Tradeoff between statistics and systematics for a PROSPECT-I absolute flux measurement

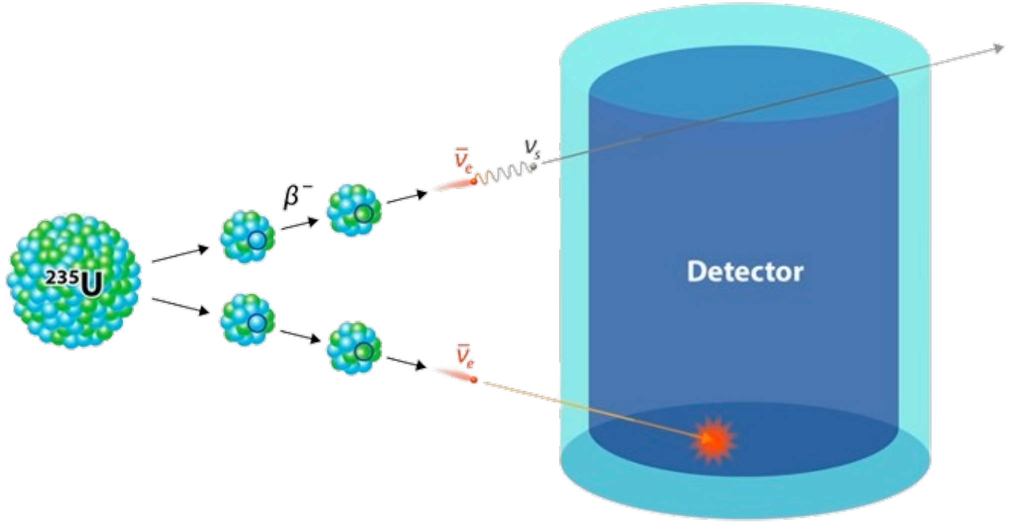
2024 MTV Workshop

March 26, 2024

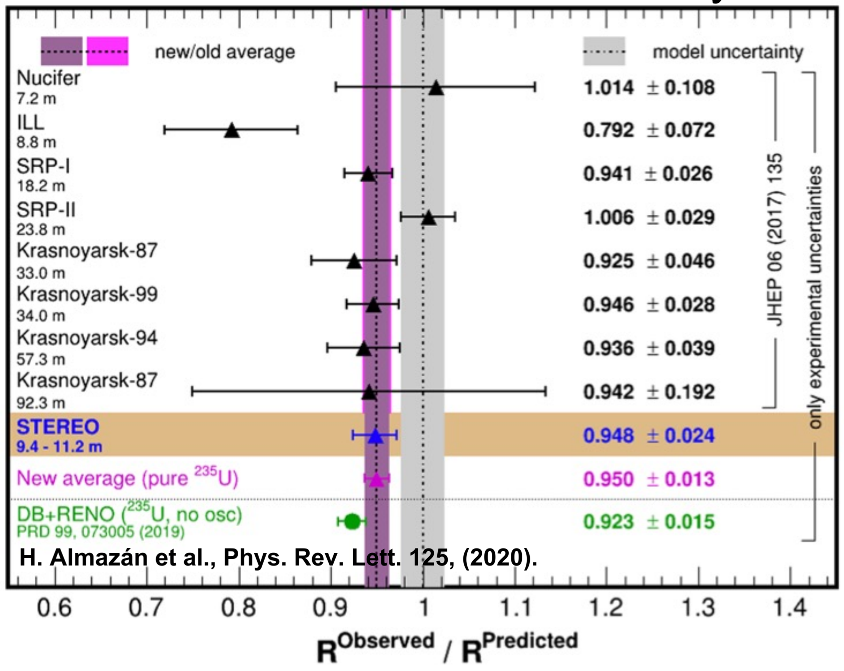
Paige Kunkle
Graduate student, Boston University
Professor Jelena Maricic
University of Hawaii at Manoa

Introduction and motivation

- Neutrinos are produced from beta decay of fission fragments inside reactor core
- They interact weakly with matter
    - Cannot be shielded or spoofed
    - Can be used to monitor nuclear reactor status, thermal power, and fissile inventory in real time with a suitable detector
- We need precise information about neutrino flux
    - Measured flux and predicted flux do not agree
    - Are flux predictions incorrect?

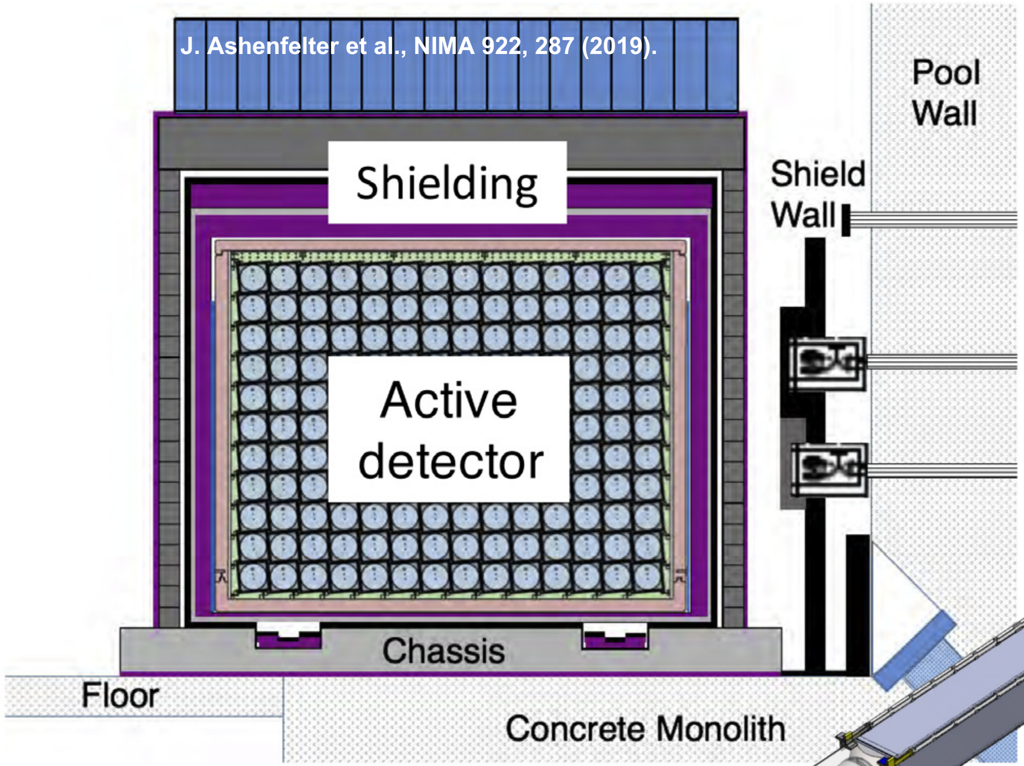


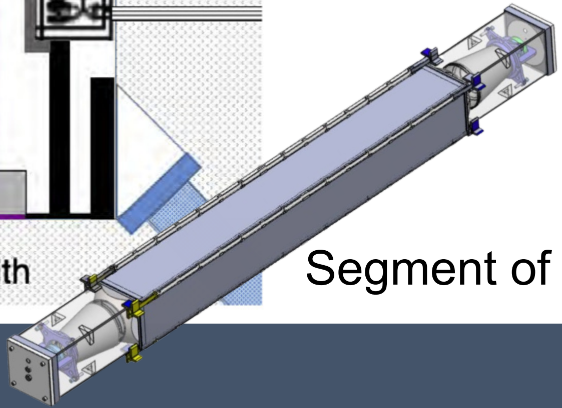
“Reactor Antineutrino Anomaly”

