PROSPECT: Precision Reactor Oscillation and SPECTrum Experiment

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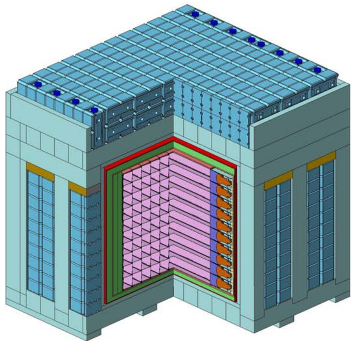
Penn Neutrino Seminar
November 20, 2015

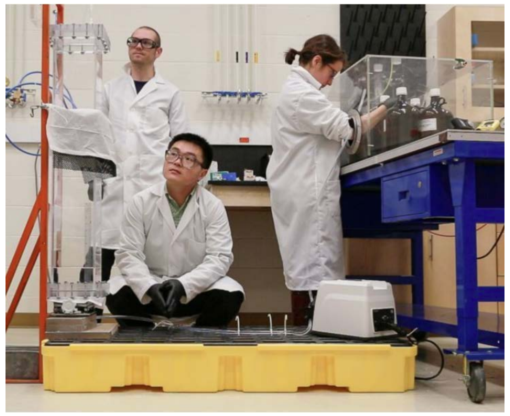
Outline

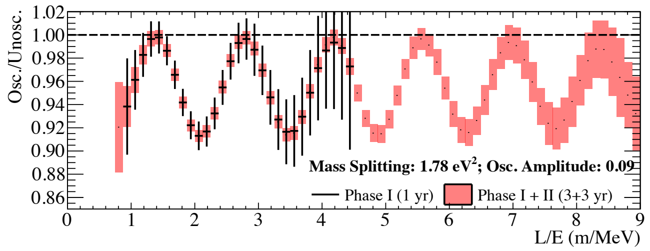
1. Introduction to neutrinos and neutrino anomalies

2. PROSPECT short baseline reactor experiment



3. PROSPECT Phase I program





4. Concluding remarks

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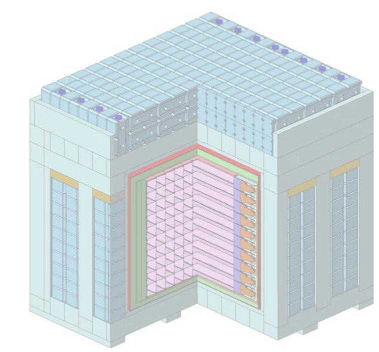

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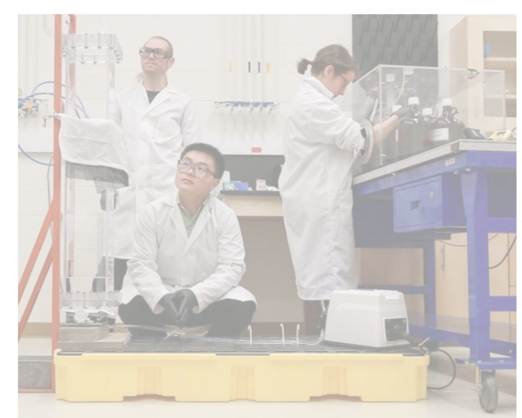
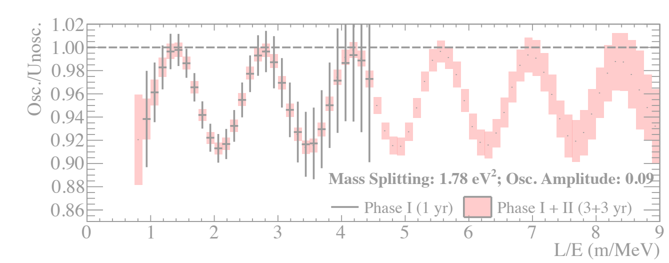




4. Concluding remarks

Beginning of neutrino physics

- neutrinos postulated by W. Pauli in 1930 to explain energy conservation in β decay

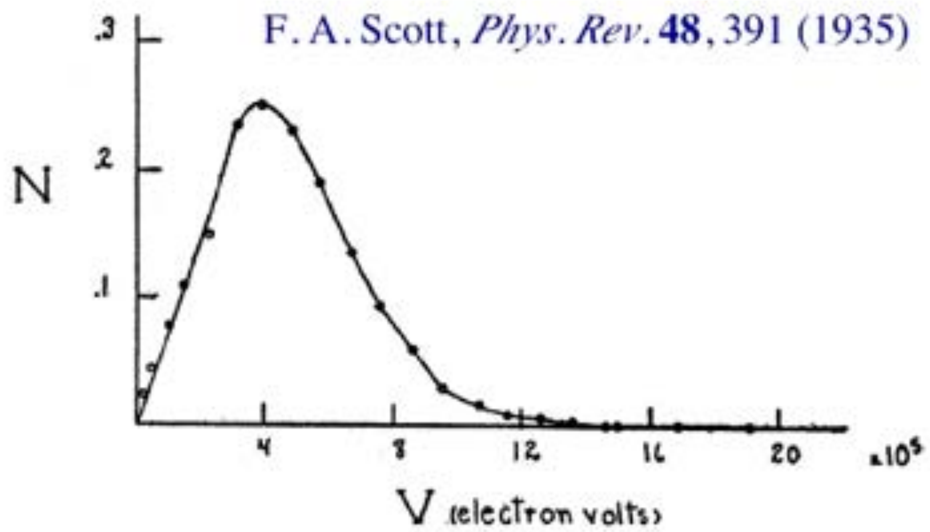
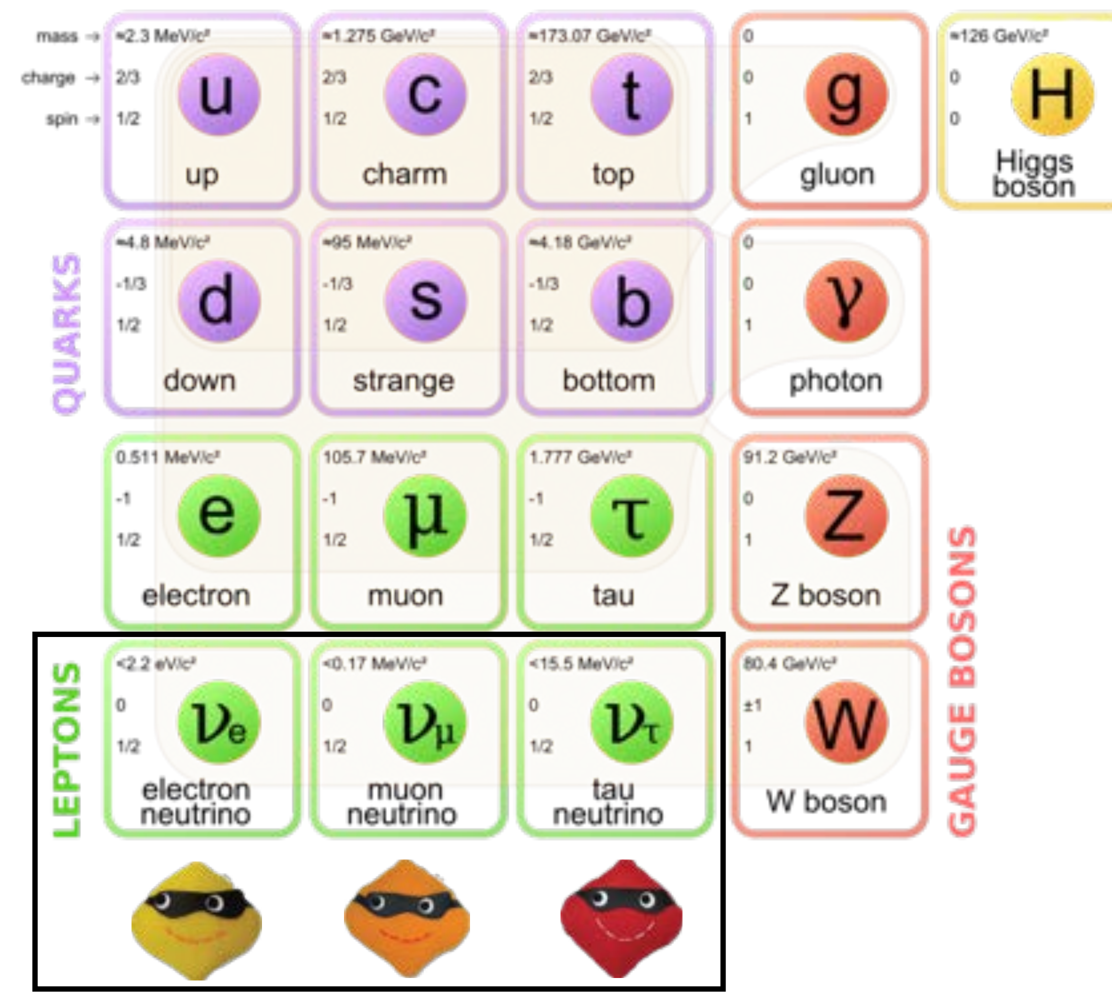


FIG. 5. Energy distribution curve of the beta-rays.

- in 1956, Cowan and Reines observed (anti-)neutrinos from a reactor

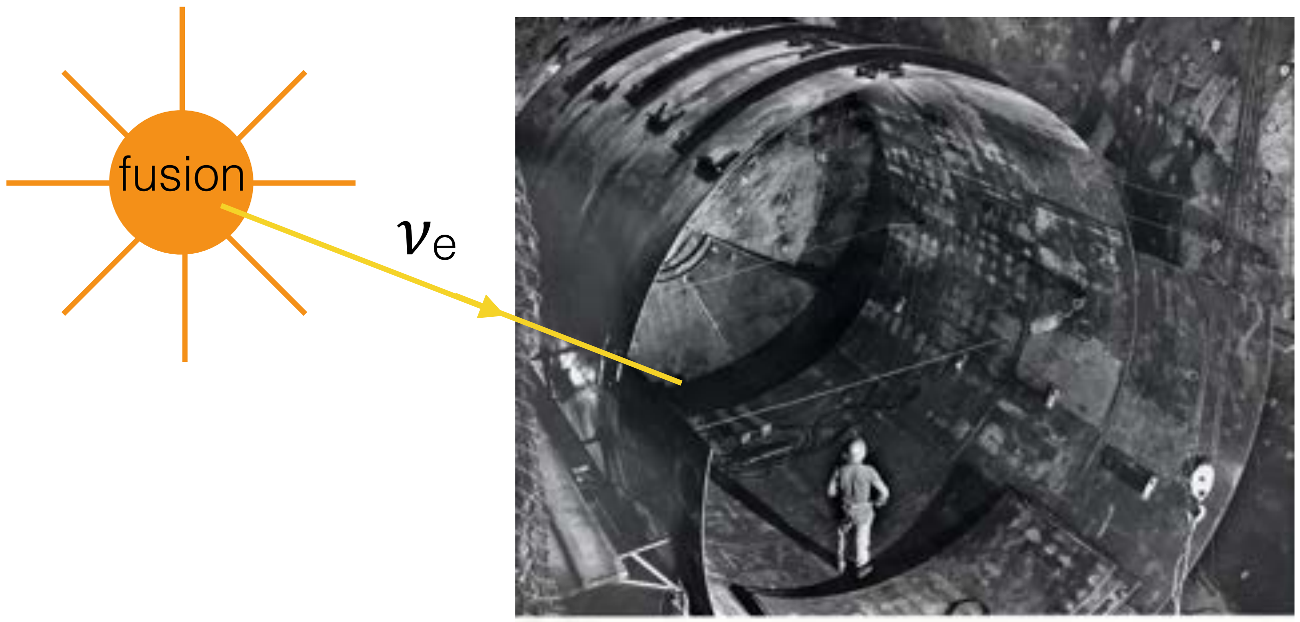
- added to the Standard Model as chargeless, massless, weakly interacting leptons that come in 3-flavors

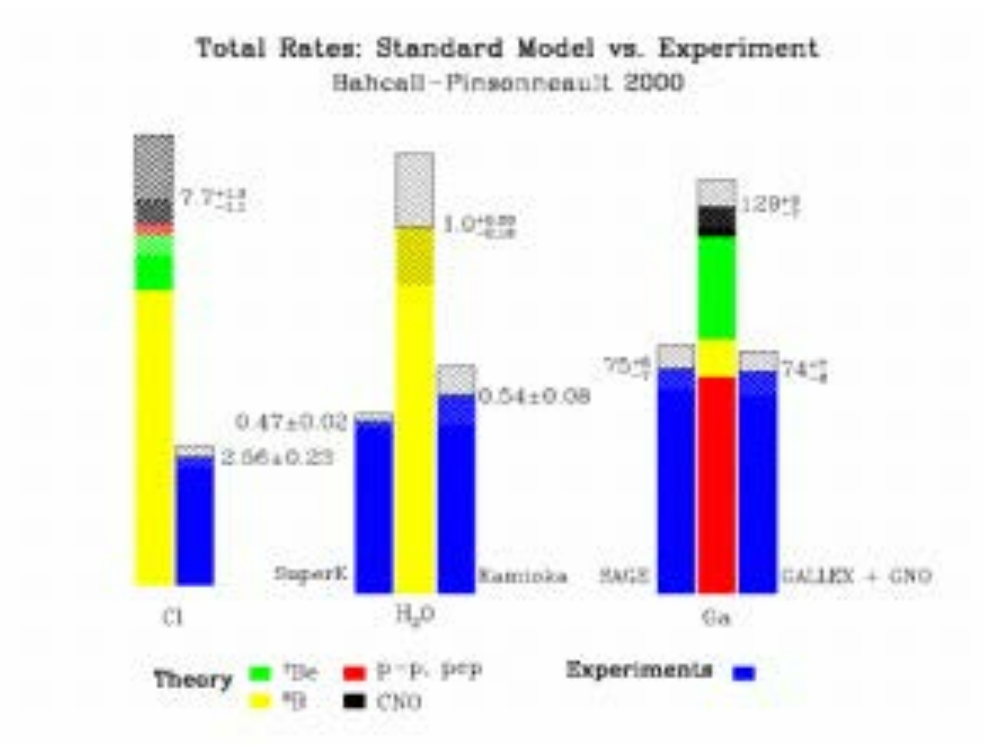
- study neutrinos from different sources (e.g. reactors, solar, atmospheric, accelerators)



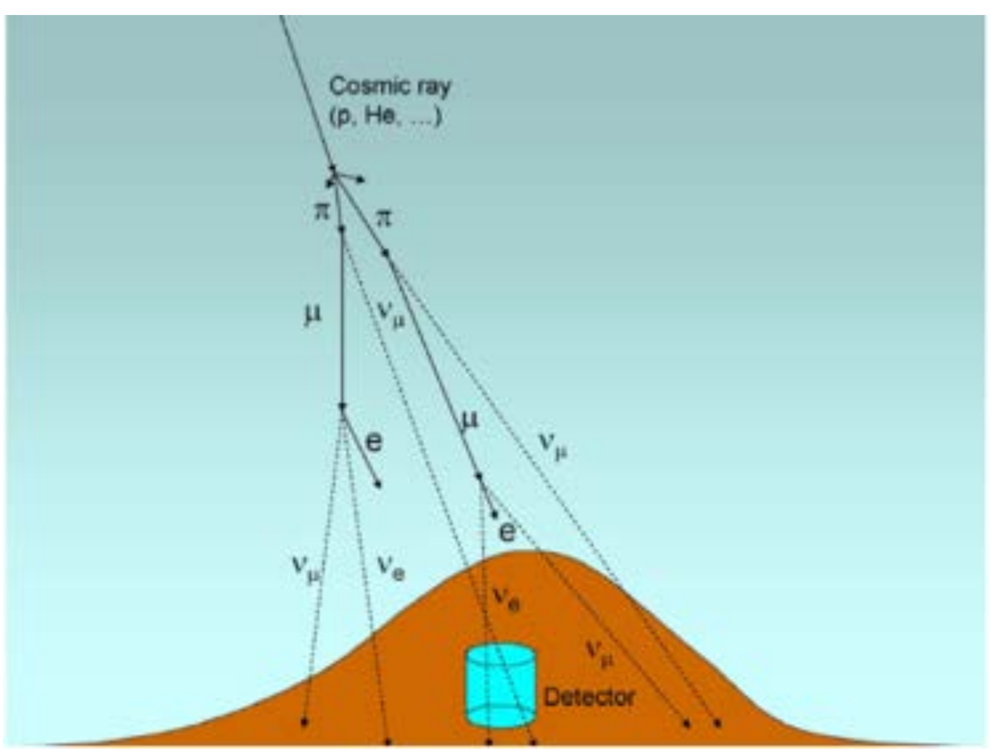
Neutrino anomalies…

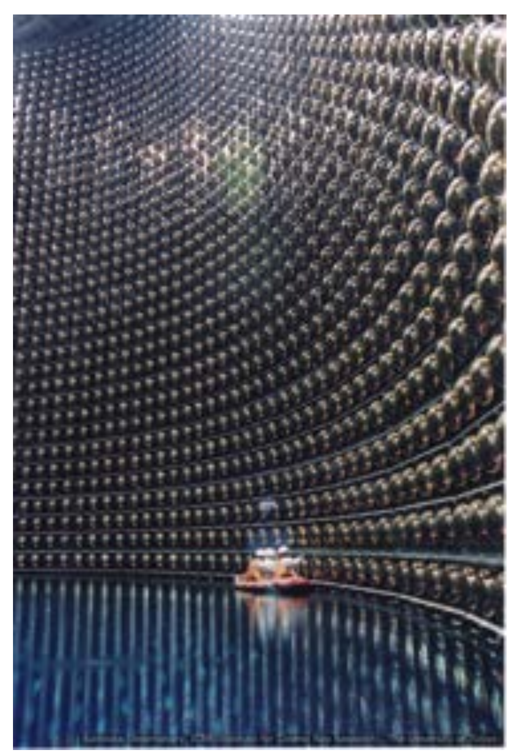
solar neutrino anomaly

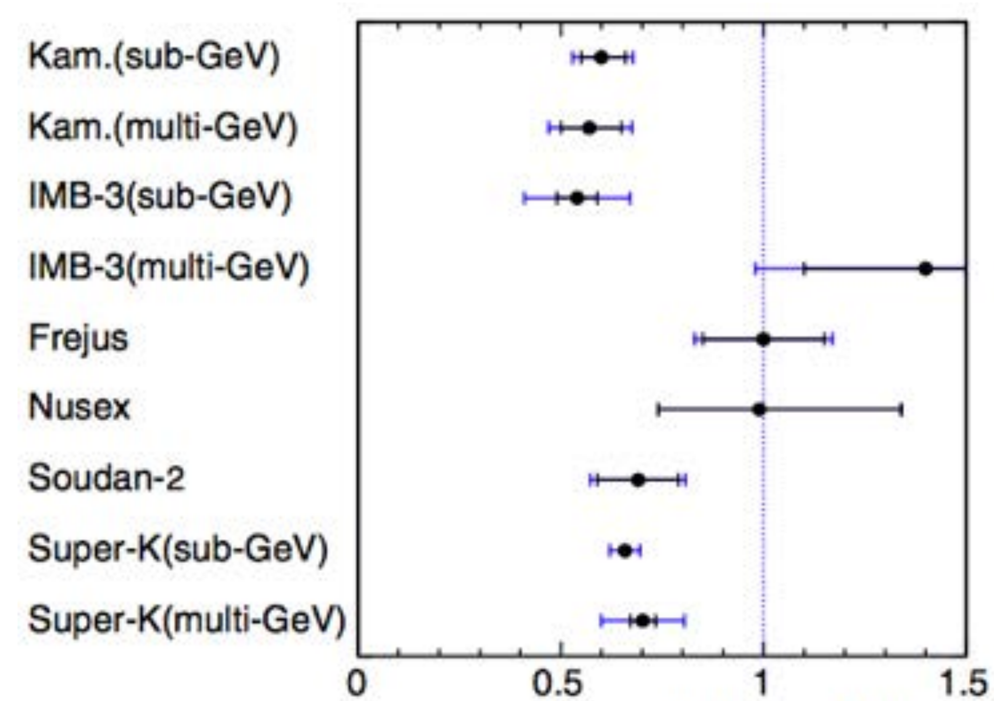




atmospheric neutrino anomaly



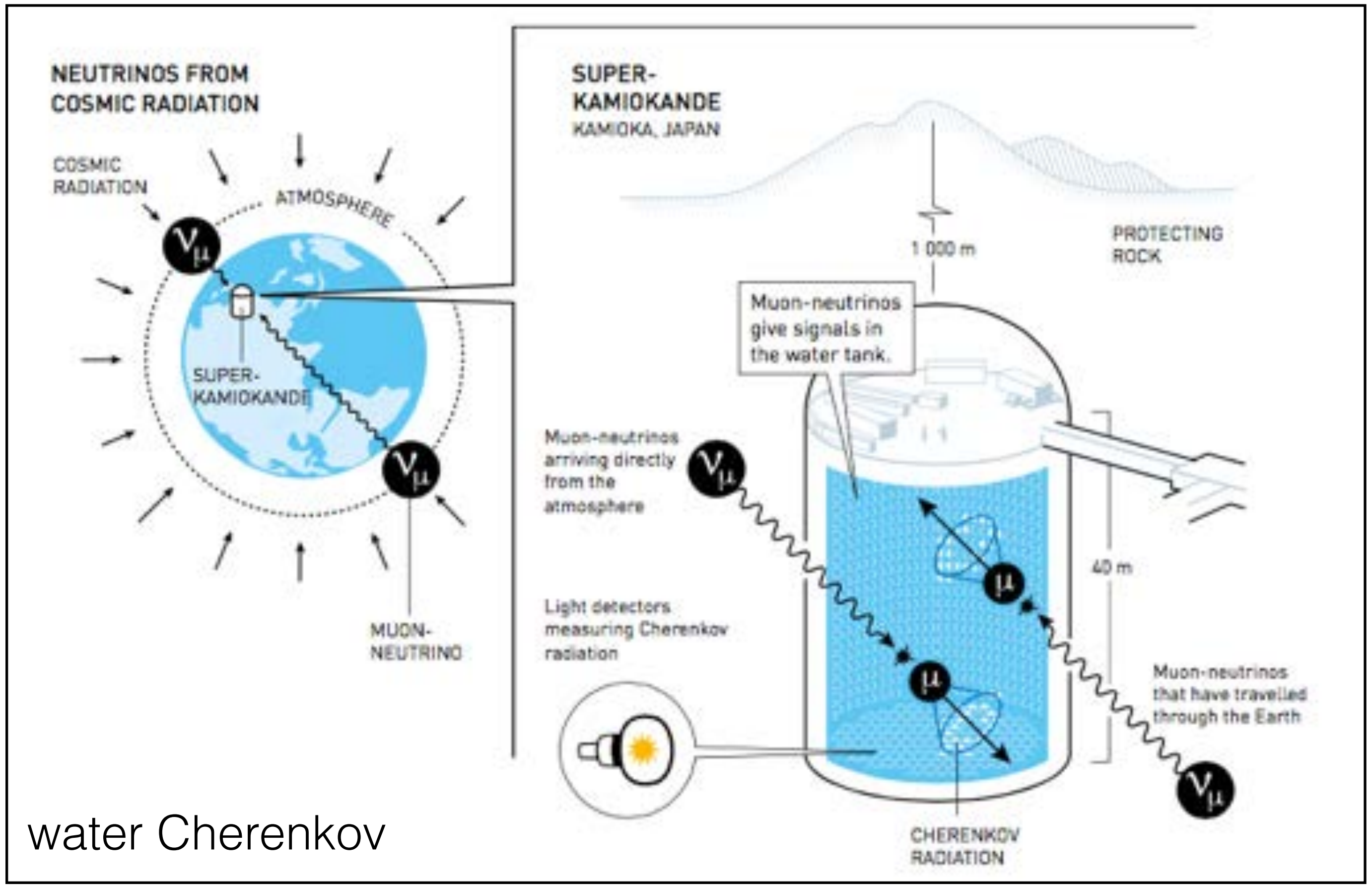




T. Kajita, New J. Phys. 6 (2004) 194

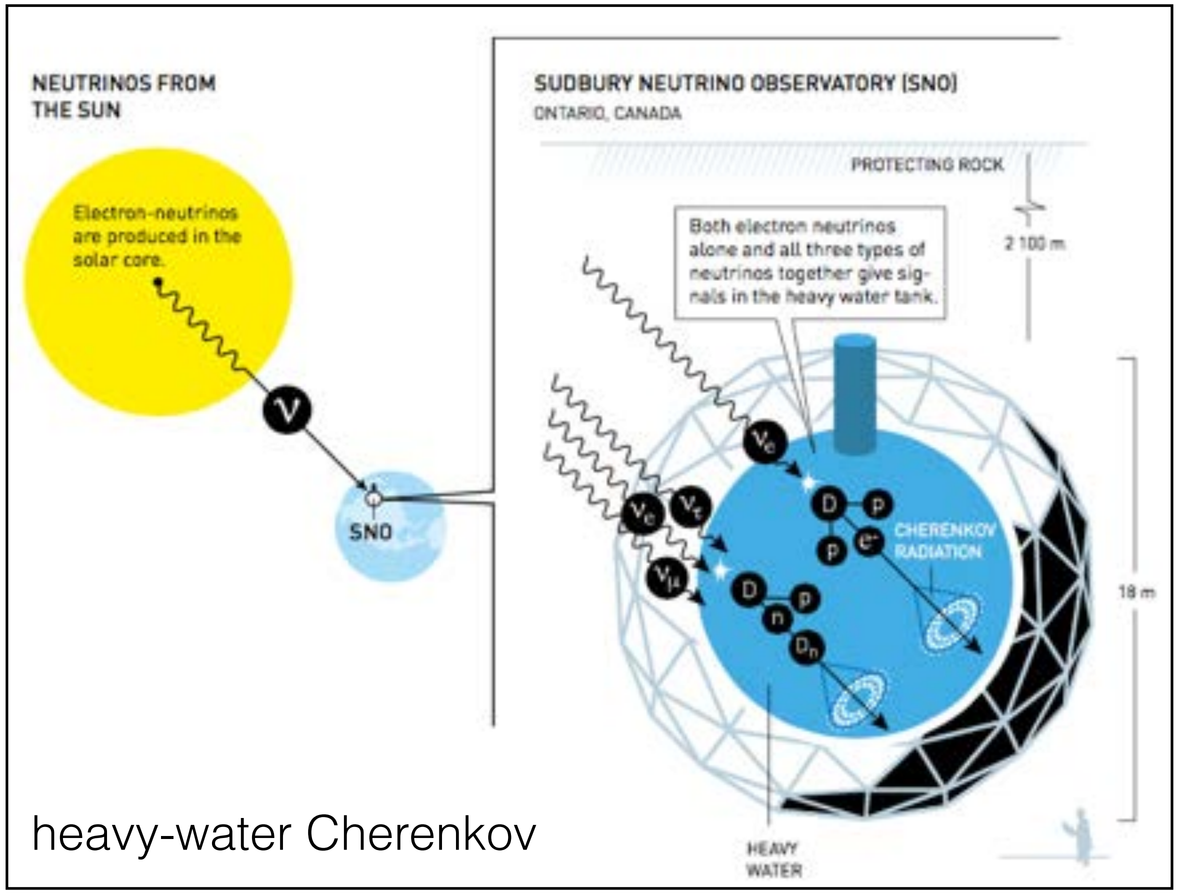
…lead to discoveries

Super-Kamiokande 1998: solved atmospheric anomaly

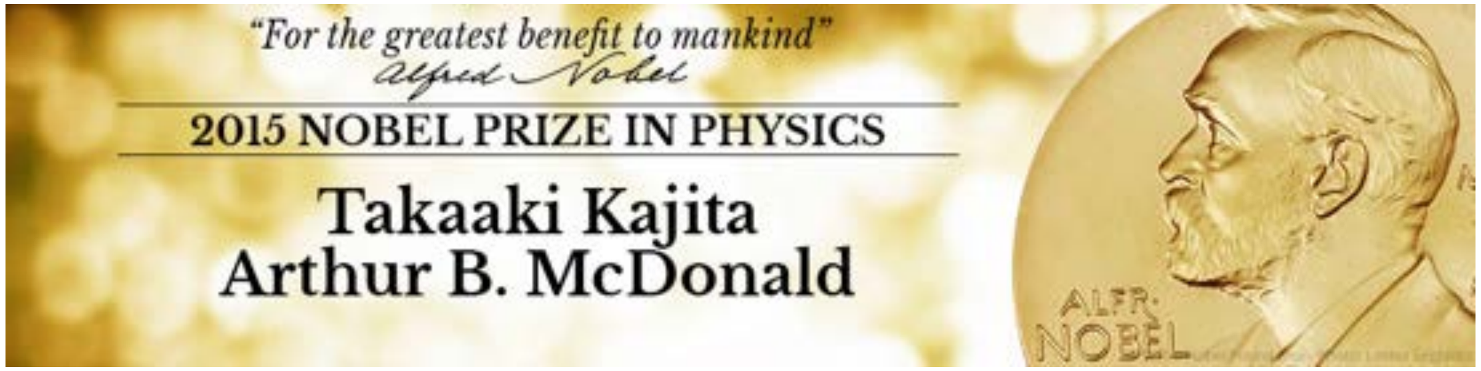


$\nu_\mu \rightarrow \nu_\tau$ oscillation through the earth

SNO 2001: solved solar anomaly



sum of all ν matched solar prediction



"for the discovery of neutrino oscillations which shows that neutrinos have mass"

Current picture of neutrino oscillation physics

Neutrinos undergo quantum mechanical oscillations between flavor and mass states, implying they are massive (although very light) particles.

weak states — *mass states*

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$where \ U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\nu 1} & U_{\nu 2} & U_{\nu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

interact — *propagate* — *PMNS mixing matrix*

atmospheric/accelerator — *reactor* — *solar*

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & -0 & 1 \end{pmatrix}$$

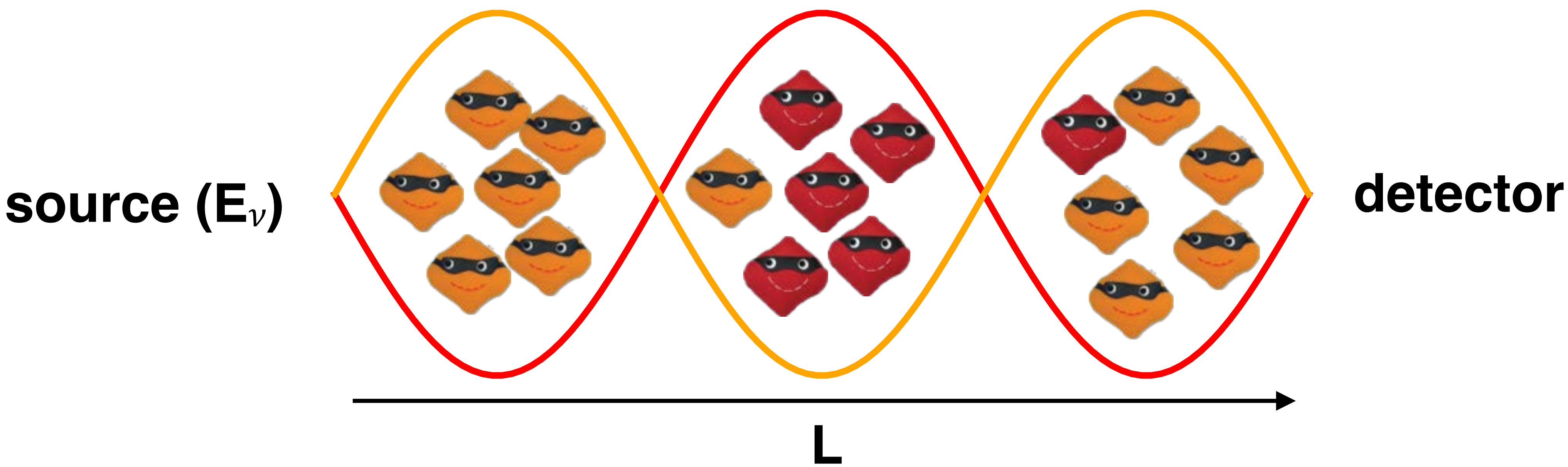
$$where \ c_{ij} = cos(\theta_{ij})$$

$$s_{ij} = sin(\theta_{ij})$$

$$\delta = CP \ phase$$

Oscillations - two neutrino approximation

$$P_{\alpha\rightarrow\beta,\alpha\neq\beta} = sin^2(2\theta)sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right) \;\; where \;\; \alpha,\beta = \nu_e,\nu_\mu,\nu_\tau$$



Parameters θ (mixing angle - amplitude) and Δm^2 (mass splitting - frequency) are defined by nature. We can target specific Δm^2 measurements by designing our experiments to have a certain L/E.

