

First results from the PROSPECT reactor neutrino experiment



Danielle Norcini
for the **PROSPECT** collaboration

Yale



U.S. DEPARTMENT OF
ENERGY

Office of
Science

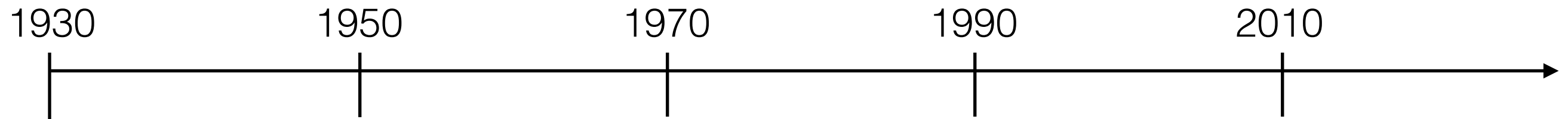


Wright
Laboratory



HEISING-SIMONS
FOUNDATION

Evolution of neutrino physics with reactor experiments



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

Properties:

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

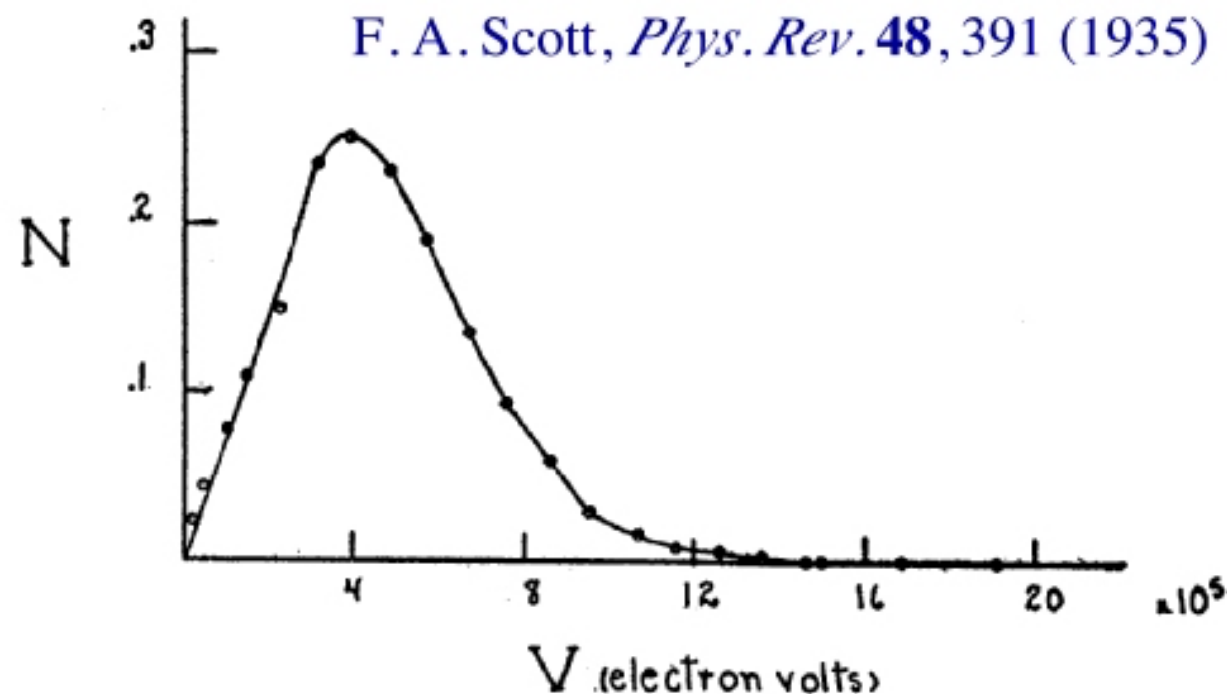
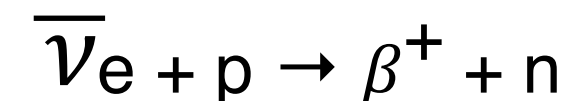


FIG. 5. Energy distribution curve of the beta-rays.

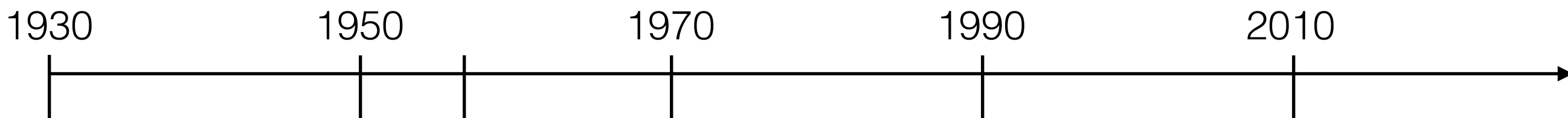
Bethe and Peierls:

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

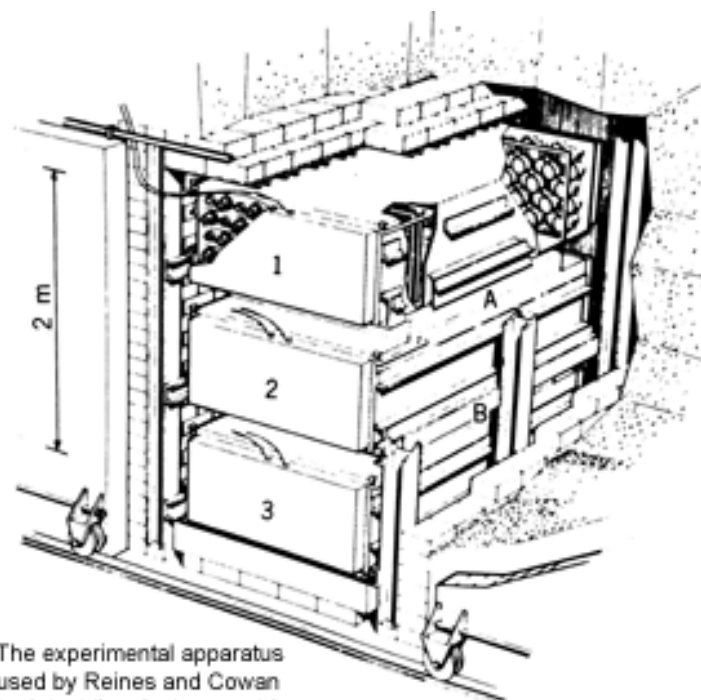
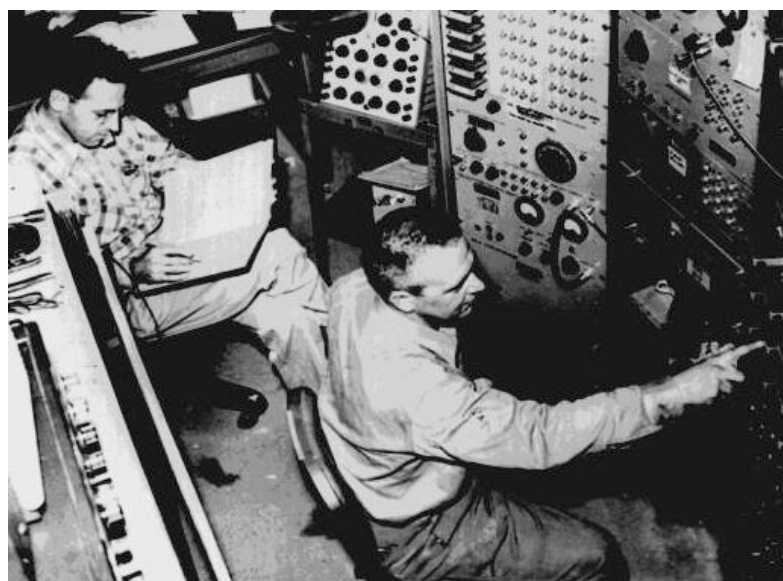


- cross-section is too small, impossible to detect!

Evolution of neutrino physics with reactor experiments



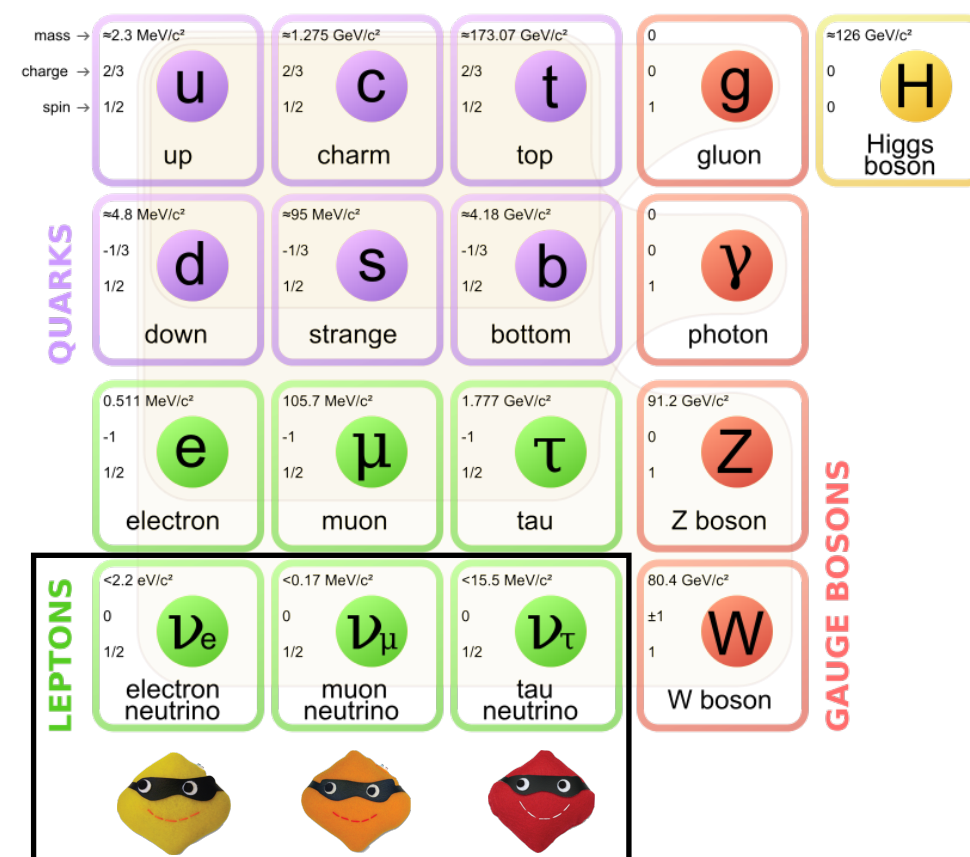
observation of (anti)neutrinos at Savannah River reactor through IBD with scintillator



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

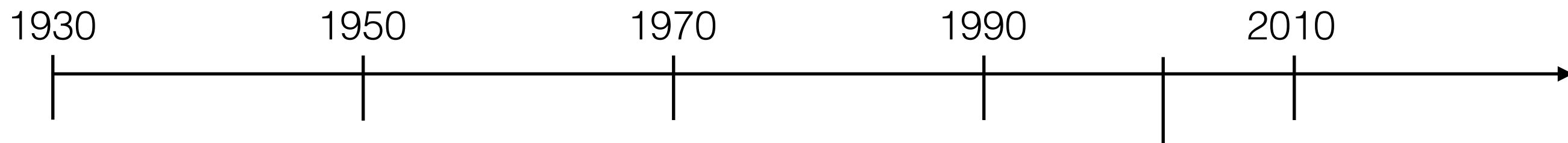


Added to Standard Model:

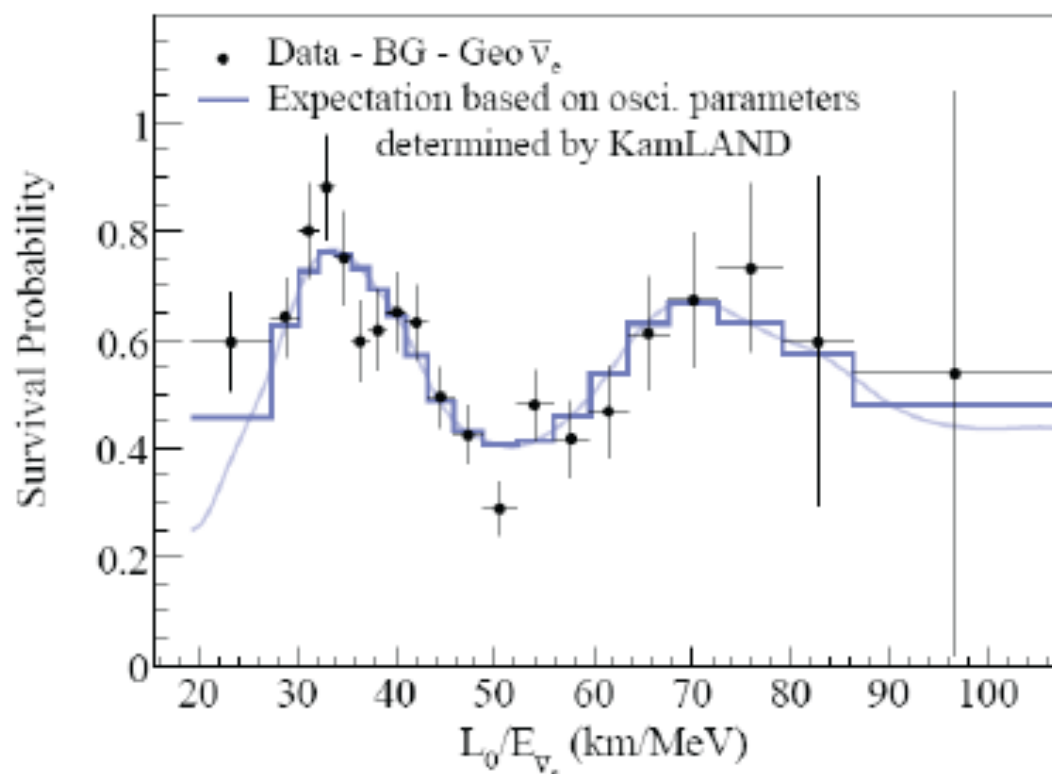


*muon and tau flavors discovered later at accelerators

Evolution of neutrino physics with reactor experiments



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



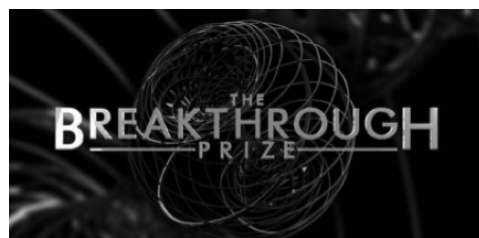
flavor states

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

interact

propagate

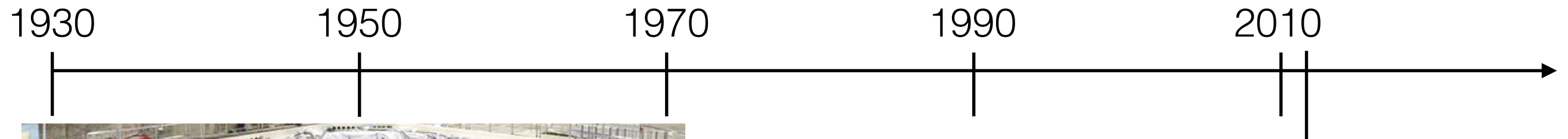
mass states



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

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

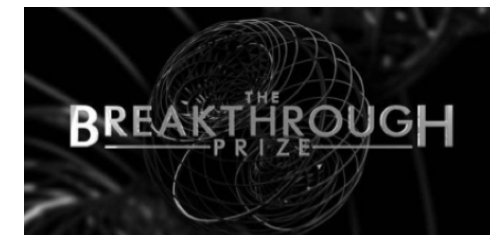
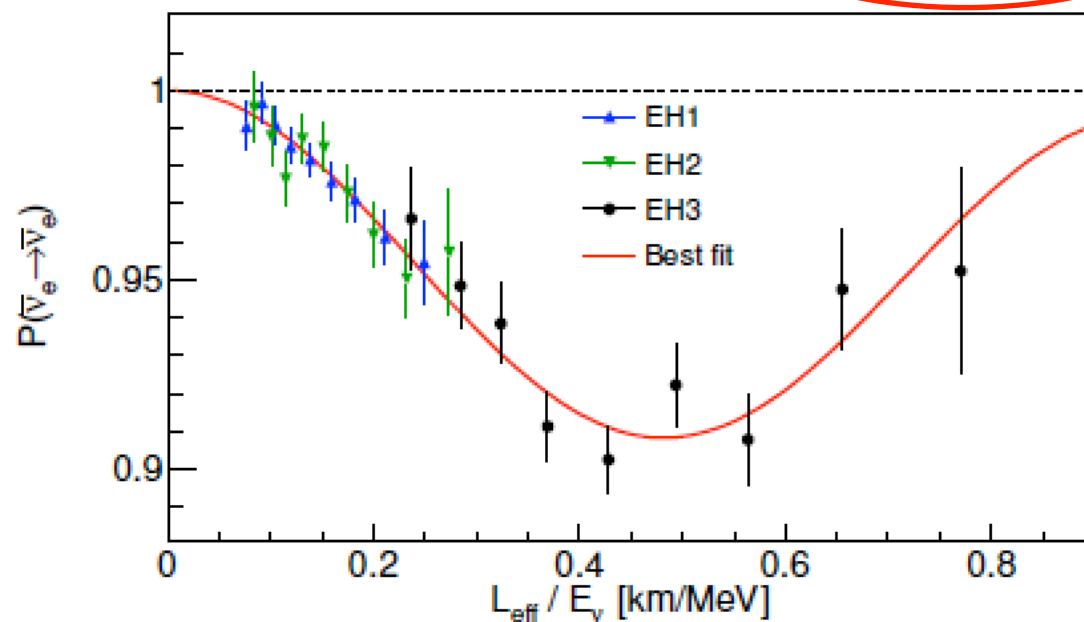
Evolution of neutrino physics with reactor experiments



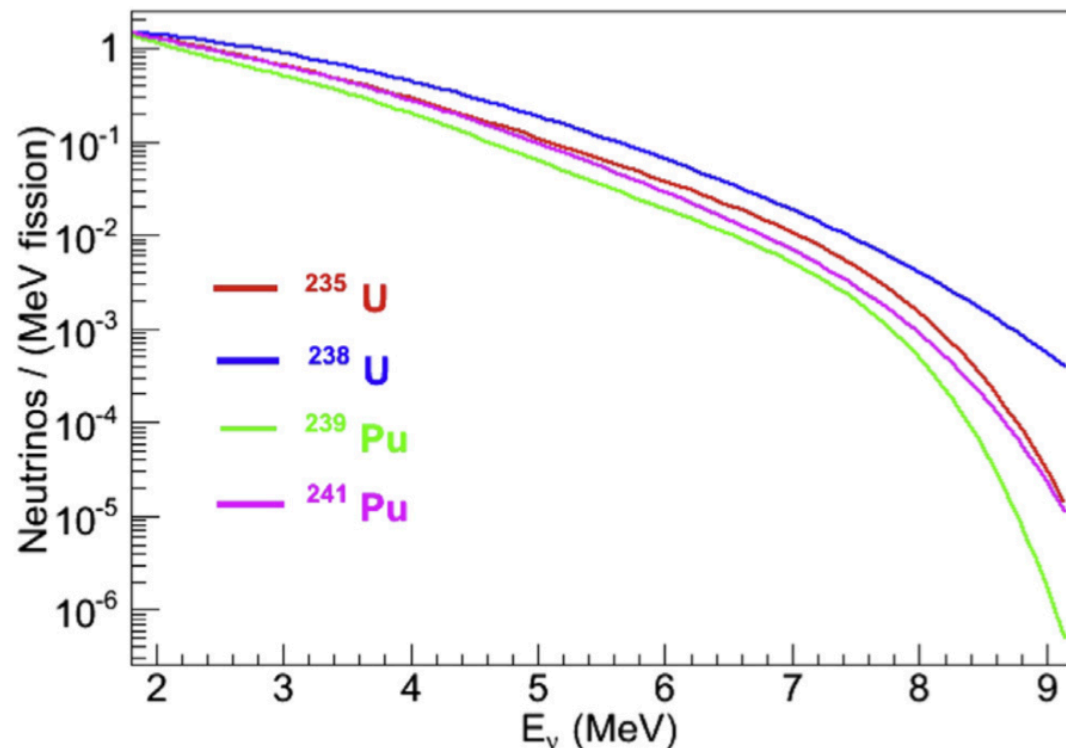
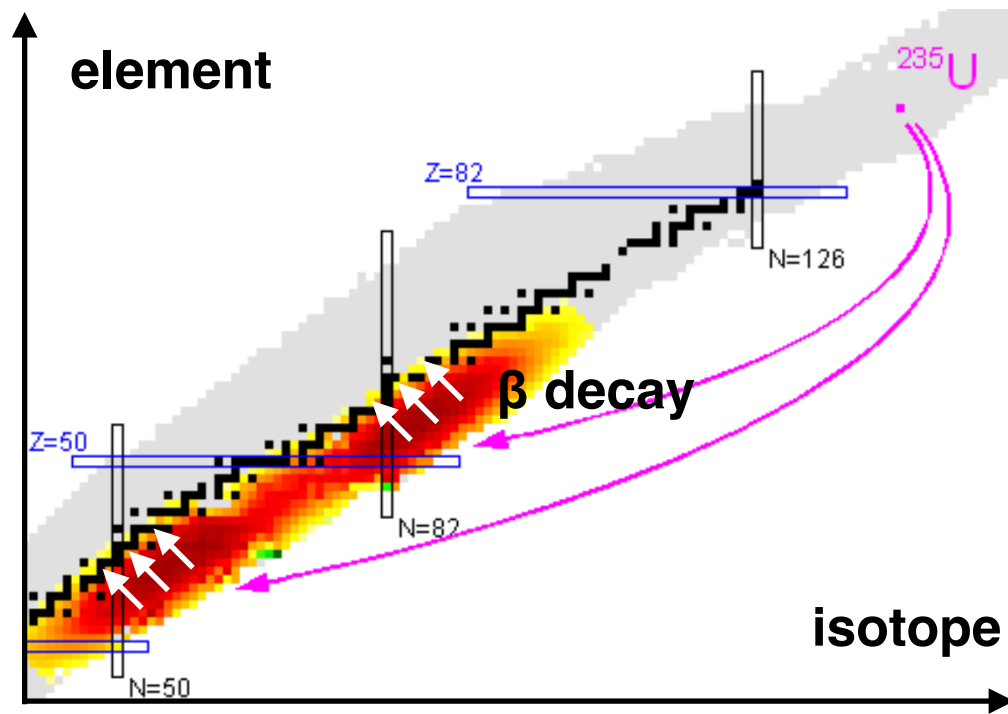
DYB, DC, RENO use near/far detectors for precision measurement of last mixing angle

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

PMNS mixing matrix

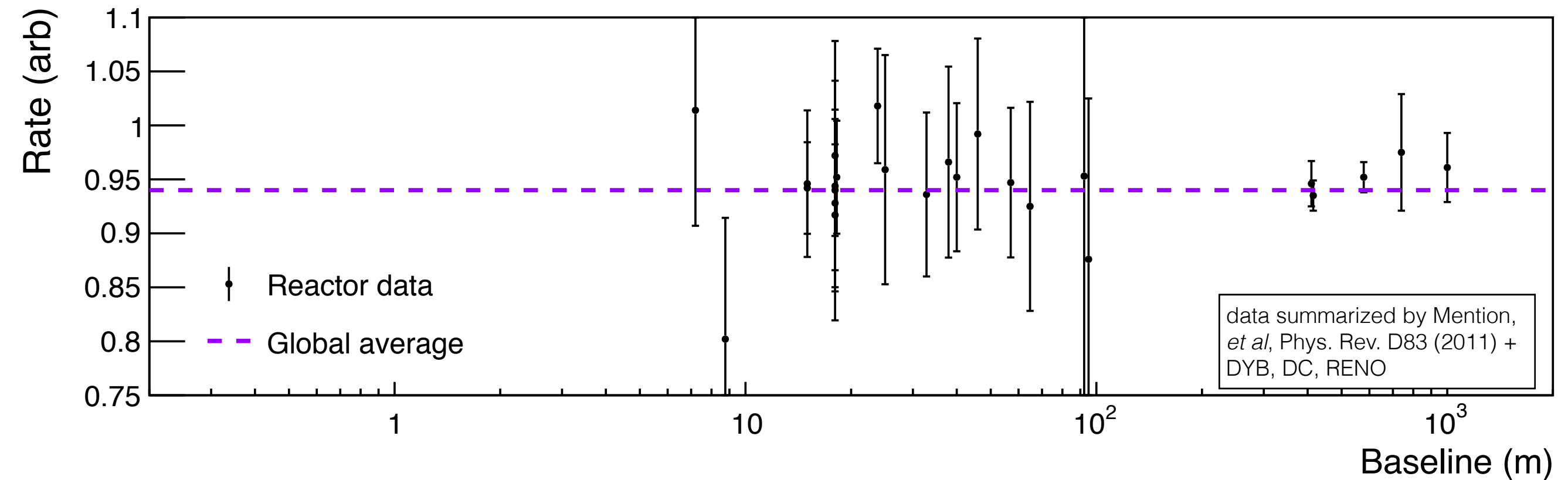


Generation of reactor antineutrinos



- fission produces neutron-rich daughters that beta decay ~ 6 times until stable
 - $1 \text{ GW}_{\text{th}} \sim 10^{20} \bar{\nu}_e/\text{second}$
 - $>99.9\%$ flux $\bar{\nu}_e$ - only from this process
 - low energy $\sim \text{MeV}$ 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, thousands of beta decay branches

