online version

Germanium Detectors

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Working Principle and Pulse Shape Analysis

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Ringberg Castle - 07/2019

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Outline

- Motivation: Germanium Detectors in $0\nu\beta\beta$ searches (LEGEND)
- Working Principle of Solid State Detectors
  - Semiconductors
  - p-n junction
- Charge Drift & Simulation
- Signal Formation
  - Weighting Potential
  - Pulses
- Using Pulse Shapes to reduce background: Multi-site vs. Single-site Event Discrimination
- Summary

Germanium in 0νββ searches

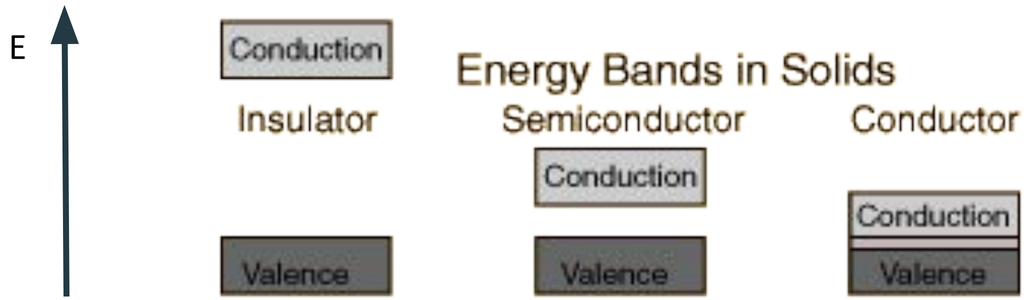
- Germanium has an isotope, ^{76}Ge, that undergoes 2νββ decay and is therefore also a candidate for 0νββ
- As a semiconductor (enriched) Germanium can be used to produce solid state detectors

  → Source = Detector

- Solid state detectors come with many favorable properties for rare event searches
  - Excellent Energy Resolution
  - Low intrinsic radioactivity
  - Fast Signal collection
  - Compact geometries

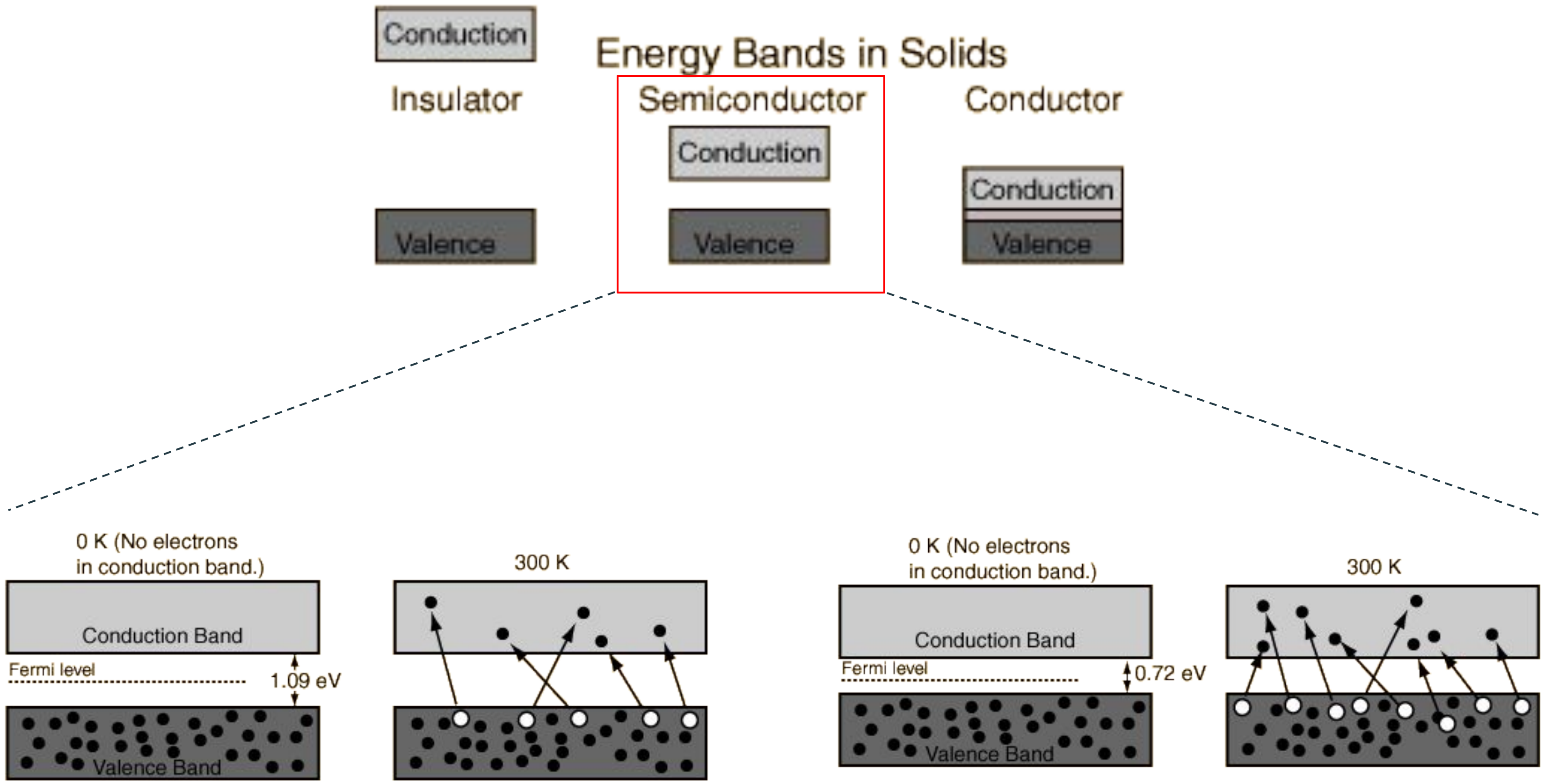
Working Principle of solid state detectors