Precision reactor antineutrino experiments

Kilometer baseline θ_{13} precision experiments: Daya Bay, Double Chooz, RENO

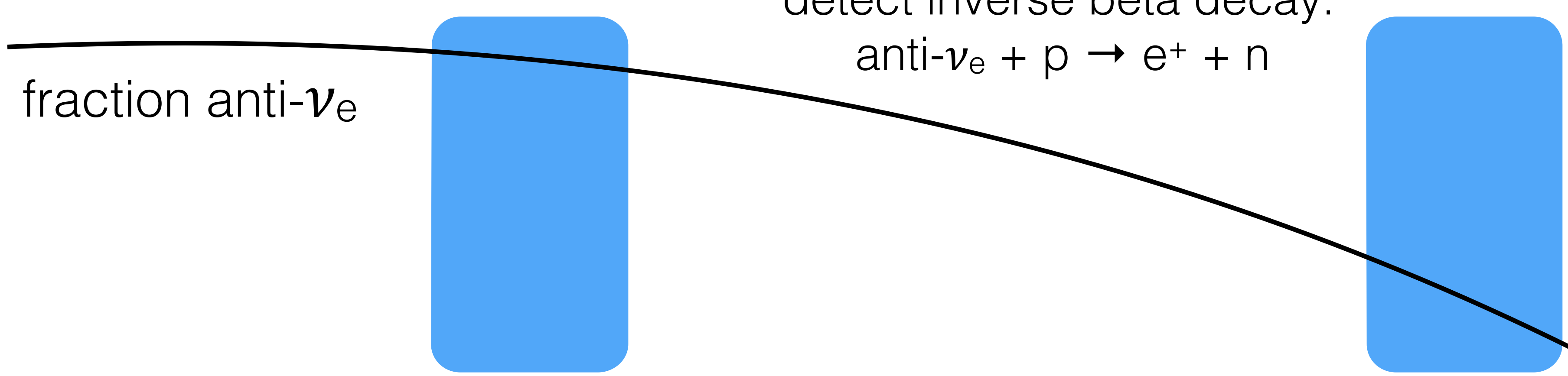
Daya Bay antineutrino detectors

Daya Bay site

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - sin^2(2\theta) sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

survival probability

reactor core

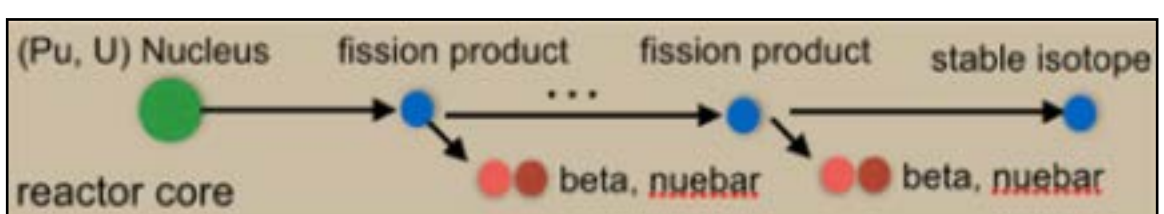


fraction anti-ν_e

detect inverse beta decay:
anti-ν_e + p → e^+ + n

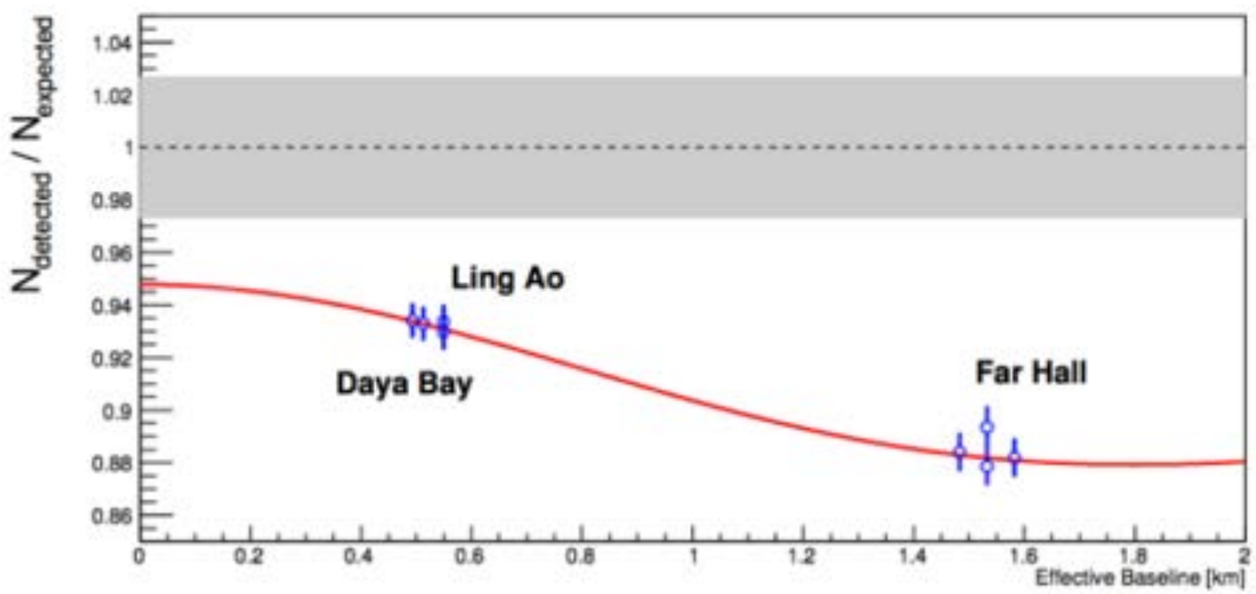
near detector

far detector

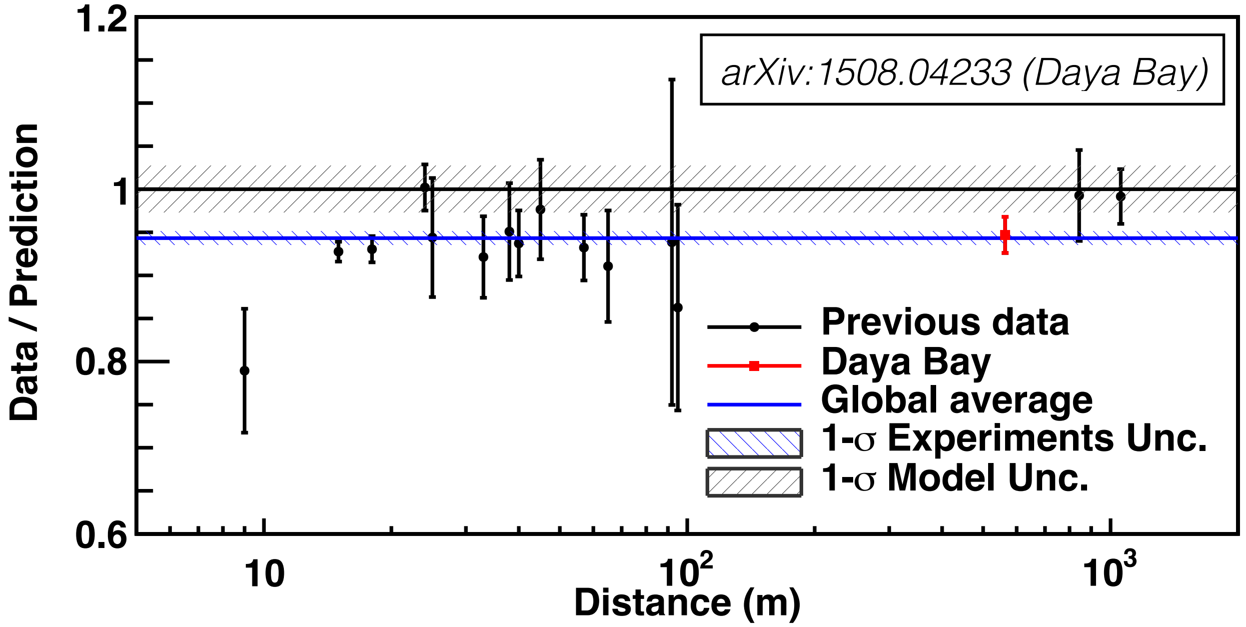


Flux measured between detectors for relative oscillation measurement. Can also be compared to predictions from reactor models.

Reactor flux anomaly



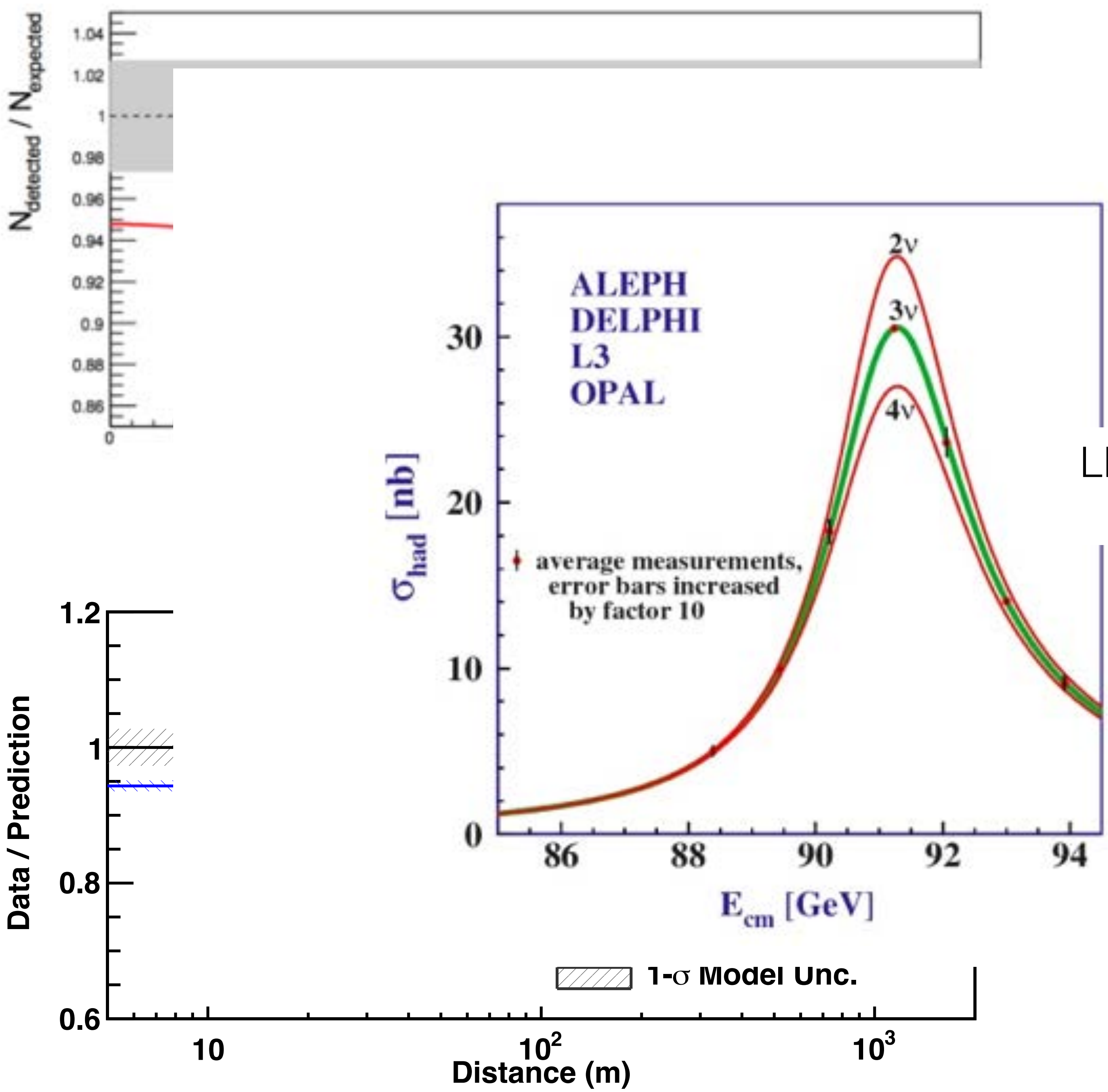
- relative counting measurement between near and far shows deficit in anti-ν_e flux
- indicates oscillations to other SM neutrino flavors over kilometer baselines
- consistent with solar, atmospheric, and accelerator data



anti-ν_e disappearance

- near and far detectors observe overall flux deficit when compared to 2011 prediction
- new measurements agree with old reactor experiments with better precision
- reactor global flux deficit ~5%

Reactor flux anomaly



far

o

LEP Z boson width measurements
only 3 active neutrinos allowed

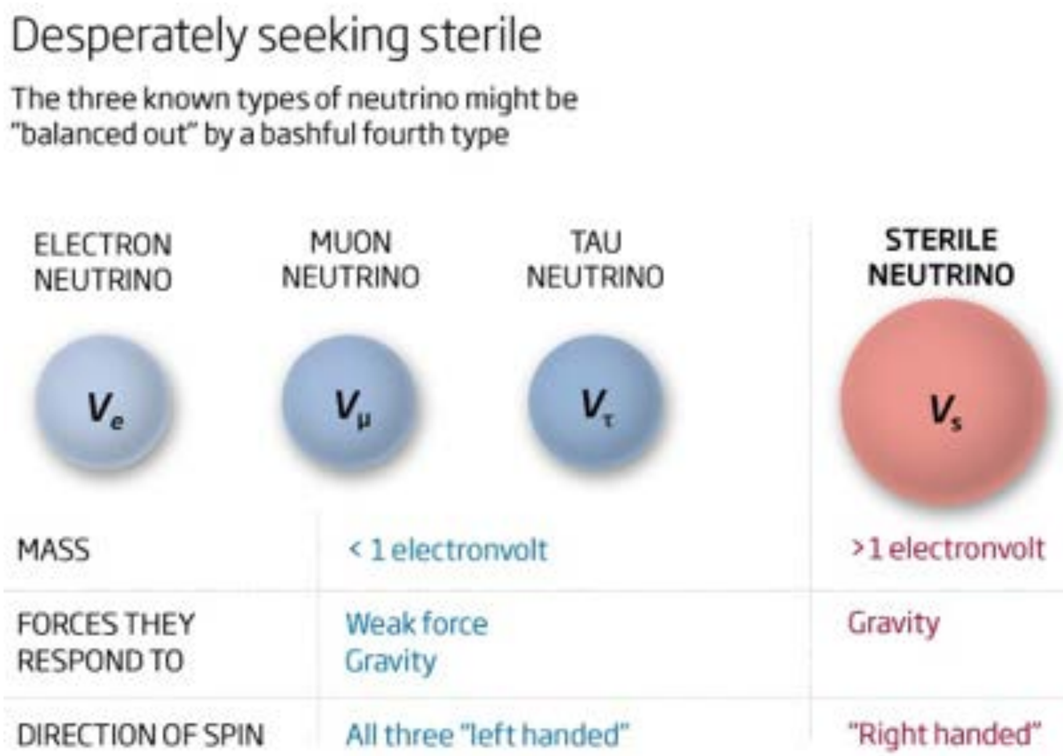
ux

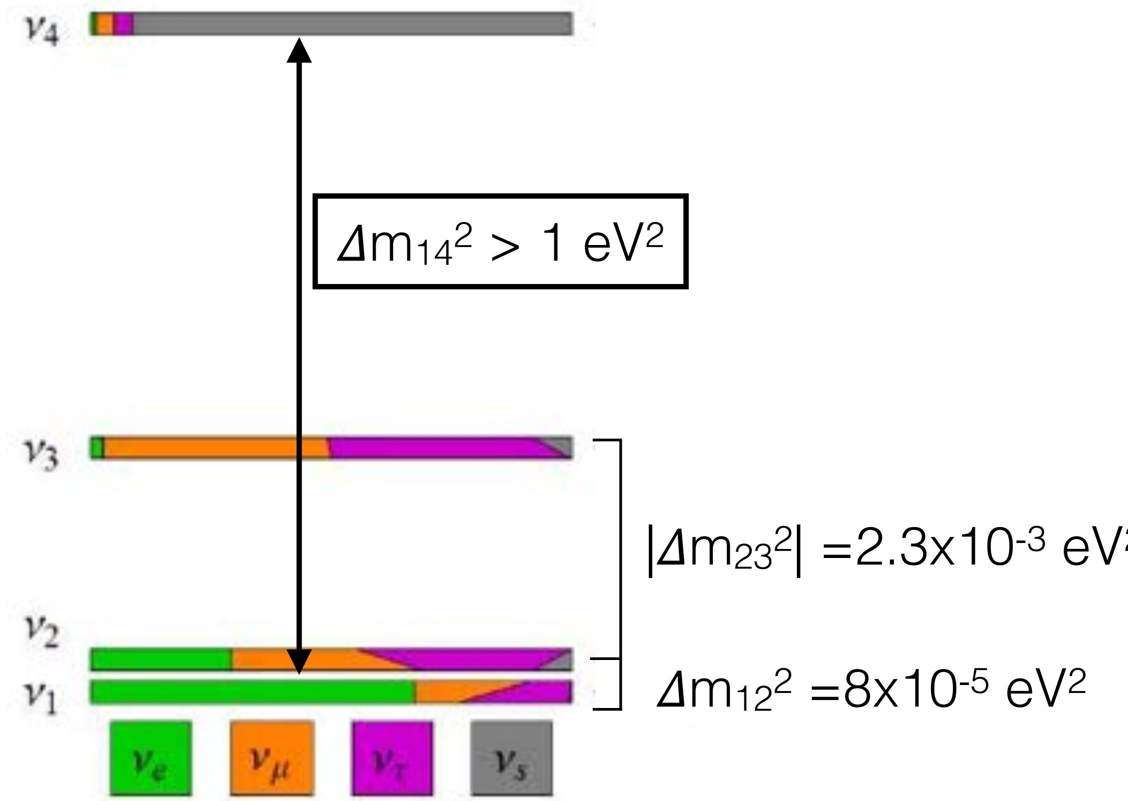
n

or

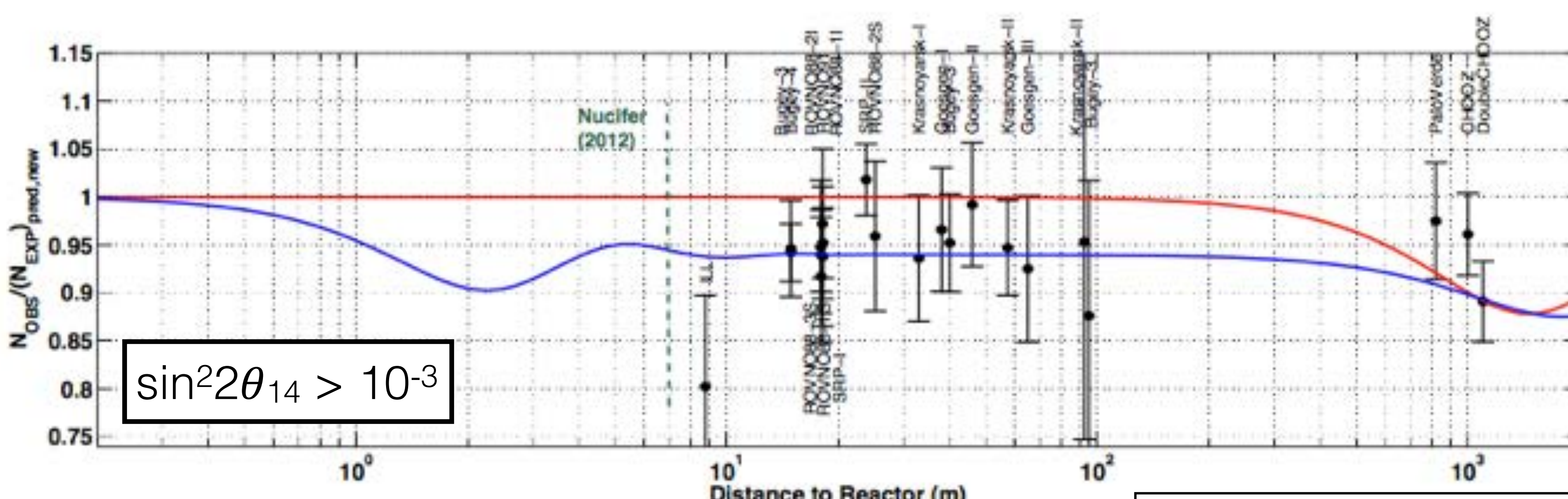
anti-ν_e disappearance

Flux hypothesis - sterile neutrino oscillations



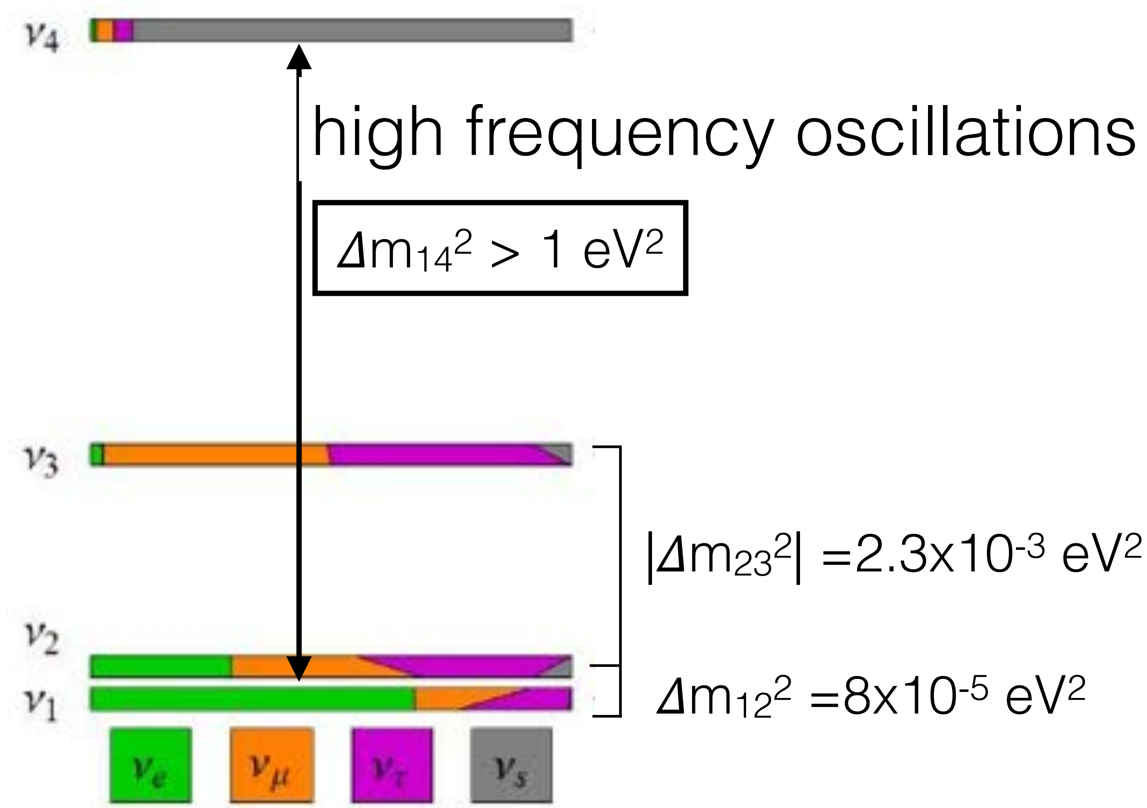


Blue shows fit to reactor data with a 3+1 neutrino model



arXiv:11204.5379 (Light sterile neutrinos white paper)

Flux hypothesis - sterile neutrino oscillations



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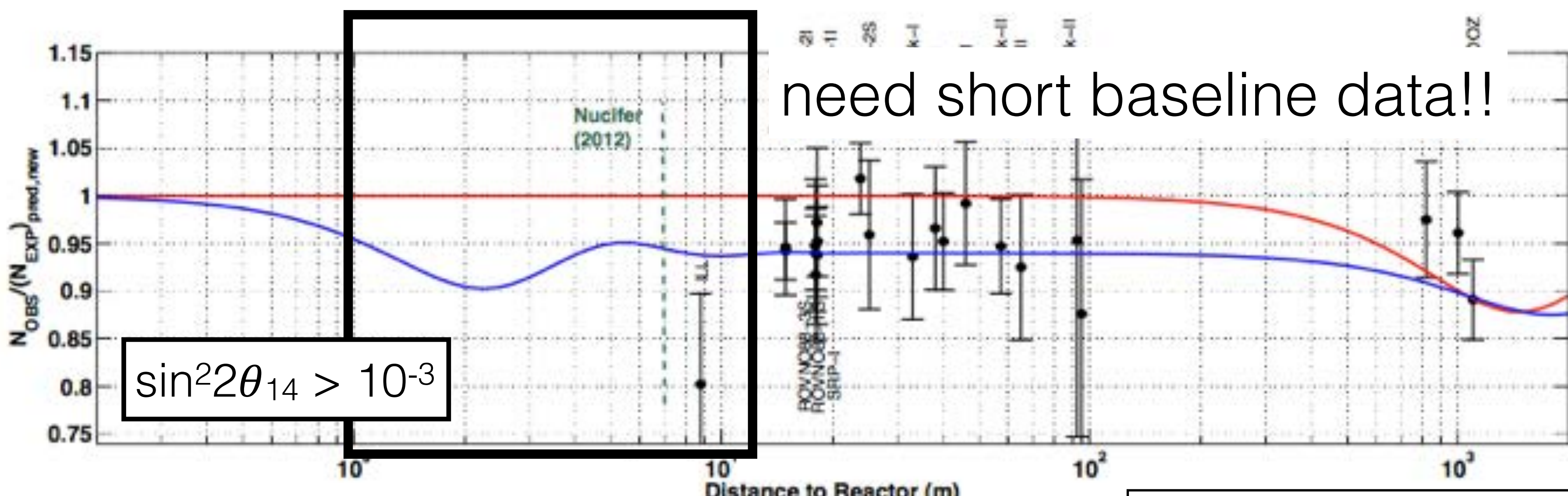

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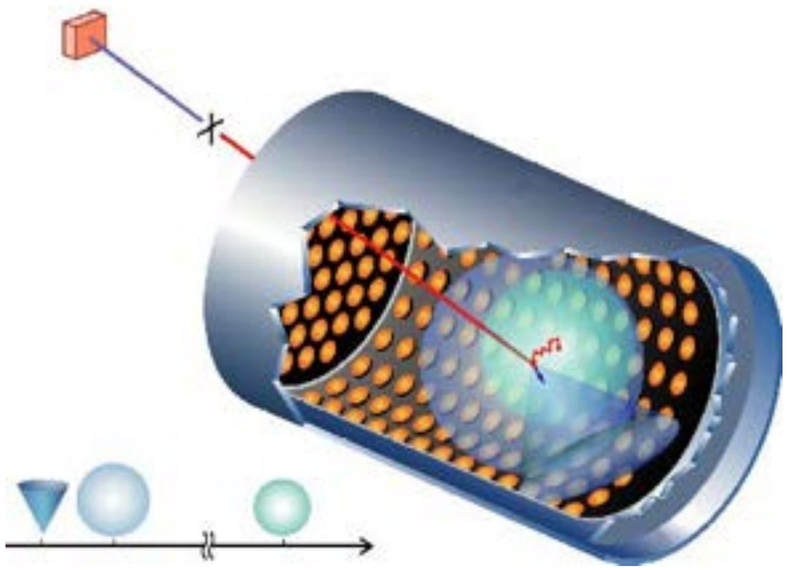
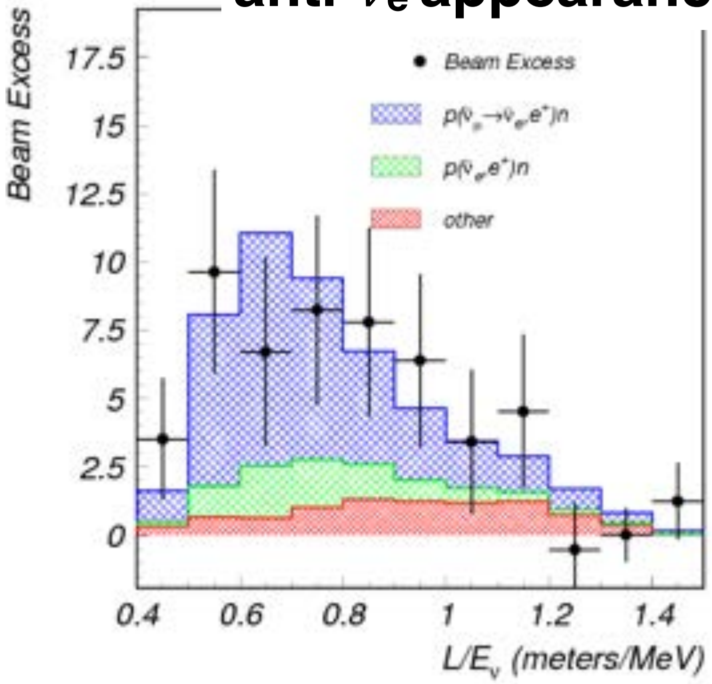
eV-scale sterile neutrinos and other anomalies

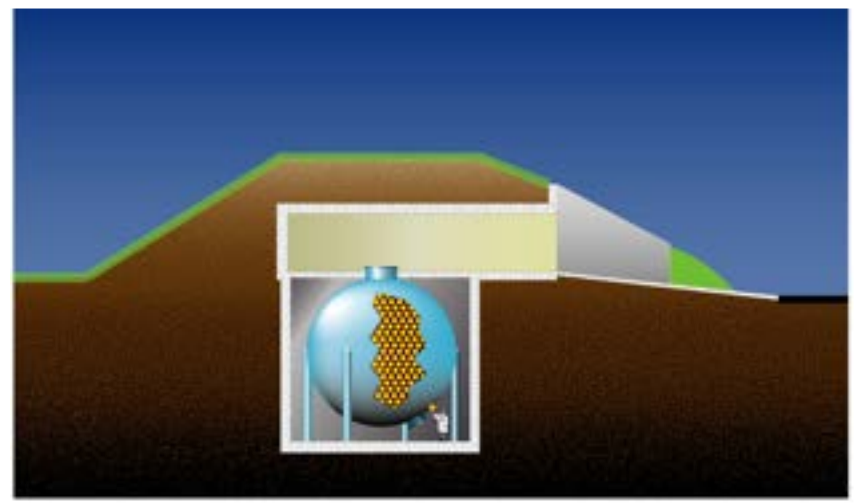
LSND
decay at rest



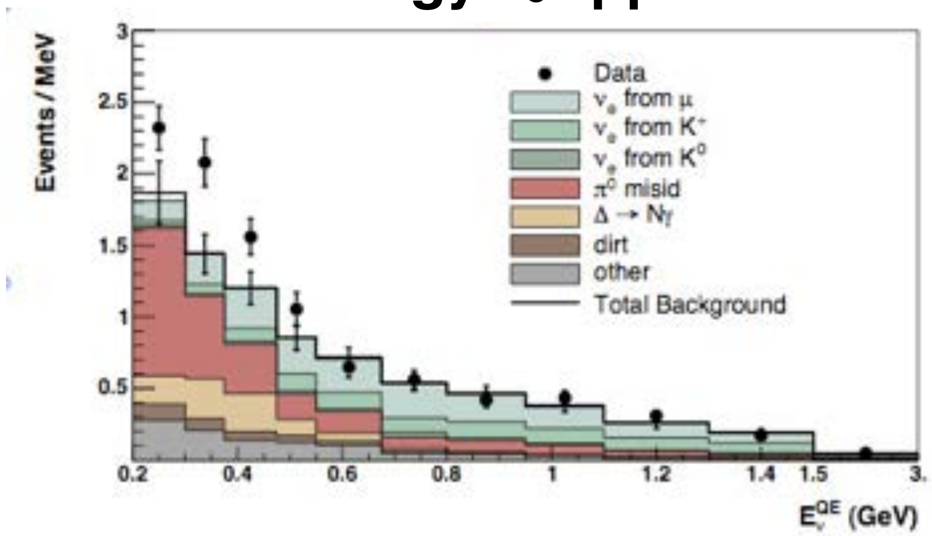
anti-ν_e appearance



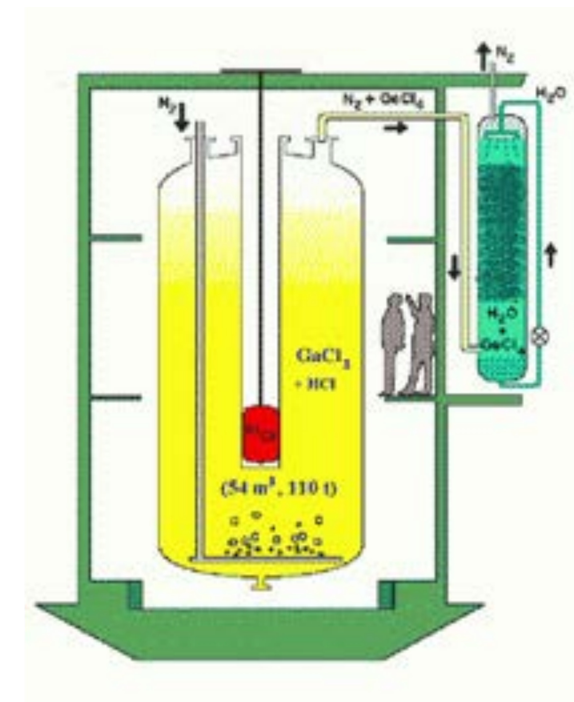
MiniBooNE
short baseline accelerator



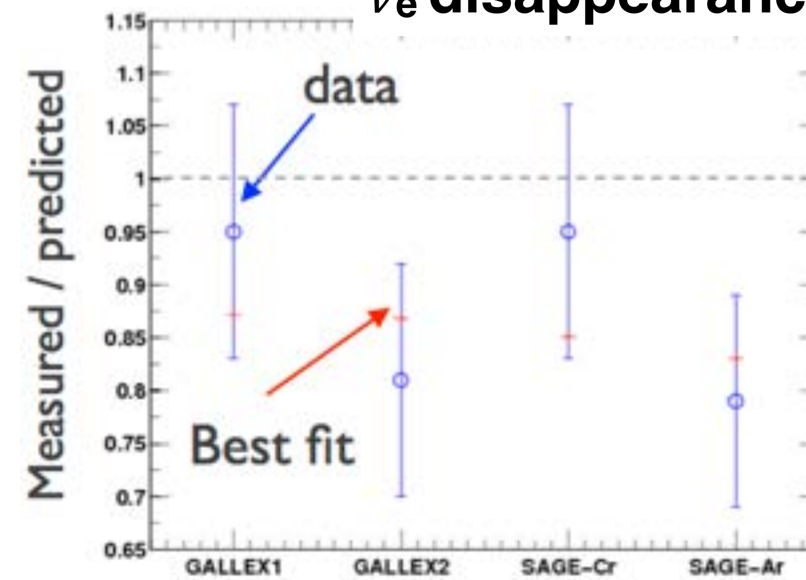
low energy ν_e appearance



GALLEX/SAGE
Ga source calibration



ν_e disappearance



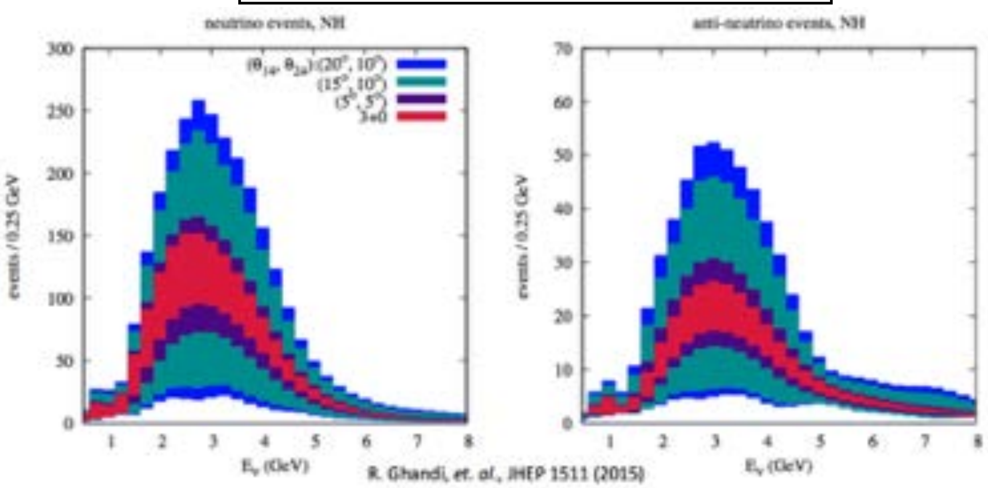
Impacts of sterile neutrinos

Of course, the addition of a each sterile state adds a set of new parameters to the mixing framework. What is the practical effect?

