The MAJORANA DEMONSTRATOR search for neutrinoless double beta decay

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on behalf of the MAJORANA COLLABORATION

The XIIIth International Conference on Heavy Quarks and Leptons

Blacksburg, Virginia, May 2016

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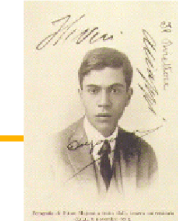
Outline

- **Detectors**
- **Implementation**
- **Background considerations**
- **Module 1 preliminary results**
- **Next generation ^{76}Ge experiment**

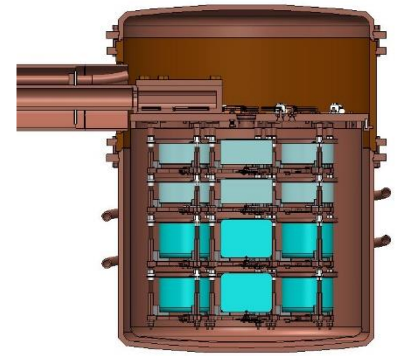
Fig: Courtesy M. Kapust

The Majorana Demonstrator ($0\nu\beta\beta$)

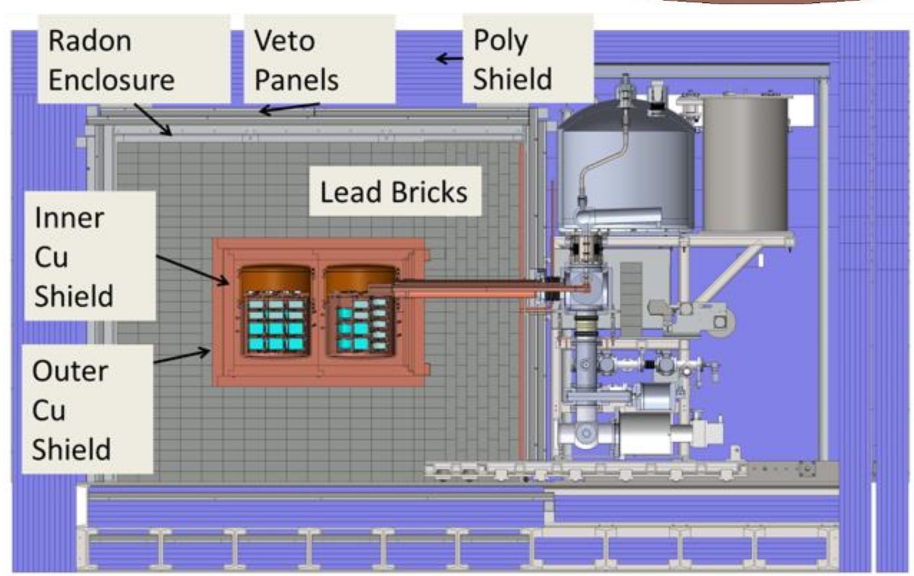


Funded by DOE Office of Nuclear Physics, NSF Particle Astrophysics, NSF Nuclear Physics with additional contributions from international collaborators

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 tonne experiment
- **44-kg of Ge detectors**
  – 29 kg of 88% enriched ^{76}Ge crystals
  – 15 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



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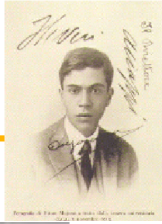
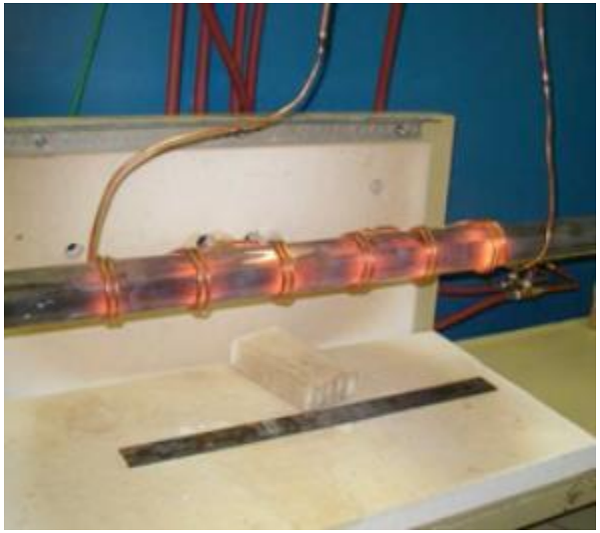
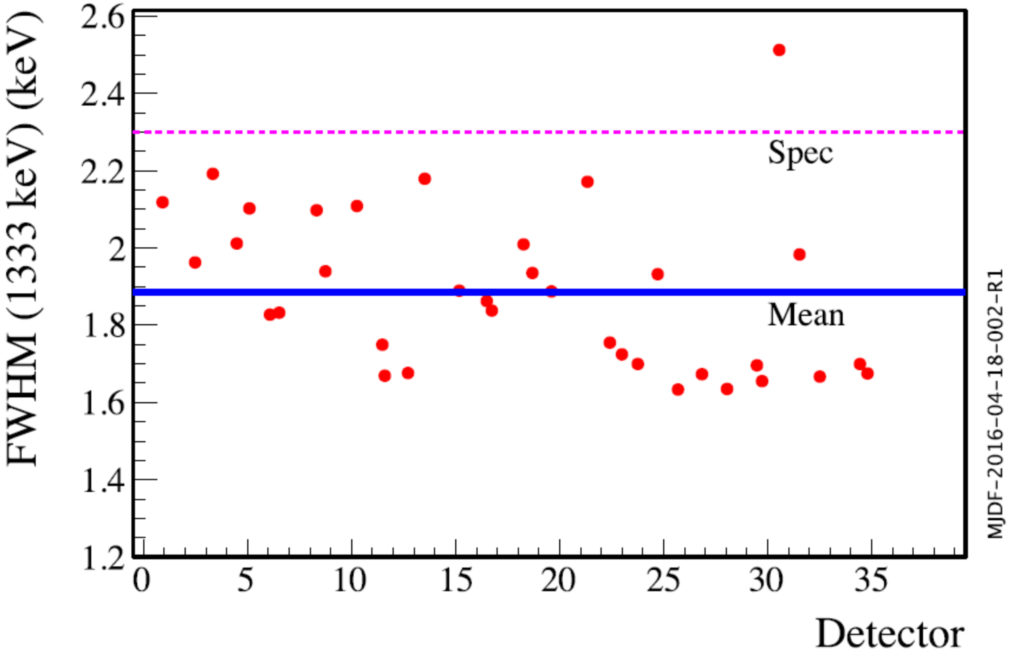
Enriched Ge detectors

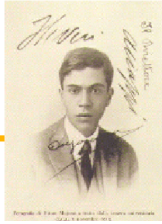


- Enriched detector production completed in June 2015.
- Limit above-ground exposure to prevent cosmic activation.
- 35 enriched PPC detectors.
- Mean FWHM at 1333 keV = 1.88 keV.
- 29.7 kg total ^{enr}Ge mass.





MJD Detectors

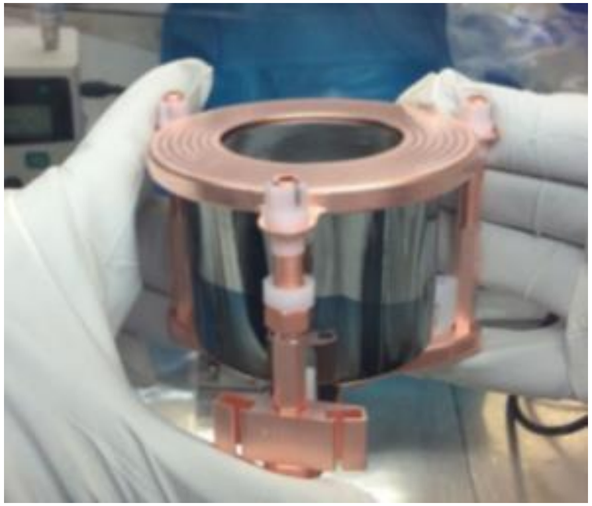


Natural detectors

- CANBERRA modified BEGe
- ~70 mm x 30 mm
- ~ 650 g each
- Made in Meriden, CT

Enriched detectors

- ORTEC Point Contact (PPC)
- ~ 70 mm x 50 mm
- ~ 900 g each
- All production (zone refinement, crystal pull and diode production) in Oak Ridge, TN



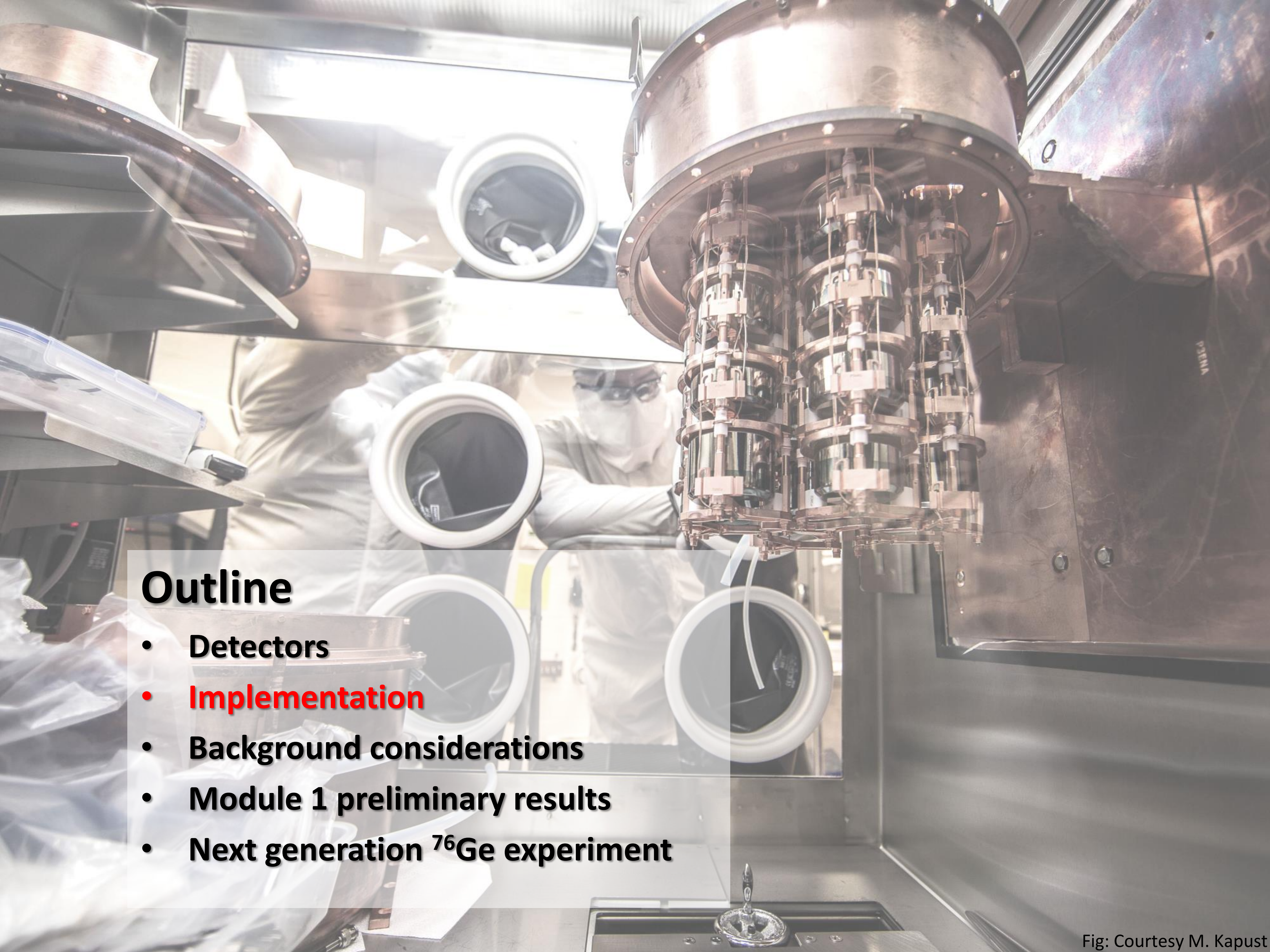


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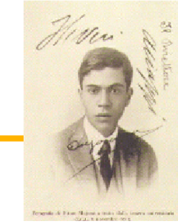
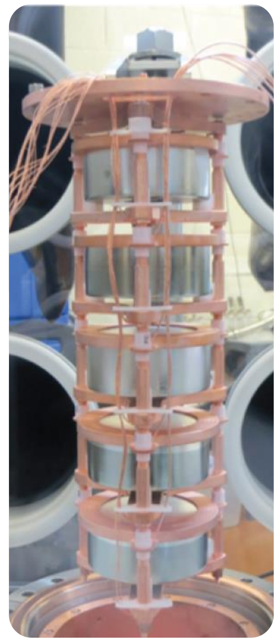
Fig: Courtesy M. Kapust

MJD Implementation



Modular approach:

Detector



String

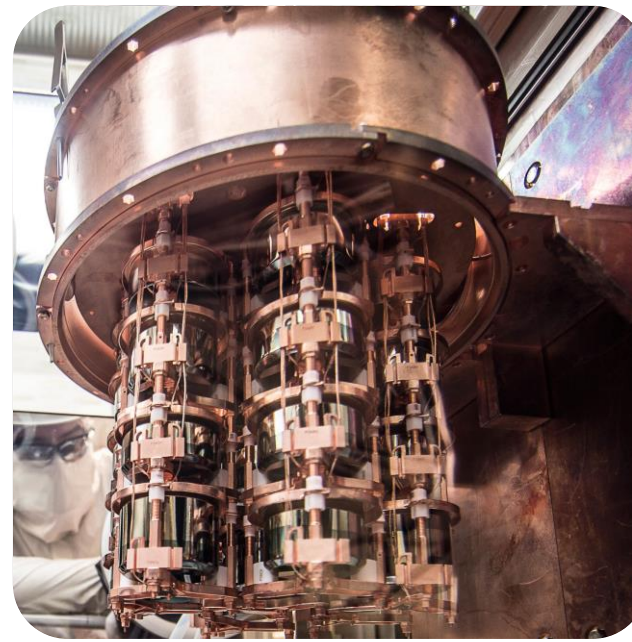
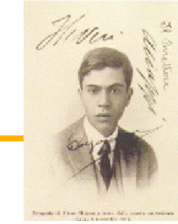


