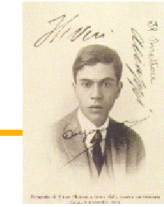

# Contamination Control and Assay Results for the MAJORANA DEMONSTRATOR Ultra Clean Components

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*For the **MAJORANA DEMONSTRATOR** Collaboration*

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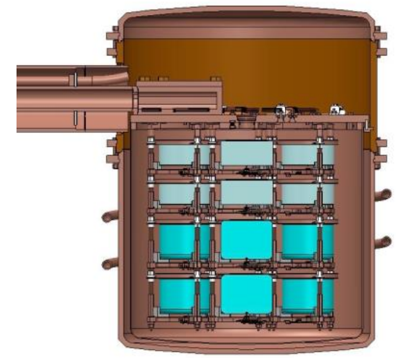
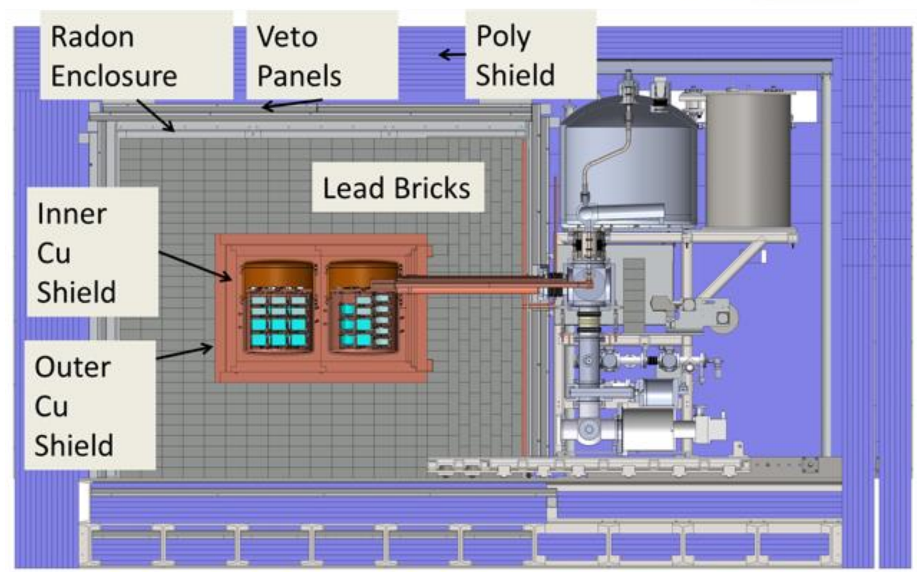
# The MAJORANA DEMONSTRATOR

Funded by DOE Office of Nuclear Physics and NSF Particle Astrophysics,
with additional contributions from international collaborators.

**Goals:** - Demonstrate backgrounds low enough to justify building a tonne scale experiment.
- Establish feasibility to construct & field modular arrays of Ge detectors.
- Searches for additional physics beyond the standard model.