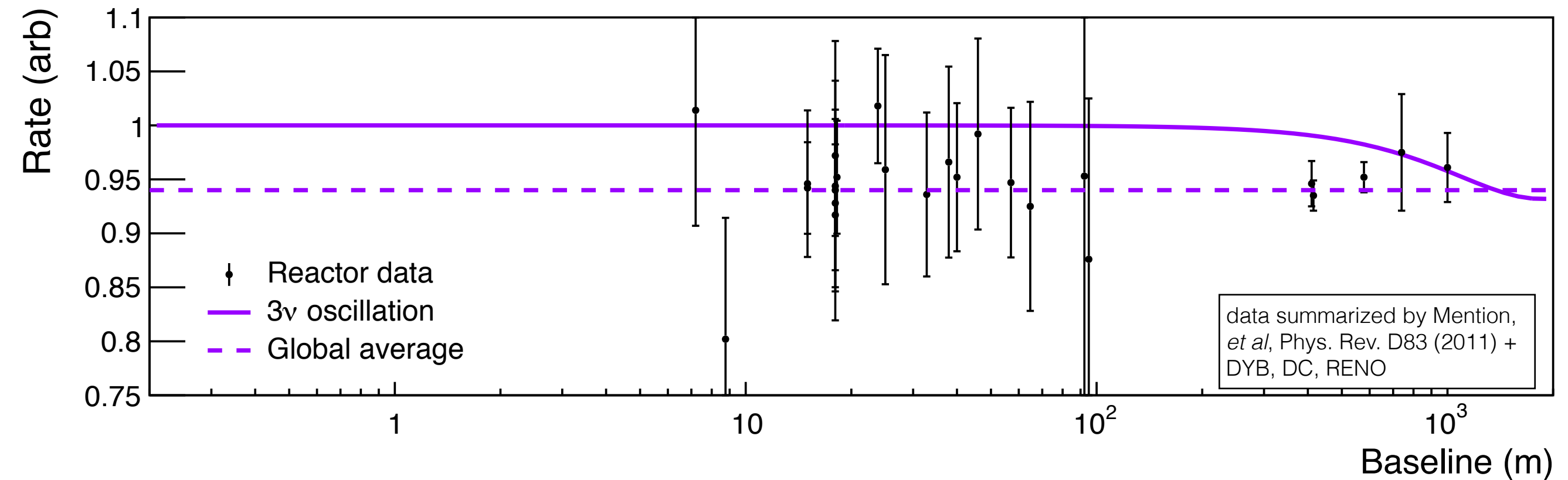
Reactor antineutrino flux deficit



- 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

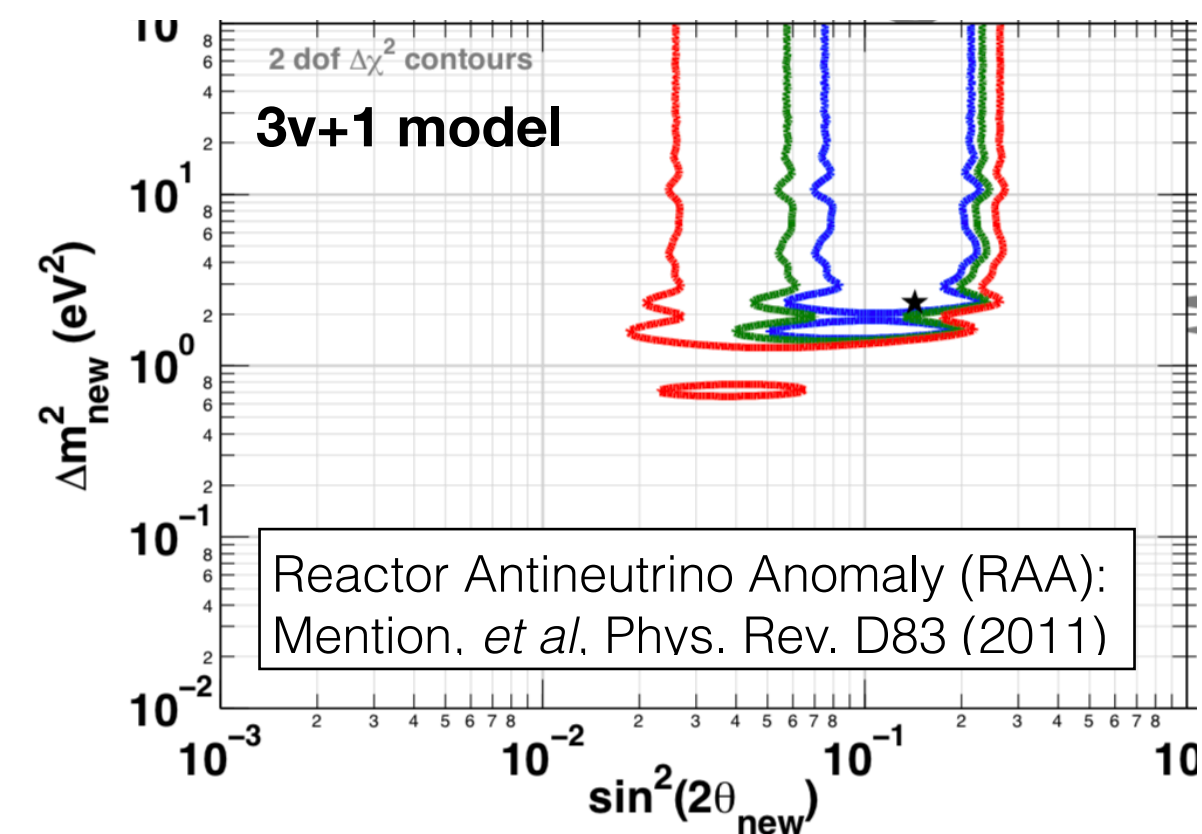
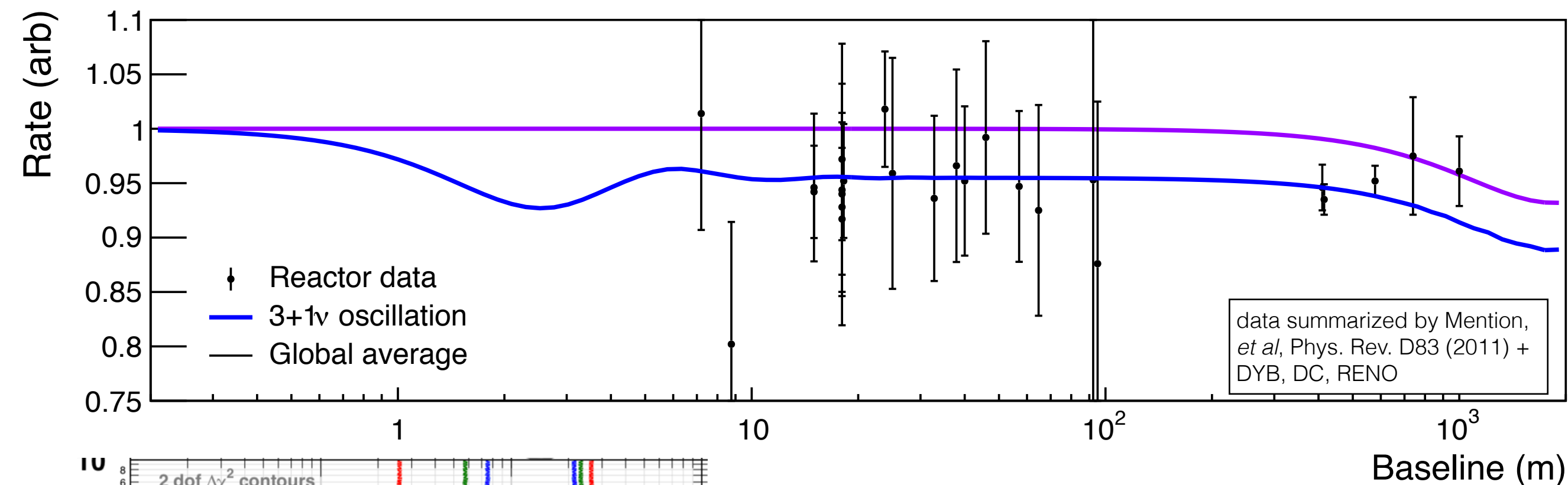
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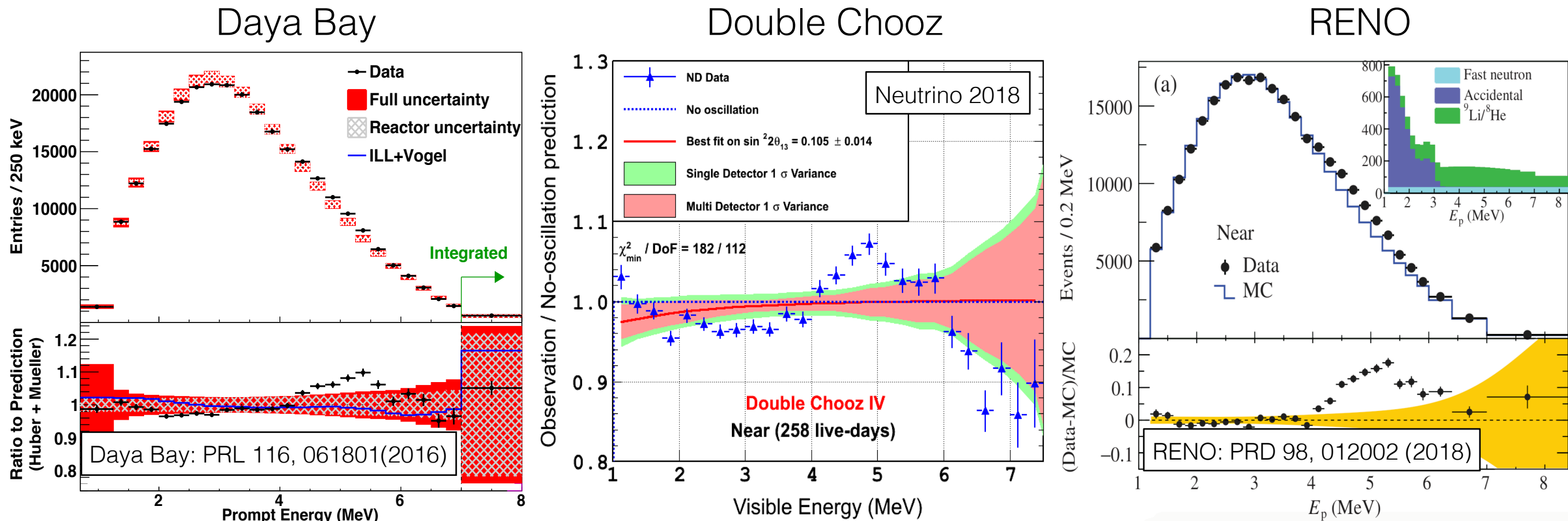
Reactor antineutrino flux deficit: 4th, sterile neutrino?



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

does an eV-scale sterile neutrino exist?

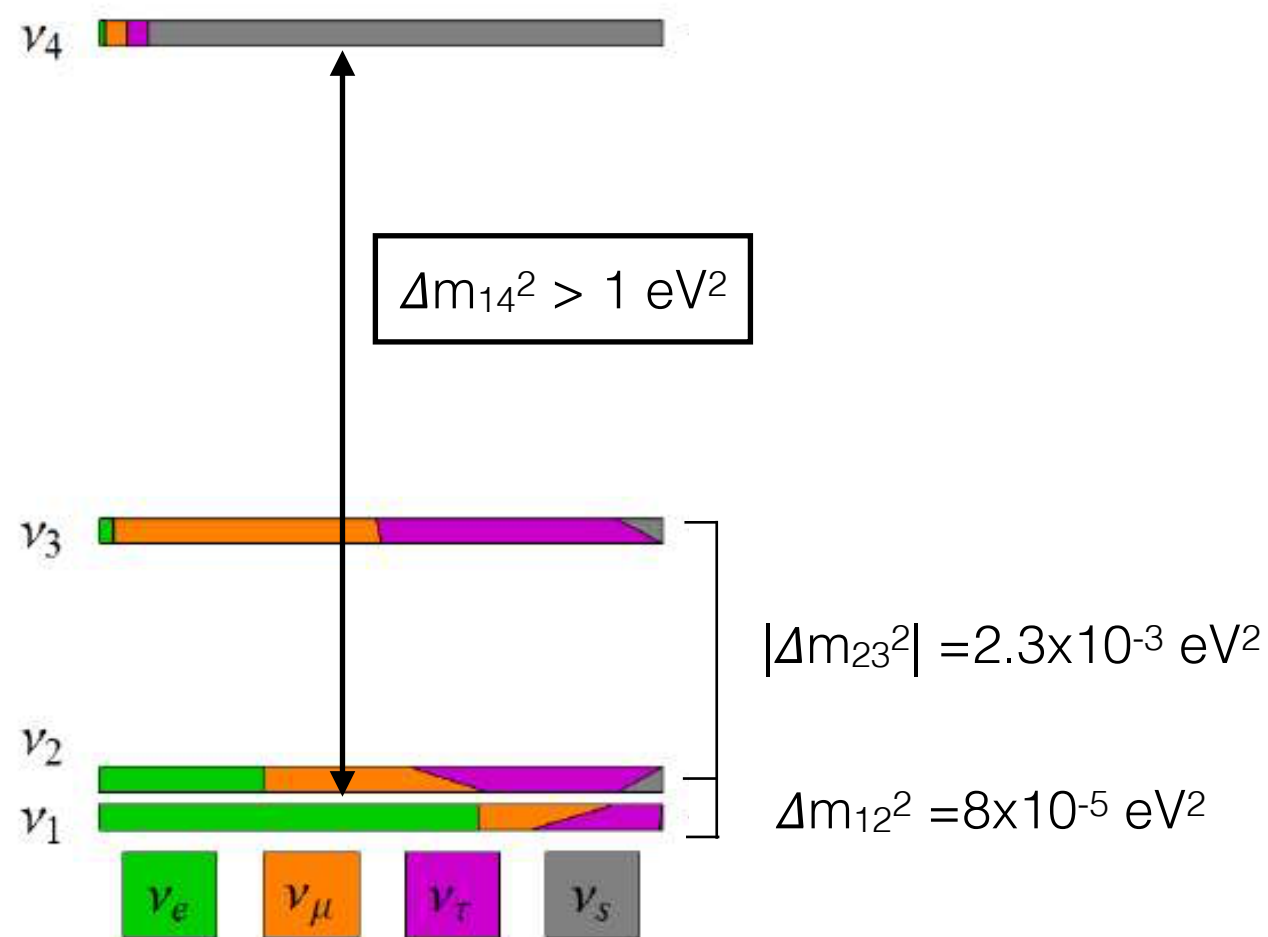
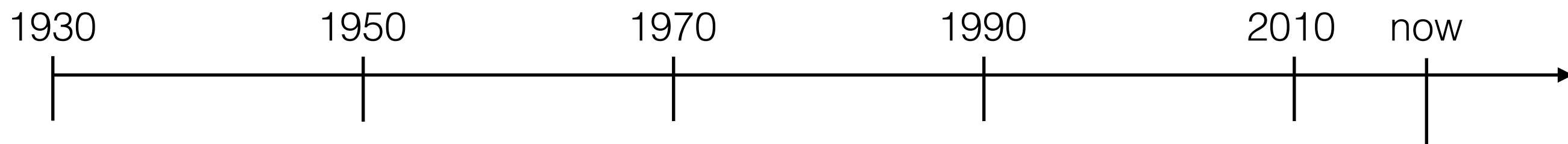
Reactor antineutrino energy spectrum deviations



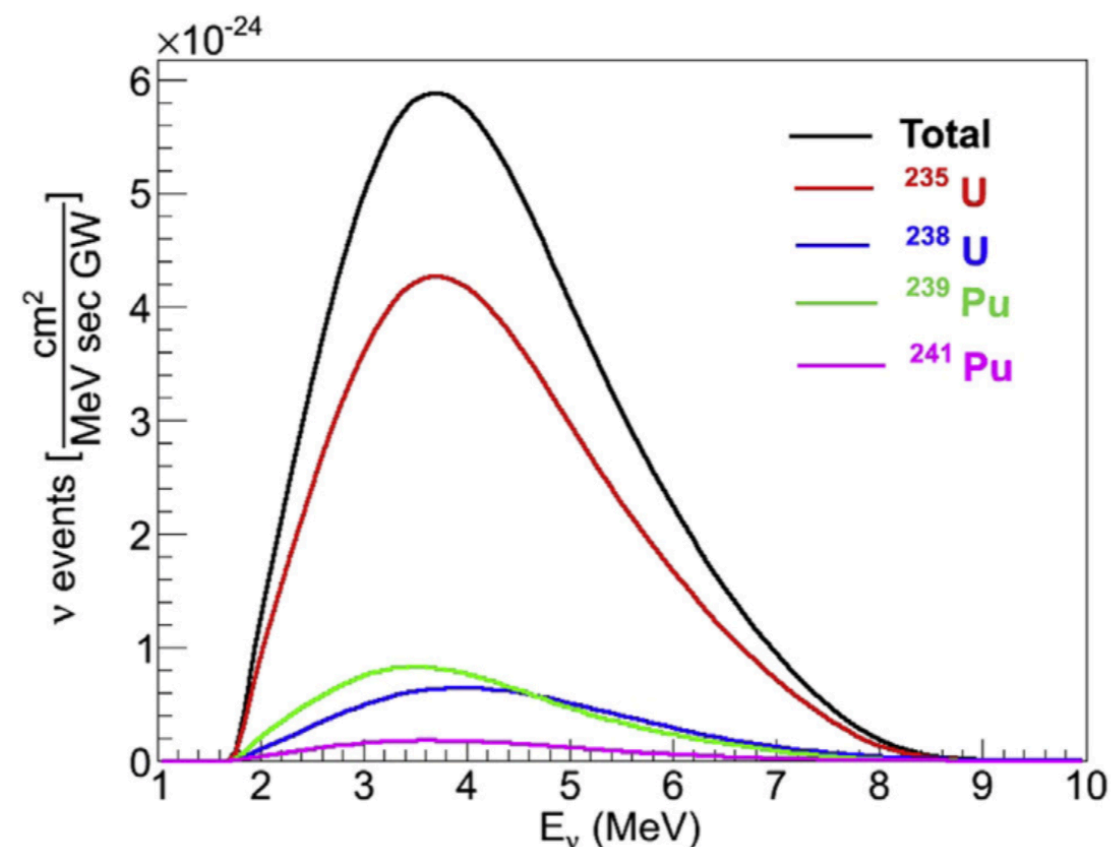
- recent expts at **power reactors** map shape of energy spectrum to percent-levels
- deviations throughout, prominent excess 4-6 MeV prompt (5-7 MeV neutrino)
- cannot be explained by the sterile neutrino introduced for flux deficit
- most likely an issue with nuclear models - one, some, all isotopes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

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

Evolution of reactor experiments with neutrino physics



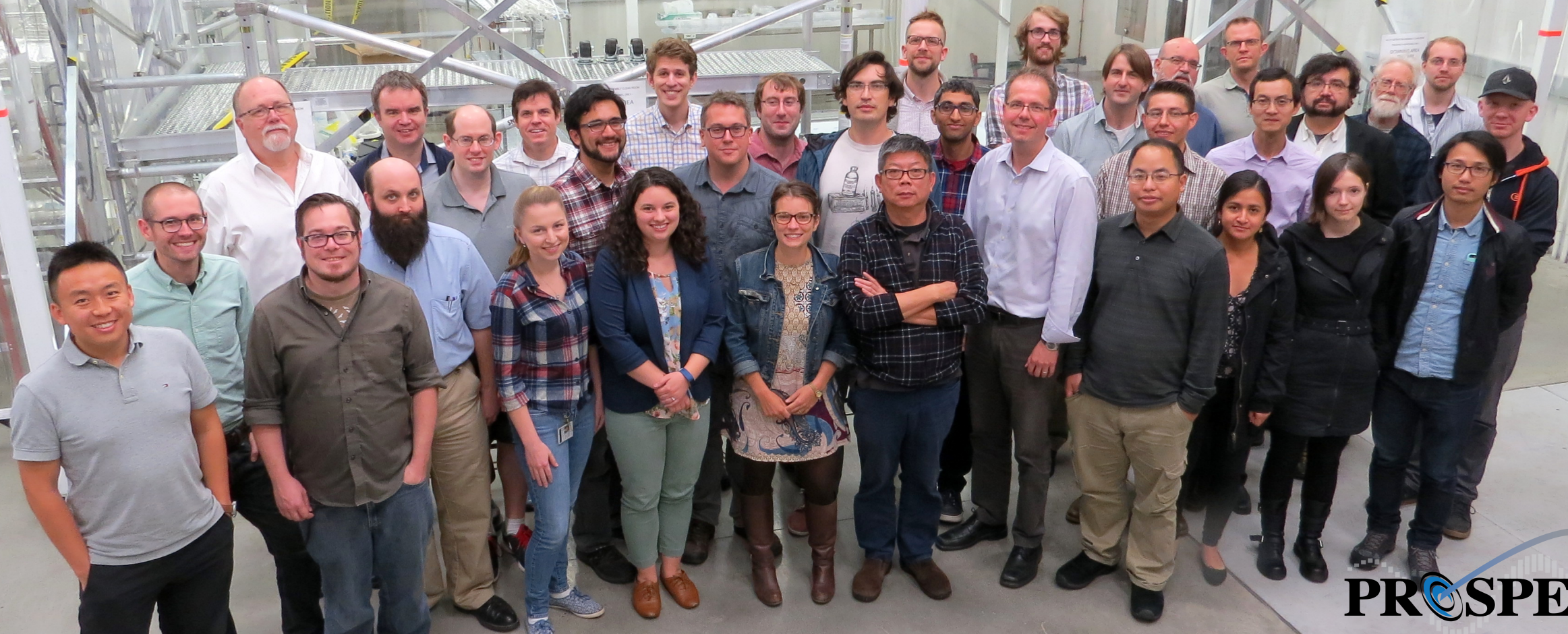
new technology to drive exploration of open neutrino physics at reactors



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



PROSPECT



Precision Reactor Oscillation and SPECTrum experiment

Scientific Goals

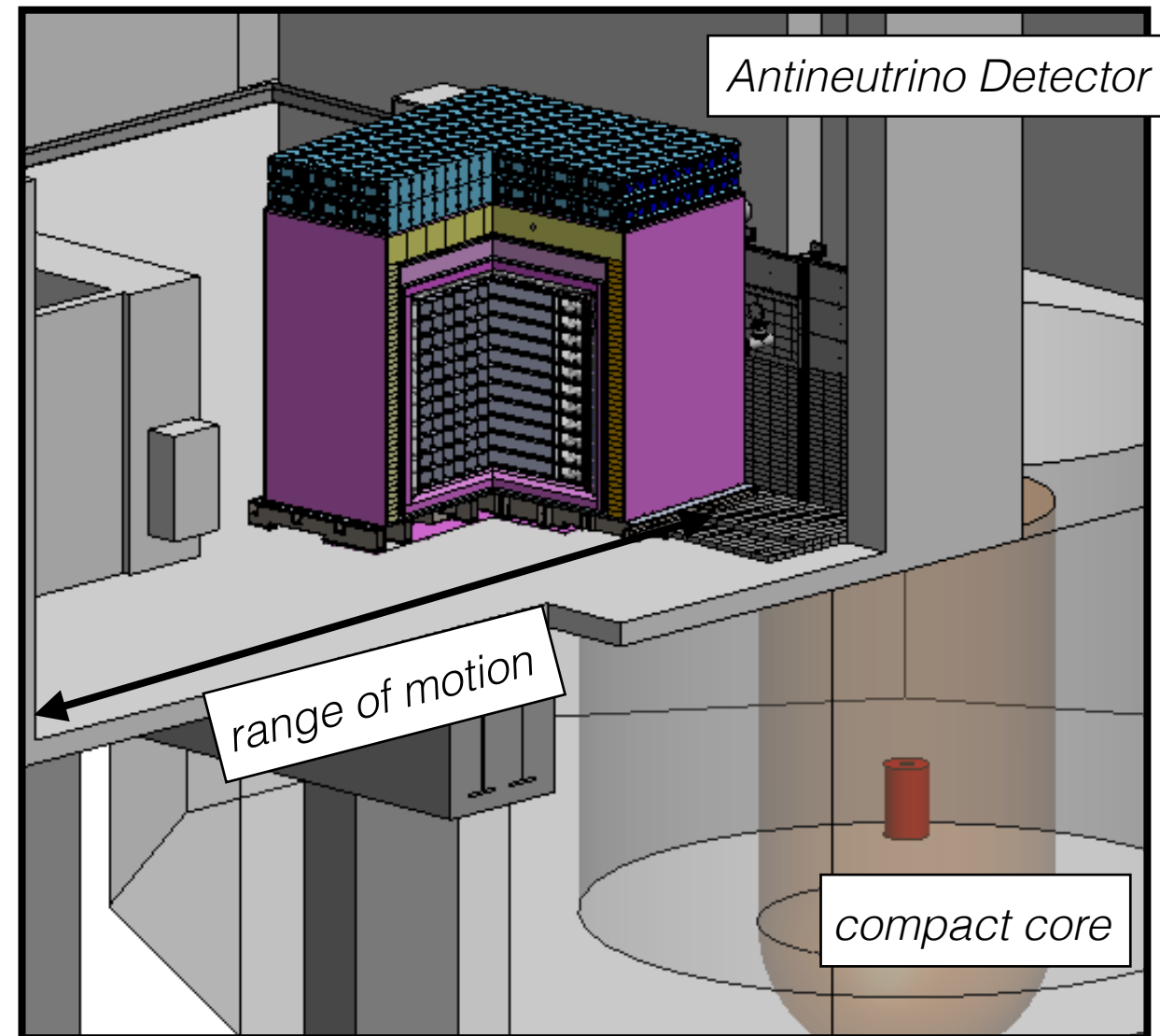
1. model independent search for eV-scale sterile neutrinos at short baselines
2. measure ^{235}U -only antineutrino spectrum to address spectral deviations

