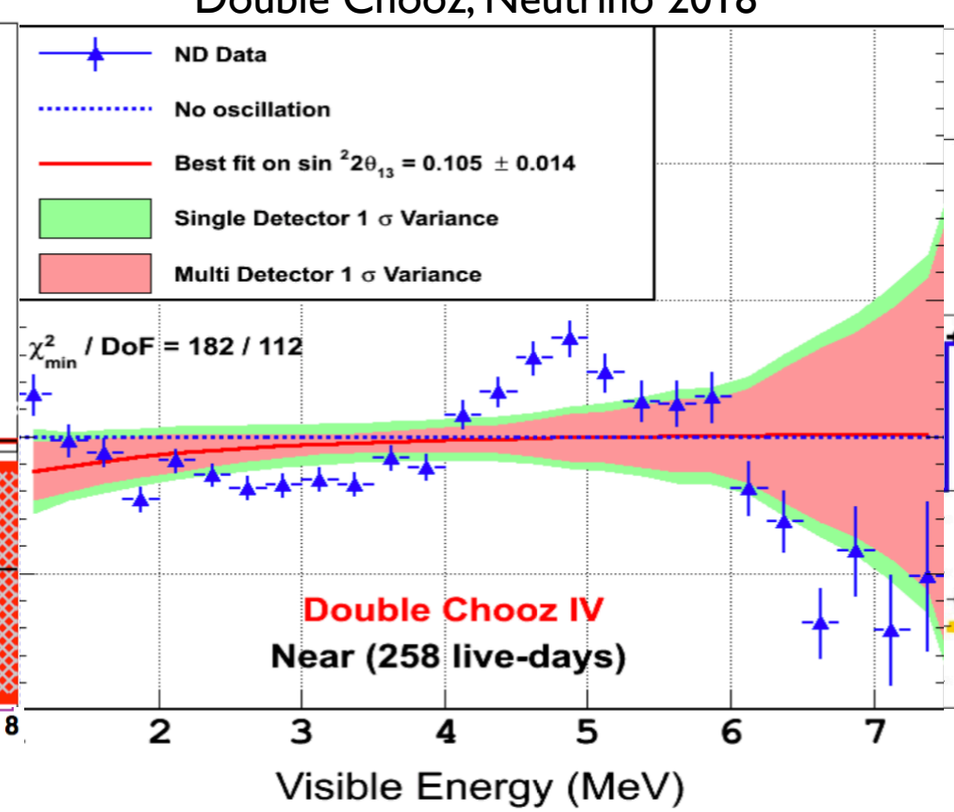
Reactor Spectrum Anomaly

- Bad news: these spectrum predictions don't match LEU data.
  - Eye is first drawn to the 'bump' in the 4-6 MeV range.
  - Zooming out: kinda just looks bad generally across the entire spectrum…
- HOW is spectrum incorrectly predicted???

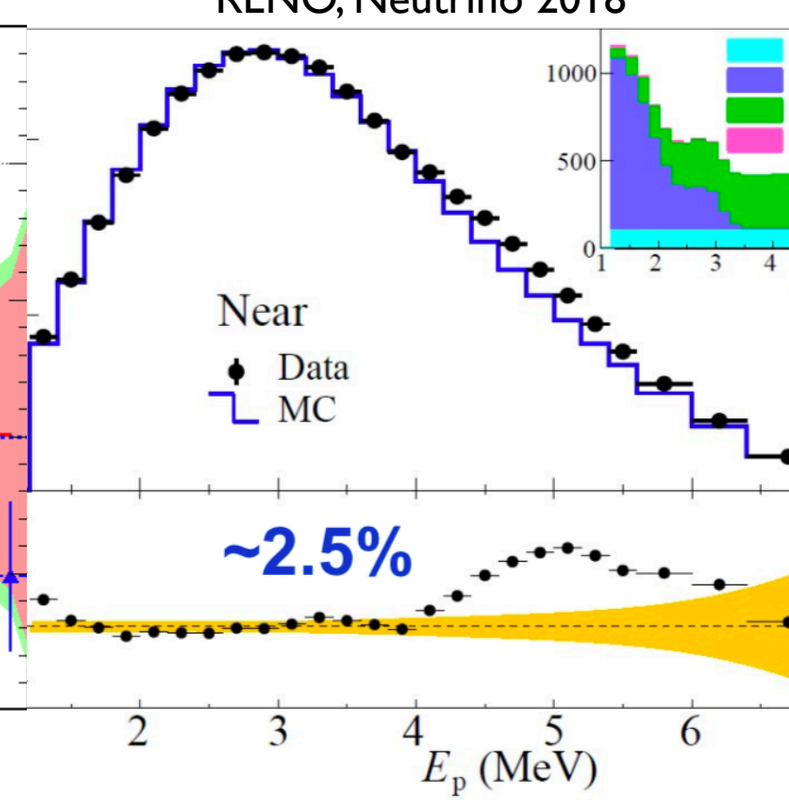
Daya Bay, CPC 41 (2017)



Double Chooz, Neutrino 2018



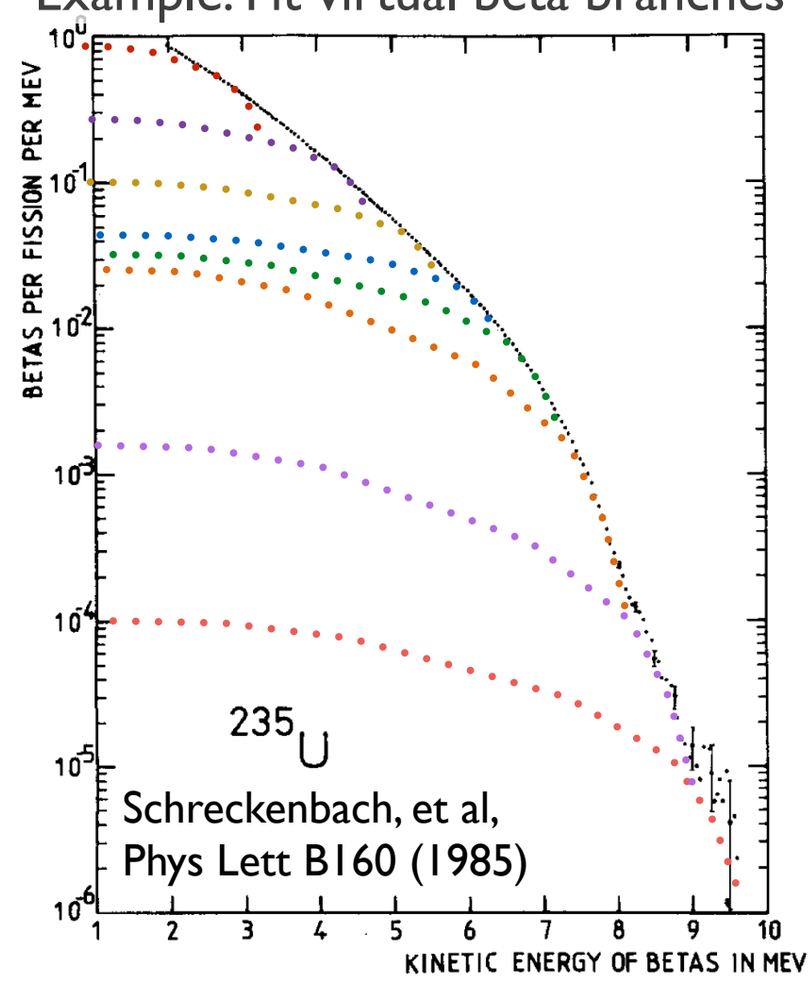
RENO, Neutrino 2018



Reactor Spectrum Predictions

- Reminder: Convert beta spectra into antineutrino spectra
- In theory, this is simple, but in practice, spectrum depends on:
  - Fermi function, which depends on nuclear charge
  - Forbidden-ness of the beta transition
  - Smaller-order corrections (nuclear size, etc.)
- Since we're fitting 'fake' beta branches, have to parameterize all these things.
  - Usually parameterize vs. E_{beta}: 'What is the average nuclear charge for branches with this Q-value?'
  - Errors arise from parameterization, which can be hard to quantify (see A. Hayes's Neutrino2018 talk)
- One idea to get more info: is prediction bad for all isotopes? Or a specific isotope?

Example: Fit virtual beta branches



Present Issues, Summarized

- Flux predictions don't match global measurements
  - Hypothesis 1: Predicted fluxes are just wrong for some (all?) isotopes
  - Hypothesis 2: Electron antineutrinos are oscillating away
- Spectrum predictions don't match global (LEU) measurements
  - Can't be from oscillations.
  - Likely a model problem. Is one isotope's prediction wrong? Or all isotopes?
- What can we do to address all of these issues????

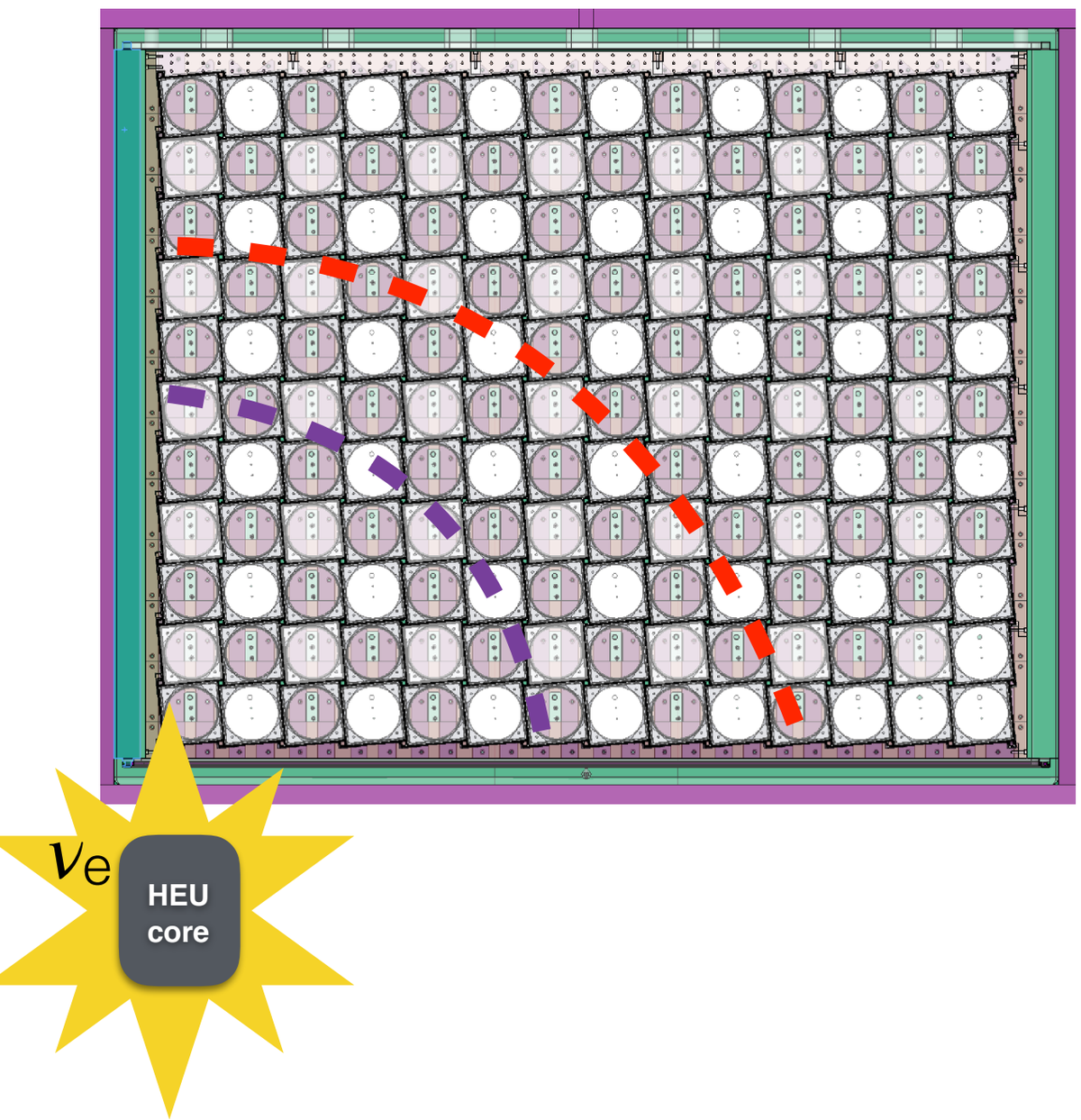
Present Issues, Summarized

- Flux predictions don't match global measurements
  - Hypothesis 1: Predicted fluxes are just wrong for some (all?) isotopes
  - Hypothesis 2: Electron antineutrinos are oscillating away
- Spectrum predictions don't match global (LEU) measurements
  - Can't be from oscillations.
  - Likely a model problem. Is one isotope's prediction wrong? Or all isotopes?
- What can we do to address all of these issues????

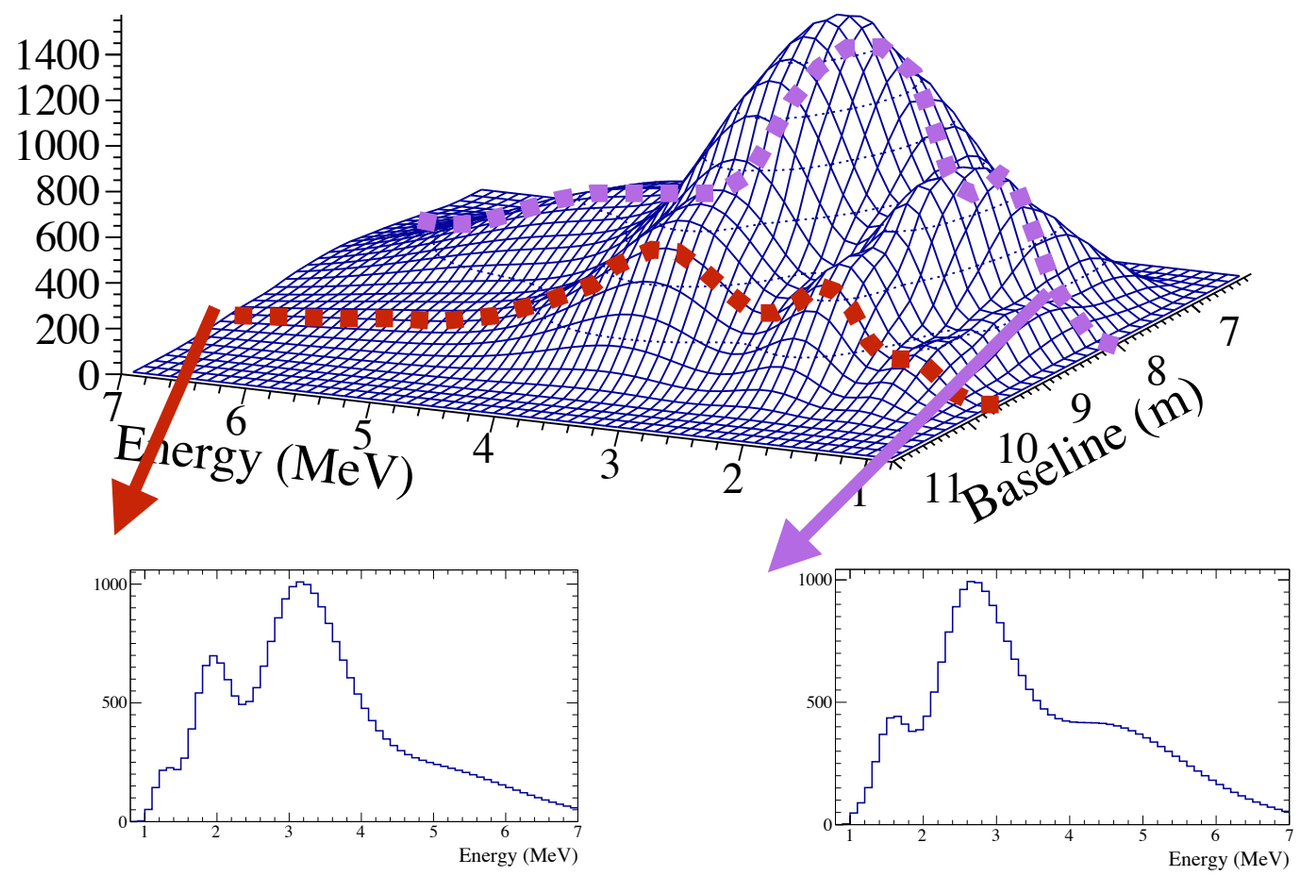
Flux-Independent Reactor Osc= Search

- Search for baseline-dependent energy spectrum distortion inside a stationary, segmented, short-baseline detector

100s of detectors in 1!



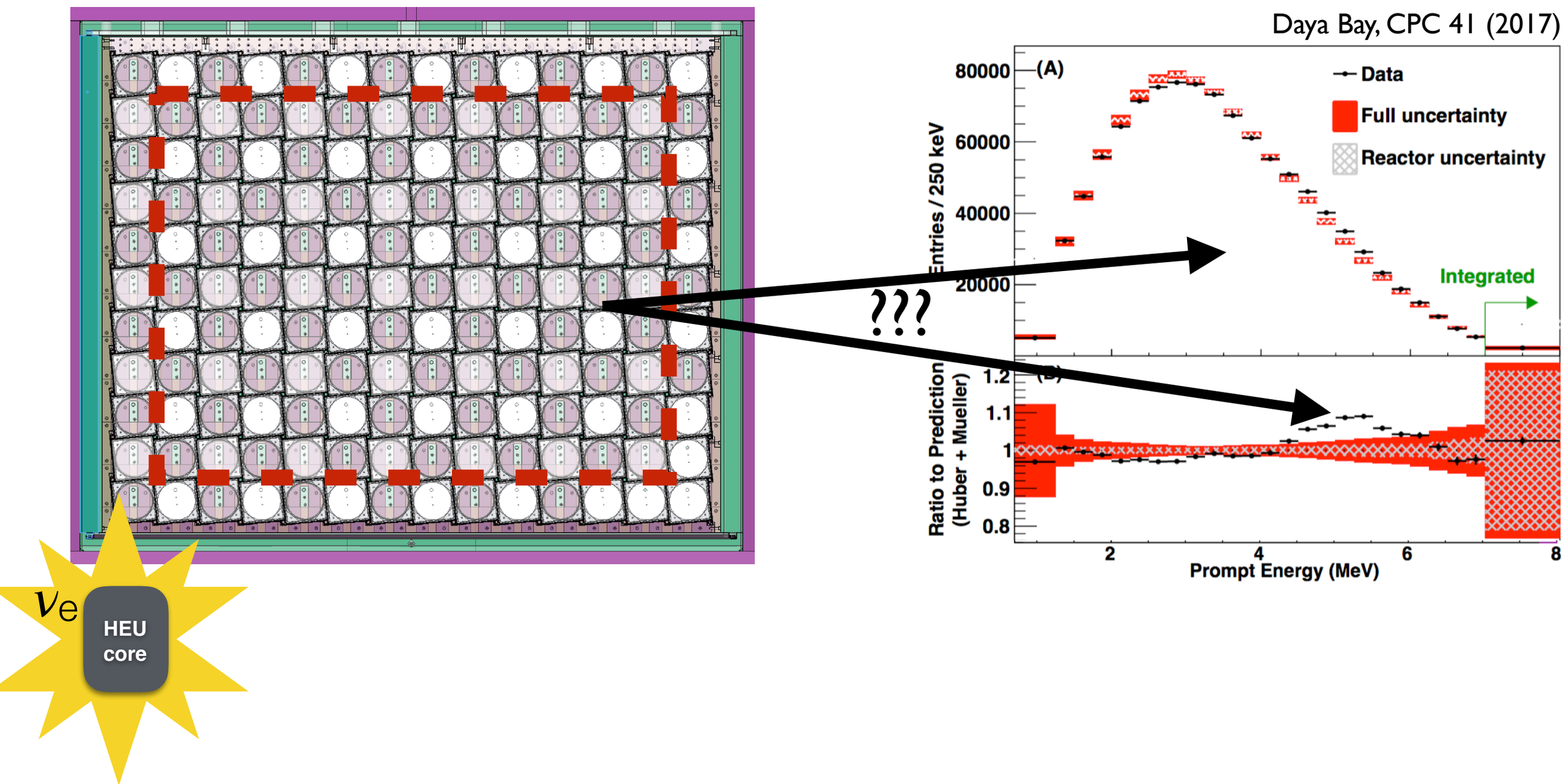
L vs E, oscillated



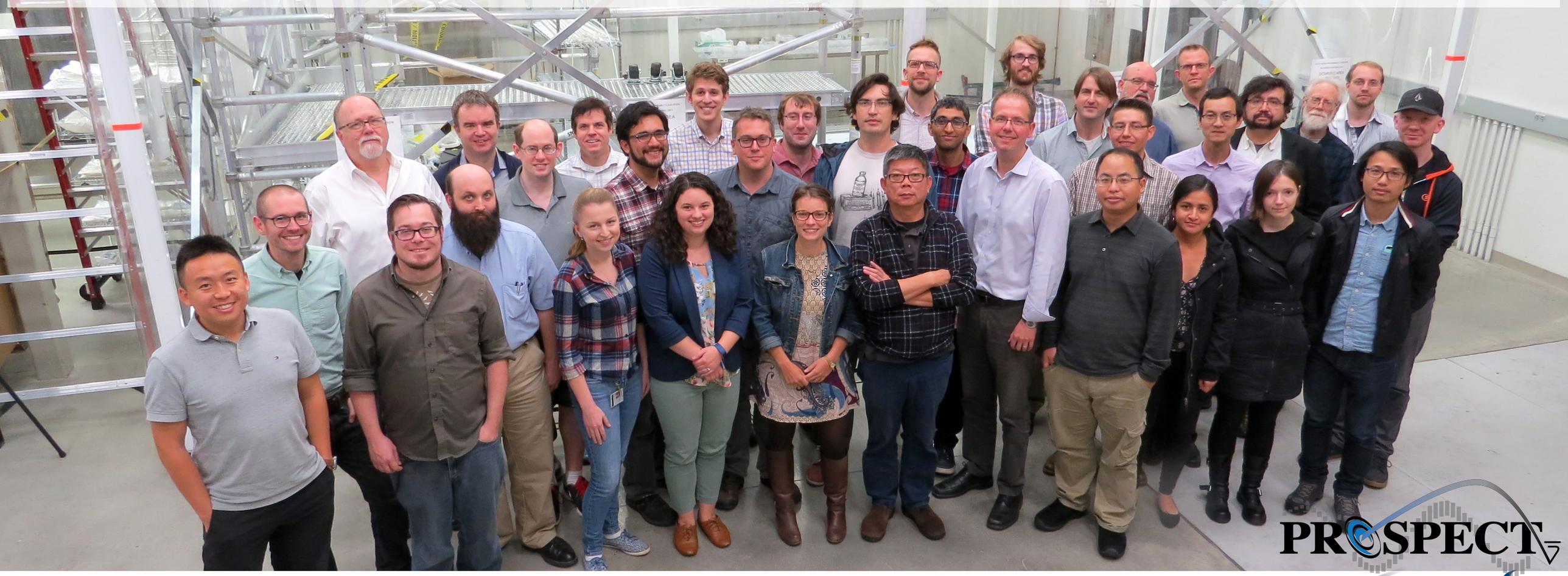
$$sin^2(2\theta)sin^2(1.27\Delta m^2\frac{L}{E_\nu})$$

$^{235}U\ \bar{\nu}_e$ Energy Spectrum Measurement

- Measure energy spectrum of $^{235}U\ \bar{\nu}_e$ using an HEU reactor
- Then ask: how do results differ for HEU and LEU reactors?
  - Can give a clue which isotopes are poorly predicted



The Precision Reactor Oscillation and SPECTrum experiment



University of Waterloo · Temple University · W&M · Georgia Tech · Le Moyne College · HFIR · Drexel University · Lawrence Livermore National Laboratory · Brookhaven National Laboratory · NIST · Oak Ridge National Laboratory · Yale

PROSPECT Experiment Overview

Scientific Goals

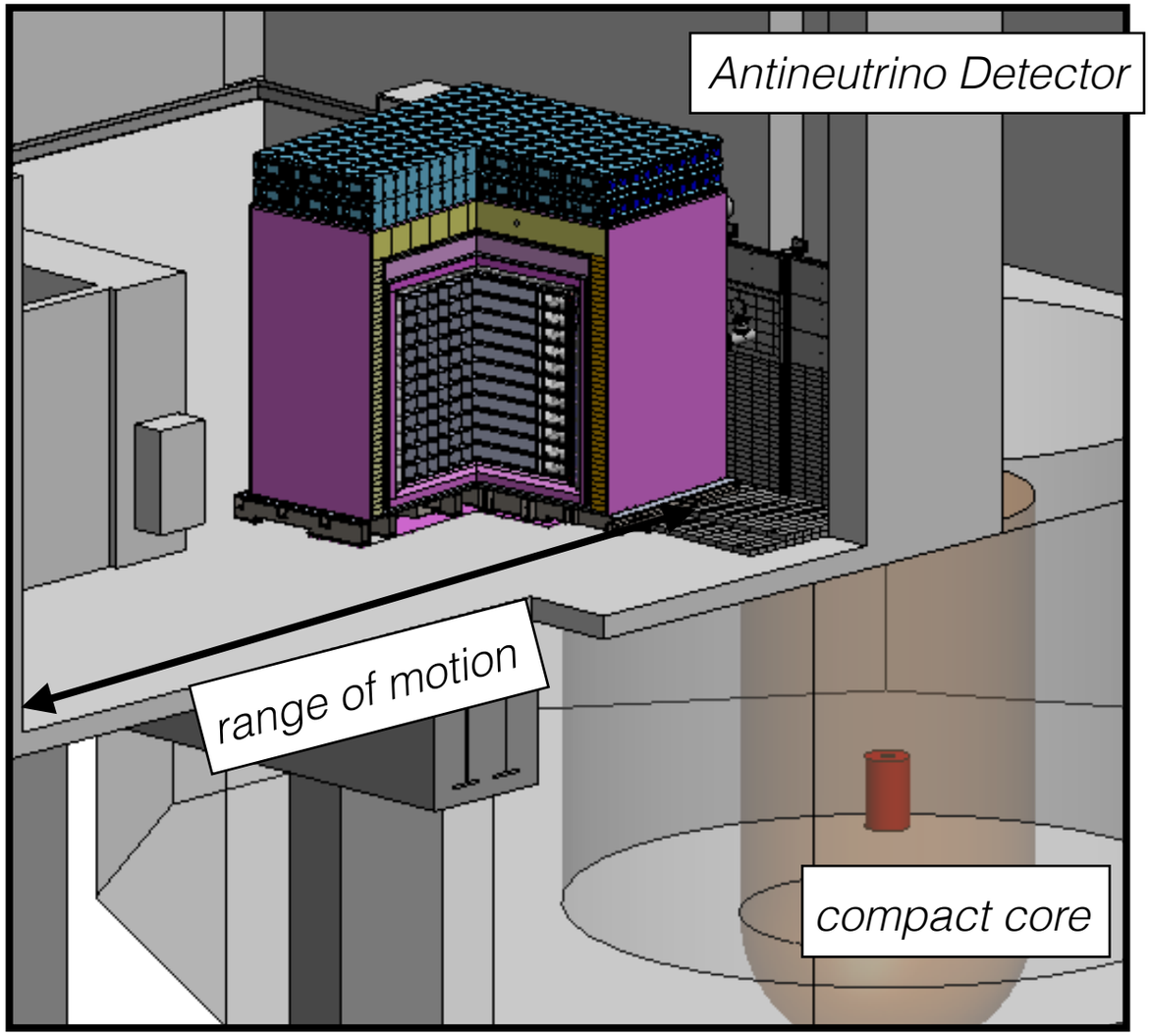
1. model independent search for eV-scale sterile neutrinos at short baselines
2. measure ^{235}U-only antineutrino spectrum to address spectral deviations

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

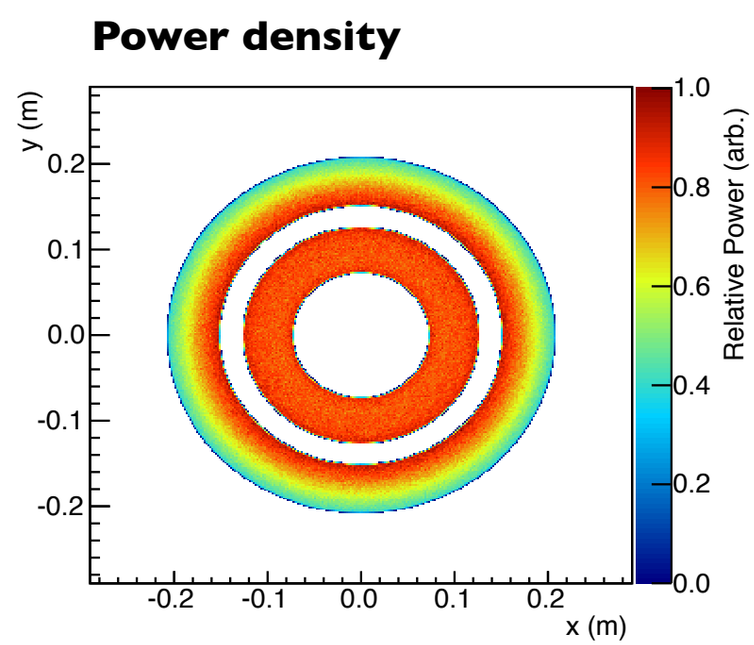
- backgrounds: cosmogenic fast neutrons and reactor gammas
- limited space: compact calorimeter
- current detector technology not well-matched for this environment

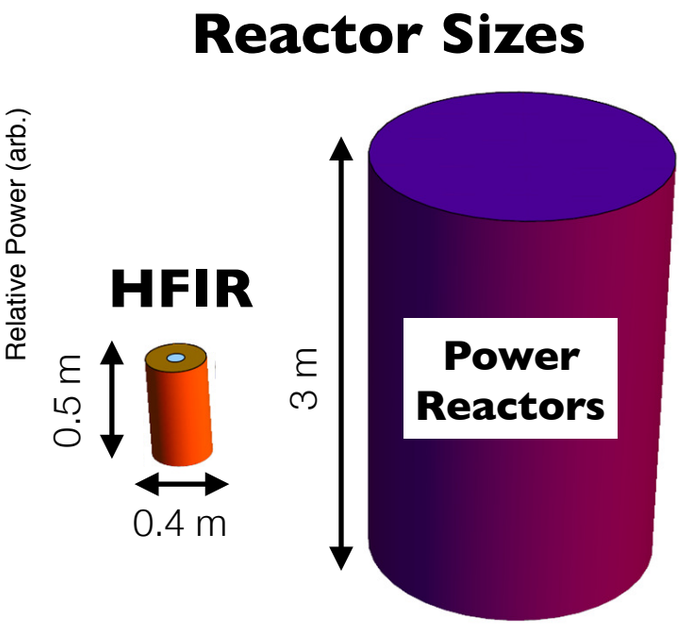


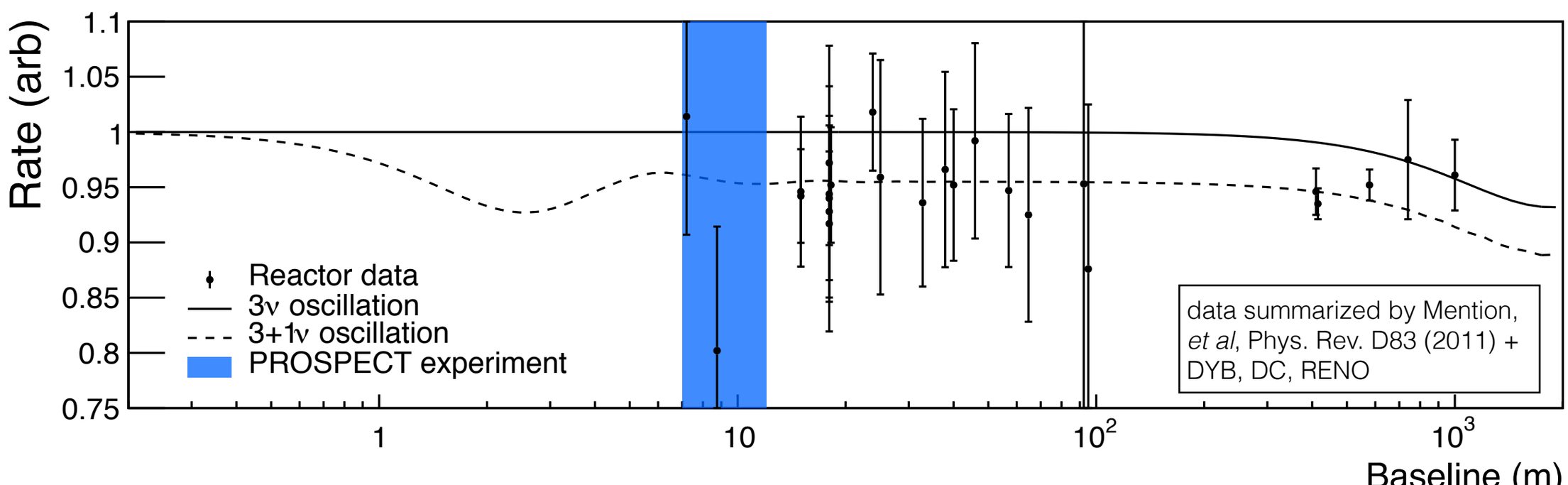
@ High Flux Isotope Reactor (HFIR), Oak Ridge National Laboratory

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







PROSPECT Experiment Overview

Scientific Goals

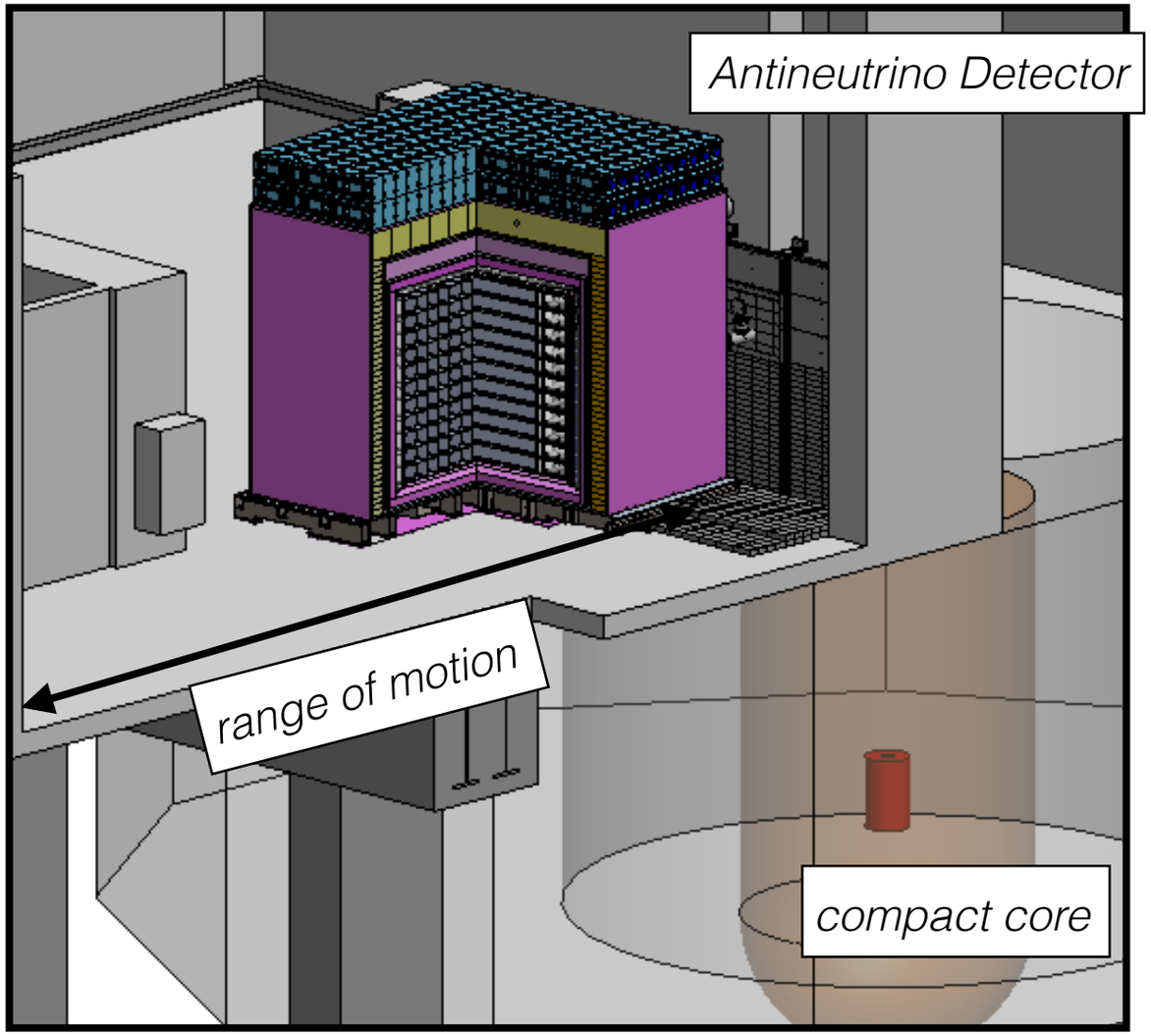
1. model independent search for eV-scale sterile neutrinos at short baselines
2. measure ^{235}U-only antineutrino spectrum to address spectral deviations

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

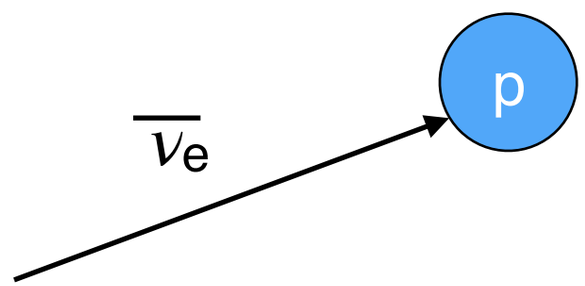
- backgrounds: cosmogenic fast neutrons and reactor gammas
- limited space: compact calorimeter
- reactor θ_{13} detector technology not well-matched for this environment



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

IBD Detection in ^{6}Li-doped LS

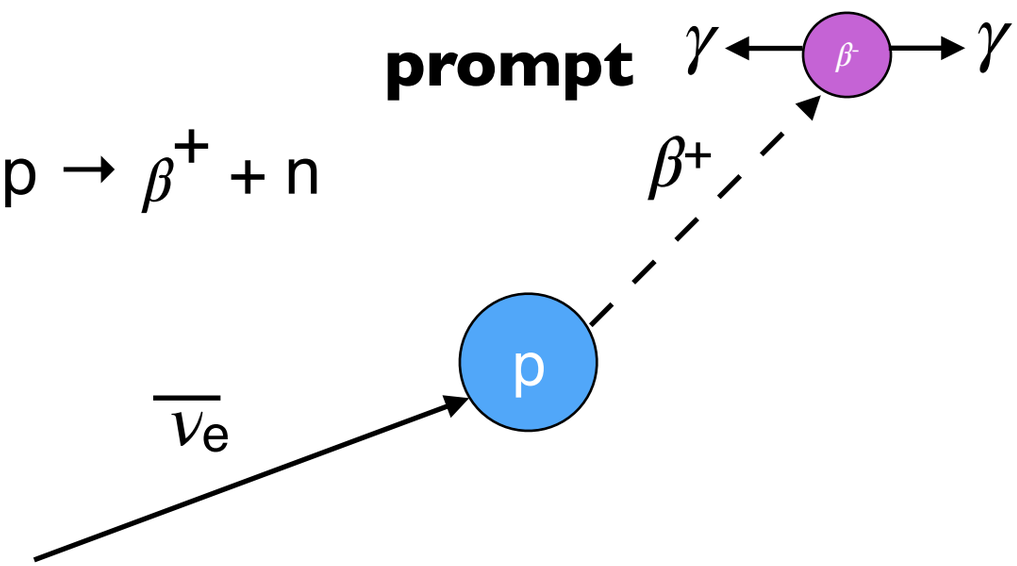
IBD: $\overline{\nu}_e + p \rightarrow \beta^+ + n$



- develop new liquid scintillator to detect IBDs near-surface reactor environment

IBD Detection in ^{6}Li-doped LS

IBD: $\overline{\nu}_e + p \rightarrow \beta^+ + n$

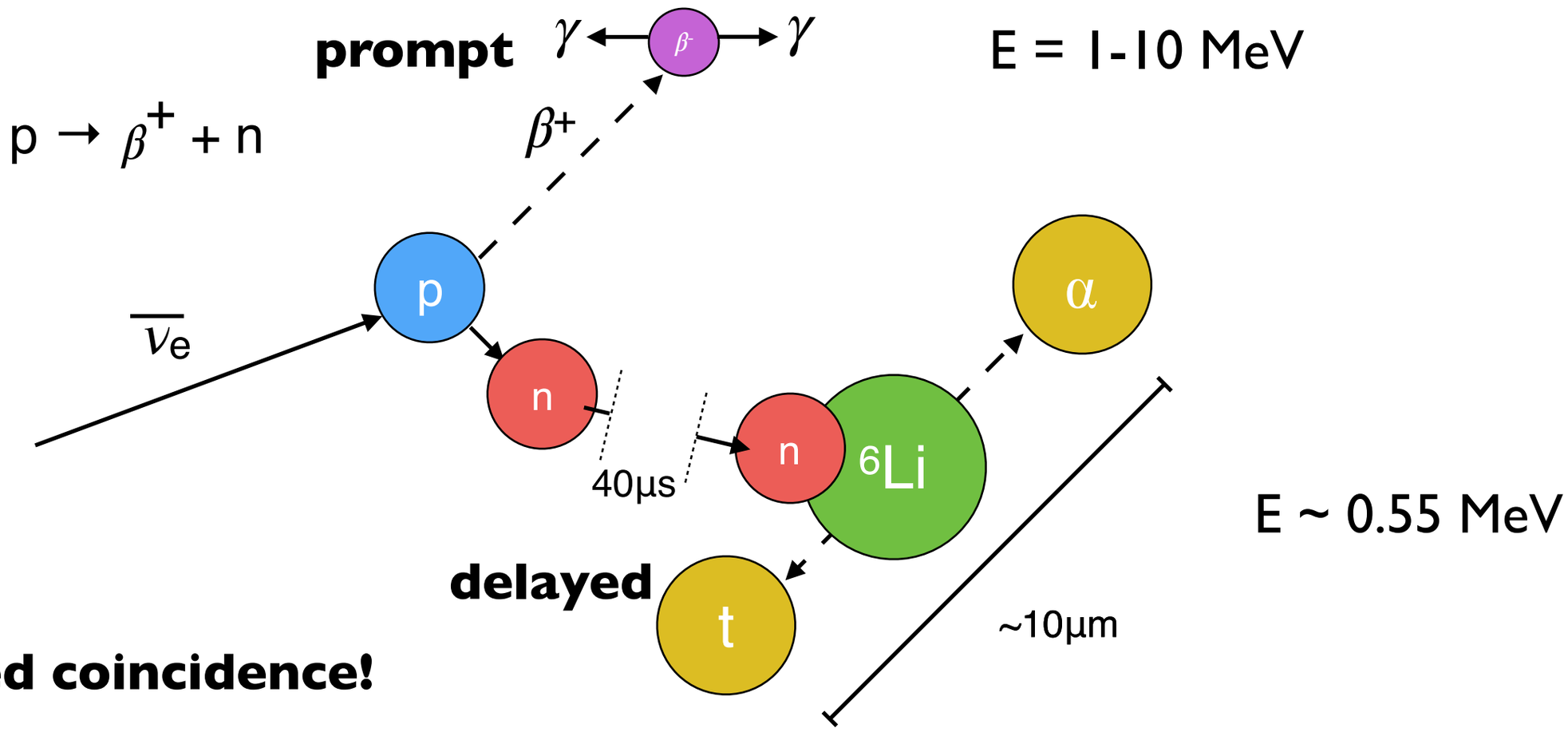


E = 1-10 MeV

- develop new liquid scintillator to detect IBDs near-surface reactor environment
- prompt (or detected) energy: positron ionization is a proxy for neutrino energy

IBD Detection in ^{6}Li-doped LS

IBD: $\overline{\nu}_e + p \rightarrow \beta^+ + n$



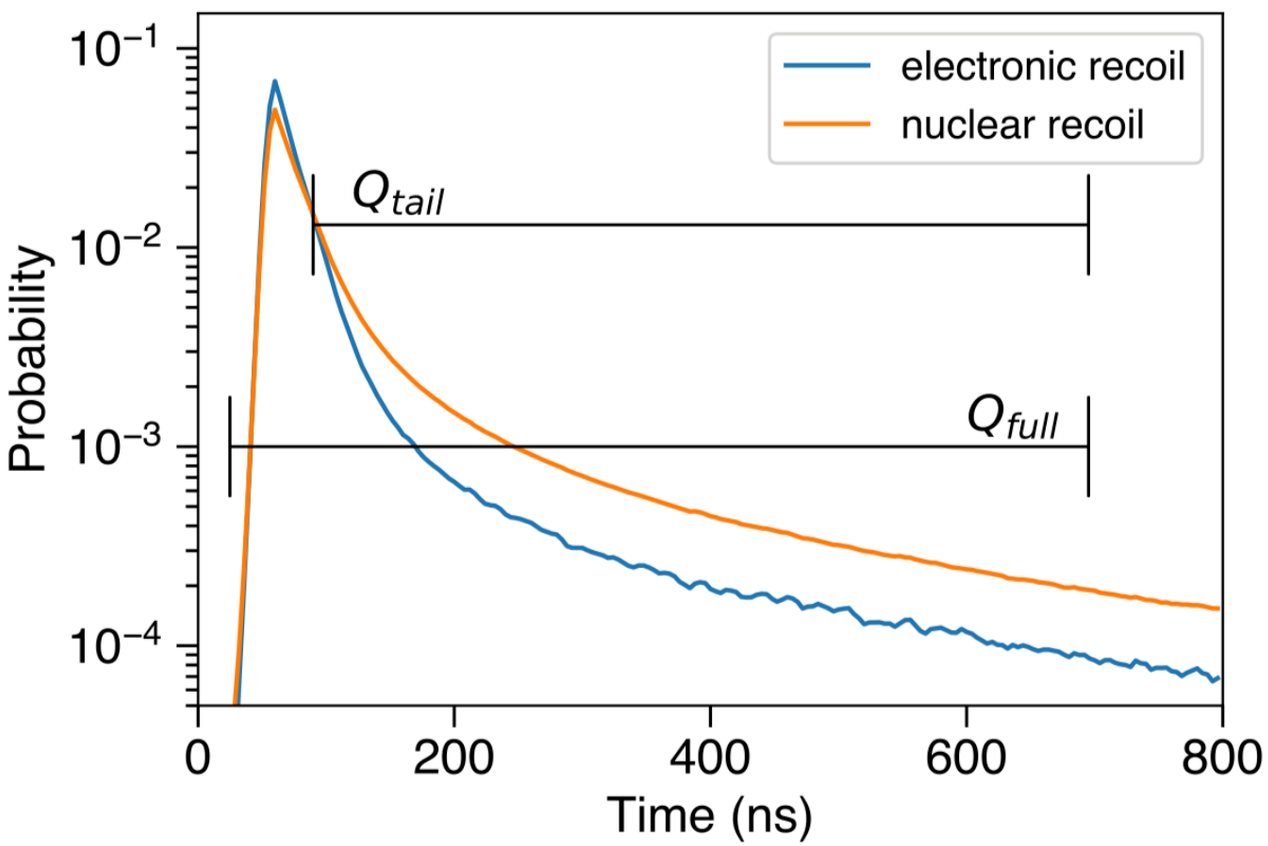
correlated coincidence!