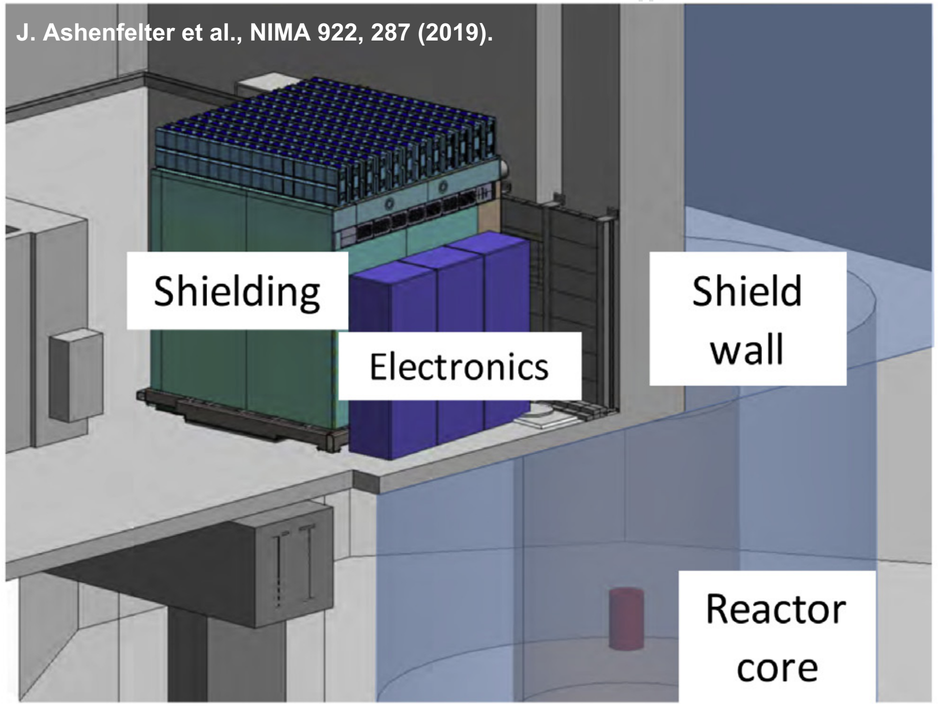


Technical approach

- Precision Reactor Oscillation and Spectrum Experiment
  - Segmented liquid scintillator target with layered shielding
  - Inverse beta decay (IBD) interactions
  - Double PMT readout




Segment of LiLS

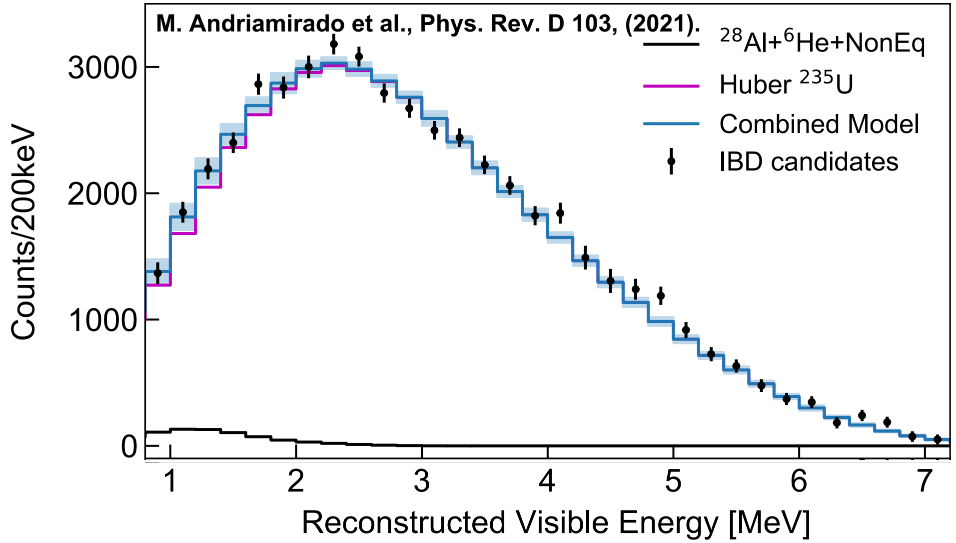


- High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL)
  - 93% ^{235}U fuel
  - 85 MWth power
  - Compact core
  - Large $\bar{\nu}_e$ flux in ~few MeV range

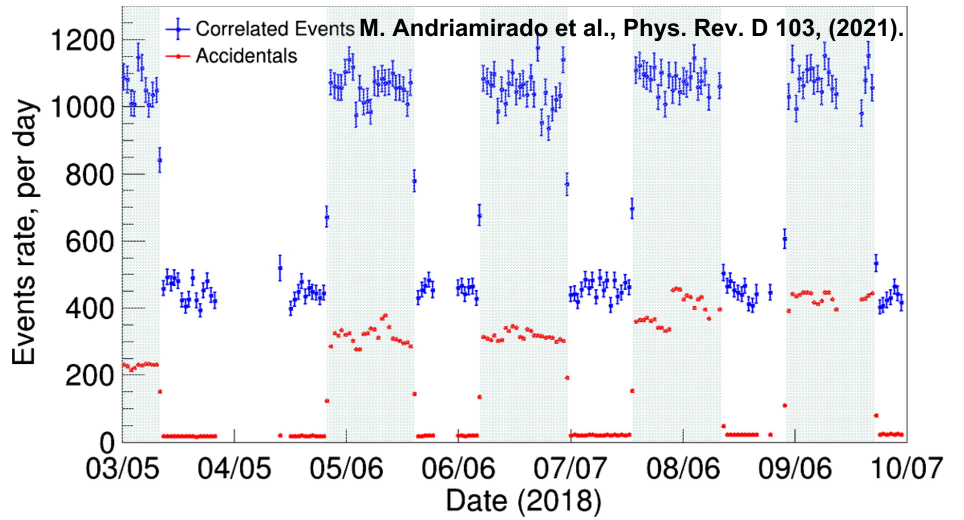
Mission relevance

- IAEA reactor safeguards are limited in scope and depth
- Short-baseline neutrino detectors offer:
  - Less intrusive option to verify reactor operations
  - Reliable + constant monitoring technology
- We can accomplish this by precisely measuring neutrino flux from a research reactor
  - Pure ^{235}U core enables exploration of measured flux deficit
  - Directly translates to monitoring commercial reactors
- Uncertainties in existing neutrino flux production models may be improved based on high precision measurement of ^{235}U flux

