Office of Nuclear Physics

The MAJORANA DEMONSTRATOR
search for neutrinoless double beta decay

C. M. O'Shaughnessy

Univ. of North Carolina & Triangle Universities Nuclear Laboratory

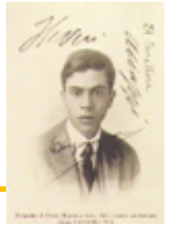
On behalf of the MAJORANA Collaboration

invisibles
neutrinos, dark matter & dark energy physics

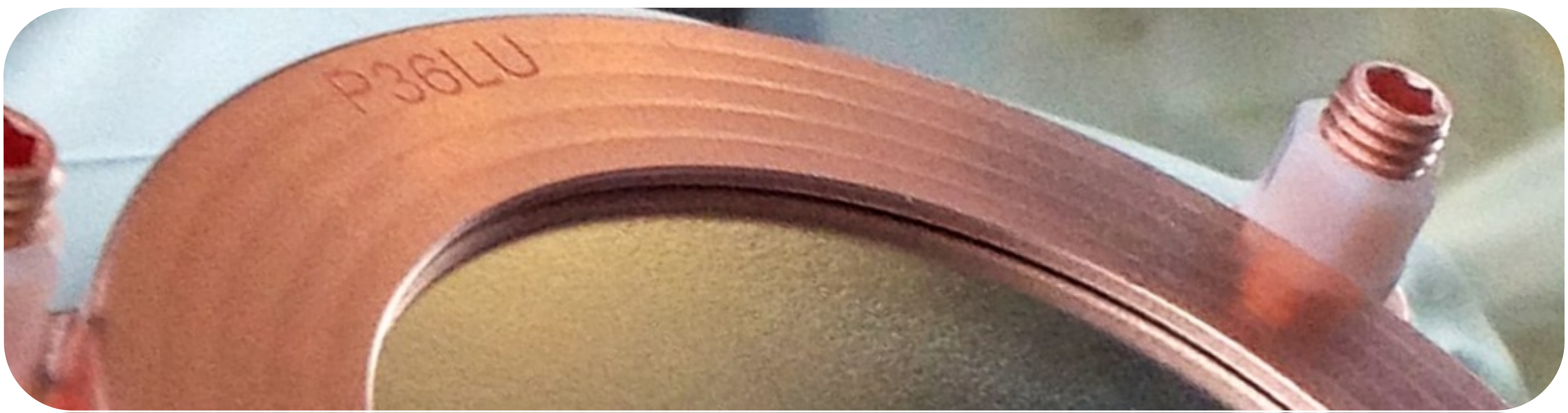
22 – 26 June 2015
Madrid, Spain

22 June 2015

Outline

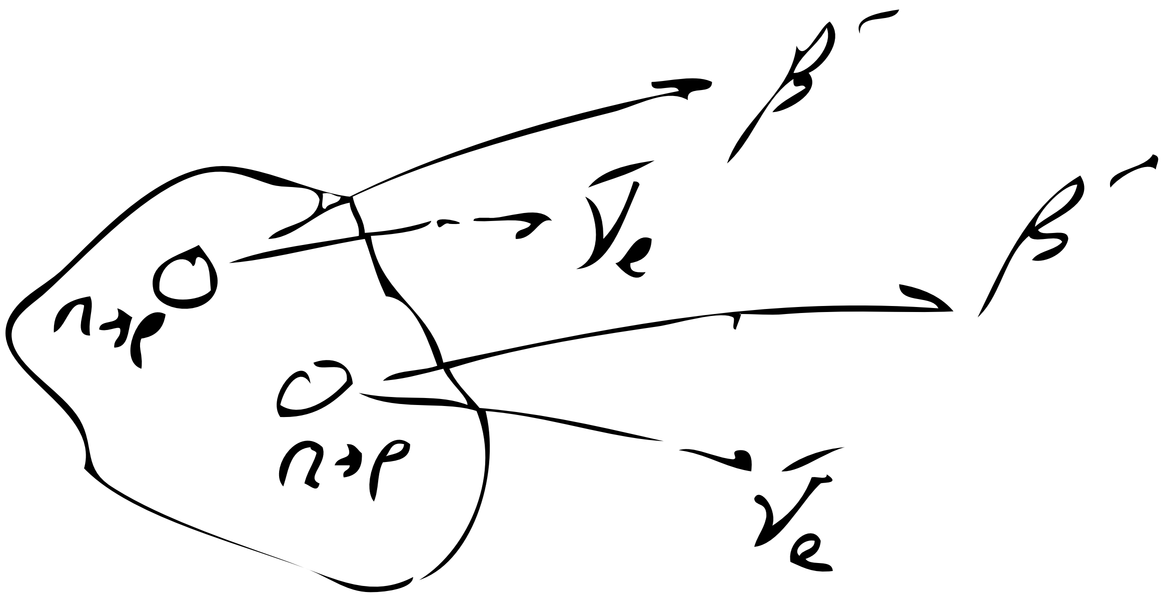


- $0\nu\beta\beta$ Sensitivity Considerations
- MAJORANA DEMONSTRATOR Overview
- Status of the DEMONSTRATOR

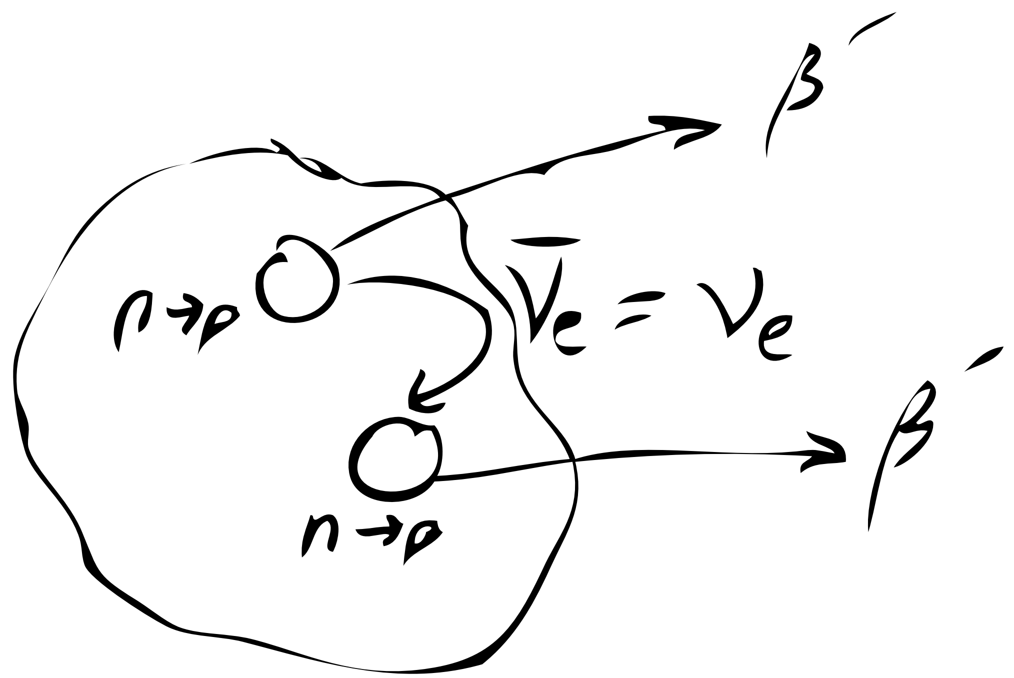


Neutrinoless ββ

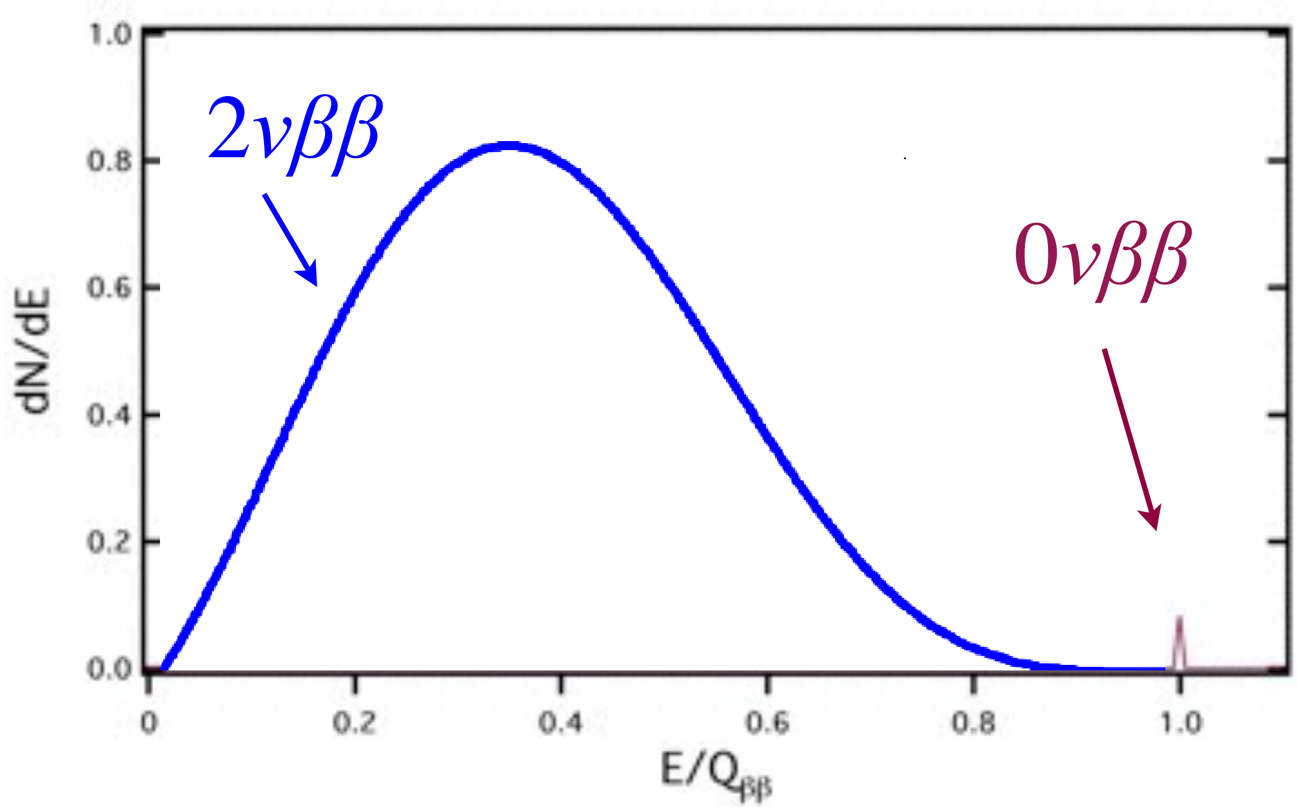
- 2νββ — $(A,Z) \rightarrow (A,Z+2) + 2e^{-} + 2\bar{\nu}_e$
  SM Allowed and observed in select even-even isotopes



- 0νββ — $(A,Z) \rightarrow (A,Z+2) + 2e^{-}$
  $\Delta L = 2$



Neutrinoless ββ



- Most sensitive experiments to date using ^{76}Ge, ^{130}Te, and ^{136}Xe have attained $T_{1/2} > 10^{25}$ years
- Typical Source Mass — exposure times of 30 - 100 kg-years

Expected 0vββ signals (cnts/tonne-year)

- Background Free

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

Half life (years)	~Signal (cnts/tonne-year)
10^{25}	500
5×10^{26}	10
5×10^{27}	1
$>10^{29}$	<0.05

- Background Limited

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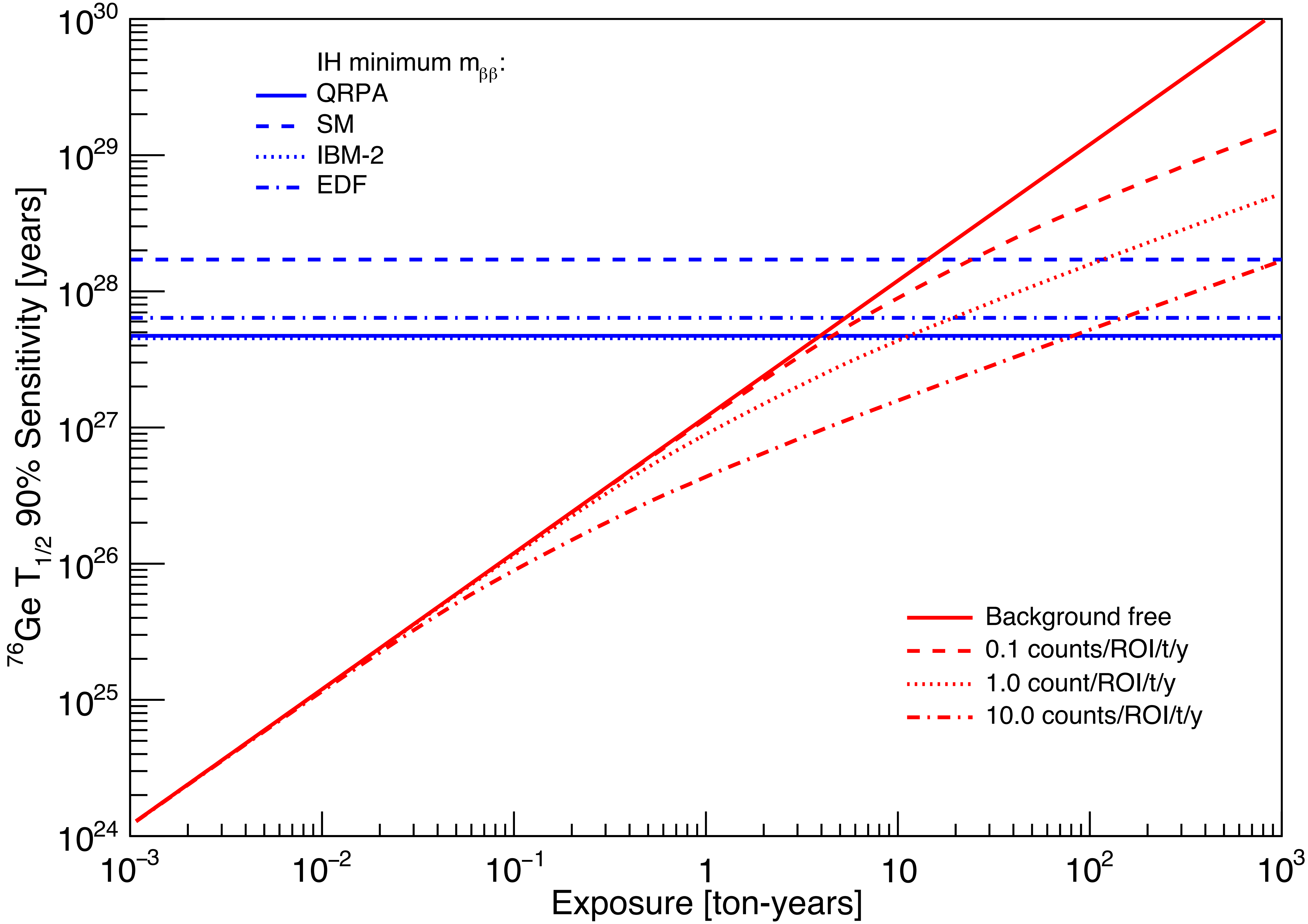
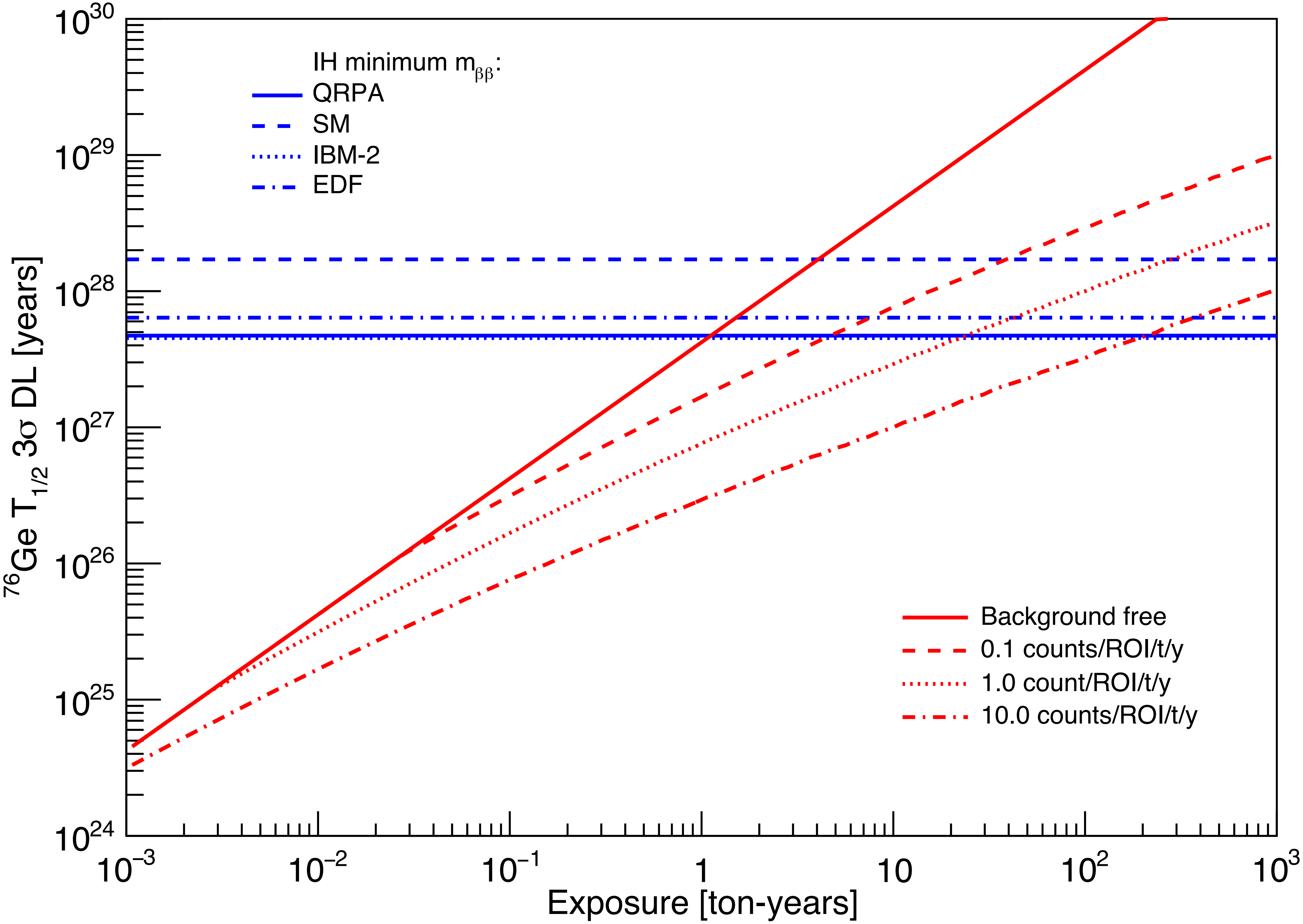
$5\text{x}10^{27}$	1
$>10^{29}$	<0.05

