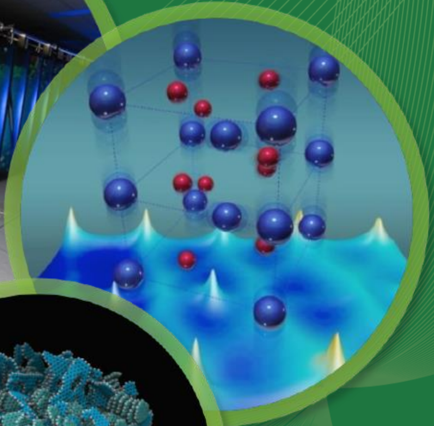
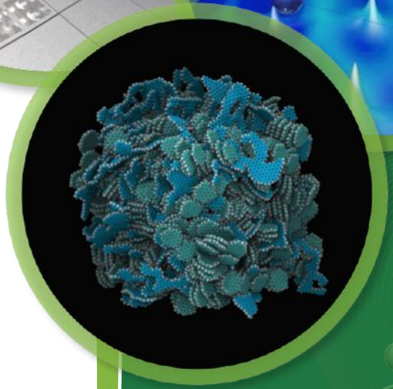
PROSPECT: The Precision Reactor Oscillation and SPECTrum experiment

James T. Matta

Oak Ridge National Laboratory

On behalf of the PROSPECT Collaboration

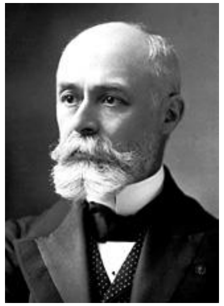




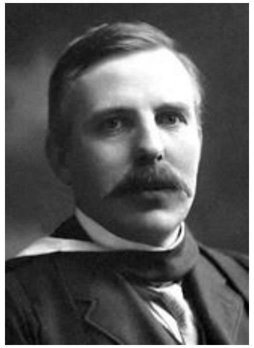
Outline

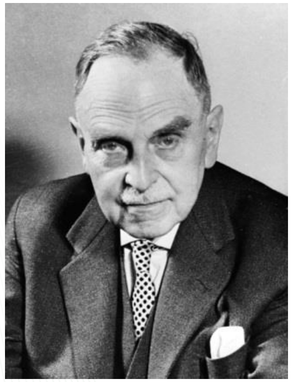
- Neutrino Physics
  - Brief history of the neutrino
  - Sources and cross-sections
  - Present day
- ORNL Neutrino Opportunities
  - HFIR
  - Fission and β-decay
- PROSPECT
- Summary

Neutrino Physics

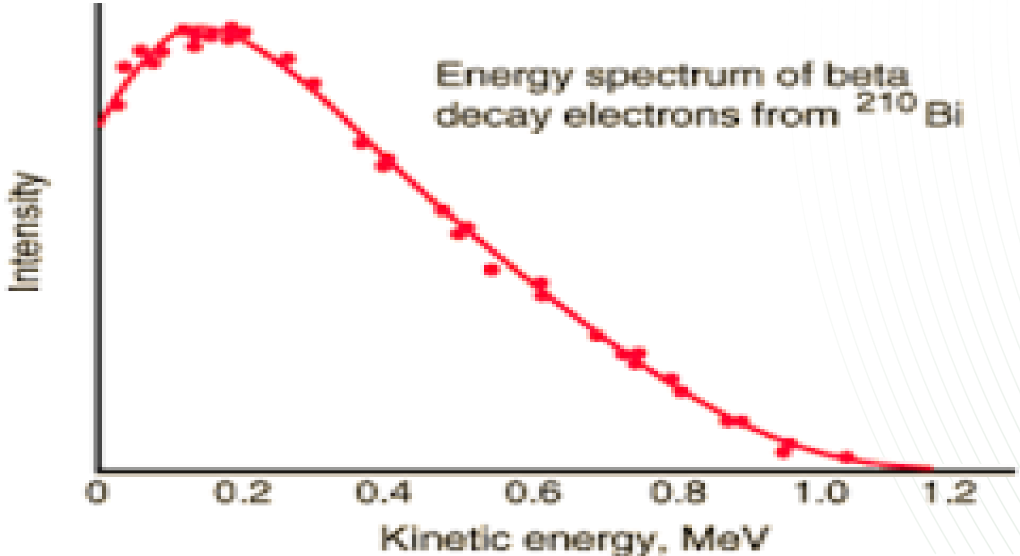
A Brief History of the Neutrino







- 1896 – Becquerel: Discovers of radioactivity
- 1899 – Rutherford: Two types of emission: α and β
- 1911 – Meitner and Hahn: βs have a continuous spectrum
- 1930 – Pauli proposes the neutrino
  - "I have done a terrible thing. I have postulated a particle that cannot be detected."



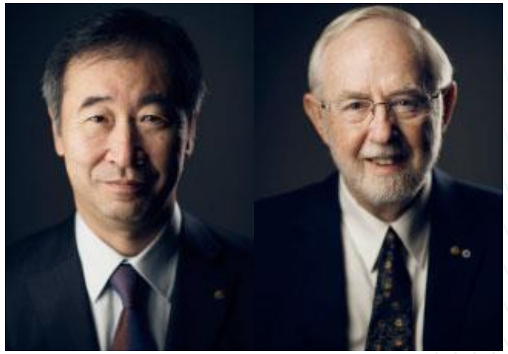
A Brief History of the Neutrino

PROSPECT

- 1956 – Cowan and Reines detect the electron neutrino
  - ½ of 1995 Nobel prize to Reines

- 1962 – Danby *et al.* detect the muon neutrino
  - 1988 Nobel prize to Lederman, Schwartz, and Steinberger
- 1970 – The Homestake Experiment - The Solar Neutrino Problem
  - ½ of 2002 Nobel Prize to Davis and Koshiba

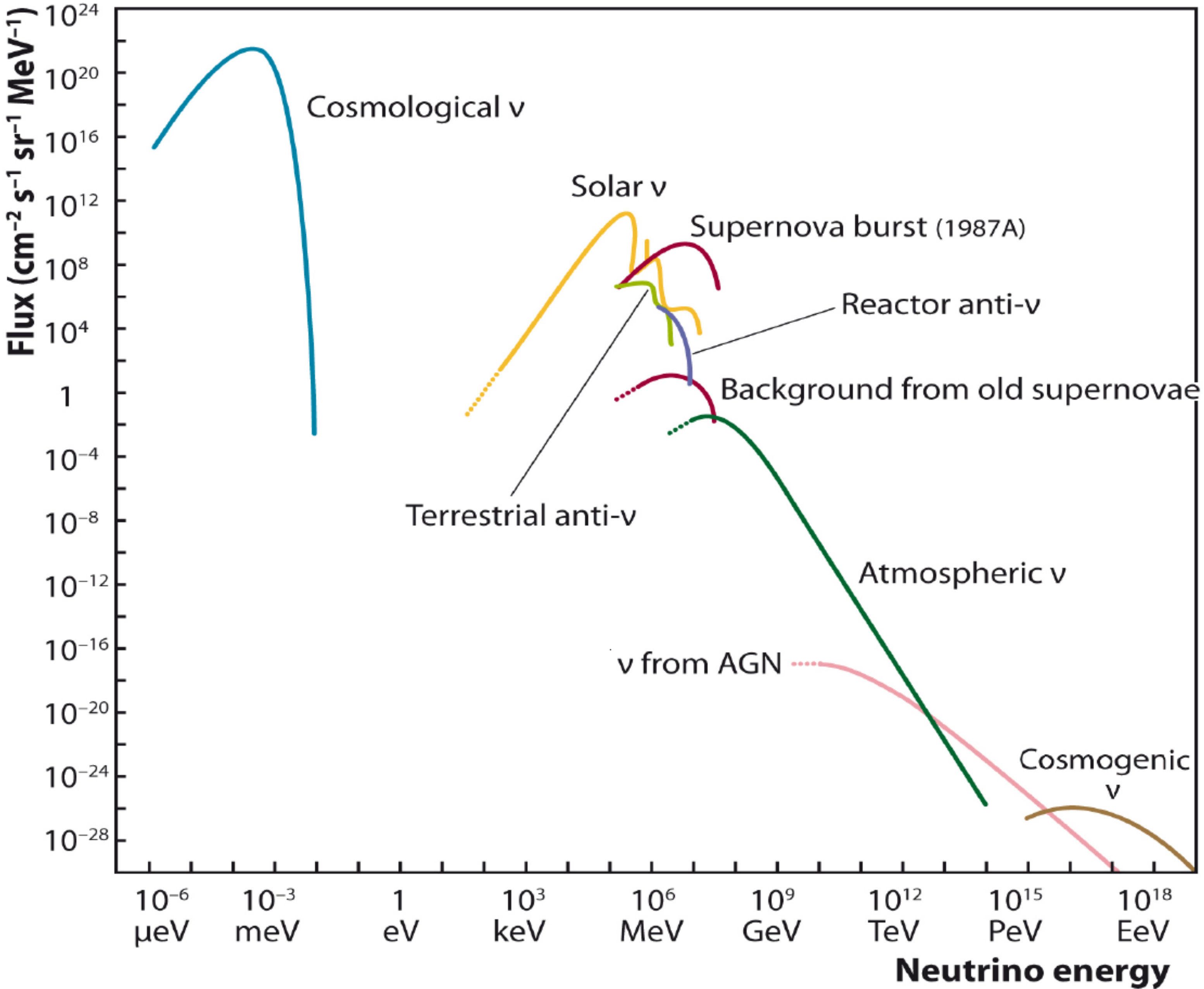
- 1998 – Neutrino Oscillations Solve the Problem
  - 2015 Nobel Prize to Kajita and MacDonald



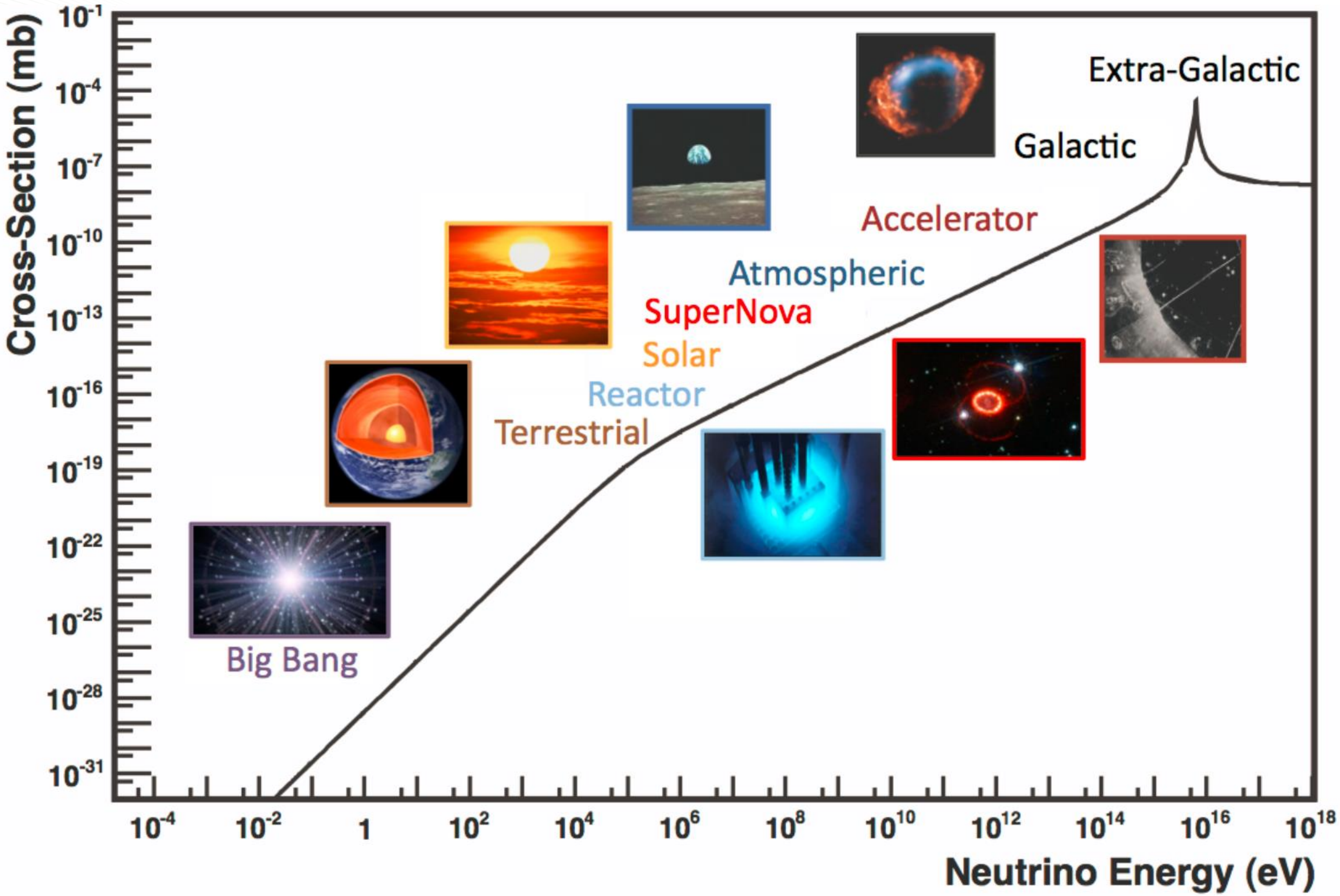
See Also: Ivan V. Anicin, The Neutrino – Its Past, Present, and Future arXiv:physics/0503172 [physics.hist-ph]

OAK RIDGE National Laboratory

Neutrino Sources: Fluxes

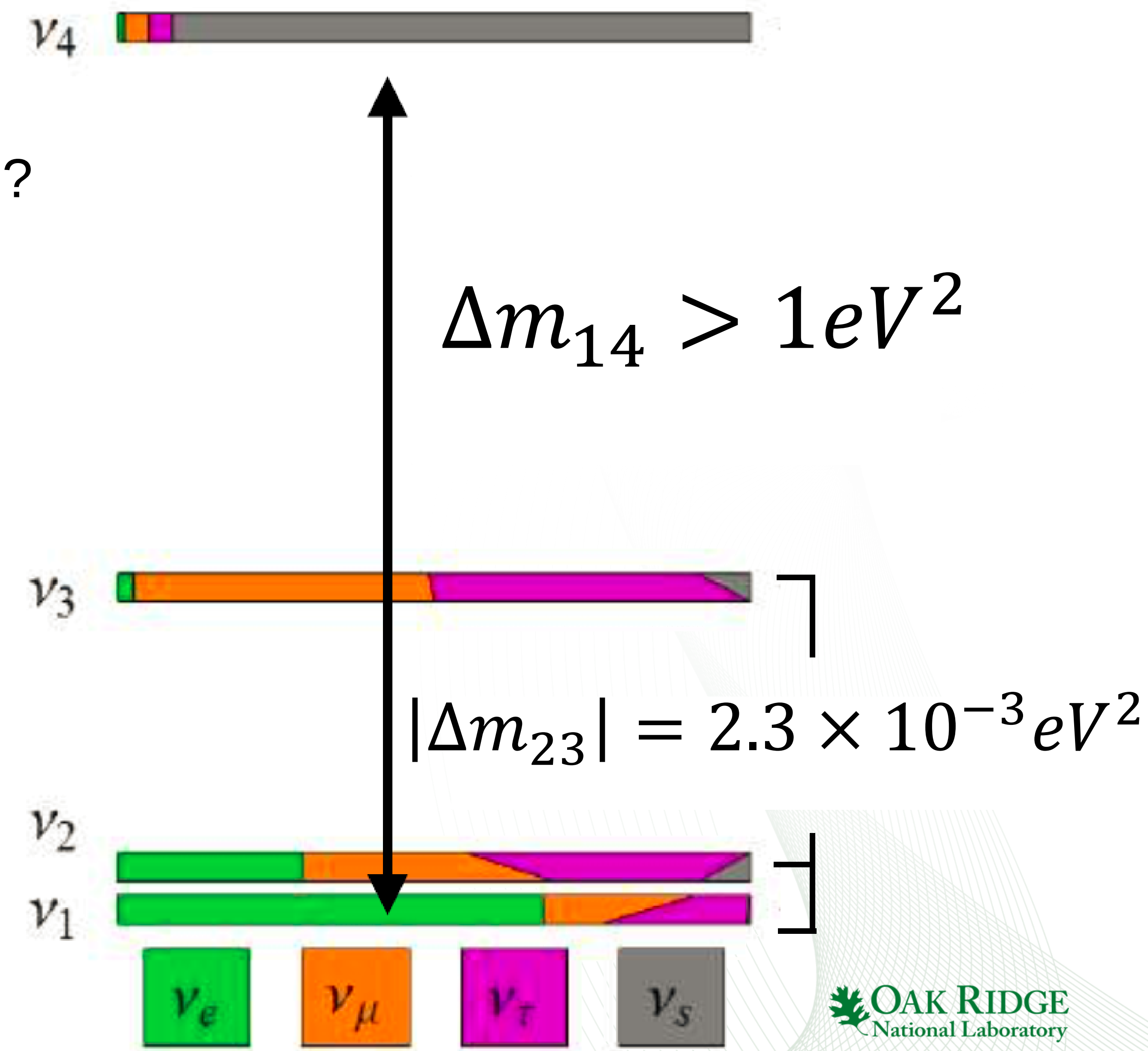


Neutrino Sources: Cross-Sections



Present Day: Open Questions

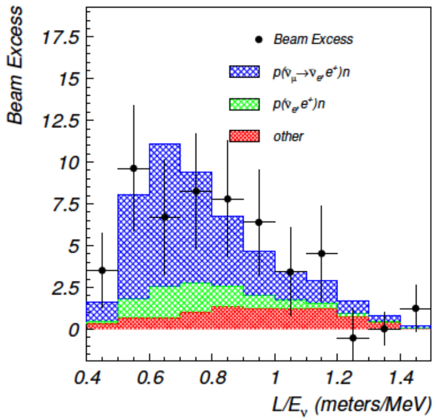
- Why are the neutrino masses so small?
- What is the neutrino mass ordering?
- Is the neutrino Majorana or Dirac?
- Are there more neutrino flavors?
- What is the source of the current anomalies?



