PROSPECTing for reactor neutrinos at short baselines

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for the PROSPECT collaboration

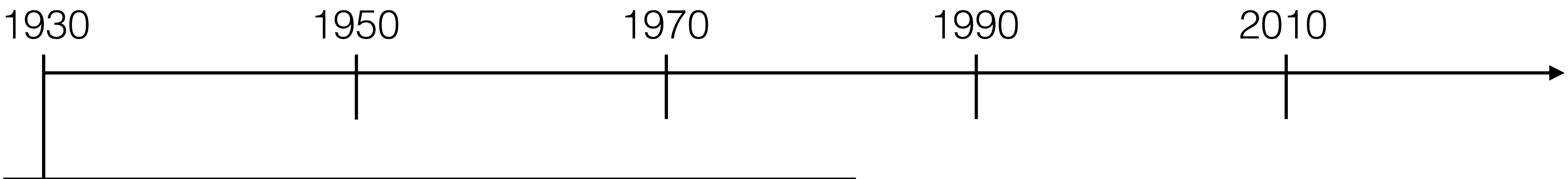
Yale

U.S. DEPARTMENT OF ENERGY | Office of Science

Wright Laboratory

HEISING-SIMONS FOUNDATION

Evolution of neutrino physics with reactor experiments



Neutrinos introduced by Pauli to save energy conservation in β decay experiments

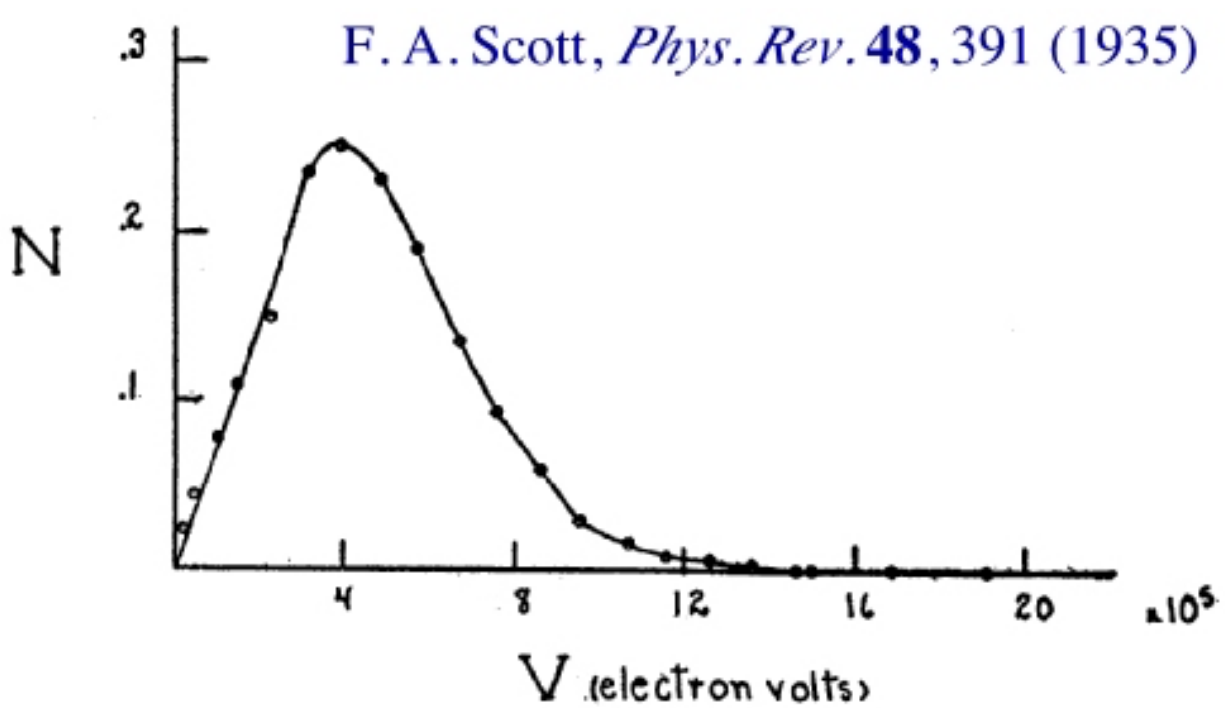


FIG. 5. Energy distribution curve of the beta-rays.

Properties:

- no electric charge
- spin 1/2 fermion
- massless or tiny
- Fermi's "weak" interaction

Bethe and Peierls:

- can we detect them?
- inverse beta decay (IBD)

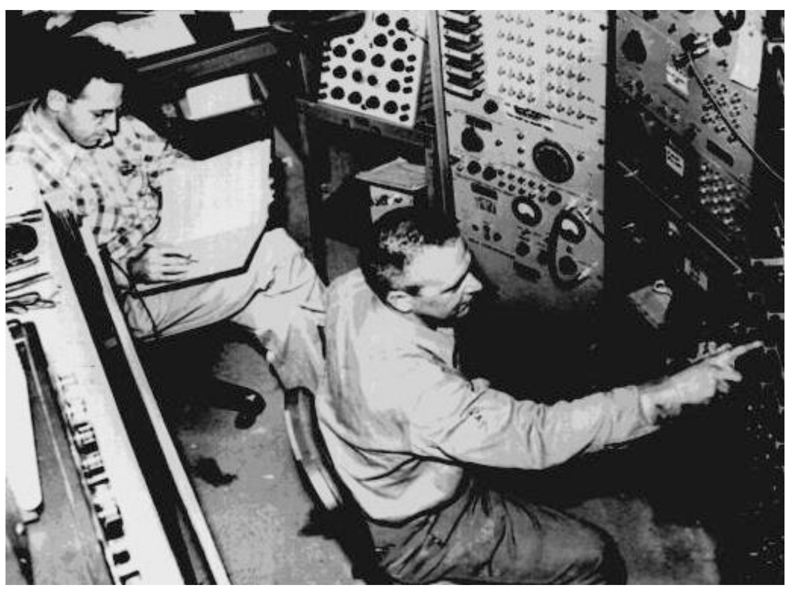
$$\overline{\nu}_e + p \rightarrow \beta^+ + n$$

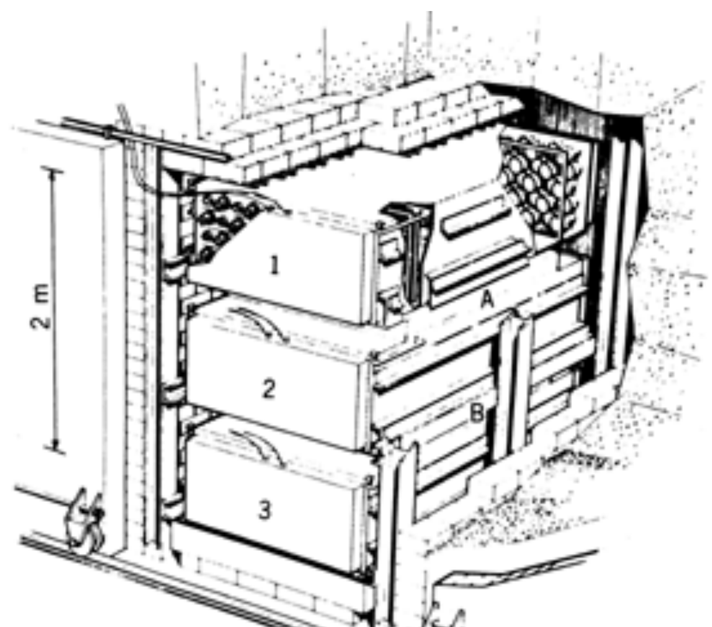
- cross-section is too small, impossible to detect!

Evolution of neutrino physics with reactor experiments

1930 1950 1970 1990 2010

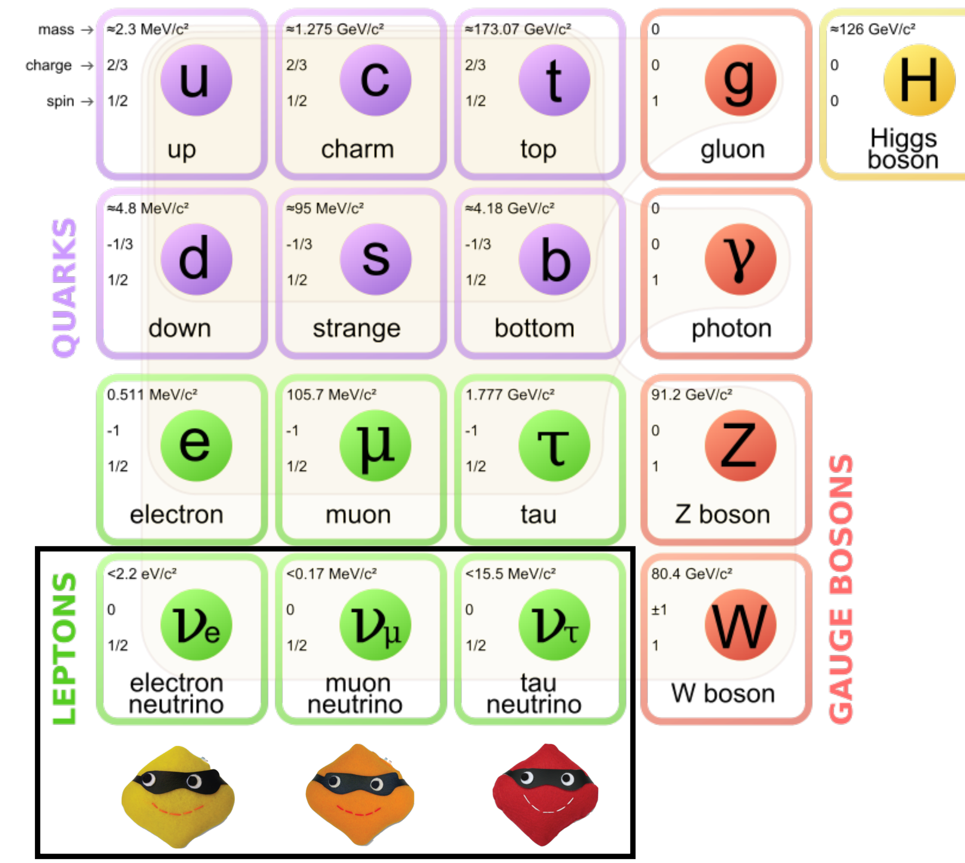
observation of (anti)neutrinos at Savannah River reactor through IBD with scintillator





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

Added to Standard Model:

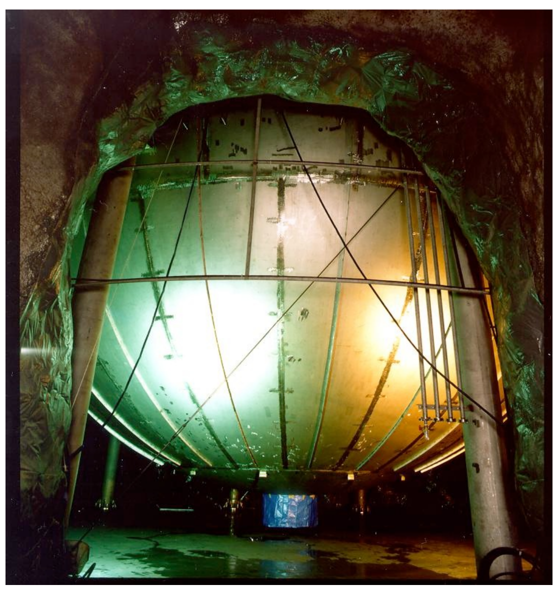


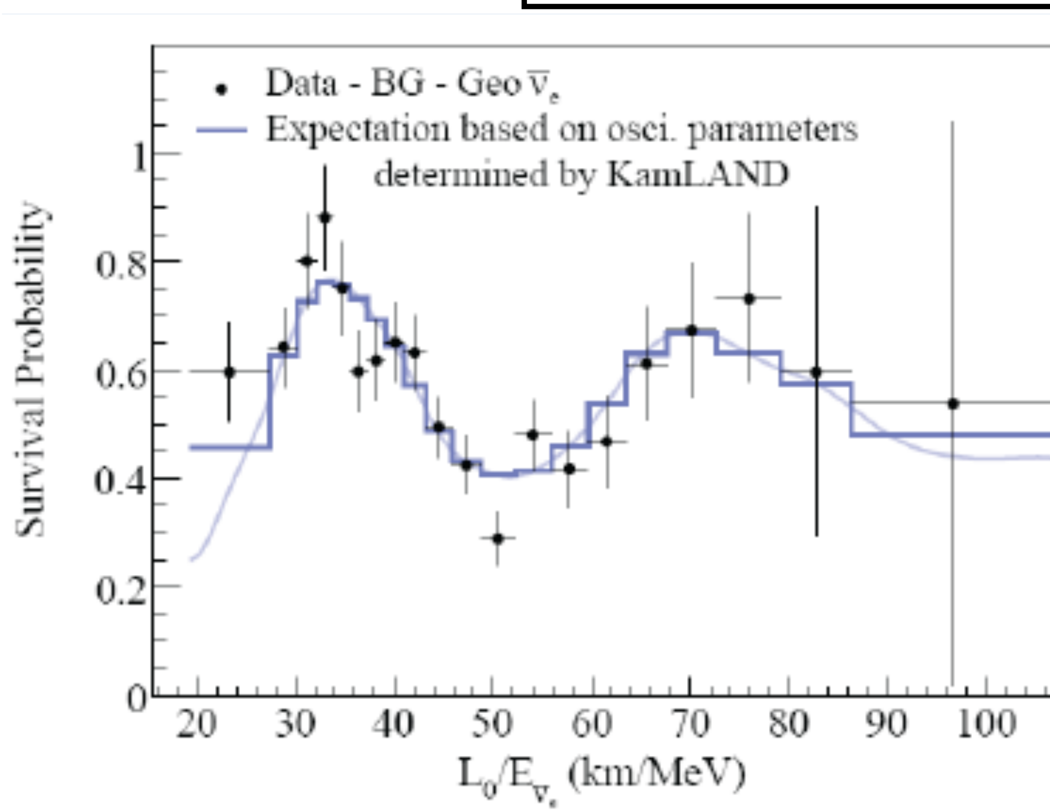
*muon and tau flavors discovered later at accelerators

Evolution of neutrino physics with reactor experiments

1930	1950	1970	1990	2010

KamLAND kiloton detector at long baselines, discovery of antineutrino oscillations (mass)





flavor states *mass states*

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

interact *propagate*

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

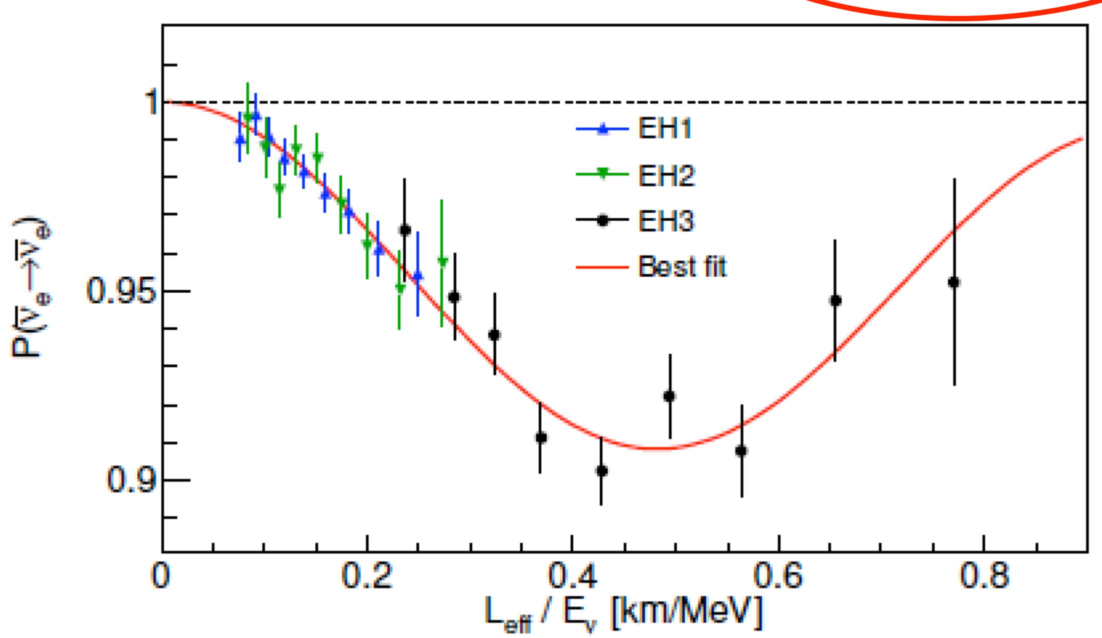
$$where\ \ \alpha,\beta = \nu_e,\nu_\mu,\nu_\tau$$

Evolution of neutrino physics with reactor experiments

1930 1950 1970 1990 2010

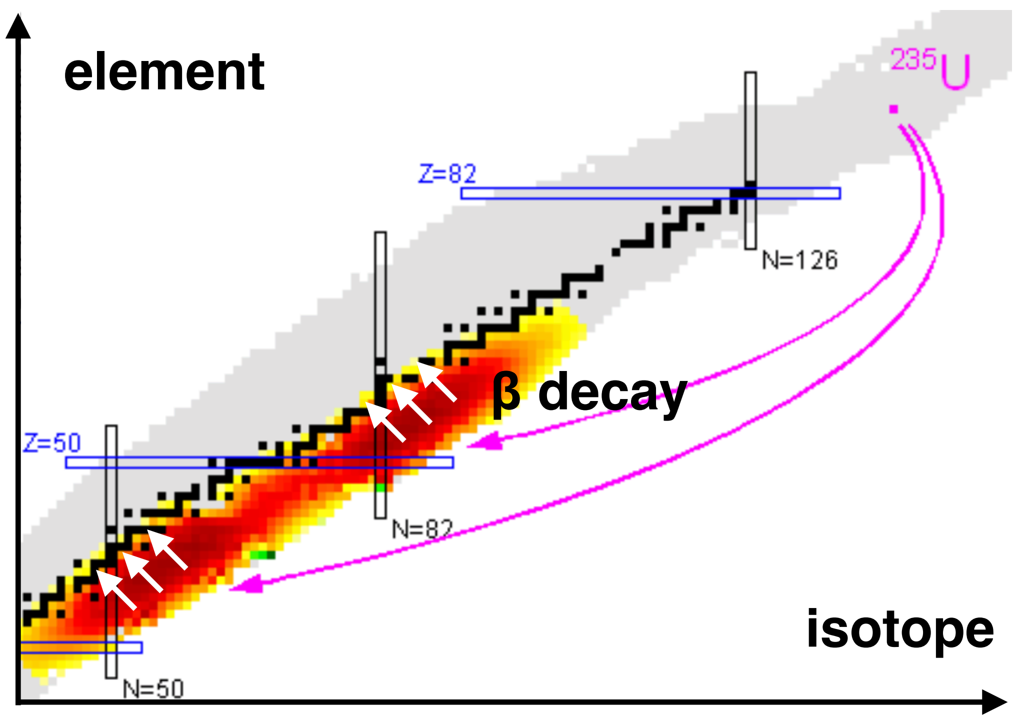
DYB, DC, RENO use near/far detectors for precision measurement of last mixing angle

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0\\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

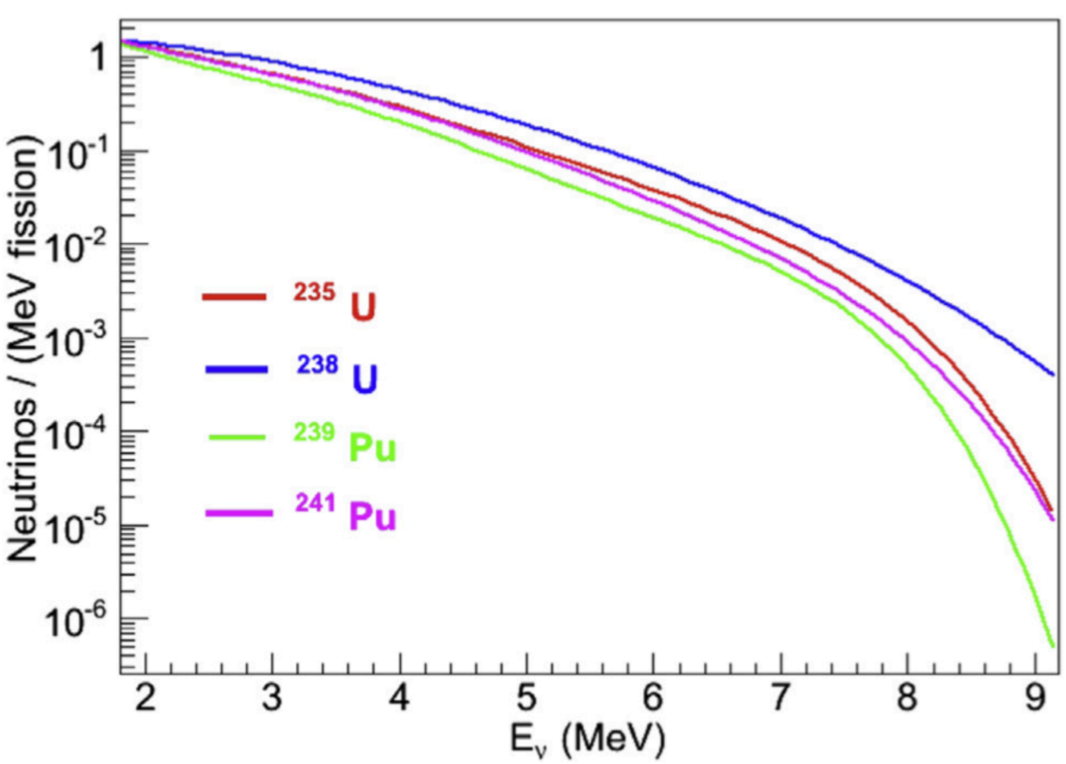


PMNS mixing matrix

Generation of reactor antineutrinos



- fission produces neutron-rich daughters that beta decay ~6 times until stable
- 1 GW_{th} ~10^{20} $\bar{\nu}_e$/second
- >99.9% flux $\bar{\nu}_e$ - only from this process
- low energy ~MeV scale neutrinos
- average energy and number of $\bar{\nu}_e$ dependent on parent fission isotopes



- **power reactors (LEU)** have low enriched uranium cores: ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu
- **research reactors (HEU)** have high enriched uranium cores: ^{235}U only
- predicting flux/spectrum is complicated

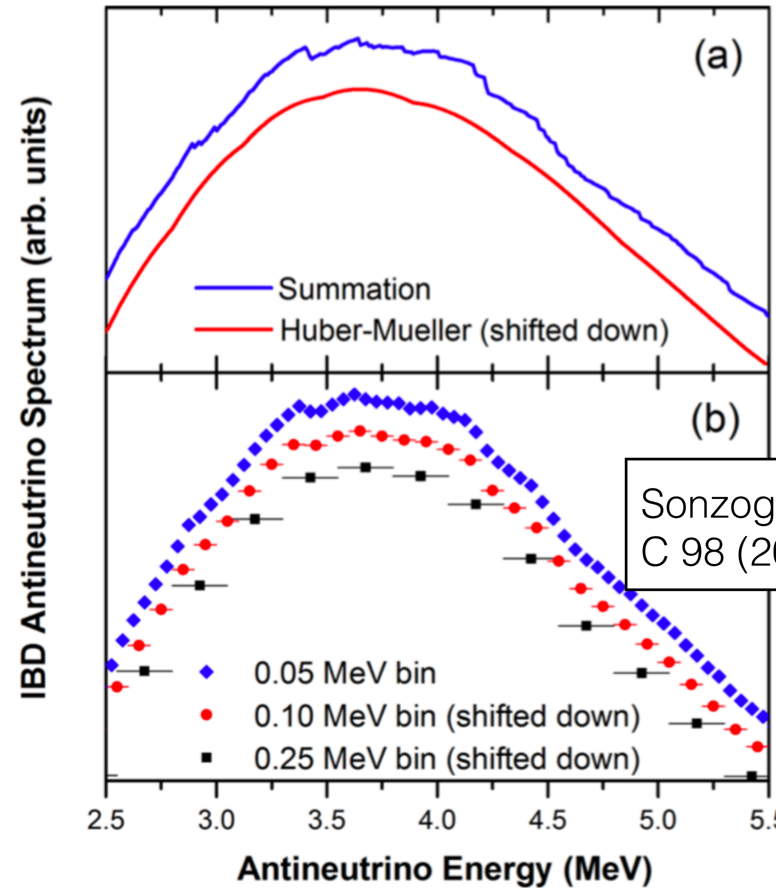
Predicting the antineutrino flux and spectrum

Two major approaches used:

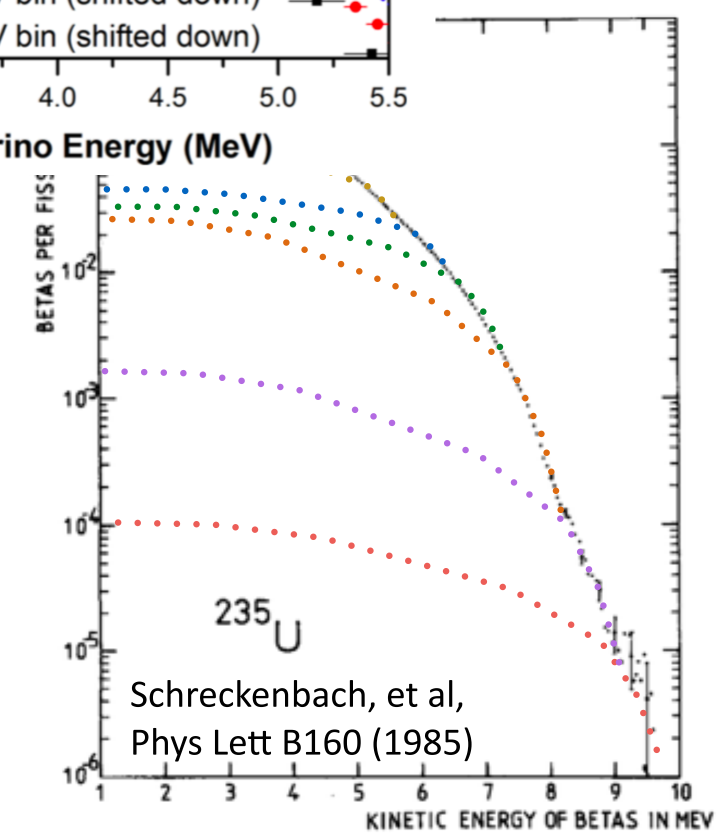
1. *Ab-initio*
    - sum the spectrum from thousands of beta branches using nuclear databases
    - *databases incomplete and large uncertainties*

$$S(E_{\bar{\nu}}) = \sum_{i=0}^{n} \underbrace{\boxed{R_i}}_{\text{Decay Rate}} \sum_{j=0}^{m} \underbrace{\boxed{f_{ij}}}_{\text{Branching Fraction}} \underbrace{\boxed{S_{ij}(E_{\bar{\nu}})}}_{\text{Spectrum}}.$$

2. Beta conversion
    - empirical measurements of beta spectra for each isotope (foils, 1980's)
    - fit with 'virtual branches' and convert to antineutrino spectra
    - *'virtual' spectra shape not well defined*

