Surface Alpha Interactions in PPC HPGe Detectors: Maximizing Sensitivity of ^{76}Ge $0\nu\beta\beta$ Searches

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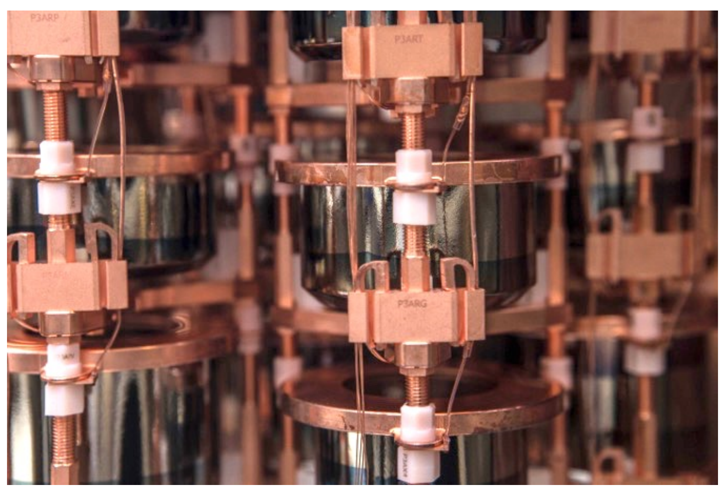
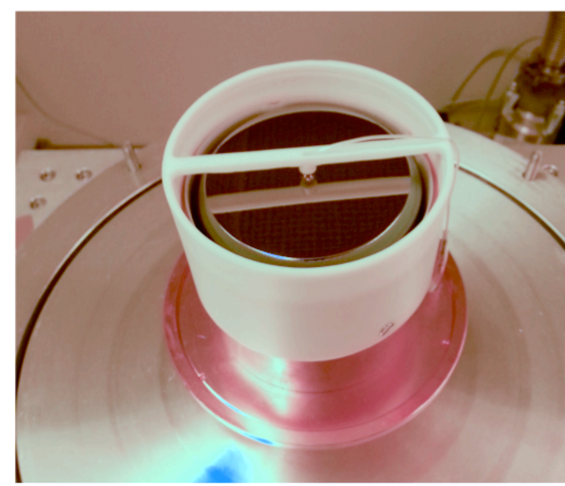
Outline

- Introduction to Neutrinoless Double Beta Decay
- PPC Detectors and Low-Background Physics
- Surface Alpha Identification with DCR
- PPC Response Measurement with TUBE
- Alpha Backgrounds in the Majorana Demonstrator

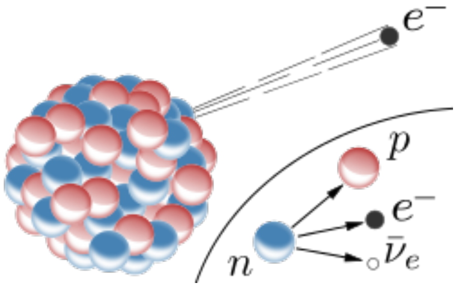


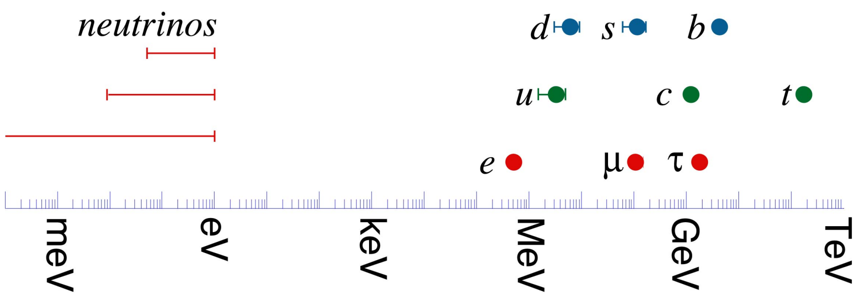


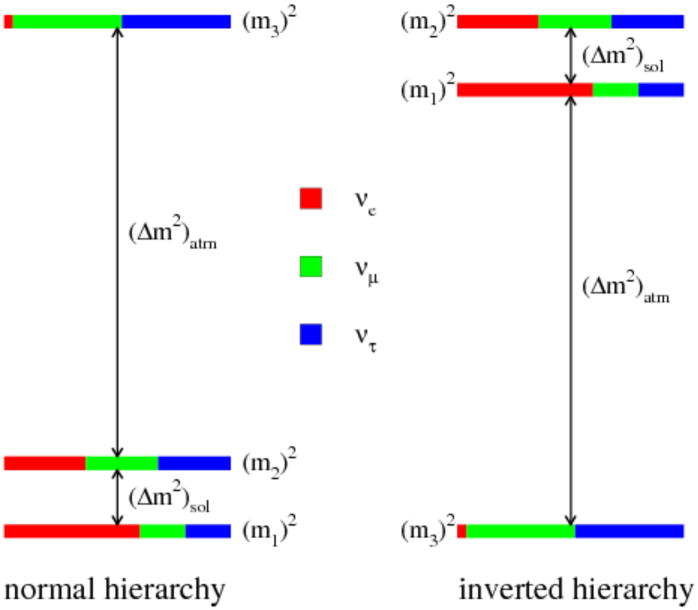
INTRODUCTION TO $0\nu\beta\beta$

Neutrino Basics

- Light, neutral particles
- Very low interaction rates
- Only υ_L and $(\bar{\upsilon})_R$ in SM
- 3 flavors, 3 mass states
- Tiny masses (<2 eV), unknown mass hierarchy



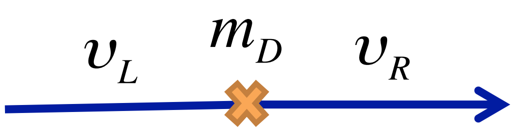




Neutrino Mass

- Mass must be BSM
- Two ways to give the neutrino mass:

Dirac:



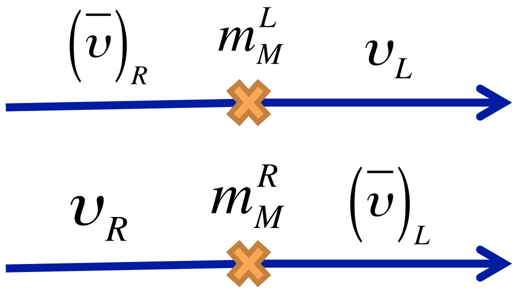
- 4 mass-degenerate states:

υ_L — makes ℓ^+

$\overline{\upsilon_R}$ — makes ℓ^-

$\underbrace{\upsilon_R \quad \overline{\upsilon_L}}$ non-interacting not in SM

Majorana:



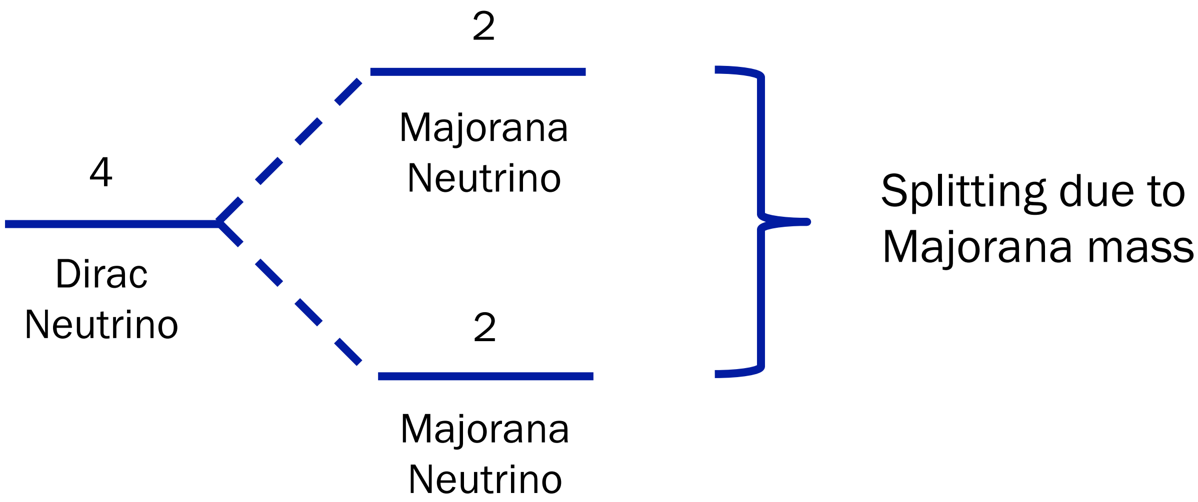
- 2 mass-degenerate states:

υ_L — makes ℓ^+

υ_R — makes ℓ^-

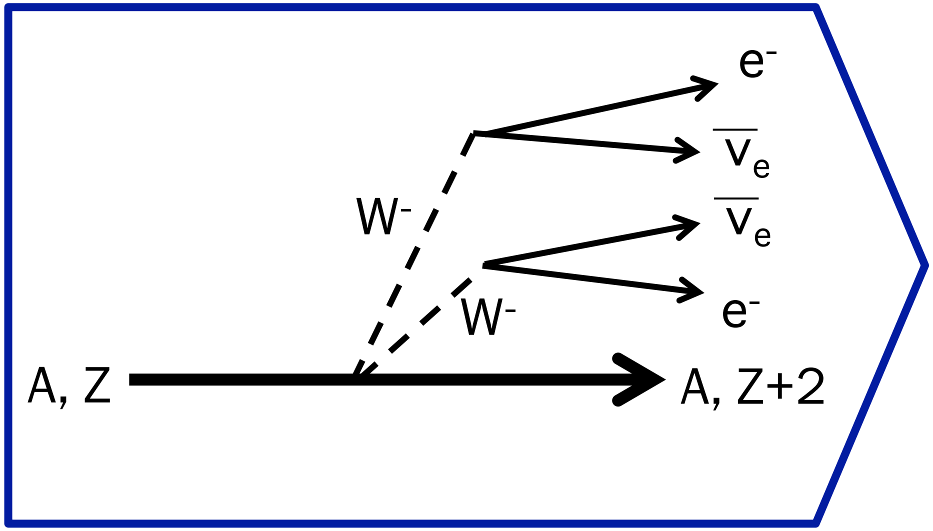
Why Majorana Neutrinos?

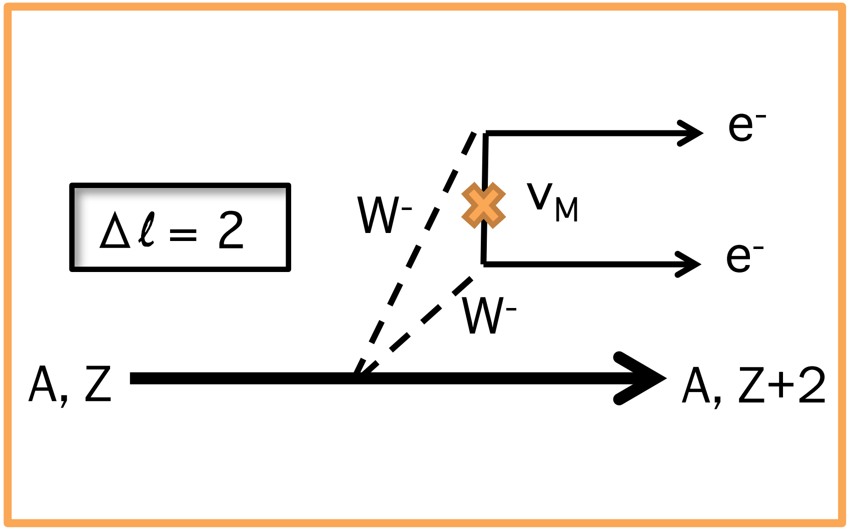
- Combine the two mass terms in a "see-saw mechanism":



- Solves the neutrino mass hierarchy problem, implications for matter/anti-matter asymmetry

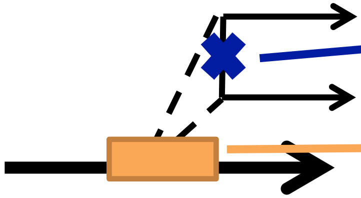
Neutrinoless Double Beta Decay





- 2νββ: a rare SM process that occurs in some nuclei
- If neutrinos are Majorana, 0νββ could occur
- Lepton number conservation is violated

The 0νββ Rate



$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}\boxed{|M_{0\nu}|^2}\left(\frac{\boxed{\langle m_{\beta\beta}\rangle}}{m_e}\right)^2 \qquad \langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$$

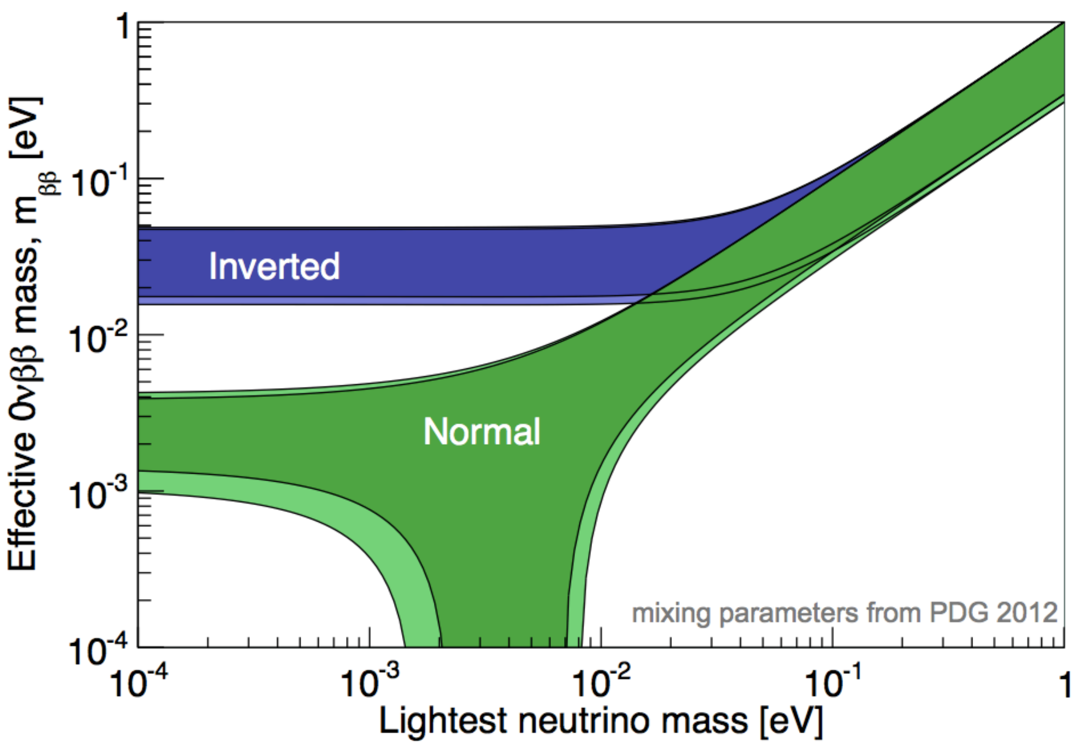


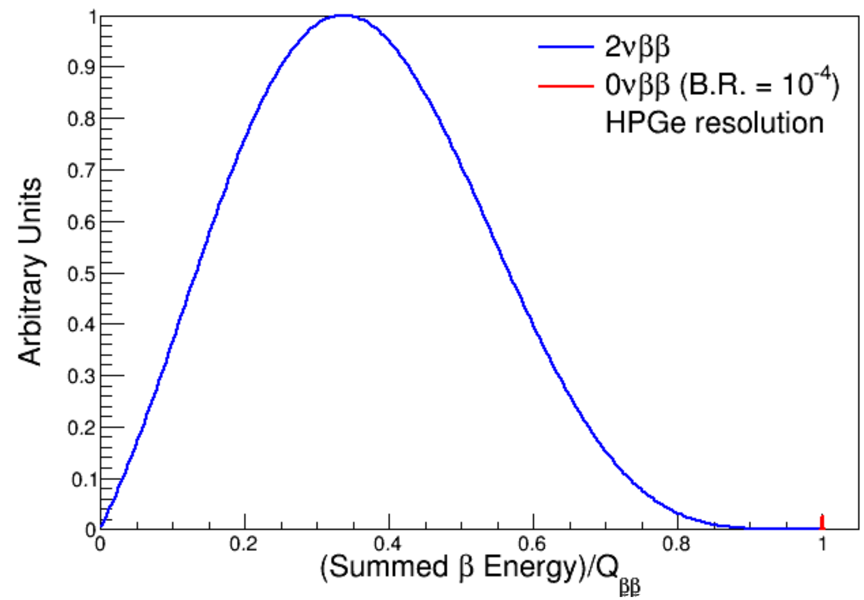
Figure courtesy of A. Schubert

- Rate depends on mixing angles and phases, neutrino mass, and mass hierarchy
- Uncertainties in:
  - $m_{\beta\beta}$: lightest ν mass, phases, hierarchy
  - Nuclear matrix elements

How to Detect 0νββ

- Current limits:

  $T_{1/2} > 10^{25}$ years
- **Don't detect neutrinos directly**
- Ignore the neutrinos, measure the rest of the energy
- Need a large mass, high efficiency, low background



The MAJORANA DEMONSTRATOR

The MAJORANA DEMONSTRATOR (MJD) is an array of enriched and natural germanium detectors that will search for the $0\nu\beta\beta$-decay of ^{76}Ge.