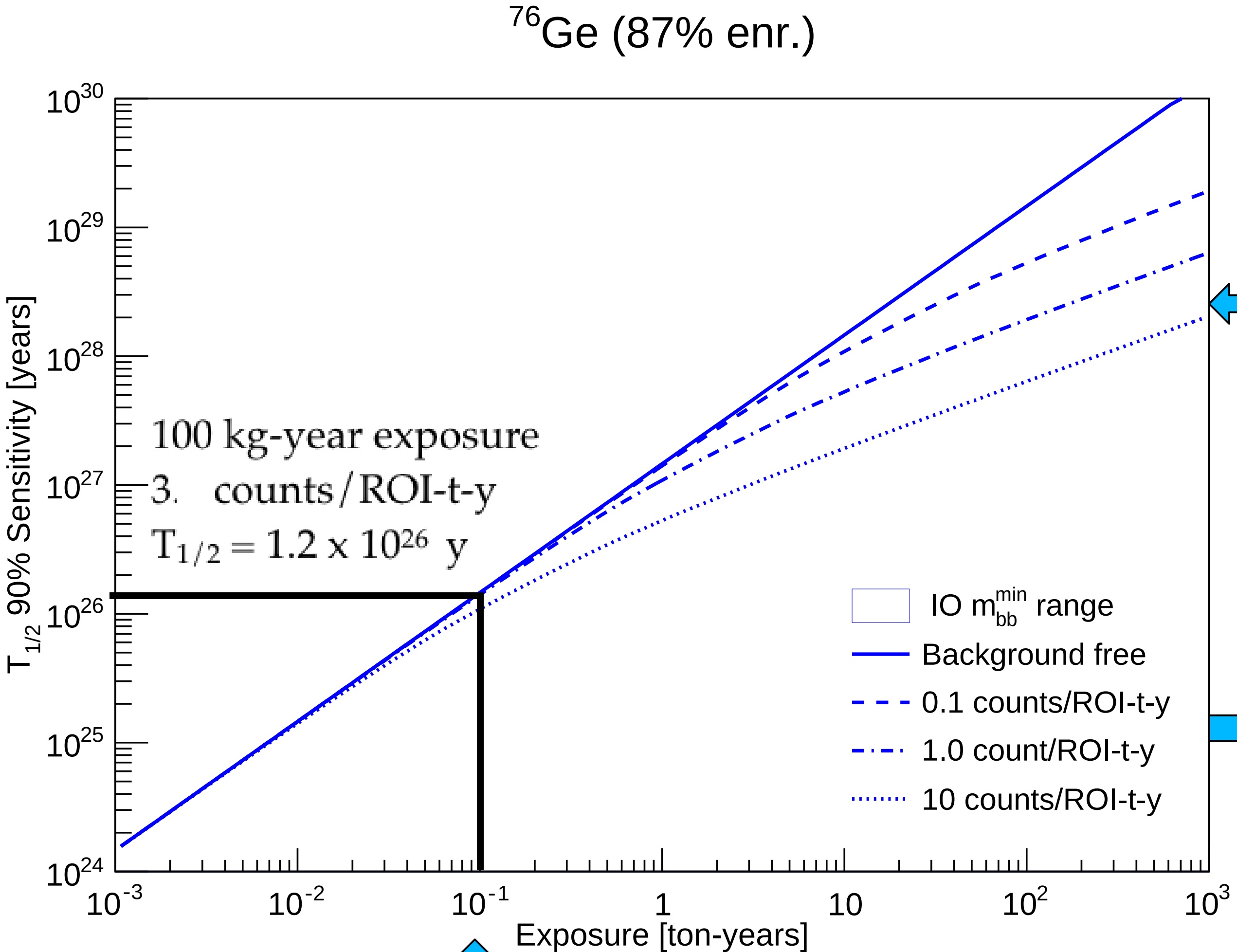


- **Located underground at 4850' Sanford Underground Research Facility**
- **Background Goal in the $0\nu\beta\beta$ peak region of interest (4 keV at 2039 keV)**
  **3 counts/ROI/t/y** (after analysis cuts) **Assay U.L. currently ≤ 3.5**
  *scales to 1 count/ROI/t/y for a tonne experiment*
- **44.1-kg of Ge detectors**
  –29.7 kg of 88% enriched $^{76}$Ge crystals
  –14.4 kg of $^{nat}$Ge
  –Detector Technology: P-type, point-contact.
- **2 independent cryostats**
  –ultra-clean, electroformed Cu
  –22 kg of detectors per cryostat
  –naturally scalable
- **Compact Shield**
  –low-background passive Cu and Pb shield with active muon veto




[N. Abgrall et al. Advances in High Energy Physics **2014**, 365432 (2014)]

# Motivation to Improve Backgrounds




Higher backgrounds significantly reduce the sensitivity *at the tonne-scale*

Background goal for the DEMONSTRATOR

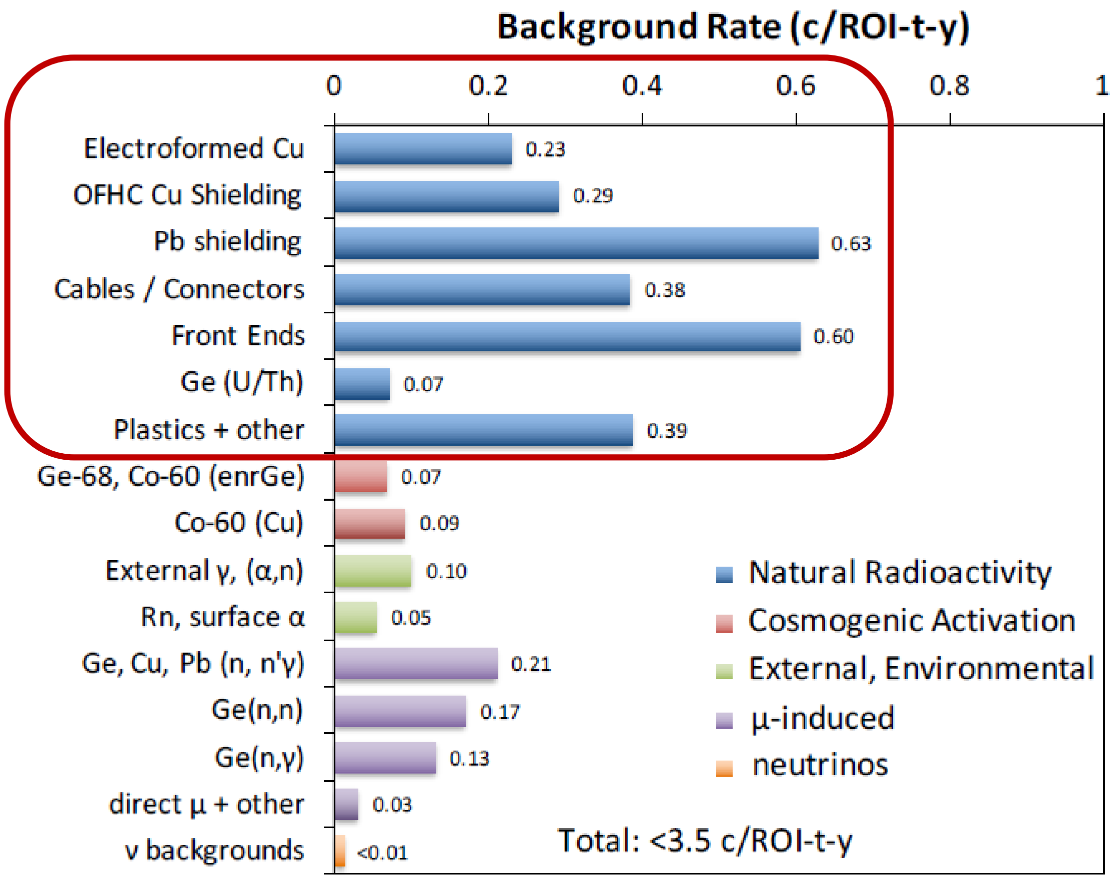
*Study and improve background rejection,* ***including contamination control***

