PROSPECTs for Short-Baseline Oscillation Searches at Reactors

May 18, 2015

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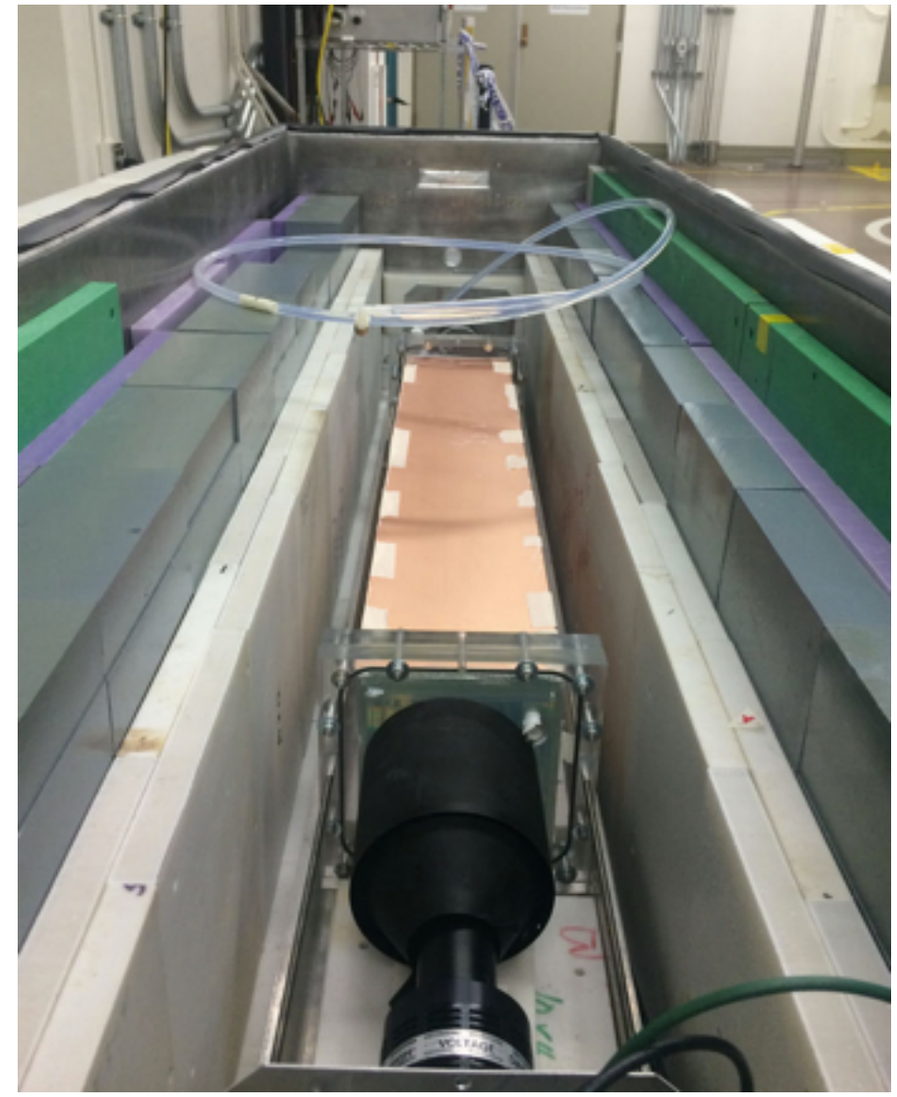
Illinois Institute of Technology

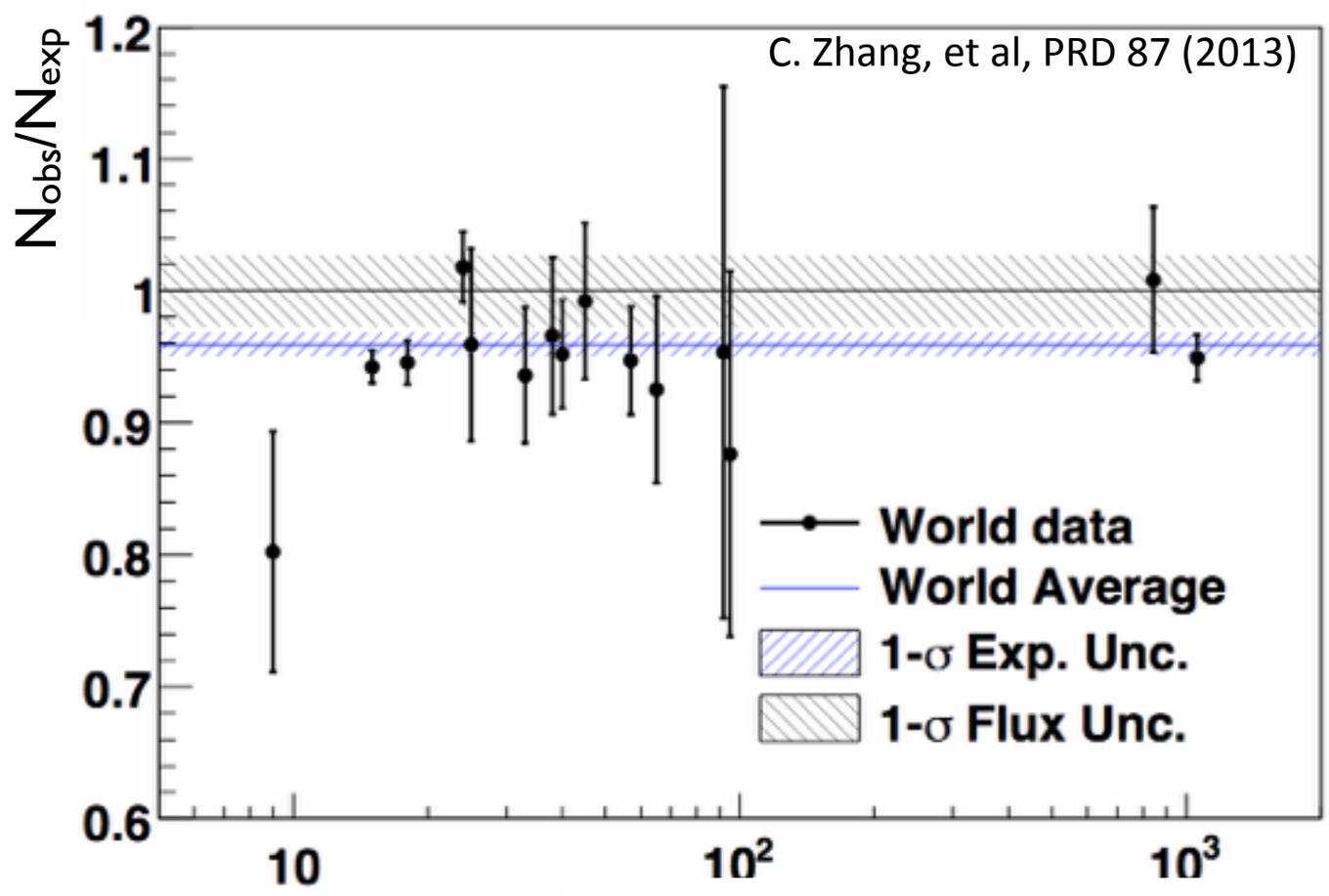


PROSPECT20 Prototype at HFIR

PROSPECT20 Prototype in Shield at HFIR

The Reactor Antineutrino Anomaly

- Existing global deficit in measured antineutrinos at all baselines
  - Improved flux prediction based on method used for decades (beta conversion)
  - Interaction channel is well-understood (inverse beta decay)
  - Measurement agrees among variety of groups, reactors, detection techniques
- **What's going on??? Is the anomaly real? What is the cause?**



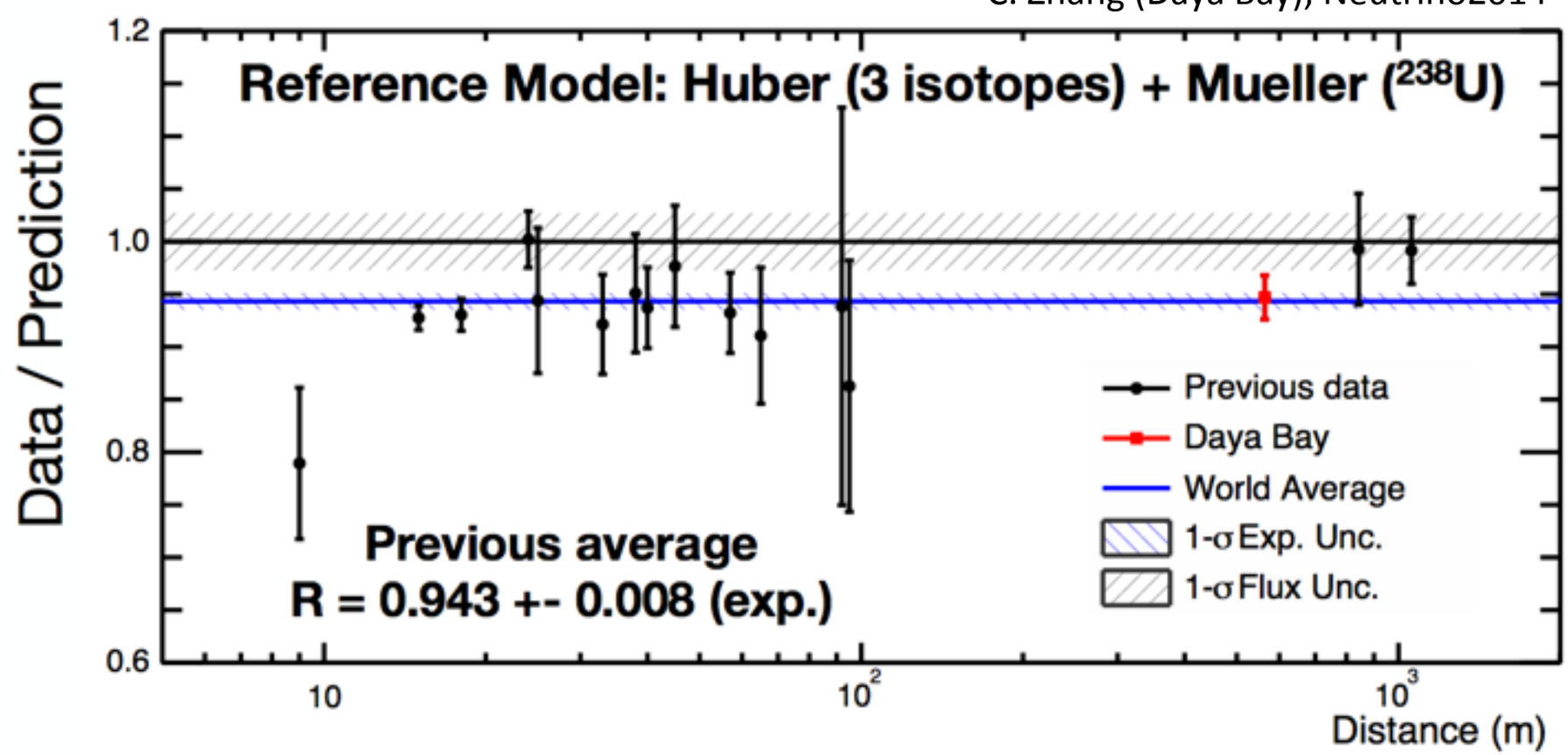
Distance to reactor (m)

Reactor Anomaly Explanations

- Do we have a 'reactor antineutrino anomaly?'
  - "No: the previous experiments could have been biased to report flux measurements that agreed with existing predictions of the time"
- Daya Bay also sees the reactor flux deficit
  - 5% deficit relative to 2011 Huber/Mueller flux prediction
  - Blind analysis: No reactor power data available until analysis is totally fixed

C. Zhang (Daya Bay), Neutrino2014

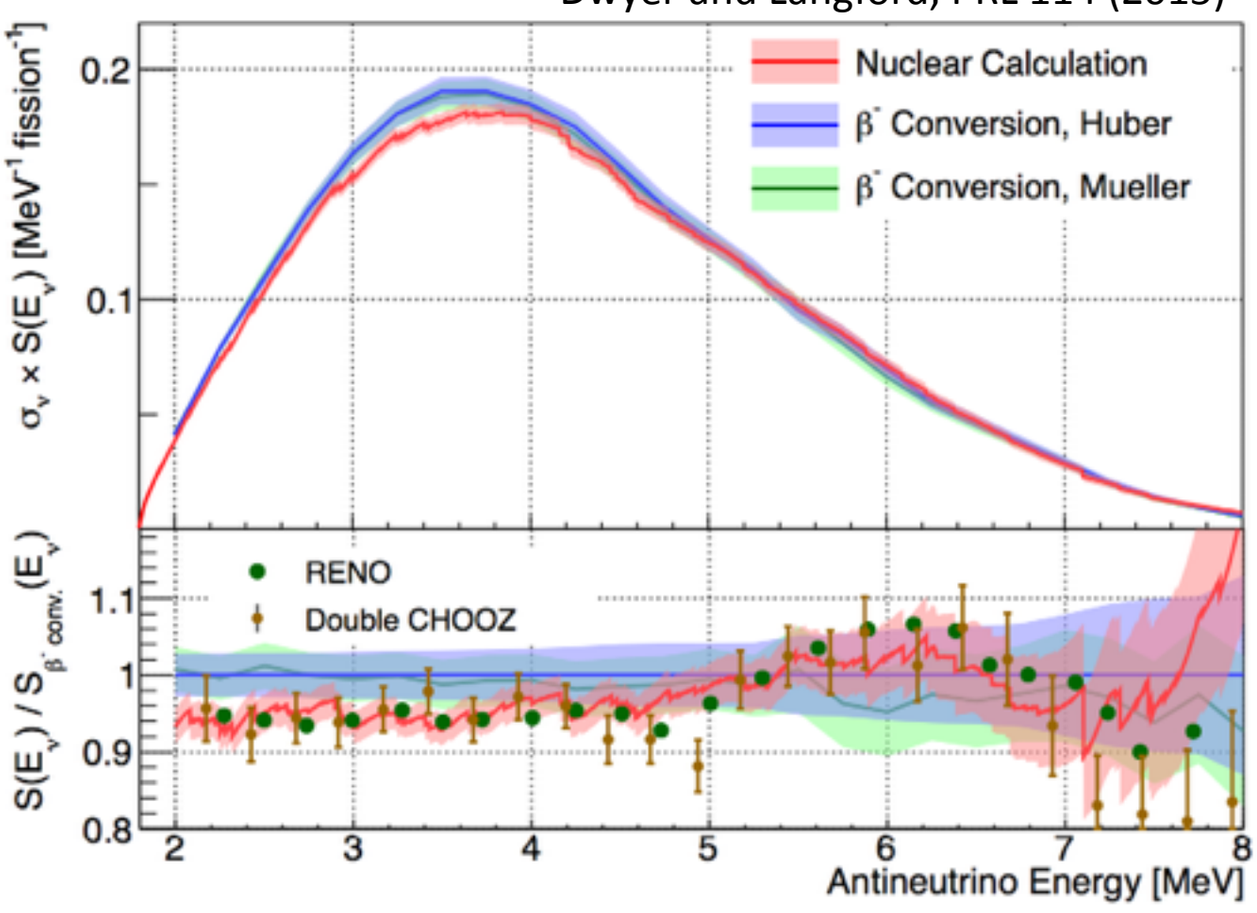
C. Zhang (Daya Bay)
Neutrino 2014



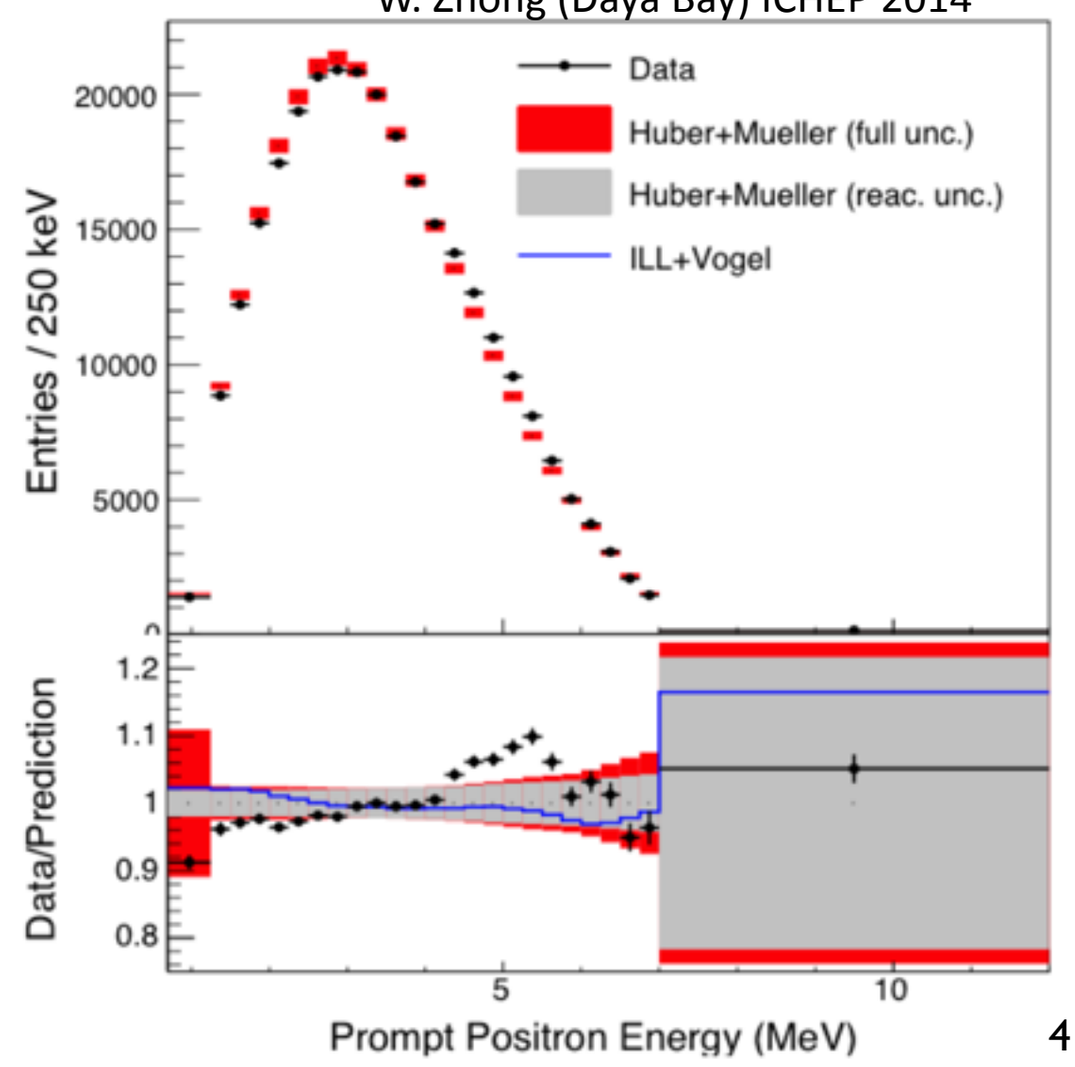
Reactor Anomaly Explanations

- Do we have a 'reactor antineutrino anomaly?'
  - "Yes: it's probably attributable to problems in the beta-to-ν_e conversion"
- Spectra from θ_{13} experiments disagree with predictions
  - "If measured spectrum doesn't match, why should measured flux?"
- **See D. Dwyer's talk tomorrow**

Dwyer and Langford, PRL 114 (2015)

