Precision Reactor $\bar{\nu}_e$ Spectrum Measurements: Recent Results and PROSPECTs

November 24, 2014

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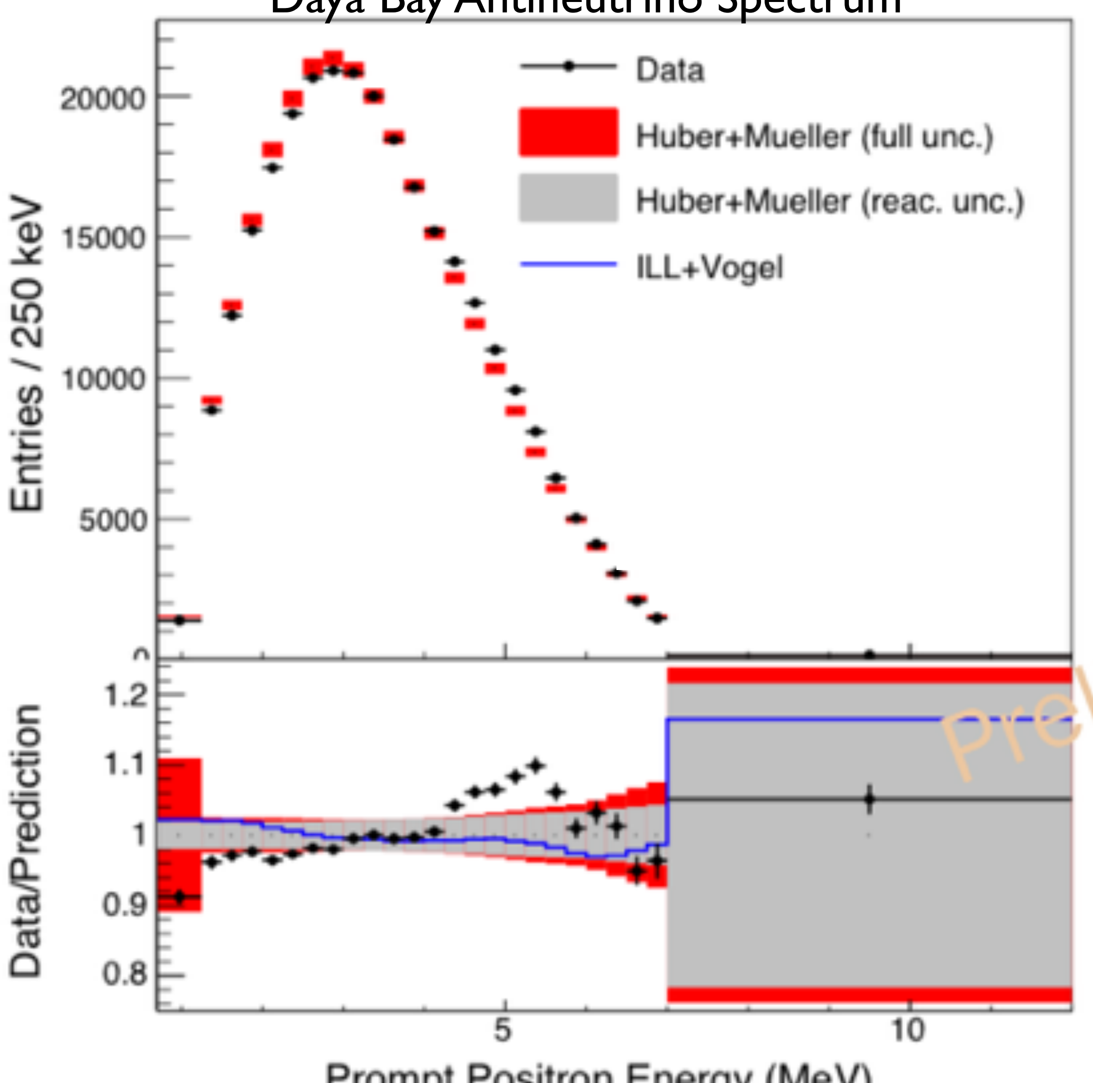
Illinois Institute of Technology

Daya Bay Antineutrino Spectrum



PROSPECT Collaboration at HFIR

Outline

- Intro: Reactor $\overline{\nu}_e$ Flux and Spectrum Predictions
- Reactor Anomaly and recent flux/spectrum measurements
- Future measurement of the $\overline{\nu}_e$ spectrum at PROSPECT
- Historical/current/future context for PROSPECT

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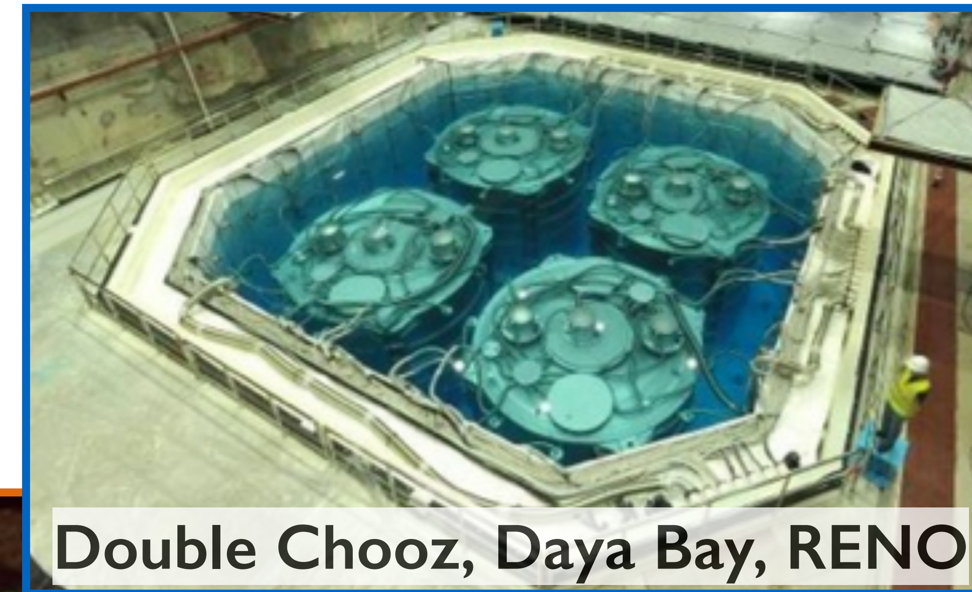
Reactor Neutrino History

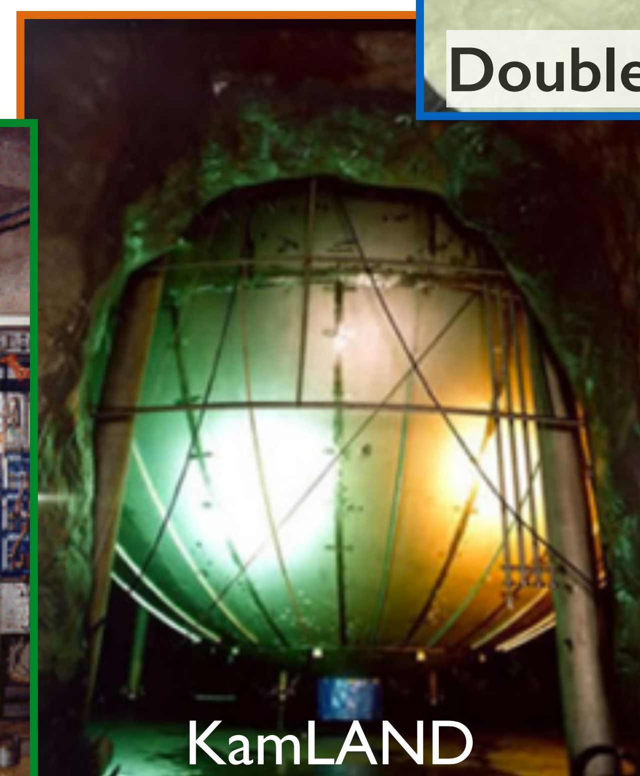
- Reactor $\bar{\nu}_e$: a history of discovery
  Many experiments, differing baselines

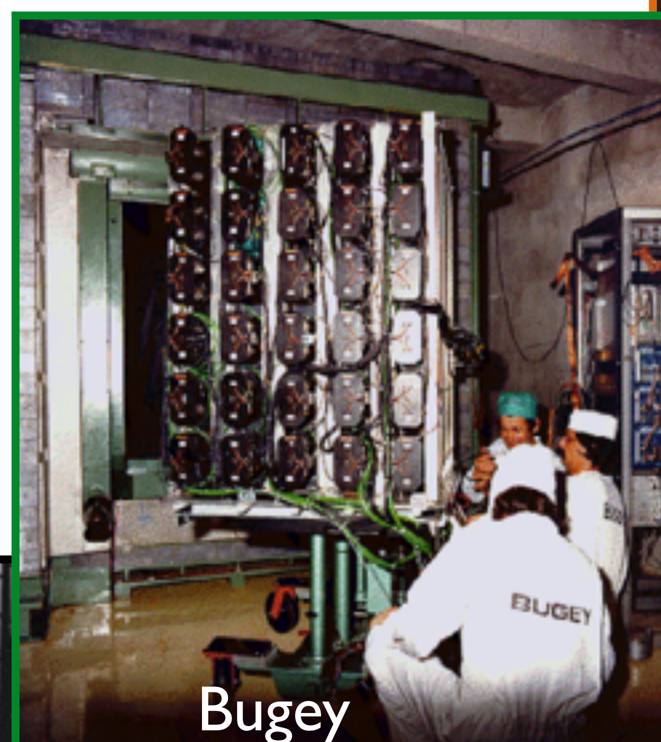
1970s-80s-90s:
Reactor flux,
Cross-section measurements


Double Chooz, Daya Bay, RENO

2010s:
θ_{13}, precision oscillation measurements

1950s: First neutrino observation


KamLAND



Bugey

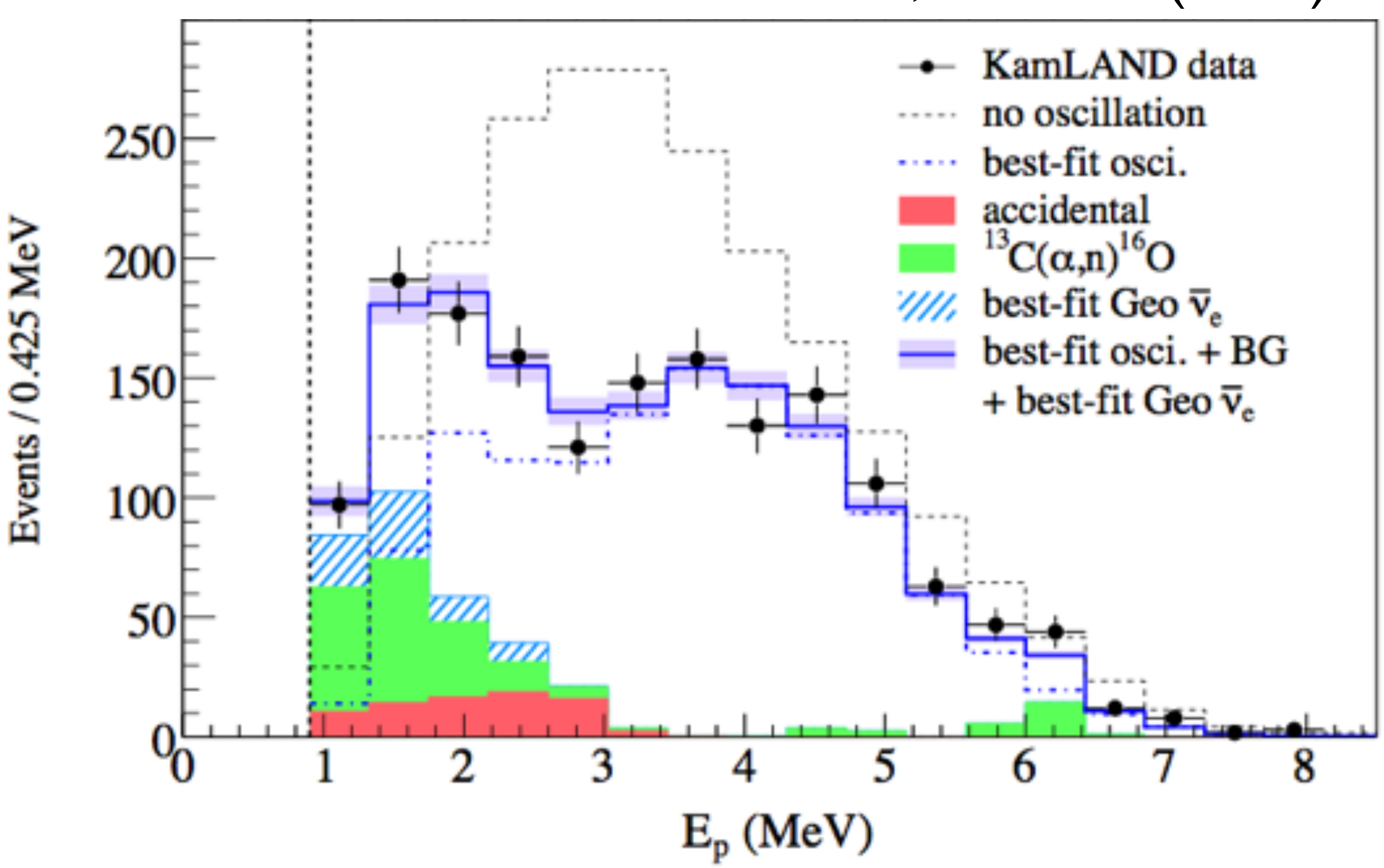

Savannah River

2000s: $\bar{\nu}_e$ disappearance,
$\bar{\nu}_e$ oscillation measurements

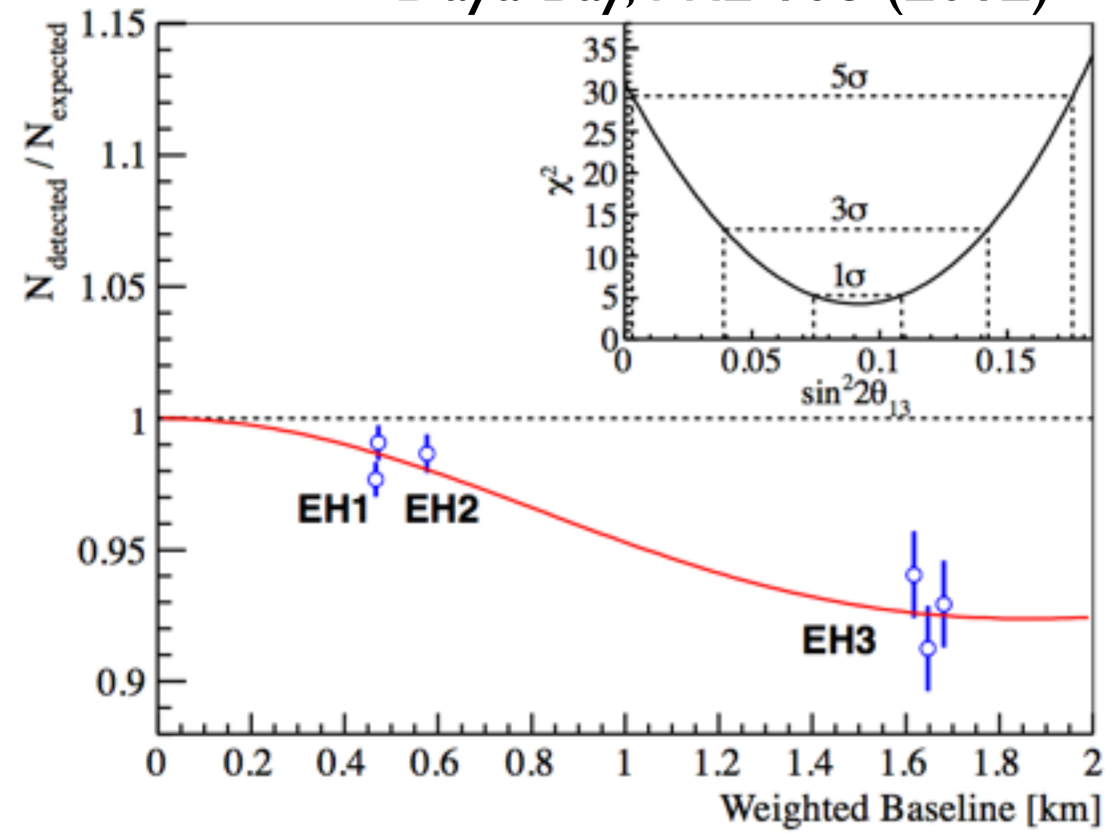
Reactor Neutrino Discovery

- How are these discoveries made?
- Comparing observed reactor neutrinos at different sites
- Comparing observed reactor neutrinos to predictions based on some model of how nuclear reactors work

KamLAND, PRL 100 (2008)



Daya Bay, PRL 108 (2012)



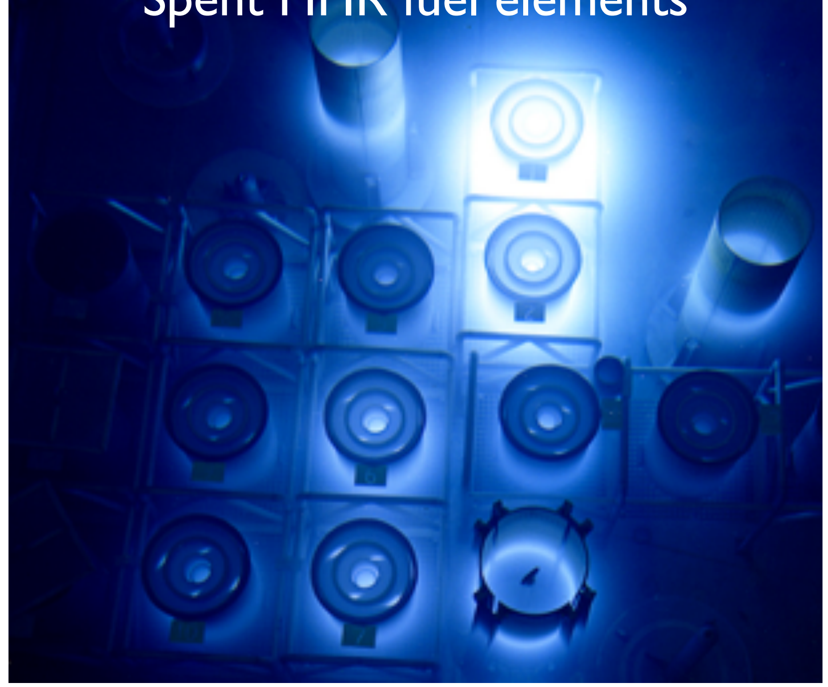
2000s: $\bar{\nu}_e$ disappearance, $\bar{\nu}_e$ oscillation measurements

2010s: θ_{13}, precision oscillation measurements

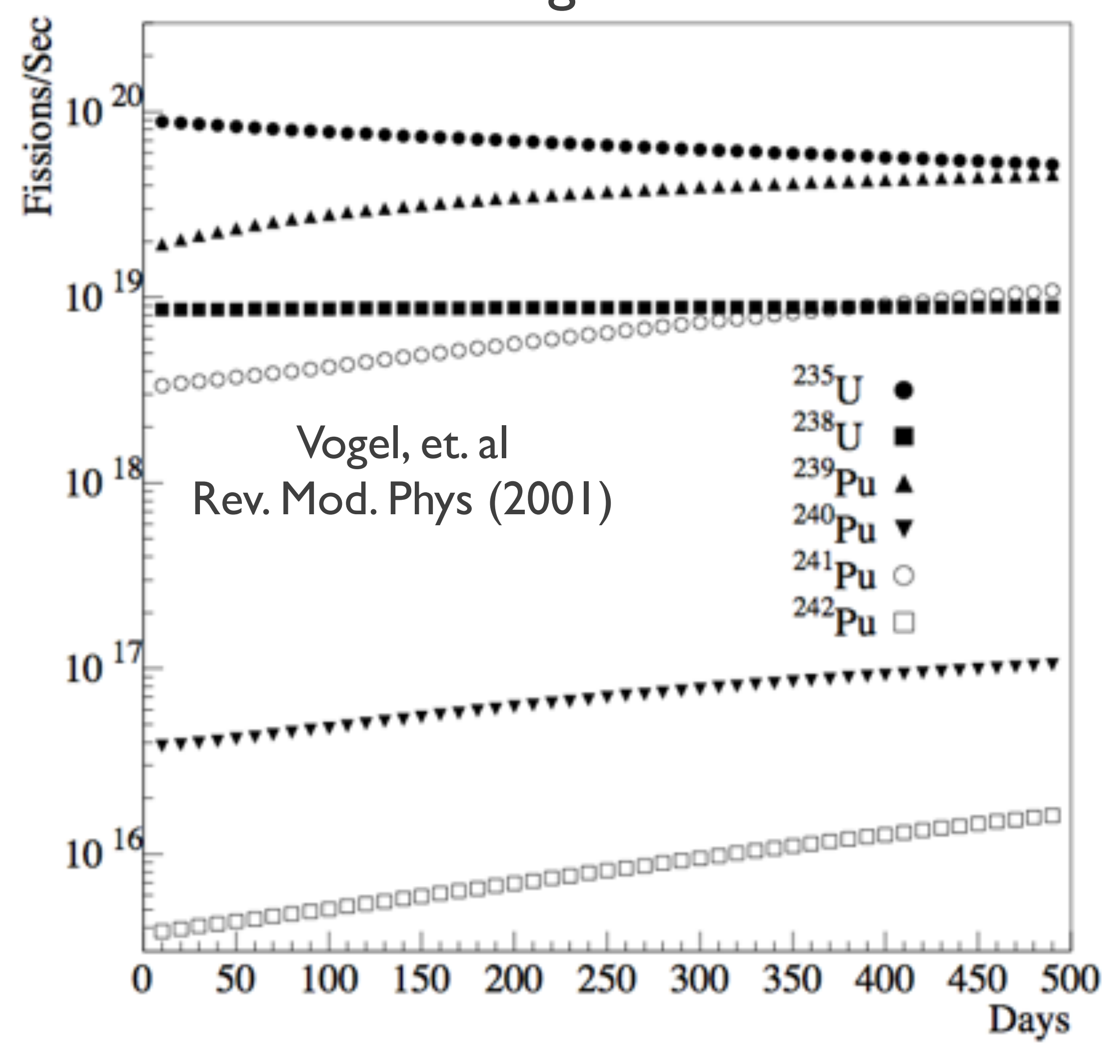
Reactor Antineutrino Production

- **Beta branches produced when fission isotopes fission**
  - Low-enriched (LEU): Many fission isotopes
  - Highly-enriched (HEU): U-235 fission only
- Overall fission rate described largely by reactor thermal power