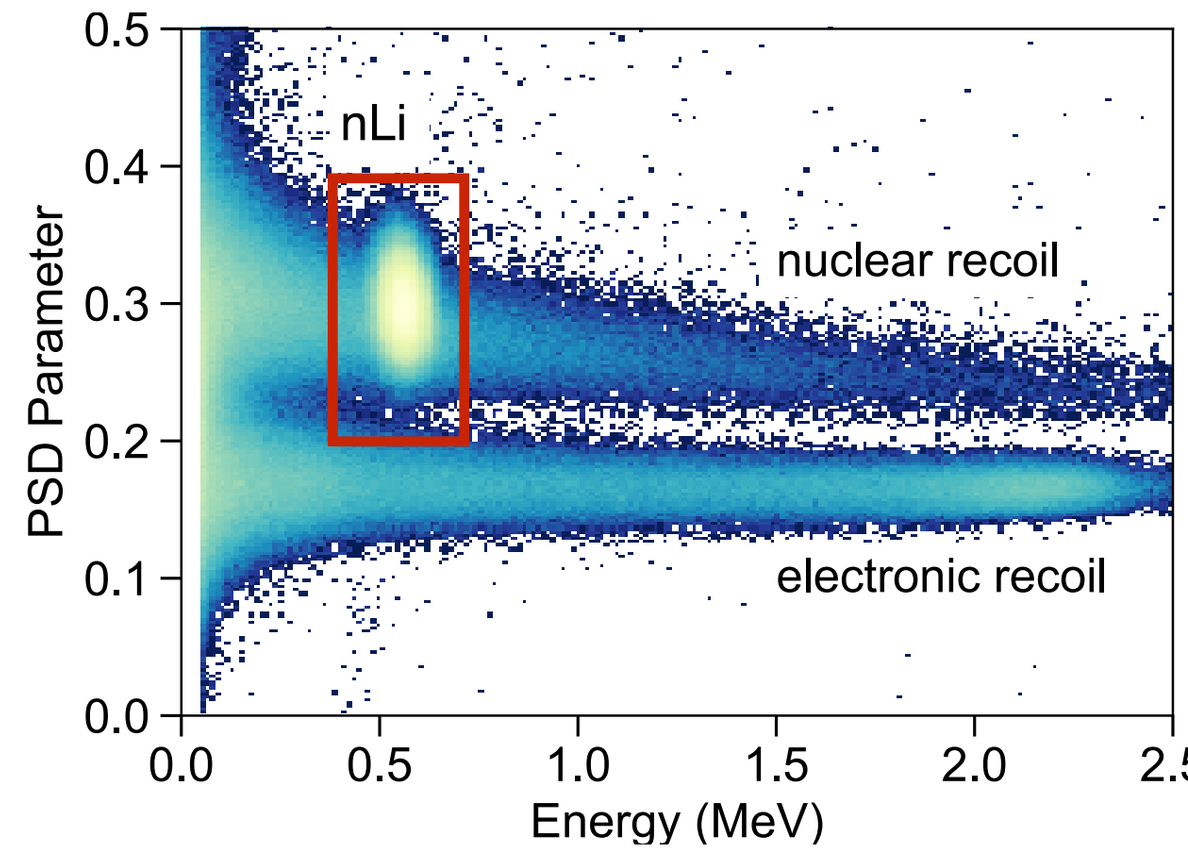
- develop new liquid scintillator to detect IBDs near-surface reactor environment
- prompt (or detected) energy: positron ionization is a proxy for neutrino energy
- development of ^{6}LiLS for neutron tag needed in compact detector as decay is highly localized in space.. within a PROSPECT segment

^{6}LiLS ideal for neutrino identification in compact, near-surface 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.



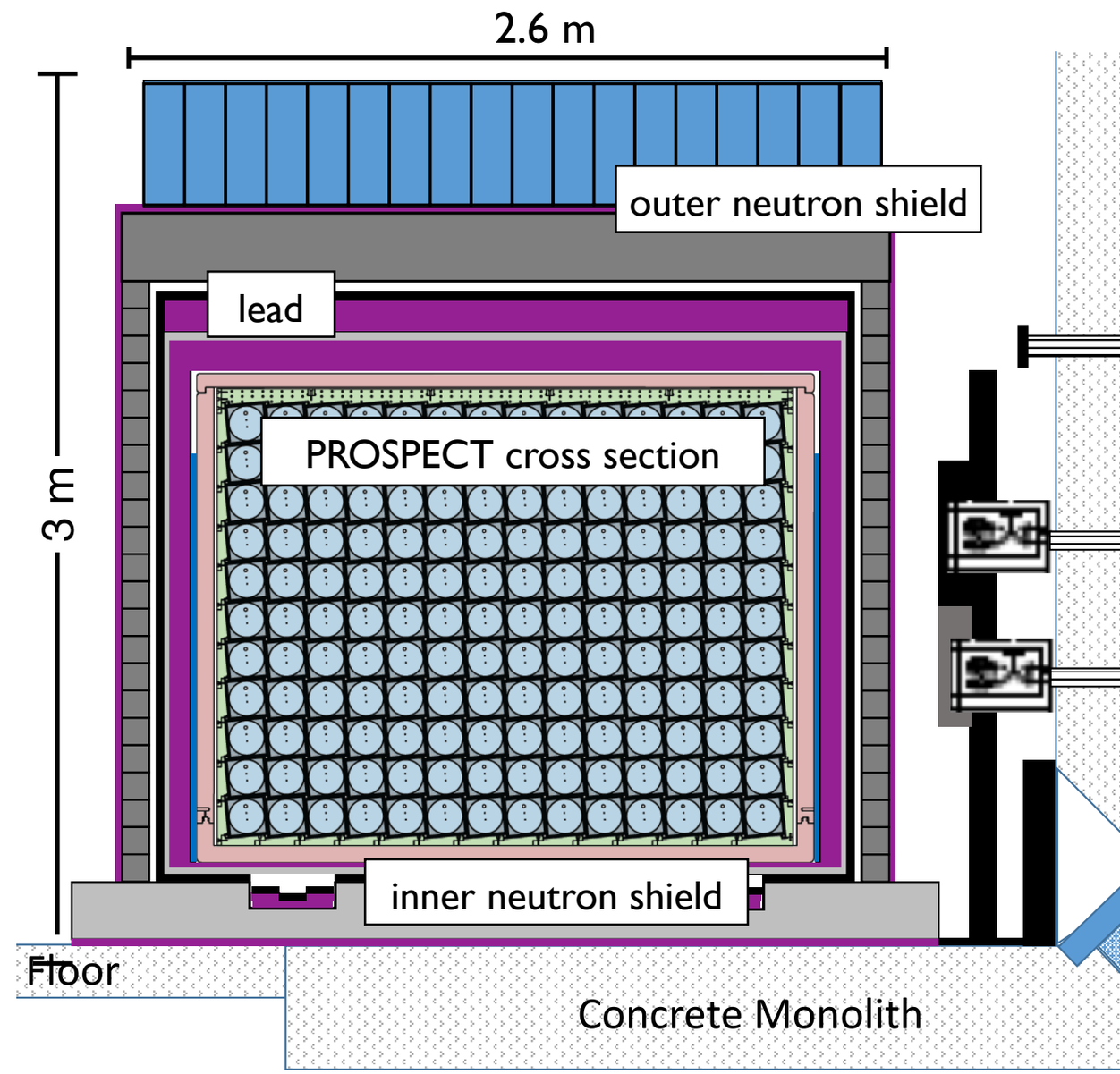


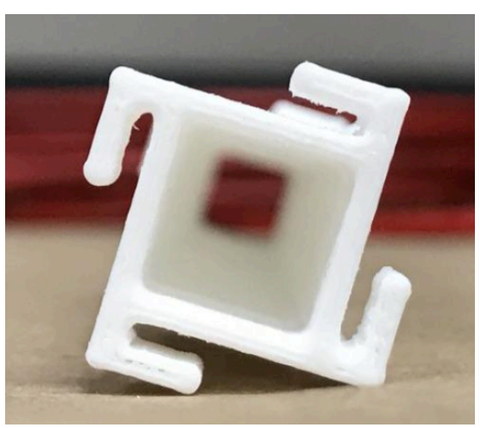
PSD = Qtail/Qfull

PROSPECT, NIM A806 401 (2016)
PROSPECT, JINST 10 P11004 (2016)
PROSPECT, JINST 13 P06023 (2018)

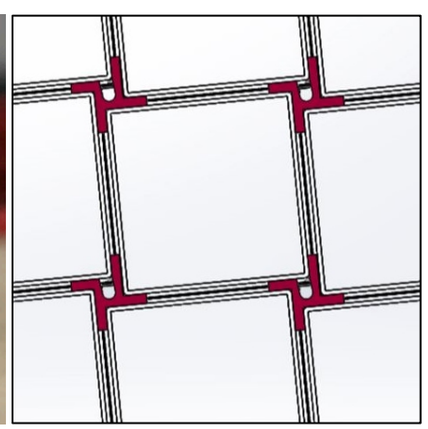
PROSPECT Segmented Detector Design

- 4 tons ^{6}Li-loaded liquid scintillator with energy resolution of <5%/MeV
- 154 segments, 119cm × 15cm × 15cm
- thin (1.5mm) highly reflective optical panels held in place by 3D printed support rods
- calibration access along each segment
- 3D position reconstruction (X,Y) with (Z) from double-ended PMT readout
- optimized shield for backgrounds at the surface and reactor

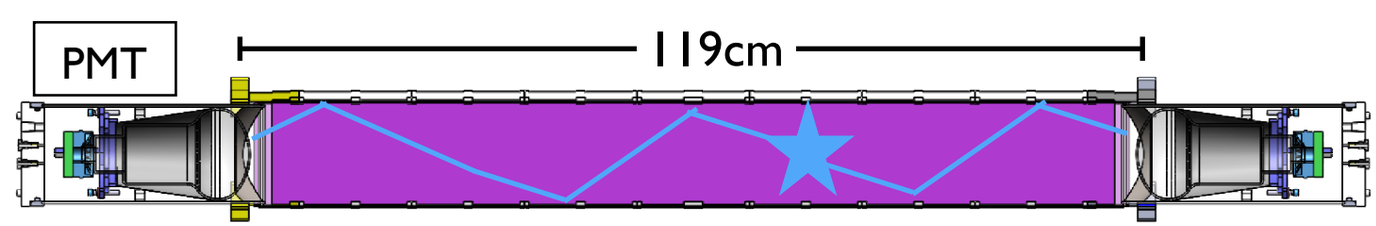




3D printed support rod



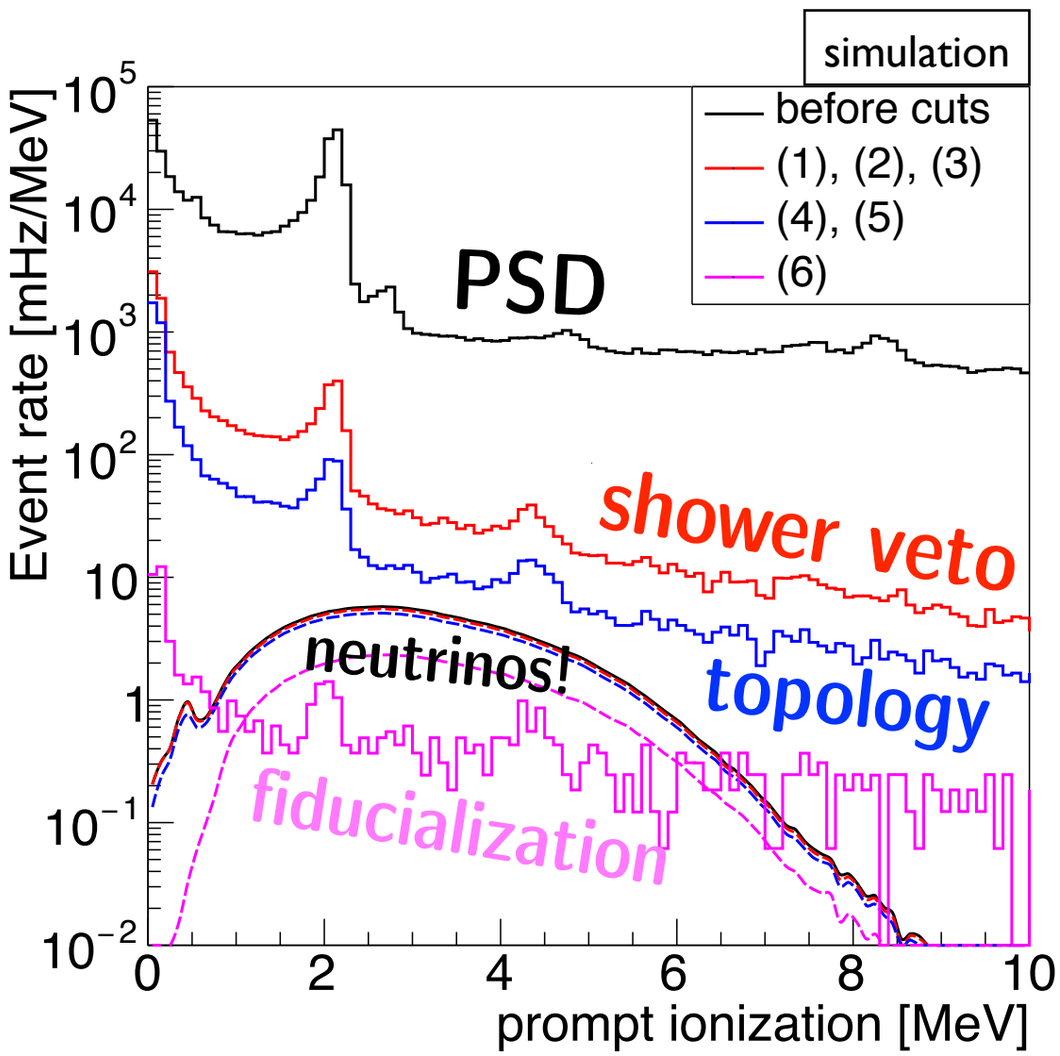
tilt for calibration access

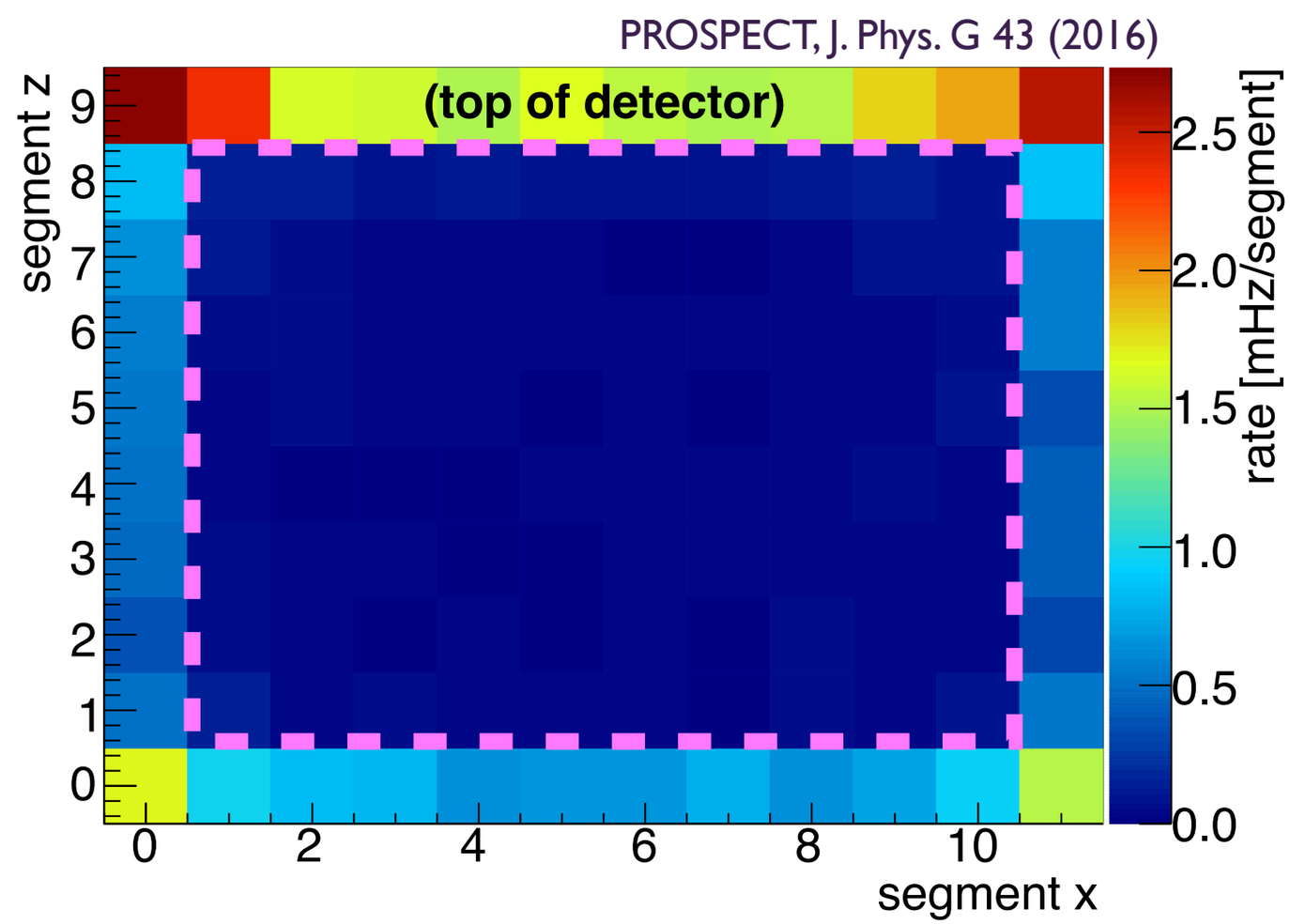


Liquid Scintillator Volume

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)





Component Fabrication

2016-2017: COMPONENT FABRICATION

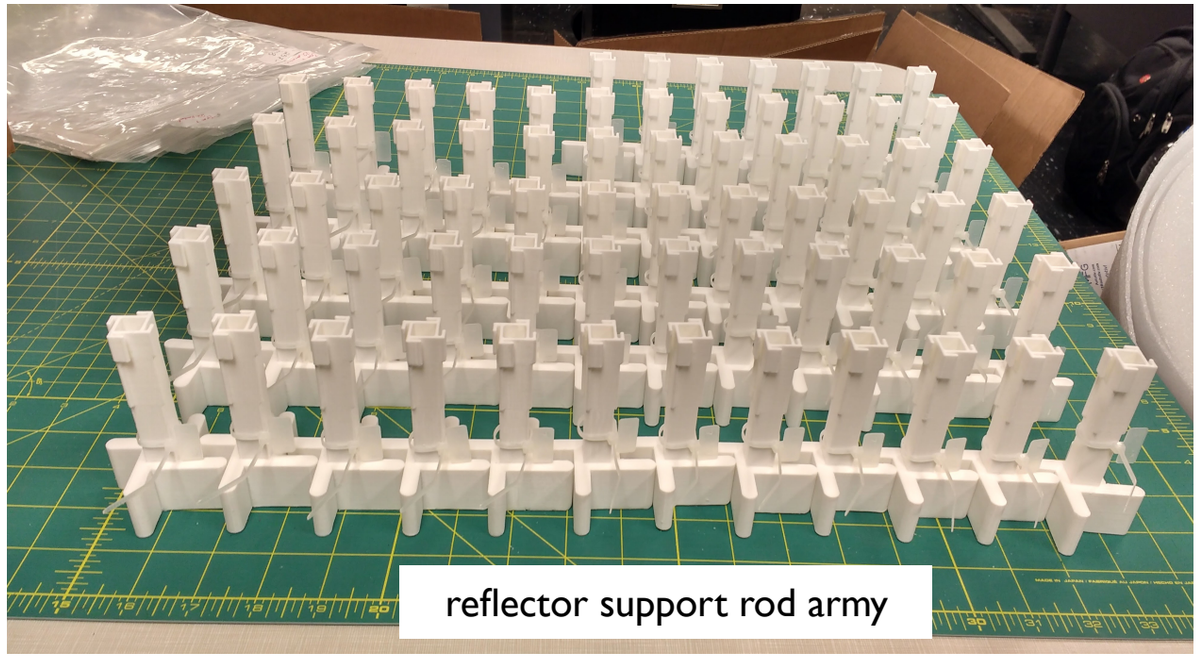
PMT housing: PMT Install

PMT housing: Burn-In Testing

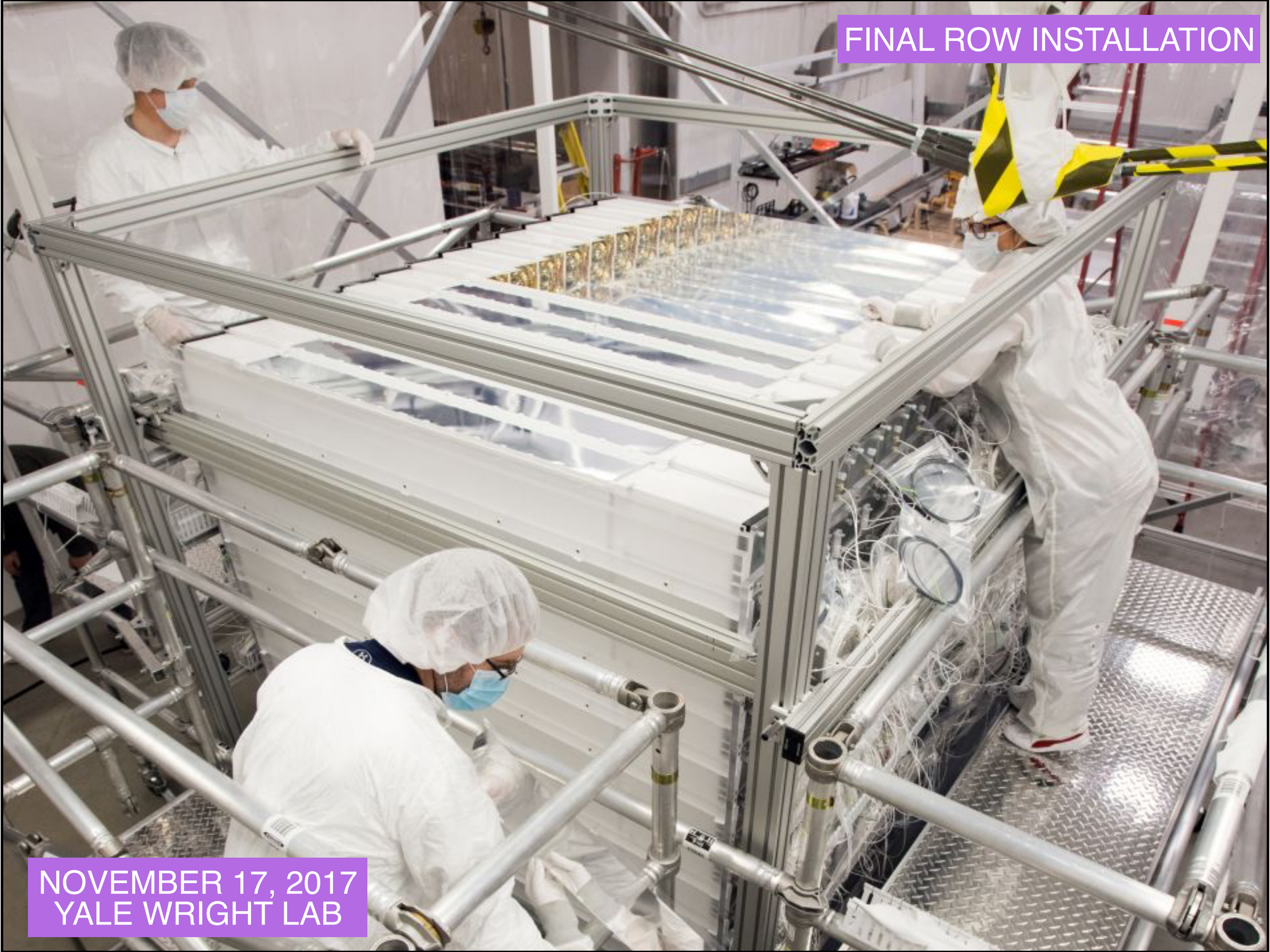
Fully laminated reflector

Liquid scintillator production

PMT housing: oil filling

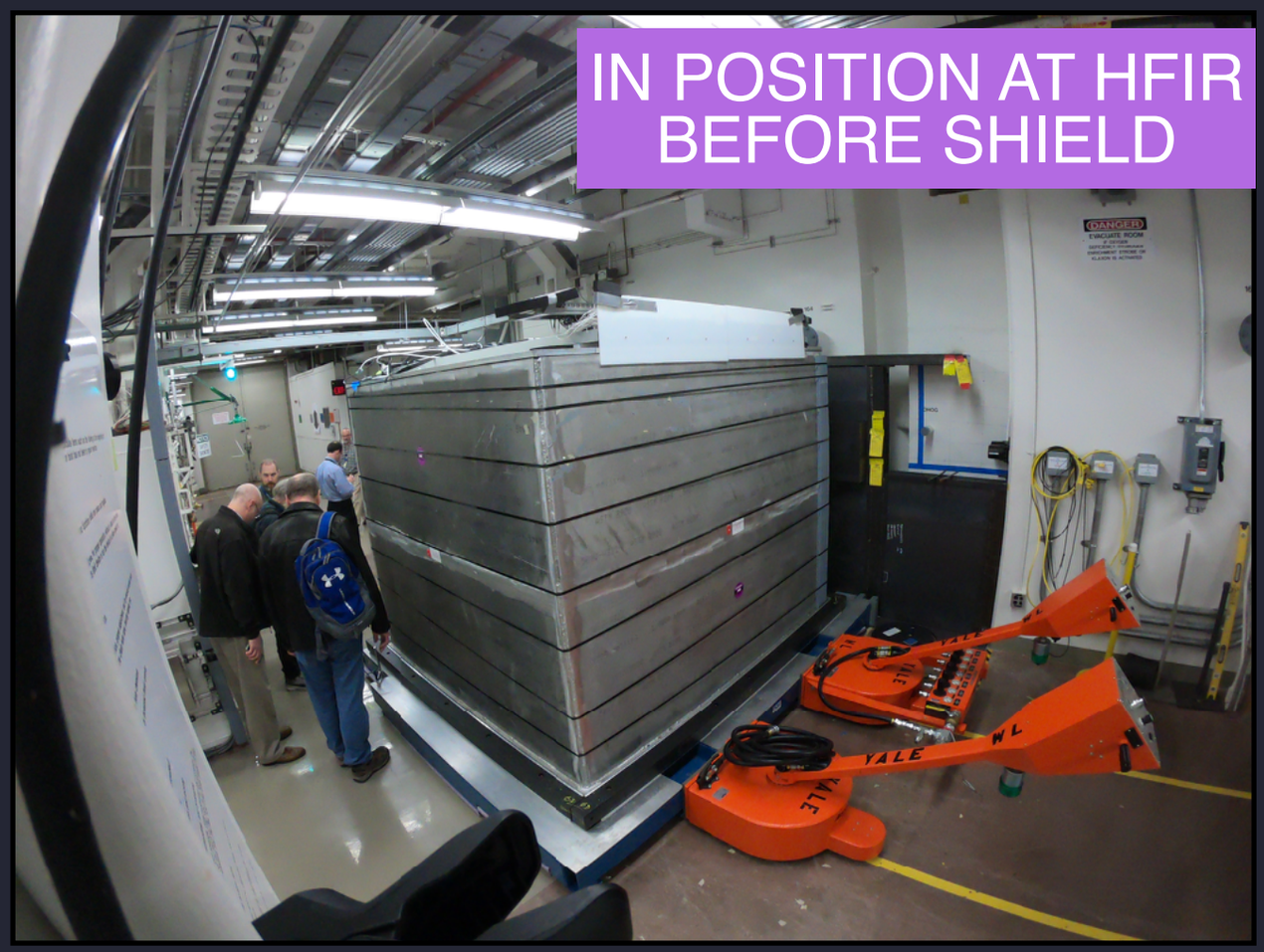

reflector support rod army

ASSEMBLY OF FIRST ROW
NOVEMBER 1, 2017
YALE WRIGHT LAB

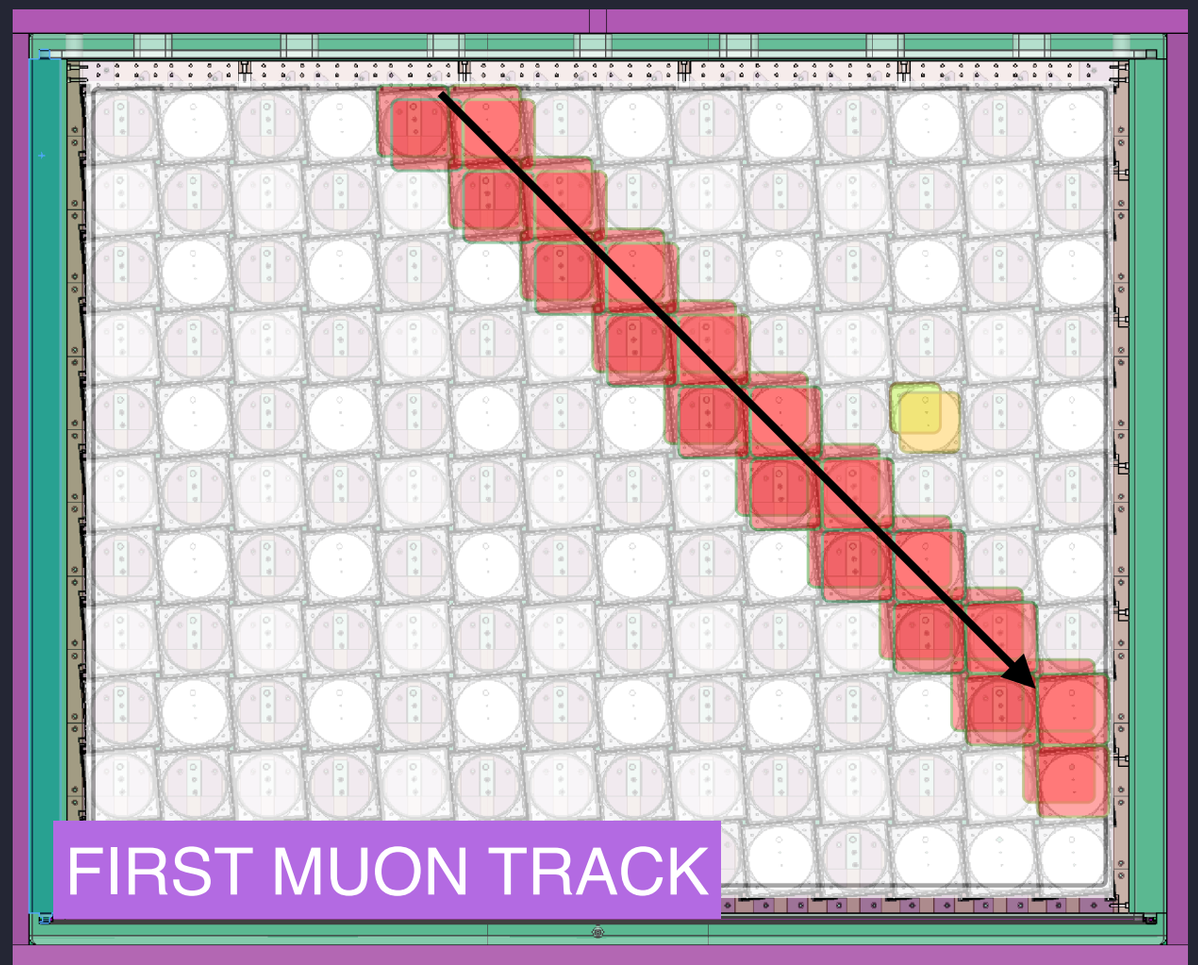

FINAL ROW INSTALLATION
NOVEMBER 17, 2017
YALE WRIGHT LAB

LATE 2017: DRY COMMISSIONING

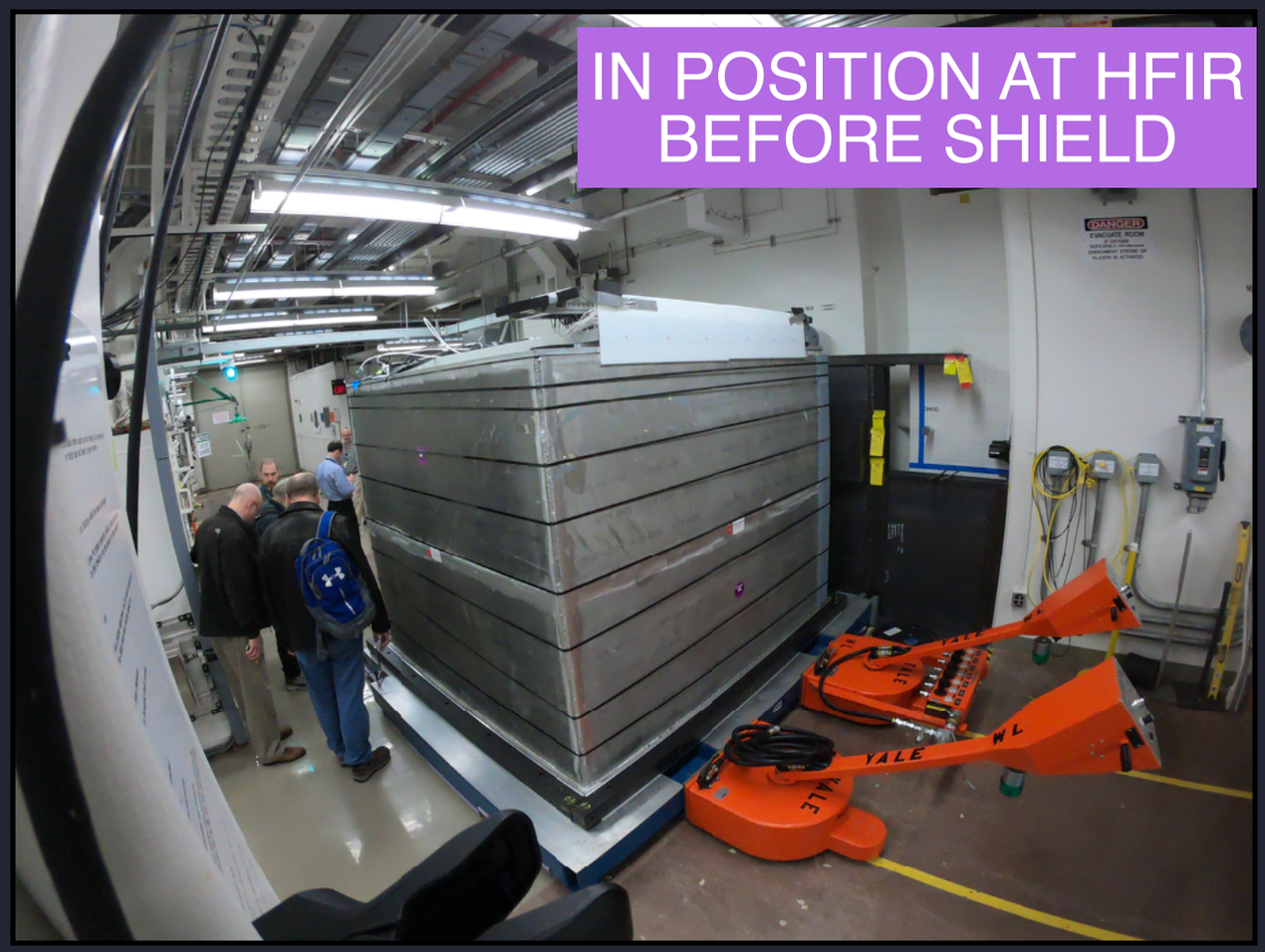
FEBRUARY 2018
ARRIVAL AT ORNL


IN POSITION AT HFIR
BEFORE SHIELD

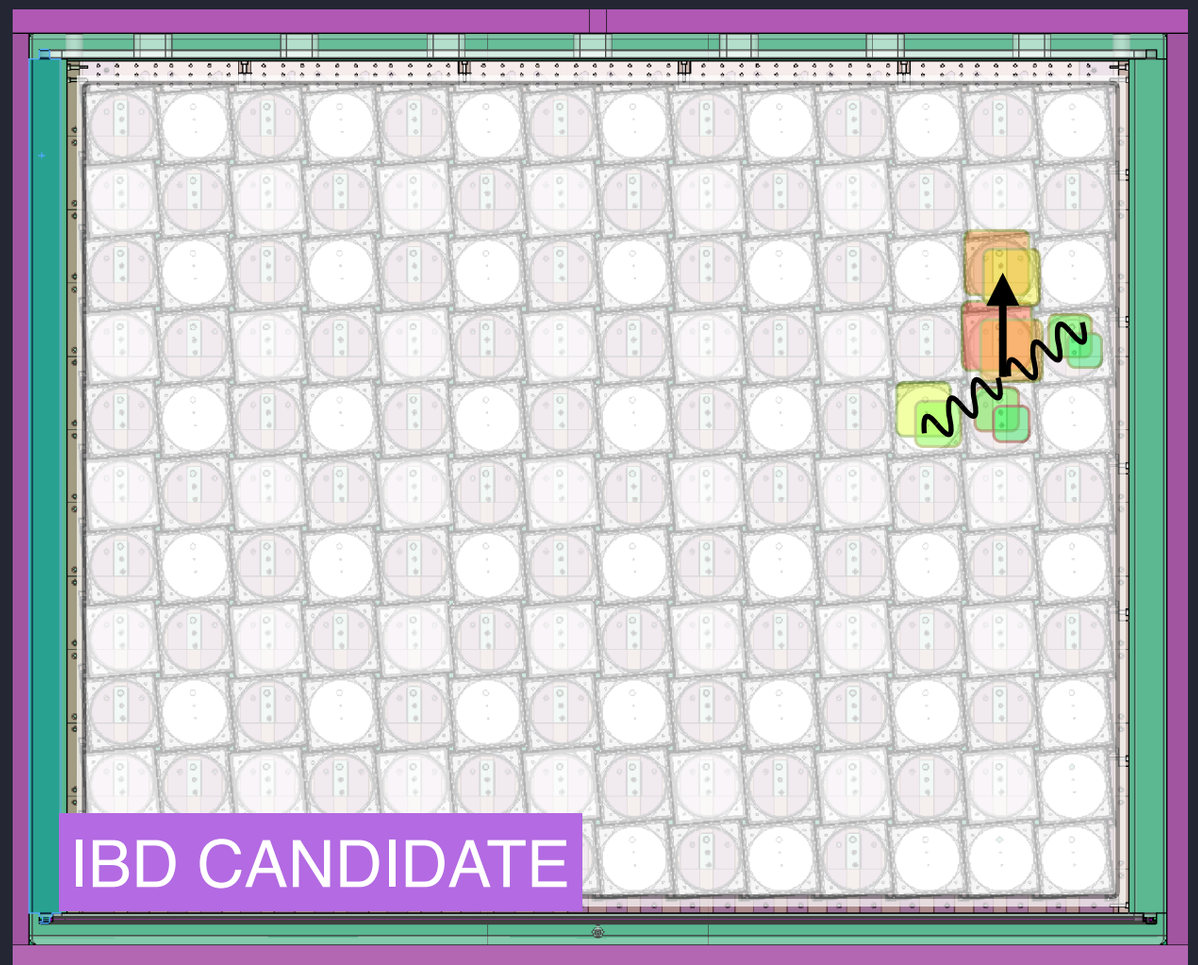
FILLING FROM
MIXING TANK


FIRST MUON TRACK

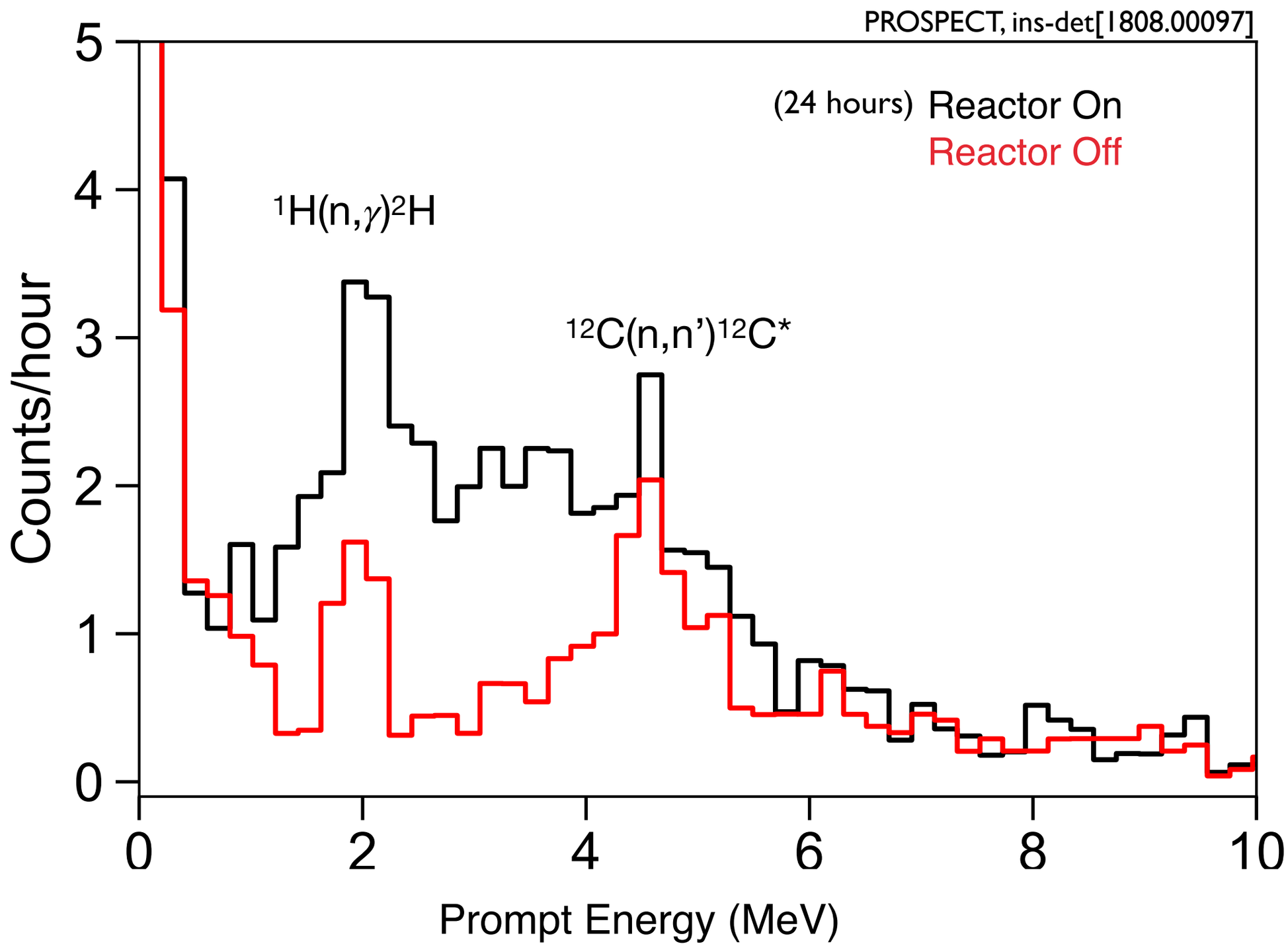
FEBRUARY 2018
ARRIVAL AT ORNL


IN POSITION AT HFIR
BEFORE SHIELD

FILLING FROM
MIXING TANK


IBD CANDIDATE

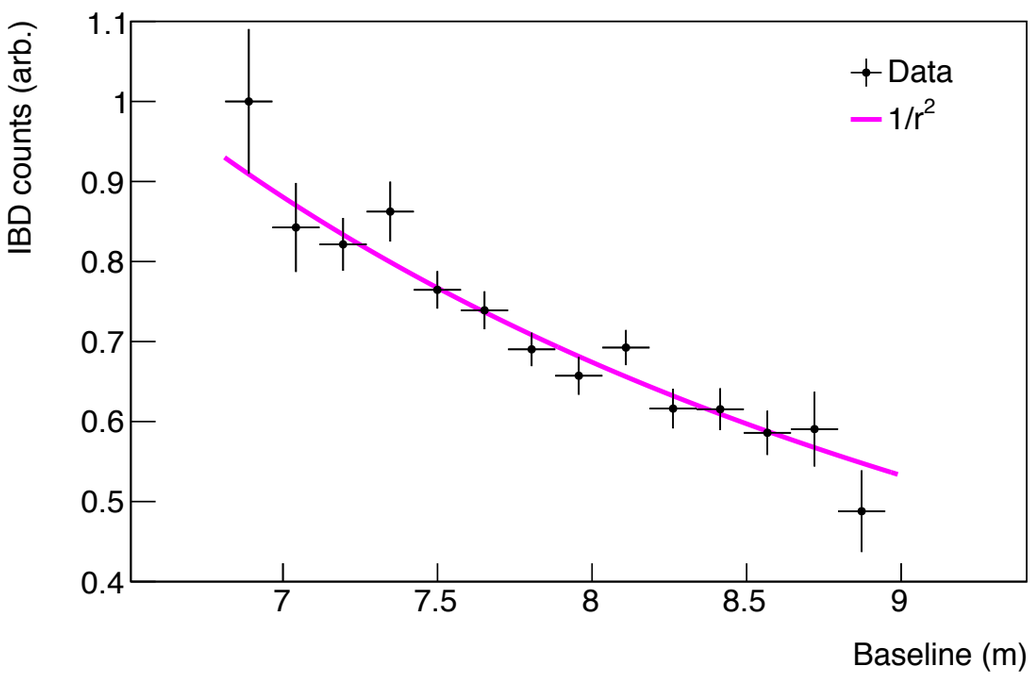
Within A Few Hours: Neutrinos!

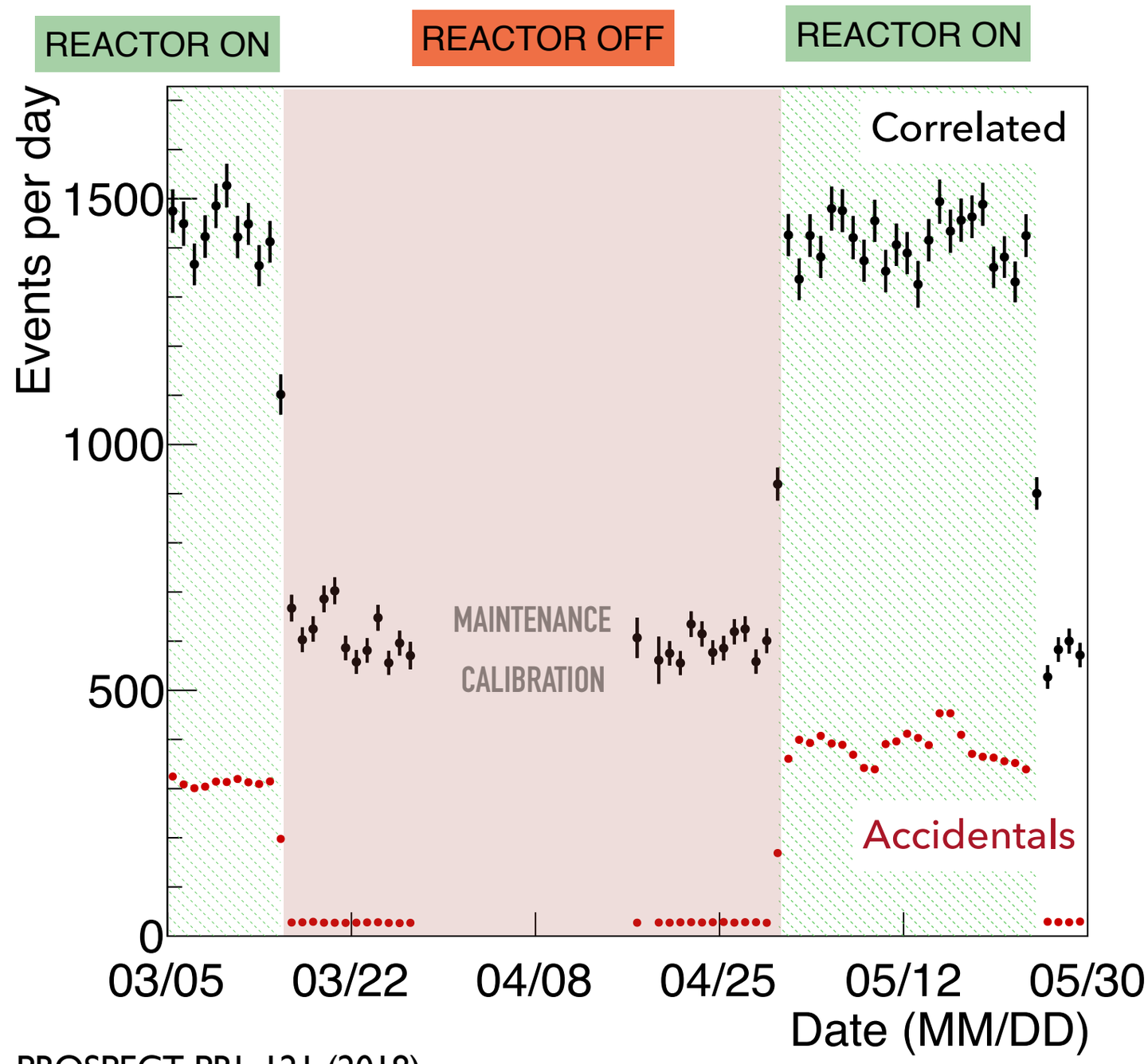


Time to 5σ reactor antineutrino detection at Earth's surface: <2 hours

Neutrino and Background Datasets

- 33 days of Reactor On
- 28 days of Reactor Off
- From 0.8-7.2 MeV prompt:
  - 24,461 IBD interactions
  - average of ~771 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 $1/r^2$ drop-off clearly visible!