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

^{76}Ge Sensitivity vs. Background

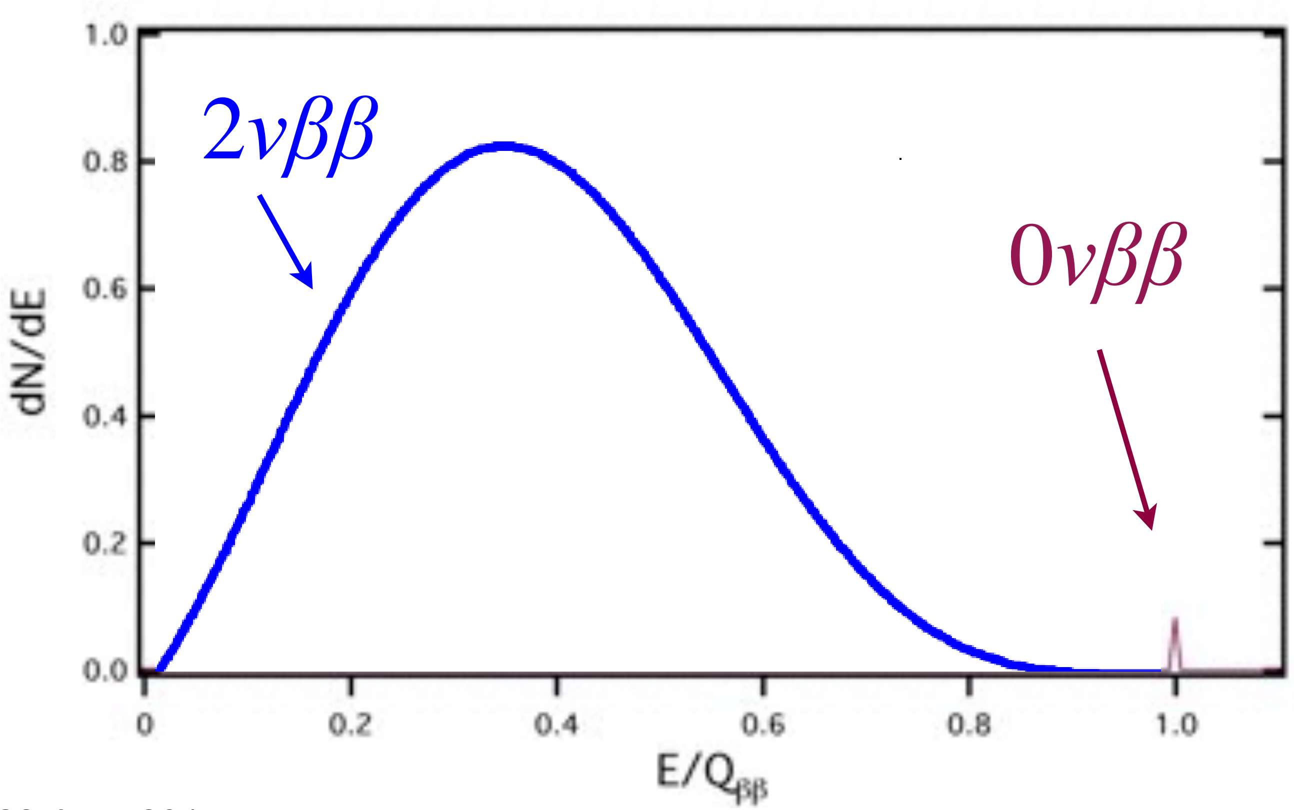


^{76}Ge Discovery vs. Background



0νββ Discovery Considerations

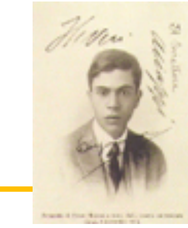
- Need large, highly efficient source mass
- Desire extremely low (near-zero) backgrounds in the 0νββ peak region
  - ➡ Signal background 1:1 or better
  - ➡ Best possible resolution, ΔE, to minimize region of interest
- Want best possible energy resolution and/or kinematical method to discriminate 0νββ from 2νββ



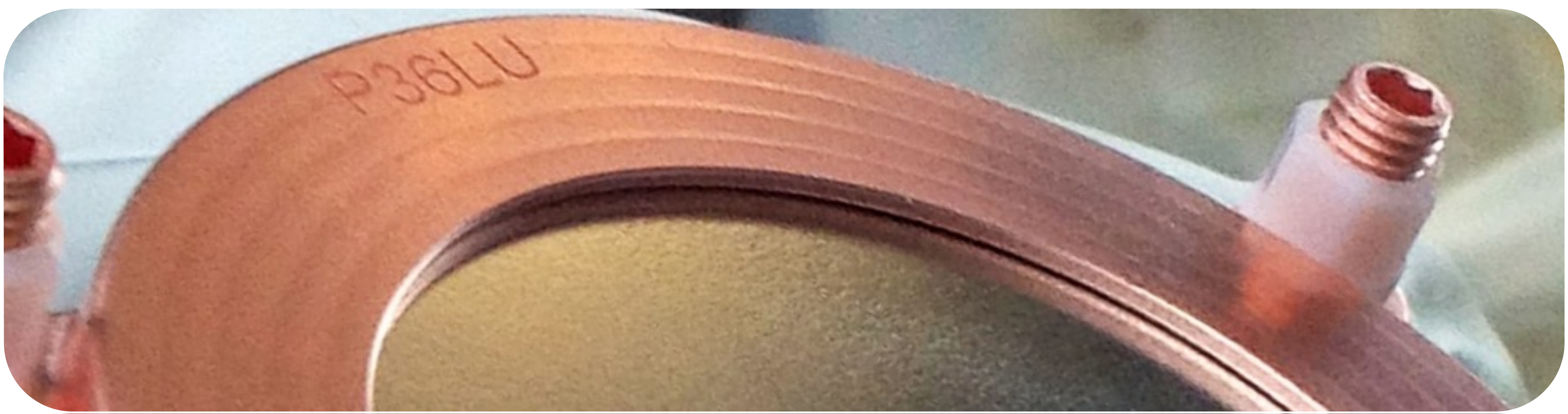
Tonne scale experiments require backgrounds of ≤1 cts / ROI-t-y

Need independent observations from different isotopes

Outline



- **0νββ Sensitivity Considerations**
- **MAJORANA DEMONSTRATOR Overview**
- **Status of the DEMONSTRATOR**



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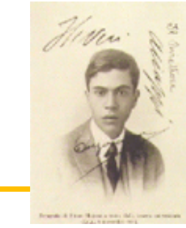
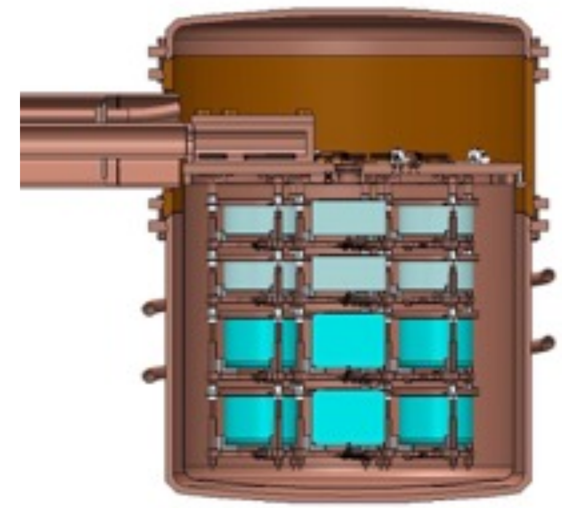
The MAJORANA DEMONSTRATOR

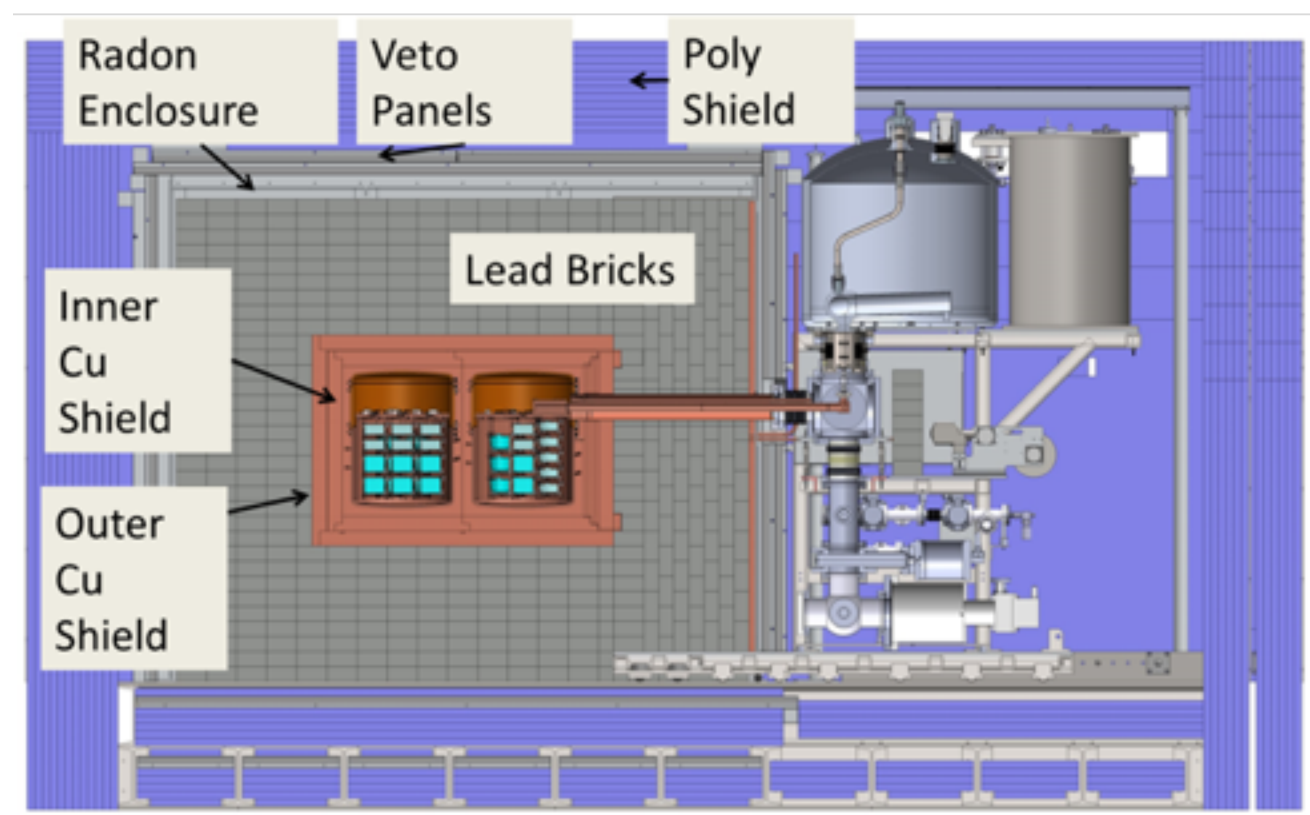


Funded by DOE Office of Nuclear Physics and NSF Particle Astrophysics,
with additional contributions from international collaborators.

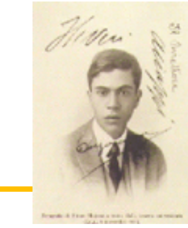
Goals: - Demonstrate backgrounds low enough to justify building a tonne scale experiment.
- Establish feasibility to construct & field modular arrays of Ge detectors.
- Searches for additional physics beyond the standard model.



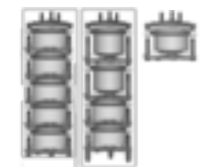
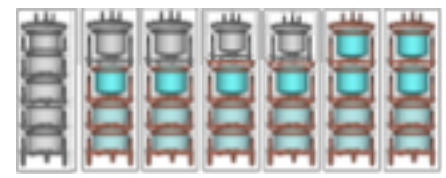
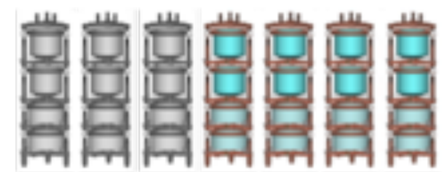
- **Located underground at 4850' Sanford Underground Research Facility**
- **Background Goal in the 0νββ peak region of interest (4 keV at 2039 keV)**
  3 counts/ROI/t/y (after analysis cuts) **Assay U.L. currently ≤ 3.5**
  scales to 1 count/ROI/t/y for a tonne experiment
- **44 kg of Ge detectors**
  – 29 kg of 87% enriched ^{76}Ge crystals
  – 15 kg of ^{nat}Ge
  – Detector Technology: 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