HFIR Core/Containment

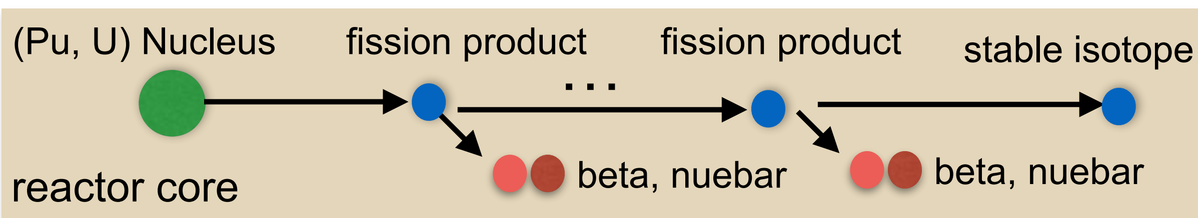

Spent HFIR fuel elements

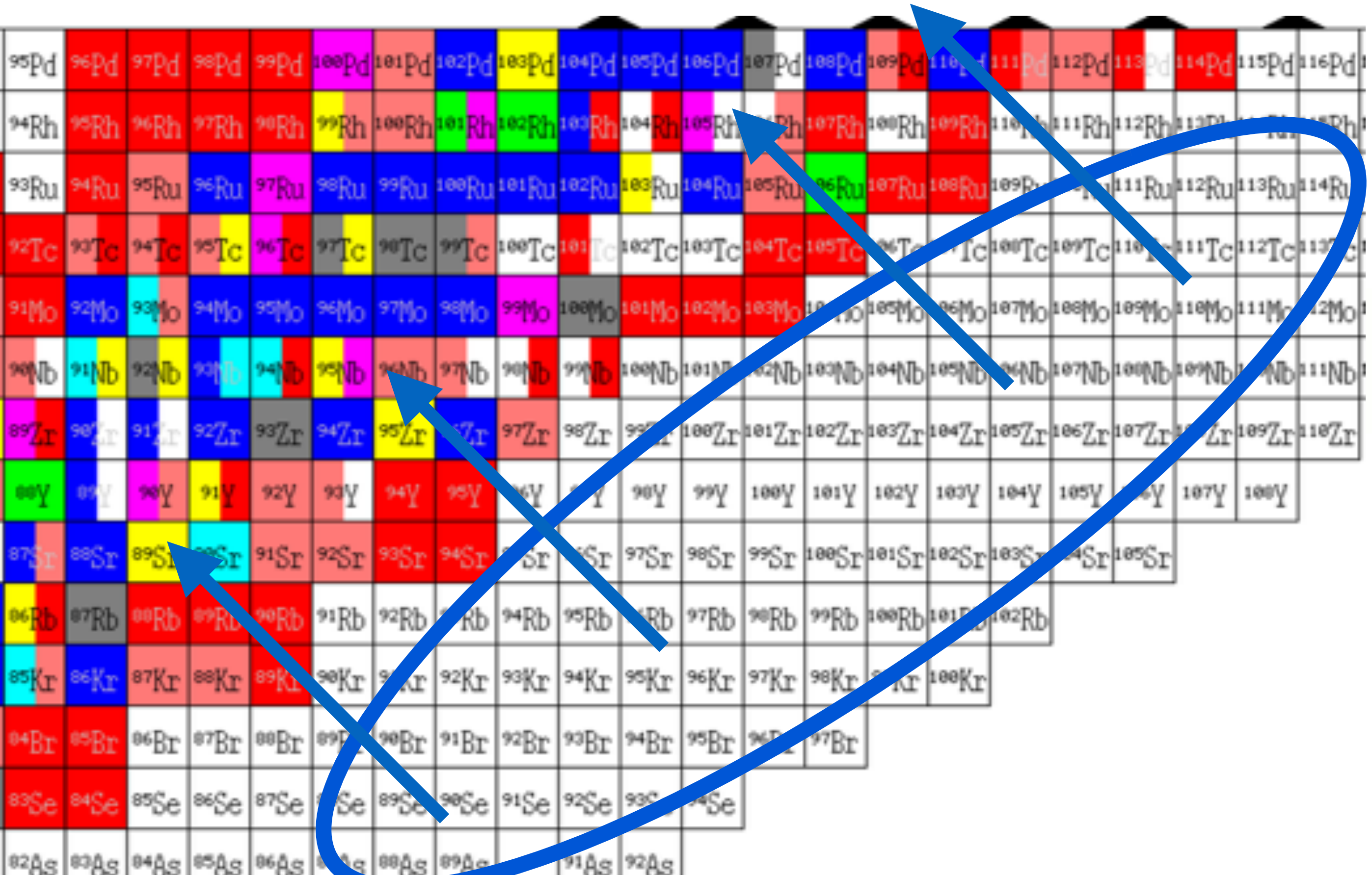
LEU Fission Fragment Contributors

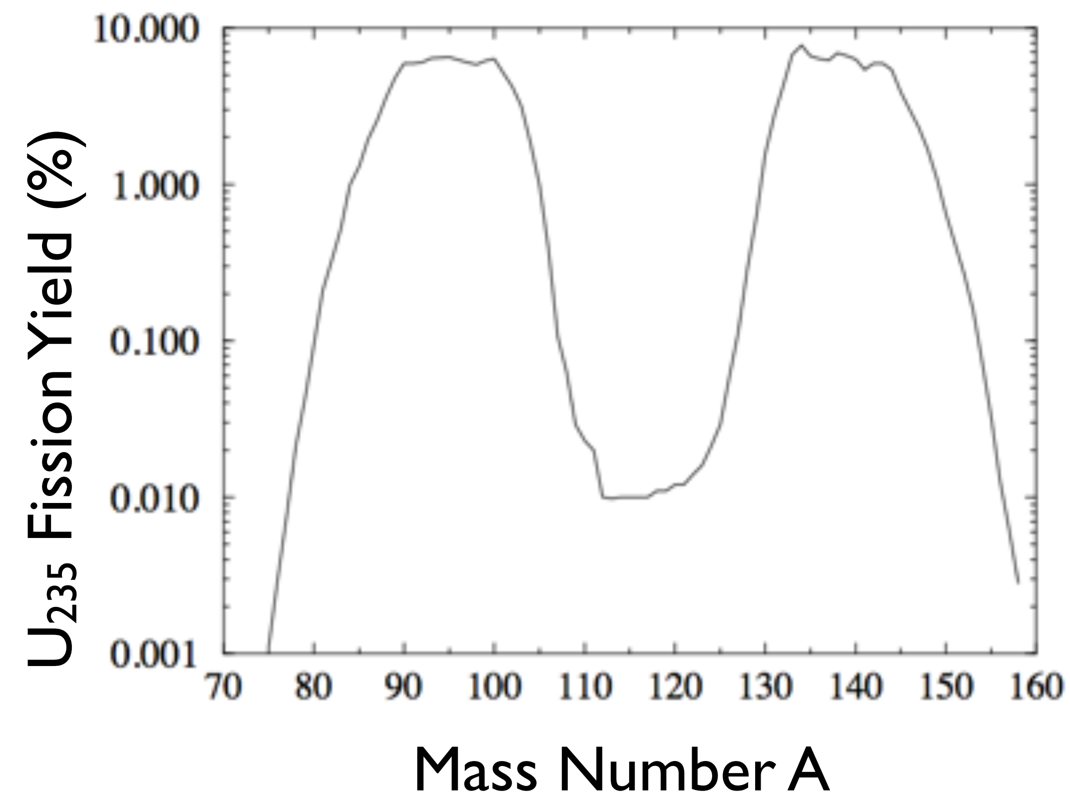


Reactor Antineutrino Production

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



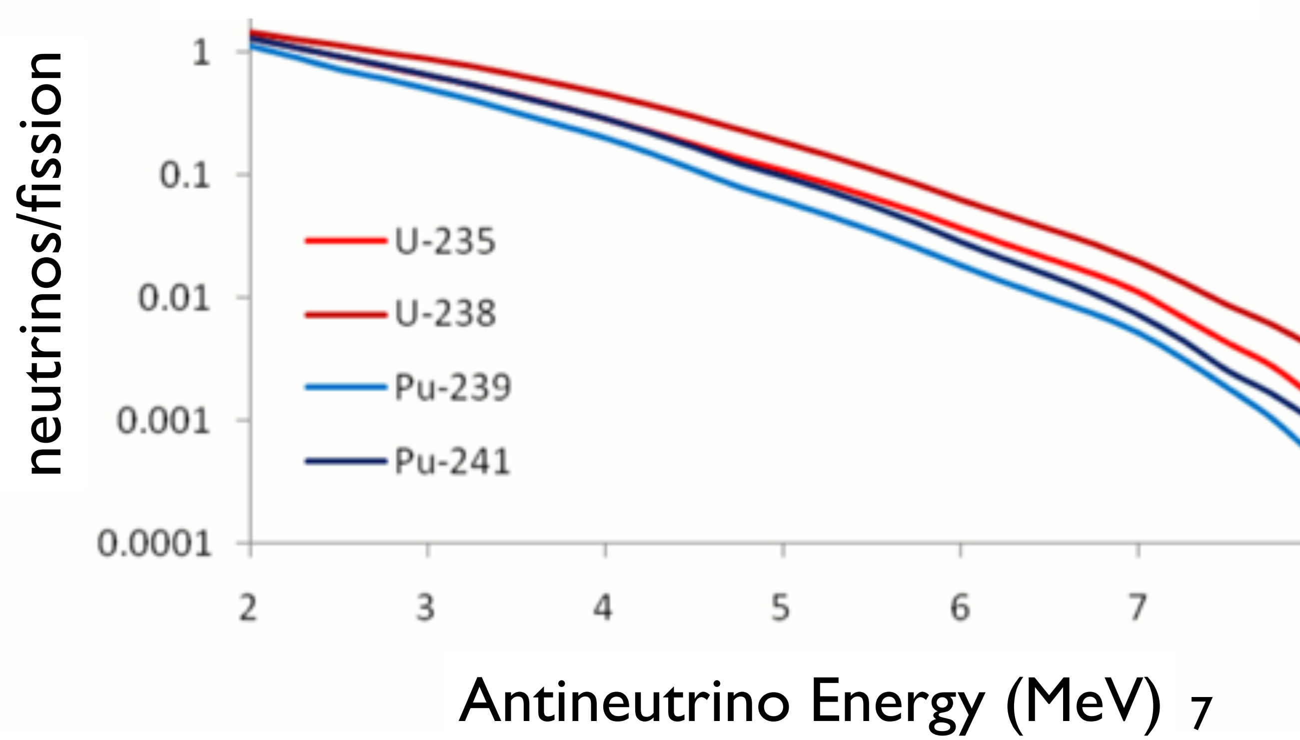




Spectrum

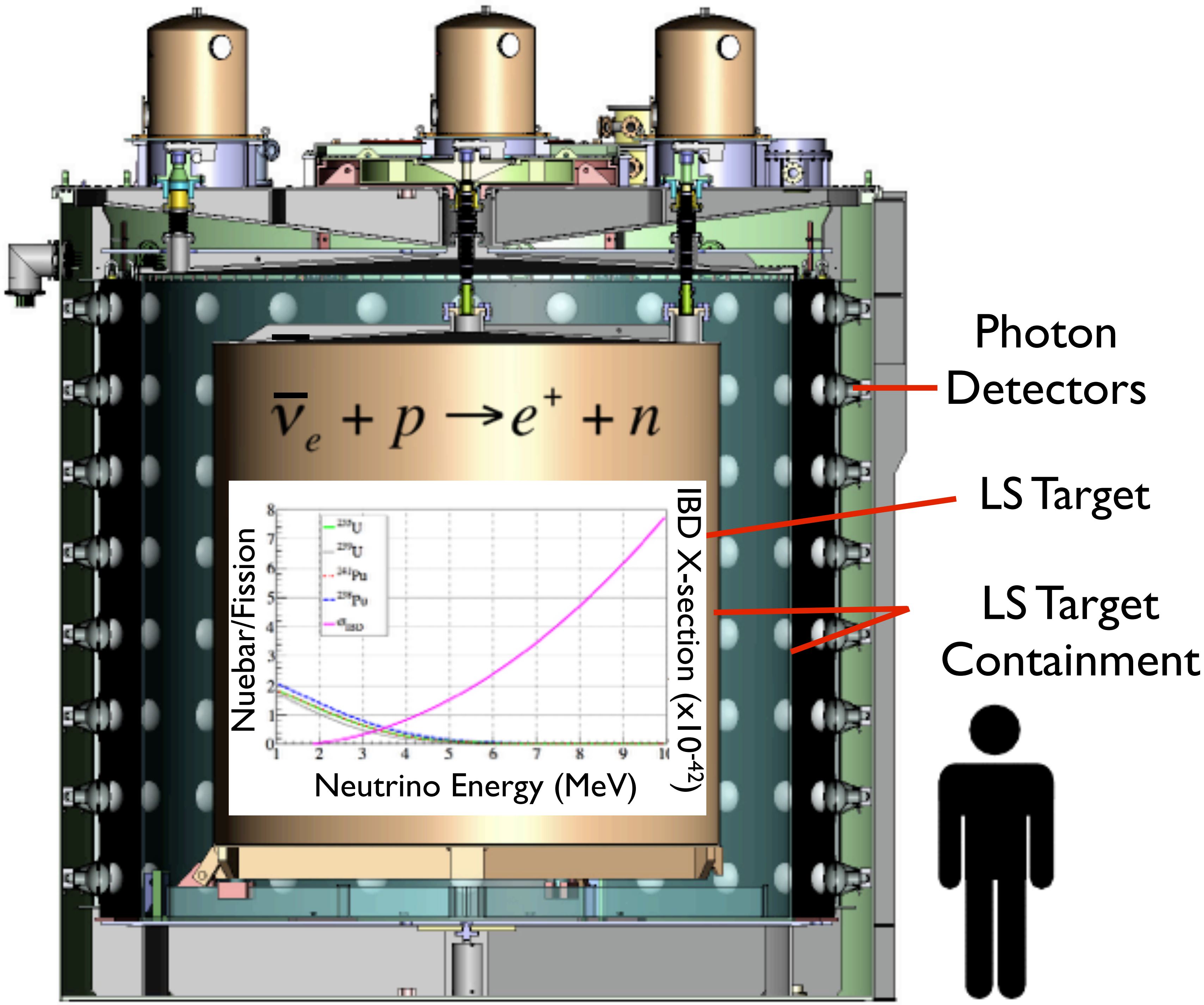
$$S(E) = \sum_i \boxed{F_i}\boxed{S_i(E)} \qquad F_i = \frac{W_{th} f_i}{\sum_k f_k E_k}$$

Fission Isotope $\boxed{i}$ Flux

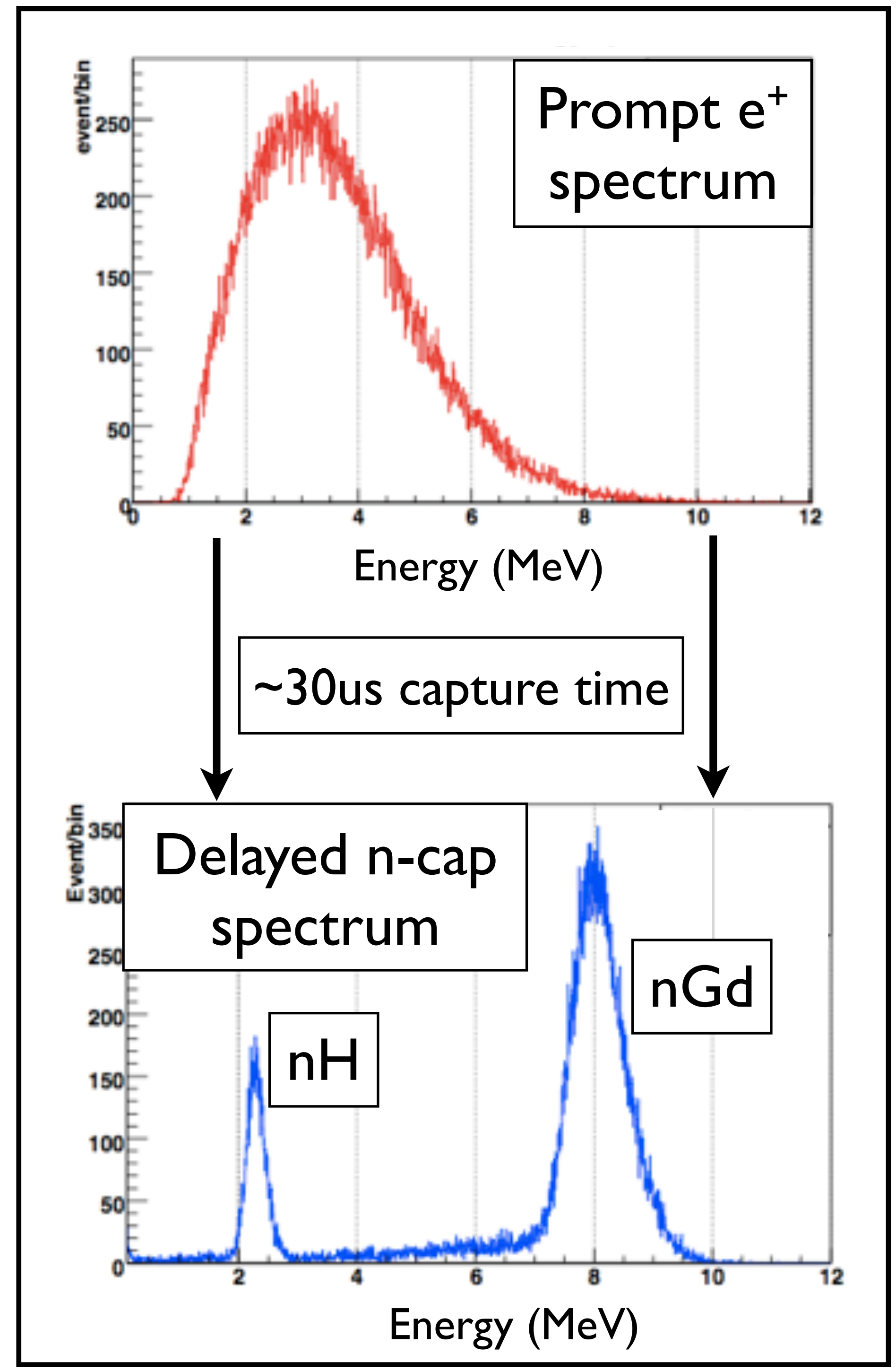


Reactor Antineutrino Detection

- 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

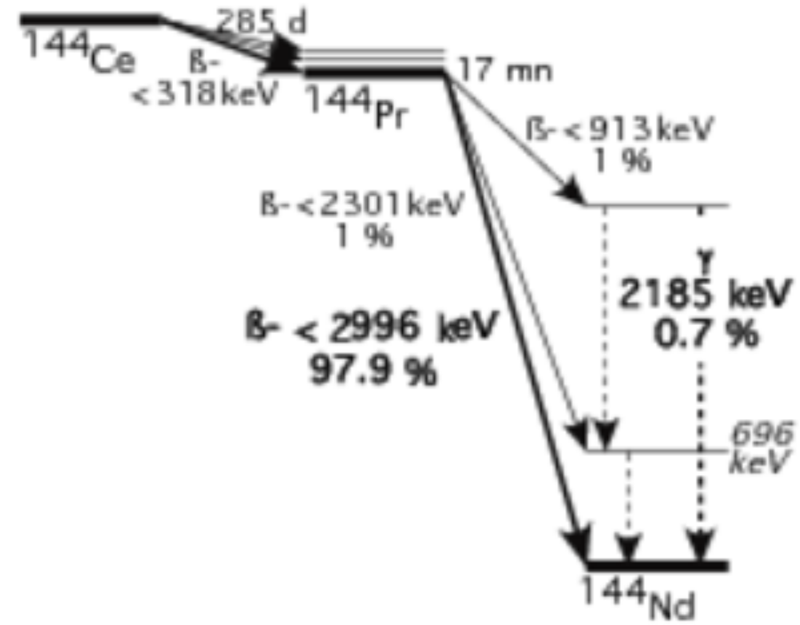
Predicting $S_i(E)$, Neutrinos Per Fission

- Two main methods:
- *Ab Initio* approach:
  - Calculate spectrum branch-by-branch 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 $\overline{\nu}_e$ 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

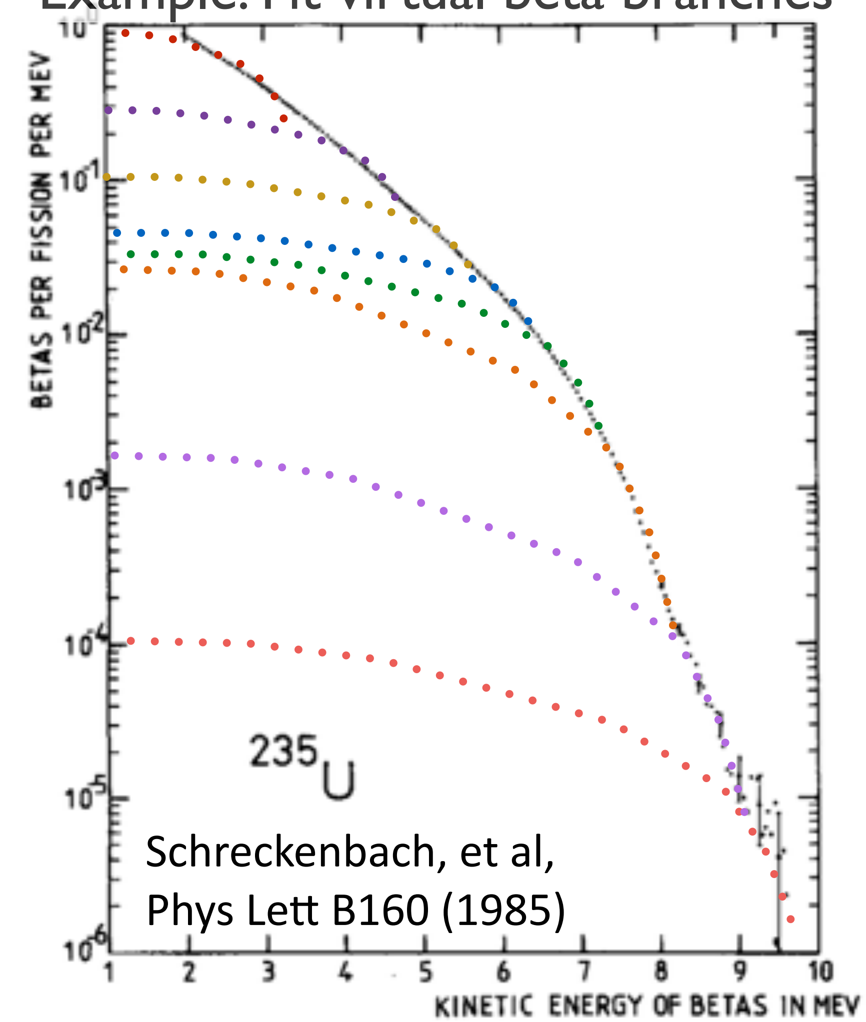
Carter, *et al*, Phys. Rev. 113 (1959)

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)

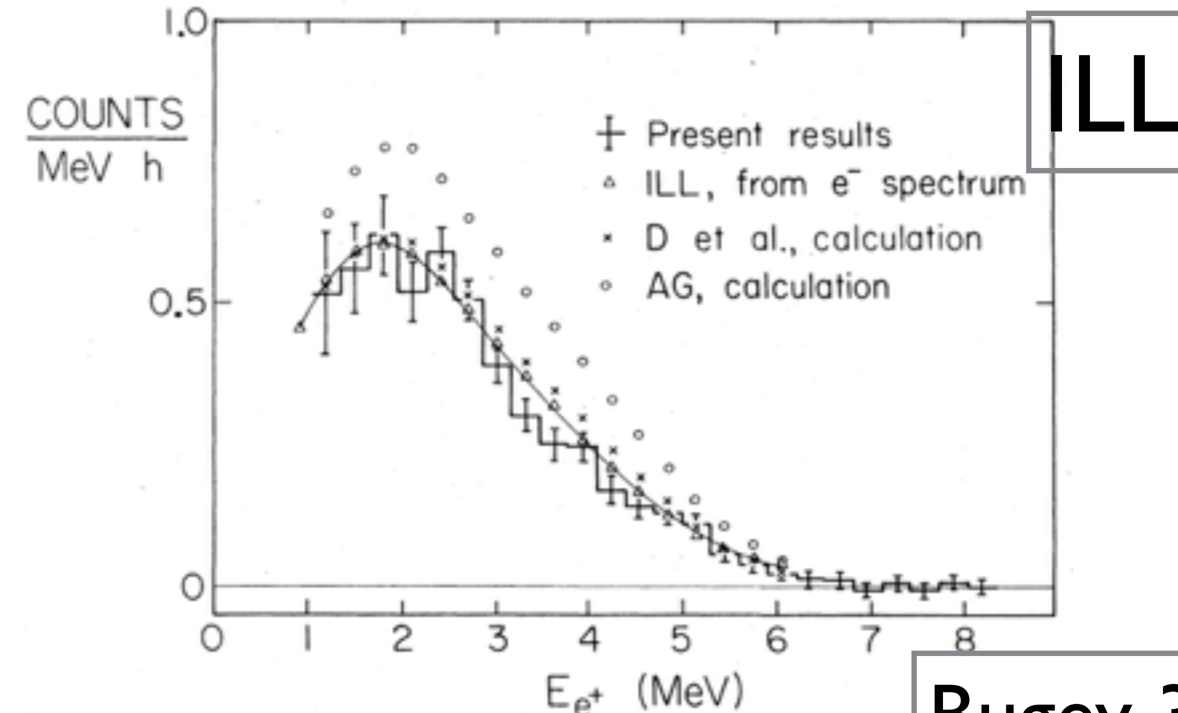
- 1980s: New reactor beta spectra: measurements — conversion now provides lower systematics

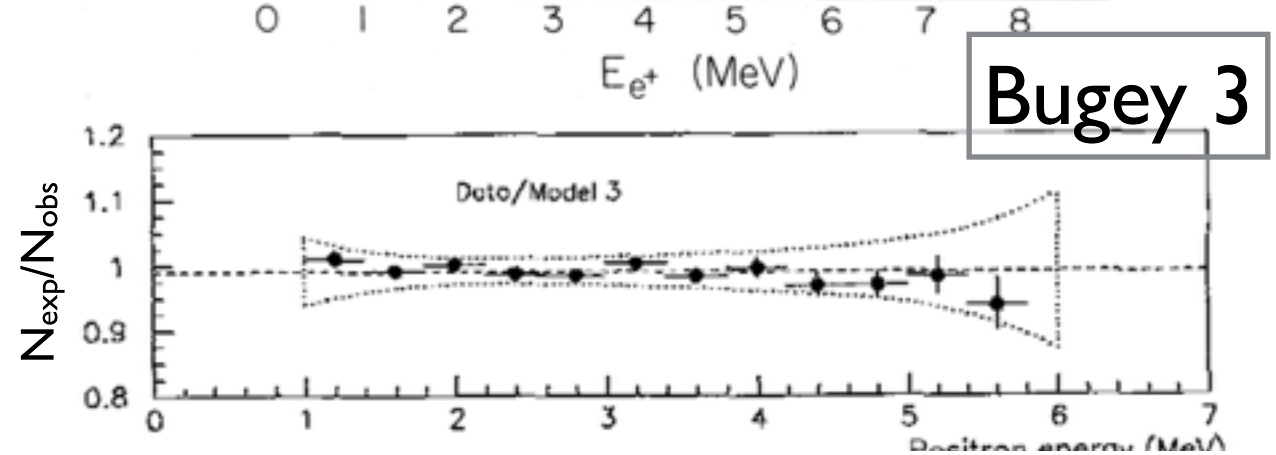
  Schreckenbach, *et al.*, Phys Lett **B**160 (1985)
  Schreckenbach, *et al.*, Phys Lett **B**218 (1989)

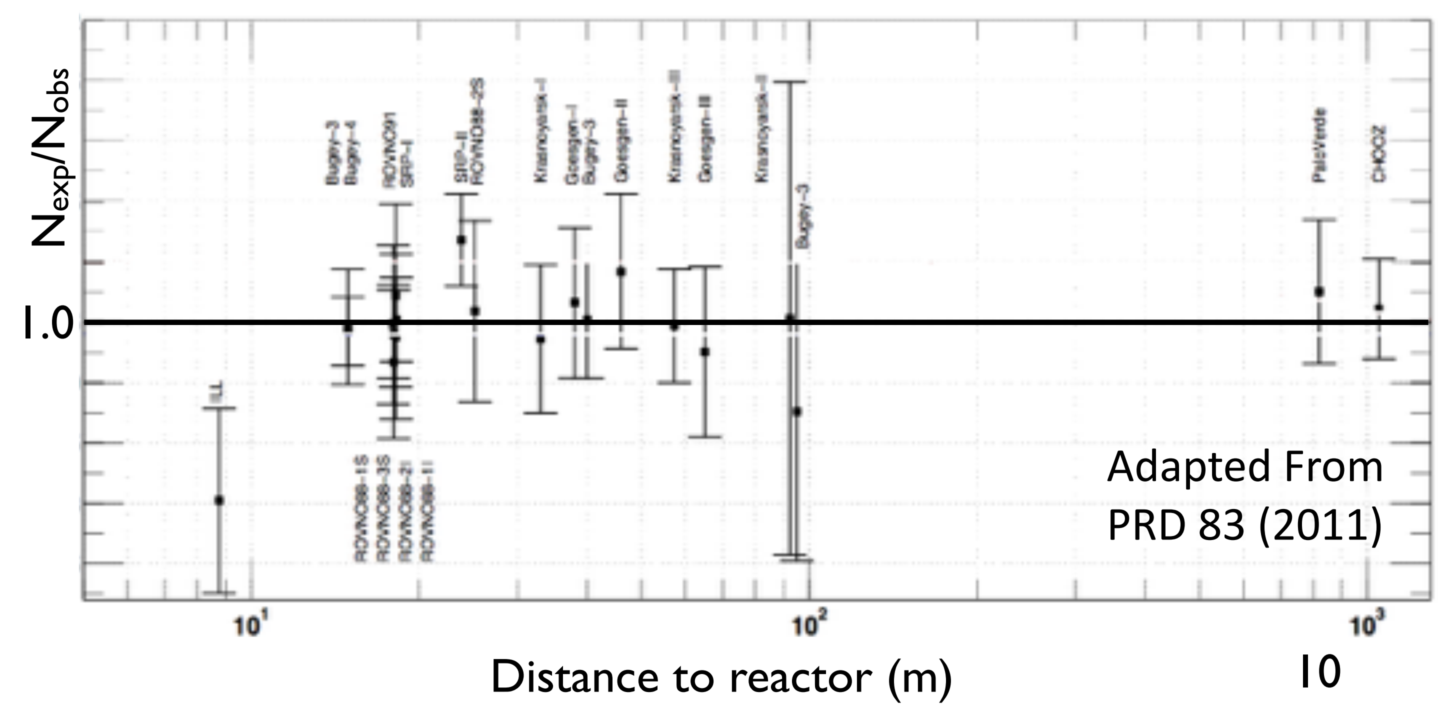
- 1990s: Bugey measurements fit converted spectrum well

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

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



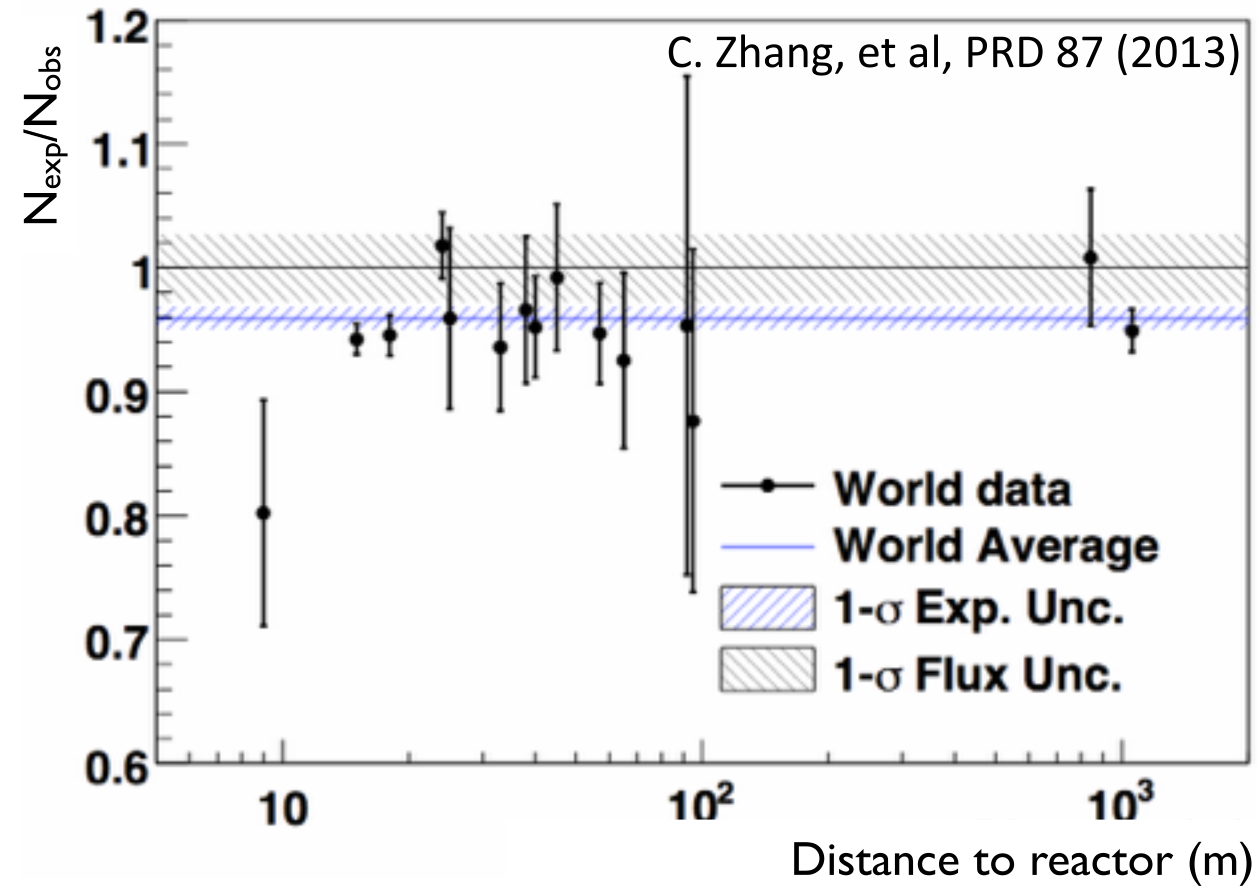


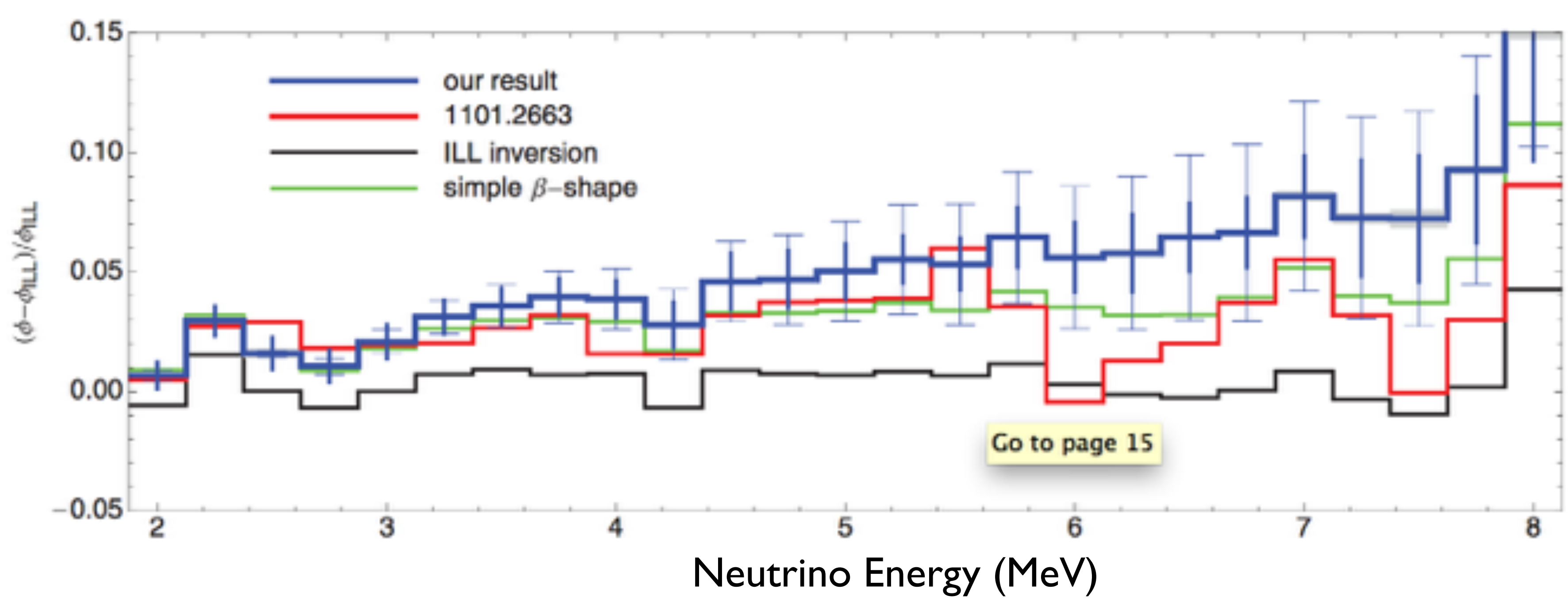


Recent History: Problems Emerge

- 2010s: Re-calculation of conversion for θ_{13} measurements
  - Start with ab initio approach
  - Subtract this from ILL beta spectra
  - Use conversion procedure on remaining beta spectrum: ~10%
  - OR Huber: virtual branches only
- Change in flux/spectrum!
  - Flux increase from:
    - Conversion (~3%)
    - X-section (1%)
    - Non-equilibrium isotopes (1%)