PROSPECT, PRL 121 (2018)

Present Issues Reminder

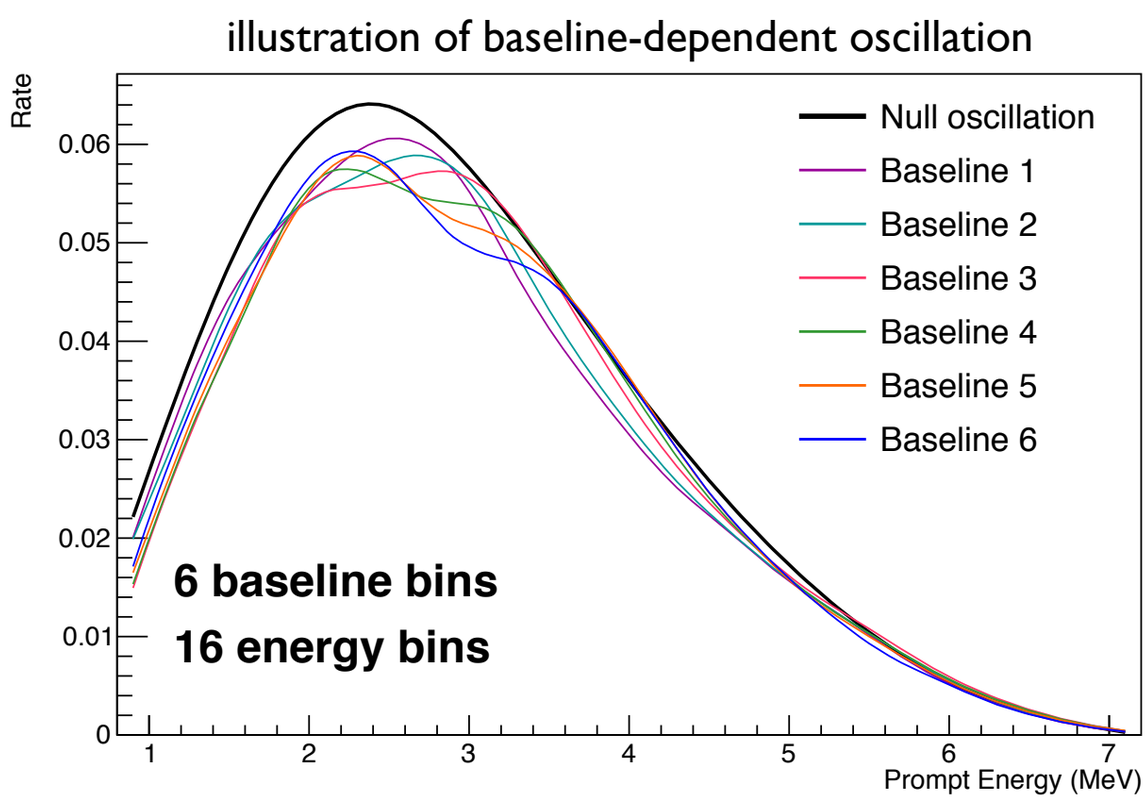
- Flux predictions don't match global measurements
  - Hypothesis 1: Predicted fluxes are just wrong for some (all?) isotopes
  - Hypothesis 2: Electron neutrinos are oscillating away
- Spectrum predictions don't match global (LEU) measurements
  - Can't be from oscillations.
  - Likely a model problem. Is one isotope's prediction wrong? Or all isotopes?
- What can we do to address all of these issues????

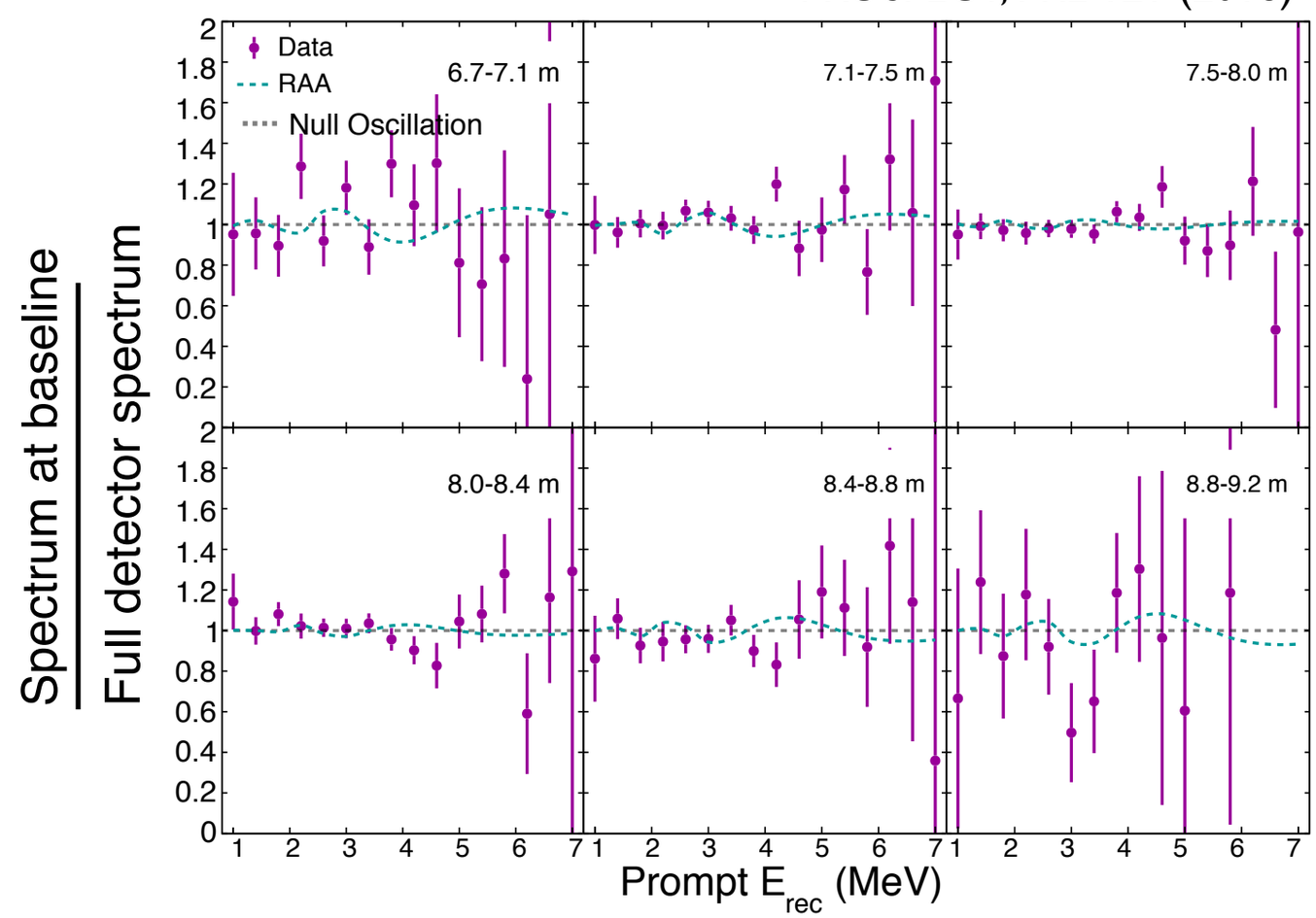
Neutrino Oscillation Measurement

- Combine data into 16 energy, 6 baseline bins
- Divide each baseline's measured energy spectrum by the full-detector measured energy spectrum
- Compare this to predicted ratio for different (Δm^2_{41}, $\sin^2 2\theta_{14}$):

$$\chi^2_{min}(\Delta m^2, \sin^2 2\theta) = \mathbf{\Delta}^{\mathrm{T}} \mathbf{V}_{\mathrm{tot}}^{-1} \mathbf{\Delta}$$

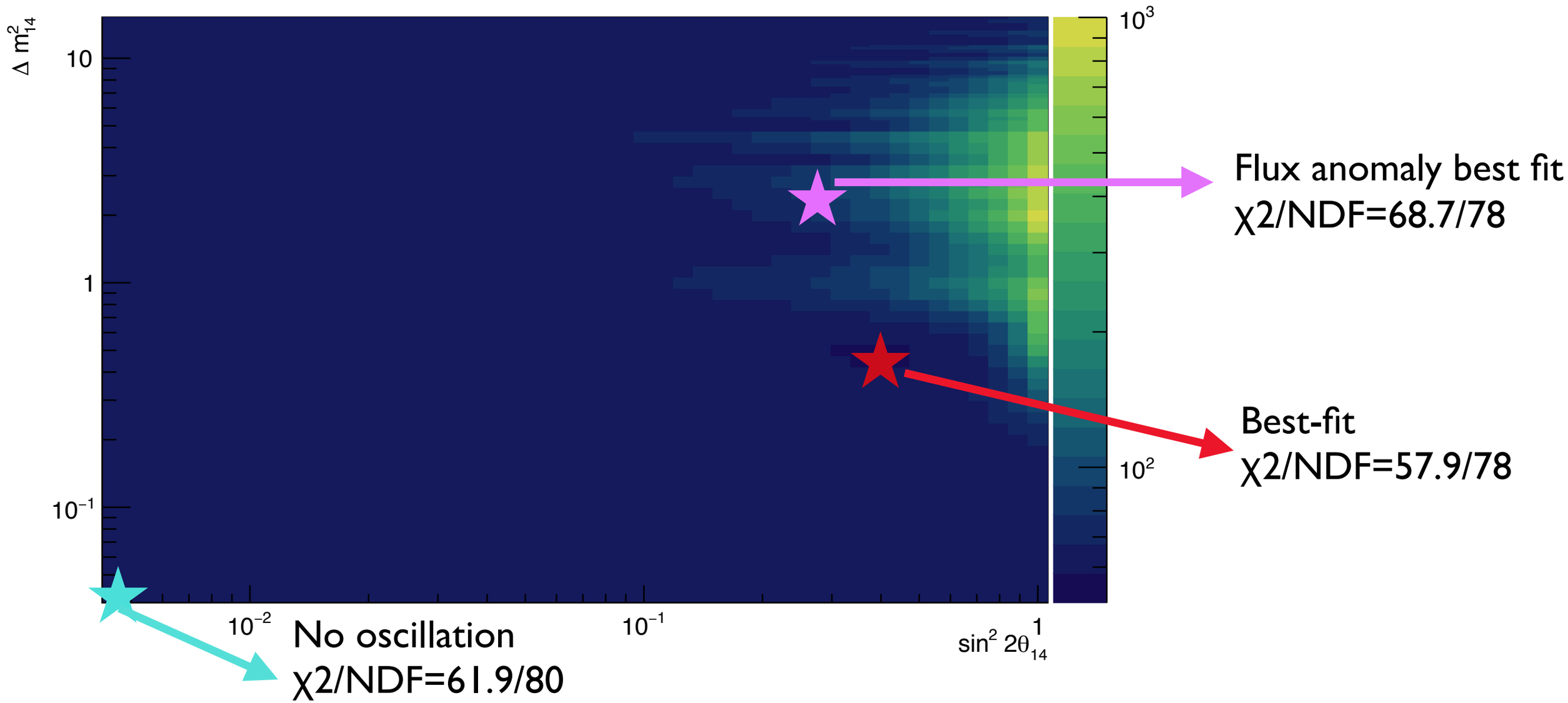
PROSPECT, PRL 121 (2018)





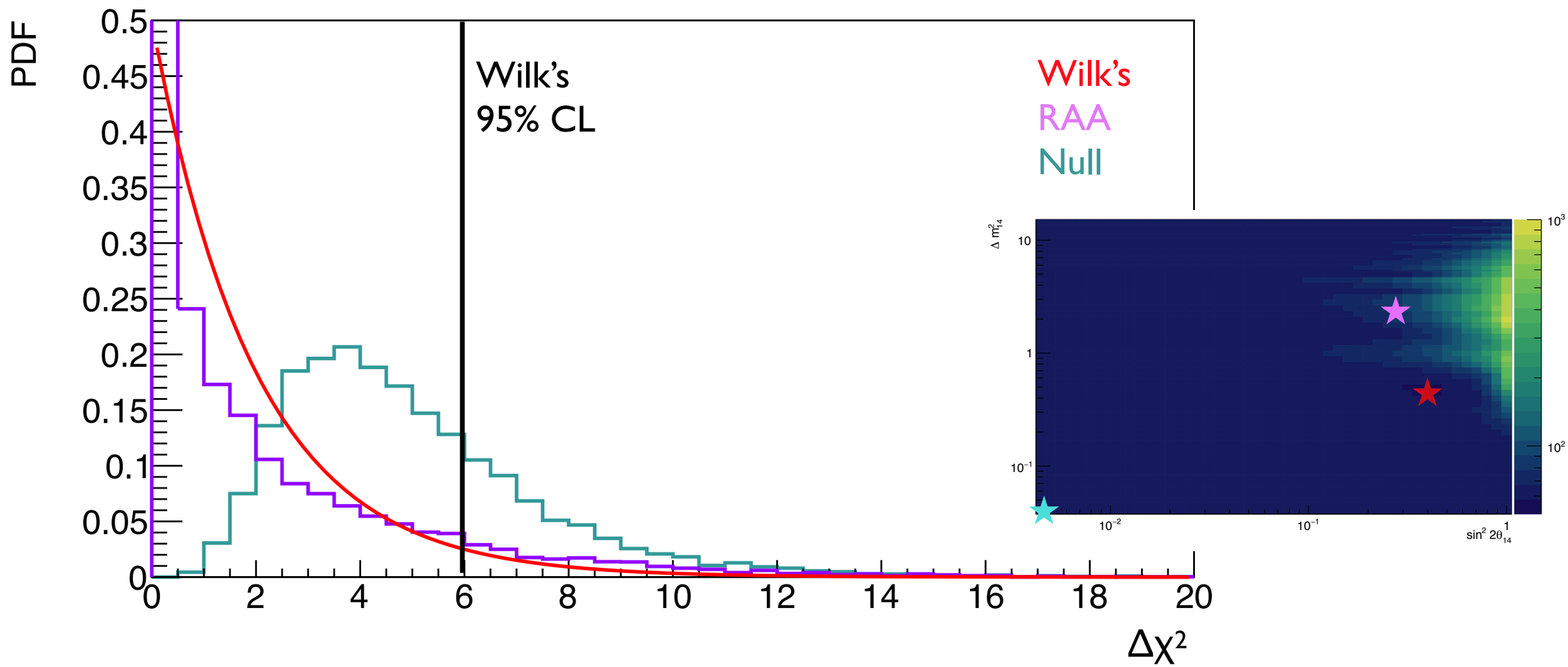
Oscillation Fit Results

- Best-fit χ^2 of 57.9/78
  - Null (reactor flux anomaly) oscillation is 4 (10.8) higher in χ^2
- What does this mean?
  - Do we rule out null oscillations? Or the osc-only flux anomaly best-fit?



Establishing Confidence Intervals

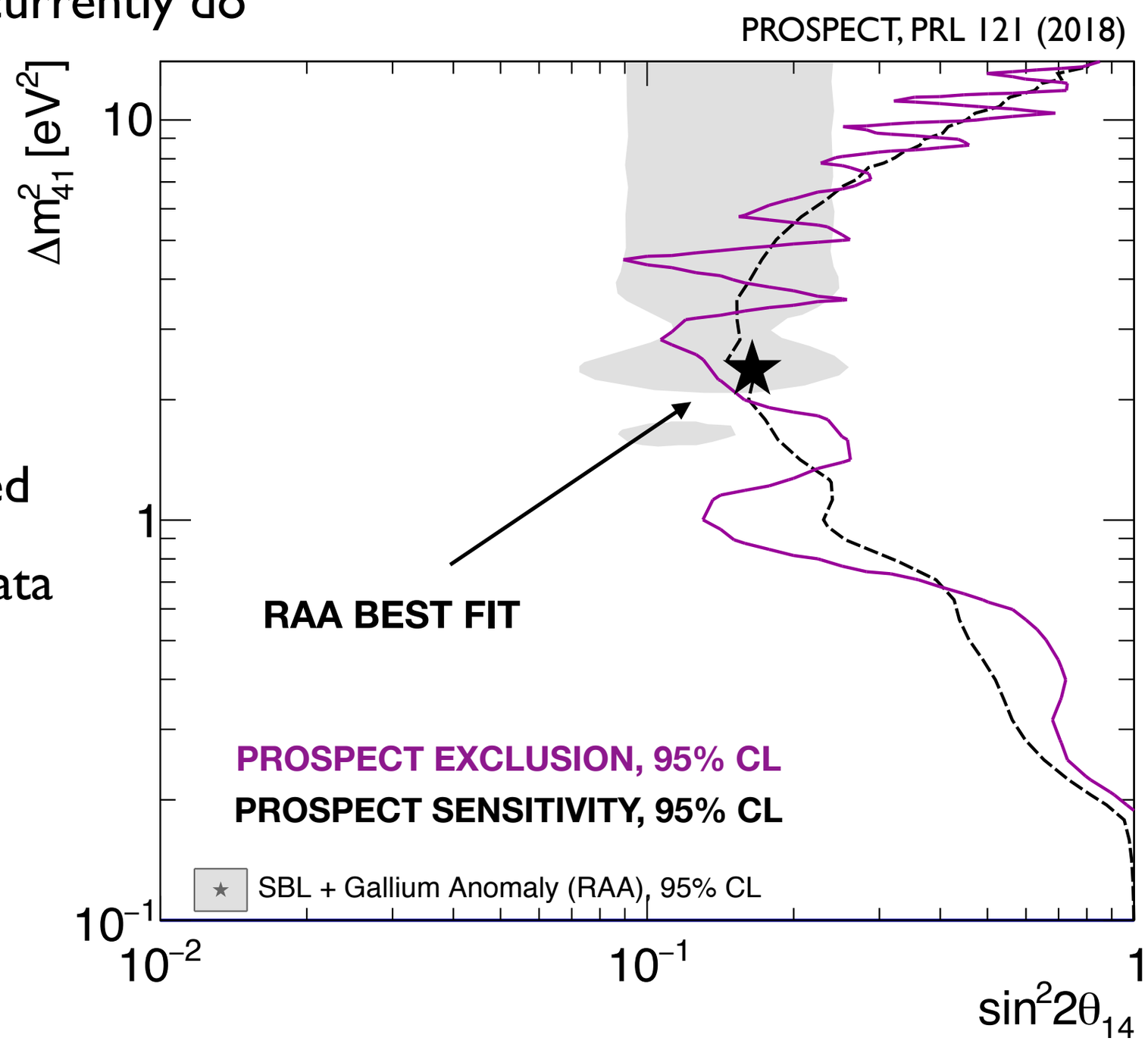
- To change $\Delta\chi^2$ to p-value preference ($X\sigma$ exclusion), usually assume that $\Delta\chi^2$ follows a χ^2 distribution
  - Generation of toy PROSPECT datasets show that this is not true for short-baseline reactor measurements with ~small osc signatures
  - Must establish confidence intervals with frequentist (Feldman-Cousins) method



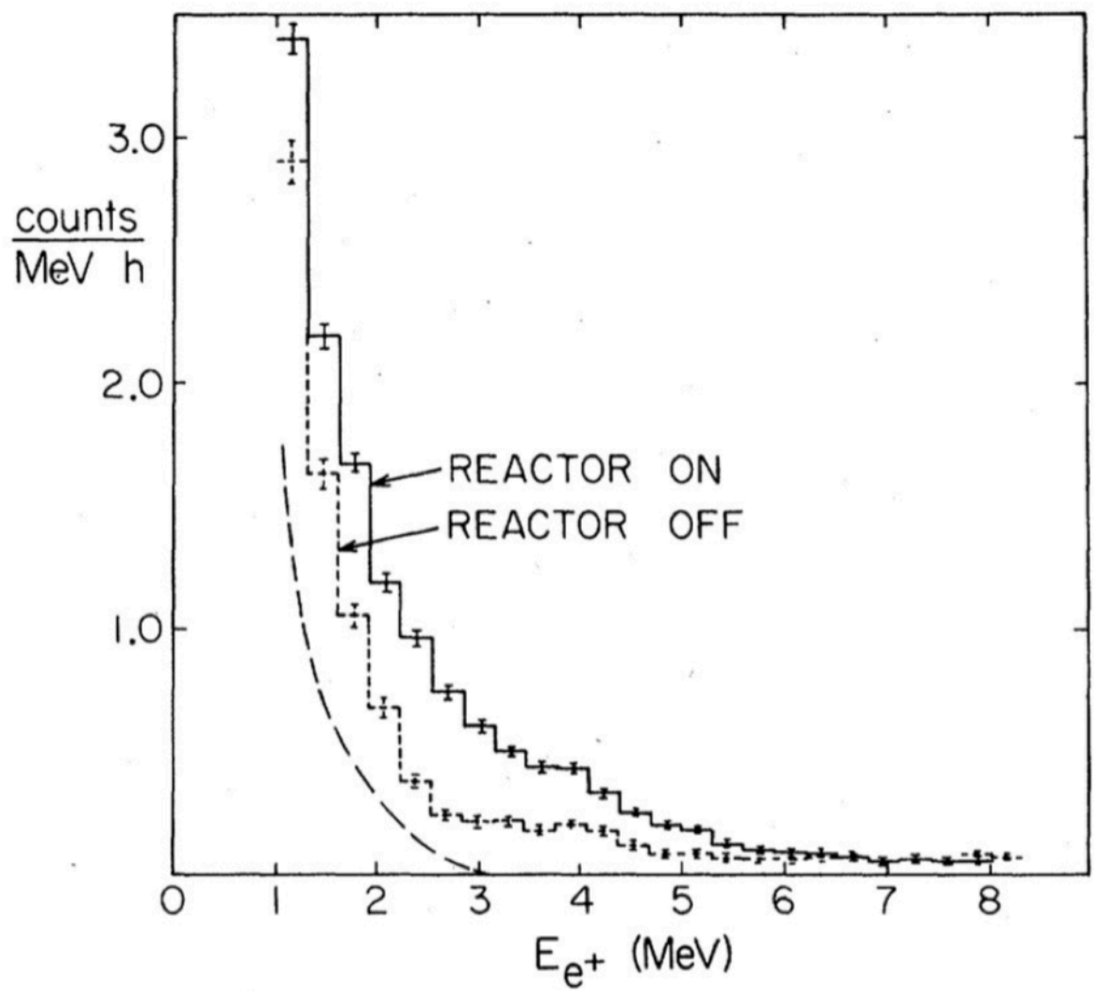
Osc Parameter Sensitivity and Exclusion

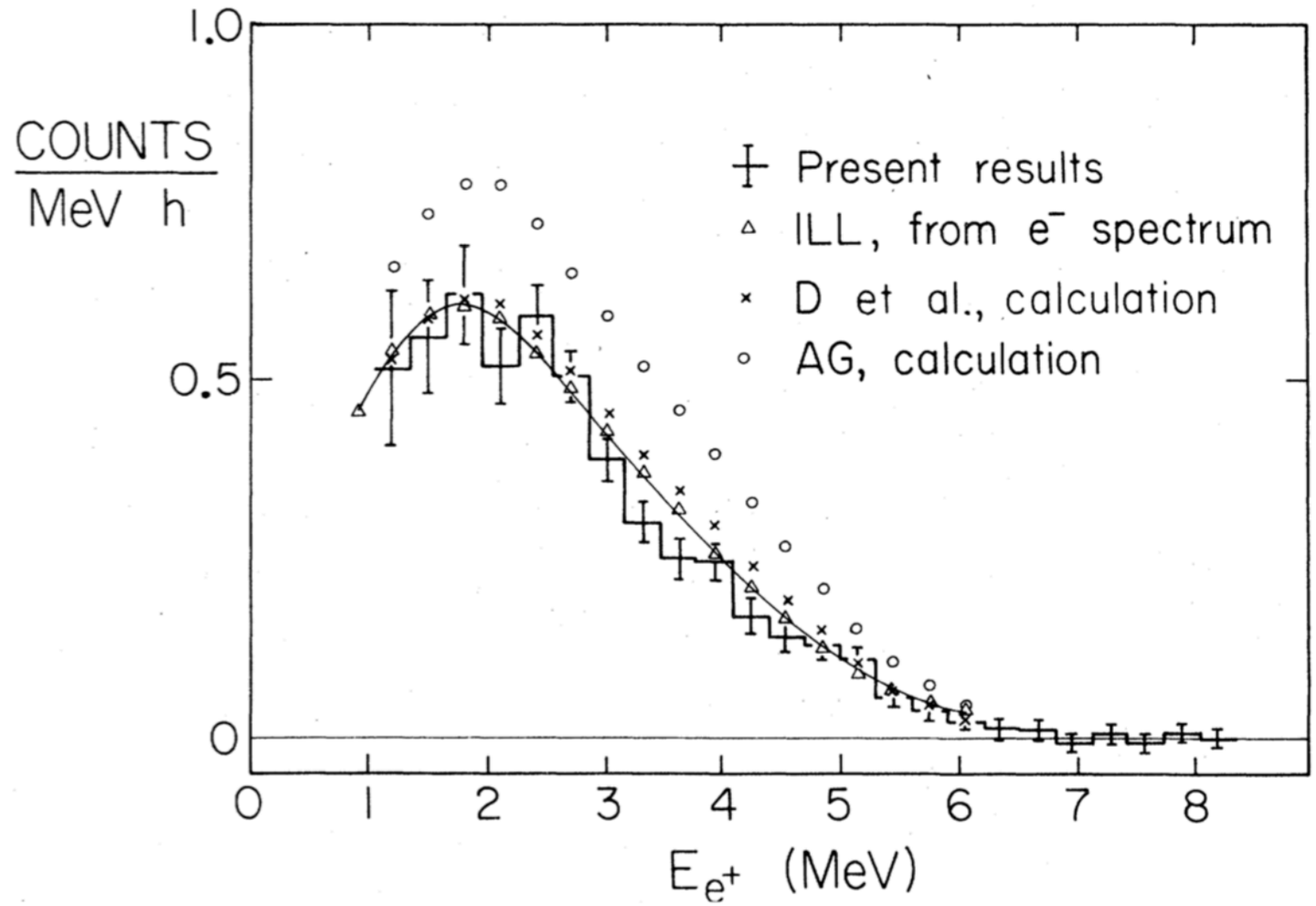
- With 33 days of reactor-on data-taking we are excluding new interesting regions of $\sin^2 2\theta_{14}$ parameter space.

  - Short-baseline reactors currently do the best in constraining this active-sterile mixing parameter
  - Rule out best-fit of the osc-only solution to the flux anomaly at 2.2σ
  - Currently statistics limited major improvements coming with additional data



Measurement of ^{235}U antineutrino spectrum

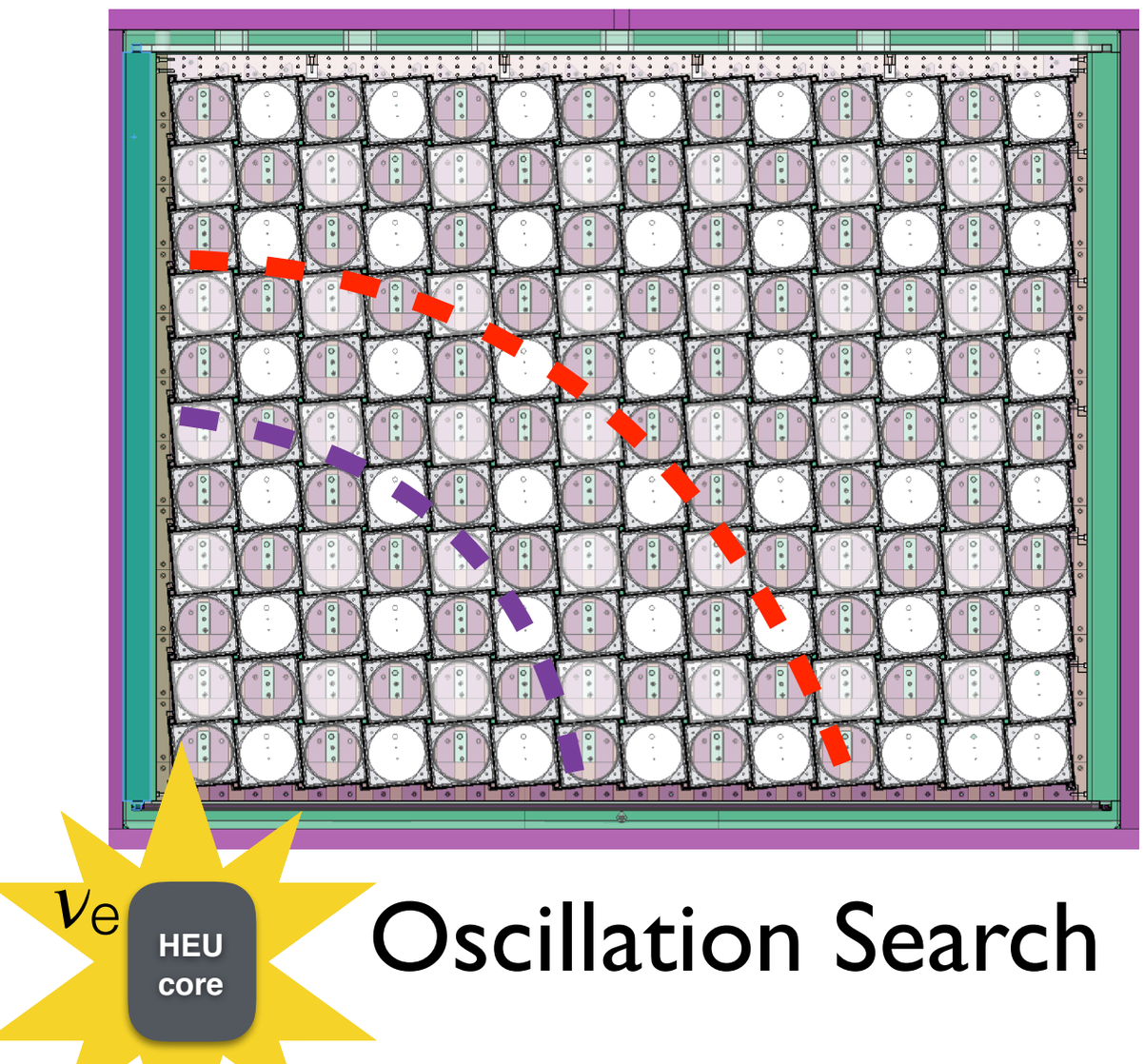




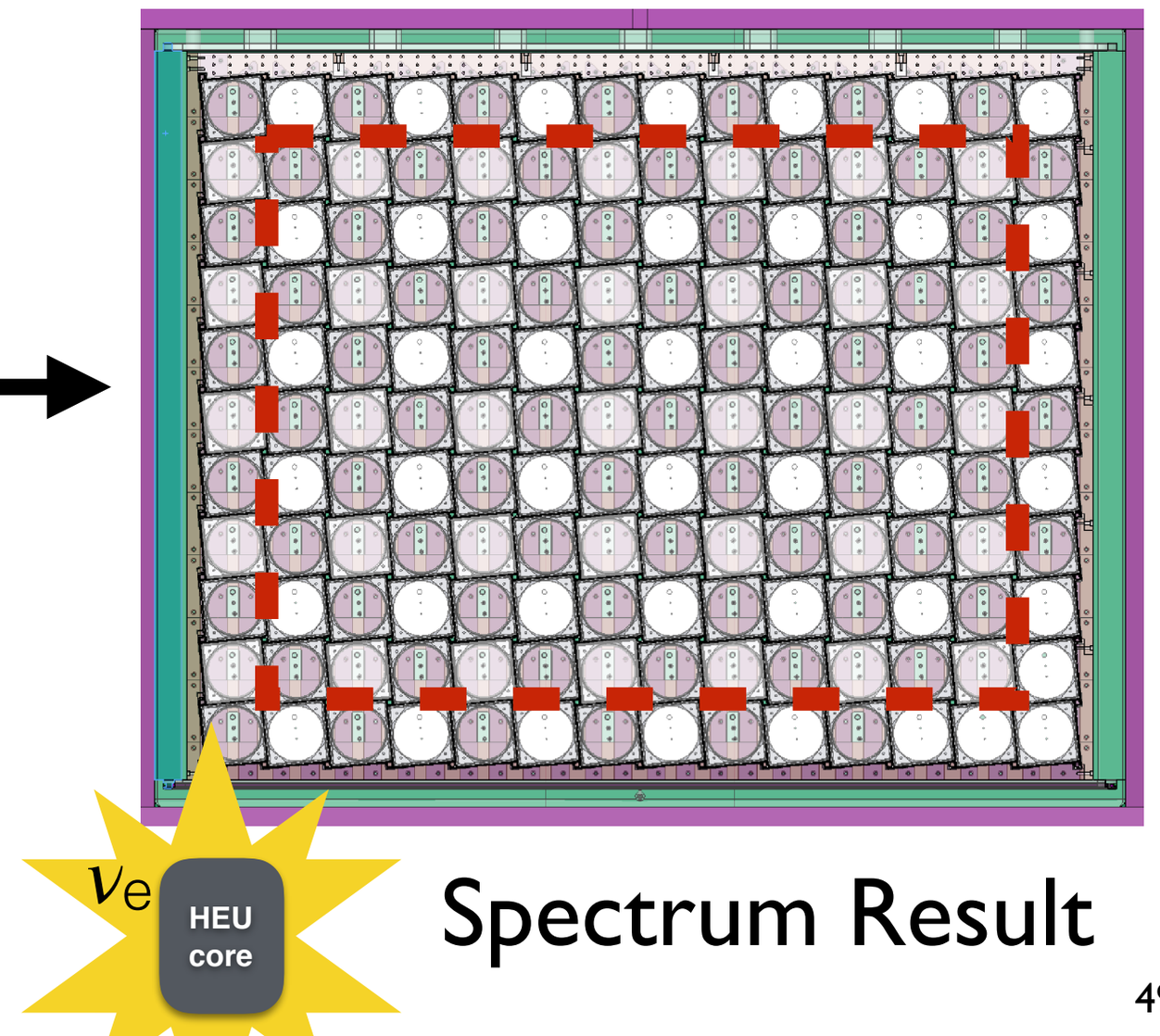
Here's the best existing measurement from an HEU reactor: 5000 events in1981 ILL experiment with copious backgrounds

Switch to Spectrum Measurement

- Search for baseline-dependent energy spectrum distortion inside a stationary, segmented, short-baseline detector
  - Datasets largely similar: 40 (33) reactor-on days for osc (spectrum) result
  - Spectrum dataset: 31,000 IBDs detected, 1.7:1 signal:background



Oscillation Search

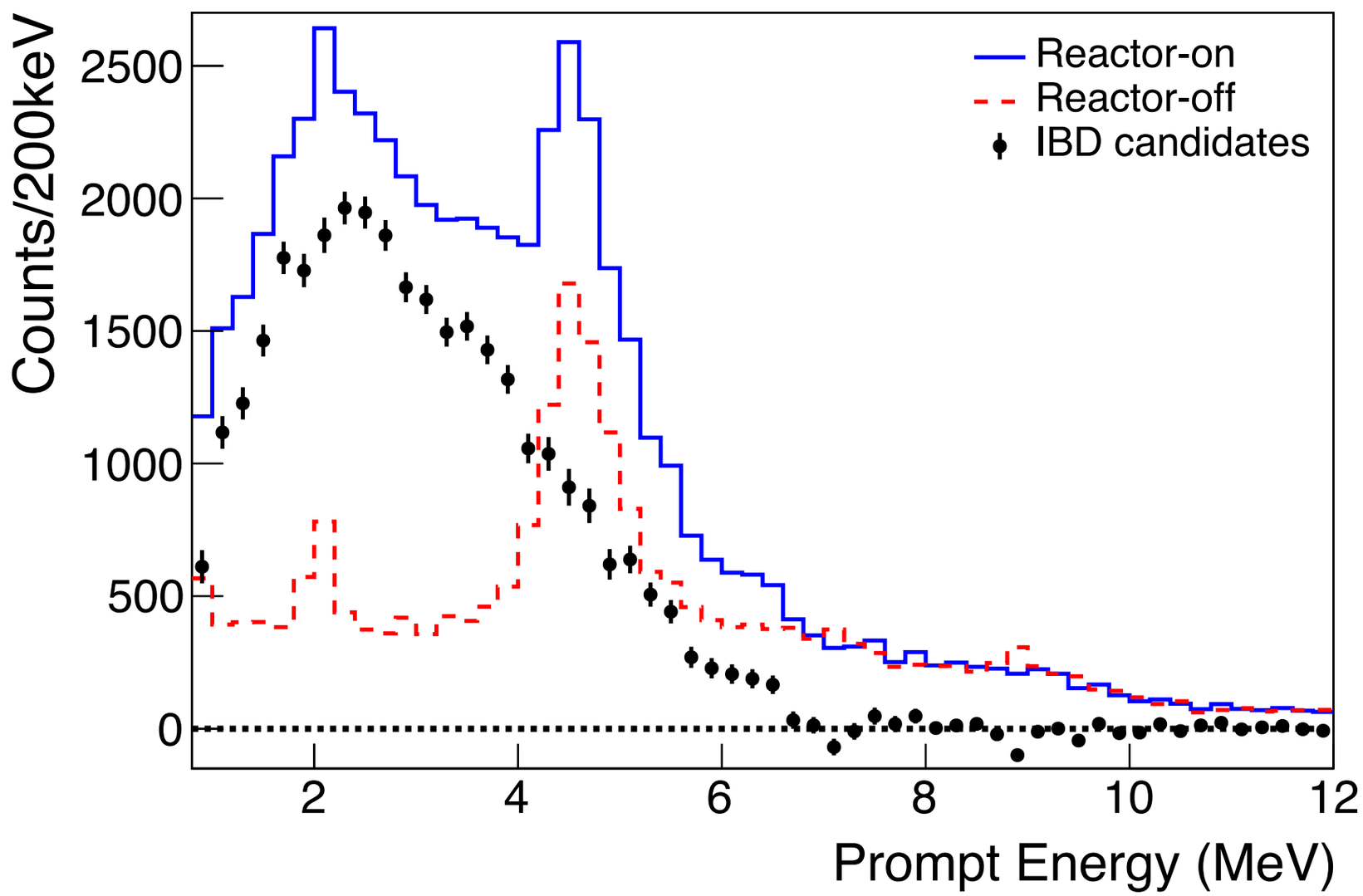


Spectrum Result

Neutrino and Background Datasets

- Look at reactor-on and reactor-off data in a different way: energy spectrum before and after on-off subtraction
  - Subtraction looks complete in high-energy sideband (good!)
  - Expected background peaks at ~2 and ~4.5 MeV cosmogenic neutrons

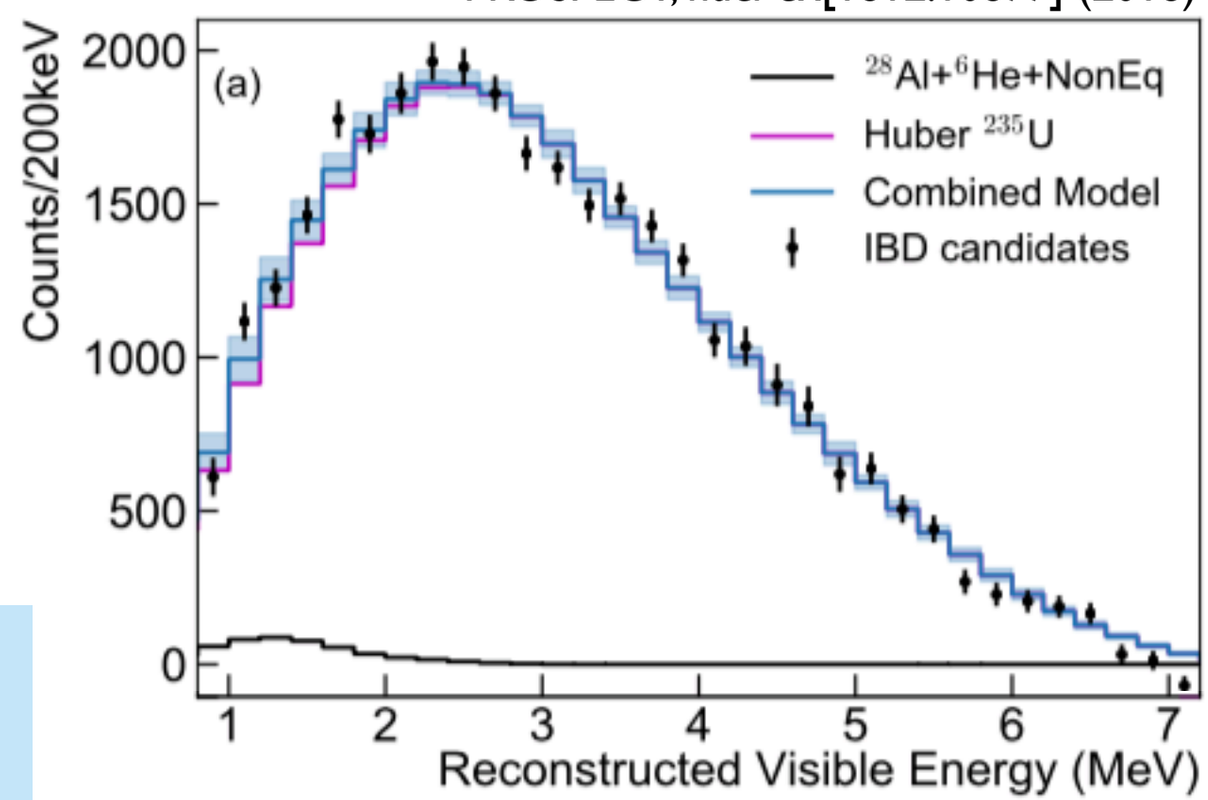
PROSPECT, [nucl-ex]1812.10877 (2018)



PROSPECT ^{235}U Spectrum Result

- Background-subtracted ^{235}U spectrum result
  - Compare to the Huber beta conversion prediction
  - Small neutrino contribution from activation of reactor components
  - Small correction for time-dependent effects in reactor fuel
- General agreement in broad spectrum features

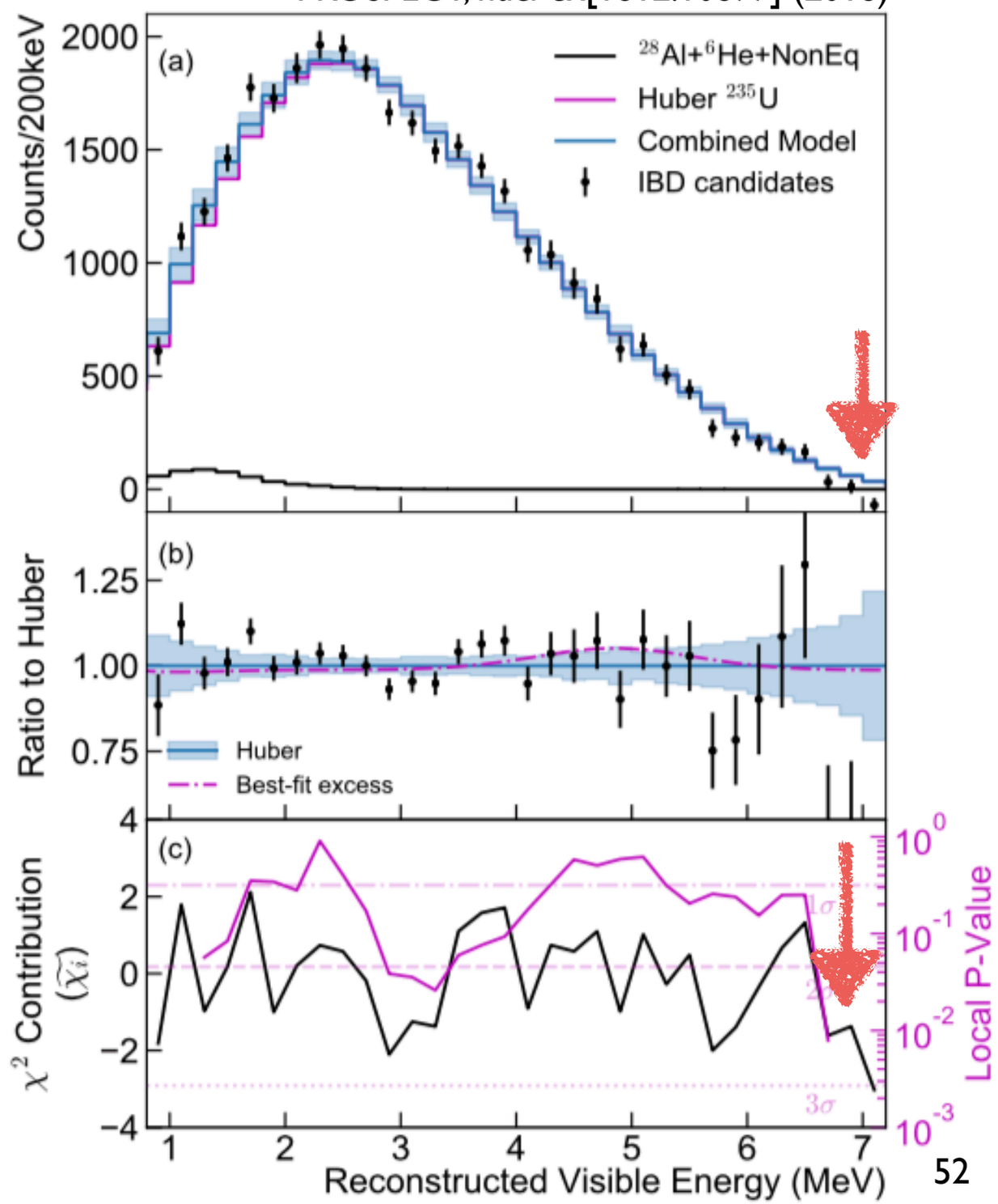
PROSPECT, nucl-ex[1812.10877] (2018)



PROSPECT ^{235}U Spectrum Result

- Background-subtracted ^{235}U spectrum result
- Is PROSPECT consistent with Huber's ^{235}U model?
  - X^2/ndf = 52.1/31; p-value = 0.01
  - So Huber broadly agrees with PROSPECT, but not a great fit
  - Worst offender is high energy; fit is OK otherwise.
    - Bkg issue? Unlucky statistics? Need more stats to know for sure.
    - Note: stats still dominate overall uncertainties across the spectrum

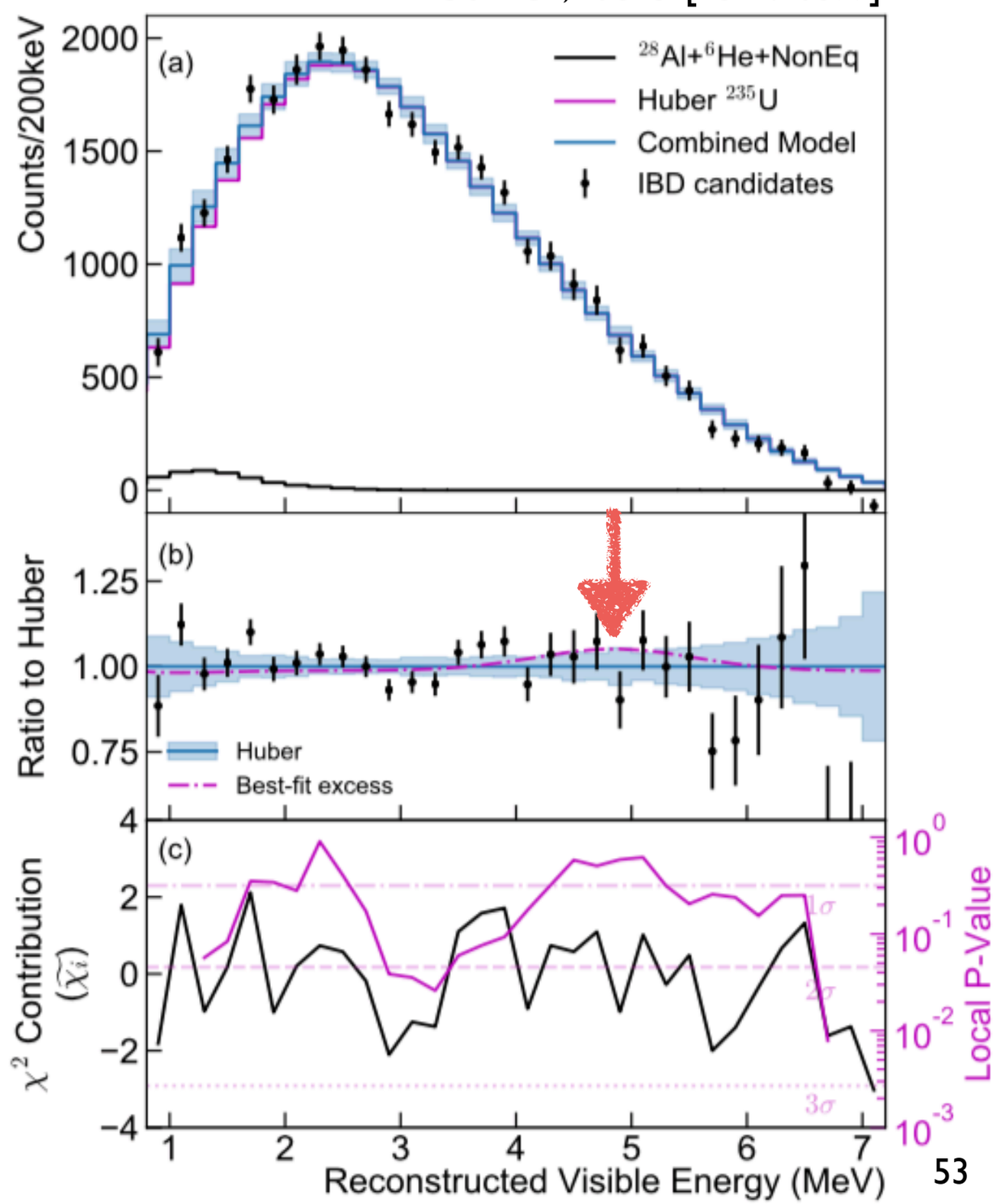
PROSPECT, nucl-ex[1812.10877] (2018)



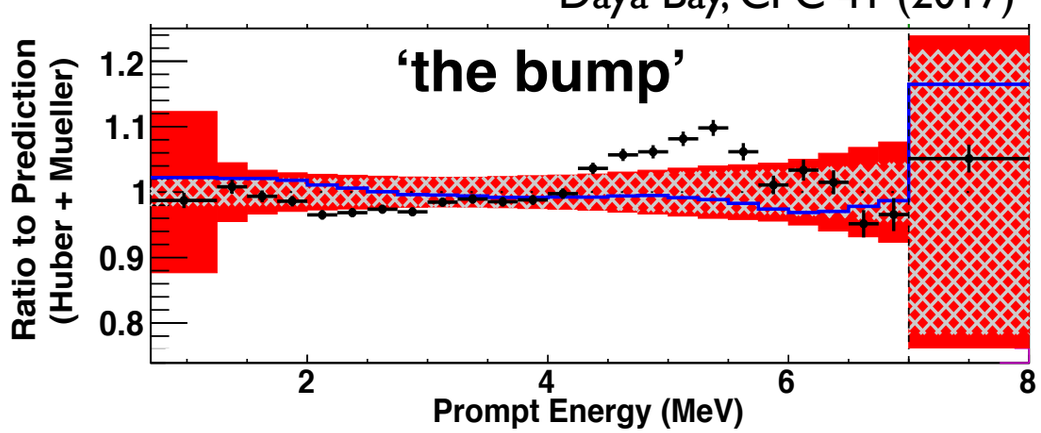
PROSPECT ^{235}U Spectrum Result

- 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, nucl-ex[1812.10877]



Daya Bay, CPC 41 (2017)



Summary

- PROSPECT has set new limits on active-sterile neutrino mixing
  - Have disfavored best-fit of osc-only reactor flux deficit hypothesis at 2.2σ
  - PROSPECT and other reactor experiments will continue to lead global sensitivity to $\sin^2 2\theta_{14}$ in the eV-scale regime for the foreseeable future
- PROSPECT has performed the best-ever measurement of the ^{235}U $\bar{\nu}_e$ spectrum
  - General, but marginal, agreement with beta conversion predictions
  - Lack of a 'large bump' in PROSPECT data with respect to prediction: indicates ^{235}U is not the sole producer of 'bumps' in LEU measurements
- Additional statistics will greatly improve both of these PROSPECT measurements in the near future.