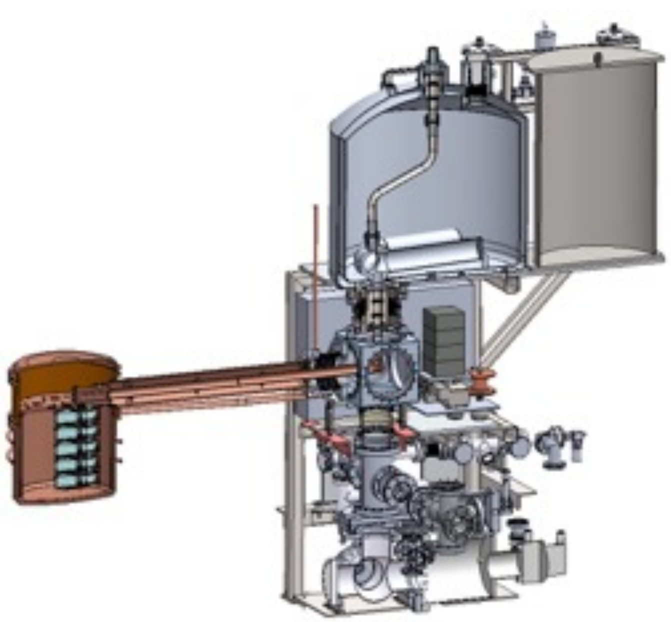


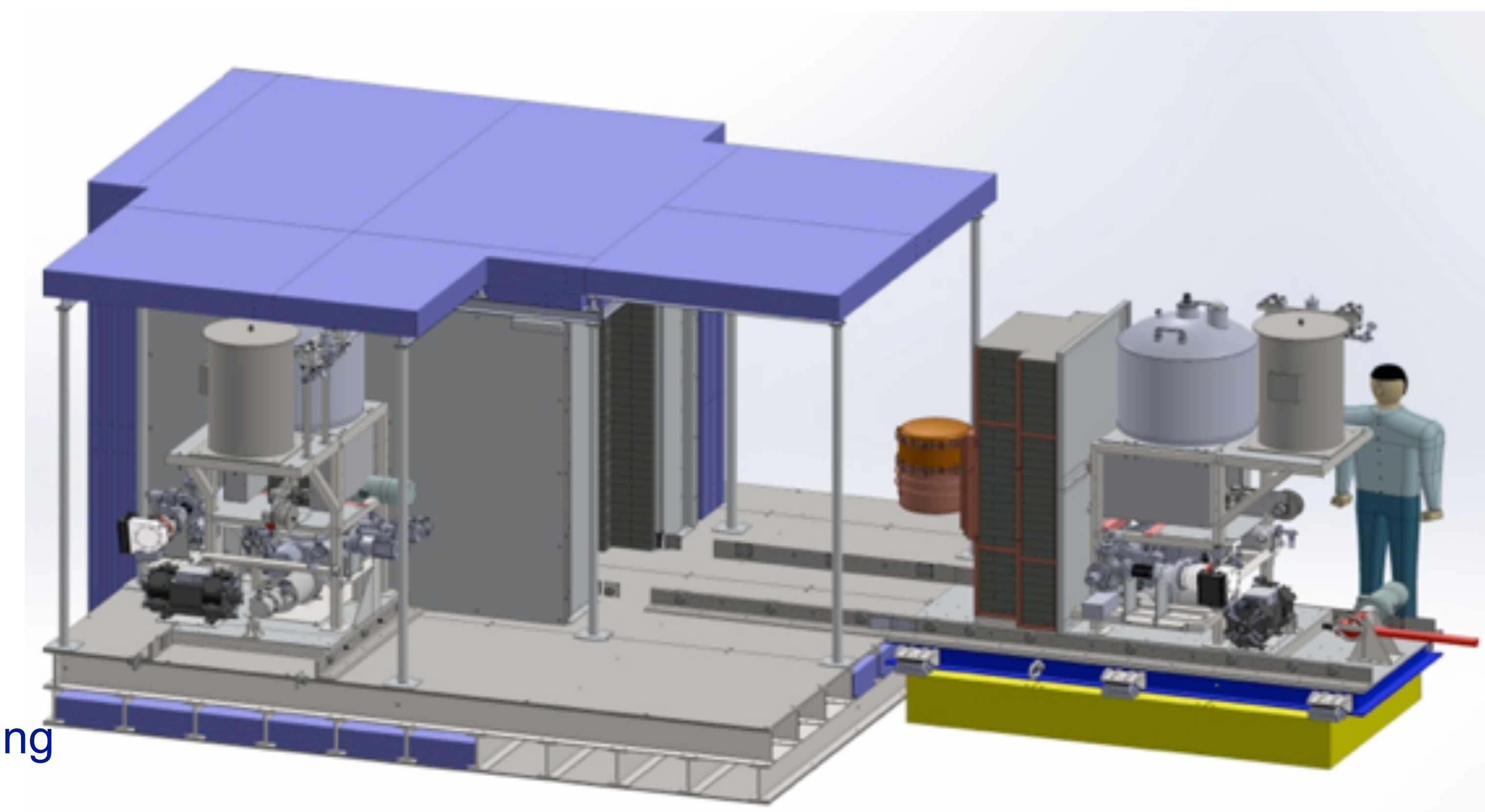
MJD Implementation



- Three Steps

		Commissioning start (Estimated)	In Shield (Estimated)
– **Prototype Module*** : 7.0 kg (10) ^{nat}Ge 3 strings		Nov. 2013	June 2014
– **Module 1** : 16.8 kg (20) ^{enr}Ge, 7 strings 5.7 kg (9) ^{nat}Ge		Sept. 2014	May 2015
– **Module 2** : (12.2 kg (14) ^{enr}Ge, 7 strings 9.4 kg (15) ^{nat}Ge)		(Sept. 2015)	(End 2015)

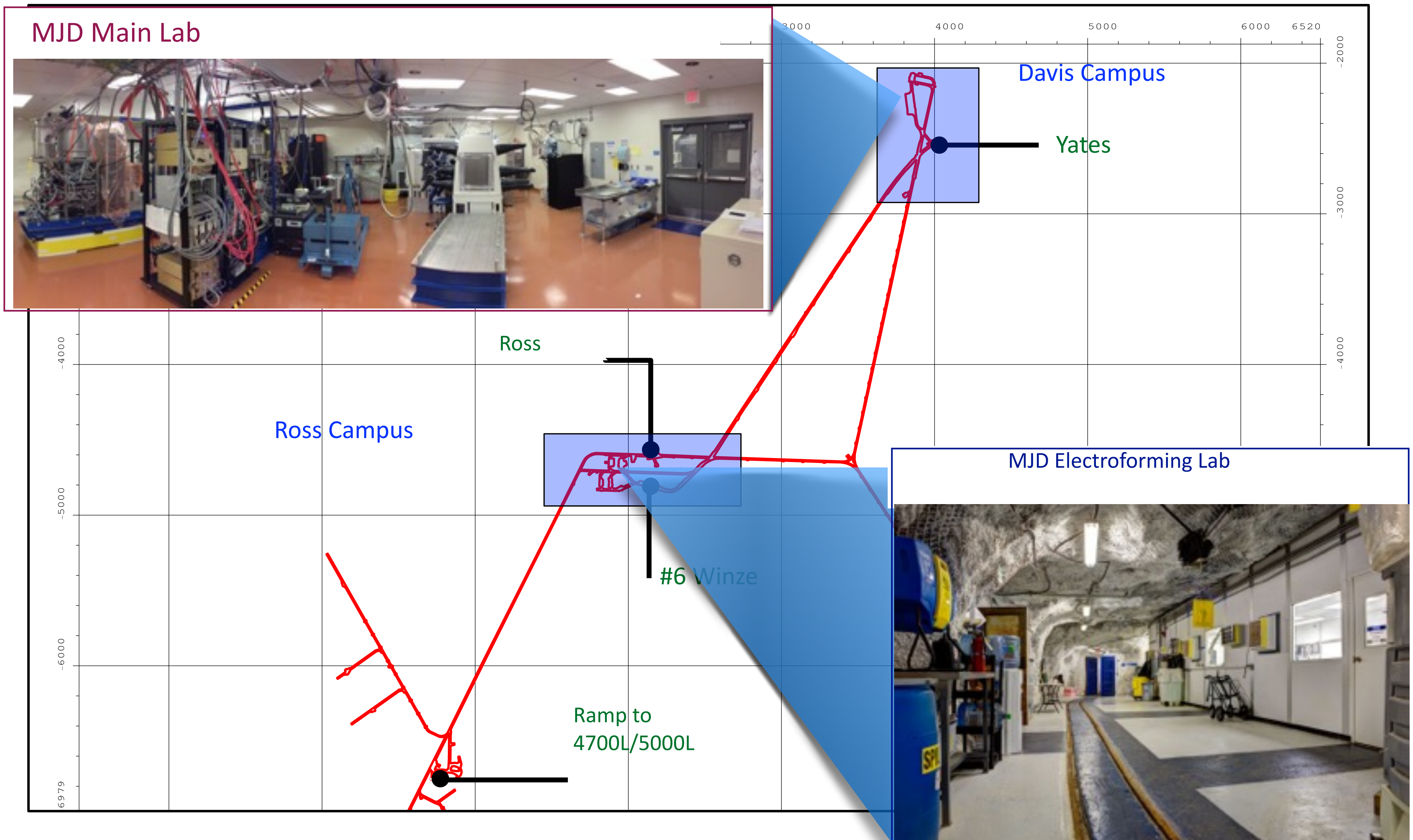




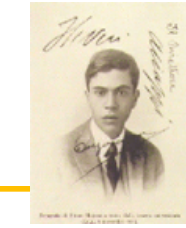
* Same design as Cryos 1 & 2, but fabricated using OFHC Cu (non-electroformed) components.

MJD underground facilities

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



MJD Electroformed Cu

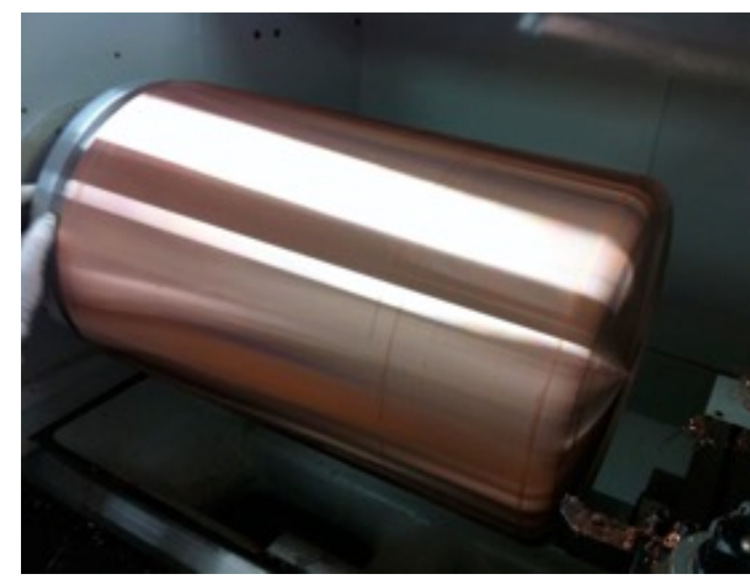


- MJD operated 10 baths at the Temporary Clean Room (TCR) facility at the 4850’ level and 6 baths at a shallow UG site at PNNL. All copper was machined at the MJD Davis campus.
- The electroforming of copper for the DEMONSTRATOR successfully completed in April 2015.
  - 2474 kg of electroformed copper 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 MJD and for other experiments.
- Based on a very recent positive evaluation of the ground support at the TCR we are evaluating continuing electroforming at the TCR or moving to the MJD Davis campus (EF Lab).

Electroforming Baths in TCR

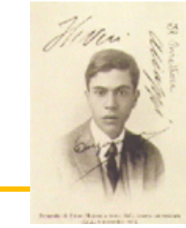
Inspection of EF copper on mandrels

EF copper after machining

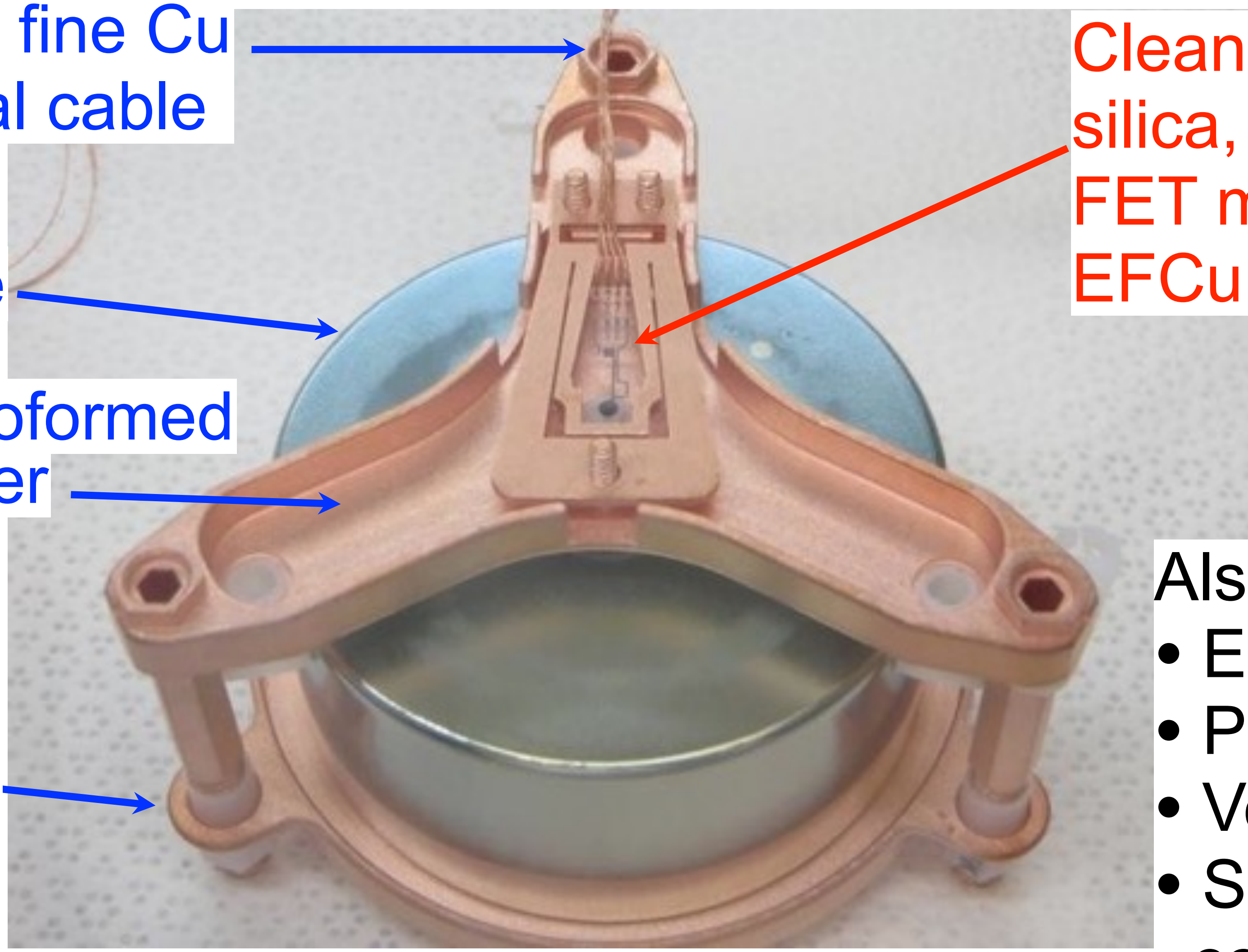


- Th decay chain (ave) ≤ 0.1 μBq/kg
- U decay chain (ave) ≤ 0.1 μBq/kg

MJD Detector Unit

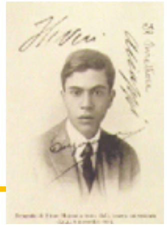


We are working with a novel palette of ultra-pure materials, while also minimizing the total amounts

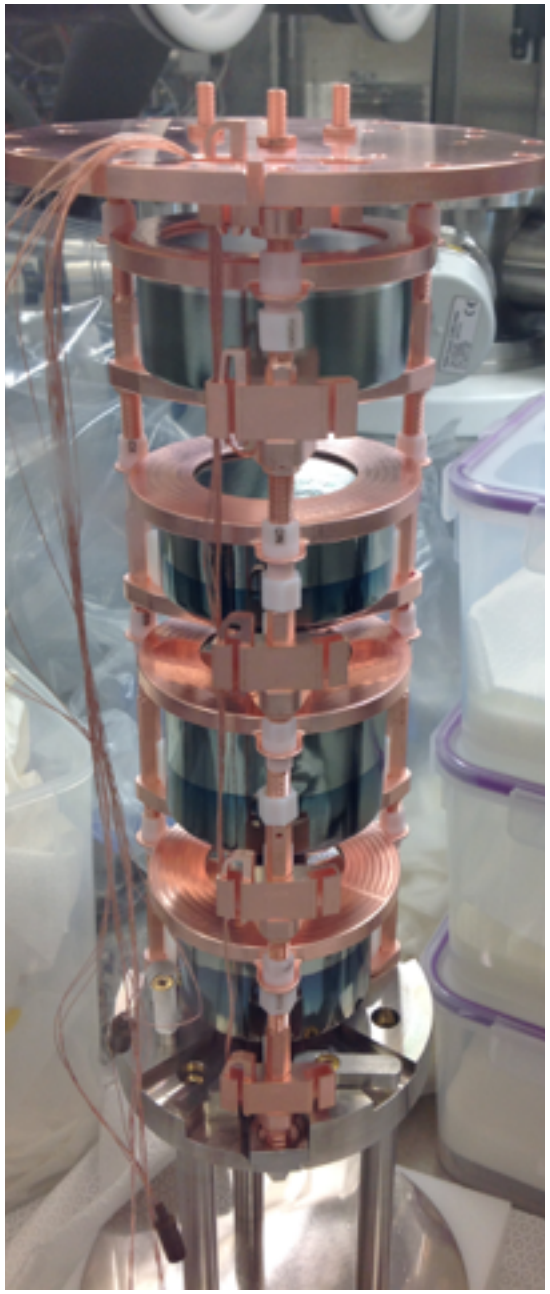


Also:
- Electroformed Cryostats
- Parylene coating / seals
- Vespel, PEEK supports
- Shields: Low-BG commercial Cu and Pb