Fig: Courtesy M. Kapust

Module

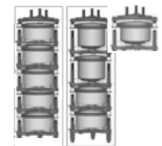
MAJORANA DEMONSTRATOR Implementation



Three Steps

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

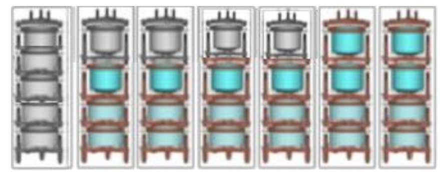
Same design as Modules 1 and 2, but fabricated using OFHC Cu Components



June 2014-June 2015

Module 1: 16.8 kg (20) ^{enr}Ge

5.7 kg (9) ^{nat}Ge



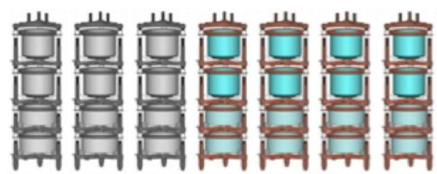
May–Oct. 2015,

Final Installations,

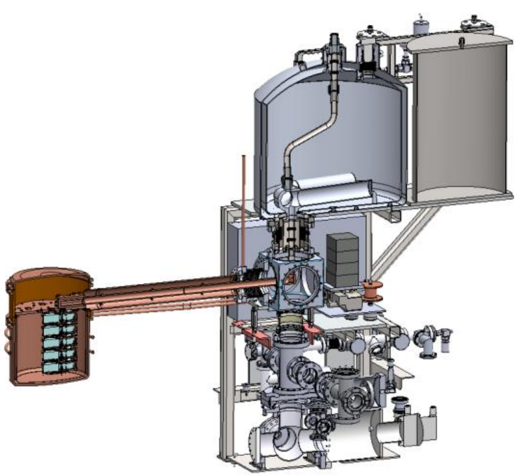
Dec. 2015 ongoing

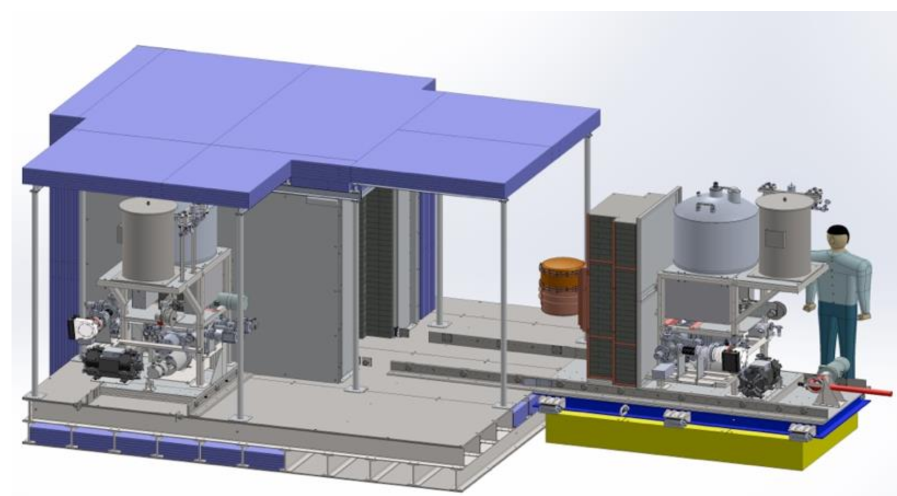
Module 2: 12.8 kg (14) ^{enr}Ge

9.4 kg (15) ^{nat}Ge

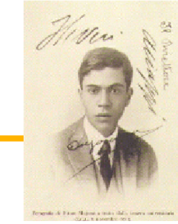


Mid 2016





MAJORANA DEMONSTRATOR Implementation



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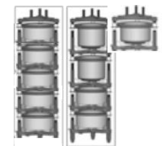

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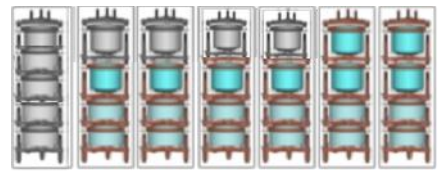

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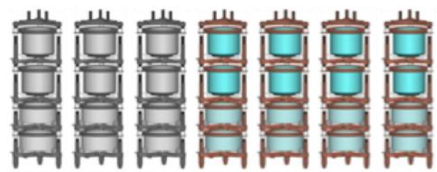

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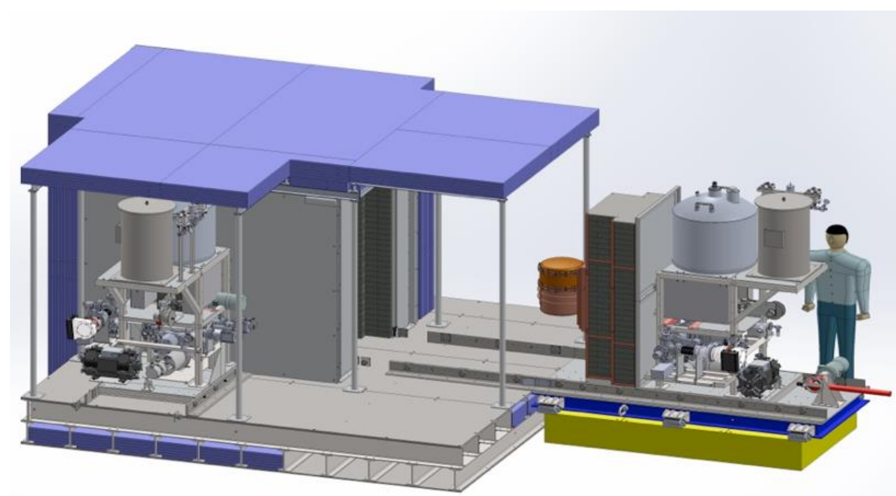
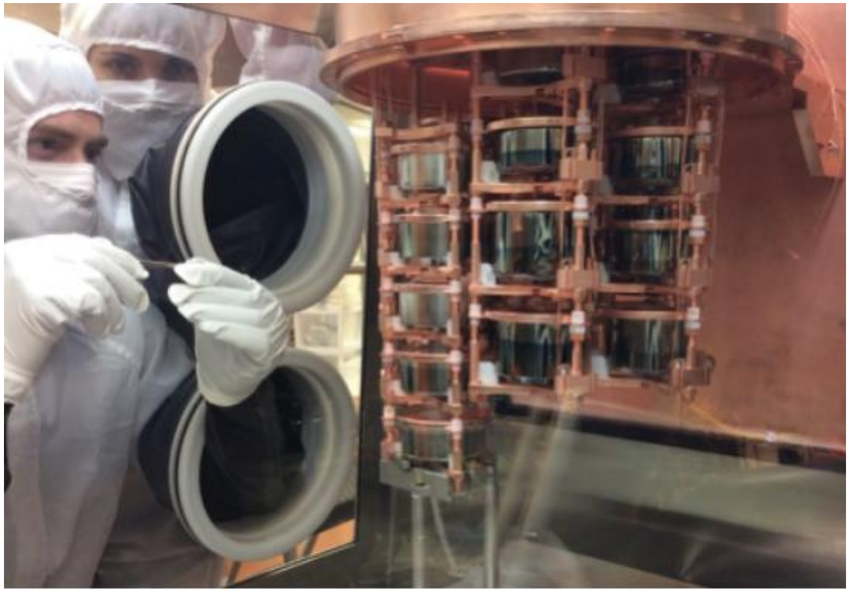


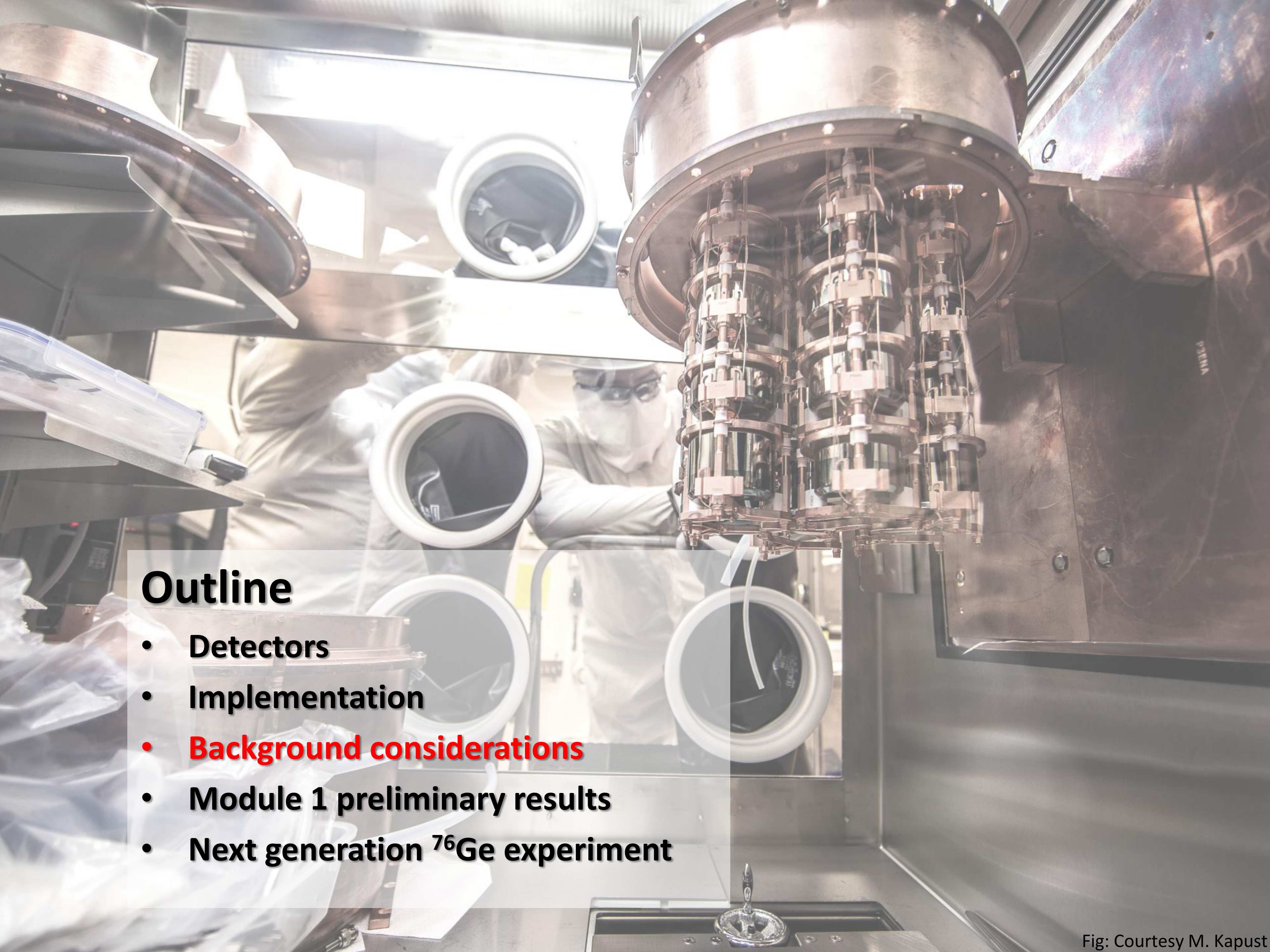
MJD Implementation

Loading of ^{enr}Ge in Cryostat 1

Fig: Courtesy M. Kapust

Loading of ^{enr}Ge in Cryostat 2





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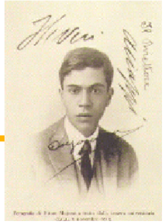
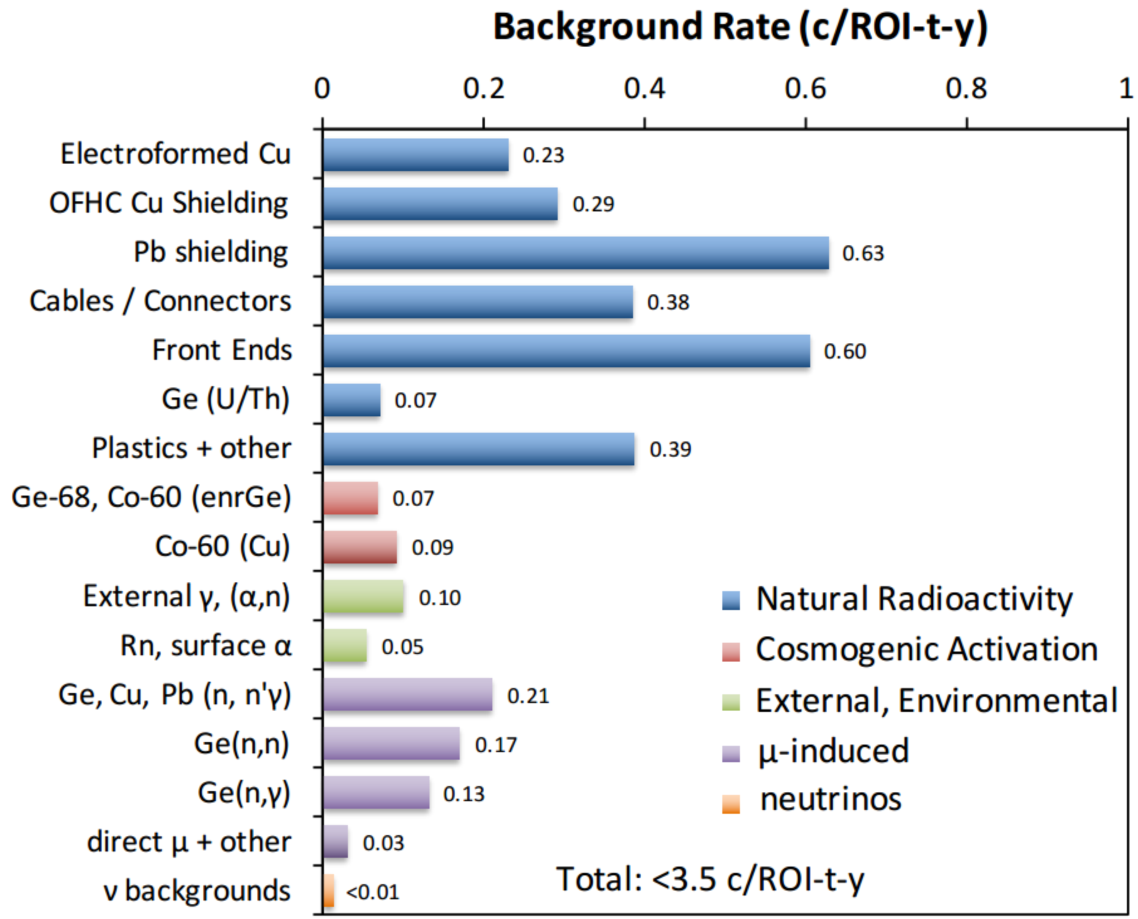
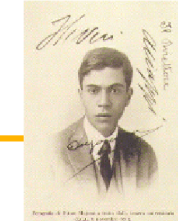
Background Model