Band structure of solids



>5 eV ~1 eV

Band structure of solids

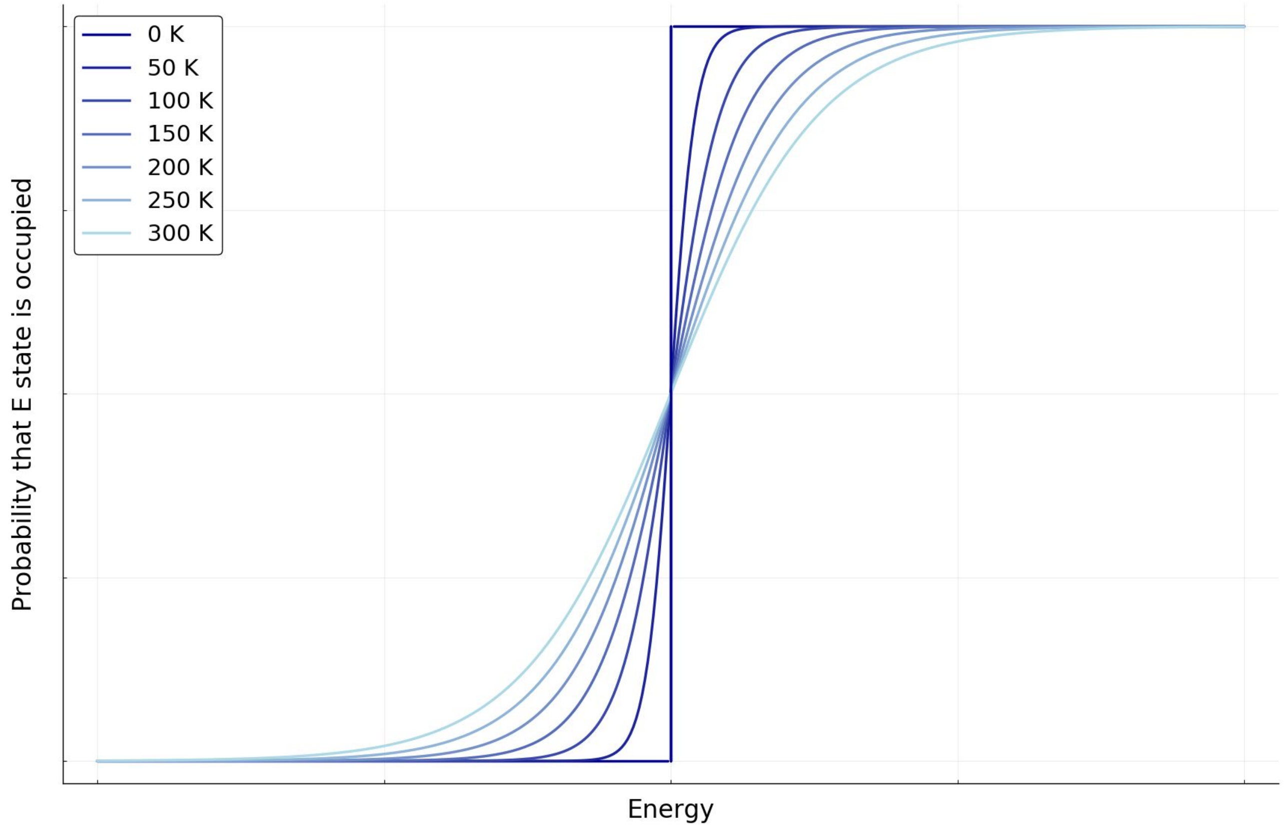


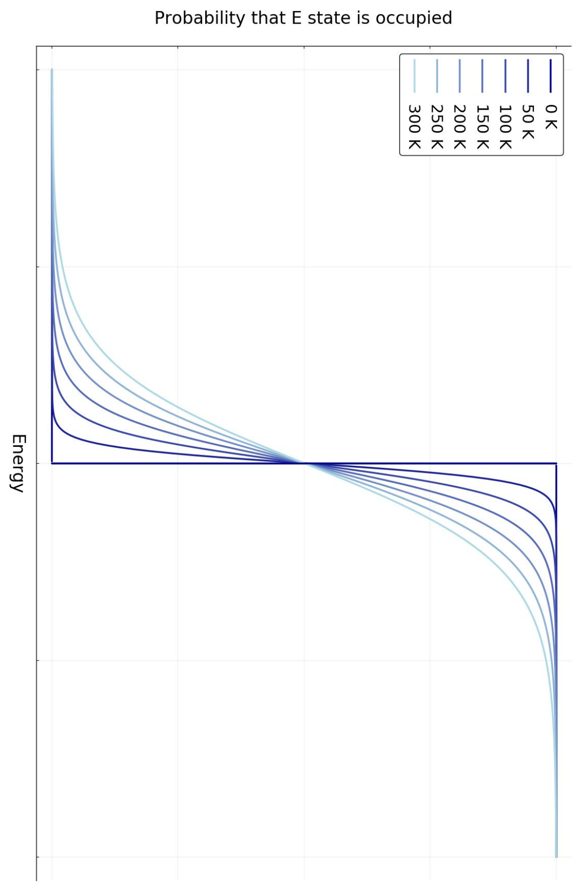
Silicon Germanium

http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html

Fermi Level and Fermi Function

$$f(E) = \frac{1}{e^{(E - E_F)/kT} + 1}$$





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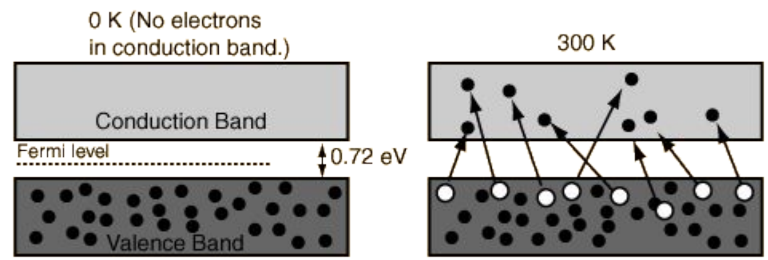