THANKS!

- Things I didn't even get to mention (quiz me later!)
  - New STEREO HEU results
  - RENO and Daya Bay Spectrum Evolution
  - DANSS and NEOS
  - Reactor IBD-CEνNS complementarity
  - New studies questioning ILL beta spectrum calibration accuracy
  - Theory studies test inaccuracies in conversion/summation methods

Active-Sterile Osc Formalism

Giunti and Lasserre, hep-ph[1901.08330]

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

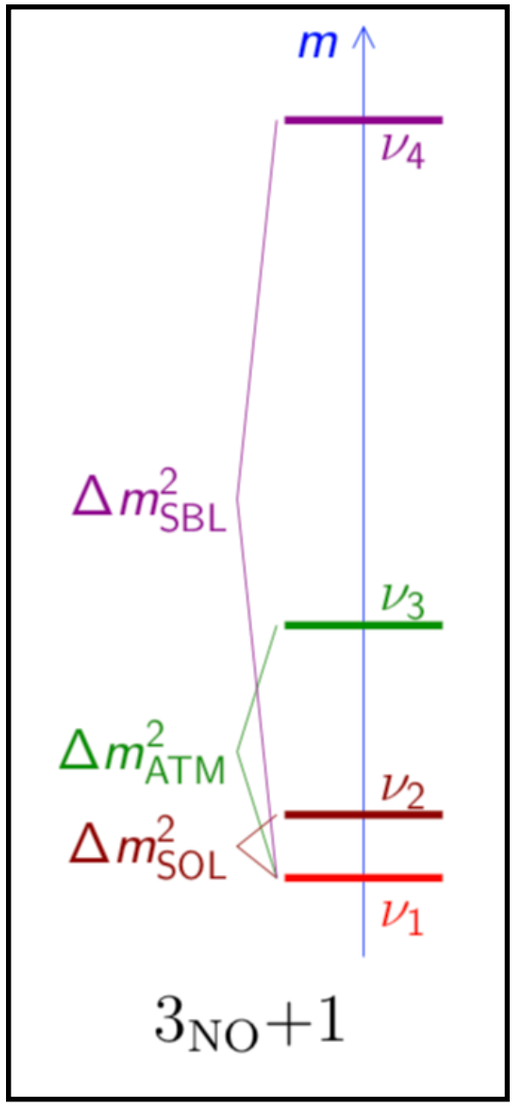
$$U = \begin{pmatrix} c_{12}c_{13}c_{14} & s_{12}c_{13}c_{14} & c_{14}s_{13}e^{-i\delta_{13}} & s_{14}e^{-i\delta_{14}} \\ \cdots & \cdots & c_{13}c_{24}s_{23} - s_{13}s_{14}s_{24}e^{i(\delta_{14}-\delta_{13})} & c_{14}s_{24} \\ \cdots & \cdots & \cdots & c_{14}c_{24}s_{34}e^{-i\delta_{34}} \end{pmatrix}$$

- Short-baseline oscillation looks like this:

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

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

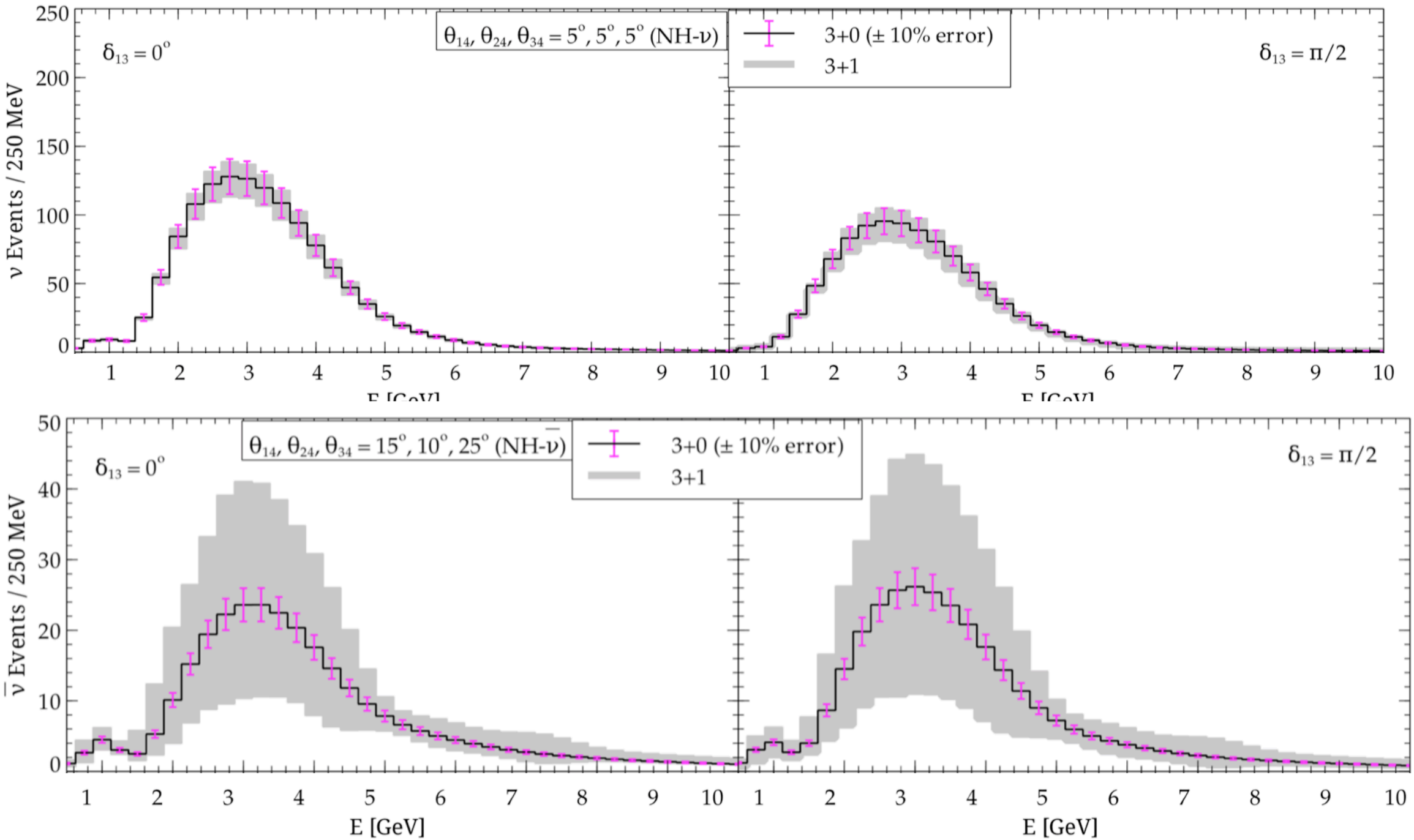
$$\sin^2 2\vartheta_{ee} = 4|U_{e4}|^2 \left(1 - |U_{e4}|^2\right) = \sin^2 2\vartheta_{14}$$ PROSPECT / short-baseline reactor

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

Active-Sterile Osc and LBL CP-Violation

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

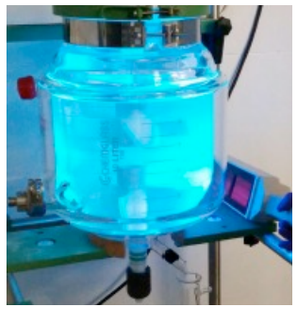
Dutta, Gandhi, Kayser, Masud, and Prakash, JHEP 2016:122
B. Kayser, 2016 PITT PACC SBN Workshop

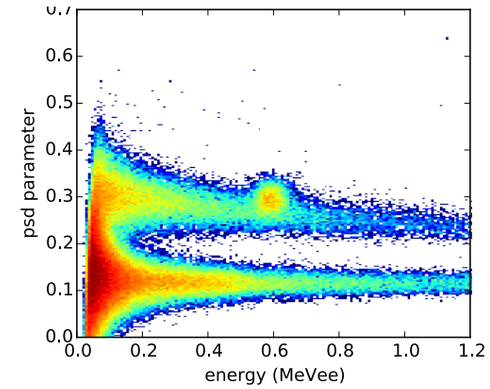


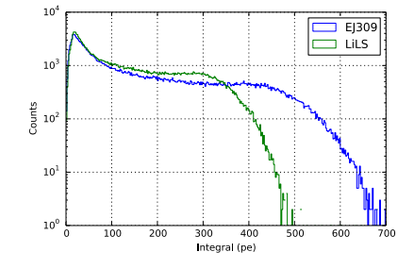
Path to segmented ^{6}LiLS detector with particle ID

PROSPECT-0.1
Develop LS
Characterize LS
Aug 2014-Spring 2015

5cm length
0.1 liters
LS, ^{6}LiLS







PROSPECT-2
Background studies
Dec 2014 - Aug 2015

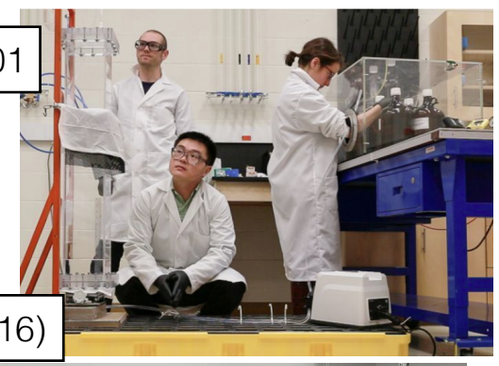
12.5 length
1.7 liters
^{6}LiLS

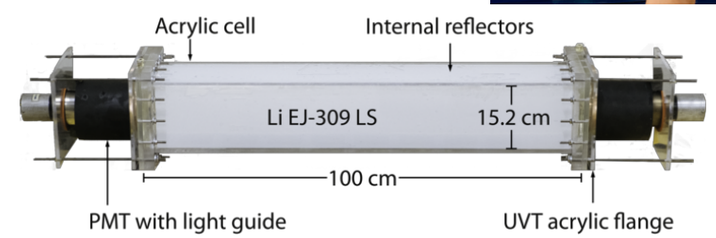
light guides
low mass reflectors

PROSPECT: NIMA A806 (2016) 401

PROSPECT-20
Segment optics
Component design
Spring/Summer 2015

1m length
23 liters
LS, ^{6}LiLS

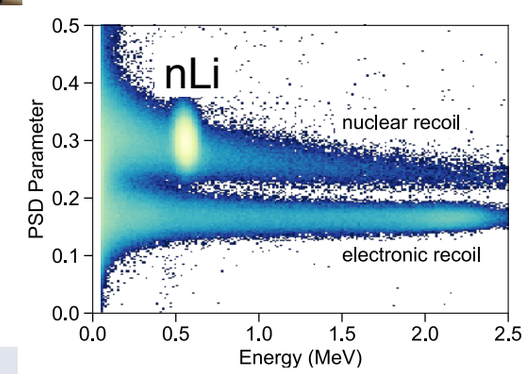




PROSPECT: JINST 10 P11004 (2016)

PROSPECT-50
Performance validation
Subsystem testbed
Simulation benchmark
2017-2018

1x2 segments
1.2m length
50 liters
LS,^{6}LiLS

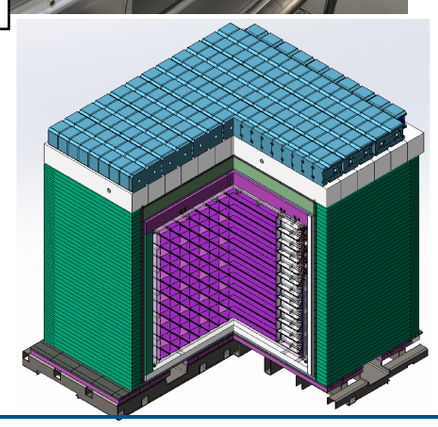


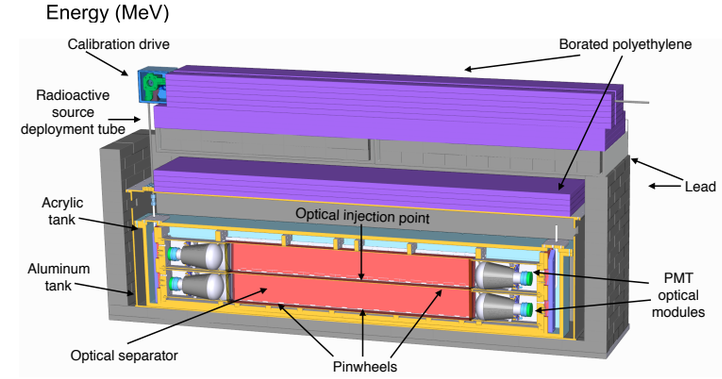
light collection
energy resolution
PSD performance

PROSPECT: JINST 13 P06023 (2018)

PROSPECT AD
Physics measurement
data taking 2018

11x14 segments
1.2m length
4 tons
^{6}LiLS





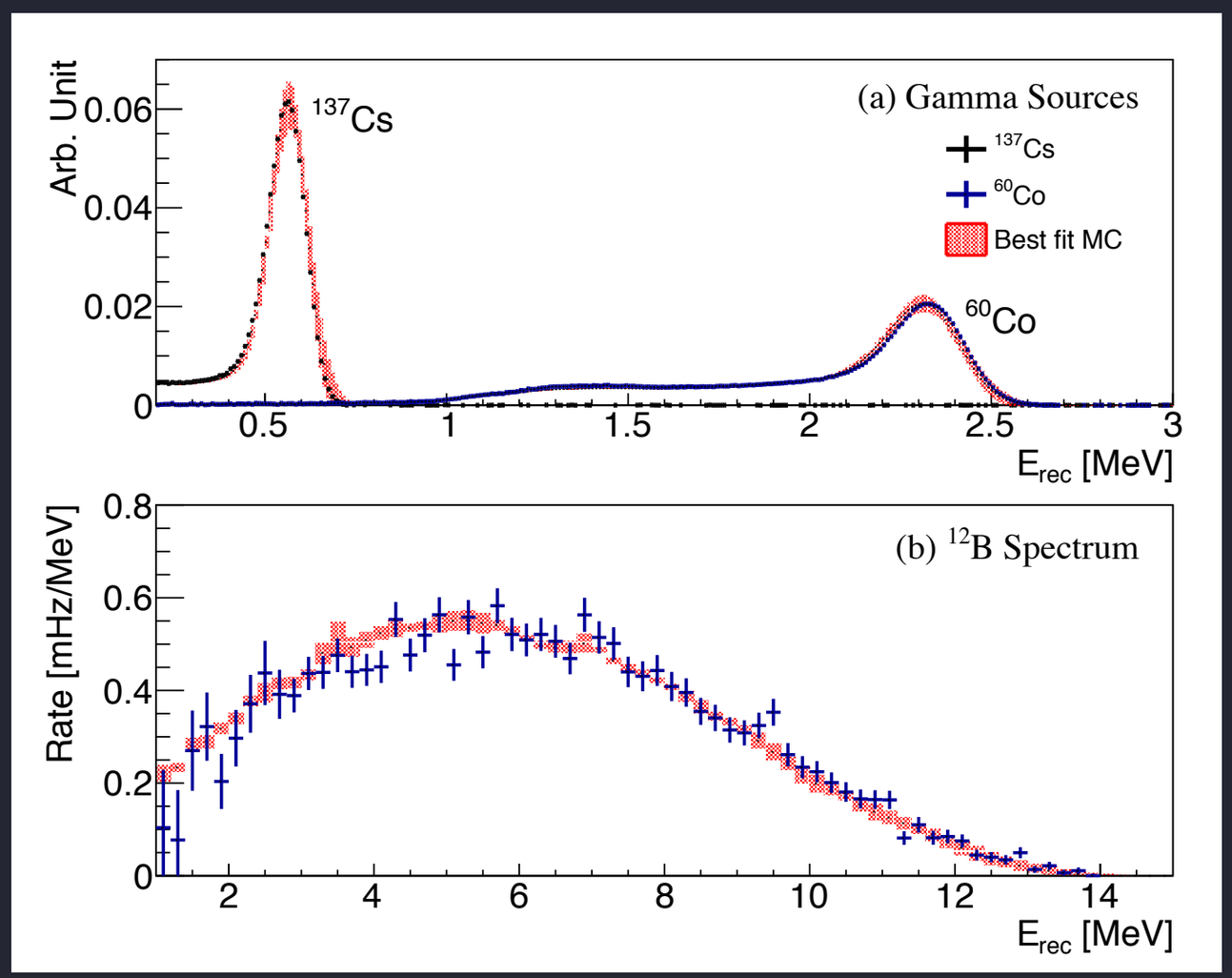
PROSPECT: arXiv:1808.00097

Energy Calibration

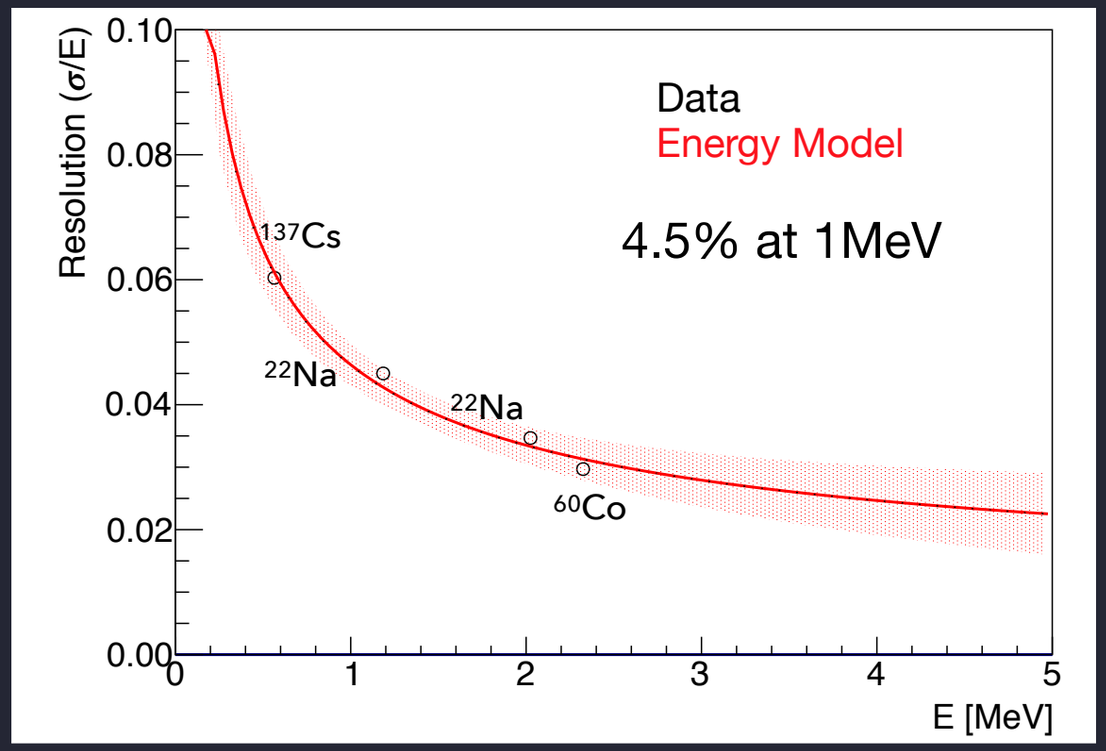
Gamma sources (^{137}Cs, ^{60}Co): Deployed throughout the detector

Fast-neutron tagged ^{12}B: High-energy beta spectrum calibration

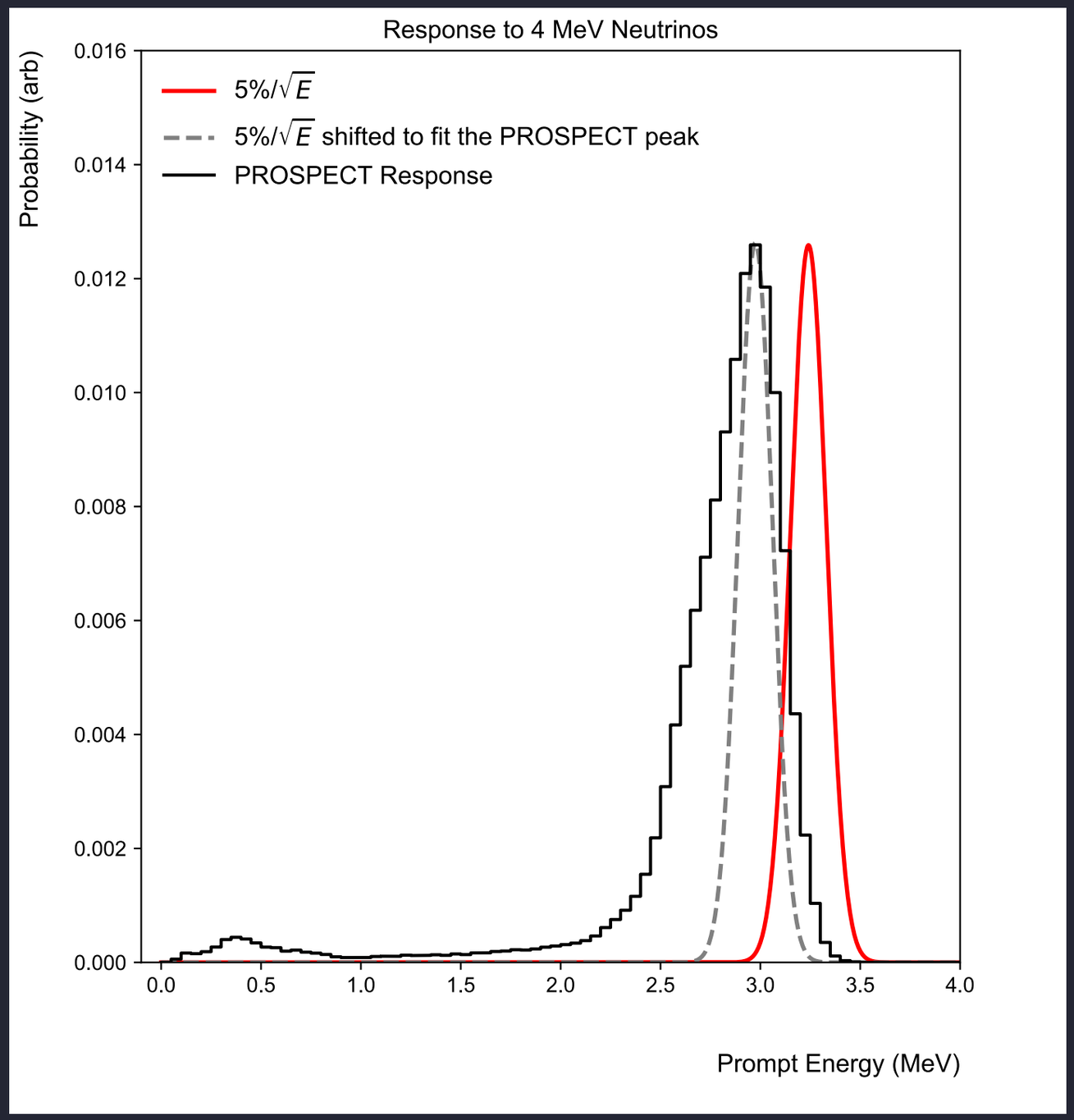
Full-detector E_{rec} within 1% of E_{true}



High light collection: 795±15 PE/MeV



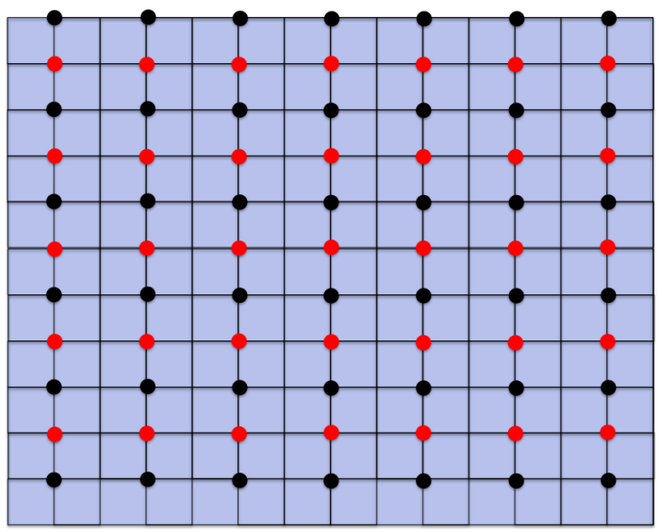
PROSPECT Response



- PROSPECT detector is **compact** with a **limited gamma catcher volume** and **modest inactive volume**
- Escaping gammas and the energy lost in the inactive volume makes the response complicated
- Additionally a small contribution of reconstructed events at ~0.5 MeV arises from IBDs originating in the inactive volume whose gammas and neutrons are detected in the active volume
- Monte Carlo-generated response matrix is used in PROSPECT to handle this complicated response
- Response matrices are similarly **required** to be able to properly model energy response of other **compact detectors**

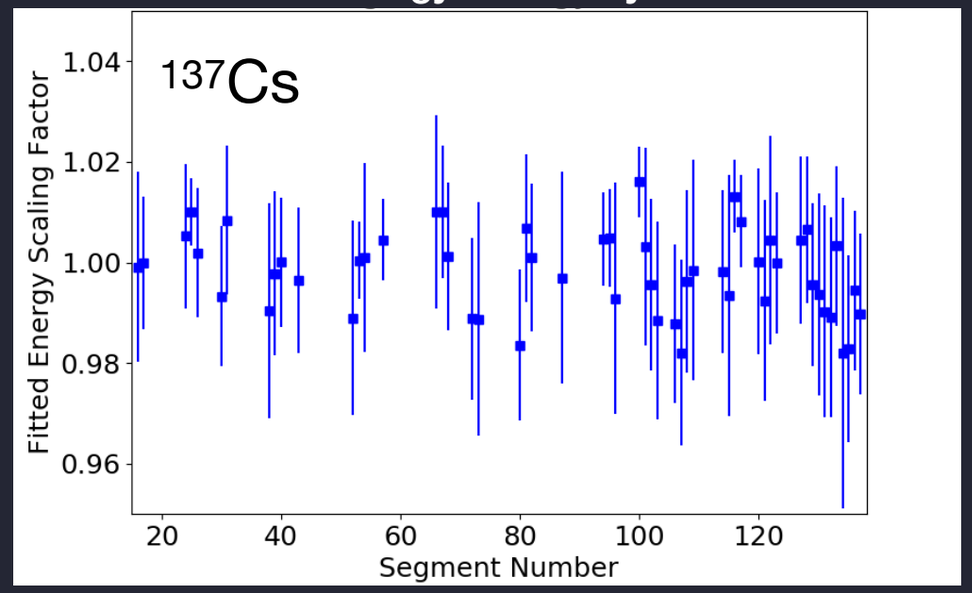
Energy Stability and Uniformity

Calibration position map

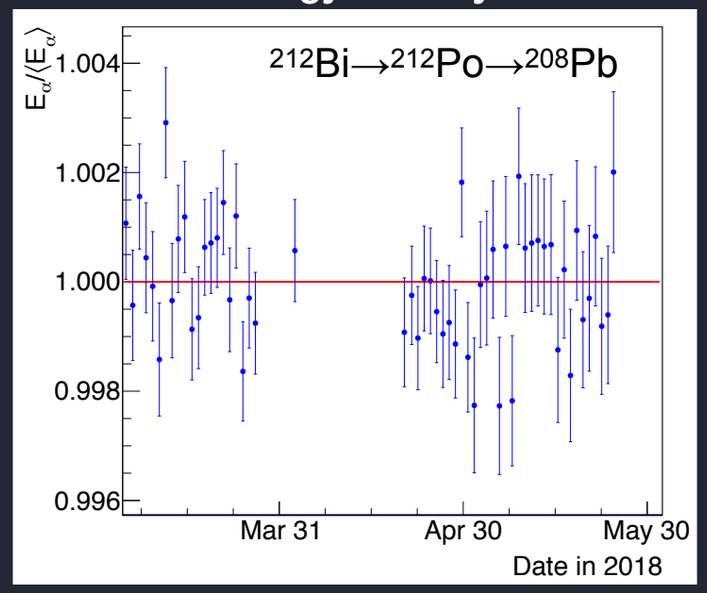


- Source Calibrations
- Optical Calibrations

Energy uniformity

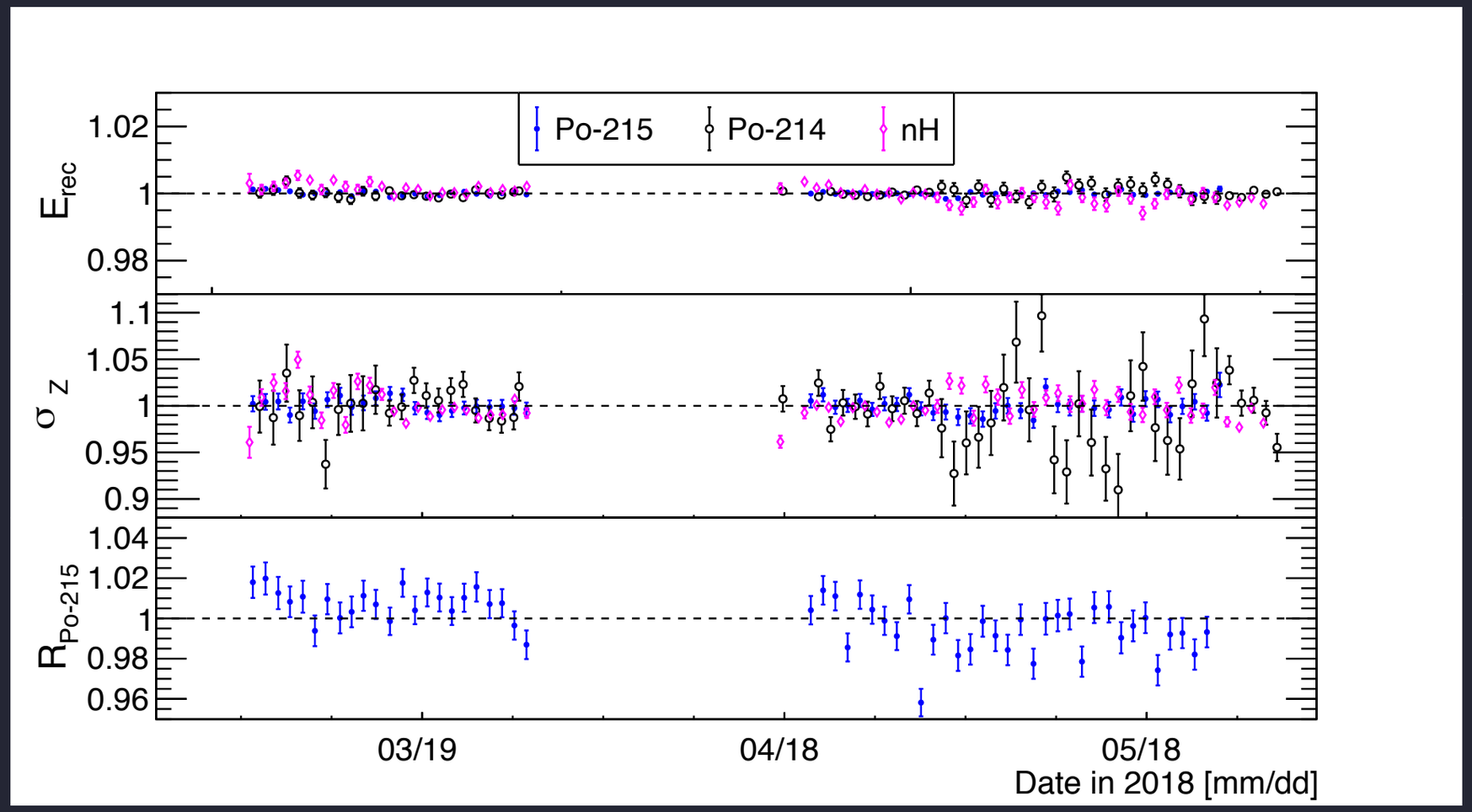


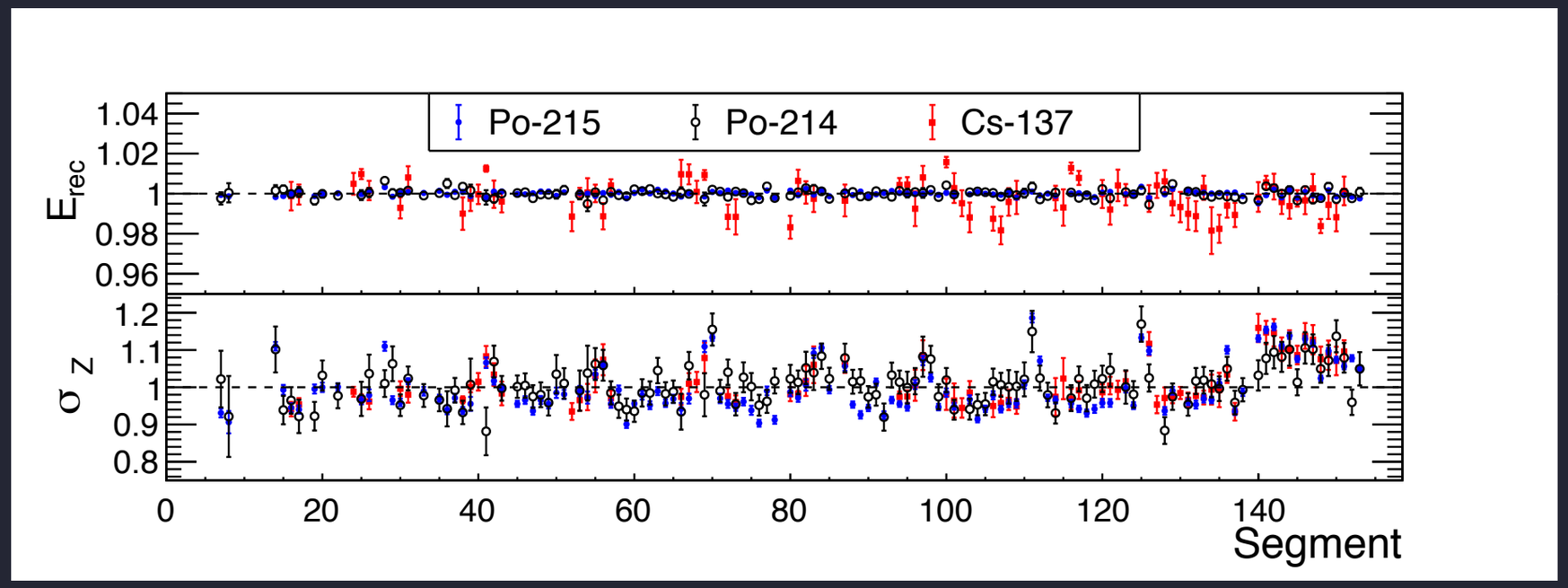
Energy stability



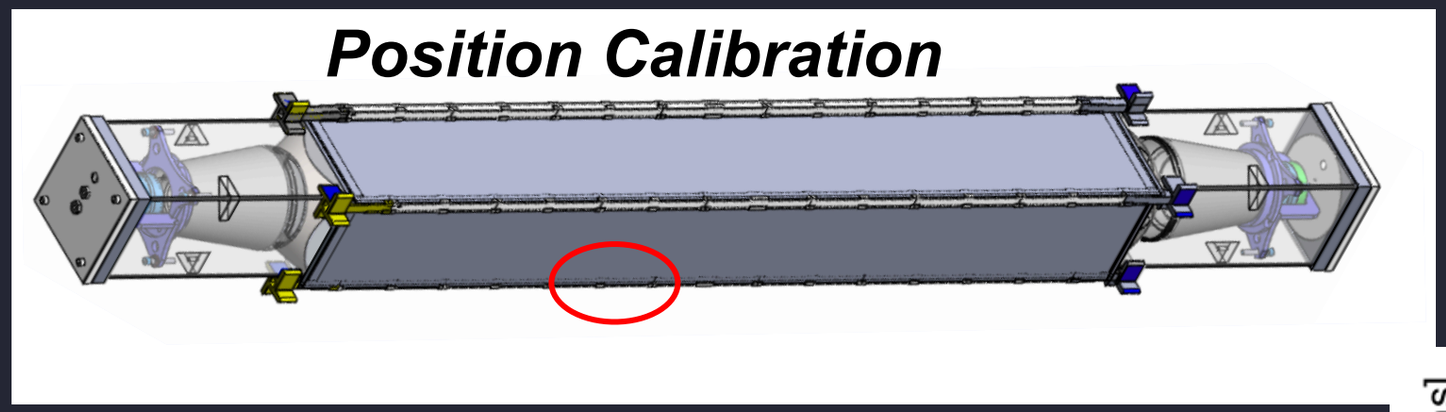
- 35 calibration source tubes throughout detector to map energy response
- Uniform segment to segment response
- Stability in reconstructed energy over time

Energy Stability and Uniformity

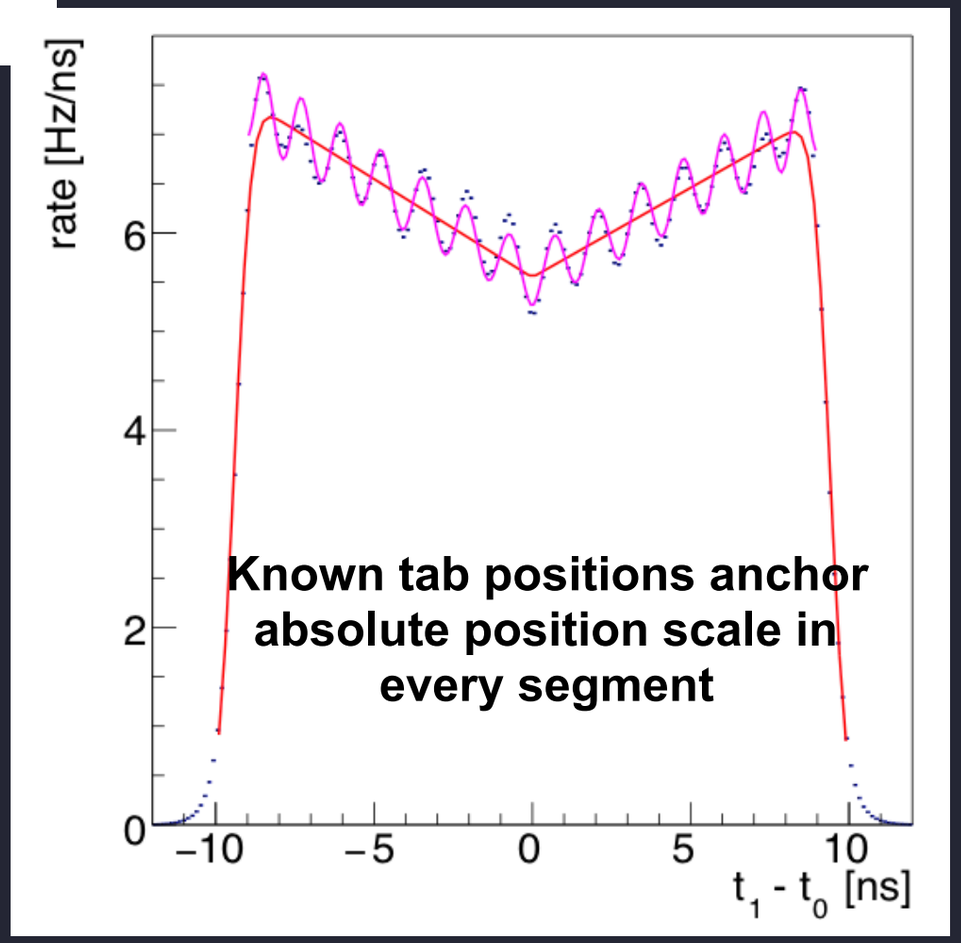




Position Calibration

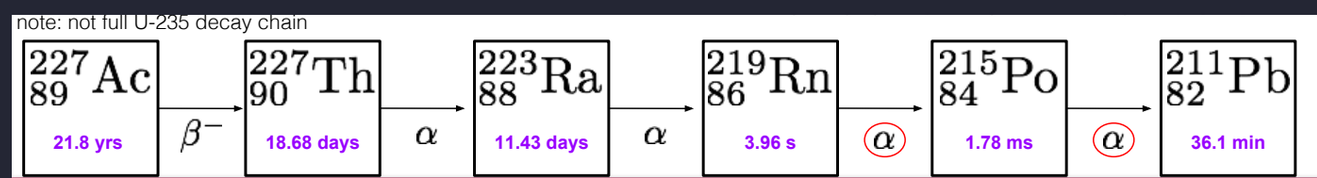


Pinwheel tabs alter local light transport, causing 'tiger stripes'

