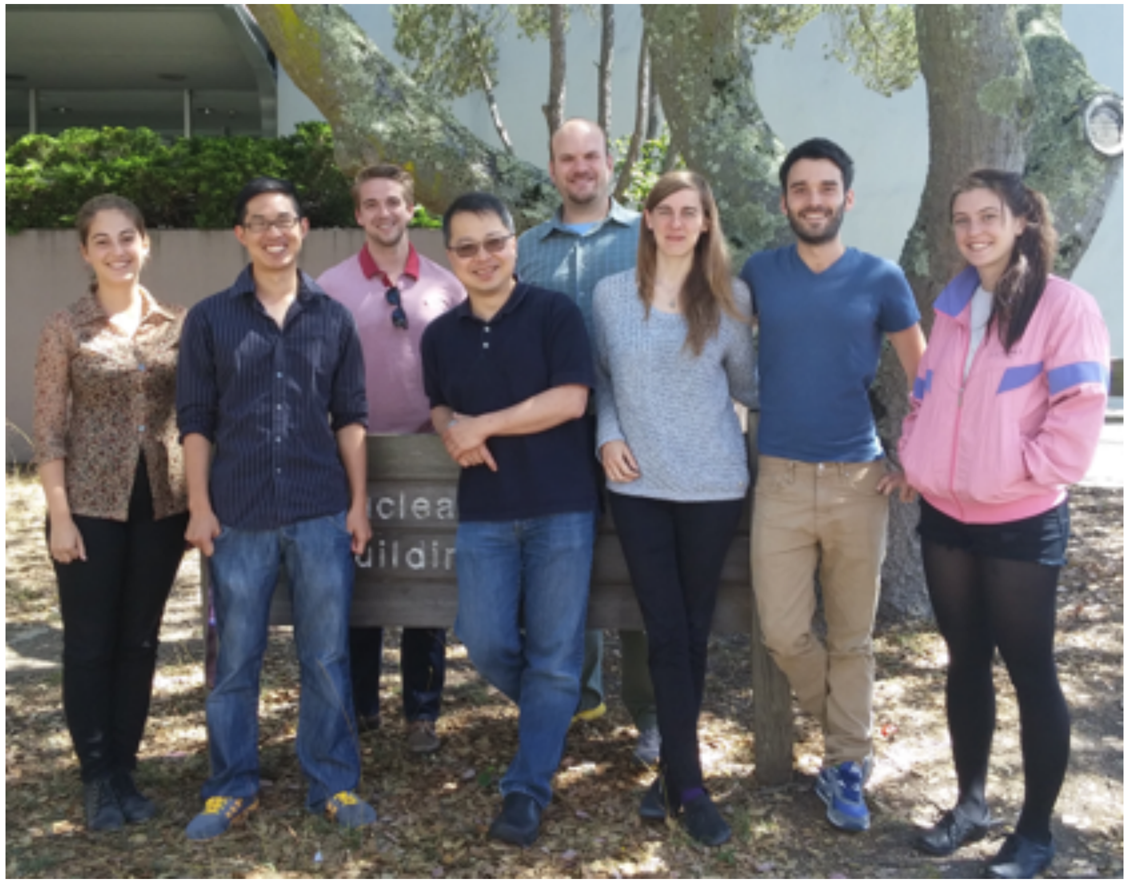
MAJORANA, KATRIN & Low Background Facility

Alan Poon

Nuclear Science Division

http://neutrino.lbl.gov
http://lbf.lbl.gov

Personnel (FY15-16)



Staff:
- Yuen-dat Chan (retiree)
- Alan Poon

Postdoc:
- Nicolas Abgrall (with ANP since 2016.05)
- Adam Bradley (industry since 2016.10)
- Susanne Mertens (tenure-track faculty at Technical University Munich since 2016.01)
- Jordan Myslik (started 2016.08)

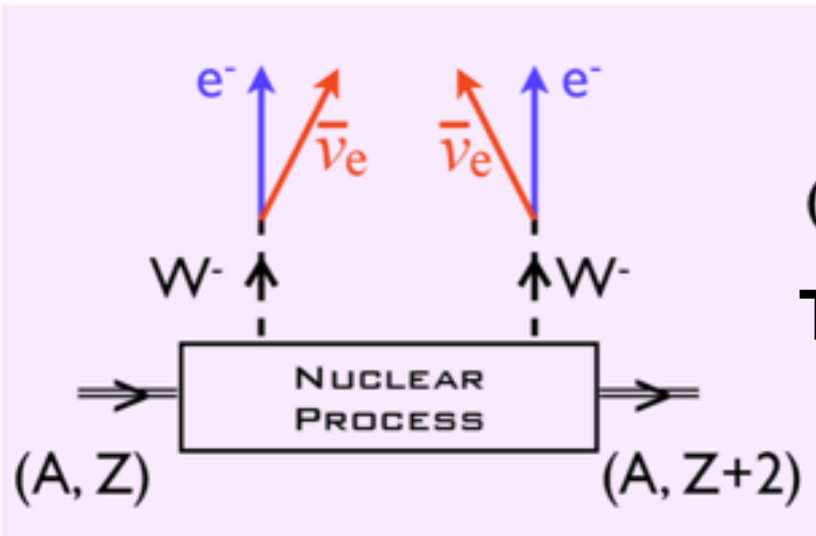
PhD student:
- Zach Harvey (Idaho State, full-time LBNL EHS staff)

MSc student:
- Alex Pan (graduated from SFSU in 2015.08, now in data science)

Undergraduate students:
- Sophia Elia (UCB Haas Scholar, now PhD at Berlin Mathematical School)
- Chiara Salemi (Summer student, Goldwater Scholar and undergraduate at UNC)

+ Support from Engineering Division, Applied Nuclear Physics and Low Background Facility

Is neutrino its own antiparticle?

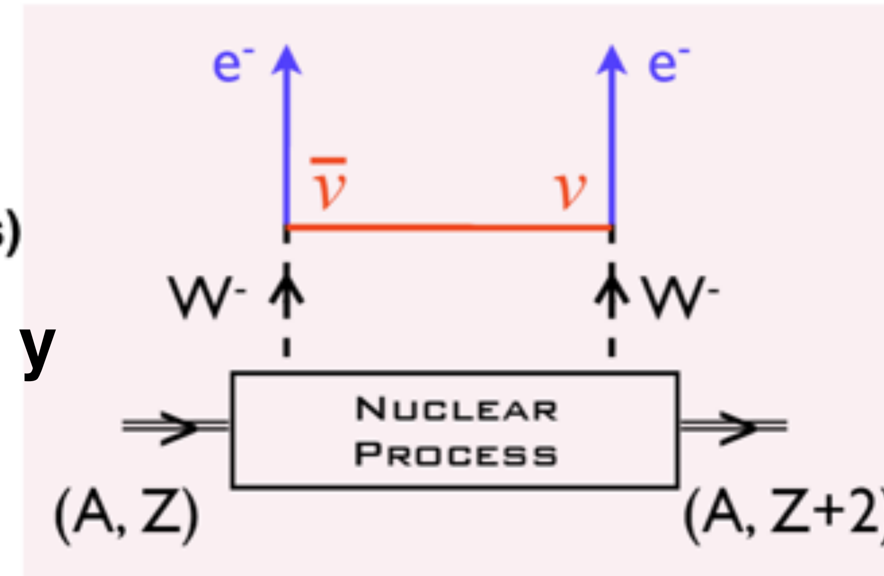


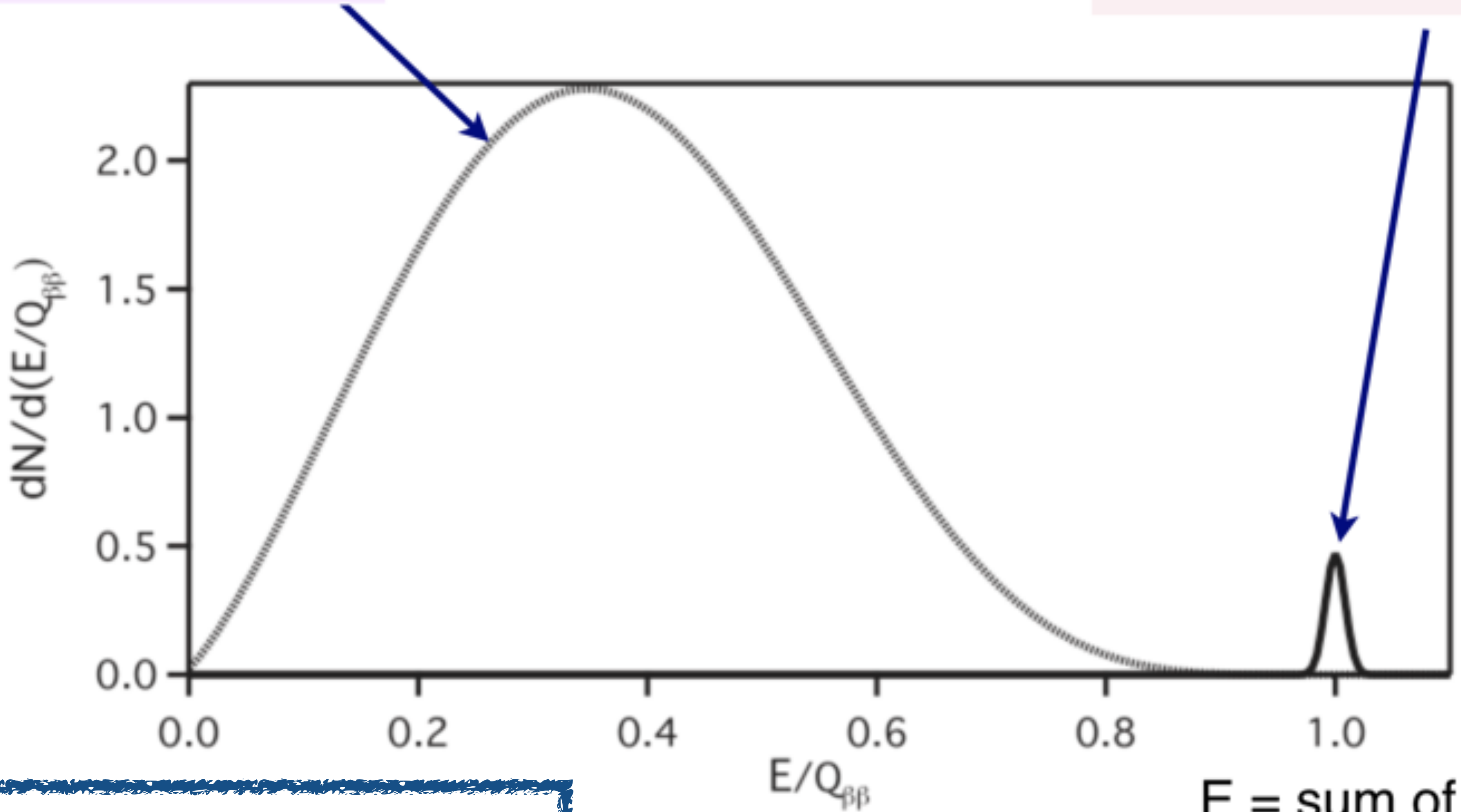
$2\nu\beta\beta$
(background)

$T_{1/2} \sim 10^{20}$ y

$0\nu\beta\beta$
(new physics)

$T_{1/2} > 10^{26}$ y





E = sum of electron energy

Energy resolution is key!

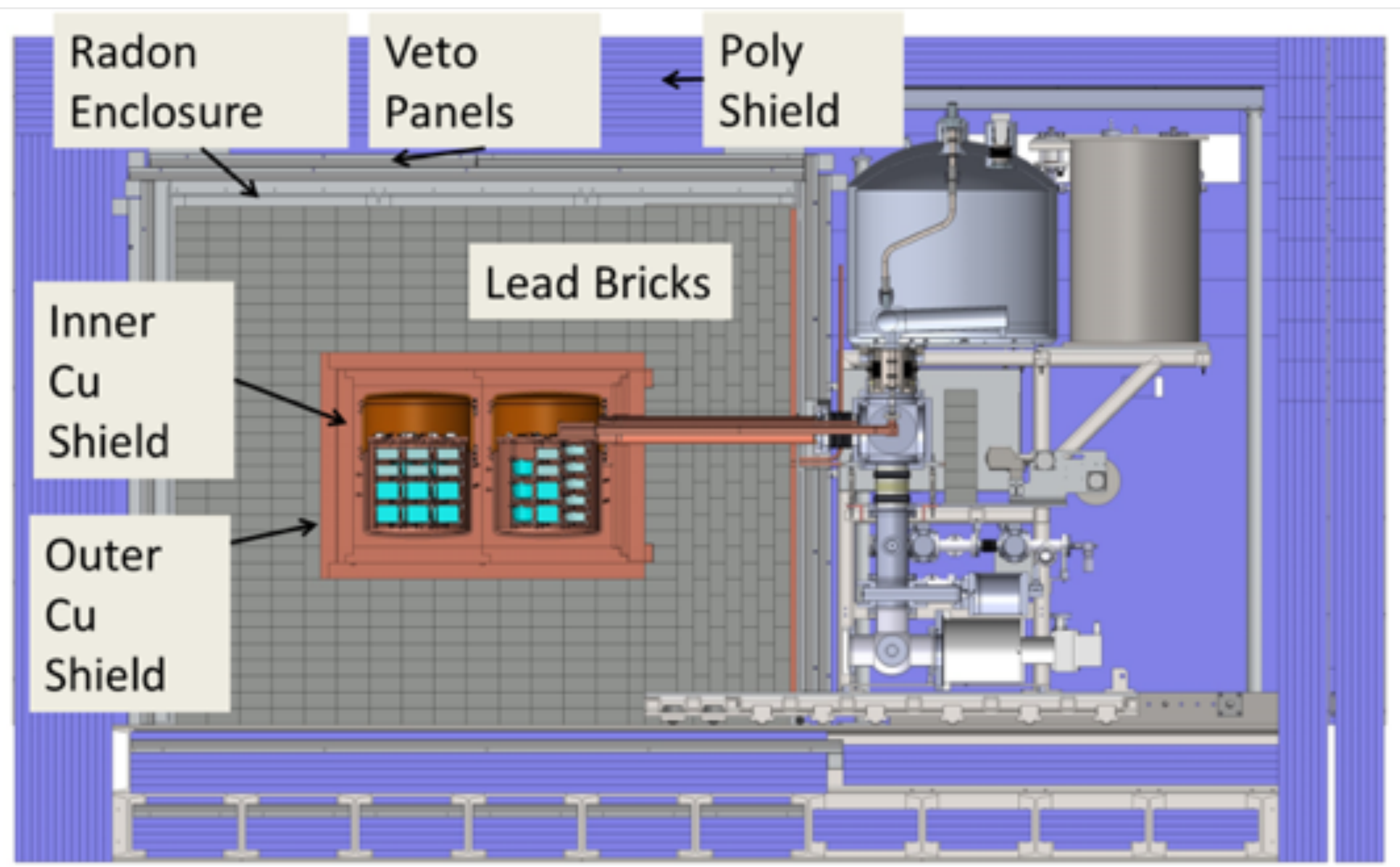
MAJORANA DEMONSTRATOR (MJD)

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.***

MJD background goal: < 3.5 counts/ROI-t-y

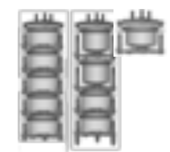
- Located underground at 4850' Sanford Underground Research Facility
- 44-kg of Ge detectors in two independent cryostats
  - 29.7 kg of 88% enriched ^{76}Ge crystals
  - 14.4 kg of ^{nat}Ge crystals
- **Highest energy resolution** among all 0νββ detector technology



MJD Implementation

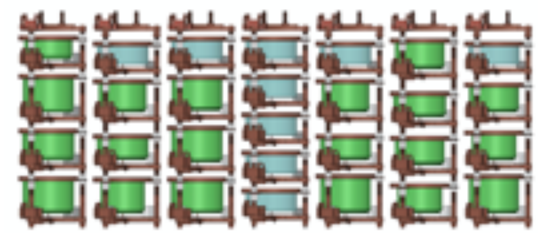
Three Steps | **In-shield running**

Prototype cryostat: 7.0 kg (10) ^{nat}Ge



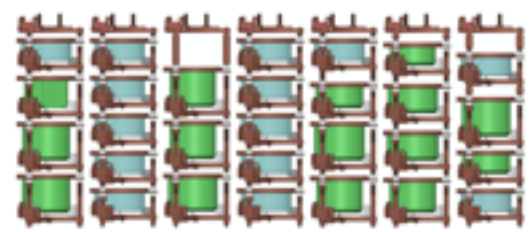
06/2014 - 06/2015

Module 1: 16.9 kg (20) ^{enr}Ge
5.6 kg (9) ^{nat}Ge

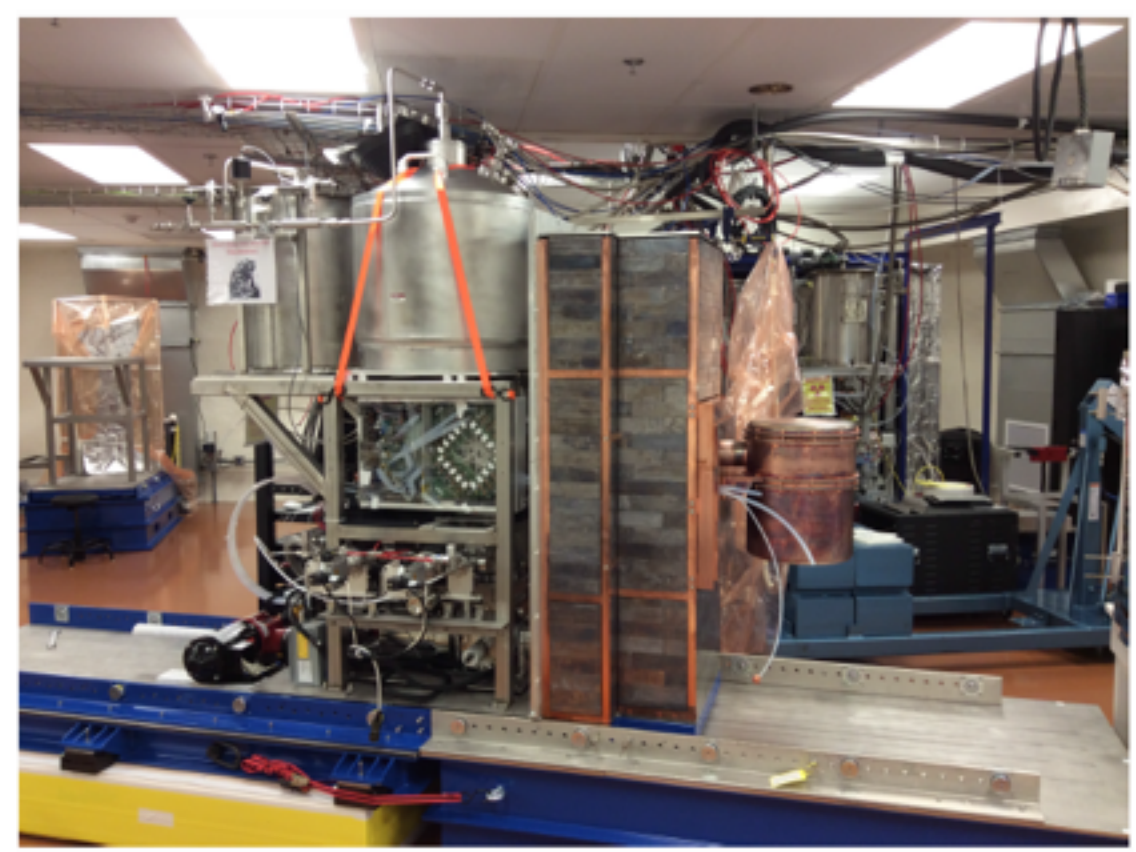


05/2015 - 10/2015
Final Installations,
12/2015 - on going

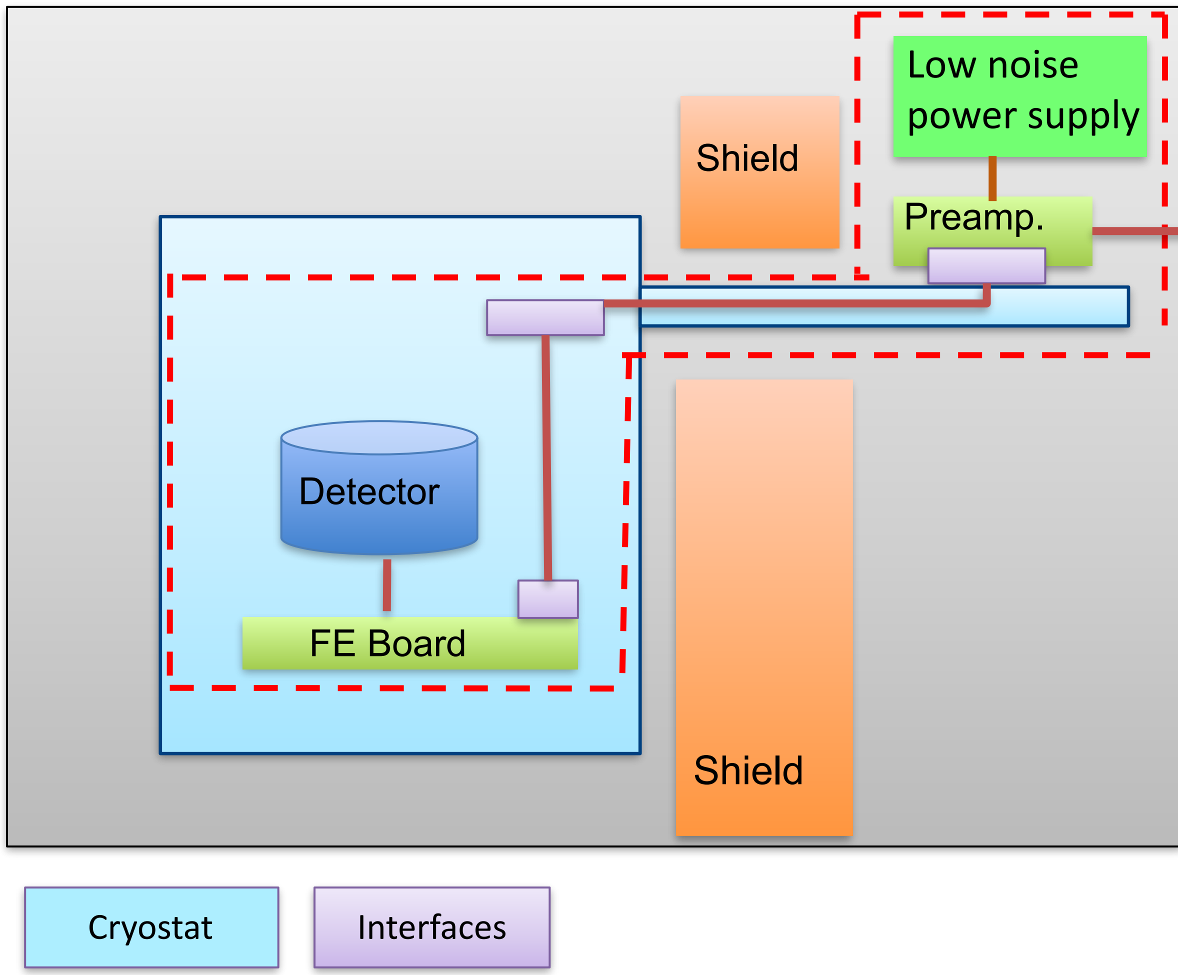
Module 2: 12.9 kg (14) ^{enr}Ge
8.8 kg (15) ^{nat}Ge