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
- Background goal: 3 counts/ROI/t/y after analysis cuts
  - $Q_{\beta\beta}$ = 2.039 MeV

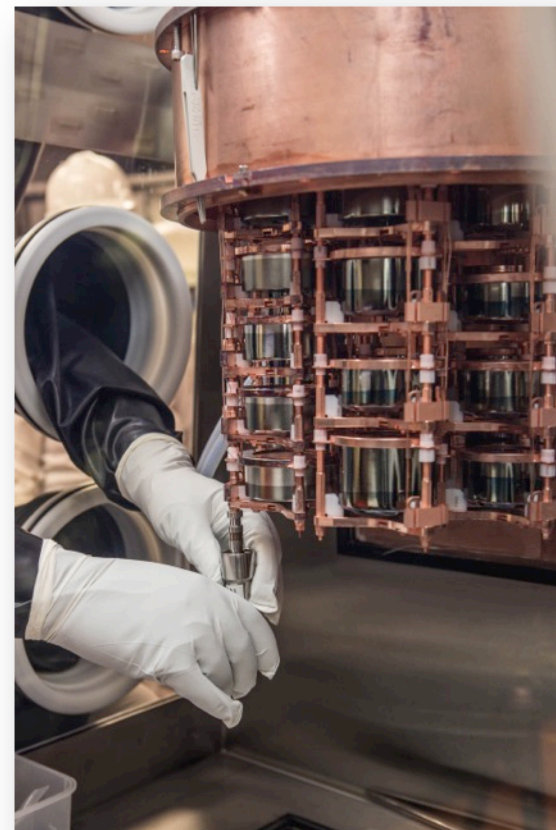
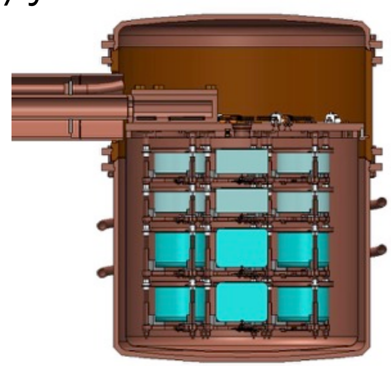
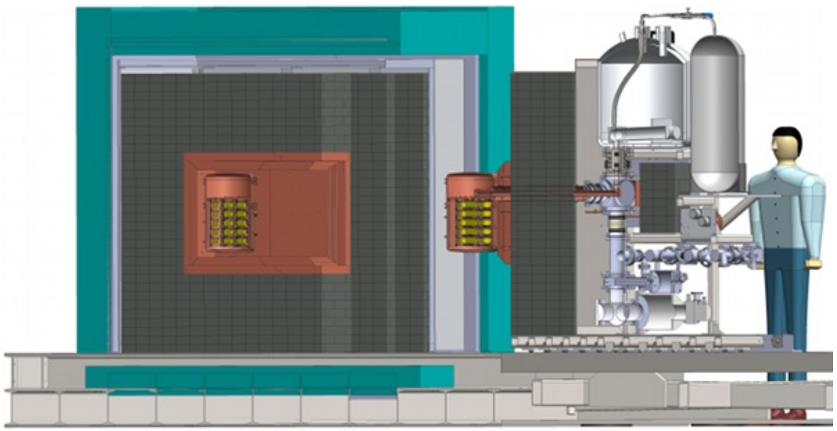


Photo by Matt Kapust



The Present and Future of ^{76}Ge $0\nu\beta\beta$

The MAJORANA DEMONSTRATOR



GERDA

- Parallel efforts using different approaches
  - MJD: Underground electroformed copper and other ultra-clean materials, mostly passive shielding
  - GERDA: Slightly higher-background materials, active shielding with LAr
- Combine best techniques for tonne-scale experiment
  - LEGEND Collaboration formed October 2016

Discovery, Background, and Exposure

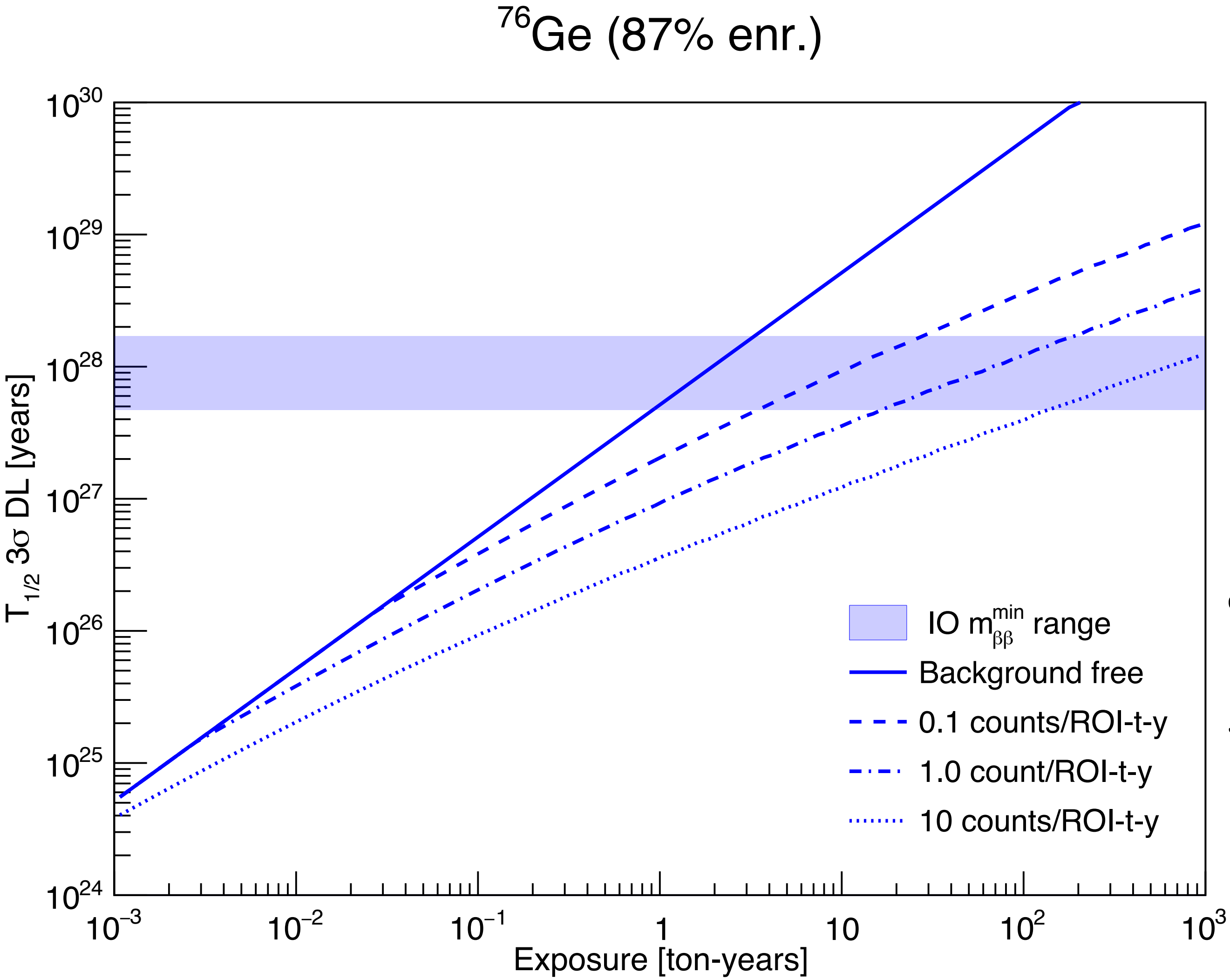
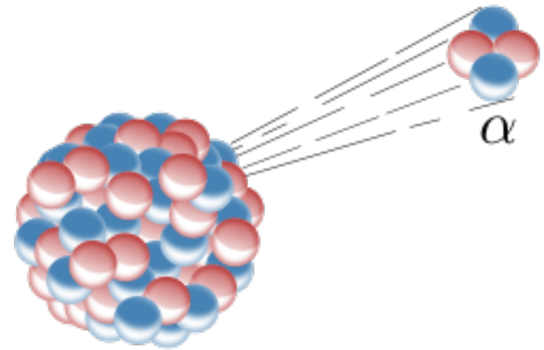
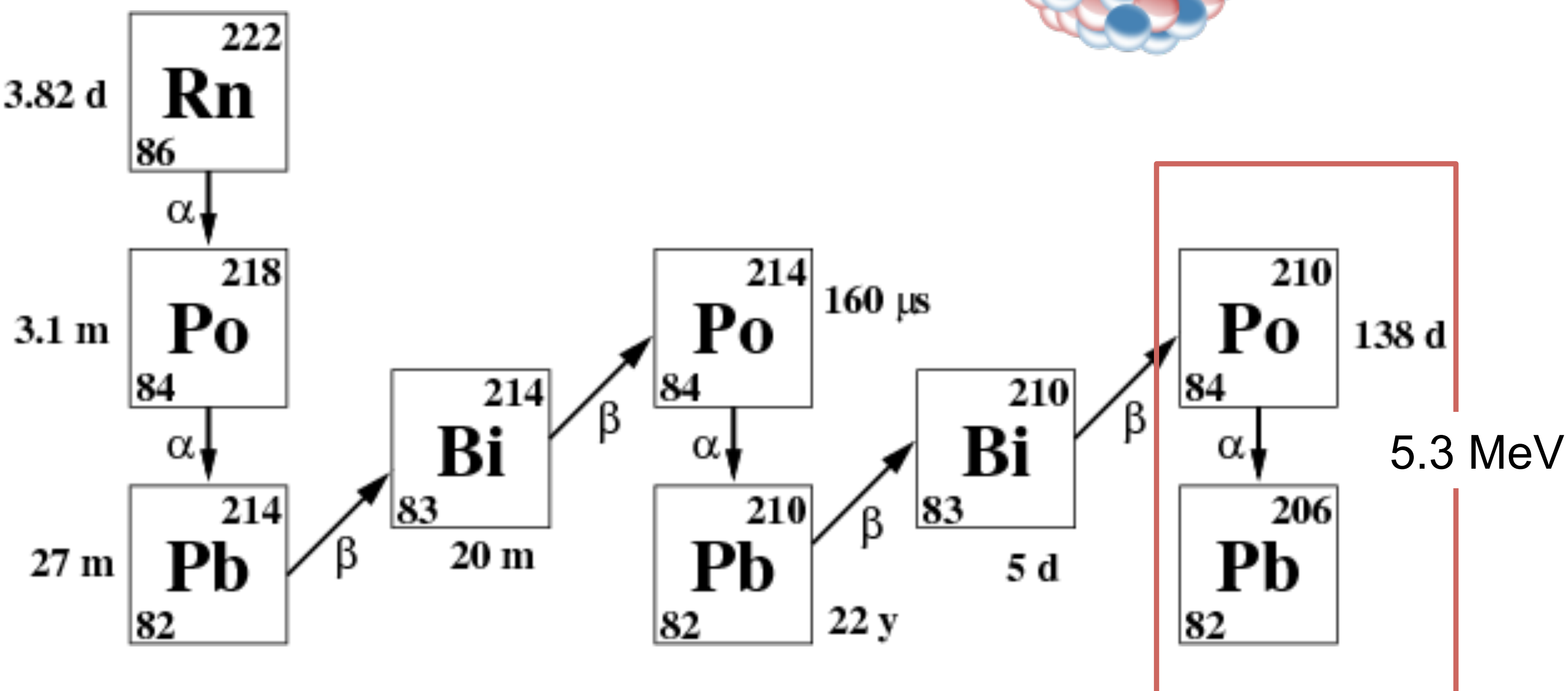


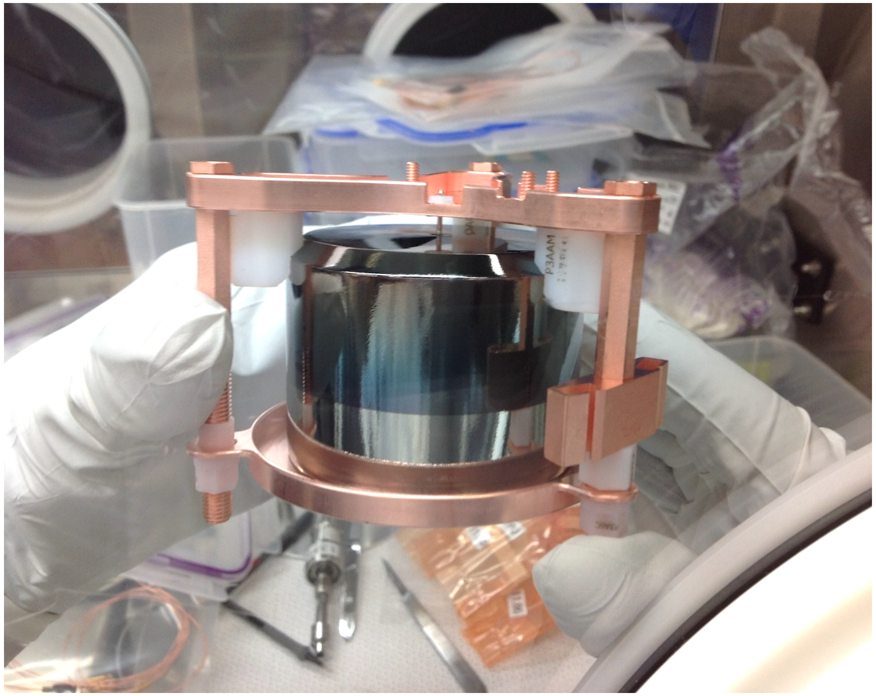
Figure courtesy of J. Detwiler

Alpha Backgrounds

- $\alpha = {}^{4}_{2}He$
- Short range, high energy
- Radon is the biggest problem

