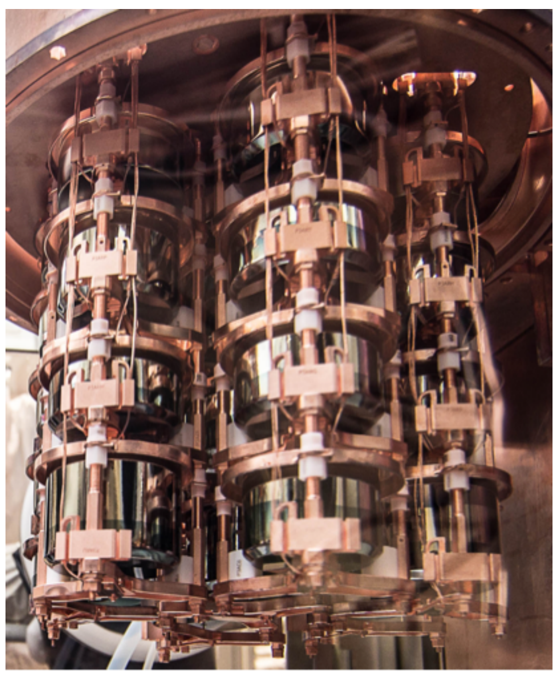
A Next-Generation ^{76}Ge $0\nu\beta\beta$ Experiment



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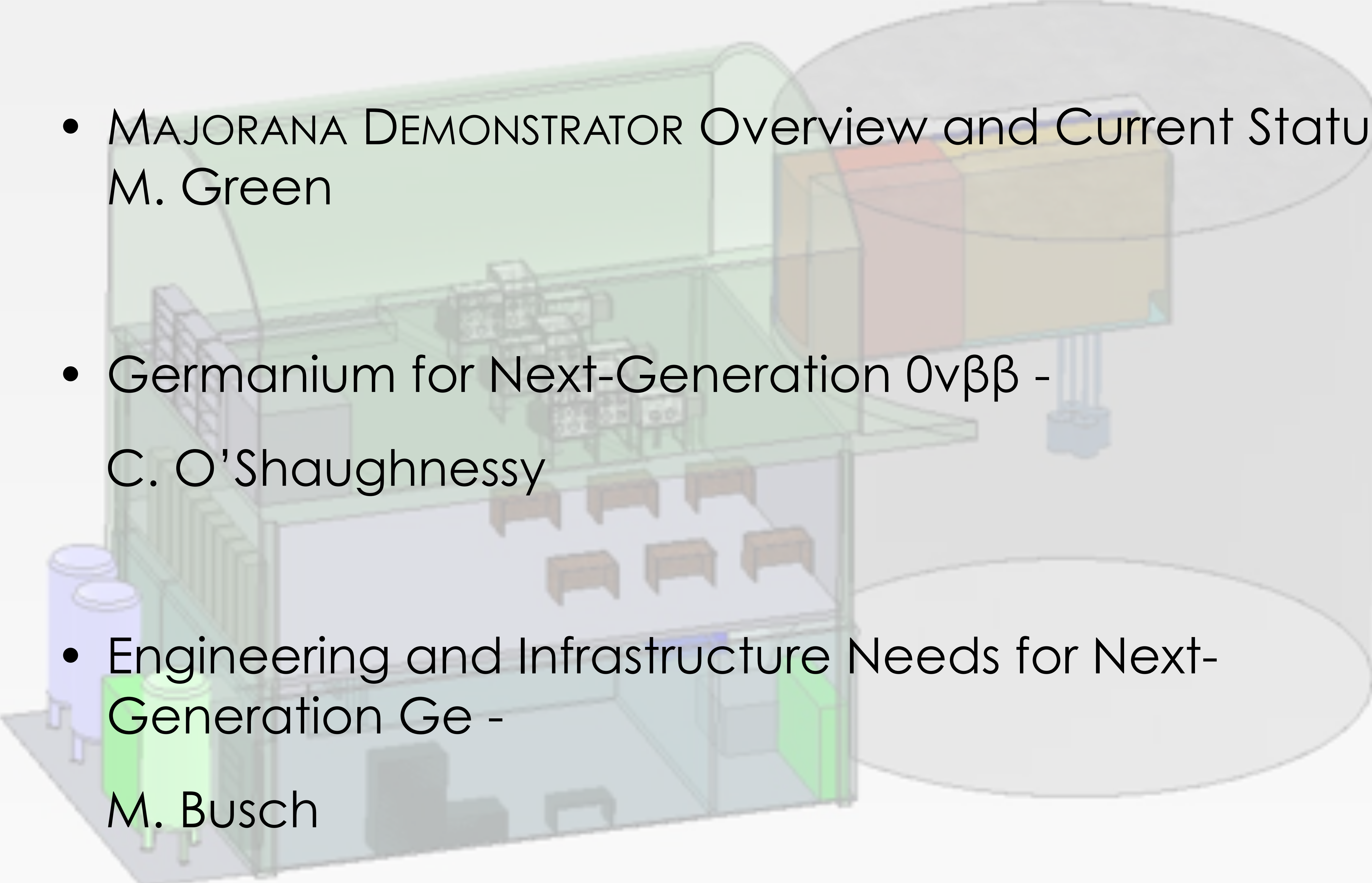
On behalf of the MAJORANA AND GERDA Collaborations

SNOLAB Future Planning Workshop
August 24, 2015

Outline



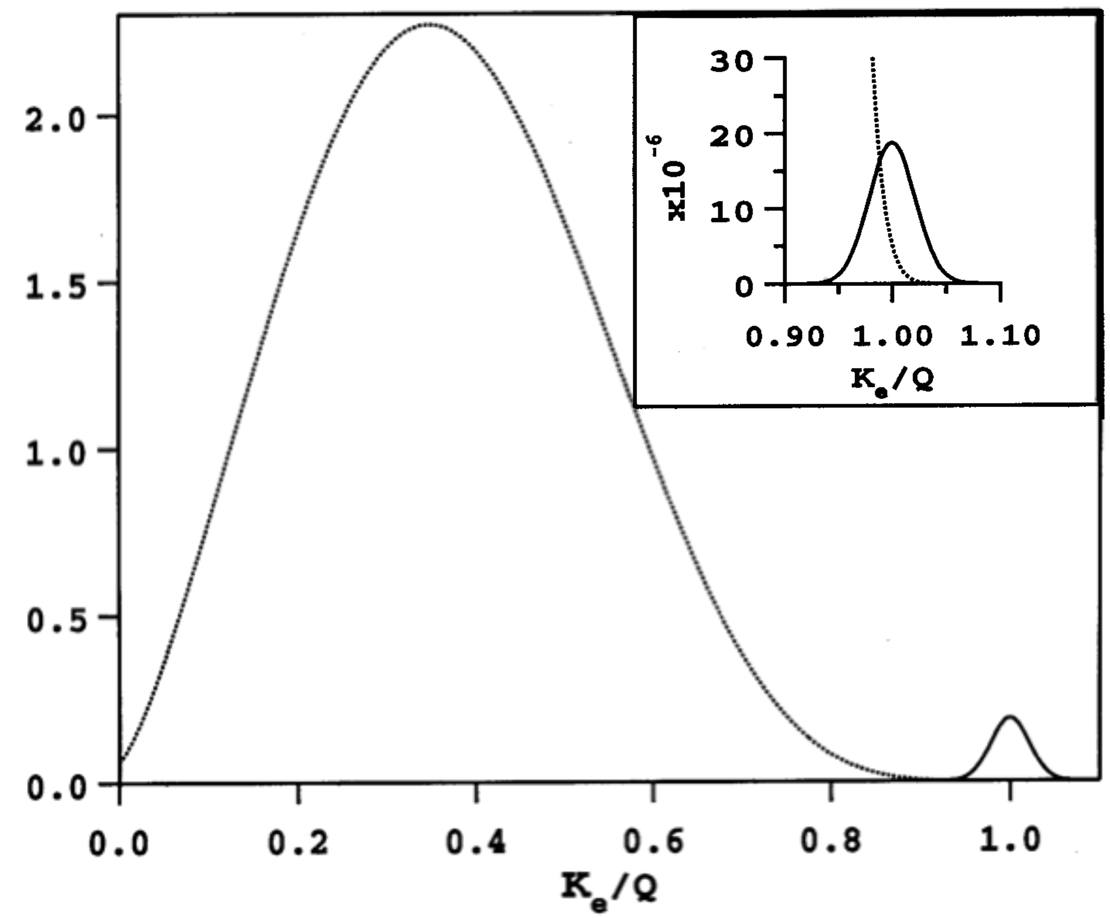
- Majorana Demonstrator Overview and Current Status - M. Green
- Germanium for Next-Generation 0νββ - C. O'Shaughnessy
- Engineering and Infrastructure Needs for Next-Generation Ge - M. Busch

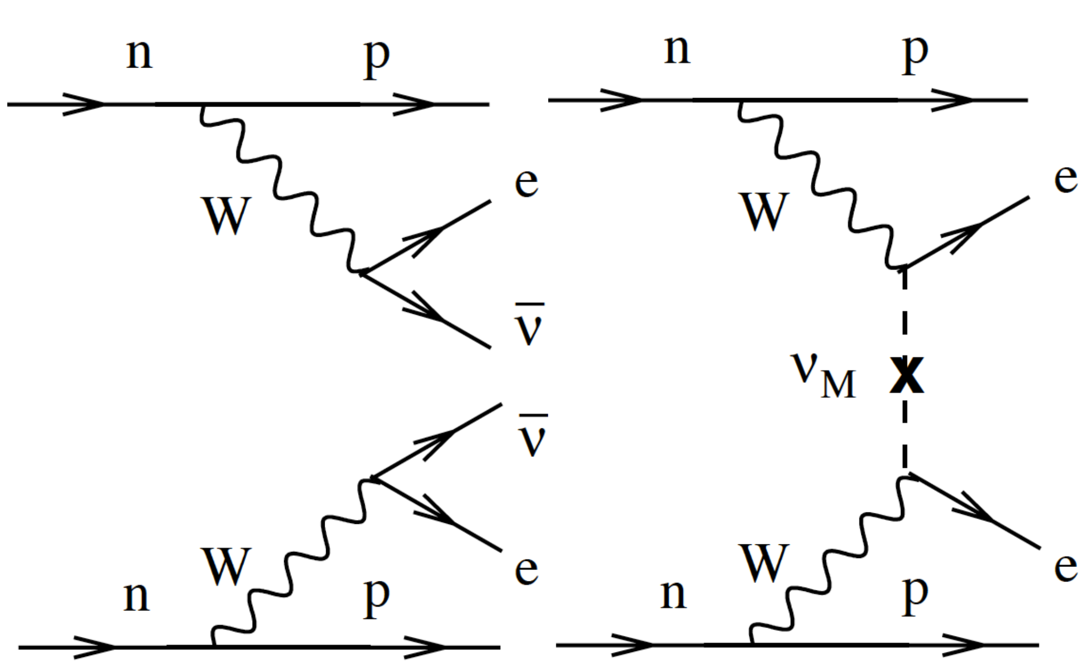
0νββ in a Slide

- 2nd-order weak interaction
- Requires ν = $\bar{\nu}$
- Lepton-number violating
- Example: virtual ν exchange

$$[T^{0\nu}_{1/2}]^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)\,|M_{0\nu}|^2\,\langle m_{\beta\beta}\rangle^2$$

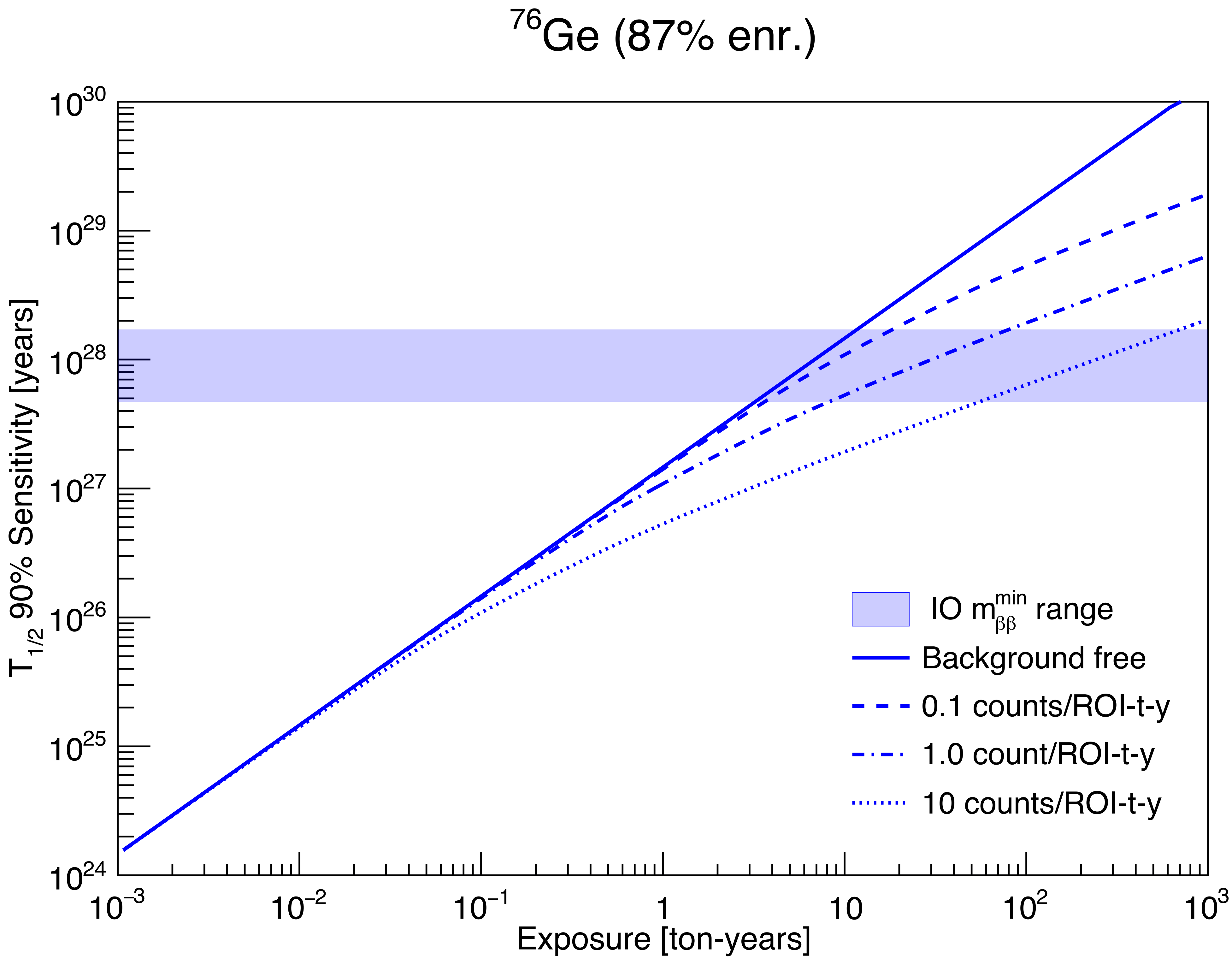
- Lifetime limits > 10^{25} yrs
- Experiments:
  - Maximize exposure (mass)
  - Minimize background





Sensitivity vs. Exposure ^{76}Ge

J. Detwiler



Inverted Ordering (IO)

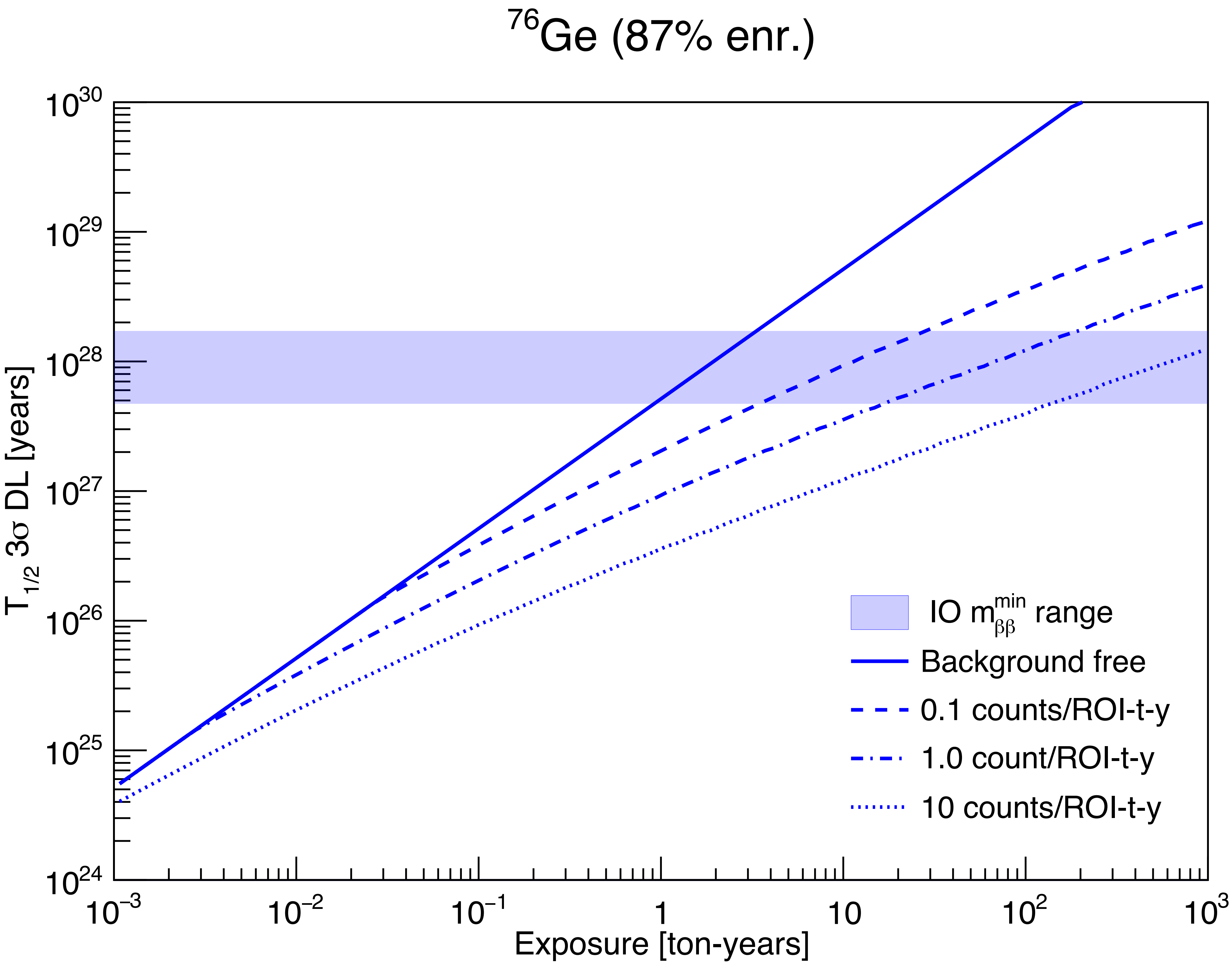
Minimum IO $m_{\beta\beta}$=18.3 meV, taken from using the PDG2013 central values of the oscillation parameters, and the most pessimistic NME for the corresponding isotope among QRPA, SM, IBM, PHFB, and EDF

Note : Region of Interest (ROI) can be single or multidimensional (E, spatial, …)

Assumes 75% efficiency based on GERDA Phase I. Enrichment level is accounted for in the exposure

3σ Discovery vs. Exposure for ^{76}Ge

J. Detwiler



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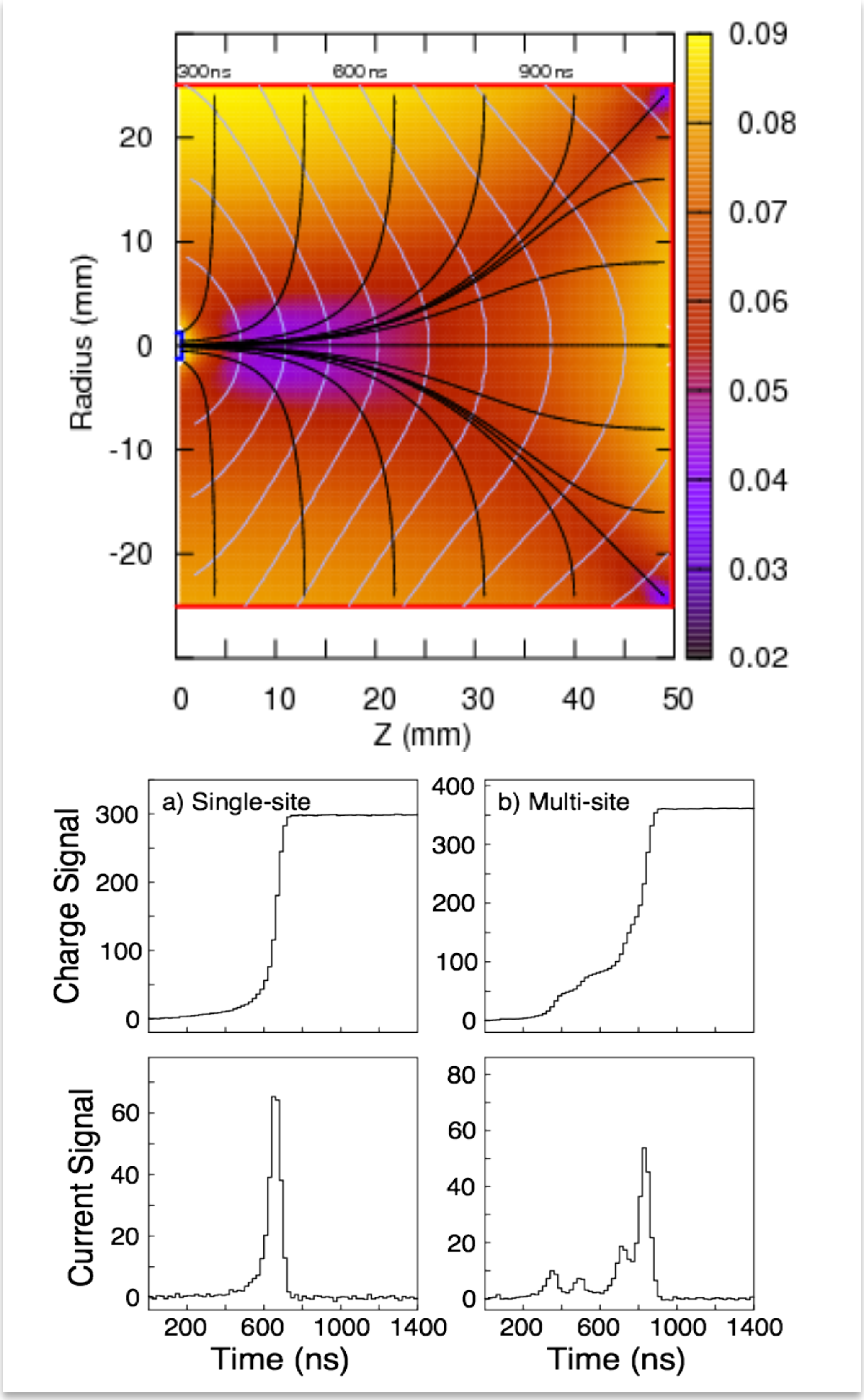
Note : Region of Interest (ROI) can be single or multidimensional (E, spatial, …)

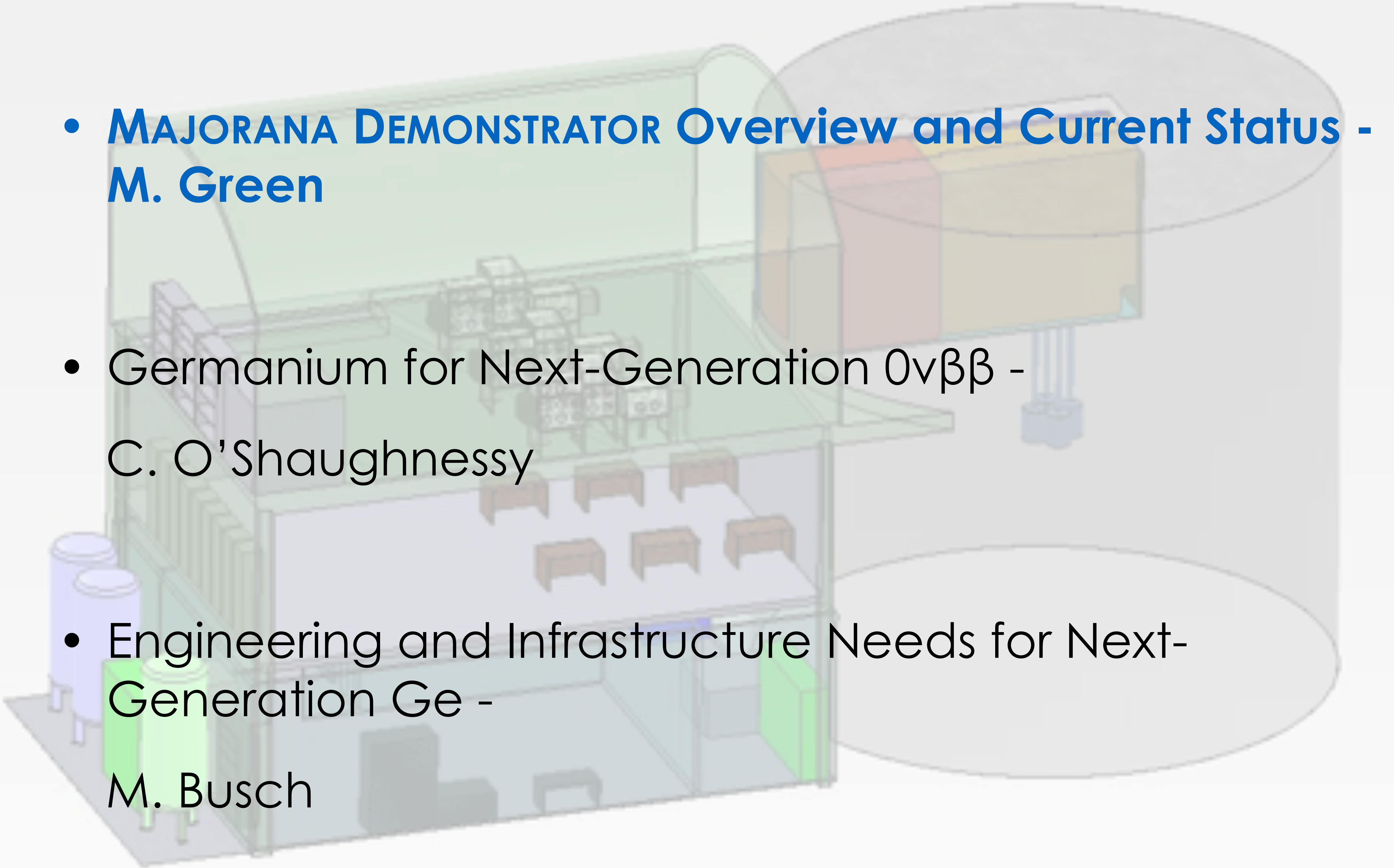
Assumes 75% efficiency based on GERDA Phase I. Enrichment level is accounted for in the exposure

Germanium for 0νββ

- Q_{val} = 2039keV
- Excellent energy resolution: <3keV FWHM @2039
- HPGe detectors inherently low-background
- Powerful background rejection techniques:
  - Granularity rejects compton scatters in multiple detectors
  - PPC timing response enables PSD of multi-site events
  - Low energy thresholds allow rejection of ^{68}Ge events



Outline



- **MAJORANA DEMONSTRATOR Overview and Current Status - M. Green**
- Germanium for Next-Generation 0νββ -

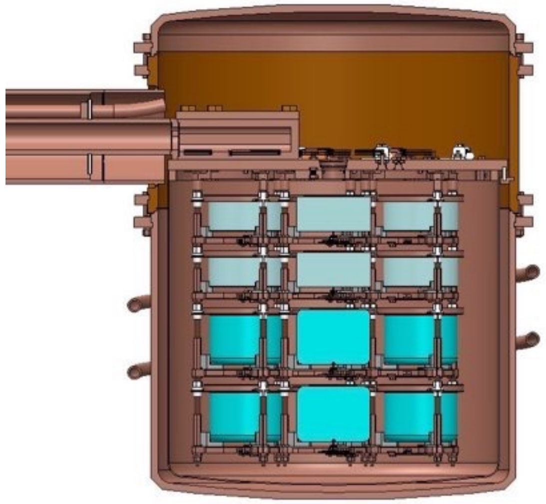
  C. O'Shaughnessy
- Engineering and Infrastructure Needs for Next-Generation Ge -

  M. Busch

The MAJORANA DEMONSTRATOR

Funded by DOE Office of Nuclear Physics and NSF Particle Astrophysics (Nuclear Physics)
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.

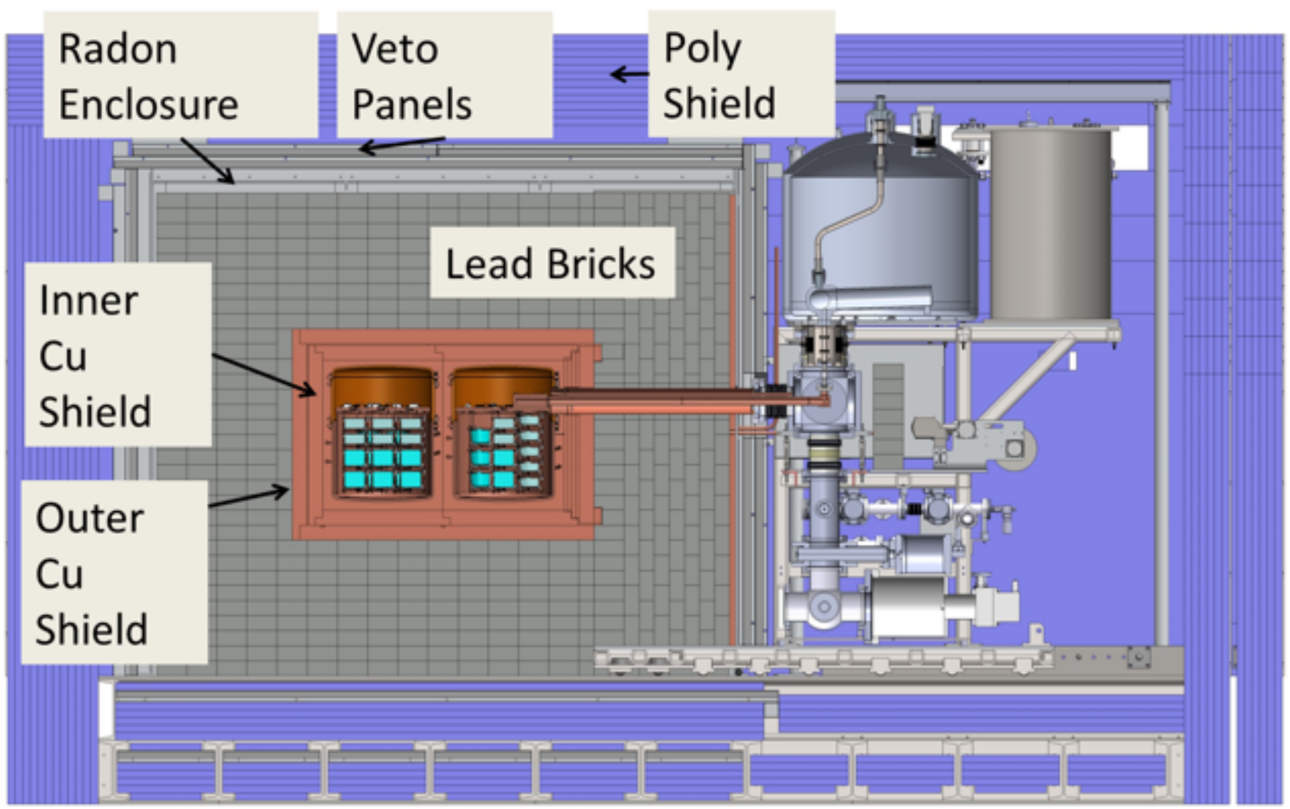


- **Located underground at 4850' Sanford Underground Research Facility**
- **Background Goal in the $0\nu\beta\beta$ peak region of interest (4 keV at 2039 keV)**

  3 counts/ROI-t-y (after analysis cuts) **Assay U.L. currently ≤ 3.5**

  scales to 1 count/ROI-t-y for a ton experiment

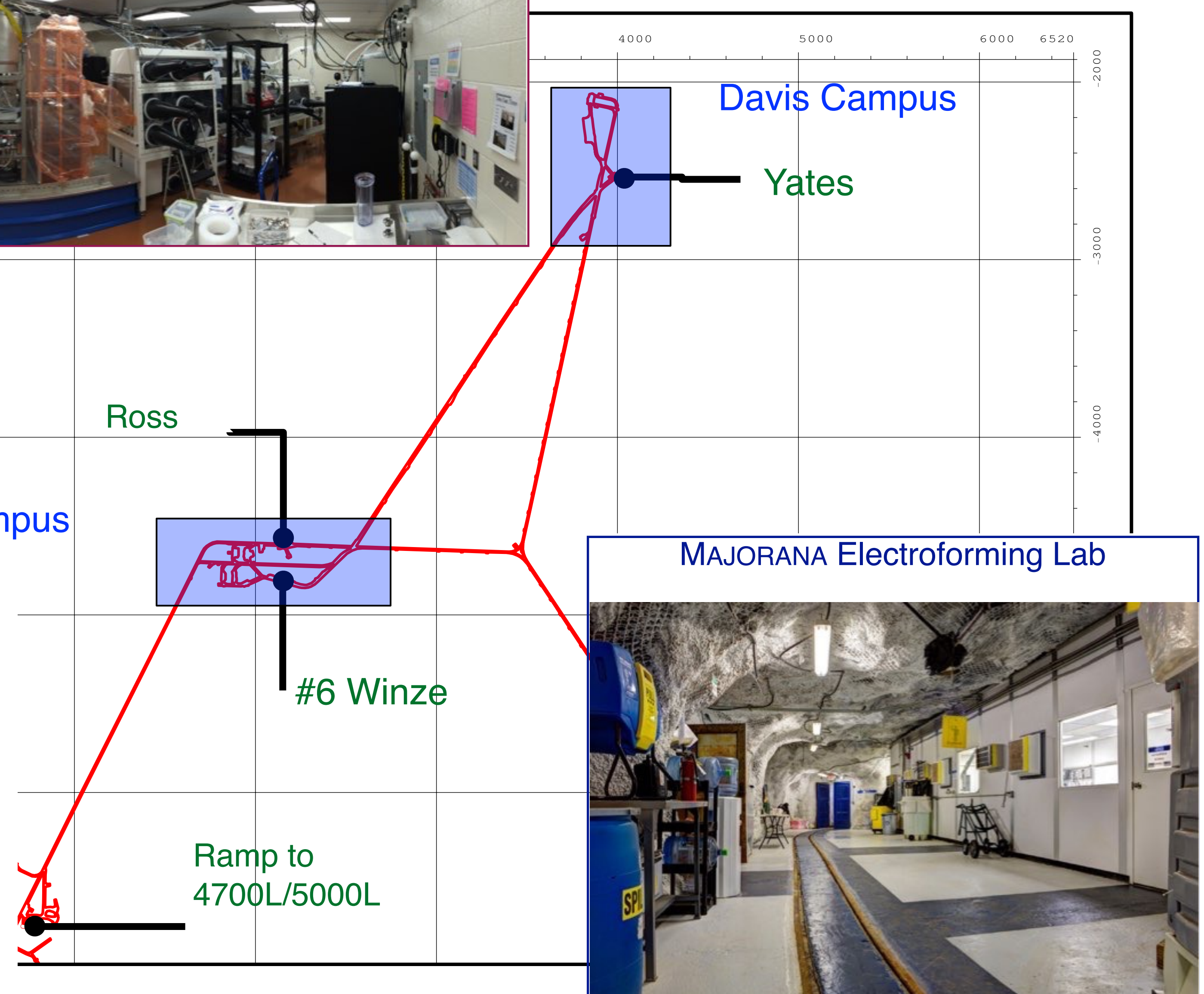
- **44.8 kg of Ge detectors**
  - 29.7 kg of 87% enriched ^{76}Ge crystals
  - 15.1 kg of ^{nat}Ge
  - Detectors: P-type, point-contact.
- **2 independent cryostats**
  - ultra-clean, electroformed Cu
  - 20 kg of detectors per cryostat
  - naturally scalable
- **Compact Shield**
  - low-background passive Cu and Pb shield with active muon veto



Deployment Location: SURF

- **MAJORANA UG site is Sanford Underground Research Laboratory**
  - Main MJD lab at 4850L Davis Campus, beneficial occupancy in Feb. 2012.
  - Operating Temporary Cleanroom Facility (TCR) at 4850L Ross Campus since Spring 2011.

