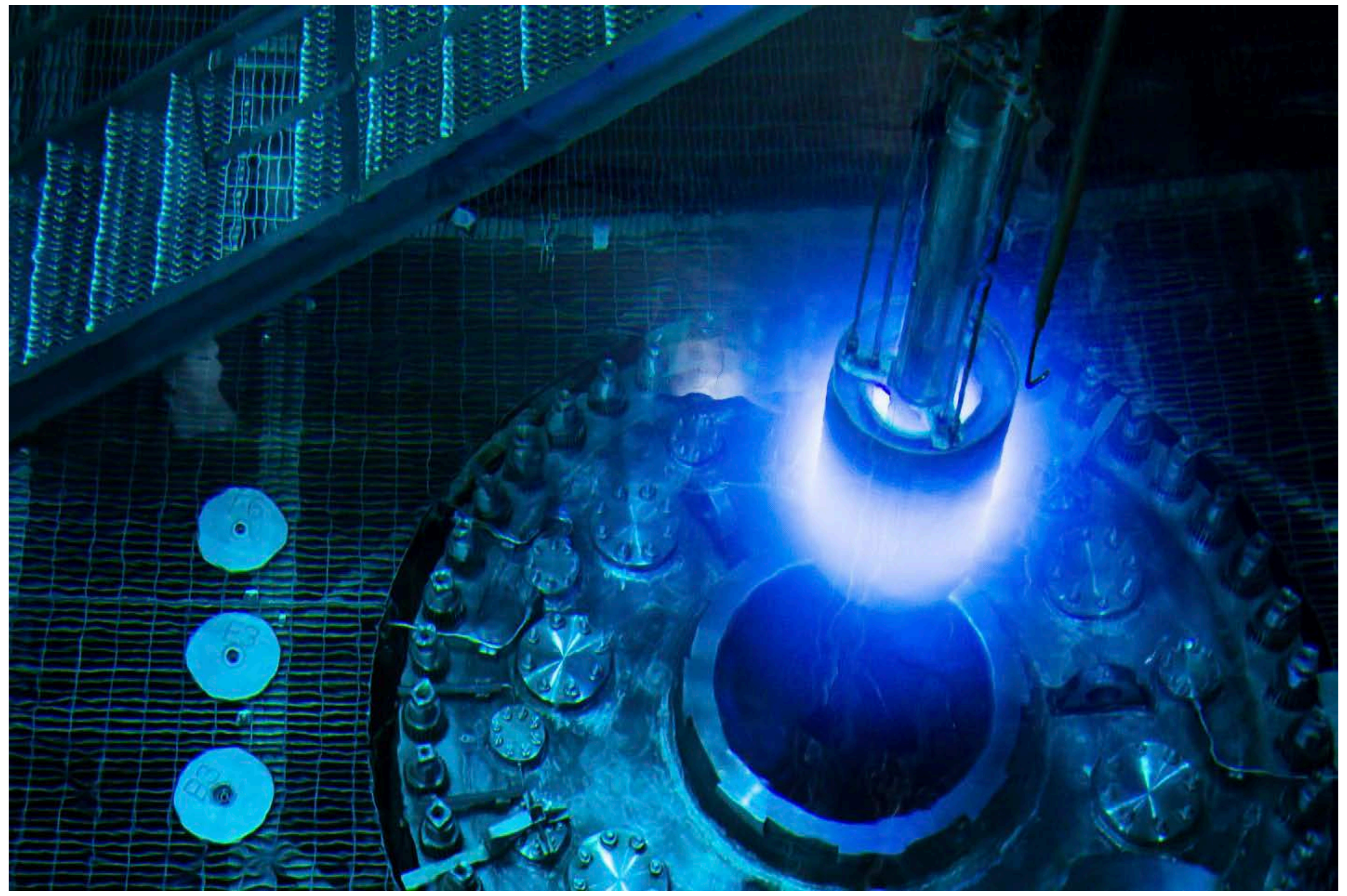
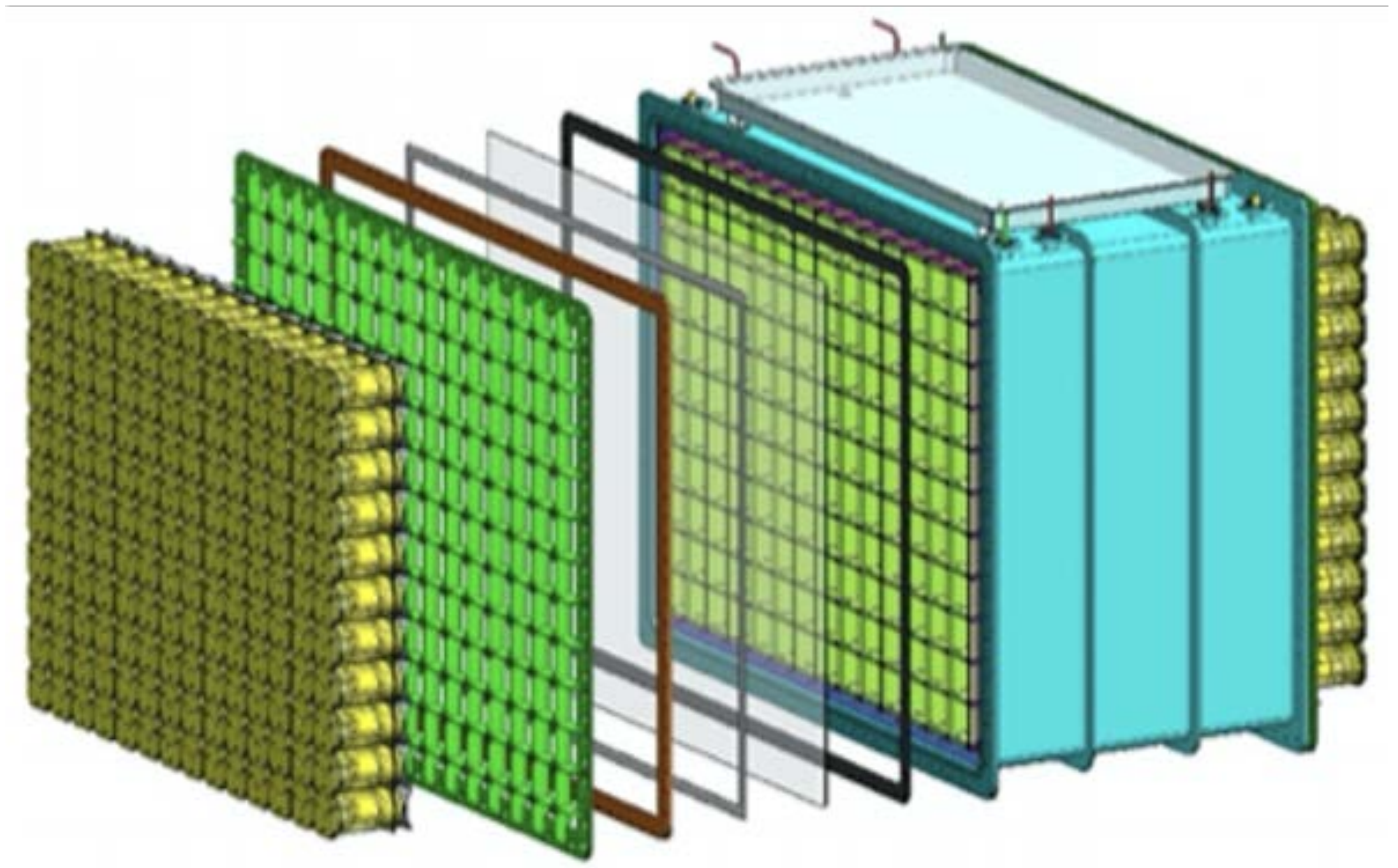
Opportunities with PROSPECT-II





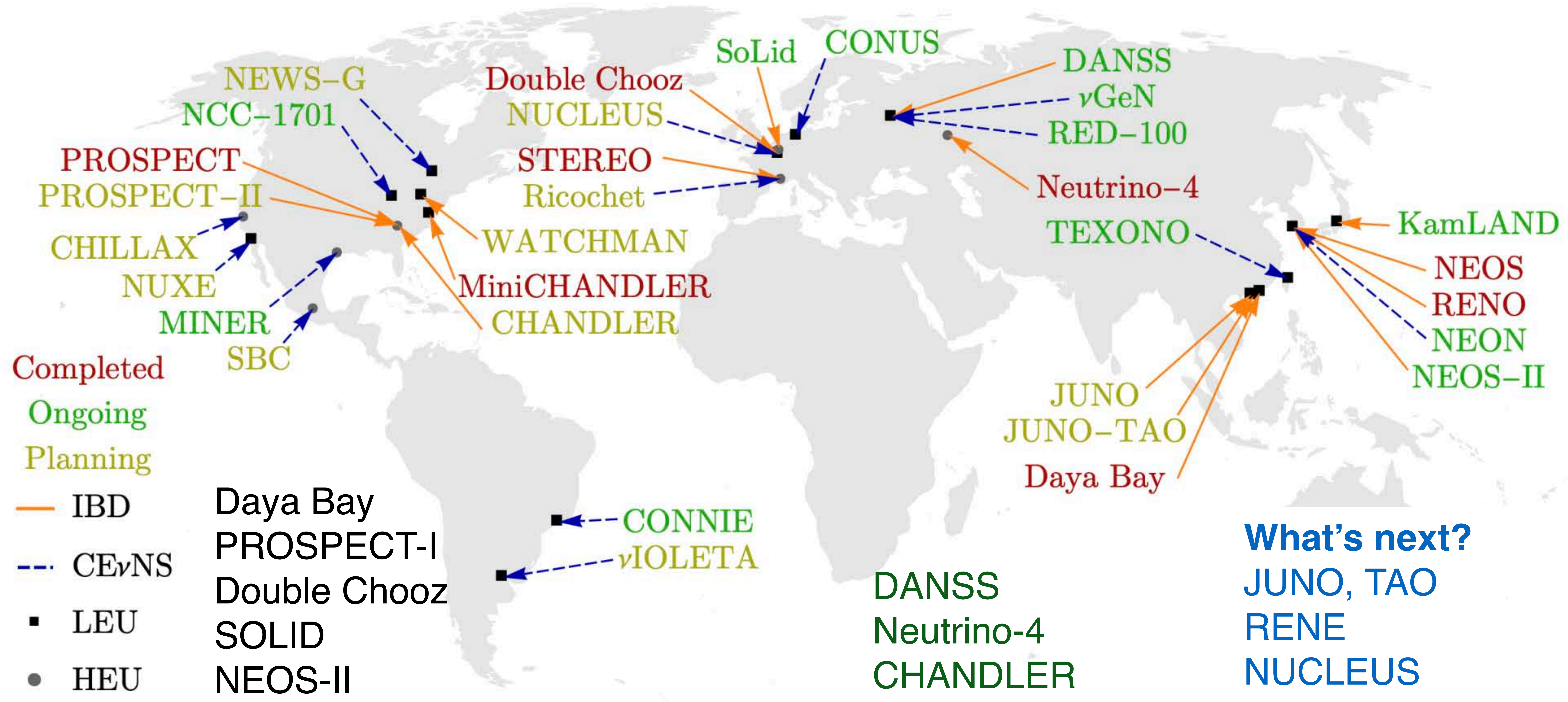
Karsten Heeger
Yale University

On behalf of the PROSPECT collaboration

Outline

- Results from PROSPECT-I and upcoming analyses
- Scientific case for continued measurements of reactor antineutrinos at short baselines
- PROSPECT detector design, evolved
- PROSPECT-II oscillation and spectrum physics
- Combing HEU and LEU measurements
- Opportunities and outlook

Reactor Experiments Worldwide



Daya Bay
PROSPECT-I
Double Chooz
SOLID
NEOS-II
are working on final analyses

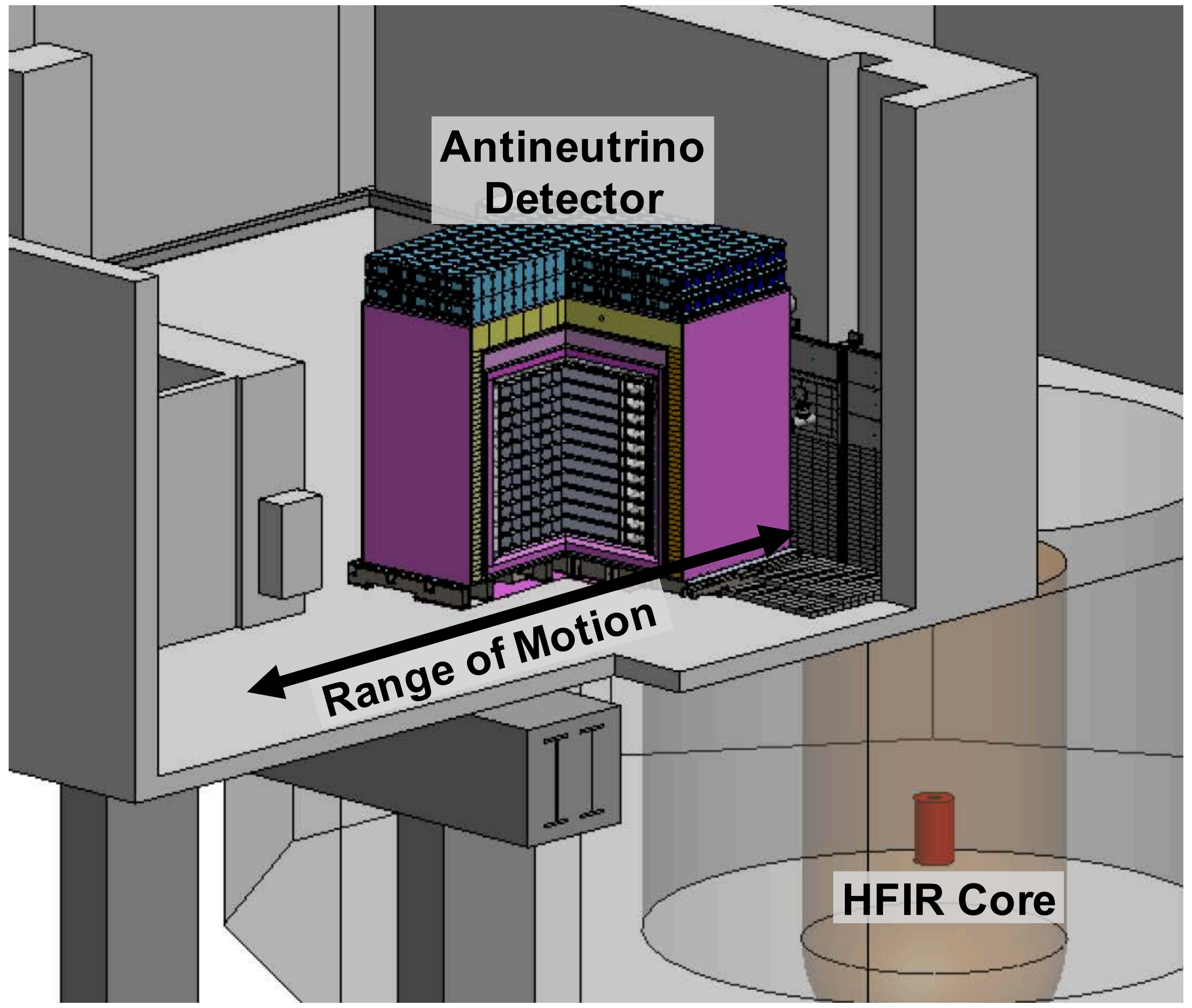
DANSS
Neutrino-4
CHANDLER
Ongoing

What's next?
JUNO, TAO
RENE
NUCLEUS
PROSPECT-II?

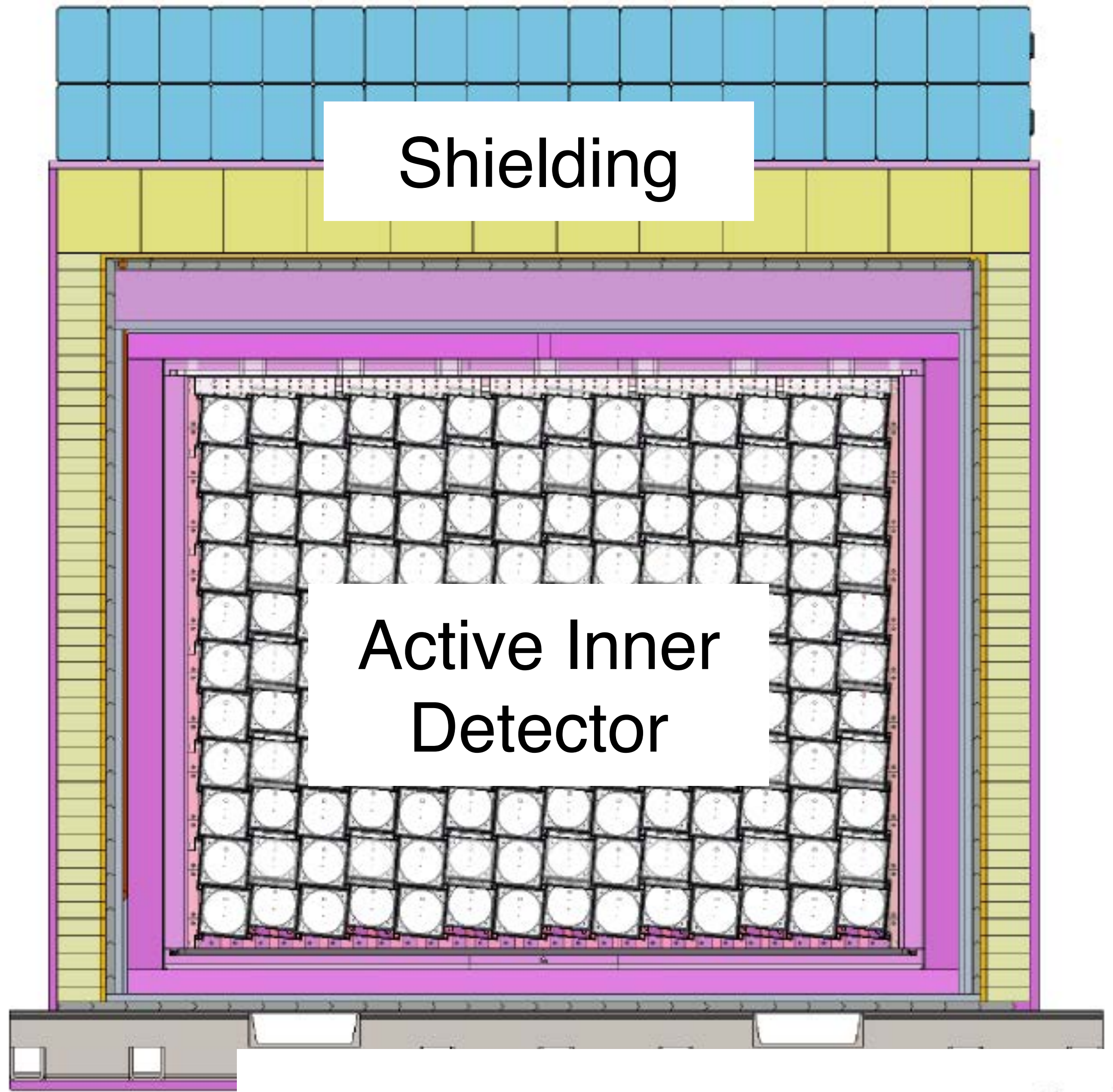
Precision Oscillation and Spectrum Experiment

Search for short-baseline oscillation at <10m

Precision measurement of ^{235}U reactor $\overline{\nu}_e$ spectrum

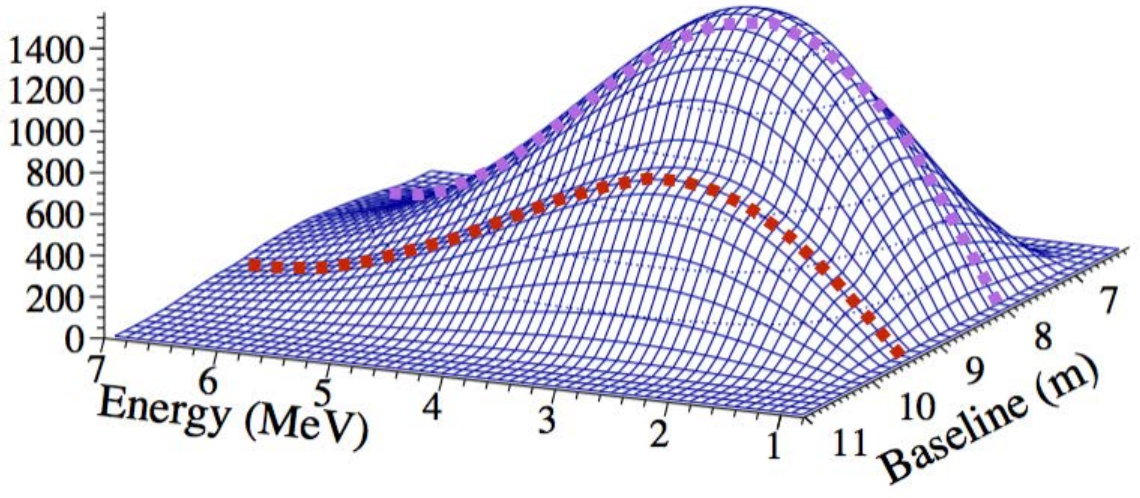


Segmented, ^{6}Li-loaded Detector

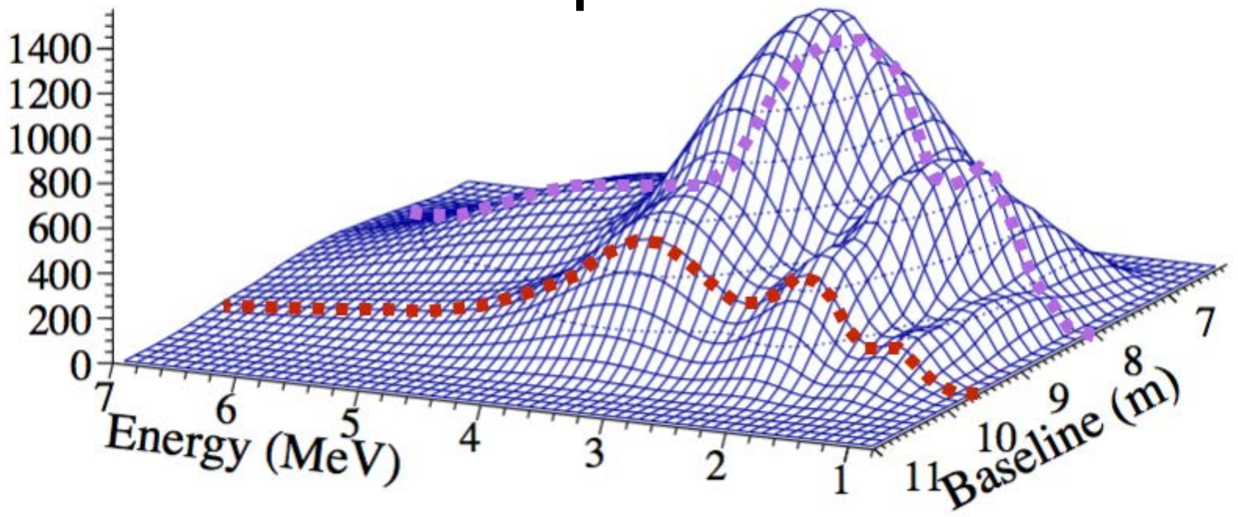


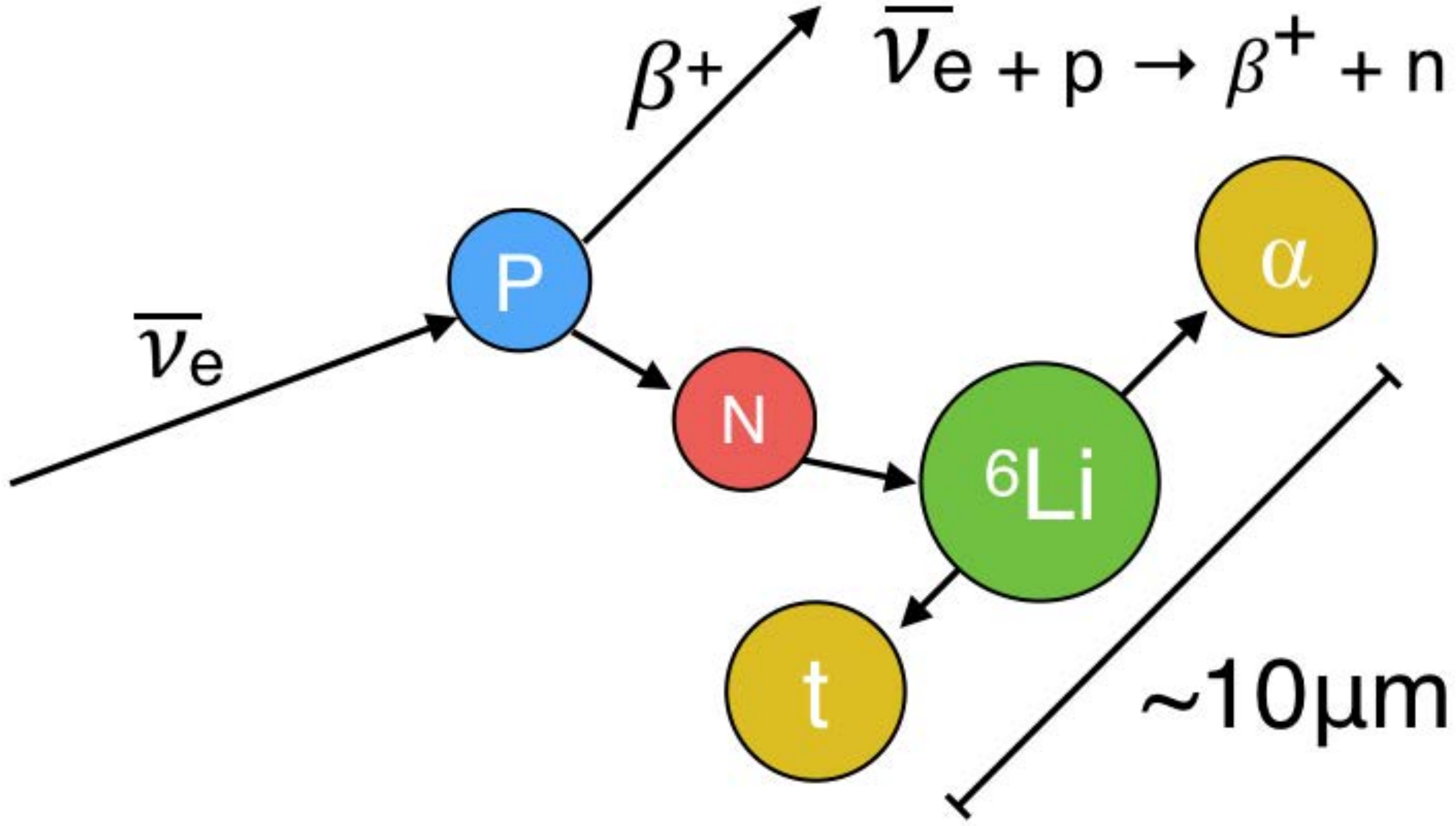
Relative measurement of L/E and spectral shape distortions

unoscillated spectrum



oscillated spectrum

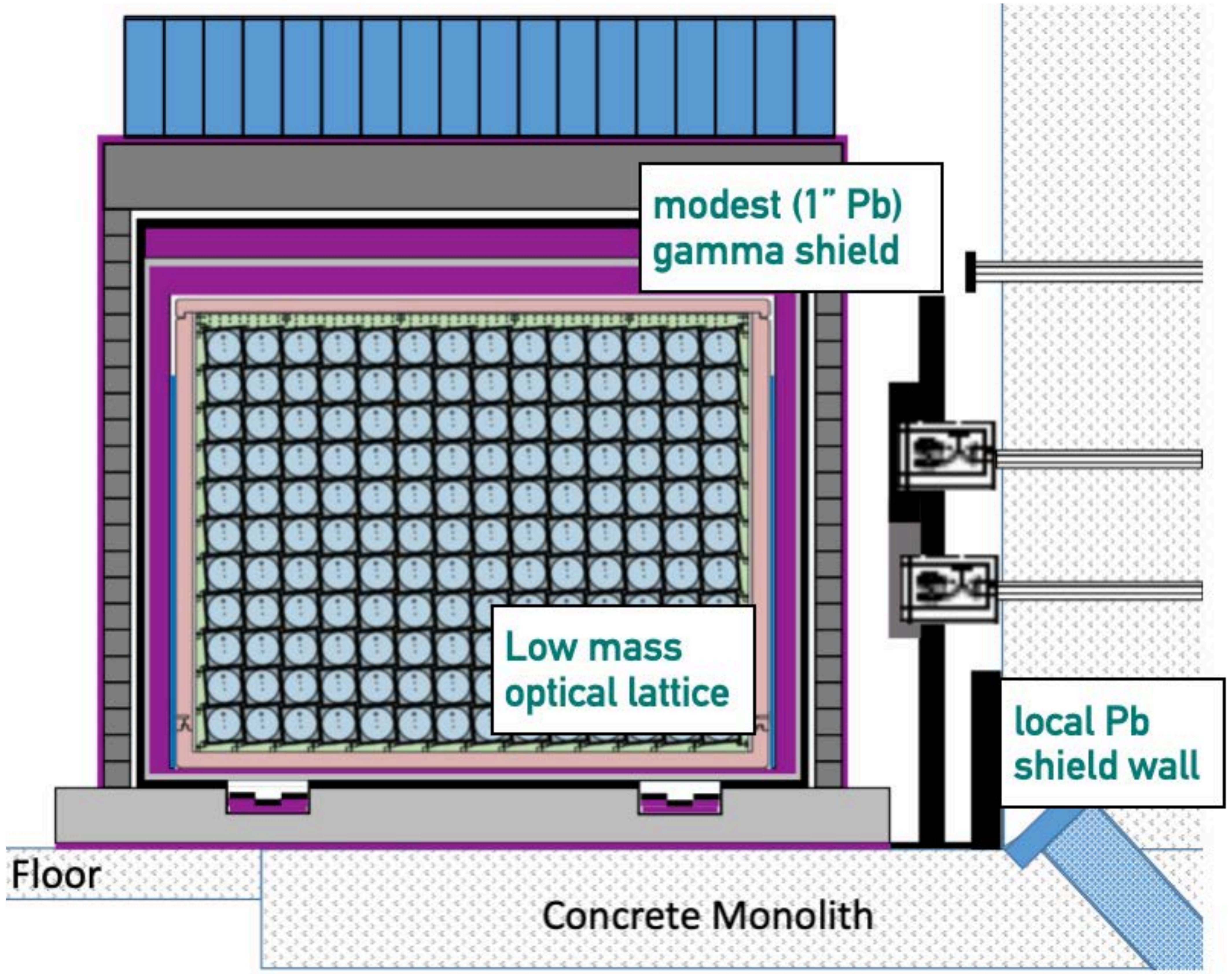


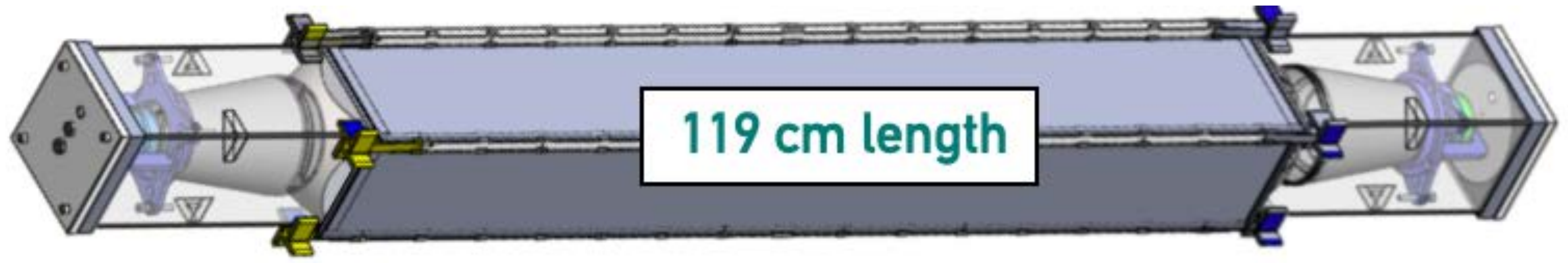


$\overline{\nu}_e + p \rightarrow \beta^+ + n$

Precision Oscillation and Spectrum Experiment

Optimized Detector





Inverse Beta Decay (IBD) $\bar{\nu}_e + p \rightarrow e^+ + n$

Antineutrinos are detected via Inverse Beta Decay (IBD)

Prompt energy gives an estimate of the antineutrino energy.