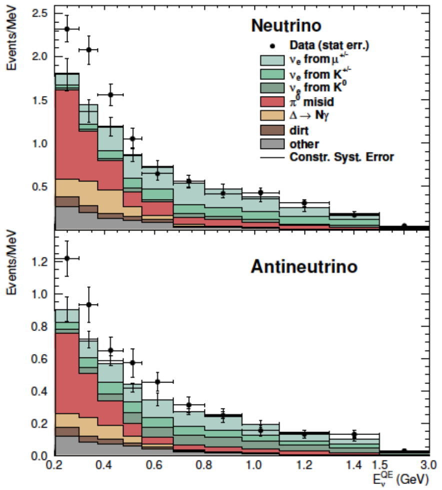
Present Day: New Anomalies

- LSND – Los Alamos National Lab
  - Observed an excess of neutrinos

LSND



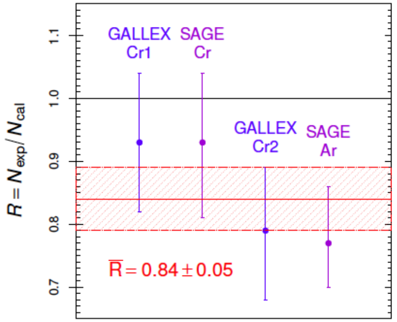
MiniBooNE



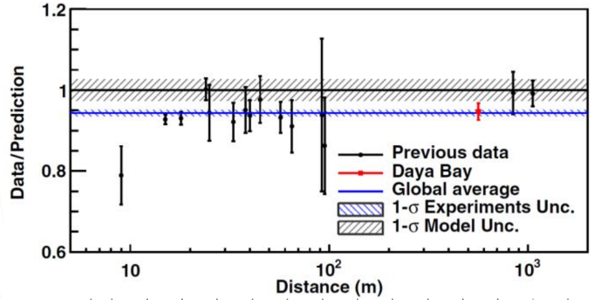
- MiniBooNE – Fermi Lab
  - Observed an excess of neutrinos below 500MeV
  - No excess above 500MeV

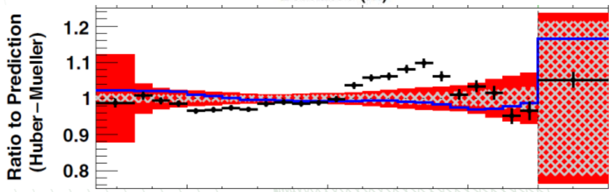
- The Gallium Anomaly
  - SAGE – Baksan Neutrino Observatory
  - GALLEX – Gran Sasso
    - Both observed deficit in neutrino induced ^{71}Ge production

GALLEX and SAGE



Reactor Deficit and Bump

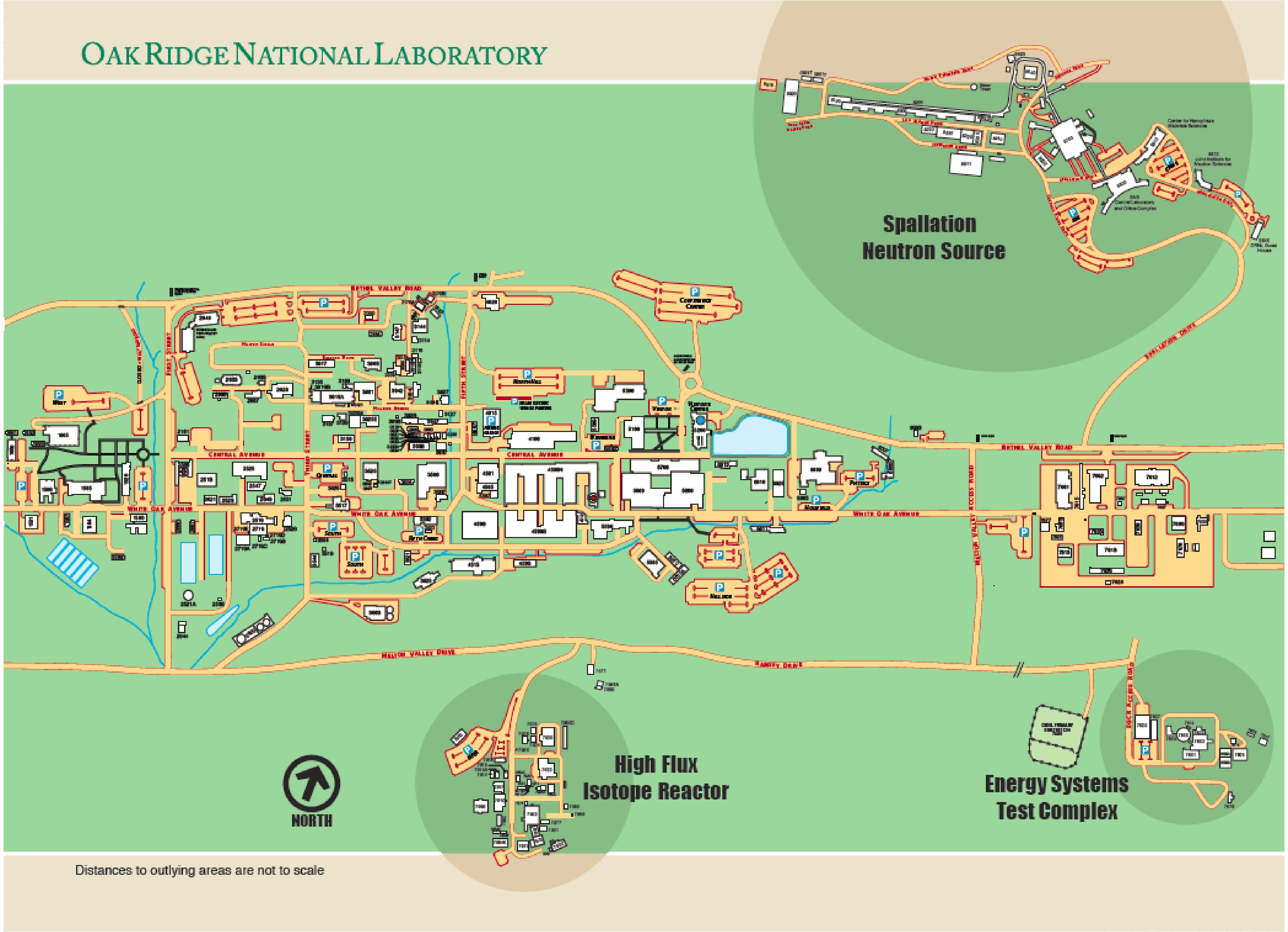




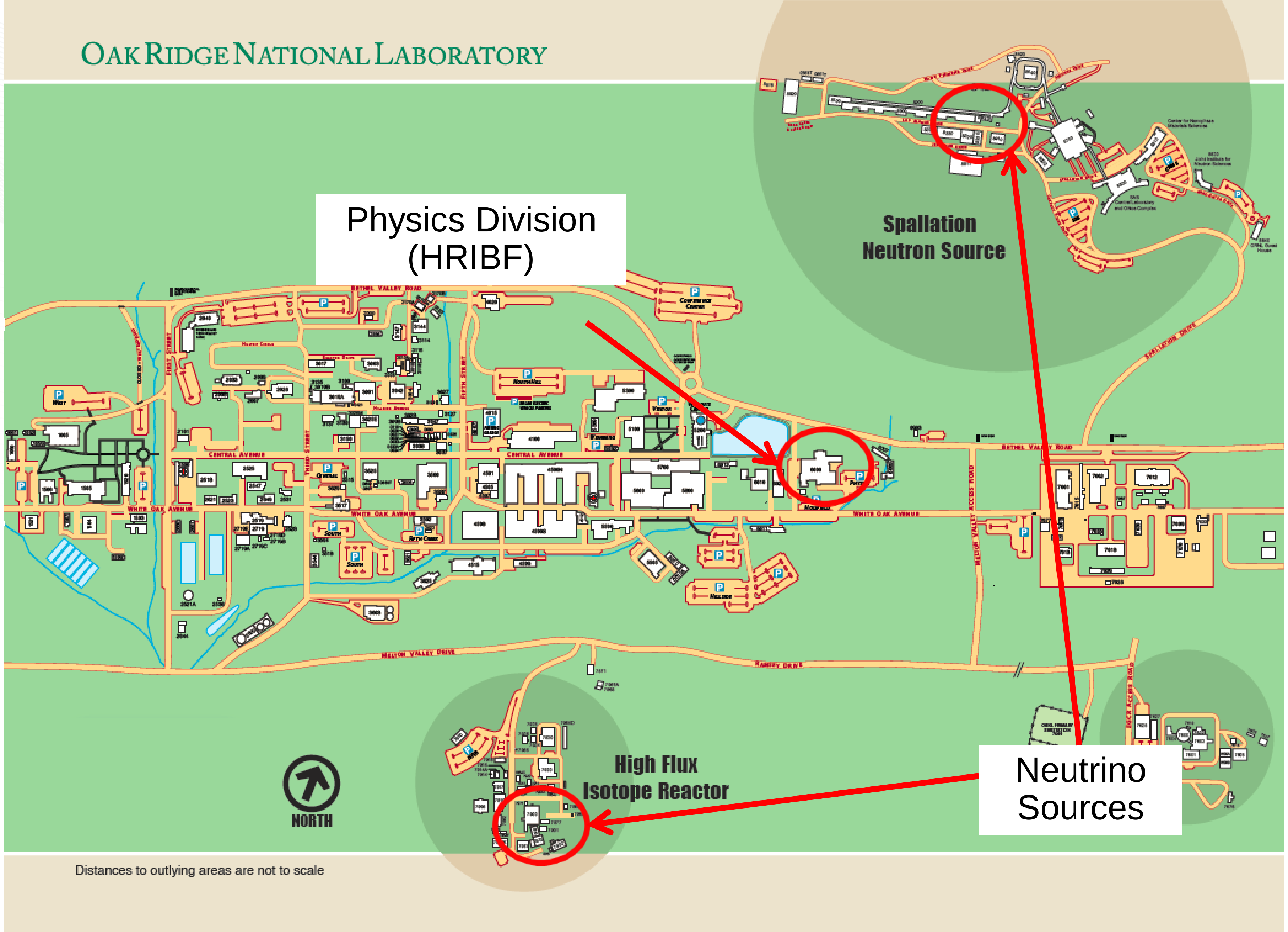
- The Reactor Anomalies
  - Deficit in measured neutrinos compared to models
  - “Bump” in shape between 4-6MeV compared to models

ORNL Neutrino Opportunities

ORNL


OAK RIDGE NATIONAL LABORATORY
Spallation Neutron Source
High Flux Isotope Reactor
Energy Systems Test Complex
NORTH
BETHEL VALLEY ROAD
CENTRAL AVENUE
WHITE OAK AVENUE
MELTON VALLEY DRIVE
Distances to outlying areas are not to scale

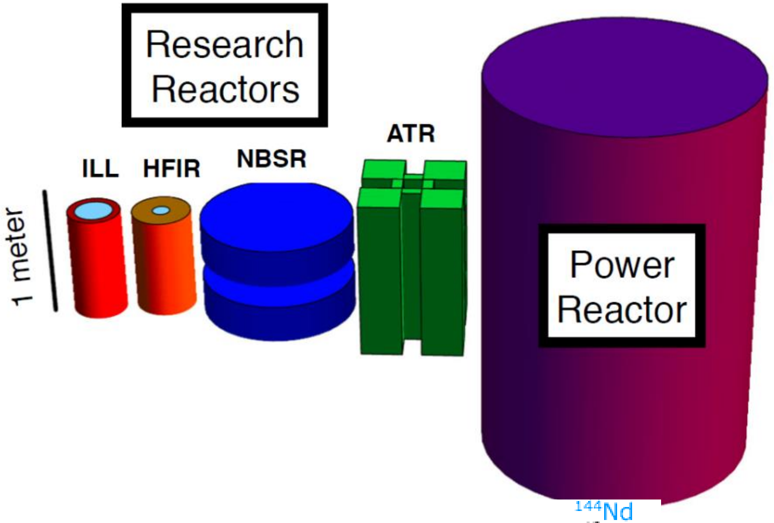
ORNL

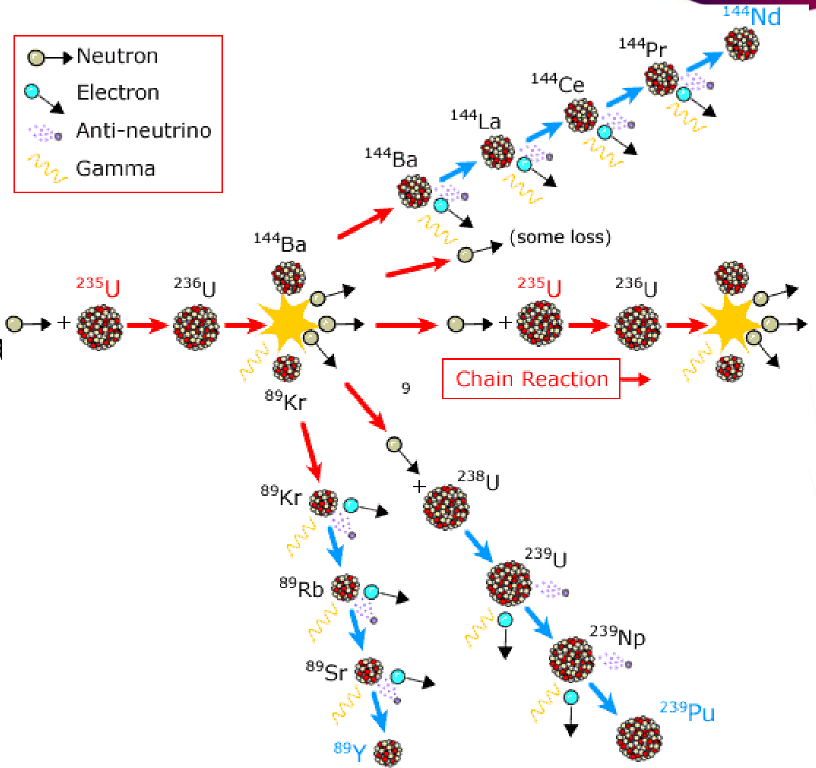

Oak Ridge National Laboratory
Physics Division (HRIBF)
Spallation Neutron Source
High Flux Isotope Reactor
Neutrino Sources
NORTH
Distances to outlying areas are not to scale

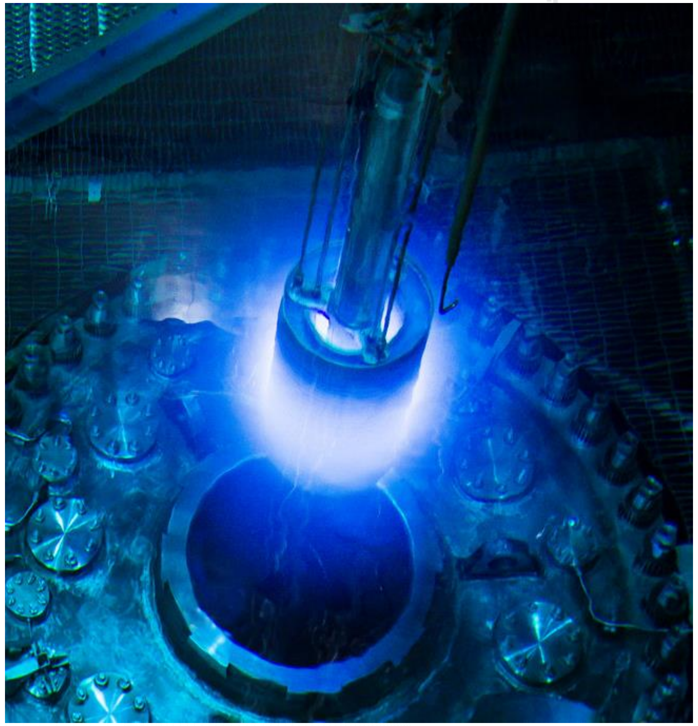
ORNL Neutrino Sources: HFIR

PROSPECT

- High Flux Isotope Reactor
  - 85 MW research reactor
  - ~93% enriched ^{235}U fuel
  - Compact Core (h=0.6m d=0.4m)
  - Very close access
  - ~24 day cycle
    - No ^{239}Pu buildup(<0.5%)
  - ~50% duty cycles
    - Excellent background characteriza