MAJORANA Main Lab



MAJORANA Electroforming Lab

Typical Cleanliness Levels

(0.5 micron particles)

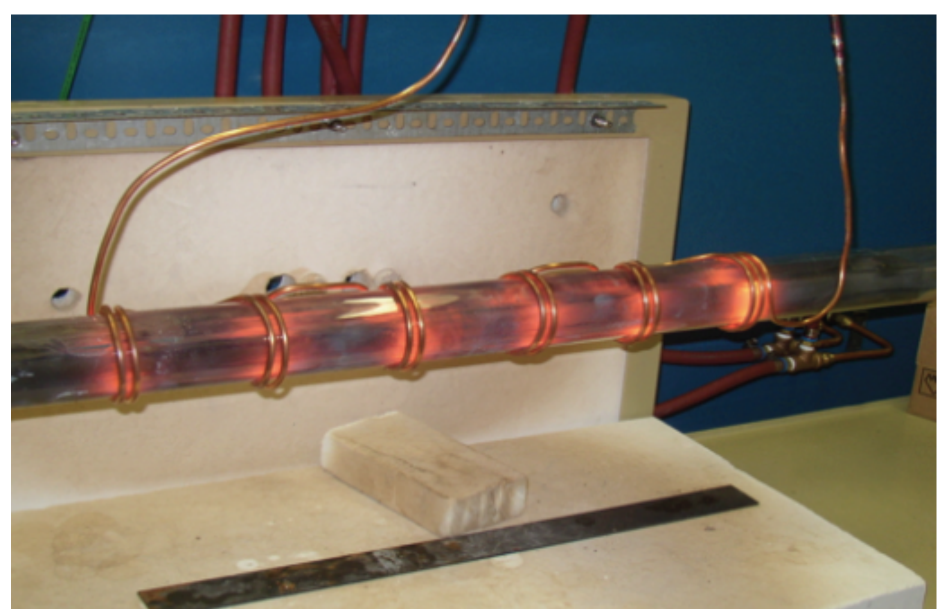
- Detector Lab
  - class 100-400
- Glove Box
  - class 10
- TCR (Electroforming)
  - class <1000

Ge Processing and Recovery

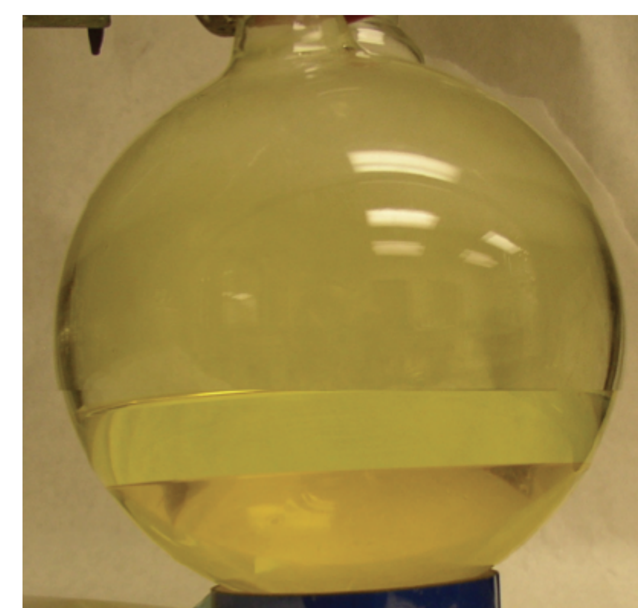
- Better than 98% yield from original 42.5-kg of ^{enr}Ge (61.7-kg of GeO_2)
- Recovered Ge from processing manufacturing waste
  - 8.4-kg of "scrap" reprocessed
    - 2.87 kg of metal from detector manufacturer reject.
    - 5.87 kg of Ge with ρ >47 Ohm-cm recovered from the manufacturing effluent and kurf.
  - Combined with 3.22 kg of remaining Ge material to yield 9.1 kg of Ge > 47 Ohm-cm
- Resulted in 74% yield of operating detectors, best to date for Ge experiments

Ge reduced in Chlorine gas

Zone refining of Ge metal

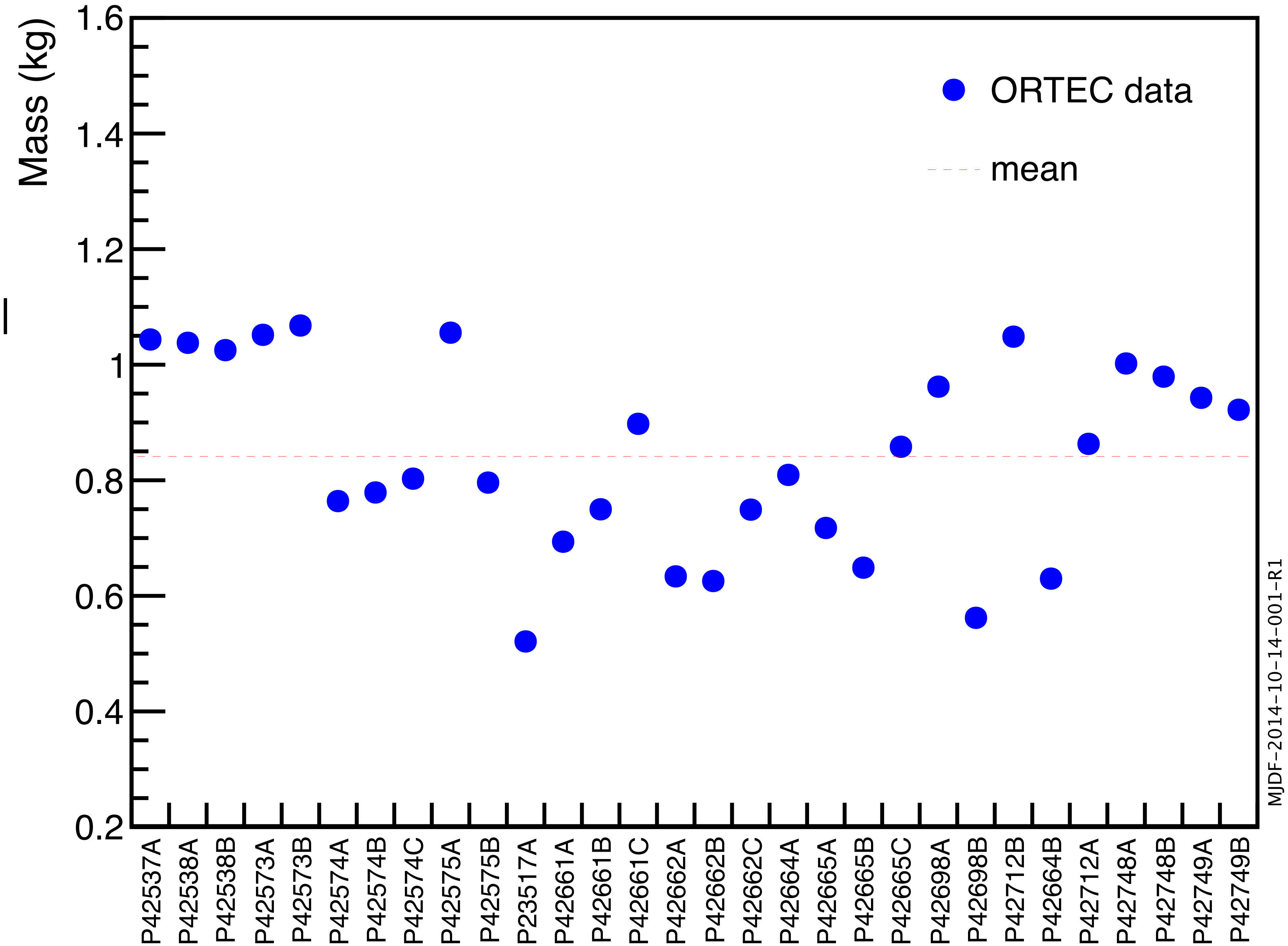


$GeCl_4$ with cover liquid



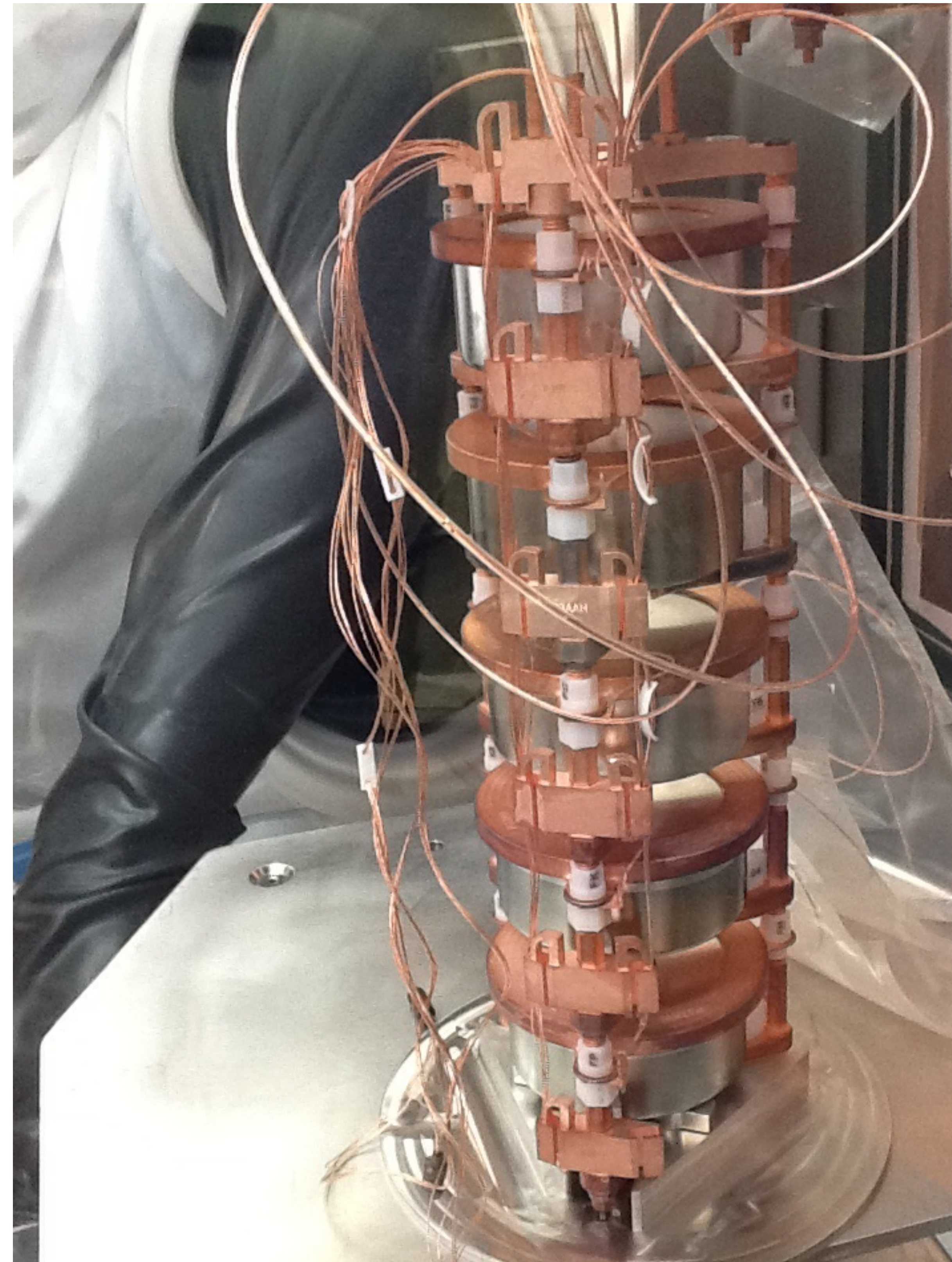
Detector Fabrication

- 29.7kg of ^{enr}Ge detectors underground at SURF
- 35 detectors total
- M_{avg} = 849g

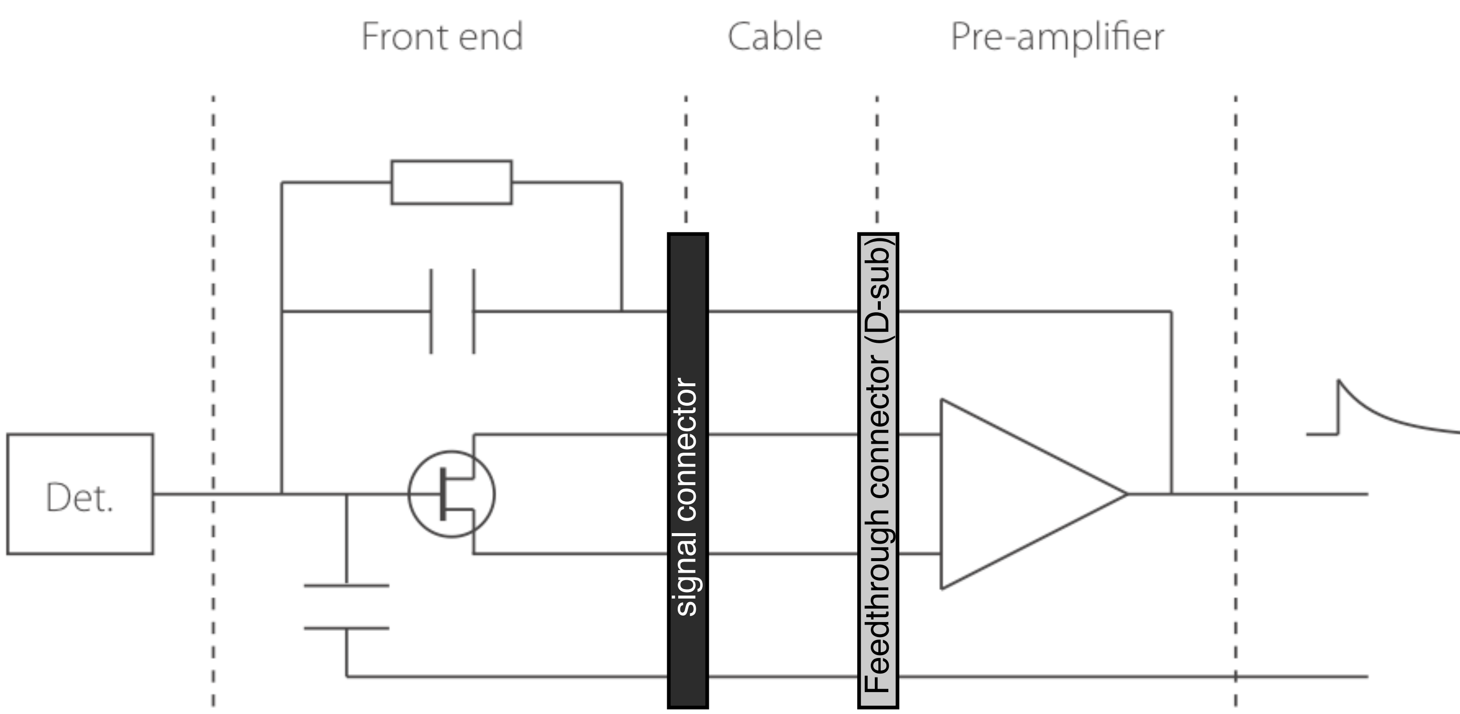


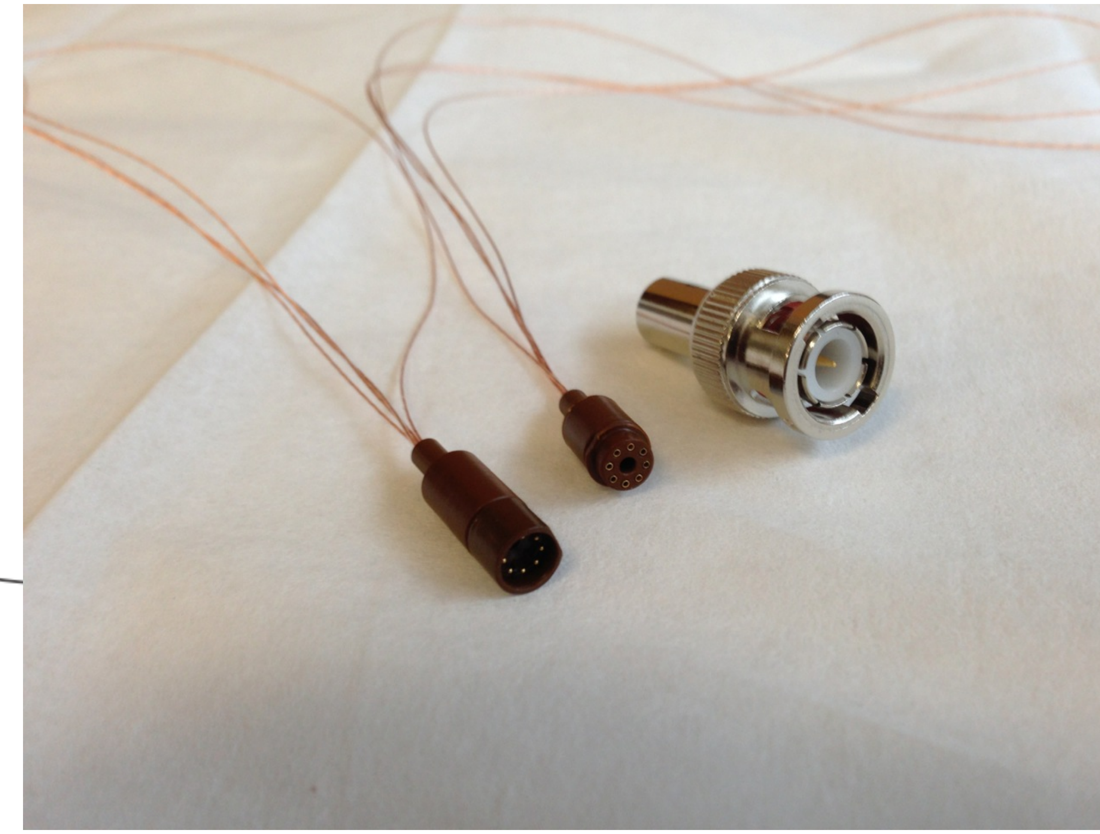
Detector Units and Strings

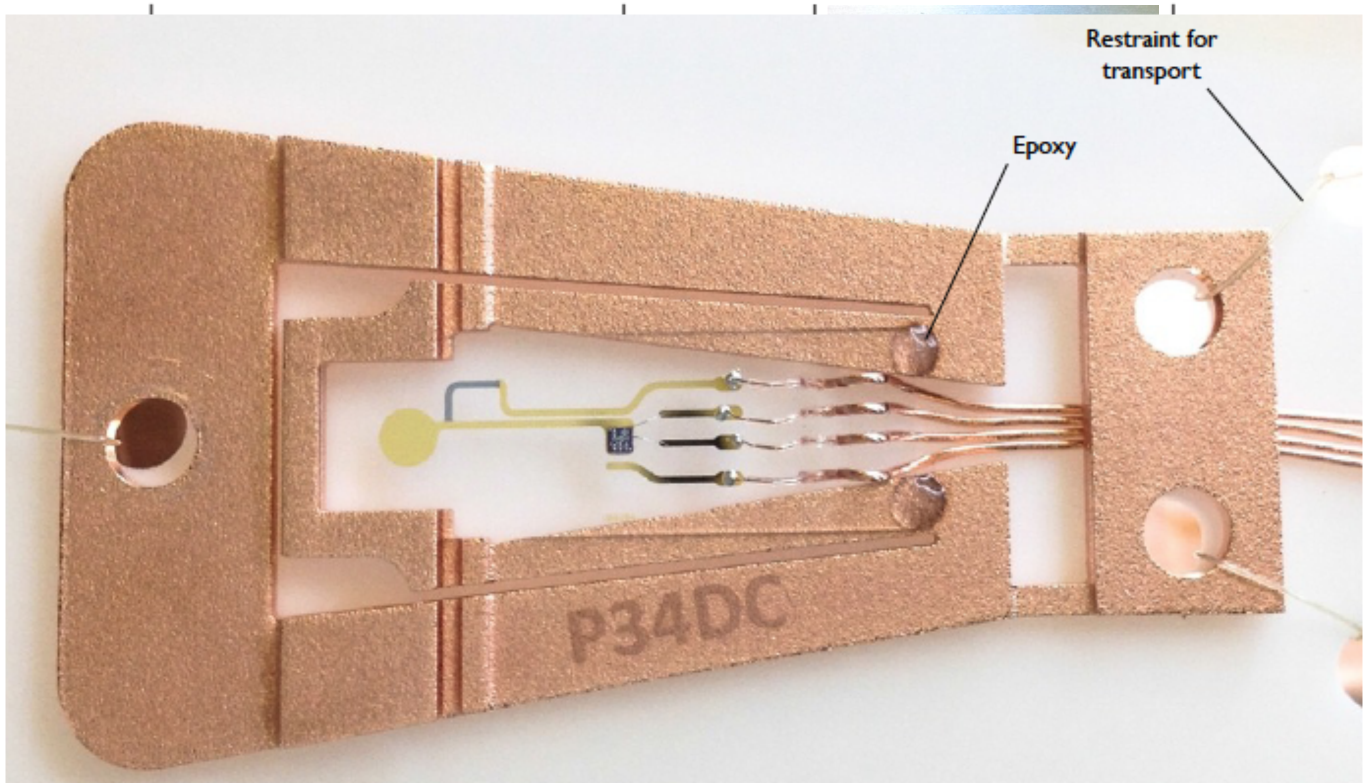
- Detectors installed in individual mounts
- Detector Units stacked into strings of 4-5 detectors each
- Low-mass Copper & PTFE

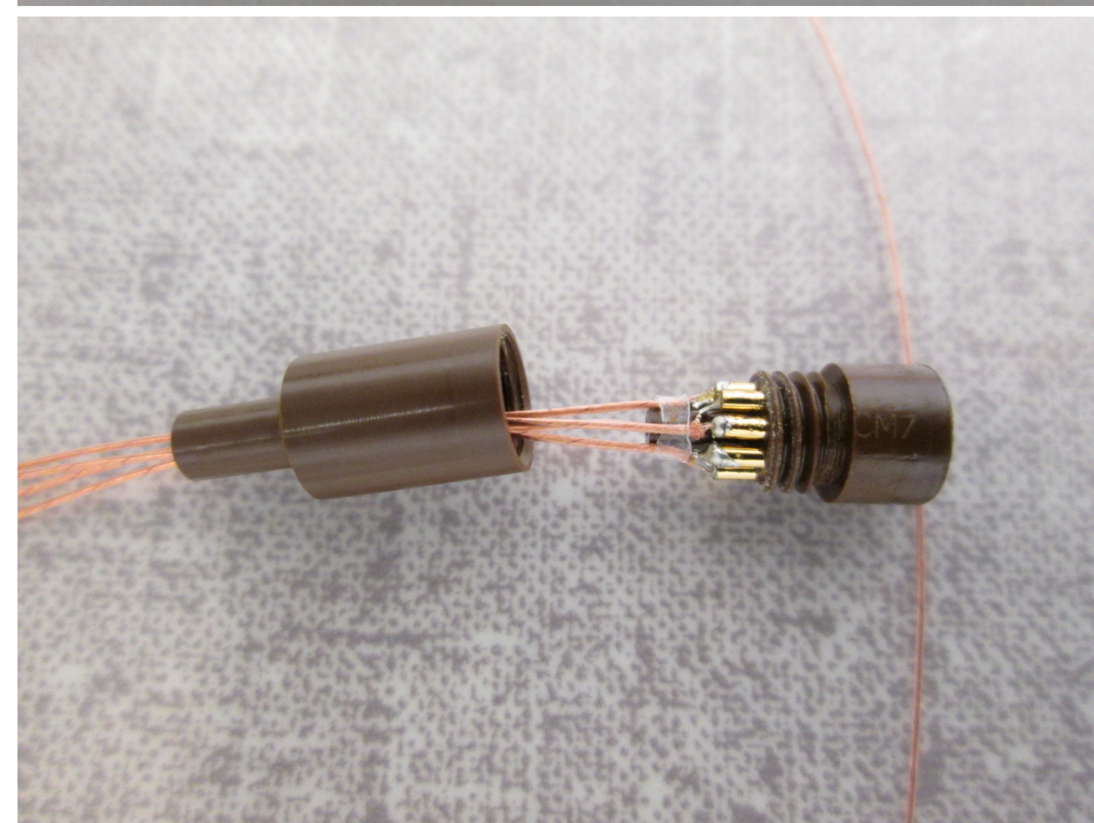


Detector Readout



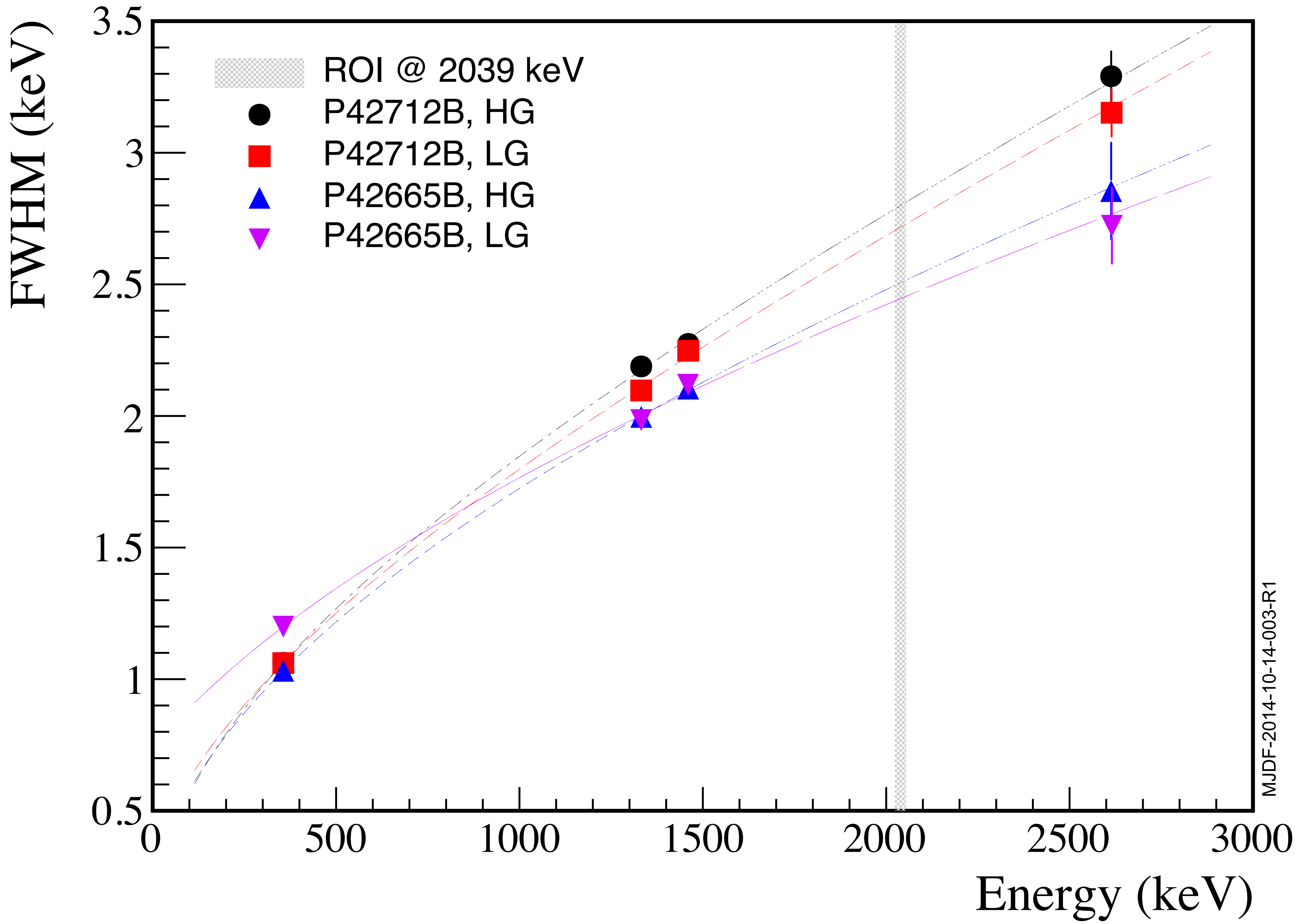






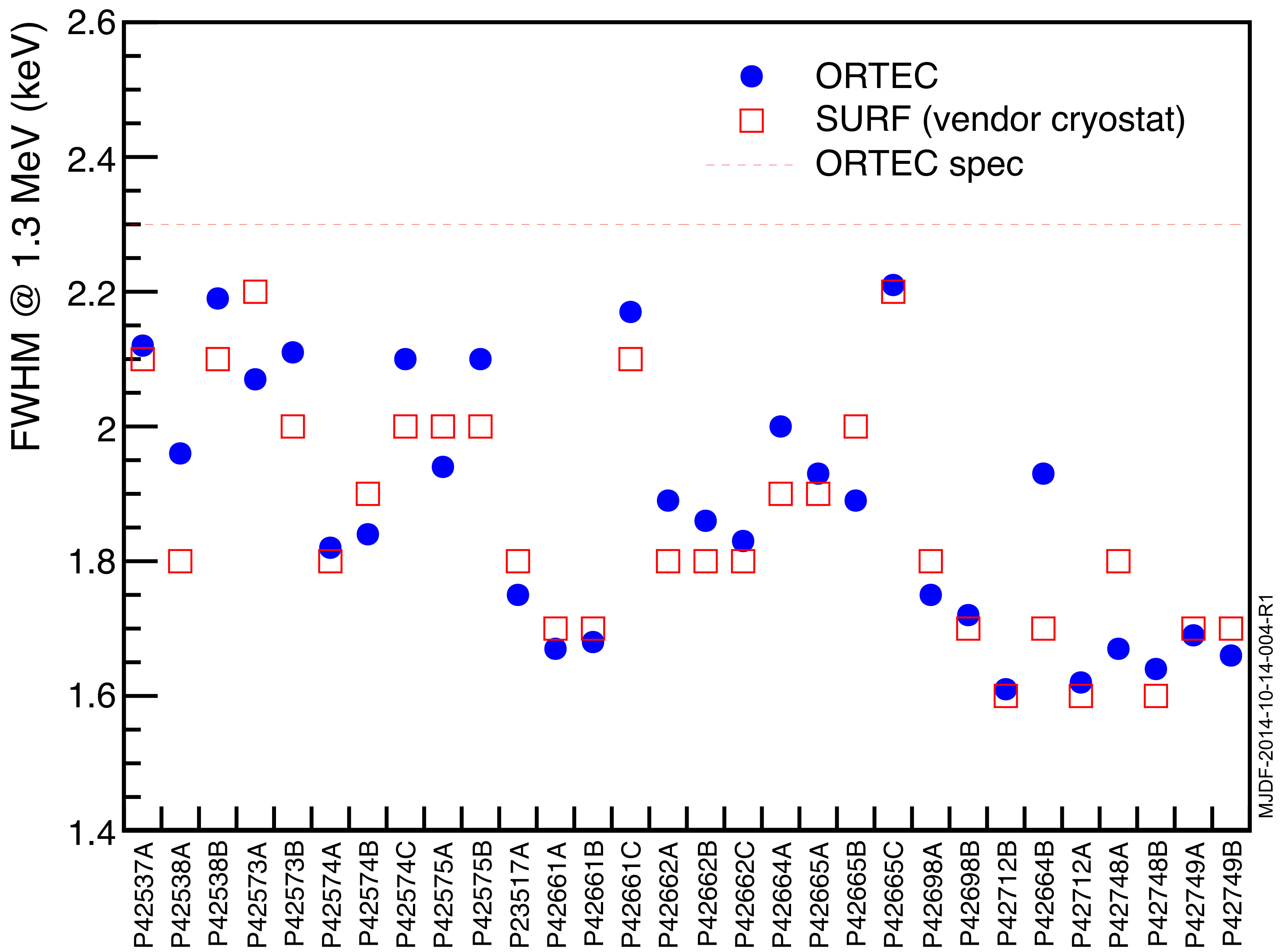
^{enr}Ge Energy Resolution in MJD String

Resolution in both high/low gain channels for two detectors



^{enr}Ge Energy Resolution

Comparison of measurements done at ORTEC and SURF within the vendor cryostat. All are better than specification.



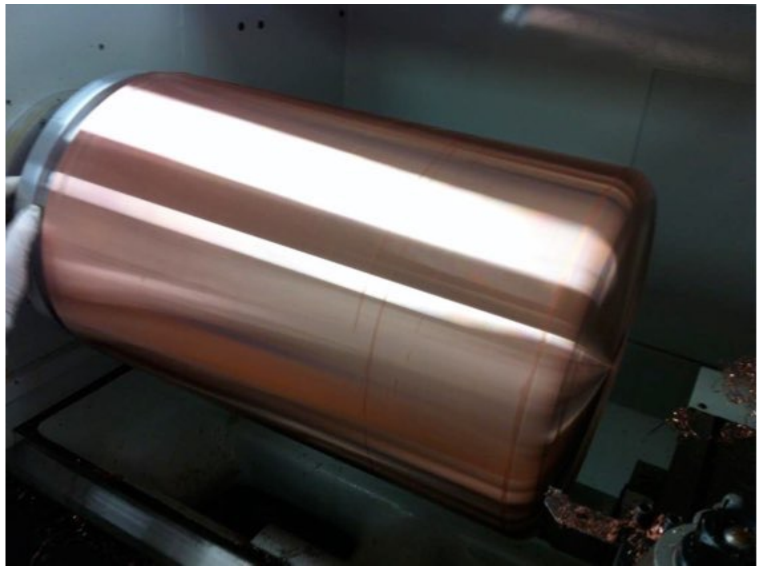
MAJORANA Electroformed Cu

- MAJORANA operated 10 baths at the Temporary Clean Room (TCR) facility at the 4850' level and 6 baths at a shallow UG site at PNNL. All copper was machined at the Davis campus.
- The electroforming of copper for the DEMONSTRATOR successfully completed in April 2015.
  - 2474 kg of electroformed copper on the mandrels
  - 2104 kg after initial machining,
  - 1196 kg that will be installed in the DEMONSTRATOR.
- We continue to operate 5 baths in the TCR as backup stock for MAJORANA and for other experiments.

Electroforming Baths in TCR

Inspection of EF copper on mandrels

EF copper after turning on lathe



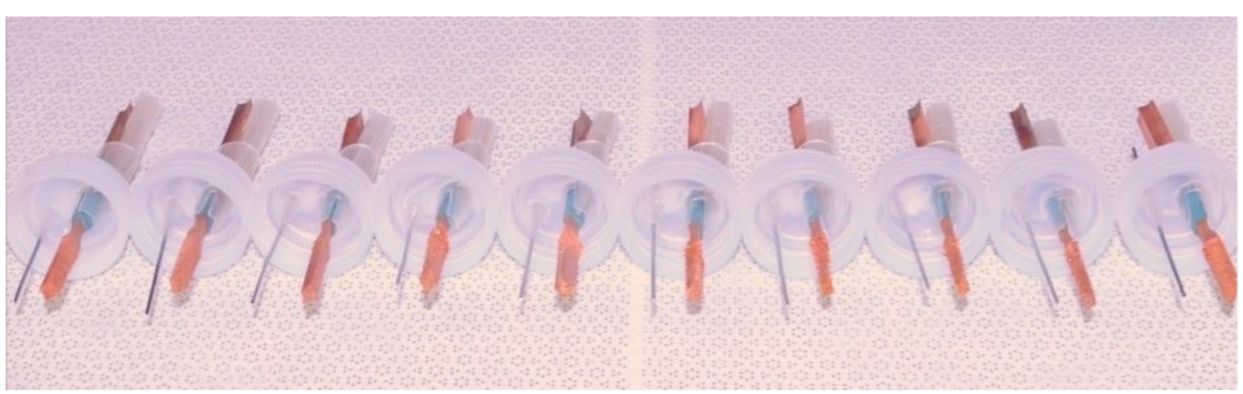
- Th decay chain (ave) ≤ 0.1 μBq/kg
- U decay chain (ave) ≤ 0.1 μBq/kg

EFCu Finished Components

MJD Materials Assay

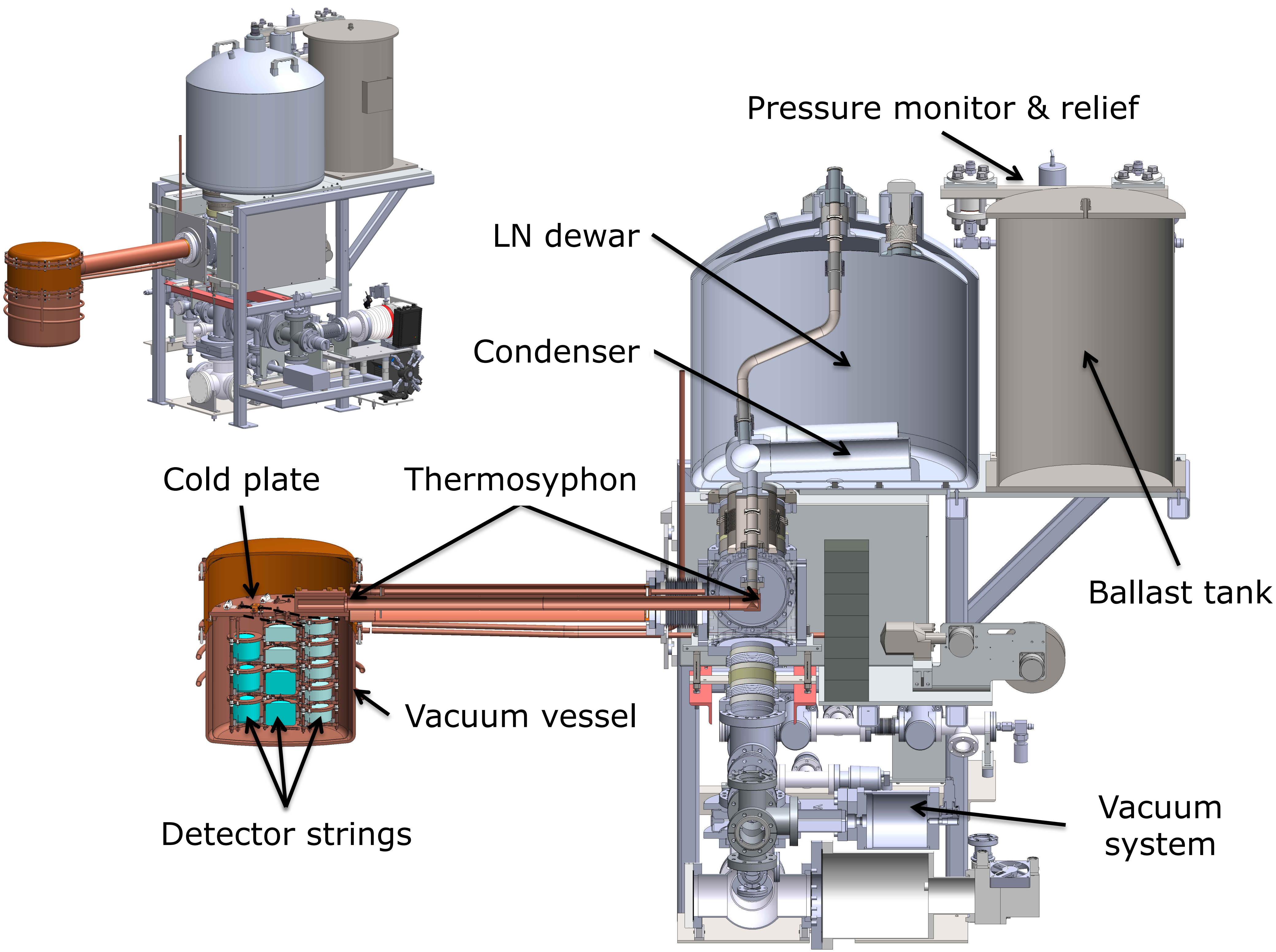
- Assay of samples from all materials used in the DEMONSTRATOR.
  - Radiometric, NAA, & ICP-MS techniques.
- Have developed world's most sensitive ICP-MS-based assay techniques for U and Th in Cu (Original MJD Goal: <0.3 μBq/kg for U & Th)
  - Current MDL (method detection limits) with iridium anode improvements
    - U decay chain 0.1 μBq ^{238}U/kg
    - Th decay chain 0.1 μBq ^{232}Th/kg
  - Sensitivities with ion exchange copper sample preparation (MDL study)
    - U decay chain <0.13 μBq ^{238}U/kg
    - Th decay chain <0.034 μBq ^{232}Th/kg

Evaluation of iridium electrodes following copper sample preparation



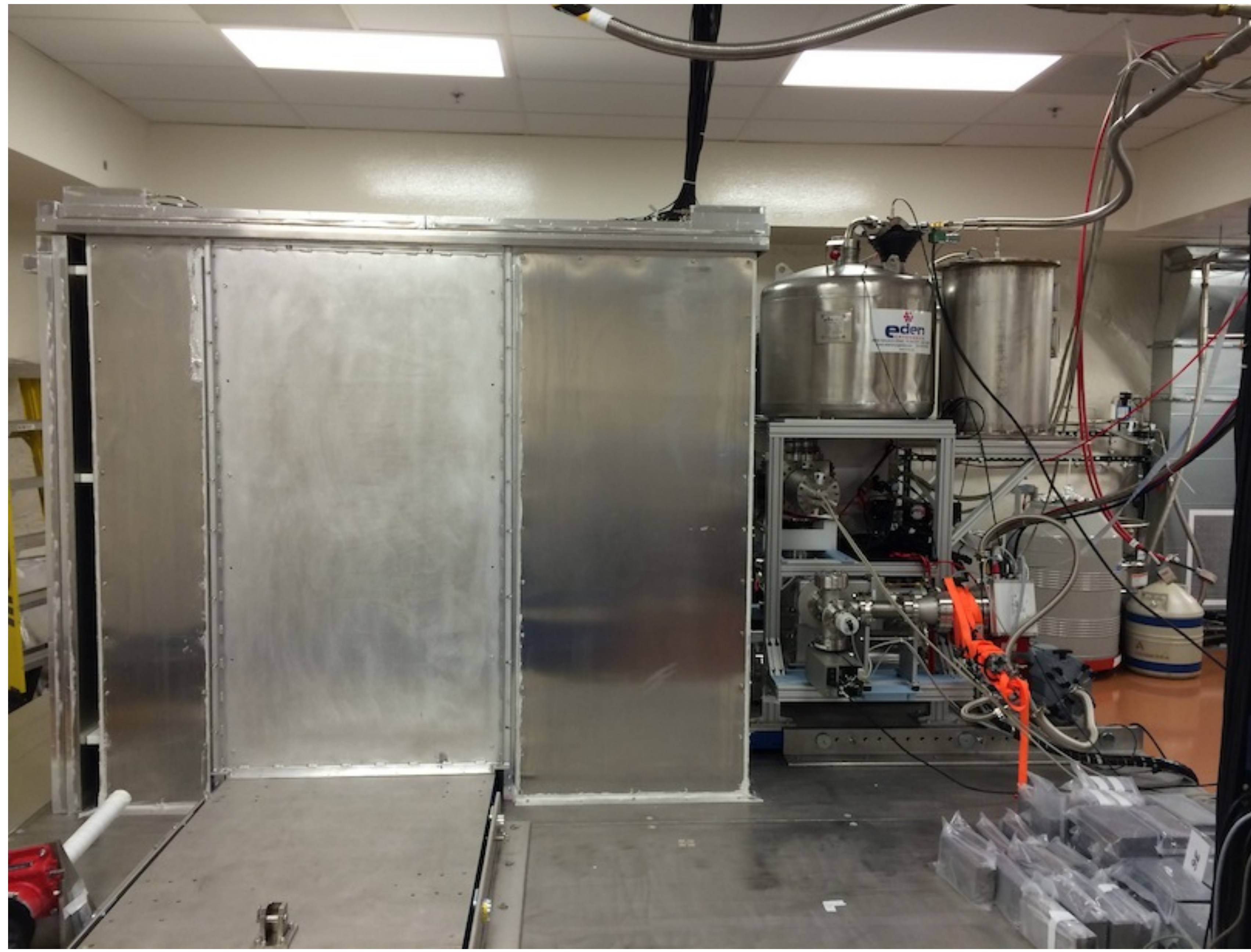
NIM A 775 (2015) 93-98

Modules


Pressure monitor & relief
LN dewar
Condenser
Cold plate
Thermosyphon
Ballast tank
Vacuum vessel
Detector strings
Vacuum system

