PROSPECTing for reactor neutrinos at short baselines

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on behalf of the PROSPECT collaboration

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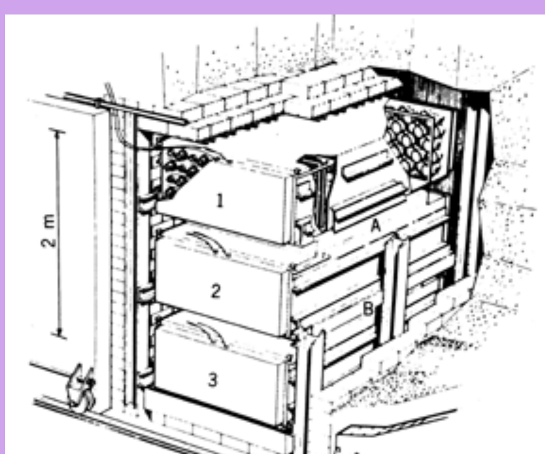
HEISING-SIMONS FOUNDATION

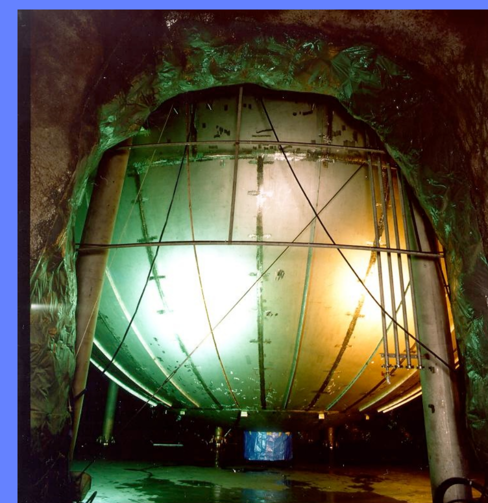
Nuclear reactors and neutrino physics history

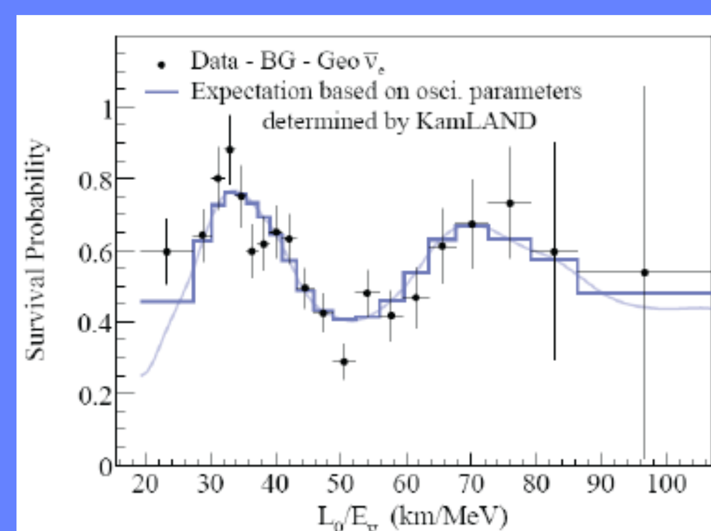
Savannah River, 1956
first observation of (anti)neutrinos



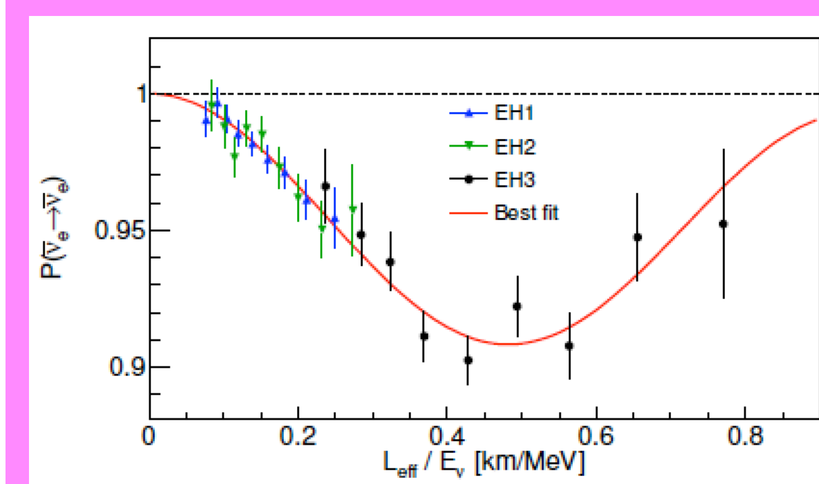
The experimental apparatus used by Reines and Cowan to detect the electron neutrino.

KamLAND, 2003
discovery of antineutrino oscillation
measurement of geoneutrinos





DYB, DC, RENO, 2012
precision measurement of θ_{13}

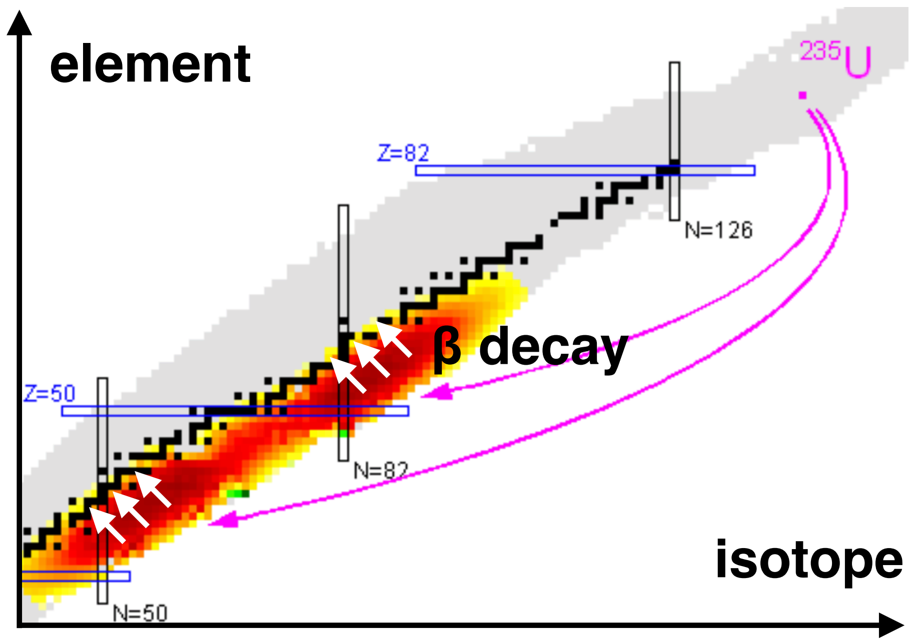


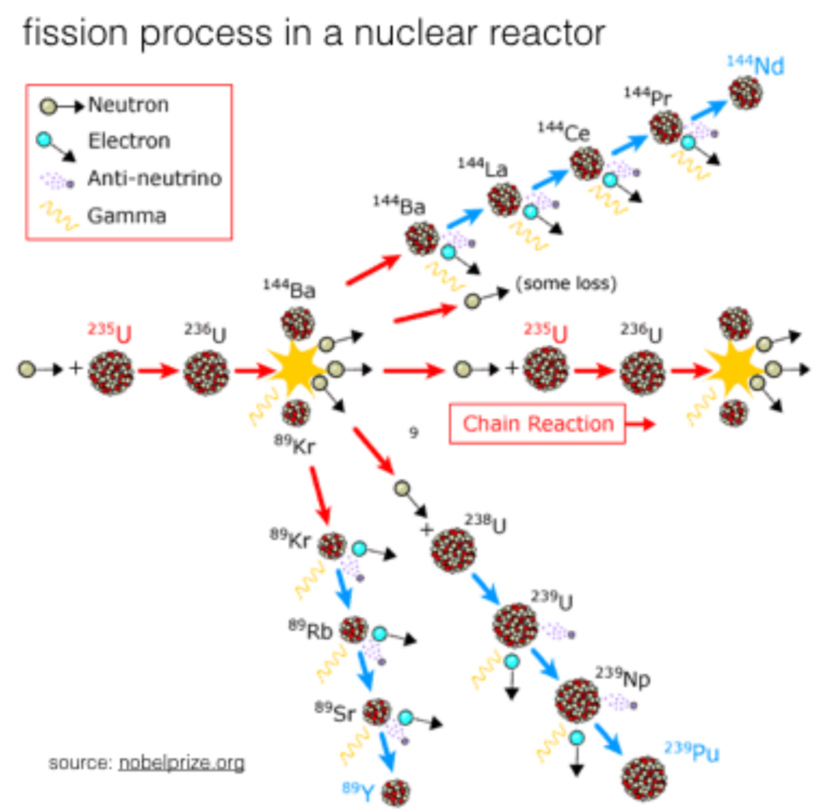
what can future reactor experiments tell us about neutrinos?

Reactor neutrinos: powerful and pure

- reactors are a powerful source: generate a lot of pure electron antineutrinos
- e.g. generation in a PWR reactor: ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu
- fission produces neutron-rich daughters that beta decay ~6 times until stable
- >99.9% flux $\bar{\nu}_e$ - only from this process
- 1 GW_{th}~10^{20} $\bar{\nu}_e$/second
- detection: inverse beta decay (IBD), coincidence tag

$$\bar{\nu}_e + p \longrightarrow e^+ + n$$



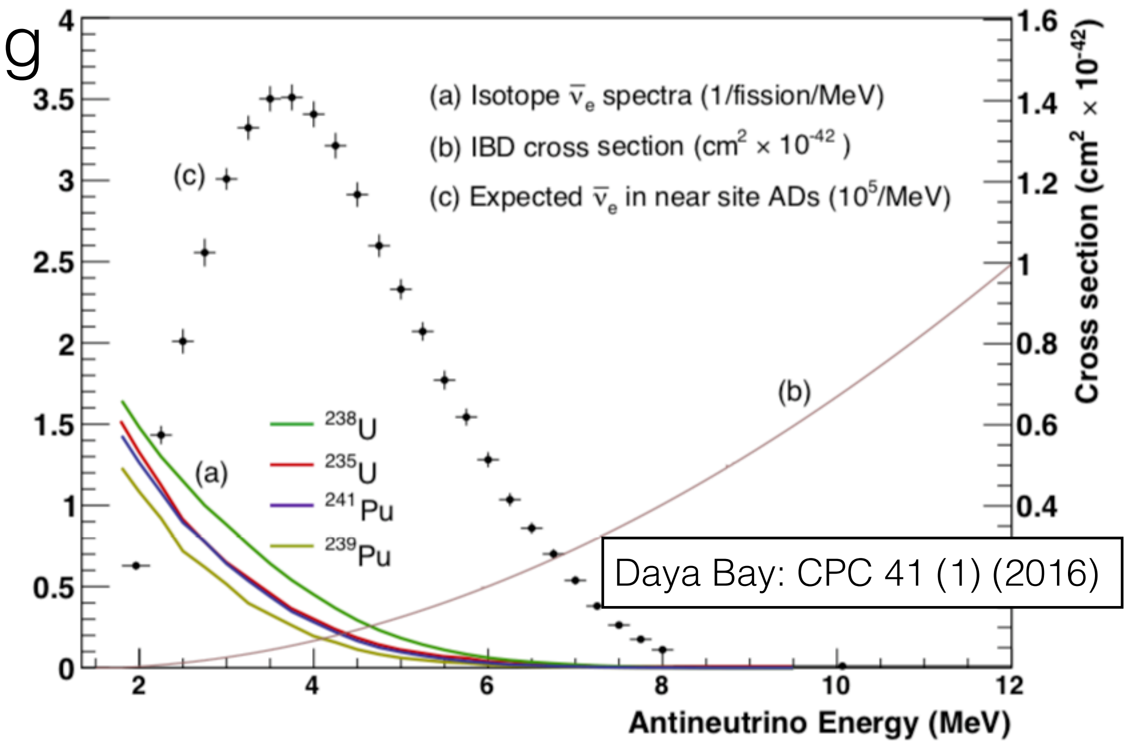


pure, prolific source of neutrinos with a workhorse detection mechanism

Measuring θ_{13} at reactors

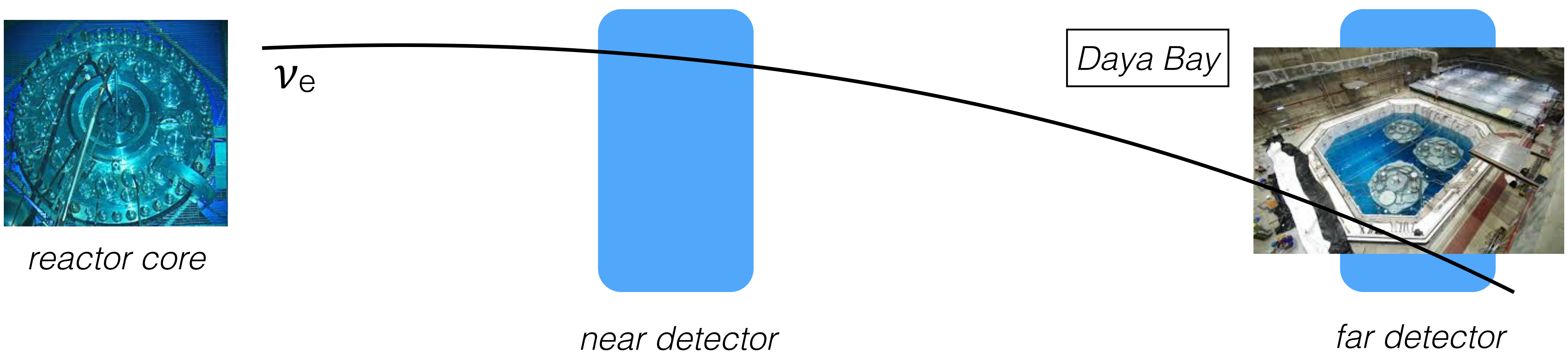
PWR reactors perfect to precisely measure mixing angle θ_{13}: Daya Bay, Double Chooz, RENO

- IBD cross section x antineutrino flux = 1.8 to 10 MeV (~low energy)
- oscillation minimum ~kilometer baselines
- complicated nuclear physics makes flux/spectrum models difficult
- use relative measurement between detectors to see oscillations



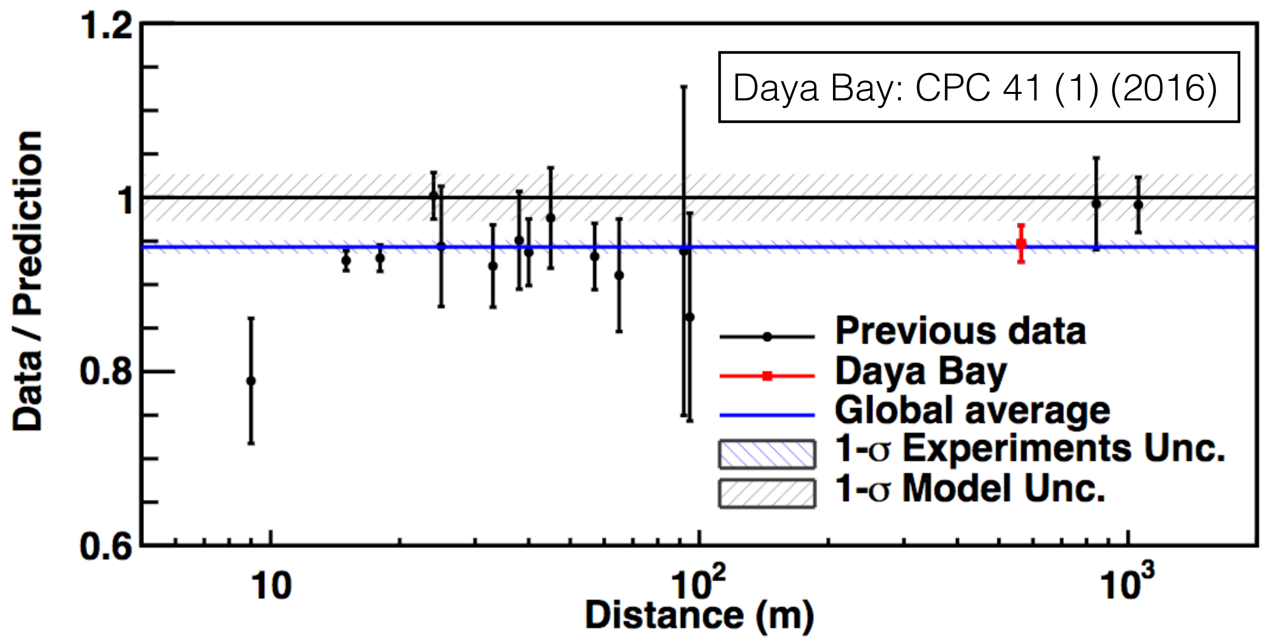
survival probability

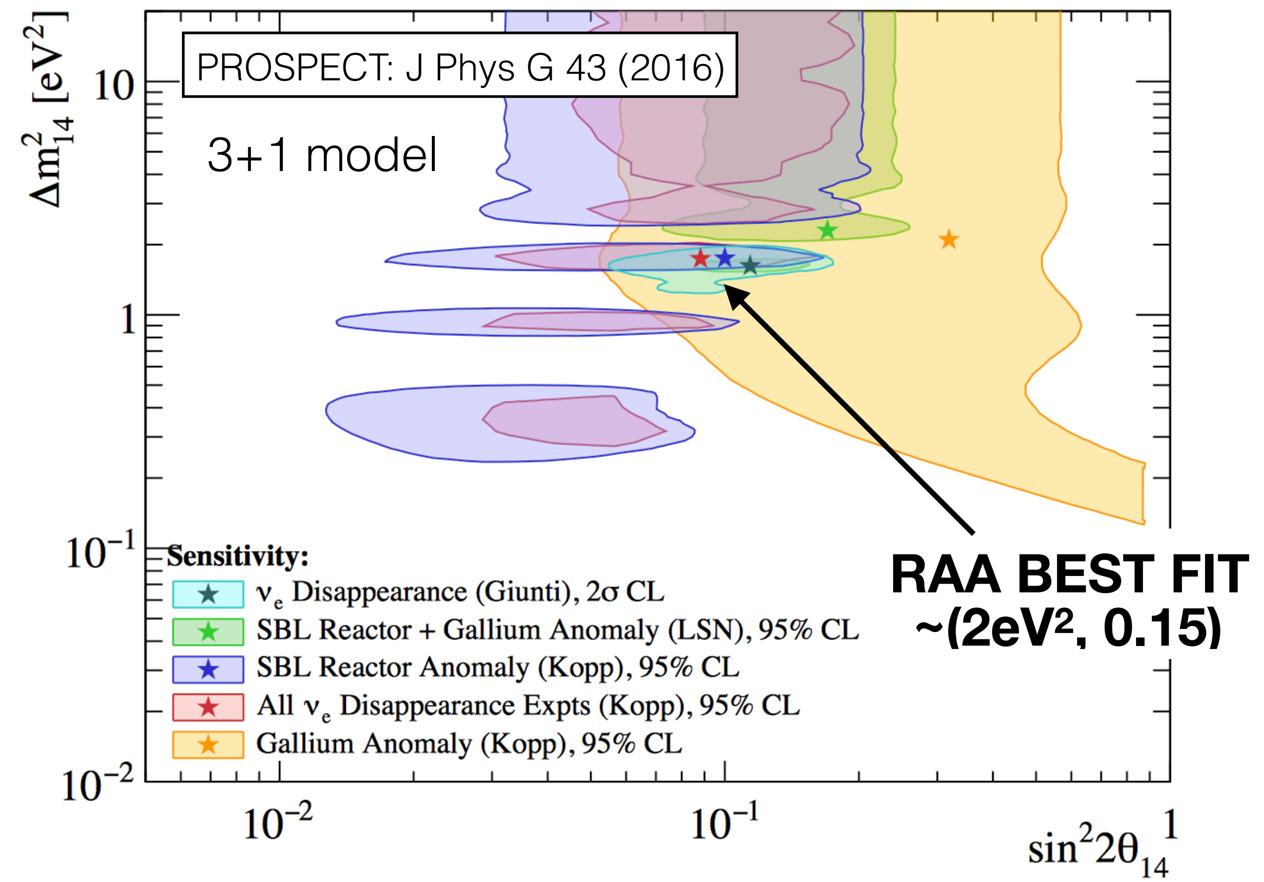
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - sin^2(2\theta)sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$



flux between detectors for relative oscillation measurement = no model needed

Precision reactor antineutrino experiments: flux



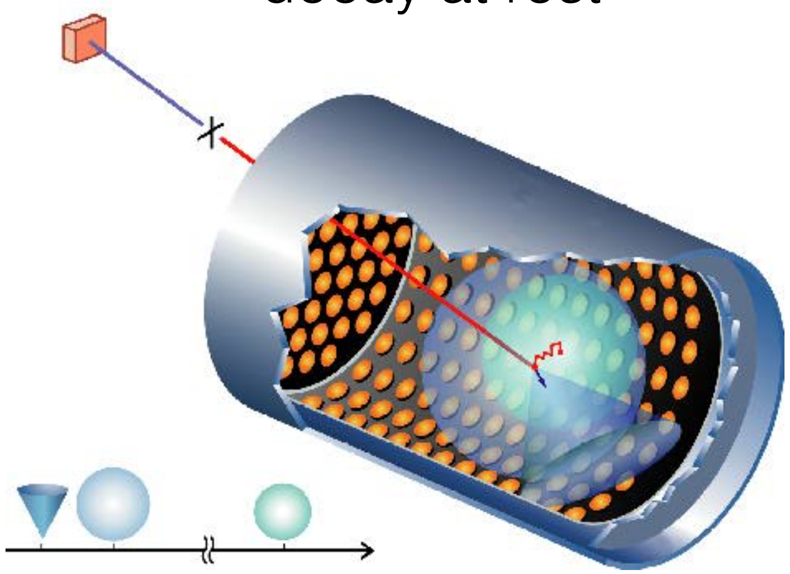


- θ_{13} also measure the flux experiments at near detectors and compare to model
- when comparing all reactor experiments to model, shows ~6% flux deficit
- model issues or is there a particle physics solution?
- Reactor Antineutrino Anomaly: meter oscillations by eV-scale sterile neutrino (Mention, *et al*, Phys. Rev. D83 (2011))
- sterile neutrinos would have major implications on neutrino physics/cosmology

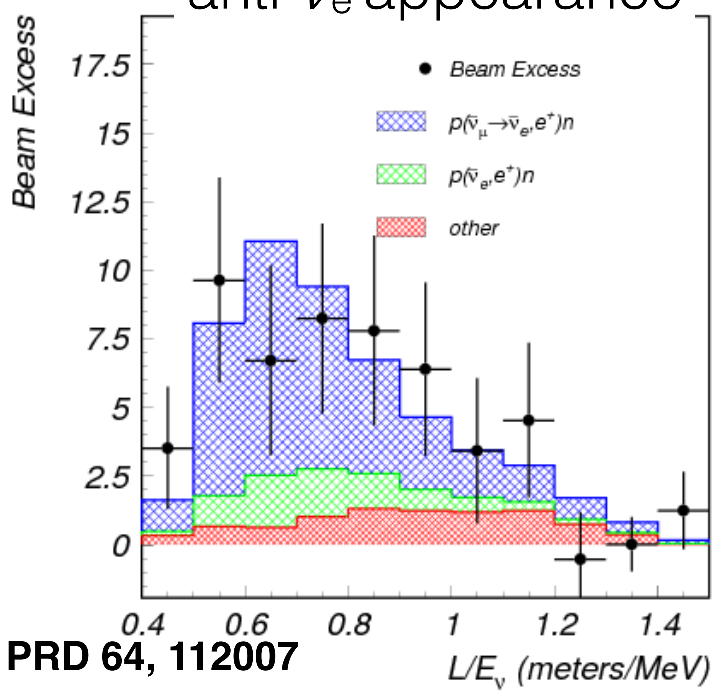
flux disagreement - does an eV-scale sterile exist?

Do other channels show sterile signs?

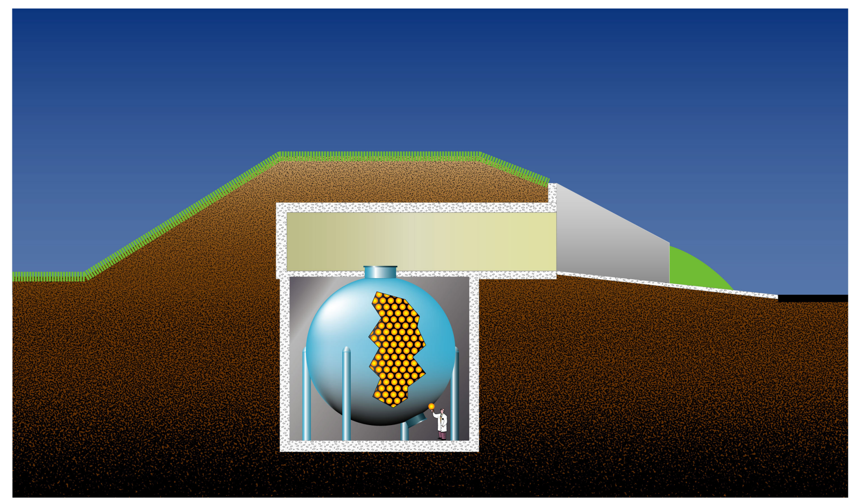
LSND
decay at rest



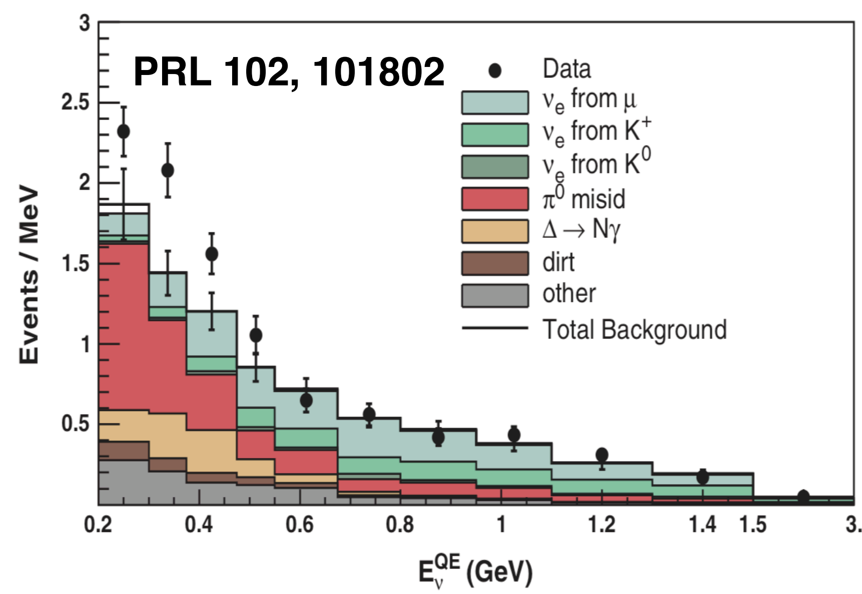
anti-ν_e appearance



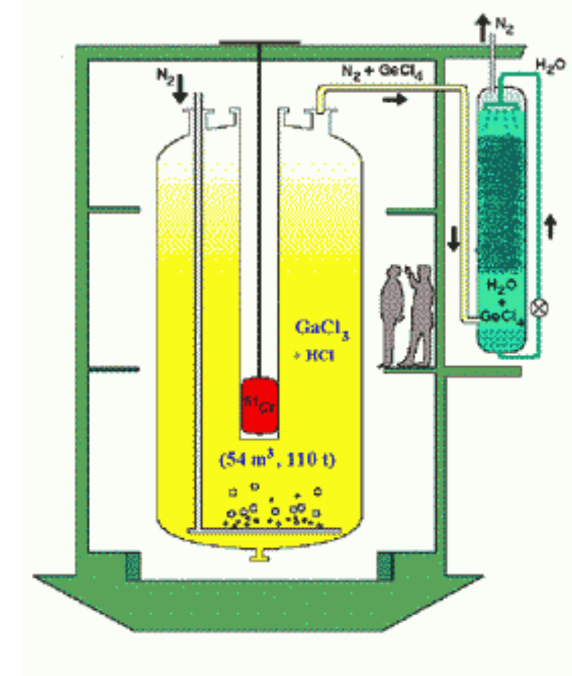
MiniBooNE
short baseline accelerator



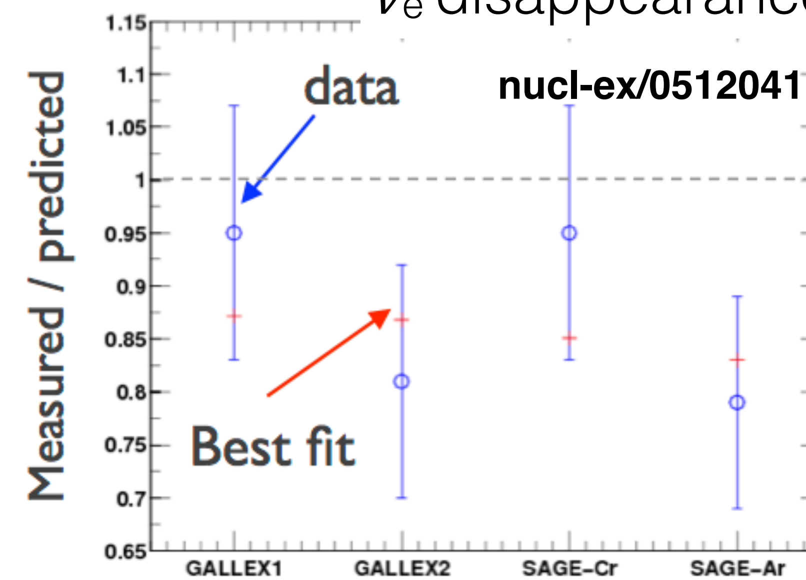
low energy ν_e appearance



GALLEX/SAGE
Ga source calibration



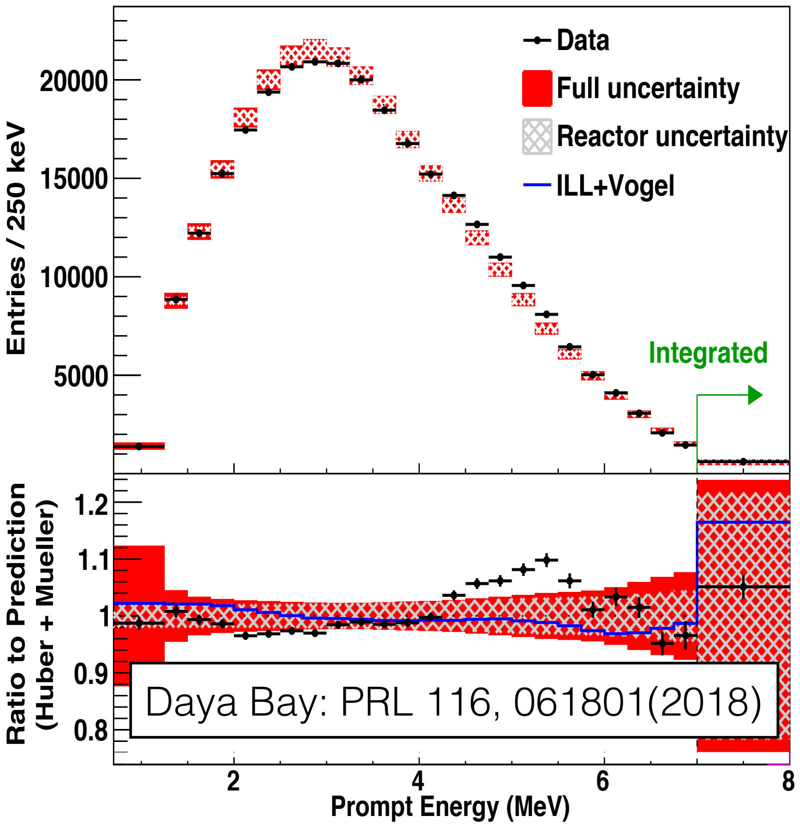
ν_e disappearance



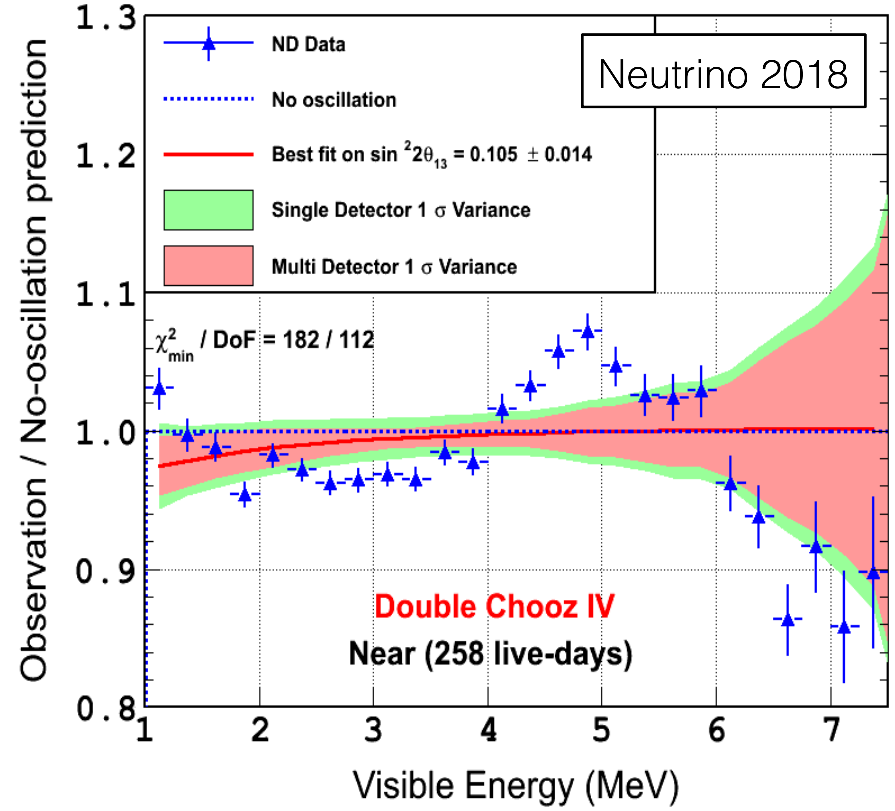
global scene motivates looking for eV-scale steriles at short baselines