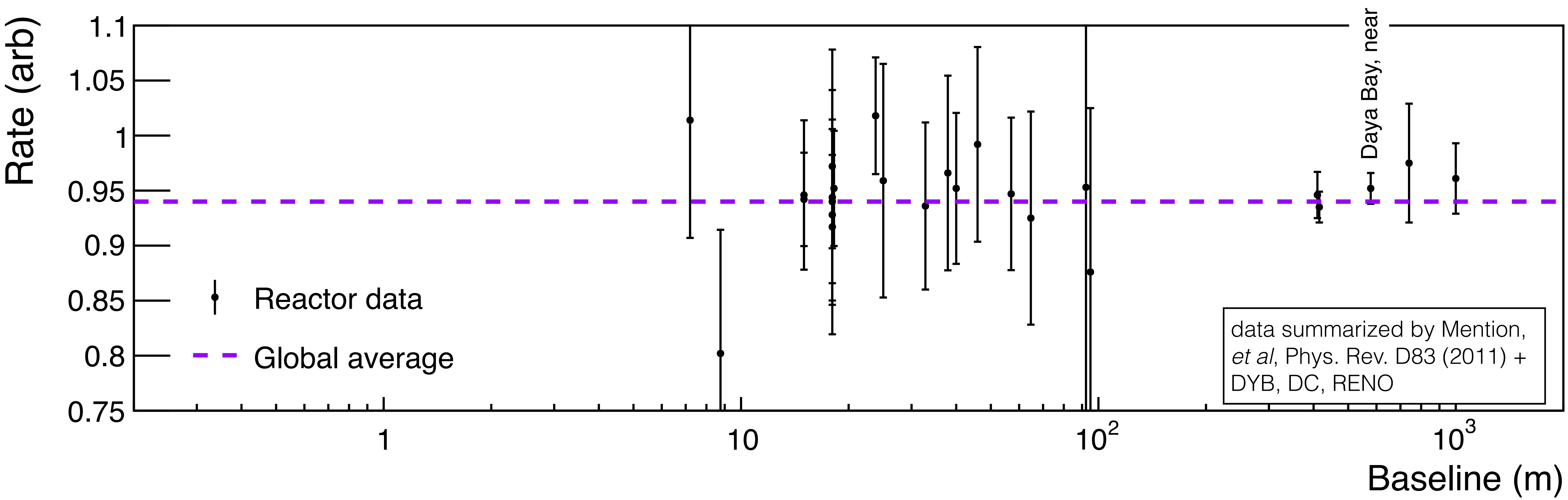


Sonzogni et al: Phys Rev C 98 (2018) 014323



Schreckenbach, et al, Phys Lett B160 (1985)

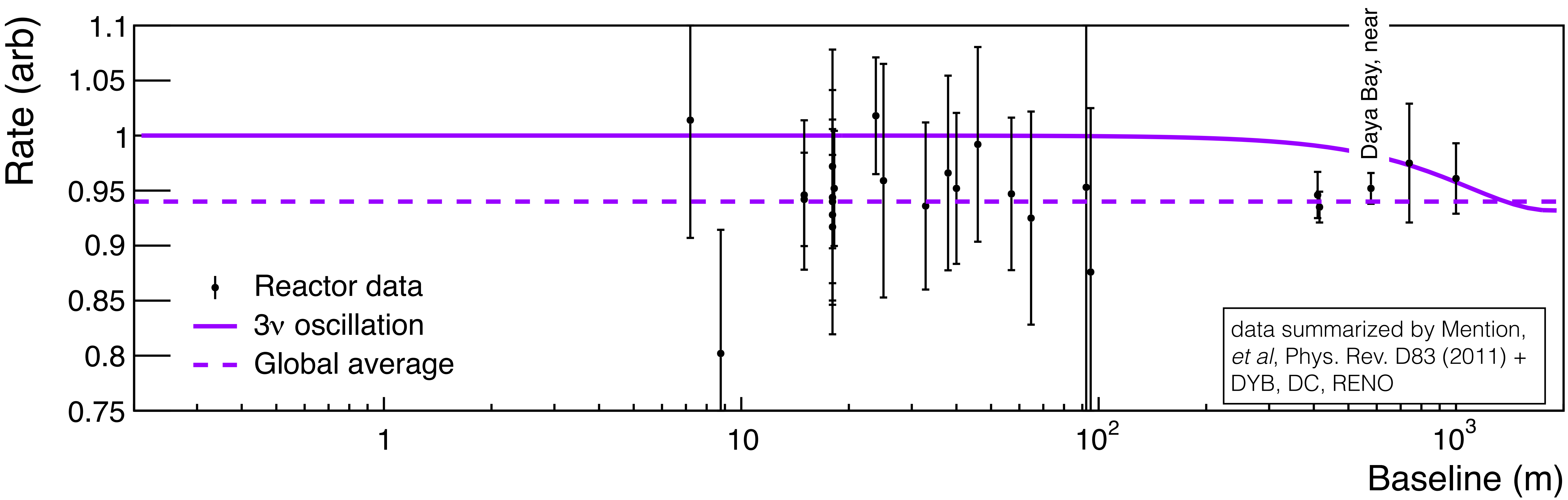
Reactor antineutrino flux deficit



- flux of global reactor data across baselines compared to reactor model with 3ν
- ~6% deficit: electron antineutrinos are missing?
- high statistics of recent experiments at ~500m baselines show deficits alone
- issues with nuclear models or is there a particle physics solution?

flux disagreement - 6% deficit when compared to reactor model

Reactor antineutrino flux deficit



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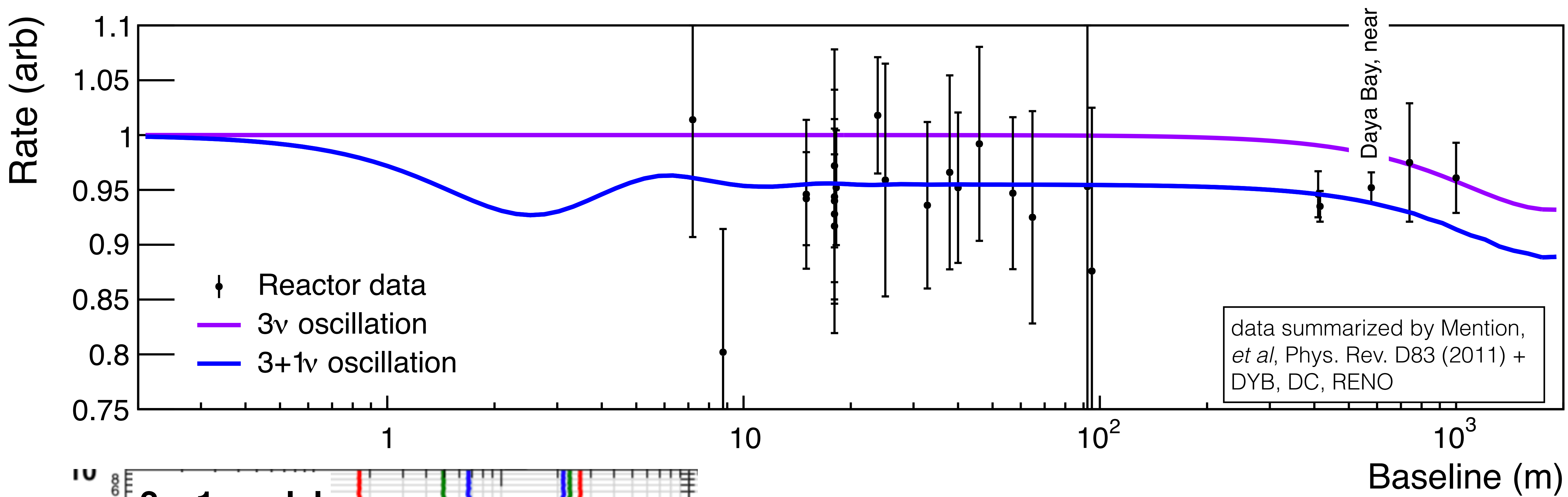
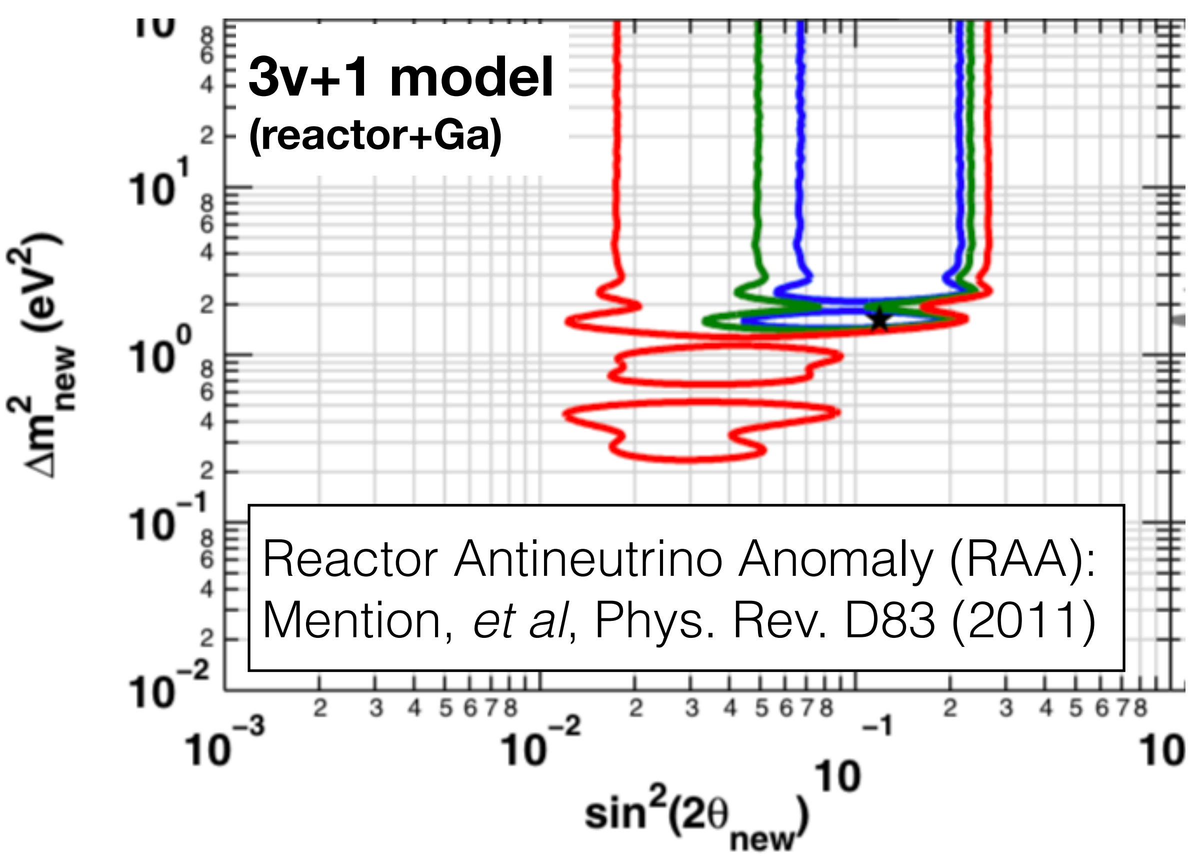
Reactor antineutrino flux deficit: 4th, sterile neutrino?



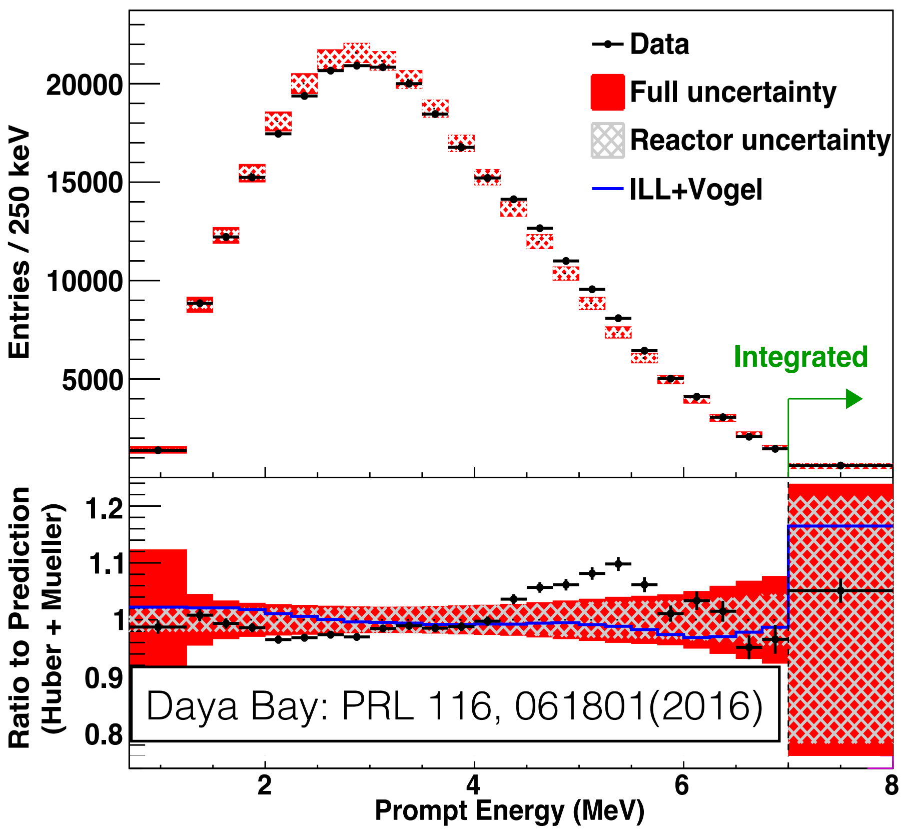


- 4th, sterile neutrino: non-weakly interacting
- high frequency oscillations (~meter baselines)
- eV-scale mass splitting, “heavy”
- sterile neutrinos would have major implications on particle physics/cosmology

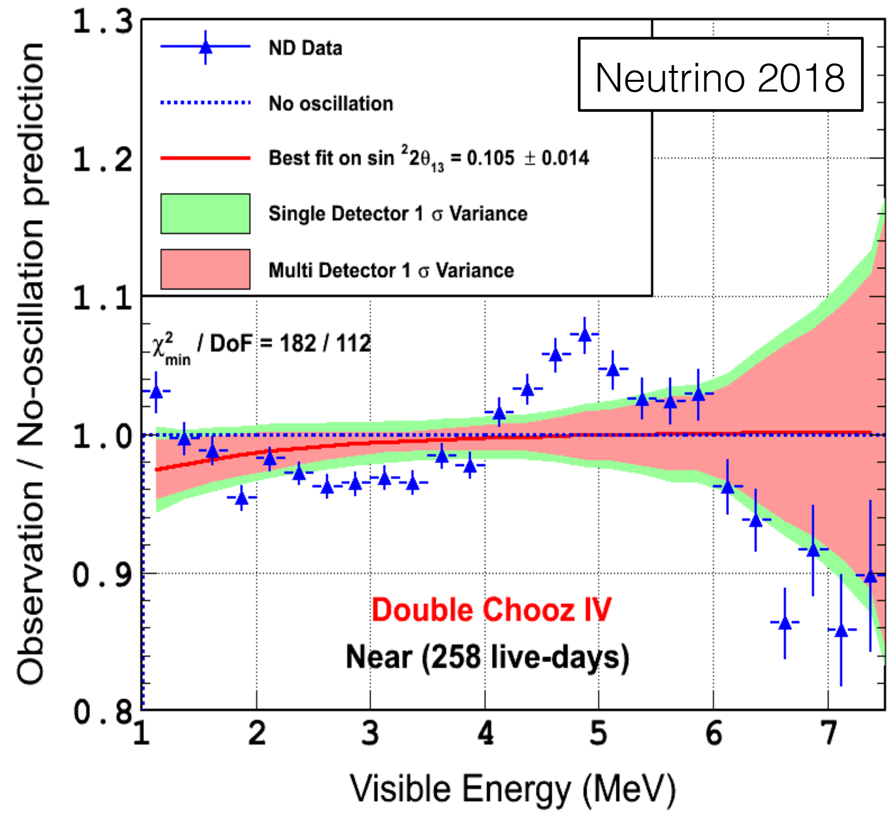
does an eV-scale sterile neutrino exist?

Reactor antineutrino energy spectrum deviations

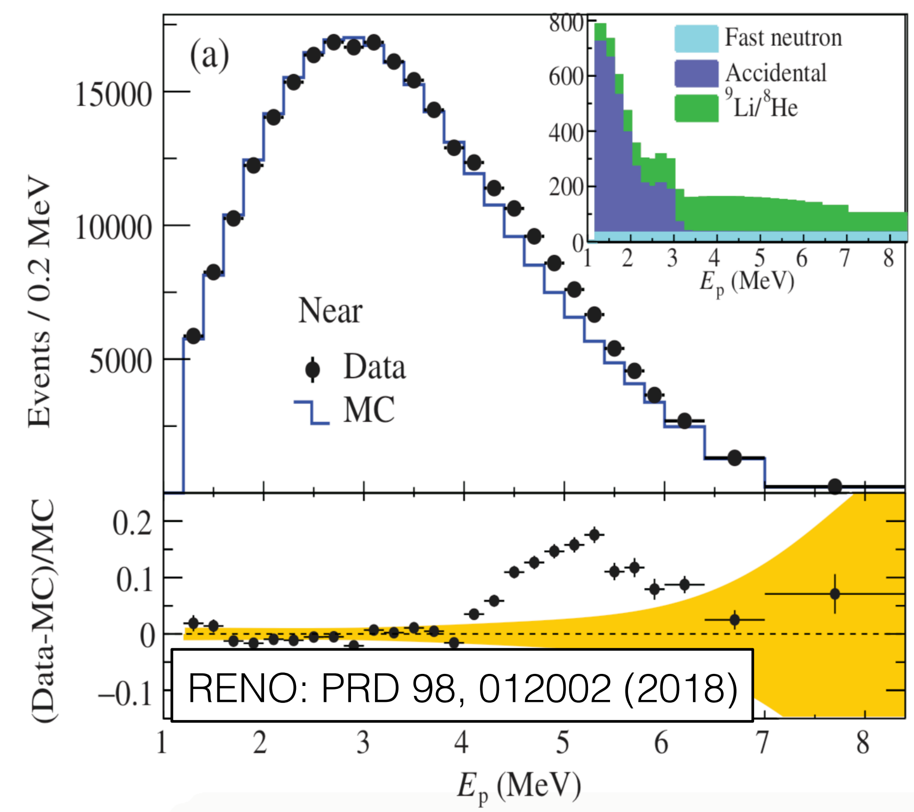
Daya Bay



Double Chooz



RENO



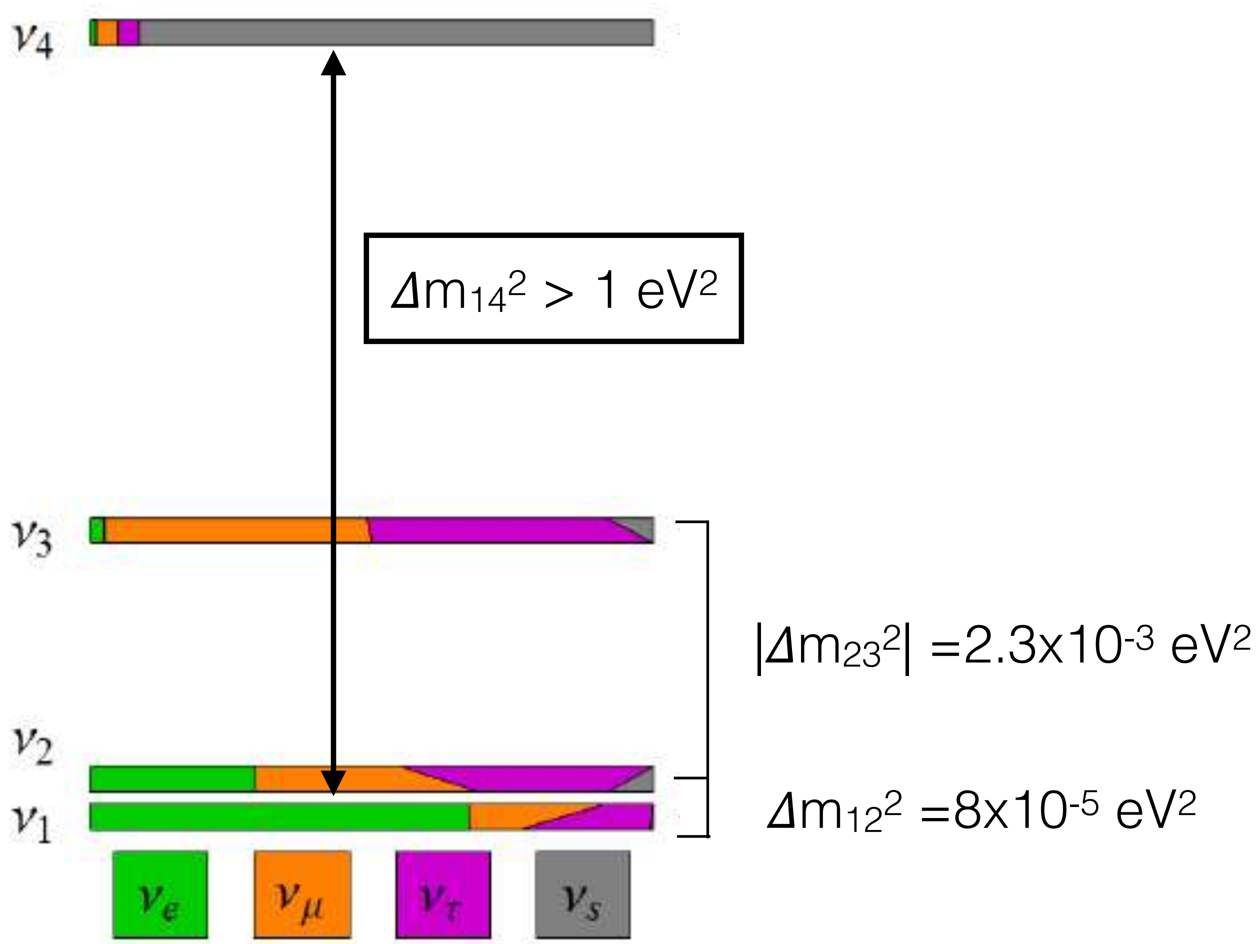
- recent expts at **power reactors** map shape of energy spectrum to percent-levels
- deviations throughout, prominent excess 4-6 MeV prompt (5-7 MeV neutrino)
- cannot be explained by the sterile neutrino introduced for flux deficit
- most likely an issue with nuclear models - one, some, all isotopes to blame?

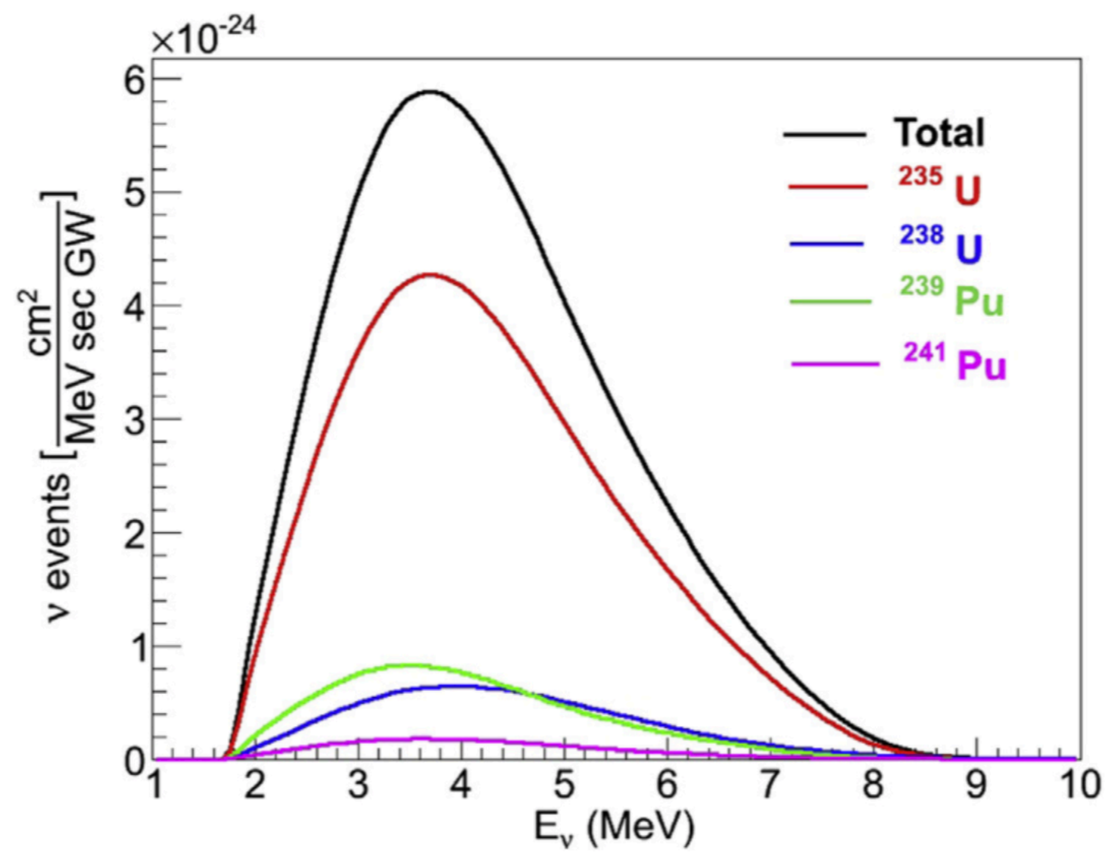
spectrum disagreement - do we model all of the fissile isotopes correctly?

Evolution of neutrino physics with reactor experiments

1930 — 1950 — 1970 — 1990 — 2010 — now

new technology to drive exploration of open neutrino physics at reactors

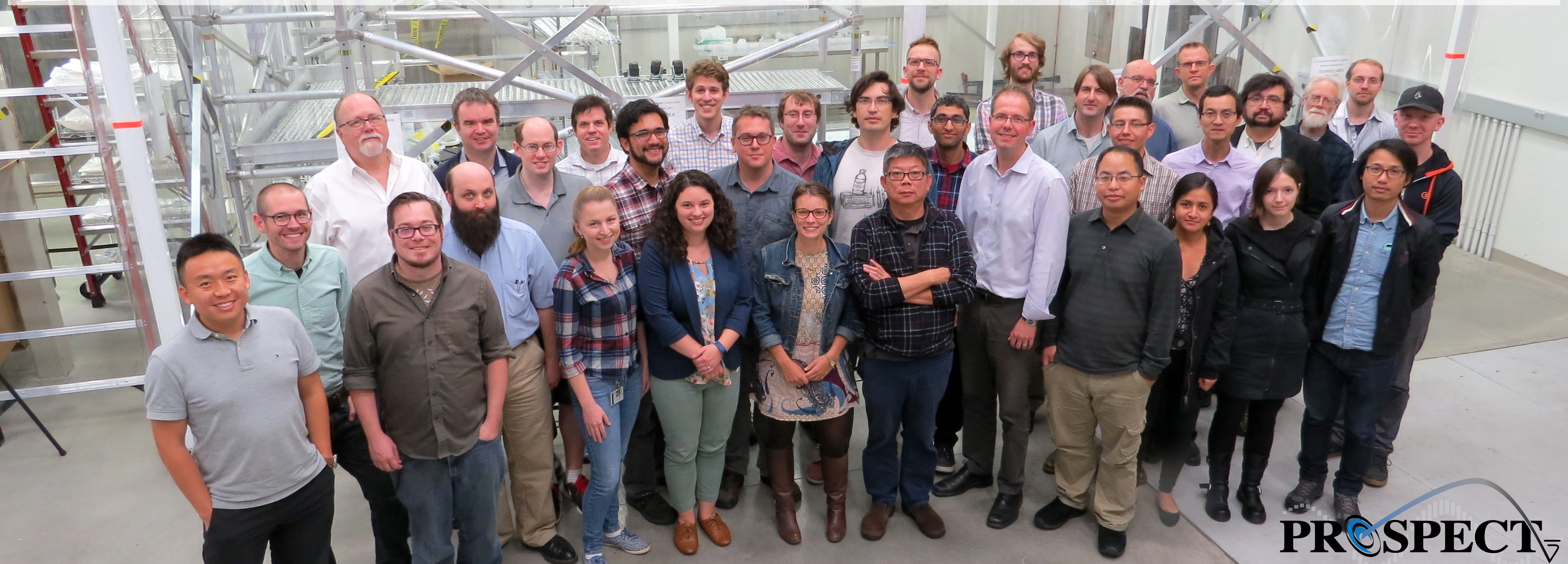




flux deficit: is there a 4th heavy, non-weakly interacting "sterile" neutrino?

the bump: do we fully understand energy spectrum of reactor neutrinos?

