Modeling Backgrounds for the MAJORANA DEMONSTRATOR

Christopher Haufe, on behalf of the MAJORANA Collaboration
LRT Workshop 2022, June 17

Sanford Underground Research Facility

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MAJORANA DEMONSTRATOR

Sanford Underground Research Facility

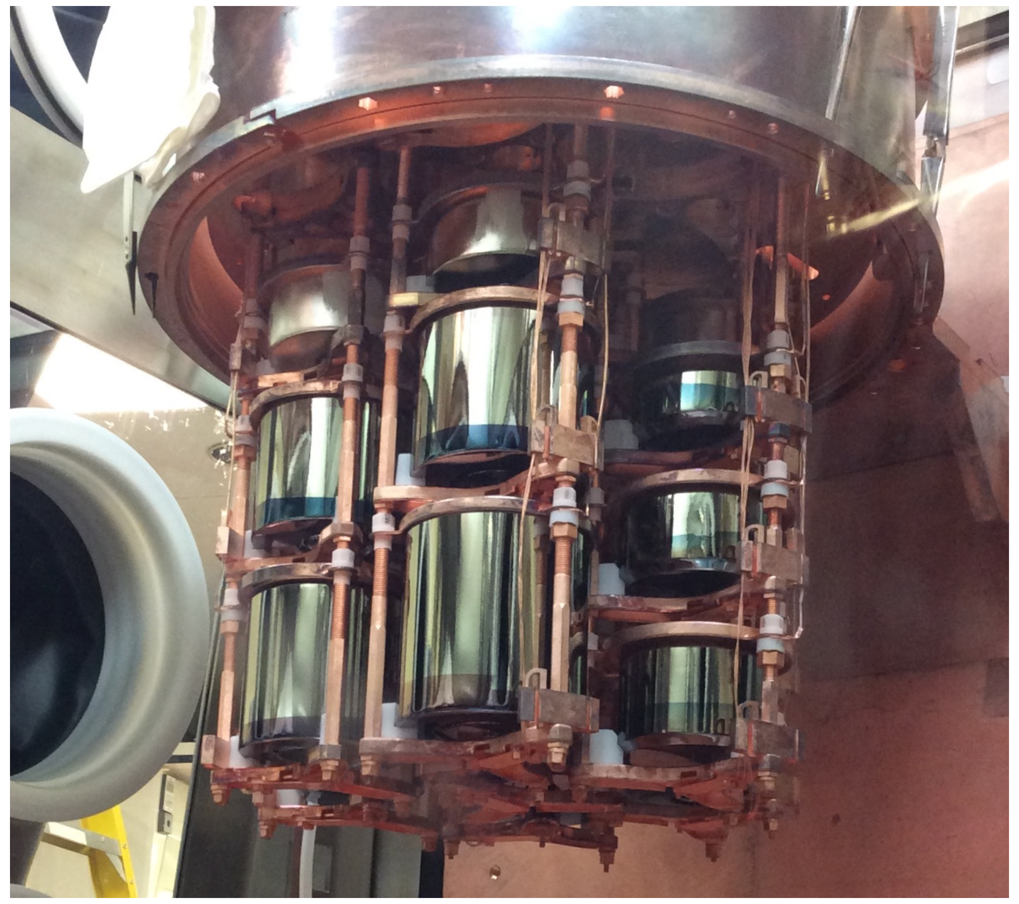
Search for neutrinoless double-beta decay of ^{76}Ge in HPGe detectors, probing additional physics beyond the standard model, and informing the design of the next-generation LEGEND experiment

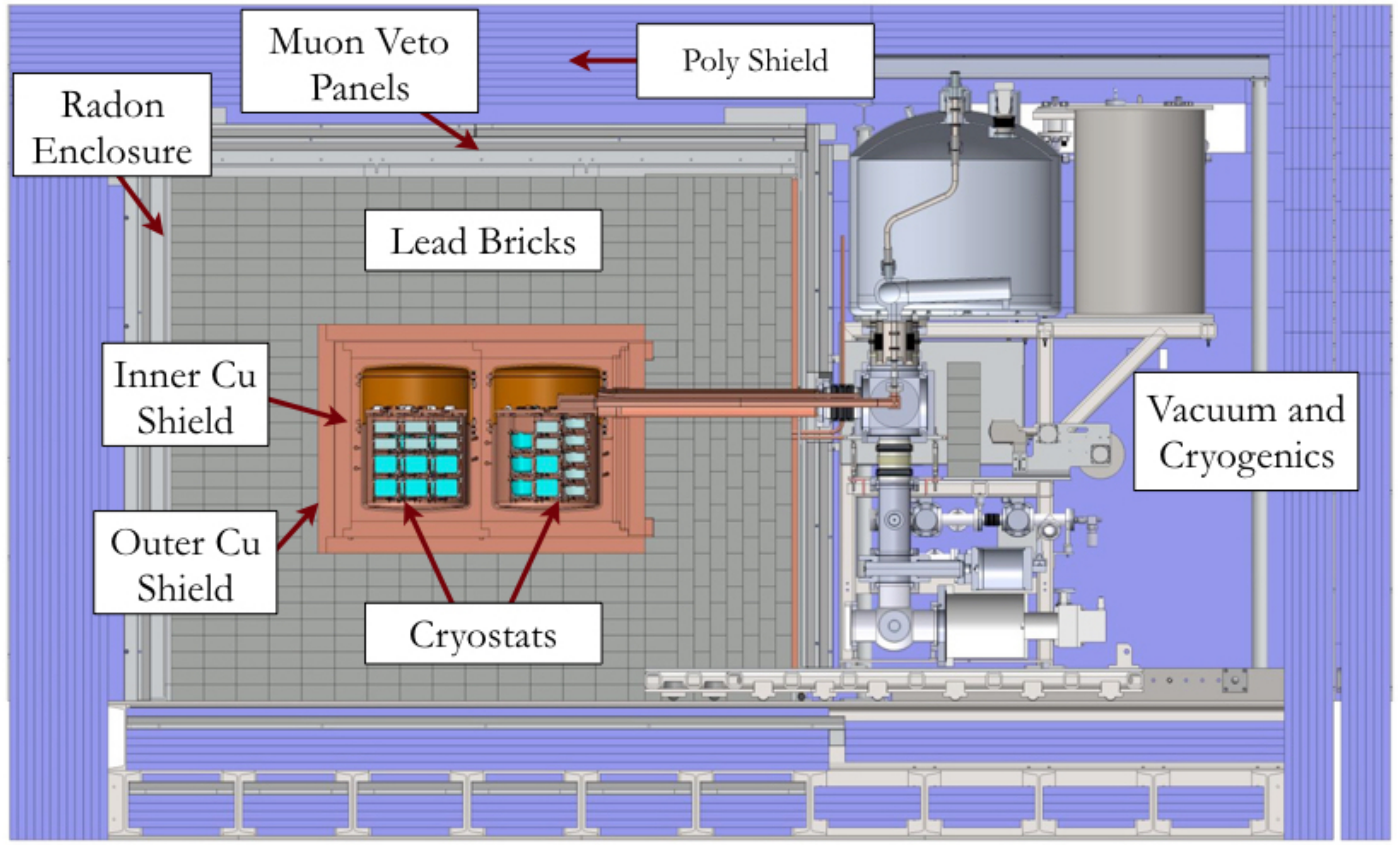
Source & Detector: Array of p-type, point contact detectors
30 kg of 88% enriched ^{76}Ge crystals - 14 kg of natural Ge crystals
Included 6.7 kg of ^{76}Ge inverted coaxial, point contact detectors in final run

Excellent Energy Resolution: 2.5 keV FWHM @ 2039 keV
and **Analysis Threshold:** 1 keV

Low Background: 2 modules within a compact graded shield and active muon veto using ultra-clean materials

Reached an exposure of ~65 kg-yr before removal of the enriched detectors for the LEGEND-200 experiment at LNGS

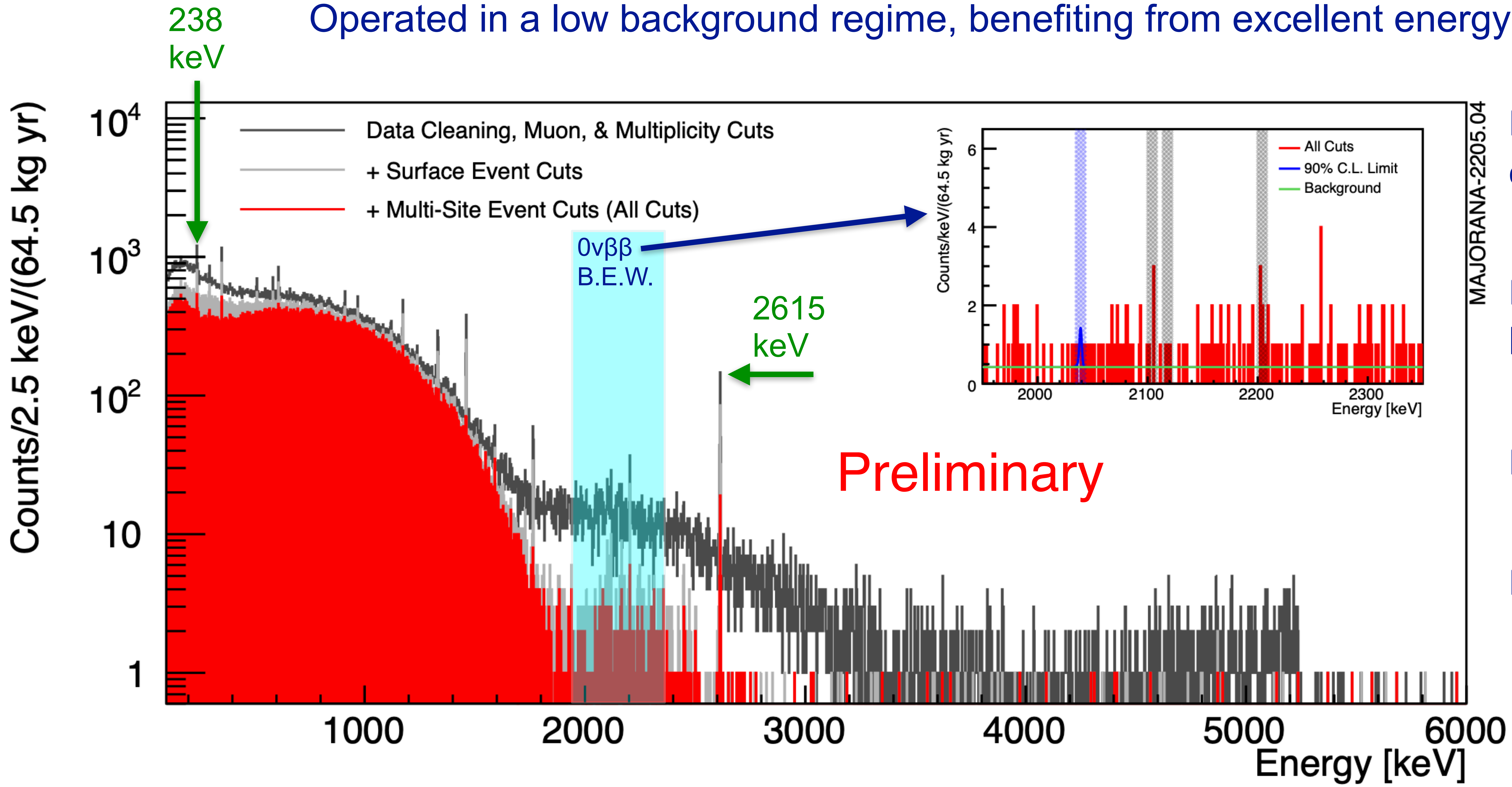




Continuing to operate at the Sanford Underground Research Facility with natural detectors for background studies and other physics

Final Exposure Spectrum

Operated in a low background regime, benefiting from excellent energy resolution



Final enriched detector active exposure:

64.5 ± 0.9 kg yrs

Background Index at 2039 keV in lowest background config:

15.7 ± 1.4 cts/(FWHM t yr)