Delayed n-Li capture is used for tagging the IBD candidates.

4 ton ^{6}Li-loaded fiducial volume

11 x 14 array of **154 optically separated segments**

Double-ended PMT readout, with light concentrators

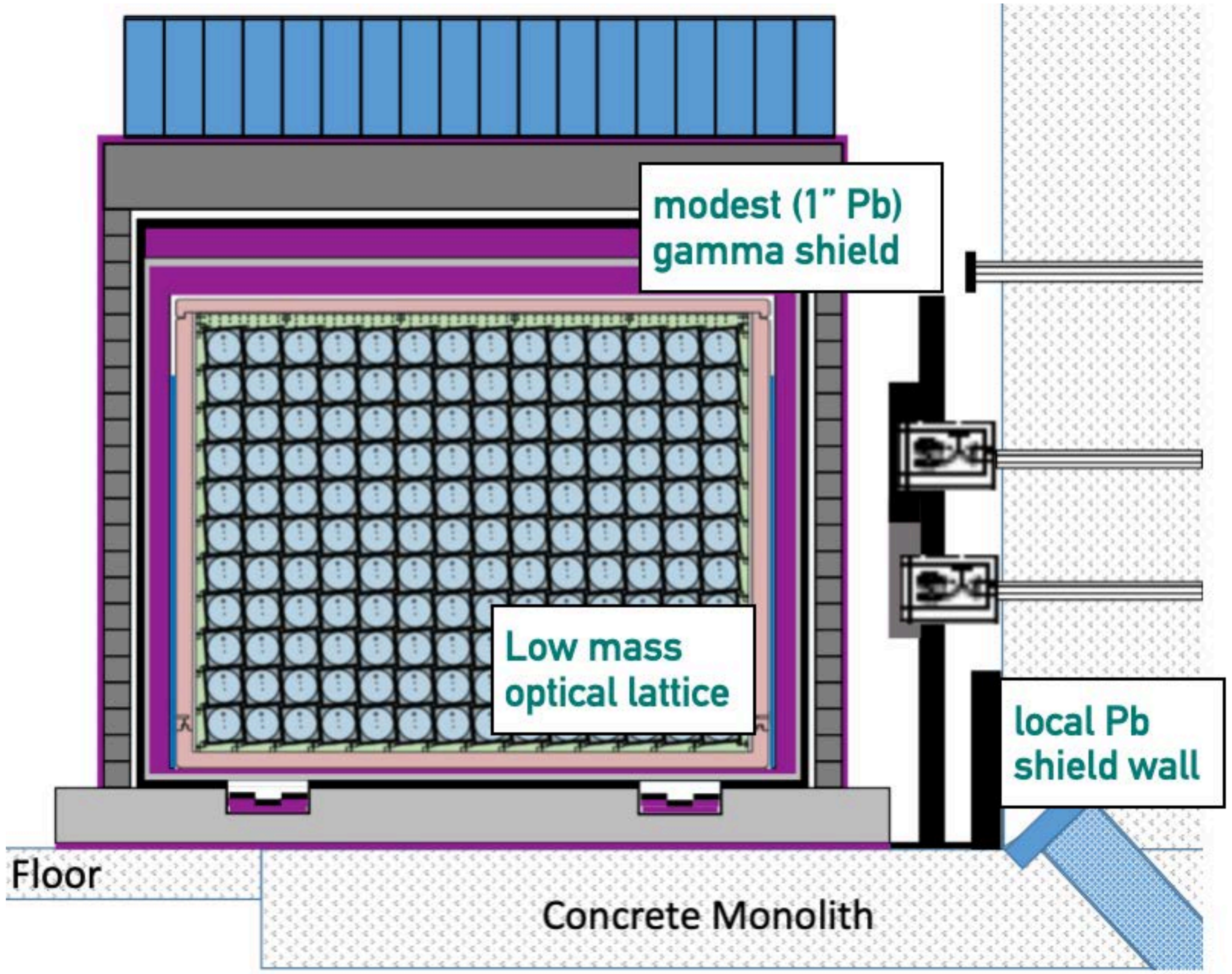
Good light collection and energy response

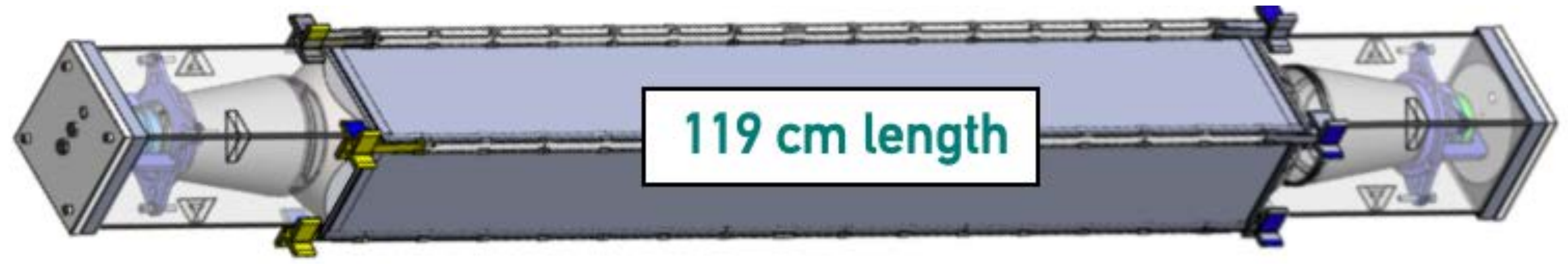
Full X, Y, Z event reconstruction

On-surface deployment with minimal shielding

Precision Oscillation and Spectrum Experiment

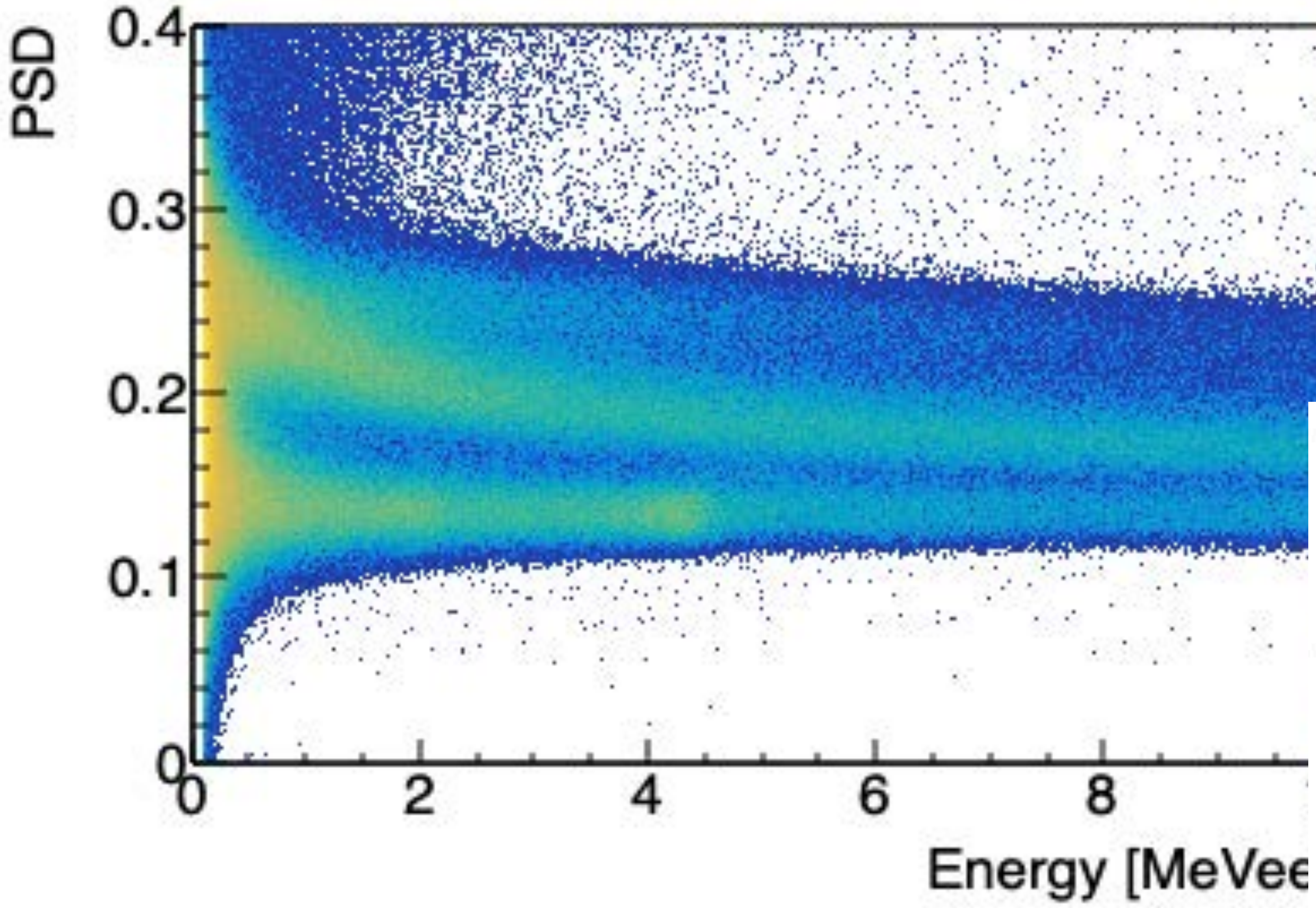
Optimized Detector

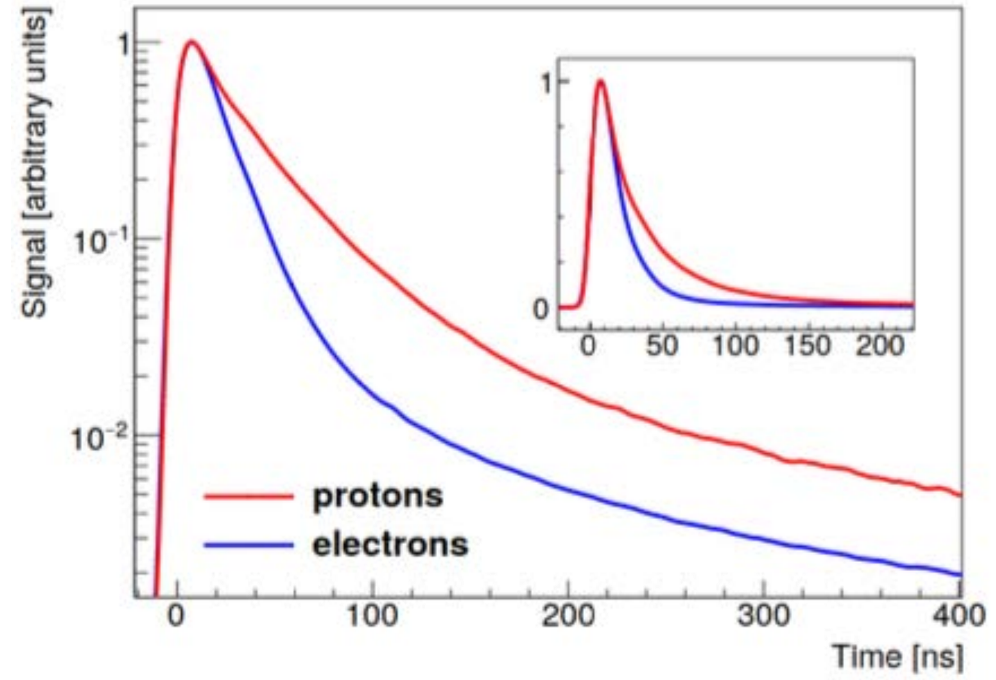


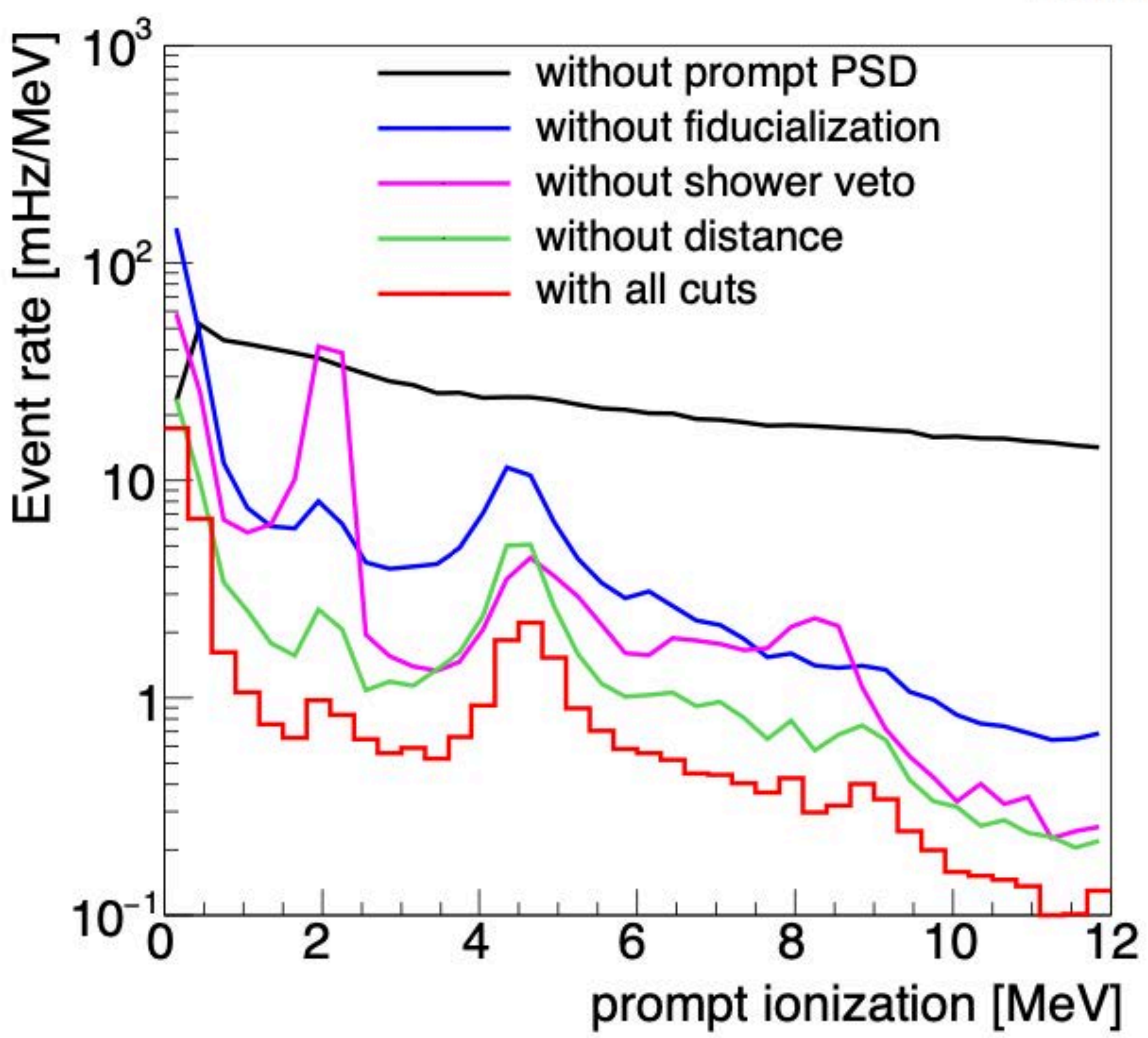


Inverse Beta Decay (IBD) $\overline{\nu}_e + p \rightarrow e^+ + n$

Particle ID capability combined with **good spatial resolution obtained via segmentation** can remove a significant fraction of the backgrounds, enabling **on-surface deployment with lightweight shielding.**

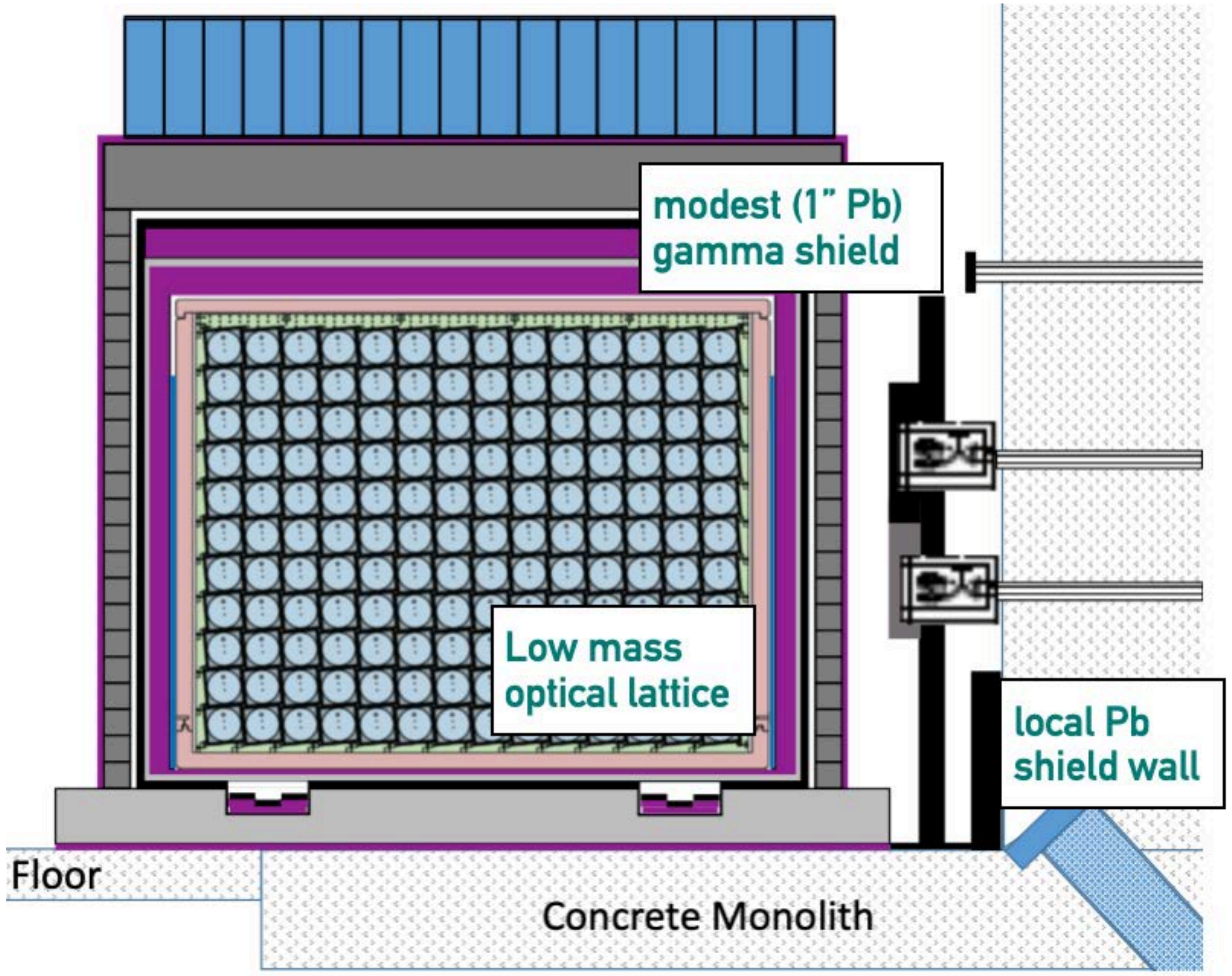


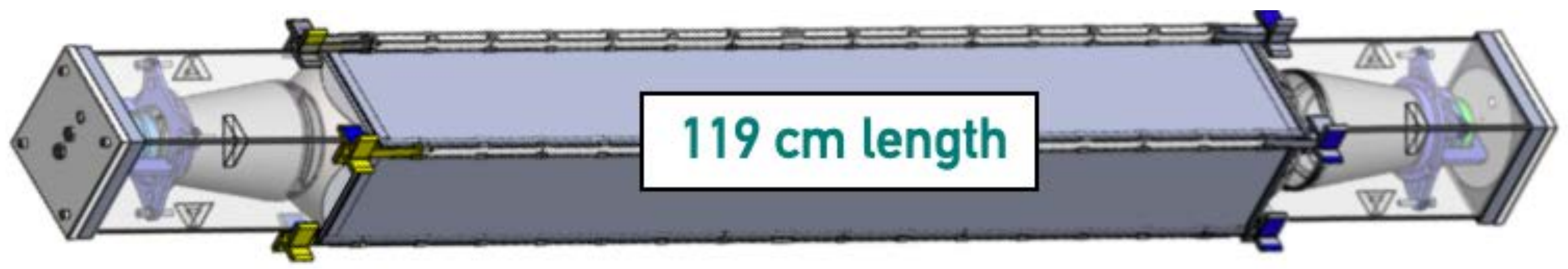




Precision Oscillation and Spectrum Experiment

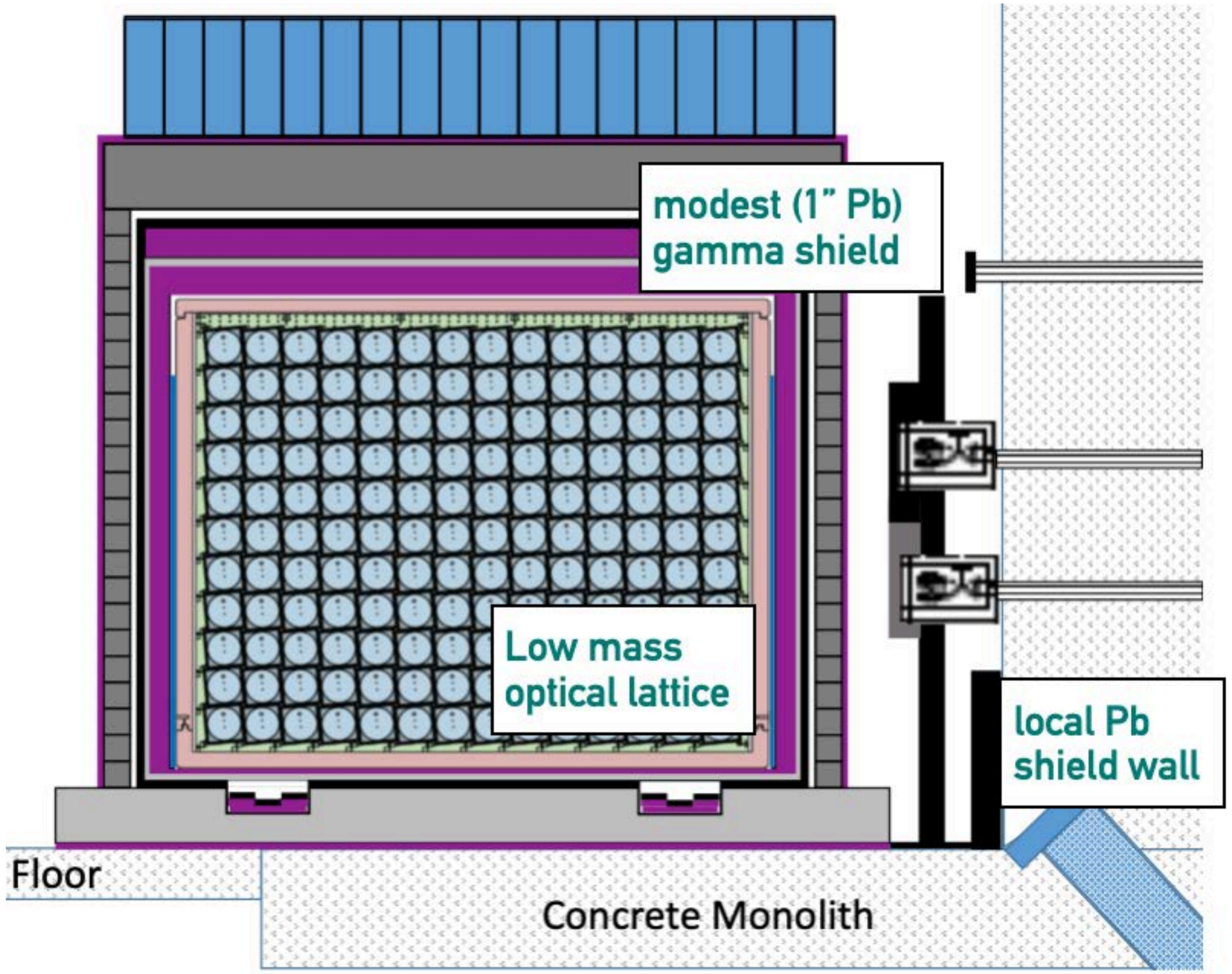
Optimized Detector

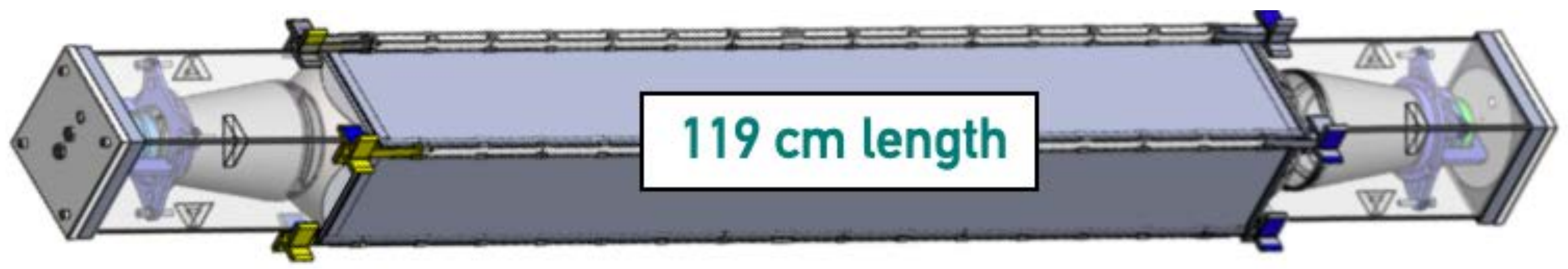




Precision Oscillation and Spectrum Experiment

Optimized Detector





Detector Performance

Double ended PMT readout <**5%√E energy resolution** (or better)

Signal to background of ~1.36:1, P-I net, (3:1 demonstrated).
Overall background suppression strategy highly successful

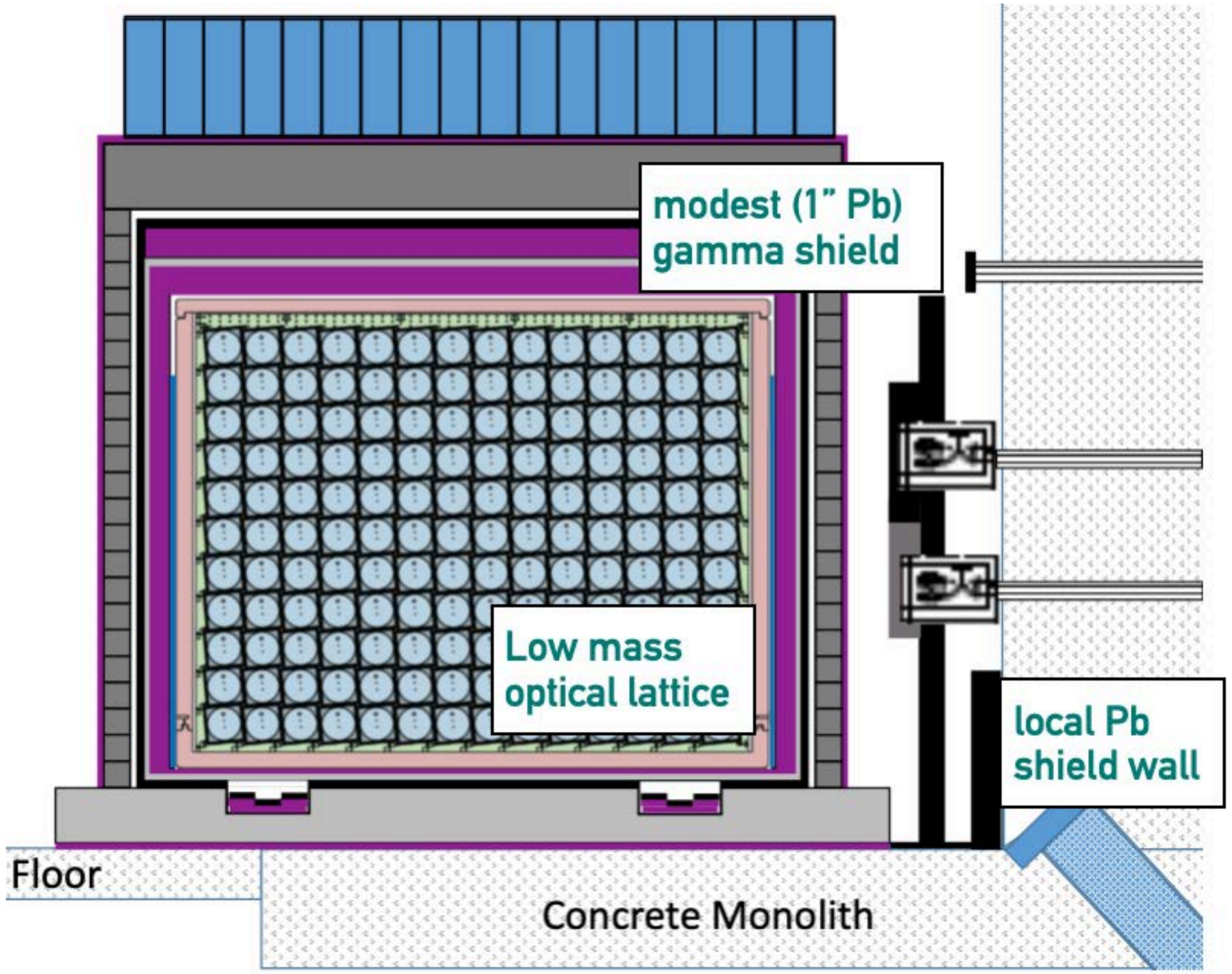
Event localization at relevant length scale
PROSPECT design provides unique sensitivity to high Δm^2

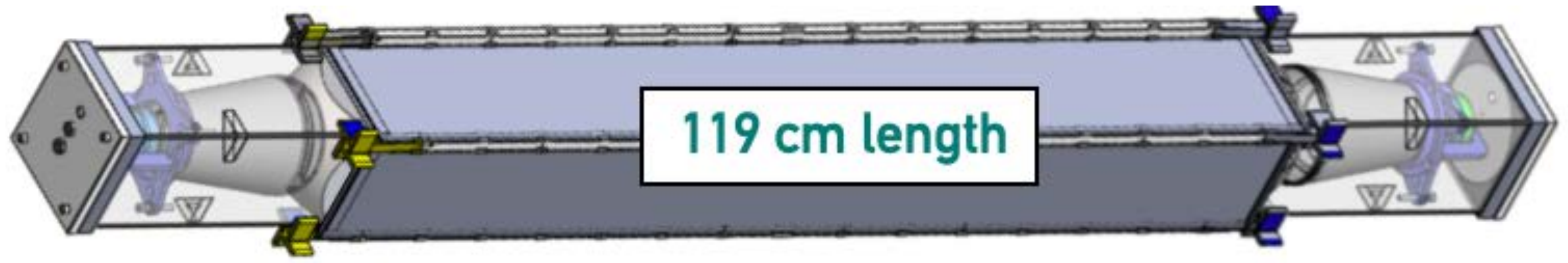
Detector response
%-level time/segment stability in reconstructed positions energies
MC model properly describes energy non-linearity and leakage

Initial LiLS, light collection, and PROSPECT-I calibration performance very good; meets or exceeds all physics requirements