# Background Budget

Projected background budget based on simulations and assay data [NIM A828 (2016) 22]

Must maintain the level of natural radioactivity measured by assay

***Requires strict cleaning and contamination control During fabrication and assembly***




When upper limit, use upper limit value as contribution

# Material Assay Properties

- Assay of samples from all materials used in the DEMONSTRATOR.
  - Radiometric, NAA, & ICP-MS techniques.
- By necessity have developed world's most sensitive ICP-MS based assay techniques at PNNL for U and Th in Cu and plastics

  (Original MJD Goal : <0.3 µBq/kg for U and Th)
  - MDL (method detection limits) with iridium anode improvements and ion exchange copper sample preparation
  - (Nuclear Instruments and Methods in Physics Research A828(2016)22–36)
    - < 0.017 ± 0.03 pg $^{238}$U/gCu
    - < 0.011 ± 0.05 pg $^{232}$Th/gCu

| | | | | | |
|---|---|---|---|---|---|
| Reportable Values | | | | | |
| | | Th-232 (µBq/kg Cu) | | U-238 (µBq/kg Cu) | |
| **Sample Name** | Stock Material | Measured Value | +/- 1s | Measured Value | +/- 1s |
| **P34MQ** | HMXIX Run 1 | <0.118 | | 0.120 | 0.040 |
| **P36CD** | HMXIII Run 1 | <0.118 | | <0.104 | |
| **P36CG** | HMXIII Run 1 | <0.117 | | <0.104 | |
| **P34N9** | HMXIX Run 1 | <0.118 | | <0.104 | |
| **P3CPH-1** | LA1HM Run 2 | <0.113 | | <0.100 | |
| **P3CPH-2** | LA1HM Run 2 | <0.114 | | <0.101 | |

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17ppq ± 3 of U

11ppq ± 5 of Th

| | | | | | |
|---|---|---|---|---|---|
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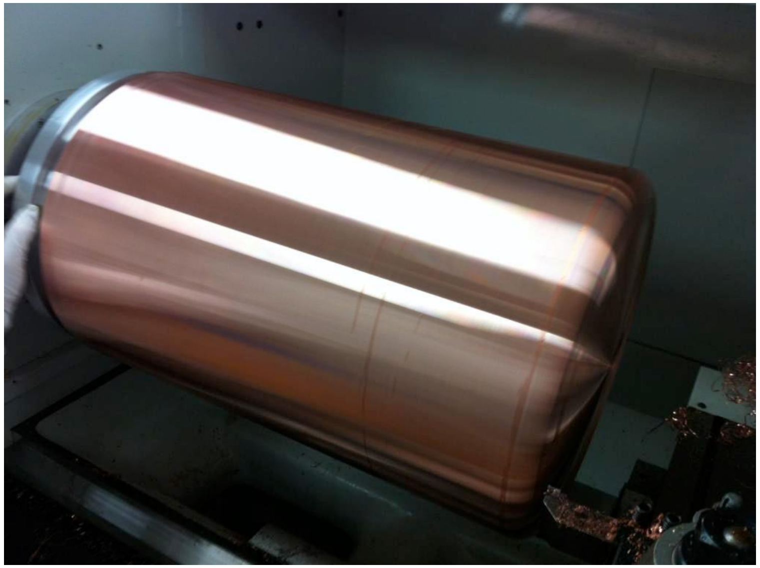
# Electroformed Cu (EFCu)

Cu is the key material for the Demonstrator:

- detector mounts
- Cryostats
- inner shielding

- *The Cu must be clean and remain clean*

- All MJD electroformed copper machined and cleaned in dedicated spaces

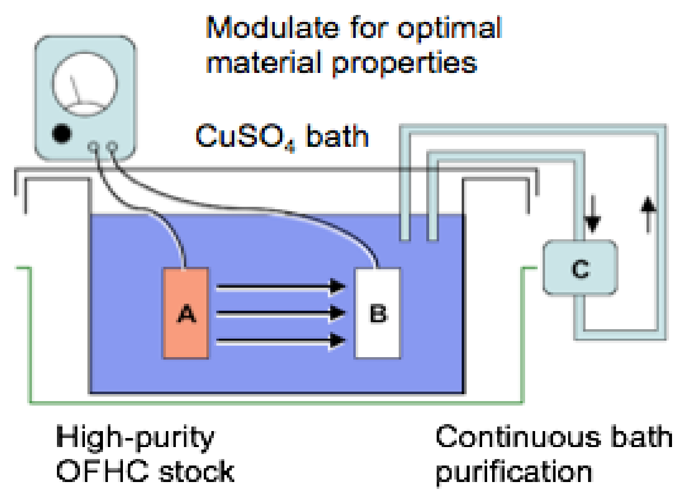


- Electroforming copper in a clean environment allows for the reduction of radioactive contaminants like U/Th while conducting the technique underground prevents cosmogenic activation of $^{60}$Co in Cu