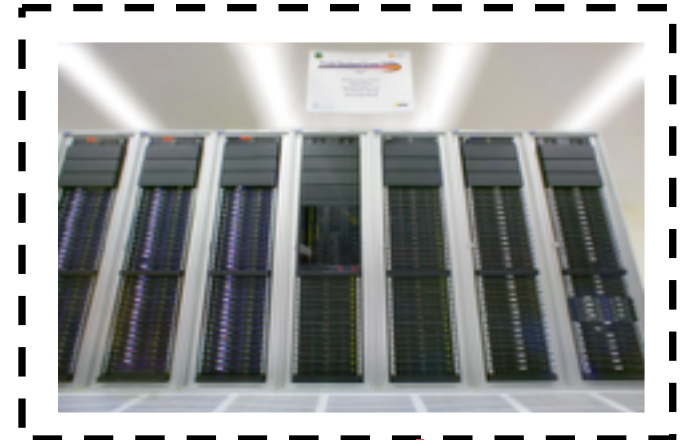


07/2016 - on going



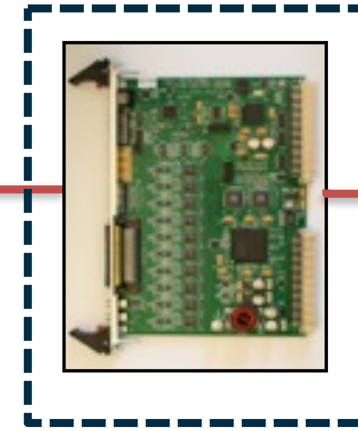
LBNL Contributions to MJD





Simulation & Analysis (WBS 1.02)

DAQ (WBS 1.10)



LBNL as task lead

LBNL significant contribution

WBS	Task Name	Institutional Responsibility
1.01	Management	ORNL, UNC, LANL, PNNL, TUNL
1.02	Simulation and Analysis	UW, all institutions
1.03	Host Site Infrastructure	LANL, SDSMT, UNC, USD
1.04	Materials and Assay	U Tenn./ORNL, LBNL, LANL, NCSU, PNNL, UNC
1.05	Electroforming	PNNL, LANL, SDSMT, UNC
1.06	Ge Production	USC, ITEP, JINR, ORNL, UNC
1.07	Detectors	LBNL, LANL, ORNL, NCSU, PNNL, SJTU, UNC, UW
1.08	Detector Modules	UNC, LBNL, LANL, PNNL, NCSU, TUNL, UW
1.09	Mech. System and Integration	USD, BHSU, LANL, U. Tenn
1.10	Data Acquisition	UNC, LBNL, LANL, ORNL, PNNL, UW
1.11	Commissioning	LBNL, LANL, Tenn. Tech., UNC, UW

Local ties

NERSC

BLBF

SDL

GRETINA

Glossary:

NERSC: National Energy Research Scientific Computing Center

BLBF: Berkeley Low Background Facility

SDL: Semiconductor Detector Laboratory

GRETINA: Gamma-Ray Energy Tracking In-beam Nuclear Array

Main LBNL Contributions to MJD

- **^{76}Ge-enriched detector procurement and production**
  - Quality assurance and **cleanliness monitoring** at vendor
  - **Coordination of enriched material transfer, detector production** and testing at vendor site and SURF

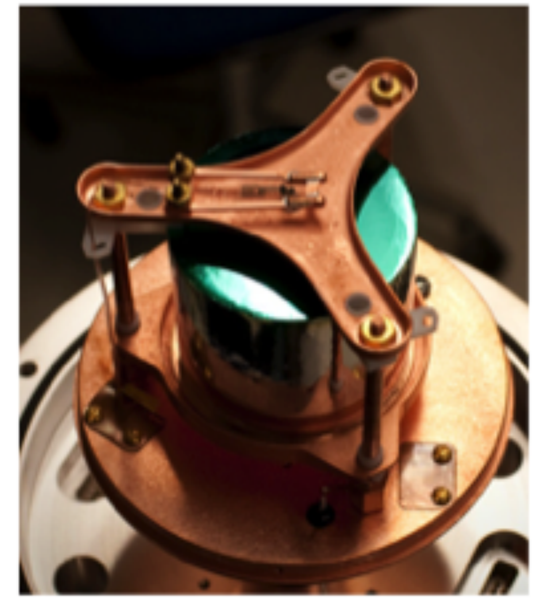
- **Signal readout development and fabrication**
  - Developed and fabricated **the most radiopure front-end** in the world
  - Developed **the most radiopure coaxial cables** in the world
  - Developed **lowest-noise front-end readout electronics in a large Ge array**

- **Detector string integration, and assembly and testing**
  - **Coordination of detector string assembly** activities underground

- **Leadership roles**
  - **Task lead** and **deputy task lead** (WBS 1.07) **- detector system**
  - **Task lead** (WBS 1.02) **- simulation and analysis** (until Detwiler departure in 2012)
  - **Deputy task lead** (WBS 1.04) **- material assay**
  - **Chair - mentoring committee**

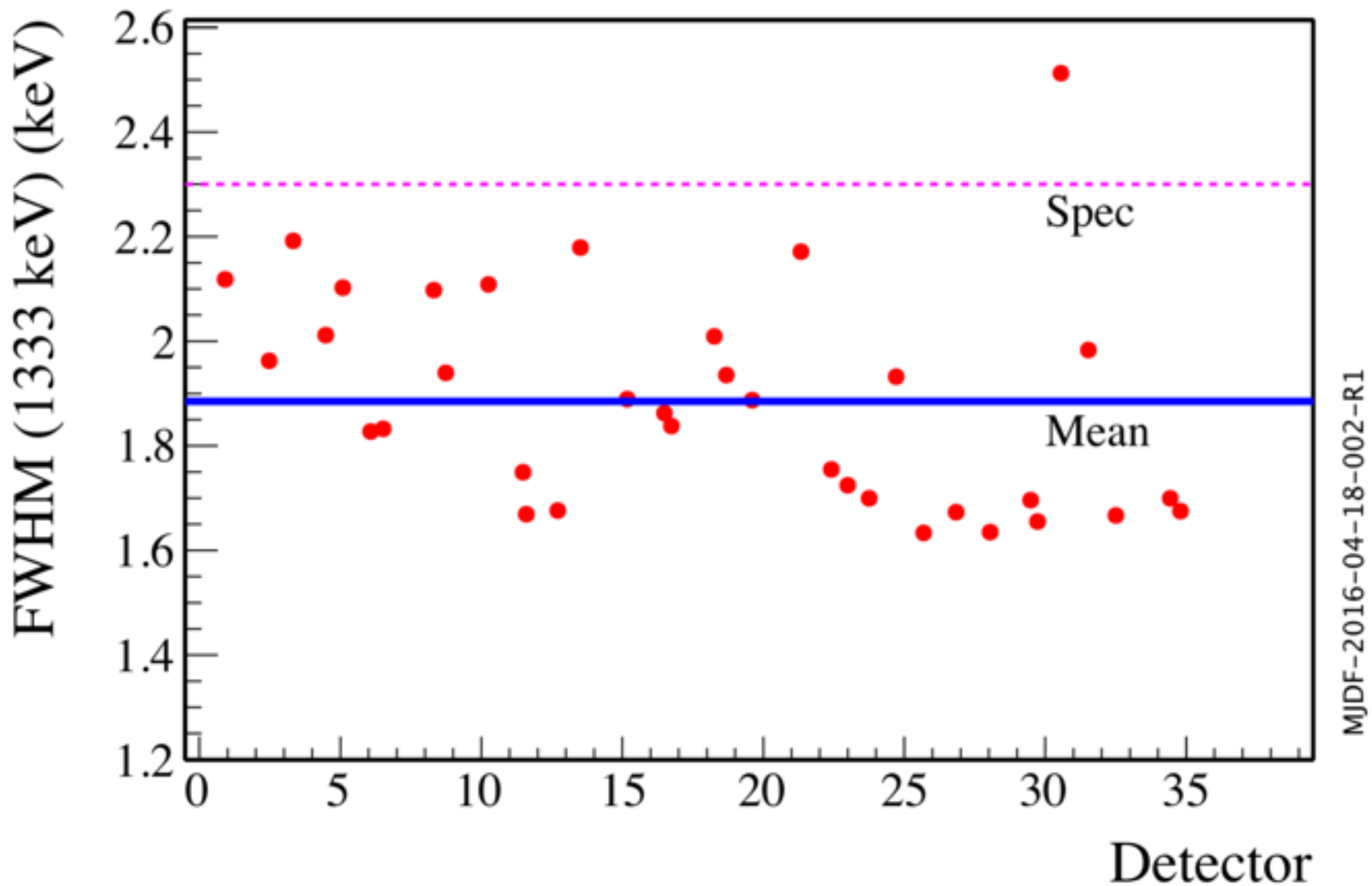
MJD ^{enr}Ge Detectors
(LBNL deliverable)

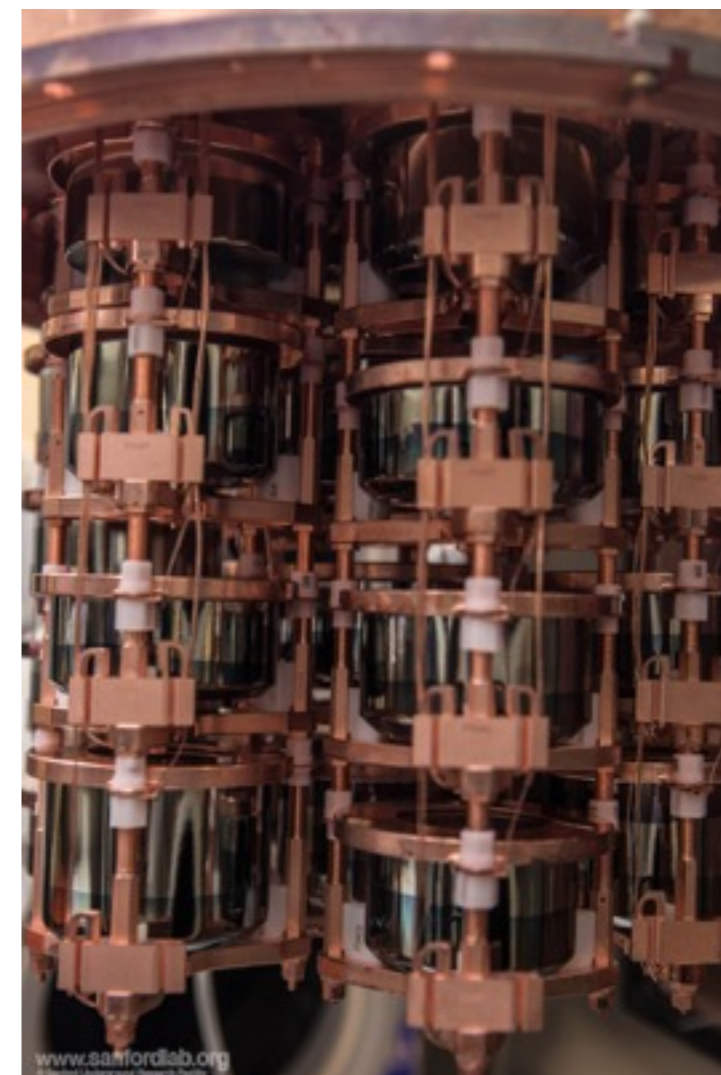
Total enriched detector mass = **29.7 kg / 35 detectors***
Mean FWHM at 1333 keV = **1.88 keV***



First integrated test

LBNL test string cryostat





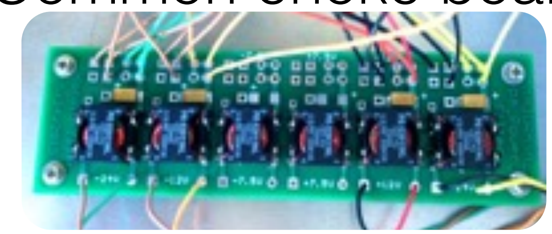
LBNL-led string assembly @SURF

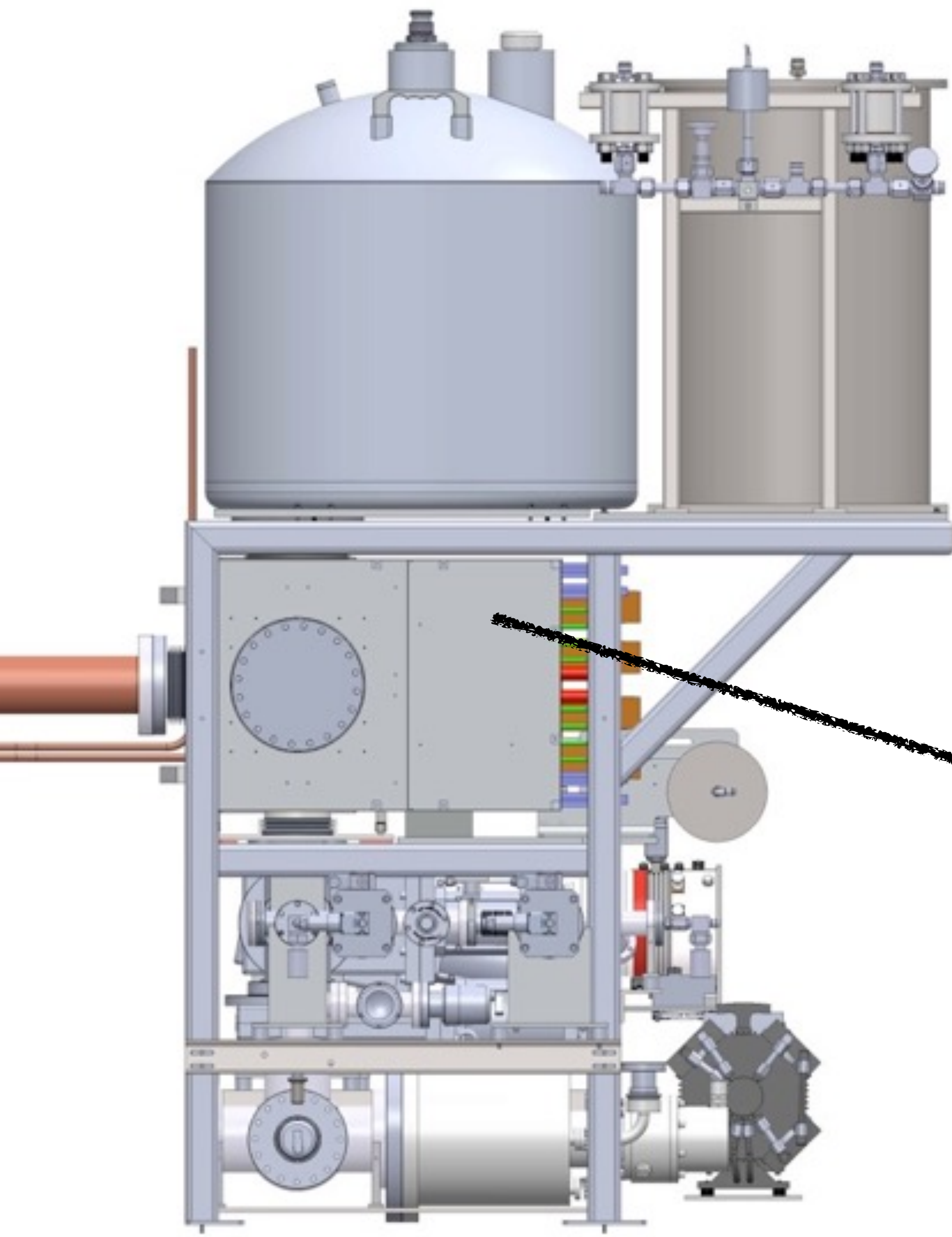
(* met DOE CD4 requirements)

MJD Electronics
(LBNL deliverable)

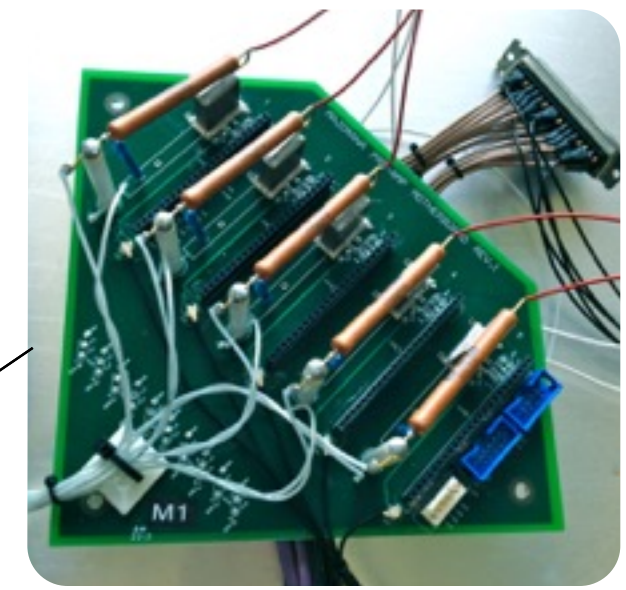
Controller card

Common choke board





Electronics enclosure



Motherboard

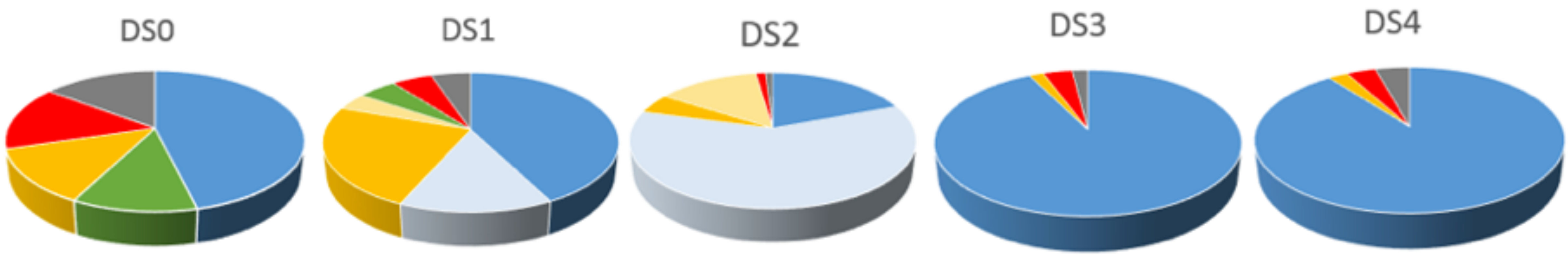
Preamp

Data Sets

		DS0 (days) Module1 No inner shield June 26, – Oct. 7, 2015	DS1 (days) Module 1 with inner shield Dec. 31, 2015 – May 24, 2016	DS2 (days) Module 1 with inner shield and multi-sampling May 24 – July 14, 2016	DS3 (days) Module 1 with inner shield Aug. 25, – Sept. 27, 2016	DS4 (days) Module 2 with inner shield Aug. 25, – Sept. 27, 2016
Total		103.15	144.50	50.97	32.37	32.36
Total acquired		87.93	136.98	50.47	31.73	30.97
Physics	*	47.70	61.34 + 20.41*	9.82 + 30.56*	29.97	29.01
High radon		11.76	7.32	-	-	
Disruptive Commissioning tests	*	13.10	34.43+ 5.92*	2.41 + 7.03*	0.57	0.78
Calibration		15.44	7.32	0.65	1.18	1.17
Down time		15.21	7.51	0.50	0.64	1.39