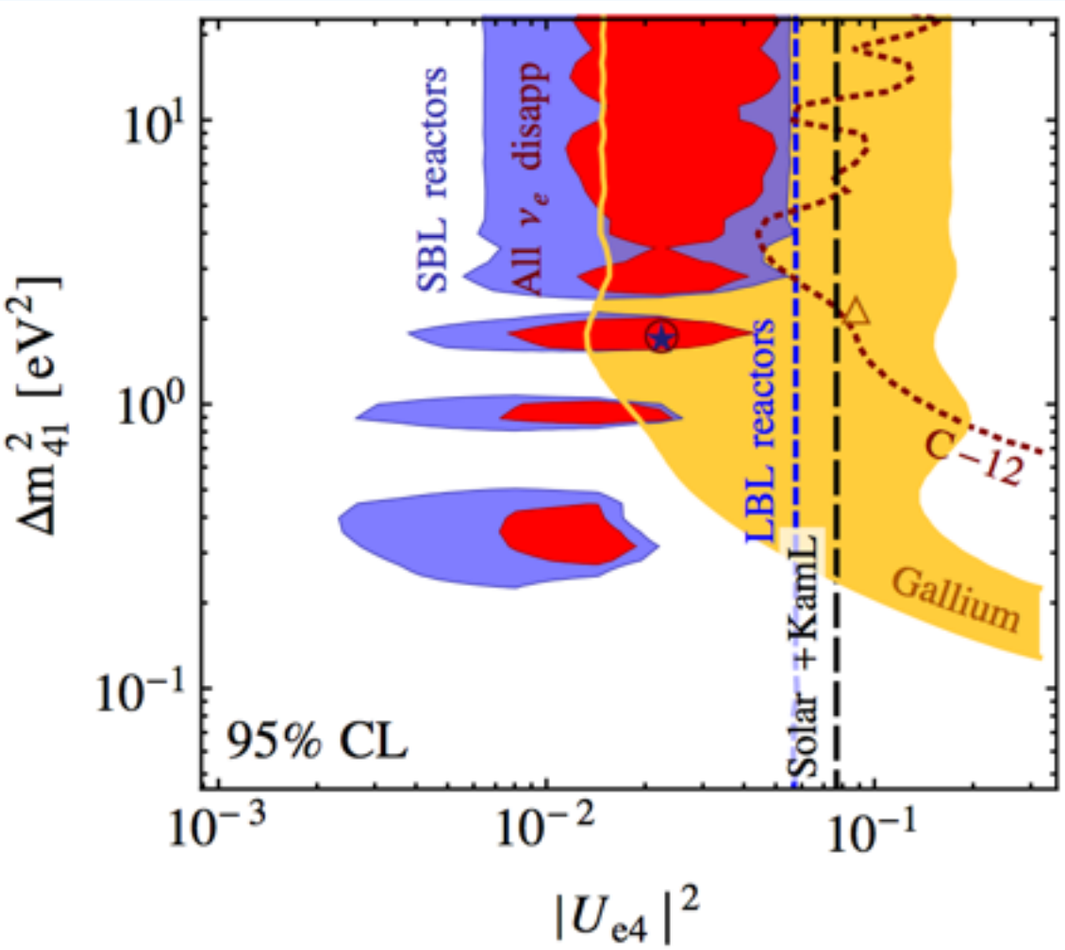


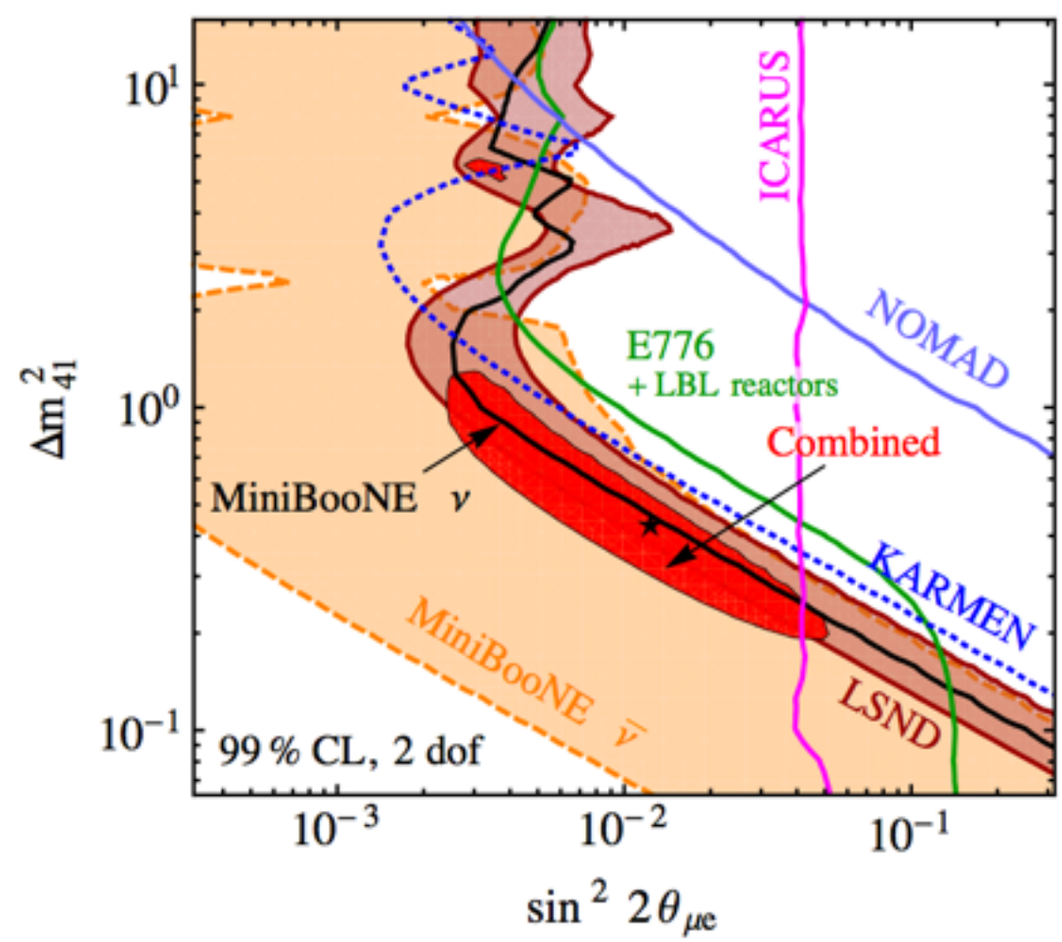
W. Zhong (Daya Bay) ICHEP 2014



Reactor Anomaly Explanations

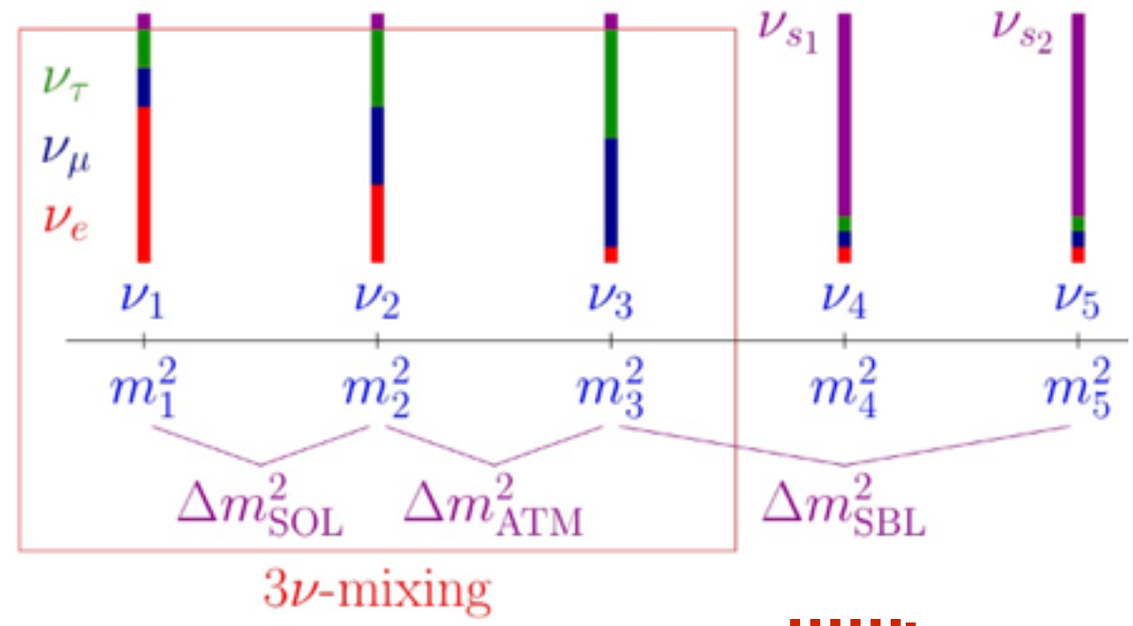
- Do we have a 'reactor antineutrino anomaly?'
  - "Yes: the deficit could result from short-baseline sterile neutrino oscillations"
- Consistent with existing nonzero hints for sterile neutrinos
  - LSND, MiniBooNE, Gallium
  - However, tension with null ν_μ disappearance measurements
- Need more oscillation data at shorter baselines (smaller L/E)





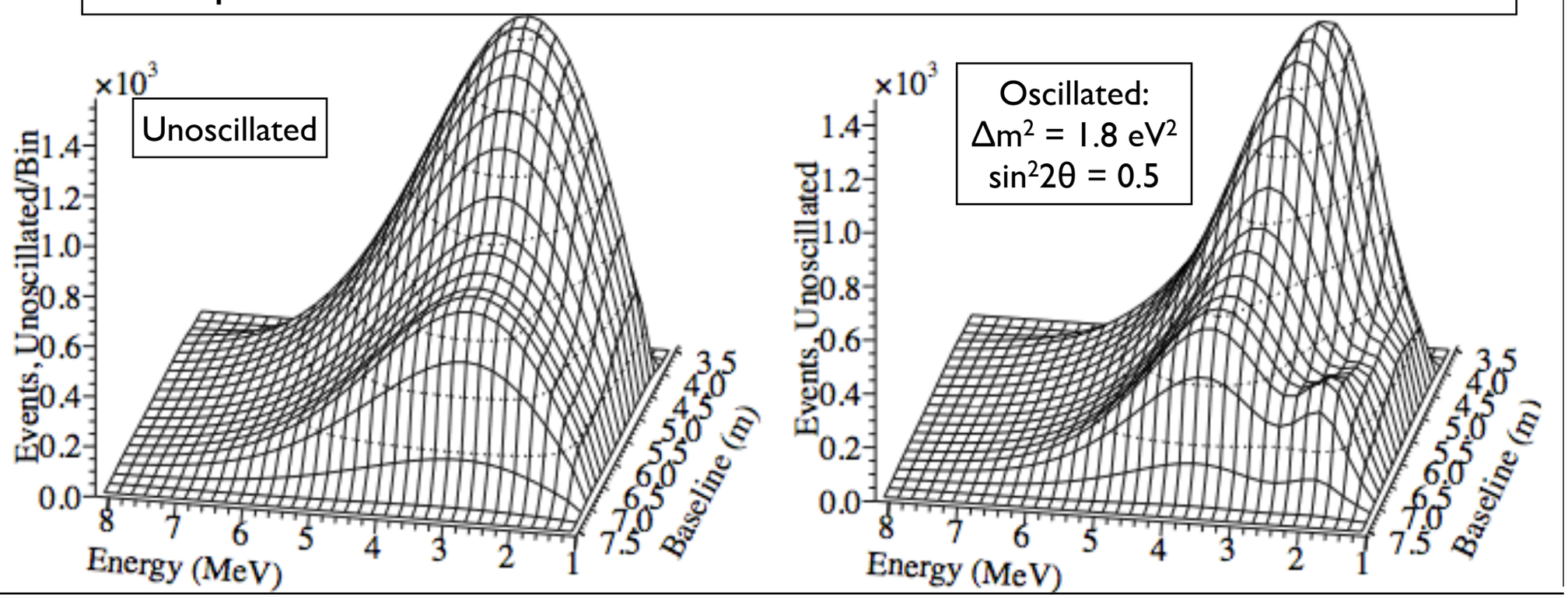
SBL Oscillation Experiments at Reactors

- Measure energy spectrum at each detector-reactor baseline
- Look for unexpected L/E distortion: oscillations
- Want to see L+E variation as sterile 'smoking gun'



$$P(\nu_a \to \nu_b) = \sin^2 2\theta \sin^2\left[1.27\Delta m^2(eV^2)\frac{L(km)}{E_\nu(GeV)}\right]$$

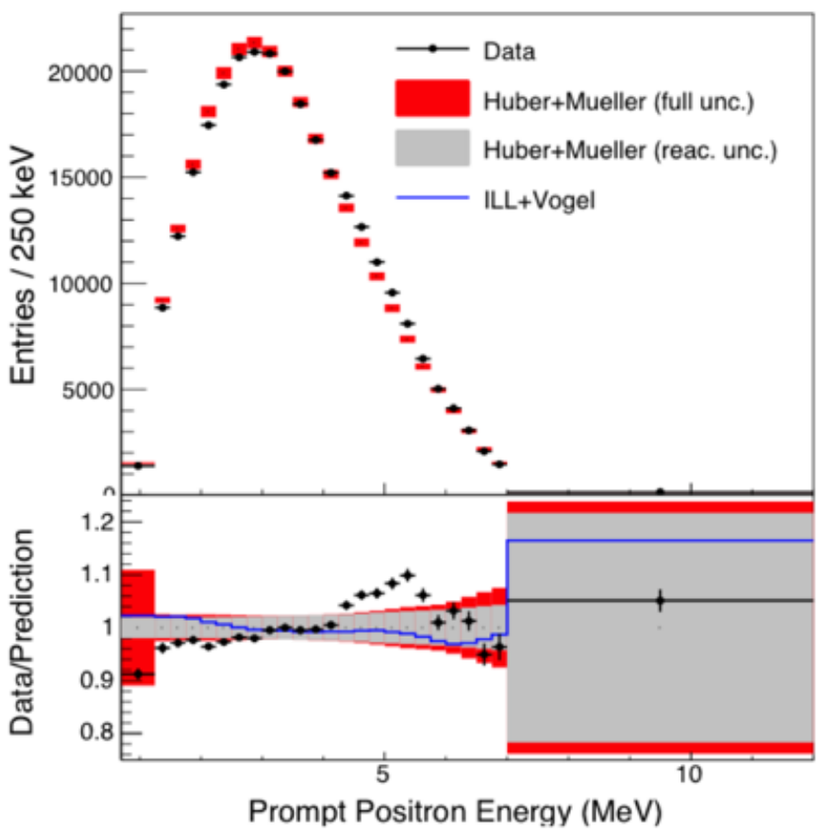
Example: 3x1x1 m³ detector, 1m³ 20 MW HEU core, 4m closest distance



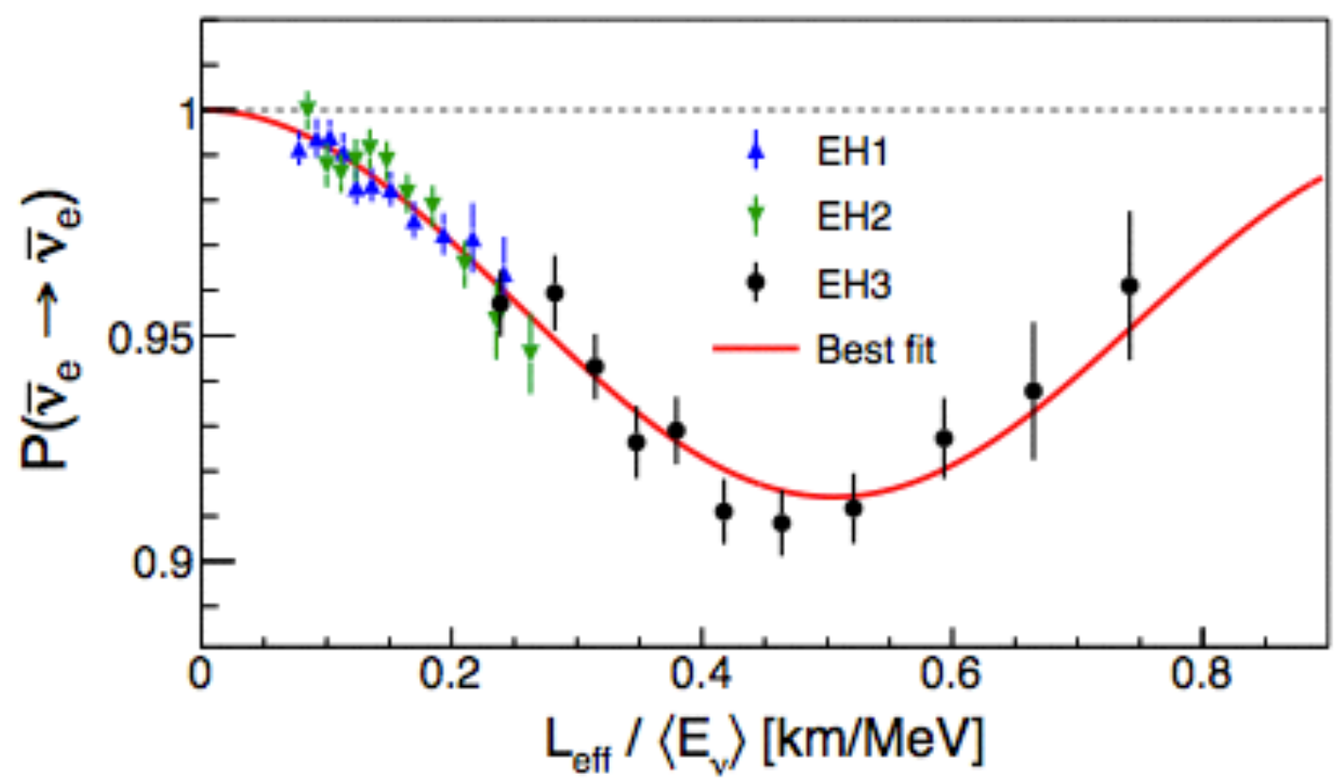
What New Data Is Needed

- To get to the bottom of this puzzle, we need new data!
  - Really want to make short-baseline versions of the plots below
- In particular, we really need:
  - A high energy-resolution detector for precisely measuring absolute spectrum
  - A high position-resolution detector for comparing spectra between baselines
  - Any successful experiment will need excellent background rejection capabilities

W. Zhong (Daya Bay) ICHEP 2014



Daya Bay arXiv[1505.03456] (2015)



Current SBL Reactor Efforts

- Wide variety of efforts SBL efforts worldwide
  - Variety of technologies achieve varying levels of position, energy resolution
  - All experiments in varying stages of R&D or prototyping
- Will focus on one illustrating case: PROSPECT
  - **P**recision **R**eactor **O**scillation and **SPECT**rum Experiment
  - Excellent performance in both energy AND position reconstruction
  - Multi-faceted background reduction strategy

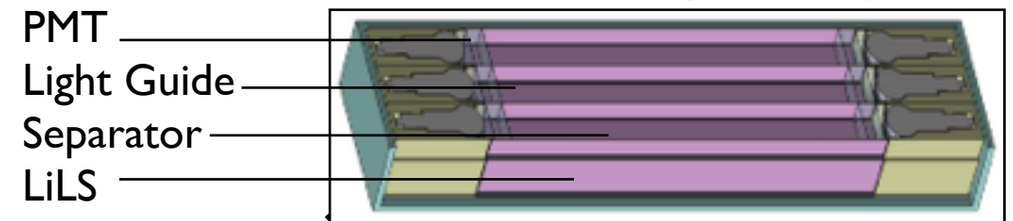
My (biased) overview of global efforts — Good : OK : Not Good

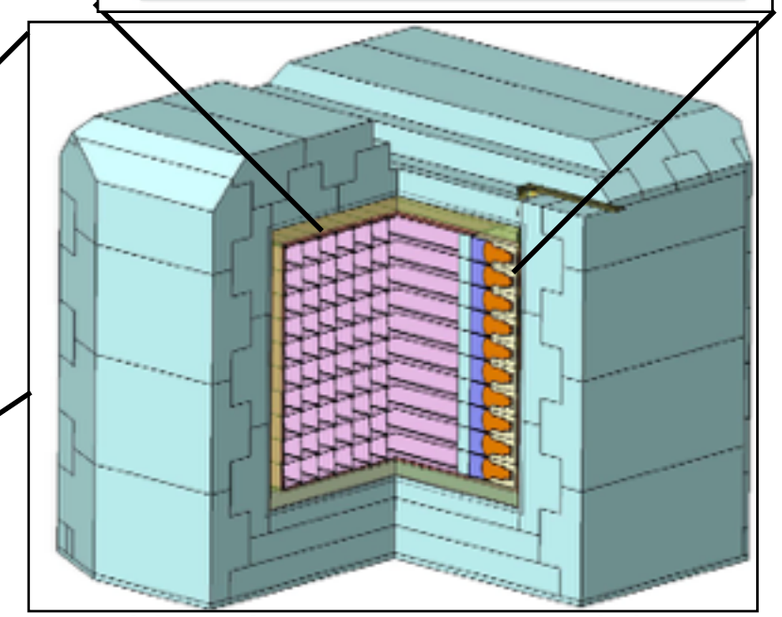
	Effort	Good X-Res	Good E-Res	L Range (meters)	Fuel	Exposure, MW*ton	Running at intended reactor?
US	**PROSPECT**	**Yes**	**Yes**	**6.5-20**	**HEU**	**185**	**Yes**
	NuLat	Yes	OK?	TBD	TBD	TBD	No
EU	STEREO	Yes	OK?	9-11	HEU	100	Yes
	SoLid	Yes	No	6-8	HEU	155	Yes
Russia	DANSS	Yes	No	9.7-12	LEU	2700	Yes
Asia	Neutrino4	Yes	OK?	6-12	HEU	150	Yes
	Hanaro	No	Yes	20-ish	LEU	30	No

PROSPECT Experimental Layout

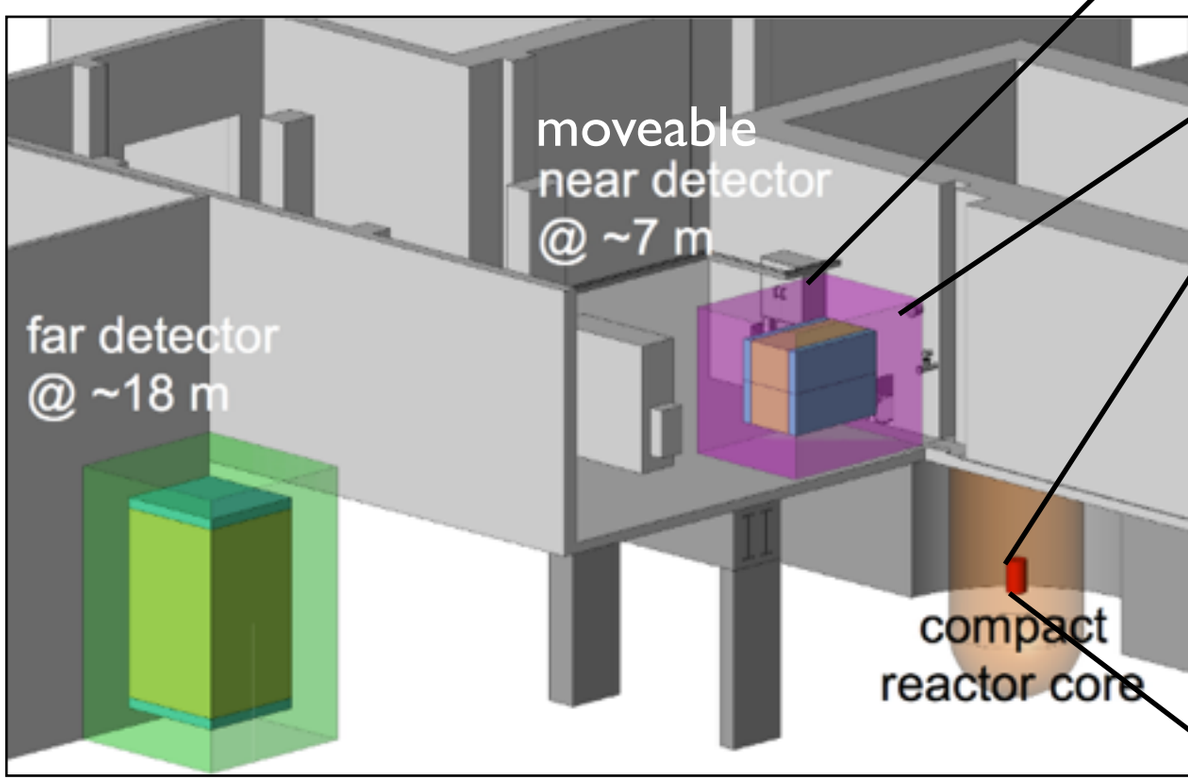
- High Flux Isotope Reactor (ORNL): ^{235}U-only reactor with 42% up-time
- Extensive passive shielding
- Li-doped segmented liquid scintillator target region: ~3 tons for near detector (Phase I)
- Moveable: ~6.5-11 m baselines