- Th decay chain (ave) ≤ 0.1 μBq/kg
- U decay chain (ave) ≤ 0.1 μBq/kg

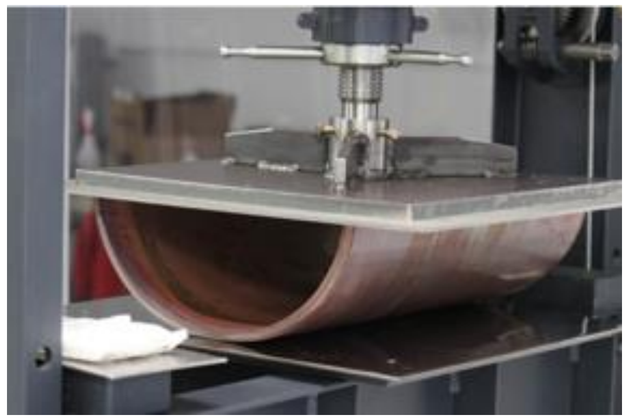
# Electroforming

- Electroplated onto 316 SS mandrels of various diameters up to 33 cm
- Operated 6 baths at the shallow UG site at PNNL and 10 at the Electroforming Lab (TCR) at the 4850’ of SURF from July 2011 - Apr. 2016
- TCR was constructed separate from main MJD laboratory (Davis Campus) at SURF allowing for 10 baths, each able to produce on the largest mandrel ~90 kg of Cu over the course of 14 months to a final thickness of 14 mm
- Average growth rate of 1 mm/month, or 0.033 mm/day
- Produced over 40 different mandrels and 2500 kg copper.



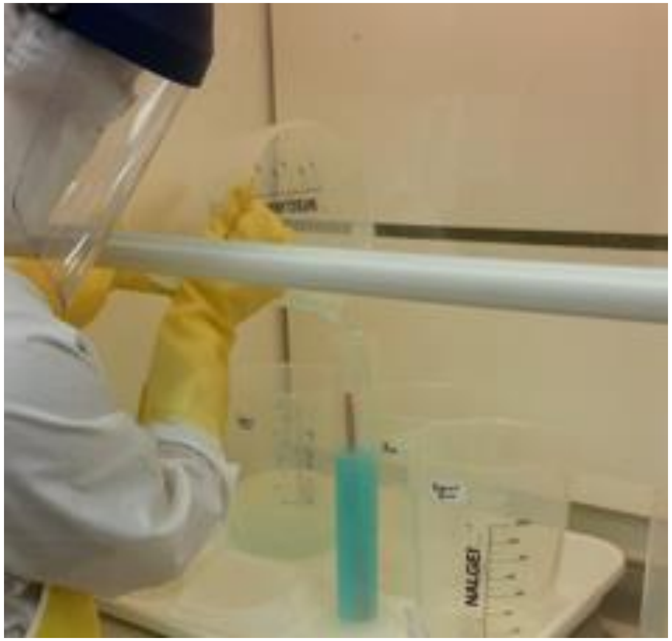
# Cu Production and Machining

- Clean machine shop adjacent to detector lab
  - Restricted to Cu, plastics, and approved stainless steel
  - Only clean, water-based cutting lubricants
  - All parts are uniquely tracked through machining, cleaning, and assembly by a custom-built database. [NIM **A779** (2015) 52] (PTDB mentioned yesterday)

# Cu Production and Machining

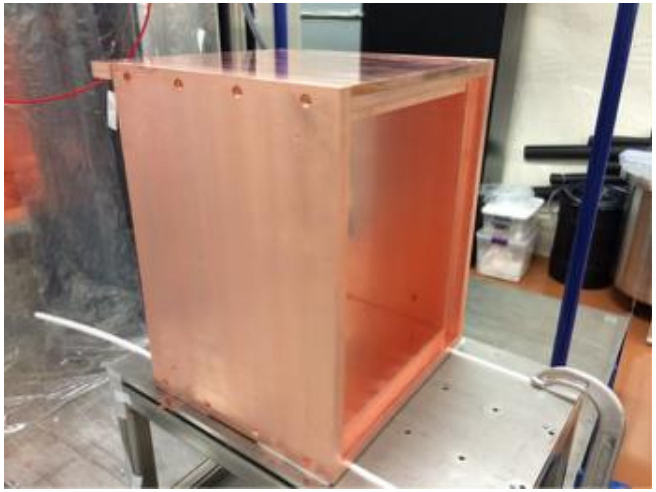
- Dedicated clean wet lab inside cleanroom for chemical etching