MJD Strings

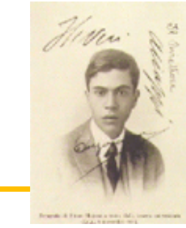


String with 3 ^{Enr}Ge PPCs and 1 ^{Nat}Ge BEGe



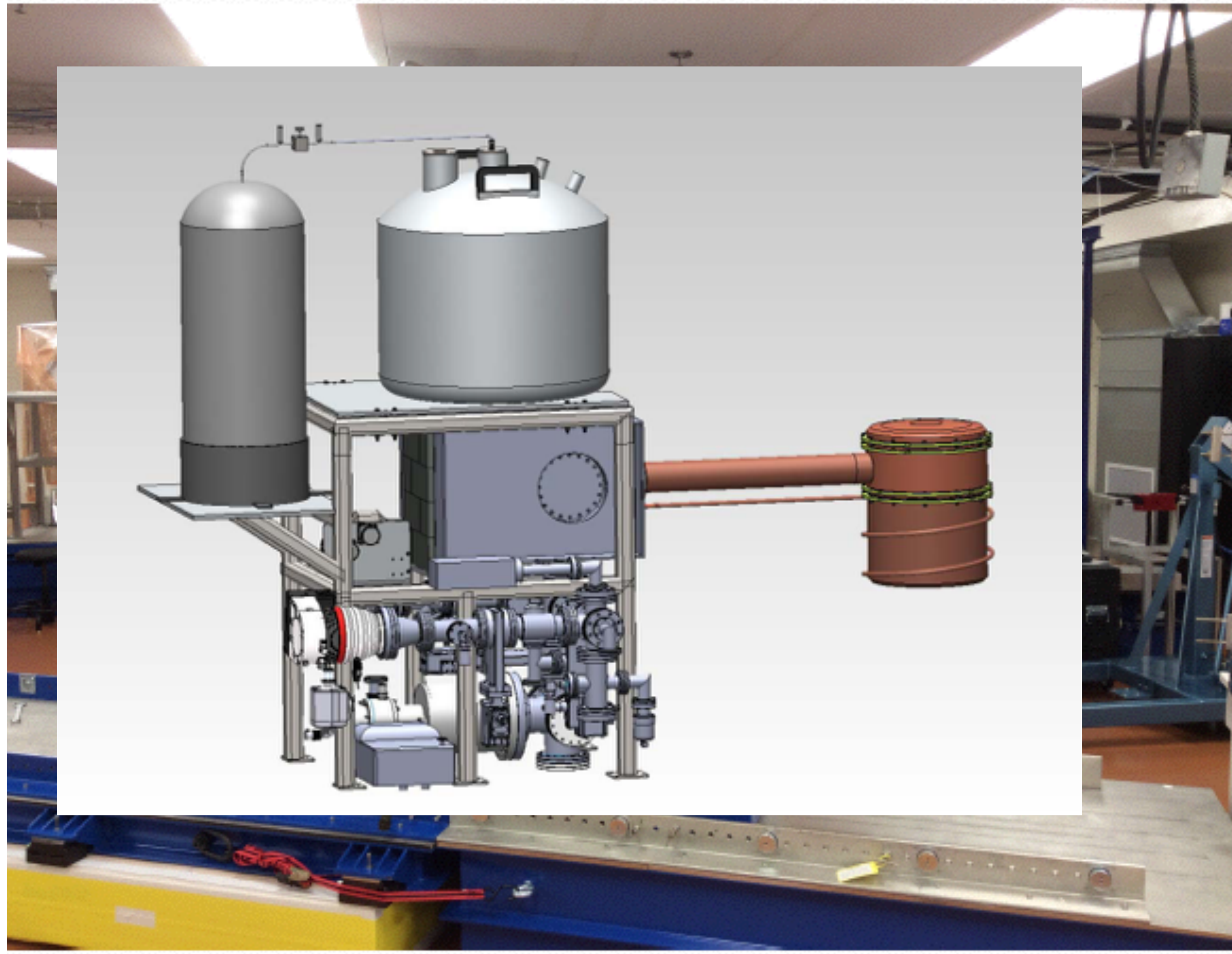
- Up to 5 detectors are mounted in 'strings'
- Strings are constructed and up to 7 loaded to the module in a nitrogen purged glovebox

Modules



A Module is:

- **Cryostat**
- **Thermosyphon,**
- **Vacuum**
- **Shield Section**
- **All resting on a movable bearing table**
- **Hov-air in routine use moving fully loaded modules**
- **Calibration system demonstrated**



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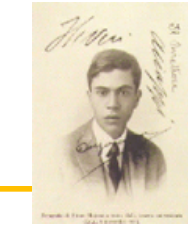
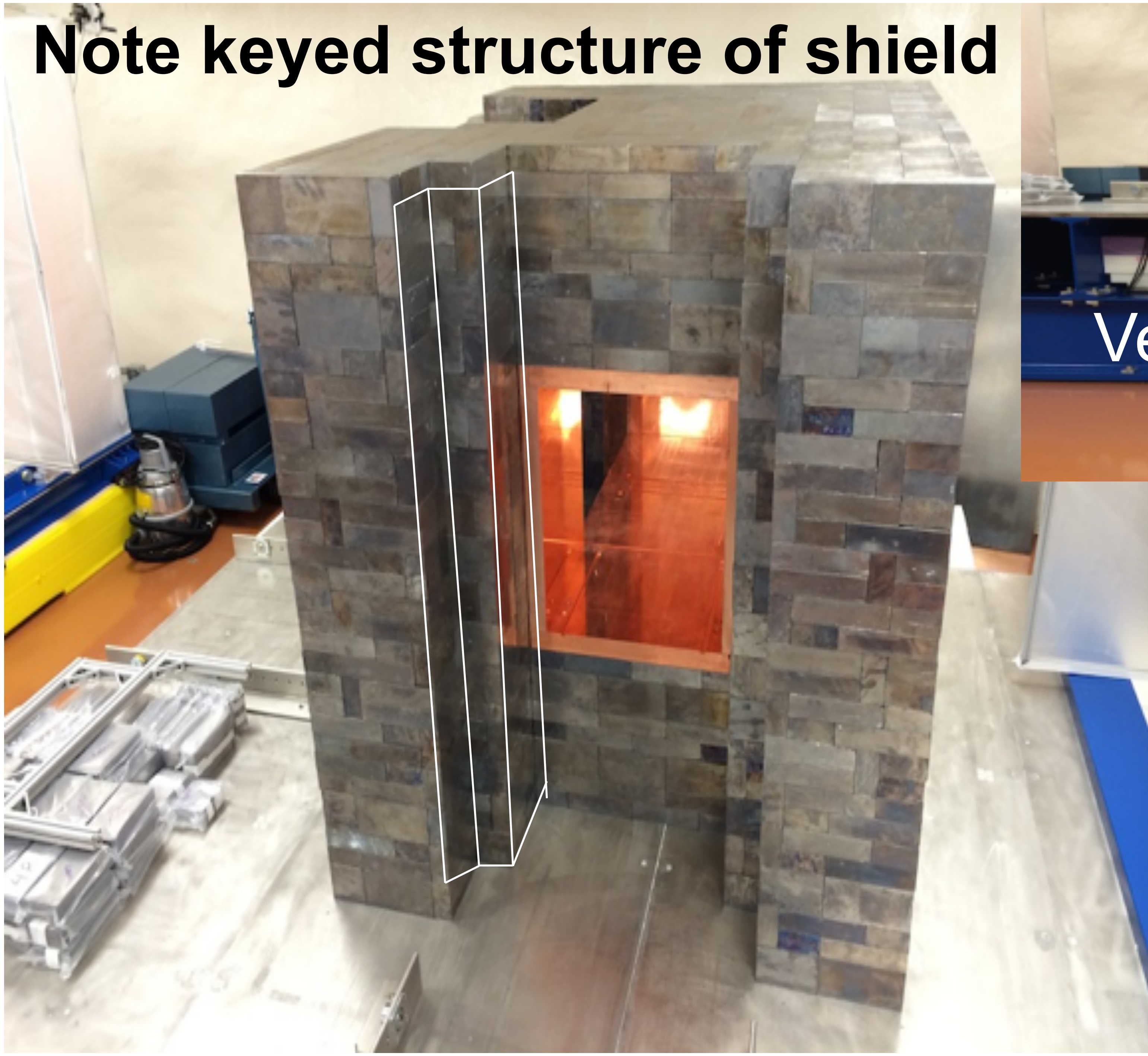
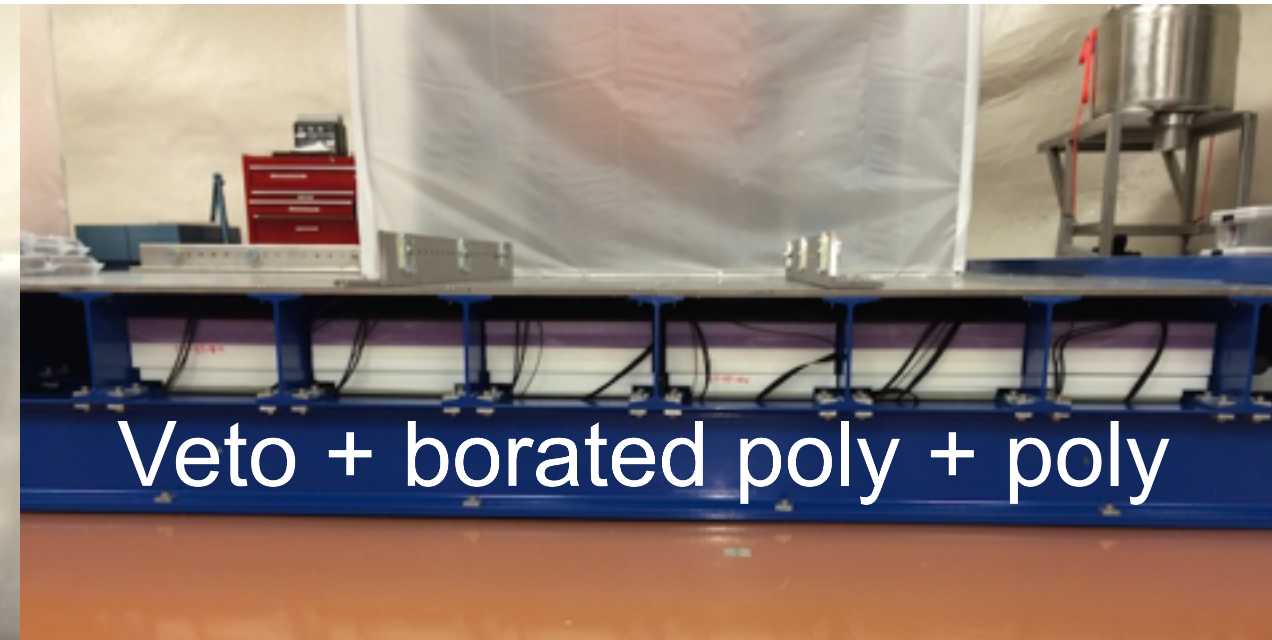
Compact Shield

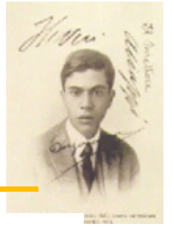






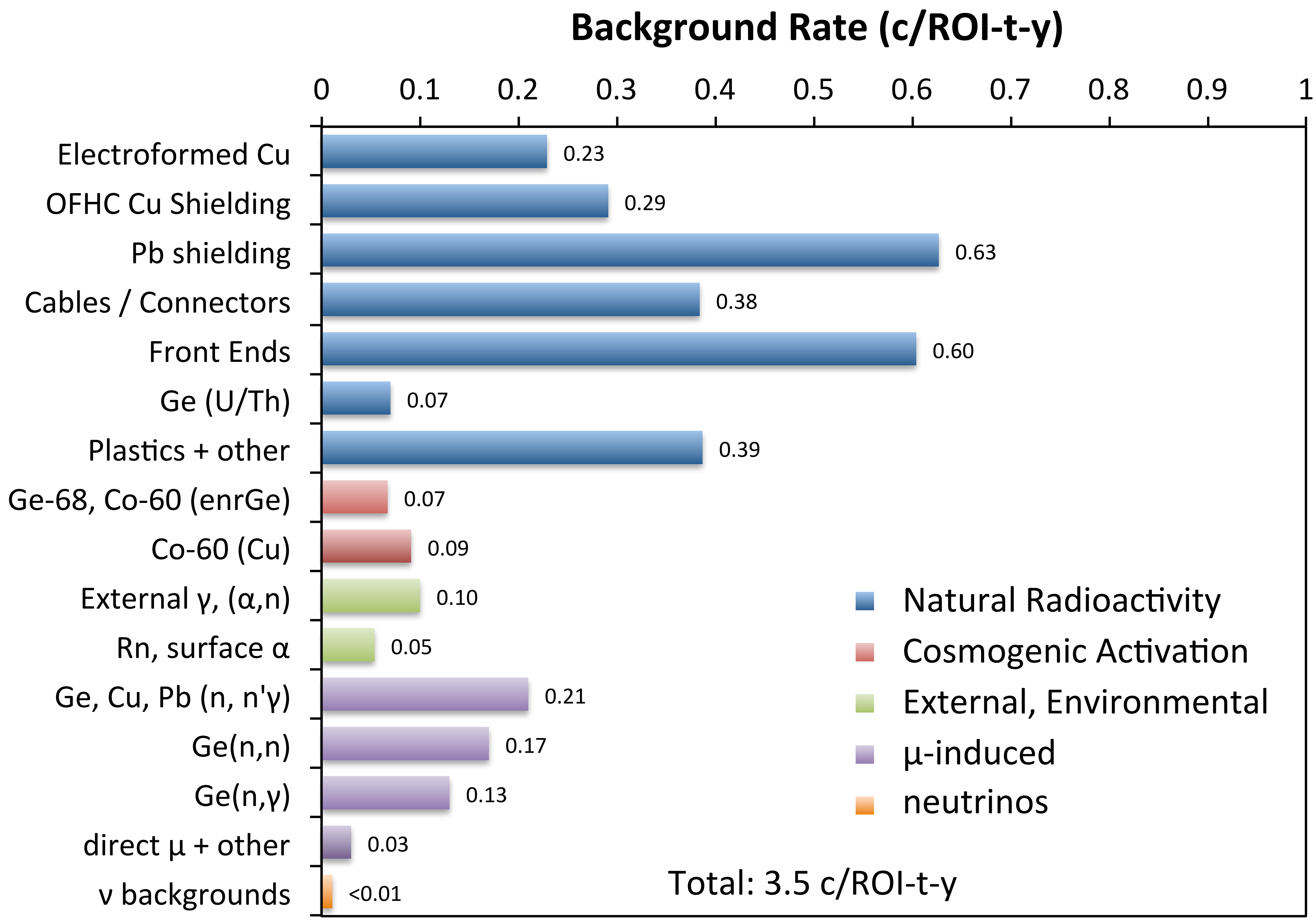
- **Pb shield constructed**
- **Outer Cu shield layer installed**
- **Rn exclusion box installed**
- **Poly layers being installed**
- **Most veto panels operational (24 of 32)**