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





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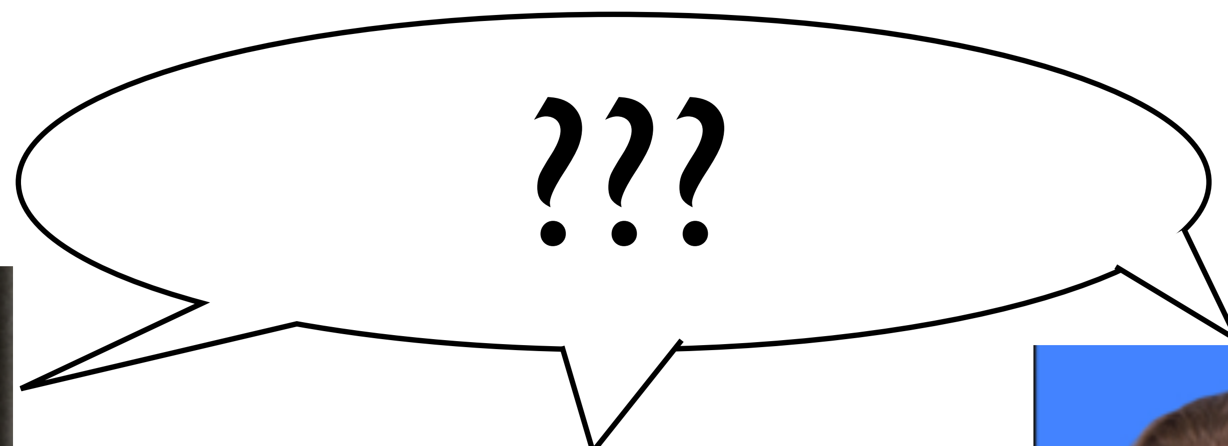
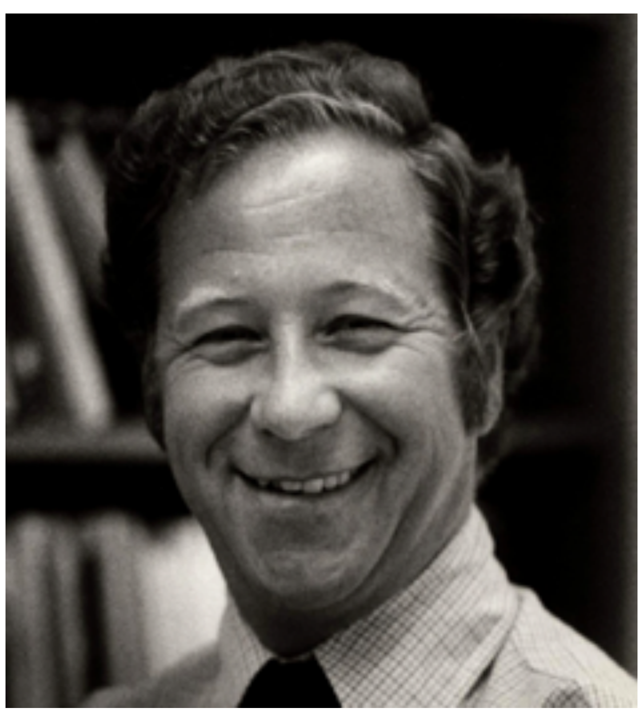
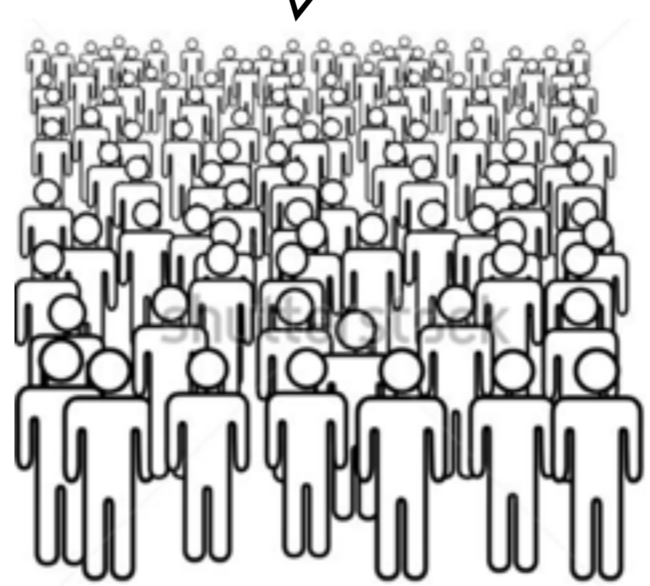
Reactor Antineutrino Anomaly?

- 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."
  - "Yes: but probably attributable to uncertainties in the beta-to-ν_e conversion."
  - "Yes: the deficit could result from short-baseline sterile neutrino oscillations."





P. Vogel, Caltech



The rest of us

T. Lasserre, CEA, France

P. Huber, VTech

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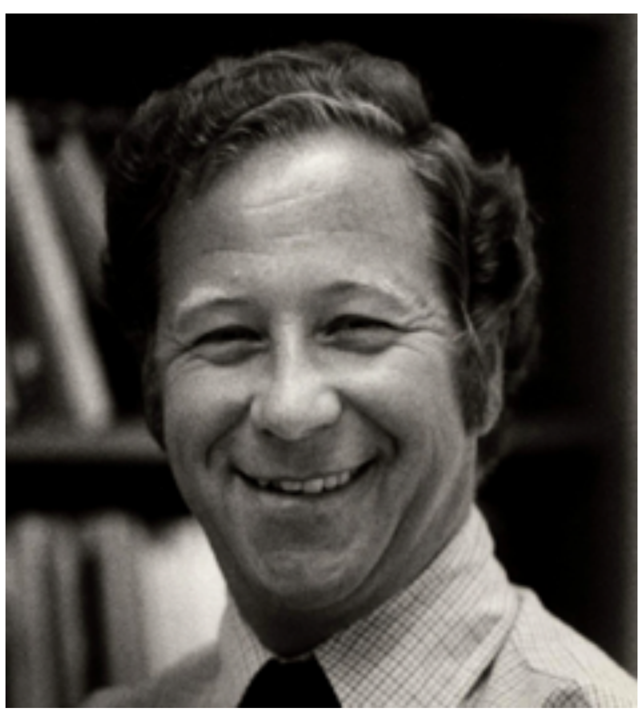
We need more data!!



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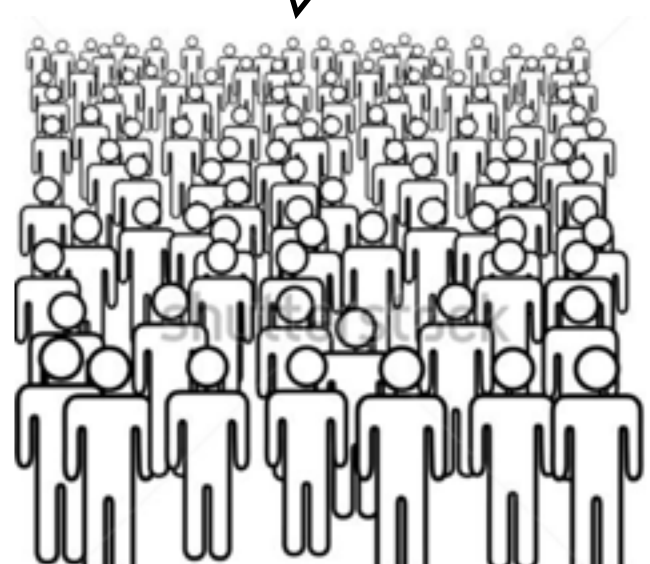

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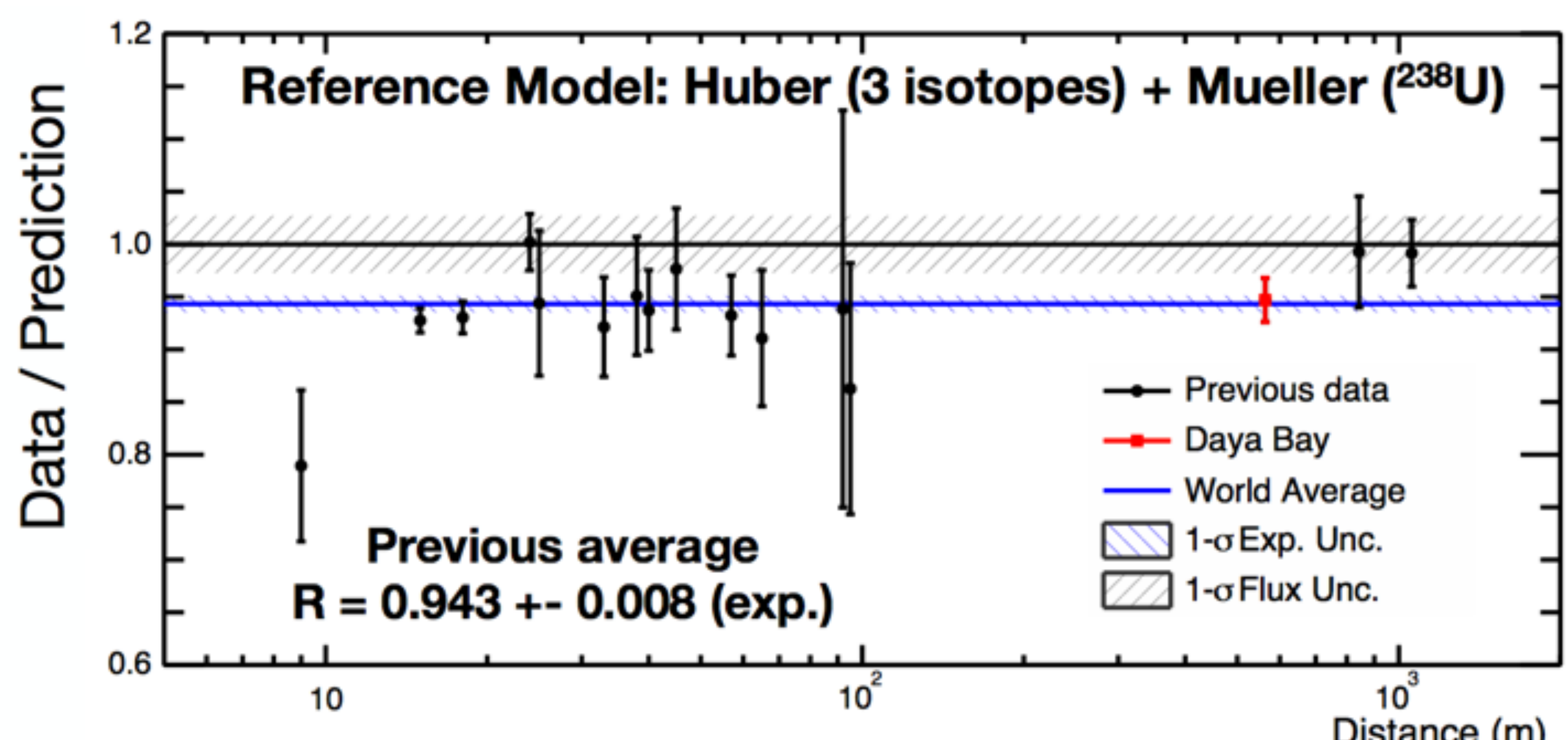
Reactor Anomaly Explanations

- 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

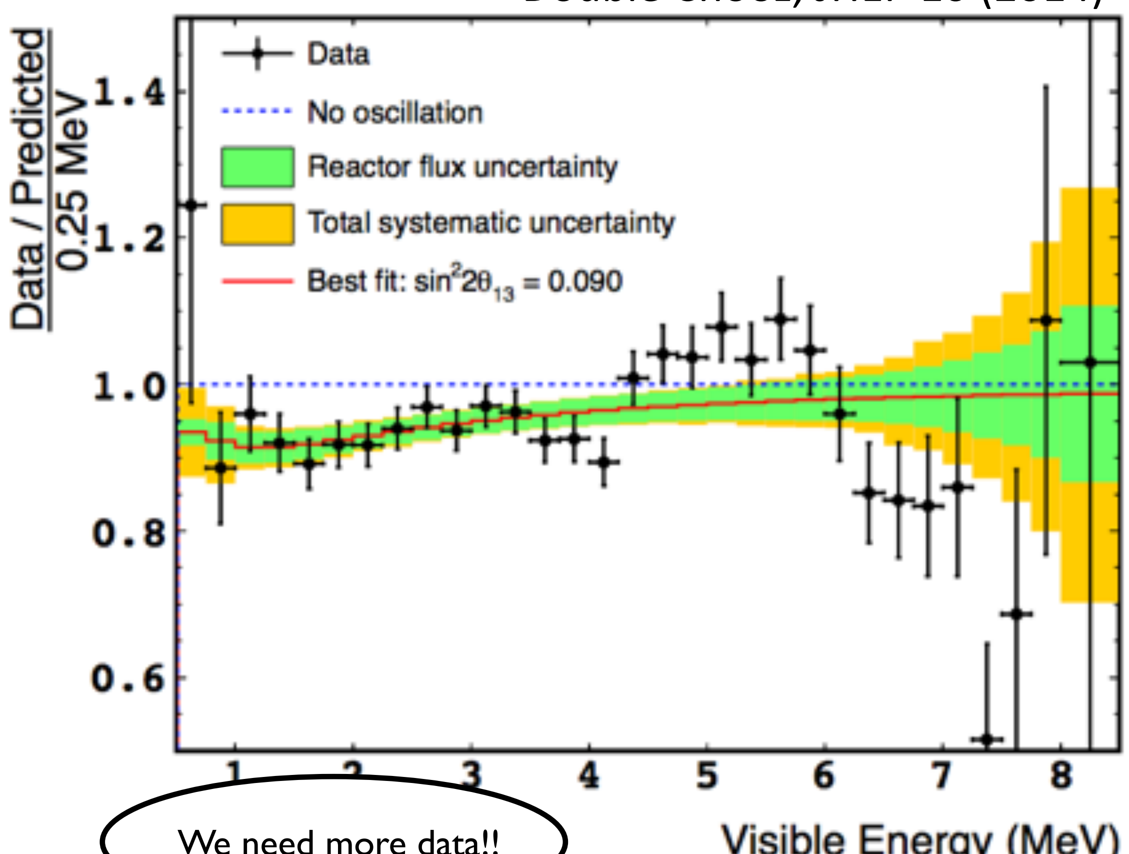
C. Zhang (Daya Bay)
Neutrino 2014



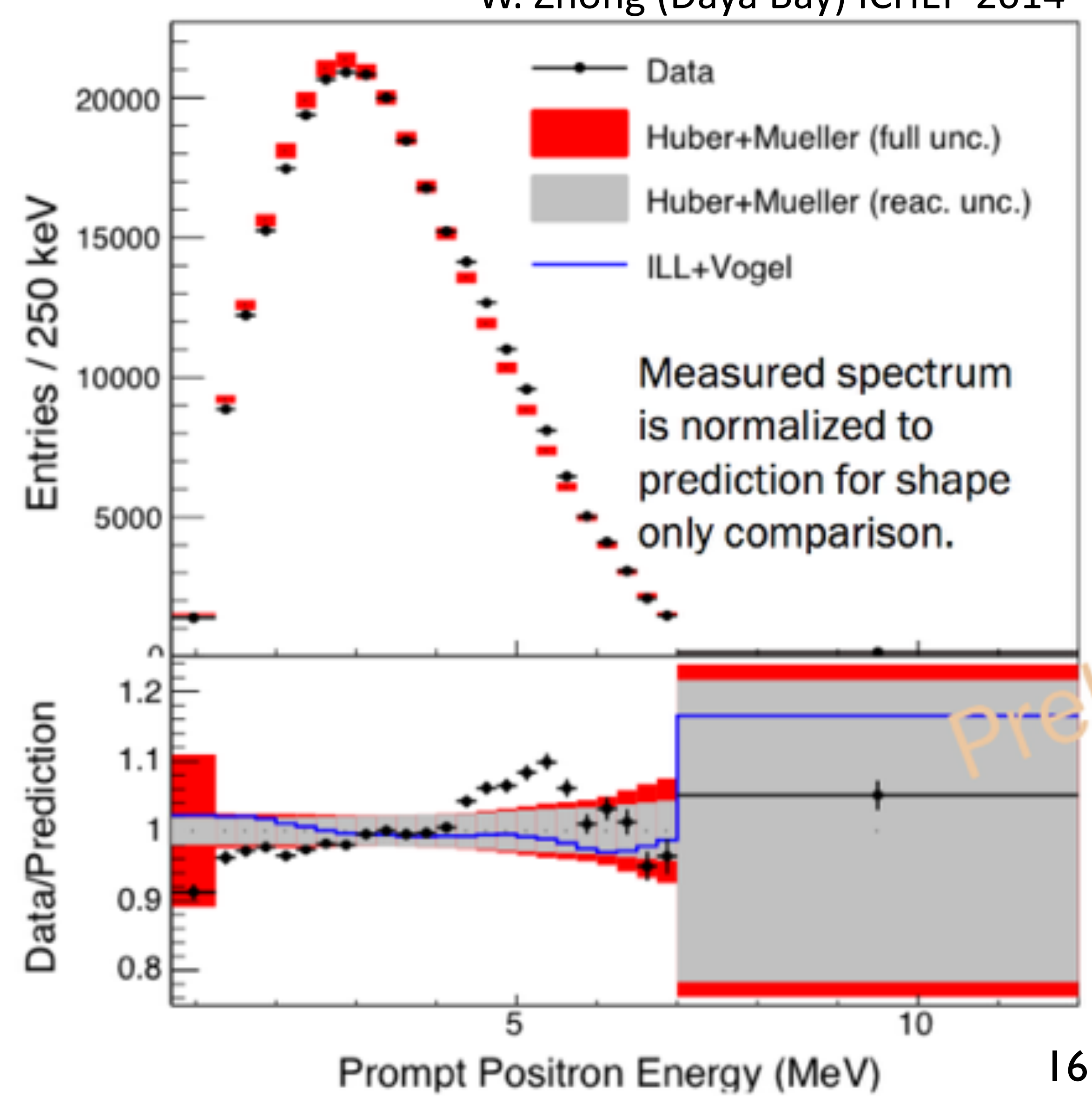
Reactor Anomaly Explanations

- 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?”

Double Chooz, JHEP 10 (2014)



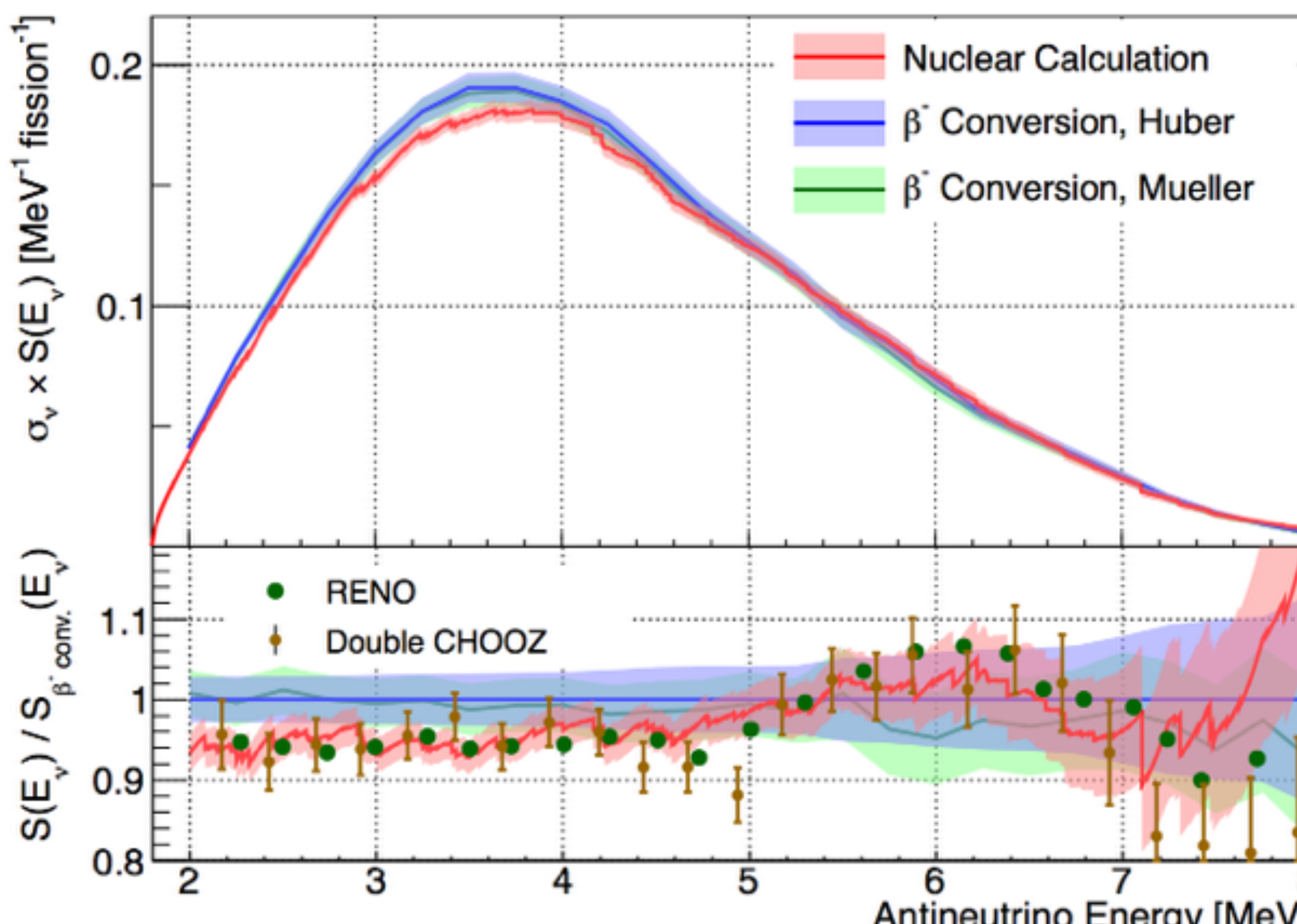
W. Zhong (Daya Bay) ICHEP 2014



Reactor Anomaly Explanations

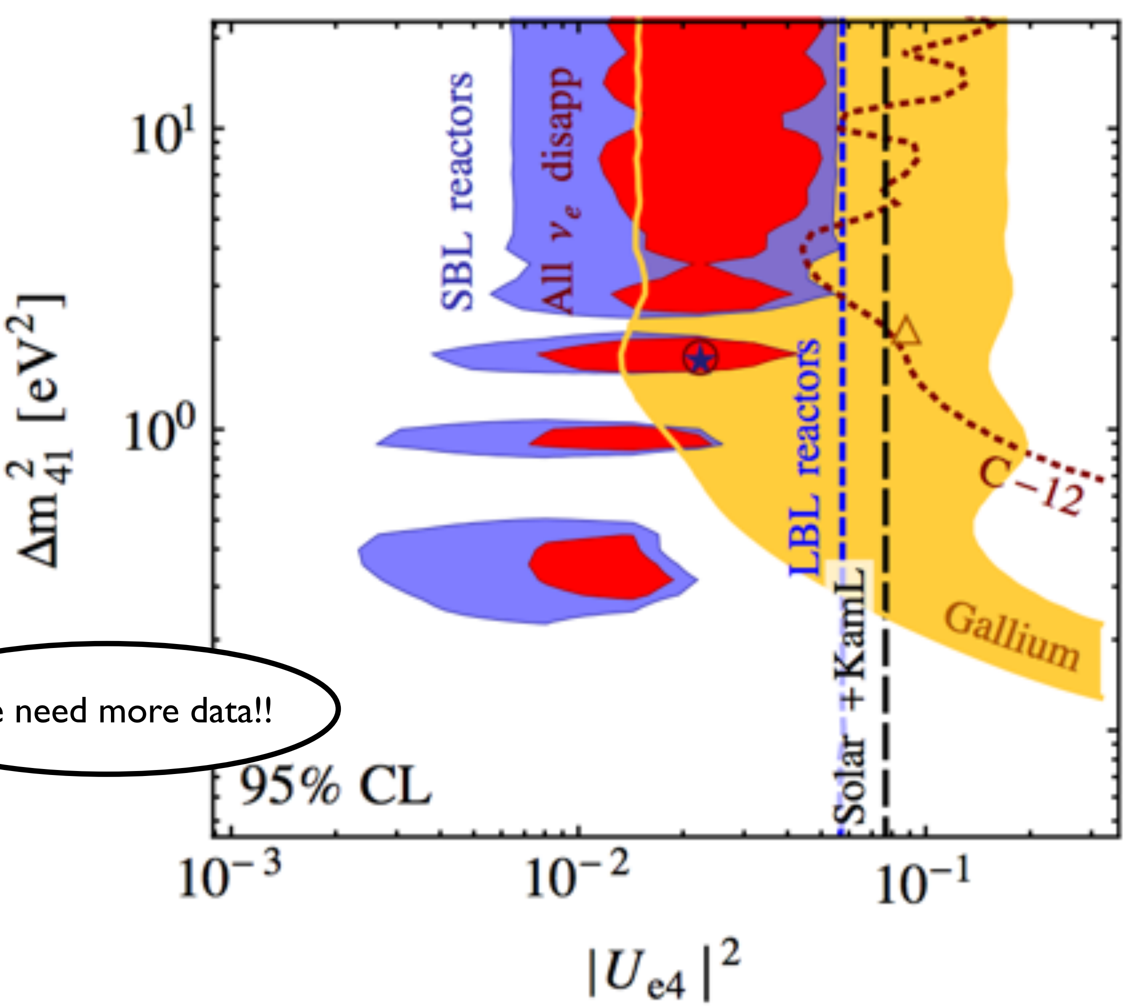
- Do we have a 'reactor antineutrino anomaly?'
  - "Yes: it's probably attributable to problems in the beta-to-ν_e conversion"
- New *ab initio* shape seems to match RENO/DC data quite well
  - But not the flux…?
  - Not enough data to constrain this situation further!

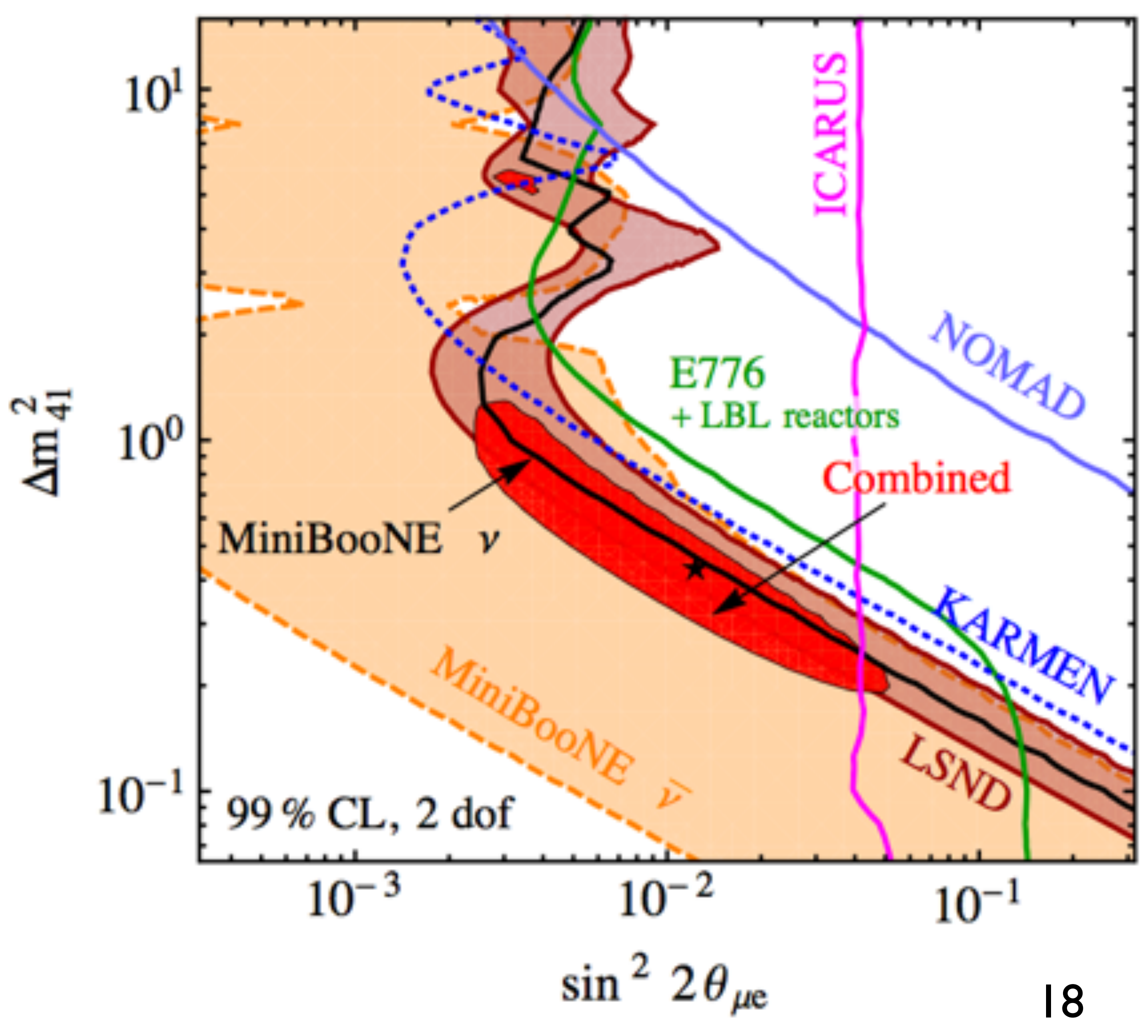
Dwyer and Langford, arxiv:[nucl-ex]1407.1281 (2014)



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…



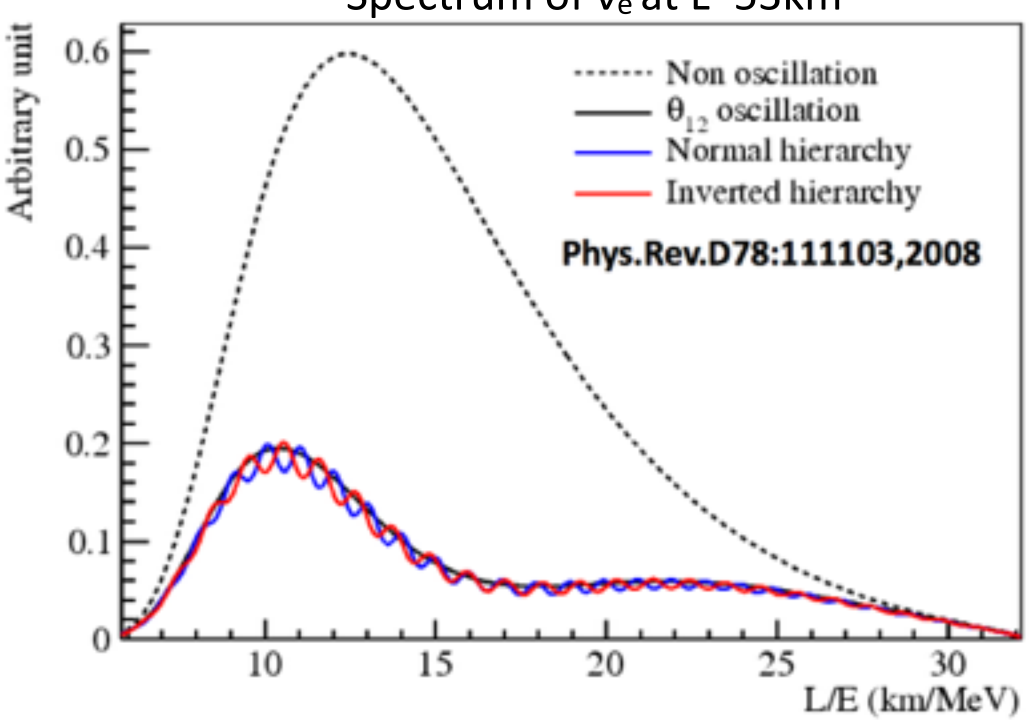


Reactor Spectrum: Why Do We Care?

