
# Low-Background Techniques Applied within the MAJORNA DEMONSTRATOR Experiment

Sanford Underground Research Facility

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On behalf of the MAJORANA Collaboration

NSF

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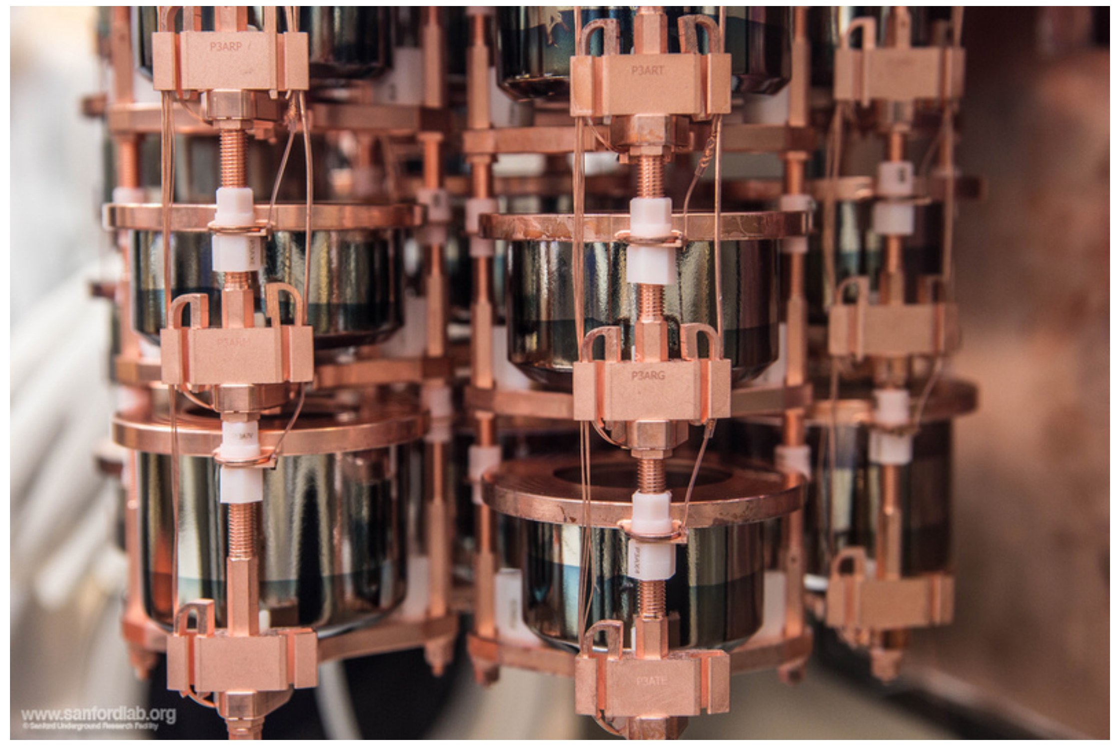
# MAJORANA DEMONSTRATOR

Searching for neutrinoless double-beta decay of $^{76}$Ge in HPGe detectors
and additional physics beyond the standard model

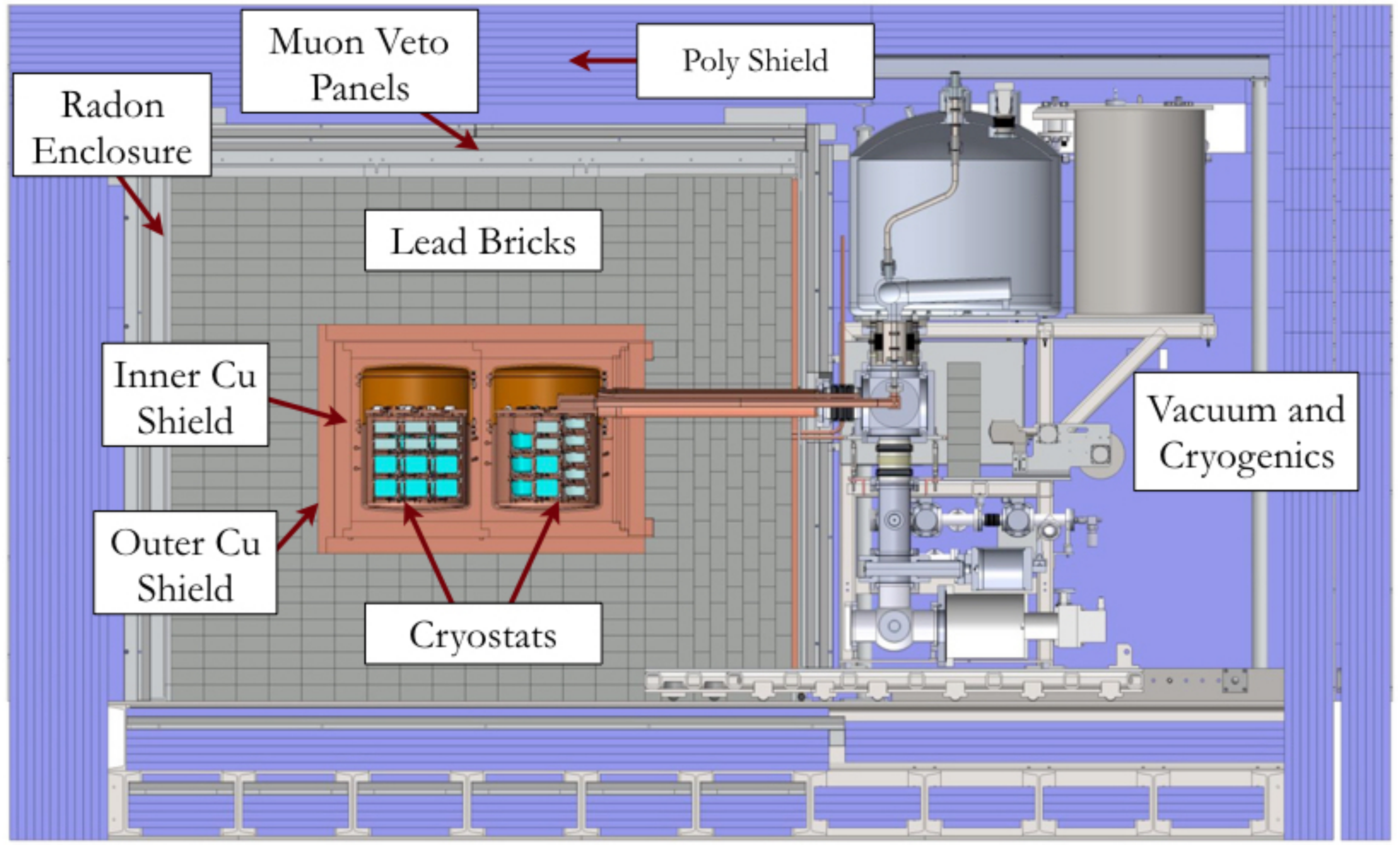
**Source & Detector:** Array of p-type, point contact detectors
29.7 kg of 88% enriched $^{76}$Ge crystals

**Excellent Energy resolution**: 2.5 keV FWHM @ 2039 keV

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

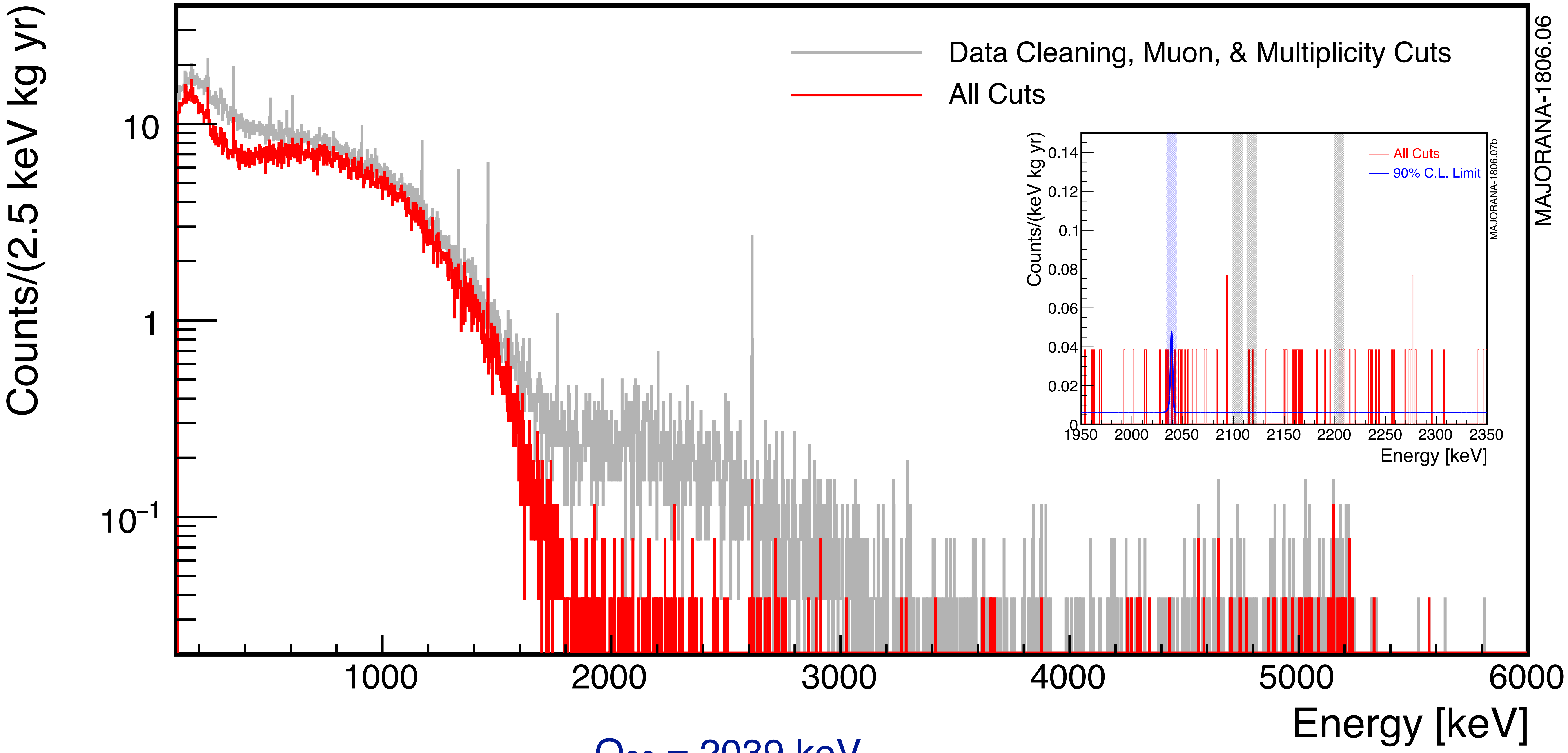


Operating underground at the 4850' level of the Sanford Underground Research Facility



# 2018 MAJORANA 0νββ Result

Operating in a low background regime and benefiting from excellent energy resolution




$Q_{\beta\beta}$ = 2039 keV

Initial Release:

PRL 120 132502 (2018)

Latest Release:
First unblinding of data
26 kg-yr of exposure

Neutrino 2018
arXiv:1902.02299

Median half-life sensitivity:

$4.8 \times 10^{25}$ yr

Full Exposure Limit:

$T^{0\nu}_{1/2} > 2.7 \times 10^{25}\,\mathrm{yr}\ (90\%\,\mathrm{CL})$

Background index at 2039 keV in the lowest background configuration:

$11.9 \pm 2.0\ \mathrm{cts/(FWHM\ t\ yr)}$

$4.7 \pm 0.8 \times 10^{-3}\ \mathrm{cts/(keV\ kg\ yr)}$

# Beyond the Standard Model Searches

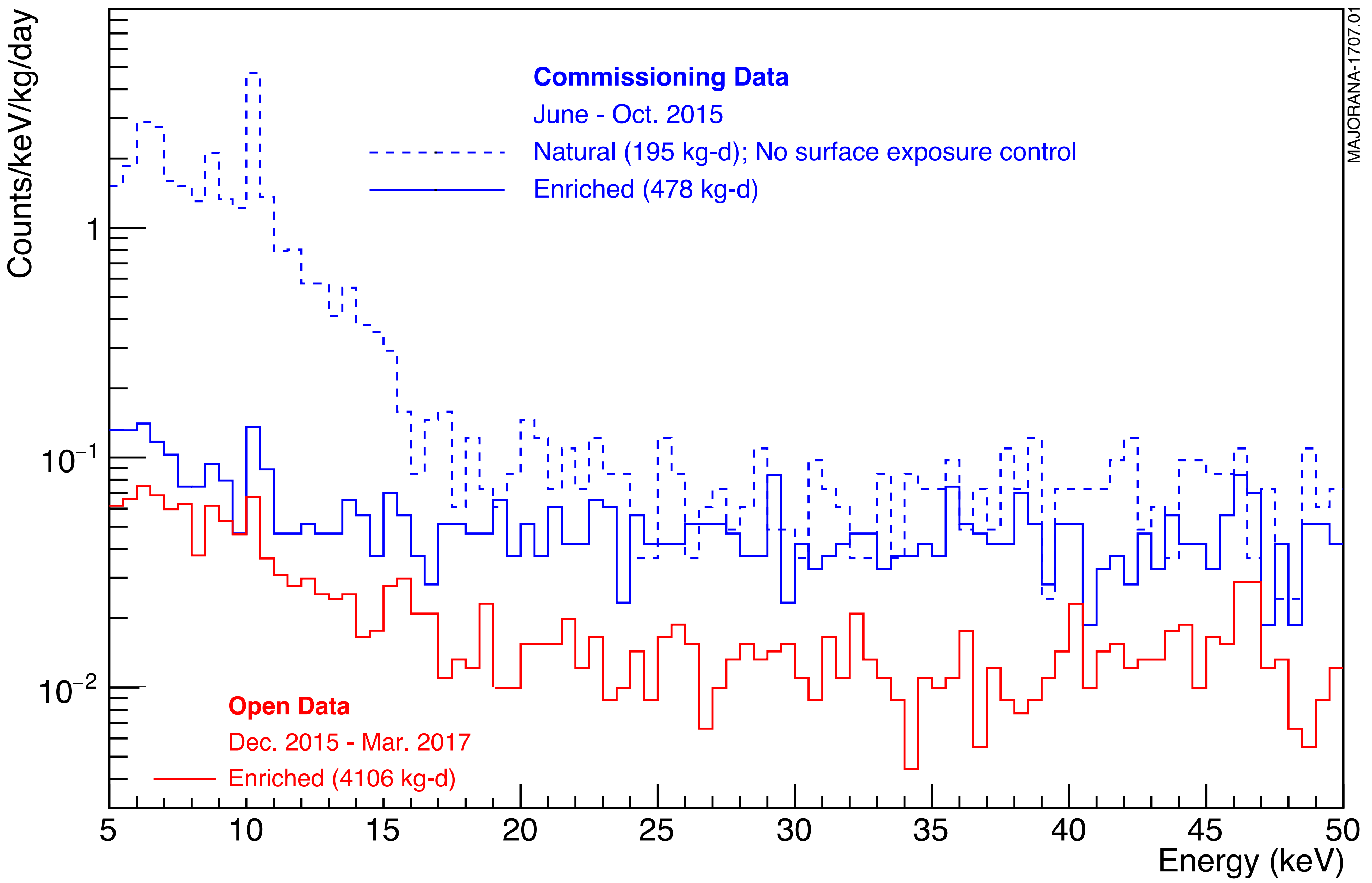
The low backgrounds, low threshold, high resolution spectra allows additional searches

Controlled surface exposure of enriched material to minimize cosmogenics

Excellent energy resolution: 0.4 keV FWHM at 10.4 keV

Ongoing effort on:

- low energy data cleaning, de-noising
- low energy cut development & efficiencies

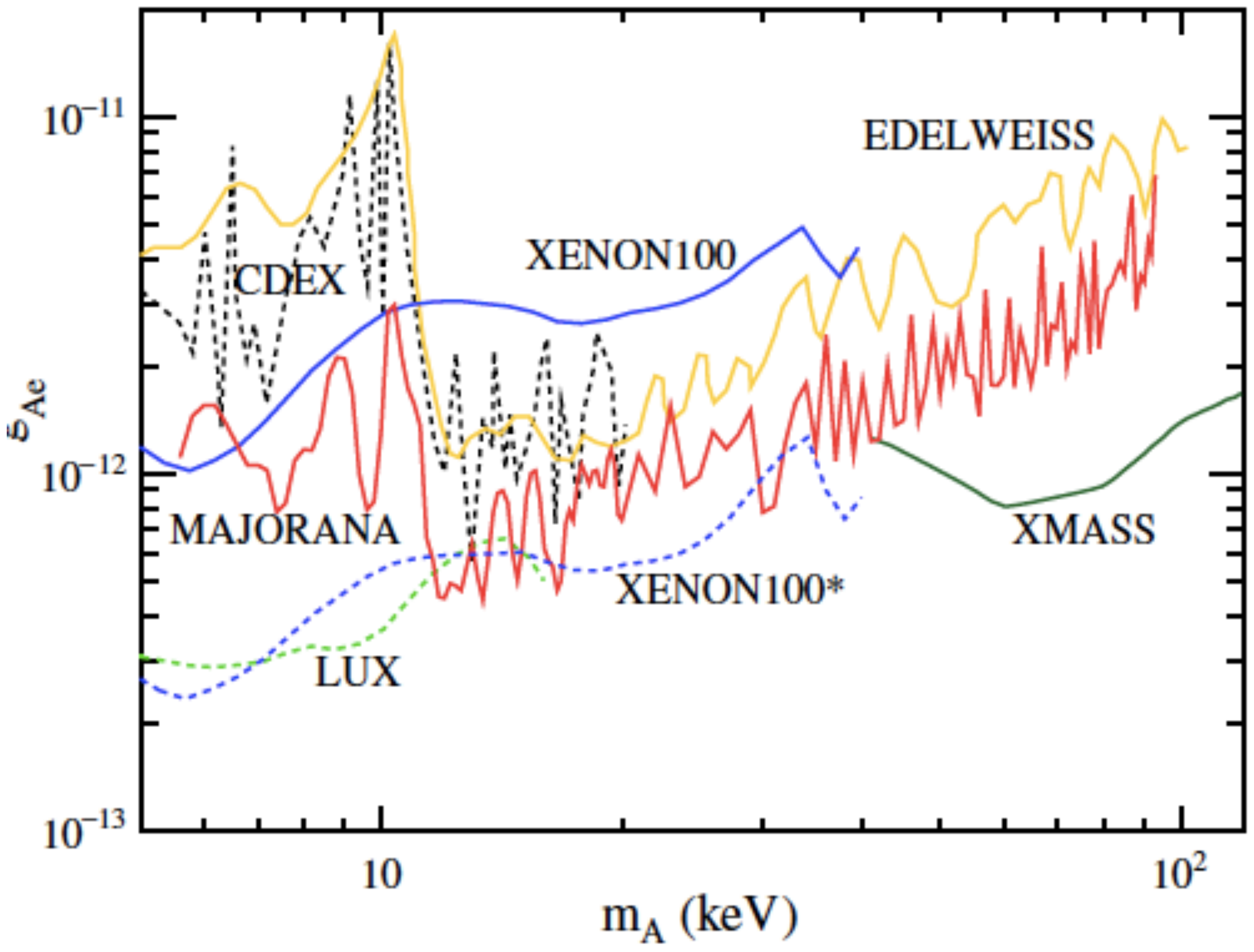



Low energy spectra during commissioning (blue) and first low-background physics running (red)

Permits low-energy physics

pseudoscalar dark matter, vector dark matter, 14.4-keV solar axion, $e^- \rightarrow 3\nu$, Pauli Exclusion Principle

PRL **118** 161801 (2017)



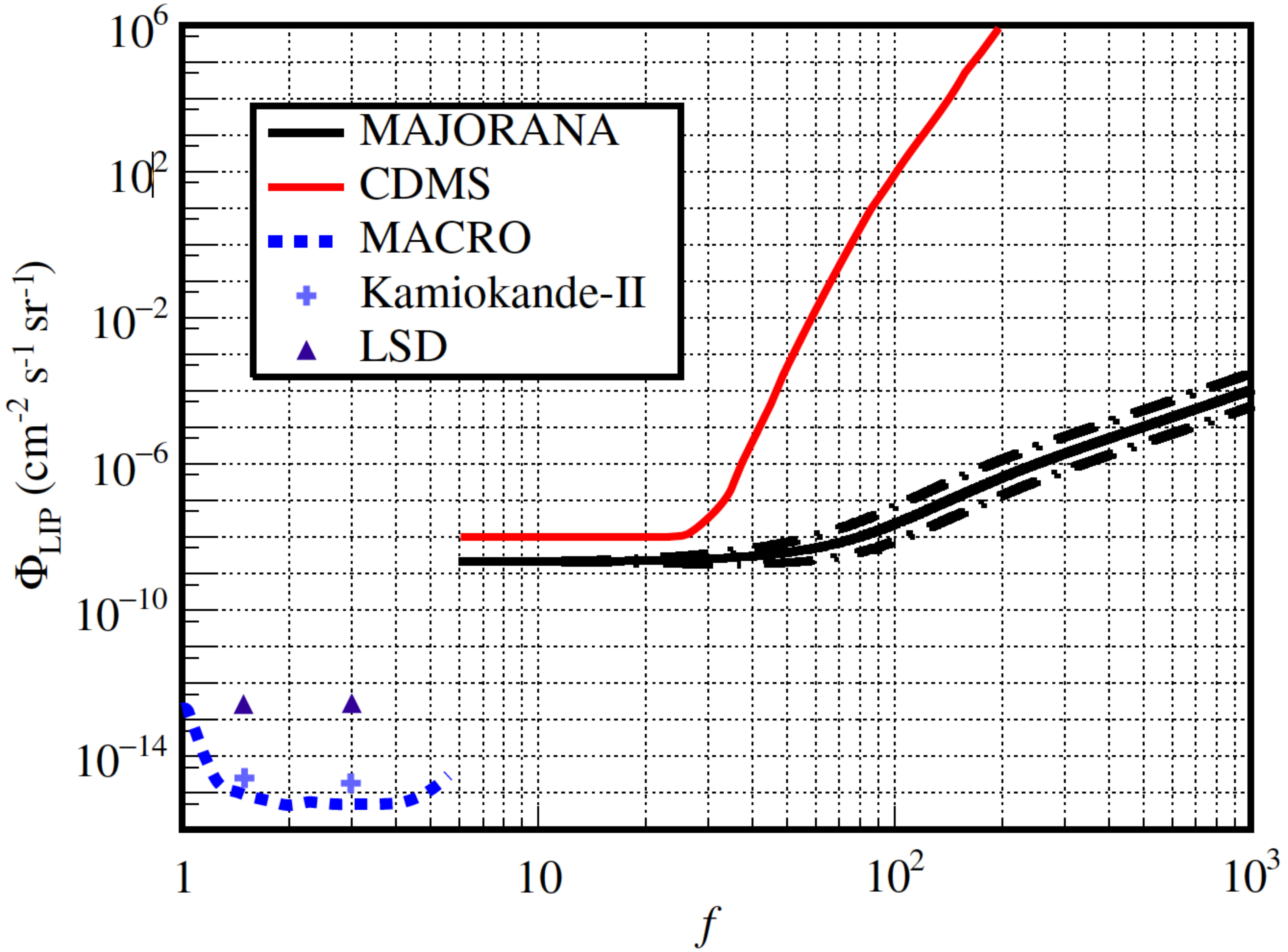

(red) The 90% UL on the pseudoscalar axionlike particle dark mater coupling

# Beyond the Standard Model Searches

The low backgrounds, low threshold, high resolution spectra allows additional searches

### First Limit on the direct detection of Lightly Ionizing Particles for Electric Charge as Low as $e$/1000

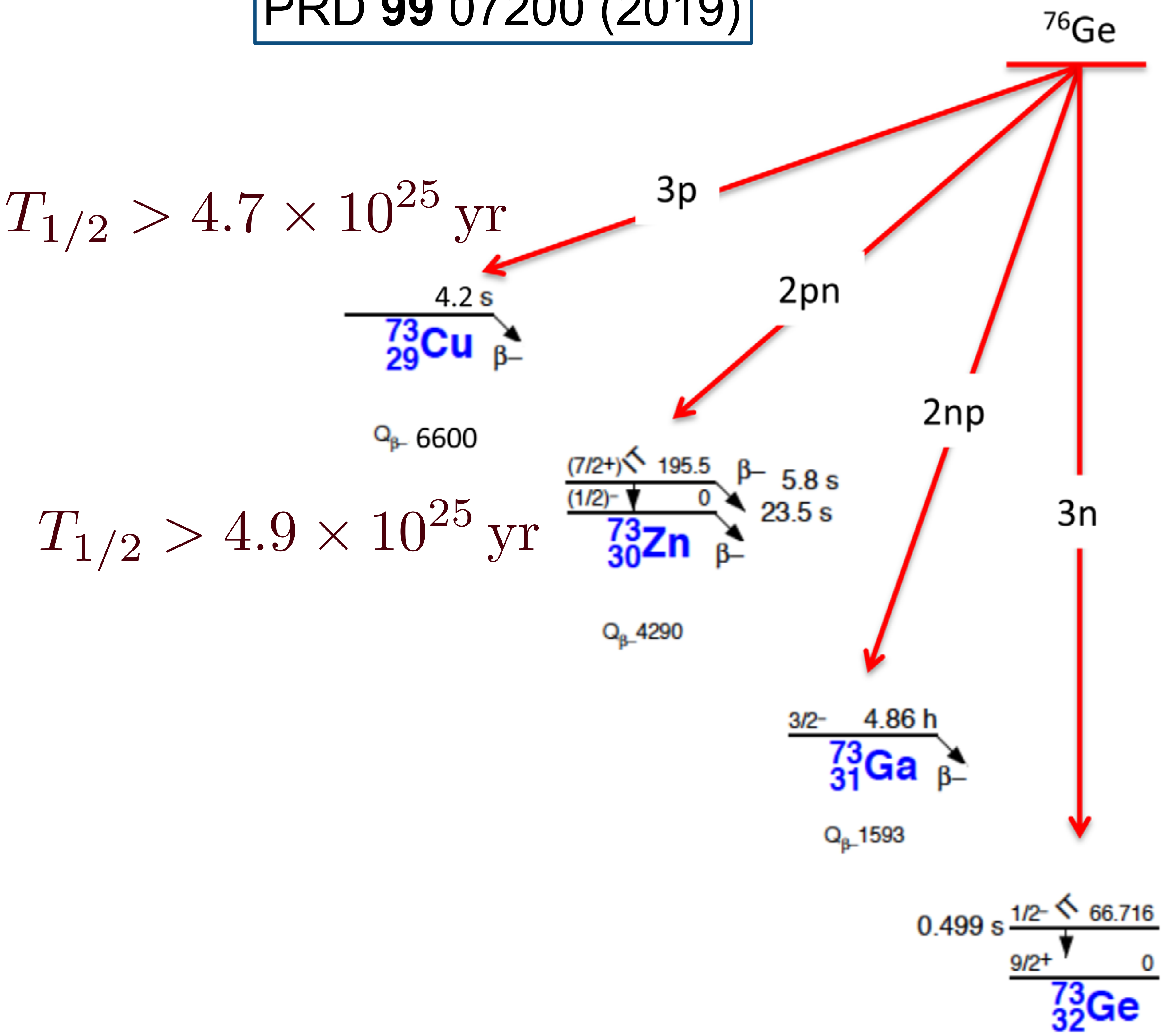
PRL **120** 211804 (2018)




The 90% UL on the Lightly Ionizing Particle flux with 1σ uncertainty bands

### Search for Tri-Nucleon Decay: A test of baryon number violation

PRD **99** 07200 (2019)



