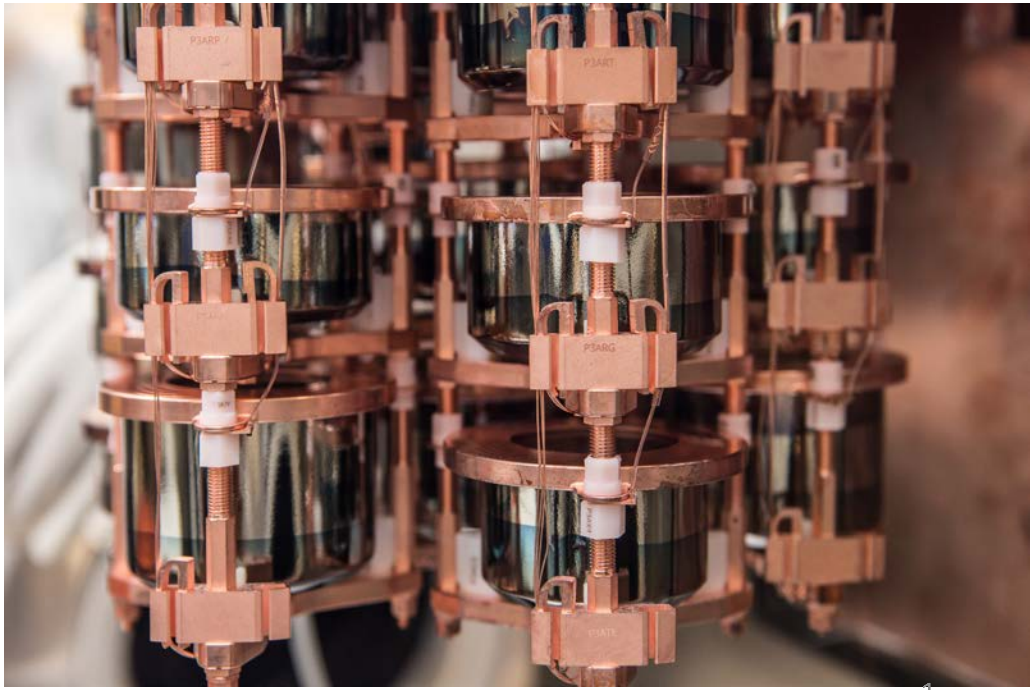
Neutrinoless double-beta decay searches in germanium and the GeRMLab

Ryan Martin

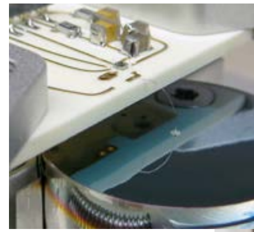
Summer students

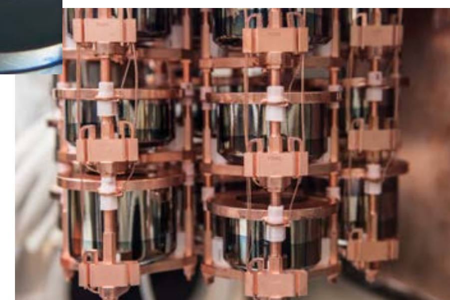
May 2022

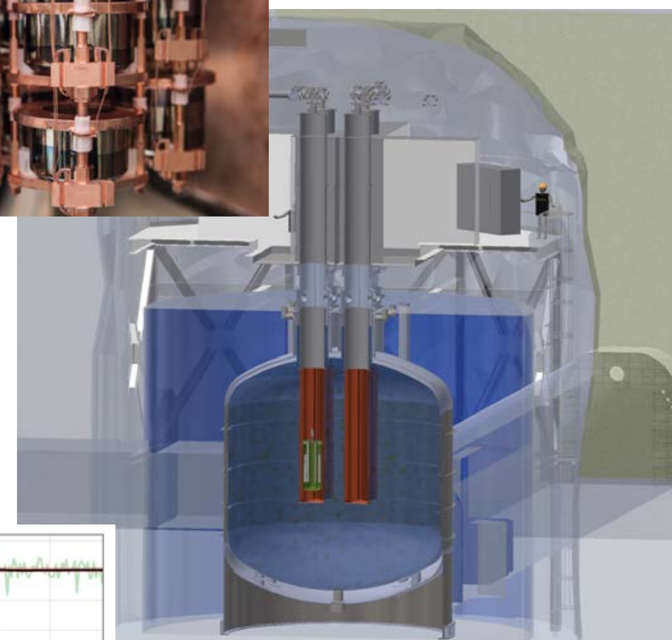


- **In-person** summer school at Queen's
- School runs 20-25th June 2022
- Cost is CAD 250 + accommodations

Introduction – Ryan Martin

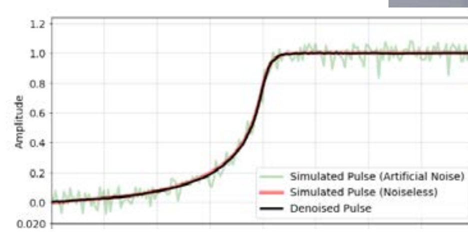






GeRMLab:

- **Ge**rmanium point contact detectors R&D
- **M**achine **L**earning tools for particle astrophysics
- CV-19 modelling Experiments we participate in:
- LEGEND, Majorana, SNO+, NEWS-G

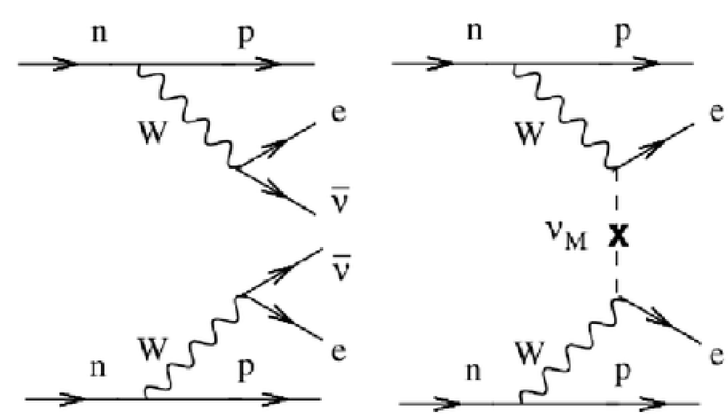


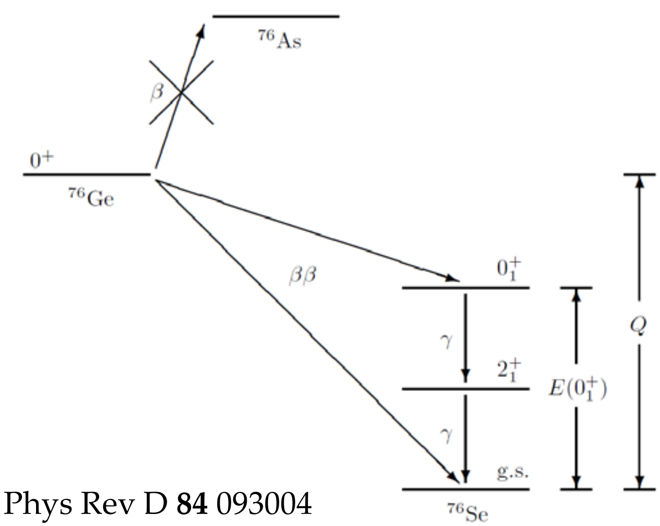
Outline

- Neutrinoless double-beta decay
- Point contact germanium detectors
- The MAJORANA DEMONSTRATOR
- LEGEND
- Work at Queen's