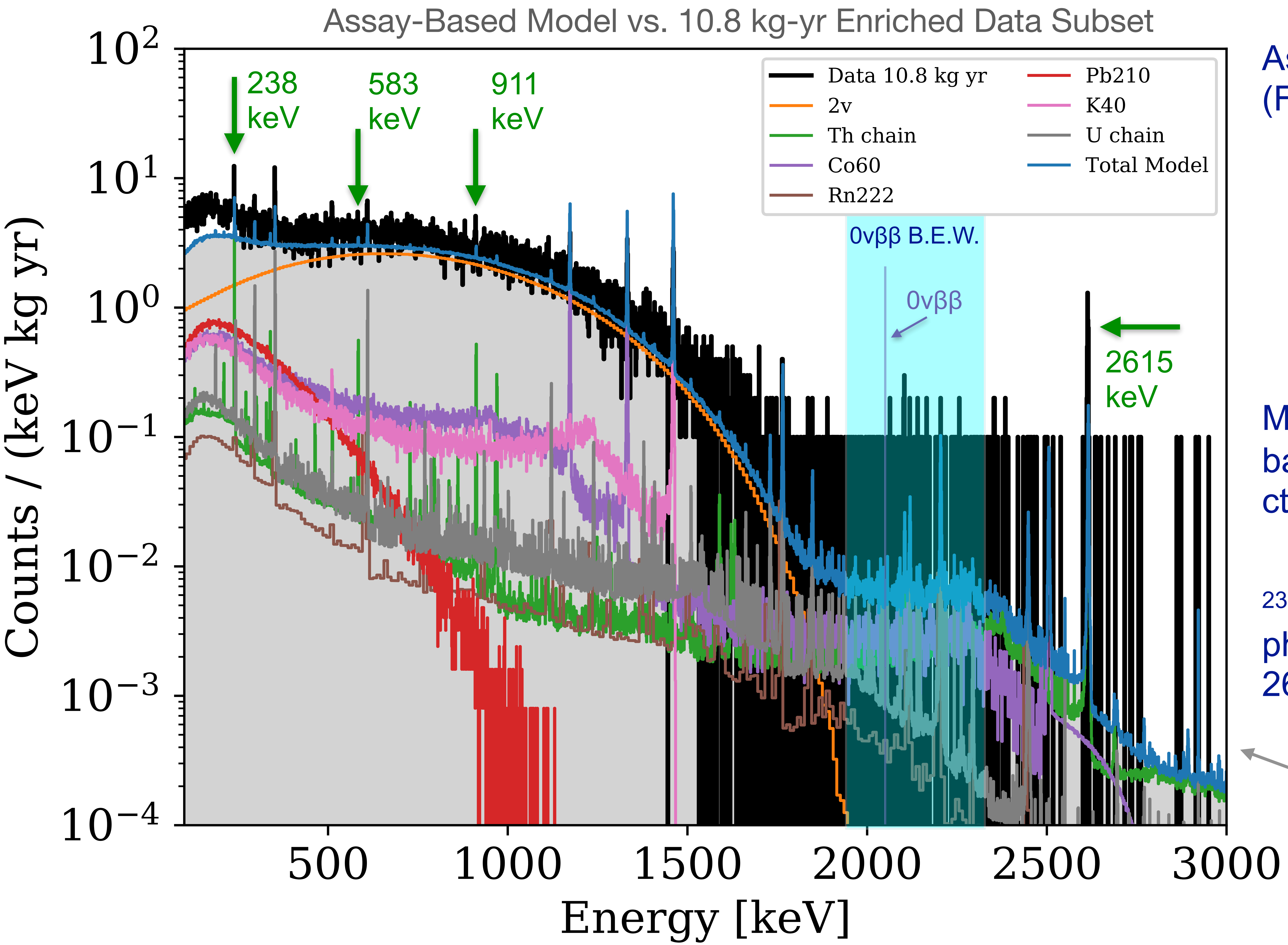
Module 1:

18.6 ± 1.8 cts/(FWHM t yr)

Module 2:

$8.4^{+1.9}_{-1.7}$ cts/(FWHM t yr)

Assay-Based Prediction vs. Data



Assay-based prediction: 2.9 ± 0.14 cts/(FWHM t y)

Based on original assay results, incorporating additional assay information, updating simulations to match as-built geometry, and using more refined techniques of quantifying uncertainties

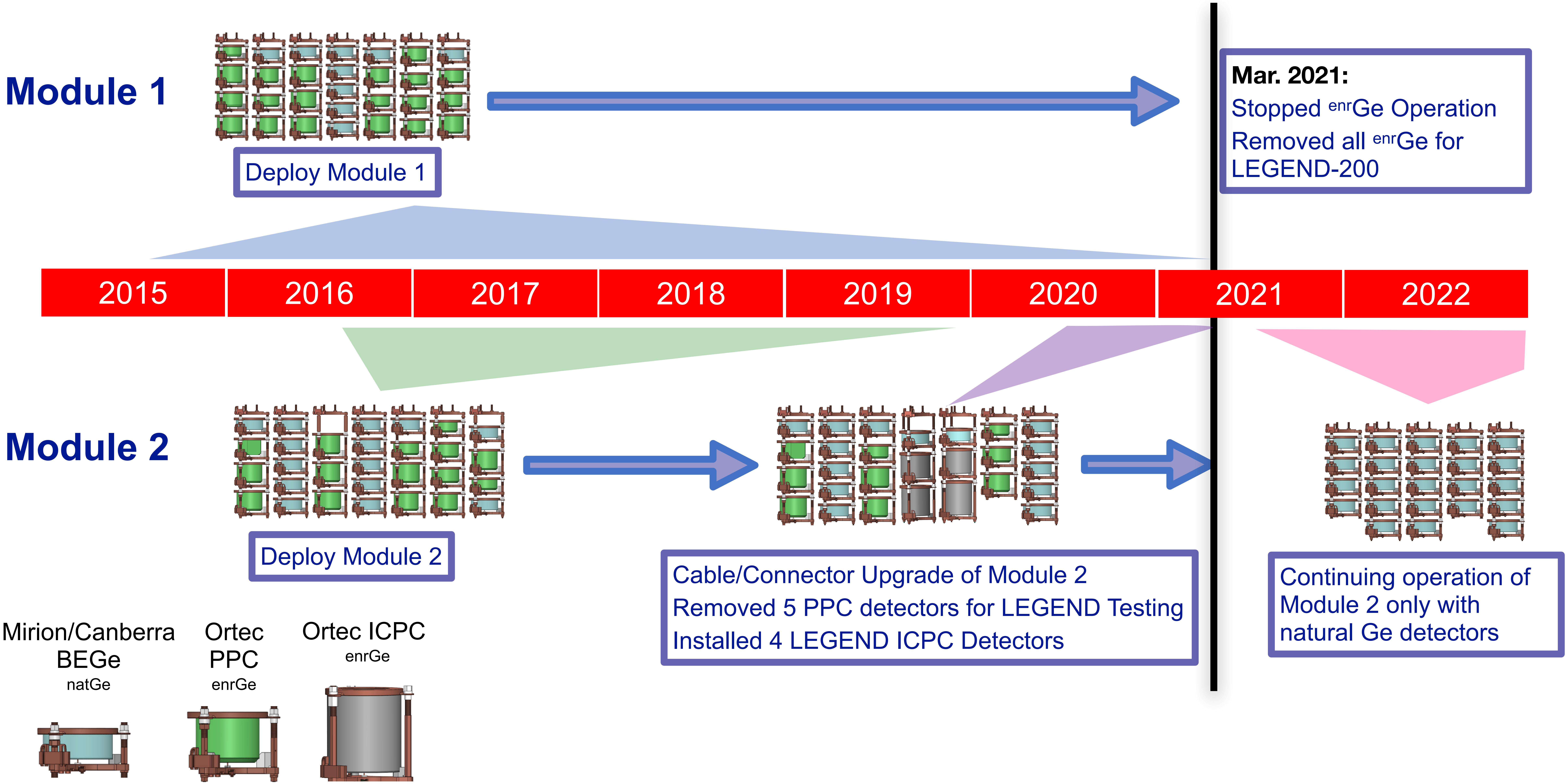
NIM A **828** 22 (2016)

Measured Background in lowest background configuration: 15.7 ± 1.4 cts/(FWHM t y) - **PRELIMINARY**

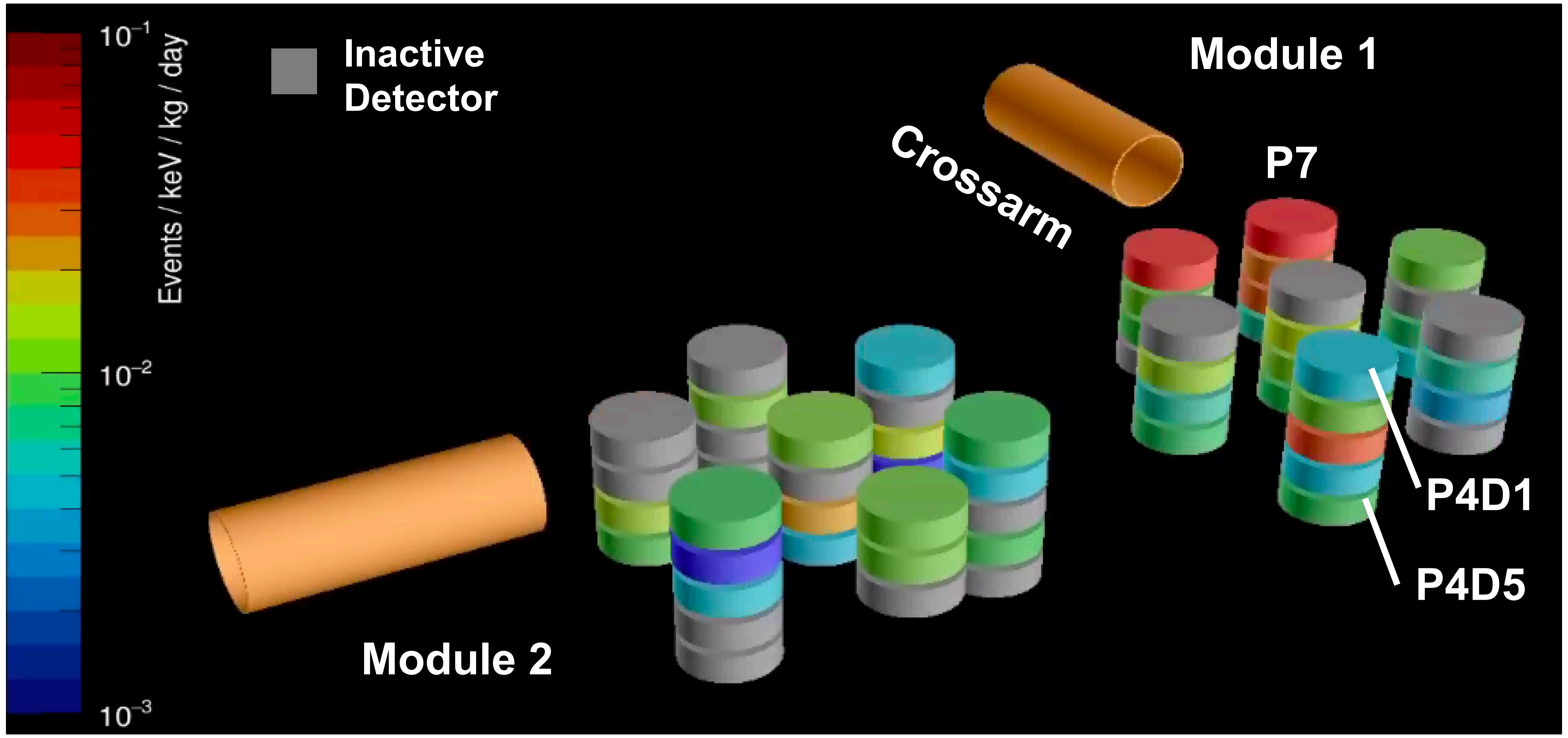
^{232}Th excess apparent at ^{208}Tl photopeaks, especially 238 keV and 2615 keV