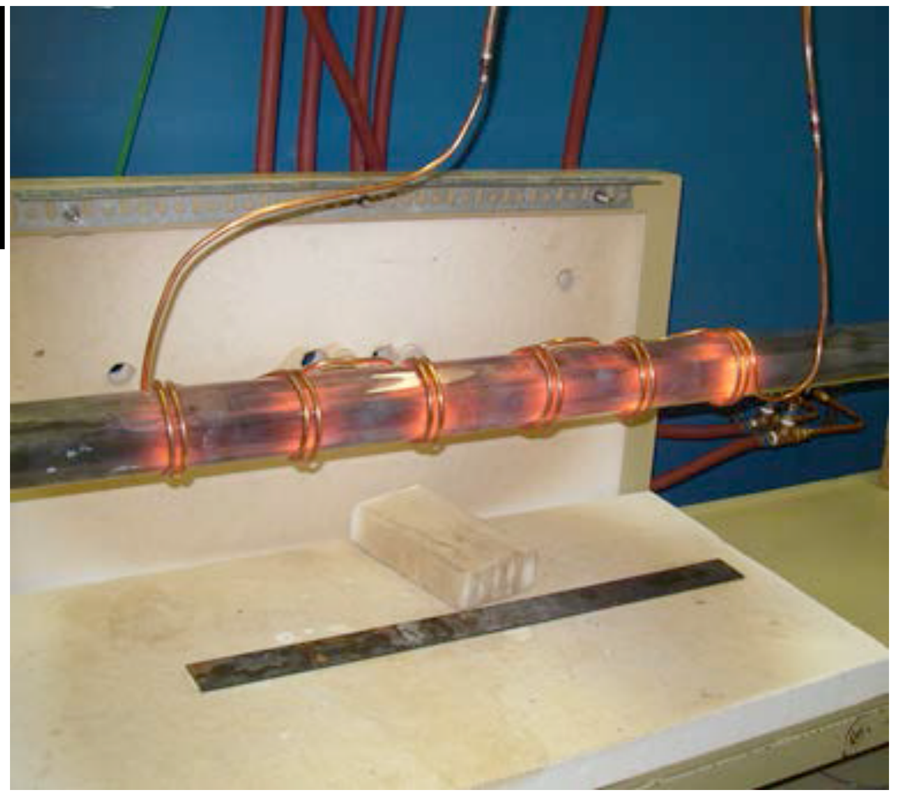

The 90% UL for two tri-nucleon decay-specific modes

# MAJORANA Approach to Backgrounds

The detector: P-type point contact

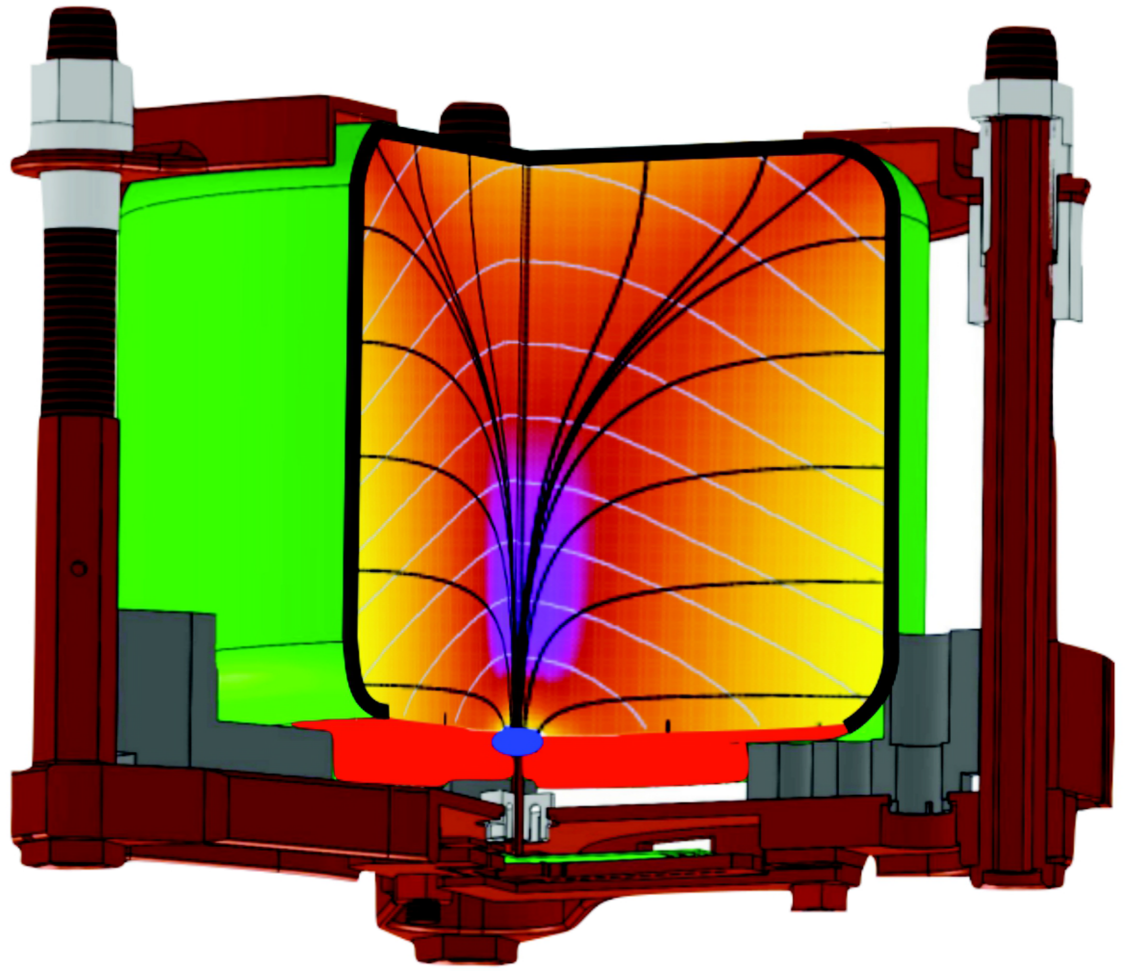
- $^{enr}$Ge metal zone refined and pulled into a crystal that provides purification
- Limit above-ground exposure to prevent cosmic activation
- Slow drift of ionization charge carriers allows separation of multiple interactions inside a detector

See F.T. Avignone LRT 2019

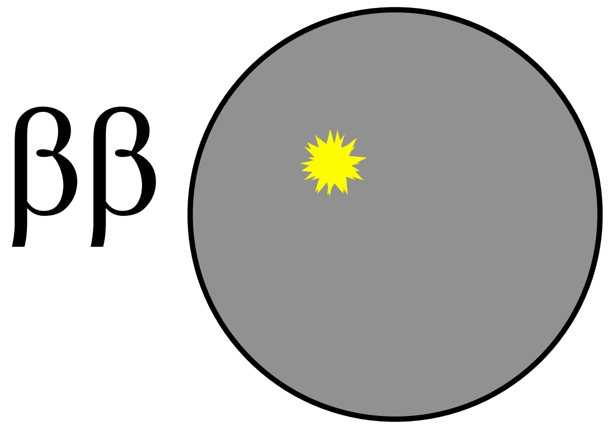


Rejection of backgrounds

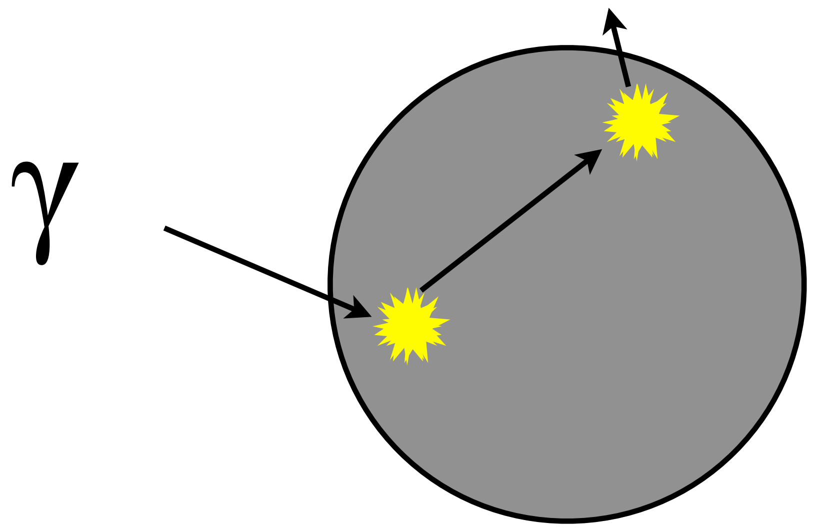
- Granularity: multiple detectors hit
- Pulse shape discrimination: no multiple hits, reject surface events
- **Ultra-pure materials with extremely low radio-isotope content to remove background radiation**

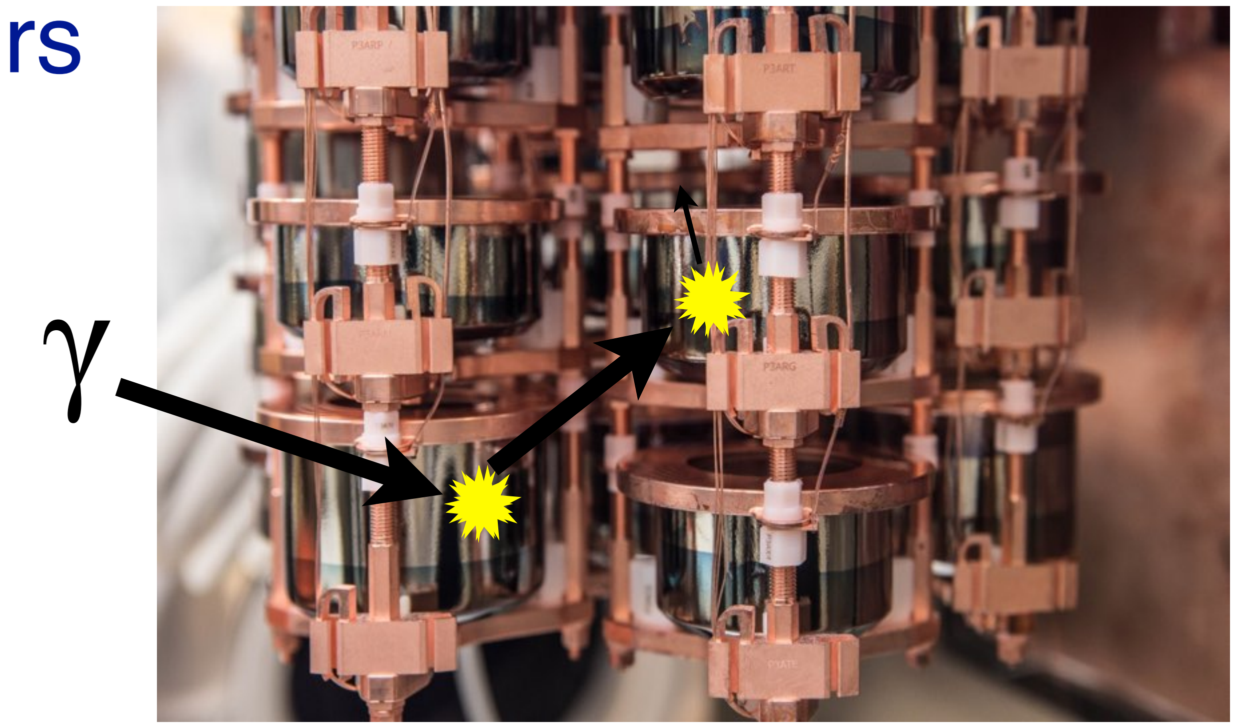


Single-site event




Multiple scatters

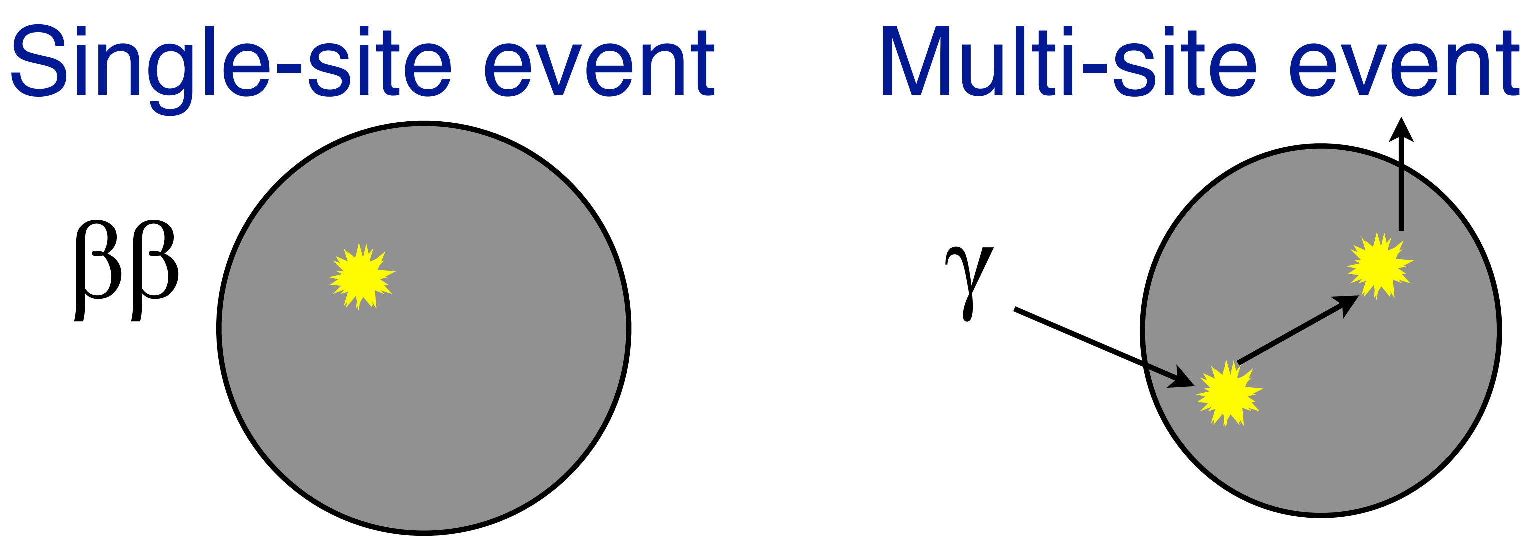


# Background Rejection: Multi-Site Events

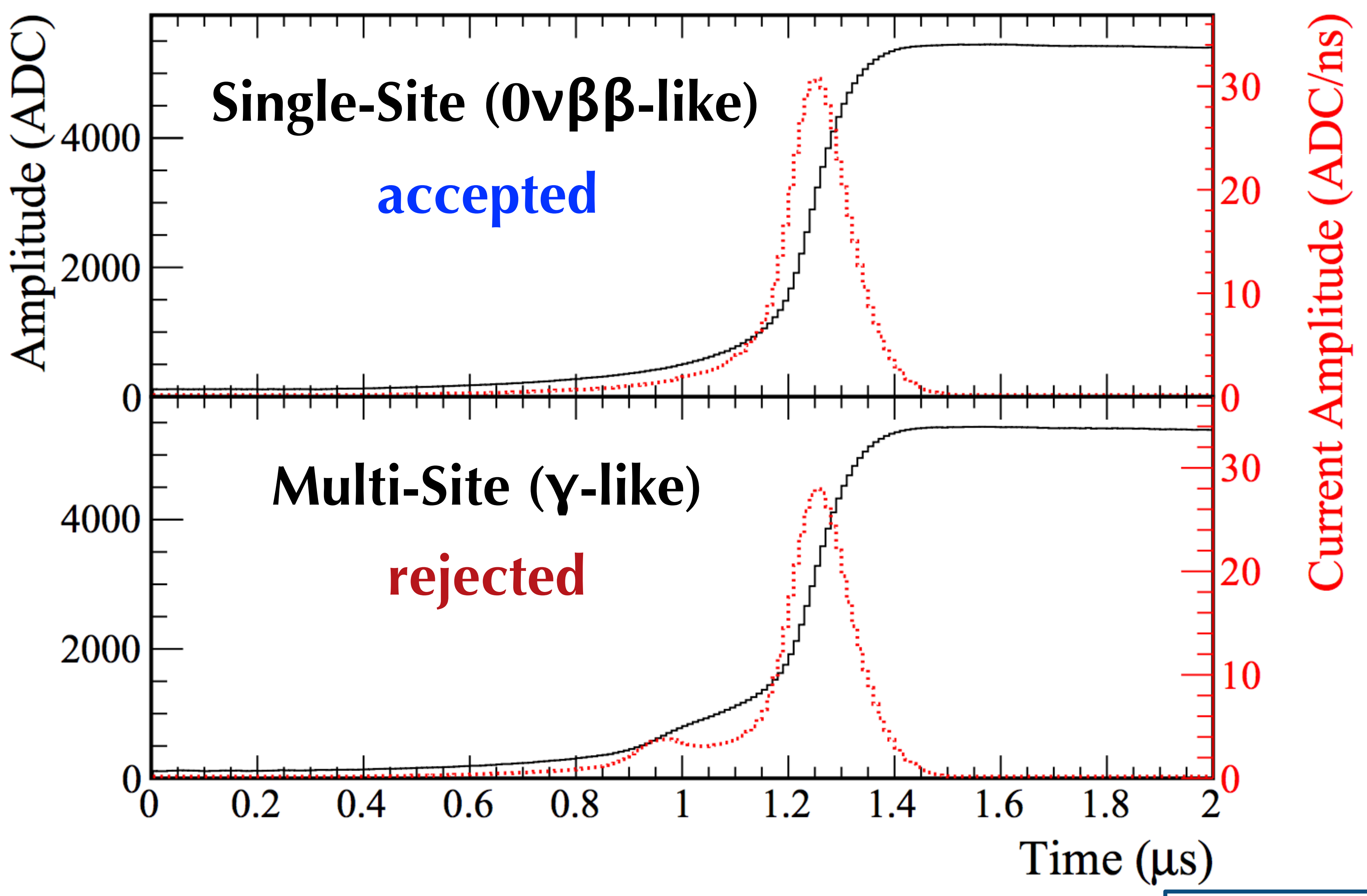
Benefit of P-type Point-Contact (PPC) style detectors for background rejection:

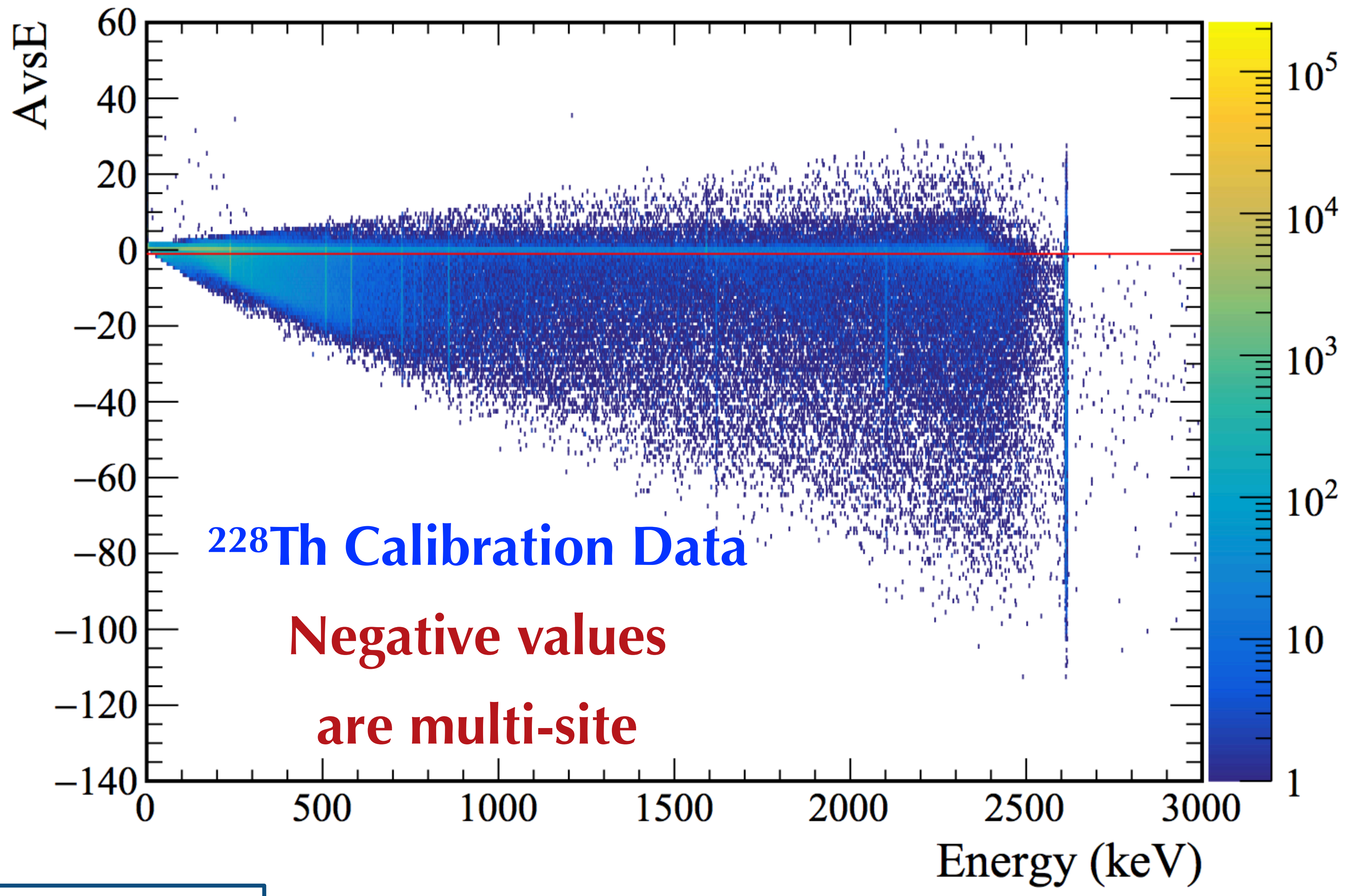
- Slow drift time of the ionization charge cloud
- Localized weighting potential gives excellent multi-site rejection



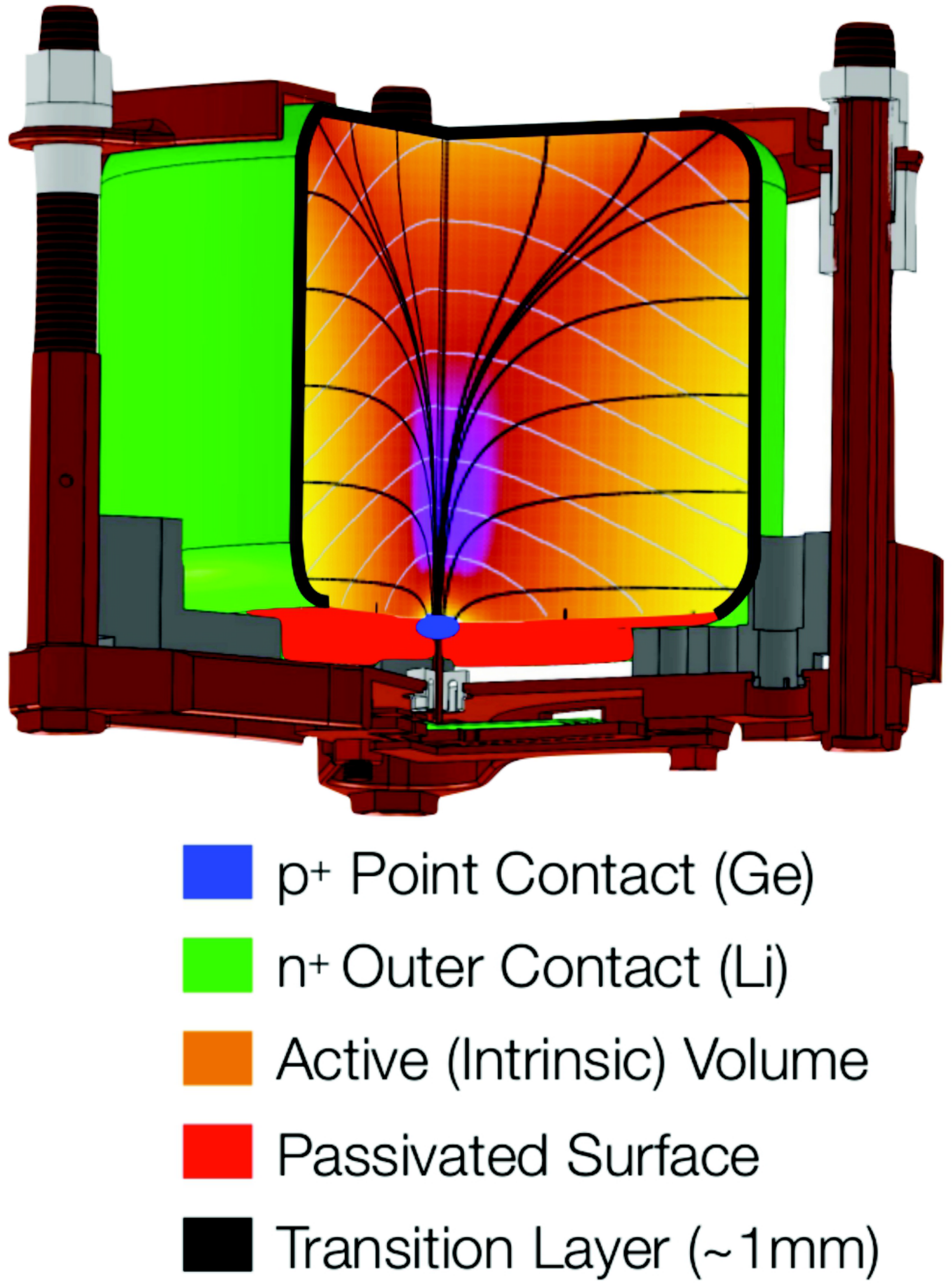

Amplitude of current pulse is reduced for a multi-site event compared to a single-site event of the same event Energy (AvsE)

Tuned to accept 90% of single-site event




arXiv: 1901.05388



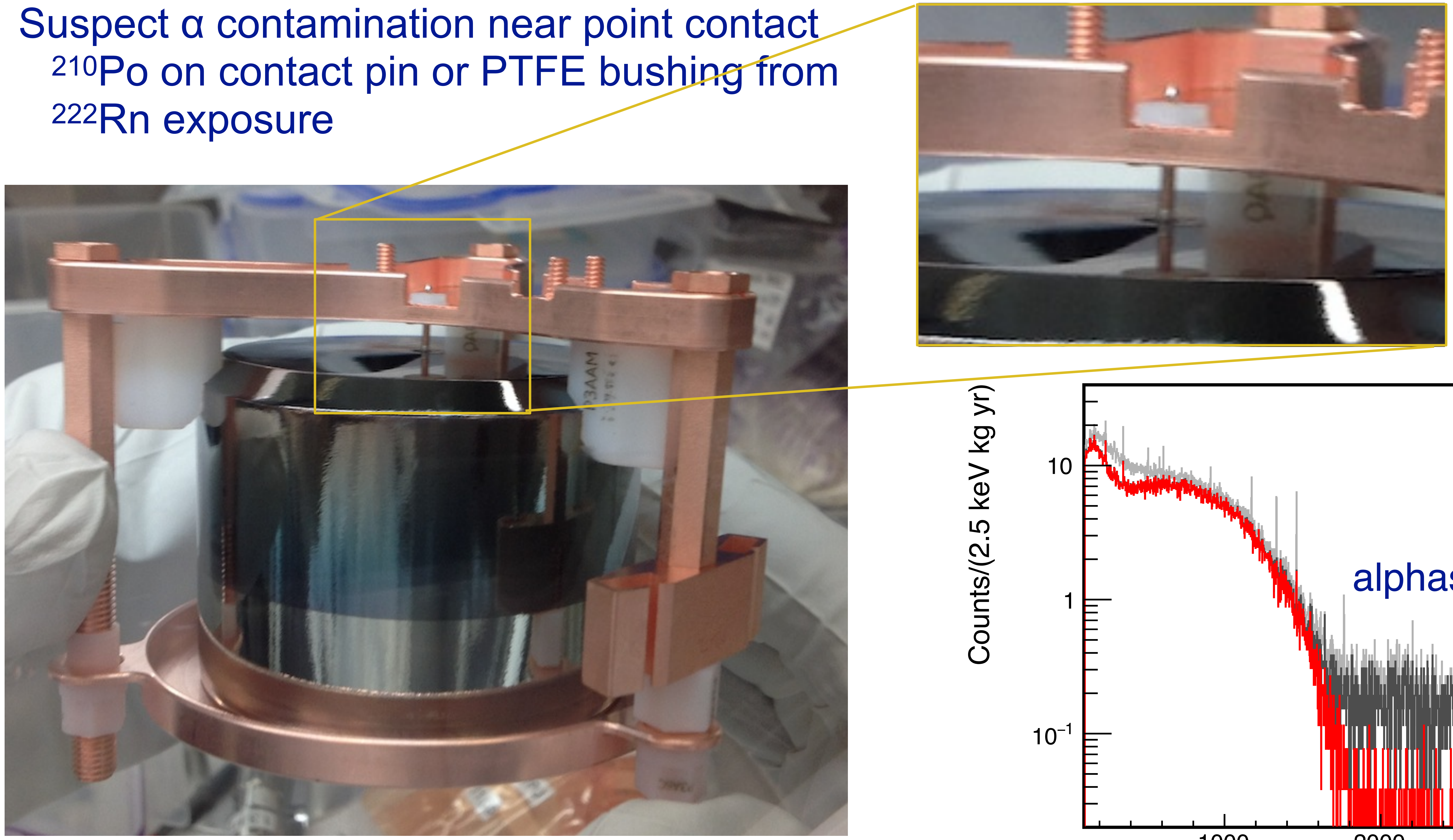
# Background Rejection: Surface Alphas

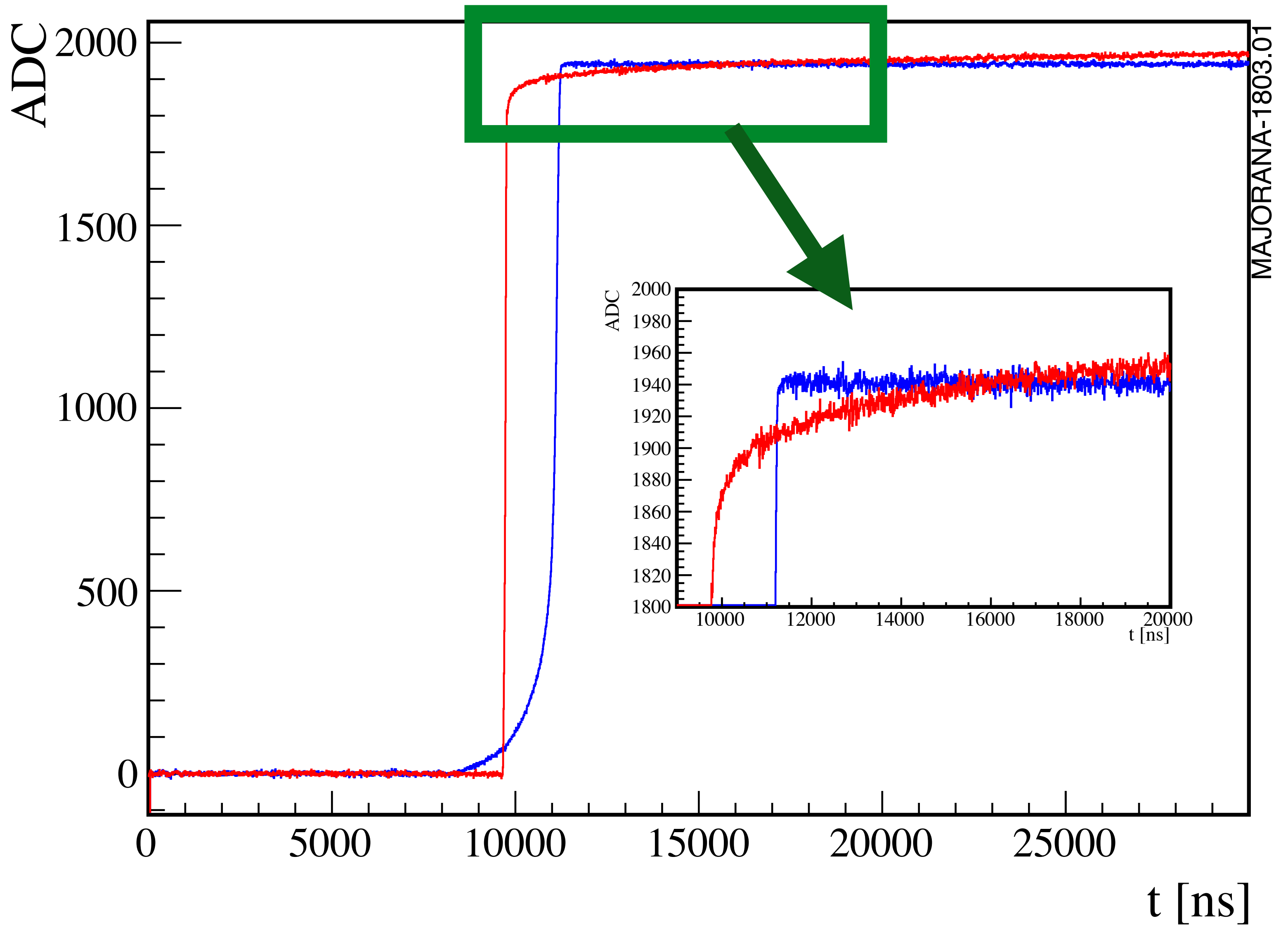
Alpha background with degraded energies observed; charge trapped at passivated surface, slowly released into bulk: *delayed charge recover* (DCR)