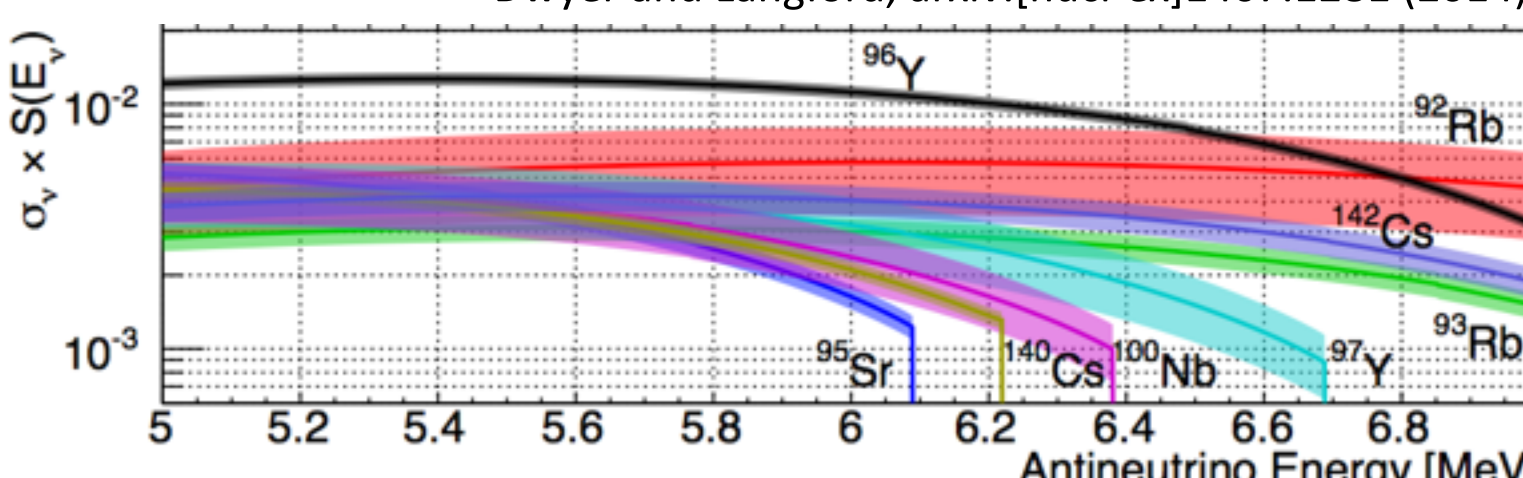
- Major implications for Standard Model if ν_s DO actually exist
- Even if they do not, ability to constrain reactor $\overline{\nu}_e$ models
  - Valuable for reactor oscillation experiments
  - Inputs to reactor modeling
  - 'Reactor spectroscopy:' probe individual branches in reactor spectrum
  - Implications for non-proliferation

Buttons Provided by Neutrino2014!
Sweater Provided by J. Asaadi

Spectrum of ν_e at L~53km



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



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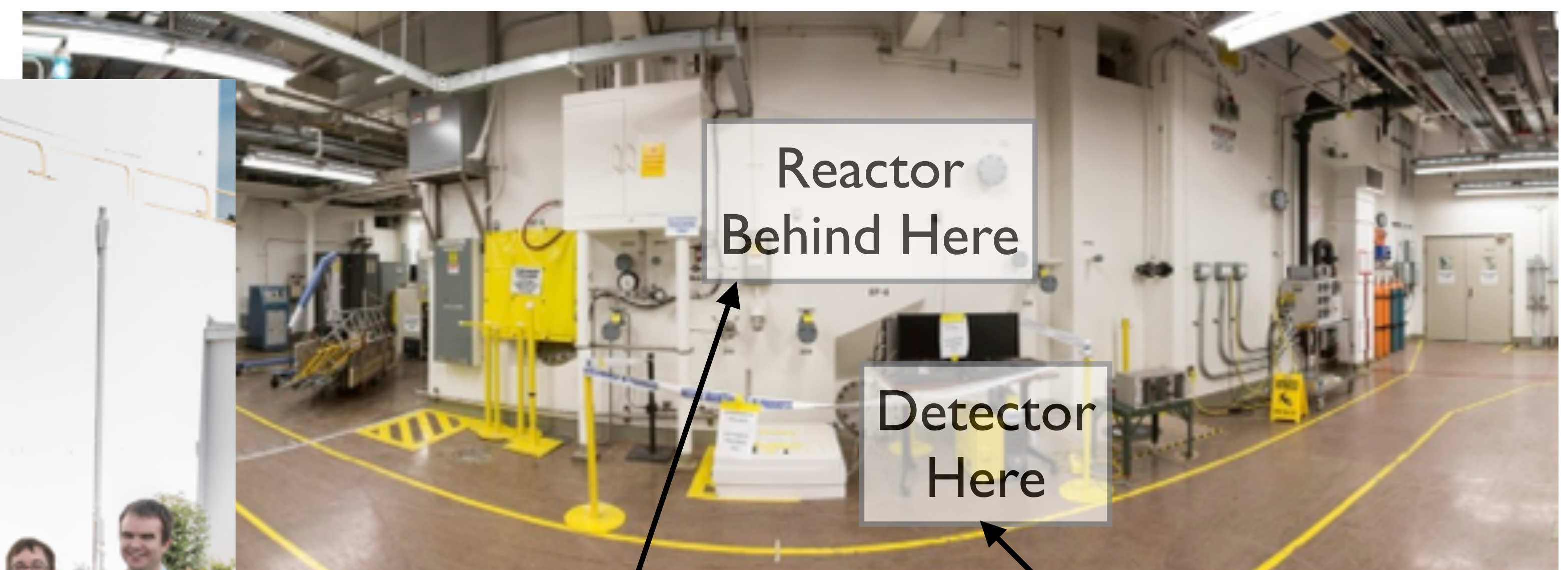
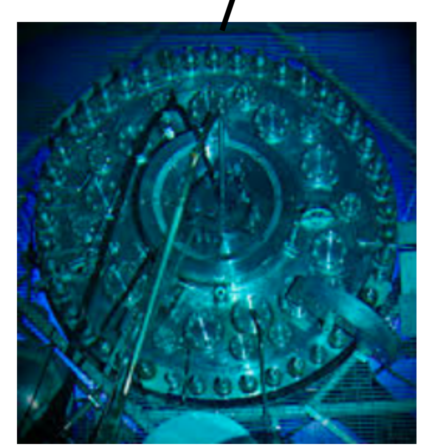
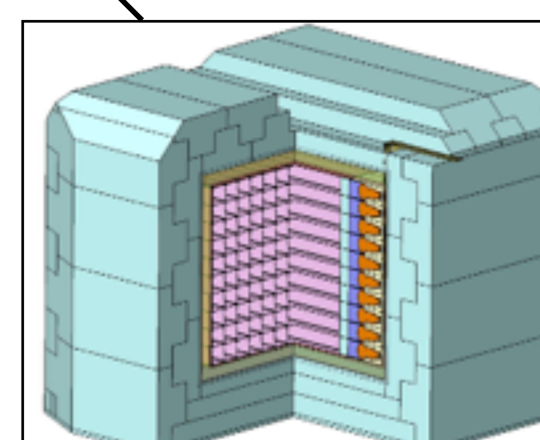
Precise Reactor Spectrum Measurements

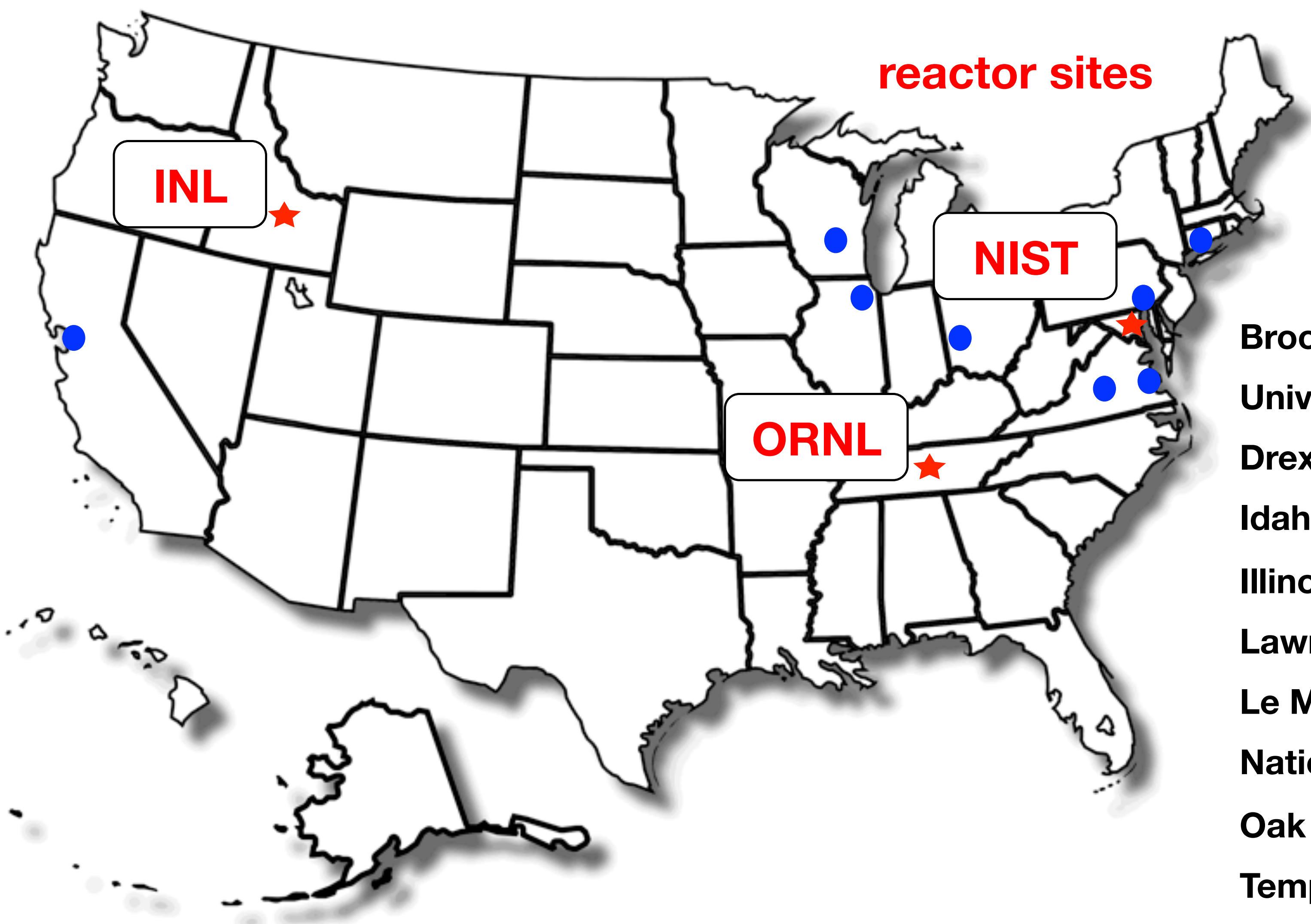
- A lot yet to be learned from/about reactor $\bar{\nu}_e$ spectra
- In particular we could really use:
  - A high energy-resolution detector for precisely measuring absolute spectrum
  - A high position-resolution detector for comparing spectra between baselines
- Enter PROSPECT: the Precision Reactor Oscillation and SPECTrum Experiment







PROSPECT Collaboration



58 collaborators
11 universities
5 national laboratories

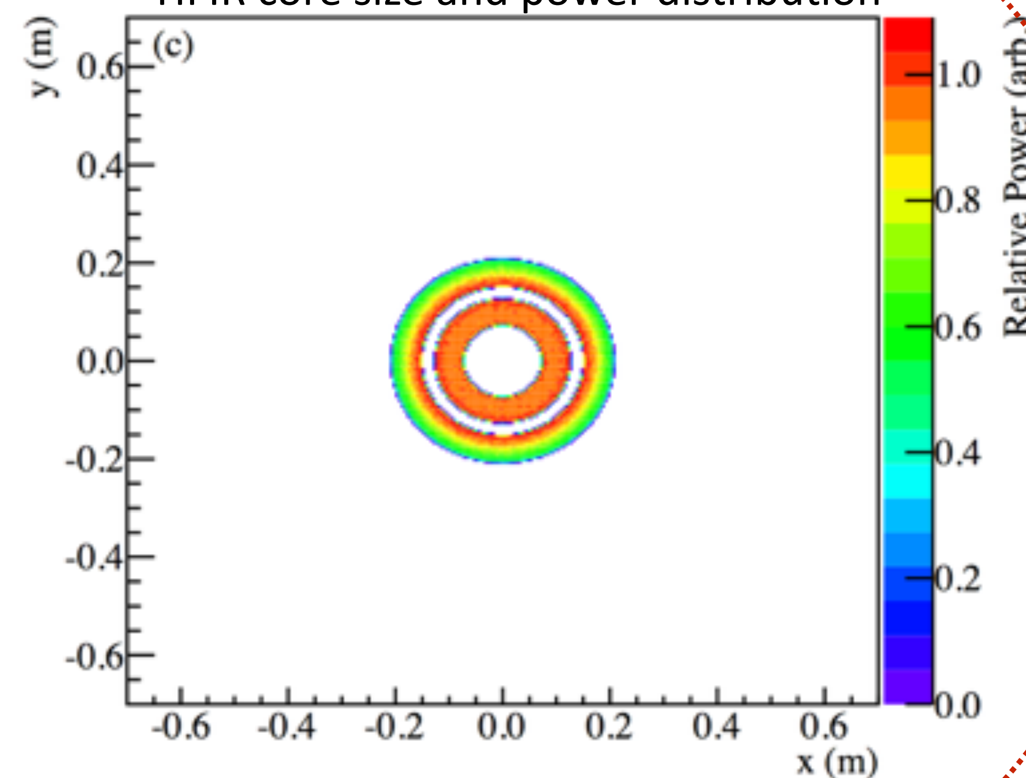
Brookhaven National Laboratory
University of Chicago
Drexel University
Idaho National Laboratory
Illinois Institute of Technology
Lawrence Livermore National Laboratory
Le Moyne College
National Institute of Standards and Technology
Oak Ridge National Laboratory
Temple University
University of Tennessee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

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

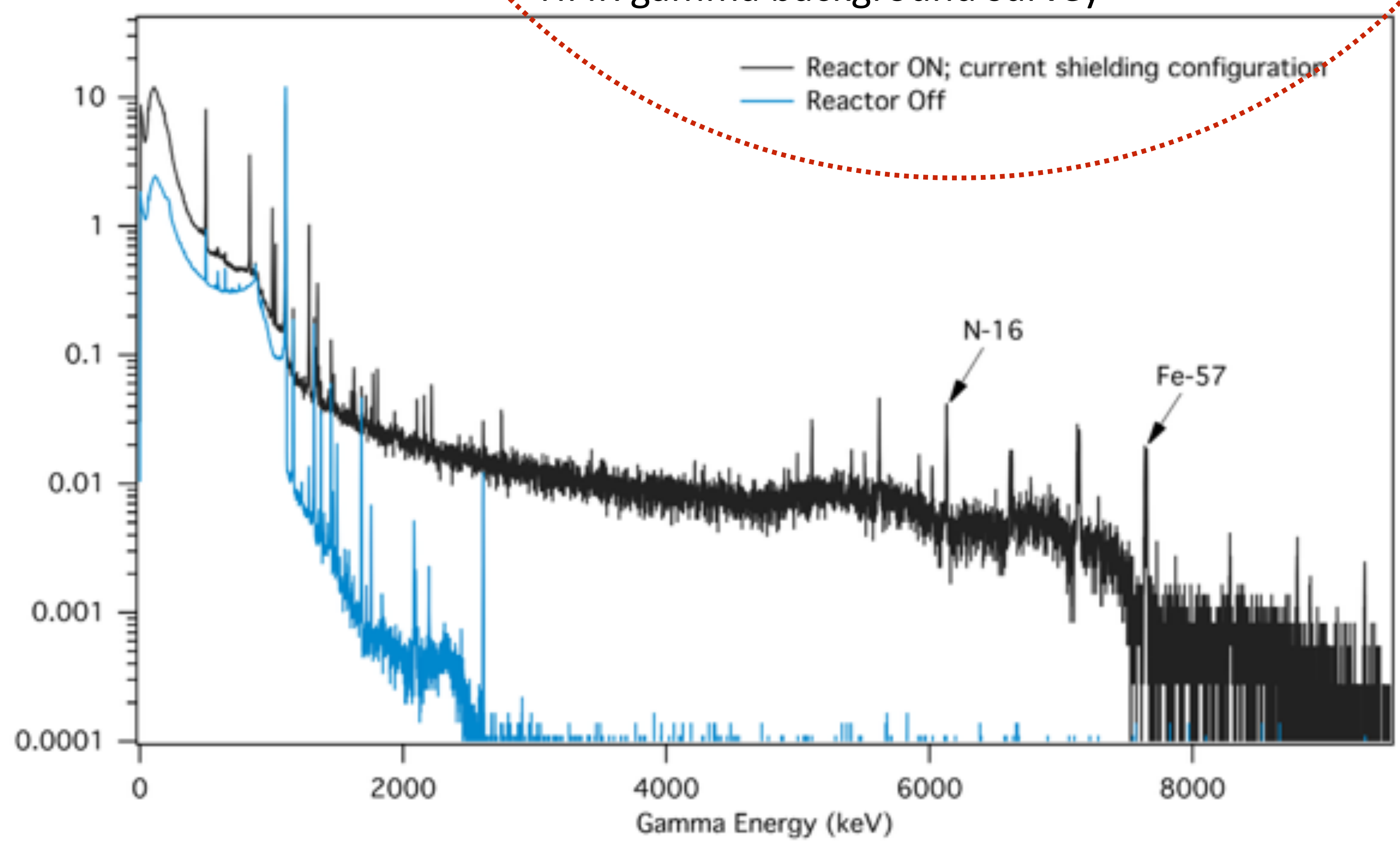
Commercial core size

HFIR core size and power distribution



HFIR core viewed from above

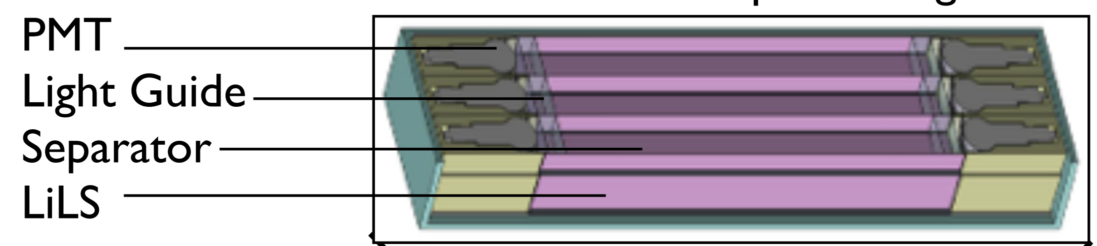
HFIR gamma background survey

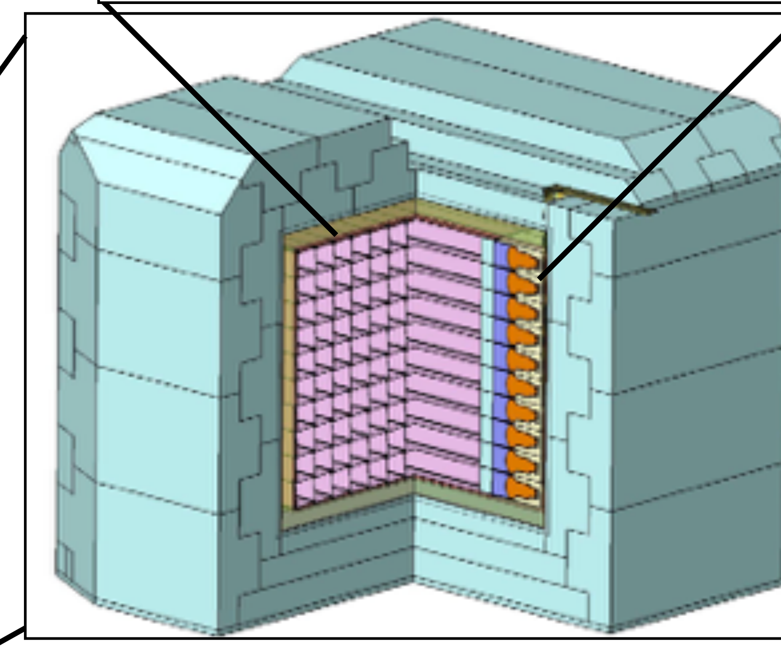


PROSPECT Experimental Layout

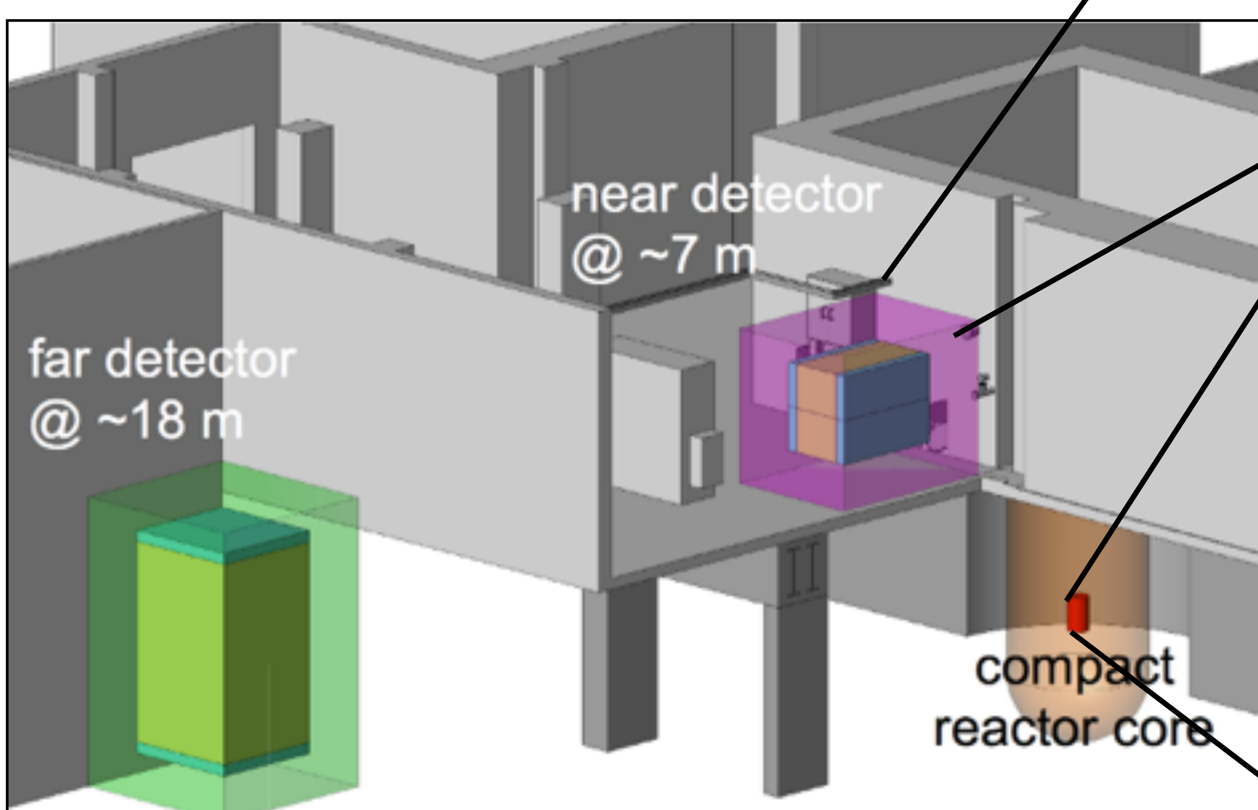
- High Flux Isotope Reactor: ORNL
- Extensive passive shielding
- Segmented liquid scintillator target region: ~3 tons for near detector (Phase I)
- Moveable: 7-11 m baselines

Sub-cell conceptual design

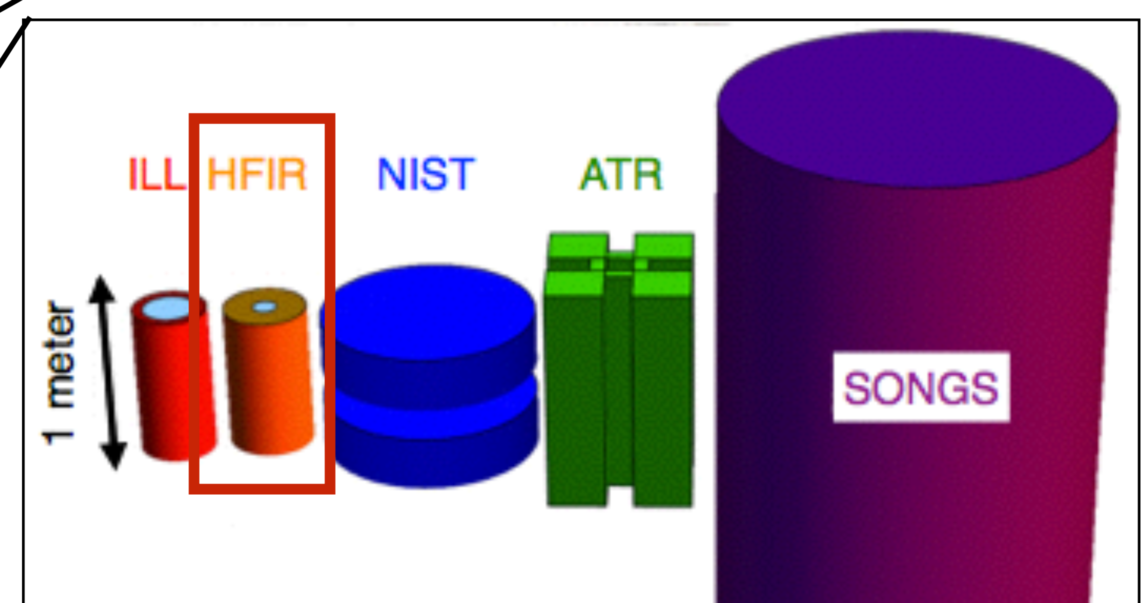




Near detector conceptual design



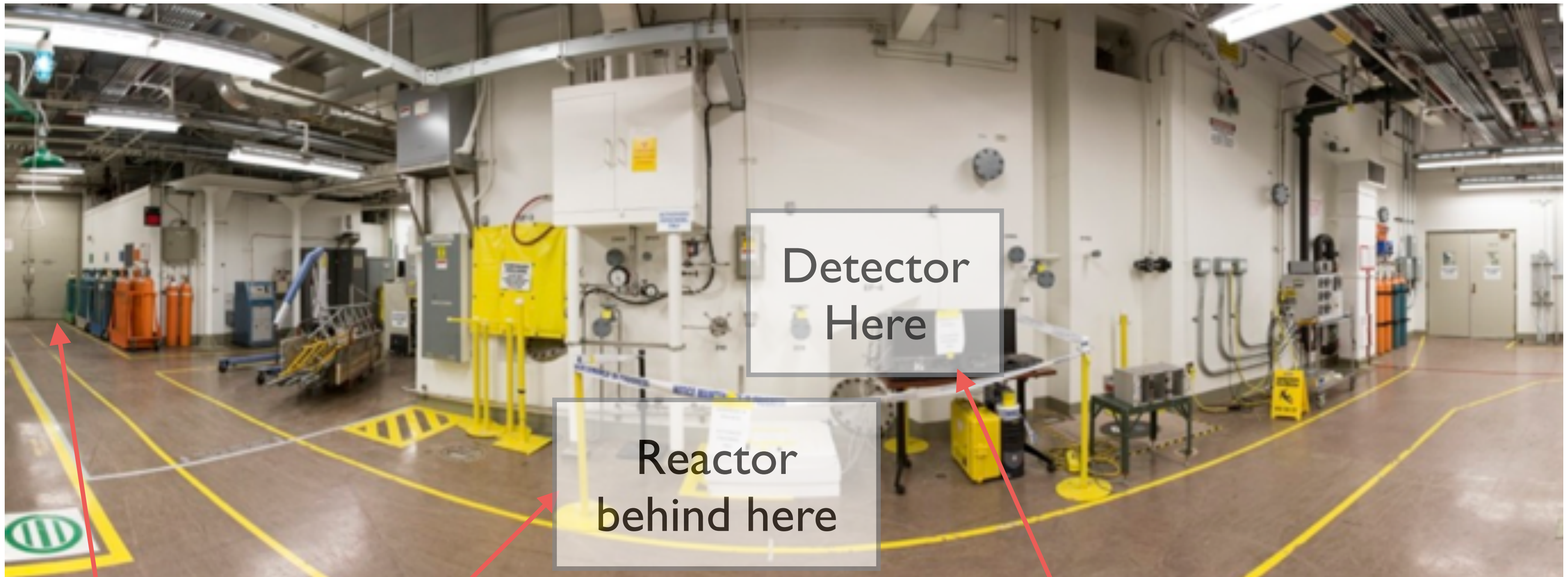
Two-detector PROSPECT deployment at HFIR