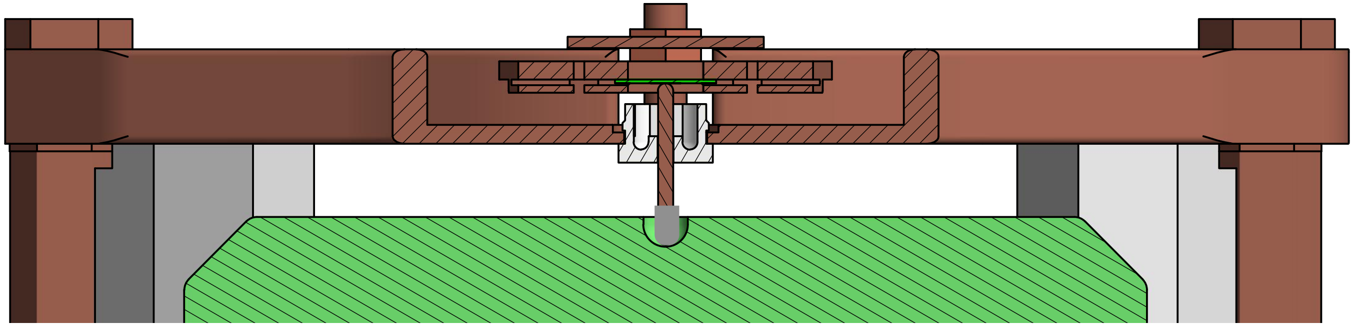






The MAJORANA Detector Unit

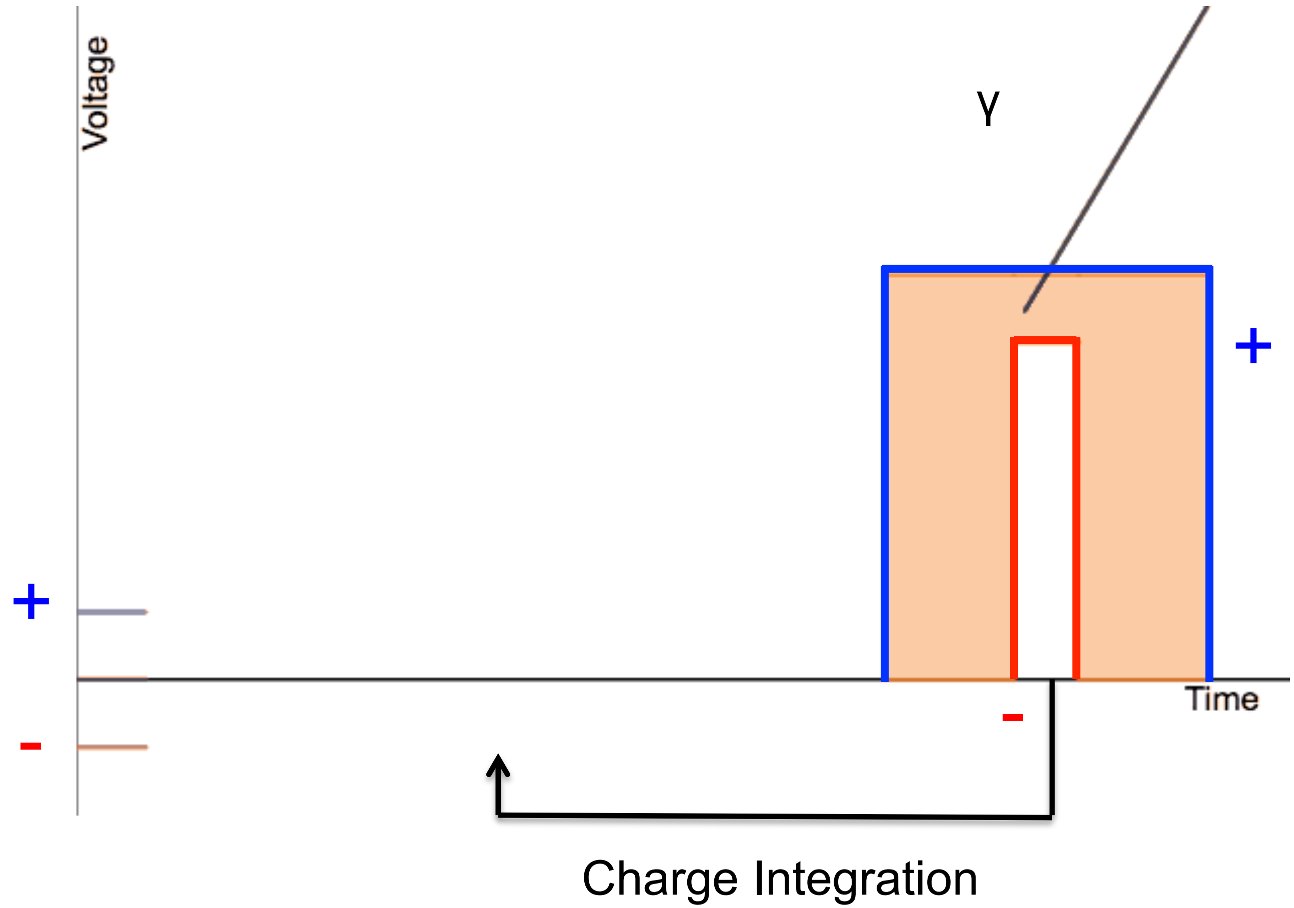
- Holds detector, cabling, front-end electronics



PPC DETECTORS AND LOW-BACKGROUND PHYSICS

HPGe Detectors

- One big Ge diode, fully depleted
- Charge proportional to energy
- Electron and hole fractions depend on position
- In MJ, use enriched Ge (88% ^{76}Ge)



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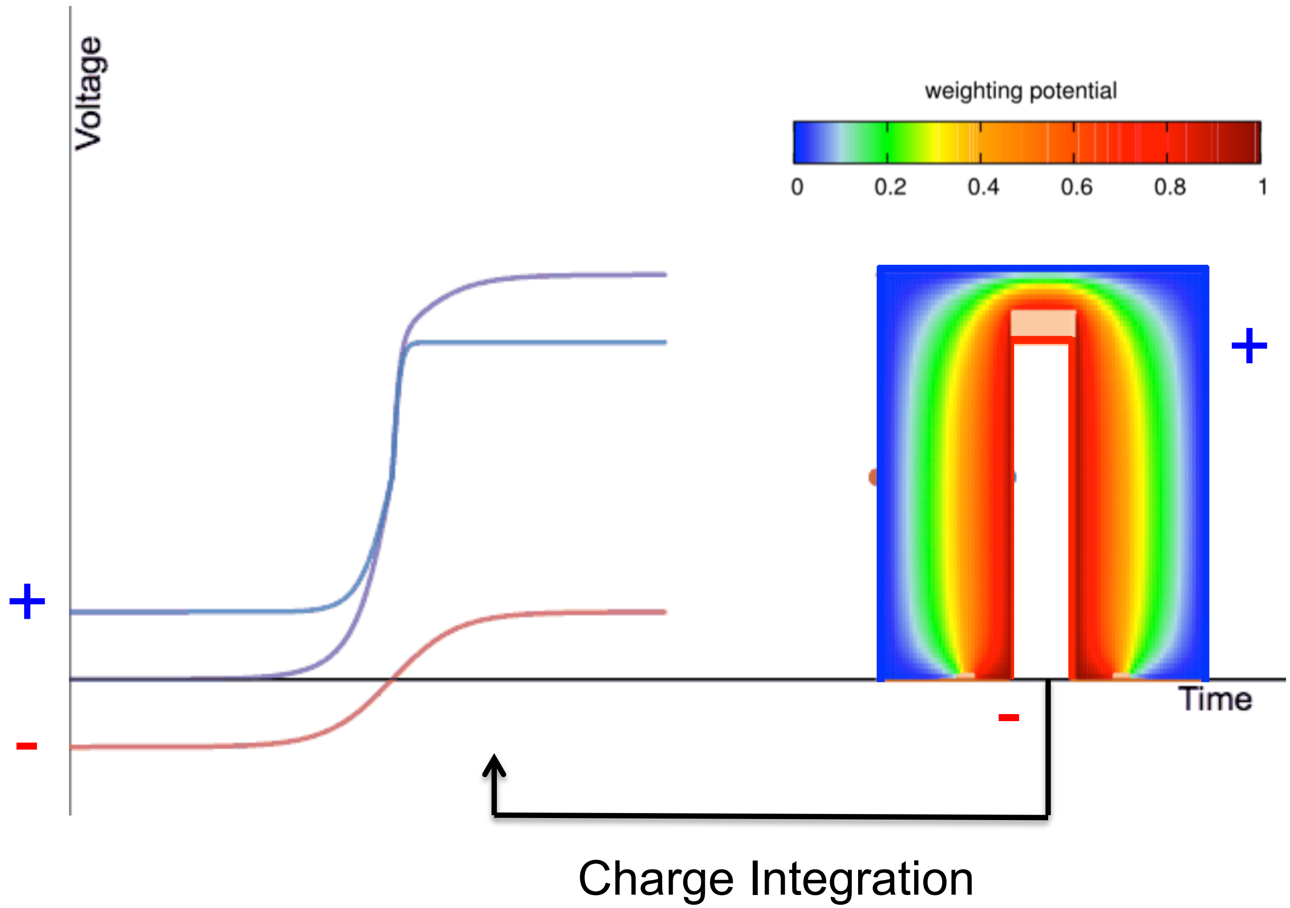
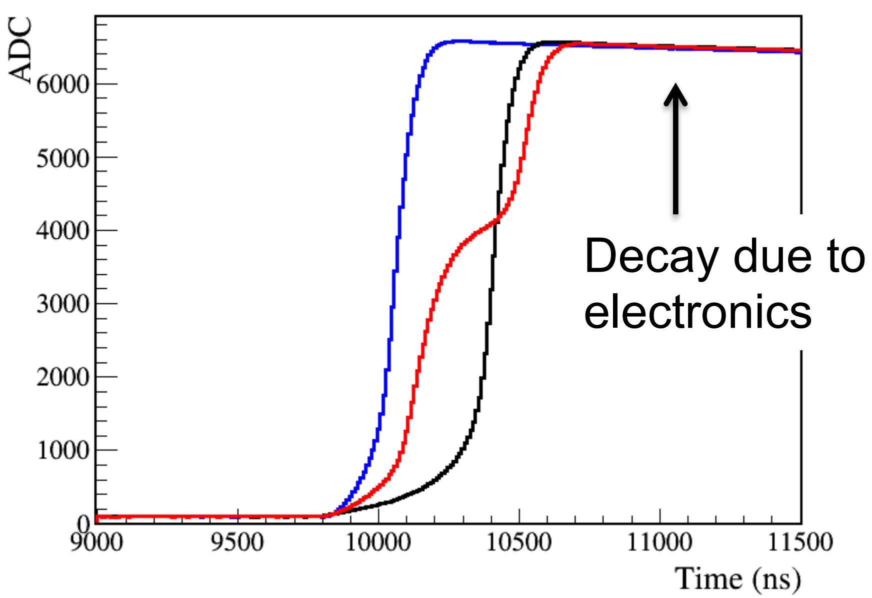
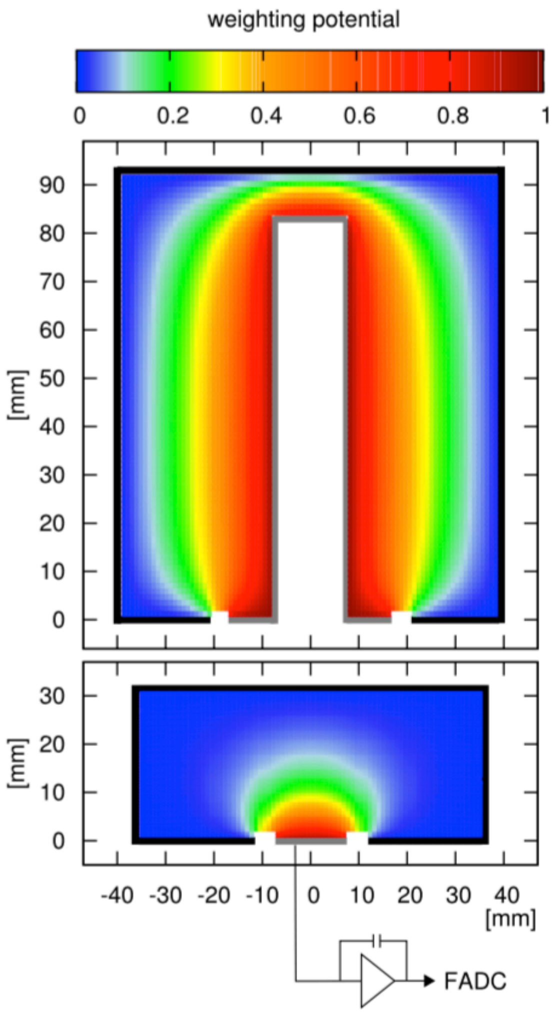


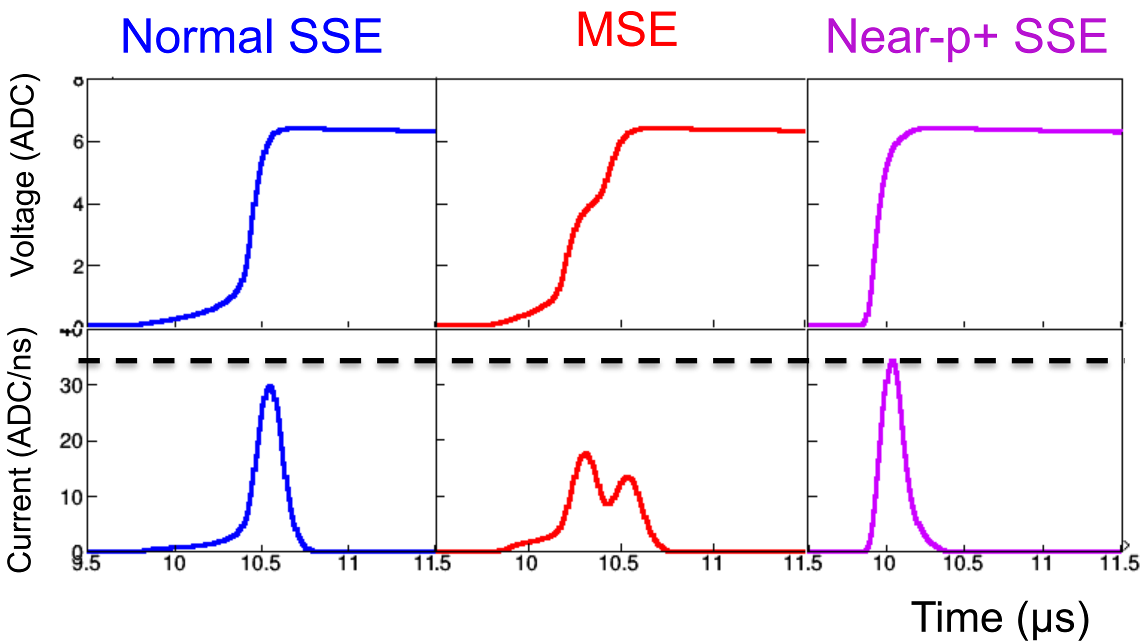
PPC Detectors

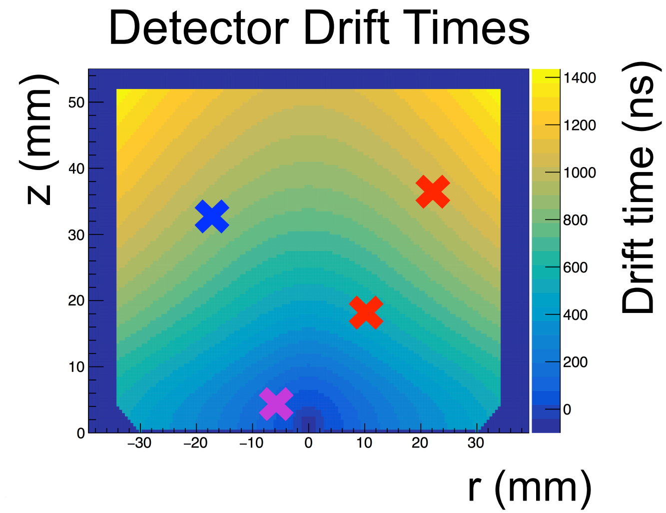
- Better resolution, lower thresholds
- Pulse shape highly dependent on position ➔ multi-site PSD





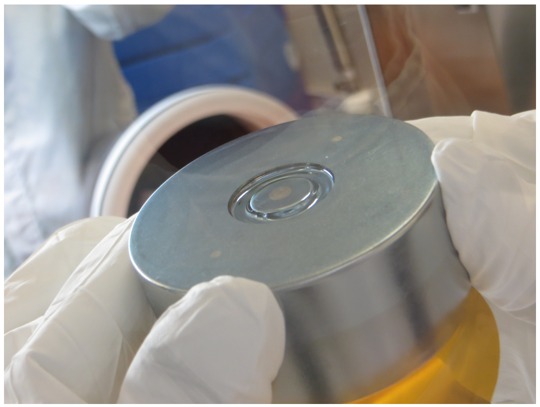
Pulse Shape Discrimination with A/E

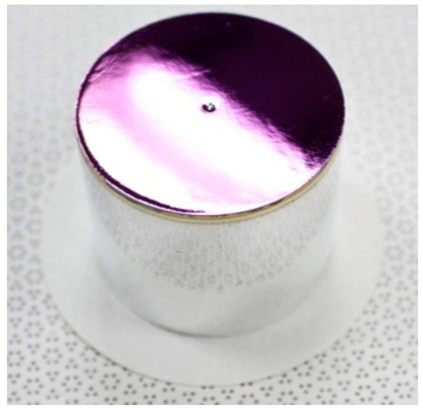


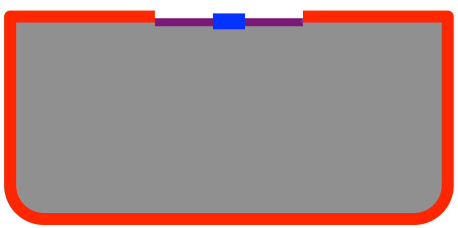


- A = maximum current, E = energy
- Multi-site events have low A/E
- Near-p+ events have high A/E