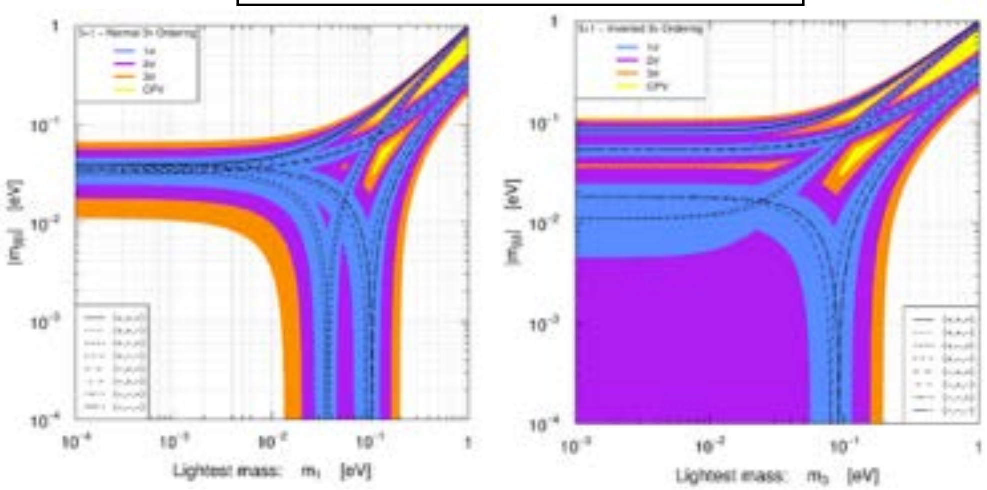
An eV-scale sterile would impact:

- long-baseline experiments measuring CP violation
- neutrinoless double beta decay observing Majorana neutrinos

DUNE response to steriles



$0\nu\beta\beta$ response to steriles

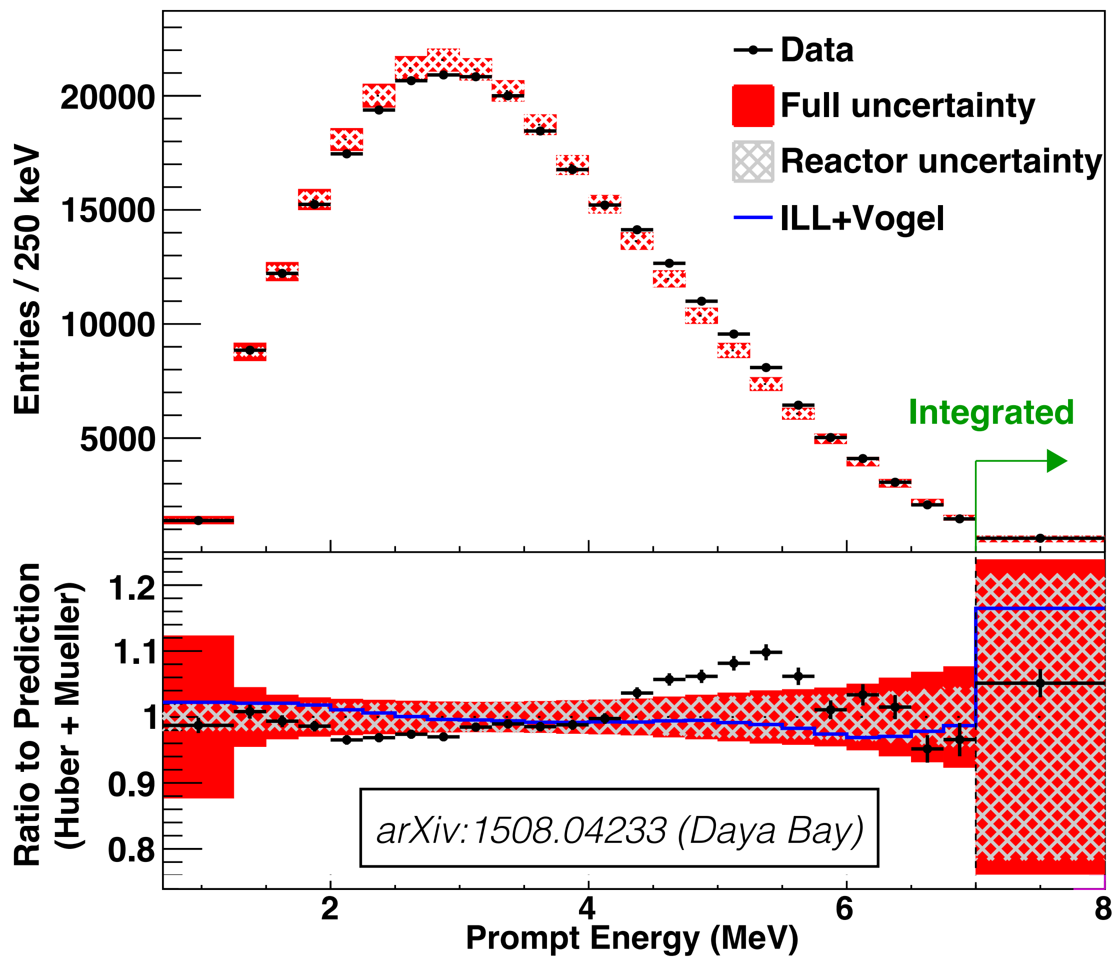


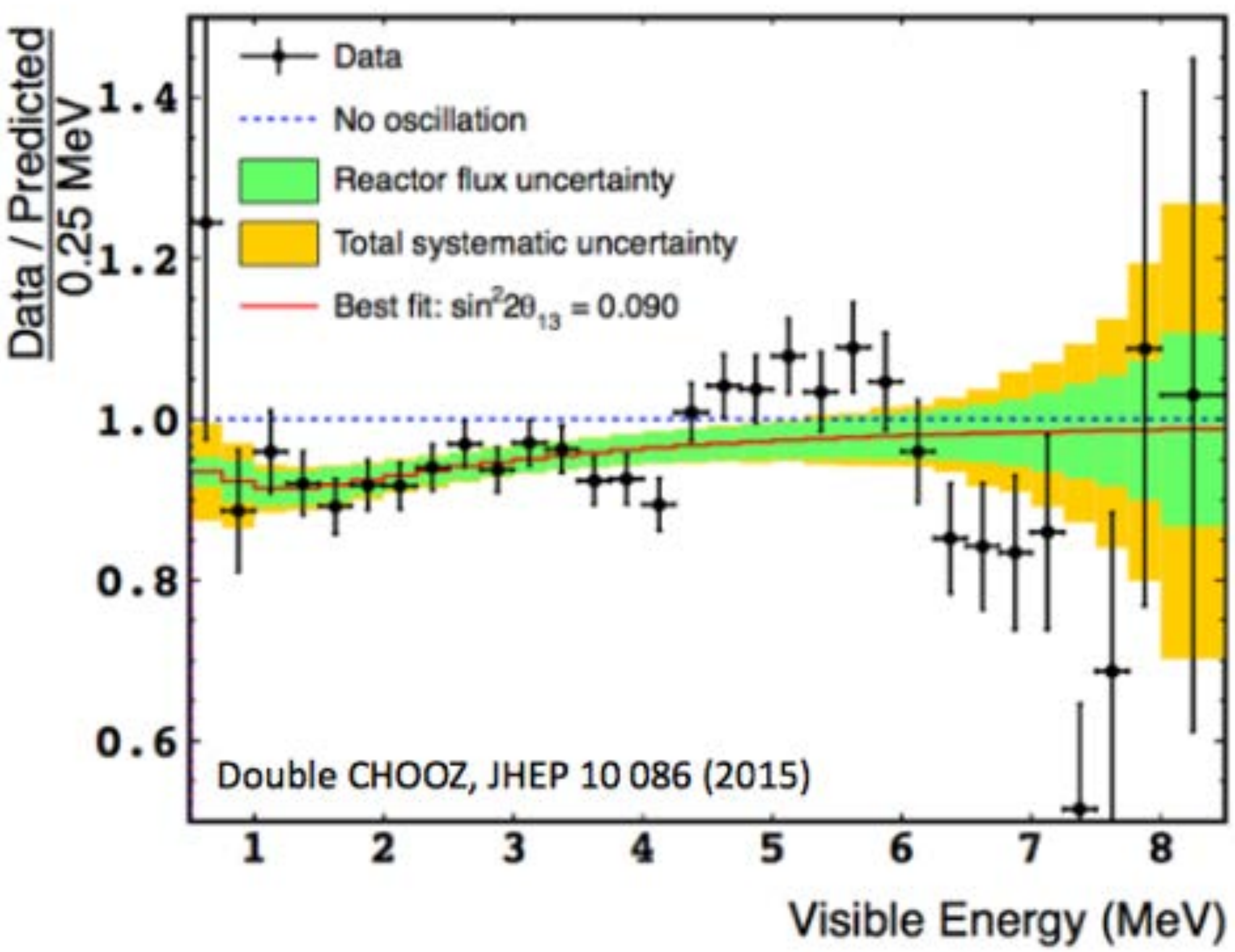
*Giunti & Zavanin, JHEP **1507** (2015)*

Steriles indicate new physics and will have a profound effect on future experiments.
We need definitive short-baseline experiments that don't rely on predictions!

Reactor spectrum anomaly

Antineutrino energy spectra from Daya Bay and Double Chooz.

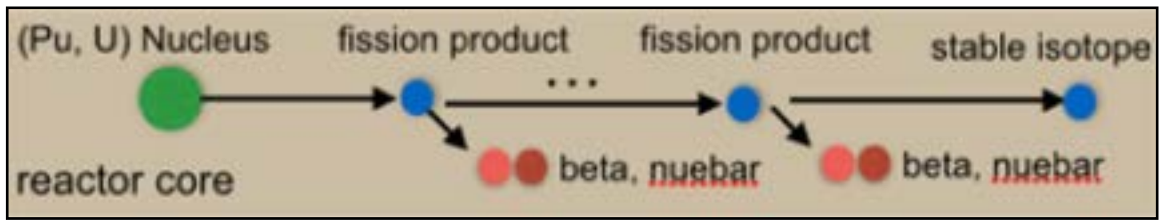




10% excess of events in the 4-6 MeV region when compared to reactor models, also known as “the bump”.

Spectrum hypothesis - deficiencies in models

- power reactor fuels composed of ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu



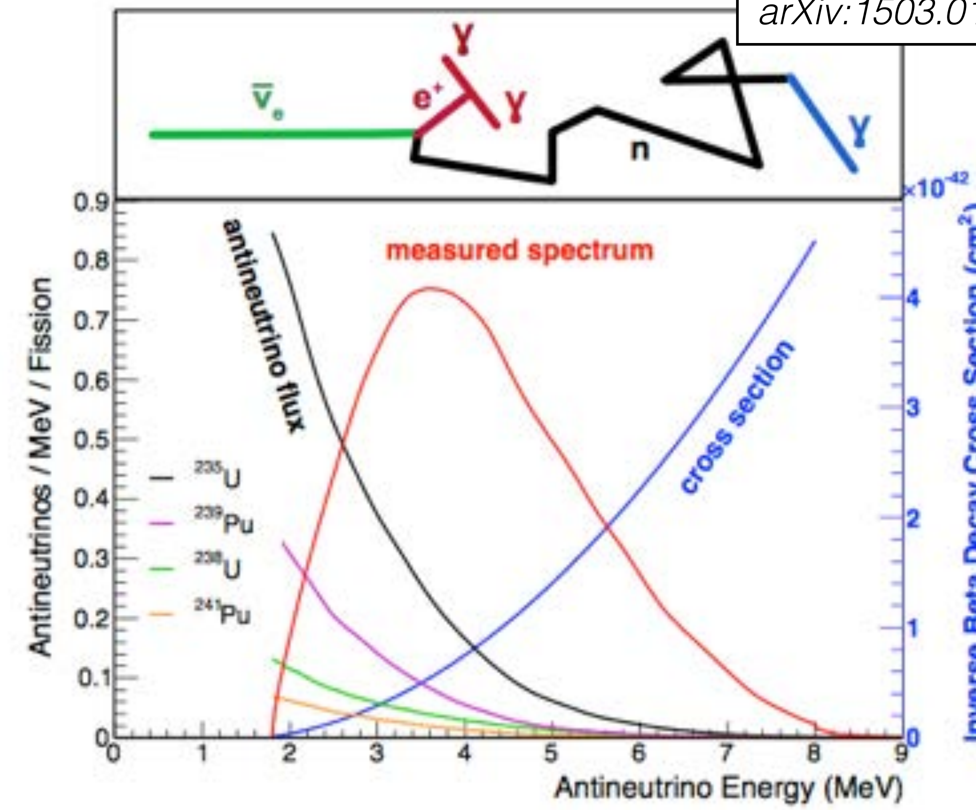
- total emitted spectrum is an admixture, thousands beta branches

Two major approaches to calculate spectrum:

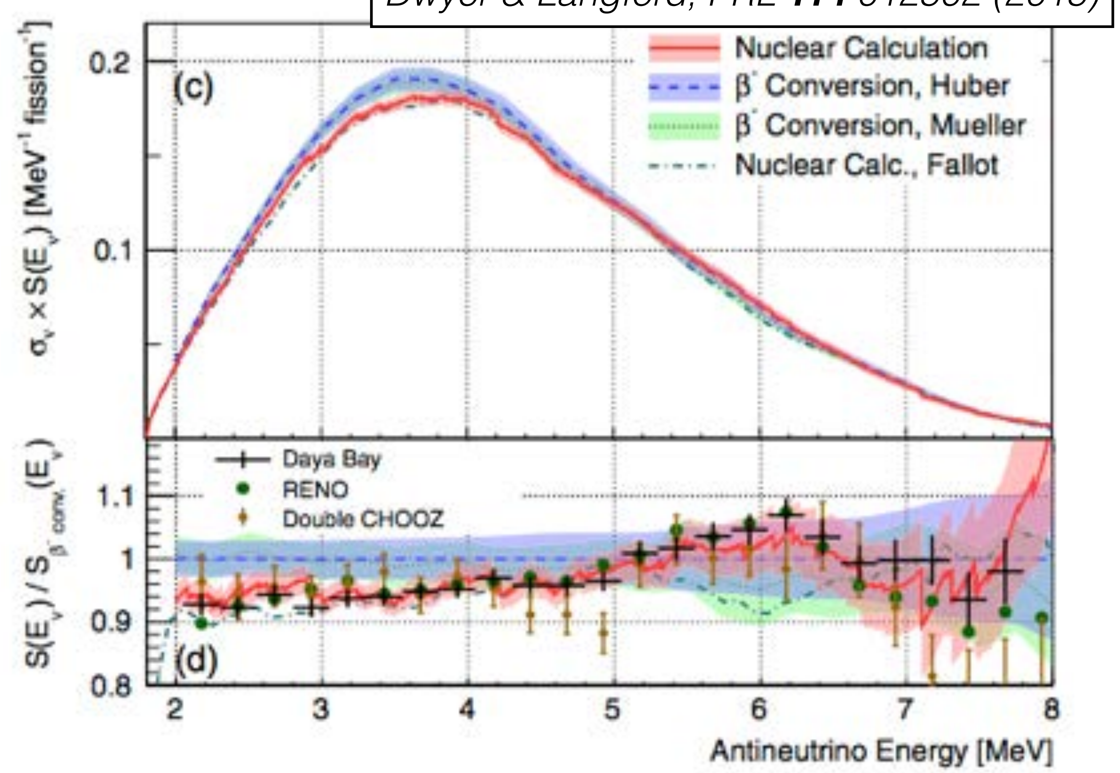
1. *Ab-initio*
   - calculate spectrum branch-by branch using beta branch databases
2. Beta conversion
   - measure beta spectrum of main isotopes
   - fit with 'virtual branches' and converted to antineutrino spectra

Both methods have complications and difficulties.

arXiv:1503.01059



*Dwyer & Langford, PRL **114** 012502 (2015)*



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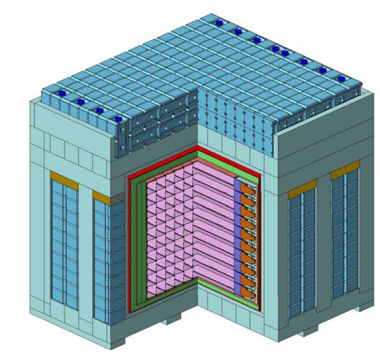

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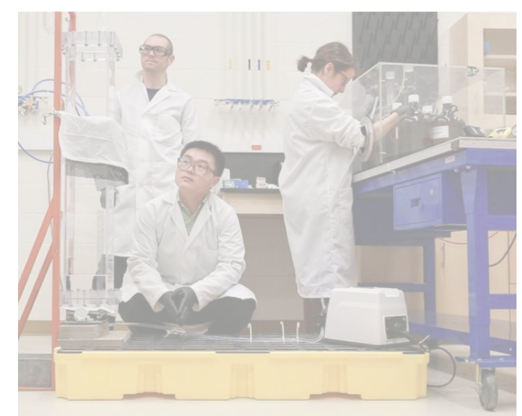
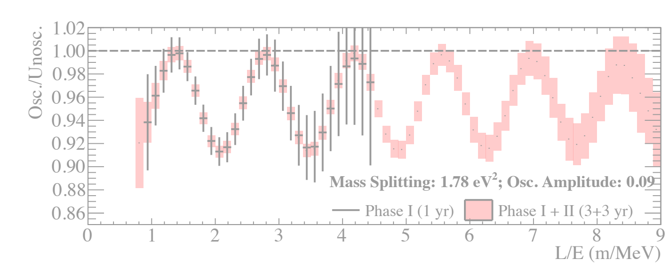


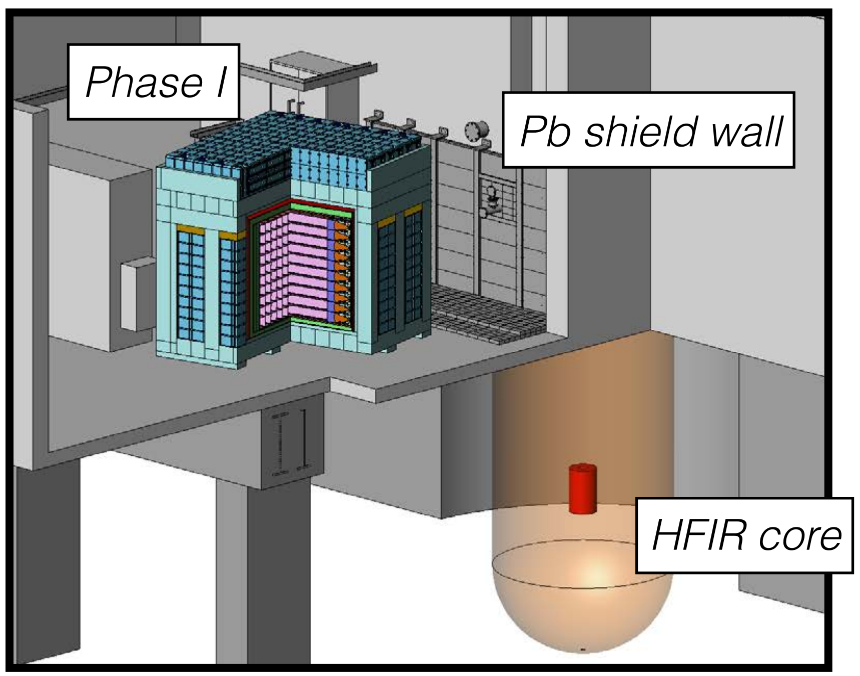


4. Concluding remarks

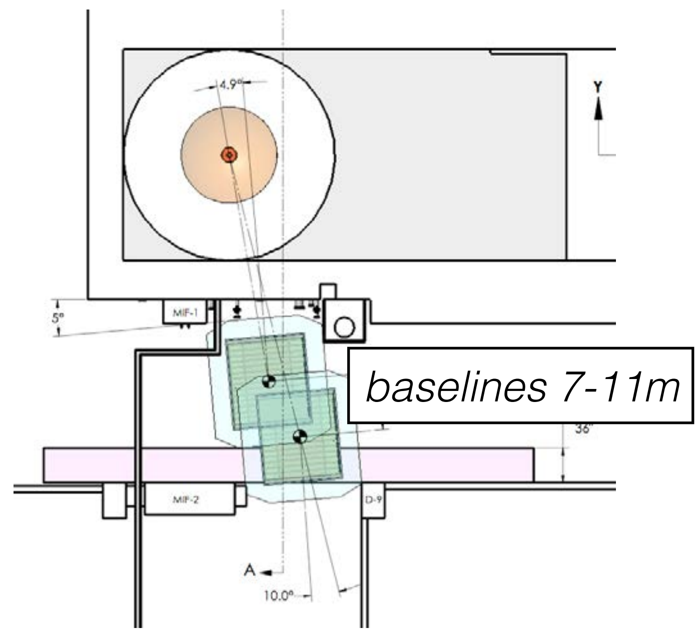
Precision Reactor Oscillation and SPECTrum experiment

Physics objectives:

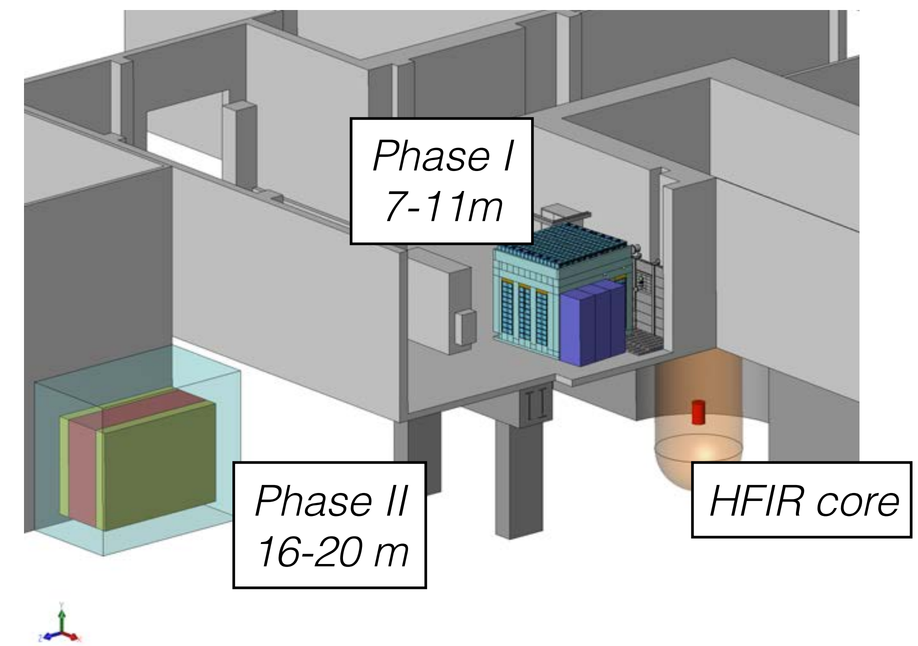
1. Search for short-baseline oscillation at distances <10 m
2. Perform a precision measurement of ^{235}U reactor anti-ν_e spectrum



phase 1



phase 1+



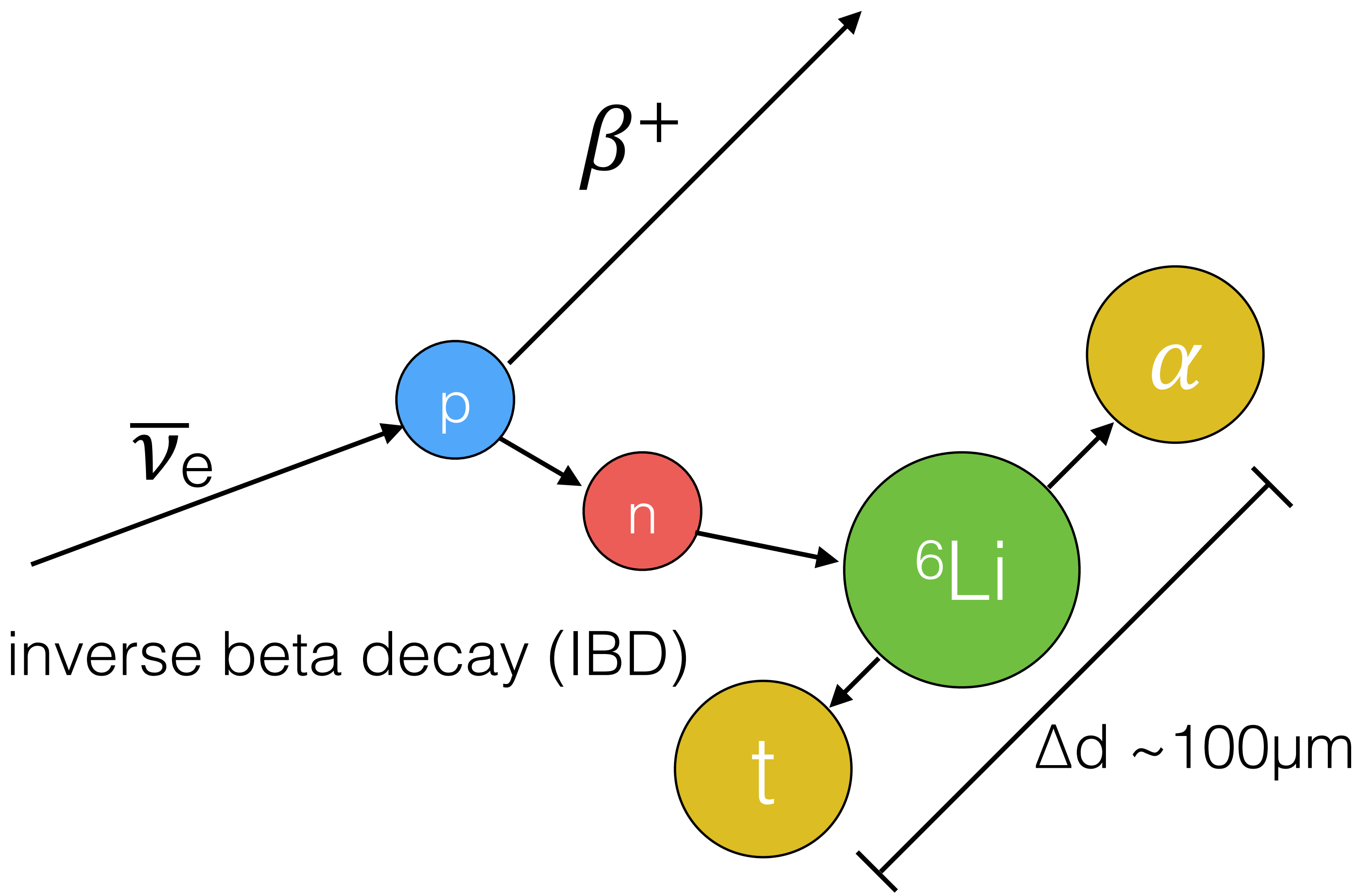
phase 2

Requirements:

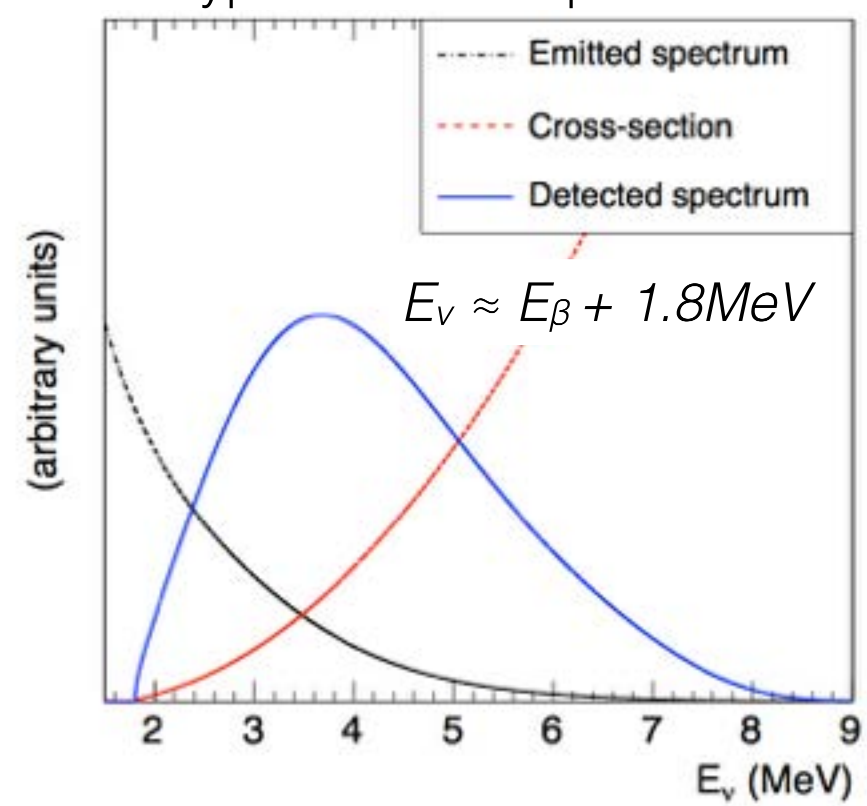
- energy resolution of 4.5%/√E (σ/E) for spectral measurement
- good position resolution for comparing spectra between baselines
- excellent background rejection capabilities at near-surface, reactor site