The Precision Reactor Oscillation and SPECTrum experiment



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Yale

Precision Reactor Oscillation and SPECTrum experiment

Scientific Goals

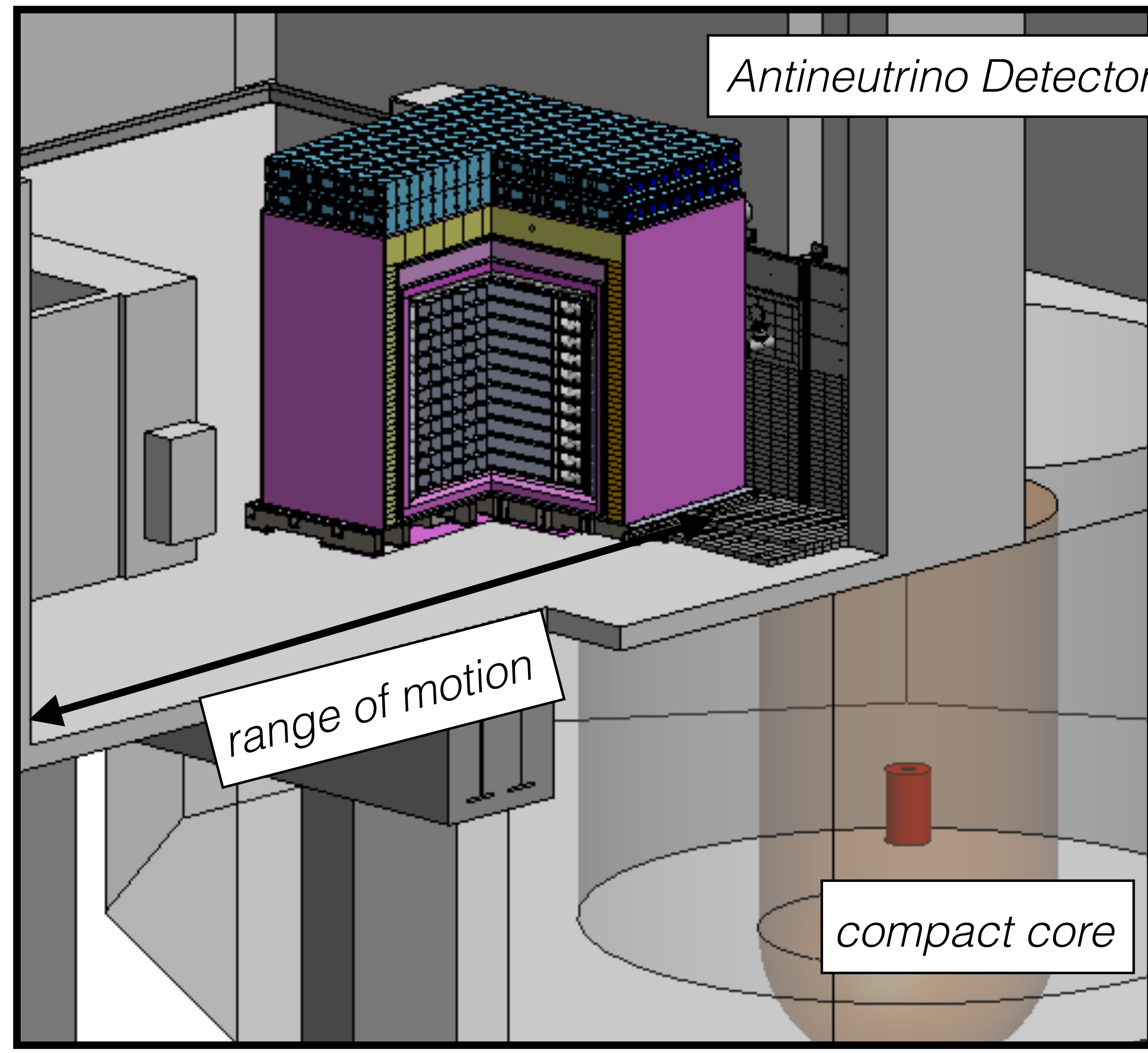
1. model independent search for eV-scale sterile neutrinos at short baselines
2. measure ^{235}U-only antineutrino spectrum to address spectral deviations

Close proximity to reactor (< 10m)

- search for sterile oscillations throughout the detector (segmented)
- high statistics for precision spectrum
- possible at research reactors, allows us to isolate a single isotope ^{235}U

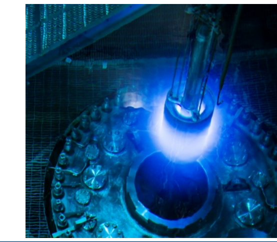
Challenges at HFIR near-surface site

- backgrounds: cosmogenic fast neutrons and reactor gammas
- limited space: compact calorimeter
- current detector technology not well-matched for this environment

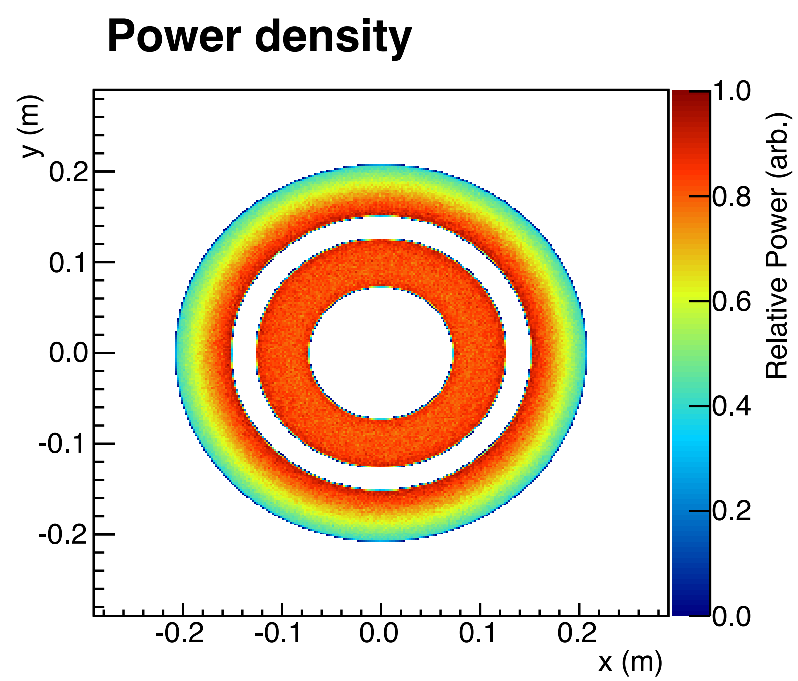


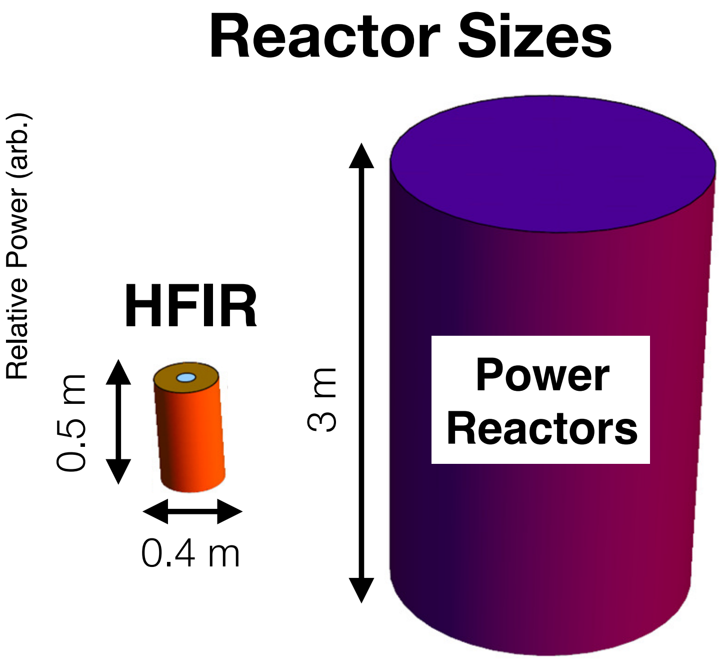
@ High Flux Isotope Reactor (HFIR), Oak Ridge National Laboratory

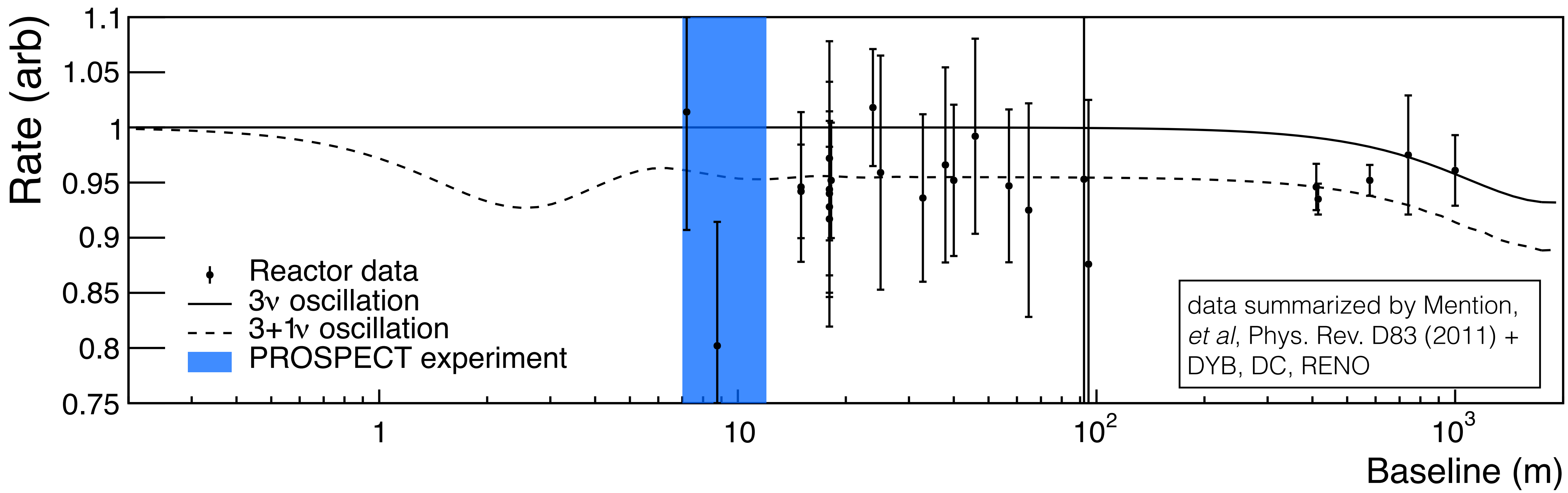
Features of the High Flux Isotope Reactor



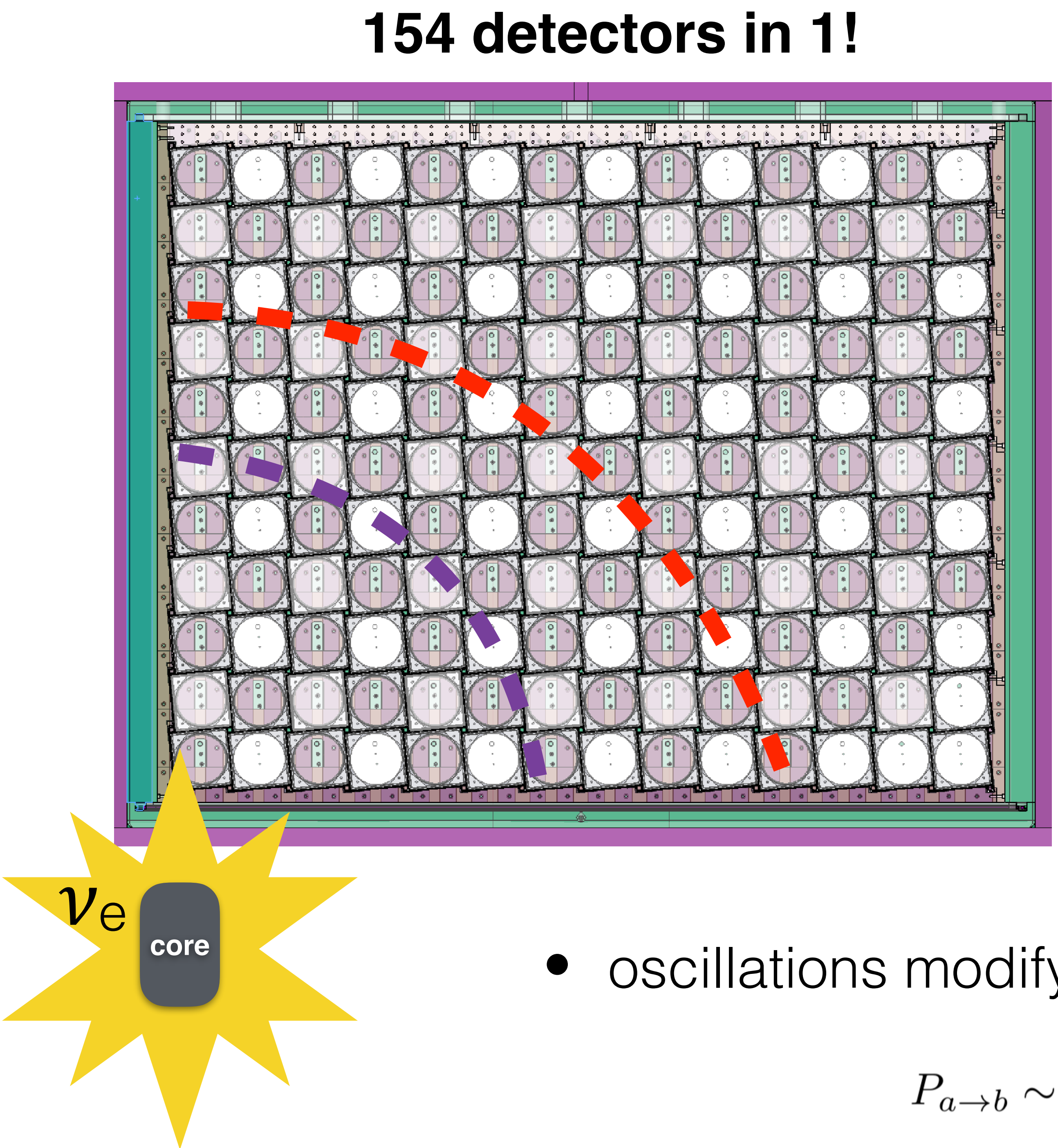
- 85MW highly enriched uranium reactor
- >99% of ν from ^{235}U fissions, effectively no isotopic evolution
- 24 day cycles, 46% reactor up time, measure backgrounds when off
- compact core (44cm diameter, 51cm tall), effectively a point source
- baselines 7-12m within mobile detector

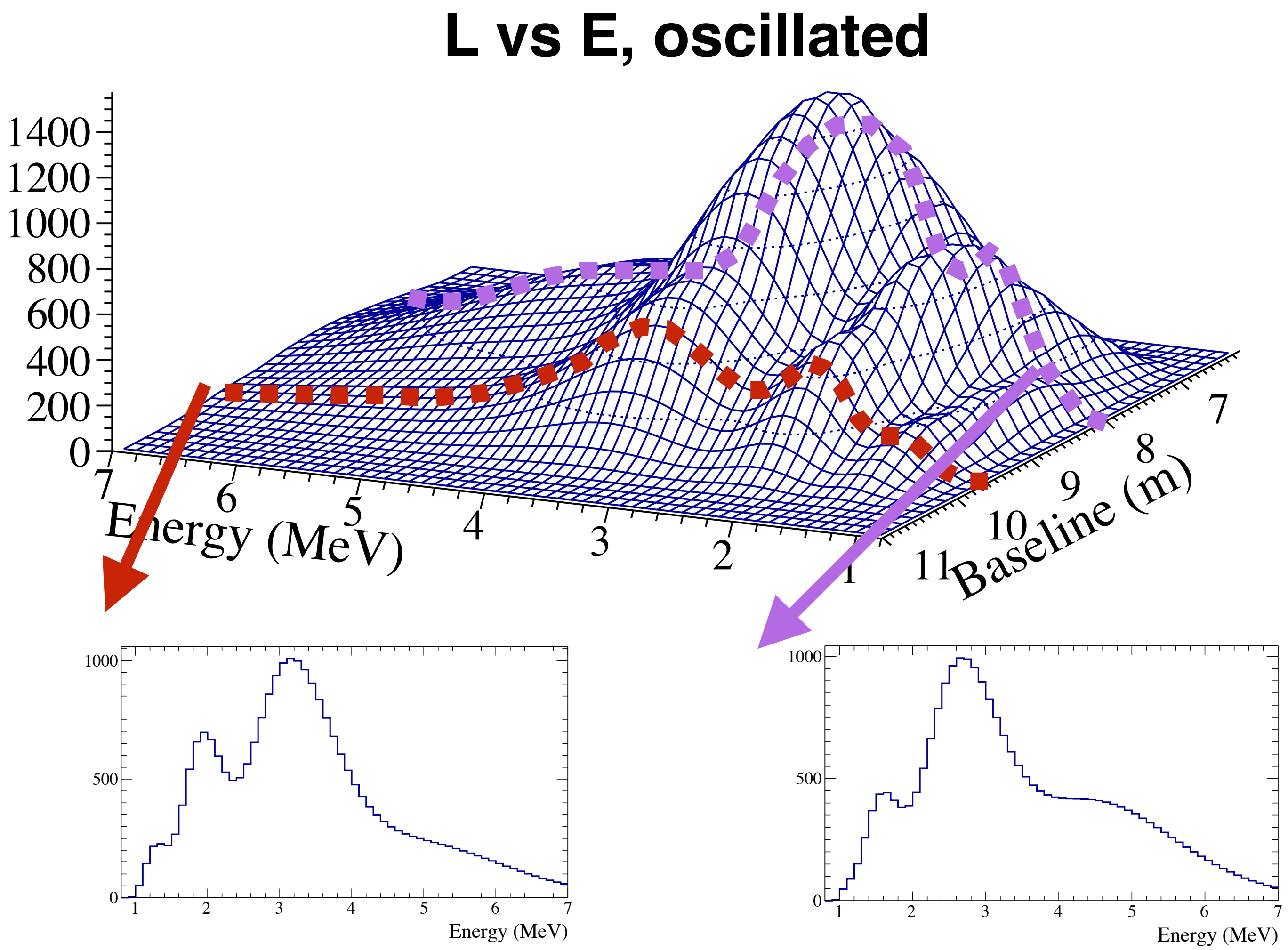






HFIR + segments: model independent sterile search





- oscillations modify energy spectrum as a function of baseline

$$P_{a\to b} \sim sin^2(2\theta_{ab}) sin^2\left(1.27\frac{\Delta m_{ab} L}{E}\right)$$

- relative comparison of segment spectrum shape to full detector spectrum, no reliance on reactor models

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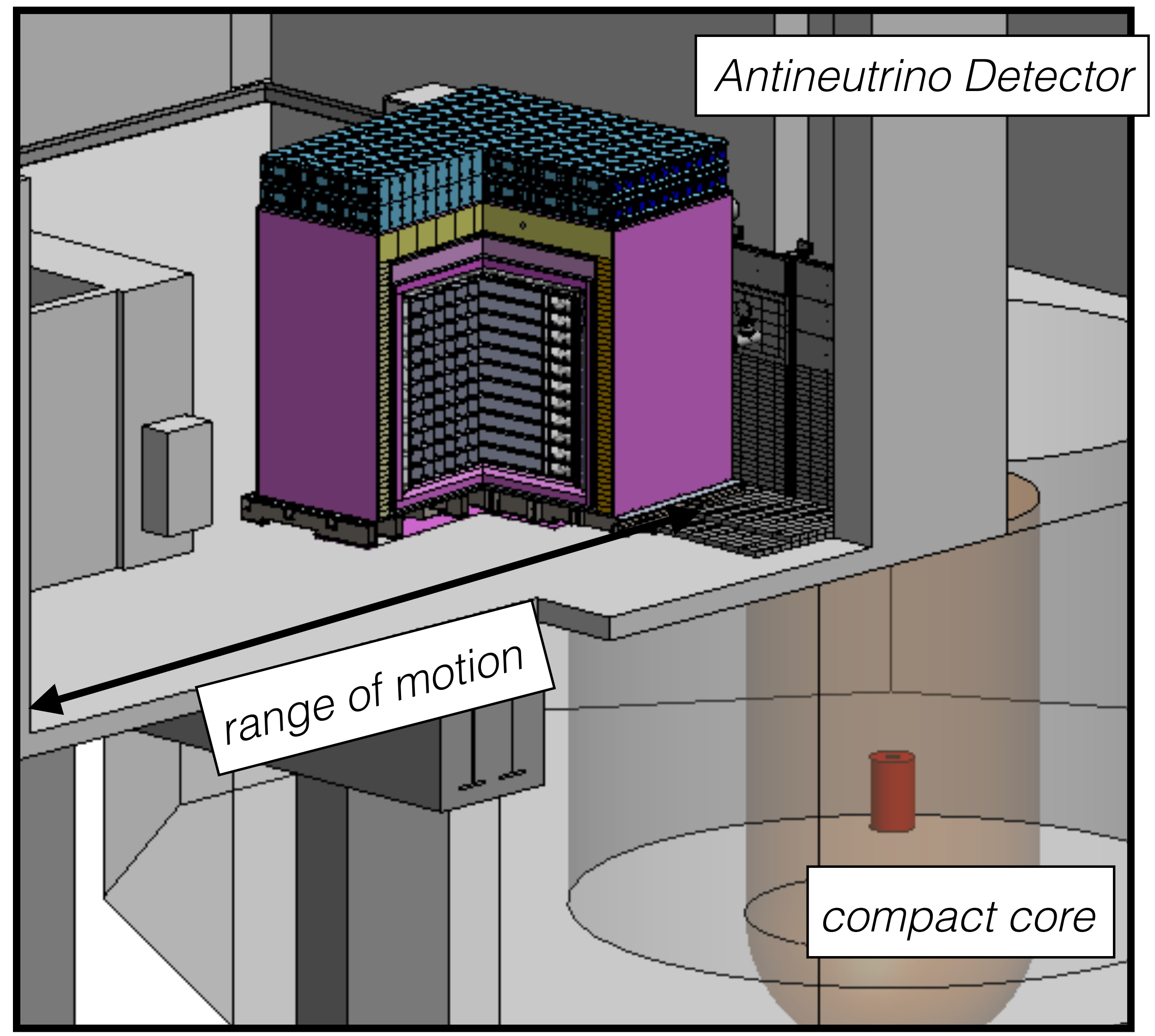
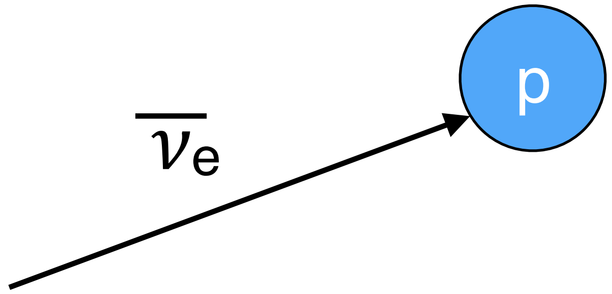


@ High Flux Isotope Reactor (HFIR), Oak Ridge National Laboratory

^{6}Li-loaded liquid scintillator: IBD detection

IBD: $\overline{\nu}_e + p \rightarrow \beta^+ + n$



- develop new scintillator to detect IBDs near-surface reactor environment
- prompt (or detected) energy: positron ionization is a proxy for neutrino energy
- development of ^{6}LiLS for neutron tag needed in compact detector as decay is highly localized in space.. within a PROSPECT segment

^{6}LiLS ideal for neutrino identification in compact, near-surface detector

^{6}Li-loaded liquid scintillator: IBD detection

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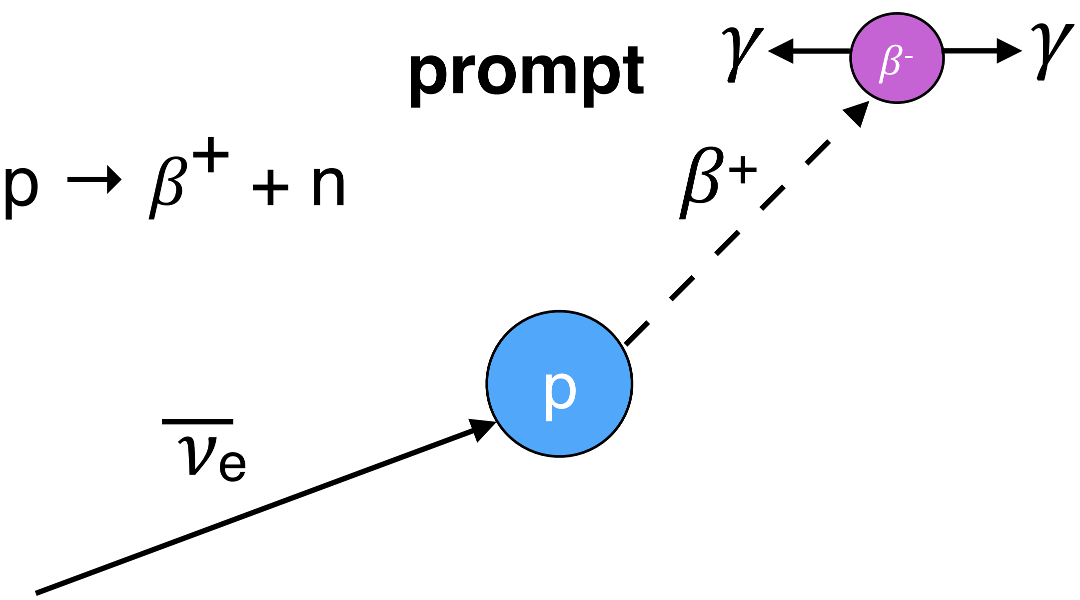
E = 1-10 MeV



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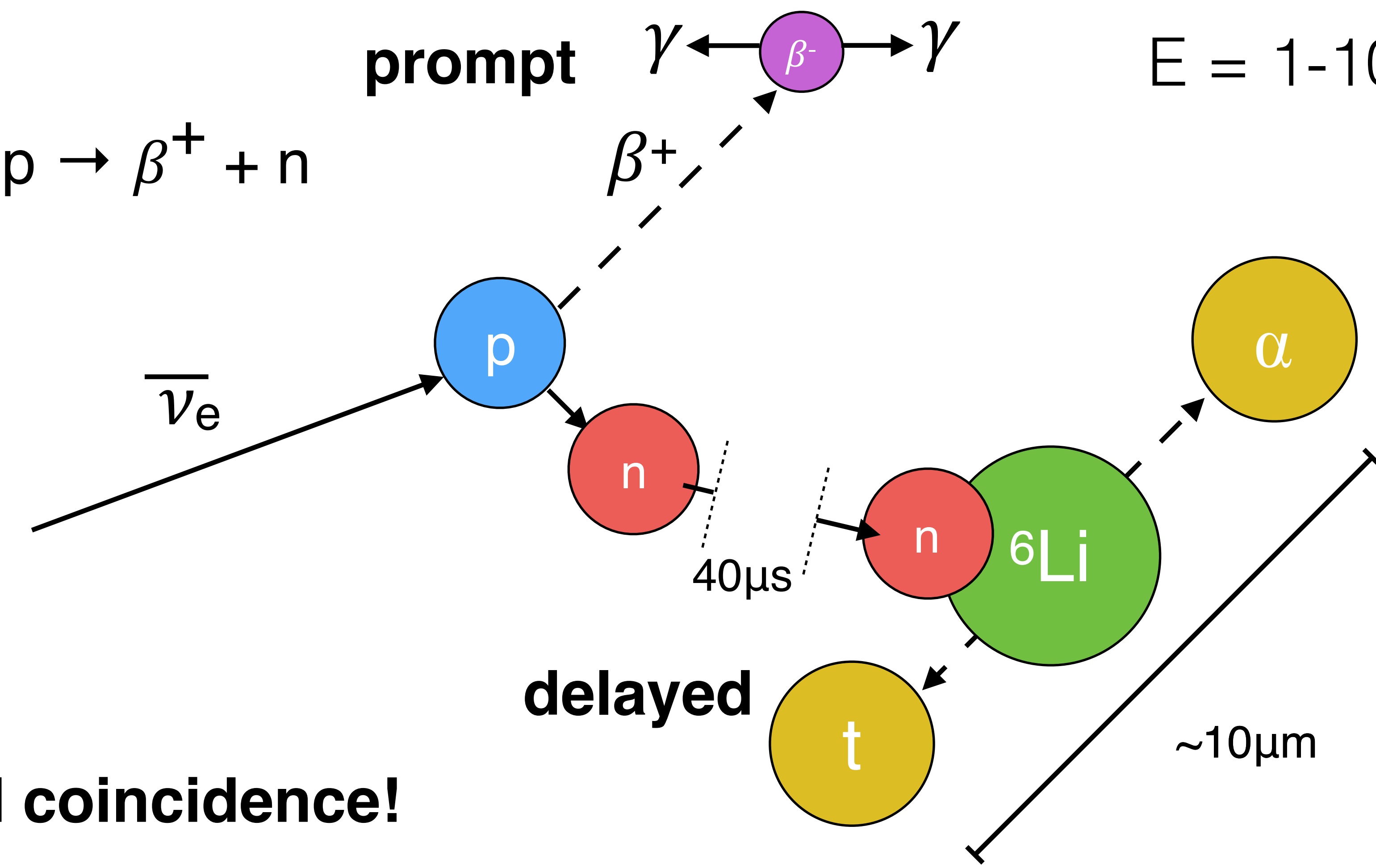

E = 1-10 MeV

E ~ 0.55 MeV

correlated coincidence!