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

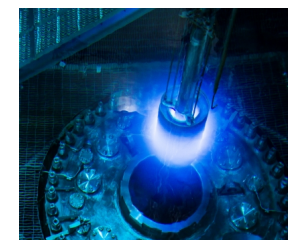
Challenges at HFIR near-surface site

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

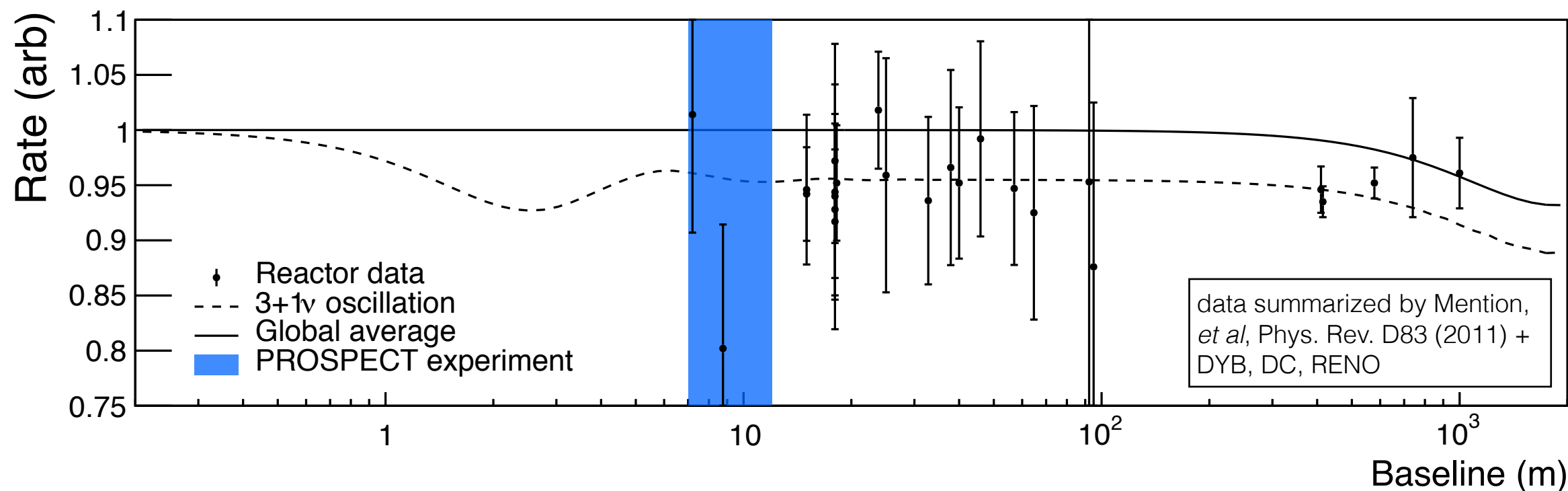
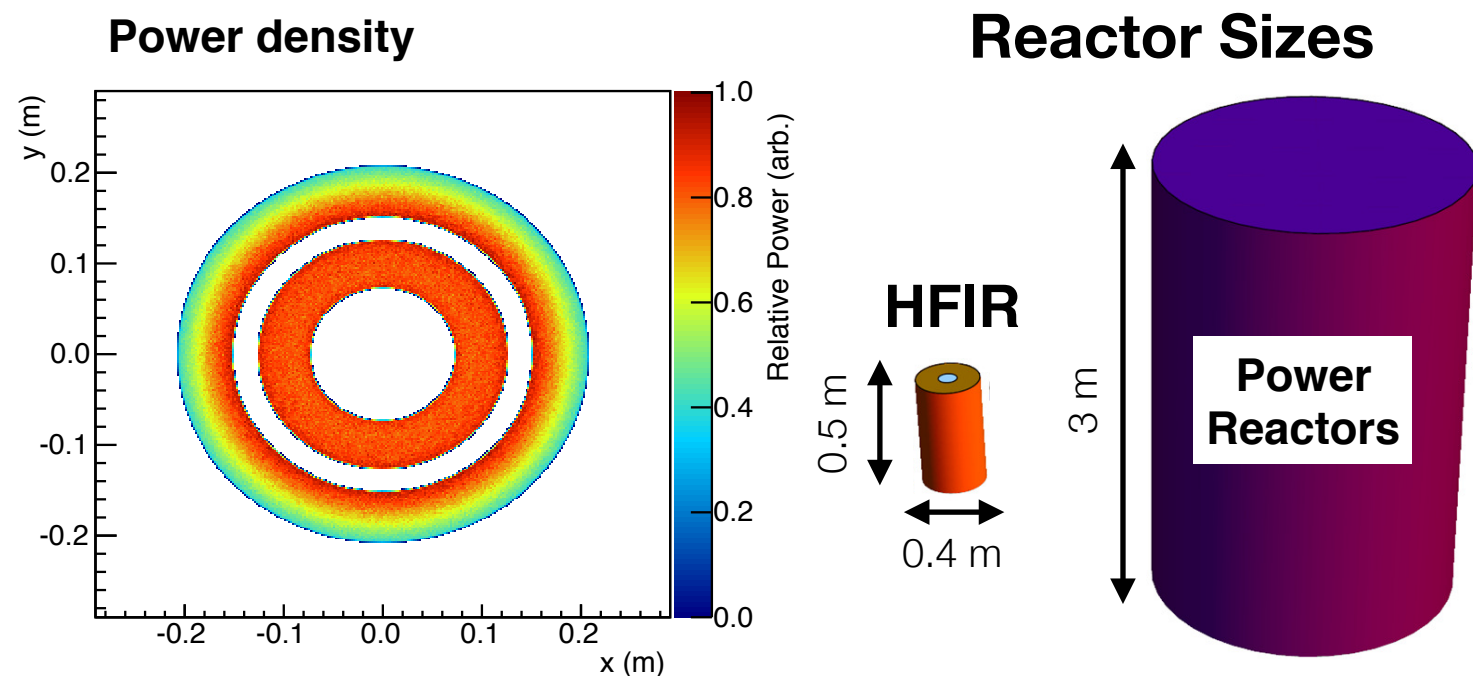


@ High Flux Isotope Reactor (HFIR),
Oak Ridge National Laboratory

Features of the High Flux Isotope Reactor

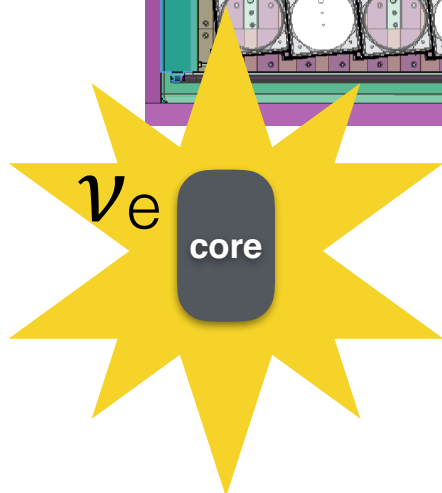
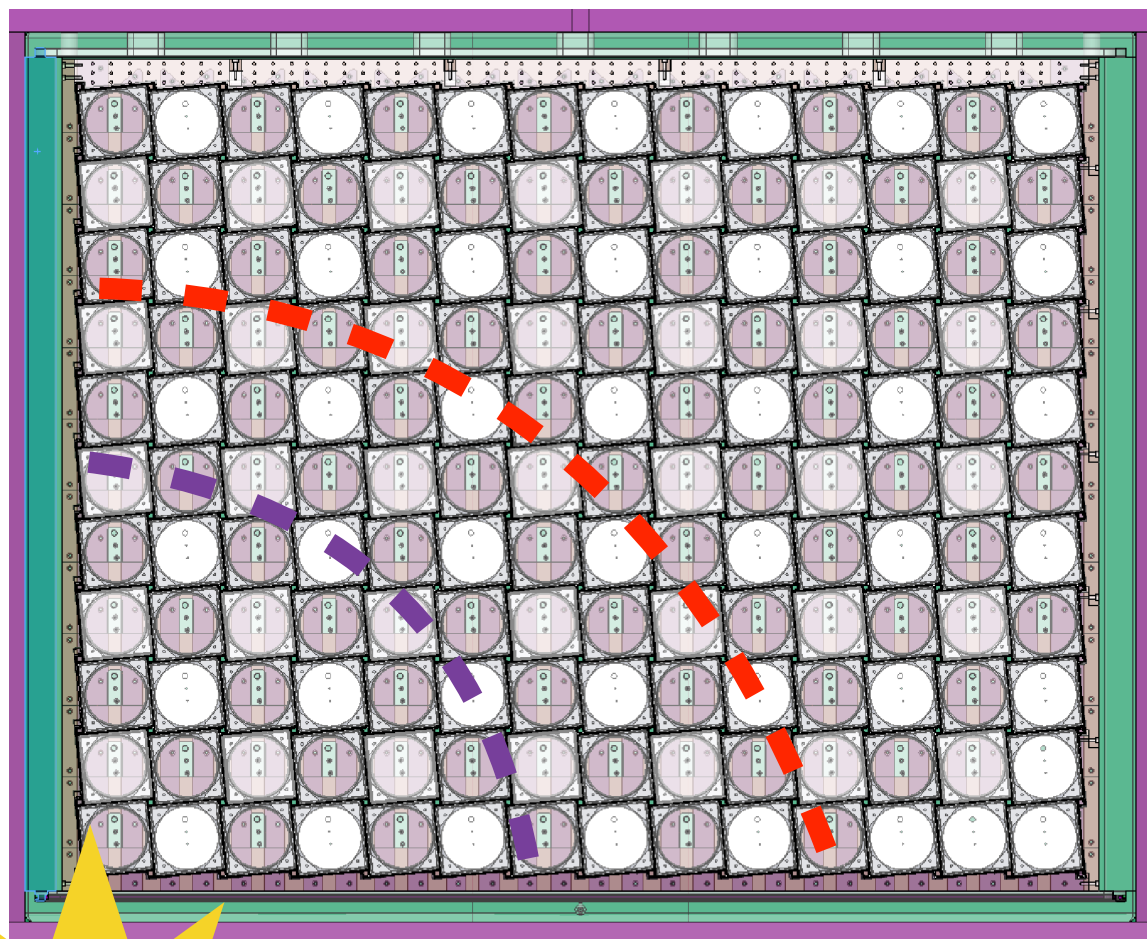


- 85MW highly enriched uranium reactor
- >99% of ν from ^{235}U fissions, effectively no isotopic evolution
- 24 day cycles, 46% reactor up time, measure backgrounds when off
- compact core (44cm diameter, 51cm tall), effectively a point source
- baselines 7-12m within mobile detector

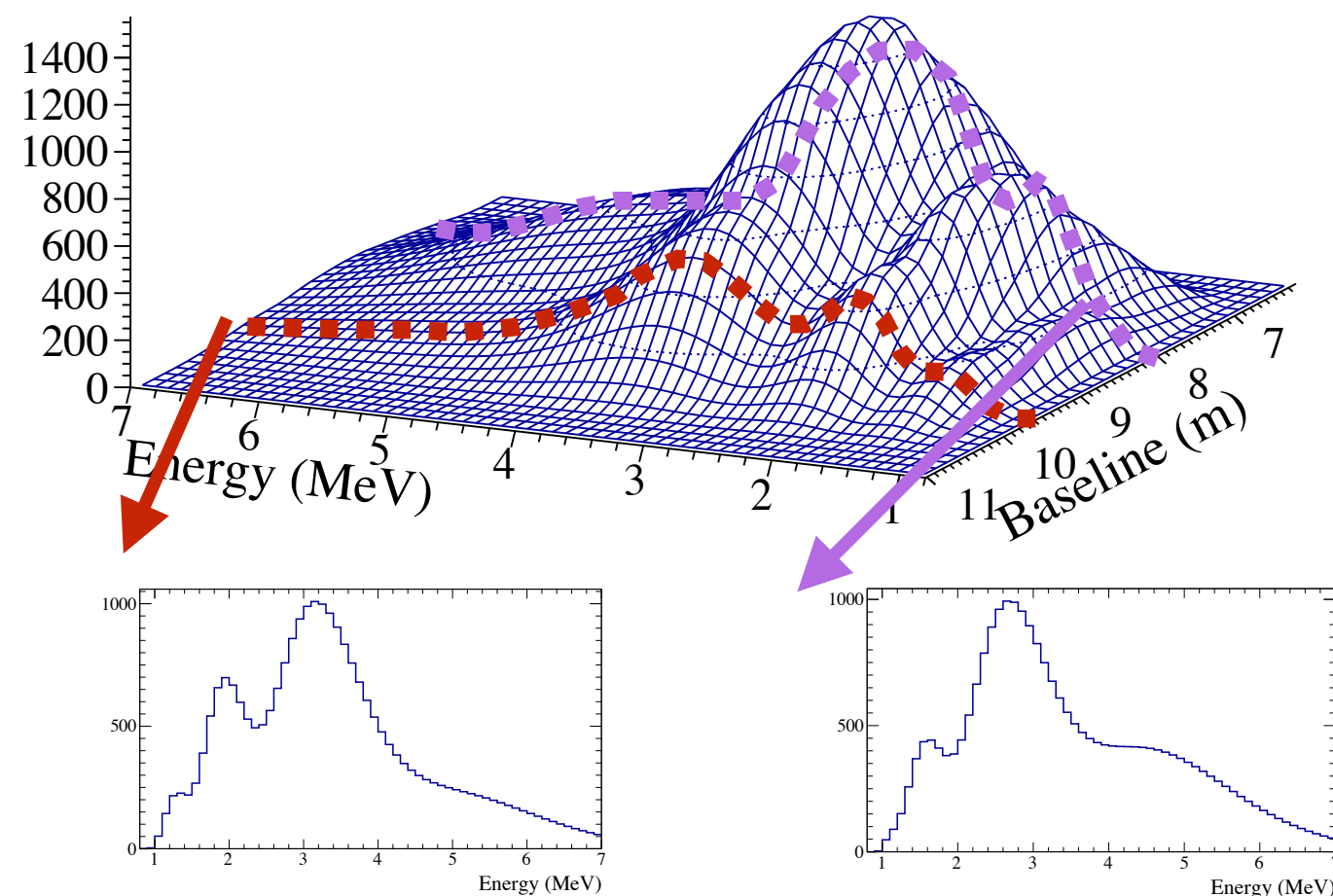


HFIR + segments: model independent sterile search

154 detectors in 1!



L vs E, oscillated



- oscillations modify energy spectrum as a function of baseline

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

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

Precision Reactor Oscillation and SPECTrum experiment

Scientific Goals

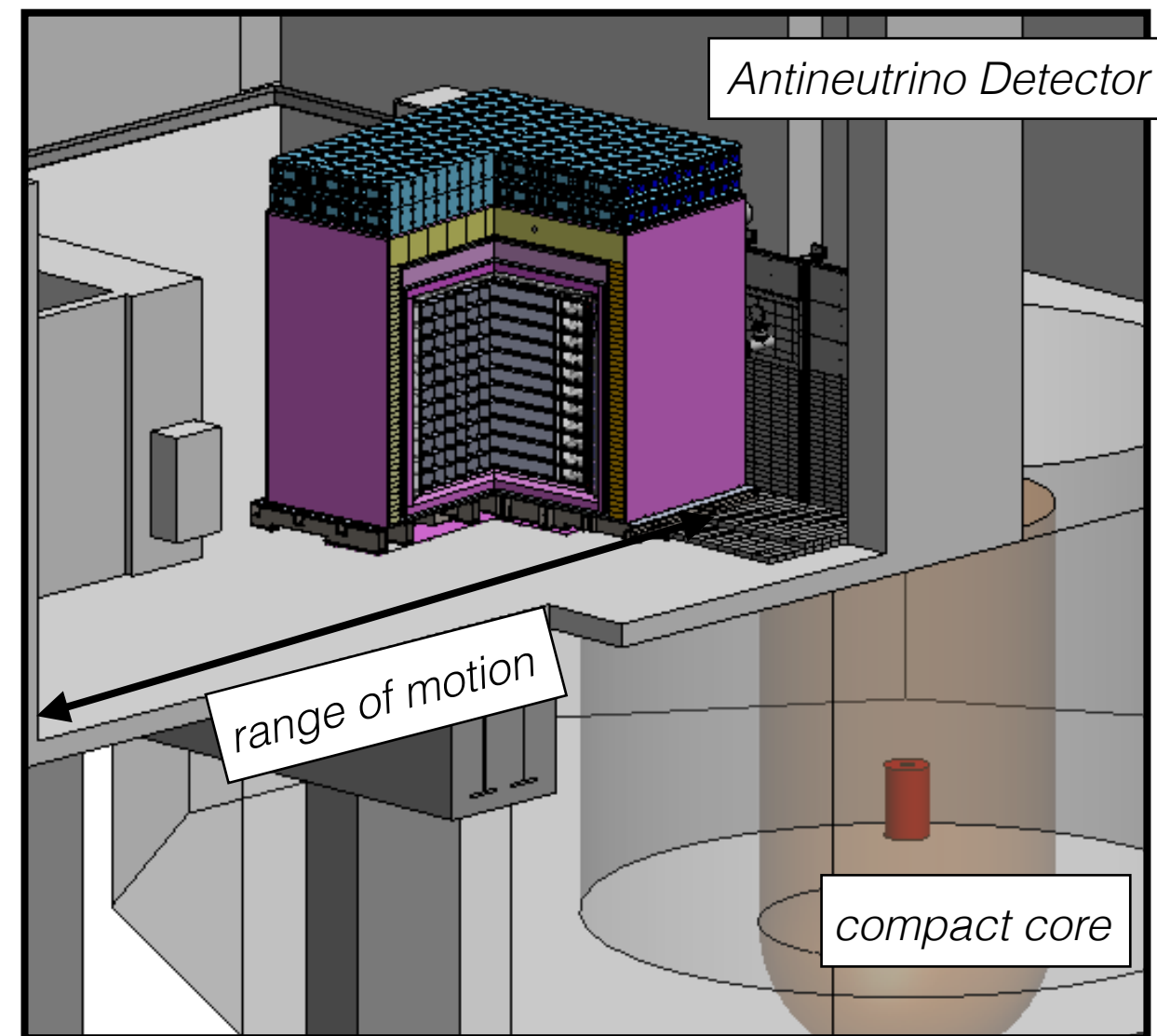
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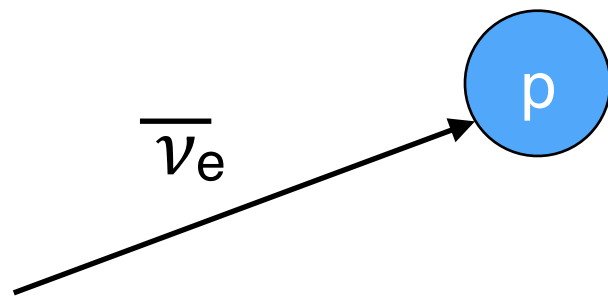
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^6Li -loaded liquid scintillator: IBD detection

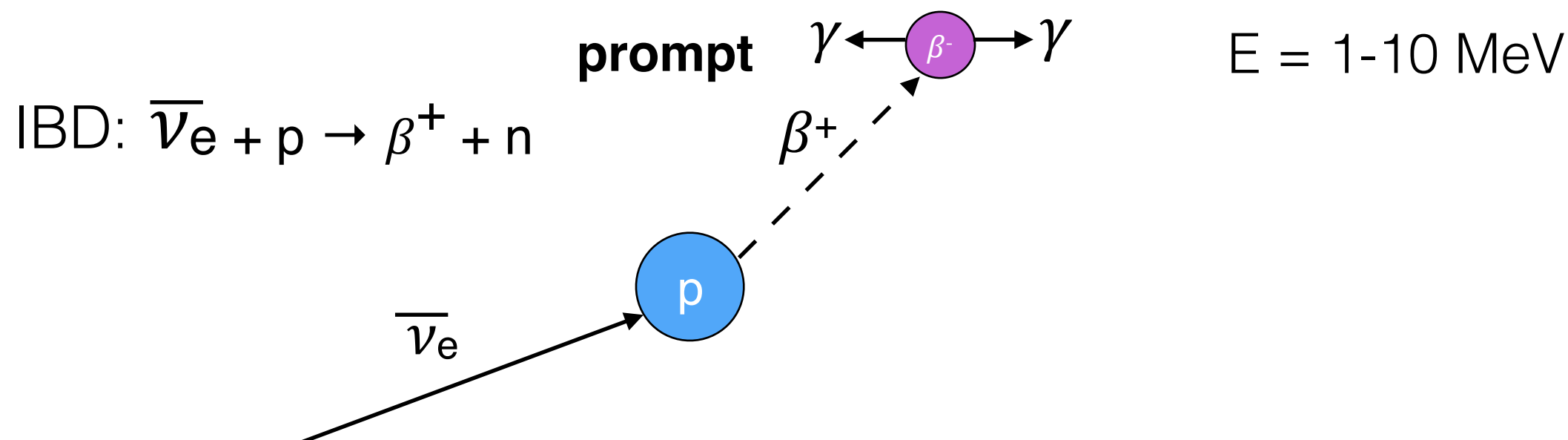
$$\text{IBD: } \bar{\nu}_e + p \rightarrow \beta^+ + n$$



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

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

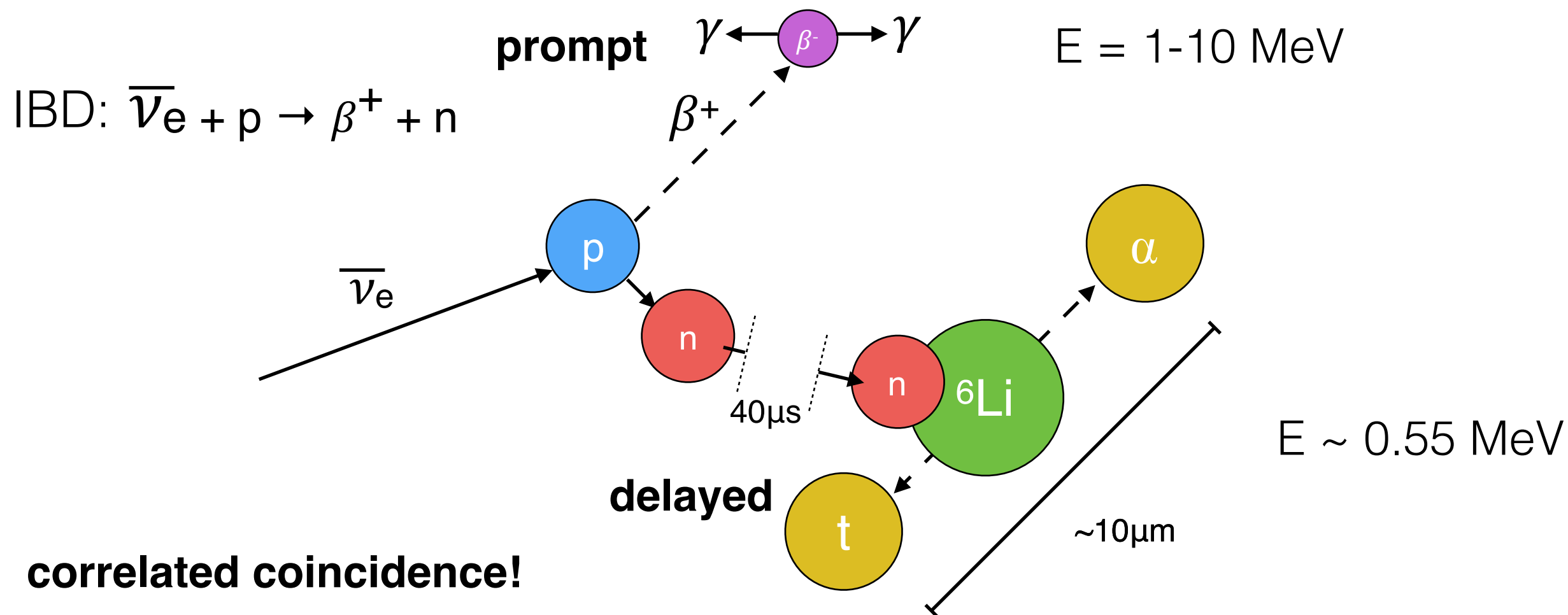
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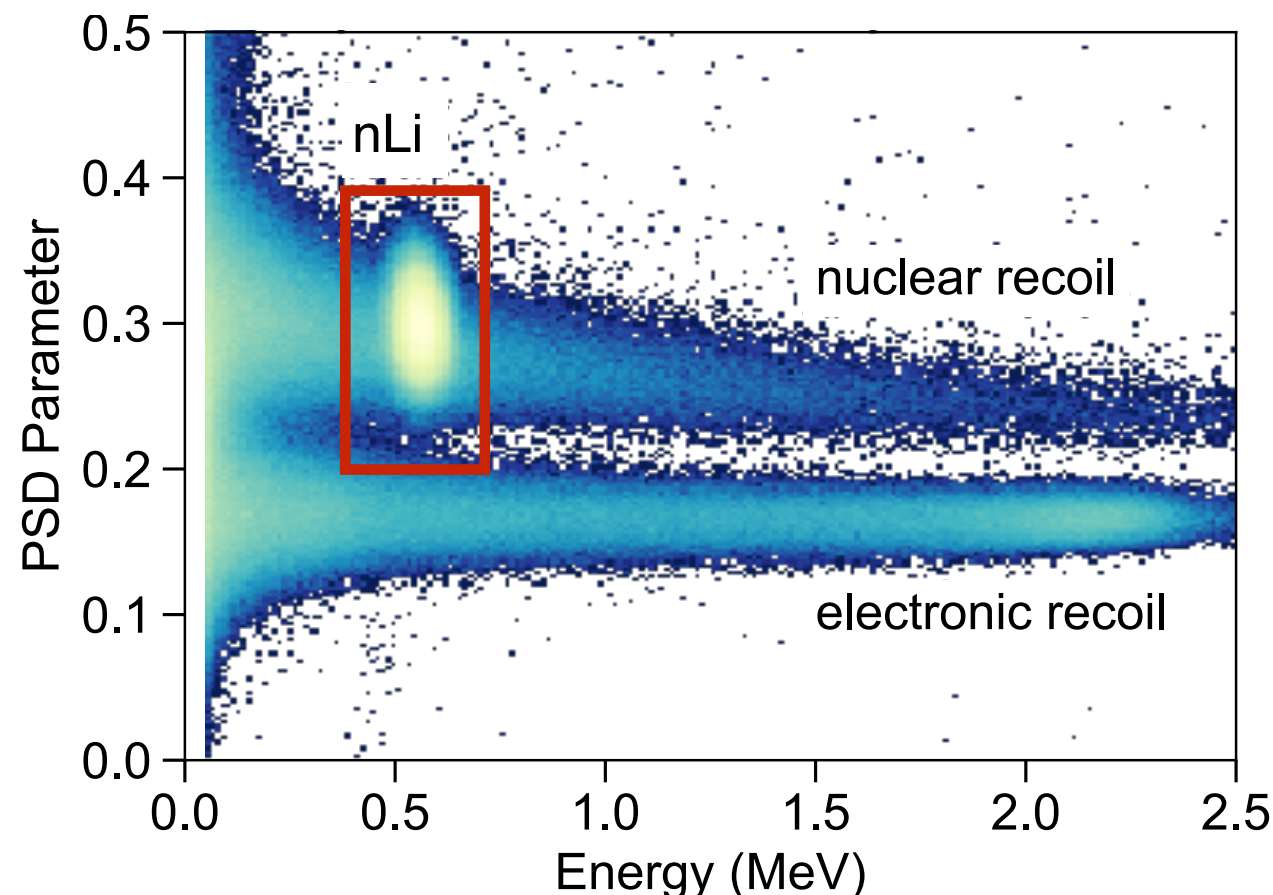
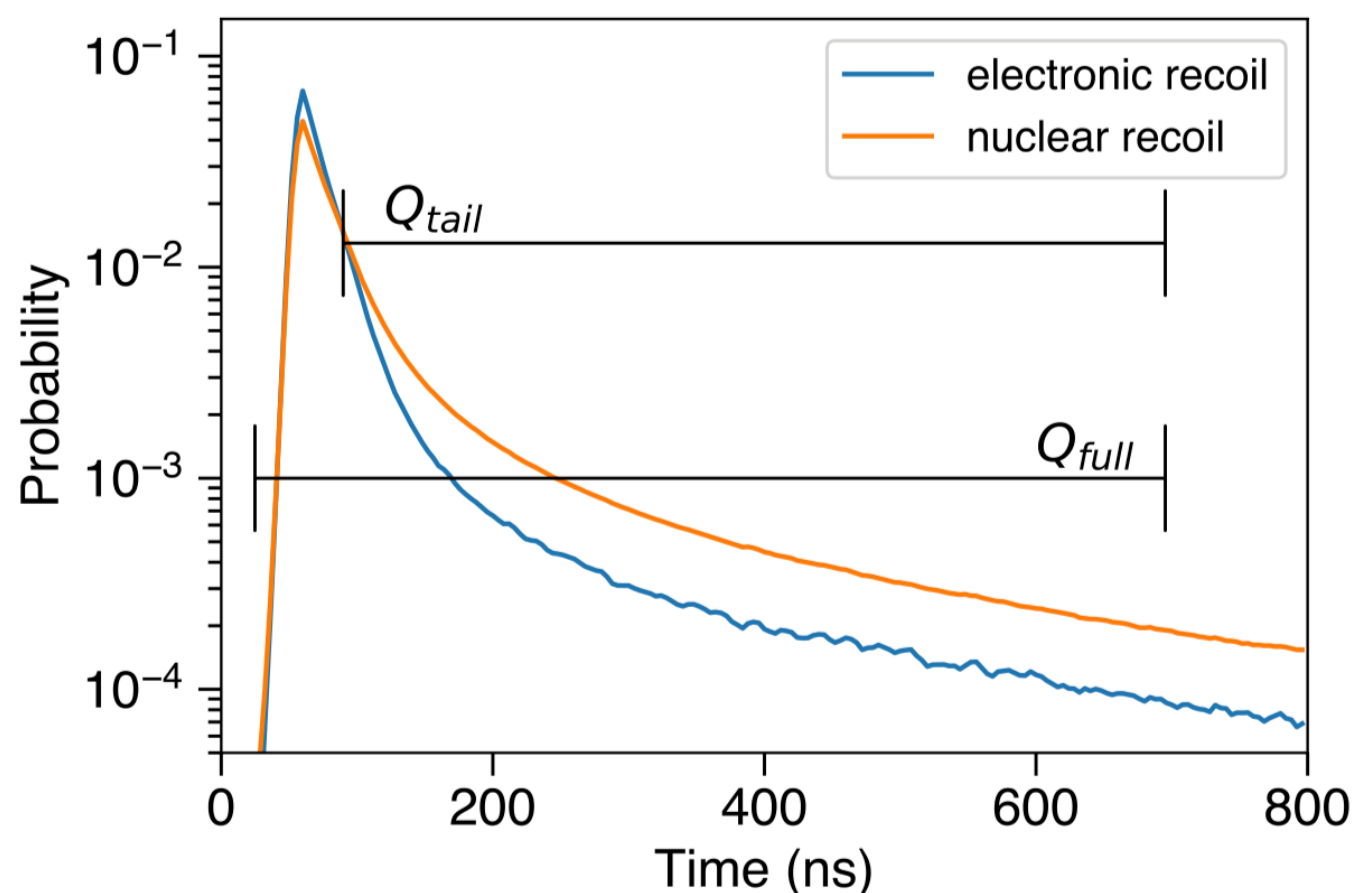