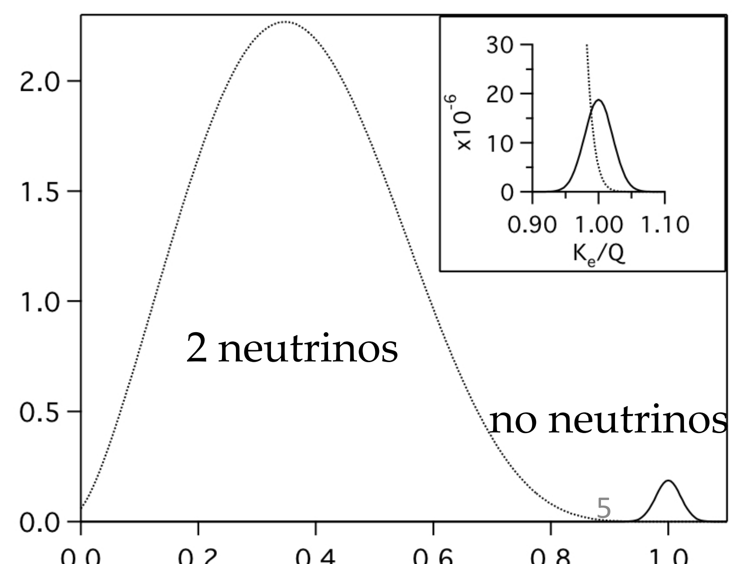
(Neutrinoless) Double beta decay

- Beta decay is forbidden in certain isotopes, while double beta decay is allowed
- If neutrinos are Majorana, a fraction of those decays may be "neutrinoless"
- This is the only practical way to show that neutrinos are Majorana
- Experimental signature is a peak at the end of the energy spectrum of the emitted electrons





Phys Rev D **84** 093004



Experimental searches for 0νββ

- Perform a "counting experiment":
  - *If no counts are seen, the half-life is at least as long as…*

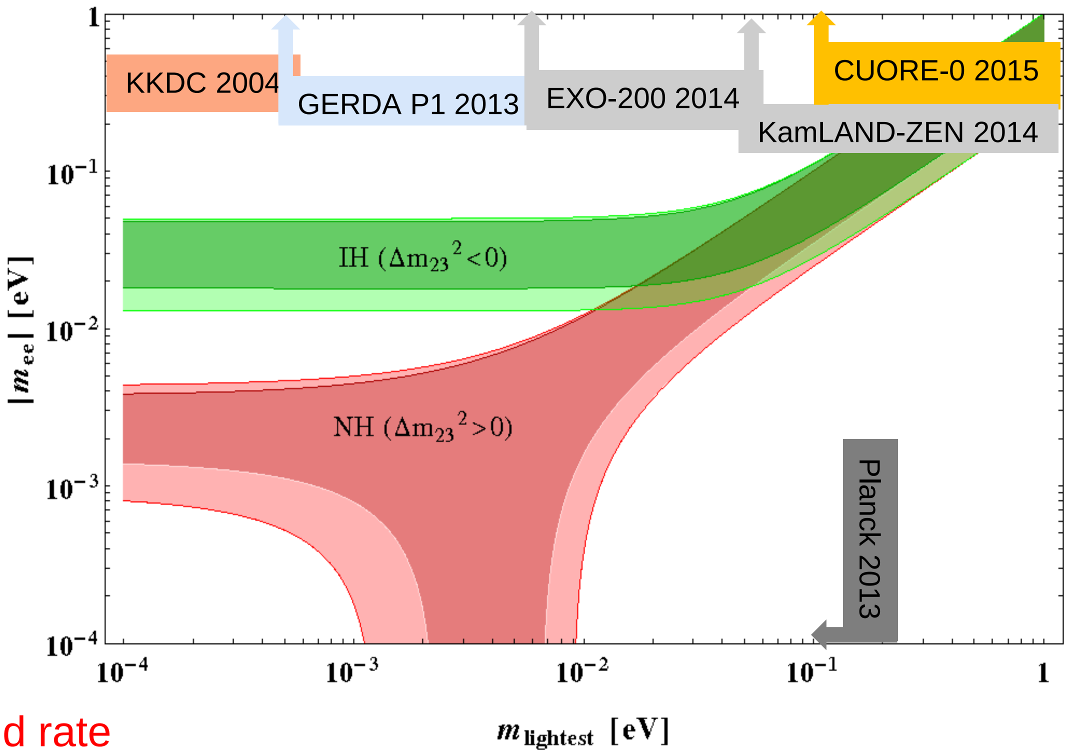
$$T^{0\nu}_{1/2} = \left(G_{0\nu} |M_{0\nu}|^2 \left(\frac{m_{ee}}{m_e} \right)^2 \right)^{-1}$$

$$m_{ee} \equiv \left| \sum_{i=1}^{3} U^2_{ei} m_i \right|$$

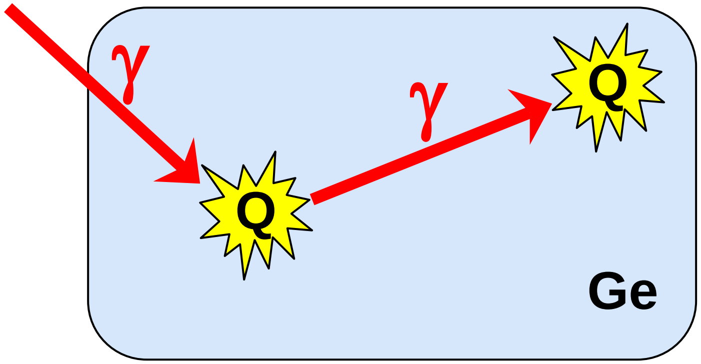
Sensitivity:

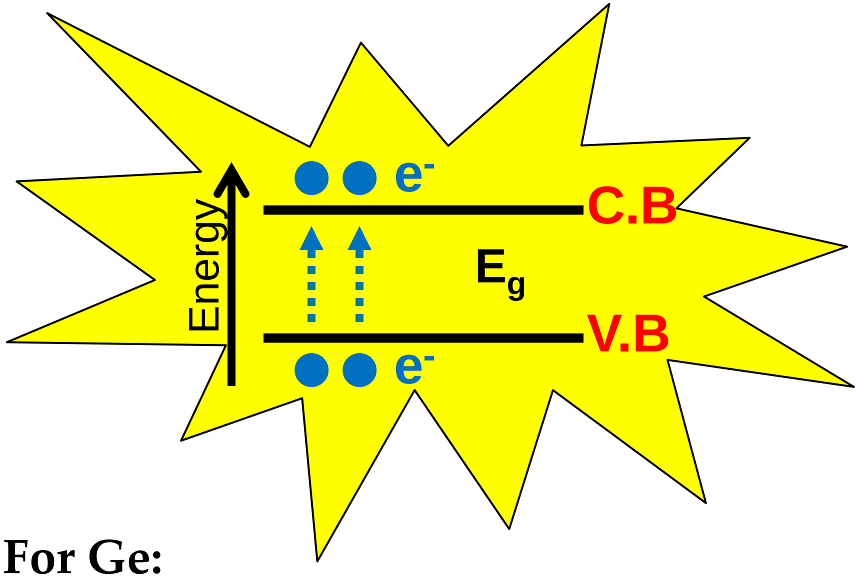
$$T^{0\nu}_{1/2} \propto a\epsilon \sqrt{\frac{Mt}{\sigma_E B}}$$

abundance → a; Detect eff. → ϵ; mass → M; live-time → t; energy resolution → σ_E; background rate → B