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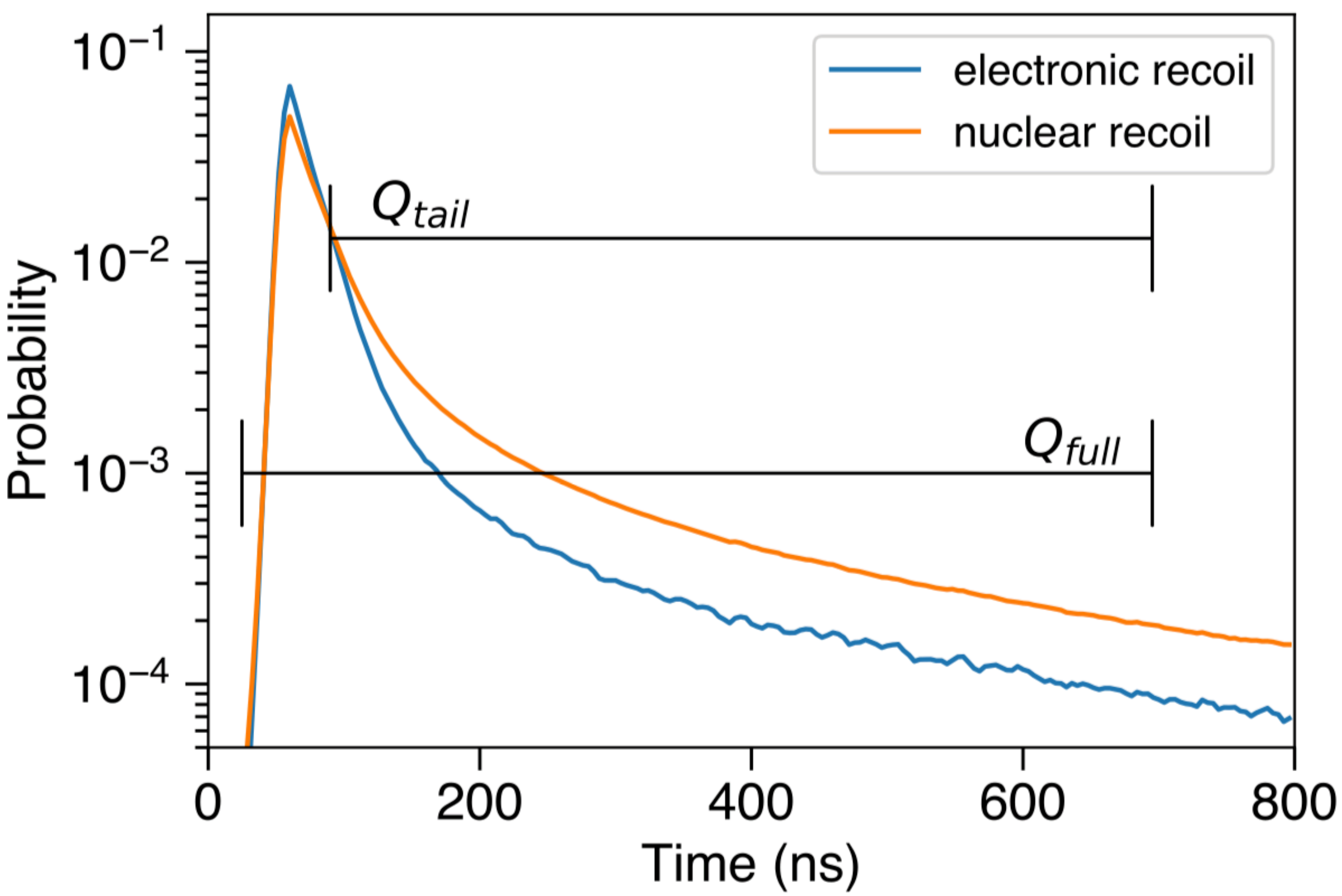
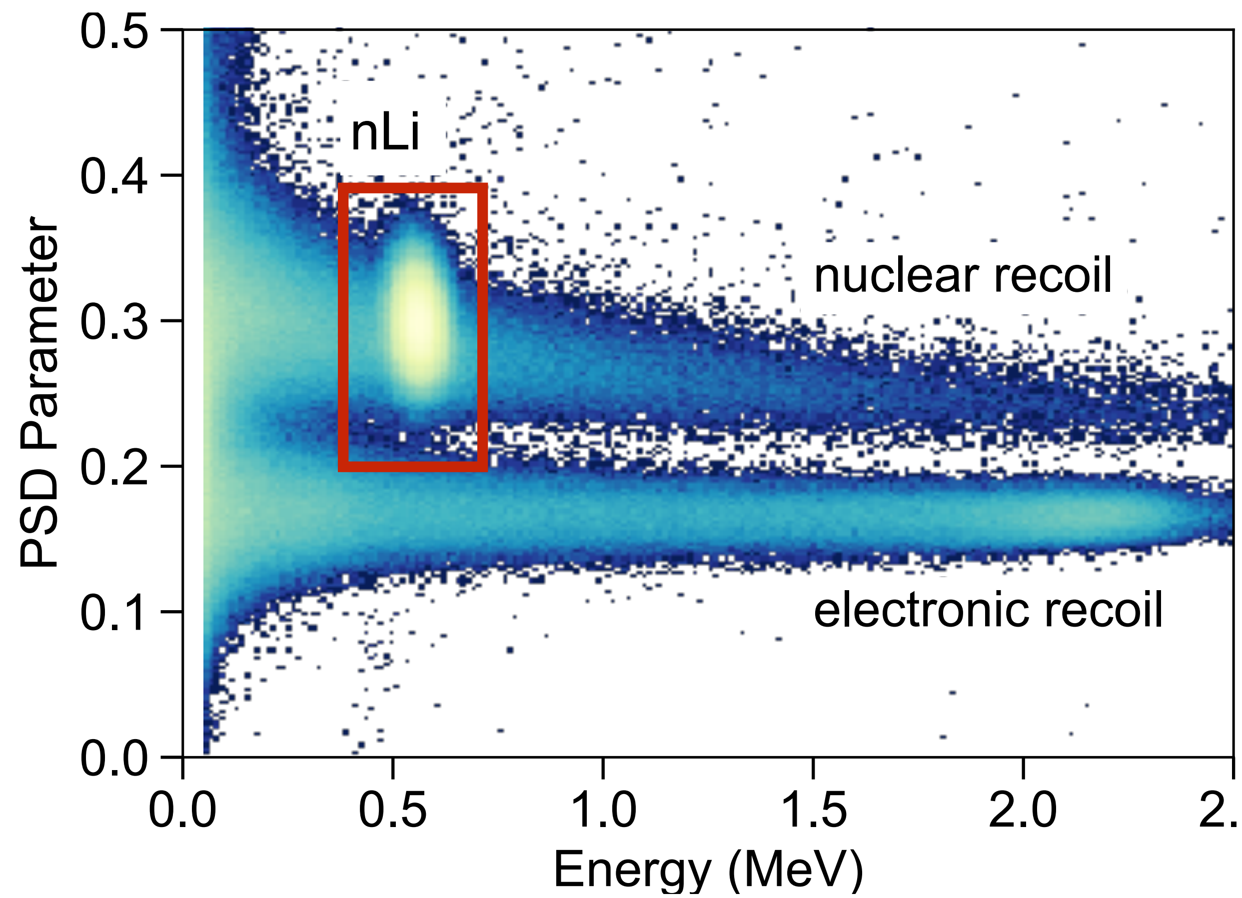
Particle identification: Pulse Shape Discrimination

Wanted to develop ^{6}LiLS with capabilities to distinguish particles through their scintillation timing profile (ionization density).





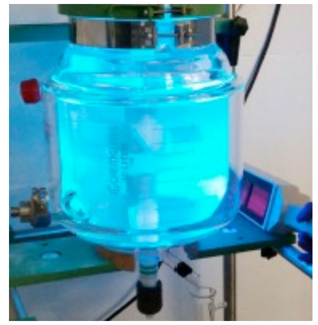
PSD = Qtail/Qfull

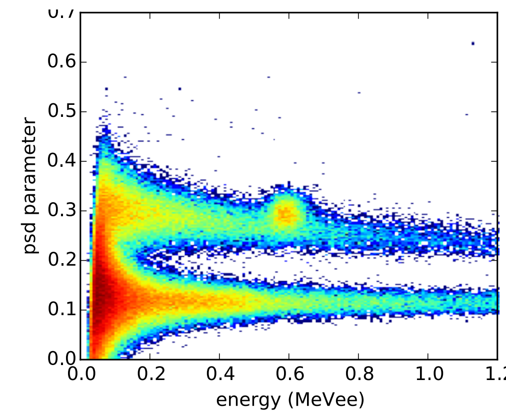
PSD adds powerful information to identify IBDs and reject backgrounds

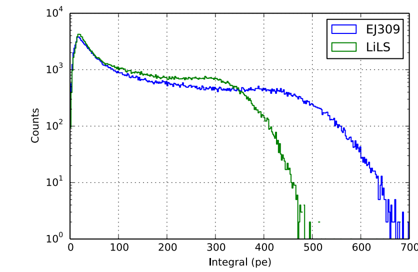
Path to segmented ^{6}LiLS detector with particle ID

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

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







PROSPECT-2
Background studies
Dec 2014 - Aug 2015

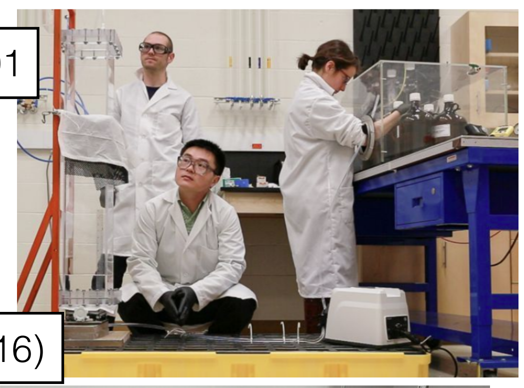
12.5 length
1.7 liters
^{6}LiLS

PROSPECT: NIMA A806 (2016) 401

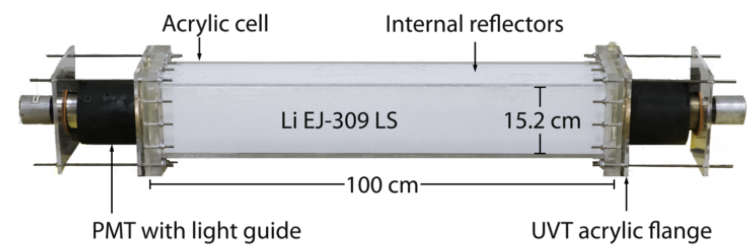
light guides
low mass reflectors

PROSPECT-20
Segment optics
Component design
Spring/Summer 2015

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



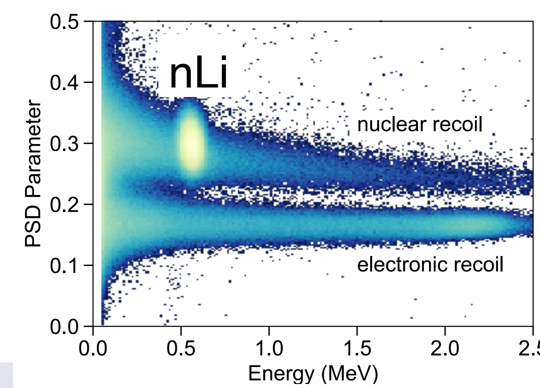
PROSPECT: JINST 10 P11004 (2016)



PROSPECT-50
Performance validation
Subsystem testbed
Simulation benchmark
2017-2018

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

PROSPECT: JINST 13 P06023 (2018)

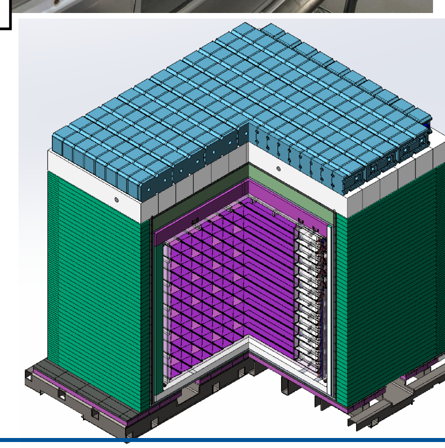
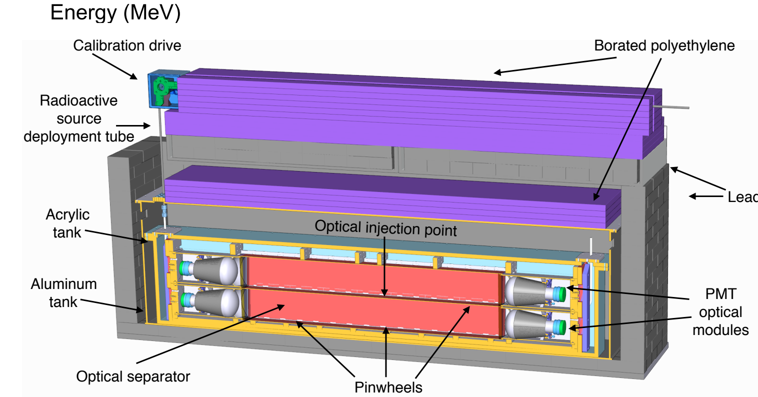


light collection
energy resolution
PSD performance

PROSPECT AD
Physics measurement
data taking 2018

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

PROSPECT: arXiv:1808.00097

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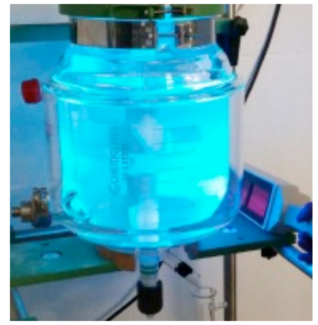

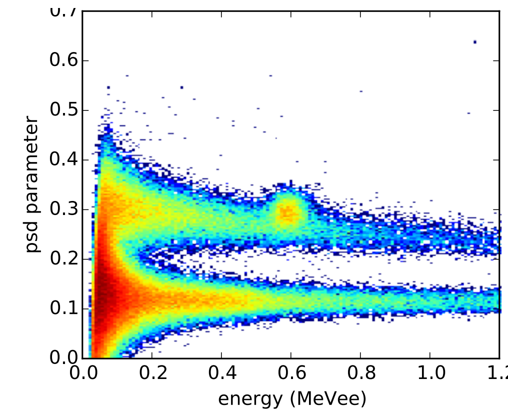

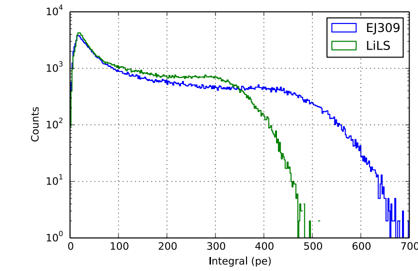

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Spring/Summer 2015

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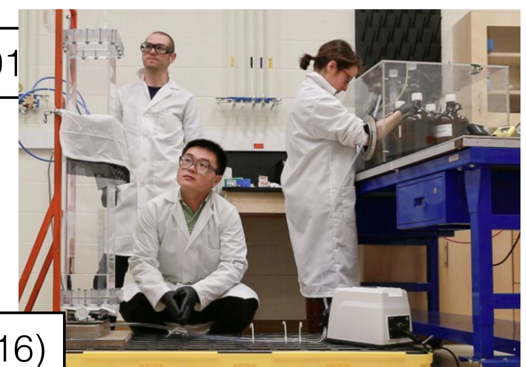

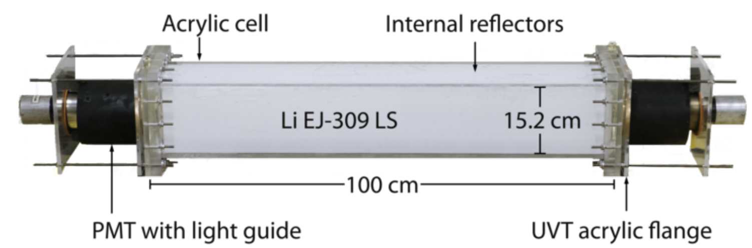

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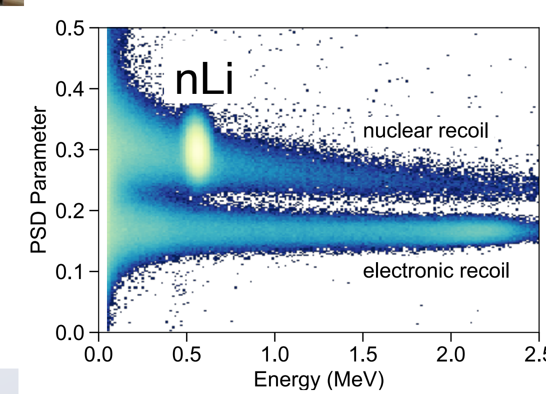
Subsystem testbed
Simulation benchmark
2017-2018

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



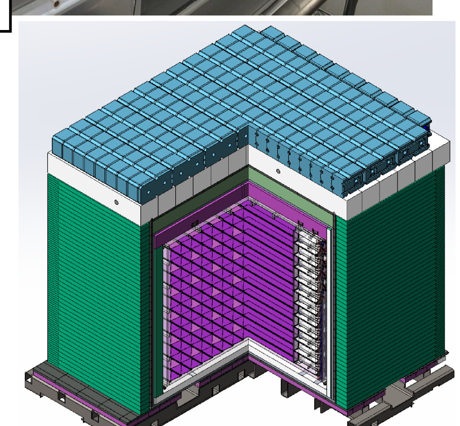
light collection
energy resolution
PSD performance

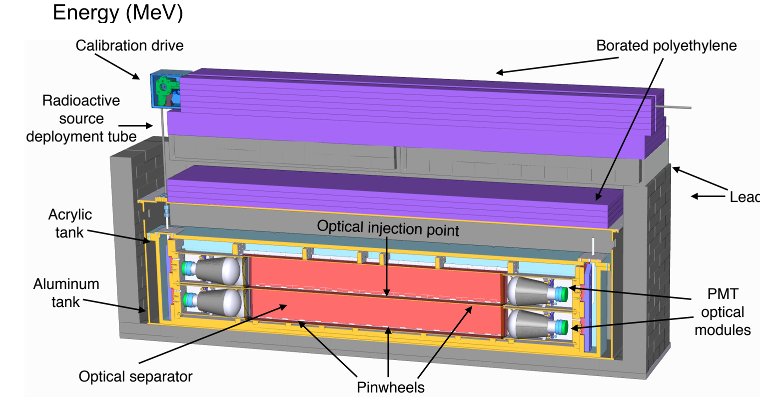
PROSPECT: JINST 13 P06023 (2018)

PROSPECT AD
Physics measurement
data taking 2018

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

PROSPECT: arXiv:1808.00097

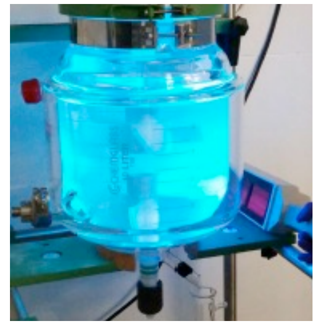


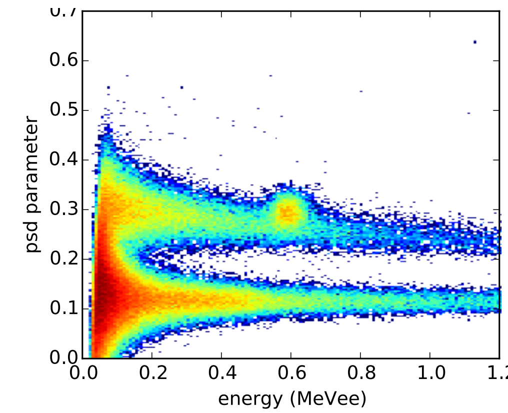


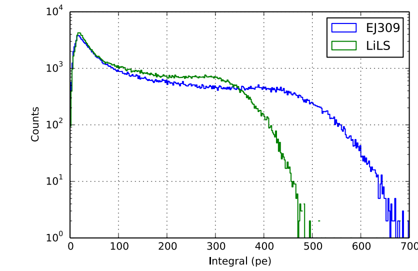
Path to segmented ^{6}LiLS detector with particle ID

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

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







PROSPECT-2
Background studies
Dec 2014 - Aug 2015

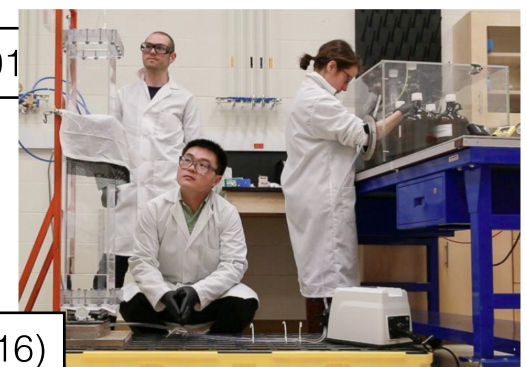
12.5 length
1.7 liters
^{6}LiLS

PROSPECT: NIMA A806 (2016) 401

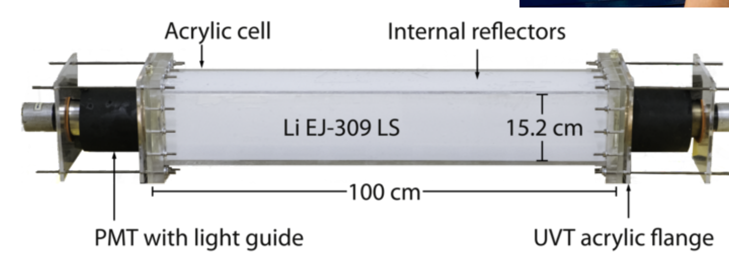
light guides
low mass reflectors

PROSPECT-20
Segment optics
Component design
Spring/Summer 2015

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



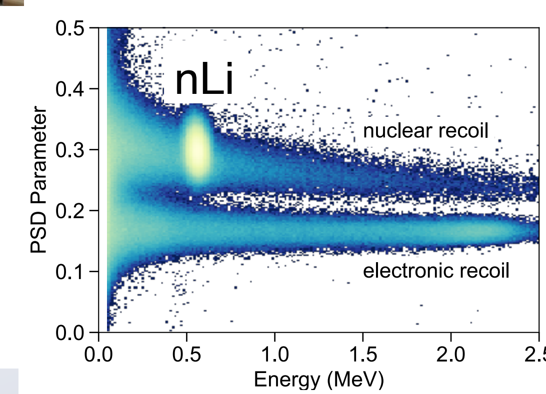
PROSPECT: JINST 10 P11004 (2016)



PROSPECT-50
Performance validation
Subsystem testbed
Simulation benchmark
2017-2018

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

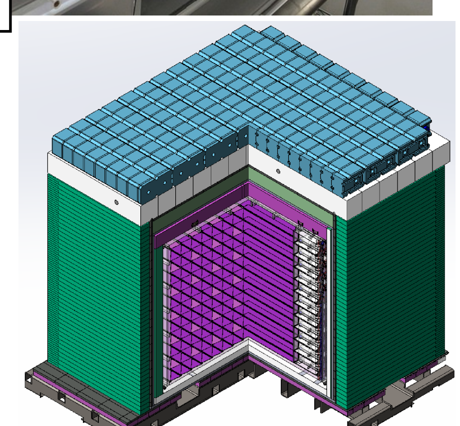
PROSPECT: JINST 13 P06023 (2018)



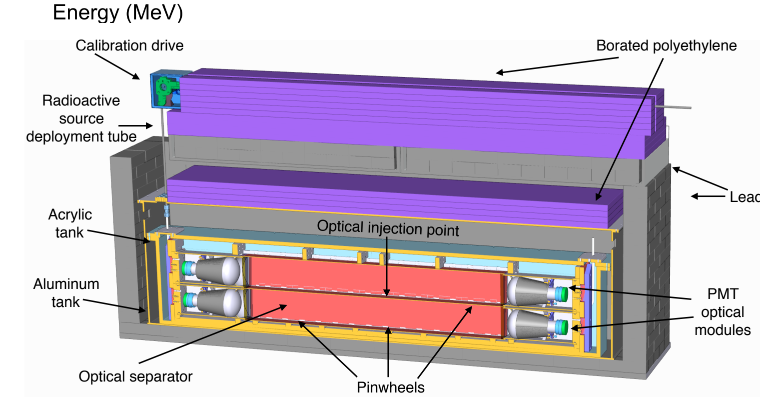
light collection
energy resolution
PSD performance

PROSPECT AD
Physics measurement
data taking 2018

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



PROSPECT: arXiv:1808.00097



Path to segmented ^{6}LiLS detector with particle ID

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Characterize LS
Aug 2014-Spring 2015