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Particle identification: Pulse Shape Discrimination

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



$$\text{PSD} = Q_{tail}/Q_{full}$$

PSD adds powerful information to identify IBDs and reject backgrounds

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

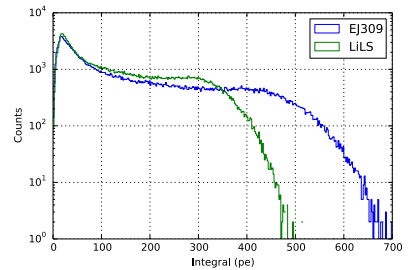
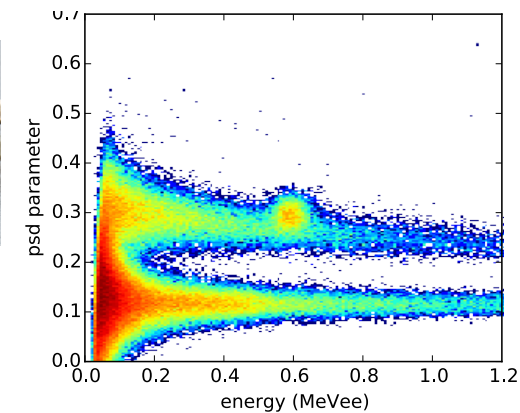
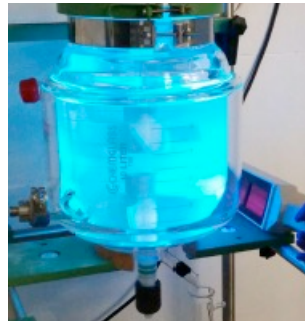
PROSPECT-0.1

Develop LS

Characterize LS

Aug 2014-Spring 2015

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



PROSPECT-2

Background studies

Dec 2014 - Aug 2015

12.5 length
1.7 liters
 $^6\text{LiLS}$



PROSPECT: NIMA A806 (2016) 401

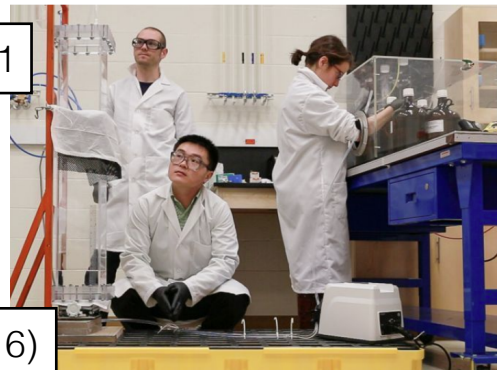
PROSPECT-20

Segment optics

Component design

Spring/Summer 2015

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



PROSPECT: JINST 10 P11004 (2016)

PROSPECT-50

Performance validation

Subsystem testbed

Simulation benchmark

2017-2018

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



PROSPECT: JINST 13 P06023 (2018)

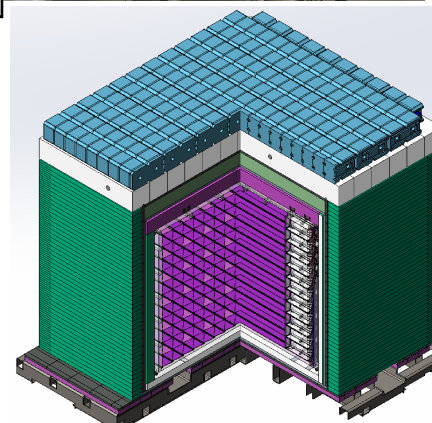
PROSPECT AD

Physics measurement

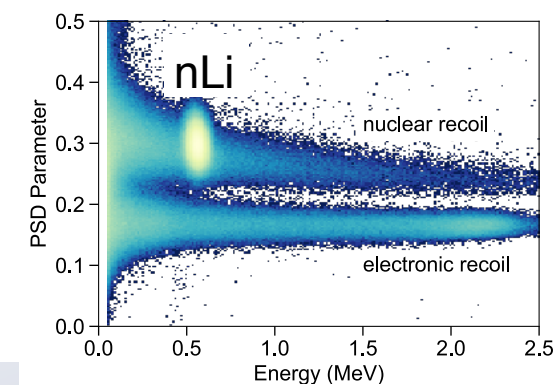
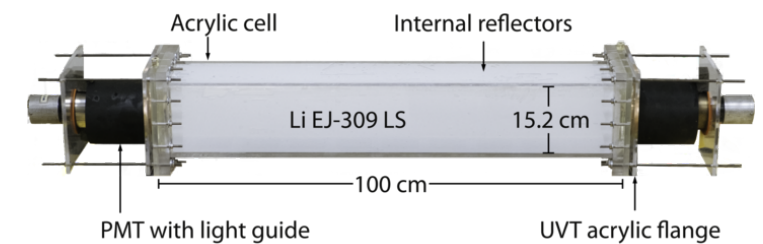
data taking 2018

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

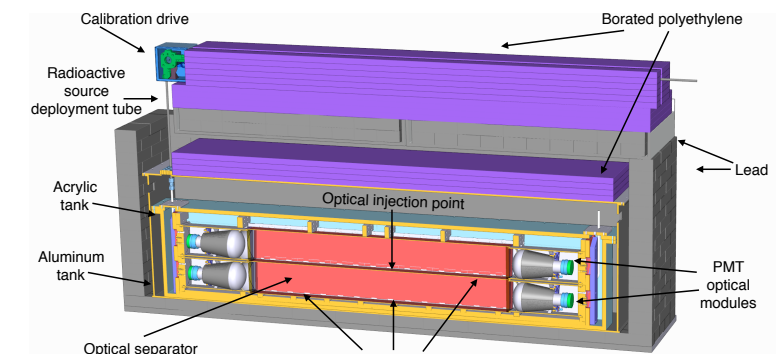
PROSPECT: arXiv:1808.00097



light guides
low mass reflectors



light collection
energy resolution
PSD performance



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

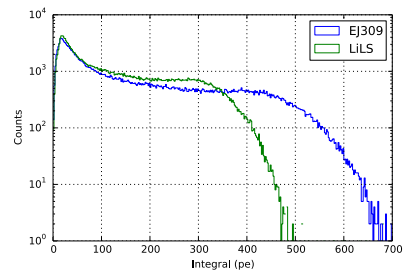
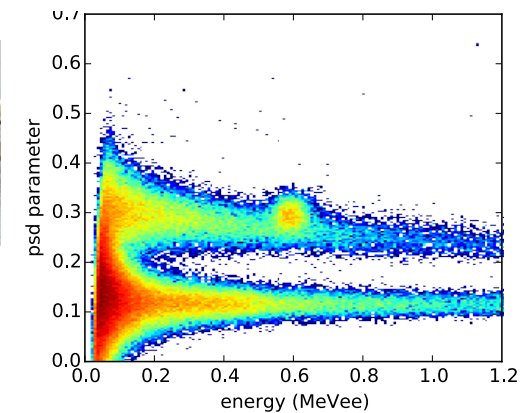
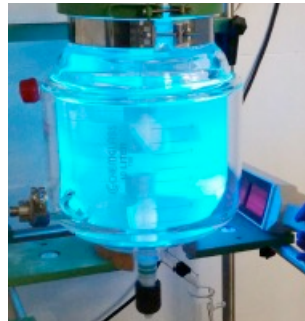
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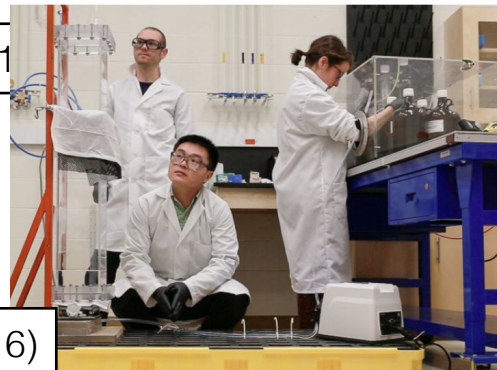
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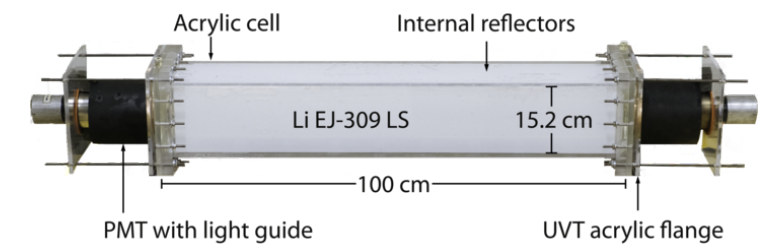
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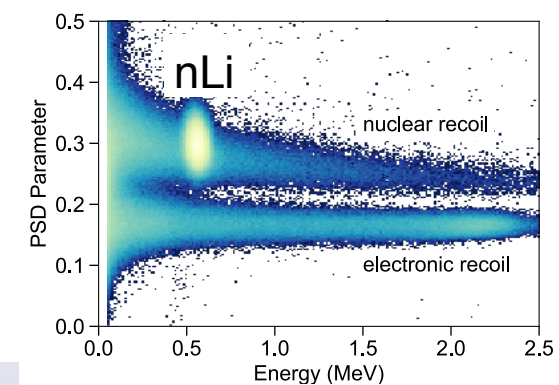
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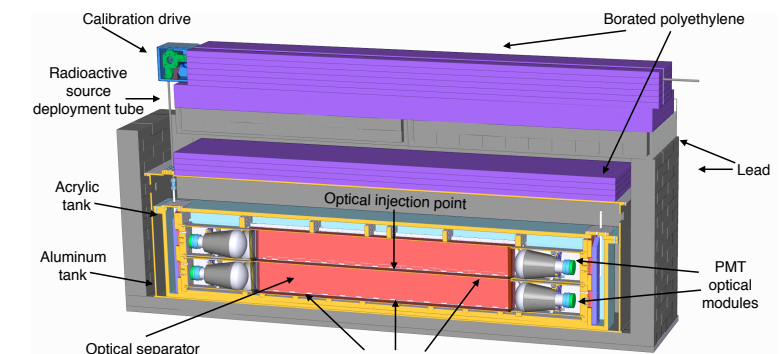
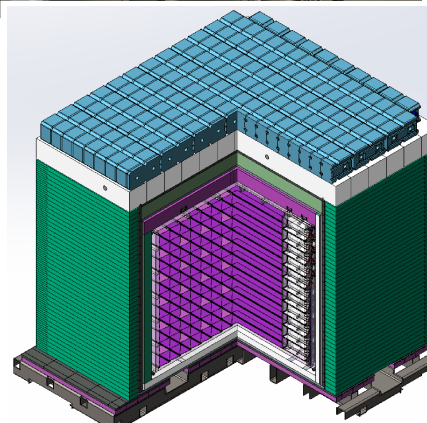
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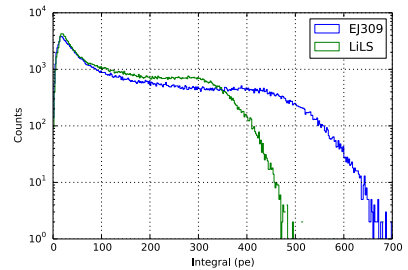
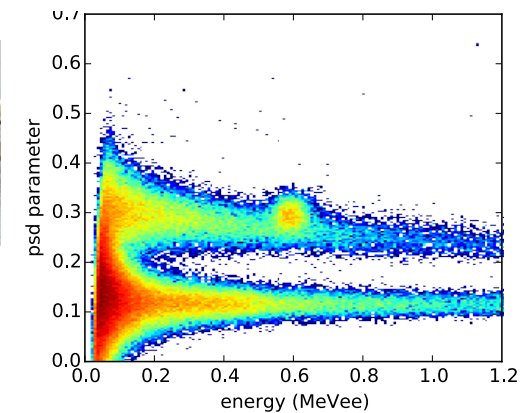
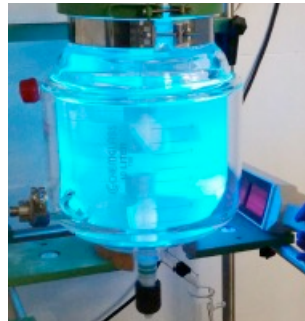
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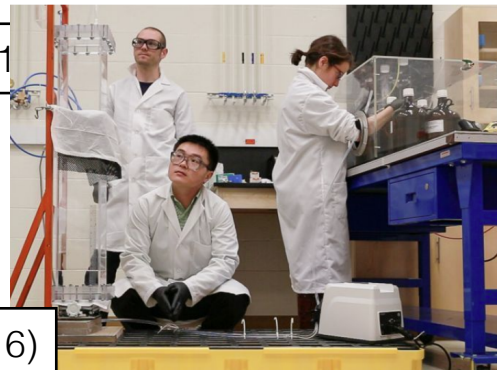
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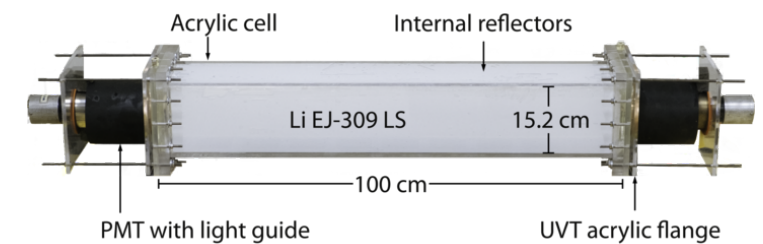
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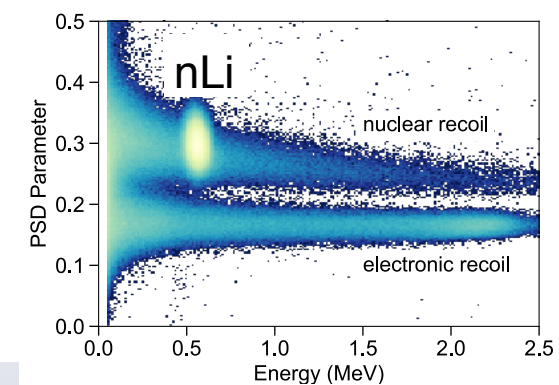
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PSD performance

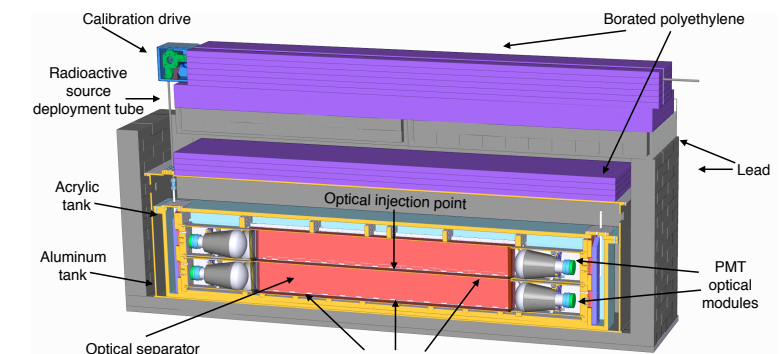
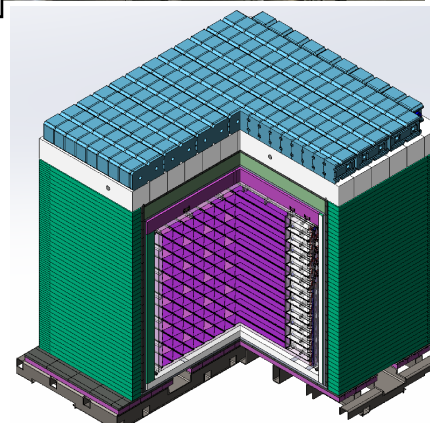
PROSPECT AD

Physics measurement

data taking 2018

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

PROSPECT: arXiv:1808.00097



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

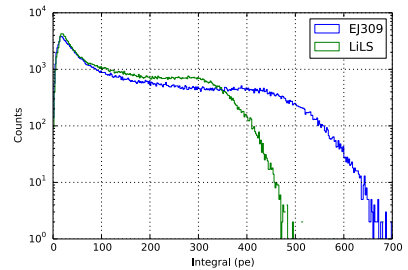
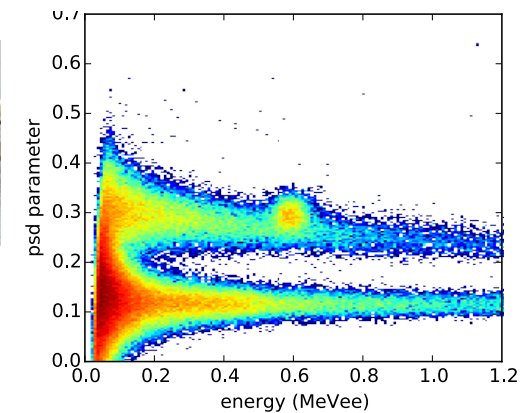
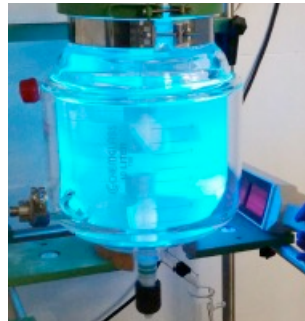
PROSPECT-0.1

Develop LS

Characterize LS

Aug 2014-Spring 2015

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



PROSPECT-2

Background studies

Dec 2014 - Aug 2015

12.5 length
1.7 liters
 ${}^6\text{LiLS}$



PROSPECT: NIMA A806 (2016) 401

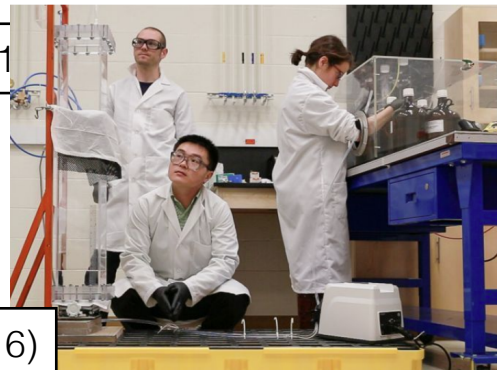
PROSPECT-20

Segment optics

Component design

Spring/Summer 2015

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



PROSPECT: JINST 10 P11004 (2016)

PROSPECT-50

Performance validation

Subsystem testbed

Simulation benchmark

2017-2018

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



PROSPECT: JINST 13 P06023 (2018)

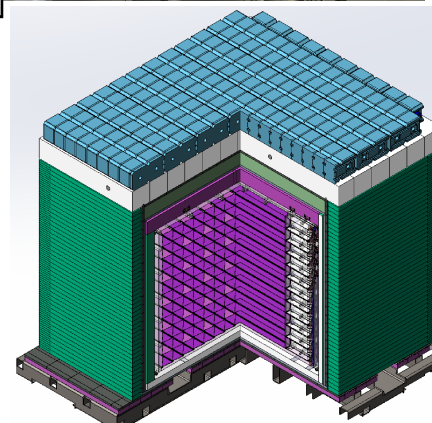
PROSPECT AD

Physics measurement

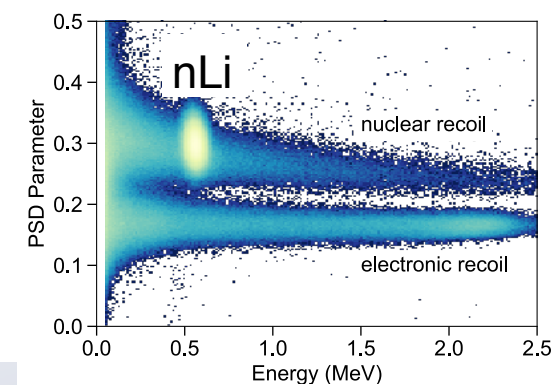
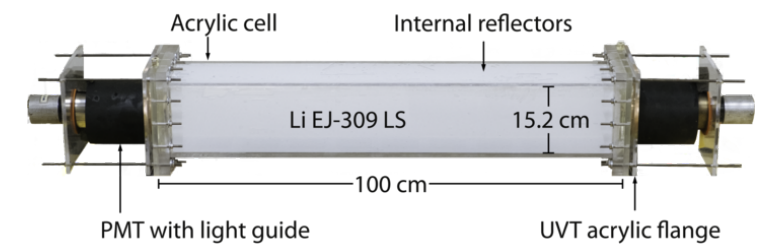
data taking 2018