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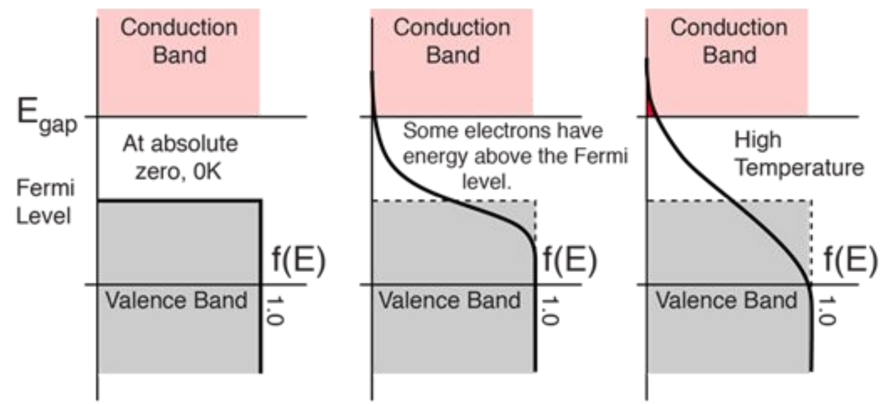
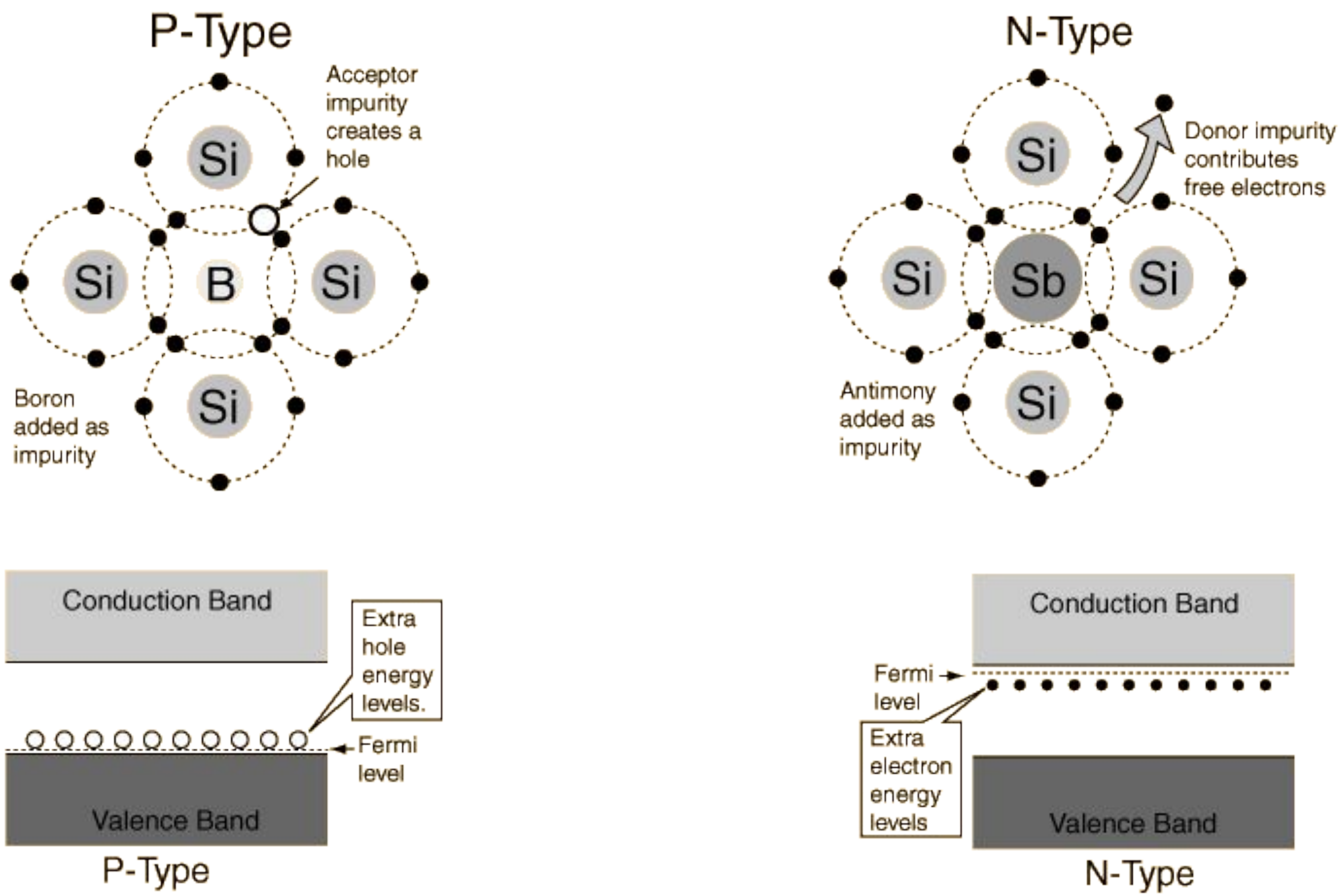


No electrons can be above the valence band at 0K, since none have energy above the Fermi level and there are no available energy states in the band gap.