Semiconductor detectors





Measure total Q to get Energy:

- Number of electron-hole pairs:

$$N = \frac{E_\gamma}{\varepsilon}$$

- Energy resolution:

$$\Delta E \propto \sqrt{FN}$$

For Ge:

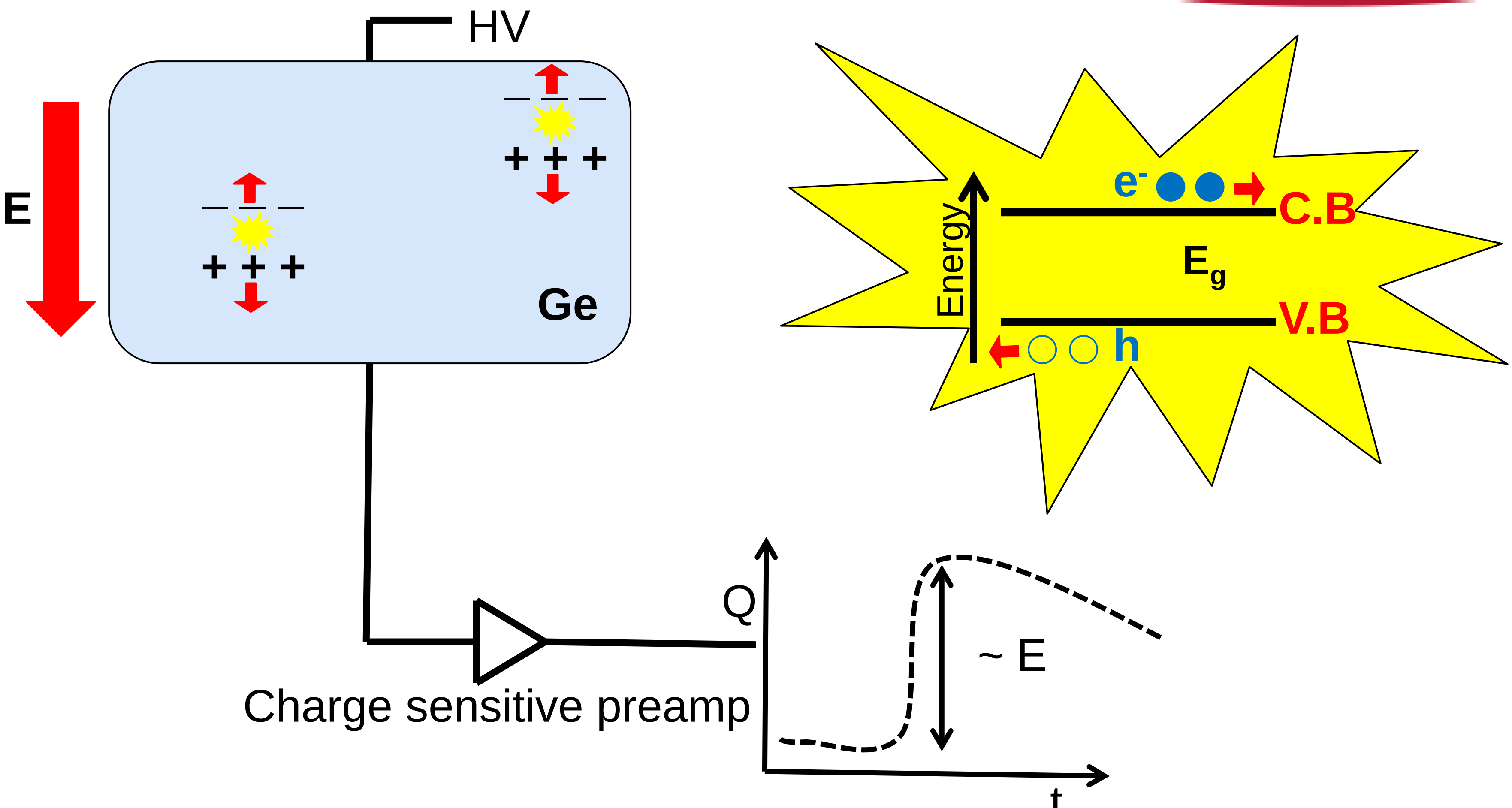
$$\varepsilon = 2.95eV, F \approx 0.1$$

- For 2MeV:

$$N \approx 700{,}000$$

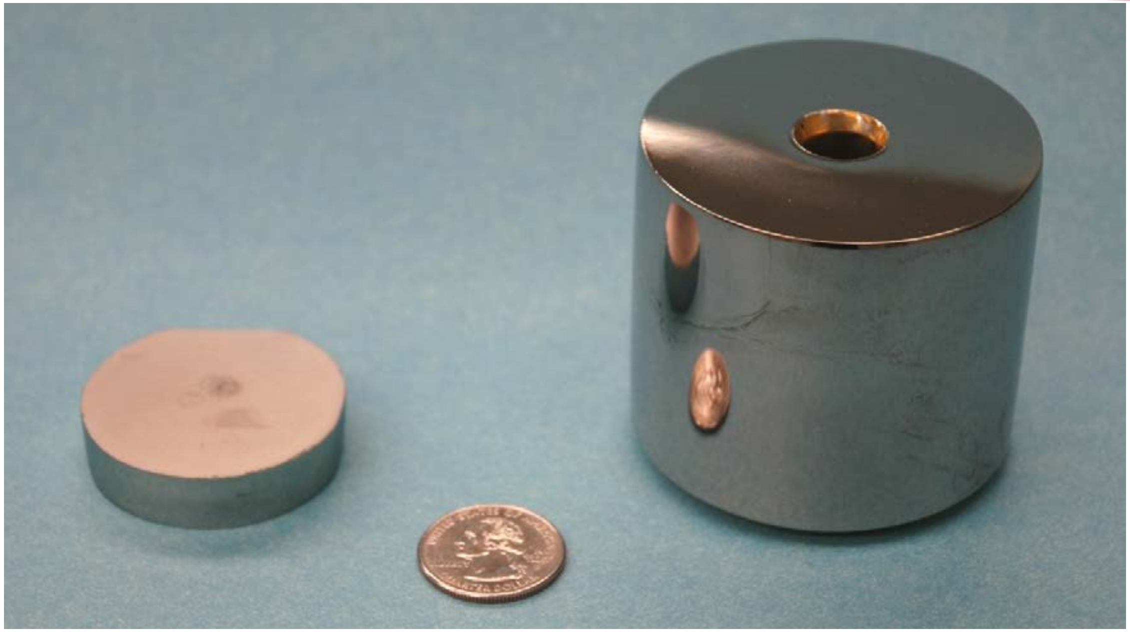
$$\frac{\Delta E_{FWHM}}{E} \approx 0.1\%$$