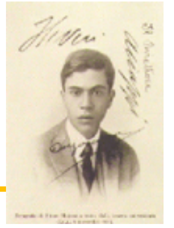
DEMONSTRATOR Background Budget



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

MJD Goal: ≤ 3.0 cts / 4 keV / t-y





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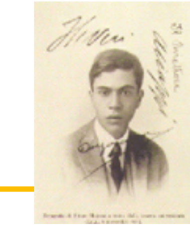
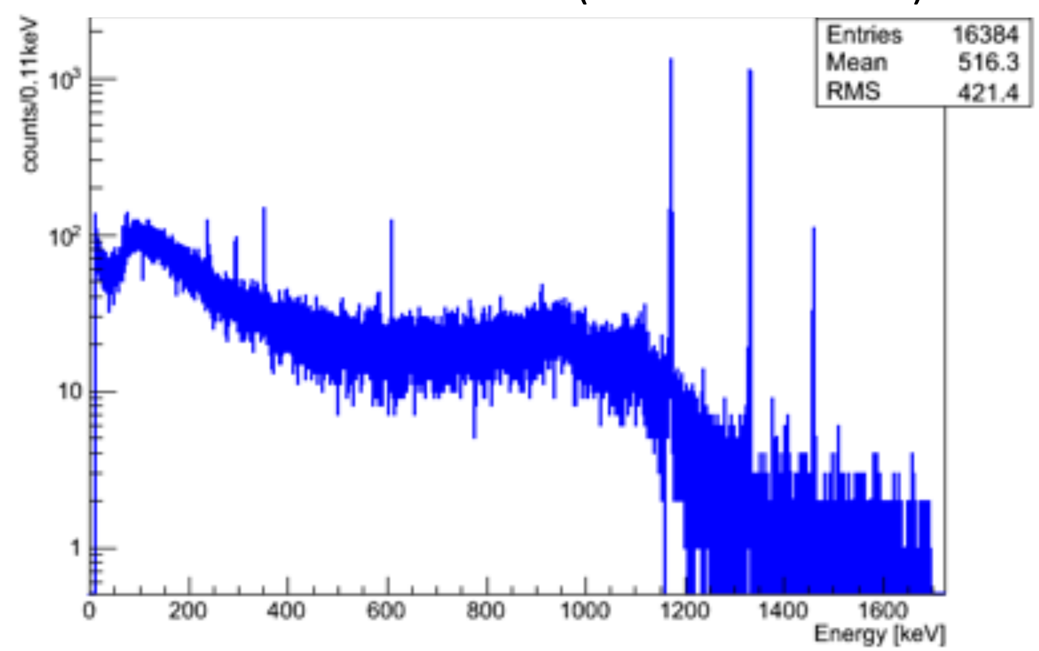
MJD Enriched Detectors



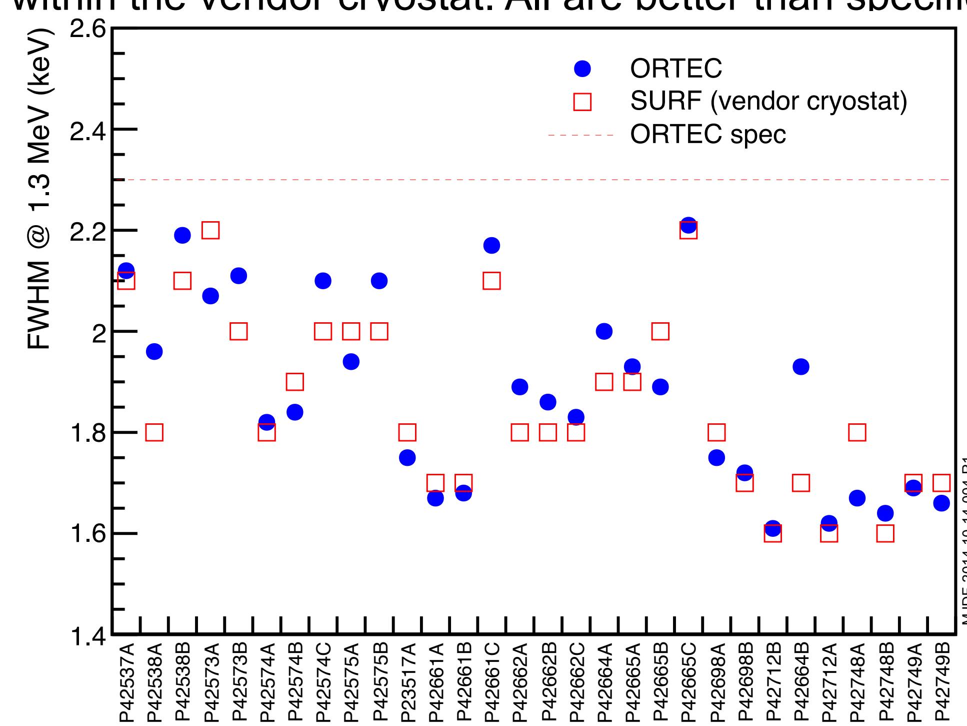
- ORTEC/AMETEK : 30 PPC detectors (25.2 kg) UG at SURF. (64% yield)
- Fabrication from Reprocessed Material (9.1 kg)
  – Produced two 4.5 kg boules
    – Two additional detectors (2 kg) January 2015
    – 2nd boule turned out to be n-type and was regrown
    – Expect three more detectors in June
- Projected enriched detectors:
  - 35 enriched PPC detectors (29.2 kg)

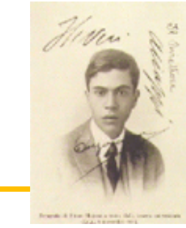
Enriched ORTEC PPC UG (60Co Calibration)



Acceptance Testing of enriched detectors UG

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



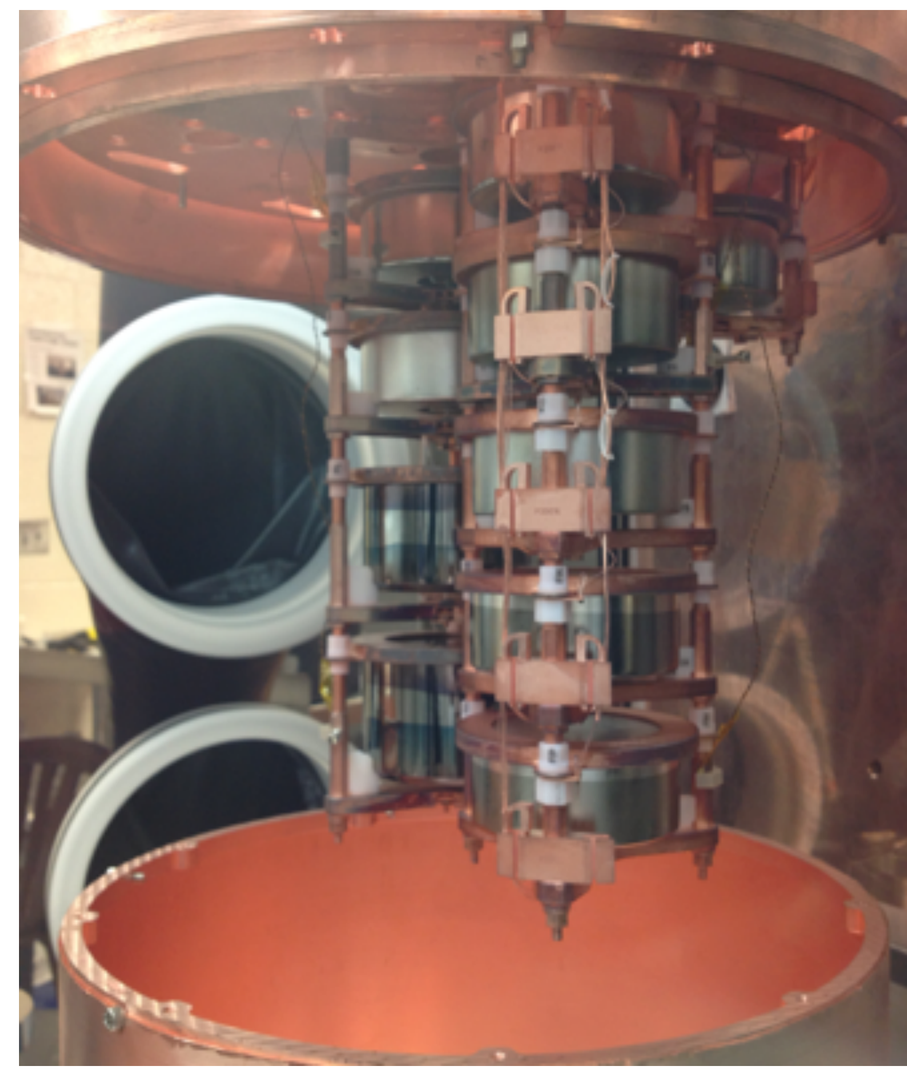


Prototype Module

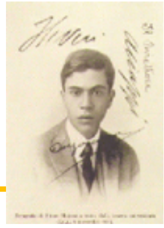
- Used for engineering and physics studies:
  cleanliness, construction procedures, DAQ, vacuum, cryogenics, etc.
- Installed and operated three strings of ^{nat}Ge detectors.
- Took data in-shield from July 2014 to June 2015, removed for Module 2 construction
- Dominant backgrounds as expected from prototyping materials:
  solder, stainless steel screws, commercial copper, etc.

Prototype Cryostat inserted into the glove box

Prototype Cryostat with three installed strings

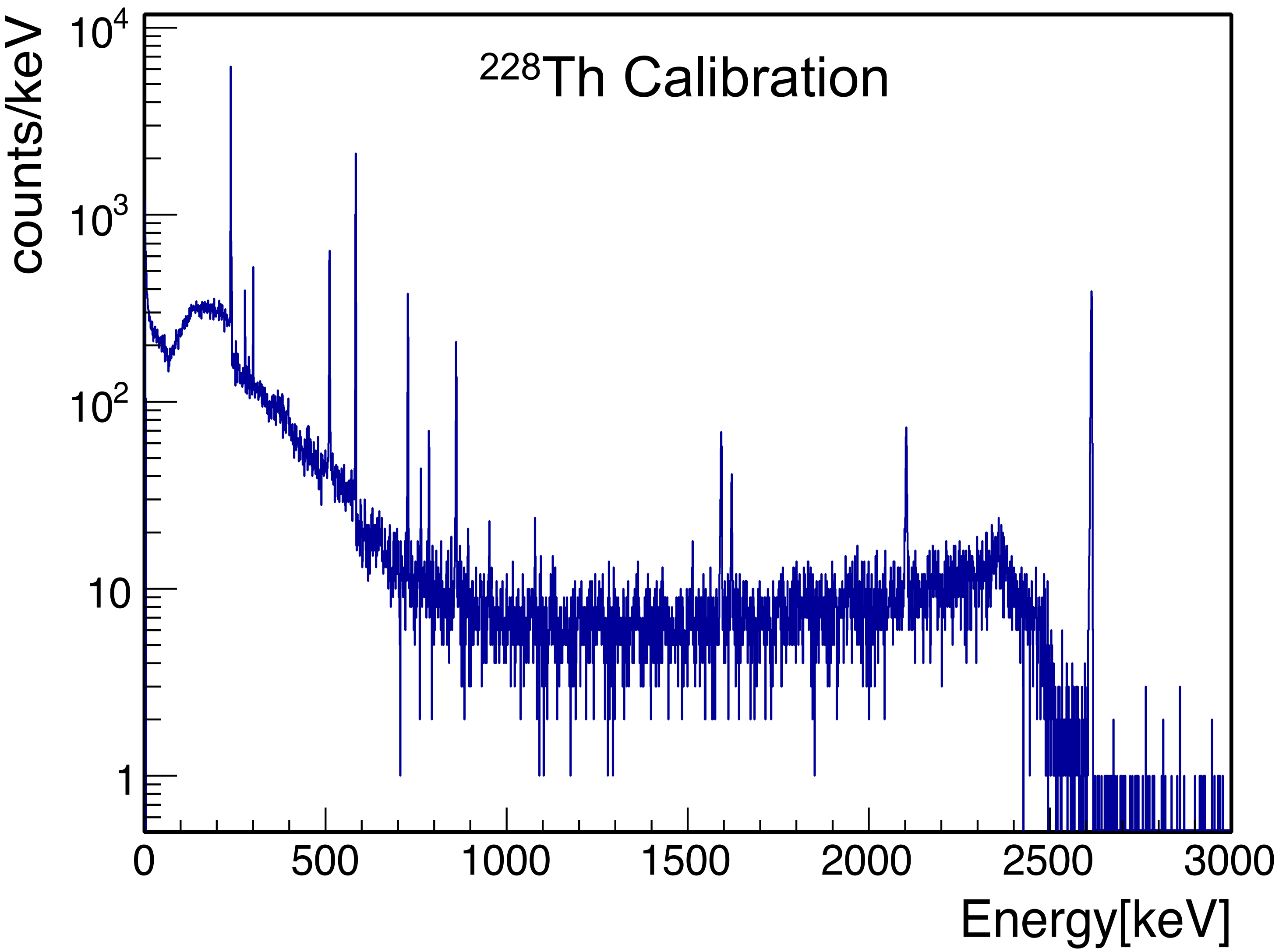


Module 1



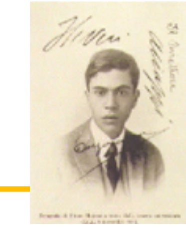
- Moved into shield end of May 2015.
- Operating 23 of 29 detectors, 14 kg enriched, 3.7 kg natural.
- Initial in-shield data taking summer 2015 followed by removal for shielding installation.

Energy Spectrum from an enriched PPC

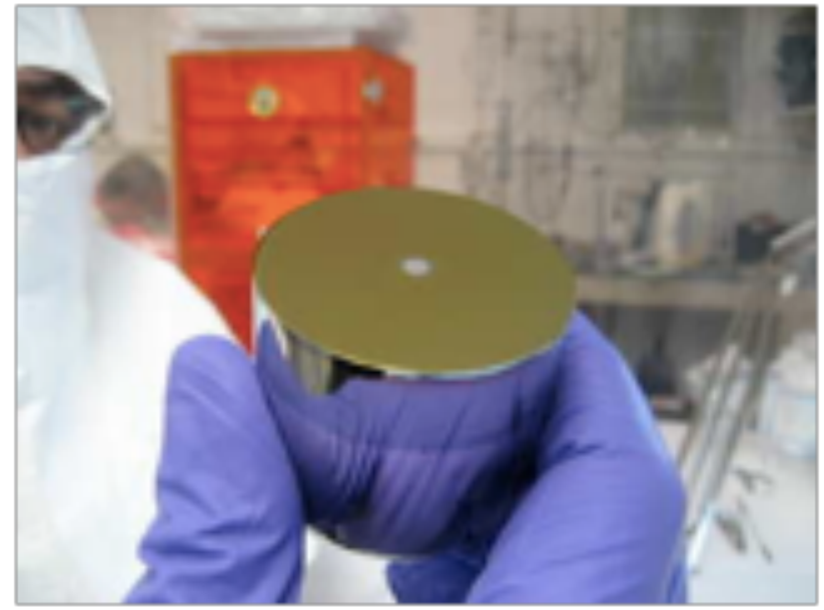


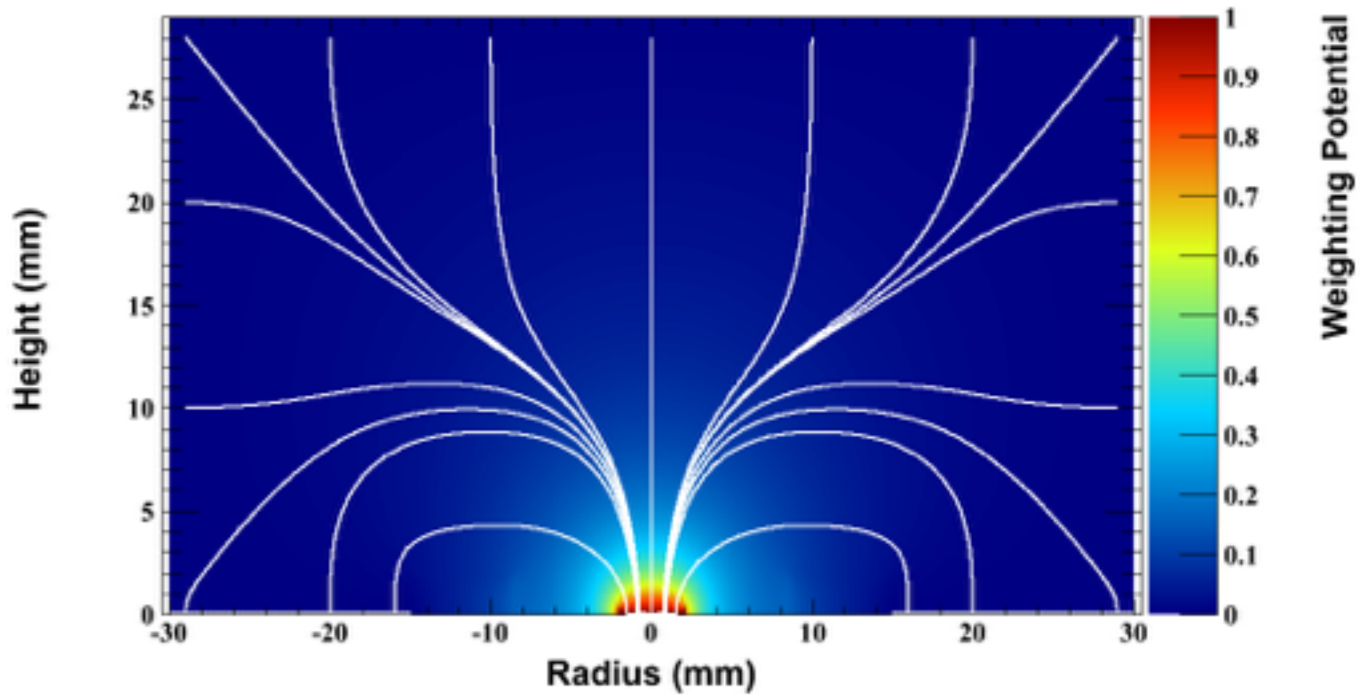
Module 1 with 7 strings installed

Other Physics with MAJORANA



- Low-E thresholds of PPC design allows for potential to cut cosmogenic backgrounds
  - **^{68}Ge—^{68}Ga time correlation cut**
- Also opens new possibilities for experiments*:
  - **WIMP Dark Matter Searches**
  - Bosonic dark matter
  - **Solar Axions**
  - Low momentum transfer neutrino-electron scattering
  - Fractionally charged Particles in cosmic-rays
  - Pauli Exclusion Principle Violation
  - Lorentz Violation
  - Electron decay
  - …
- Enrichment reduces low-E backgrounds

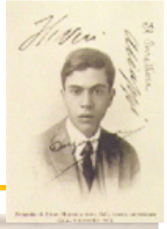




* Coherent neutrino nuclear scattering

Barbeau et al., JCAP 09 (2007) 009; Luke et al., IEEE Trans. Nucl. Sci. 36, 926(1989).