- Developing a model of the detector response
- Cut with a parameter related to slope of tail after the rising edge

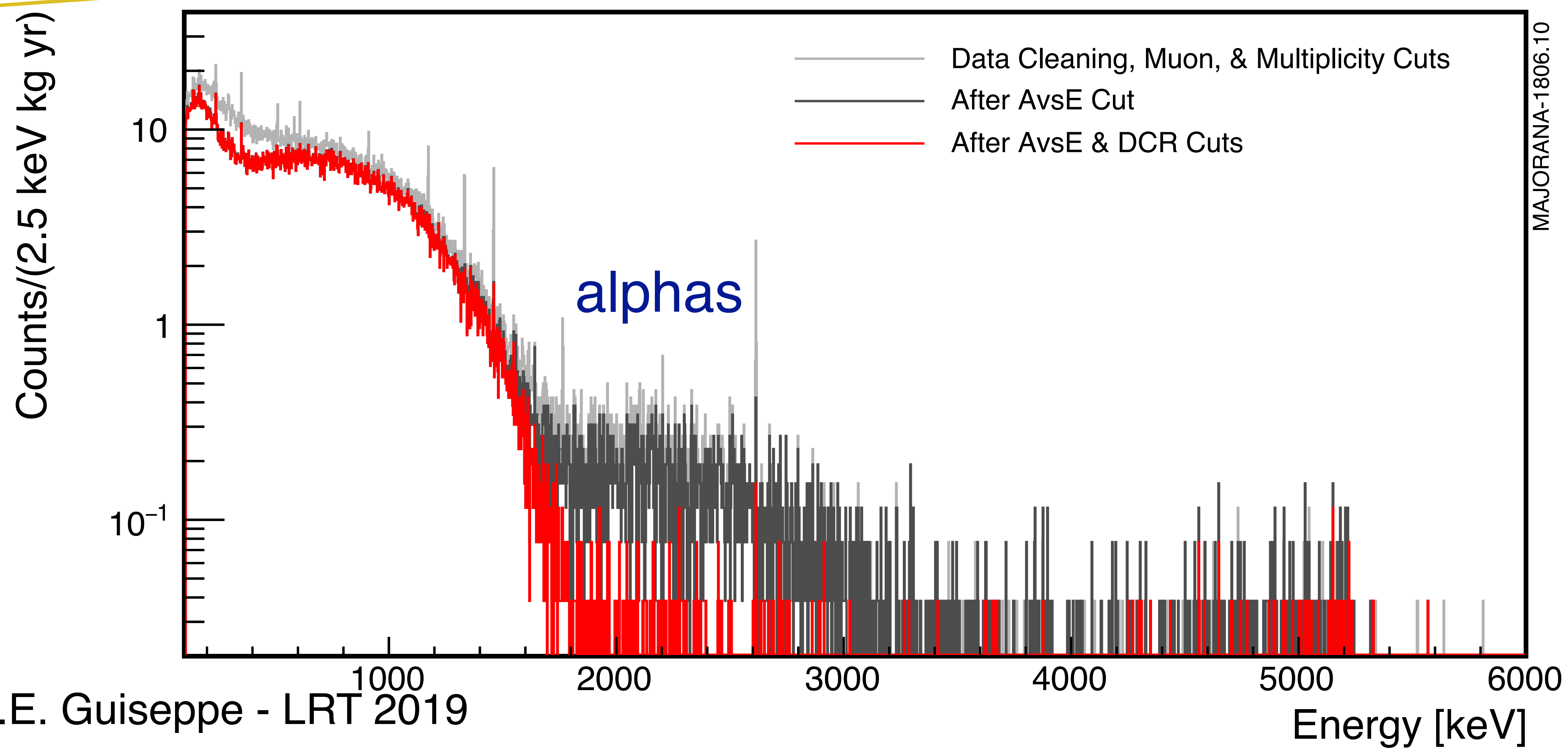
Suspect α contamination near point contact

- $^{210}$Po on contact pin or PTFE bushing from $^{222}$Rn exposure





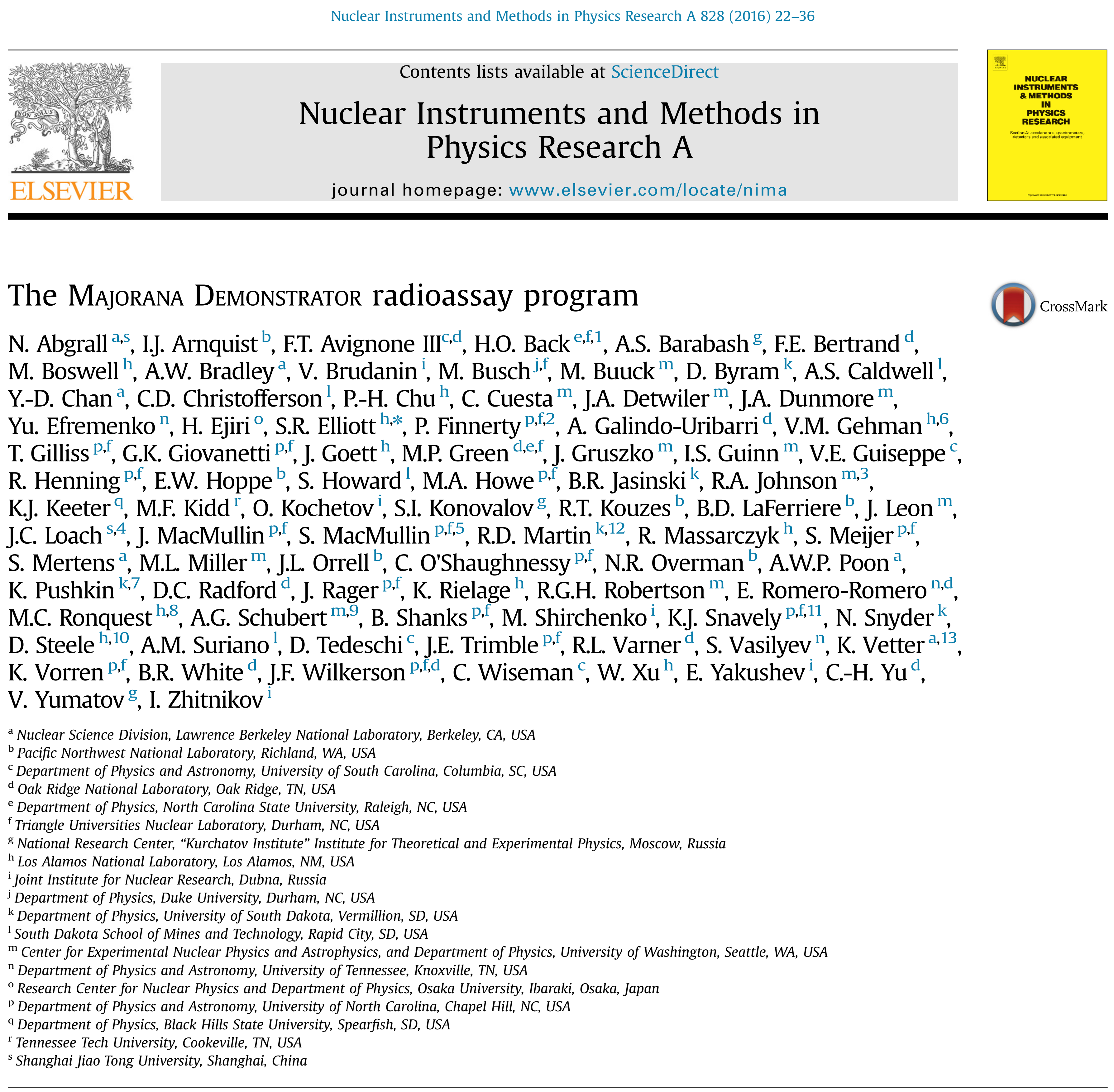

Tuned to accept 90% of single-site event



# Achieving Ultra-Pure Materials

Material purity was central to the Majorana Demonstrator design

- The efforts of the community were very useful in our selection of components
  - i.e. radiopurity.org, the EXO assay paper [NIM **A591** (2008) 490–509]
- Initial background budget based our own certification of candidate materials



Nuclear Instruments and Methods in Physics Research A 828 (2016) 22–36

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The MAJORANA DEMONSTRATOR radioassay program

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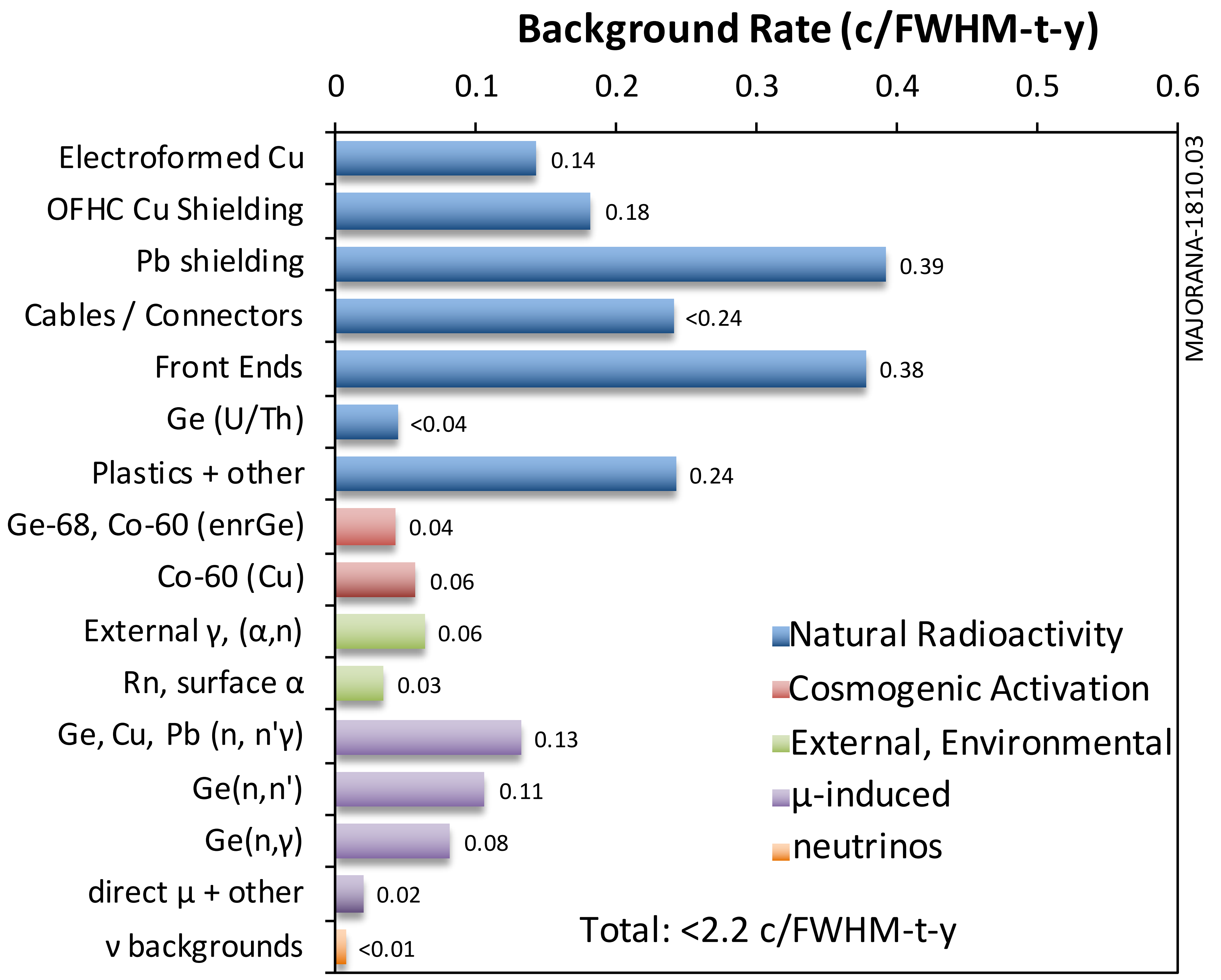
Initial assay-based background budget



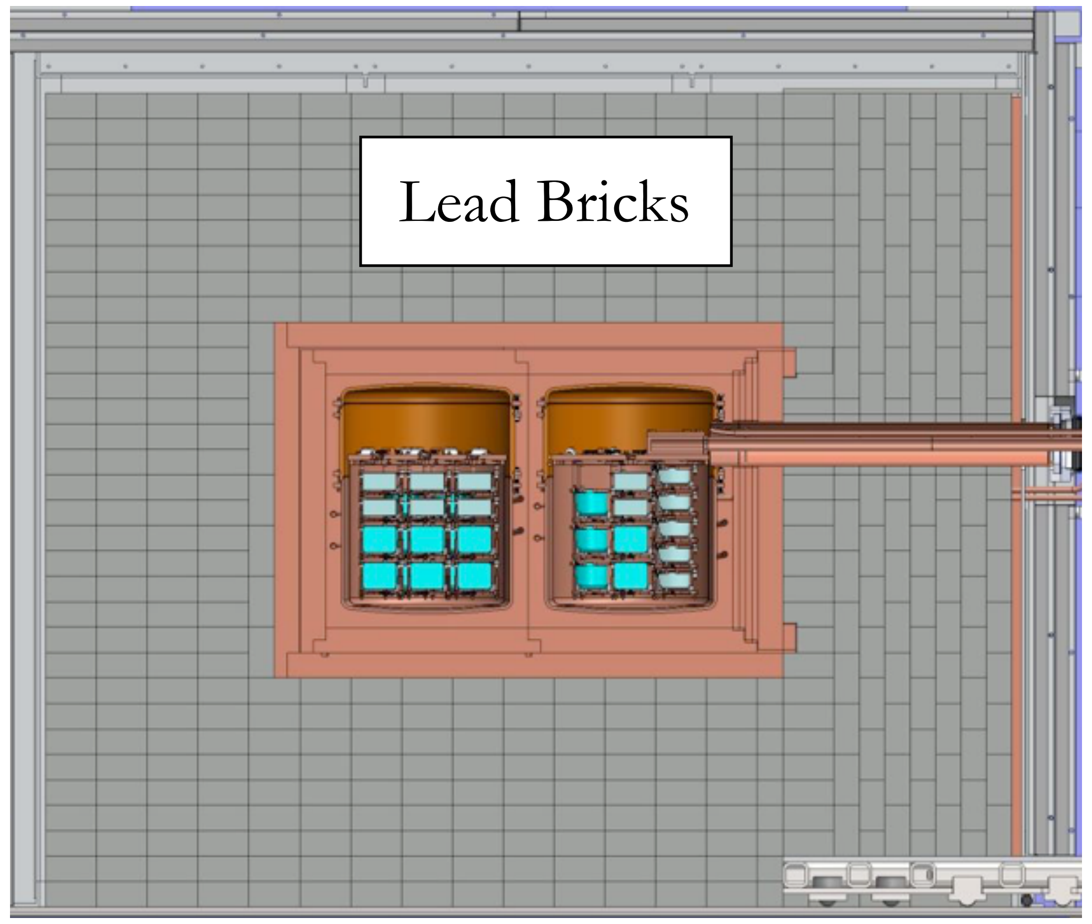

NIM **A828** (2016) 22–36 arXiv:1601.03779

# Pb Shielding

Pb shielding material selected from two sources based on initial assays

Virgin Doe Run Pb and bricks from a decommissioning low-background facility at U. Washington

Initial screening assay by GDMS: <32 uBq/kg Th, <110 uBq/kg U

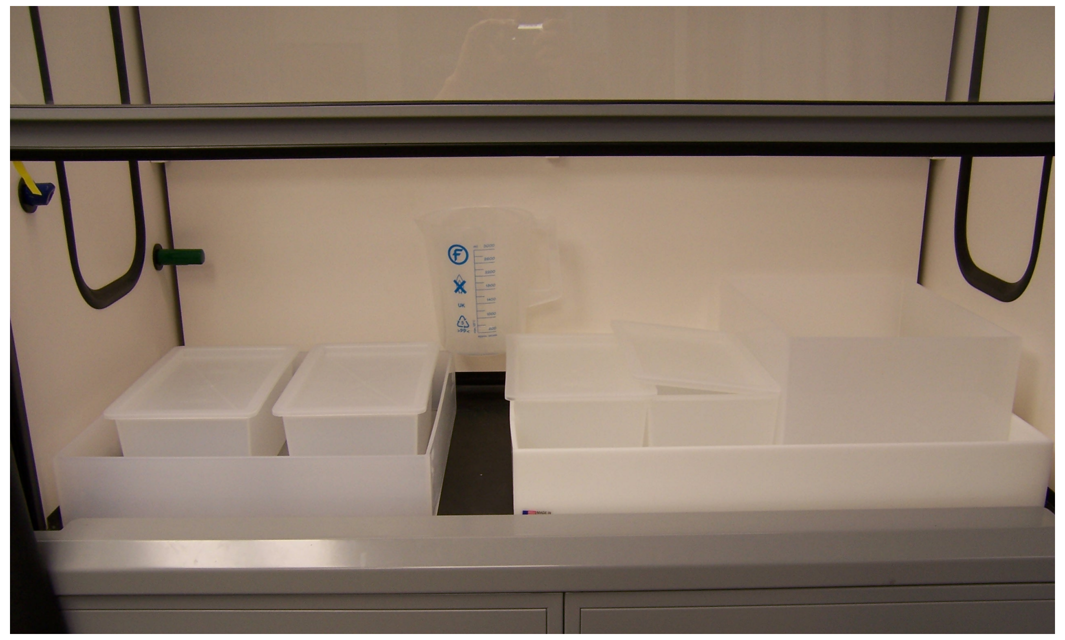



New production of virgin Doe Run Pb

Low-BG facility at U Washington

Over 6800 Pb bricks processed through our dedicated Pb cleaning facility

Surface cleaning with pure acetic acid soak and scrub, then $HNO_3 + H_2O_2$ etch



Final assay certification of sampled bricks after cleaning:

Average:
5.3 +/- 5.3 µBq/kg Th
36 +/- 25 µBq/kg U

Processed 50 bricks/day
(includes unpacking, rinses, drying, triple bagging, packing)

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# Commercial Cu Shielding

Outer Cu shielding made from commercial C10100 (OFHC) plates; 0.6-cm surface layer removed

Selected acceptable material after assay of traceable starting material (cake) and finished (rolled) product

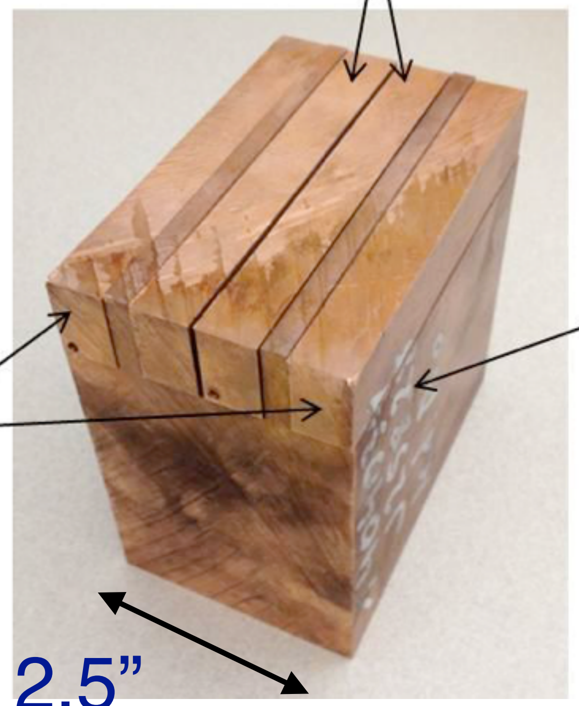
- Starting “cake” material from Aurubis (Germany)
- Rolled into plates by KME (Germany)
- Rough cut by Southern Copper (USA)

Cake Sample


Assay results acceptable

1.1(2) µBq/kg $^{232}$Th
1.25(3) µBq/kg $^{238}$U

Rolled Sample

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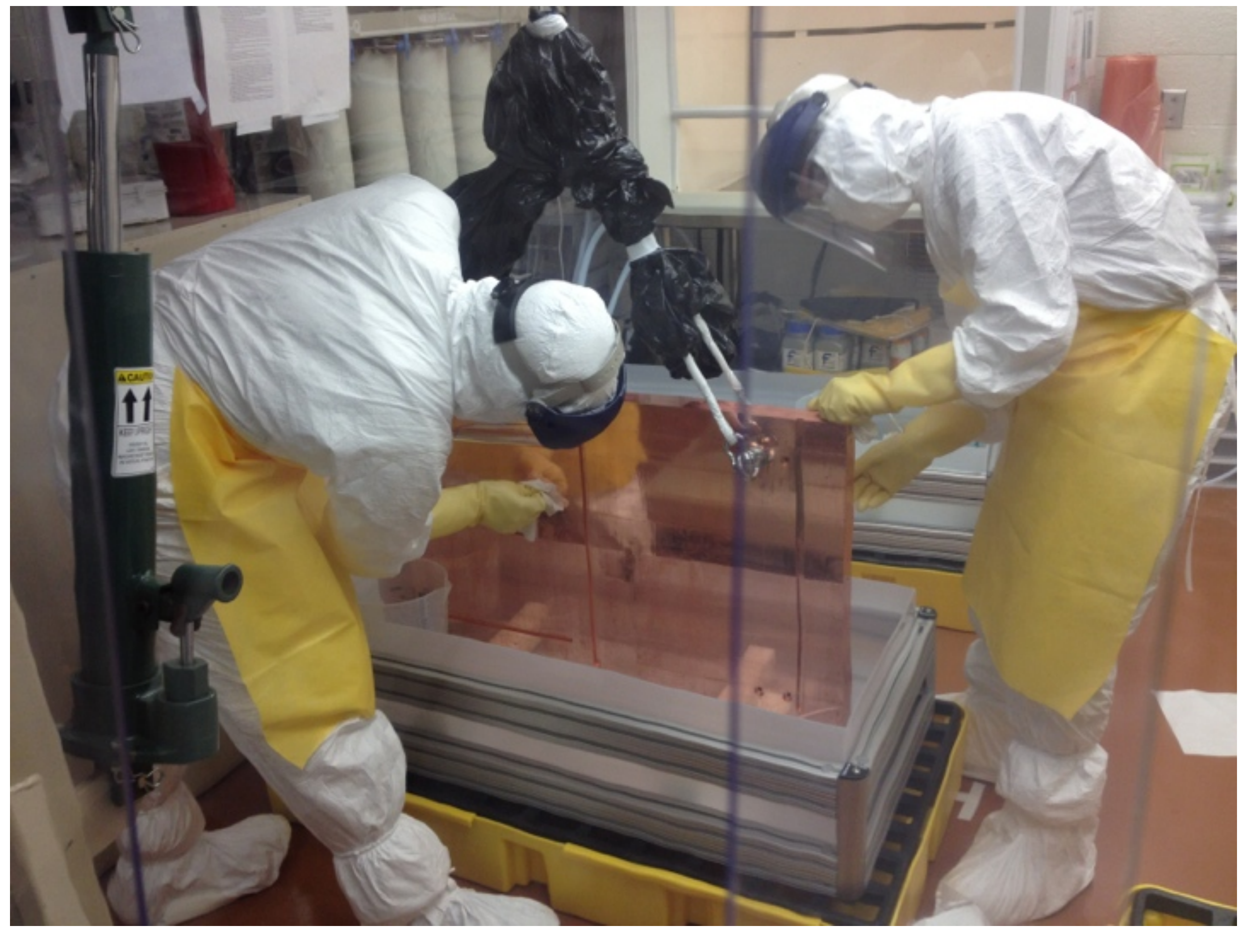
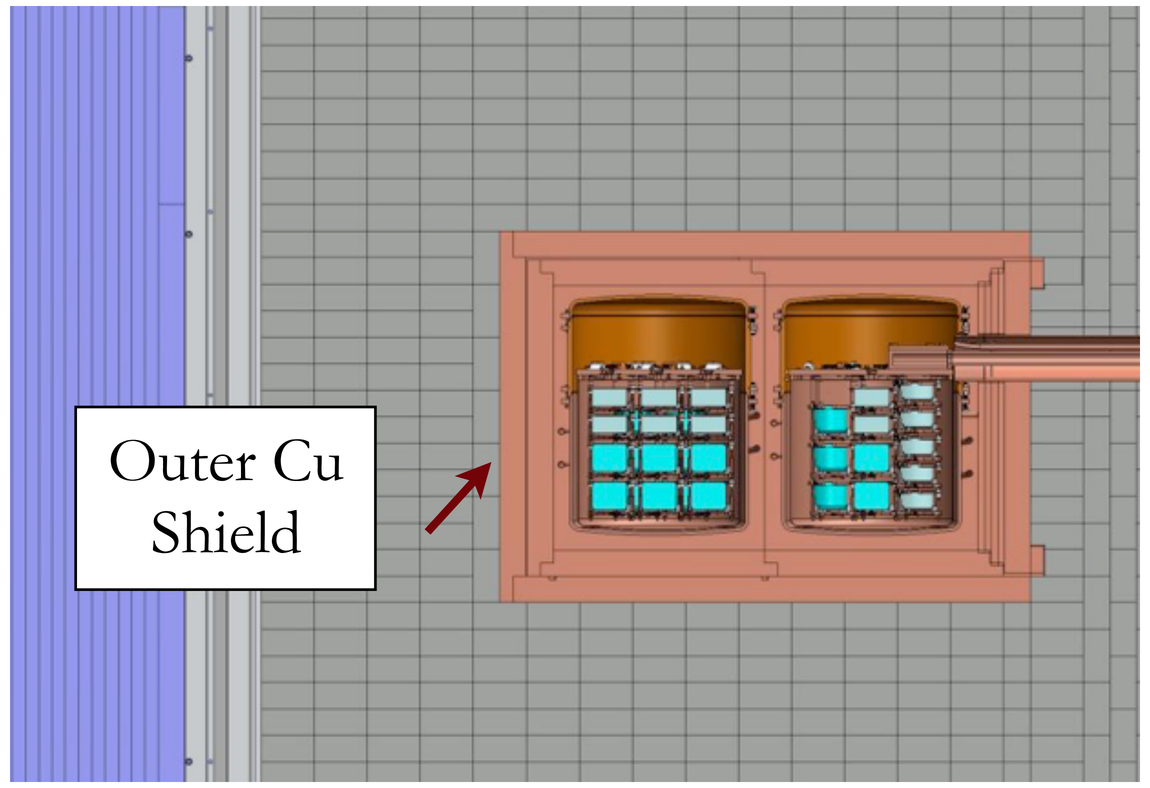
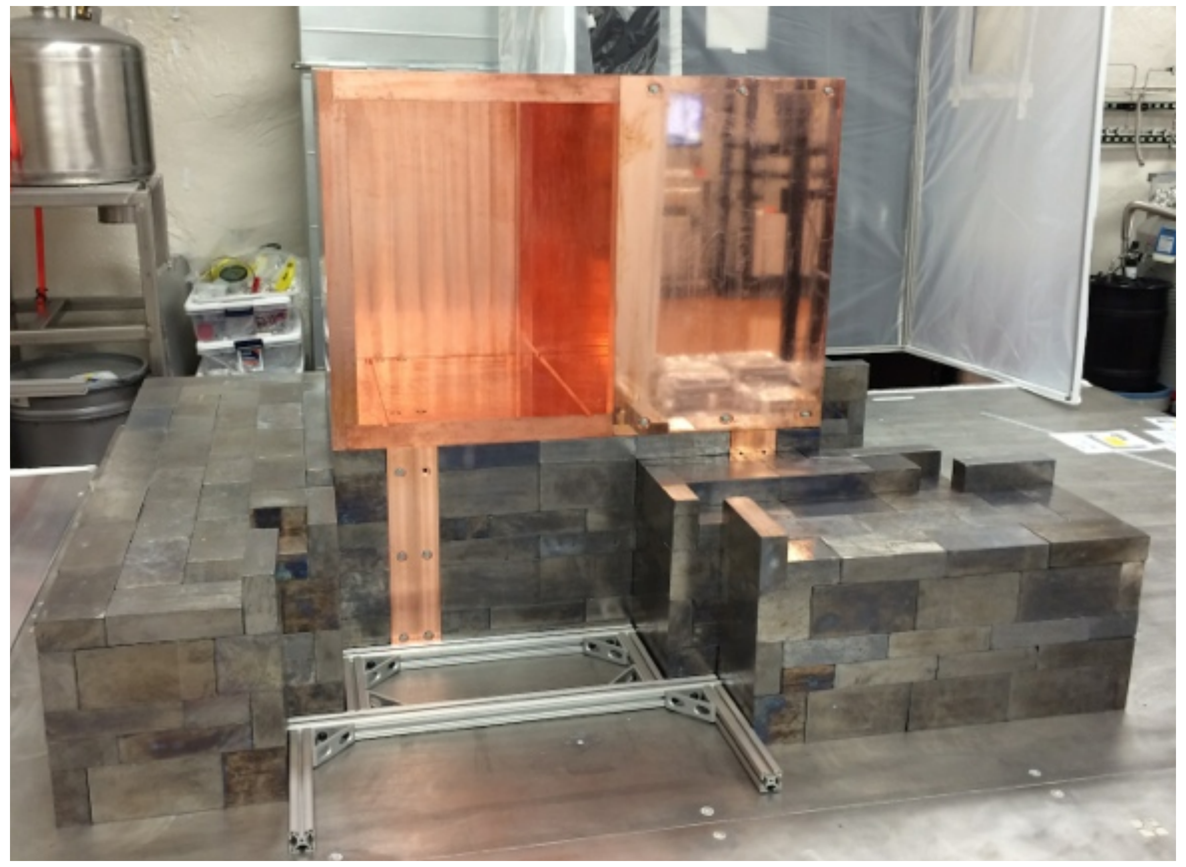
Cu Plates cleaned and etched before assembly