Delayed charge recovery (surface alpha) cut and data cleaning cuts applied

MAJORANA Run Configuration & Timeline

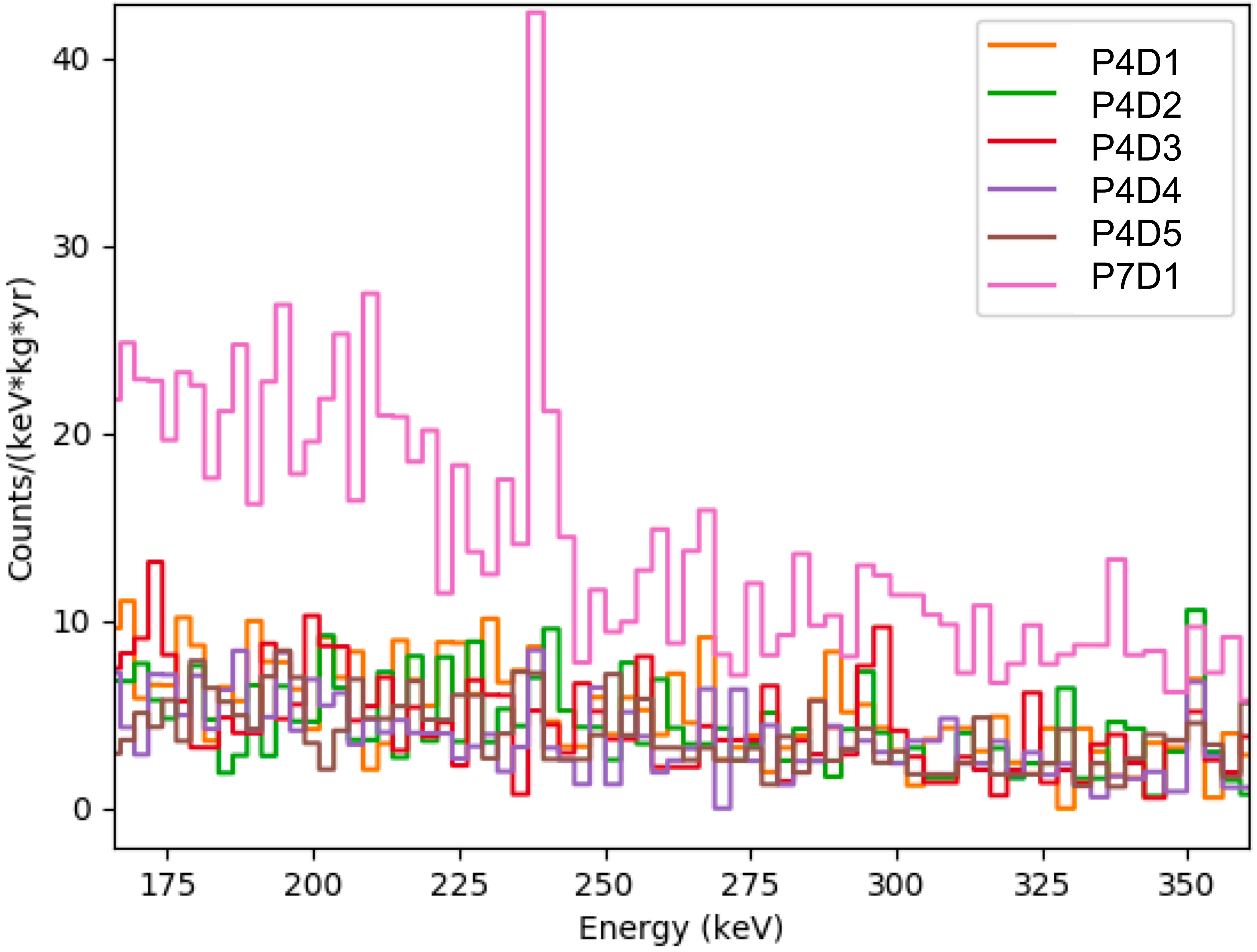


Evidence of Non-Uniform Background Excess



2615 keV rate in datasets prior to upgrade

238 keV ^{212}Pb Peak (from ^{232}Th Chains) in Module 1 Natural Detectors*



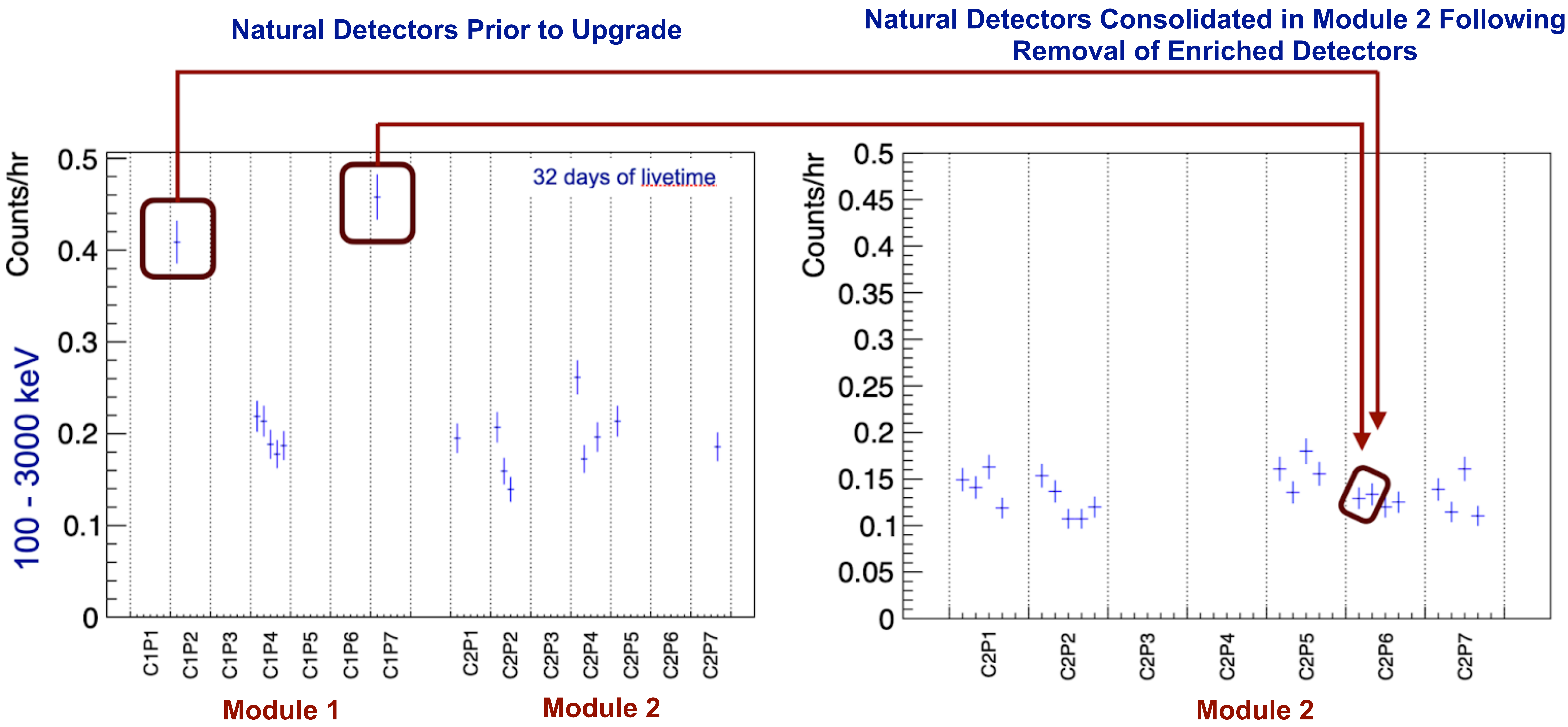
The 238 keV gamma line will be reduced in intensity by more than 70% in 1 cm of copper (compared to only 30% reduction in intensity of 2615 keV gamma)

- Only a small amount of shielding can be between ^{238}Th source and detector near Module 1 crossarm.

*One near-crossarm natural detector that was biased down early in data is omitted from spectrum due to limited statistics

Enriched detectors have been studied but are not included in plot

Natural Detector Event Rates



The two natural detectors which saw an excess of events between 100 and 3000 keV when positioned next to the Module 1 crossarm no longer had elevated rates after being moved to a new location in Module 2.

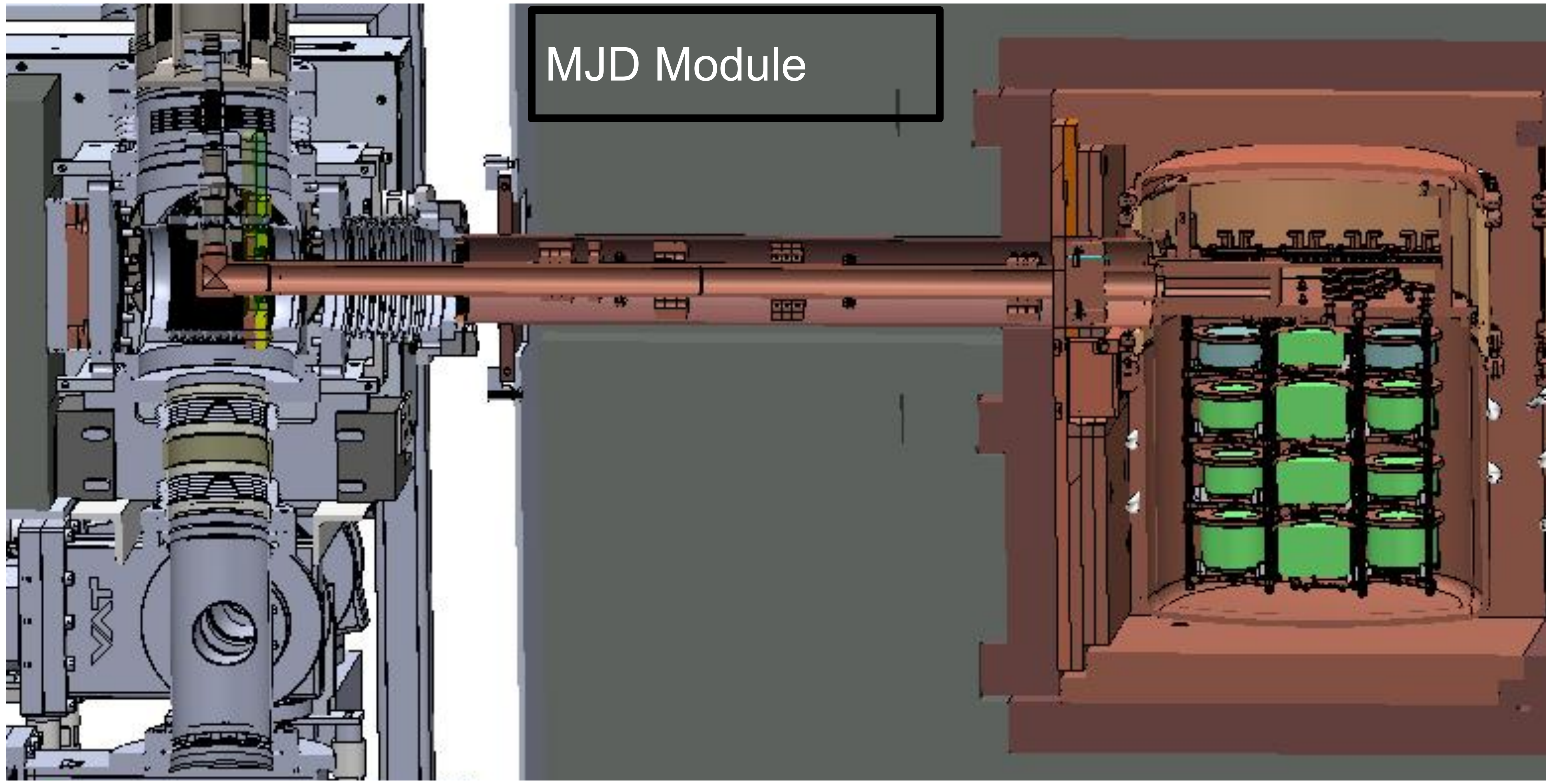
Background Modeling Foundations and Goals

Simulations

MaGe/Geant Monte Carlo simulations model the as-built geometry of the experiment, including around 4000 parts.

Includes the following decay-chains or isotopes:

- ^{238}U chain
- ^{40}K
- ^{76}Ge ($2\nu\beta\beta$)
- ^{222}Rn
- ^{57}Co
- ^{232}Th chain
- ^{60}Co
- ^{210}Pb
- ^{68}Ge



Earlier Studies

The excess ^{232}Th observed in data does not indicate a source within the Ge detector array (front end electronics, detector holders, etc.).

Based on studies of relative peak intensities and rates of coincident gammas in the ^{232}Th chain

Gamma simulations of the cube region (magenta) ruled out a far "shine-path" source.