PROSPECT measured $E_{\bar{\nu}_e}$ spectrum



HFIR daily neutrino rate



Defining absolute flux

- Observed IBD cross section per fission:

$$\sigma_f^{obs} = \frac{N^{obs}}{\frac{P_{th}}{\langle E_f \rangle} \frac{N_p}{4\pi L^2} \epsilon}$$

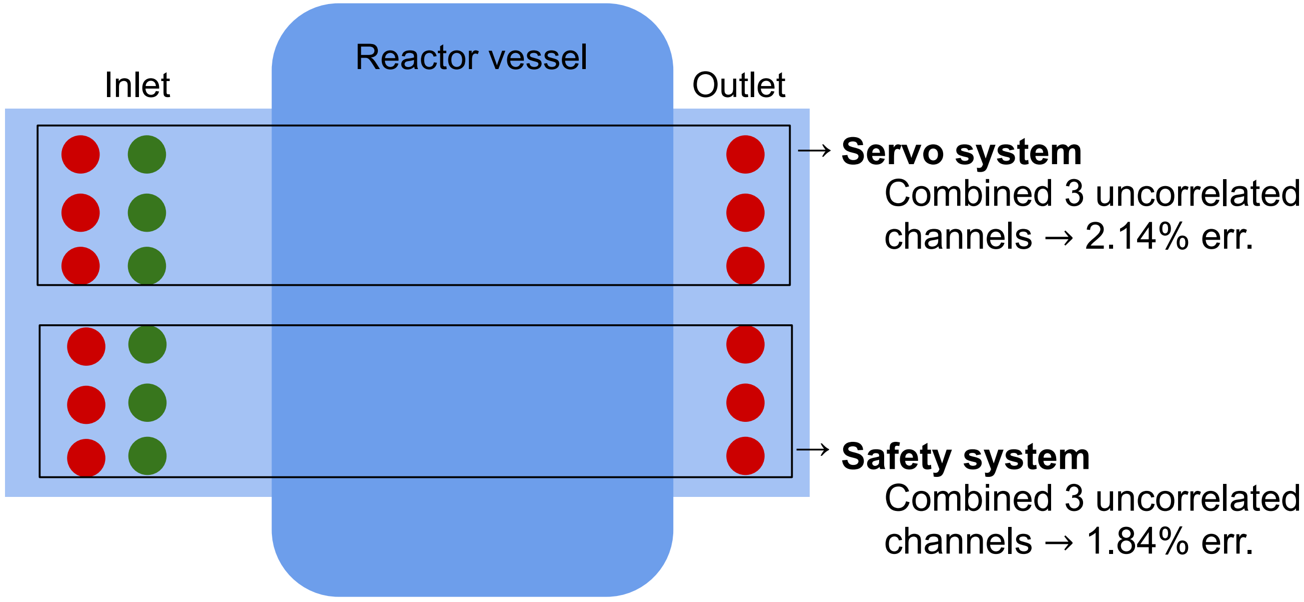
N^{obs} → Number of observed IBD candidates
P_{th} → Reactor thermal power
$\langle E_f \rangle$ → Energy released per fission
N_p → Number of protons in fiducial volume
L → Baseline
ϵ → Signal detection efficiency

- Total uncertainty on the flux measurement (σ_f^{obs}) is determined by propagating the uncertainty on each factor
  - PROSPECT has capability to compute HFIR's absolute flux with world-leading precision ~2.5%
  - High statistics → Leading uncertainties are the systematics

Determining number of fissions and targets

$$\sigma_f^{obs} = \frac{N^{obs}}{\frac{P_{th}}{\langle E_f \rangle} \frac{N_p}{4\pi L^2} \epsilon}$$

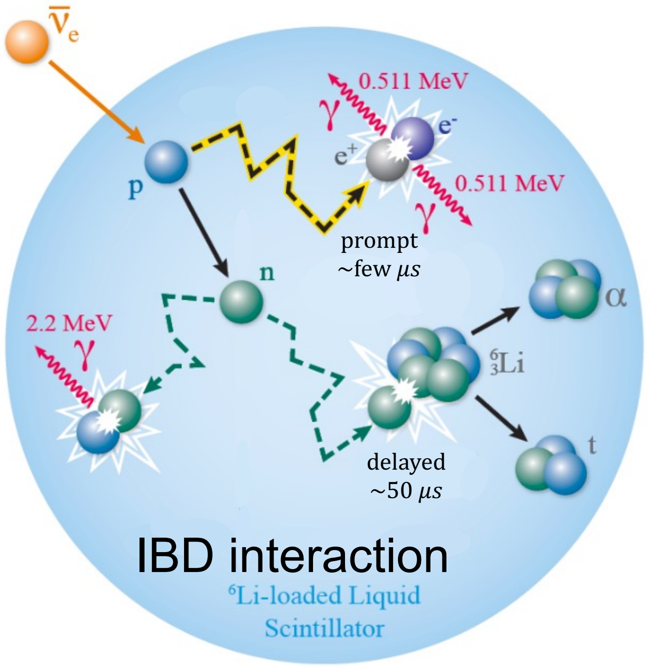
- Reactor thermal power: 1.40% uncertainty
  - Sensors in primary coolant loop monitor temperature and flow rate of coolant as it transports heat out of the core.



3 inlet + 3 outlet temperature sensors (RTDs) for each system

3 flow rate sensors (Venturi tubes) for each system

- Target density: ~1% uncertainty
  - Combustion measurements determine number of protons in scintillator active volume.

