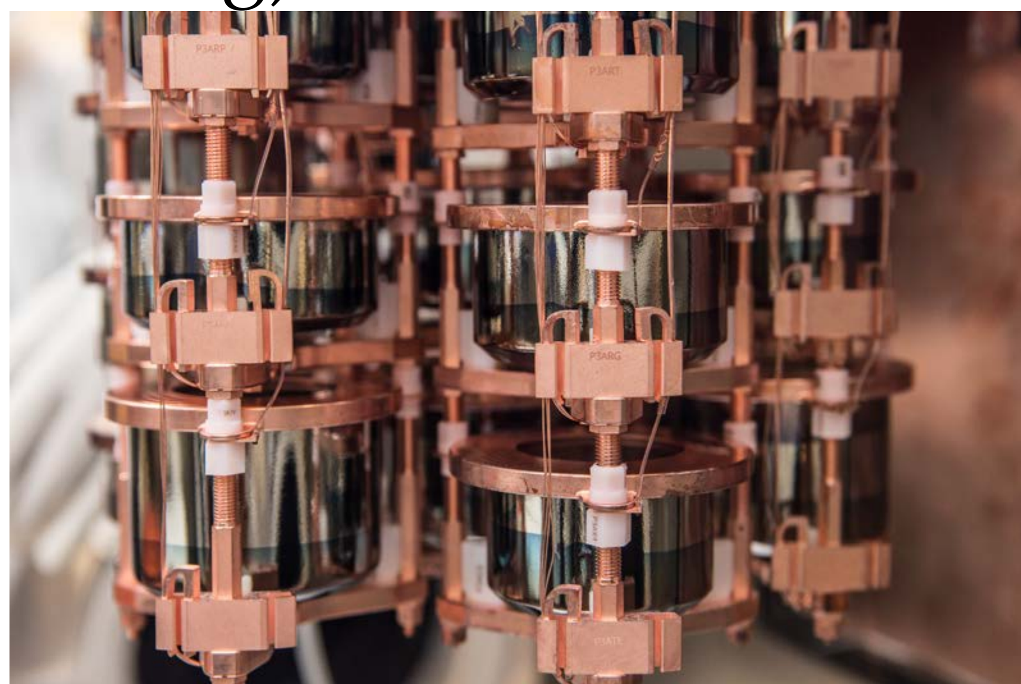
The GeRM lab (Germanium, Majorana/LEGEND, Machine Learning, Covid modelling)



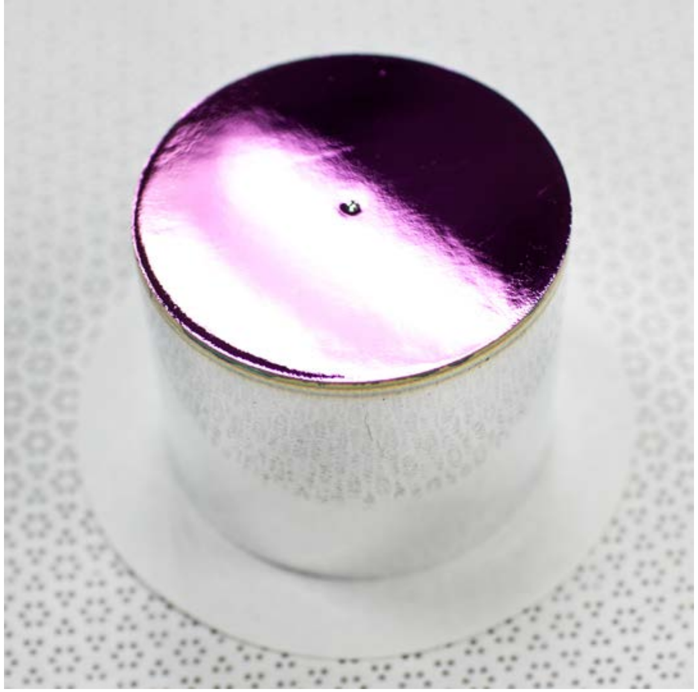
Ryan Martin

Summer students

May 2021

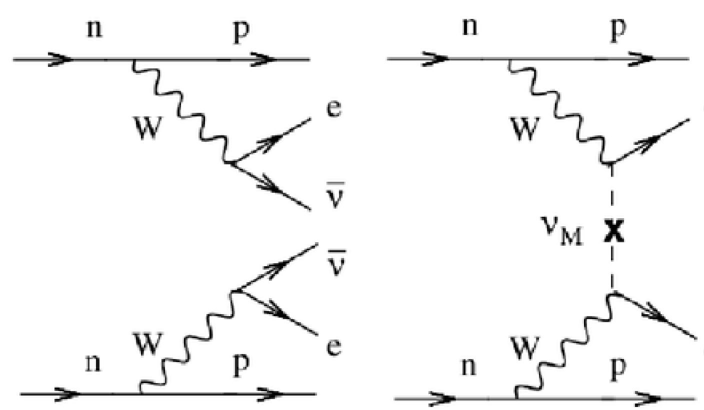
Outline

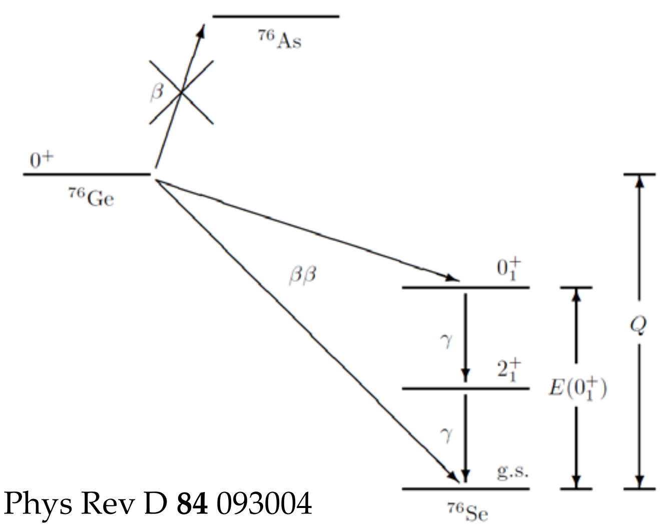
- Neutrinoless double-beta decay
- Point contact germanium detectors
- The MAJORANA DEMONSTRATOR
- LEGeND
- Work at Queen's