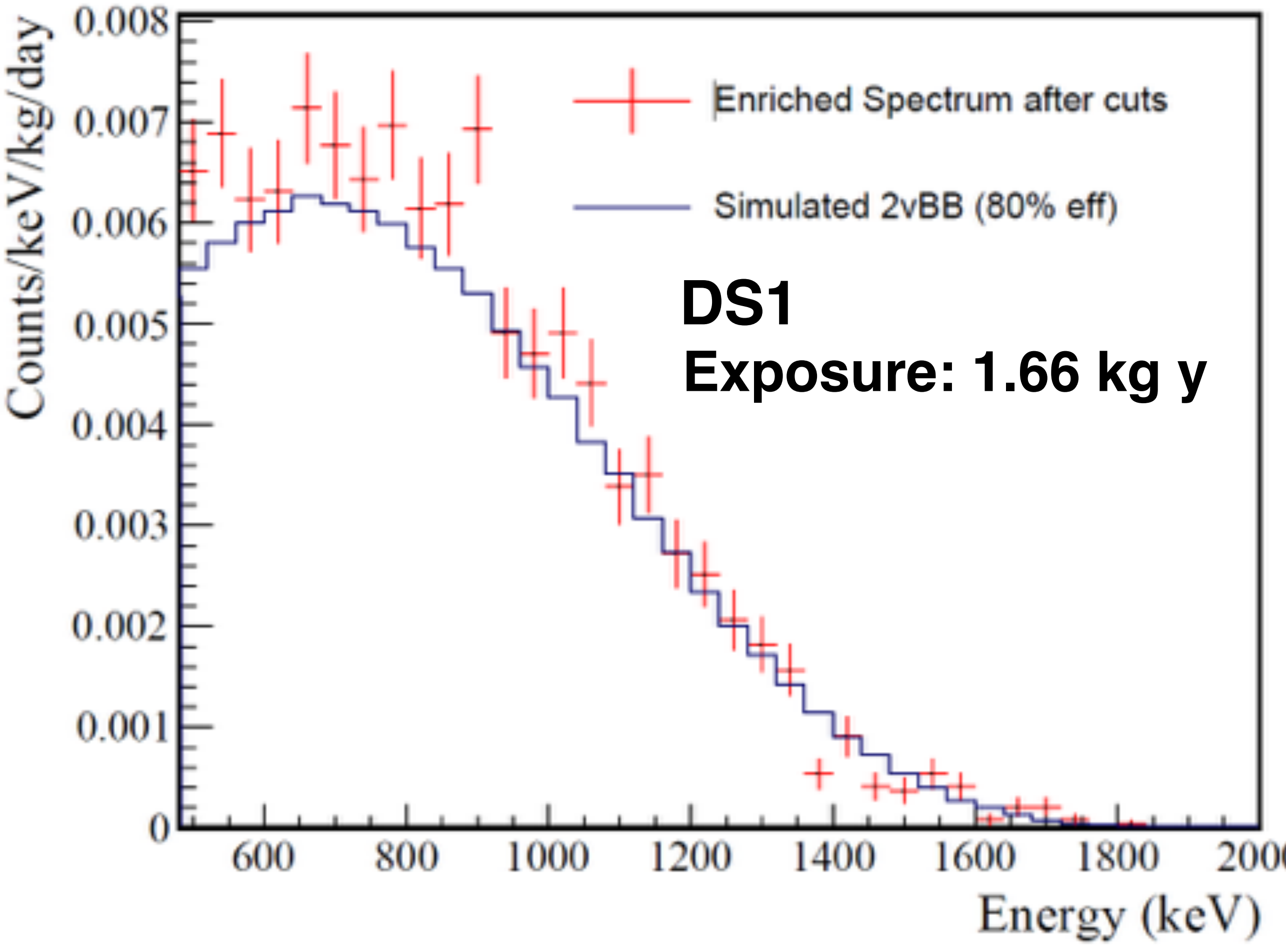
* Blind data

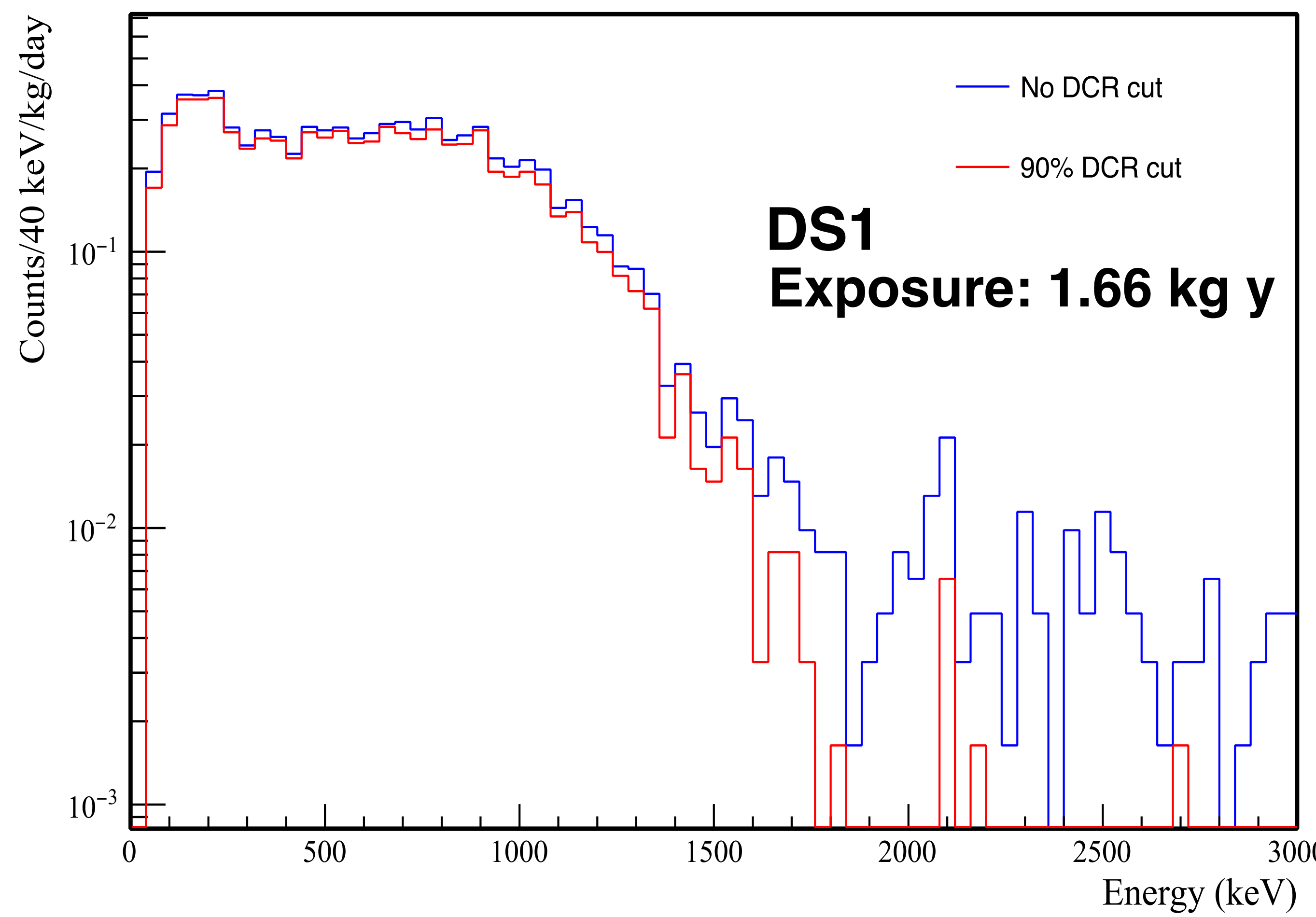
Released in June 2016



~93% live (phys+cal)

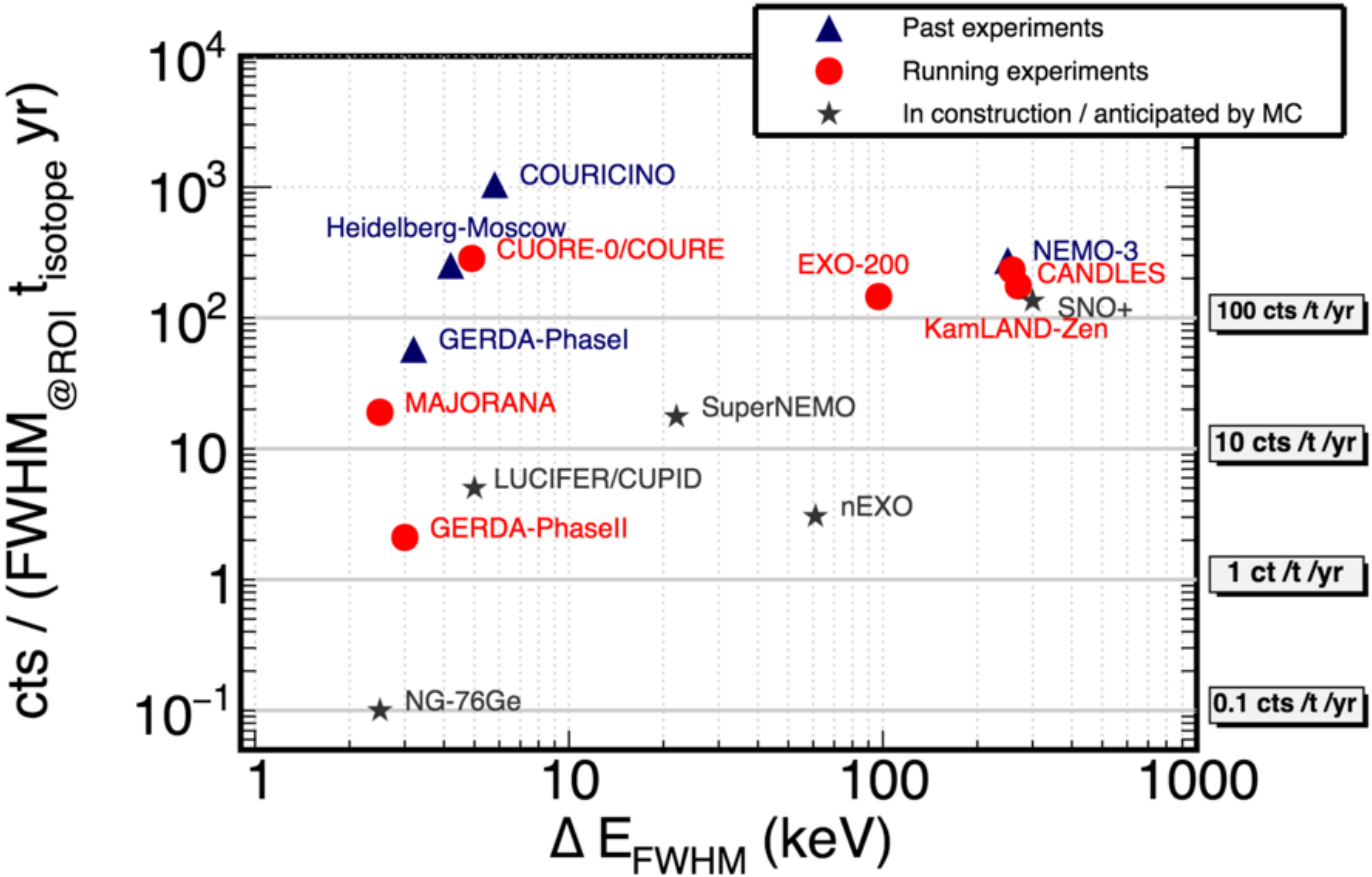
First release of MJD background data (June 2016)



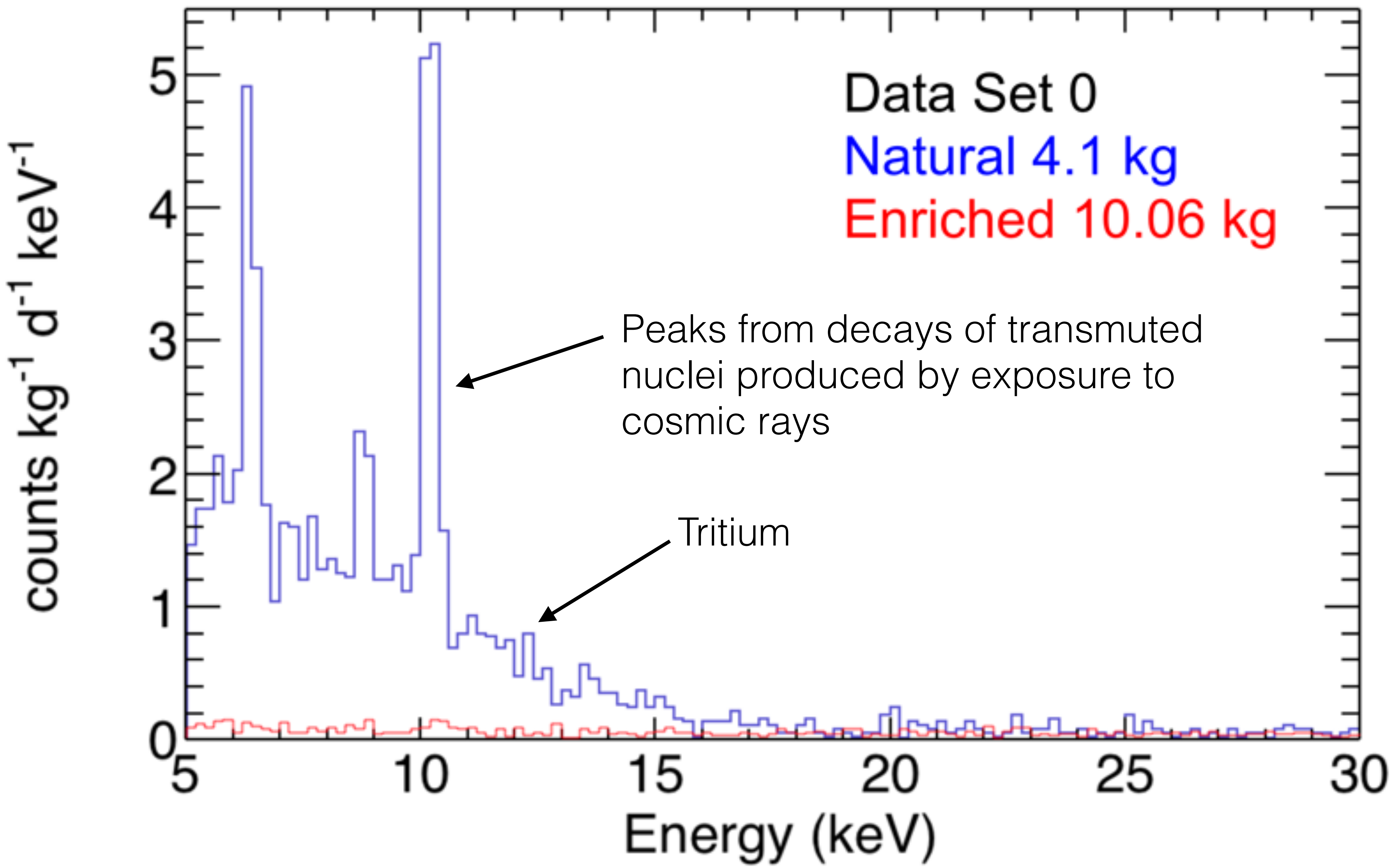


- Only 5 survived in 400 keV window. Background rate is 23^{+13}_{-10} counts/(ROI t y) for a 3.1-keV ROI, (68% CL).
- Background index is **$(7.5^{+4.5}_{-3.4})\times10^{-3}$ counts/(keV kg y)**. ***Better than all other currently-running detector technologies*** *(but higher than GERDA-II)*.
- DS0+DS1 open data (no event in ROI): **$T_{1/2}(0\nu\beta\beta)$ > 3.7 x 10^{24} years (90% CL)**.
- Low statistics results. All analysis cuts are still being optimized.

Background Comparison



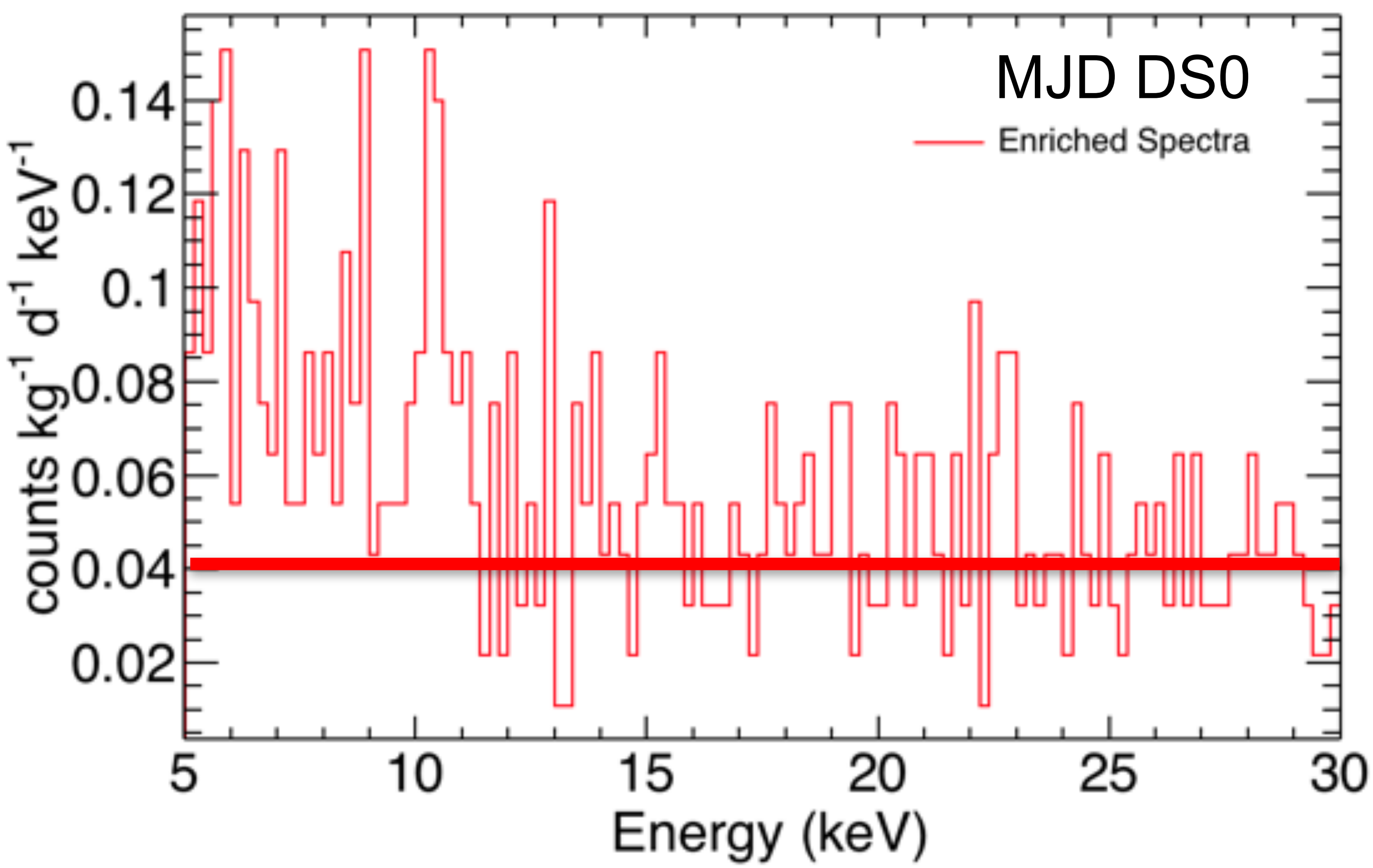
First release of background data

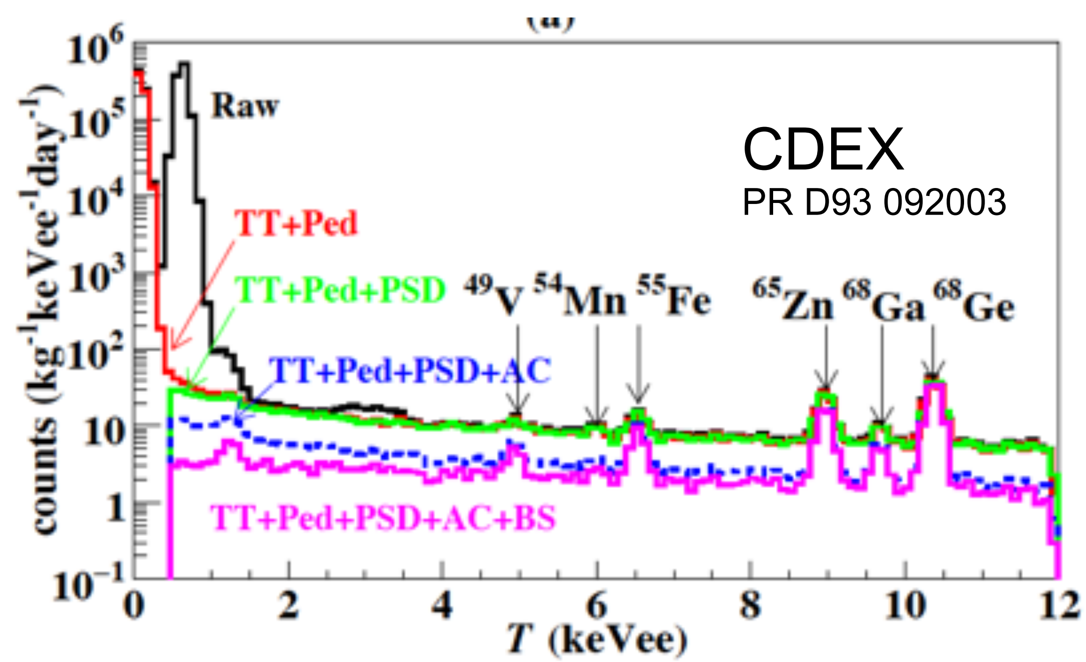


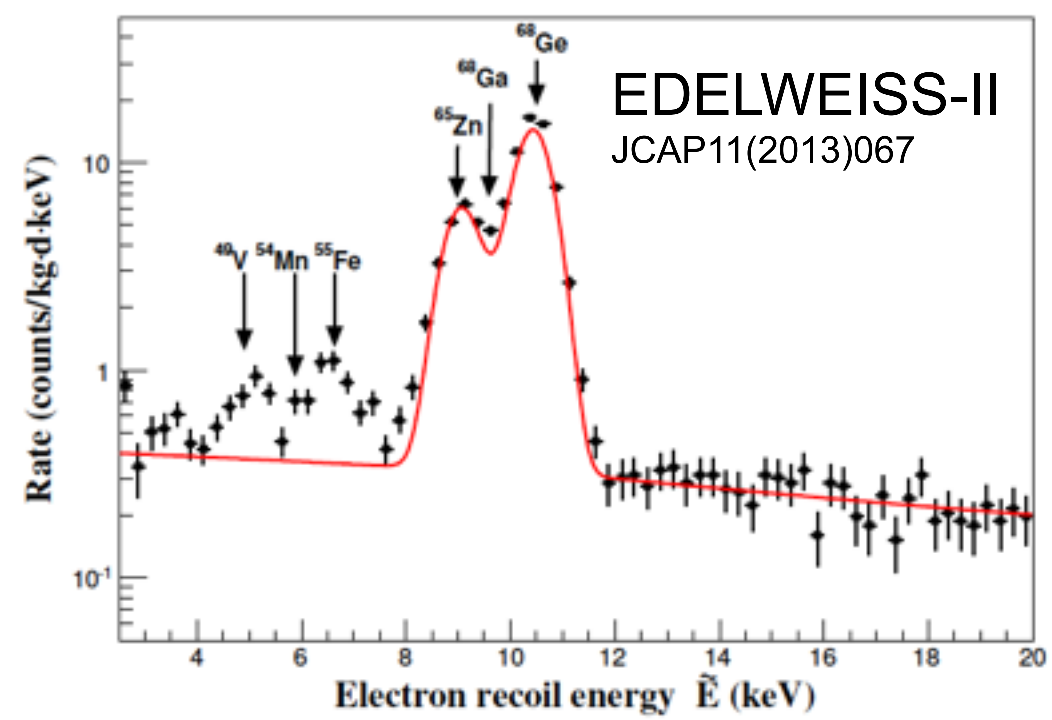
Extreme care to minimize cosmic-ray exposure during enriched detector production (LBNL responsibility) resulted in **exceptionally low cosmogenic backgrounds**.

Very Low Background – Data Set 0

The BG in DS0 at 20 keV: ~0.04 cnts/(kg keV d).

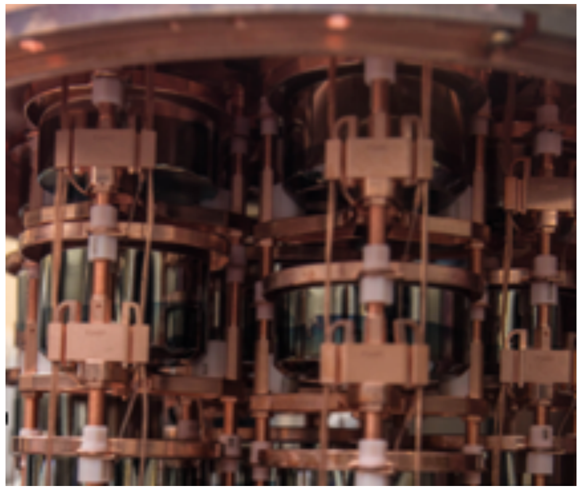






Low background in low-energy regime - extended low-energy physics program to search for physics beyond the Standard Model.