Precision Oscillation and Spectrum Experiment

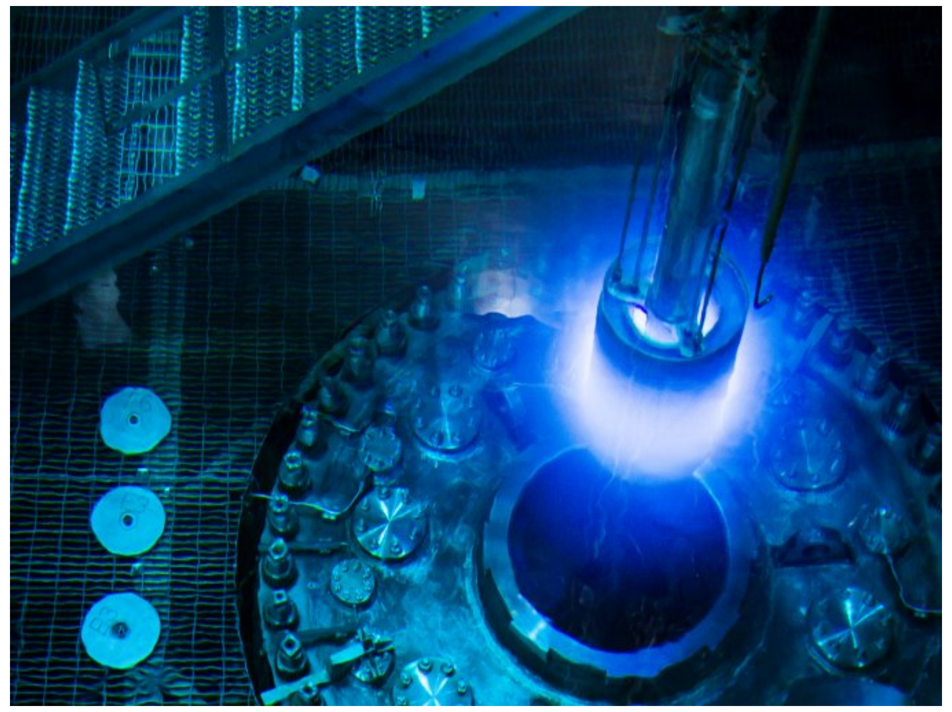
Optimized Detector





HEU Reactor

High Flux Isotope Reactor (HFIR)



HEU core

>99% of antineutrino flux from ^{235}U fission (85 MW)

duty-cycle: 24 days cycle

compact core: height (0.5 m), diameter (0.4 m)

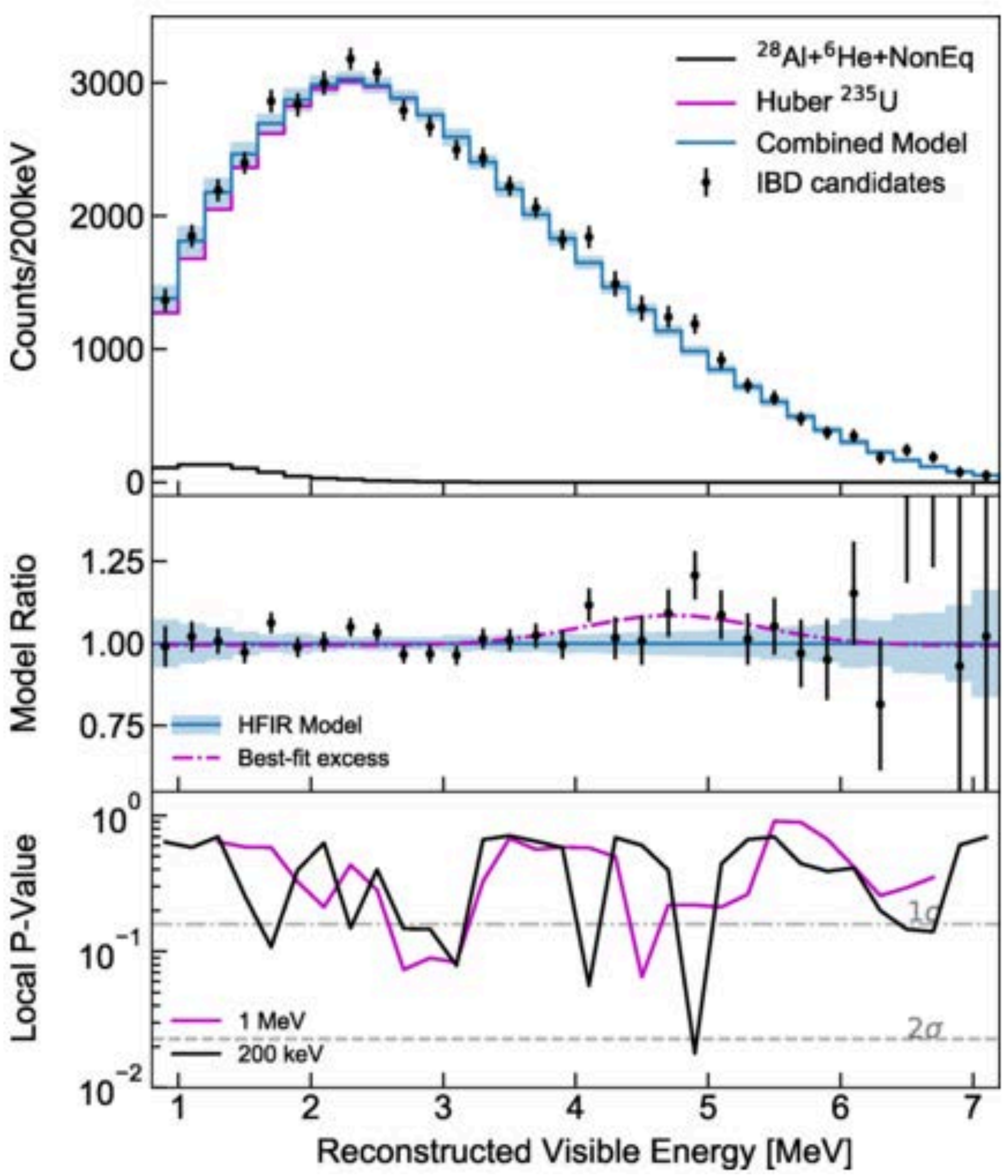
baseline: 7-9m, can probe high Δm^2

HFIR at ORNL is a user facility with easy access

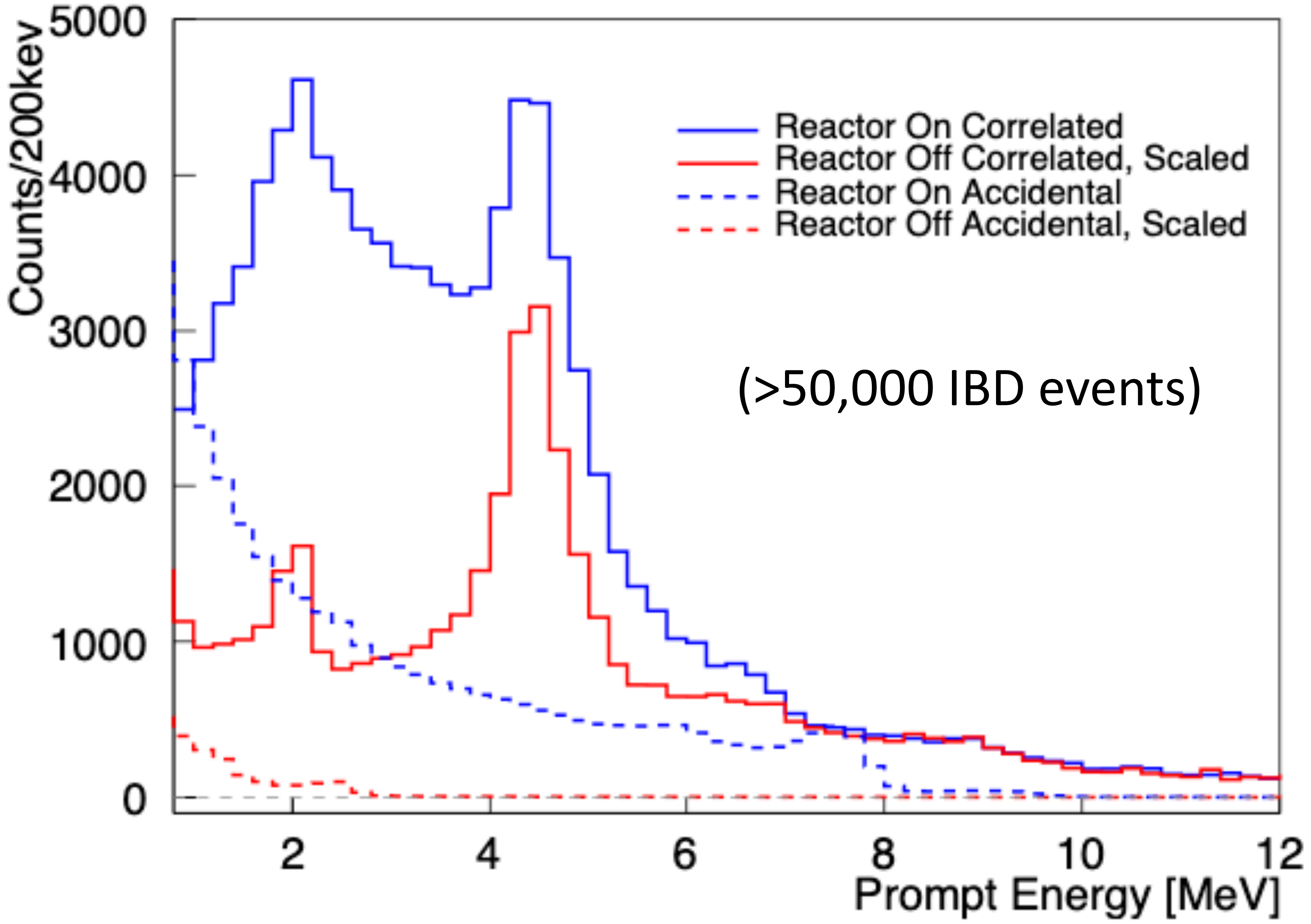
other neutrino experiments (COHERENT) nearby

PROSPECT-I Results

Measurement of ^{235}U Spectrum

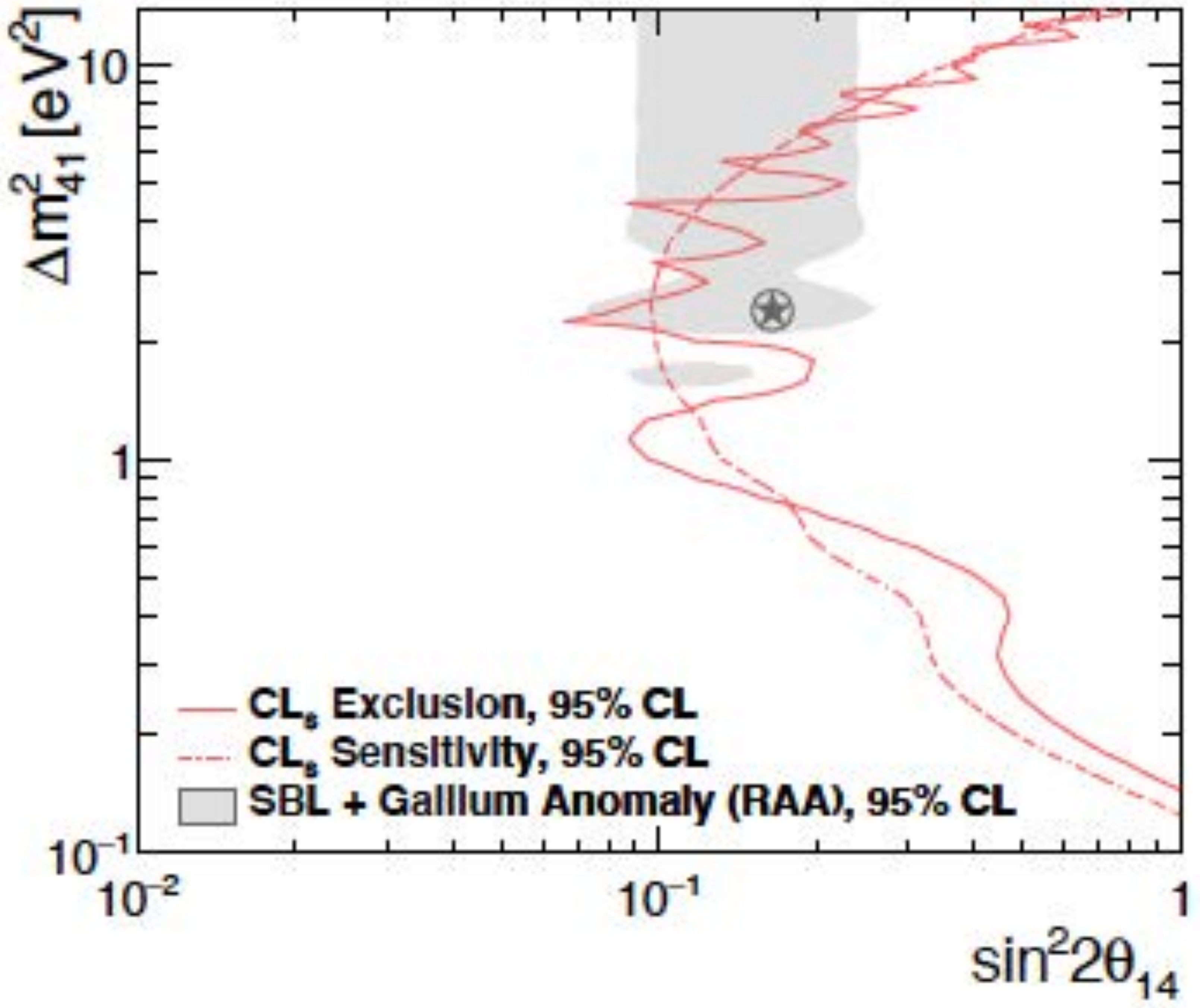


On surface detector with minimal shielding



First on-surface detector to achieve S/B > 1 with minimal shielding

Constraints on eV-sale sterile neutrinos



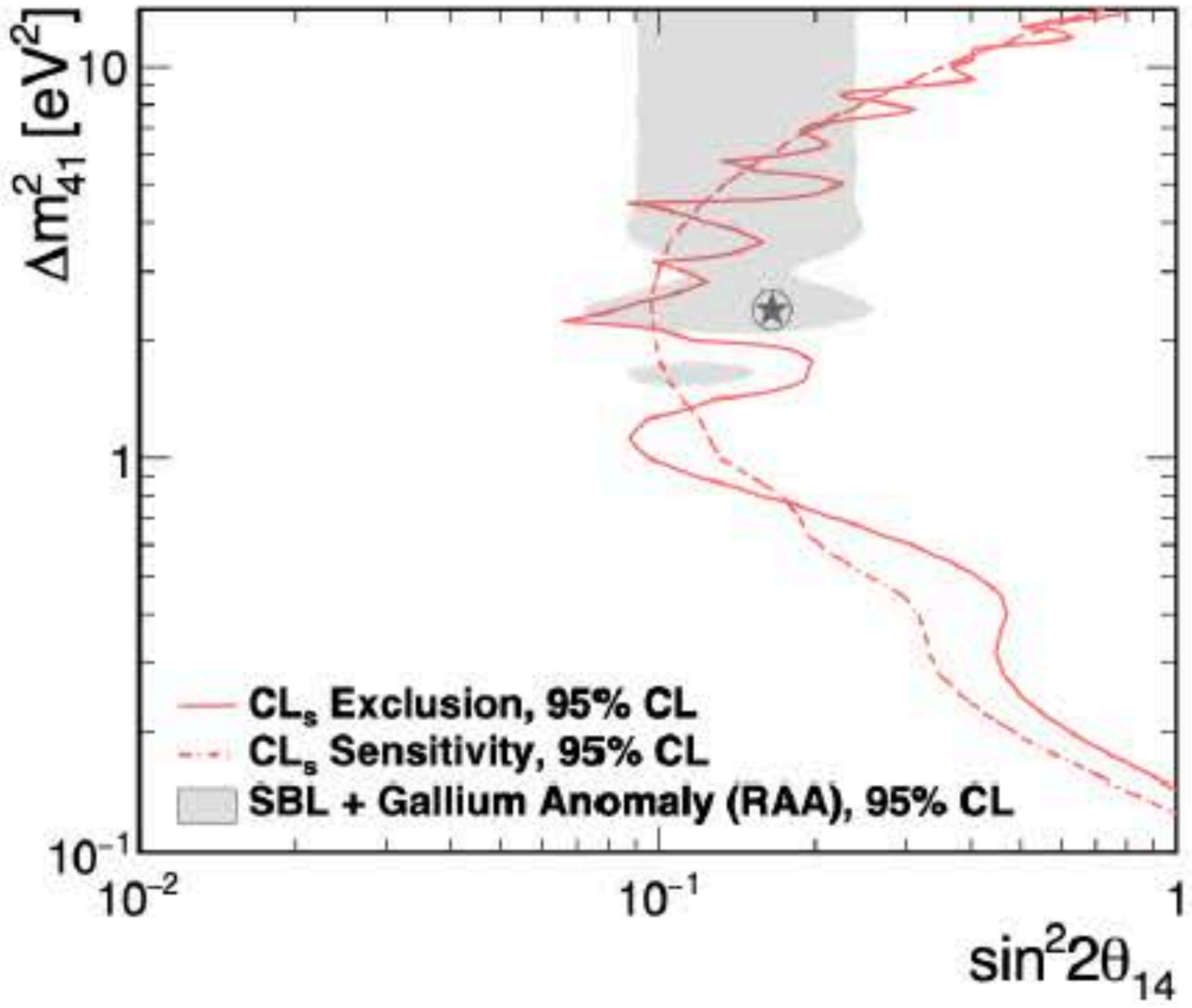
Set new limits on eV-scale sterile neutrinos

PROSPECT achieved principal goals - *What's next?*

Forthcoming Results from PROSPECT-I Data:

Oscillation

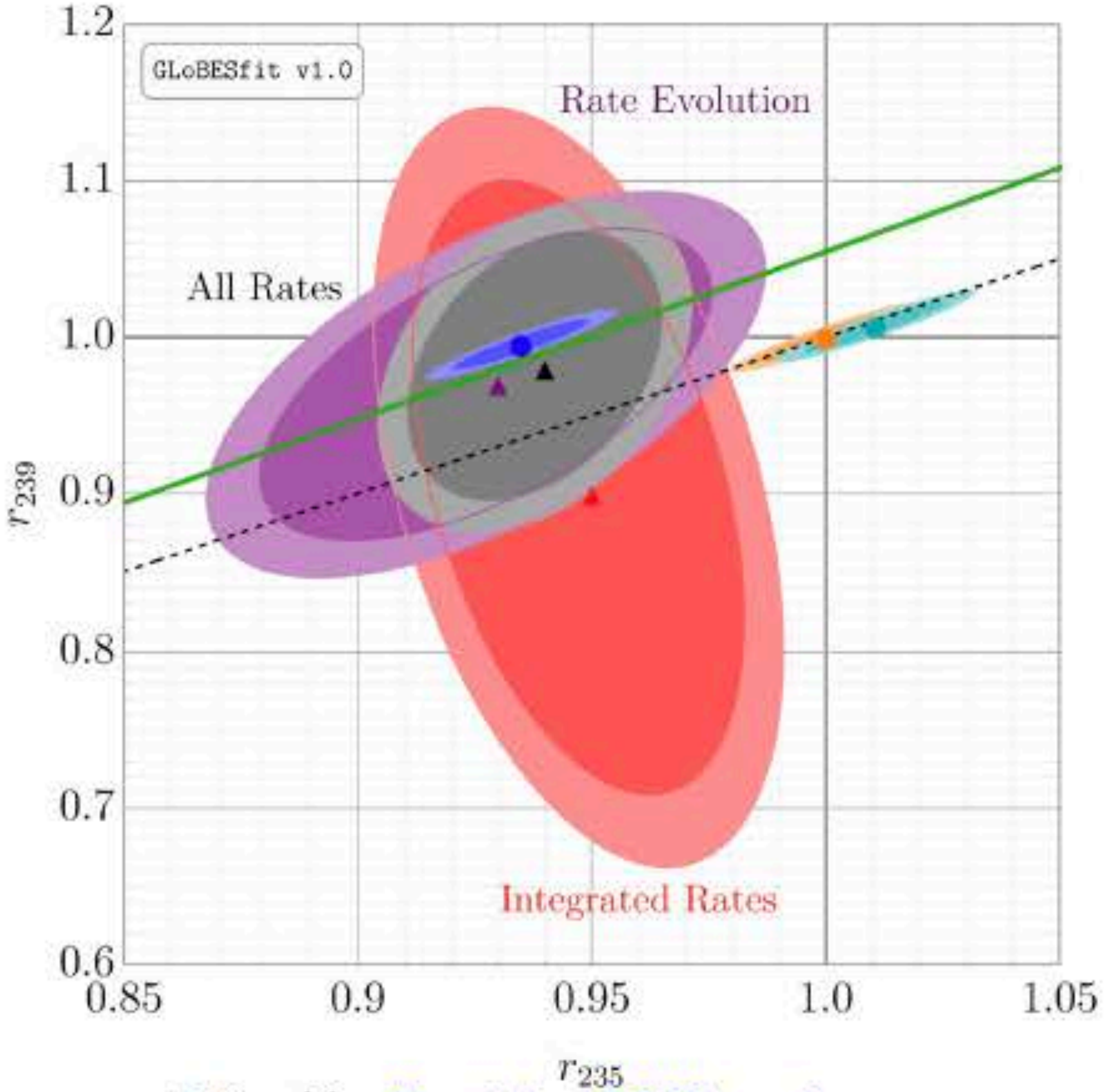
- Will perform 5-period oscillation analysis with PROSPECT-I IBD dataset
- Improved statistical power → improved oscillation sensitivity
- Finer baseline, multi-period, low-statistics binning requires CNP χ^2 to avoid bias
- Expect result in mid-2023



PROSPECT, PRD 103, 032001 (2021)

Absolute Flux

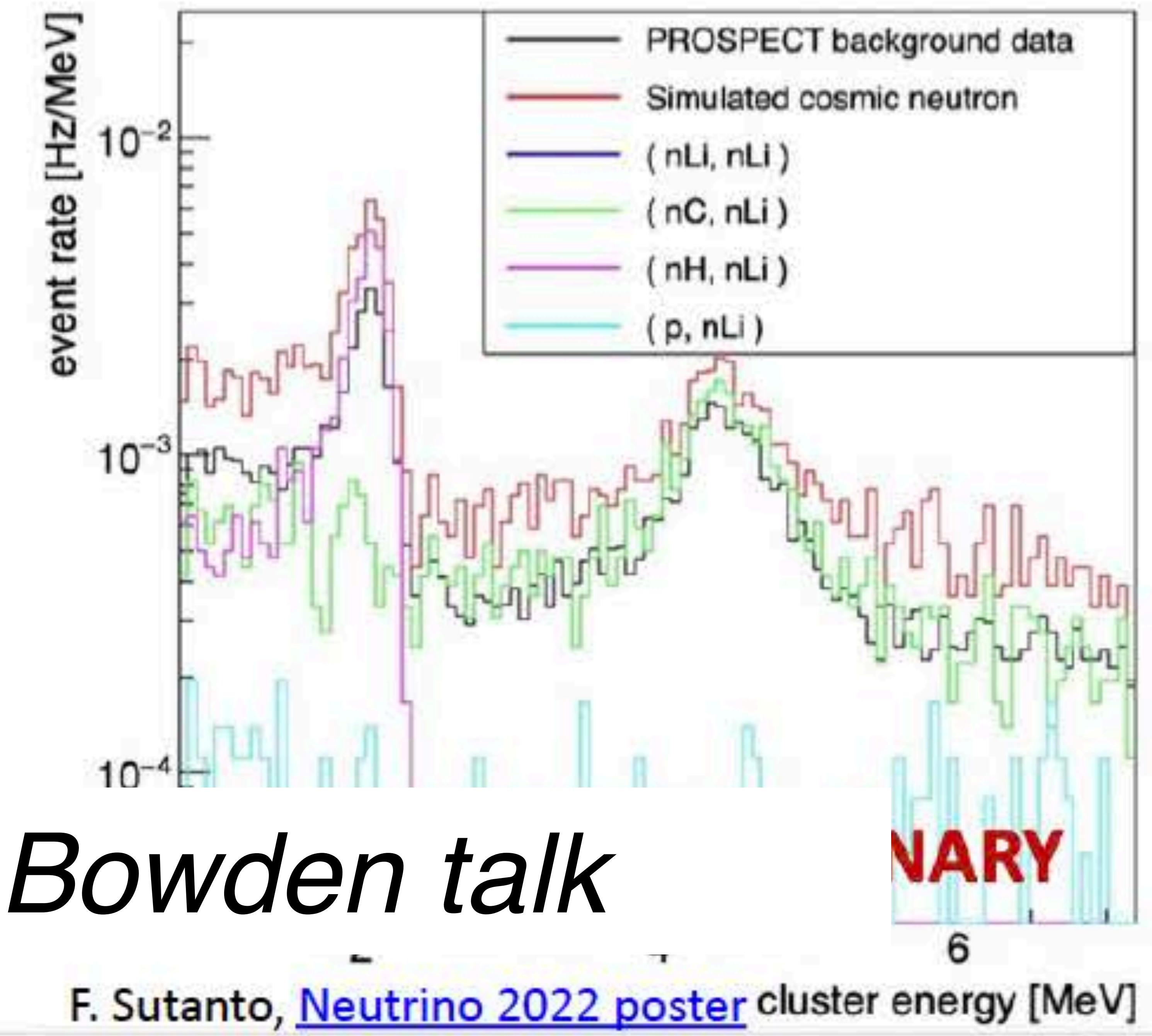
- New PROSEPCT-I measurement will further constrain ^{235}U yield w/ < 3% uncertainty:
  - Statistics better than 1.5%
  - Expect systematics ~ 2% (mostly Rx power)
- Anticipated result later in 2023
- Guides ~1.5% PROSPECT-II measurement to improve ^{235}U, ^{239}Pu, & ^{238}U yields



P. Kunkle, Neutrino 2022 poster

IBD Backgrounds

- Use PROSPECT-I data to provide insigh into background mitigation for aboveground IBD detection
- Have achieved reasonable data and simulation agreement & identified important background classes