(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





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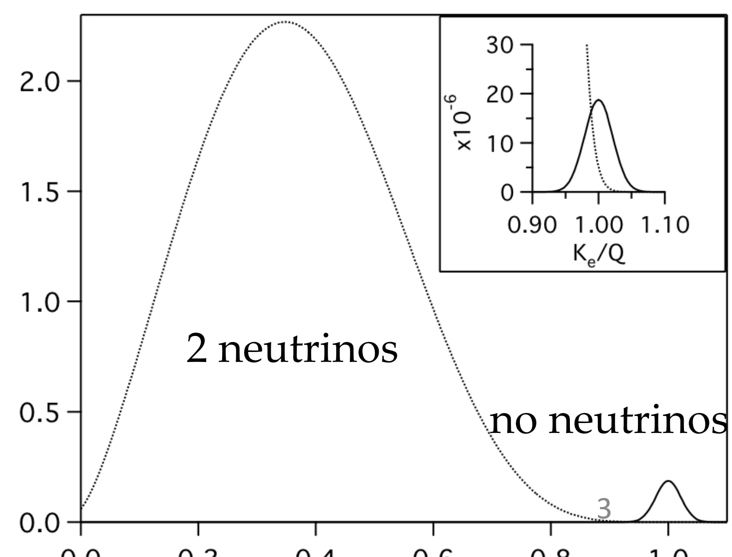


Experimental searches for 0νββ

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

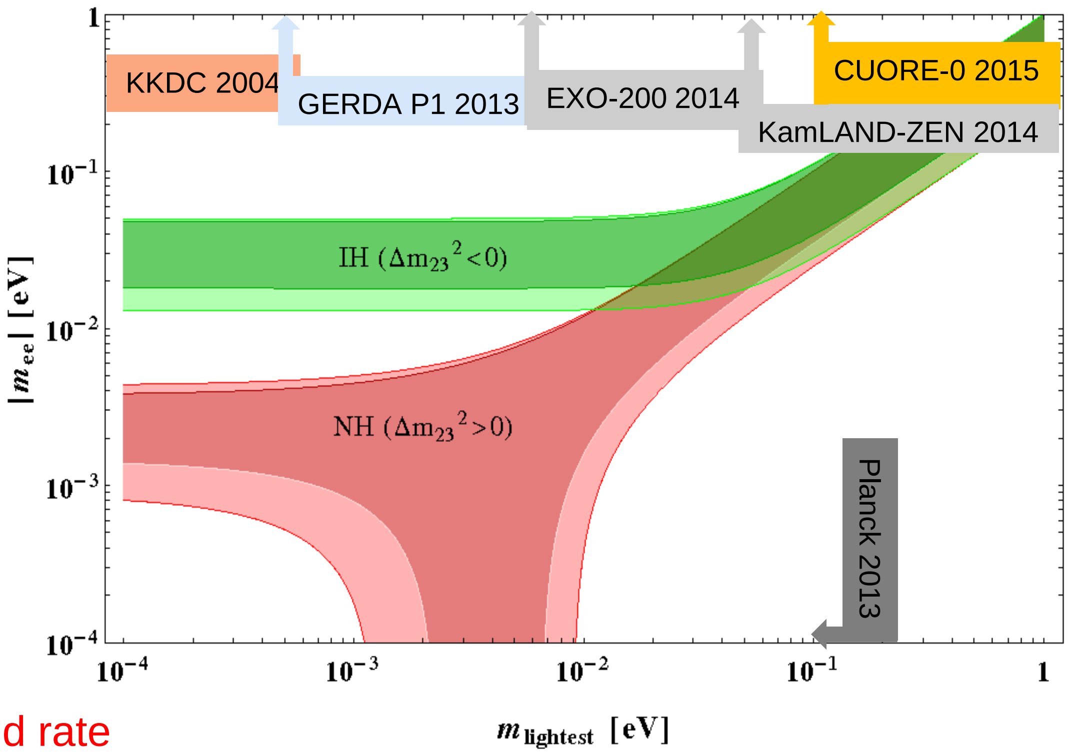
$$T_{1/2}^{0\nu} = \left(G_{0\nu} |M_{0\nu}|^2 \left(\frac{m_{ee}}{m_e} \right)^2 \right)^{-1}$$

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

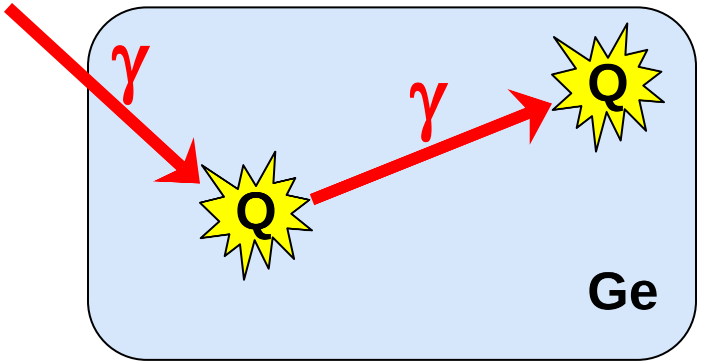
Sensitivity:

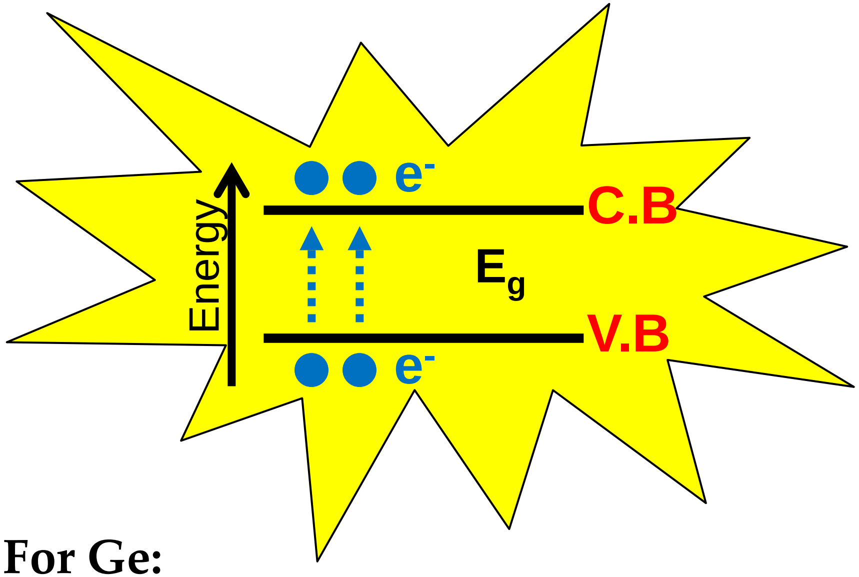
$$T_{1/2}^{0\nu} \propto a\epsilon \sqrt{\frac{Mt}{\sigma_E B}}$$