Detection mechanism - lithium liquid scintillator

prompt ($t_0 = 0$): 1-10MeV annihilation



typical reactor spectrum

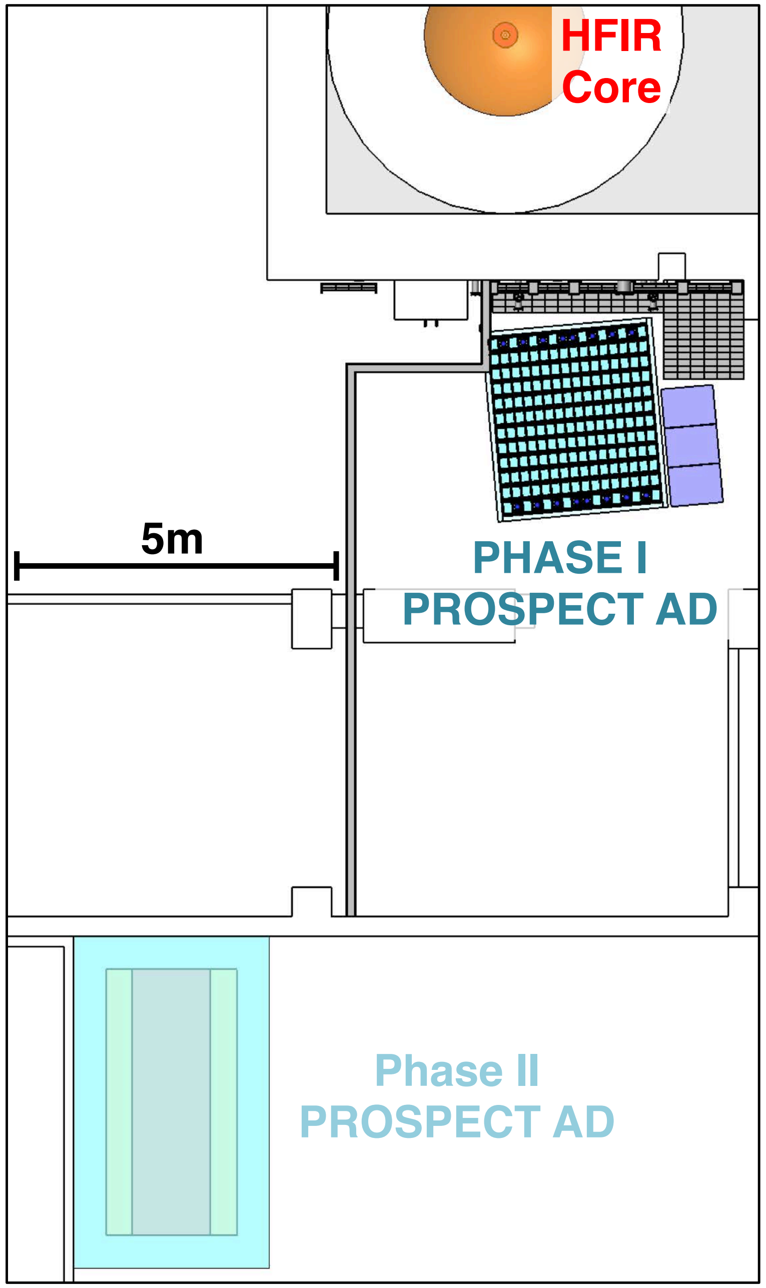


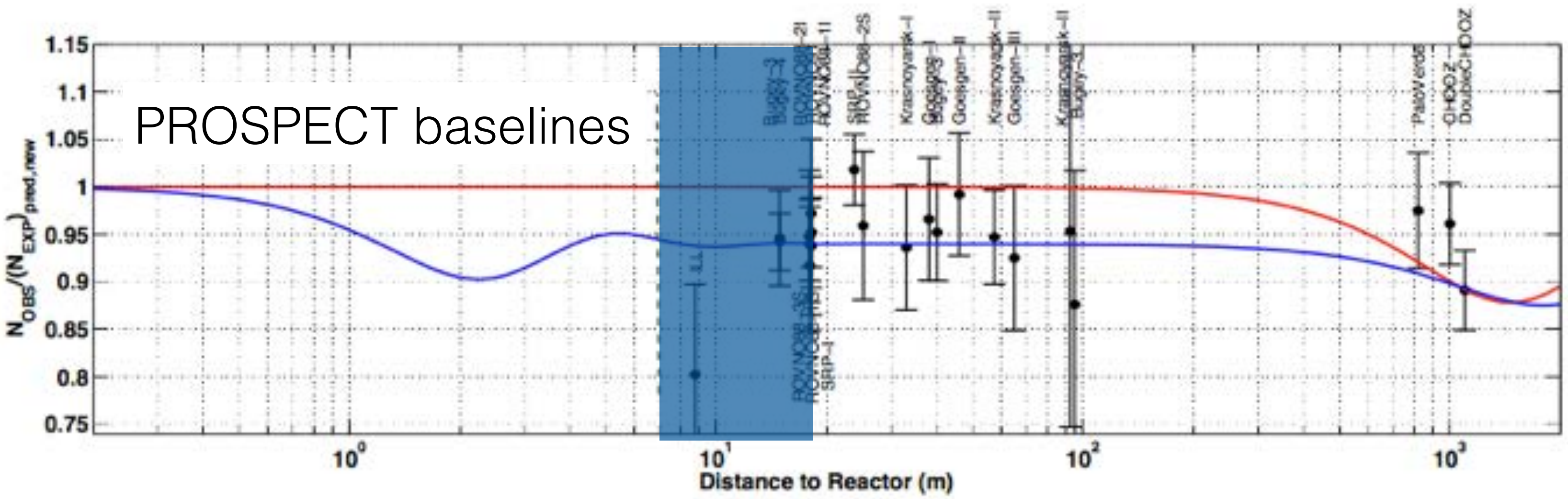
delay ($t_c = 40\mu s$): 0.6MeV_{ee} (n, ^{6}Li) capture

coincidence of these two signals indicates an IBD event

PROSPECT site - High Flux Isotope Reactor (HFIR)

power: 85MW (research)
fuel: highly enriched uranium (^{235}U)
core shape: cylindrical
size: h=0.5m r=0.2m (compact)
duty-cycle: 41%
baselines: 7-11m, 16-20m





Background challenges and measurements

Experimental set-up: near-surface, short-baseline liquid scintillator (LS) detectors

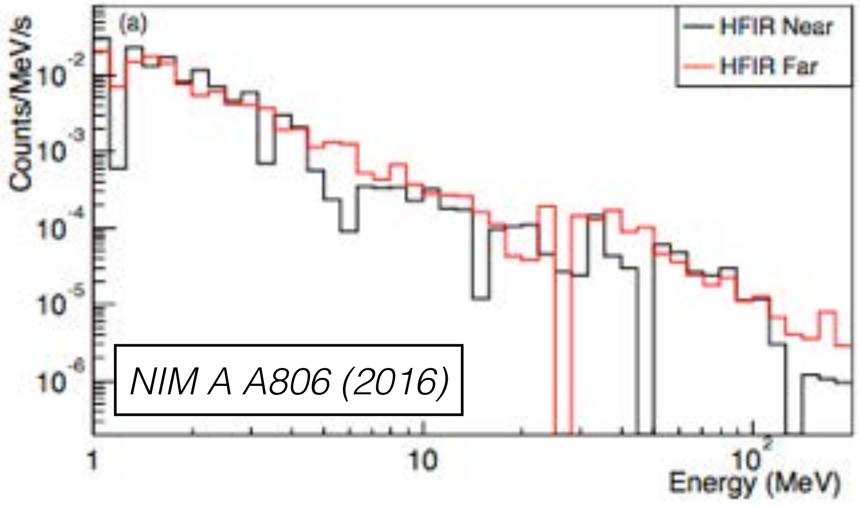
Correlated Backgrounds:

- cosmogenic fast neutrons
- multiple neutron captures

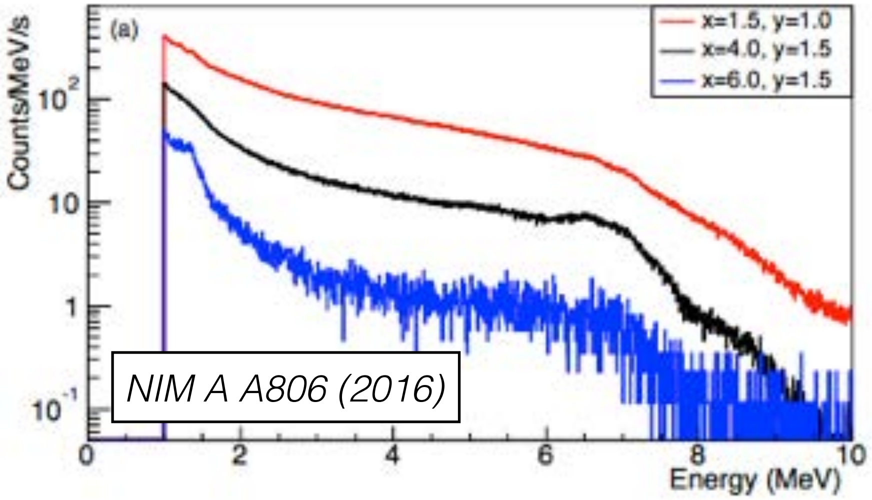
Uncorrelated Backgrounds (accidentals):

- reactor-related gammas
- gammas from internal backgrounds (^{232}Th, ^{40}K)

Cosmogenic fast neutrons



Unshielded gammas (near)



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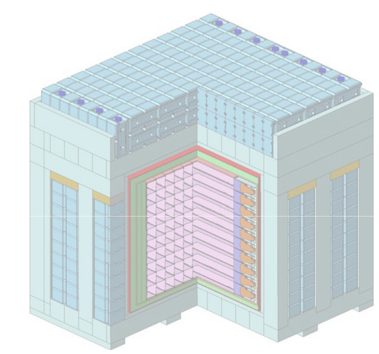

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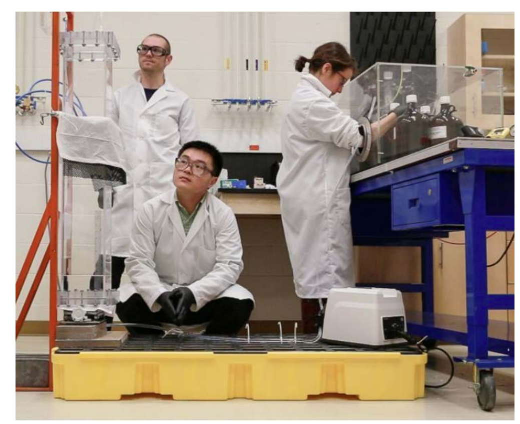
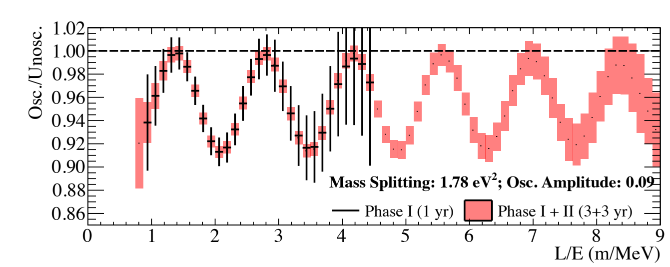




4. Concluding remarks

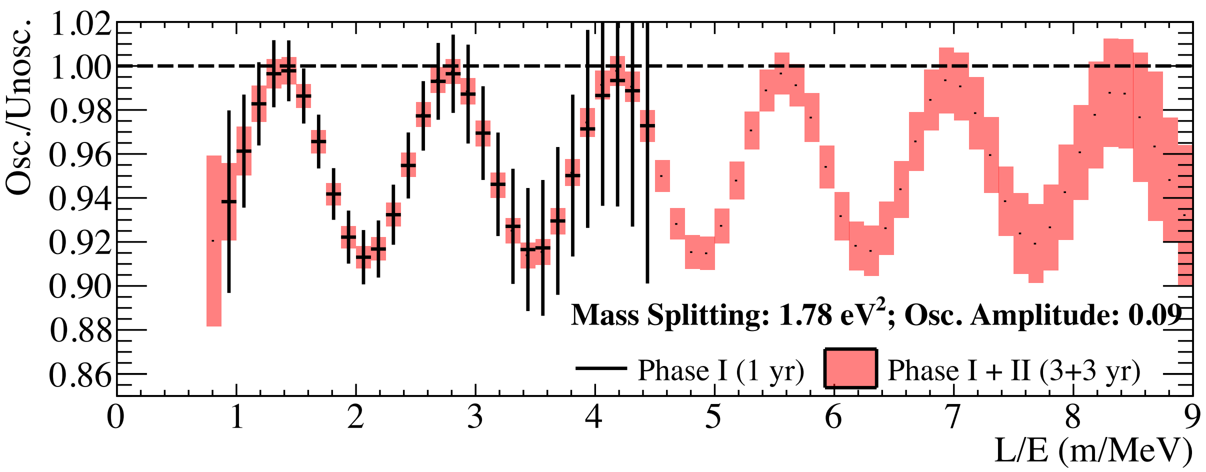
Short-baseline, near-surface detection techniques

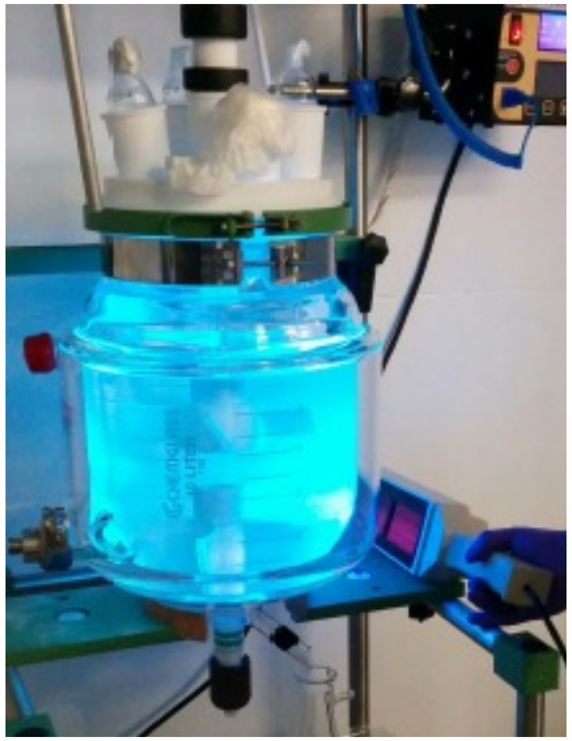
1. **Segmented detector**
   - relative oscillations between segments
   - several pure L/E measurements
   - independent of predictions

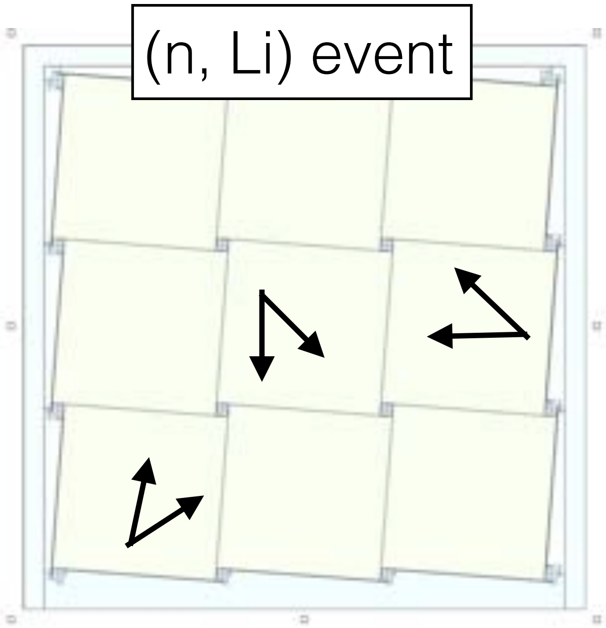
2. **Novel ^{6}Li liquid scintillator**
   - distinct (α, triton) signature
   - highly localized, time and space
   - separate from reactor γ energy
   - good energy resolution
   - excellent pulse-shape discrimination
   - safe, non-flammable

3. **Shielding design**
   - localized Pb reactor wall
   - neutron shielding package

4. **Compact, HEU reactor**
   - point source of neutrinos
   - one fuel isotope

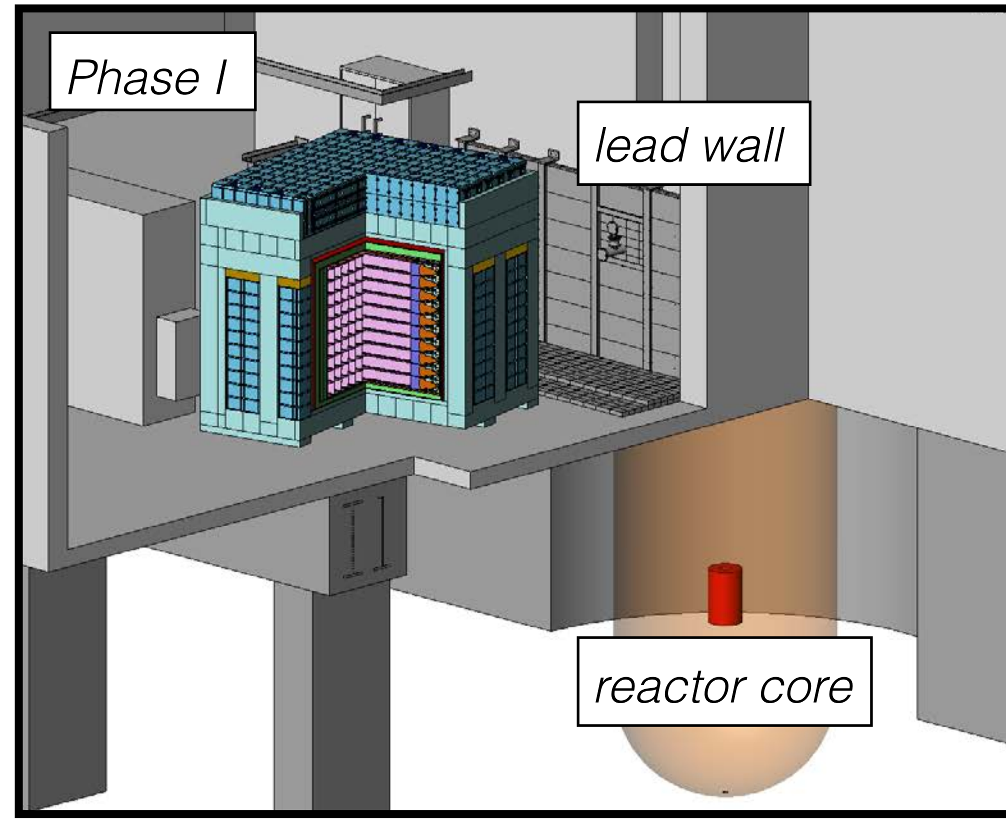






PROSPECT Phase I detector

High Flux Isotope Reactor (ORNL)

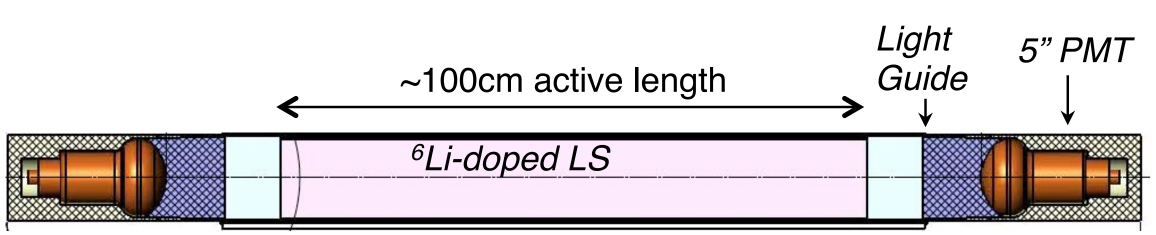


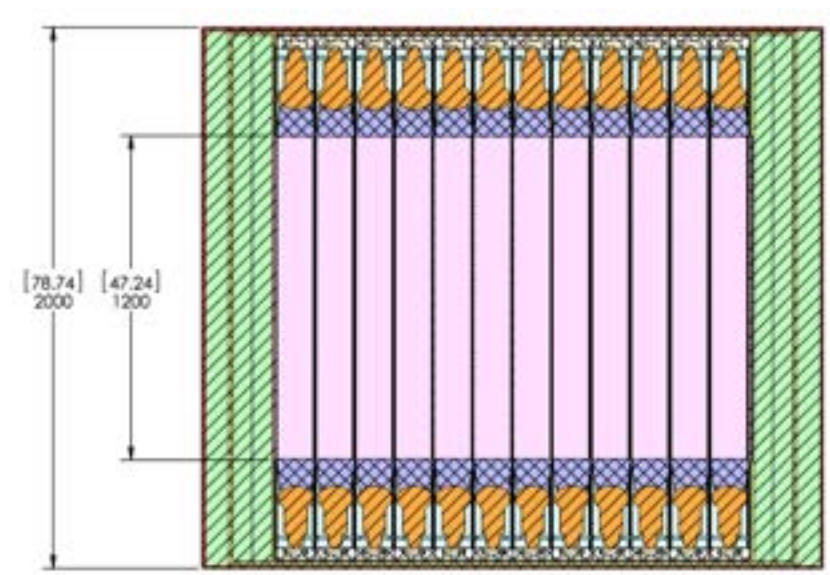
Phase 1 near detector:

- 3 tons ^{6}Li-loaded EJ-309 liquid scintillator
- 10x12 segmented array
- low-mass optical separators
- segment size: 120x15x15 cm^3
- double-ended PMT readout
- movable, baseline coverage 7-11m

Physics goals:

1. probe sterile ν parameter space at 3σ in 1 calendar year
2. precision measurement of ^{235}U neutrino spectrum





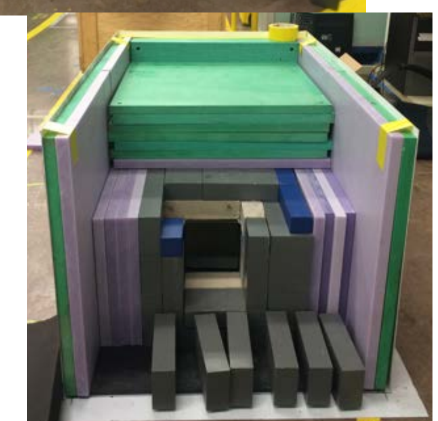
Phased detector development approach

PROSPECT-0.1
Characterize LS
Aug 2014
Spring 2015

5cm
0.1liter
LS, ^{6}LiLS

PROSPECT-2
Background studies
Winter 2014-15
Aug 2015

12.5cm
1.7 liter
^{6}LiLS

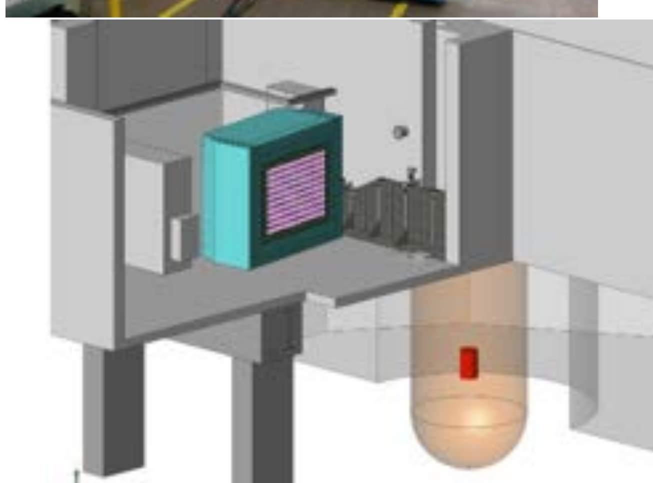


PROSPECT-20
Characterize segment
Spring-Summer 2015

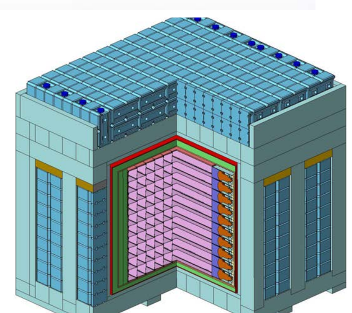
1m
23 liter
LS, ^{6}LiLS

PROSPECT-60
Mechanical prototype
Late 2015*

1m
60 liter (1x2)
^{6}LiLS segments



PROSPECT-2k
Physics measurement
Late 2016*



1m
3 tons
^{6}LiLS segments

*technically driven schedule

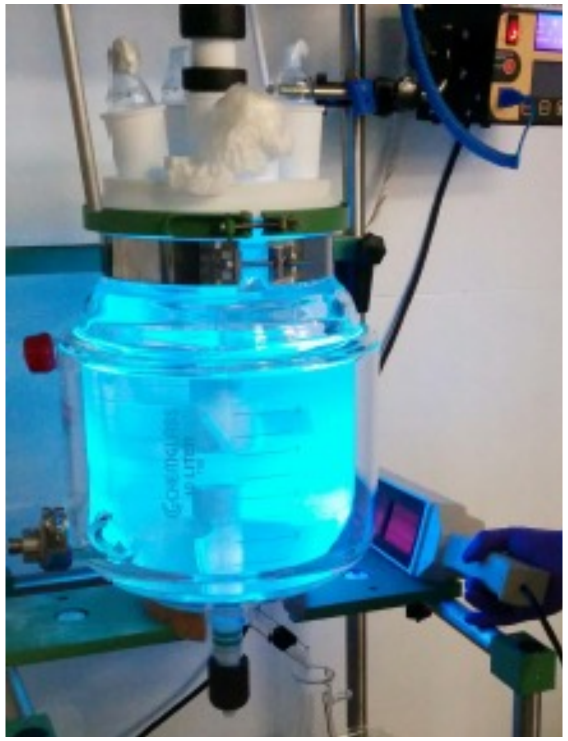
Lithium-loaded liquid scintillator (LiLS) development

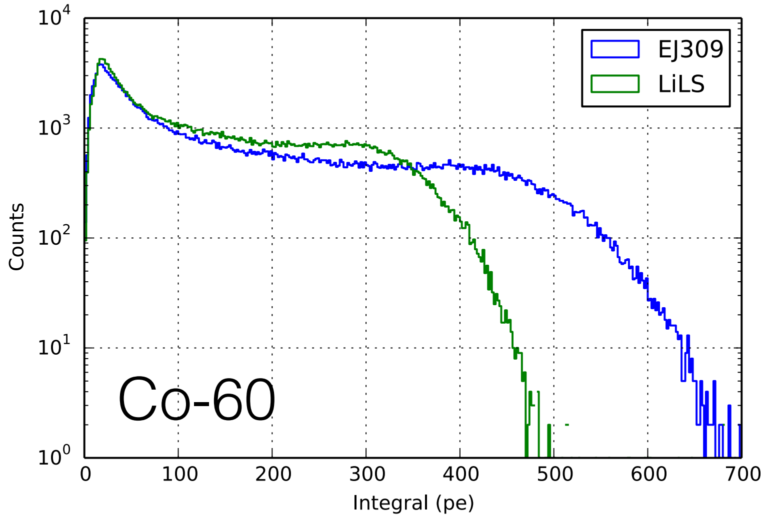
Novel scintillator cocktail:

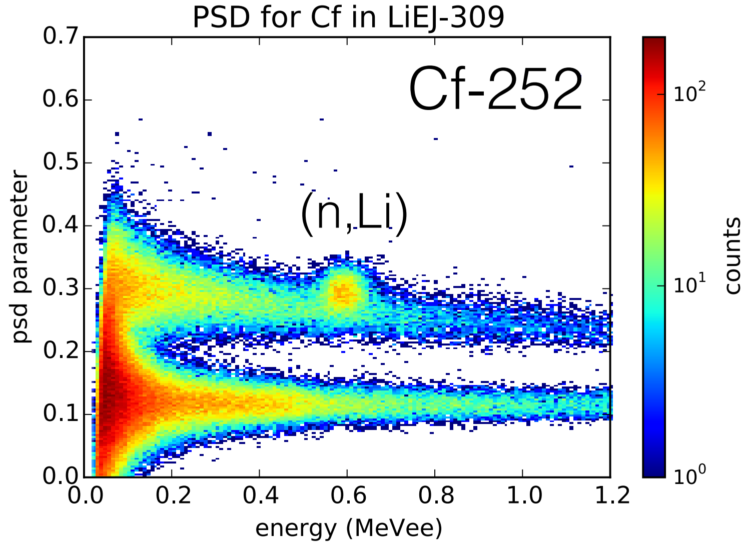
- PSD LiLS that is non-toxic, non-flammable
- extensive studies with LAB, Ultima Gold
- EJ-309 gave best light yield, PSD

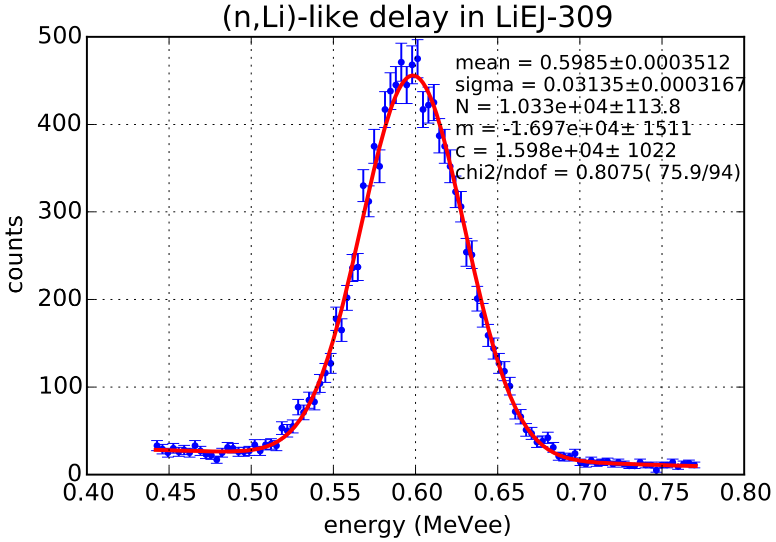
Scintillator specs (PROSPECT-0.1):

- Light Yield$_{EJ\text{-}309}$ = 11500 ph/MeV
- Light Yield$_{LiLS,\ measured}$ = 8200 ph/MeV
- prominent neutron capture peak in LiLS
- PSD FOM at (n, Li) is 1.79
- energy resolution (σ/E) of 5.2% at 0.6MeV$_{ee}$





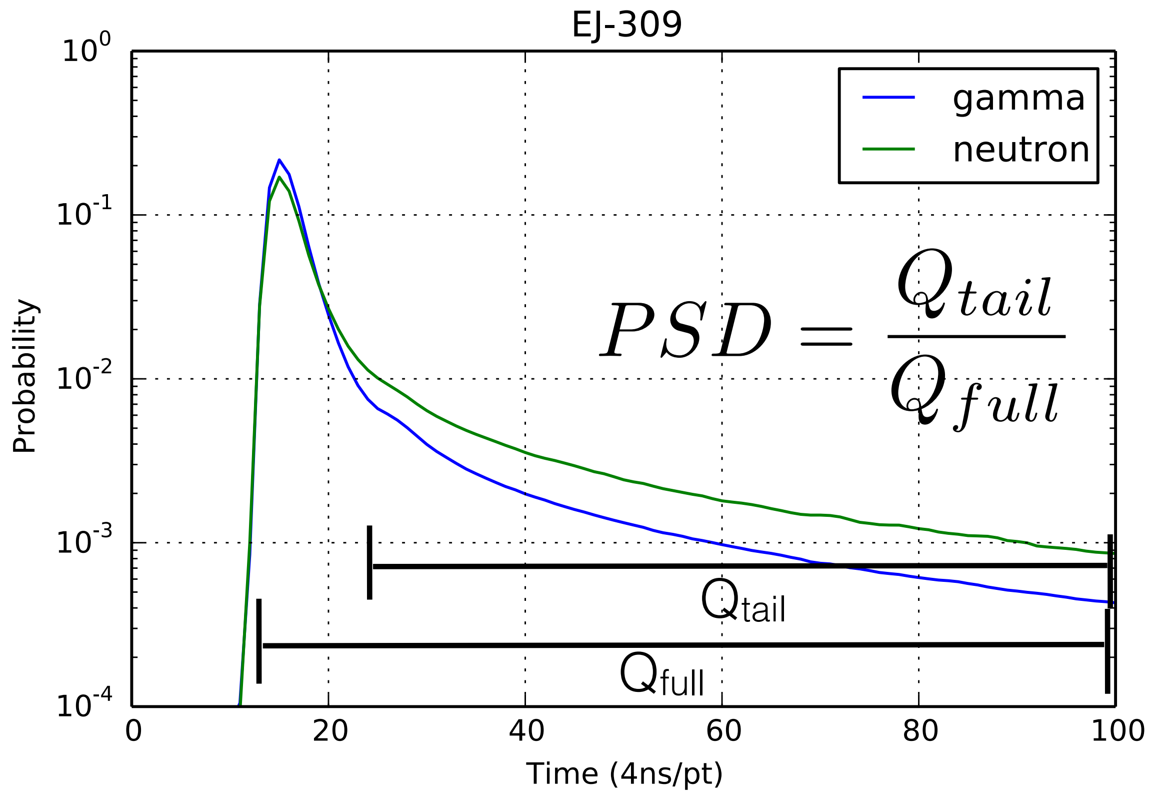


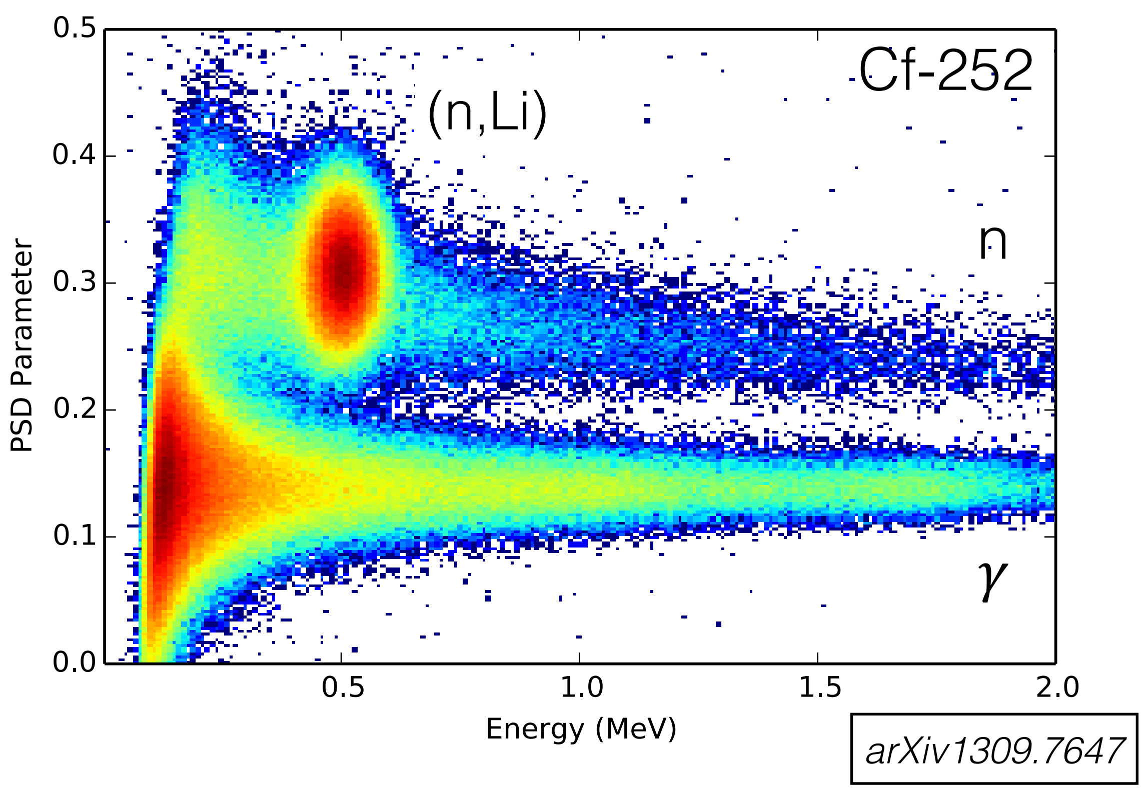


developed novel LiLS with excellent light yield, PSD, and neutron capture capabilities

Pulse-shape discrimination

Can take advantage of how different particles deposit energy in scintillator using pulse-shape discrimination (PSD). Gives particle identification information.