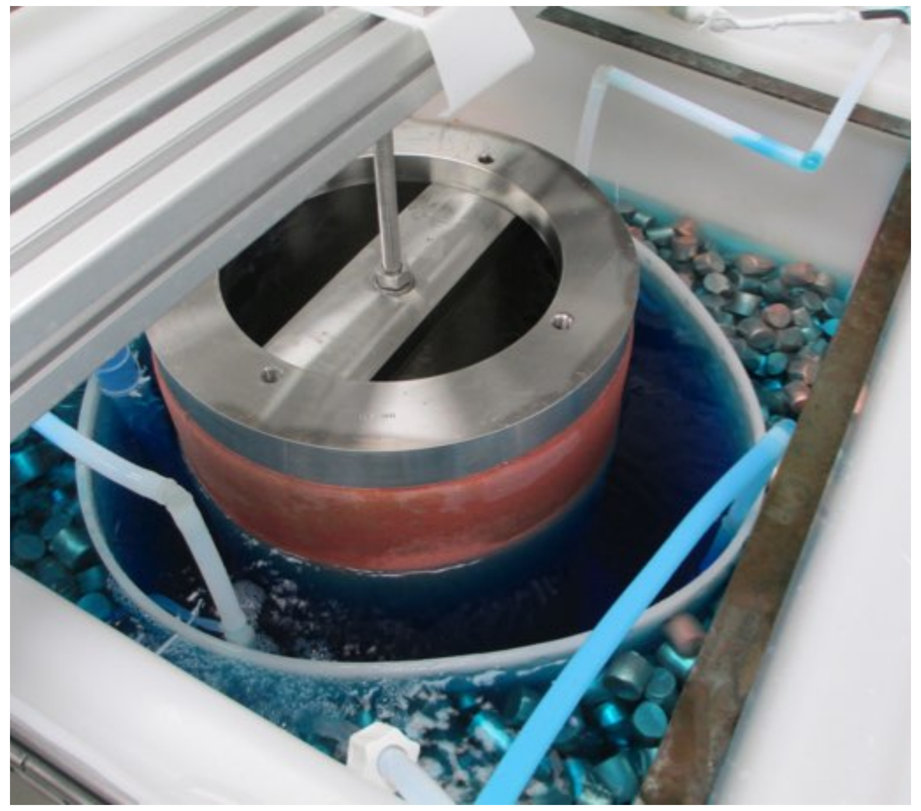


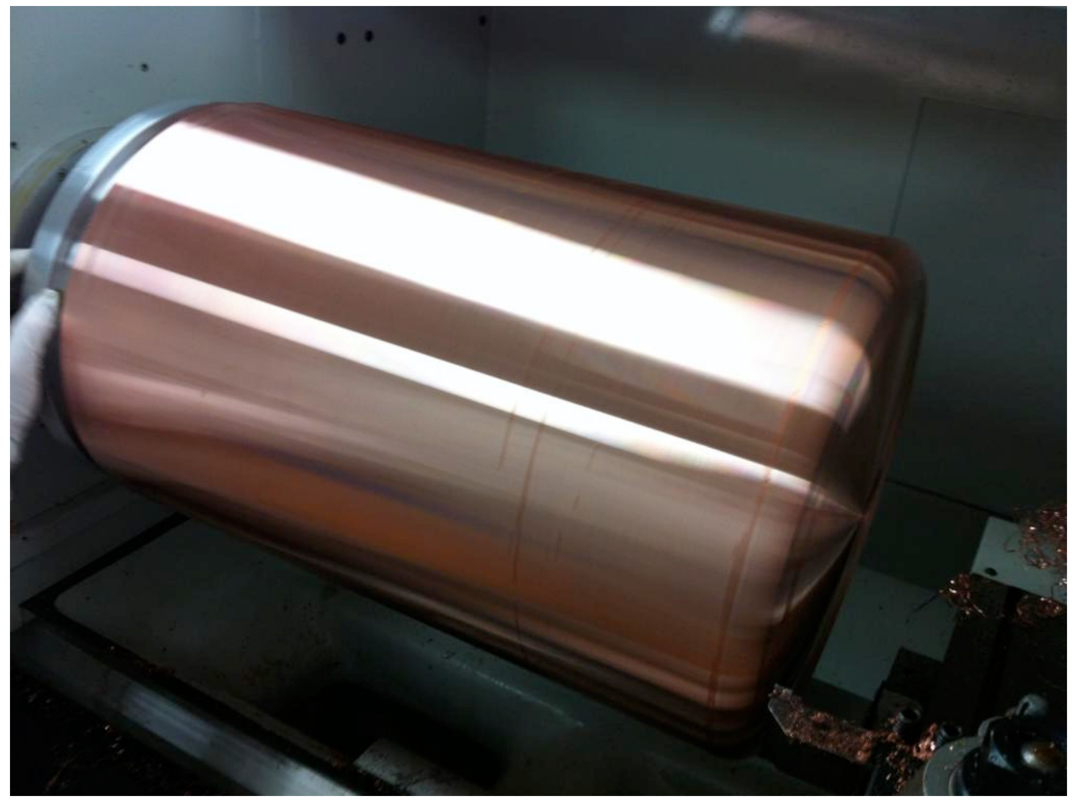
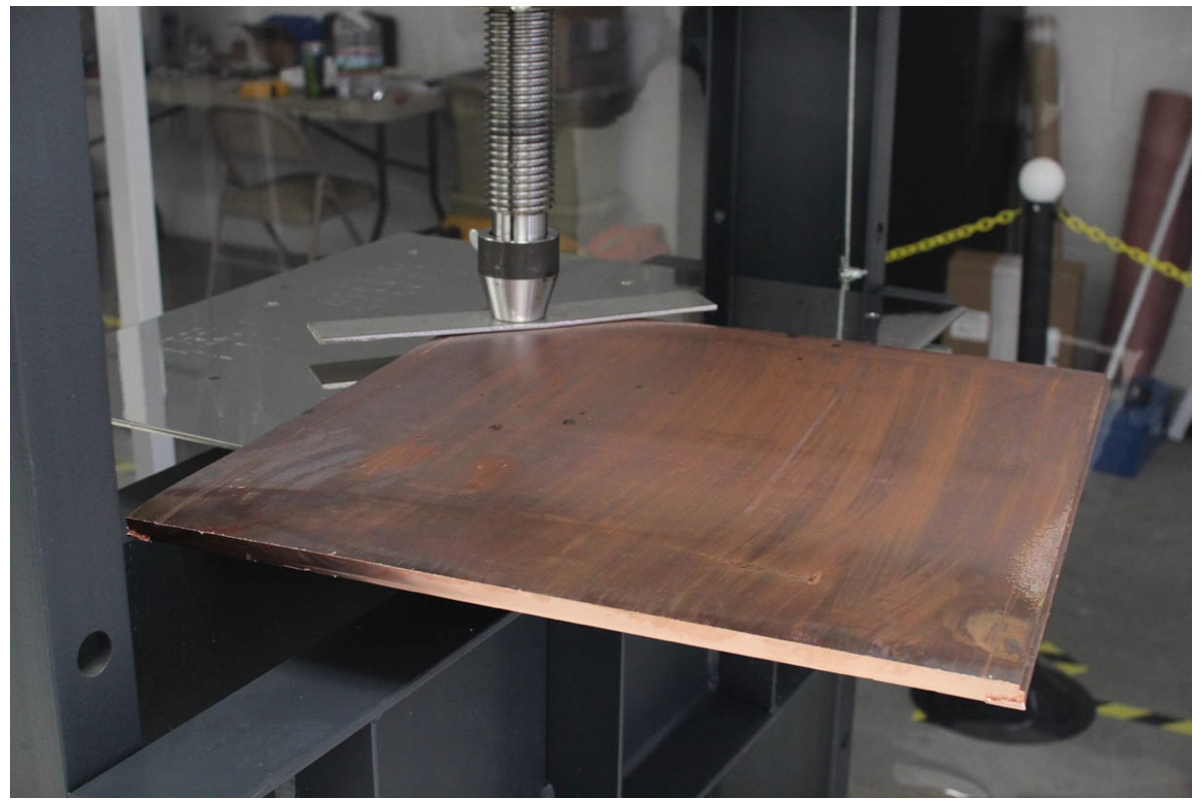


# Electroformed Cu Production

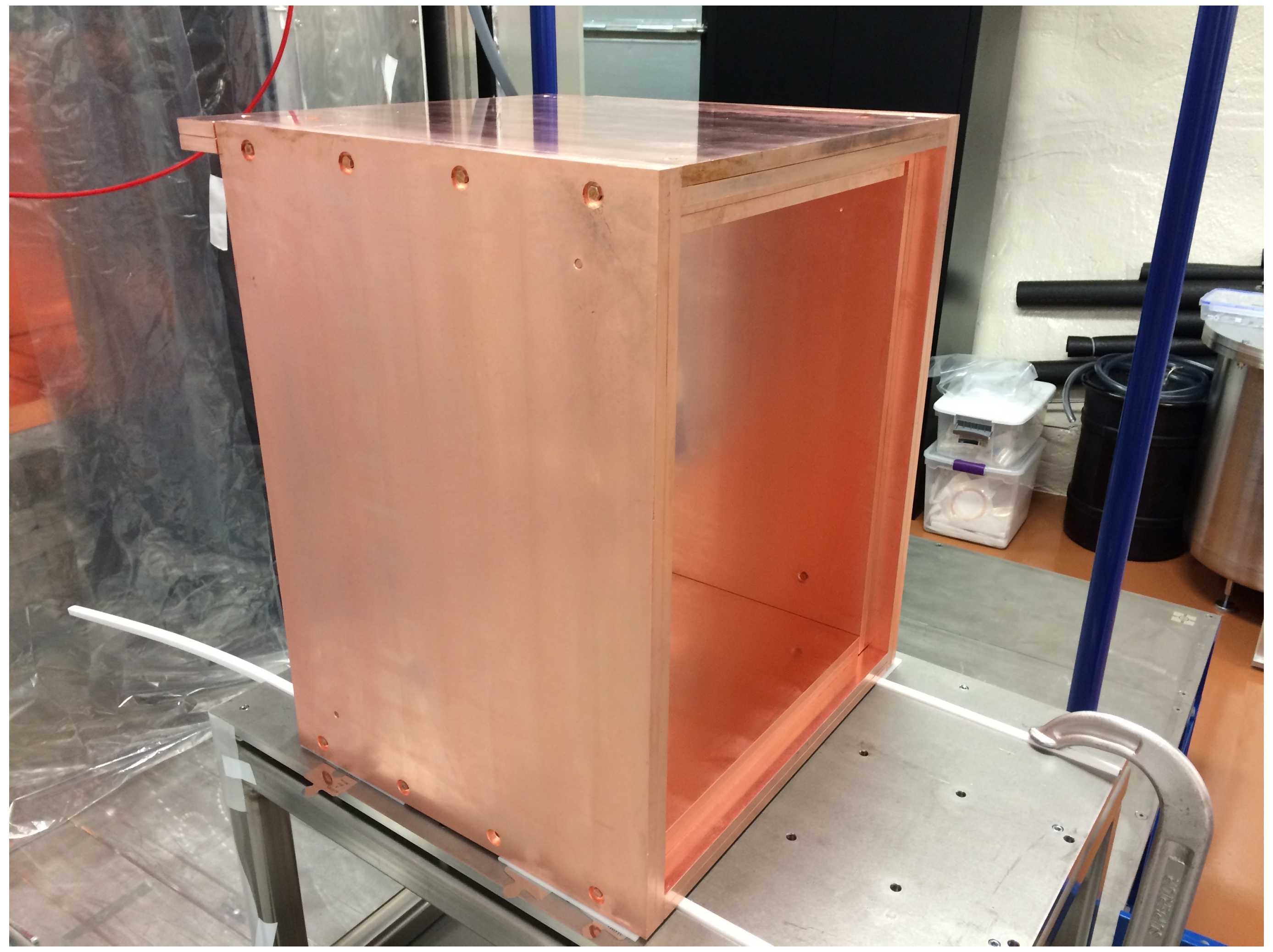
MAJORANA operated 10 baths at SURF on the 4850’ level and 6 baths at a shallow UG site at PNNL

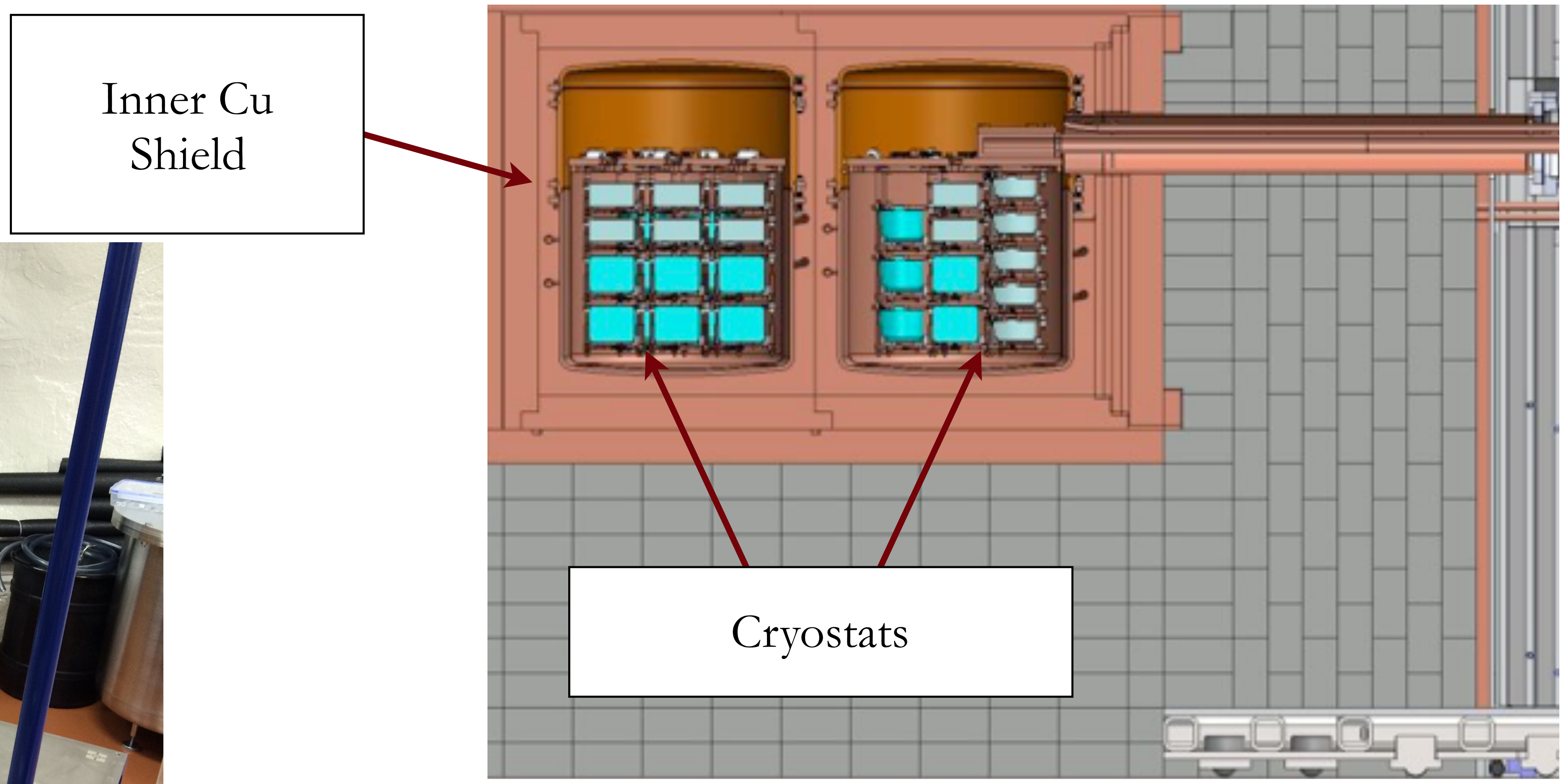



Assay results of bulk

<0.1 μBq/kg $^{232}$Th
<0.1 μBq/kg $^{238}$U



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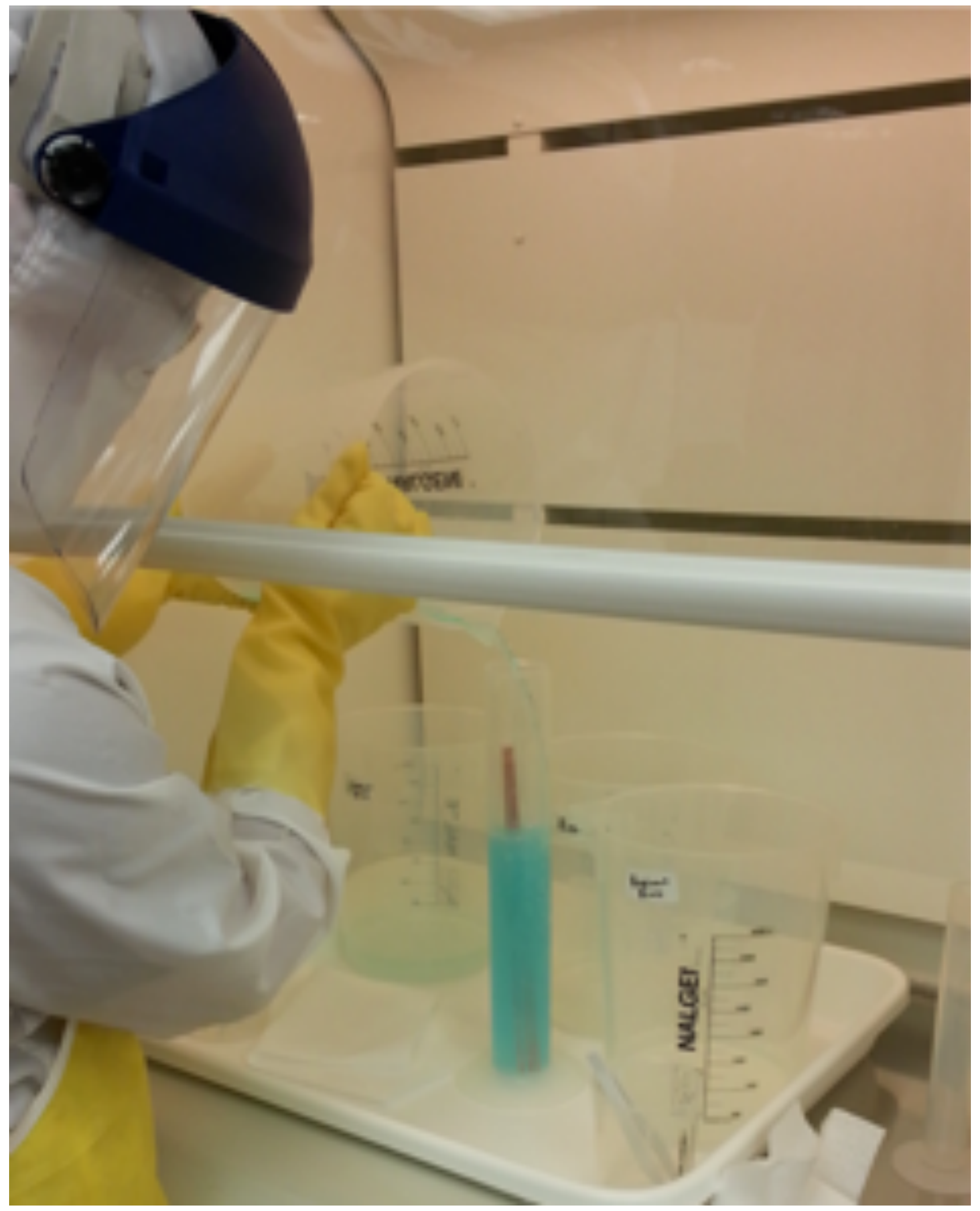
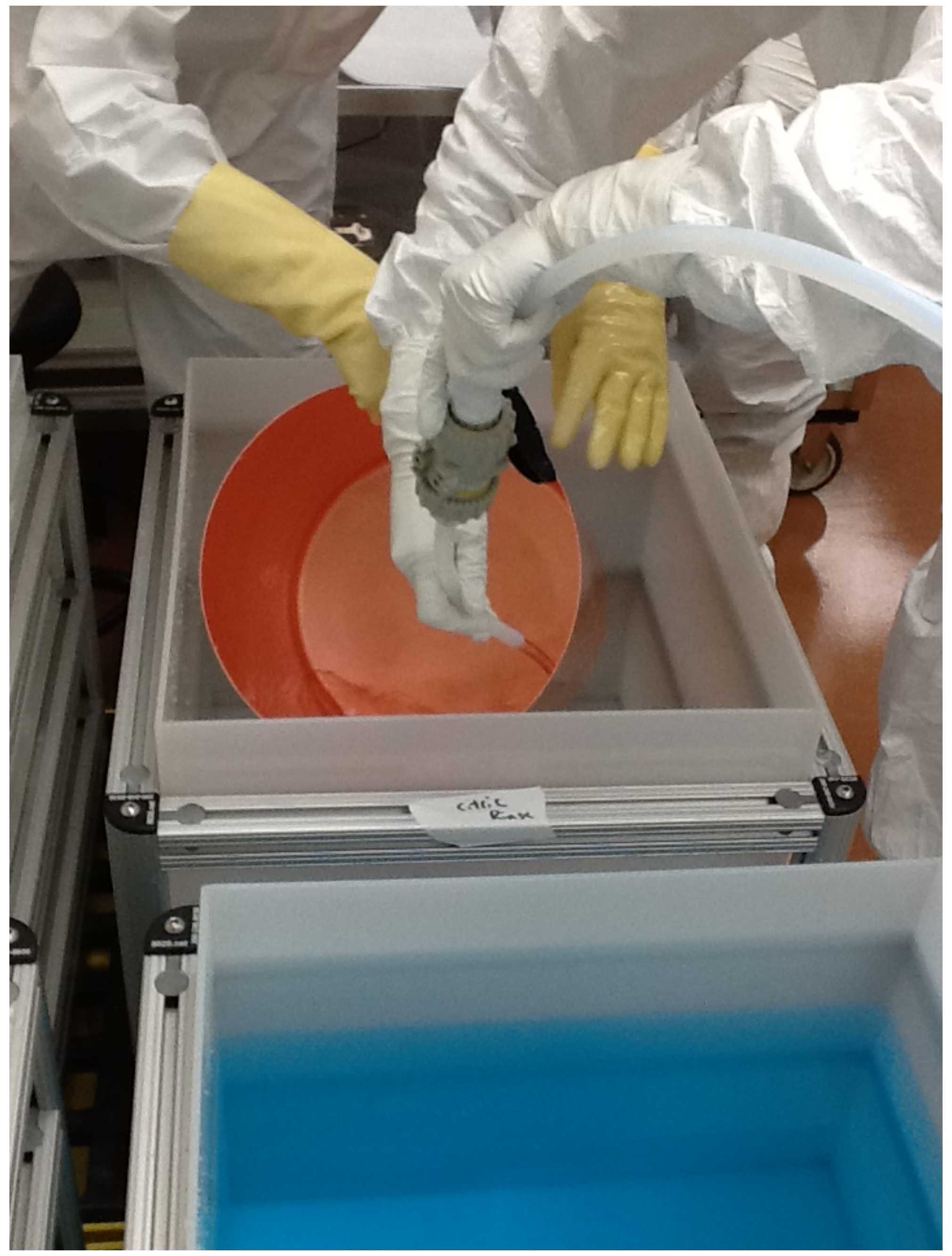
# MAJORANA Cu Part Cleaning

After machining, all Cu parts cleaned of surface contamination based on established procedures

Surface etch ($CuSO_4$ + $H_2O_2$) and passivation

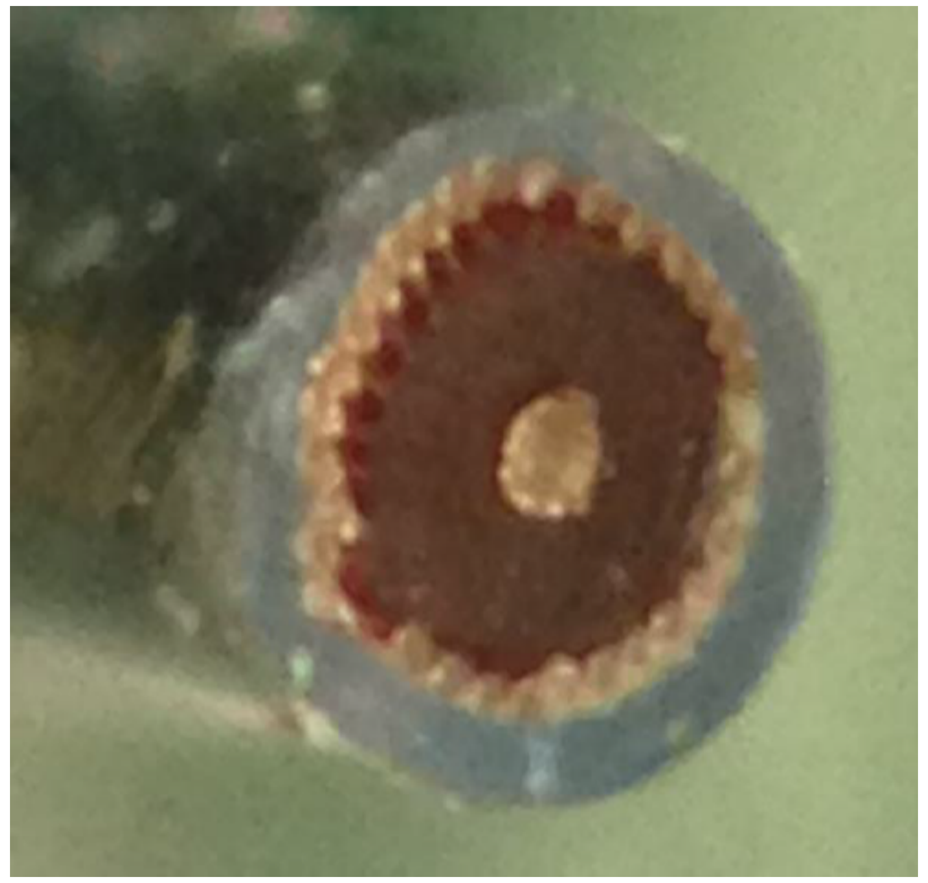
*modified from* Hoppe et al.
NIM **A579** (2007) 486–489