Precision reactor antineutrino experiments: spectrum

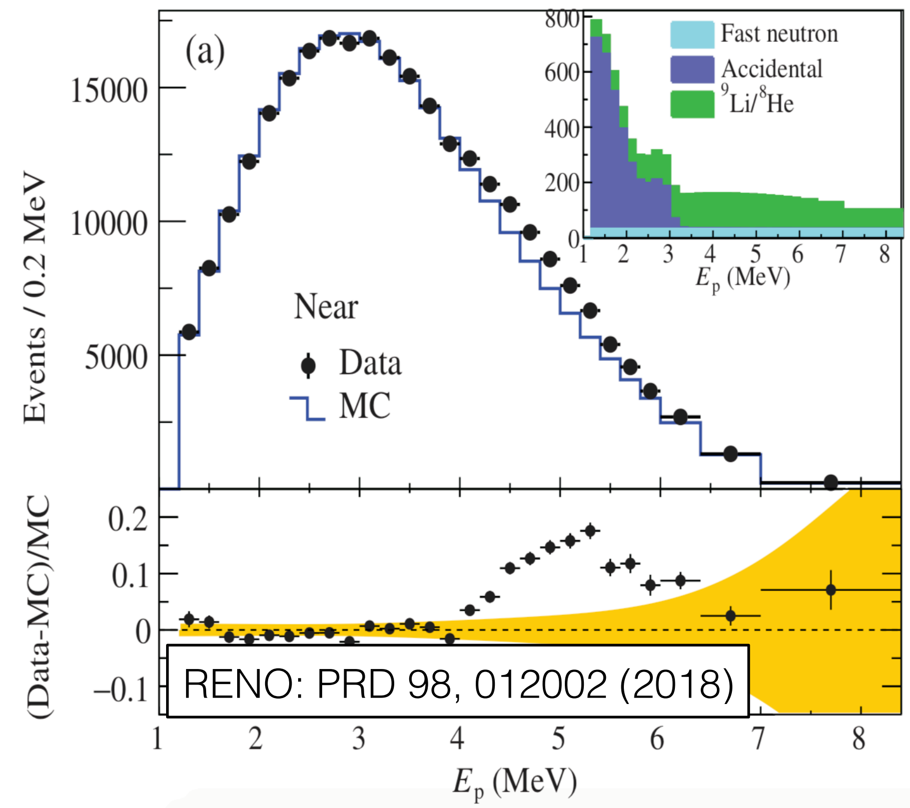
Daya Bay



Double Chooz



RENO

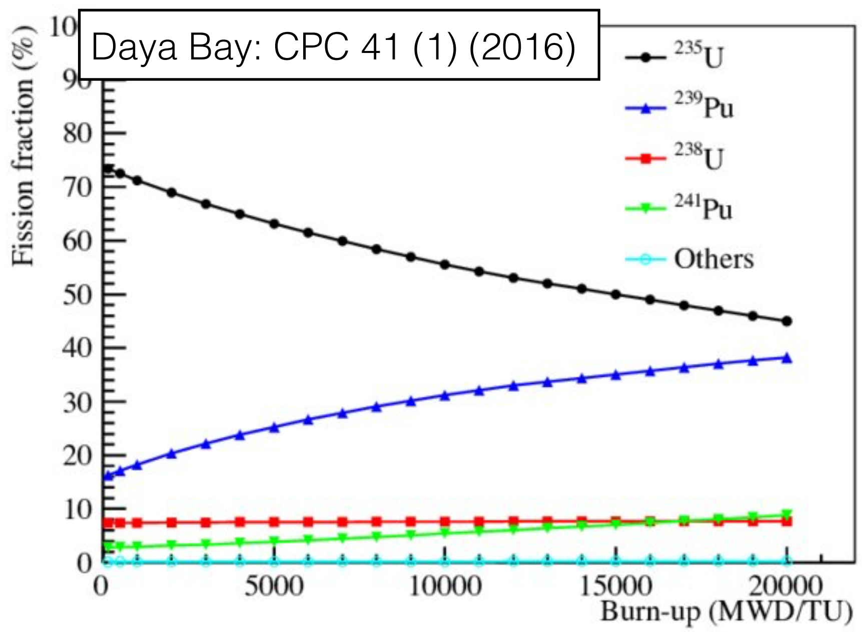


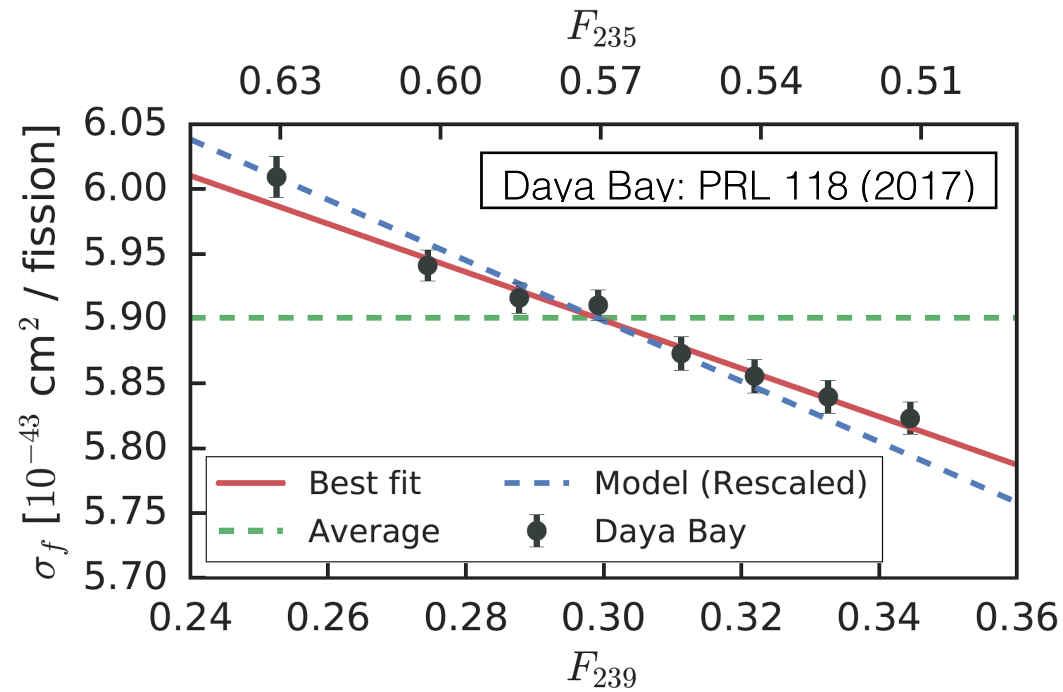
- precision reactor experiments led to further evaluation of models
- deviations throughout the spectrum measured, prominent excess 4-6 MeV prompt
- cannot be explained by a sterile neutrino
- is it an issue with the models - one, some, all isotopes?

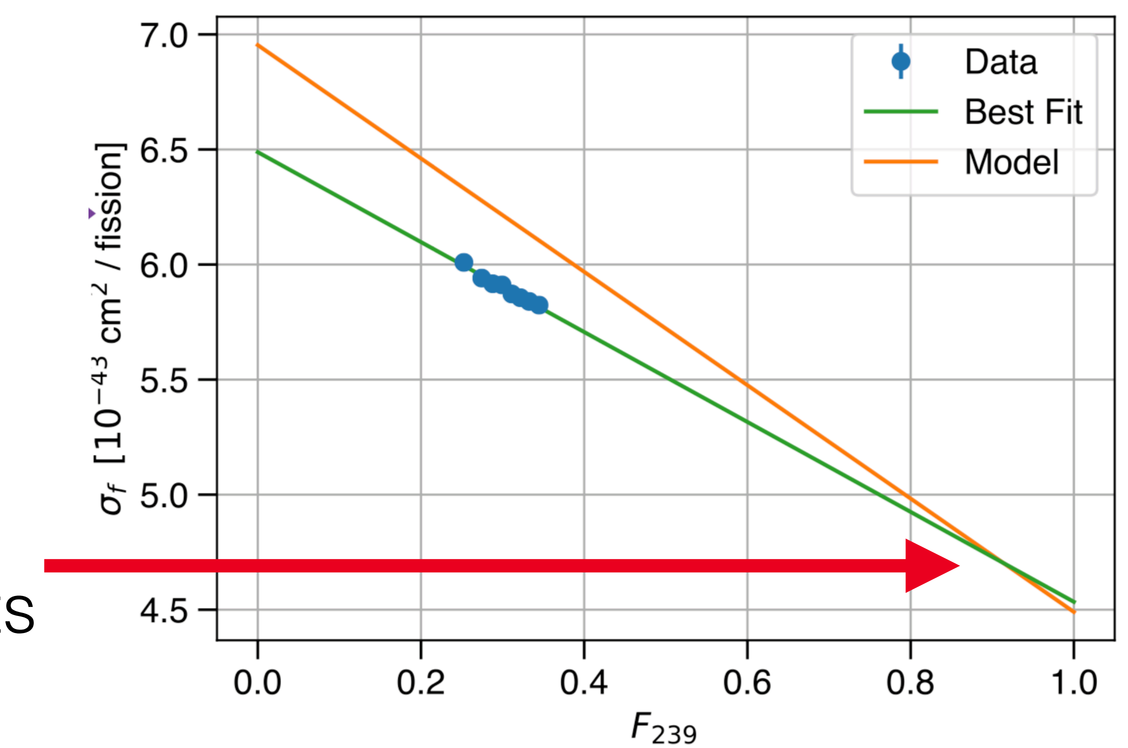
spectrum disagreement - do we model all of the fissile isotopes correctly?

Other complications - fuel evolution at PWR reactors

Fuel composition changes over time as fissile isotopes burn and build up.







- DYB, RENO show that the size of the flux deficit is dependent on the fuel content
- flux models are getting something wrong
- ^{235}U may be the issue, IBD yield/fission hints that this isotope is the problem

multi-isotope fuel evolves over time further complicated models

Recapping the reactor scene

1. When comparing to model, reactor neutrino experiments globally observe fewer neutrinos than predicted.

2. θ_{13} experiments show significant data-model discrepancies in spectrum.
   *2018 re-evaluation of 1980's Gosgen also shows it (arXiv:1807.01810)

3. Measurements at PWR reactors are further complicated by evolving fuels and IBD fission yields.

need new experiments that provide clarity to the reactor situation

θ_{13} experiments were successful using the relative oscillation measurement approach with two detectors to avoid model systematics.

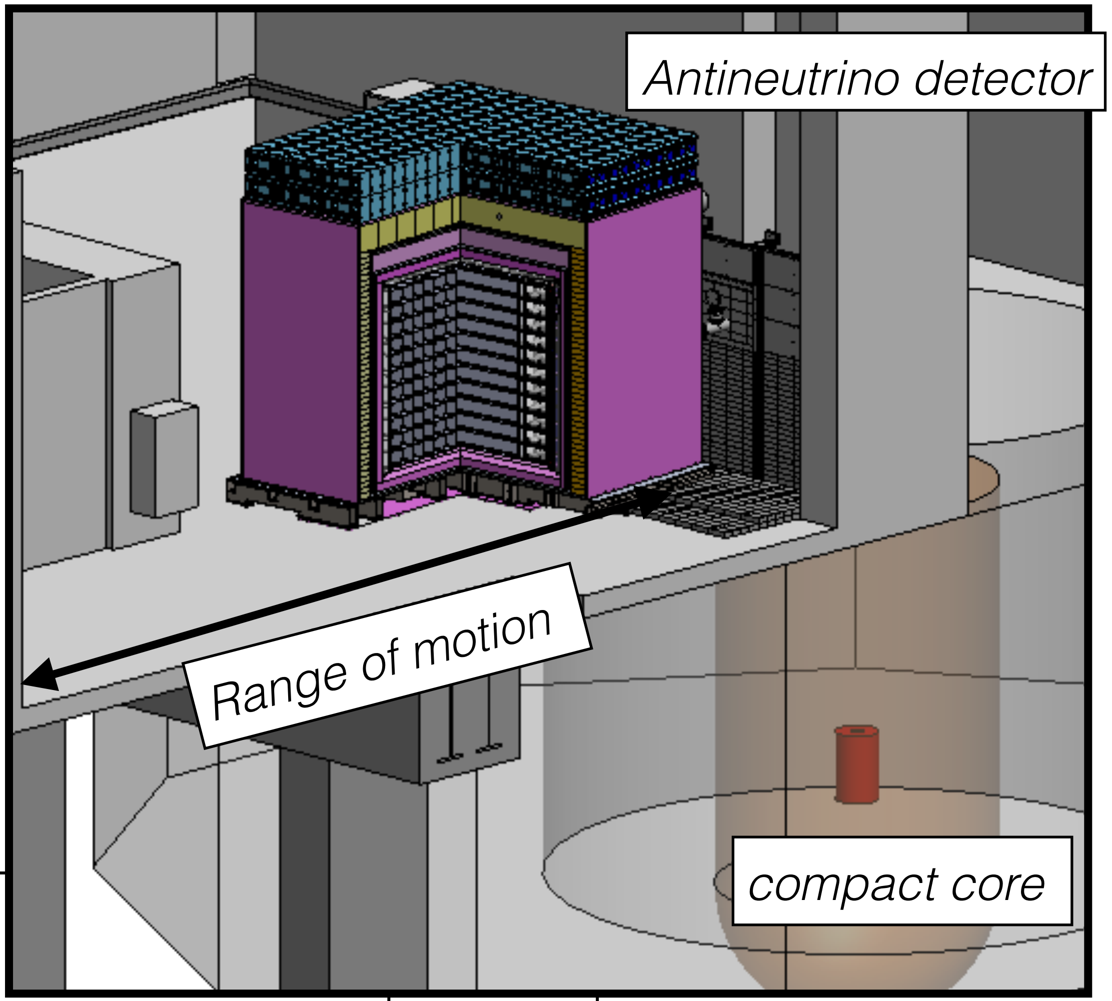
Precision Reactor Oscillation and SPECTrum experiment

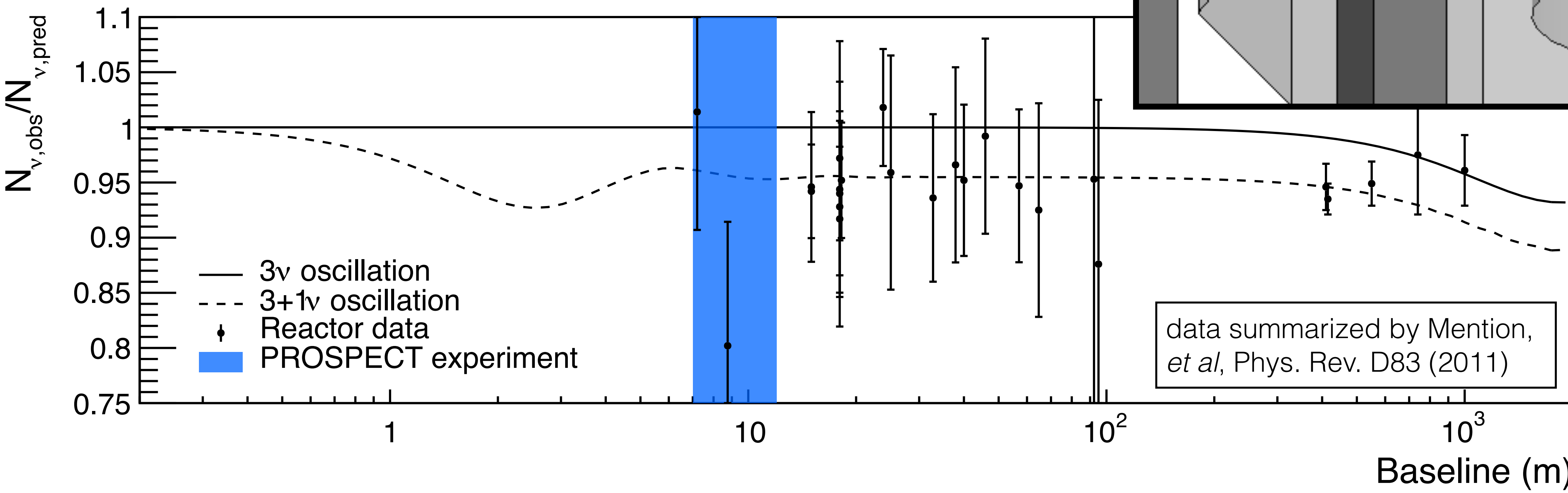
Goals:

1. perform model independent search for eV-scale sterile neutrinos at distances 7-12 m

2. make a precision measurement of ^{235}U reactor antineutrino spectrum

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

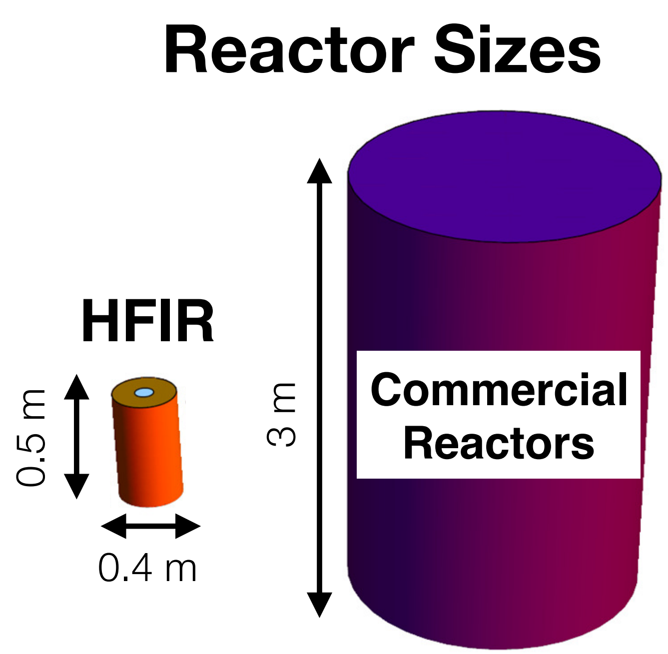


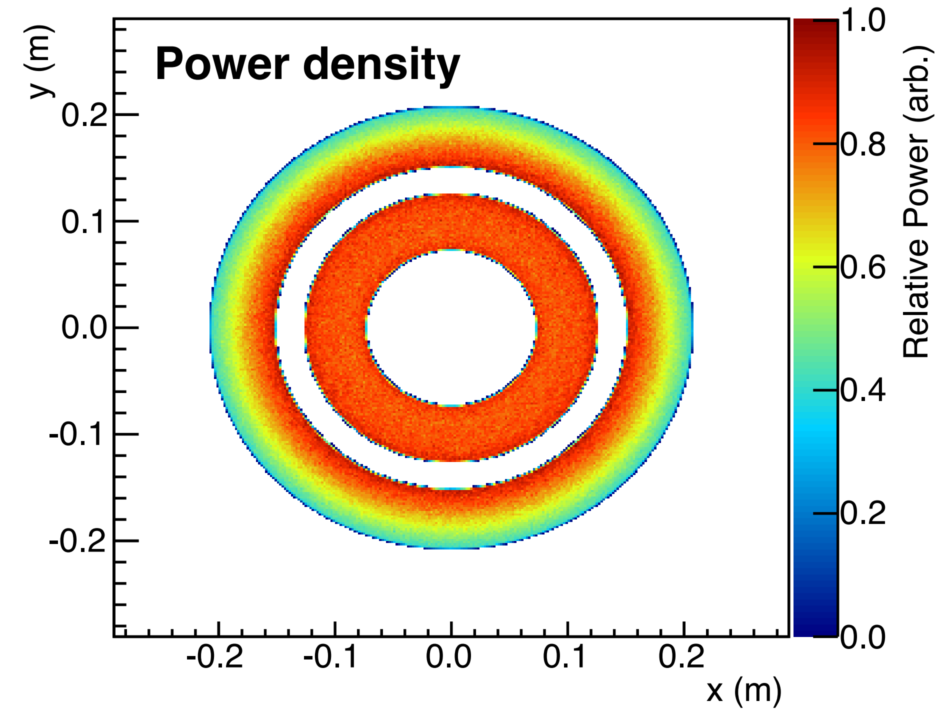


PROSPECT will probe unexplored baselines while measuring the ^{235}U spectrum

Neutrino source: High Flux Isotope Reactor @ ORNL

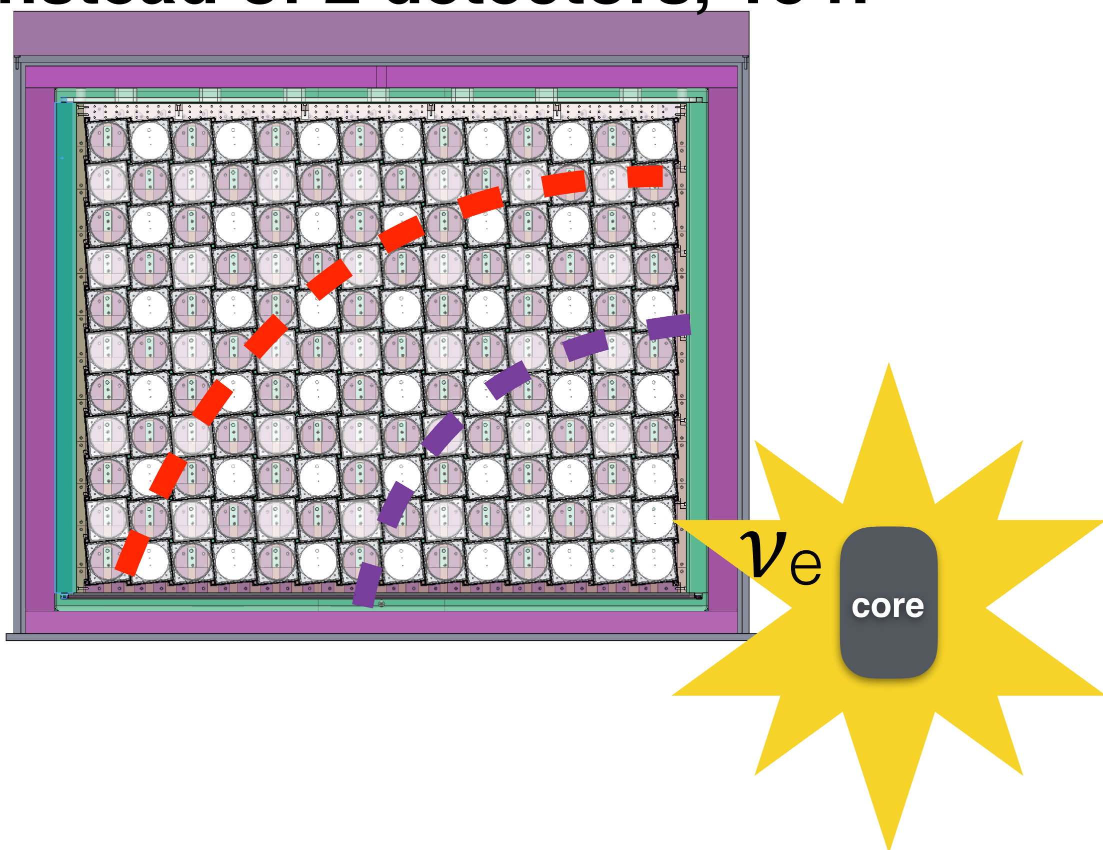
- 85MW highly enriched uranium reactor
- >99% of ν from ^{235}U fissions, effectively no isotopic evolution
- compact core (44cm diameter, 51cm tall)
- 24 day cycles, 46% reactor up time
- detailed study of surface cosmogenic backgrounds (PROSPECT: NIMA A806 (2016) 401)





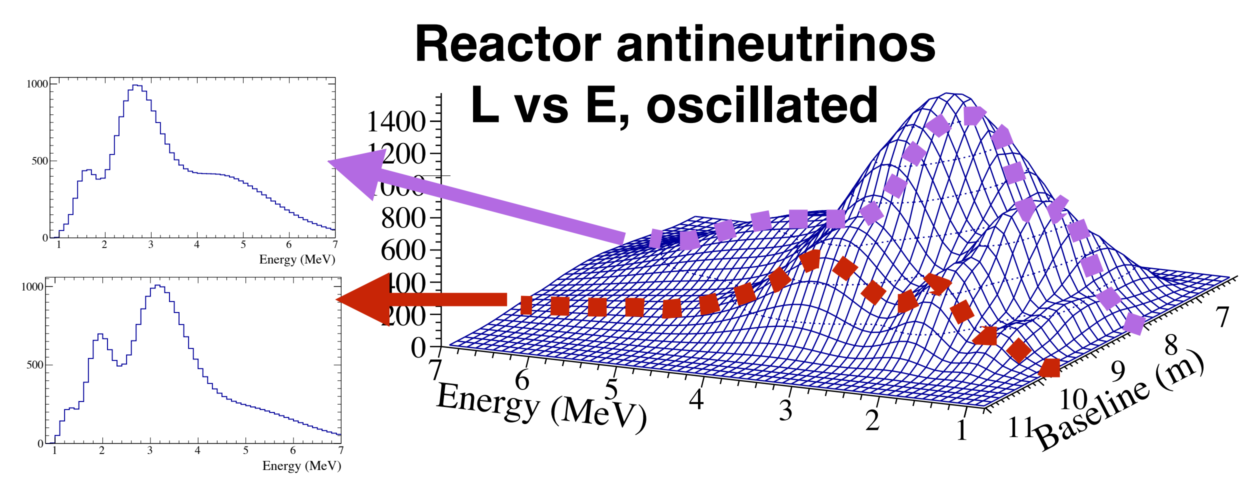
Experimental strategy at HFIR reactor

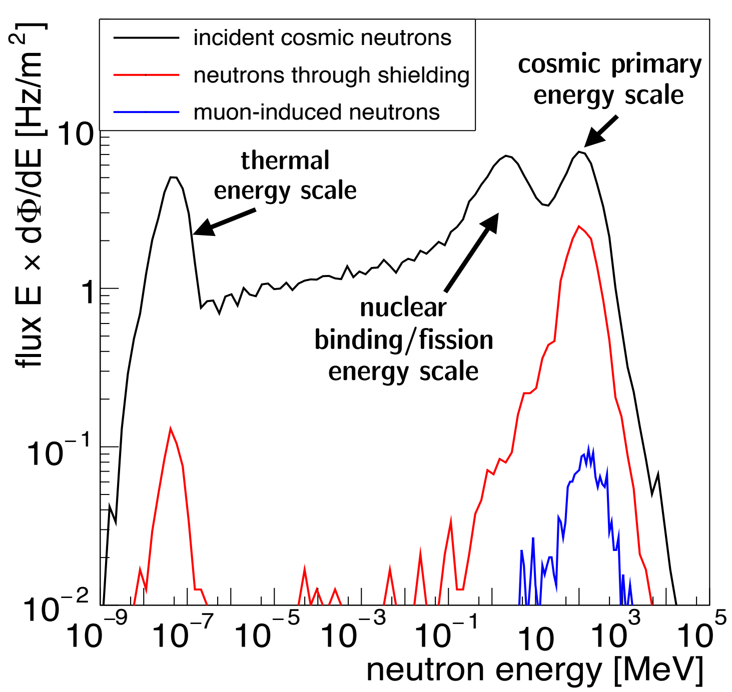
instead of 2 detectors, 154!