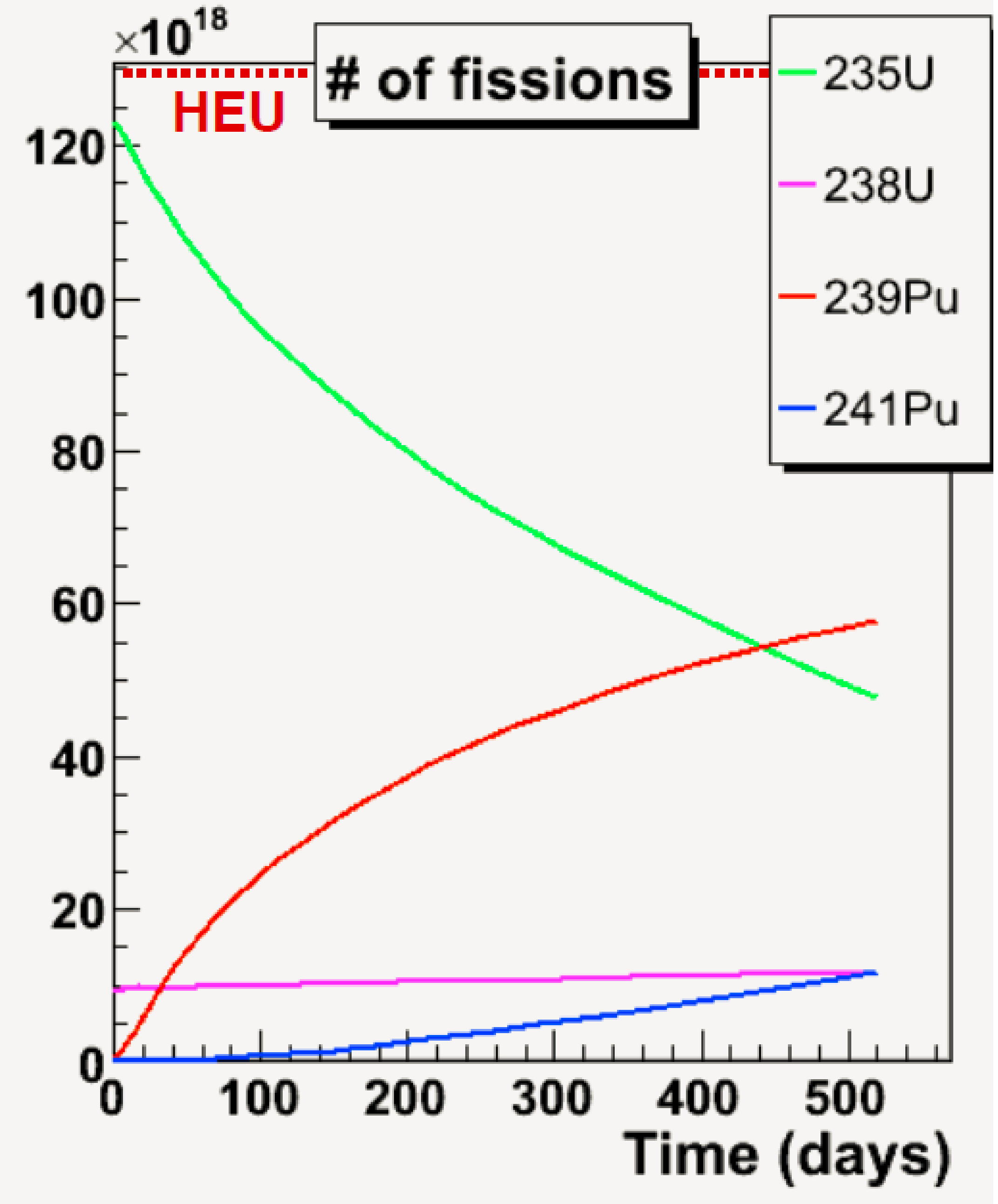


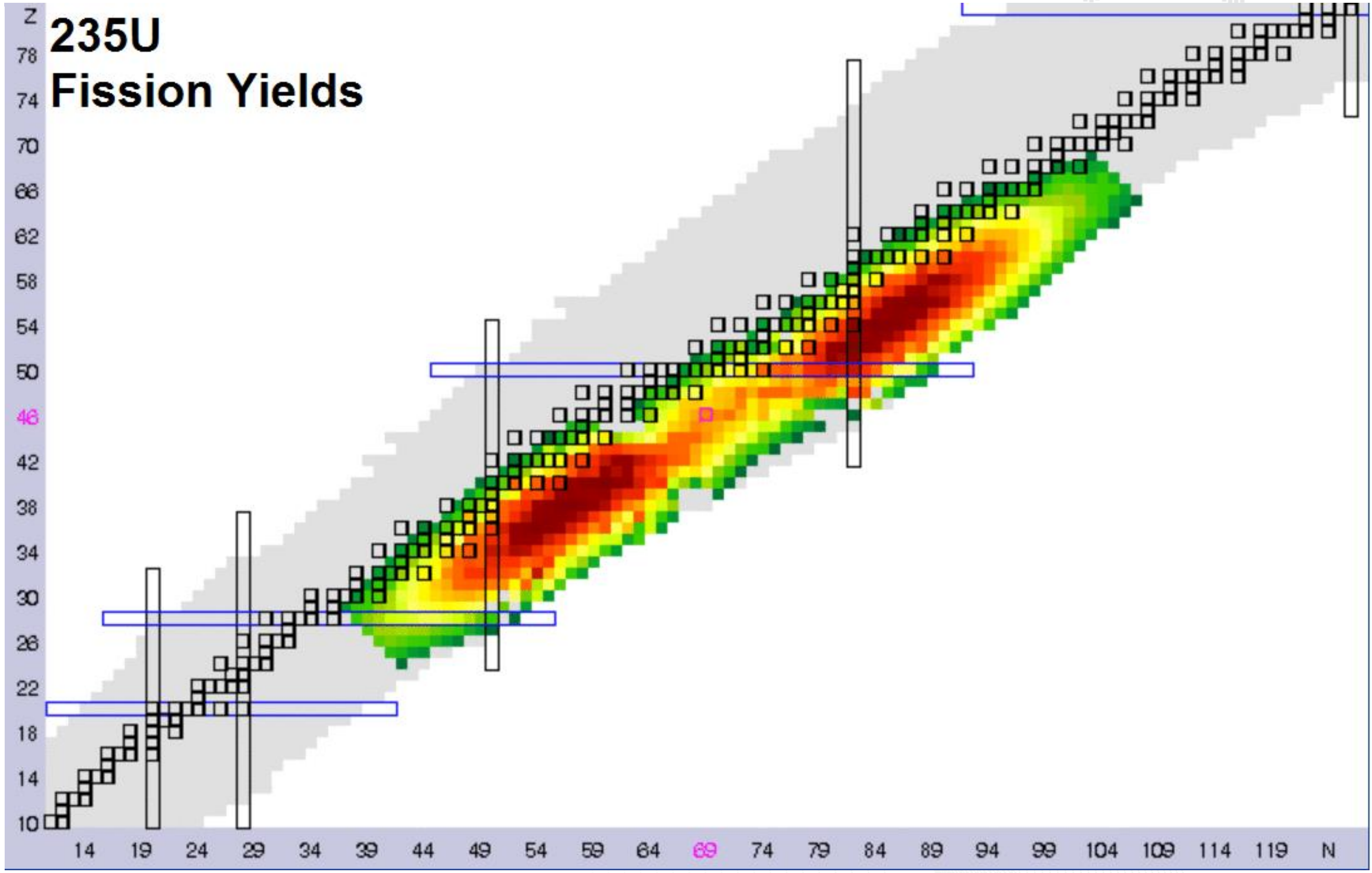




OAK RIDGE National Laboratory

Fission



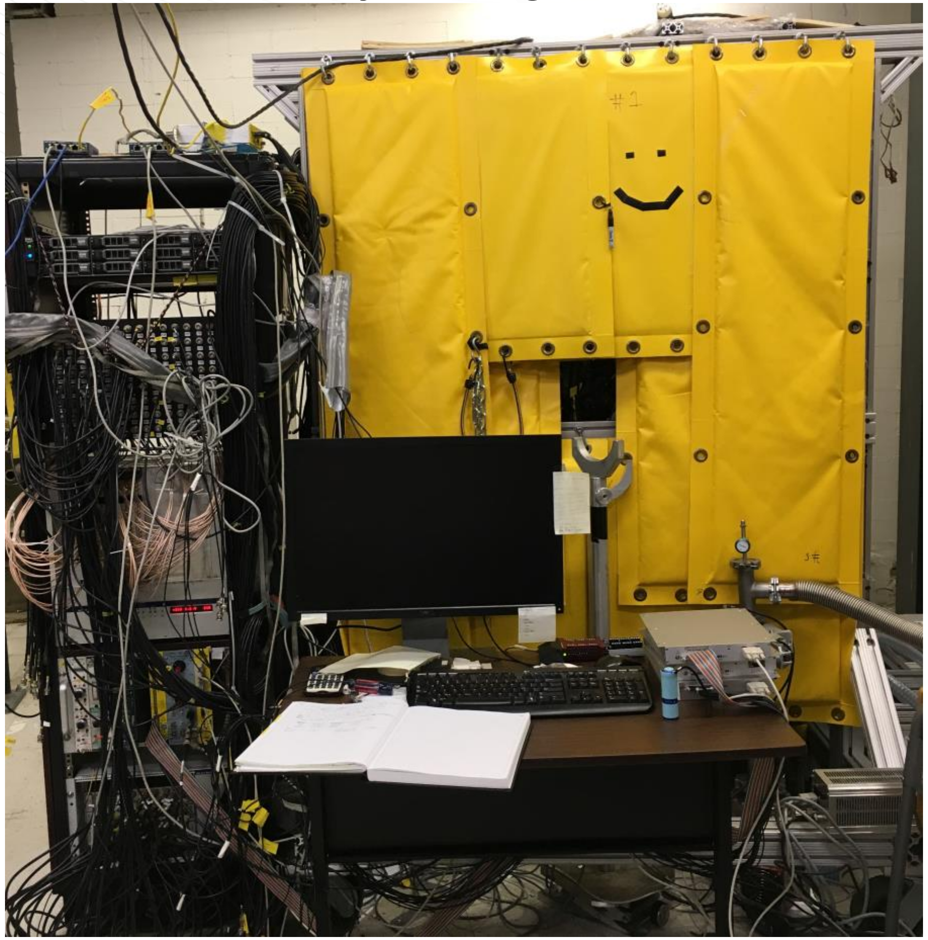


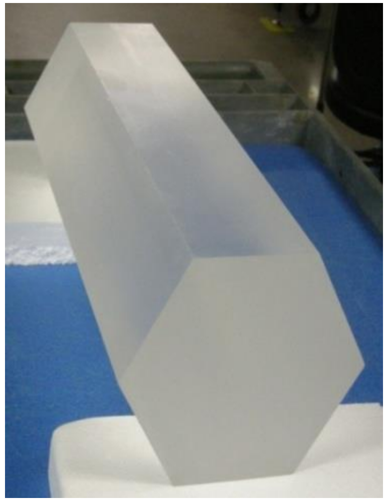
Yields change between fuel isotopes

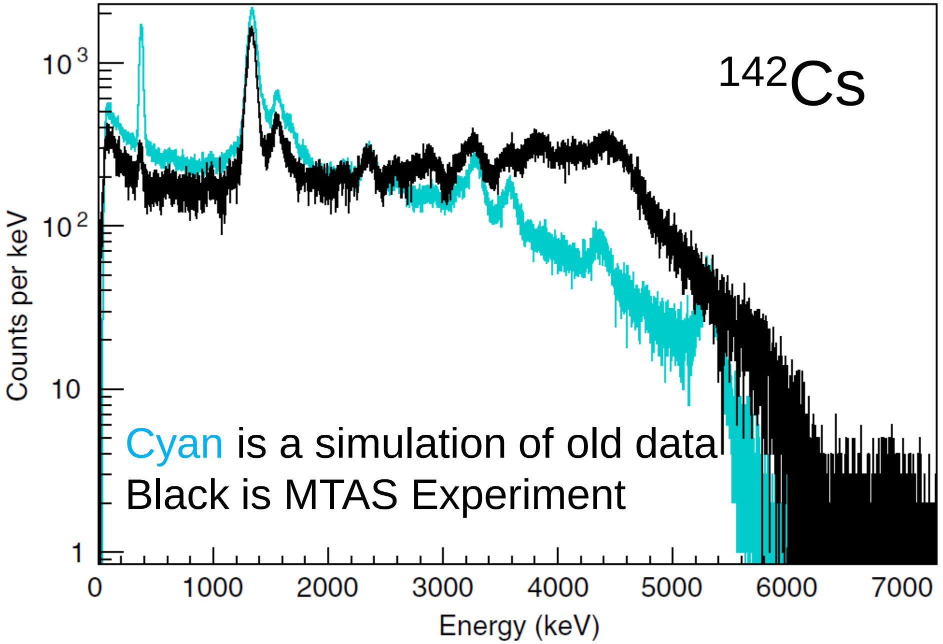
LEU reactors have highly time dependent fission fractions

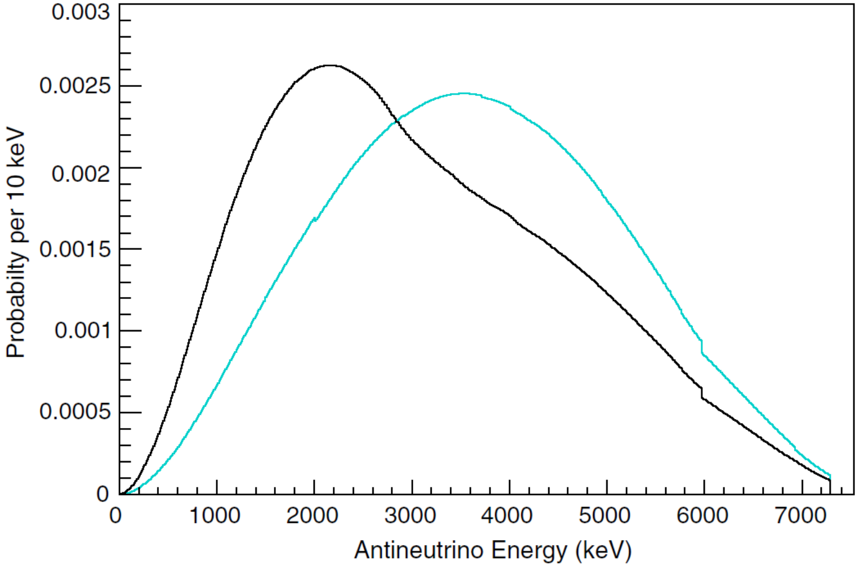
Modular Total Absorption Spectrometer - MTAS

~1ton of NaI(Tl)
Allows measurement of total gamma-ray energy output of fission daughters, extract β-decay strength functions





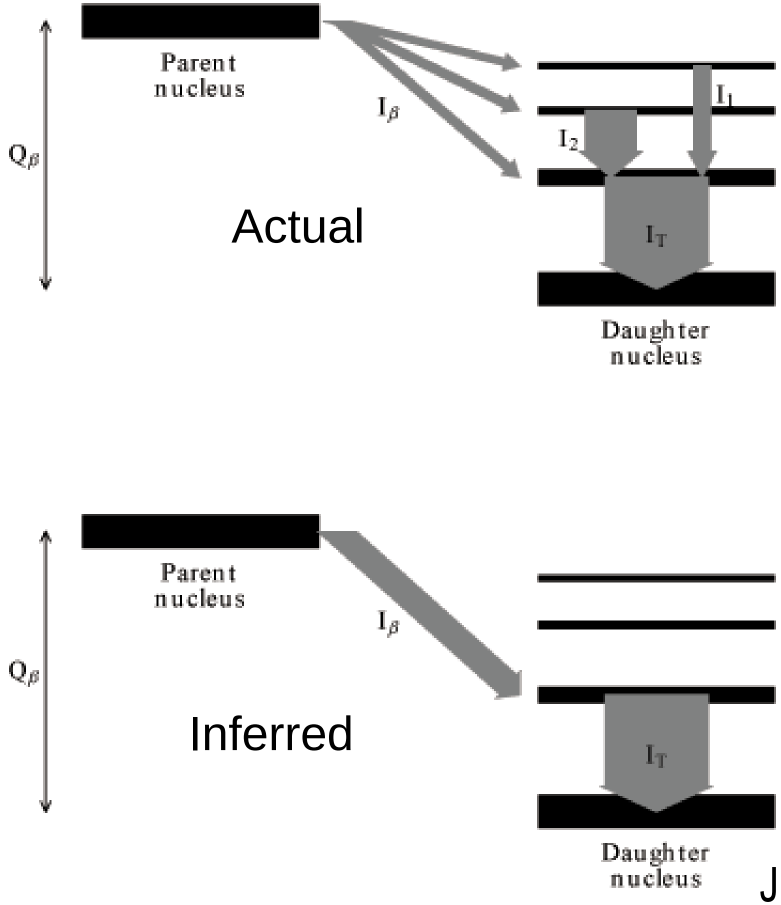


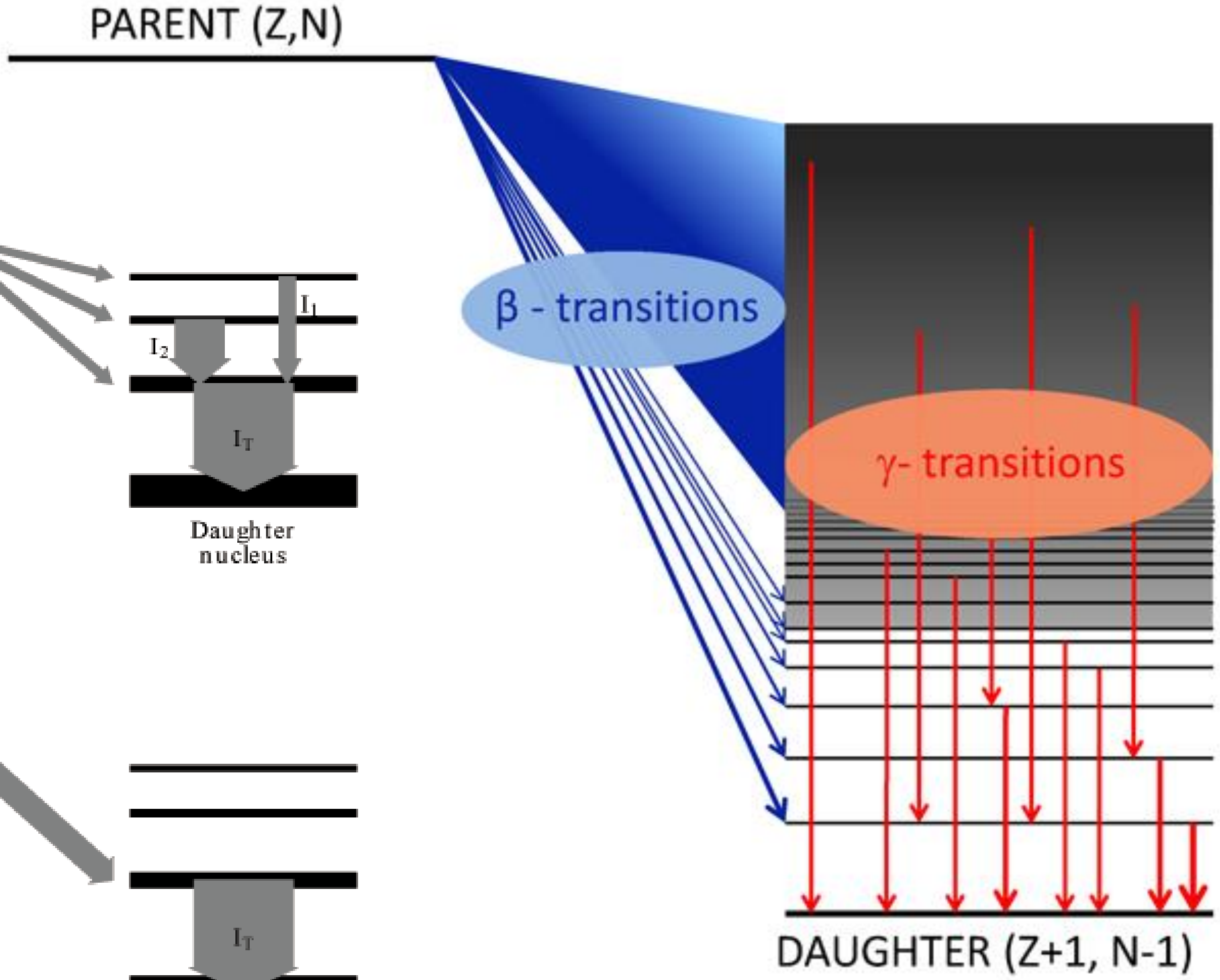


These measurements show that the β-decay neutrino spectra have lower energies than previously thought

MTAS – Why is it necessary? The Pandemonium Effect

- Fragmentation of decay strength at high excitation energy due to high level density.
  - Low efficiency high resolution experiments overestimate the branching to low energy levels.
  - Shifts deduced $\bar{\nu}_e$ spectra up