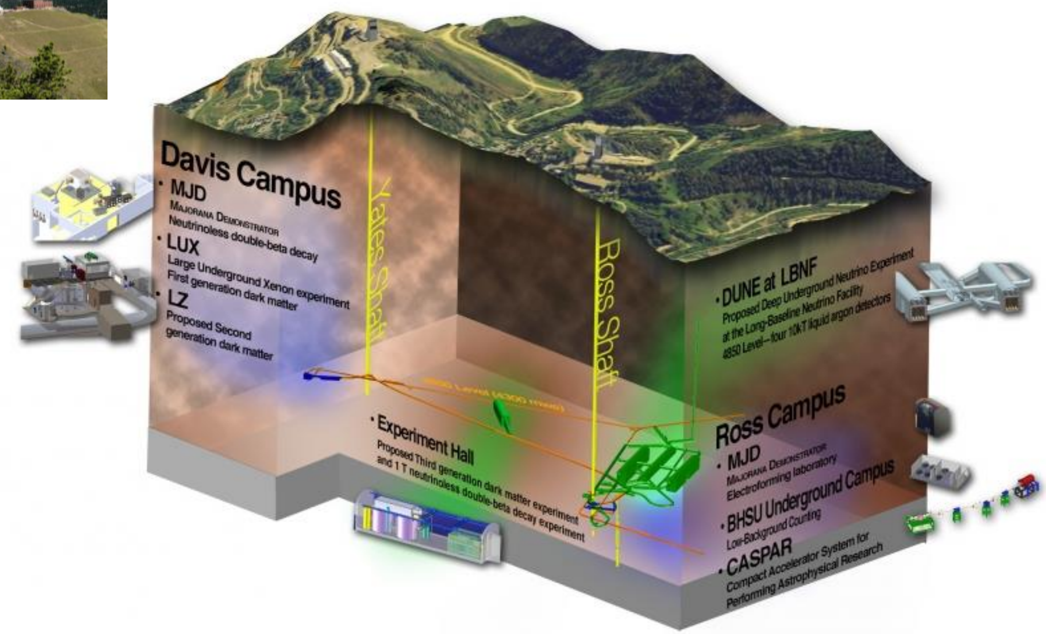
- Extensive campaigns to qualify, procure and produce clean materials.
- Based on achieved assays of materials, when UL used UL as contribution.
- NIM A 828 (2016) 22

MAJORANA Underground Laboratory

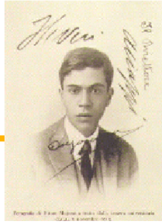


Davis Campus at the Sanford Underground Research Facility

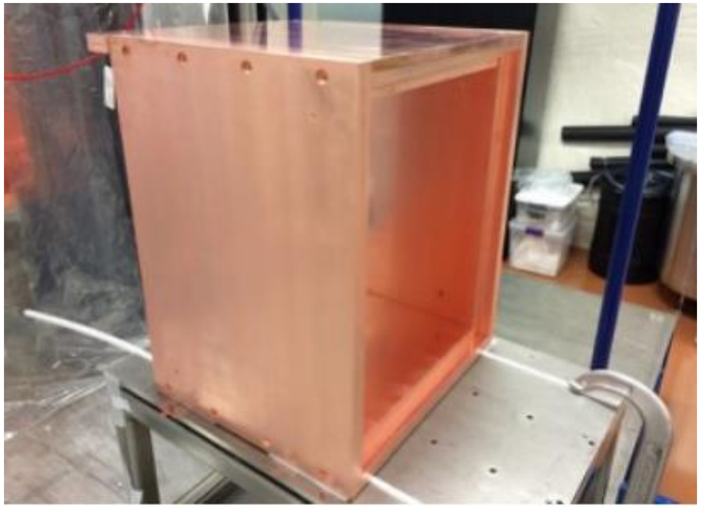
- 4,850 feet below the surface.
- Cosmic ray shielding.
- Clean room conditions.



Shield



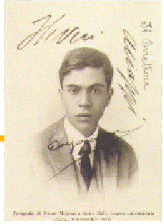
- Inner electroformed copper layer installed
- Outer copper shield installed
- Pb shield installed
- Rn exclusion box installed
- Poly layers being installed
- Veto panels operational
  arXiv:1602.07742
- Calibration system demonstrated



Inner electroformed copper shield

Outer copper + lead shield

Shield



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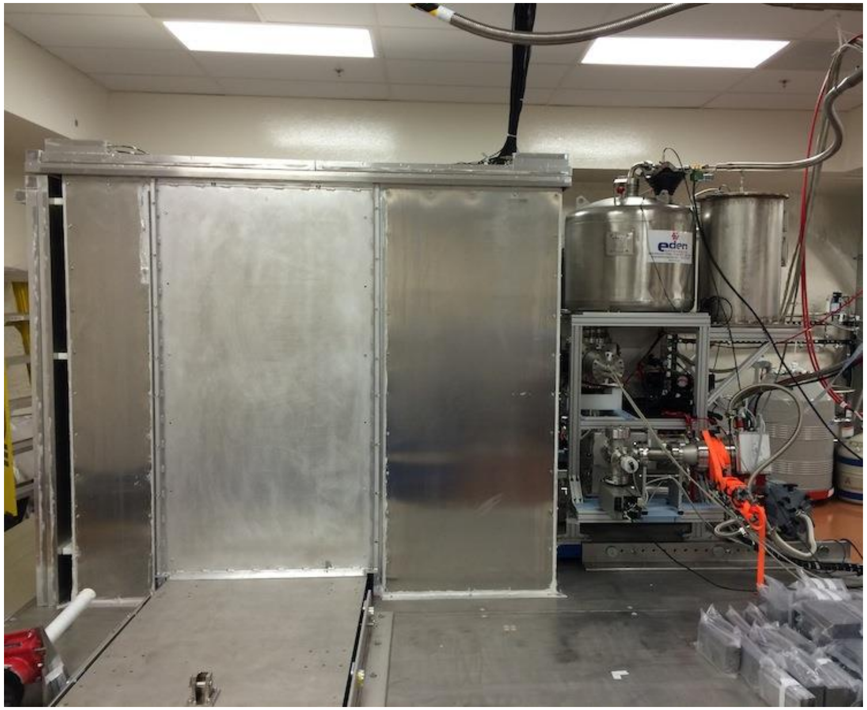
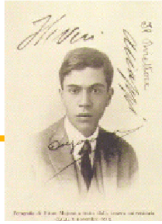


Radon exclusion box

Veto + borated poly + poly

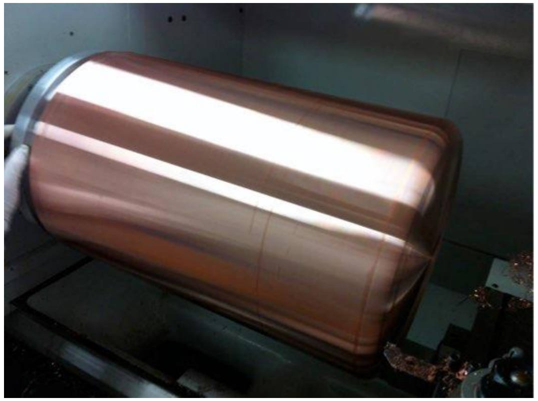
Electroformed copper



- MAJORANA operated 10 baths at the Temporary Clean Room 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 May of 2015 but we continued to operate baths in the TCR for additional material until March 2016.
  - 2654 kg of electroformed copper produced
  - 1196 kg was installed in the DEMONSTRATOR

Electroforming Baths in TCR

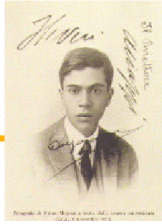
Inspection of EF copper on mandrels



EF copper after turning on lathe

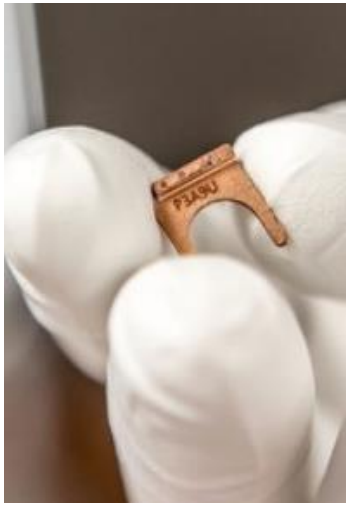
Th decay chain (ave) ≤ 0.1 µBq/kg

U decay chain (ave) ≤ 0.1 µBq/kg

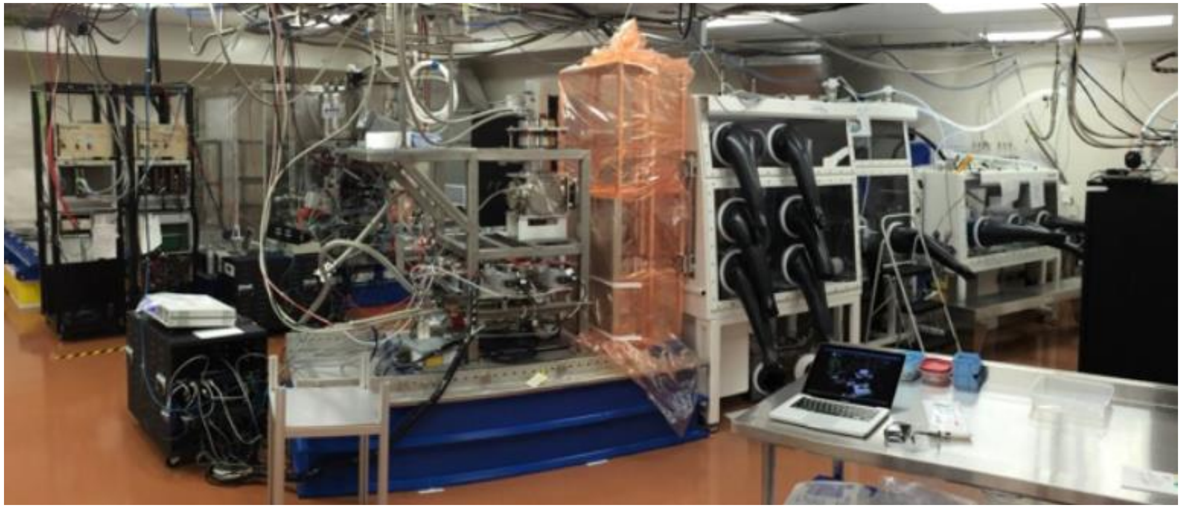


Copper production and machining

- Cu machining in an underground clean room machine shop complete April 2016.
- All parts are uniquely tracked through machining, cleaning, and assembly by a custom-built database. NIMA 779 (2015) 52.
- Cleaning of Cu parts by acid etching and passivation.
- Electroformed parts stored in nitrogen.