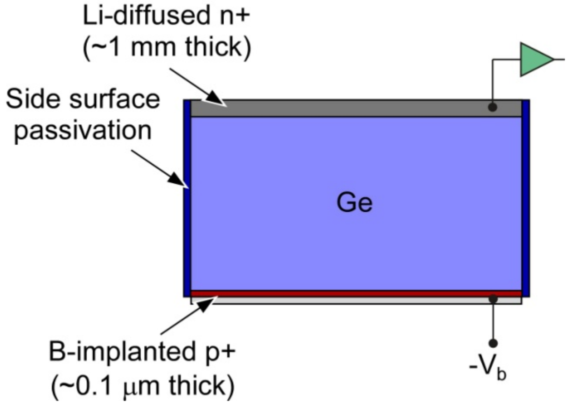
Semiconductor detectors

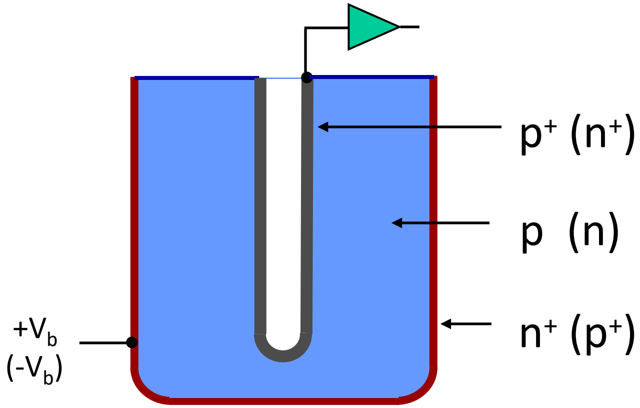


- Apply E-field to collect charges
- Low noise preamp to measure charge and obtain good energy resolution

"Classic" germanium detectors

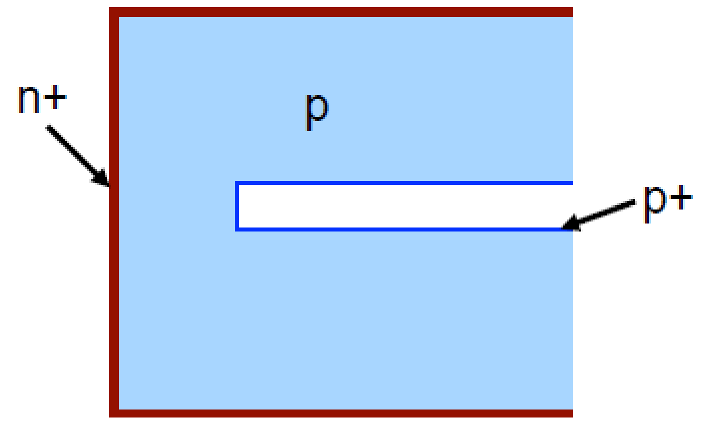




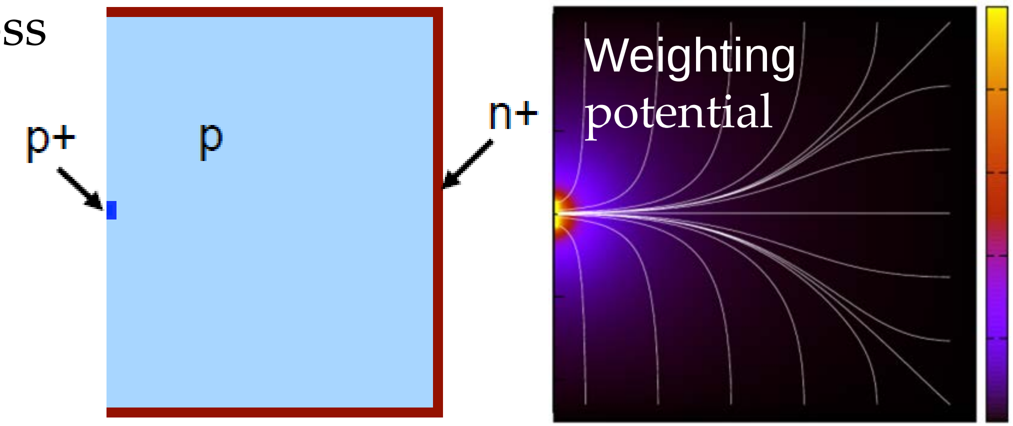


PPC detectors

- P-type Point Contact HPGe
- First one developed by Collar and Barbeau (2008)
- Small point contact to readout charge, low capacitance, low noise
- Thick outer contact (n+, lithium diffused), strongly attenuates alphas
- Large variation in drift times across the detector volume