Current and future work…



MJD Analysis

Focus:

- Instrumental backgrounds
- Radioactive backgrounds
- *Search for 0νββ*

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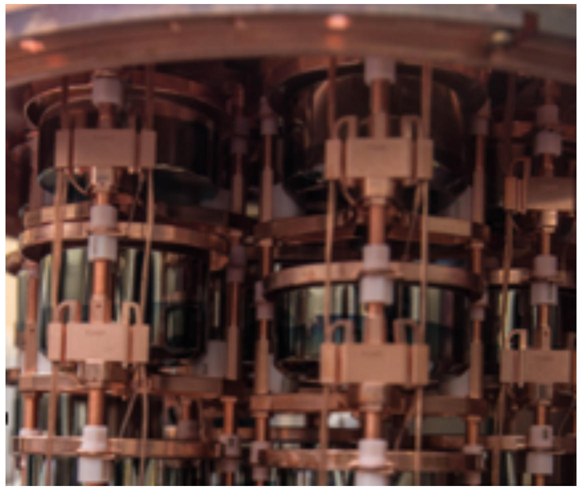

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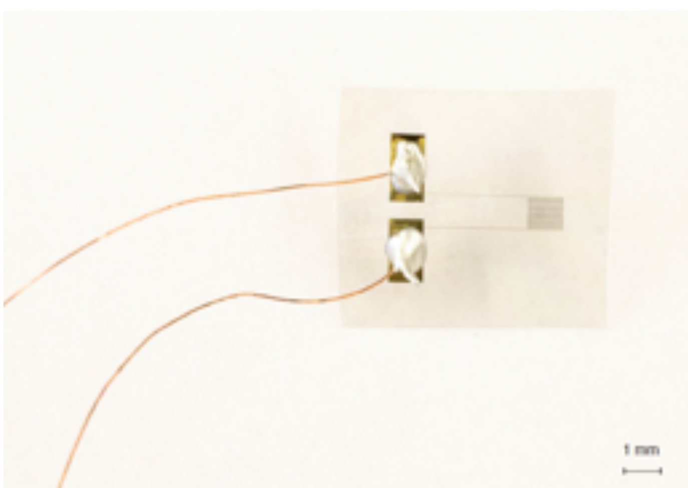

Clean flexible circuitry

- Development of clean circuitry and passive electronic components for next-generation 0νββ and dark matter experiments

A. Dhar *et al.*, *A Low-Background Parylene Temperature Sensor,* JINST **10** P12002

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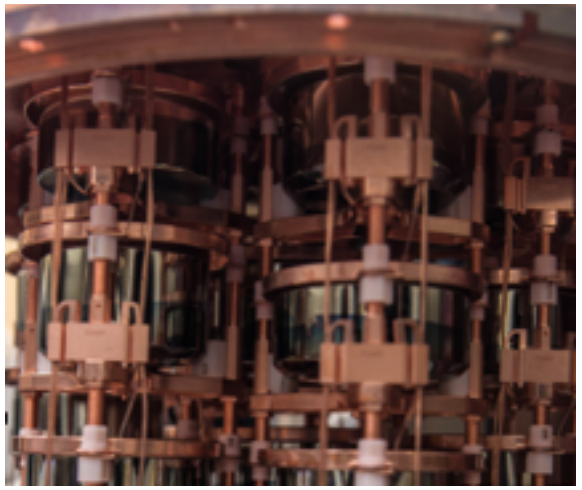

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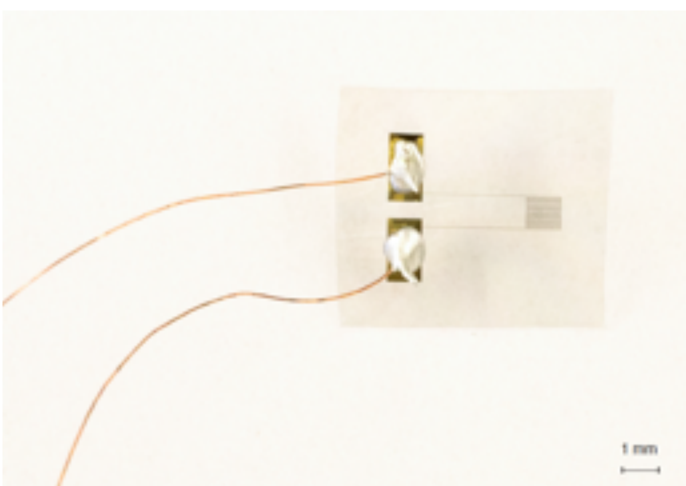

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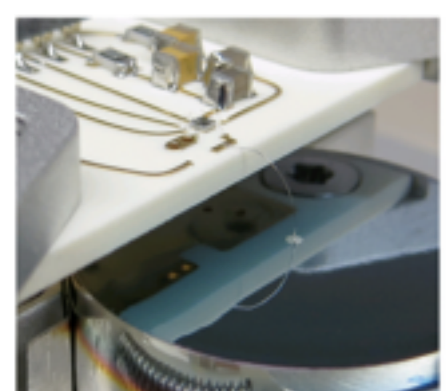
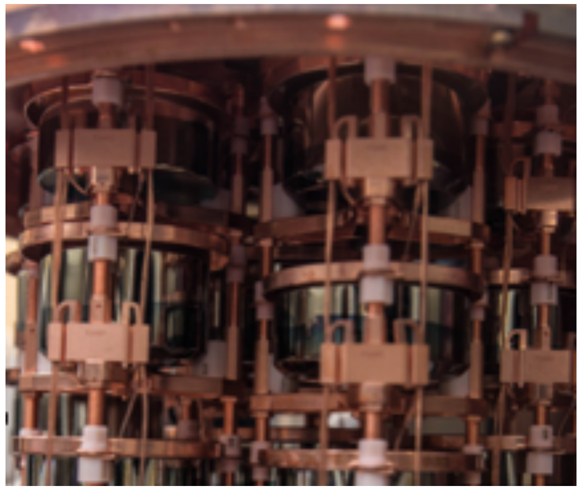


Next-Gen readout
- Collaboration with Applied Nuclear Physics Program to develop clean ASIC-based readout system
- Test readout performance in vacuum and liquid cryogen (in collaboration with TUM)

Current and future work…



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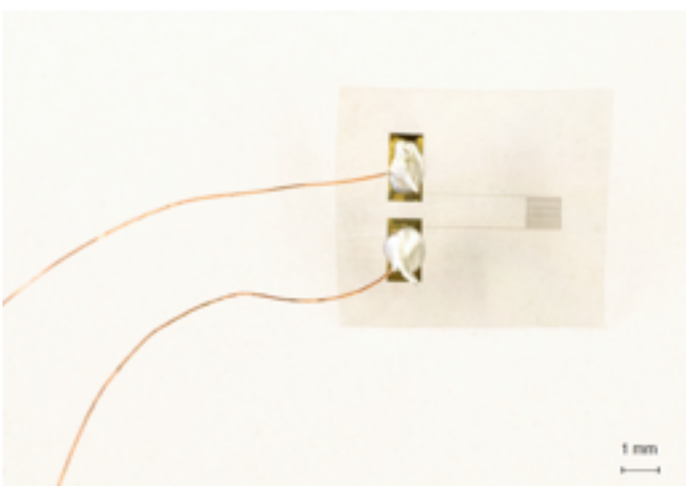

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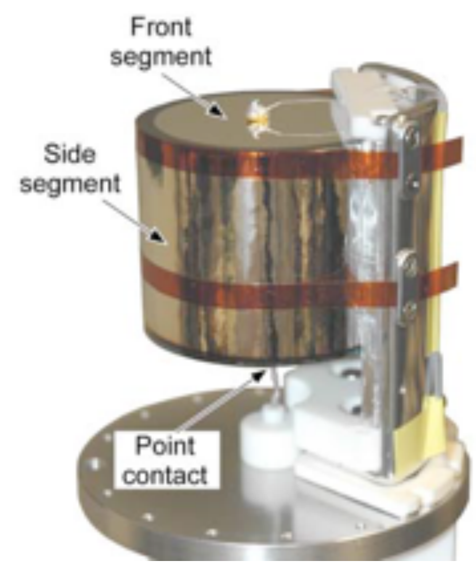
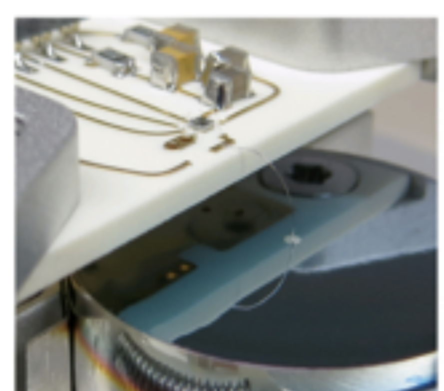


Ge detector optimization

- Investigations of detector designs to optimize detector surface alpha background rejection (dominant background in MJ)



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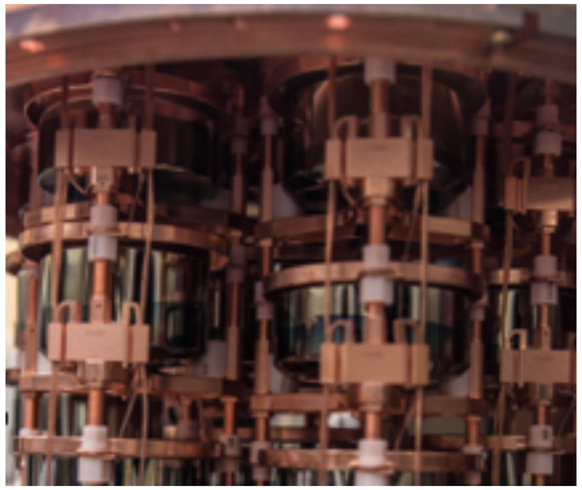

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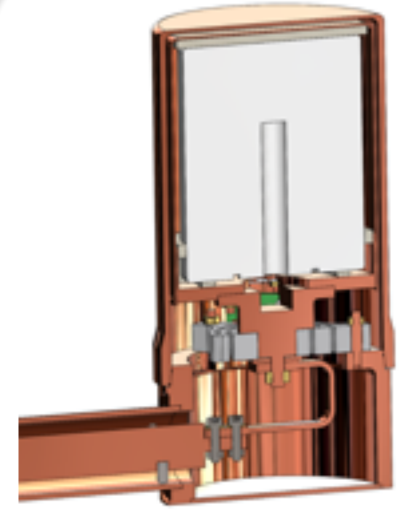
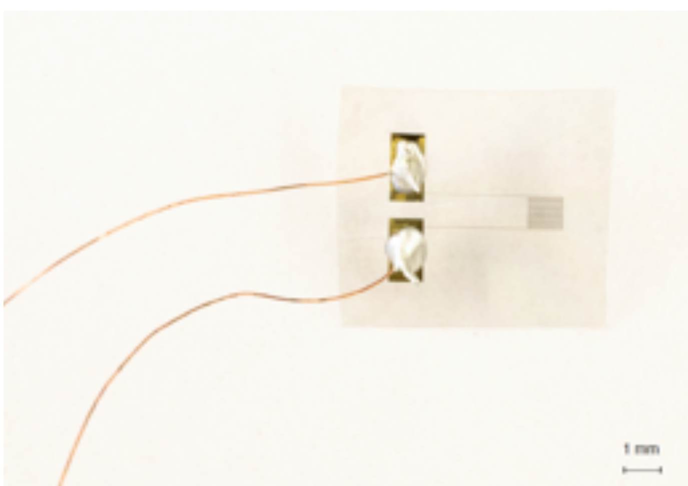


State-of-the-art γ screener

- Integration of MJ and GERDA technology
- Collaboration with MPI-Heidelberg, TUM and Gran Sasso to build the most sensitive screener in the world



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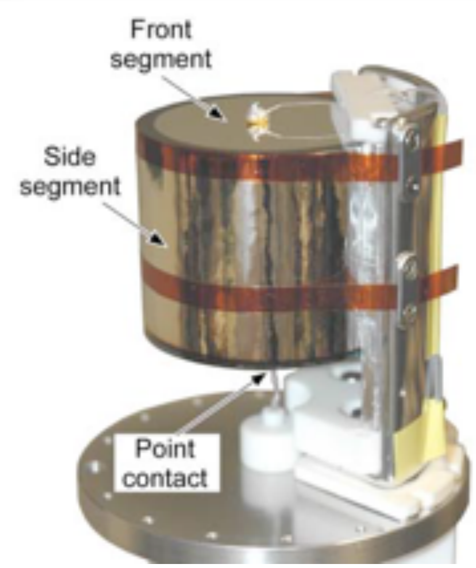

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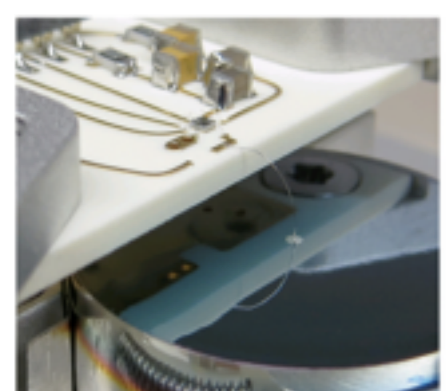

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Next Generation ^{76}Ge Experiment

Working cooperatively with GERDA and other interested groups toward the establishment of a next-generation ^{76}Ge $0\nu\beta\beta$-decay experimental collaboration to build an experiment to explore the inverted ordering region of the effective mass.

Joint MAJORANA-GERDA Meeting
Nov. 2015 Kitty Hawk

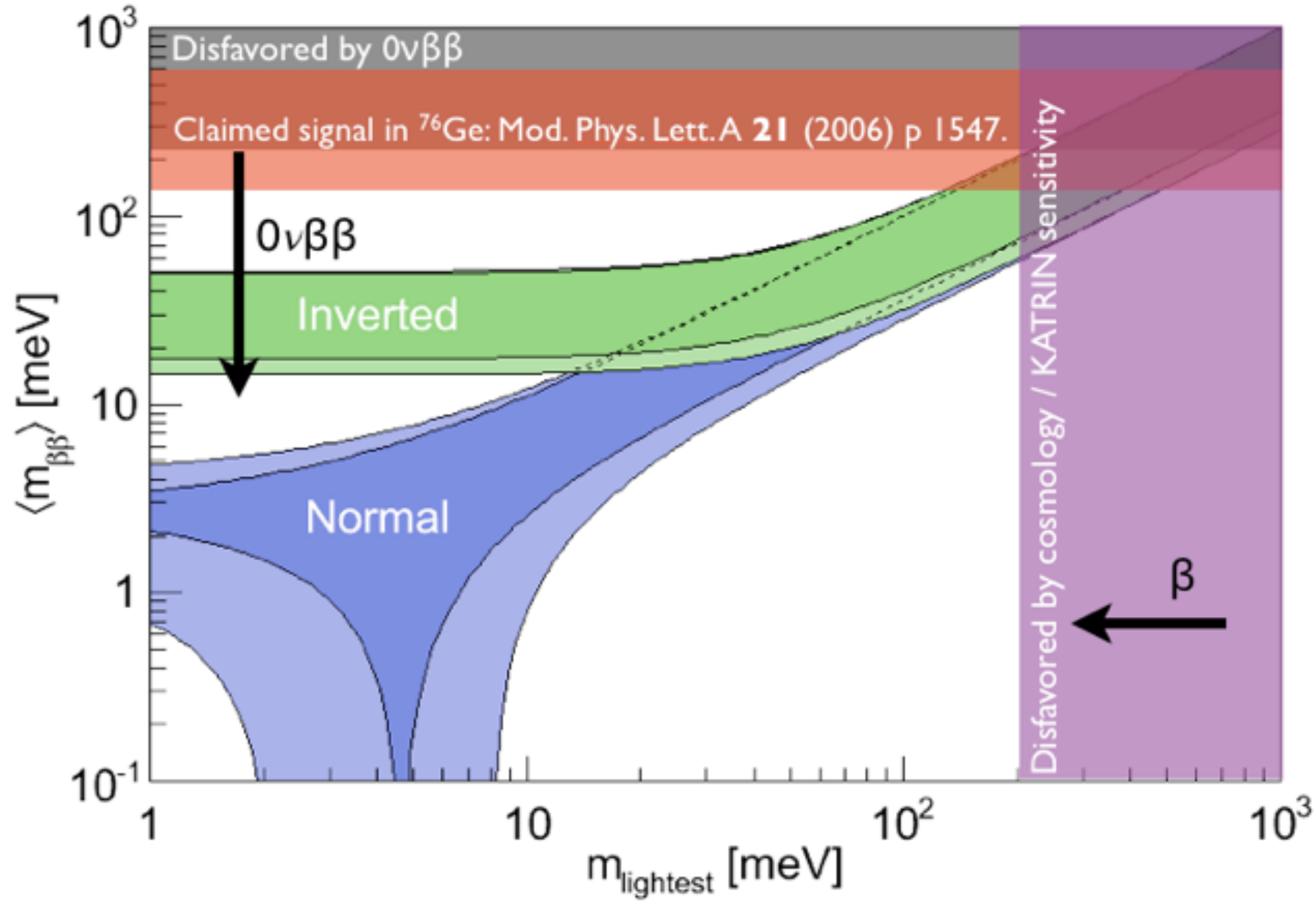
Meeting of Interested Parties
April 2016 Munich

Next Meeting
Oct. 27-29, Atlanta, GA

Probing the neutrino mass scale

ββ decays:

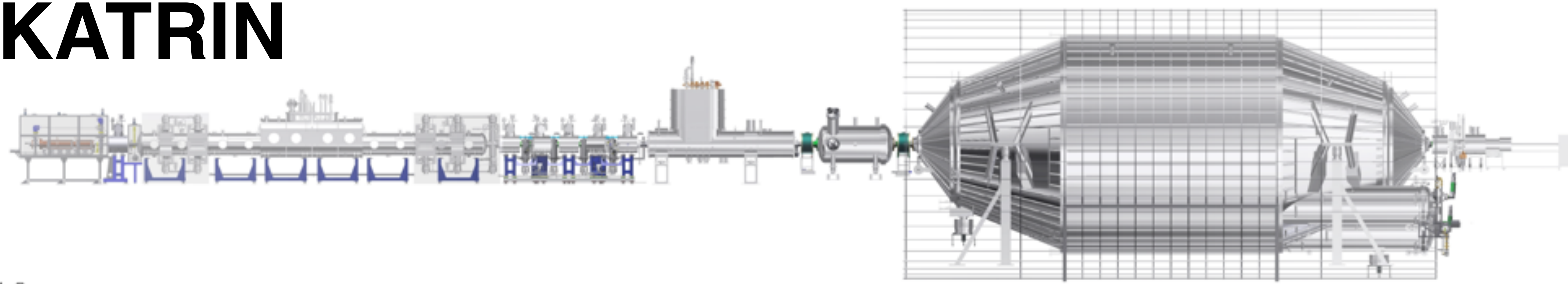
$$m_{\beta\beta} = \sum_{i=1}^{3} \left| U_{ei}^2 m_i \right|$$

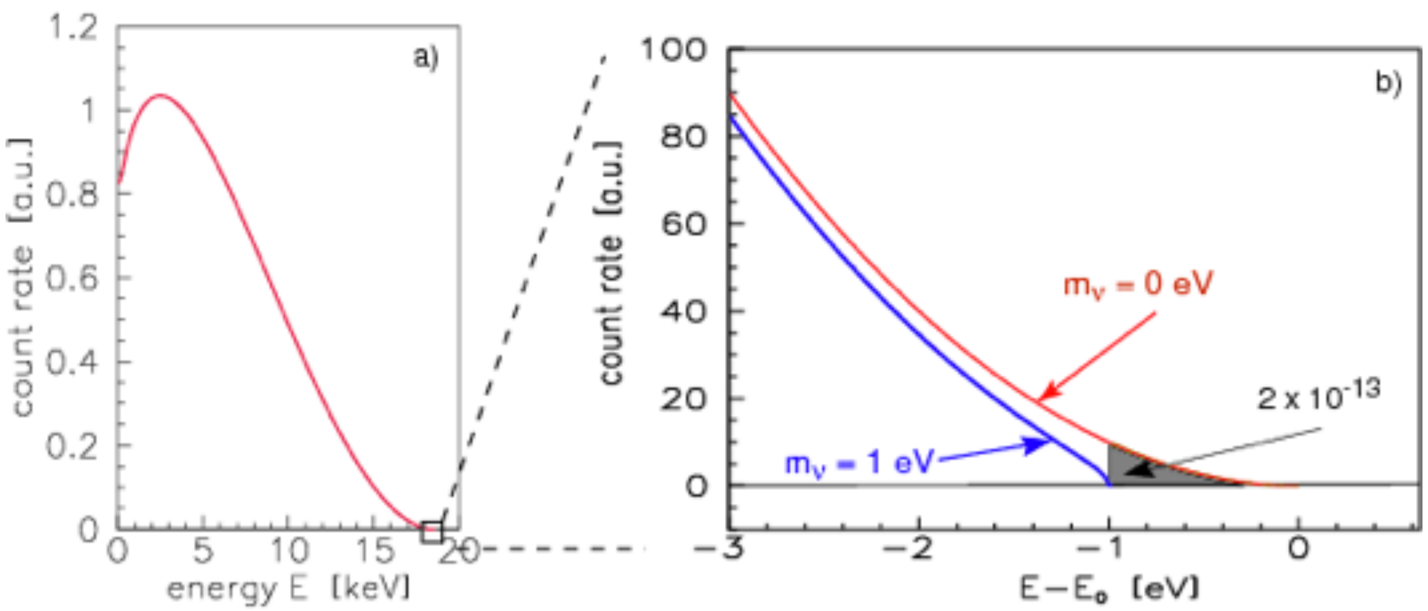


β decays:

$$m_\beta = \sqrt{\sum_{i=1}^{3} \left| U_{ei} \right|^2 m_i^2}$$

KATRIN

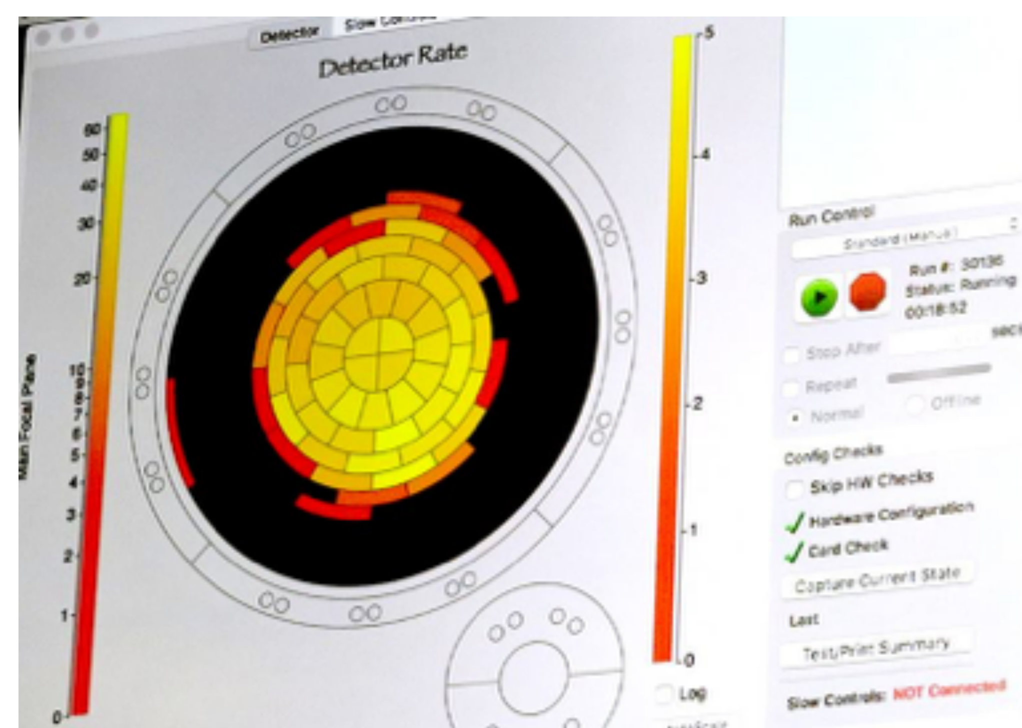




- Design goal: **0.2 eV** on m_β (90% CL)