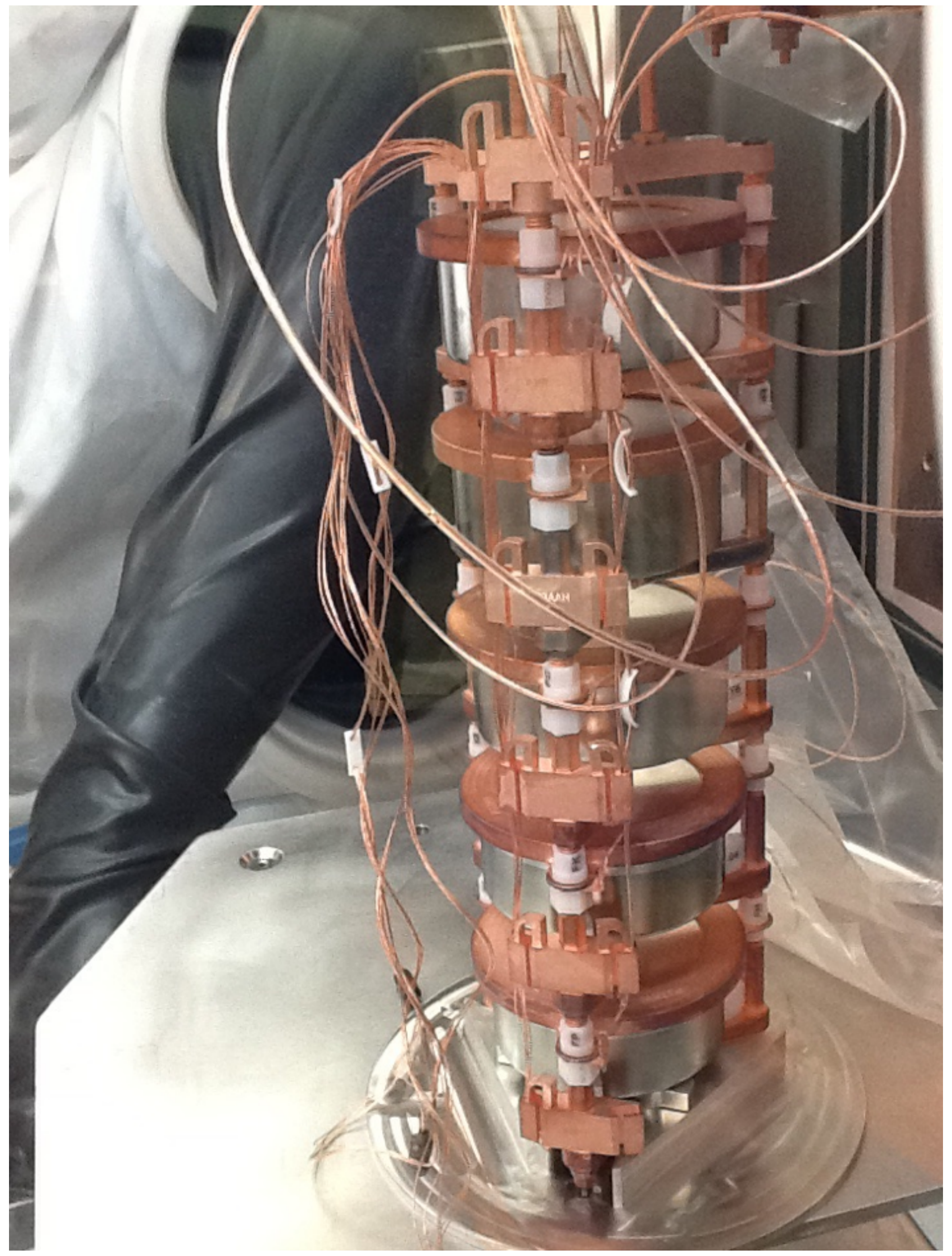


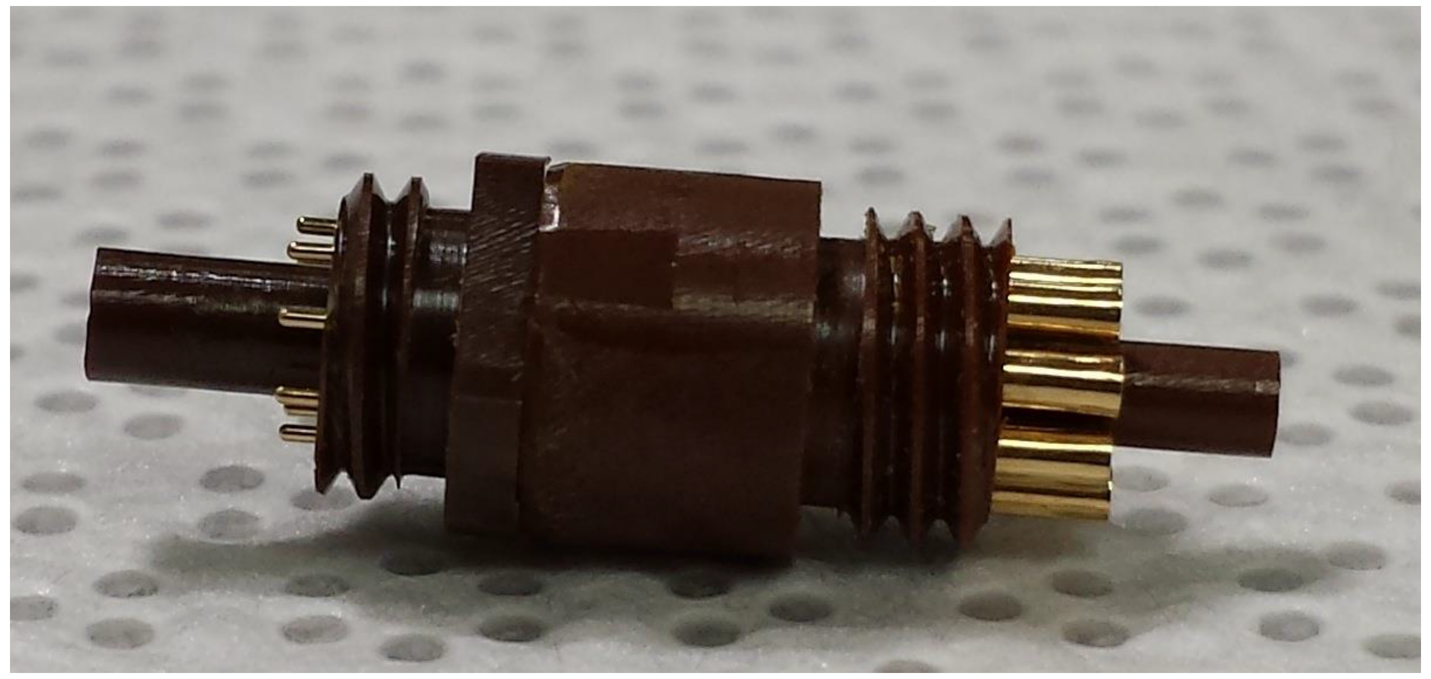
# Cables and Connectors

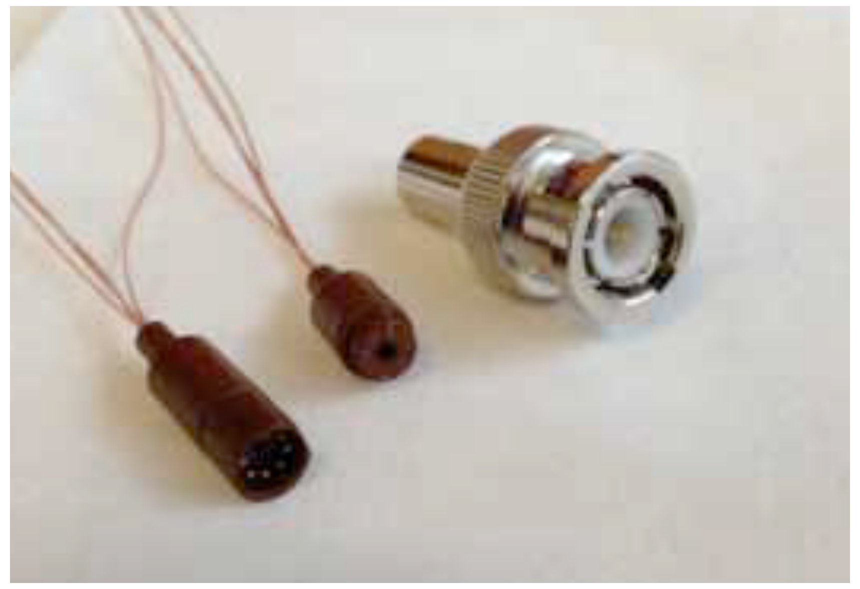
- The signal and HV cables were produced by Axon' using certified materials
  - Dupont™ and Daiken Neoflon™ FEP dielectric and outer jacket from two different stocks
  - California fine wire central AWG34.5 and AWG40.5 conductors
  - Axon' AWG50 ground shield
  - Modified manufacturing steps to mitigate contamination and enforced cleanliness protocols of final products
  - Raw materials prior to cable production and finished cables assayed by ICPMS at PNNL



- Custom connectors after survey of commercial products
  - Mil-Max® gold-plated brass pin receptacles without BeCu contact springs
  - Vespel® housing to secure pins and sockets
    - Leached with $HNO_3$, stored in $N_2$ environment
  - SnAg alloy solder of cables to connectors; FEP tubing for strain relief
  - Full-body assay of complete connector: 0.52 µBq/ch Th, 1.64 µBq/ch U







NIM **A828** (2016) 22–36

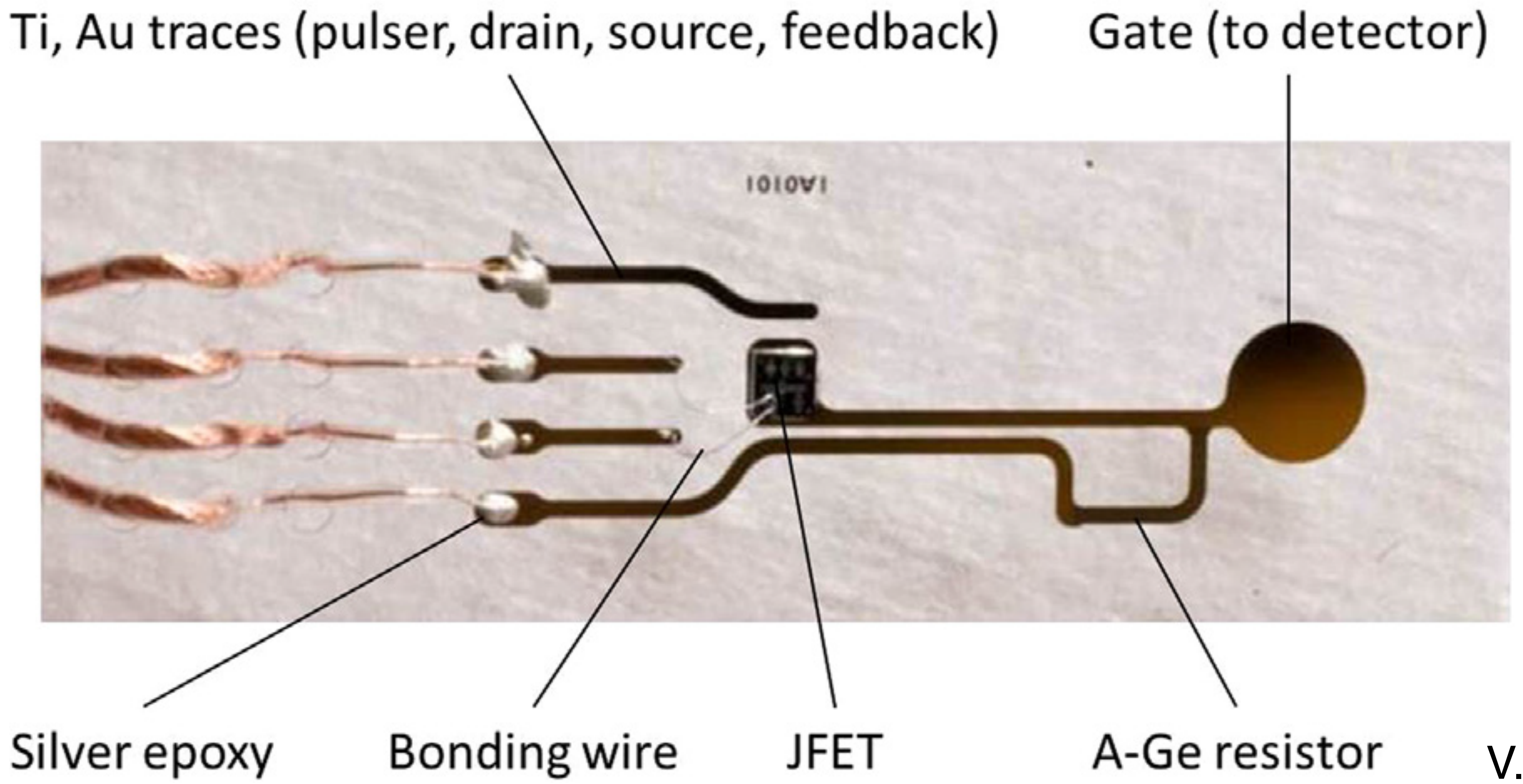
# Front End Electronics

Custom front end board designed with component materials selected from ICPMS assay

- Fused silica substrate with a photolithographic pattern for conductive traces and resistance
  - Highly polished wafers cleaned before photolithography in DI water and 10% $HNO_3$ decreased U/Th levels
  - Thicker traces (1-10 μm) deposited and removed for assay
- JFET affixed using assayed silver epoxy
- Cables bonded with silver epoxy; ultrasonically-drilled holes for strain relief

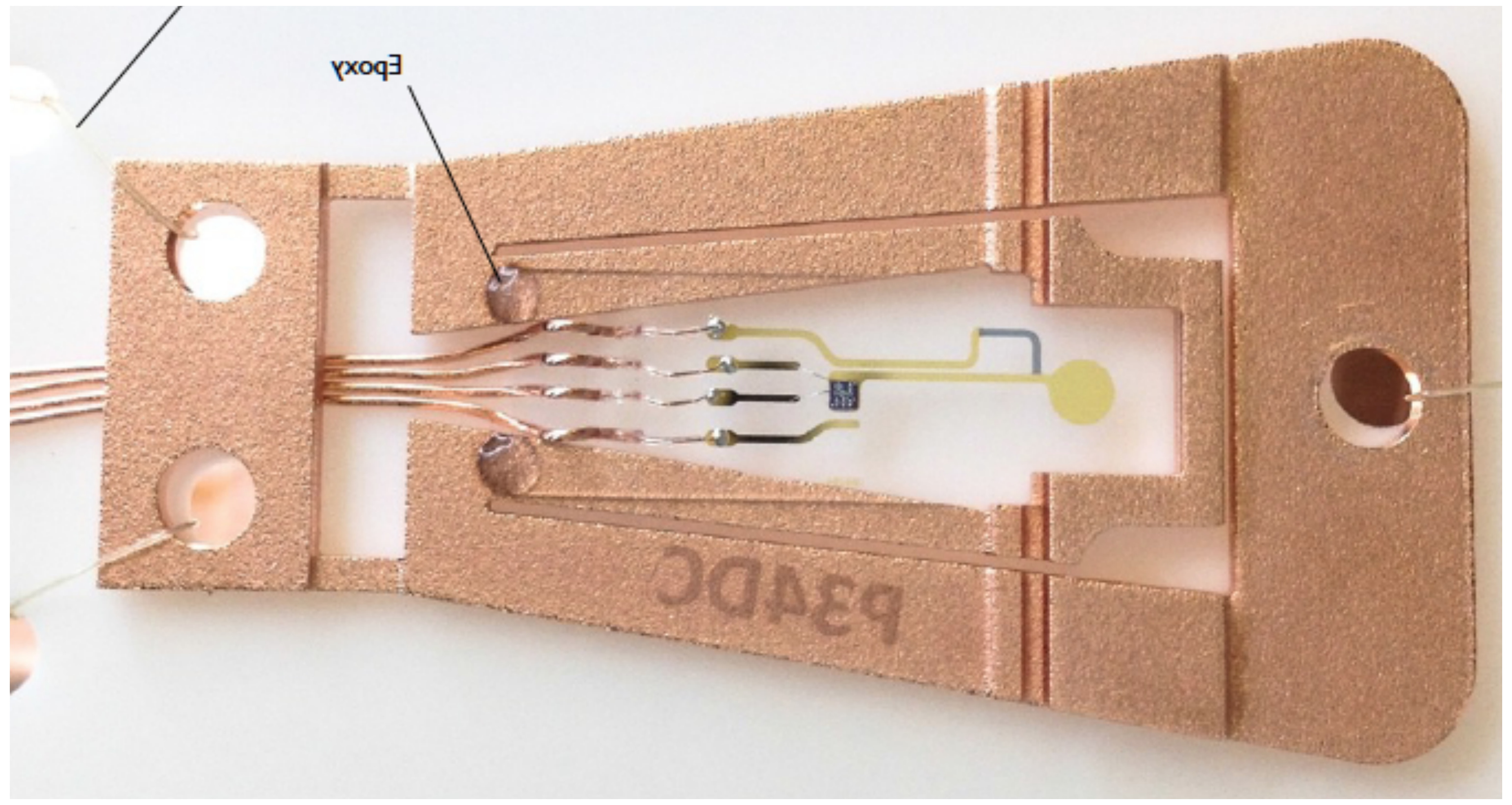
ICPMS assay of fabricated boards to evaluate contamination during the production process

- Dissolved in a microwave reaction system with $HNO_3$ and HF solutions




full-body assay
6.5 mBq/kg Th
10.6 mBq/kg U

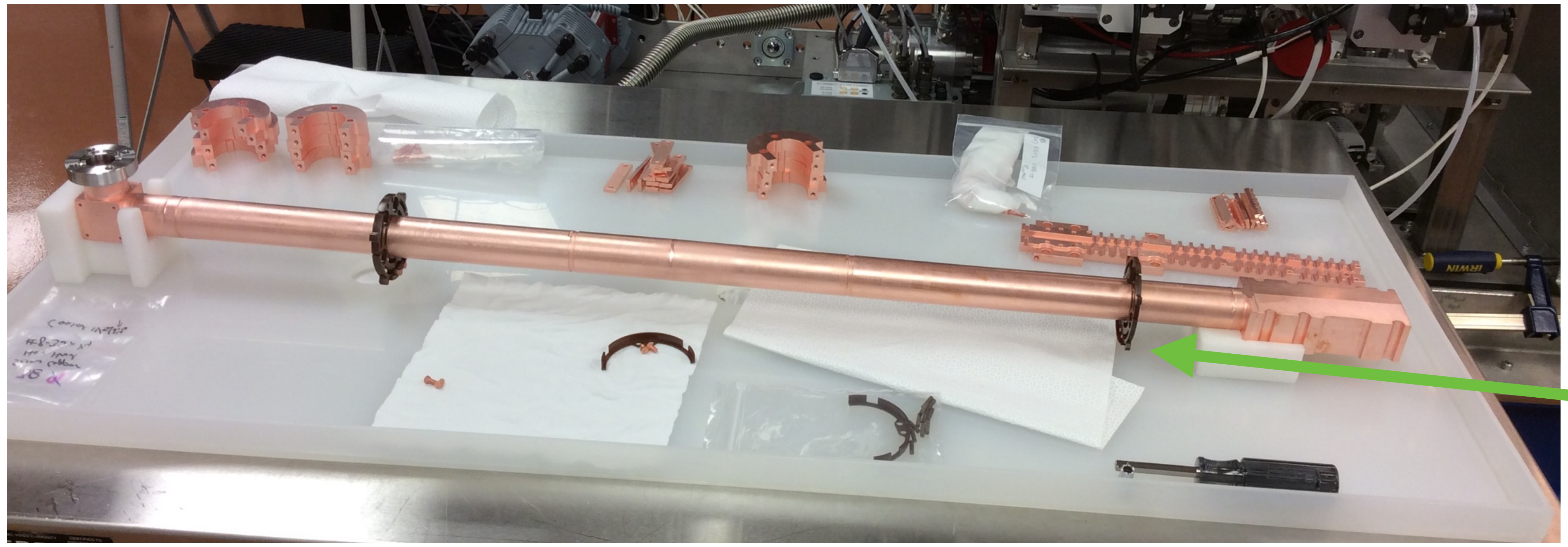
NIM **A828** (2016) 22–36



# Plastics

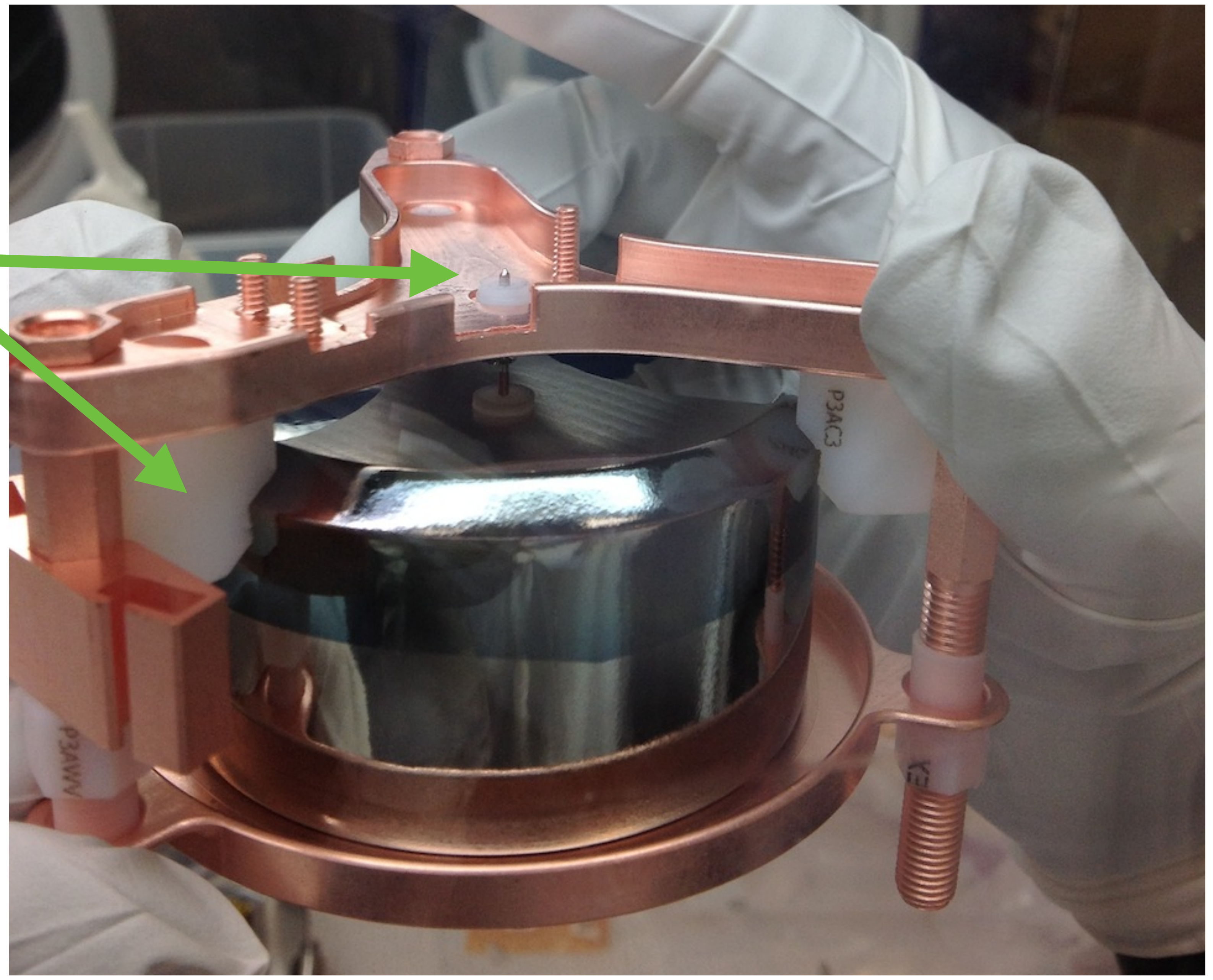
Various plastics assayed and certified for low-background use

- PTFE (NXT-85) detector supports and electrical insulators
- PTFE cryostat seals and calibration track tubing
- PEEK (Victrex®) and Vespel® for their load-bearing rigidity