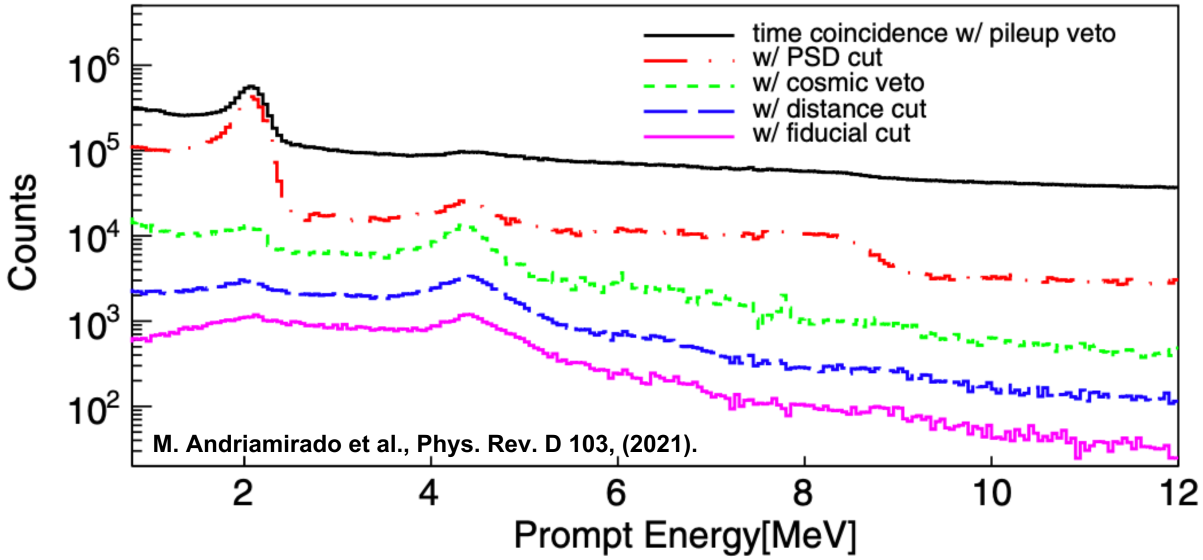


Statistics and detector baseline

$$\sigma_f^{obs} = \frac{N^{obs}}{\frac{P_{th}}{\langle E_f \rangle} \frac{N_p}{4\pi L^2} \epsilon}$$

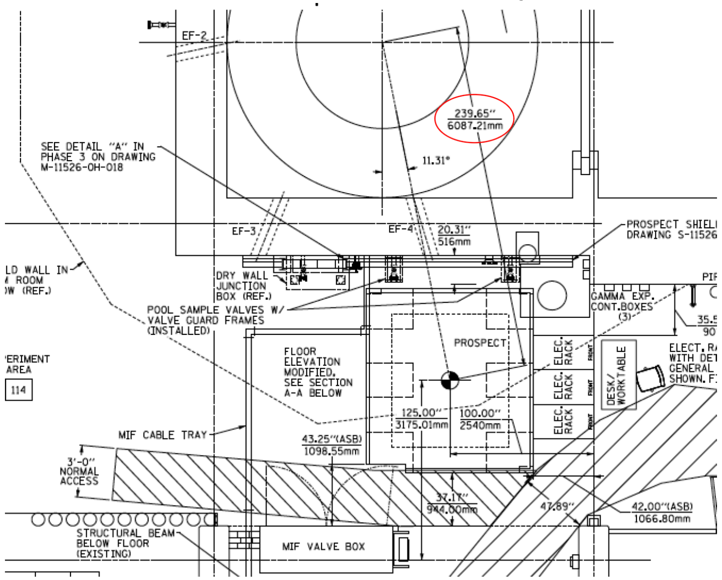
- Number of observed IBD candidates: <1% uncertainty
  - Cuts on prompt + delayed event timing, position, PSD, energy, and fiducial volume to select IBD events and reject backgrounds

Series of cuts applied to prompt E spectrum



- Detector baseline: 2.52% uncertainty
  - Survey measurements performed within reactor complex using optical ranging equipment.

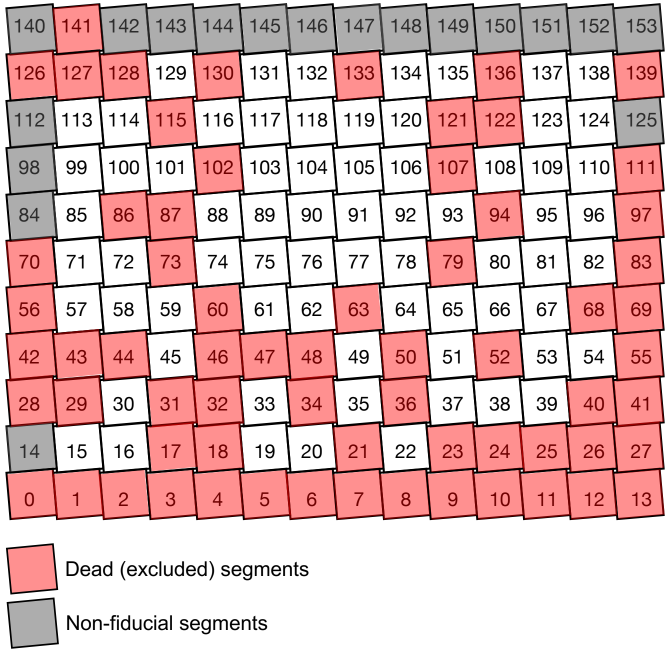
HFIR survey



$$\sigma_f^{obs} = \frac{N^{obs}}{\frac{P_{th}}{\langle E_f \rangle} \frac{N_p}{4\pi L^2} \epsilon}$$

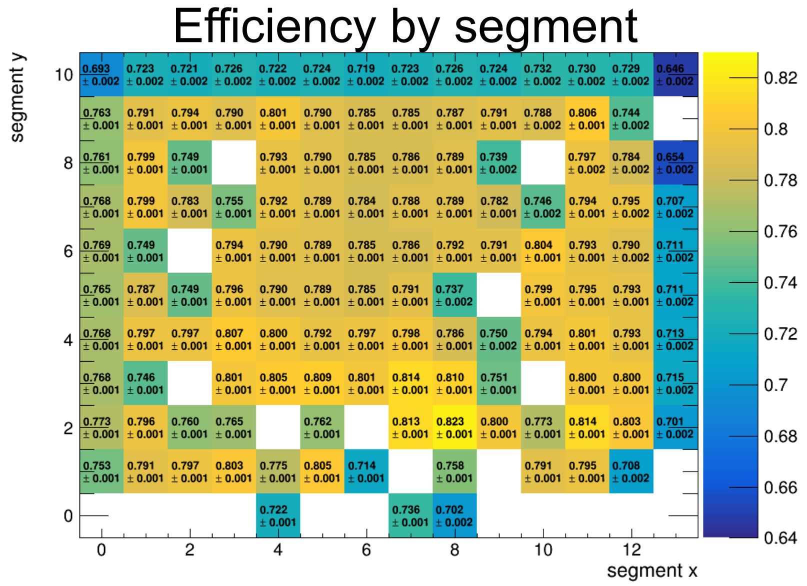
Next Steps: IBD detection efficiency

- Degradation of detector performance
  - Liquid scintillator leaked into the PMT housings at the end of some segments
  - Address dead segment impact using fiducialization, single-ended event reconstruction, and data-splitting



- Detection efficiency: <2% uncertainty
  - Number of detected IBD events in live active volume relative to total IBDs in live active volume.