# Finished Cu Product Assay

- Initially established that the electroformed Cu stock met the radiopurity specifications of the DEMONSTRATOR.
- We understood we had to maintain an assay campaign to verify the finished parts remained pure
- The various handling conditions of each type of part introduce unique pathways for surface contamination of U/Th.
- Should contamination occur, we would be most sensitive to the large mass, large surface area components that surround the entire array:

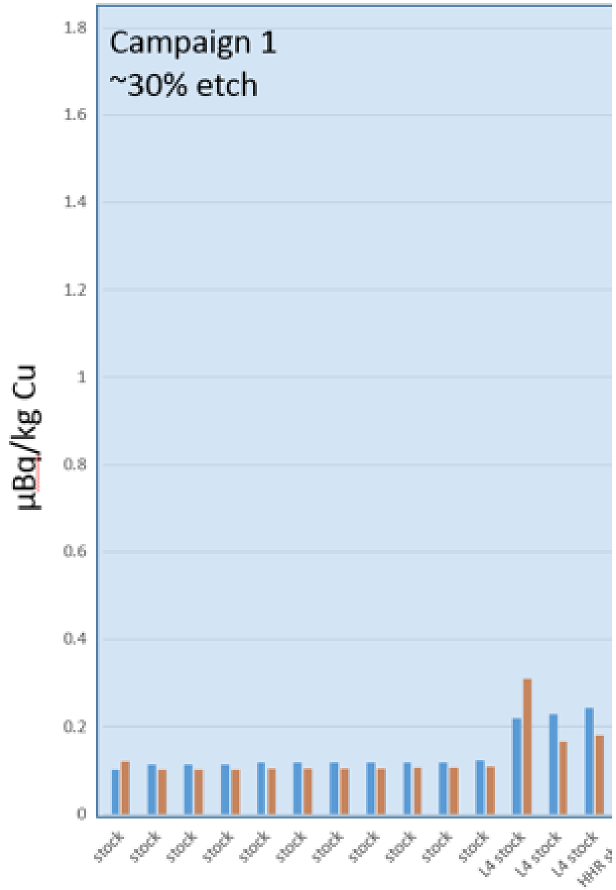
The inner Cu shield



The cryostat containing the Ge detectors

# EFCu Assay Campaign 1

- Minimal handling scenario, closest to bulk stock material
  - Cu samples pulled from normal DEMONSTRATOR production
  - Cu removed from mandrels and cut into test samples
  - Sent to PNNL, cleaned, rinsed, etched for 30% mass removal
  - Fully digest remaining part, assay the etchant