J.C. Hardy et al. PLB **71**, 307

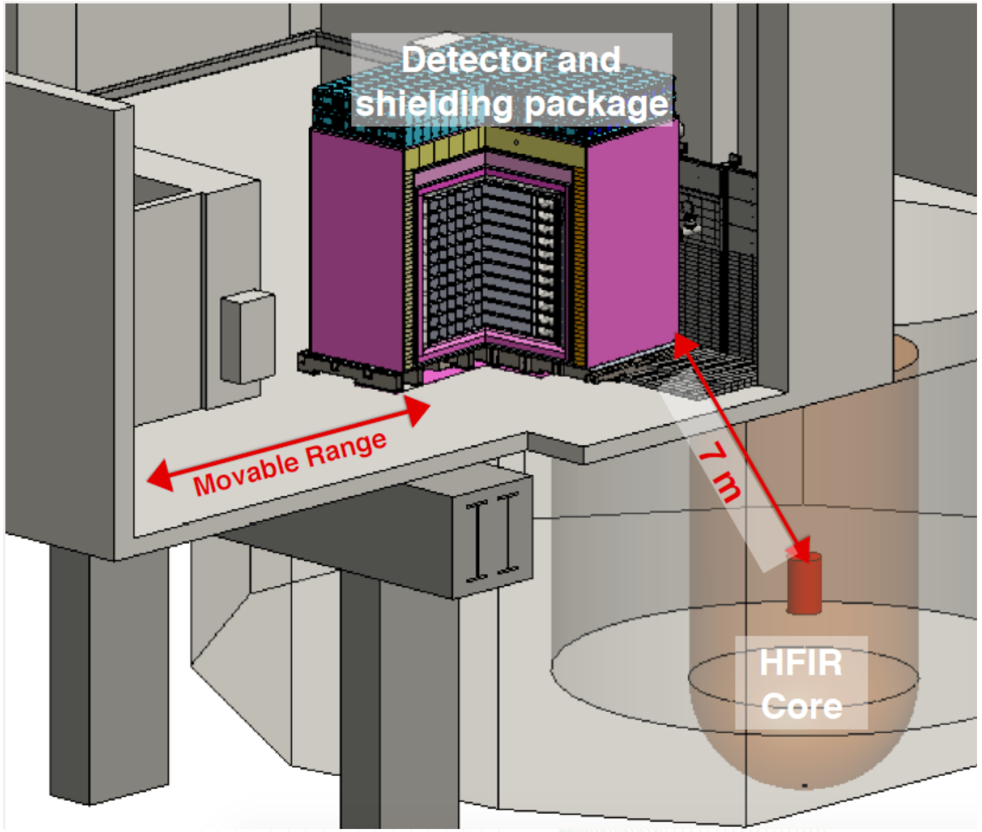
PROSPECT

PROSPECT Outline

- Overview
- Motivation
- The Detector
- Backgrounds
- Progress

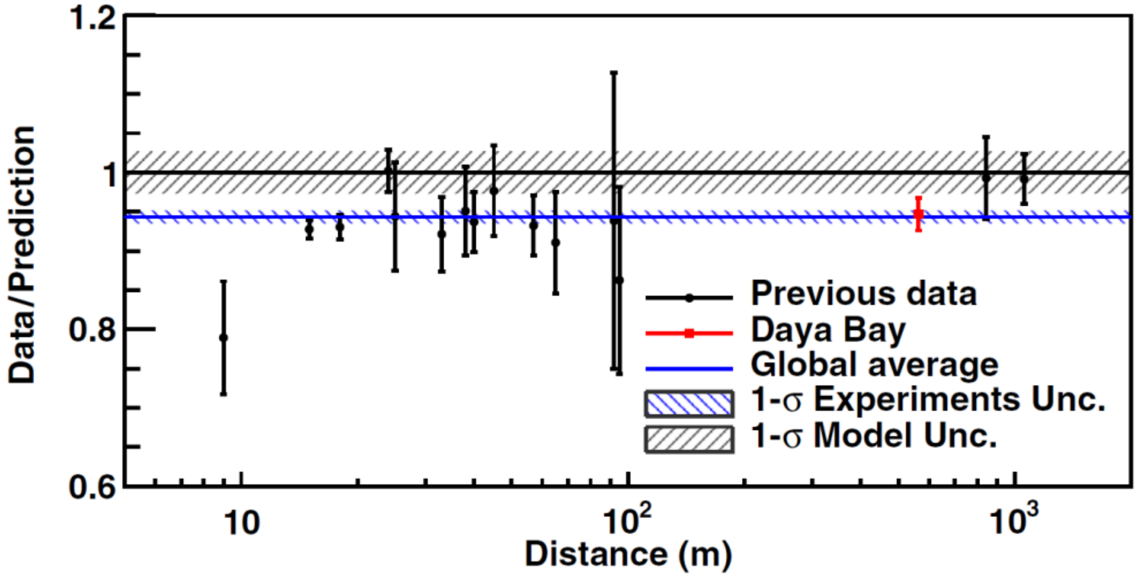
Overview

- Model independent search for neutrino oscillations into eV-scale sterile states
- Precision measurement of an HEU reactor spectrum with the best energy resolution to date
- Complement existing LEU reactor measurements
- Most precise ^{235}U spectrum measurement
- Compare reactor $\bar{\nu}_e$ spectrum models
- Provide a benchmark for future reactor $\bar{\nu}_e$ experiments
- ~160k IBD/year
- Resolution better than $4.5\%/\sqrt{E}$
- S/B of 3:1
- We also hope to:
    - Measure total absolute reactor flux
    - Observe $\bar{\nu}_e$ from spent nuclear fuel

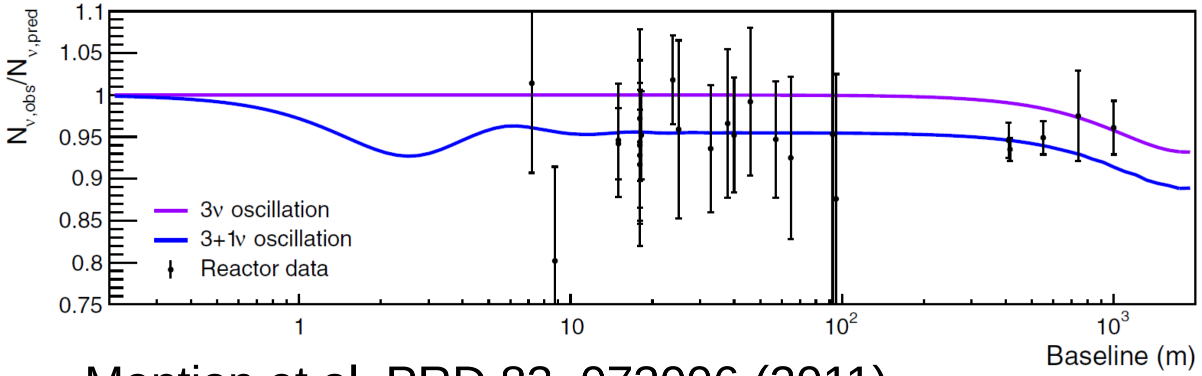


Motivation - Reactor Anomalies

PROSPECT



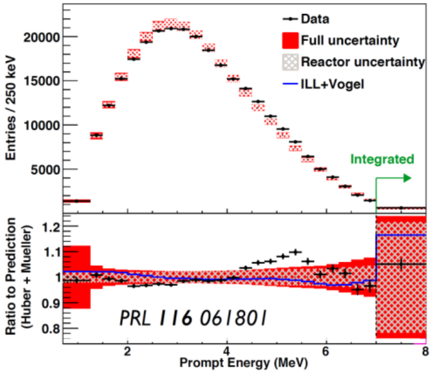
- Measured Flux Shortfall
  - Bad β-decay data or oscillation to a sterile neutrino?



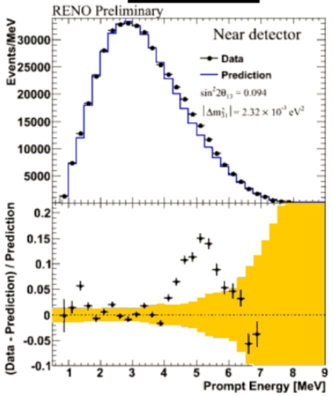
Mention et al. PRD 83, 073006 (2011)

- Bump at 4-6 MeV
  - Problem with a single fission fuel isotope or multiple?

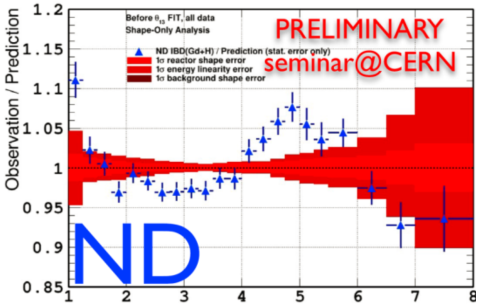
Daya Bay



RENO



Double Chooz



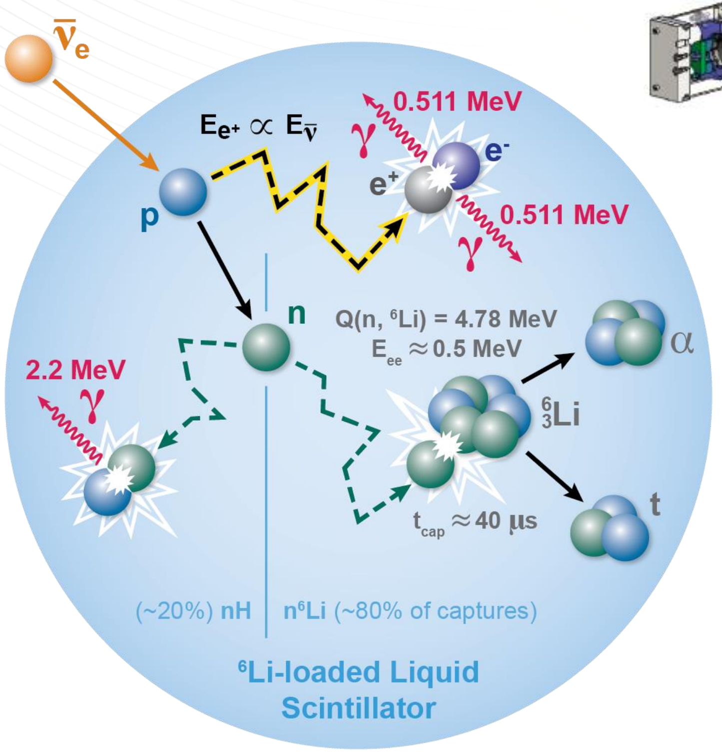
Oak Ridge National Laboratory

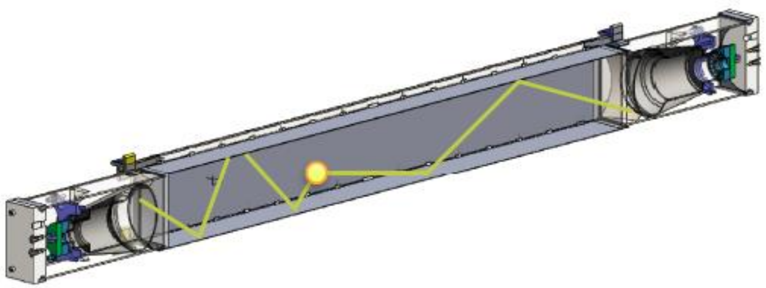
Motivation - Reactor Modeling and Monitoring

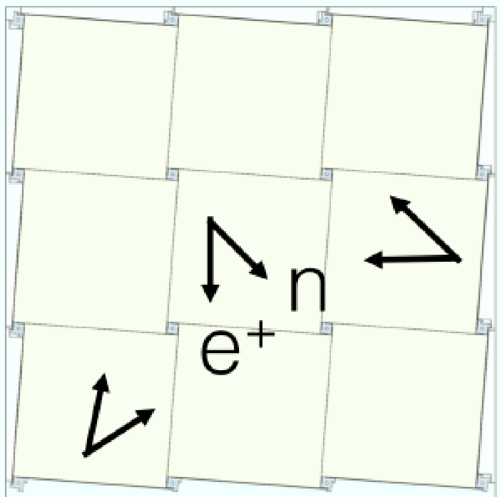
- Neutrinos are excellent messenger particles for harsh environments
  - Putting a detector inside a reactor will destroy it
  - Putting a non-neutrino detector outside a reactor will give heavily scattered and shifted results
  - Putting a neutrino detector outside a reactor allows you to directly monitor activity in the core, and possibly, type of core

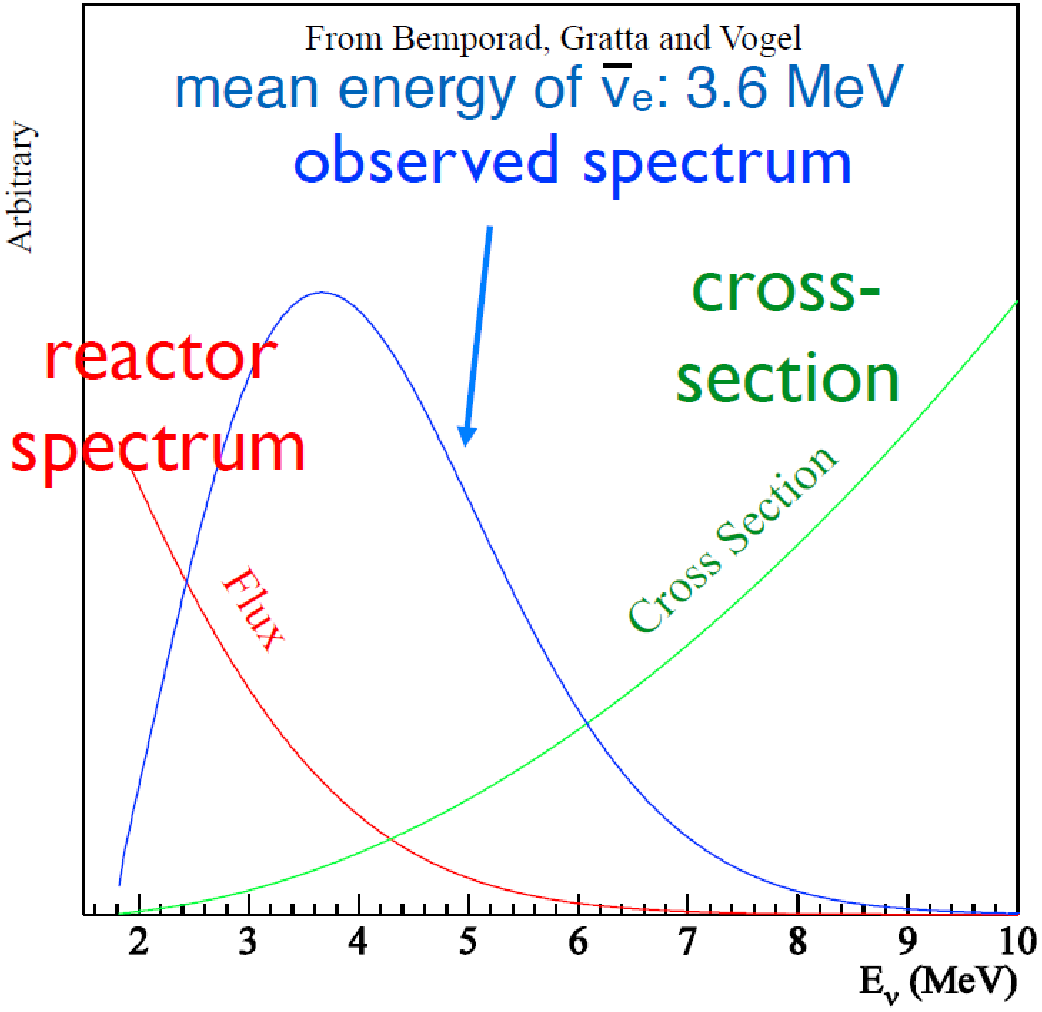
The Detector - Principle of Detection

Detection By:
Inverse β-decay (IBD)

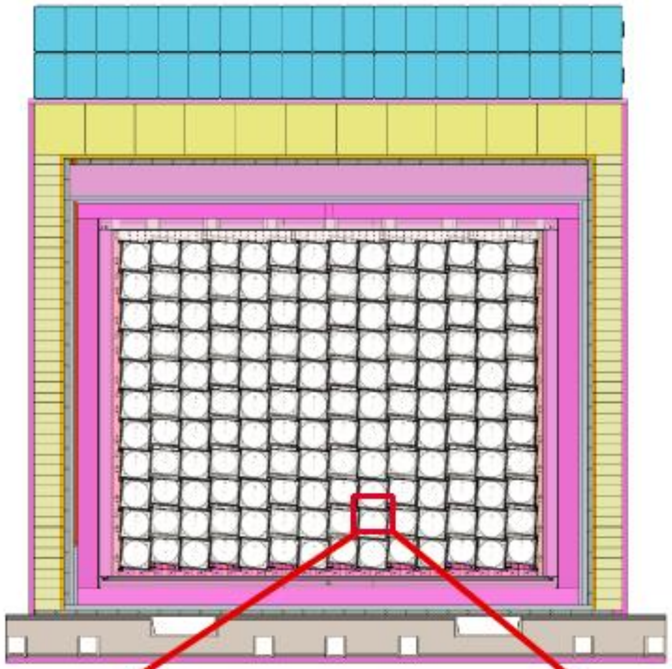




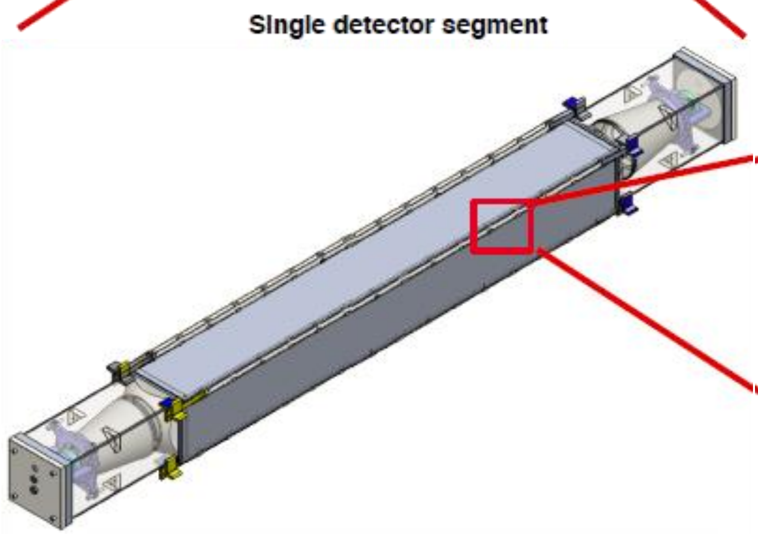


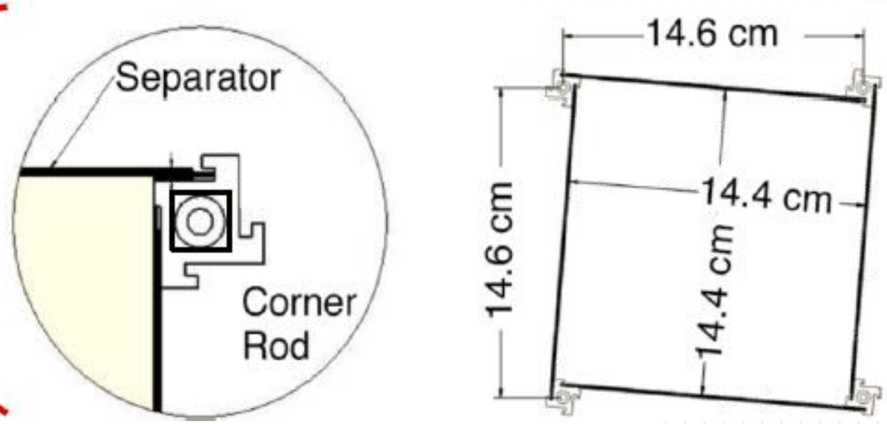


The Detector - Design

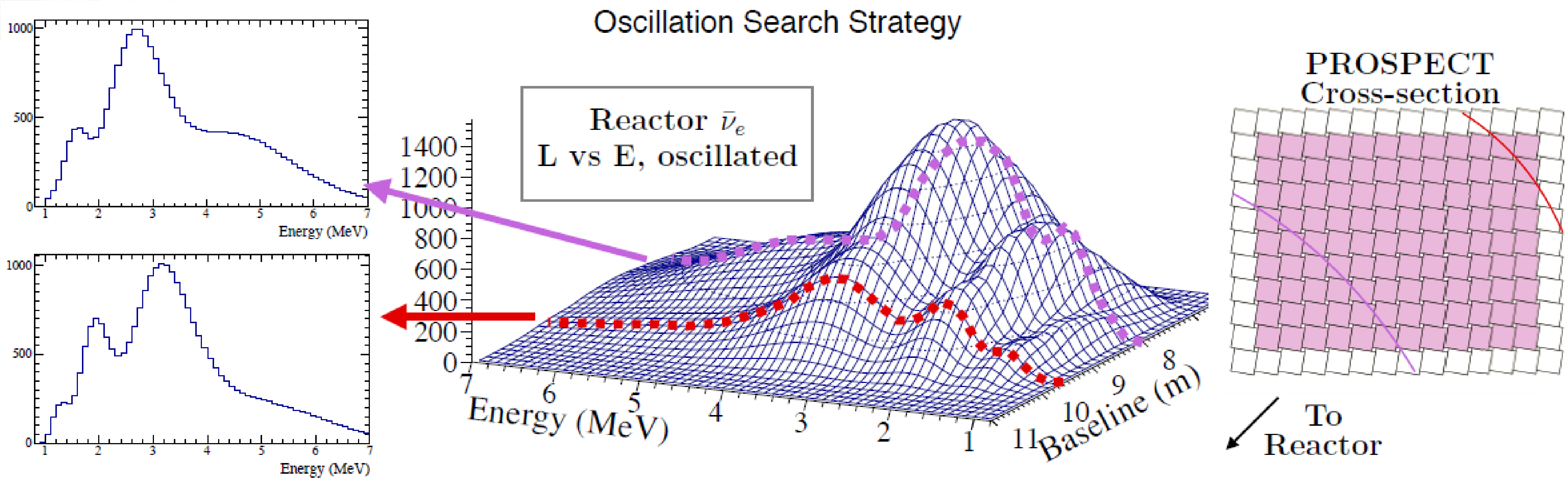


- **~4ton** ^{6}Li-loaded liquid scintillator detector
- Optically divided into 14x11 identical segments
  - *i.e.* 154 detectors
- Low mass optical separators
  - Minimal dead material
- Double-ended readout
- Access for calibration *in-situ*