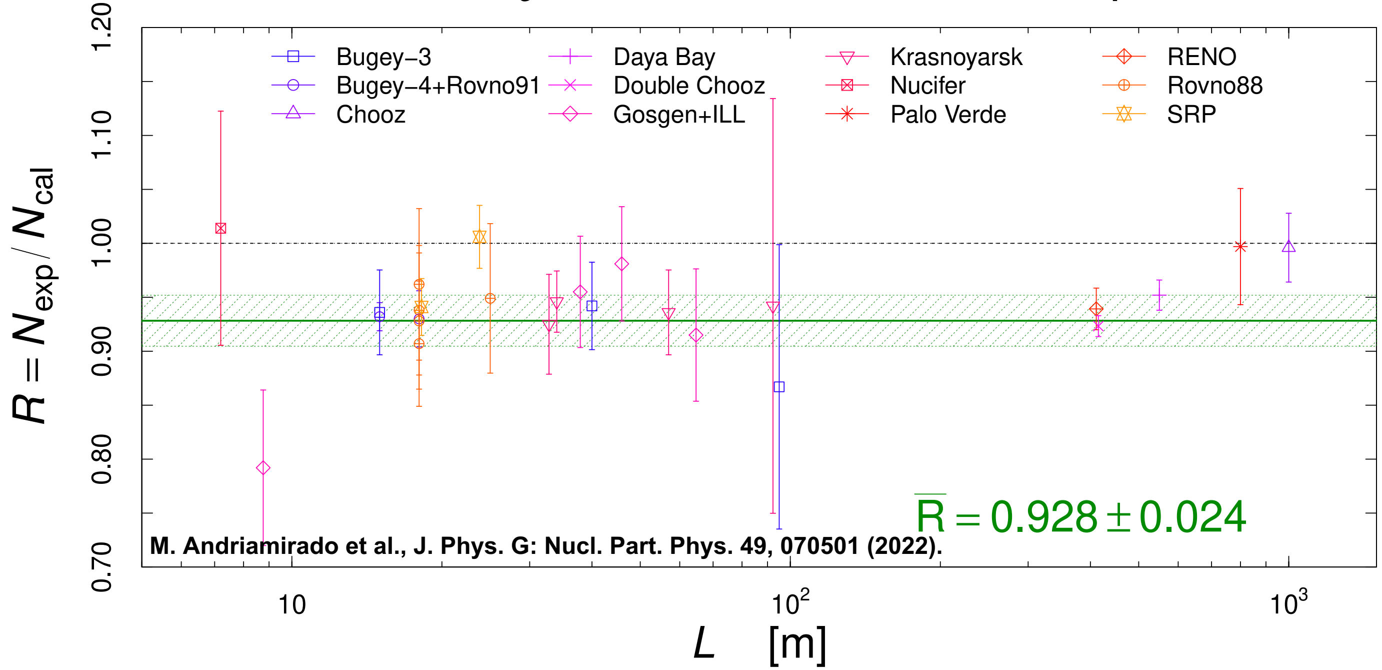
$$\epsilon = \frac{N(\text{Selected IBD events})}{N(\text{Total IBD interactions})}$$



Expected Impact

- World-leading precision measurement of ^{235}U neutrino flux with final uncertainty ~2.5%
  - Constrain reactor physics explanations of reactor neutrino flux and spectrum anomalies
  - Improve uncertainties in existing ^{235}U flux production models

Measurements of reactor $\bar{\nu}_e$ flux relative to conversion-predicted flux models



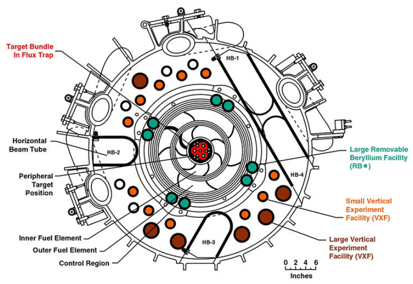
National Nuclear Security Administration

BOSTON UNIVERSITY

MTV Impact

- Collaborations with national labs: ORNL, LLNL, BNL, NIST
- Site visits: HFIR complex at ORNL
- Conference proceedings:
  - INMM & ESARDA Joint Annual Meeting
  - Science, Peace, Security
  - Neutrino
  - APS DNP + DPF
- Upcoming publications:
  - Short-Baseline Absolute Reactor Antineutrino Flux Measurement with the PROSPECT Experiment at HFIR. *Physical Review D.* The PROSPECT Collaboration. *(in prep).*
  - The Potential of Antineutrino Detectors for Remote Reactor Monitoring, Discovery, and Exclusion Applications. *The Nonproliferation Review.* A. Bernstein, F. Dalnoki-Veress, J. Hecla, P. Kunkle, J. Learned. *(under review).*
- Technology collaborations: Drexel University, GIT, University of Hawaii, IIT, Susquehanna, Temple University, University of Tennessee, University of Waterloo, University of Wisconsin, Yale University

OAK RIDGE National Laboratory | HIGH FLUX ISOTOPE REACTOR



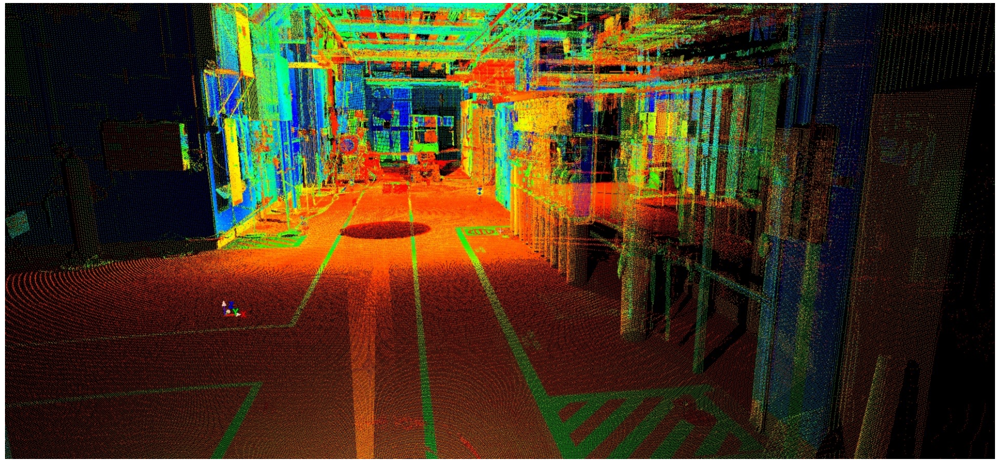
National Nuclear Security Administration