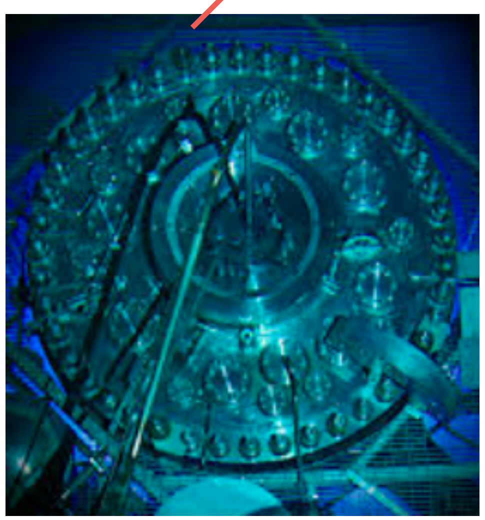
HFIR core shape and relative size comparison

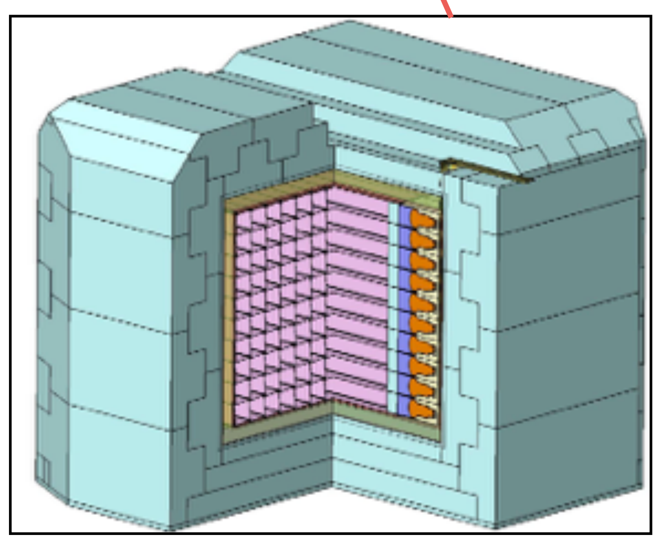
PROSPECT Location at HFIR

HFIR Main Level Hallway

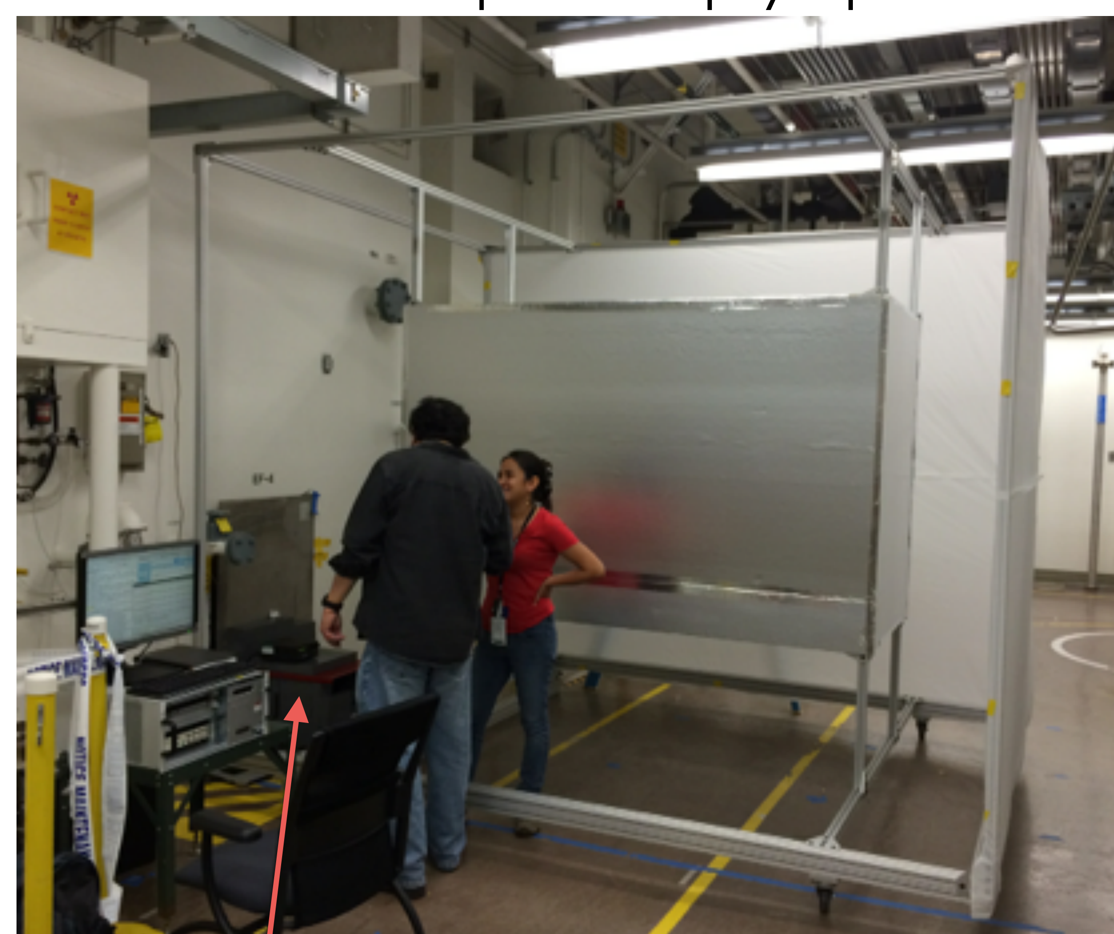


Wide door to grade level: bring detector subsystems in here





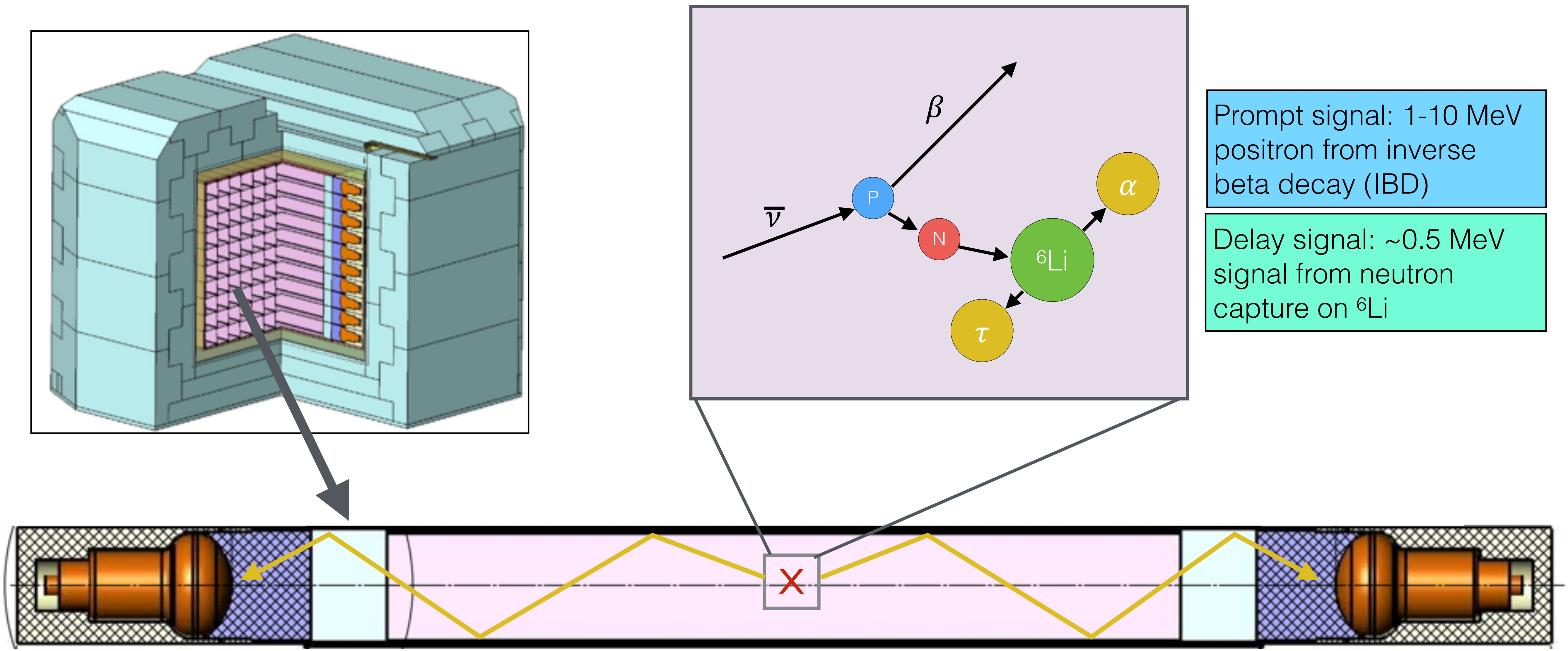
Detector mockup in true deployed position



Gamma background survey detectors

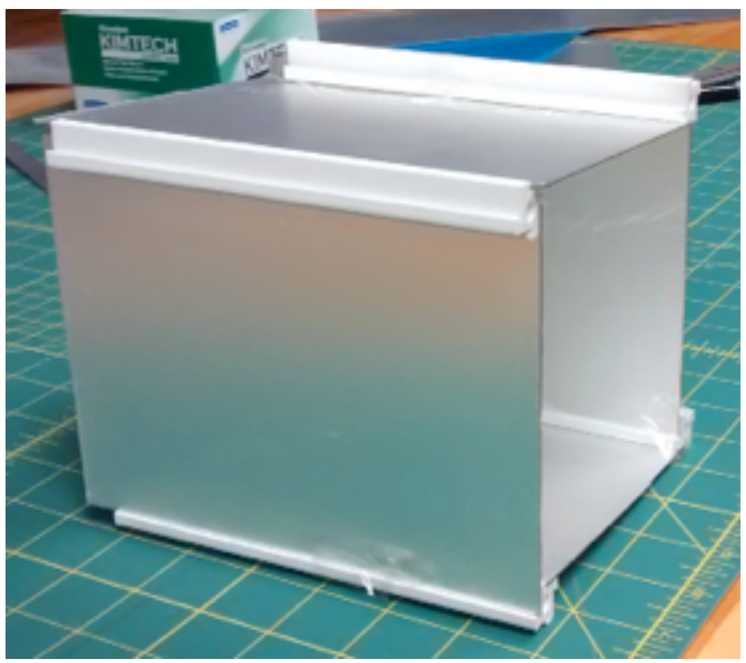
IBD Detection in Target

- Inverse beta interactions in Li-loaded PSD 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



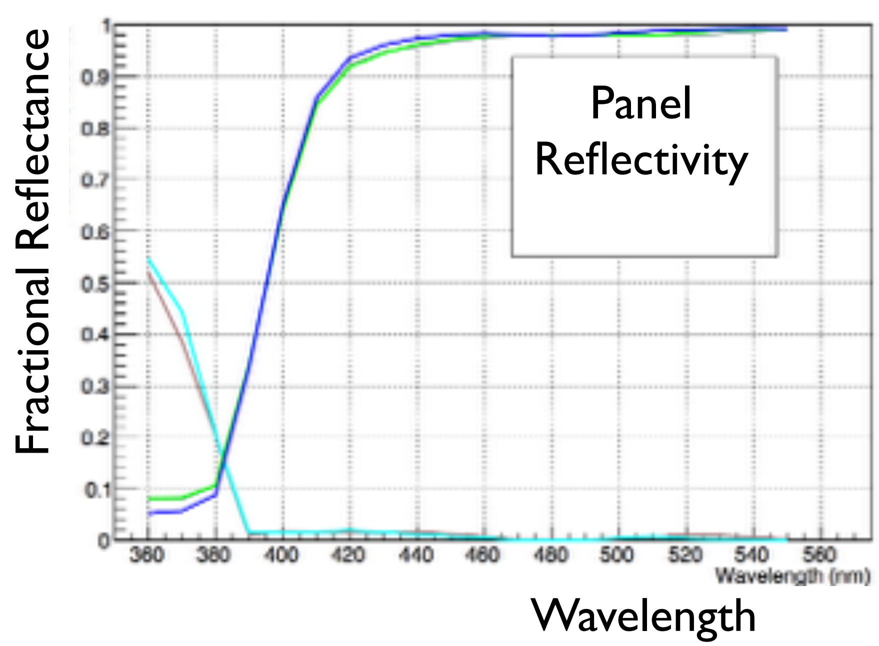
Detector Target R&D

- Reflecting segment system
  - Fabrication method identified
  - Testing differing materials

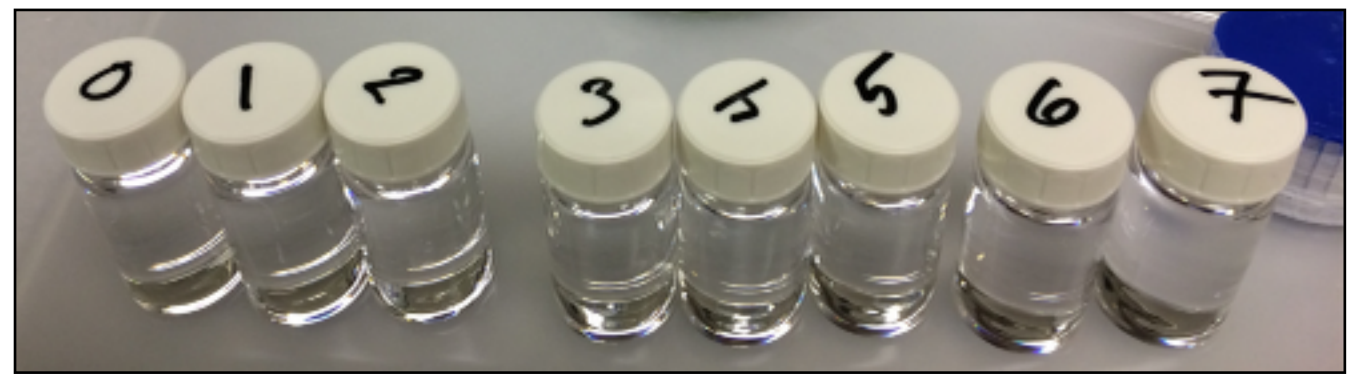


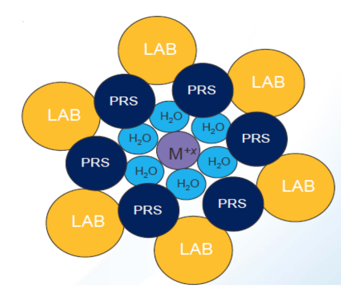
Short Mockup Segment

Specular Panel



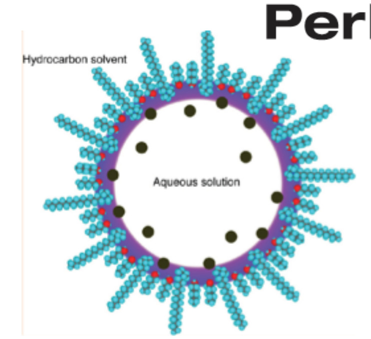
- Li-loaded Scintillator
  - Formulation methods identified
  - Numerous candidates produce desired scintillation light yield, timing





PSD enhanced LAB-LS doped with BNL ^{6}Li chemistry

PerkinElmer

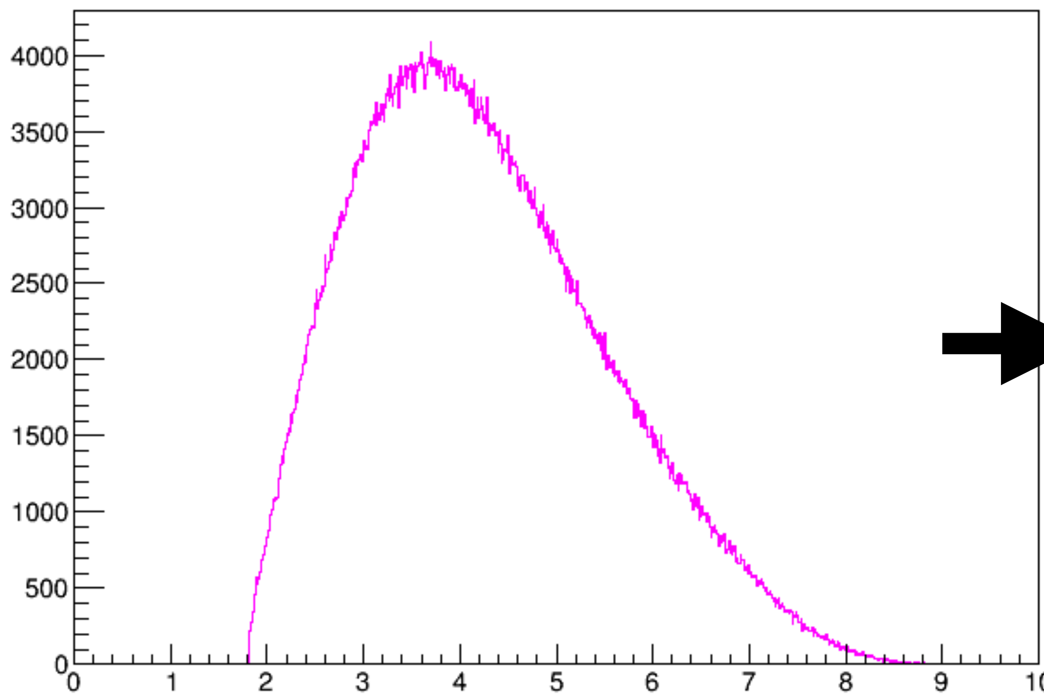


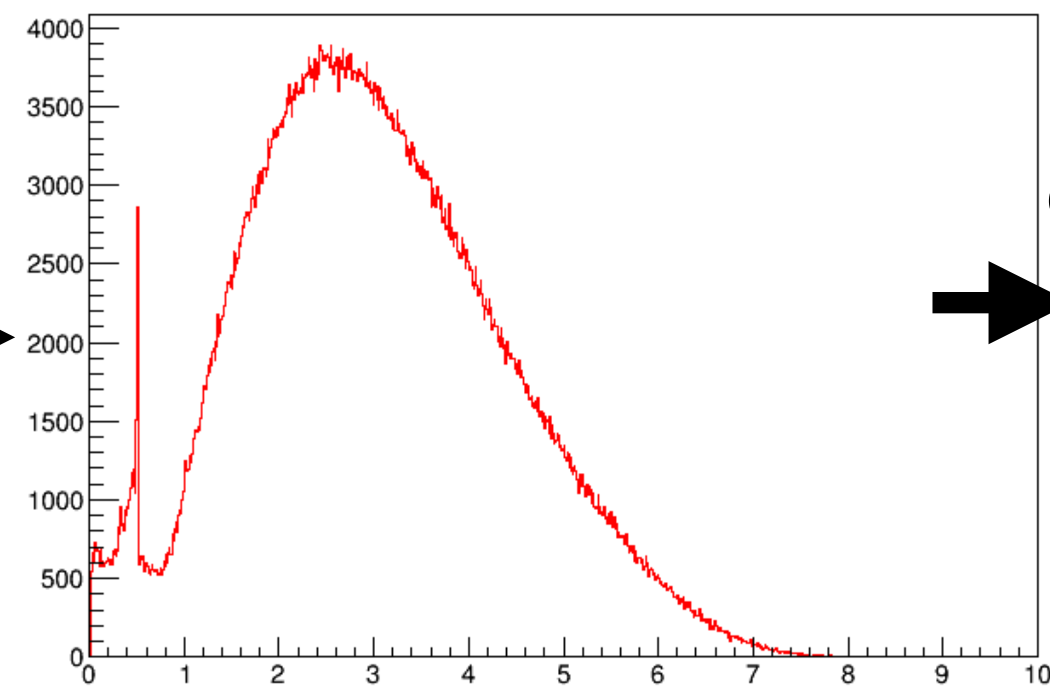
Ultima-Gold doped with NIST ^{6}Li micro-emulsion

IBD Detector Response: Simulation

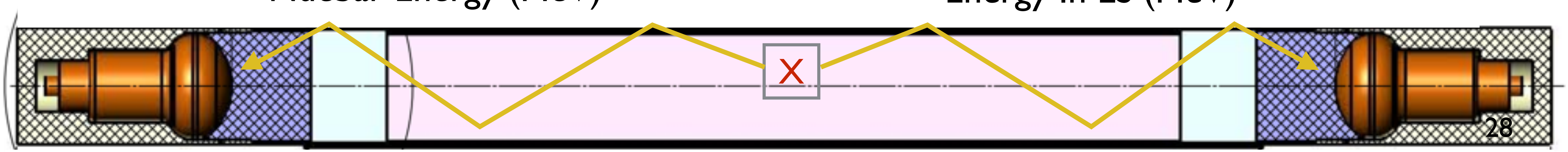
- Must reconstruct e^+ energy with high resolution and low bias
- Model response with lab-benchmarked simulations
  - Energy deposition outside LS
  - Normalization and linearity of light production, collection, etc. with energy
  - Light yield variations along cell
  - Variations between cells

PROSPECT detector simulations





Optics simulations, Relative cell response simulations underway



IBD Detector Response: Simulation

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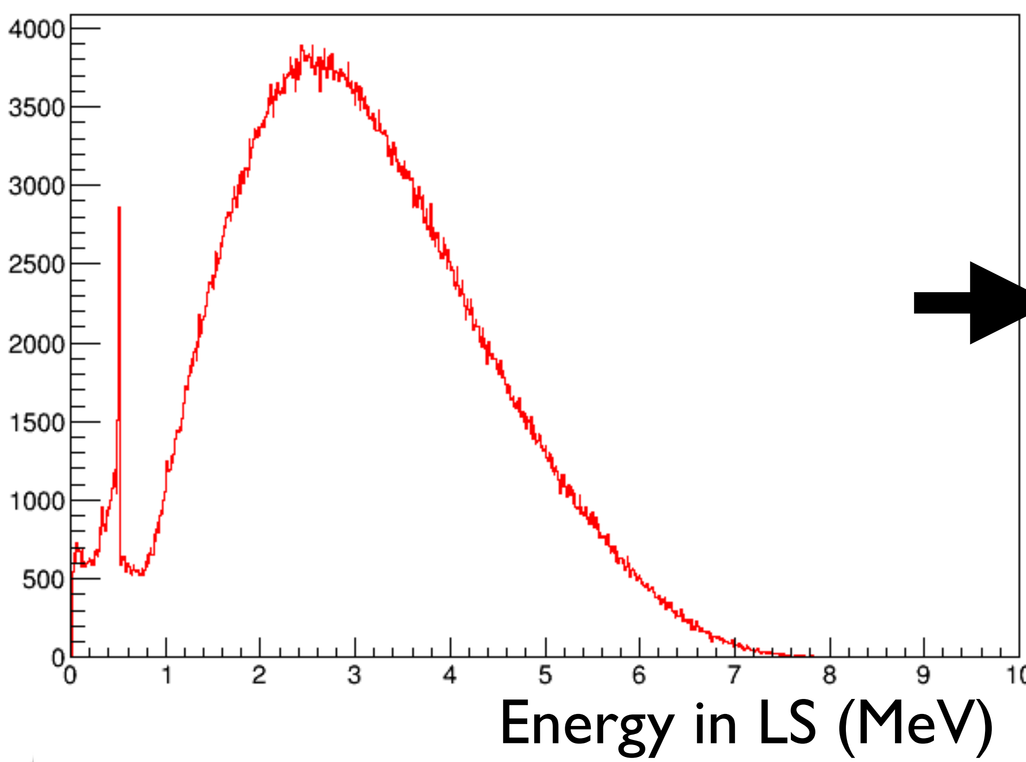
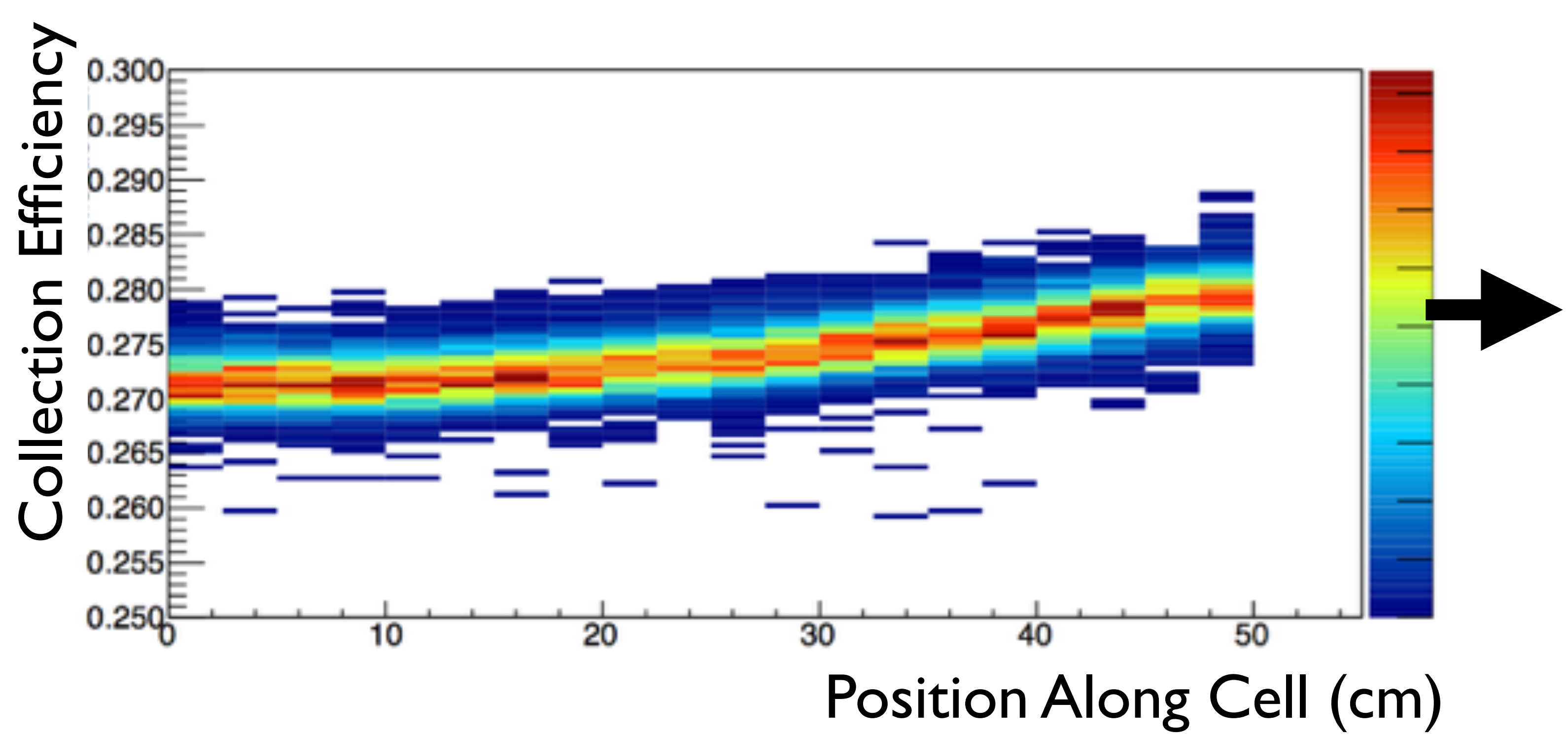
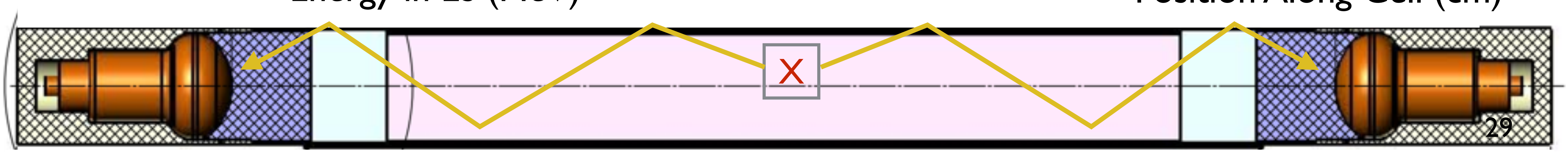
PROSPECT detector simulations