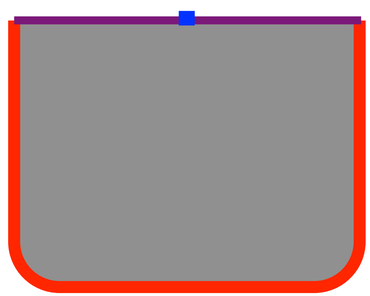
Surface Events







Canberra BEGe Geometry
MJD natural detectors
GERDA enriched detectors



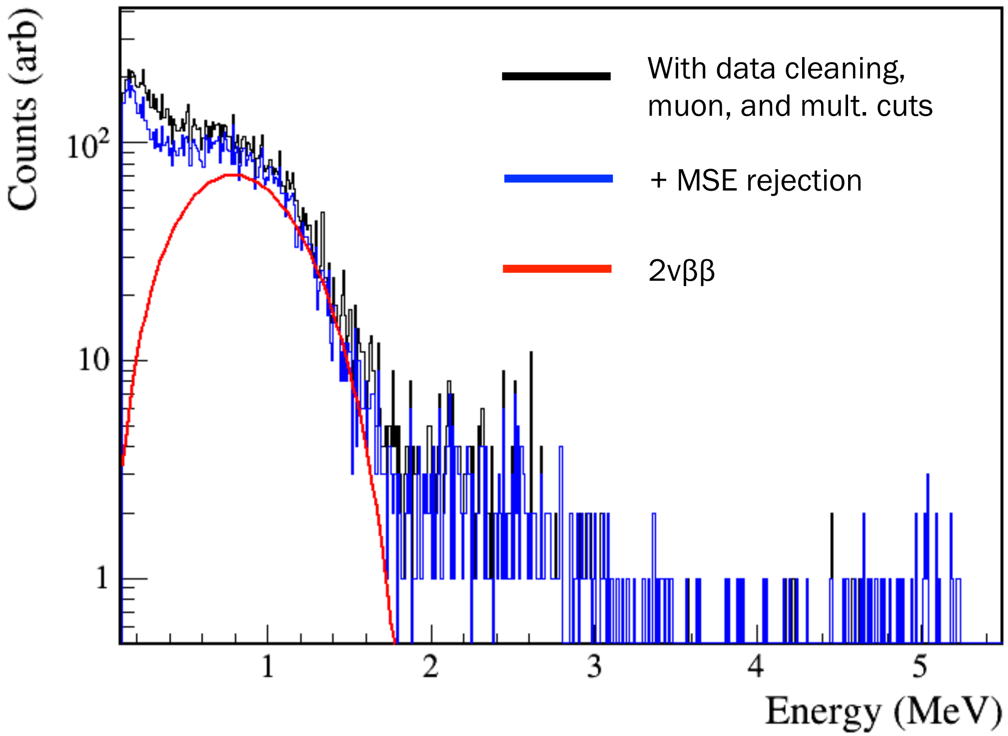
ORTEC Geometry
MJD enriched detectors

- n^+ contact: .5 mm diffused lithium
    - α's don't penetrate
- p^+ contact: .3 μm implanted boron
    - α's barely lose energy
    - Very fast drift, easy to ID with PSD
- Passivated surface: very thin, but poor charge collection

IDENTIFYING SURFACE ALPHAS WITH DCR

α Background in MJD

The Preliminary MJD Spectrum

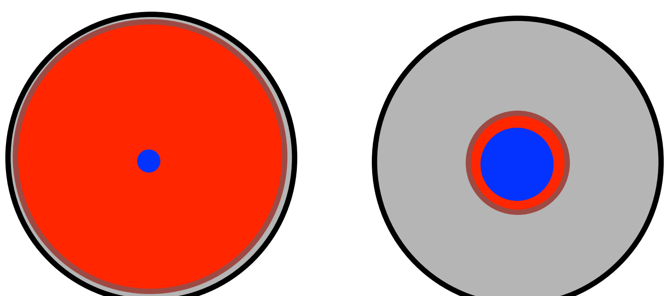


- Clear ^{210}Po peak
- Extra structure below 3 MeV
- ROI backgrounds far above level expected from assay
- Dominant background in ROI

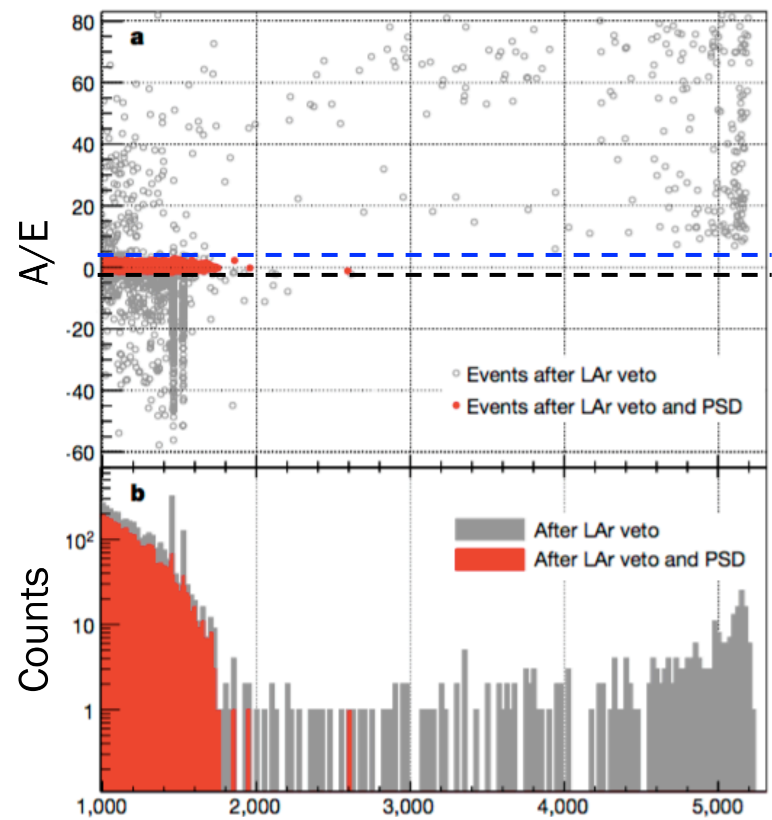
GERDA's α Background

- Approx. 1/2 of ROI events after LAr veto
- Not ^{210}Pb supported,
  - $t_{1/2}$ = 138 days
- Smaller passivated surface
  - Fewer α events
  - All passivated surface events have high A/E

ORTEC BEGe

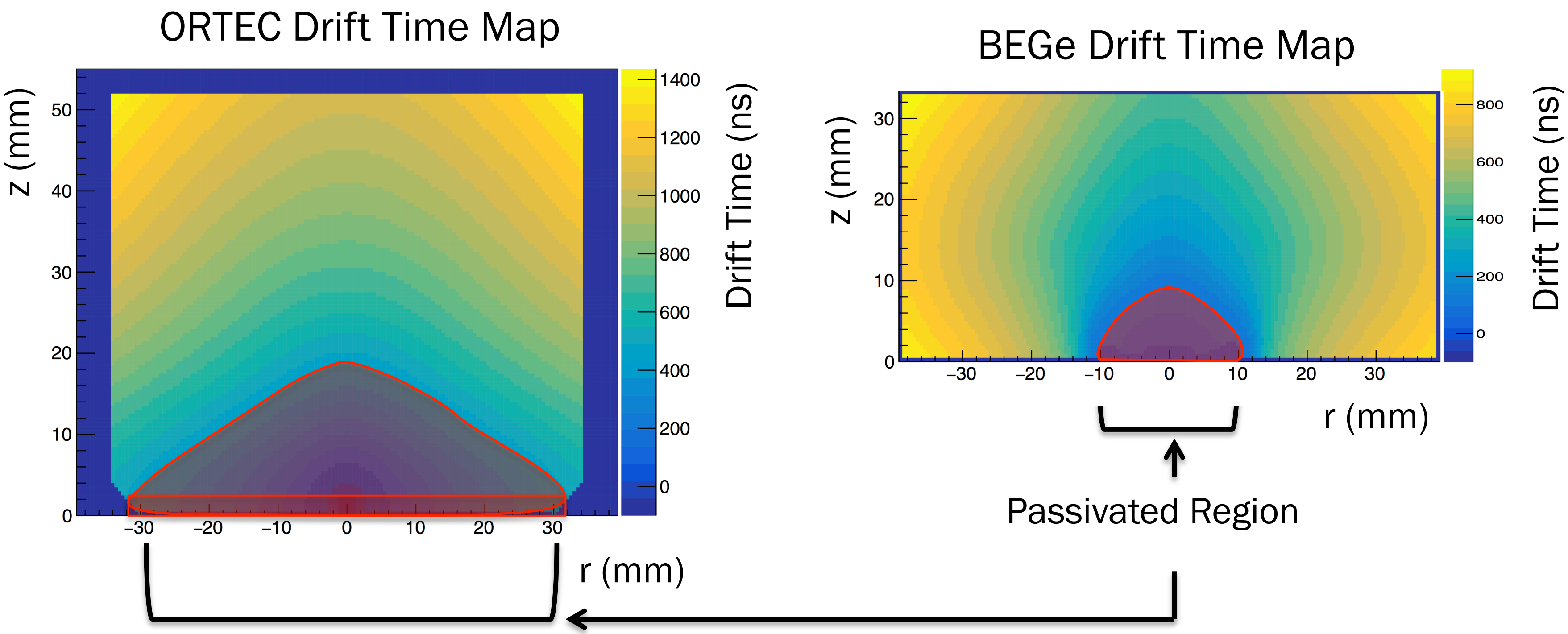


GERDA Spectrum and PSD



The GERDA Collaboration. Background-free search for neutrinoless double-decay of ^{76}Ge with GERDA. Nature, 544(7648):47–52, 04 2017.

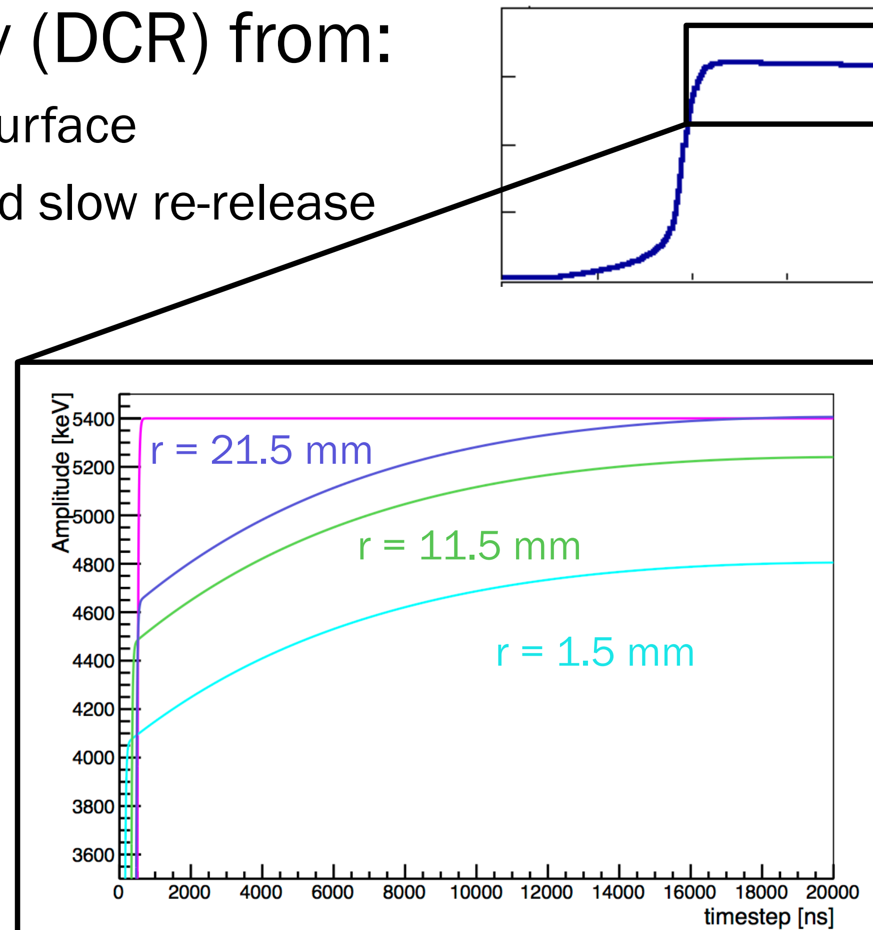
Detector Geometry and α Rejection

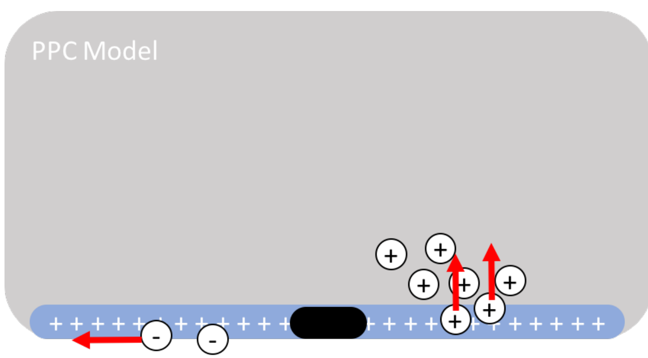


- High A/E is a fiducial volume cut– removes bulk events
- Would be better to cut based on specific surface behavior

Passivated Surface Pulse Shapes

- Some of the charge collected normally
- Delayed charge recovery (DCR) from:
  - Surface drift of electrons on surface
  - Near-surface hole trapping and slow re-release
- Simulated with siggen