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

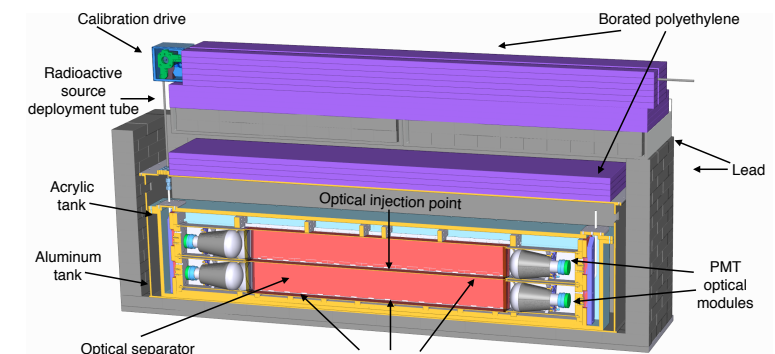
PROSPECT: arXiv:1808.00097



light guides
low mass reflectors

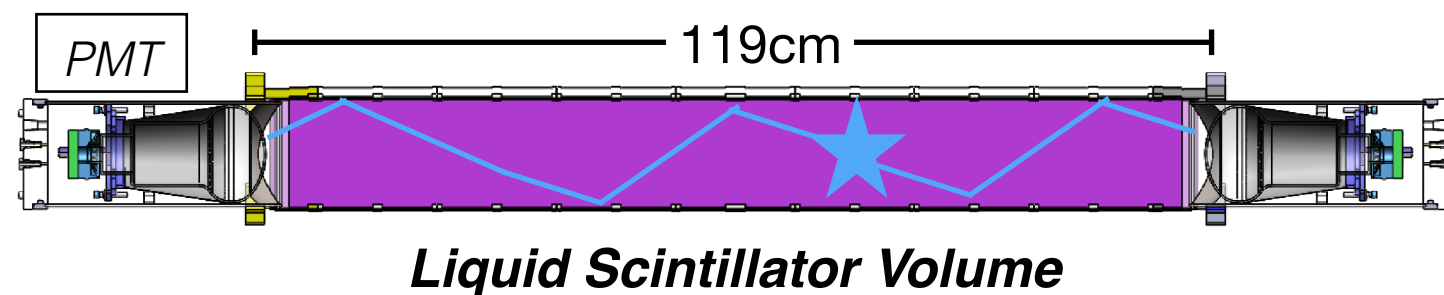
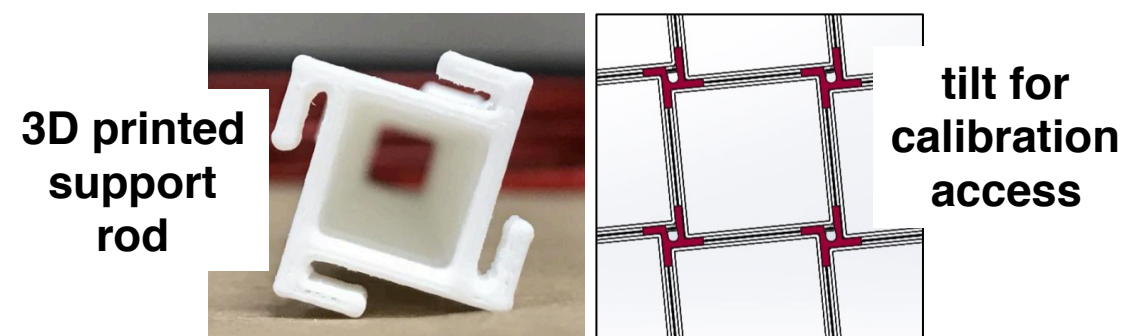
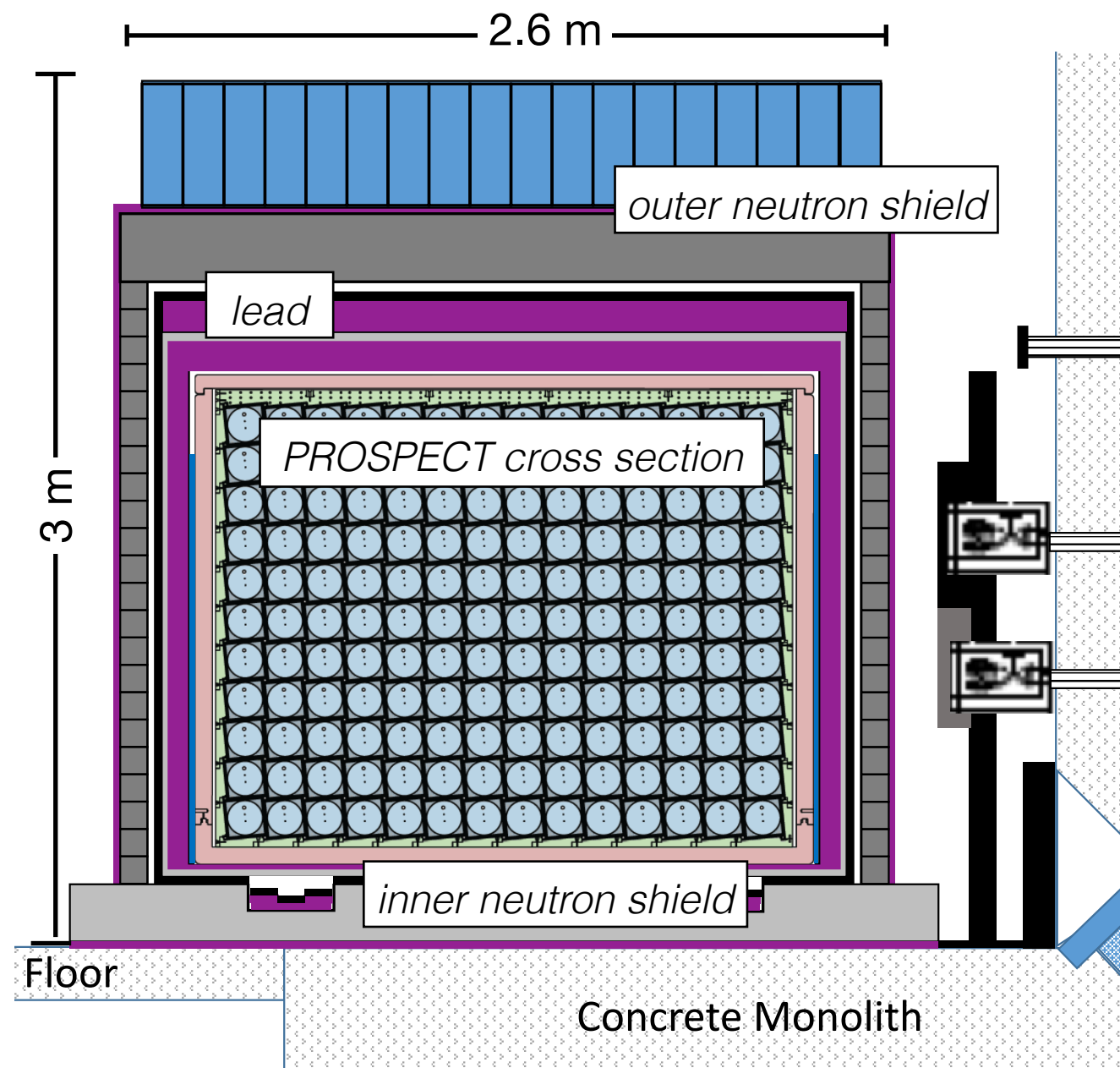


light collection
energy resolution
PSD performance

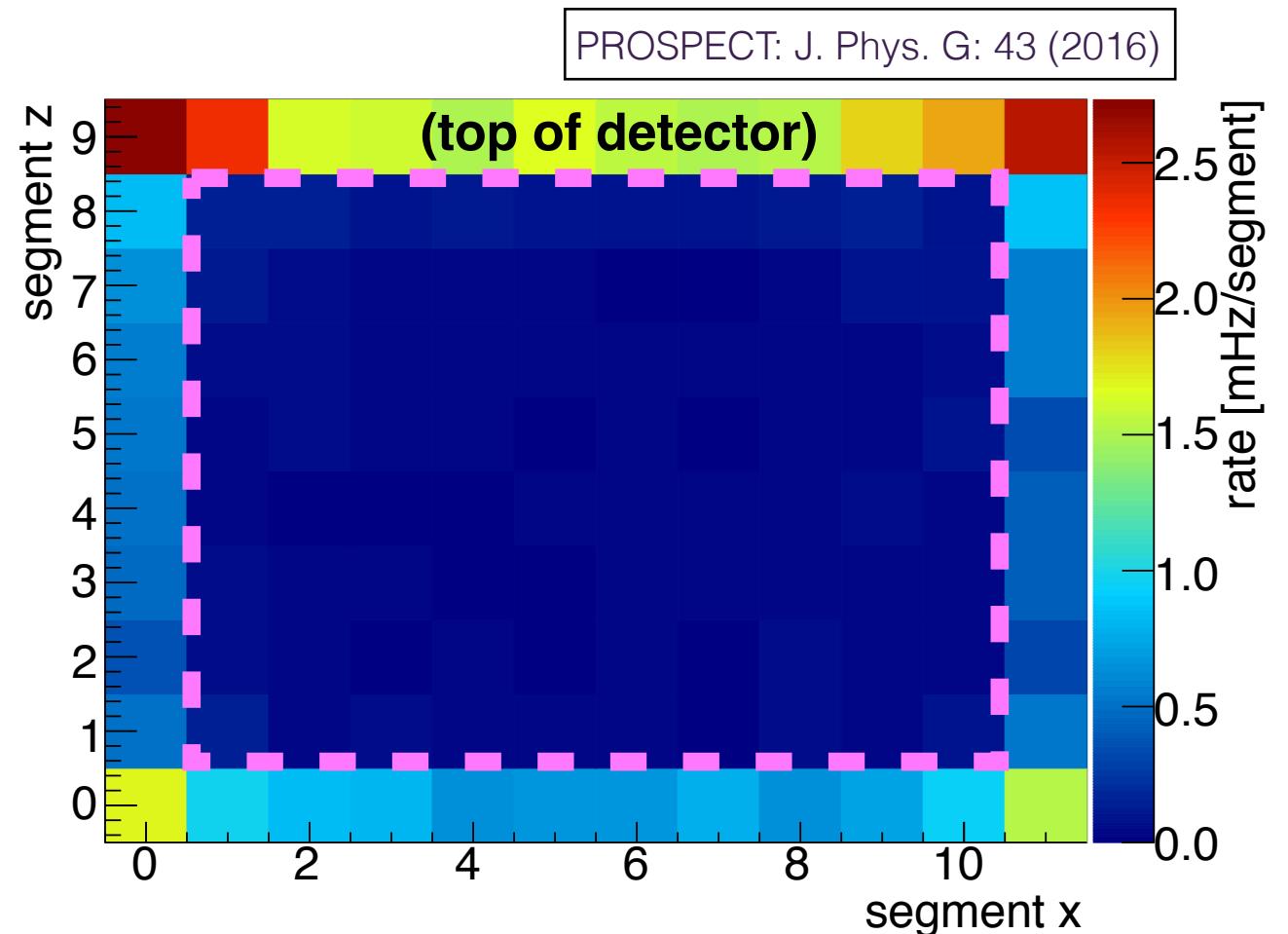
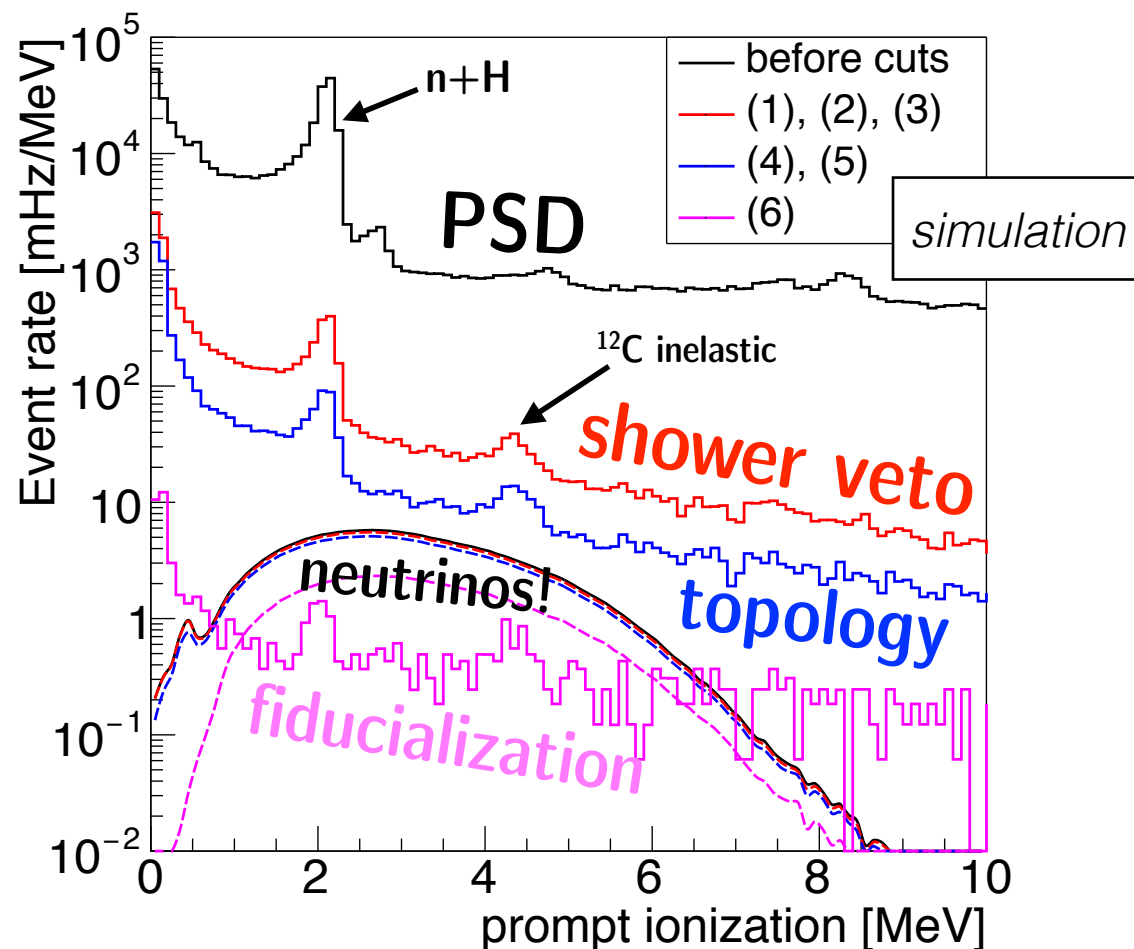


PROSPECT segmented detector design

- 4 tons ^6Li -loaded liquid scintillator with energy resolution of 4.5%/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, ^6Li 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

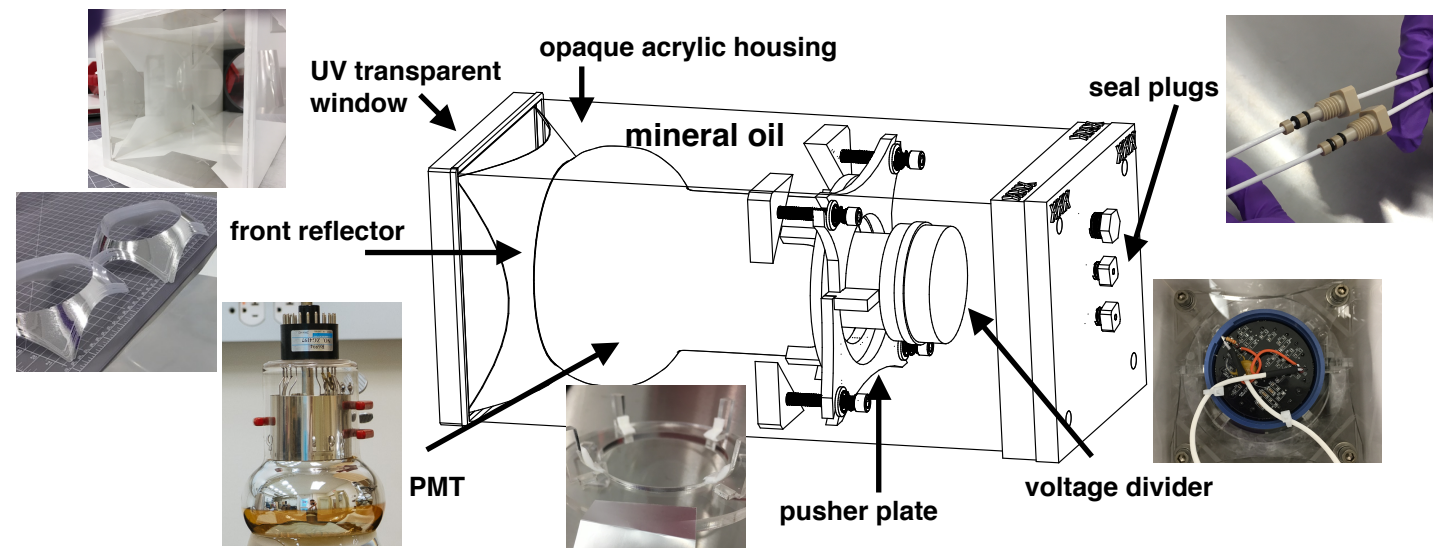
Construction + Installation



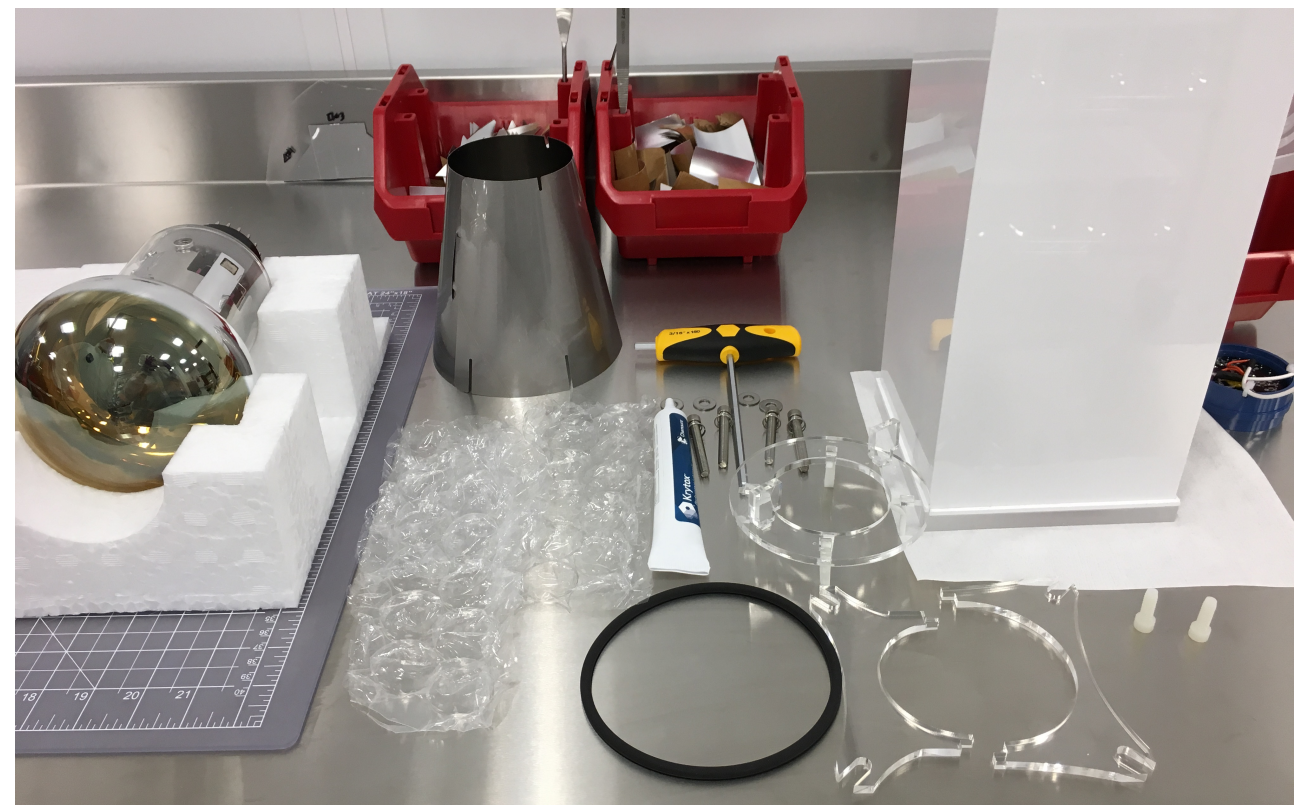
Optical module assembly @ Yale Wright Lab

- 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

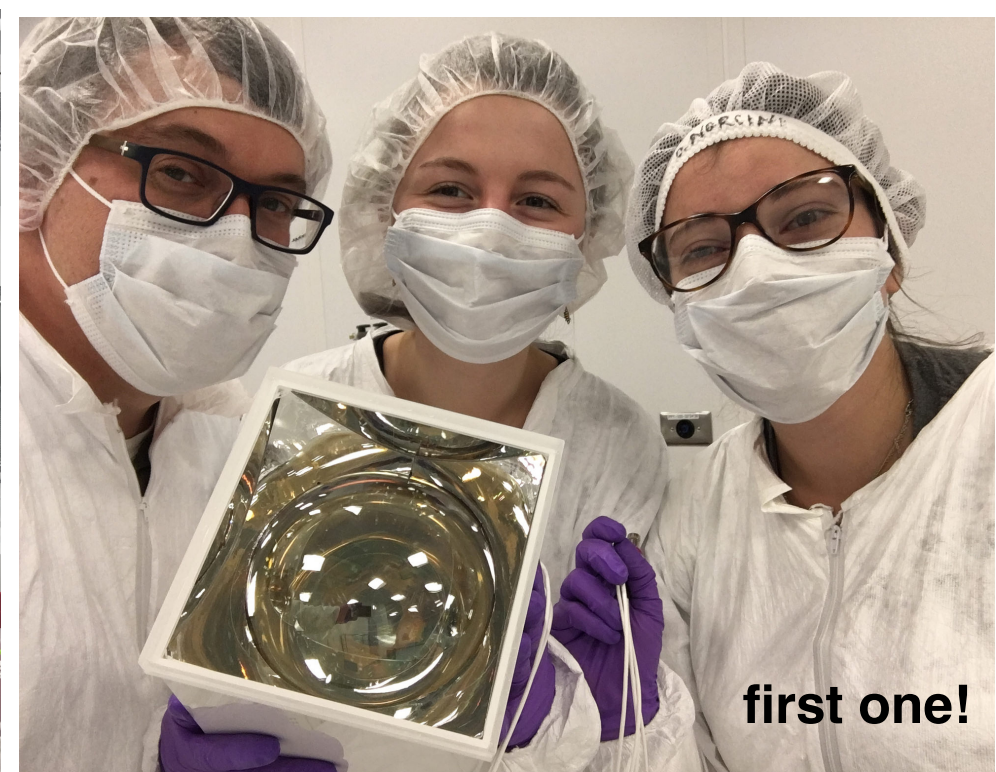
Modules in liquid volume: scintillator approved!



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!