Sub-cell conceptual design

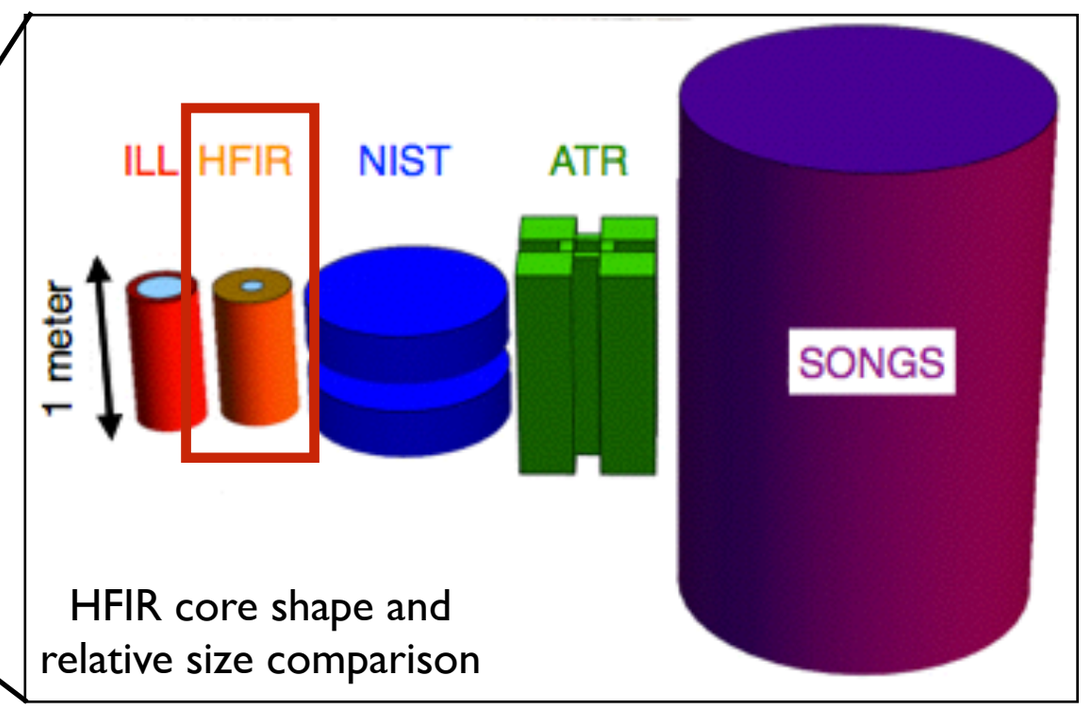




Near detector conceptual design



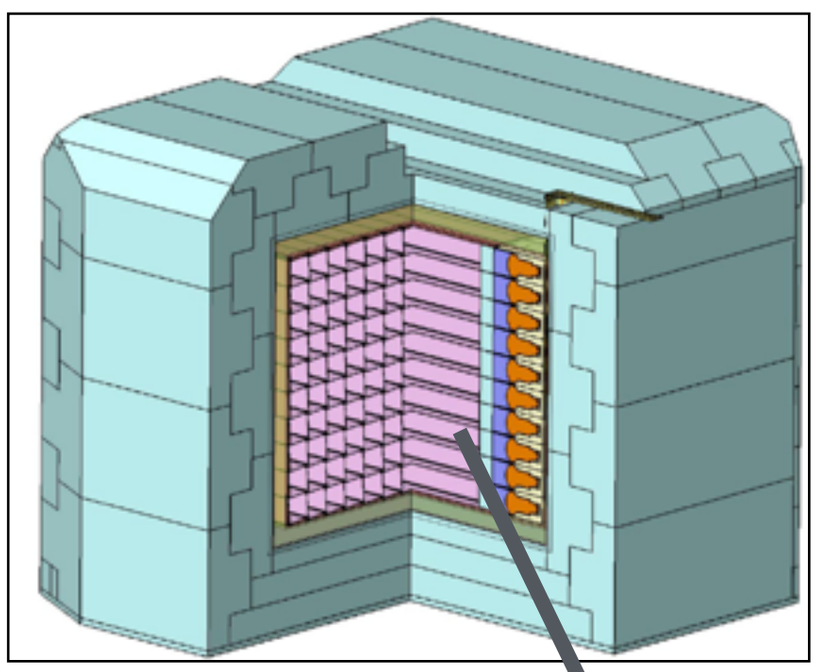
Two-detector PROSPECT deployment at HFIR

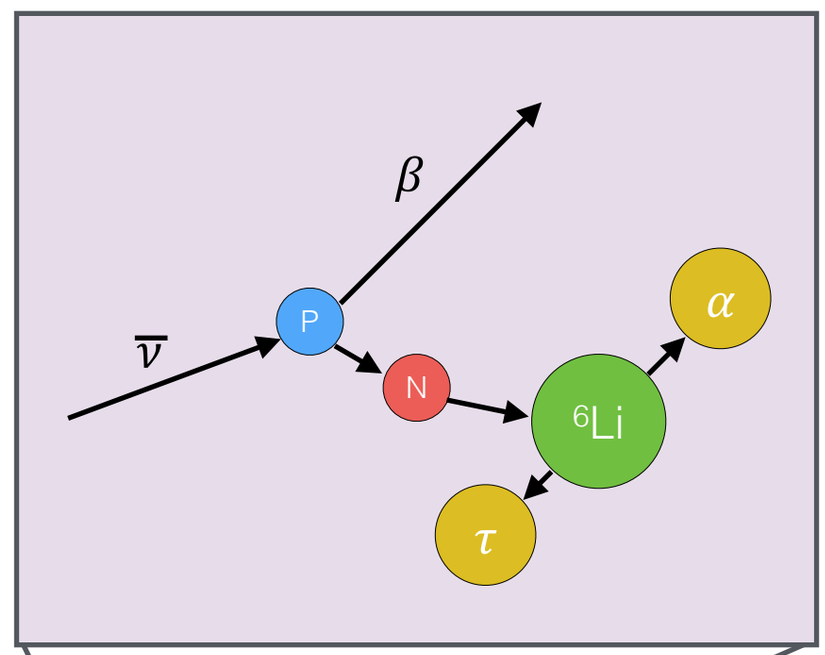


HFIR core shape and relative size comparison

PROSPECT Neutrino Detection

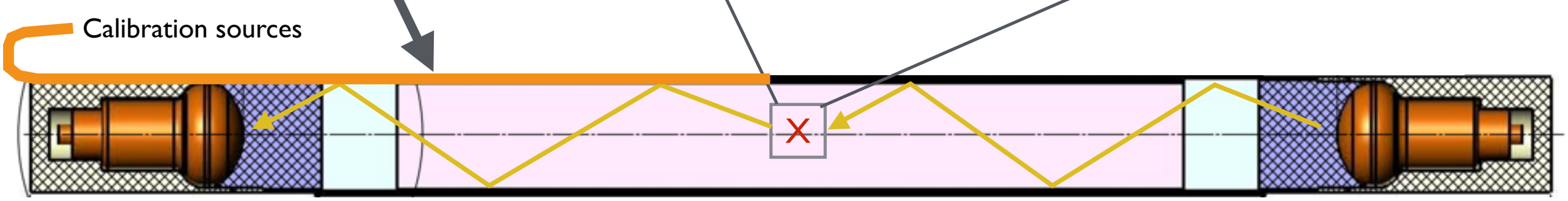
- Inverse beta interactions in Li-loaded EJ309 liquid scintillator
- 10 x 14 optically decoupled cells: ~15cm x 15cm x 100cm each
- Specularly reflecting cell walls quickly guide light to PMTs
- System can meet position/energy resolution requirements





Prompt signal: 1-10 MeV positron from inverse beta decay (IBD)

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



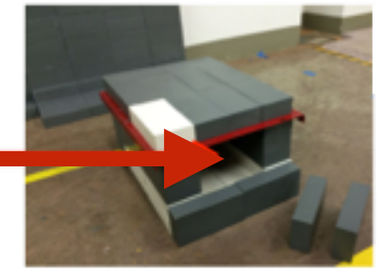
PROSPECT Prototype Demonstrations

Run DAQ,
Remote data-taking

See n-Li + PSD

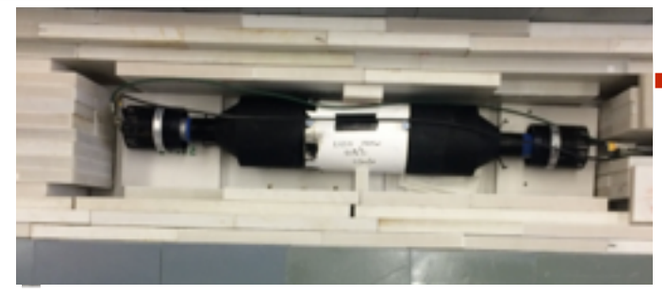
PROSPECT 0.1*
Aug 2014

2 inches

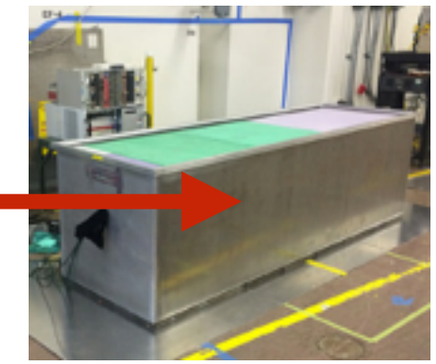


Demonstrate shielded
background rates

PROSPECT 2*
Dec 2014 -
Mar 2015



5 inches



Demonstrate full
timing and PE response

PROSPECT 20*
Mar 2015

1 meter

PROSPECT 200

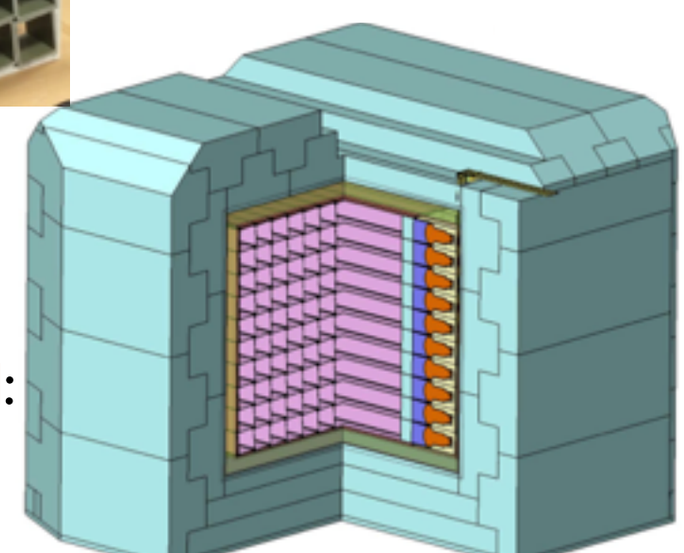
3x3x1meter
mockup at IIT

Deploy final design concepts

Observe relative segment responses

See antineutrinos

PROSPECT Phase I:
1 detector, moveable



Oscillation physics

Absolute spectrum

PROSPECT Phase II:
2 detectors

* Deployment complete!!!!

Approximate mass kg

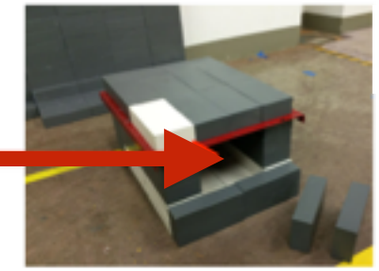
PROSPECT Prototype Demonstrations

✓ Run DAQ, Remote data-taking

✓ See n-Li + PSD

PROSPECT 0.1 *
Aug 2014

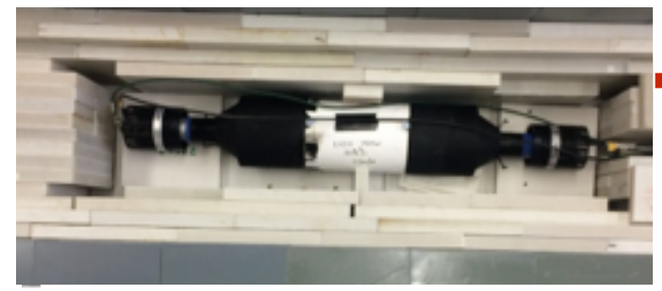
2 inches



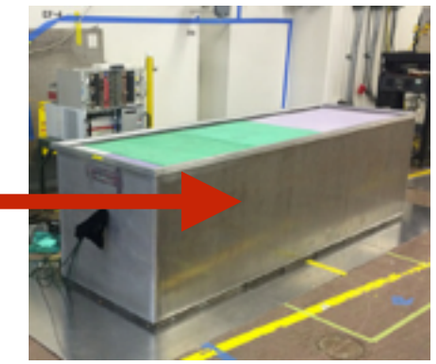
✓ Demonstrate shielded background rates

✓ Demonstrate full timing and PE response

PROSPECT 2 *
Dec 2014 - Mar 2015



5 inches



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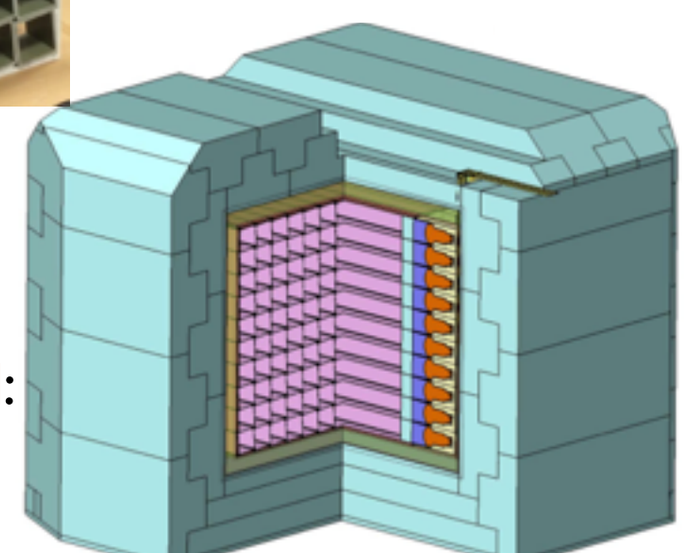


Oscillation physics

Absolute spectrum

PROSPECT Phase II:
2 detectors

* Deployment complete!!!!

Approximate mass kg

Demonstrating Key Requirements

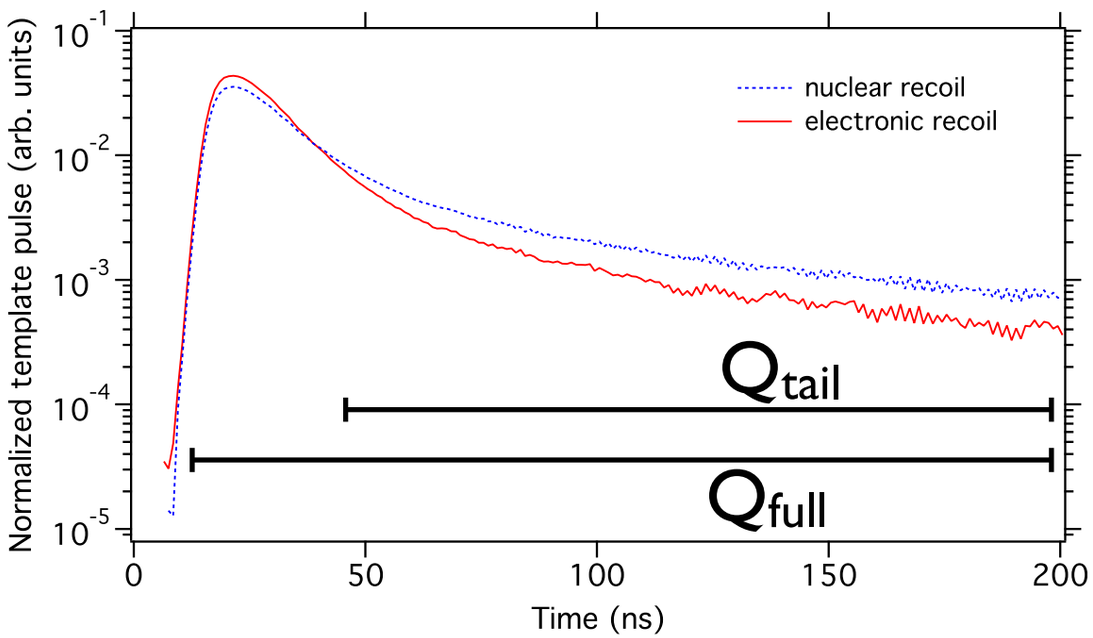
- To accomplish physics goals, a SBL reactor experiment needs:
  - Understanding of energy scale and energy and position resolution
  - Control of backgrounds at on-surface near-reactor location
- Prototyping program will demonstrate PROSPECT's abilities in all of these areas.

PROSPECT20 meter-long cell at HFIR

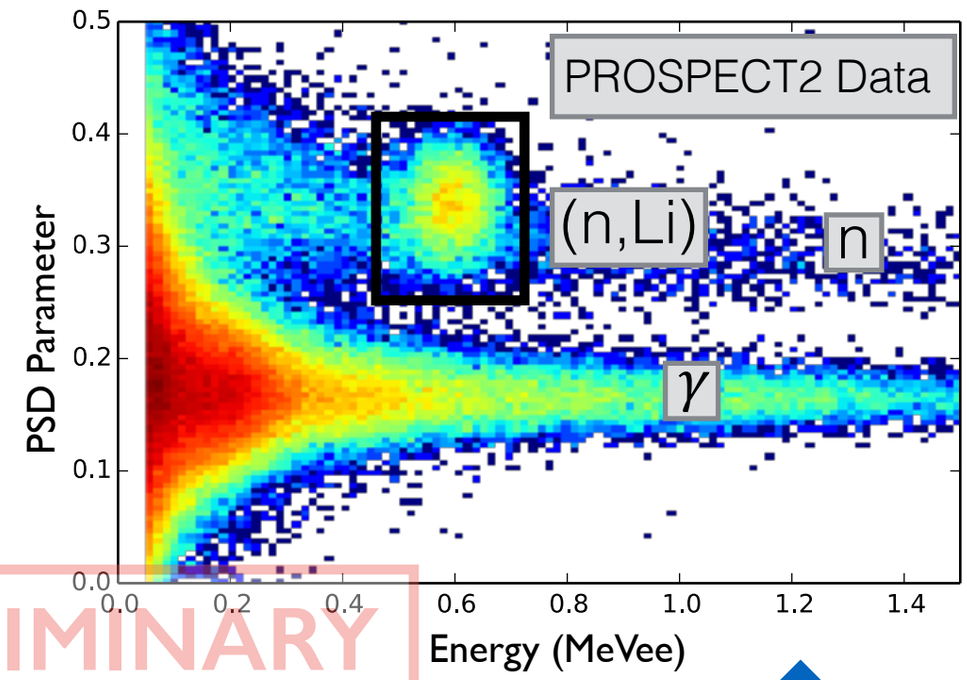
PROSPECT20 at HFIR in full shielding package