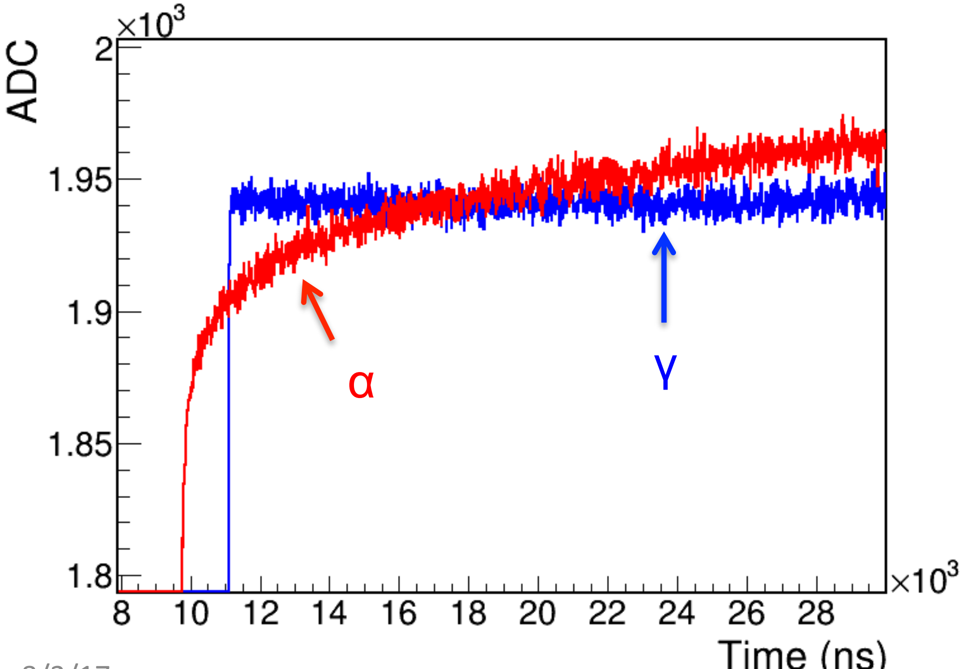


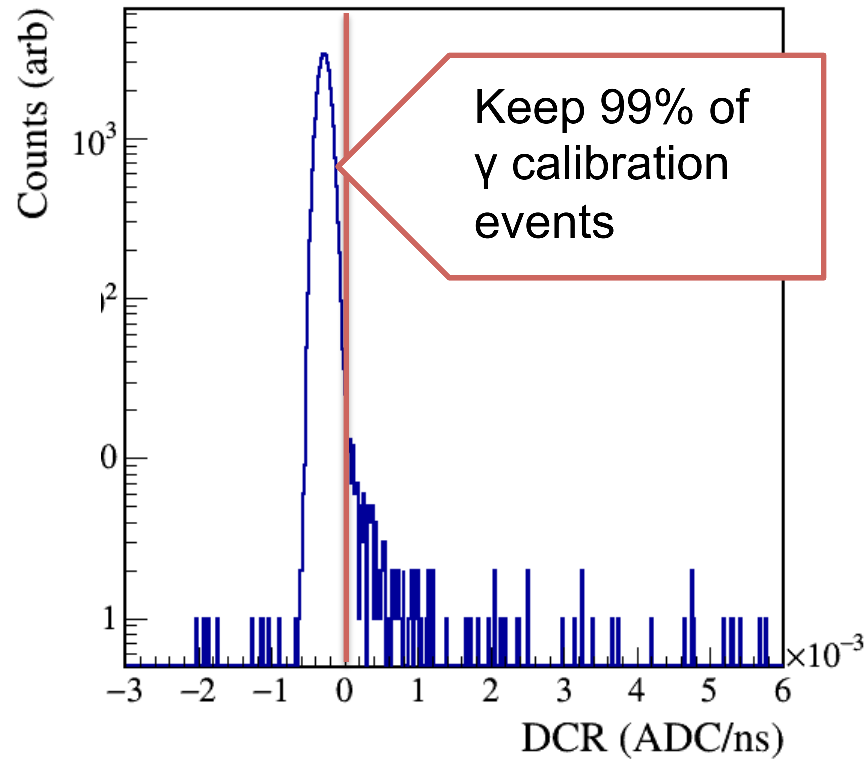


- Siggen developed by David Radford
- Simulations by Susanne Mertens

The DCR PSD Parameter

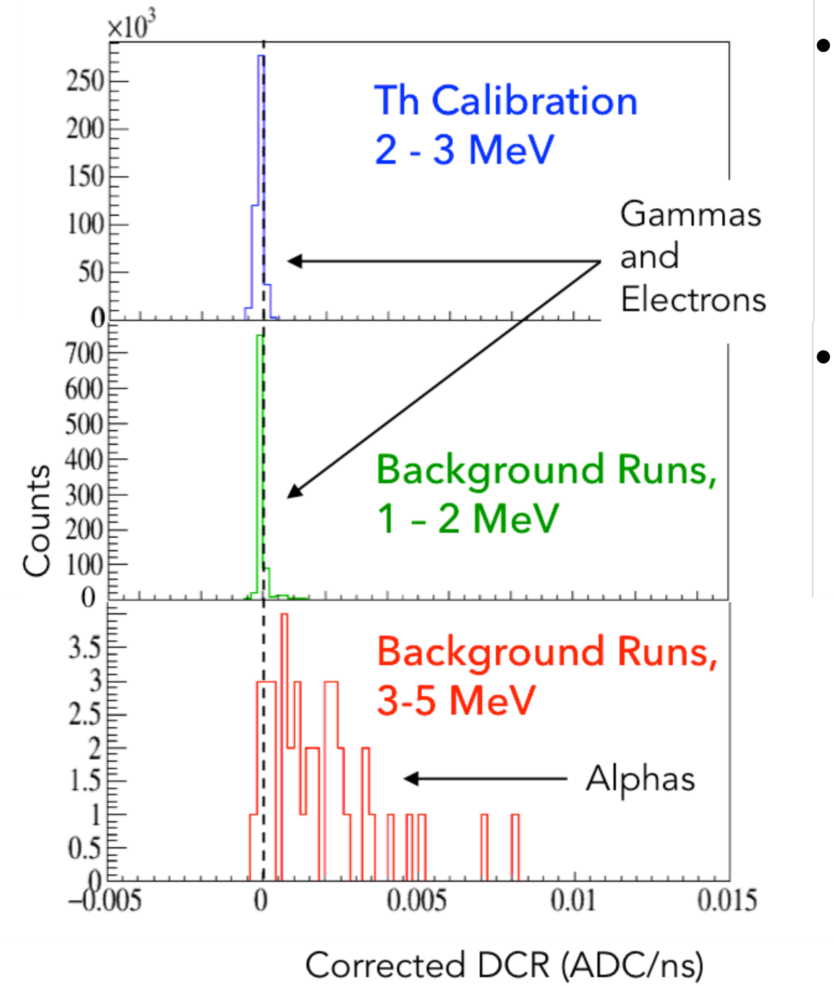
- Correct for decay from electronics
- Measure slope of tail
- Cut events with high DCR



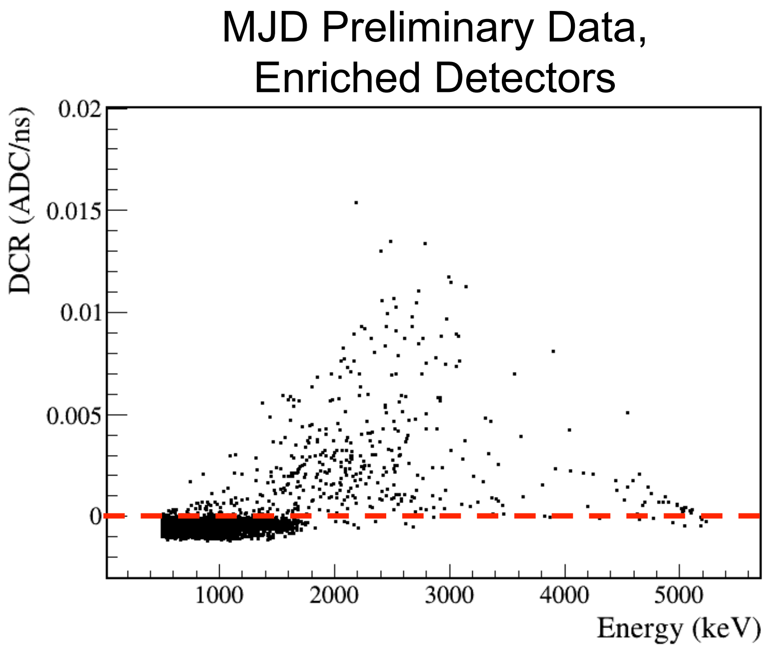


- Publication in preparation

Preliminary Tests in MJD



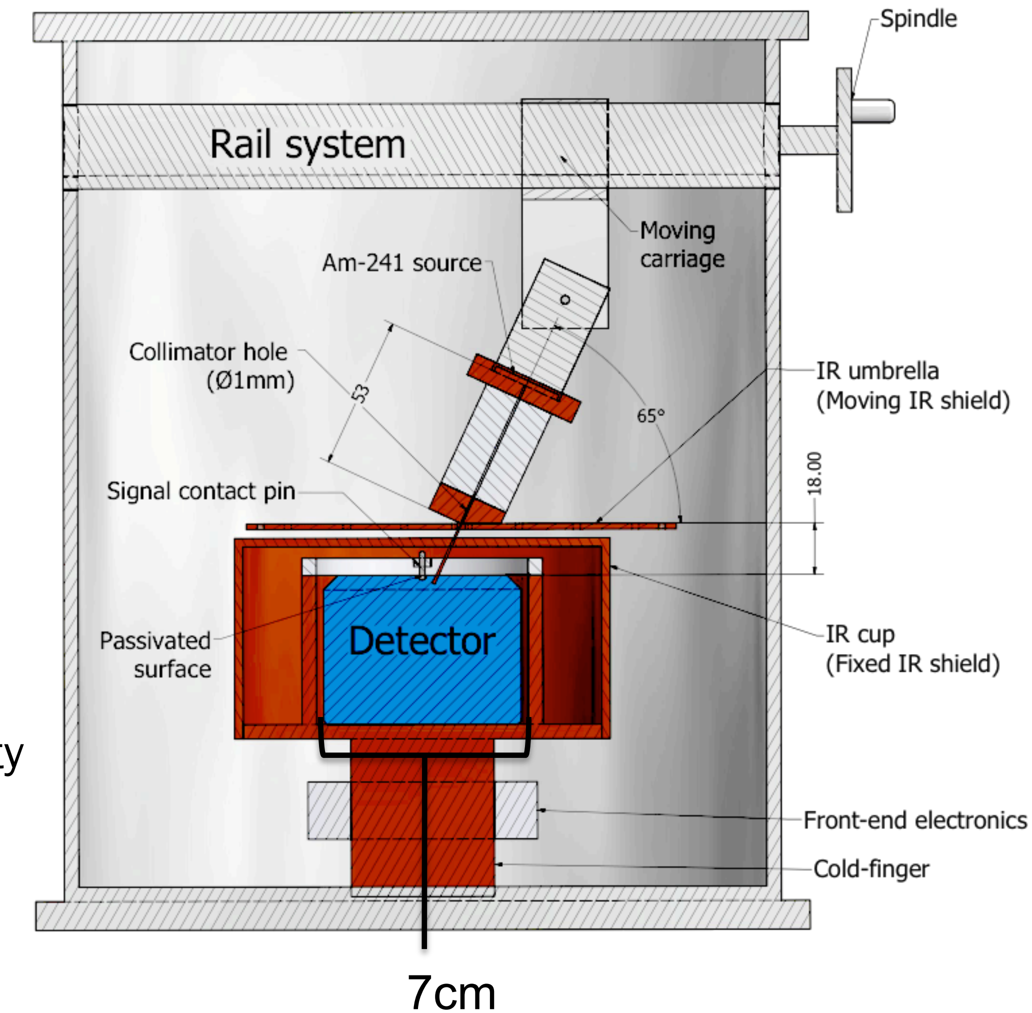
- Events cut:
  - 10% of single-site calibration events between 1 and 2.38 MeV
  - 16.4% with energy between 1 and 2 MeV
  - 88.4% with energy between 2 and 3 MeV
- Need dedicated α data to validate



MEASURING PPC RESPONSE WITH TUBE

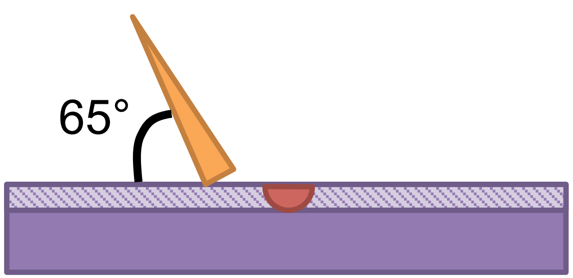
The TUM Upside-Down BEGe (TUBE) Scanner

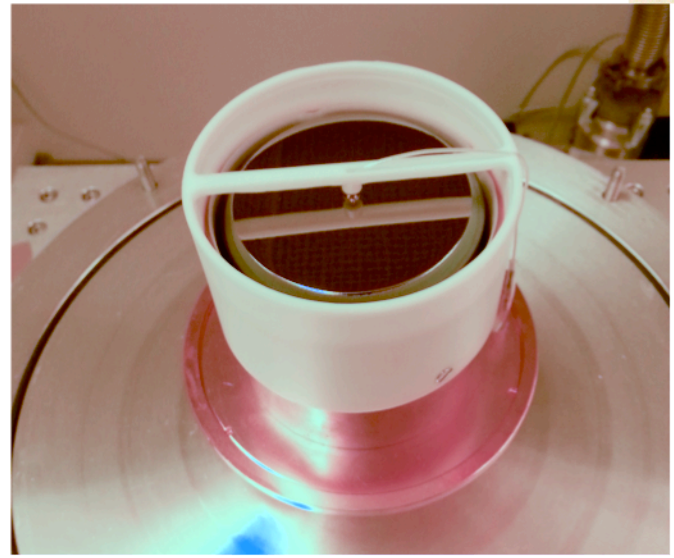
- First joint work between GERDA and MJD groups
- Adapted existing alpha scanning system to scan MJD detector
- Questions:
  - Energy spectrum
  - E vs. R
  - DCR vs. R
  - Charge loss mechanism
  - A/E and DCR complementarity
  - DCR α rejection power

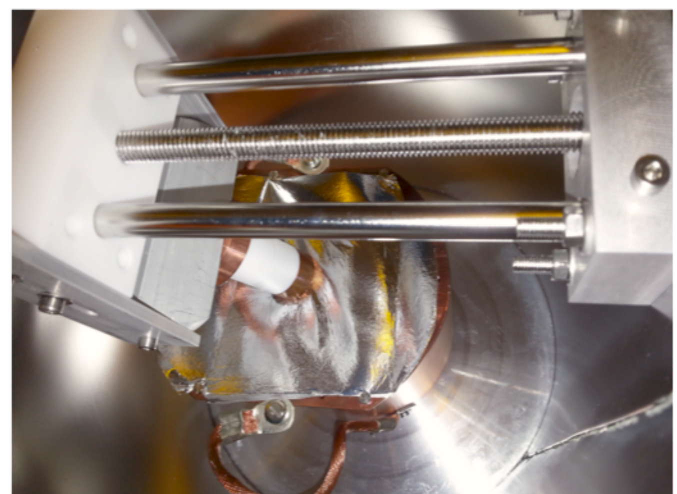


TUBE Measurements

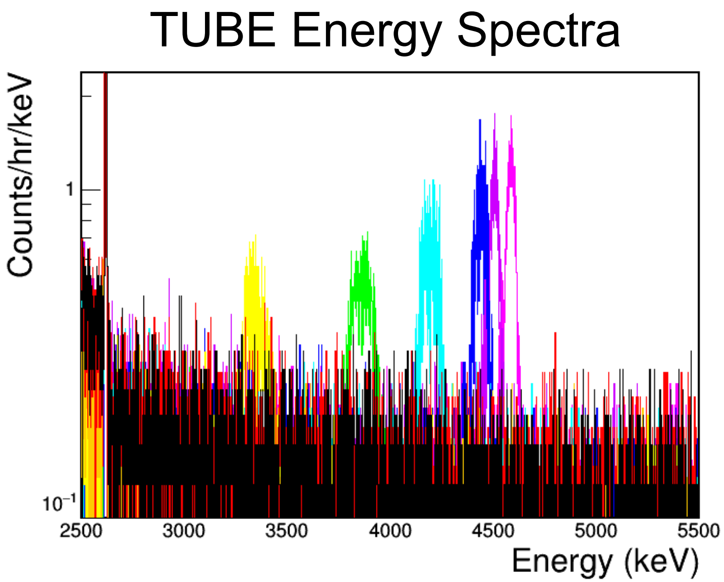
- First assembled Sept. 2016, data taken Feb. – June 2017
- ^{241}Am source:
  - 5.486 MeV α, 20 keV line-width
  - 40 kBq, 65 events/hour
  - 1 mm collimator ➔ 1.8mm spot size
- Scanned every 1.5 mm, 65° angle of incidence, some extra half-positions
- Distances from point-contact are radial
- 24 hours per scan position