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:

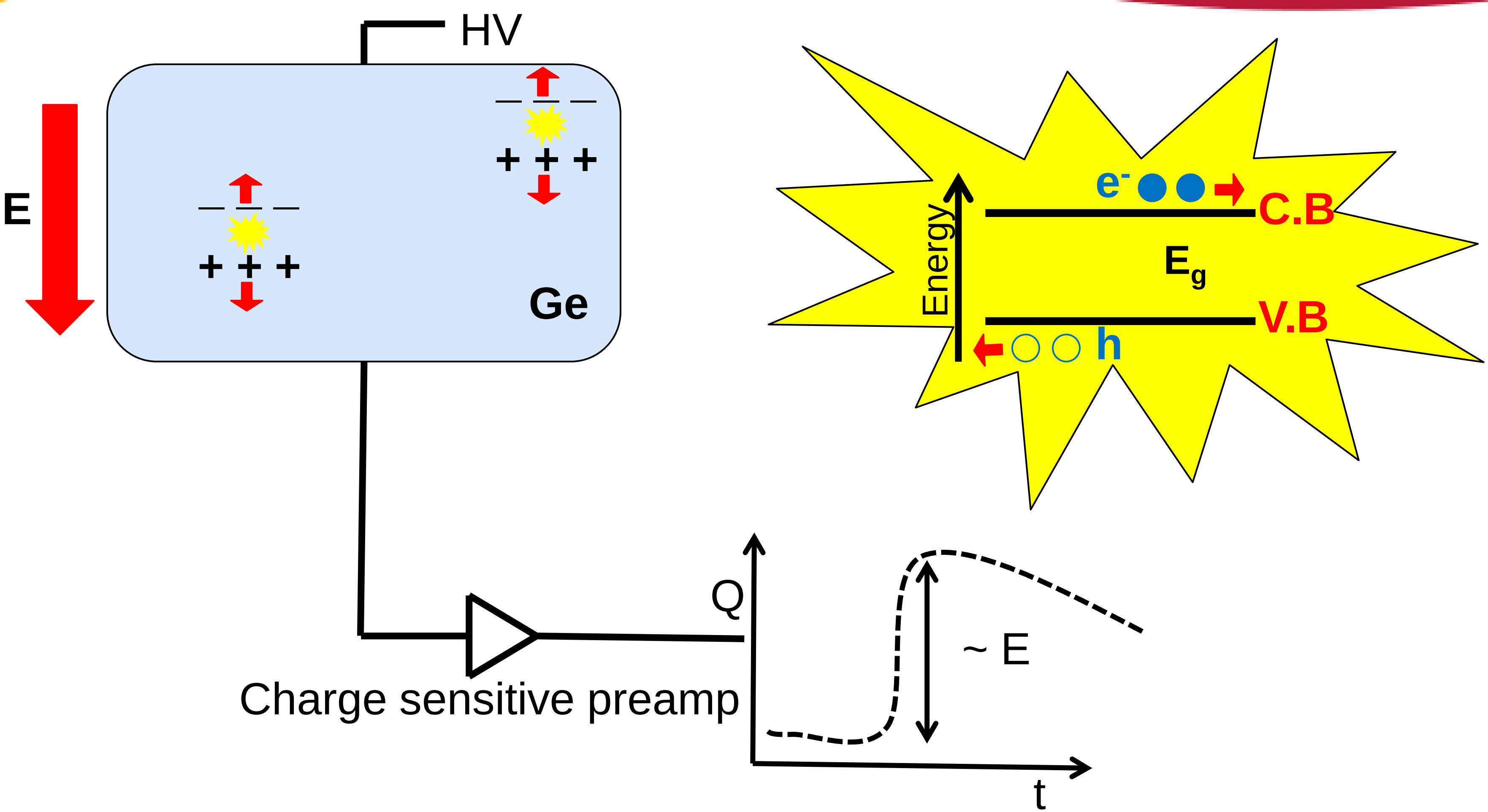
$$\varepsilon = 2.95eV, F \approx 0.1$$

- For 2MeV:

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

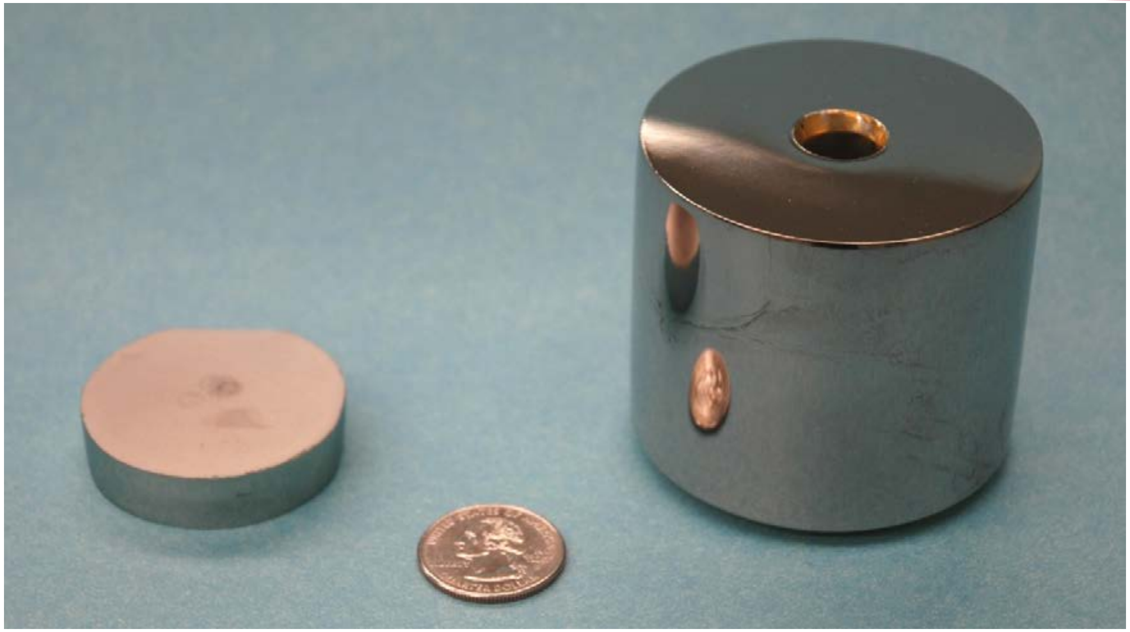
$$\frac{\Delta E_{FWHM}}{E} \approx 0.1\%$$