Background Rejection, Signal Selection

- Reduce backgrounds: Li-capture and pulse-shape discrimination



$$PSD = \frac{Q_{tail}}{Q_{full}}$$



PRELIMINARY

Signal, Main Backgrounds

Inverse Beta Decay

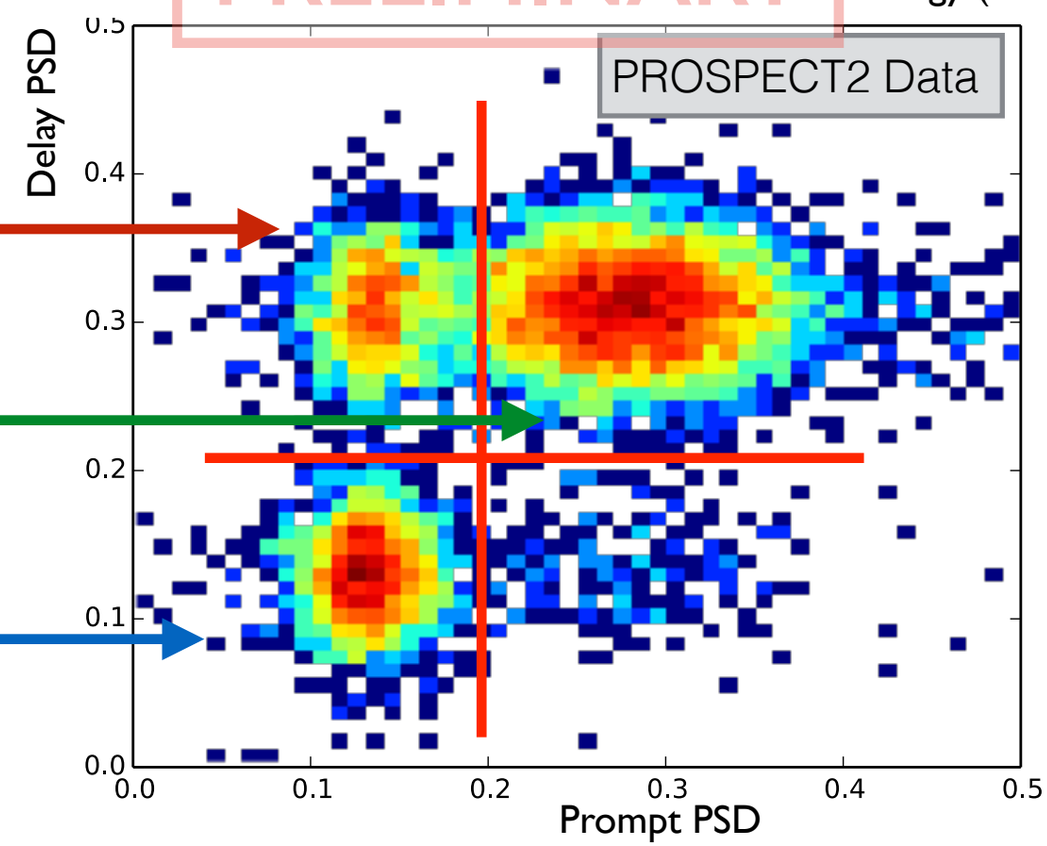
γ-like prompt, n-like delay

Fast Neutron

~~n-like prompt, n-like delay~~

Accidentals

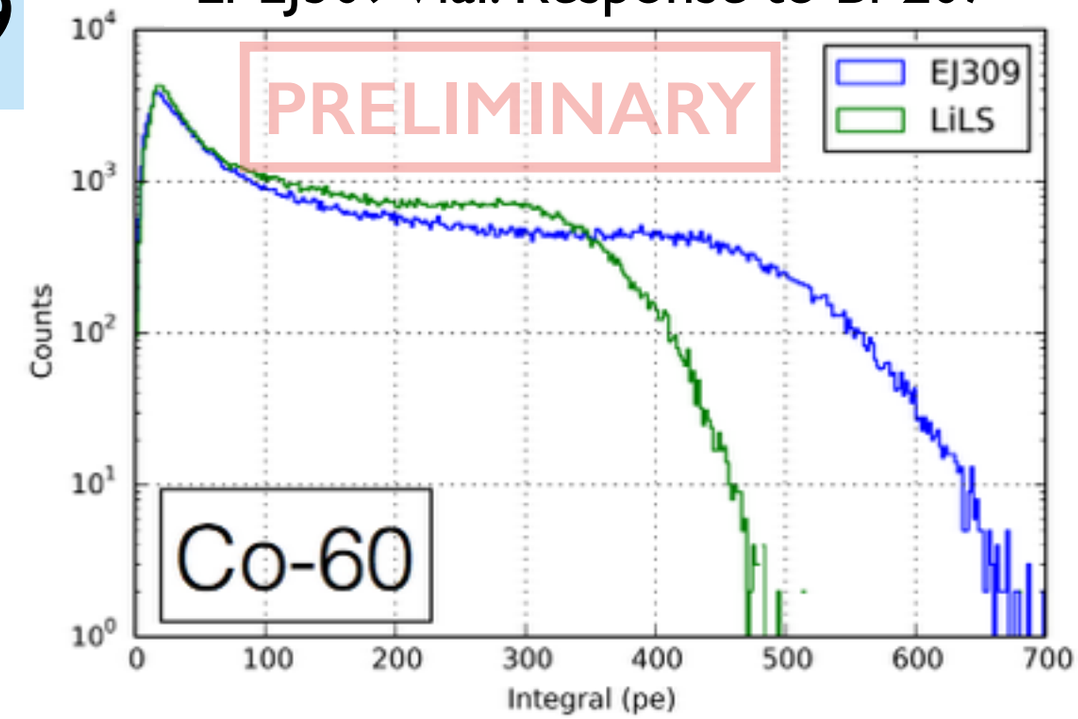
~~γ-like prompt, γ-like delay~~



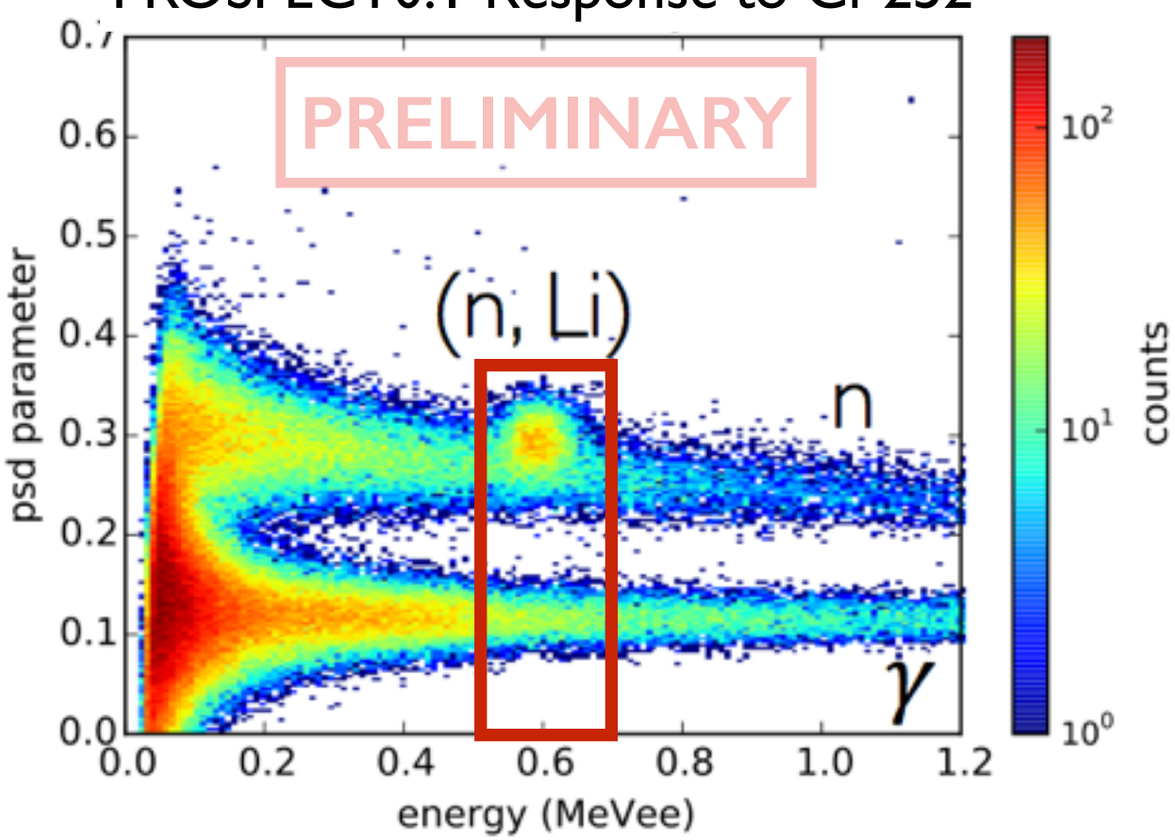
Demonstration: Energy Response

- Light yield remains high for Li-EJ309
  - 8200 photons/MeV (11500 for EJ309)
  - Sufficient for 4-5% full-cell resolution
  - Good PSD simultaneously attained
- Excellent uniformity along full cell

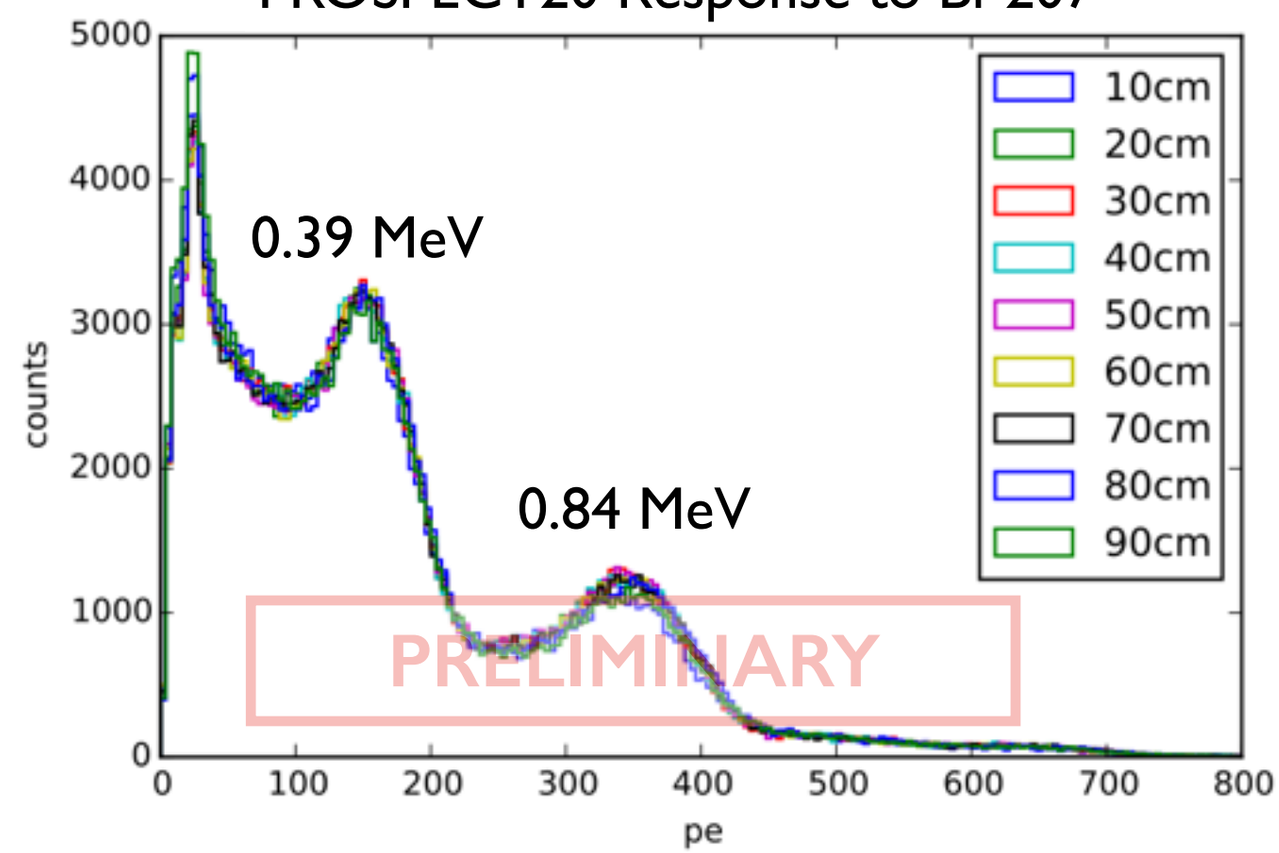
Li-EJ309 Vial: Response to Bi-207



PROSPECT0.1 Response to Cf-252



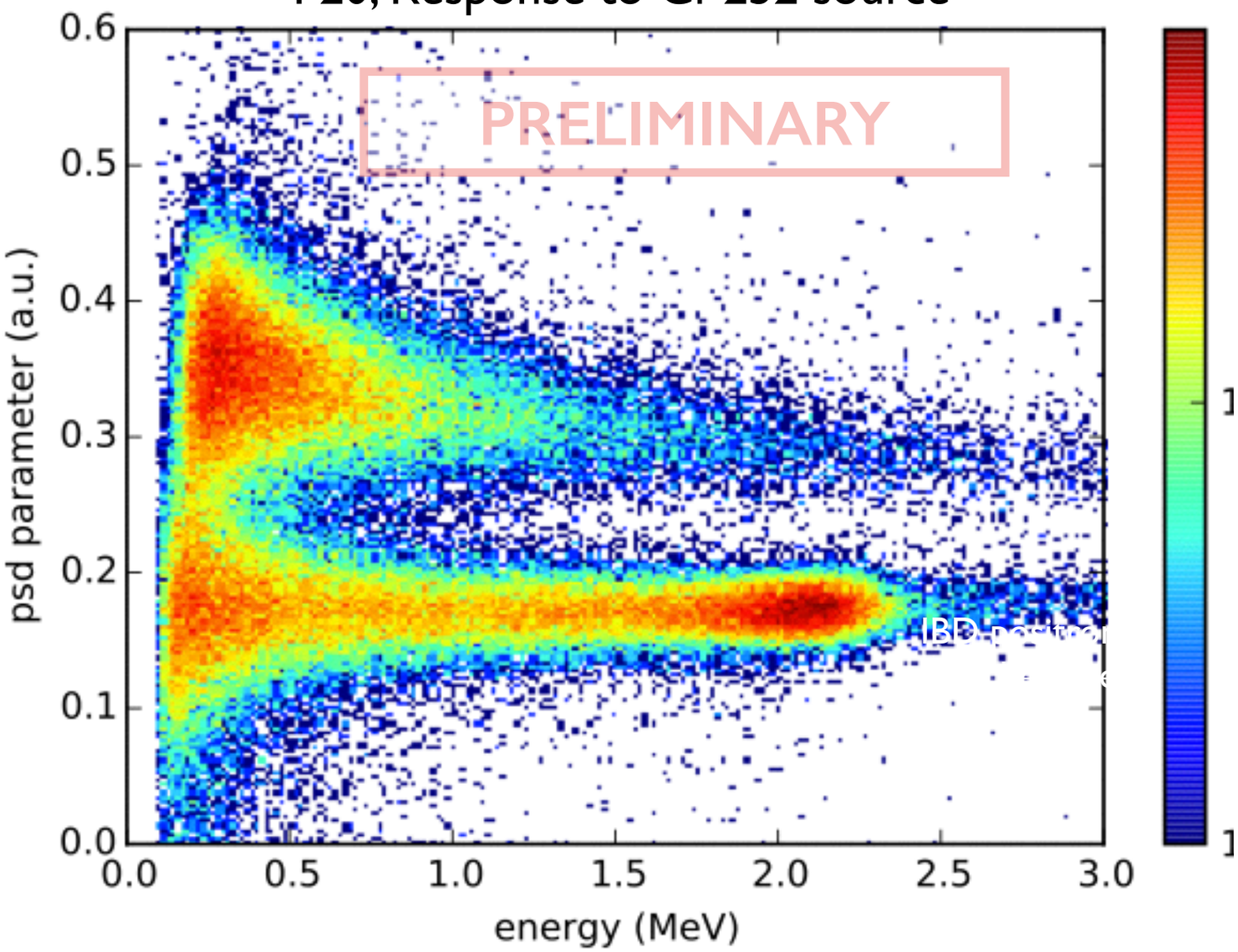
PROSPECT20 Response to Bi-207



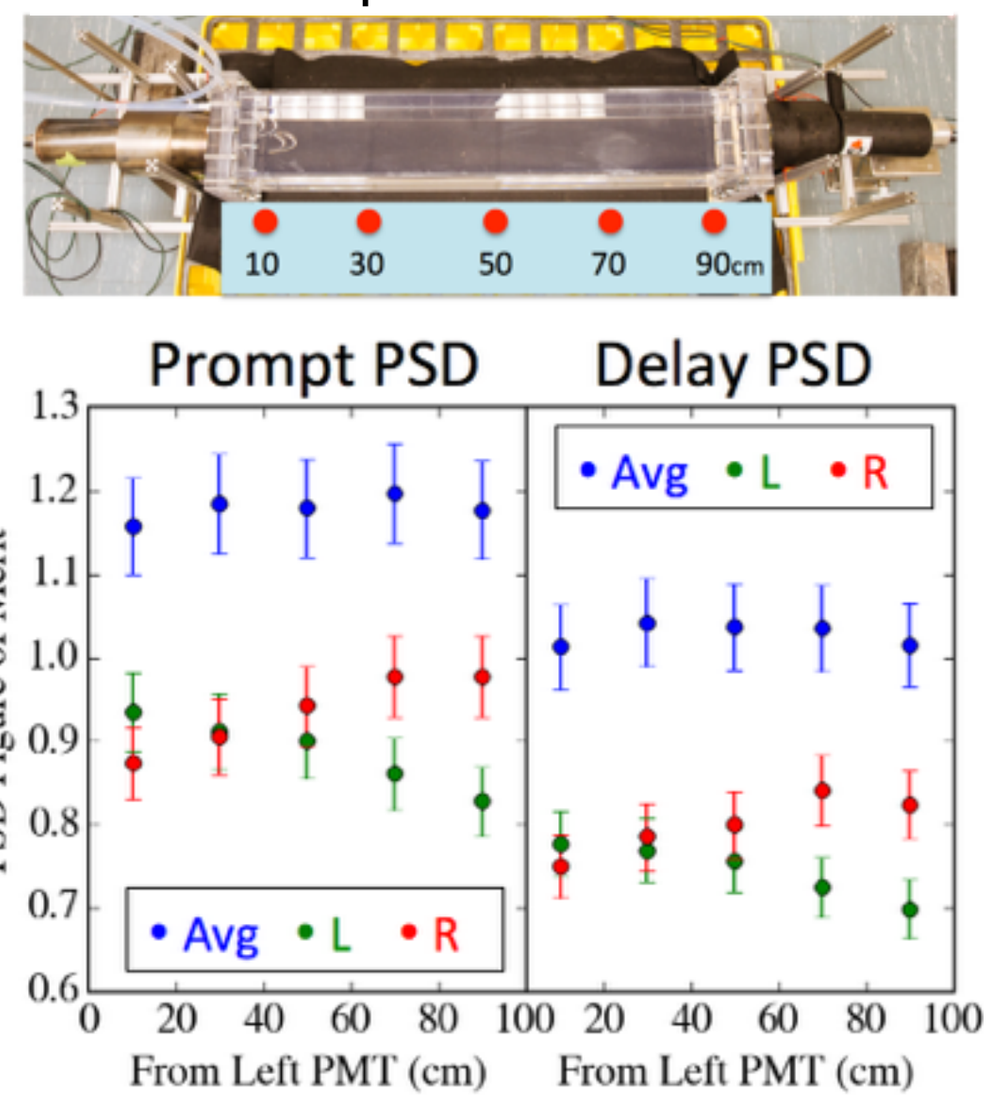
Demonstration: PSD

- PSD is maintained even at large cell sizes
  - Ability to reject many neutron-related, reactor gamma backgrounds
  - PSD highly uniform over entirety of meter-length cell