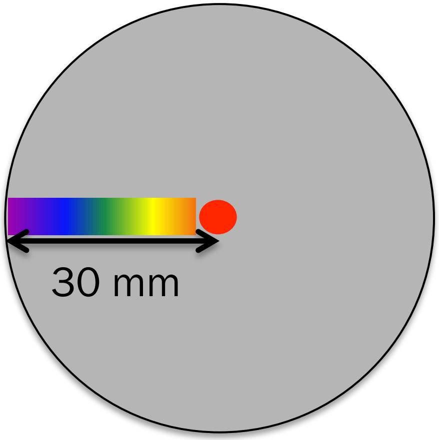


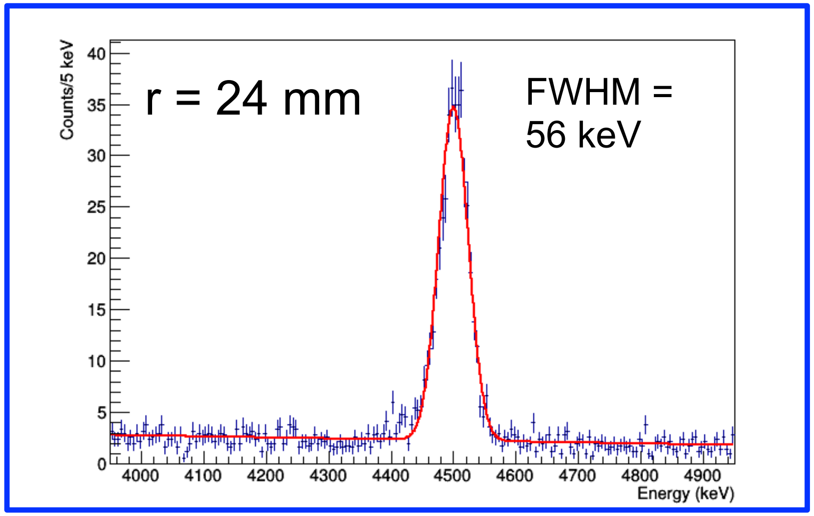


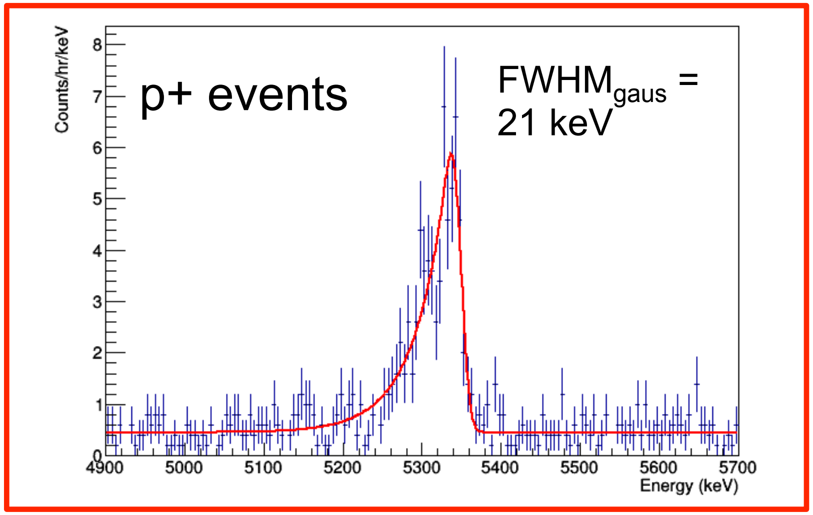


Alpha Energy



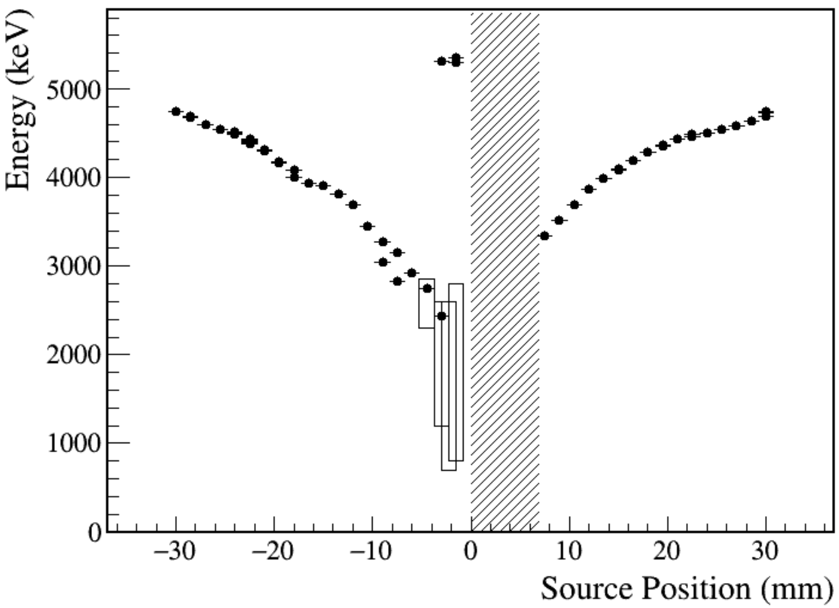




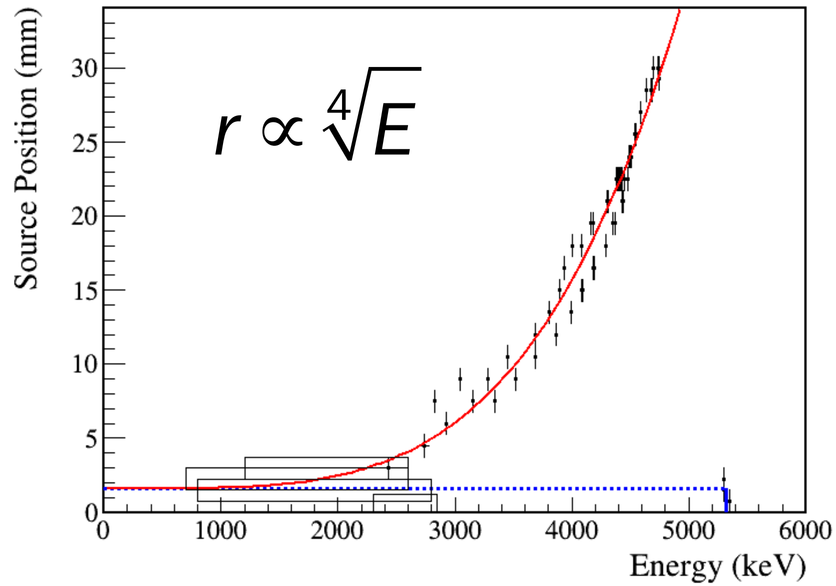


E vs. R

E vs. R



Fitting to R vs. E

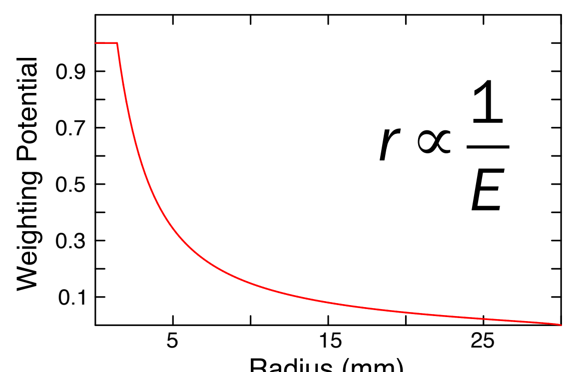


- Passivated surface:

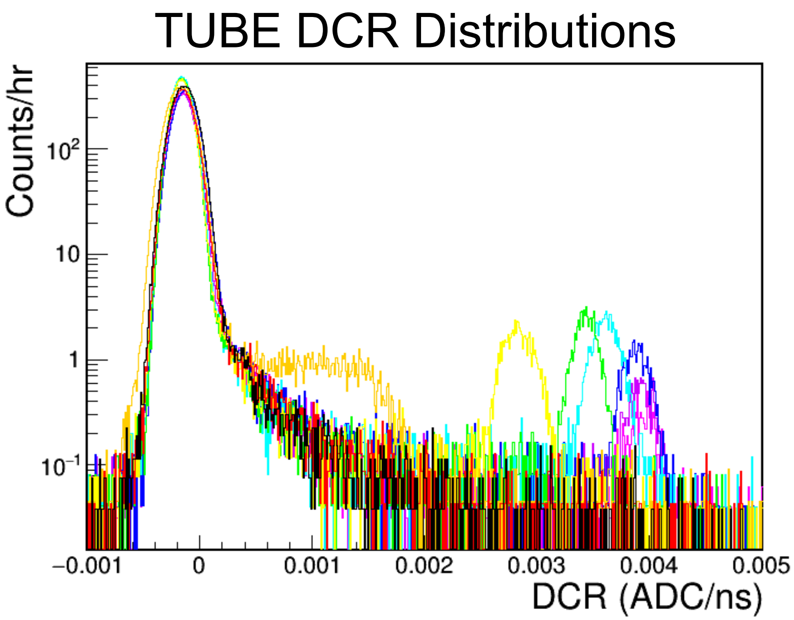
  $r = aE^4 + r_p$

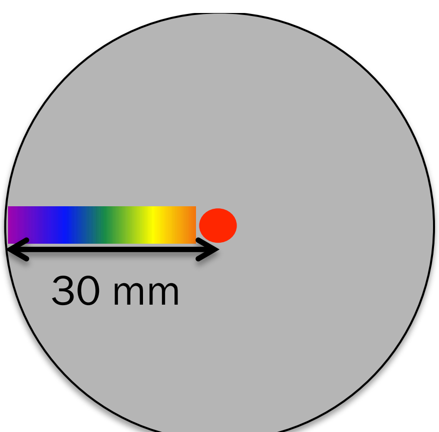
- Can't just be electron loss!

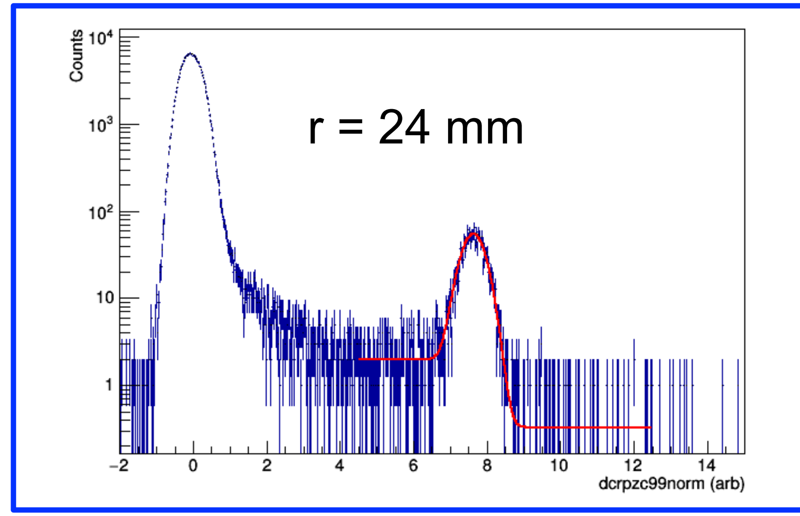
WP at Passivated Surface

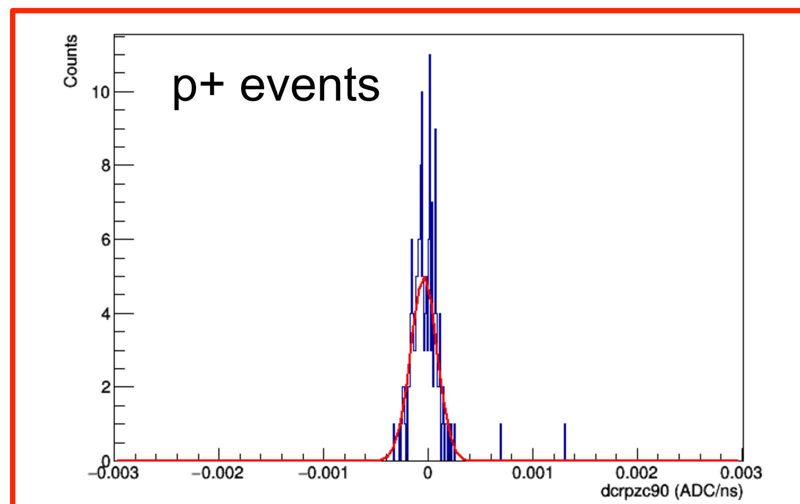


Alpha DCR


TUBE DCR Distributions
Counts/hr
10^2
10
1
10^{-1}
−0.001
0
0.001
0.002
0.003
0.004
0.005
DCR (ADC/ns)

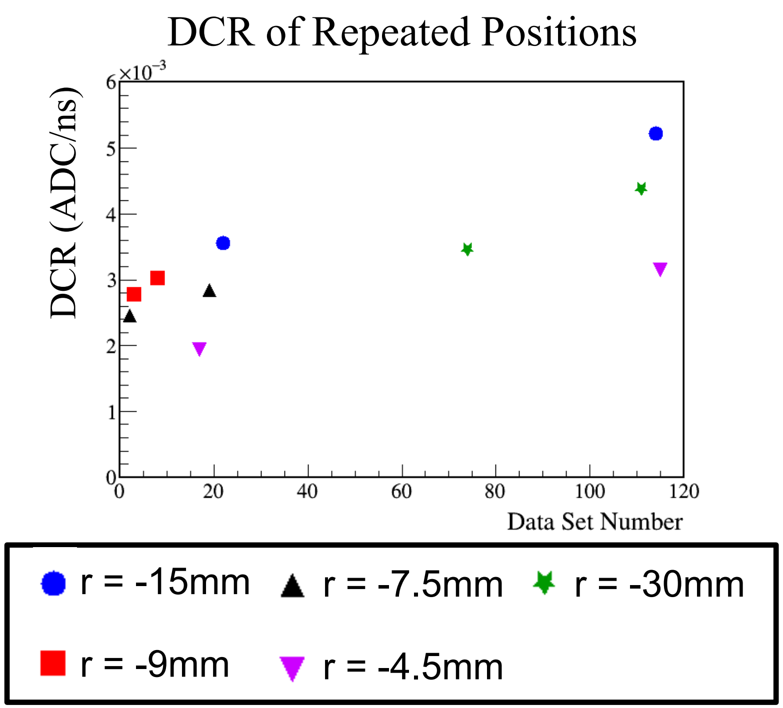

30 mm

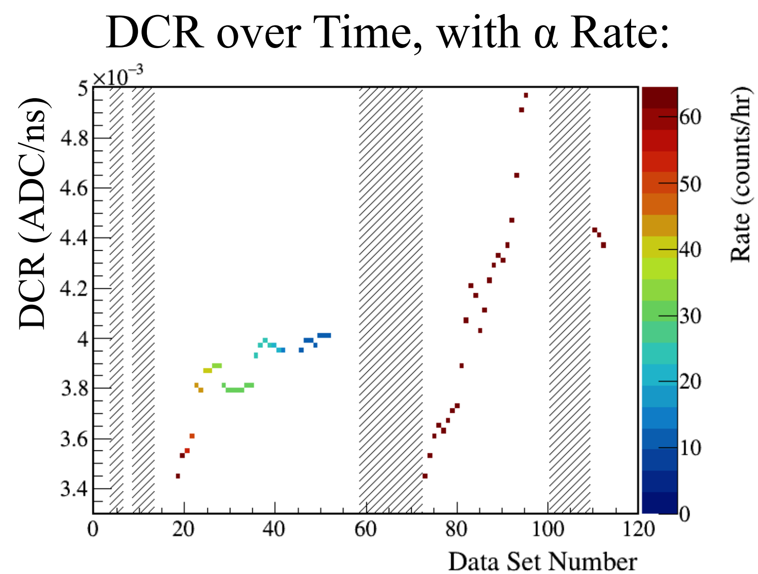

Counts
10^4
10^3
10^2
10
1
r = 24 mm
−2
0
2
4
6
8
10
12
14
dcrpzc99norm (arb)


Counts
10
8
6
4
2
0
p+ events
−0.003
−0.002
−0.001
0
0.001
0.002
0.003
dcrpzc90 (ADC/ns)