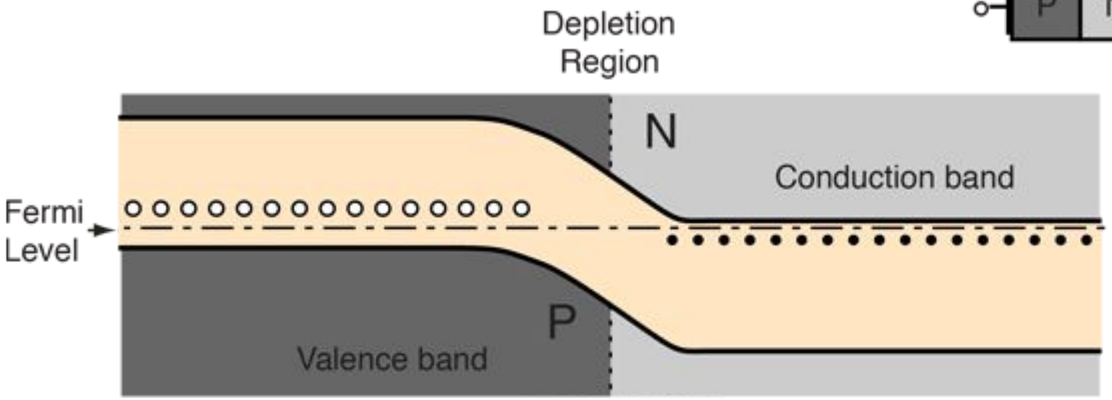
At high temperatures, some electrons can reach the conduction band and contribute to electric current.