Beam-line closed on 9/23/2016

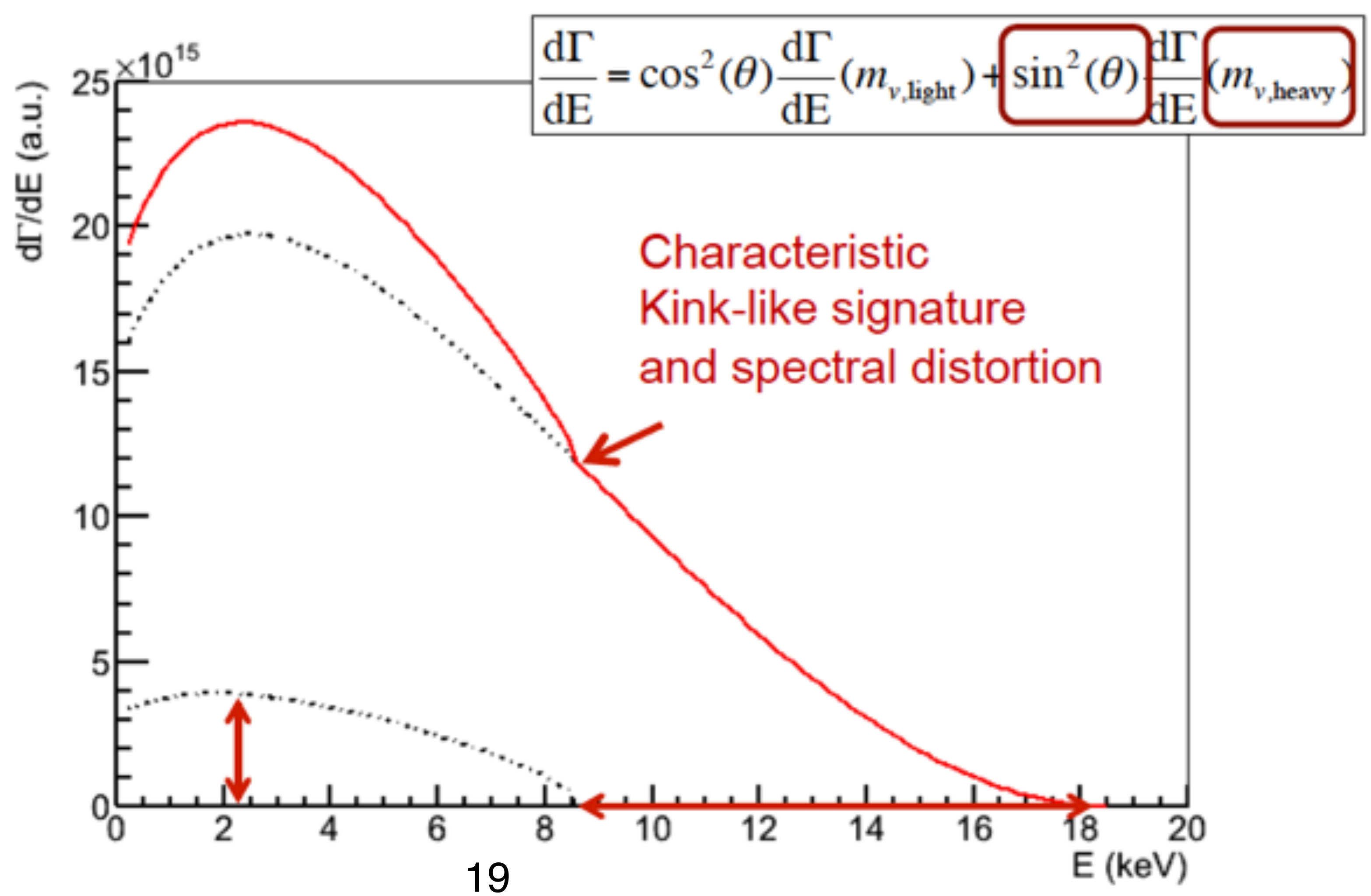
“First-light” on 10/14/2016



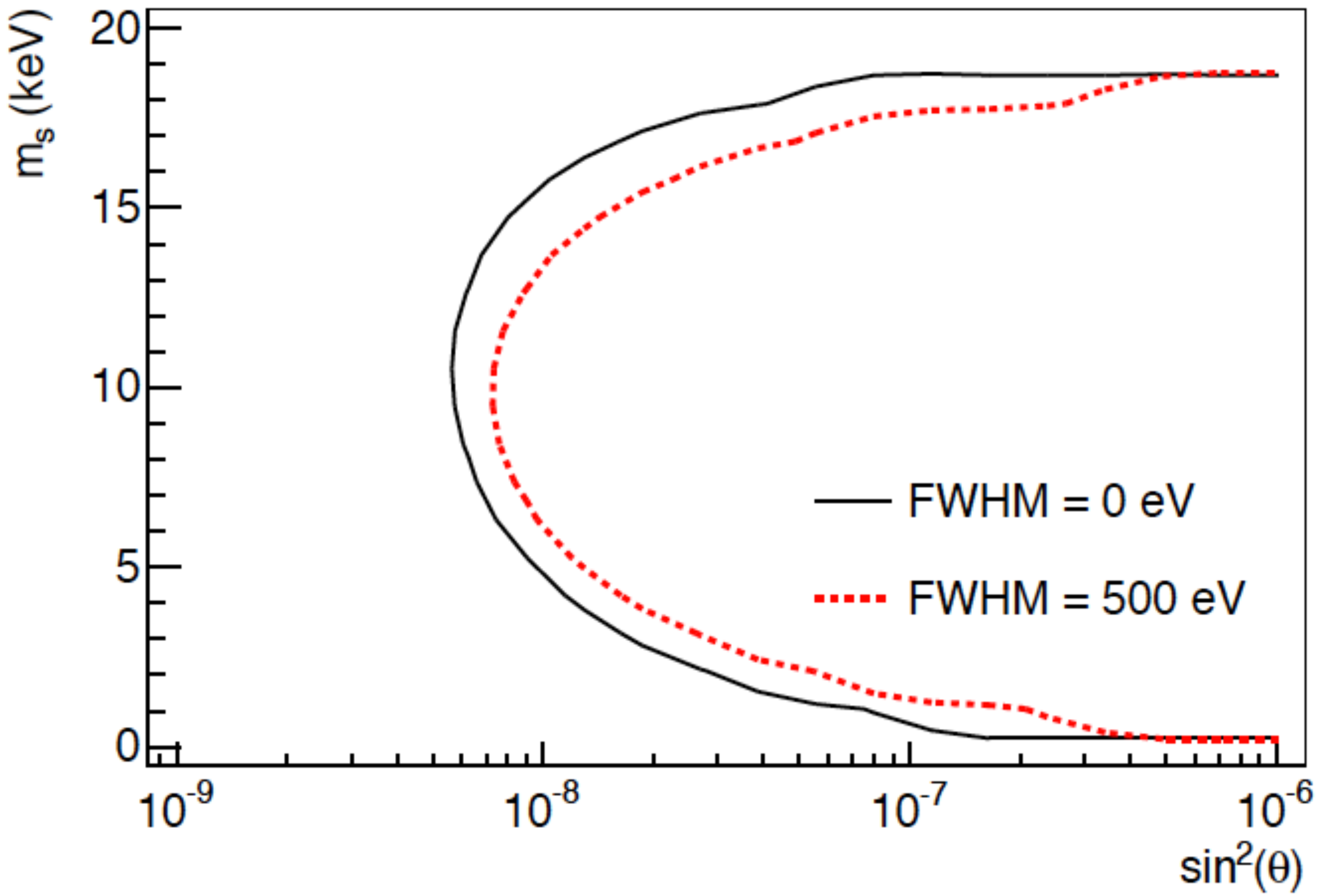
KATRIN - LBNL Contributions

- Conceptual design of calibration system [to 2009]
- Chair, Publication Committee
- Analysis software development
- Manage NERSC computing resources for US collaboration.
- Material assays: gamma counting and Rn analysis
- Physics sensitivity studies: m_β and sterile neutrino search

keV-sterile neutrinos search



KATRIN - Sterile Neutrino Search



S. Mertens *et al.*, *Sensitivity of Next-Generation Tritium Beta-Decay Experiments for keV-Scale Sterile Neutrinos*, JCAP 02, 020 (2015).

S. Mertens *et al.*, *Wavelet Approach to Search for Sterile Neutrinos in Tritium Beta-Decay Spectra*, Phys. Rev. **D91**, 042005 (2015)

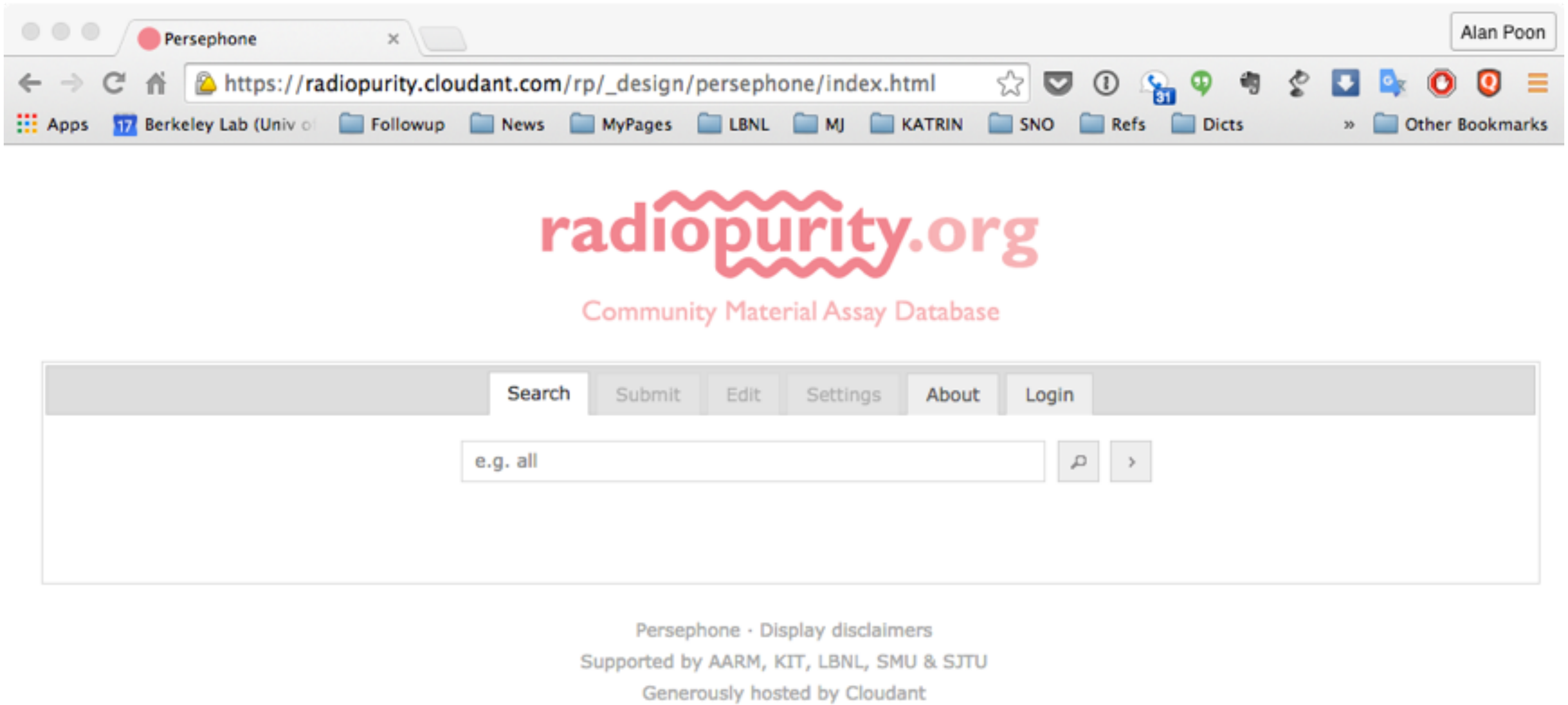
Berkeley Low Background Facility (BLBF)

	Local Site LBNL	Remote Site SURF 4850 L
Overhead burden	Low-activity serpentine 1.5m min. thickness	4300 m.w.e. overburden
Dominant backgrounds	Cosmic ray muons [muon vVeto in use]	Residual activity in detector and shielding
Detectors	1 x 115% n-type & 1 x 85% p-type	2 x 85% p-type 1x 30% p-type
Shielding	4” Pb, 0.5” OFHC Cu, N_2 purge	8” Pb, 0.5” OHFC Cu, N_2 purge

Counting room at SURF

- **Has been providing services to the physics community and LBNL for 60 years**
- **Member of Nuclear Science and Security Consortium**
  - training of next generation radioassay experts
- **Supported many groundbreaking underground/physics projects:**

radiopurity.org



A project started in our group, adopted by the international community

Experiments are adding their radioassay results to this database

J.C. Loach *et al.*, *A Database for Storing the Results of Material Radio-purity Measurements*
Nucl. Instr. Meth. A839 (2016) 6-11

Visitors in the last 5 years

- The MJD-KATRIN group attracts foreign students and postdocs, *funded by their respective countries*, to conduct neutrino and Ge detector research at LBNL.
- Typical stay is 3 - 12 months
- Strong connection to KIT, the lead institution for KATRIN.

Kai Dolde, KIT Diplom student (KATRIN, supported by DAAD)

Stefan Groh, KIT PhD student (KATRIN, supported by KHYS)

Marco Kleesiek, KIT PhD student (KATRIN, supported by KHYS)

Alexander Hegai, Tuebingen PhD student (GERDA, supported by DAAD)

Markus Hoetzel, KIT PhD student (KATRIN, supported by KHYS)

Anton Huber, KIT Diplom student (KATRIN, supported by DAAD)

Marc Korzeczek, KIT Diplom student (KATRIN, supported by DAAD)

Jing Liu, Tokyo U Postdoc (HPGe research supported by Kamioka Obs.)

Sebastian Schams, KIT Diplom student (KATRIN, supported by DAAD)

Christopher Schmitt, Tuebingen PhD student (GERDA, supported by DAAD)

Summary

- The MAJORANA-KATRIN group has an exciting scientific program to probe lepton number violation and neutrino mass scale down to ~0.2 eV:
  - Neutrinoless Double Beta Decays ($m_{\beta\beta}$): MAJORANA DEMONSTRATOR
  - Tritium Beta Decays (m_{β}) : KATRIN
- The strength of our group:
  - Extensive experience in low-background experiments (since SNO)
  - Radiopure materials and fabrication techniques
  - Radiopure and low-noise electronics for Ge detectors
  - Analysis expertise
- Well-positioned to take on lead roles in future low-background experiments.
- The endeavors benefit greatly from the range of expertise and unique infrastructures that exist at LBNL.
- The rich research culture and environment attract the best young scientists to Berkeley, and expose them to a broad research program in neutrino physics and underground science.

Backup

…for a Majorana neutrino

Personnel (FY13-16)

- **Publications**: 29 (23) refereed journals
- **Invited talks**: 31

- **Significant services to the physics community and collaborations, and education:**
  - Task lead and deputy task lead for MAJORANA DEMONSTRATOR detector task (WBS 1.07)
  - Deputy task lead for MAJORANA DEMONSTRATOR material assay task (WBS 1.04)
  - Member of MAJORANA Executive Council
  - Elected young member representative of MAJORANA Executive Council
  - Co-chair of MAJORANA Mentoring Committee
  - Chair of KATRIN Publication Committee
  - Member of KATRIN Collaboration Board
  - Member of APS Committee on Education, and K-12 subcommittee
  - Member of APS DNP Program Committee
  - Member of APS DNP Education Committee
  - Chair of the Selection Committee of APS Prize to a Faculty Member for Research in an Undergraduate Institution
  - Member of APS Working Group to review the US Next Generation Science Standards
  - Member of NSF Robert Noyce Teacher Scholarship Selection Committee
  - Member of LUX-ZEPLIN (LZ) CD2/3b and CD3c Director's Review Committees
  - Member of LZ conceptual, preliminary design and final design review committees
  - Member of SURF Radioactivity Contamination Committee
  - Member of Ad Hoc Steering Committee of the Interest Group on Neutrinos and Fundamental Symmetries
  - Scientific Secretary of International Workshop on Double Beta Decay and Neutrinos 2014, 2016
  - Member of the Low Radioactivity Techniques Workshop International Advisory Committee 2015, 2017
  - Organizing Committee for FS&N Town Meeting and Pre-Town Meeting for the US Long Range Plan in Nuclear Physics
  - Local Organizing Committee, Conference for Undergraduate Women in Physics 2014 in Berkeley
  - Mini-symposium on Instrumentation for Beyond Standard Model Physics at DNP2016
  - Mini-symposium on The Reactor Neutrino Anomaly at DNP2016
  - Chair of LBNL Nuclear Science Day for Girl Scouts and Boy Scouts

Recognitions (FY13-16)

SNO: Nobel Prize, Breakthrough Prize

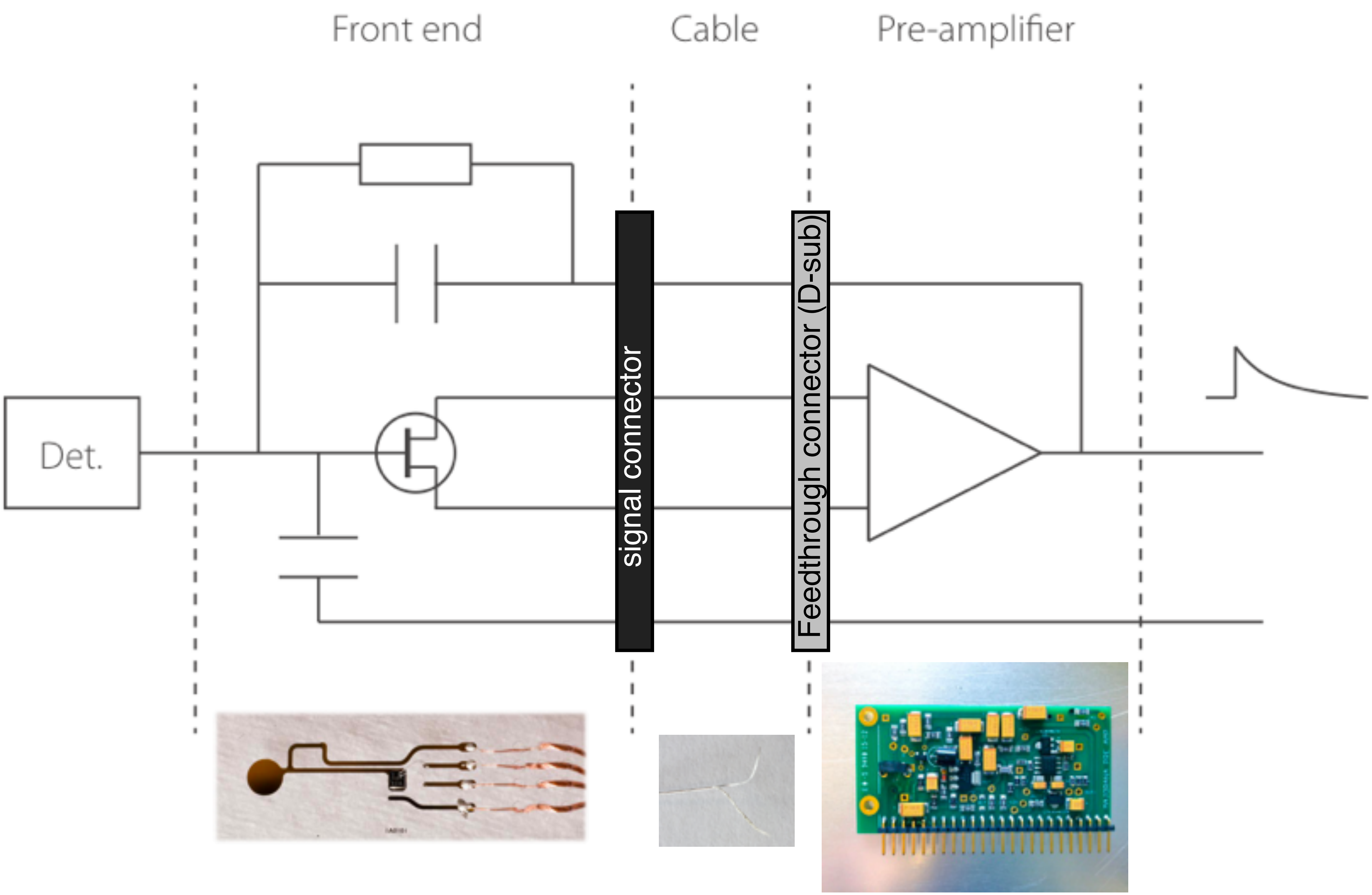
KamLAND: Breakthrough Prize

Susanne Mertens: Alexander von Humboldt Foundation

Feodor Lynen Fellow

Alan Poon: APS Fellow

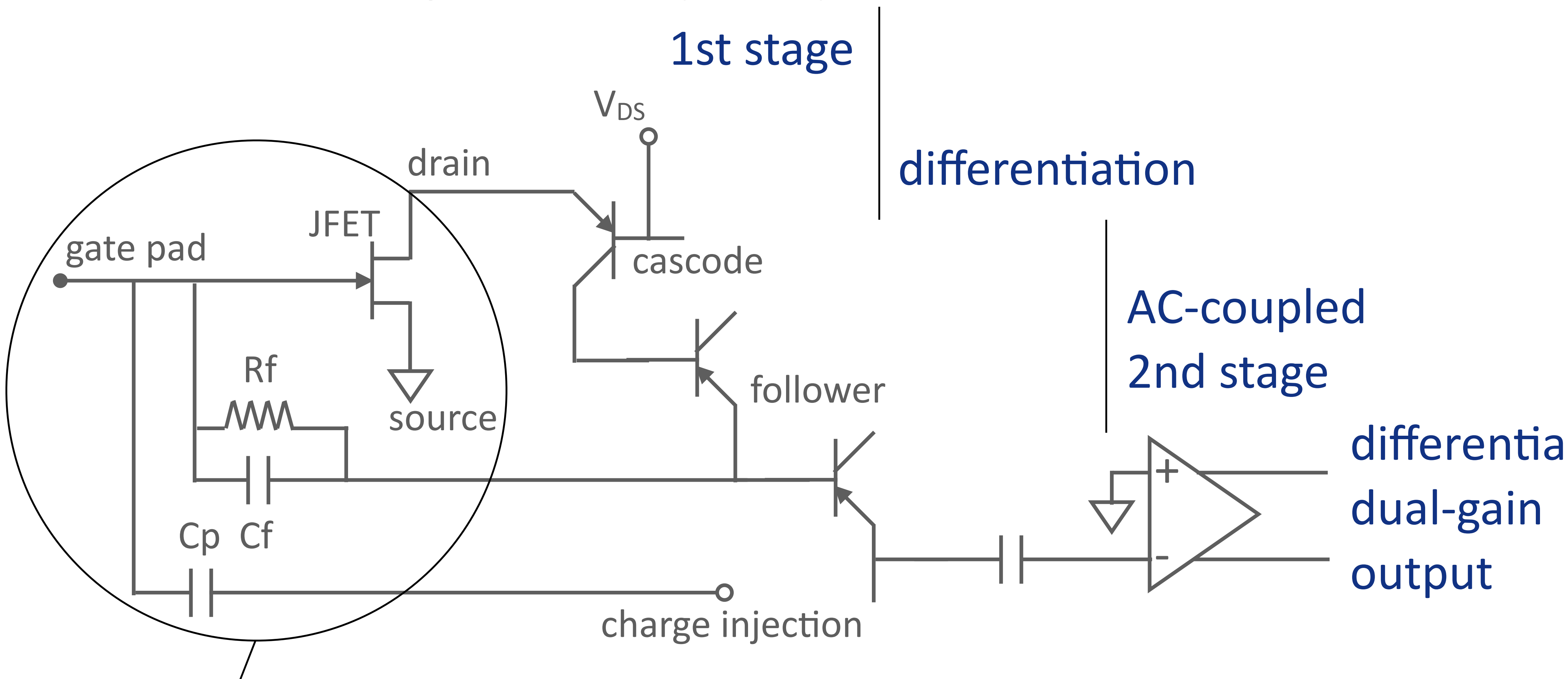
Readout Electronics

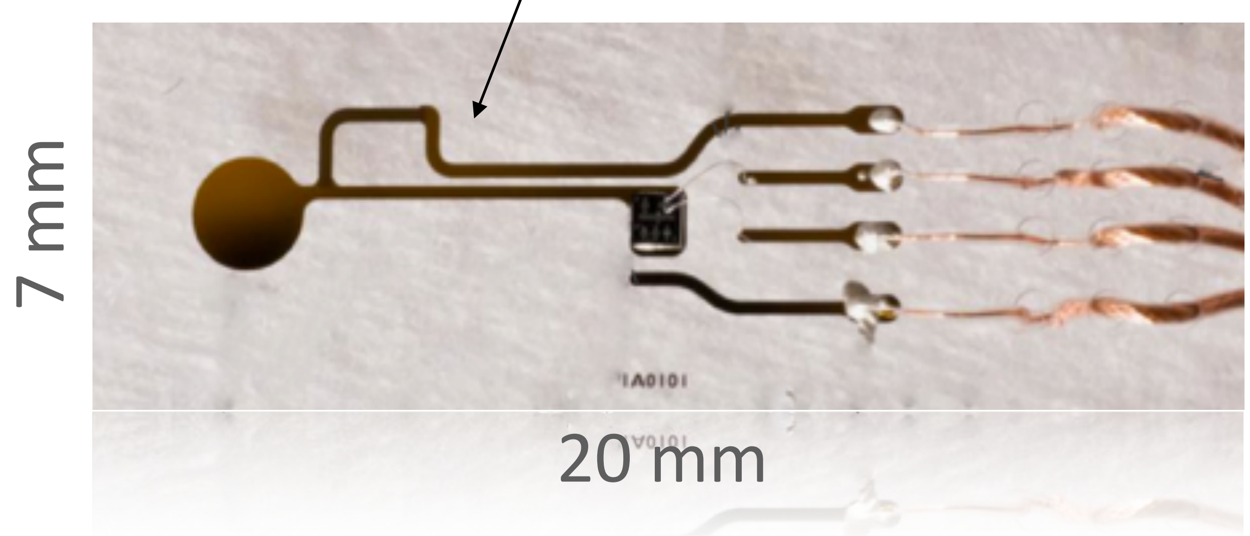


- Established workspace at a class-100 cleanroom for front-end production

Overview of MJD LMFE-preamp

Resistive feedback charge-sensitive preamplifier:





front-end:

n-channel JFET
Rf ≈ 10 GΩ @ 85K
Cf = 0.17 pF
Cp ≈ Cf

External control (10%) on drain to source current (via V_{DS})

Reduced the component count by using stray capacitance

IEEE Nucl. Sci. Symp. Conf. Rec. 2011, 1976 (2011).