N. Bowden talk

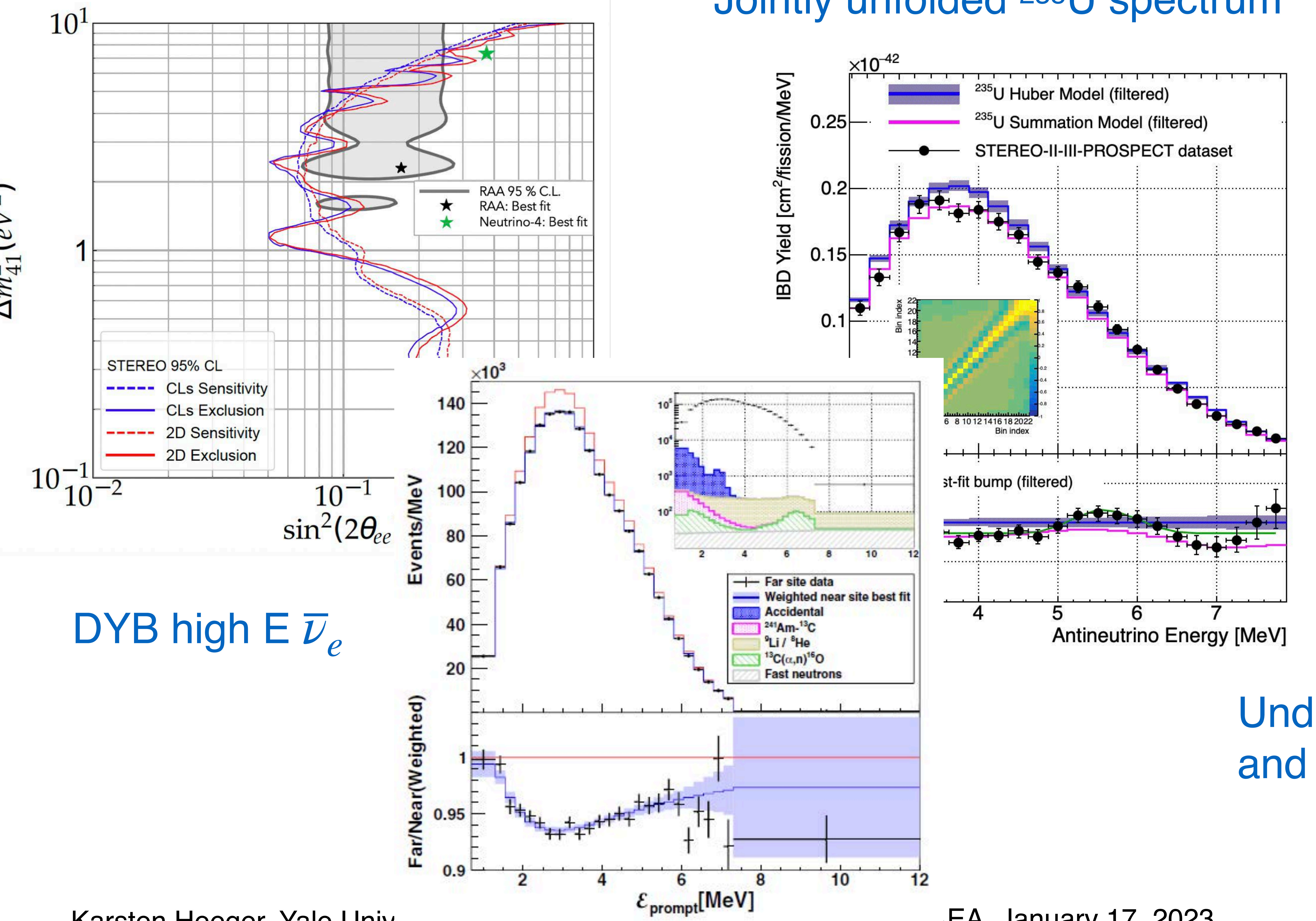
F. Sutanto, Neutrino 2022 poster

Results from Other Experiments

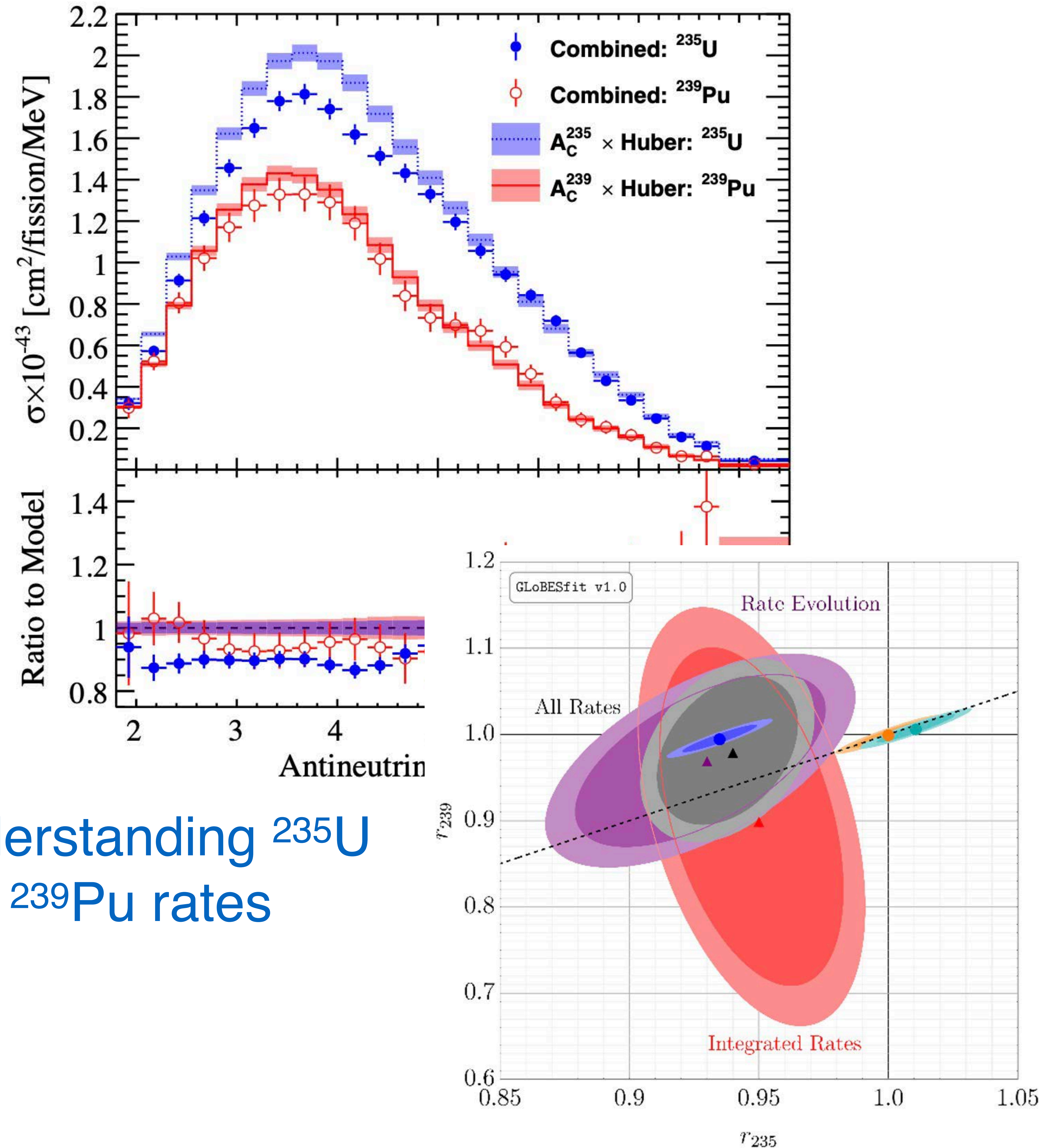
STEREO oscillation

STEREO+PROSPECT
Jointly unfolded ^{235}U spectrum

DYB+PROSPECT
Jointly unfolded ^{235}U and ^{239}Pu

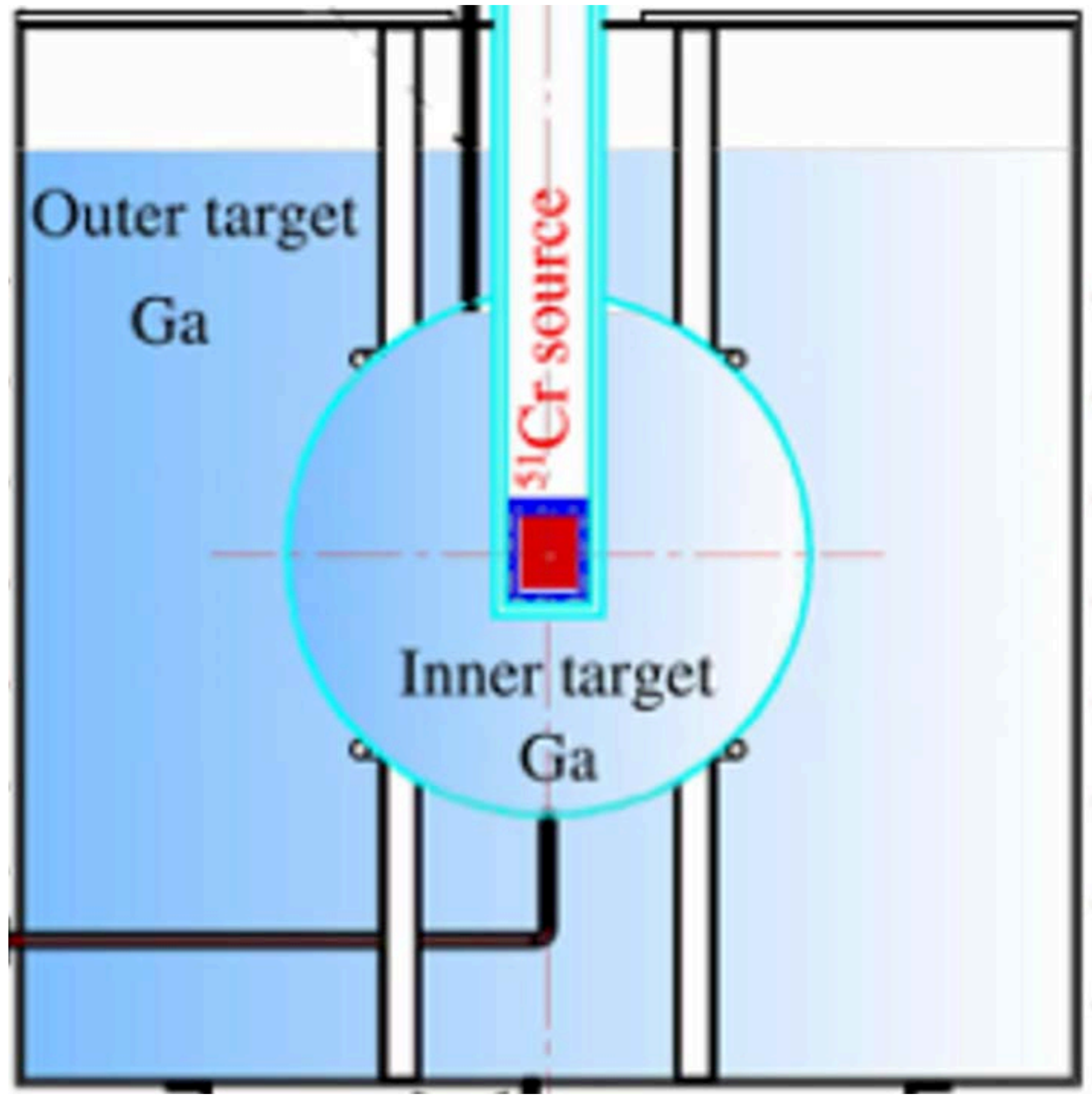


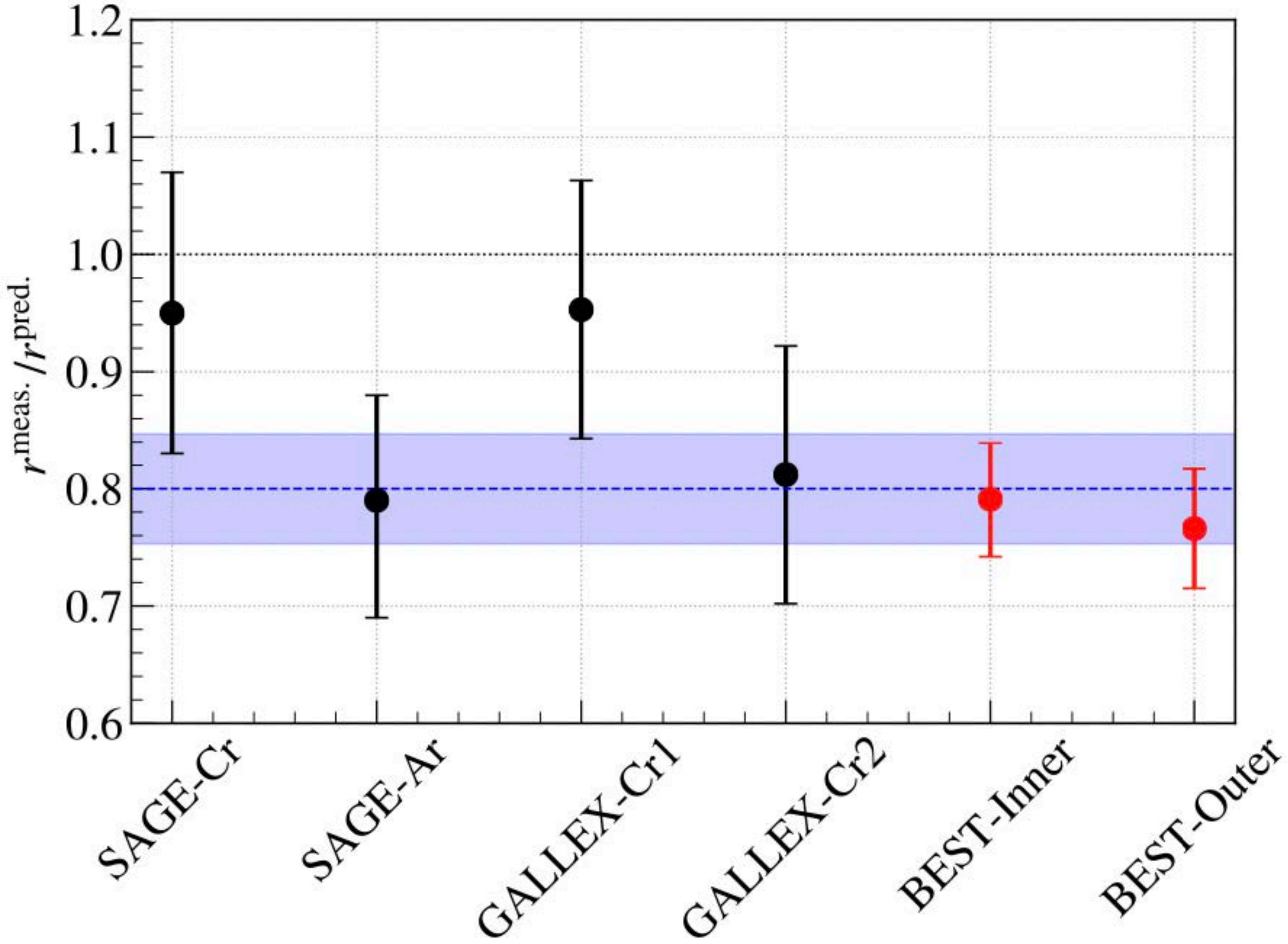
DYB high E $\overline{\nu}_e$

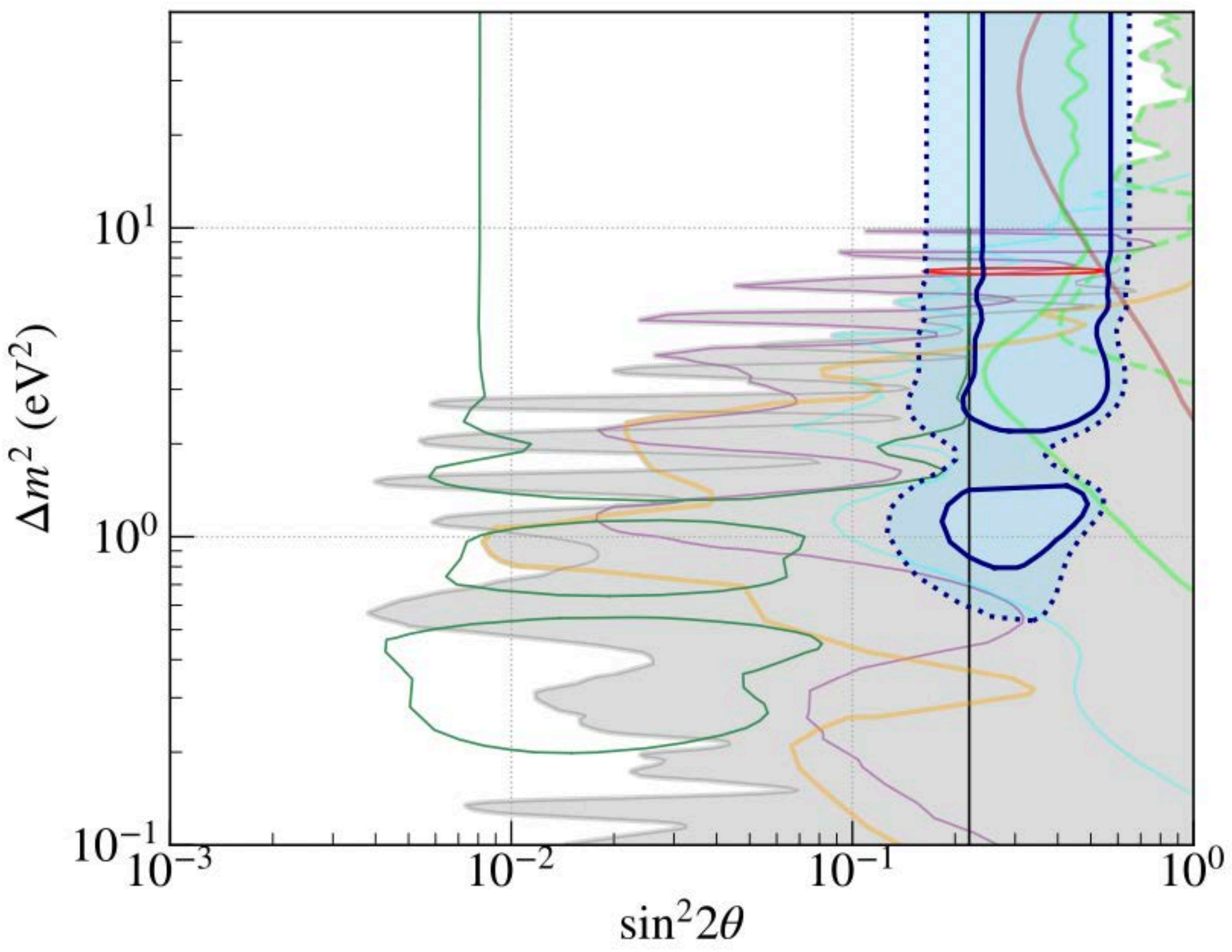


Understanding ^{235}U and ^{239}Pu rates

Ga Anomaly: BEST Experiment



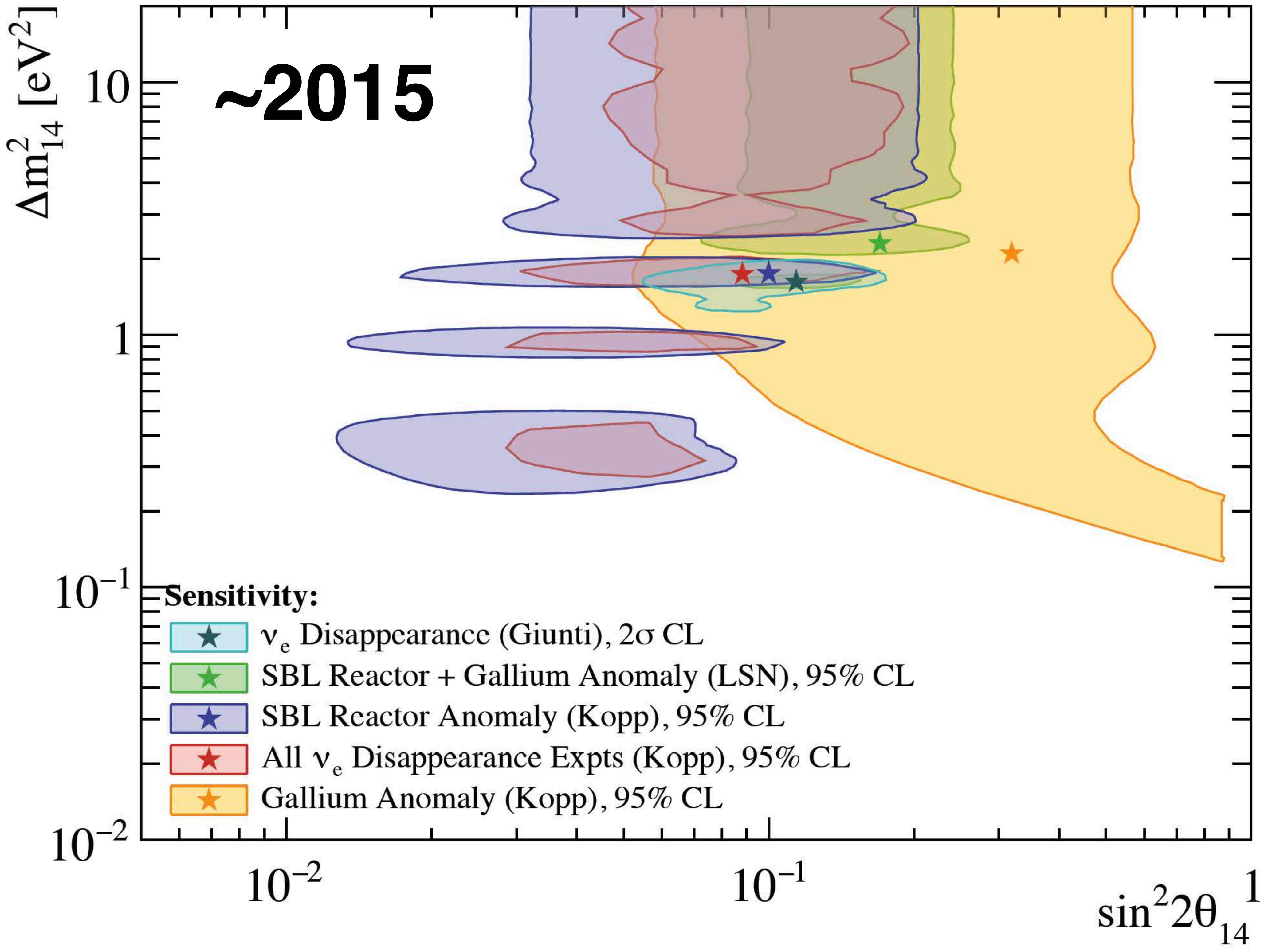


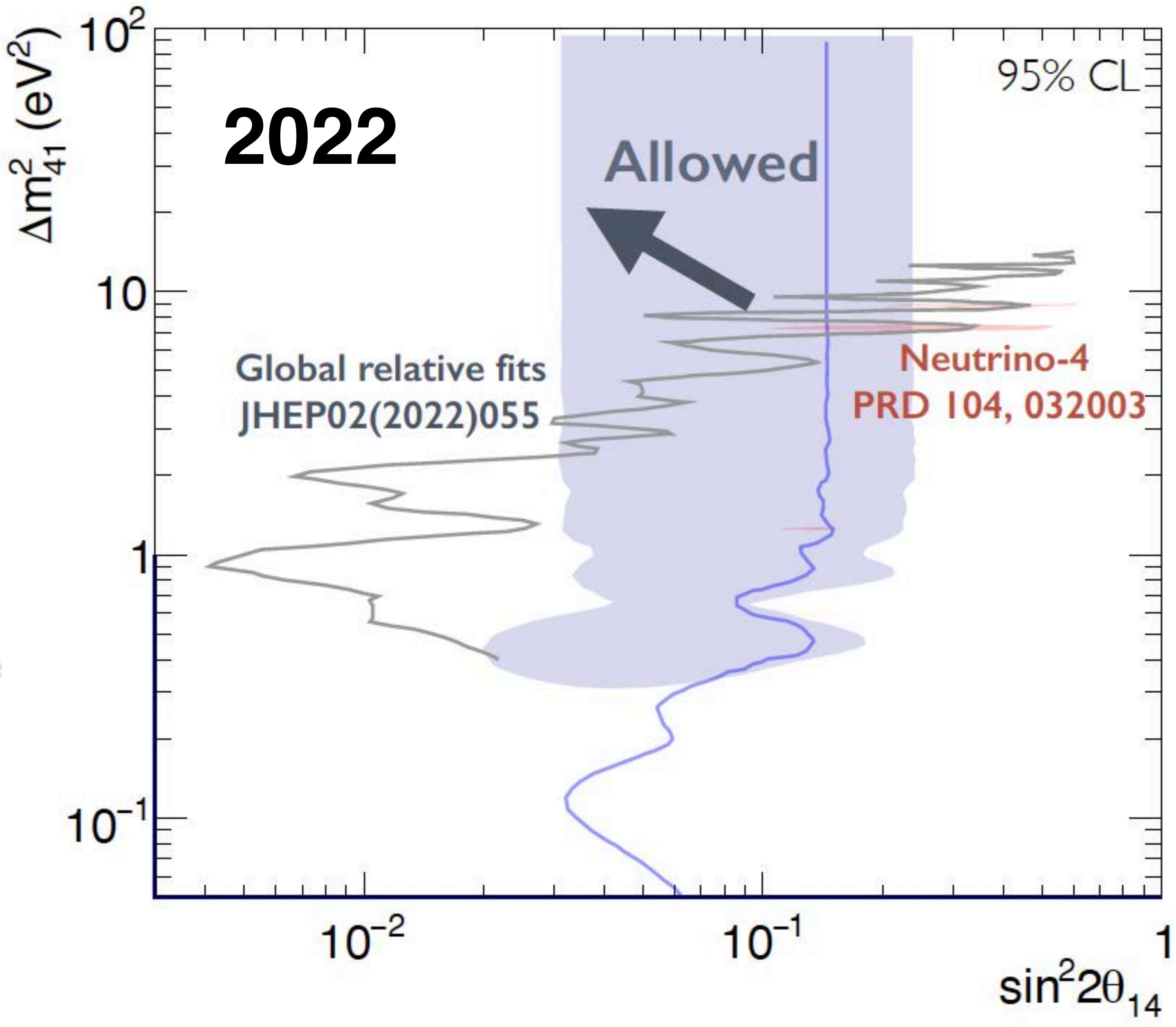


BEST, PRL 128, 232501 (2022)

- Solar neutrino experiments with an intense radioactive source: $^{71}\text{Ga} + \nu_e \rightarrow {}^{71}\text{Ge} + e^-$
- GA is recently confirmed by BEST experiment (~20% deficit in both inner and outer target volumes)
- Gallium experiments cannot disambiguate between effects arising from oscillations or an unknown production effect.

Short Baseline Anomalies: 2015 - Present





Reactor Antineutrino Anomaly **(RAA)** and Gallium Anomaly **(GA)** could be explained by eV-scale sterile neutrinos

Similar parameter space as suggested by the appearance experiments, prompted development of several SBL experiments

Significant portion of the suggested parameter space excluded**, high $\Delta m^2 > 5$ eV^2 yet to be excluded**

Spectral measurements are model-independent

Reactor + Gallium + β-decay + Solar Experiments

Global Constraints

Major portions of 3+1 suggested parameter space by GA excluded by relative reactor spectral data,

KATRIN starting to exclude parameter space from high Δm^2

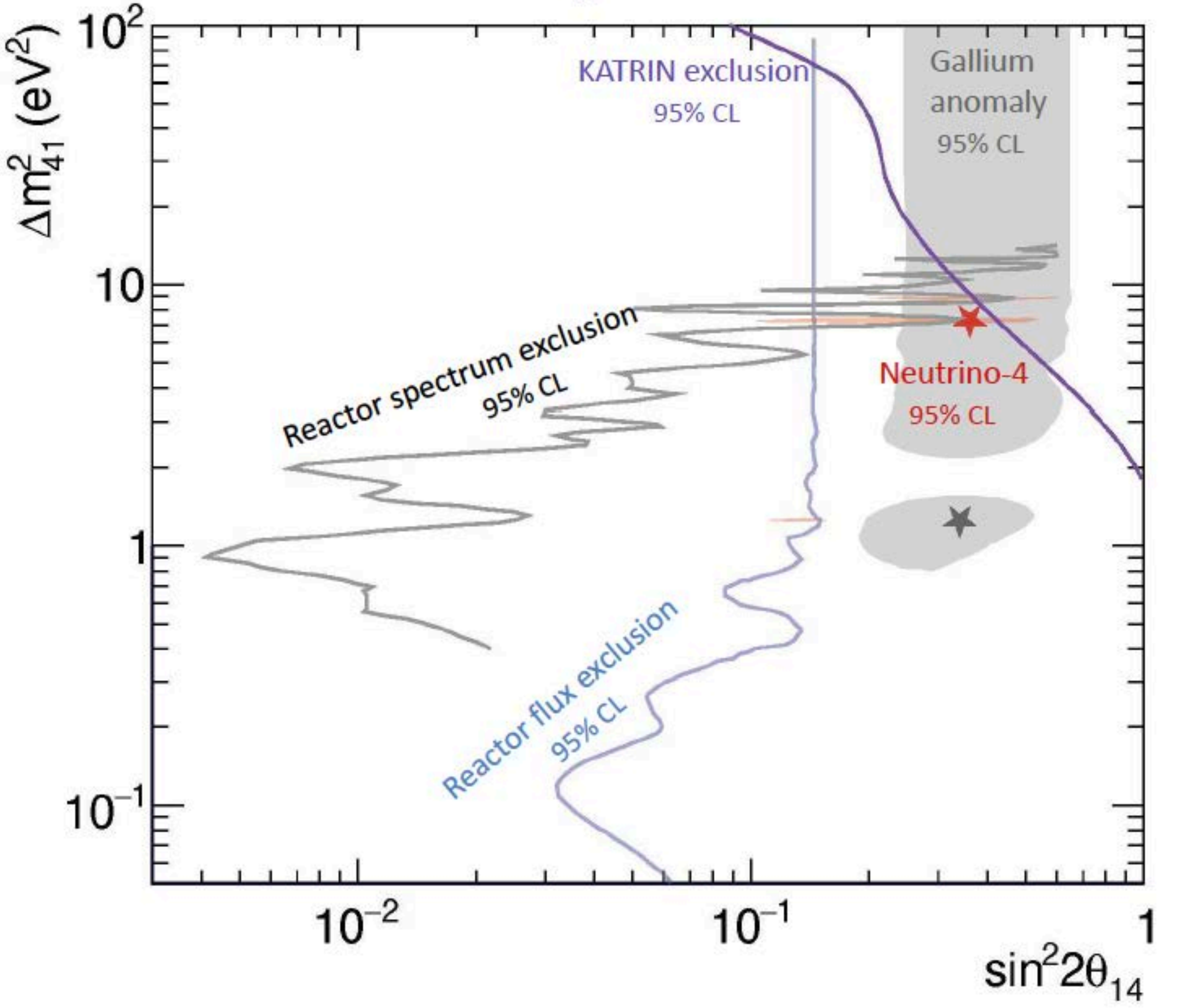
Solar experiments exclude all of the suggested parameter space in agreement with reactor rates

The deficit from GA is too high to be compatible with reactor rates

3+1 model seem increasingly less likely to explain combinations of datasets

Baseline-dependent reactor spectra are needed to fully exclude eV-scale sterile neutrinos

Global (θ_{14}, Δm^2) results



Remaining Neutrino Anomalies

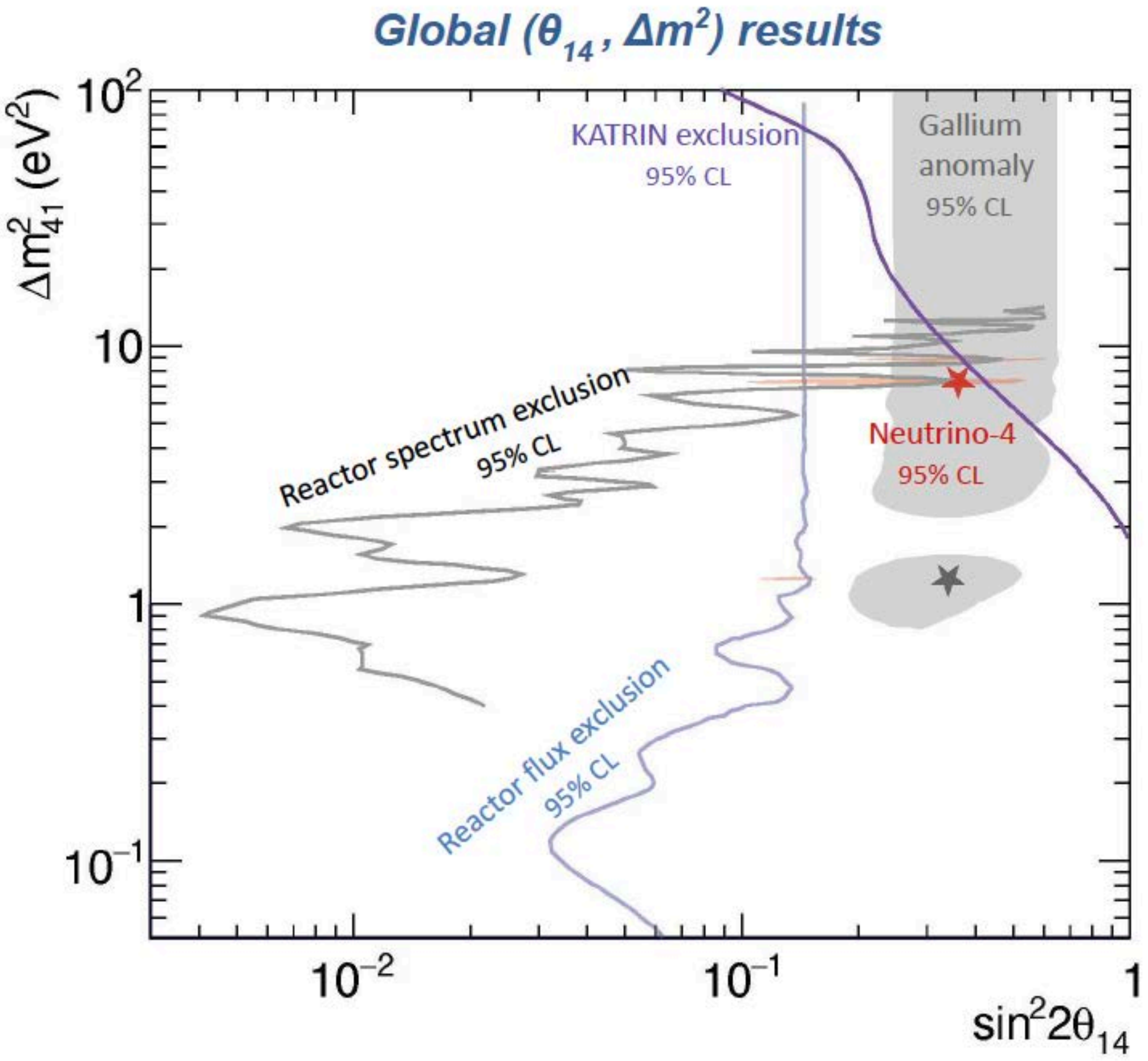
Gallium & Reactor Flux Anomalies

- BEST has strengthened GA, in tension with reactor experiments
- Updated reactor flux and spectrum exclusions only limit $\sin^2 2\theta_{14}$ to ~0.1 at high Δm^2
- Neutrino-4 claim of L/E oscillation discovery remains; other experiments note non-zero best fit points