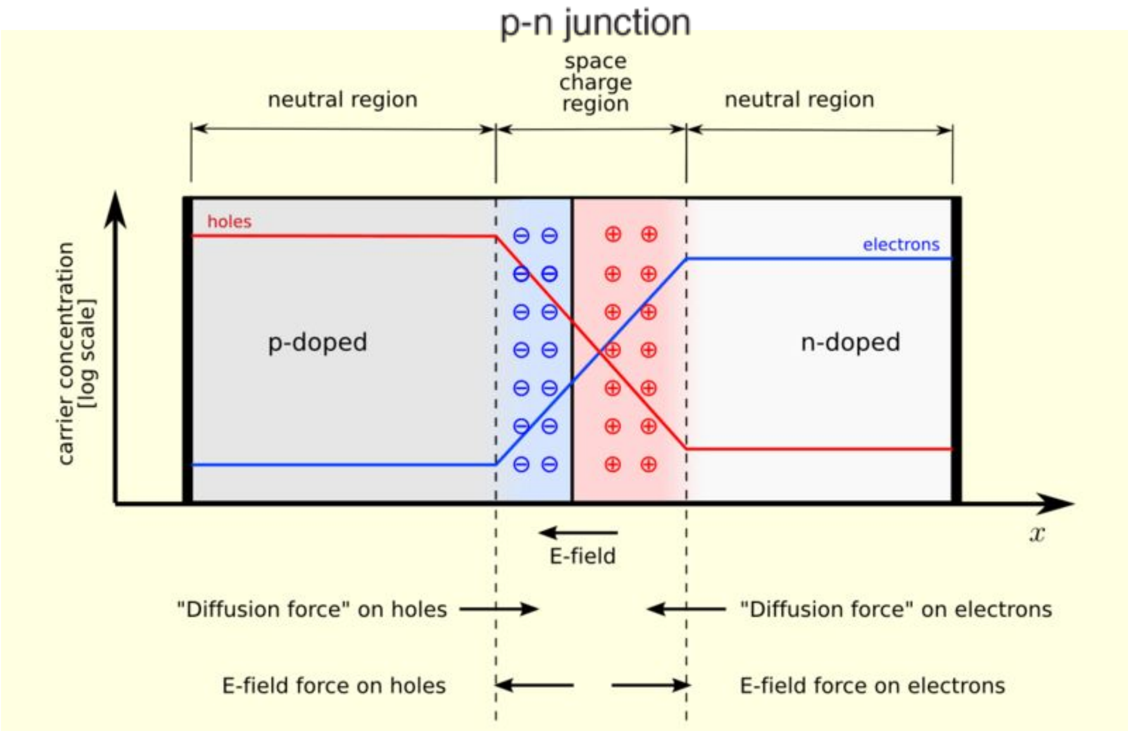
Doping of Semiconductors



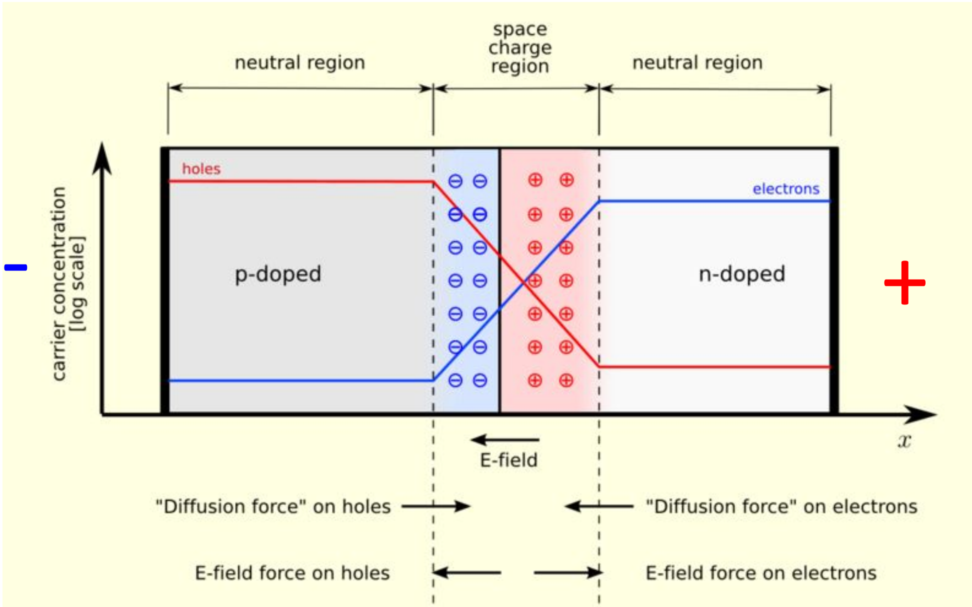
p-n junction


P
N


Depletion
Region
N
Conduction band
Fermi
Level
P
Valence band


p-n junction
neutral region
space
charge
region
neutral region
carrier concentration
[log scale]
holes
electrons
p-doped
n-doped
x
E-field
"Diffusion force" on holes
"Diffusion force" on electrons