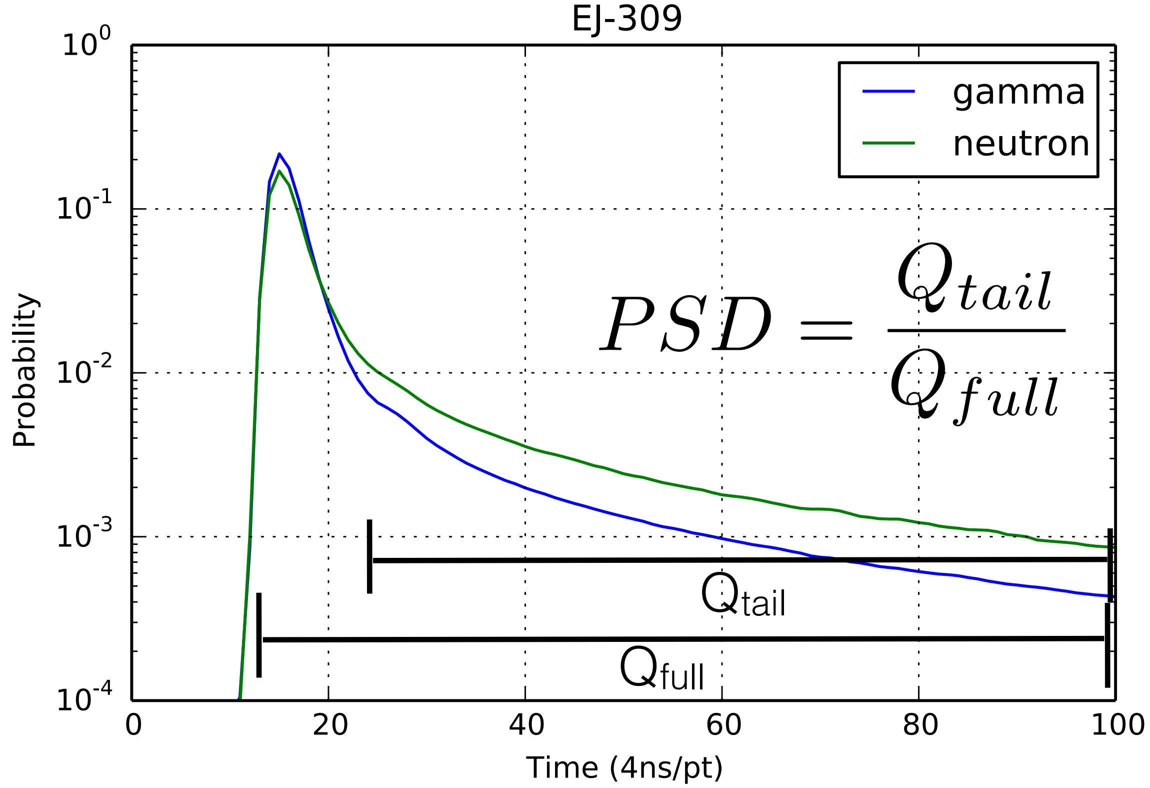


PROSPECT-2 (LiLS)

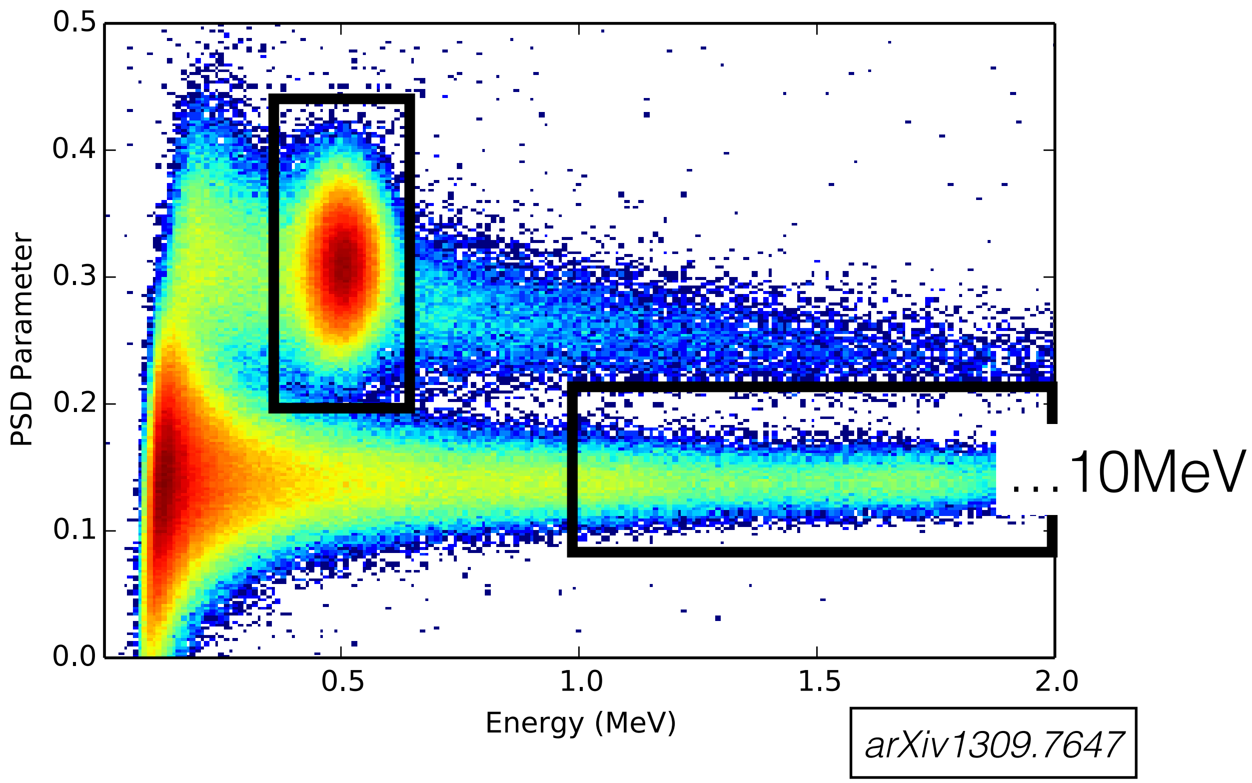
particle classification: light particles = "gamma-like", heavy charged = "neutron-like"

Pulse-shape discrimination

Can take advantage of how different particles deposit energy in scintillator using pulse-shape discrimination (PSD). Gives particle identification information.



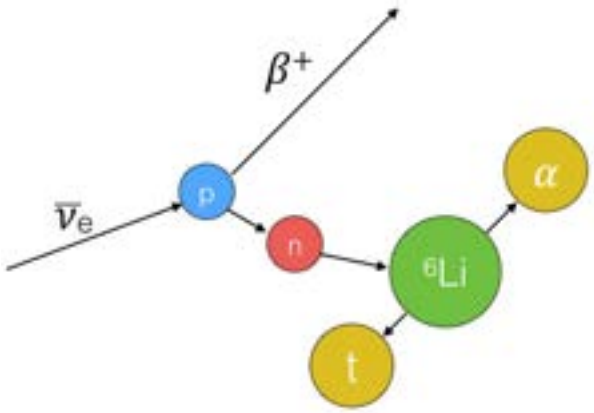
energy+PSD cuts for prompt and delay signals



PROSPECT-2 (LiLS)

particle classification: light particles = “gamma-like”, heavy charged = “neutron-like”

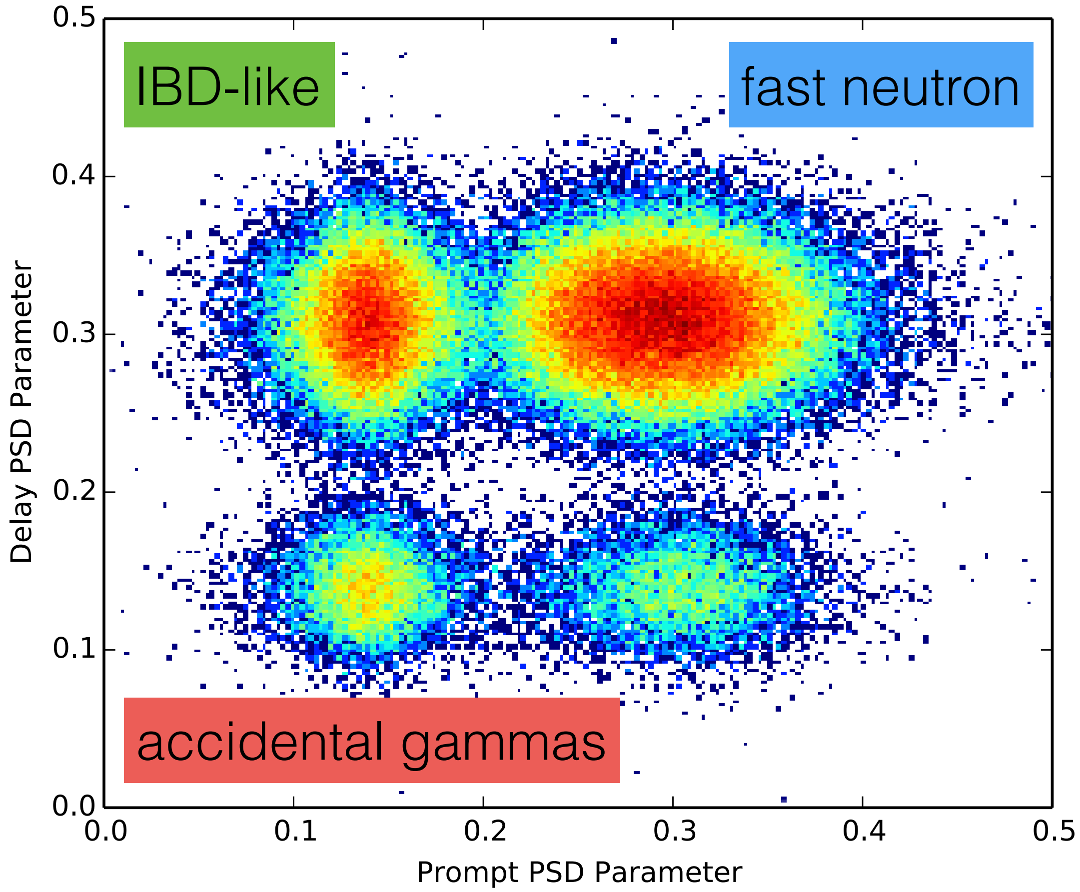
Tackling backgrounds with PSD



prompt signal: 1-10 MeV positron from inverse beta decay
delay signal: 0.6 MeV signal from neutron capture on ^{6}Li

PSD signatures	
Signal	inverse beta decay γ-like prompt, n-like delay
Background	fast neutron n-like prompt, n-like delay
	accidental gamma γ-like prompt, γ-like delay

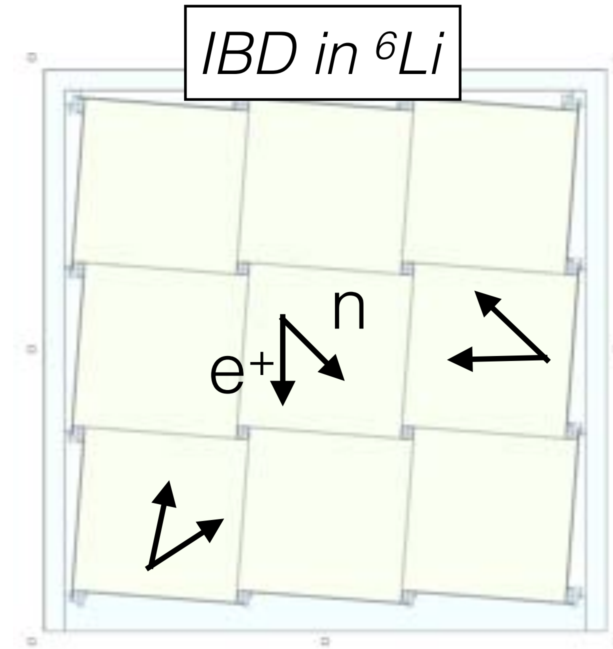
PROSPECT-2 (LiLS)



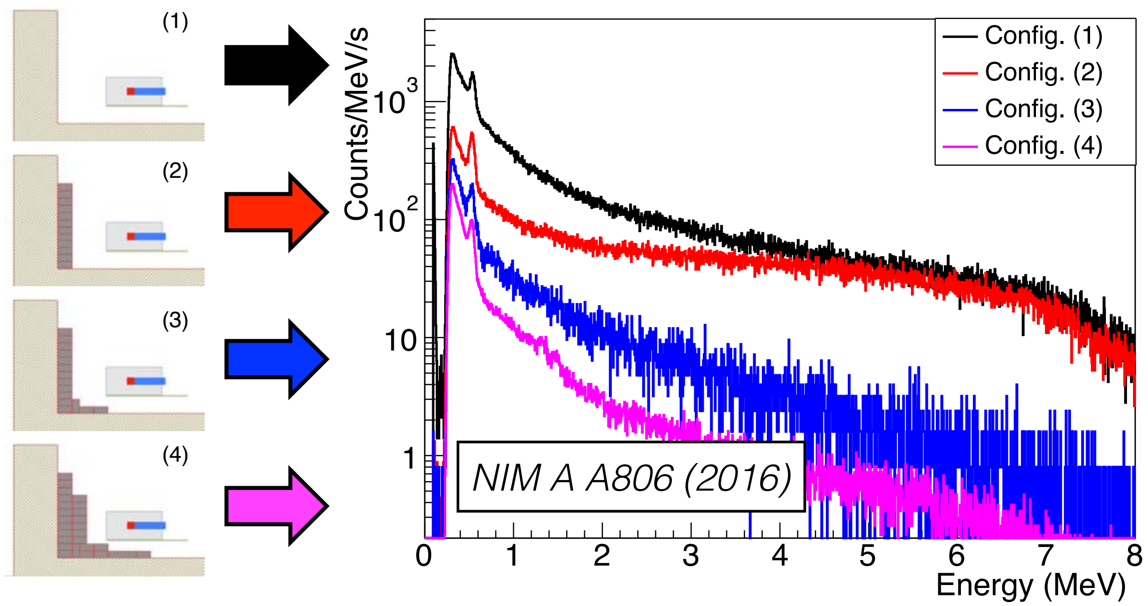
particle ID strongly suppresses cosmogenic correlated and reactor-induced uncorrelated backgrounds

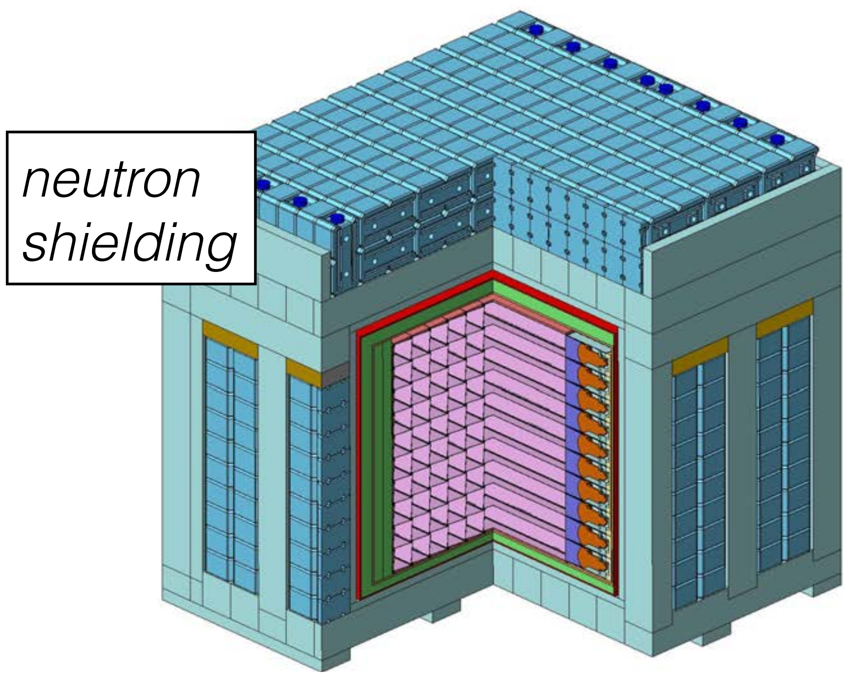
Tackling backgrounds with detector design

- the neutron capture on ^{6}Li allows for event localization, and combined with the localized e^+ gives a spatial correlation in addition to the IBD temporal correlation
- easy fiducialization to control gamma backgrounds
- designed localized shielding to suppress cosmogenic and reactor correlated backgrounds
- cosmogenic neutron backgrounds can be subtracted with reactor-off data sets



effect of increasing lead wall on gammas



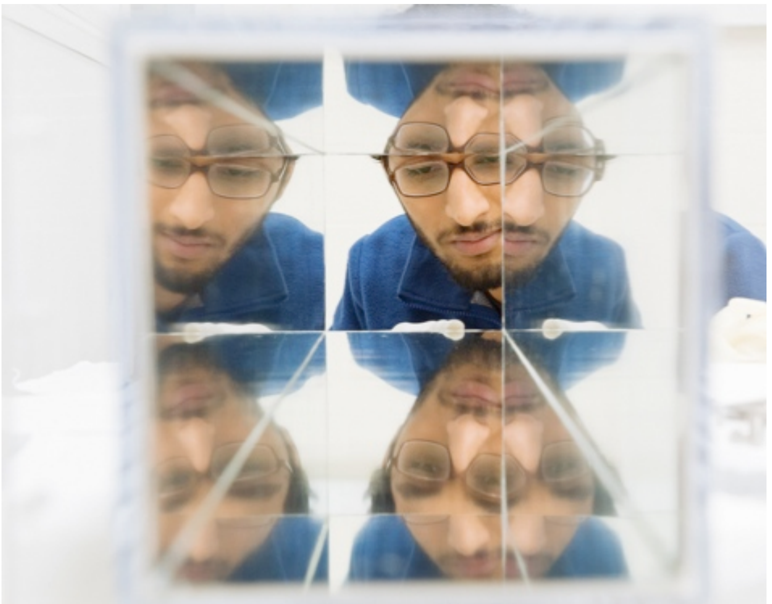


detector structure and passive shielding designed for near-surface backgrounds

Compatibility and design of low-mass separators

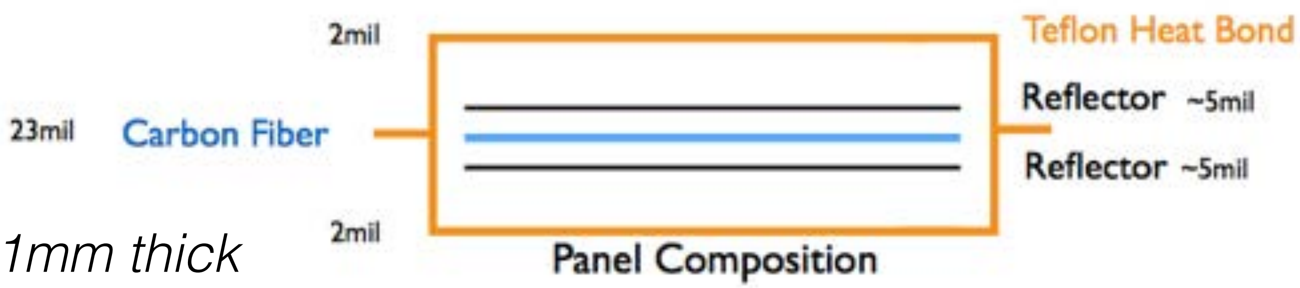
Compatibility:

- extensive material compatibility testing required to ensure long-term LS performance
- focus on materials proven in recent experiments - PTFE, acrylic, polypropylene, …
- long-term mechanical stability verified

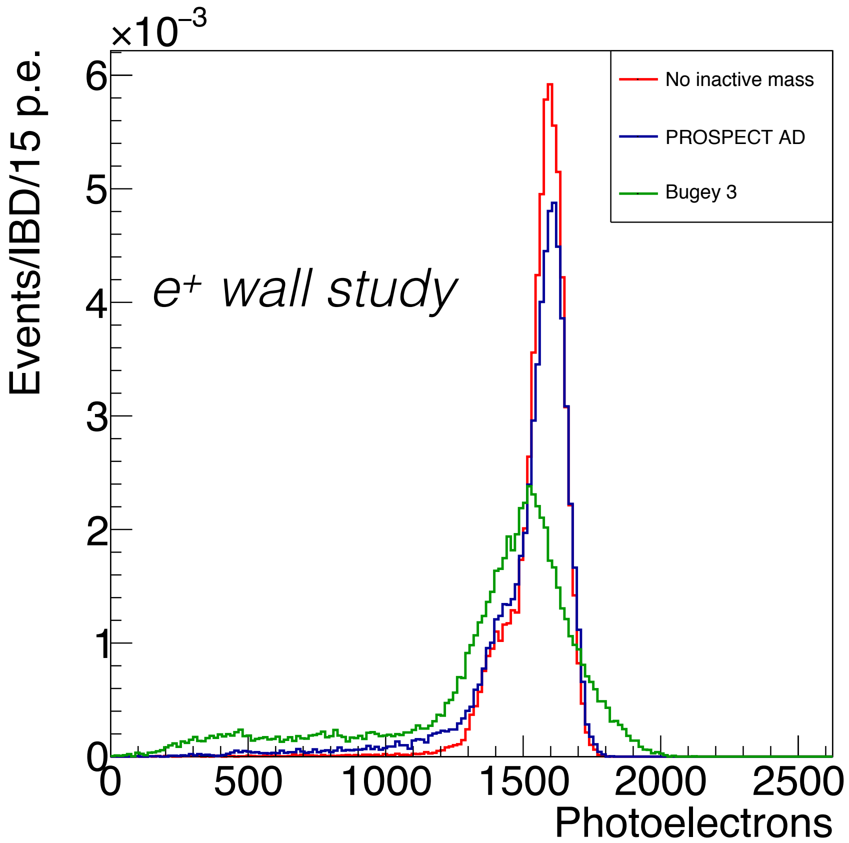


Separators:

- physics goals demand low inactive mass, high reflectivity, and long-term compatibility
- developed multi-layer system meeting all requirements
- fabrication procedures for full-scale system under validation

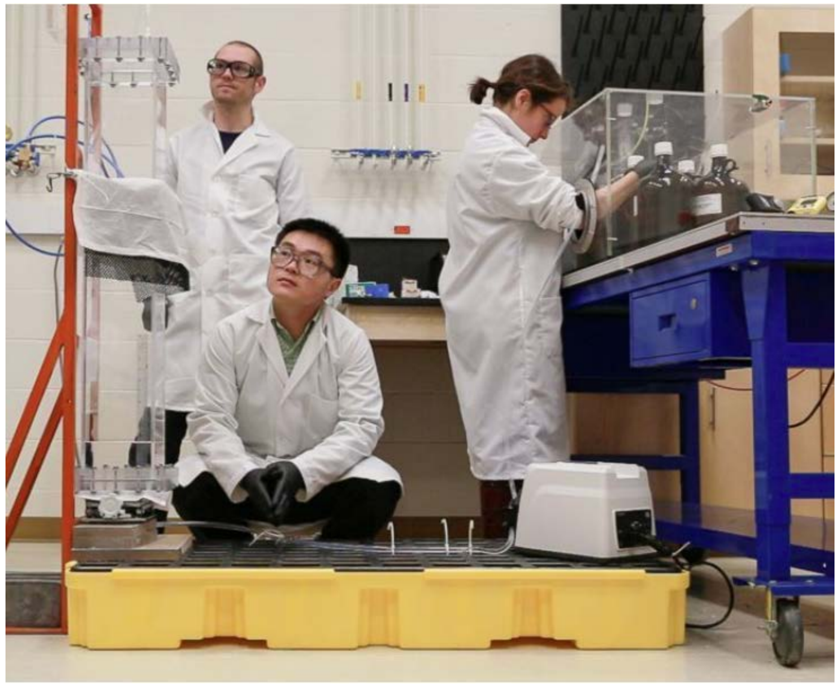


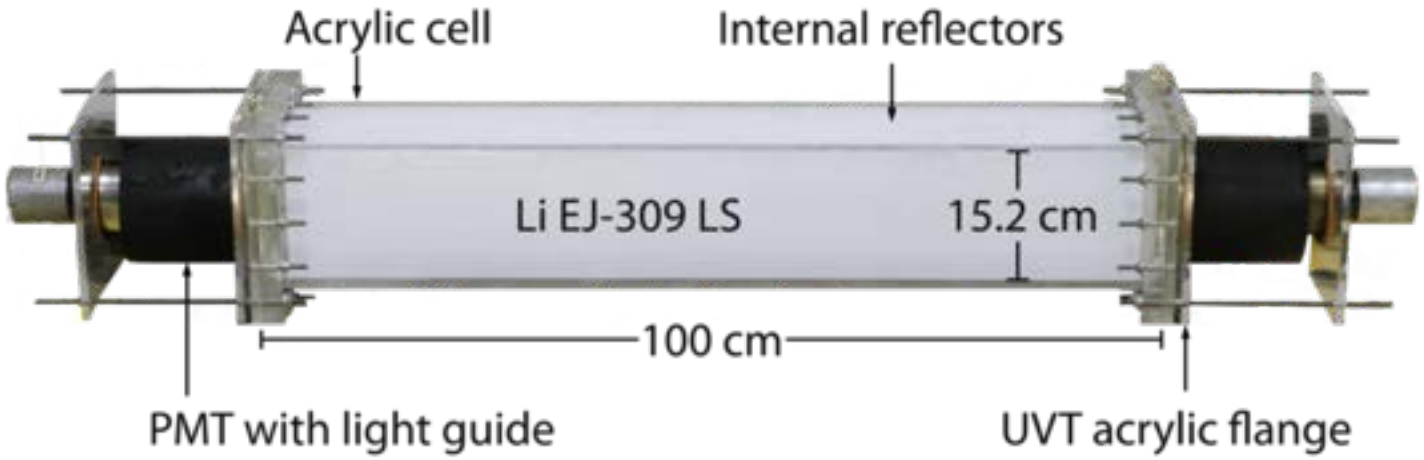
1mm thick

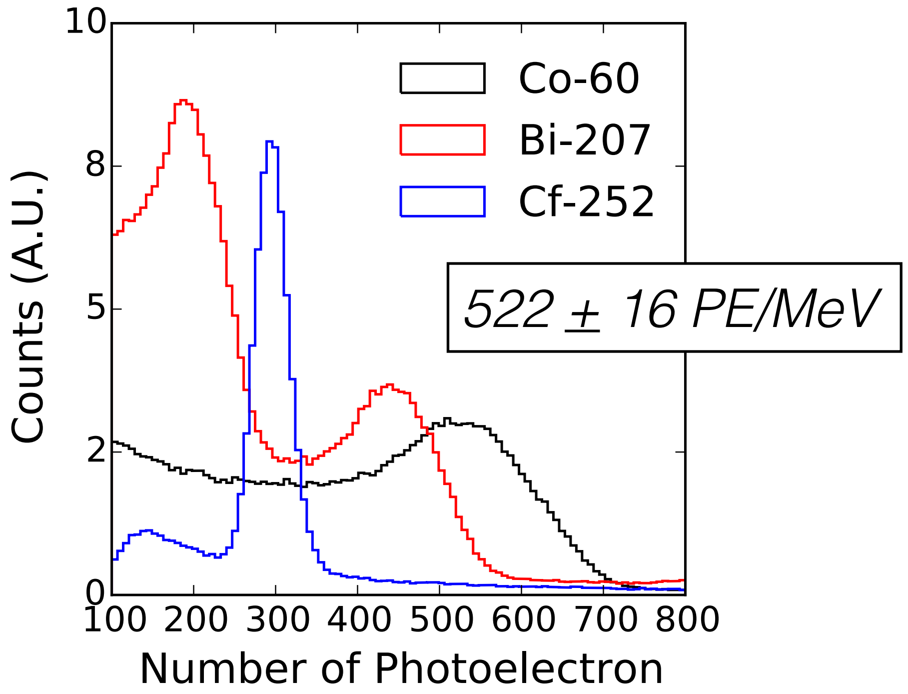


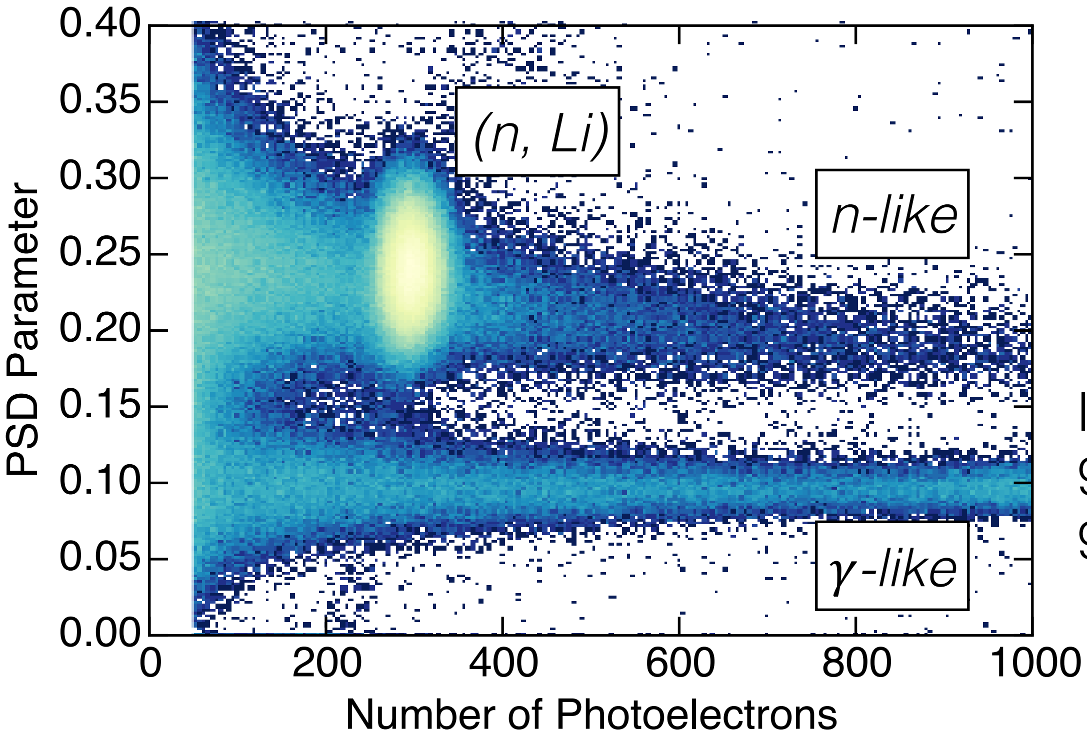
produced robust low-mass separators from LS-compatible materials

PROSPECT-20 segment studies









low energy (0.5-0.7MeV) :
99.99% rejection of γ
99% acceptance n events

LiLS with realistic geometry, above target light collection goal with excellent PSD