MJD CD4 Key Performance Parameters*

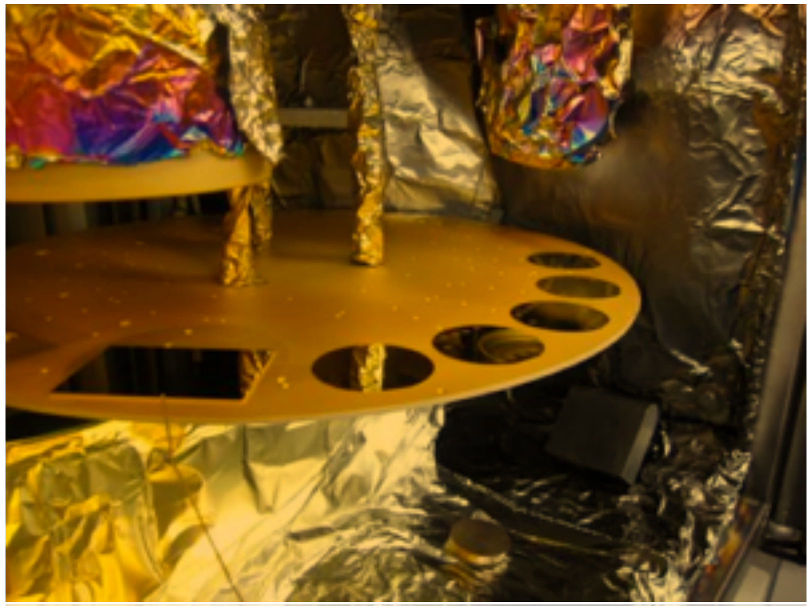
Item	Requirement	KPP	LBNL delivered
Ge detectors	HPGe detectors enriched to ≥86% in ^{76}Ge	≥ 15 kg	29.7 kg
HPGe spectroscopic performance**	FWHM at 60 keV	< 1.5 keV	0.42 keV
	FWHM at 2614 keV (^{208}Tl)	< 5 keV	3.1 keV
	FWHM at 2039 keV ($Q_{\beta\beta}$)	< 4 keV	2.6 keV

* Only KPPs that are relevant to LBNL deliverables listed

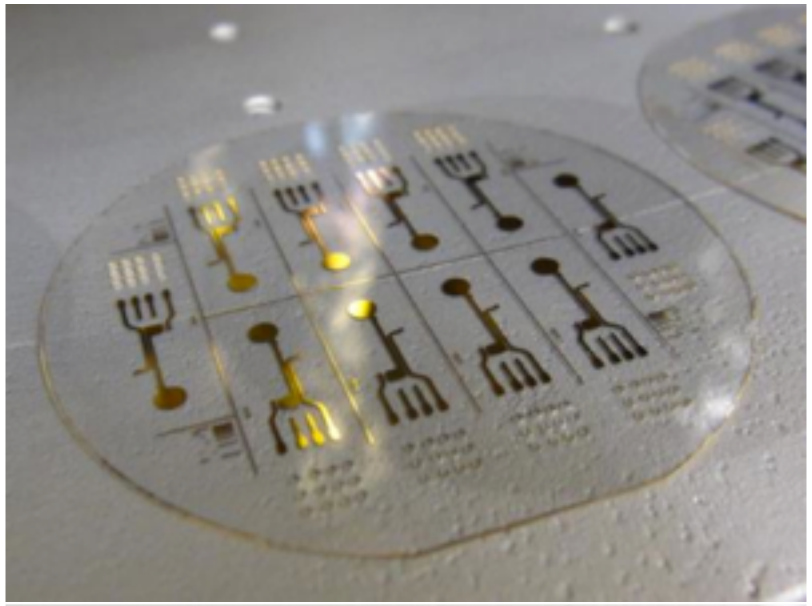
** Module 1 data only; Module 2 calibration being analyzed