Fitting Goals

- Measure the $2\nu\beta\beta$ half life of ^{76}Ge
- Confirm the source of the excess ^{232}Th background
- Provide full model of backgrounds observed in the DEMONSTRATOR with well-quantified uncertainties that can be used in future searches for BSM processes, such as deviations of the $2\nu\beta\beta$ spectral shape

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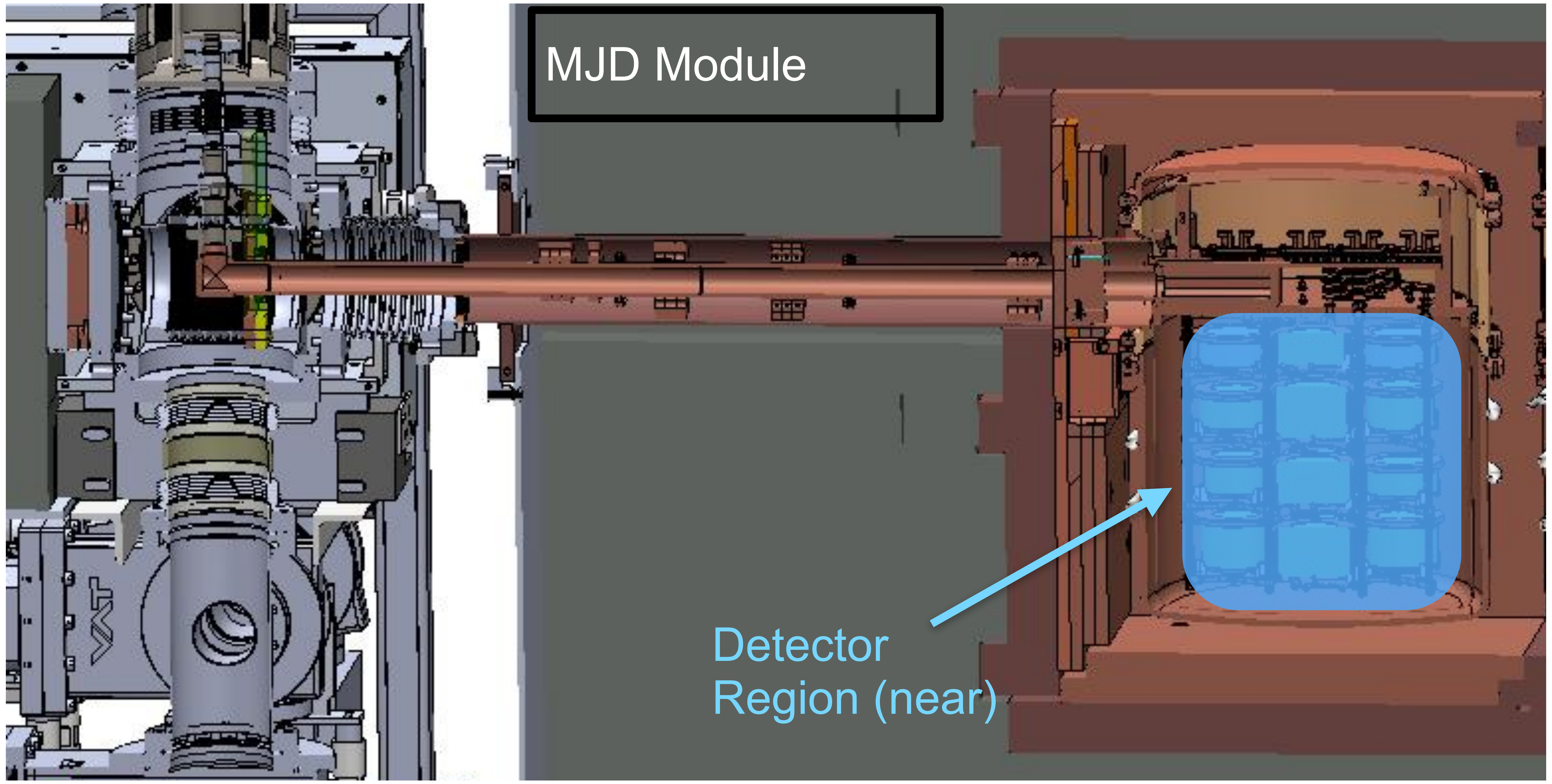

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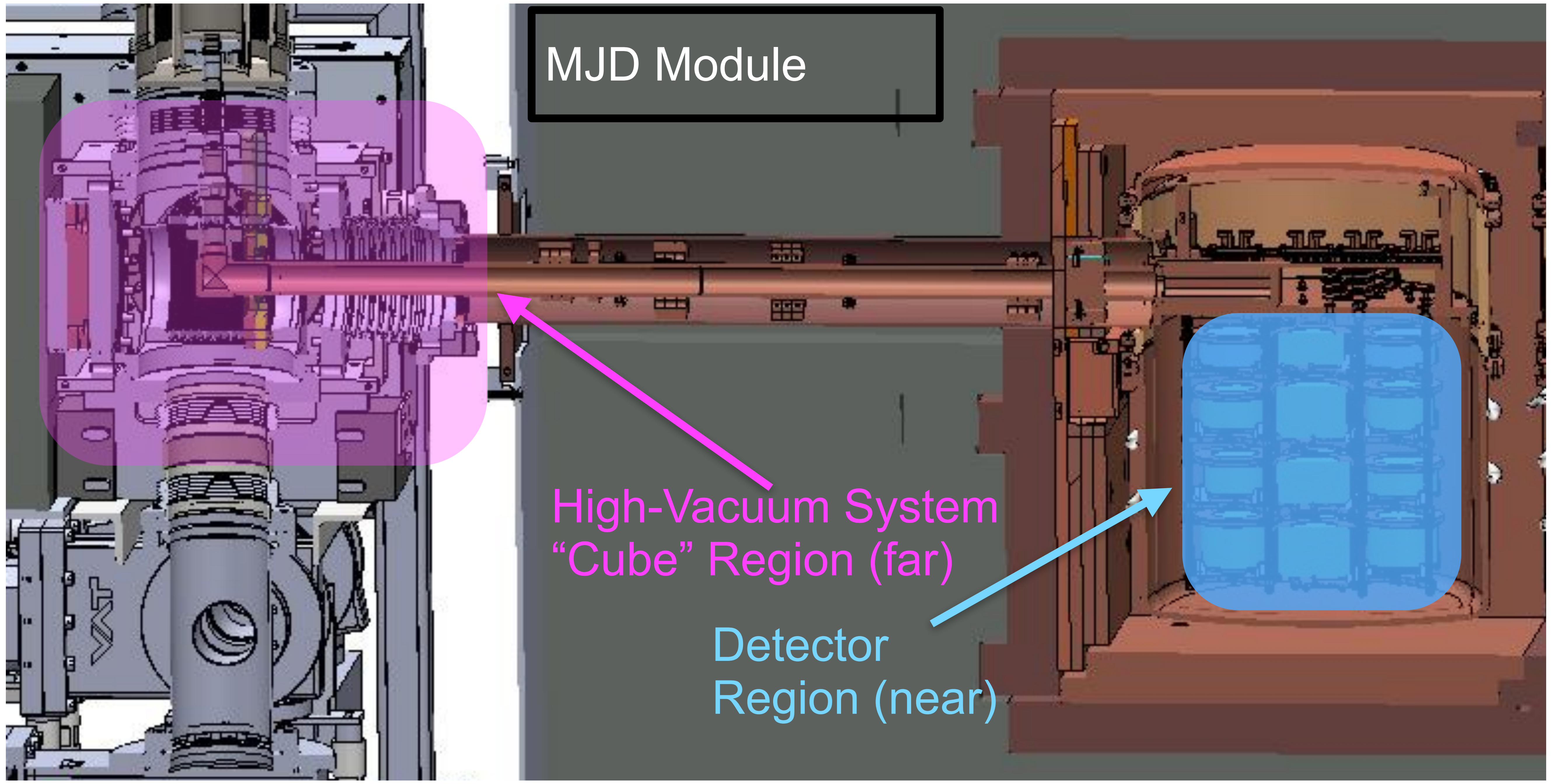

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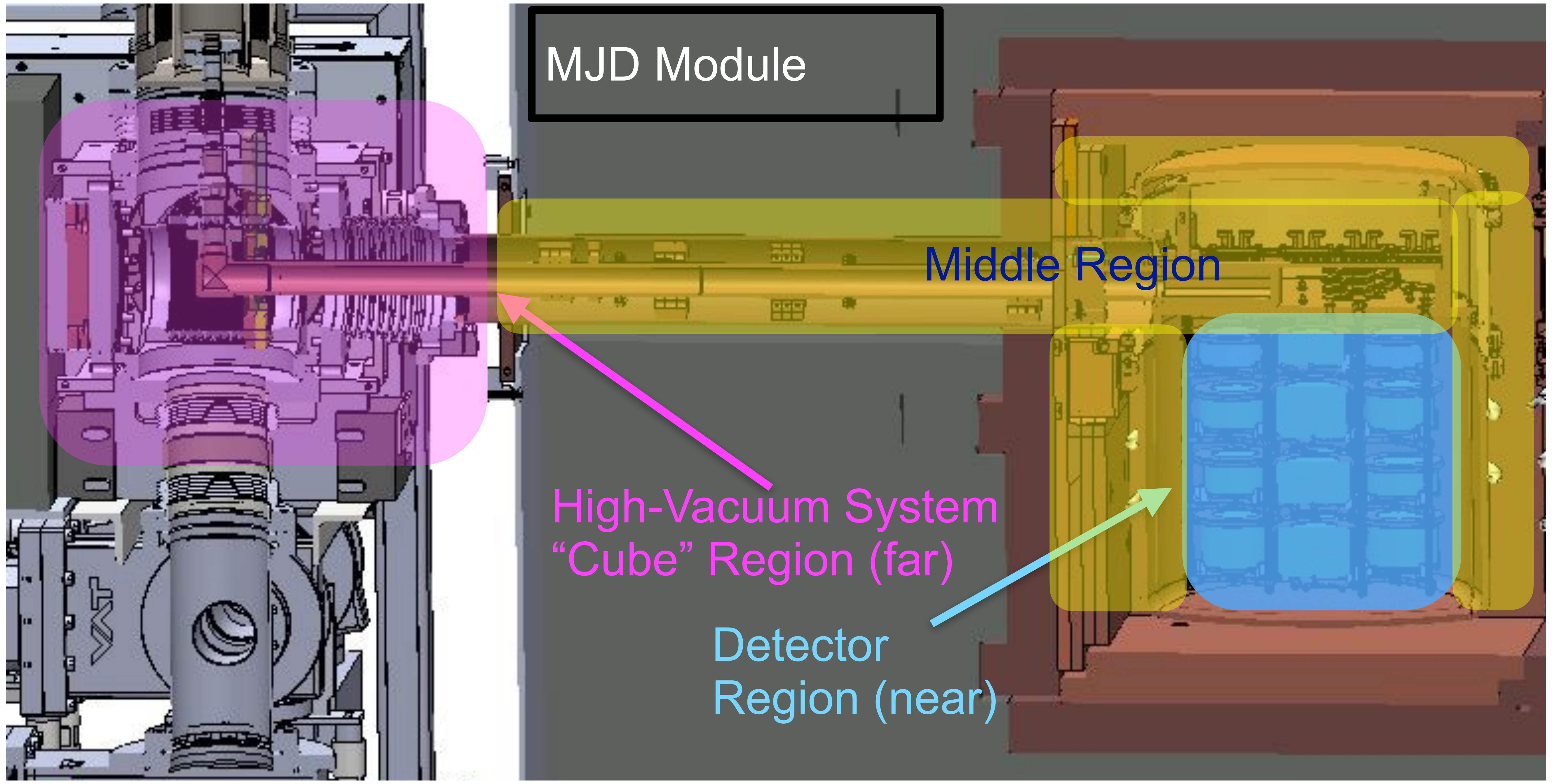

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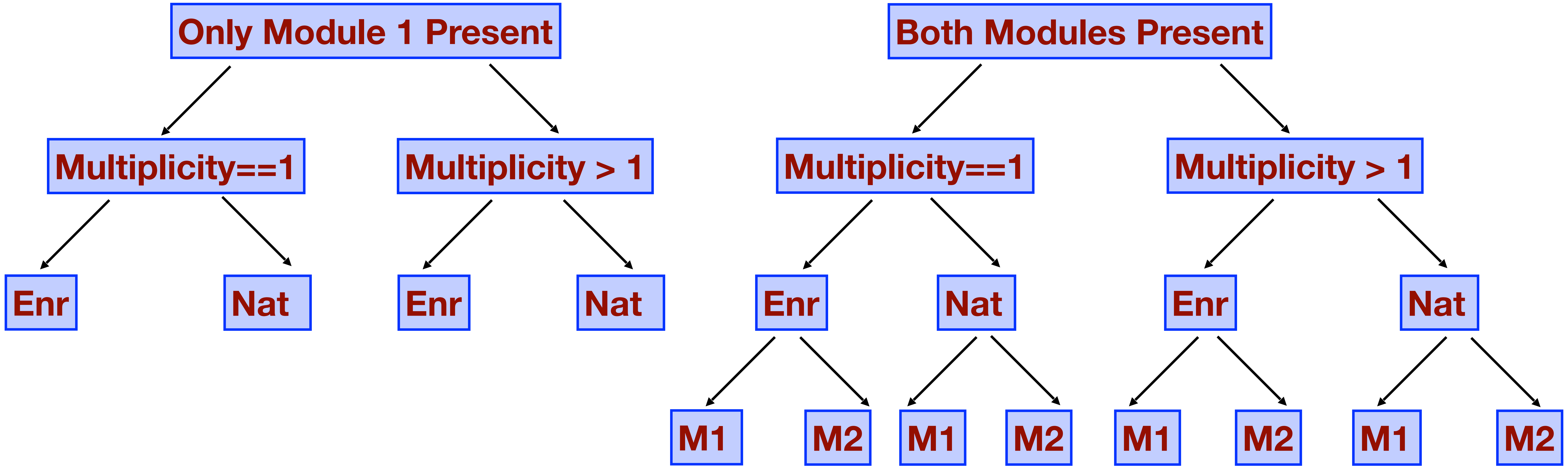
Background Model Fitting Details

Both Frequentist and Bayesian Fits

- Fitting from 100 keV to above the 2615 keV ^{232}Th peak
- Cut applied to data to remove surface alphas
- Floating ~100 source activities
  - ~4000 parts sorted into 27 component groups, based on location
  - Coupled with up to 9 decay chains each

12 independent energy spectra are simultaneously fit



Details of Frequentist Fit

- Variable binning scheme
- Barlow Beeston likelihood (accounts for limited statistics in simulations)
- No assay information incorporated
- Utilizes migrad minimizer from minuit python package