Glovebox assembly

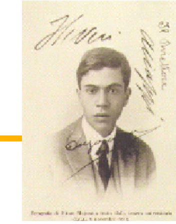


Detector GB

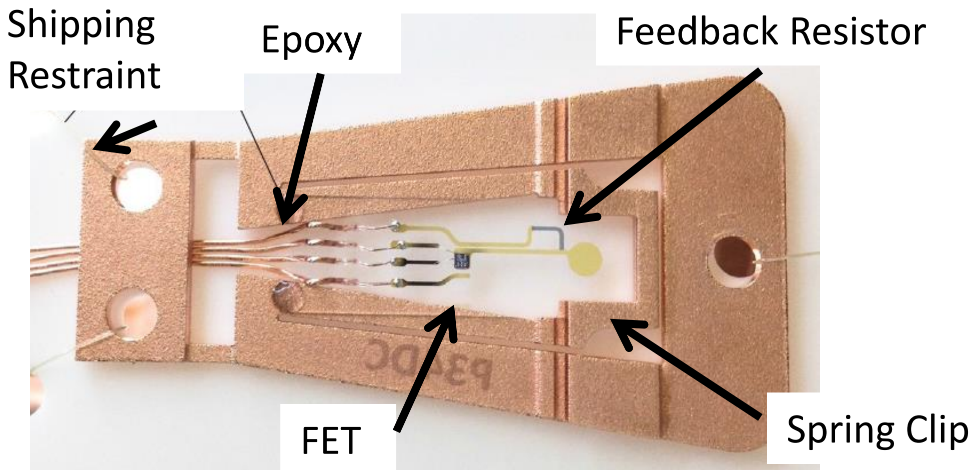
String GB (top view)

Module GB

Front-end electronics, cables and connectors



- Front-end board

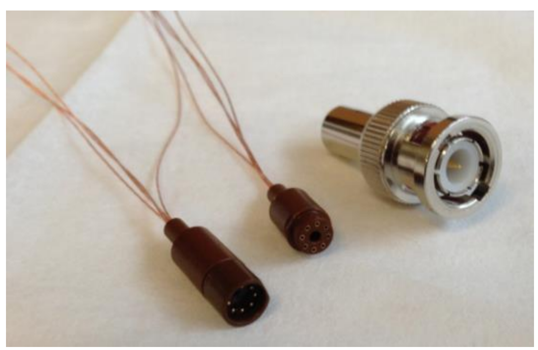


Clean Au+Ti traces on fused silica, amorphous Ge resistor, FET mounted with silver epoxy, EFCu + low-BG Sn contact pin

- Cables
  - Axon' Picoax® HV and signal cables.
  - HV testing of cables and connectors. [NIM A 823 (2016) 83]

- Signal Connectors

  In-house machined from Vespel.
  Low background solder and flux.



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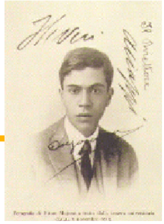
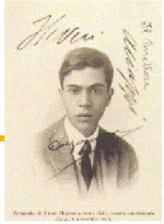
Data set parameters



Data Set	Prototype Module	Module 1 no inner shield	Module 1 with inner shield
mnemonic	**DS-PM**	**DS0**	**DS1**
Operation Dates	9/18/14 – 4/17/15	6/26/15 – 10/7/15	12/31/15 – 4/14/16*
Run Time	211 d	103.15 d	104.68 d
Live Time	138.22 d	47.73 d	54.70 d
Fraction Live	0.65	0.46	0.52
Enriched Ge Exposure	0 kg d	510.2±1.1 kg d	650.41±0.30 kg d
Natural Ge Exposure	701.7 kg d	186.6±0.6 kg d	91.35±0.15 kg d

*Data taking ongoing

Data set parameters



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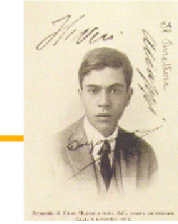
*Data taking ongoing

Dry-run of analysis and data production

Found known backgrounds and addressed 2 observed backgrounds:

- Added additional shielding in the crossarm.
- Replaced the cryostat seals with low radioactivity versions.

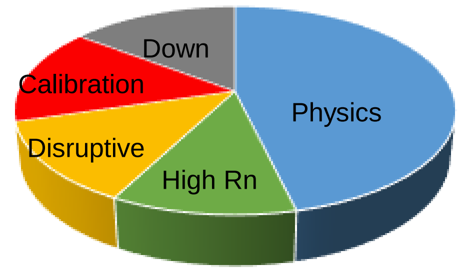
Data set parameters



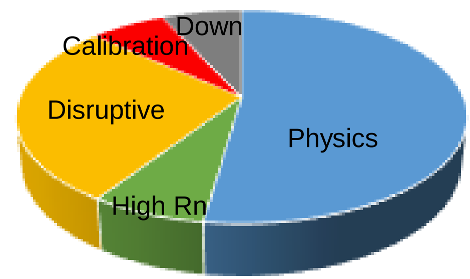
	DS0 (days) No inner shield June 26, – Oct. 7, 2015	DS1 (days) with inner shield Dec. 31, 2015 – Apr. 14, 2016*
Total	103.15	104.68
Total acquired	88.04	97.49
Physics	47.73	54.70
High radon	11.76	7.32
Disruptive Commissioning tests	13.10	28.61
Calibration	15.44	6.86
Down time	15.11	7.19

*Data taking ongoing

DS0

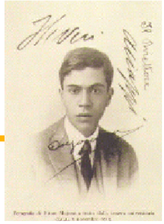


DS1

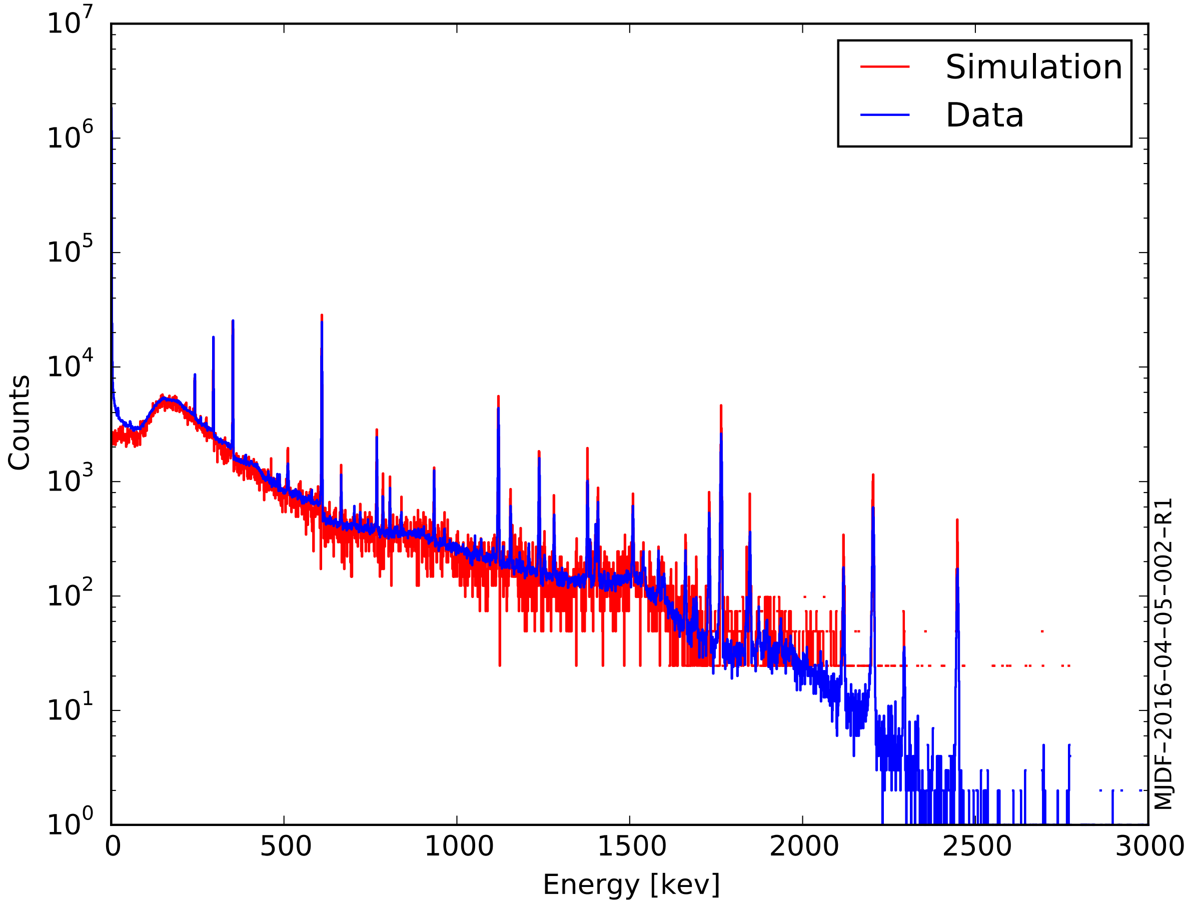


Oct – Dec, 2015 Break for Module 1 improvements

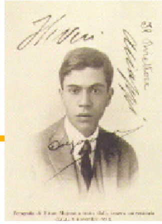
Module 1 commissioning



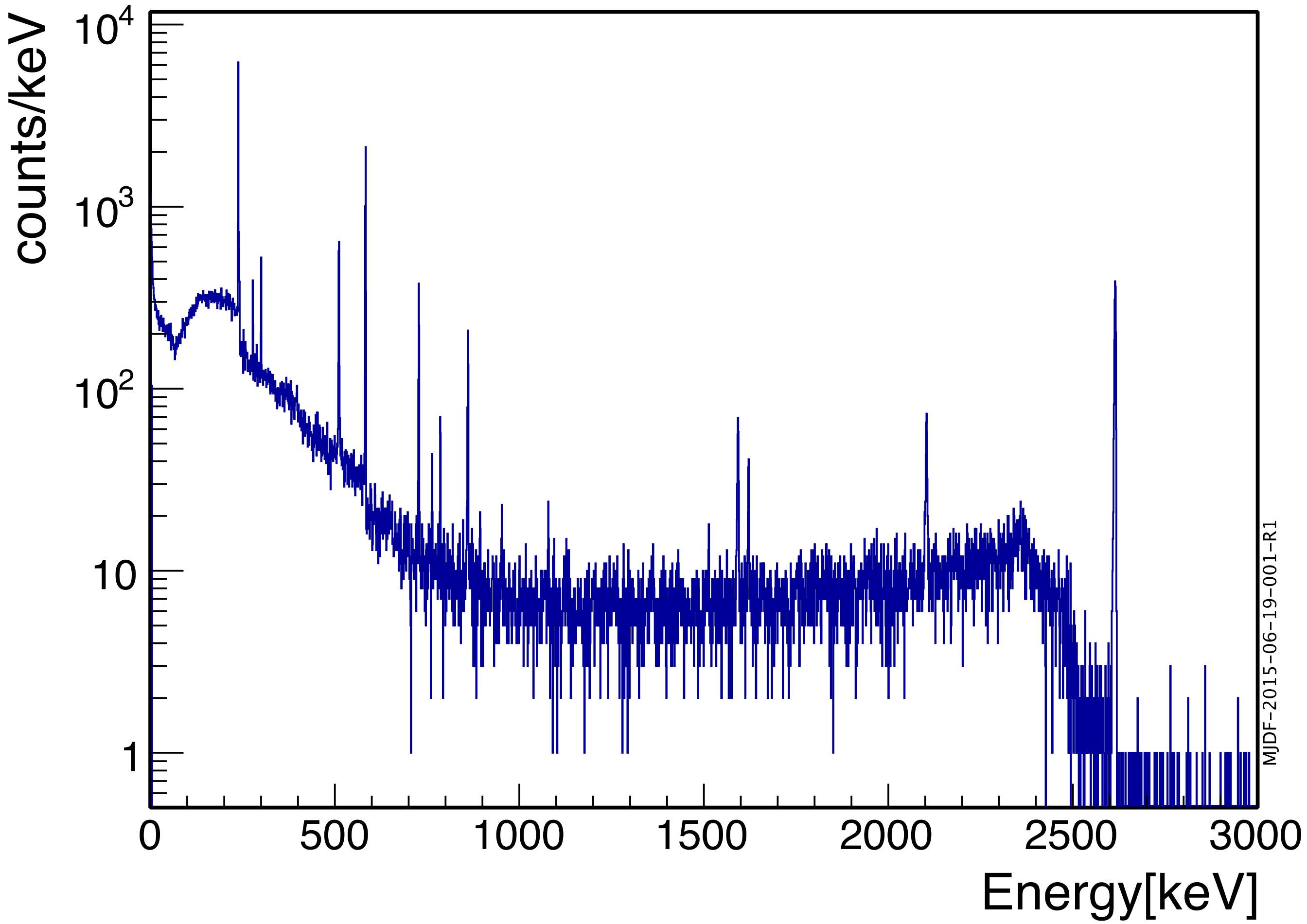
- Rn purge test Sept. 2015, during Module 1 commissioning.
- Rn simulation compared to data. Fit around 609-keV peak
- Fit is 8.5 pCi/L, near room value of ~7 pCi/L, but no value for shield level.