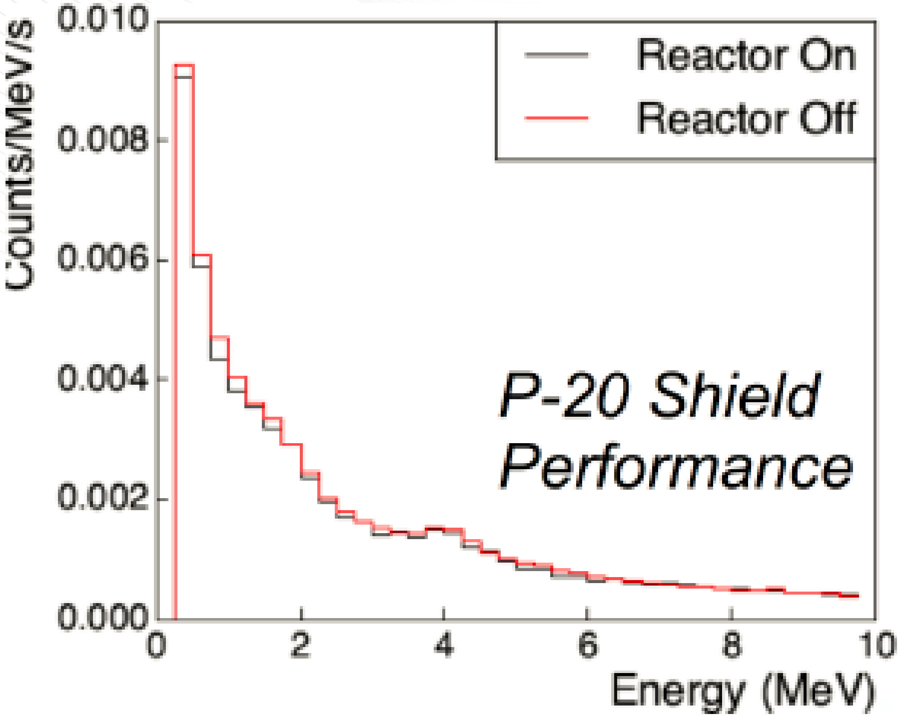


The Detector - Oscillation Search



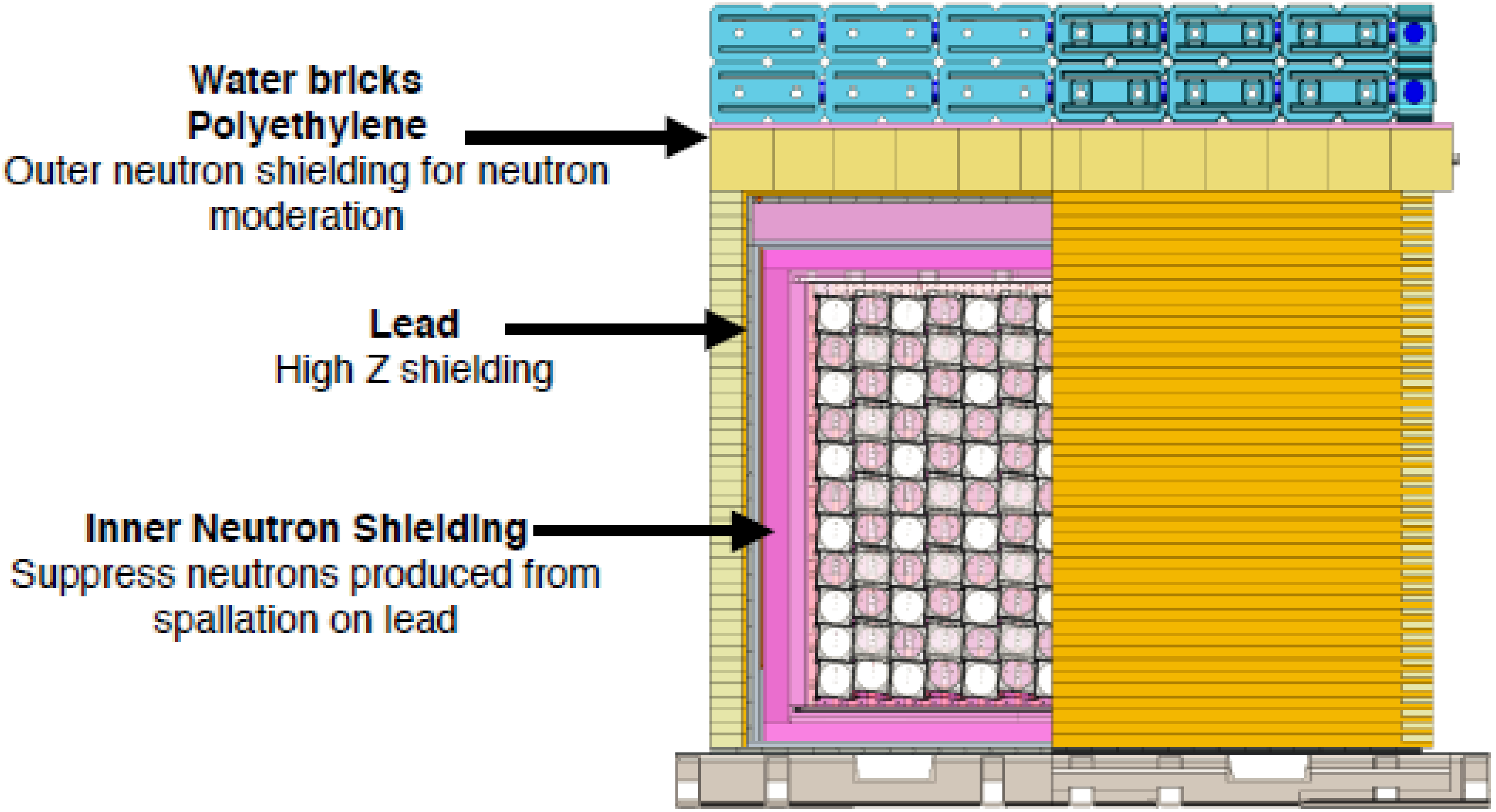
- Relative spectrum measurement between independent detectors
- Segmentation gives clear baseline dependency
- Independent of reactor flux and spectrum models
- Relative measurement and movement minimize systematic errors

Backgrounds - Shielding



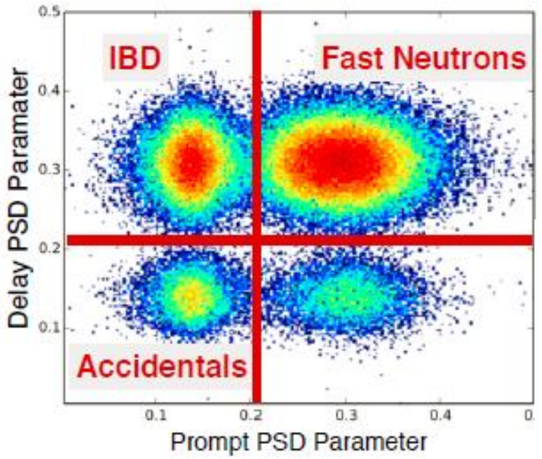
Local shielding joining reactor wall

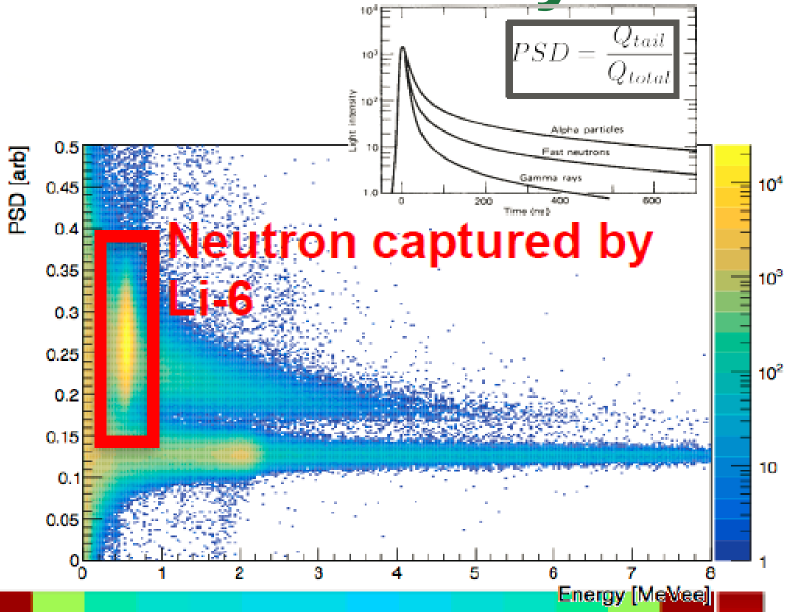
Multi-layer passive shielding



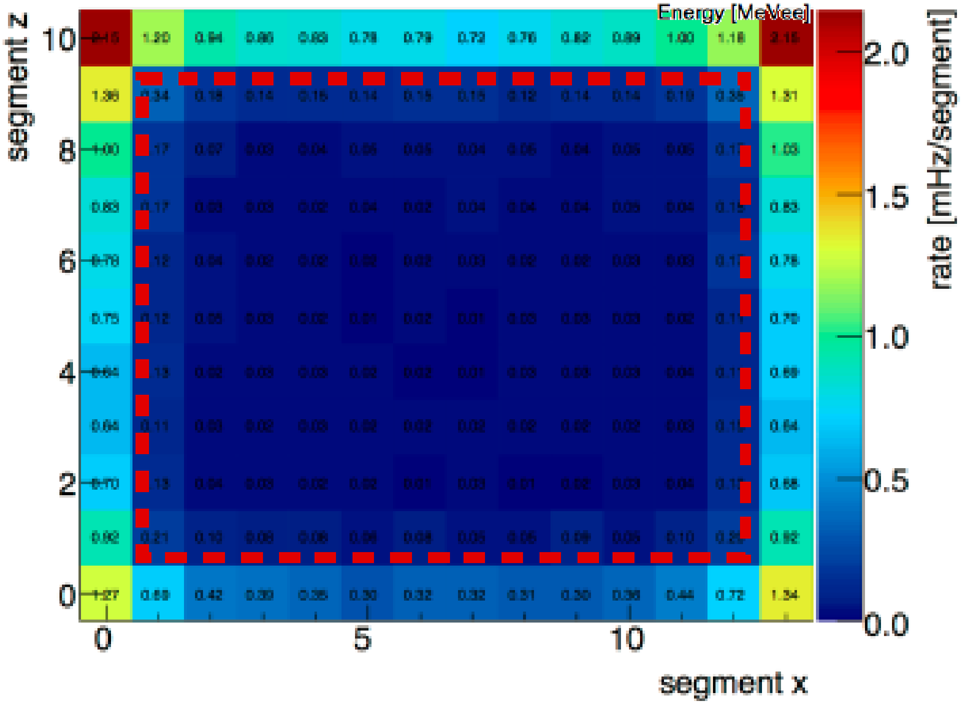
Backgrounds - Reduction by Cuts

Pulse shape discrimination removes most accidental coincidences and backgrounds

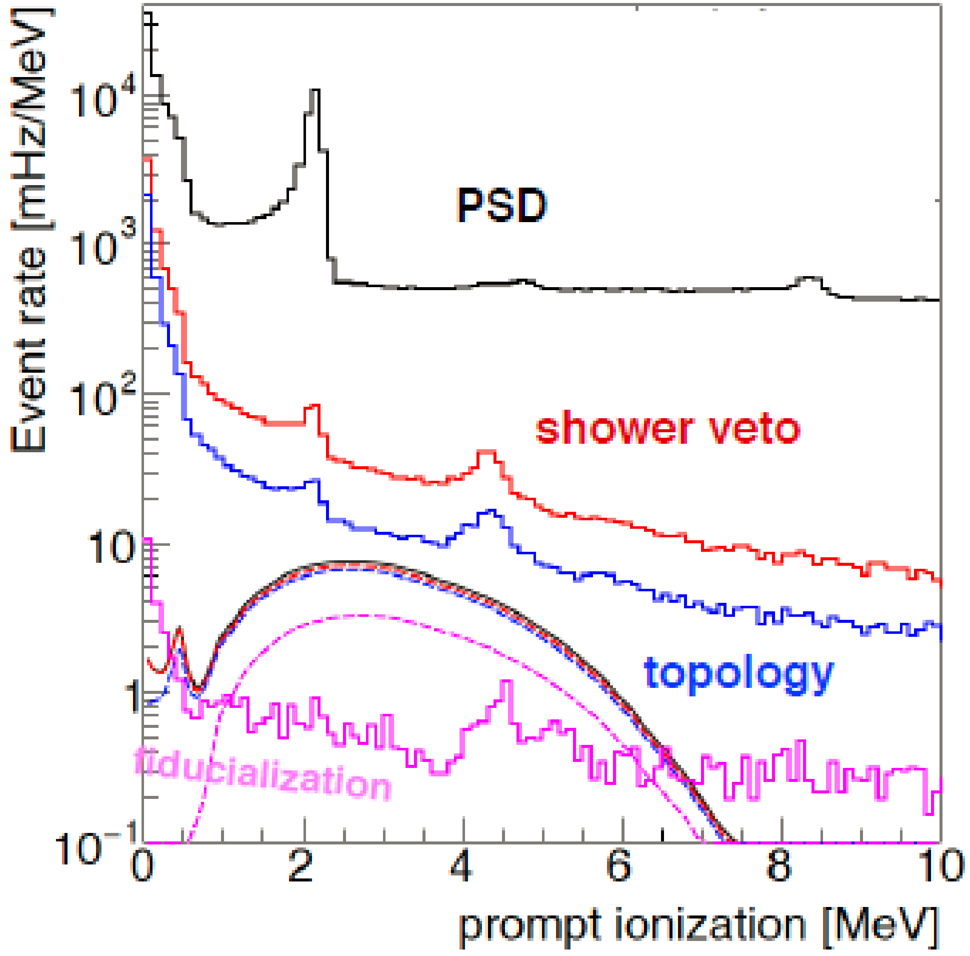




Fiducialization removes worst of gamma-ray background



Further cuts that can be applied



Background Characterization

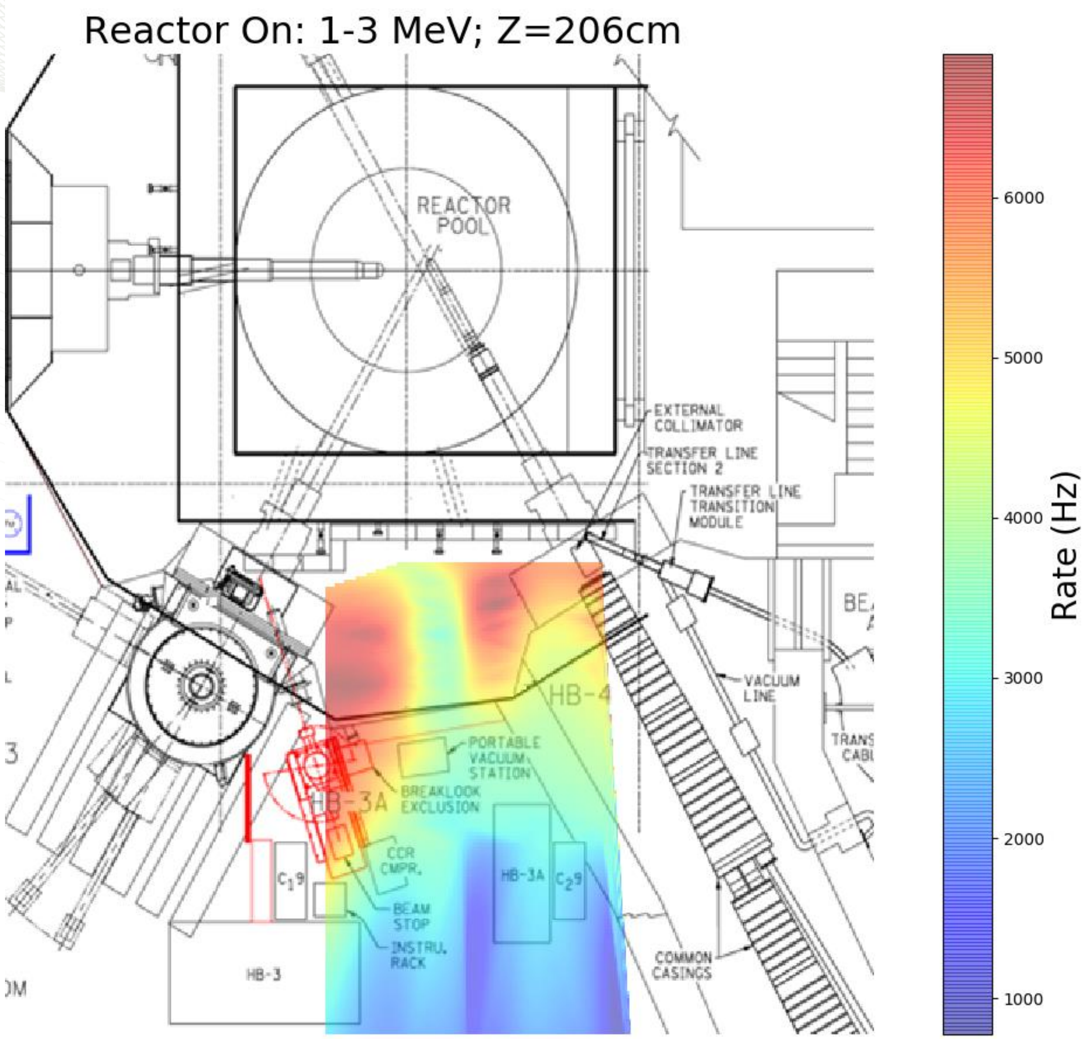
- Thermal Neutron Backgrounds
- Gamma-ray Backgrounds
- Stray Magnetic Fields
- Cosmic Ray Backgrounds