Details of Bayesian Fit

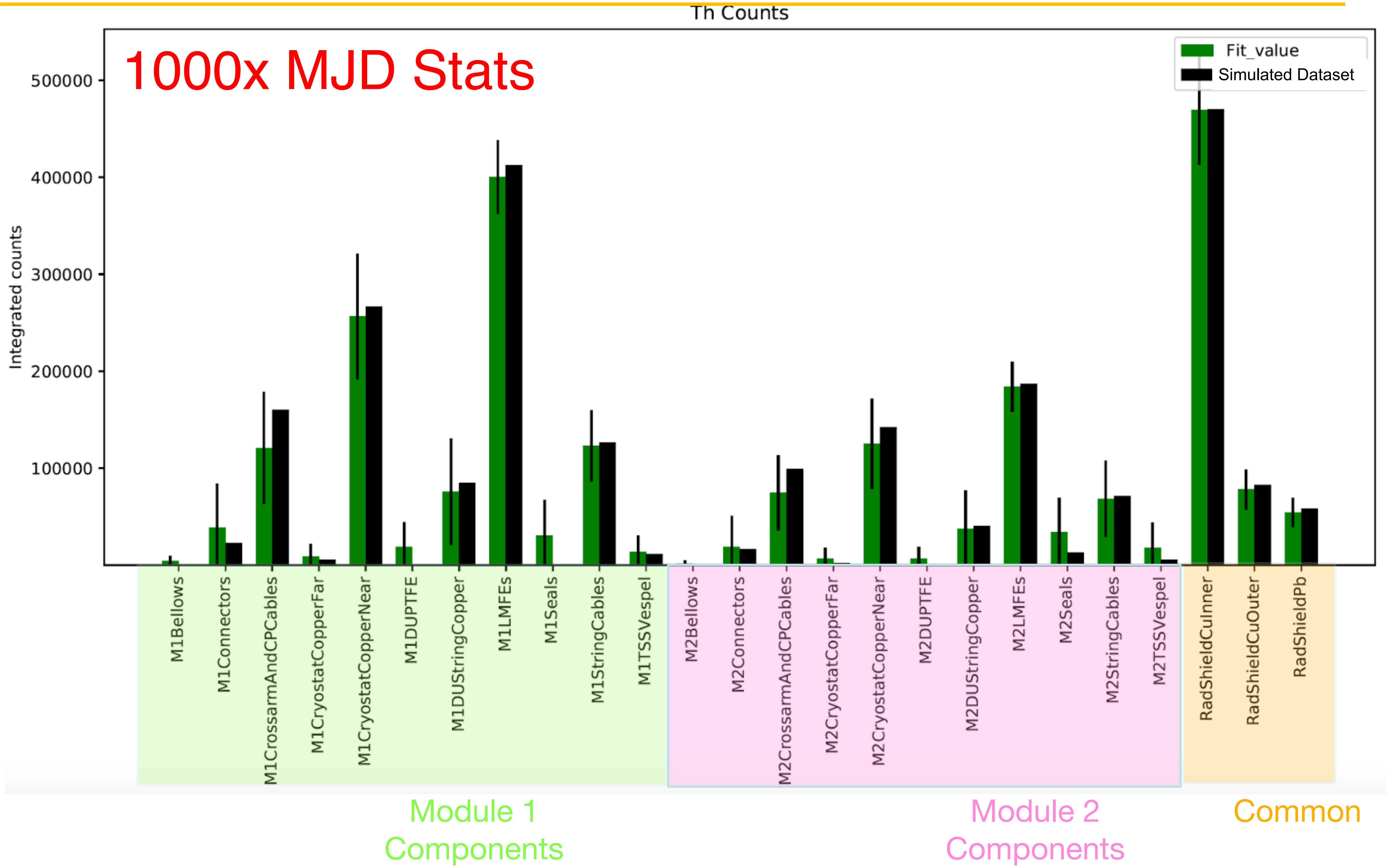
- Fixed-width binning
- Poisson likelihood
- Assay values used to inform truncated Gaussian priors
- Utilizes HMC-like posterior sampler from PyMC3 python package

Method Validation Using Simulated Data

Systematic studies are being performed using **simulated datasets** in order to evaluate the performance of the fitting algorithms and refine the techniques applied to data.

To generate a **simulated dataset**:

- A model is constructed by summing ~100 simulated spectra, each weighted by a known activity density (typically the component's assay value)
- Data randomly sampled from model



The frequentist fitting algorithm was tested with simulated data from a model assuming assay activity values and an exposure **approximately equal to the DEMONSTRATOR's total exposure.**

- The magnitude of each distribution's standard deviation (indicated by the error bars in the plot below) indicates that **there is not sufficient statistics** to disentangle the contributions of different Th sources if these sources are at assay-predicted levels.

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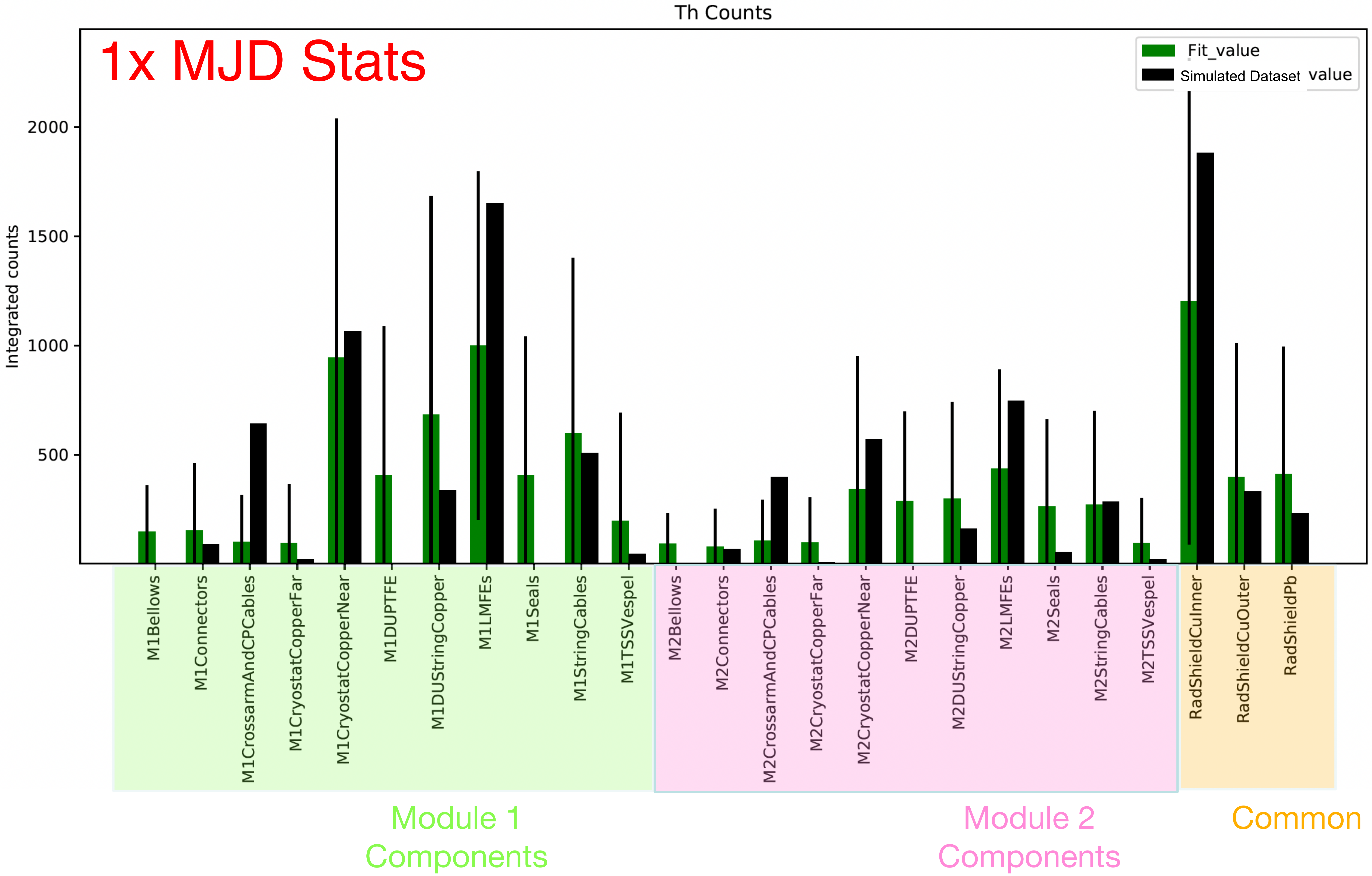

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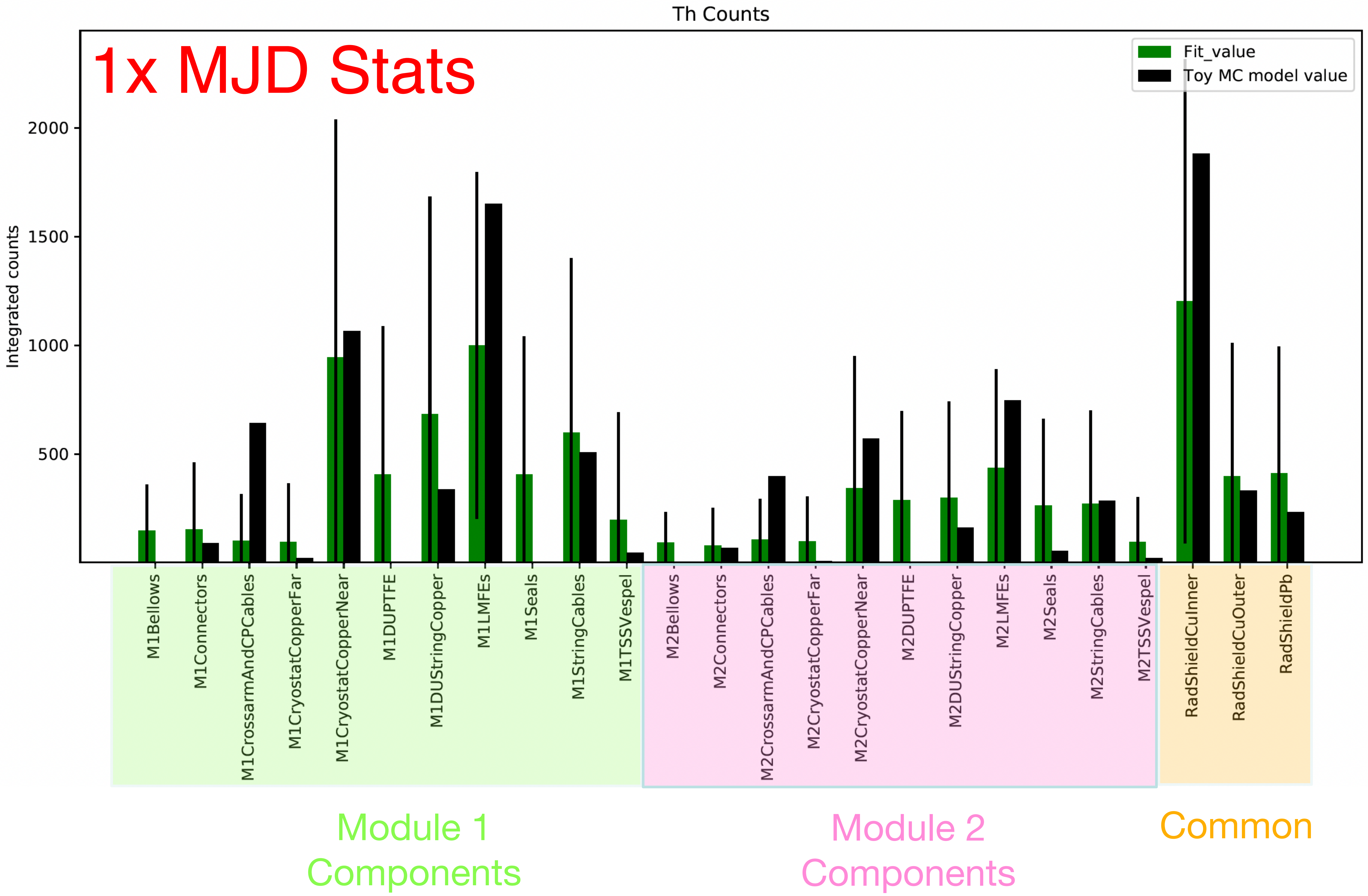
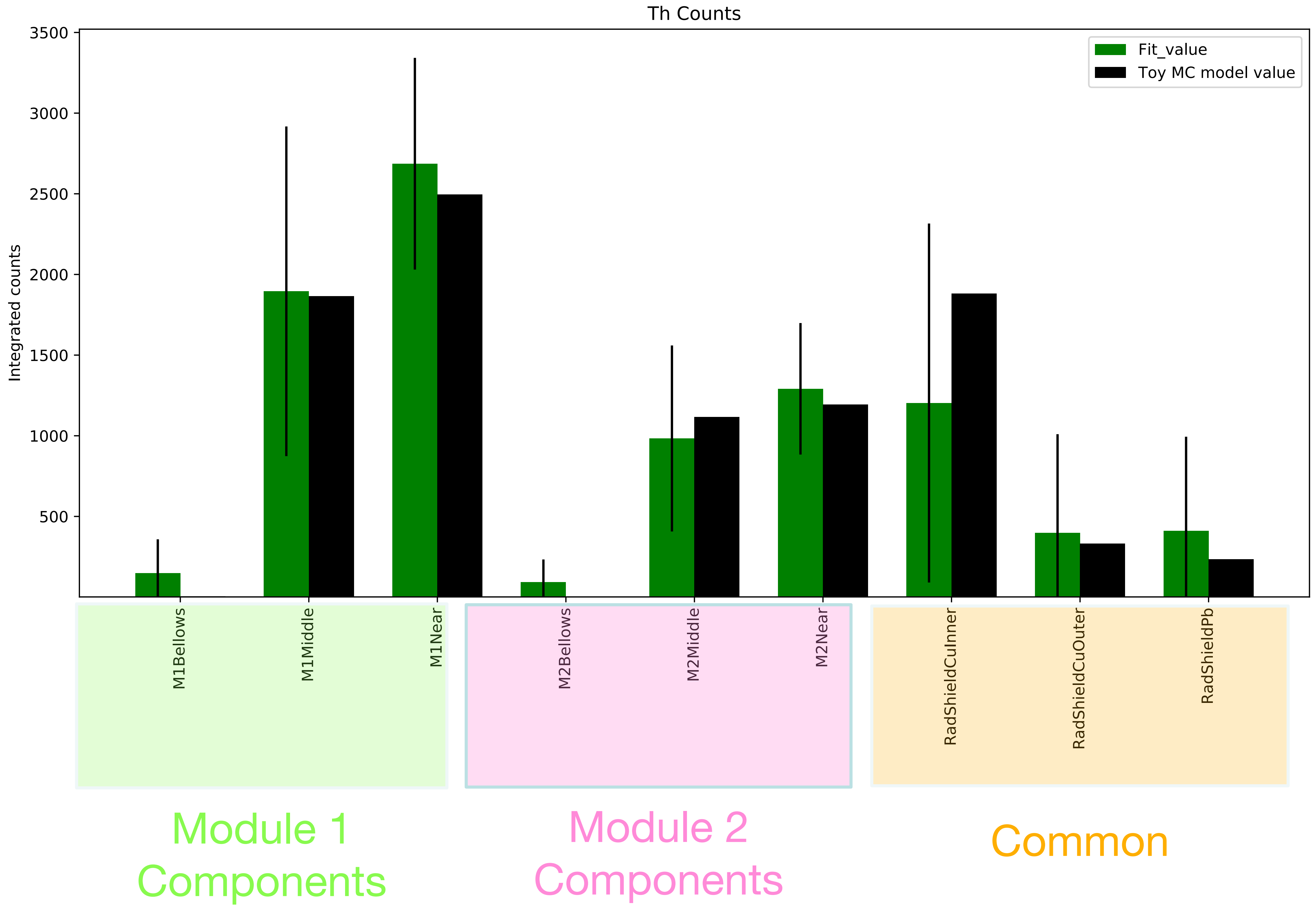
Method Validation Using Simulated Data