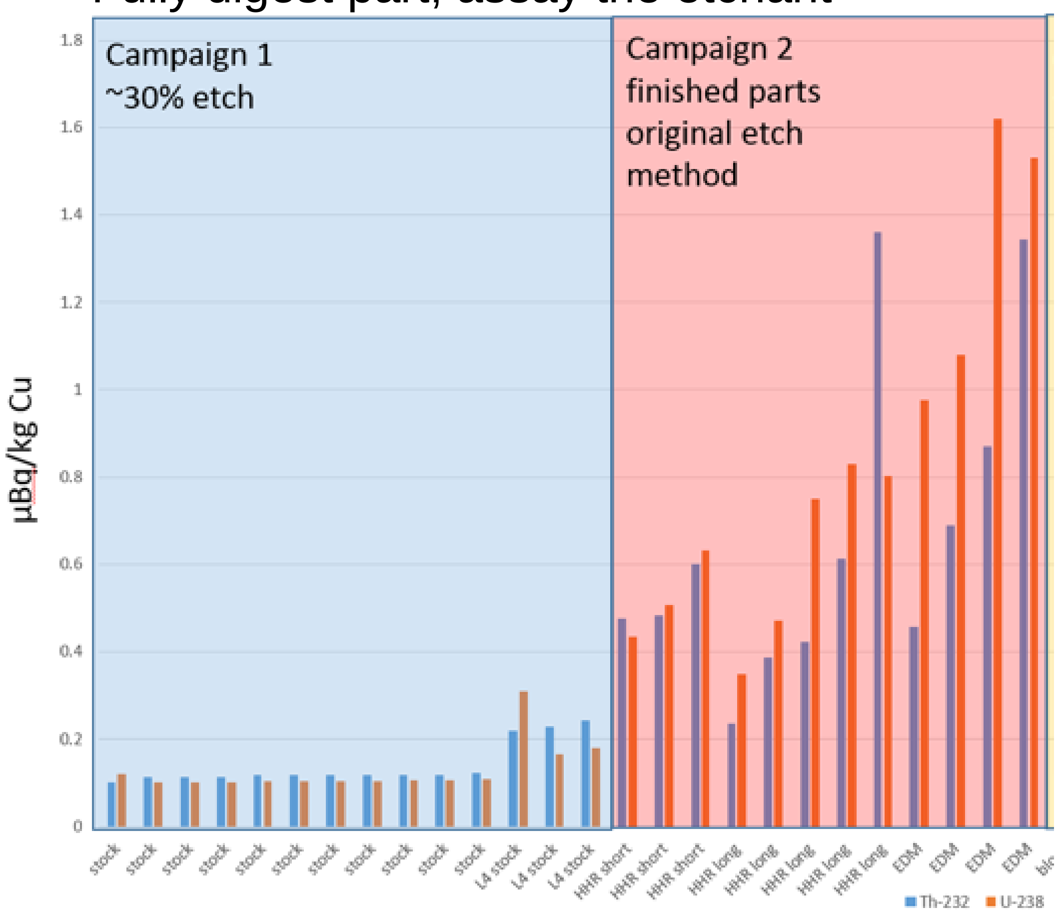



The assay results of the stock EFCu material are acceptable.

This is good!

# EFCu Assay Campaign 2

- More realistic handling scenario, more like an original finished part
  - Additional handing in the machine shop, more variety of tools
  - Standard etching procedure at SURF, dry $N_2$ storage
  - Sent to PNNL for assay, sample taken as is (no processing)
  - Fully digest part, assay the etchant




*Elevated surface contamination observed*

*Consequences for the* D*EMONSTRATOR depend on which components have this level of contamination*

*Results normalized per mass, but not all parts have same surface area to mass ratio*

*e.g. Results **not** acceptable for the inner Cu shield (which had not been processed yet!)*

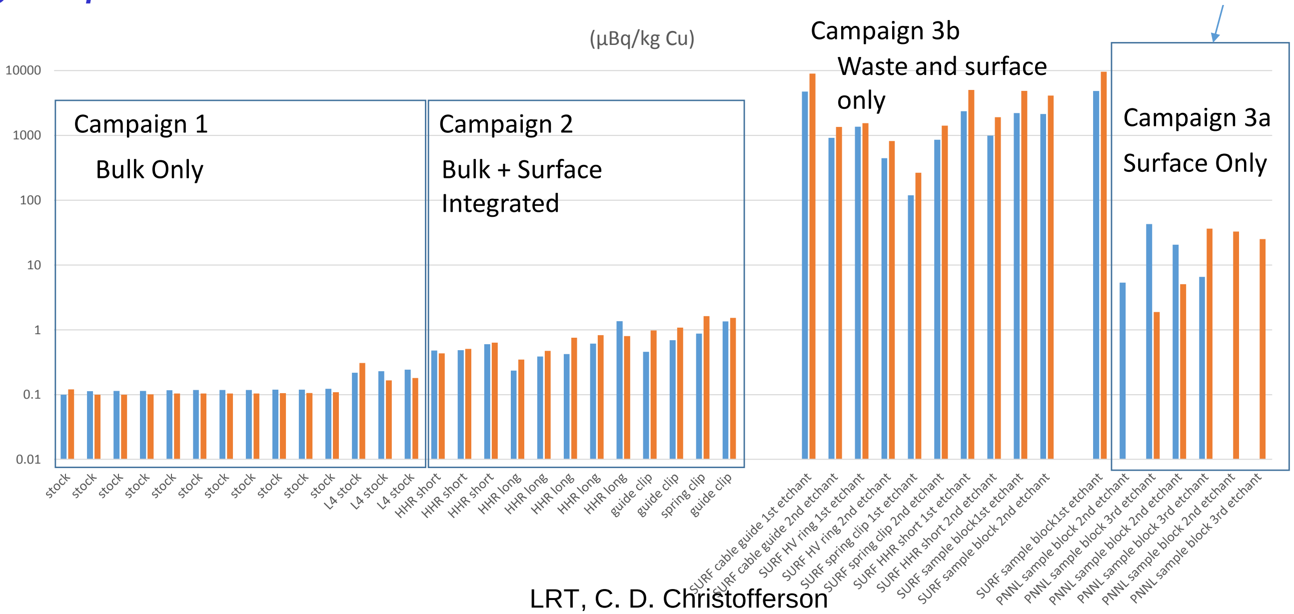
# EFCu Assay Campaign 3

- Two-part study to confirm the previous observations are a surface vs. bulk effect
  - Similar starting test samples
  - Part 3a: Additional *surface* etches at PNNL, assay etchants
  - Part 3b: Multiple standard/original etches at SURF, collect etchants, send to PNNL

Now only looking at the etchant left from surface etches (not full digestion of part)

*Observed even higher assay levels suggesting processing introduced all contaminants.*

*Extrapolating among the results of multiple etches gave a prediction for the necessary depth of Cu removal to remove surface contamination*