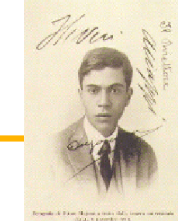
^{228}Th Calibration Spectrum in Module 1

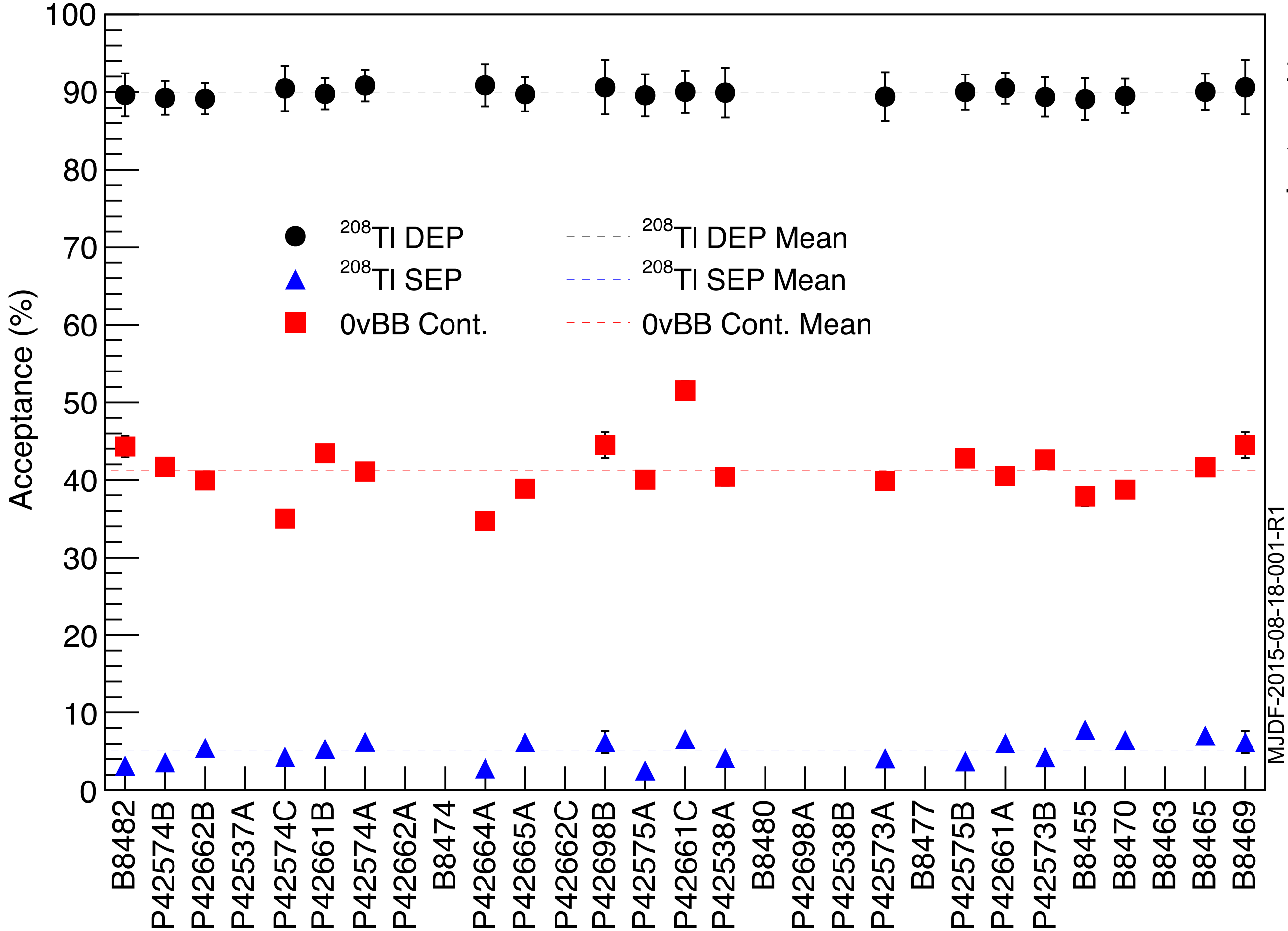


One enriched detector spectrum within a string mounted in Module 1 and inside shield. FWHM 3.6 keV at 2.6 MeV



Ge Detector PSD in Module 1

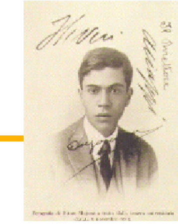


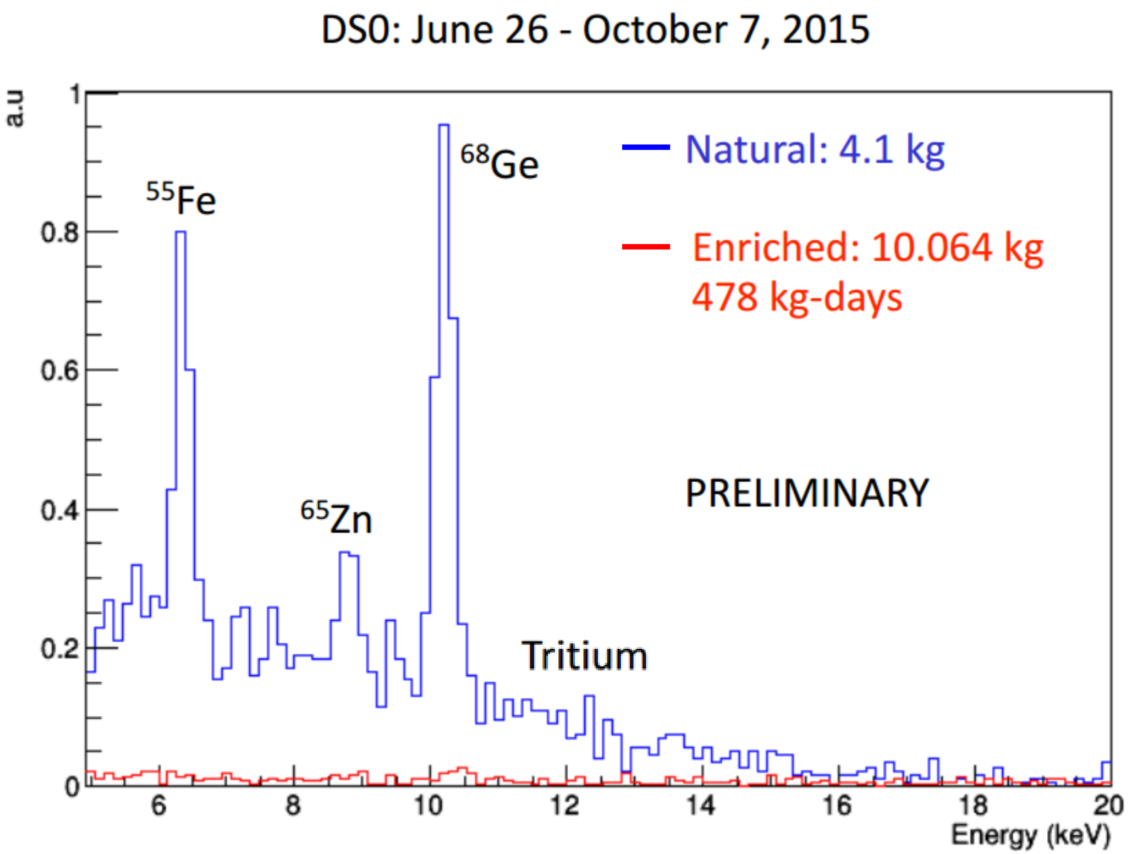


^{208}Tl DEP (single site events) fixed to 90%

^{208}Tl SEP (multi-site events) reduced to <10%

Low-Energy Spectrum Commissioning Data





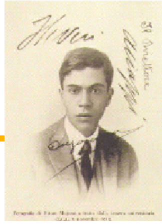
Physics we are sensitive to in this energy region:

- Pseudoscalar dark matter coupling
- Vector dark matter coupling
- 14.4 keV solar axion
- 11.1 keV electron decay
- 10.6 keV Pauli Exclusion violating decay

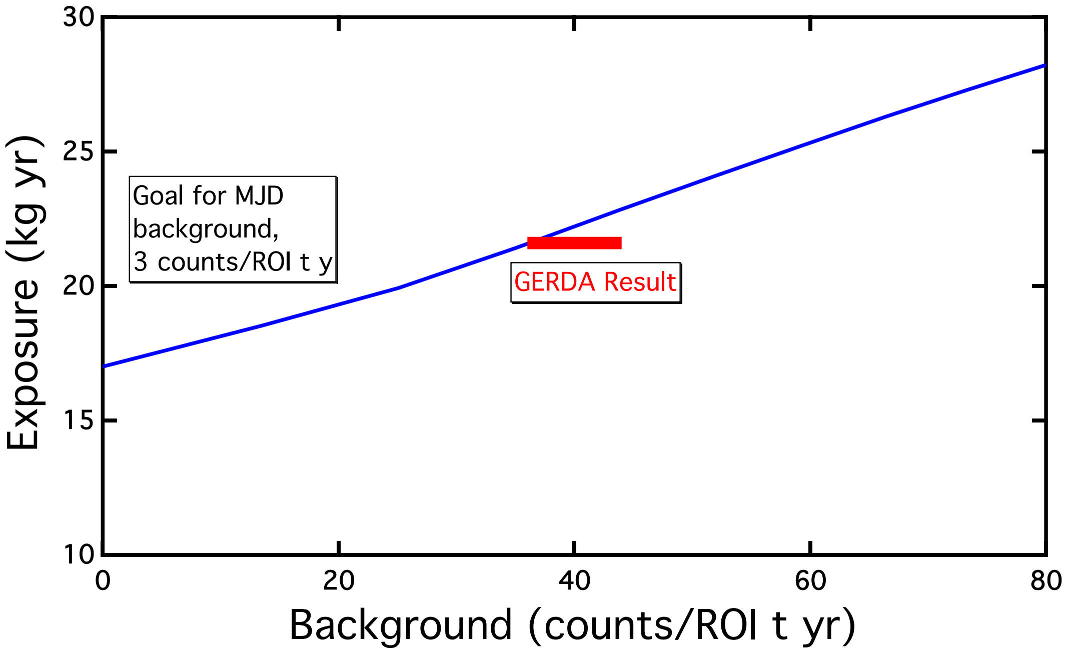
Production rate of Tritium and other isotopes.

Significant reduction in low-E background in enriched detectors.

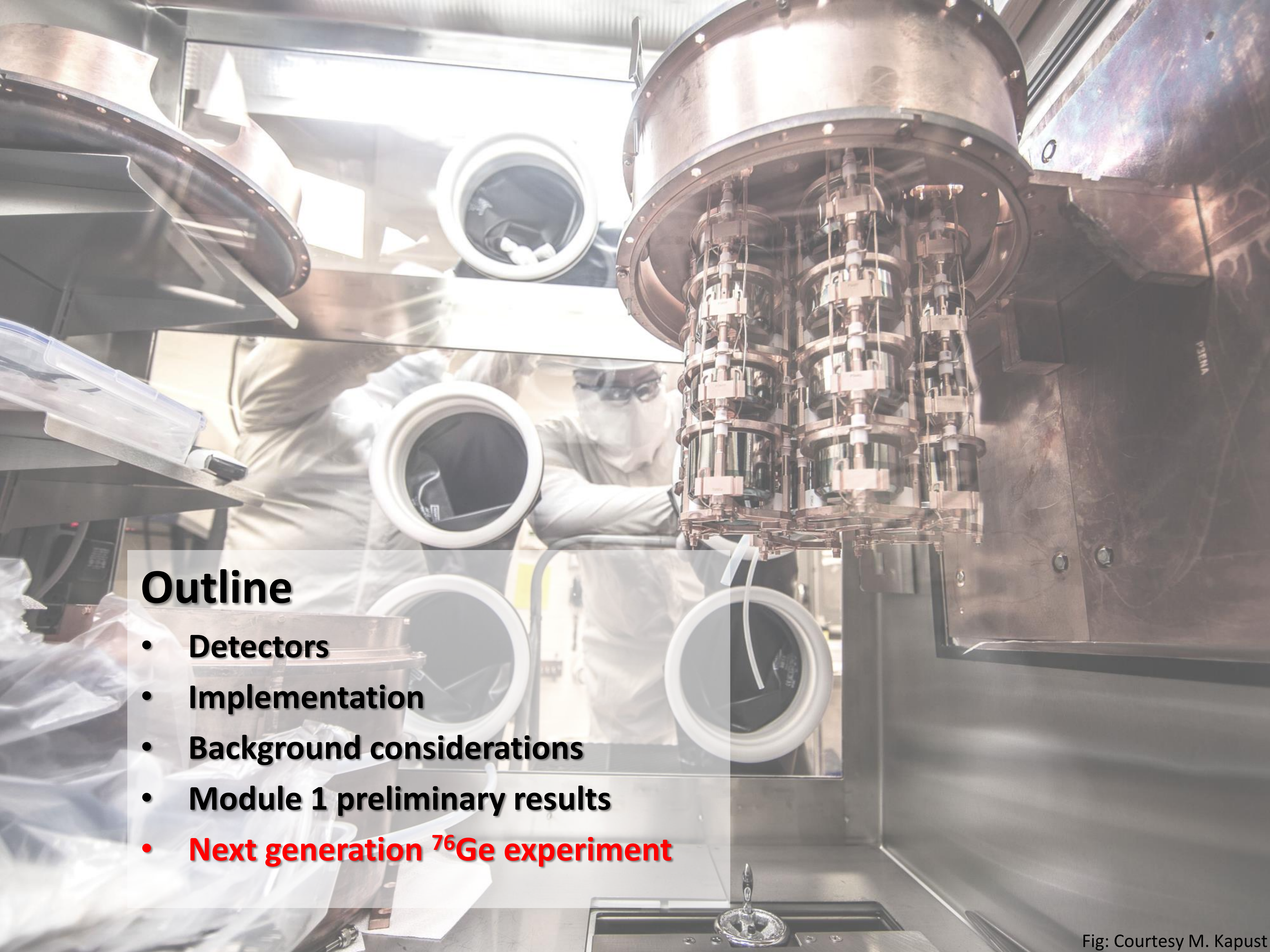
The MAJORANA Blindness Plan



Minimum exposure to reach 2.1x10^{25} yr half-life limit as a function of background.



- Data pre-scaling scheme, 25% open. 31 h open followed by 93 h blind.
- If background is near goal, require 15-20 kg yr of exposure to reach present half-life limit in Ge. Hence plan to remove blindness after 15 kg yr.
- Specialized physics analyses (dark matter, e.g.) will have different blind exposure requirements based on physics goals. A certain region of the spectrum may have blindness removed at a lower exposure, for example.