Goal - spectrum measurement:
✓single isotope (most abundant in PWR)

Goal - sterile neutrino search:
✓access to short baselines
✓compact core
✓static IBD yield
✓segmented detector = relative measurement



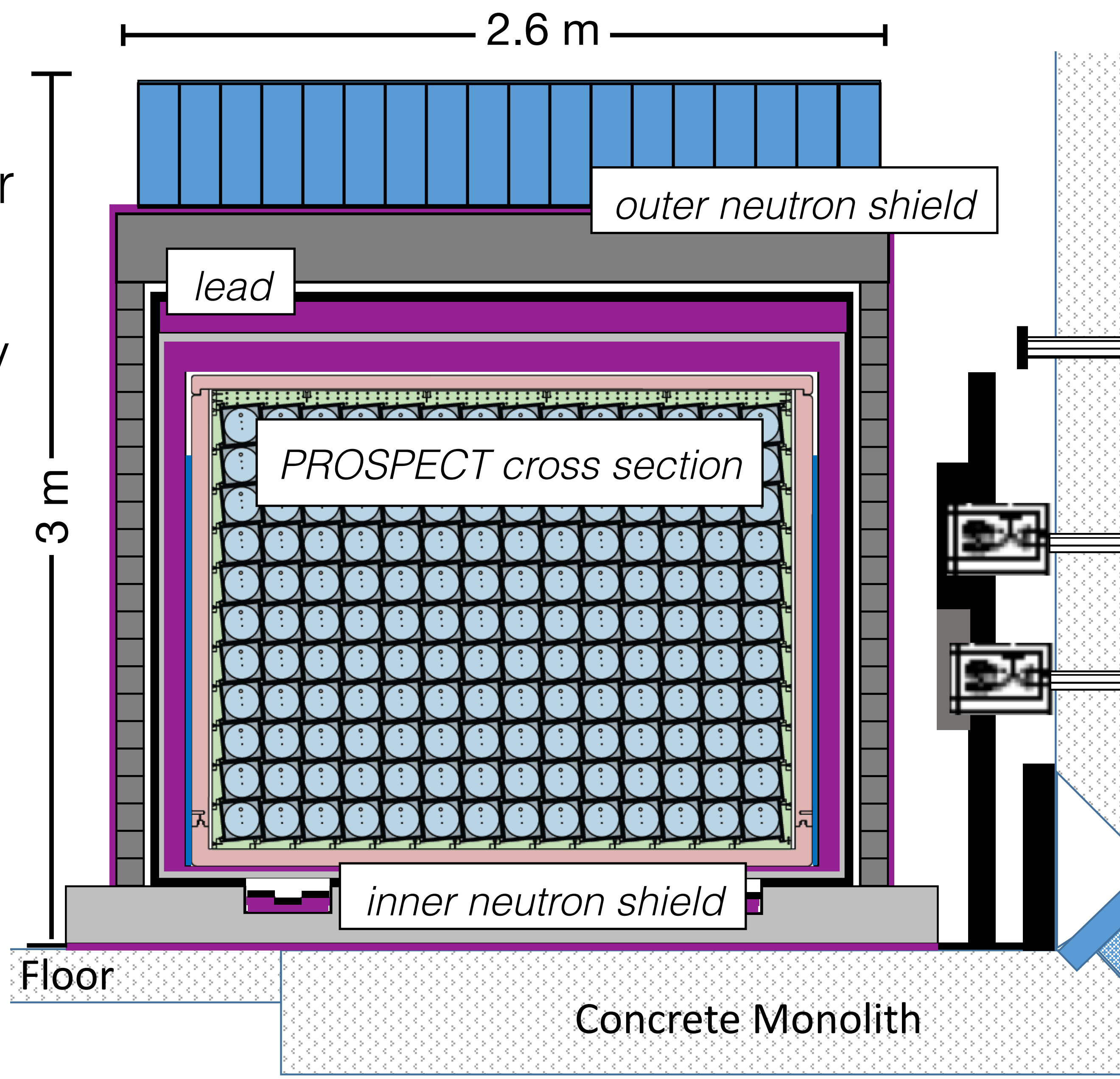


Nothing is perfect…
- limited overburden = cosmogenic fast neutrons are dominant IBD-like background
- possible reactor generated accidental backgrounds

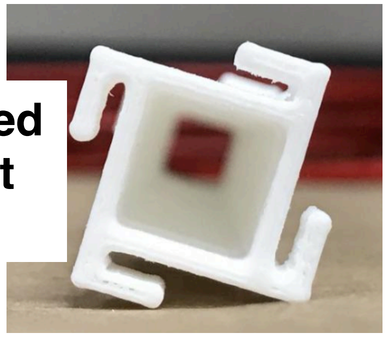
PROPSECT segmented detector design

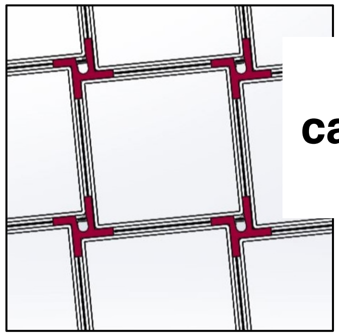
Realization of experiment strategy:

- target/detection: ^{6}Li-loaded liquid scintillator
- 154 segments, 119cm x 15cm x 15cm
- thin (1.5mm) optical panels held in place by 3D printed support rods
- 25 liters/segment, **total mass: ~4 tons**
- segmentation enables:
  - calibration access throughout volume
  - 3D position reconstruction (X, Y) with (Z) from double-ended PMT readout
  - fiducialization
- optimized shield for cosmogenics

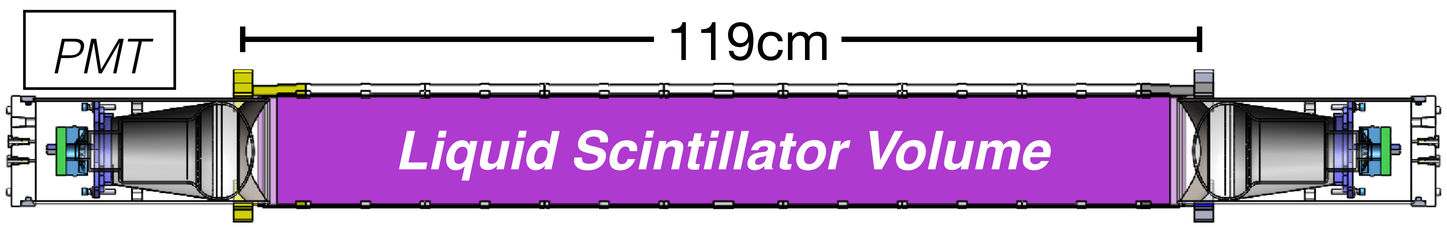


3D printed support rod

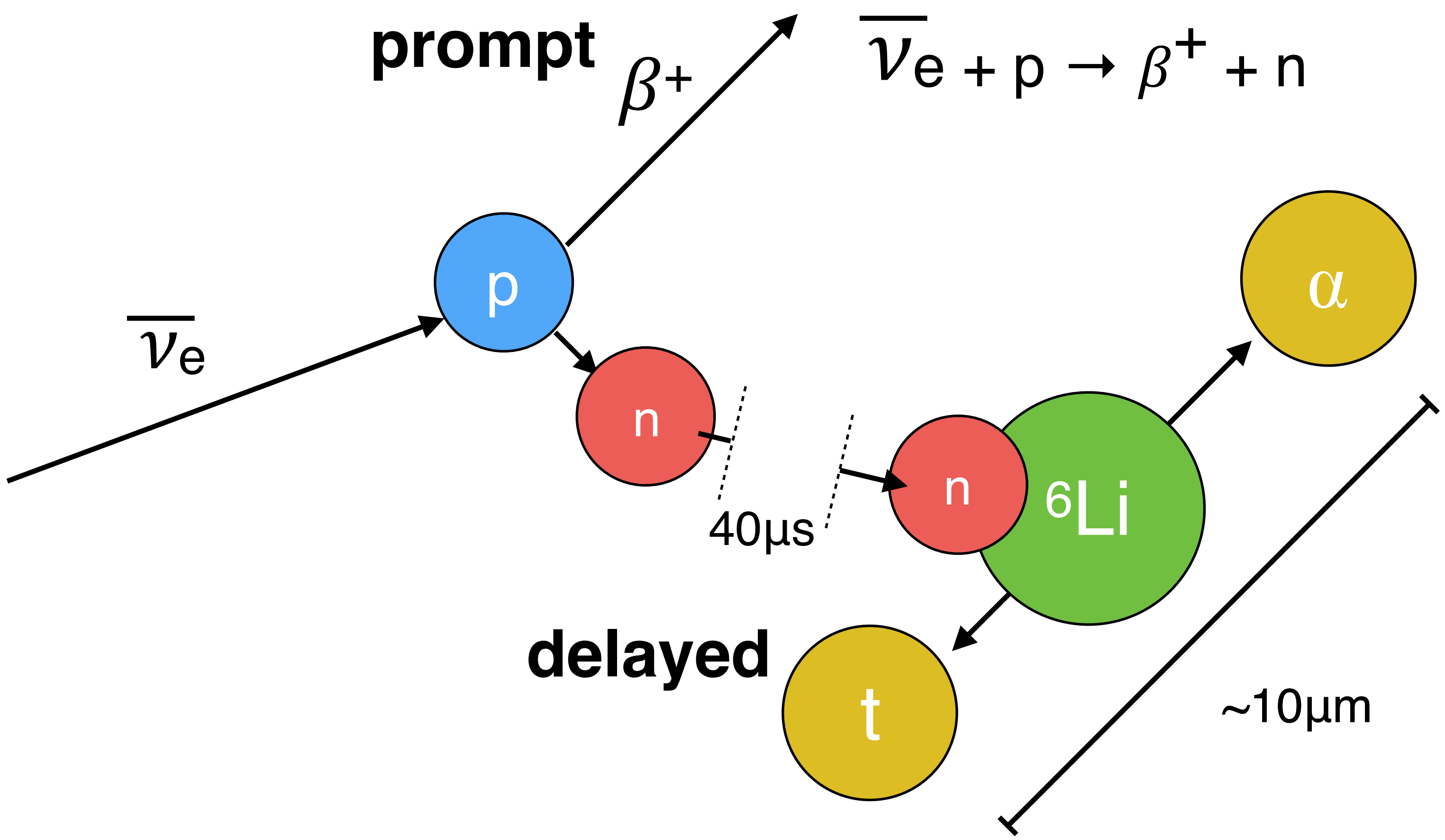




tilt for calibration access



Detection with ^{6}Li-loaded liquid scintillator

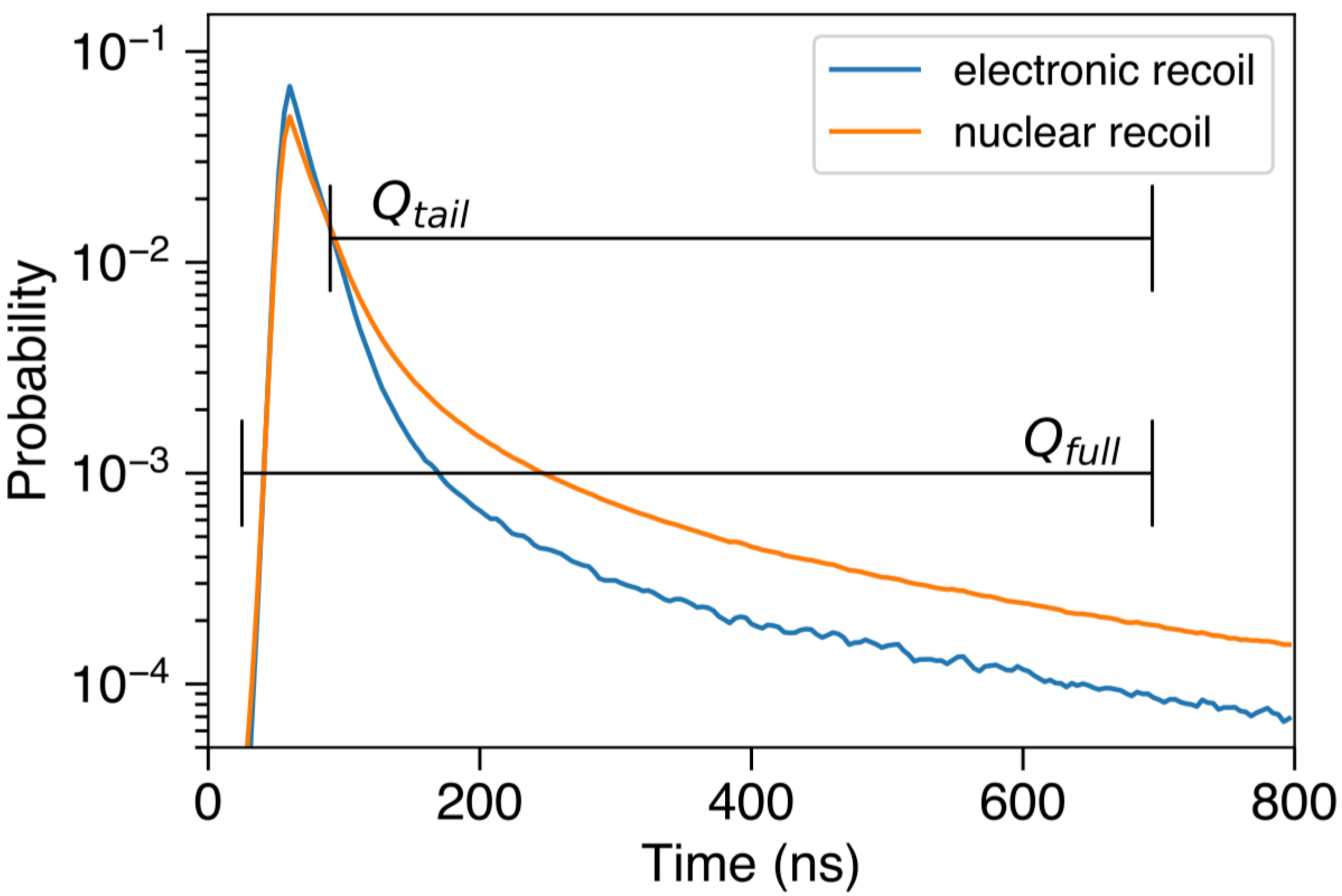


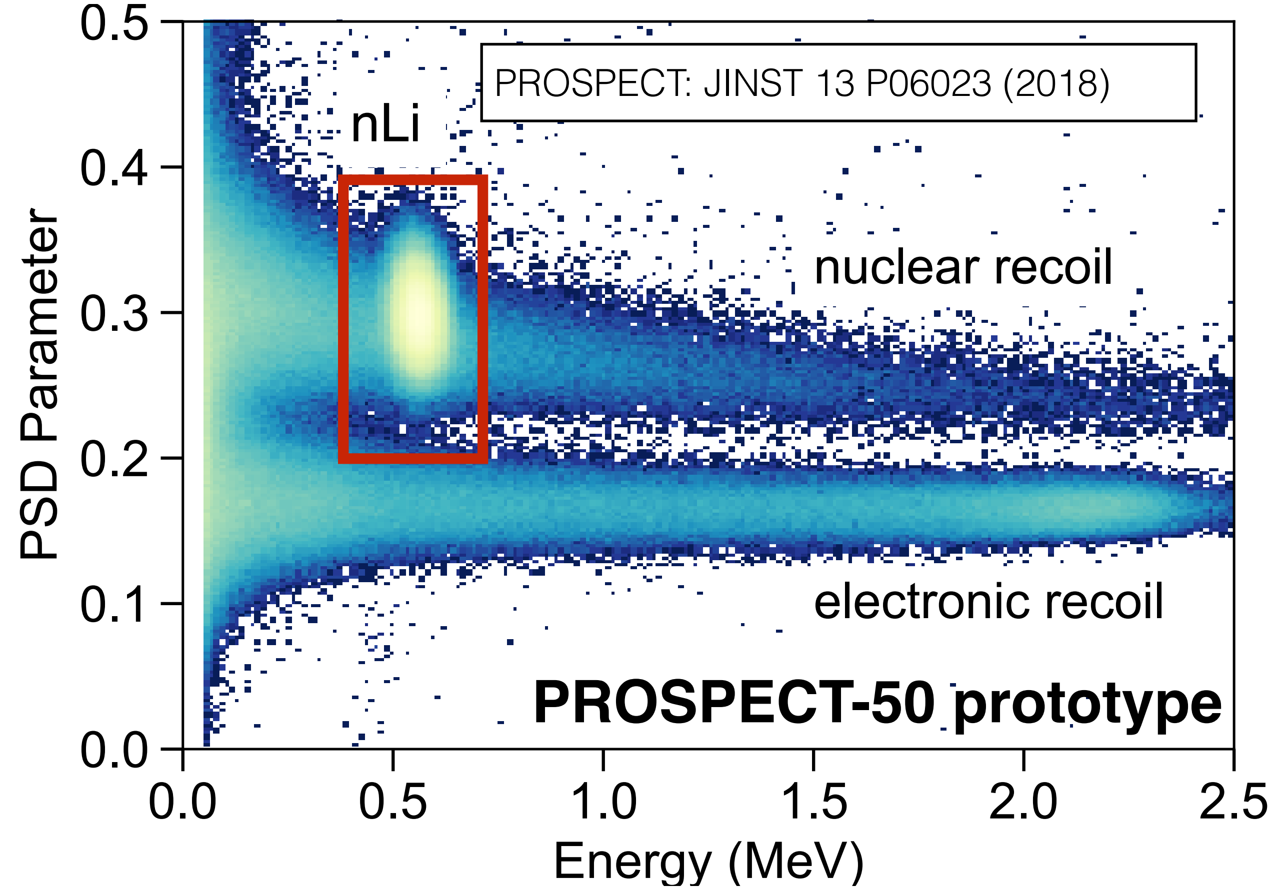
- custom developed ^{6}LiLS based on EJ-309, non-toxic and non-flammable
- compact detector needs a capture agent that is highly localized, within segments
- minimize position dependent efficiency
- spatial and temporal cuts to identify IBDs and reject backgrounds

^{6}LiLS provides event localization and identification required for a compact detector

Pulse shape discrimination (PSD)

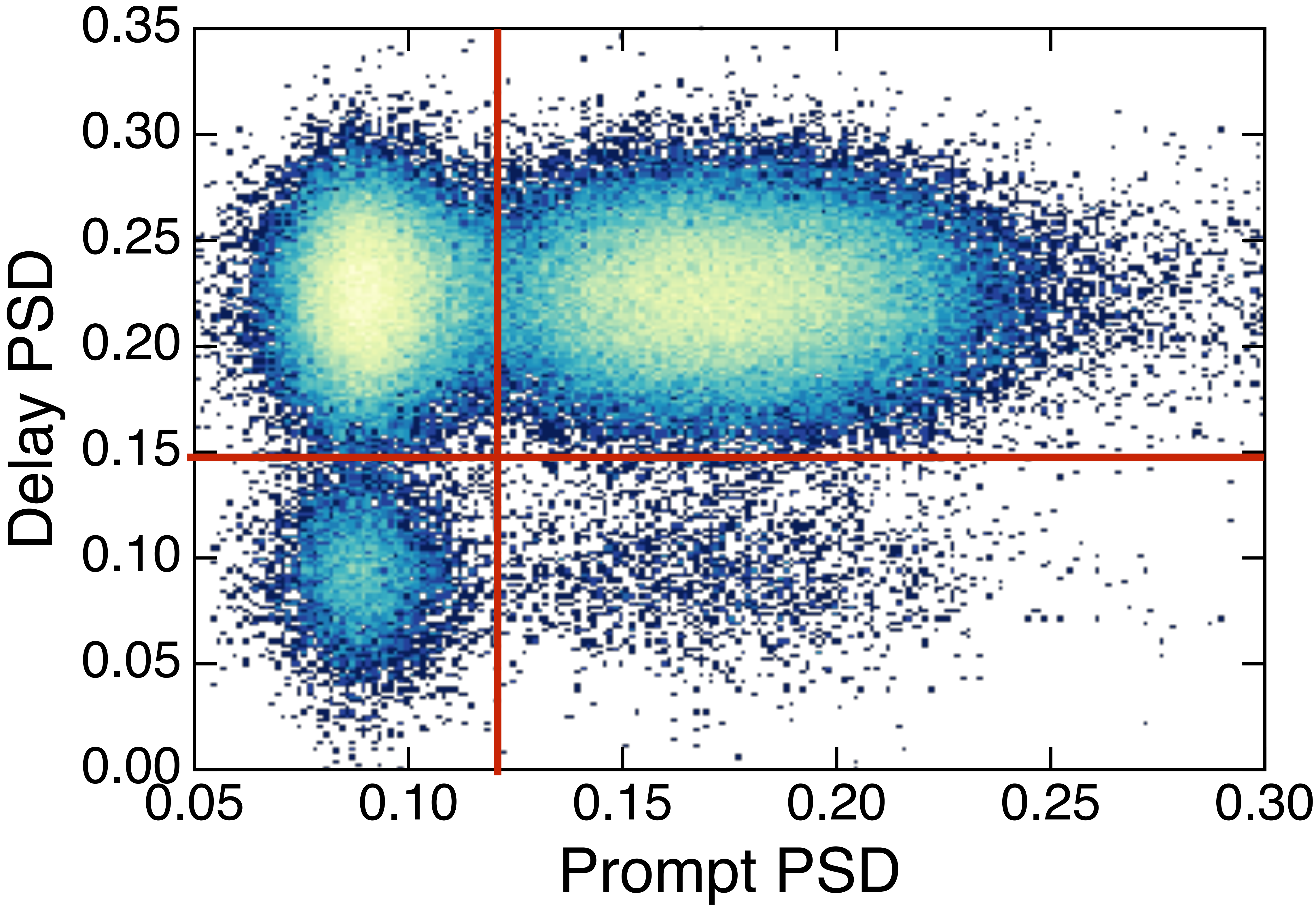
Even better handle on IBD acceptance and background rejection with particle ID.



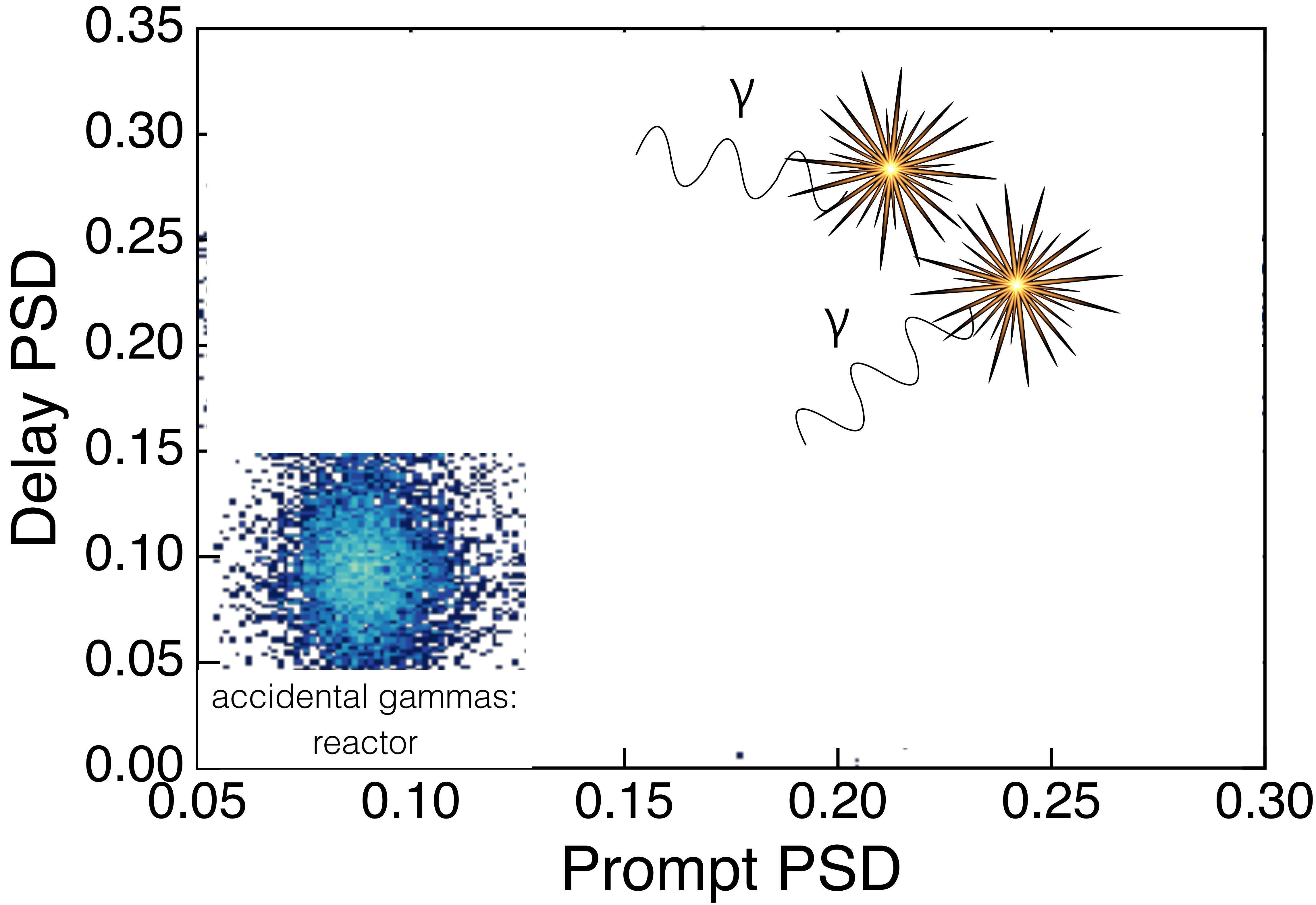


PSD can identify particle type through shape of pulse

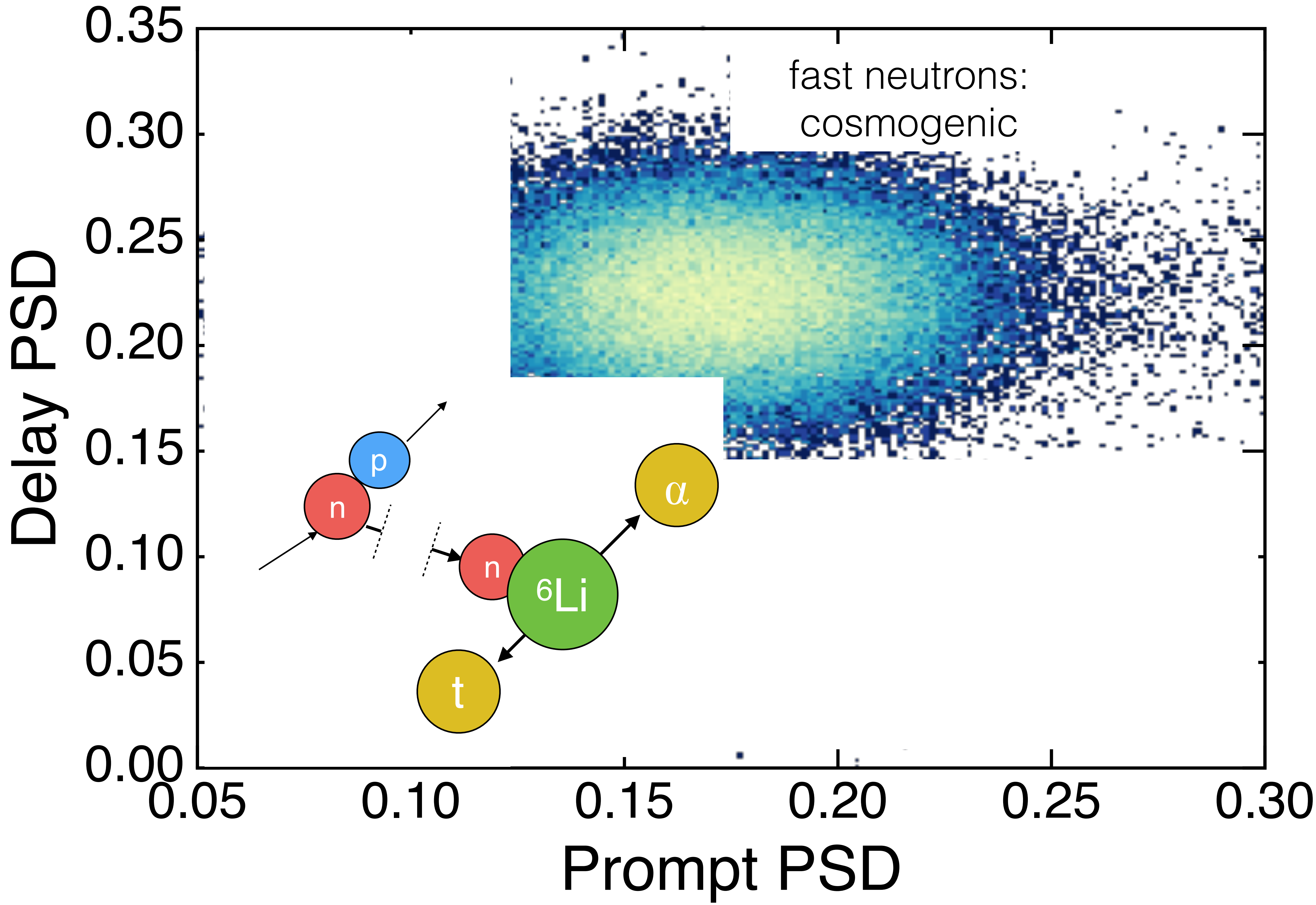
Classification of events using PSD



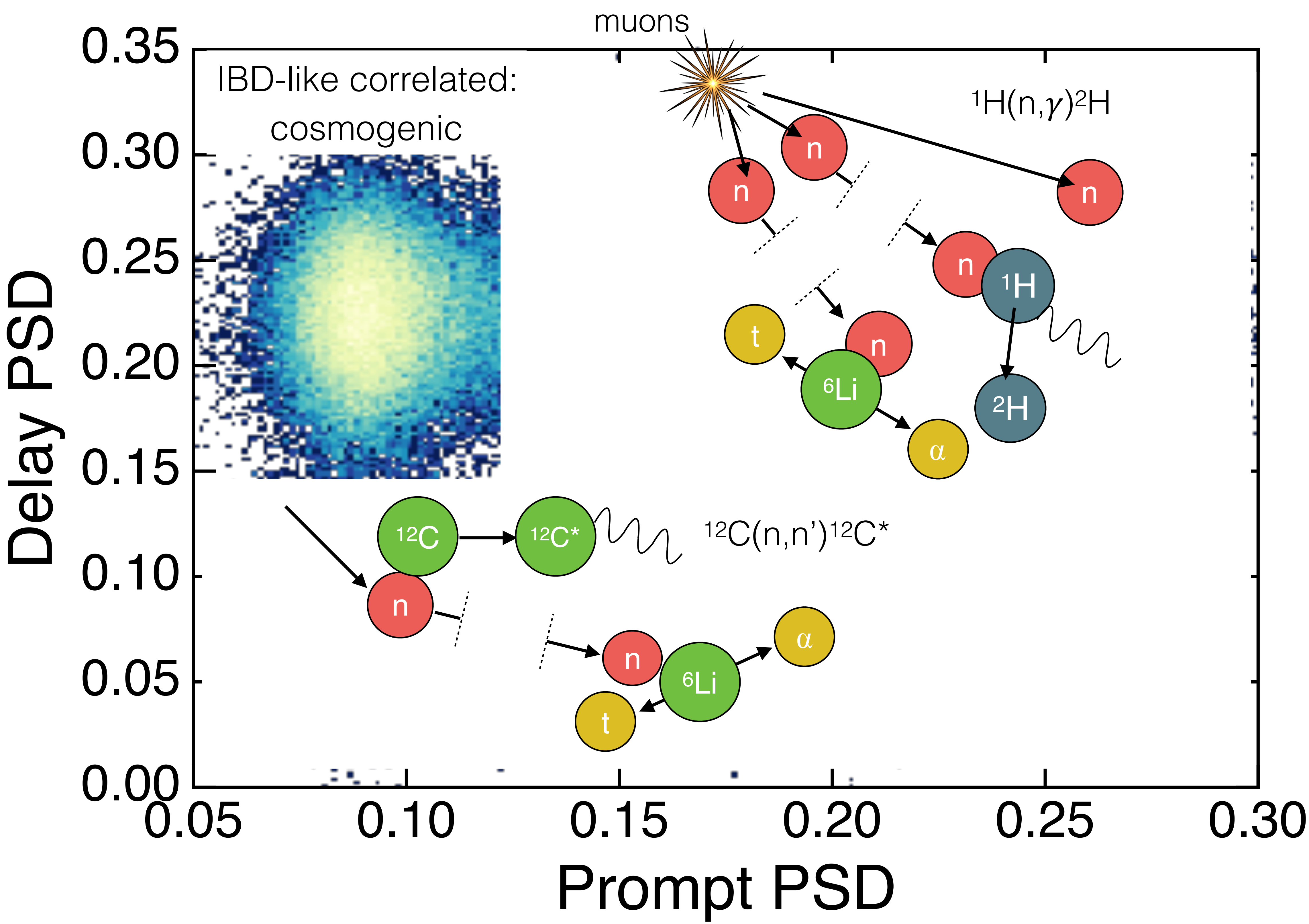
Classification of events using PSD



Classification of events using PSD



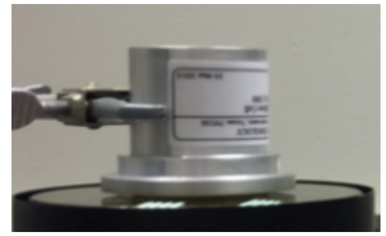
Classification of events using PSD

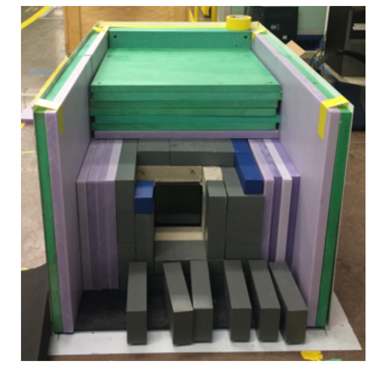


Roadmap: R&D of ^{6}Li-loaded LS detectors

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

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



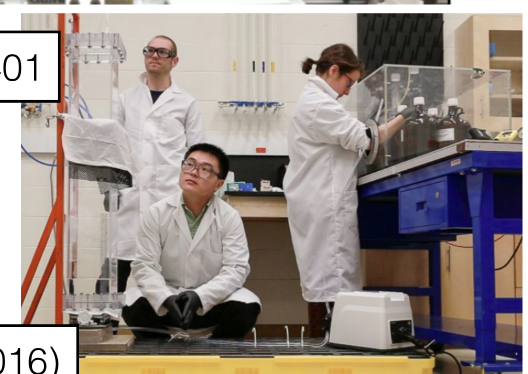


multi-layer shielding

PROSPECT-2
Background studies
Dec 2014 - Aug 2015

12.5 length
1.7 liters
^{6}LiLS

PROSPECT: NIMA A806 (2016) 401

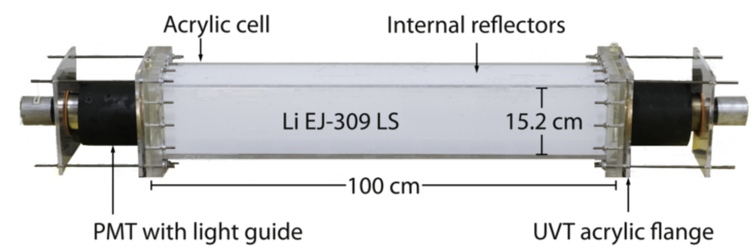


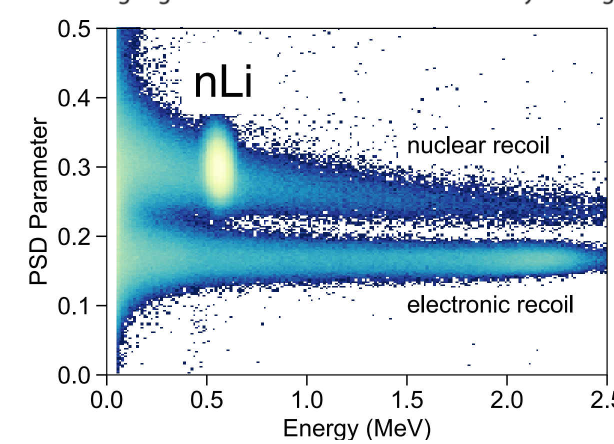
light guides

PROSPECT-20
Segment optics
Background studies
Spring/Summer 2015

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

PROSPECT: JINST 10 P11004 (2016)





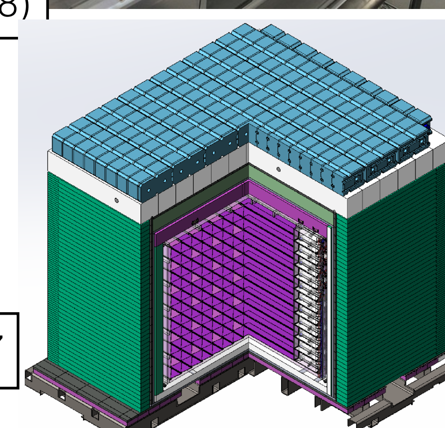
PROSPECT-50
Performance validation
Simulation benchmark
2017-2018

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

PROSPECT: JINST 13 P06023 (2018)