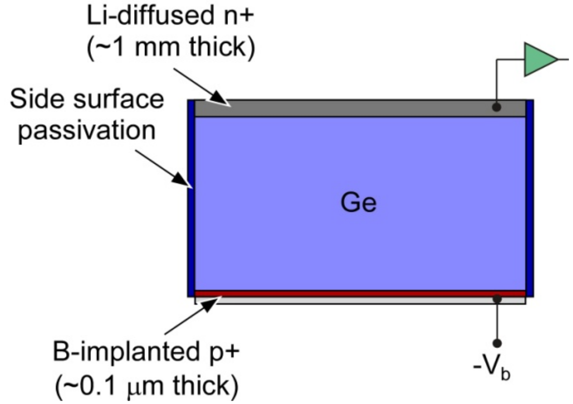
Semiconductor detectors

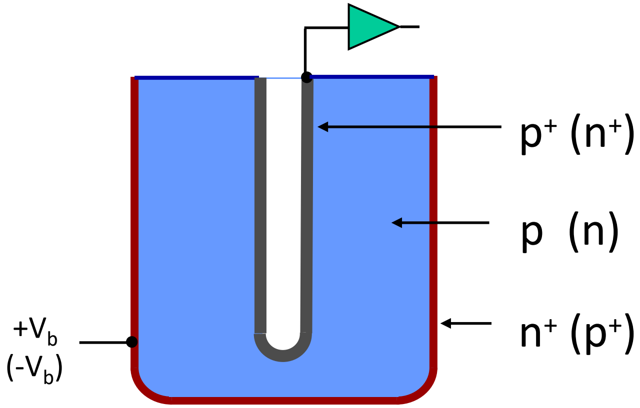


- Apply E-field to collect charges
- Low noise preamp to measure charge and obtain good energy resolution