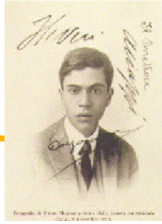


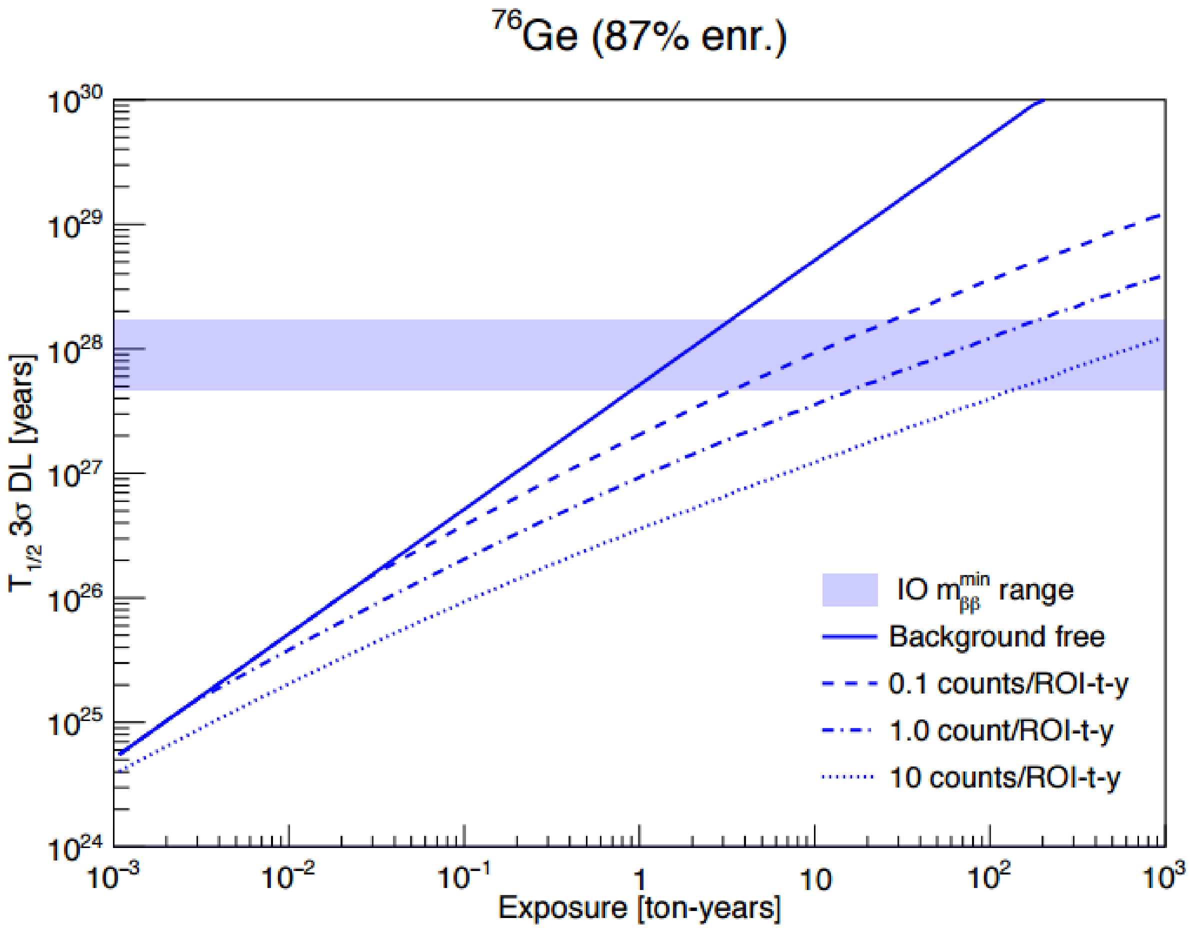
Outline

- Detectors
- Implementation
- Background considerations
- Module 1 preliminary results
- Next generation ^{76}Ge experiment

Fig: Courtesy M. Kapust

Sensitivity vs. Exposure ^{76}Ge





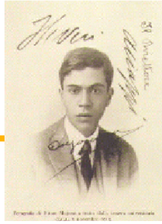
Inverted Ordering (IO) Minimum IO mββ=18.3 meV, taken from using the PDG2013 central values of the oscillation parameters, and the most pessimistic NME for the corresponding isotope among QRPA, SM, IBM, PHFB, and EDF.

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

J. Detwiler

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

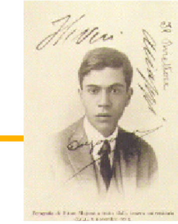
Next generation ^{76}Ge experiment



Working cooperatviely with GERDA and others towards the establishment of a single ^{76}Ge $0\nu\beta\beta$-decay collaboration to built a large experiment to explore the inverted hierarchy region.

- Joint MJD - GERDA meeting
  Nov. 2015, Kitty Hawk, NC
- Meeting on the Next Generation ^{76}Ge Experiment
  April 2016, Munich, Germany

Next generation ^{76}Ge experiment



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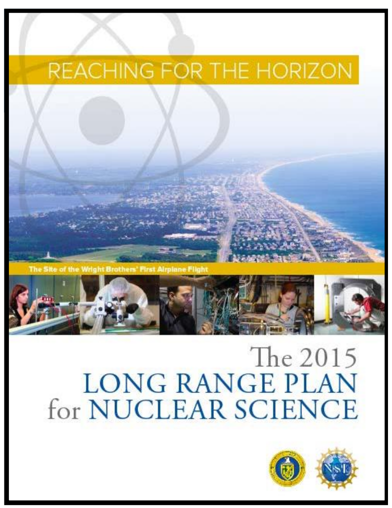
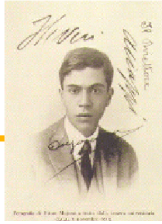
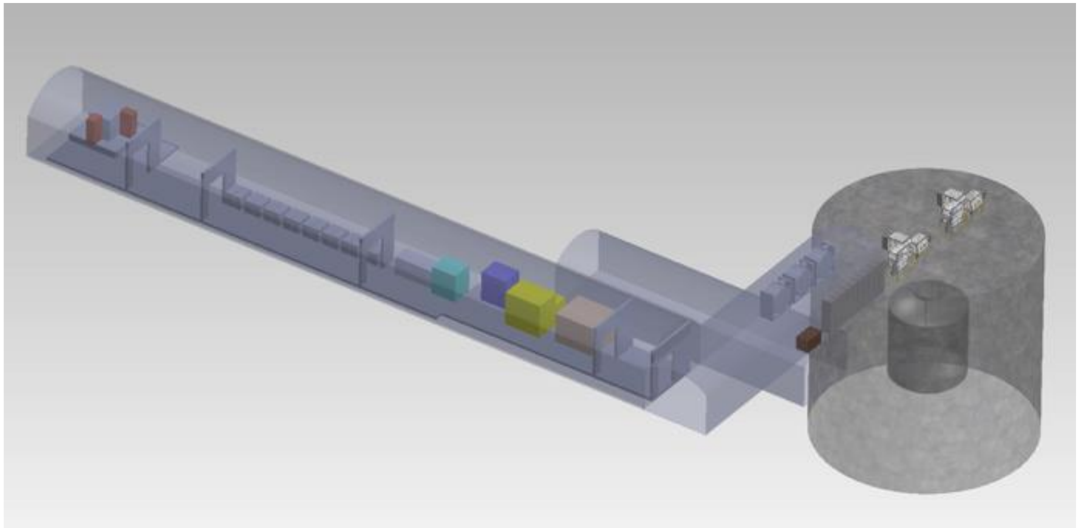


Leading a tonne-scale $0\nu\beta\beta$ experiment is the highest priority new activity for the US Nuclear Physics community as indicated in the latest Long Range Plan for nuclear science in the US recently released by the Nuclear Science Advisory Committee (NSAC).

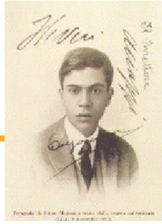
Next generation ^{76}Ge experiment



- Anticipate down-select of best technologies, based on results of the two experiments.
- Moving forward is predicated on demonstration of projected backgrounds.
- Work to be done to go from a conceptual design to a viable, competitive proposal.
  - Robust signal and high voltage connectors
  - Ultra-clean materials
  - Alternative detector designs
  - Detector signal readout
  - Cryostat and detector mount designs
  - Enrichment
  - Cooling and shielding
  - Required depth



Summary



Goal:

- Demonstrate backgrounds needed for a tonne scale $0\nu\beta\beta$ experiment.
- 5 year run (108 kg-years): $T_{1/2} > 1.6\ 10^{26}$ years (90 % CL)

  $T_{1/2} = 4.3\ 10^{25}$ years (5σ discovery)

Configuration:

- 44-kg of Ge detectors, in two independent cryostats.
- 29 kg of 88% enriched ^{76}Ge crystals; 15 kg of natGe, P-type point-contact detectors.

Module 1:

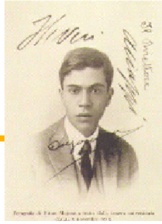
- Installed in-shield and taking low background data since January 2016.
- End-to-end analysis underway from July - Oct. 2015 dataset to shake down data cleaning and analysis tools (relatively insensitive because of partial shielding).
- Expect to have first background information from 2016 run in the summer.

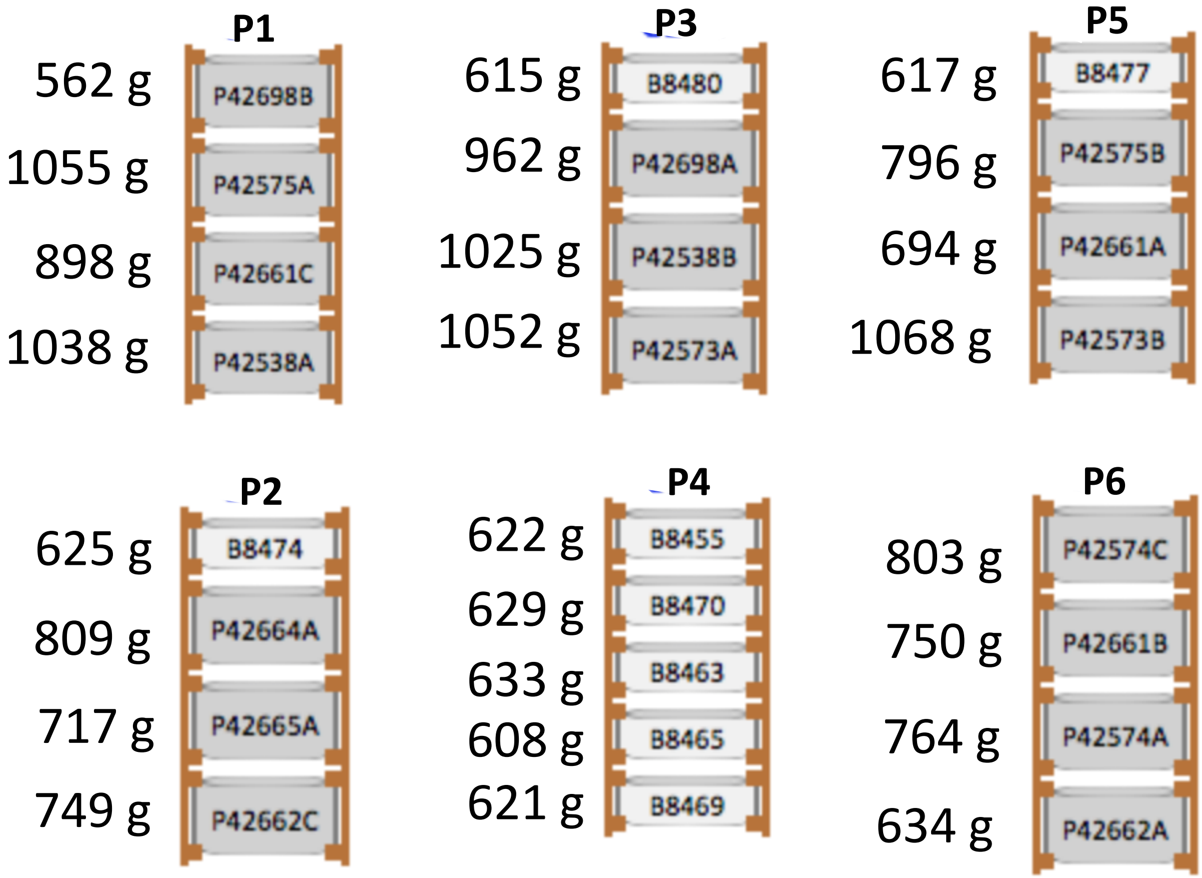
Module 2:

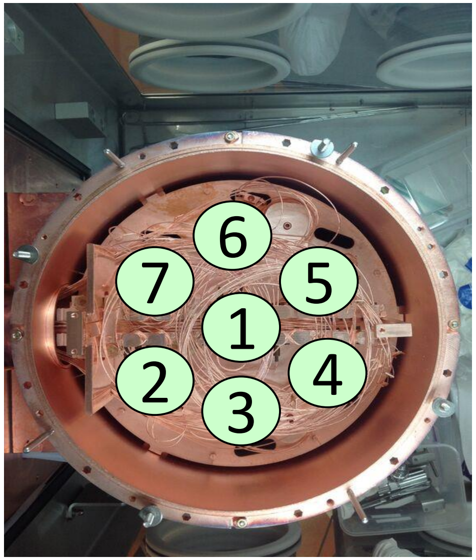
- Construction and assembly proceeding on schedule, in-shield commissioning beginning ~ June 2016.