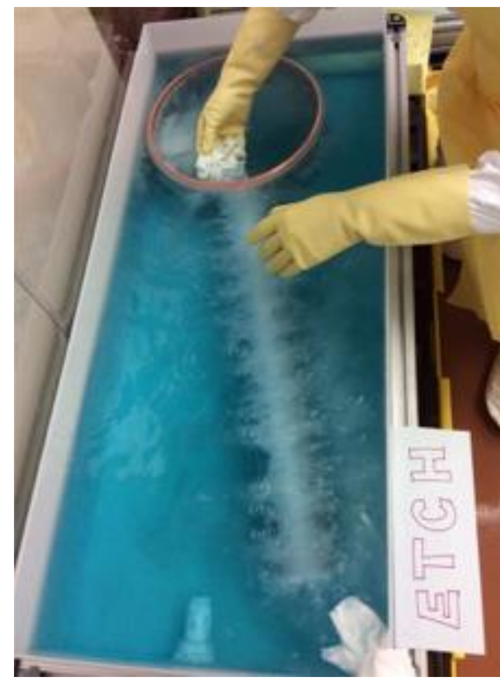


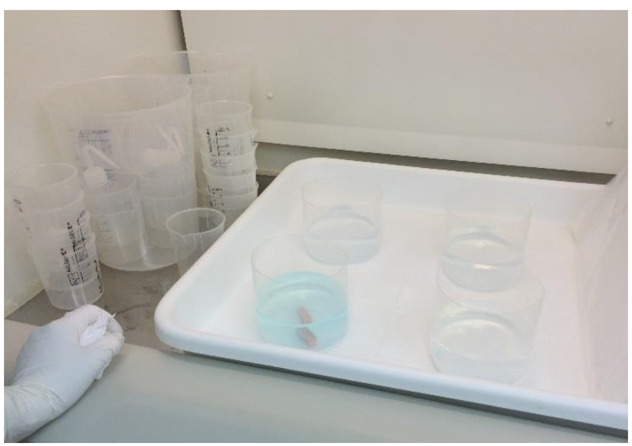
# Changes in the Process

- Changed from PNNL previous method the handling and process procedures based on results:
  - *New leached etching bins, unique beakers, brushes, etc.*
  - *New goal of a deeper etch depth yet no compromise to material properties*
  - *Calibration of the solutions before, during, after etching to witness and confirm etching efficiency along with control of µm copper removed.*
  - *Detailed handling requirements at each step to avoid cross contamination, additional QA requirements.*

Timing implications:

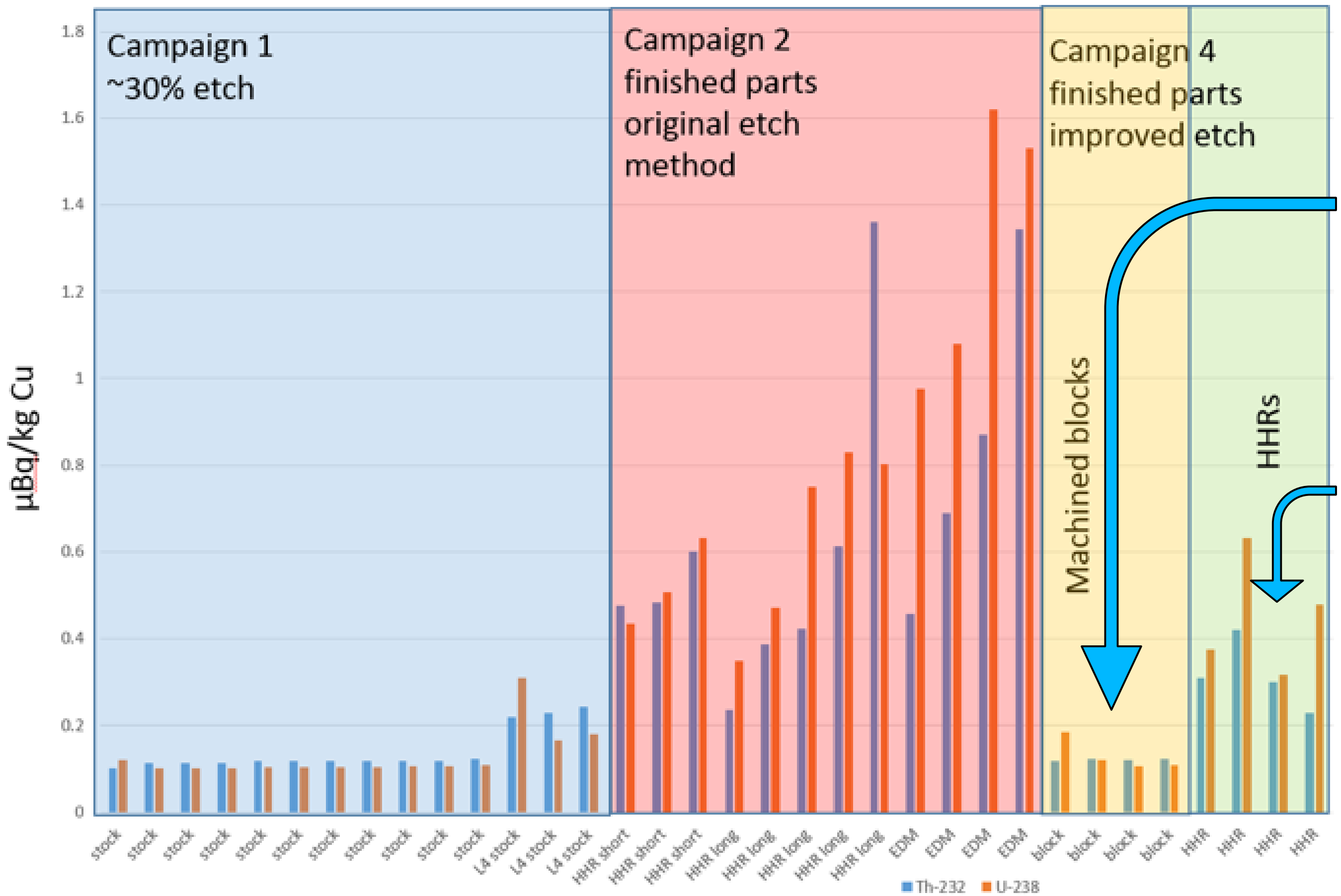
- Module 1 parts complete and assembled
- Inner Cu shield will use the new process
- Module 2 parts will use the new process