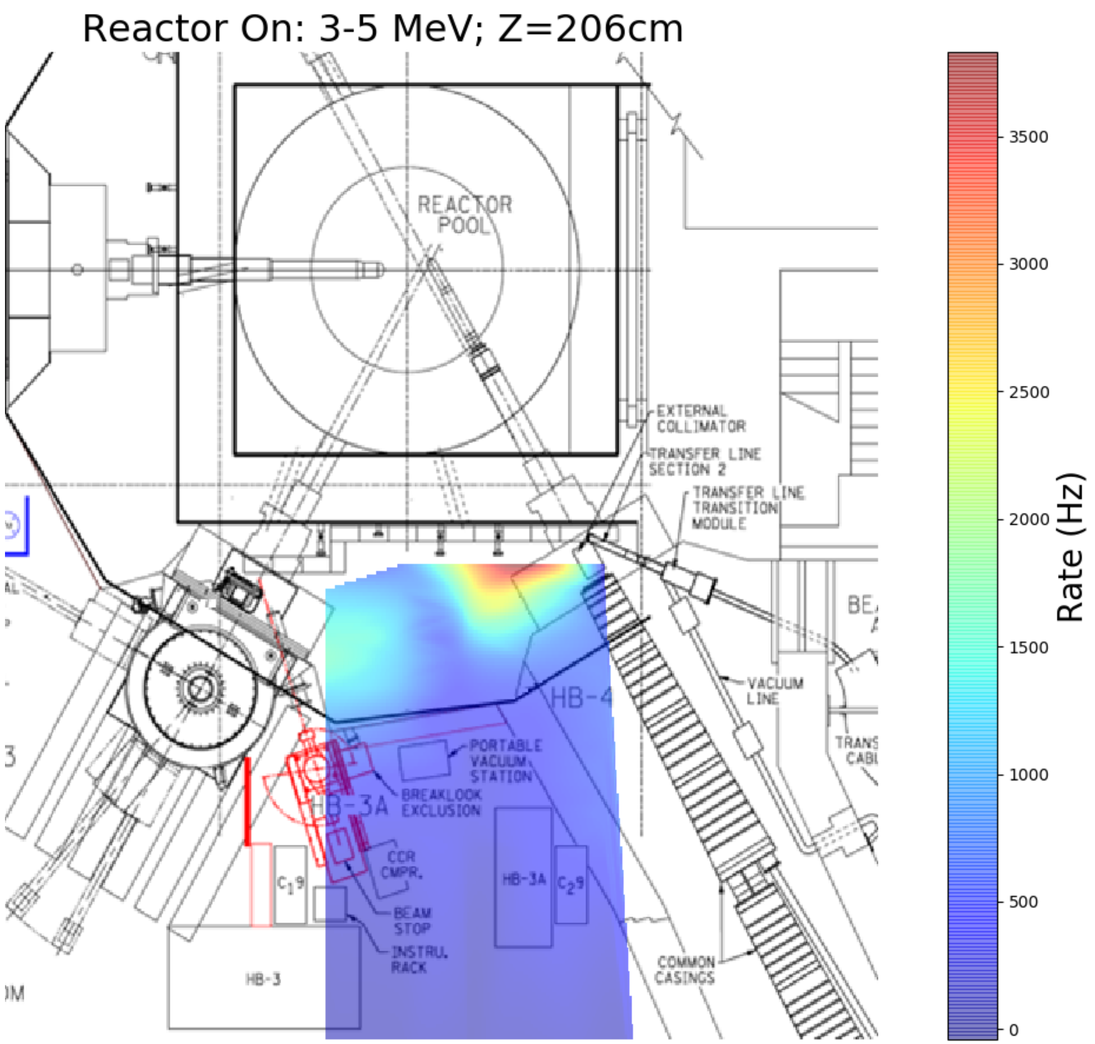
Backgrounds - Characterization

- Detector Array for measurement of Neutrons and Gammas (DANG)
  - 8 large volume NaI(Tl) detectors
    - 2”x4”x16”
  - 6 NE213 liquid scintillator detectors
    - 1.2 Liters
  - 2 ^{3}He Detectors
    - 2”x24” 10 Bar
  - Custom DAQ Oak Ridge Conditions at HFIR DAQ (ORCHID)
    - Designed to cope with very high rates

Backgrounds – Spatial Variance

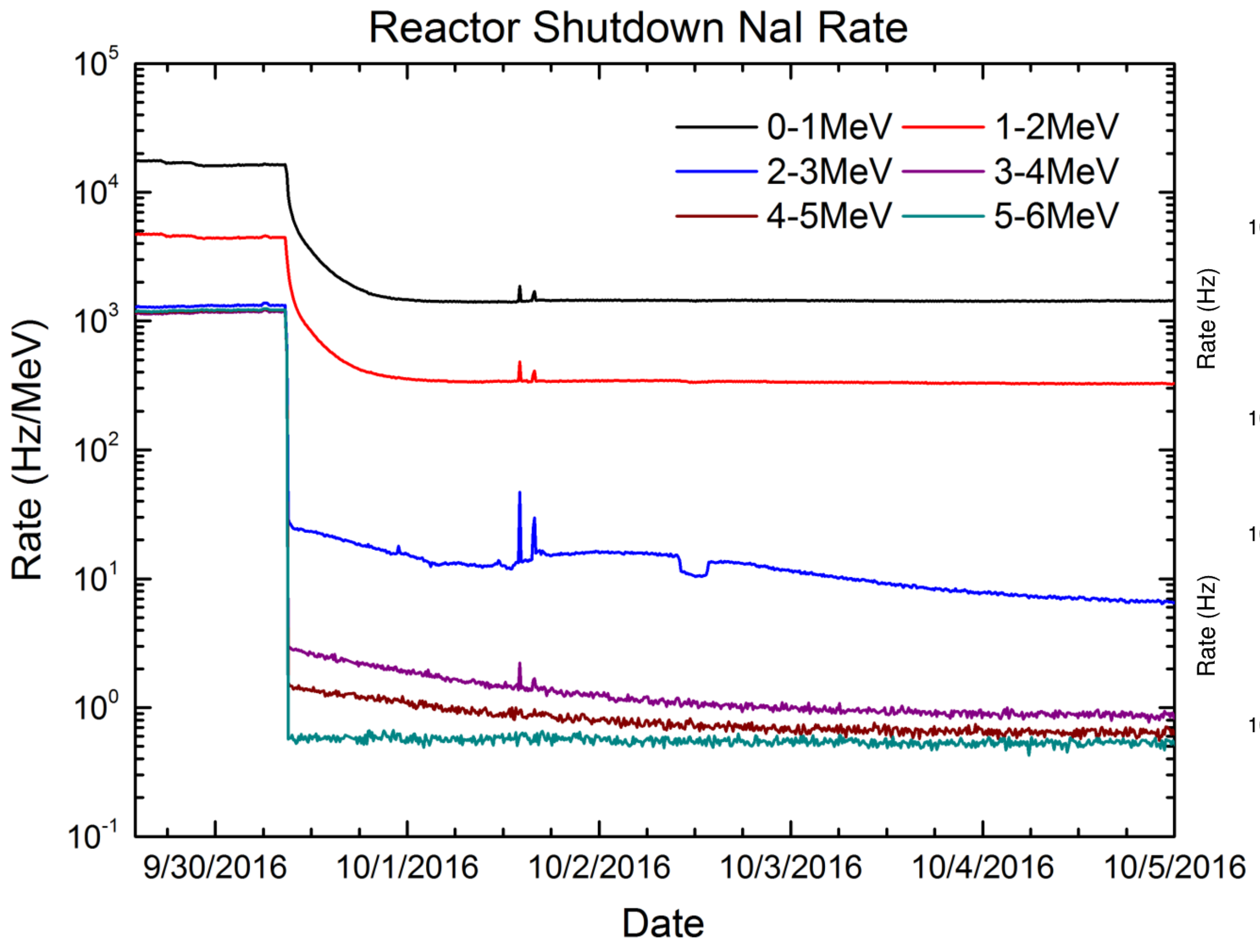
PROSPECT

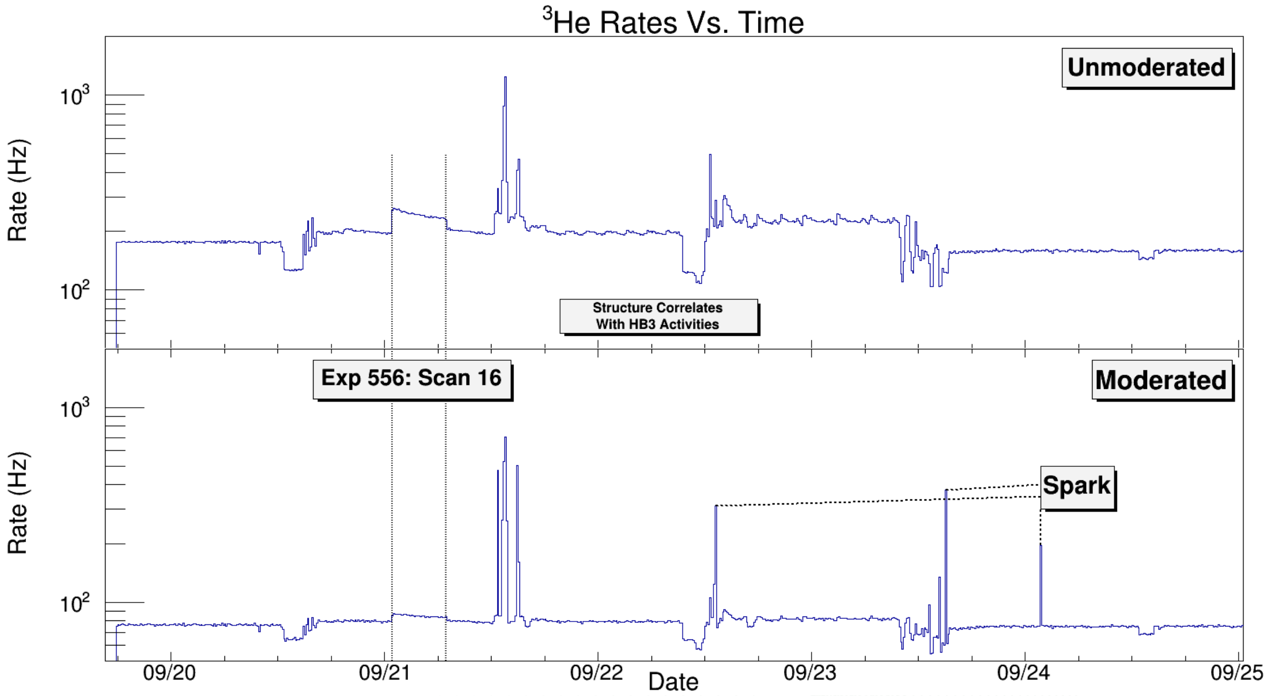




OAK RIDGE National Laboratory

Backgrounds – Temporal Variance



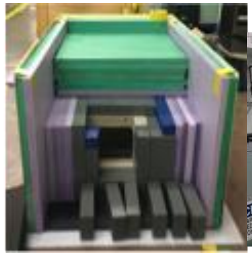


Current Progress - Timeline

PROSPECT-0.1
Characterize LS
Aug 2014-Spring 2015

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


multi-layer
shielding

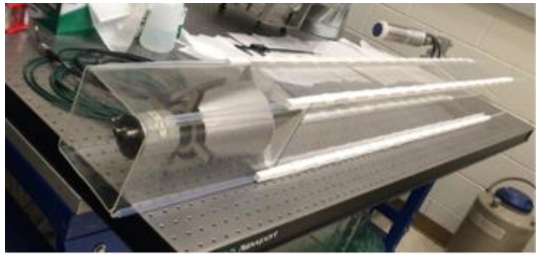



PROSPECT-2
Background studies
Dec 2014 - Aug 2015

12.5 cm length
1.7 liters
^{6}LiLS

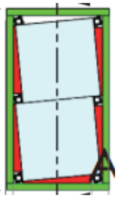
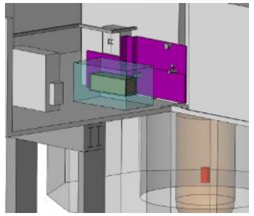
PROSPECT-20
Segment characterization
Scintillator studies
Background studies
March 2015

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

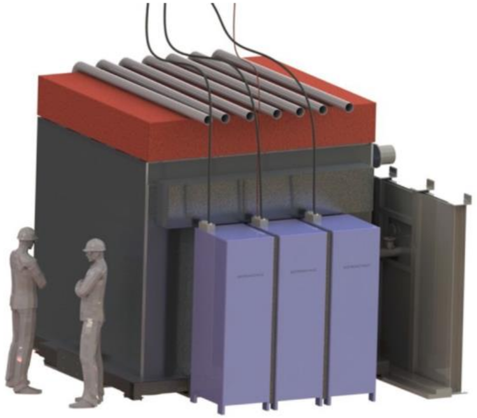
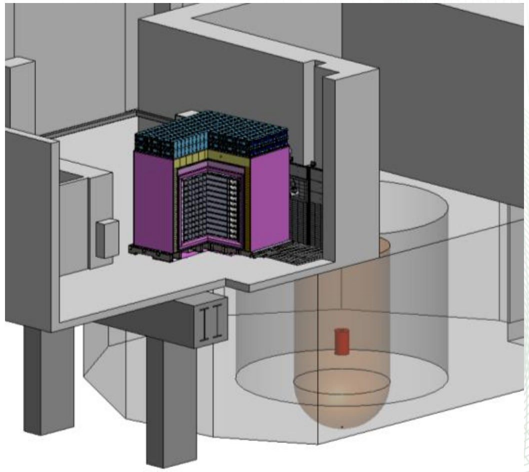
PROSPECT-50
Baseline design prototype
Feb 2016

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

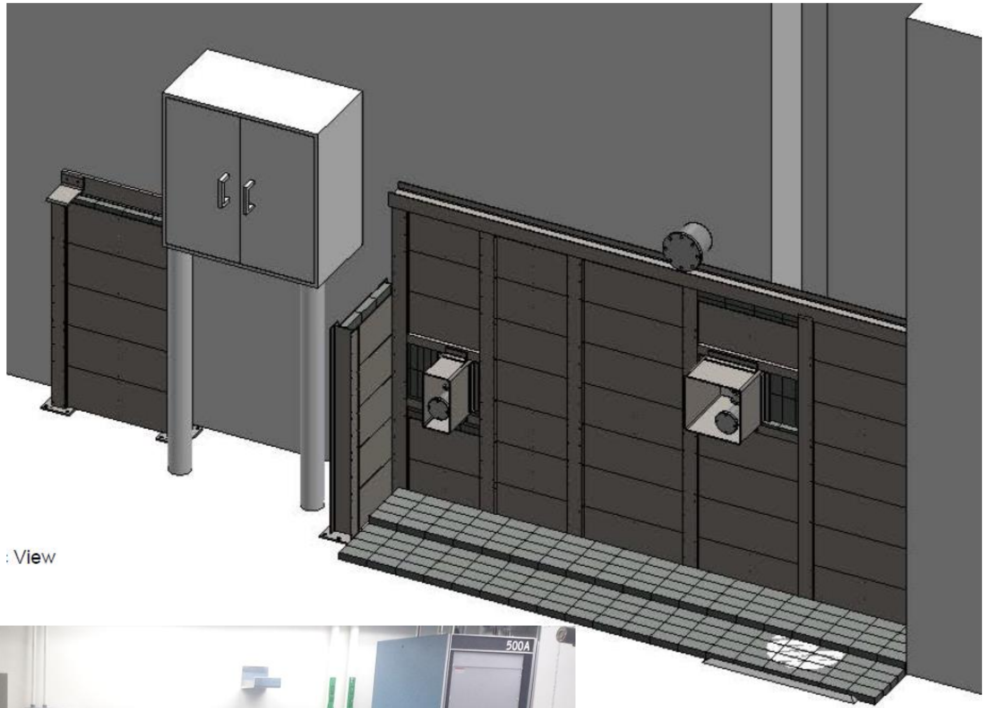
PROSPECT
Full Detector
Jan/Feb 2018

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

Site Preparation

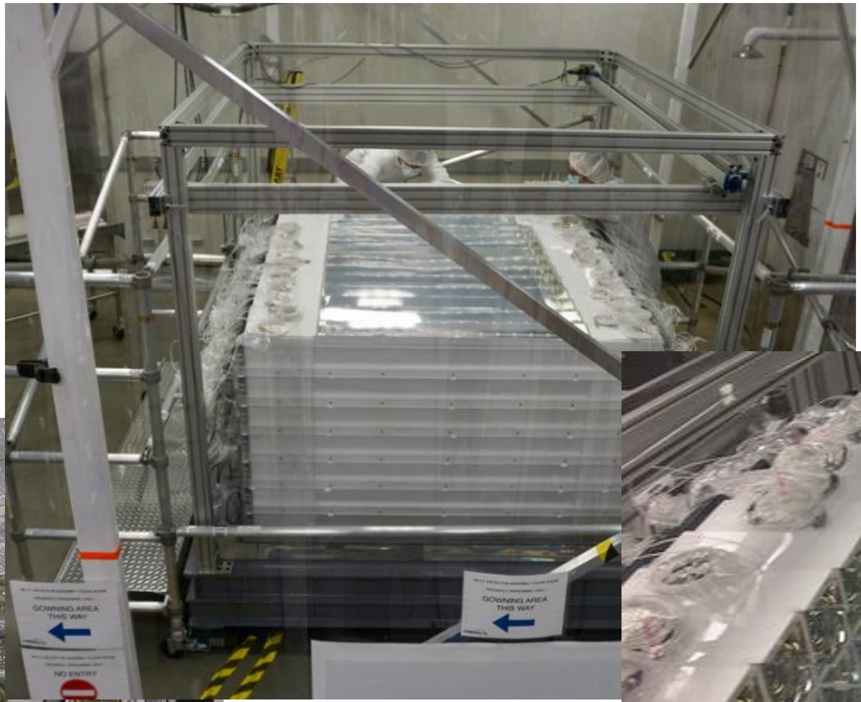
- Activities
  - Installation of shield wall for background reduction
  - Leveling of floor for detector movement system
  - Removal of partition wall for detector movement.