"Classic" germanium detectors

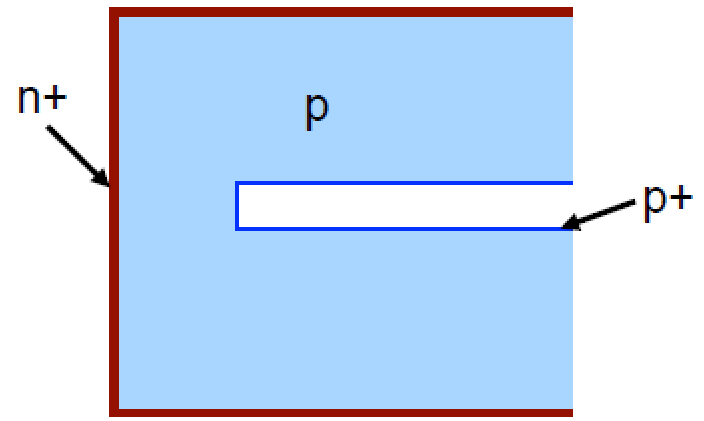




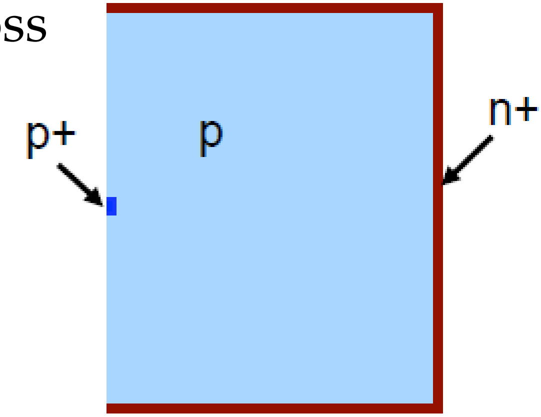


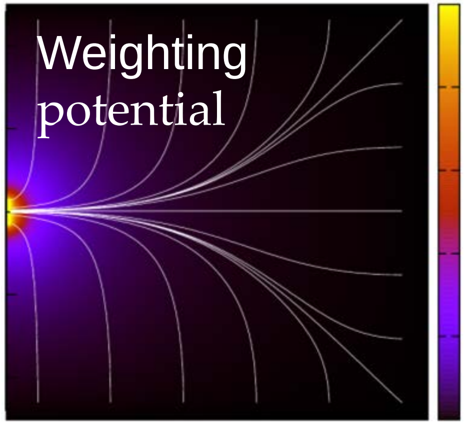
PPC detectors

- 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



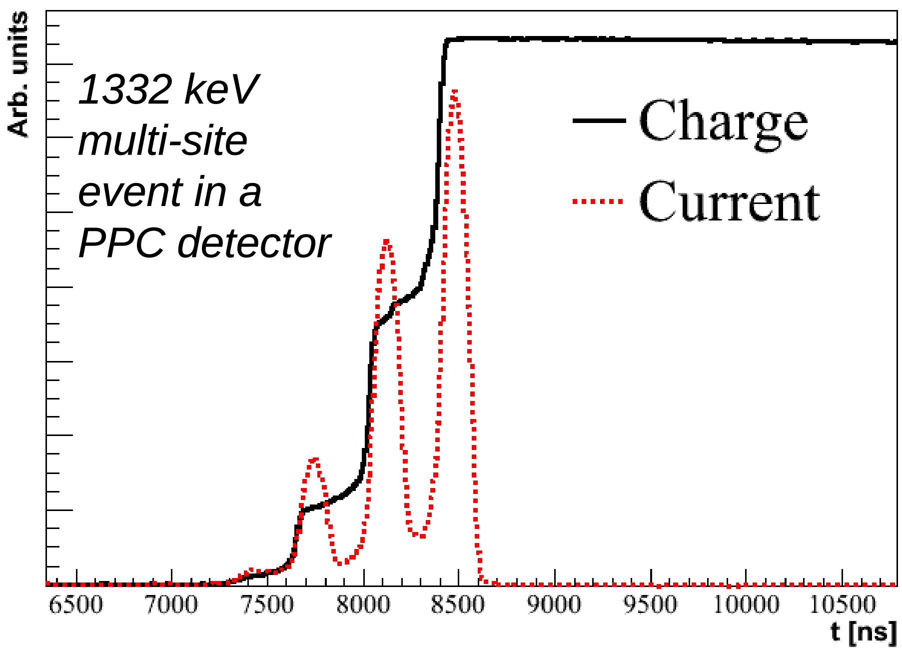
Semi coaxial detector



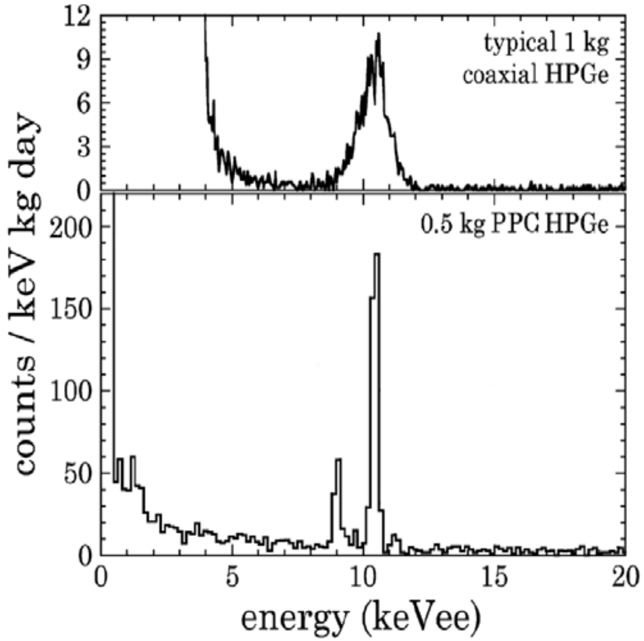


Point contact detector

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

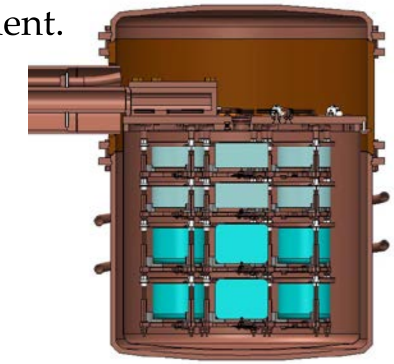
The MAJORANA collaboration

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
NC State University
The University of Tennessee
Osaka University
Pacific Northwest National Laboratory
Queen's University
University of South Dakota

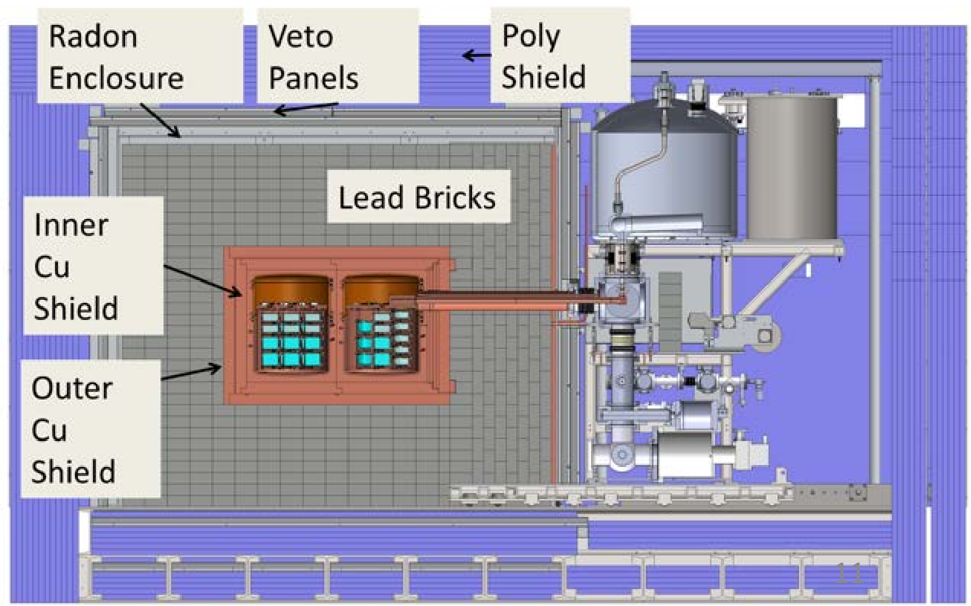
The MAJORANA DEMONSTRATOR

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

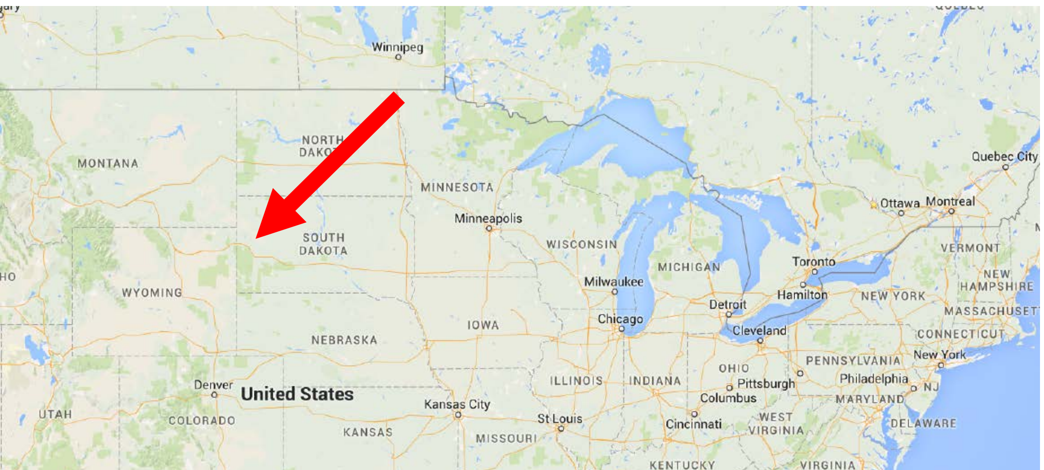
Goals:
- Demonstrate backgrounds low enough to justify building a tonne scale experiment.
- Establish feasibility to construct & field modular arrays of Ge detectors.
- Searches for additional physics beyond the standard model.