P20, Response to Cf-252 source

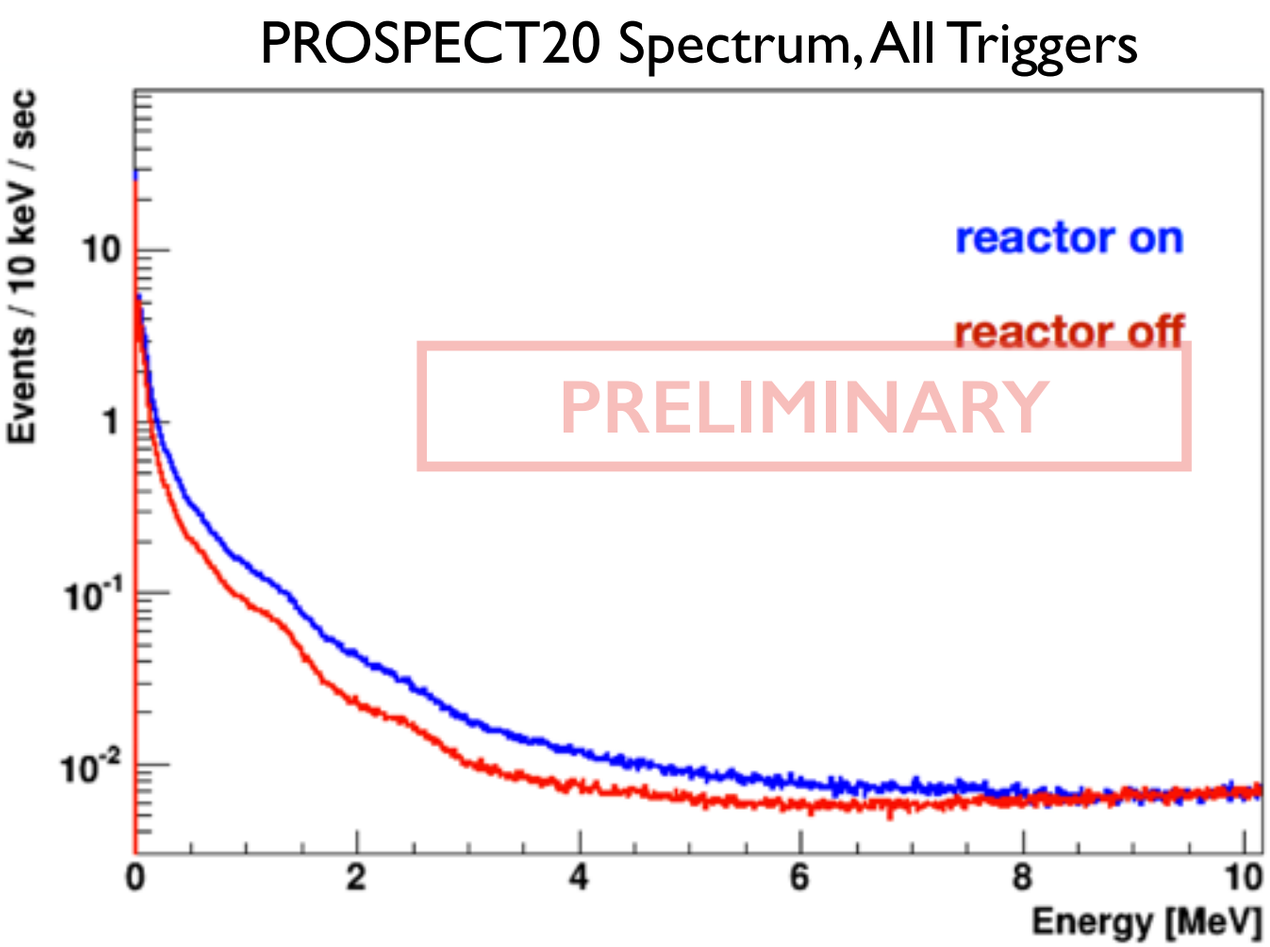


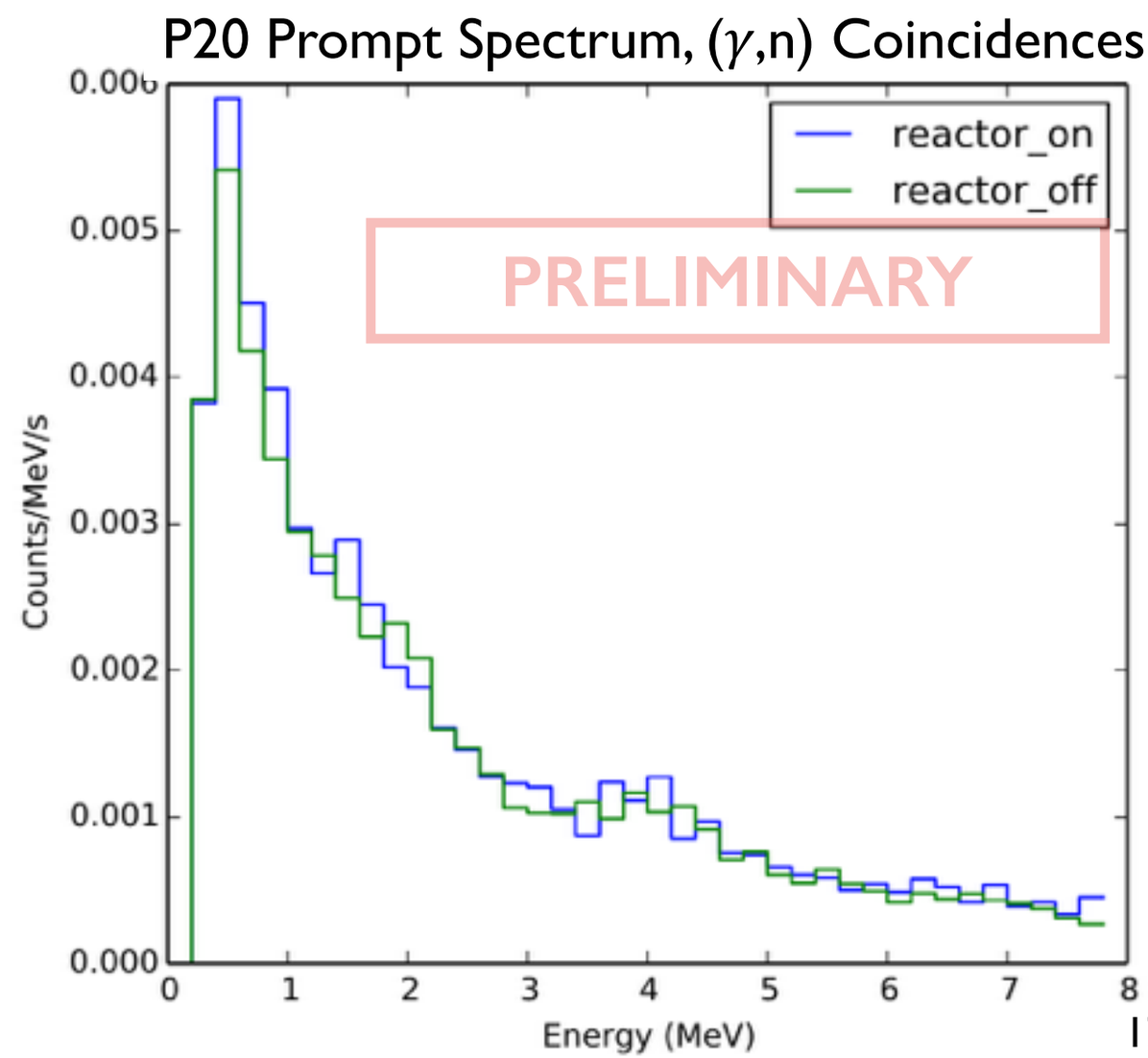
P20 PSD Response to Cf-252 source



Demonstration: HFIR Backgrounds

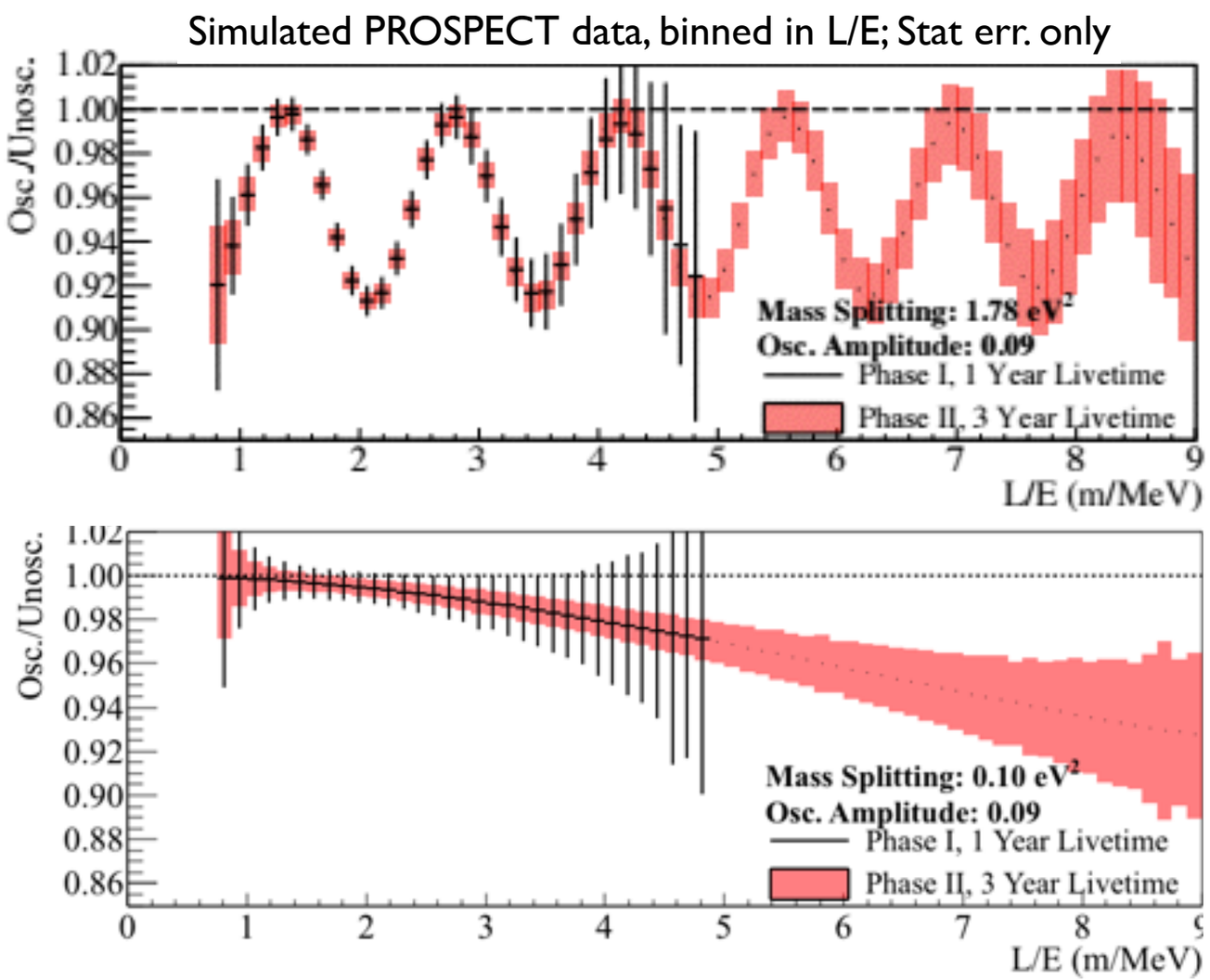
- Sub-dominant change in trigger and (γ,n) rate with reactor status
  - Reduction of cosmogenic backgrounds are primary concern
  - Reactor-off periods will be very valuable
- Data-matched PROSPECT MC will provide full S:B estimate
  - Major cosmogenic reductions from topology, multiplicity expected in full cell

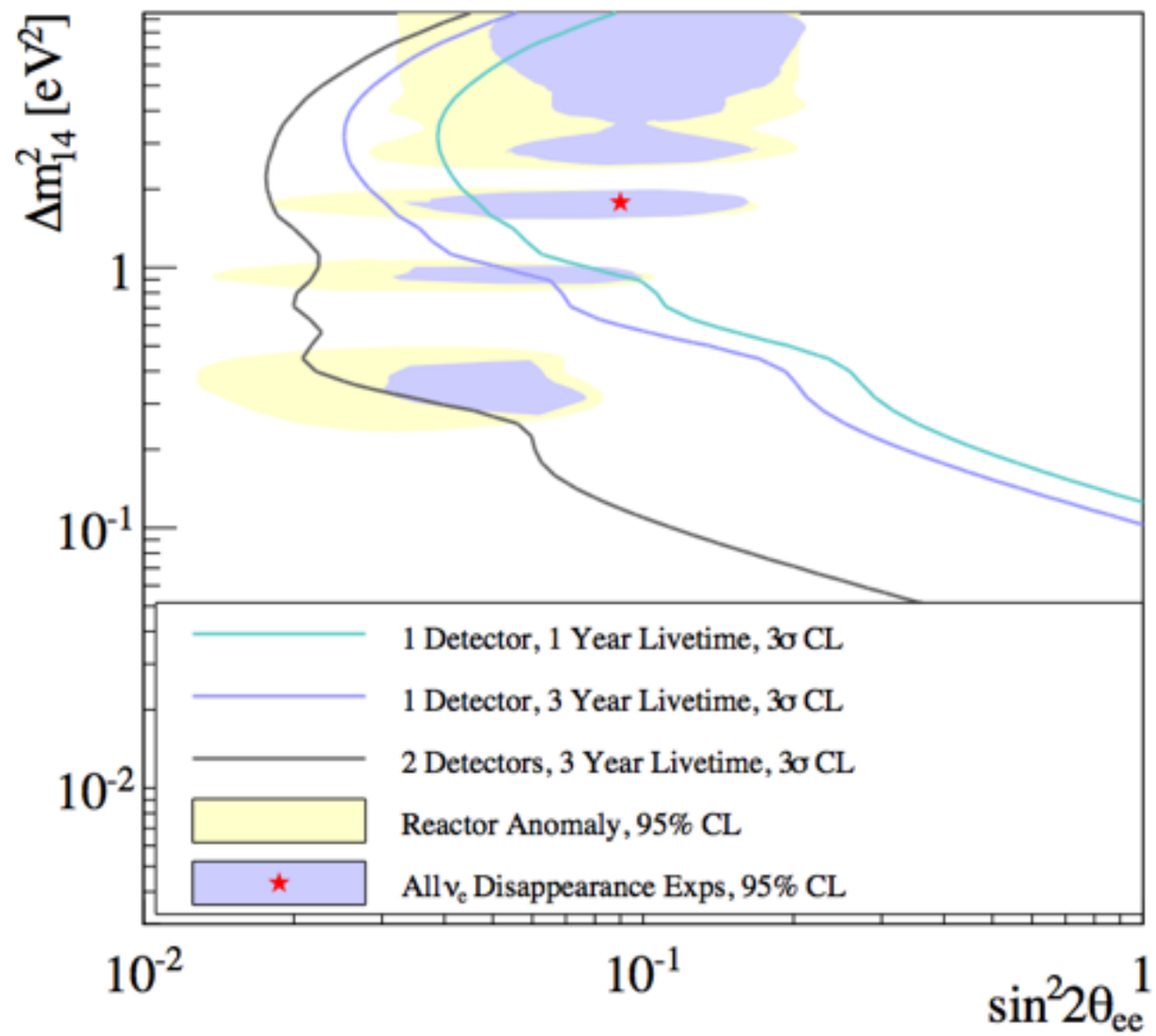




PROSPECT Oscillation Sensitivity

- **Excellent oscillation discovery potential at PROSPECT**
  - If new sterile neutrino is where global fits suggest, it's very likely we'll see it with a year's data
  - No reliance on absolute spectral shape or normalization: pure relative L/E measurement
  - Complimentary to current/future neutrino efforts (SBN ν_e app, SBN/MINOS+/IceCube ν_μ dis)



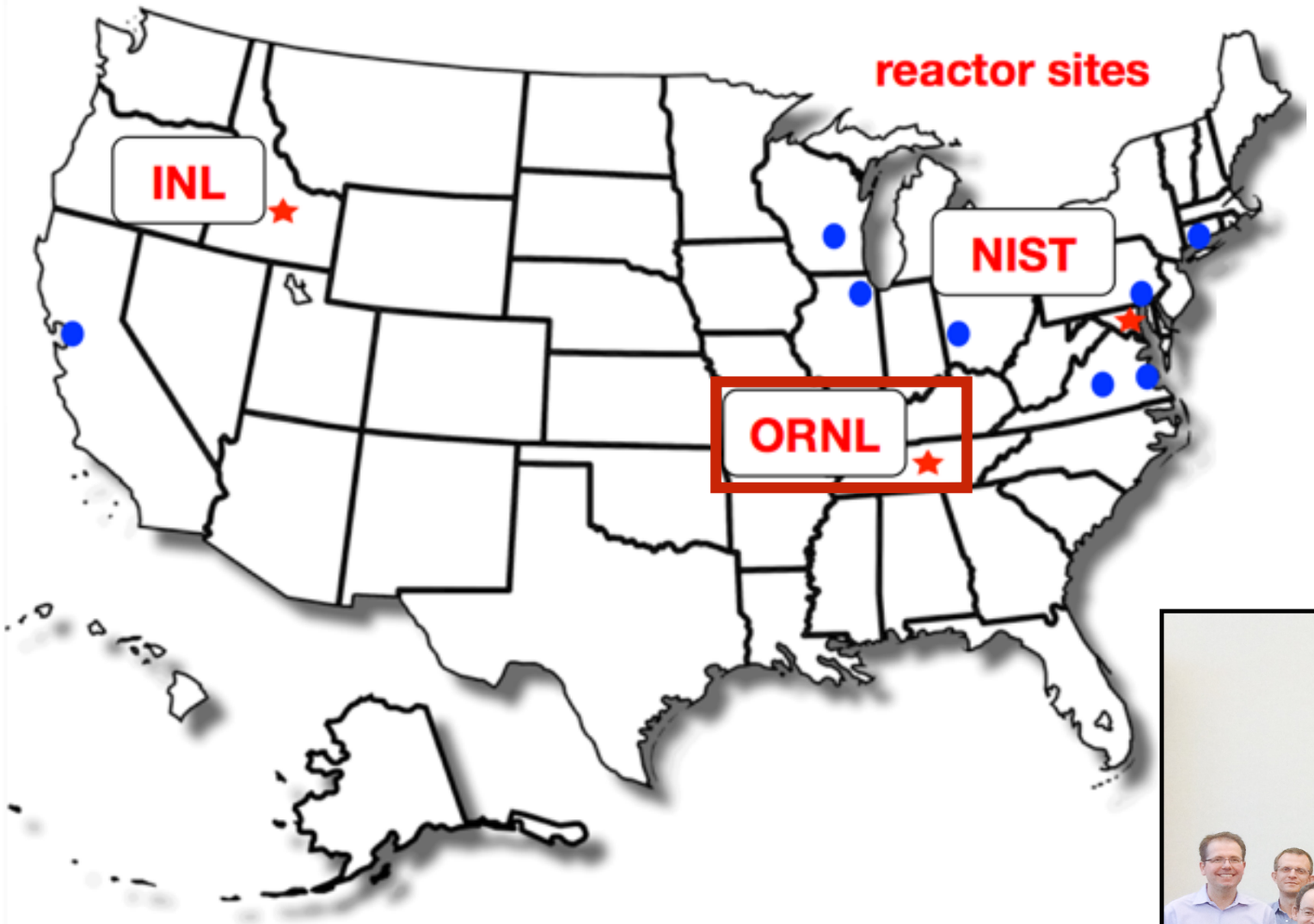


Summary

- Additional data is necessary to resolve the Reactor Anomaly
- High-resolution SBL reactor measurements can significantly constrain the favored hypotheses
  - Relative spectral measurements at multiple baselines has sterile discovery potential with a single year of data
  - High-resolution absolute measurements provide new constraints on reactor antineutrino production
- PROSPECT has the experience, development, and infrastructure in place for the world's pre-eminent SBL reactor effort.
  - Segmented LiLS design provides excellent resolution in position and energy
  - Have been characterizing HFIR site, prototypes for over a year at HFIR

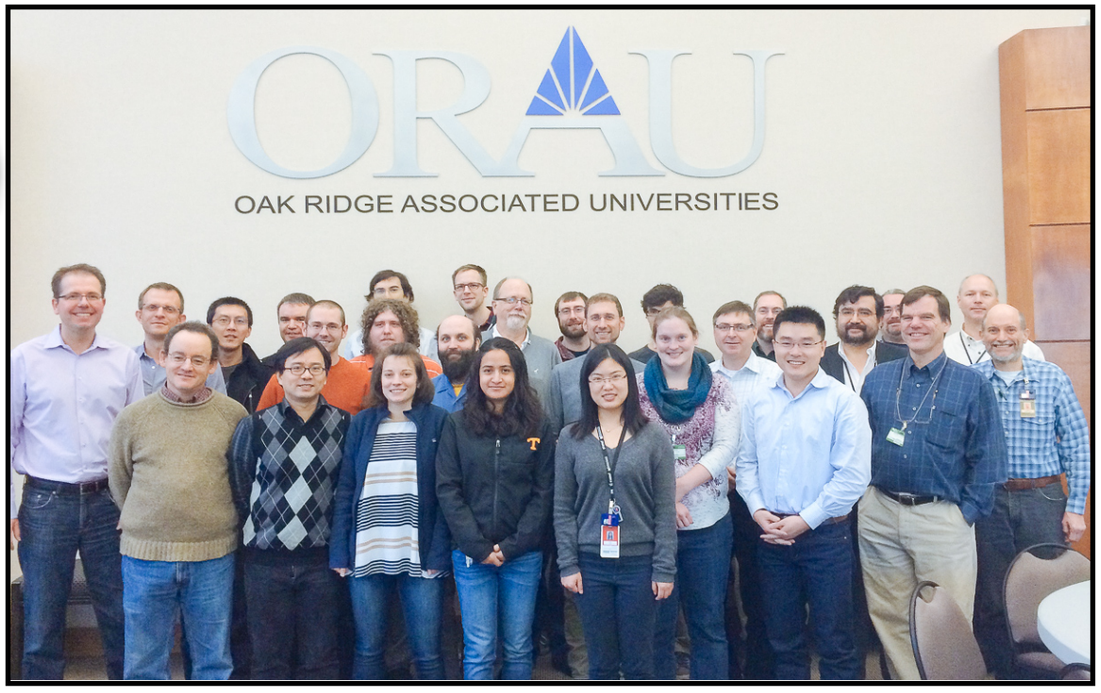
Thanks!