BOSTON UNIVERSITY

Conclusion

- Summary of the systematic errors impacting the absolute neutrino flux measurement with PROSPECT gives current uncertainty of $\pm 3.78\%$
  - Decreasing uncertainties on baseline and detection efficiency to ~1% improves uncertainty in absolute flux to $\pm 2.44\%$
- Final measurement will demonstrate how well an above-ground detector can monitor the power of a research reactor
- Supports NNSA mission by using precision monitoring technology to prevent diversion of weapons-usable material from nuclear reactors

Point cloud map of experiment room



Acknowledgements

The Consortium for Monitoring, Technology, and Verification would like to thank the DOE-NNSA for the continued support of these research activities.

This work was funded by the Consortium for Monitoring, Technology, and Verification under Department of Energy National Nuclear Security Administration award number DE-NA0003920

Backup

What does an absolute flux measurement report?

- Can we look at a single isotope (^{235}U) and report the number of antineutrinos released per fission?
  - No → IBD experiments only detect antineutrinos above the IBD threshold ($\frac{1}{3}$ of total neutrino flux)

- Instead we can report IBD cross section per fission σ_f:

$$\sigma_f = \int S(E_\nu)\sigma(E_\nu)dE_\nu$$

IBD cross section per fission

IBD cross section

$\bar{\nu}_e$ spectrum from reactor

- Can also report the ratio of observed IBD rate σ_f^{obs} to the predicted IBD rate σ_f^{pred} using conventional ^{235}U absolute reactor neutrino production models:

$$R = \frac{\sigma_f^{obs}}{\sigma_f^{pred}}$$

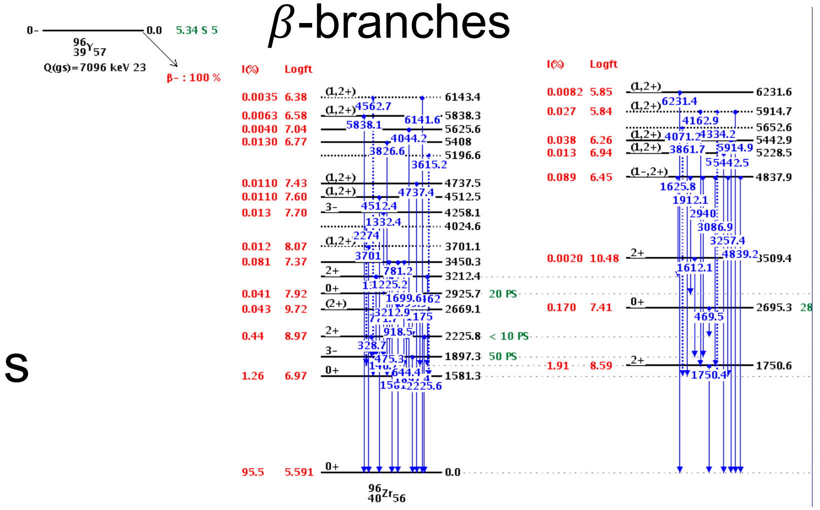
- Expectation: Observed flux and predicted flux consistent within error bars

Neutrino flux production models

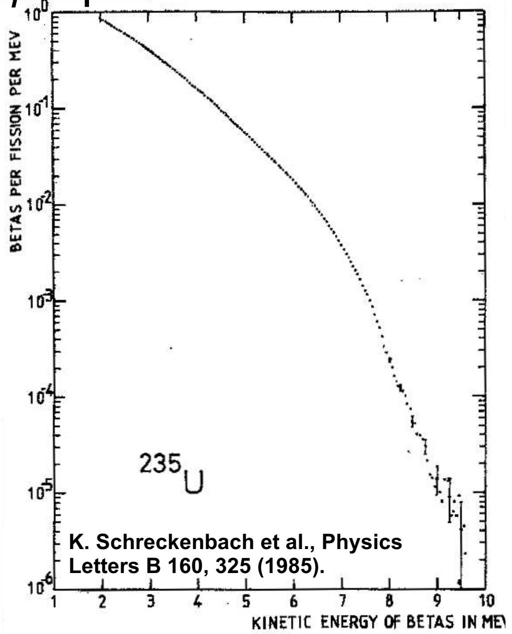
- Two flux prediction methodologies:
  - Ab-initio method
    - Summation of decay rates convolved with branching fractions of β-decays from isotopes in core to final nuclear states
  - β spectrum conversion
    - Conversion of electron spectrum of fission isotopes into $\bar{\nu}_e$ spectrum

- Different fissile antineutrino spectrum models are used to predict the reactor antineutrino flux and spectrum
  - ILL + Vogel model
  - Huber + Mueller model
  - Kopeikin model