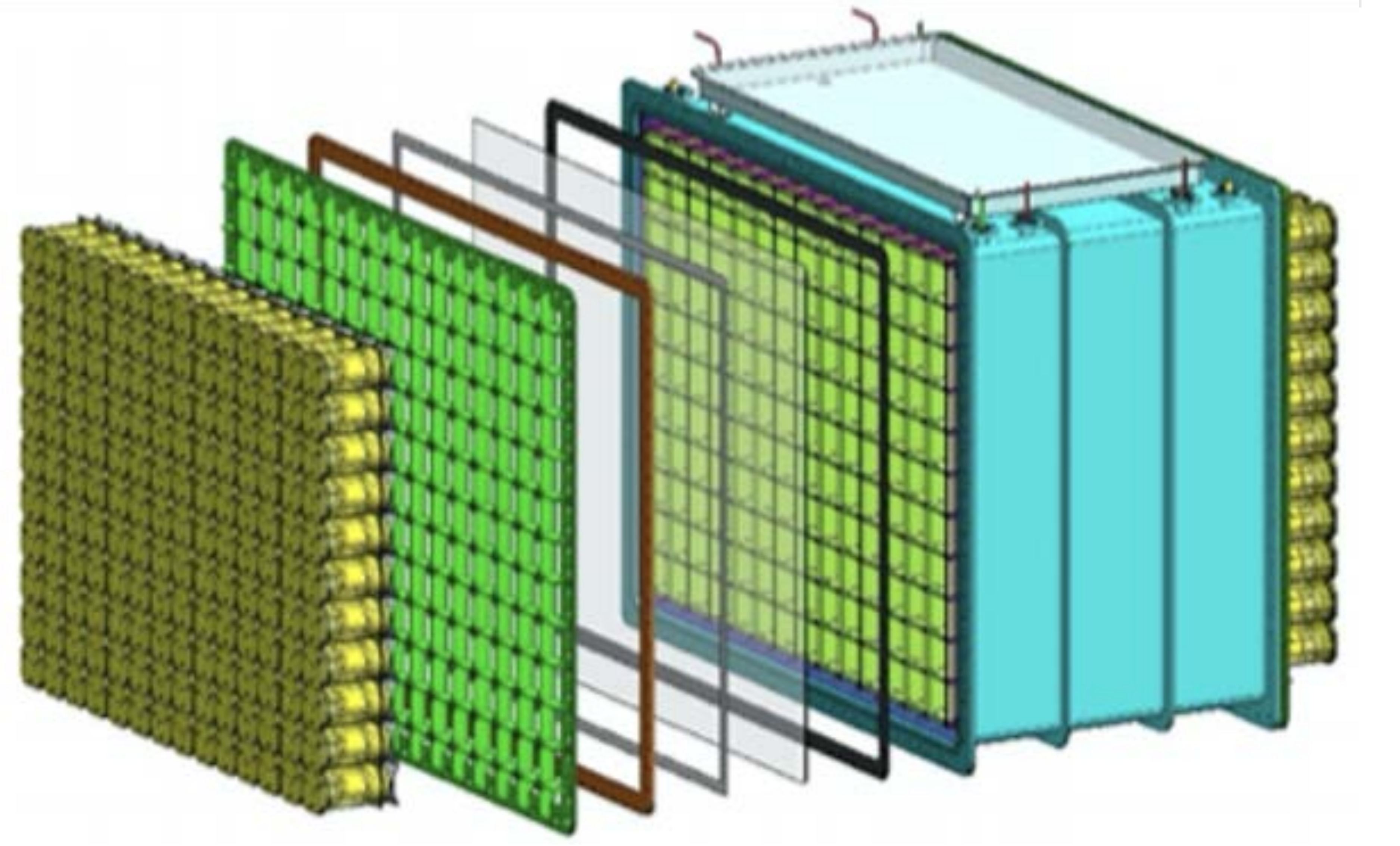
Looking Beyond θ_{14}

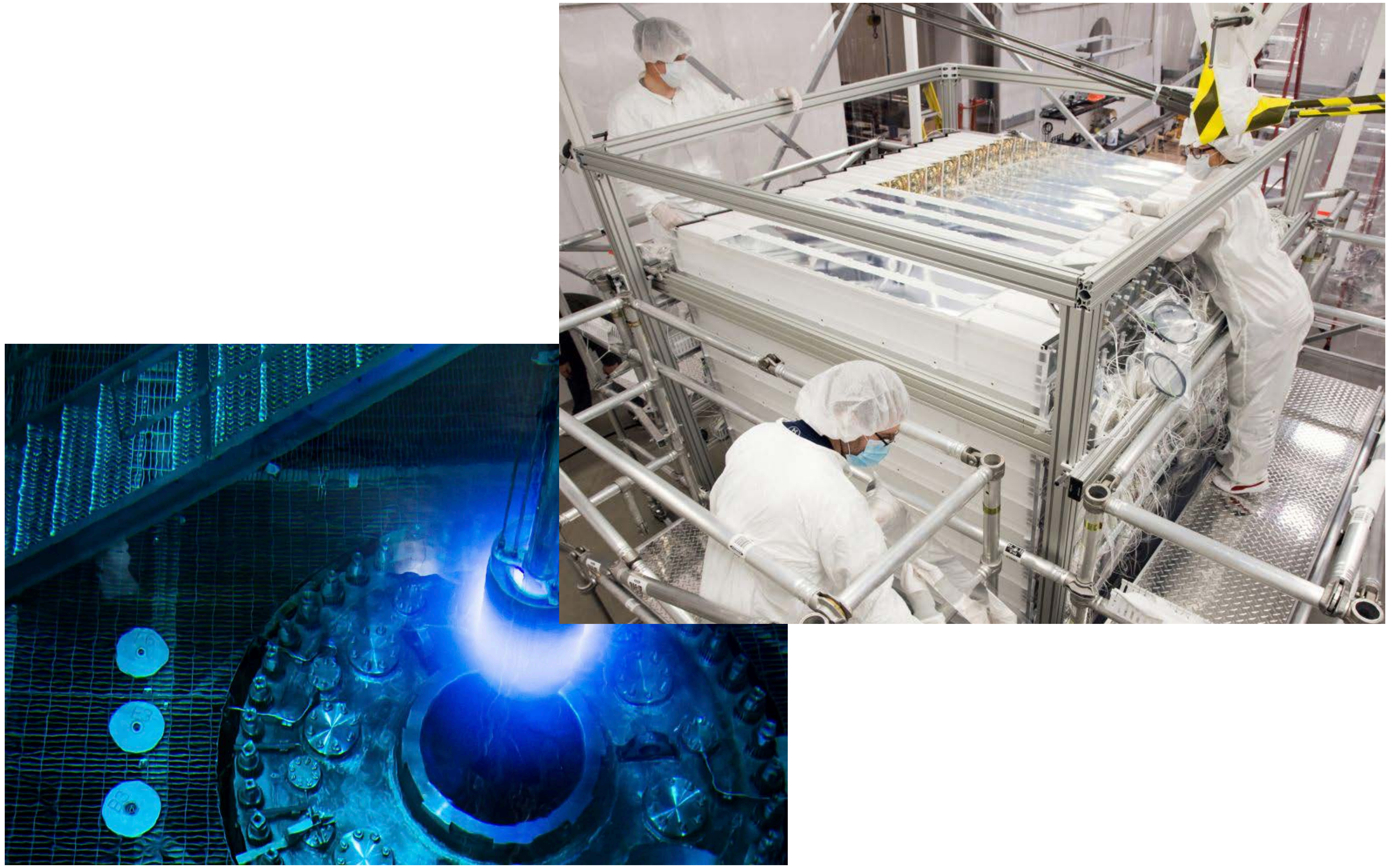
- Electron-flavor contribution to LSND and MiniBooNE anomalies remains unknown
- Potential for BSM anomaly explanations

Opportunity to explore BSM physics



Going Beyond PROSPECT-I





PROSPECT-I Performance

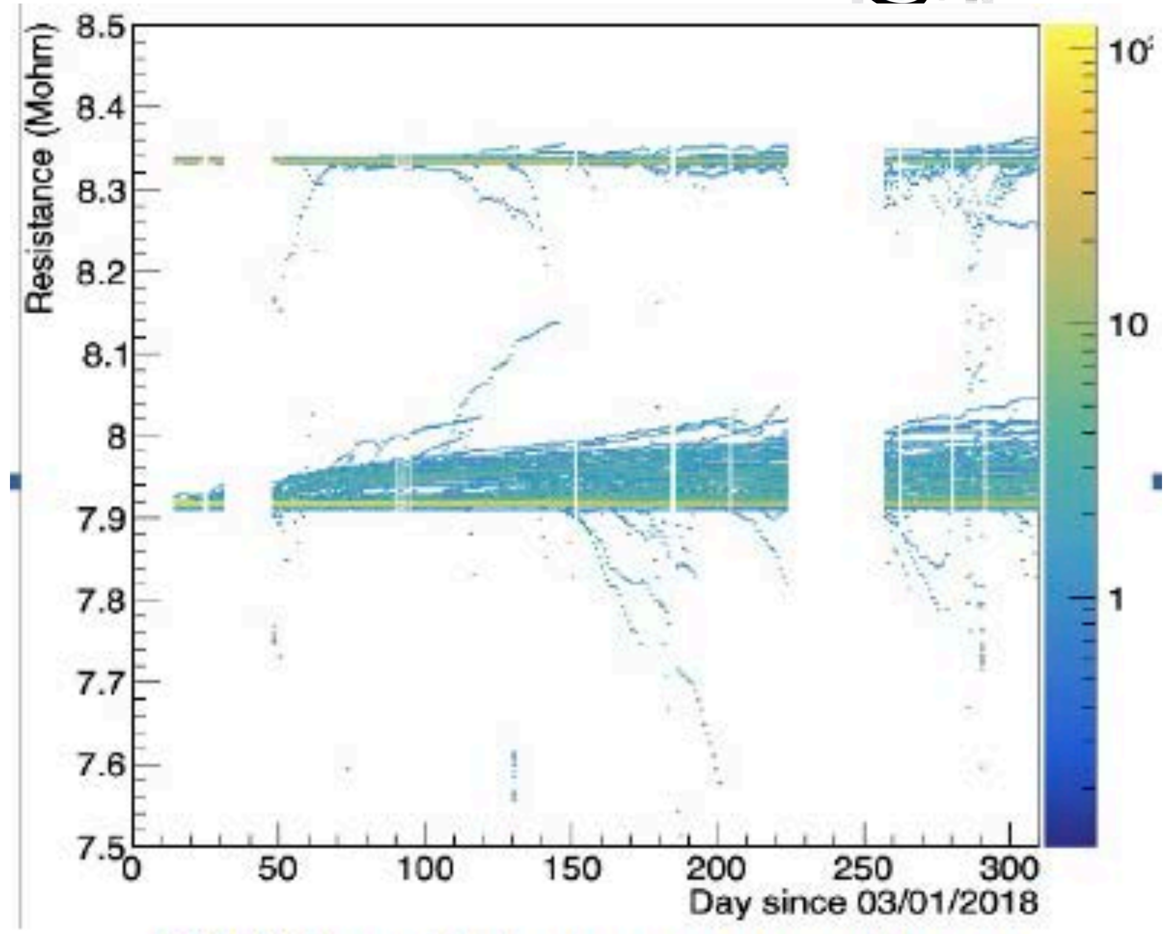
Detector degradation

Shortly after turning on detector, PMTs started showing anomalous resistance and were turned off

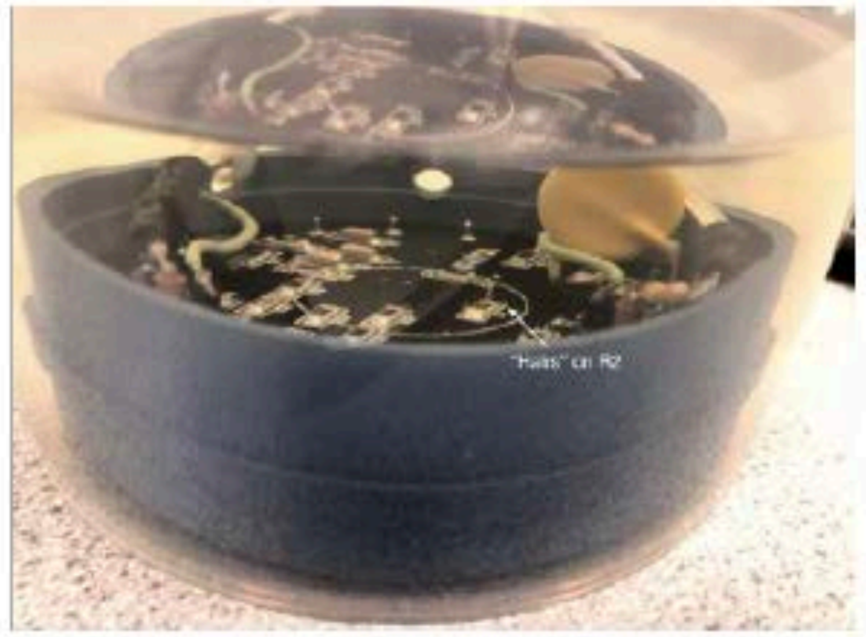
- Understood as LiLS ingress into housing
- Bench tests have reproduced behavior

Light collection calibration curves showed consistent trends throughout detector and over time

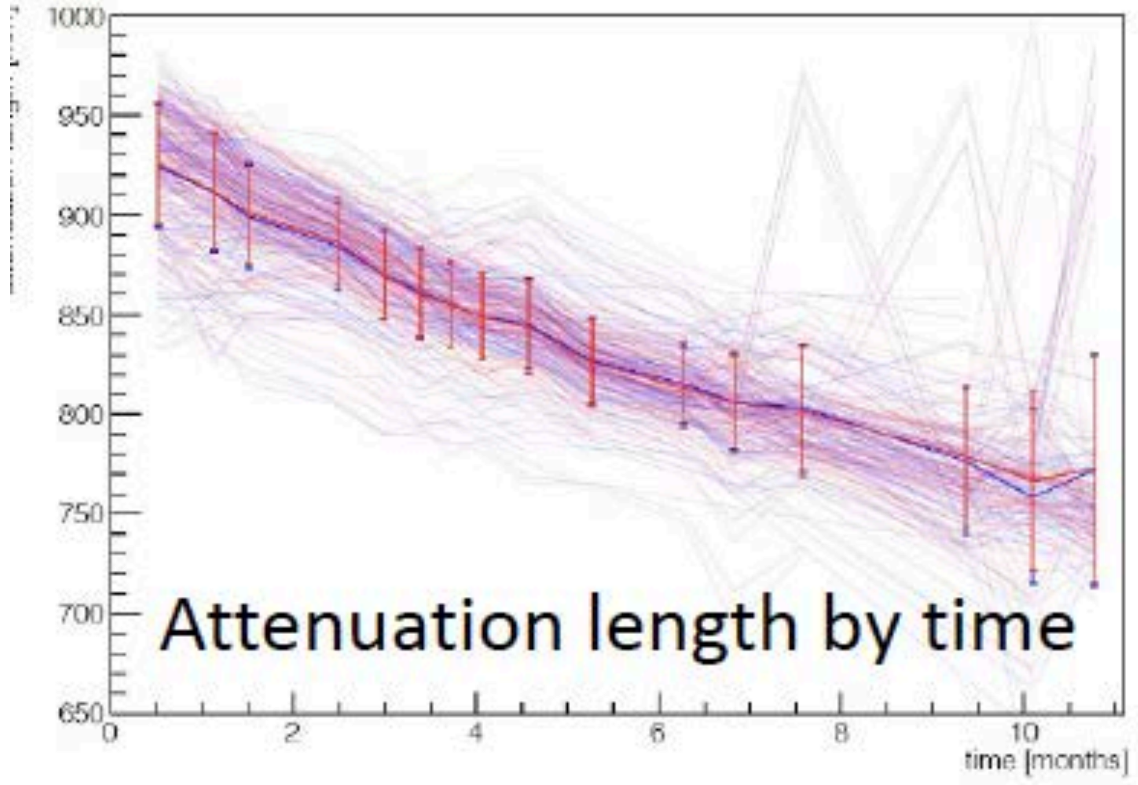
- Both effective attenuation length and light yield degraded ~ 10-15%
- Energy resolution degrades (e.g. P-I Eres 4.5%→5.6% @ 1 MeV)
- Eventual loss of ability to select ^{6}Li capture at segment end



PMT resistance over time



LiLS benchtop divider tests



Attenuation length by time

PROSPECT-II: Evolution of PROSPECT-I

Performance **+ Stability**

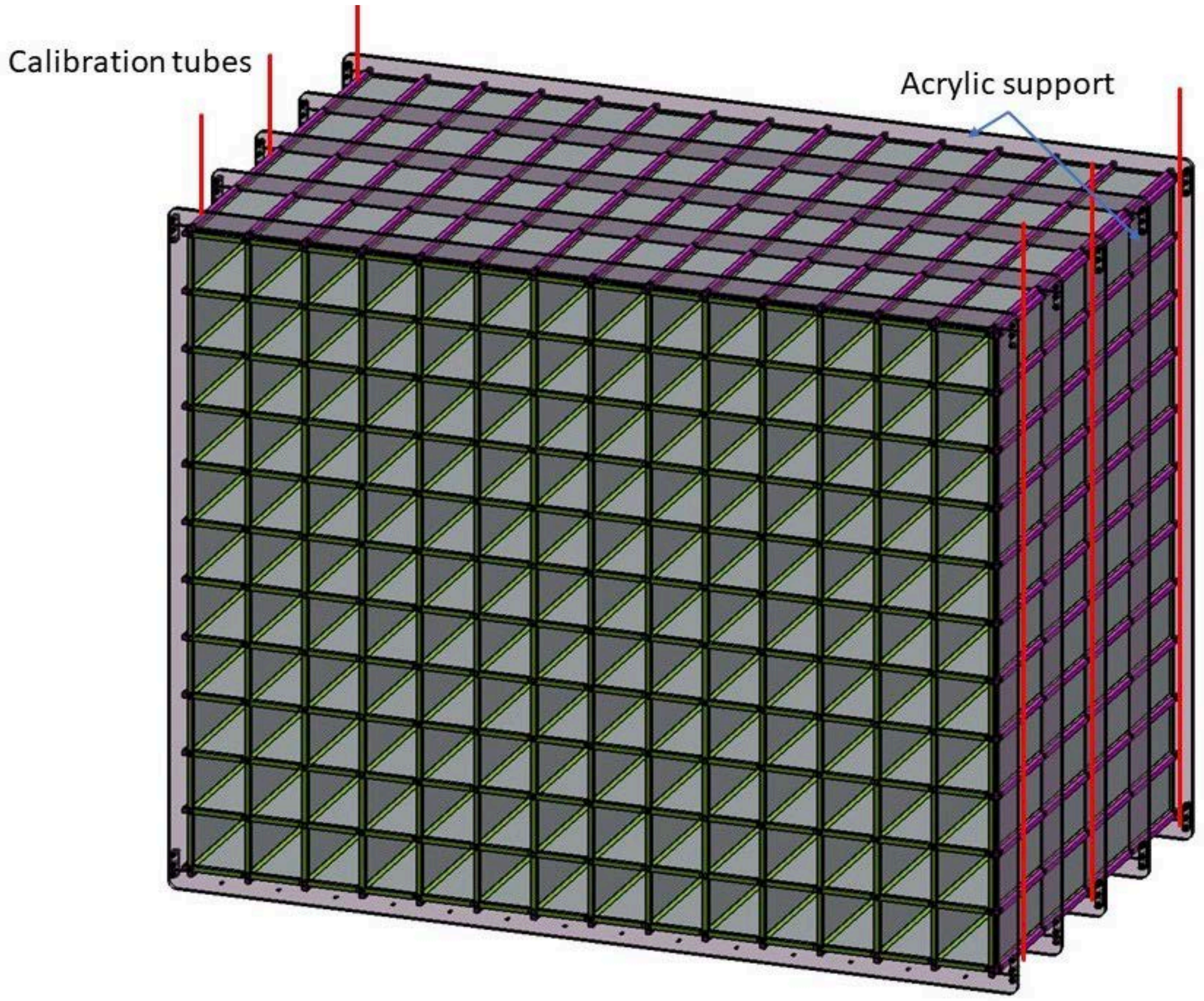
Match initial performance while improving stability (maintain similar segment pitch, same scintillator formulation, etc…)

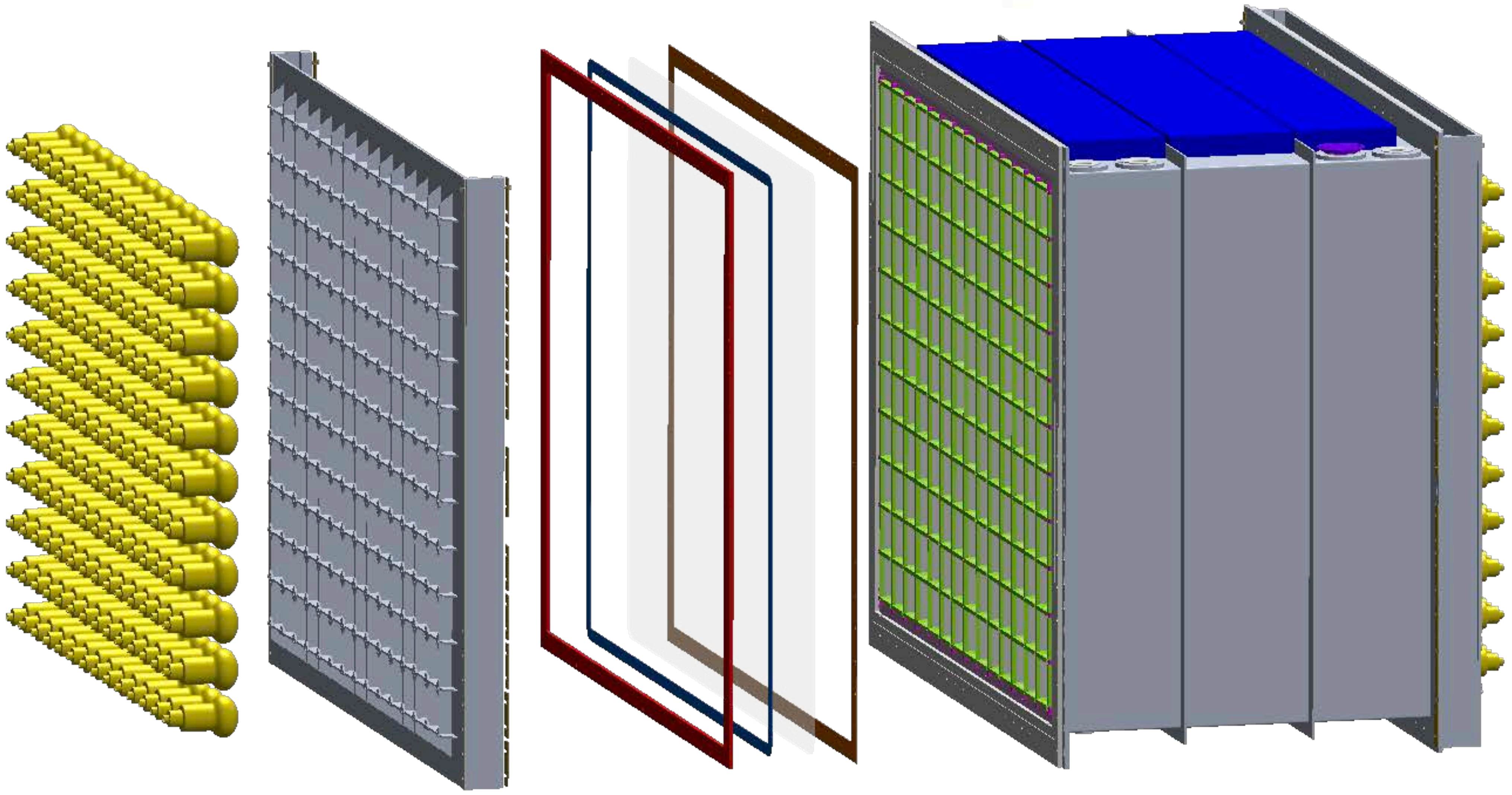
Remove PMTs from active volume and unify type

— Essentially eliminates P-I failure mode
— Replace 80 ET tubes to increase detector uniformity
— Additional 70 reduce risk of reuse
— All new potted voltage dividers

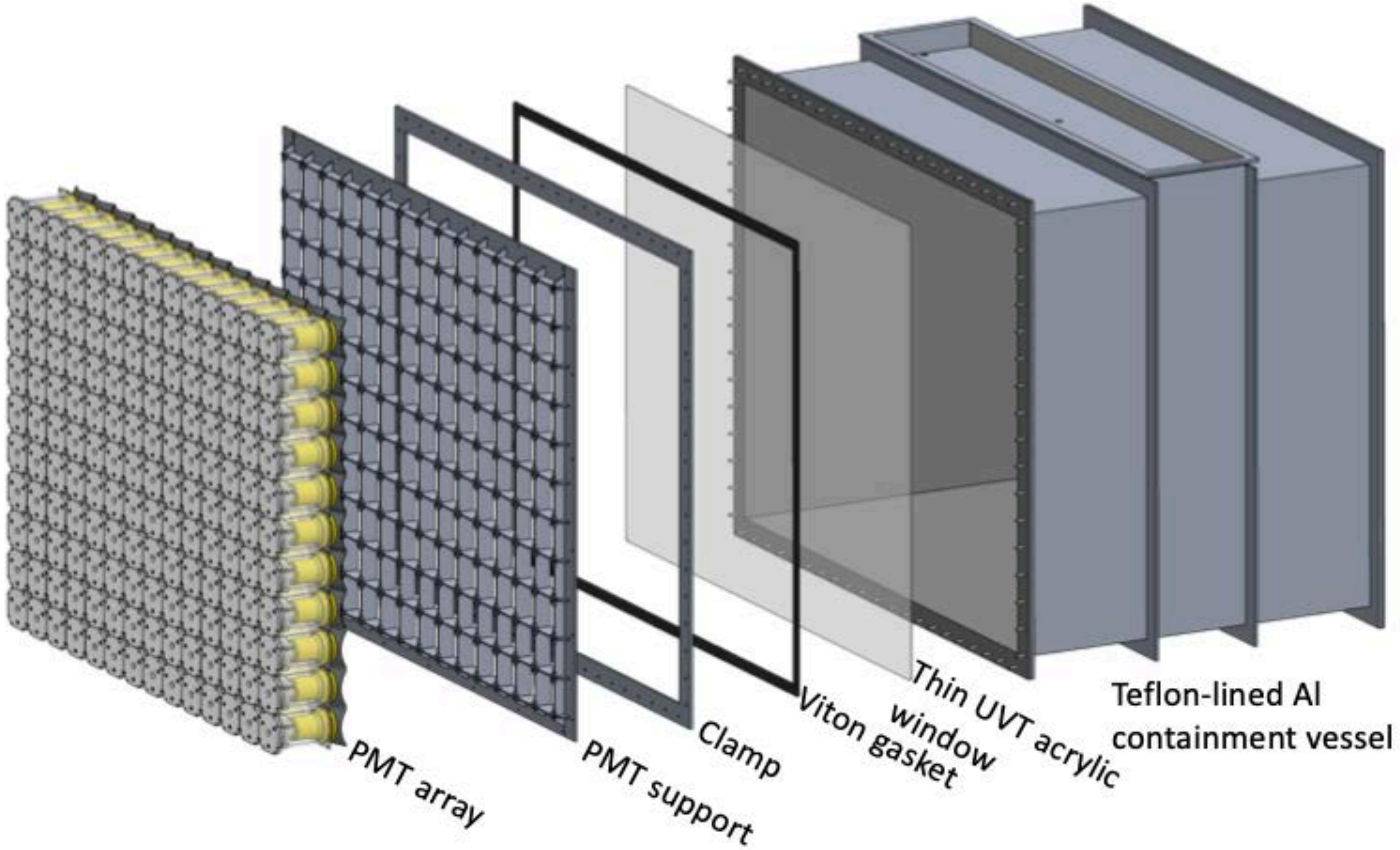
Reduce LiLS exposure to materials

Reduce oxygen quenching, improve cover gas control





PROSPECT-II Design



High ~ 4:1 signal:background ratio

Planned ~2 year deployment at HFIR, ORNL

~50% reactor on-time

Retains successful elements of PROSPECT-I

- 14x11 optically segmented ^{6}Li-doped liquid scintillator with minimal shielding

- located 7-9m from HEU core of HFIR (+ possible LEU site)

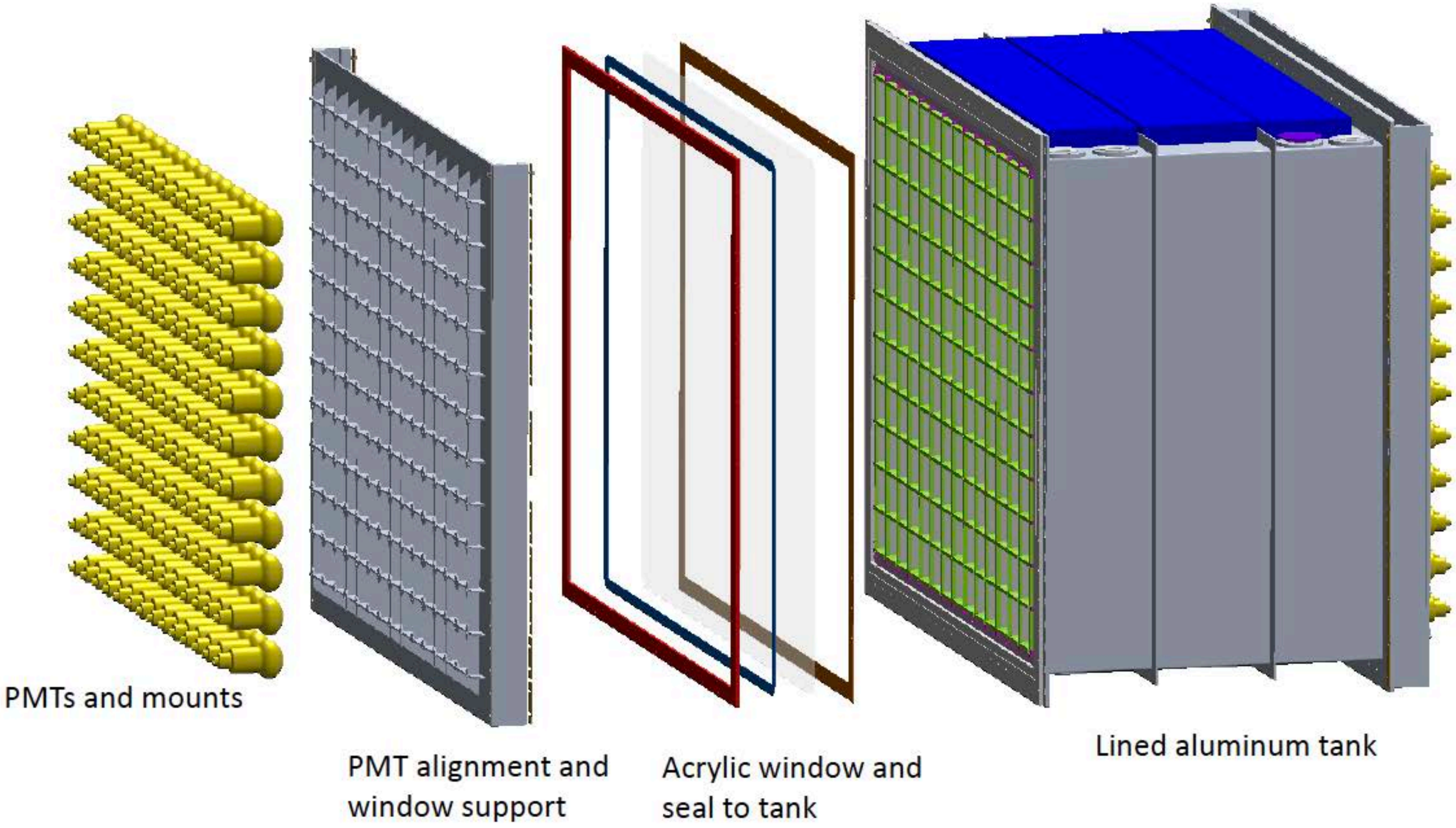
Moves PMTs out of liquid scintillator volume to avoid contacts with other materials

Increases signal collection capacity with 20% longer segments, 20% increased ^{6}Li loading, longer data-taking period -> 10x effective statistics at HFIR

External calibration system instead of calibration tubes inside active volume, simplifies design

Designed to deploy at multiple sites

PROSPECT-II Design



Finishing design details, ready to be built

PROSPECT-II Inner Containment Vessel

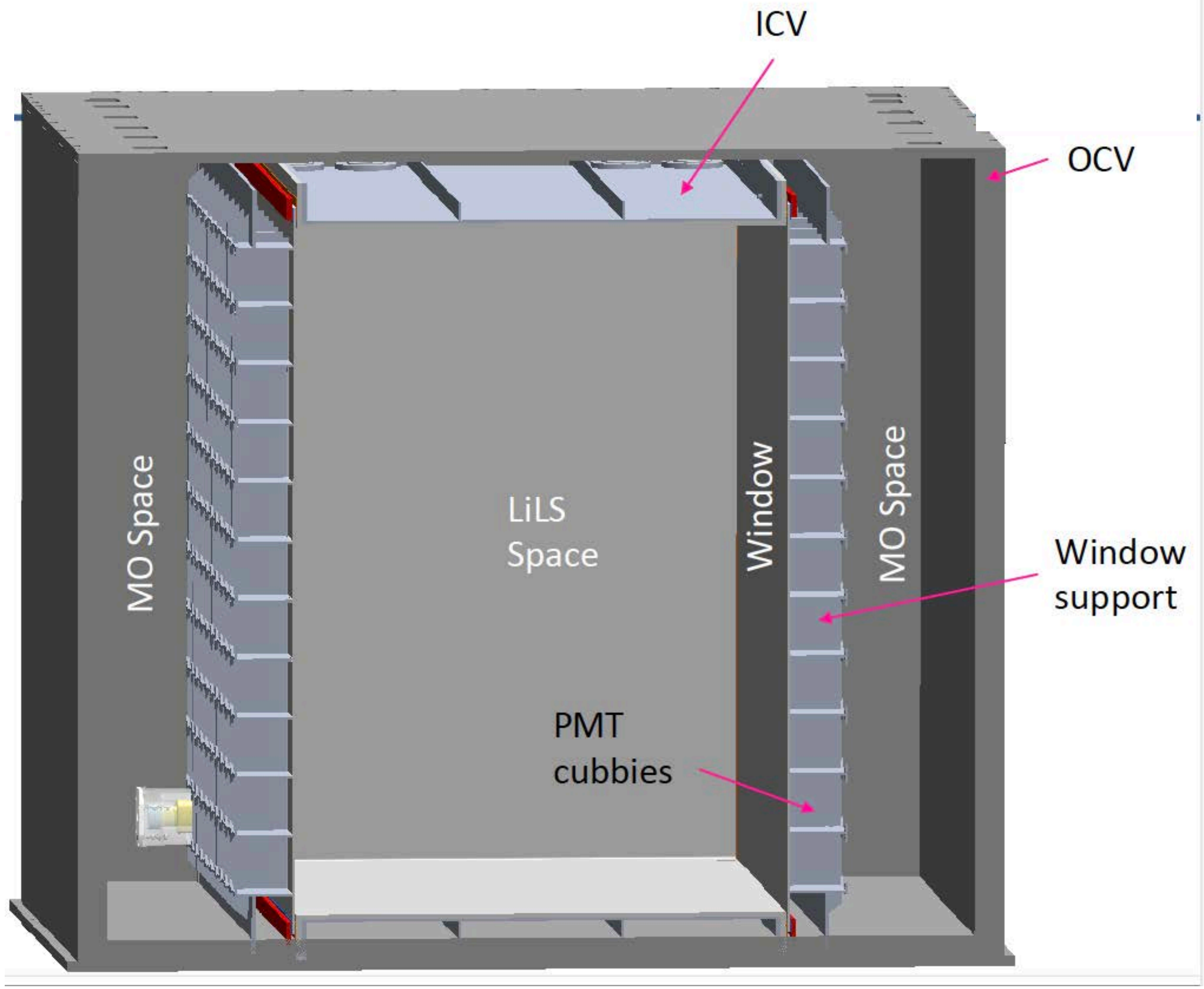
The inner tank (ICV) and its windows separate the LiLS and MO.