Results of Fit to Simulated Data → Same Results Recombined to Larger Location-Based Groups

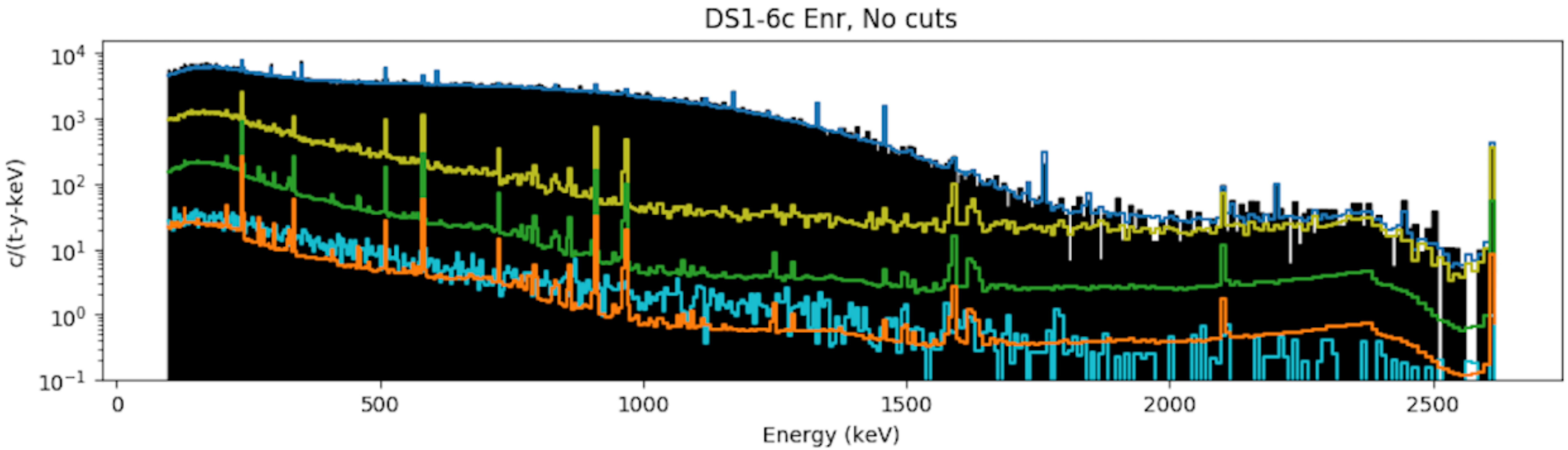




Anticorrelations between component groups in similar locations makes it challenging to determine the exact component group from which an excess originates at this level of statistics.

Combining fitted counts into larger groups after the fitting process typically shows that the region of the excess ^{232}Th can still be accurately determined

Frequentist Fit to Data, ^{232}Th Spectrum



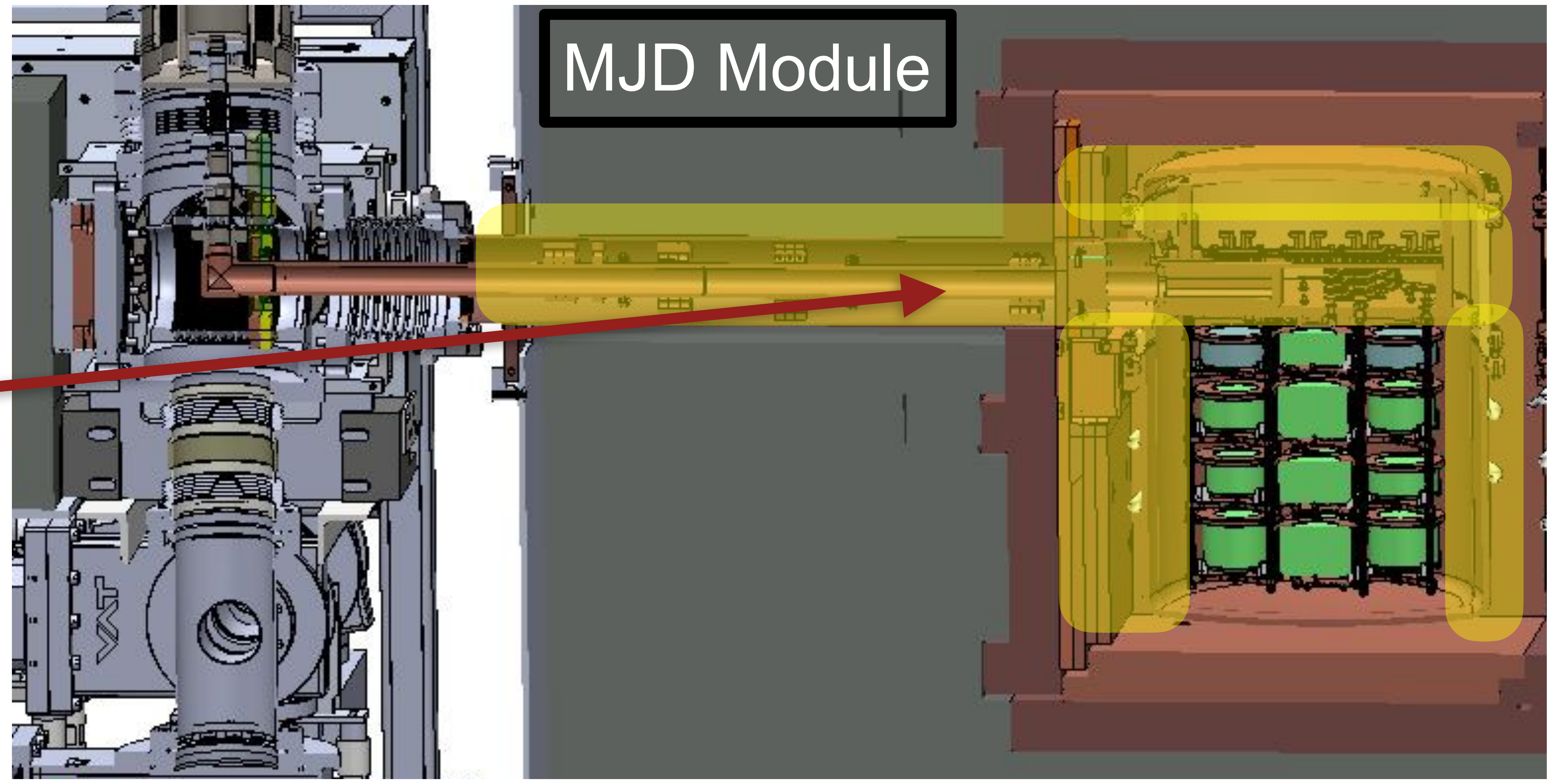
18.3 kg-yr exposure

Data cleaning and surface alpha cuts applied

Fit to open data is consistent with initial studies that indicate ^{232}Th source not being a near detector source or far detector source

Module 1 groups are generally fitting higher in ^{232}Th than Module 2 groups

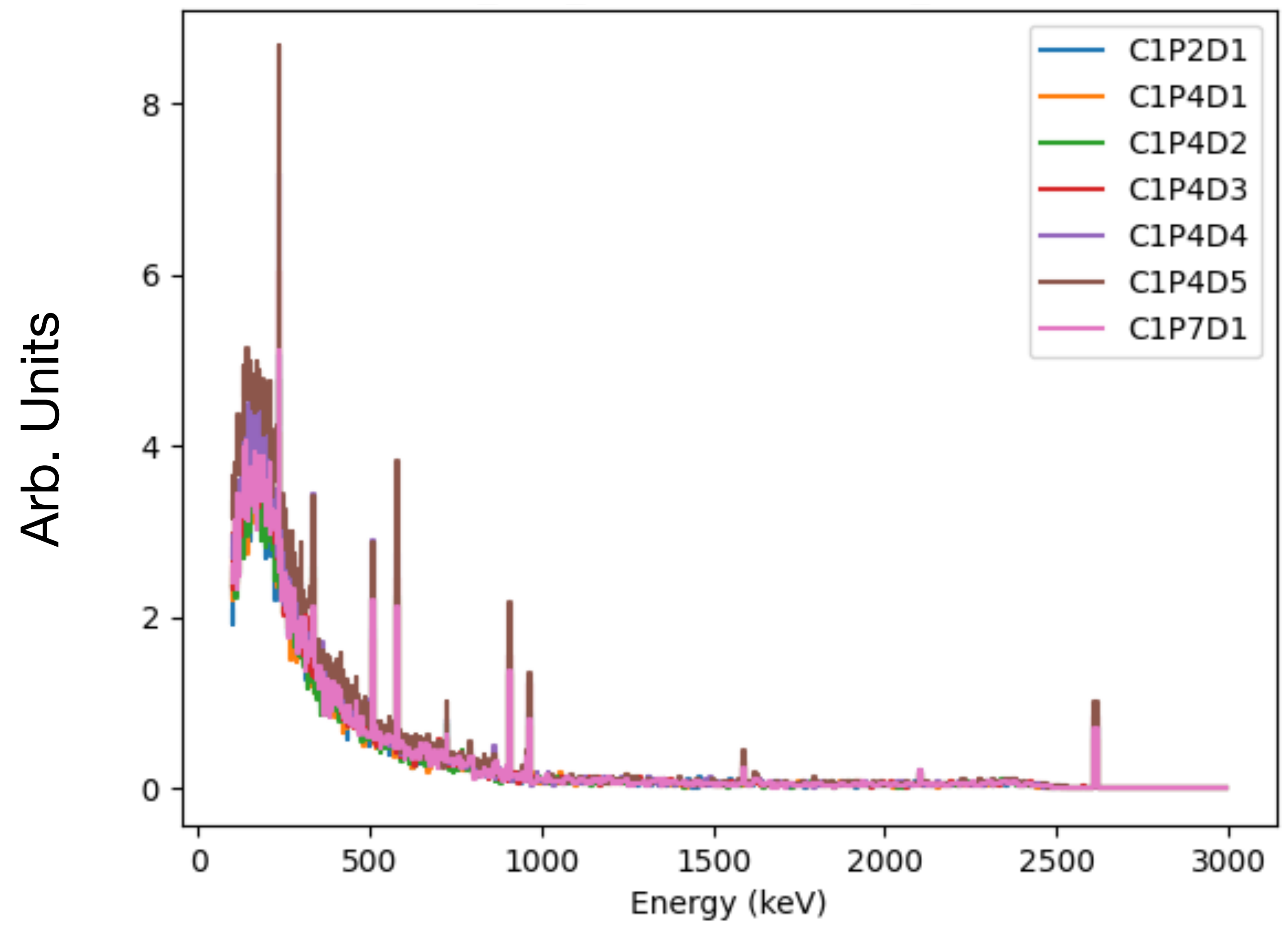
Th_M1Middle group includes copper parts to the crossarm, thermosyphon, and interfaces to the cryostat (yellow region).
Consistent with evidence that the source of the ^{232}Th excess is in this region of Module 1.