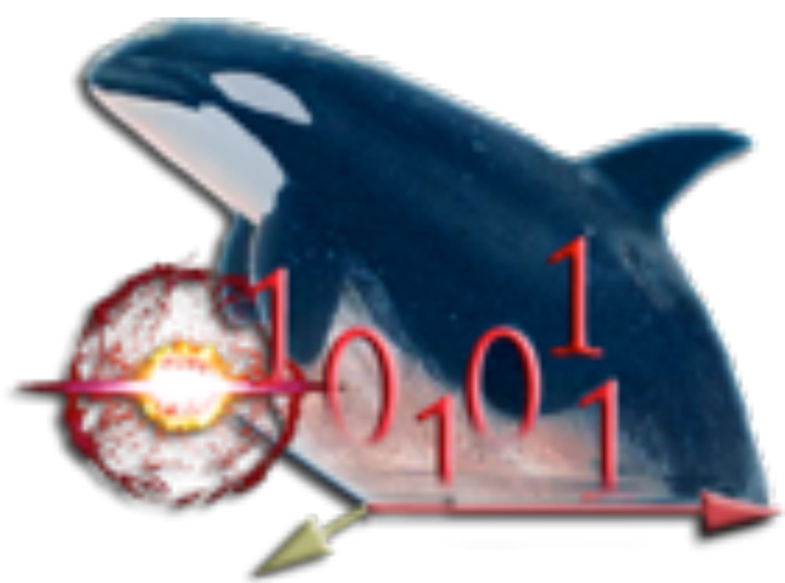
Modules

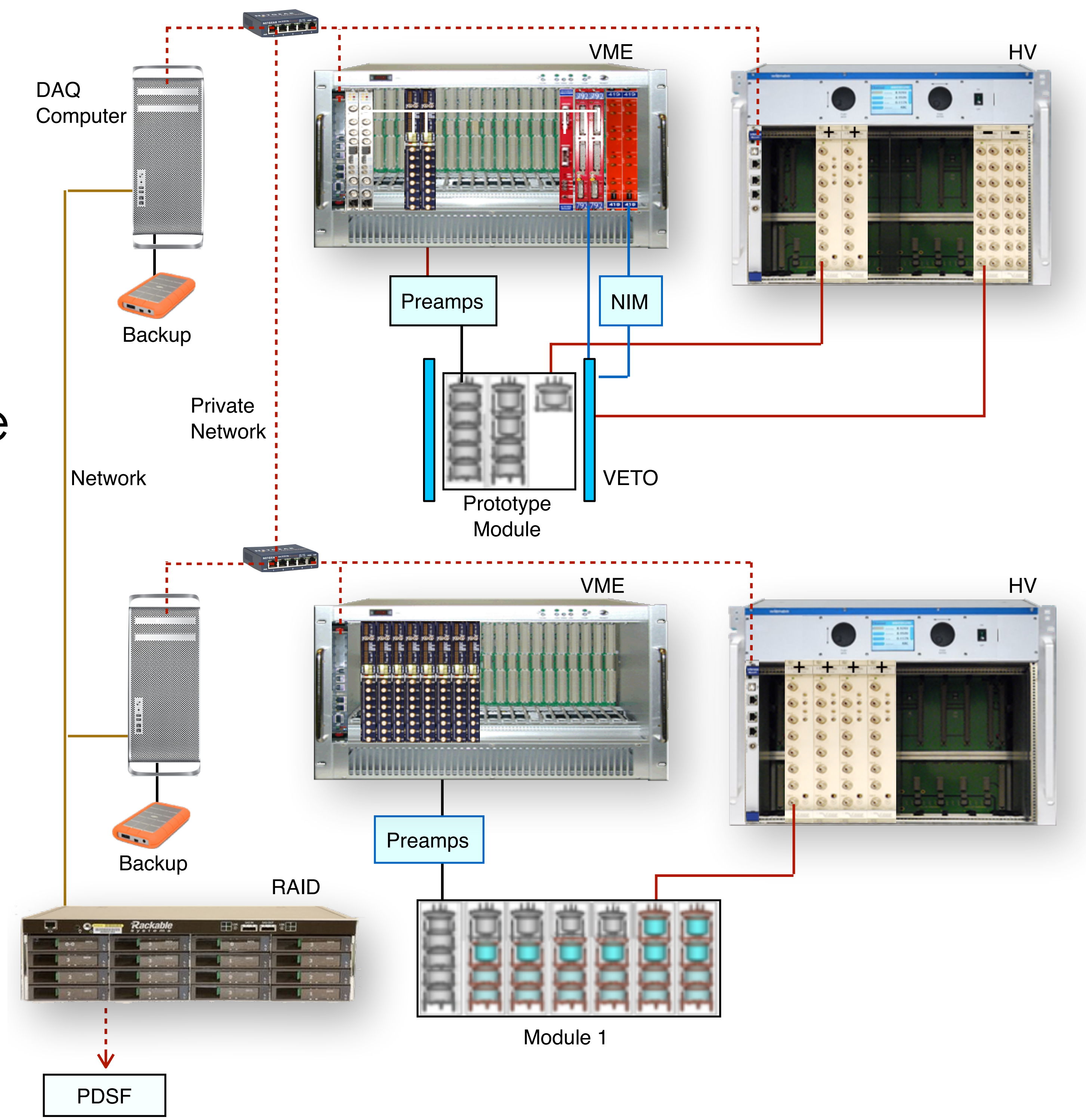
Shield



DAQ

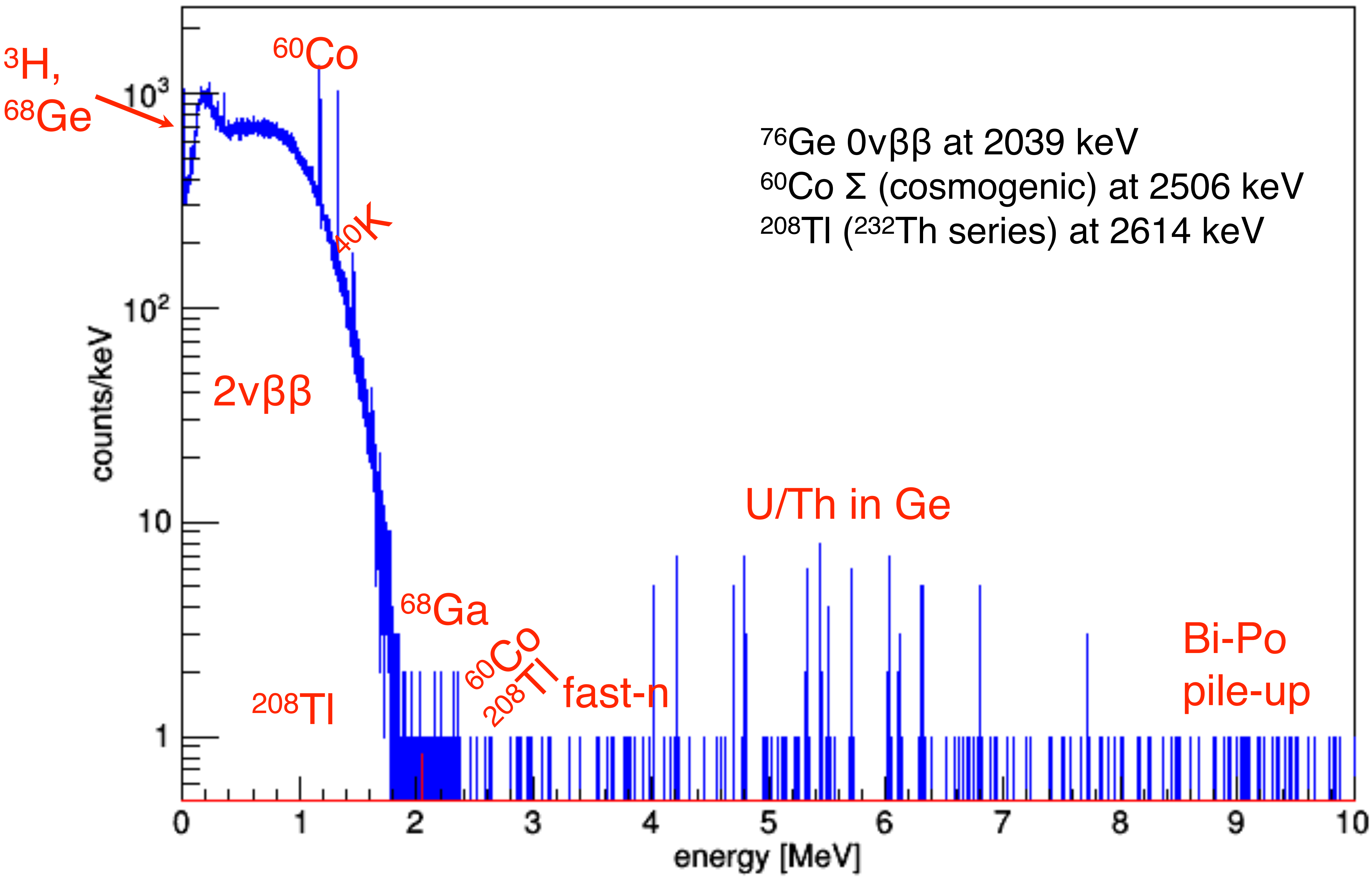
- 10ch, 14-bit, 100Mhz FPGA-based waveform digitizers from Gretina Collaboration
- Single board computer VME controller
- ORCA-based DAQ software
- Data shipped to PDSF (NERSC) for processing and analysis





MAJORANA DEMONSTRATOR Simulation

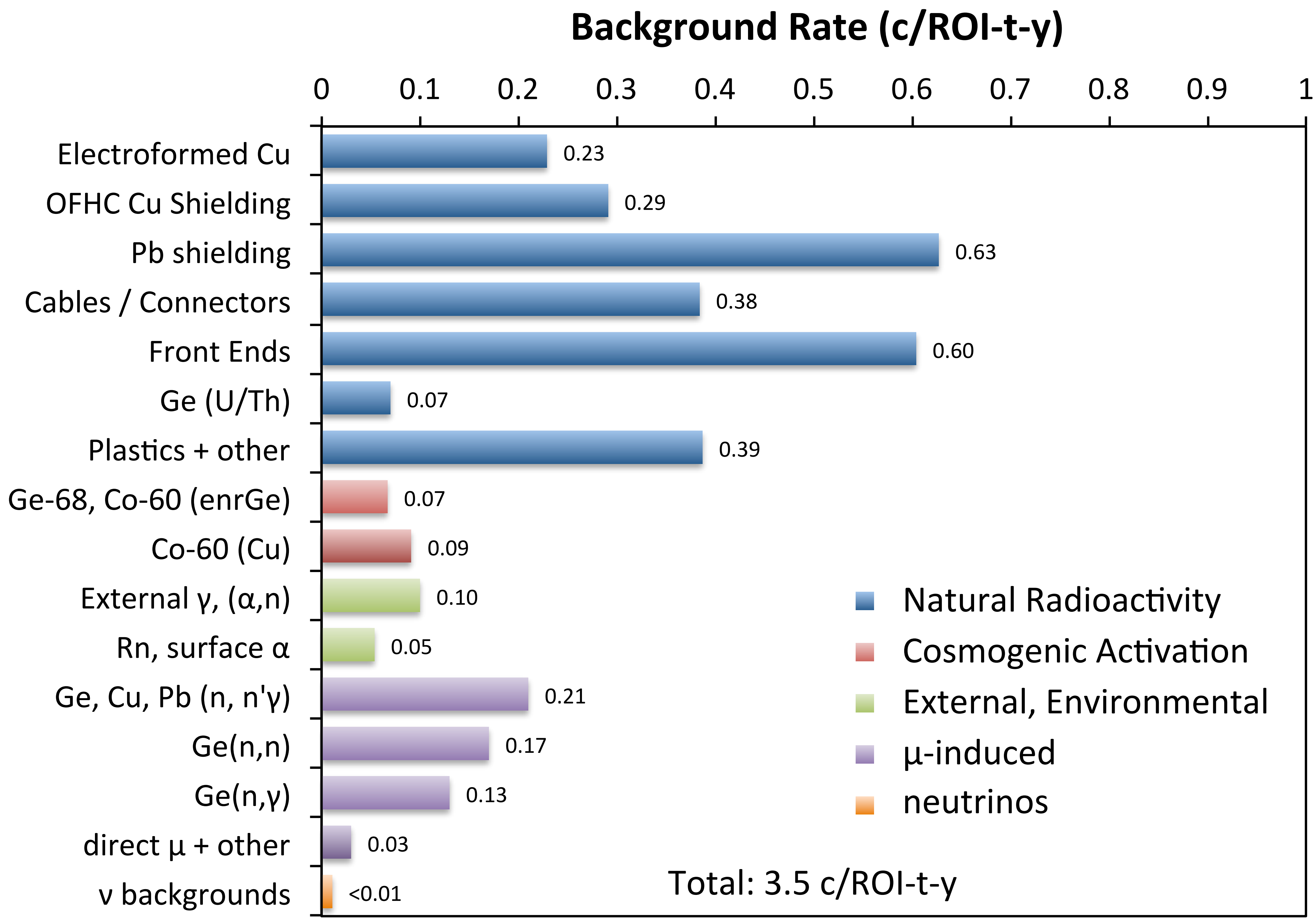
5 year MJD run: 30 kg 87% enriched ^{76}Ge; 92% fiducial; 90% livetime (108 kg-years)



DEMONSTRATOR Background Budget

Based on achieved assays of materials
When UL, use UL as the contribution

Goal: ≤ 3.0 cts / ROI-t-y
(Scales to 1.0 cts / ROI-t-y for a larger experiment)

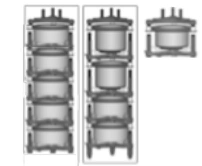


MJD Implementation

Three Steps

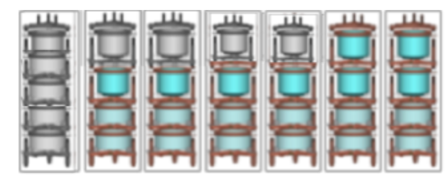
In Shield

– **Prototype Module*** : 7.0 kg (10) ^{nat}Ge
3 strings



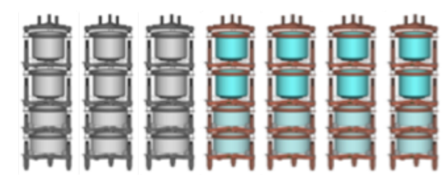
June 2014

– **Module 1** : 16.8 kg (20) ^{enr}Ge,
7 strings 5.7 kg (9) ^{nat}Ge

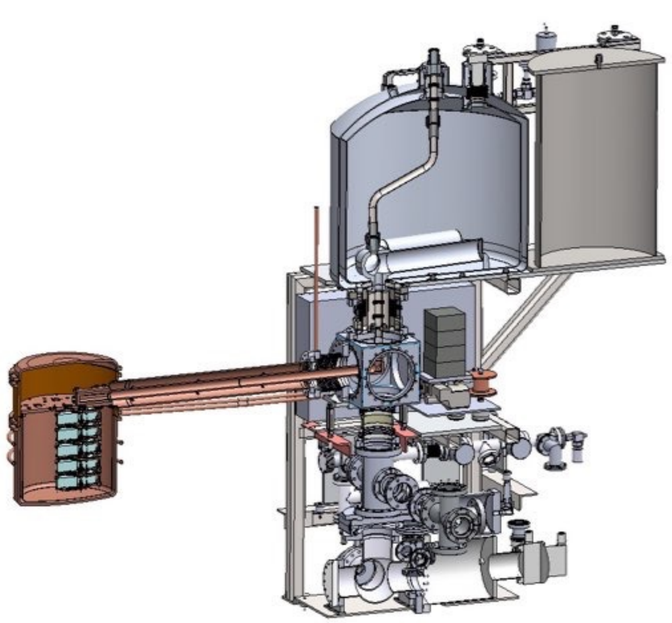


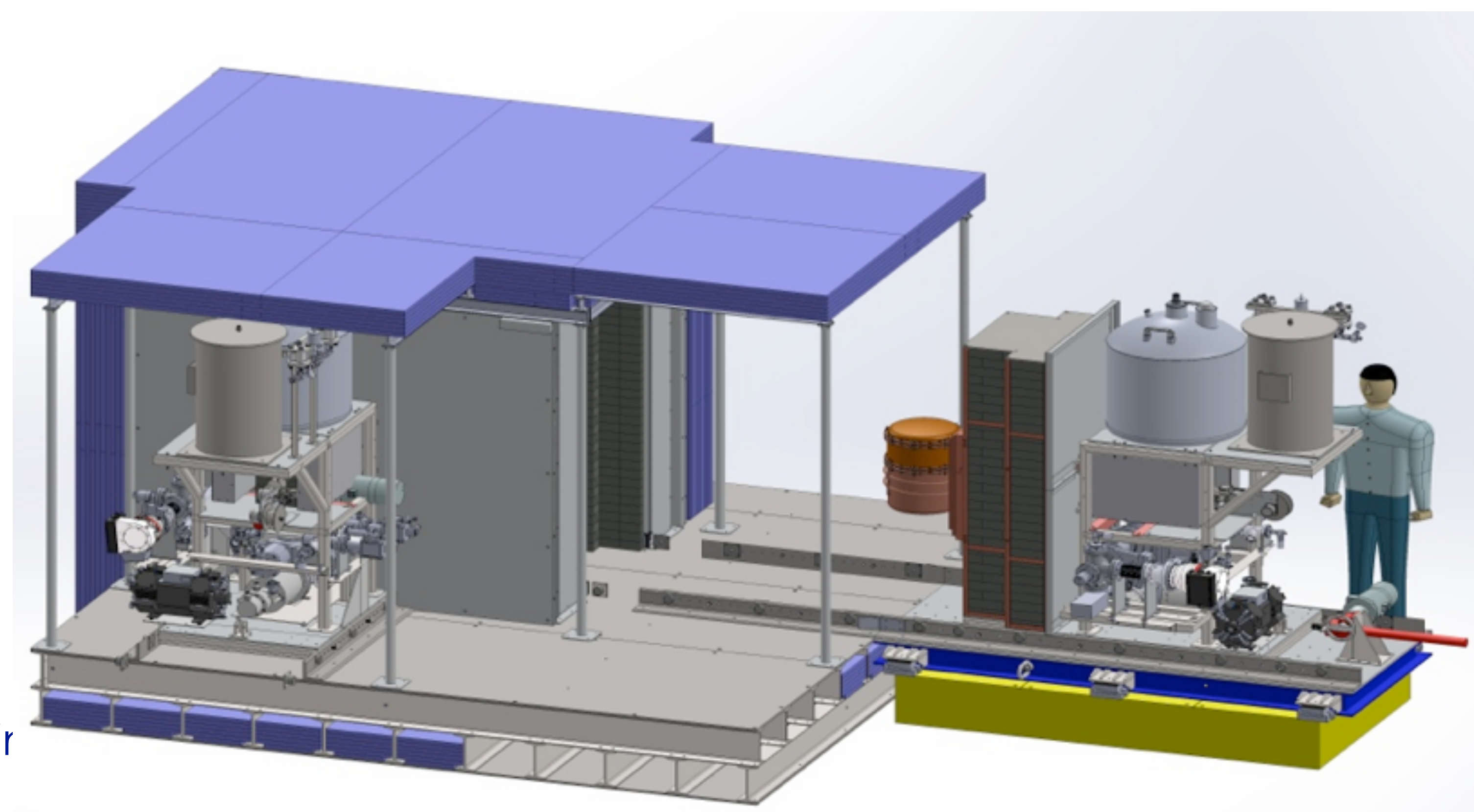
May 2015

– **Module 2** : (12.9 kg (15) ^{enr}Ge,
7 strings 9.4 kg (15) ^{nat}Ge)



End 2015 (est)



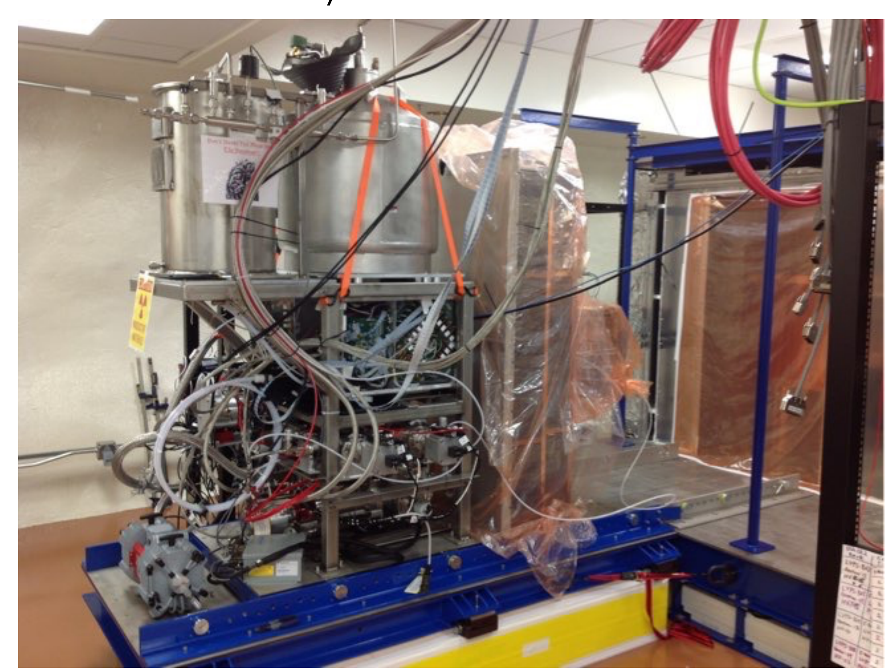


* Same design as Cryos 1 & 2, but fabricated usir
OFHC Cu (non-electroformed) components.

MJD Module 1 Status

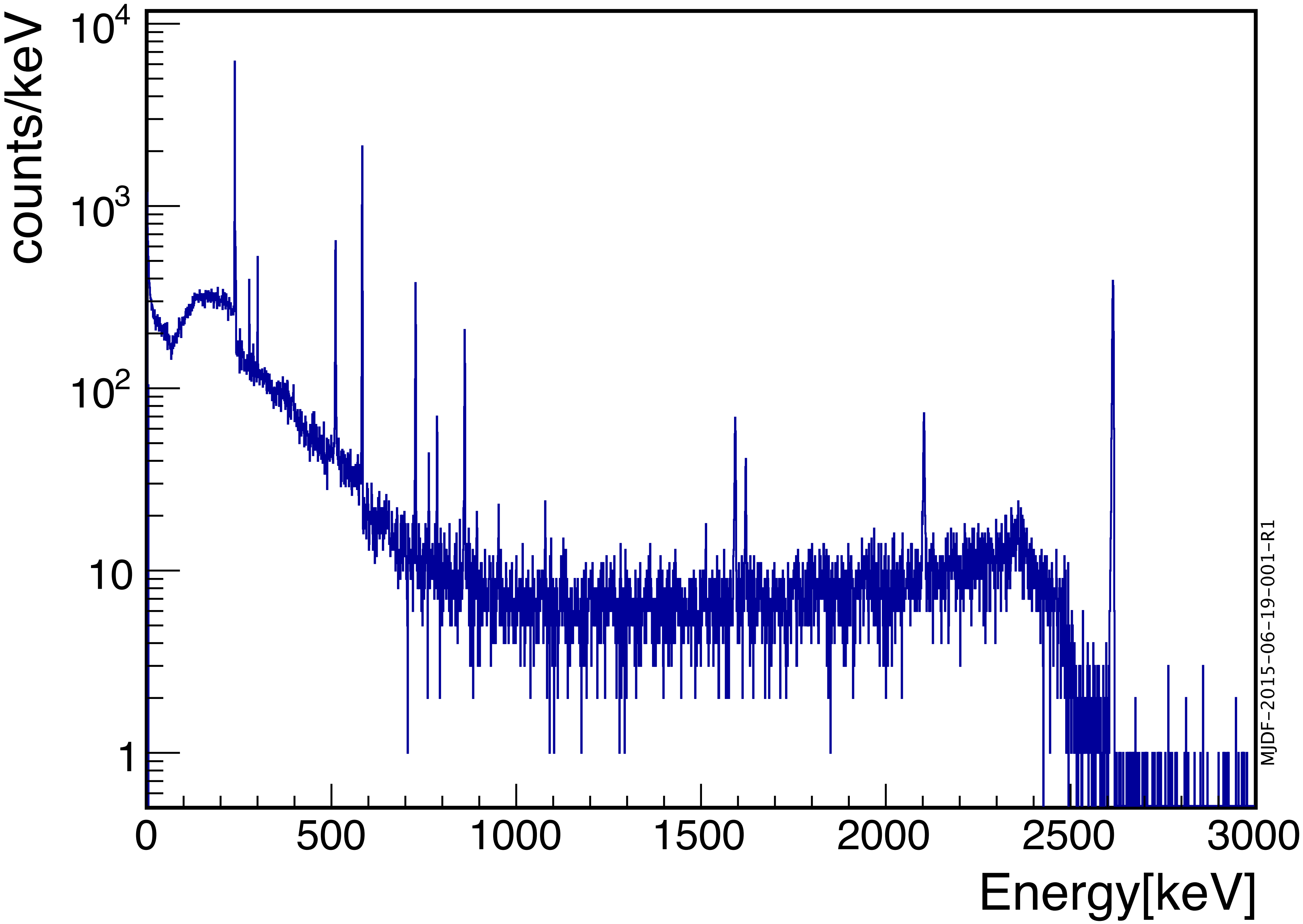
- May 2015
  - Prior to cool-down 28 of 29 detectors showed good baselines
  - Efforts to seal with low-background parylene gaskets failed, switch to Kalrez® o-rings for initial commissioning. Investigating additional alternate low-background seals.
- June 2015
  - In shield, with 23 of 29 detectors operating. Non working detectors — signal connector (3), HV connection (1), leakage current (1), HV or front end (1).
  - Inner electroformed copper shield not installed (machining underway), outer poly shield, partially installed.
  - Commissioning (completed in July), calibration, background runs.
- Sept. - Oct. 2015
  - Remove from shield, install inner copper shield, open cryostat, attempt to fix connectors and HV connections, install low-background vacuum seals, return to shield.

Module 1 - ready for insertion into shield



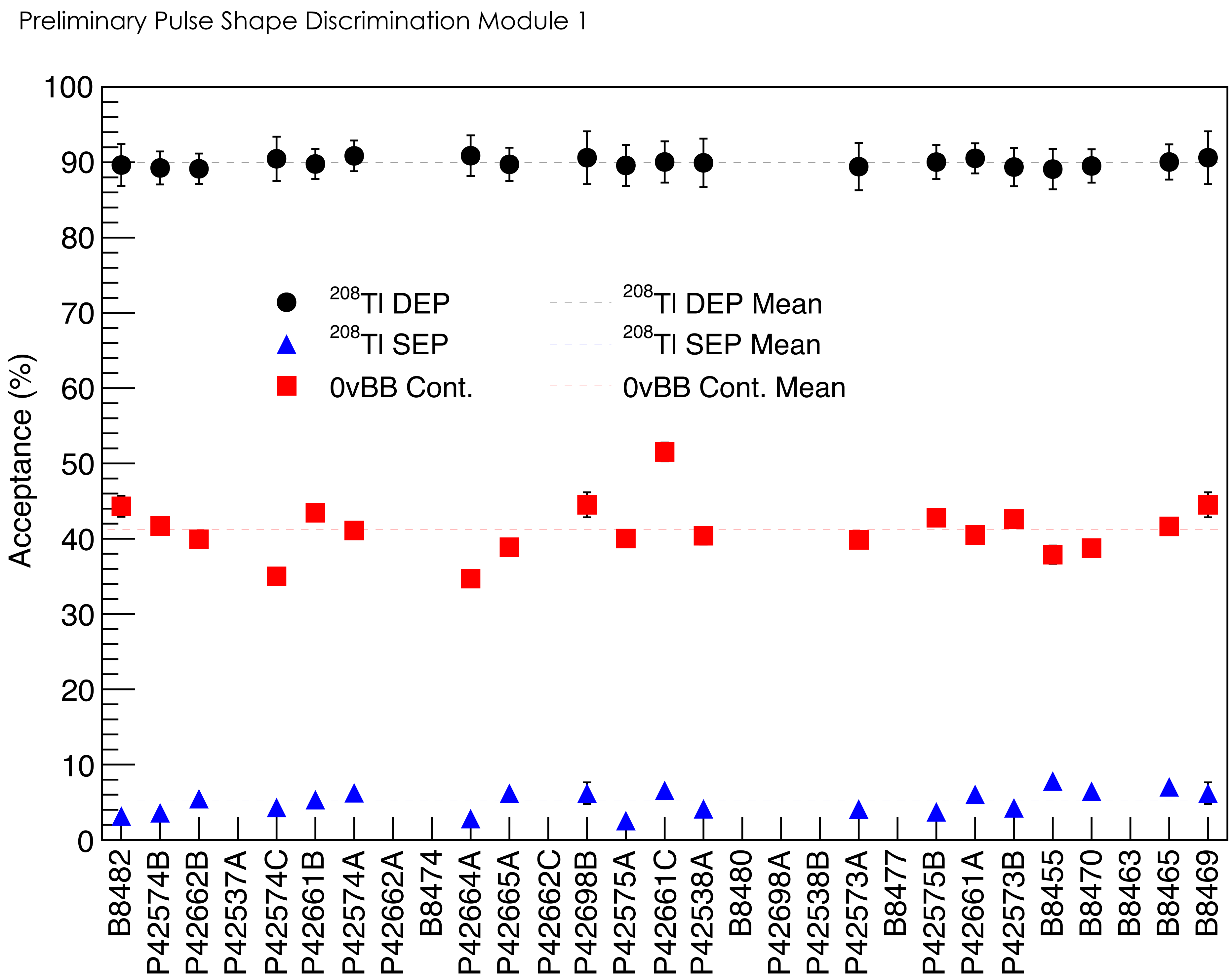
^{228}Th Calibration Spectrum in M1

One enriched detector spectrum within a string mounted in Module 1 and inside shield. FWHM 3.6 keV at 2.6 MeV



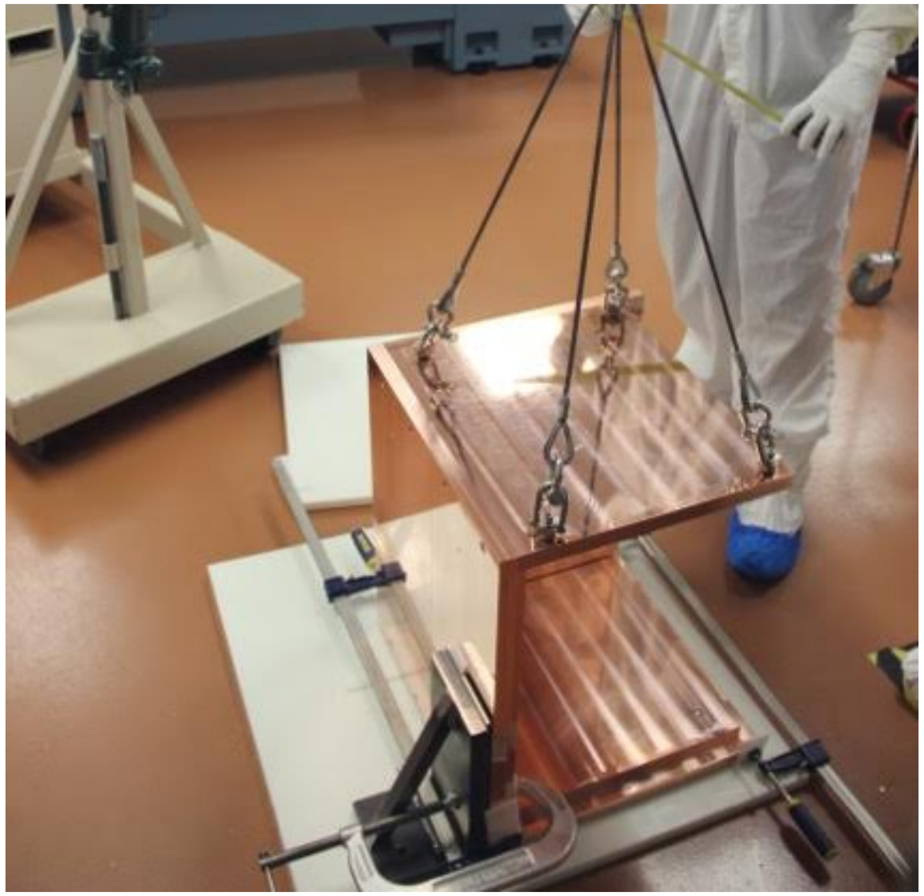
M1 Pulse-Shape Discrimination

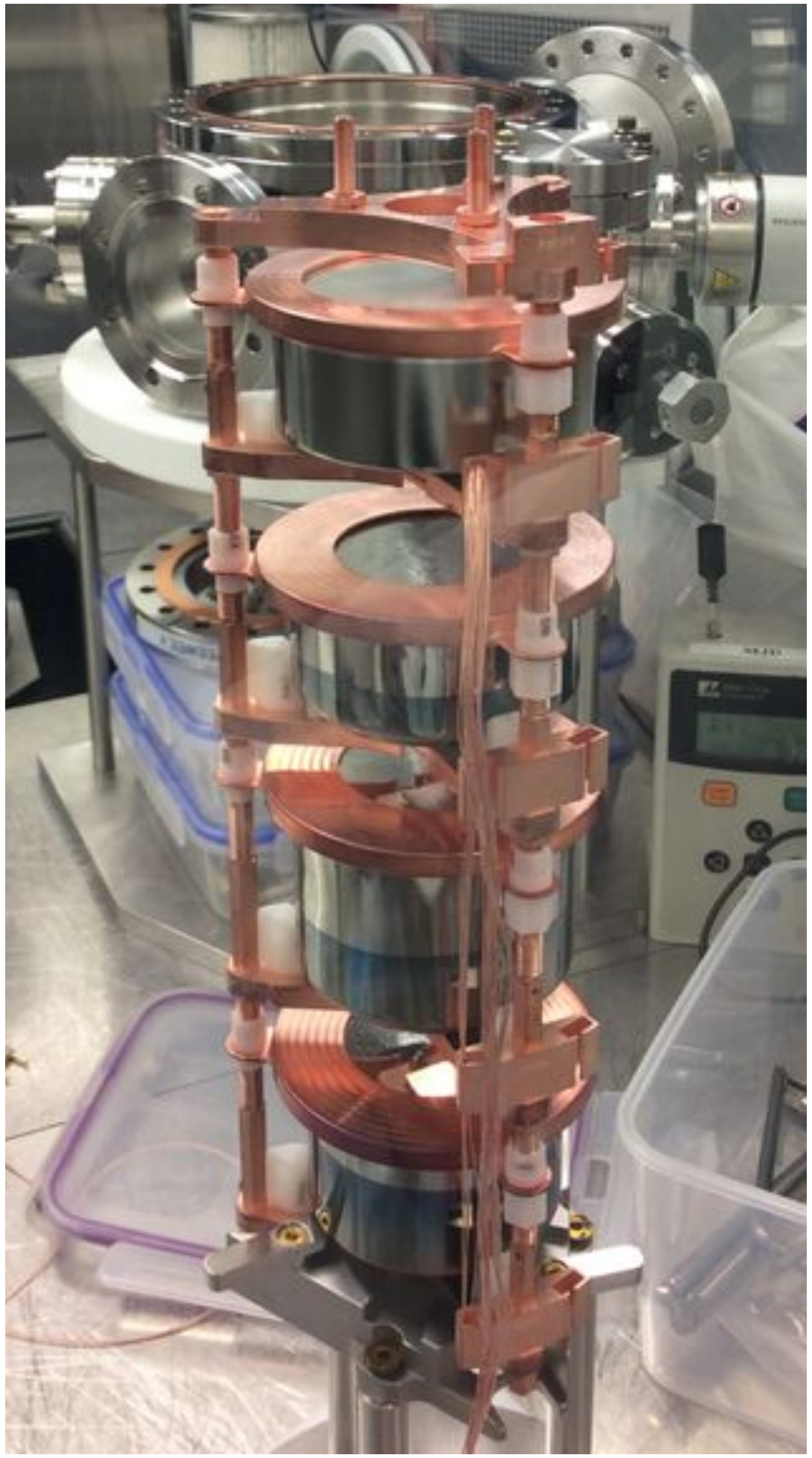
M1 Pulse-Shape Discrimination



MJD Module 2 Status

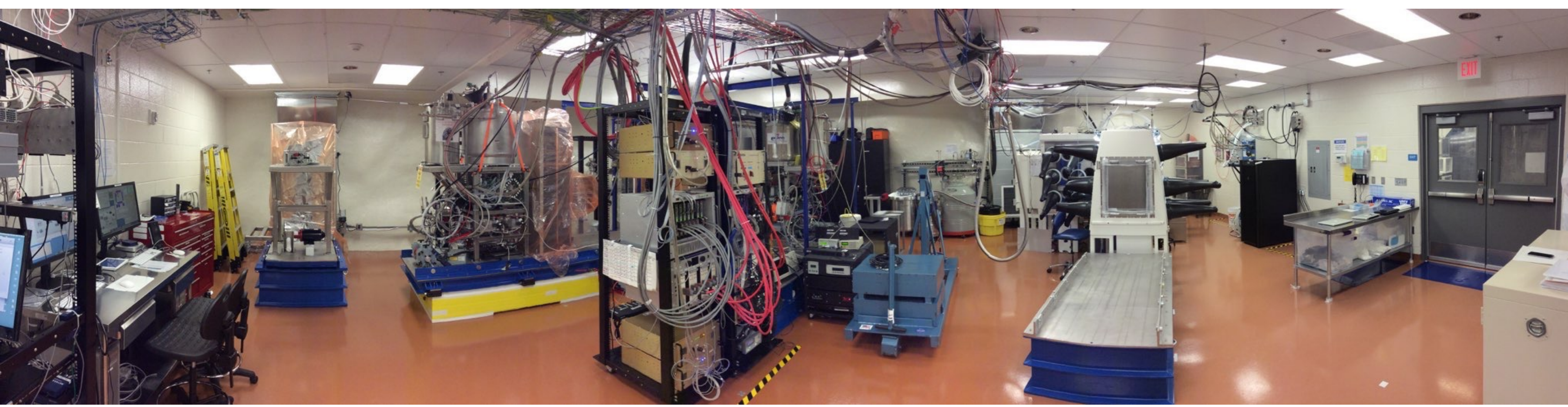
- Inner Cu shield in fabrication
- Vacuum system assembled
- Cryostat components fabricated
- 1st string assembled





MAJORANA DEMONSTRATOR Summary

- From assays, the background budget projects to : < 3.5 counts/4 keV/t-y. MJD goal of 3.
- Assay campaign completed. ICP-MS assays show that the Cu electroformed underground is very clean.
- 29.7 kg of characterized enriched detectors underground. Successful Ge recovery.
- Module 1 with 7 strings started in-shield measurements in June.
- Phased start of operations in 2015 as we complete fabrication and assembly of Module 2.