Only LiLS, optical lattice, source tubes are inside the ICV.

ICV tank and outer containment are filled and drained simultaneously to reduce hydrostatic pressure.

The acrylic windows are 0.25 inches thick and are supported from the outside by the window support structure, which also supports the PMTs.

The ICV tank is welded aluminum and rotolined with ETFE fluoropolymer. This protects the LiLS and the tank metal from each other.



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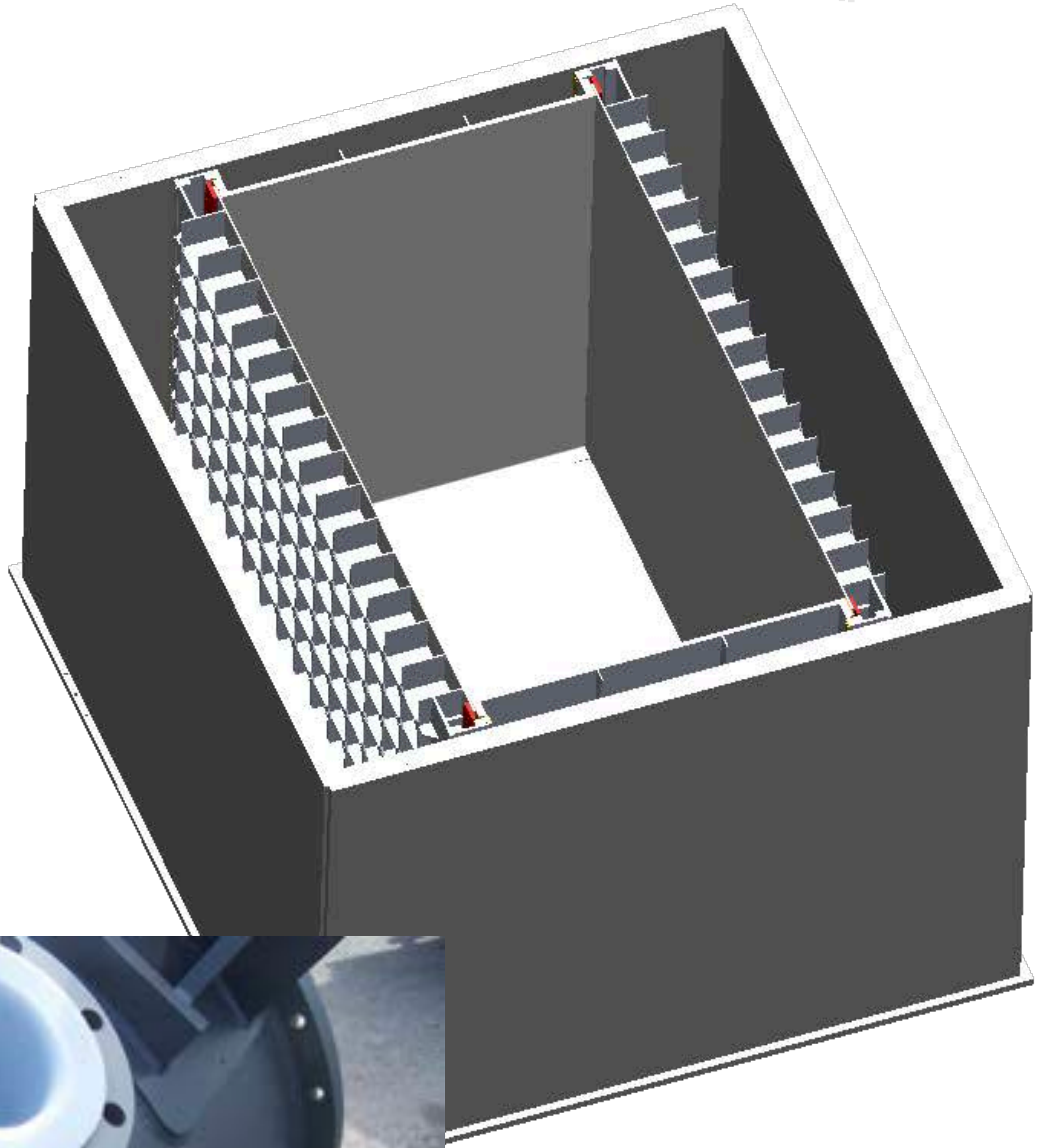
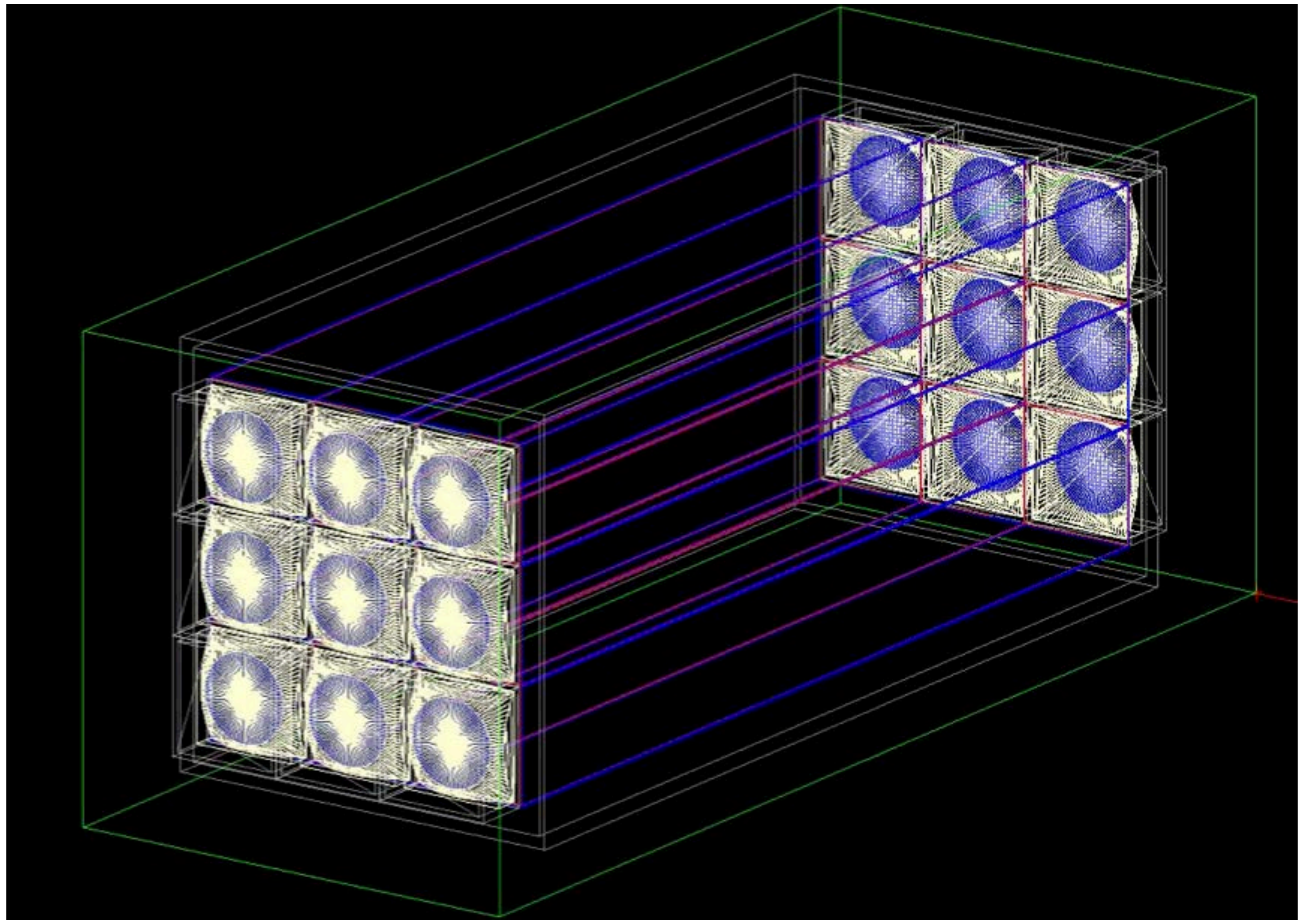
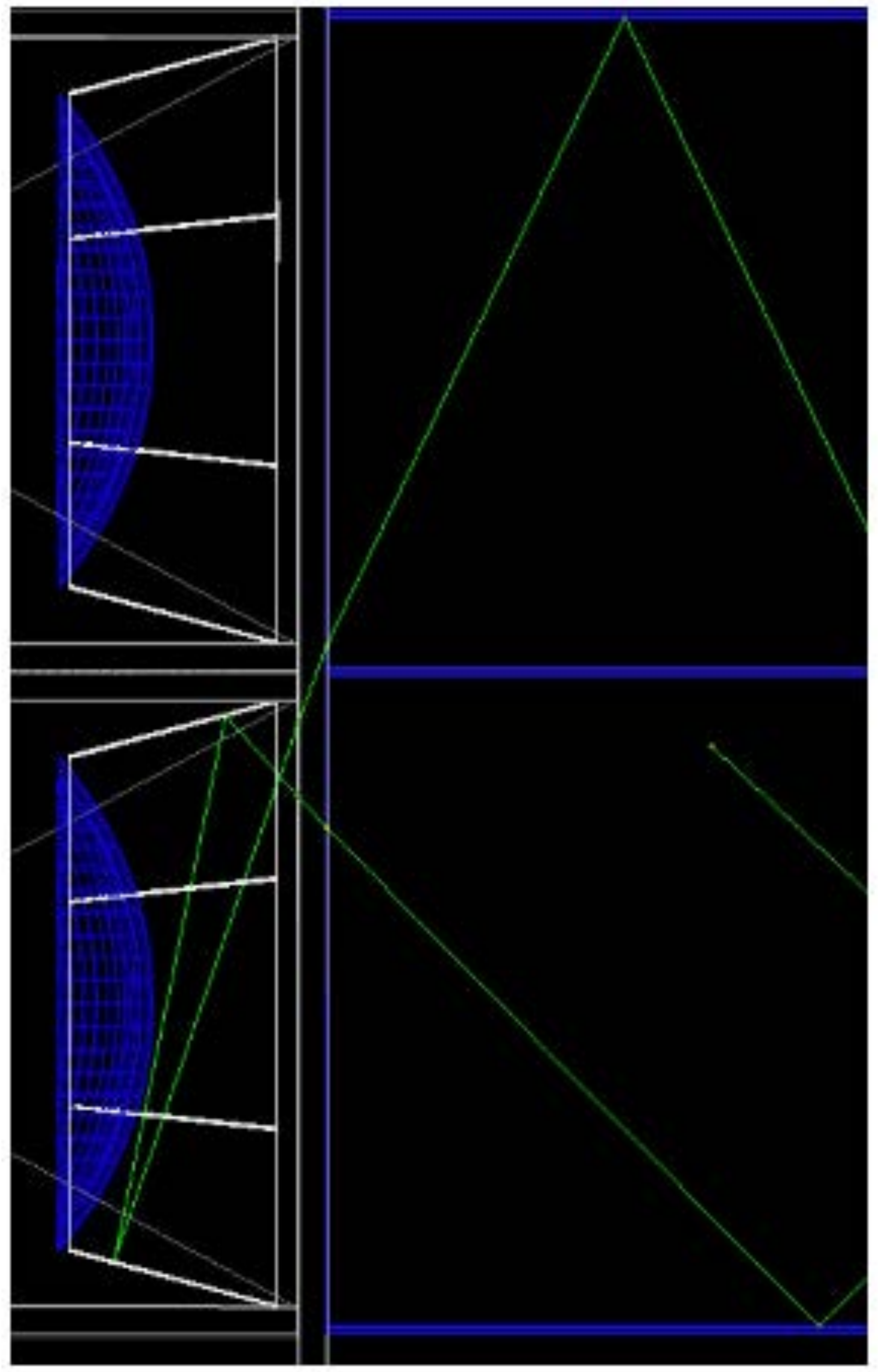
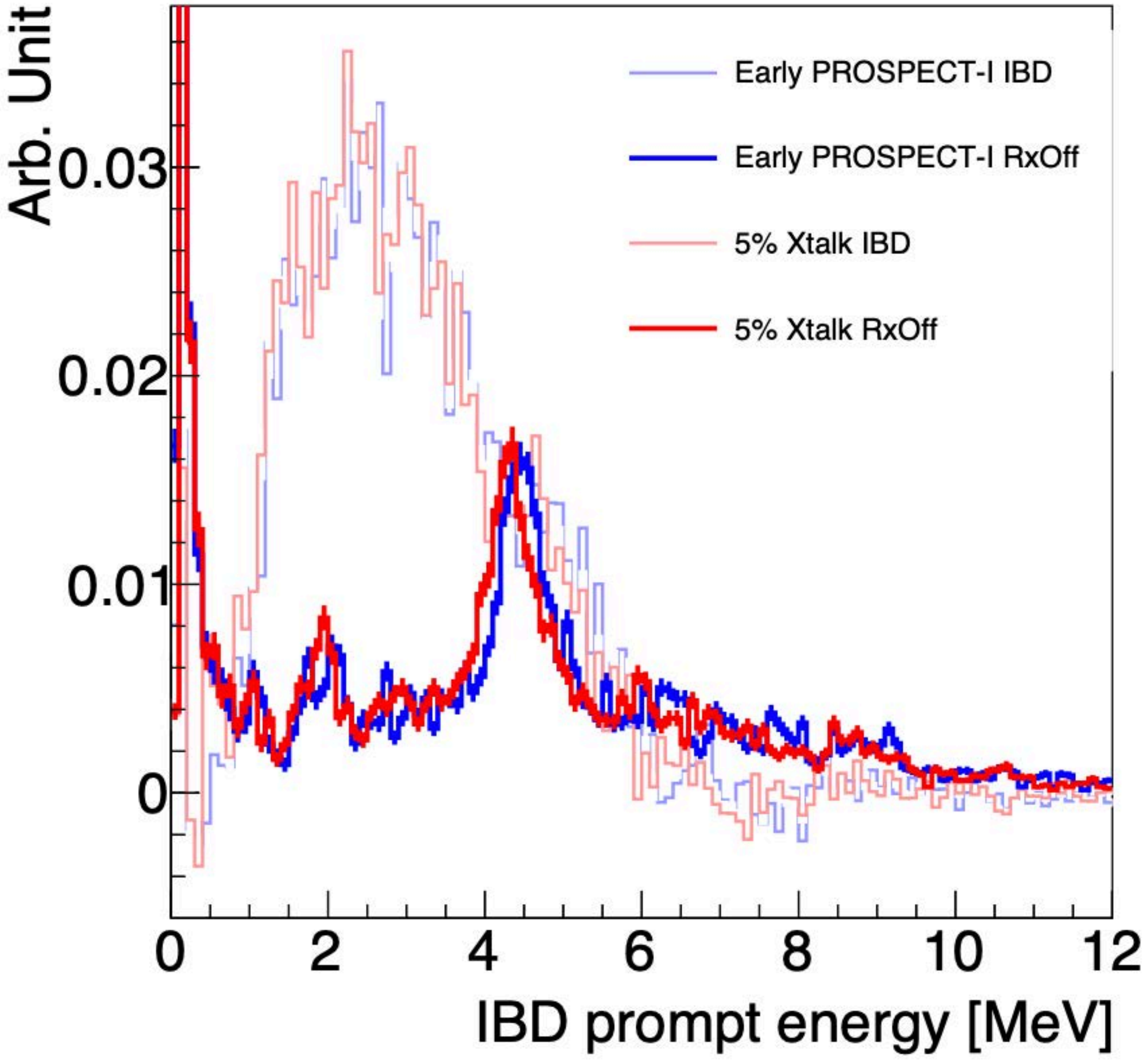


PROSPECT-II PMT Interface

Cross-talk between segments







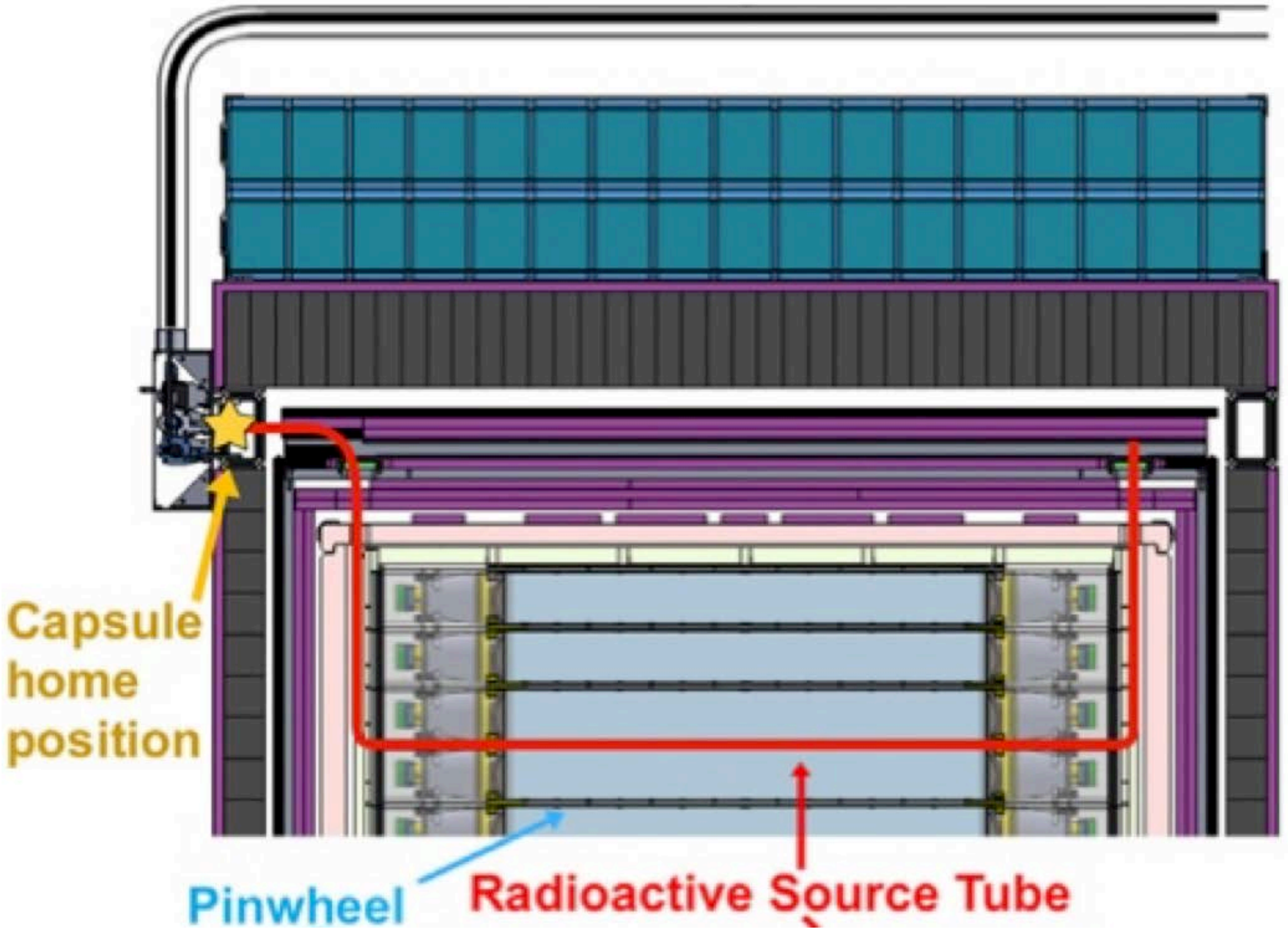
- Acrylic windows allow for light leakage from one segment to neighboring segments
- Optical model benchmarked by matching light curve measured on PROSPECT-I prototype, data-driven simulation

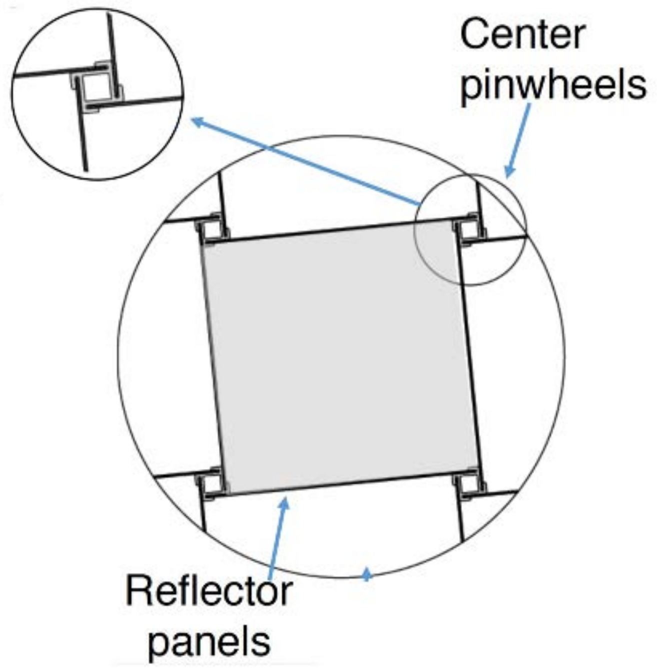
minimal cross-talk between segments (5% target is achievable!) minimal impact on signal selection/ background rejection,