PROSPECT AD
Physics measurement
data taking 2018

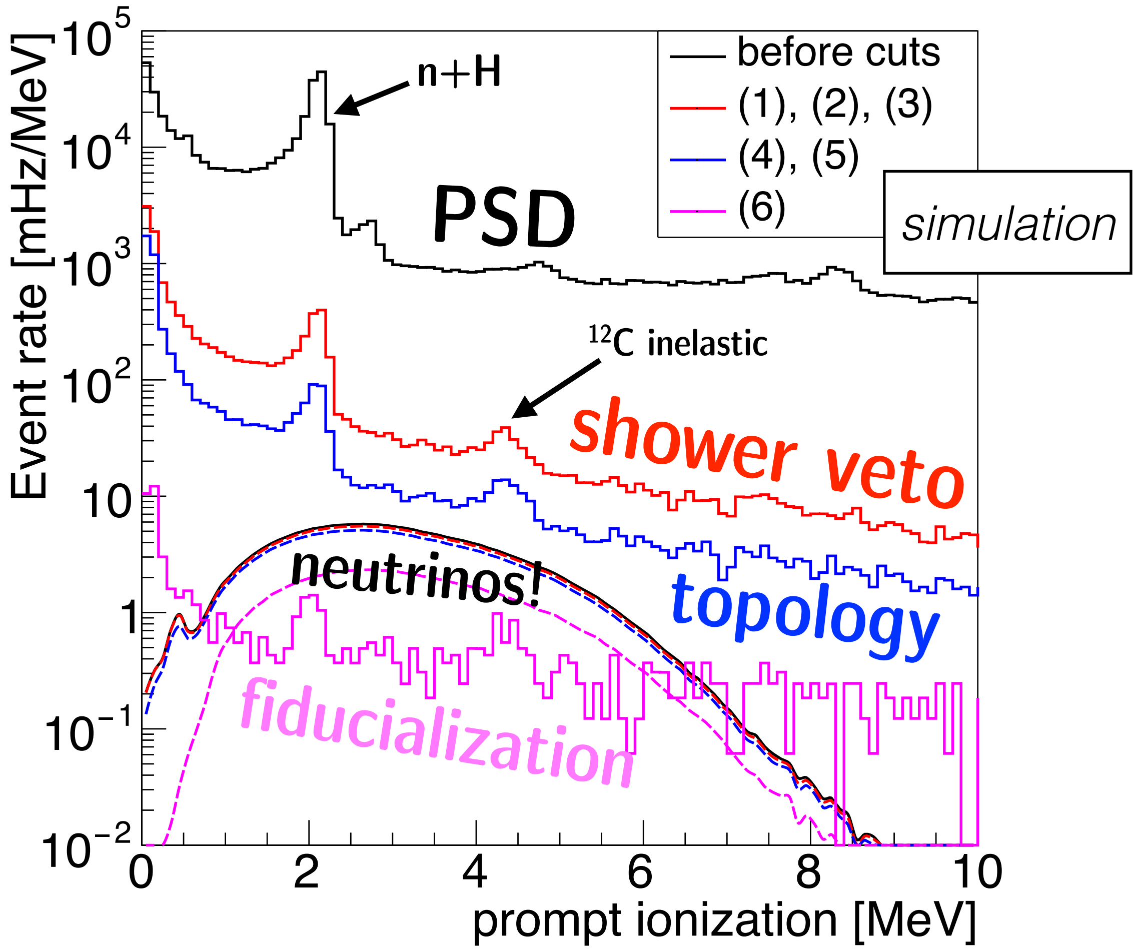
11x14 segments
1.2m length
4 tons
^{6}LiLS

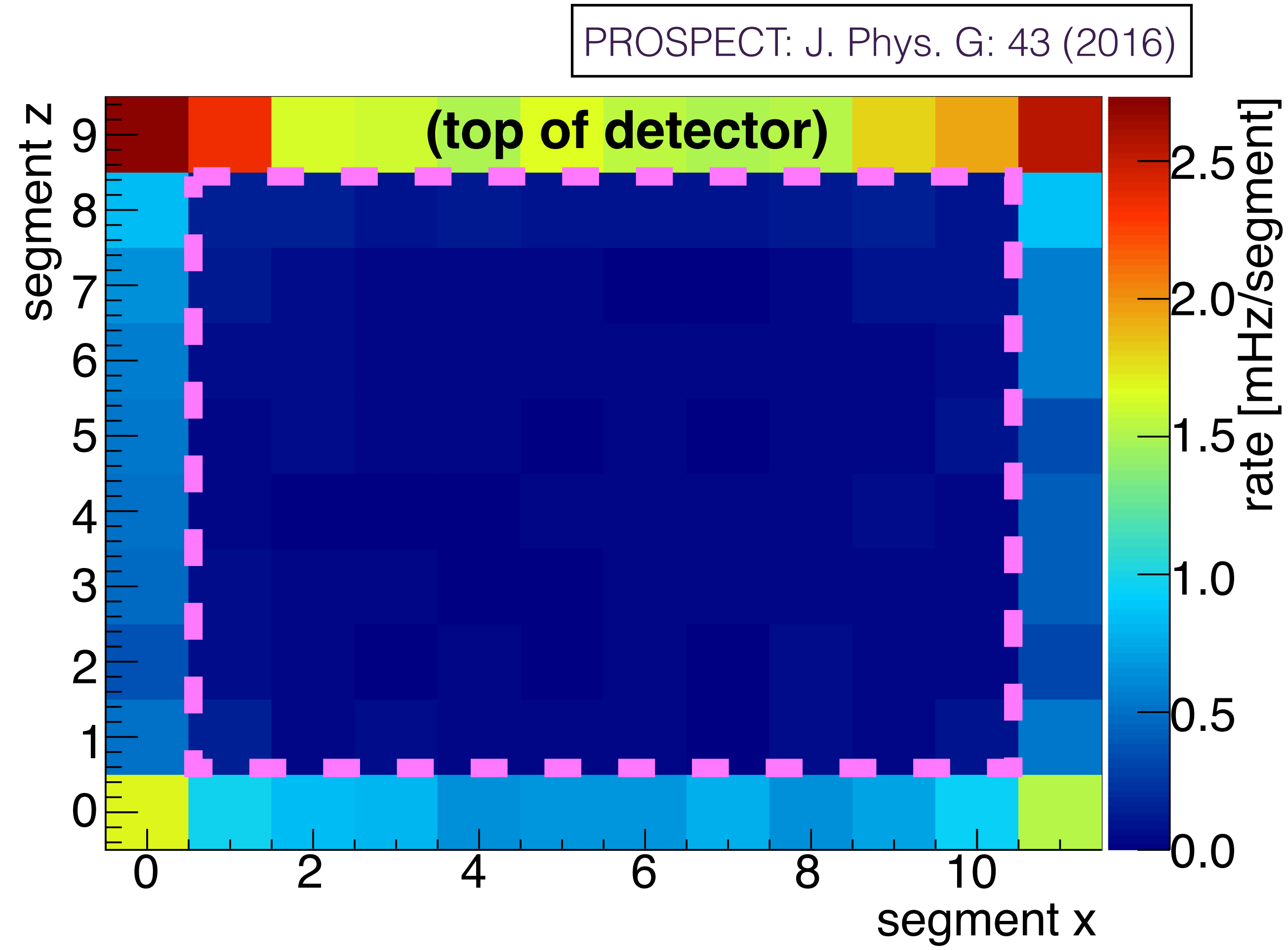


PROSPECT: arXiv:1808.00097

light collection
energy resolution
PSD performance

Can we combat the backgrounds? YES!



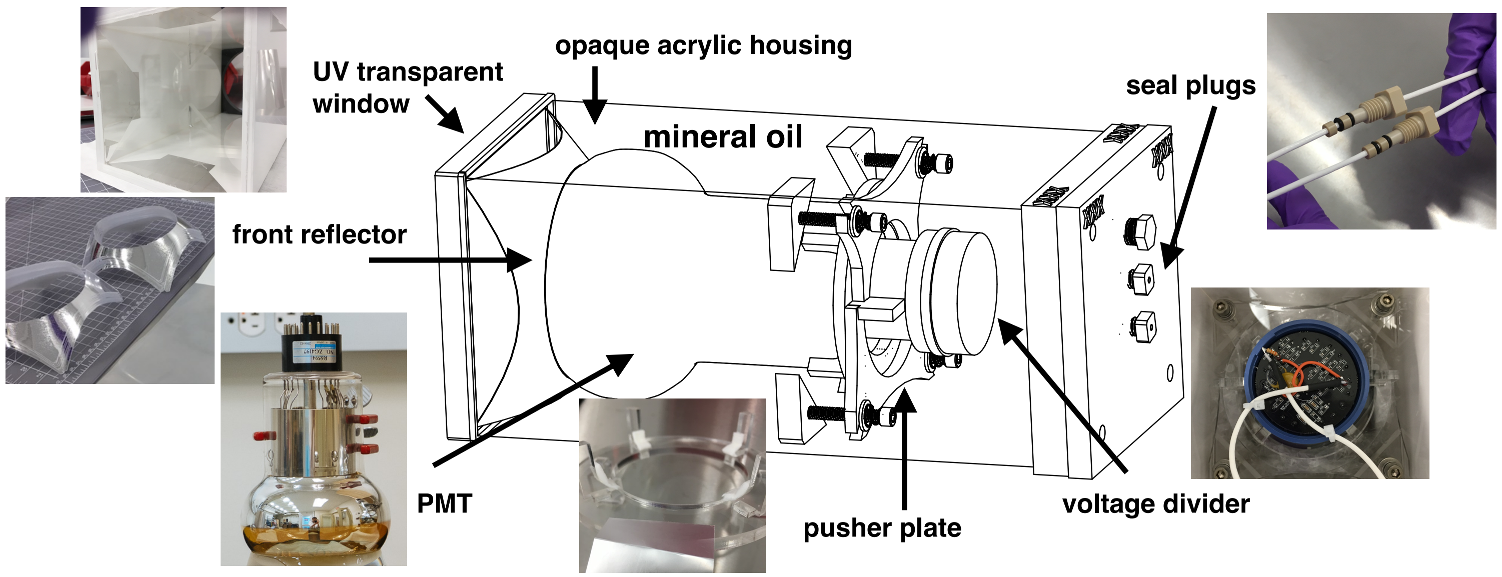


- knowledge from R&D program used to demonstrate feasibility of design
- combination of PSD, shower veto, topology, and fiducialization (clipped cosmogenics) cuts provide >10^4 active background suppression
- with validation of concept and detector experience, ready to build…

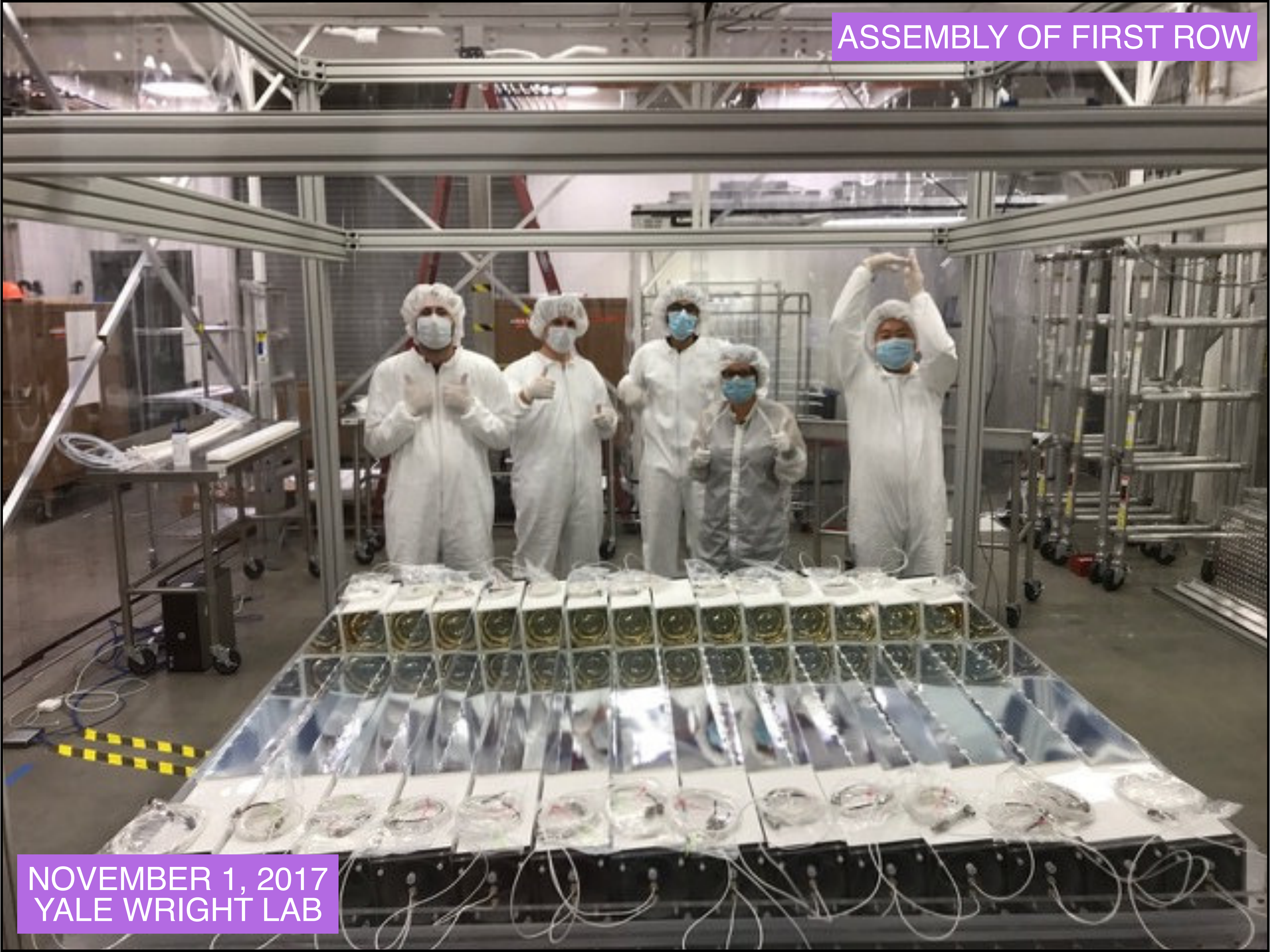
a combination of passive and active shielding enables a surface neutrino experiment

Optical module construction @ Yale

Modules in liquid volume: scintillator approved!



OCTOBER 25, 2017
YALE WRIGHT LABORATORY

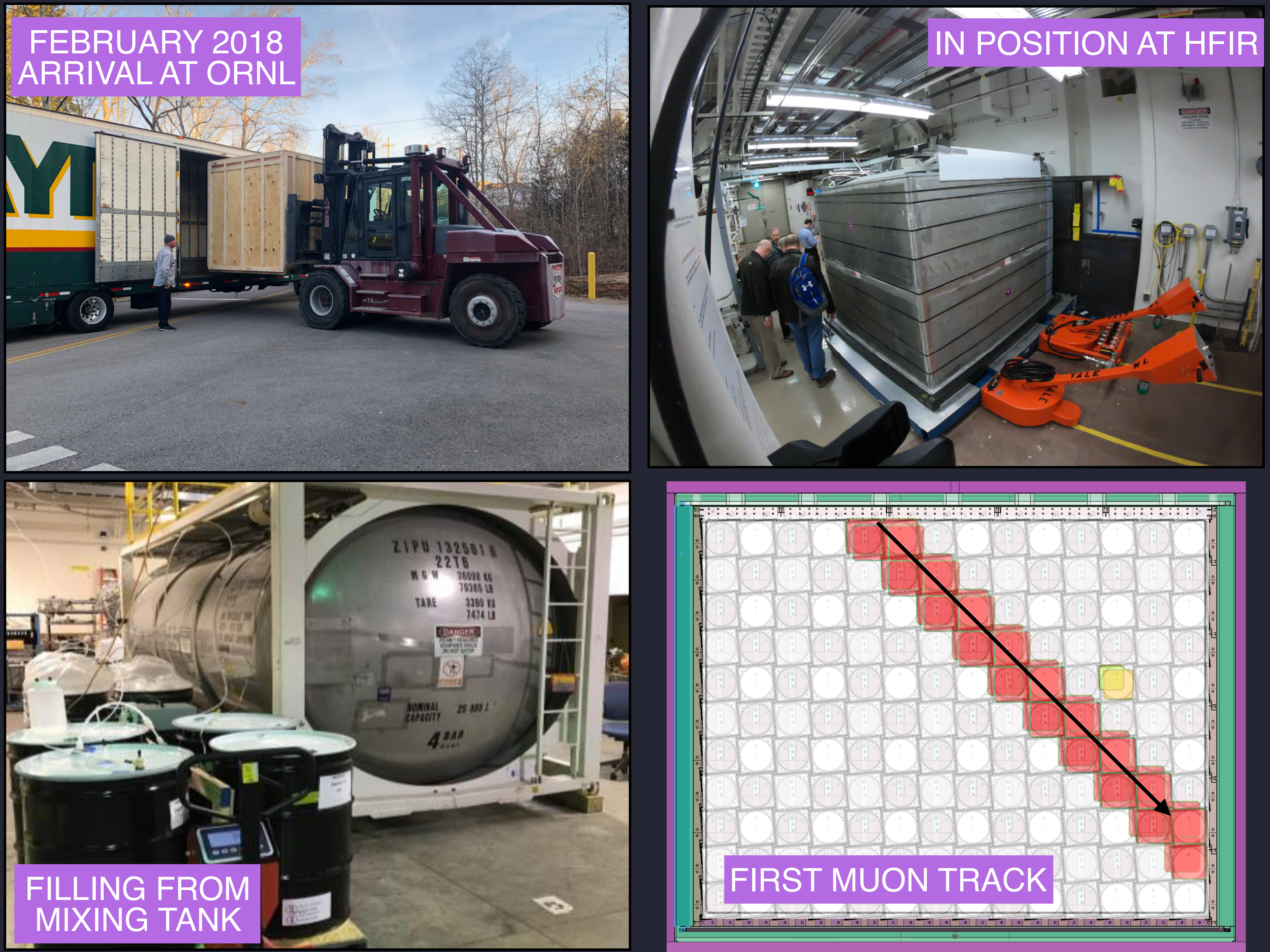

ASSEMBLY OF FIRST ROW
NOVEMBER 1, 2017
YALE WRIGHT LAB

PROSPECT layer in 30 seconds

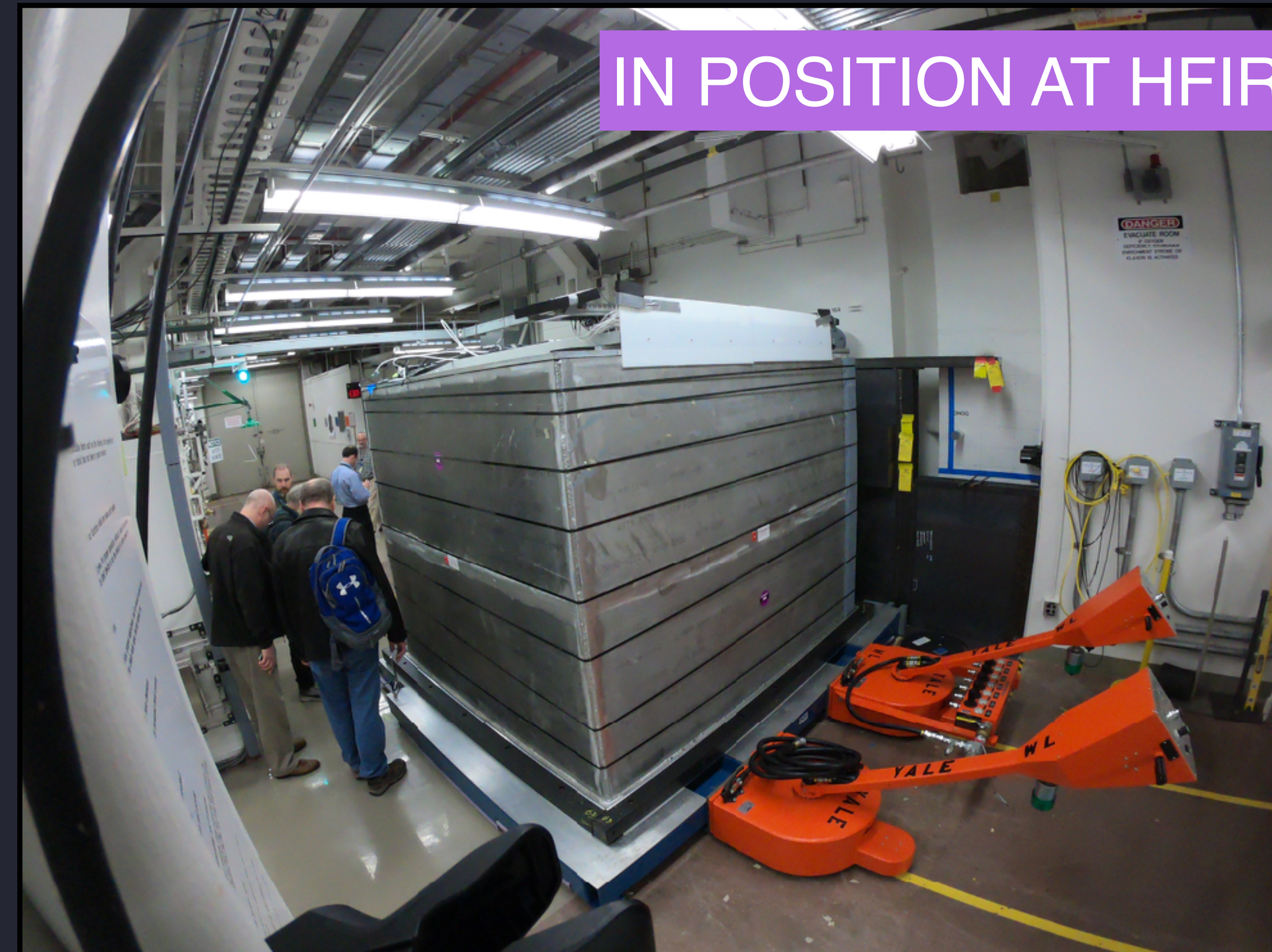
NOVEMBER 17, 2017
FINAL ROW INSTALLATION


AHHHHH!

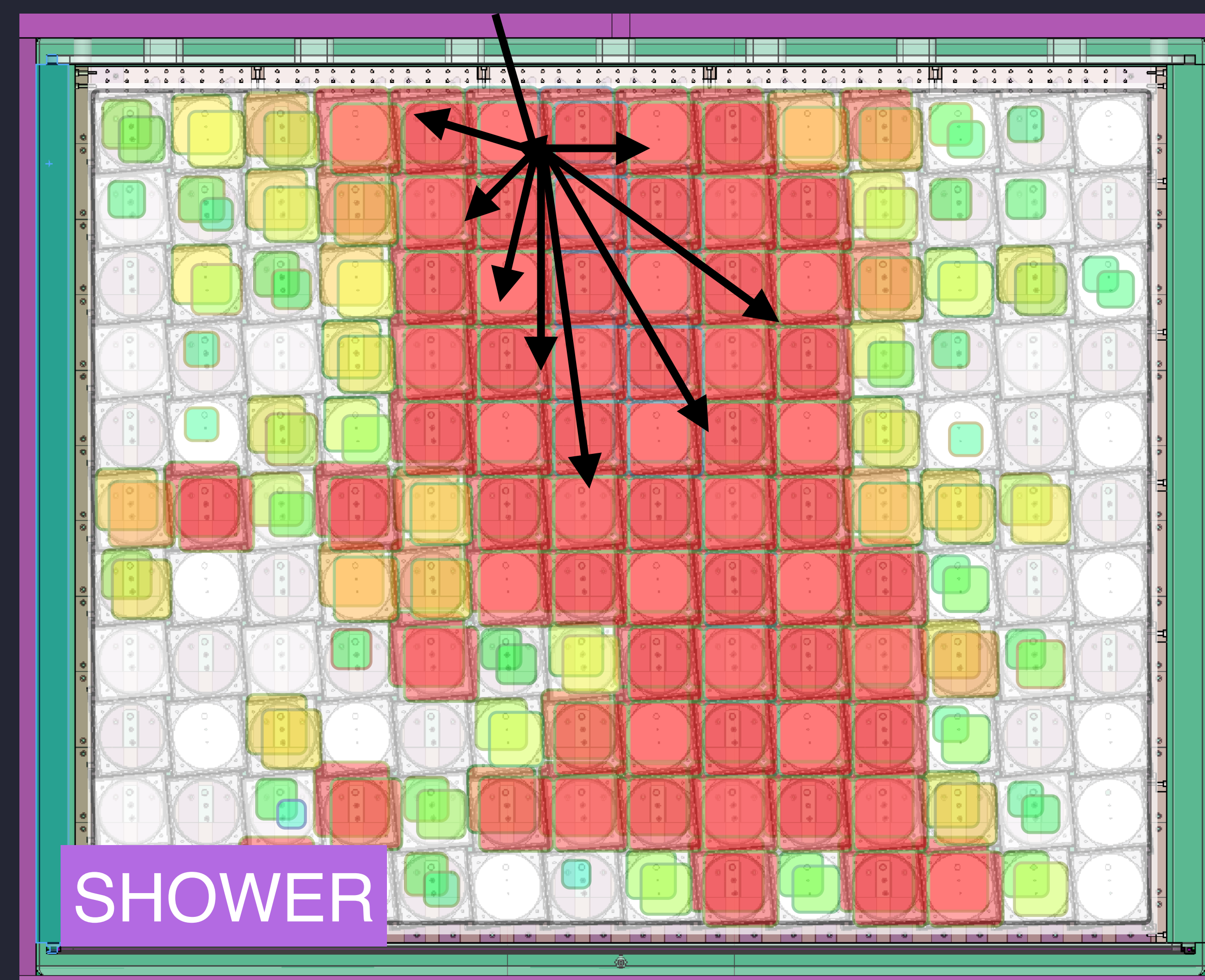

6½ TON CAP
WL 110
DEC 2017 - JAN 2018
DRY COMMISSIONING AT YALE


FEBRUARY 2018
ARRIVAL AT ORNL
IN POSITION AT HFIR
FILLING FROM
MIXING TANK
FIRST MUON TRACK
ZIPU 132501 8
22T6
TARE
NOMINAL
CAPACITY
4 BAR
DANGER
YALE