IBD Detector Response: Simulation

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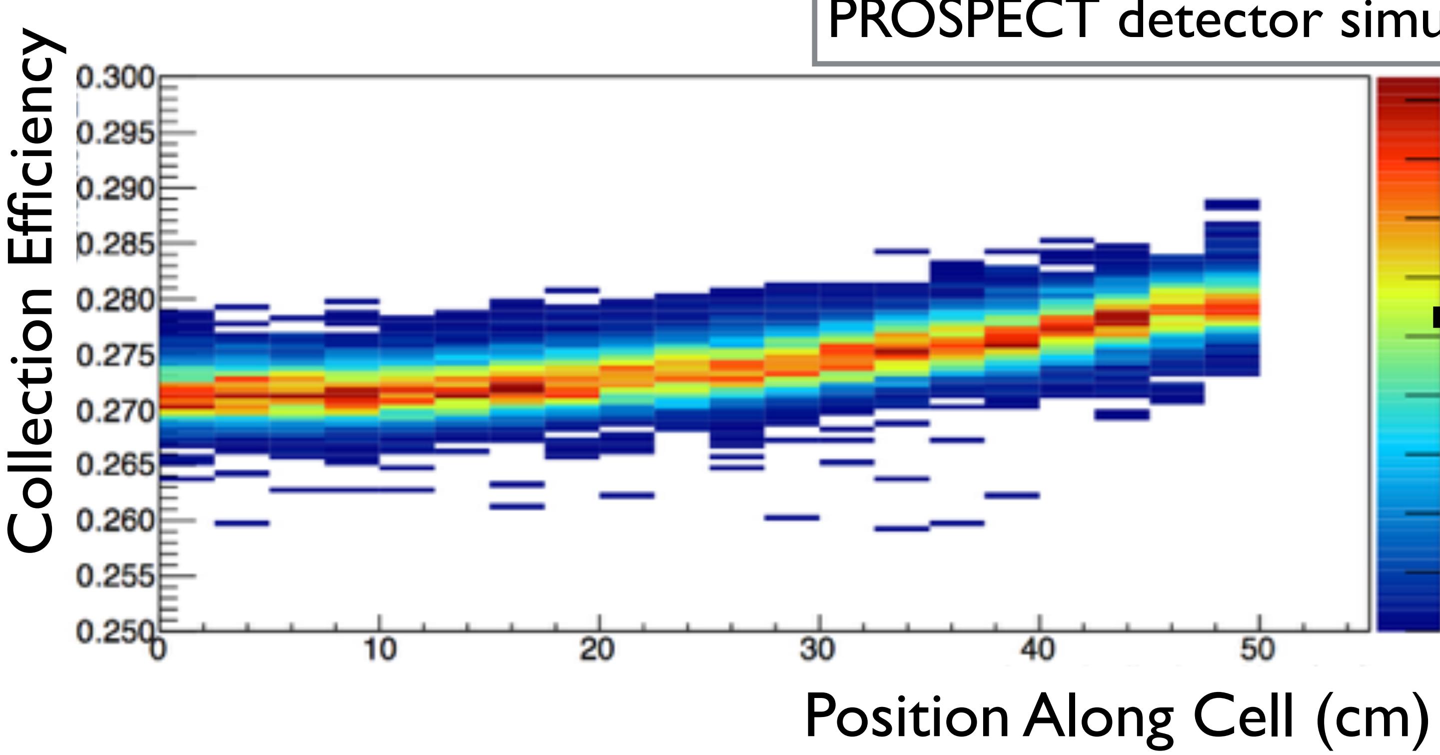
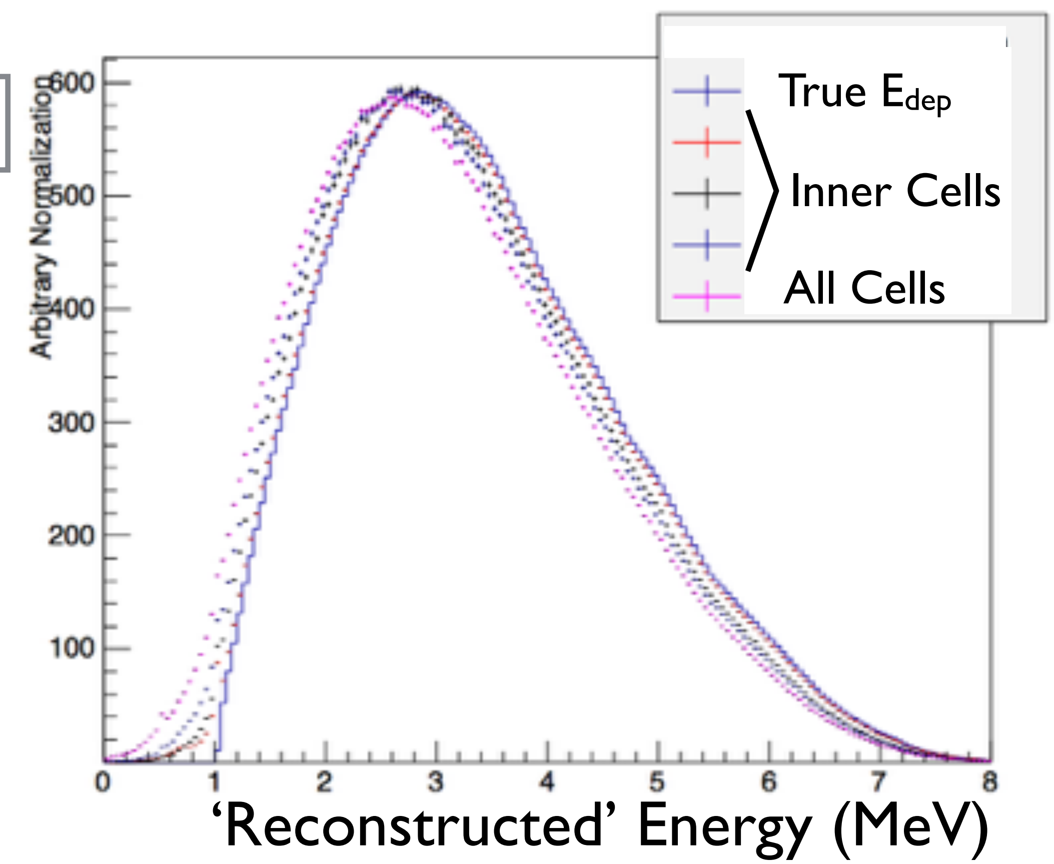
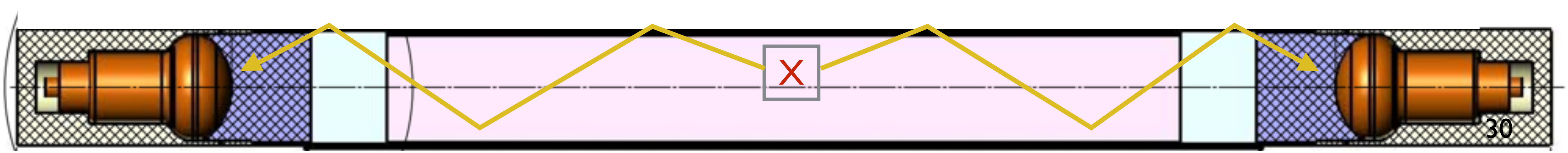
PROSPECT detector simulations

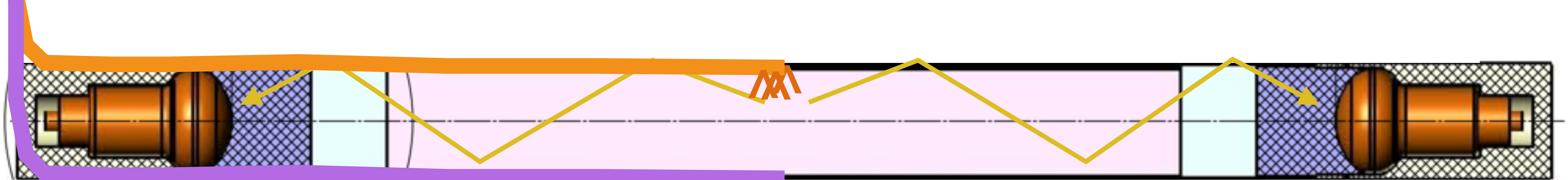




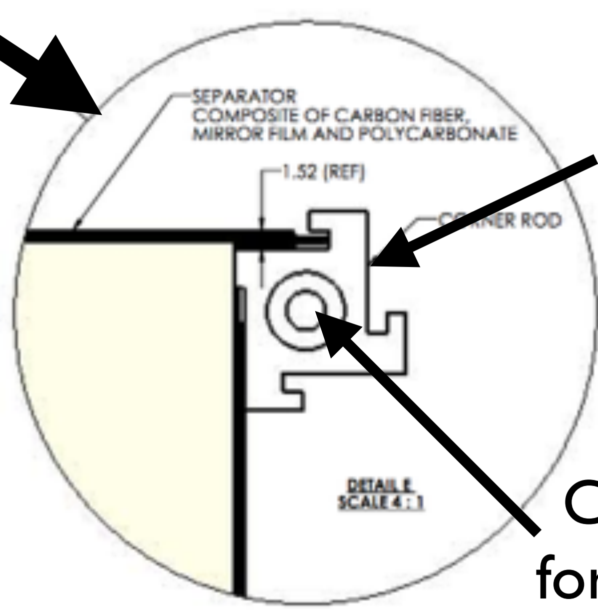


IBD Detector Response: Calibration

- Must reconstruct e^+ energy with high resolution and low bias
- Characterize detector response with calibration sources
  - Fiber-delivered light sources
  - Guide tube-delivered gamma, neutron sources
  - Background sources: muons, radioactive backgrounds, spallation products

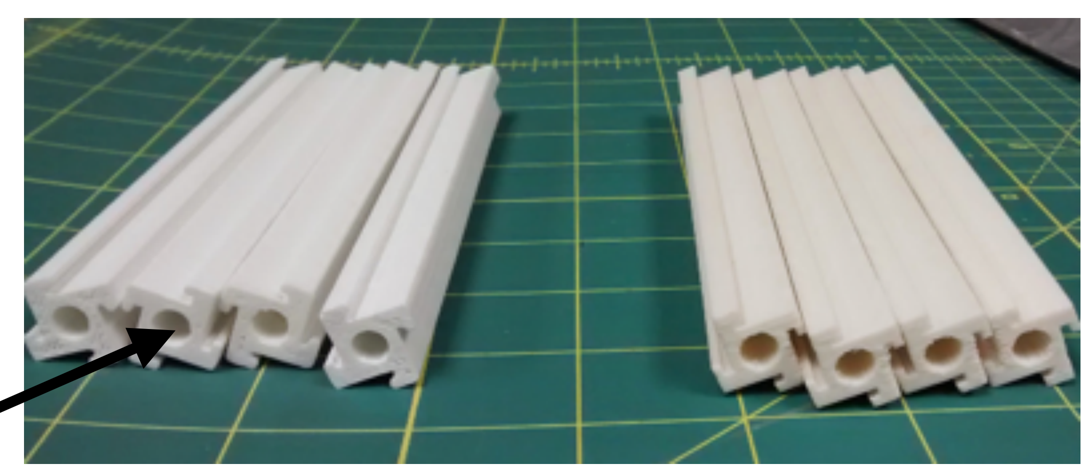


End view



Rigid rods hold reflecting walls in place

Center hole in rod for fibers, guide tubes



3D-printed rod prototypes

IBD Detection Backgrounds

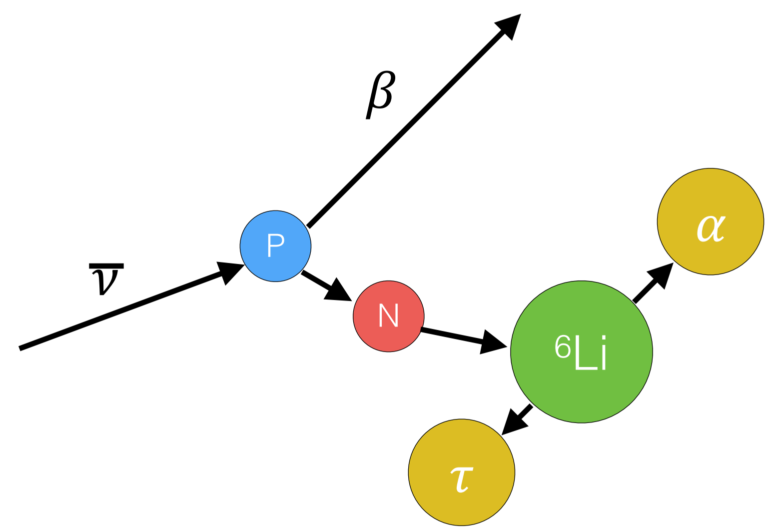
- Have a highly sensitive detector operating at the surface in the direct vicinity of an operating nuclear reactor
- Major design challenge: background reduction
- Aiming for S:B ratio of 1:1

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



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

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

Background Surveys

Neutron Rate/ Spectrum

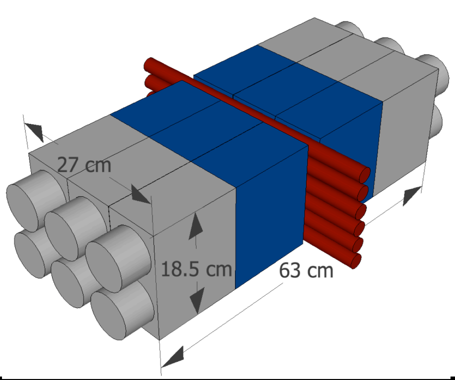
2” Stilbene Organic Crystal

Relative fast neutron flux at all sites

“REM Ball”

Moderated ^{3}He tube measured absolute thermal neutron flux at all sites

FaNS-1 Capture-gated Neutron Spectrometer



Plastic scint. & 3He tubes measured spectrum and absolute flux at HFIR

γ-ray Rate/ Spectrum

Moderate Resolution:

Same NaI(Tl) detectors used at all sites to provide relative comparison

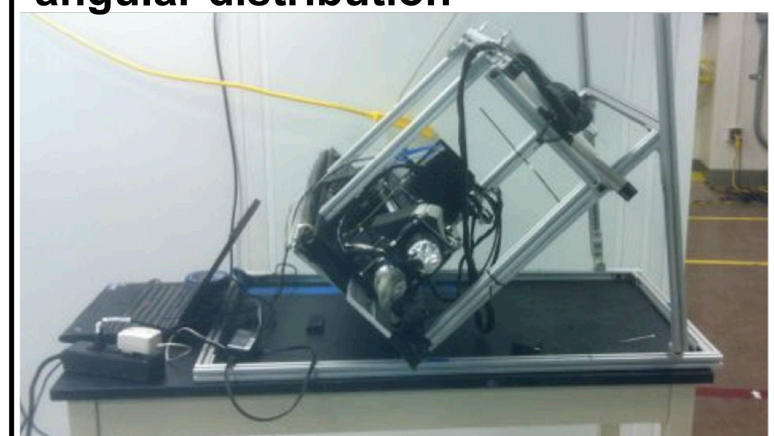
High Resolution:

Different HPGe and LaBr spectrometers used to identify background sources

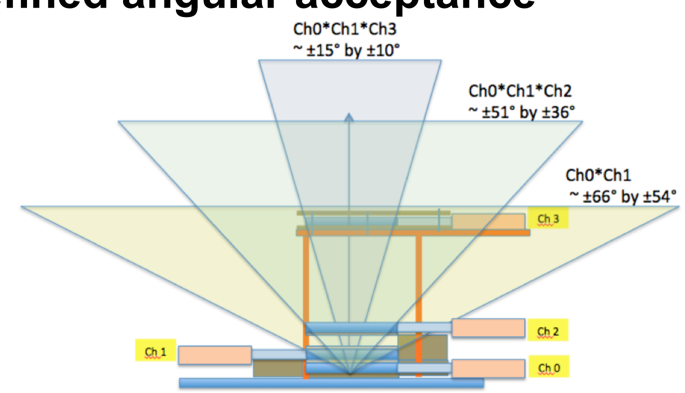
Muon Rate/ Distribution

Muon telescope assembled from 3 plastic scint. panels gives flux and angular distribution

Telescope was tilted to measure angular distribution



Different panel combinations defined angular acceptance



From T. Classen

Background Surveys

Neutron Rate/

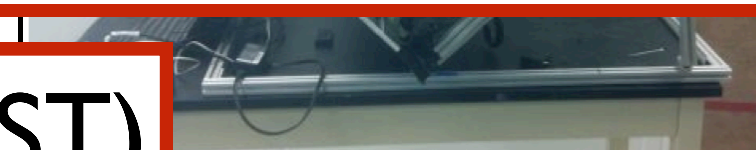
Fast Neutron Rates

Muon Rate/

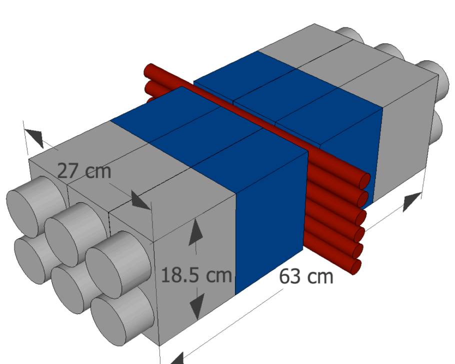
Location	Rate 4 – 14.5 MeV (mHz)	Rate 10-14.5 MeV (mHz)
ATR Near	4.7 ± 0.3	1.0 ± 0.1
HFIR Near	2.2 ± 0.2	0.3 ± 0.1
NIST Near	2.8 ± 0.2	0.8 ± 0.1
ATR Far	1.8 ± 0.2	0.4 ± 0.1
HFIR Far	3.5 ± 0.2	0.6 ± 0.1
NIST Far	2.8 ± 0.2	0.8 ± 0.1

sites

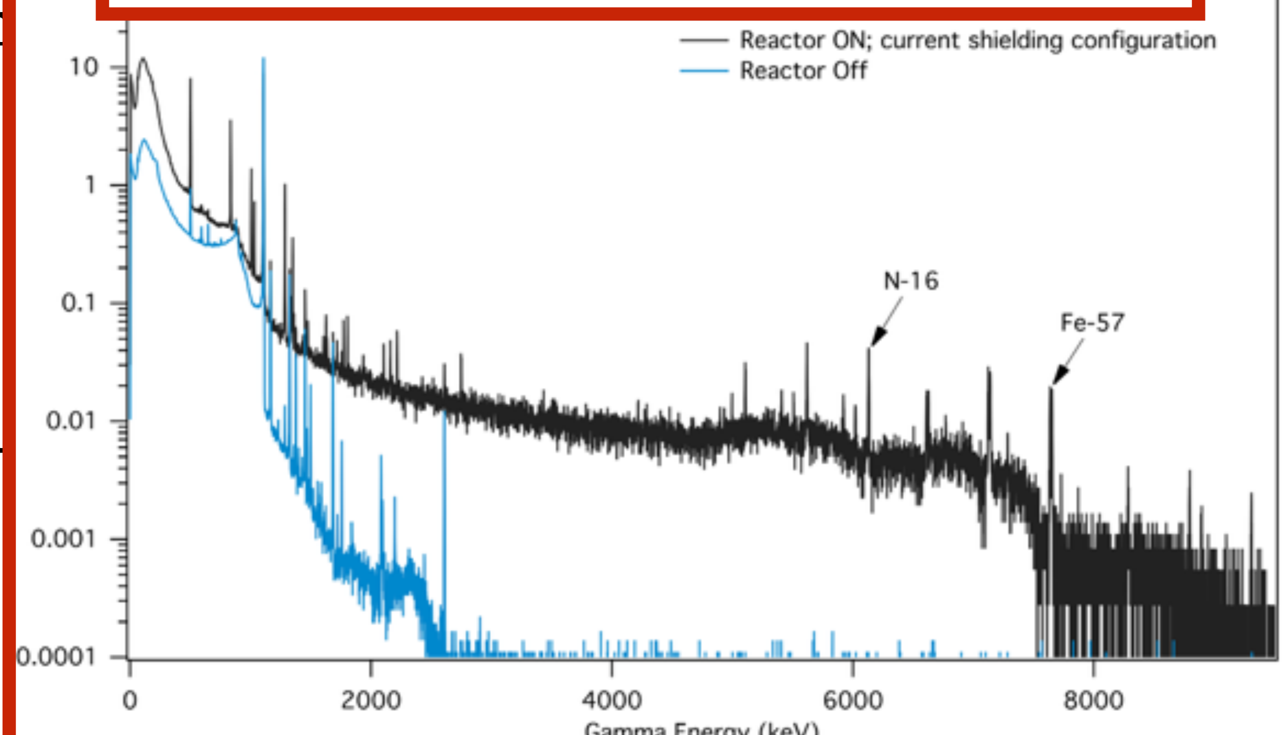
l background sources



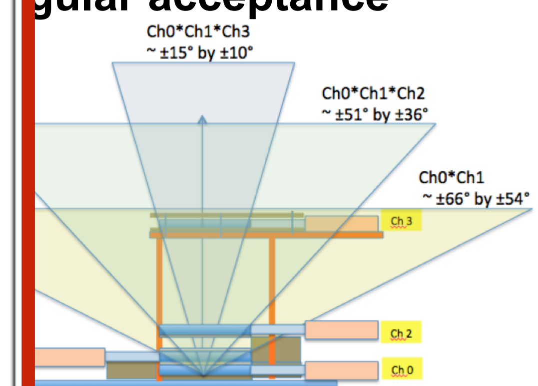
FaNS-1 Capture-gated Spectrom



Gamma Spectra (NIST)



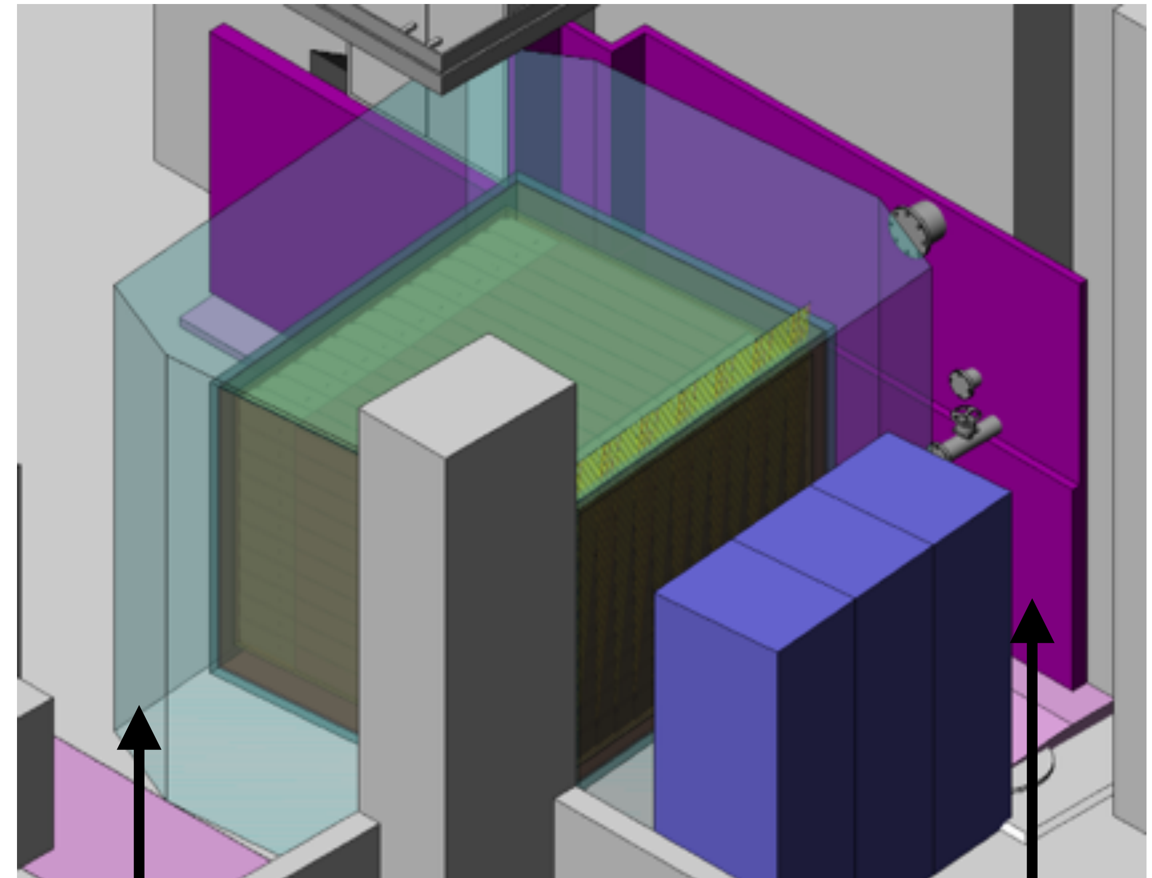
anel combinations
gular acceptance

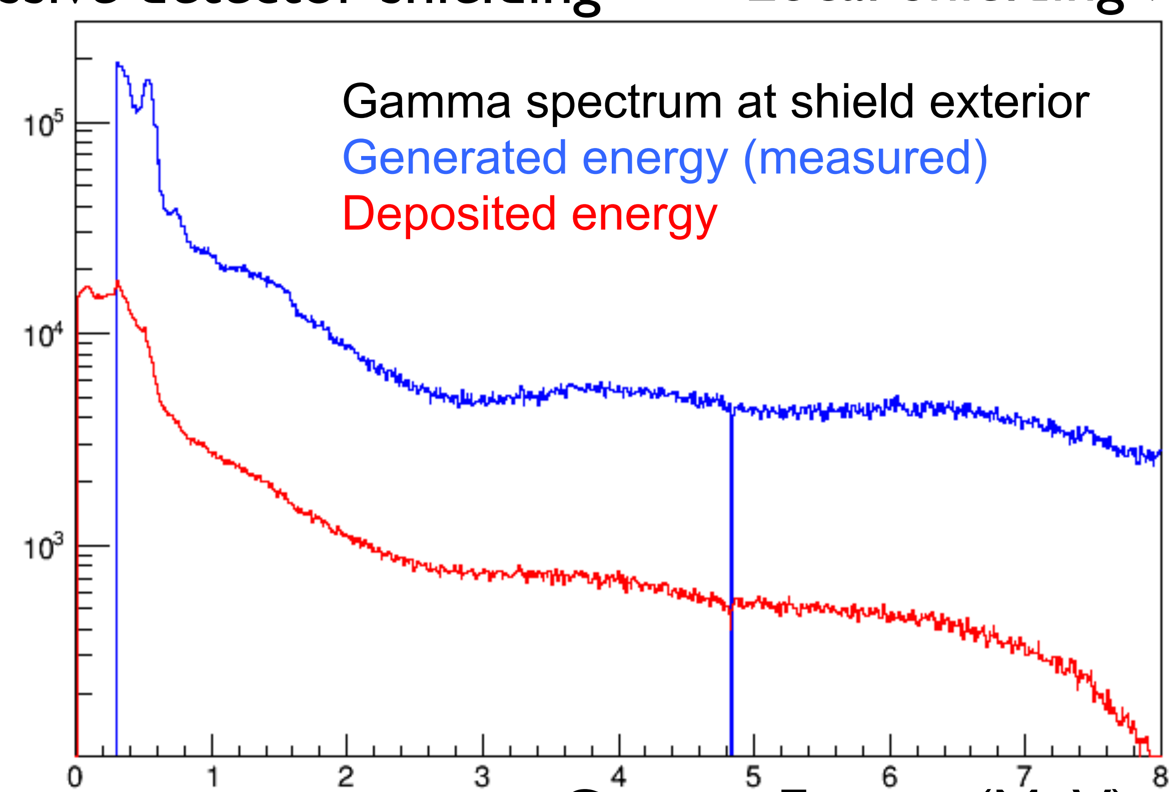


Paper on results in preparation

Background Shielding

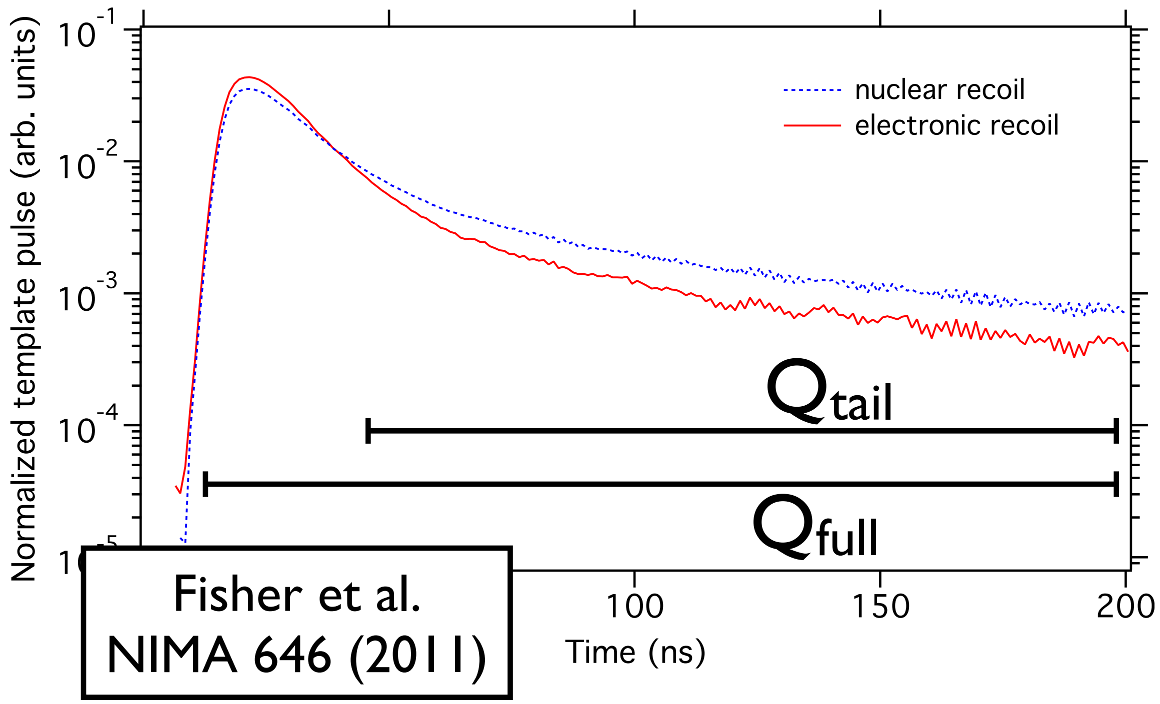
- Shielding package designed based on background surveys, available space constraints
- Local lead shielding wall
  - Addresses 'hot' gamma regions
- Shielding encompassing entire detector
  - Li-Poly, B-Poly (neutrons), Lead (gammas)
- Investigating benefits of a muon veto system
- Backgrounds and effects of shielding have been simulated.