Unexpected Result: DCR Stability

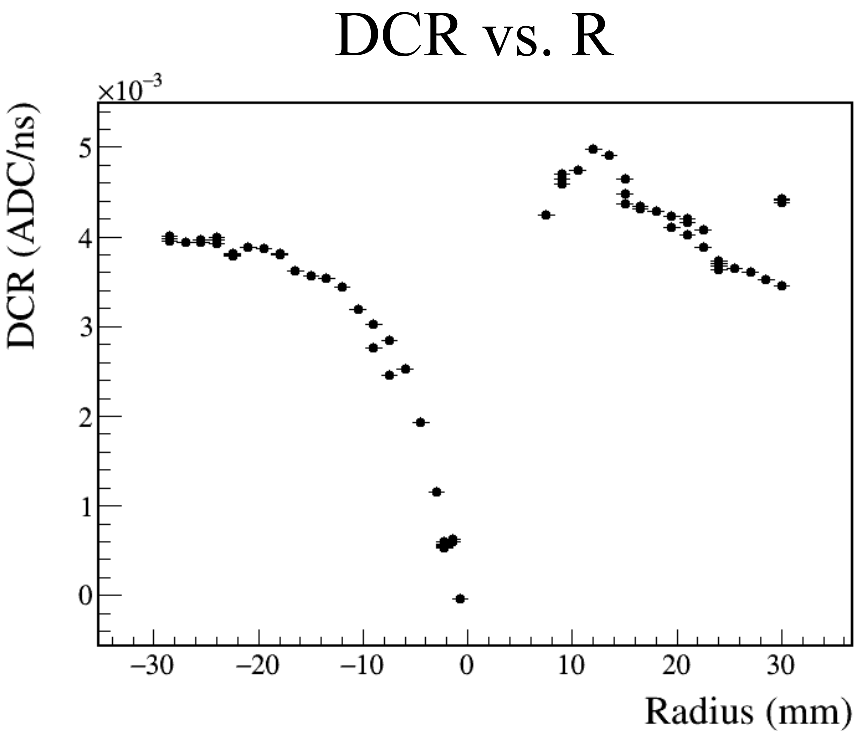
- DCR values increase over time, high α rate appears to cause charge build-up. Drops when source is removed from surface.
- 2 leading theories about mechanism, can test in the future
- Not relevant for MJD (rate is ~5 orders of magnitude lower)





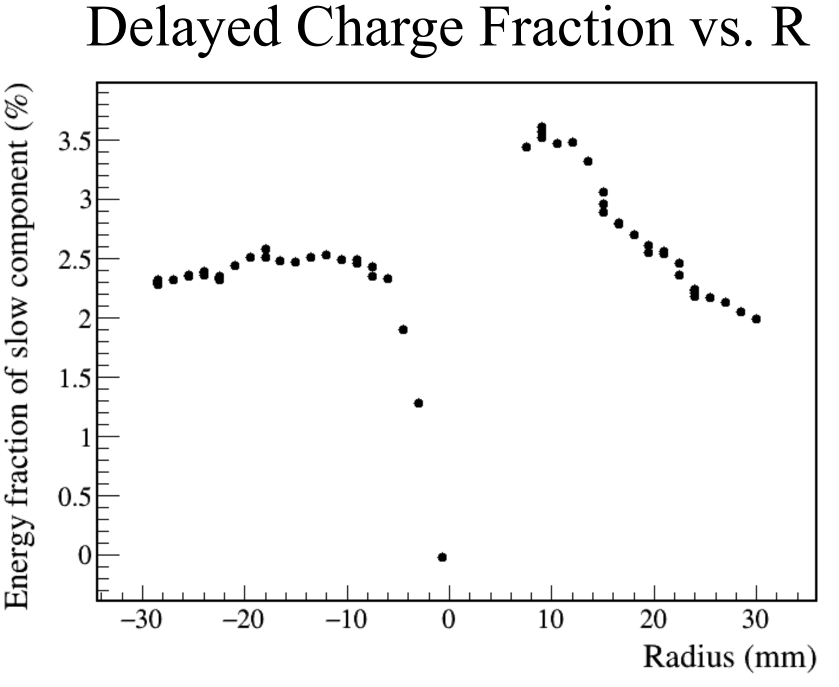
Higher integrated rate, larger increase in DCR

DCR vs. R



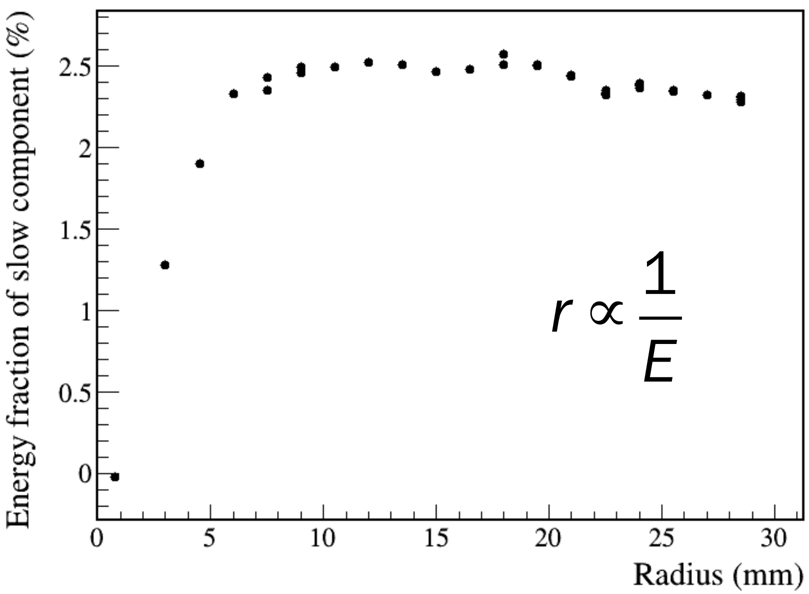
Events near p+ contact have rapidly falling DCR

2 – 3.5% of event energy is collected as delayed charge at positions more than 8mm away from p+ contact:

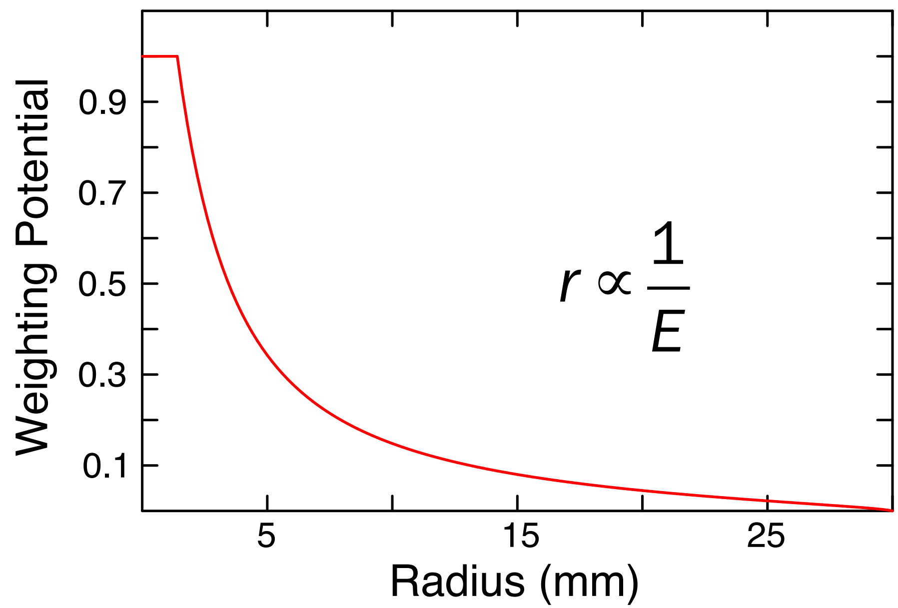


Charge Loss Mechanism

Delayed Charge Fraction vs. |R|

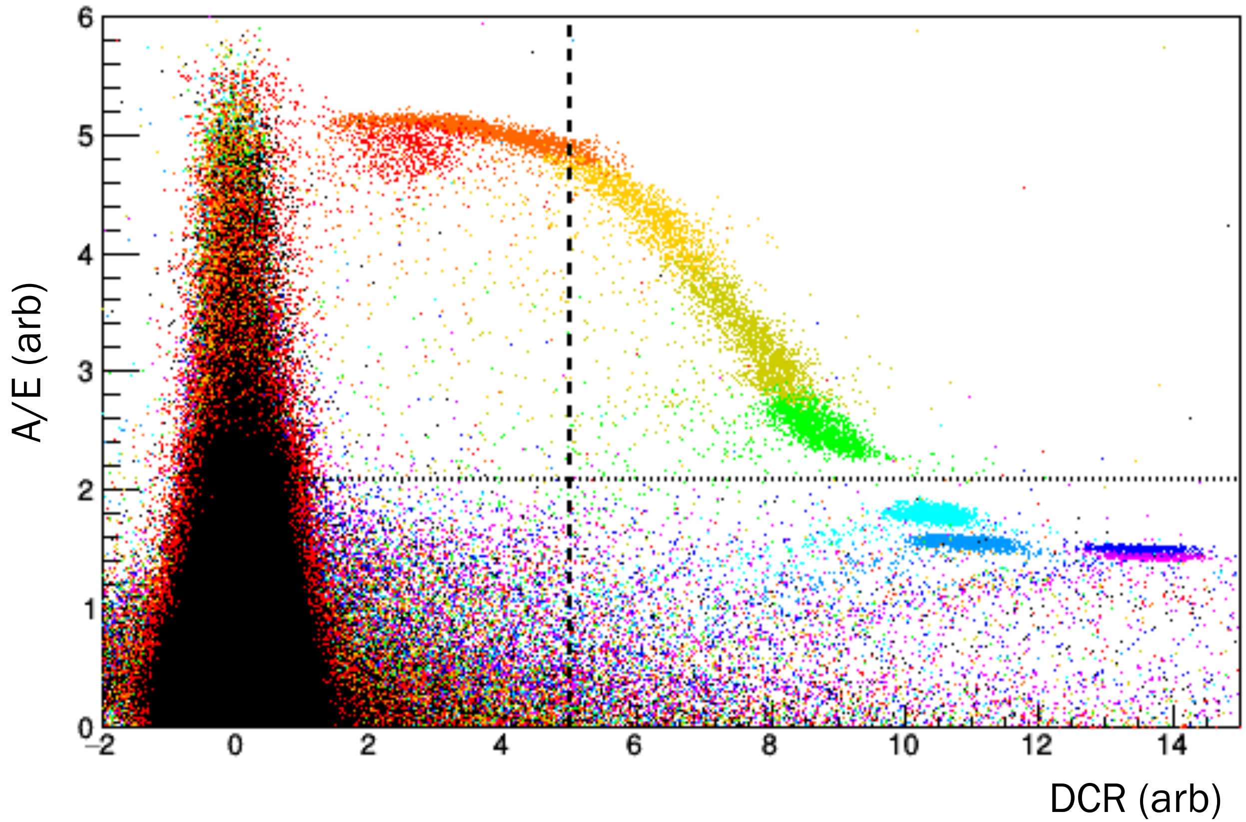


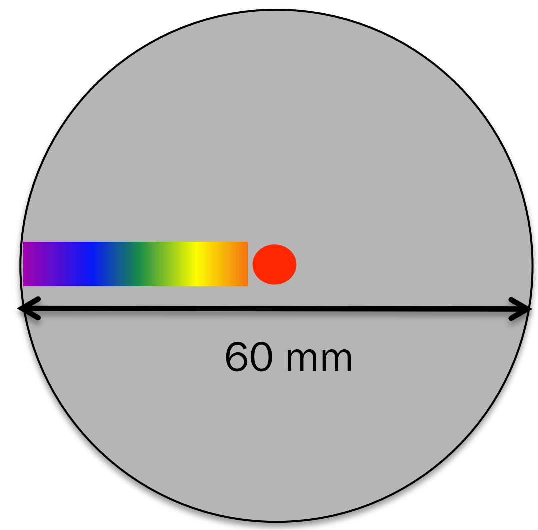
WP at Passivated Surface



- DCR increases with energy and radius
  - ➢Hole recovery dominates DCR mechanism
  - ➢Suggests near-surface trapping & rerelease

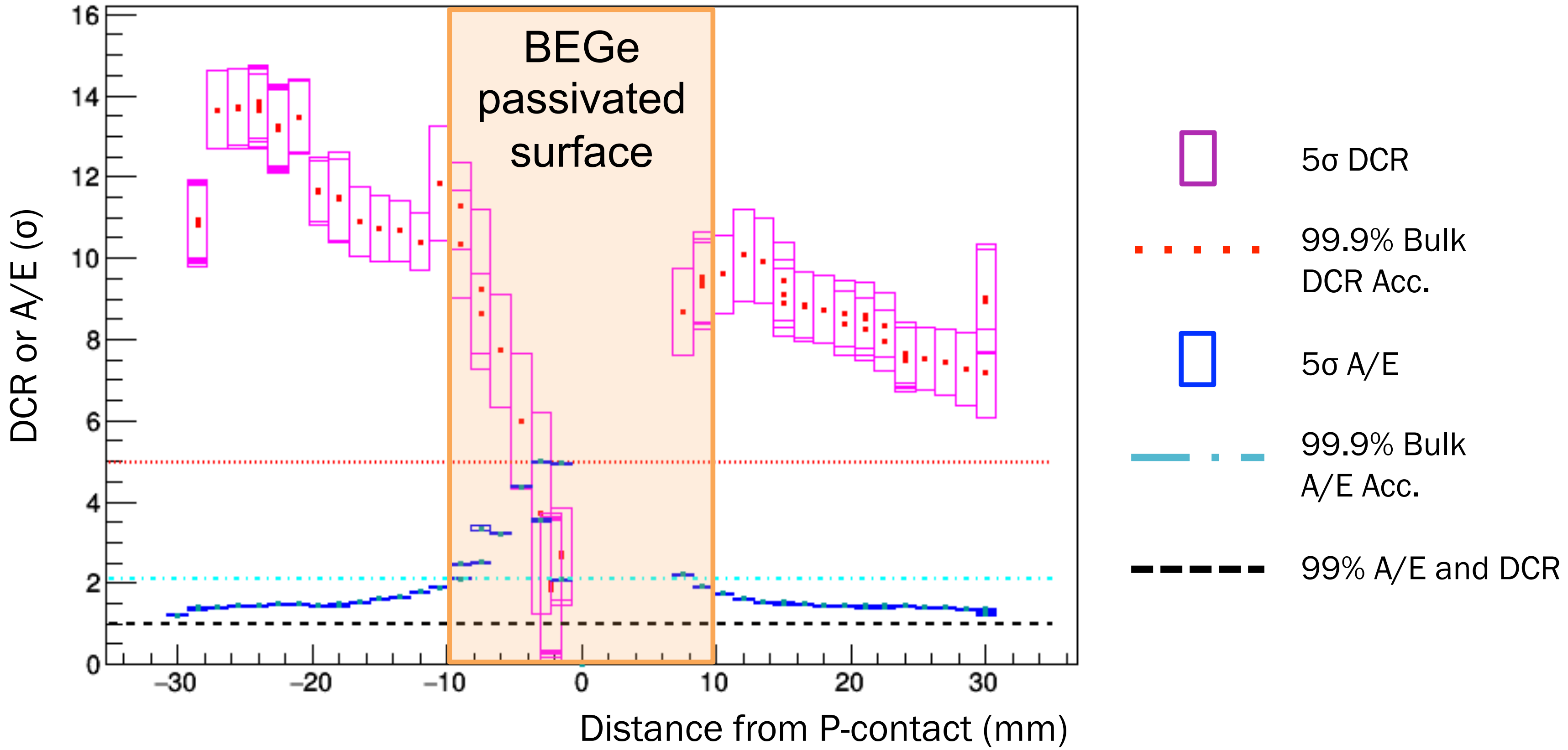
A/E and DCR Complementarity





- All positions fall above 99.9% on either A/E or DCR
- We should be able to remove ~all α events w/ minimal sacrifice