Acknowledgements



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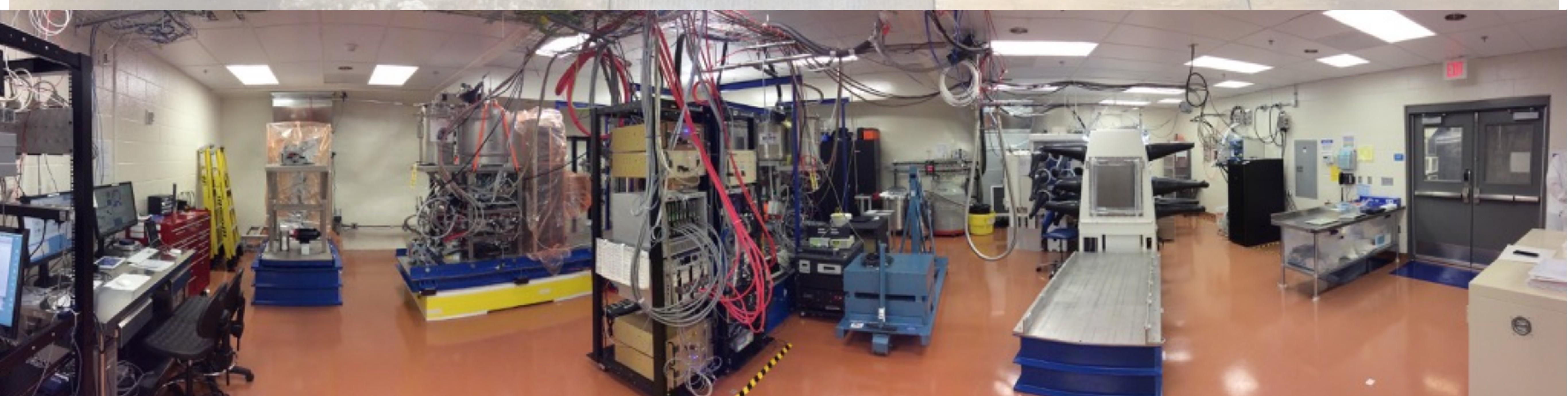
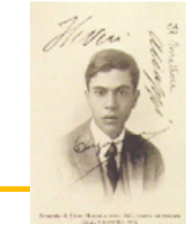
MAJORANA DEMONSTRATOR Summary

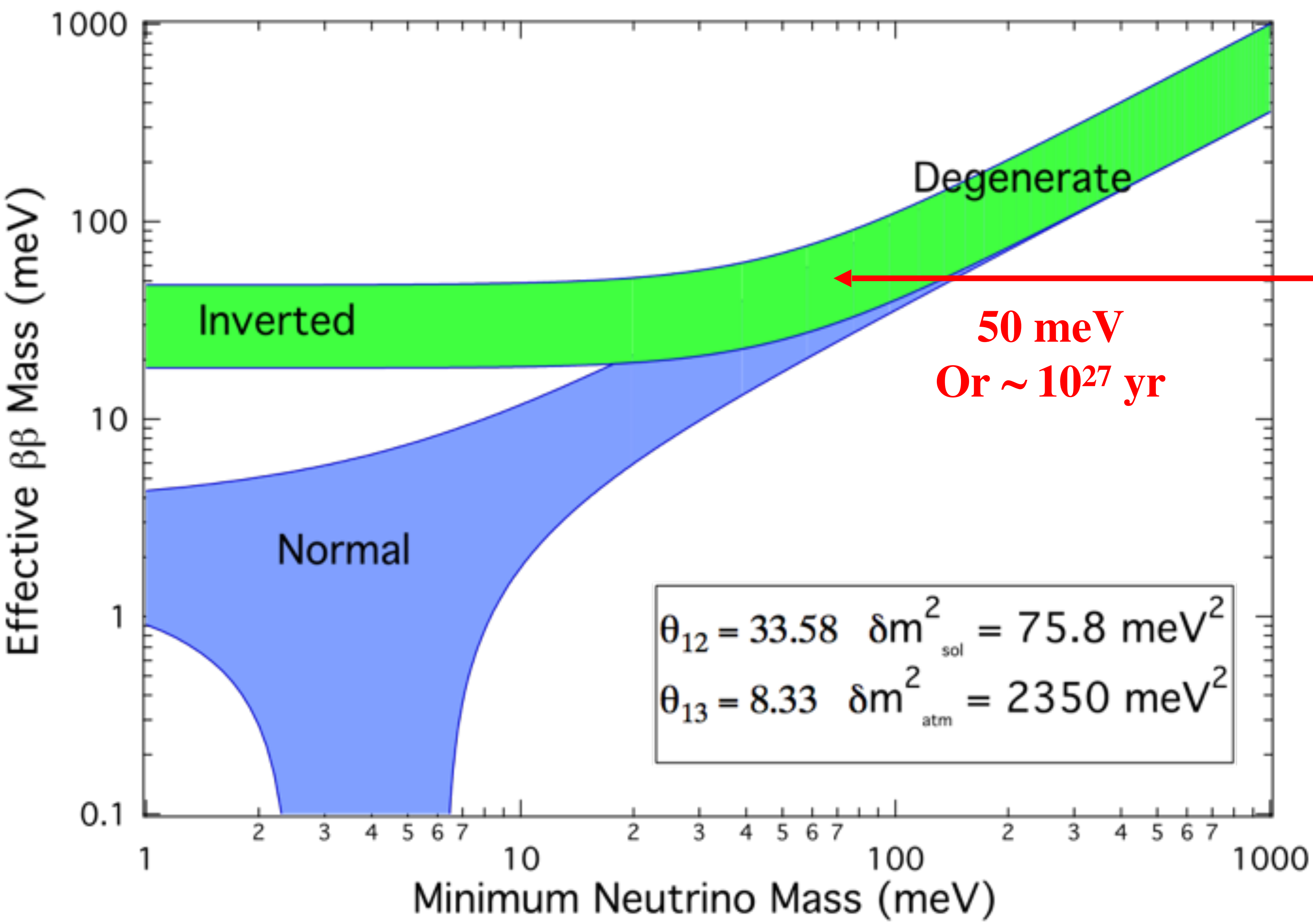
- Copper electroforming for MJD is completed.
- Detector production completed, including extra production from reprocessed materials.
- From assays, background budget projects to:
  < 3.5 counts/4 keV/t-y, close to the original MJD goal of 3.
- Prototype Module successfully completed its mission in June 2015.
- Module 1: First low background module containing enriched detectors, deployed in-shield late May 2015.
- Commissioning and engineering runs for Module 1 have started.
- Staging for Module 2 assembly has begun.



Supporting Slides

0νββ Sensitivity

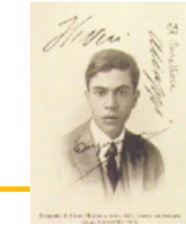




Even a null result will constrain the possible mass spectrum possibilities!

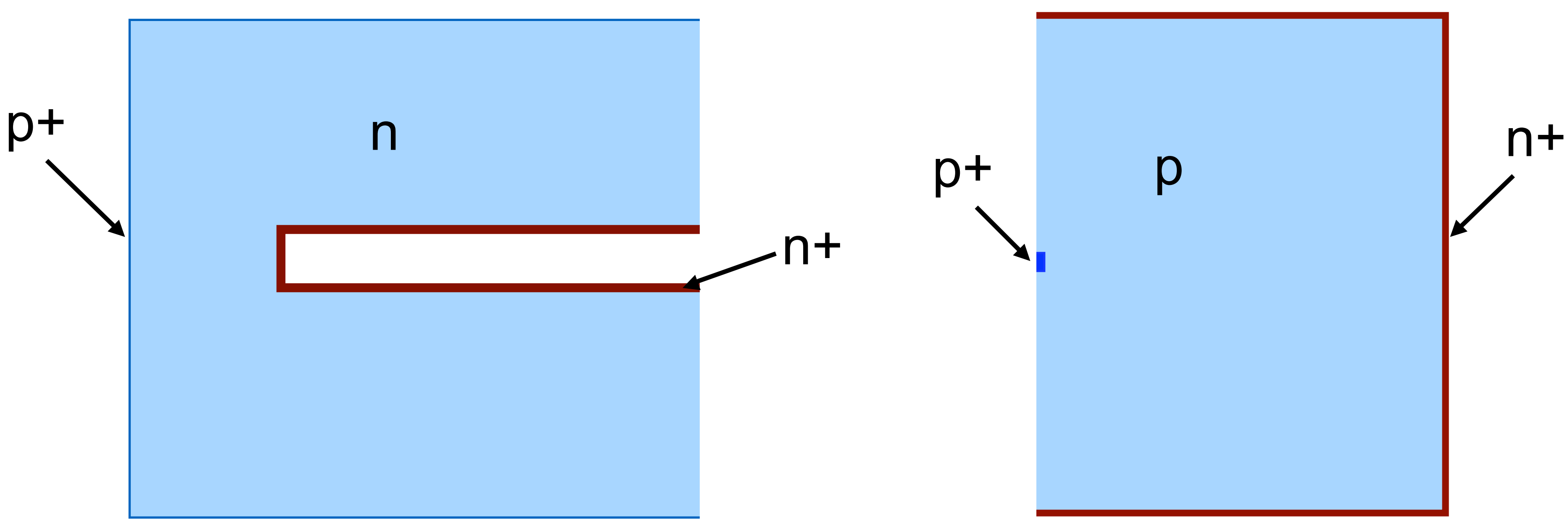
A $m_{\beta\beta}$ limit of ~15 meV would disfavor Majorana neutrinos in an inverted hierarchy.

Point Contact Detectors (PPC)



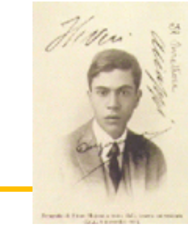
Luke et al., IEEE trans. Nucl. Sci. 36 , 926(1989); P. S. Barbeau, J. I. Collar, and O. Tench, J. Cosm. Astro. Phys. 0709 (2007).

- Ultra-low background requires PSA rejection of multi-site gamma events
- Initially considered coaxial n-type detectors with modest segmentation
- Chose P-type Point-Contact (PPC) detectors
  - No deep hole; small point-like central contact
  - mm thick n+ outer contact
  - Localized weighting potential gives excellent multi-site rejection
  - Low capacitance (~ 1 pF) gives superb resolution at low energies



N-type Coaxial   P-type Point Contact

Point Contact Detectors (PPC)



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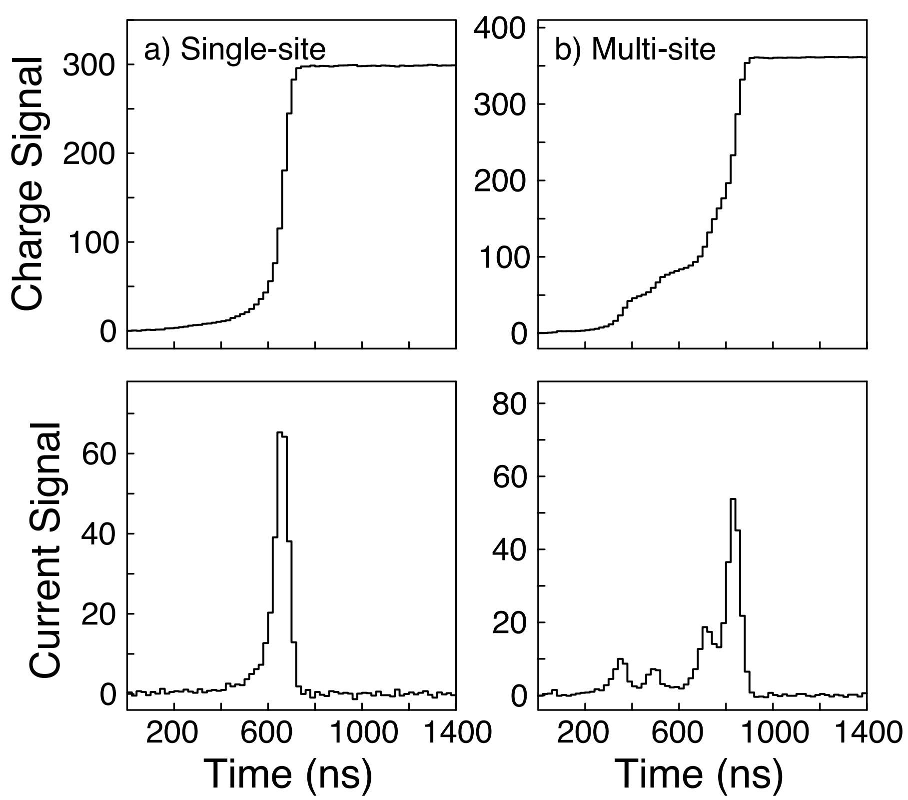
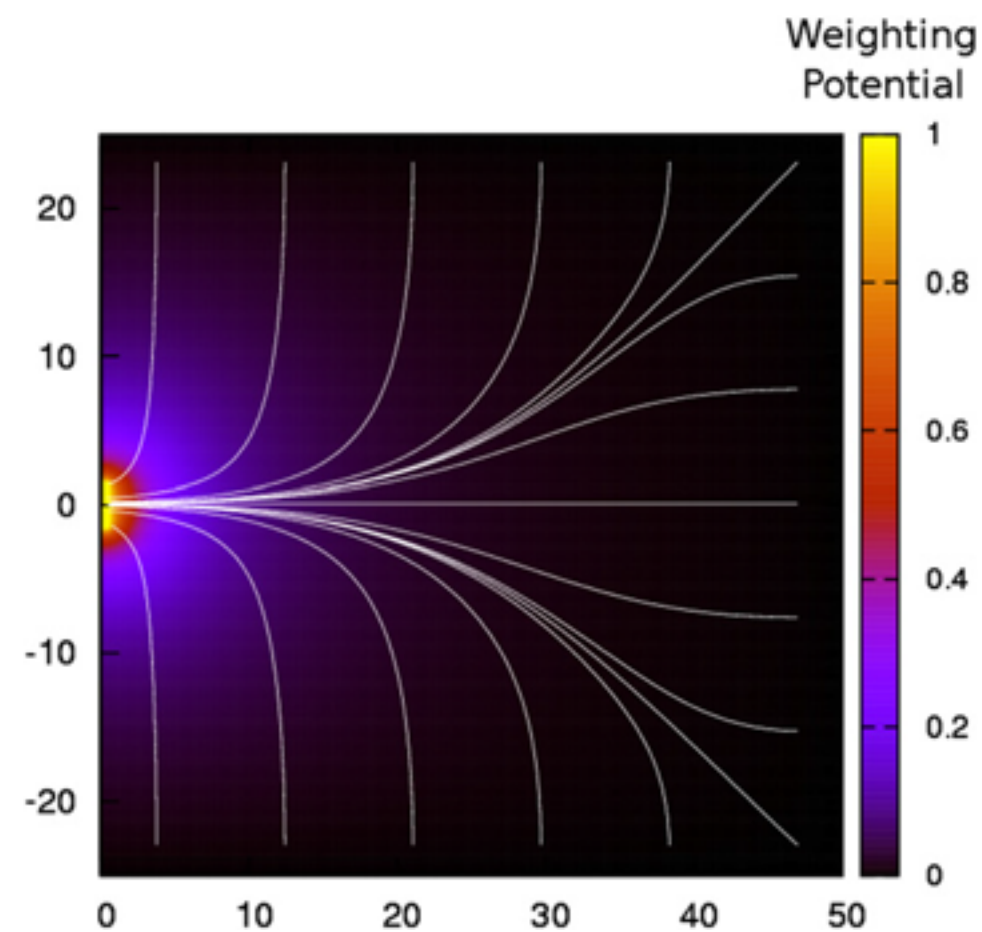
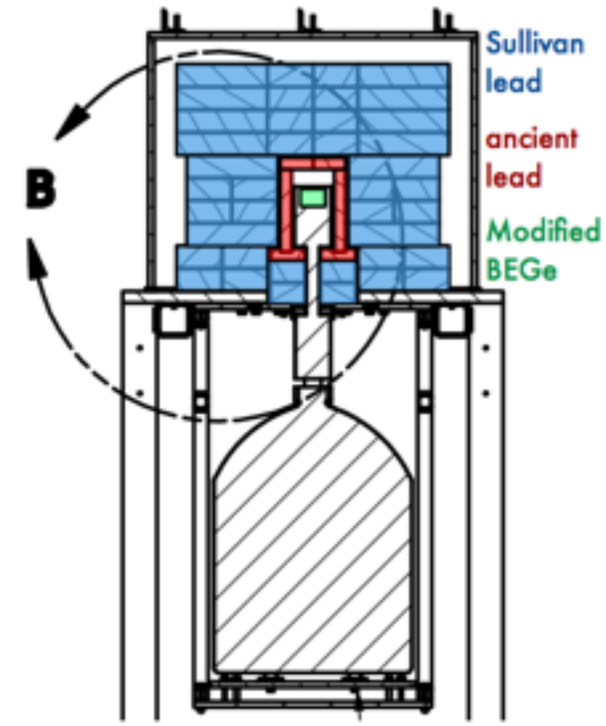