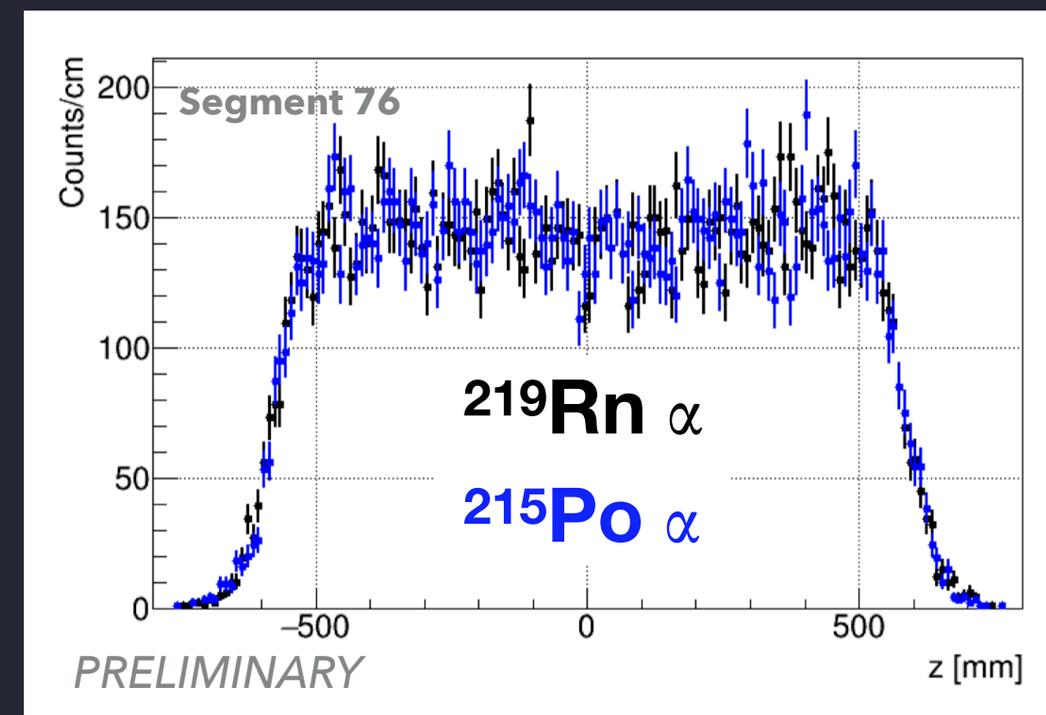


Relative Segment Volume Calibration

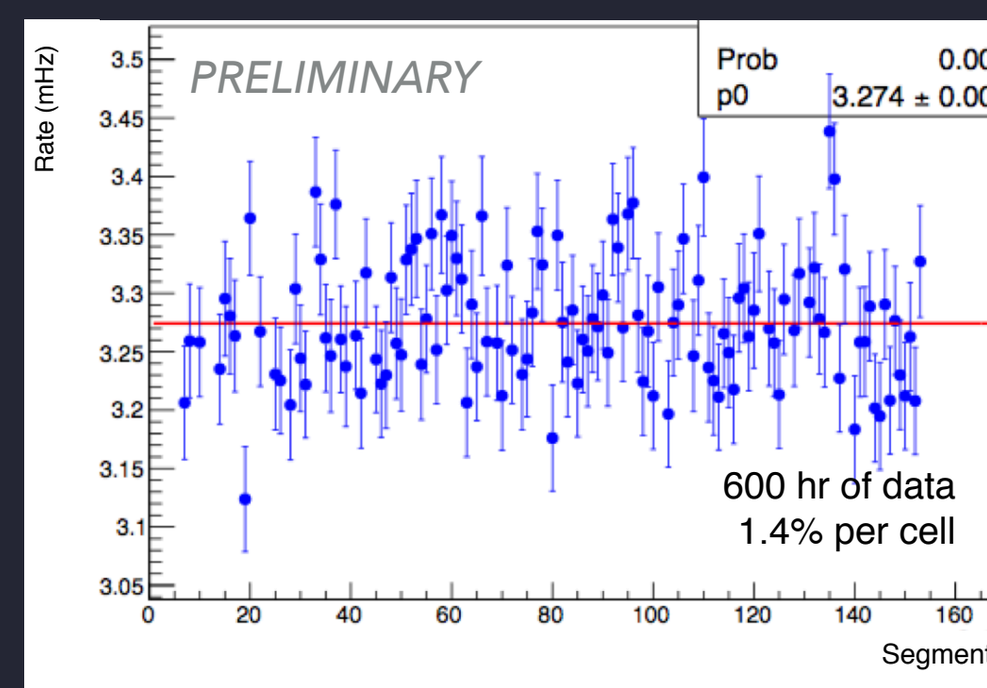
- Relative mass vital for oscillation search
- Survey during assembly: < 1% variation



- ^{227}Ac added to LS prior to filling
- Double alpha decay (^{219}Rn→^{215}Po→^{211}Pb), highly localized, 1.78ms half-life, efficient selection straightforward,
- Measured absolute z-position resolution of < 5cm
- Direct measurement of relative target mass in each segment



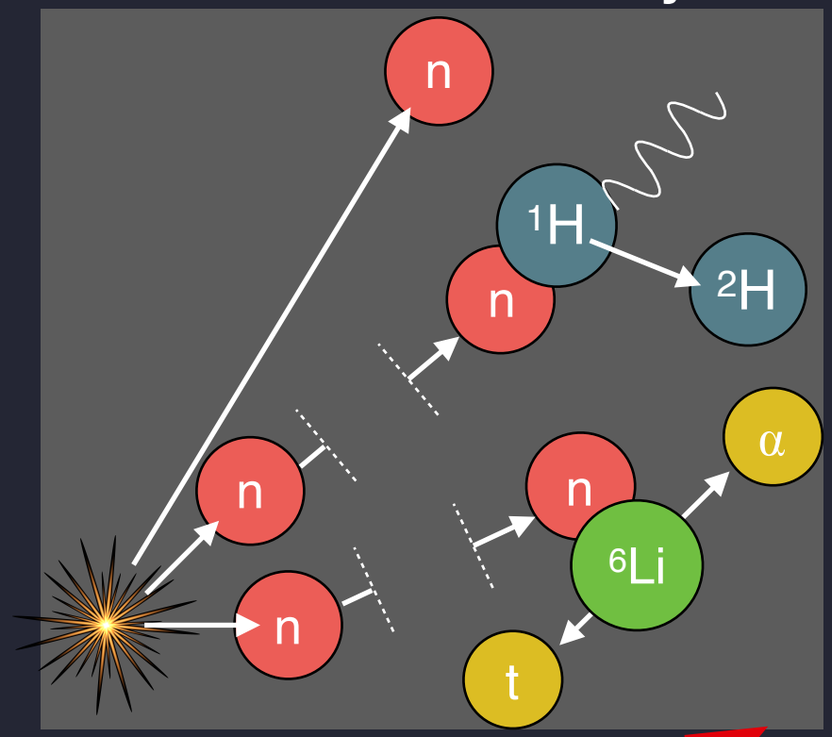
Uniformity in rates within segment



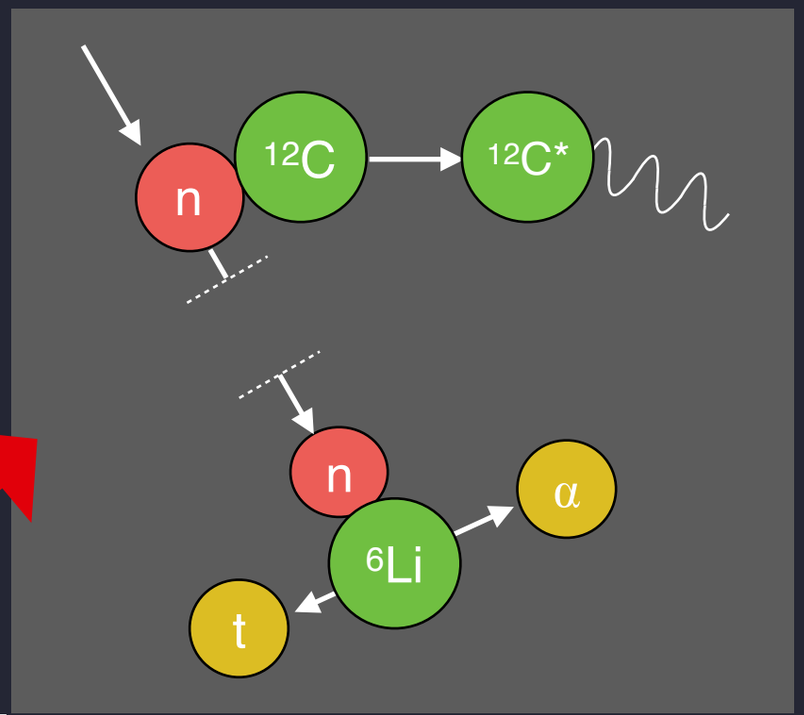
Uniformity in rates between segments

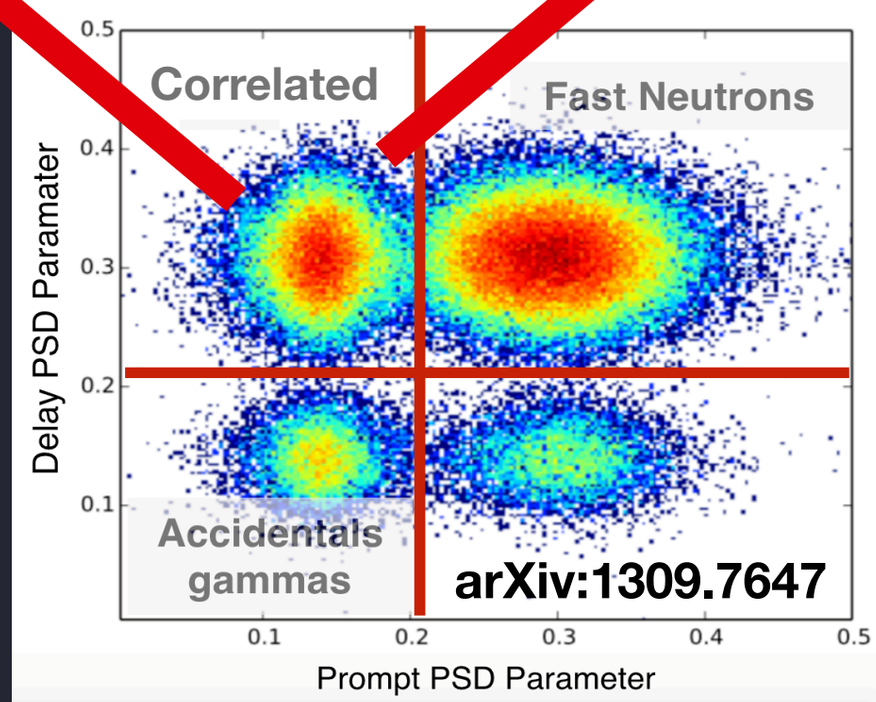
Other Backgrounds

Correlated nH followed by nLi



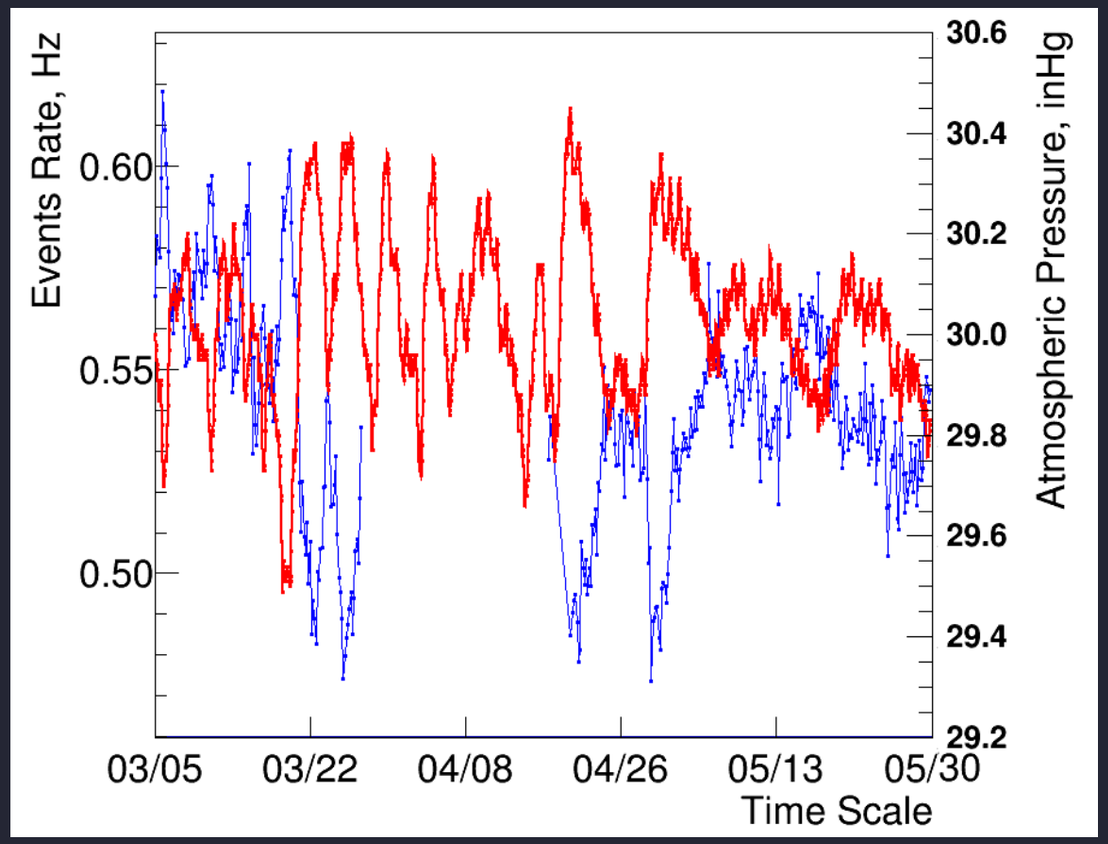
Correlated inelastic scattering on ^{12}C followed by nLi

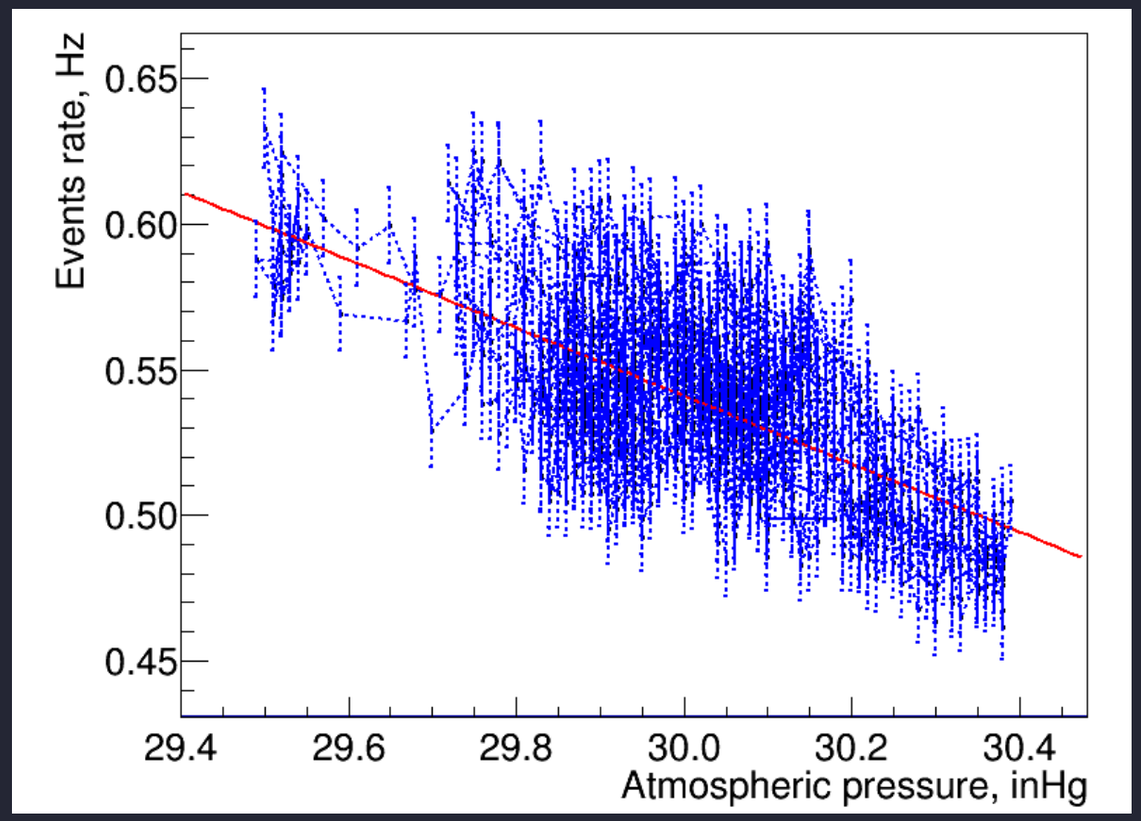




Cosmogenics are the main source for these two background classes

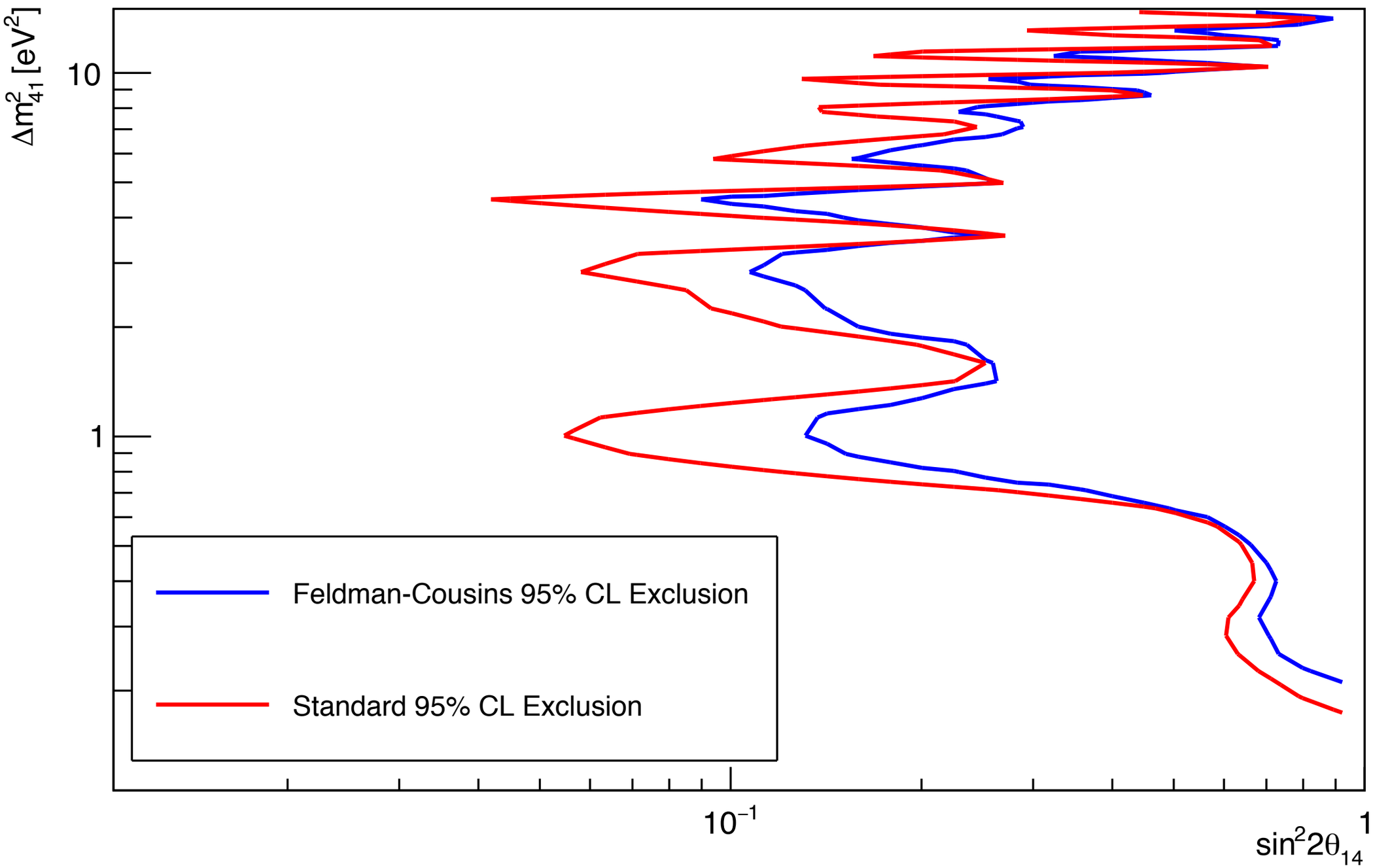
Cosmogenic Background Variations



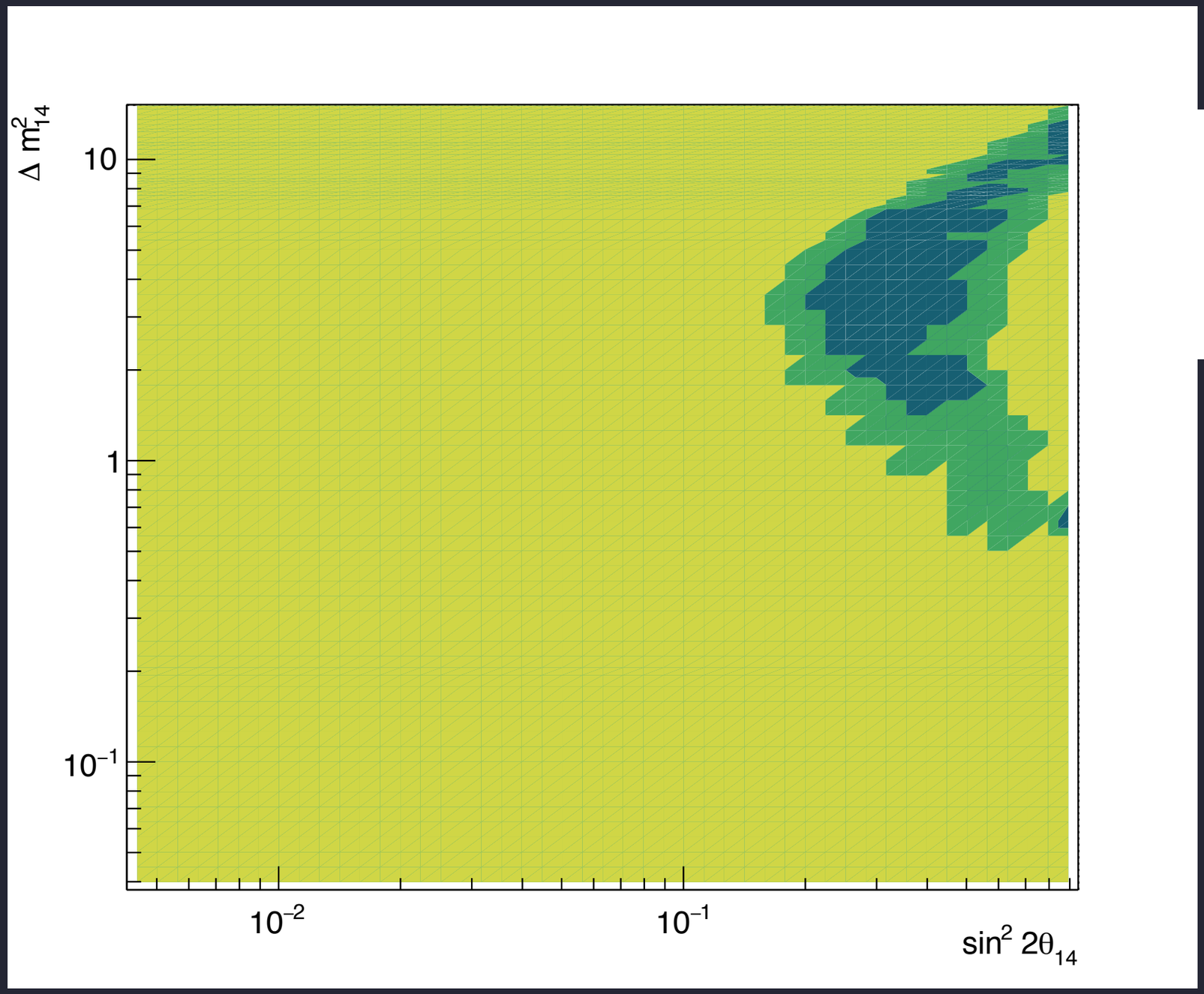


- Cosmogenic backgrounds are slightly dependent on the atmospheric pressure
- Measure correlation between pressure and background rates during reactor-off time
- Scale the backgrounds during reactor-off time using this correlation

Why use FC ?


Δm^2_{41} [eV^2]
10
1
10^{-1}
1
$\sin^2 2\theta_{14}$
Feldman-Cousins 95% CL Exclusion
Standard 95% CL Exclusion

Why use FC ?



Correct coverage

Undercoverage

Overcoverage

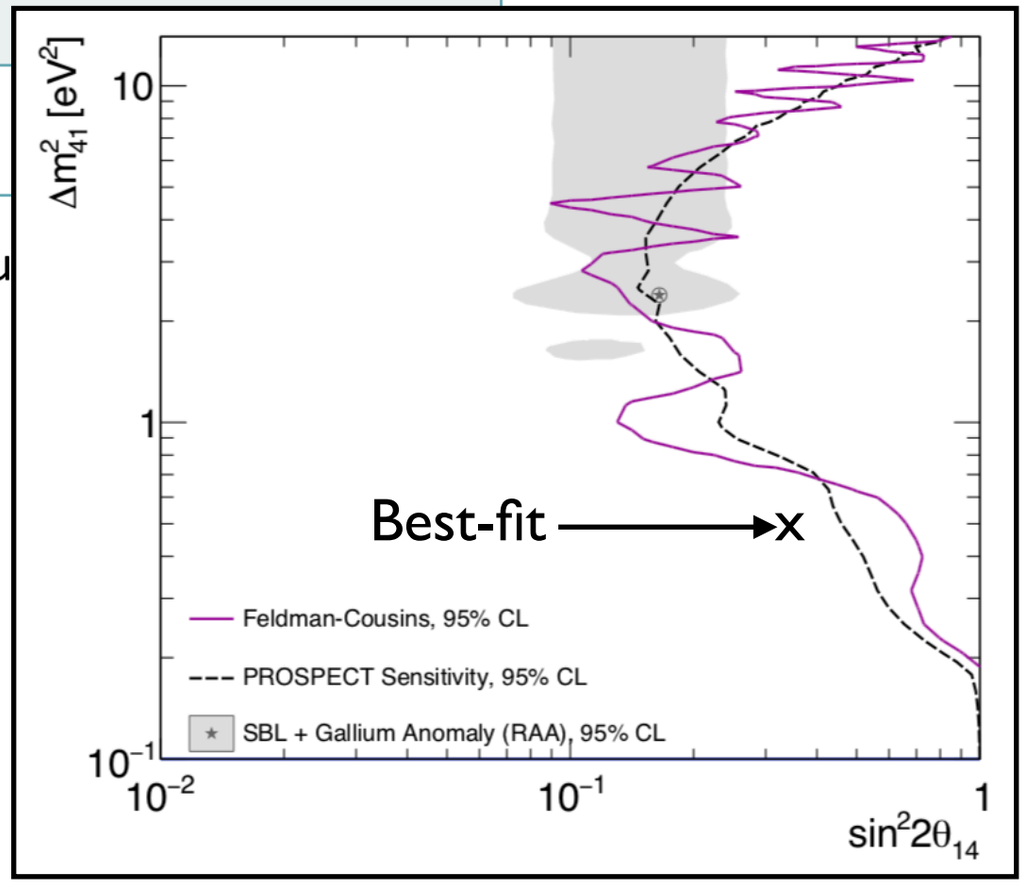
- If probability contained in the Wilk's theorem-defined chi2 values <(>) 0.95 then that point is undercovered (overcovered)
- Chi2 = +/- 1 taken as threshold to define the right coverage
- => undercoverage **if P(6.99) < 0.95** and
  overcoverage **if P(4.99) >0.95**

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

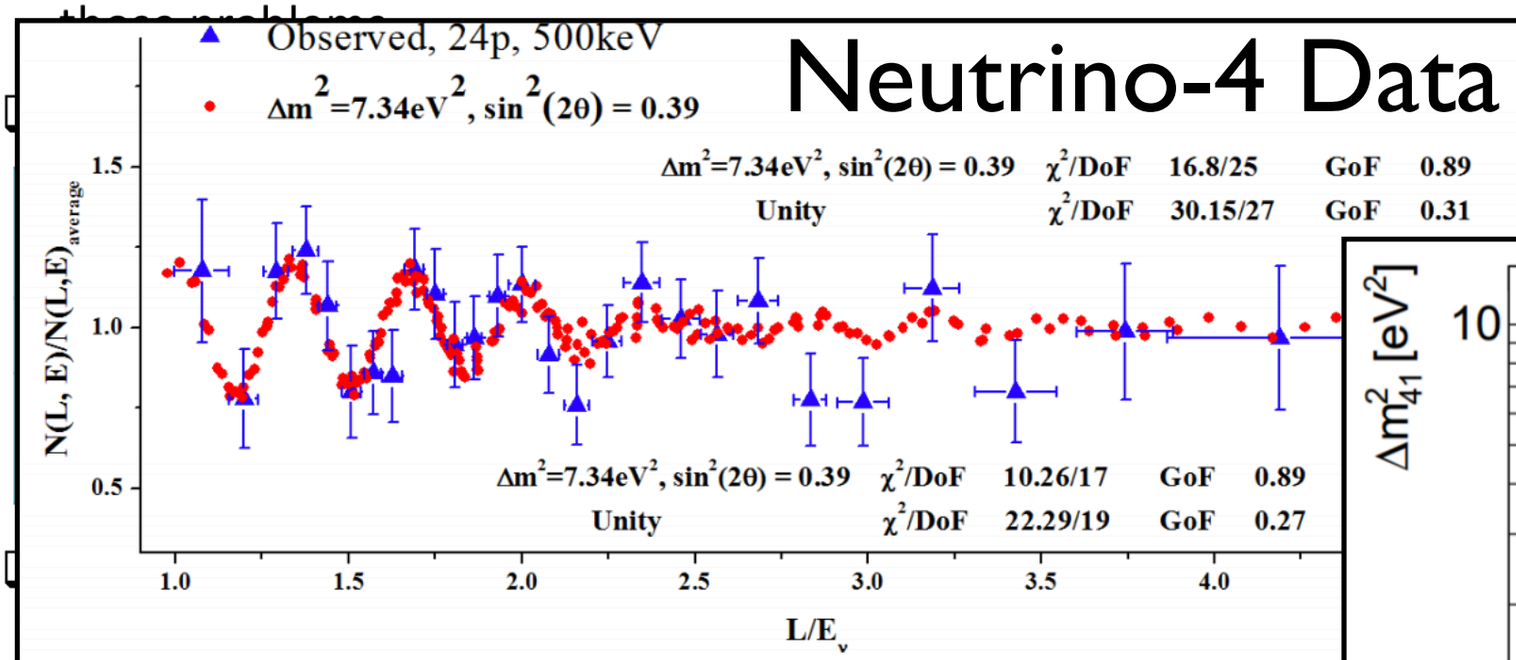
- If standard (incorrect) confidence levels used instead of Feldman-Cou
  - We say 3ν is less compatible with data than it actually is
- Illustrates an importance of using Feldman-Cousins



Neutrino-4

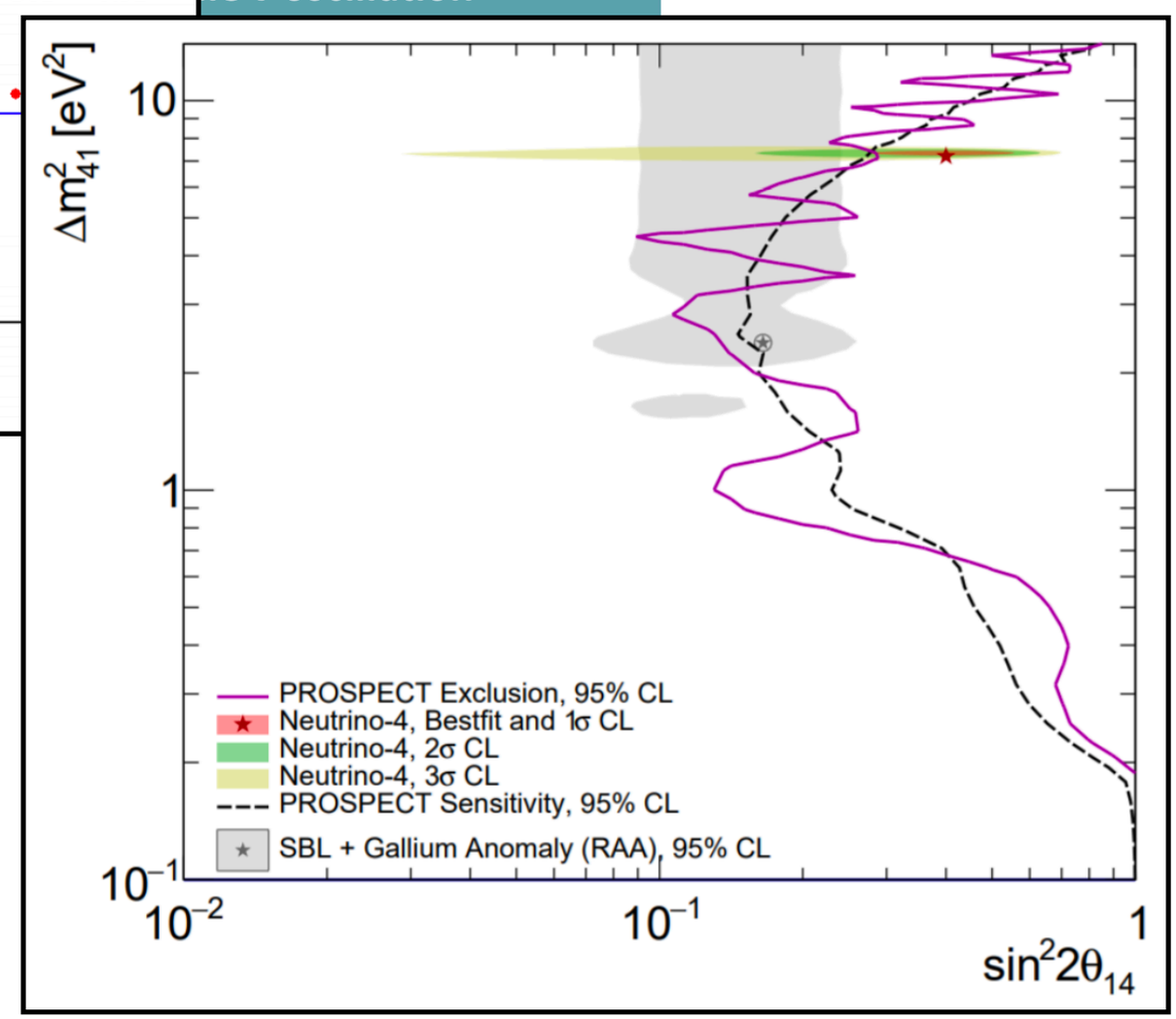
Feldman-Cousins Approach

- 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

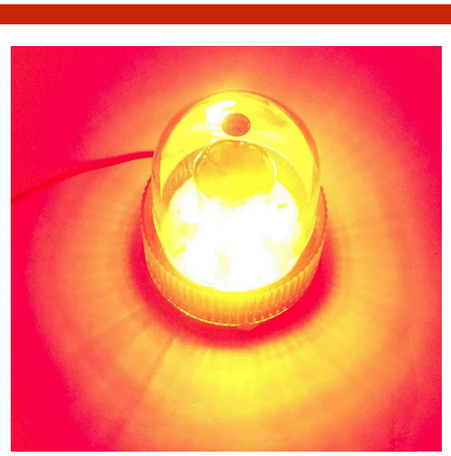


thods:

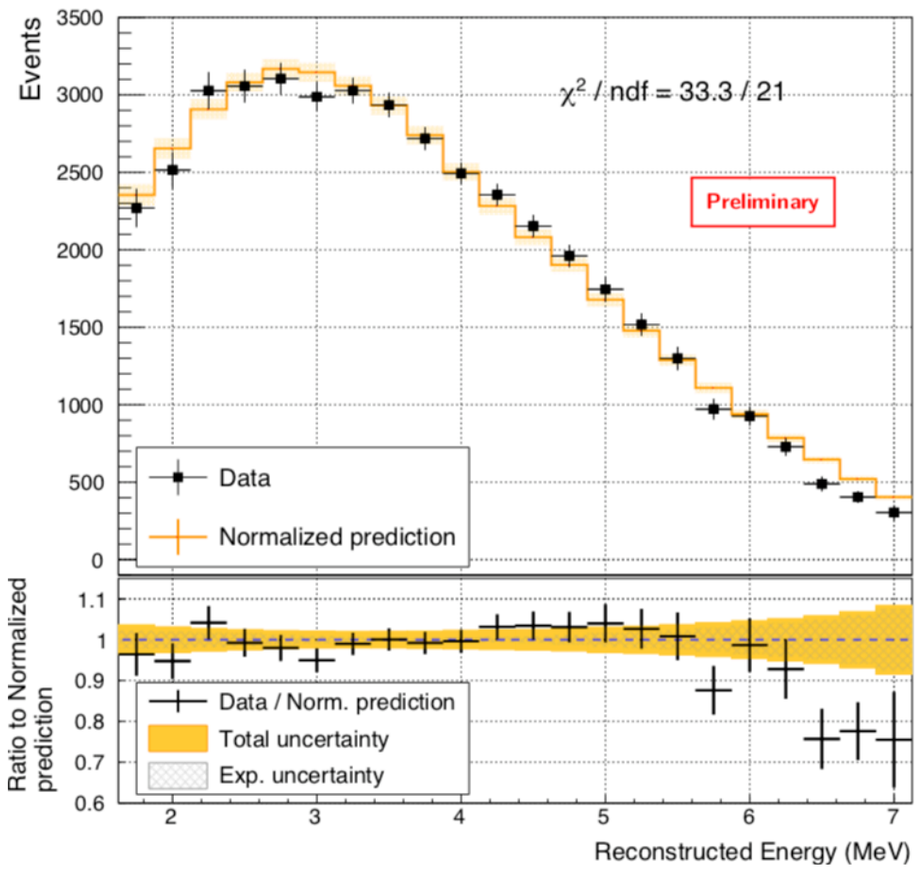
ile ν oscillation

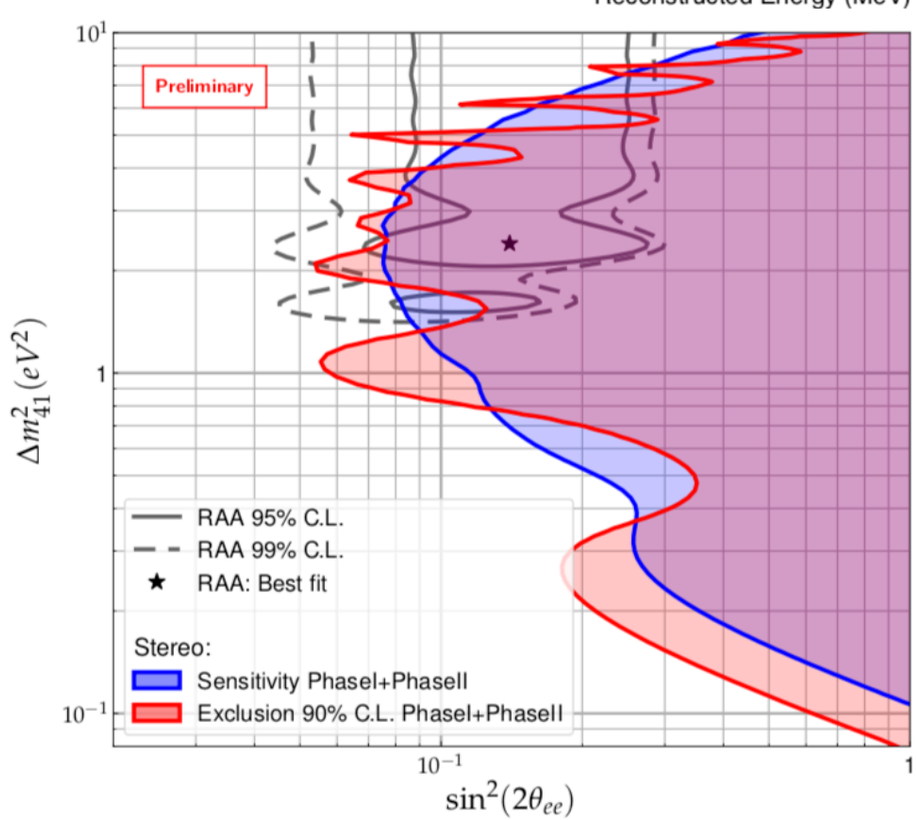


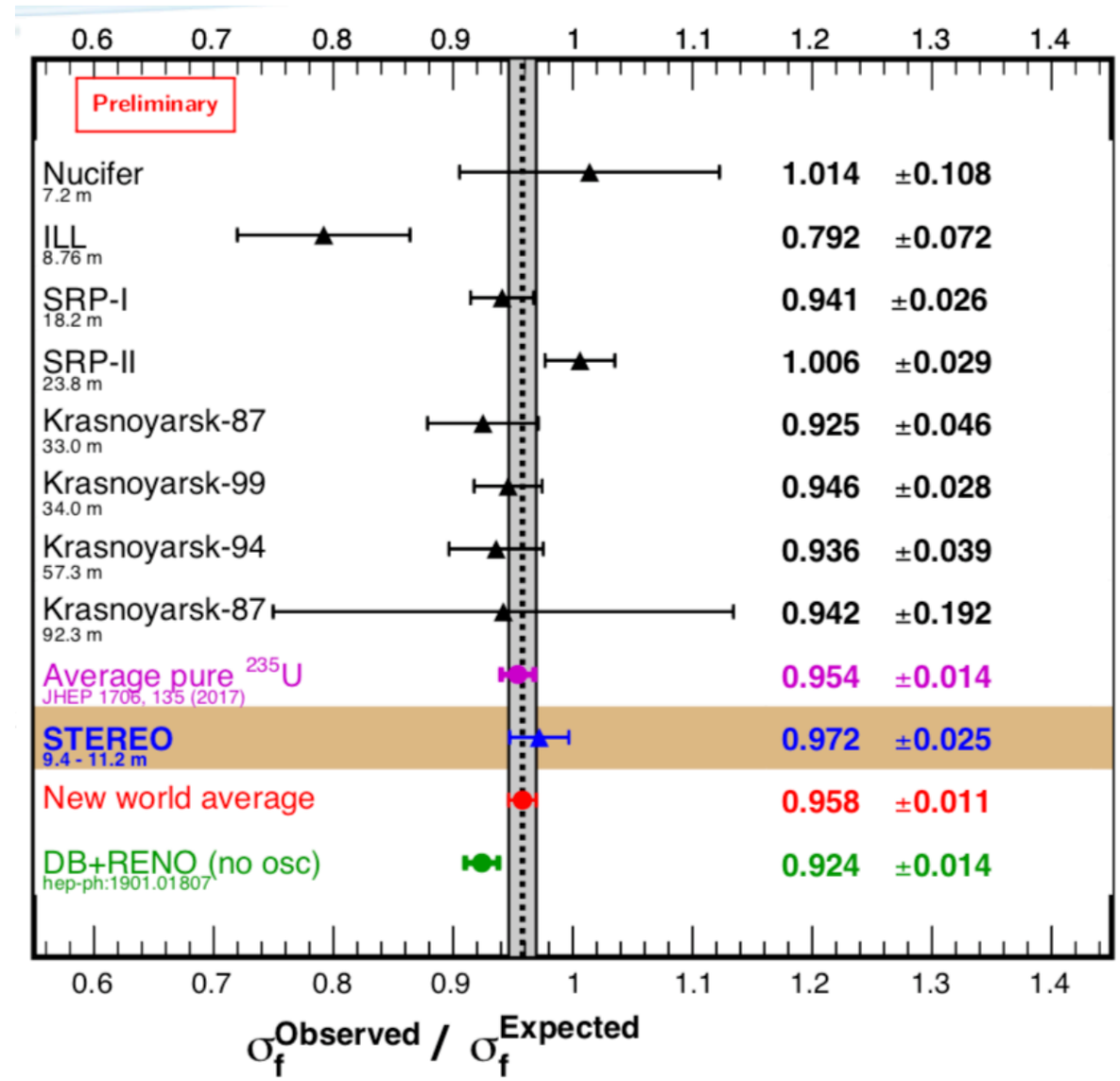
- Illustrates an importance of using Feldman-Cousins



New STEREO Results at Moriond19



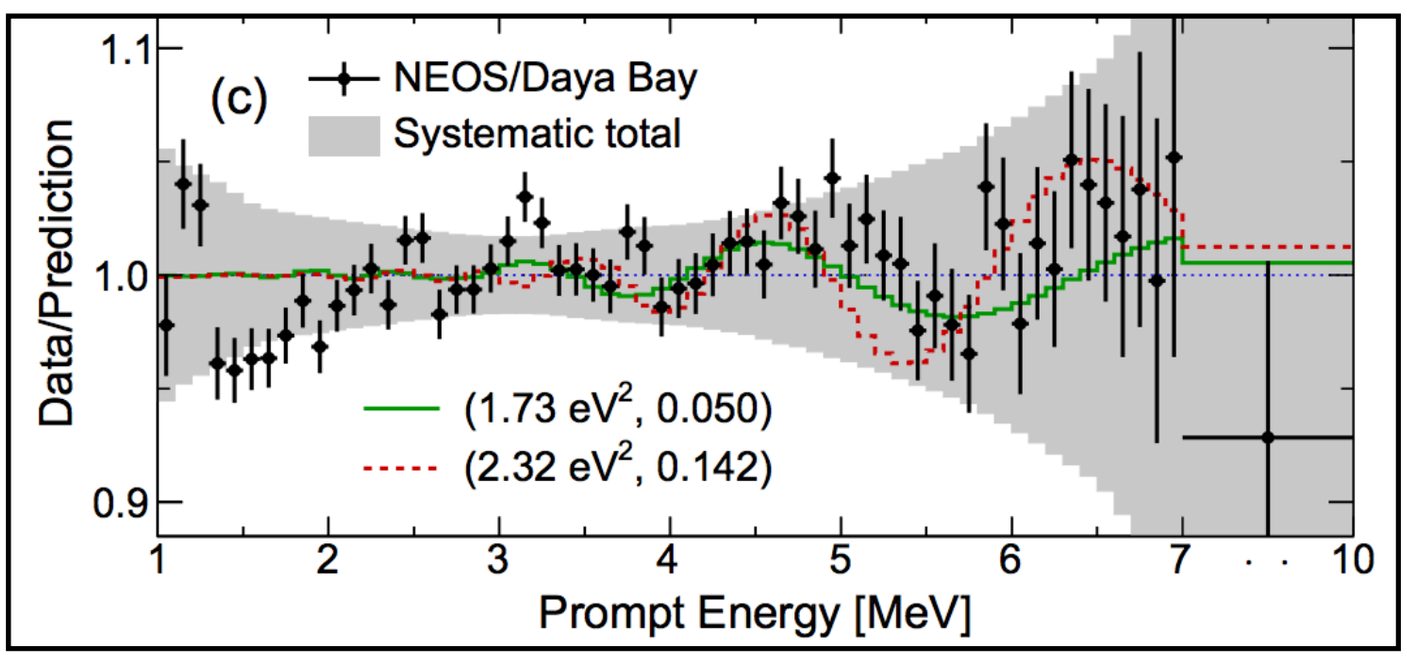


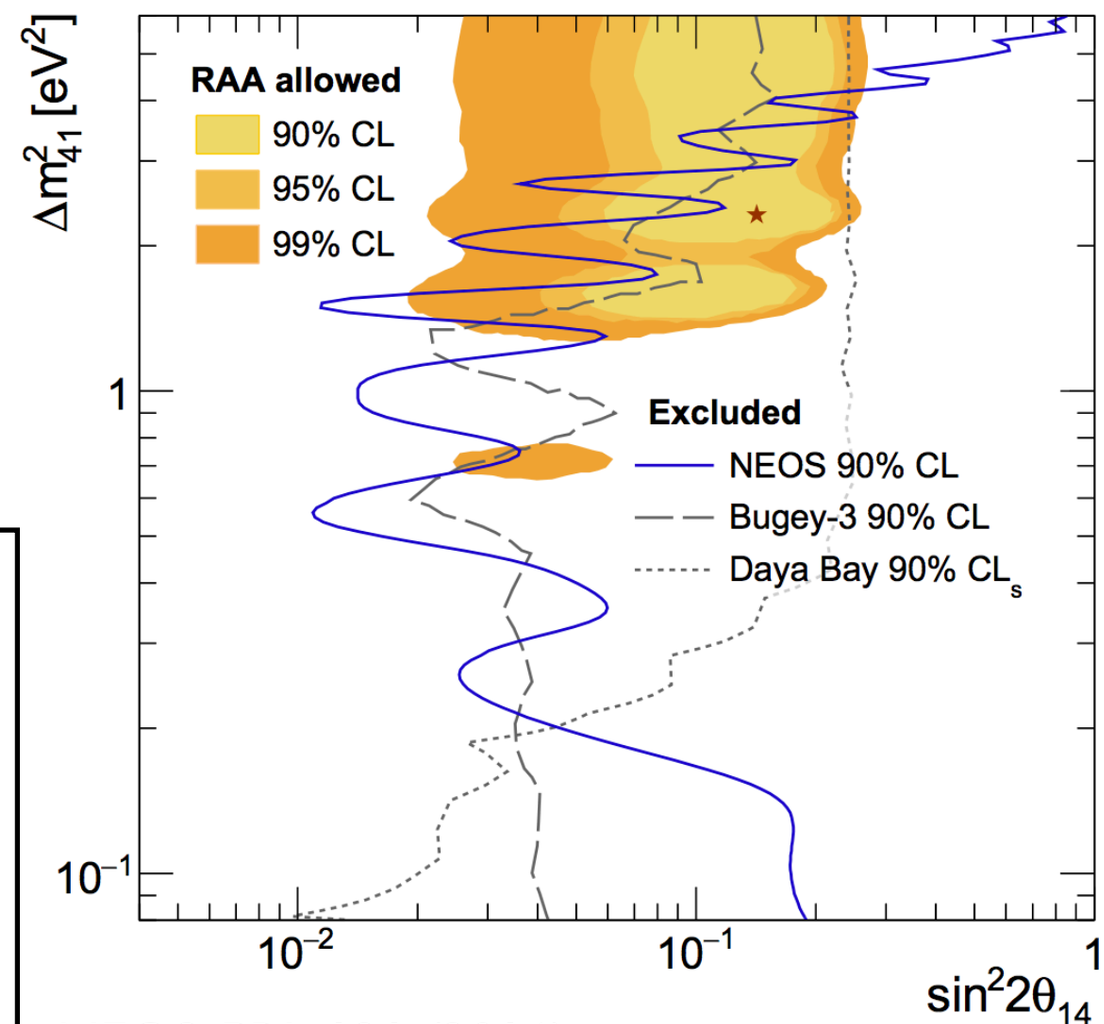


- Wow! Nice!
- Interested to see closer comparisons to PROSPECT, global fluxes, θ_{13} experiments