Production: wafers

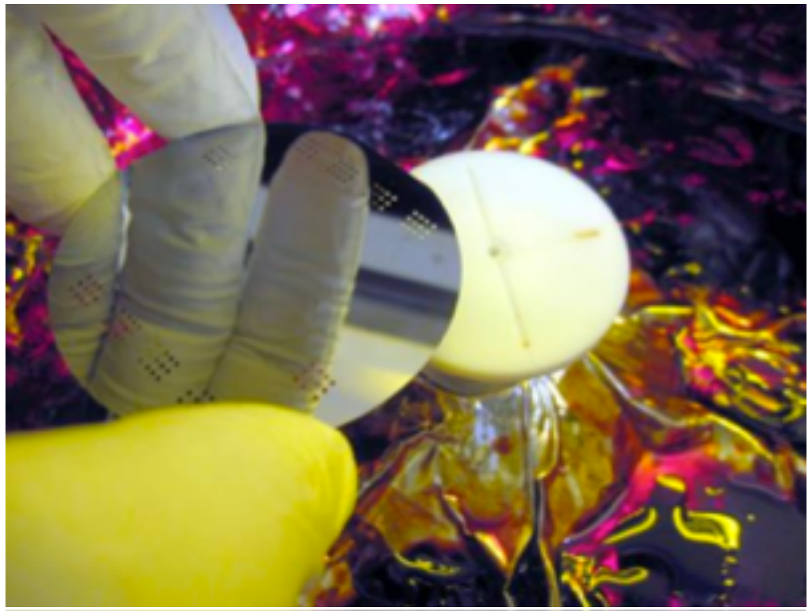
Ti/Au sputtering



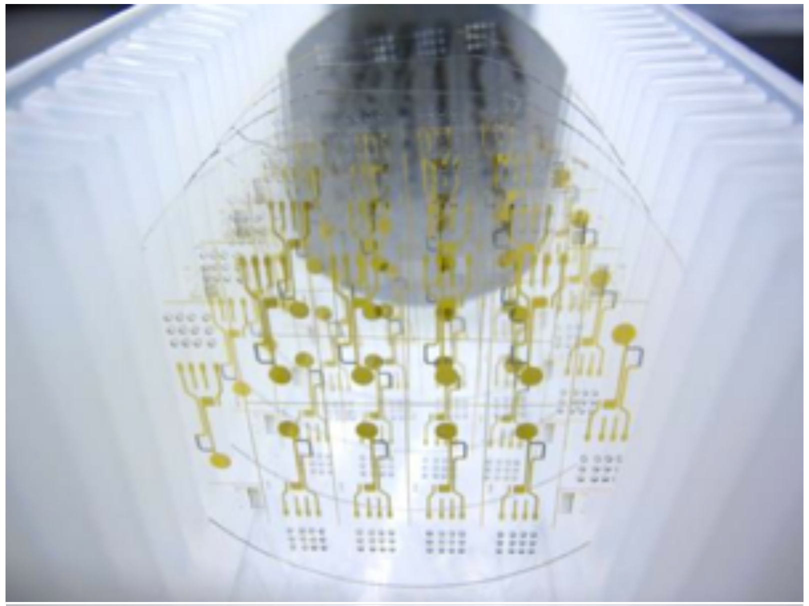
patterning traces



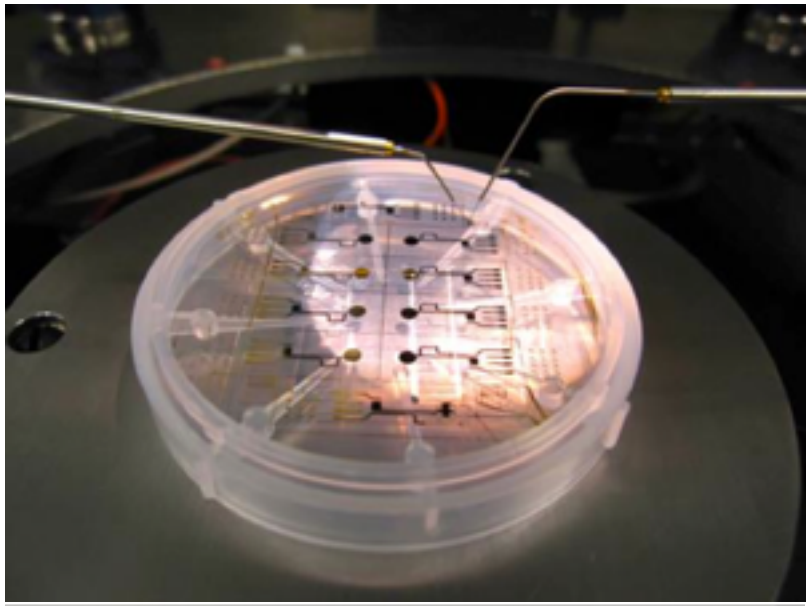
aGe sputtering



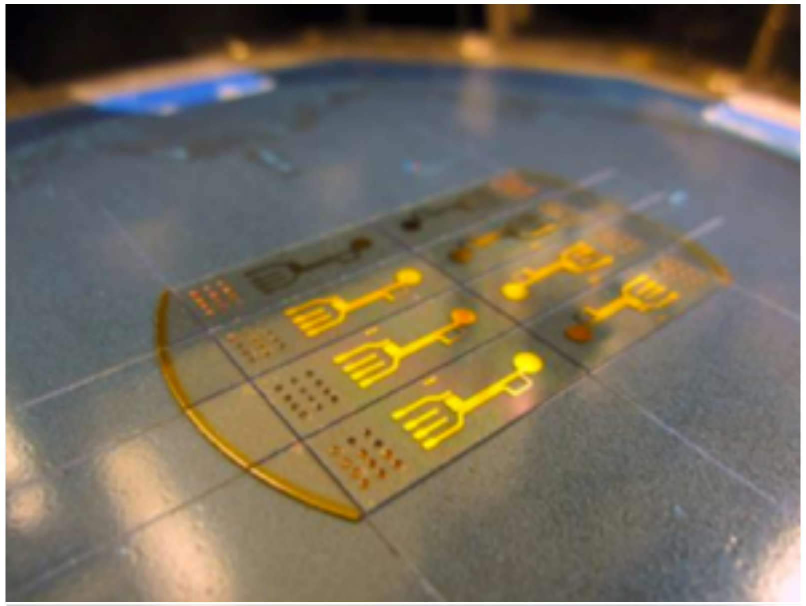
patterning aGe



electrical tests

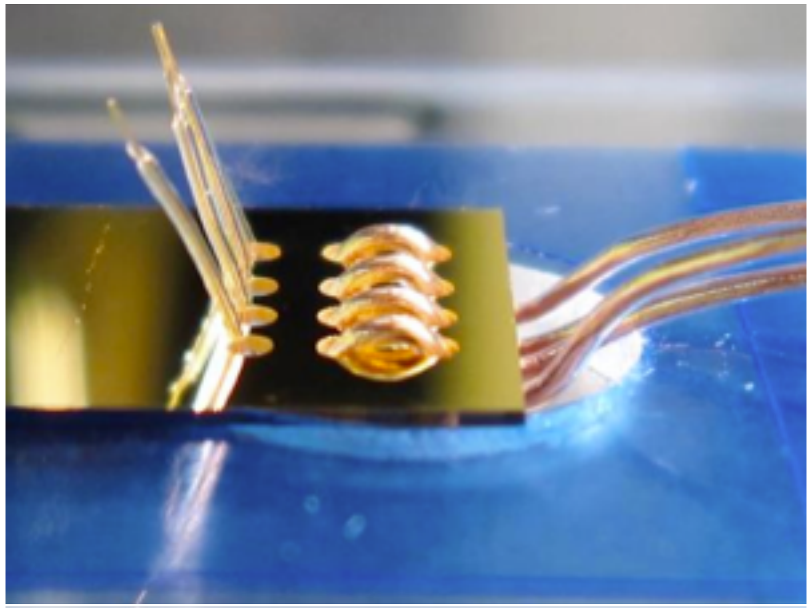


dicing boards

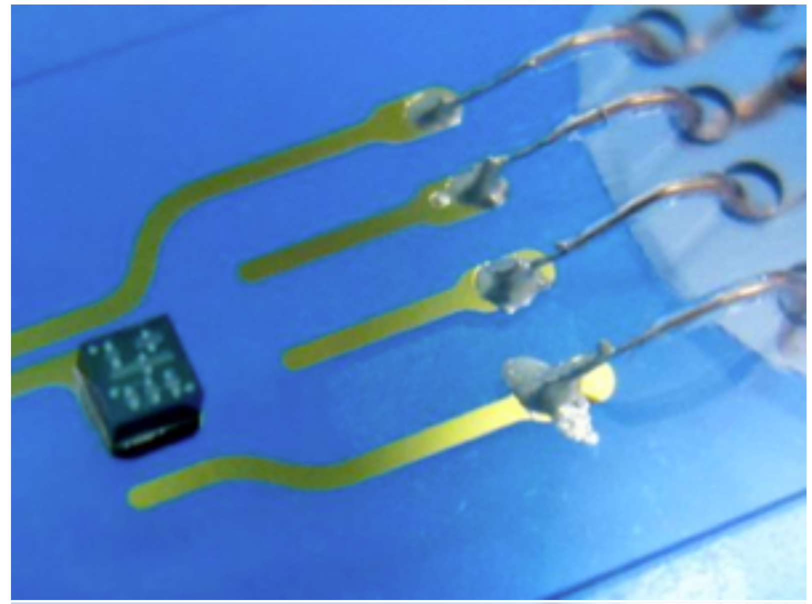


Production: on-board electronics

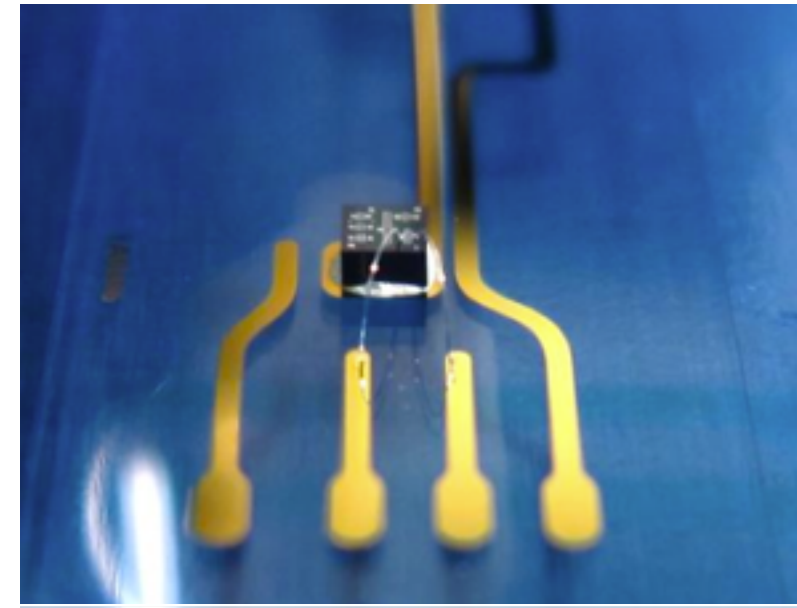
cable threading



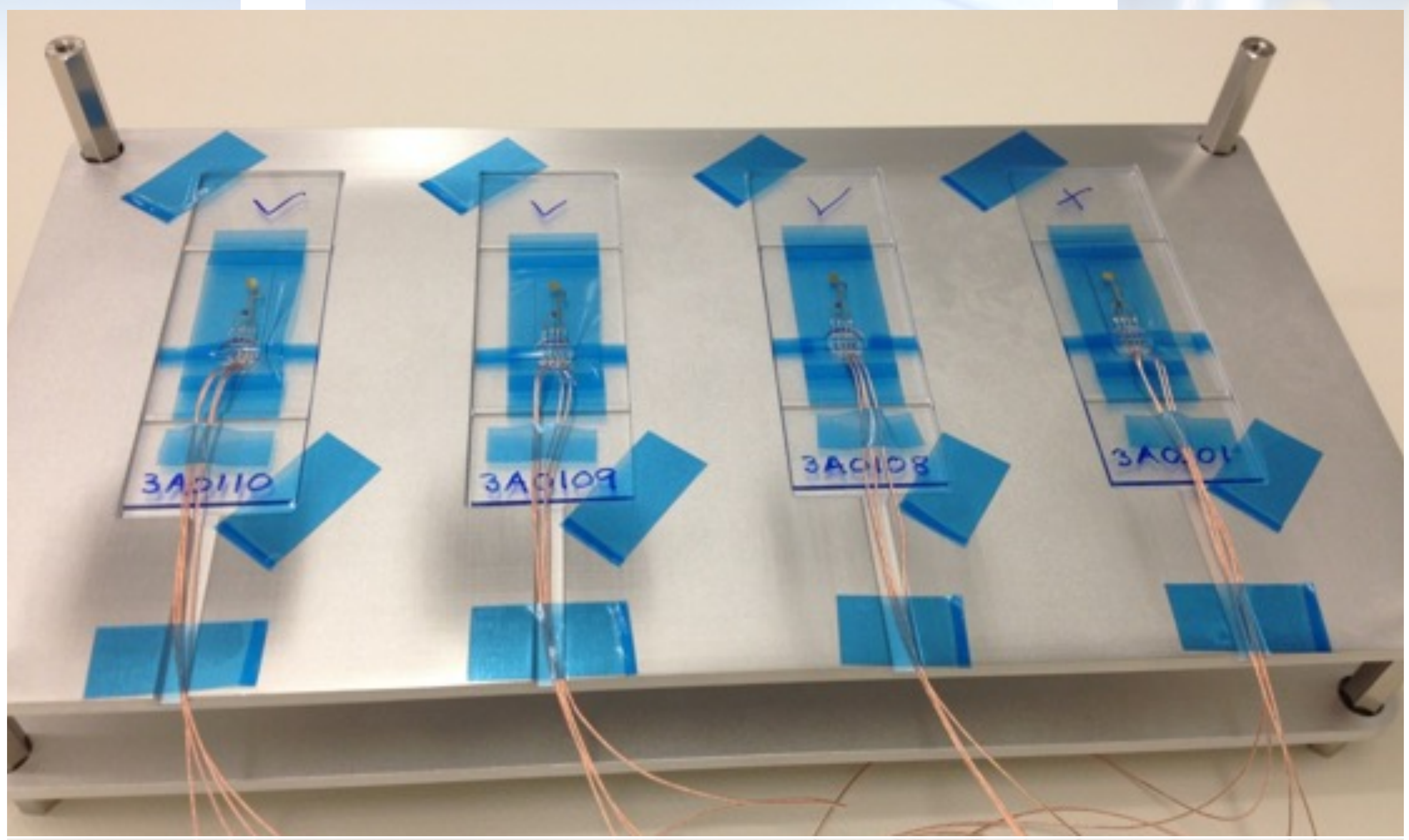
silver epoxying



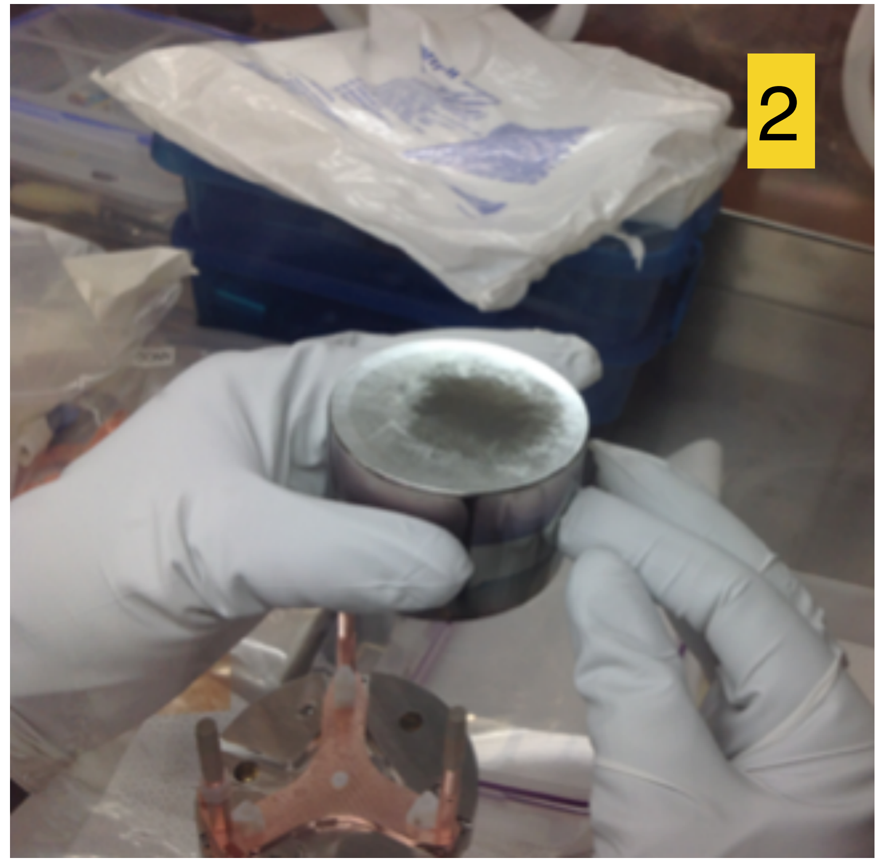
wire bonding

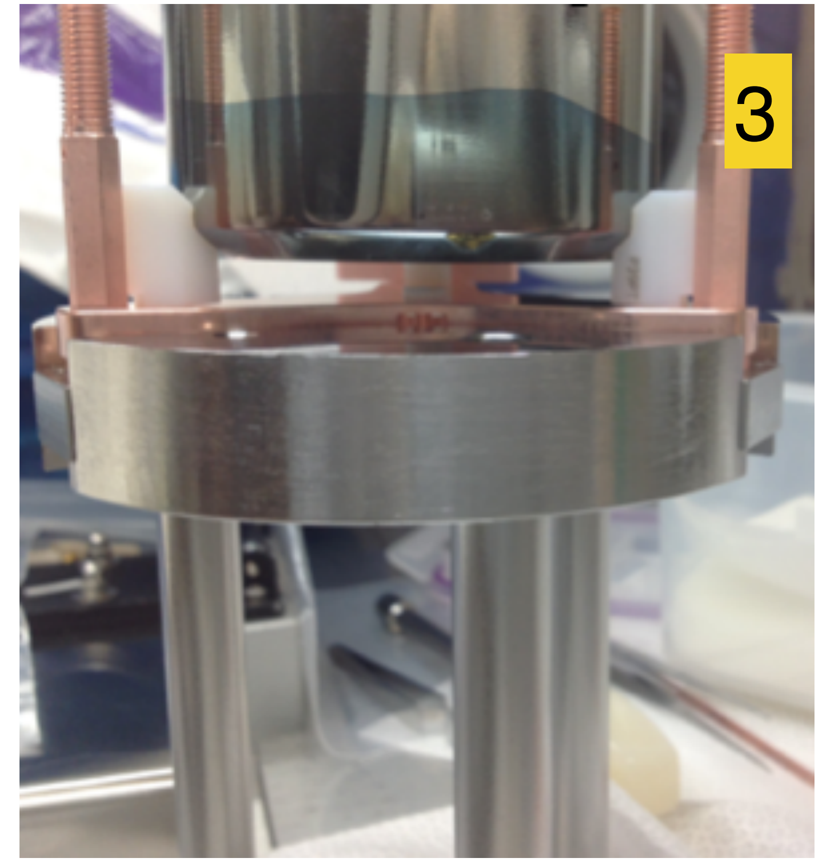


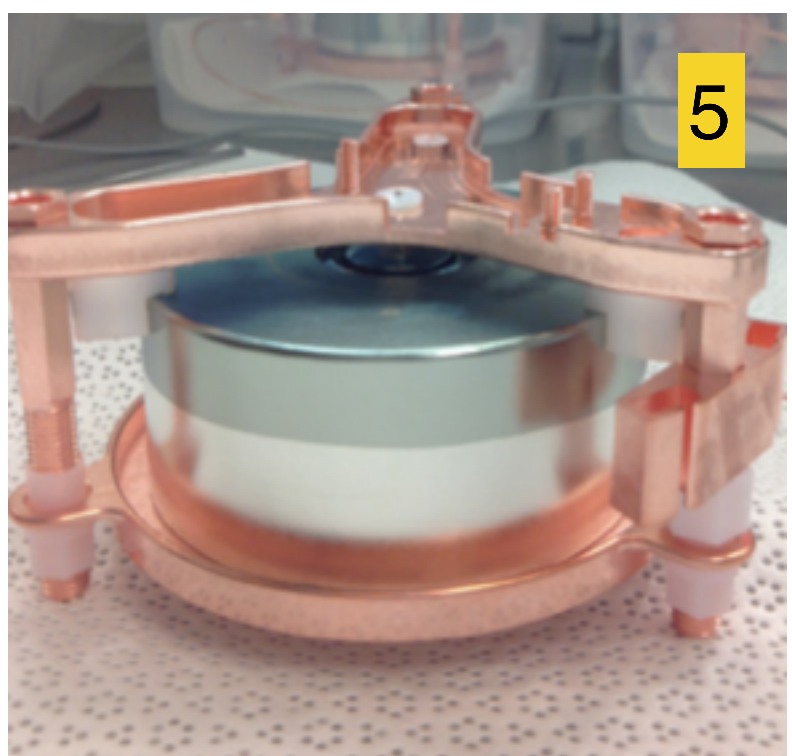
transport tray

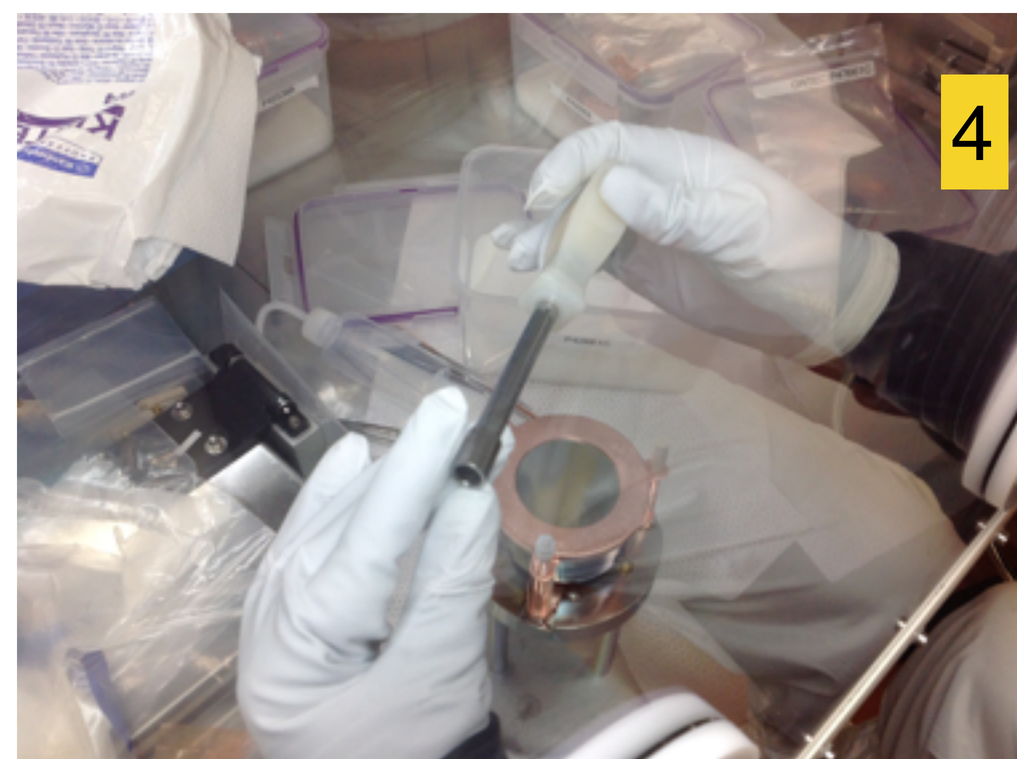


Building Detector Units

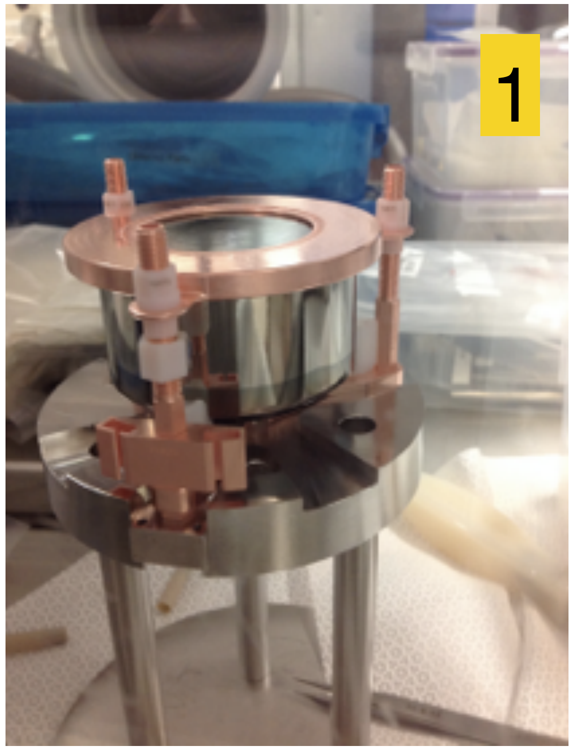


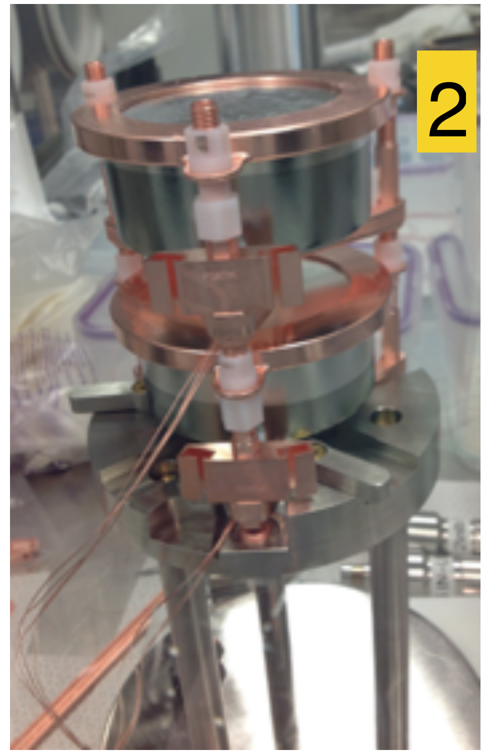


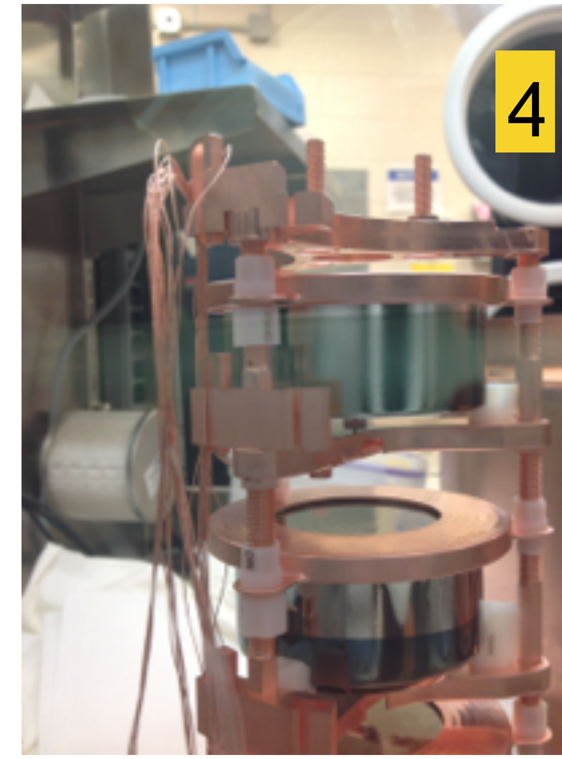


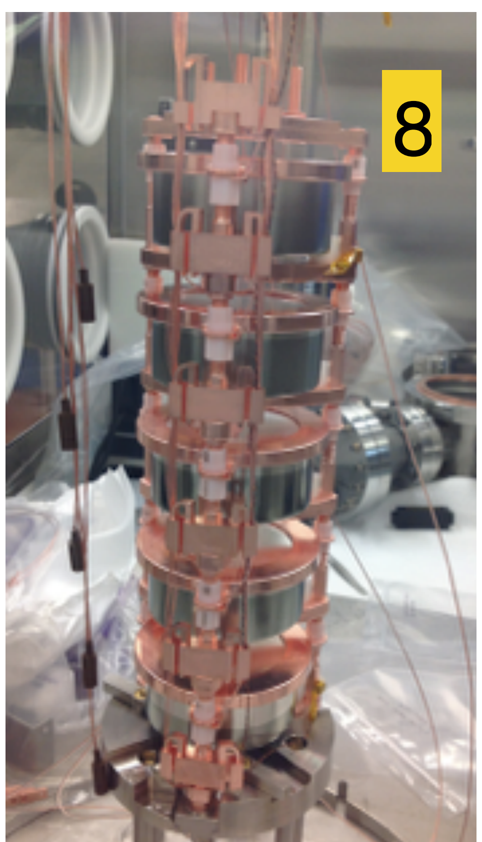


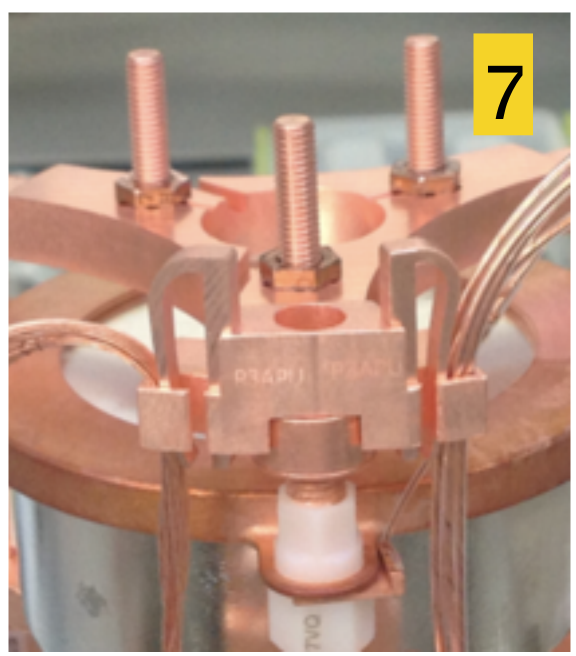
Building Strings

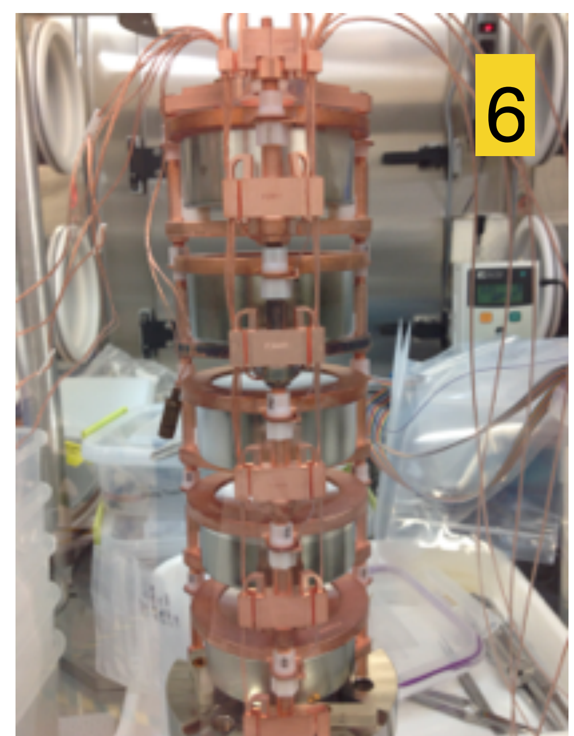


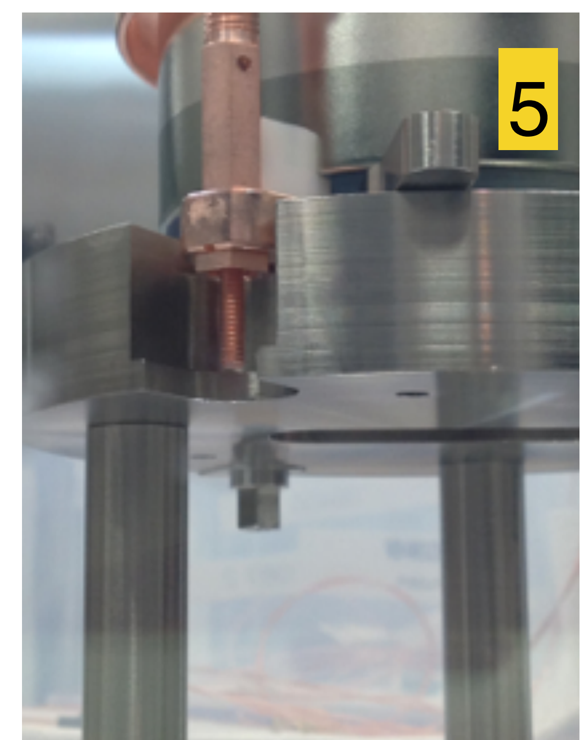












Front-end Electronics

Cleaning area

To class 100 room

Gowning room

Humidity control down to 40%

- Allocated to Majorana:

HP LN tank provides boil-off for dry boxes

Two-bench work station

Long range laminar flow

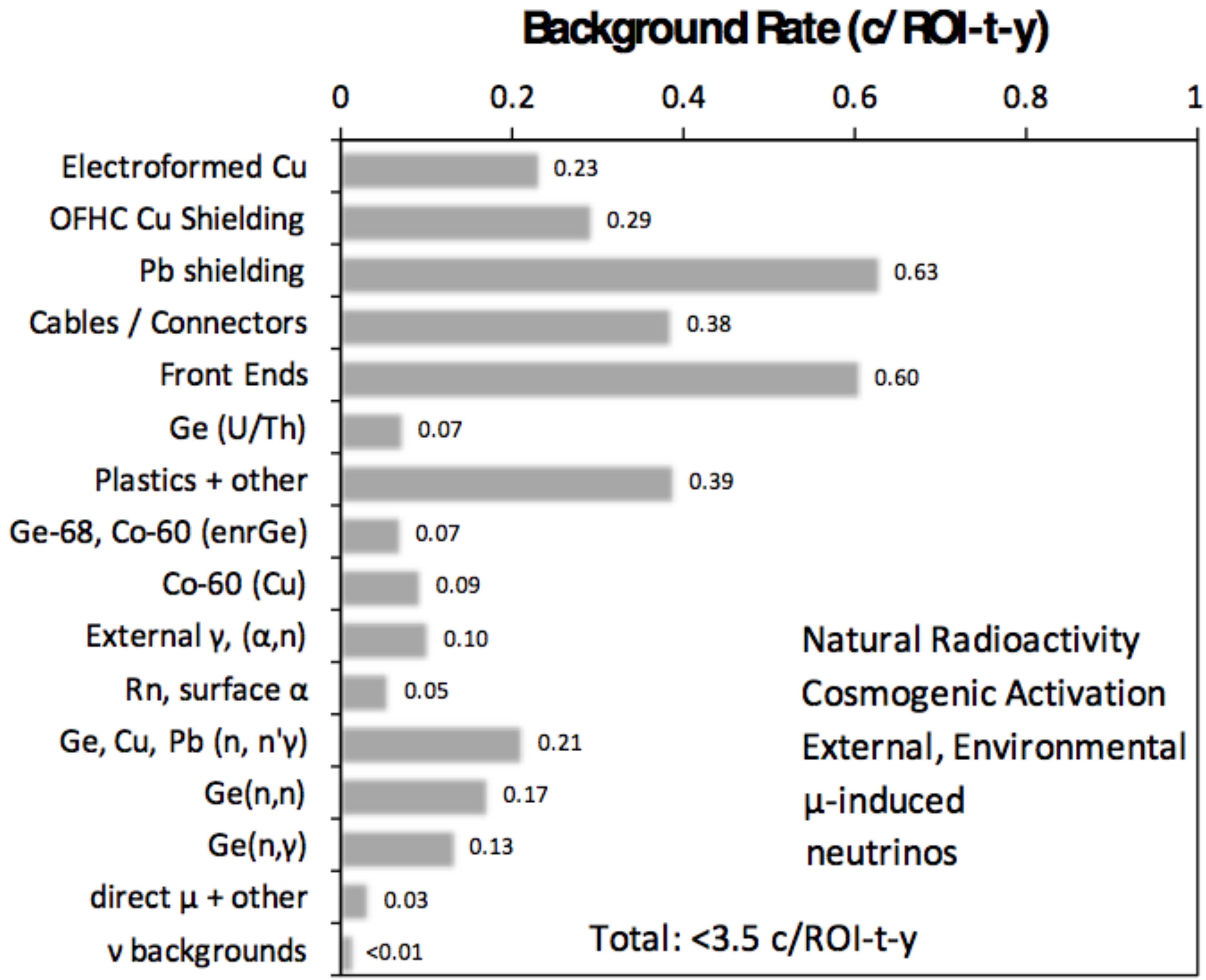
Copper strap

Conductive floor

HEPA filter work station for sensitive production steps

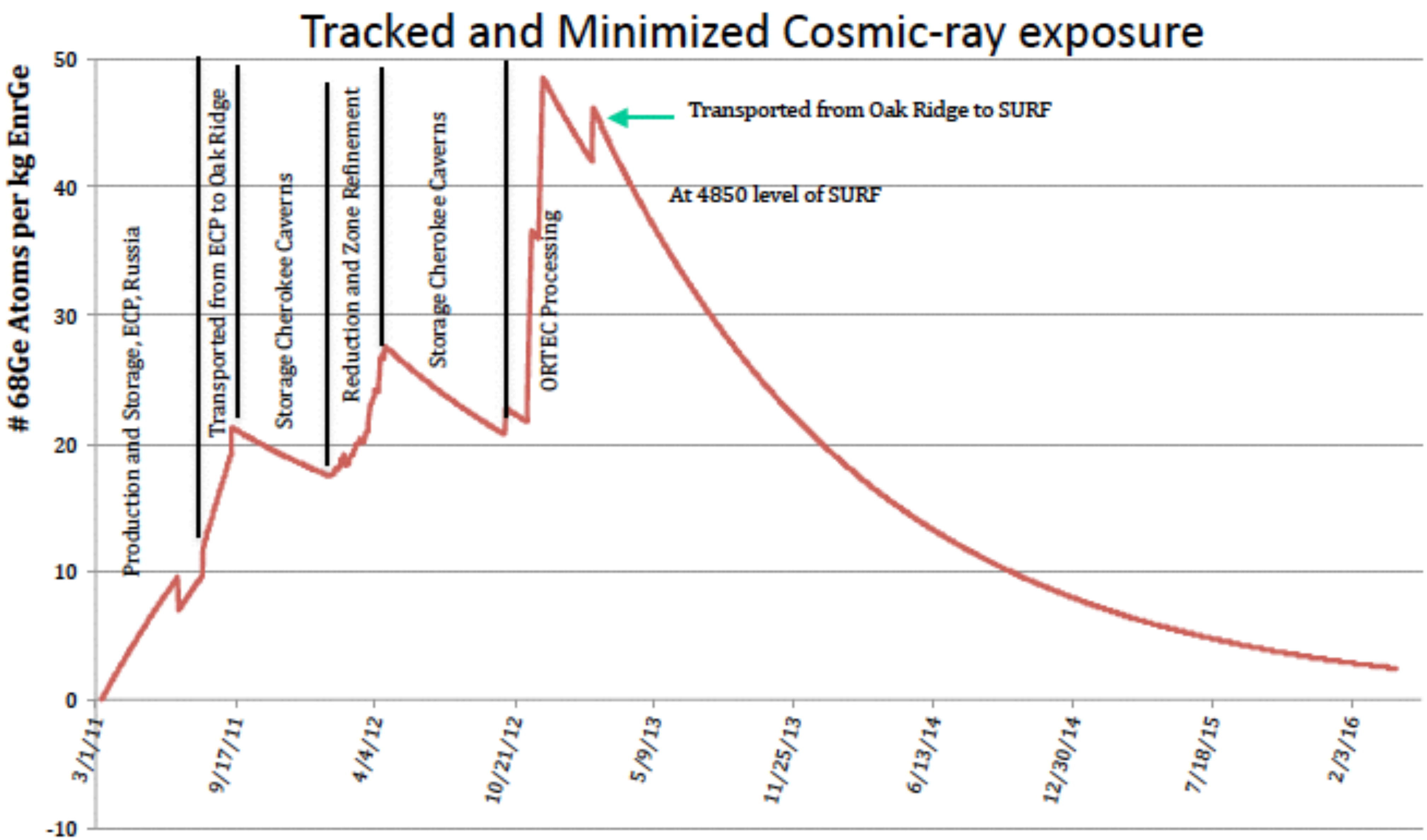
- Established workspace at a class-100 cleanroom for front-end production