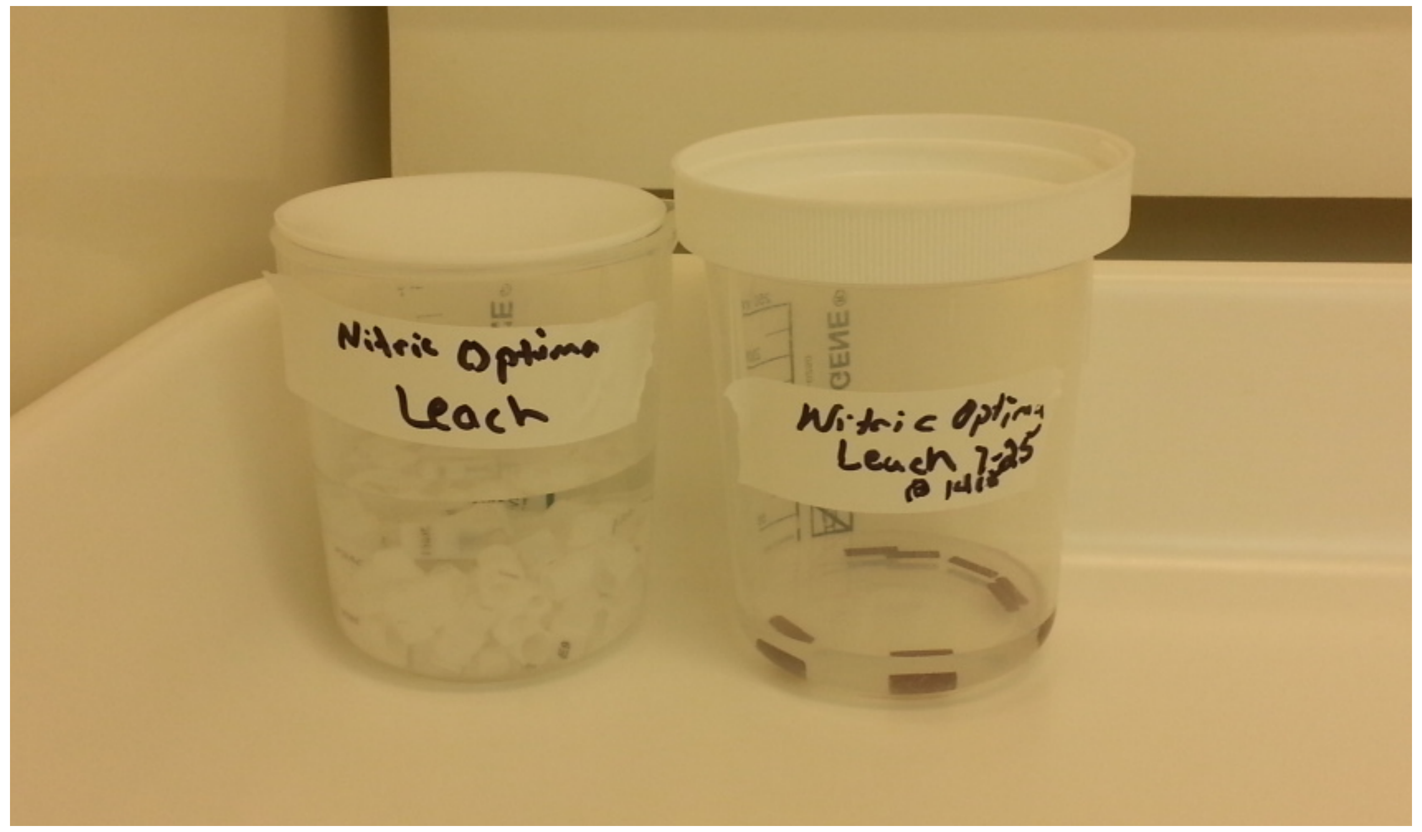


Vespel

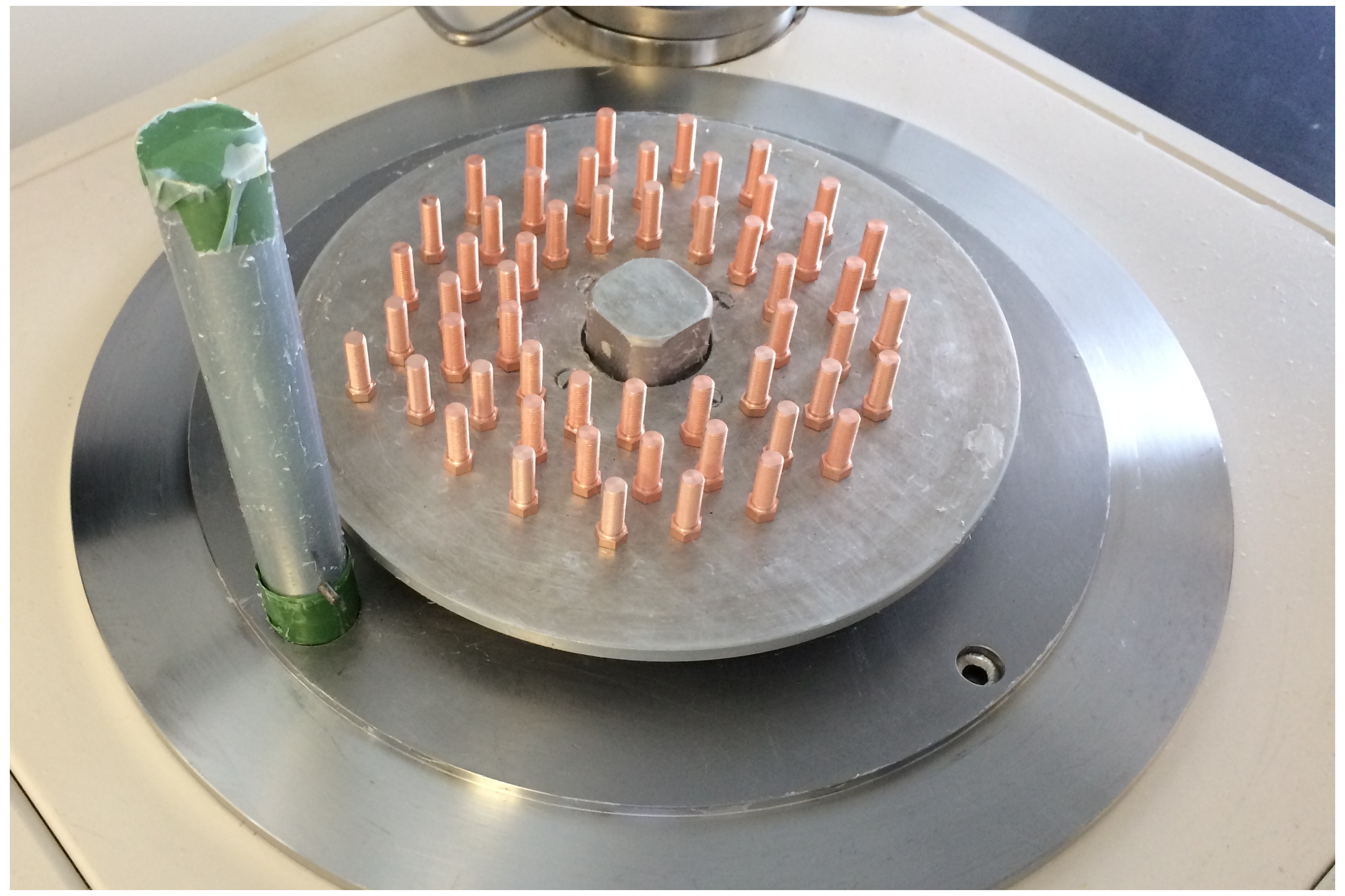
PTFE



After in-house machining, surfaces cleaned by 72-hr $HNO_3$ leach

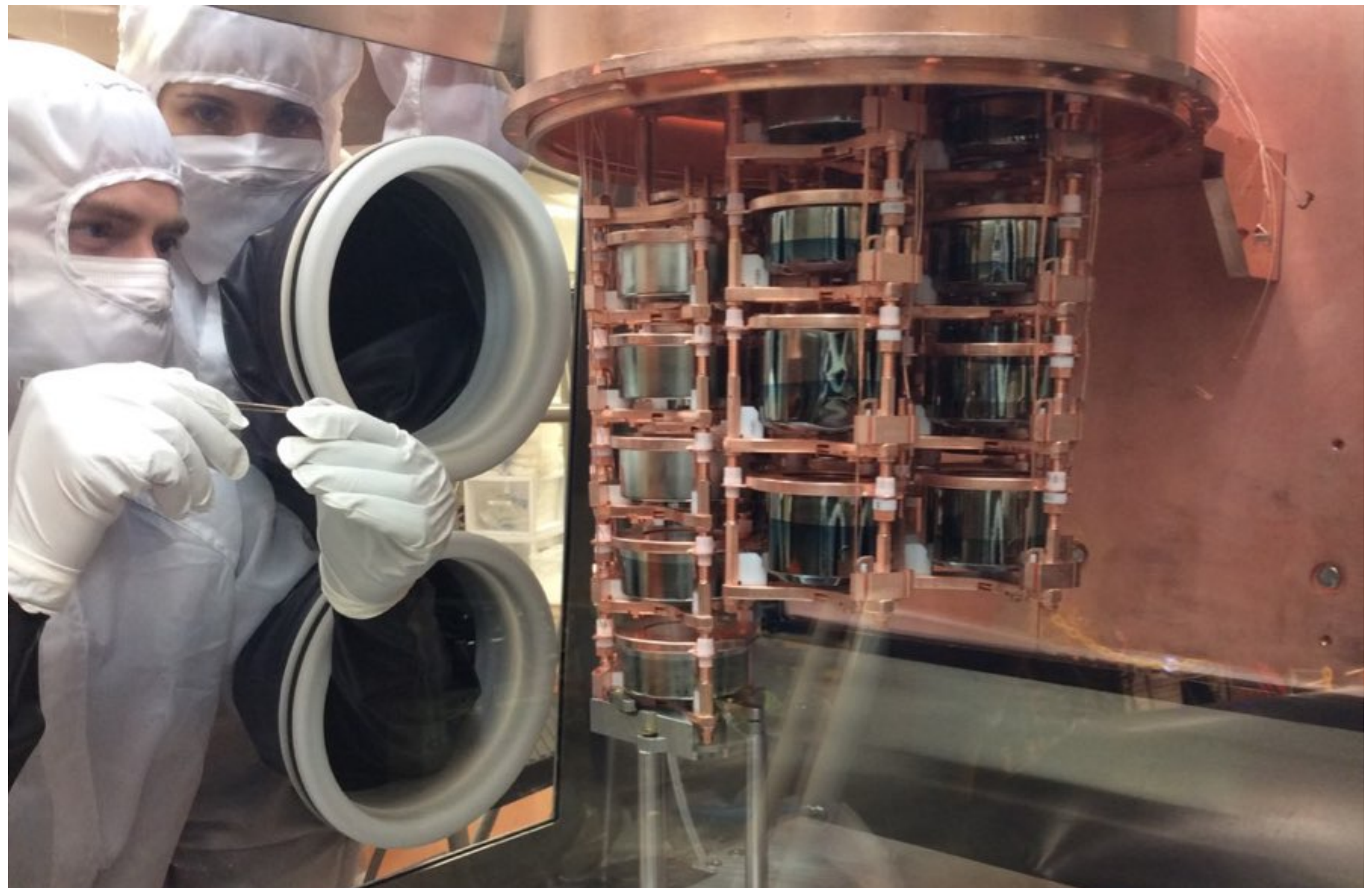



Parylene coating of threaded hardware as anti-galling agent

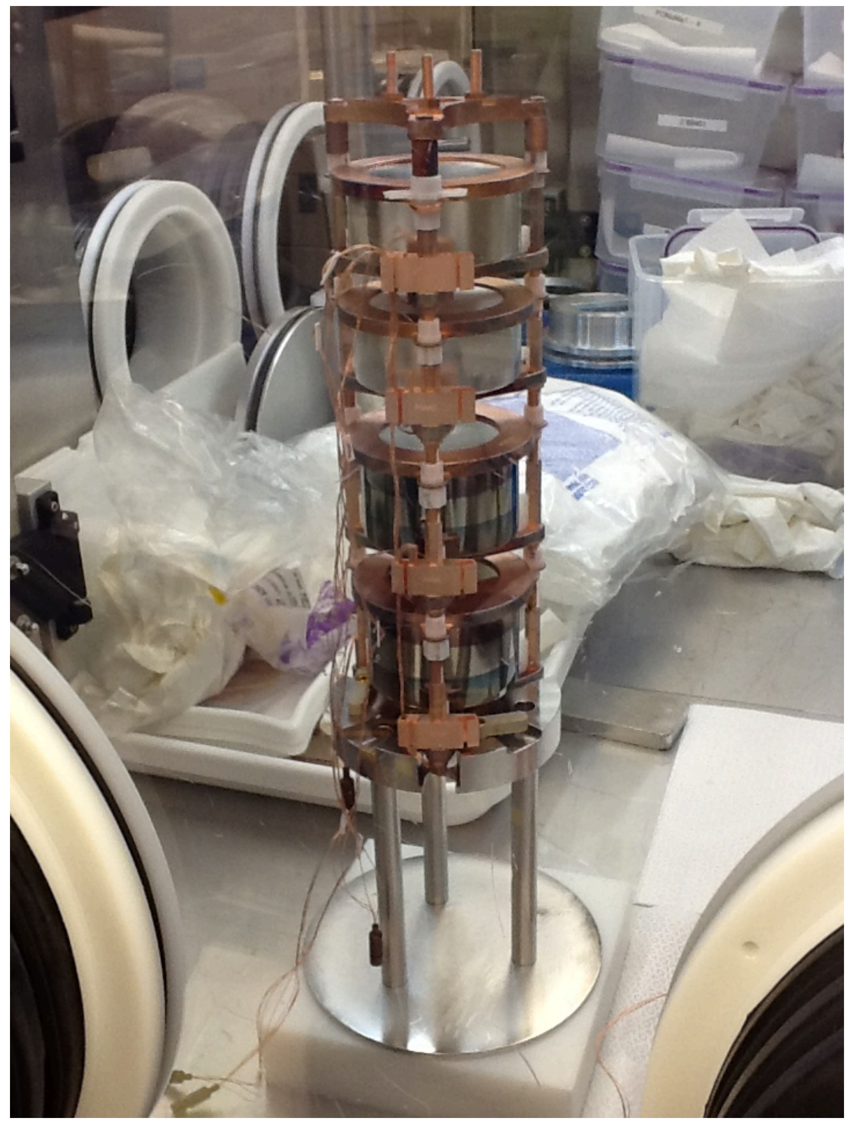
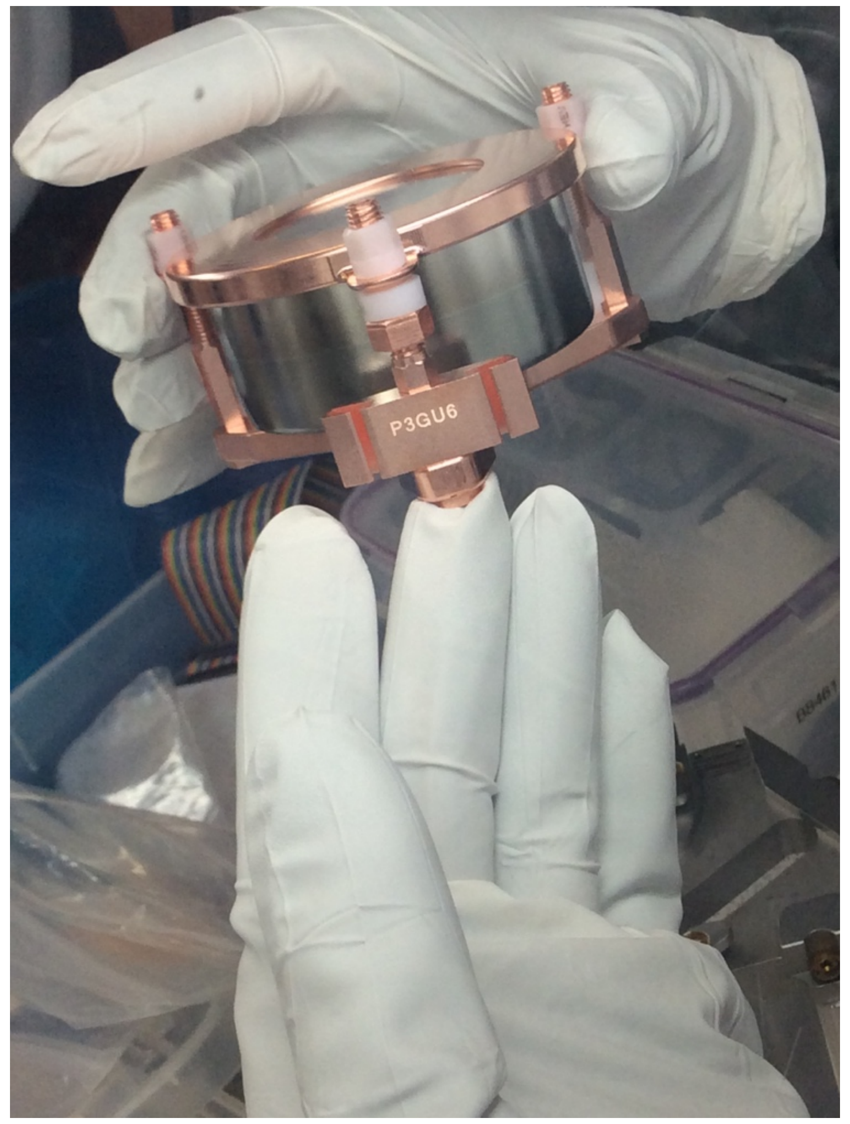


# Detector Assembly

Dedicated glove boxes with a purged $N_2$ environment for detector assembly and material storage



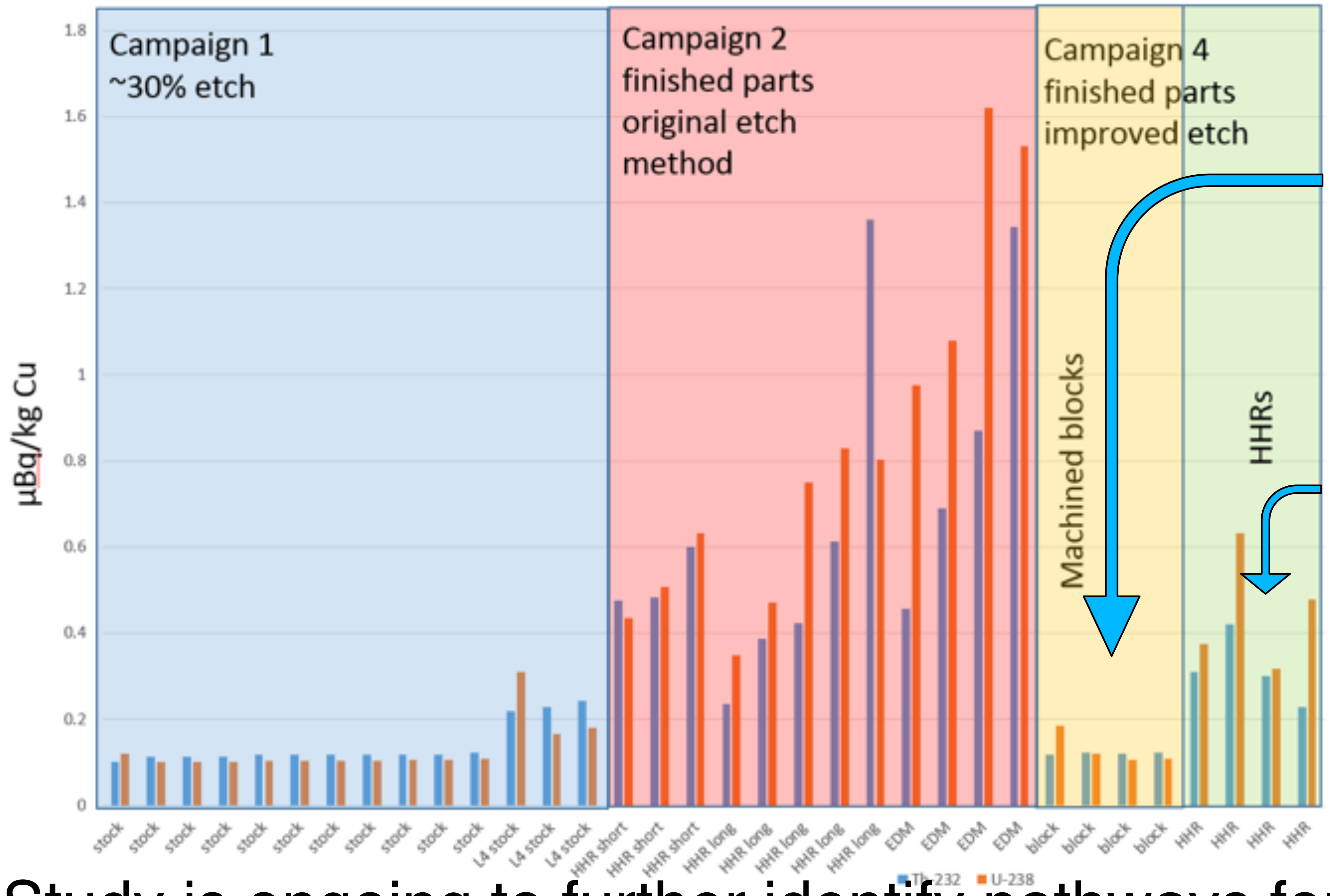



# Improved MAJORANA Cu Part Cleaning

Maintained an validation campaign to verify the finished parts remained pure

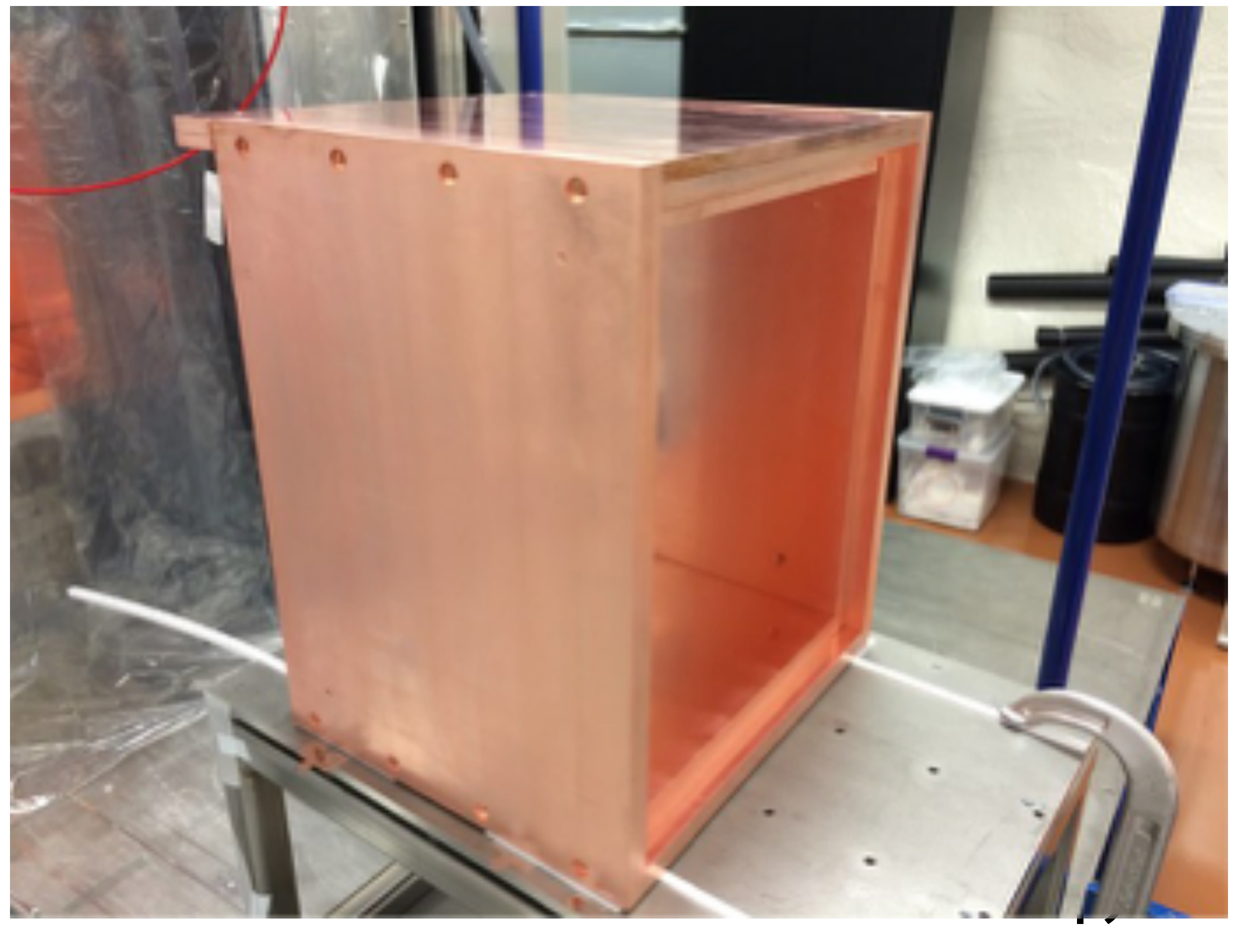
- Concerned that various handling conditions introduces unique pathways for surface contamination of U/Th.
- Should contamination occur, most sensitive to the large mass, large surface area components
- Contamination of parts during processing confirmed
  - Results not acceptable for the inner Cu shield (which had not been processed yet!)
- Predicted the depth of Cu removal to remove surface contamination
- Revised procedures and adopted additional QA requirements.

bulk stock material | original finished part | new procedure




See C. Christofferson LRT 2017
arXiv:1711.10361

Machined blocks essentially back to starting stock radiopurity:
Acceptable for inner shield plates



Detector mounting components also improved, and acceptable

Study is ongoing to further identify pathways for surface contamination

# Background Model Development

Initial assay measurements with early simulations with assumed simulations and expected detector configuration

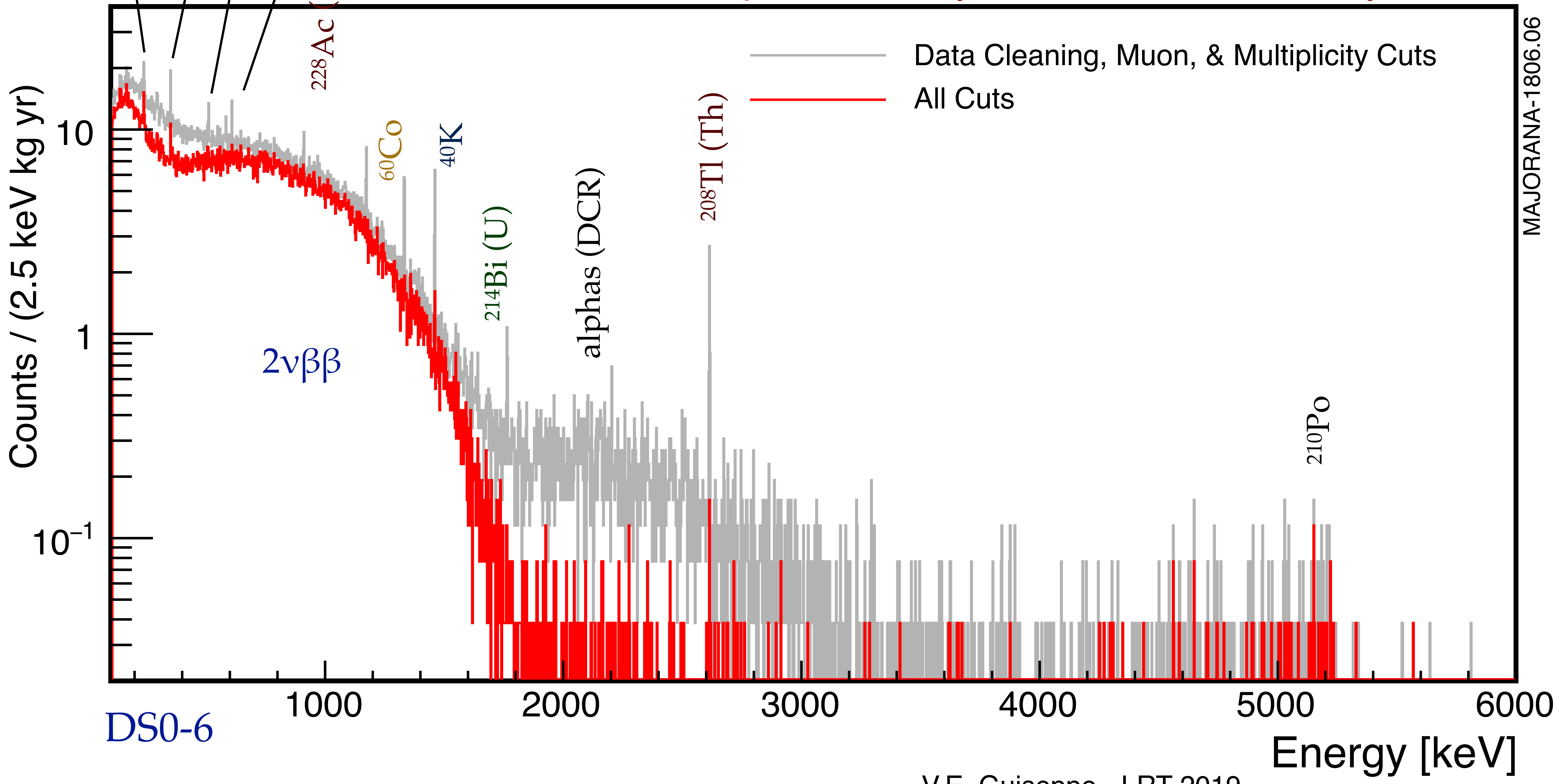
Initially predicted $< 2.2$ cts/(FWHM t y) at $Q_{\beta\beta}$

Measured Background: $11.9 \pm 2.0$ cts/(FWHM t yr)

arXiv:1902.02299

Reviewing new assay information, as-built geometry and simulations, detector configurations, and updated physics lists

Goals: Generate an updated assay-based model & Identify the residual backgrounds that survives PSD




Develop a background model to fit the observed energy spectra

- MaGe/Geant4 simulations with the as-built geometry of experiment
- ~4000 parts, ~70 unique designs
- ~40 component groups of related parts

# Background Model Development

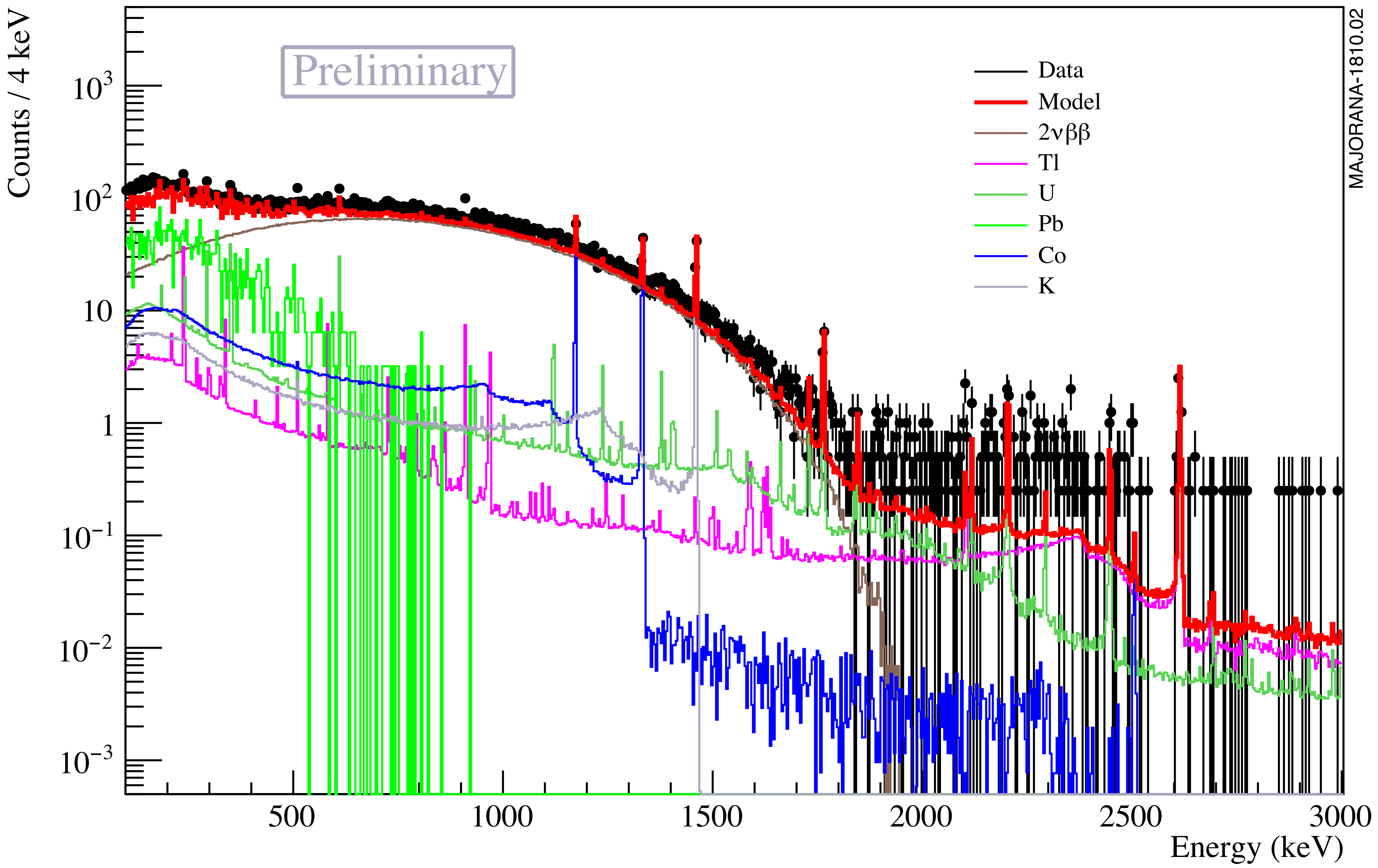
Initial spectral fits suggest that the dominant source of background above assay estimates is not from nearby components

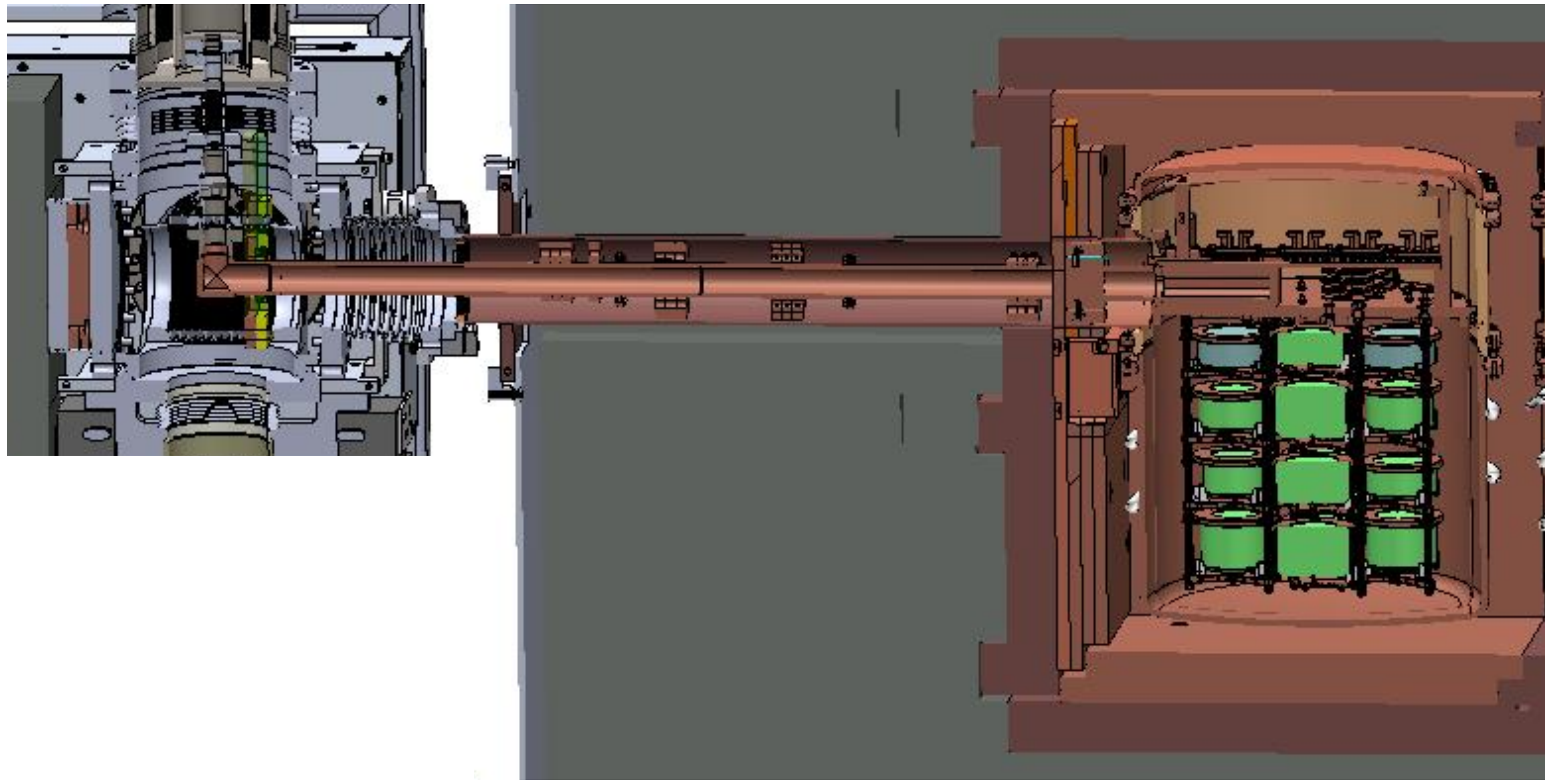
- Based on the energy dependence of the peak intensities
- Also Consistent with the low rate of detector coincidences observed
  - One observed coincidence between 583 and 2614 keV 208Tl-decay gammas. Factor of 5-10 more expected for sources near detectors