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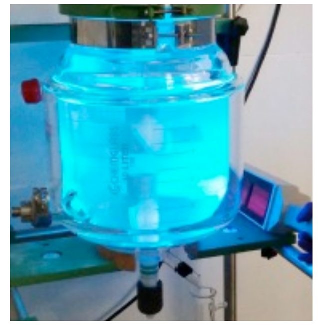

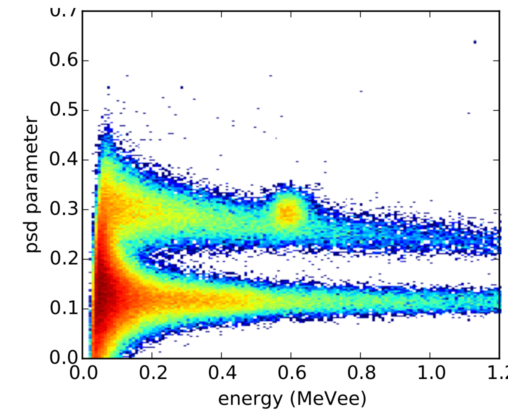

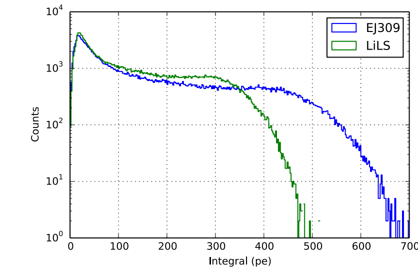

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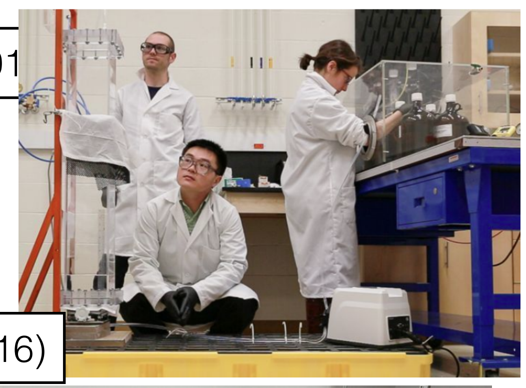
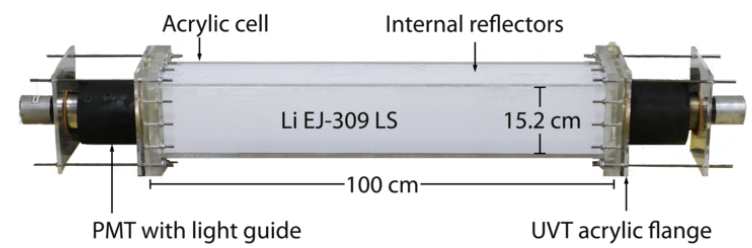


PROSPECT: JINST 10 P11004 (2016)



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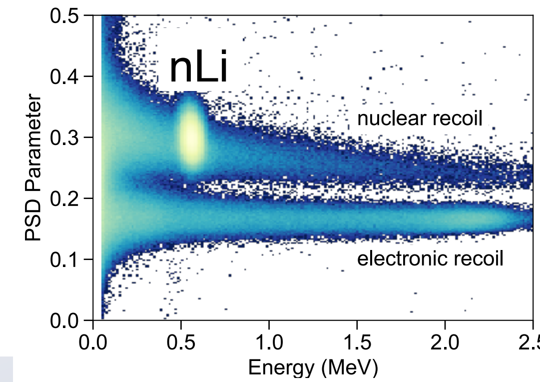

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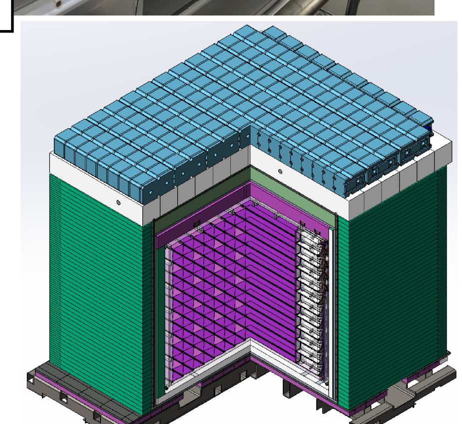
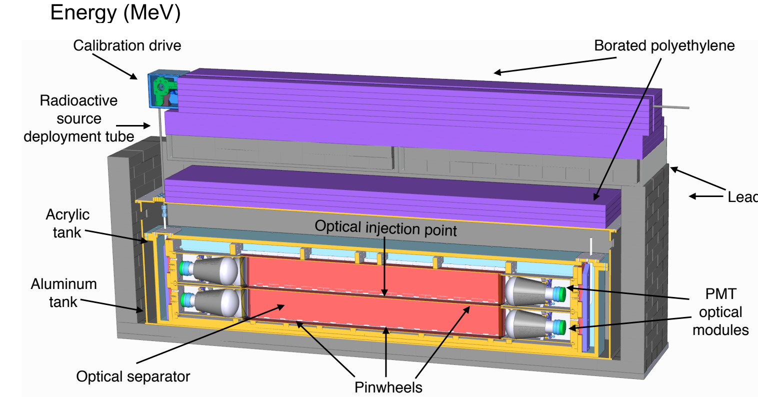
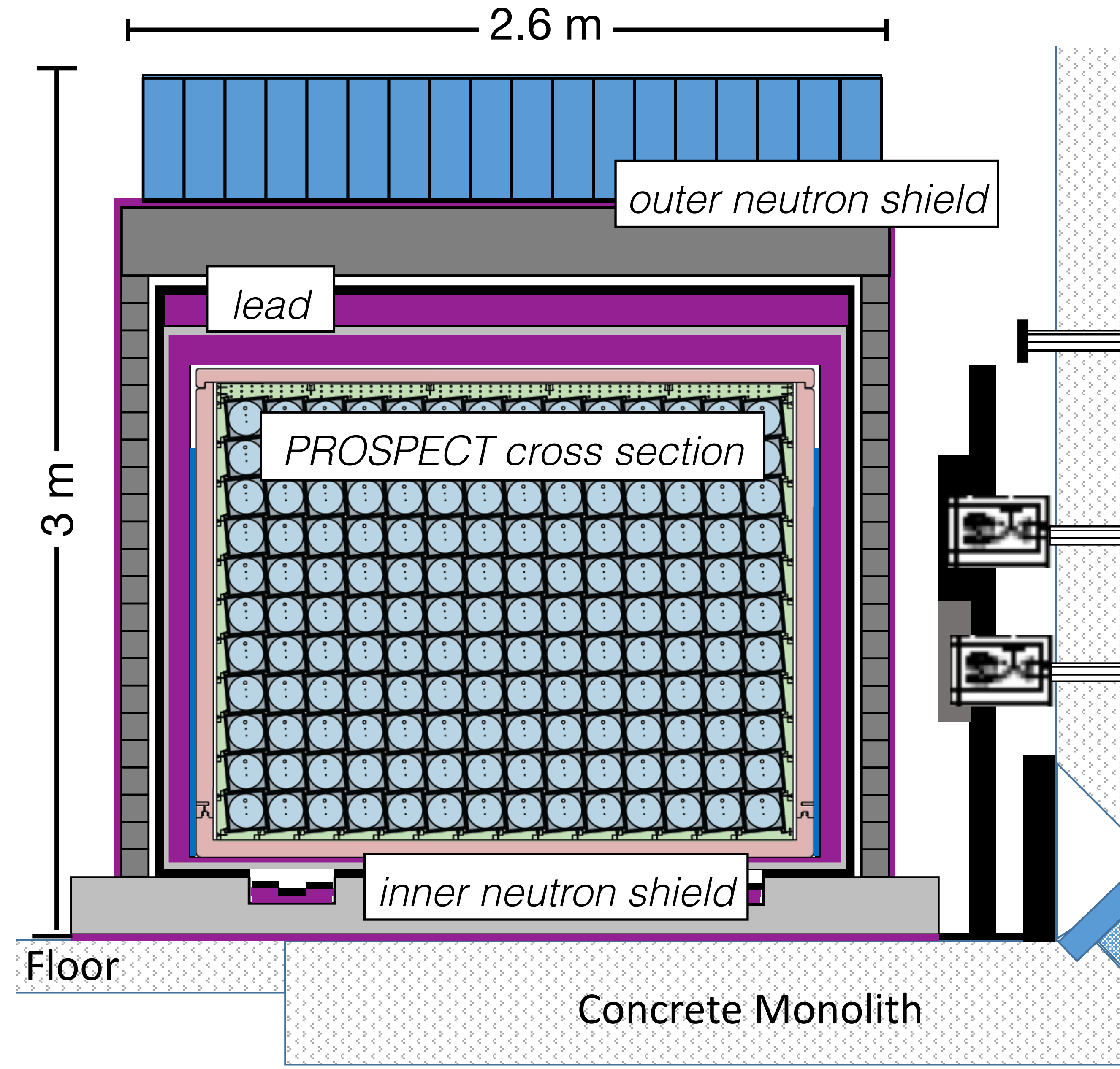
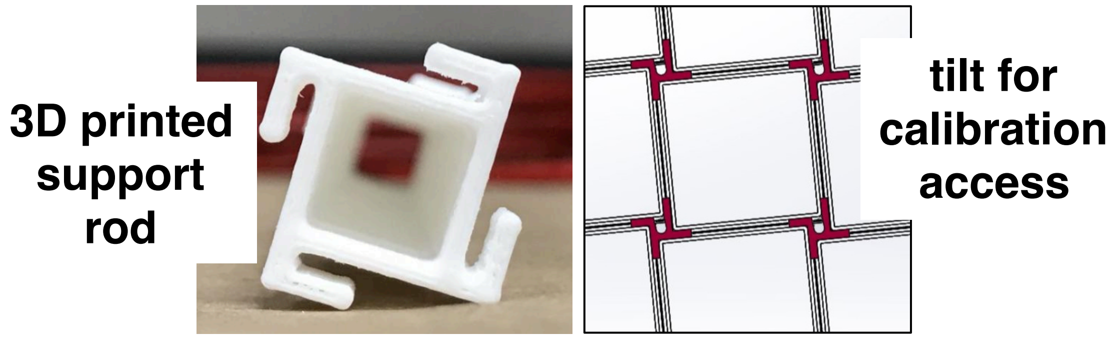


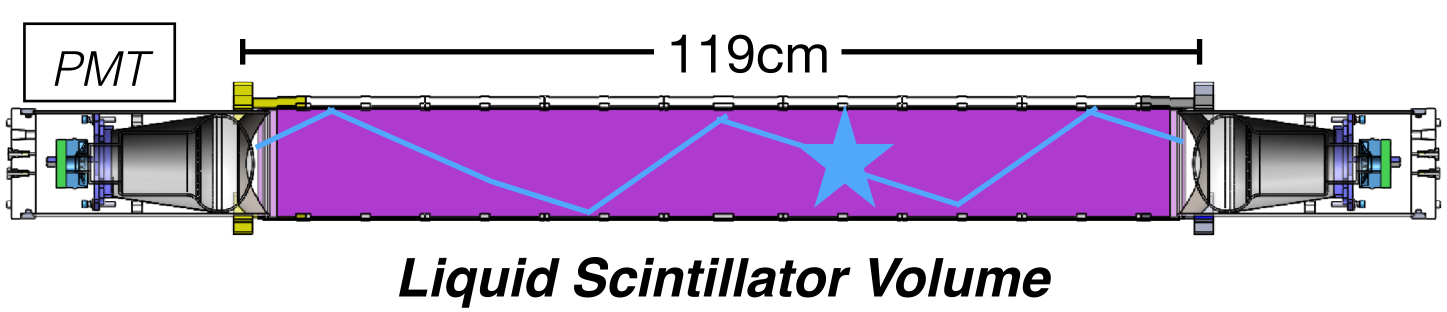


PROSPECT segmented detector design

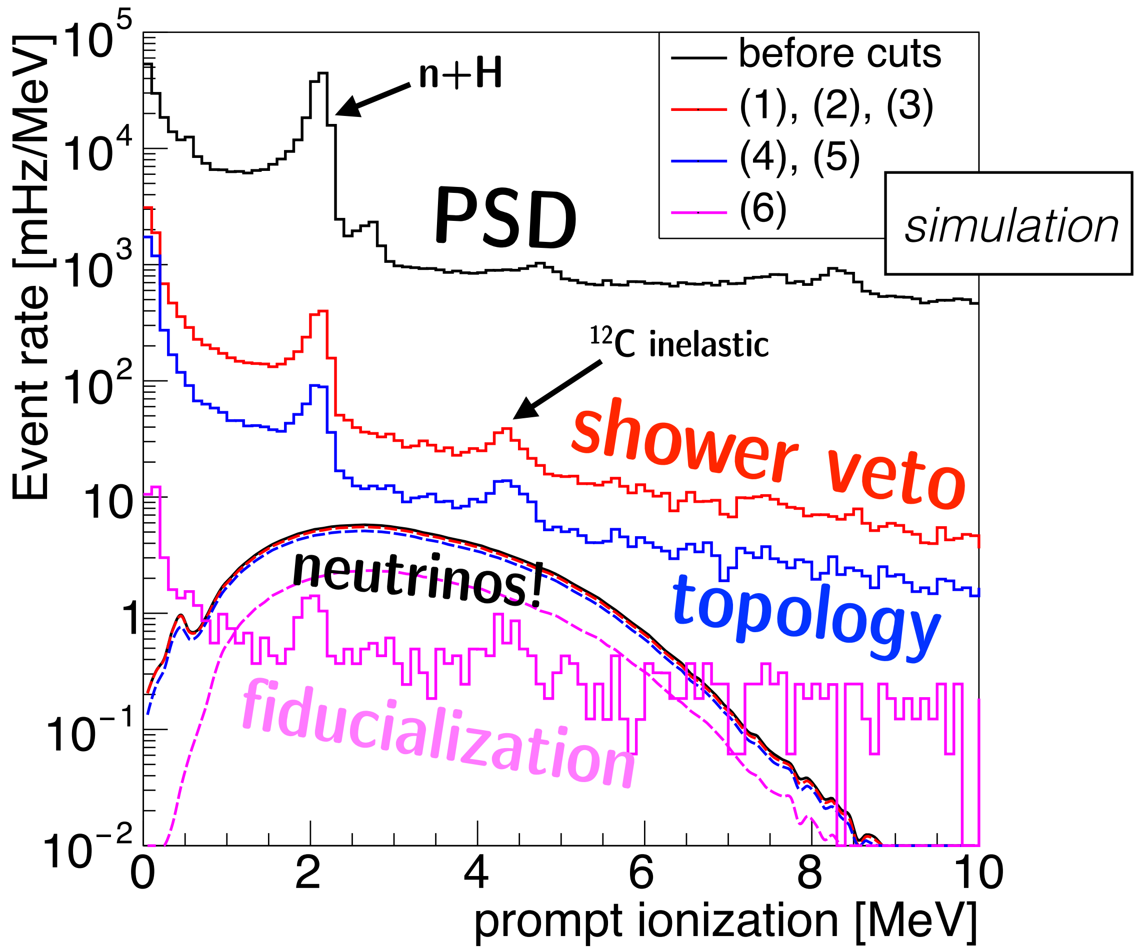
- 4 tons ^{6}Li-loaded liquid scintillator with energy resolution of <5%/MeV
- 154 segments, 119cm x 15cm x 15cm
- thin (1.5mm) highly reflective optical panels held in place by 3D printed support rods
- calibration access along each segment
- 3D position reconstruction (X, Y) with (Z) from double-ended PMT readout
- optimized shield for backgrounds at the surface and reactor

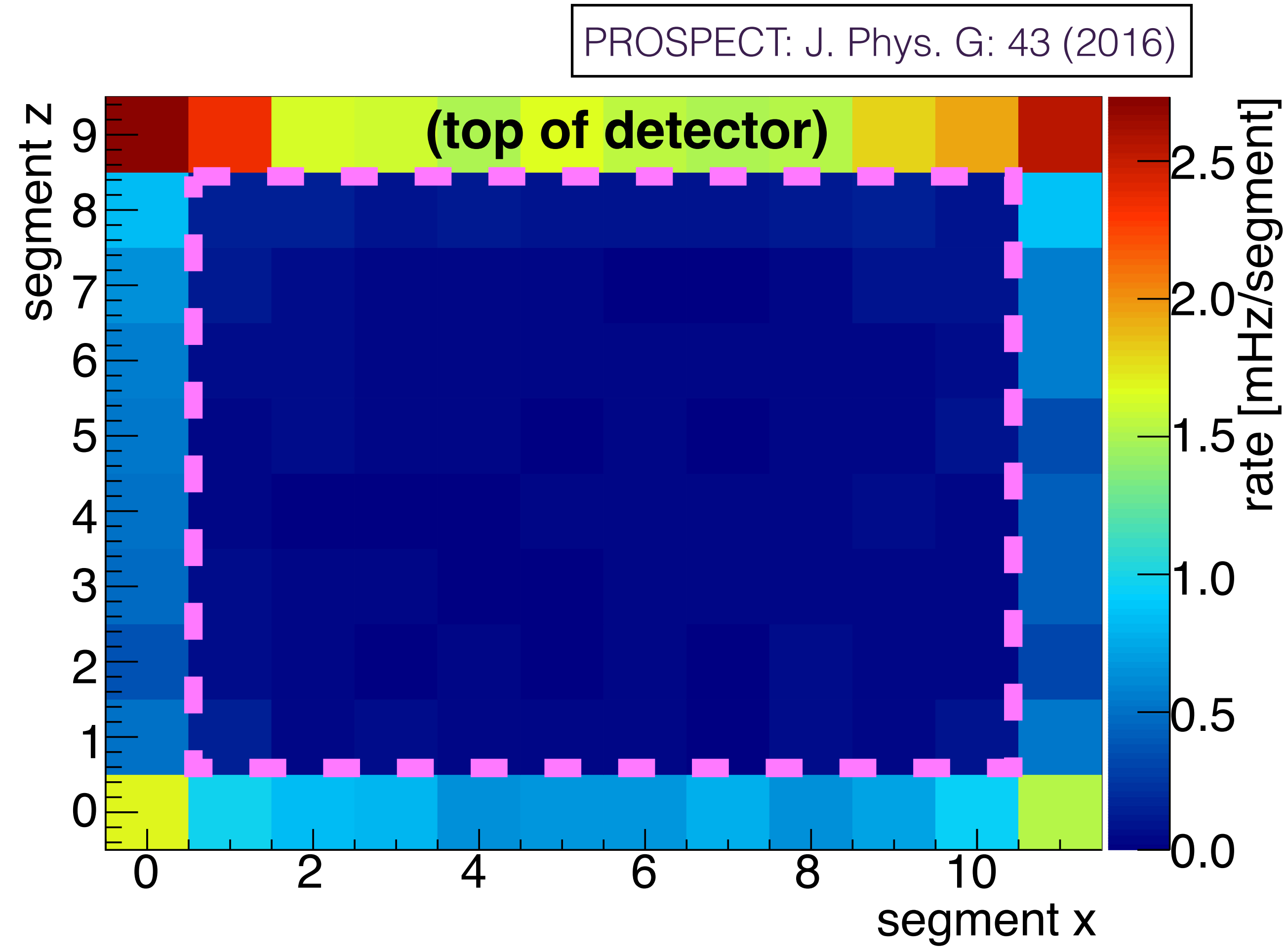






Surface detector to combat backgrounds





- near-surface backgrounds: cosmogenic fast neutrons, reactor-related gammas
- combination of segmentation, ^{6}Li liquid scintillator, particle ID powerful
- **PSD**, **shower veto**, **topology**, and **fiducialization** cuts provide >10^4 active background suppression (signal:background > 1)

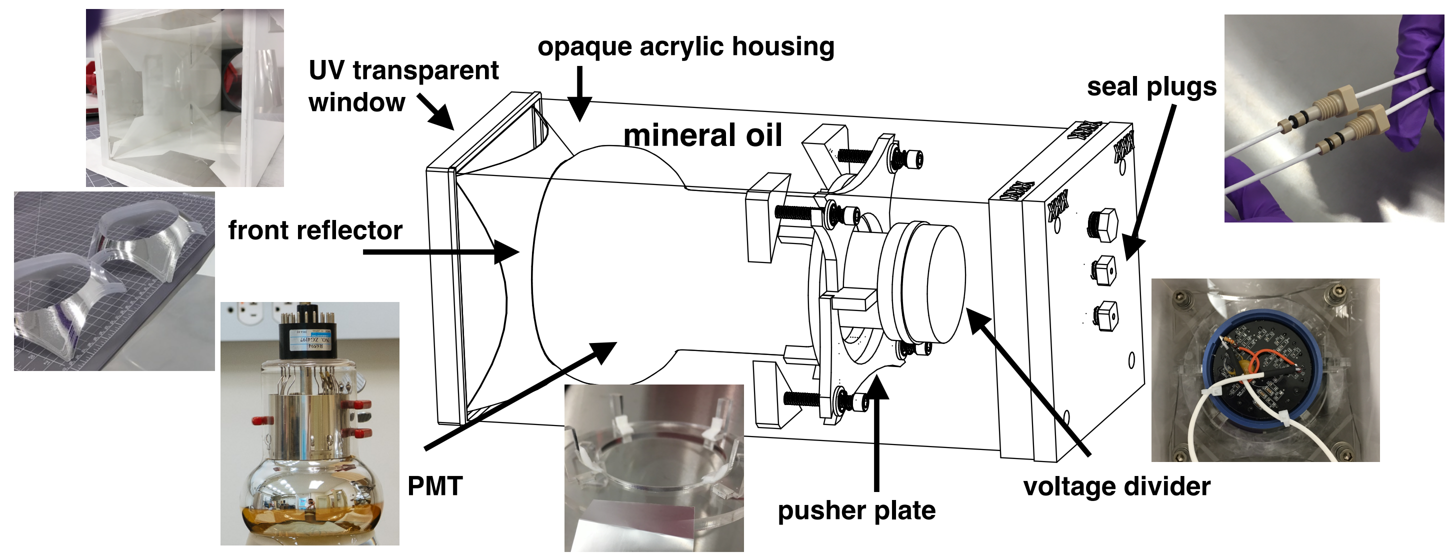
optimized detector design for background ID and suppression

Construction + Installation

Optical module assembly @ Yale Wright Lab

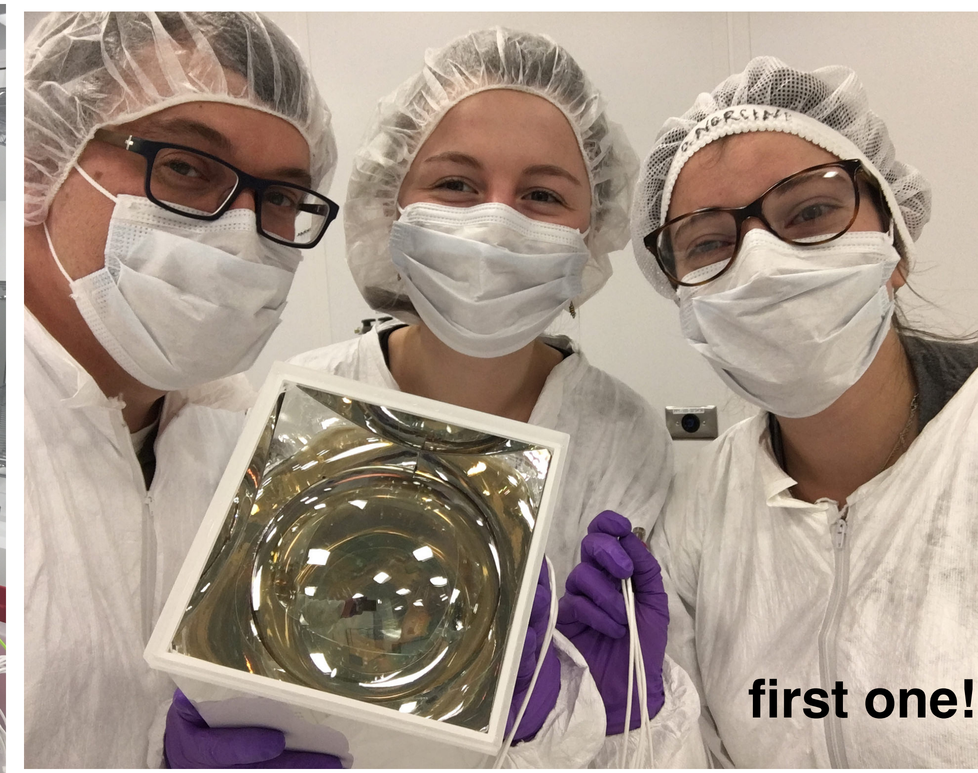
- lead construction of ~350 PMT modules in clean room
- each ~50 parts, many made by us
- developed procedures to clean, assemble, QA measurements, test
- worked with and trained collaborators

Modules in liquid volume: scintillator approved!