Simulation to benchmark prototype data

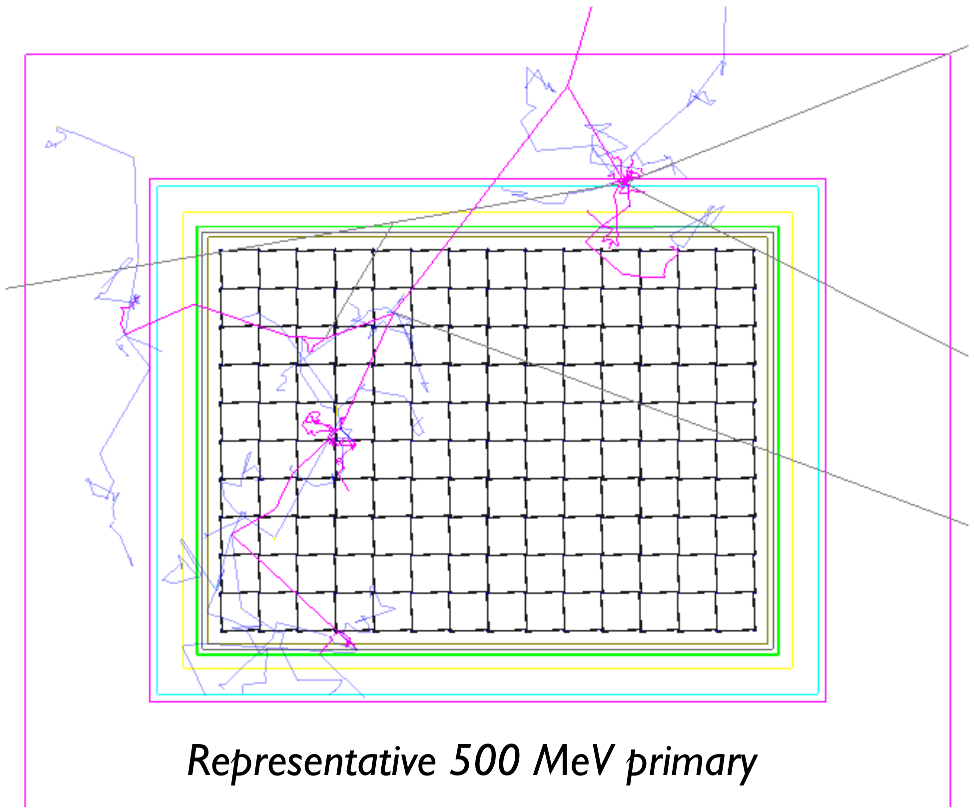
Simulations have been developed to meet distinct needs:

1. **Segment design**
   simulations further used to optimize light transport, shielding etc in context of science goals

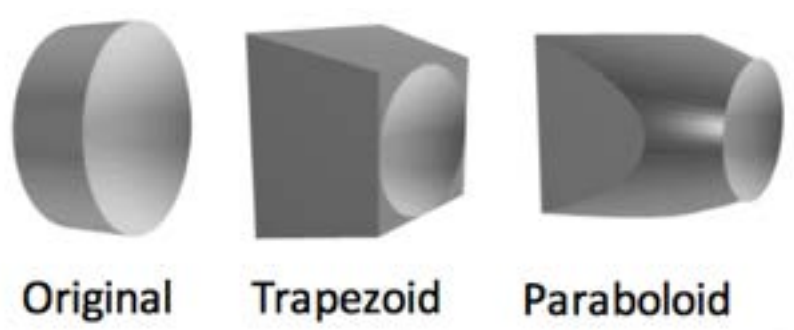
2. **Background mitigation**
   develop single flexible Monte Carlo, benchmark against prototypes, enable extrapolation to full detector

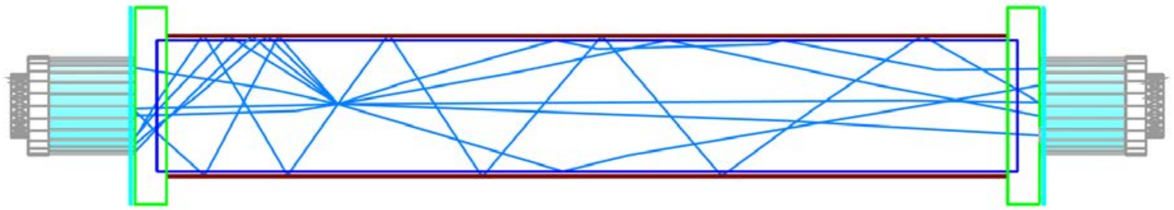
3. **Detector response**
   detailed model of detector response ensures PROSPECT has precision spectral measurement capability

Phase 1 cosmic neutron event



Representative 500 MeV primary





simulation of PROSPECT-20 with optical transport

prototyping program has enabled validation of mechanics, detector response, and simulation models

Simulation to benchmark prototype data

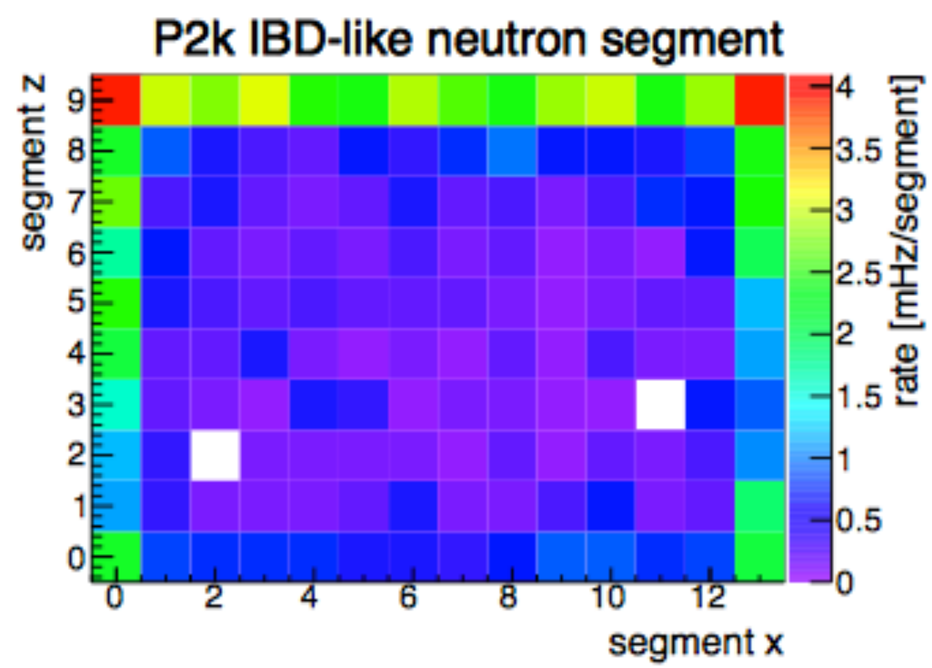
Simulations have been developed to meet distinct needs:

1. **Segment design**
   simulations further used to optimize light transport, shielding etc in context of science goals

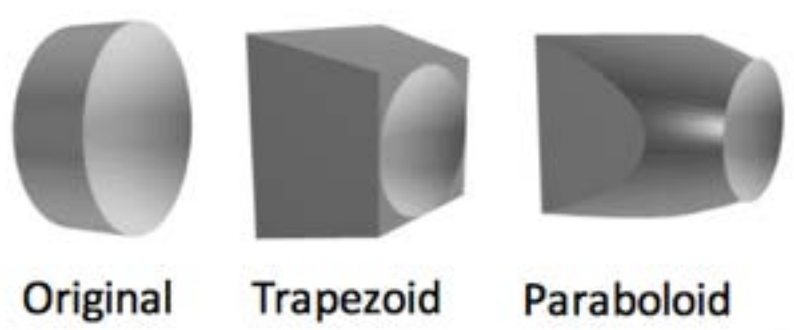
2. **Background mitigation**
   develop single flexible Monte Carlo, benchmark against prototypes, enable extrapolation to full detector

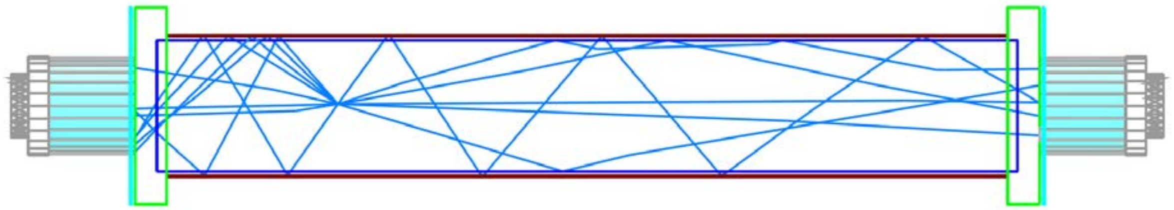
3. **Detector response**
   detailed model of detector response ensures PROSPECT has precision spectral measurement capability

power of fiducialization



Representative 500 MeV primary

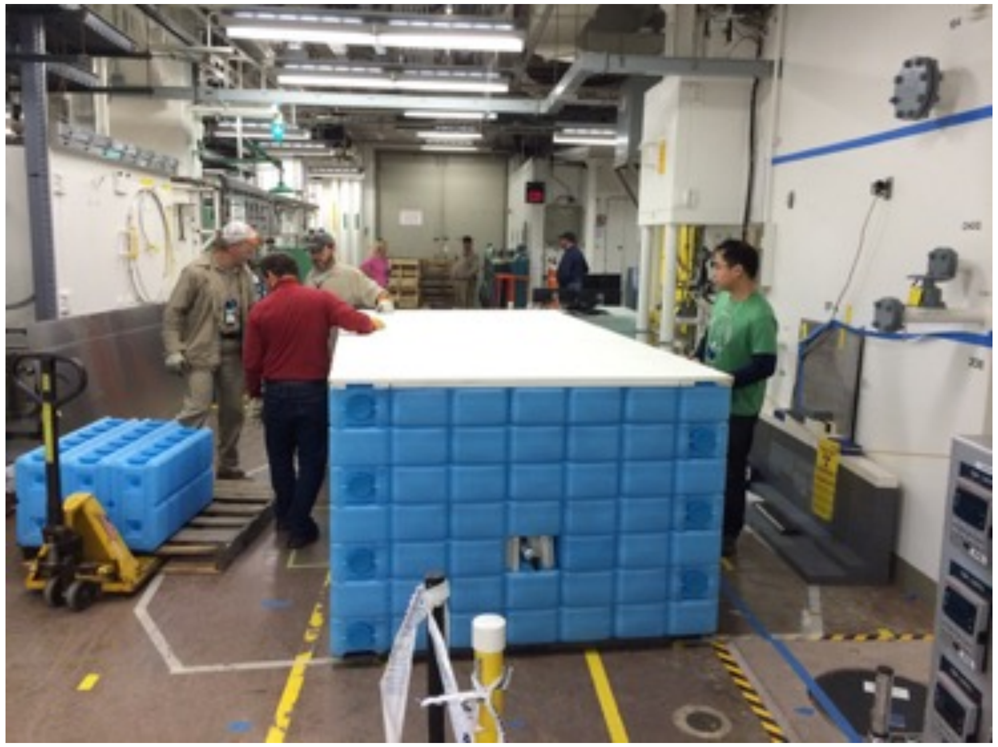


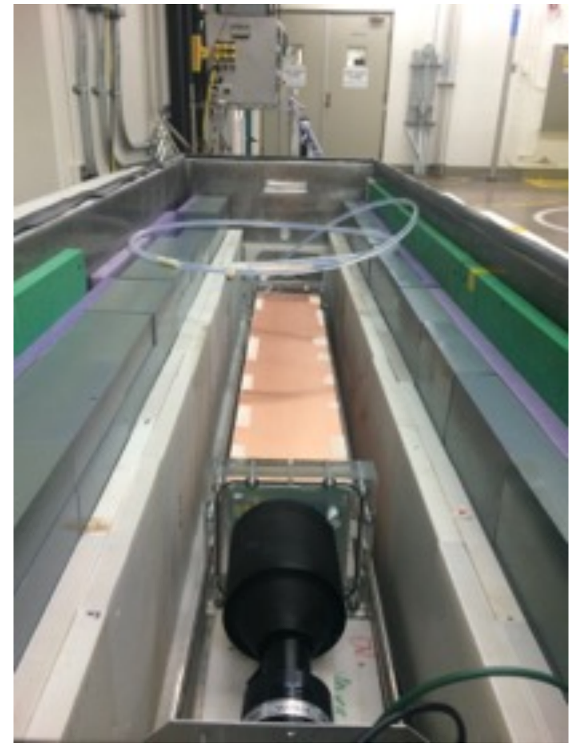


simulation of PROSPECT-20 with optical transport

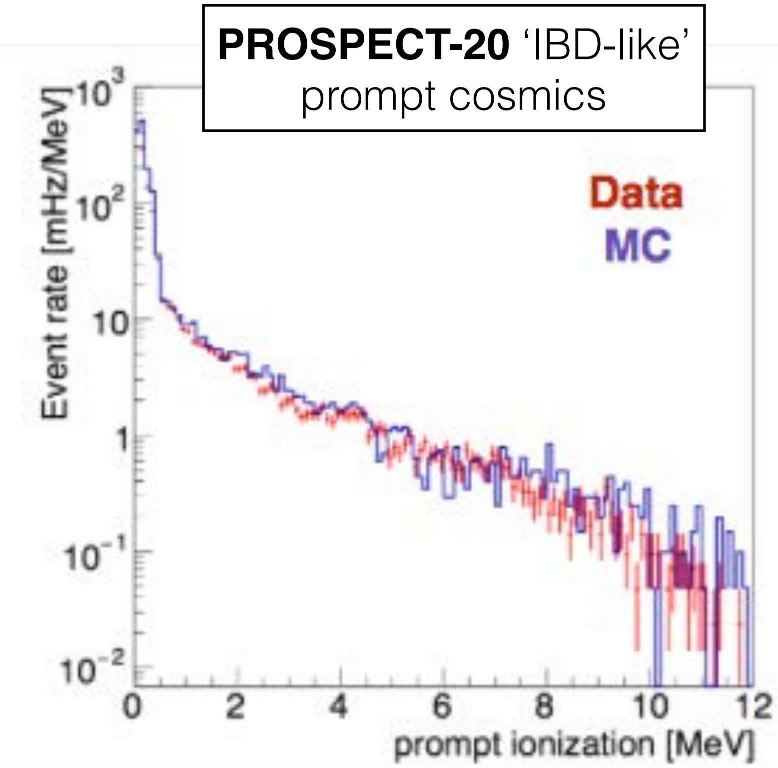
prototyping program has enabled validation of mechanics, detector response, and simulation models

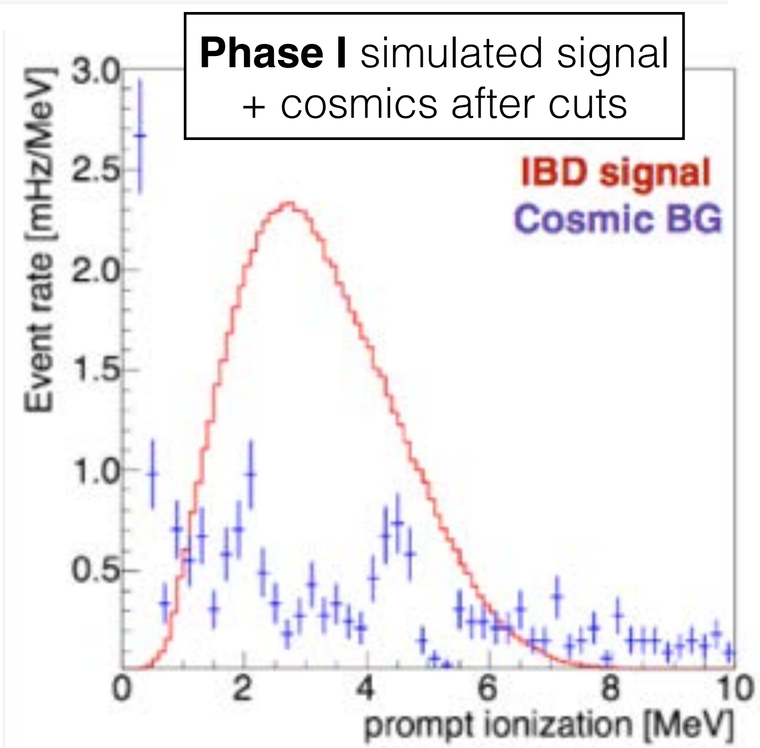
Validation of Monte Carlo from HFIR data





PROSPECT-20 at HFIR





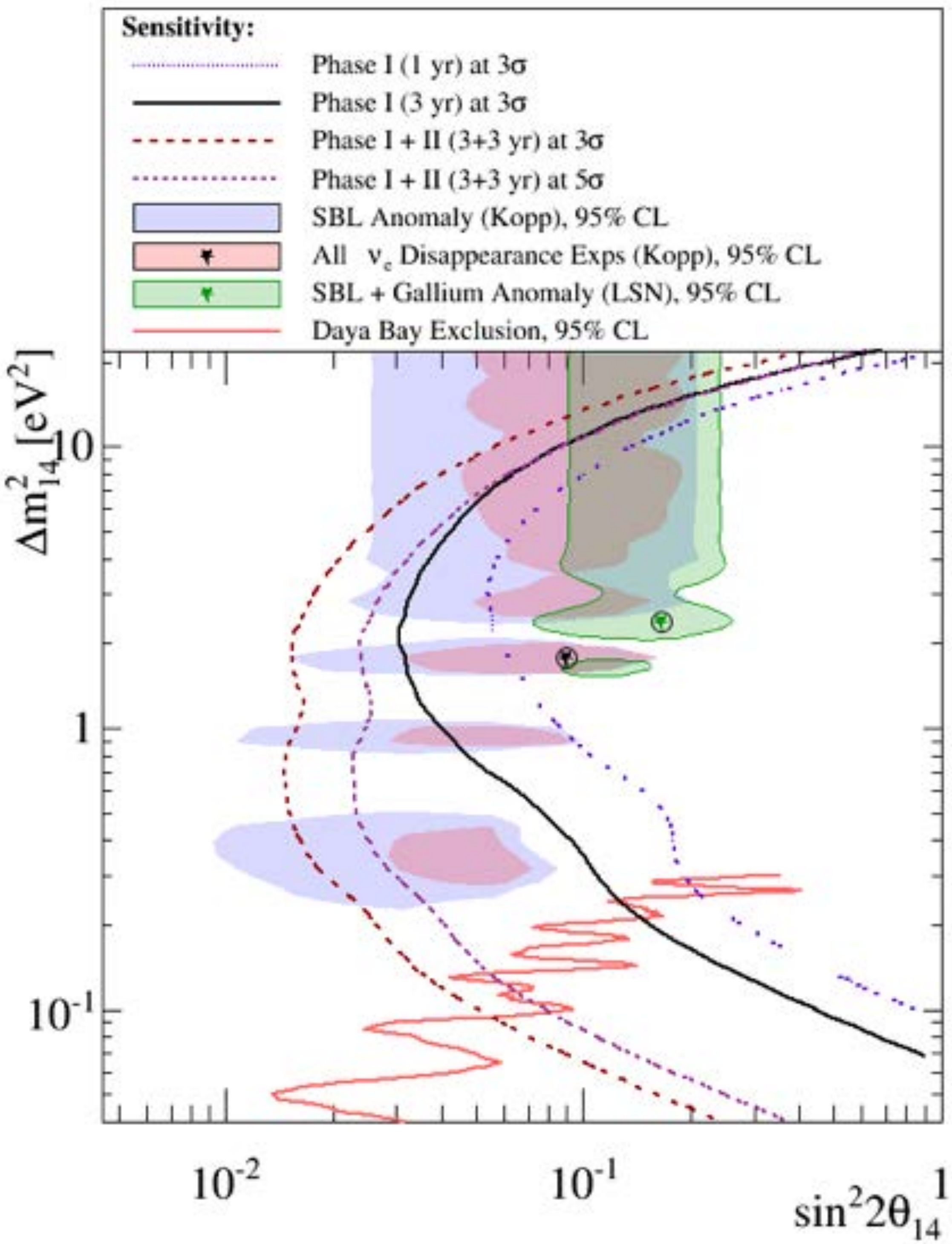
- PROSPECT-20 measured cosmic backgrounds during reactor-off
- PROSPECT-20 'simple' Monte Carlo agrees reasonably with data

- confident in extrapolating MC to Phase I detector
- after series of effective cuts, can reach S:B > 3:1
- surpasses physics goals target
- will measure these backgrounds during reactor-off time in Phase I

prototype deployment validated background MC to project Phase I S:B

PROSPECT Phase I physics reach

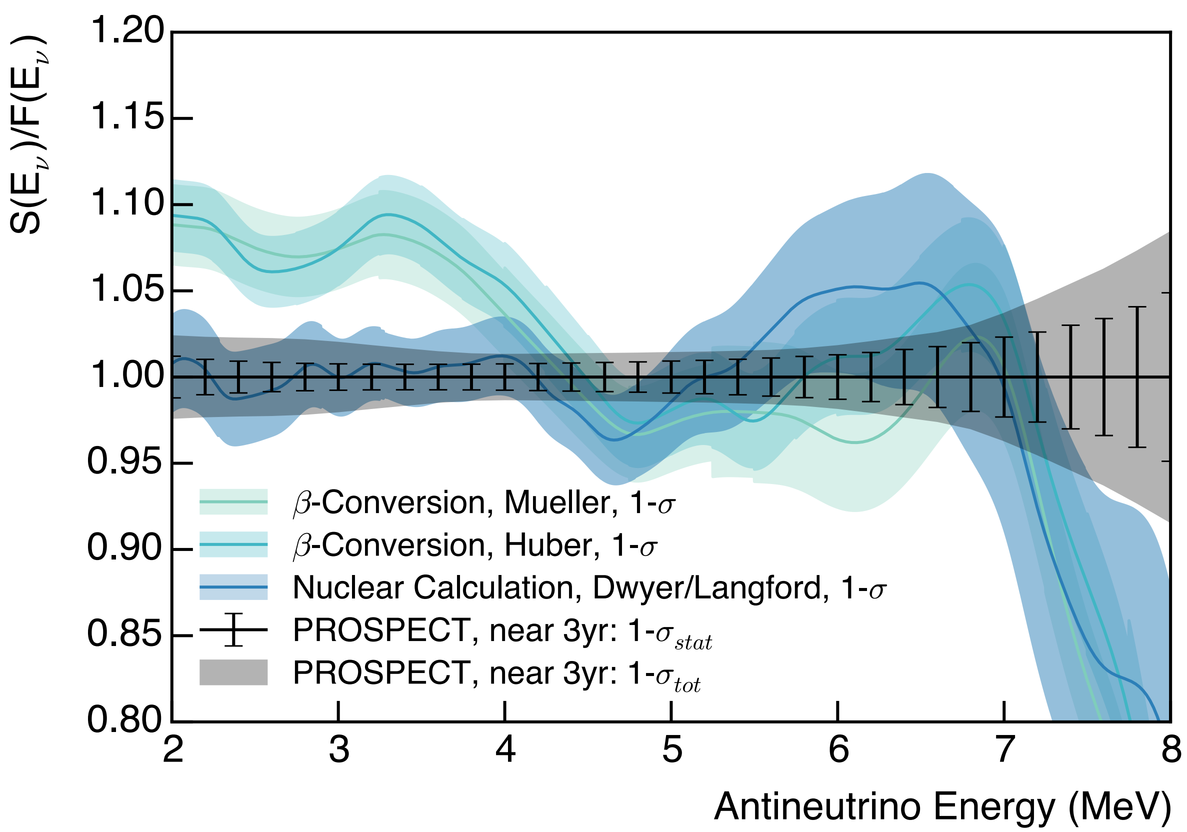
Sterile neutrino search



Sensitivity parameters:

- fiducialized volume: 8x10 segments
- segment fiducialization: 90x15x15 cm^3
- S:B: 3:1 for nearest position + Phase II
- energy resolution: 4.5%/√E
- position resolution: 15cm

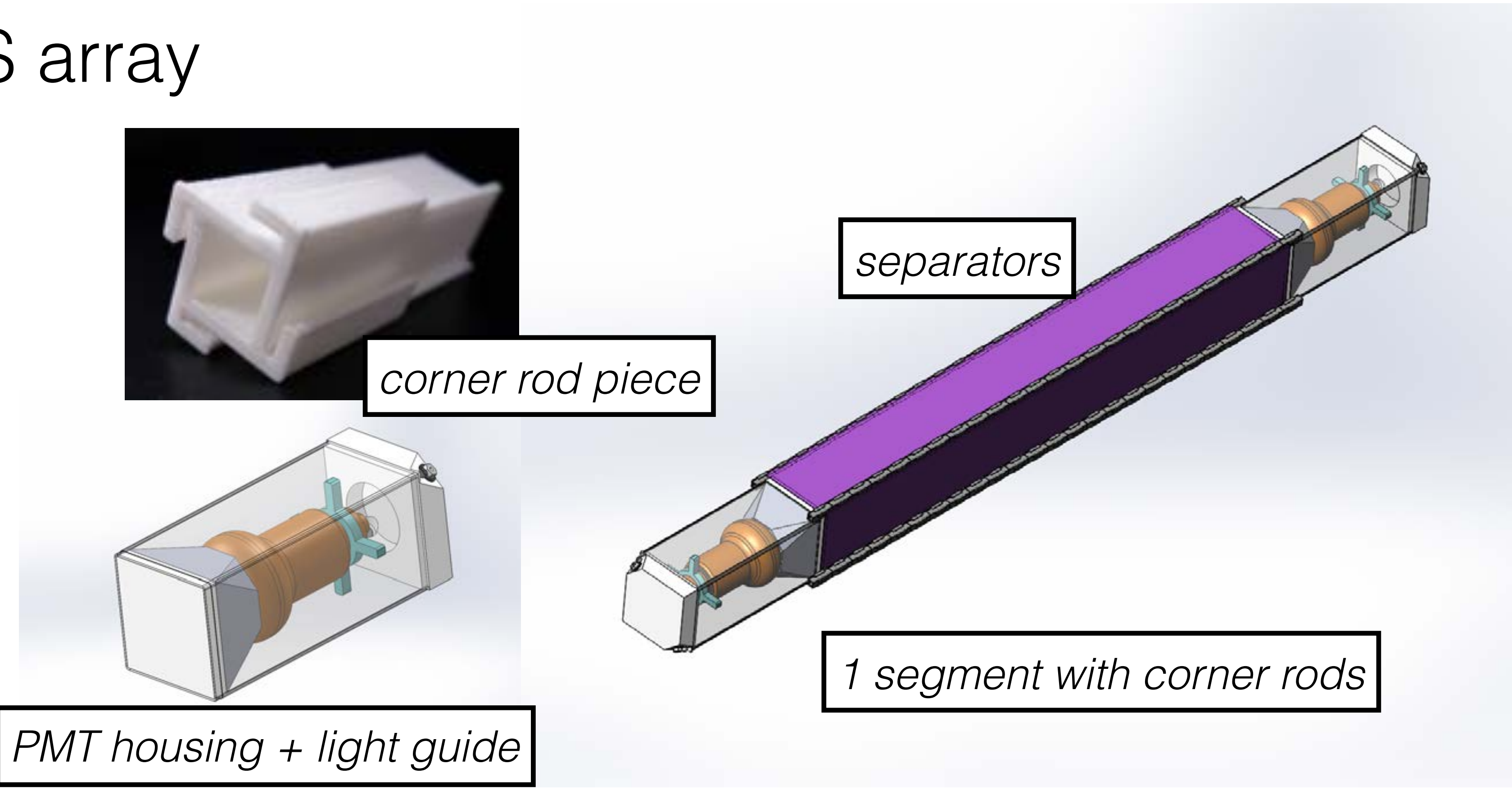
Spectral measurement



What we are currently working on

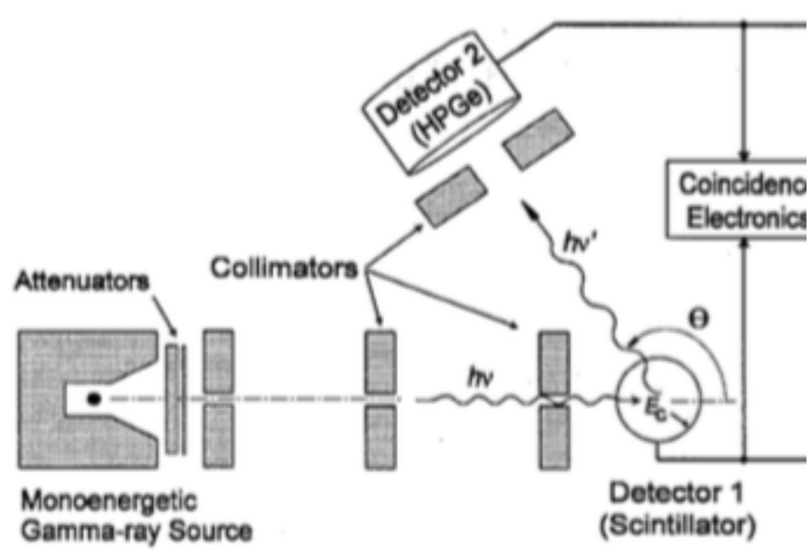
1. PROSPECT-60 1x2 LiLS array

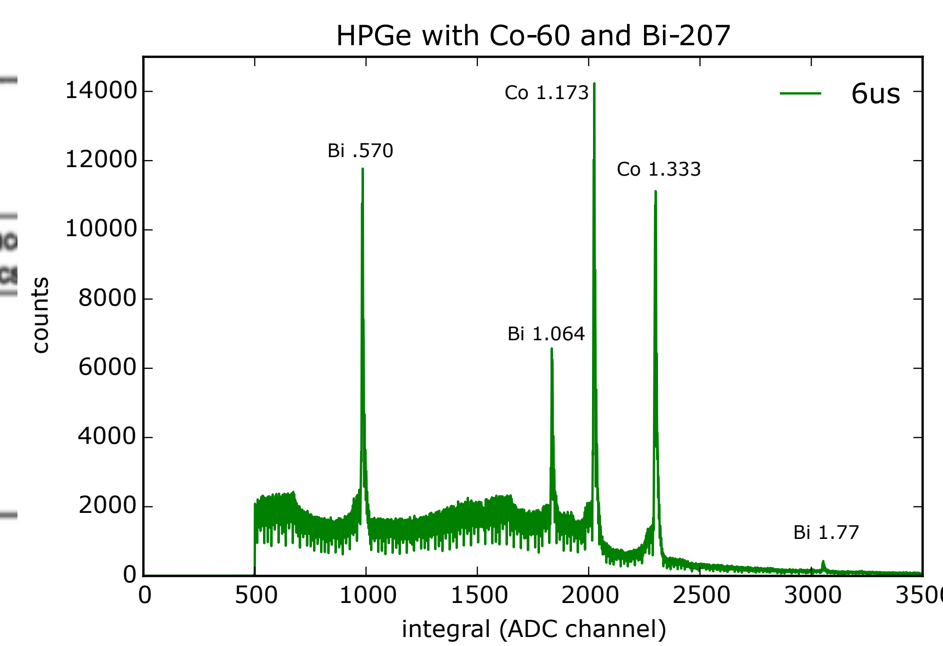
Mechanical prototype to validate detector components and test operation of subsystems.



2. LS nonlinearity measurements

Study non-linearities in scintillator at low energies using mono-energetic electrons using Compton coincidence spectrometer.

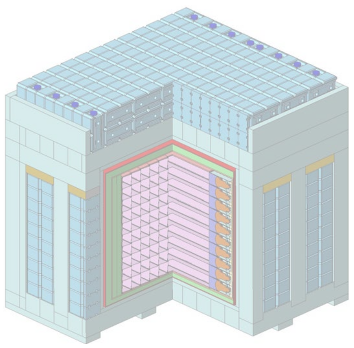




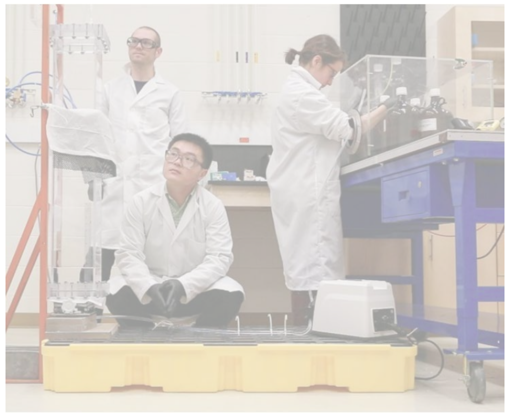
Outline

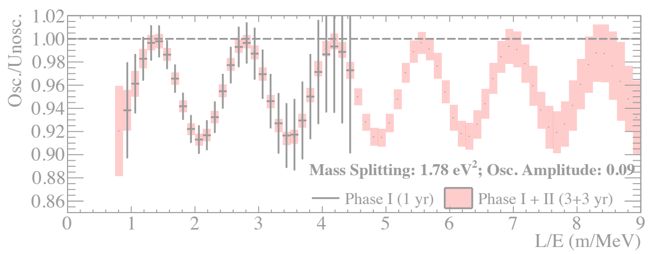
1. Introduction to neutrinos and neutrino anomalies

2. PROSPECT short baseline reactor experiment



3. PROSPECT Phase I program





4. Concluding remarks

Concluding statements

1. Anomalies have led to great discoveries in the history of neutrino physics.

2. The reactor anomaly entails both a flux deficit hinting at sterile neutrinos and a spectral deviation, the PROSPECT experiment can address both.