Identifying missing spectral components

Using coincidence studies to constrain spectral fits

No multisite cut, activities fit to background spectrum



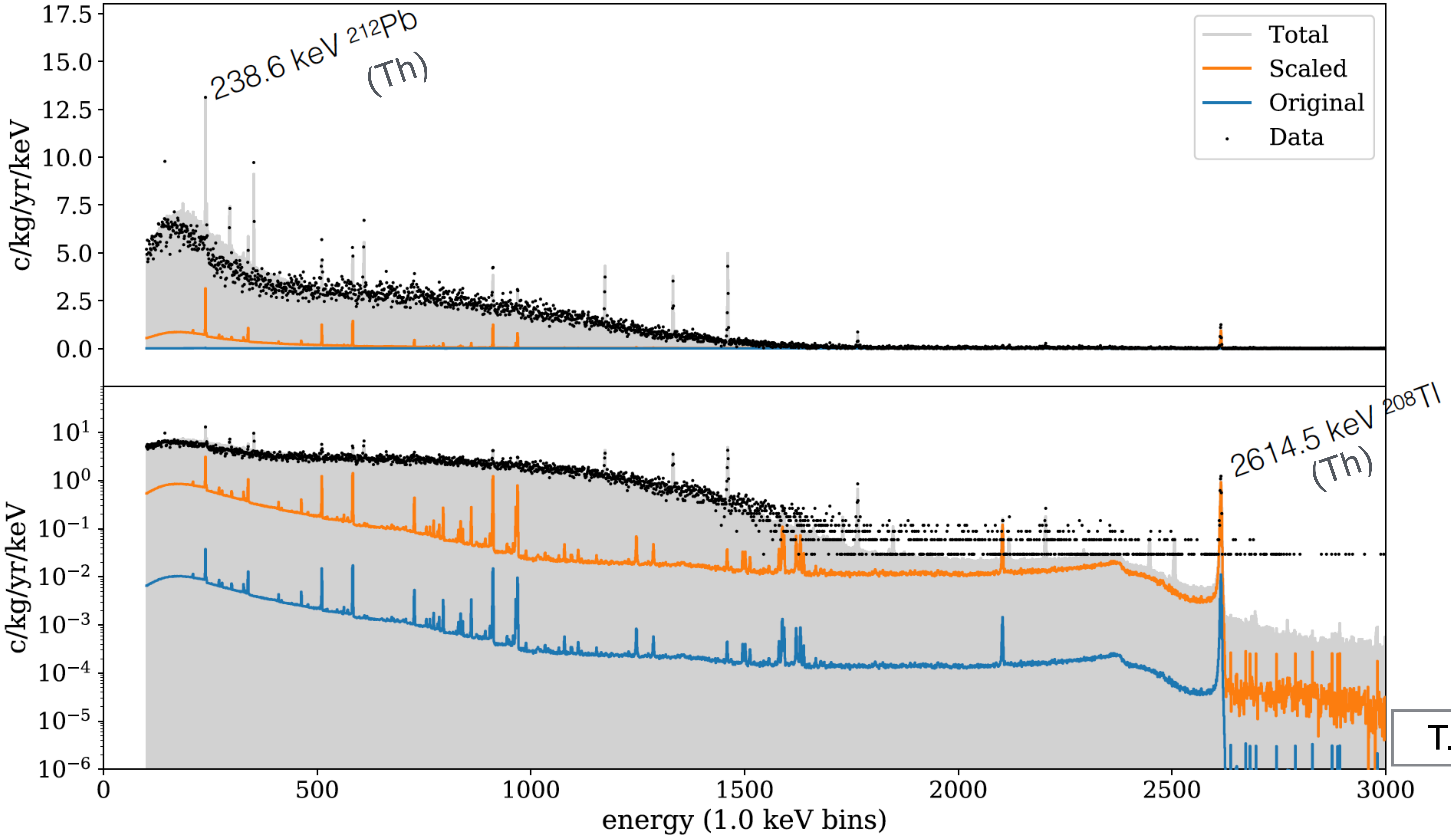
Initial spectral fits missing strength at high energies

# Background Model Development: An example

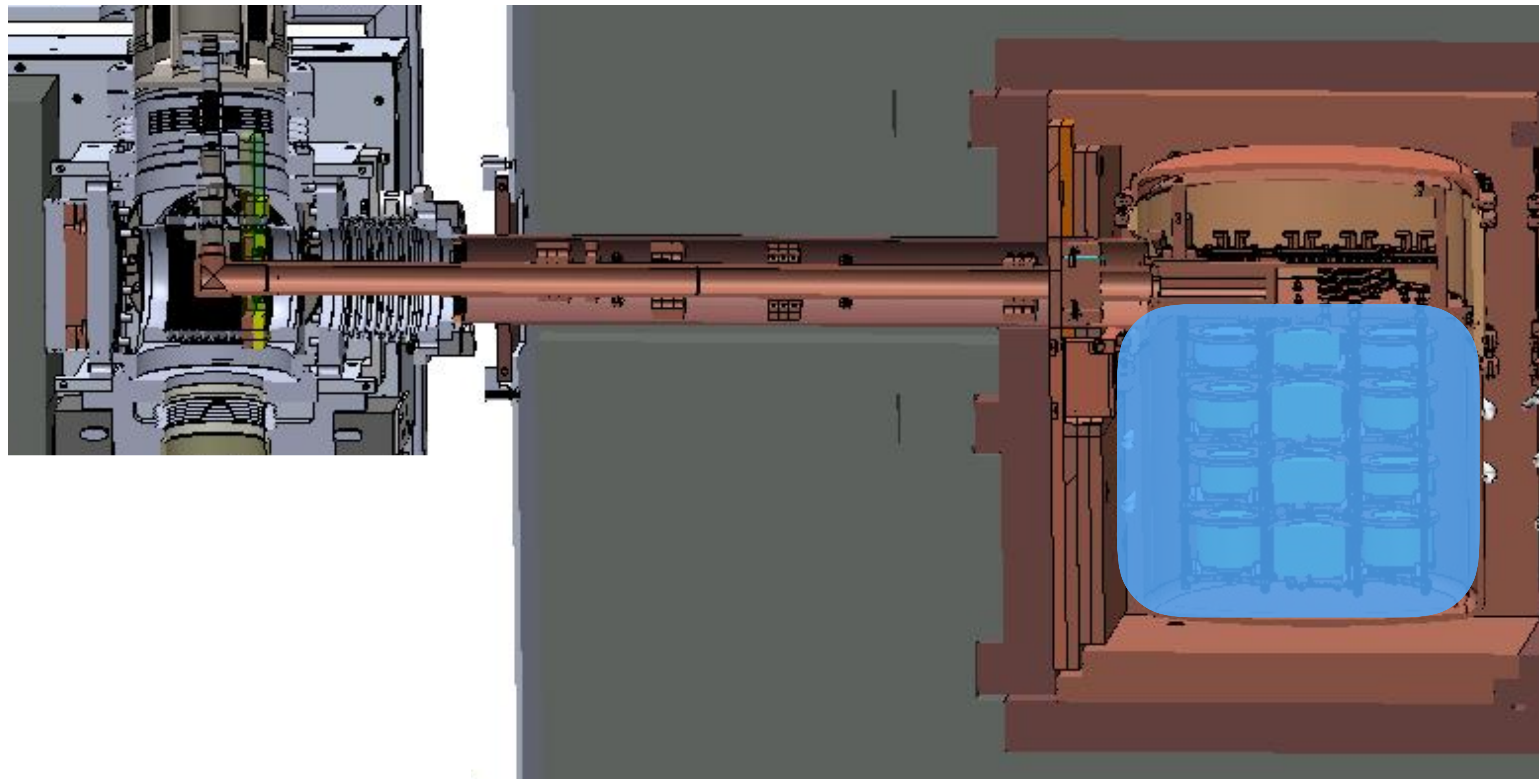
Initial spectral fits suggest that the dominant source of background above assay estimates is not from nearby components

Based on the energy dependence of the peak intensities

A scaling of a *distant* component matches both the 239-keV and 2615-keV peak intensities from the $^{232}$Th chain




Distant ≈ Outside of the Ge-detector array



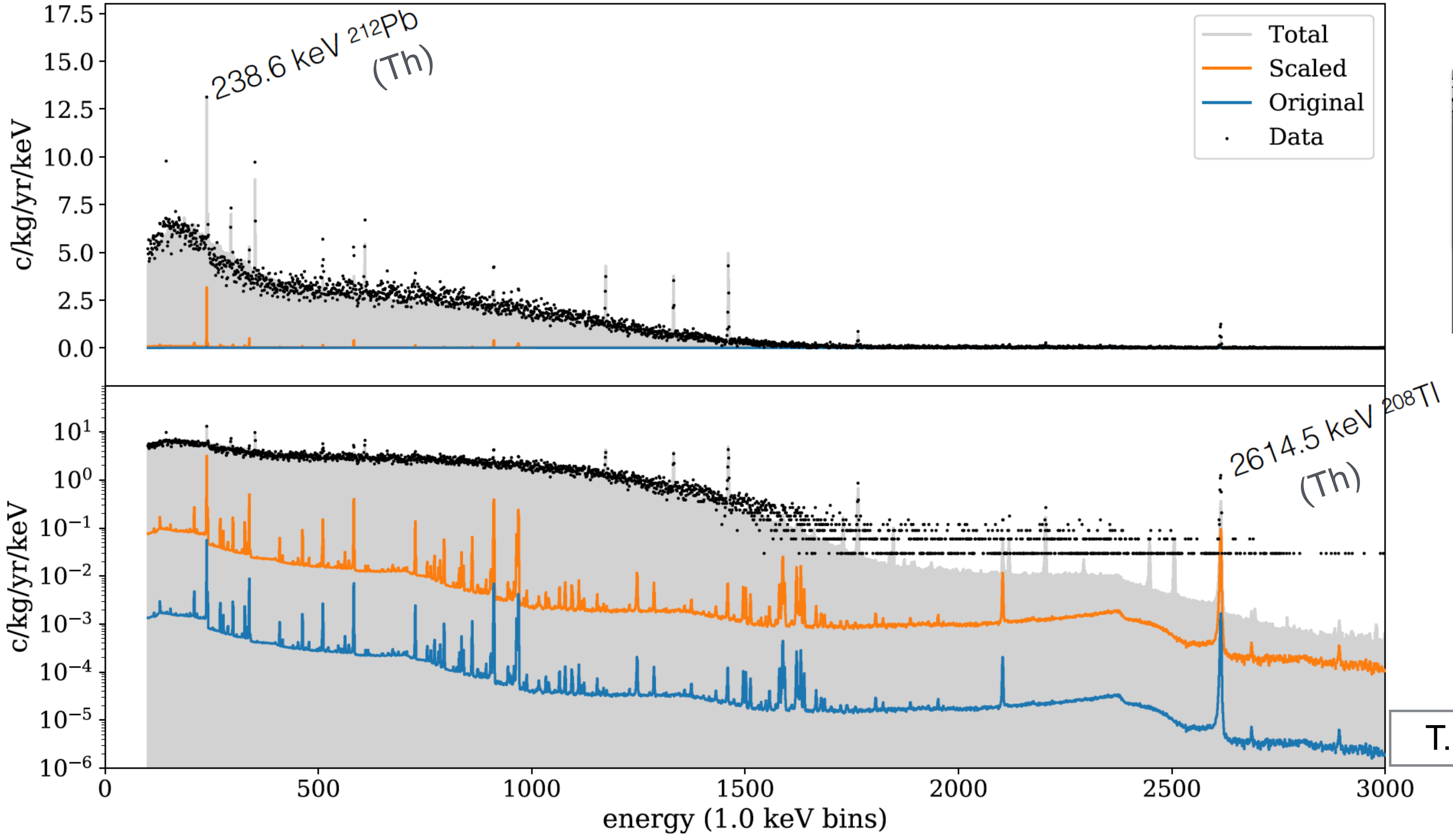
T.F. Gilliss, UNC, PhD Dissertation 2019

# Background Model Development: An example

Initial spectral fits suggest that the dominant source of background above assay estimates is not from nearby components

Based on the energy dependence of the peak intensities

A scaling of a nearby component scaled to the 239-keV peak underestimates the 2615-keV peak intensity from the $^{232}$Th chain




Nearby ≈ Within of the Ge-detector array

T.F. Gilliss, UNC, PhD Dissertation 2019

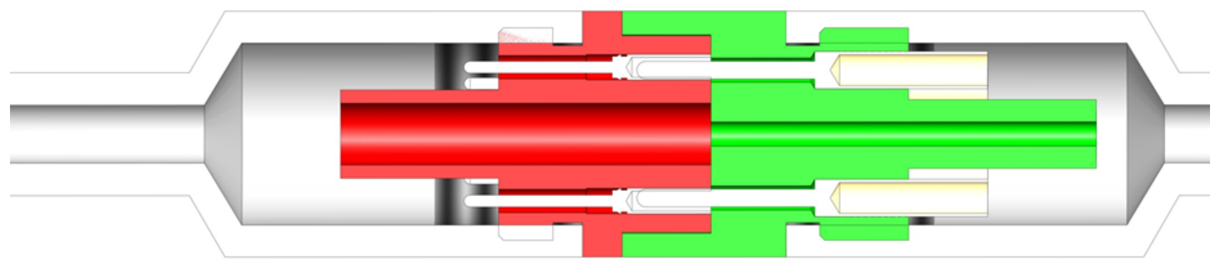
# Cable and Connector Improvements

An upgrade of the Demonstrator planned for late 2019 to improve channel reliability and backgrounds

See M. Busch LRT 2017 arXiv:1712.04985

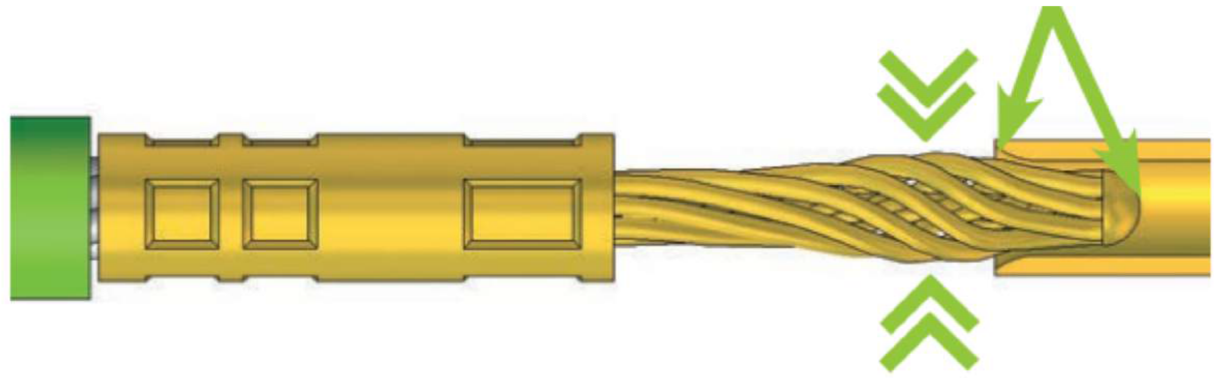
## Connectors

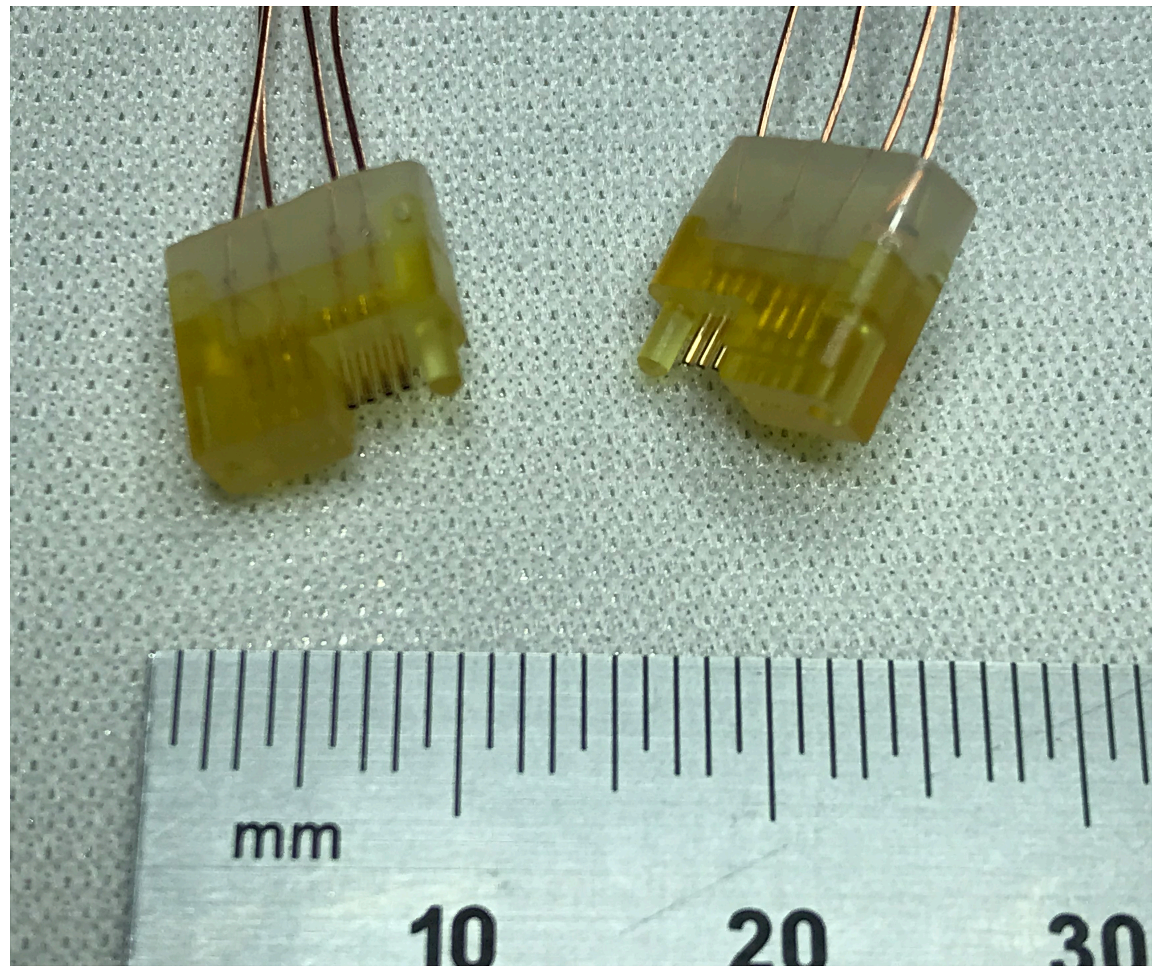
Current design relies on radially mis-aligned pins for contact



full-body assay
0.52 µBq/ch Th
1.64 µBq/ch U

Implementing custom connectors that incorporate a twist pin mechanism






All components
0.36 µBq/ch Th
0.46 µBq/ch U

## Cables

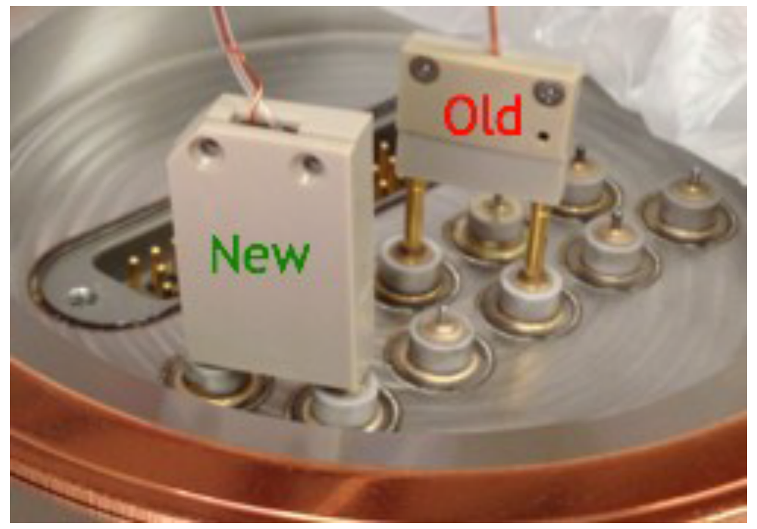
Original BG budget estimate: 2.2 uBq/kg Th; 145 uBq/kg U
- deemed acceptable, but limited sampling statistics

many components based on limits.

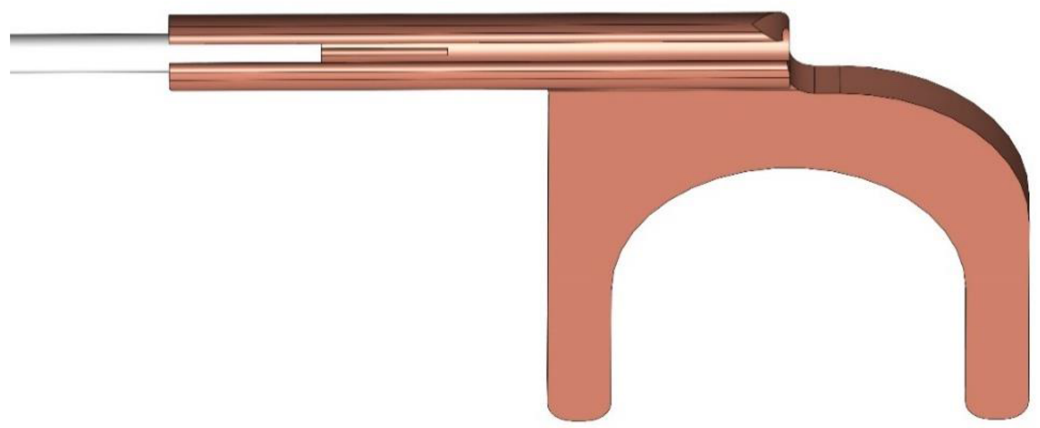
Continued to work with Axon' to produce clean cables

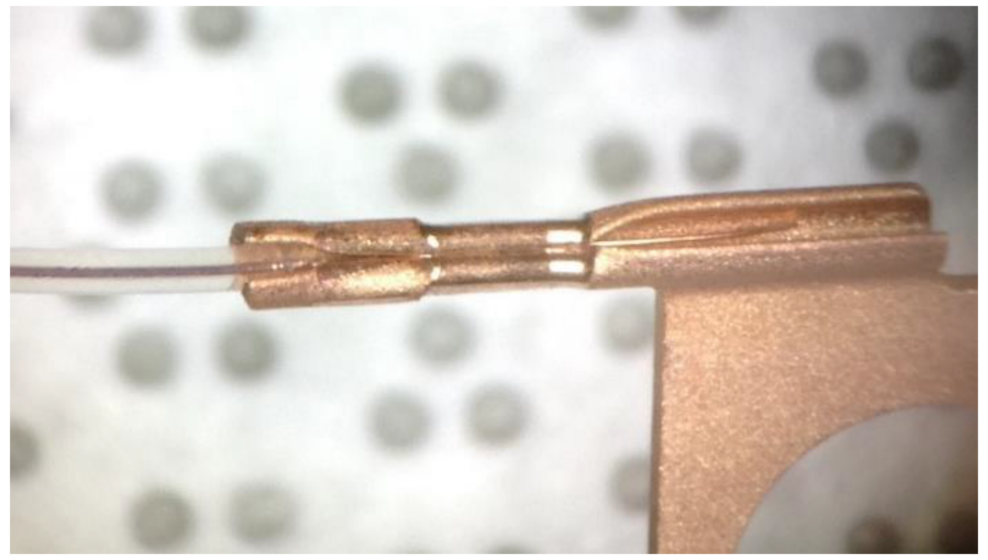
- Improved ICPMS assay at PNNL: Separation of Cu and FEP components from full body digestion
- Original cable BG may be higher than original estimate, running improved assay method on leftover cables
- Will deploy new cables with better confidence of actual background contribution

## HV Connections




Better HV crimp at the detector and flange





# Summary and Outlook

- MAJORANA DEMONSTRATOR construction complete, continuing to take data in its final configuration since Spring 2017
  - Latest limit from 26 kg-yr exposure: >2.7 x $10^{25}$ yr (90% C.L.); sensitivity 4.8 x $10^{25}$ yr (90% C.L.) arXiv:1902.02299
- Background Model under development
  - Initial background fits are informing possible distribution of background sources
  - Goal of a full background model consistent with the data - inform design of next generation experiments
- Optimization of analysis cuts underway to improve background rejection
  - New results and improved analysis reported later this year - stay tuned
- Low background + low threshold + energy resolution allows for broad physics program

  PRL **118** 161801 (2017) | PRL **120** 211804 (2018) | PRD **99** 07200 (2019)

- Planning an upgrade to improve channel reliability and background
- Expect to reach 50-70 kg-yr exposure with sensitivity in the range of $10^{26}$ yr half-life before decommissioning for LEGEND-200
  - Next Generation $^{76}$Ge: LEGEND is selecting the best technologies, based on what has been learned from GERDA and the MAJORANA DEMONSTRATOR