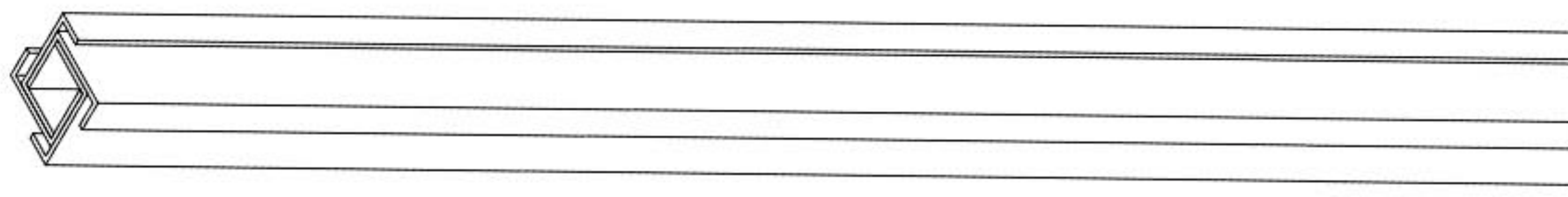
PROSPECT-II External Calibration Design

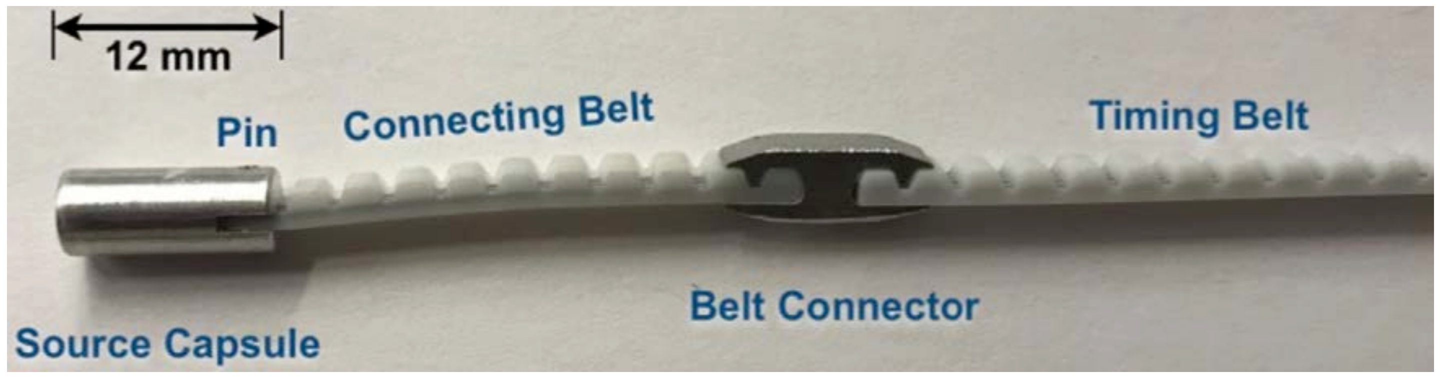
PROSPECT-I in-situ internal calibration

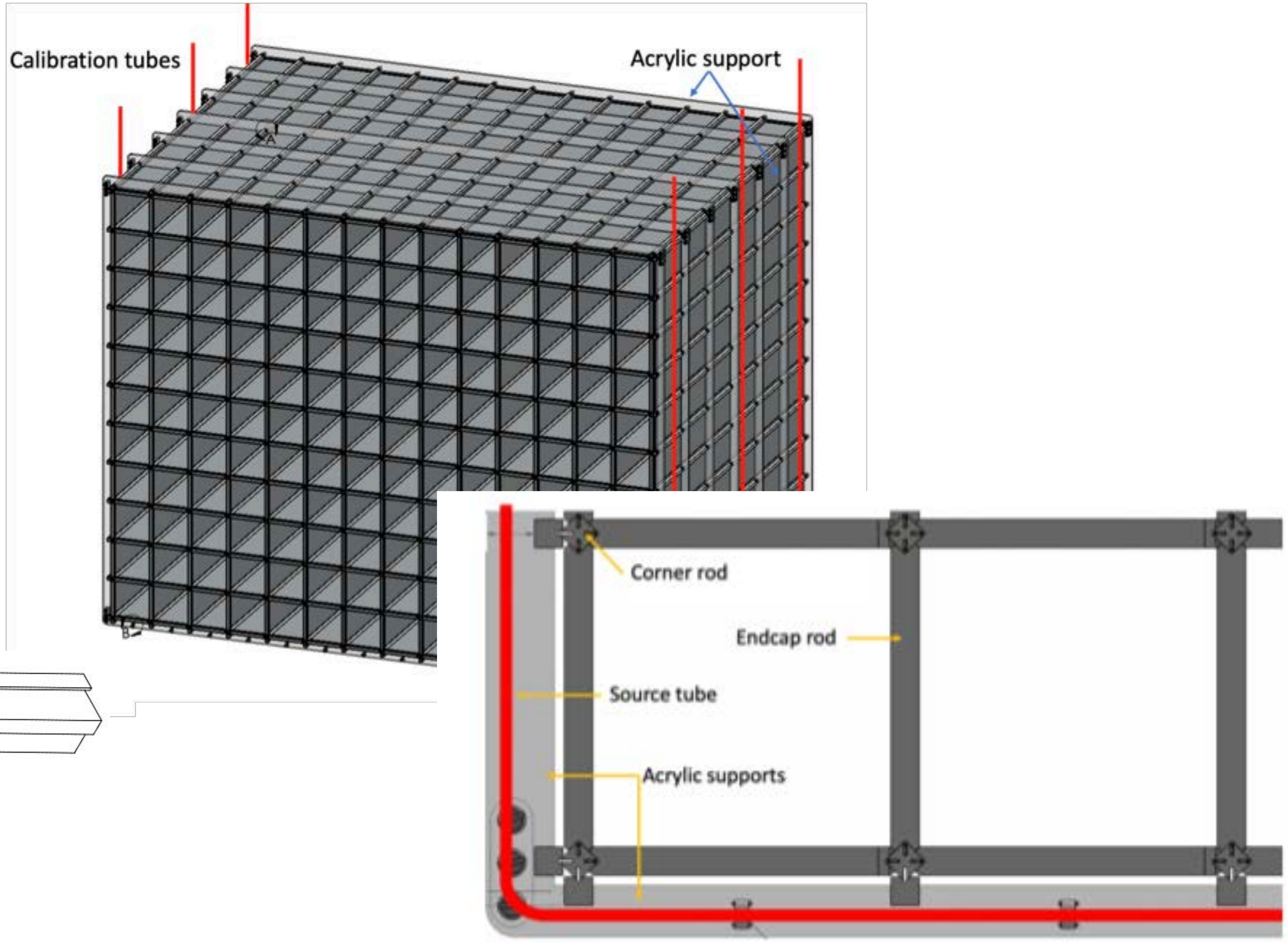
PROSPECT-II external calibration design





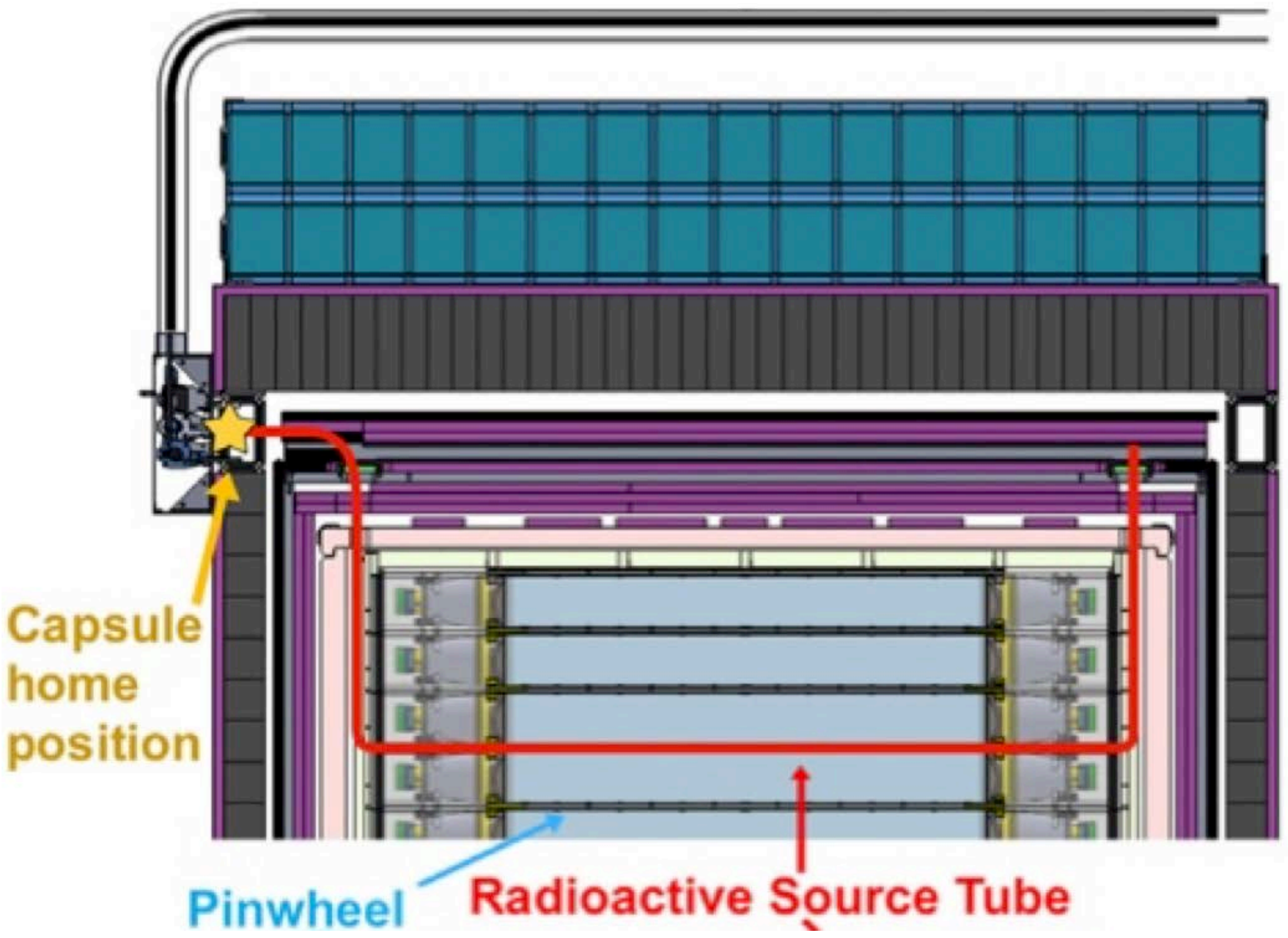


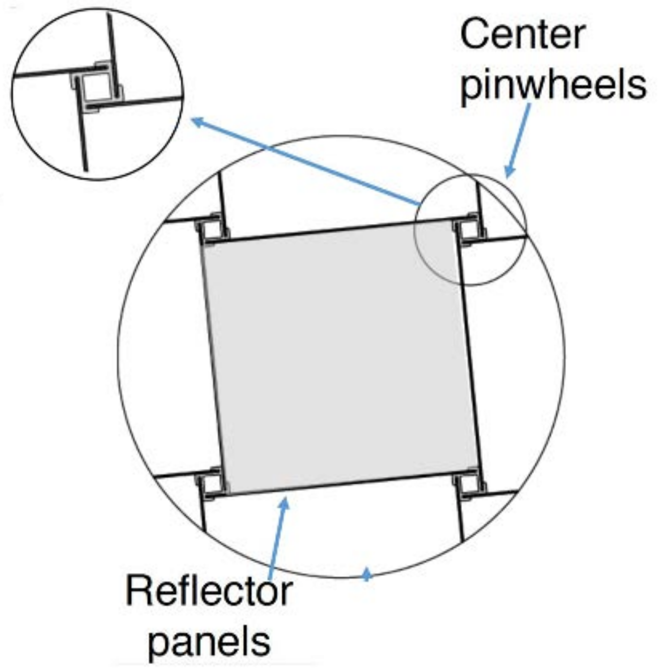


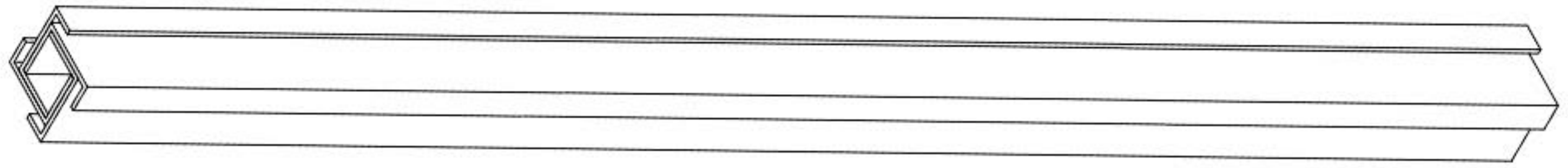


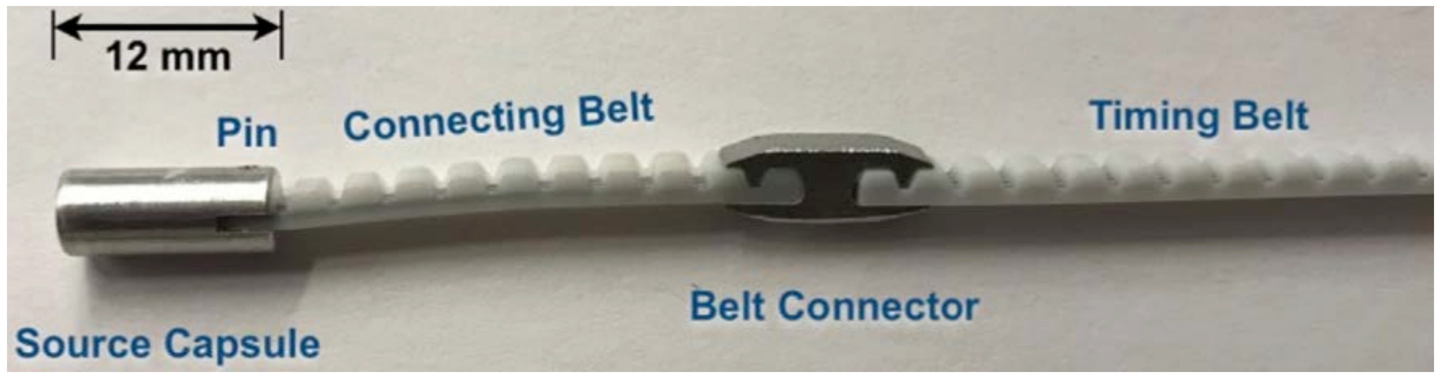
PROSPECT-II External Calibration Design

PROSPECT-I in-situ internal calibration

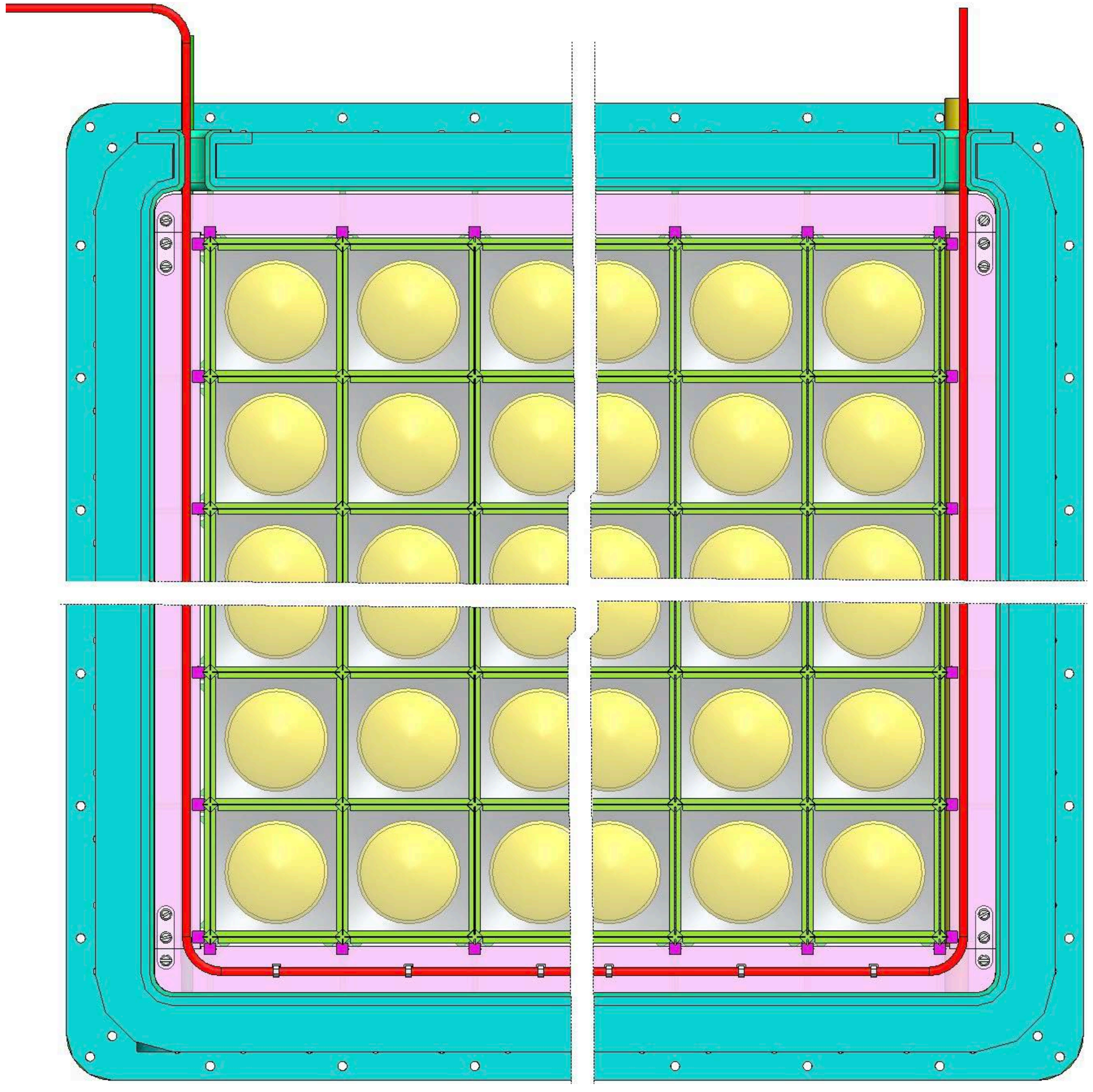






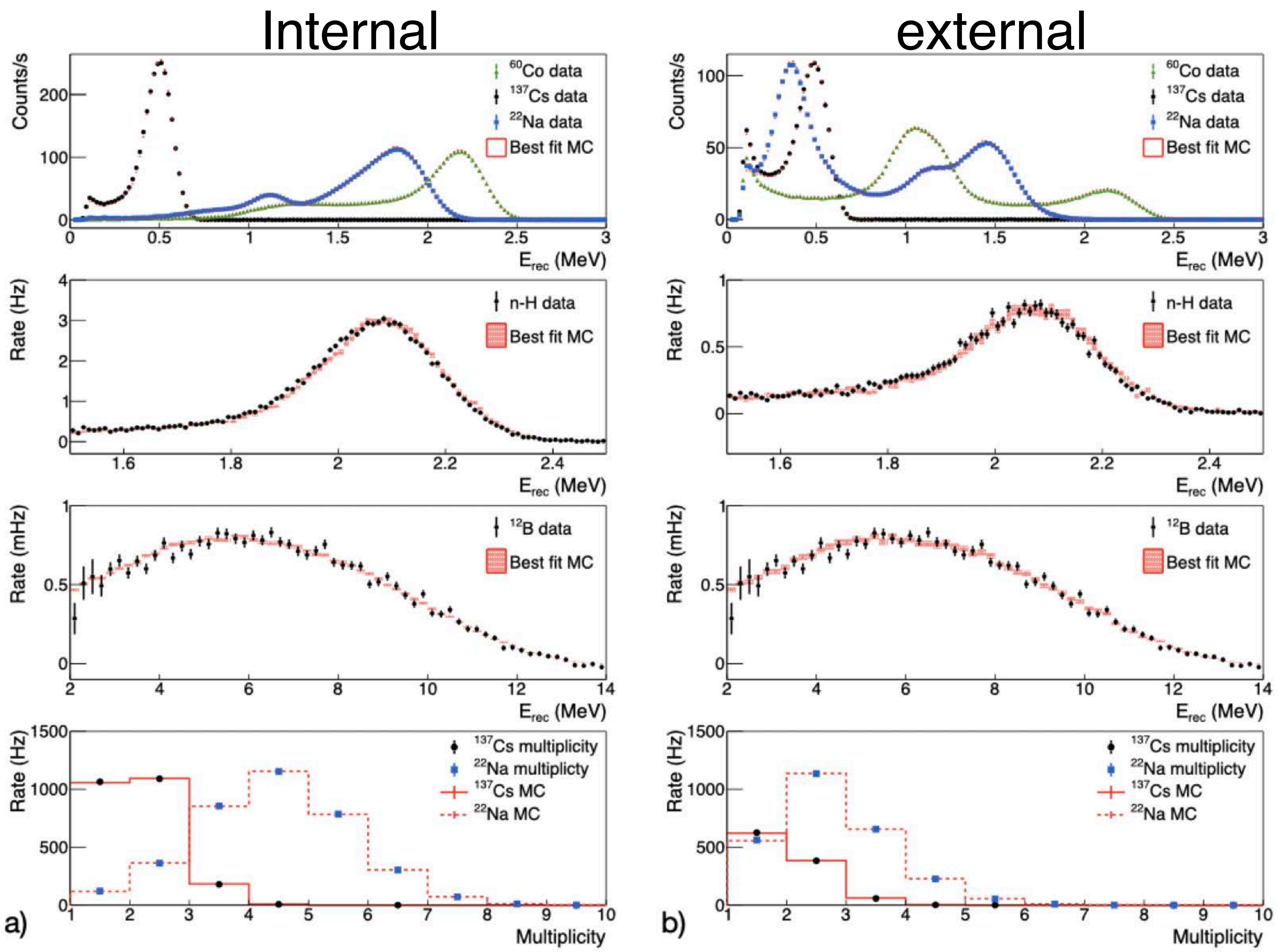


PROSPECT-II external calibration design

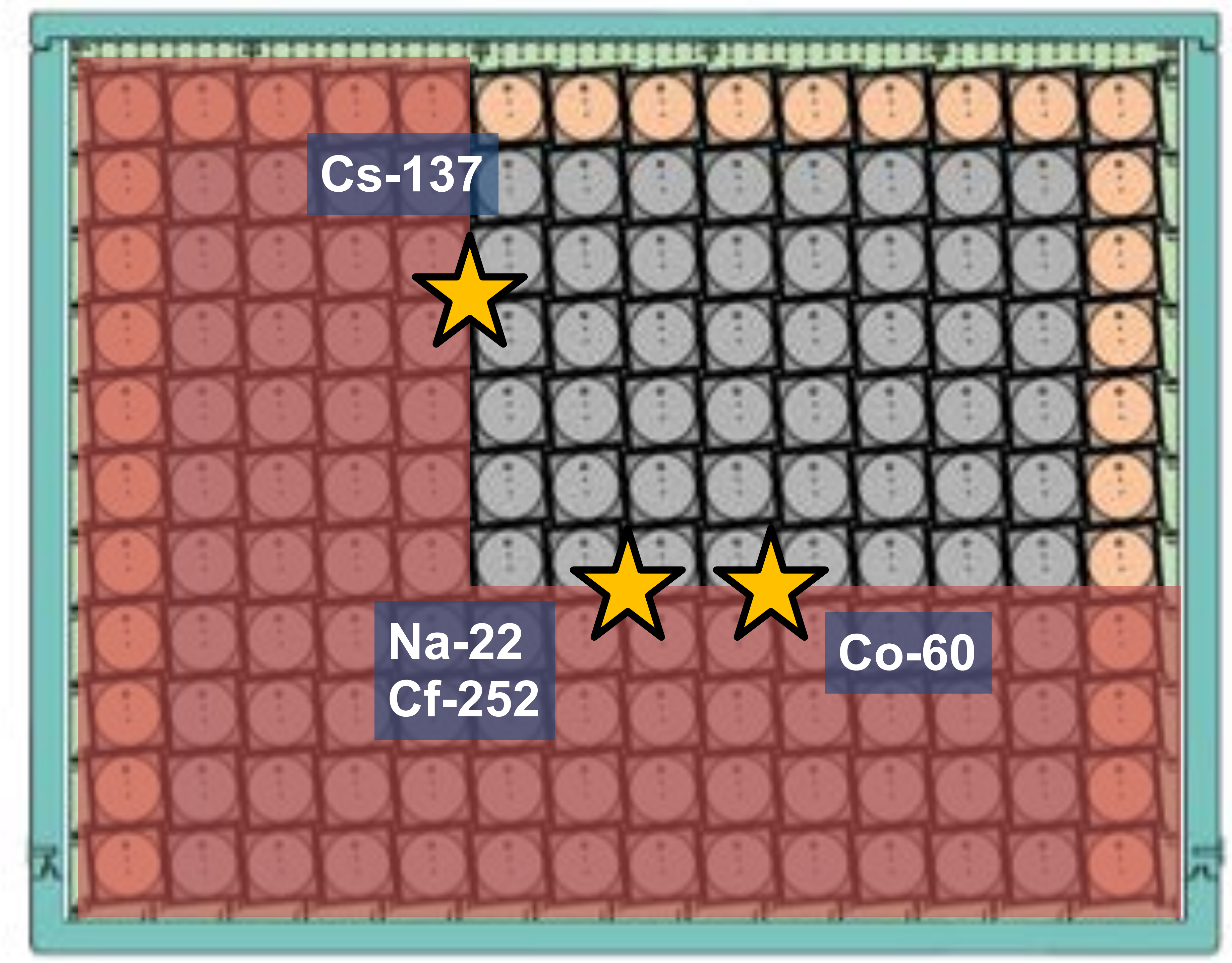


PROSPECT-II External Calibration Design

Design Validation



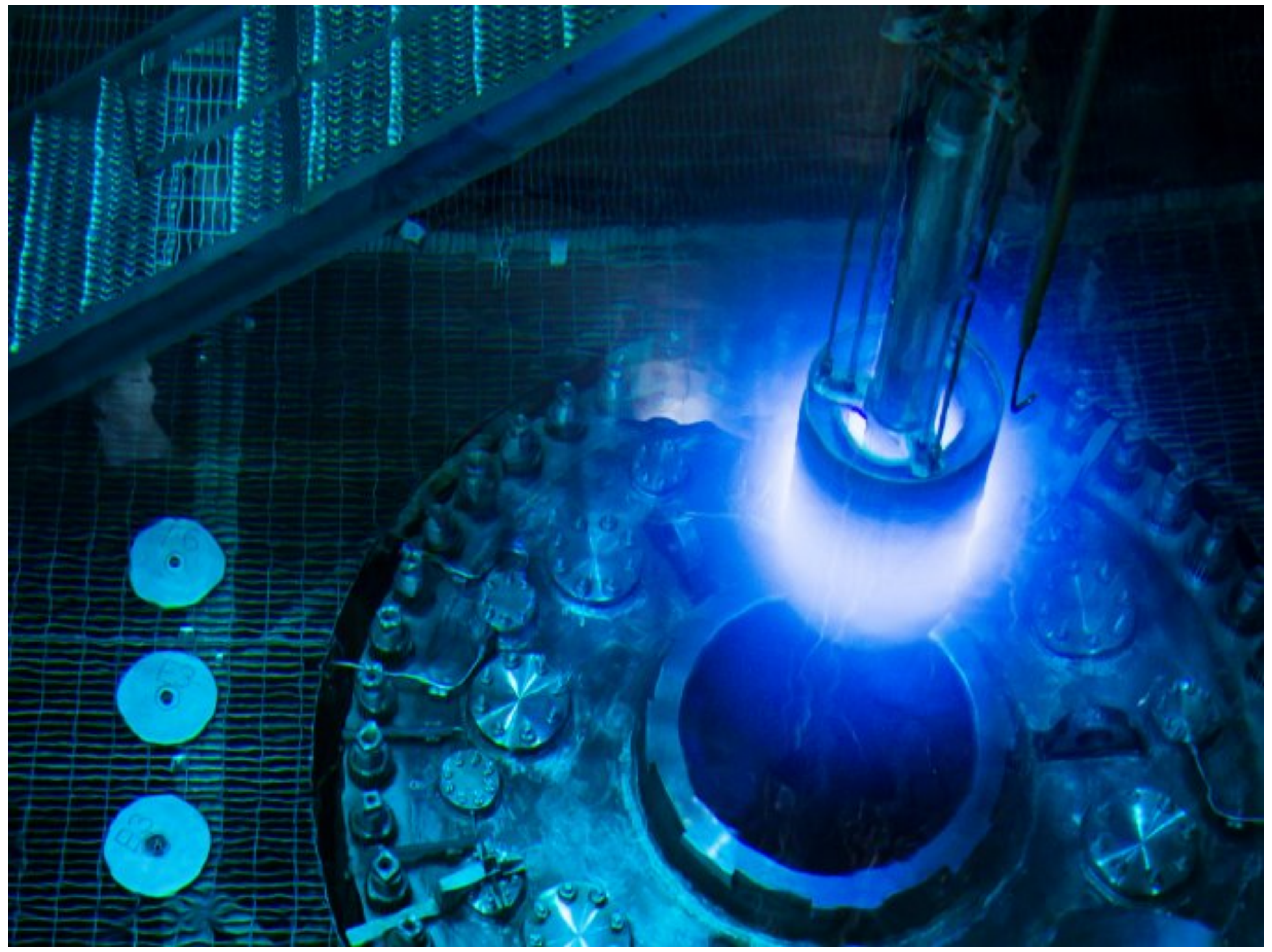
PROSPECT collaboration
arXiv: 2211.09582



Use PROSPECT-I data to simulate external source deployment.
Good agreement in energy and segment multiplicity responses is observed.

Performance of external calibration is comparable to internal calibration

PROSPECT-II Deployment at HFIR, ORNL



HFIR remains an attractive site for HEU measurement

Operating cadence has reduced since 2018
14 cycle data collection: ~ 2.5 - 3.0 years operation

FY24

Oct-23 | Nov-23 | Dec-23 | Jan-24 | Feb-24 | Mar-24 | Apr-24 | May-24 | Jun-24 | Jul-24 | Aug-24 | Sep-24

SNS: FY24A | PPU 2MW Target Ramp to 2 MW @ 1.3 GeV after 1250 hrs @ 1.7 MW

HFIR: EOC 504 | 505 | EOC 505 | 506 | EOC 506 | 507 | EOC 507 | 508 | EOC 508 | 509 | EOC 509 | 510 | EOC 510

2024: 5 cycles

FY25

Oct-24 | Nov-24 | Dec-24 | Jan-25 | Feb-25 | Mar-25 | Apr-25 | May-25 | Jun-25 | Jul-25 | Aug-25 | Sep-25

SNS: | FY25A | 2MW Operations | FY25B | 2MW Operations

HFIR: 511 | EOC 511 | 512 | EOC 512 | 513 | EOC 513 | 514 | EOC 514 | 515 | EOC 515

2025: 6 cycles

FY26

Oct-25 | Nov-25 | Dec-25 | Jan-26 | Feb-26 | Mar-26 | Apr-26 | May-26 | Jun-26 | Jul-26 | Aug-26 | Sep-26

SNS: 2MW Operations | FY26A | 2MW Operations | FY26B | 2MW Operations

HFIR: | 516 | EOC 516 | 517 | EOC 517 | 518 | EOC 518 | 519 | EOC 519 | 520 | EOC 520 | 521 | EOC 521

2026: 5 cycles

FY27

Oct-26 | Nov-26 | Dec-26 | Jan-27 | Feb-27 | Mar-27 | Apr-27 | May-27 | Jun-27 | Jul-27 | Aug-27 | Sep-27

SNS: 2MW Operations | FY27A | 2MW Operations | FY27B | 2MW Operations

HFIR: | 522 | EOC 522 | 523 | EOC 523 | 524 | EOC 524 | 525 | EOC 525 | 526 | EOC 526

2027: 4+ cycles

🟩 Neutron Production

Revised 9/21/22. The working schedule for the Spallation Neutron Source (SNS) and the High Flux Isotope Reactor (HFIR) is subject to change in response to

User access, on/off cycle,
several more years of running before long outage

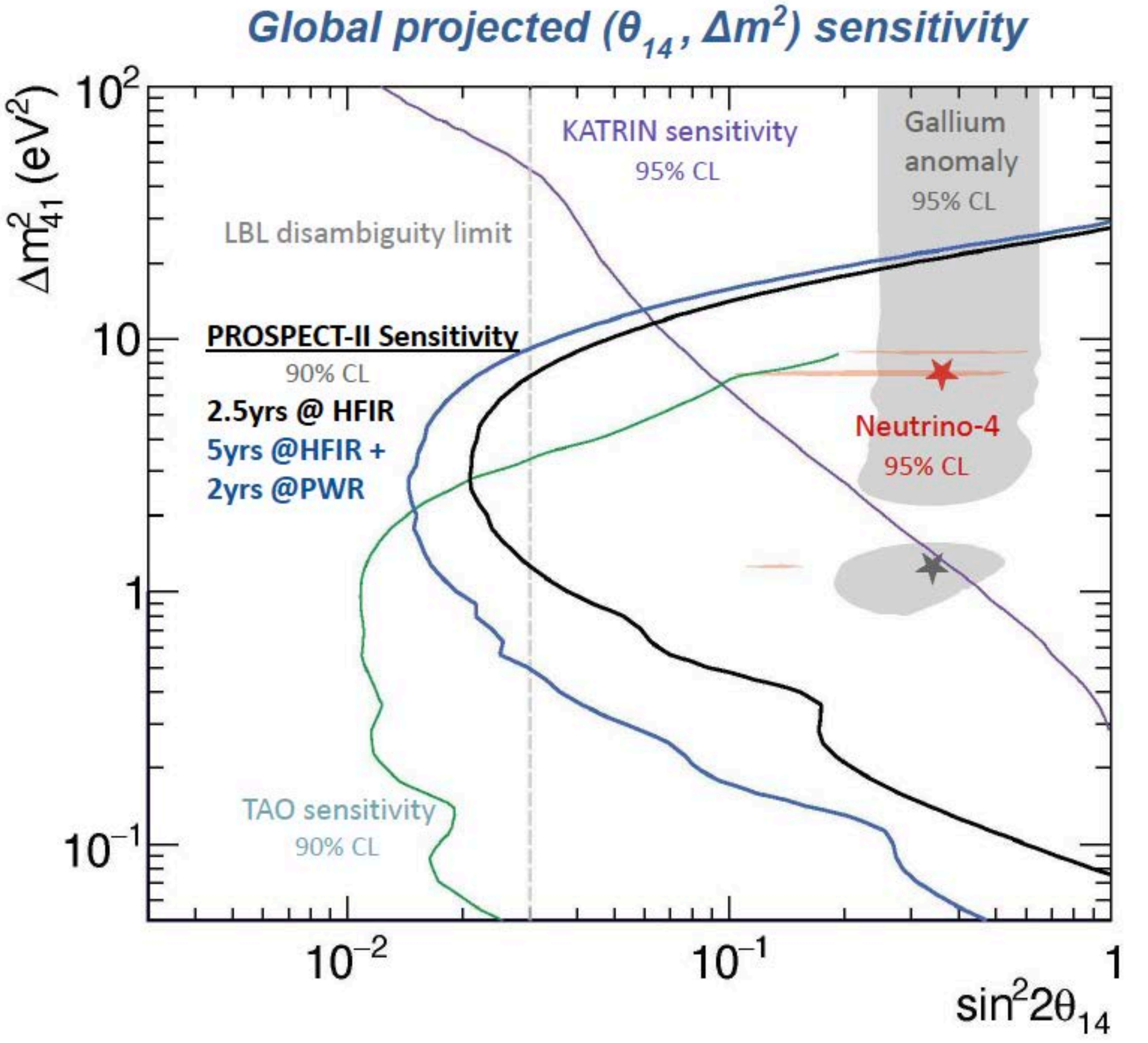
PROSPECT-II - Oscillation Physics

Best θ_{14} sensitivity of any experiment at high Δm^2 (~10 eV^2). Only approach to cover this weakly constrained region in next 5-10 years, KATRIN sterile search on similar timescale

Provides stringent test of Neutrino-4 claim

Resolves potential ambiguities in long-baseline physics

Pure electron-flavor source: distinct constraints on BSM interpretations of BEST, MiniBoone, LSND



PROSPECT-II - Oscillation Physics

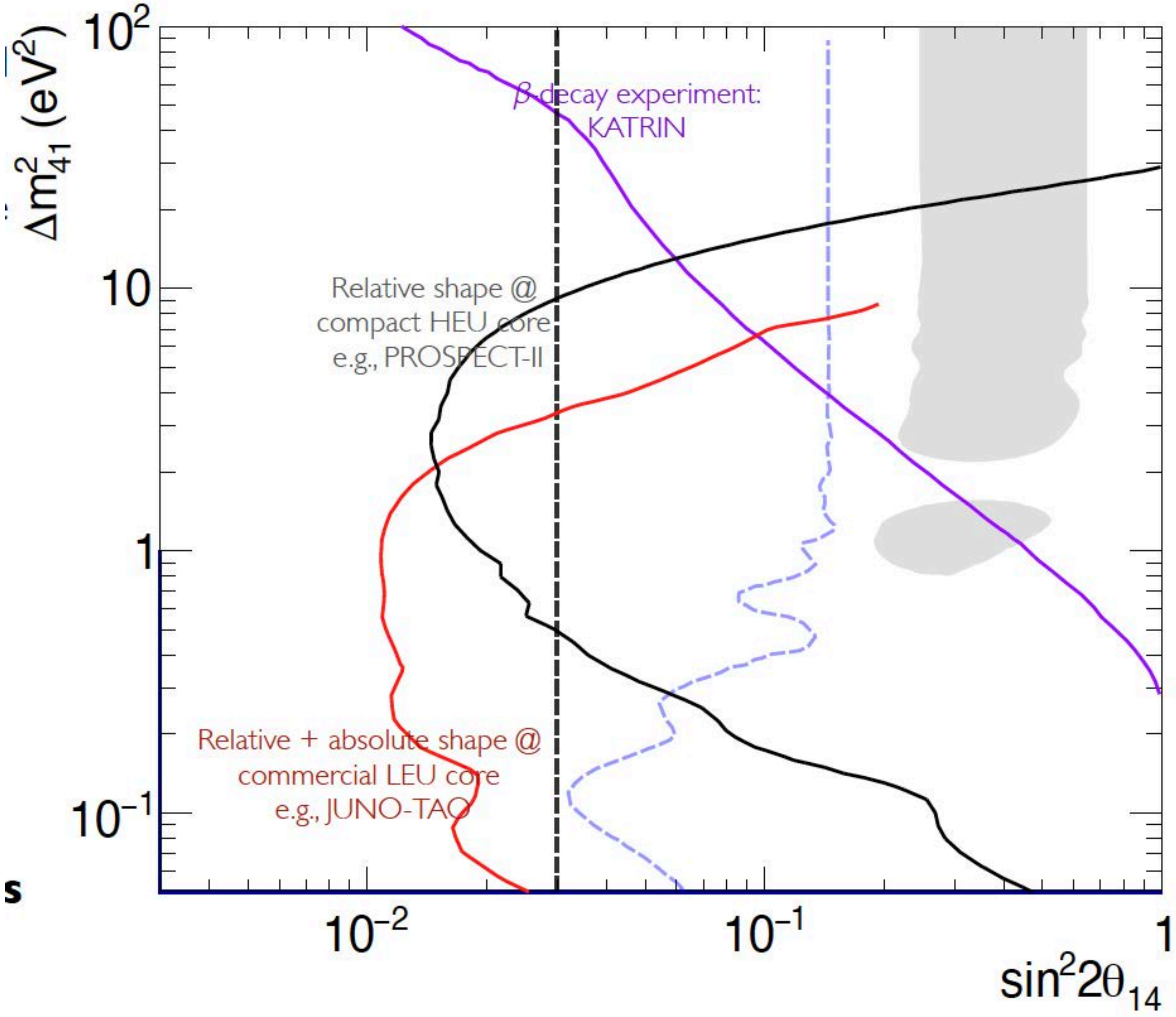
Reactor neutrino experiments exclude most of the 3+1 sterile neutrino suggested parameter space

New data and updated models increasingly suggest reactor mismodeling as the cause of RAA

Meanwhile, the significance of gallium anomaly is strengthened by BEST experiment

Models beyond 3+1 sterile neutrinos increasingly need to be invoked to reconcile all data

Complementary data from upcoming and planned reactor and radioactive source experiments will be needed to identify the sources of the anomalies