Backup

Module 1 String Layout

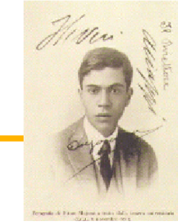






P#####L ORTEC PPC, enriched, detector mass 16.8 kg
B#### Canberra BEGe, natural, detector mass 5.7 kg
29 total detectors

Module 1 Detector Status

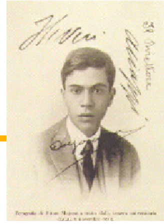


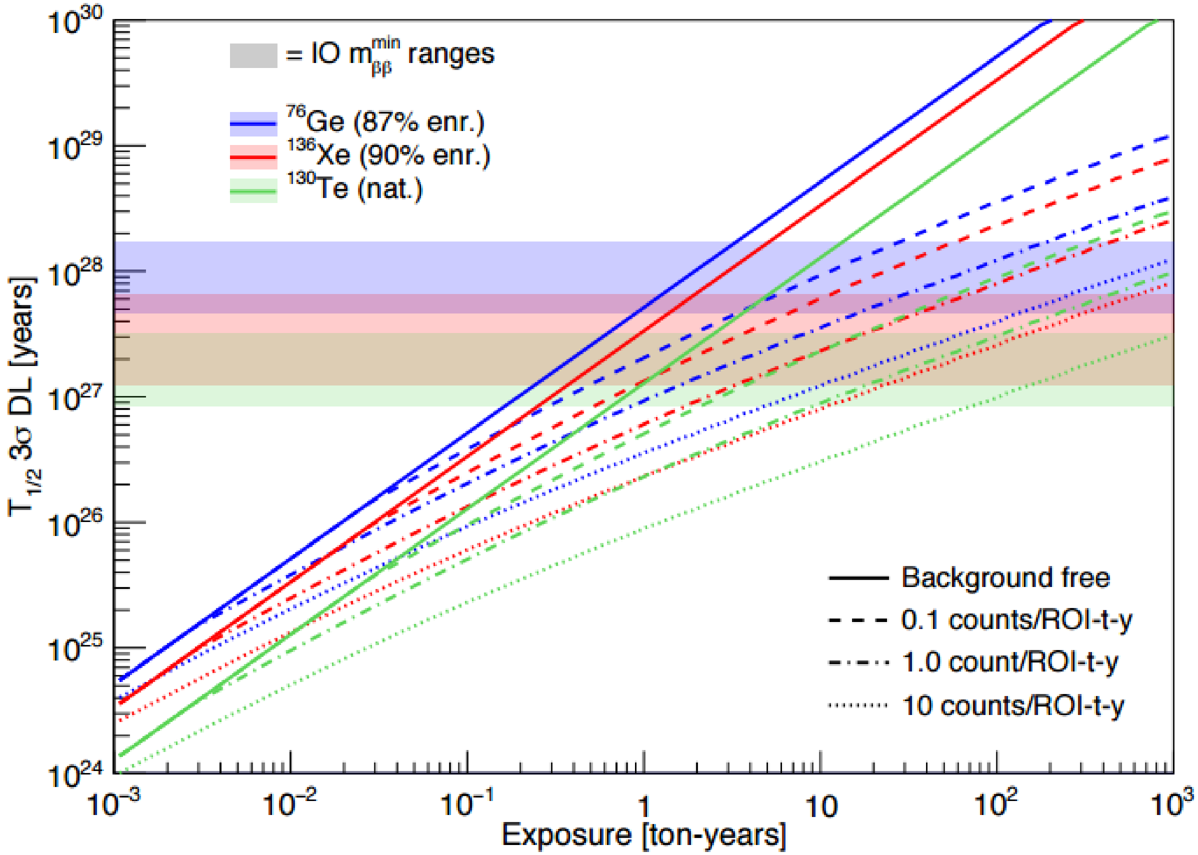
	6/26/15 – 10/7/15	12/31/15 – Present
mnemonic	**DS0**	**DS1**
Total Number of Detectors Installed	29	29
Enriched Detectors Num. used in Analysis	20 14	20 15
Natural Detectors Num. used in Analysis	9 7	9 3
Active Natural Mass	3.9 kg of 5.7 kg	1.7 kg of 5.7 kg
Active Enriched Mass	10.7 kg of 16.8 kg	11.9 kg of 16.8 kg

Unbiased Detectors - Lost connections, leakage current, noisy response, HV instability

May re-work Module 1 as Module 2 commissioning progresses

Discovery Level





Inverted Ordering (IO)

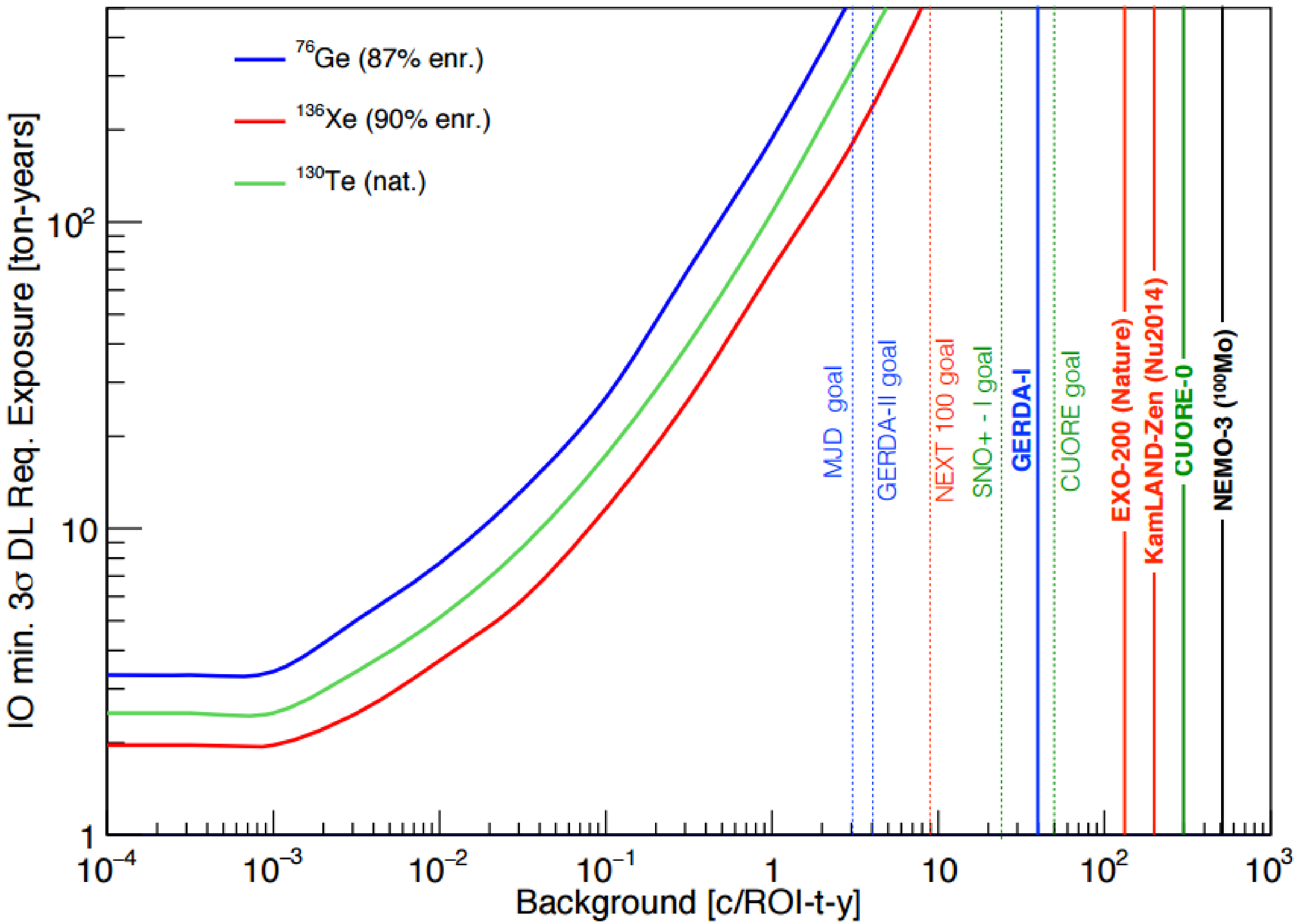
Minimum IO $m_{\beta\beta}$=18.3 meV, taken from using the PDG2013 central values of the oscillation parameters, and the most pessimistic NME for the corresponding isotope among QRPA, SM, IBM, PHFB, and EDF

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

J. Detwiler

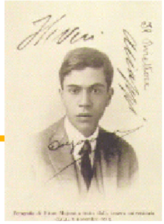
Assumes 75% efficiency based on GERDA Phase I. Enrichment level is accounted for in the exposure

Discovery Level

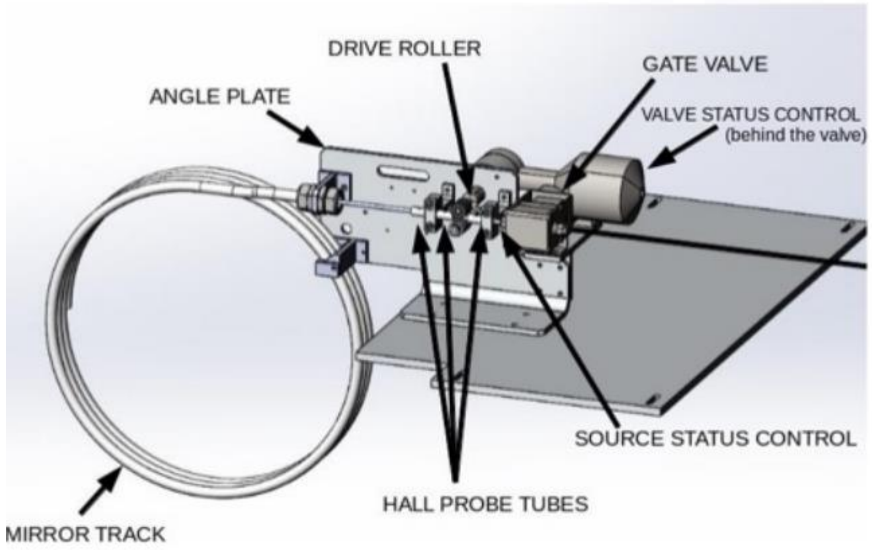


J. Detwiler

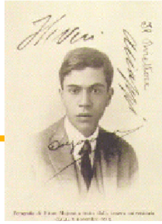
Calibration System



- Line sources are deployed from outside the shielding within a tube that surrounds each cryostat.
- ^{228}Th (11.6 kBq) and ^{60}Co (6.3kBq) sources available.
- Calibration tube is externally purged during calibration.
- Several sensors monitor the position of the source and the status of the system.



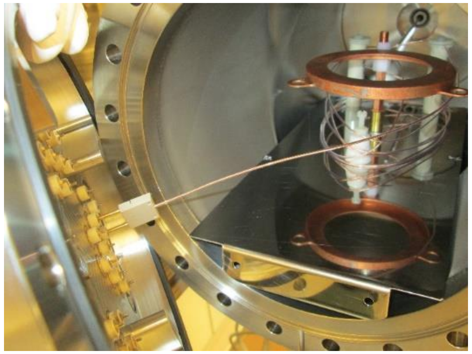
High voltage testing for the MAJORANA DEMONSTRATOR



NIM A 823 (2016) 83
arXiv:1603.08483

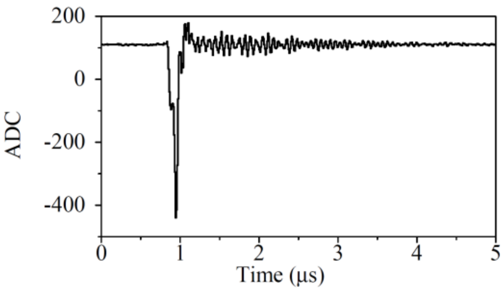
Study of surface micro-discharge (μD) induced by high-voltage.
Can damage the front-end electronics or mimic detector signals.

- R&D measurements determined improvements of the cable layout and feedthrough flange model selection:
  - μD rate increases with the applied voltage.
  - Coiling radius should be at least 10 times greater than the cable radius.
  - Strip-back length of the cable should be greater than 0.5 inches.
  - Electropolishing the copper pieces that have sharp edges reduces μD's.
  - "Pee-wee" flange selected



HV cable and flange being characterized

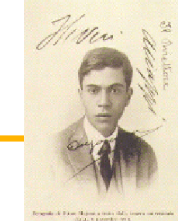
- MAJORANA DEMONSTRATOR cables (133) and feedthroughs (280) were characterized
  - Leakage current testing of the feedthroughs: 97% of the pins exhibited <2 μA.
  - μD rate per cable: no issues were found with any of the cables (< 5 μD/h/cable).
- Study of μD occurrence in the MAJORANA DEMONSTRATOR:
  - Average values rates are 0.017 ± 0.009 μd/h in the prototype module and 0.30 ± 0.03 μd/h in Module 1.
  - μD rate is below the upper limits obtained in the characterization measurements.