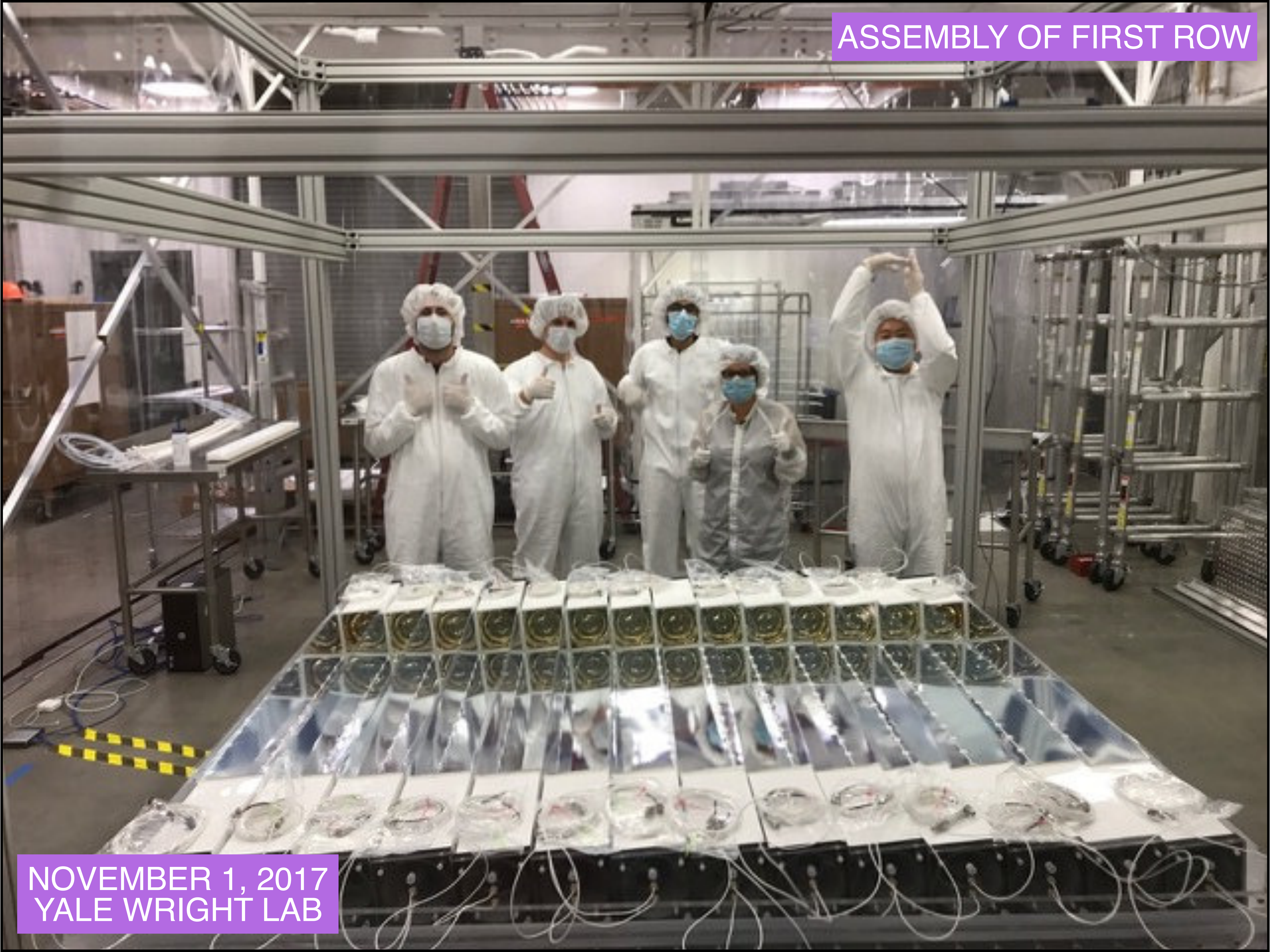


NOVEMBER 2016-2017
YALE WRIGHT LABORATORY

Optical module assembly @ Yale Wright Lab



NOVEMBER 2016-2017
YALE WRIGHT LABORATORY


ASSEMBLY OF FIRST ROW
NOVEMBER 1, 2017
YALE WRIGHT LAB

PROSPECT layer in 30 seconds


NOVEMBER 17, 2017
FINAL ROW INSTALLATION

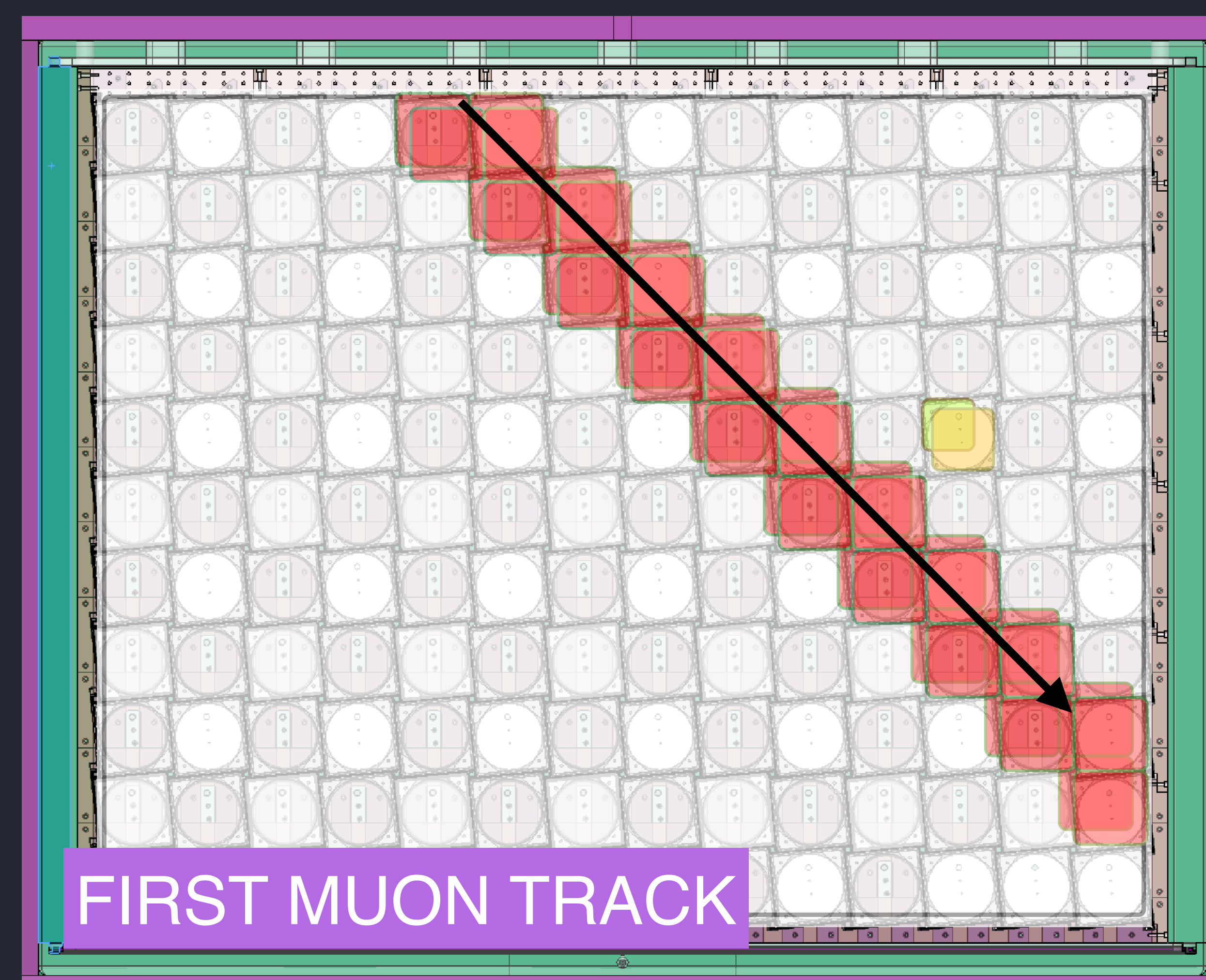

AHHHHH!


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

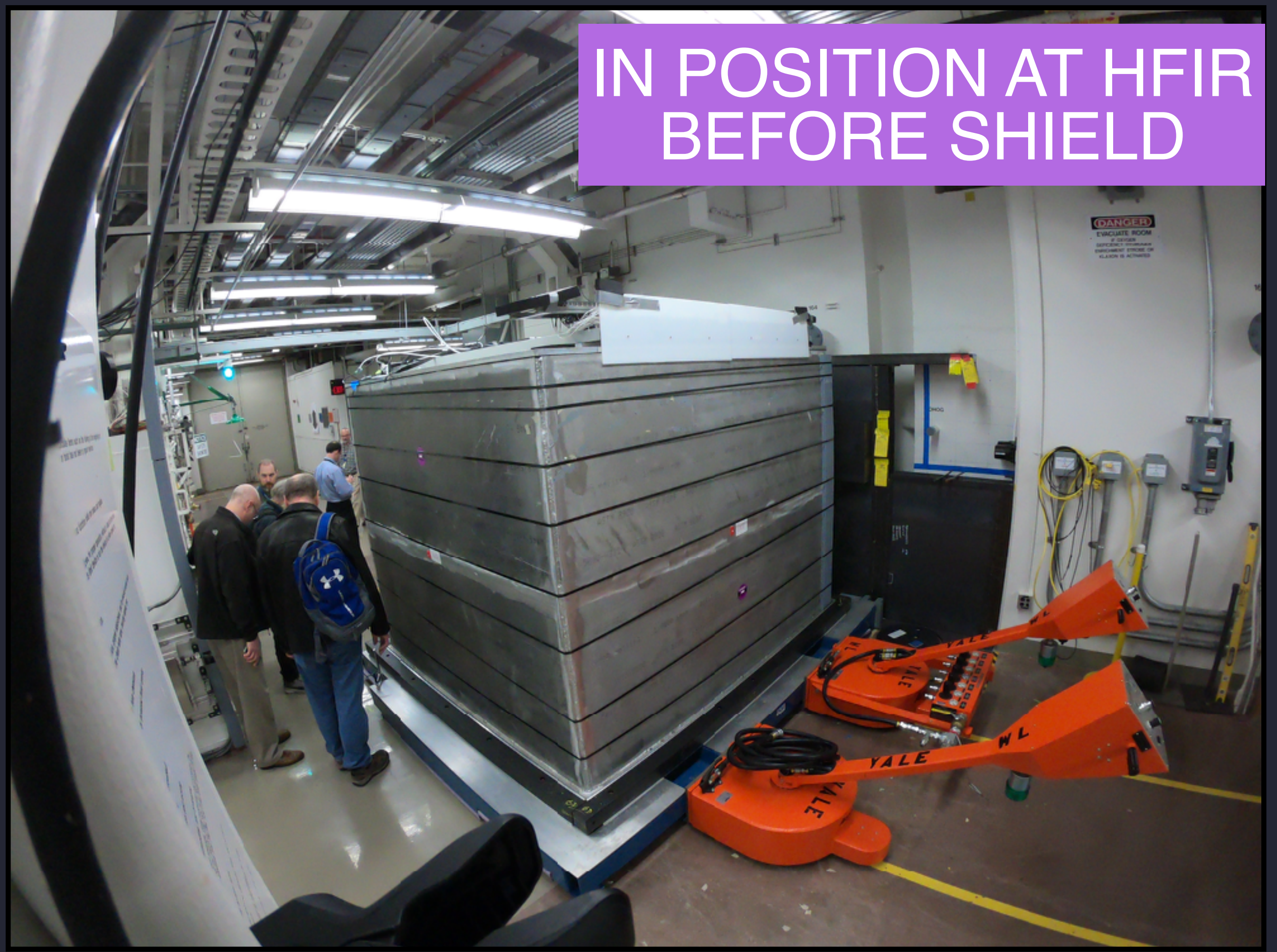

FEBRUARY 2018
ARRIVAL AT ORNL


IN POSITION AT HFIR
BEFORE SHIELD

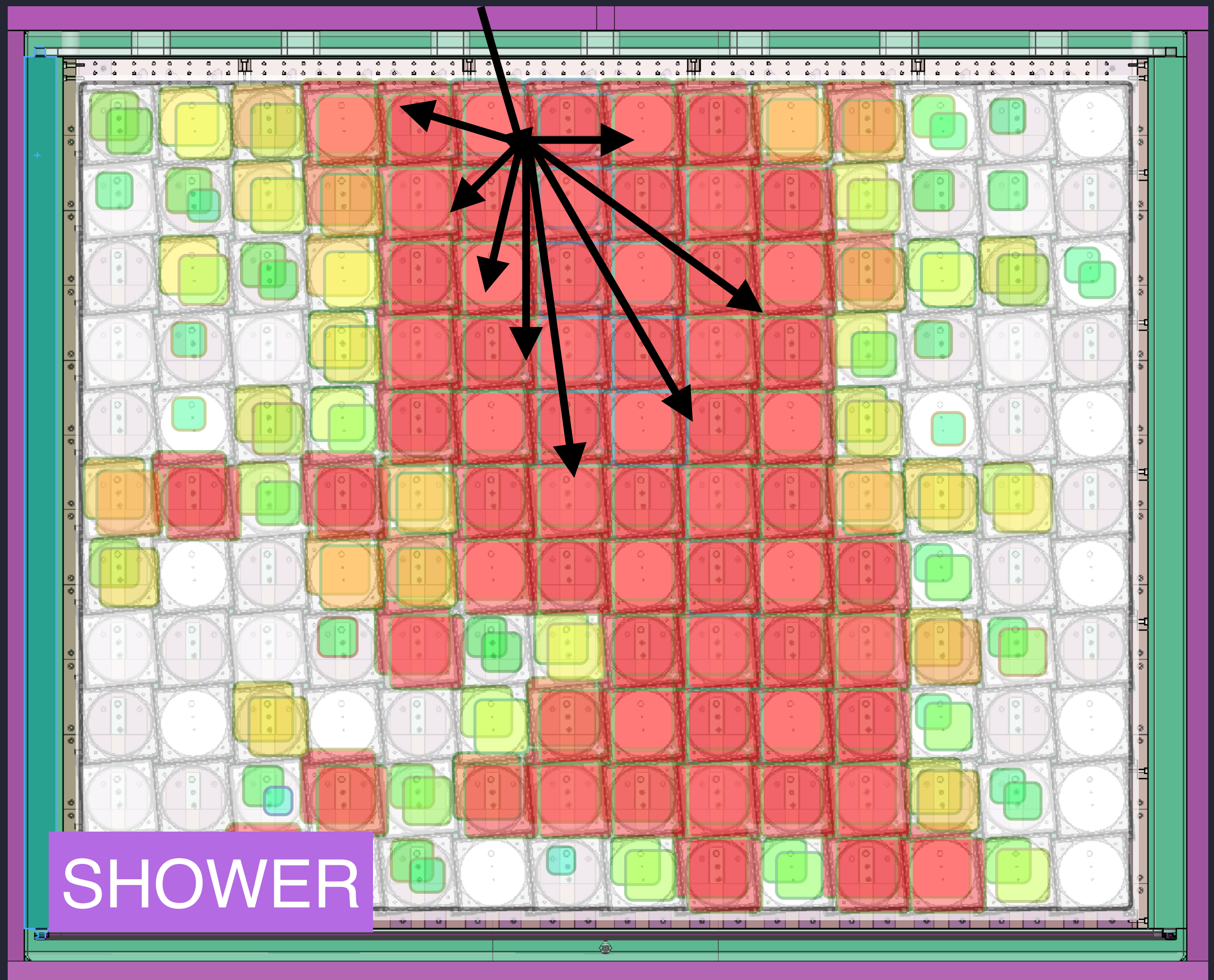

FILLING FROM
MIXING TANK


FIRST MUON TRACK


FEBRUARY 2018
ARRIVAL AT ORNL


IN POSITION AT HFIR
BEFORE SHIELD

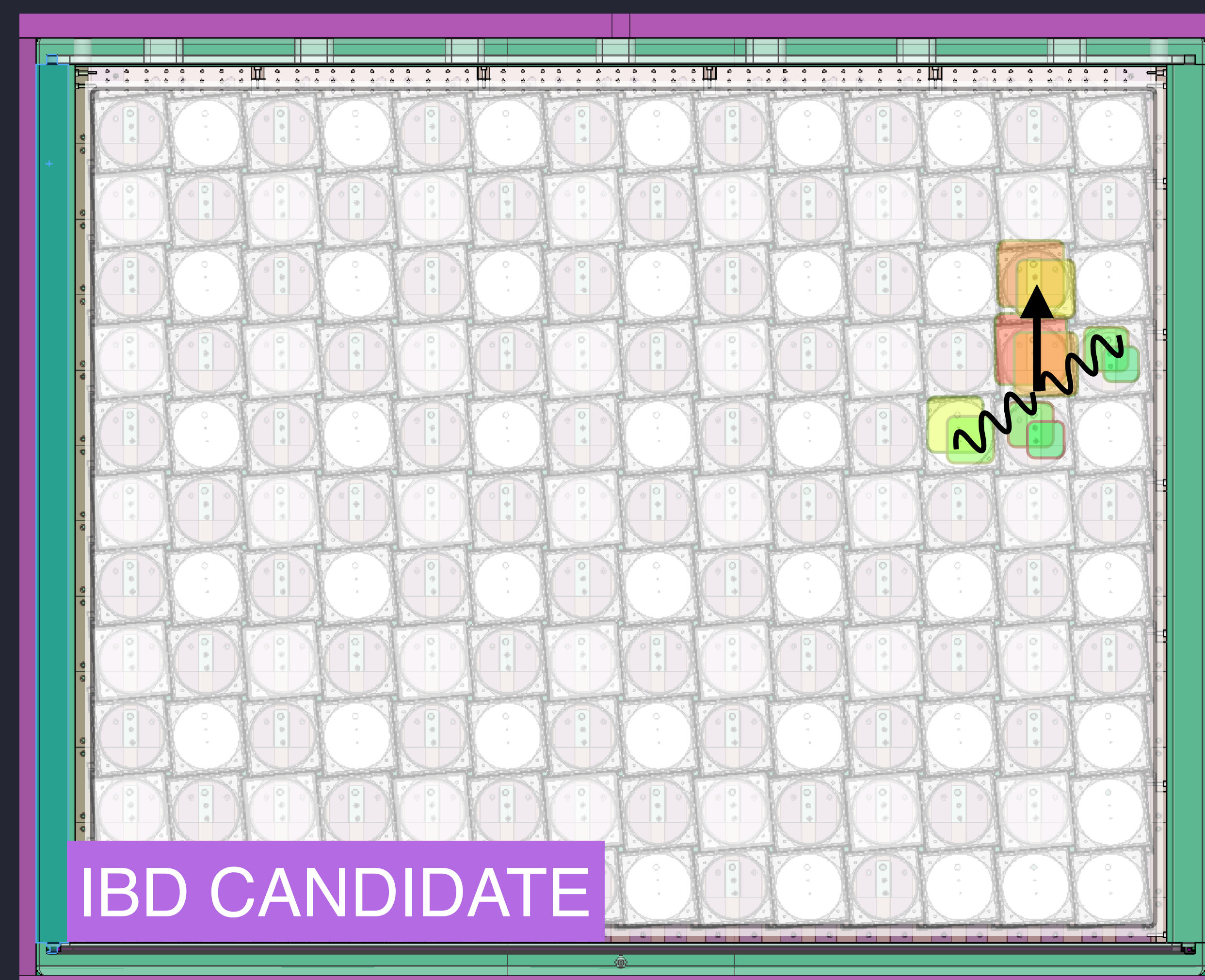

FILLING FROM
MIXING TANK


SHOWER

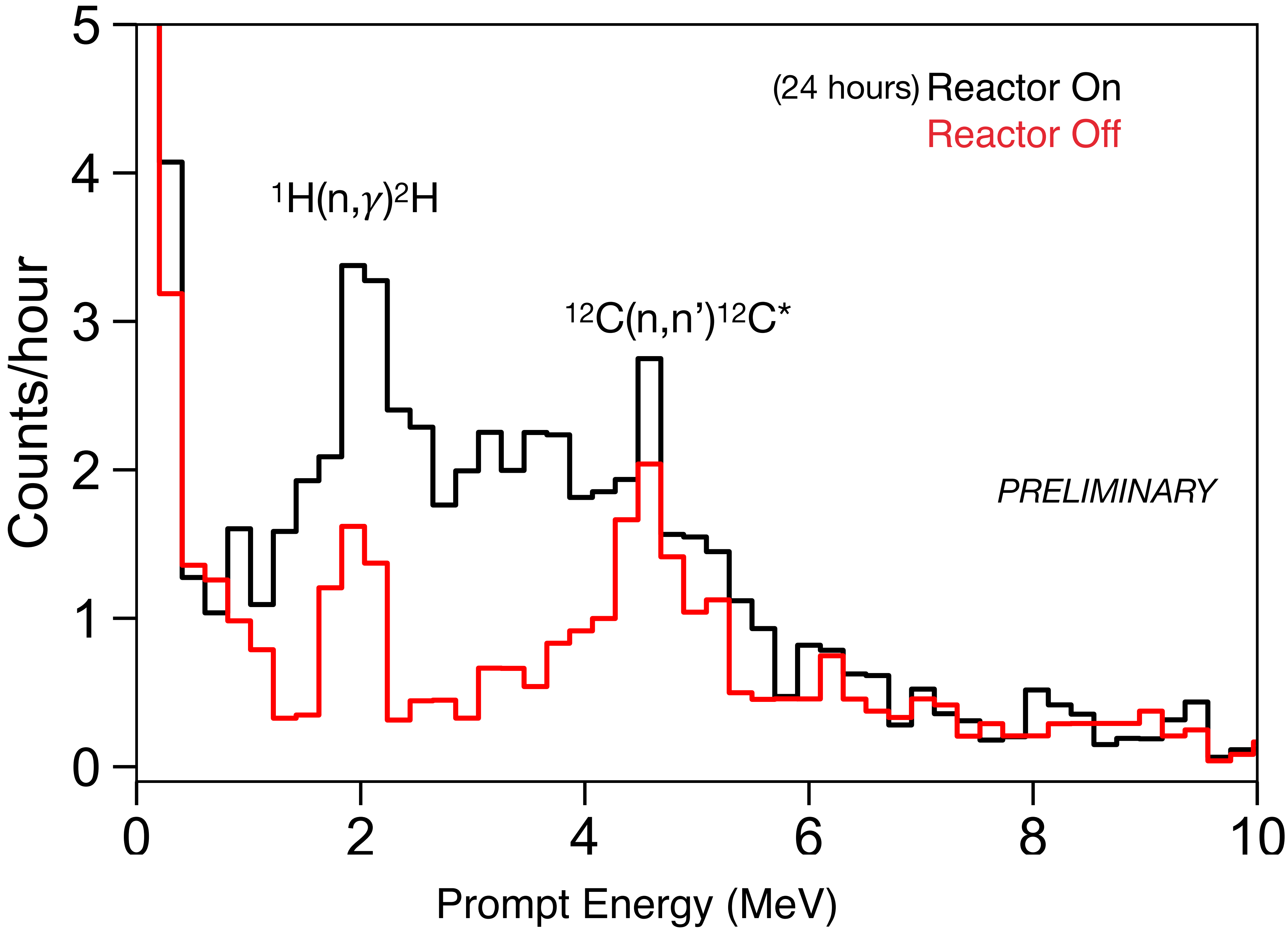

FEBRUARY 2018
ARRIVAL AT ORNL


IN POSITION AT HFIR
BEFORE SHIELD


FILLING FROM
MIXING TANK

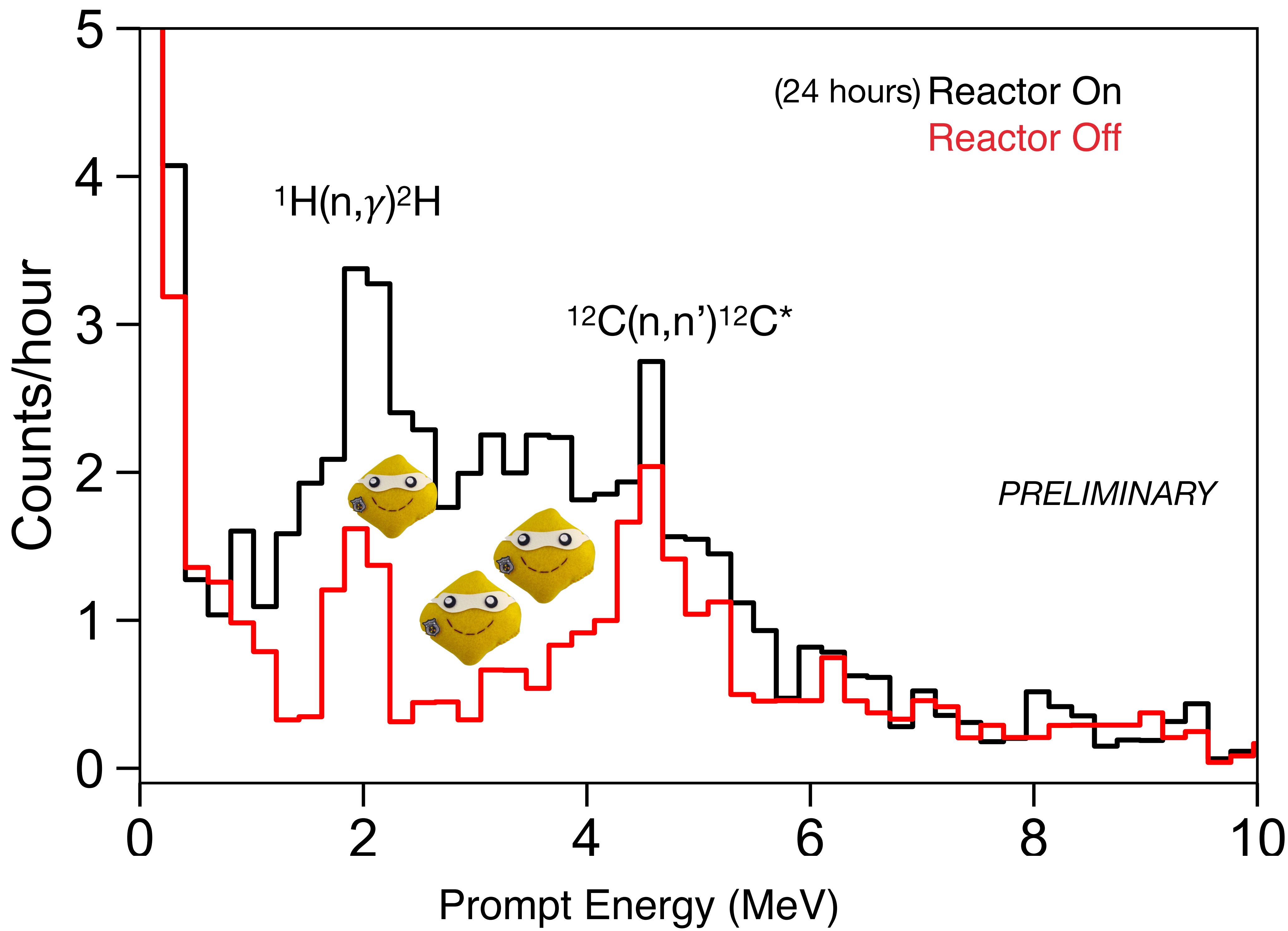

IBD CANDIDATE

Within a few hours.. neutrinos!



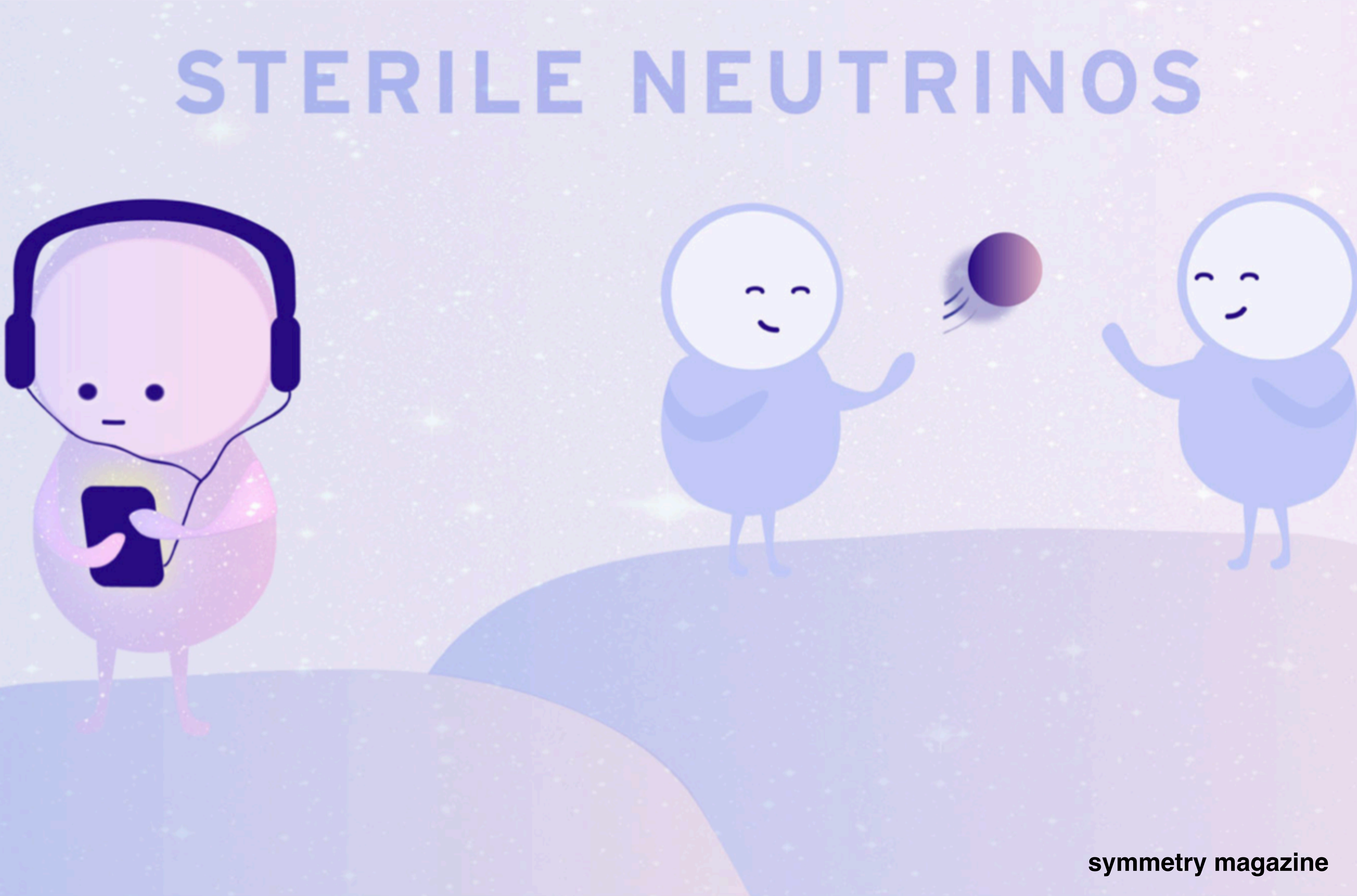
time to 5σ reactor antineutrino detection at Earth's surface: < 2 hours

Within a few hours.. neutrinos!