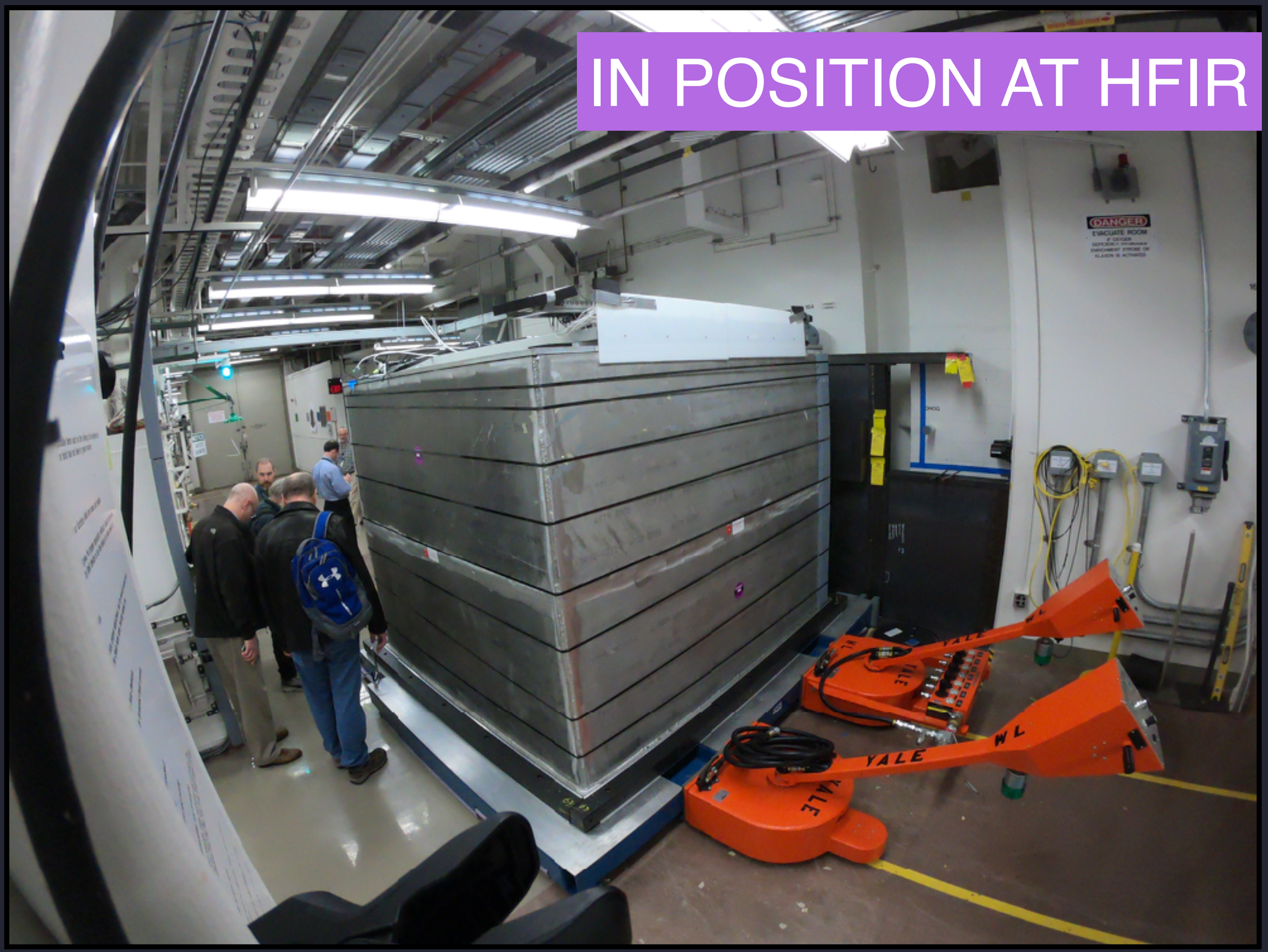

FEBRUARY 2018
ARRIVAL AT ORNL


IN POSITION AT HFIR
YALE

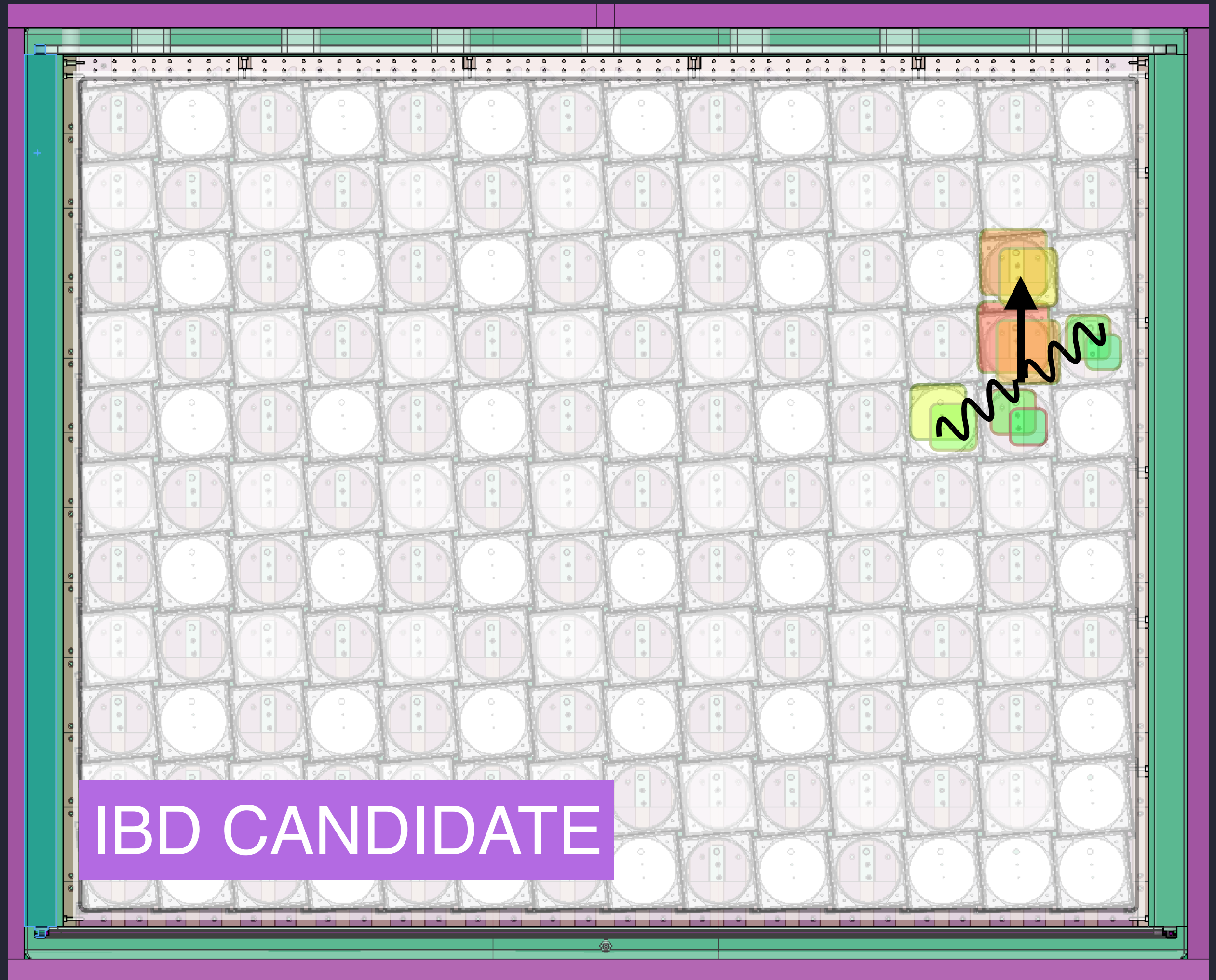

FILLING FROM
MIXING TANK
DANGER
4 BAR


SHOWER


FEBRUARY 2018
ARRIVAL AT ORNL

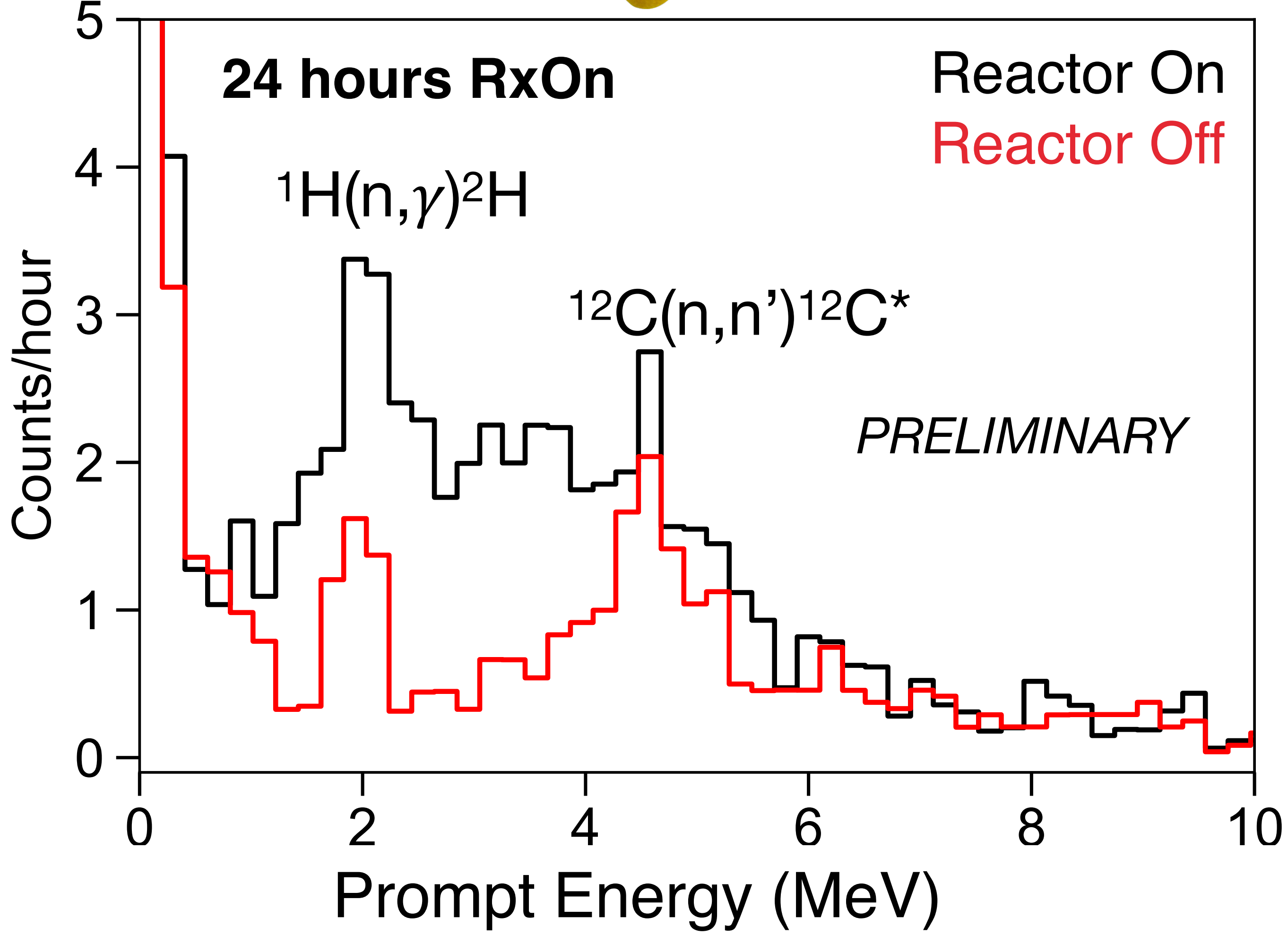

IN POSITION AT HFIR


FILLING FROM
MIXING TANK


IBD CANDIDATE

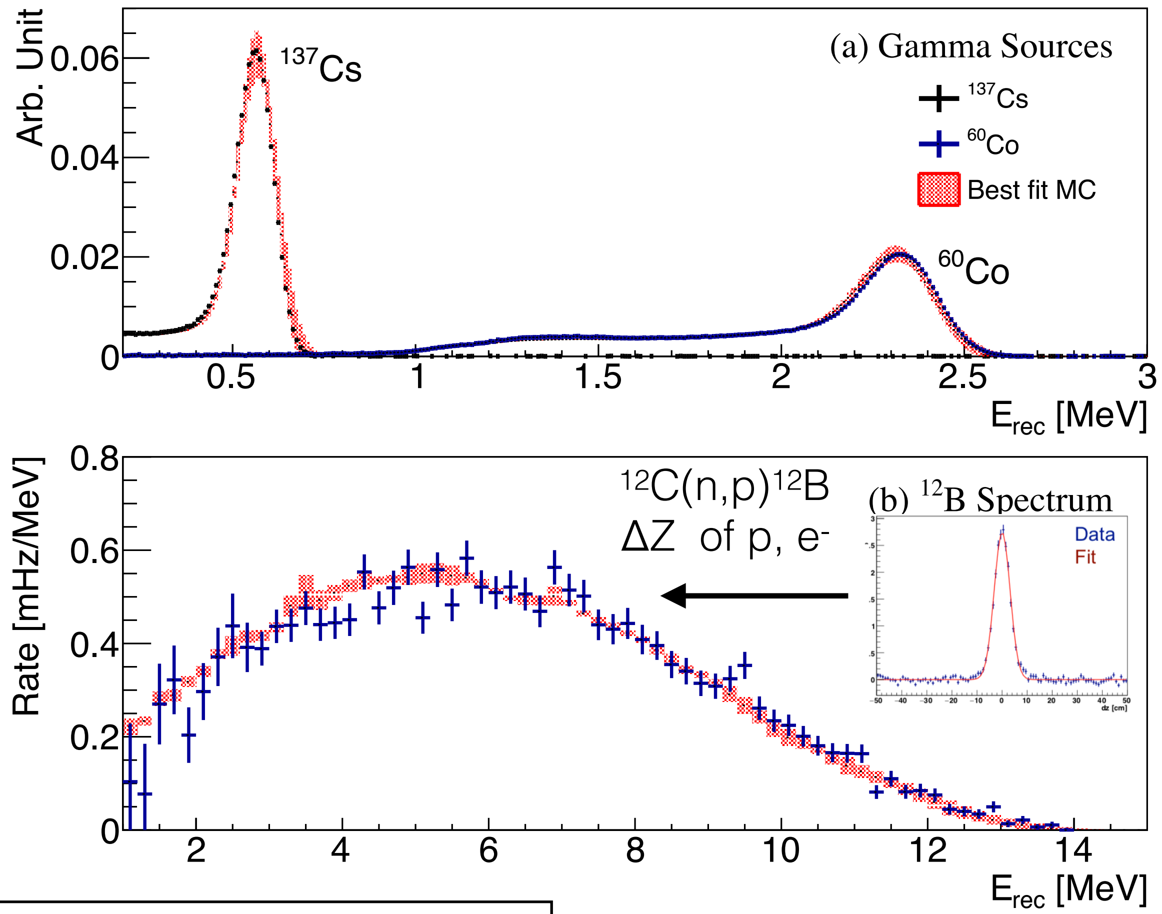
Within a few hours.. neutrinos!

- **March 5, 2018**: fully assembled detector began operation
- **Reactor On**: 1254±30 correlated events between [.8, 7.2] MeV
- **Reactor Off**: 614±20 correlated events (first off day March 16) benefit of being at a research reactor!
- subtract RxOn and RxOff for antineutrino spectrum
- distinct peaks in background from neutron interactions with H and ^{12}C



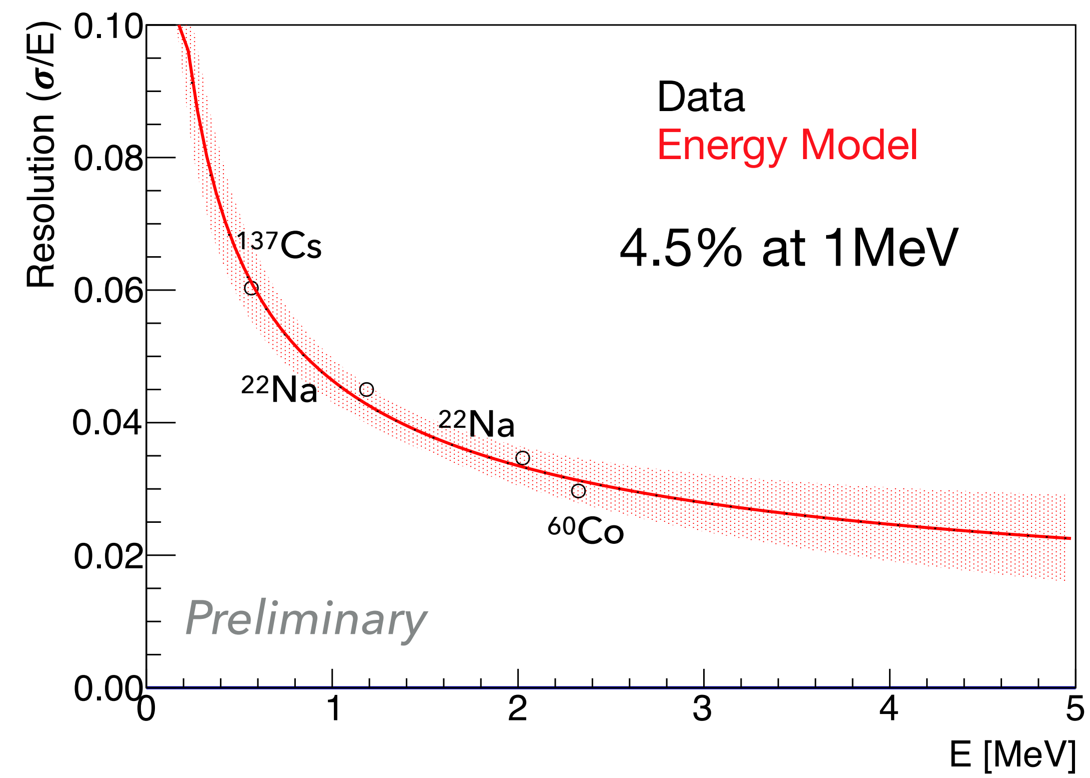
time to 5σ reactor antineutrino detection at Earth's surface: < 2 hours

Energy reconstruction



PROSPECT: arXiv:1806.02784

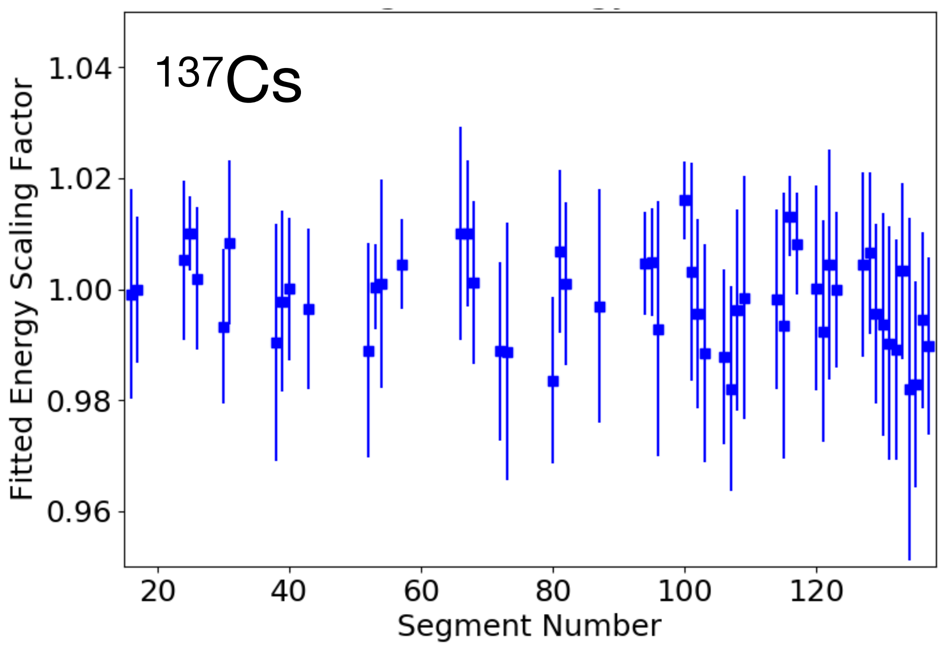
- ensure energy reconstruction is performing
- gamma sources deployed throughout detector, measure single segment and full detector response
- beta spectrum from proton PSD tagged ^{12}B production for high energy calibration
- full detector E_{rec} within 1% of E_{true}

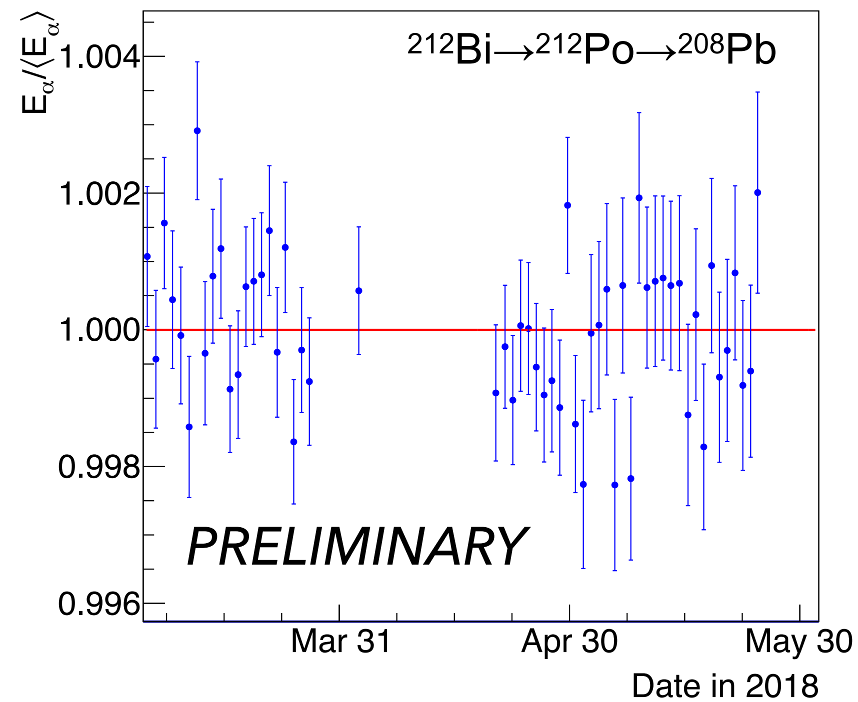


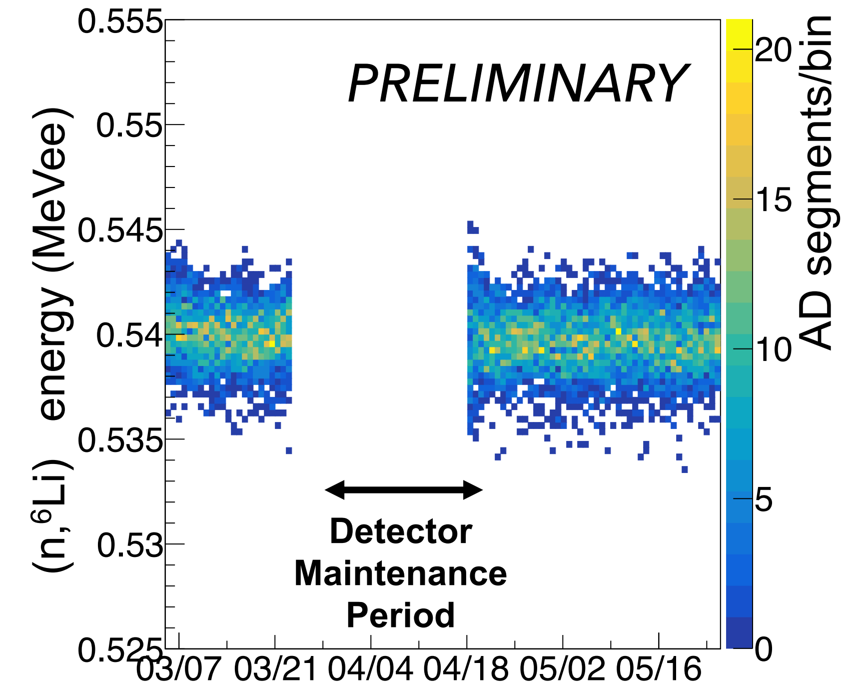
- high light collection: 795±15 PE/MeV
- resolution includes geometric/dark current

good energy reconstruction and resolution performance

Energy stability and uniformity







Need to ensure reconstruction is uniform over the 154 segments and time…

- many calibration and distributed intrinsic sources to look at the data in different ways (e.g. ^{137}Cs, BiPo α's, nLi)
- map energy response of each segment, uniformity ~1%
- map energy response of each segment over time, stability <1%

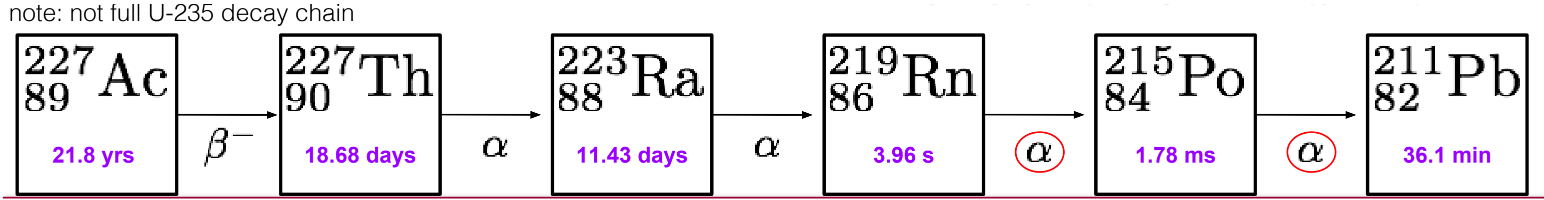
energy reconstruction is stable throughout the detector over time

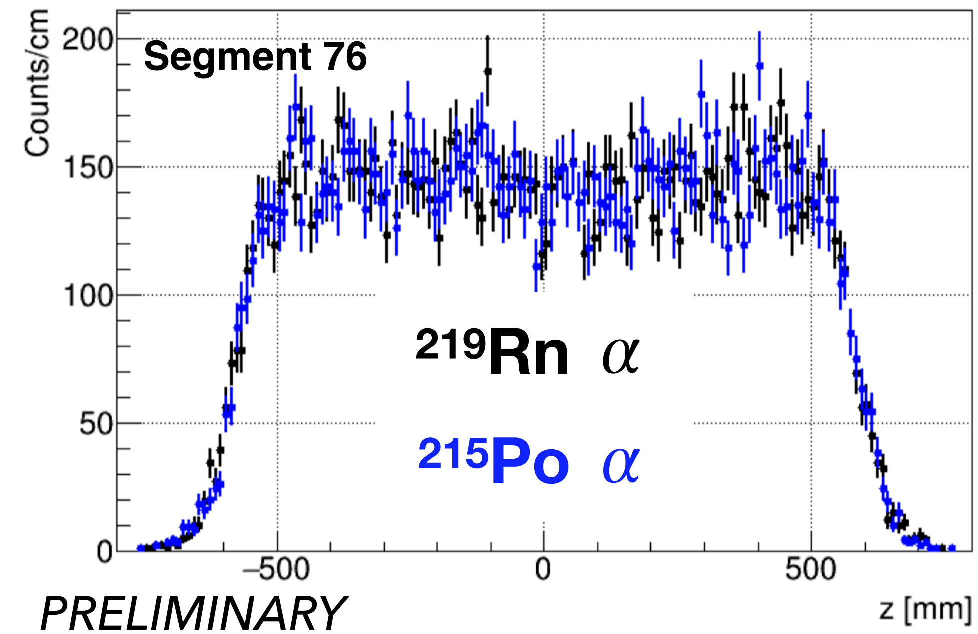
^{227}Ac for relative volume and position resolution

When 1 detector is really 154 individual detectors…

- relative mass and position resolution vital for oscillation search

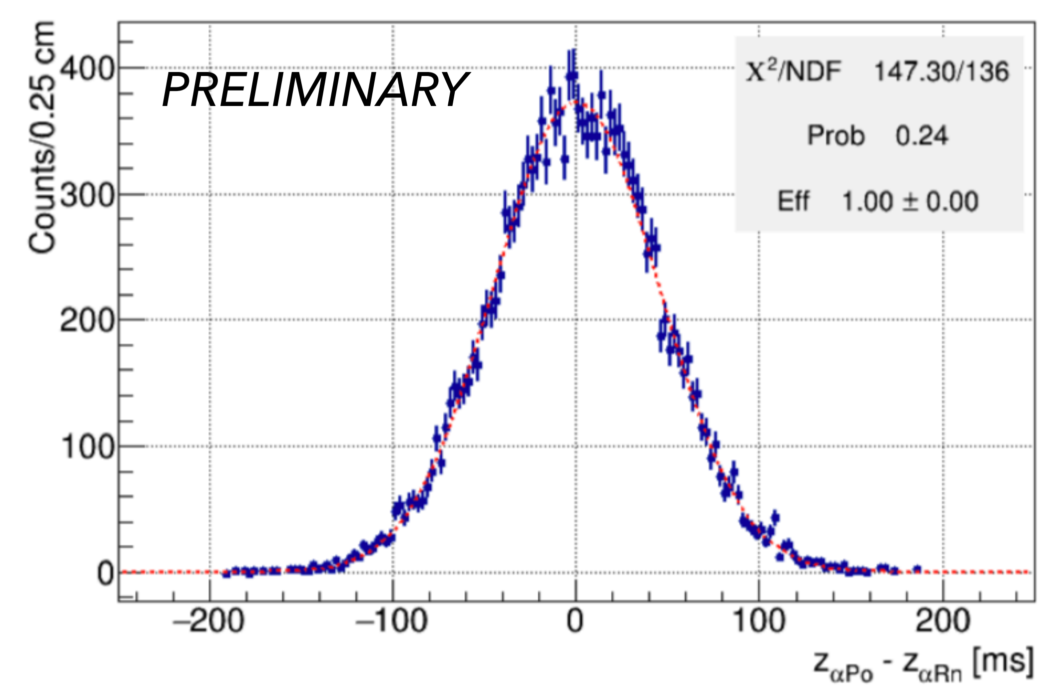
note: not full U-235 decay chain





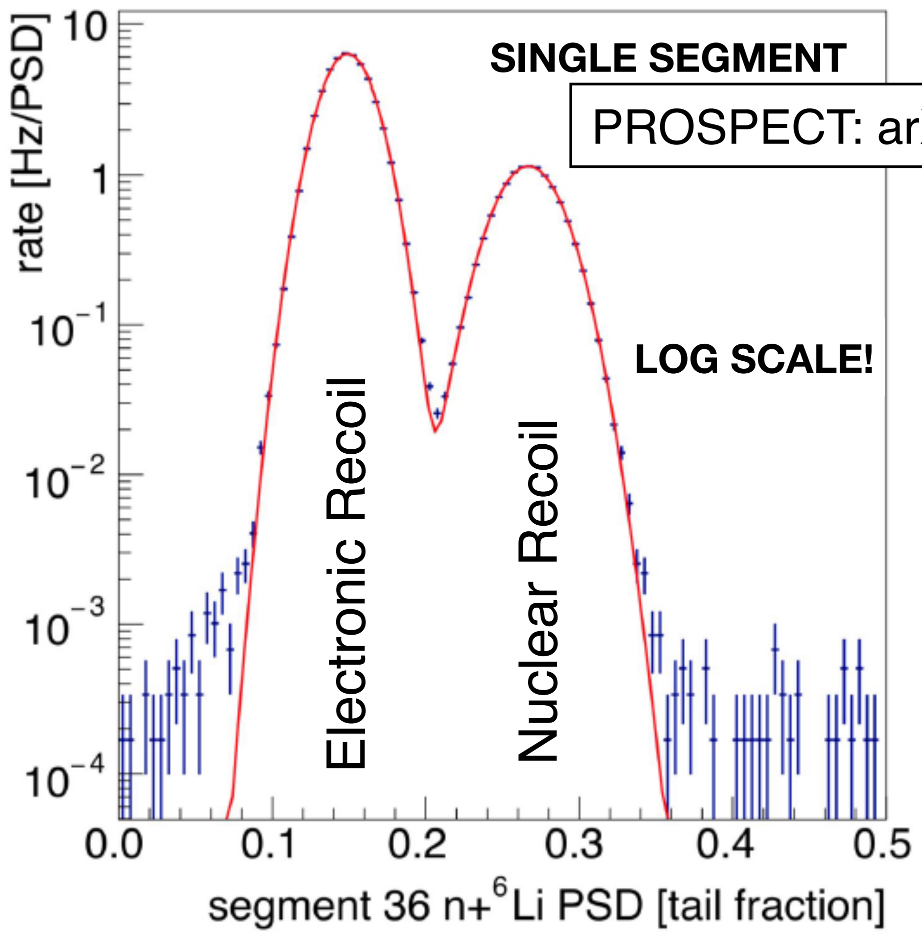
Uniformity in rates within segment

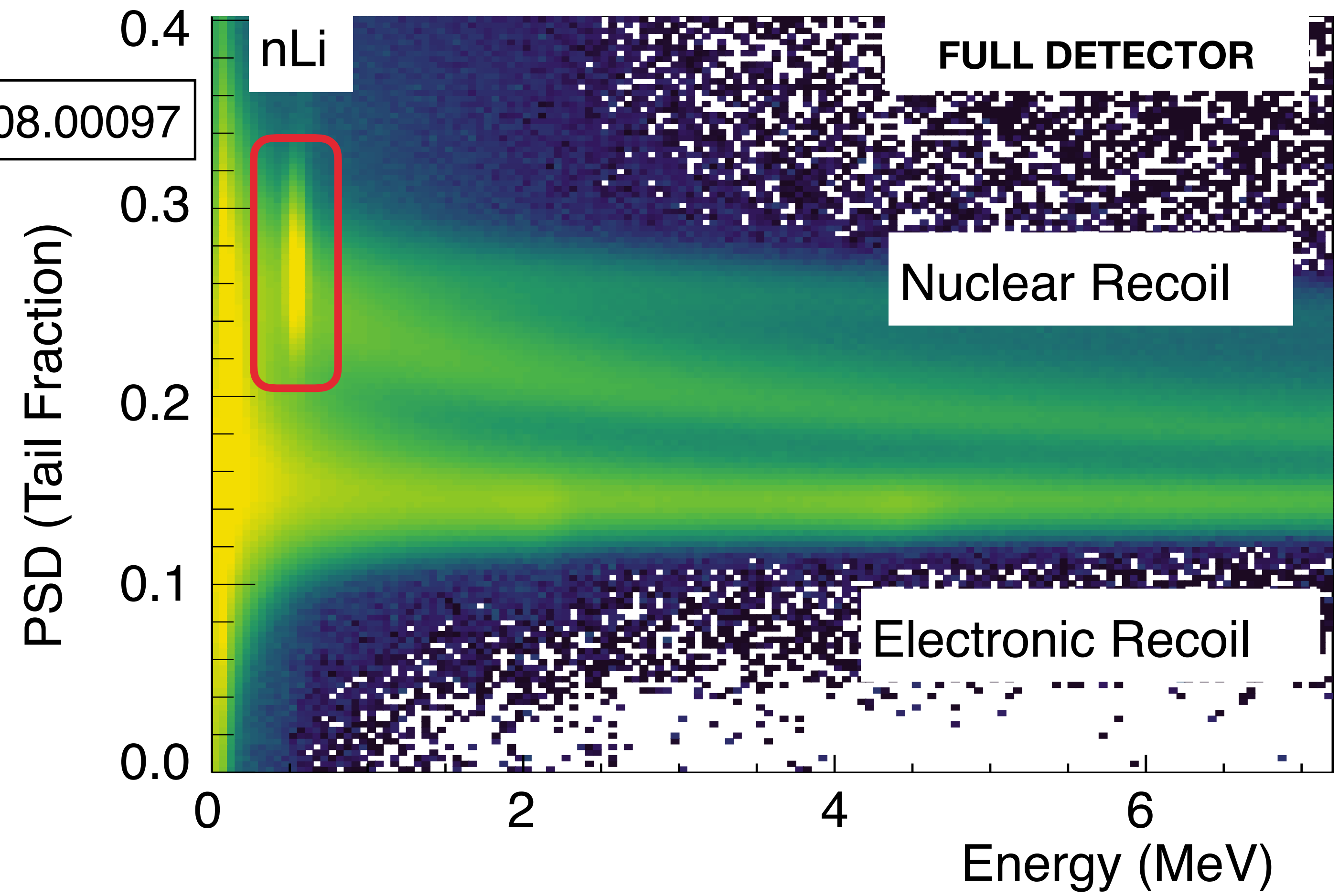
- ^{227}Ac uniformly distributed in LS prior to filling
- double alpha decay (^{219}Rn→^{215}Po→^{211}Pb), highly localized, 1.78ms half-life, not in our signal window
- variation of relative target mass in each segment < 1.5%
- measured absolute z-position resolution of < 5cm



very small volume variation and good position resolution

Pulse shape discrimination performance





- excellent particle ID of gamma interactions, neutron captures, and nuclear recoils
- dominant backgrounds: cosmogenic fast neutrons, reactor-related gamma rays
- vast majority identified and rejected by PSD for prompt and delayed signals
- tag IBDs with high efficiency and high purity

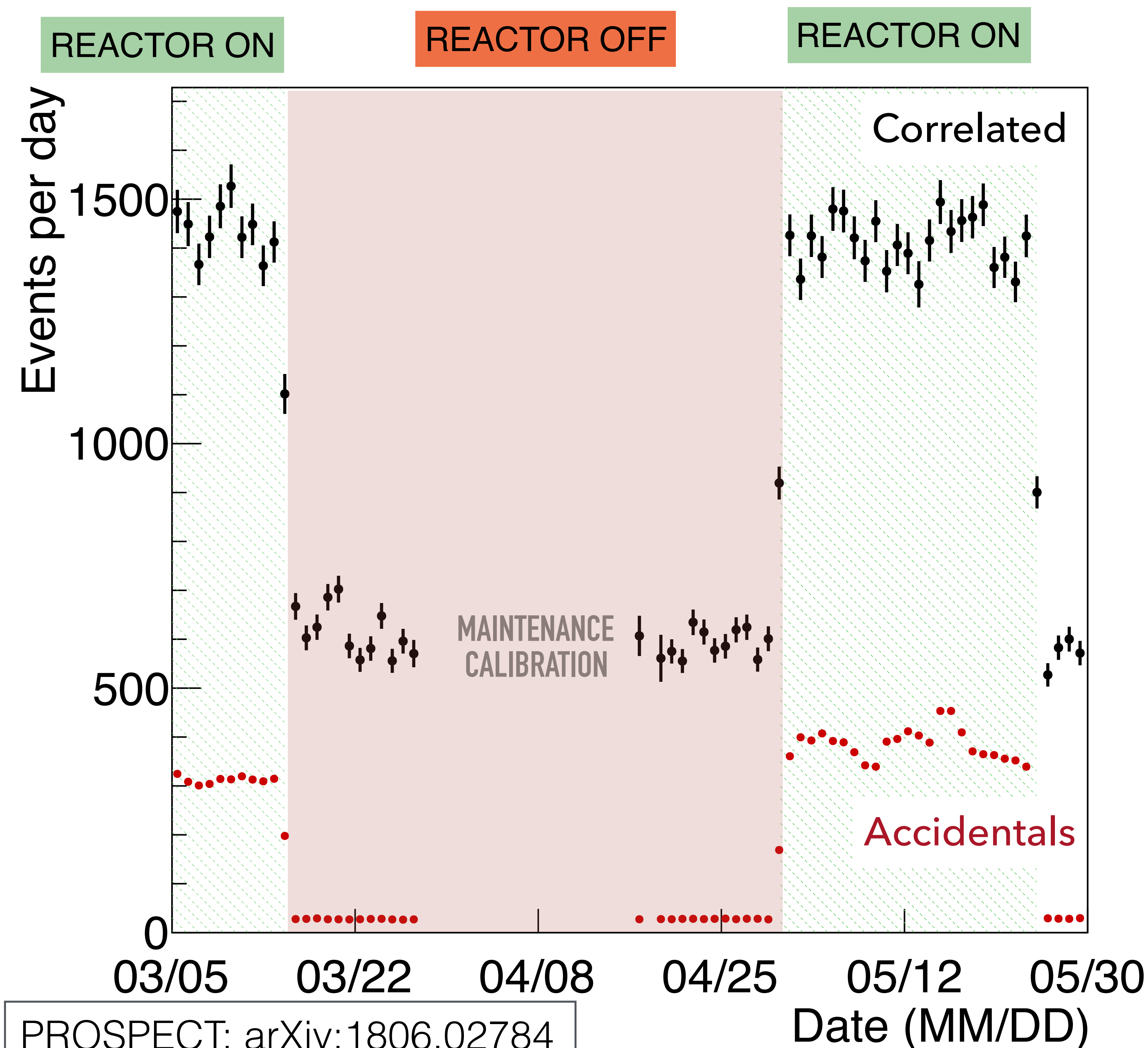
excellent pulse shape discrimination performance