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- **Germanium for Next-Generation 0νββ - C. O'Shaughnessy**

- Engineering and Infrastructure Needs for Next-Generation Ge - M. Busch

Rates (Sensitivity) Per Unit Mass

R.G.H. Robertson, MPL A **28** (2013) 1350021 (arXiv 1301.1323)

Typically phase space is expressed in activity per atom, not per unit mass.

$$\left[T^{0\nu}_{1/2}\right]^{-1} = G_{0\nu} g_A^4 \left|M_{0\nu}\right|^2 \left|\frac{\langle m_{\beta\beta}\rangle}{m_e}\right|^2$$

The phase space $G_{0\nu}$ is in activity per atom

$$\lambda_{0\nu}\frac{N}{M} = \frac{\ln(2) N_A}{A m_e^2} G_{0\nu} g_A^4 \left|M_{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2$$

$$\equiv H_{0\nu} g_A^4 \left|M_{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2$$

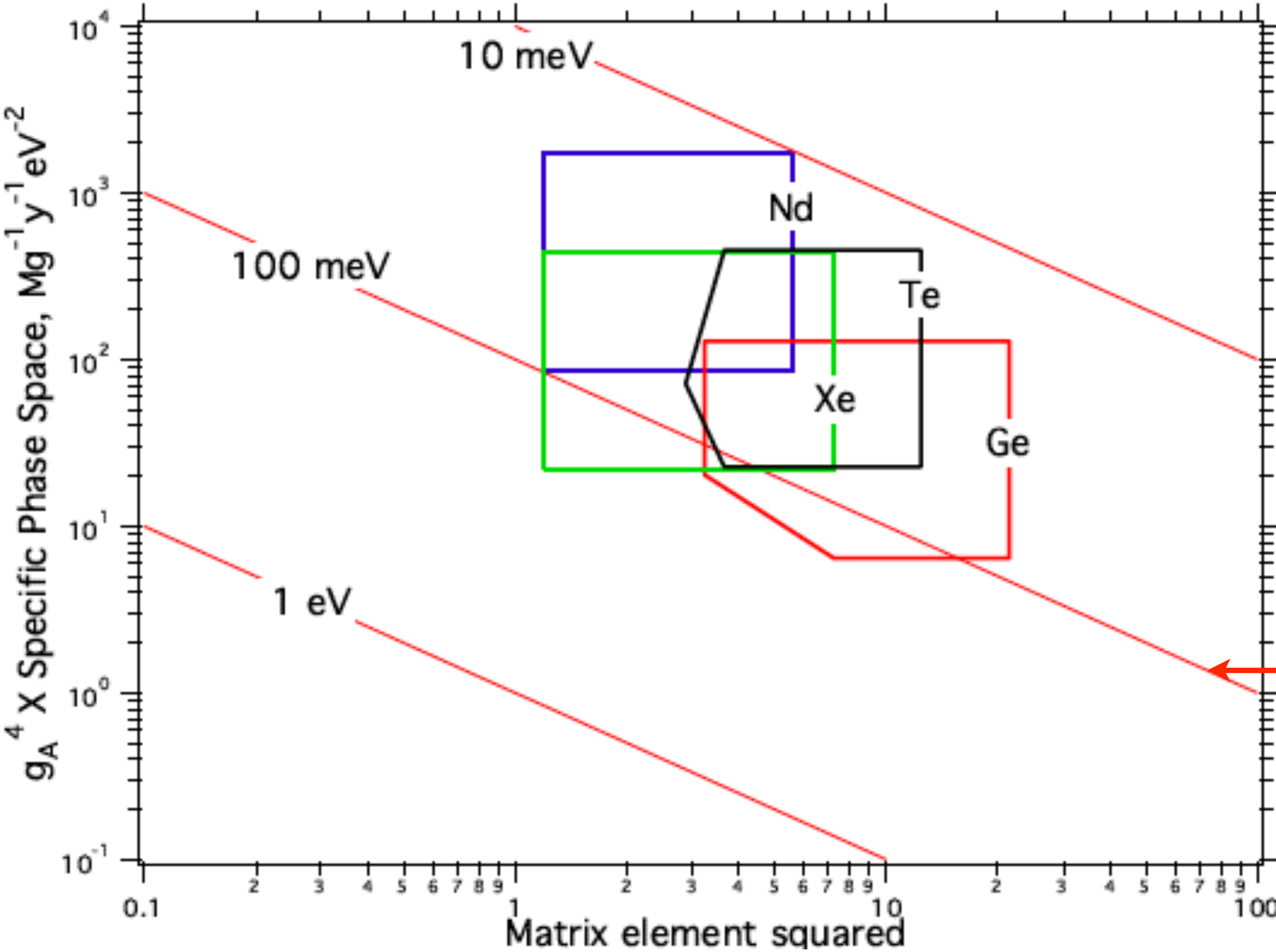
The phase space $H_{0\nu}$ is in activity per unit mass

Sensitivity to <$m_{\beta\beta}$>

R.G.H. Robertson, MPL A
28 (2013) 1350021
(arXiv 1301.1323)

For Ge, Te, Xe, Nd

← uncertainty on NME^2 →

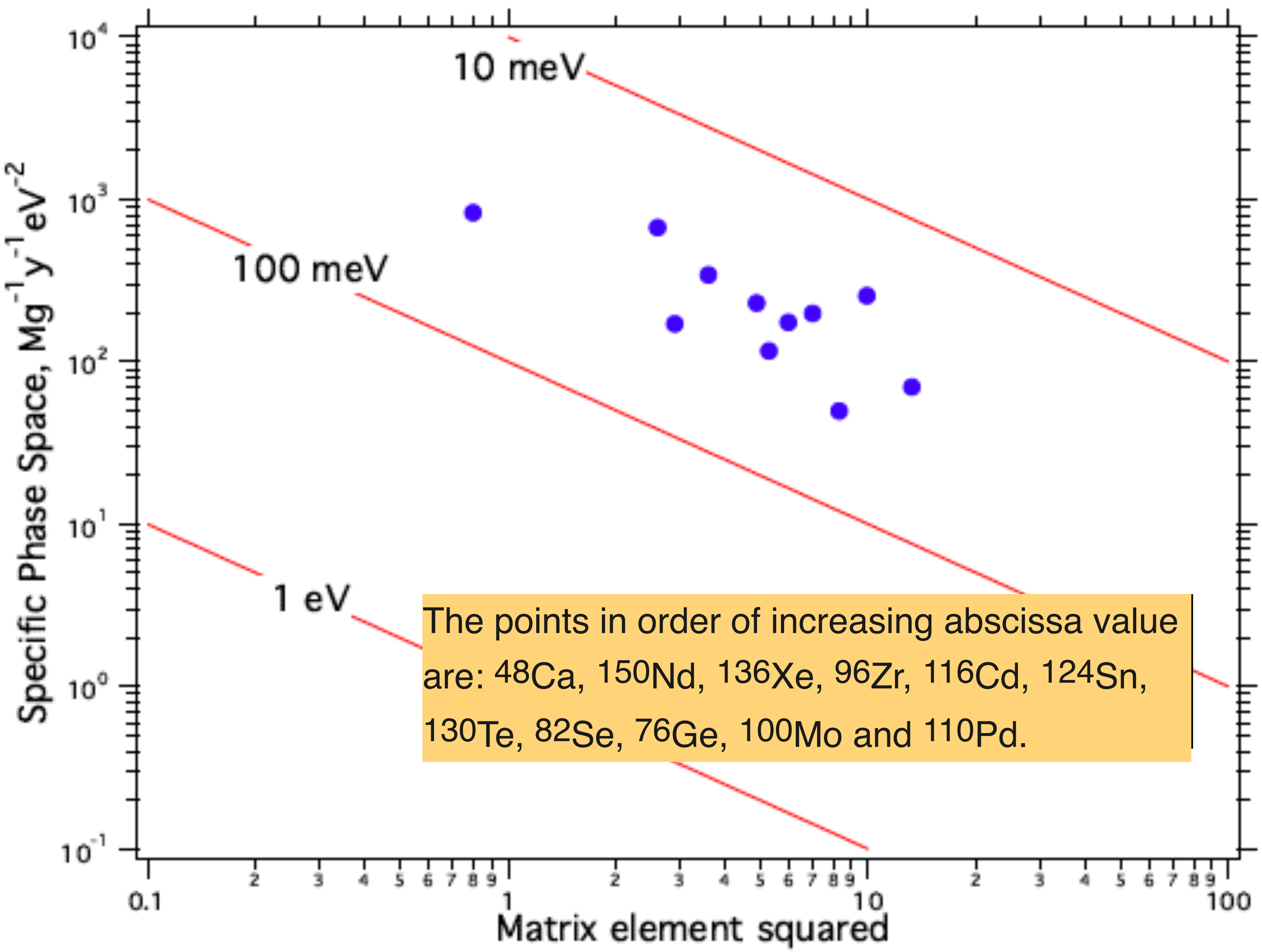


↑ uncertainty on value of g_A^4 ↓

Signal of 1 cnt/t-y for corresponding values of NME and g_A

Sensitivity per unit mass of isotope

➡ Isotopes have comparable sensitivities in terms of rate per unit mass



The points in order of increasing abscissa value are: ^{48}Ca, ^{150}Nd, ^{136}Xe, ^{96}Zr, ^{116}Cd, ^{124}Sn, ^{130}Te, ^{82}Se, ^{76}Ge, ^{100}Mo and ^{110}Pd.

R.G.H. Robertson, MPL A **28** (2013) 1350021 (arXiv 1301.1323)

Inverse correlation observed between phase space and the square of the nuclear matrix element .

geometric mean of the squared matrix element range limits & the phase-space factor evaluated at g_A=1

0νββ Signals & Sensitivity

Half life (years)	~Signal (cnts/tonne-year)
10^{25}	500
5×10^{26}	10
5×10^{27}	1
5×10^{28}	0.1

$$\left[T_{1/2}^{0\nu}\right] \propto \varepsilon ff \cdot I_{abundance} \cdot Source\ Mass \cdot Time$$

Background free

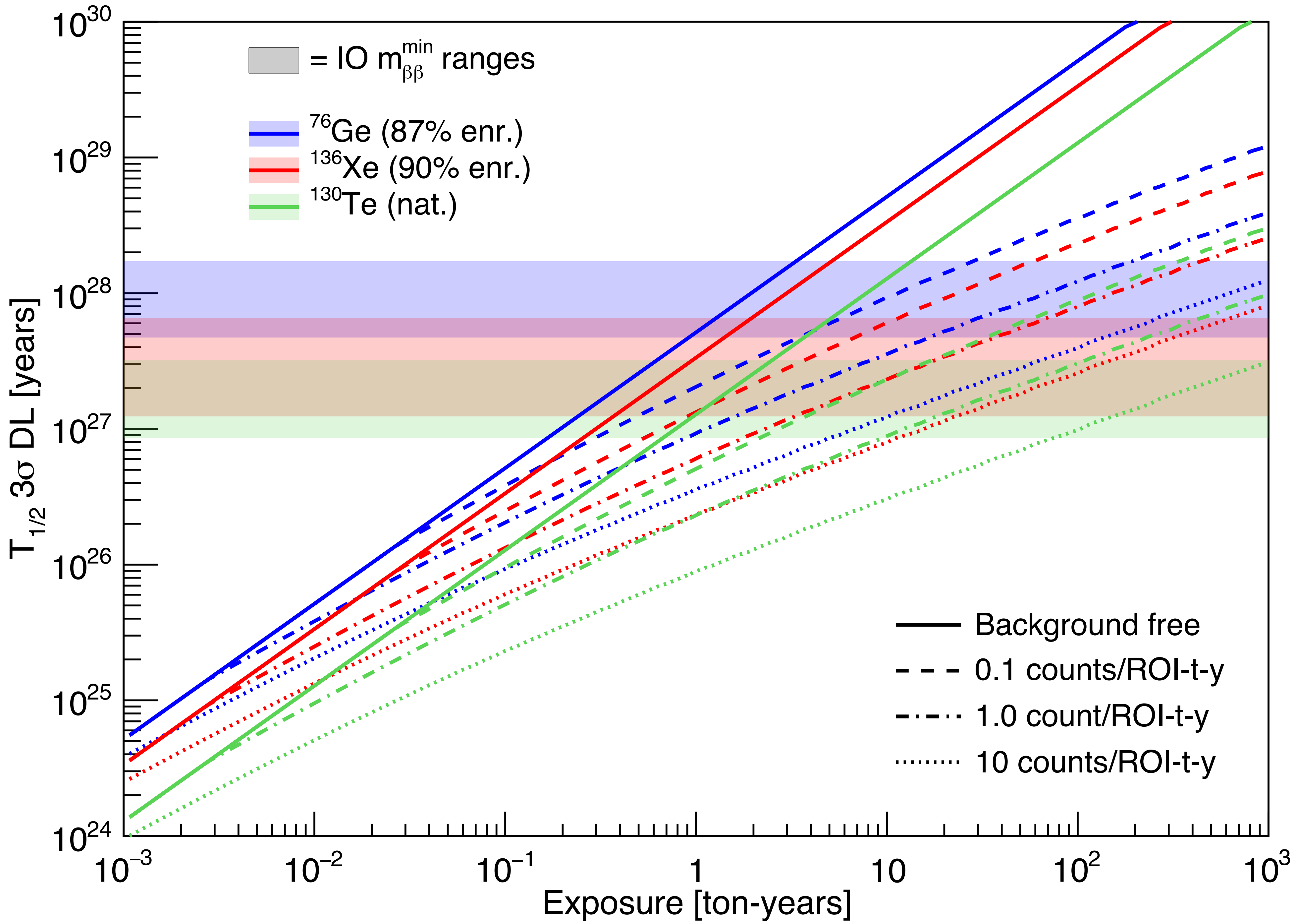
$$\left[T_{1/2}^{0\nu}\right] \propto \varepsilon ff \cdot I_{abundance} \cdot \sqrt{\frac{Source\ Mass \cdot Time}{Bkg \cdot \Delta E}}$$

Background limited

Note : Backgrounds do not always scale with active detector mass

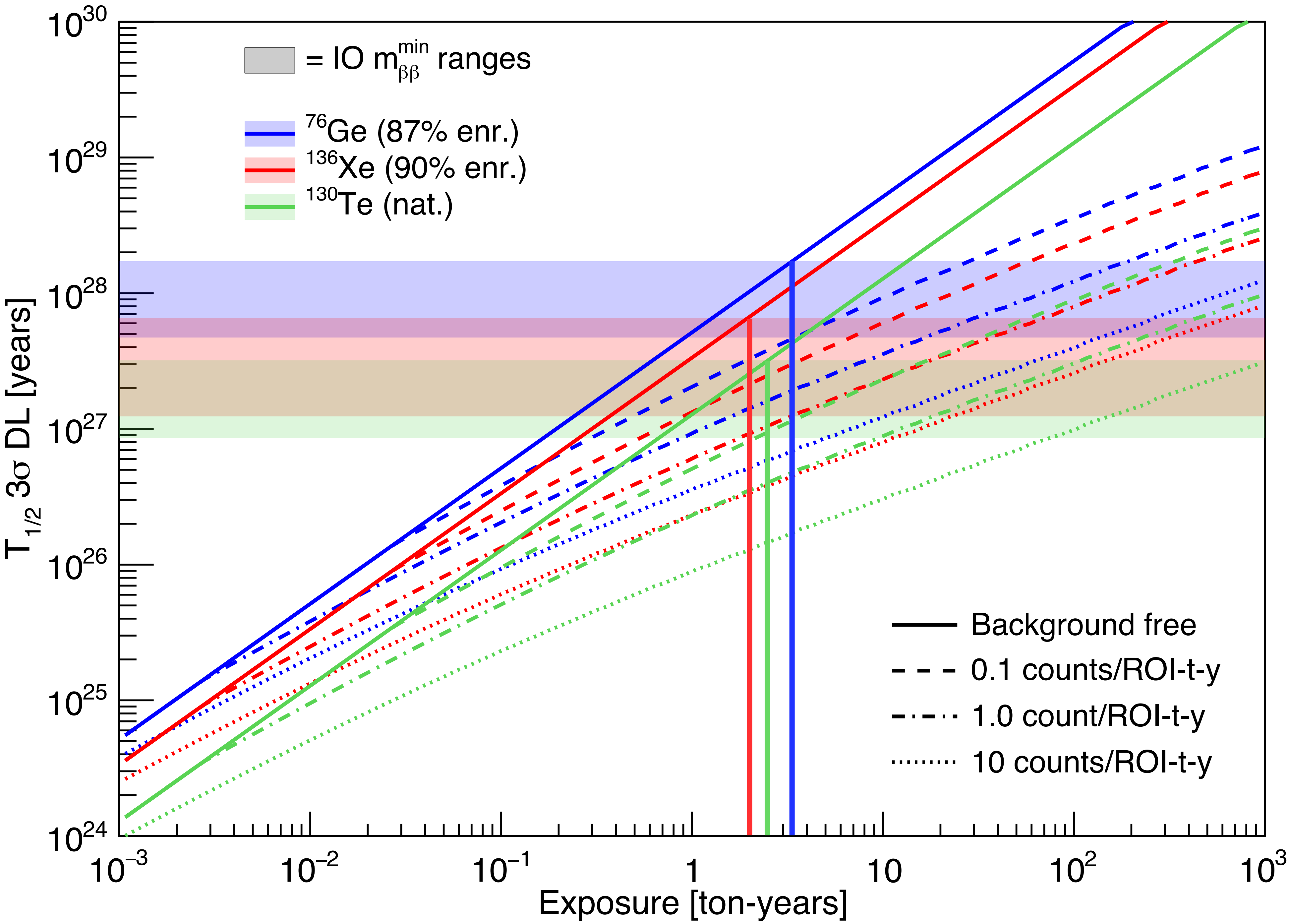
3σ Discovery vs. Exposure

J. Detwiler



3σ Discovery vs. Exposure

J. Detwiler

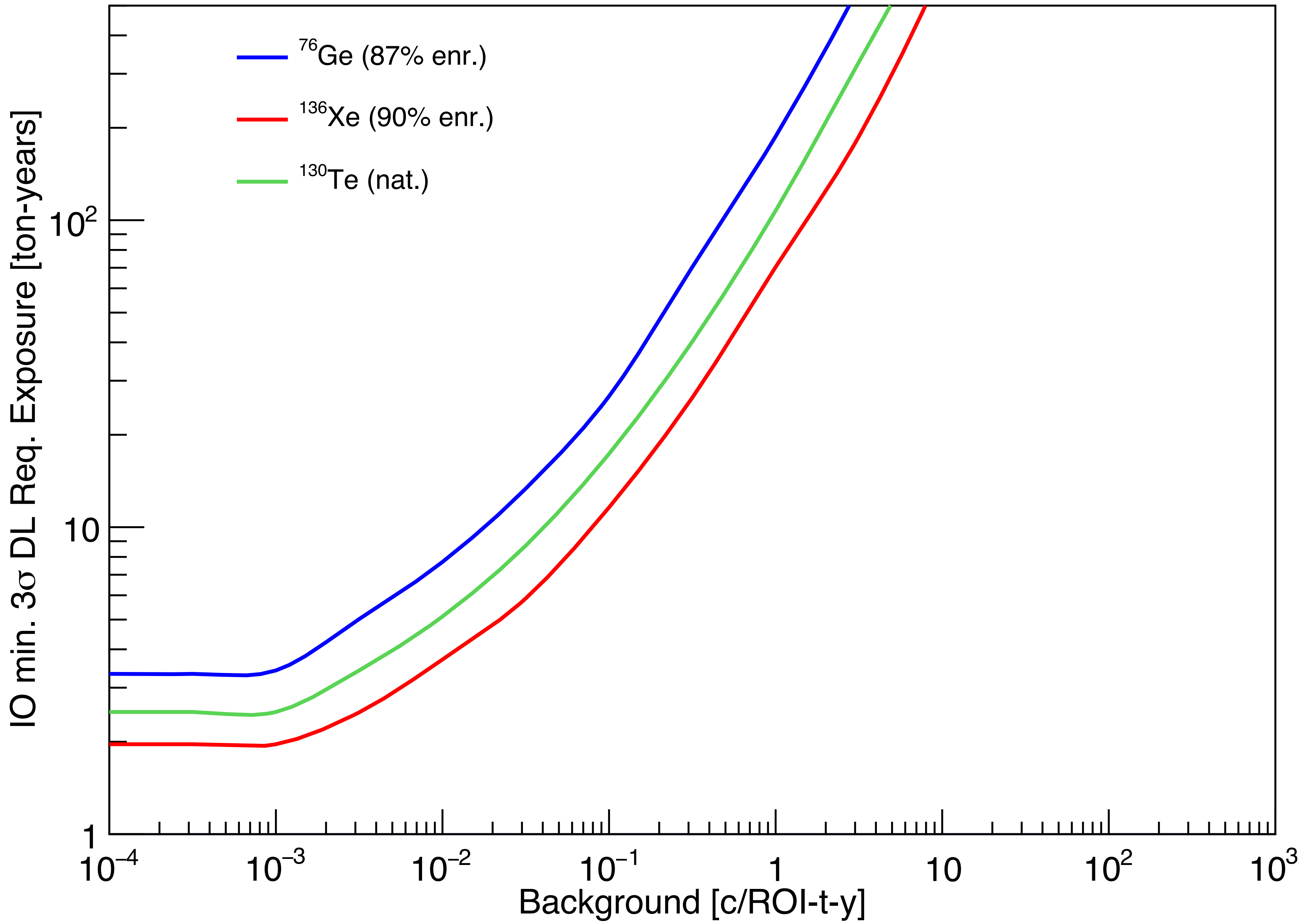


Conclusion:

Based on current knowledge, and planned enrichment levels, isotopes have roughly comparable sensitivities per unit mass, when comparing for the best case of zero backgrounds.

Required 3σ Exposure vs. Background

J. Detwiler

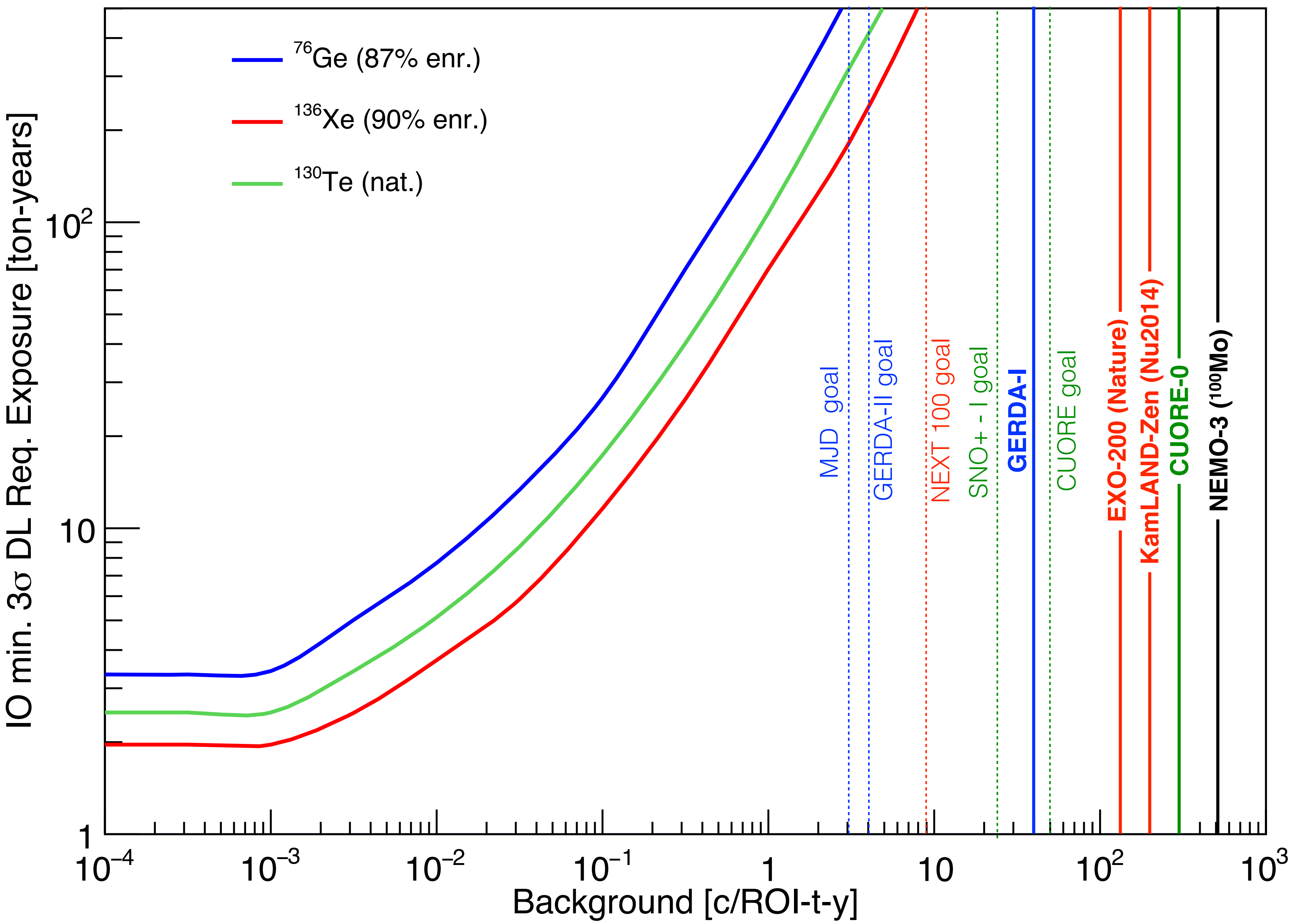


"Required" exposure assuming minimum IO $m_{\beta\beta}$=18.3 meV, taken from using the PDG2013 central values of the oscillation parameters, and the most pessimistic NME for the corresponding isotope among QRPA, SM, IBM, PHFB, and EDF

Note : Region of Interest (ROI) can be single or multidimensional (E, spatial, …)

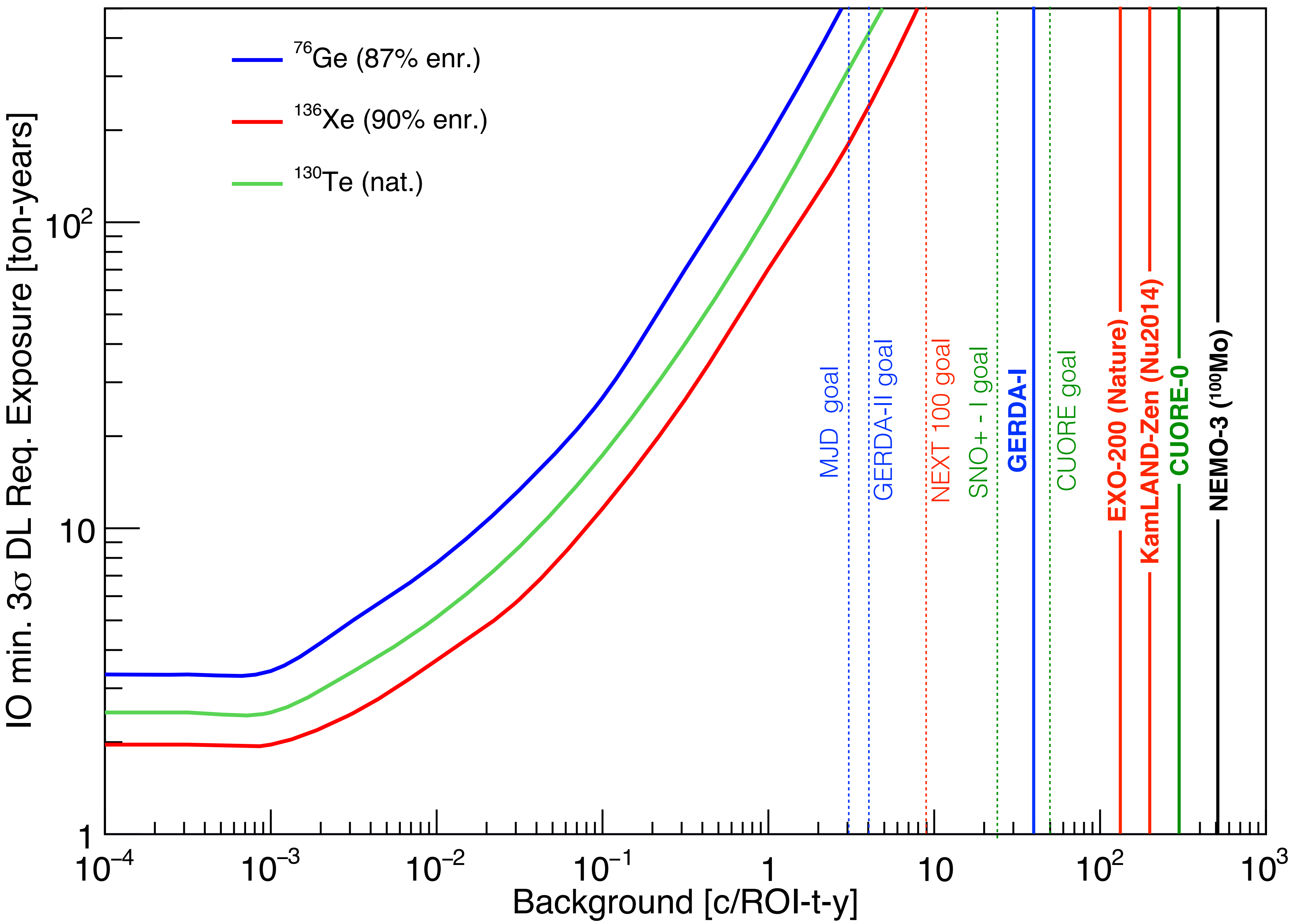
3σ Discovery vs. Background

J. Detwiler



3σ Discovery vs. Background

J. Detwiler

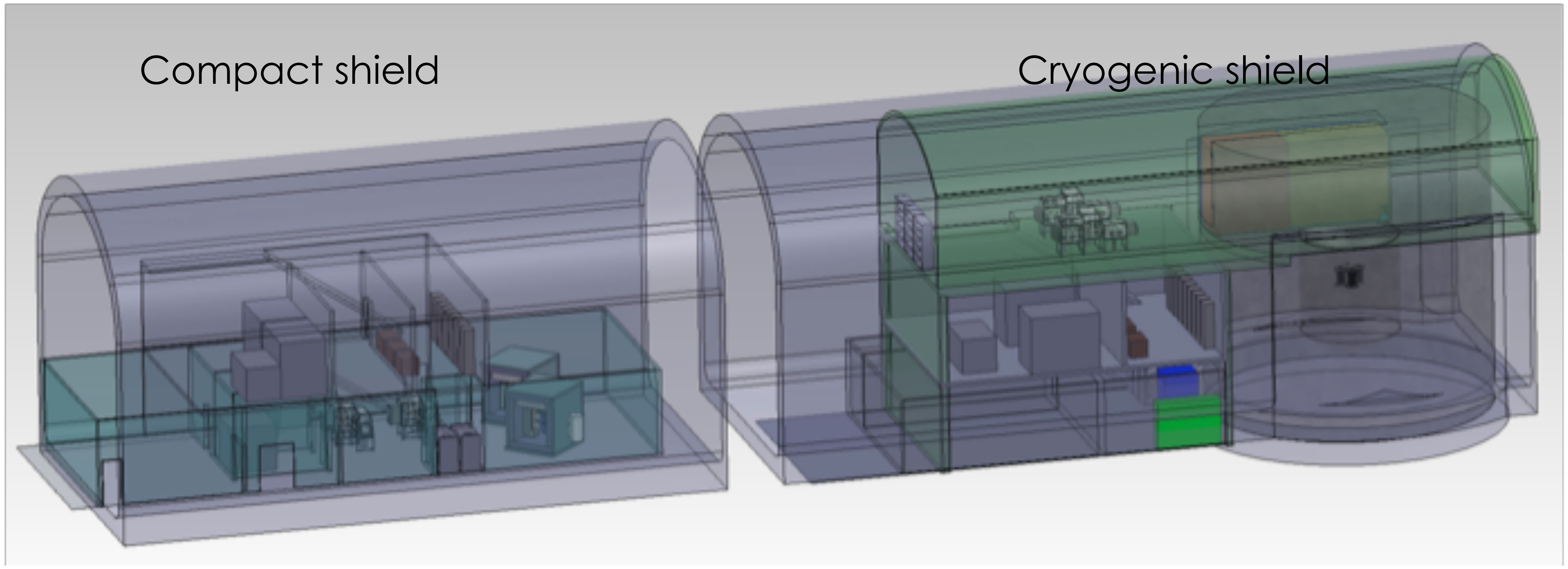


Take away:

Realistically, a next generation experiment should aim for backgrounds at or below 0.1 c/ROI-t-y

Next Generation ^{76}Ge

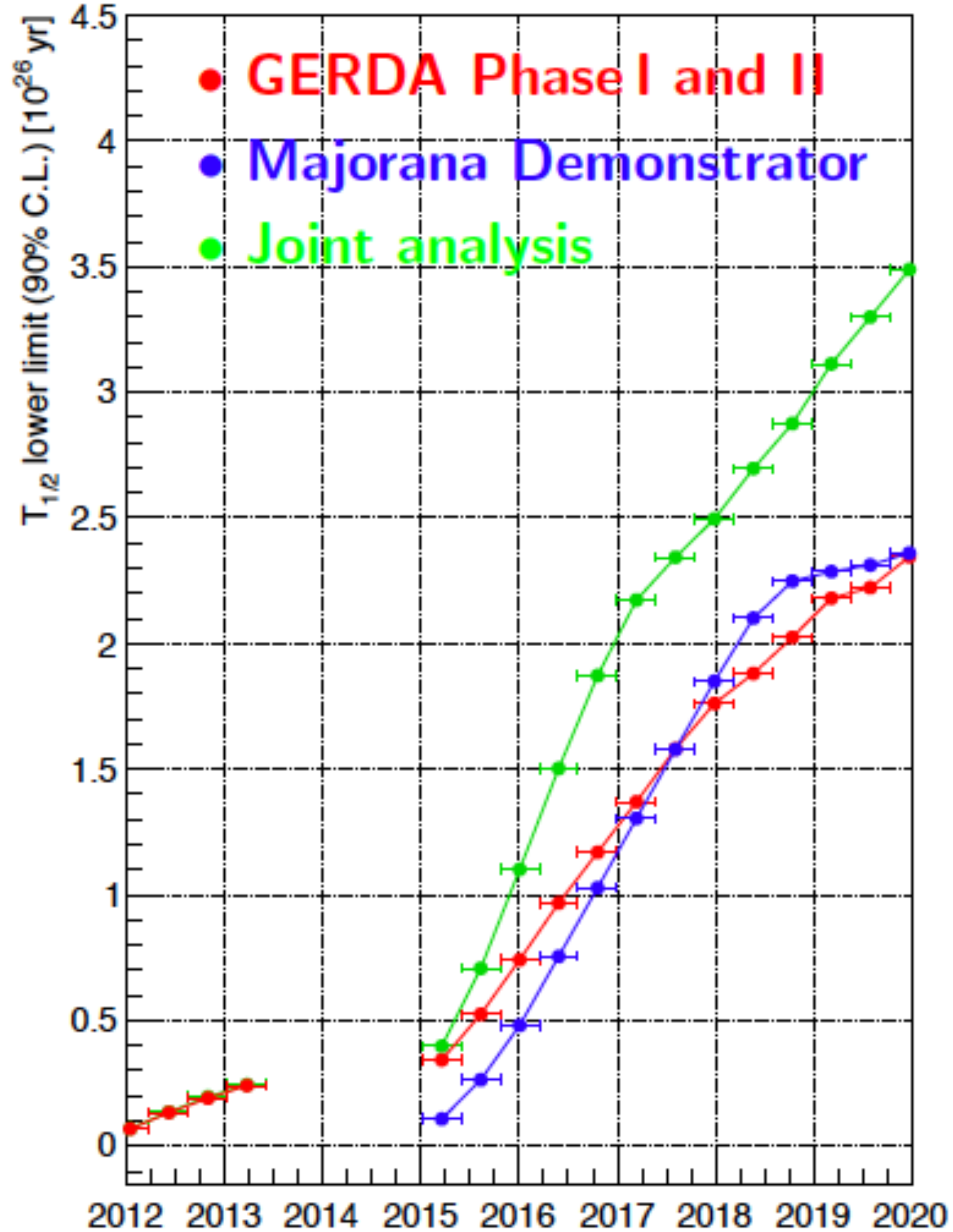
- MAJORANA and GERDA are working towards the establishment of a single international ^{76}Ge 0νββ collaboration.
- Envision a phased, stepwise implementation;
  e.g. 250 → 500 → 1000 kg
- Assuming background of 0.1 c / ROI-t-y
  5 yr 90% CL sensitivity: $T_{1/2} > 6.1 \cdot 10^{27}$ yr
  5 yr 3σ discovery: $T_{1/2} \sim 5.9 \cdot 10^{27}$ yr
- Moving forward predicated on *demonstration* of projected backgrounds by MJD and/or GERDA, and eventual further reductions at the large scale.
- Anticipate down-select of best technologies, based on results of the two experiments.