Testing Steriles: NEOS

- 2016: Compare spectra between two experiments at different baselines: NEOS (25m) and Daya Bay (~500m)
  - NEOS: compact detector underground in commercial reactor's tendon gallery
  - Everyone knows DYB…
- No strong evidence for steriles
  - Limited by uncorrelated DYB-RENO systematics
  - Limited by larger core size and distance



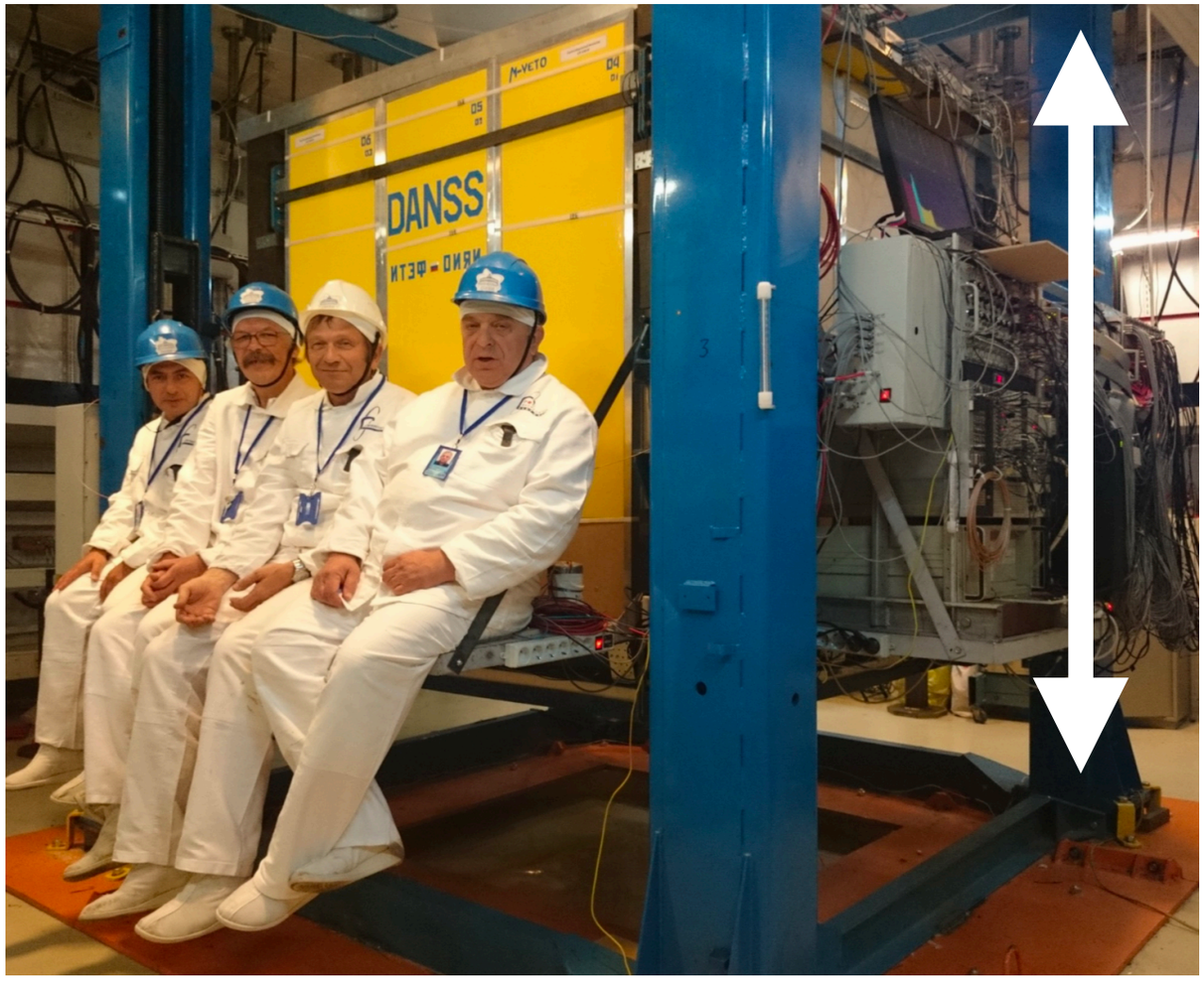


NEOS, PRL 121 (2016)

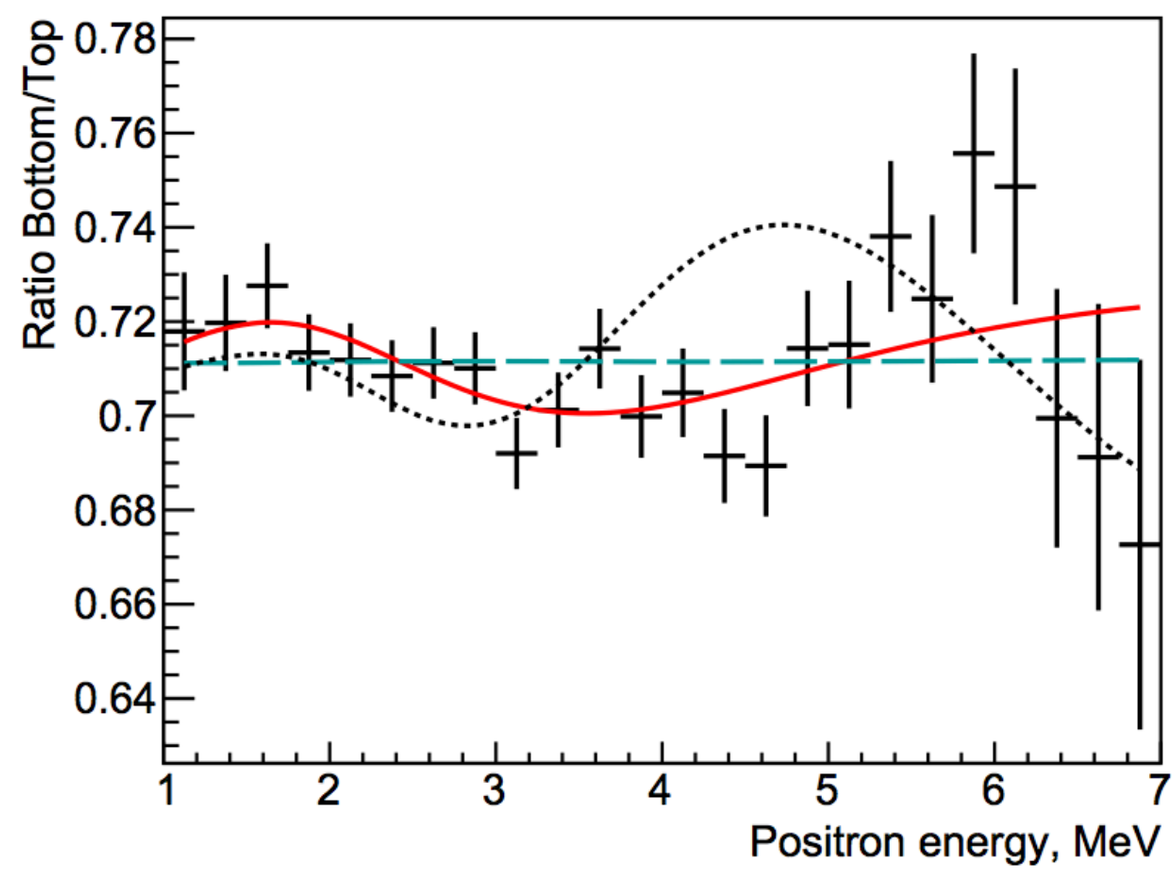
DANSS

- 2018: Compare spectra between the same detector deployed at two different baselines (10.7m and 12.7m)
  - Commercial 3m-length reactor — 5000 events per day! Awesome!
  - Have presented relative spectra between locations

Reactor up here

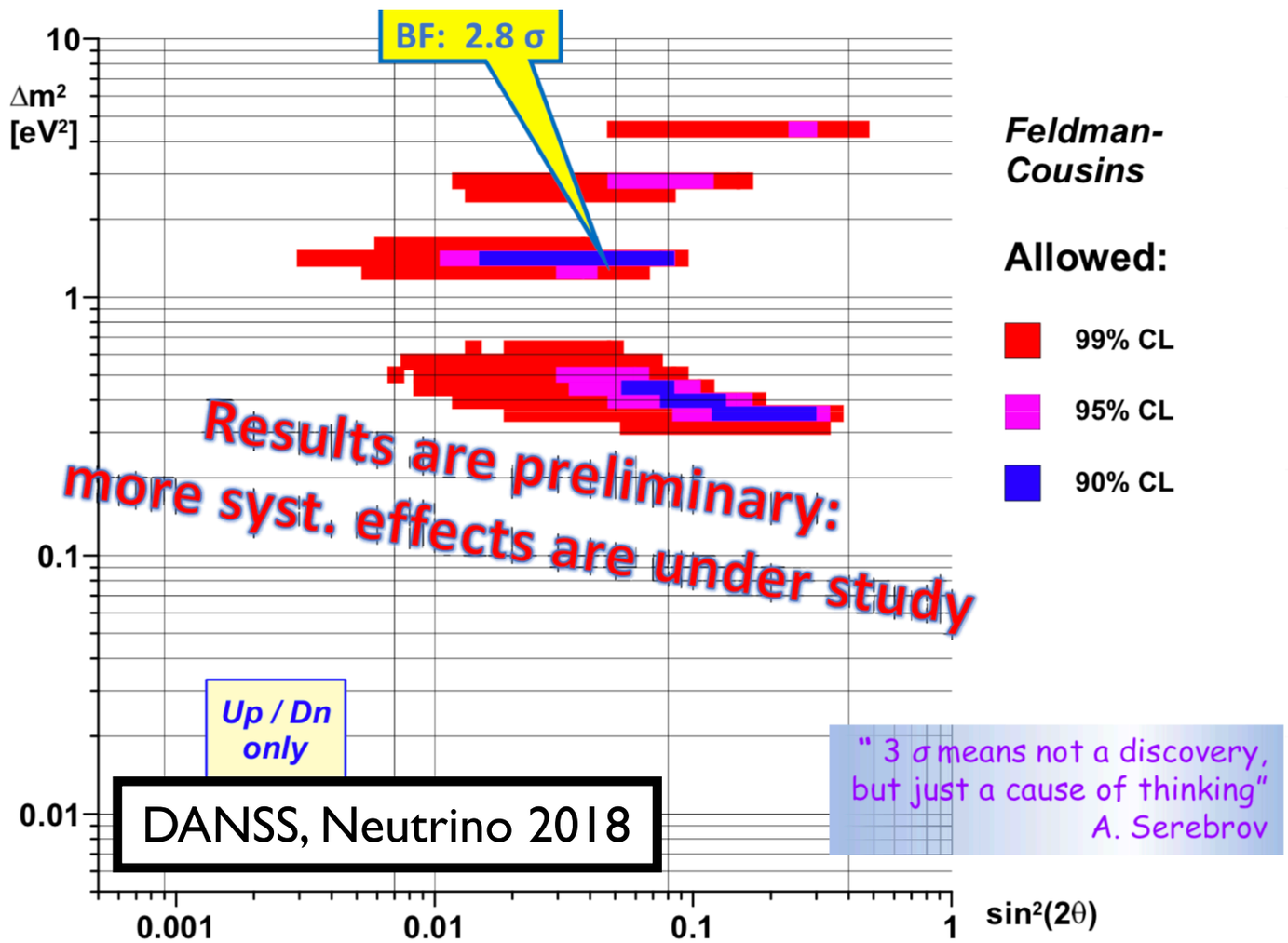


DANSS, PLB 787 (2018)

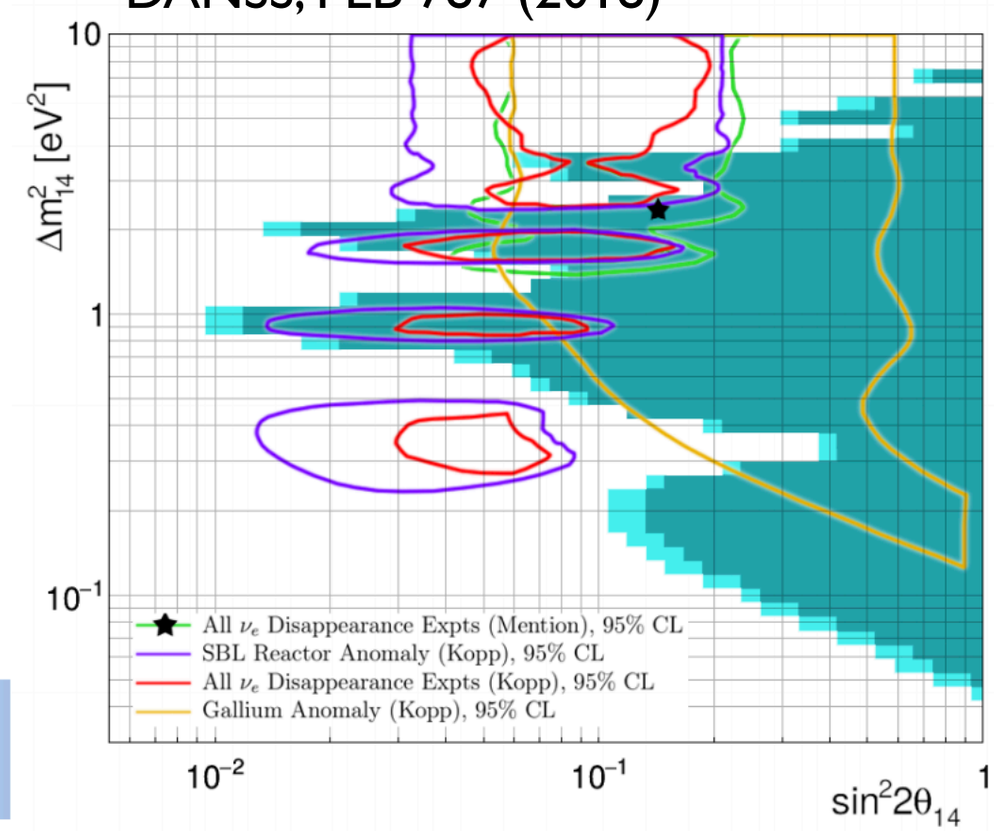


DANSS

- 2018: Compare spectra between the same detector deployed at two different baselines (10.7m and 12.7m)
  - Published results (Phys Left B): no steriles yet
  - Neutrino 2018: showed 3σ allowed region; not sure what to make of this
  - Statements about some systematics still needing to be investigated

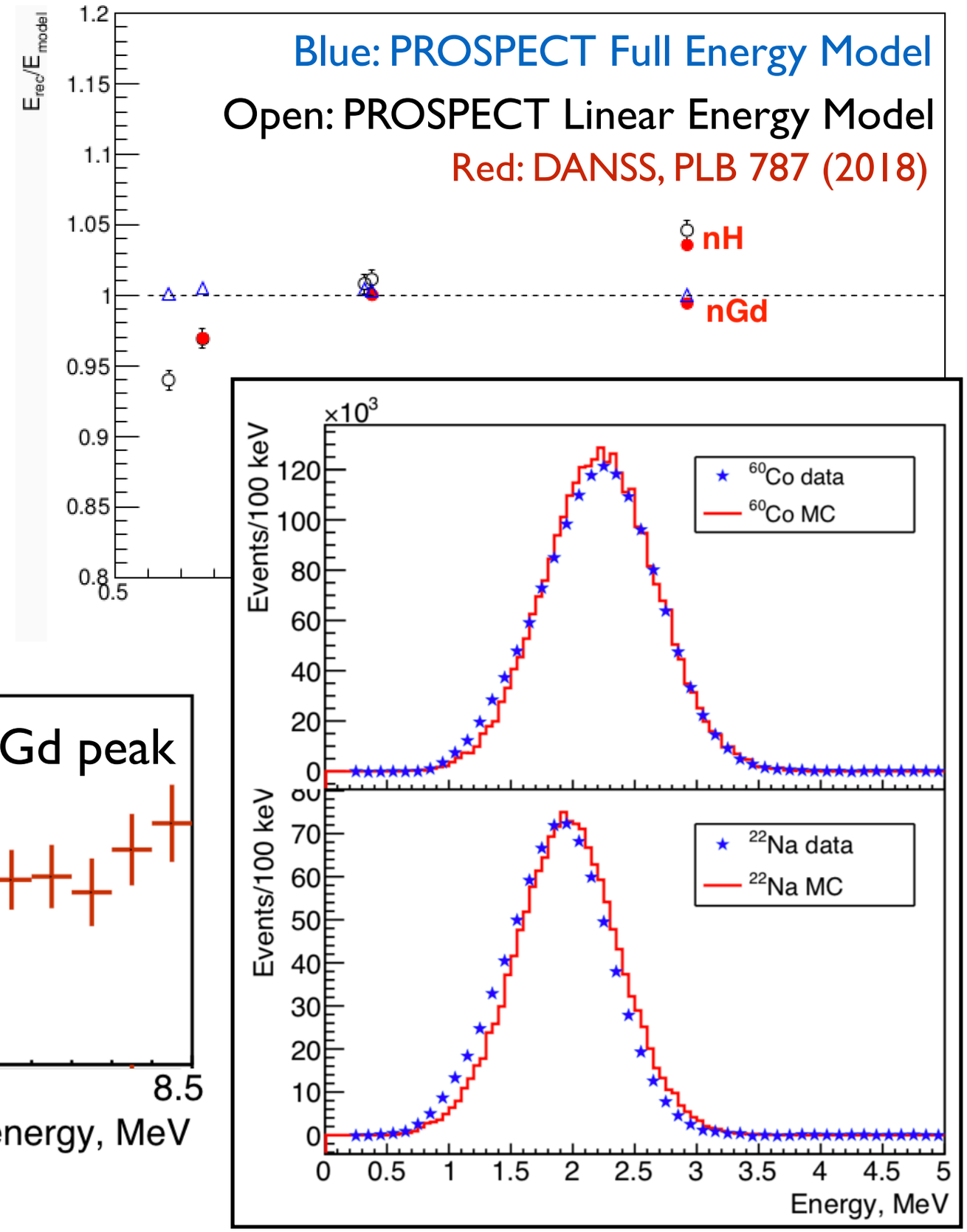


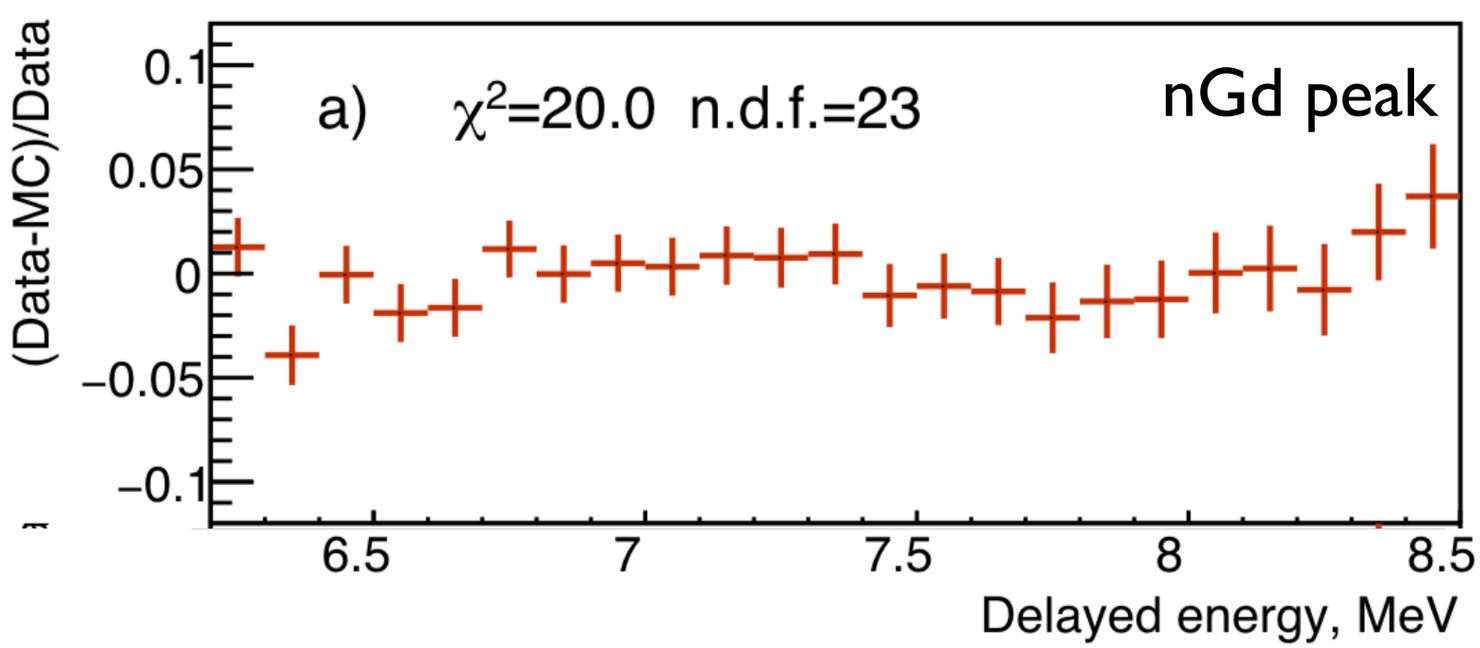
DANSS, PLB 787 (2018)



DANSS: Systematics

- DANSS systematics
  - E-scale at high energy seems well-calibrated — great!
  - What about low (<4 MeV) E?
  - What about relative low-E calibrations between positions?
  - Temperature fluctuations between different positions?

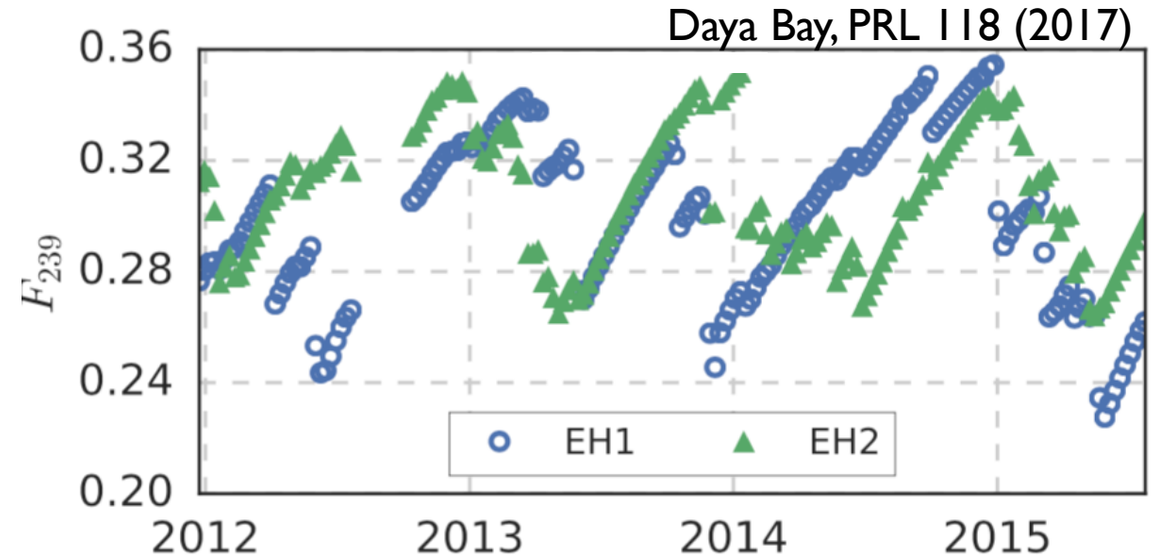




Testing Fluxes: Daya Bay Evolution

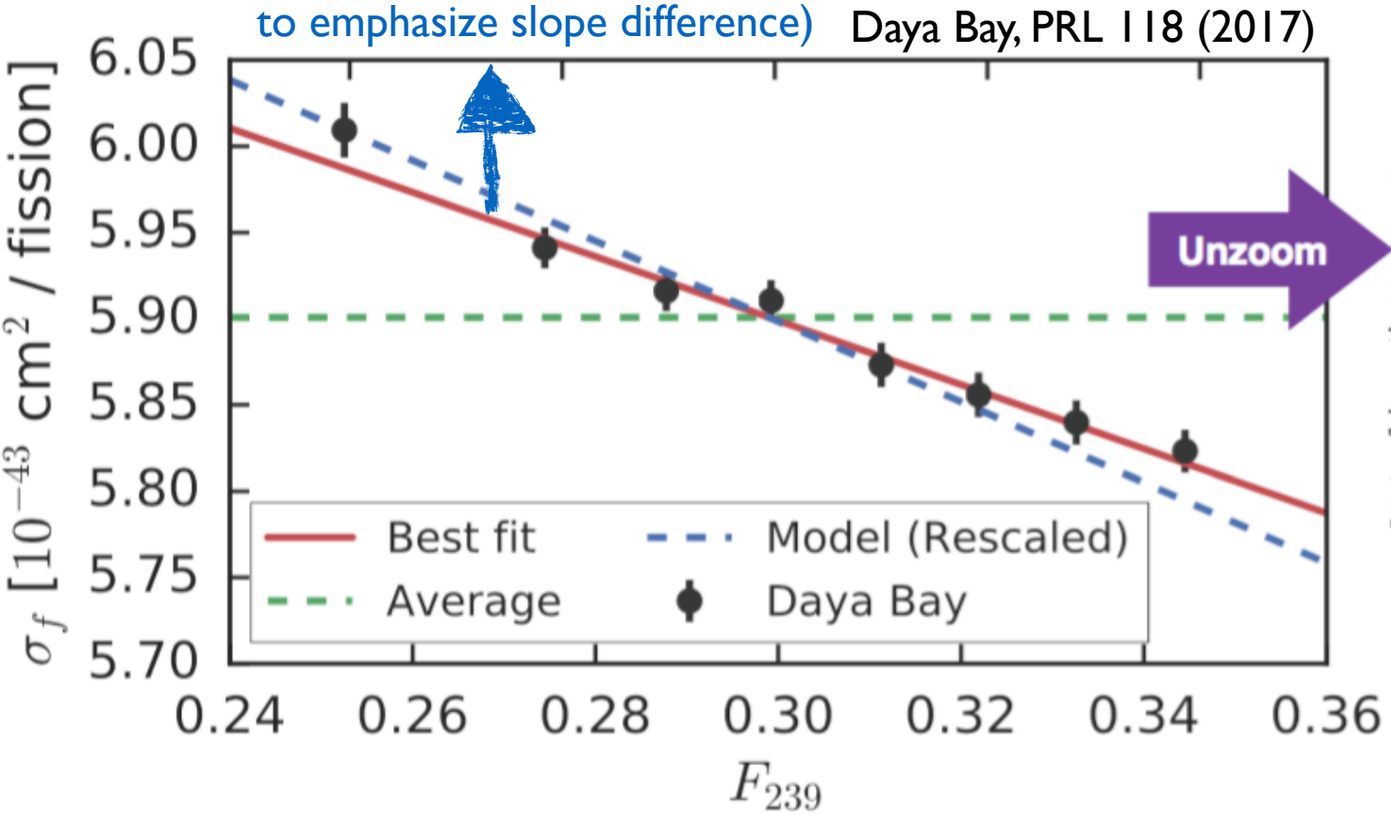
- Measure IBD yields during periods with differing fuel content.
- Flux anomaly's size depends on how much ^{235}U is burning
- Sterile neutrinos cannot explain this result
- Points towards flux problems

Daya Bay, PRL 118 (2017)

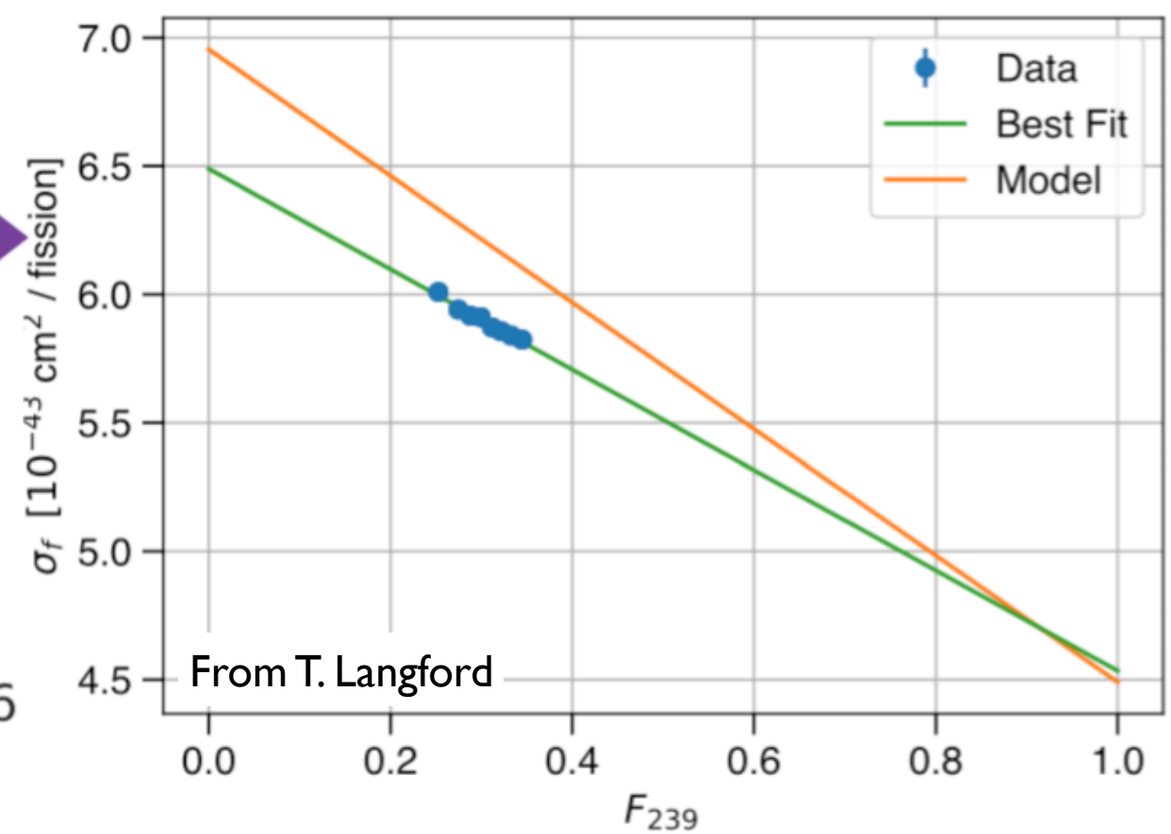


(Blue line scaled down to emphasize slope difference)

Daya Bay, PRL 118 (2017)



Unzoom

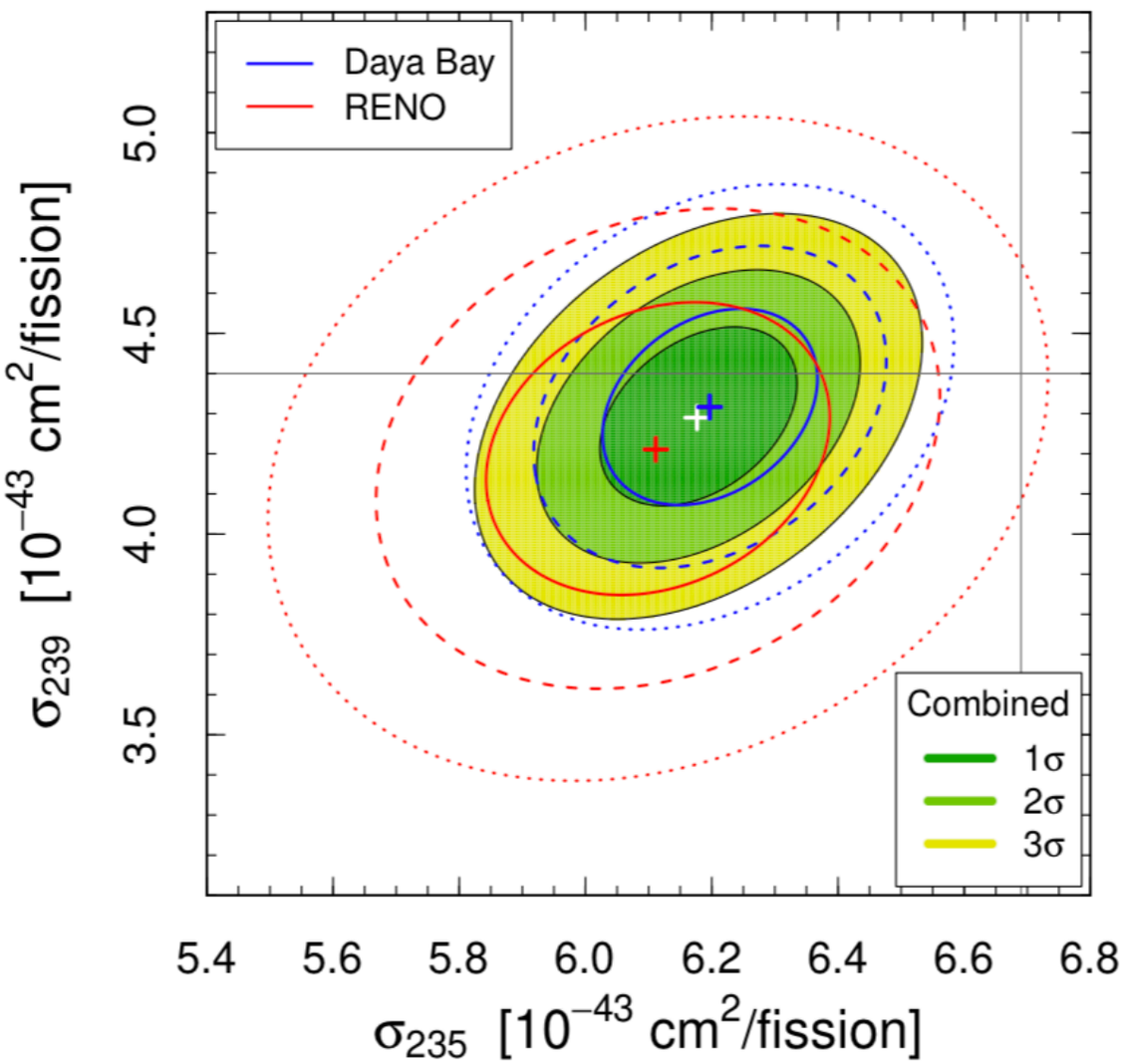


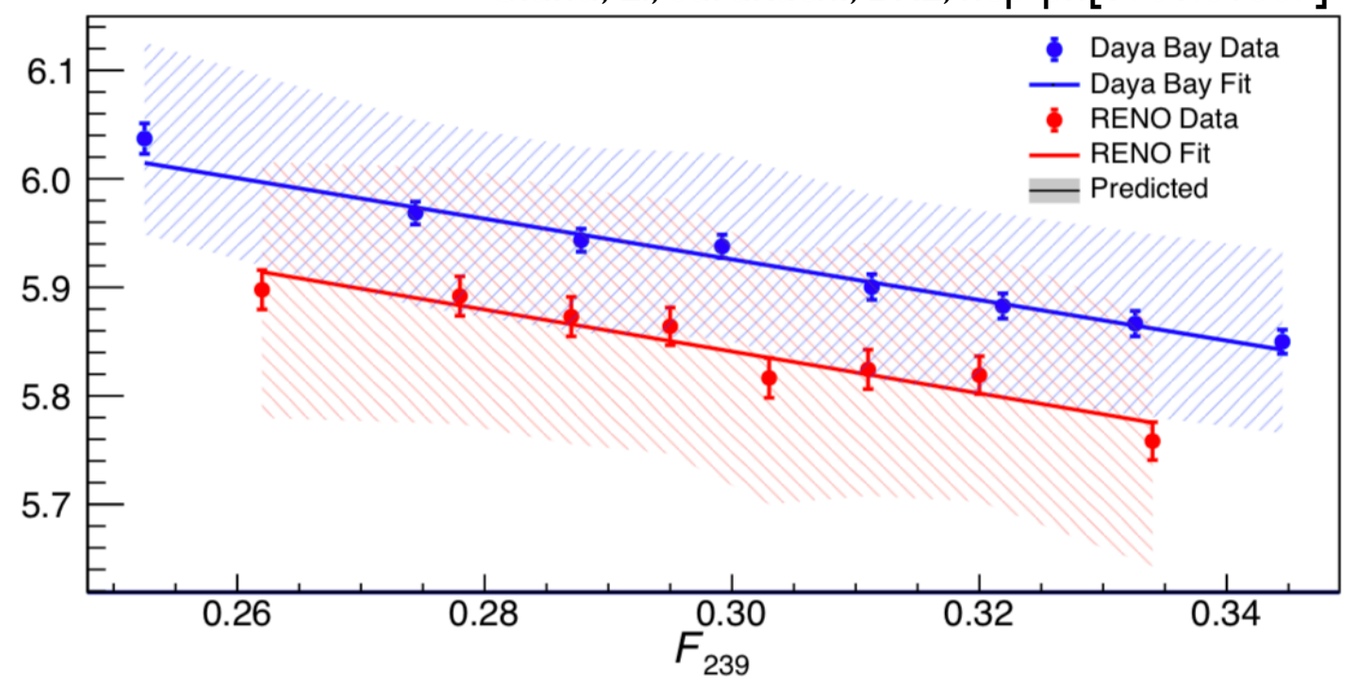
From T. Langford

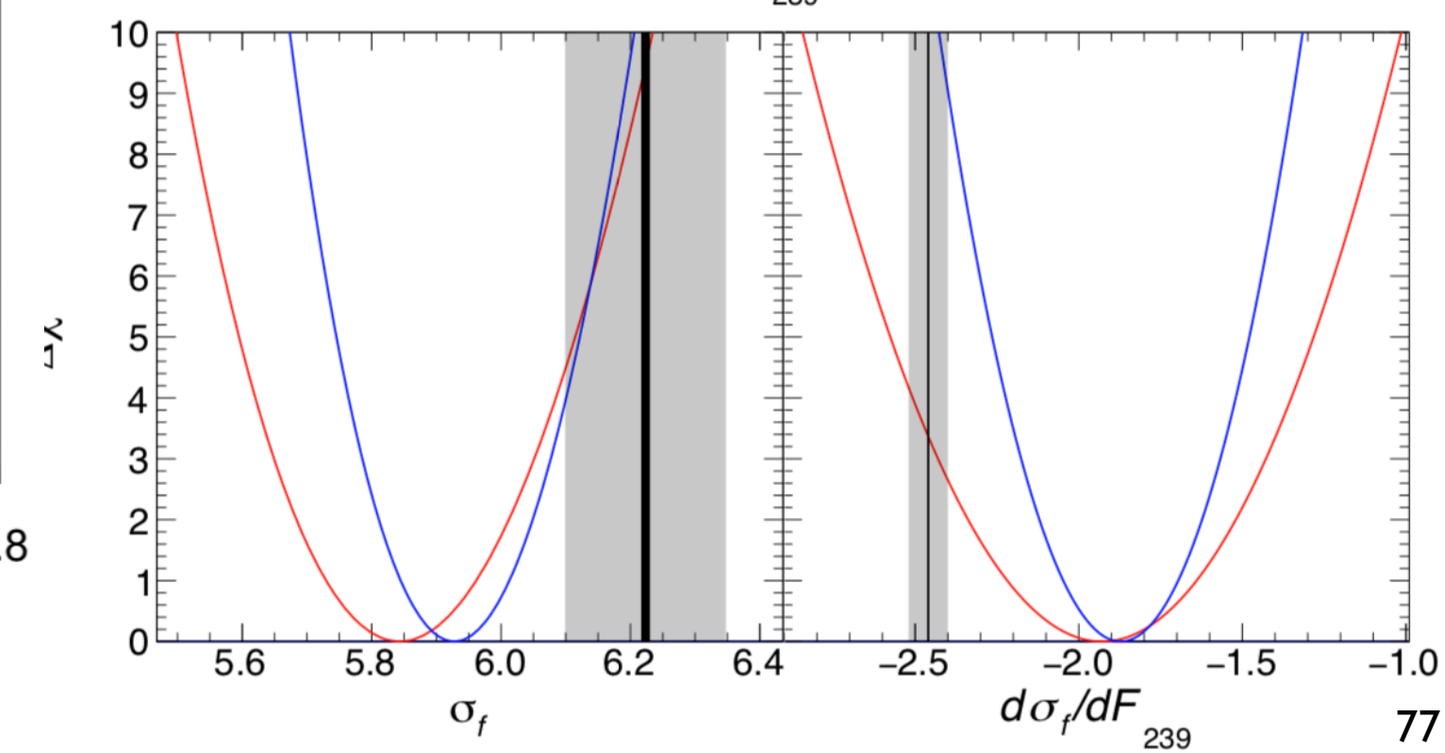
Testing Fluxes: RENO+DYB Evolution

- RENO sees similar behavior — flux evolution badly predicted
  - No-osc fits indicate ^{235}U prediction is too high.

Giunti, Li, Surukuchi, BRL, hep-ph[1901.01807]



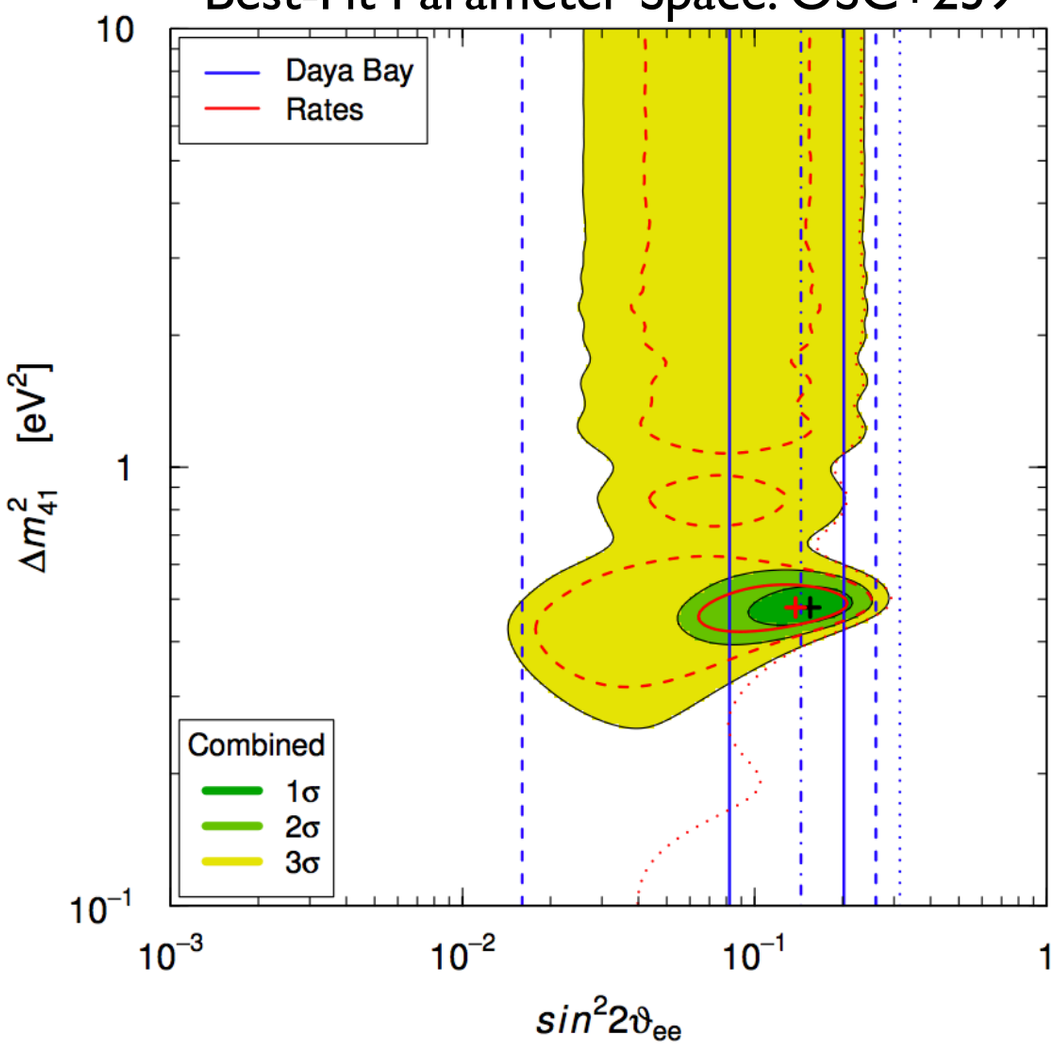




Global Flux Fits

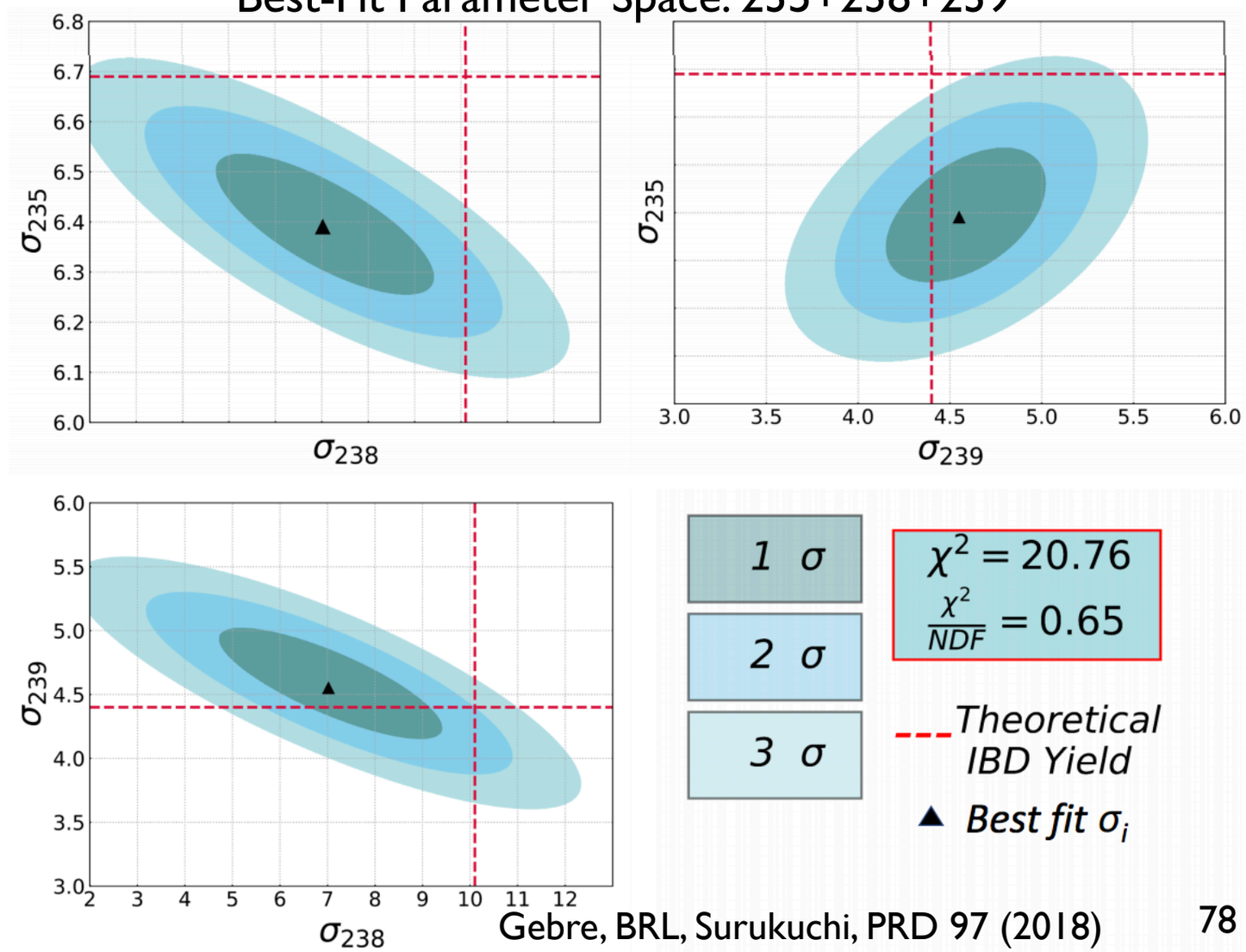
- What if we fit ALL global flux data: HEU, LEU, flux evolution?
  - No-Osc fits indicate ^{235}U and ^{238}U flux predictions are off!
  - 'Hybrid' models with both oscillations and incorrect fluxes also fit well
  - Q: Is older HEU data really reliable (STEREO@Moriond — A: Seems so…?)
- Need more osc constraint, more fluxes to totally resolve this!