A/E and DCR α Rejection Power



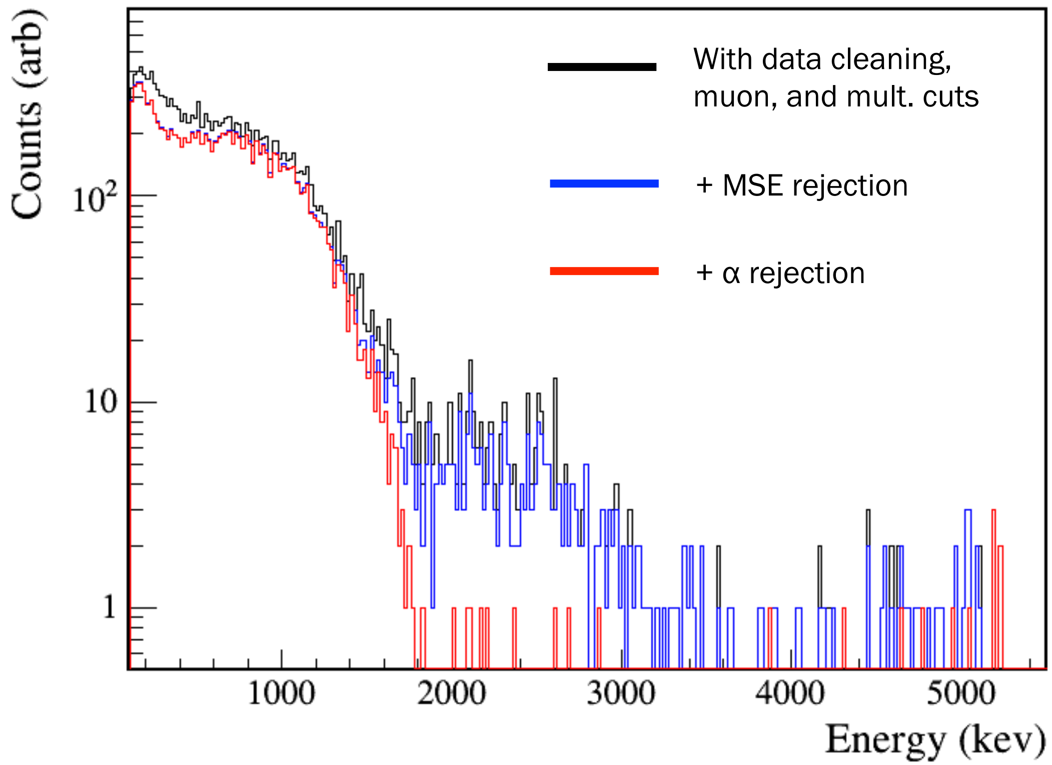
- Suggests that the transition is at ~8mm
- Publication in preparation

ALPHA BACKGROUNDS IN MJD

DCR and Alpha Backgrounds

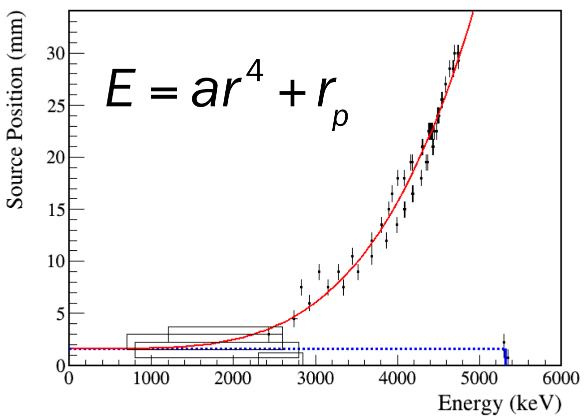
- DCR reduces ROI background rate by a factor of 31
- After cut, ROI backgrounds are within uncertainty of 3 counts/ ROI/t/y
- At current exposure, improves 0νββ limit by 24%
- After 5 years of running, improves sensitivity by a factor of 3
  - Corresponds to \$8.5m-worth more ^{76}Ge

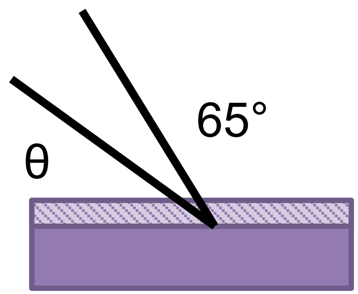
MJD Preliminary Spectrum, Enriched Detectors

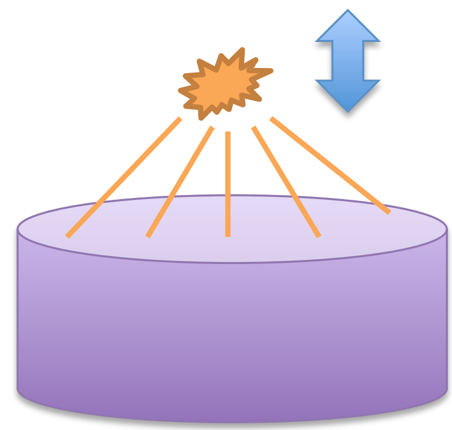


Pin-point Background Modeling

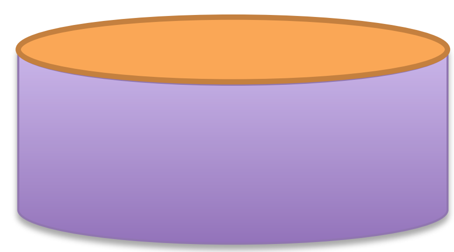
- Using TUBE α spectrum, distinguish between background sources







or



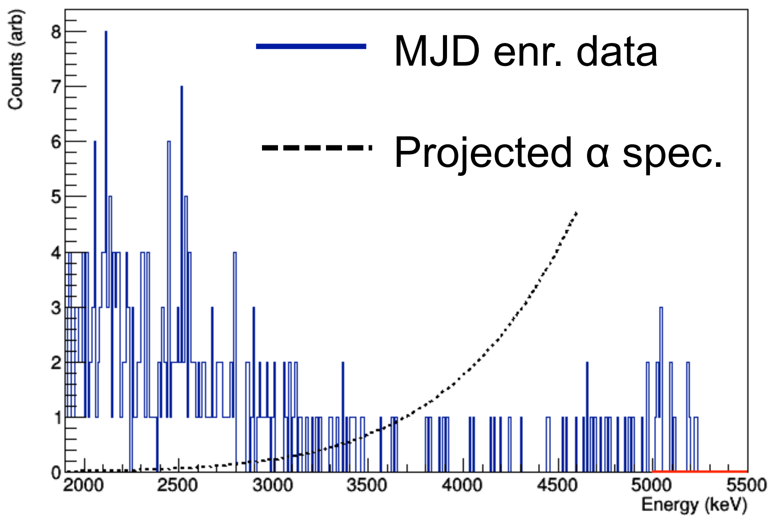
- Completely analytic, for now

A few caveats:

- rescale energies (^{210}Po, not ^{241}Am)
- p+ deadness fraction
- p+ α peak shape

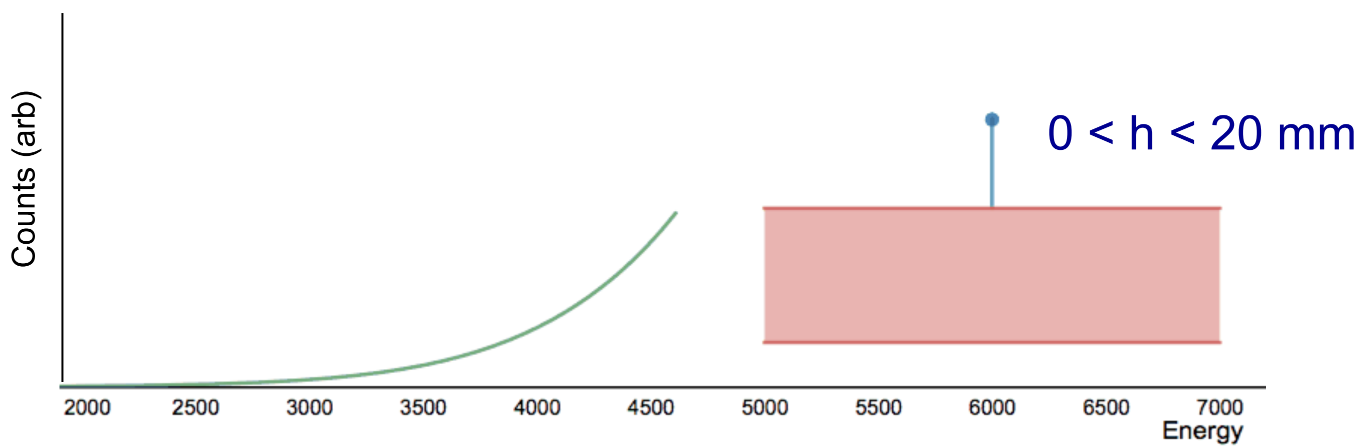
Testing Two Models

Constant Across Surface



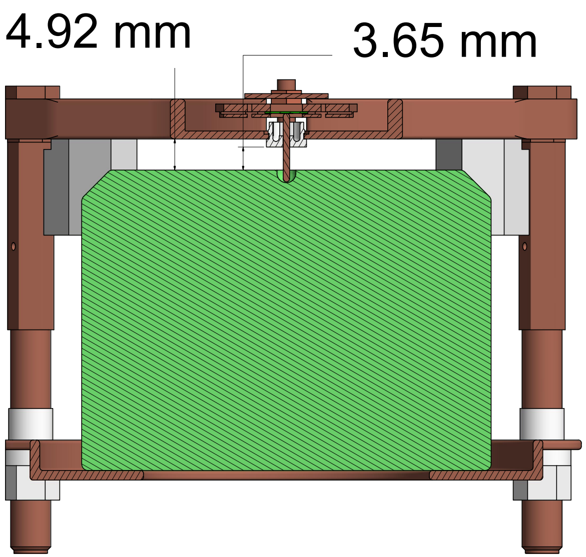
- Can immediately discard constant model

Point Source Above Surface

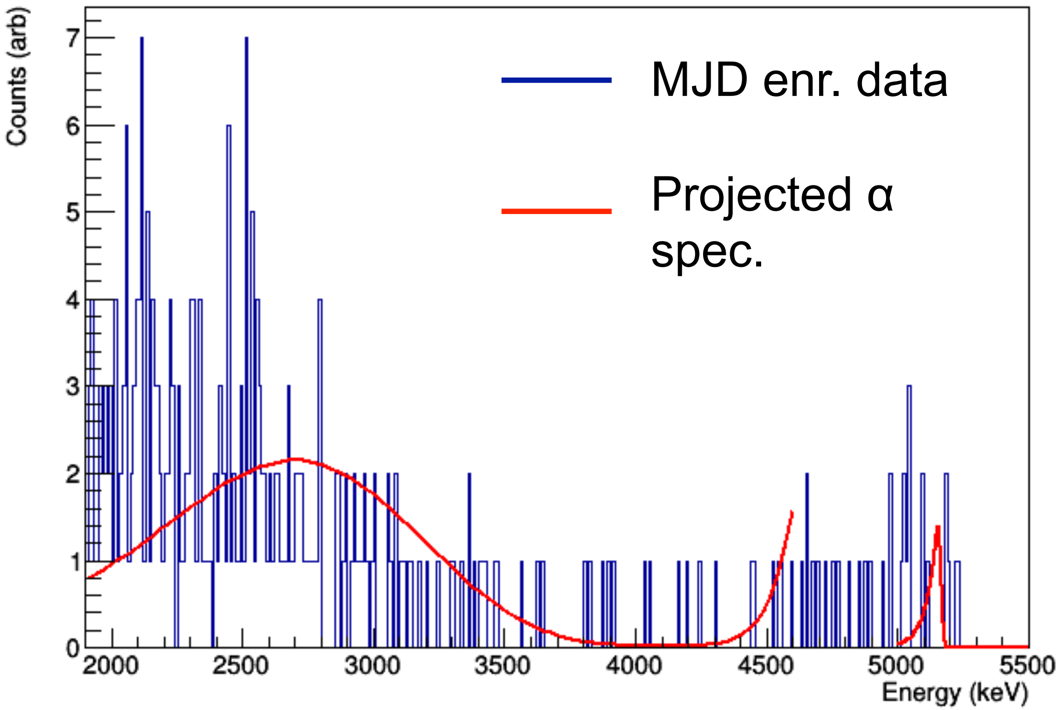


Fitting to α Source

- Just two free parameters: height and overall scaling (α rate)
- Strongly suggests plastic bushing is responsible
- Full simulation needed



Fitting α Spectrum to MJD Data



h ~3.8 mm

Conclusion

- I have characterized PPC charge collection near the passivated surface and identified the cause of the observed delayed charge recovery.
- Using the DCR cut, the MJD background has been reduced by a factor of ~30, improving sensitivity by a factor of 3.
- Using TUBE results, we can model the spectrum of α events, even identify their source. Then high-α background parts can be removed in MJD and avoided in LEGEND.
- Improved understanding of PPC behavior can drastically improve our ability to search for rare events and BSM physics, like 0νββ.

Thank You to:

- the money:
  - UW Physics, ARCS, NSF, and DOE

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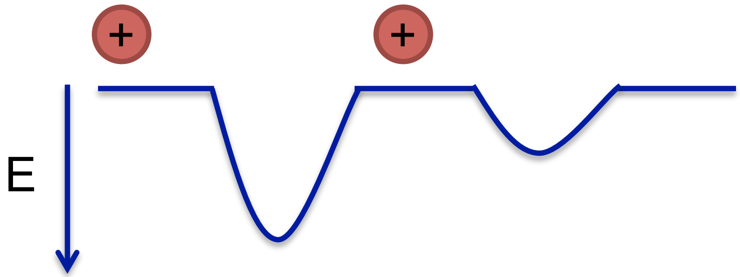
- the MAJORANA and GERDA Collaborations, and all of the staff at CENPA
- the MJ groups at UW and at TUM
- my committee, and particularly to Jason
- all of my family and friends

EXTRA SLIDES

Unexpected Result: DCR Stability

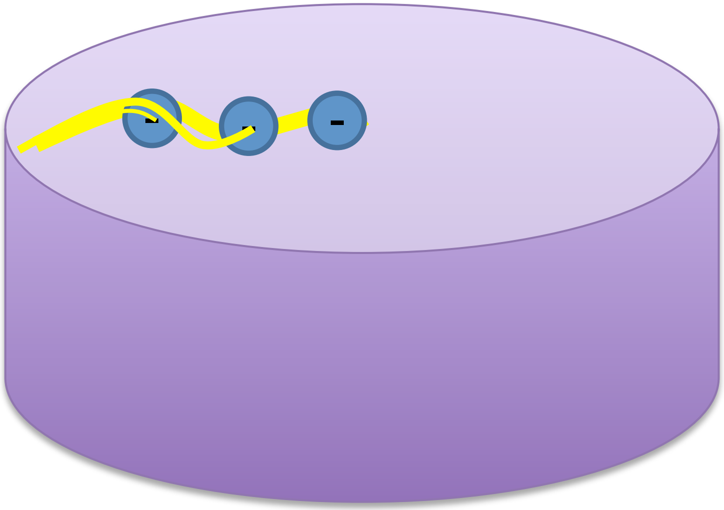
- Two potential causes

Deep trap filling:



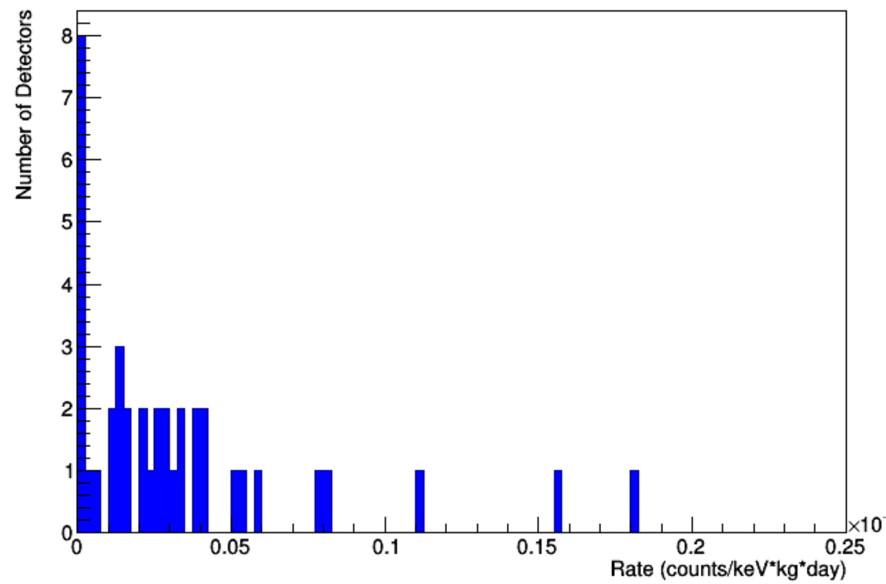
Test under changing temperature to distinguish

Surface channel formation:



MJD Alpha Backgrounds

- Identified high α-rate detectors
- ^{210}Po *is* Pb-supported 
- But α rejection is already good, and can still be improved



7 detectors have rates inconsistent with the average