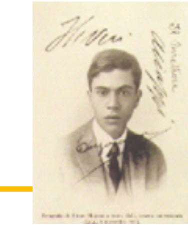


MALBEK

- (Majorana Low-background BEGe Experiment at KURF)
- MALBEK is a 450-g R&D mod.- BEGe detector, mounted in a low-background cryostat. R&D for Majorana
- MALBEK is operating since 2010 at KURF (1450 m.w.e.), located in Ripplemead, VA. Goals:
  - Systematically characterize spectrum.
  - R&D low-energy triggering and DAQ (low-energy pulses difficult to distinguish from noise).
  - R&D PSA in low-energy region
  - Background model verification
  - Dark Matter search

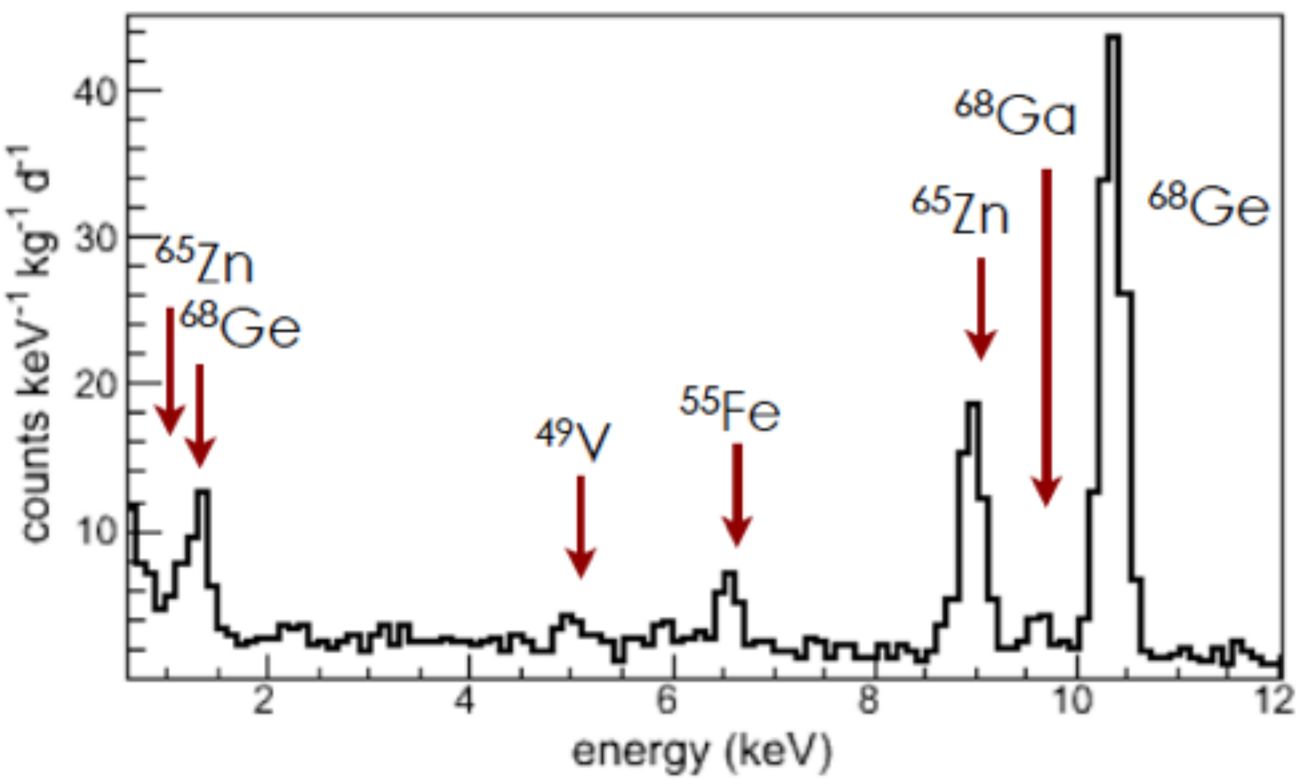


Backgrounds from Ge Crystals

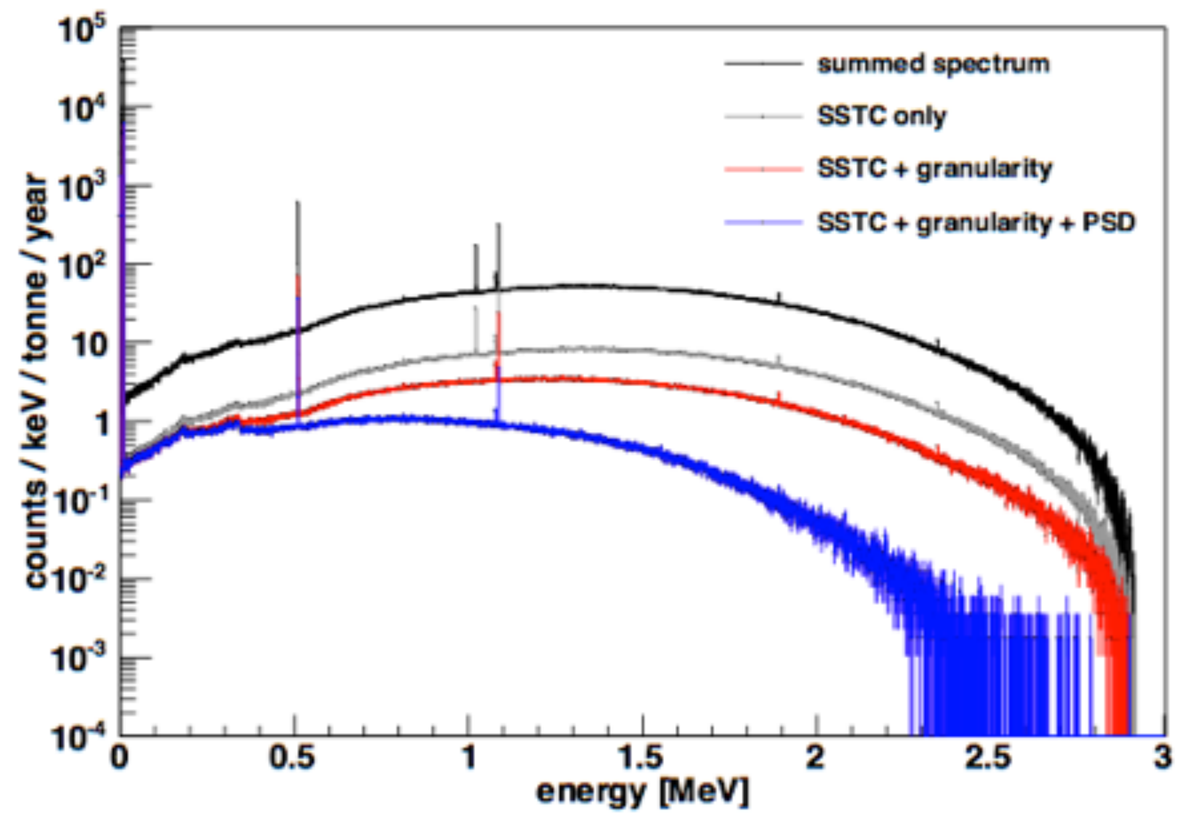


^{68}Ge(EC, $T_{1/2}$ = 270 d) → ^{68}Ga(90% 1.9 MeV β^+, $T_{1/2}$ = 68 min):

Data from MJD R&D detector - MALBEK



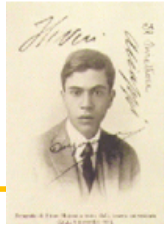
Simulations for the DEMONSTRATOR

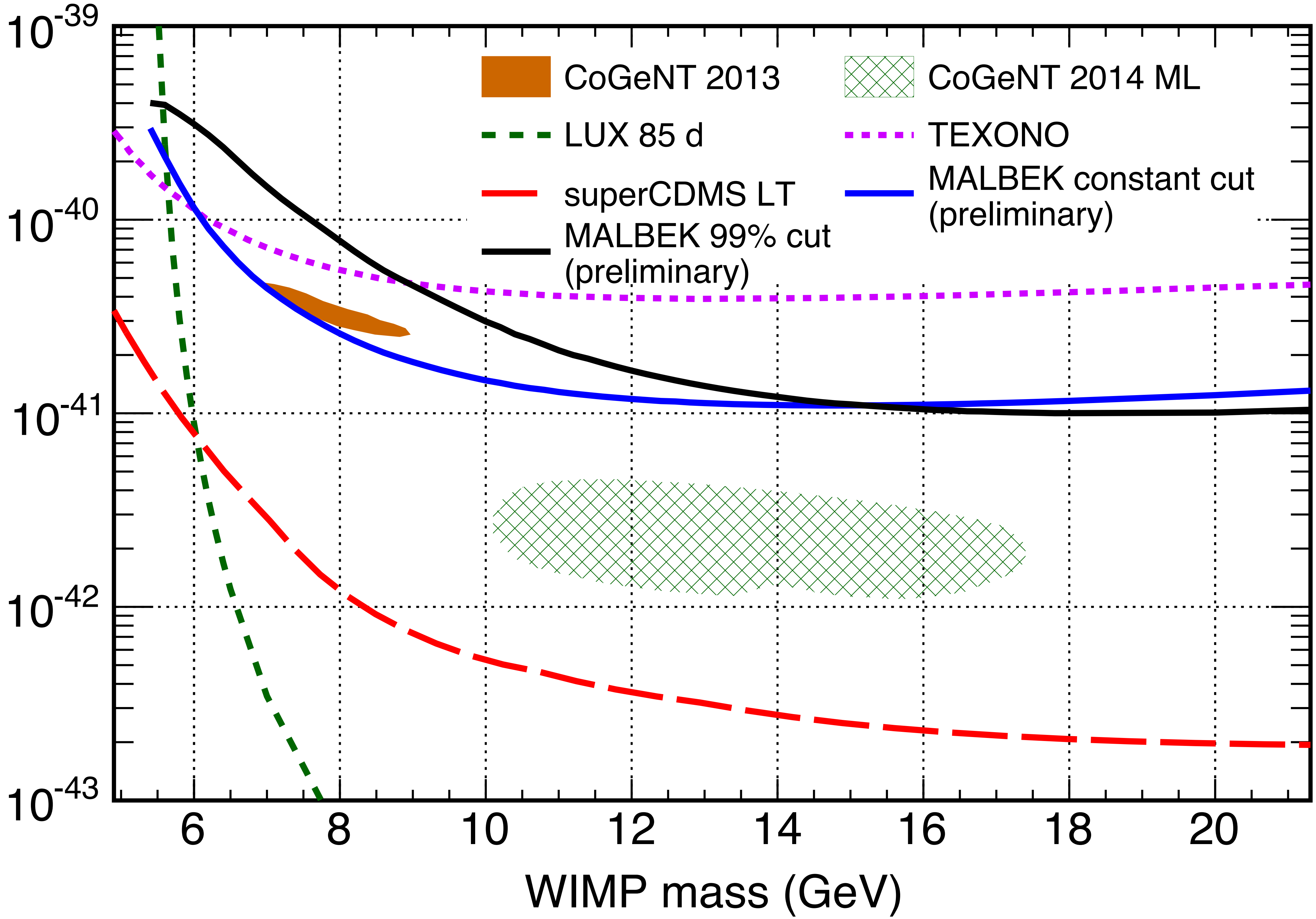


– **S**ignal **S**election in **T**ime **S**election tag ^{68}Ge decay via K-shell (~10 keV, 86.4%), L-shell (~1 keV, 11.5%) de-excitations