Best-Fit Parameter Space: OSC+239



Giunti, et al, JHEP 10:143 (2017)

Best-Fit Parameter Space: 235+238+239

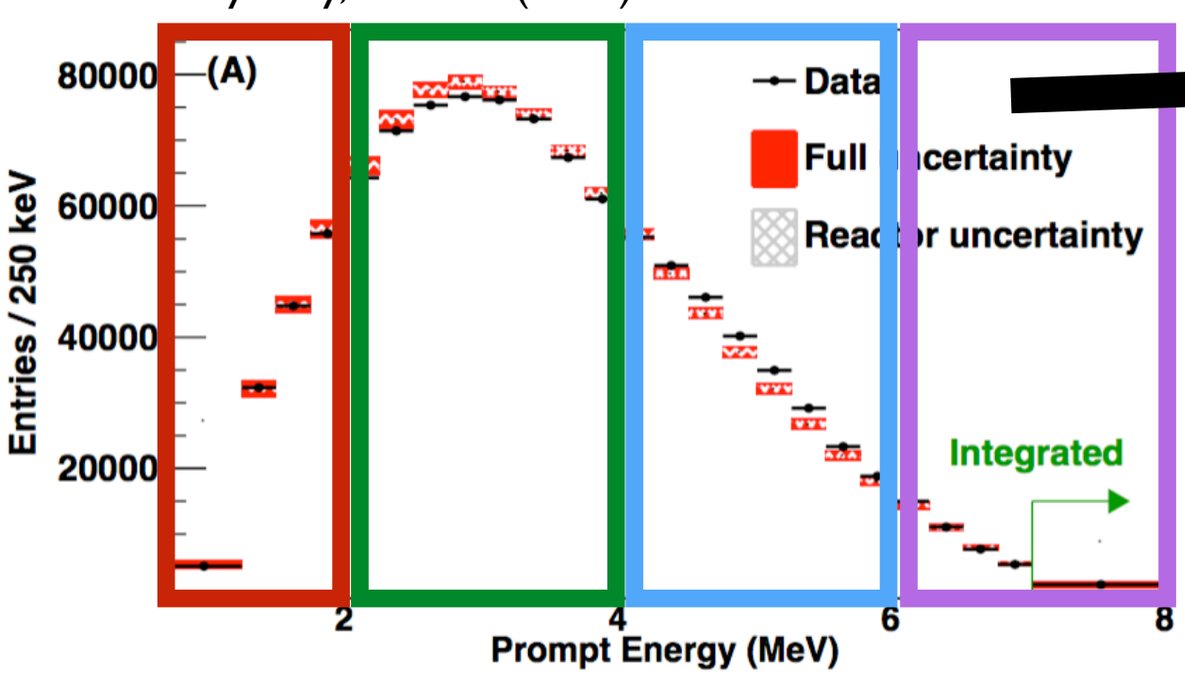


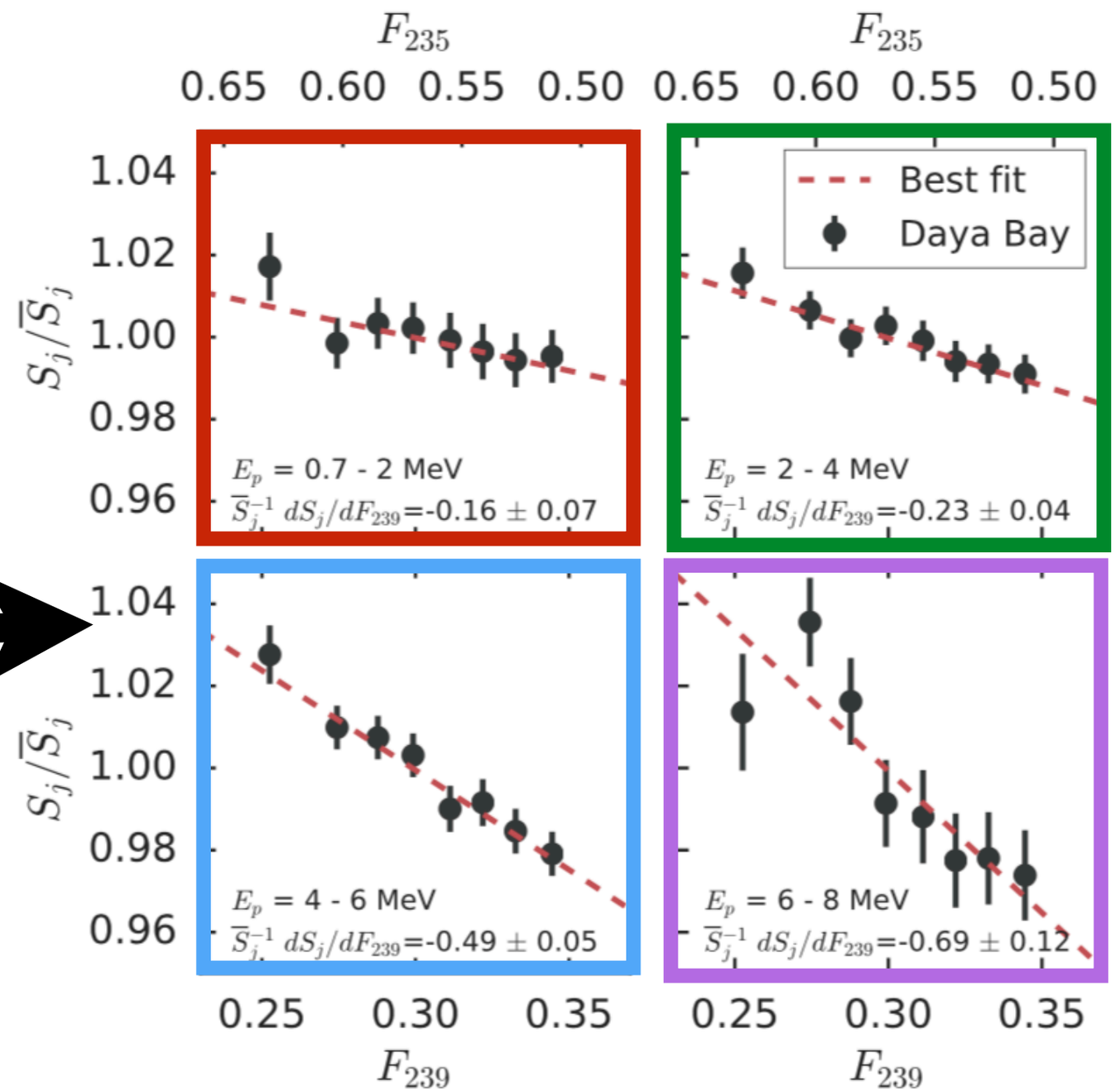
Gebre, BRL, Surukuchi, PRD 97 (2018)

Isotopic Origins: Daya Bay

- Daya Bay approach: does bump size change with fuel content?
  - Would indicate if a single isotope is preferentially responsible for it

Daya Bay, CPC 41 (2017)

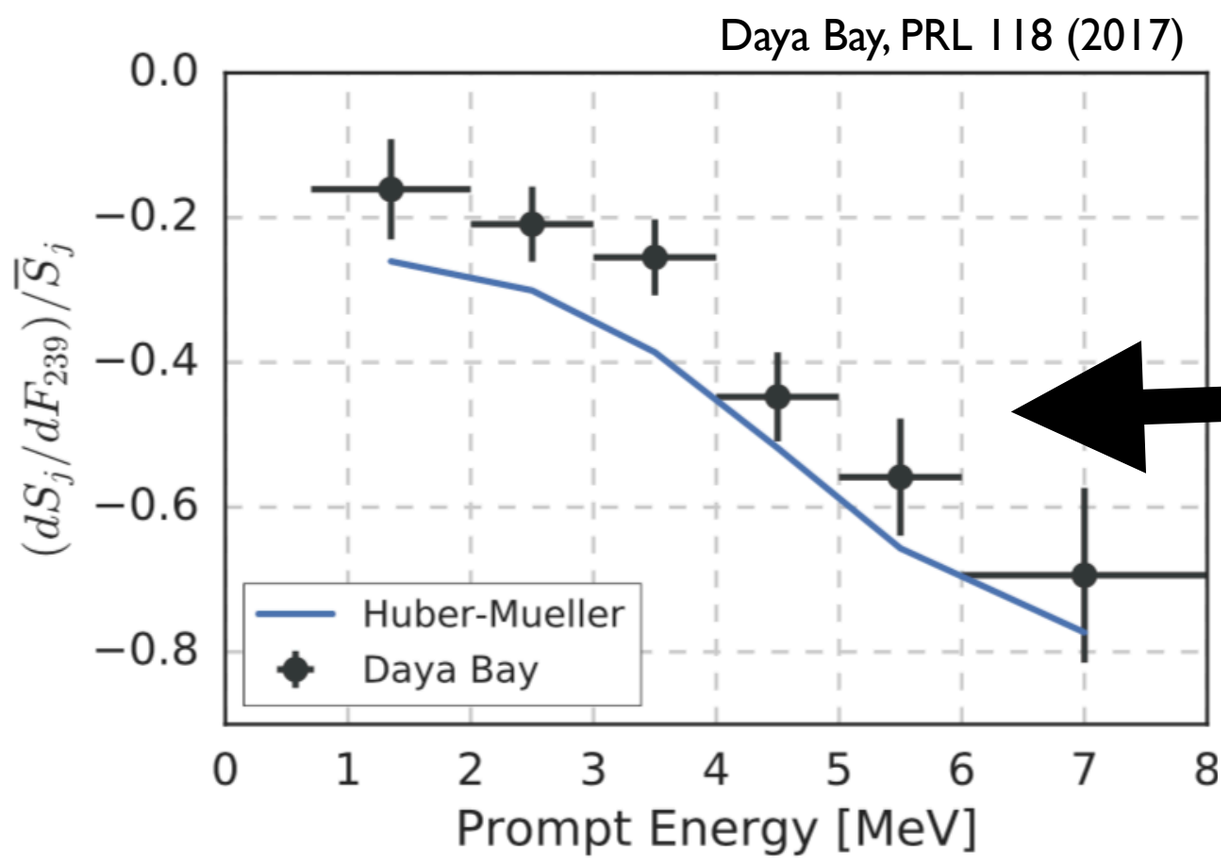


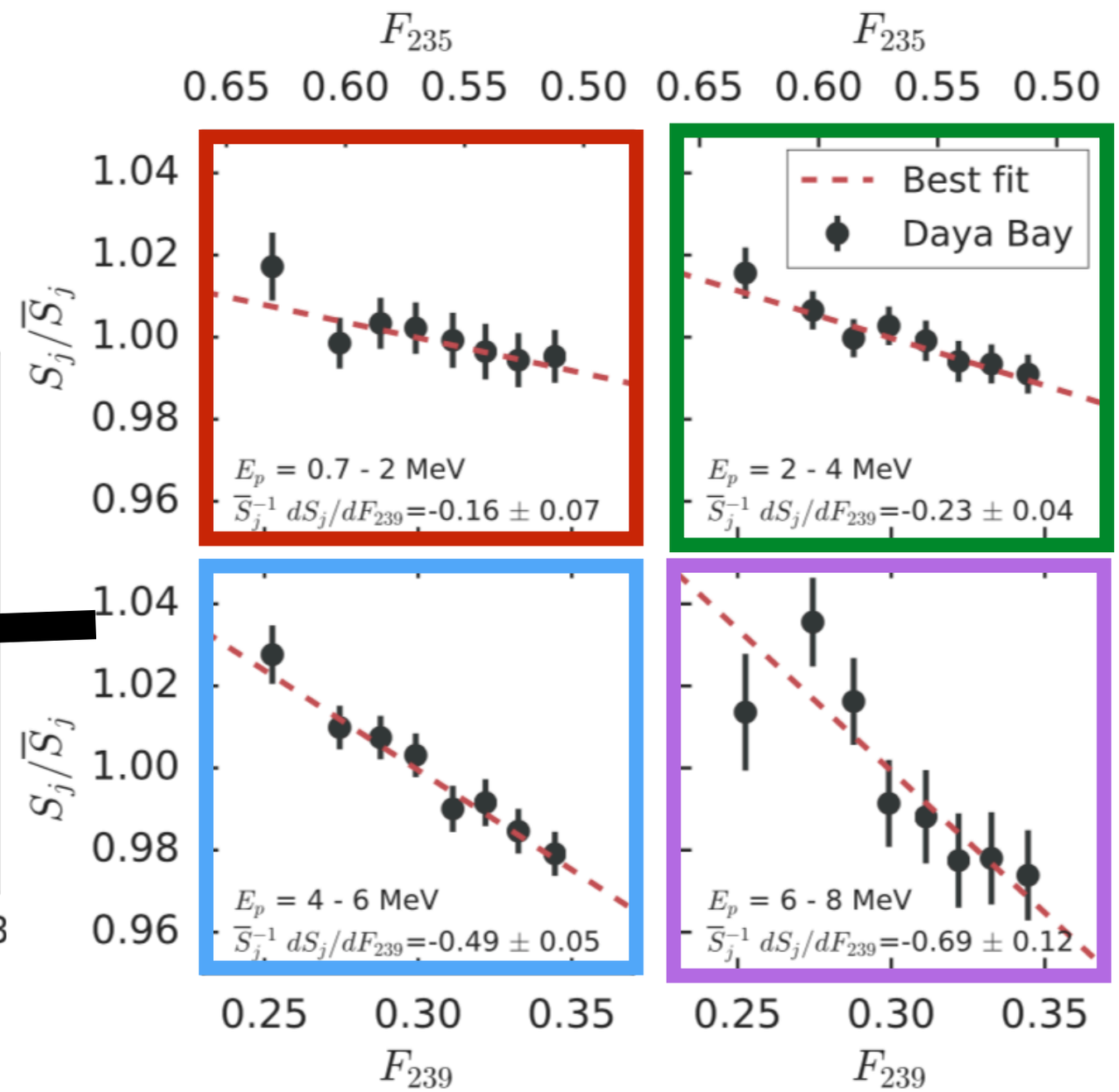


Daya Bay, PRL 118 (2017)

Isotopic Origins: Daya Bay

- Daya Bay approach: does bump size change with fuel content?
- Nothing uniquely odd happening in 4-6 MeV region…
  - Not enough statistics to draw a valuable conclusion, though



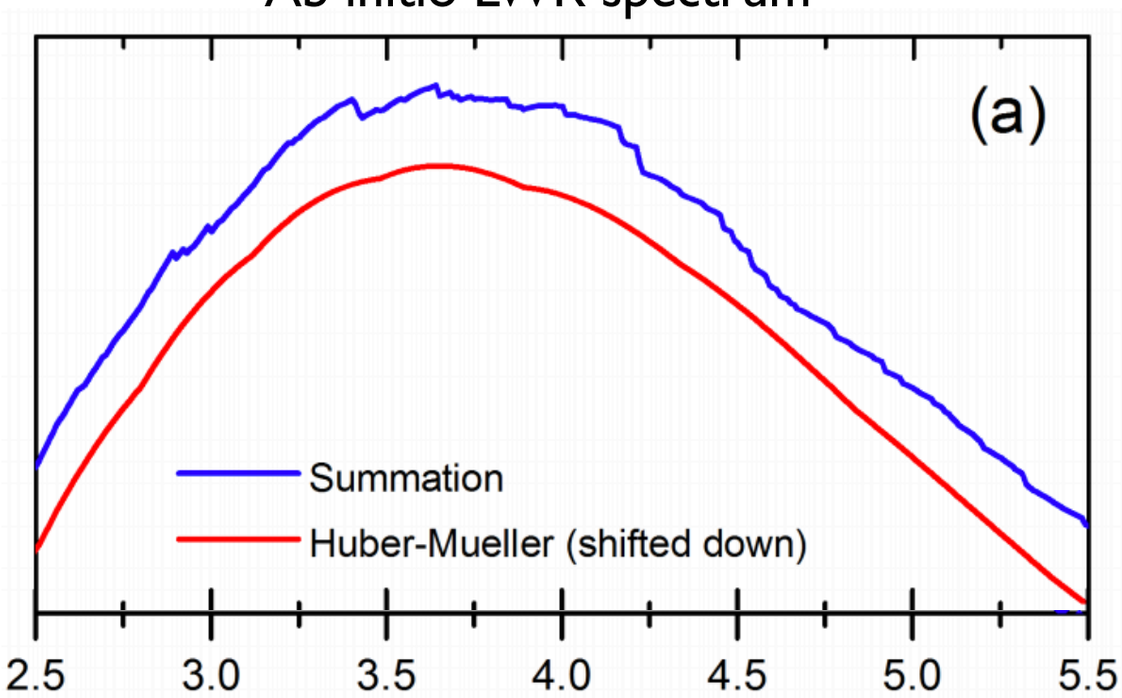


Daya Bay, PRL 118 (2017)

Fine Structure: A Problem For JUNO?

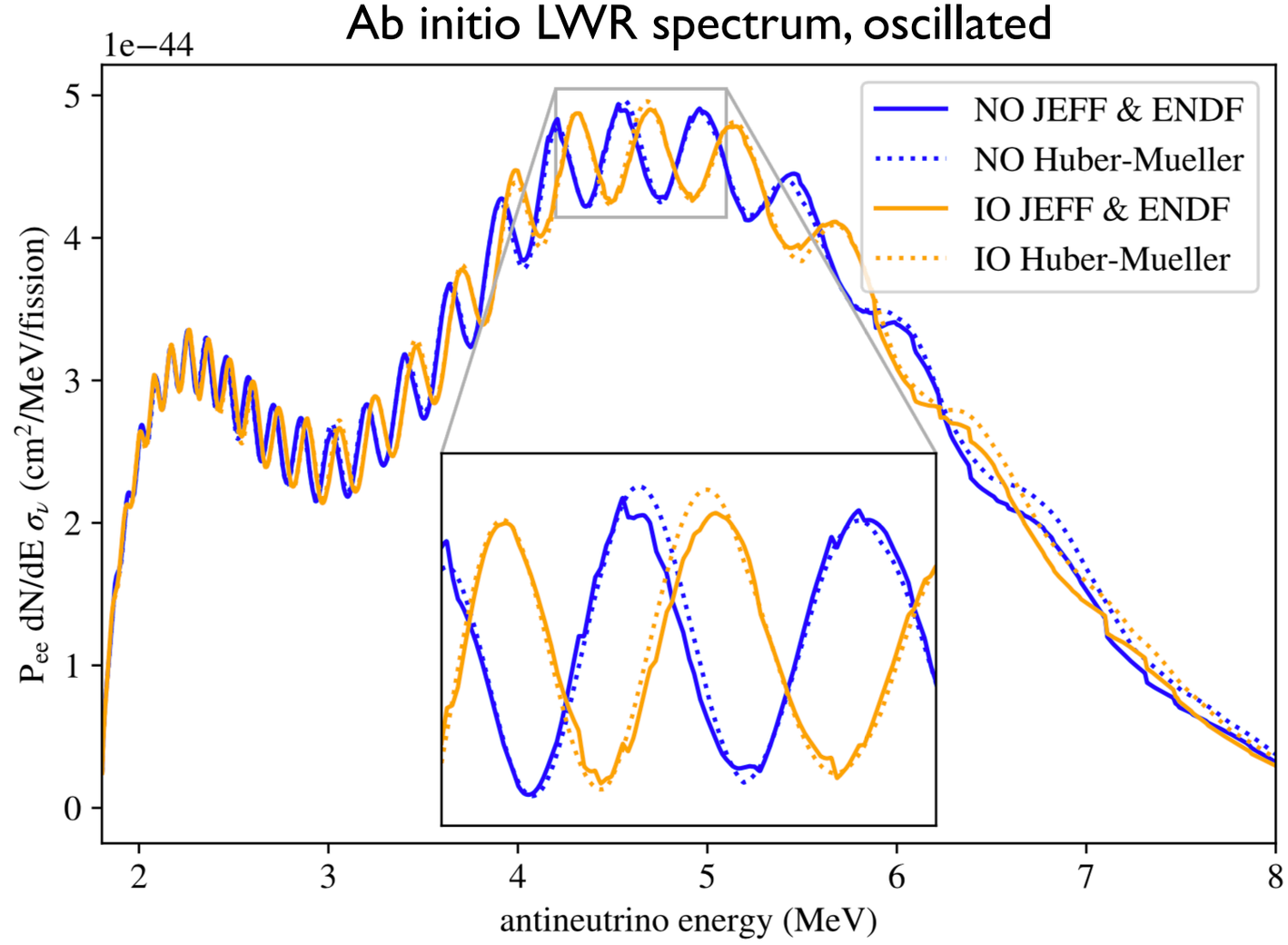
- Another ill-defined aspect of spectrum: fine structure
  - Arises from endpoints of individual beta branches in aggregate spectrum
  - Do fine structure wiggles obscure wiggle frequency from oscillations, and thus mass hierarchy measurements at reactors?

Ab initio LWR spectrum



Sonzogni et al, PRC 98 (2018)

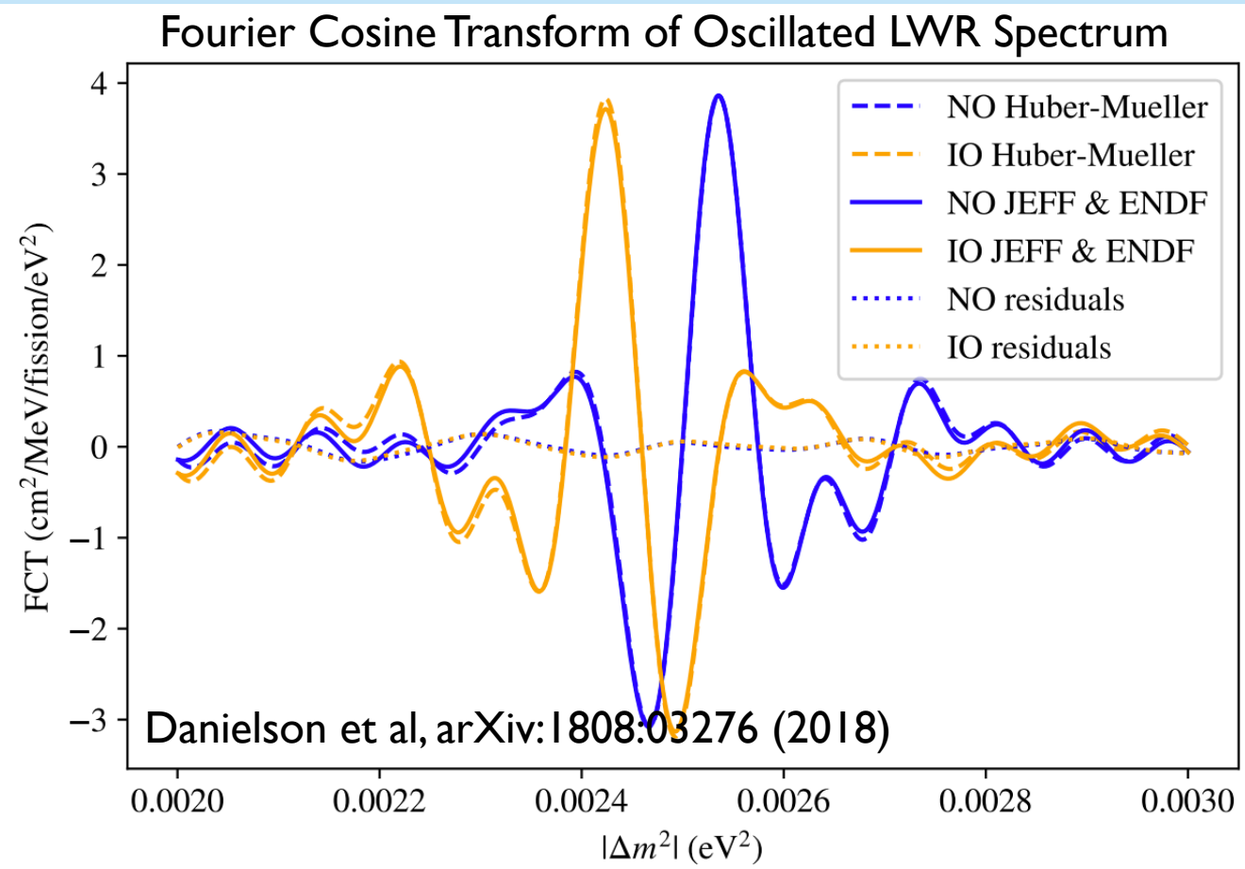
Ab initio LWR spectrum, oscillated



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

Fine Structure: A Problem For JUNO?

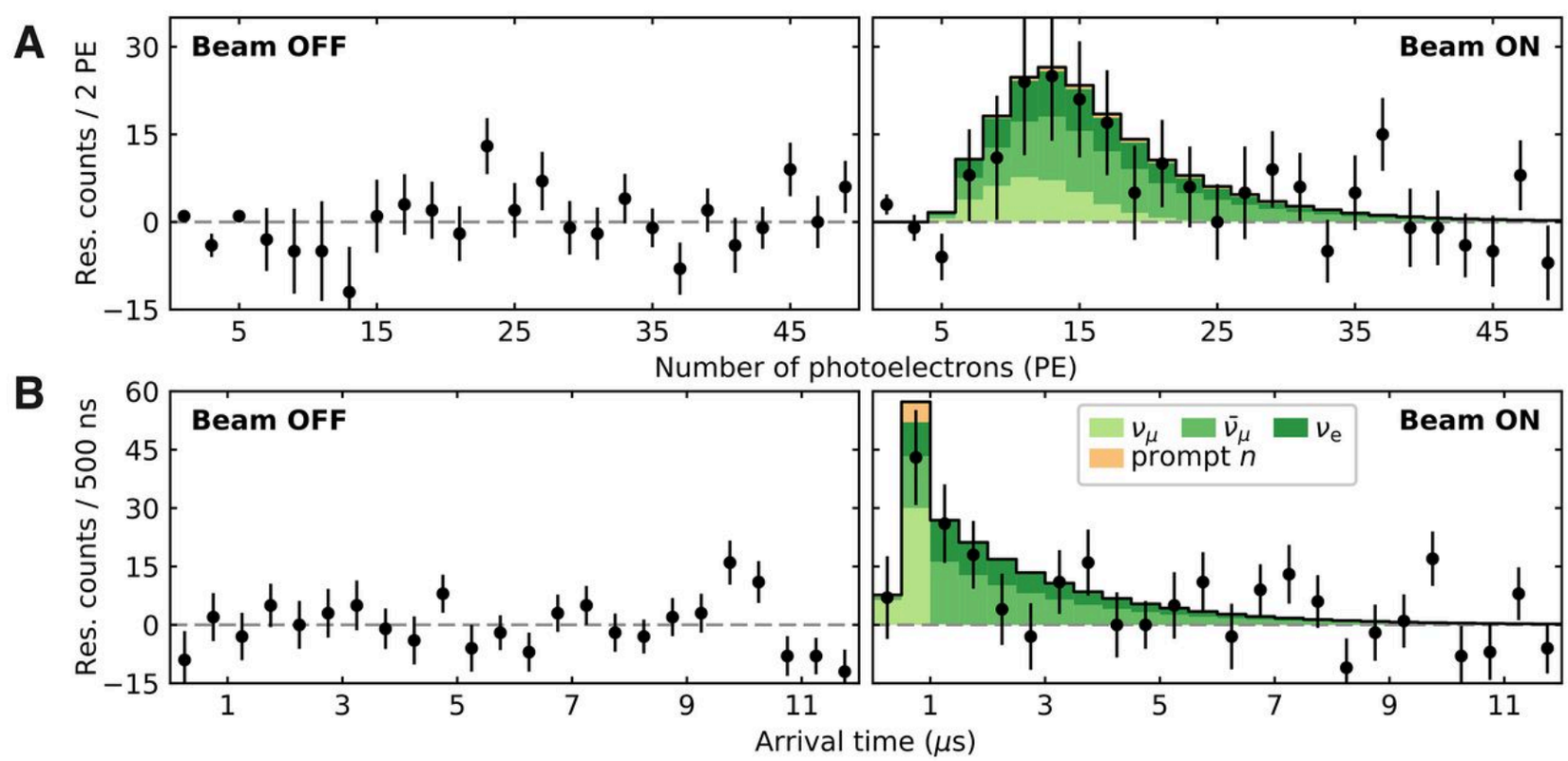
- Nuclear theorists: fine structure features are too small to affect the mass hierarchy measurement.
  - Demonstrated using a Fourier decomposition approach
- Some discussion appears to continue in community?
  - 'Fourier decomposition not used by JUNO…'
  - 'One specific energy range matters for hierarchy;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

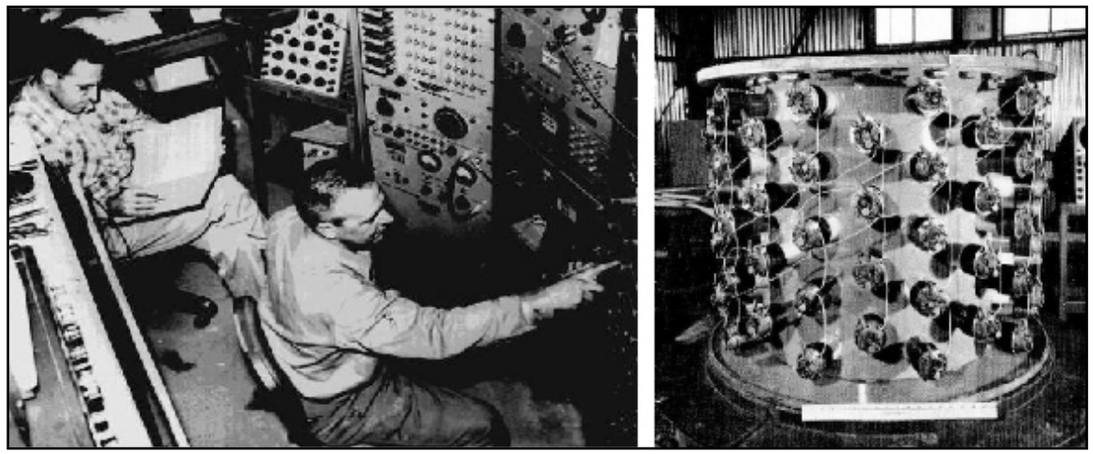
IBD-CEvNS Complementarity

- CEvNS is predicted by standard model with high precision
  - Precision <u>absolute</u> 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!!

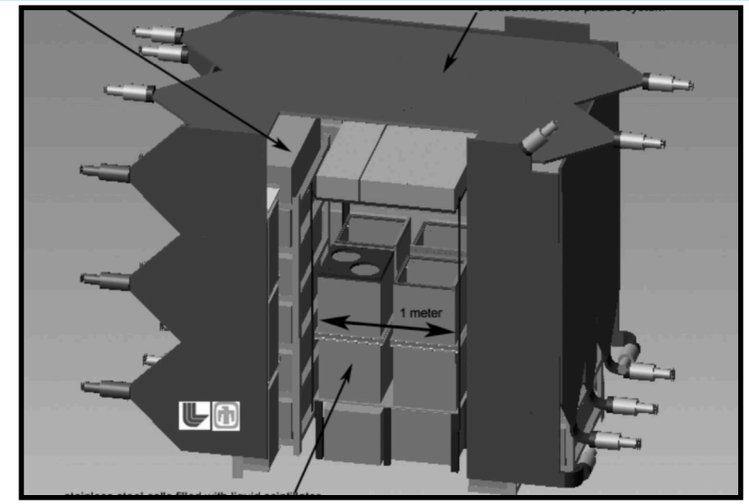


Reactor Neutrino Monitoring Advances

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

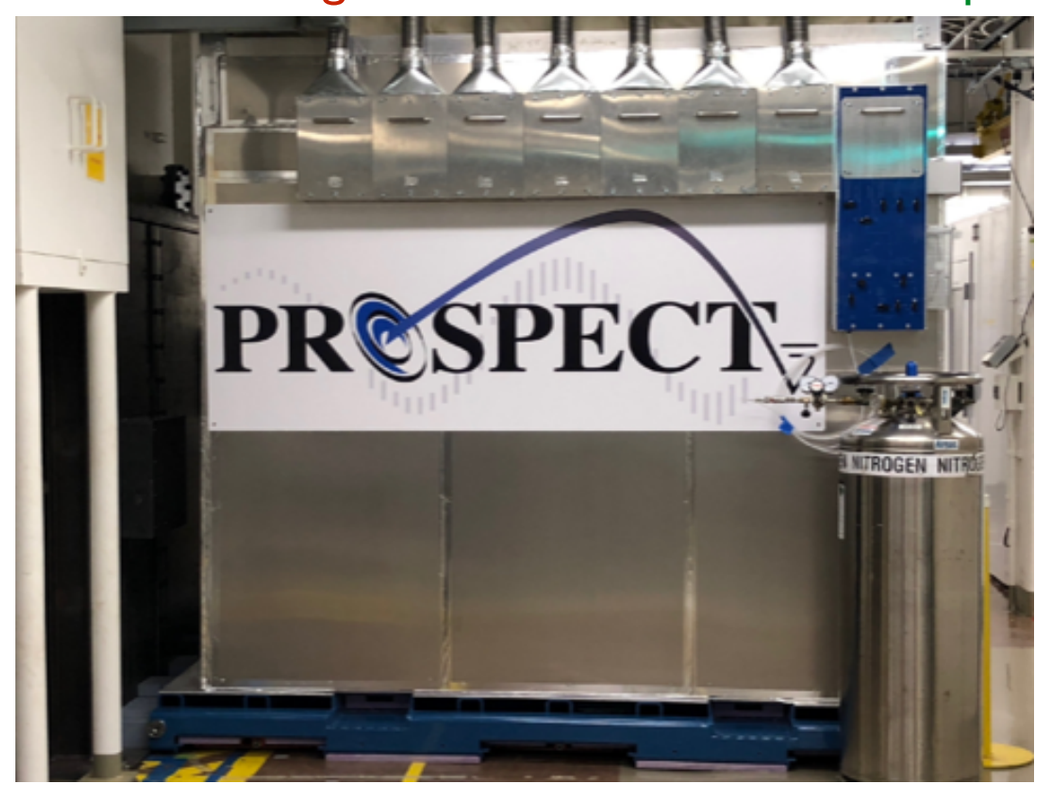


1950s: First Detection; ~1000 counts in 1 month; 5 background counts per 1 antineutrino count (S:B 1:5)



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

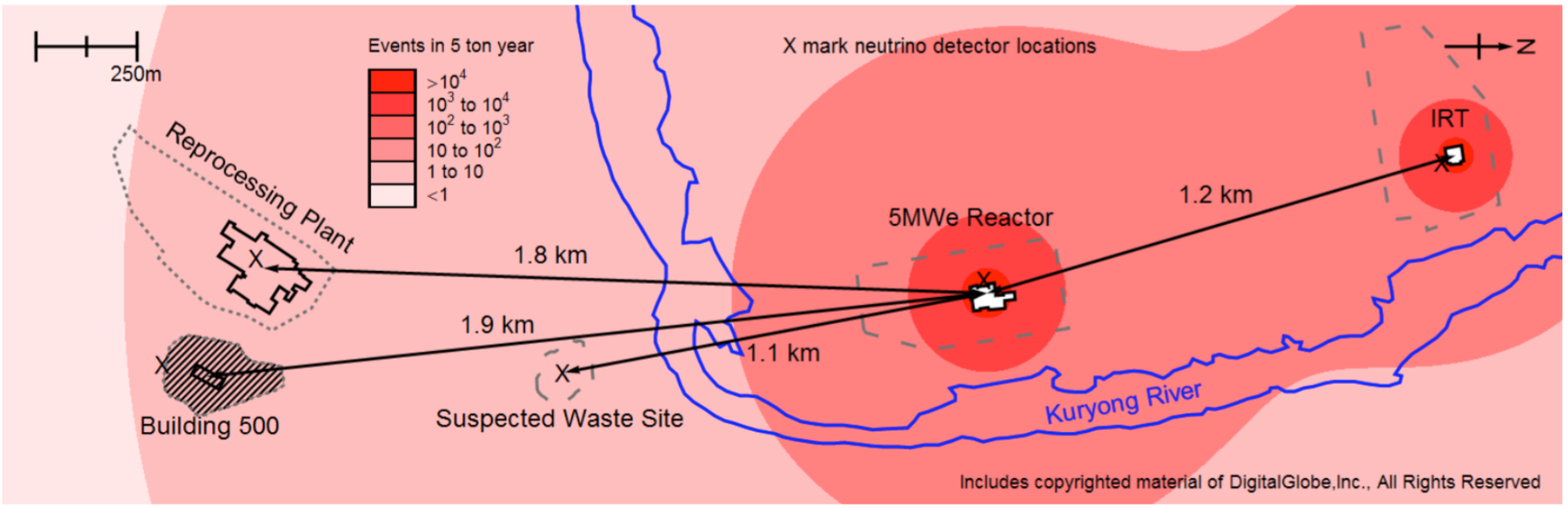
1980s: Bugey: ~1000 counts per day, S:B 10:1, but only underground. flammable/corrosive solvent detector liquids

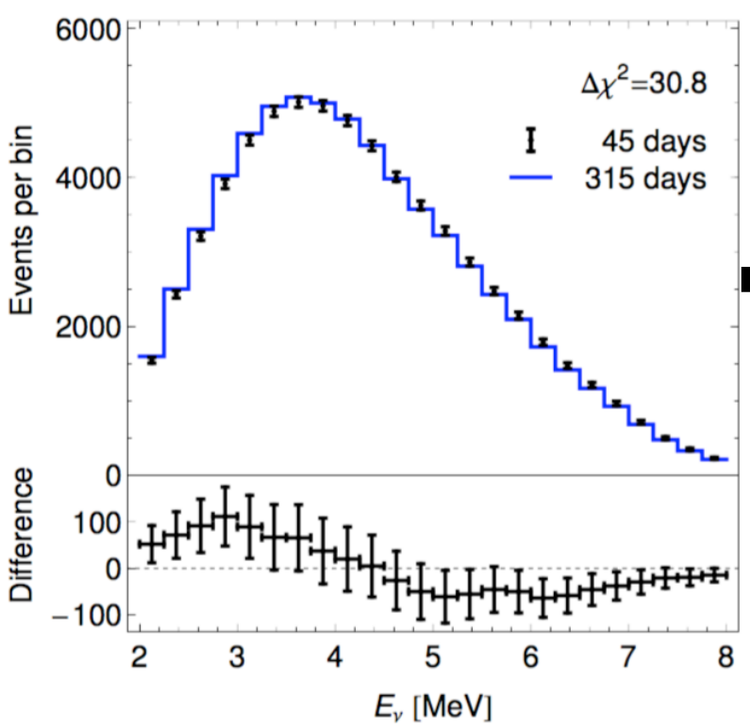


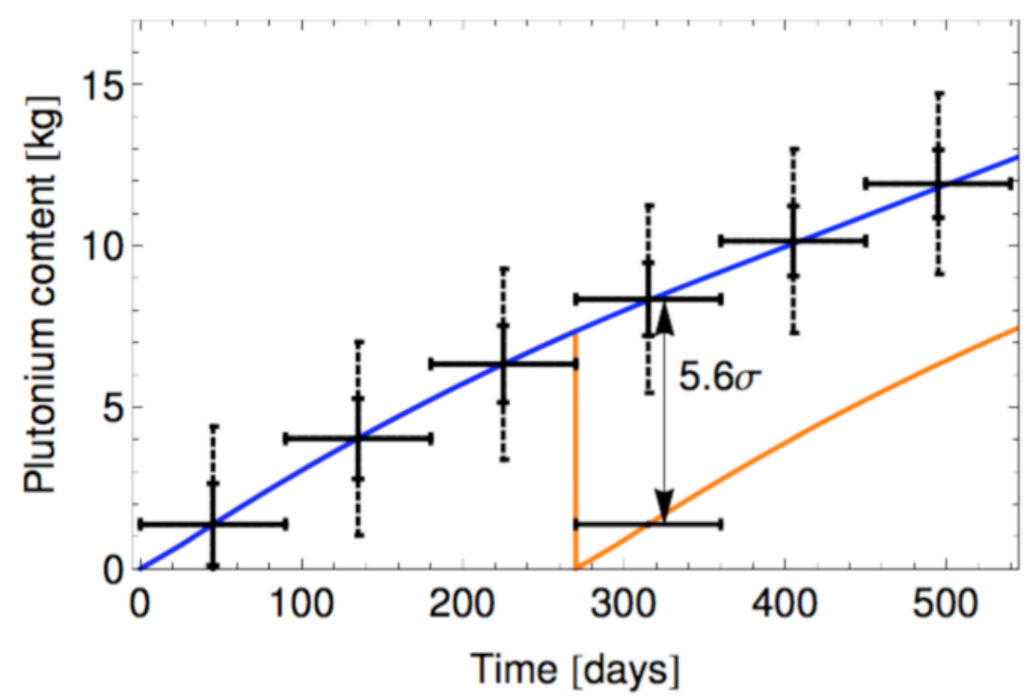
NOW: PROSPECT detector: ~750/day from only 80MW reactor, S:B 1:1 on surface, 'safe' plug-n-play detector

Spectrum Measurement Applications

- Note: An experimental demonstration of reactor monitoring
  - Theory-based case-studies of Iranian, North Korean nuclear reactors: arXiv[1403.7065], arXiv[1312.1959]
  - Unambiguous monitoring of reactor's ^{239}Pu content utilizing a reactor's antineutrino spectrum