3. The PROSPECT R&D program has:
   - successfully deployed multiple prototype detectors
   - developed a detailed understanding of near-surface backgrounds at HFIR
   - developed technology required for the Phase I detector
   - produced simulation models validated against prototype data

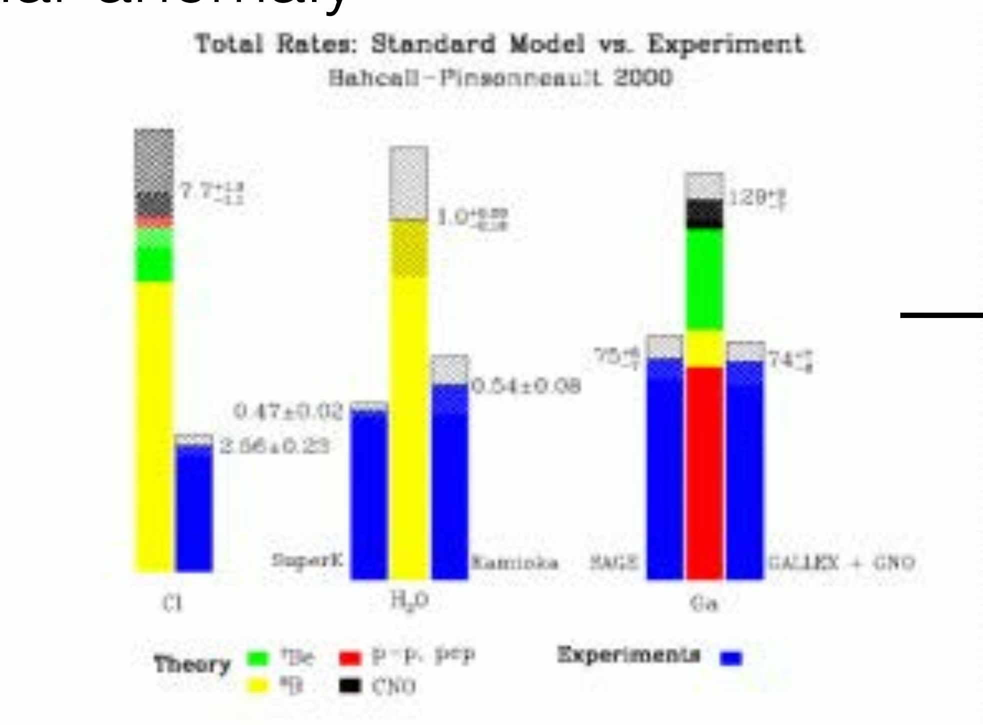
4. PROSPECT Phase I is ready to proceed with precision ^{235}U spectrum measurement and cover the sterile global best fit in 1 calendar year at 3σ

The PROSPECT Collaboration

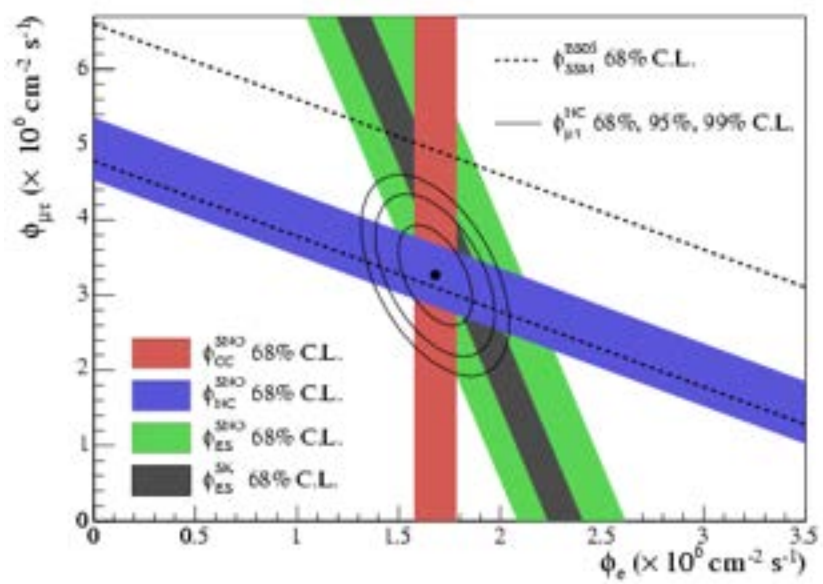
4 national laboratories | 9 universities | 63 collaborators | prospect.yale.edu

Anomalies lead to discoveries

solar anomaly



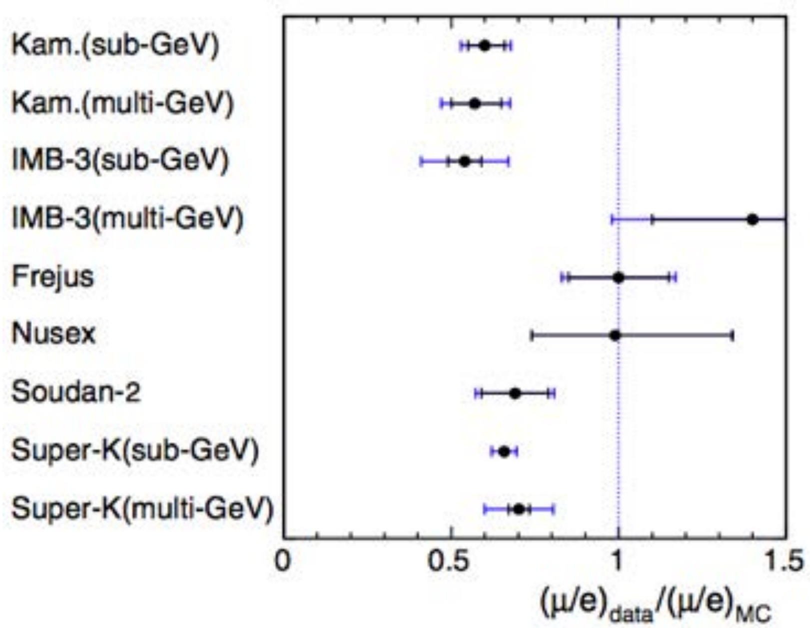
SNO 2001



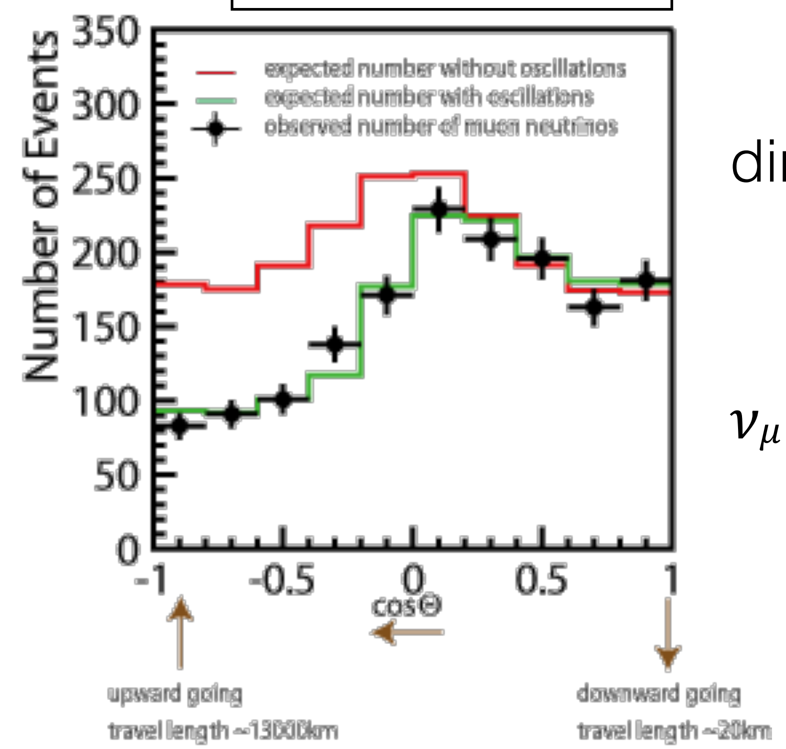
detected all flavors

total matches solar prediction

atmospheric anomaly



Super-Kamiokande 1998



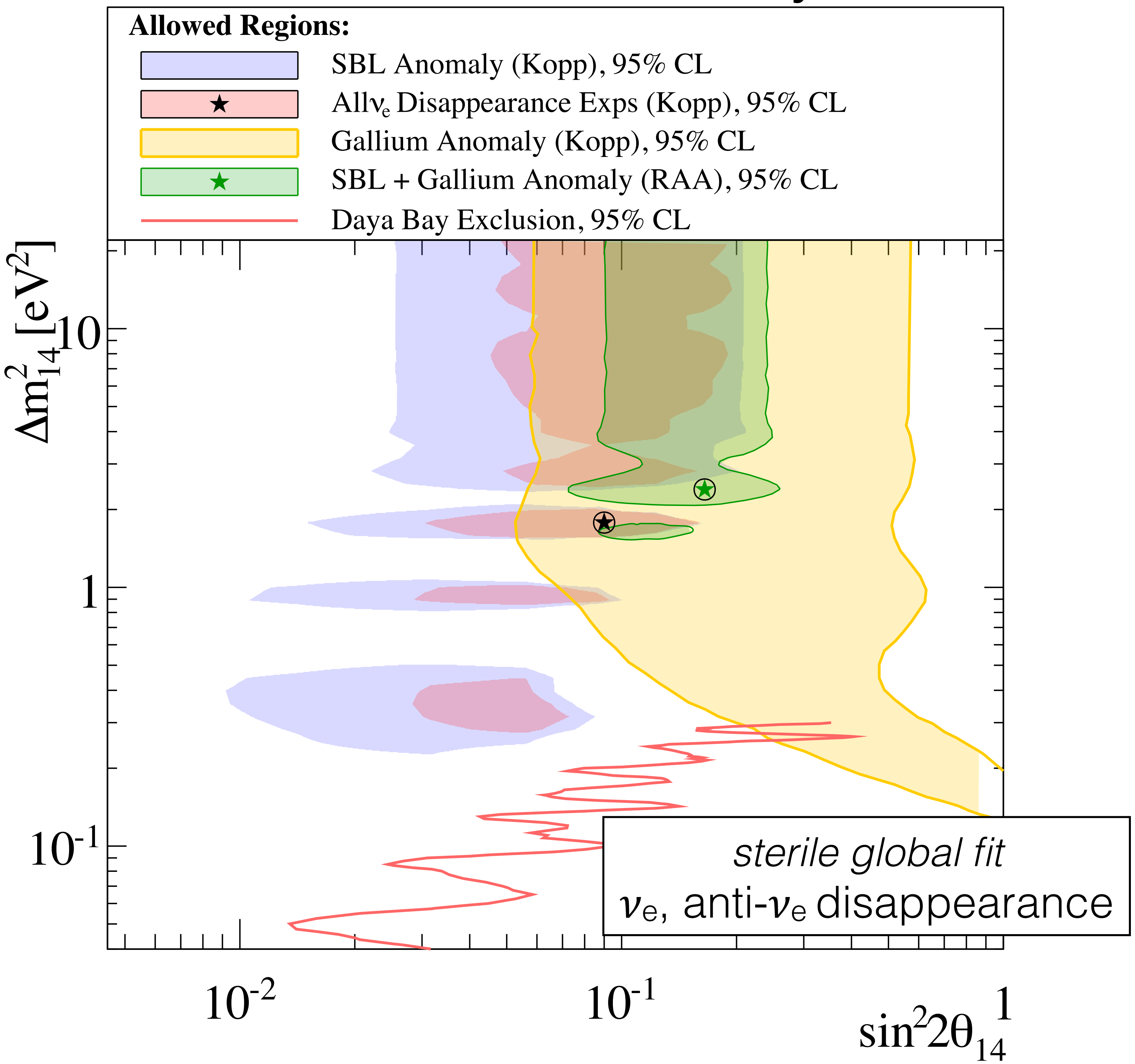
directional info

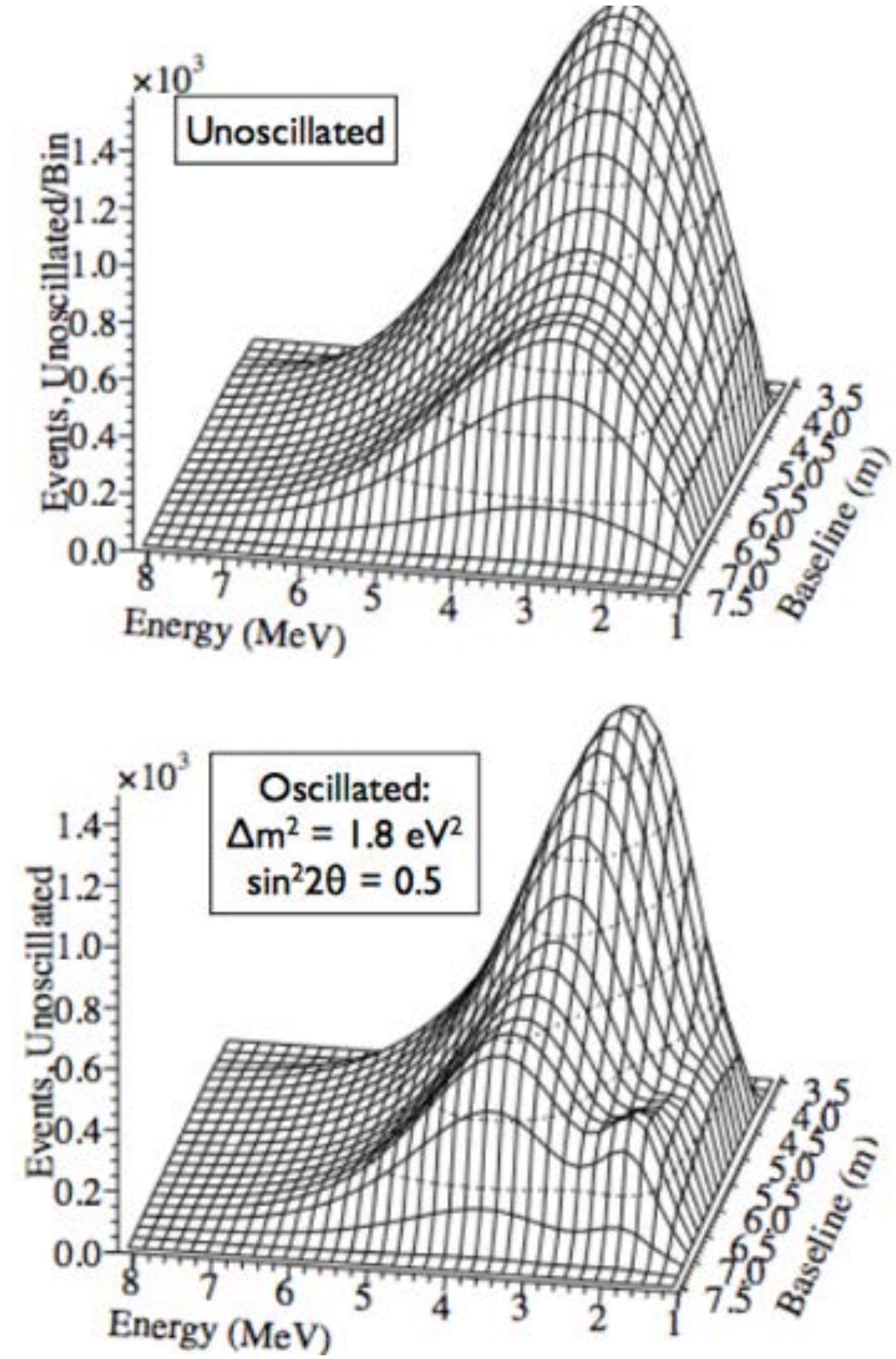
$\nu_\mu \rightarrow \nu_\tau$ oscillation

T. Kajita, New J. Phys. 6 (2004) 194

Where to look for sterile neutrinos?

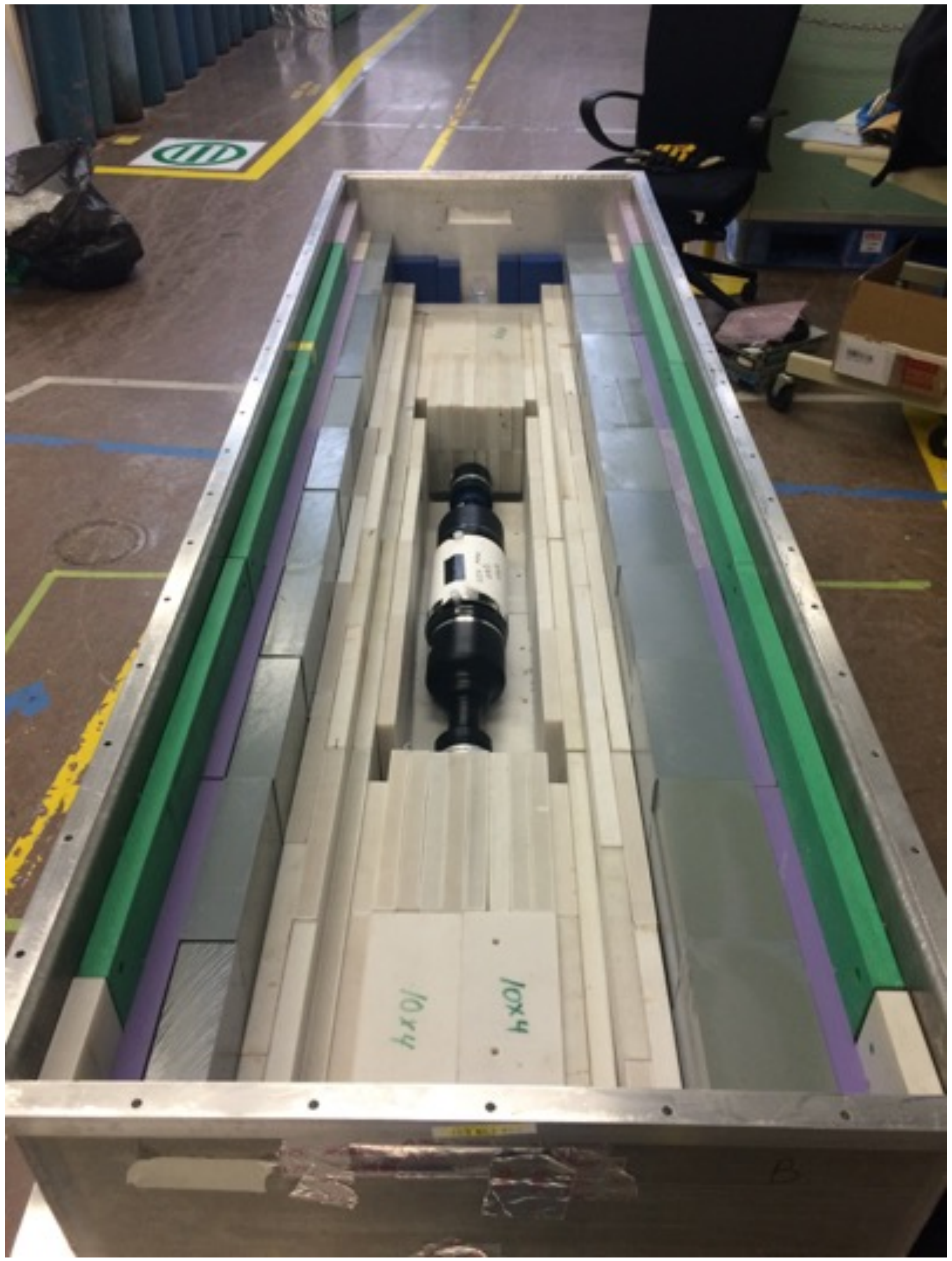
Reactor anomaly





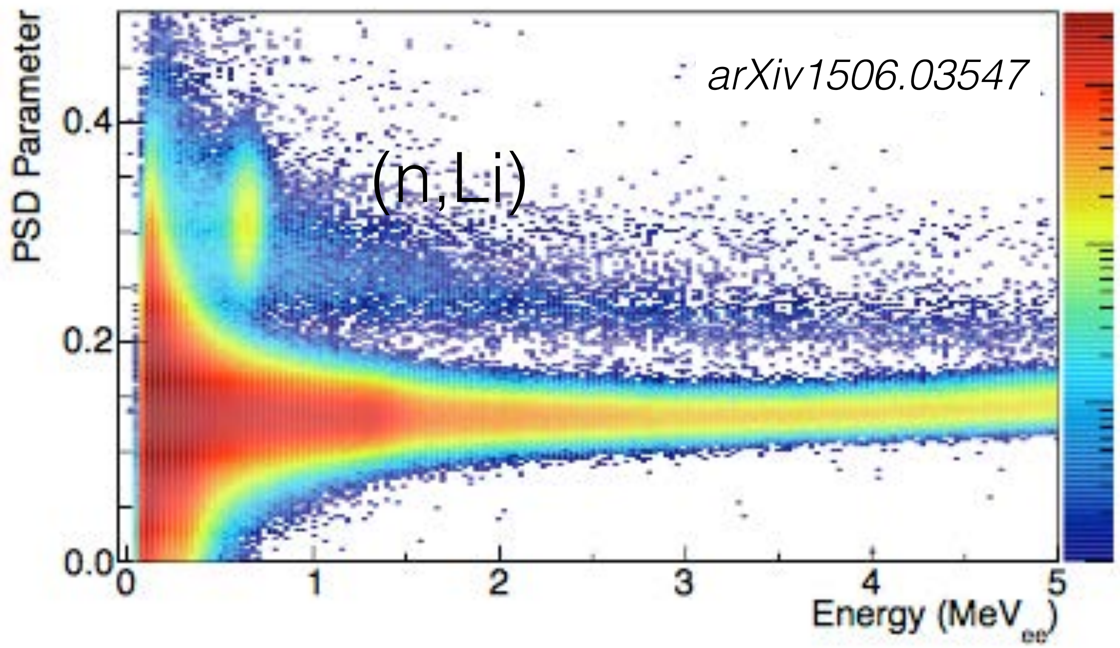
PROSPECT: Hands-on science

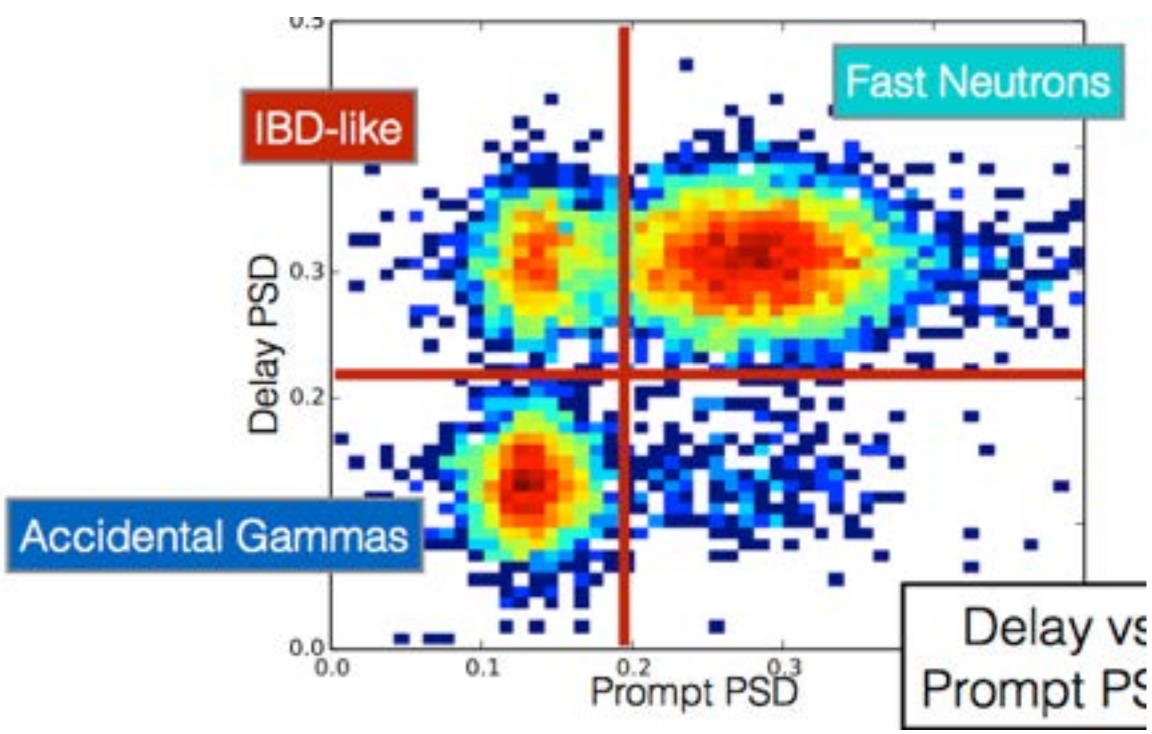
Back-up: PROSPECT-2 at HFIR



Detector geometry: 1.7L cylinder
Scintillator: Li-loaded EJ-309
PMTs: 5” flat ET9823
Shielding: poly, Pb, Bpoly
Reflectors: diffuse Gore
DAQ: CAEN 1720 (12bit)
Purpose: background reduction method

PROSPECT-2 at HFIR



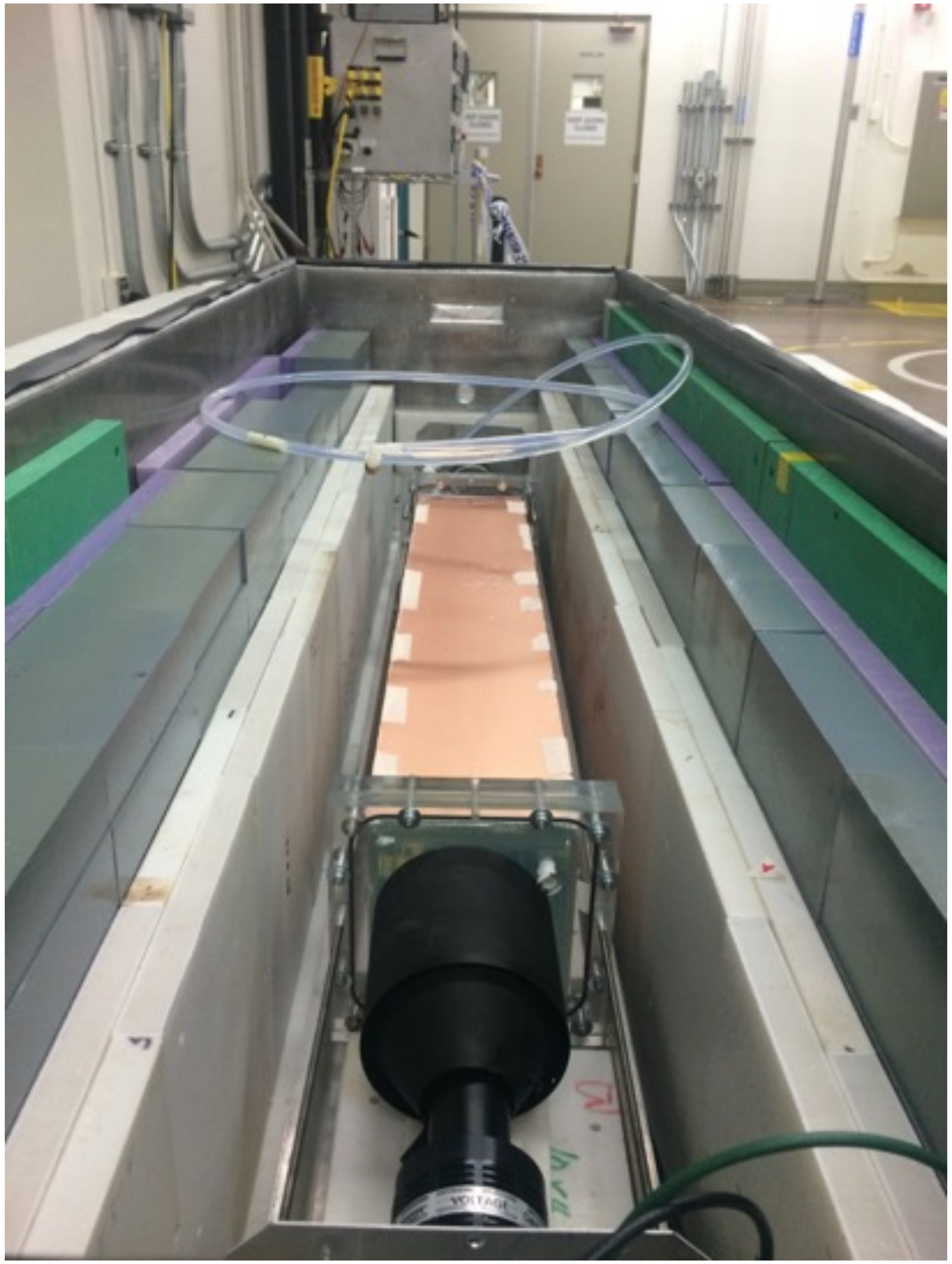


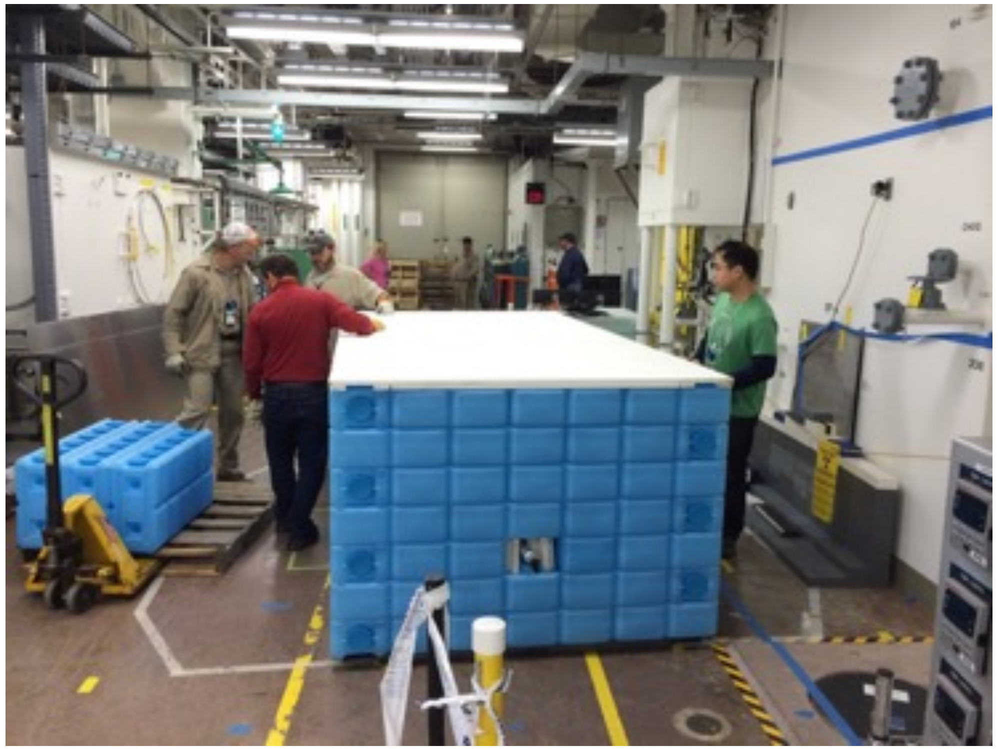
Coincidence analysis:

- cosmogenic fast neutrons (real)
- cosmogenic showers (multiple captures)
- reactor-related gammas (accidental)

PSD cuts on prompt and delayed signals rejects many of these backgrounds.