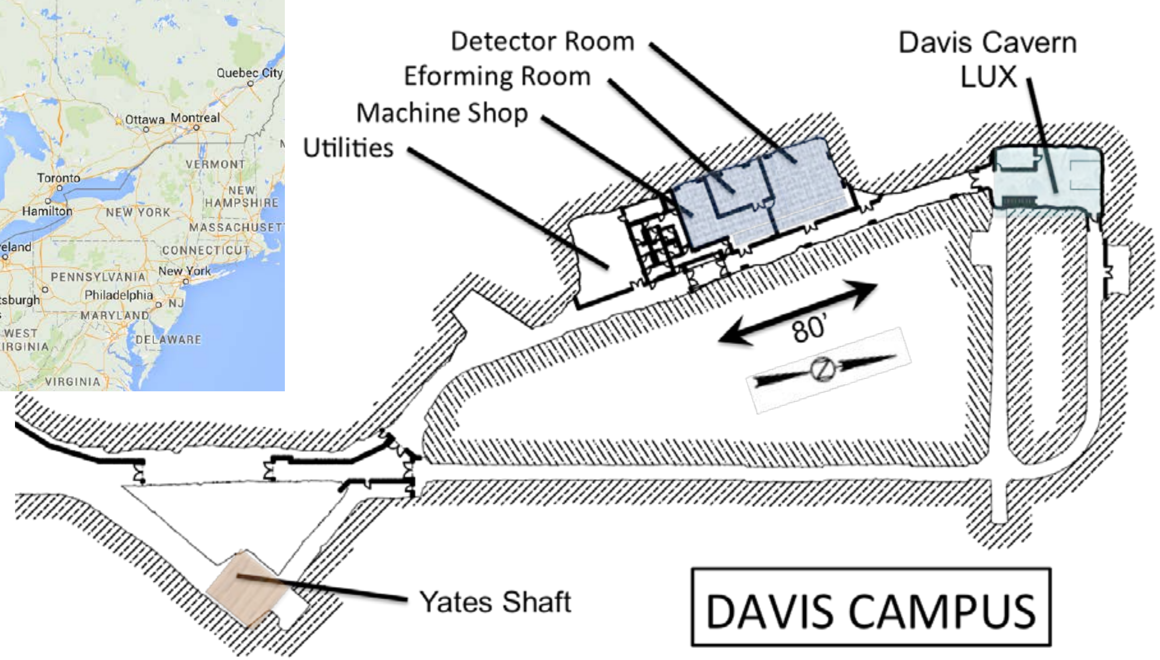


- Located underground at 4850′ Sanford Underground Research Facility
- 44-kg of Ge detectors
  - 29 kg of 87% enriched ^{76}Ge crystals
  - 15 kg of ^{nat}Ge
  - Detector Technology: P-type, point-contact.
- 2 independent cryostats
  - ultra-clean, electroformed Cu
  - 22 kg of detectors per cryostat
  - naturally scalable
- Compact Shield
  - low-background passive Cu and Pb shield with active muon veto



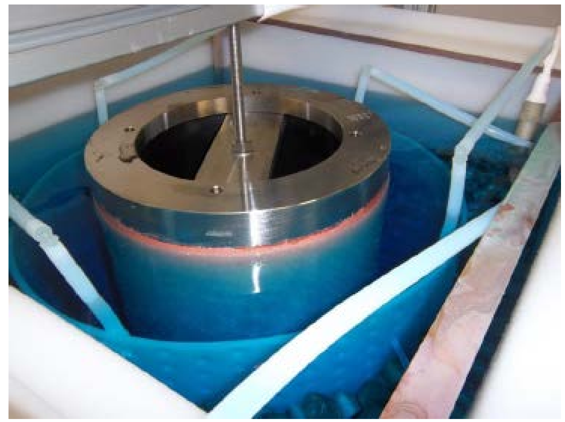
Sanford Underground Research Facility





The cleanest copper in the world

The temporary clean room at SURF (4850)

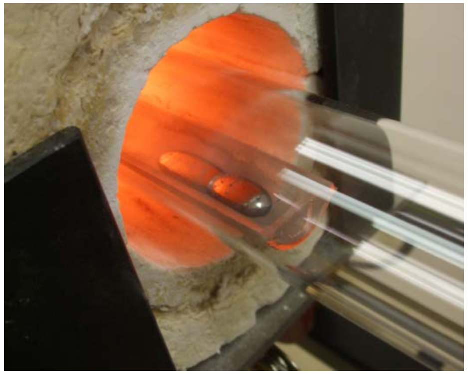


Copper being electroformed on a stainless steel mandrel

A clean machine shop underground

Enriched detector processing

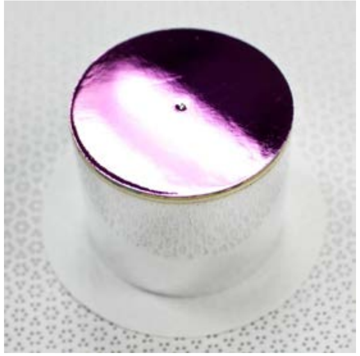
Enrichment *to >87% at Electro-Chemical Plant (ECP) in Russia*