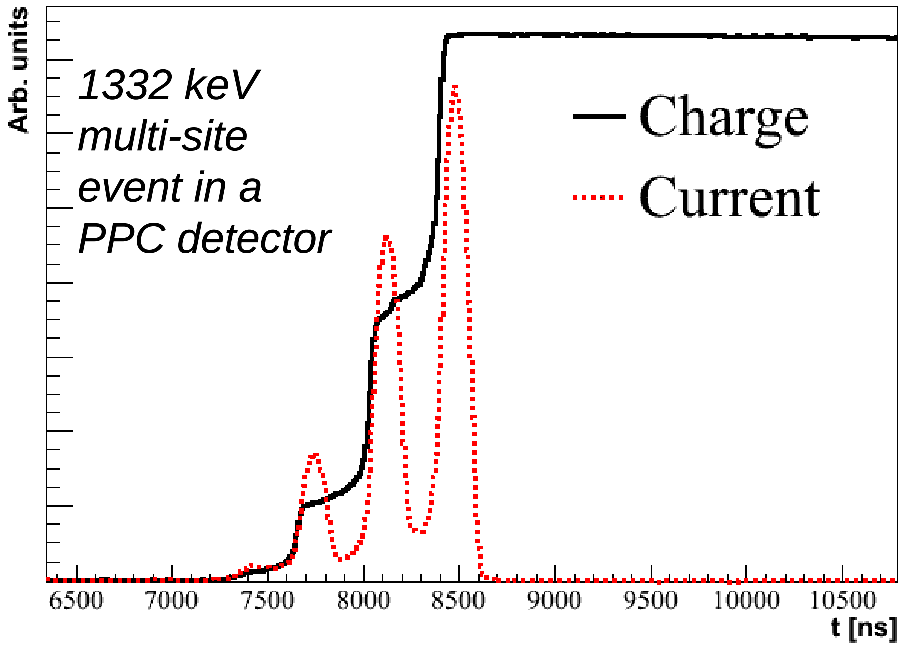


Semi coaxial detector

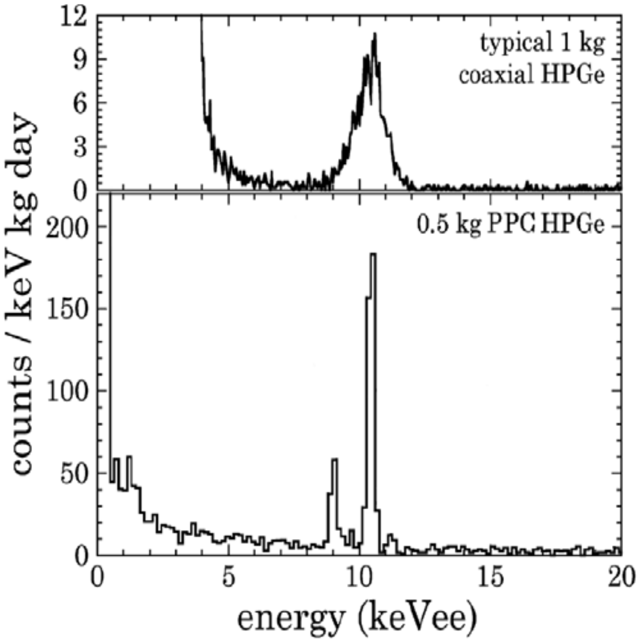


Point contact detector

Properties of PPC detectors



PRL **101** 251301 (2008)



- Sharp weighting potential allows multi-site events to be identified
- Gamma rays at 2MeV typically scatter more than once

- Small capacitance results in low noise and excellent performance at low energies

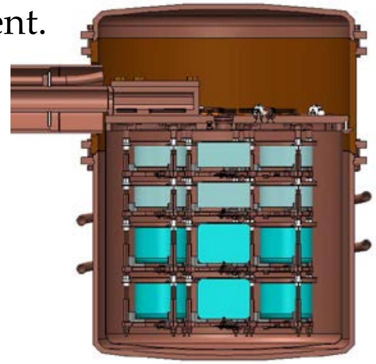
The MAJORANA collaboration

Black Hills State University · Duke University · ITEP · Joint Institute for Nuclear Research · Berkeley Lab · Los Alamos National Laboratory · Oak Ridge National Laboratory · TUNL · The University of North Carolina at Chapel Hill · University of South Carolina · Tennessee Tech University · M · NC State University · The University of Tennessee · Osaka University · Pacific Northwest National Laboratory · Queen's University · W · University of South Dakota

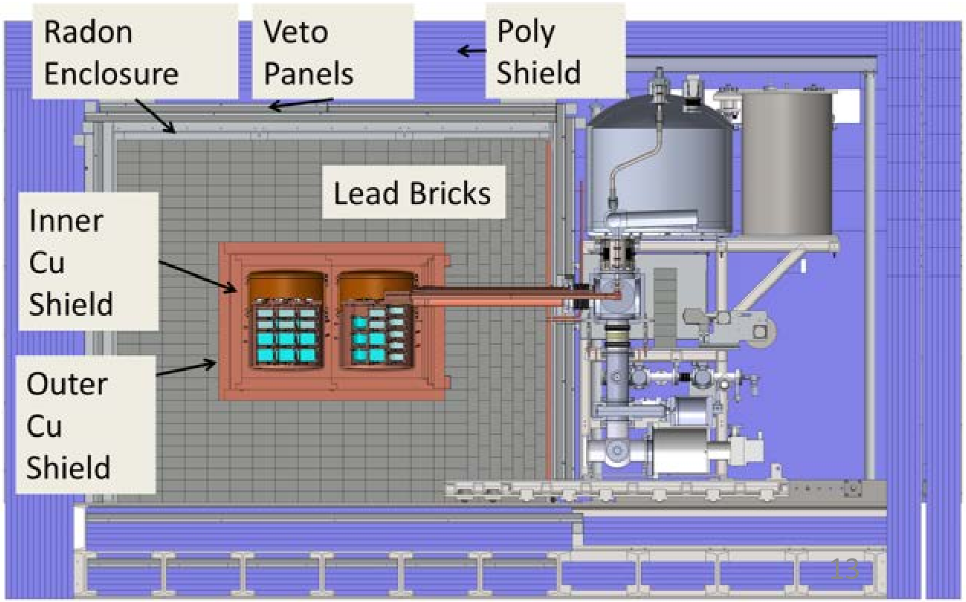
The MAJORANA DEMONSTRATOR

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

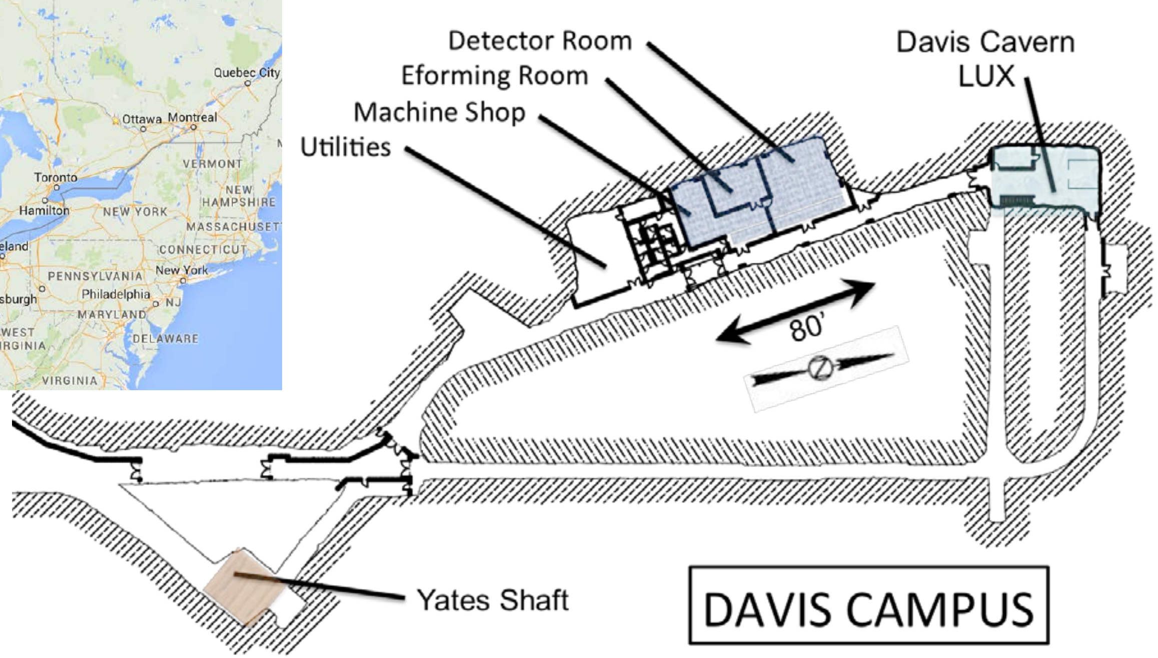
Goals: - Demonstrate backgrounds low enough to justify building a tonne scale experiment.
- Establish feasibility to construct & field modular arrays of Ge detectors.
- Searches for additional physics beyond the standard model.