Towards a Ton Scale 0νββ Experiment

- Recent & Upcoming Joint meetings
  - MAJORANA - GERDA, Sept. 2013, Santa Fe
  - Sino-German Ge Workshop, May 2014, Beijing,
  - Large Scale 0ββ, July 2014 MPP Munich
  - MAJORANA - GERDA, Dec. 2014, Heidelberg
  - Sino-German Ge Workshop, October 2015, Kreuth, Germany
  - MJD-GERDA, Nov. 2015, Kitty Hawk, NC
  - Open Ton Scale Ge Meeting, Spring 2016

- MAJORANA - GERDA
  - Considering joint analysis of combined data from GERDA Phase II and MJD
  - MaGe Simulations framework
  - Coordinated efforts on large scale R&D
  - Discussions on potential first "staging" for ton scale, 200 kg

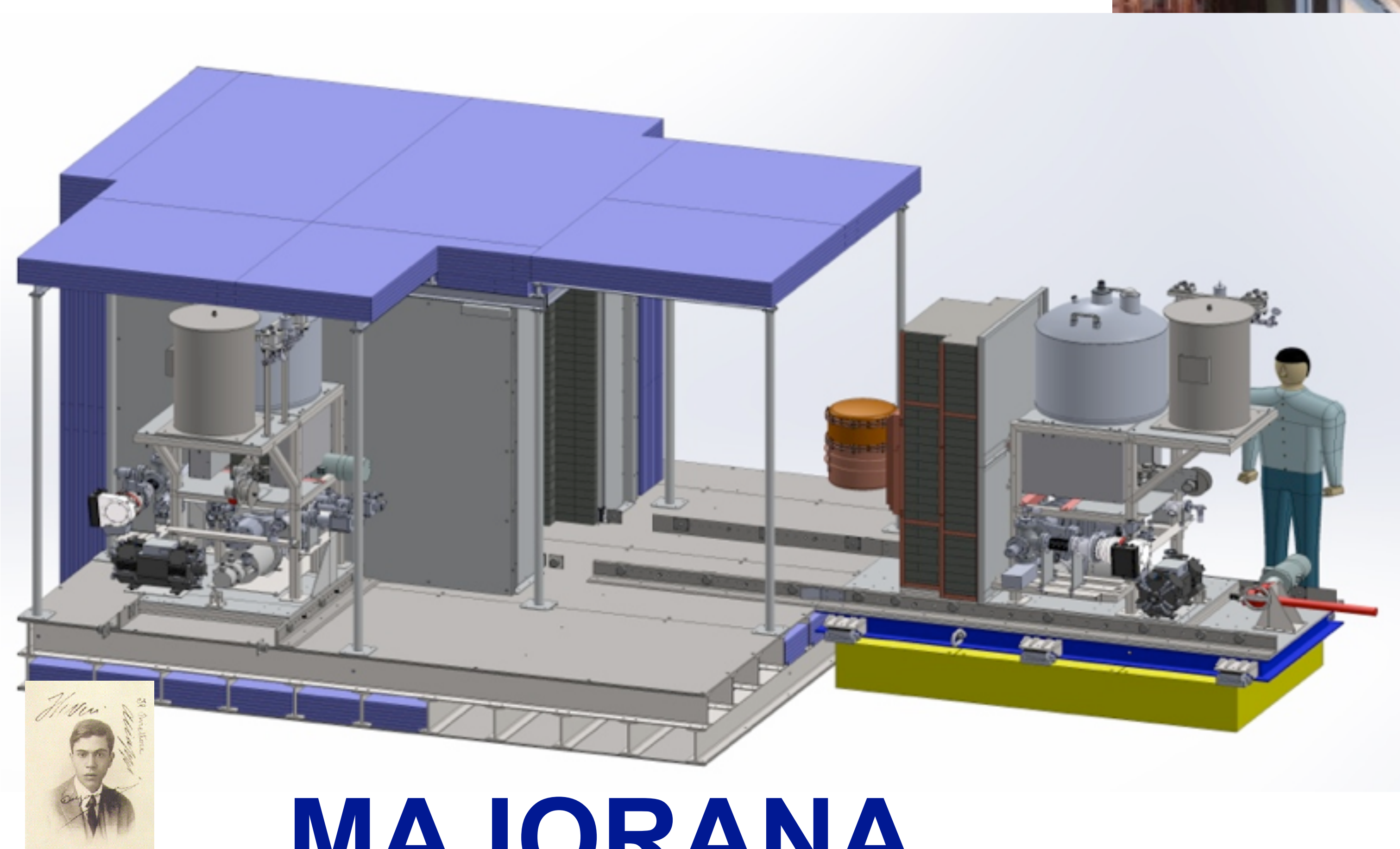


Matteo Agostini, TUM, GERDA
arXiv:1506.06133

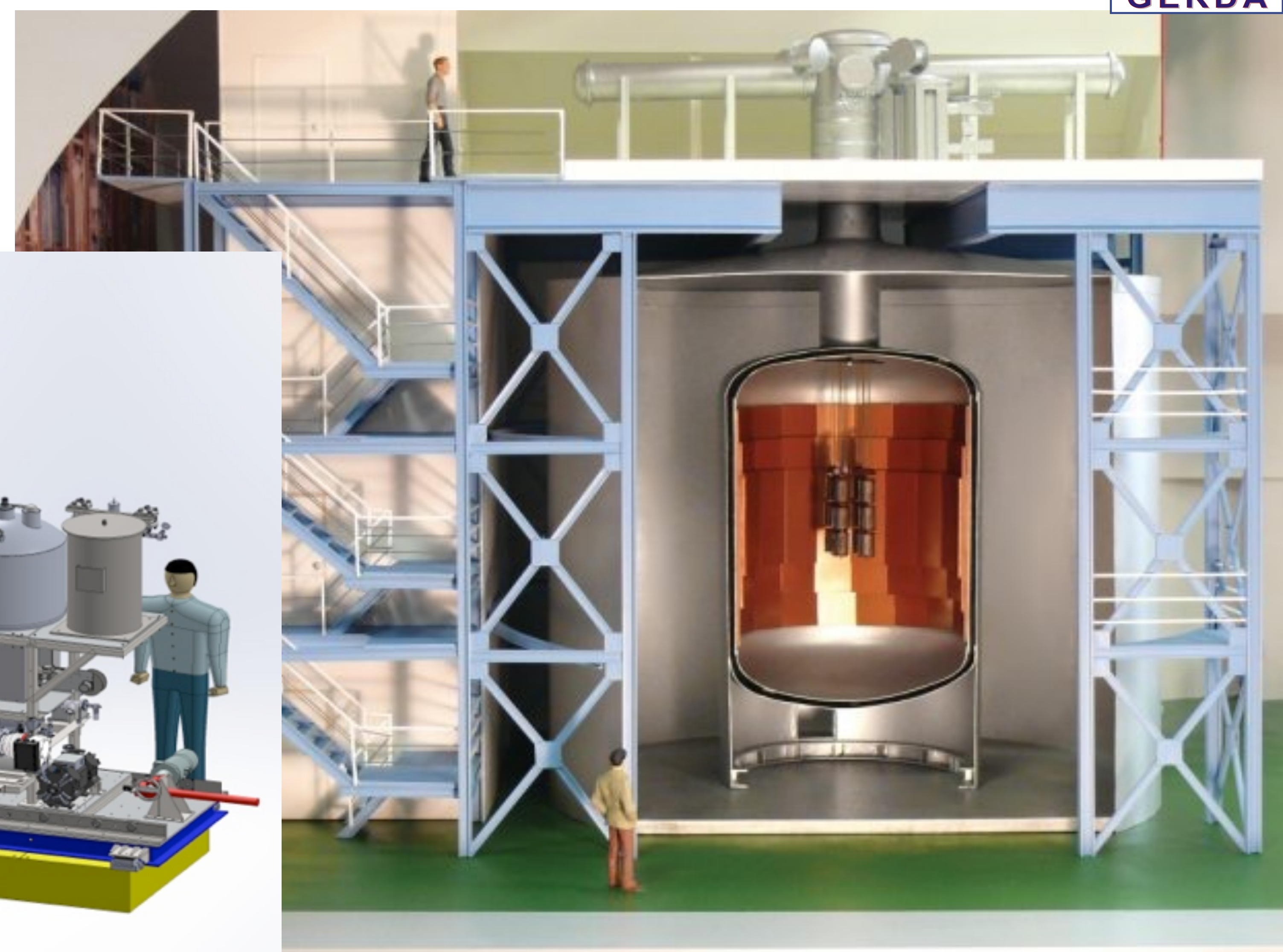
Background Reduction Techniques

- MAJORANA — Ultrapure Cu & Pb
  - Vacuum cryostat
  - Passive Pb & Cu compact shield

- GERDA — Liquid Argon and Water Shield
  - Bare Detectors in cryoliquid
  - Low-Z active shield

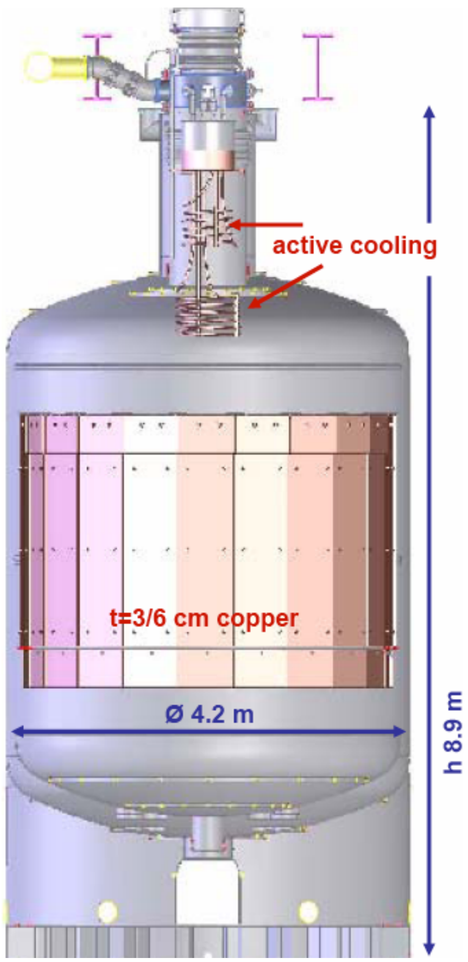


MAJORANA

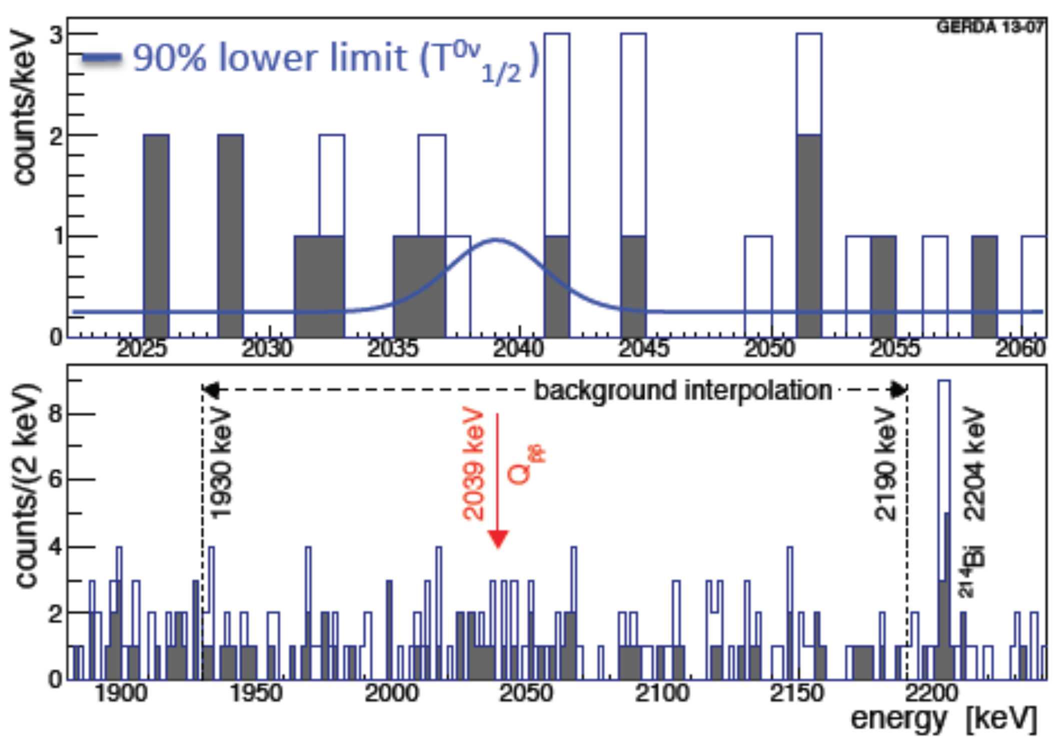


GERDA

GERDA ^{76}Ge Phase I (2014)



- 87% enriched ^{76}Ge detectors (crystals) in LAr
- $Q_{\beta\beta}$=2039 keV
- 14.6 kg of 86% enriched ^{76}Ge (6 p-type semi-coax detectors from H-M & IGEX). (4.8 keV FWHM @ $Q_{\beta\beta}$)
- 3 kg of 87% enriched BEGe enriched detectors (5 detectors) (3.2 keV FWHM @ $Q_{\beta\beta}$)
- Single-site, multi-site pulse shape discrimination

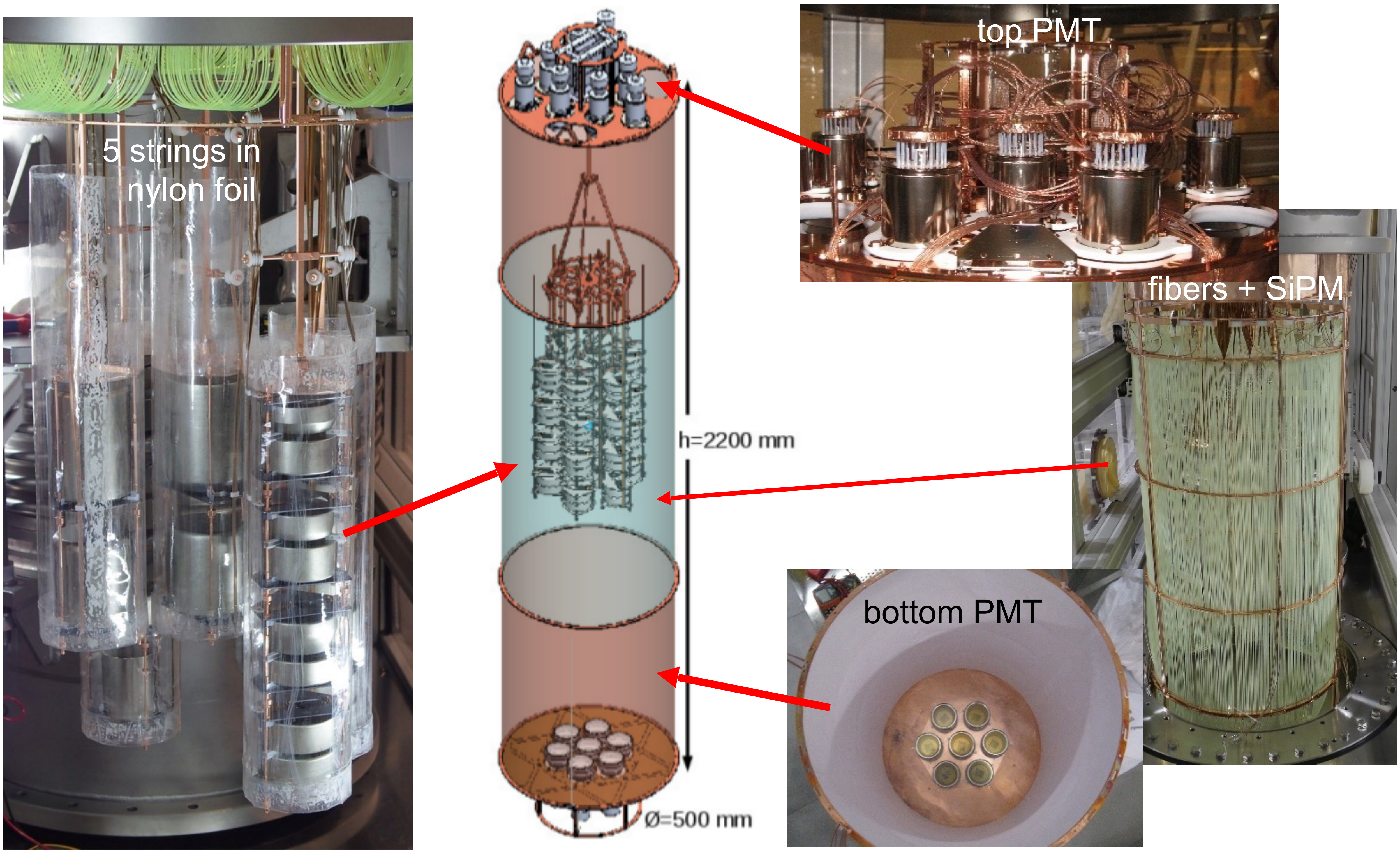


- 21.6 kg-year exposure
- Frequentist
  $T_{1/2} > 2.1 \times 10^{25}$ y (90% CL)
- Bayesian
  $T_{1/2} > 1.9 \times 10^{25}$ y (90% CL)

GERDA Collaboration, PRL 111 (2013) 122503
Eur. Phys. J. C (2014) 74:2764

GERDA Phase II

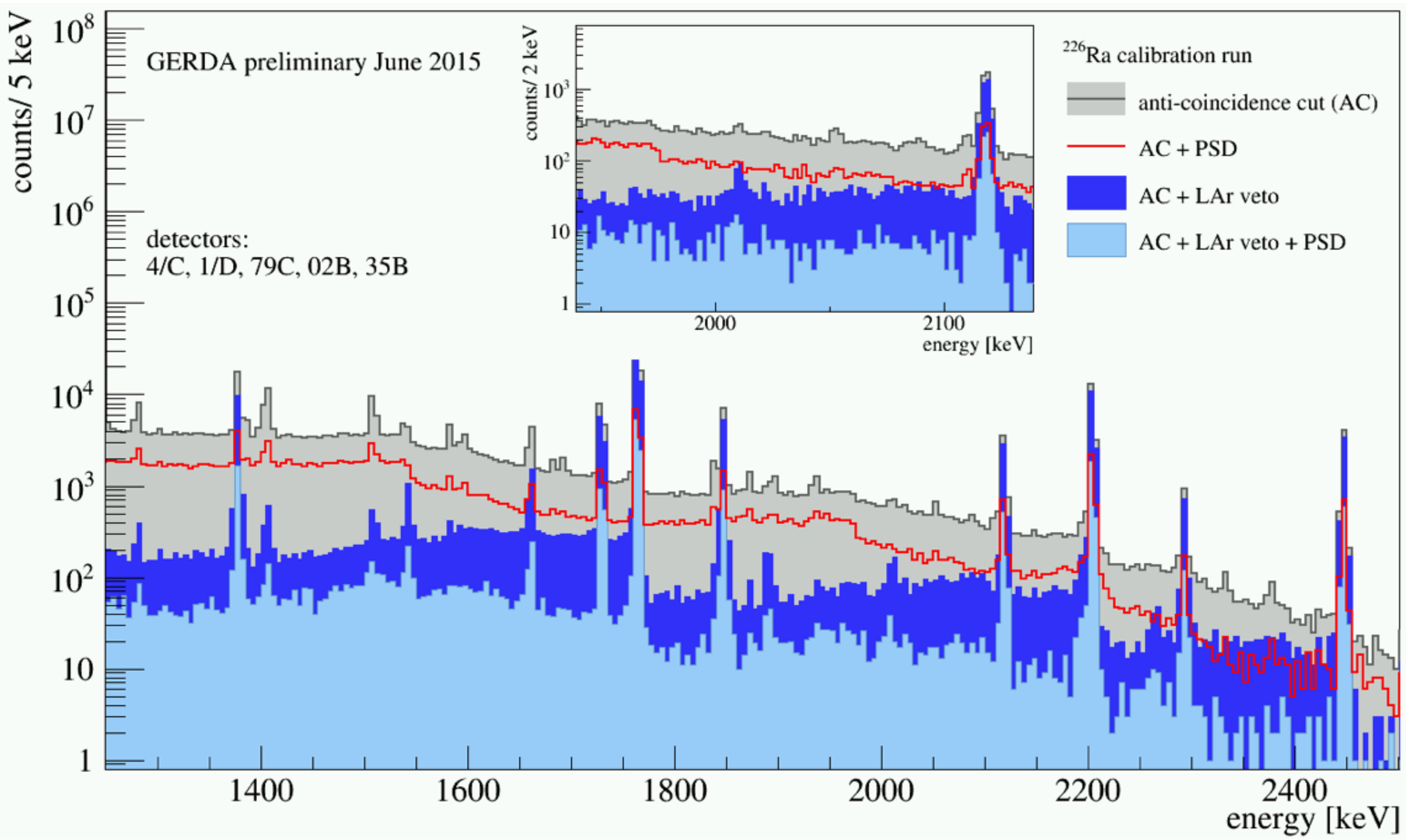
modified almost everything relative to Phase I, now: veto + most detectors installed



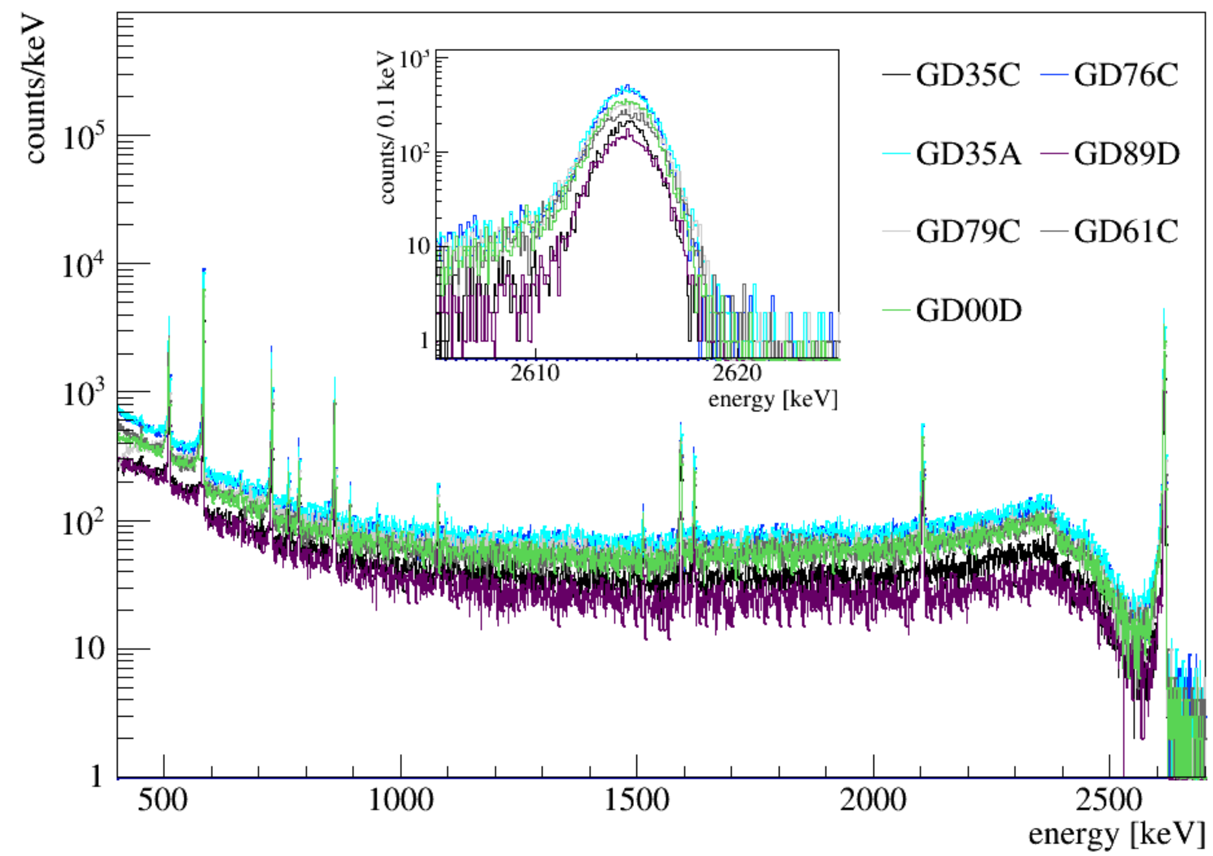
Initial Performance with Active Shield

GERDA

226Ra calibration data



Preliminary 228Th calibration (1 string)



combined rejection ~30 at 2039 keV (90% accept.)
for 228Th calibration source rejection factor ~300

energy resolution @ 2.6 MeV between 2.6 and 3.4 keV (FWHM) for BEGe

past dominant backgrounds expected to become small in Phase II

noise still to be improved for some det., some detectors have high current and might need repair by manufacturer
→ more iterations before Physics run

Challenges Beyond Phase II

- Background: for quasi-background-free operation beyond Phase II need to further reduce backgrounds
  - argon veto & cleaner materials (e.g. Cu, PTFE a la MJD)→ **Ra** & **Th** should be ok
  - **^{42}Ar**: needs further study e.g. in (existing) test cryostat
    - options: thicker n+ layer, limit volume from which **^{42}Ar** is collected, PSD, depleted Ar, …
  - **muon** induced background e.g. neutrons → ^{77m}Ge, cut on delayed coincidences

- Argon veto: need to detect light produced inside a compact array of detectors,
  - need to reduce radioactivity

- Detector operation: in Phase I 2 of 8 detectors had higher current after 18 months
  - operation; could be cured at LNGS. What fraction in Phase II?

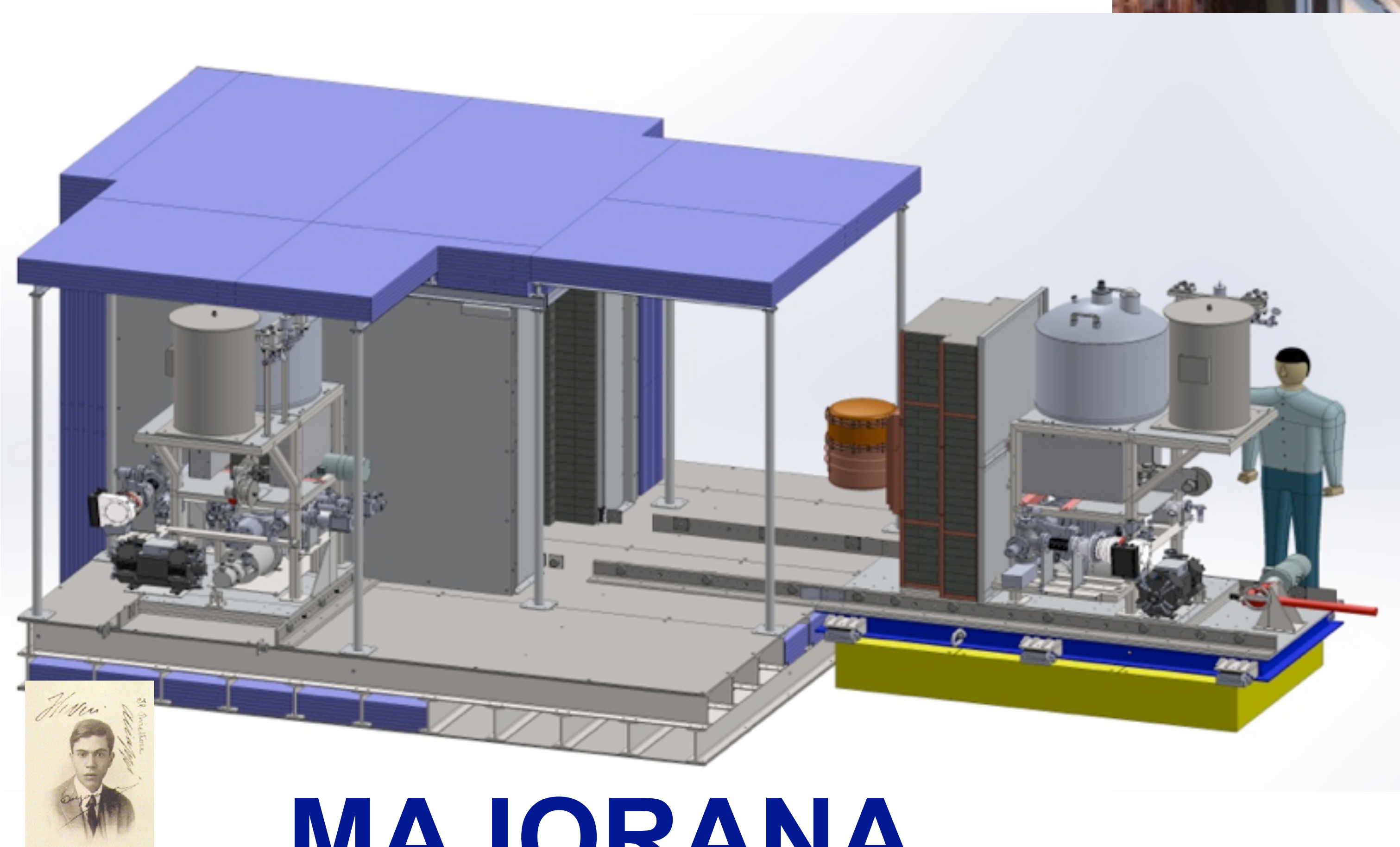
- Engineering for large number of detectors (e.g. feedthroughs, cable chains, …)
  - no fundamental problem, might need iterations → cost + time

Experience from Phase II running extremely important for any future large scale Ge experiment

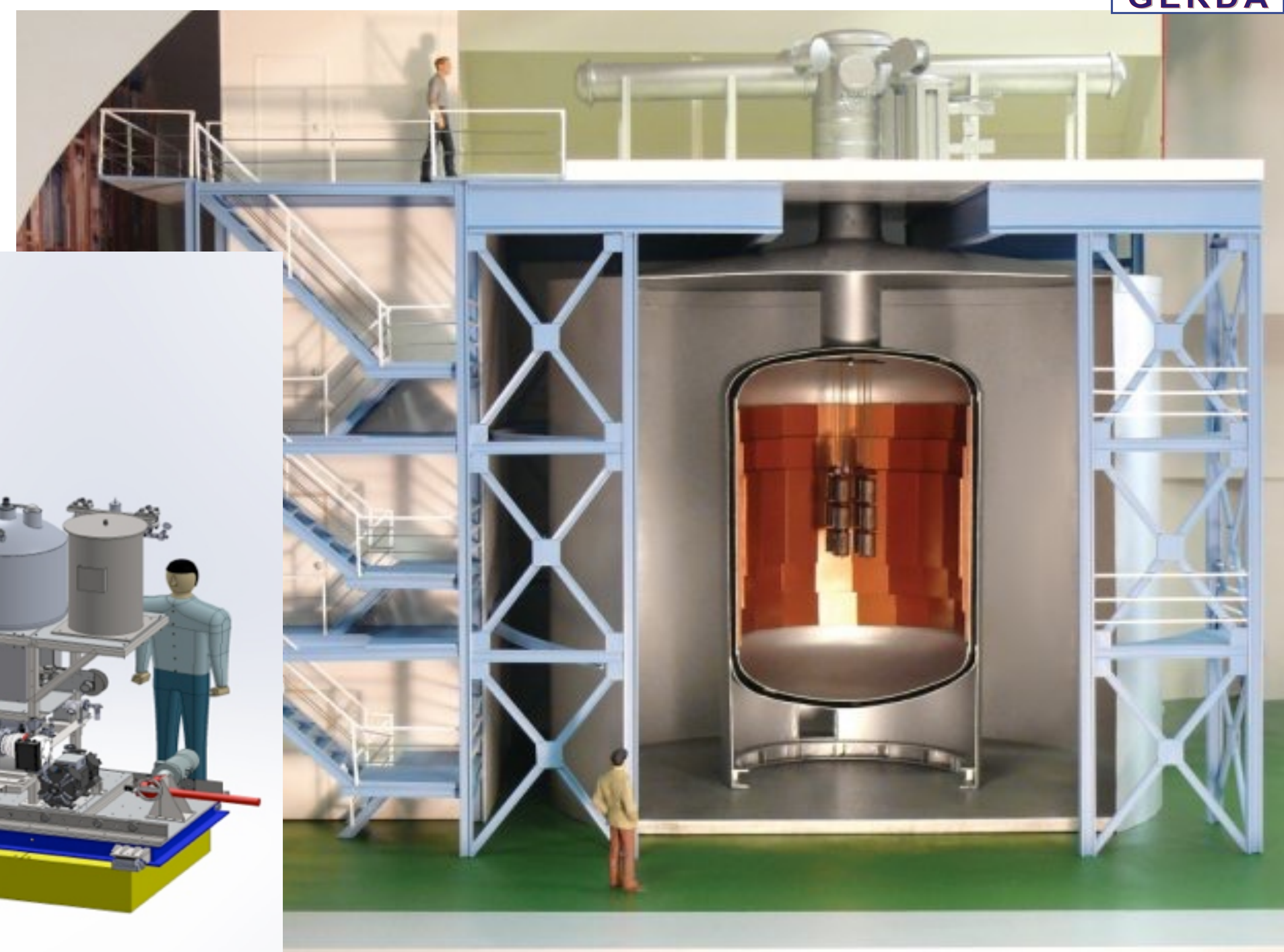
Background Reduction Techniques

- MAJORANA — Ultrapure Cu & Pb
  - Vacuum cryostat
  - Passive Pb & Cu compact shield

- GERDA — Liquid Argon and Water Shield
  - Bare Detectors in cryoliquid
  - Low-Z active shield



MAJORANA

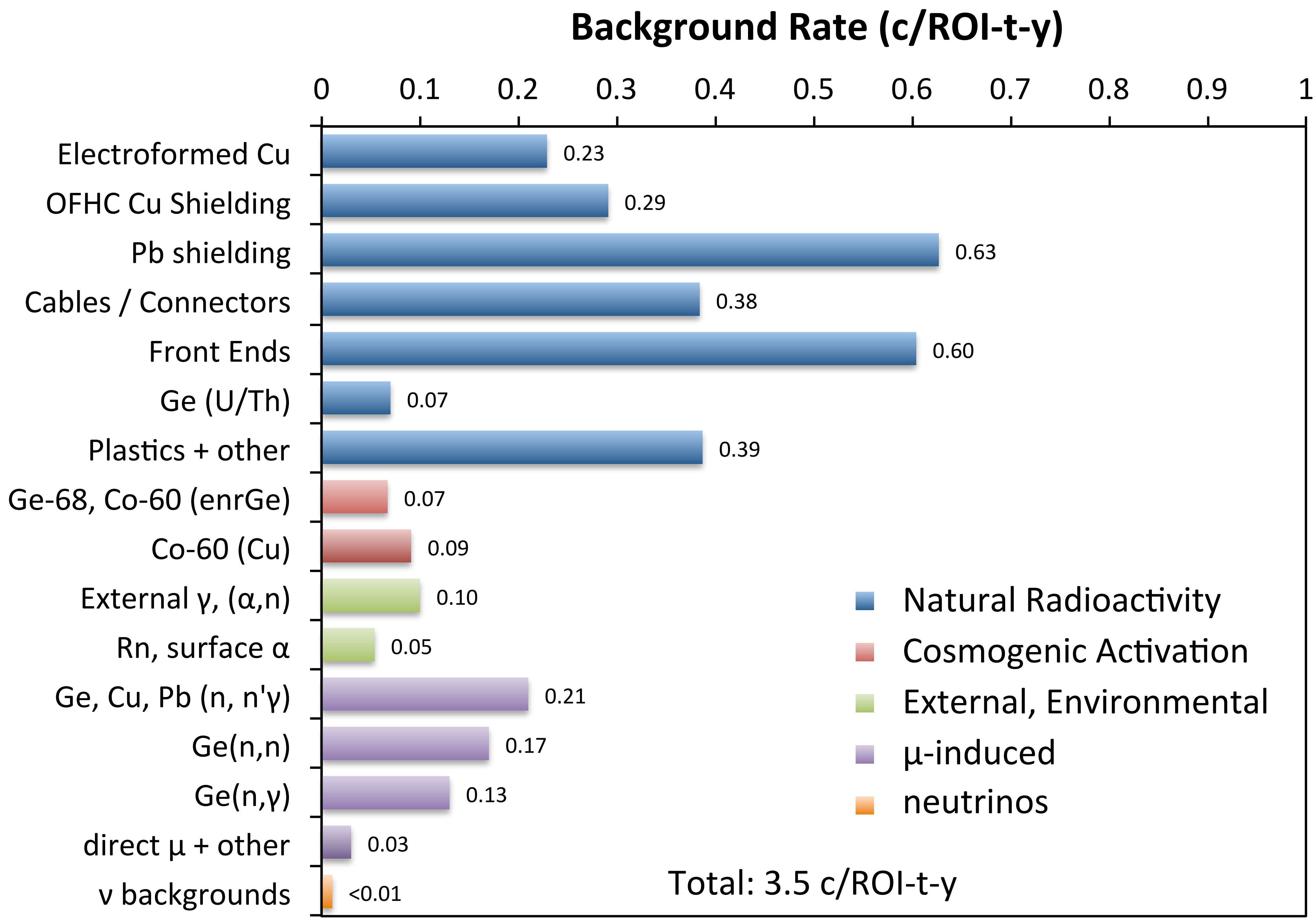


GERDA

DEMONSTRATOR Background Budget

Based on achieved assays of materials
When UL, use UL as the contribution

Goal: ≤ 3.0 cts / ROI-t-y
(Scales to 1.0 cts / ROI-t-y for a larger experiment)

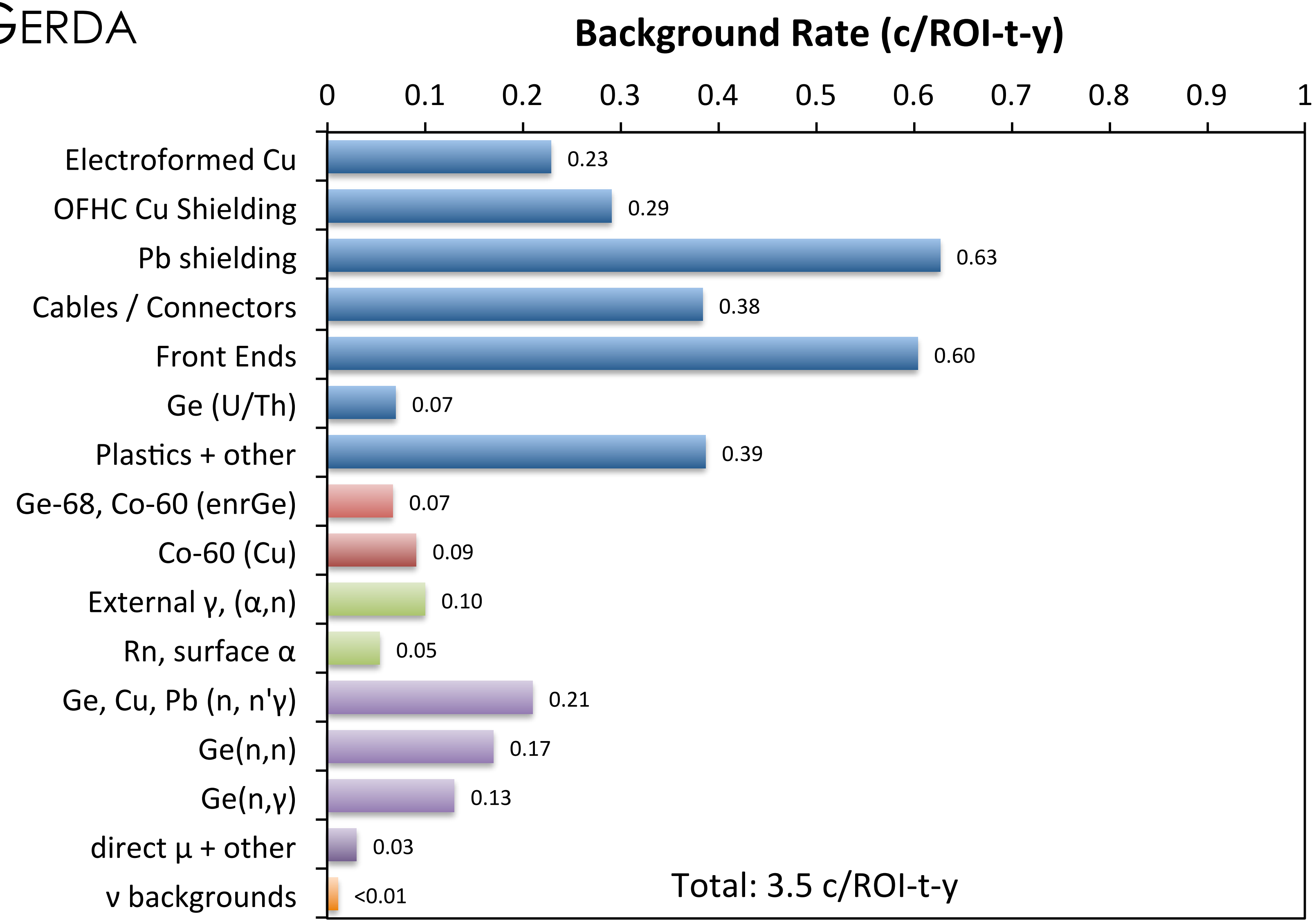


Next-Generation Experiment

If MJD and GERDA Phase II reach their background goals of 3-4 c/ROI-t-y, that would scale to 1 c/ROI-t-y for a large scale Ge experiment.

Based on both discovery level and sensitivity considerations, would like to aim for a total background budget of ≤ 0.1 c/ROI-t-y.

Building on MAJORANA and GERDA how does one get there?