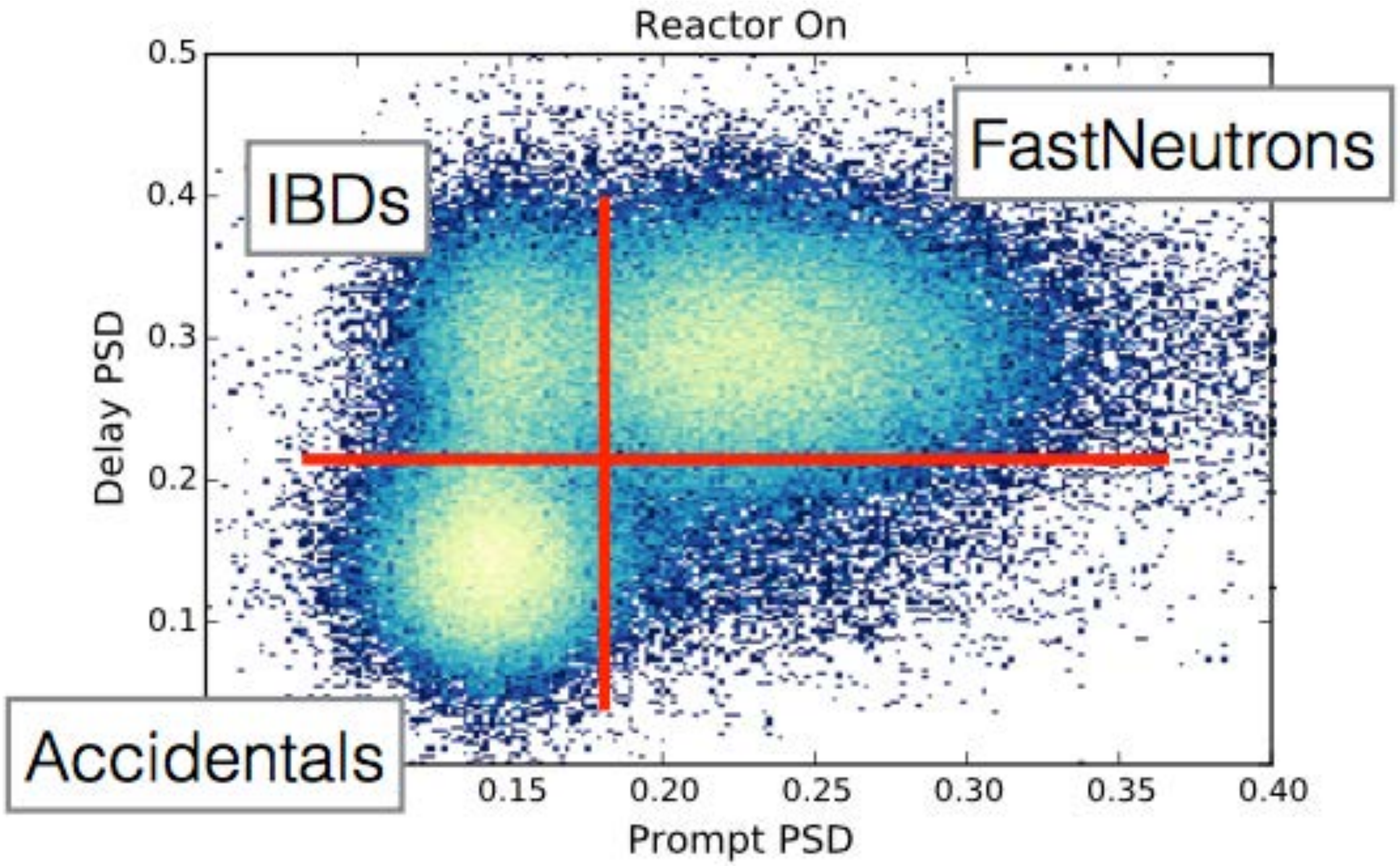
Back-up: PROSPECT-20 at HFIR

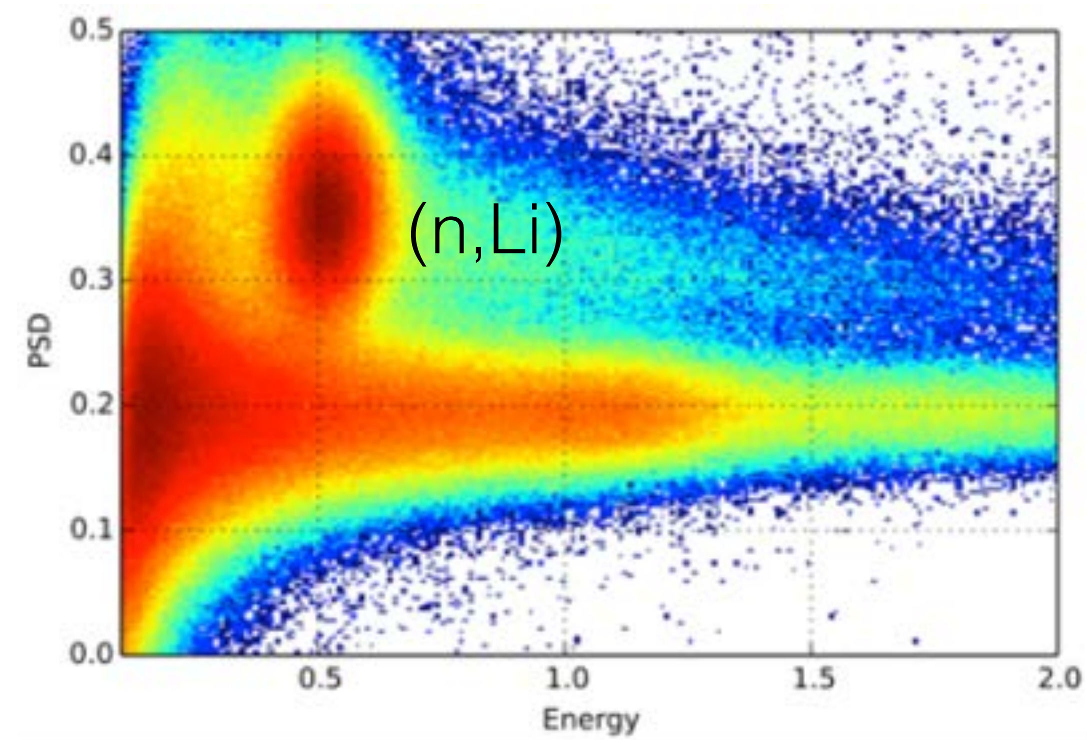


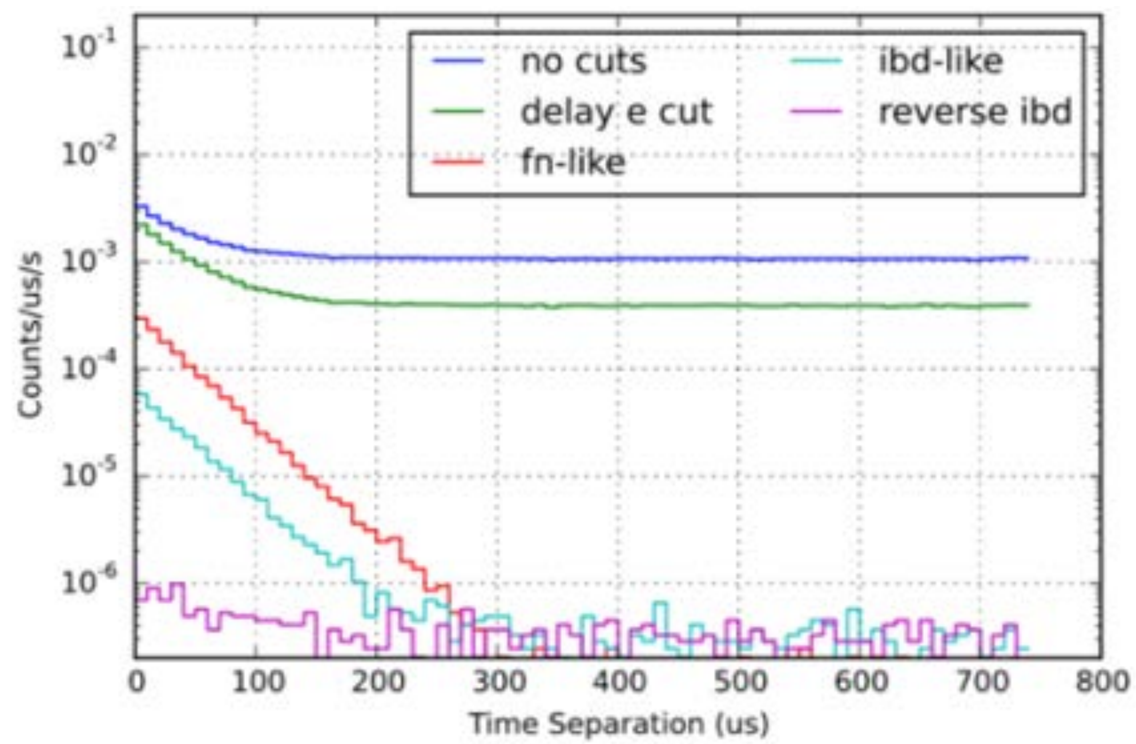


Detector geometry: 23L 1-meter rectangle
Scintillator: Li-loaded EJ-309
PMTs: 5” flat ET9823
Shielding: poly, Pb, Bpoly, water bricks
Reflectors: 3M SolarMirror
DAQ: CAEN 1720 (12bit)
Purpose: Operate full PROSPECT segment

PROSPECT-20 at HFIR







Accidentals reduced significantly with energy and PSD cuts.

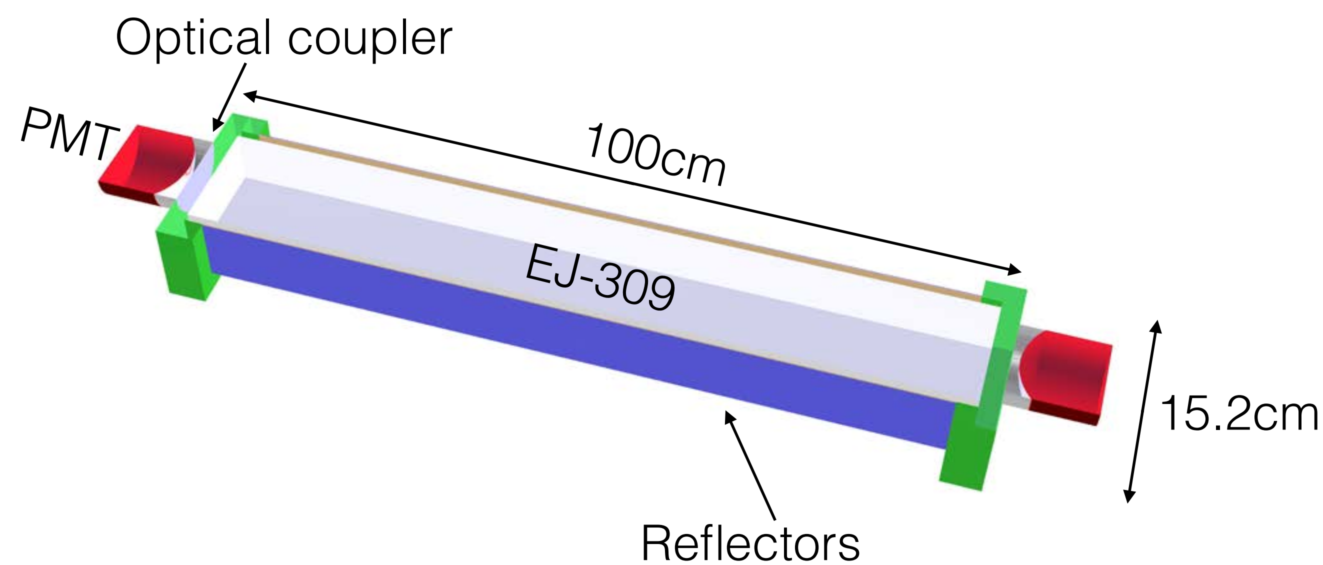
Back-up: PROSPECT-20 at Yale

Optics optimization studies:

- Reflector type
- Reflector coupling
- PMT read-out
- Compare to simulation

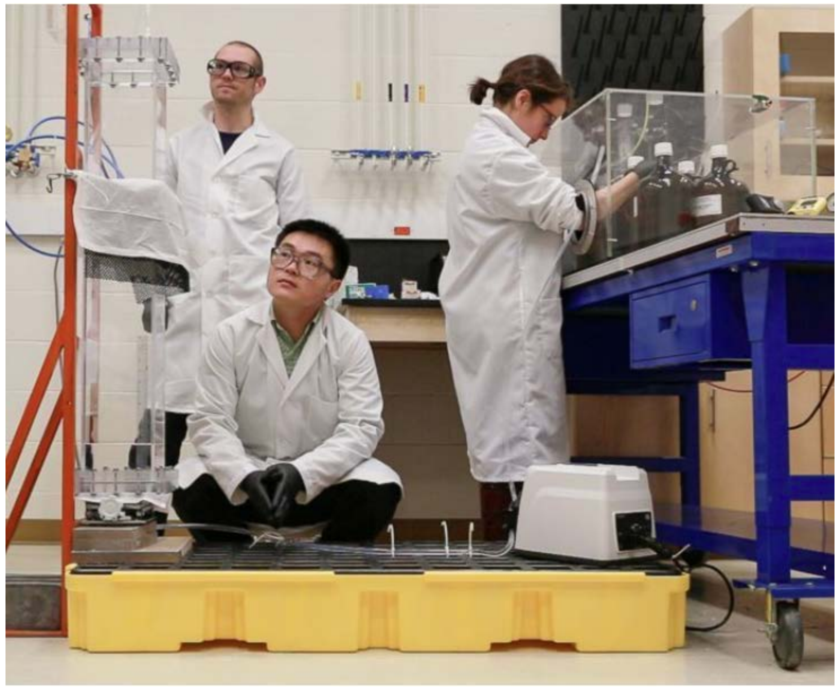
Soon to come:

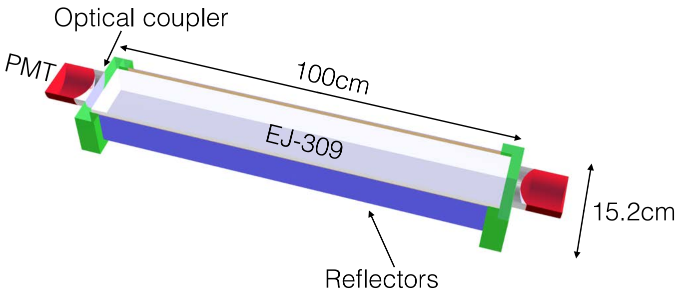
- Optical coupler geometries
- Li-loaded EJ-309

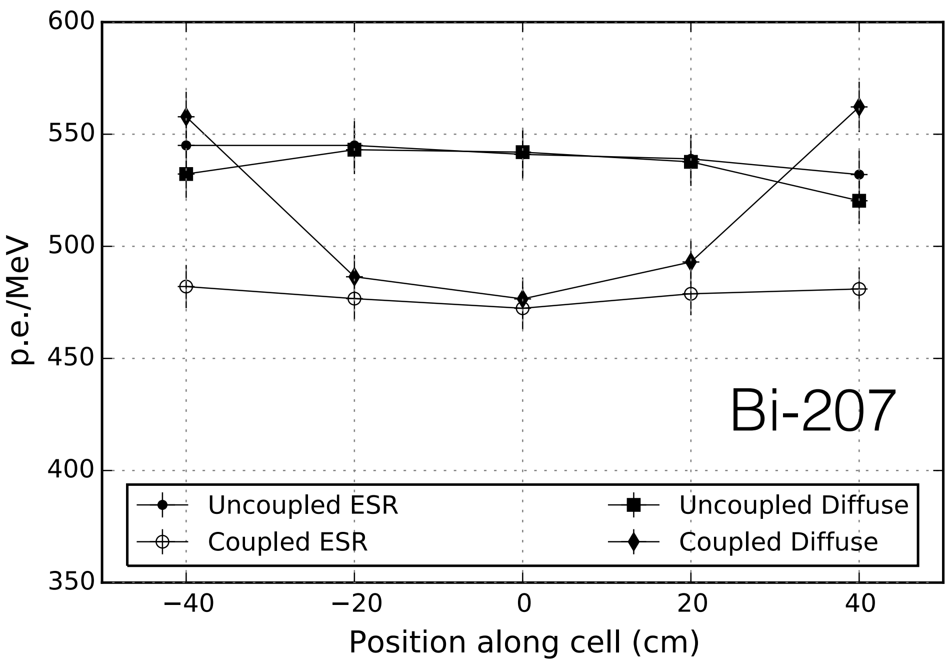


Detector geometry: 23L 1-meter rectangle
Scintillator: EJ-309
PMT(s): 5” spherical Hamamatsu R6594
Shielding: Pb
Reflectors: variable
DAQ: CAEN 1730 (14bit)
Purpose: optimize optics of full segment

Segment response: light collection and PSD studies







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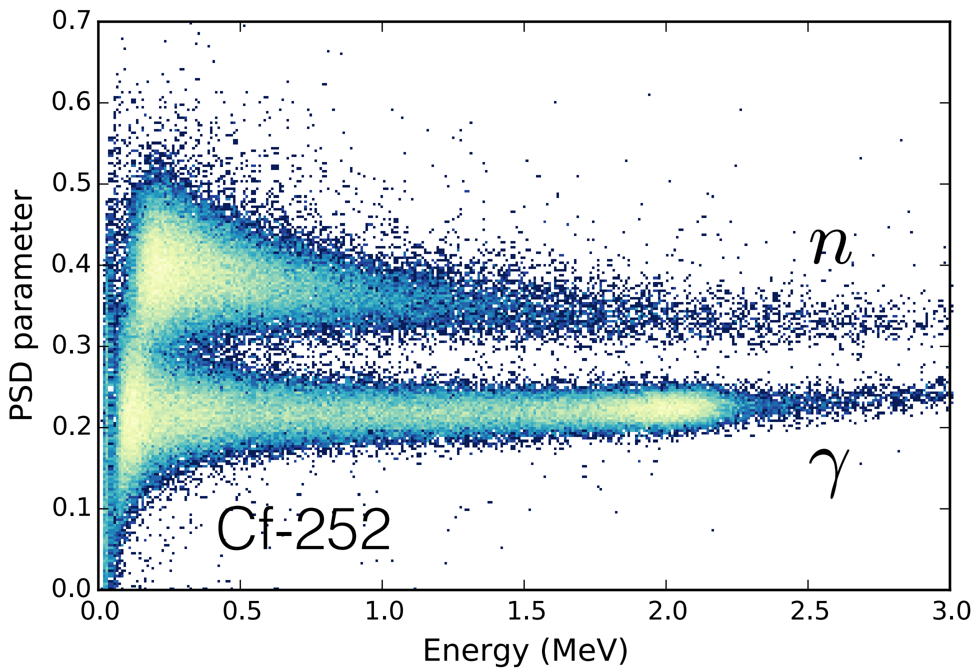


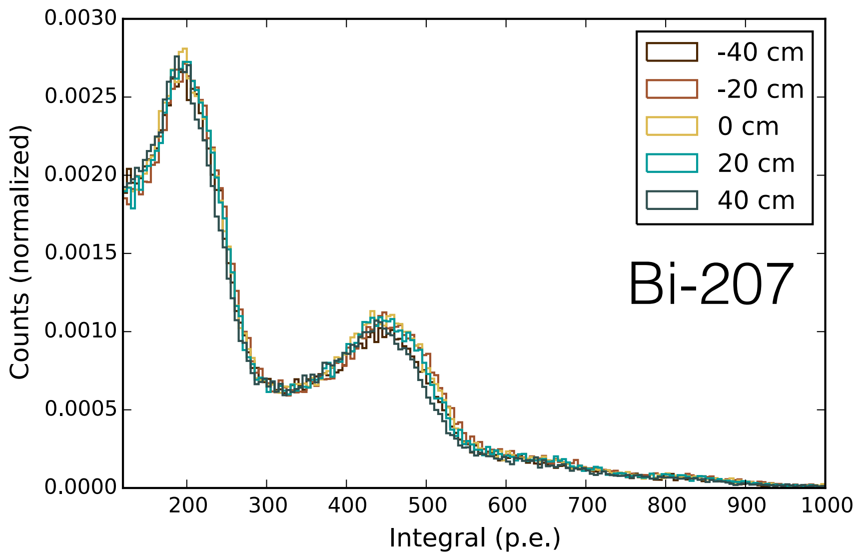
PROSPECT-20atYale (EJ-309):

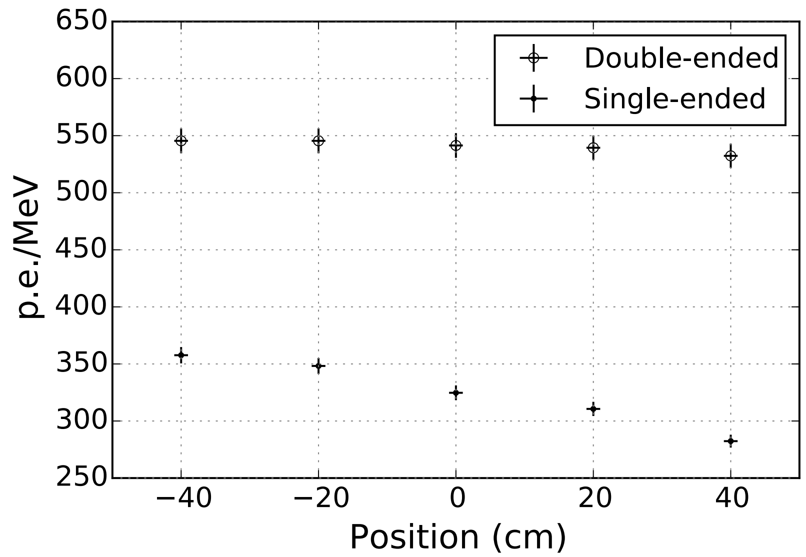
- optimize collection, PSD with air-coupled specular *external* separators
- average light collection: 527$\pm$ 10 photoelectrons/MeV
- low energy PSD (0.5-0.7MeV) allows for 99.99% rejection of γ, 99% acceptance n events
- *can improve geometry using internal separators*

excellent PSD is obtained in realistic geometry at target light collection of 500pe/MeV

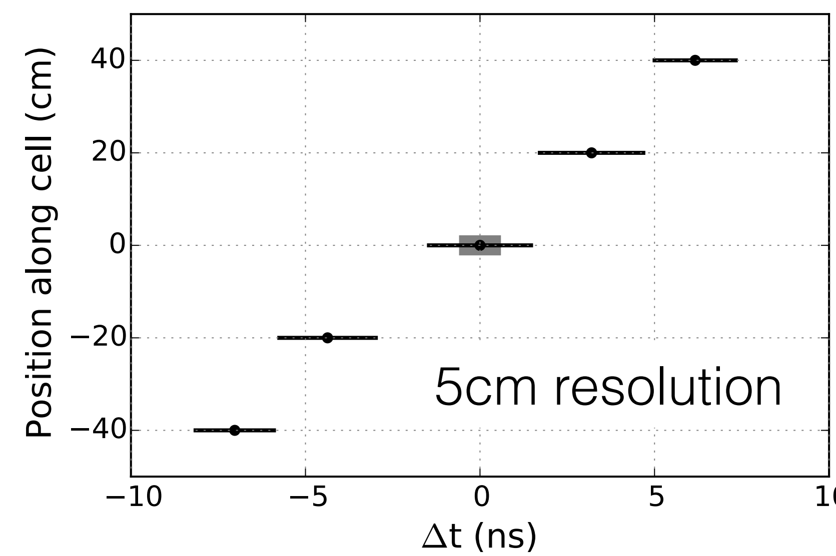
Segment response: double-ended readout

light collection measurements

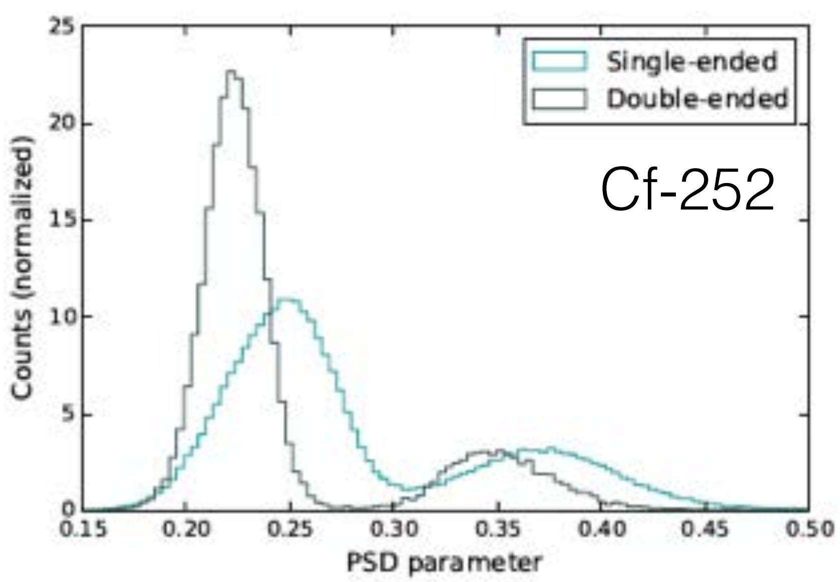


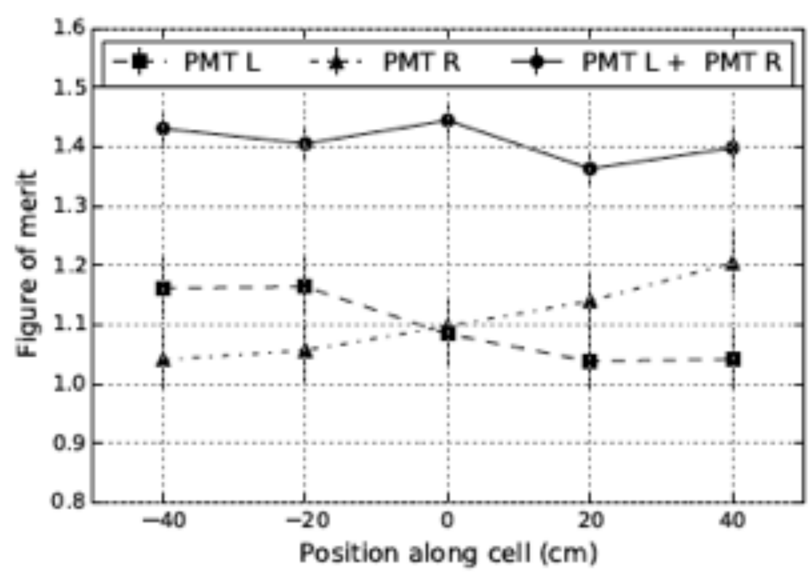


position reconstruction (timing)



pulse-shape discrimination





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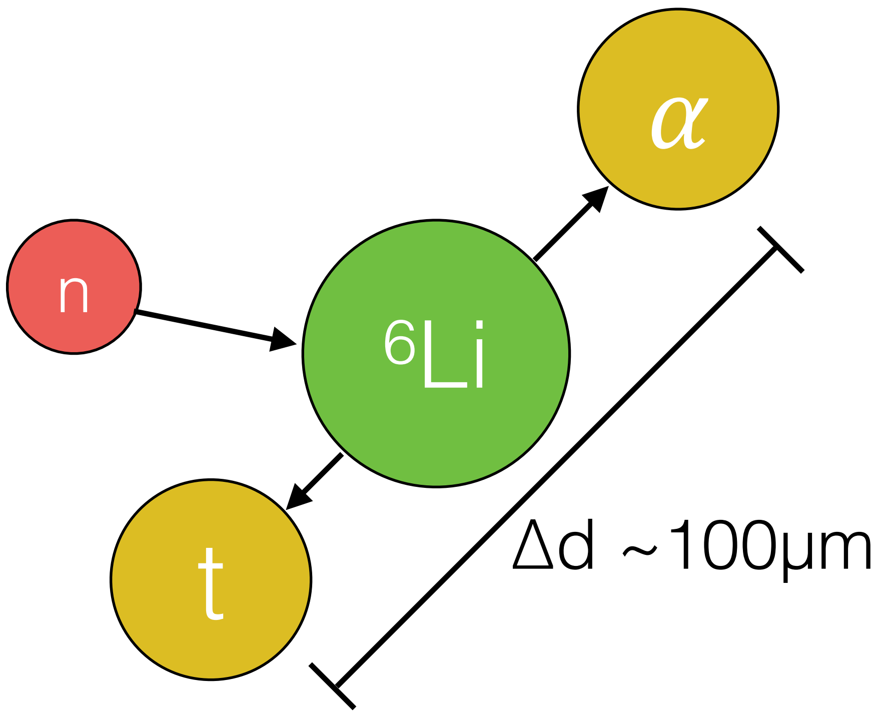
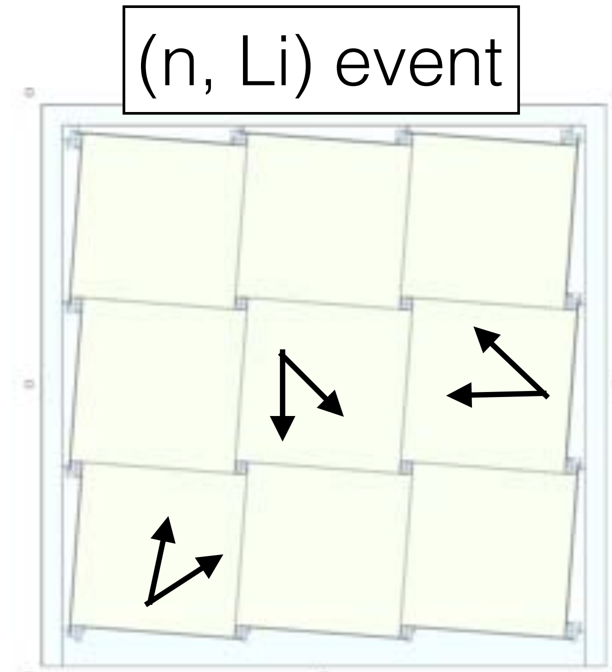
double-ended readout allows for uniform optical collection, enhanced PSD, and axial position resolution

Lithium dopant in liquid scintillator

1. Small detectors that do not have full calorimetry information. But, neutron capture on ^6Li allows for single-site topology.

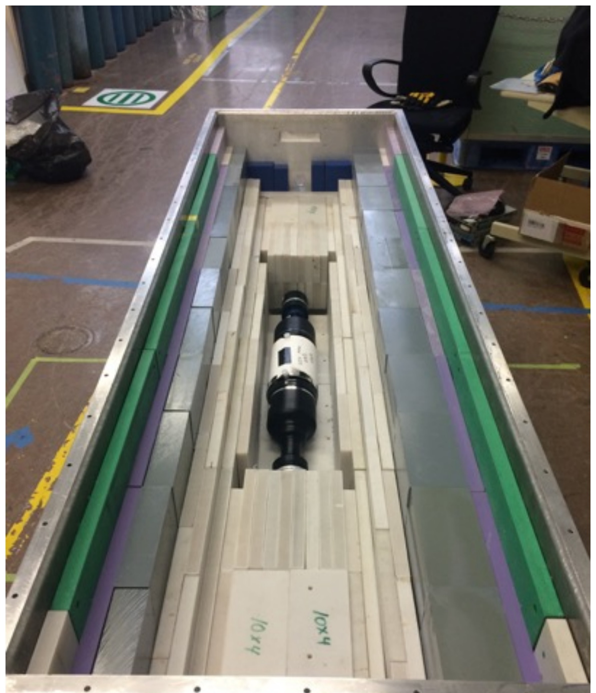




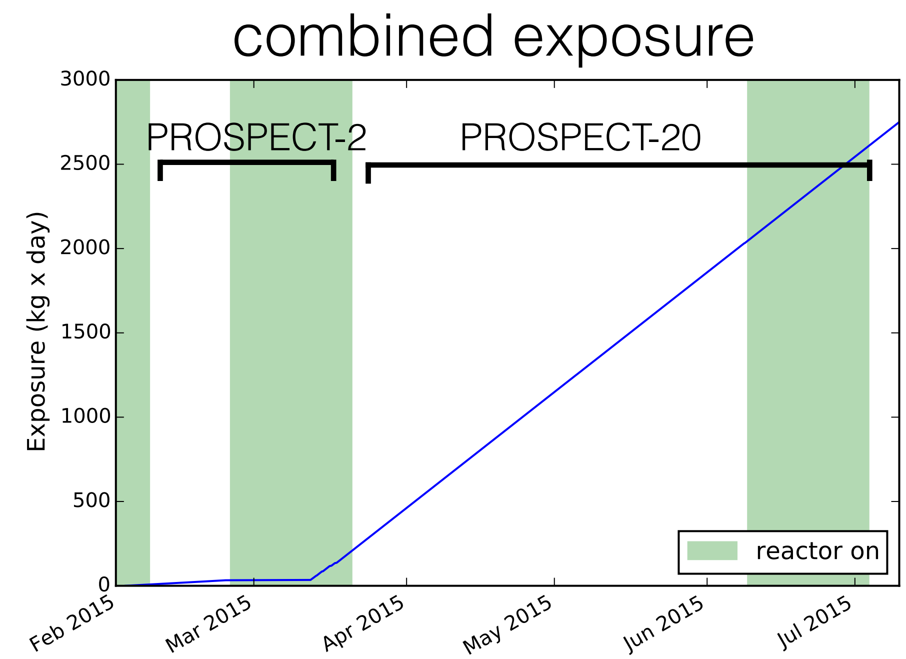
2. PROSPECT will be in a high gamma environment, with energies ranging from 1-10MeV. This background will not interfere with neutron captures since (n, Li) events fall in the "n-like" pulse shape discriminate (PSD) band.

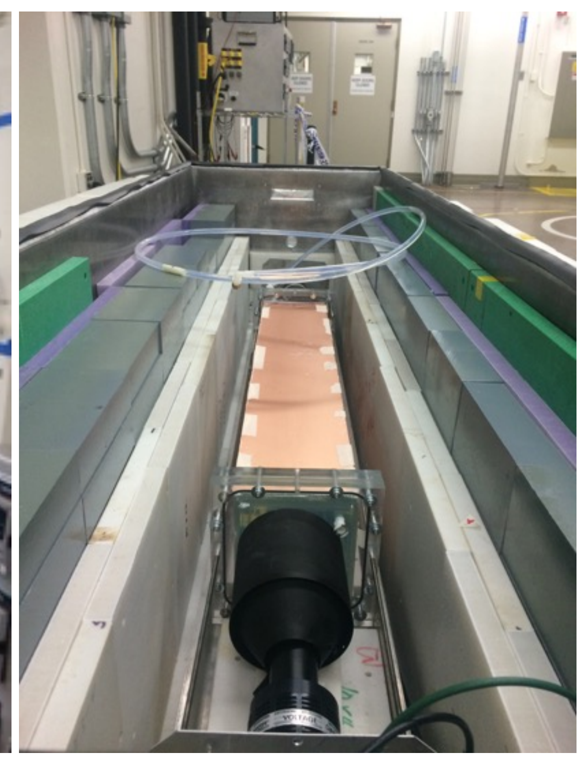
Can contain (n, Li) events in segments and extract from backgrounds.

Validation of MC from prototypes at HFIR site



PROSPECT-2 at HFIR





PROSPECT-20 at HFIR