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

Zone-refinement *by commercial vendor*

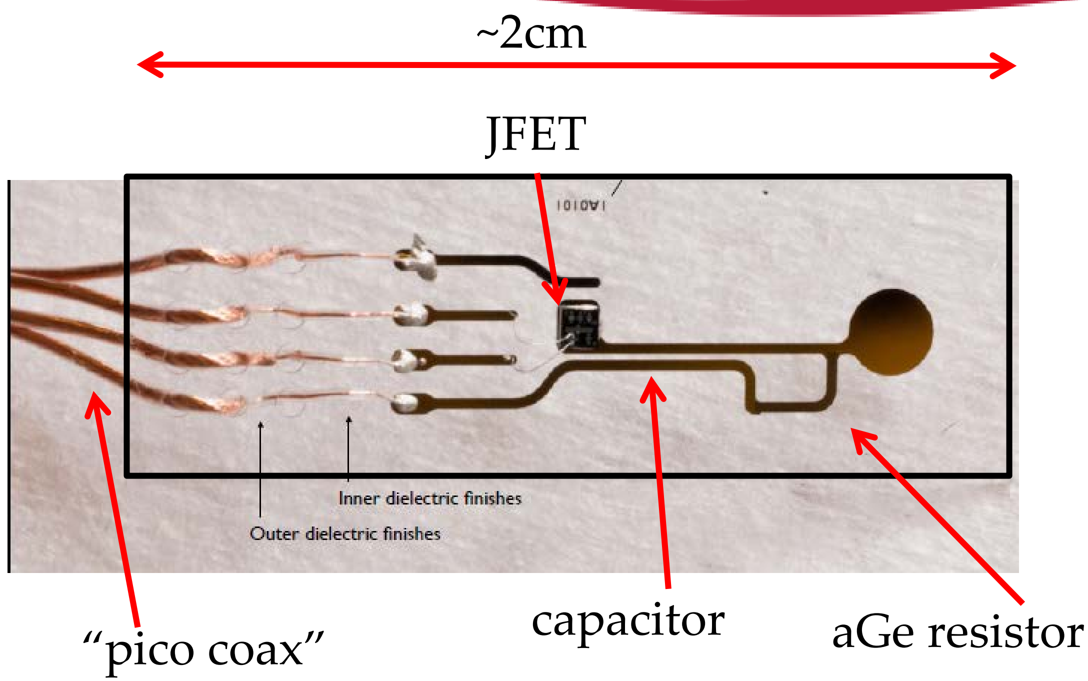
Pull crystal *by commercial vendor*



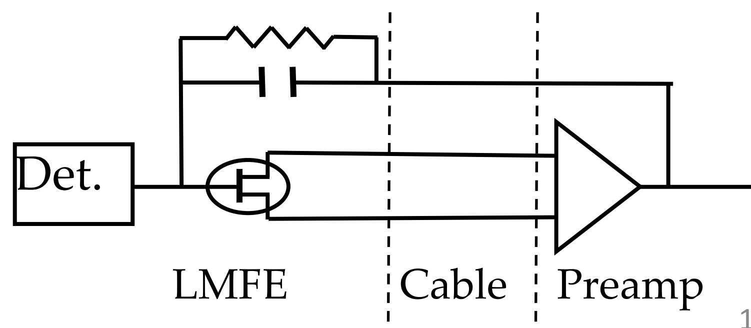
Detector fabrication

Instrumenting the PPCs

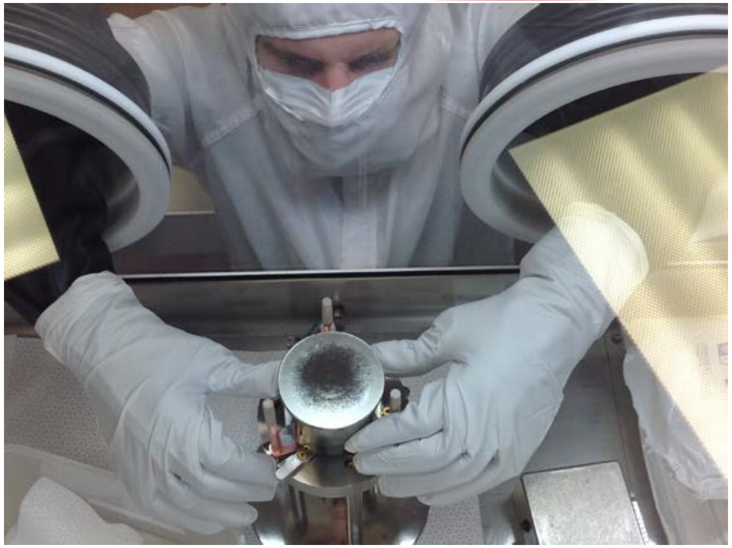
Detector unit

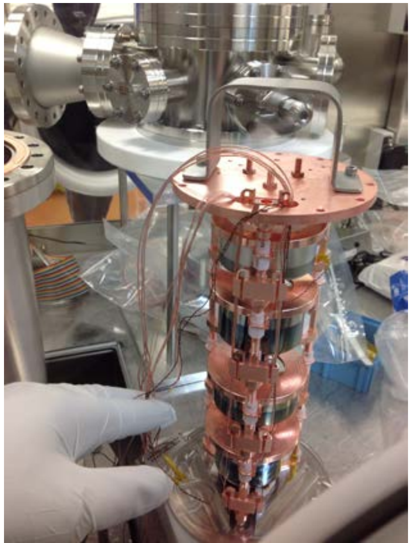


- Developed ultra-low background low noise readout



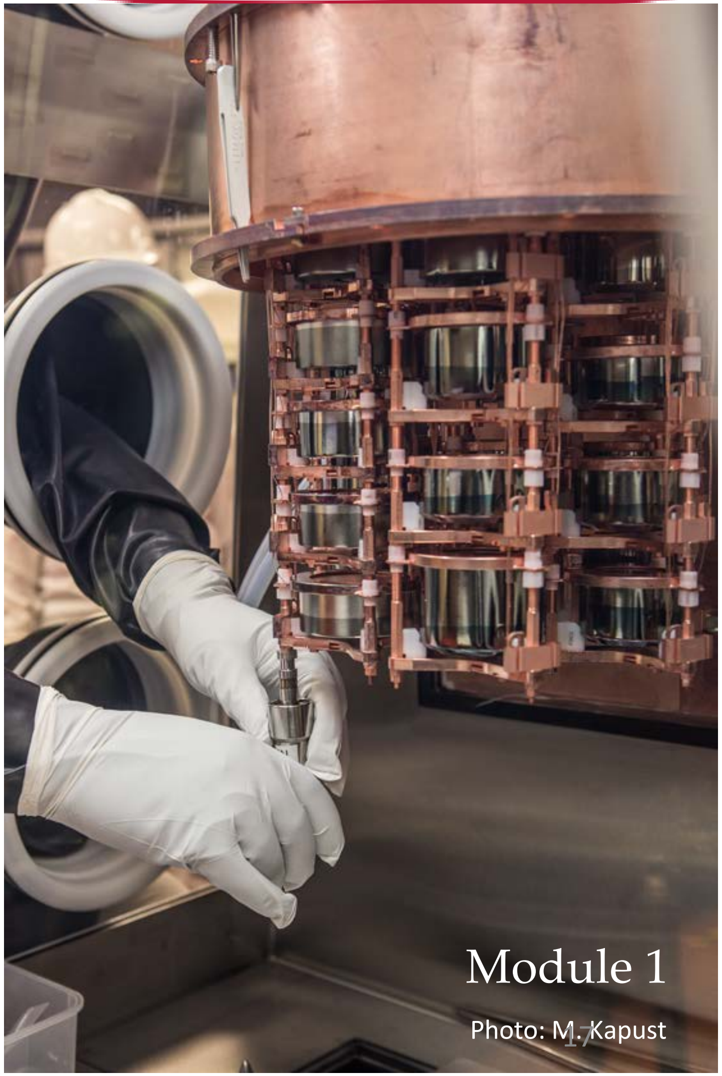
Assembly in the glove box





Modules

Prototype Module



Module 1

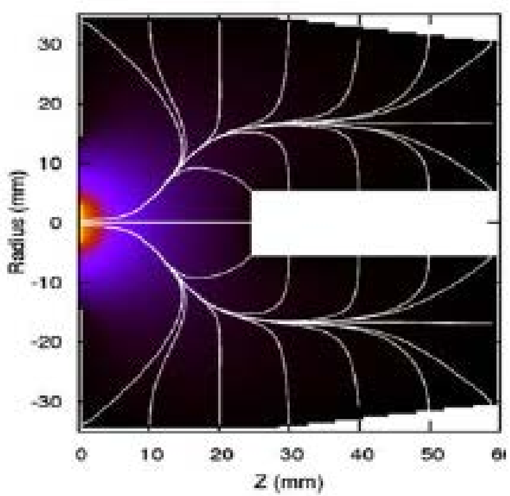
Photo: M. Kapust

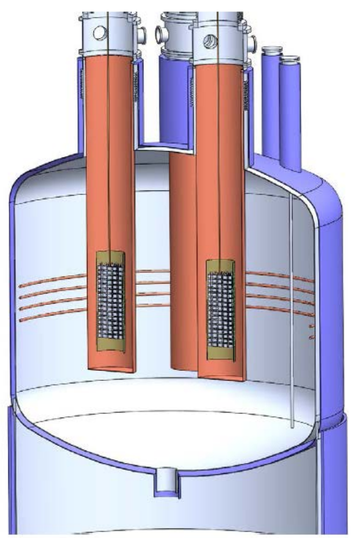
Large Experiment with enriched Germanium for Neutrinoless double-beta Decay (LEGeND)

- Primarily, a combination of the MJD and GERDA collaboration, with some participation from CDEX
- New collaborators joining (and welcome!)

Timeline:

- LEGeND-200 → 200kg in GERDA ~2021 (~150kg of new material):
    - MJD+GERDA detectors
    - New large mass detectors (Inverted coax, ICPC)
- LEGeND-1000 → 1000+kg, multiple L200-like modules in an underground lab



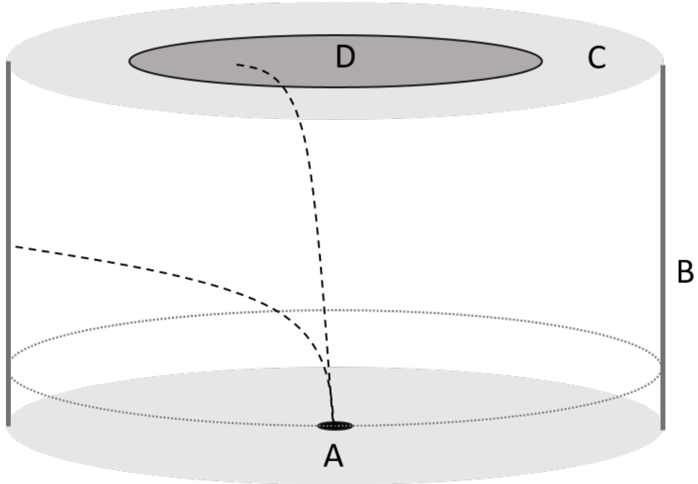


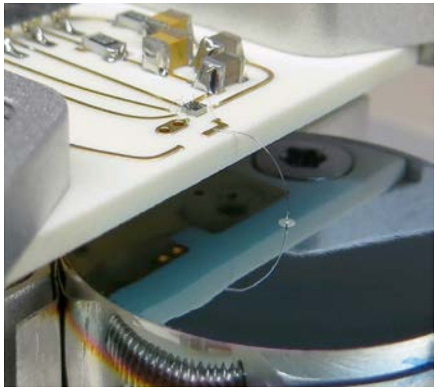
Work at Queen's

- **ORTEC PPC:** 1kg detector identical to the enriched ones in MJD:
    - Study properties of surface events (Li and passivated layers)
    - Develop ML based slow pulse identification, de-noising

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

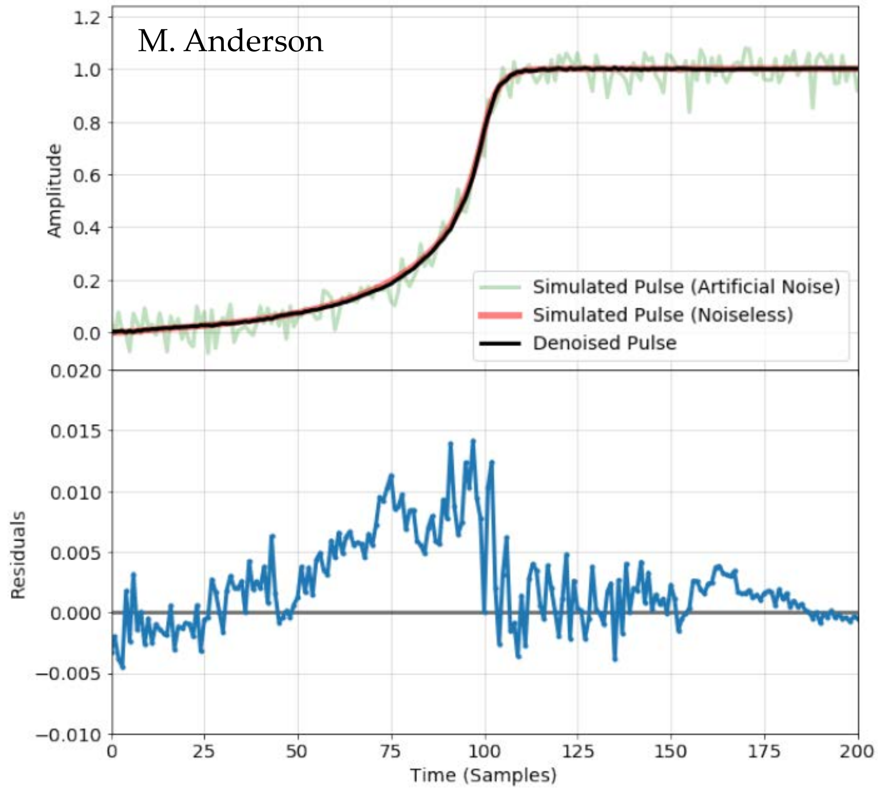
- Developing novel ASIC based electronics:
    - A preamp in a cubic millimetre
    - How to make it work in LAr?

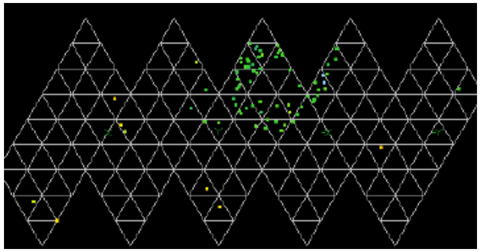




Machine learning

- 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 (or paid!) time, get in touch!