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

Search for



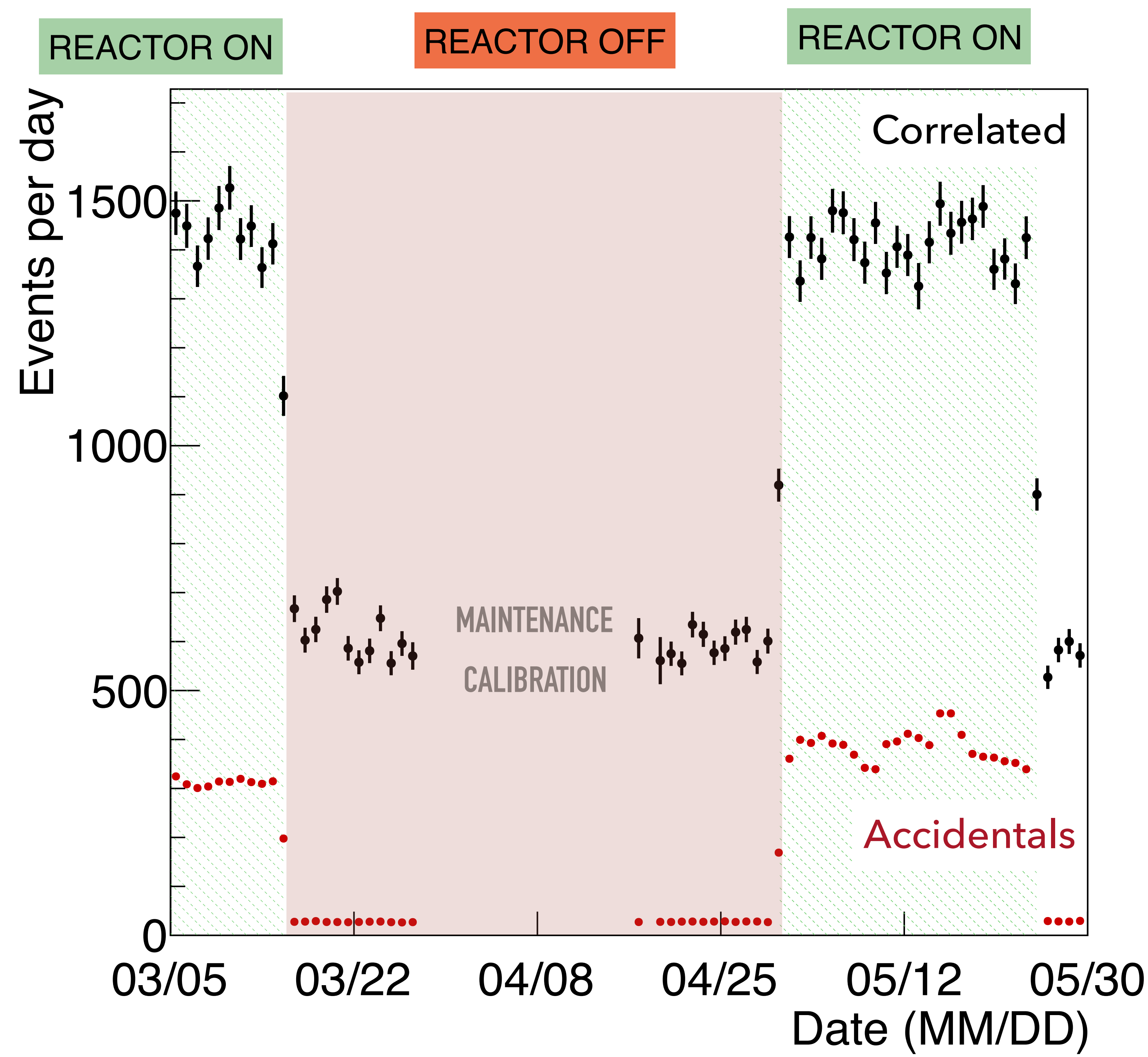
symmetry magazine

Oscillation data as reactor monitor

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

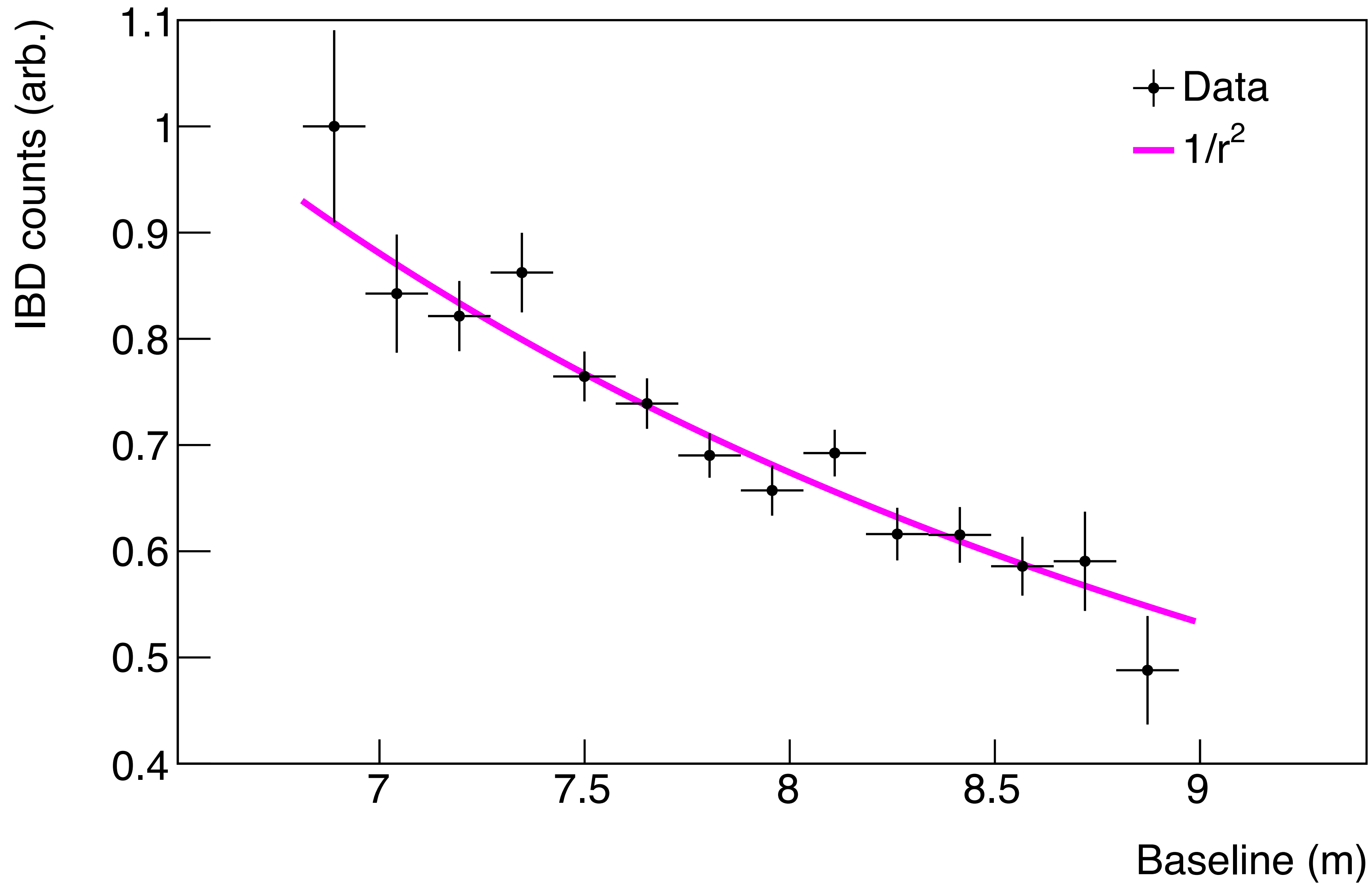
From 0.8-7.2 MeV prompt:

- 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



best signal:background achieved for antineutrino detection on Earth's surface

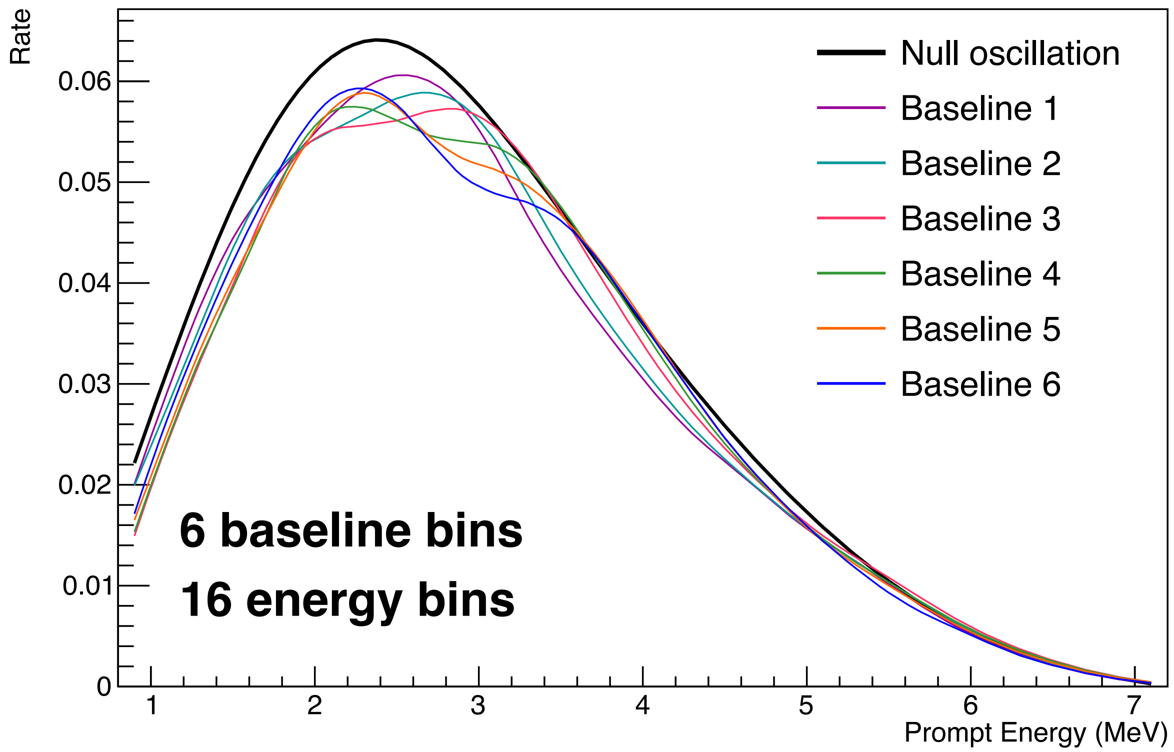
IBD rate vs baseline

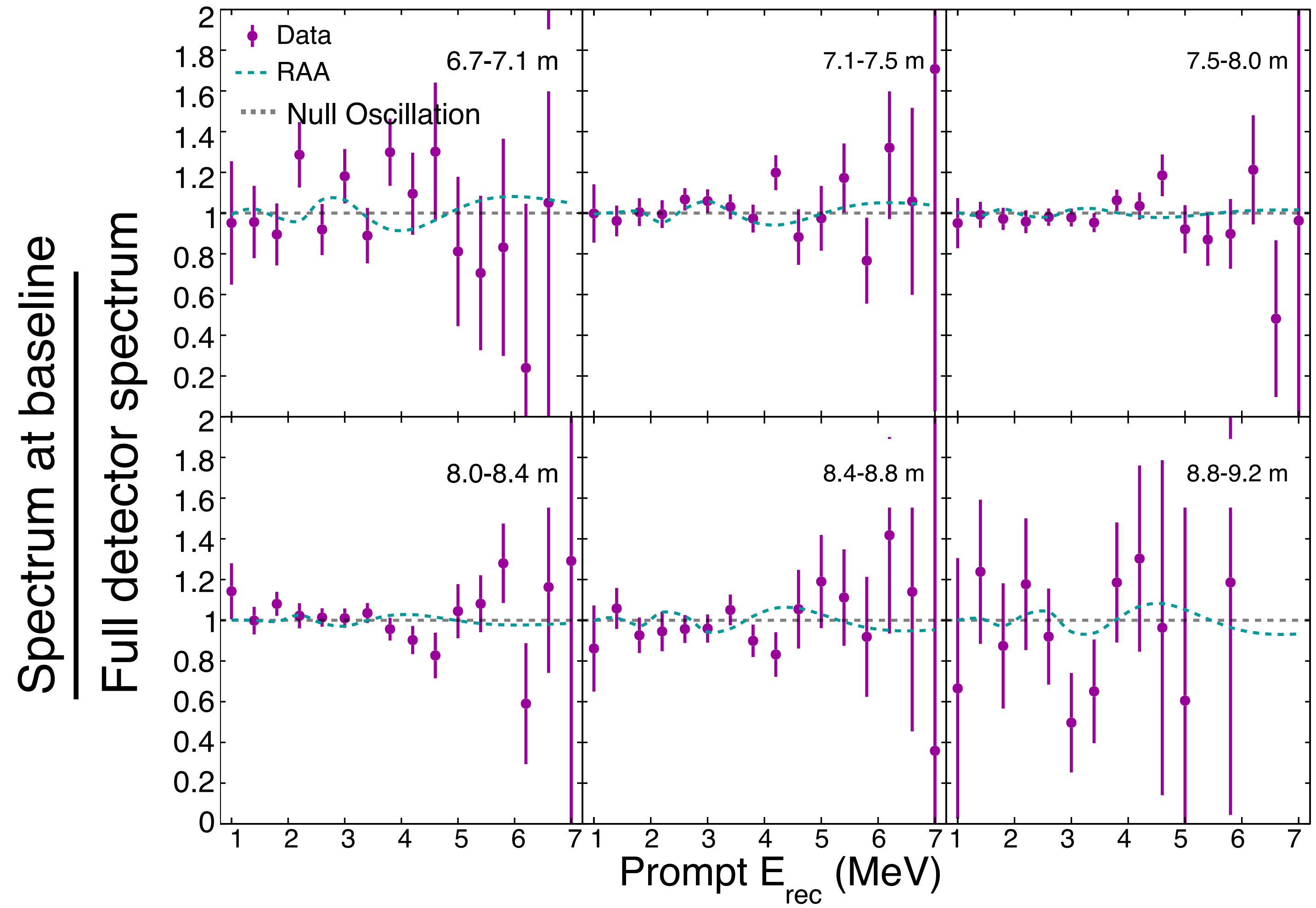


- 14 baseline measurements within the detector at a single location
- observation of $1/r^2$ behavior throughout detector volume
- fun fact: 40% flux decrease from front of detector to back!!

Oscillation search in baseline + energy (L/E)

illustration of baseline dependent oscillation

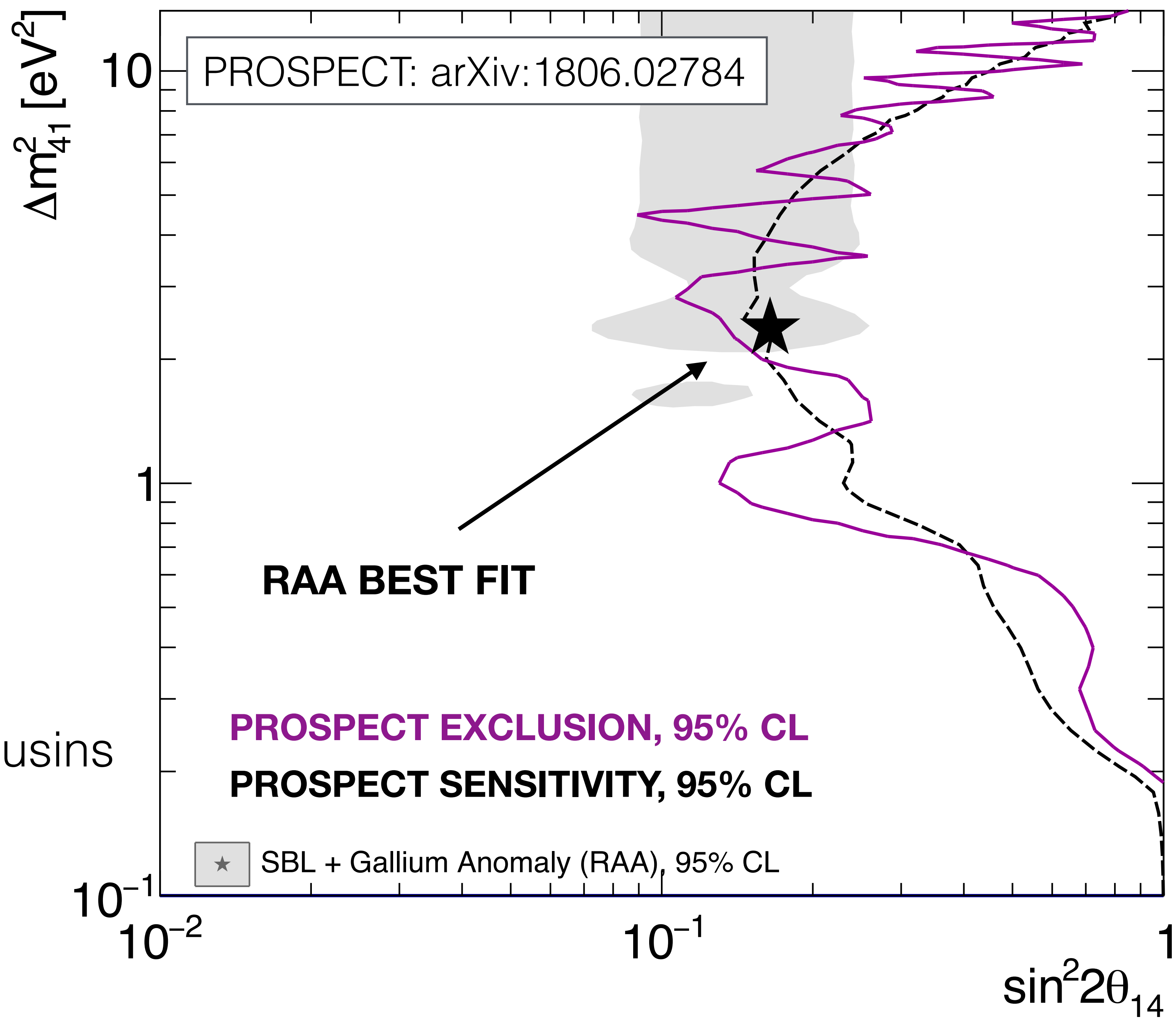




- combine baseline with energy information (L/E) enhances sensitivity
- compare spectra from 6 baselines to measured full-detector spectrum
- relative sterile oscillation search, **independent of reactor models**

Sterile neutrino sensitivity and exclusion

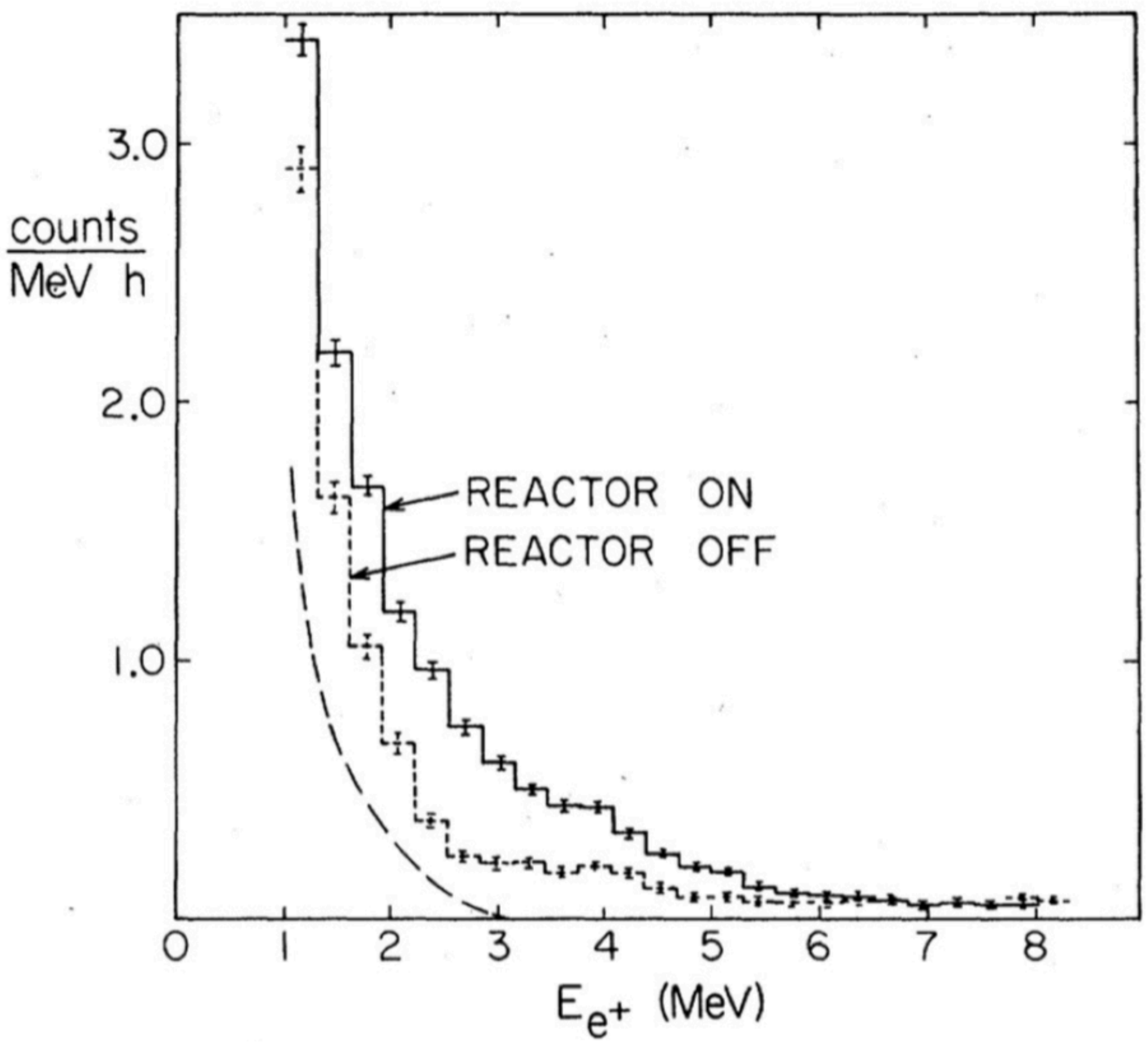
With 33 days reactor-on data, probing interesting region of sterile parameter space

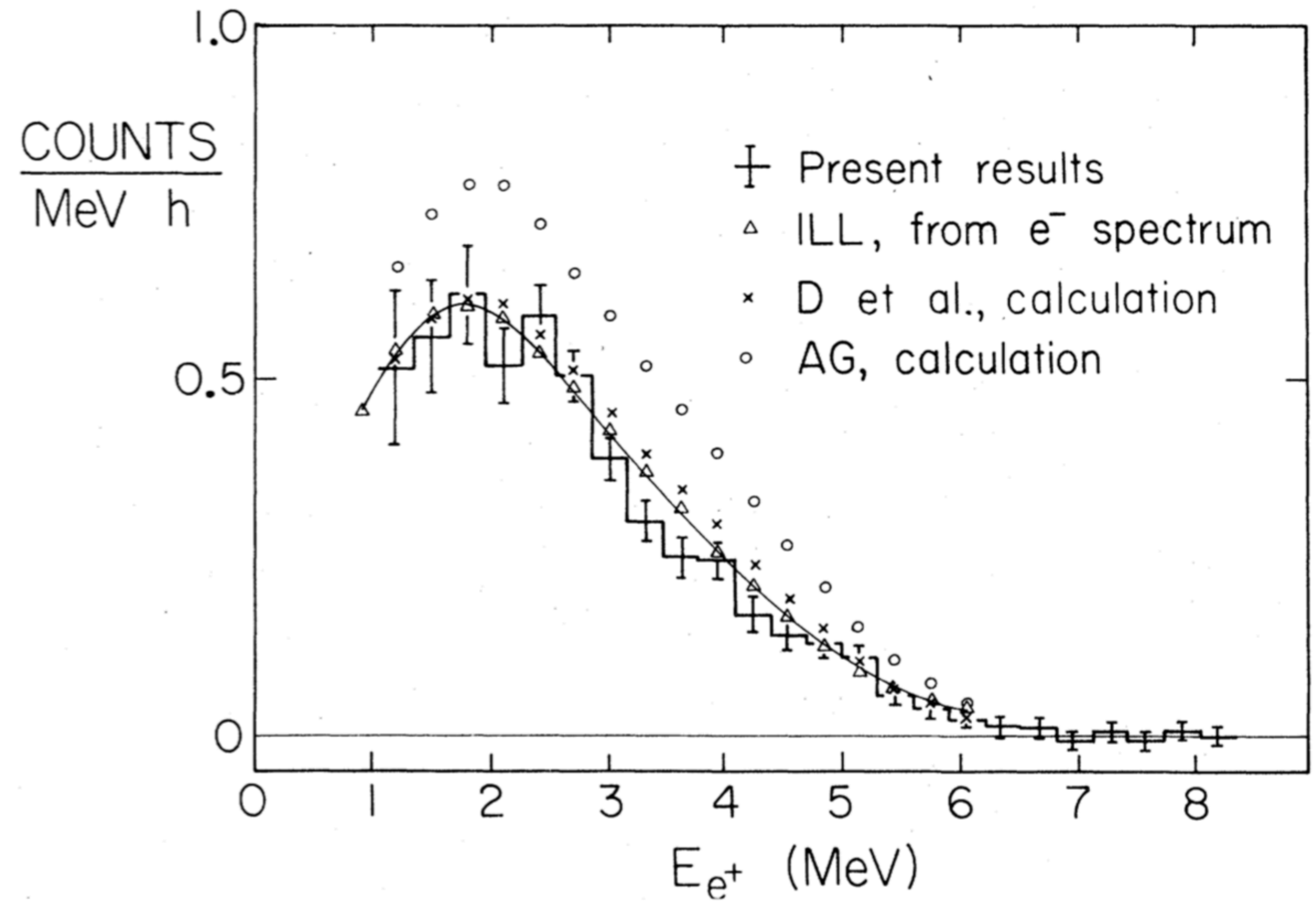


uses Feldman-Cousins

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

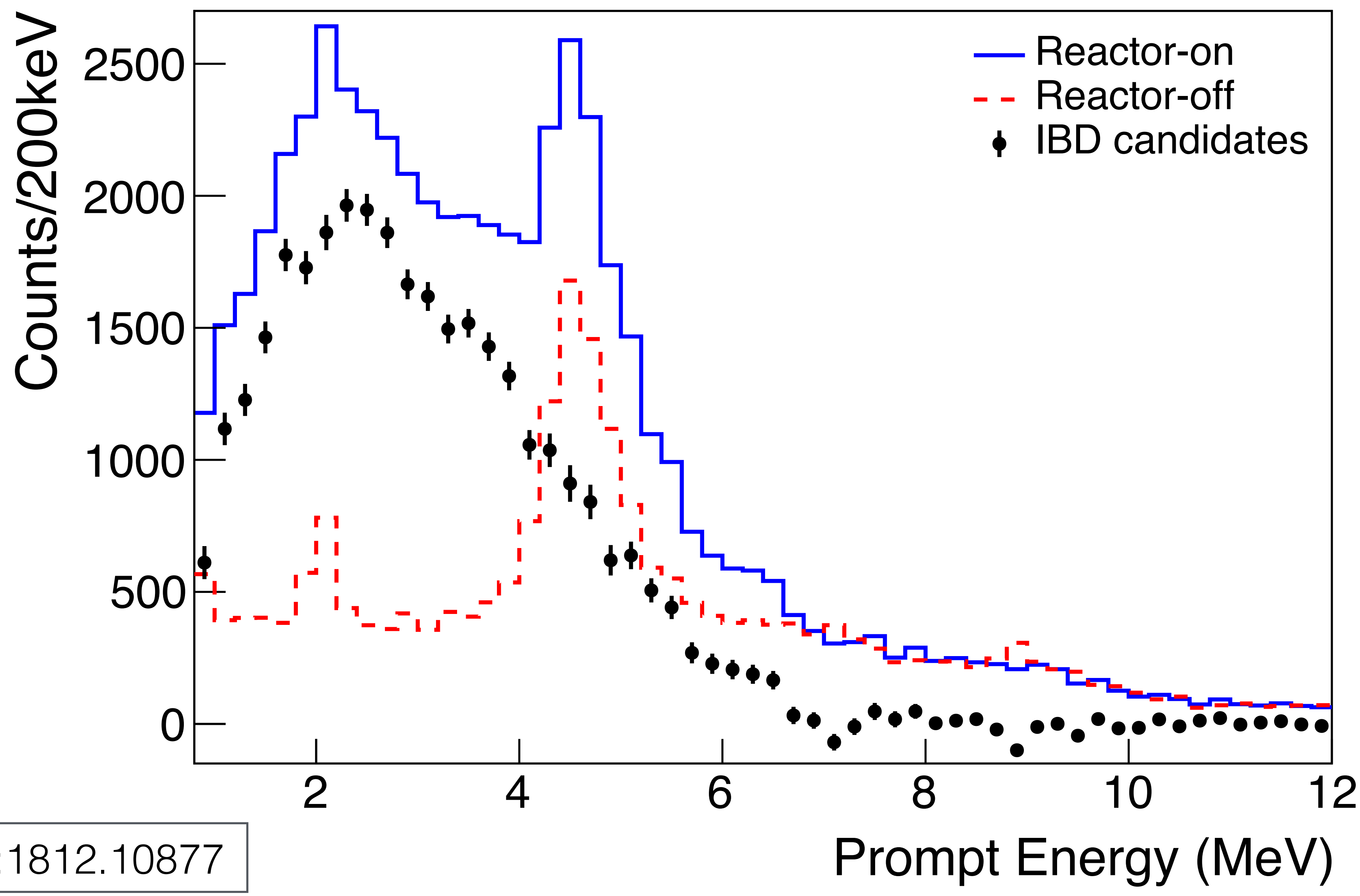
Measurement of ^{235}U antineutrino spectrum