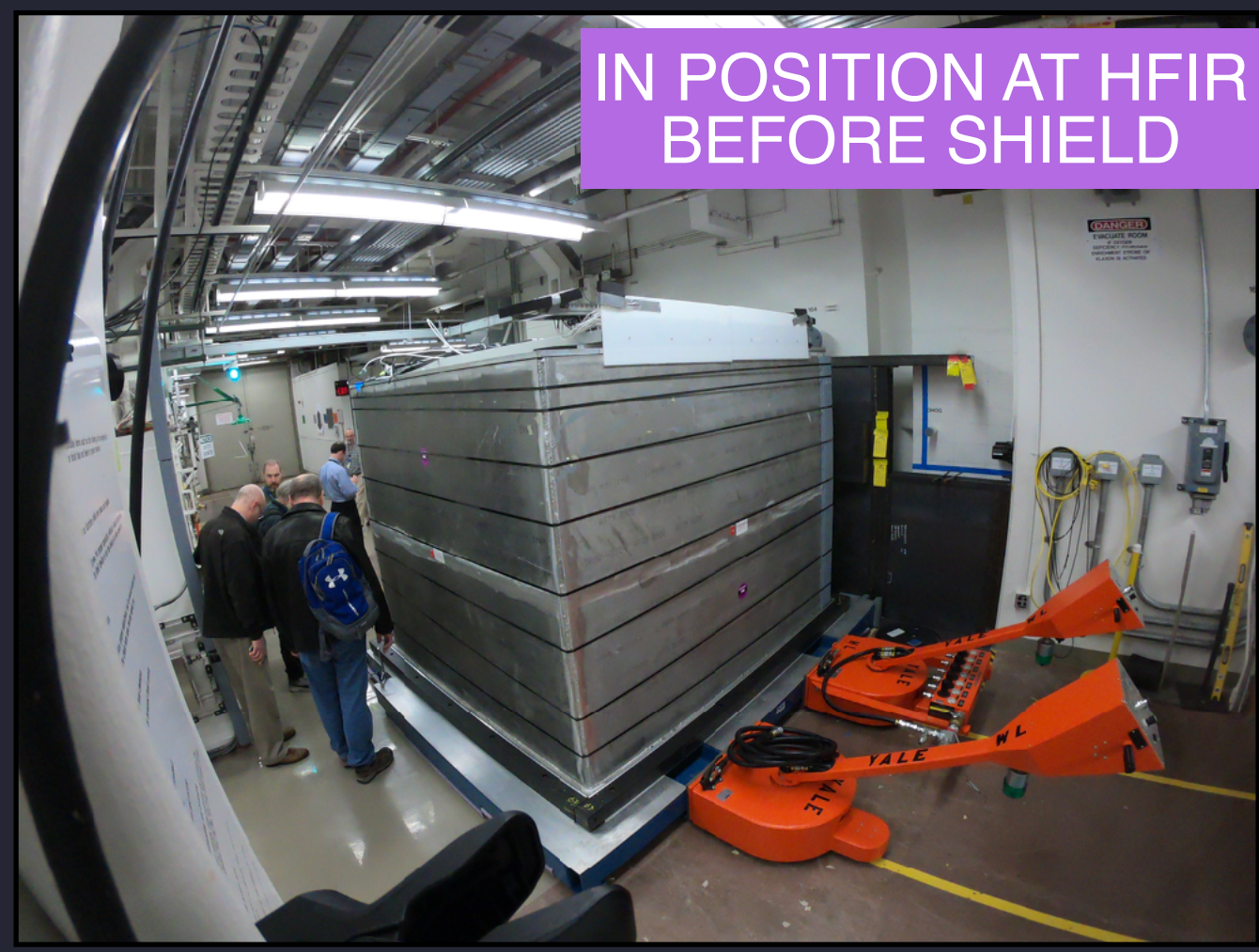


DEC 2017 - JAN 2018
DRY COMMISSIONING AT YALE

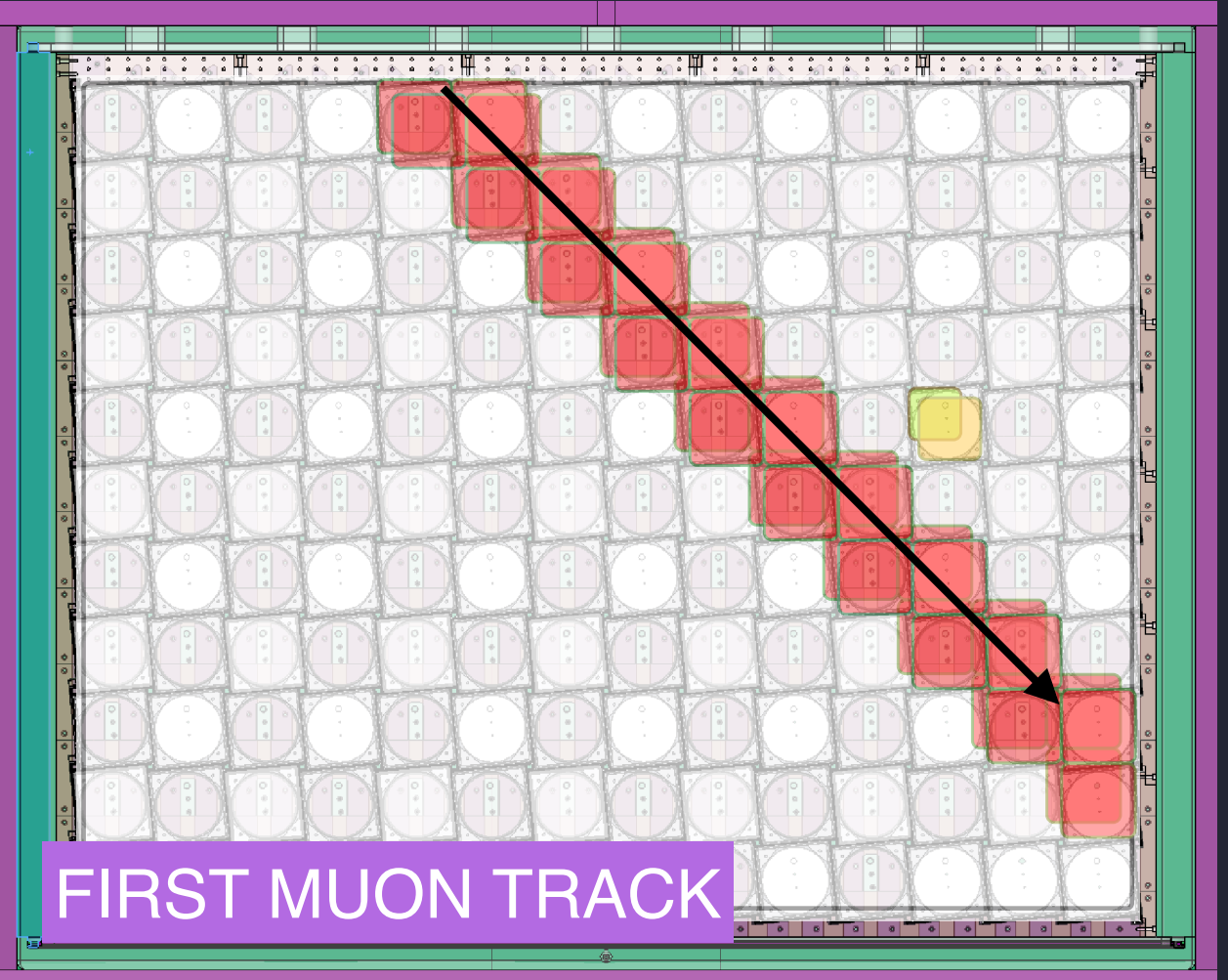
FEBRUARY 2018
ARRIVAL AT ORNL



IN POSITION AT HFIR
BEFORE SHIELD



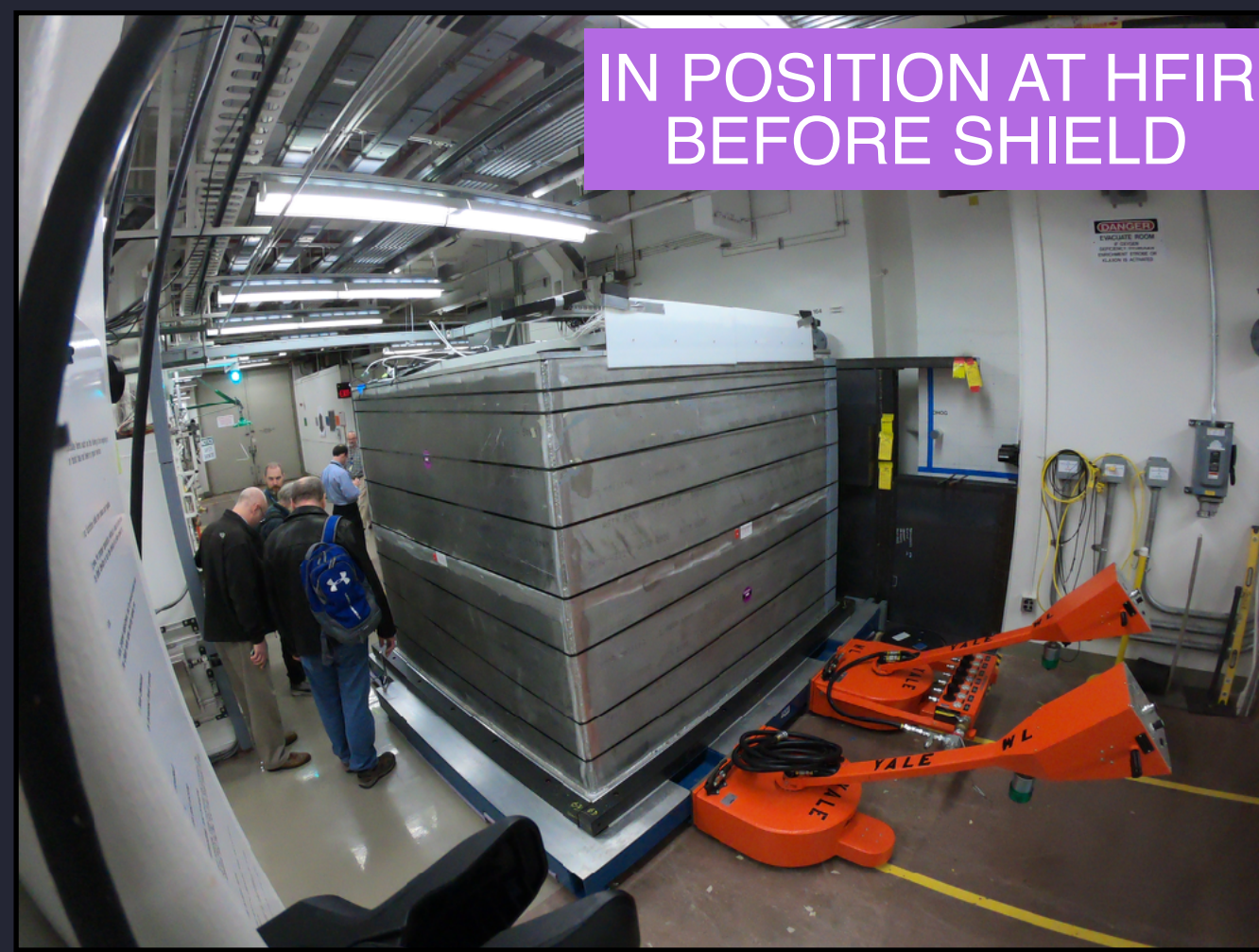
FILLING FROM
MIXING TANK



FIRST MUON TRACK



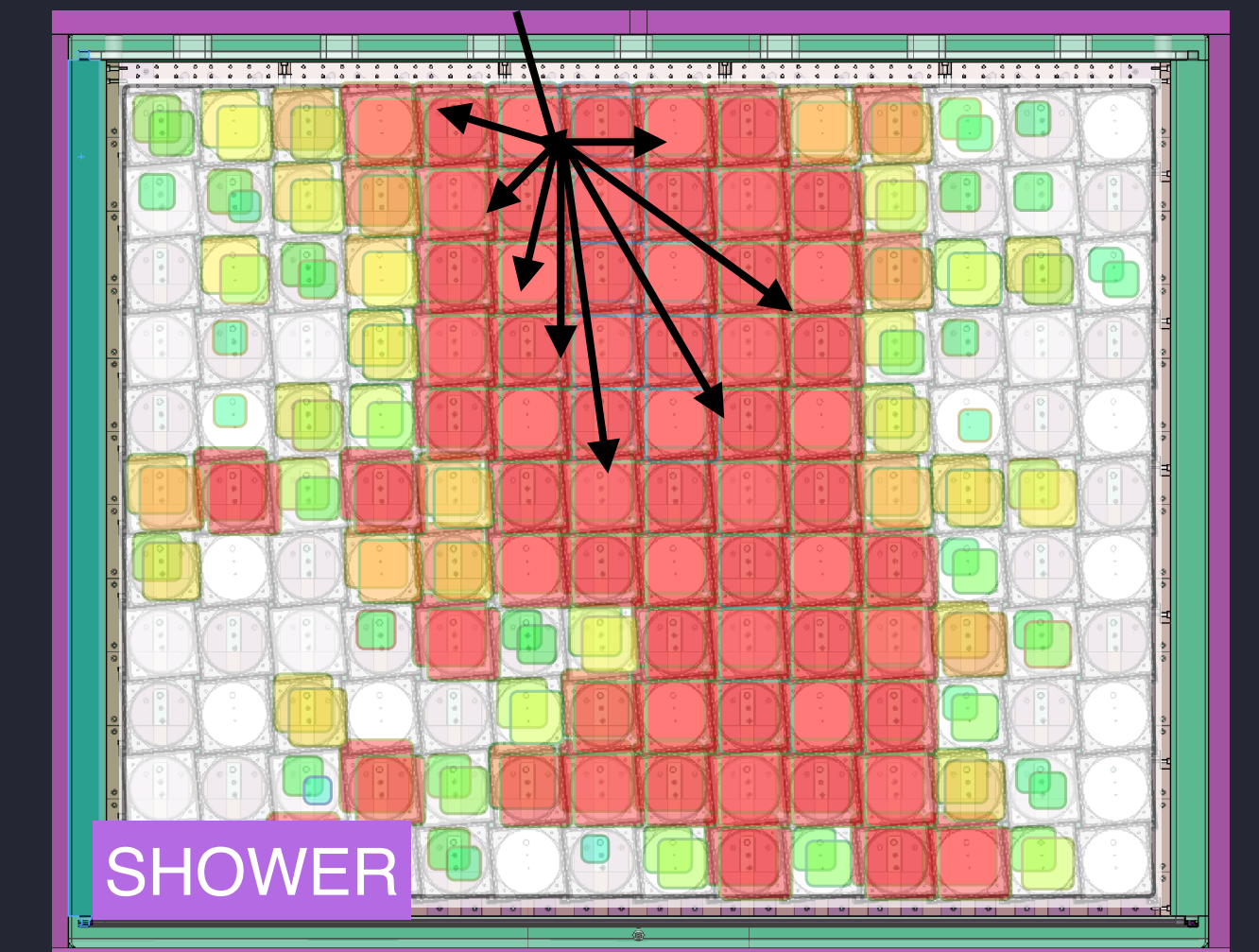
FEBRUARY 2018
ARRIVAL AT ORNL



IN POSITION AT HFIR
BEFORE SHIELD



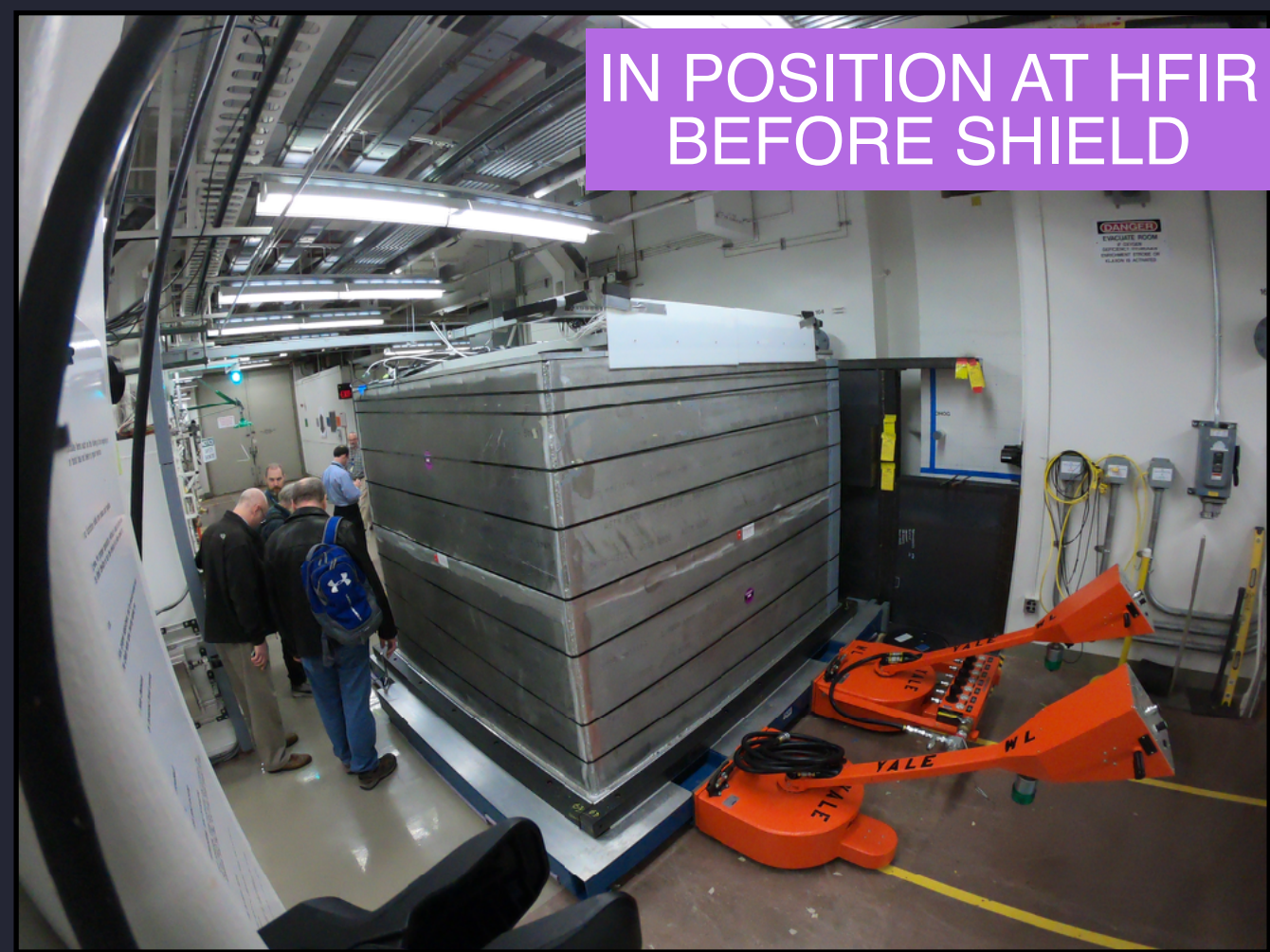
FILLING FROM
MIXING TANK



SHOWER



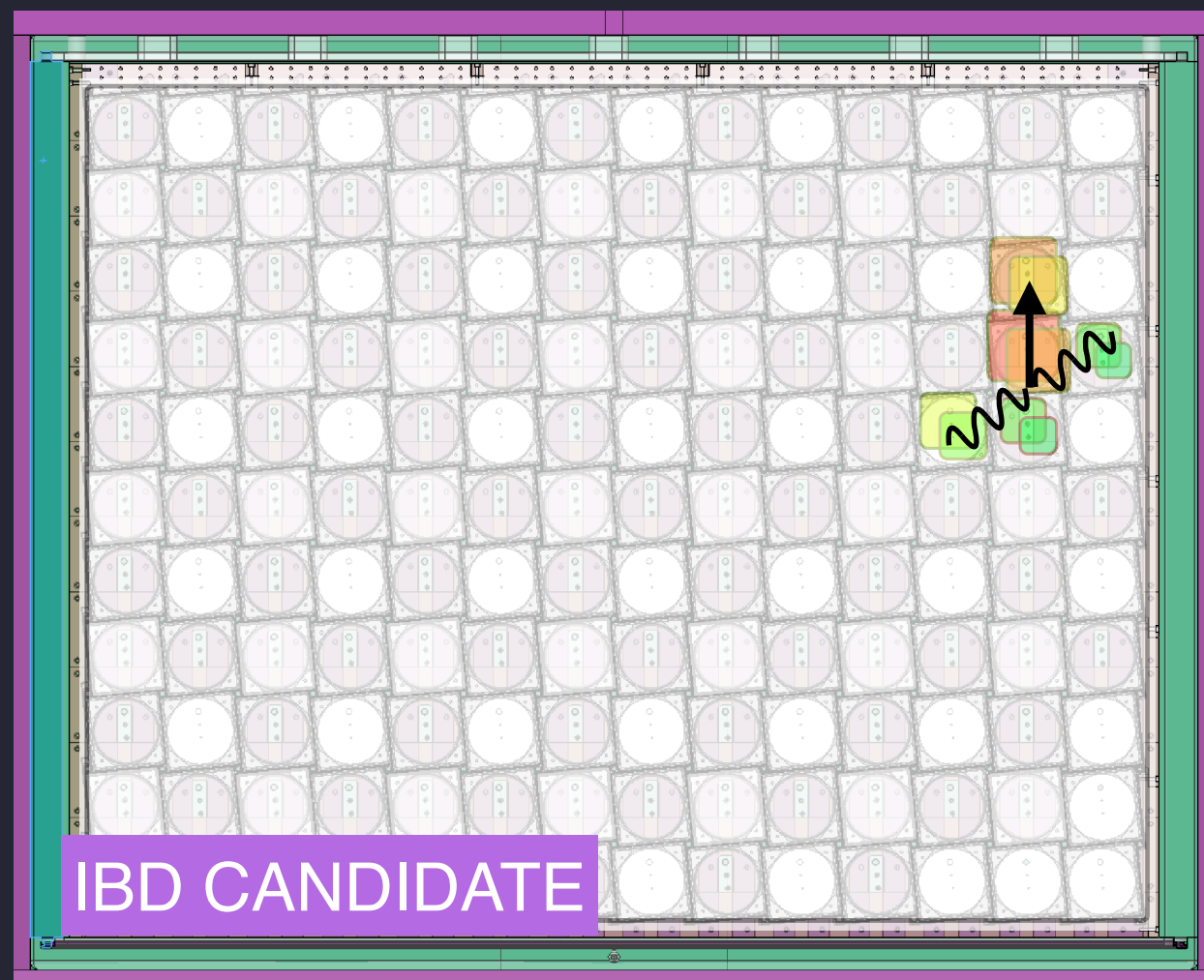
FEBRUARY 2018
ARRIVAL AT ORNL



IN POSITION AT HFIR
BEFORE SHIELD

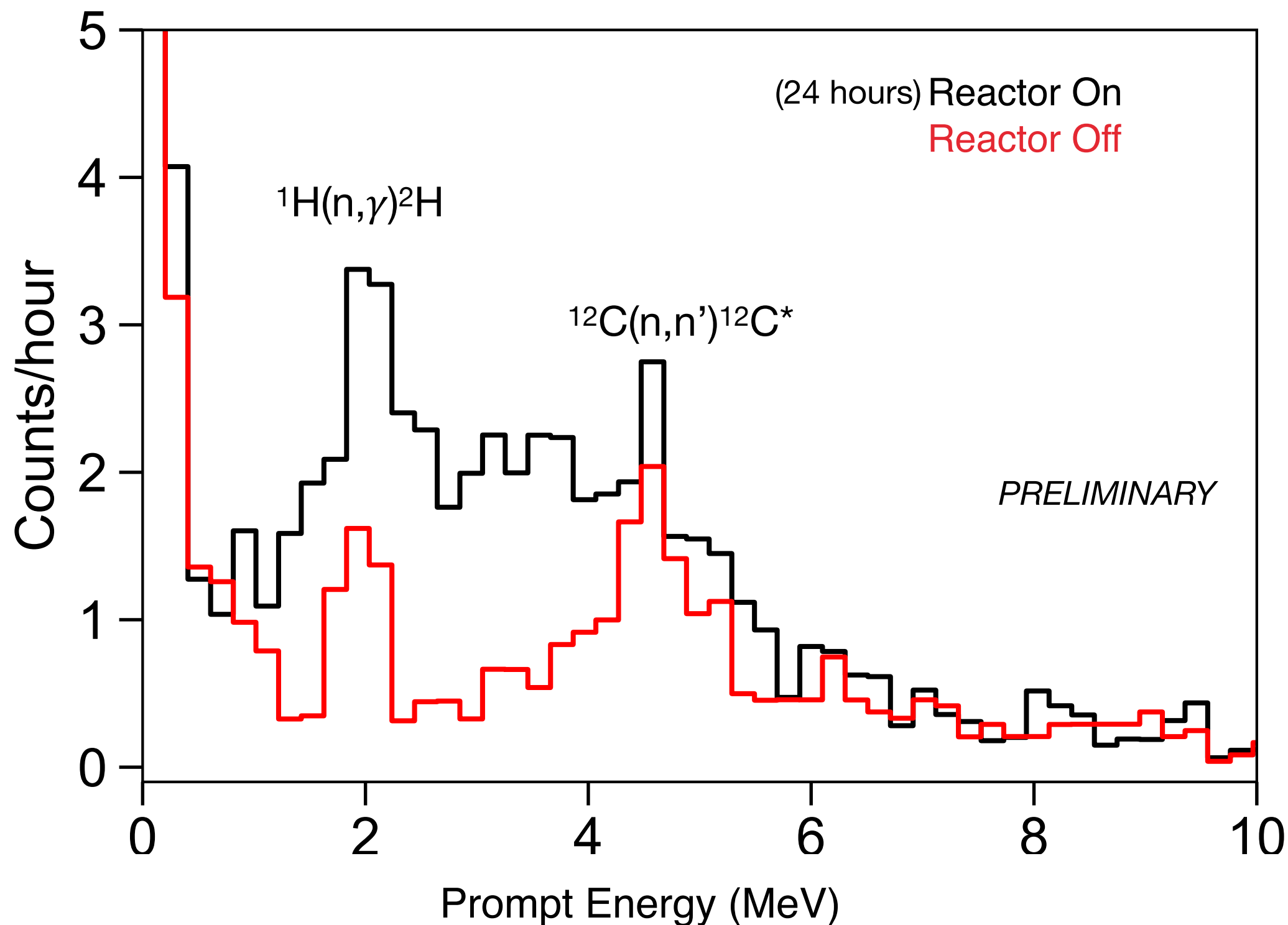


FILLING FROM
MIXING TANK



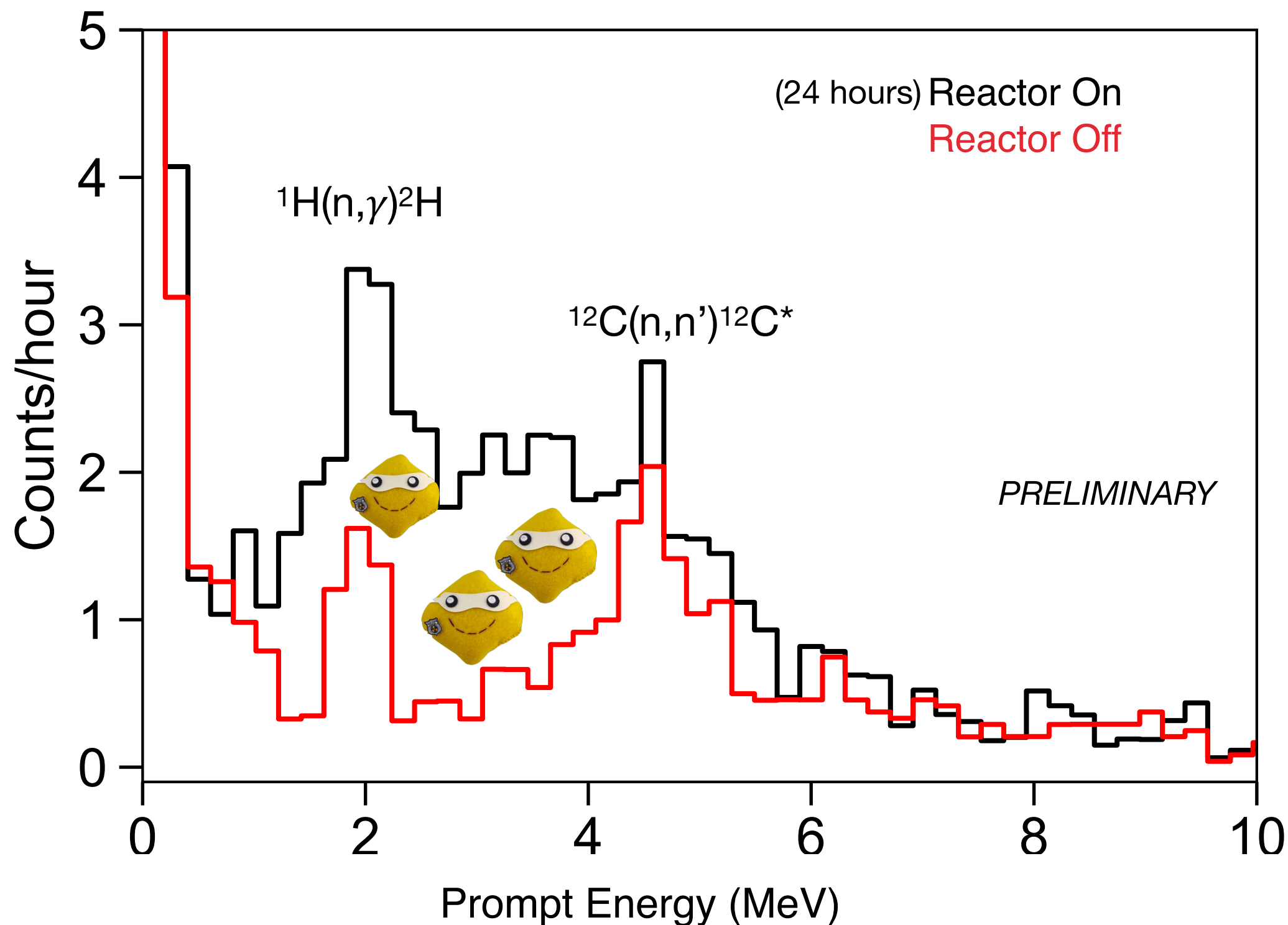
IBD CANDIDATE

Within a few hours.. neutrinos!