Sterile neutrino analysis dataset

- 33 days of **Reactor On**
- 28 days of **Reactor Off**

From 0.8-7.2 MeV prompt:

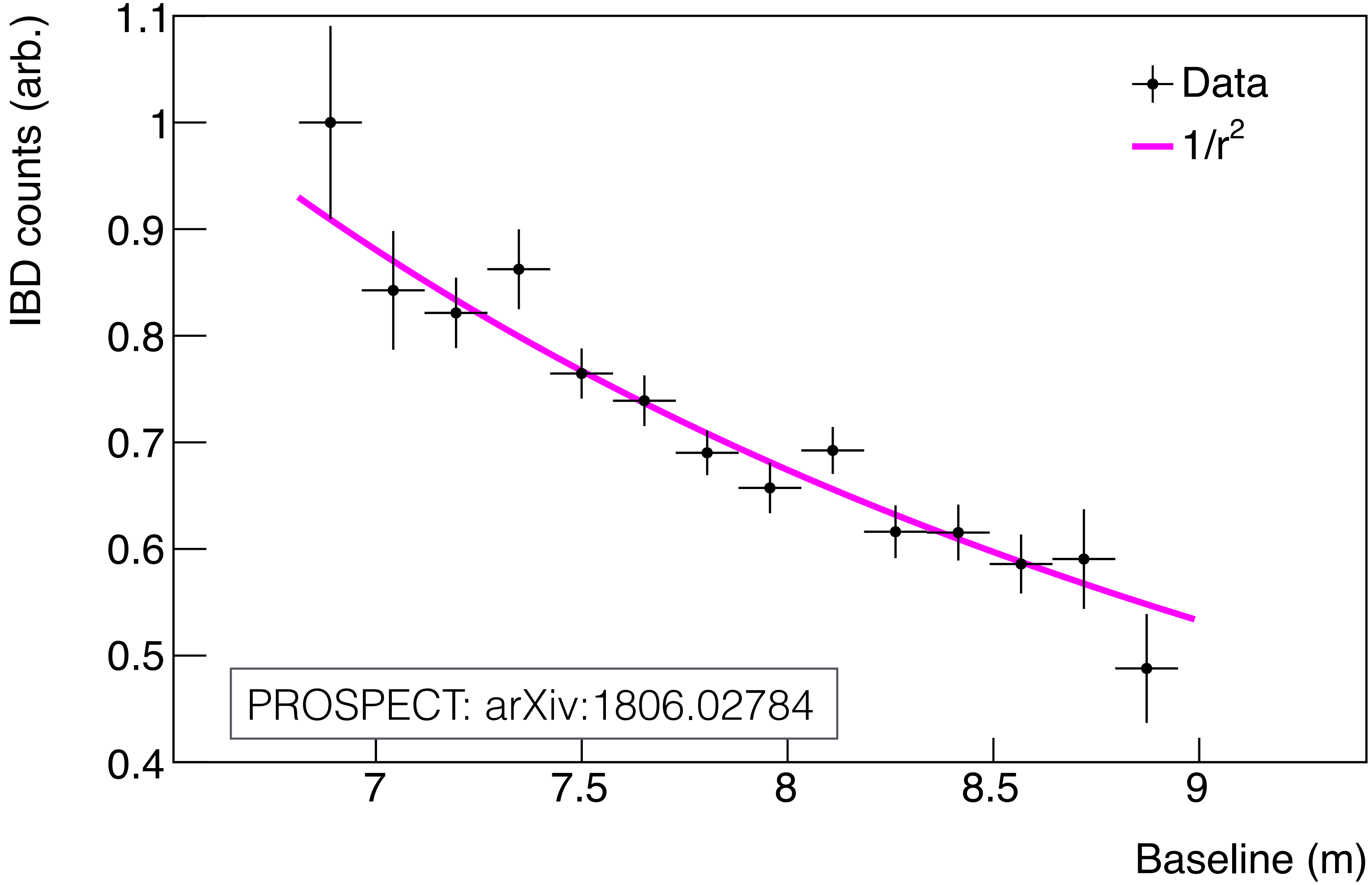
- 24,461 IBD interactions
- average of ~771 IBDs/day
- correlated S:B = 1.32
- accidental S:B = 2.20
- IBD event selection defined and frozen on 3 days of data



PROSPECT: arXiv:1806.02784

best signal:background achieved on-surface (< 1 mwe overburden)

IBD rate vs baseline

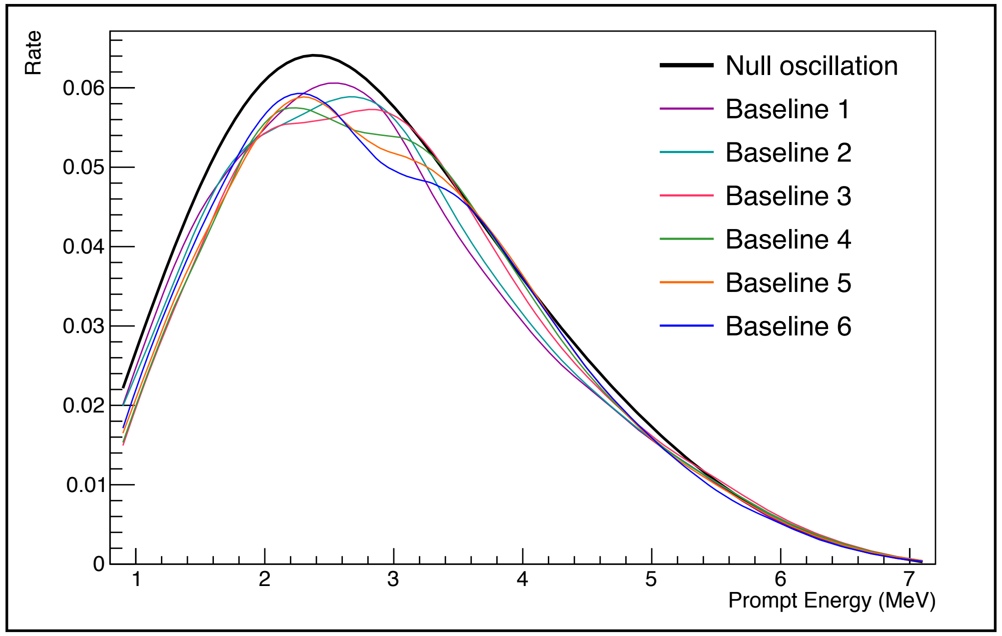


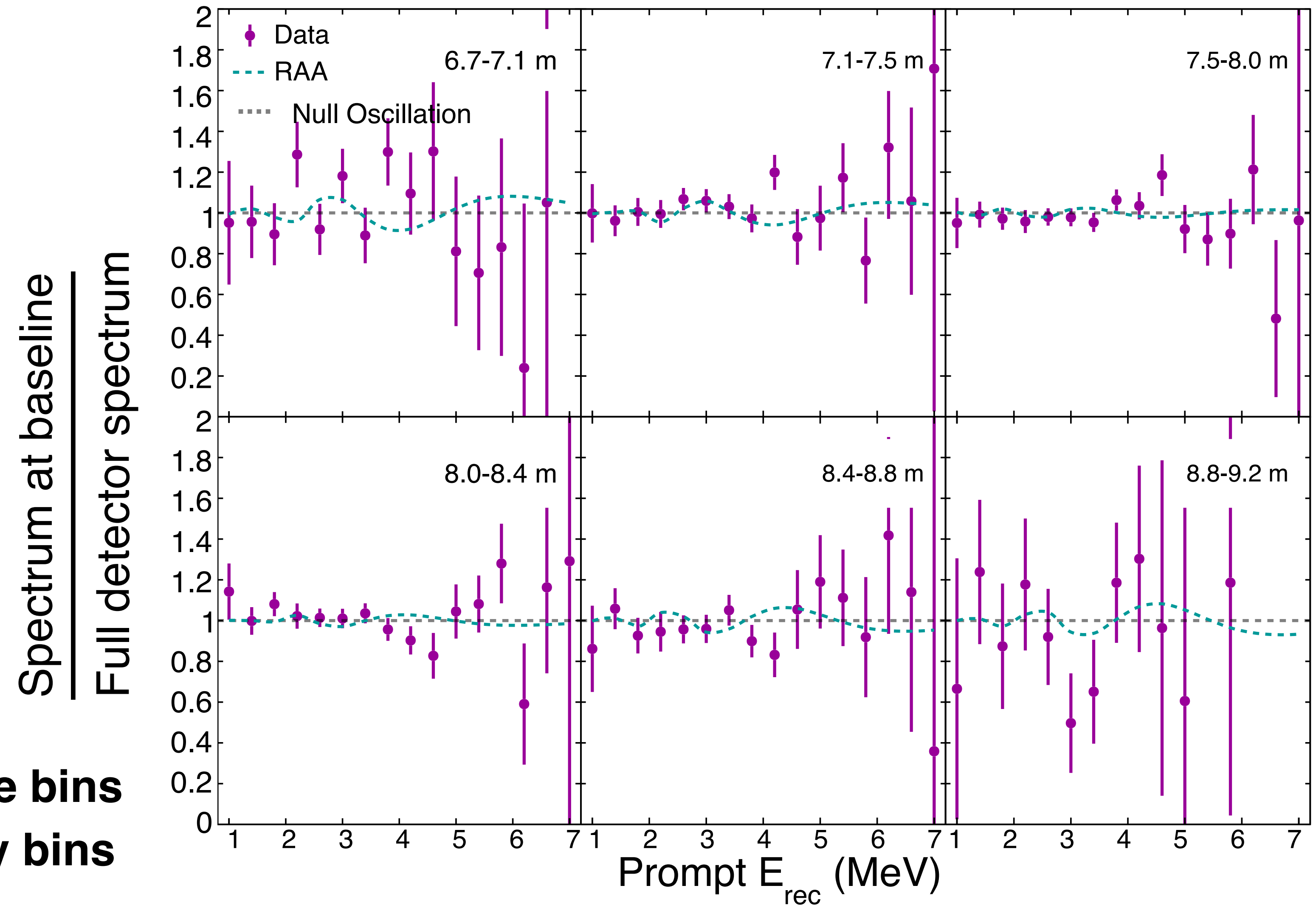
- bin events from 108 fiducial segments into 14 baseline bins
- observation of $1/r^2$ behavior throughout detector volume
- 40% flux decrease from front of detector to back as expected

IBD spectrum vs baseline

PROSPECT: arXiv:1806.02784

illustration of baseline dependent oscillation





6 baseline bins

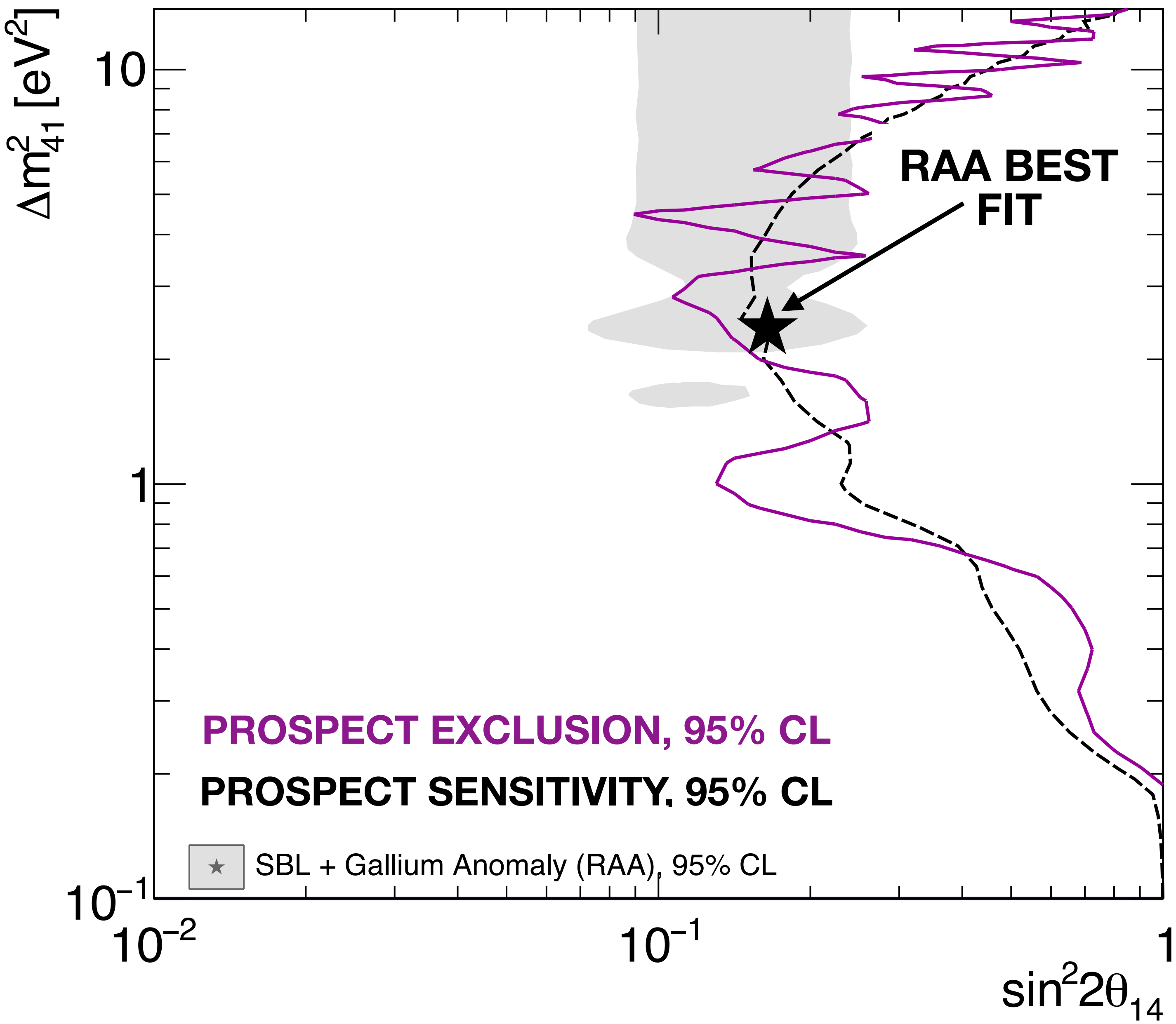
16 energy bins

- sterile oscillations would distort content of energy bins
- compare spectra from 6 baselines to measured full-detector spectrum
- baseline-energy (L-E) ratio analysis is independent of reactor models

Sterile neutrino search with first dataset

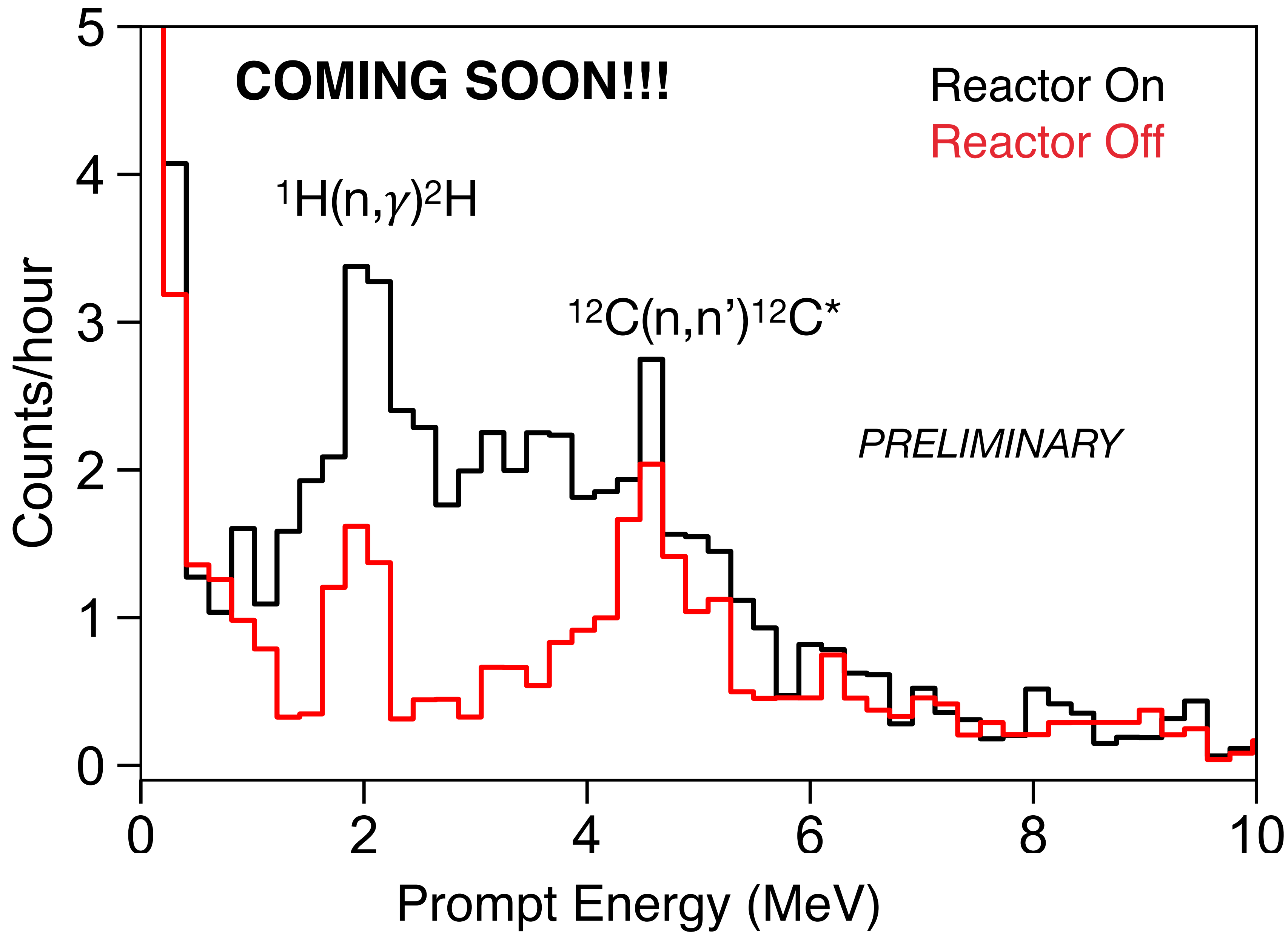
- compare measured L-E spectra to normalized full detector spectrum for each (Δm^2, $\sin^2 2\theta$) to build χ^2
- this includes covariance matrices to capture all stat+sys uncertainties
- to determine confidence intervals use Feldman-Cousins approach
- generate χ^2 map for each (Δm^2, $\sin^2 2\theta$) with PROSPECT-like toy MC
- 95% exclusion curve based on 33 days Reactor On operation
- direct test of the Reactor Antineutrino Anomaly

PROSPECT: arXiv:1806.02784



first result: disfavors RAA best-fit point at >95% (2.2σ)

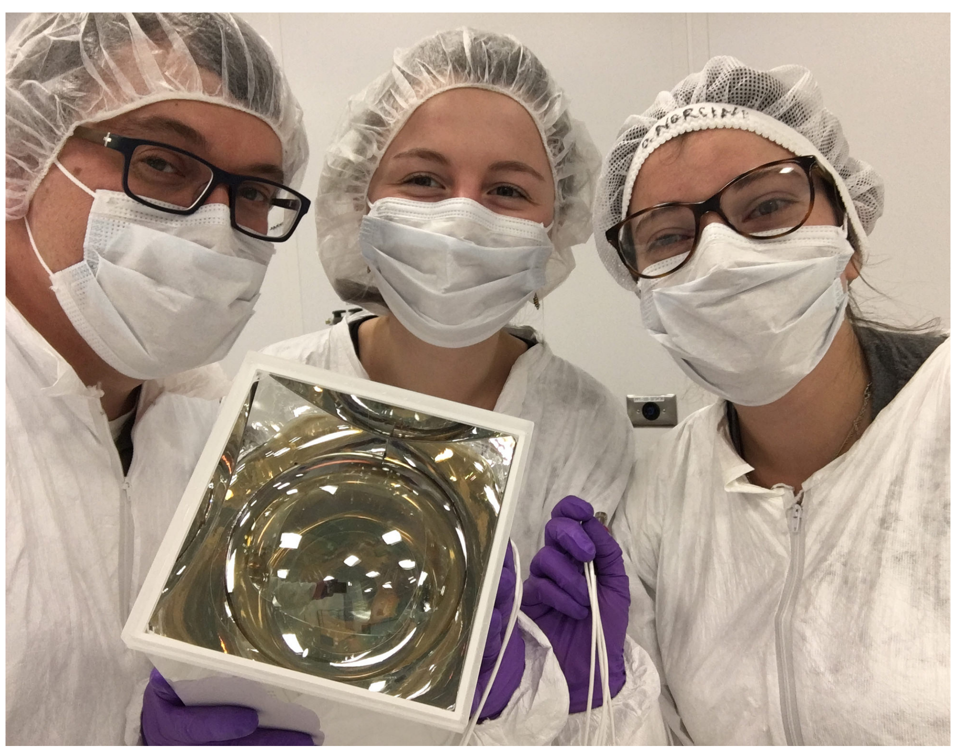
World leading ^{235}U antineutrino spectrum



PROSPECT: J. Phys. G: Nucl. Part. Phys. 43 (2016) 113001

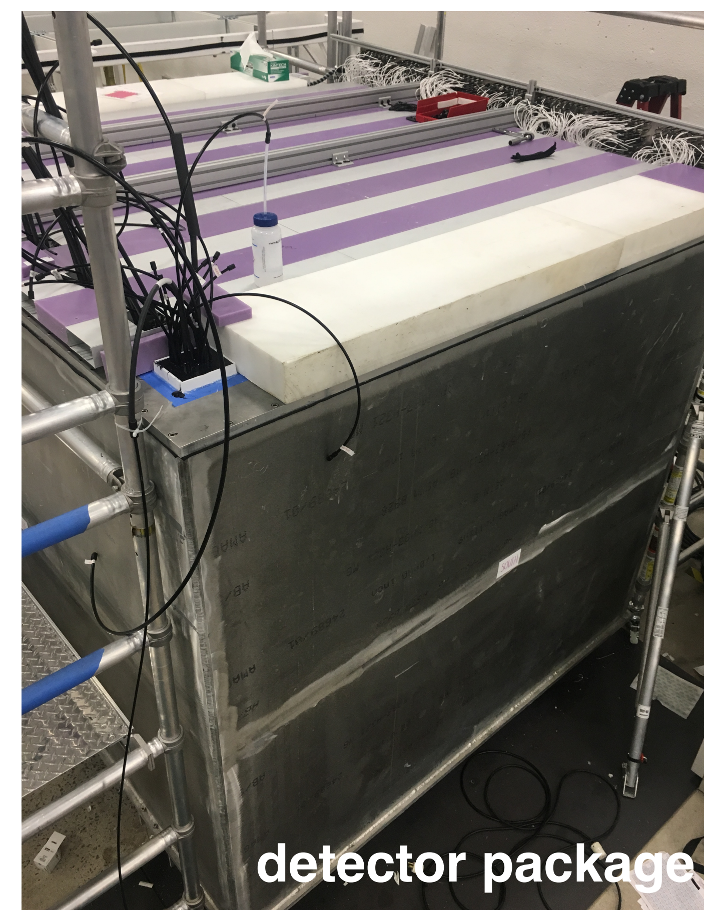
Stay tuned for PROSPECT

1. Reactors are an incredible source of neutrinos and new experiments at short baselines could uncover new physics.
2. PROSPECT is a unique, segmented near-surface neutrino detector that has
    - driven an extensive R&D program with ^{6}LiLS scintillation detectors
    - constructed and installed the detector in <2 years
    - observed neutrinos at an HEU reactor at 5σ in ~2 hours on surface.
3. PROSPECT disfavors the RAA sterile neutrino hypothesis at 2.2σ and spectrum on it's way!



first optical module!

inner detector



detector package

Feldman-Cousins approach

- Using Feldman-Cousins,

  p-value for 3ν oscillation hypothesis = 0.58 ($\chi2$/NDF = 61.9/80)

  p-value for RAA sterile oscillation hypothesis = 0.013 ($\chi2$/NDF = 68.7/78)

  (Best fit has $\chi2$/NDF = 57.9/78 (Δm^2, $\sin^2 2\theta$)=(0.50, 0.35))

- Using standard (incorrect) confidence level assignment (using Wilk's theorem):

  p-value for 3ν oscillation hypothesis = 0.14

  p-value for RAA sterile oscillation hypothesis = 0.005

- If standard (incorrect) confidence levels used instead of Feldman-Cousins:

  We say 3ν is <u>less</u> compatible with data than it actually is!

- Shows the importance of using Feldman-Cousins

Sterile analysis analysis selection

PROSPECT: arXiv:1806.02784

Cut	Accepted value
prompt cluster PSD	within 3σ of electronic recoil band mean
delay cluster PSD	above 3.6σ of electronic recoil band mean
delay cluster E_{rec}	$0.46 < E_{rec}(\mathrm{MeV}) < 0.60$
prompt-delay coincidence time	(+1, +120)us
prompt-delay position spread in segment (along z)	within 1 segment (14cm), within 1 adjacent segment (18cm)
muon veto	delay within (0,+100)us of muon cluster (E_{rec} > 15MeV)
fast neutron veto	delay within (-200,-200)us of FN cluster (high PSD, E_{rec} > 0.25MeV)
fiducial (along z) veto	within outermost layer of segments (14cm)

Modeling the antineutrino energy spectrum

Two major approaches to calculate spectrum:

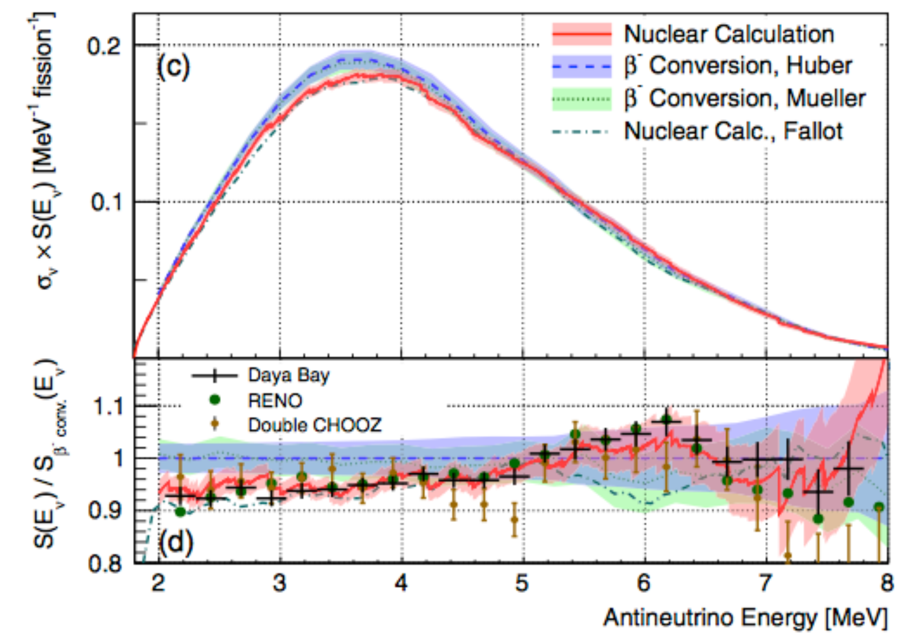
Decay Rate, Branching Fraction, Spectrum

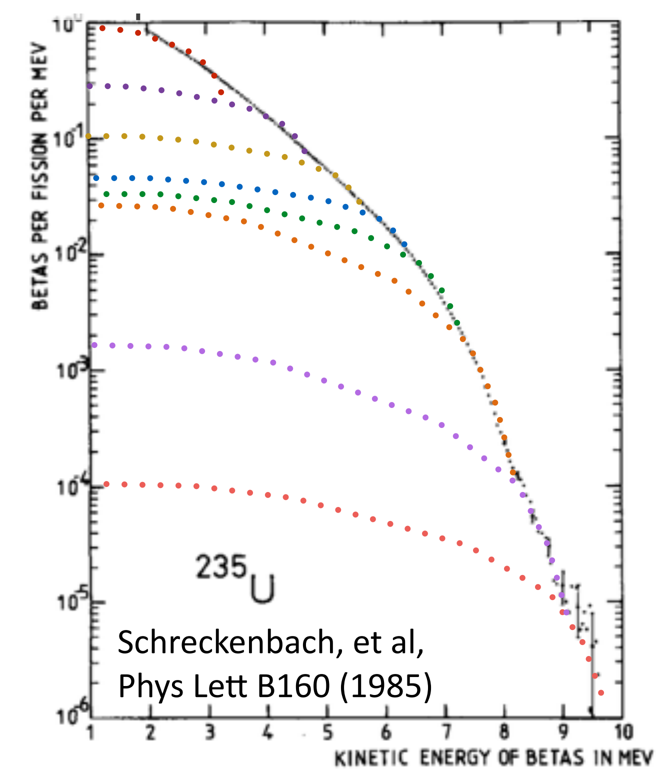
$$S(E_{\bar{\nu}}) = \sum_{i=0}^{n} \boxed{R_i} \sum_{j=0}^{m} \boxed{f_{ij}} \boxed{S_{ij}(E_{\bar{\nu}})}.$$

1. *Ab-initio*
   - sum the spectrum from thousands of beta branches using nuclear databases
   - databases incomplete and large uncertainties

2. Beta conversion
   - empirical measurements of beta spectra for each isotope (foils, 1980's)
   - fit with 'virtual branches' and converted to antineutrino spectra
   - avoids messy beta branch physics
   - Huber model most modern, popular
     Phys. Rev. C 85, 029901 (2012)