MJD Background Estimates



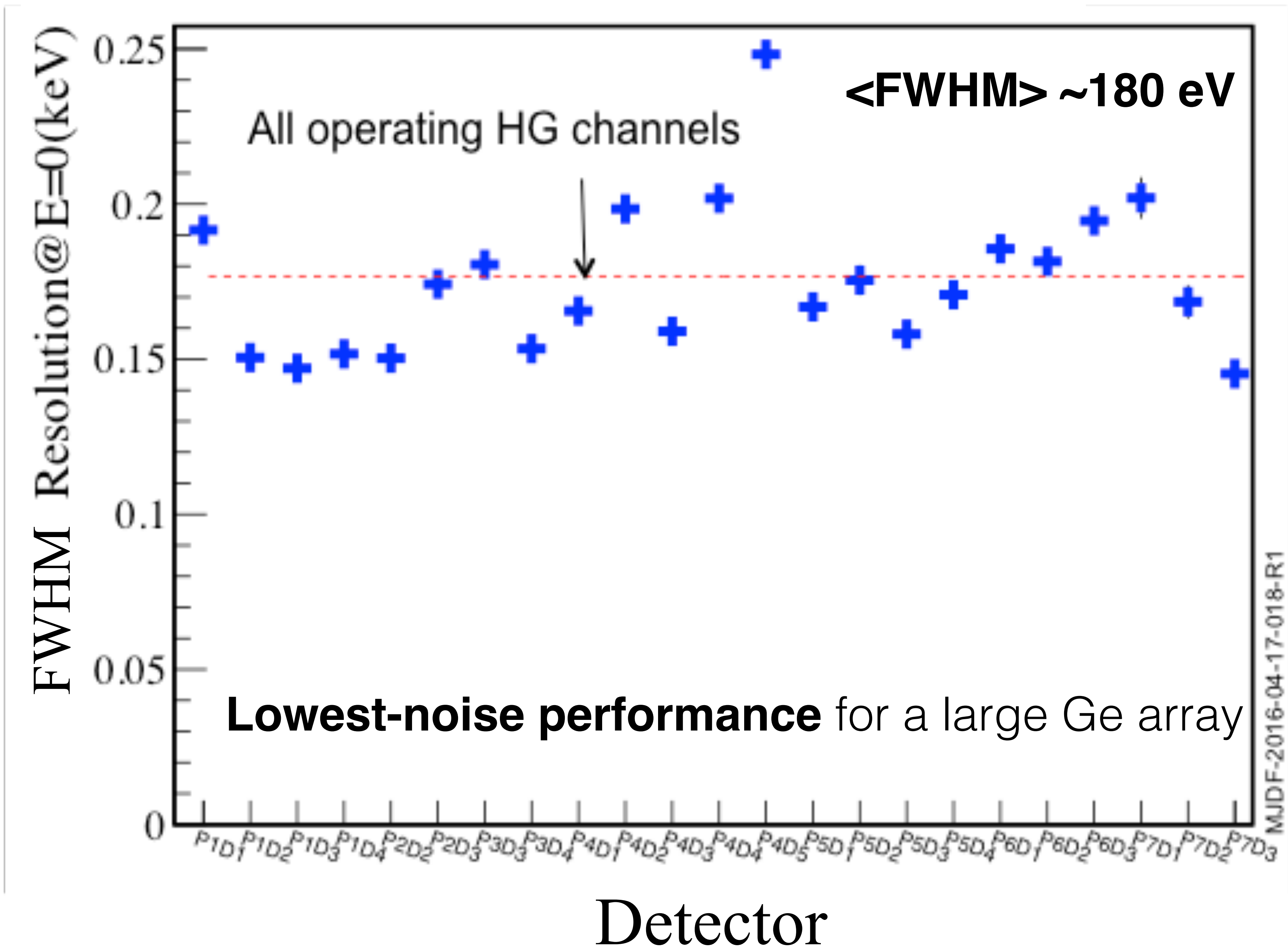
^{68}Ge Production in Detector P42537A

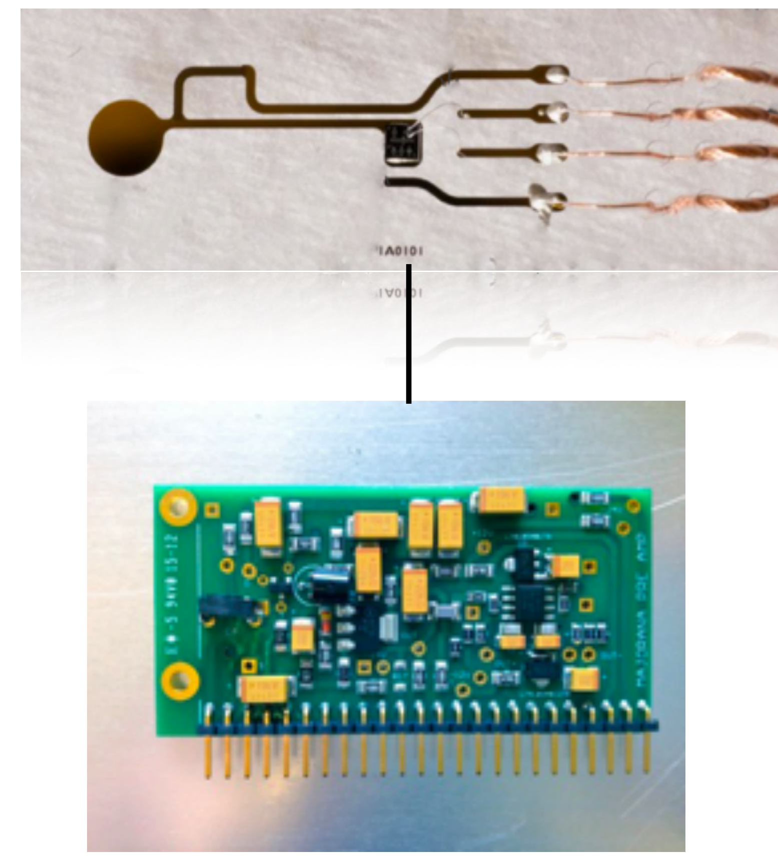
Cosmic ray exposure minimized throughout all processes
Typical sea-level equivalent exposure is about 35 d for the enriched detectors.



Noise performance

Module 1 calibration data



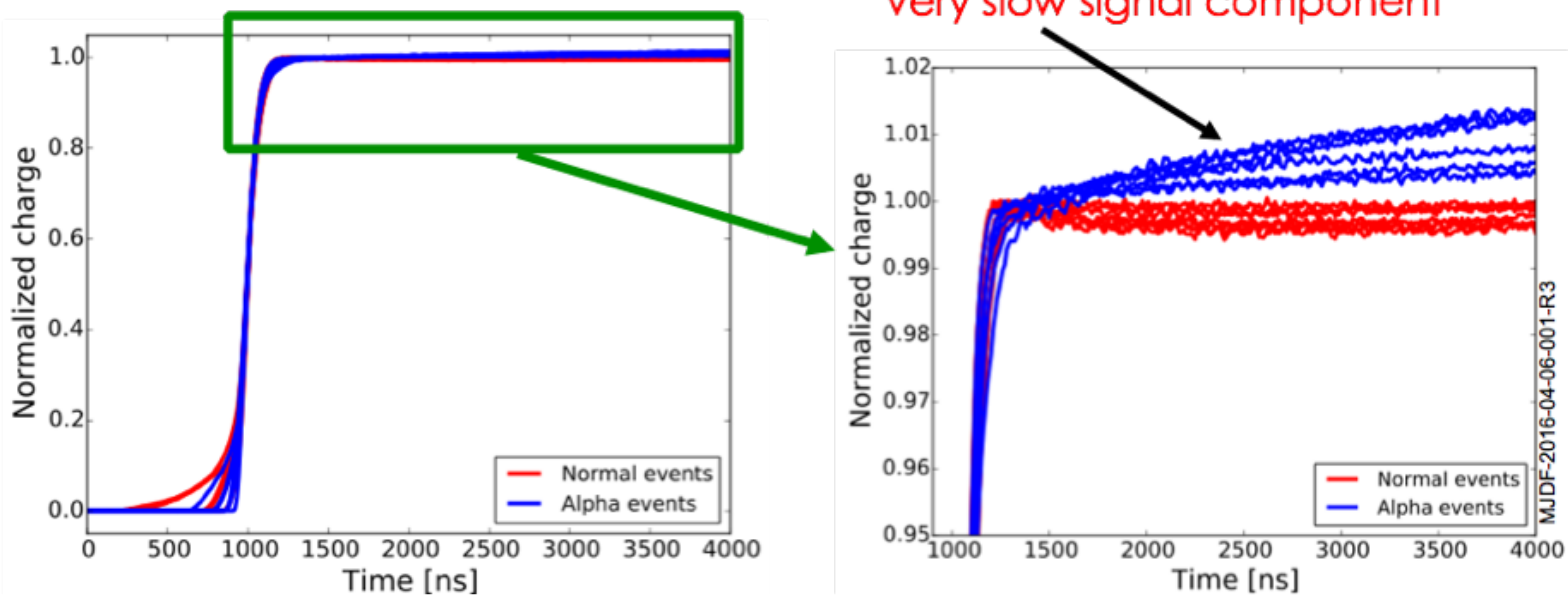


The Delayed Charge Recovery Cut for α's

- Alpha background response observed in Module 1 commissioning (DS0)
- Identified as arising from alpha particles impinging on passivated surface.
- Results in prompt collection of some energy, plus very slow collection of remainder.
- Produces a distinctive waveform allowing a high efficiency cut.

Example pole-zero corrected waveforms

Slow drift of charges along passivated surface results in very slow signal component



See talk by C. Cuesta, DD.4

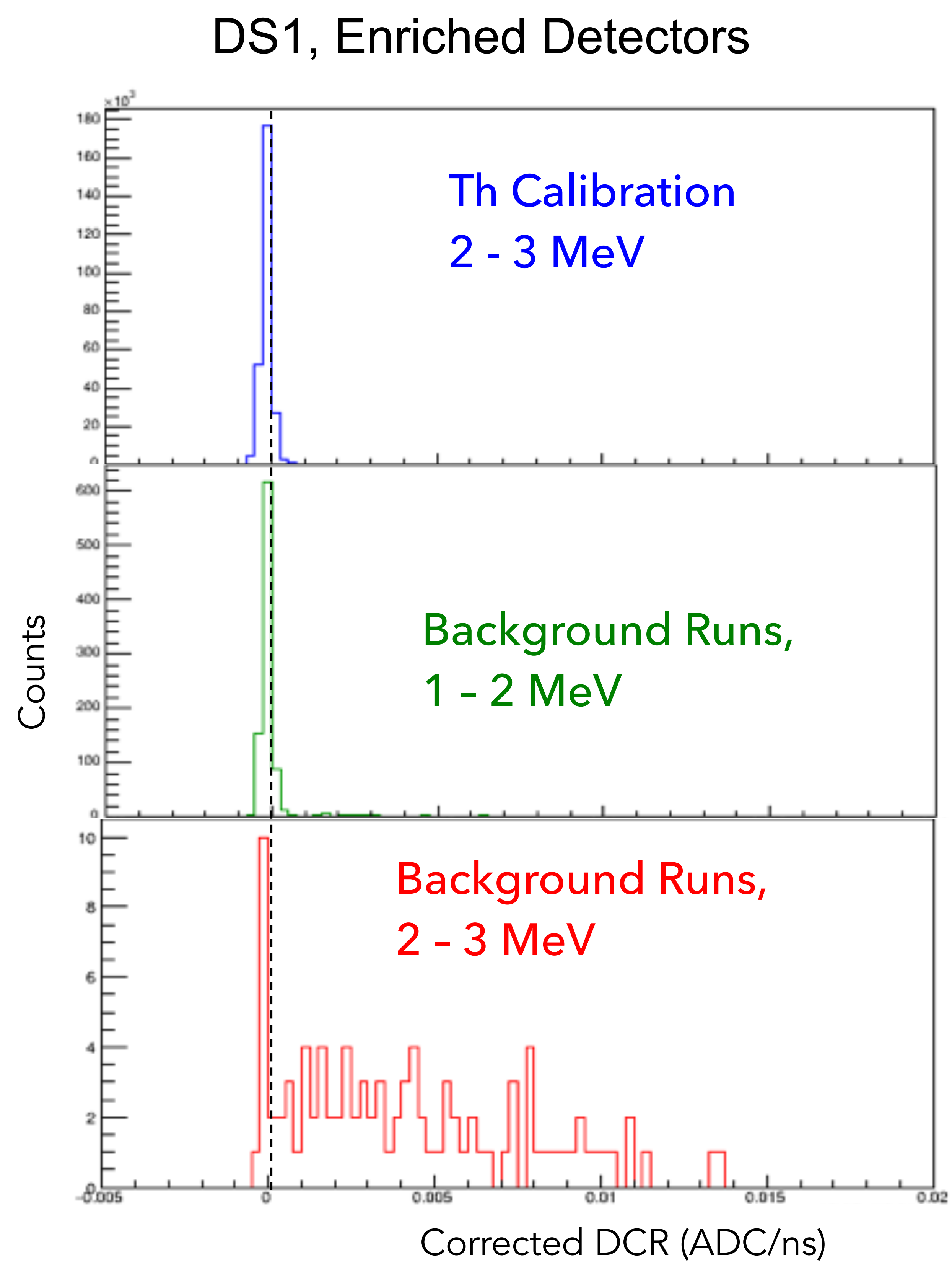
DS1 DCR Cut and Bulk-Event Response

Removes most events above 2 MeV in the background spectrum, which are α candidates. Cut is 90% efficient for retaining events within detector bulk. Only ~5% of α's survive cut.

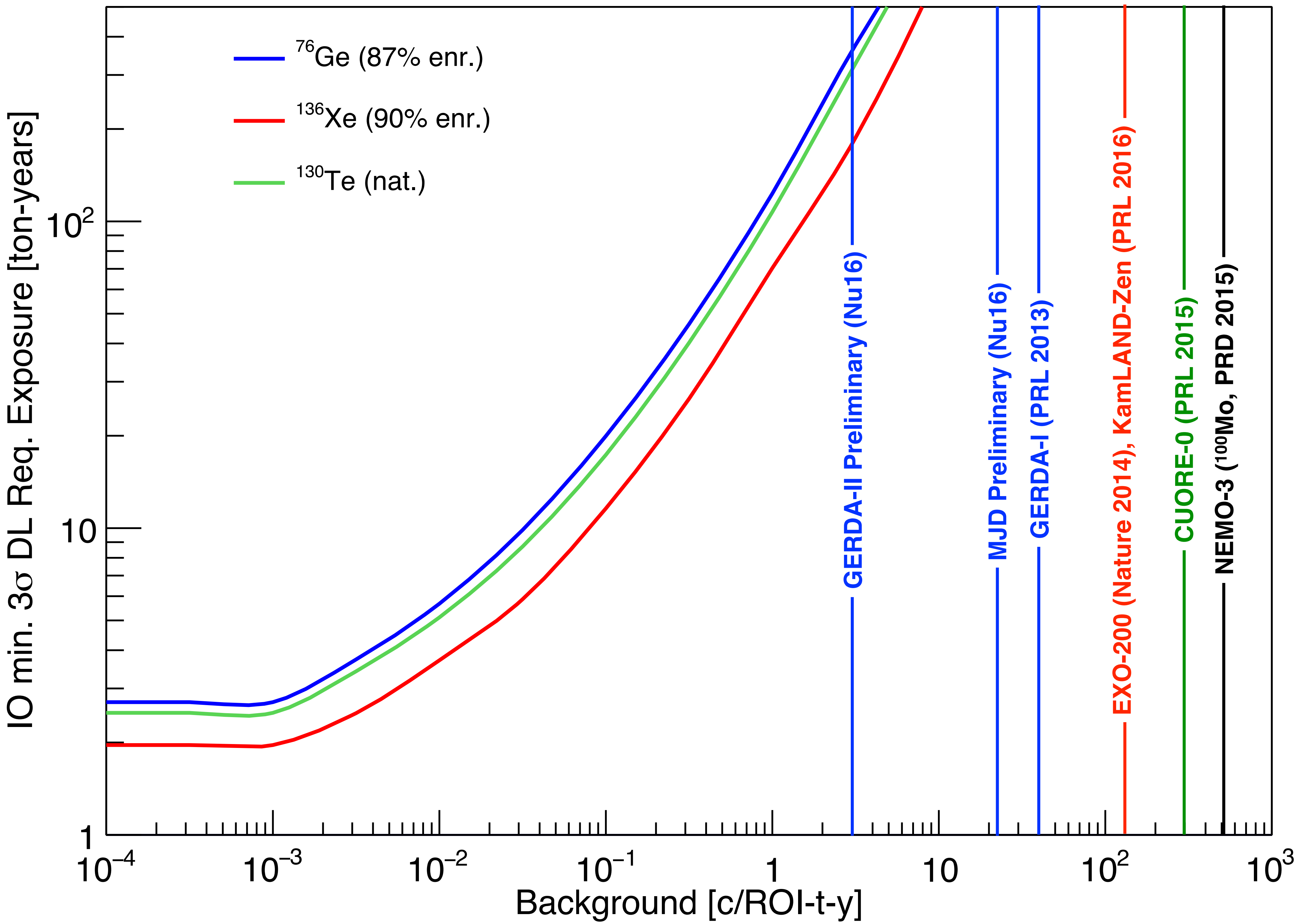
During calibration runs γ events survive cut.

During Background runs $\beta\beta(2\nu)$ events survive cut.

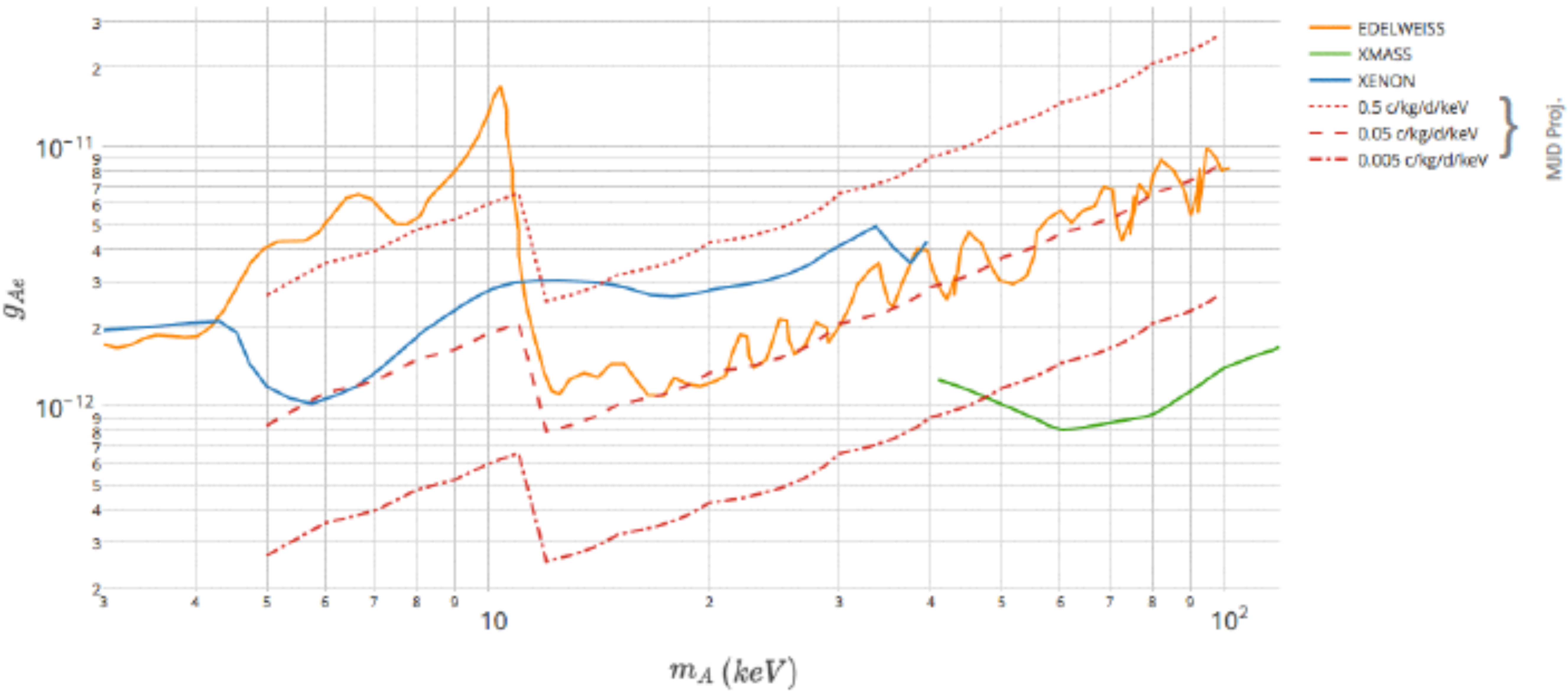
Candidate α events from background runs are removed.



Required Exposure to Cover the IH



Bosonic Dark Matter Analysis



Low Background Facility

Counting Sensitivities [for ~1kg samples]	Berkeley Site [~1 day]	SURF Site [~2 weeks]
U series	0.5 ppb (6 mBq/kg)	10 ppt (0.1 mBq/kg)
Th series	2.0 ppb (8 mBq/kg)	30 ppt (0.1 mBq/kg)
K	1.0 ppm (30 mBq/kg)	20 ppb (0.6 mBq/kg

LBNL – neutrino, underground and γ-ray projects

1990s → Now