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

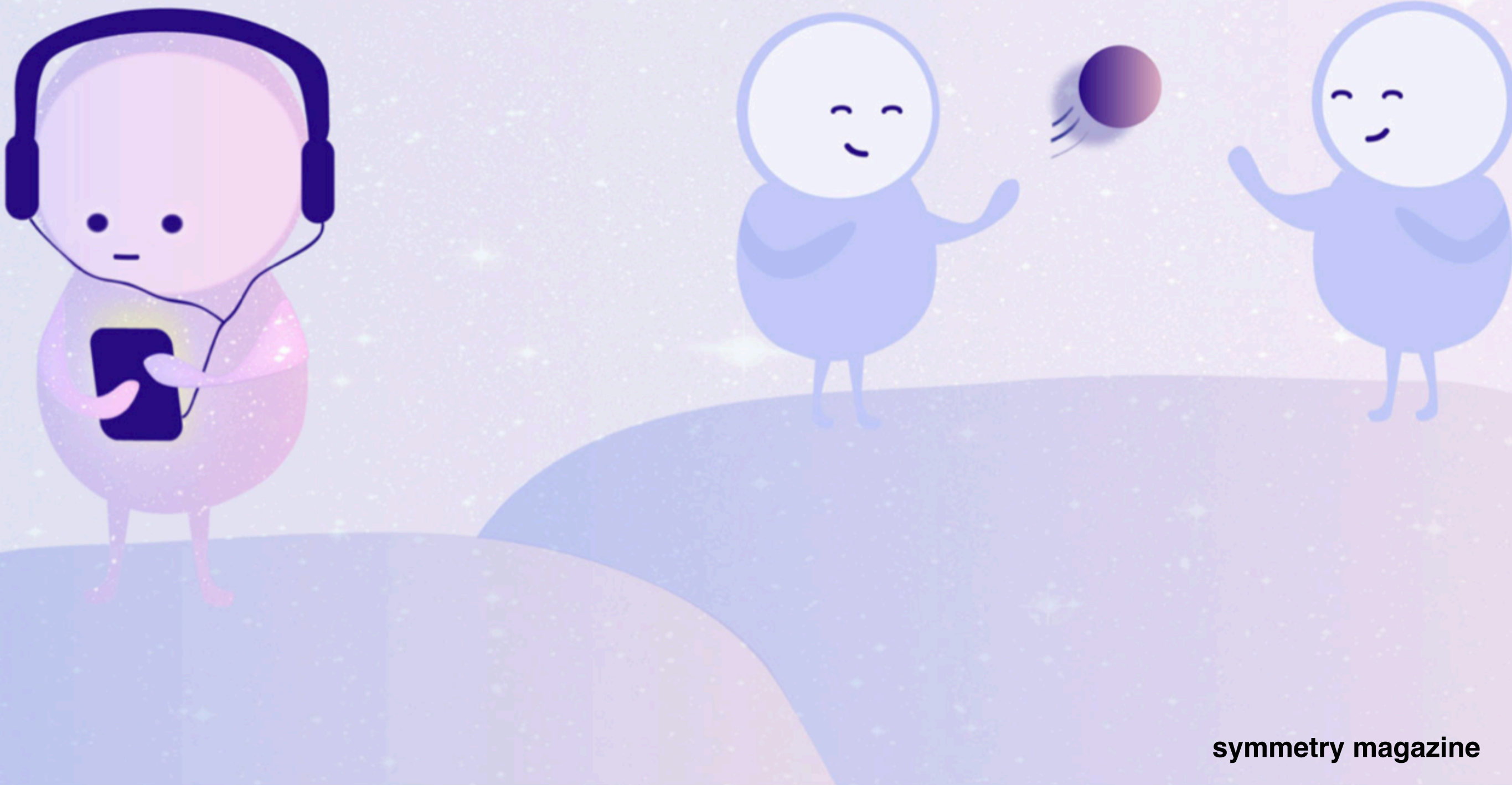
Within a few hours.. neutrinos!



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

Search for

STERILE NEUTRINOS

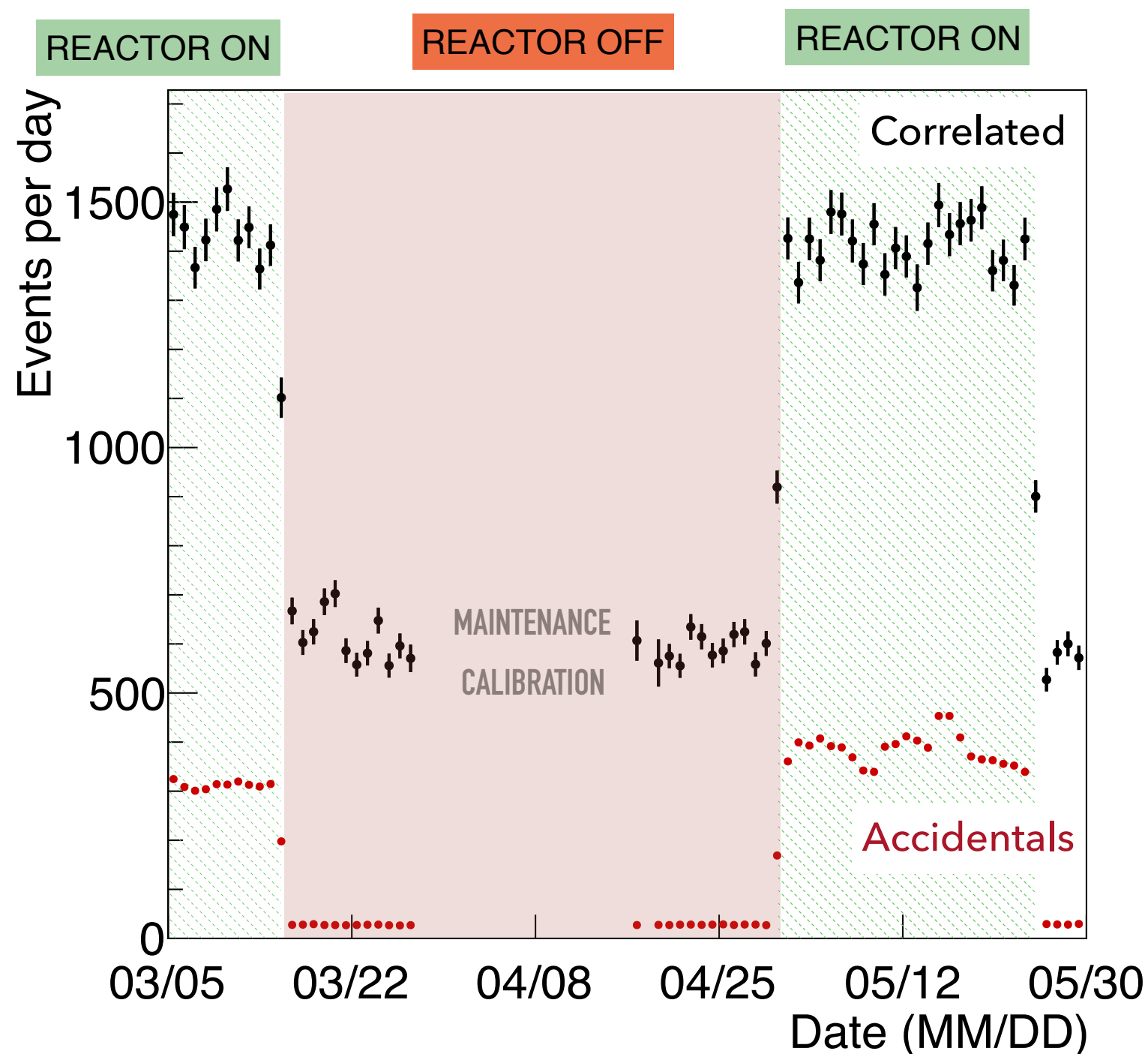


Oscillation data as reactor monitor

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

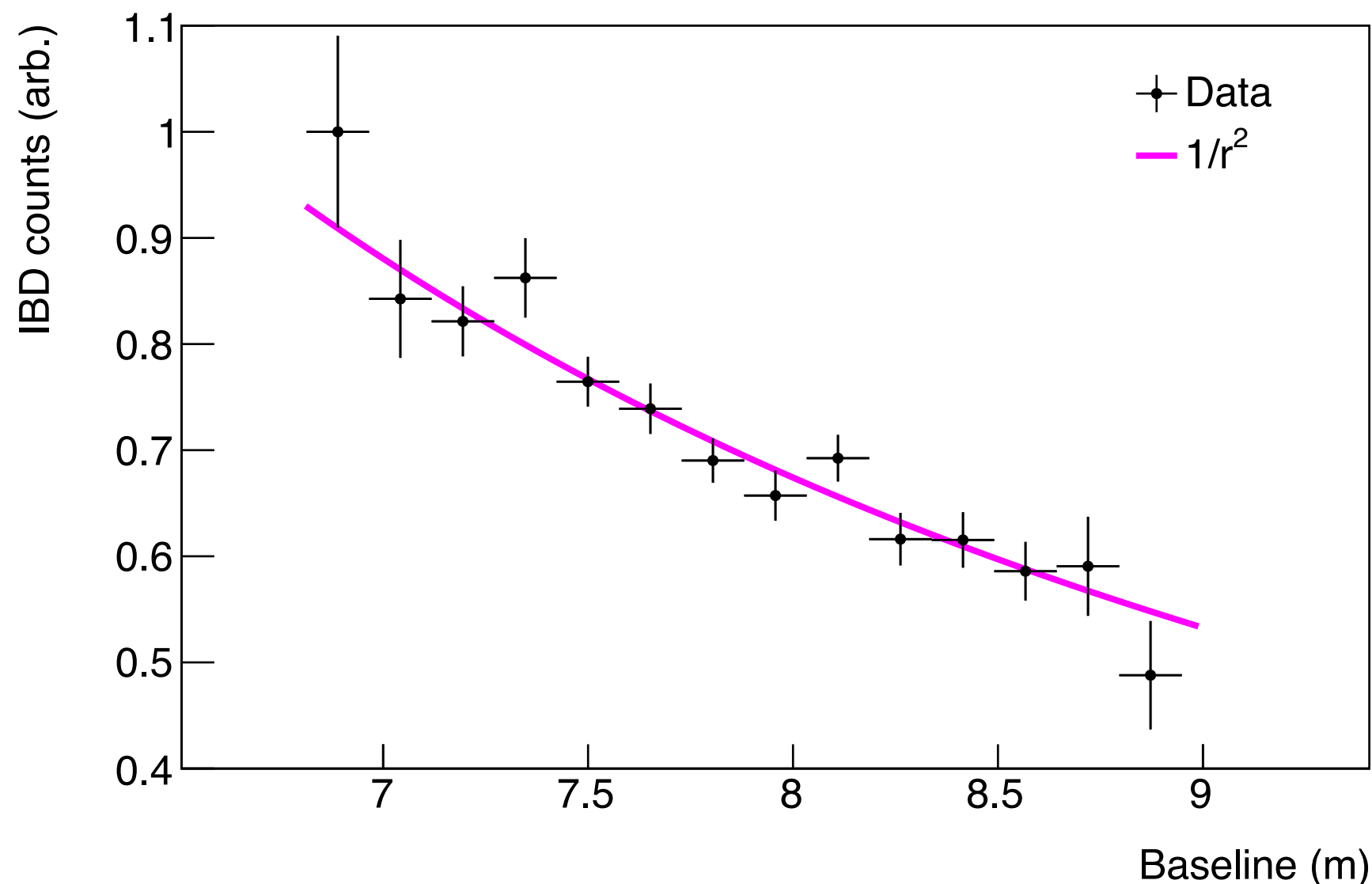
From 0.8-7.2 MeV prompt:

- 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

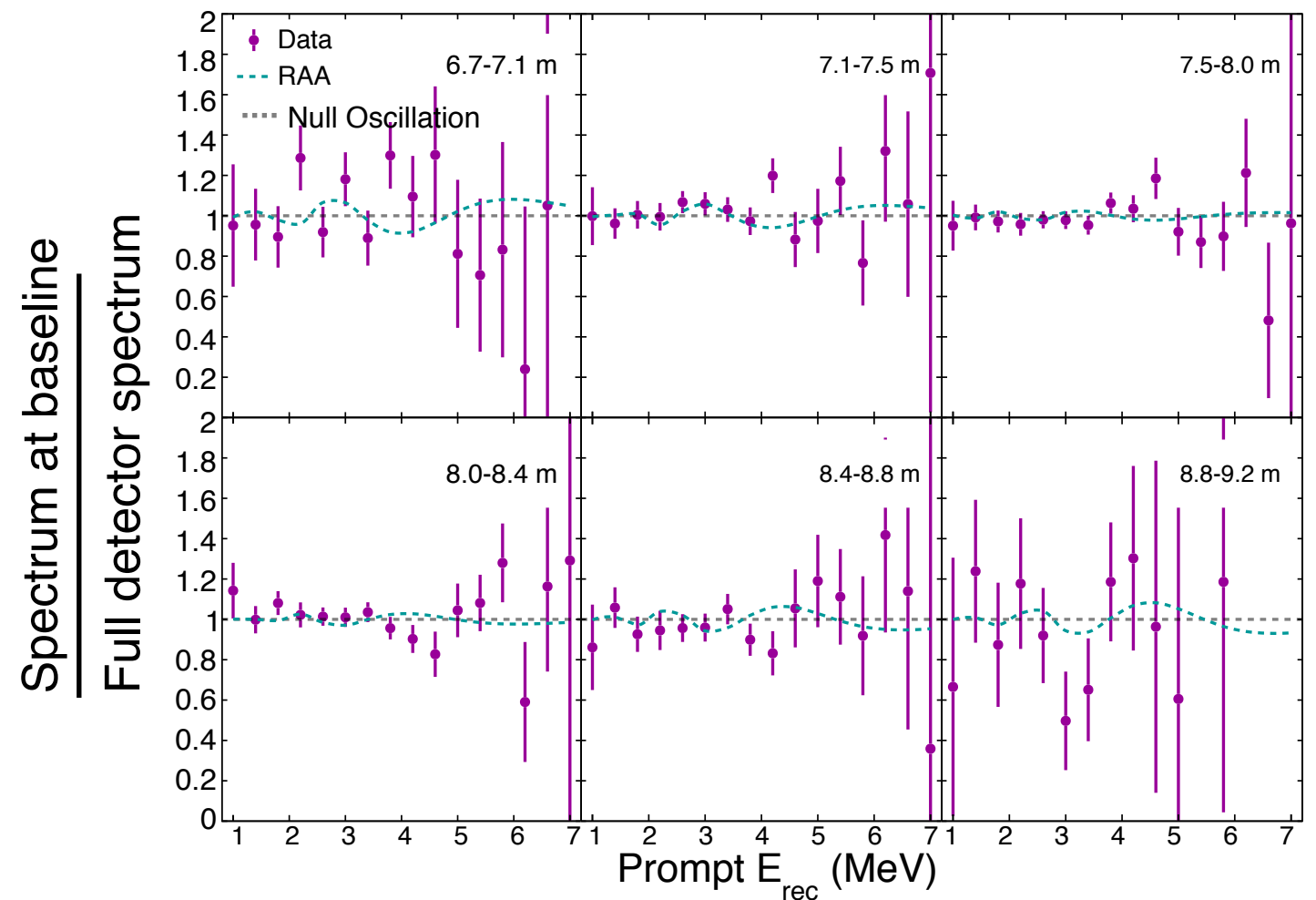
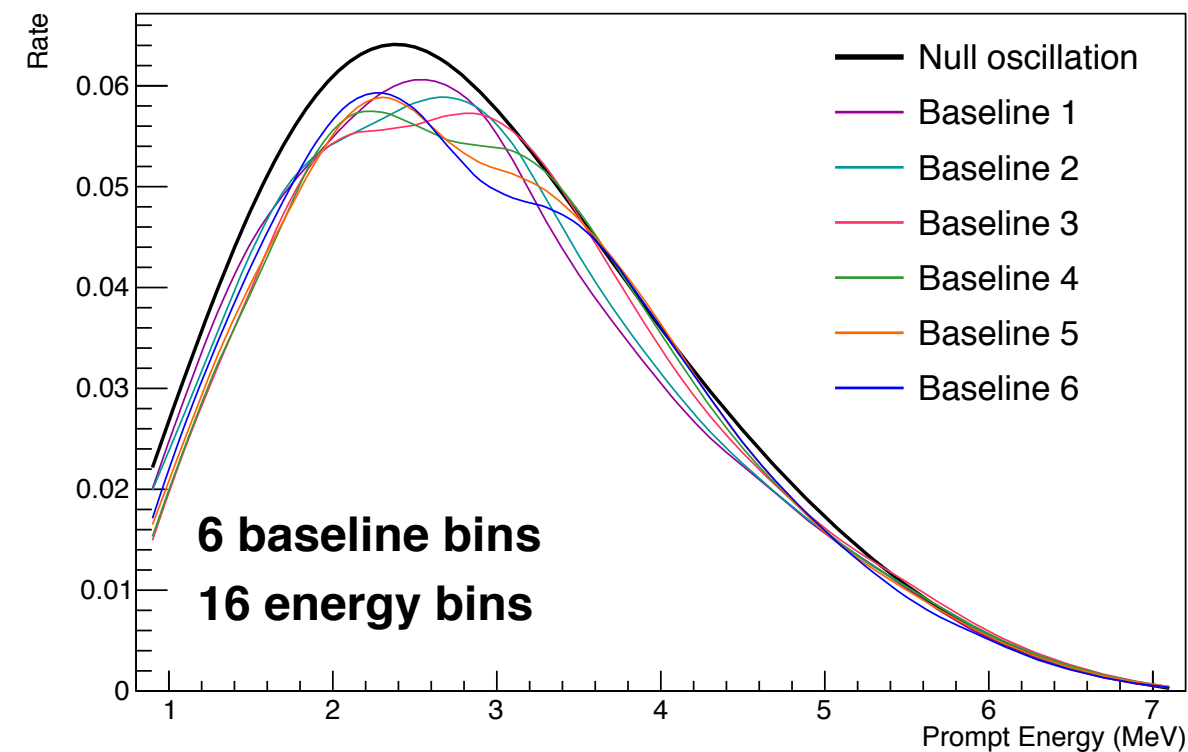
IBD rate vs baseline



- 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)

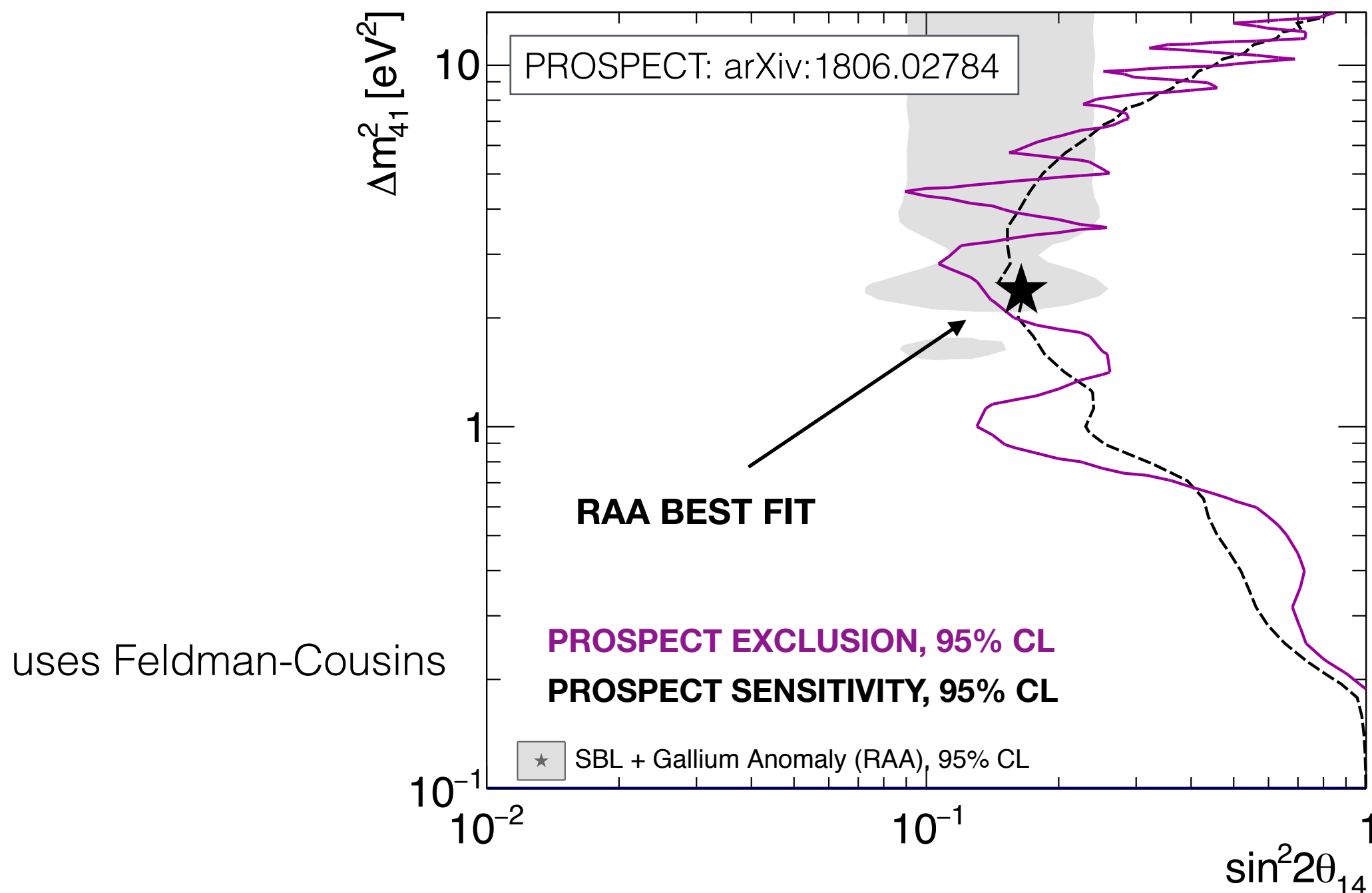
illustration of baseline dependent oscillation



- 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**

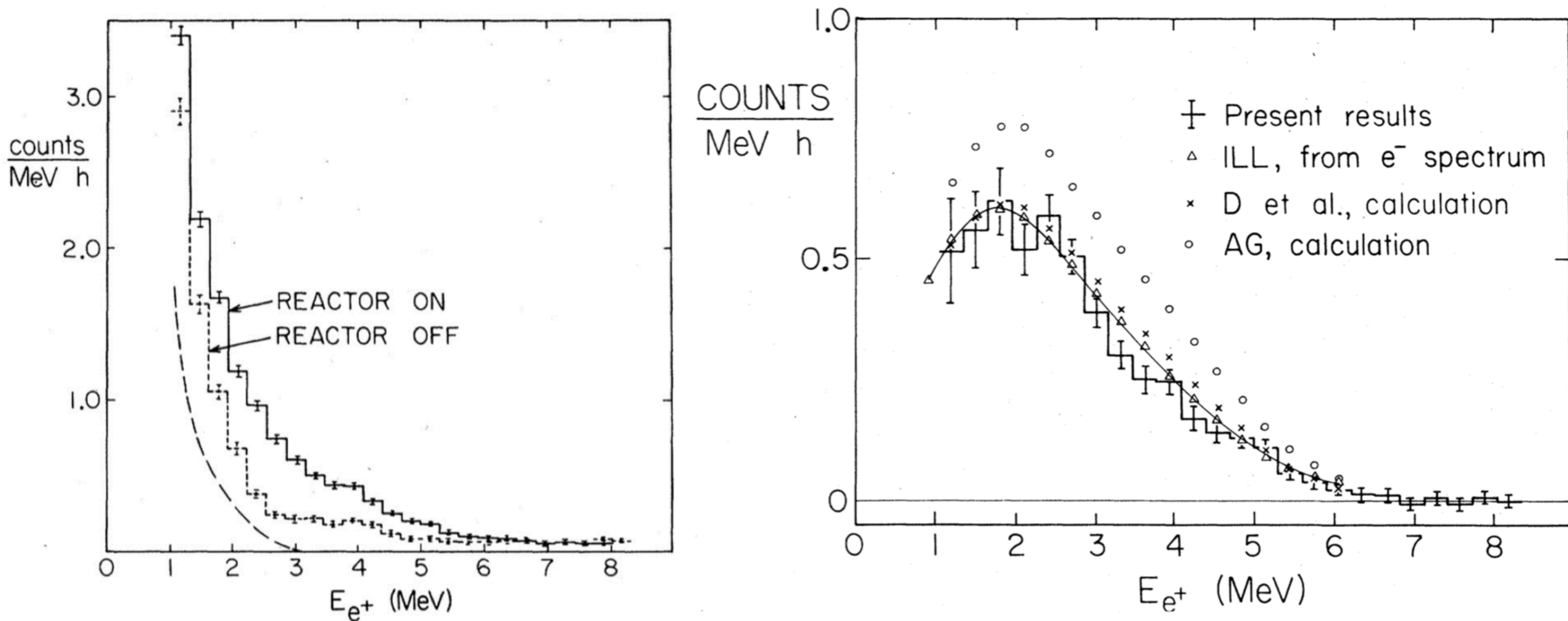
Sterile neutrino sensitivity and exclusion