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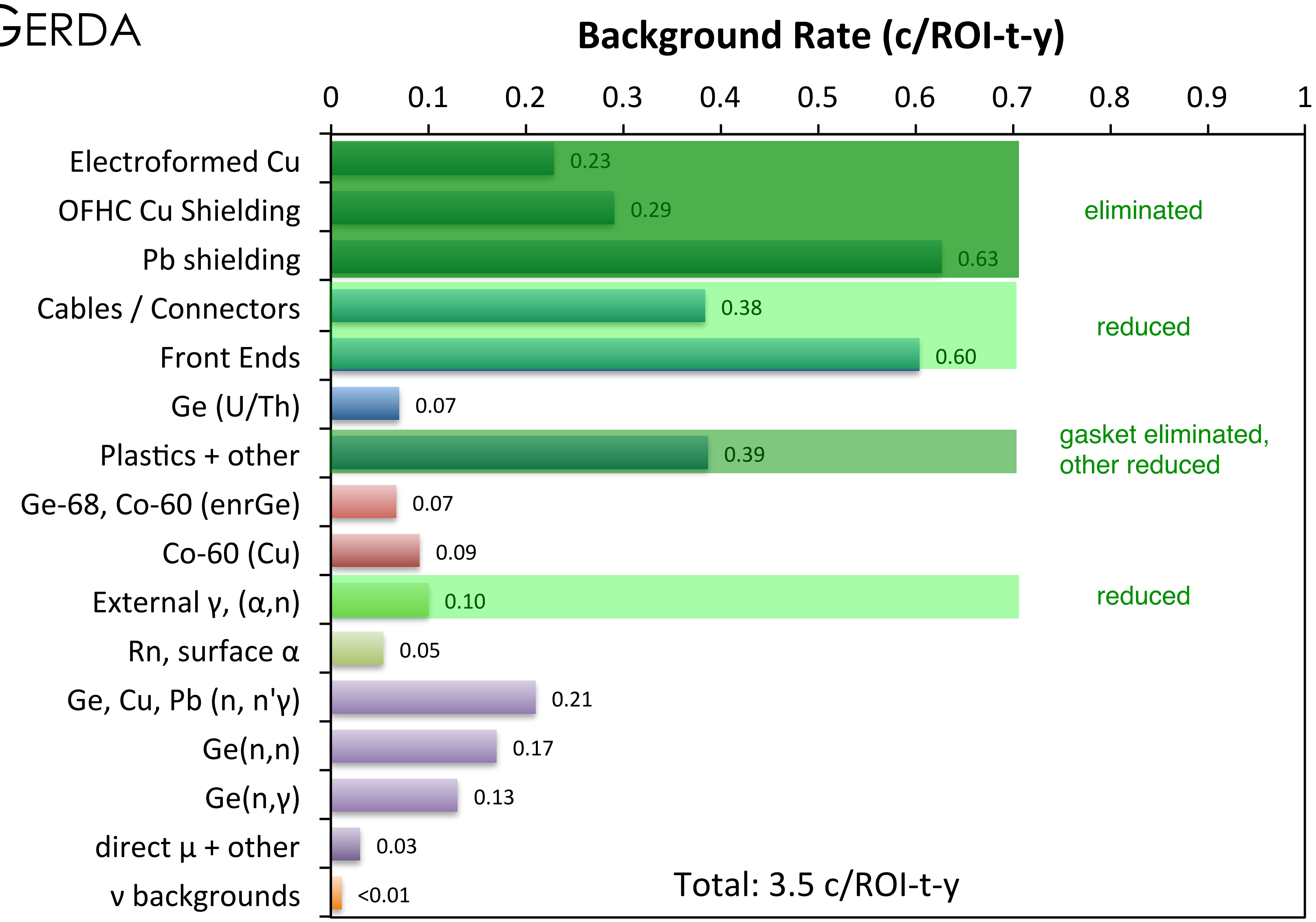
Building on MAJORANA and GERDA how does one get there?

- clean, active shield



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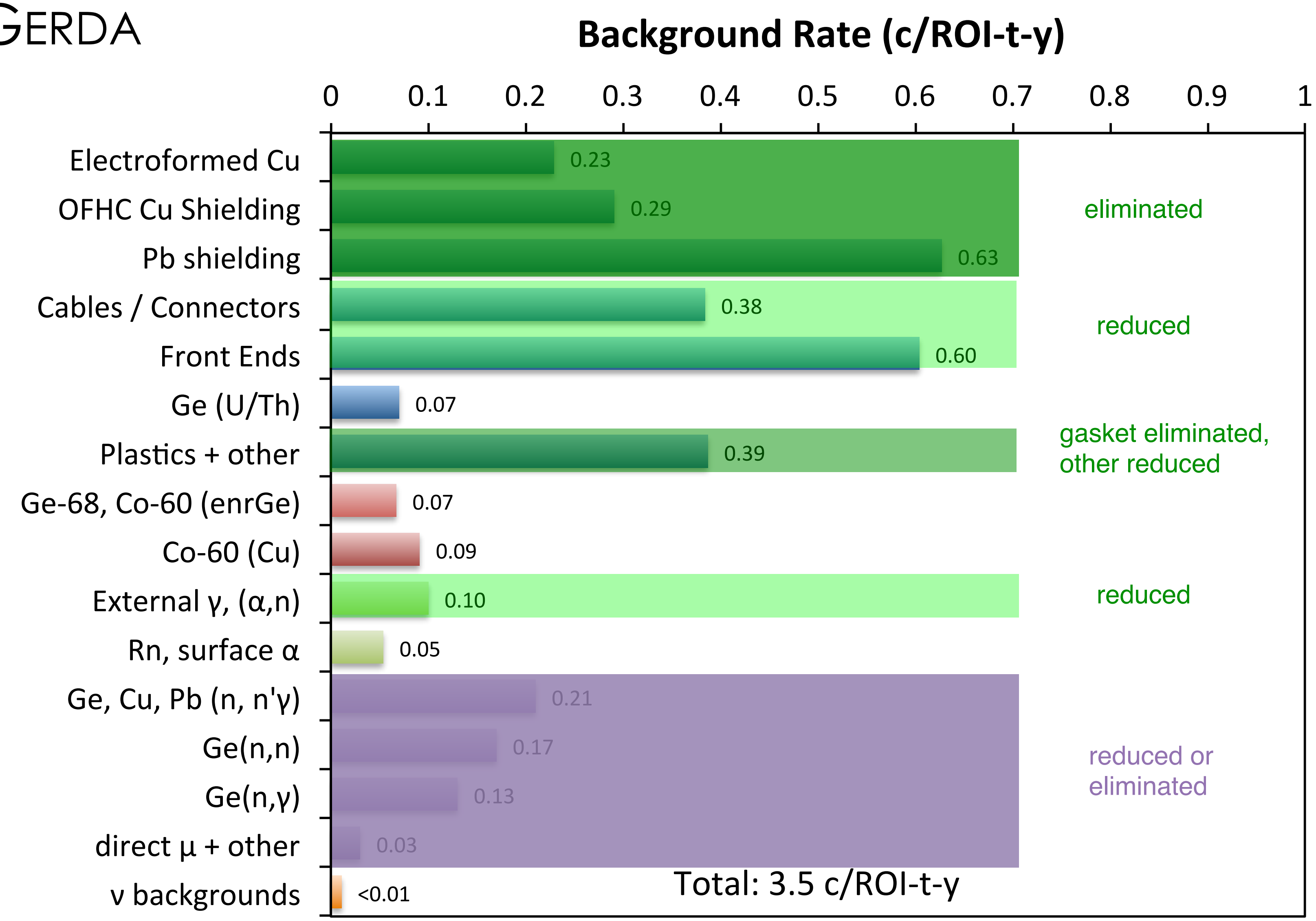
Building on MAJORANA and GERDA how does one get there?

- clean, active shield
- deeper and/or active shield



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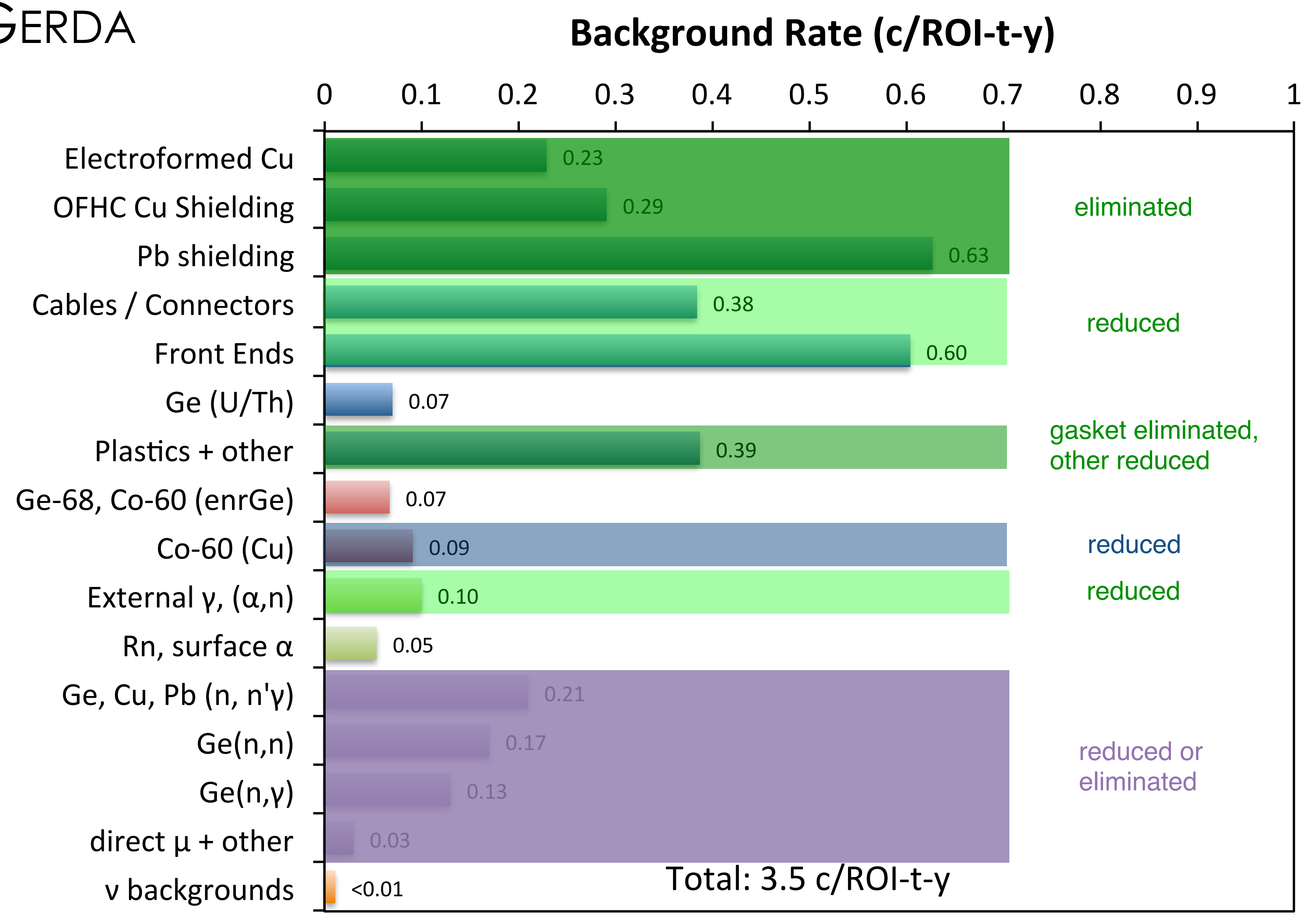
Building on MAJORANA and GERDA how does one get there?

- clean, active shield
- deeper and/or active shield
- EF all Cu underground



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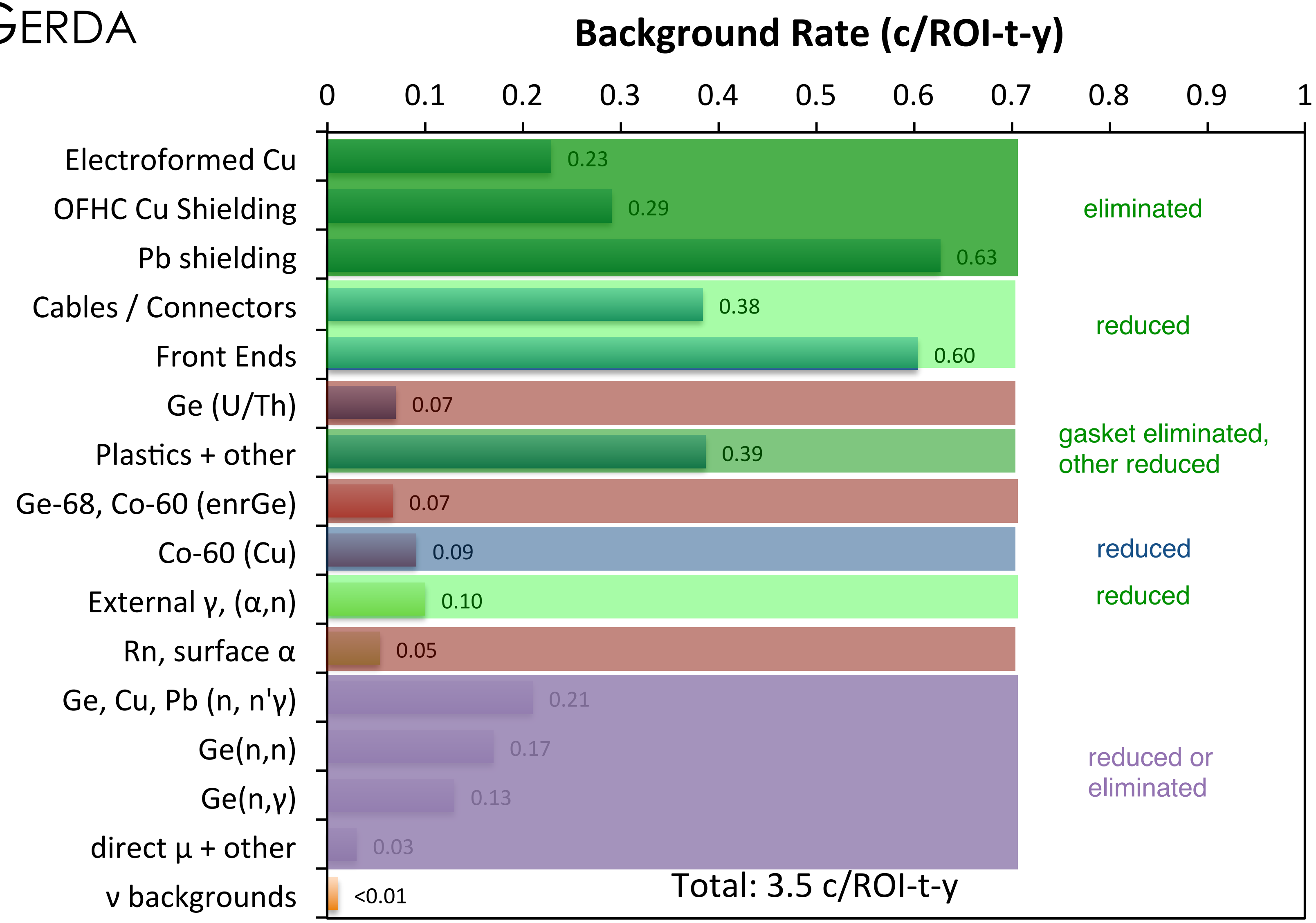
Based on both discovery level and sensitivity considerations, would like to aim for a total background budget of ≤ 0.1 c/ROI-t-y.

Building on MAJORANA and GERDA how does one get there?

- clean, active shield
- deeper and/or active shield
- EF all Cu underground
- Learn from MJD & GERDA II (values are largely upper limits)



Next Generation 0νββ R&D

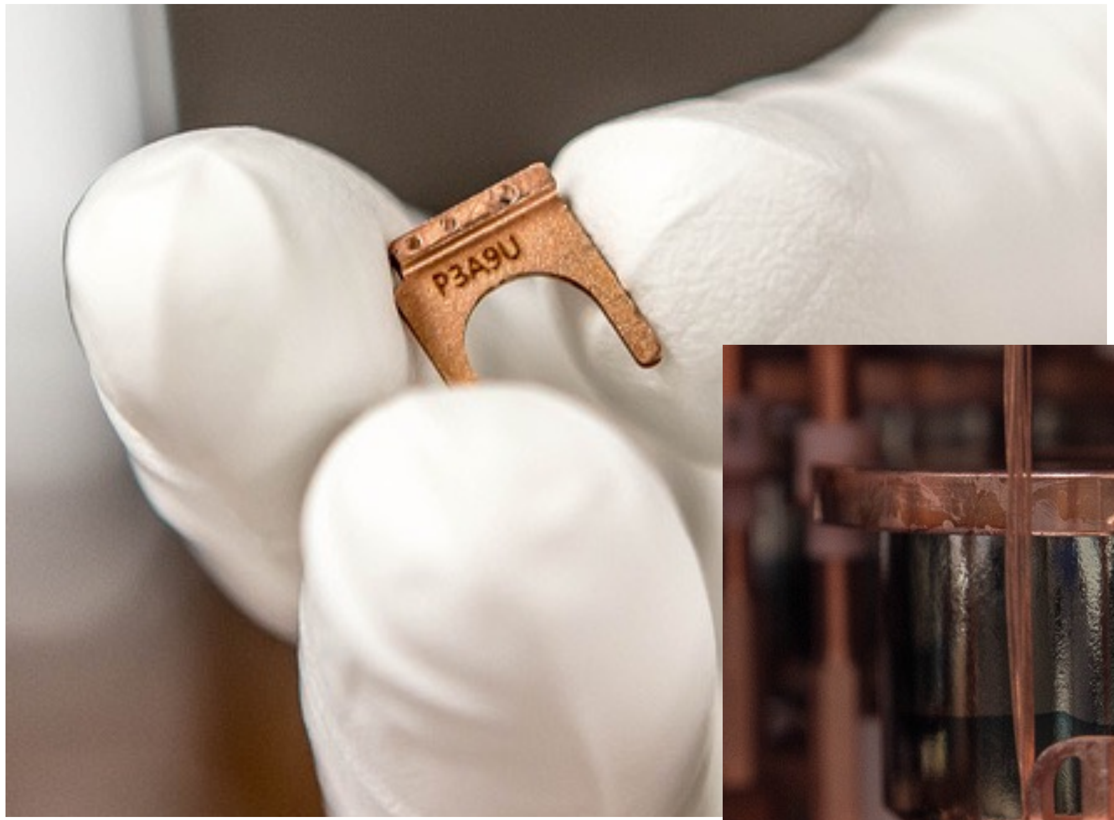
- Robust Signal and High Voltage Connectors
- Ultra-Clean Materials
- Required depth
- Cooling and shielding
- Alternative Detector Designs
- Detector Signal Readout
- Cryostat and Detector Mount Designs
- Enrichment

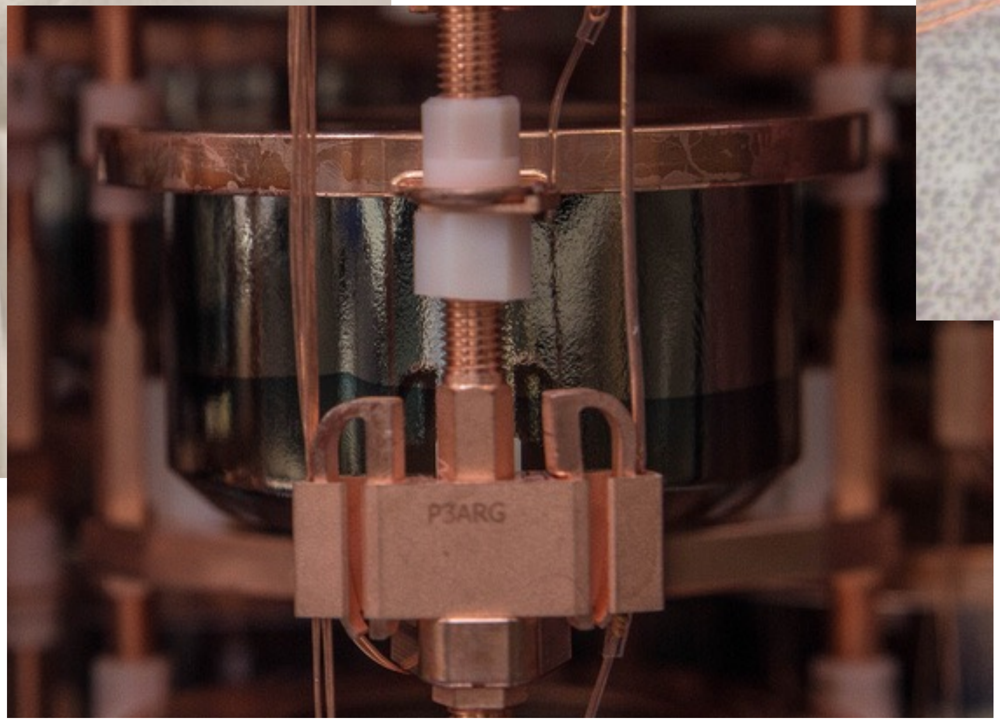
Applicable to any future experiment

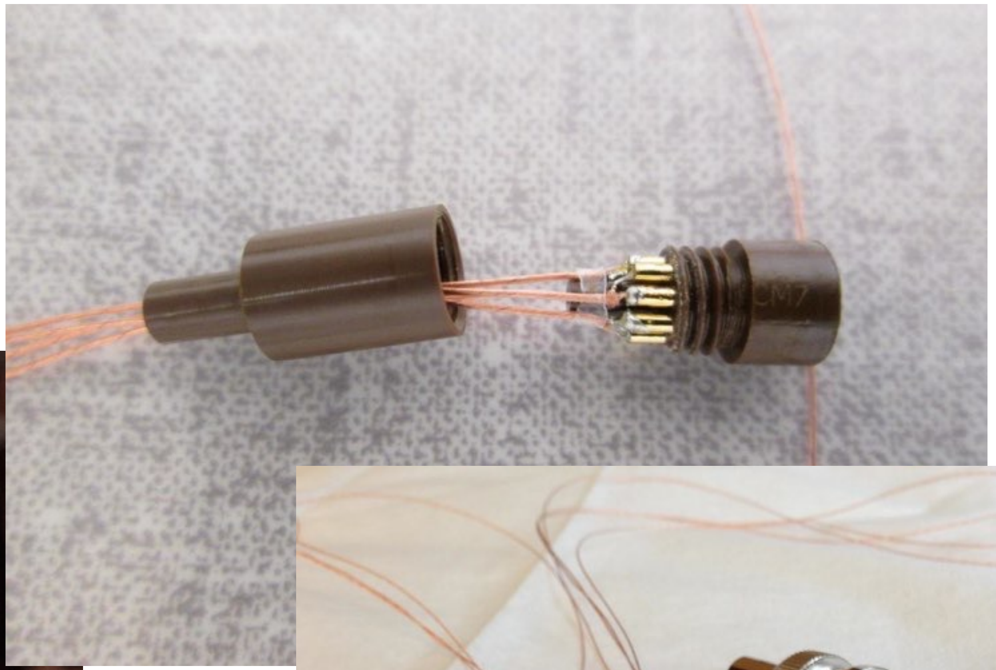
Specific to ^{76}Ge

Robust Signal & High Voltage Connectors

- MAJORANA has produced some of the lowest activity cables and connectors currently in use.
- Tension between low-activity components and robust electrical connections (e.g. clean spring material). Both MAJORANA and GERDA have encountered connection or connector issues.

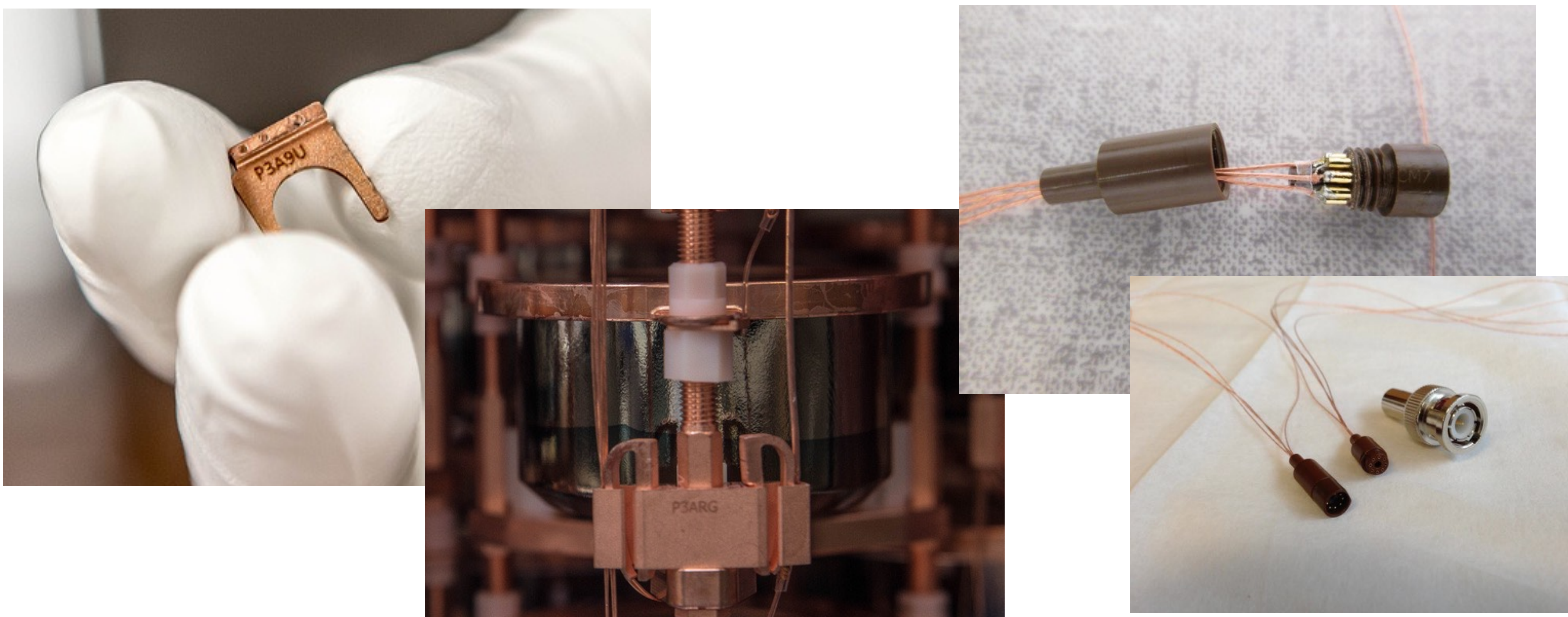






Robust Signal & High Voltage Connectors

- Proposed to apply current knowledge to developing next generation cables, working in conjunction with commercial vendors.
  - Connector design
  - High voltage contact design
  - Improve Cu wire radiopurity
- outcomes from all of these activities can be applied toward or utilized in all the proposed next-generation 0νββ and DM experiments.



Ultraclean Materials

- Improved electroforming with larger mandrels and improved reliability
  - Larger mandrels could allow for more cost-effective production of ultra-clean Cu
  - Would like to optimize process in terms of growth rate

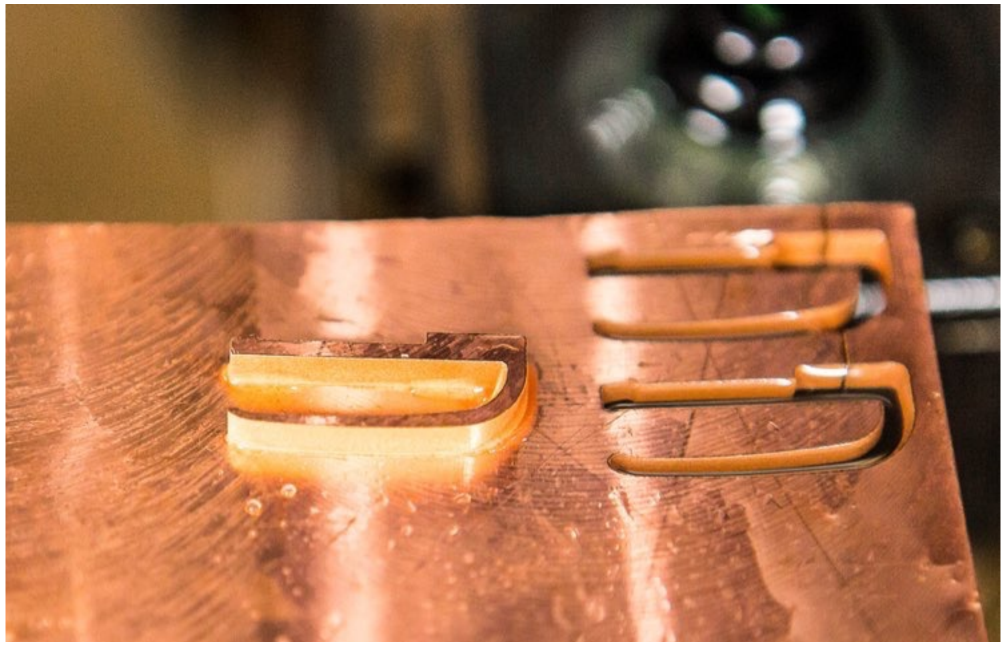
- Electroforming Cu Alloys
  - Copper is ductile and difficult to machine
  - Additional materials will simplify mechanical designs

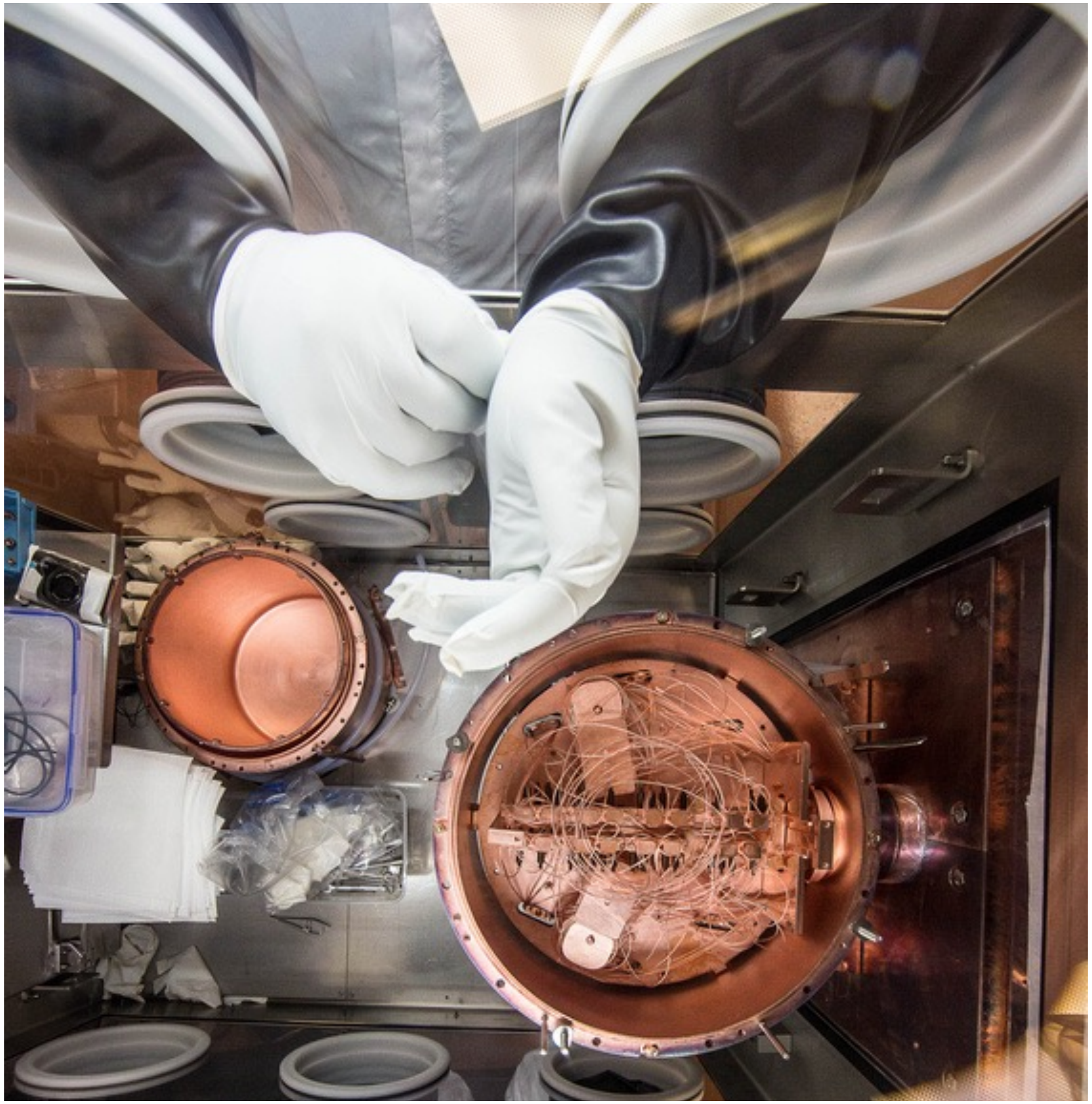
Ultraclean Materials

1.0 μBq/kg 228Th = 0.2465 ppt

1.0 μBq/kg 238U = 0.08041 ppt

- Have observed that small parts have small measurable activity of U & Th
  (0.2 to 1.0 μBq/kg, while bulk material is at upper limit of sensitivity (≤ 0.1 μBq/kg).
- This has a neglible impact on MJD, but is important for next-generation experiments.





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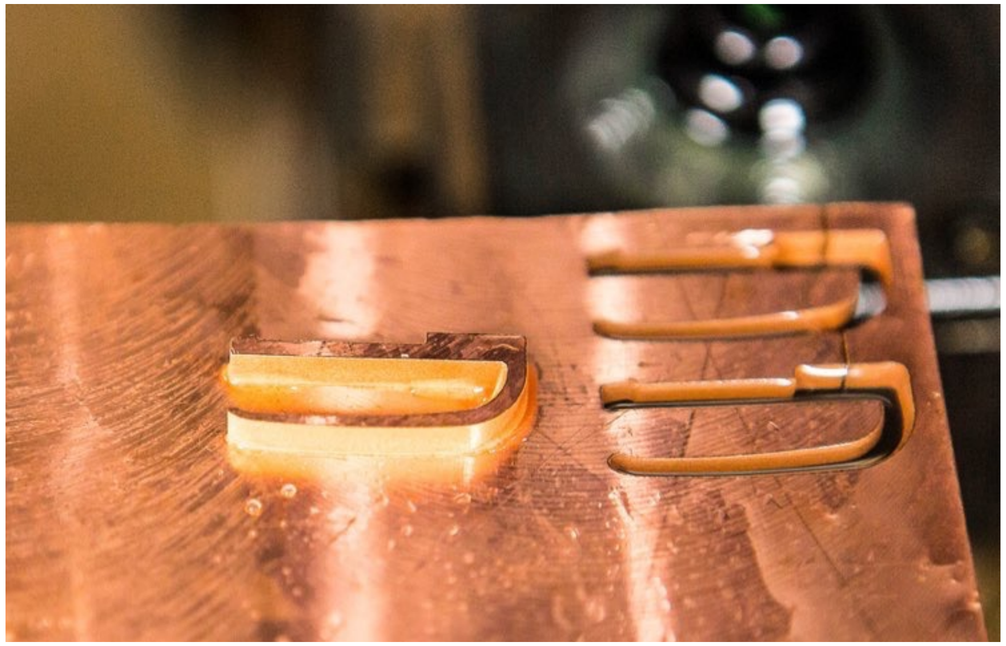
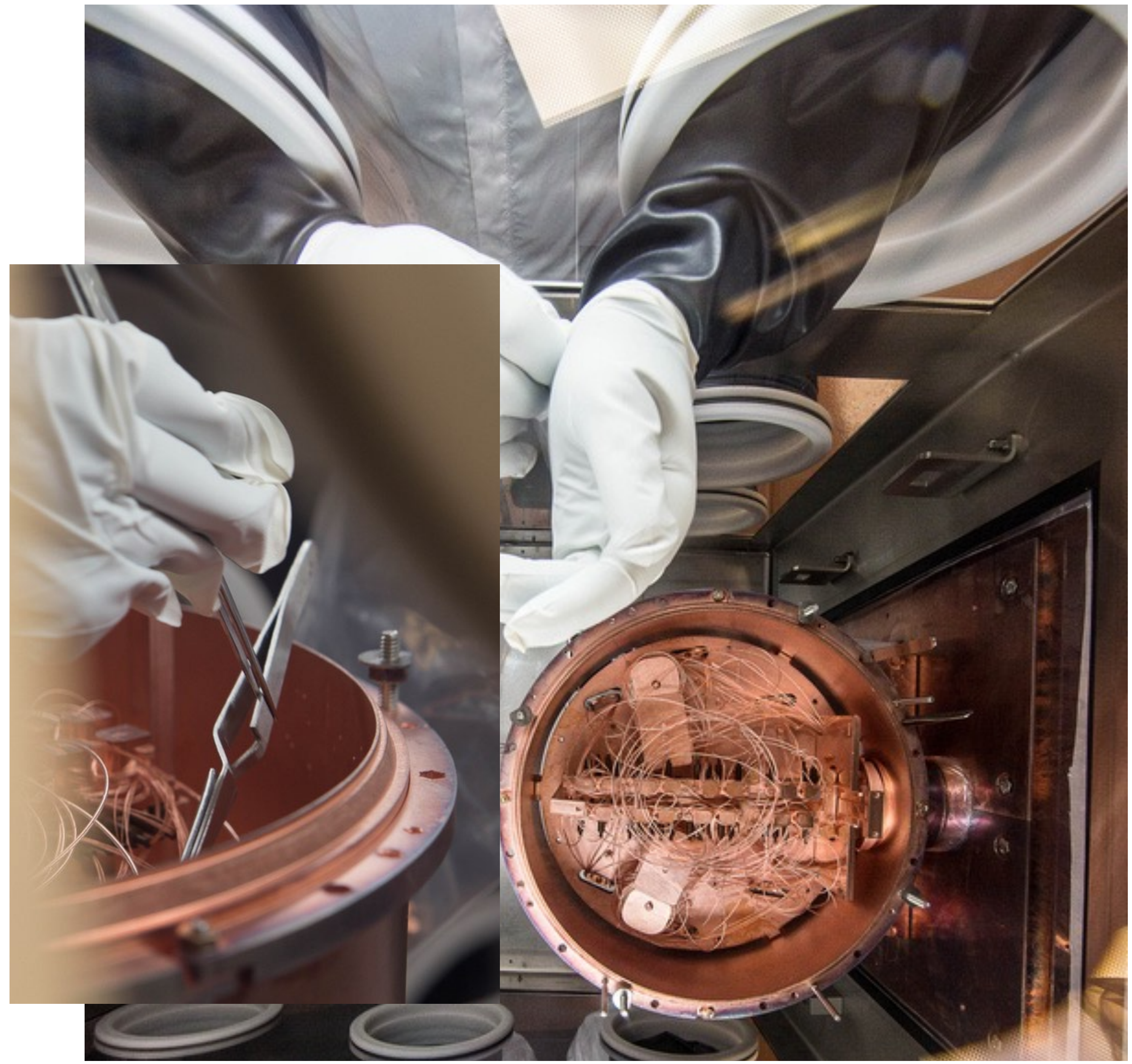
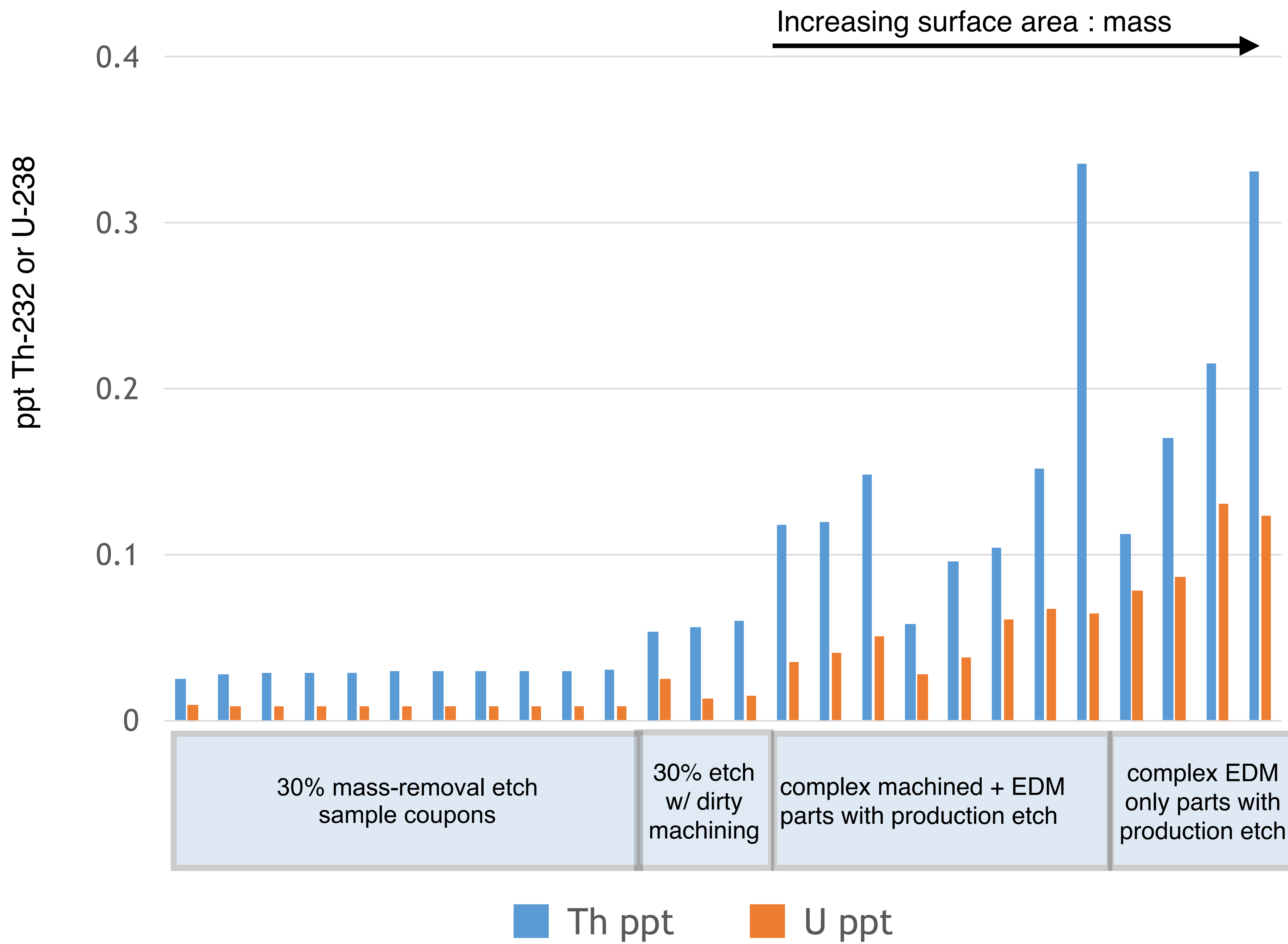