μD event in Module 1

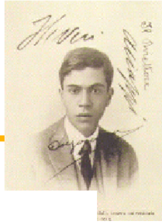
Stable configuration achieved, and the cables and connectors can supply HPGe detector operating voltages without exhibiting discharge

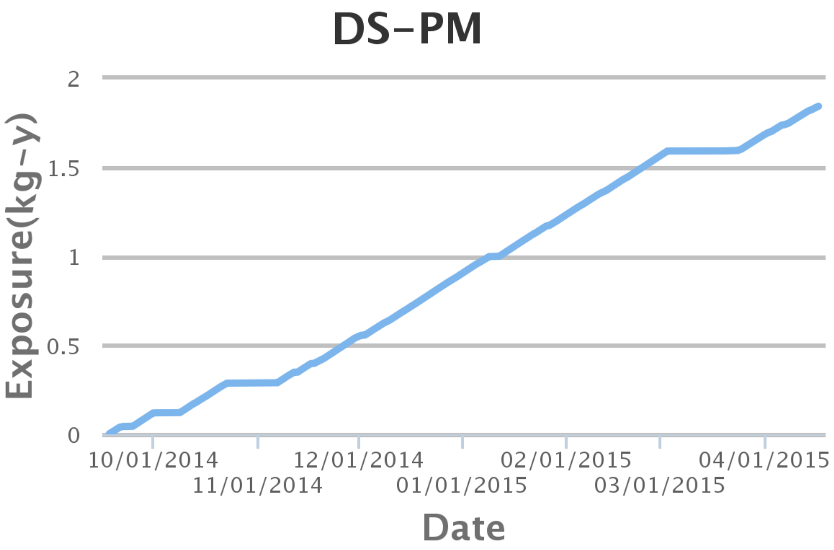
Module 1 improvements Fall 2015

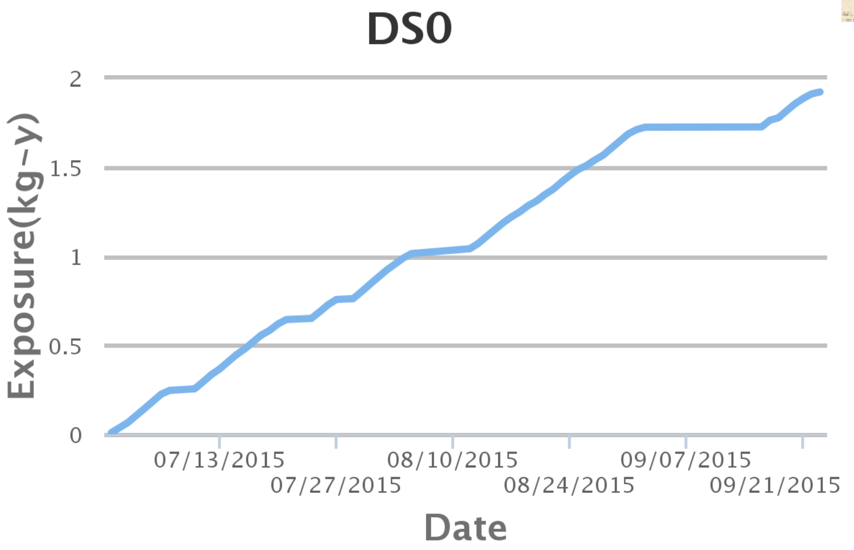


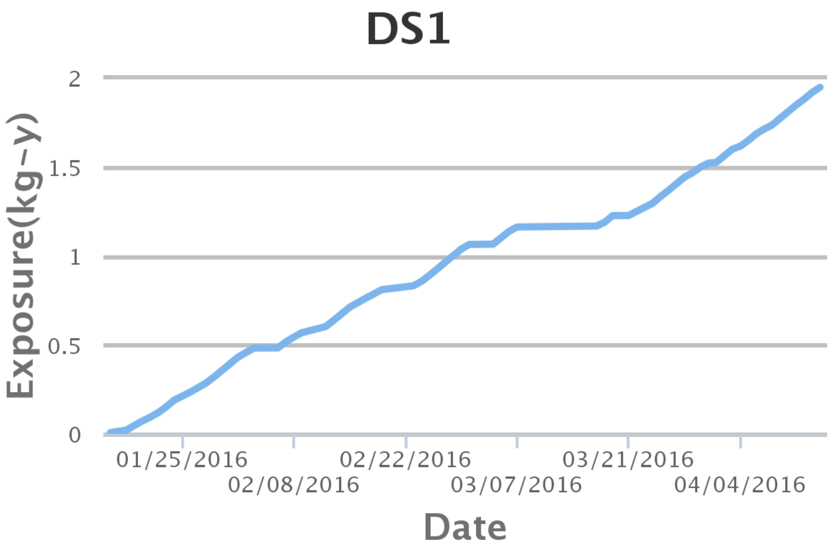
- Operated in-shield June 2015 - Oct. 2015
  - Partial shielding and some high-background components
- During Oct.- Dec. 2015 performed planned improvements to Module 1.
  - Installed inner Cu shield: Decrease background contribution from outer Cu shield and Pb by factor of about 10.
  - Replaced Kalrez O-rings in cryostat: These o-rings contributed to our background. Replaced with PTFE.
    - Kalrez: Th ~ 2000-4000 ppt. Expect about 80 c/ROI t y.
    - PTFE sheet: significant reduction in BG compared to Kalrez.
- Crossarm Shielding: Added to decrease background contributions from electronics-breakout box region.
- Repaired non-operating detectors and upgrade cables:
  - Repairing non-operating detectors (cable connection, HV connection, LMFE replacement, …)

Exposure

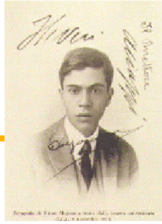


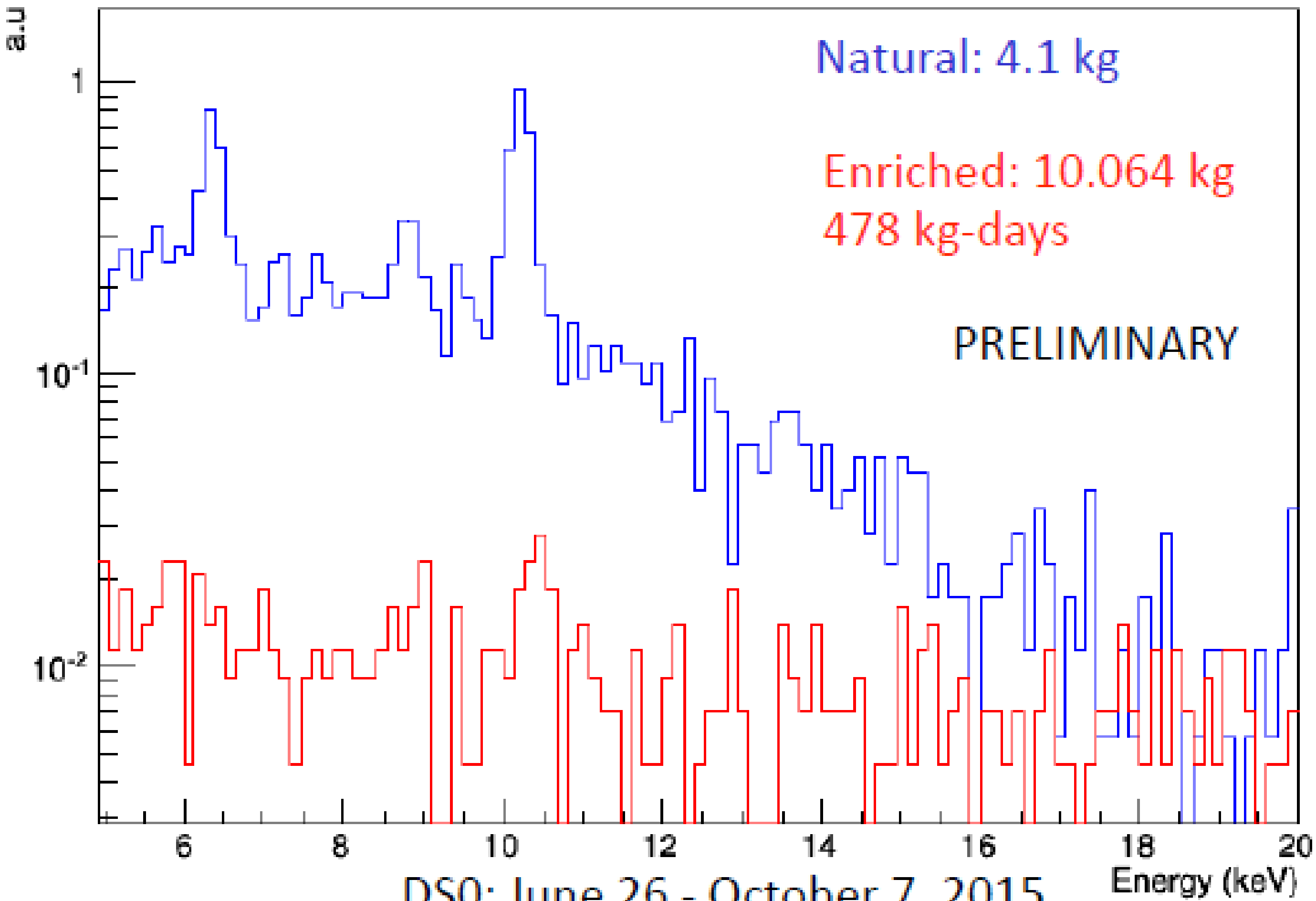

DS-PM
Exposure(kg-y)
2
1.5
1
0.5
0
10/01/2014
11/01/2014
12/01/2014
01/01/2015
02/01/2015
03/01/2015
04/01/2015
Date


DS0
Exposure(kg-y)
2
1.5
1
0.5
0
07/13/2015
07/27/2015
08/10/2015
08/24/2015
09/07/2015
09/21/2015
Date


DS1
Exposure(kg-y)
2
1.5
1
0.5
0
01/25/2016
02/08/2016
02/22/2016
03/07/2016
03/21/2016
04/04/2016
Date

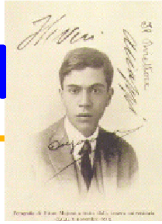
Low-energy spectrum (log scale)

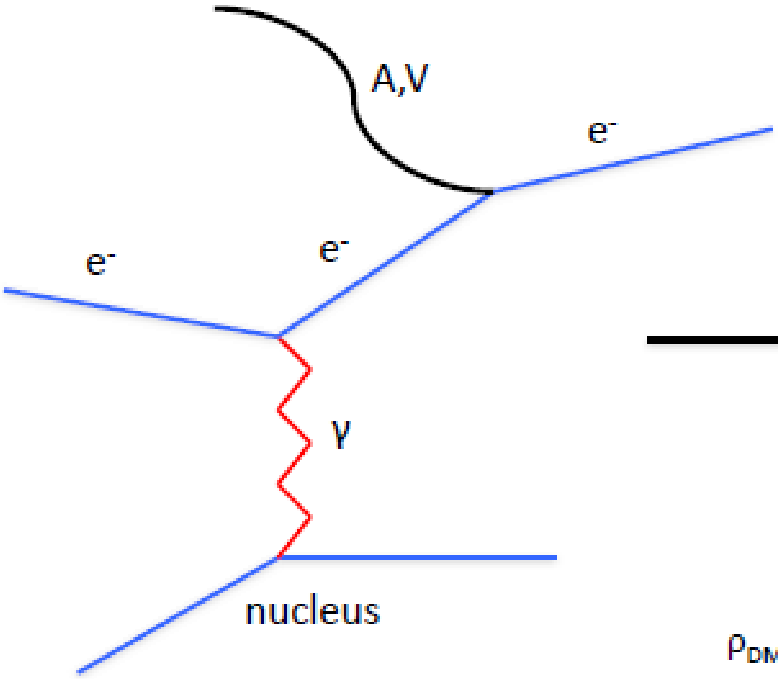


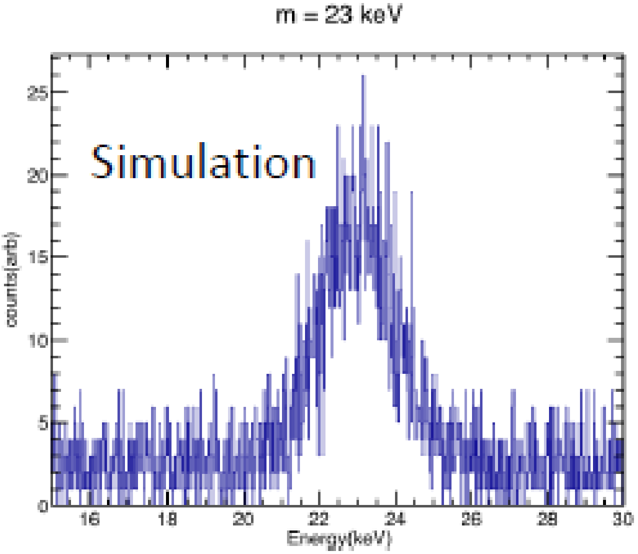


DS0: June 26 - October 7, 2015

Example: Light (1-100 keV-scale) Bosonic DM





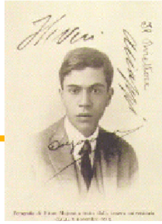


$\rho_{DM} = 0.3$ GeV/cm^3 $\beta = v/c \sim 0.001$

- Low threshold PPC Ge detectors well suited for keV-scale DM search
- Pseudoscalar (ALPs) or Vector DM could deposit rest mass-energy in detector

See: M. Pospelov, A. Ritz, and M. Voloshin, Phys. Rev. D, 78, 115012 (2008).

NSAC Subcommittee (highlights added)



The Subcommittee recommends the following guidelines be used in the development and consideration of future proposals for the next generation experiments:

1.) Discovery potential: Favor approaches that have a credible path toward reaching 3σ sensitivity to the effective Majorana neutrino mass parameter $m_{\beta\beta}$=15 meV within 10 years of counting, assuming the lower matrix element values among viable nuclear structure model calculations.

2.) Staging: Given the risks and level of resources required, support for one or more intermediate stages along the maximum discovery potential path may be the optimal approach.

3.) Standard of proof: Each next-generation experiment worldwide must be capable of providing, on its own, compelling evidence of the validity of a possible non-null signal.

4.) Continuing R&D: The demands on background reduction are so stringent that modest scope demonstration projects for promising new approaches to background suppression or sensitivity enhancement should be pursued with high priority, in parallel with or in combination with ongoing NLDBD searches.

5.) International Collaboration: Given the desirability of establishing a signal in multiple isotopes and the likely cost of these experiments, it is important to coordinate with other countries and funding agencies to develop an international approach.

6.) Timeliness: It is desirable to push for results from at least the first stage of a next-generation effort on time scales competitive with other international double beta decay efforts and with independent experiments aiming to pin down the neutrino mass hierarchy.