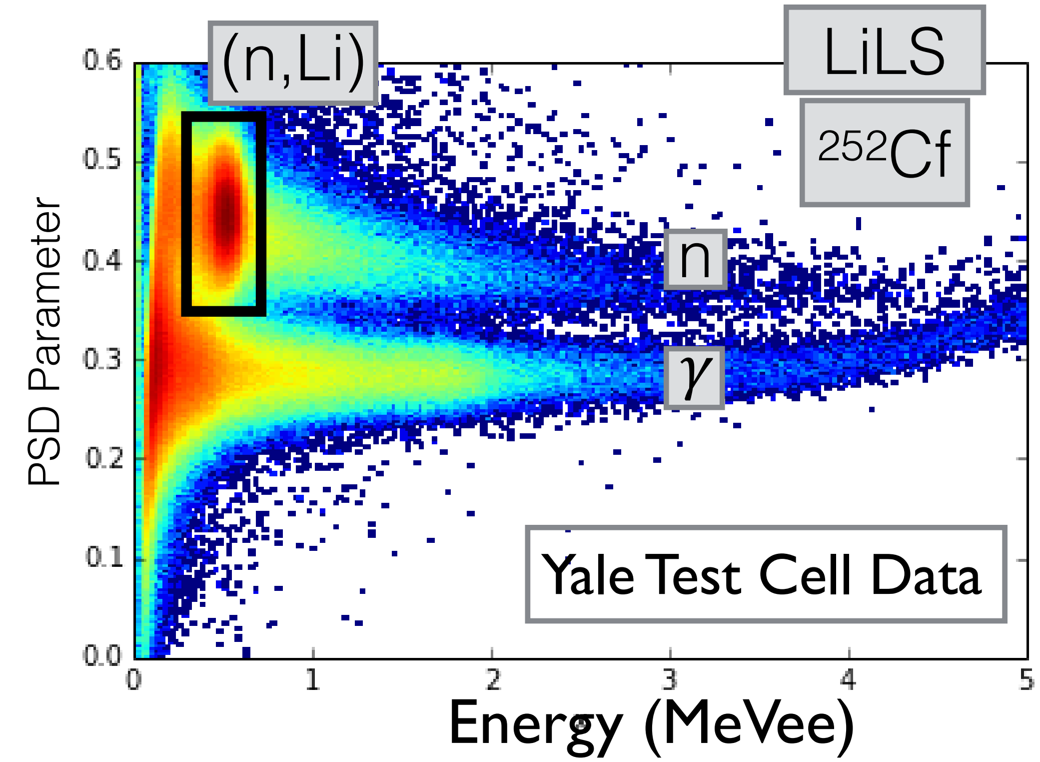


Background Rejection, Signal Selection

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



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



Signal, Main Backgrounds

Inverse Beta Decay

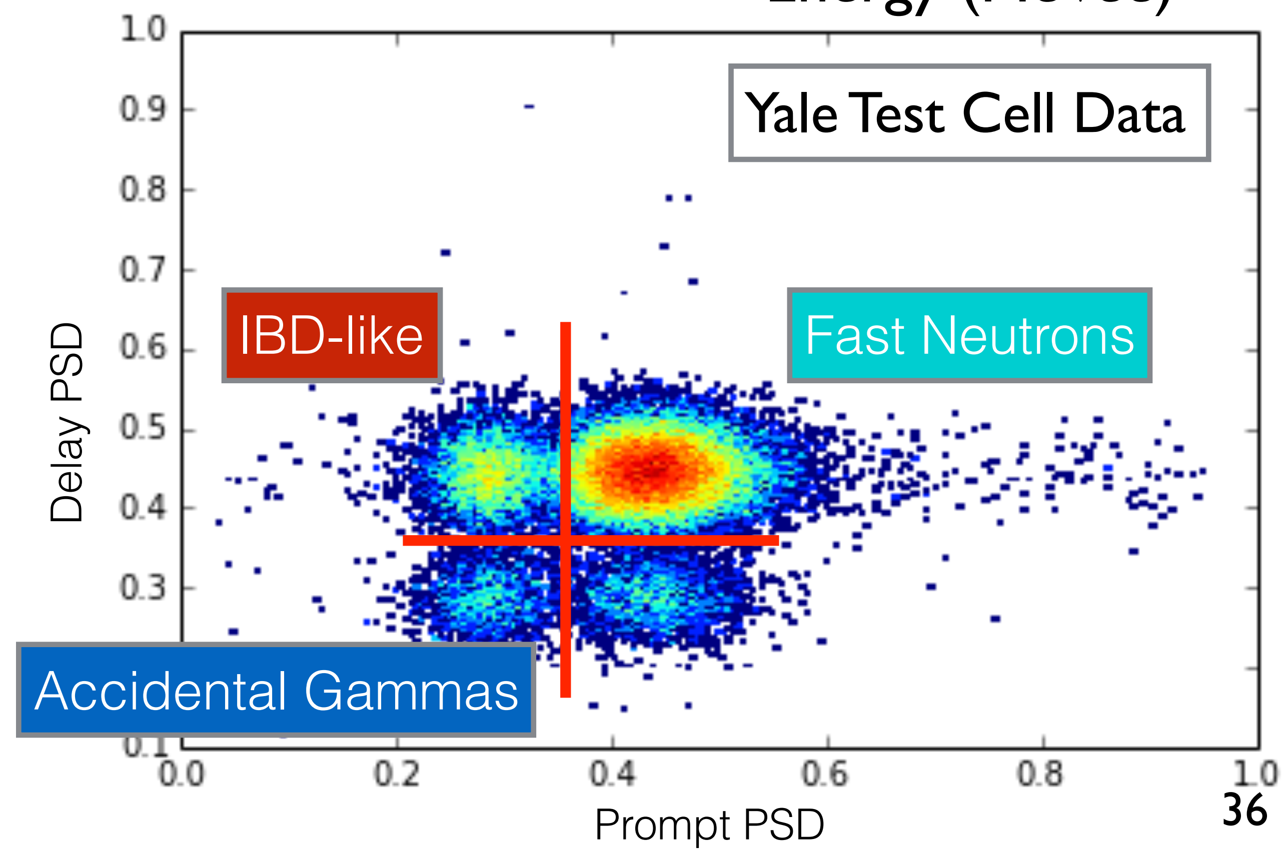
γ-like prompt, n-like delay

Fast Neutron

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

Accidentals

γ-like ~~prompt, γ-like~~ delay



PROSPECT: Scaling Up

Measure n bkgs

Run DAQ, Remote data-taking

See LS PSD

See n-Li + PSD

Demonstrate shielded background rates

Demonstrate full-cell PSD, light yield

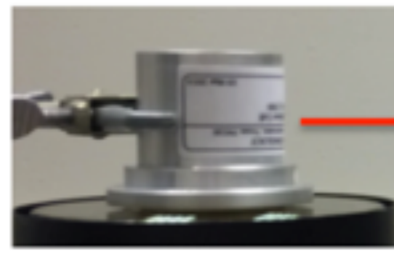
Deploy final design concepts

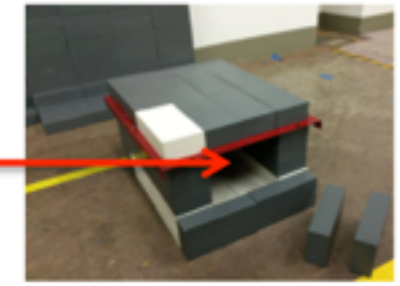
Observe relative segment responses

See antineutrinos?

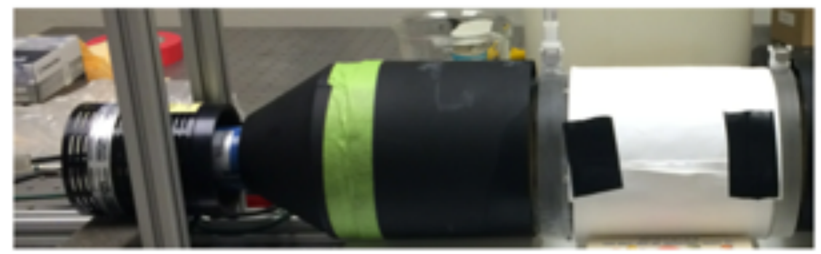
Physics!

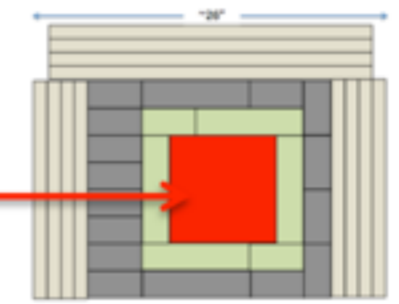
PROSPECT 0.1 *
Aug. 2014



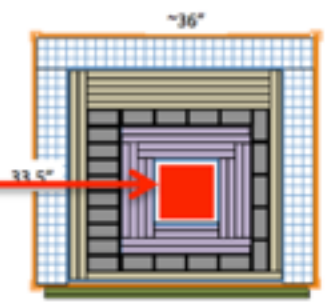


PROSPECT 2 *
Dec. 2014

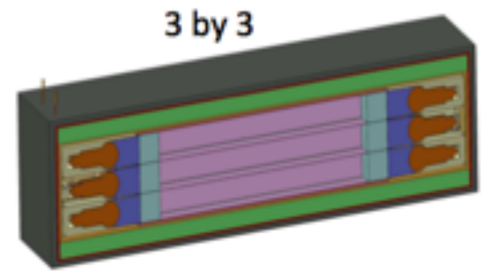


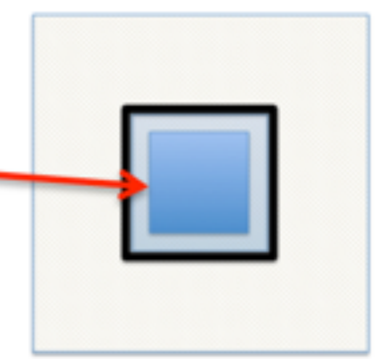


PROSPECT 20 *
Jan. 2015

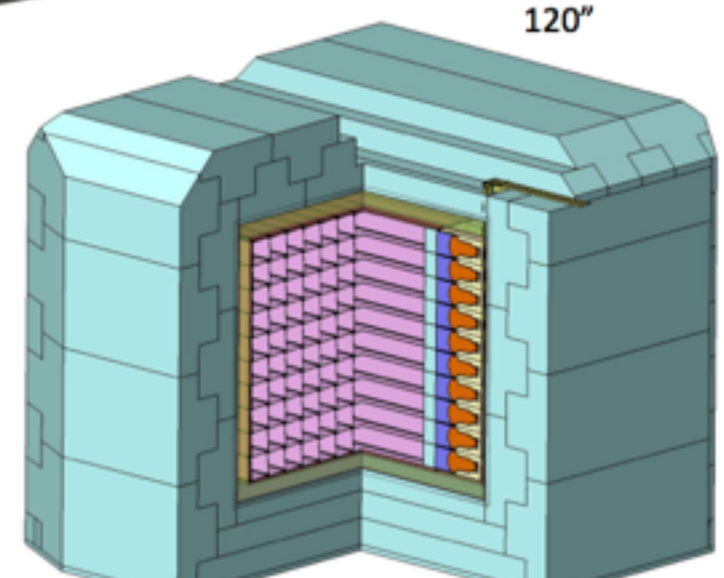


PROSPECT 200





PROSPECT 2ton

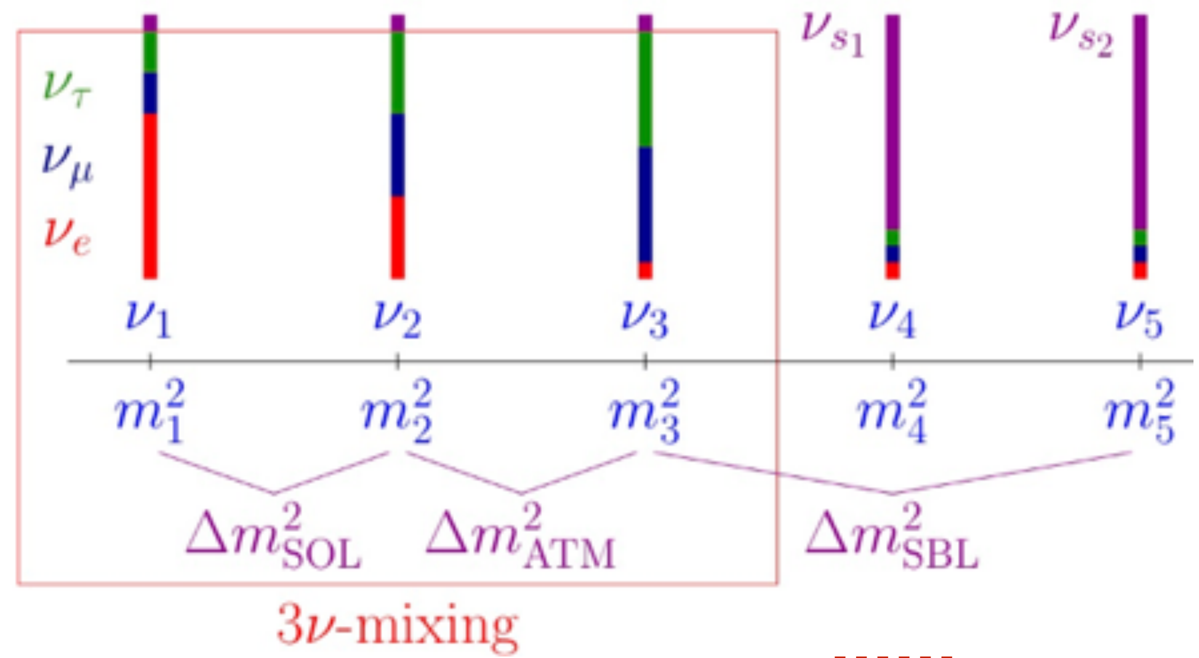


* Deployment complete/imminent

Approximate mass kg

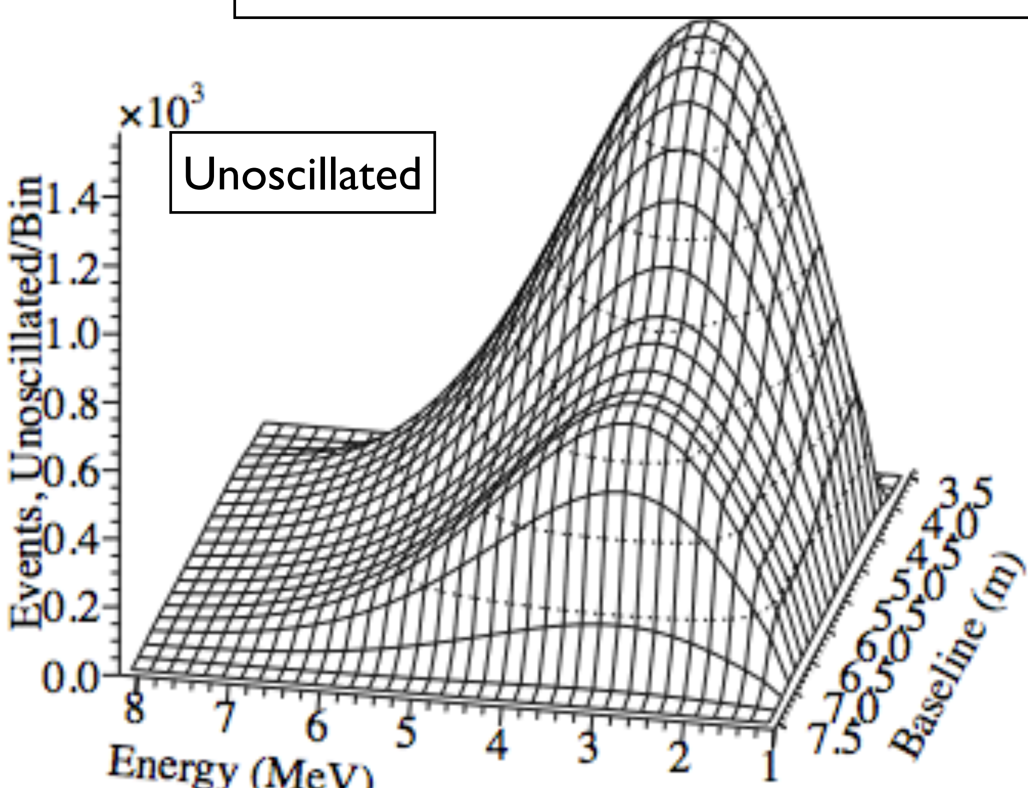
PROSPECT Physics: Oscillations

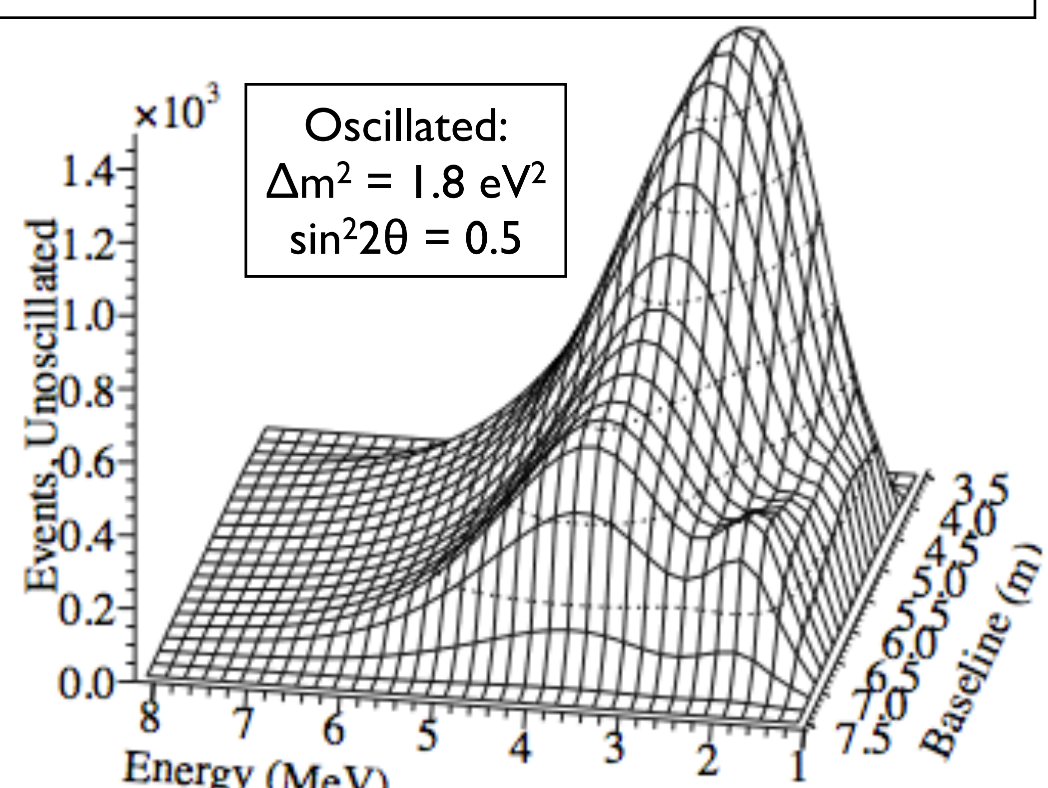
- Measure energy spectrum separately in each segment
- Look for unexpected L/E distortion: oscillations
  - Mass splitting wouldn't match observed three-neutrino splittings: fourth (sterile) neutrino



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

One 3x1x1 m^3 detector, 1m^3 20 MW HEU core, 4m closest distance





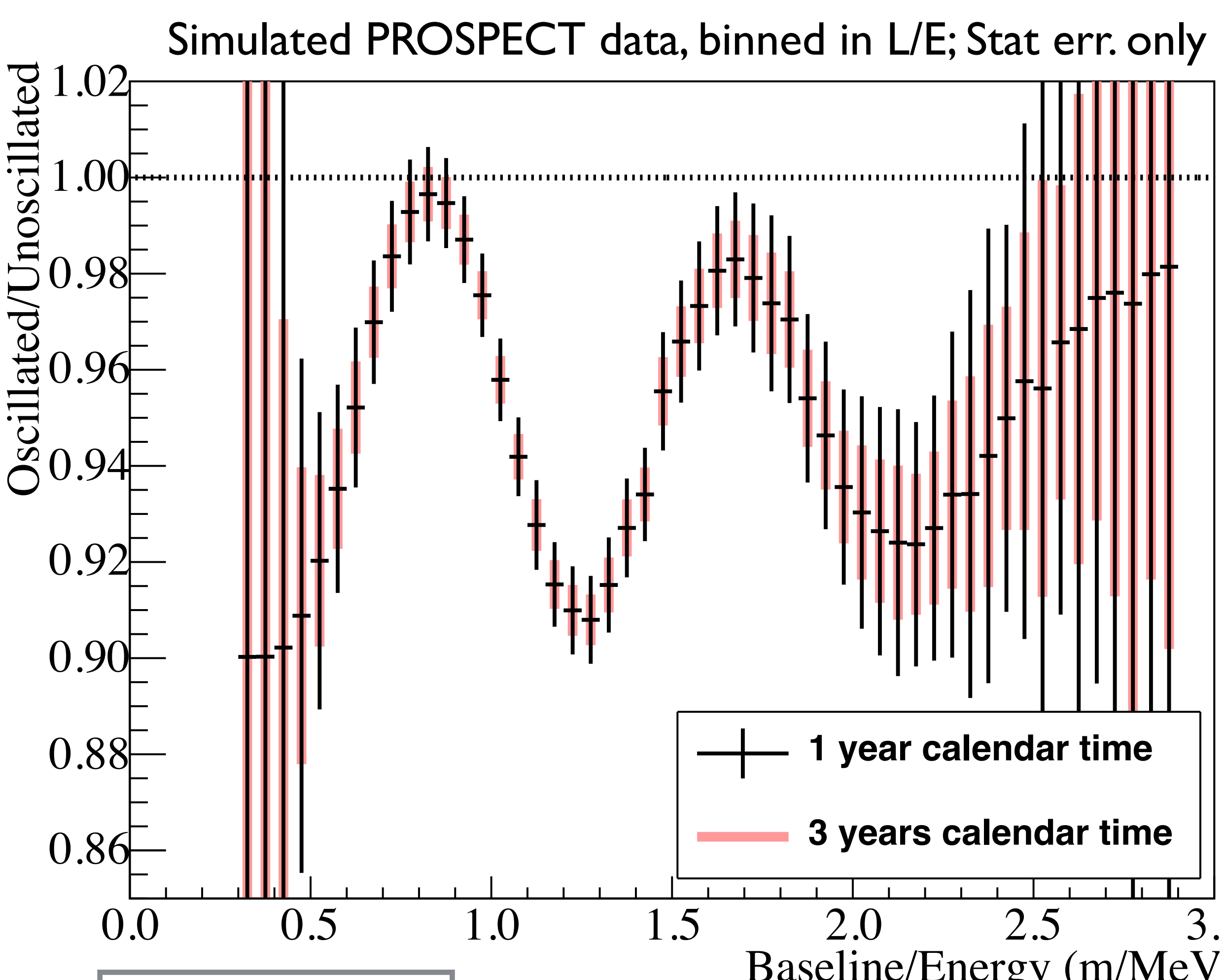
30% Efficiency

15cm position resolution

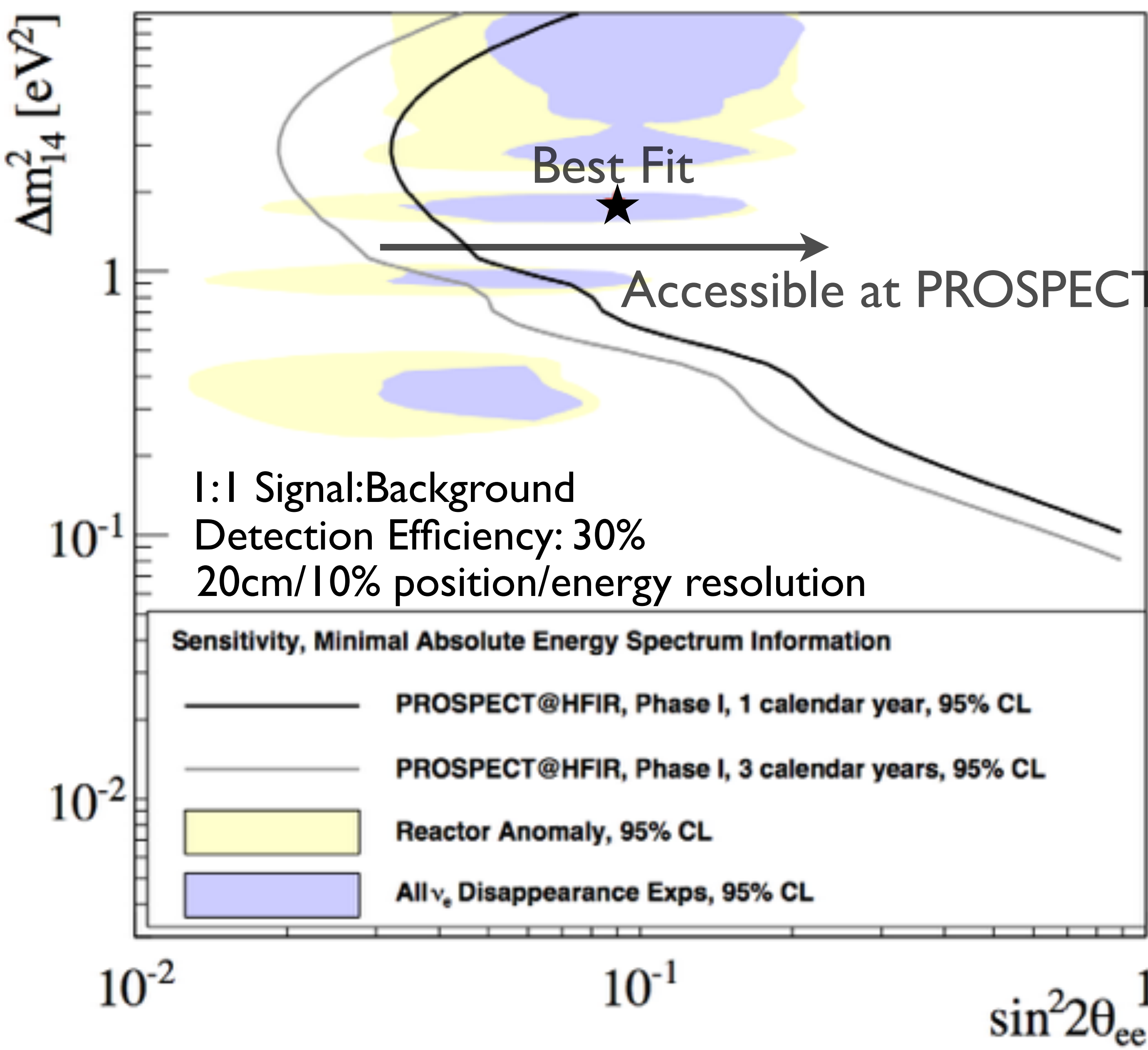
10%/Sqrt(E) Energy Resolution

PROSPECT Physics: Oscillations

- Excellent oscillation discovery potential at PROSPECT
  - If new sterile neutrino is where global fits suggest, it's very likely we'll see it!
  - No reliance on absolute spectral shape or normalization: pure relative measurement
  - Good coverage with a single detector and one/three calendar years of data-taking