- Located underground at 4850′ Sanford Underground Research Facility
- 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
  - 22 kg of detectors per cryostat
  - naturally scalable
- Compact Shield
  - low-background passive Cu and Pb shield with active muon veto

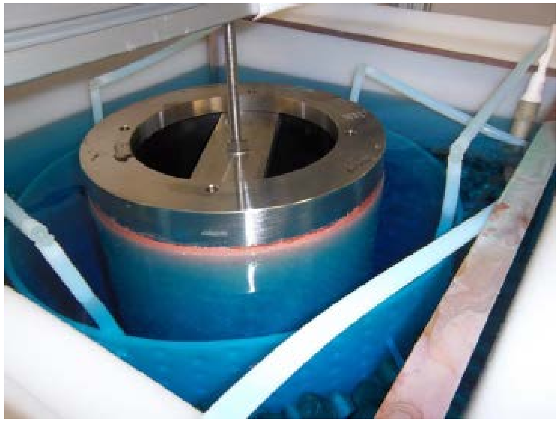


Sanford Underground Research Facility



The cleanest copper in the world

The temporary clean room at SURF (4850)

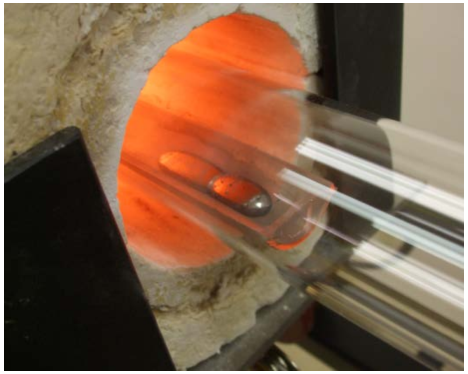


Copper being electroformed on a stainless steel mandrel

A clean machine shop underground

Enriched detector processing

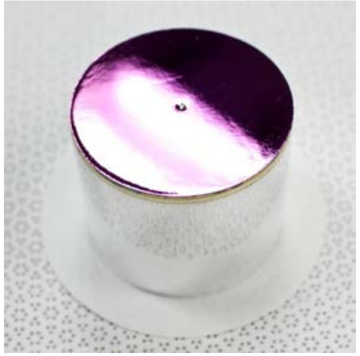
Enrichment *to >87% at Electro-Chemical Plant (ECP) in Russia*