# EFCu Assay Campaign 4

- Improved handling and processing
  - Started with *Machined blocks* [proxy for shield plates - low area/mass ratio] and *Hollow Hex Rods* (HHRs) [a detector/string component with high area/mass ratio]
  - New etching process & deeper etch at SURF, full digestion assay at PNNL




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

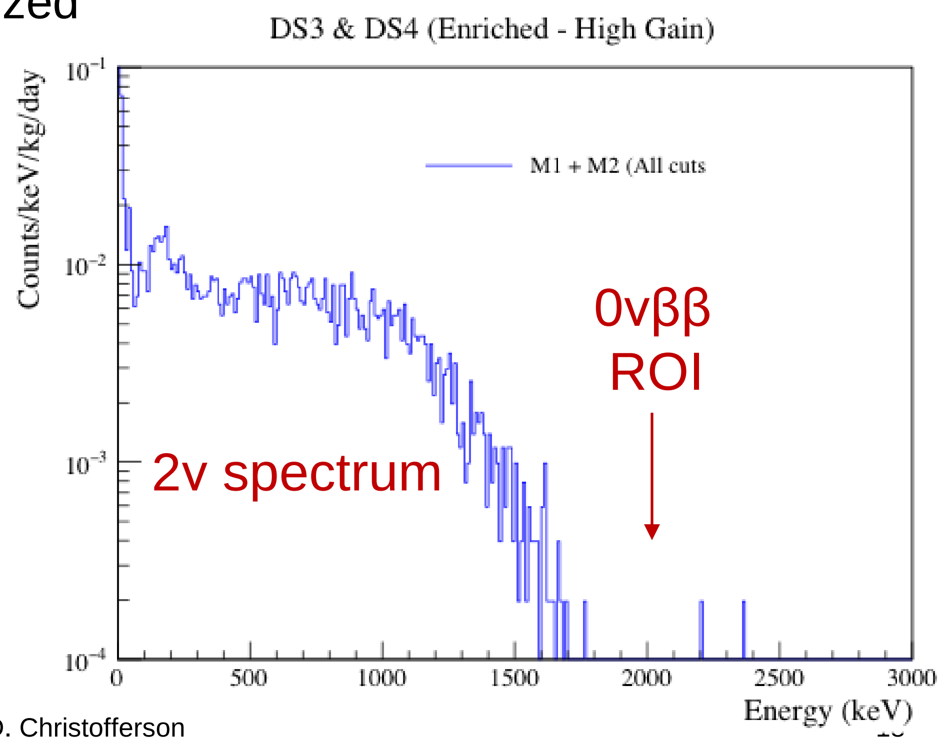
*Detector mounting components also improved, but still acceptable*

# Effect on the DEMONSTRATOR

- The MAJORANA DEMONSTRATOR is taking data in phases called *Data Sets*
- Data Set 3 & 4
  - *Latest public release*
  - Exposure: 1.39 kg/y
  - After cuts, 1 count in 400 keV window centered at 2039 keV (0νββ peak)
  - Projected background rate is **5.1 $^{+8.9}_{-3.2}$ c/(ROI t y)** for a 2.9 (M1) & 2.6 (M2) keV ROI (68% CL)
  - Background index **1.8 x 10$^{-3}$ c/(keV kg yr)**
  - Analysis cuts are still being optimized

Consistent with our expectation of 3.5 c/(ROI t y) based on assays and simulations.

The overall handling and processing of the electroformed Cu appears acceptable.



# Summary

Building on the success of many low background programs and experiments, the MAJORANA DEMONSTRATOR has achieved:

- The successful production of ultra-pure underground electroforming Cu
- An effective initial procedure to handle and process materials to control the surface U/Th contamination of Cu parts
- A parallel study to systematically evaluate the handling and processing procedure for the range of Cu components used
- An improved handling and processing procedure was developed and confirmed by ICP-MS assay data. Expect components to be a radiopurity levels consistent with the bulk stock material. (separate study for $^{210}$Po)
- The Demonstrator's initial backgrounds are amongst the lowest backgrounds in the ROI achieved to date (approaching GERDA's recent best value).
- Ongoing analysis of the current data (10 kg-years) as we continue to acquire more data, we will be able to make a quantitative statement on the backgrounds in Modules 1 and 2.