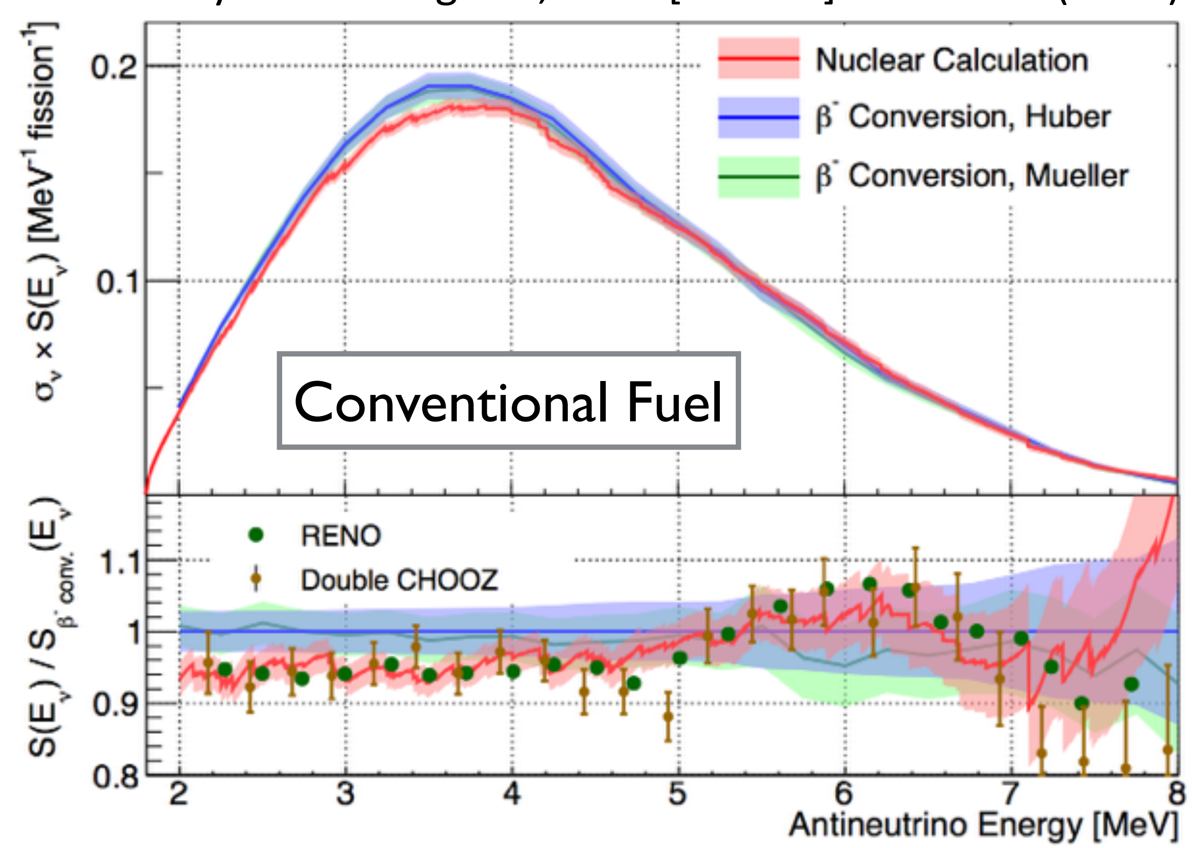
Inputs:
3+1 Oscillations
$\Delta m^2 = 2.0$ eV^2
$\sin^2 2\theta_{13} = 0.1$

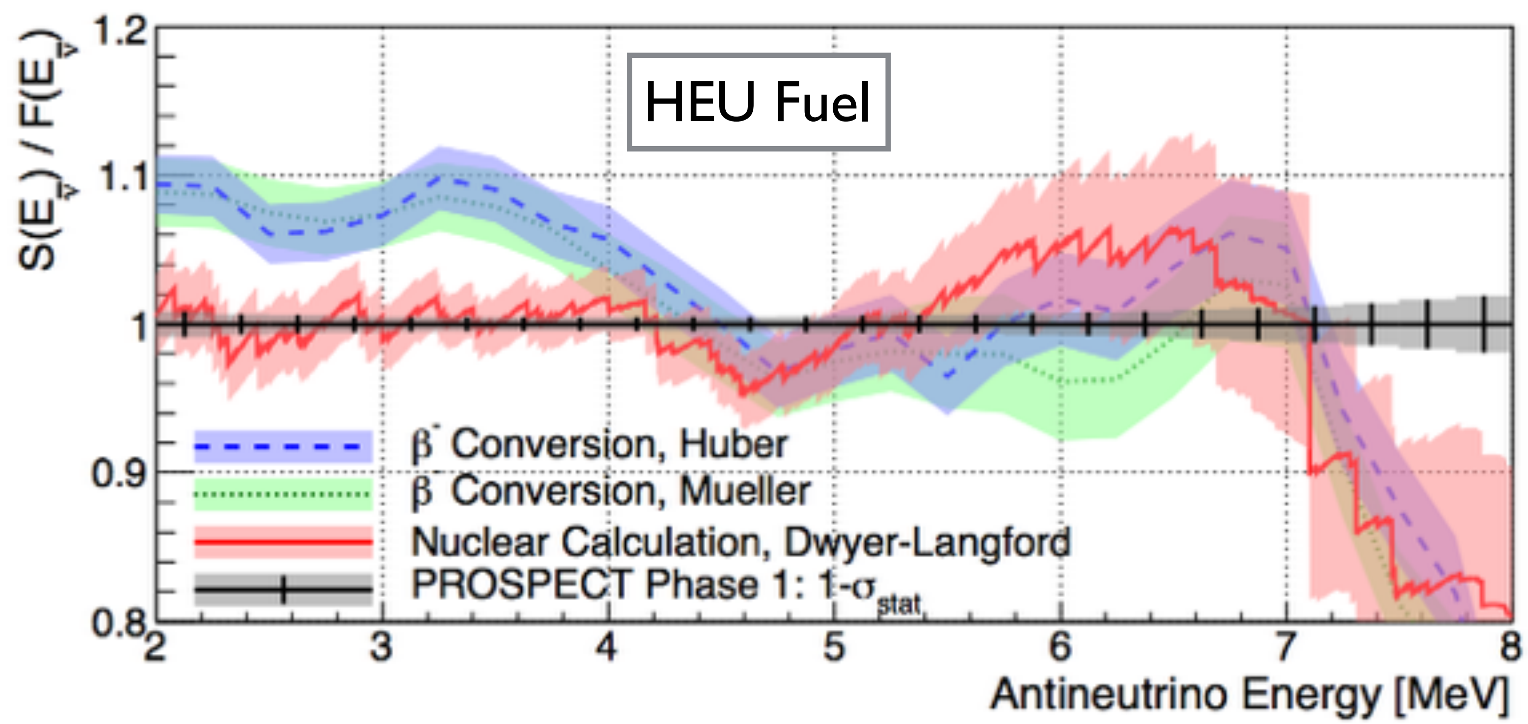


PROSPECT Physics: Absolute Spectrum

- **What is the correct model?**
  - Have data points for conventional fuel (^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu)
  - What about HEU fuel (^{235}U only)? Provides additional model constraint
- Benefits of HFIR:
  - 1 core versus many cores (Daya Bay, RENO)
  - Easier to model, isolate features in 1 isotope's beta branches?
- 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)

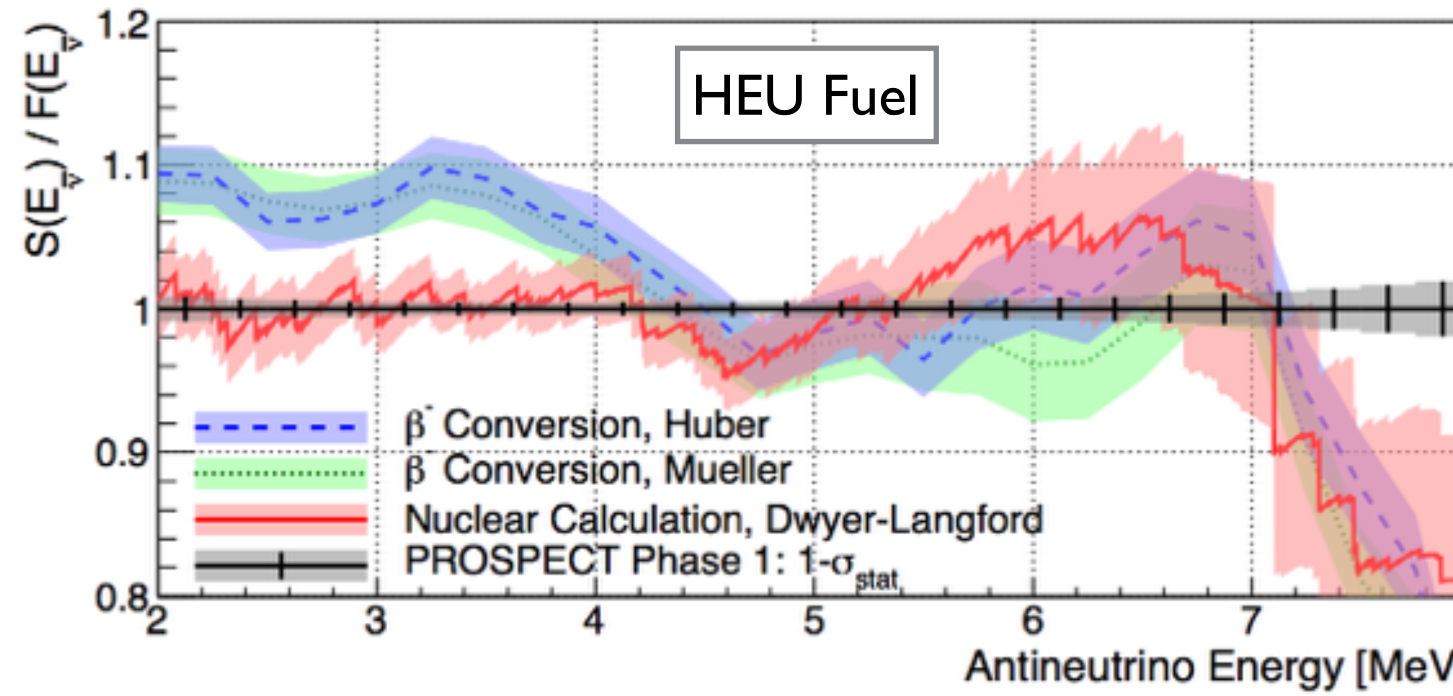


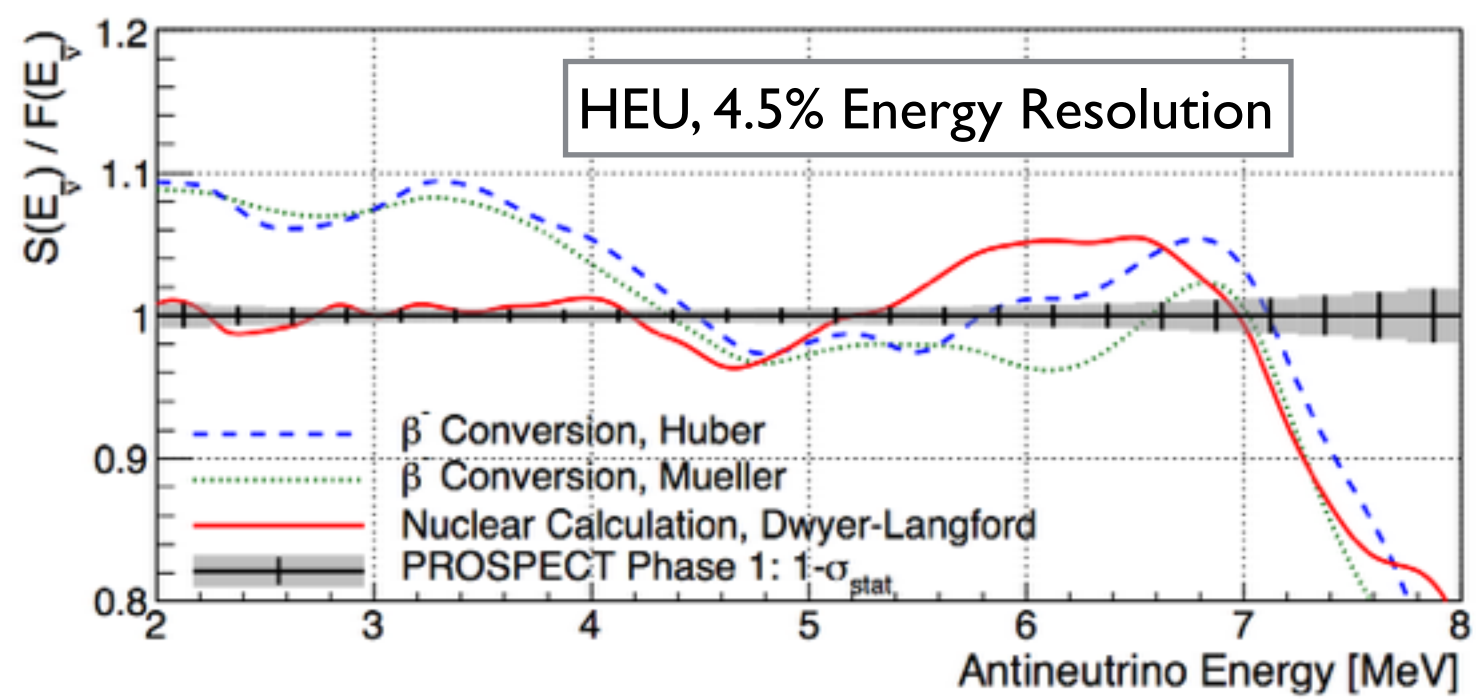


PROSPECT Physics: Absolute Spectrum

- How much fine structure exists in reactor spectrum?
  - Ab initio calculations suggest significant fine structure from endpoints of prominent beta branches

- PROSPECT can provide highest-ever energy resolution on the spectrum
  - Goal resolution: 4-5%
  - Thus, best measurement of this fine structure
  - Provide constraints on yields, endpoints of various branches (reactor spectroscopy)?
  - Provide input for future high-resolution reactor experiments (JUNO)?



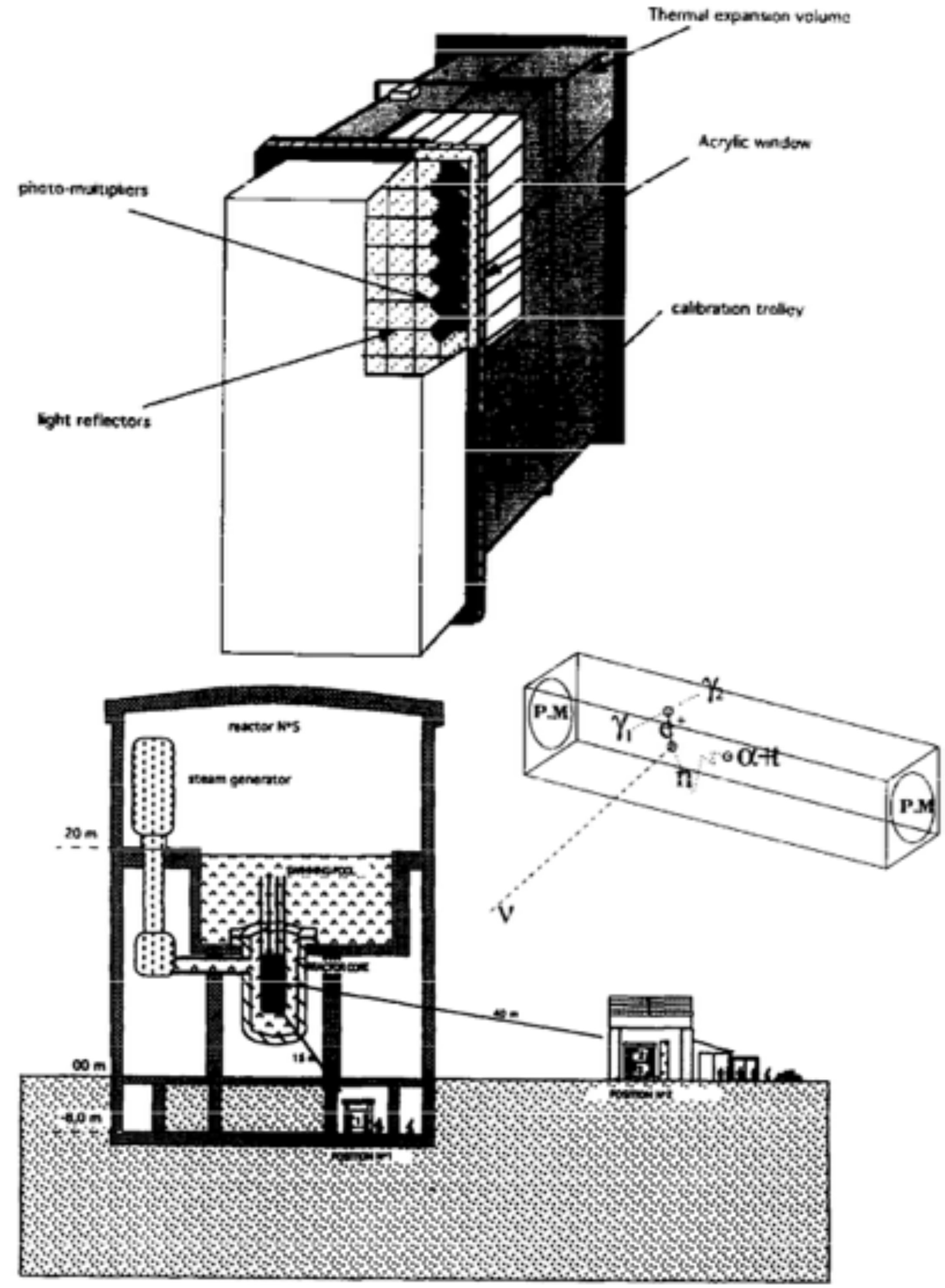


Outline

- Intro: Reactor $\overline{\nu}_e$ Flux and Spectrum Predictions
- Reactor Anomaly and recent flux/spectrum measurements
- Future measurement of the $\overline{\nu}_e$ spectrum at PROSPECT
- Historical/current/future context for PROSPECT

Historical Context

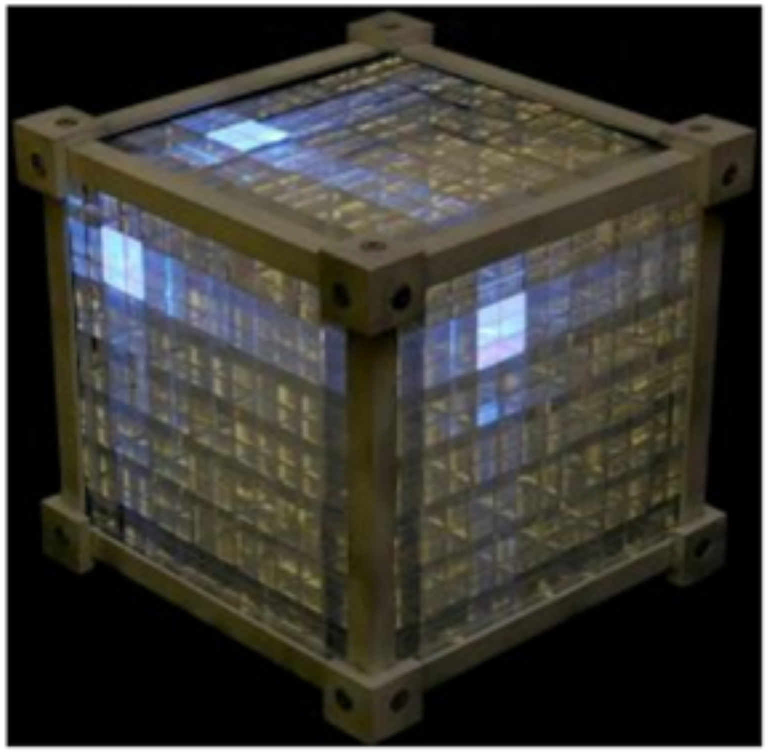
- A similar experimental setup in the past: Bugey-3
    - Segmented short-baseline LiLS detector
- PROSPECT Pros:
    - Smaller reactor core, closer to core: better for SBL oscillation search
    - Stable scintillator: Bugey's degraded after a few months in near detector!
    - Smaller target dead volume: ~2% versus >15% for Bugey
    - Aim for better light yield, PSD
- PROSPECT Con: No Overburden
    - 14+ mwe (Bugey-3), <10 mwe (PROSPECT)
    - Bugey had 25:1 S:B

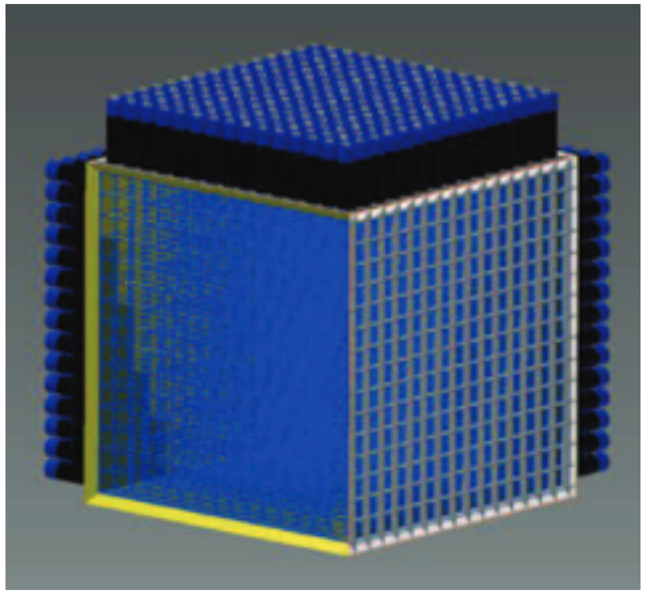


US Context

- NuLat: Another effort to measure SBL reactor neutrinos in US
- Based on LENS optical lattice concept
- 2.5” B-loaded solid scintillator cubes, stacked together into lattice
- Observed on all sides by 1350 PMTs
- Test at 20MW NIST reactor, Data deployment at reactor aboard US Navy Ship
- Design, simulation and sensitivity studies underway currently
- Also proposed: coherent scattering at reactors

LENS detector concept





NuLat design drawing

Lattice concept in lab

International Context

- Many experiments: Russian, European, Asian Efforts
- Key physics considerations (besides stats)
  - Oscillation: Baseline proximity, range, resolution
  - Spectrum: Energy resolution
- PROSPECT: Relatively unique in designing toward both goals

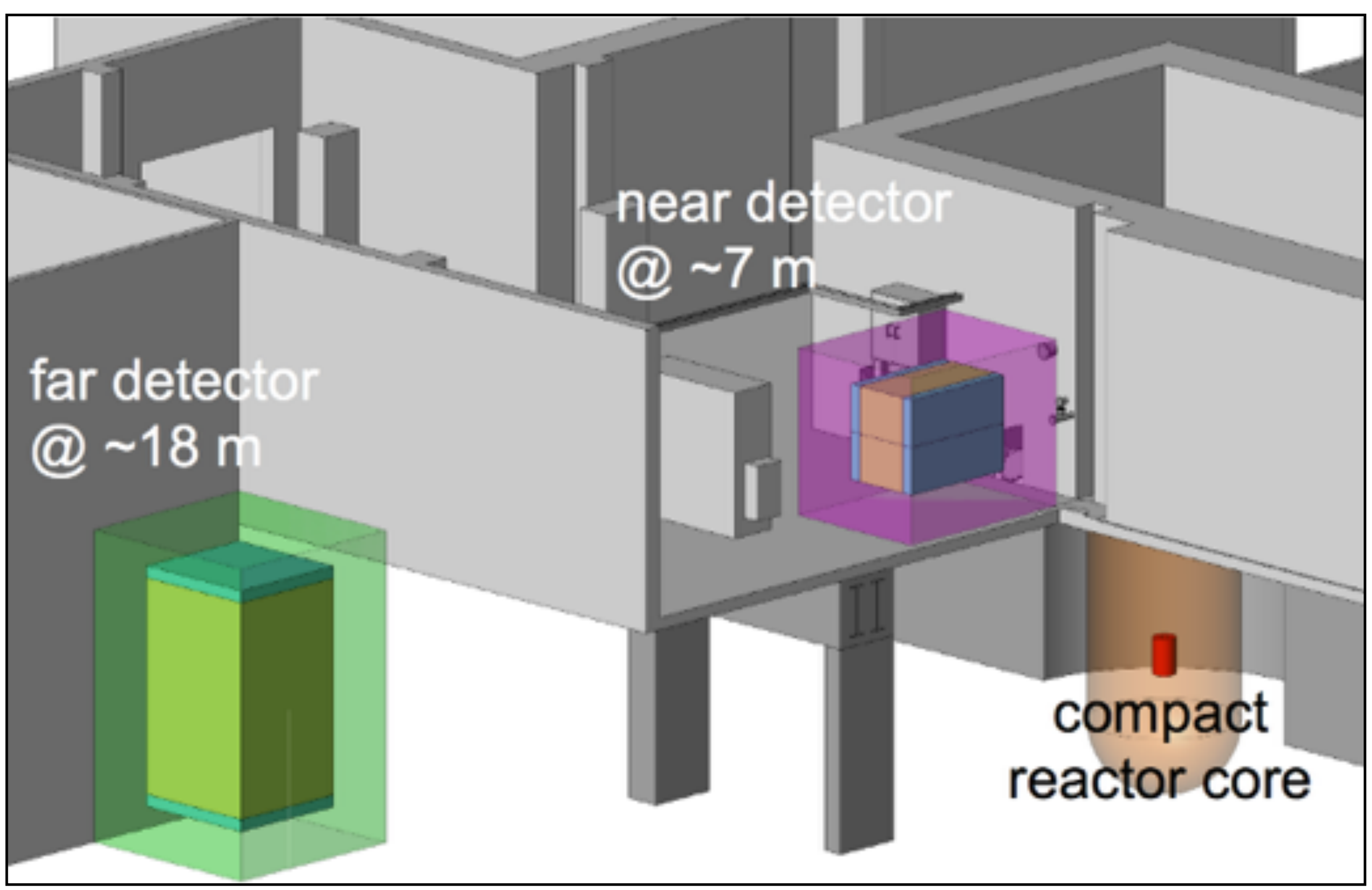
My (biased) overview of global efforts

	Effort	n-Capture Agent	Good X-Res	Good E-	L Range?	Fuel?	Exposure, MW*ton
Us	PROSPECT	Li	Yes	Yes	7-11+	HEU	185
	Nucifer	Gd	No	Yes	7	HEU	56
EU	STEREO	Gd	Yes	Yes	9-11	HEU	100
	SoLid	Li	Yes	No	6-8	HEU	155
Russia	DANSS	Gd	Yes	No	9.7-12	LEU	2700
	Neutrino4	Gd	Yes	Yes	6-12	HEU	150
Asia	Hanaro	Li/Gd	No	Yes	6-??m	Both	30

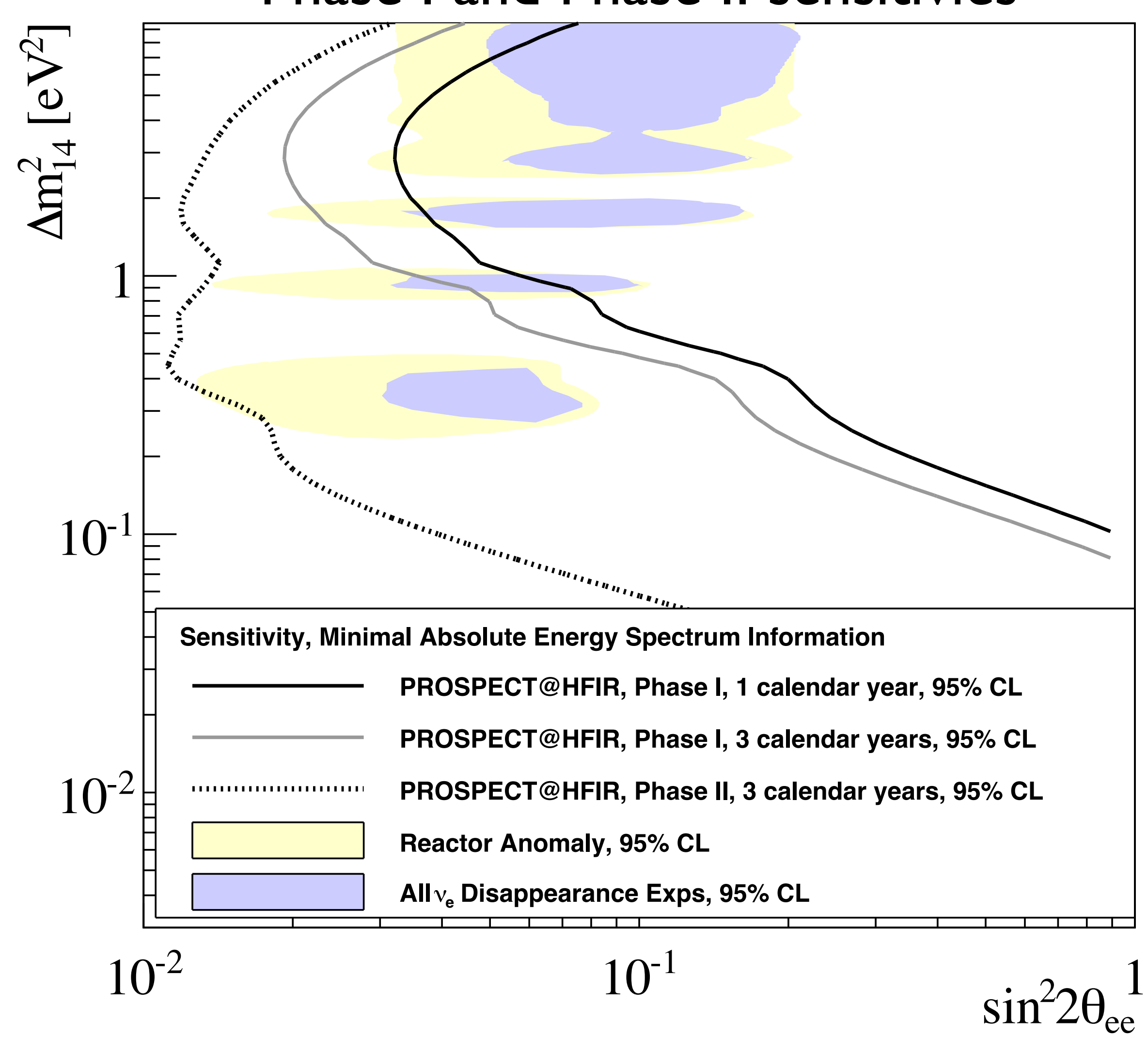
Looking to Future

- Eventual PROSPECT Goal: Near and far detector (Phase II)
  - 4-10x larger far detector installed after near detector running
  - Provides broad, highly sensitive oscillation search
  - Far detector can provide highly-fiducialized, high-resolution spectrum

HFIR, Near and Far detectors



Phase I and Phase II sensitivies



Summary

- Much has been learned about the absolute reactor nuebar flux and spectrum in the past 2-3 years
- More data is needed to address persisting questions
- PROSPECT can provide valuable new data by measuring HEU reactor $\bar{\nu}_e$ at short baselines
  - High position resolution allows a precise relative spectral measurement for testing the sterile neutrino solution to the reactor anomaly
  - High energy resolution allows a precise absolute spectral measurement for providing new constraints on reactor models
  - Valuable conclusions can be drawn with 1 calendar year of data
- R&D and prototype deployments at HFIR are well underway

END