Reduction *to Ge metal at Electrochemical Systems Inc. (ESI)*

Zone-refinement *by commercial vendor*

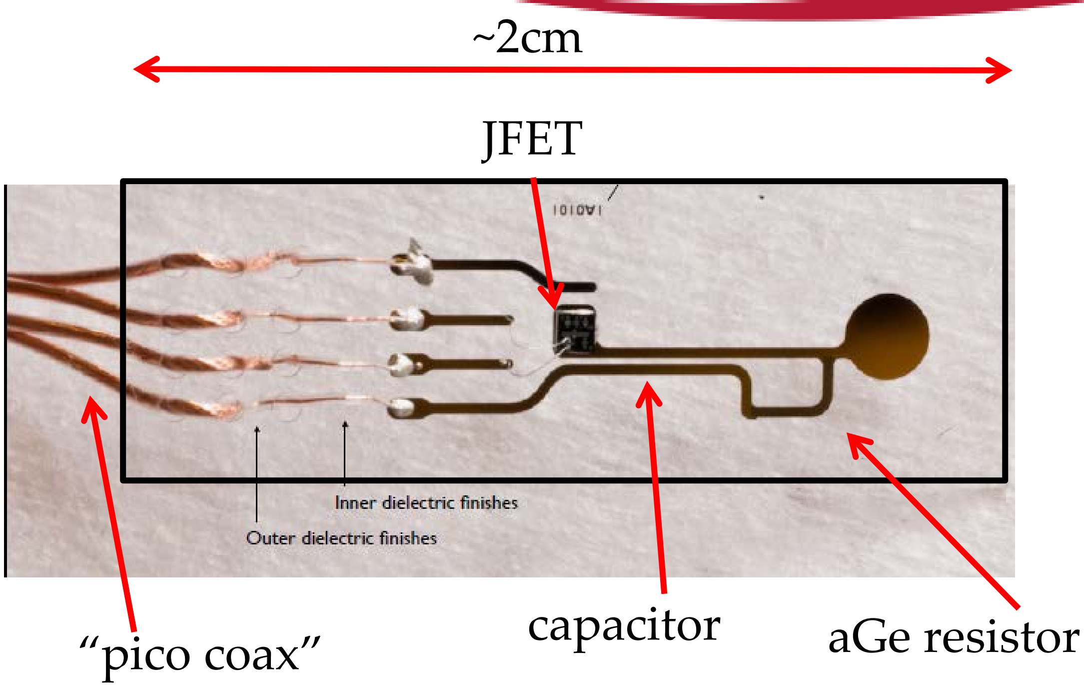
Pull crystal *by commercial vendor*



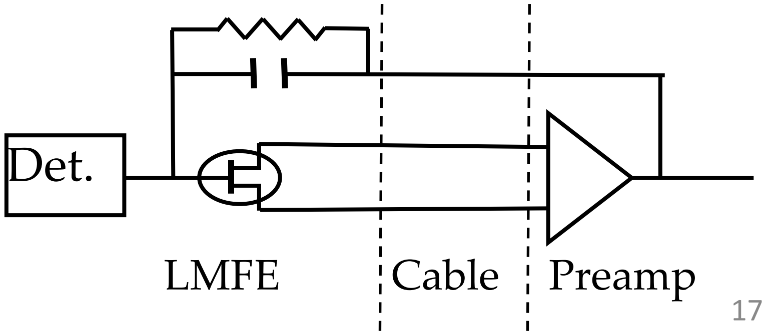
Detector fabrication

Instrumenting the PPCs

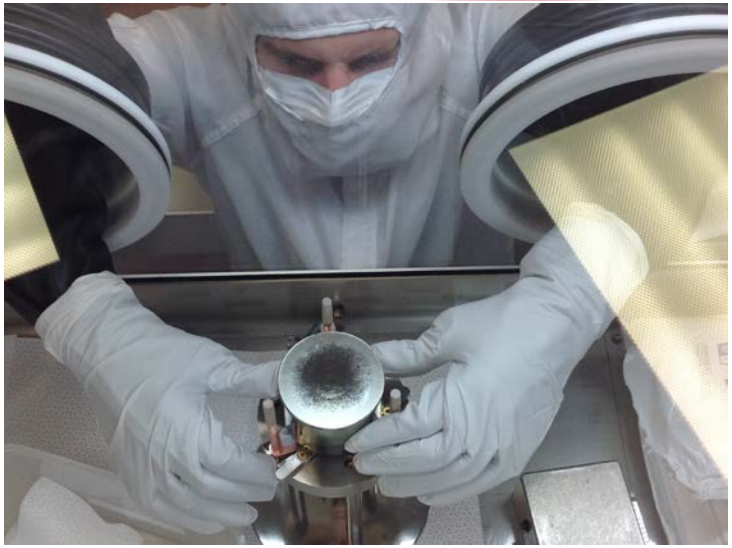
Detector unit

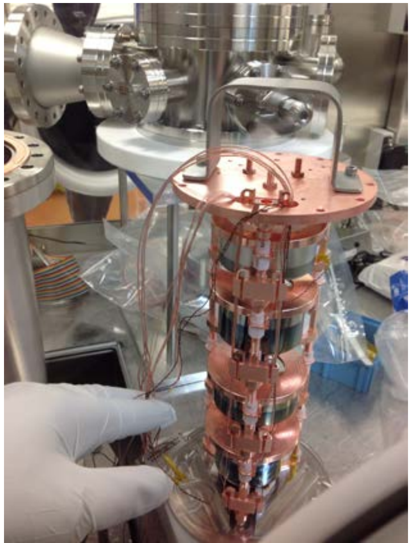


- Developed ultra-low background low noise readout



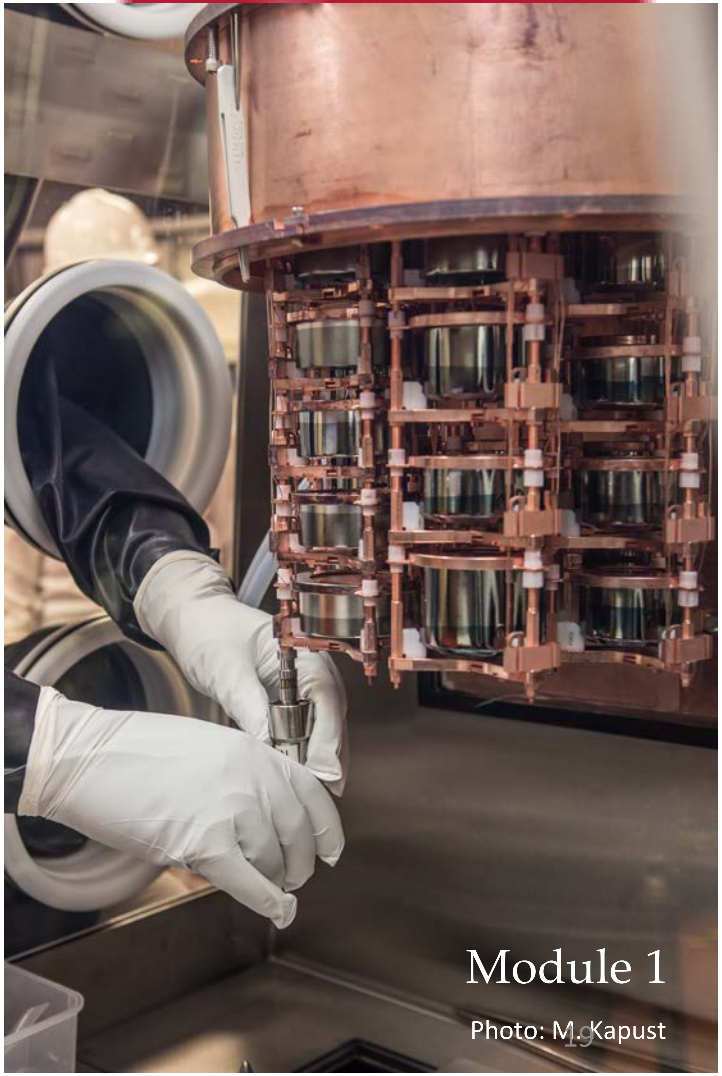
Assembly in the glove box



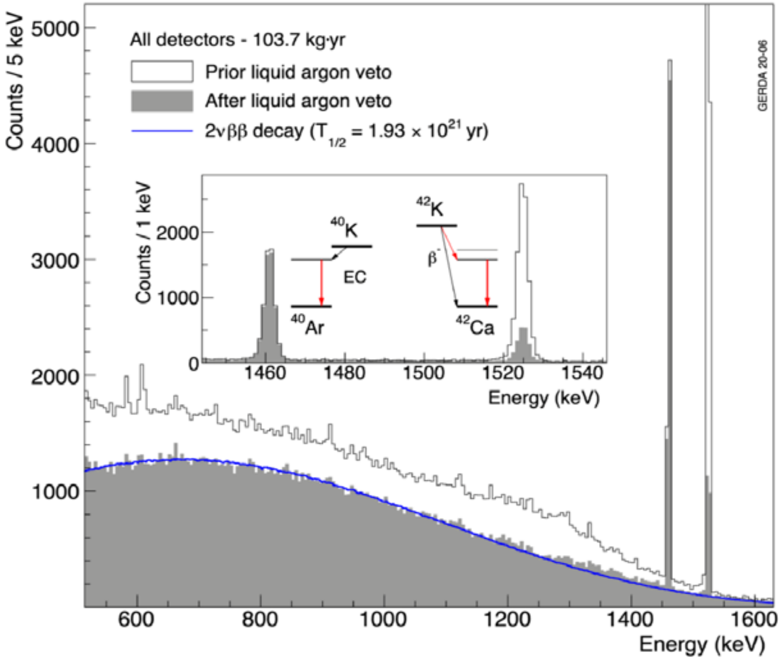


Modules


Prototype Module
www.sanfordlab.org


Module 1
Photo: M. Kapust

The GERDA Experiment



Rejecting events based on veto is enough to see the 2νββ spectrum!

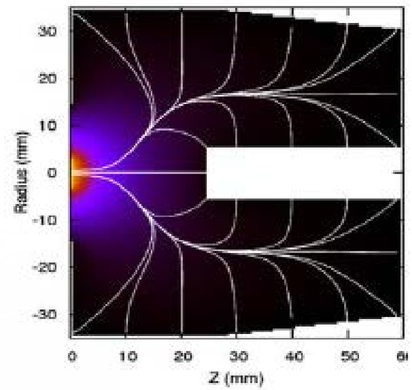
- A similar scale experiment to the Majorana Demonstrator
- 35kg of detectors, mix of point contact (BEGe) and coaxial
- Operated detectors bare in liquid argon (cooling, shielding, veto)

The LEGEND program

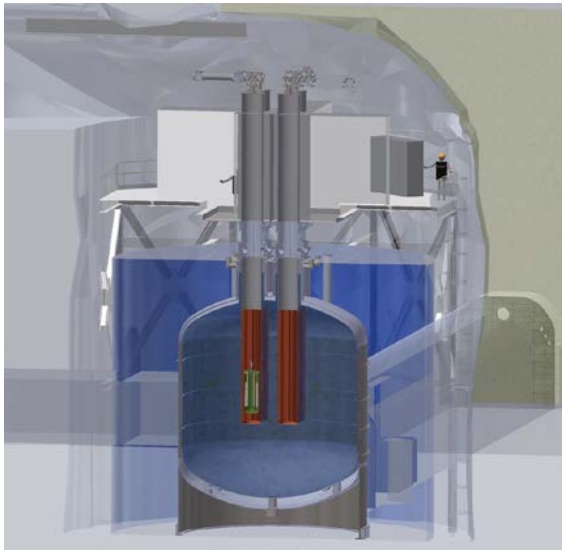
- LEGEND: Large Enriched Germanium Experiment for Neutrinoless ββ Decay
- Originally formed by members of the MAJORANA and GERDA collaborations
- **Goal**: 3σ detection of a $0\nu\beta\beta$ signal in ^{76}Ge for half-lives of **10^{28} years** (lower end inverted mass hierarchy)
- **Method**:
  - Phased approach to retire technological risks
  - Re-use of demonstrated technologies from the MAJORANA DEMONSTRATOR and GERDA experiments:
    - Electroformed copper
    - Low mass front-end electronics
    - Immersion in liquid argon
  - Develop new technologies:
    - ICPC detectors
    - Scintillating structural materials
    - Electronics
- **Program**:
  - L-200 experiment to deploy 200kg of enriched detectors and make use of the existing GERDA infrastructure at LNGS
  - L-1000 proposed for 1000kg of enriched detectors (baseline at SNOLAB)