Construction

LiLS Accumulation
Is Nearly Finished

PMT Housing Production Is
Finished



Construction of
cell layers

Summary

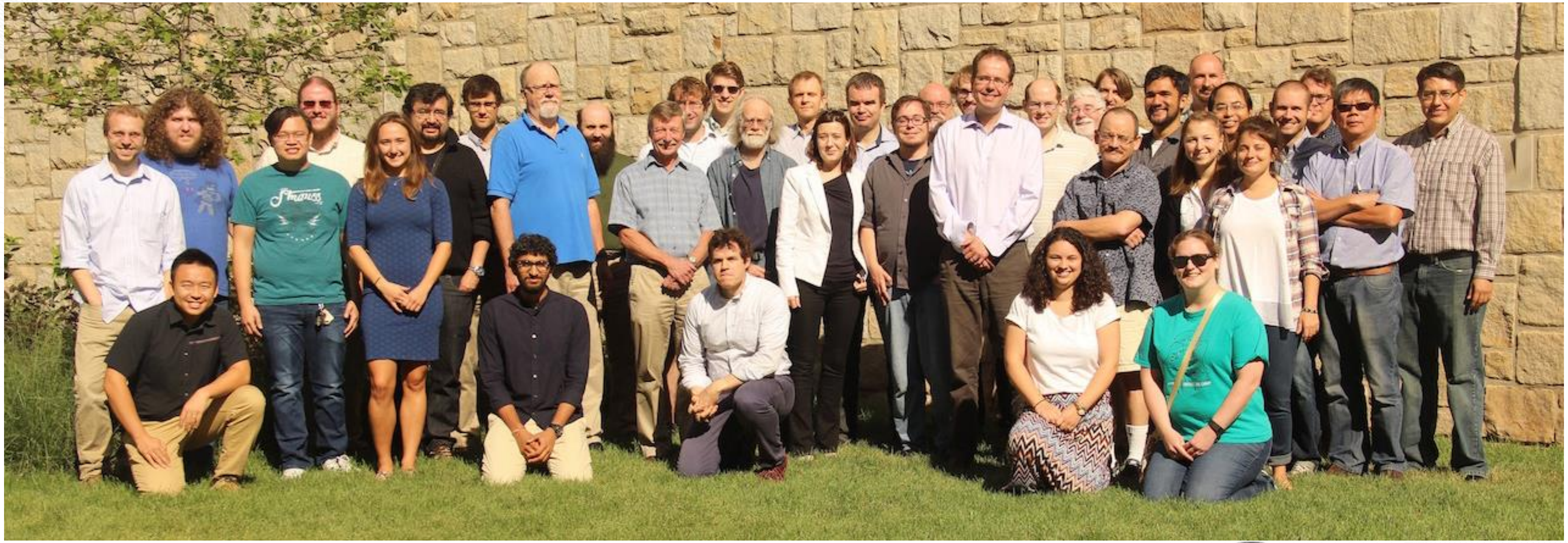
PROSPECT

- PROSPECT will:
  - Make a precision ^{235}U spectrum measurement, complementing LEU measurements.
  - Make a model independent search that will cover the sterile neutrino oscillation best-fit point at better than 3σ in one calendar year
    - Cover favored regions at 3σ in 3 years
  - Test ^{235}U as the source of the 4-6MeV “bump”
- Detector construction is proceeding quickly.
- Detector will be in HFIR before the end of December
- First data taking will begin before the end of Feb 2018
- Preparations for deployment are in full swing
- Backgrounds, reactor on and off, have been characterized

OAK RIDGE National Laboratory

The PROSPECT Collaboration

4 National Labs 10 Universities 68 Collaborators



Supported by:

prospect.yale.edu

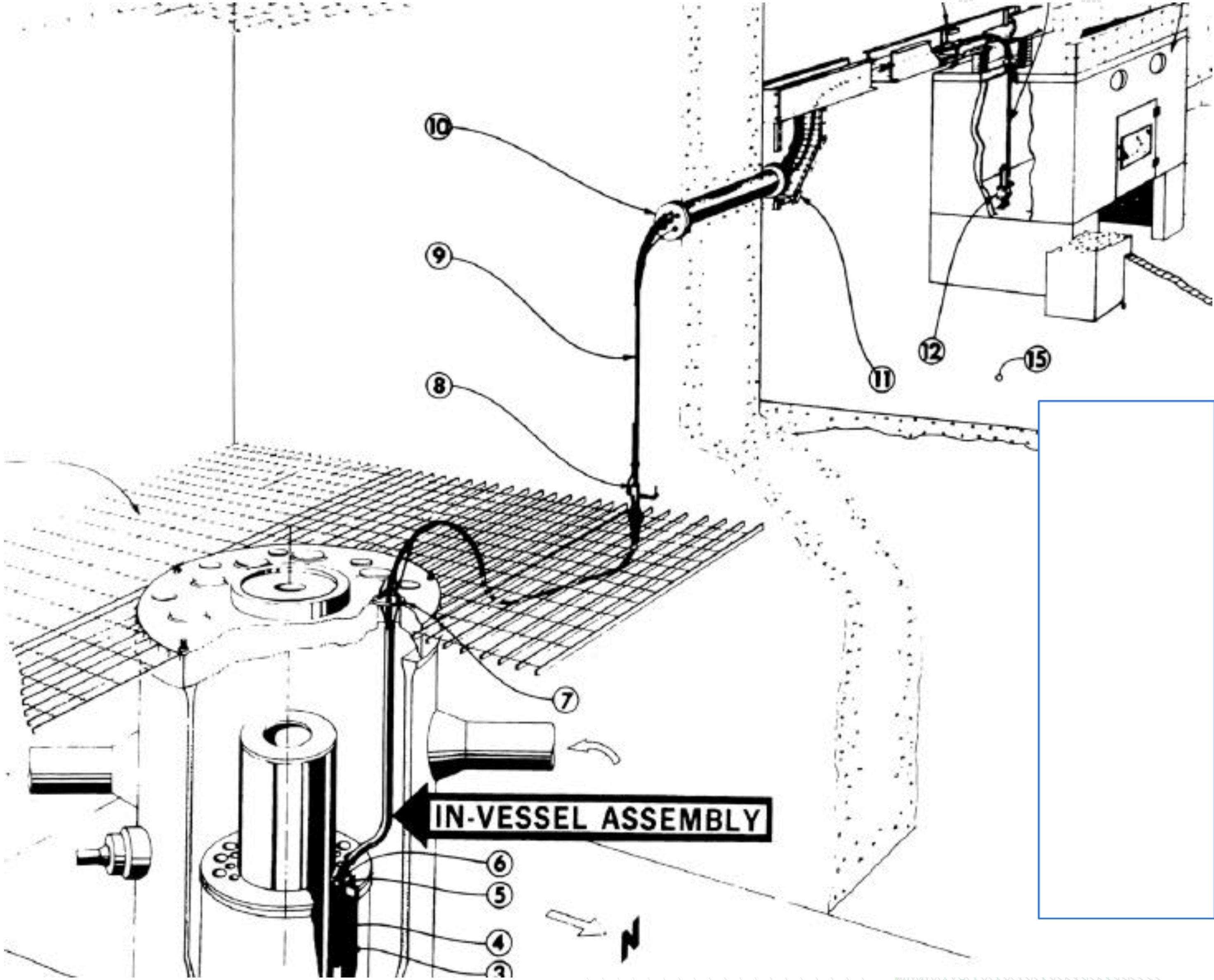
Backup

International Competition

Experiment	Neutrino Source	Overburden (mwe)	Detection Material	Segmentation	Optical Readout	Particle ID Capability
DANSS (Russia)	3000 MW Reactor LEU Fuel	~50	Inhomogeneous PS & Gd Sheets	2D, ~5mm	WLS fibers	Topology only
NEOS (South Korea)	2800 MW Reactor LEU Fuel	~20	Homogeneous Gd-doped LS	None	Direct double ended PMT	Recoil PSD only
nuLat (USA)	40 MW Reactor HEU Fuel	few	Homogeneous ^{6}Li-doped PS	Quasi-3D, 5cm 3-axis Optical Lattice	Direct PMT	Topology, recoil & capture PSD
Neutrino4 (Russia)	100 MW Reactor HEU Fuel	~10	Homogeneous Gd-doped LS	2D, ~10cm	Direct single ended PMT	Topology only
PROSPECT USA	85 MW Reactor HEU Fuel	few	Homogeneous ^{6}Li-doped LS	2D, 15cm	Direct double ended PMT	Topology, recoil & capture PSD
SoLid (UK Fr Bel US)	72 MW Reactor HEU Fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm multiplex	WLS fibers	Topology, capture PSD
Chandler (USA)	72 MW Reactor HEU Fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm 2-axis Opt. Latt	Direct PMT/WLS Scint	Topology, capture PSD
Stereo (France)	57 MW Reactor HEU Fuel	~15	Homogenous Gd-dopes LS	1D, 25cm	Direct single ended PMT	Recoil PSD
SOX (Italy)	2-4 PBq ^{144}Ce or 200-400 PBq ^{51}Cr	~3400	Homogenous undoped LS	Virtual, Photon Time of Flight	Many PMTs	

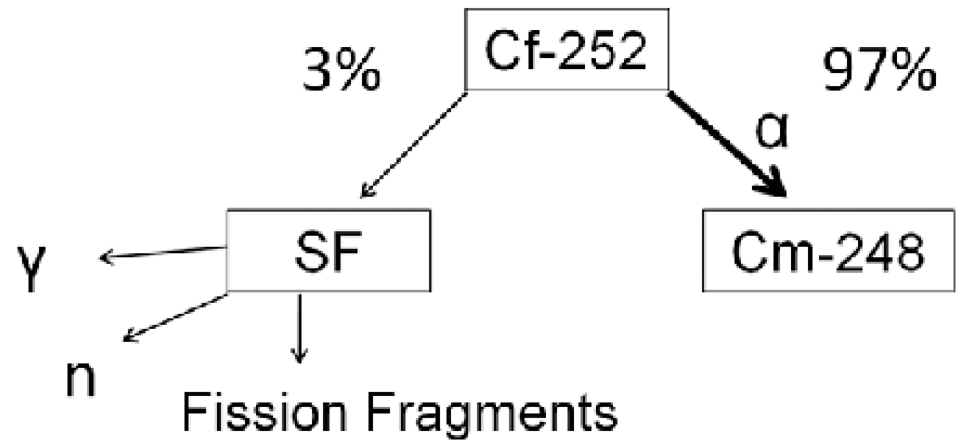
NAA Sources

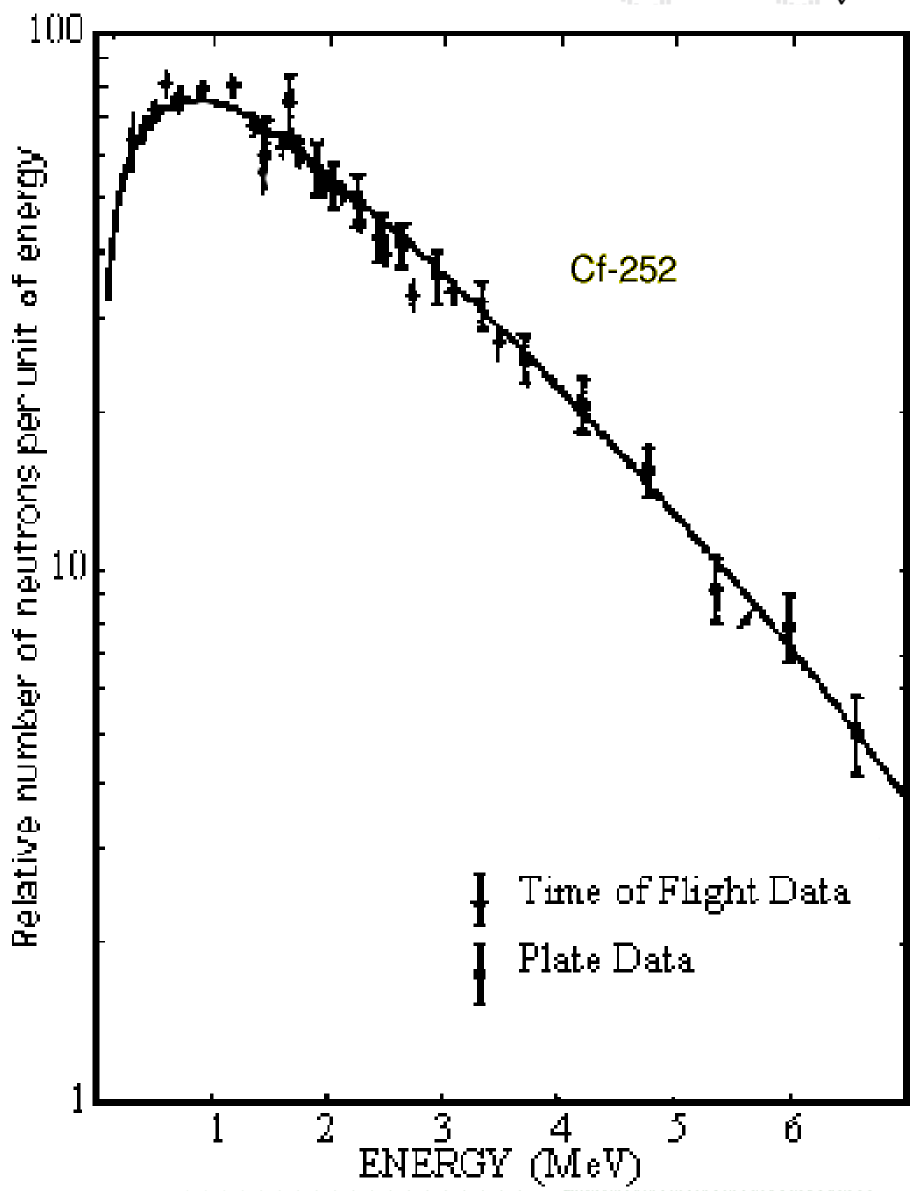
- Exotic gamma-ray sources, on demand
  - High Energy
    - ^{24}Na
    - ^{49}Ca
    - ^{56}Mn
  - Low Energy
    - ^{113}Sn
    - ^{139,141}Ce
    - ^{182}Hf
    - ^{198}Au



^{252}Cf Source

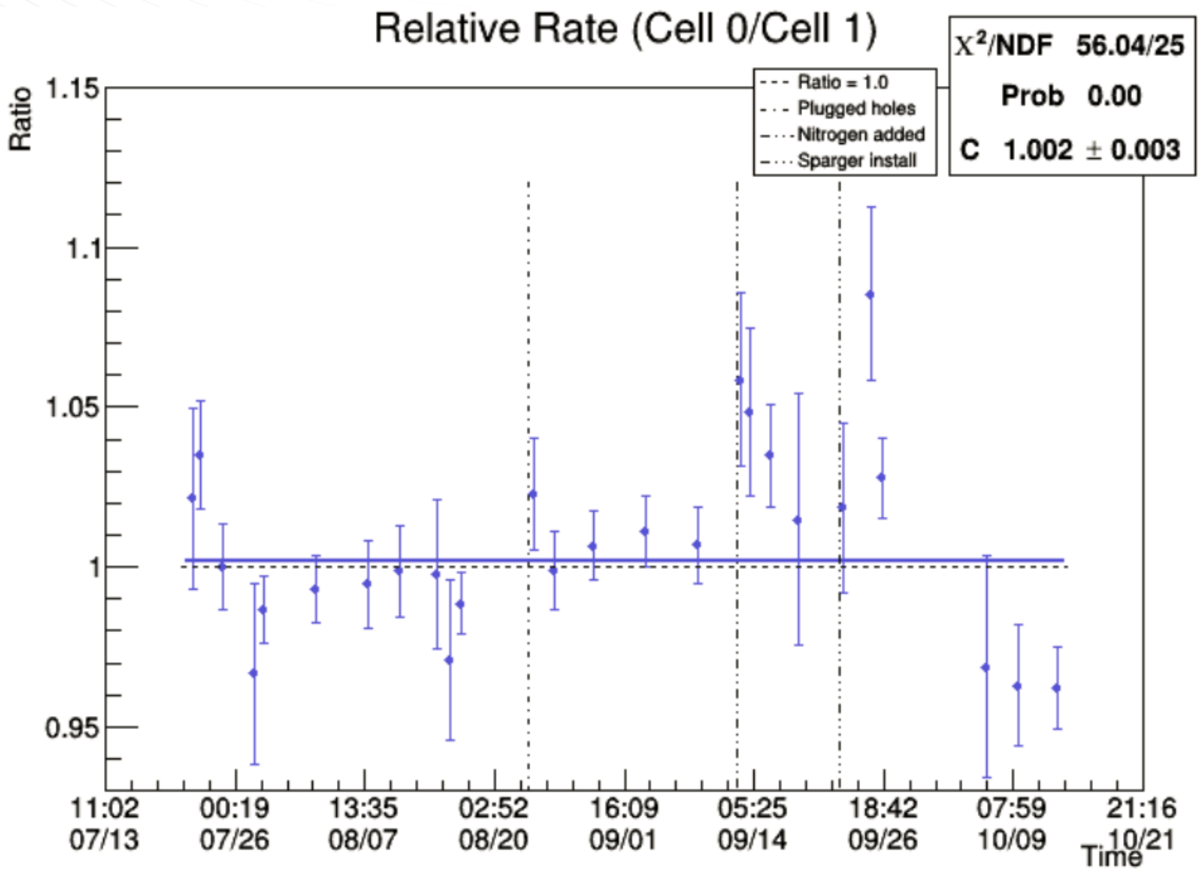
- Material produced at HFIR
  - ~100 neutrons per second
  - Made by dilution of stronger source solution
    - Stronger source benchmarks strength of weaker

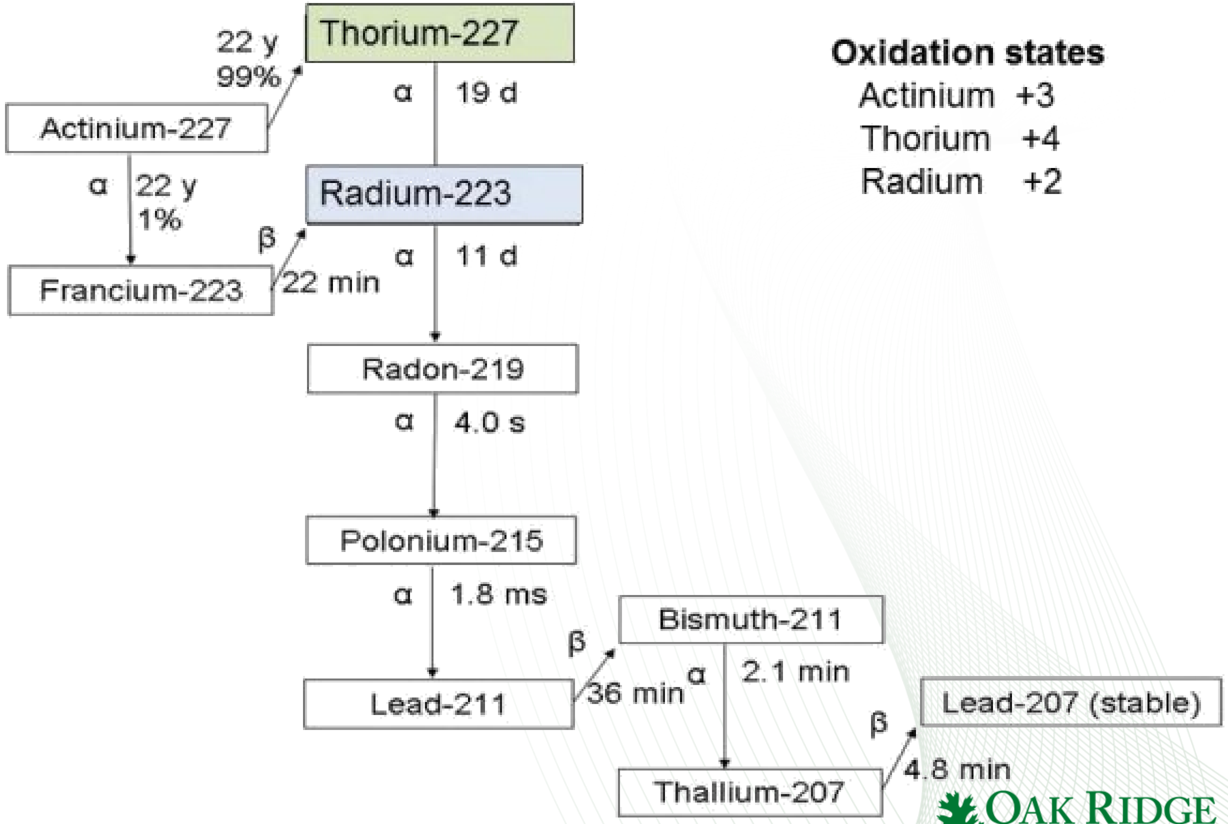




^{227}Ac Spike

- Dissolve 2Bq of ^{227}Ac in LiLS
- Allow relative calibration of cell volume
- Allows testing position reconstruction systematics