β-branches



β-spectrum from fission



K. Schreckenbach et al., Physics Letters B 160, 325 (1985).

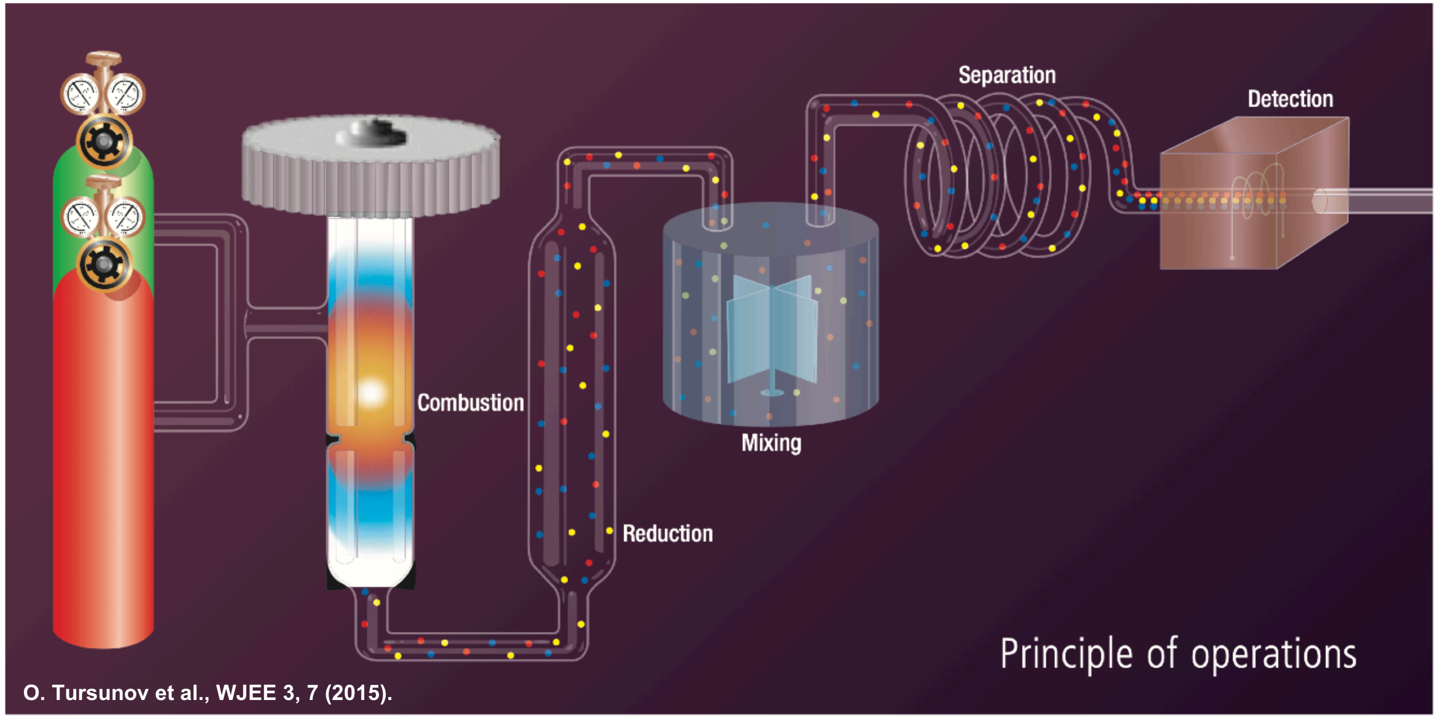
Energy released per fission

$$\sigma_f^{obs} = \frac{N^{obs}}{\frac{P_{th}}{\langle E_f \rangle} \frac{N_p}{4\pi L^2} \epsilon}$$

- "Effective" average energy per fission is given by $E_f = E_{tot} - \langle E_\nu \rangle - \Delta E_{\beta\gamma} - E_{n\gamma} + E_{nc}$
- E_{tot} is the mass excess per fission
  - STEREO recalculated using cumulative fission yields to get (−173.15 ± 0.07) MeV
- $\langle E_\nu \rangle$ is the energy lost by neutrino escape
  - Must account for neutrinos from neutron capture and fuel evolution and subtract neutrinos from long lived isotopes
  - STEREO saw a 5% correction to the neutrino energy loss for these effects (0.3% for E_f)
- $\Delta E_{\beta\gamma}$ is the energy not added to the power because of long lived isotopes
  - Must be calculated for HFIR
  - Small effect at (0.6 ± 0.1) MeV for STEREO → ~0.3%
- Must also account for the energy/fission change from ^{239}Pu (small)
  - Known for HFIR as 200.5 MeV/fission at beginning of cycle and 200.9 MeV/fission at end of cycle → ~0.2% change
- $\langle E_{n\gamma} \rangle$ is the energy lost due to escaping neutrons and gammas
  - Must be calculated for HFIR
- E_{nc} is the energy added by neutron capture
  - Calculated reaction rates must be evaluated in terms of heat
  - STEREO saw 5% effect at (10.3 ± 0.2) MeV
- On par for final value comparable with STEREO at E_f = (203.41 ± 0.26) MeV estimated 0.12% uncertainty

Combustion measurements

$$\sigma_f^{obs} = \frac{N^{obs}}{\frac{P_{th}}{\langle E_f \rangle} \frac{N_p}{4\pi L^2} \epsilon}$$

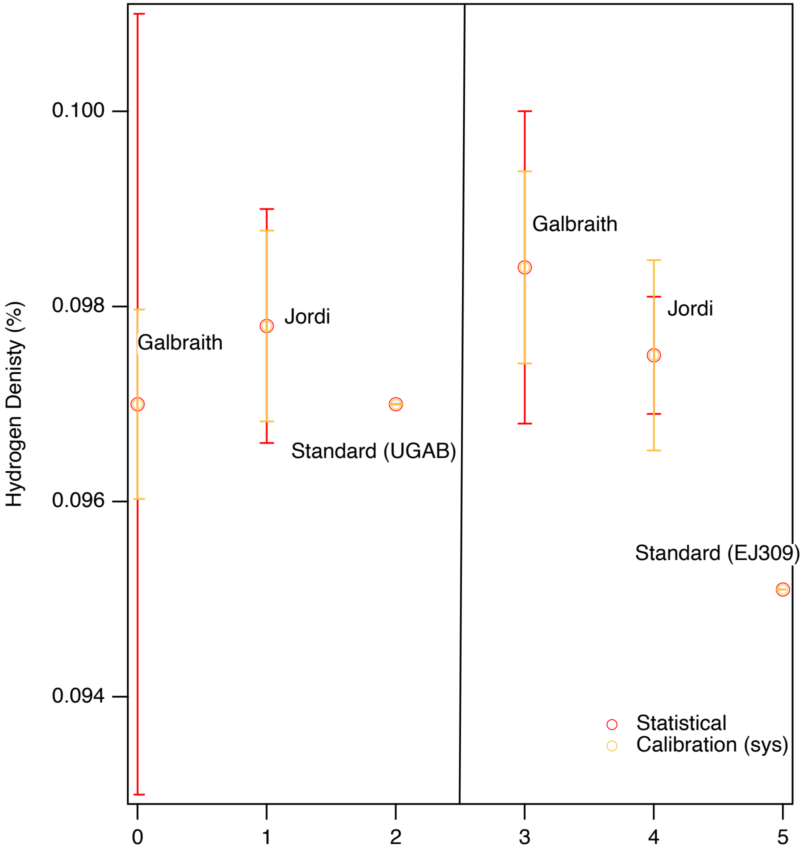


1) Sample is combusted completely in pure Oxygen and reduced to the elemental gases CO_2, H_2O, N_2 and SO_2. Various catalysts aid the process