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



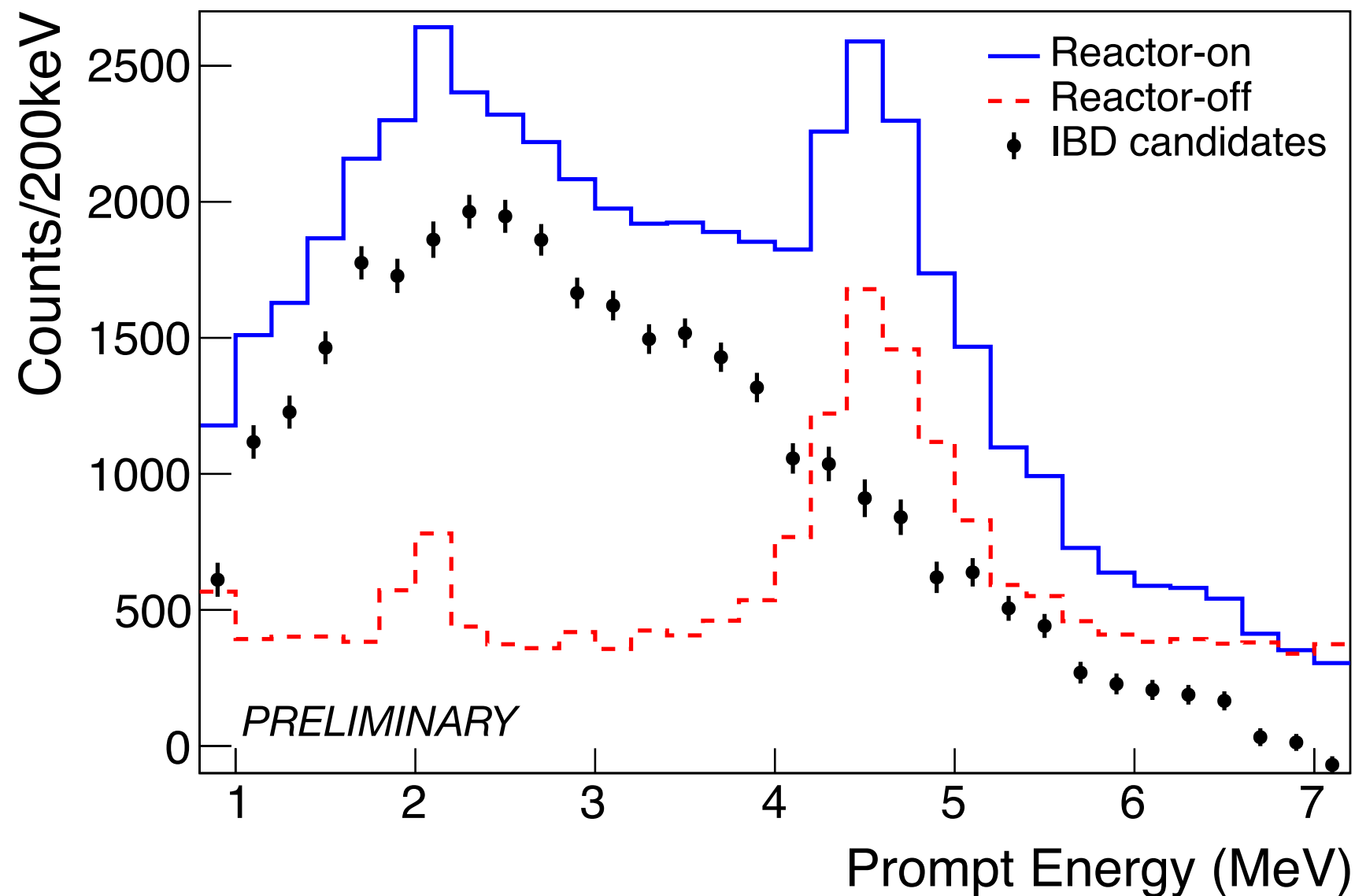
first oscillation result: disfavors RAA best-fit point at >95% (2.2 σ)

Measurement of ^{235}U antineutrino spectrum



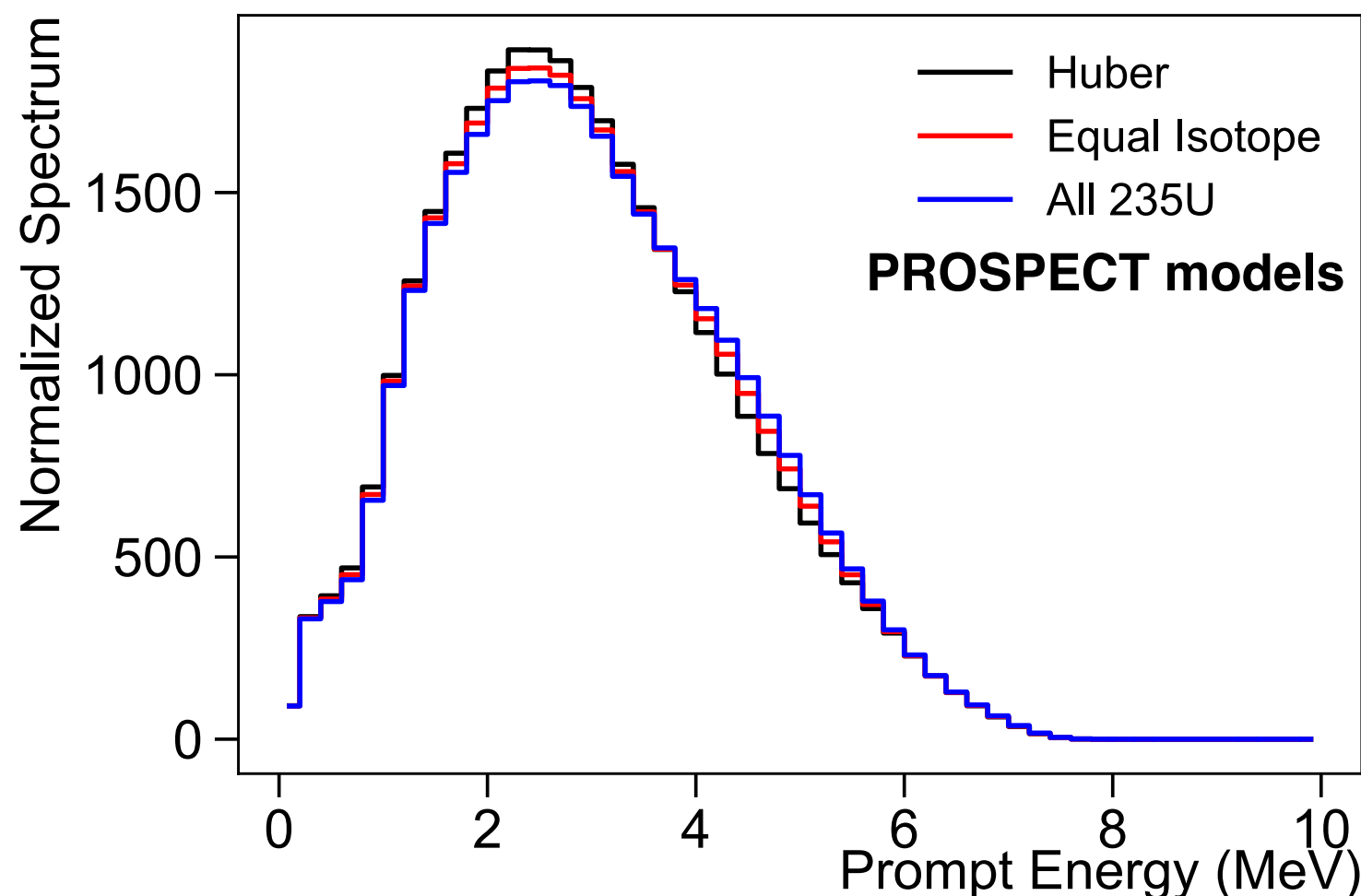
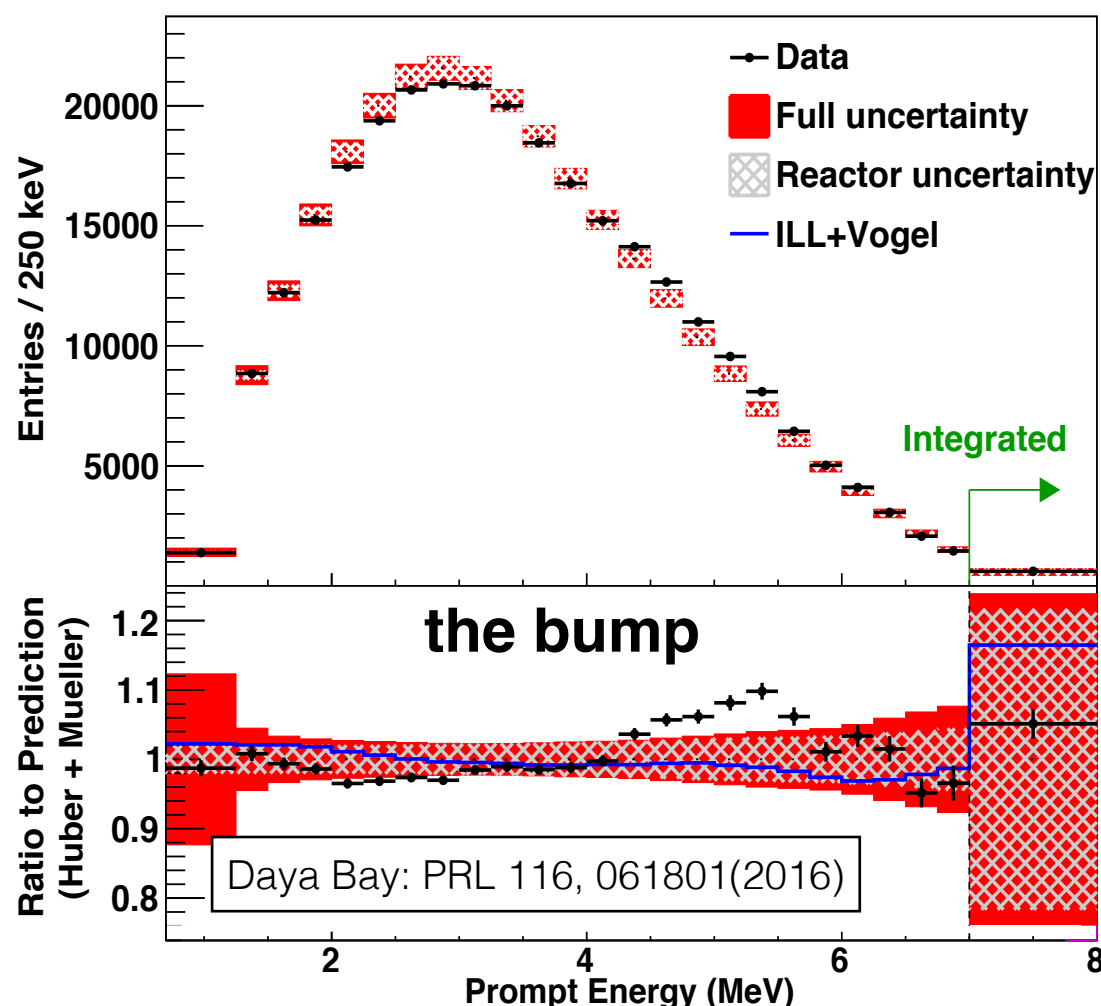
only existing measurement from 1981 ILL experiment, 5000 events

World leading ^{235}U antineutrino spectrum



- 40.3 days reactor-on, 37.8 days reactor-off exposure
- ~31,000 IBDs detected at 4.5%/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



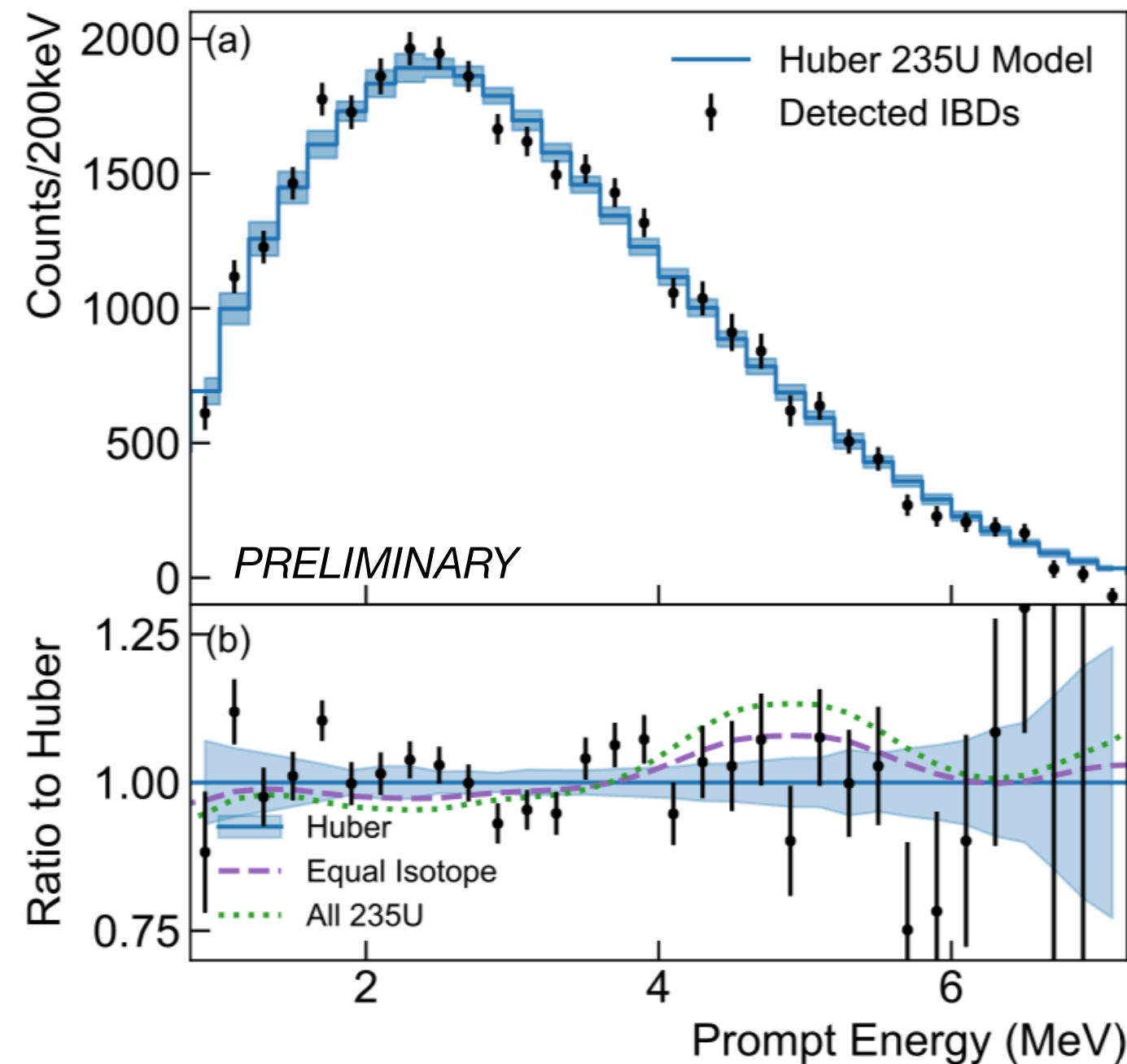
Data-based hypotheses to explain physics observed at power reactors:

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



Huber hypothesis (standard):

- $\chi^2/\text{ndf} = 52.7/31$

Equal isotope hypothesis:

- $\chi^2/\text{ndf} = 53.2/31$

All ^{235}U hypothesis:

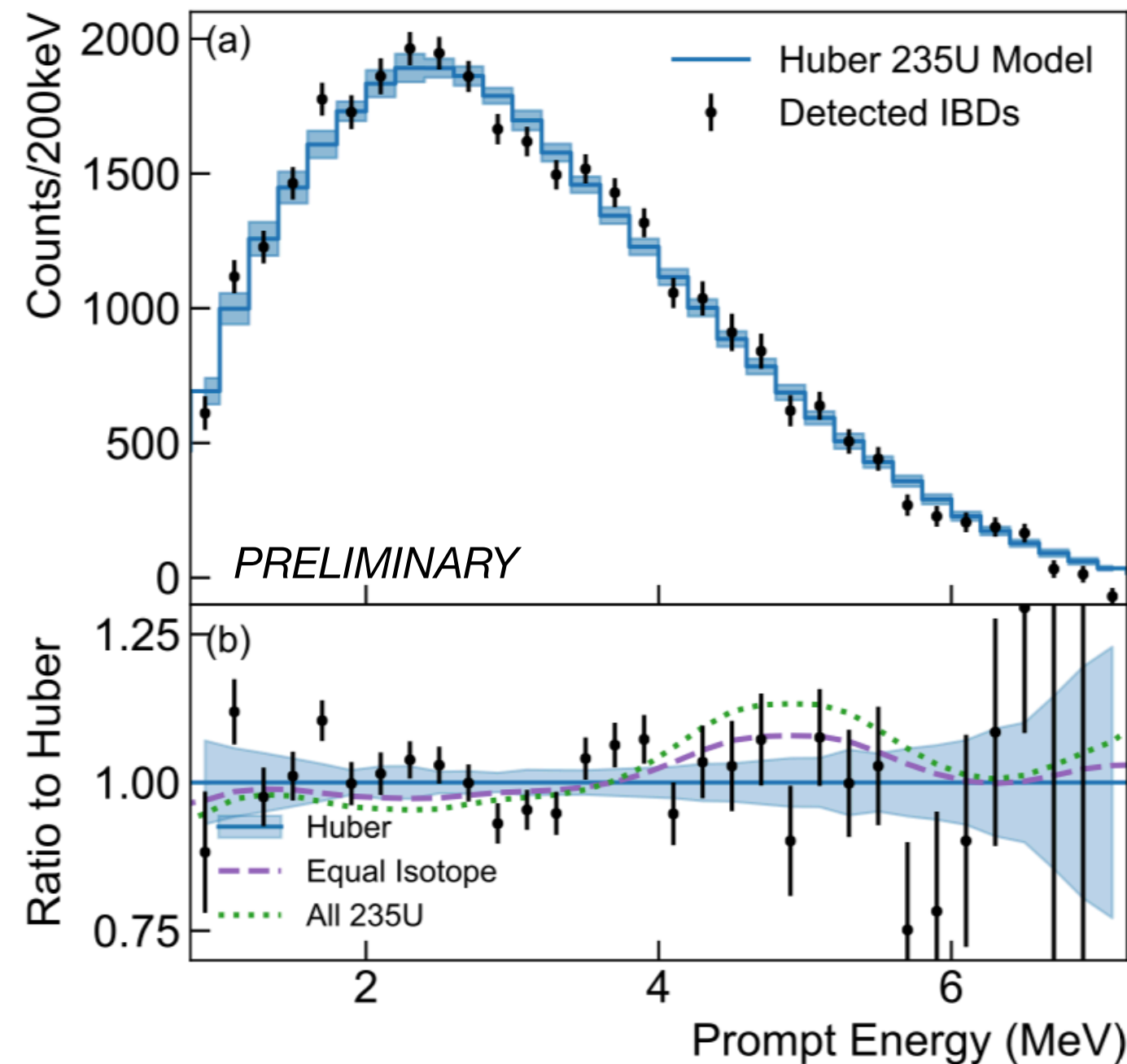
- $\chi^2/\text{ndf} = 60.2/31$

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



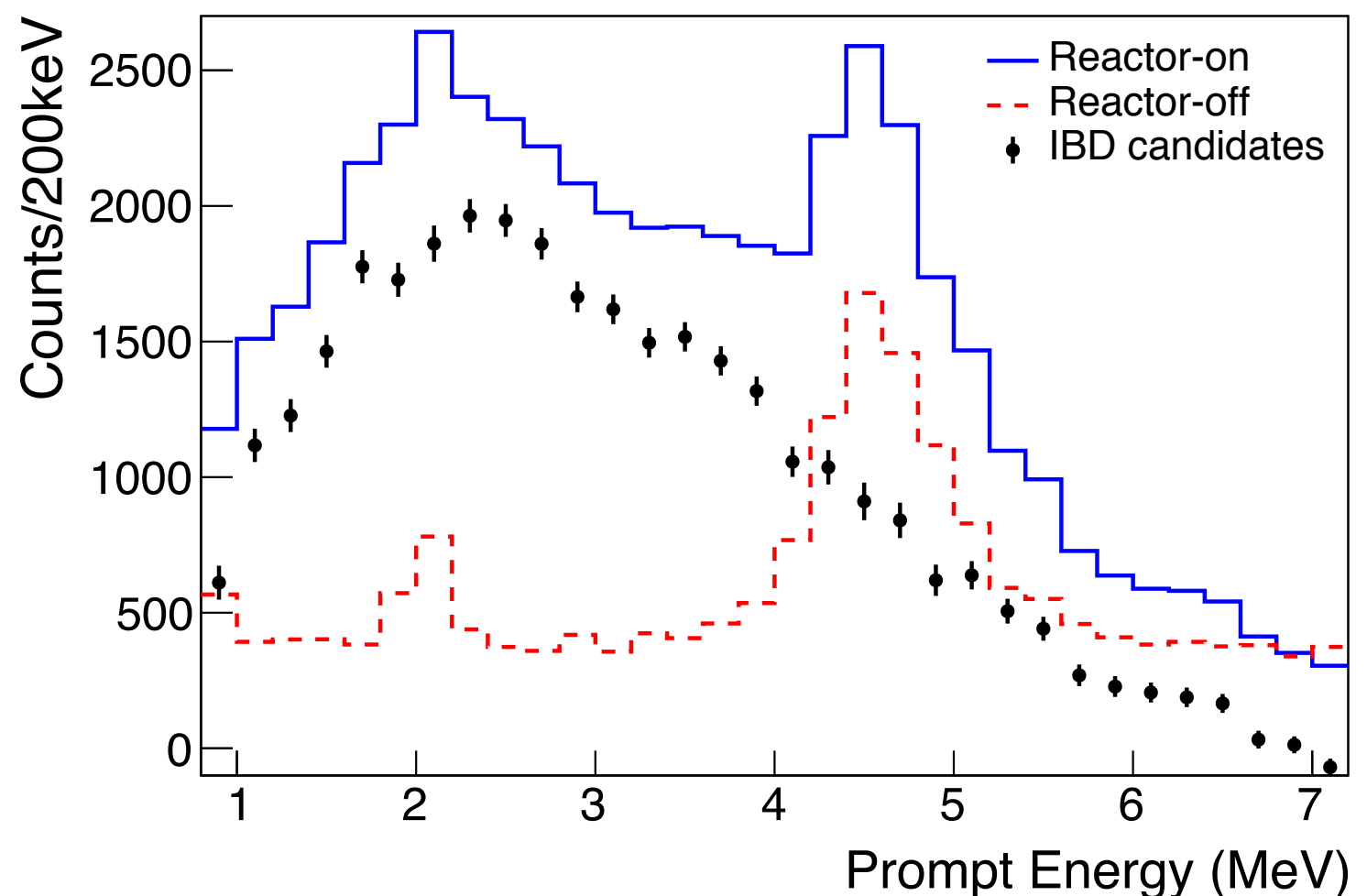
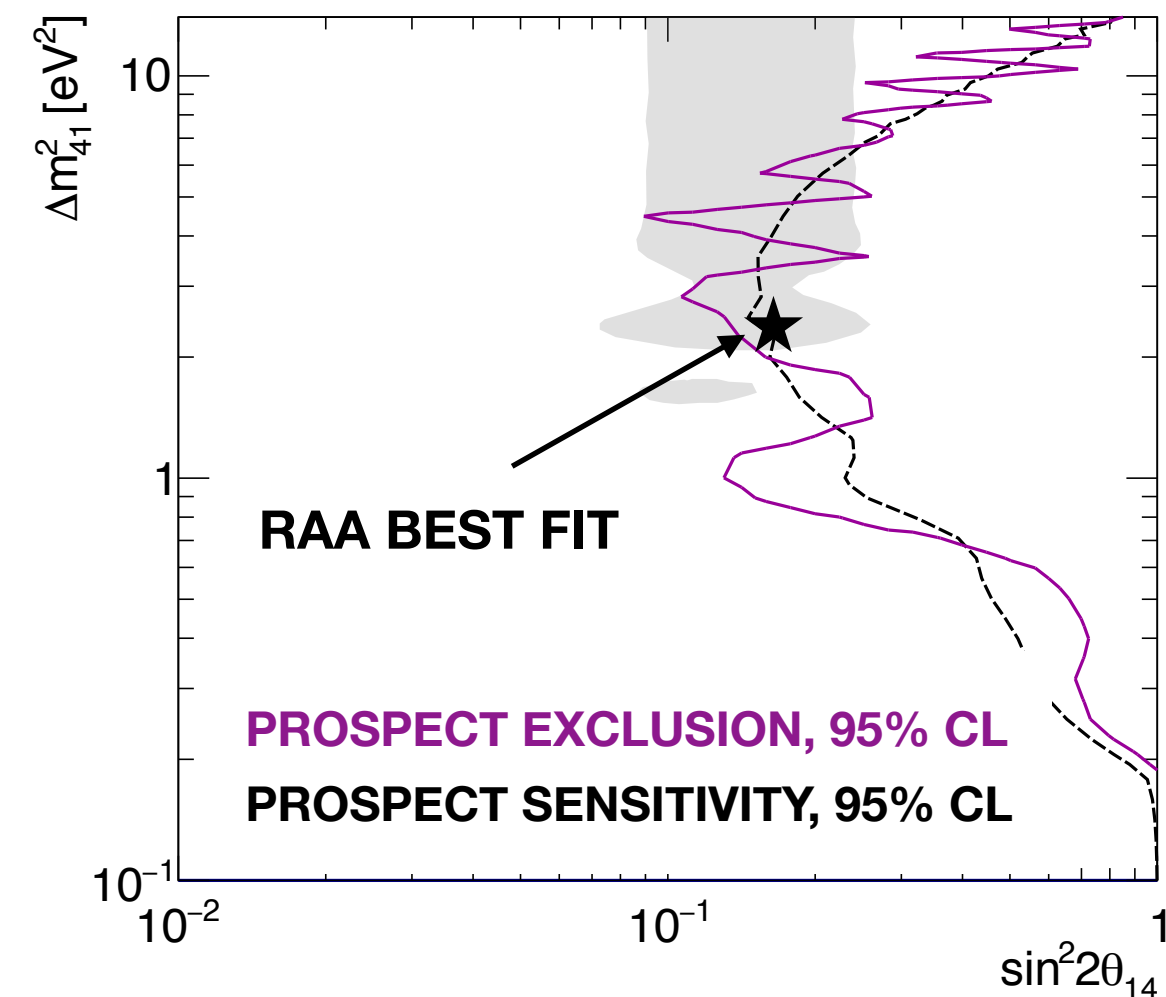
- if all of the “bump” was from ^{235}U , expect $\sim 20\%$ effect, we do not see it
- *implies some fraction of excess comes from other isotopes, not solely ^{235}U*
- current spectrum is statistics limited and cannot determine if it is a problem with all isotopes or non- ^{235}U

*shape only comparisons

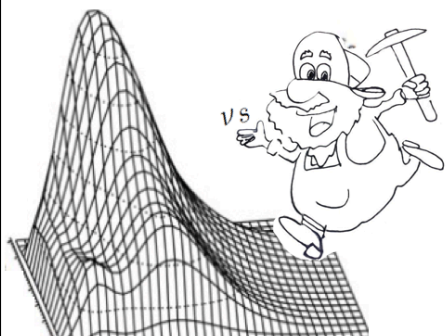
first spectrum result: disfavors the all ^{235}U hypothesis at 3σ

PROSPECT_ν : 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



PROSPECT