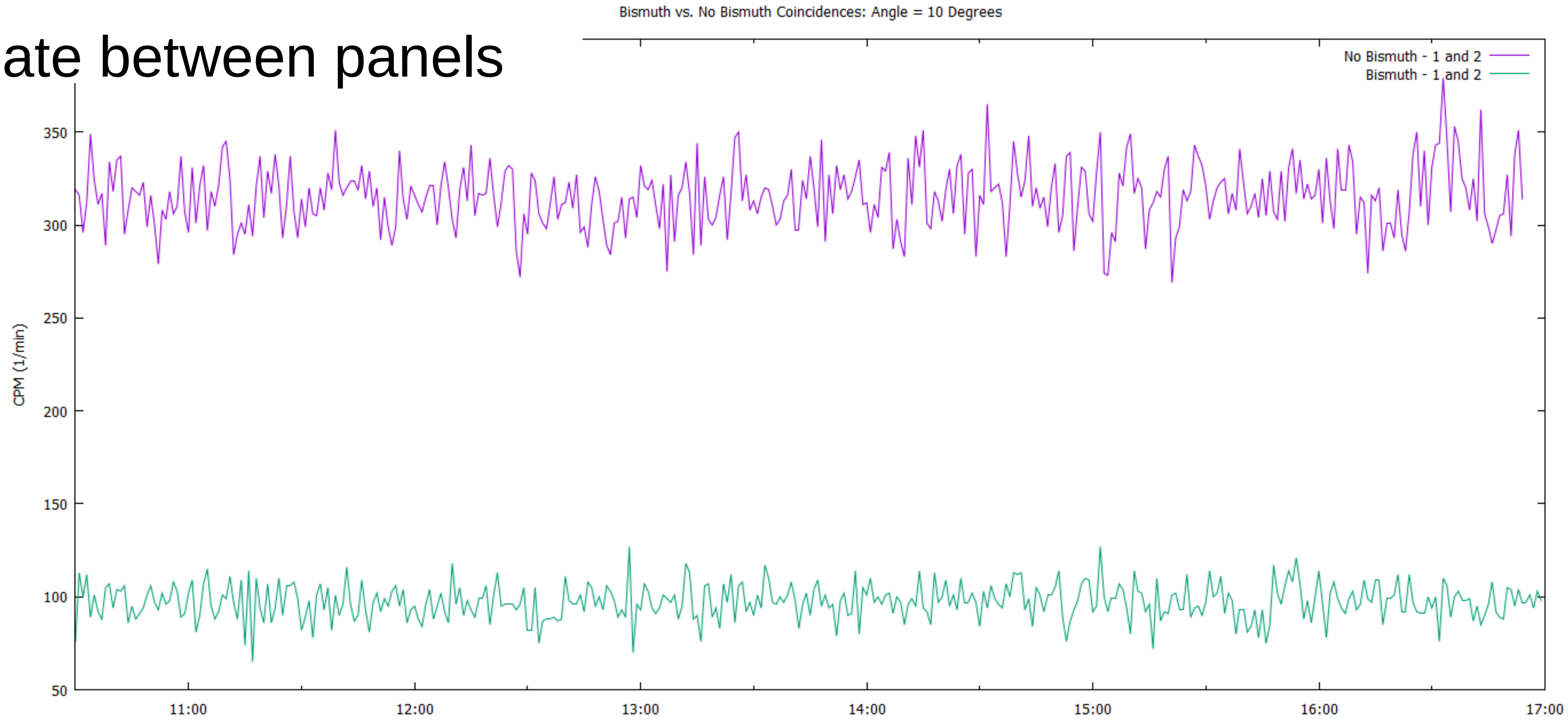




Oxidation states
Actinium +3
Thorium +4
Radium +2

Cosmic Ray Measurements and Plans

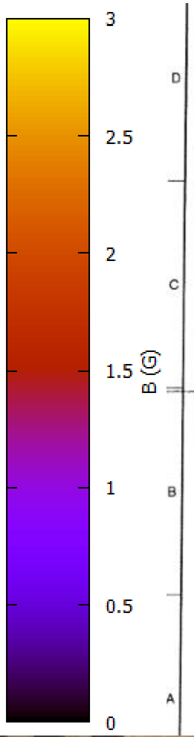
- Simple plastic panel coincidence counter
  - Removable bismuth plate between panels

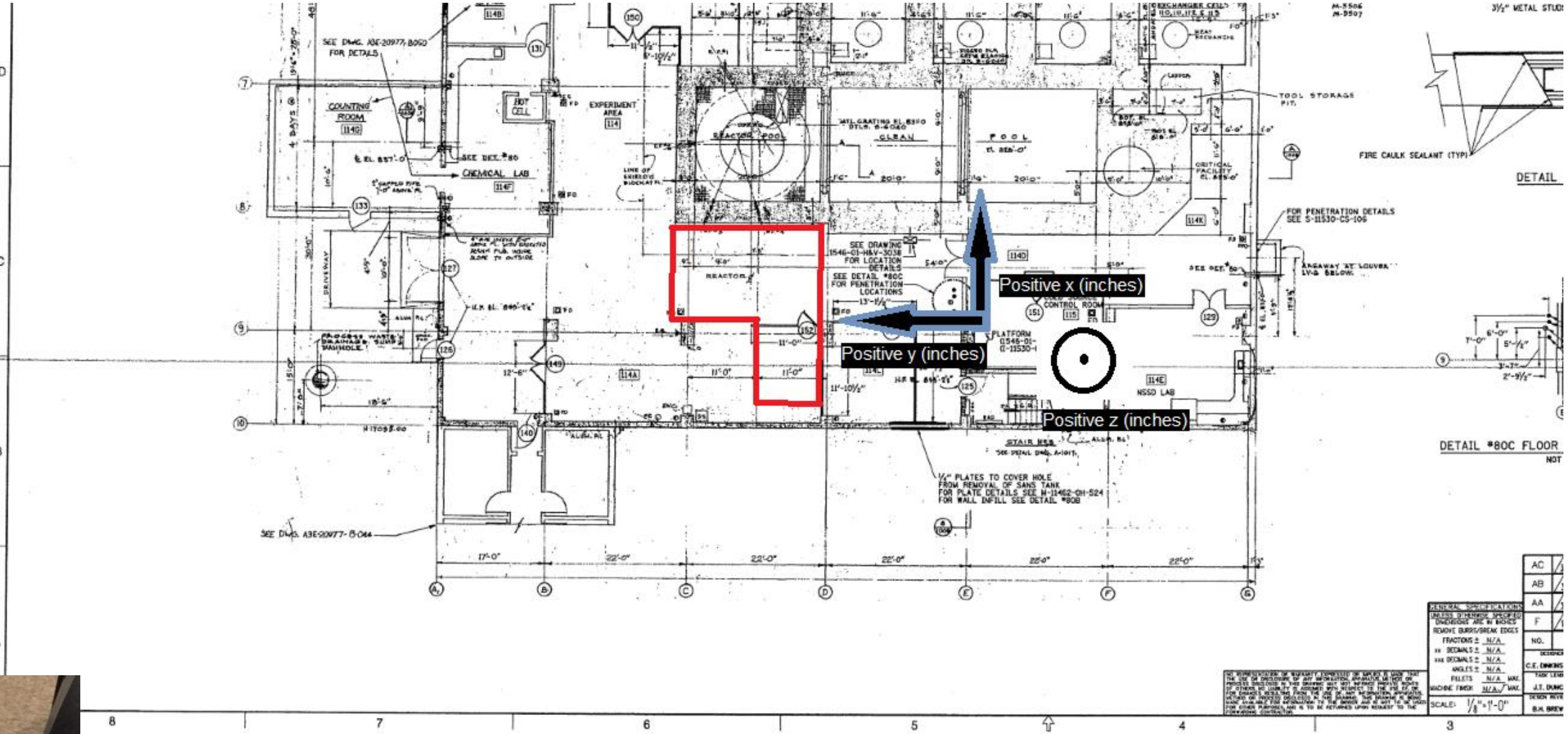


Magnetic Field Maps

Stereo invested in magnetic shielding do we need to?

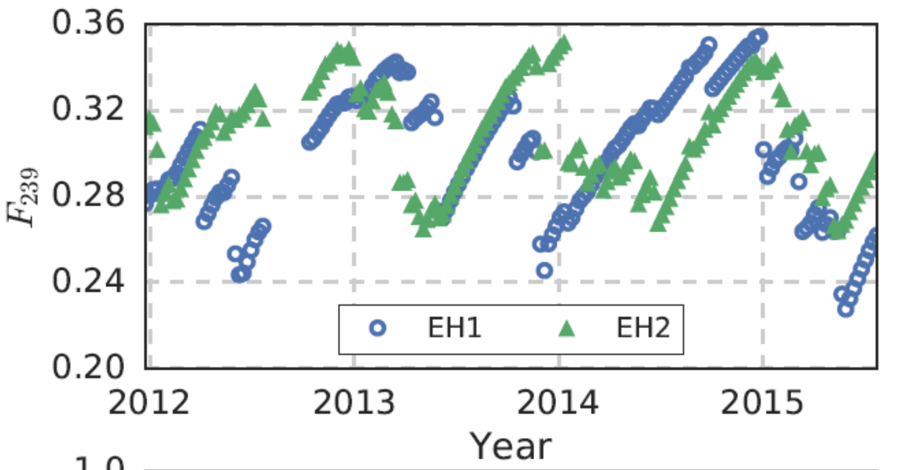
Nope

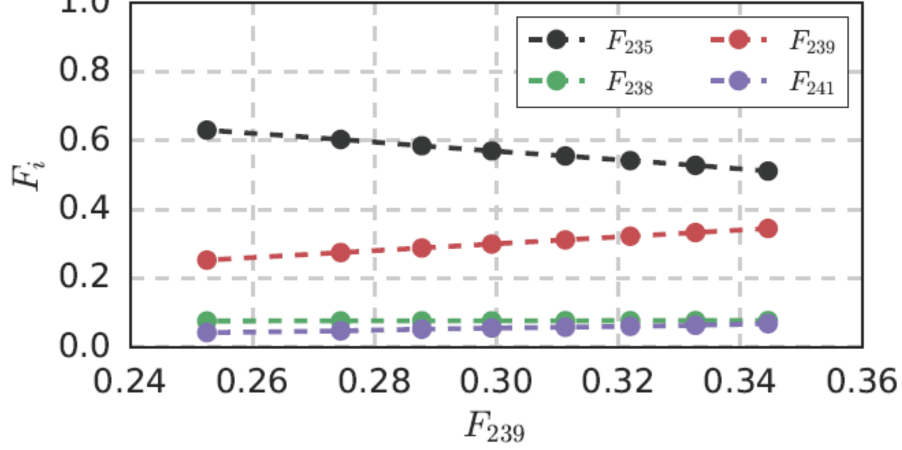


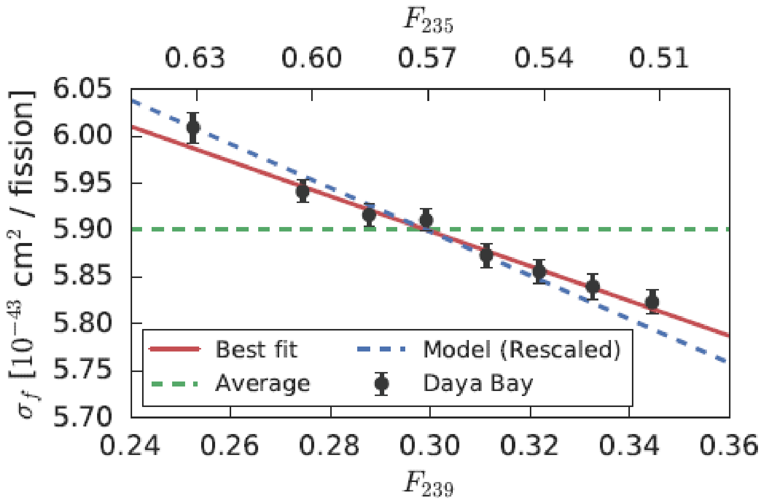


HMMT-6J18-VF hall probe connected to a Lakeshore 475 DSP gaussmeter

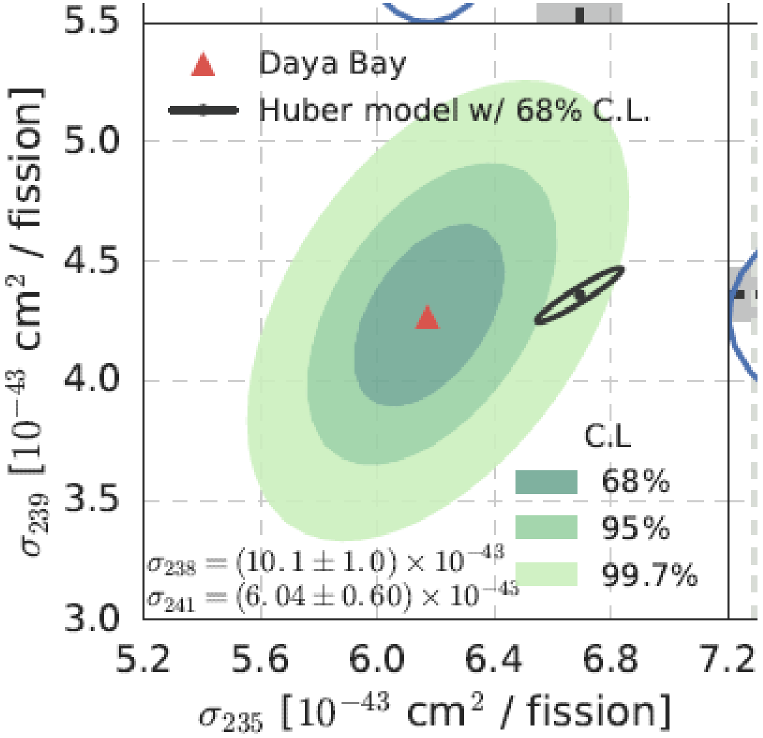
Recent Daya Bay Result





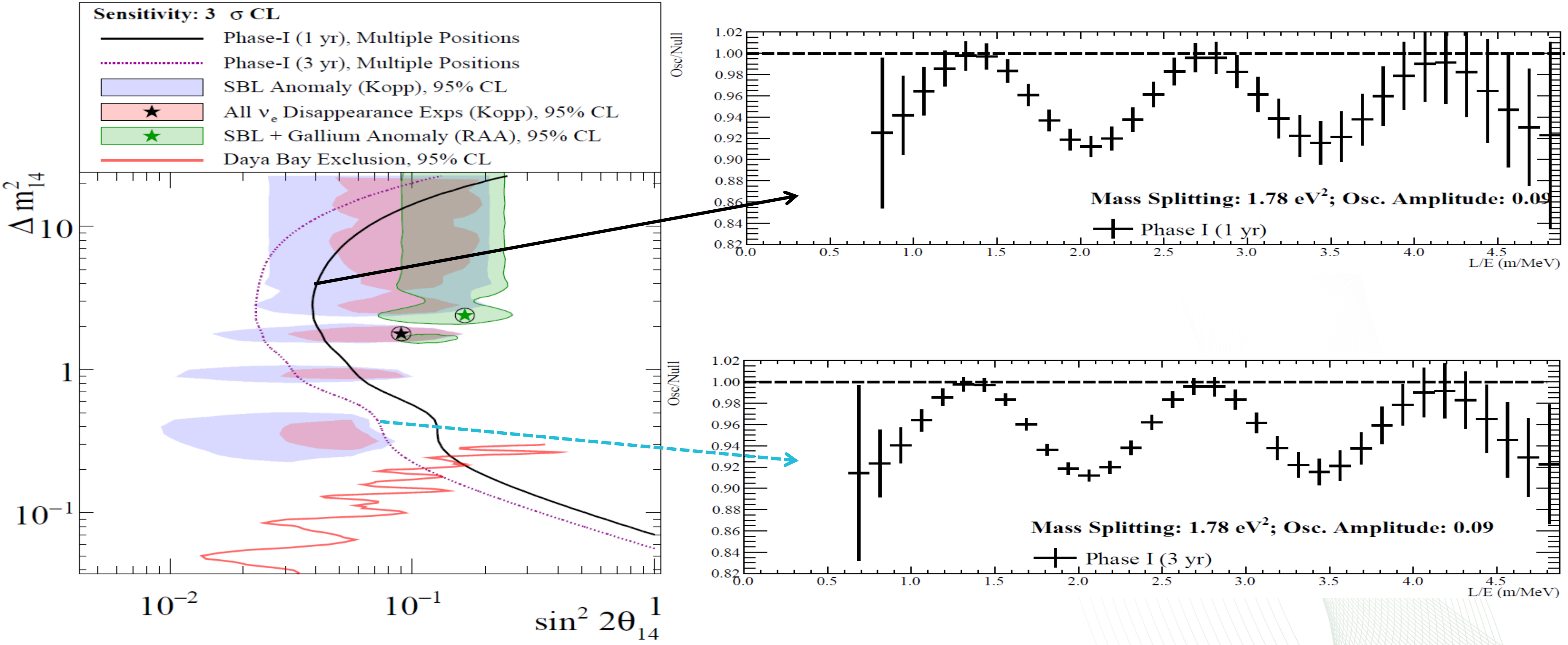


Daya Bay has **not** shown that neutrino oscillations don't play a role. Disagreements could be a combination of effects: issues with the $\bar{\nu}_e$ yield from ^{235}U **and** new physics



Daya Bay Collaboration Phys. Rev. Lett. **118**, 251801 (2017)

Oscillation Search



Why a Movable Detector?