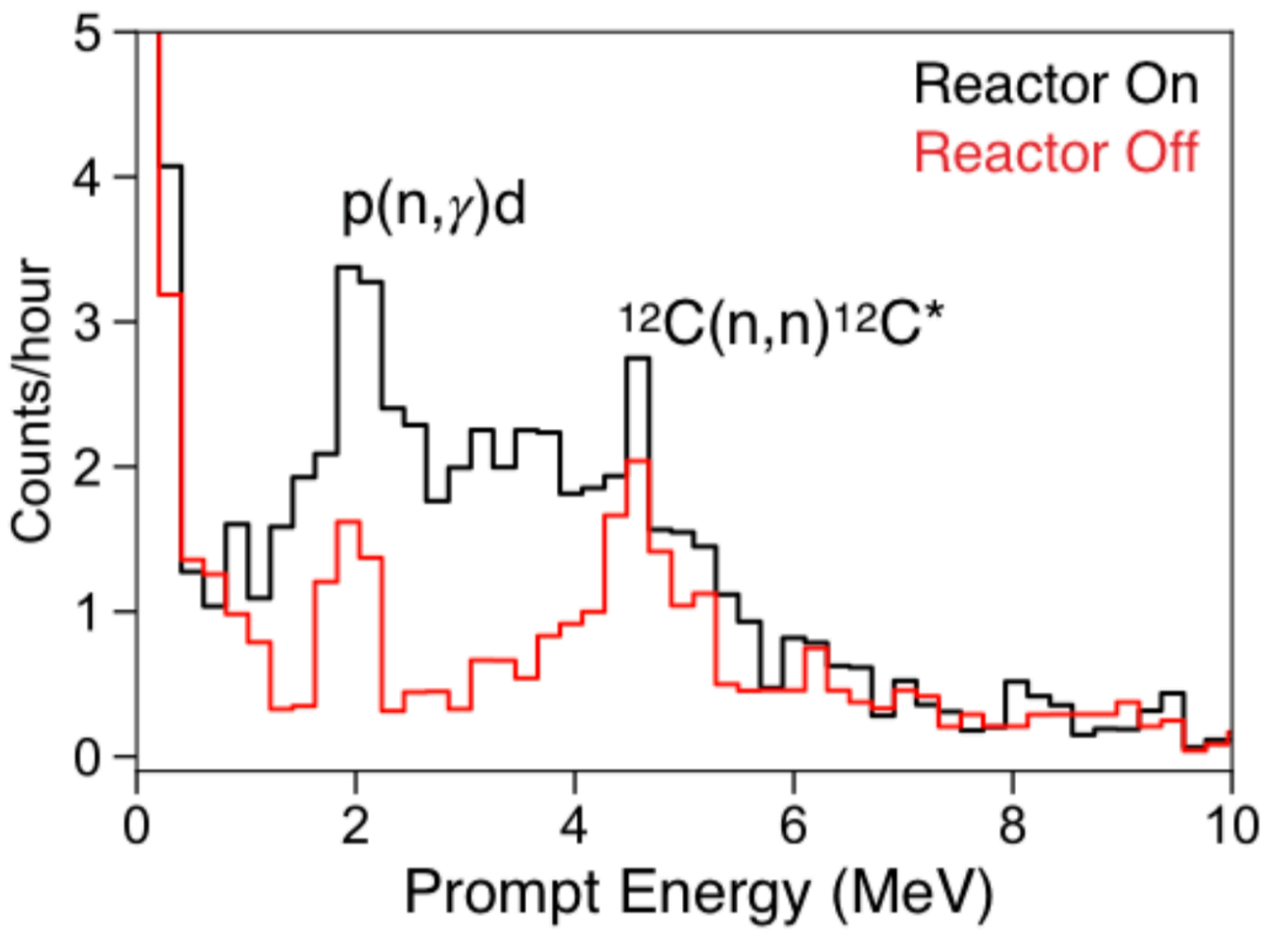


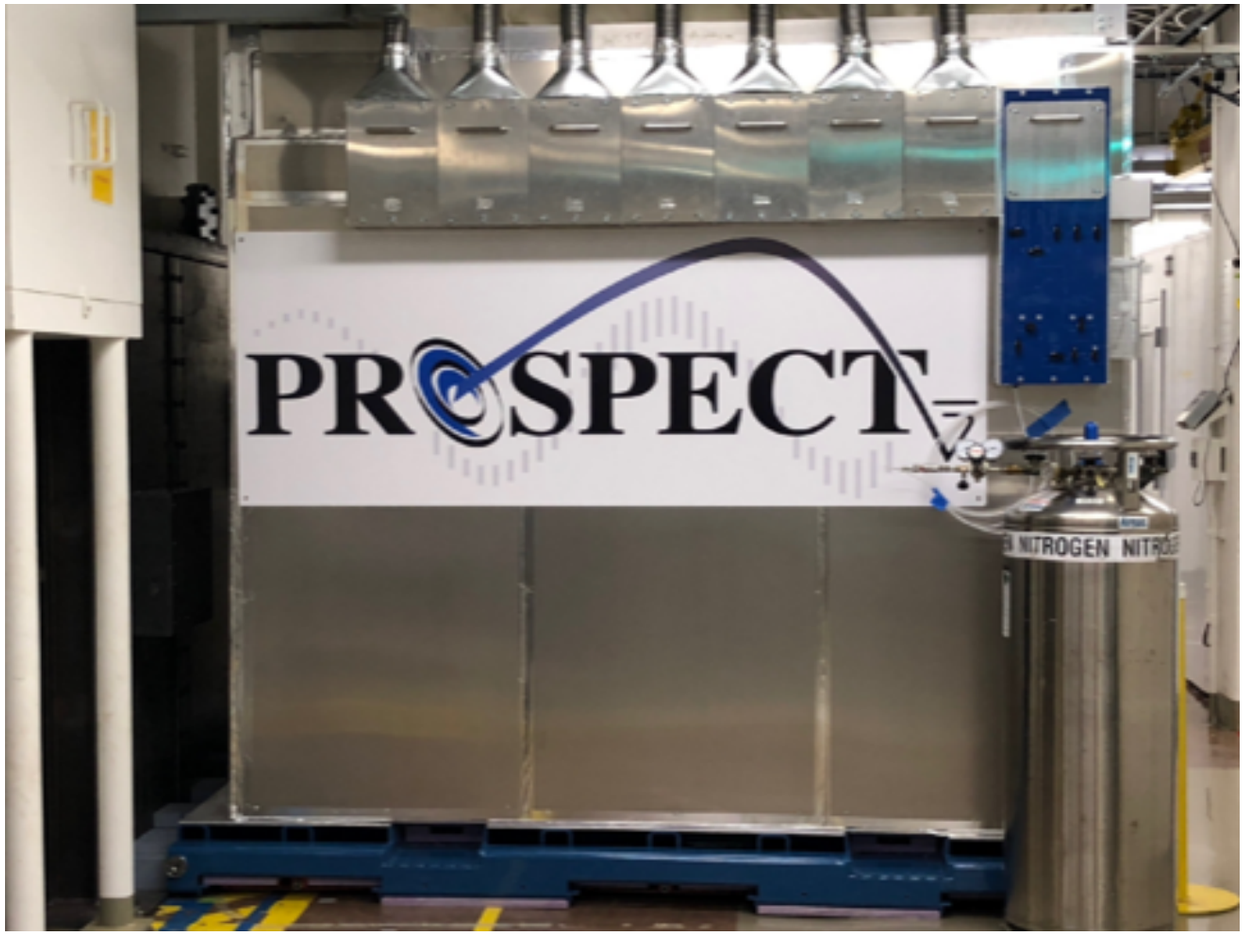




Flux Measurement Applications

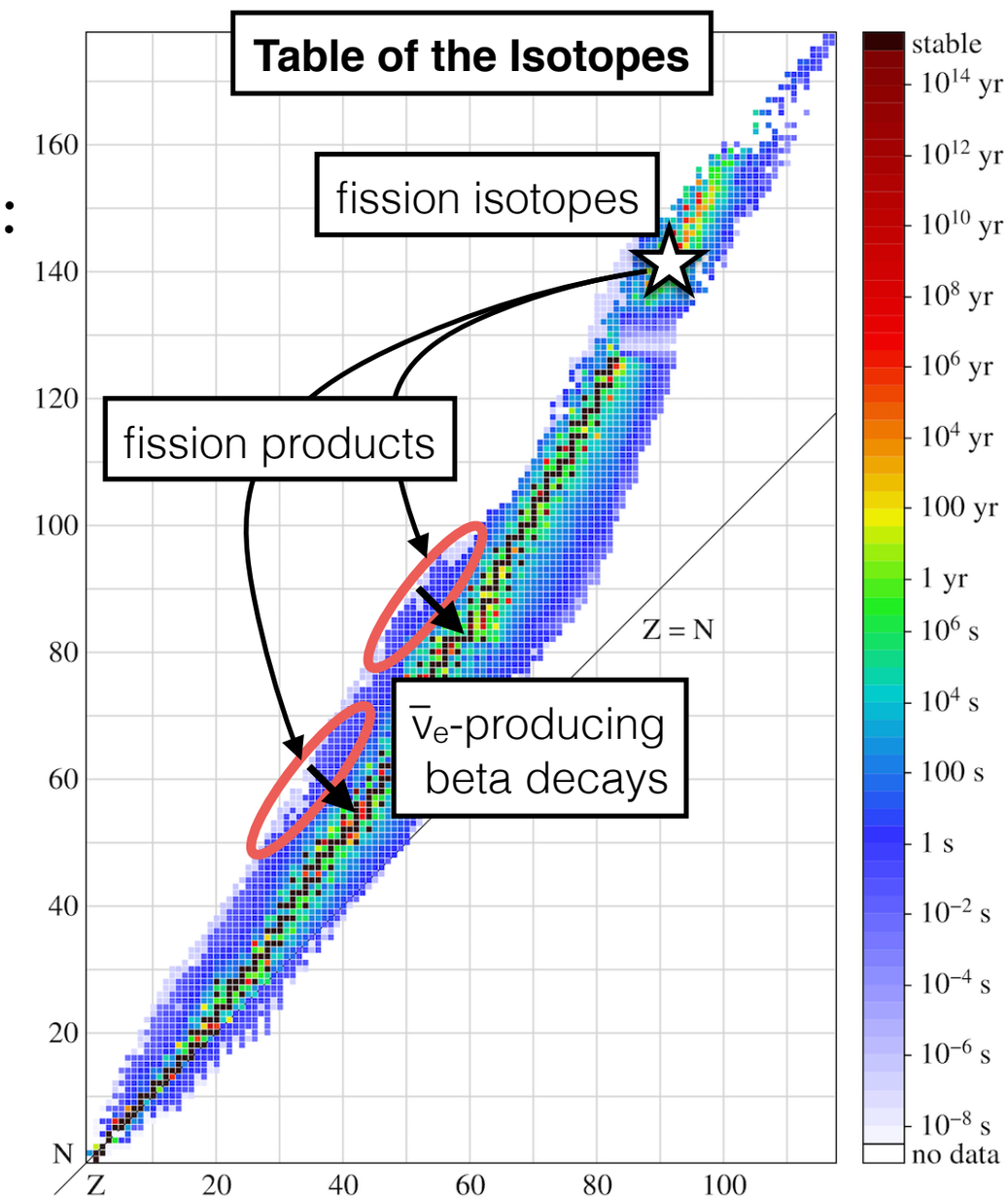
- Can perform ex-situ reactor power monitoring with compact inverse beta decay detectors
- May be helpful for specialized reactors (sodium-cooled, high-pressure gas-cooled), etc.
- We now have tech for doing this on-surface (PROSPECT)





Bad Flux Prediction Possibilities

- A litany of hypotheses HOW the fluxes could be incorrect:
  - Maybe it's specifically related to beta-decays:
    - Maybe forbidden decays aren't treated properly. Hayes, et al, **PRL** 112 (2014), **PRD** 92 (2016)
    - Maybe fission isotope beta spectrum measurements are wrong. Letourneau and Onillon @ AAP 2018
  - Maybe it's specifically related to fission yields:
    - Fission yield databases are incorrect! Sonzogni, et al **PRL** 116 (2016)
    - Fission yield dependence on neutron energy not considered correctly? Littlejohn, et al **PRD** 97 (2018)
  - Maybe there's an issue with *ONLY* U238?
    Hayes, et al **PRD** 92 (2016); Gebre, et al **PRD** 97 (2018)
  - Etc…

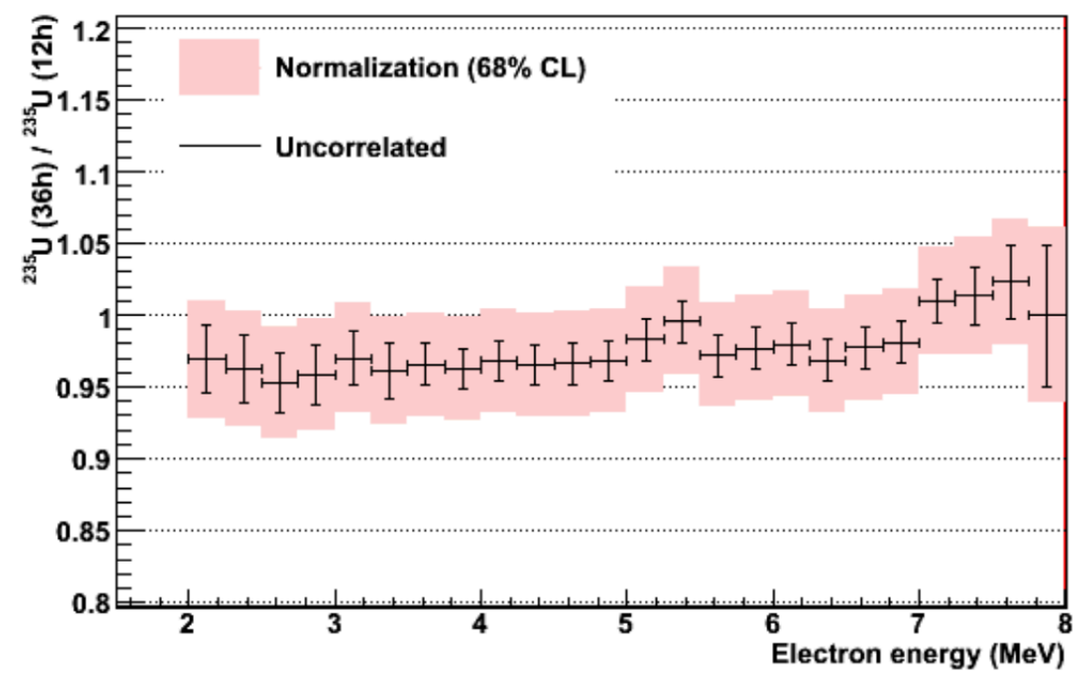


Flux Results

- Letourneau and Onillon: "Investigation of the ILL spectra normalization," presented at AAP 2018 in Livermore, CA

Four measurement performed at the ILL in the 80's

- **^{235}U(1):** [1] *K. Schreckenbach et al., PLB99 (1981) 251*
  - ↳ Normalized on: **^{197}Au(n,e$^-$)^{198}Au**
- **^{235}U(2):** [2] *K. Schreckenbach et al.", PLB160 (1985) 325*
  - ↳ Normalized on: **^{207}Pb(n,e$^-$)^{208}Pb and β-decay following ^{115}In(n, γ)^{116m}In**
- **^{239}Pu:** [3] *F. Feilitzch et al.", PLB118 (1982) 162*
  - ↳ Normalized on: **^{197}Au(n,e$^-$)^{198}Au and ^{115}In(n,γ)^{116}In**
- **^{241}Pu:** [4] *A.A Hahn et al., PLB218 (1989) 365*
  - ↳ Normalized on: **^{207}Pb(n,e$^-$)^{208}Pb and ^{115}In(n,e$^-$)^{116m}I**

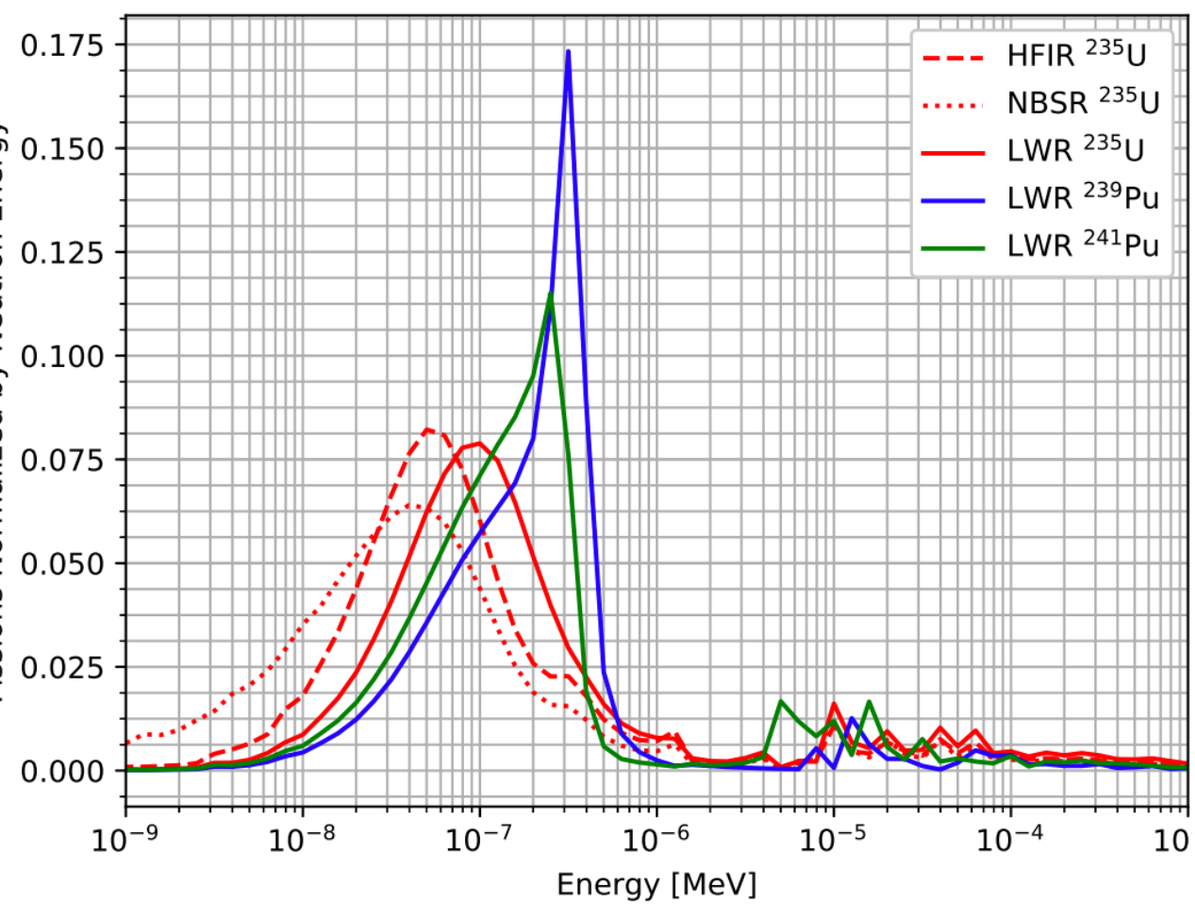


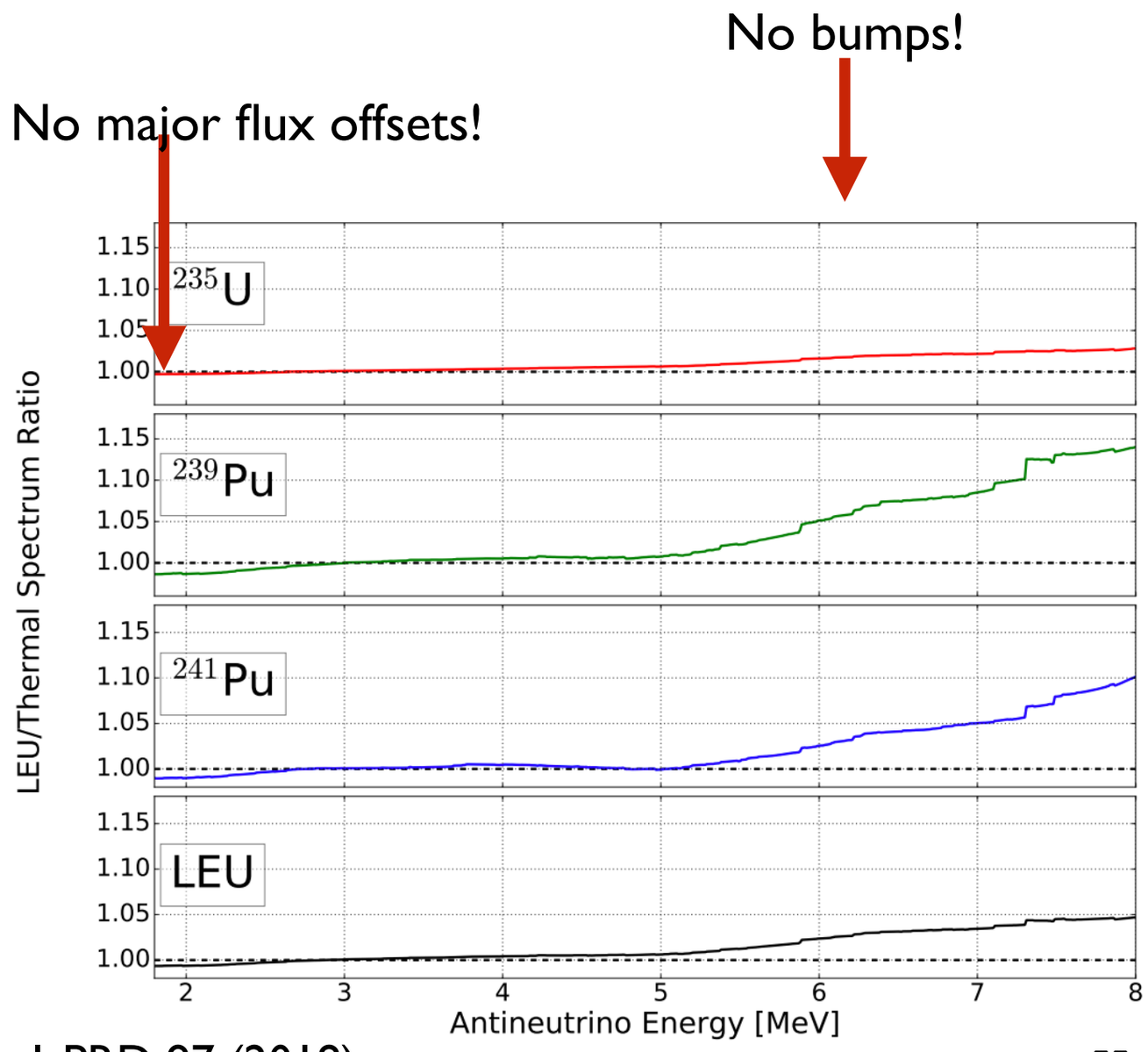
Ratio of the two measured electron-energy spectra for ^{235}U from [1] (36 h) and [2] (12 h).

- Neutron flux calibrated out through <u>relative measurement with respect to well-known</u> neutron cross-sections
  - Looks like some of the 'well-known' cross-sections may have been wrong
  - This adds a 5% shift between 235 and 239 - solves DYB flux evolution?

Incorrect Spectrum: Theory Studies

- Do non-thermal neutrons cause the bump?
  - ILL neutrons are thermal; LEU are NOT — different fission yields!
  - This difference has only minor impact on antineutrino fluxes and spectra.



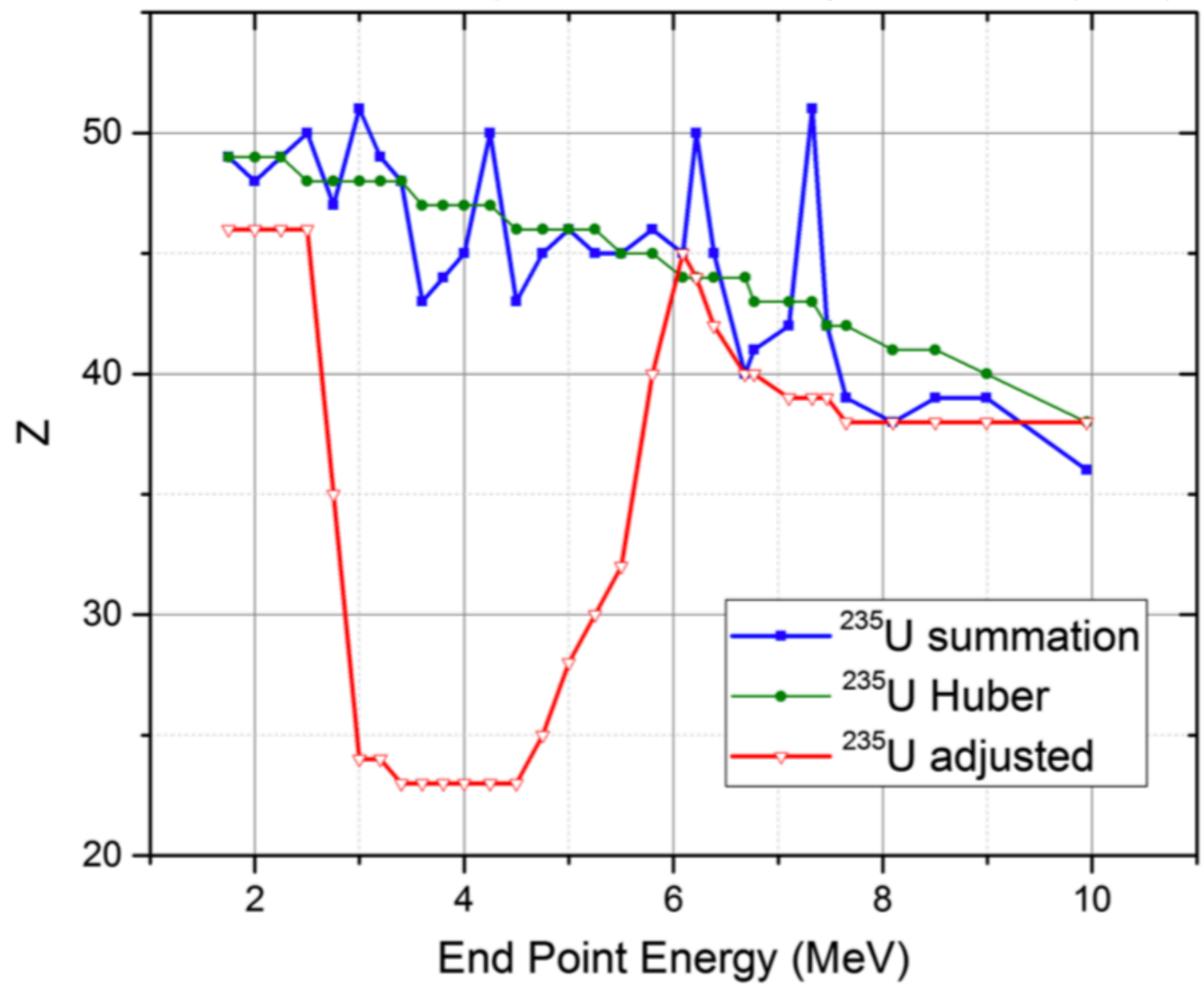


Littlejohn et al, PRD 97 (2018)

Incorrect Spectrum: Theory Studies

- Could incorrect effective nuclear charge cause the bump?
  - 'How bad would effective charge have to be to make it cause a bump?'
  - A: <u>really bad</u>, beyond what could be reasonably expected in nuclear physics…
  - So this is not the cause.

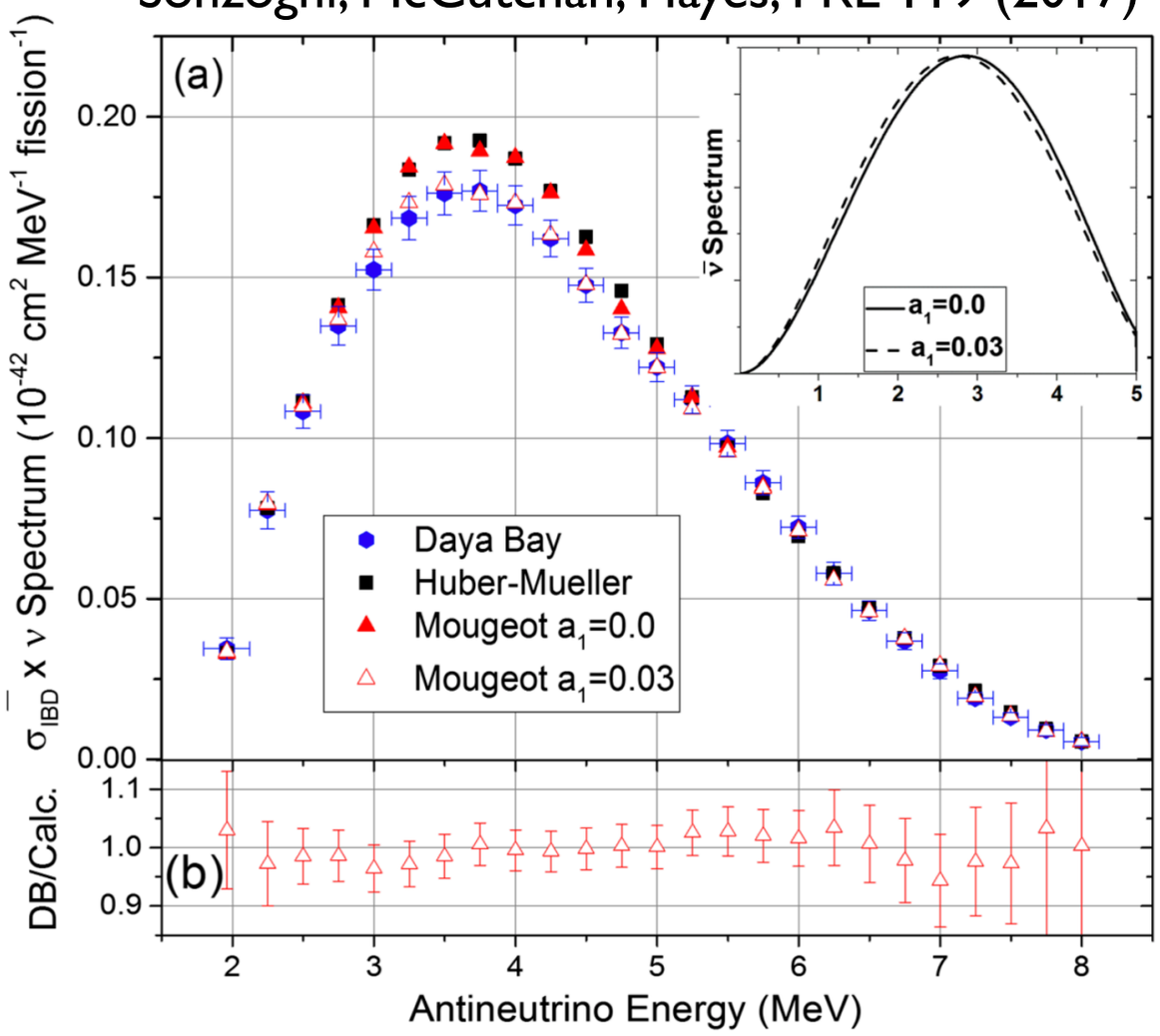
Sonzogni, McCutchan, Hayes, PRL 119 (2017)



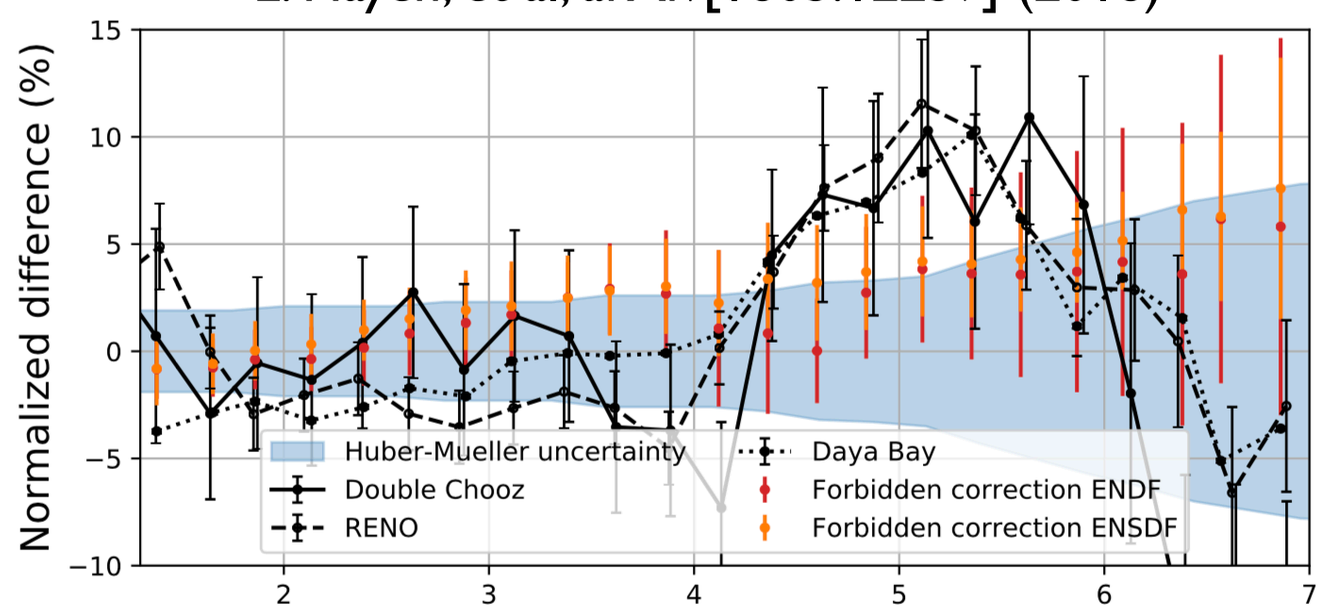
Incorrect Spectrum: Theory Studies

- Could incorrect forbidden shapes cause the bump?
  - A: It seems possible; multiple theory groups seem to agree on this.

Sonzogni, McCutchan, Hayes, PRL 119 (2017)



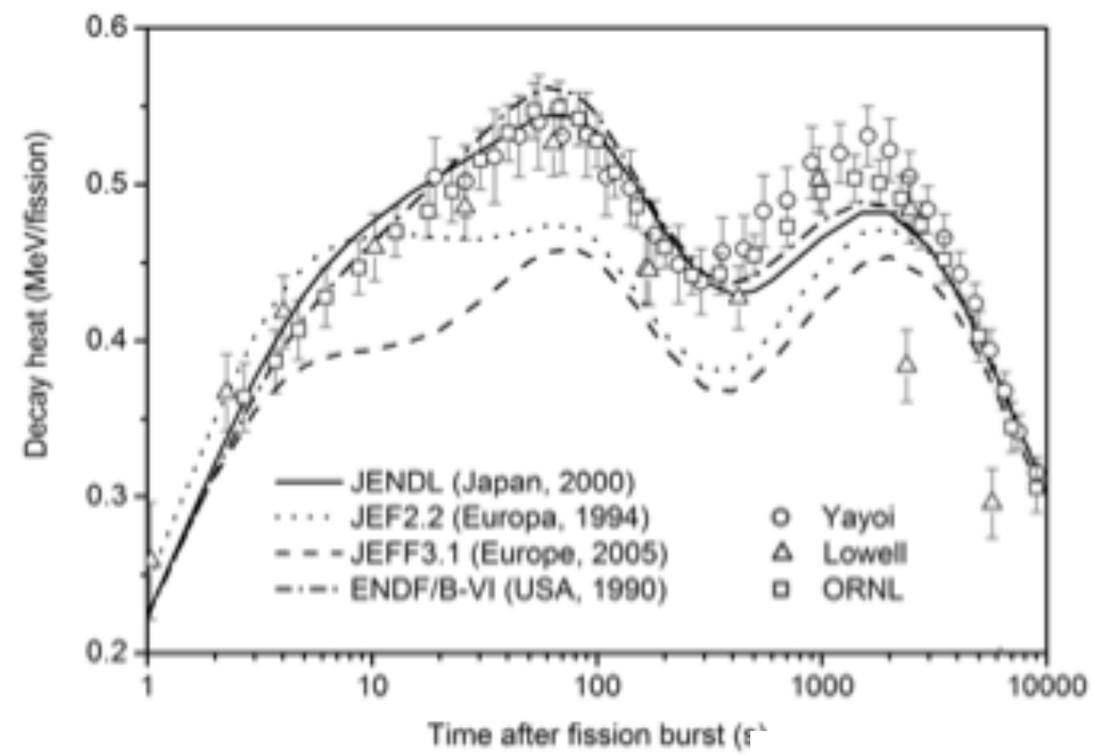
L. Hayen, et al, arXiv[1805.12259] (2018)



Reactor Spectroscopy: Application

- Why is there more decay heat than predicted 3-3000s after a reactor is turned off???
- Means we need higher cooling safety factors during reactor-off periods: This costs $$$!!!
- Hypothesis: maybe we measured branching fractions of some rare isotopes incorrectly…

Figure 3. Electromagnetic decay heat following thermal fission burst of ^{239}Pu – data from JENDL, JEF-2.2, JEFF-3.1 and ENDF/B-VI are shown together with experimental data from Yayoi, Lowell and Oak Ridge National Laboratory

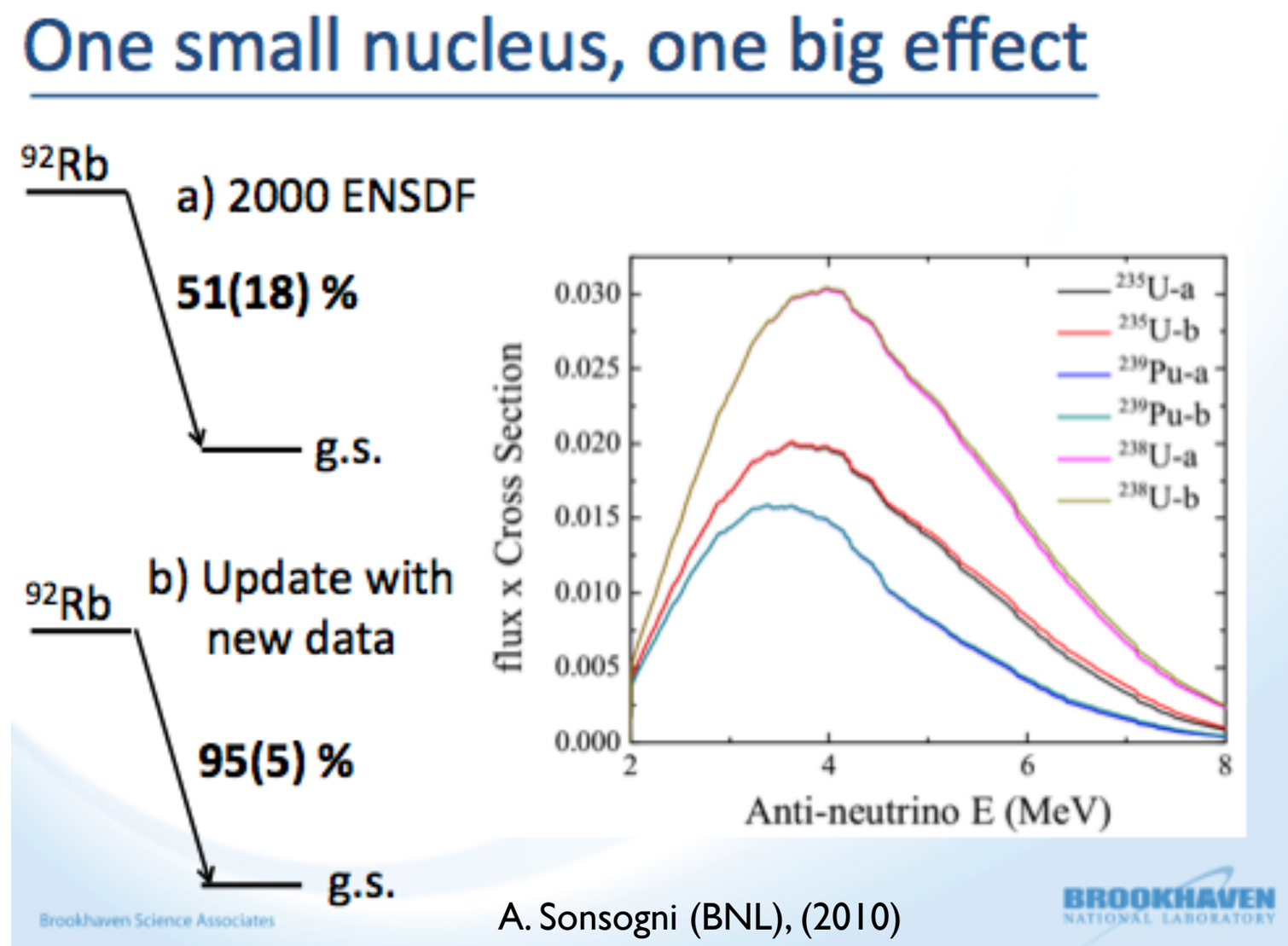


VOLUME 25 Nuclear Science NEA/WPEC-25

ASSESSMENT OF FISSION PRODUCT DECAY DATA FOR DECAY HEAT CALCULATIONS

Reactor Spectroscopy: Example

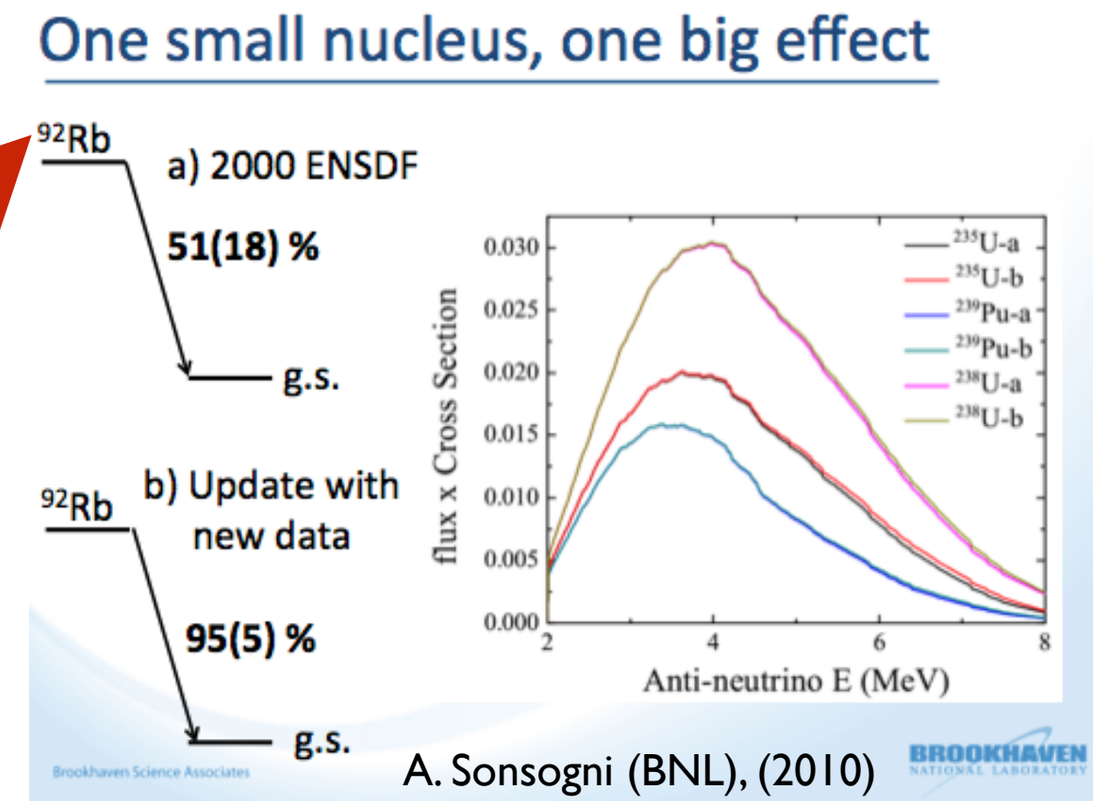
- TAGS:
  Total absorption gamma spectroscopy
- Measure total gamma energy, not individual gamma energies
- Allows ID of levels, BRs much easier

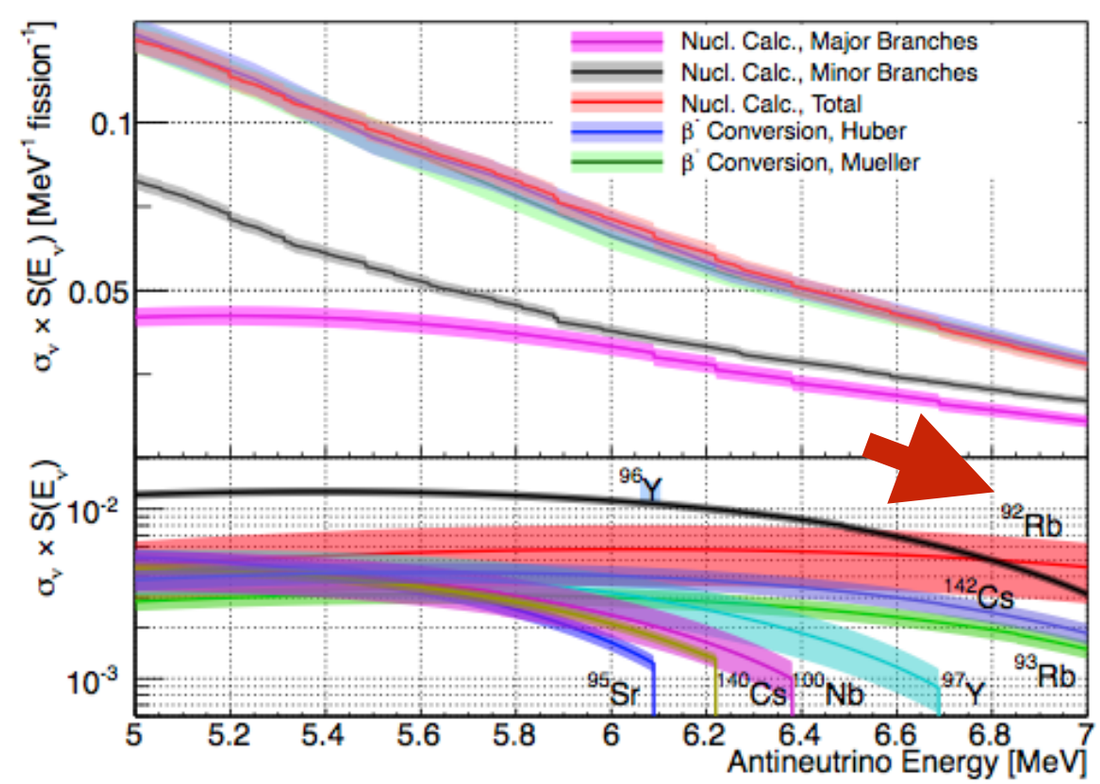


- If branching ratios are known better, decay released in those decays will be modelled better
- Better model = smaller safety factor = $$$ saved.

Reactor Spectroscopy: Implications

- 5 MeV 'bump' region produced by many isotopes of great concern to this decay heat measurement!
- Two anomalies from the same source?
- Reactor spectroscopy measurements can provide:
  - Direct check on existing TAGS measurements
    - TOTALLY different systematics!
  - NEW data if TAGS has not been done!
  - Isotopes: Rb-92, Sr-97, Cs-142





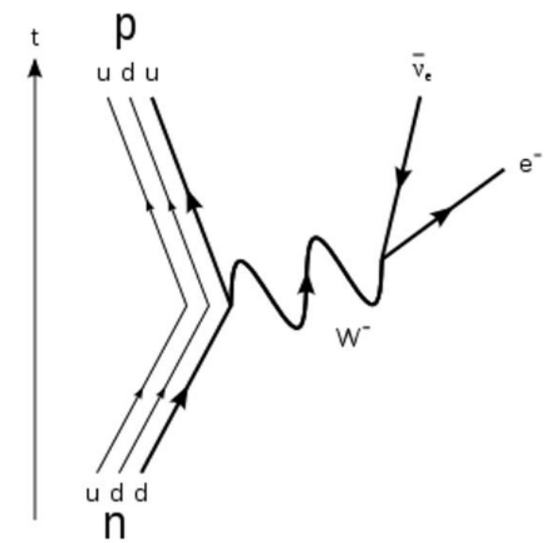
Beta Decay Recap

- W-mediated weak interaction
- Use Fermi's Golden rule to calculate:

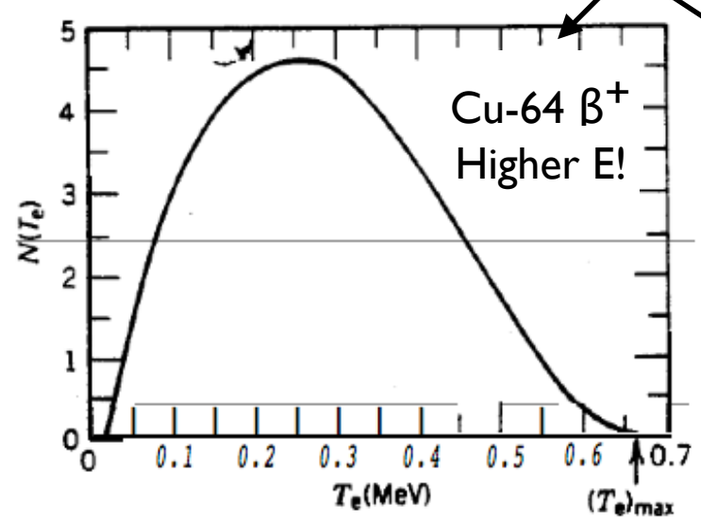
$$N_\beta(W) = K\,\underbrace{p^2(W - W_0)^2}_{\text{phase space}}\,F(Z, W)$$

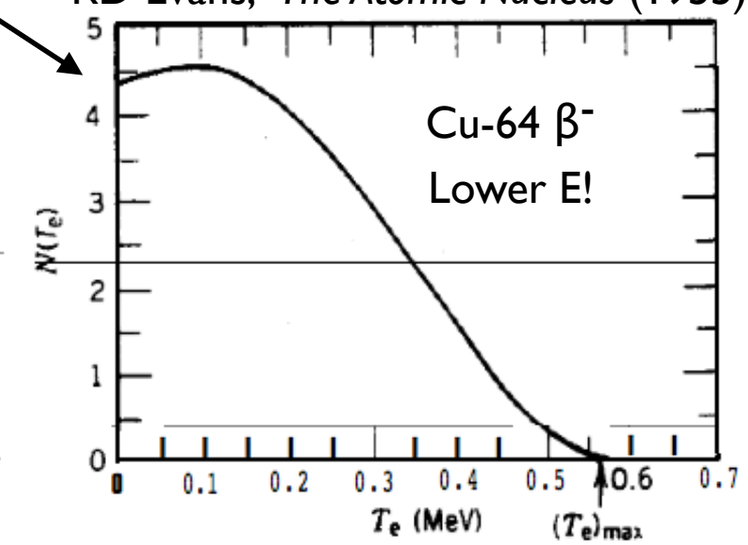
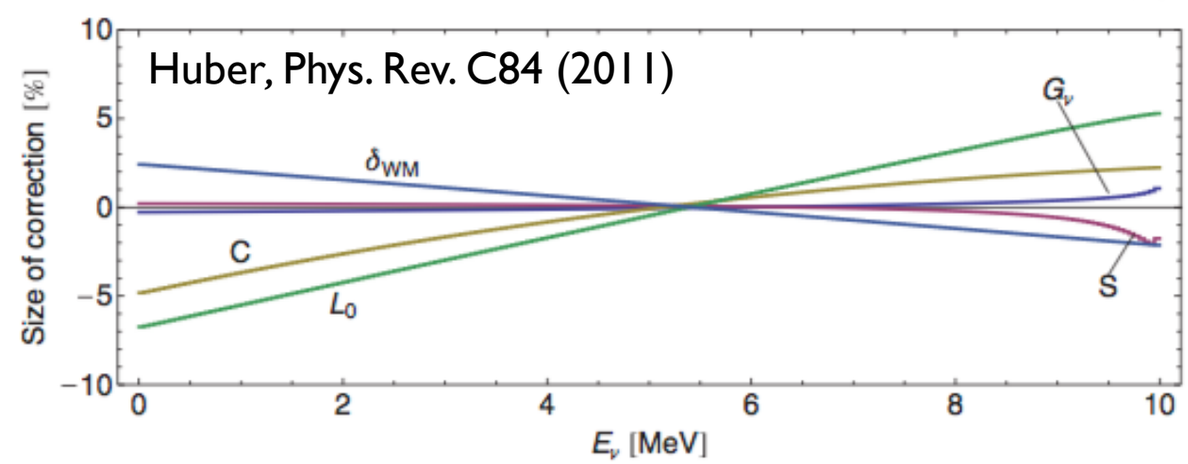
From nuclear matrix element: Extra factors of p pop in here for beta decays

QED correction: semi-classicaly, positive nucleus attracts product beta; lowers its energy



RD Evans, *The Atomic Nucleus* (1955)





- Other corrections:
  - Finite size: C, L_0
  - Electron screening: S
  - Radiative corrections: C
  - Weak magnetism: d_{wm}