Large Experiment with enriched Germanium for Neutrinoless double-beta Decay (LEGeND)

L-200



Inverted Coax Point Contact detector geometry



L-1000 at SNOLAB

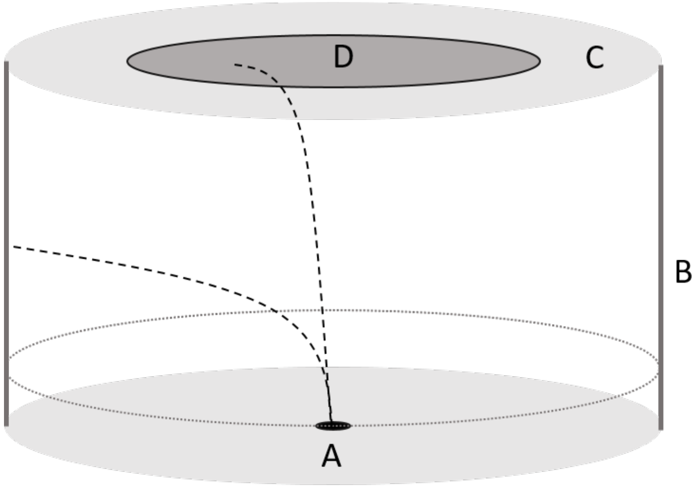
Primarily, a combination of the MJD and GERDA collaborations

Phased approach that reuses the best of MJD and GERDA:

- **LEGeND-200** → 200kg in GERDA (~150kg of new material):
  - MJD+GERDA+new ICPC
  - MJD Electronics
  - GERDA cryostat
- **LEGeND-1000** → 1000+kg, multiple L200-like modules likely in SNOLAB:
  - New ASICs electronics
  - Low background LAr

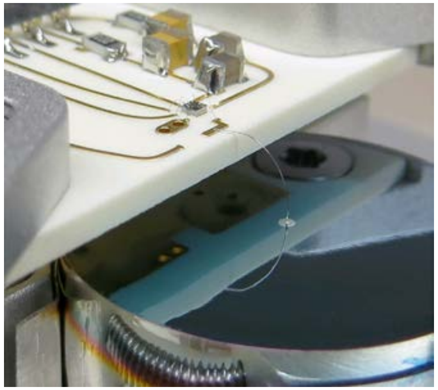
Work at Queen's

- **ORTEC PPC:** 1kg detector identical to the enriched ones in MJD:
  - Study properties of surface events (Li and passivated layers)
  - Develop ML based algorithms (denoise, risetime, etc)



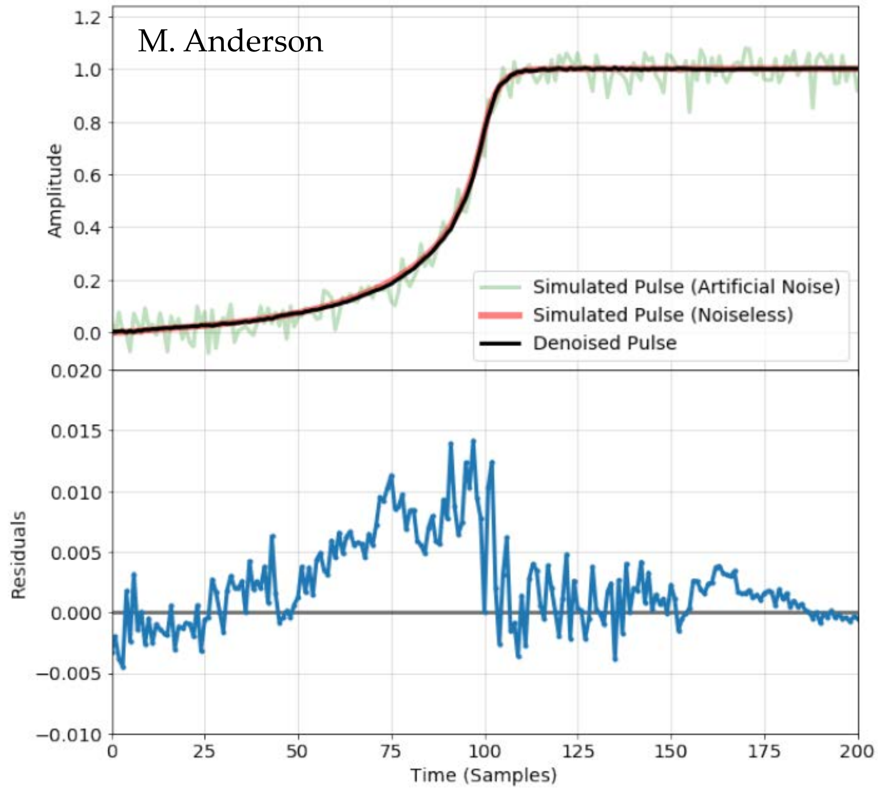
- **Large Mass PPC**: 2.4kg segmented
  - Study charge collection in a large mass detector:
    - Z-position localization
    - Temperature dependence
  - Study pulse shape discrimination

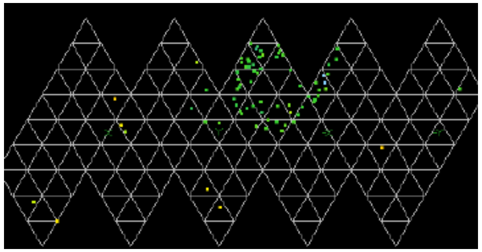
- Developing novel ASIC based electronics:
  - A preamp in a cubic millimetre



Machine learning

- Also host a computing server (neutrino) with GPU
- Developing machine learning tools of use for particle astrophysics community:
  - Algorithms to handle sparse data for event reconstruction (e.g. SNO+ water phase)
  - Algorithms to classify events on an event by event basis (e.g. tagging neutron captures, data cleaning)
  - Algorithms to machine learn de-noising





Simulate pulse → add noise → train to learn the simulated pulse from the noisy pulse (it's more complicated than that)

COVID-19 - Modelling

- Our group++ is also developing a Monte Carlo model of COVID-19, as a fun side project
- Mostly undergraduate led! Have received funding over the school year.
- Opportunity for our group members to:
  - Learn/practice some coding that is relevant to physics (MC method)
  - Learn something interesting
  - Work as a "collaboration" on a tractable problem with many components (literature search, data collection, validation, coding, etc)
- If this sounds interesting to you and you have some free time, get in touch!