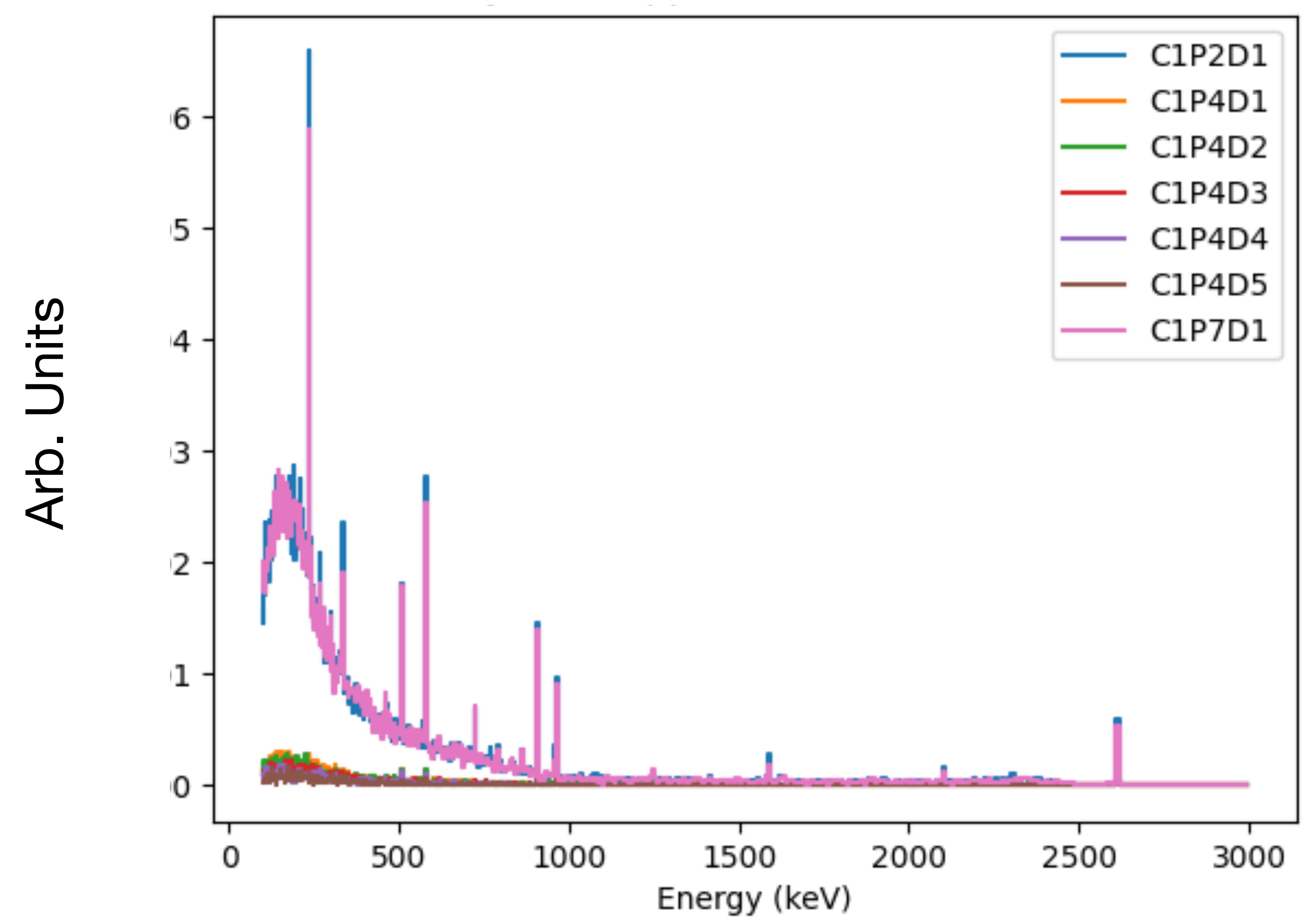
Simulations vs. Data

Simulated Spectra

Thorium Spectra for Module 1 Natural Detectors | **Inner Cu Shield** Source



Thorium Spectra for Module 1 Natural Detectors | **Crossarm Region Cu Components** Source

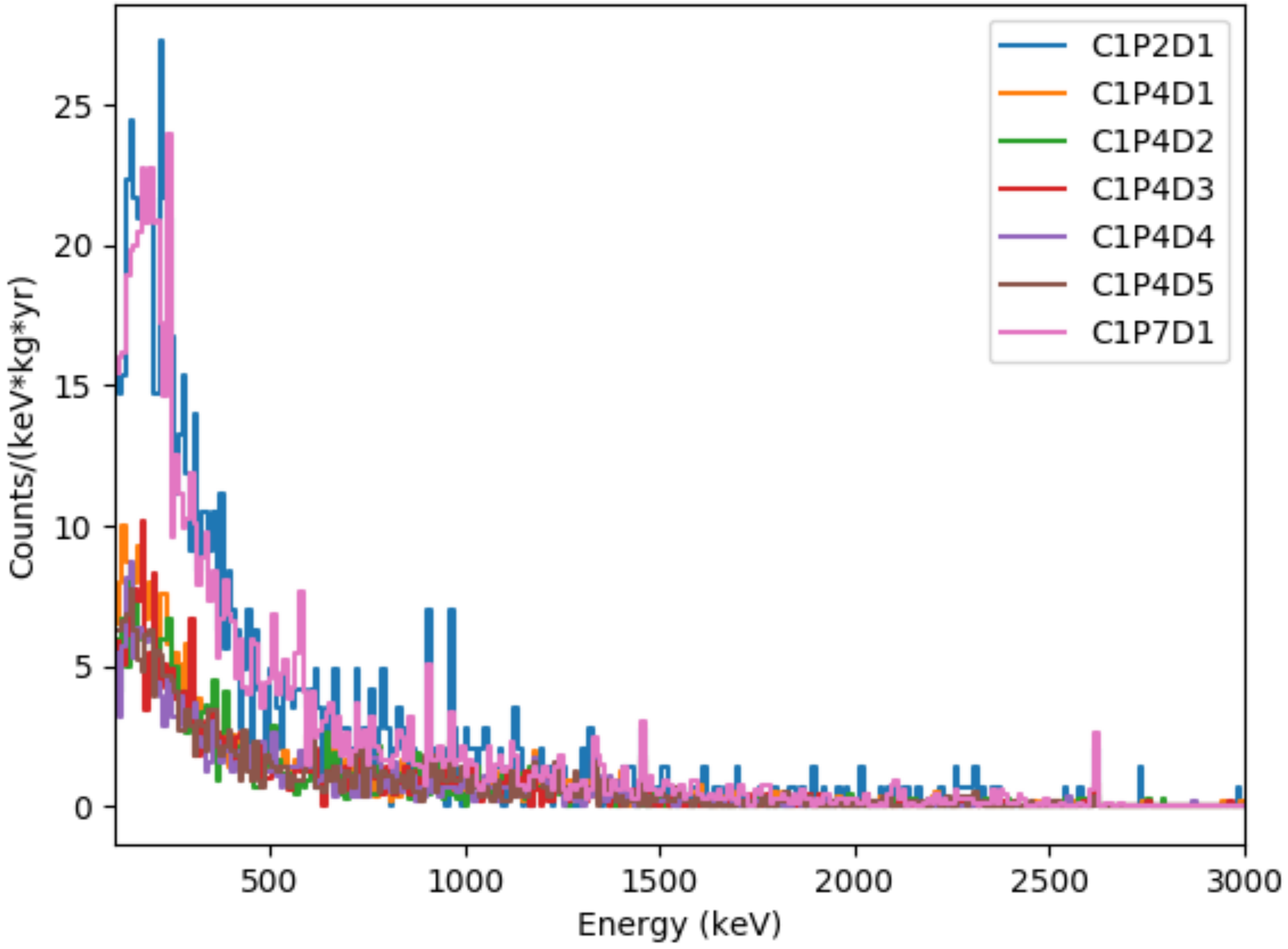


Inconsistent

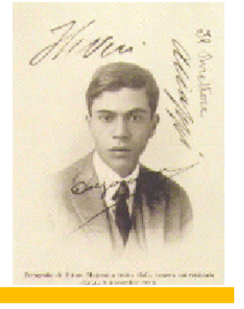
Consistent

Data Spectra

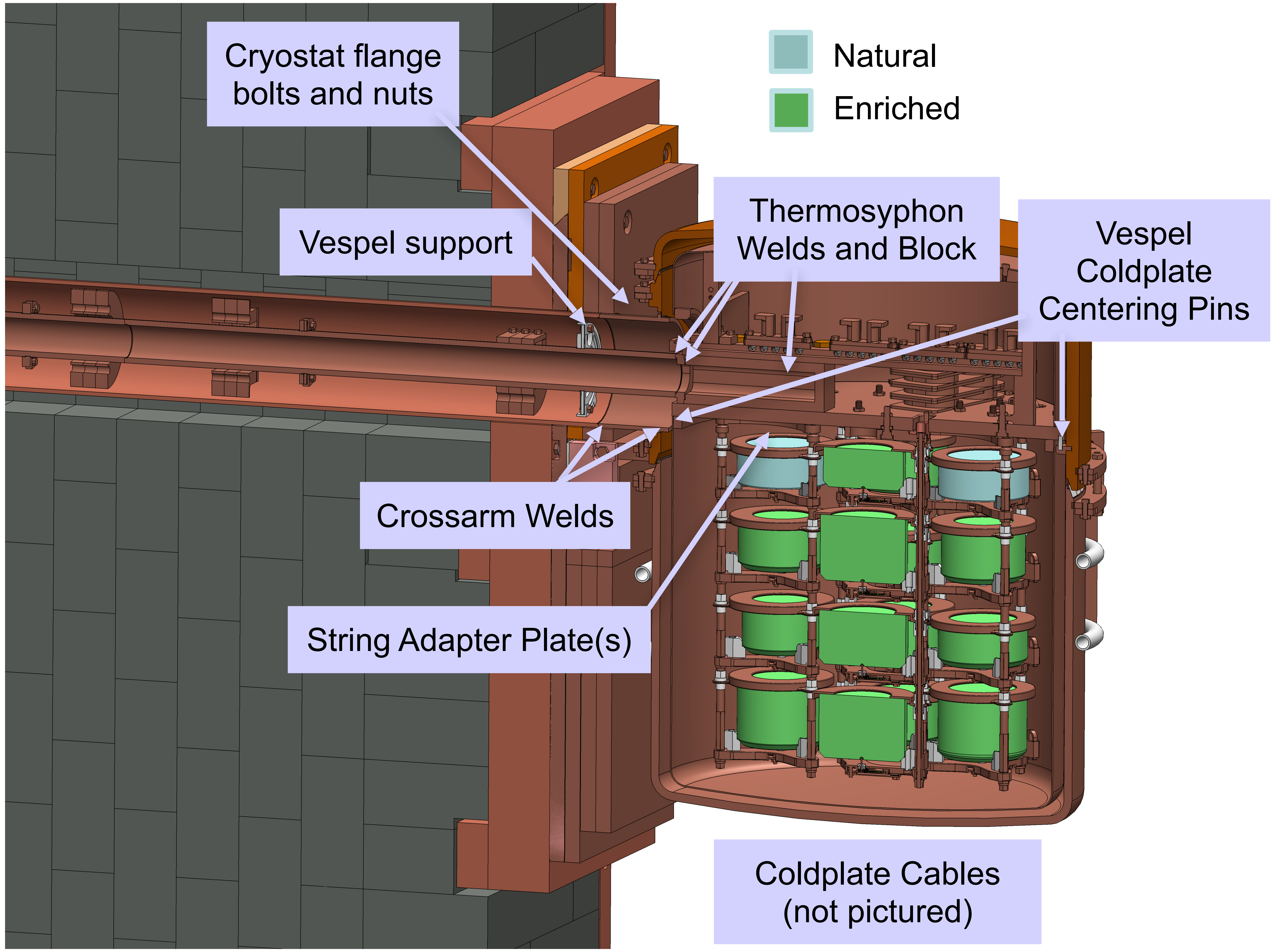
Module 1 Natural Detectors | 18.3 kg-yr Data Subset



Candidate Components for Excess



Individual components were identified as candidate sources of the excess based on their location and simulations.