PROSPECT Collaboration



10 universities
6 national laboratories

Brookhaven National Laboratory
Drexel University
Idaho National Laboratory
Illinois Institute of Technology
Lawrence Berkeley National Laboratory
Lawrence Livermore National Laboratory
Le Moyne College
National Institute of Standards and Technology
Oak Ridge National Laboratory
Temple University
University of Tennessee
Virginia Tech University
University of Waterloo
University of Wisconsin
College of William and Mary
Yale University



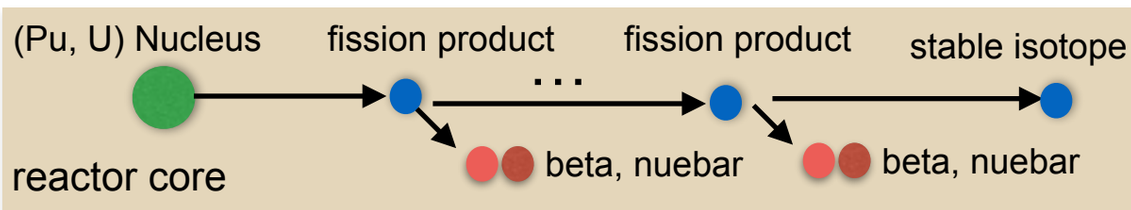
Updated whitepaper
arXiv:1309.7647

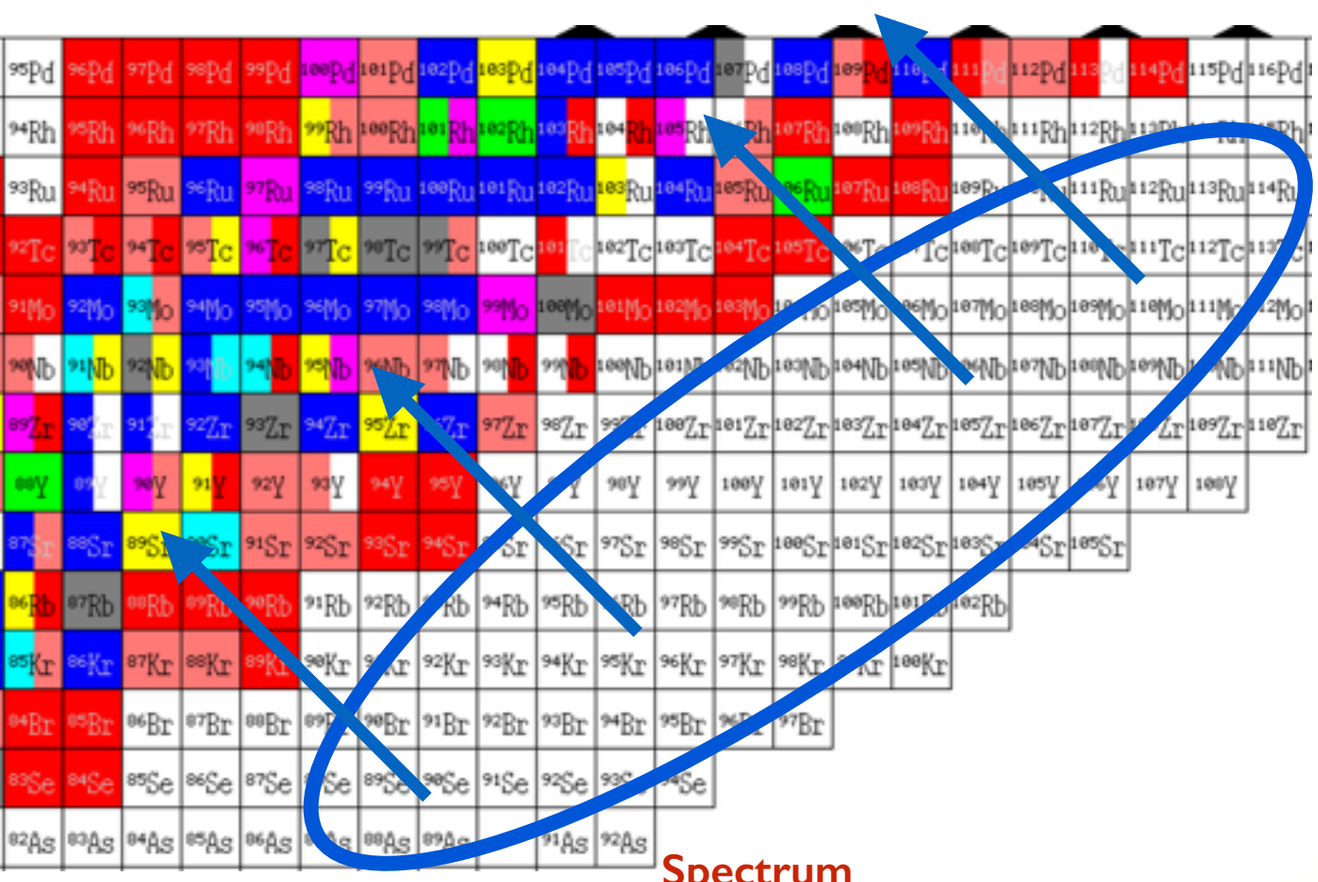
Website
http://prospect.yale.edu/

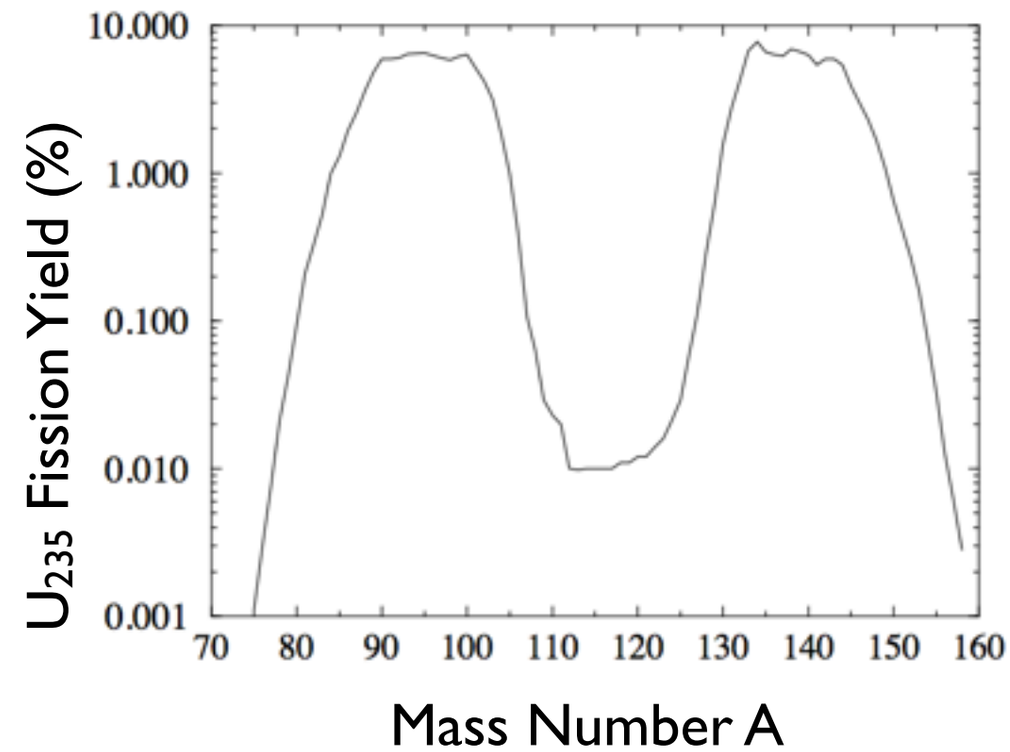
Backup

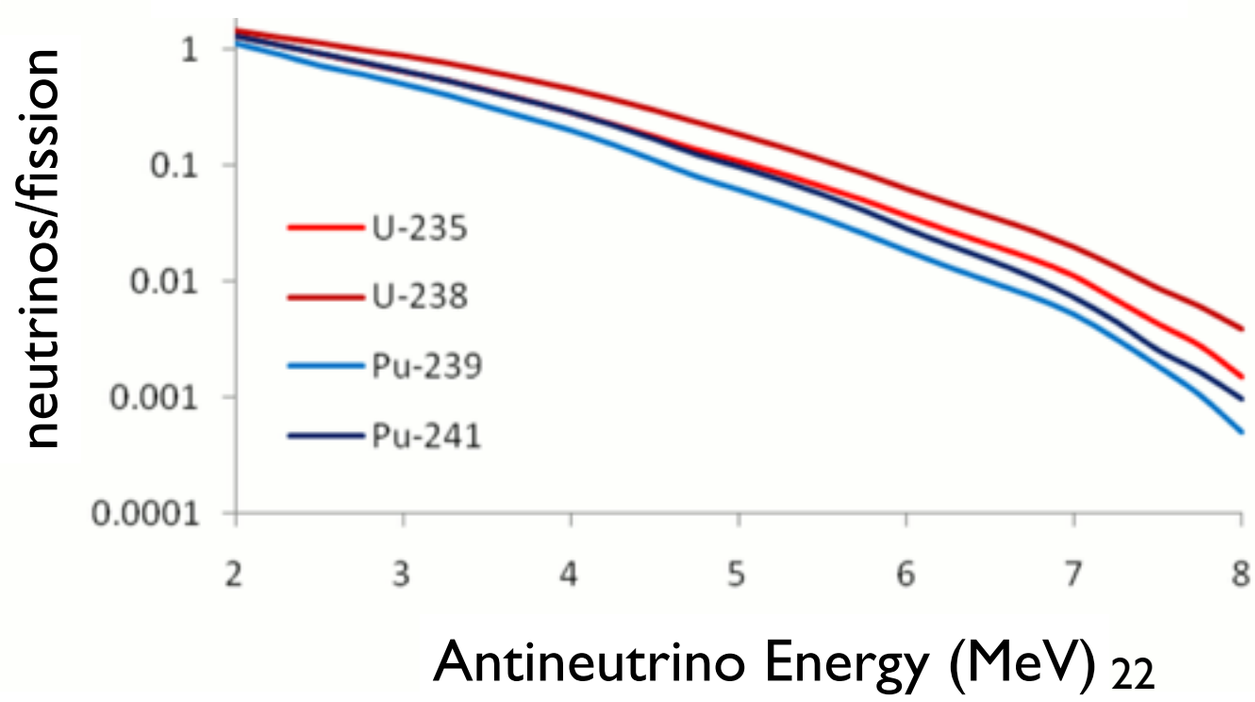
Reactor Antineutrino Production

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









Spectrum

$$S(E) = \sum_i F_i S_i(E) \qquad F_i = \frac{W_{\mathrm{th}} f_i}{\sum_k f_k E_k}$$

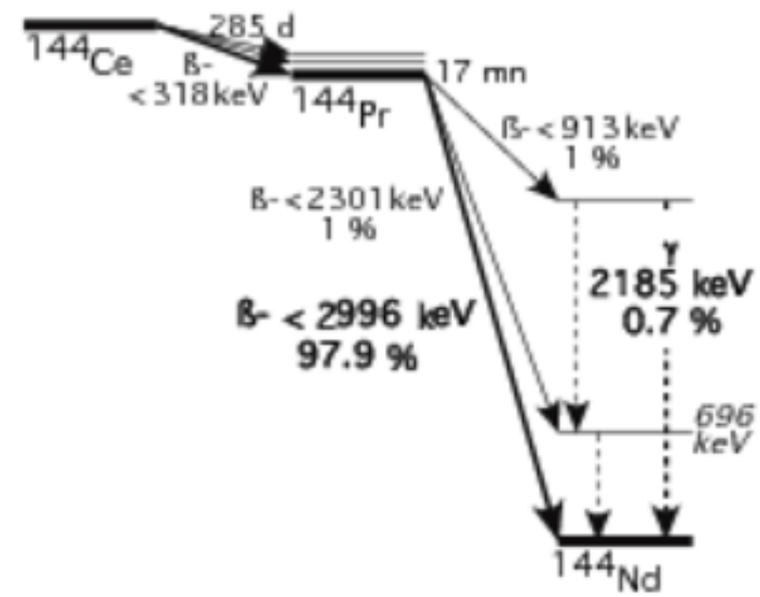
Fission Isotope i Flux

Predicting $S_i(E)$, Neutrinos Per Fission

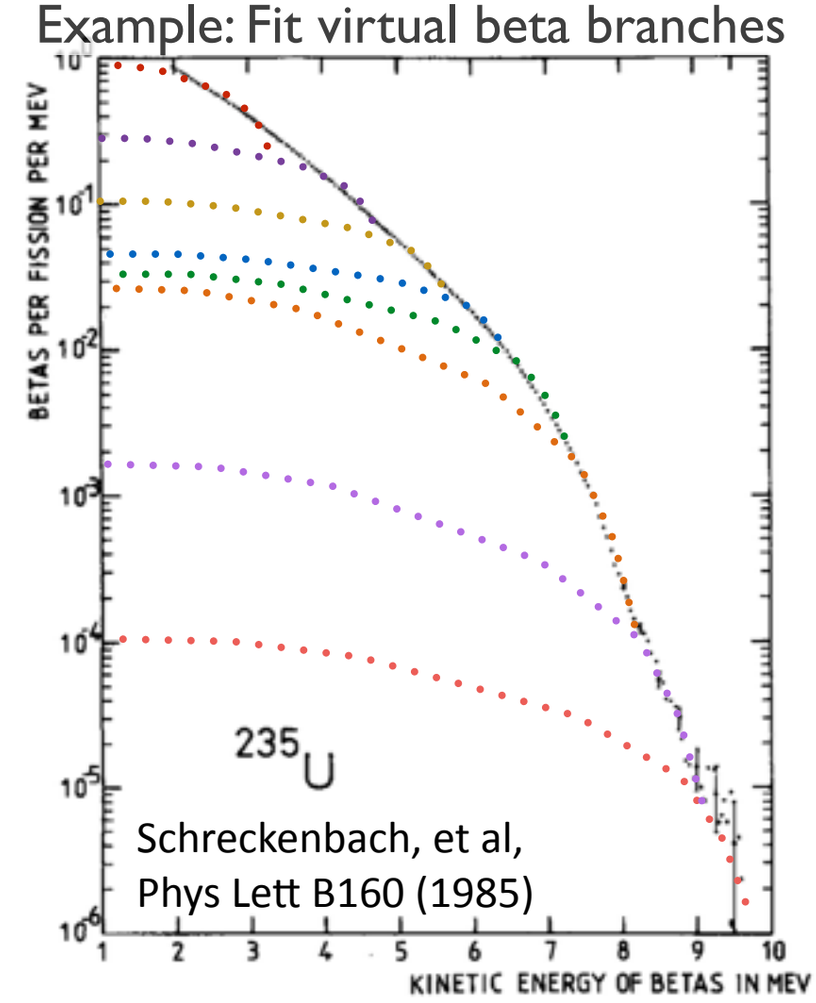
- Two main methods:
- *Ab Initio* approach:
  - Calculate spectrum branch-by-branch using beta branch databases: endpoints, decay schemes
  - **Problem:** many rare beta branches with little information; infer these additions
- Conversion approach
  - Measure beta spectra directly
  - Convert to $\bar{\nu}_e$ using 'virtual beta branches'
  - **Problem:** 'Virtual' spectra not well-defined: what forbiddenness, charge, etc. should they have?
- Devised in 50's, each method has lost and gained favor over the years

  Carter, *et al*, Phys. Rev. 113 (1959)
  King and Perkins, Phys. Rev. 113 (1958)

Example: Ce-144 Decay Scheme



Example: Fit virtual beta branches



Predicting $S_i(E)$, Neutrinos Per Fission

- Early 80s: ILL $\bar{\nu}_e$ data fits newest *ab initio* spectra well

  Davis, Vogel, *et al.*, **PRC** 24 (1979)
  Kown, et al., **PRD** 24 (1981)

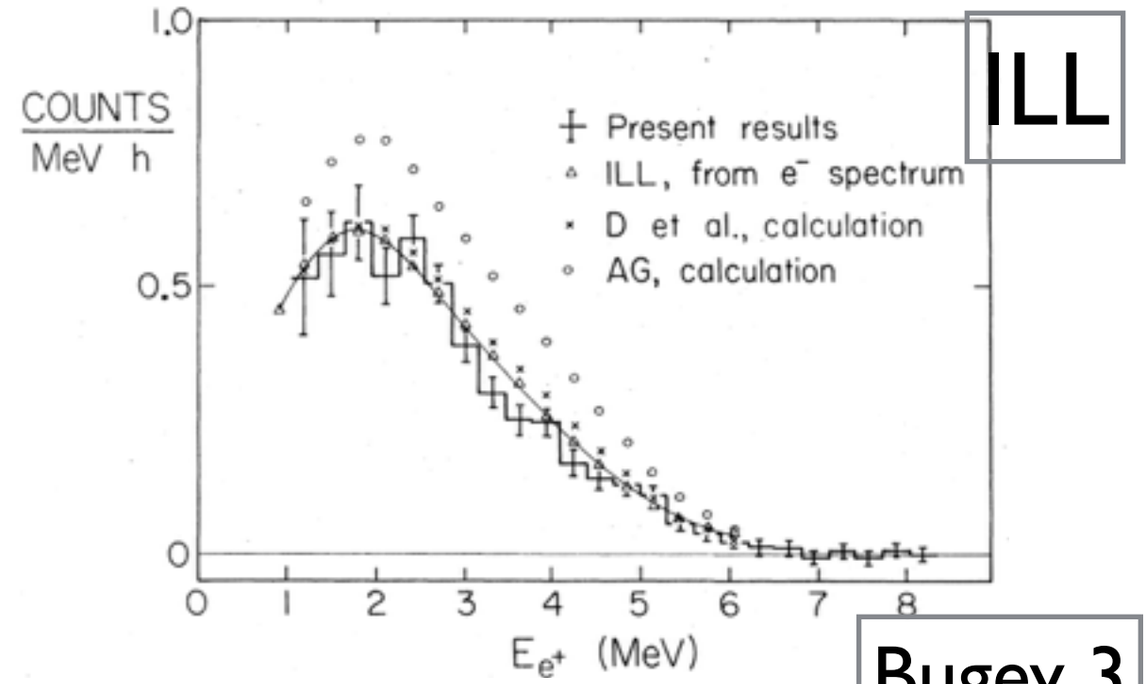
- 1980s: New reactor beta spectra: measurements — conversion now provides lower systematics

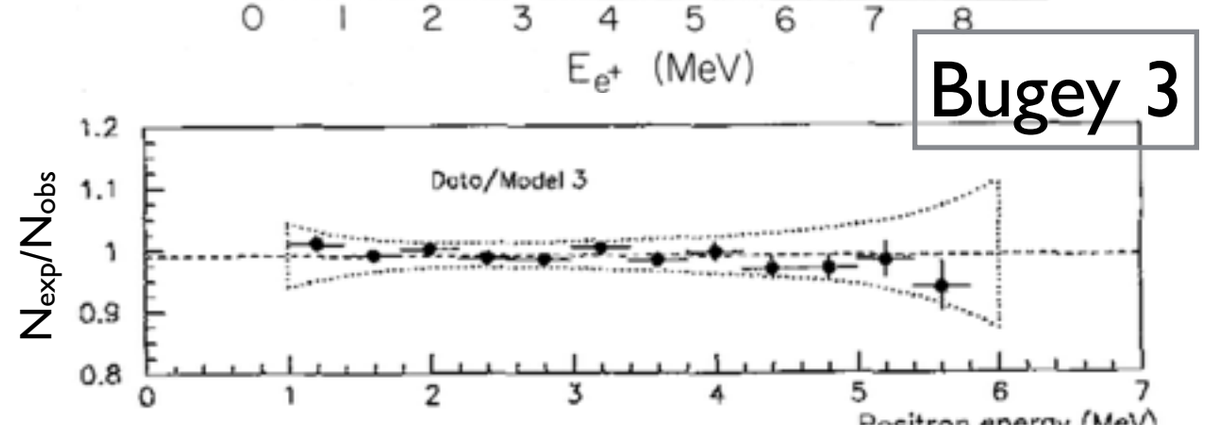
  Schreckenbach, *et al.*, Phys Lett **B**160 (1985)
  Schreckenbach, *et al.*, Phys Lett **B**218 (1989)

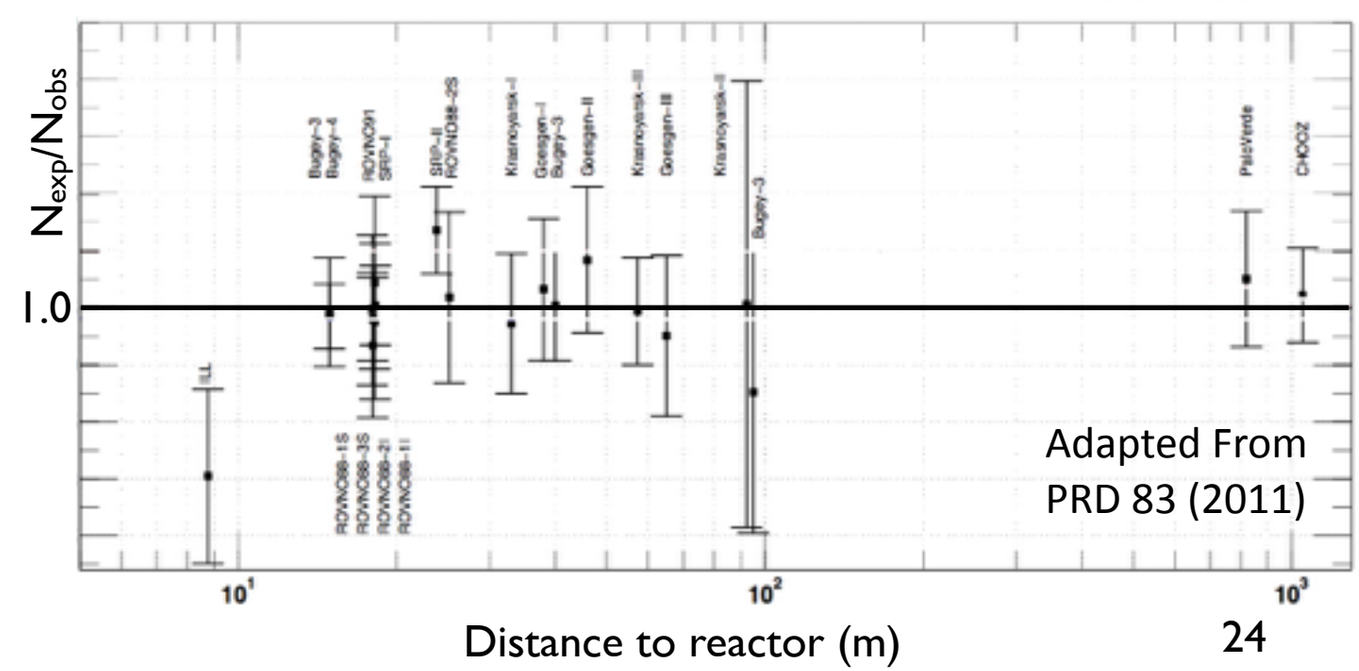
- 1990s: Bugey measurements fit converted spectrum well

  B. Achkar, *et al.*, Phys Lett B374 (1996)

- 1980s-2000s: Predicted, measured fluxes agree







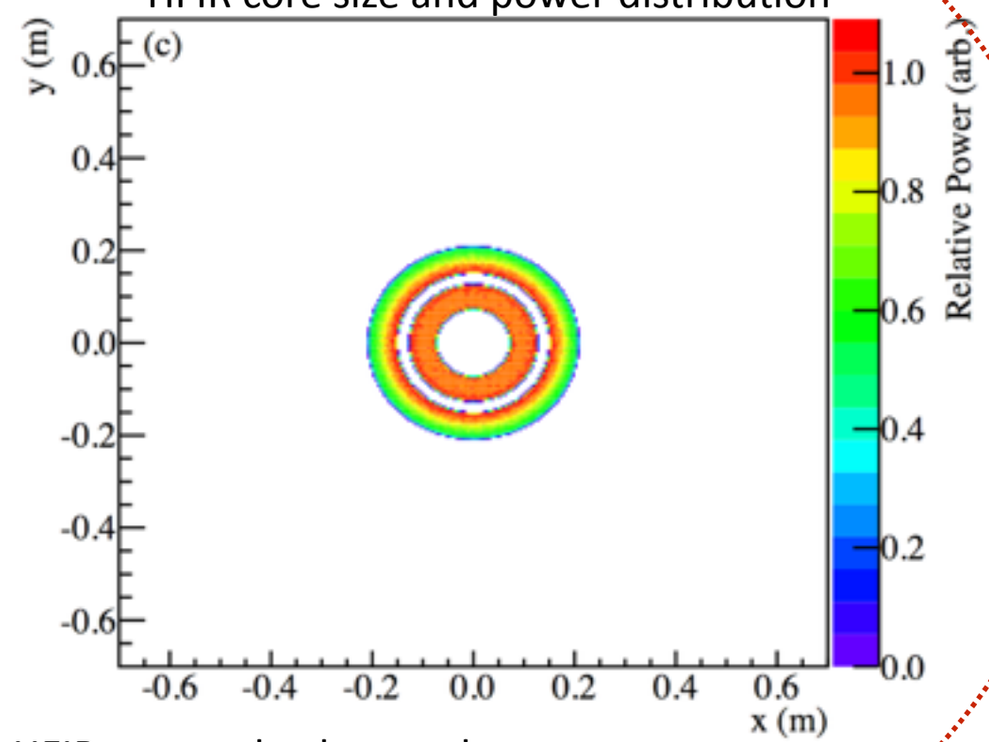
Adapted From PRD 83 (2011)