only existing measurement from 1981 ILL experiment, 5000 events

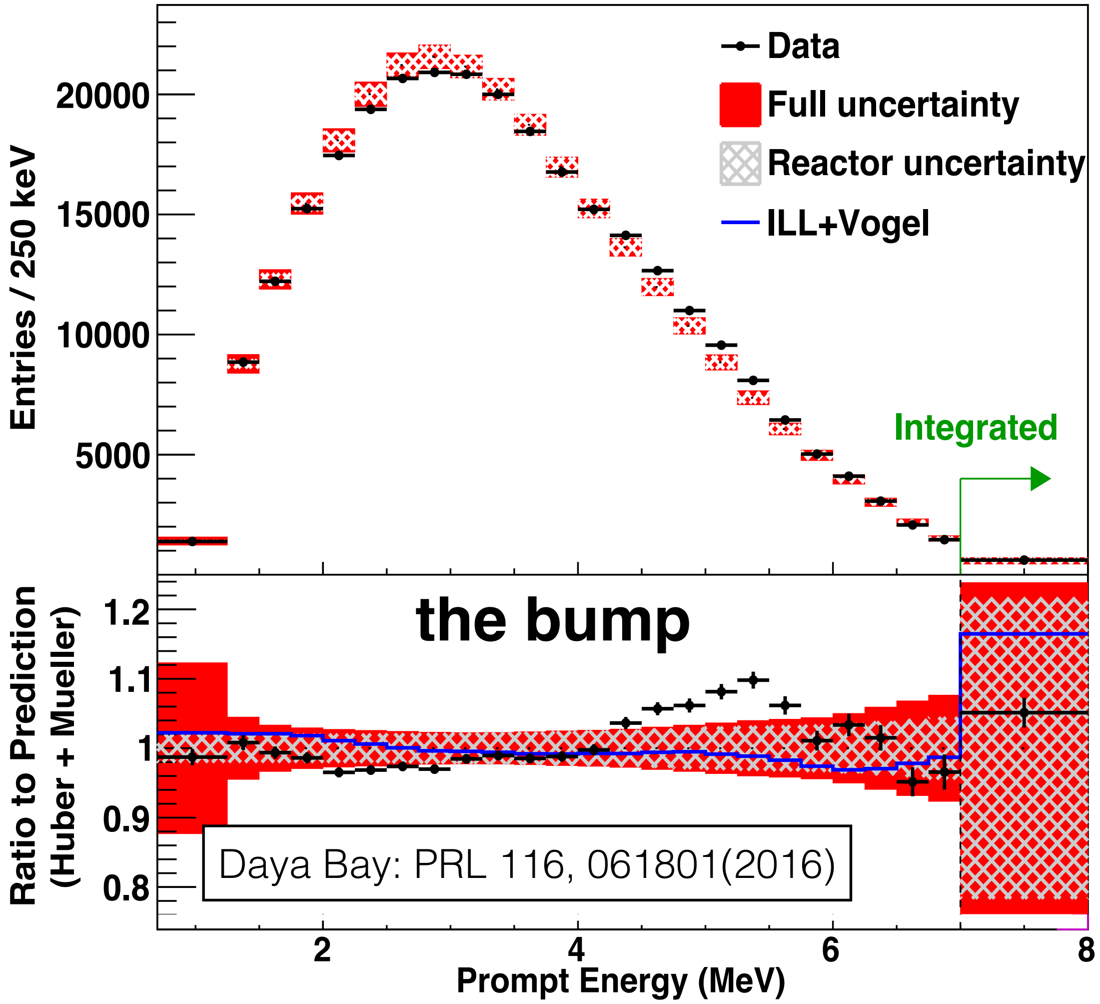
World leading ^{235}U antineutrino spectrum

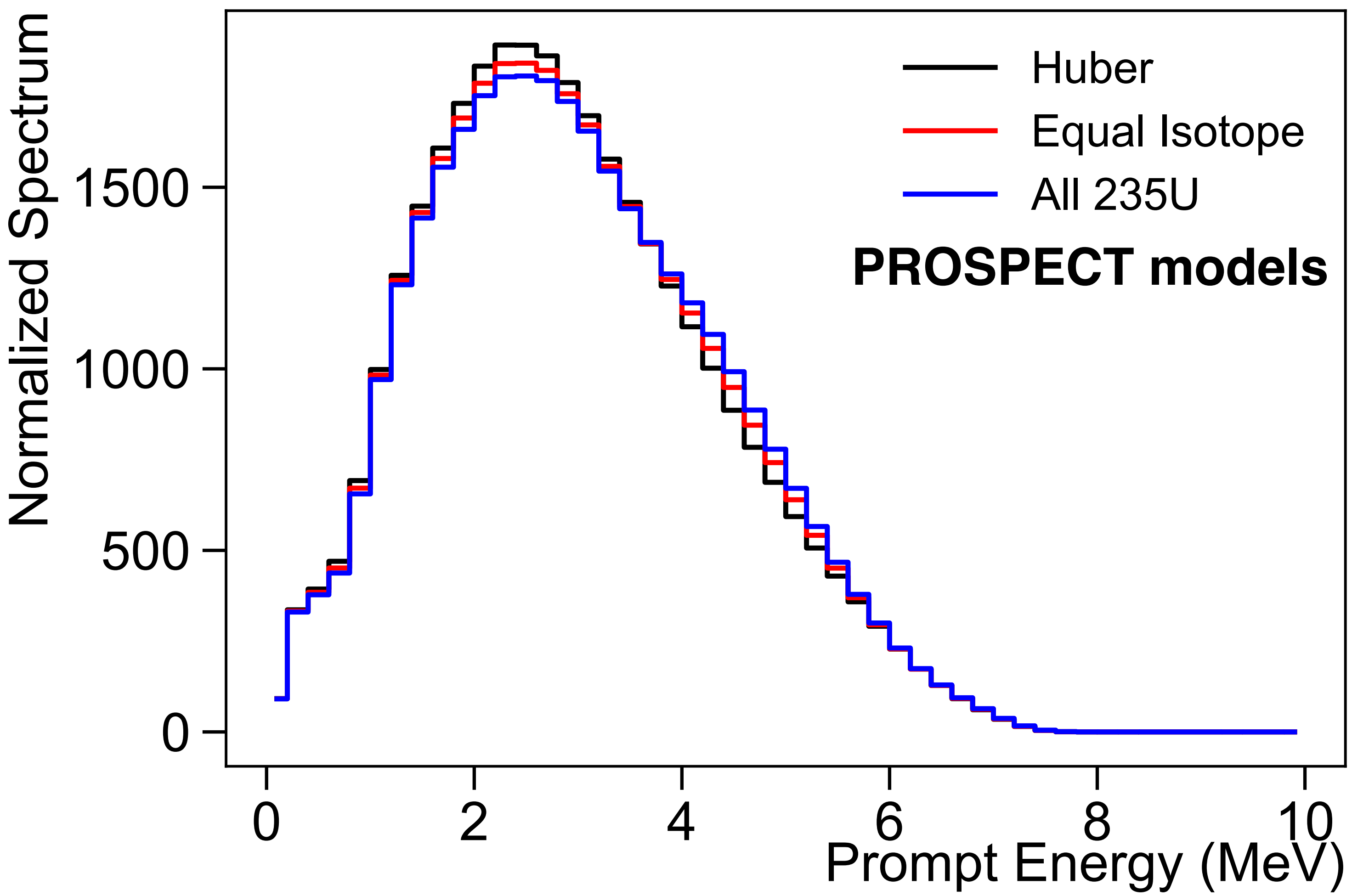


PROSPECT: arXiv:1812.10877

- 40.3 days reactor-on, 37.8 days reactor-off exposure
- ~31,000 IBDs detected at 4.8%/MeV energy resolution
- 6x more statistics than ILL in about half the exposure time
- improved signal:background ~1.7, with no overburden!

Hypotheses to explain “the bump” in energy





Data-based hypotheses to bracket the physics observed at power reactors:

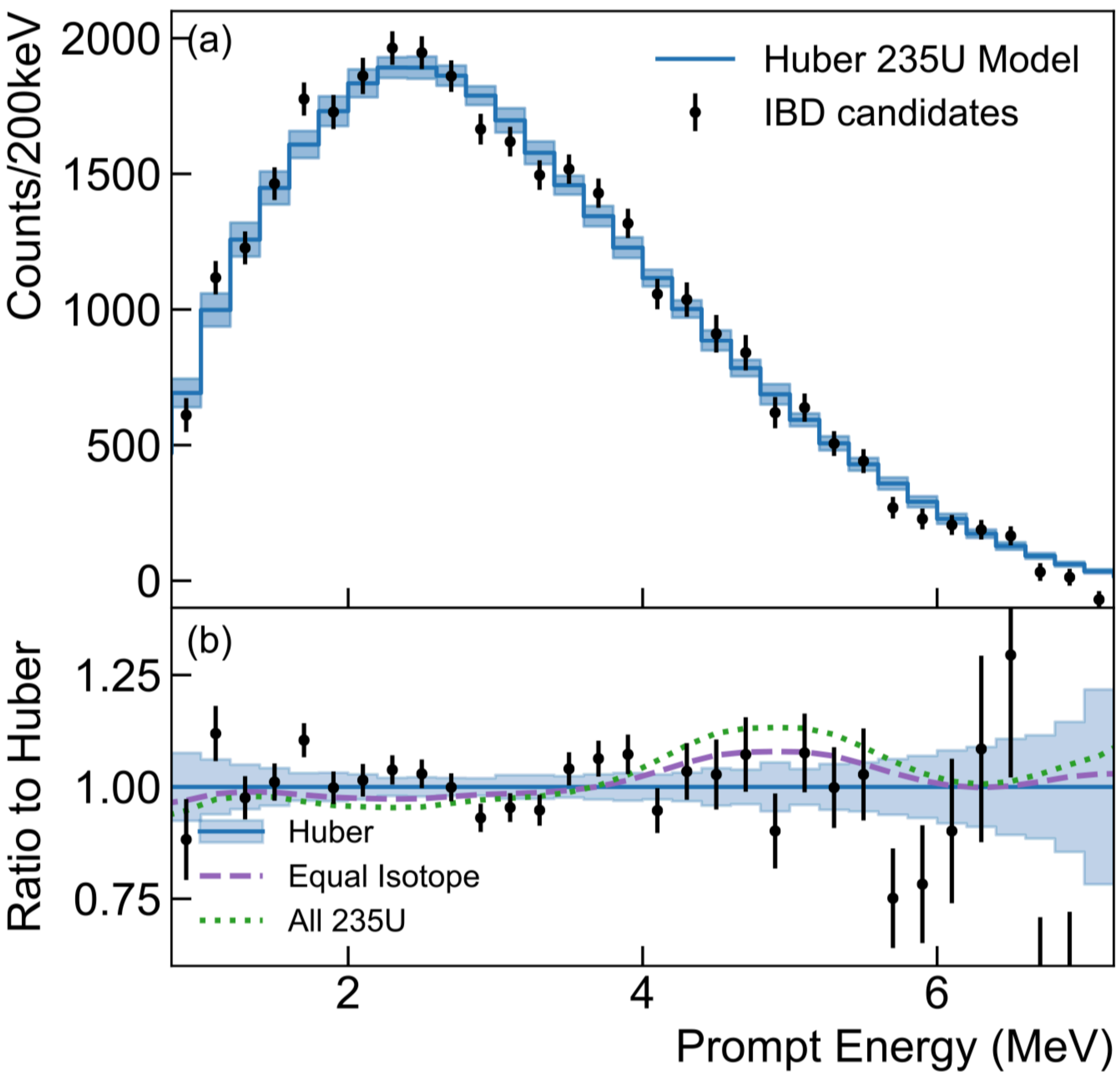
Huber = deviation is in other 3 LEU isotopes (Huber ^{235}U is correct)

Equal isotope = deviation is shared equally by all 4 LEU parent isotopes

All ^{235}U = deviation caused only by ^{235}U (maximal change to Huber ^{235}U)

Energy spectrum comparison to models

PROSPECT: arXiv:1812.10877



Huber hypothesis (standard):

- χ^2/ndf = 51.6/31

Equal isotope hypothesis:

- χ^2/ndf = 52.1/31

All ^{235}U hypothesis:

- χ^2/ndf = 58.9/31

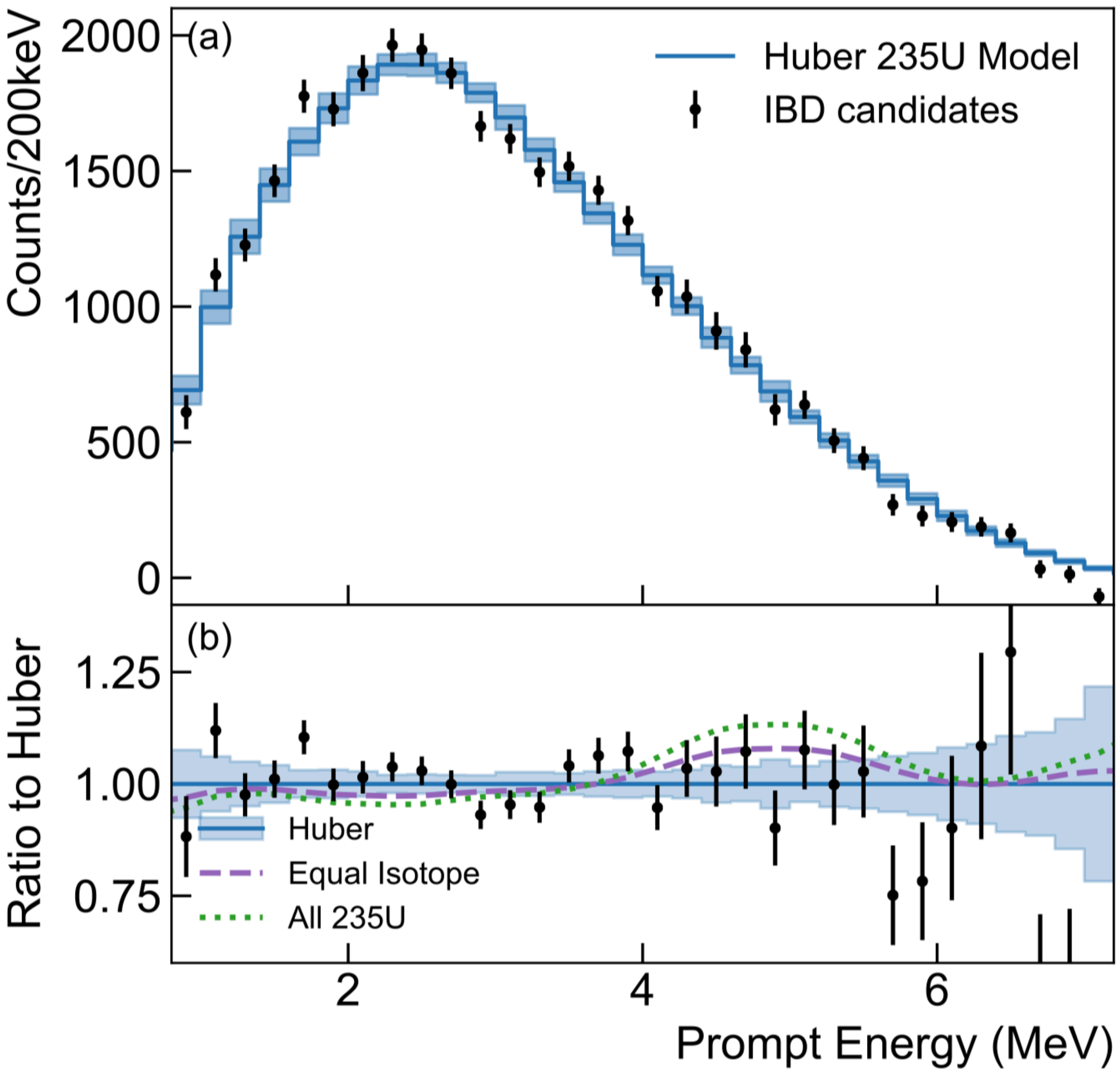
Frequentist $\Delta\chi^2$ comparisons:

- does the PROSPECT data favor any of the models over others?
- no strong preference for Equal Isotope hypothesis over Huber prediction
- disfavor All ^{235}U hypothesis at 3σ

first spectrum result: disfavors the all ^{235}U hypothesis at 3σ

Interpretation of PROSPECT energy spectrum

PROSPECT: arXiv:1812.10877



- if all of the "bump" was from ^{235}U, expect ~20% effect, we do not see it
- *implies some fraction of excess comes from other isotopes, not solely ^{235}U*
- current spectrum is statistics limited and cannot determine if it is a problem with all isotopes or non-^{235}U

*shape only comparisons

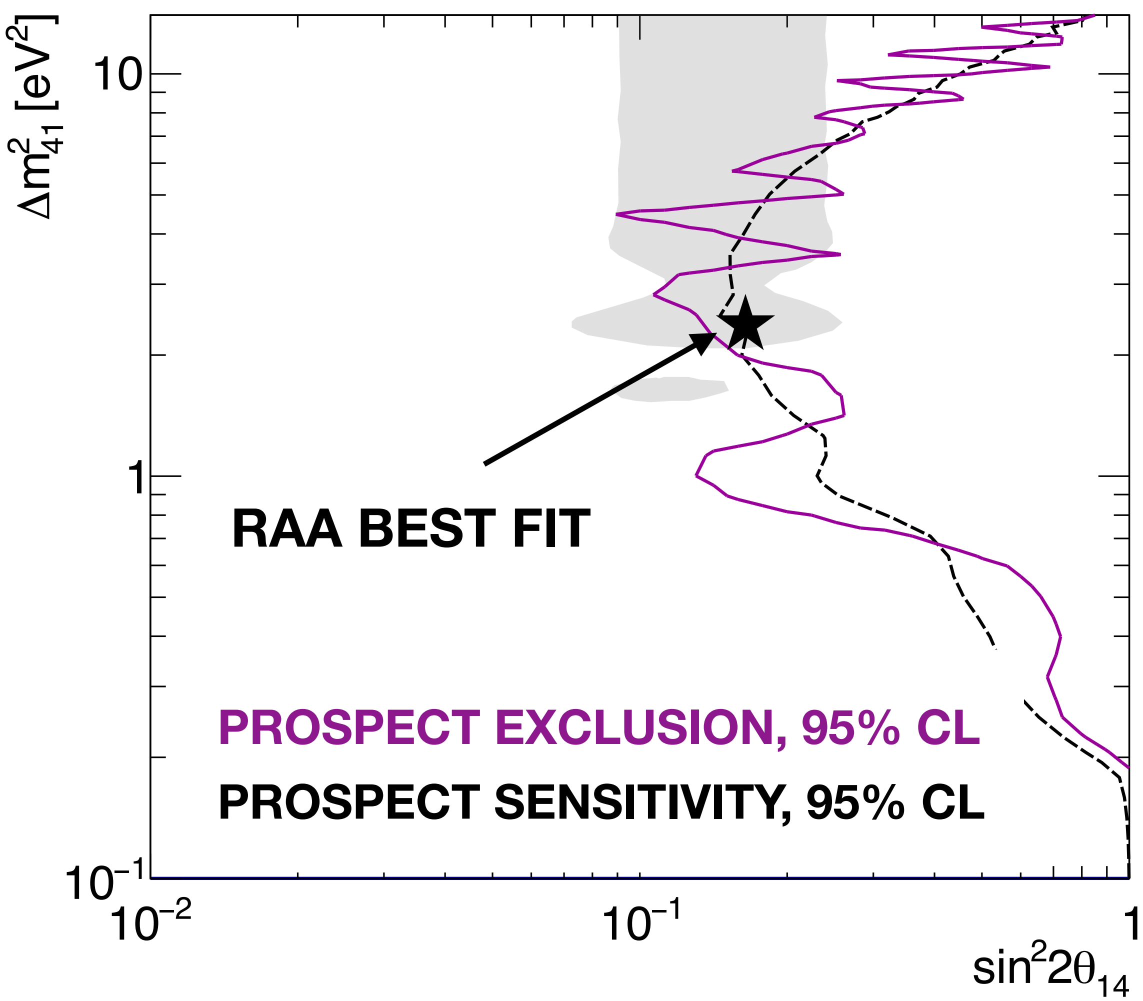
first spectrum result: disfavors the all ^{235}U hypothesis at 3σ

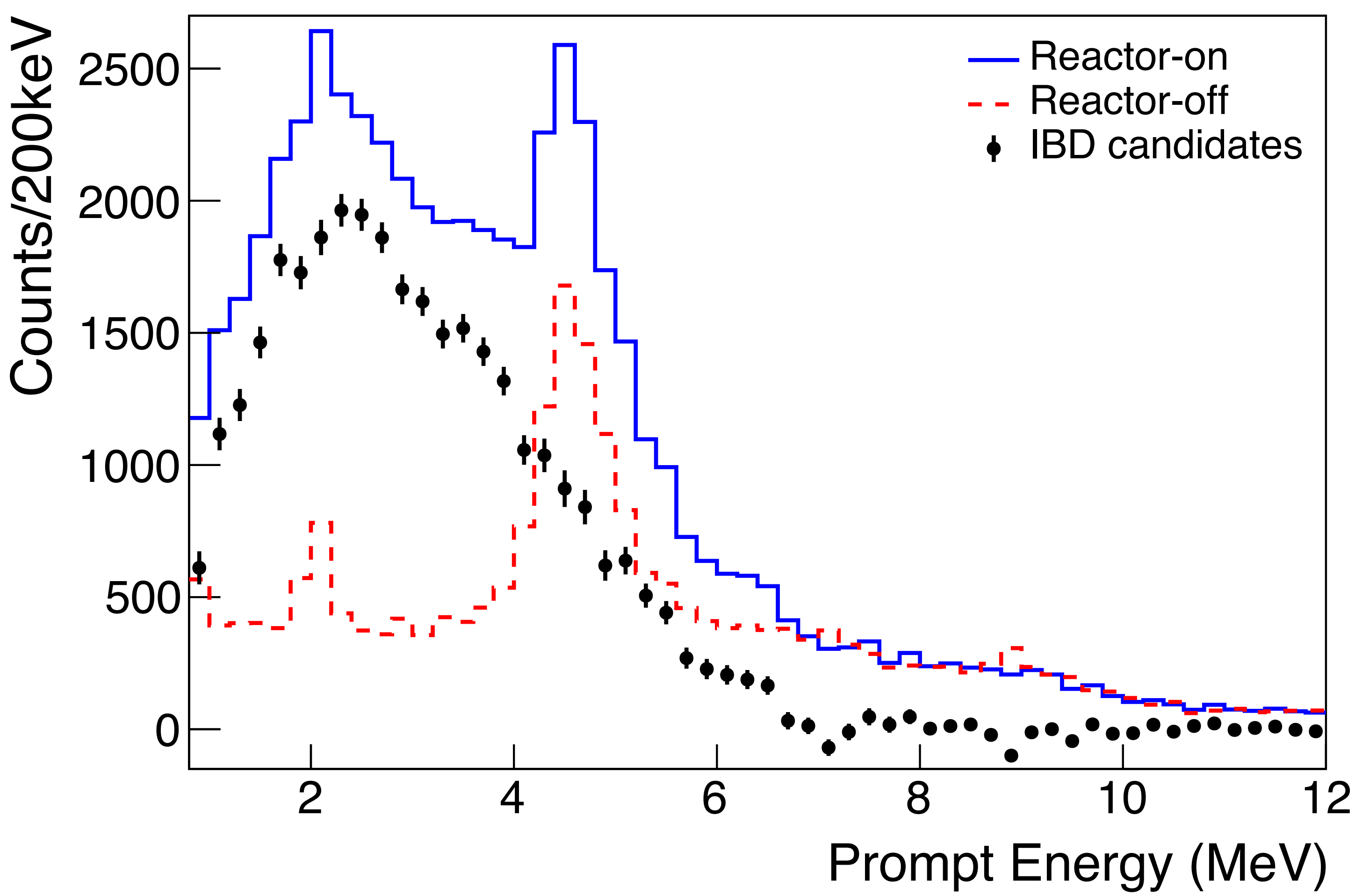
PROSPECT: from R&D, construction, to physics

1. 30-40 days of data: first oscillation results probe interesting region of sterile parameter space and world-leading measurement of ^{235}U antineutrino spectrum

2. Made possible by the development of a detector that can measure neutrinos on the Earth's surface

3. This opens possibilities for us to learn more about neutrinos from reactors






PROSPECT
vs
PROSPECT