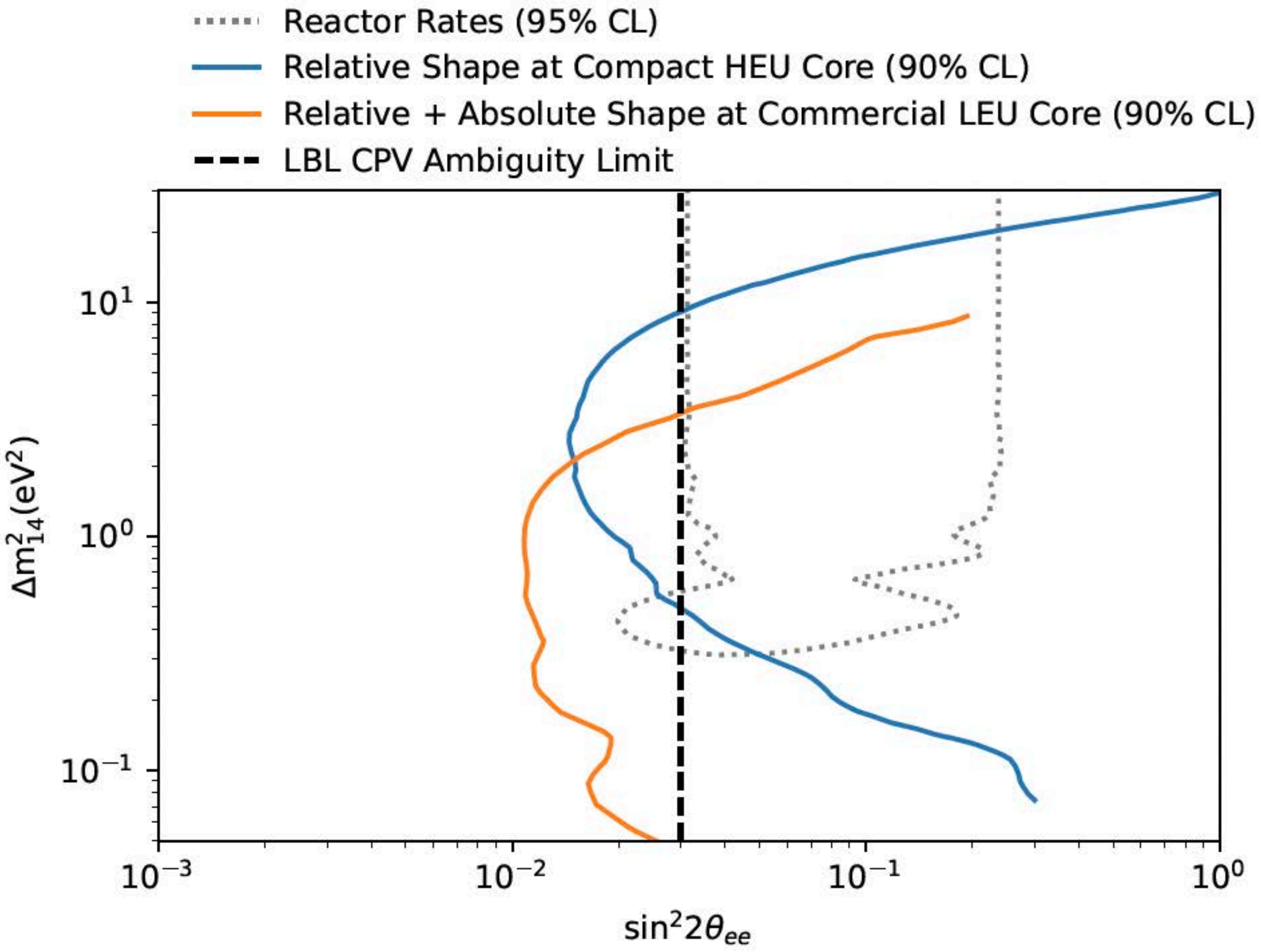


Oscillation Physics - Complementarity of LEU and HEU Experiments

Example projected sensitivities (90% CL) to sterile neutrinos for future measurements performed at

- **compact-core (blue), HEU**

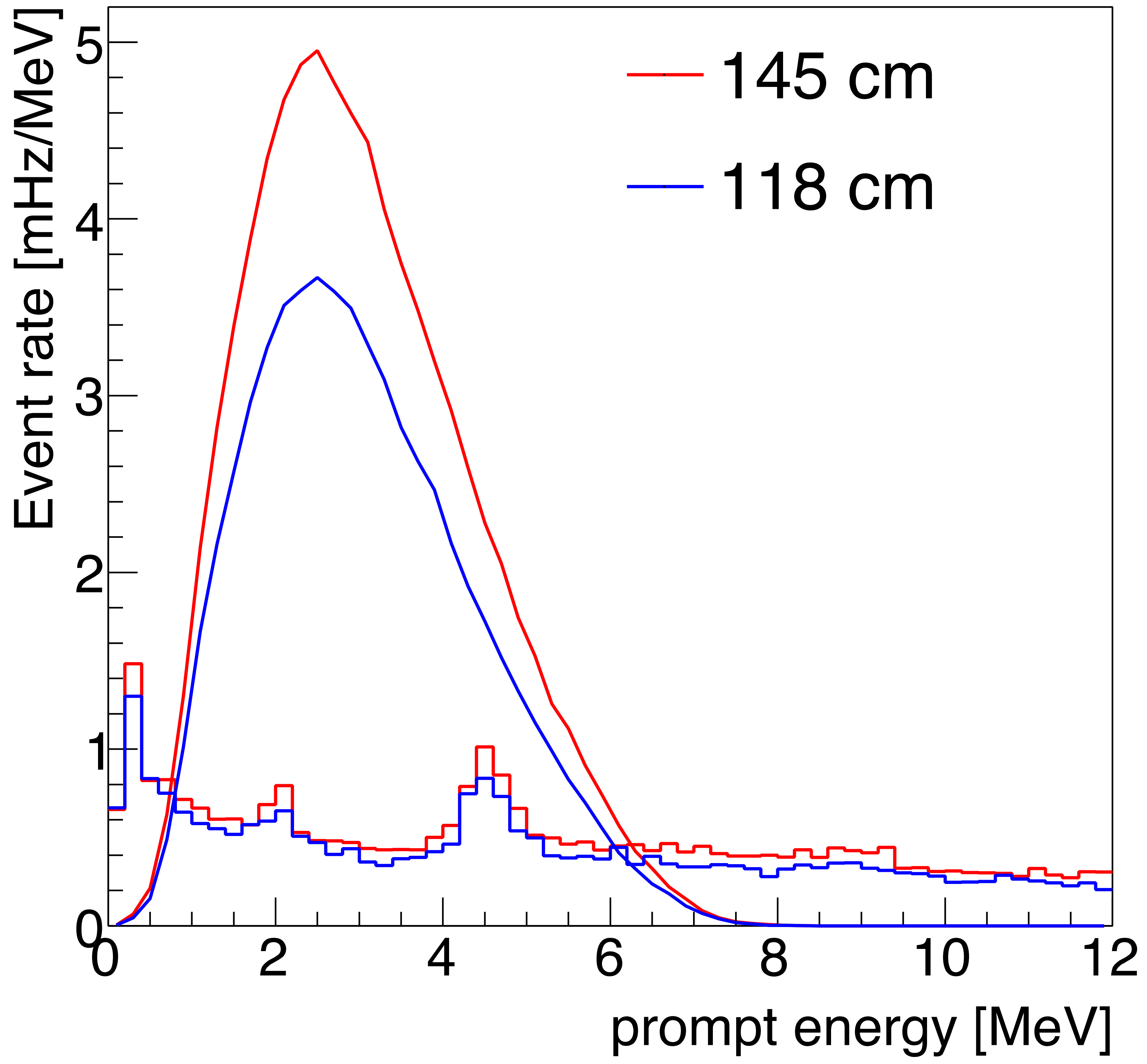
- **larger commercial (orange) reactor cores, LEU**



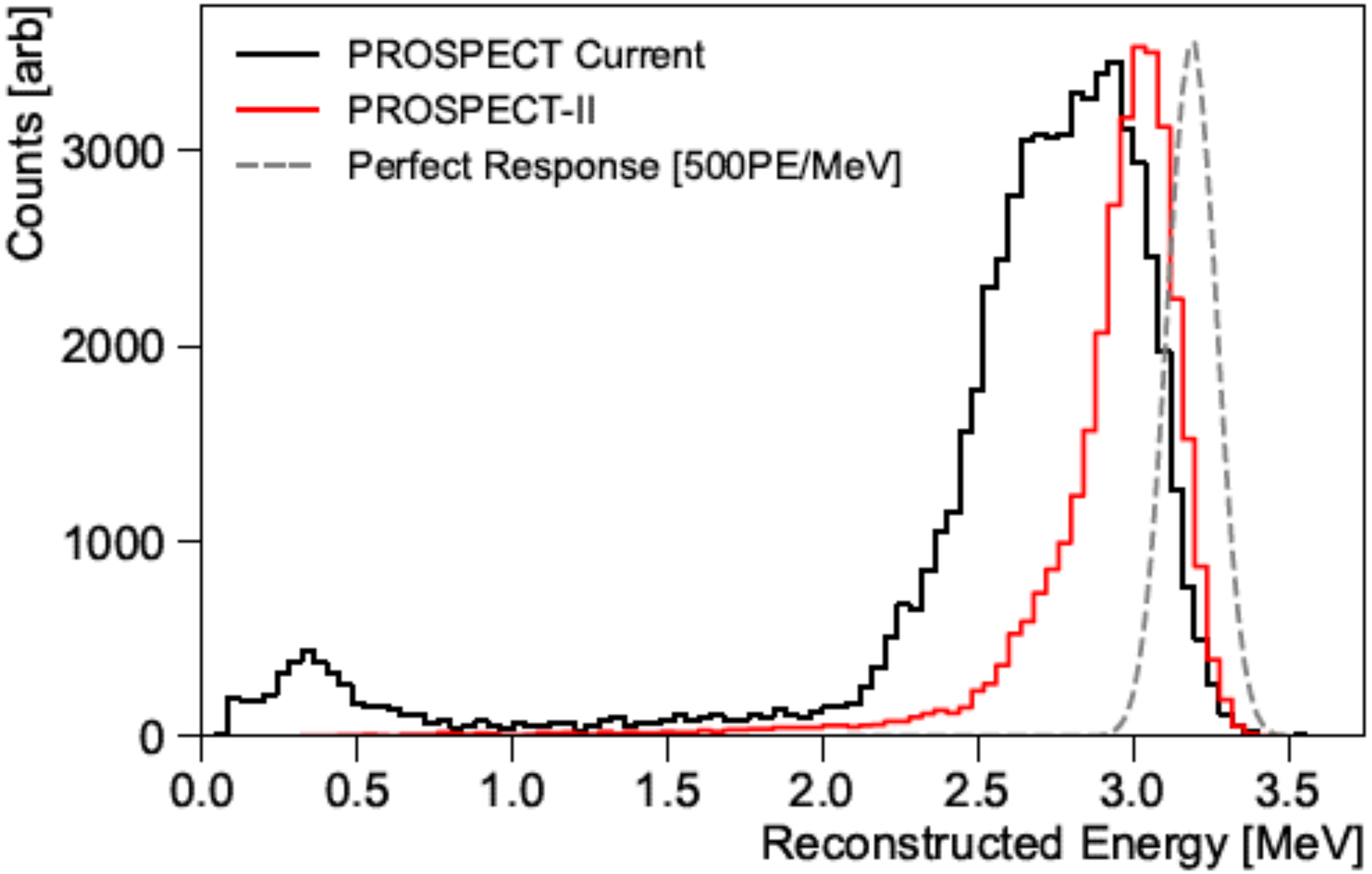
arXiv:2209.05352

PROSPECT-II - Spectrum

Highest precision spectrum from future reactor-based measurement



PROSPECT Collaboration
J.Phys.G 49 (2022) 7, 070501



detector response to monoenergetic 4 MeV $\overline{\nu}_e$ for the PROSPECT-II detector (red) and PROSPECT-I (black)

PROSPECT-II - Spectrum

Highest precision spectrum from future reactor-based measurement

Precision on ^{235}U spectrum shape measurement will exceed that achievable in LEU-based evolution measurement

uncertainties will be at the level of claimed model uncertainties

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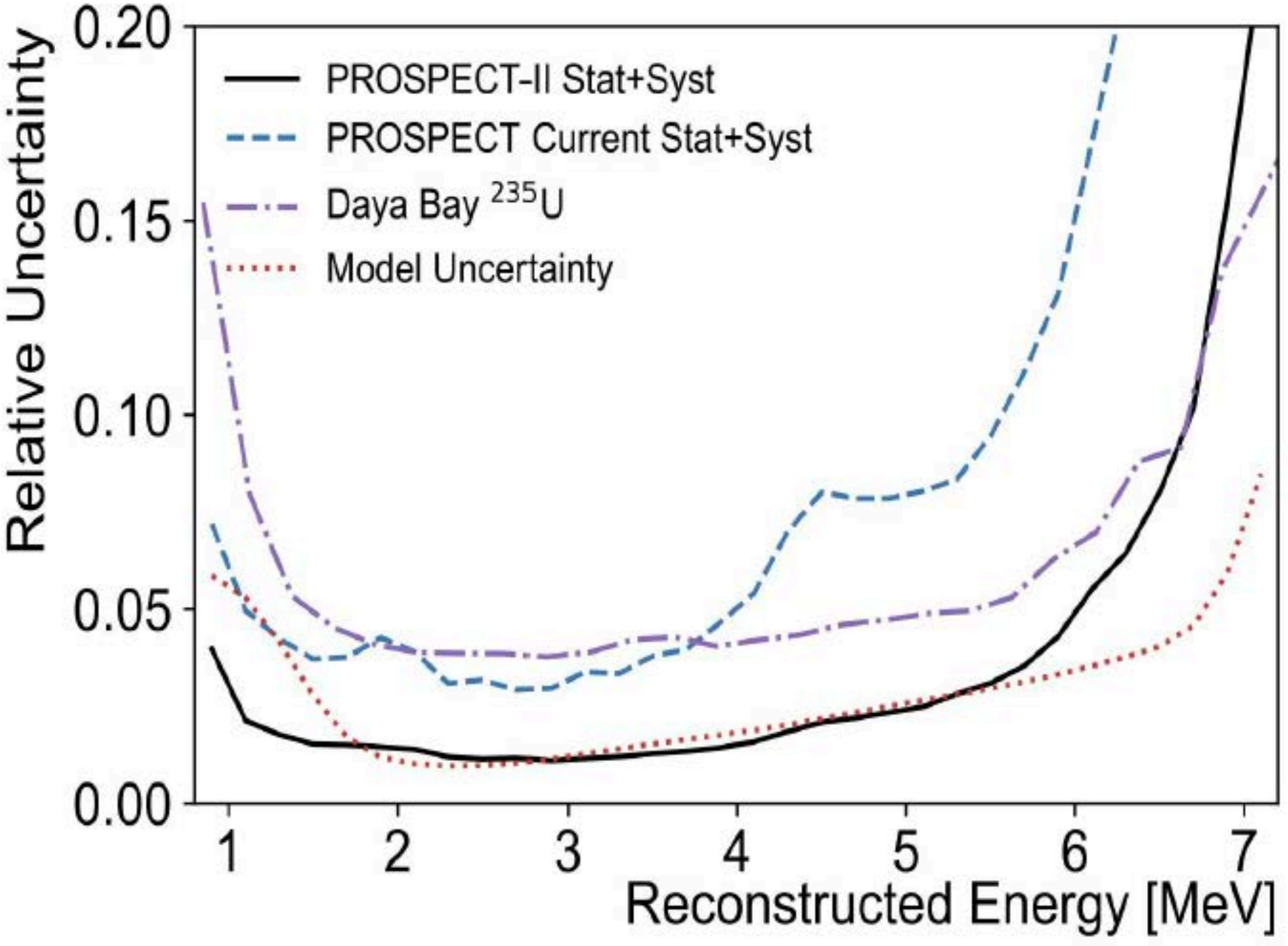
J.Phys.G 49 (2022) 7, 070501

>2x increase in ^{235}U spectrum precision



PROSPECT-II - Spectrum

Highest precision spectrum from future reactor-based measurement

Basic science: CEvNS experiments, BSM searches

Probe 'bump' in spectrum: is it due to ^{235}U?

Neutrino applications, e.g. reactor monitoring

Reactor measurements as 'Nuclear Data'

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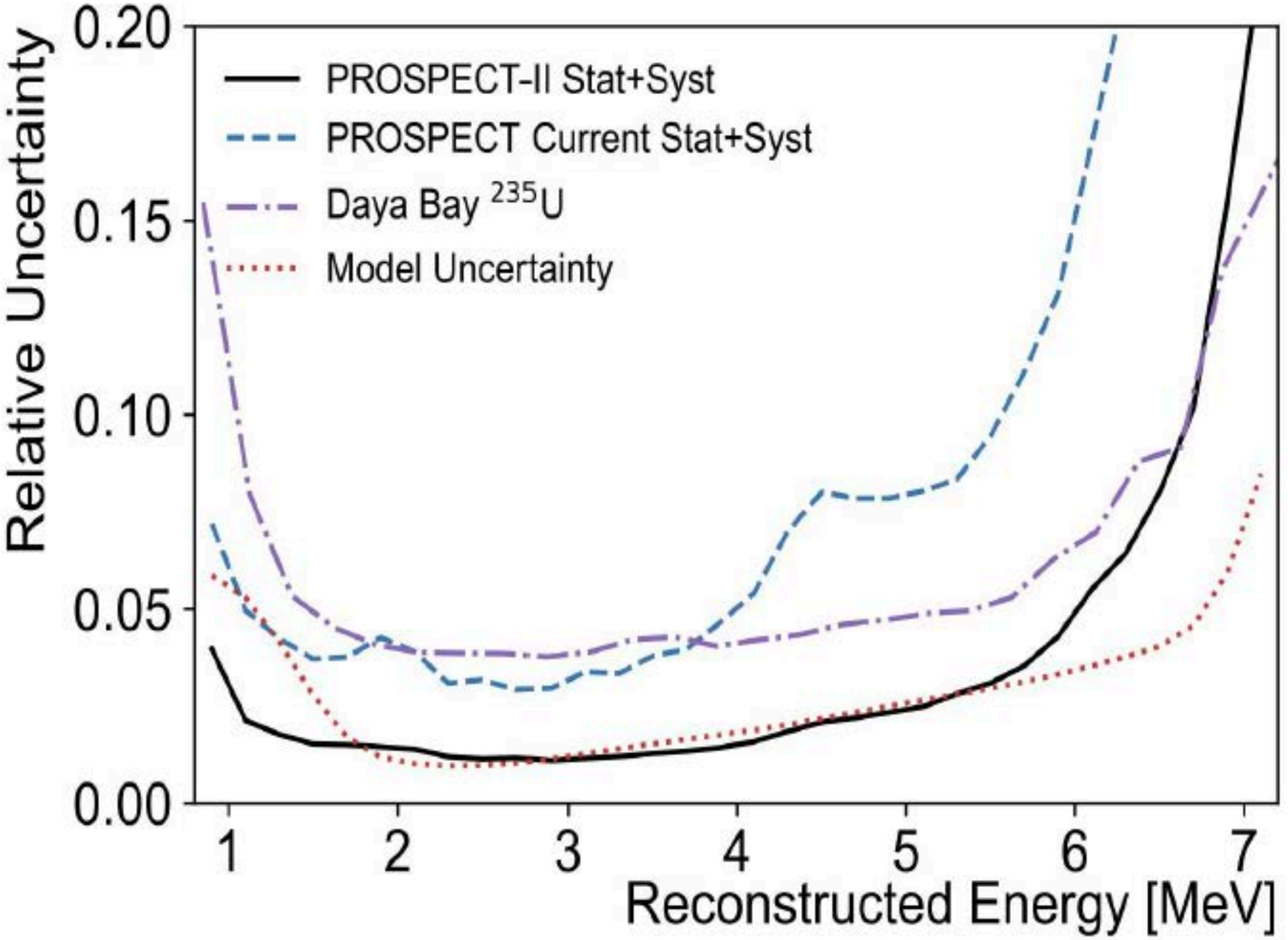
J.Phys.G 49 (2022) 7, 070501

>2x increase in ^{235}U spectrum precision



PROSPECT-II - Spectrum

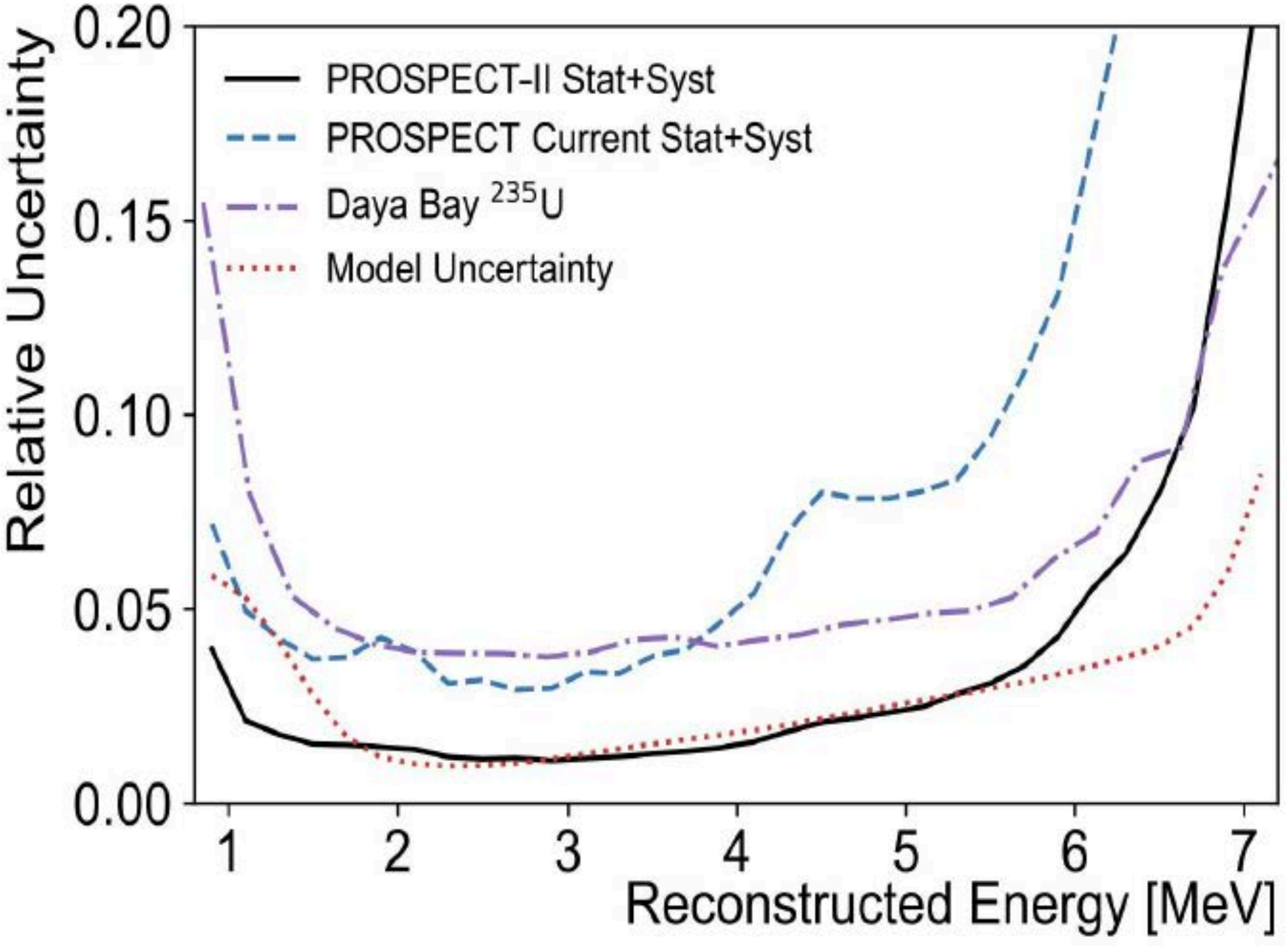
Highest precision spectrum from future reactor-based measurement

Opportunity to further build connections with other communities and agencies

- DNN R&D supported efforts: Nu Tools, Far-field WbLS Testbeds, & Mobile Antineutrino Demonstrator

- Nuclear Data Inter Agency Working Group (e.g. WoNDRAM)

>2x increase in ^{235}U spectrum precision



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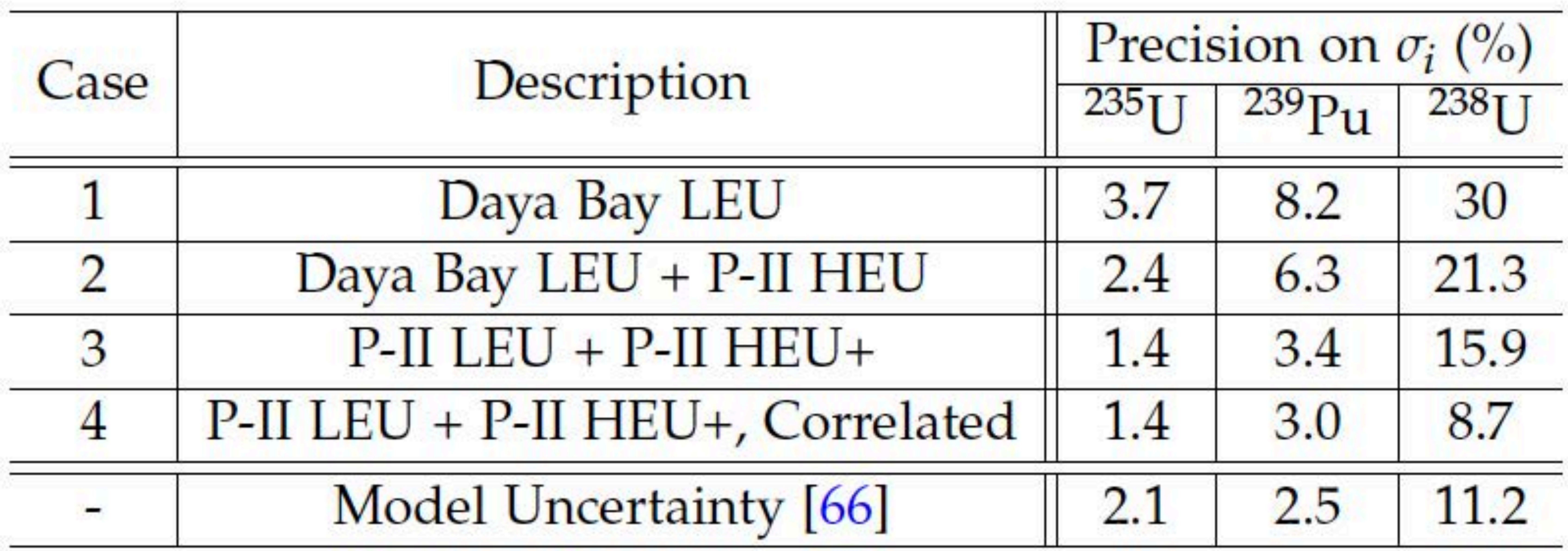
PROSPECT-II - Combining LEU/HEU Measurements

Constraints on IBD yields of ^{235}U, ^{239}Pu, and ^{238}U from future hypothetical datasets from LEU and HEU reactors, given as a percentage of the best fit yield.



Case	Description	Precision on σ_i (%)		
		^{235}U	^{239}Pu	^{238}U
1	Daya Bay LEU	3.7	8.2	30
2	Daya Bay LEU + P-II HEU	2.4	6.3	21.3
3	P-II LEU + P-II HEU+	1.4	3.4	15.9
4	P-II LEU + P-II HEU+, Correlated	1.4	3.0	8.7
-	Model Uncertainty [66]	2.1	2.5	11.2

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’P-II’ refers to PROSPECT-II, ’HEU+’ refers to a HEU-based measurement with thermal power uncertainty improved from 2% to 1%, and ’Correlated’ refers to correlated detector systematics between HEU and LEU measurements.

PROSPECT-II designed to be deployed at multiple reactor sites

PROSPECT-II Science Goals

Search for mixing between active and sterile neutrinos in the mass-splitting range of 1-20 eV^2, covering a region beyond the reach of other reactor experiments;

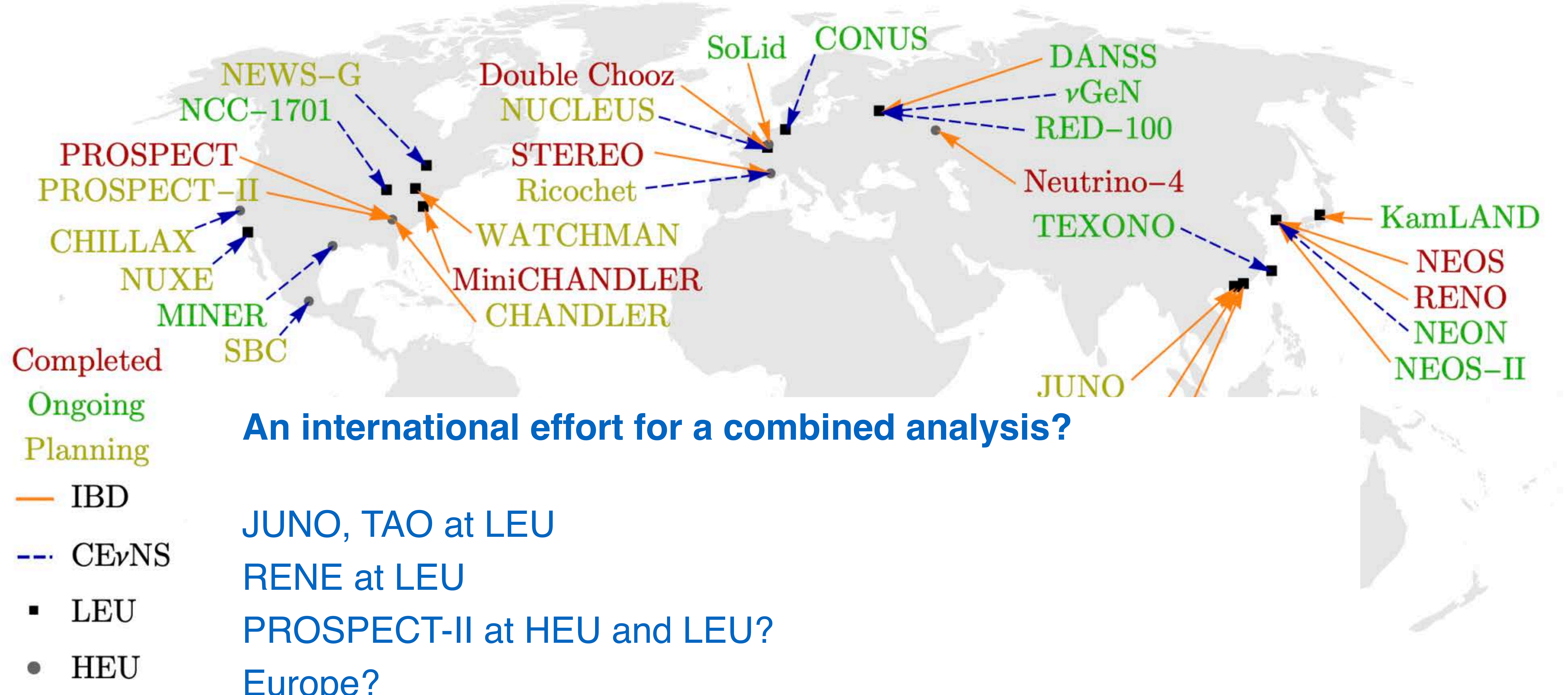
Extend sensitivity to the sterile mixing angle $\sin^2 2\theta_{14}$ below 0.03 in the ~1-10 eV^2 mass splitting range, to inform the interpretation of long-baseline CP violation experiments;

Reduce ^{235}U spectrum uncertainties below 5%, uniquely constraining reactor predictions;

Perform an absolute measurement of the ^{235}U neutrino yield and improve the robustness of the global yield picture for the three dominant fission isotopes ^{235}U, ^{239}P, and ^{238}U;

Enable a future program with highly correlated detector systematics at an LEU reactor to strengthen oscillation, spectrum, and flux measurements.

An Opportunity for LEU+HEU Measurements?



An international effort for a combined analysis?

JUNO, TAO at LEU

RENE at LEU

PROSPECT-II at HEU and LEU?

Europe?

Summary and Outlook

PROSPECT-I performed well in terms of background rejection, resolution, segmentation, and PID in LiLS. **Achieved principal goals** in measuring spectrum, searching for oscillations, and demonstrating on-surface operation. Performance degradation of PROSPECT-I is understood and addressed in new design.

PROSPECT-II design retains successful elements of PROSPECT-I, improvements include:

- PMTs out of the scintillator volume, use of an external calibration system
- **Detector is relocatable**, allowing for HEU and LEU measurements with same detector minimizing detection system-related uncertainties.

A two-year run at HFIR with PROSPECT-II provides:

- Coverage of 1-20 eV^2 region beyond the reach of other reactor experiments
- Addresses GA and RAA regions when combined with future KATRIN
- Helps clear CPV ambiguity, and tests Neutrino-4
- **New HEU spectrum measurement with uncertainties at level of claimed model uncertainties**

International collaboration on future short-baseline efforts?

PROSPECT

prospect.yale.edu

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HEISING-SIMONS FOUNDATION

U.S. DEPARTMENT OF ENERGY

GRFP

14 Institutions, 70 collaborators

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NIST

Le Moyne College

Drexel

University of Hawai'i

University of Waterloo

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Yale