Candidates were pulled for assay measurements.

Component	Sensitivity [mBq]	Upper Limit [mBq]
Module 1 Crossarm Weld 1	~1*	<0.52
Module 1 Crossarm Weld 2	~6*	<1.3
Module 1 Thermosyphon Welds	~4*	<0.72
Vespel Support Ring	3	Final result under review.
Vespel Coldplate Centering Pins	1	Assay in-progress
Thermosyphon Mounting Bolts	1	Assay in-progress
String 2 and String 7 Adapter Plates	1	Ruled-out by use in Module 2
Cryostat Flange Bolts and Nuts	1	Assay in-progress
Thermosyphon Block	1	Assay in-progress
Module 1 High Voltage and Signal Cables	1	Assay in-progress

*Listed sensitivity for the welds is also the activity required to explain the ^{232}Th excess based off peak scaling of simulations to data.

Conclusions and Outlook

- Two open questions in observed background
  - There is a quantitative discrepancy in backgrounds between both modules in the region of interest
  - There is a quantitative discrepancy between the uniform background rates predicted by assay and the non-uniform background rate identified by the data.
- Two natural detectors adjacent to the Module 1 crossarm observed high integrated count rates and prominent ^{232}Th peaks compared to other detectors
  - Elevated rates in the 238 keV peak indicate a source in the portion of the crossarm region close to the array
  - High rates did not persist after detectors were moved to a new location
- Simulations of components in the middle region show good qualitative agreement with data
- Method validation demonstrates our ability to fit at low statistics
  - Fitting algorithms perform well on high statistics simulated datasets, but not as well on low statistics simulated datasets at the level of MJD’s full exposure.
  - By consolidating component groupings, the region of a ^{232}Th excess can be determined.
  - At low statistics, method validation shows that we can fit the $2\nu\beta\beta$ rate with reasonable precision
- Frequentist fits are consistent with data
- Future efforts in support of a complete background model of the MAJORANA DEMONSTRATOR
  - Studies of individual detector spectra in both enriched and natural detectors will support further background model fits with increased exposure
  - Assays underway of other components from areas near high rate detectors. Welds and vespel support ring ruled out.

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This material is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, the Particle Astrophysics and Nuclear Physics Programs of the National Science Foundation, and the Sanford Underground Research Facility.

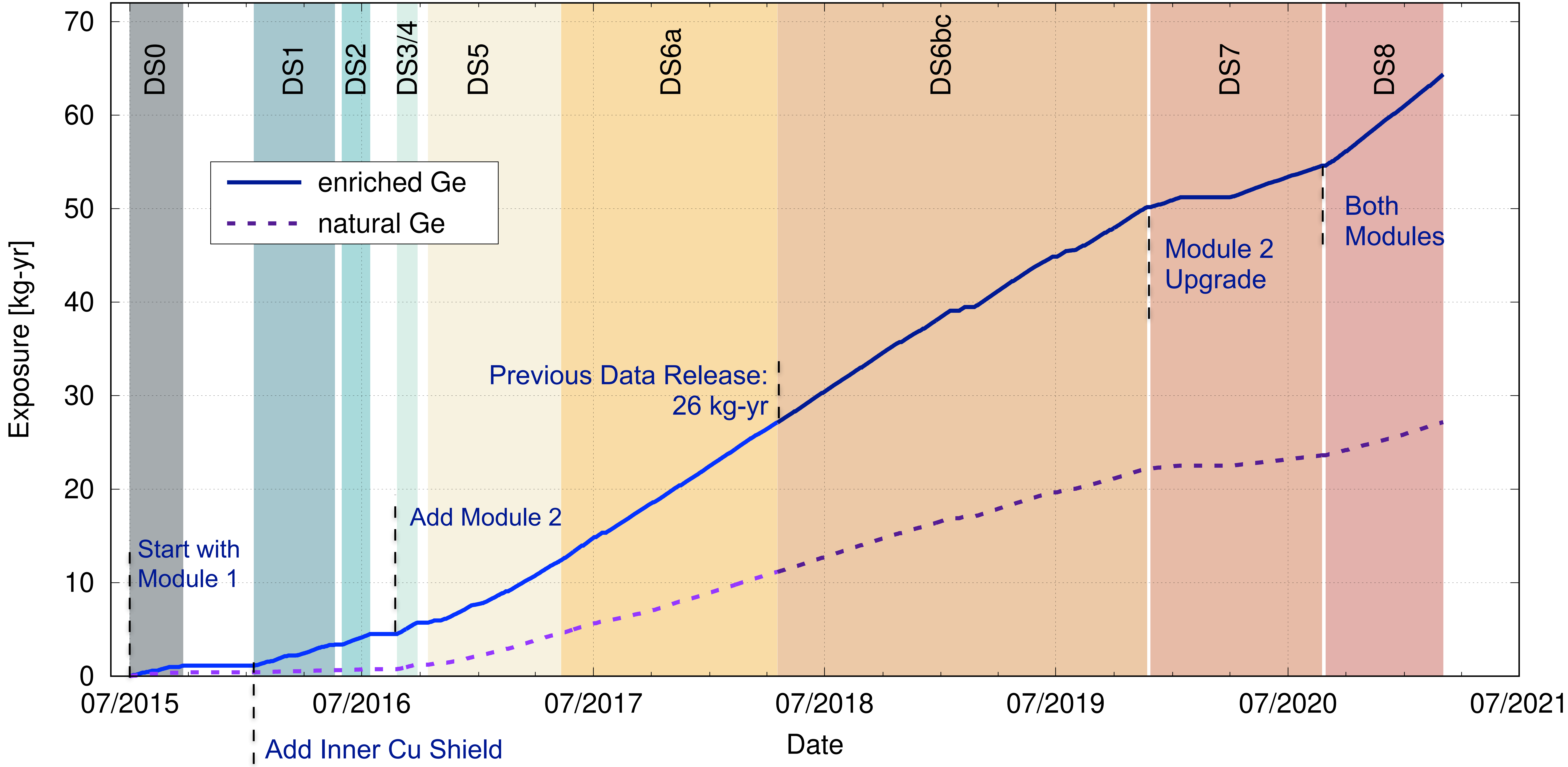
Backup Slides

Background Model Fitting and Datasets

Using subsets of data that correspond to 18.3 kg-yrs enriched Ge exposure, 26.7 kg-yrs enriched + natural Ge exposure

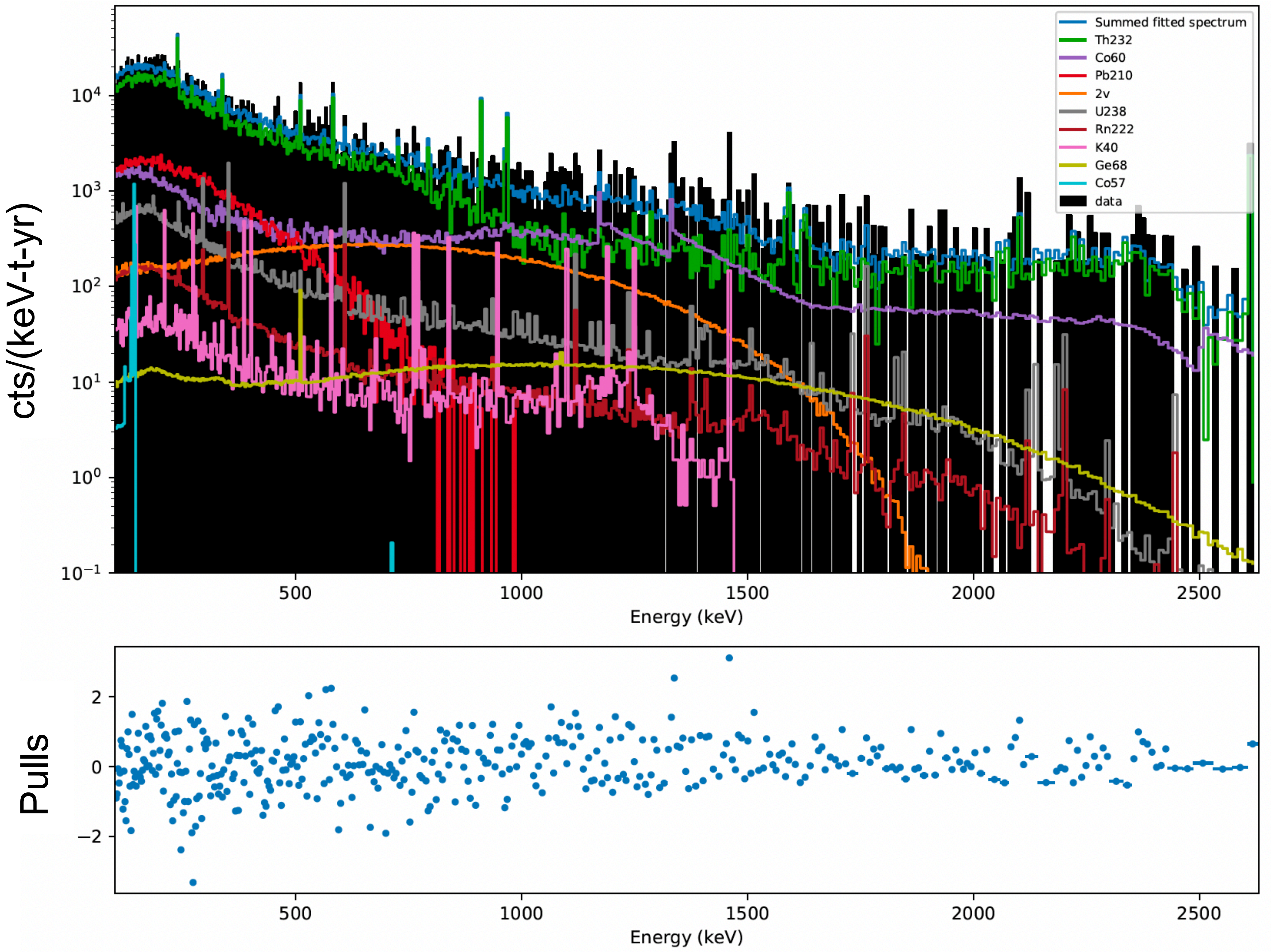
Testing fitting tools on open data to understand systematics.

Will expand fits to full set of data covered by blindness scheme, increasing exposure by more than a factor of 3.



Simulations of Candidate High Activity Components

Example of Scaling Simulation to 238 keV Peak in High Rate Detector



Simulations were compared to data using methods including scaling to the 238 keV peak in a high rate detector and single component fits.

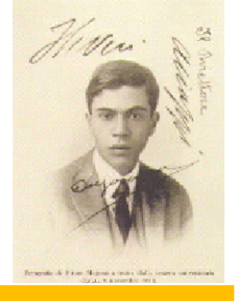
- Reasonable agreement with data achieved at similar activities with different methods

Results of Scaling to 238 keV Peak

	Required Activity (mBq)	Enriched Background Index in cts/(FWHM-t-yr)
Published Low Background Dataset		11.9 ± 2.0
Assay Model, no excess		2.9
Module 1 Crossarm Welds	0.97 - 6.3	5.12 - 10.3
Module 1 Thermosyphon Welds	2.7 - 6.5	7.7 - 14.5
Module 1 Vespel Support	4.0	8.04

- The source of the excess in natural detectors could be a significant contributor to the excess observed in the $0\nu\beta\beta$ ROI for enriched detectors after cuts
- Estimated activities and further simulations indicated that the DEMONSTRATOR's current configuration was sufficiently sensitive to assay welds formerly located in Module 1

Assay Measurements of Selected Module 1 Components



Components that previously made up the Module 1 crossarm were cut to isolate candidate high activity parts.

These parts were then placed inside the Module 2 shielding (but outside the cryostat) to perform an in-situ assay with the array of natural detectors.

	Module 1 Crossarm Weld 1	Module 1 Crossarm Weld 2	Module 1 Thermosyphon Welds
Activity Required to Explain Excess [mBq]	~1	~6	~4
Upper Limit [mBq] (95% CL)	< 0.52	< 1.3	< 0.72

Preliminary analysis of assay data and comparisons to simulations of the assay configuration suggests that **the welds do not have sufficiently high activity to account for the excess previously observed in high rate Module 1 natural detectors.**

- Provides additional support to the understanding that electron beam welding can be used in low background experiments