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

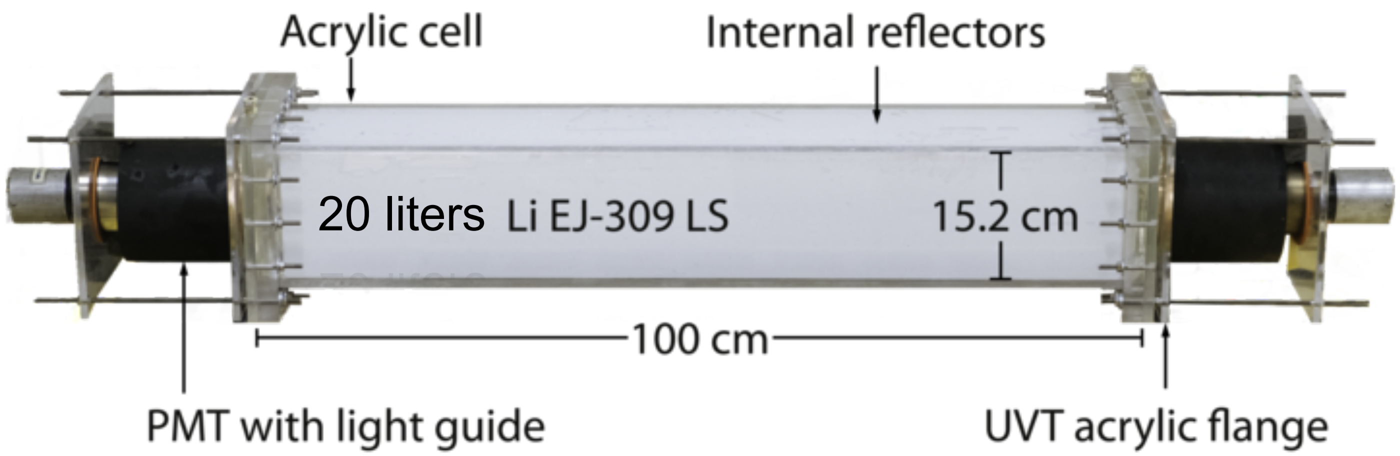


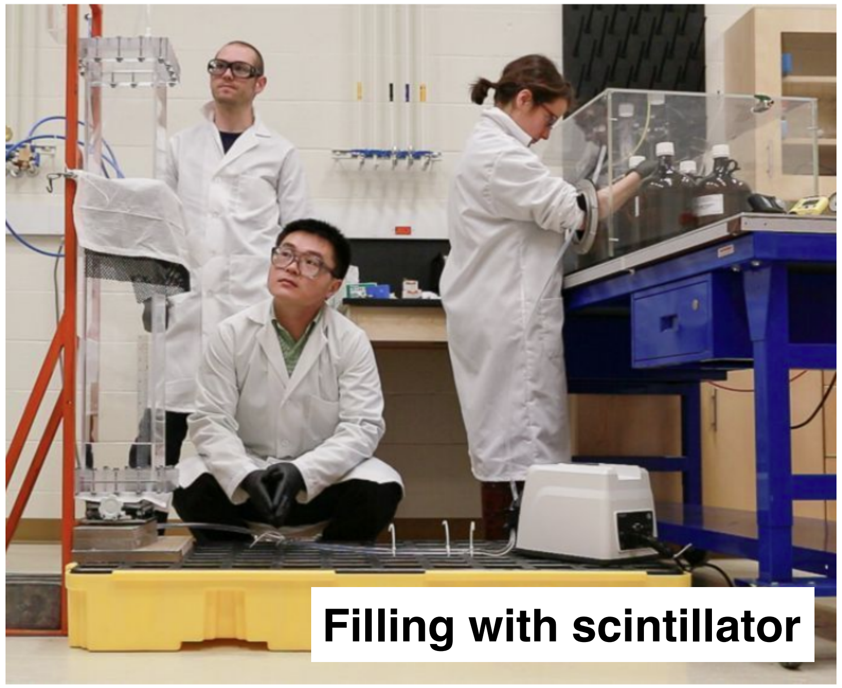


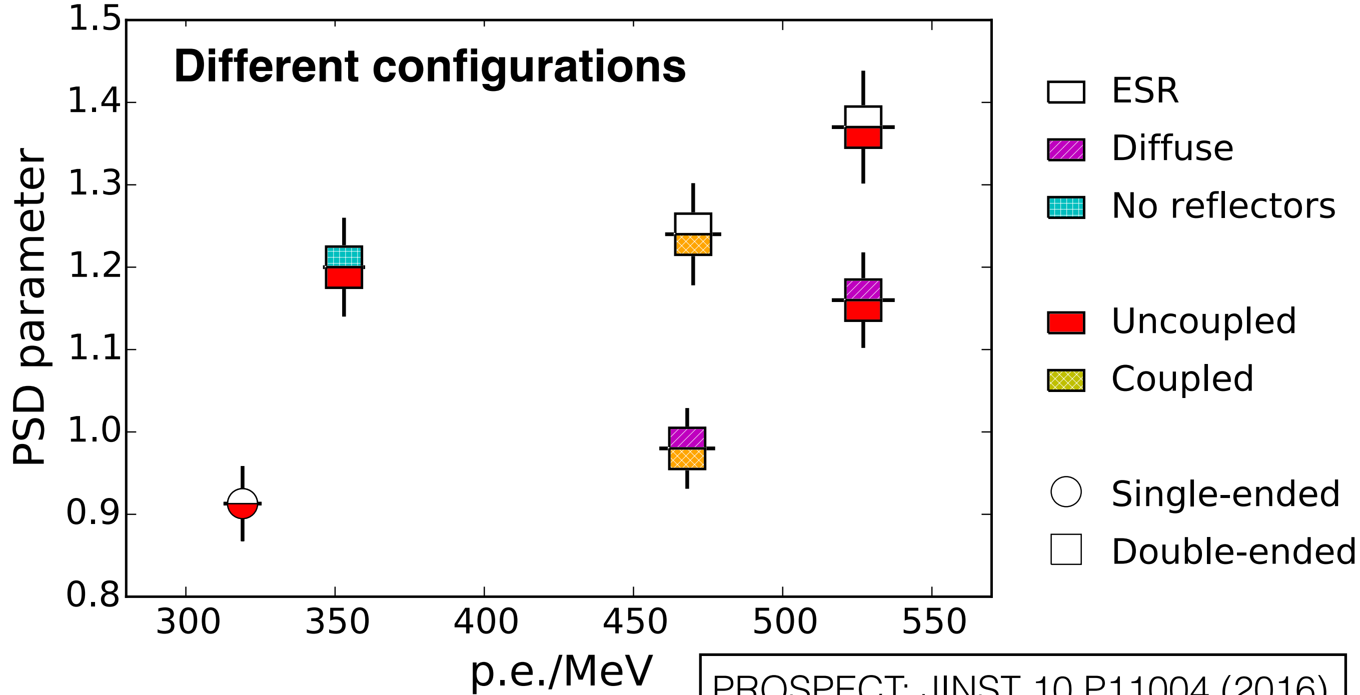
Schreckenbach, et al, Phys Lett B160 (1985)

predicting reactor spectra is complicated and uncertainties are currently large

Designing the segments: PROSPECT-20





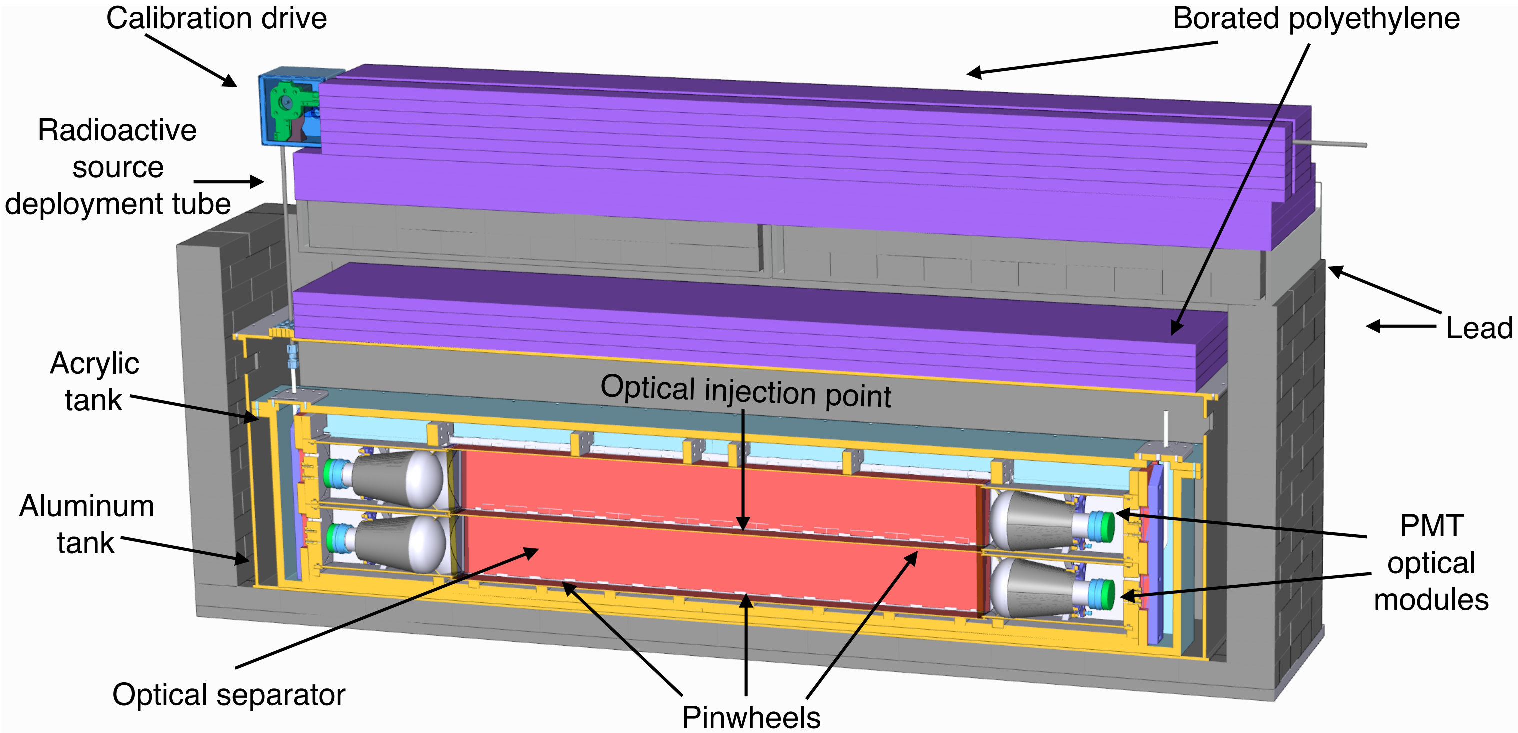


PROSPECT: JINST 10 P11004 (2016)

First test of realistic geometry:

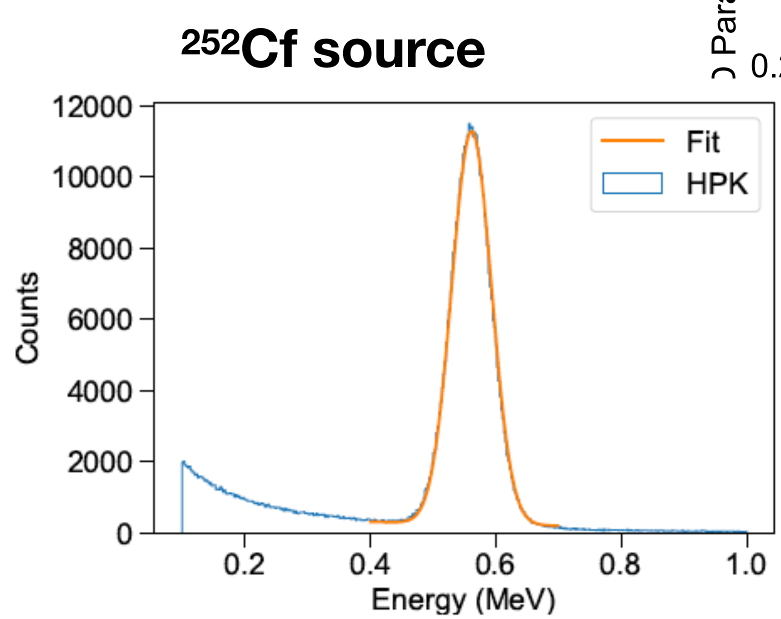
- experience working with ^{6}Li-loaded liquid scintillator
- type of reflectors: specular
- type of coupling: coupled (technically easier)
- readout: double-ended PMT
- light guide: yes!
- @ HFIR site for background studies

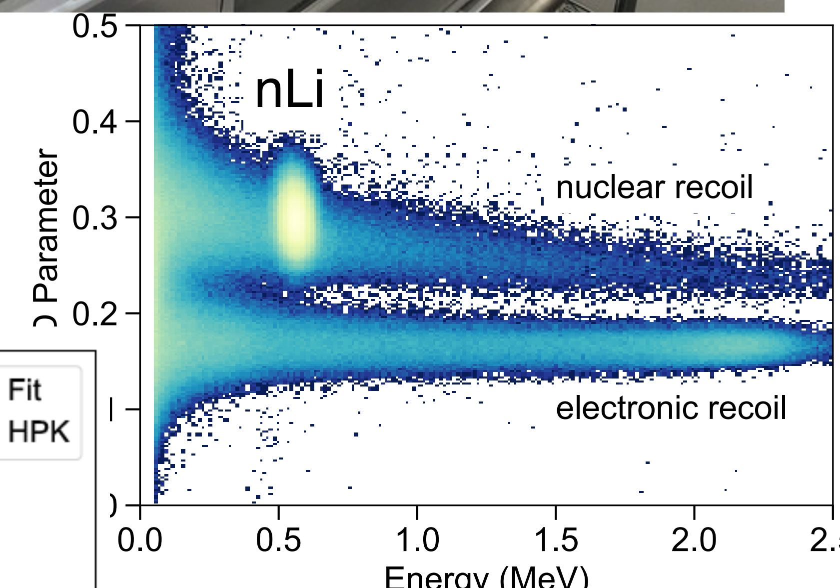
Demonstrating performance: PROSPECT-50



Demonstration of performance and testbed for subsystems:

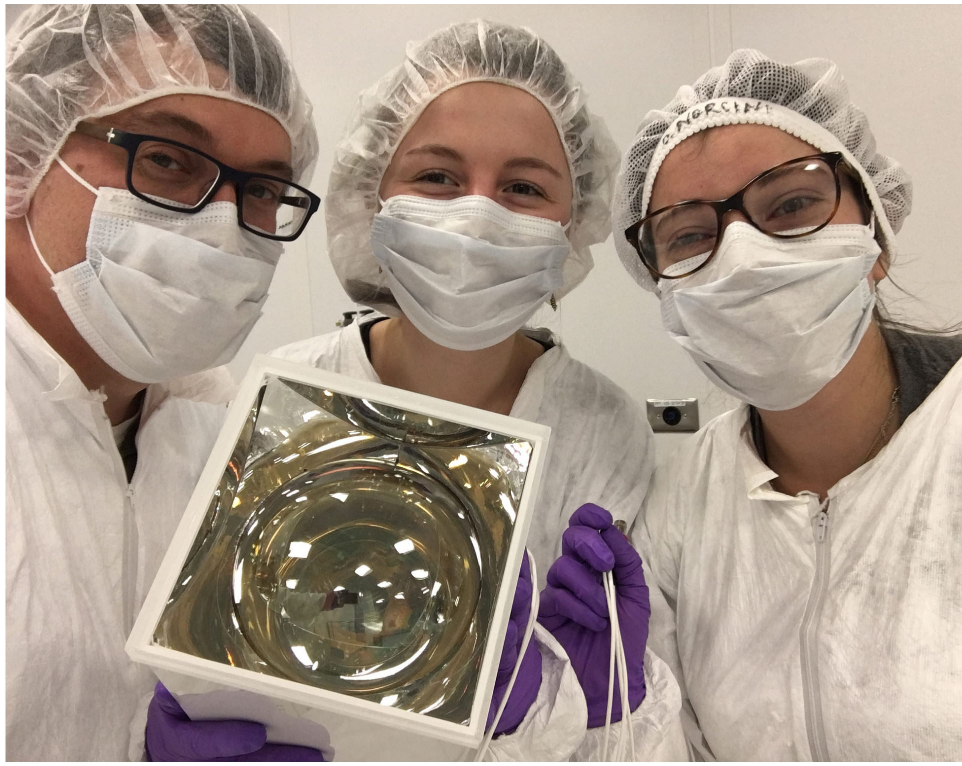
- optical separators, PMT module
- radioactive, optical calibration
- shielding concept
- light collection: 850 PE/MeV
- resolution (σ): 4% @ 1MeV
- PSD: excellent separation
- multi-segment background studies





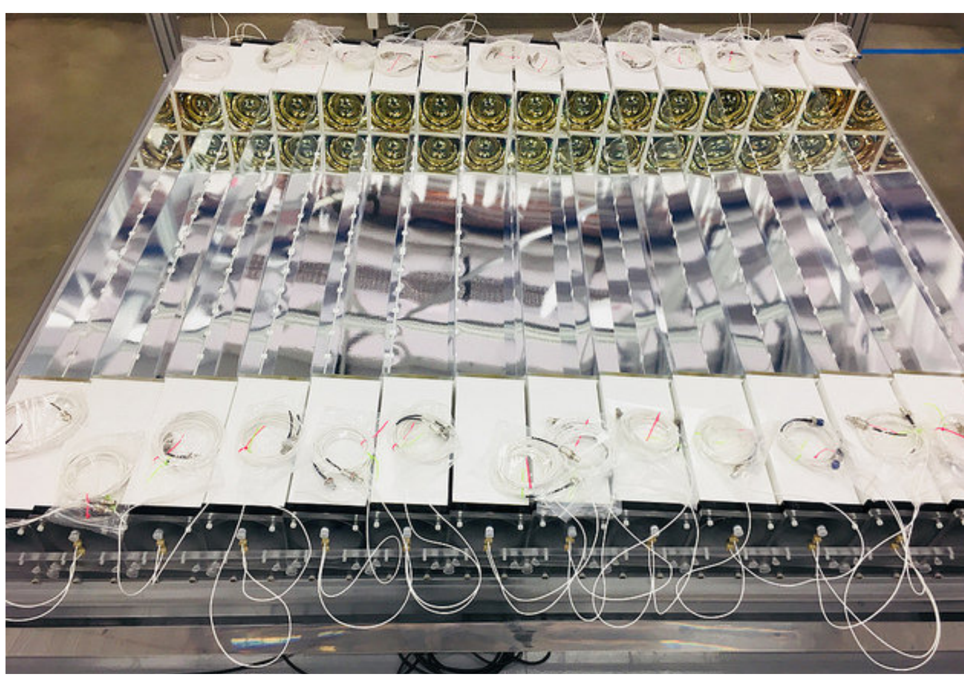
PROSPECT: JINST 13 P06023 (2018)

Construction of PROSPECT complete!



first optical module!

lots of channels = lots of cables

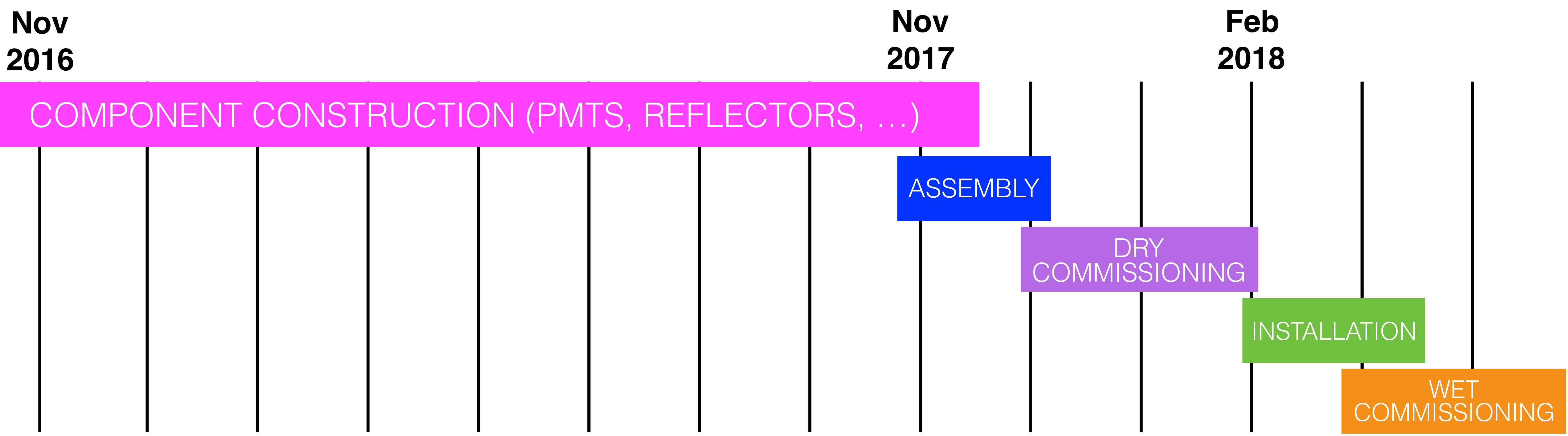


birdseye view

secondary containment

outer shield test

… that was quick!

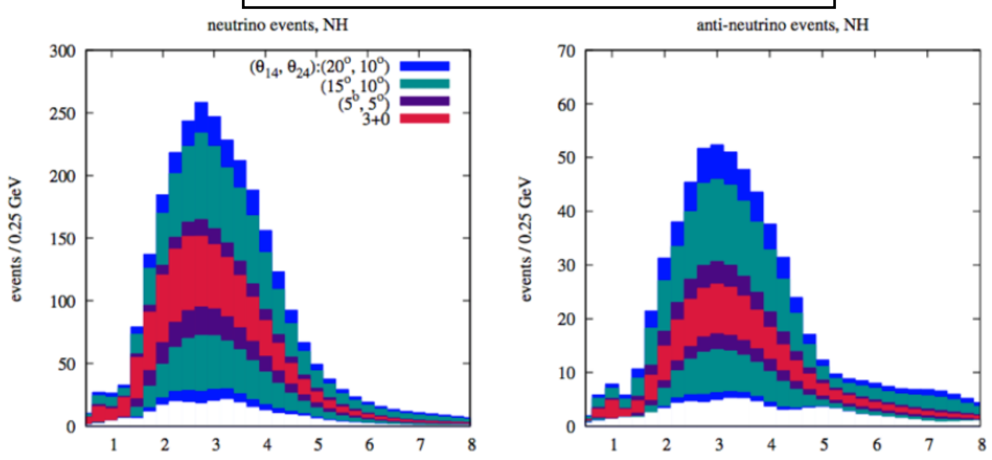


finished detector component construction in 1 year
component construction to installation ~16 months
online in Spring 2018!

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?

DUNE response to steriles

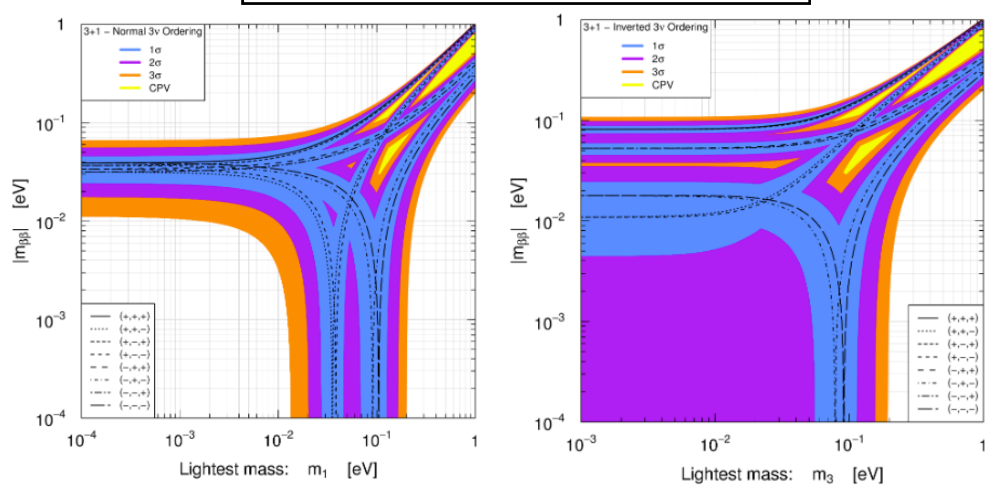


R. Ghandi, *et. al.*, JHEP 1511 (2015)

An eV-scale sterile would impact:

- long-baseline experiments measuring CP violation, especially at large mixing angles has dramatic effect
- neutrinoless double beta decay observing Majorana neutrinos, allowed regions are greatly changed

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

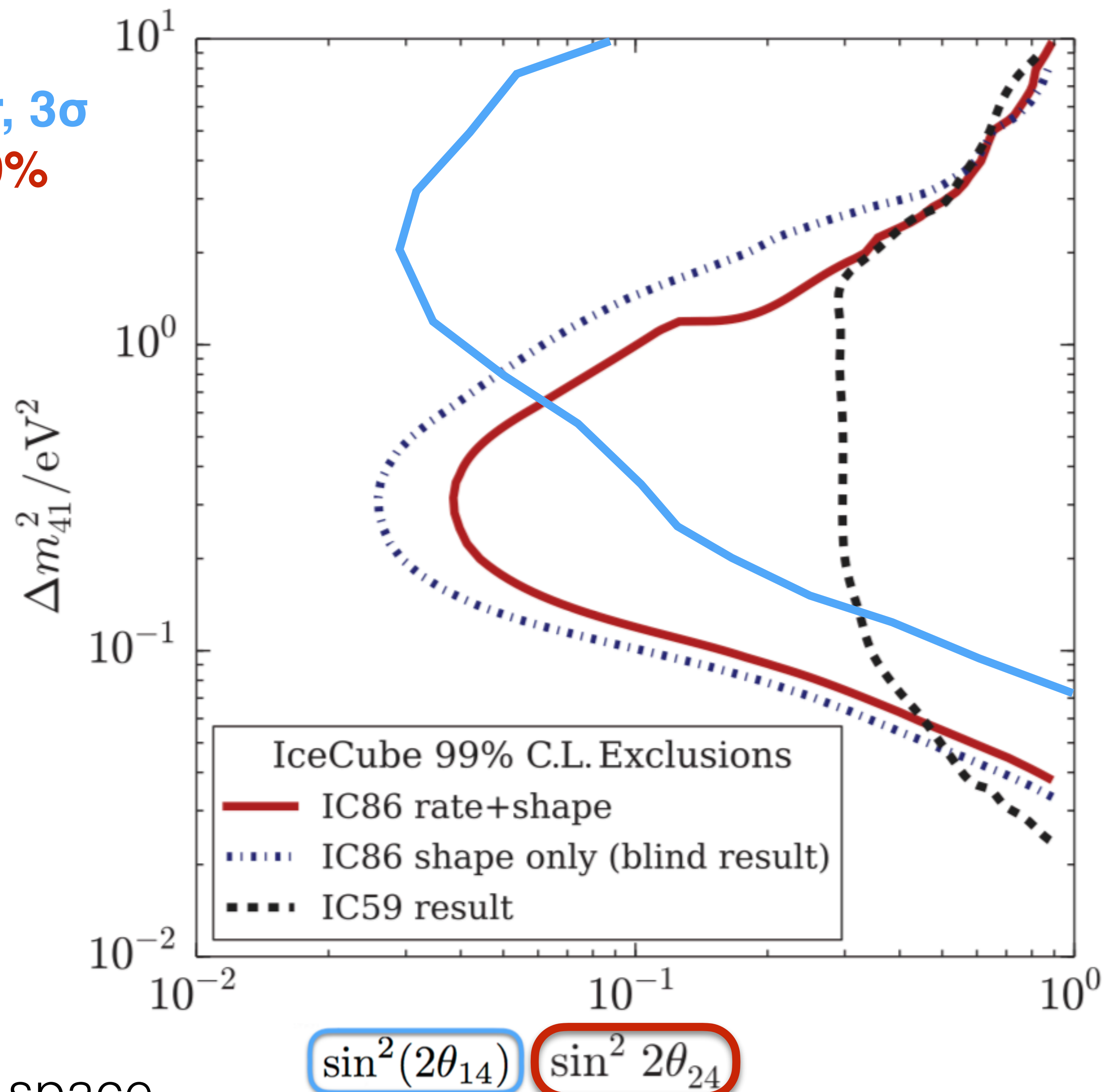


*Giunti & Zavanin, JHEP **1507** (2015)*

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!

Steriles with IceCube

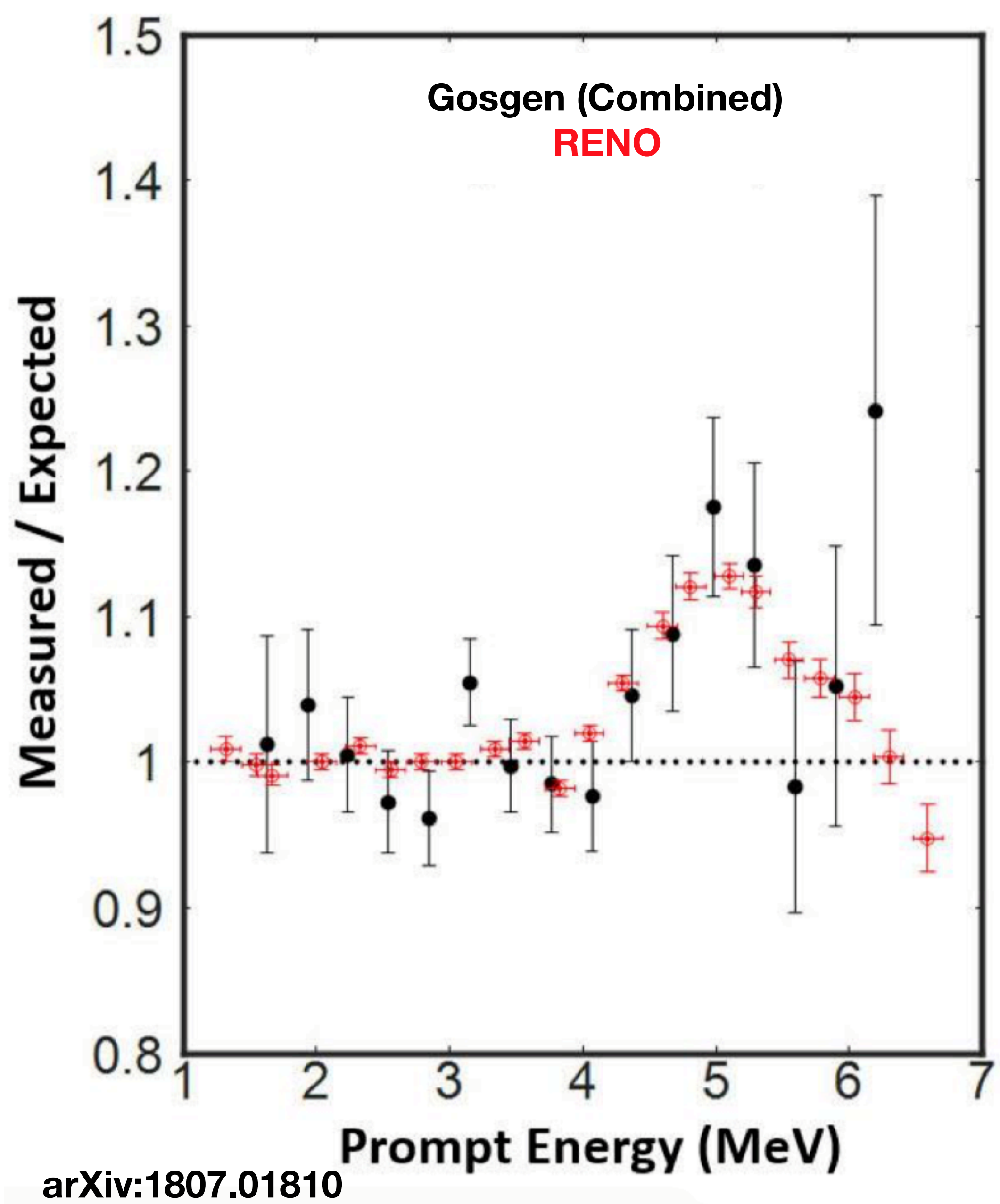
PROSPECT 3yr, 3σ
IceCube 1yr, 99%



Complimentary space, different channels

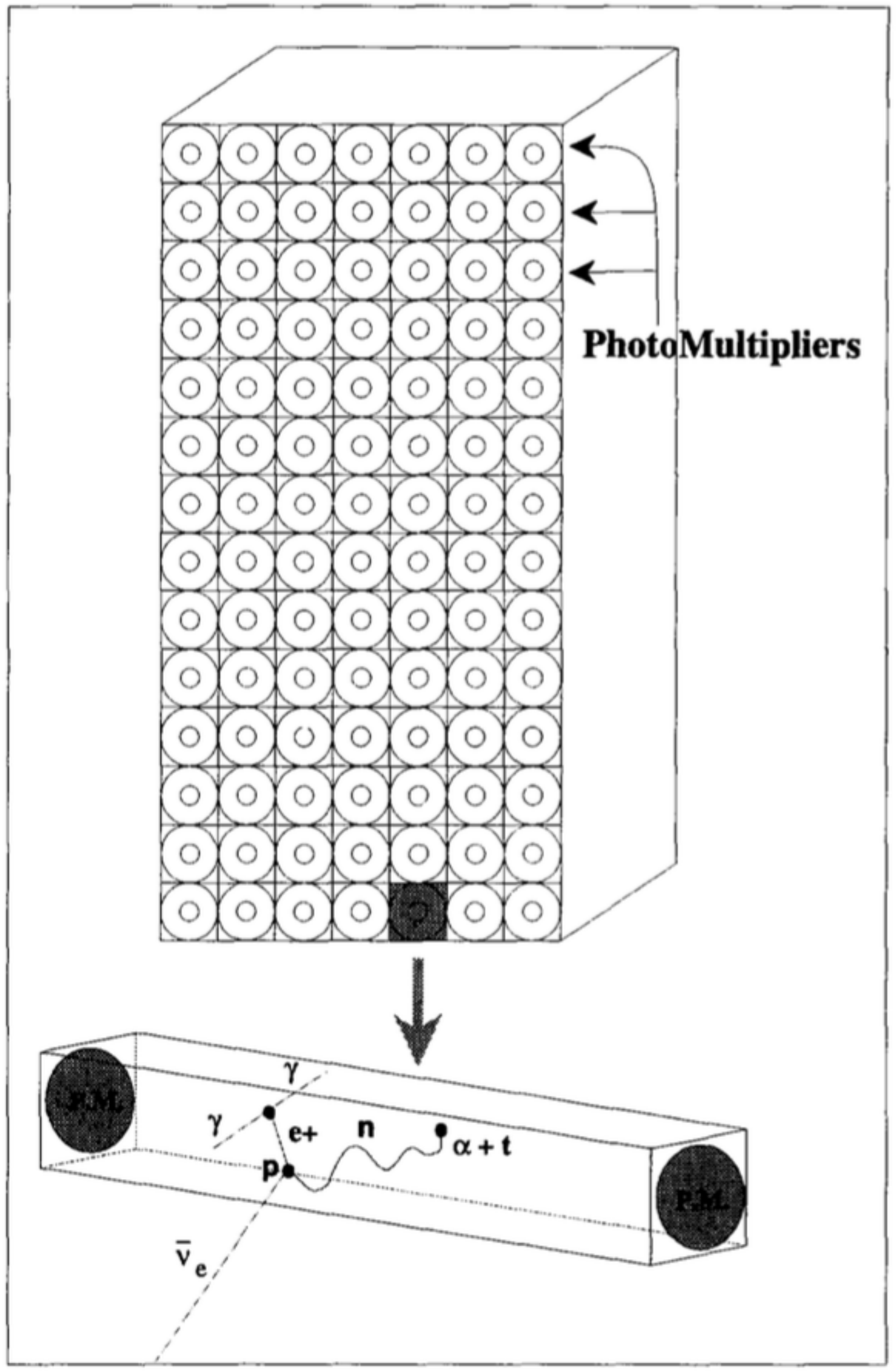
adapted from IceCube: PRL 117, 071801 (2016)