High-Flux Isotope Reactor at ORNL

- Compact 85MW Core
- HEU: constant U-235 $\bar{\nu}_e$ spectrum
- 42% reactor up-time (5 yearly cycles)
- Available detector location at 6+ m
- Have surveyed reactor backgrounds

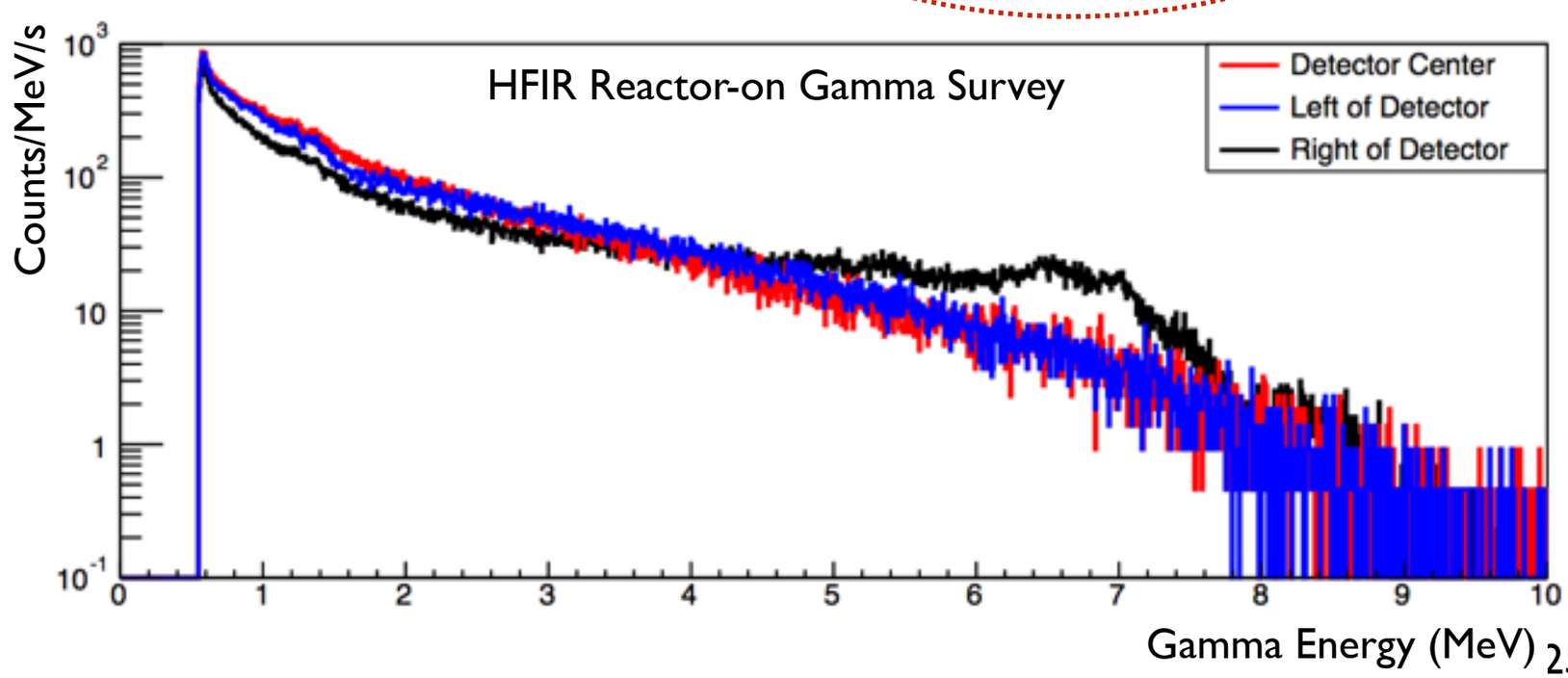
Commercial core size

HFIR core size and power distribution

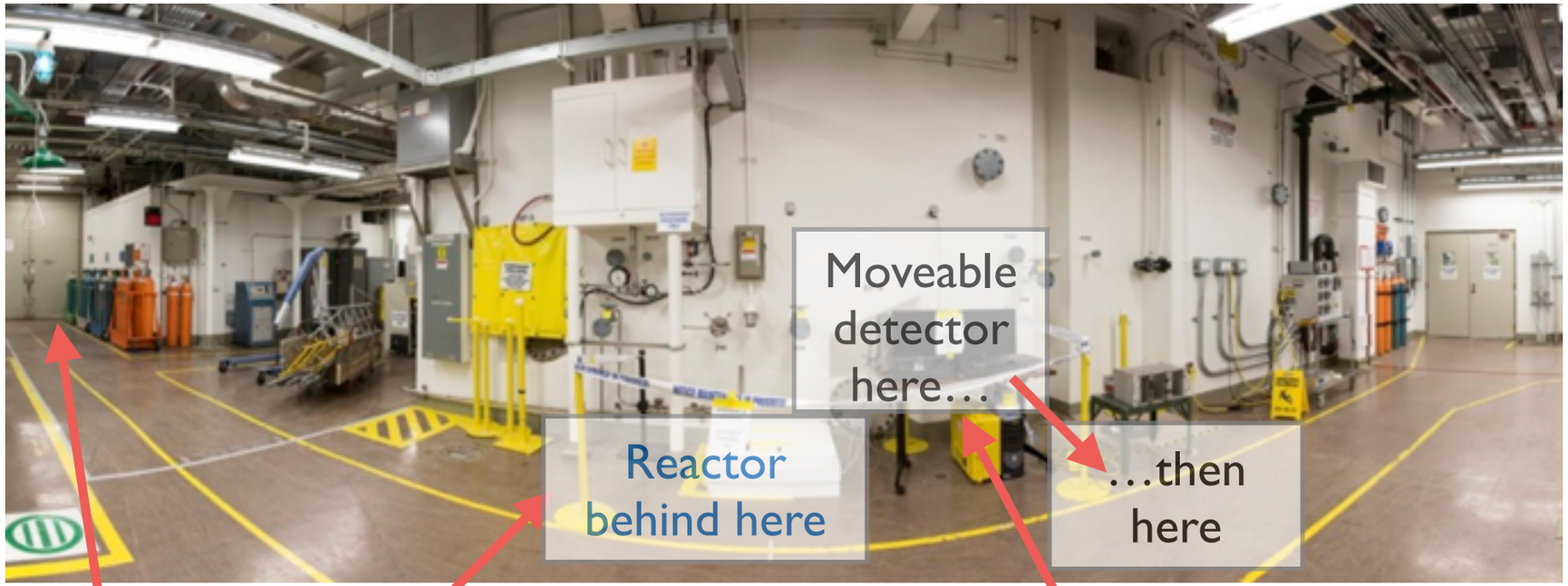


HFIR gamma background survey

HFIR core viewed from above

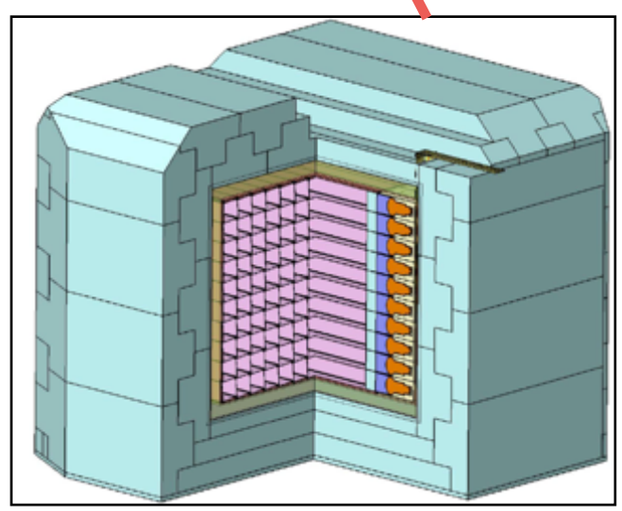


PROSPECT Location at HFIR

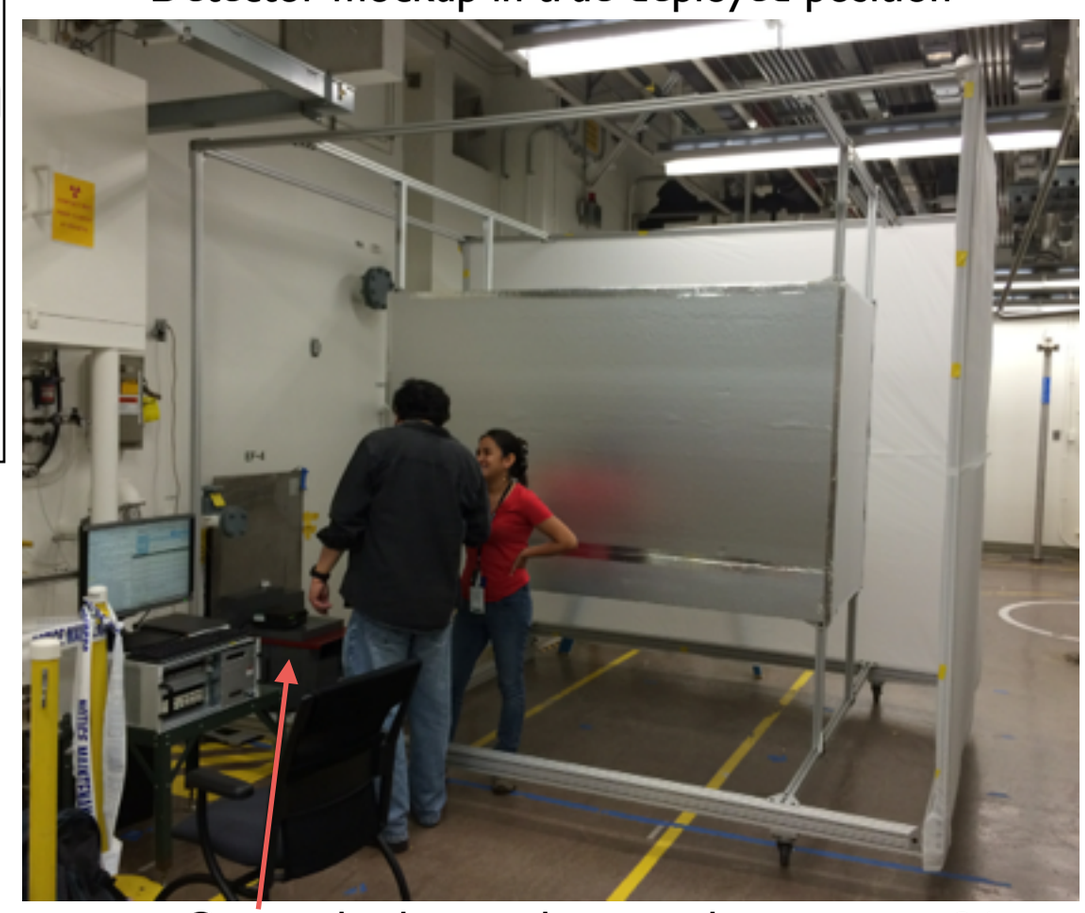


HFIR Main Level Hallway

Wide door to grade level: bring detector subsystems in here



Detector mockup in true deployed position

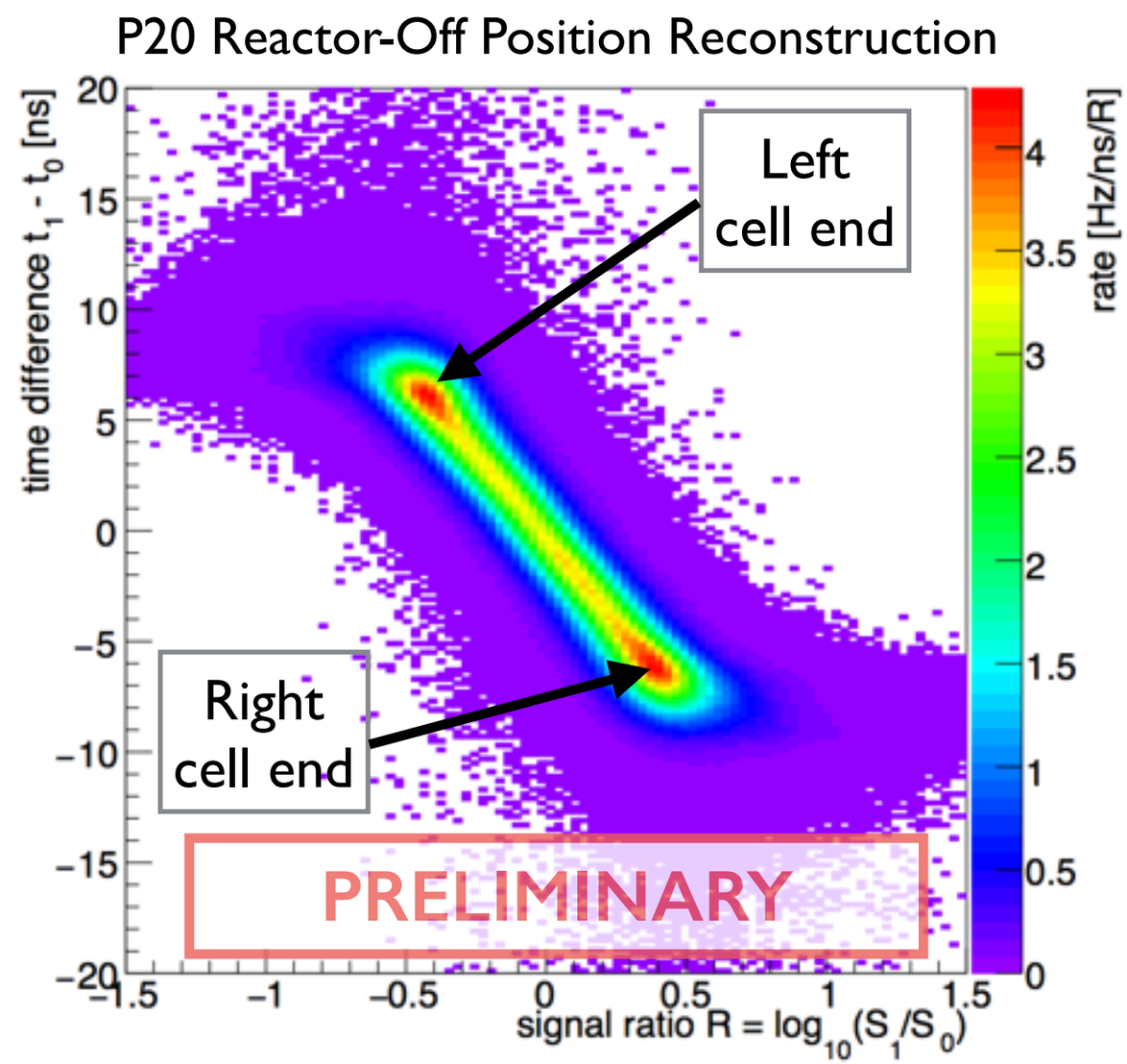


Gamma background survey detectors

Have been working in this location for > 1 year; PROSPECT prototypes operating here since August 2014!

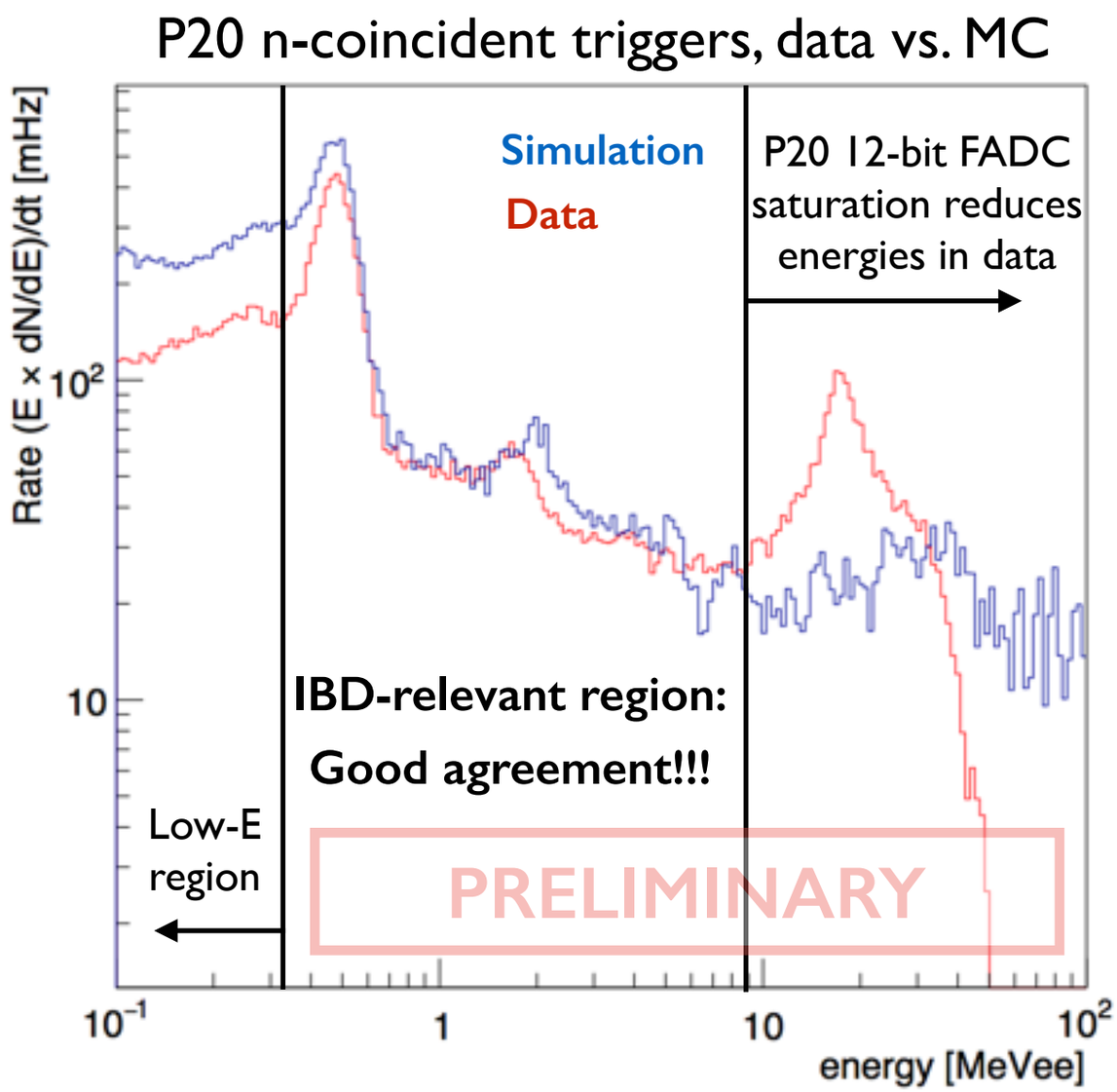
P20 Demonstration: Topology

- Examine charge, arrival time ratios between cell's PMTs
  - Closer PMT to interaction will have more charge, shorter time
- Resolution along cell better than 10cm
  - More topology background rejection capability than we were expecting!
- Segmentation gives resolution in other two dimensions



P20 Demonstration: Sim/Data Agreement

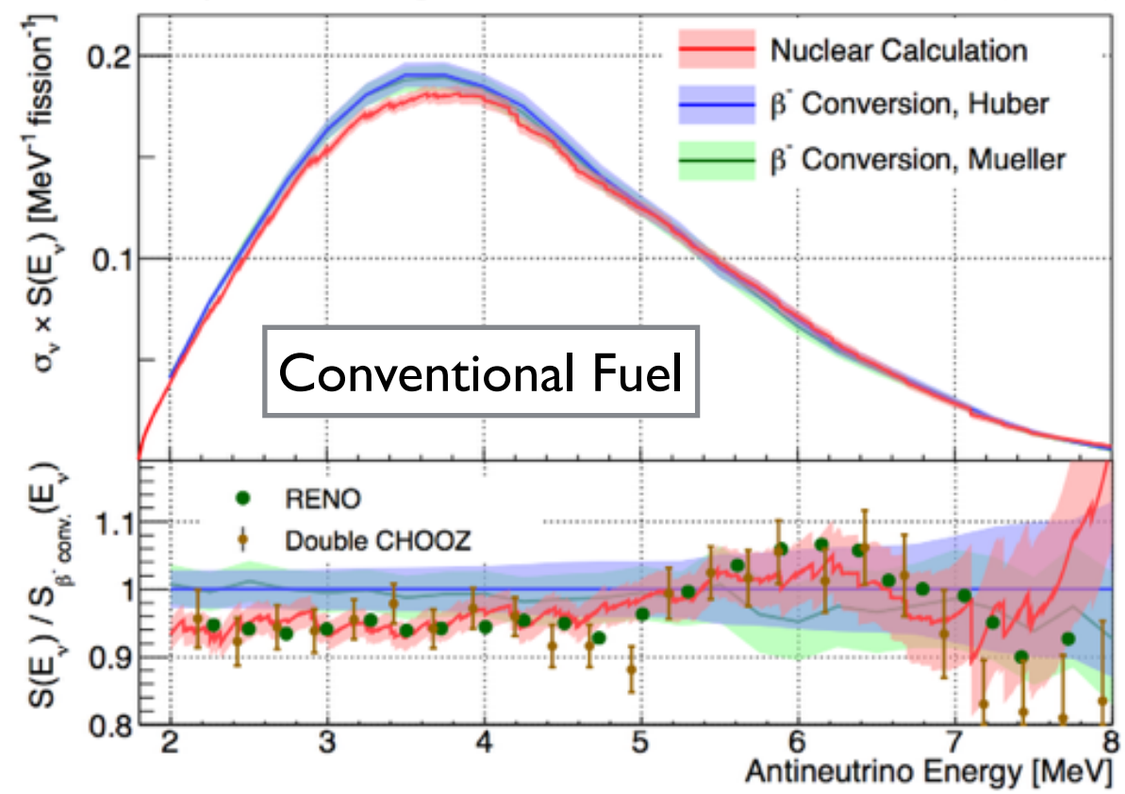
- Have CRY- and Goldhagen-based cosmogenic neutron, muon sim
- Shows n-coincidences in good agreement with data
  - Provides confidence in modeling of full PROSPECT detector backgrounds
- Data-matched simulation will give predicted S:B for PROSPECT