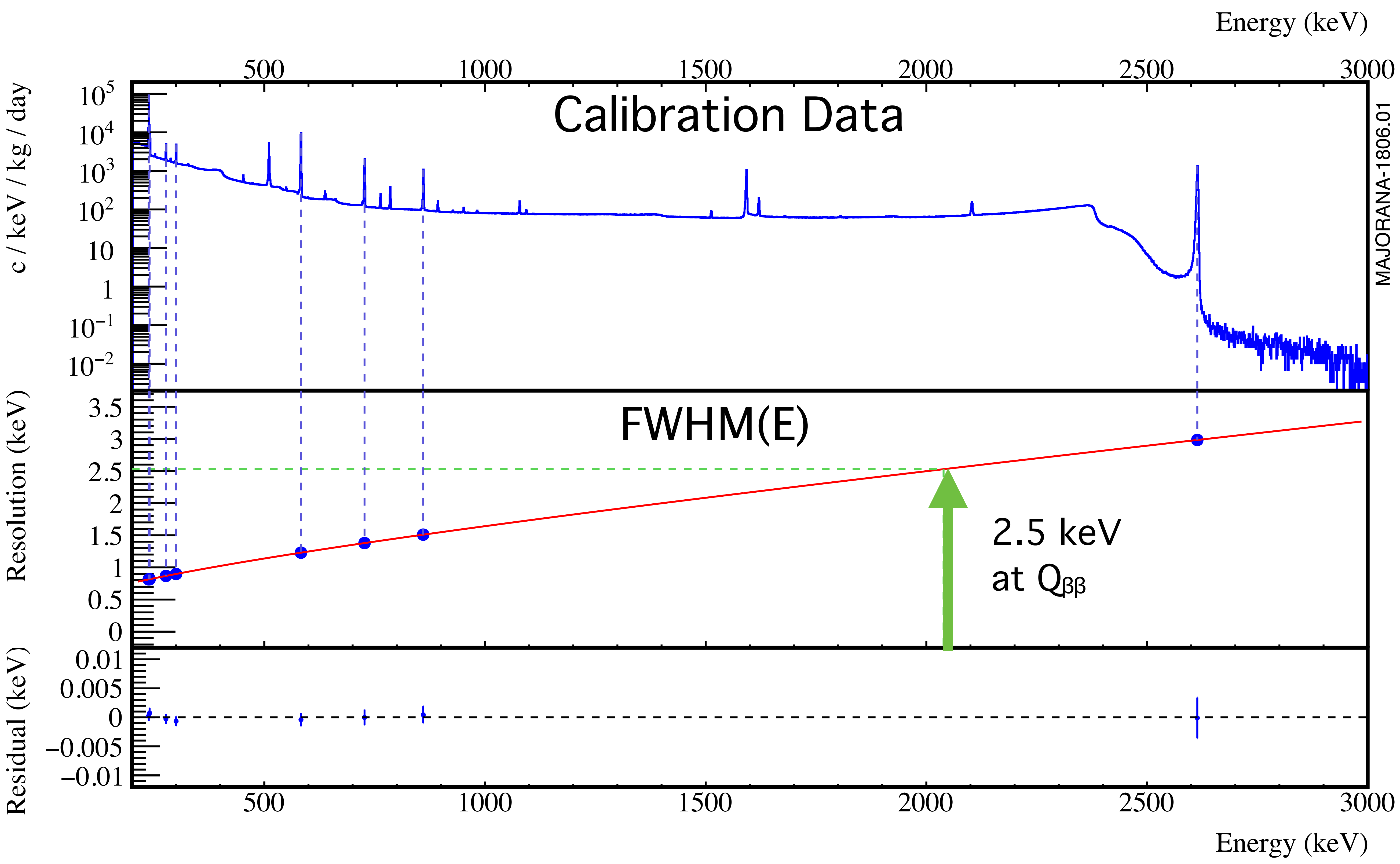
    M. Green LRT 2019

# Calibration and Energy Performance

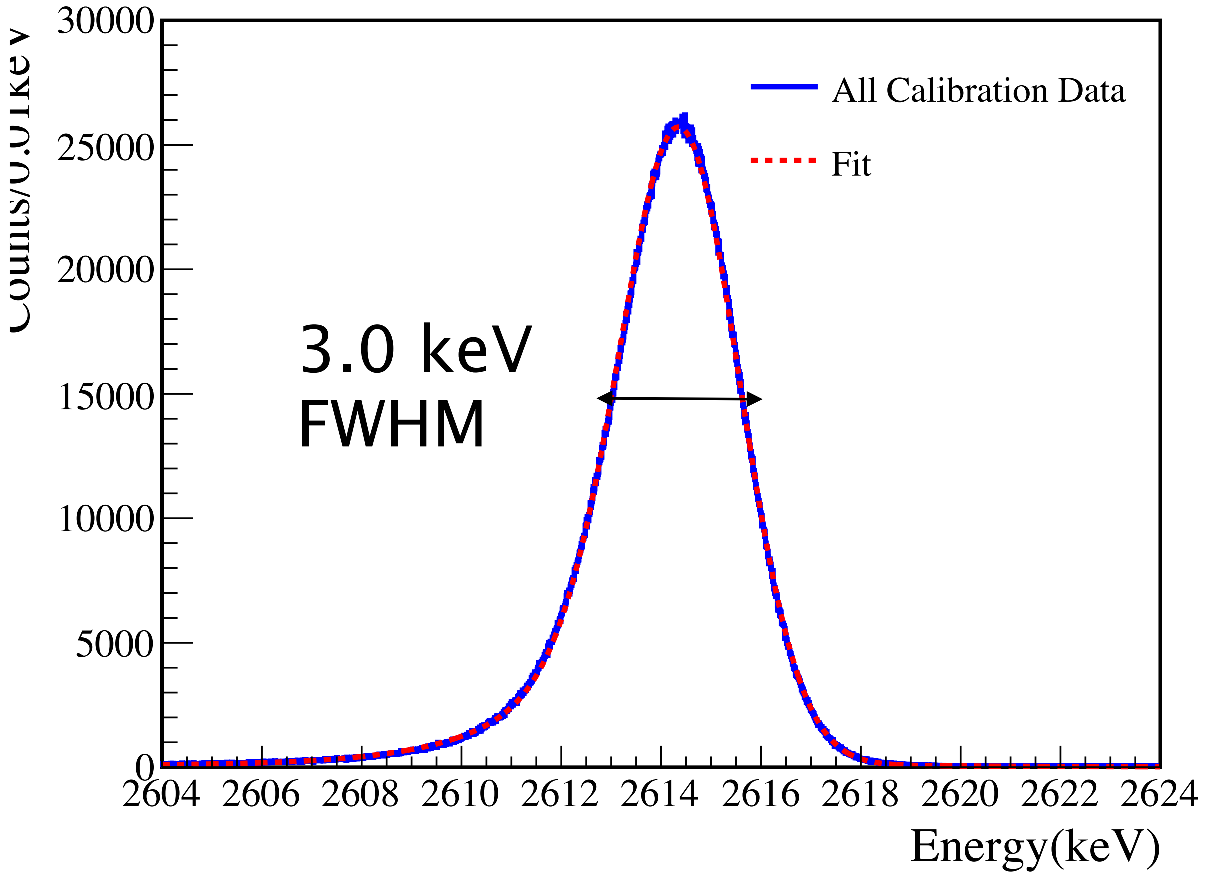
- Calibration of the detector array with a $^{228}$Th line source
  - Source is inserted and retracted for scheduled calibrations
  - Provides energy calibration, gain stability checks, and tuning of single-site (DEP) and multi-site (SEP) cuts

[NIMA **872**,16 (2017) arXiv:1702.02466]

- Excellent energy resolution attained improved by charge trapping and ADC nonlinearities corrections

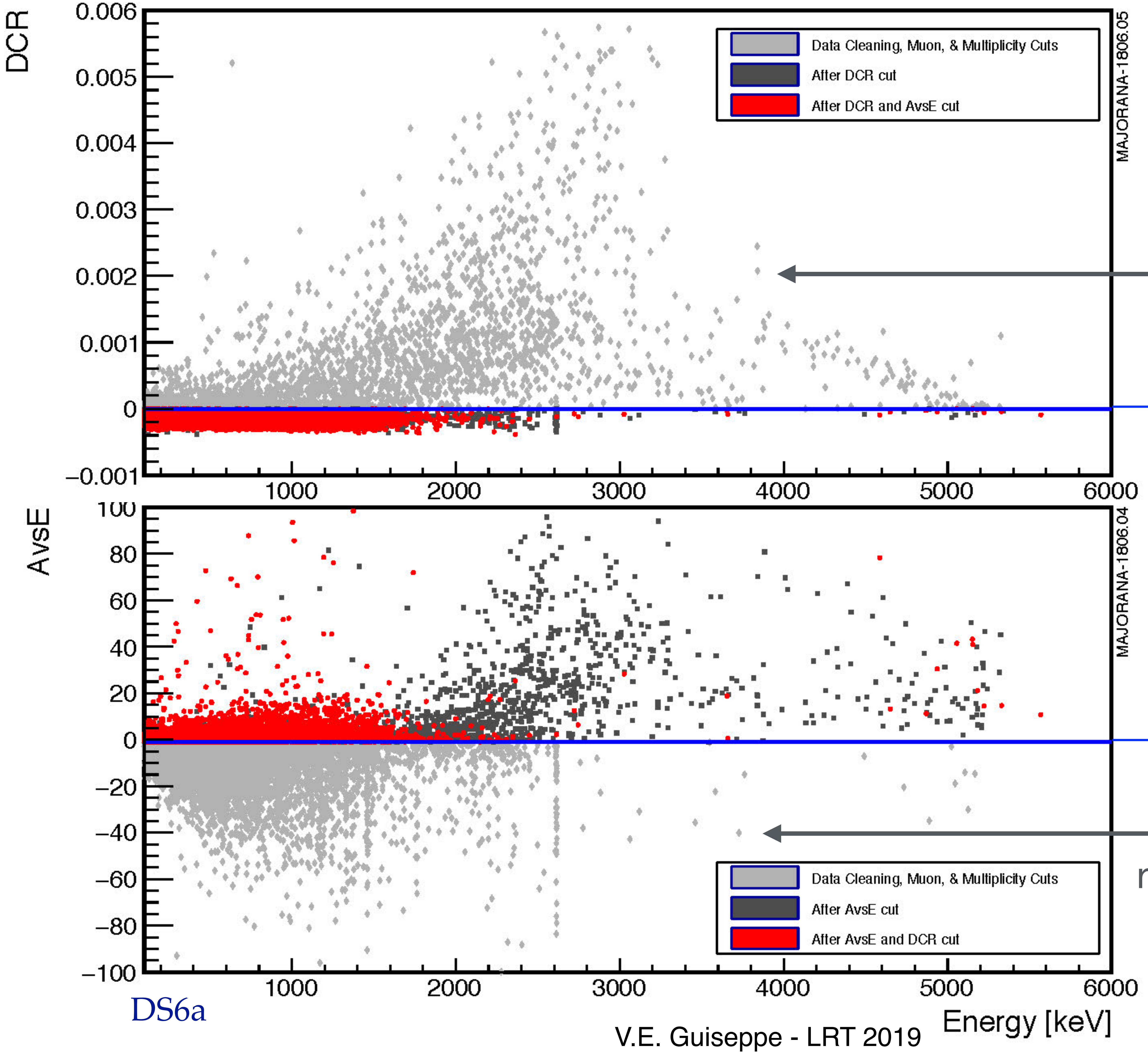



$^{208}$Tl 2615 keV Peak




Best achieved for $0\nu\beta\beta$ searches!

# Background Rejection: PSA Performance




Last year of data:
12.7 kg-yr exposure

High DCR:
alpha events

Signal region for DCR

Signal region for AvsE

Low AvsE:
multi-site events

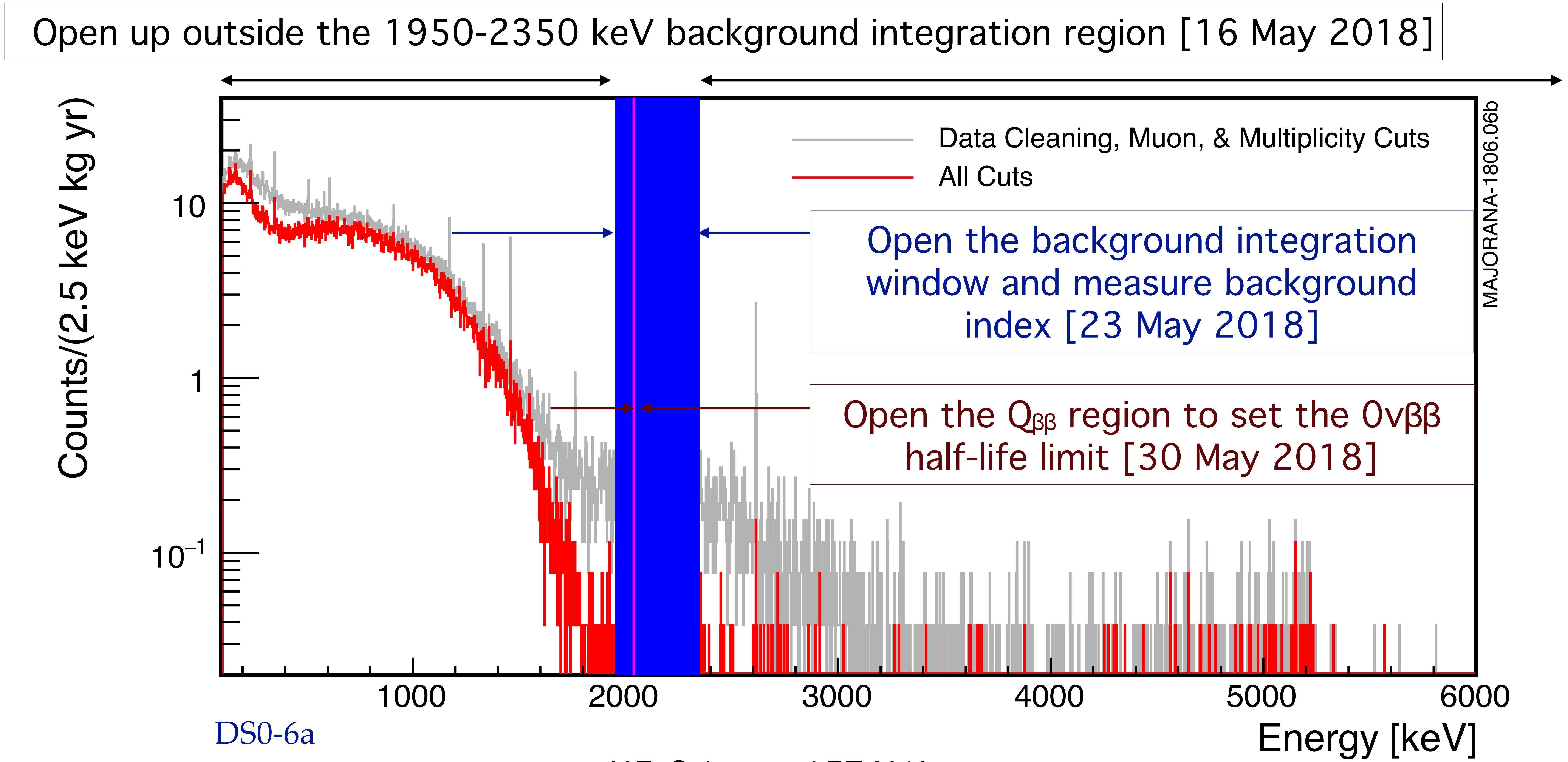
# Blindness Implementation

Data is split for statistical blindness:

Each 31 hours of open data is followed by 93 hours of completely blind data

Unblinding in phases to perform data quality and consistency checks

(<100 keV and multiple-detector events remain blind for other studies)

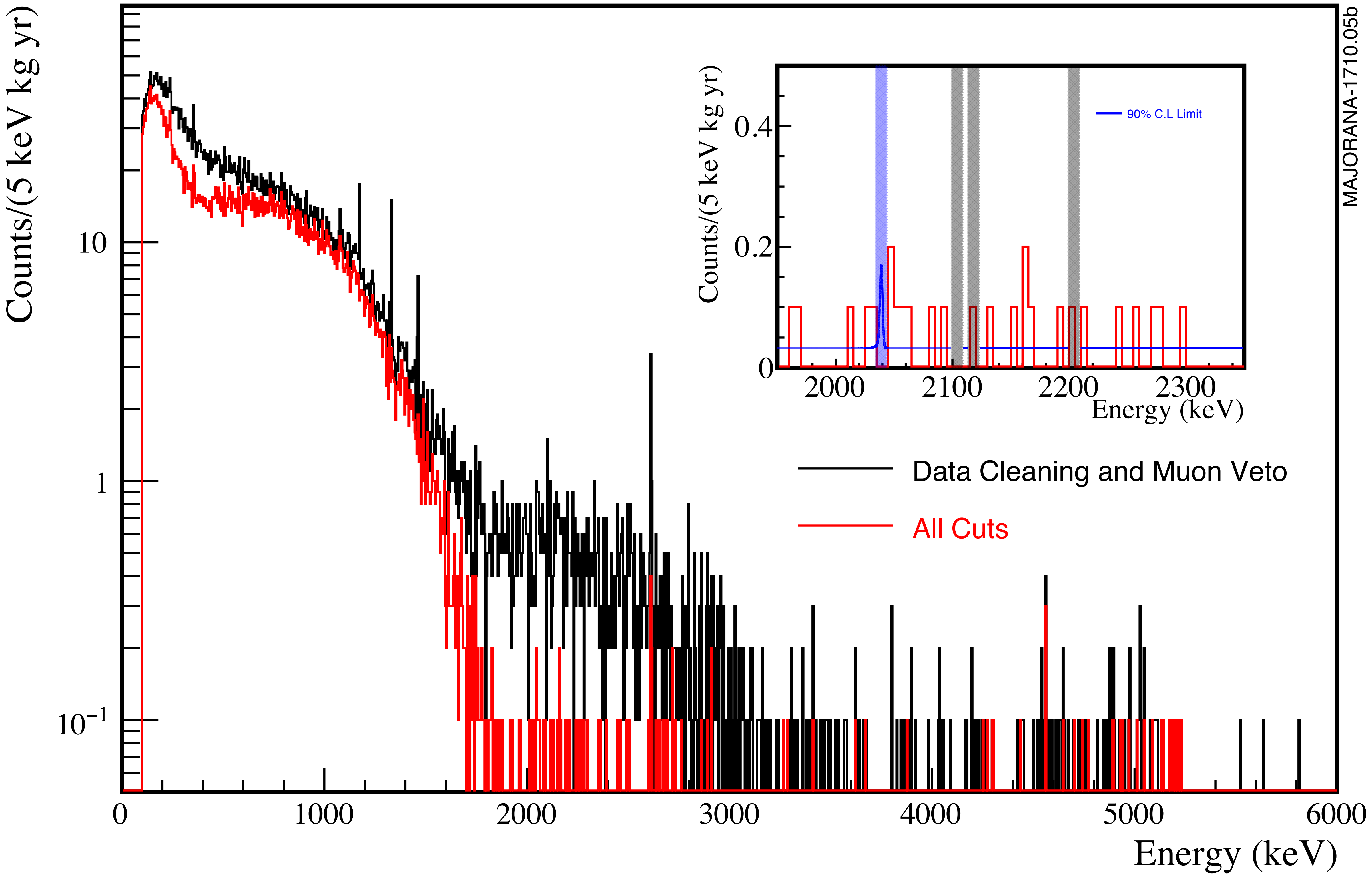


# 2017 0νββ Result

First result announced in Oct. 2017

Only open data: 9.95 kg-yr ($^{enr}Ge$)

arXiv:1710.11608; PRL **120** 132502 (2018)




Median Sensitivity:

$2.1 \times 10^{25}$ yr (90%CL)

Full Exposure Limit

$T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr (90% CL)

Full Exposure Background

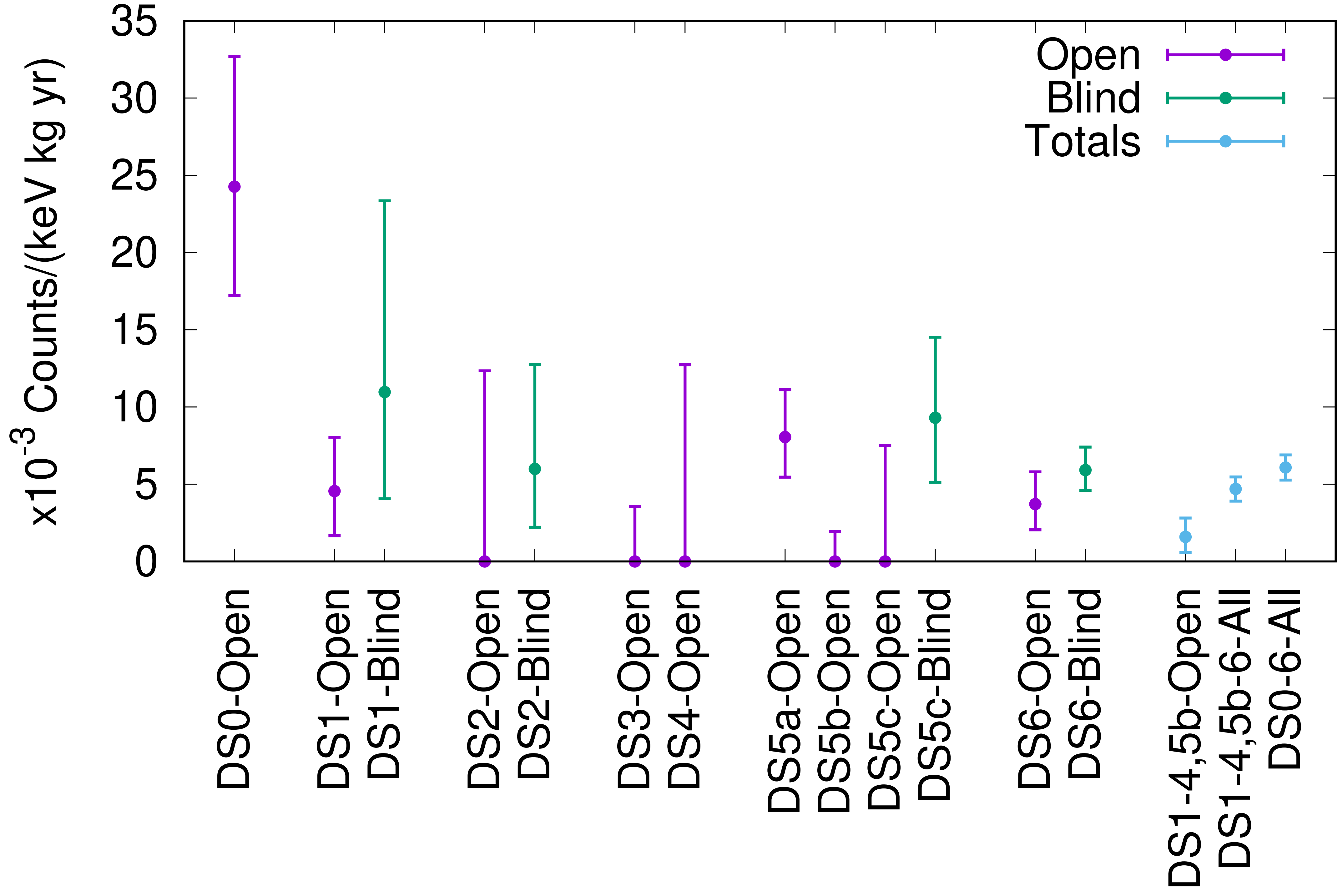
$17.8 \pm 3.6$ cts/(FWHM t yr)

Lowest background configuration

Active Exposure: 5.24 kg yr ($^{enr}Ge$)

Background rate: $4.0^{+3.1}_{-2.5}$ cts/(FWHM t yr); $1.6^{+1.2}_{-1.0} \times 10^{-3}$ counts/(keV kg yr)

# Background Index




| | **Lowest Background Configuration** | **Full Dataset** |
|---|---|---|
| 2017 Result | $1.6^{+1.2}_{-1.0} \times 10^{-3}$ cts/(keV kg yr) | $6.7 \pm 1.4$ cts/(keV kg yr) |
| [PRL **120** 132502 (2018)] | $4.0^{+3.1}_{-2.5}$ cts/(FWHM t yr) | $17.8 \pm 3.6$ cts/(FWHM t yr) |
| 2018 Result | $4.7 \pm 0.8 \times 10^{-3}$ cts/(keV kg yr) | $6.1 \pm 0.8 \times 10^{-3}$ cts/(keV kg yr) |
| | $11.9 \pm 2.0$ cts/(FWHM t yr) | $15.4 \pm 2.0$ cts/(FWHM t yr) |

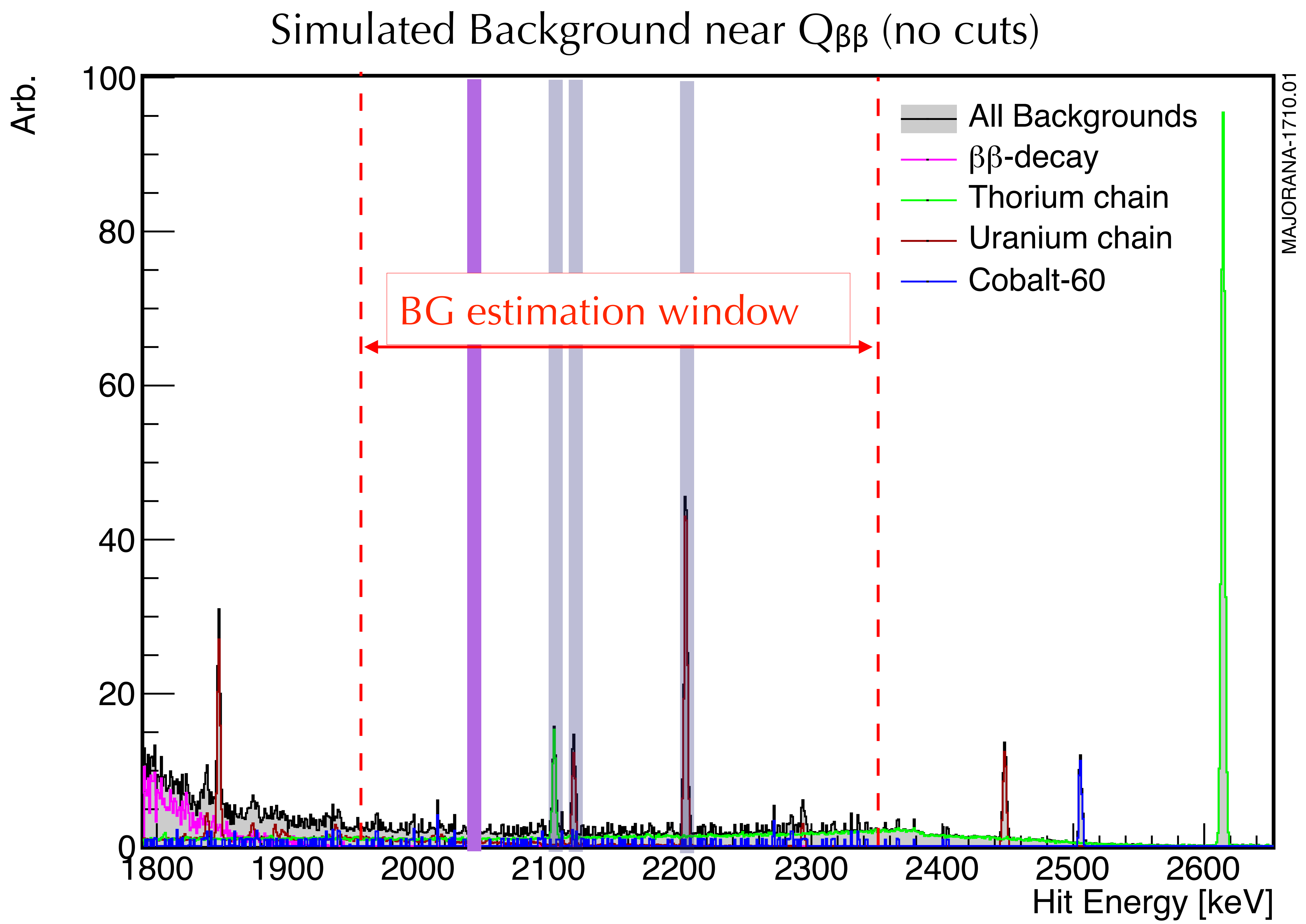
# 360 keV Background Integration Window

Simulated background PDFs, relative scaling based on assay results

Flat between 1950 keV and 2350 keV

- Remove ±5 keV around $Q_{\beta\beta}$ and prominent γ lines

Use counts in this window to estimate background level at $Q_{\beta\beta}$




Exclude:
2099 - 2109 keV
2113 - 2123 keV
2199 - 2209 keV

2034 - 2044 keV
$Q_{\beta\beta}$ = 2039 keV

# $^{76}$Ge Processing

Dedicated facility in Oak Ridge to reduce the $GeO_2$, zone refine the reduced metal, and recovery the scrap germanium. NIMA **877,** 314 (2018)

Reduction and Zone Refining

- 98.3% yield of >47 Ω-cm Ge from 42.5 kg of $^{enr}$Ge (60.4 kg GeO2)

ORTEC produced 35 $^{enr}$Ge detectors of total mass 29.7 kg

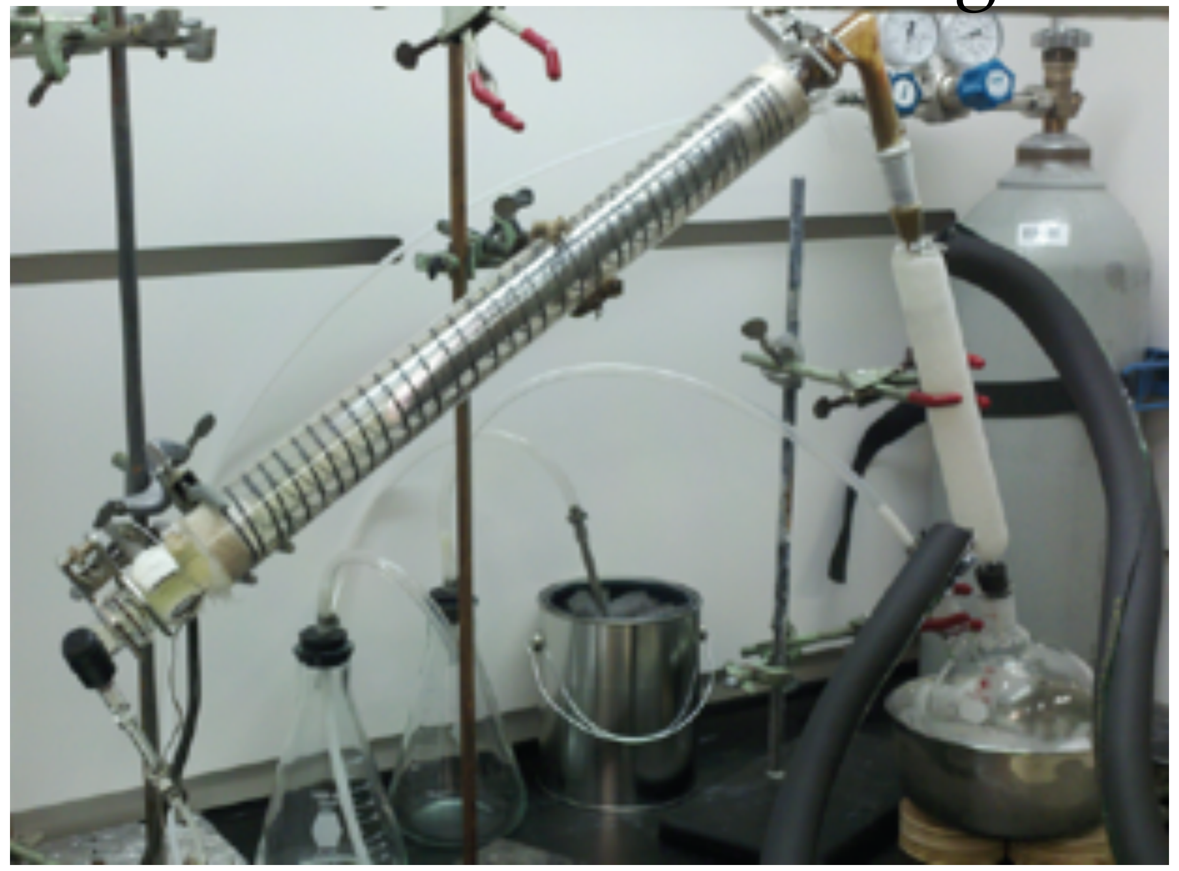
- Includes material recovered by our team

Final yield of detectors is 70% (with R&D showing up to 85% is possible)

- Best to date

Material stored and transported shielded from cosmic rays

Ge reduced in Chlorine gas



Zone Refining of Ge Metal