Gosgen spectral deviation

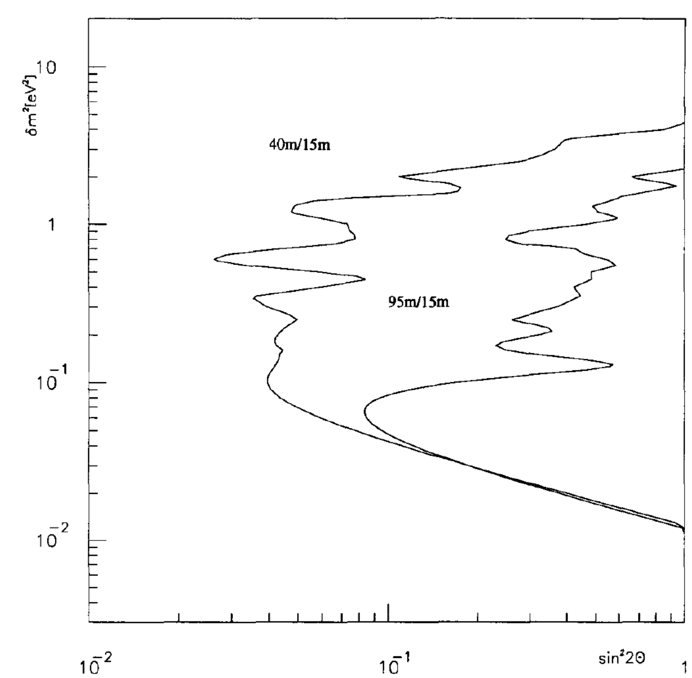


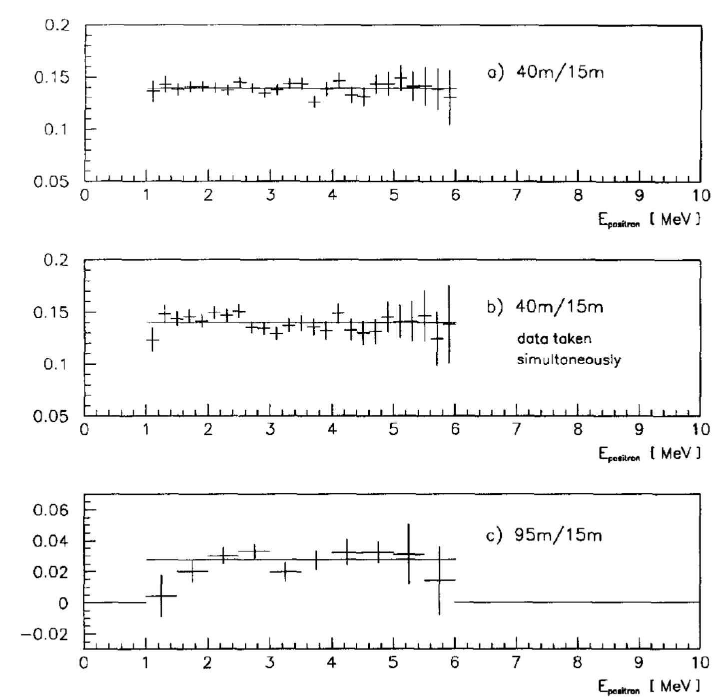
Re-evaluation (2018) of Gosgen(1980's) experiment also showed a bump in 4-6 MeV region

Bugey 3



- similar to PROSPECT detector technology
- baselines15, 40, 95 m
- Li-6 loaded PSD capable liquid scintillator
- optically segmented
- no oscillations with absolute or relative analyses
- LiLS degraded over time
- ~15% dead volume (as opposed to ~4% for PROSPECT)





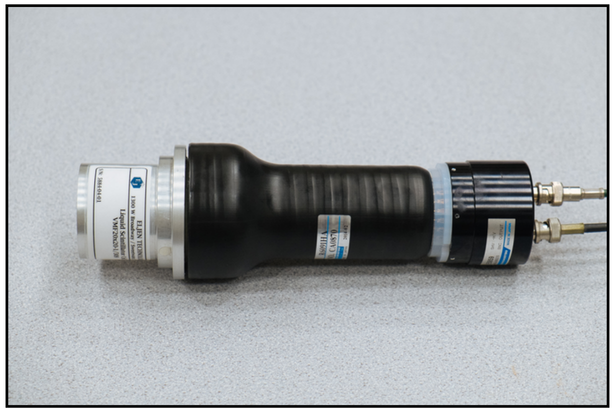
Lithium-loaded liquid scintillator (LiLS) development

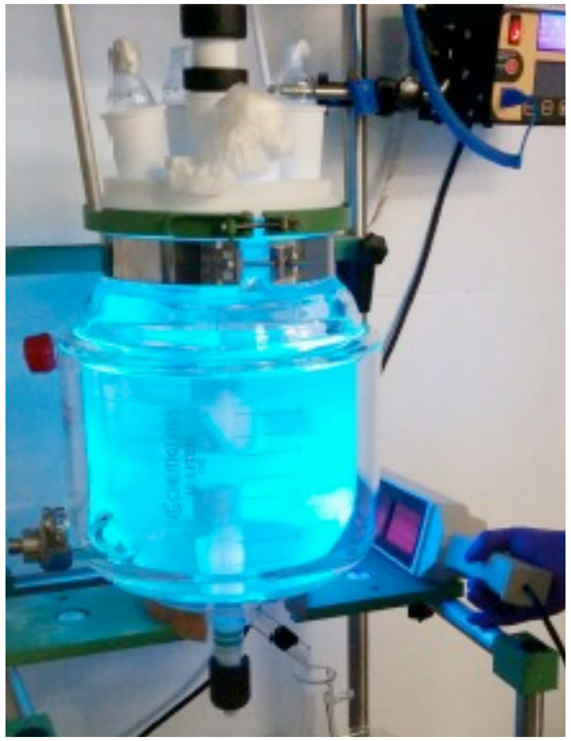
Novel scintillator cocktail:

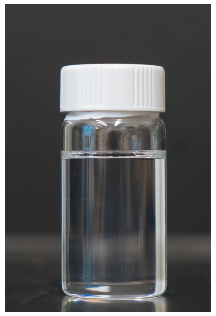
- PSD LiLS that is non-toxic, non-flammable
- extensive studies with LAB, Ultima Gold
- EJ-309 gave best light yield, PSD

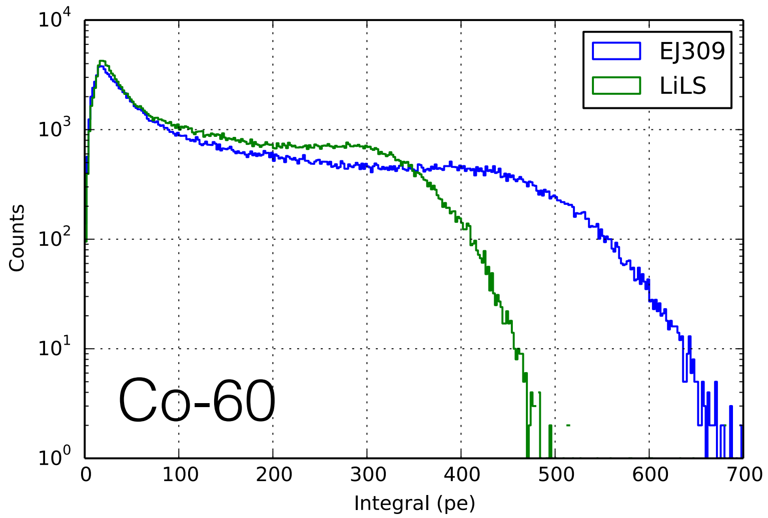
Scintillator specs (PROSPECT-0.1):

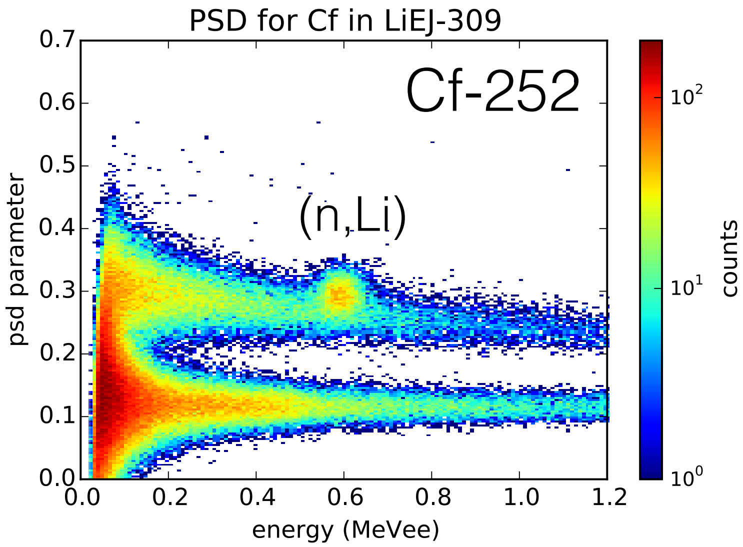
- Light Yield$_{EJ\text{-}309}$ = 11500 ph/MeV
- Light Yield$_{LiLS,\ measured}$ = 8200 ph/MeV
- prominent neutron capture peak in LiLS
- PSD FOM at (n, Li) is 1.79
- energy resolution (σ/E) of 5.2% at 0.6MeV$_{ee}$

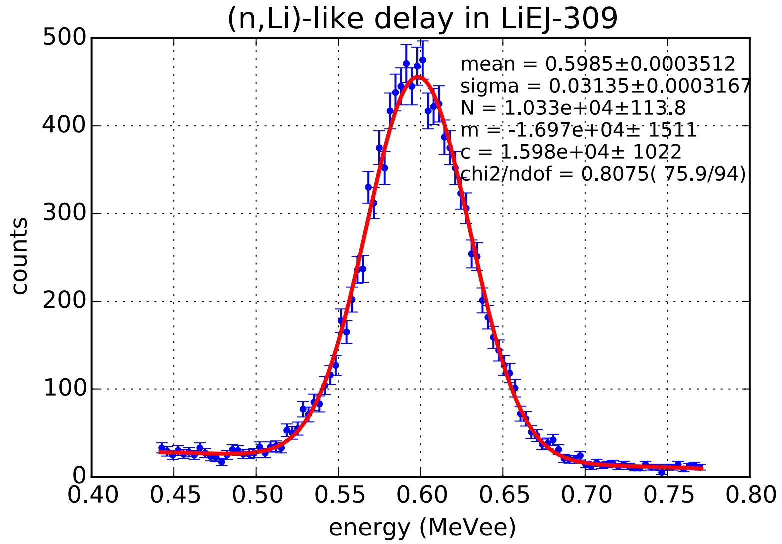








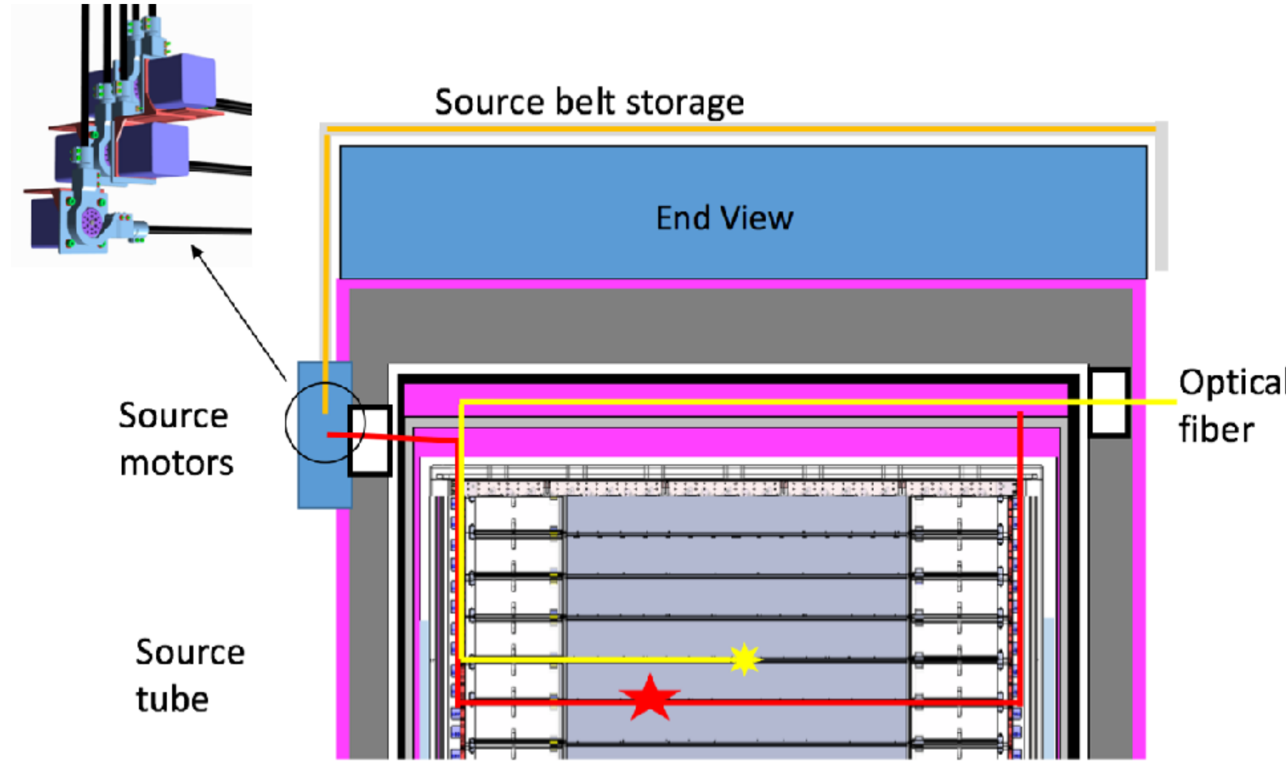


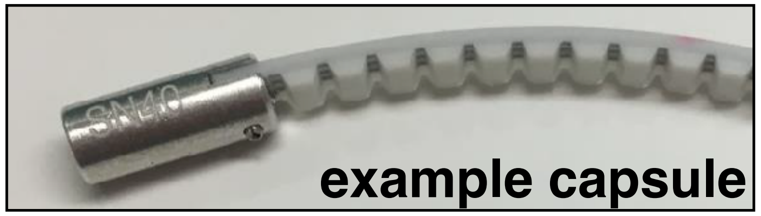


developed novel LiLS with excellent light yield, PSD, and neutron capture capabilities

Calibration system

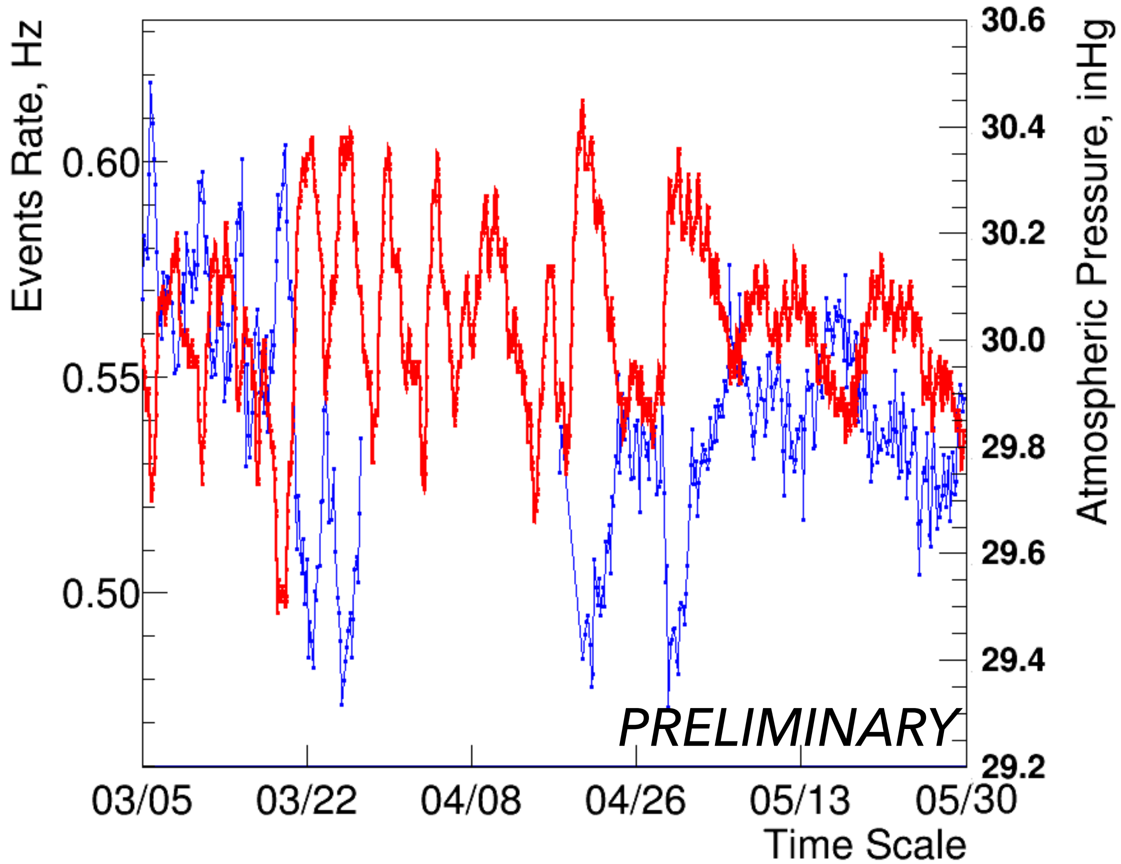
- motorized source deployment system between segments
- no optical effect of source deployment
- 35 positions throughout detector, calibrate individual segments and full detector
- mm-precision source positioning
- gamma calibration for energy scale and reconstruction
- Cf252 neutron source for efficiency calibration and neutron transport
- optical calibration of every segment with laser via optical fibers

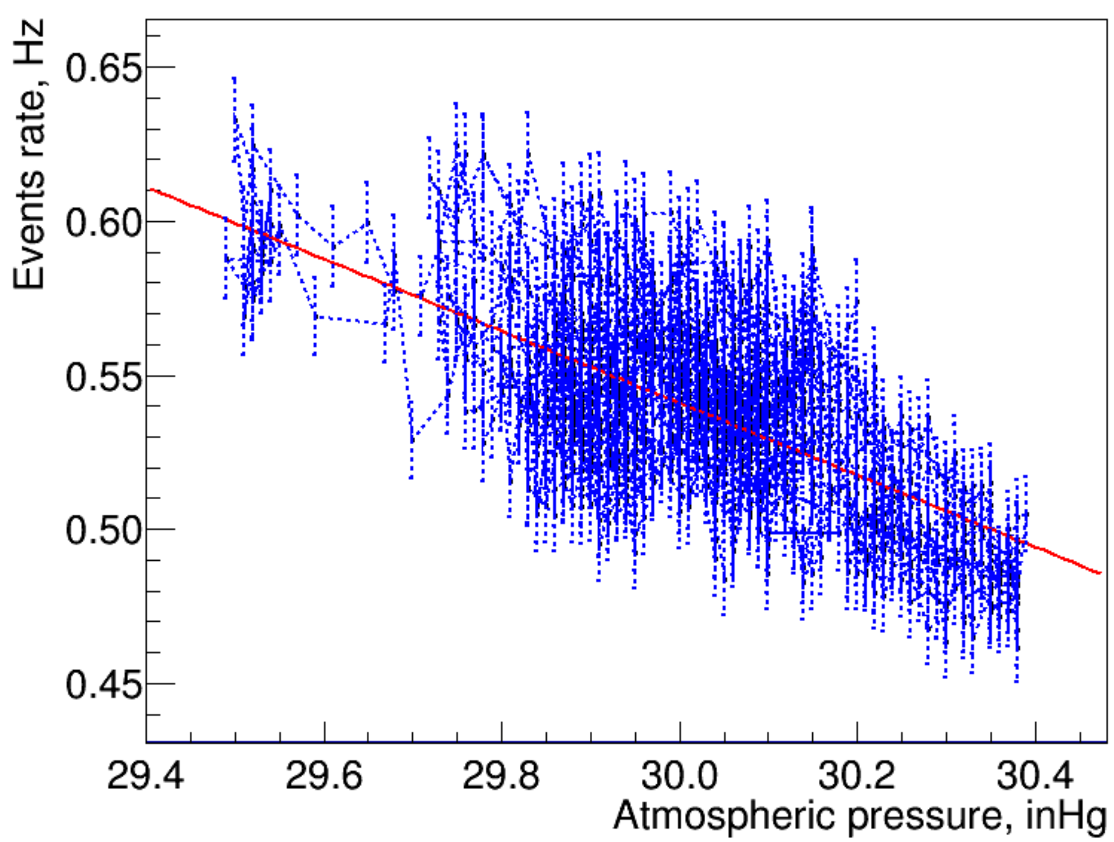




Source	Decay [keV]
^{22}Na	e^{+} -> 511 γ, 1274 γ
^{60}Co	1173 γ, 1332 γ
^{137}Cs	662 γ
^{68}Ge	e^{+} -> 511 γ
^{252}Cf	Spontaneous fission -> n

Time dependence of cosmogenic backgrounds





- correlation between cosmogenic backgrounds and atmospheric pressure
- measure correlation during reactor off time, and use it to correct background subtraction during reactor on

Building chi2

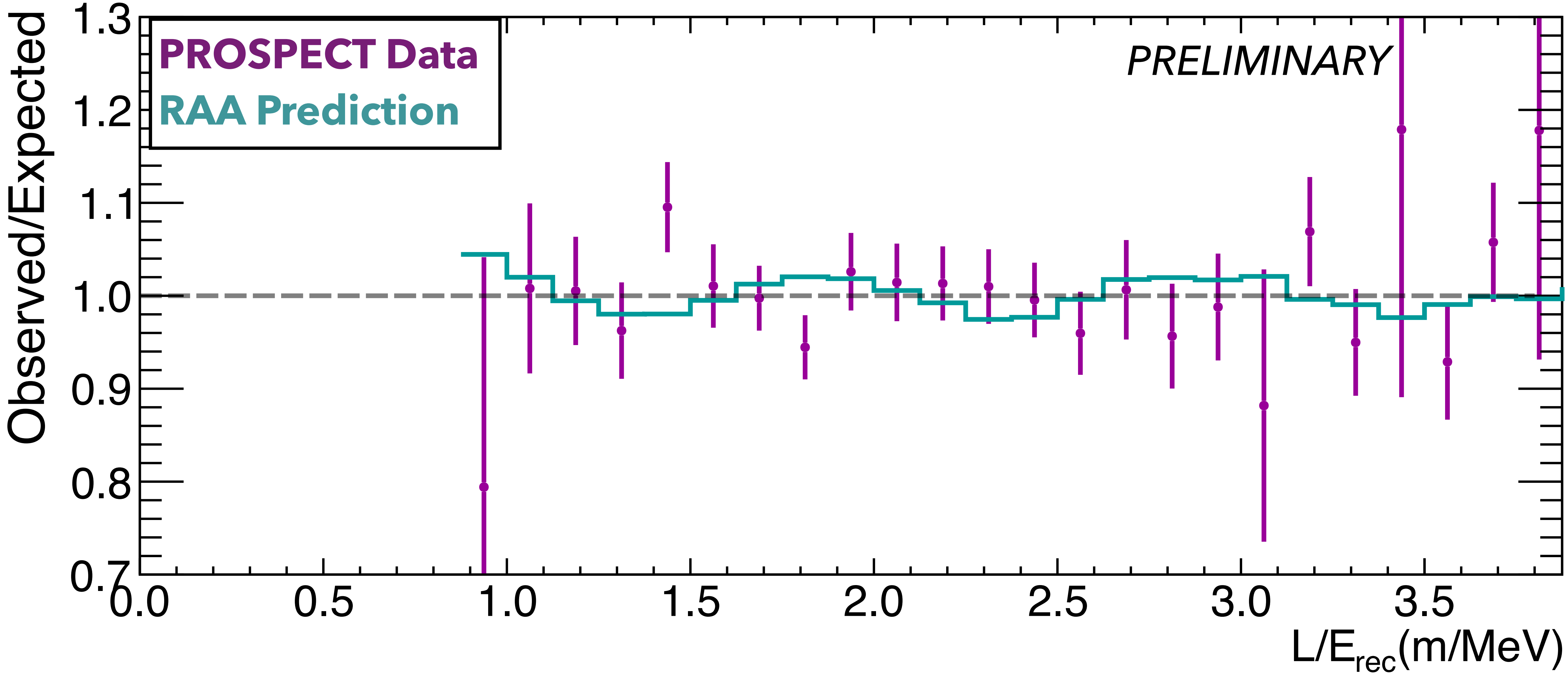
$$\chi^2 = \mathbf{\Delta}^{\mathrm{T}} \mathrm{V}_{\mathrm{tot}}^{-1} \mathbf{\Delta}$$

$$\mathbf{\Delta}_{l,e} = O_{l,e} - O_e \frac{E_{l,e}}{E_e}$$

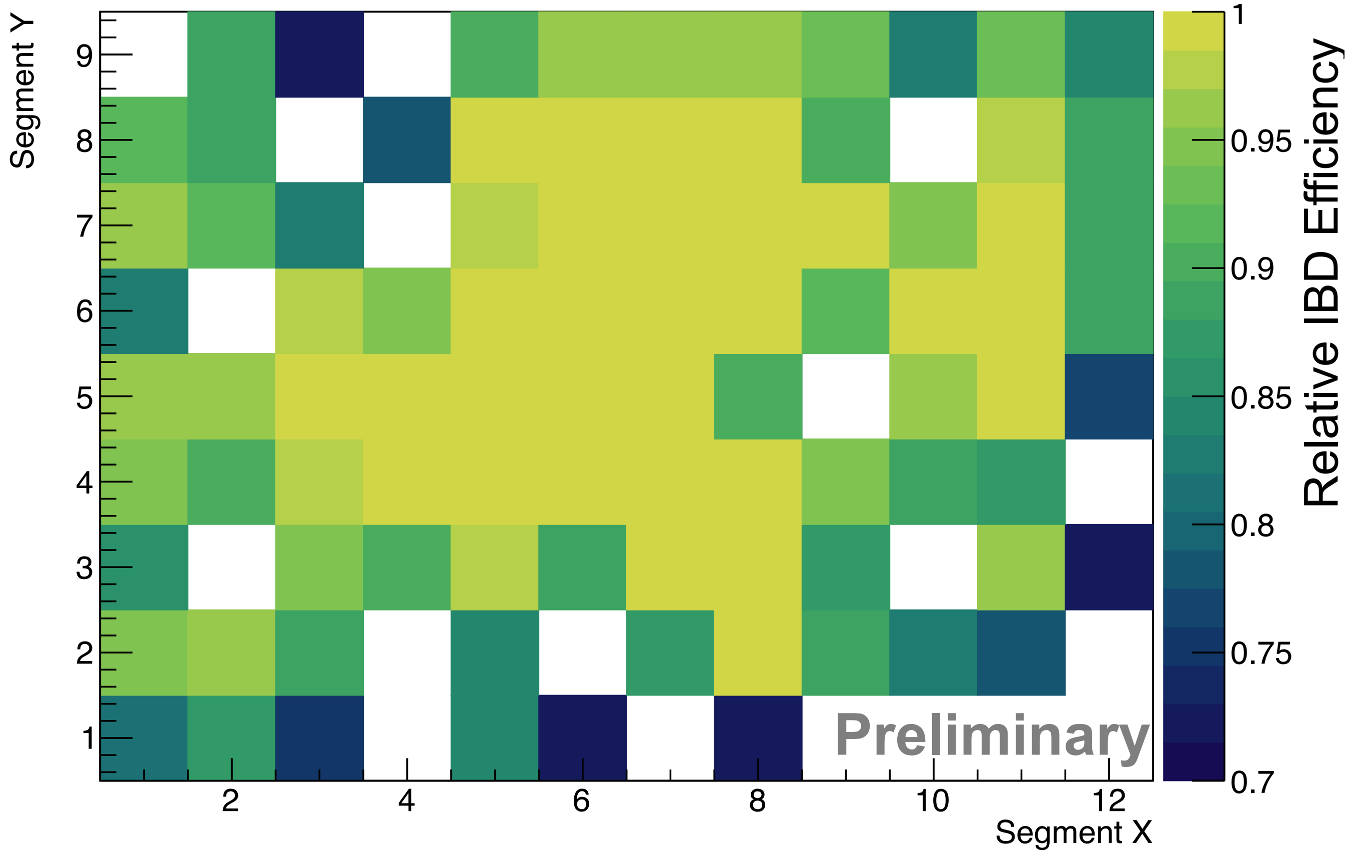
$$O_e = \sum_{l=1}^{L} O_{l,e}, \ E_e = \sum_{l=1}^{L} E_{l,e}$$

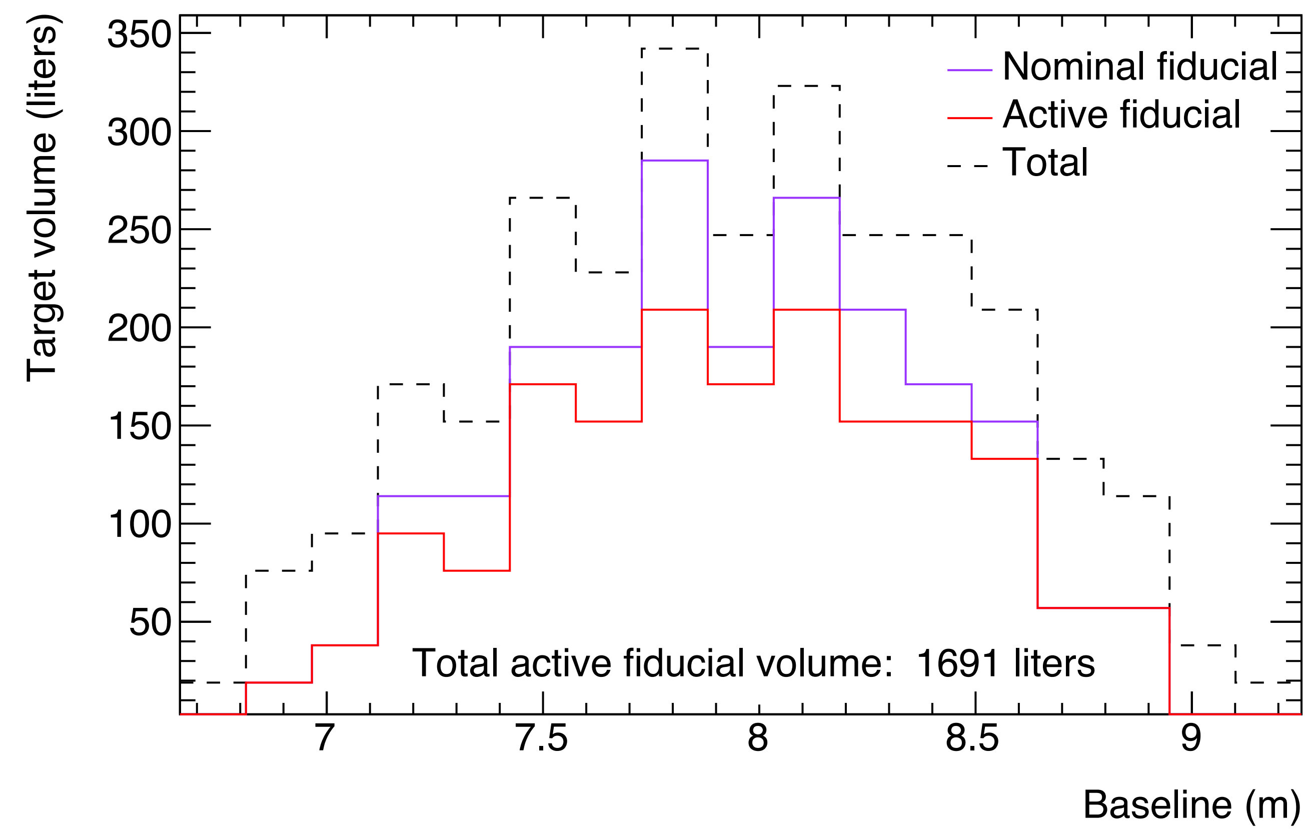
$$E_{l,e} = E_{l,e}^{null} \cdot \left(1 - \sin^2 \theta_{\text{new}} \sin^2 \left(1.27 \Delta m_{\text{new}}^2 \frac{L}{E_\nu}\right)\right)$$

Measured L/E ratio



Segments included in oscillation analysis





- a small number of PMTs have displayed current instabilities
- evenly distributed across baselines
- cause under investigation, these channels have been turned off out of caution
- efficiency impact on neighboring segments taken into account
- high-segmentation and large target mass limits impact on physics analyses