Samples vs Finished Parts



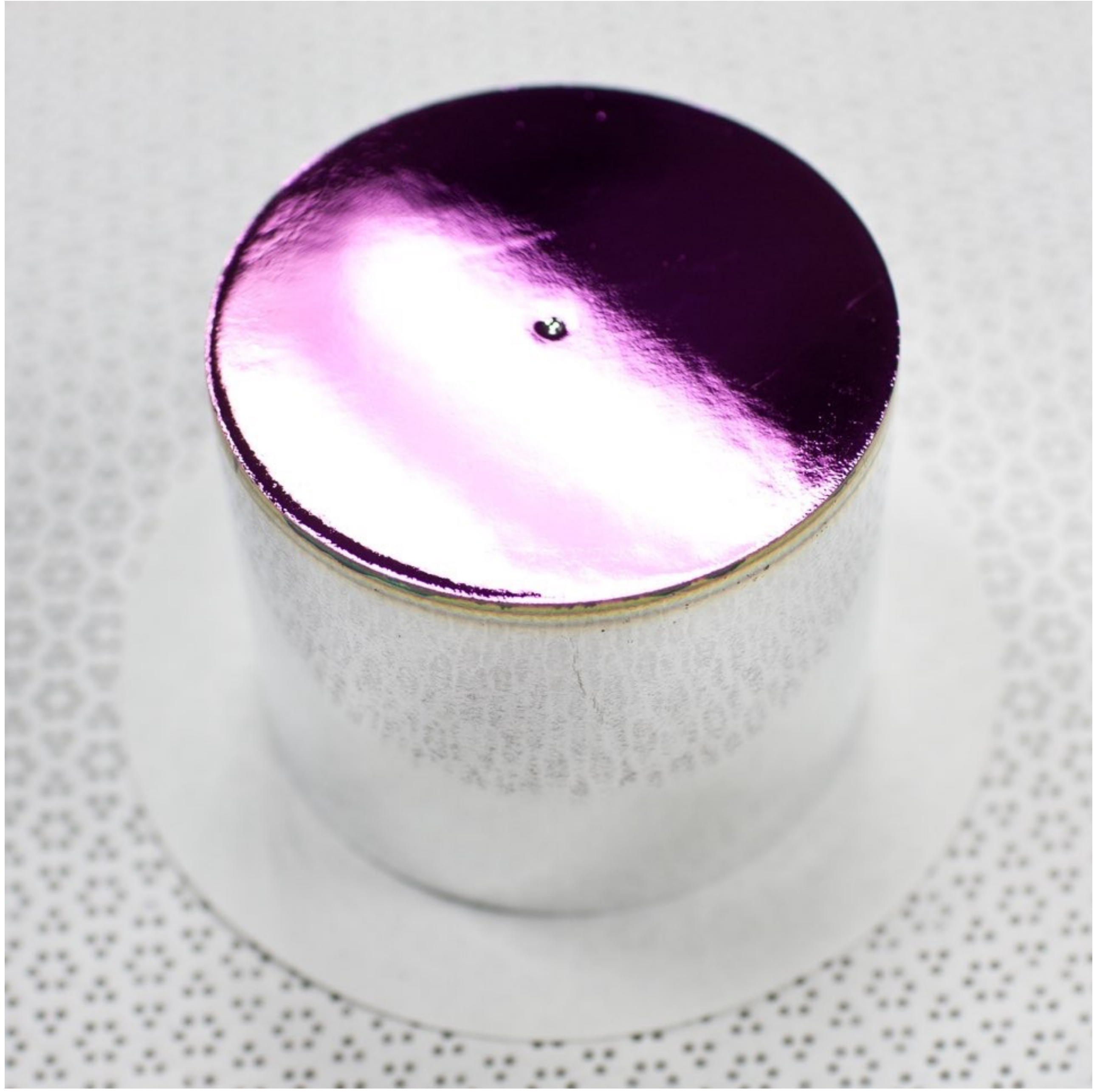
Ultraclean Materials

- Clean welding techniques
  - Much of the ^{60}Co activity is associated with taking the material to the surface for e-beam welding.
  - Would like to develop a method for underground, clean room compatible welding of materials.

- Future plans include tests with:
  - Alternative welding techniques
  - Welding alloys
  - Weld assays

Detector Development

- Typical detector:
  - Diameter ~68mm
  - Height ~48mm
  - Mass ~1 kg
  - Active volume ~90%
- Larger detectors
  - Utilize valuable germanium more efficiently
  - Reduced electronics, surface area, small parts
- Explore alternatives to thick Li contacts
  - Improved fiducial volume
  - Decreased slow pulses
  - Must balance sensitivity to alphas



Front-End Electronics

- Current Design:
  - Clean Au+Ti traces on fused silica, amorphous Ge resistor, FET mounted with silver epoxy, EFCu + low-BG Sn contact pin
  - Feedback loop closed at 1st stage outside shield
  - At the limit of cable length

- Feasibility study of in-situ amplification with a custom ASIC

- Integrated signal processing into the custom ASIC optimized for operation at cryogenic temperature

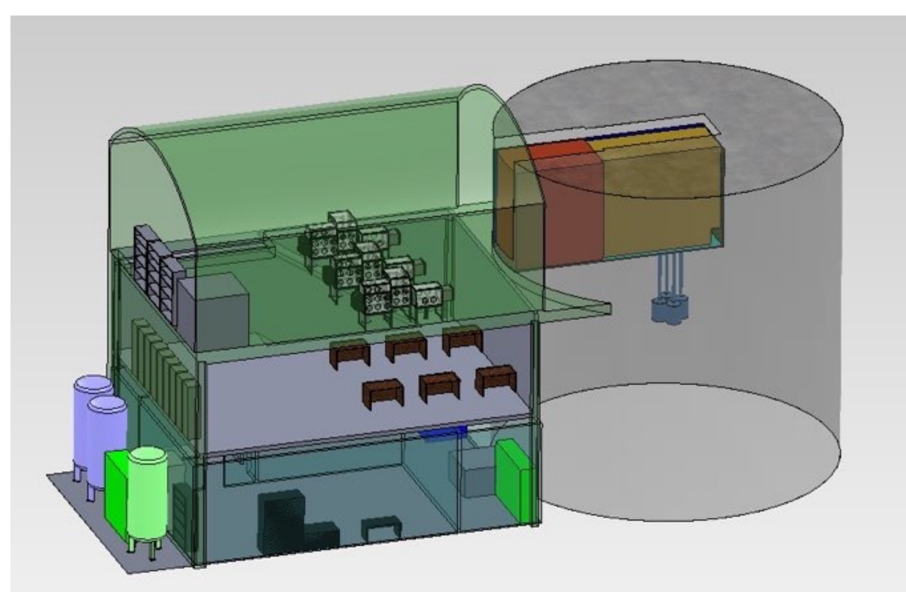
Other Next-Generation 0νββ R&D

- Enrichment
  - The scale and cost of U.S. based enrichment is being examined in an ONP Isotopes Program funded study at ORNL (Isotopes group).
    - A positive side benefit would be the capital investment in a U.S. facility for the stable isotopes program.
  - An alternate enrichment concept is being investigated by an Isotopes Program funded 2-year study at PNNL.

- Required depth
  - Using the Demonstrator data to learn how neutron- and muon-induced backgrounds scale with deployment depth. This directly impacts the siting decision of a Next-Generation Ge Experiment.

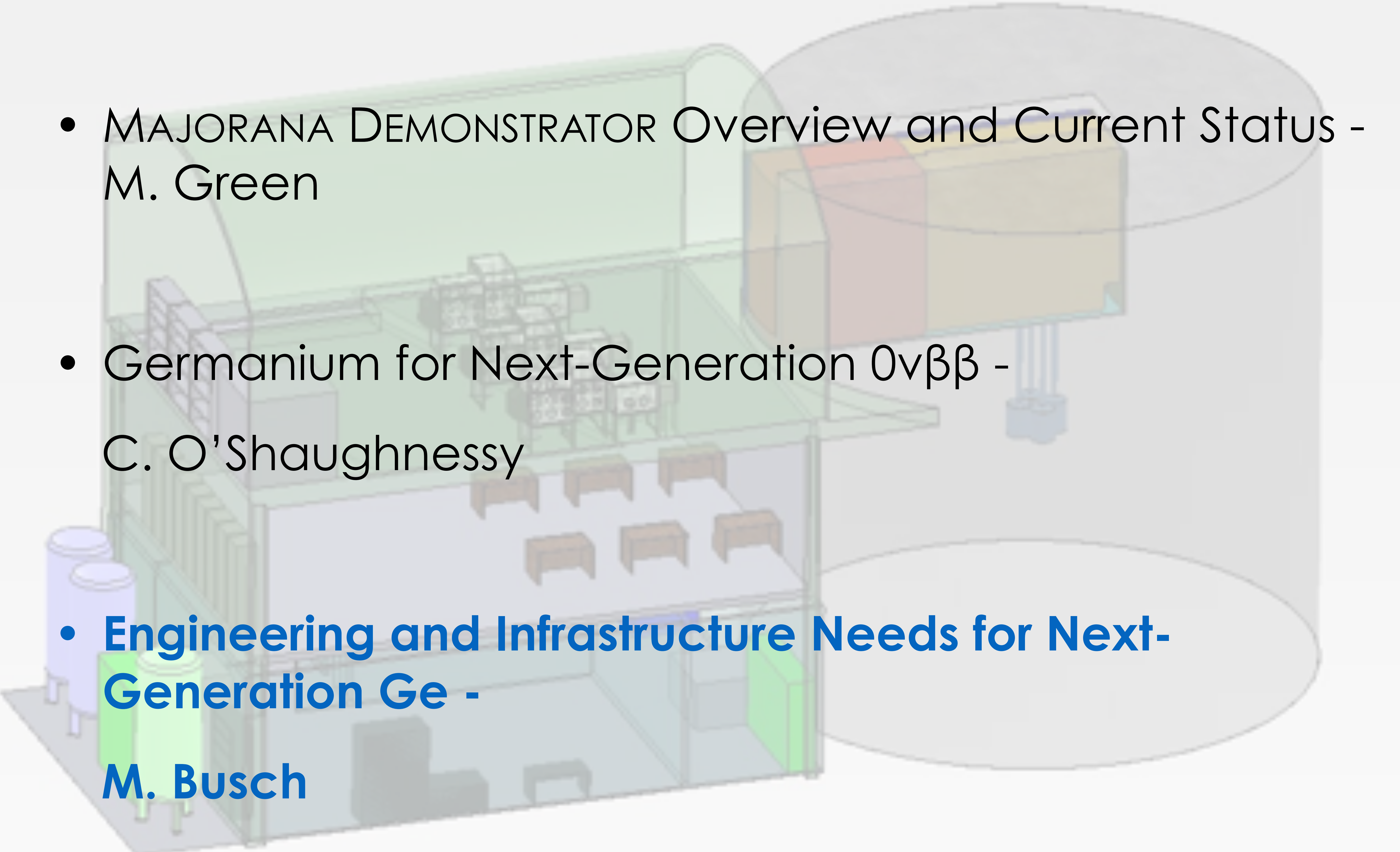
Next-Generation ^{76}Ge 0νββ Experiment

- All isotopes are comparable in terms of sensitivity per unit mass.
- Backgrounds are the key to all future 0νββ experiments.
- To date, ^{76}Ge has achieved the lowest backgrounds of all 0νββ measurements. Moving forward with ^{76}Ge is predicated on *demonstration* of projected backgrounds by MAJORANA and/or GERDA Phase II, and eventually realizing even further reductions at the large scale.
- Both the MAJORANA DEMONSTRATOR, with Module 1,and GERDA Phase II have started collecting initial data. We expect to have initial understanding of backgrounds during 2016.
- Based on what has already been learned, an active shield will likely be required for the large scale.



Hybrid shield

Outline



- MAJORANA DEMONSTRATOR Overview and Current Status - M. Green

- Germanium for Next-Generation 0νββ -

  C. O’Shaughnessy

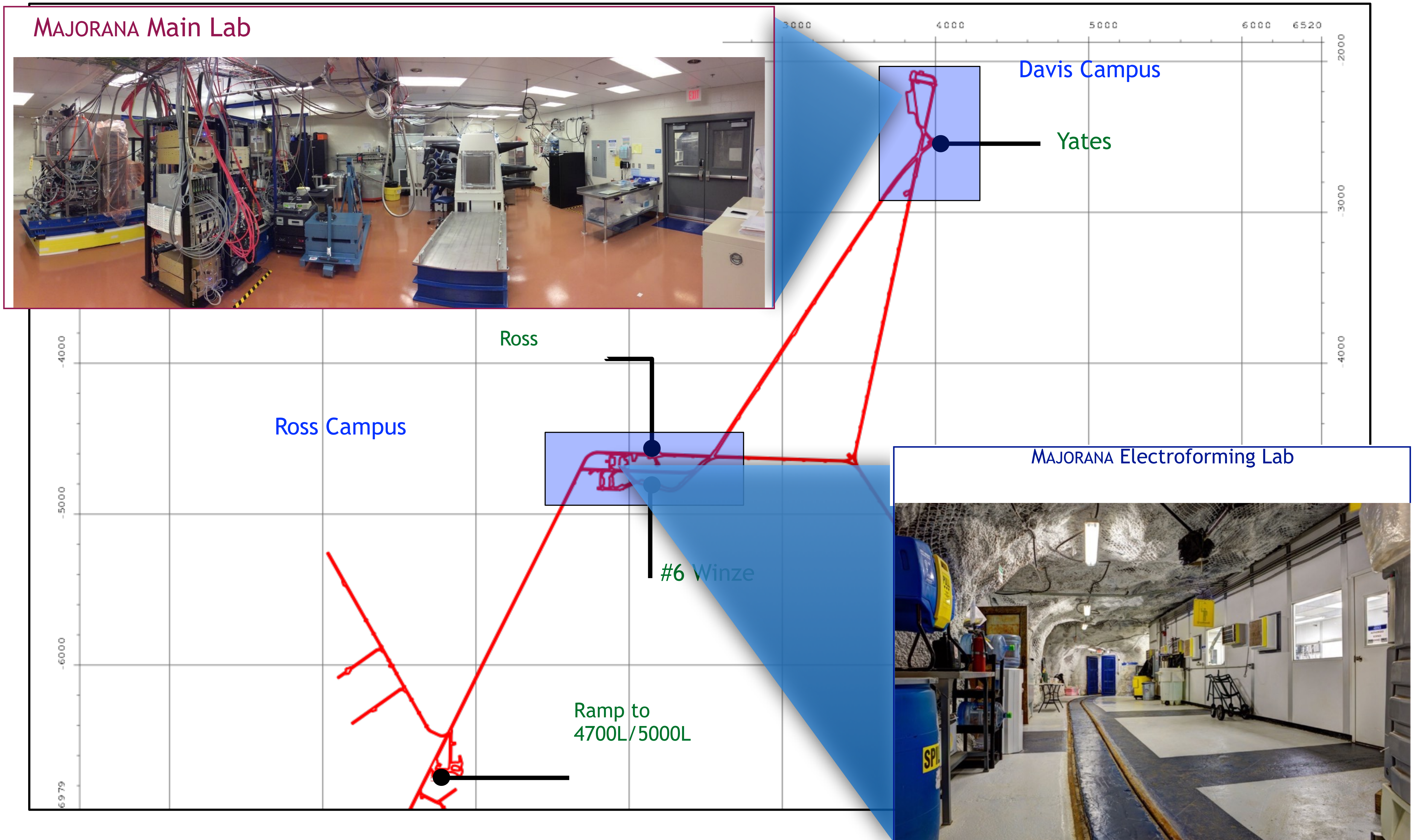
- **Engineering and Infrastructure Needs for Next-Generation Ge -**

  M. Busch

Outline

- Facility performance of SURF for MAJORANA DEMONSTRATOR
- Concept layout of Next-Generation Experiment and facility requirements
- R&D ideas for optimizing fabrication and assembly

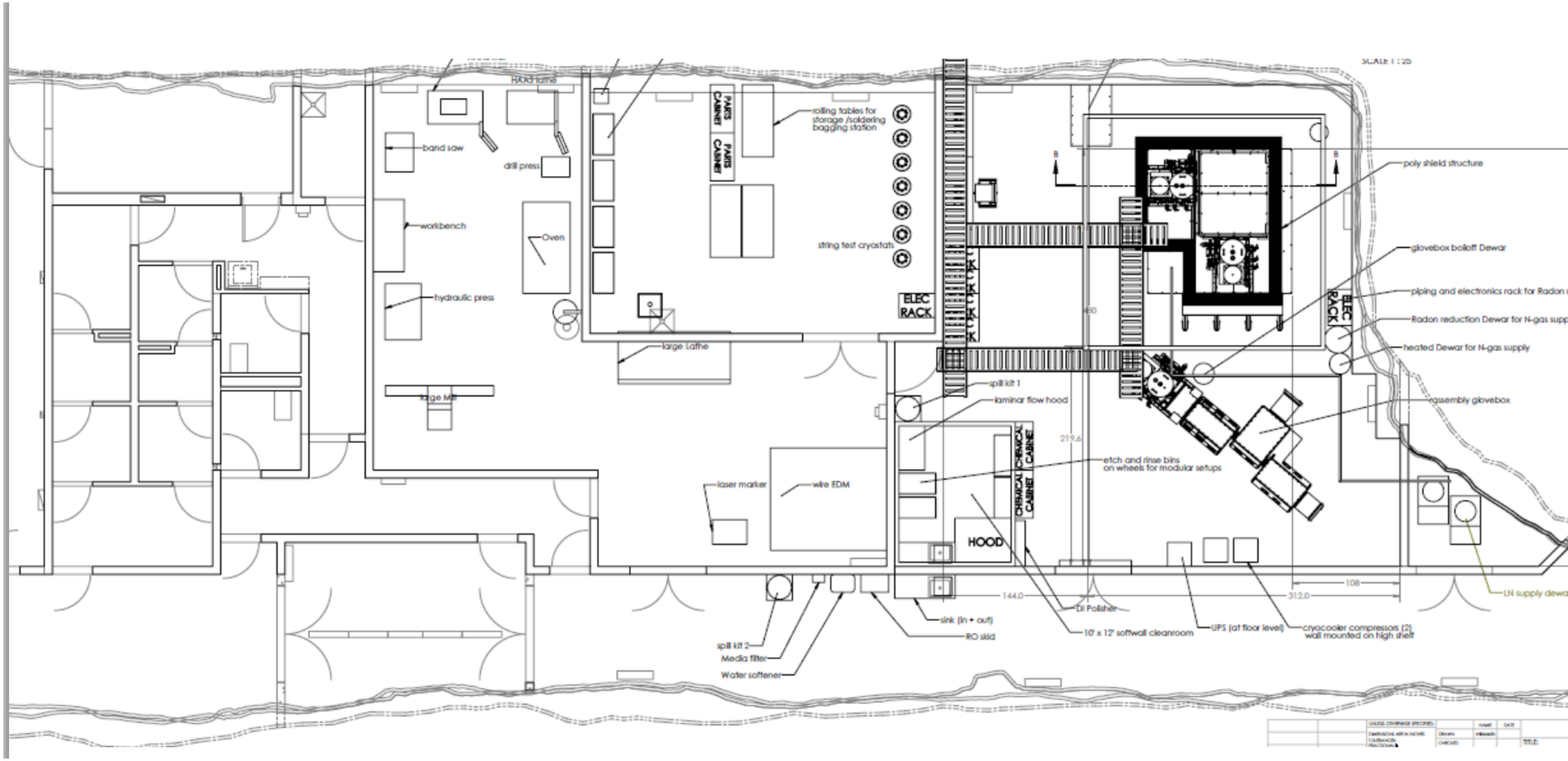
MAJORANA DEMONSTRATOR at SURF



Eforming Facility at SURF

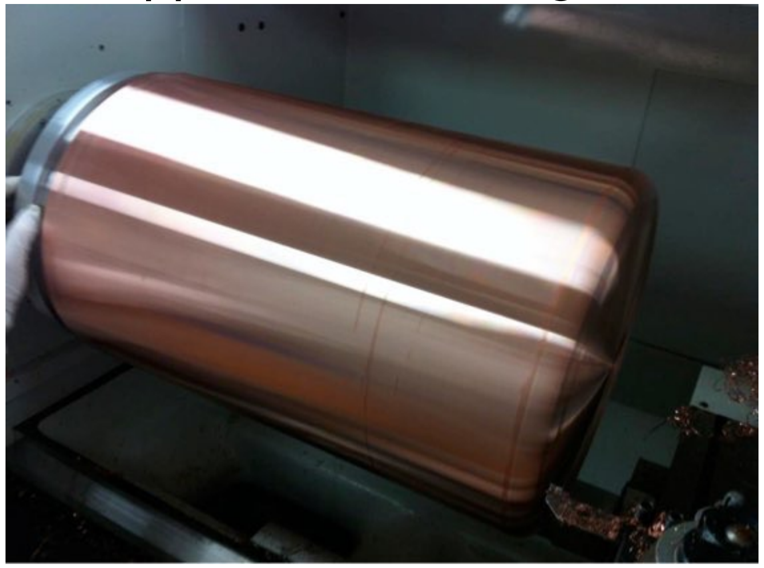
- Generally good cleanroom performance, but susceptible to window A/C wear and external conditions.
- Acid fumes during initial cleaning leads to corrosion of electronics. Computers moved to ante room.
- Waste stream:
  - Initial setup requires 200L/bath of 3 Molarity Nitric Acid
  - 300-400L/bath/yr Cu-Sulfate, electrowinned to ~2pH Sulfuric Acid

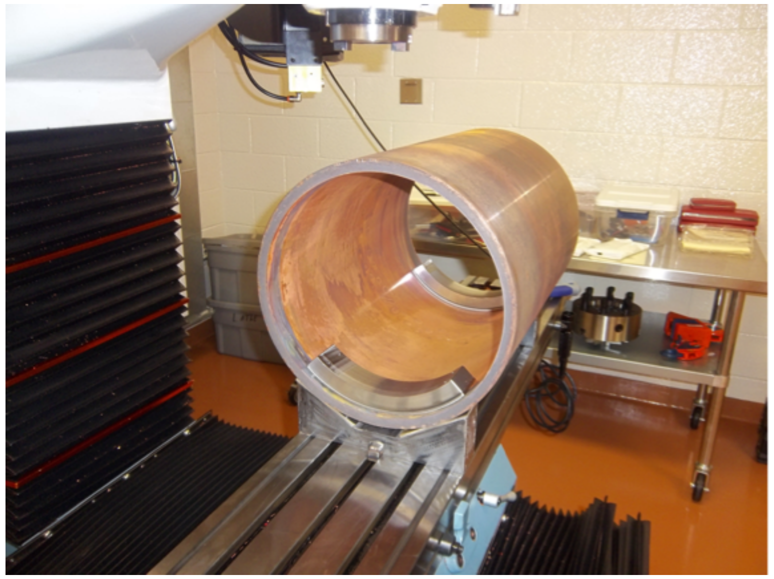
Davis Campus at SURF

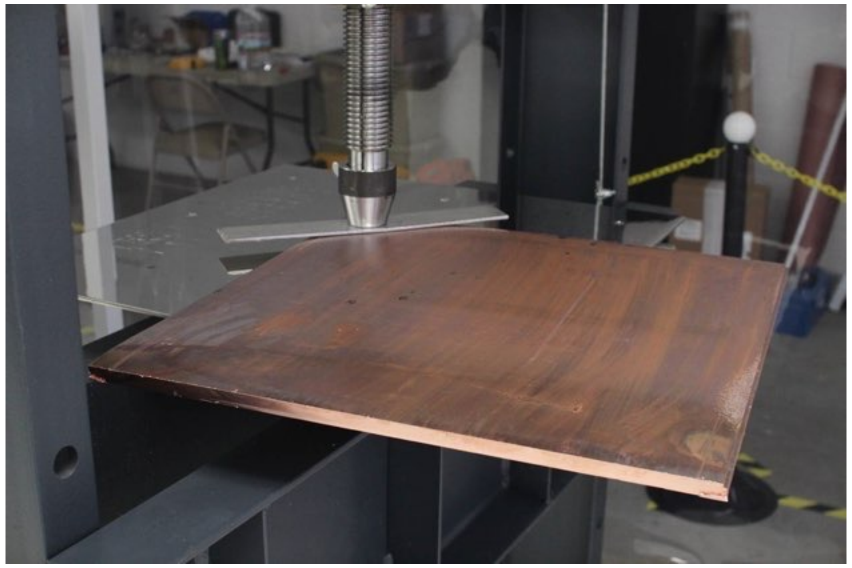


Initial Machining of UGEFCu

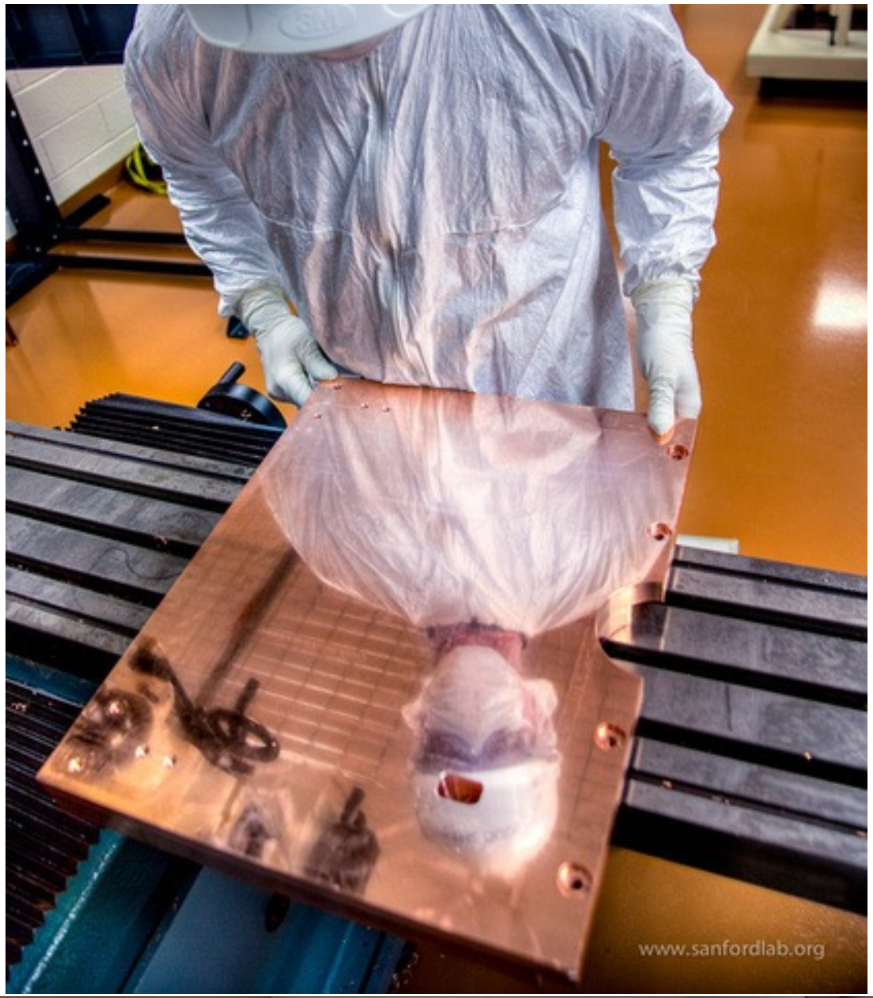
EF copper after turning

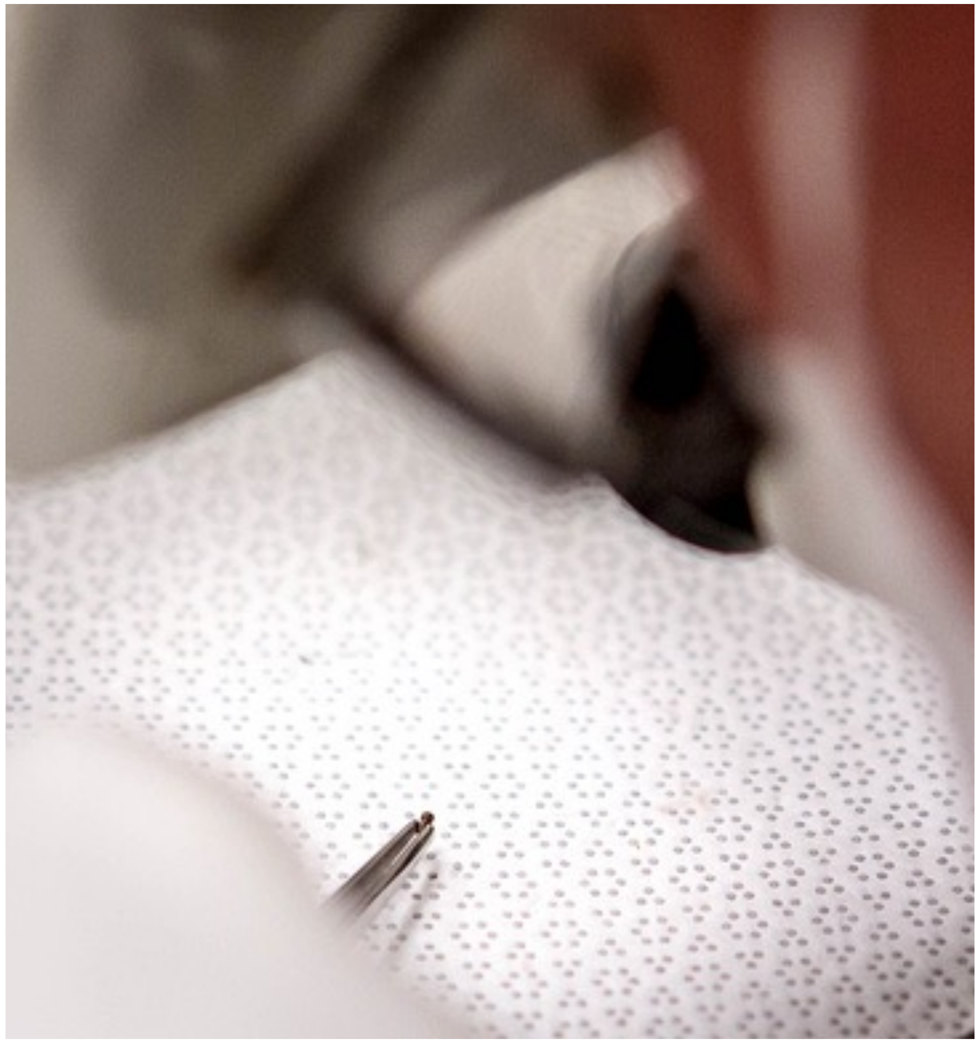


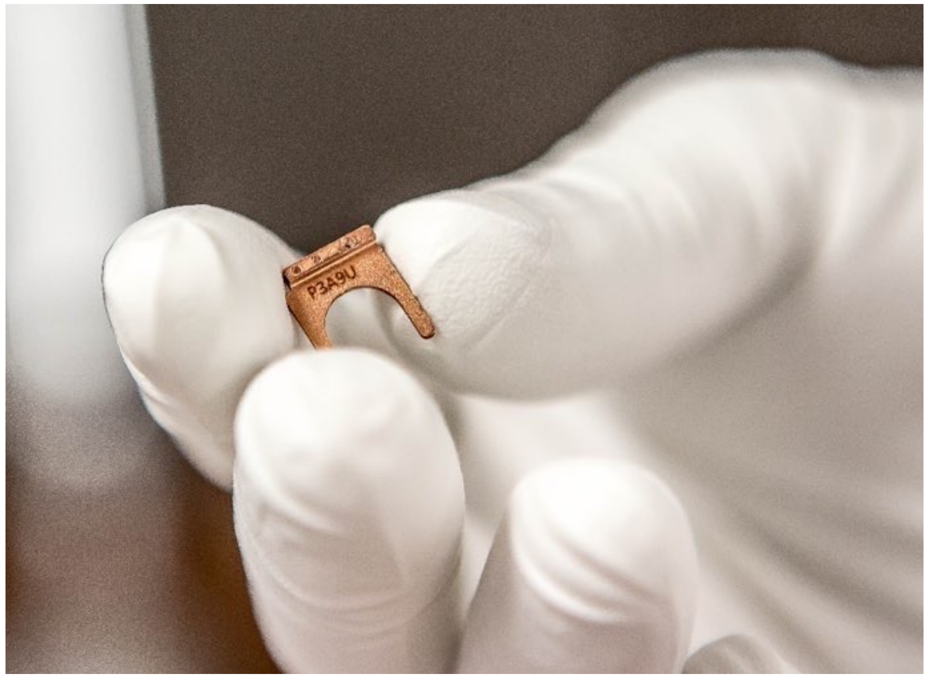




Final Machining







Cleanroom Performance

Class ISO 146144-1 (Federal Standard 209E)	Average Airflow Velocity m/s (ft/min)	Air Changes Per Hour	Ceiling Coverage
ISO 8 (Class 100,000)	0.005 – 0.041 (1 – 8)	5 – 48	5 – 15%
ISO 7 (Class 10,000)	0.051 – 0.076 (10 -15)	60 – 90	15 – 20%
ISO 6 (Class 1,000)	0.127 – 0.203 (25 – 40)	150 – 240	25 – 40%
ISO 5 (Class 100)	0.203 – 0.406 (40 – 80)	240 – 480	35 – 70%
ISO 4 (Class 10)	0.254 – 0.457 (50 – 90)	300 – 540	50 – 90%
ISO 3 (Class 1)	0.305 – 0.457 (60 – 90)	360 – 540	60 – 100%
ISO 1 – 2	0.305 – 0.508 (60 – 100)	360 – 600	80 – 100%

From Terra Universal website (cleanroom vendor)

“Particle Count” = # of particles of 0.5 micron or larger per cubic foot, roughly equivalent to Federal Standard 209E Class # rating

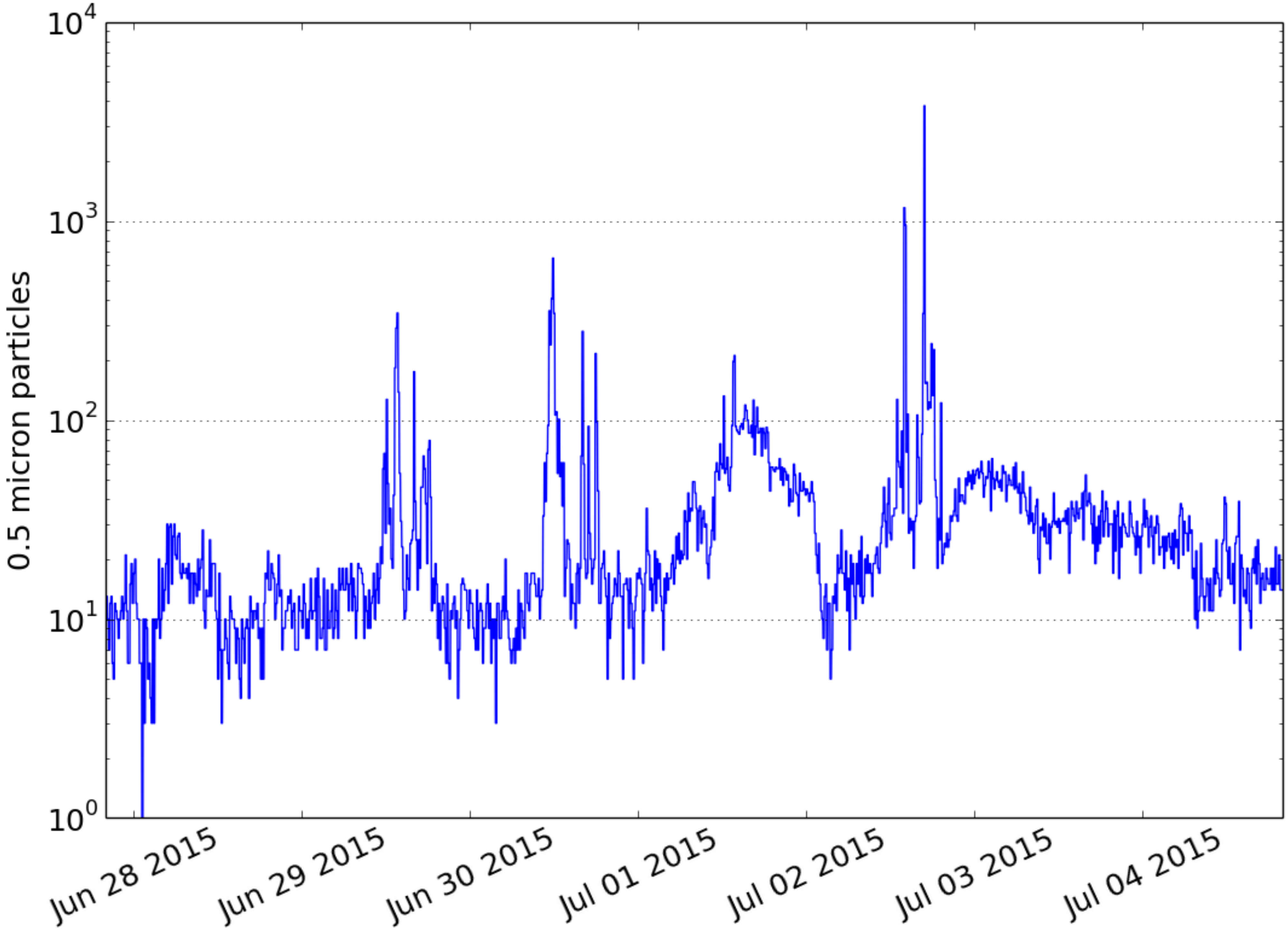
Air Exchange is Duct-Limited at SURF

MAJORANA SURF Cleanrooms

Room	air exchanges / hr	particle count at rest (size > 0.5μm)	particle count in use (size > 0.5μm)
Component path			
eforming (TCR)	60	10-500	50-1000
machine shop	13	50-200	50,000-200,000
chemical lab	220	0	0-10
glovebox	2-5 (N_2)	0	0-50
Personnel path at Davis Campus			
common corridor	32	1,000-10,000	~10,000
detector room	20	20-100	100-500
string testing room	14	20-100	100-500