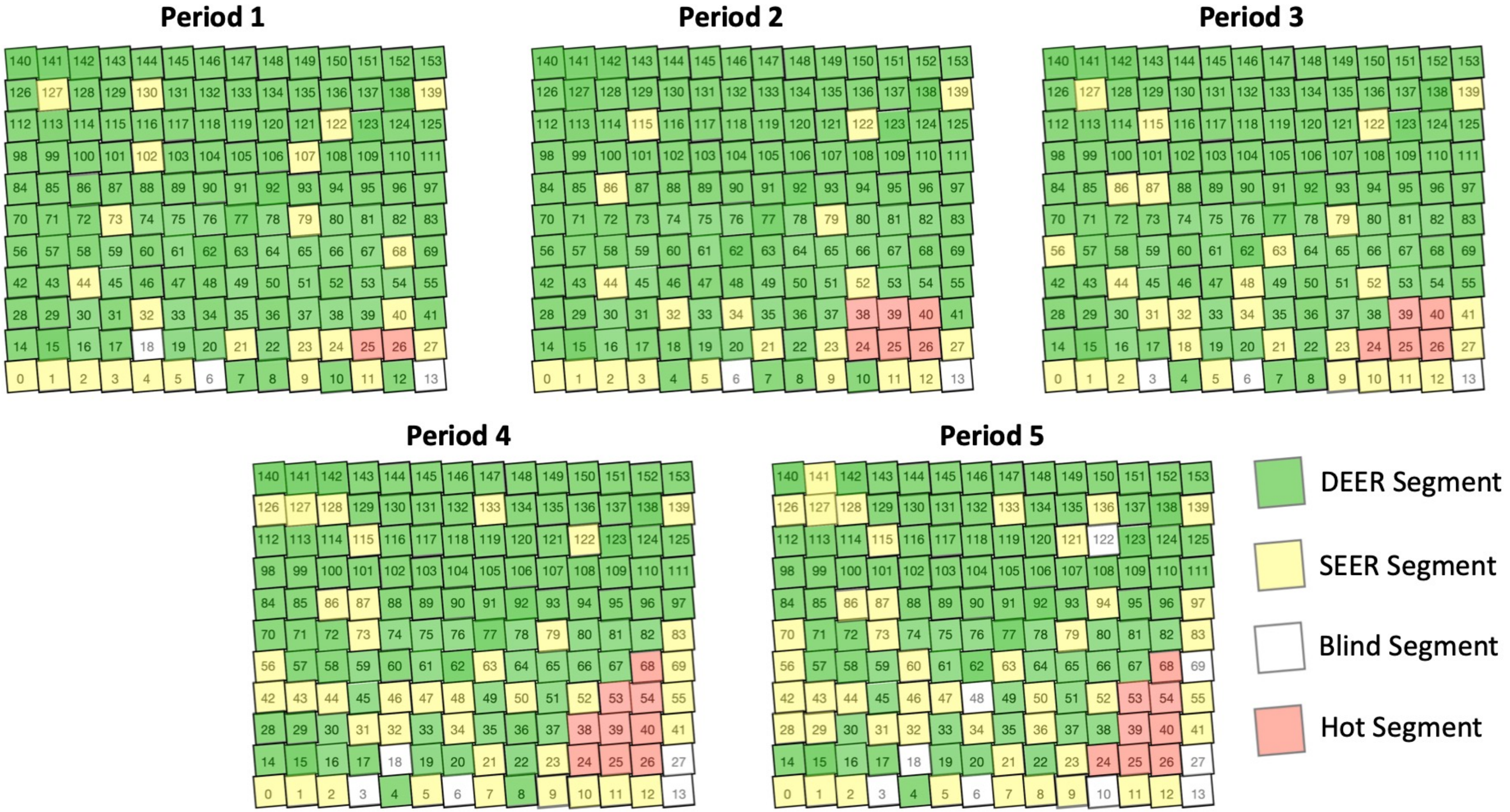
2) Gases are rapidly mixed and precisely maintained at controlled conditions of pressure, temperature and volume. Gases are mechanically homogenized

3) Separation via Frontal Gas Chromatography

4) Gas measured by a thermal conductivity detector



Data-splitting detector configurations



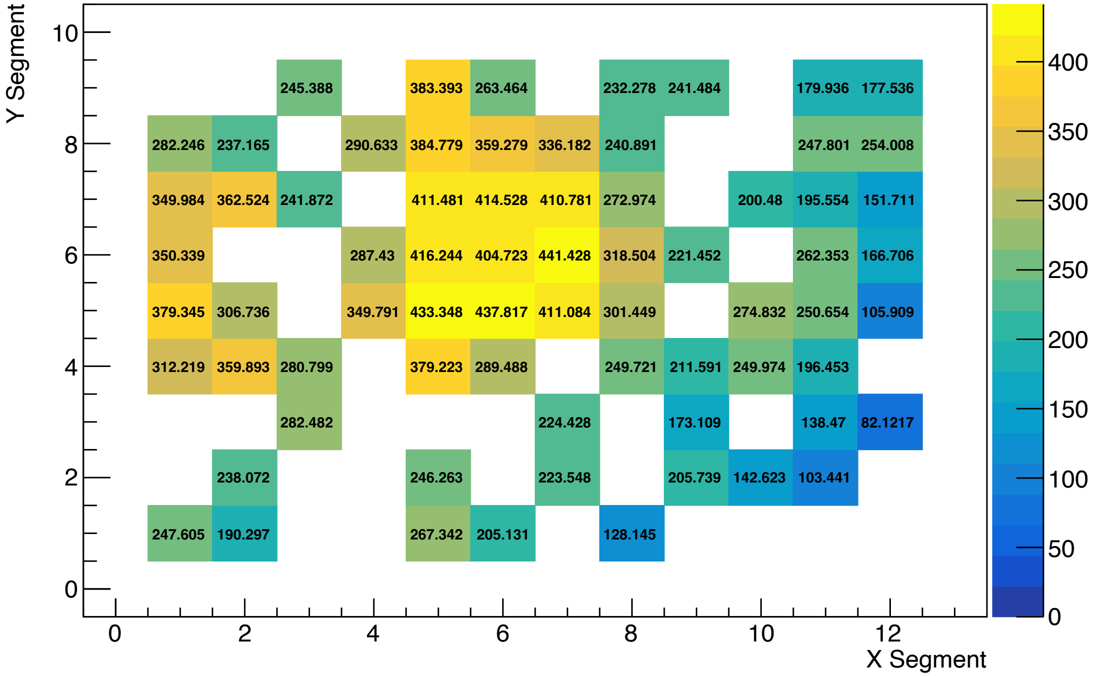
Dead volume correction

$$IBD_{Effective} = \sum_{0.8\ MeV}^{7.2\ MeV} \frac{1}{(\frac{\sigma_{IBD}}{IBD})^2}$$

$$\sigma_f^{obs} = \frac{N^{obs}}{\frac{P_{th}}{\langle E_f \rangle} \frac{N_p}{4\pi L^2} \epsilon}$$

- Address dead segment impact using fiducialization, single-ended event reconstruction, and data-splitting

Effective IBDs for:
- Full dataset (5 periods)
- Segments with 2 live PMTs



Effective IBDs for:
- Periods 2 & 3
- Segments with 1 or 2 live PMTs