  – If one observes ^{68}Ge decay in a detector veto for several half-lives

90% Confidence Limit

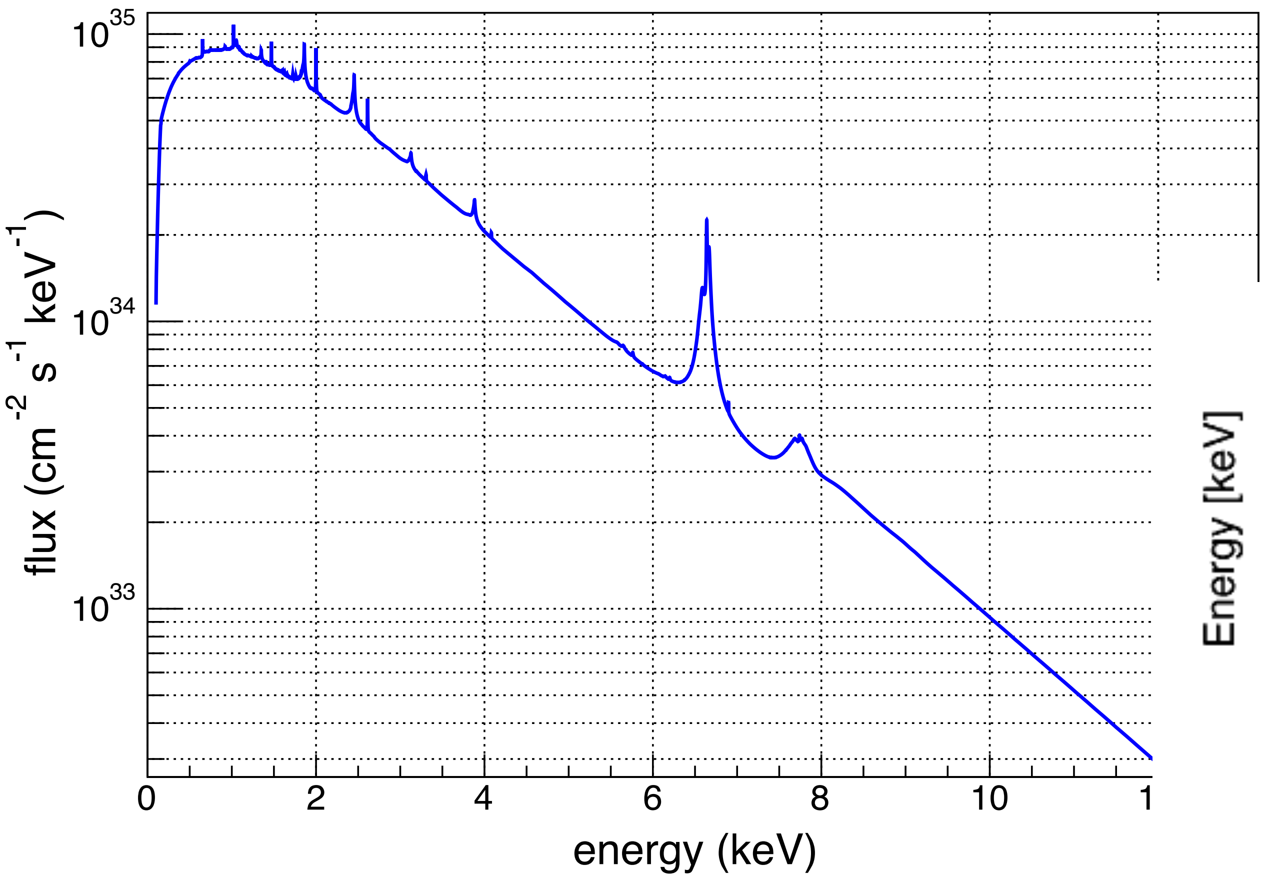




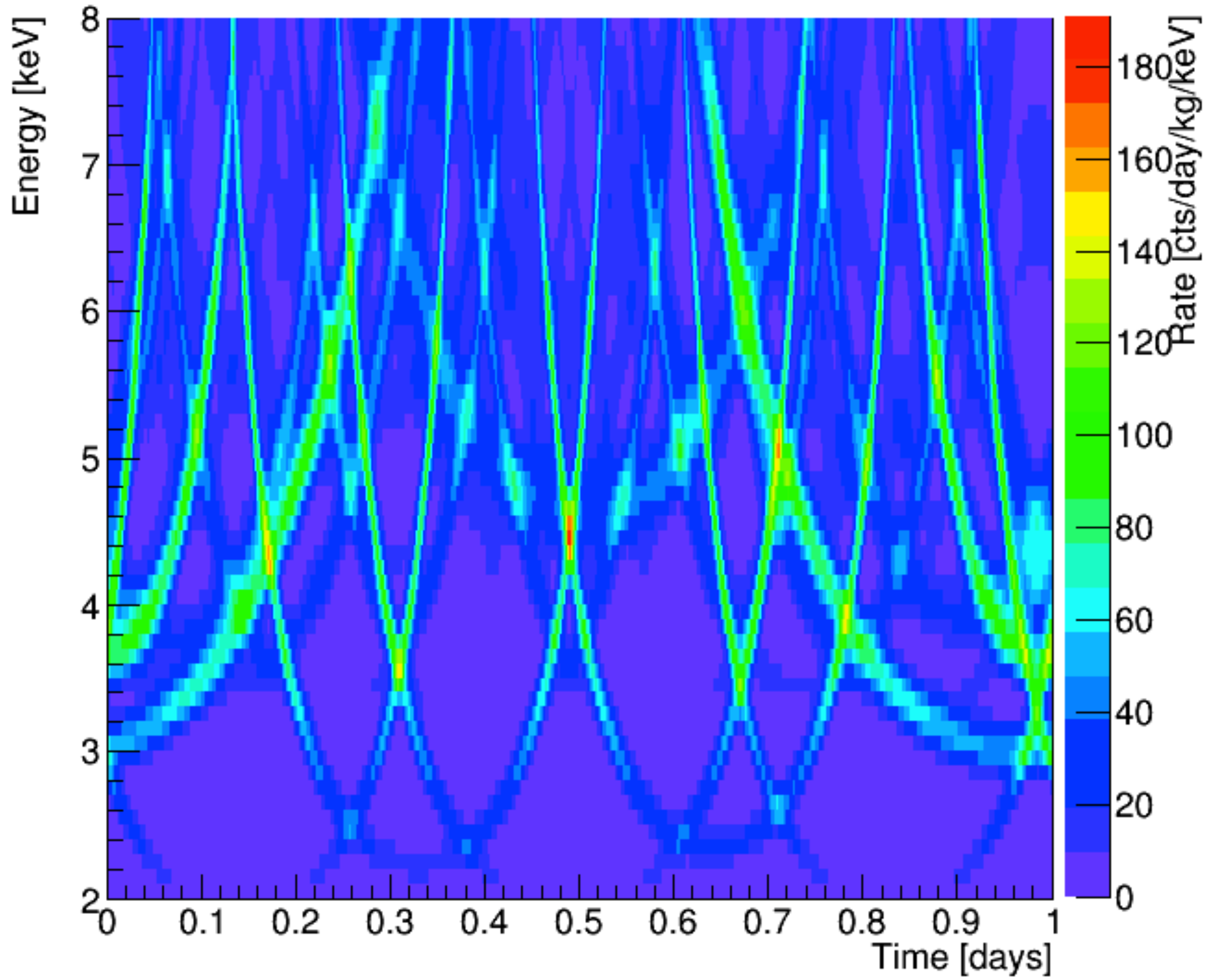
Solar Axions

J. Redondo,

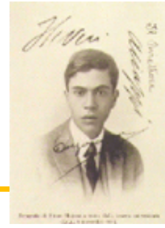
J. Cosmol. Astropart. Phys. 2013 no. 12, (2013) 008



- Solar axions are converted to x-rays in the detector — Primakoff effect



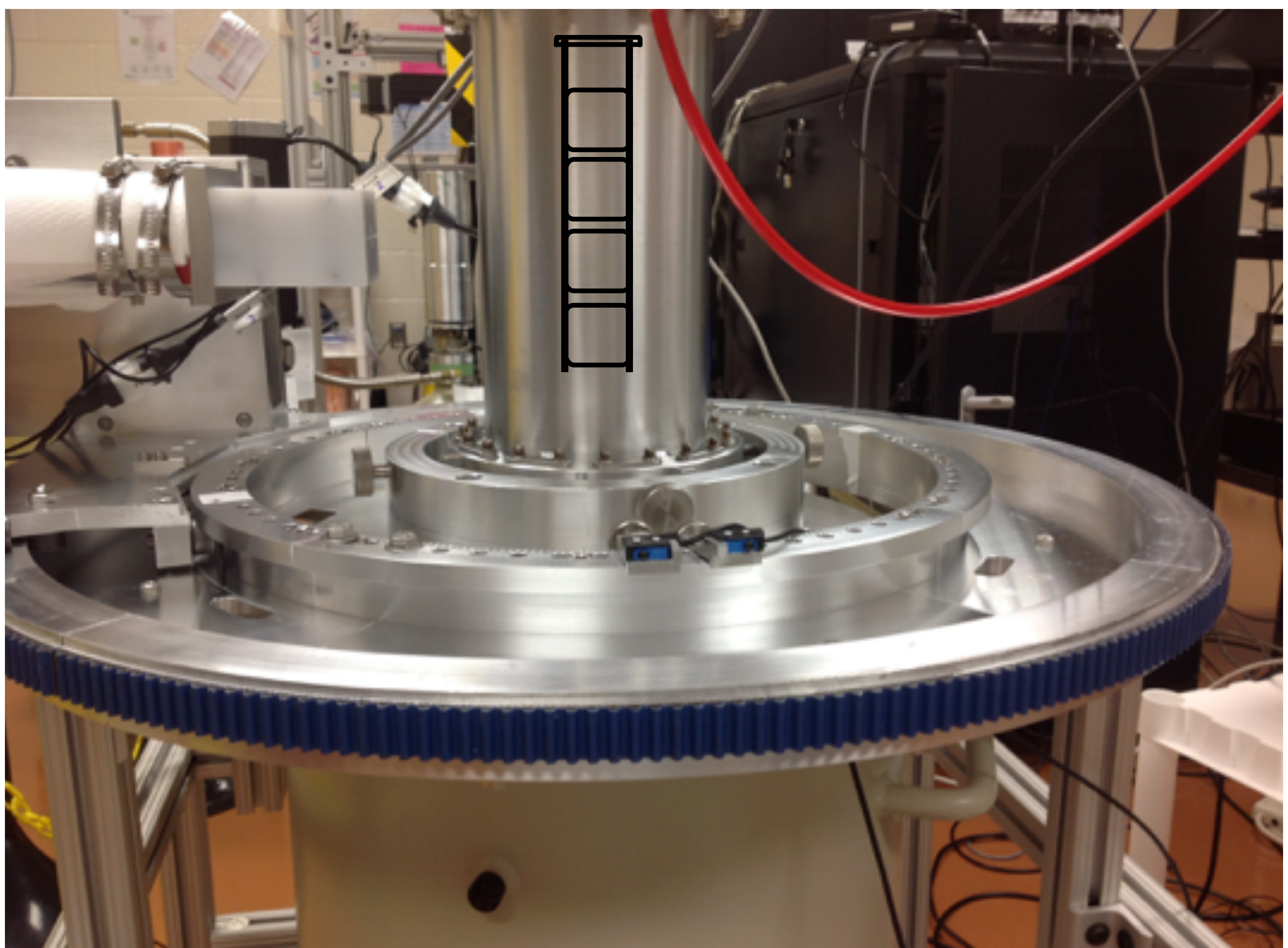
- Rates vary as the bragg conditions from the solar position

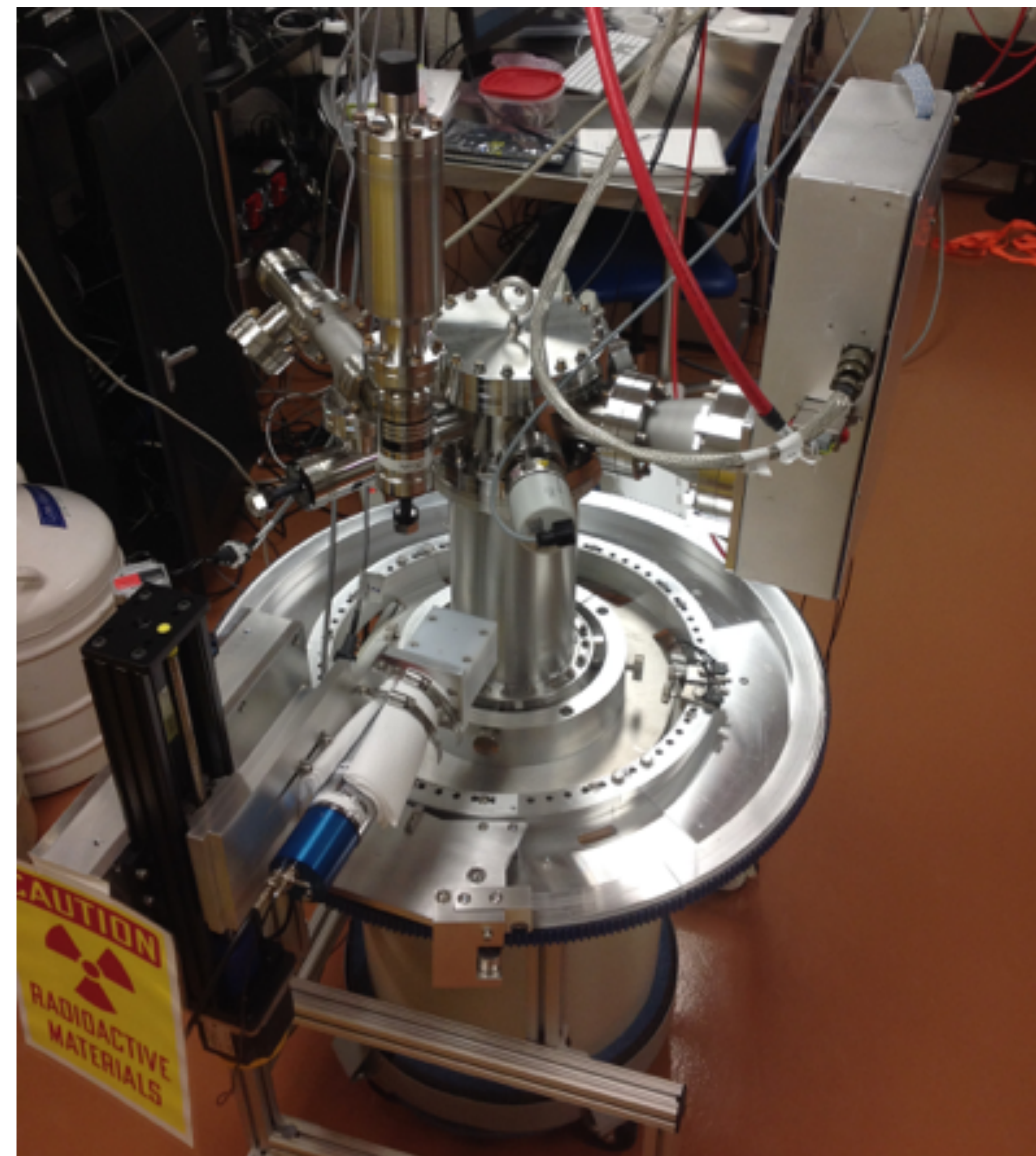


MJD String Characterization

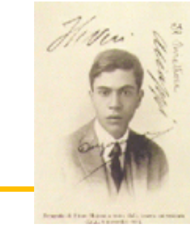
- String Performance and Characterization
- Study drift times using ^{133}Ba — utilizing 356 keV and 81 keV coincidences
- PSA efficiency as a function of position

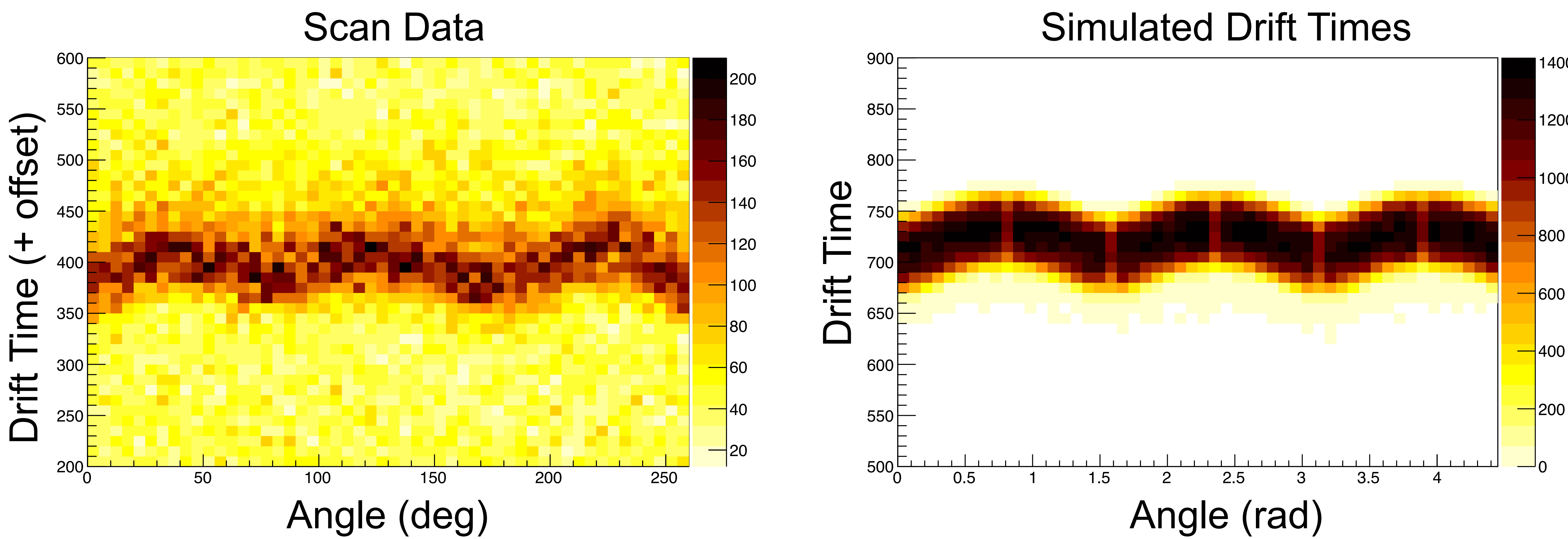
Azimuthal Scanning Table





Crystal Axis Measurements





- Using Pulse Shape Simulation as a template can extract crystal axis from automated ^{133}Ba scan data
- Still must minimize dataset and angular uncertainty
- Work on implementing in string test cryostat
- Plan to characterize a subset of detectors