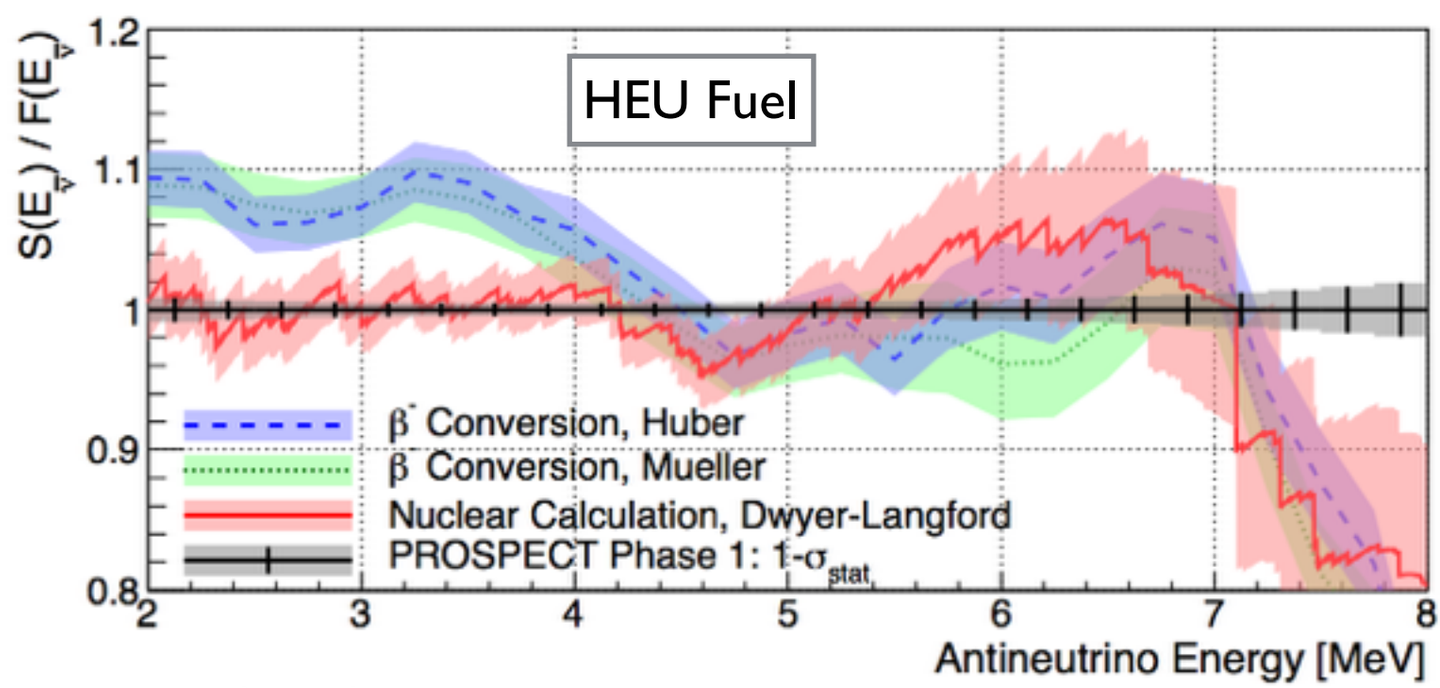


PROSPECT Physics: Absolute Spectrum

- What is the correct model?
  - Have data points for conventional fuel (^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu)
  - HEU (^{235}U): independent constraint
- Benefits of HFIR:
  - 1 core versus many cores (Daya Bay, RENO)
  - Easier model: only 1 isotope, no time-dependence
- Implications for reactor monitoring:
  - Example: what if 5MeV bump isn't present for HEU fuel?
  - In that case 'bump' size would be a proxy for ^{239}Pu concentration in core

Dwyer and Langford, arxiv:[nucl-ex]1407.1281 (2014)





Forbidden Decay Handling

- 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

- Hayes, et. al, PRL 112 (2014): conversion result highly dependent on forbidden-ness of virtual branches
  - Capable of shifting predicted flux downward by 5%
  - Has not been shown what forbidden decay treatment would reproduce both reactor beta and nuebar spectra — but it might be possible to do so

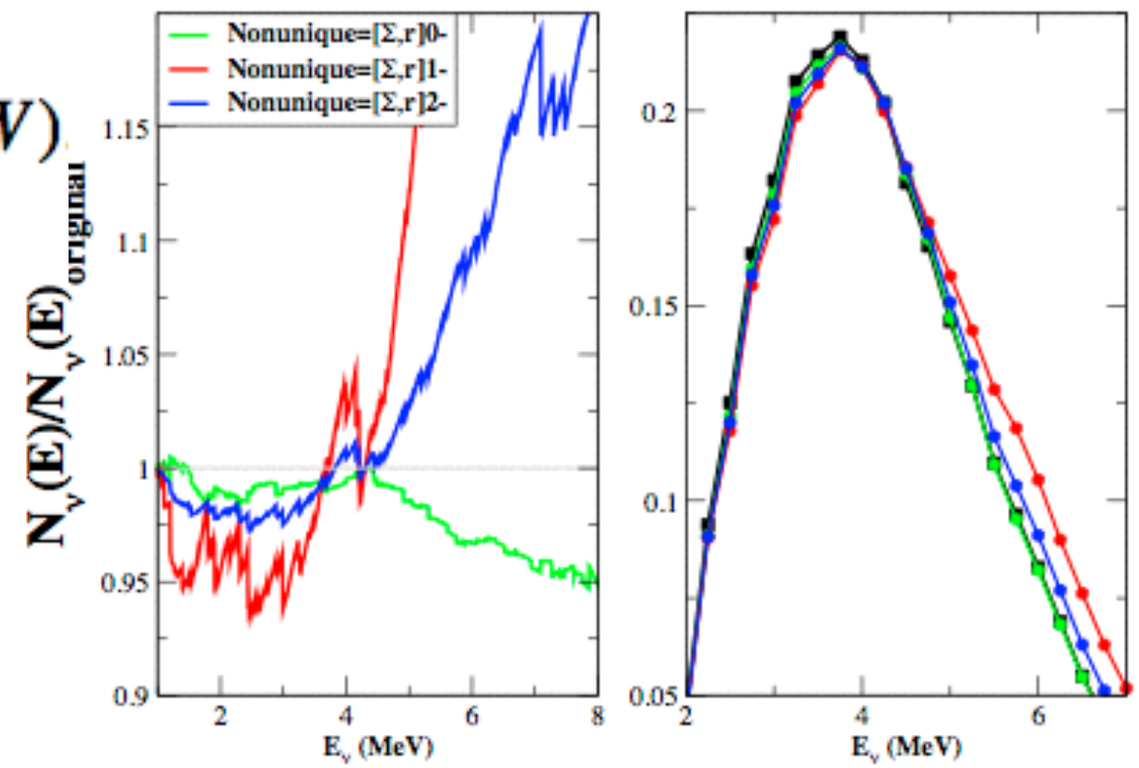
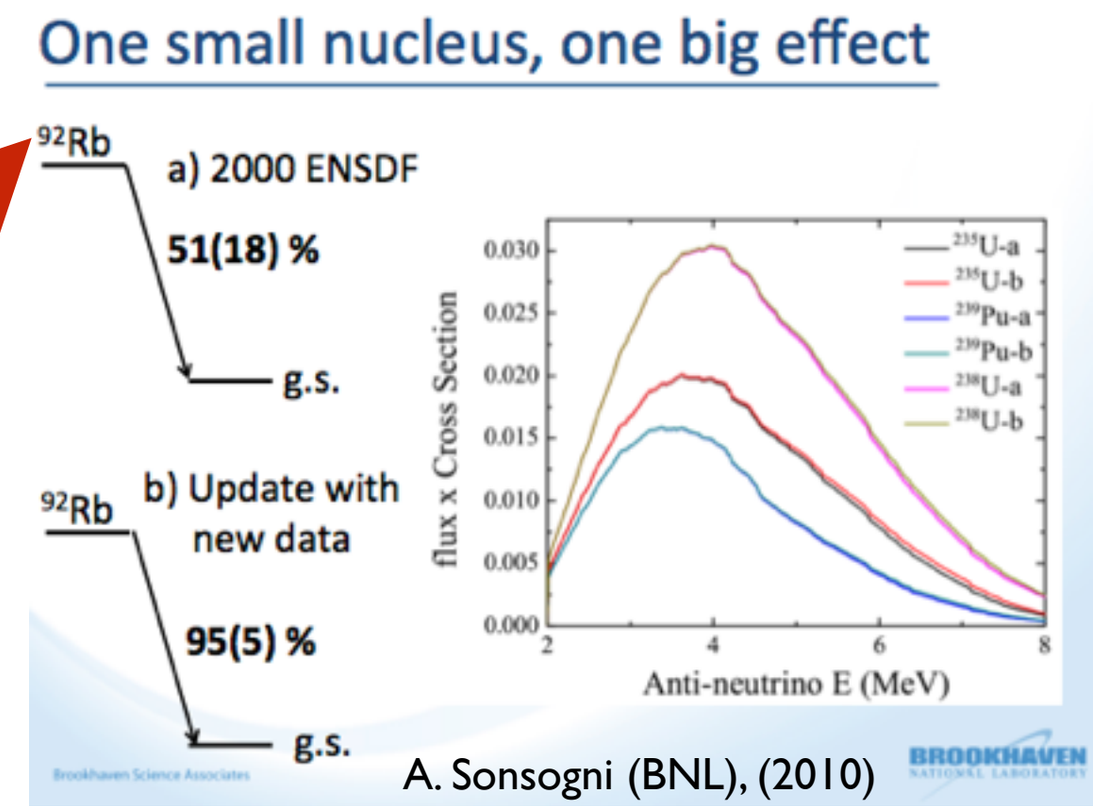
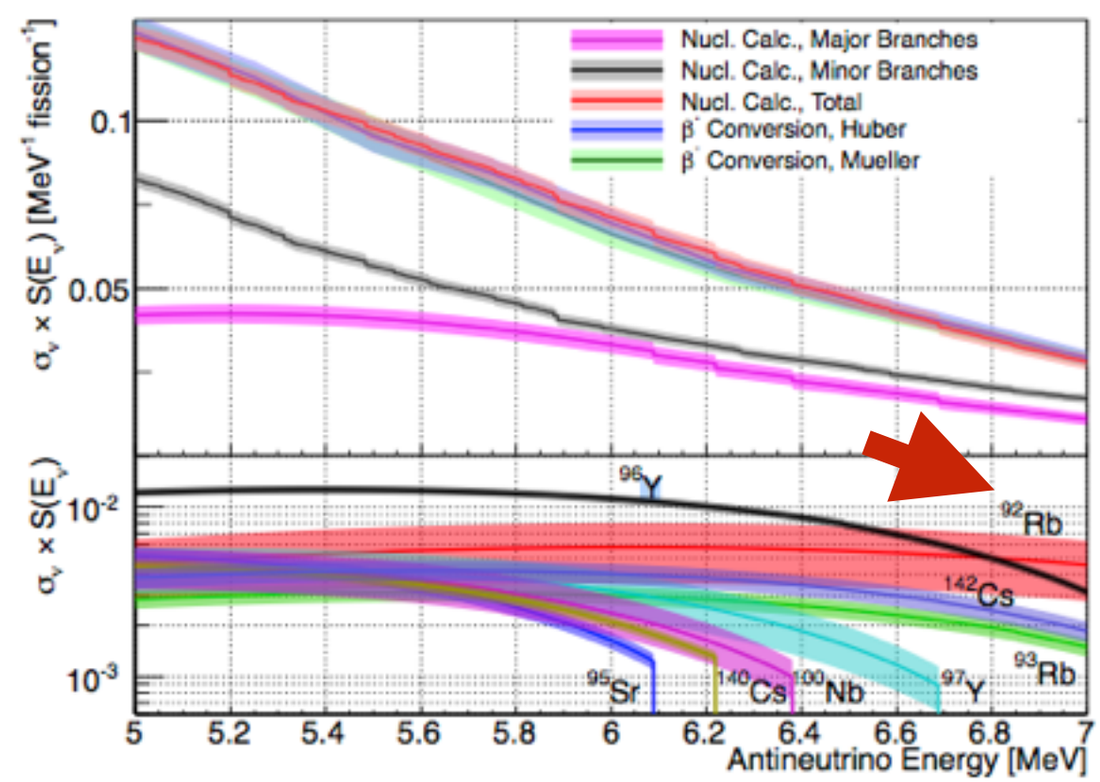


FIG. 3: Different treatments of the forbidden GT transitions contributing to the antineutrino spectrum summed over all actinides in the fission burn in mid-cycle [21] of a typical reactor. The left panel shows the ratio of these antineutrino spectra relative to that using the assumptions of Ref. [4]. The right panel shows the spectra weighted by the detection cross section, where the additional curve in black uses the assumptions of Ref. [4]. The spectra are strongly distorted by the forbidden operators, being lower below the peak and in some cases more than 20% larger above the peak than Ref. [4]. The corresponding change in the number of detectable antineutrinos relative to [4] is -0.75%, 5.8% and 1.85% for the $0^-, 1^-$, and 2^- forbidden operators, respectively.

Ab Initio Disagreements

- 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

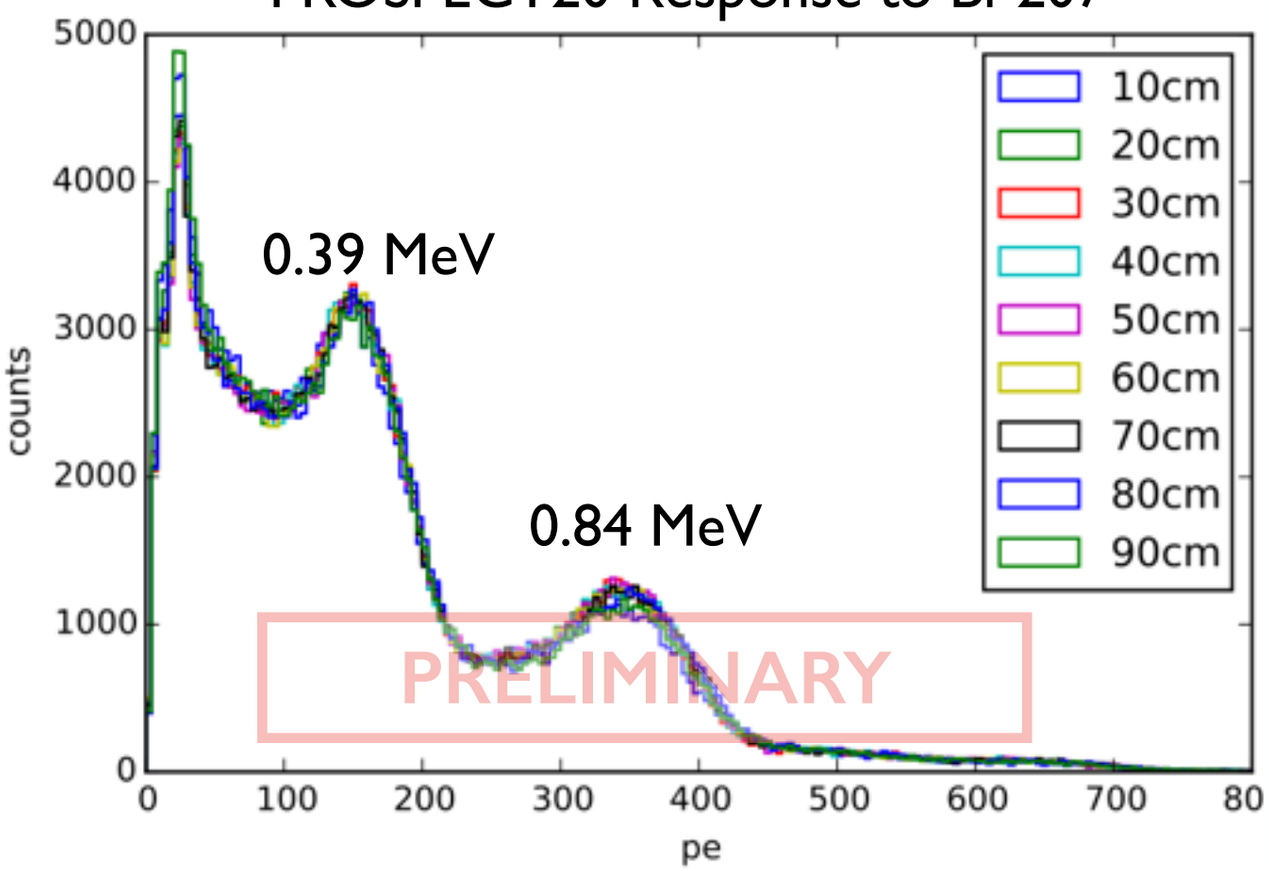
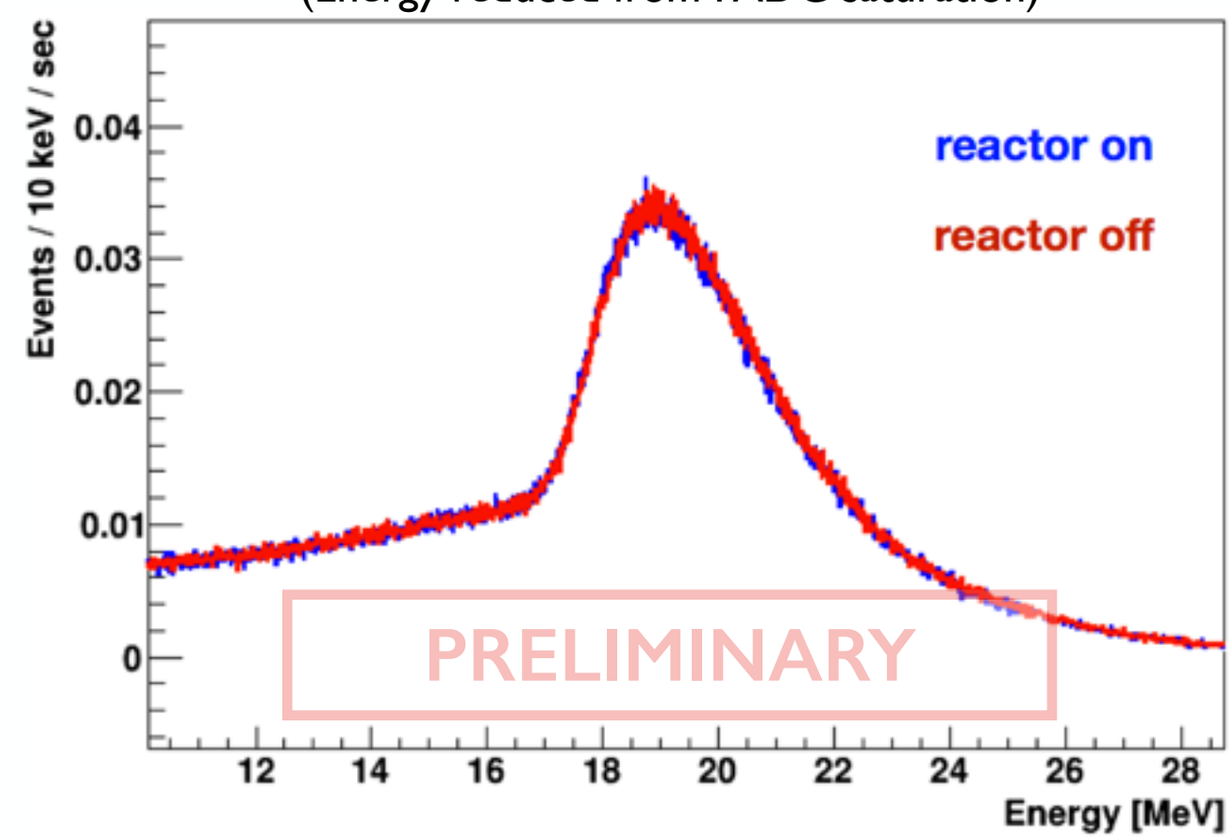




P20 Demonstration: Energy Response

- High, uniform, and stable light collection in full-length cell
  - Exact PE yield is likely to be different in full PROSPECT cells
- Good energy resolution visible
  - Existing P20 PE yield is high enough to achieve 4-5% energy resolution goal
- Many background peaks, calibration sources to choose from

PROSPECT20 Response to Bi-207



Muon MIP Peak in PROSPECT20
(Energy reduced from FADC saturation)