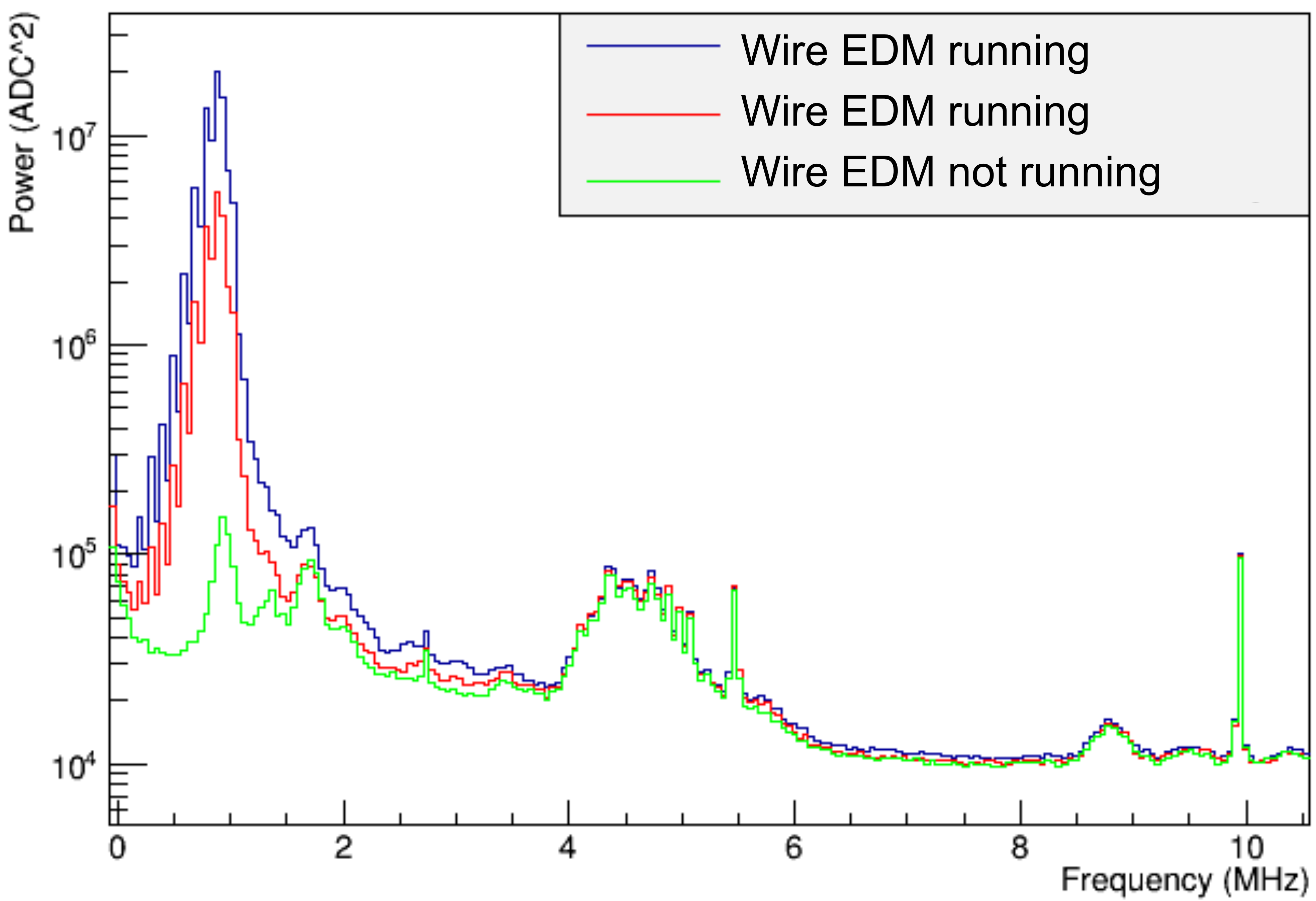
Typical Week for Shop and DR

Typical Week for Detector Room



Machine Shop Electrical/EMF Noise

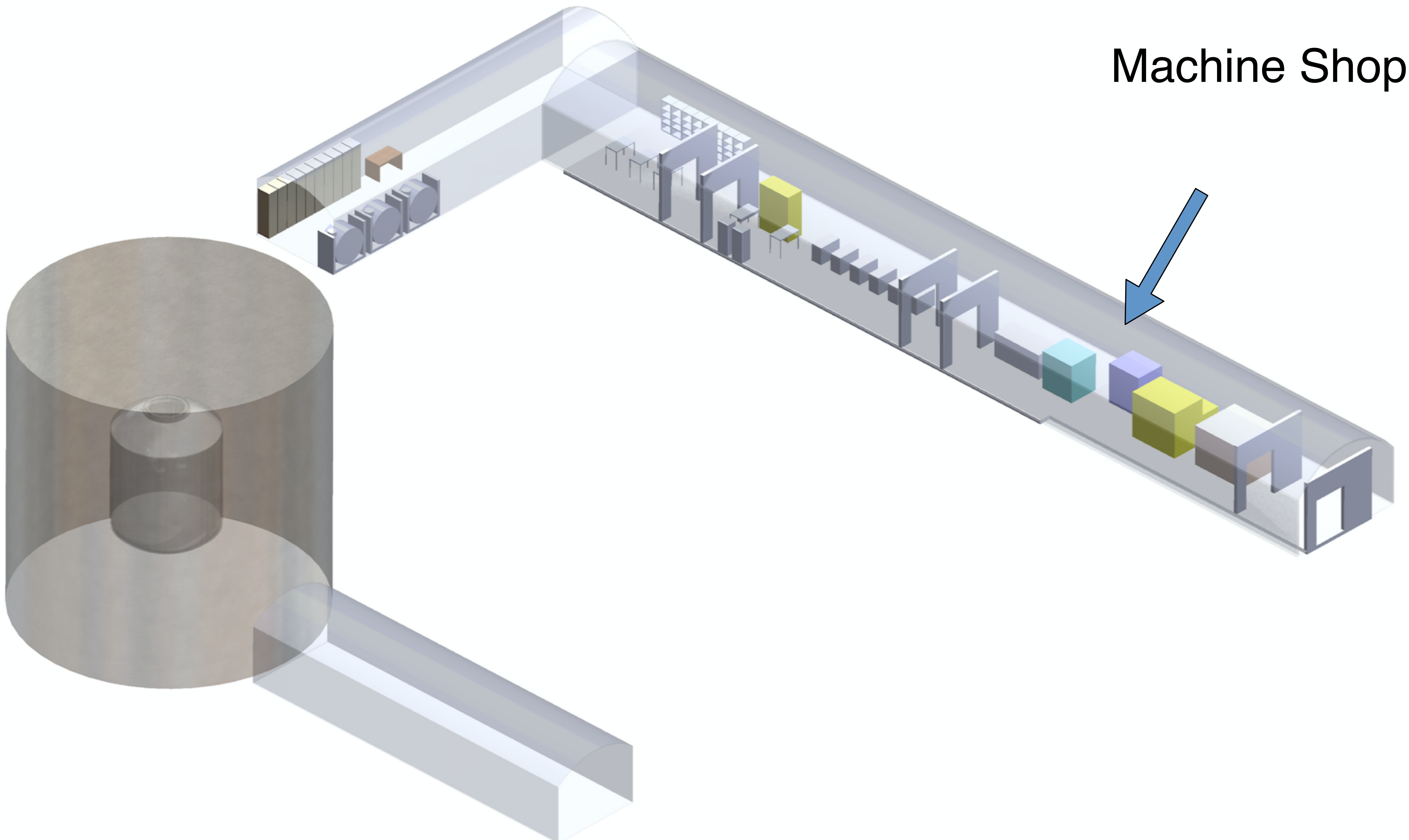
Typical Noise Spectra, Prototype Module



Improvements for a Future Facility

- Physically and electrically isolate machine tools from experiment while maintaining clean process flow
- Determine source(s) of part contamination and focus on these areas for improved process control and/or cleanliness (R&D in process)
- Design inventory control, waste handling, assembly, and test plan into facility
- Add clean welding capabilities to machine shop or assembly area
- Incorporate more production tooling in shop, cleaning, and assembly for improved process control and increased throughput

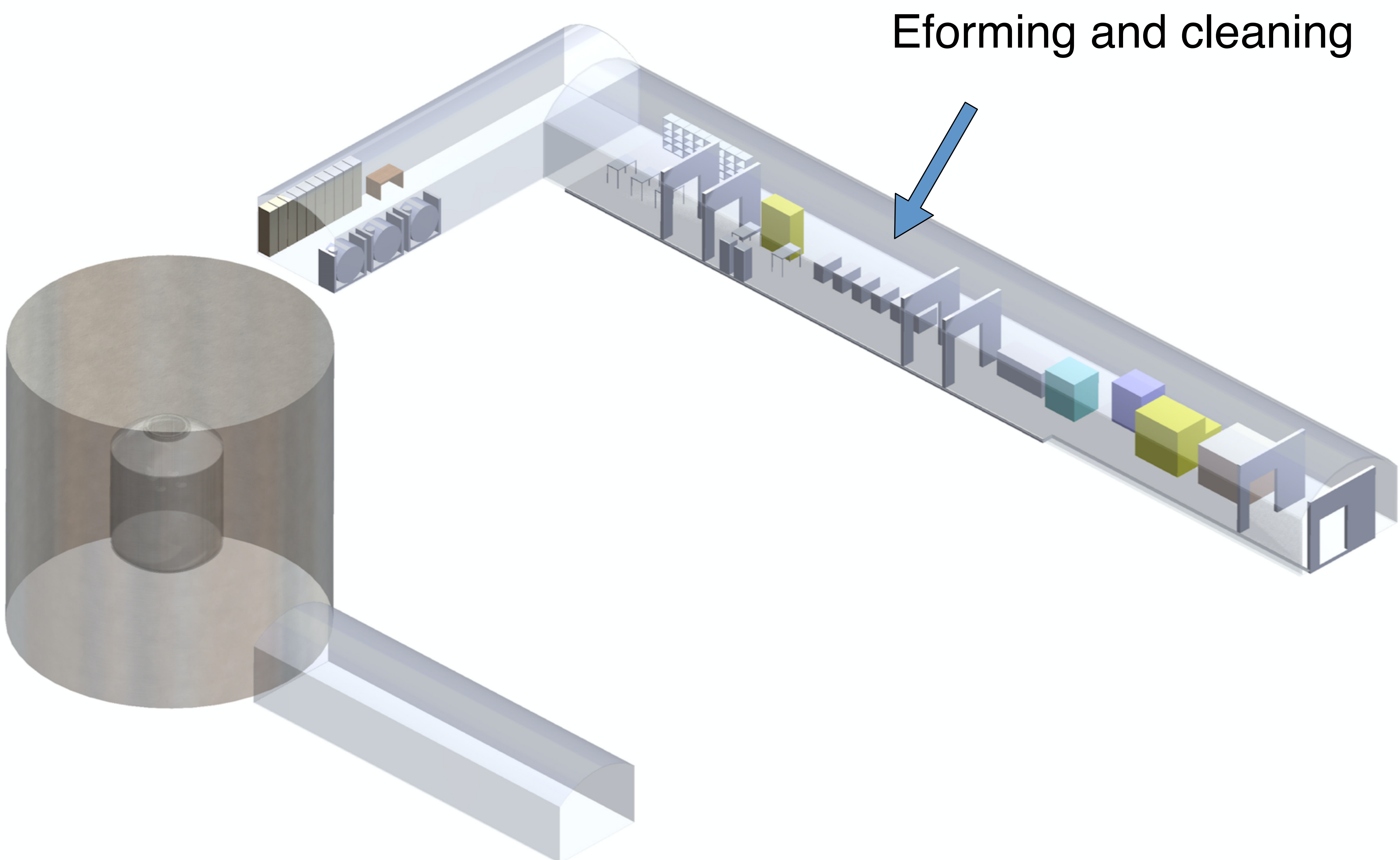
Conceptual Layout



Machine Shop Improvements

- Could be remote, but quick access to etching facility may be more important
- Include space for clean material and parts storage and QC
- Airlock isolation doors shown
- Include welding facility
- 2nd-tier clean shop for tooling fabrication would be useful
- Ideas to reduce particle counts:
  - Investigate cryogenic tool cooling: http://www.coolclean.com/cooling.php
  - Investigate high-throughput smoke/mist eliminators at tools
  - Investigate brushless motor drives for tools

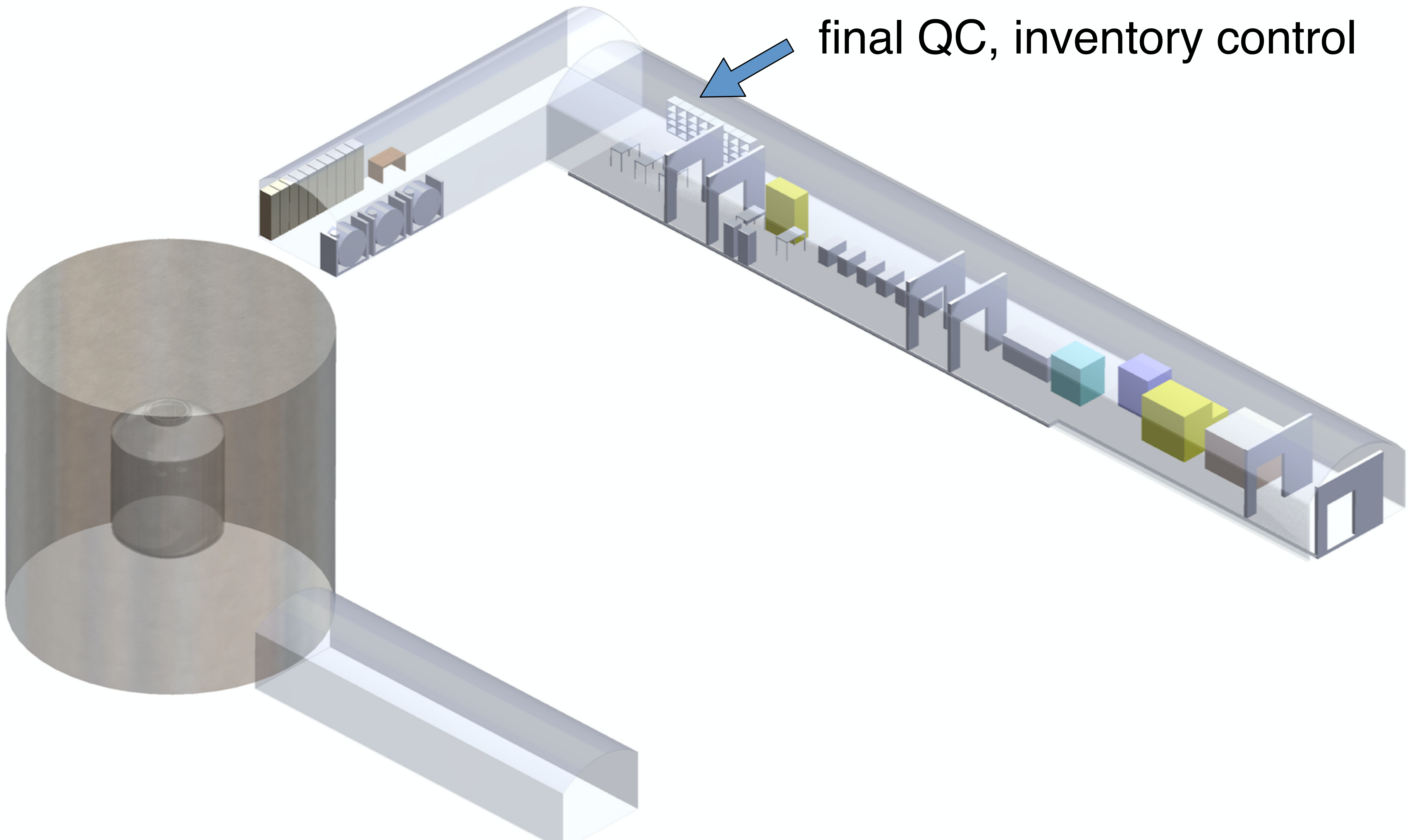
Conceptual Layout



E-Forming & Cleaning Improvements

- Combined space simplifies waste handling and handling expertise, similar cleanliness requirements and challenges
- Etching could happen in large fume hood or sealed and recirculated glovebox to improve process control and reduce environmental impact to surrounding space.
- Glovebox/drybox part drying requires high gas throughput.

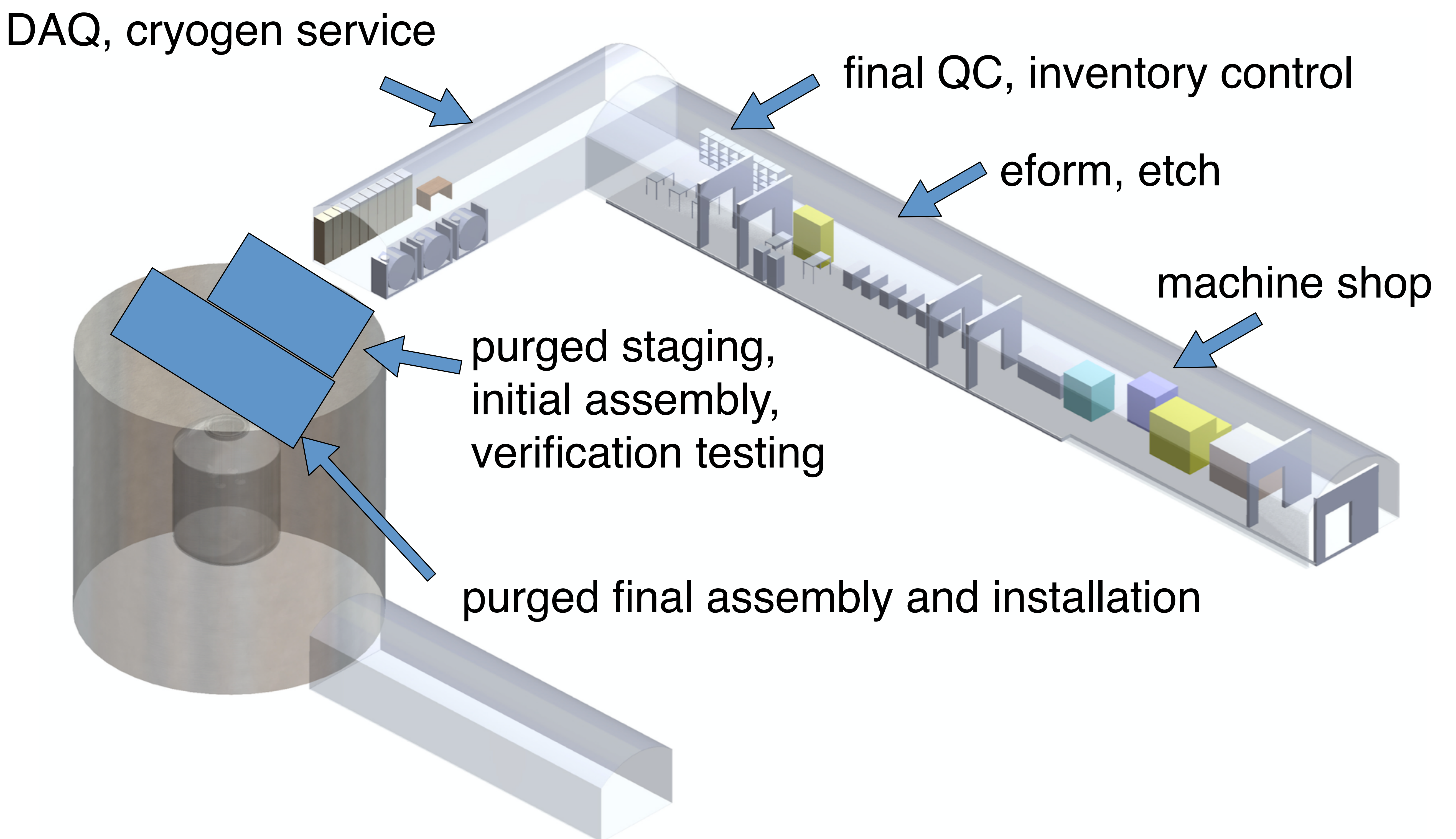
Conceptual Layout



Final Staging

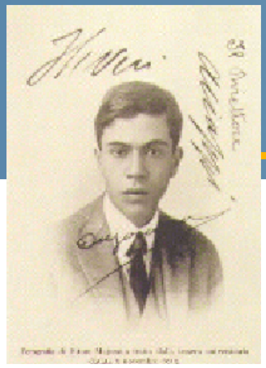
- Glovebox transfer from etching dryer to purged storage and on to purged assembly glove boxes would eliminate exposure to Rn.
- Mini-warehouse style encoded modular shelving (in purged environment) would simplify inventory management

Conceptual Layout



Facility Needs Summary

- Final science needs will not be final until MAJORANA DEMONSTRATOR and GERDA analyze data.
- Cleanliness can be improved, but new assay studies will inform areas of concentration and primary concern.
- Large machine tools may need to be in surface cleanroom.
- E-forming and etching lab have special cleanliness and isolation needs, waste handling requirements.



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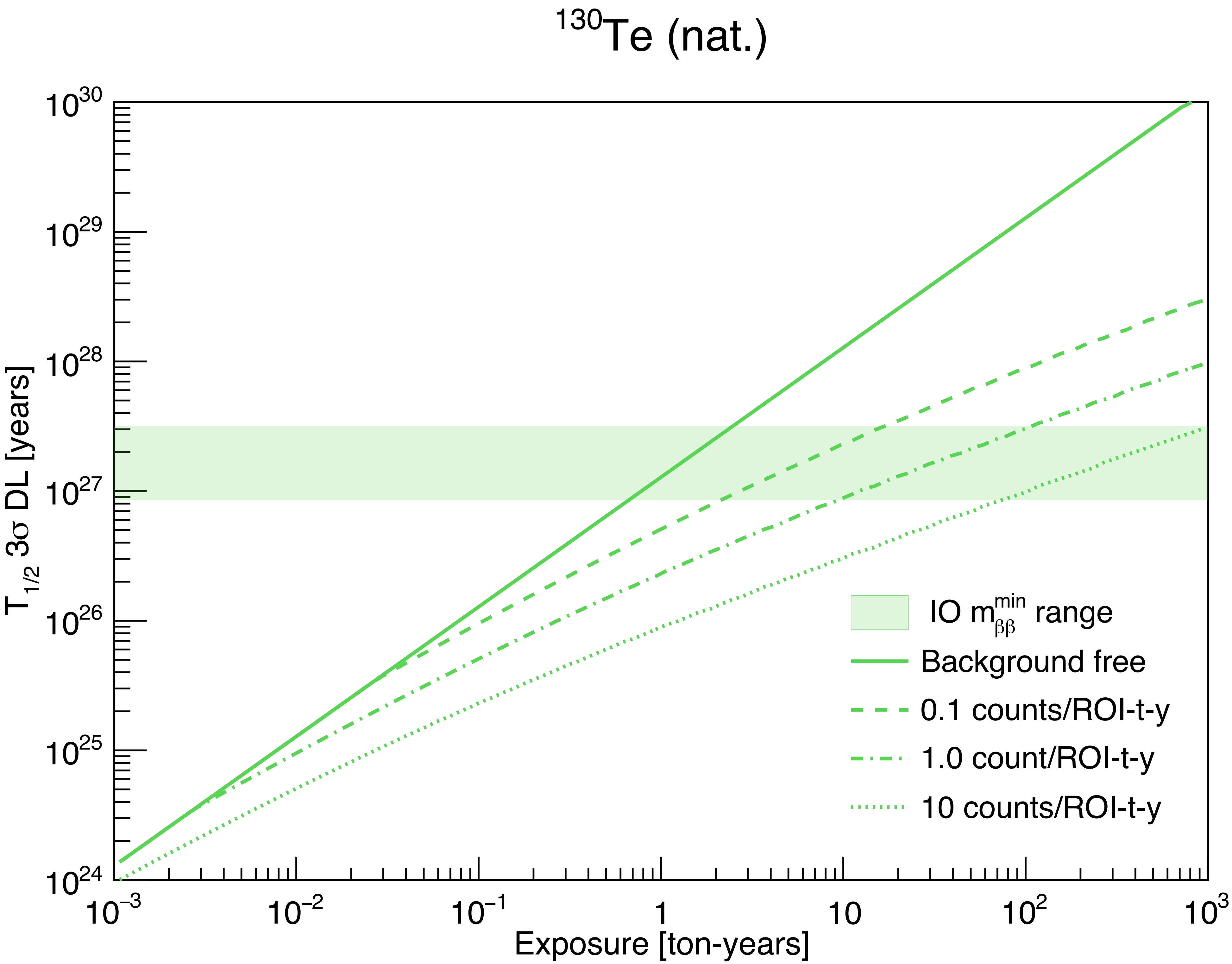
Extra Slides

3σ Discovery vs. Exposure for ^{130}Te

J. Detwiler



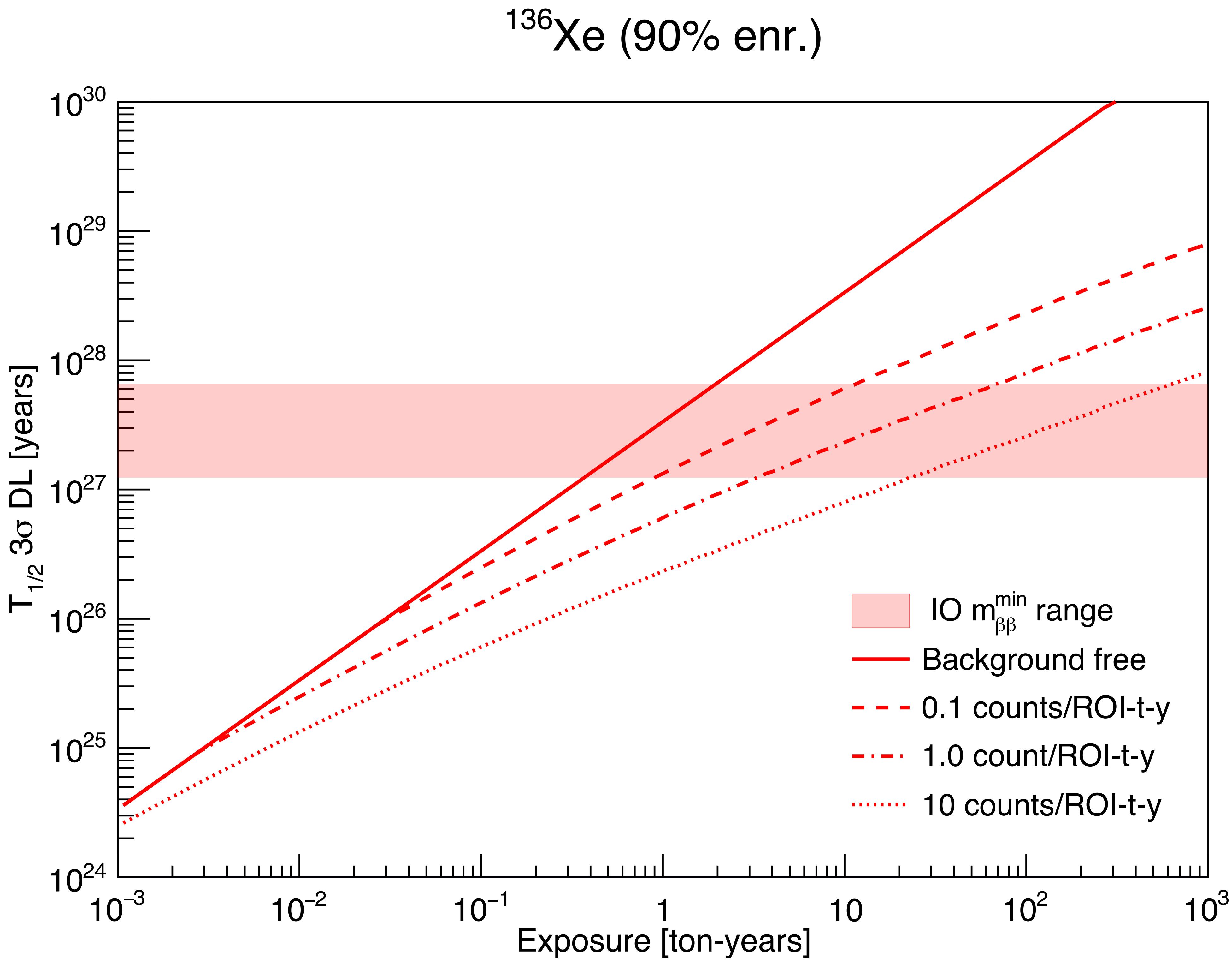
Inverted Ordering (IO)

Minimum IO $m_{\beta\beta}$=18.3 meV, taken from using the PDG2013 central values of the oscillation parameters, and the most pessimistic NME for the corresponding isotope among QRPA, SM, IBM, PHFB, and EDF

Note : Region of Interest (ROI) can be single or multidimensional (E, spatial, …)

Assumes 81% efficiency based on CUORE-0. Natural Te is accounted for in the exposure

3σ Discovery vs. Exposure for ^{136}Xe



Inverted Ordering (IO)

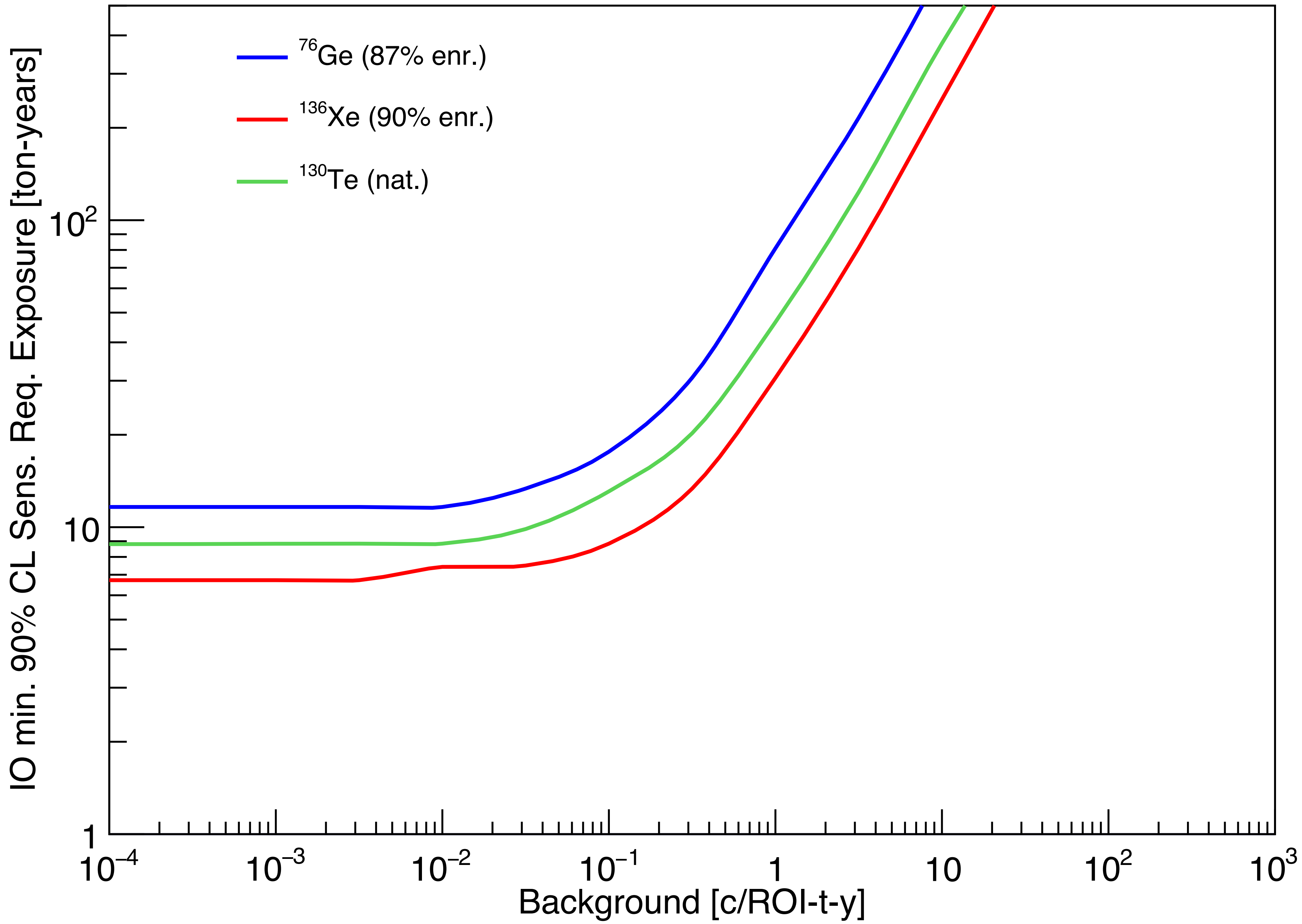
Minimum IO $m_{\beta\beta}$=18.3 meV, taken from using the PDG2013 central values of the oscillation parameters, and the most pessimistic NME for the corresponding isotope among QRPA, SM, IBM, PHFB, and EDF

Note : Region of Interest (ROI) can be single or multidimensional (E, spatial, …)

Assumes 84% efficiency based on EXO 200. Enrichment level is accounted for in the exposure

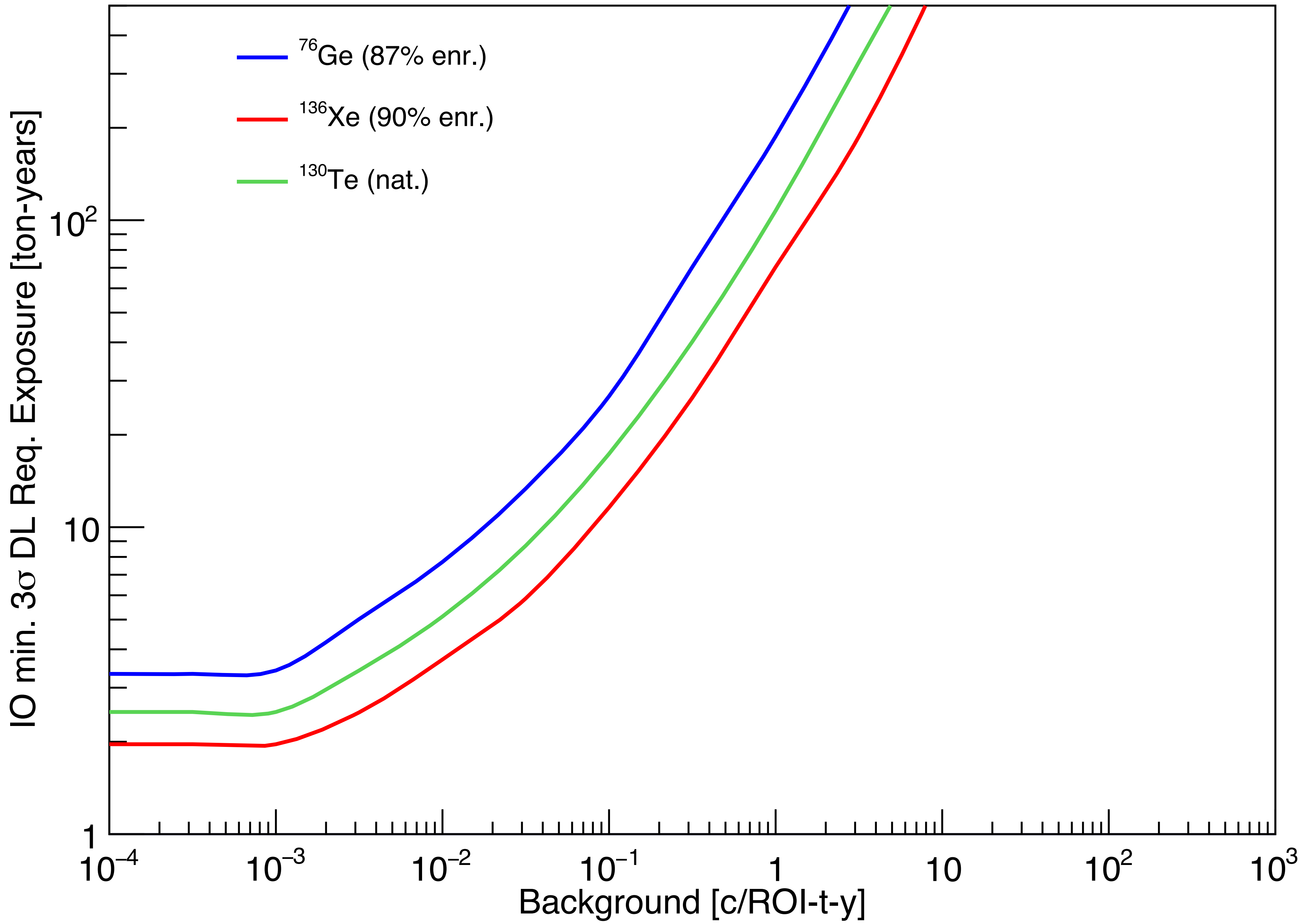
Required Sensitivity vs. Background

J. Detwiler



Required 3σ Exposure vs. Background

J. Detwiler



"Required" exposure assuming minimum IO $m_{\beta\beta}$=18.3 meV, taken from using the PDG2013 central values of the oscillation parameters, and the most pessimistic NME for the corresponding isotope among QRPA, SM, IBM, PHFB, and EDF

Backgrounds in experiments

From NSAC Long Range Plan Resolution Meeting $0\nu\beta\beta$ talk V. Cirigliano & J.F. Wilkerson

Experiment		Mass [kg] (total/FV*)	Bkg (cnts/ROI-t-y)†	Width (FWHM)	
CUORE0	^{130}Te	32/11	300	5.1 keV ROI	Measured
EXO-200	^{136}Xe	170/76	130	88 keV ROI	Measured
GERDA I	^{76}Ge	16/13	40	4 keV ROI	Measured
KamLAND-Zen (Phase 2)	^{136}Xe	383/88	210 per t(Xe)	400 keV ROI	Measured
CUORE	^{130}Te	600/206	50	5 keV ROI	Projected
GERDA II	^{76}Ge	35/27	4	4 keV ROI	Projected
MAJORANA DEMONSTRATOR	^{76}Ge	30/24	3	4 keV ROI	Projected
NEXT 100	^{136}Xe	100/80	9	17 keV ROI	Projected
SNO+	^{130}Te	2340/160	45 per t(Te)	240 keV ROI	Projected

* FV = $0\nu\beta\beta$ isotope mass in fiducial volume (includes enrichment factor)
† Region of Interest (ROI) can be single or multidimensional (E, spatial, …)