E-field force on holes
E-field force on electrons

Reverse Bias

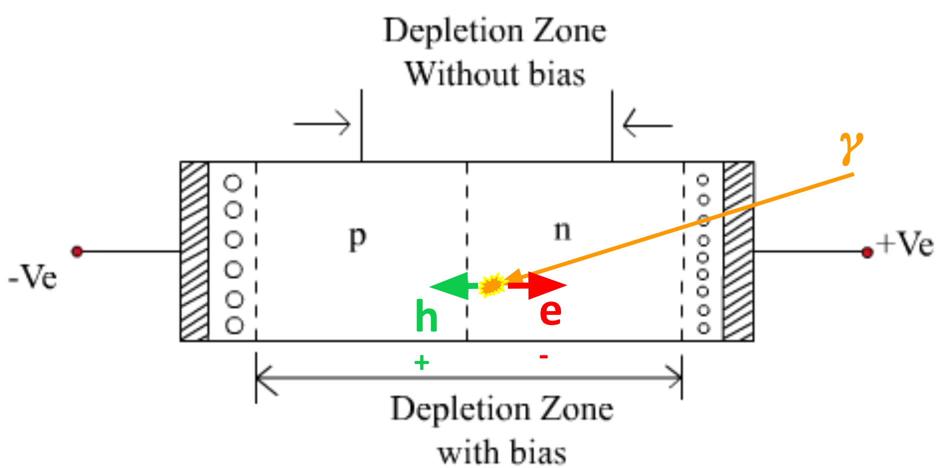


https://en.wikipedia.org/wiki/P%E2%80%93n_junction

A p-n junction is a **diode**.

Applying a
reverse bias (+ on n-side, - on p-side)
increases the depleted region
→ fixed space charges, E-Field,
no free charge carriers

The depleted region is the "active region" of the detector
→ Full depletion!



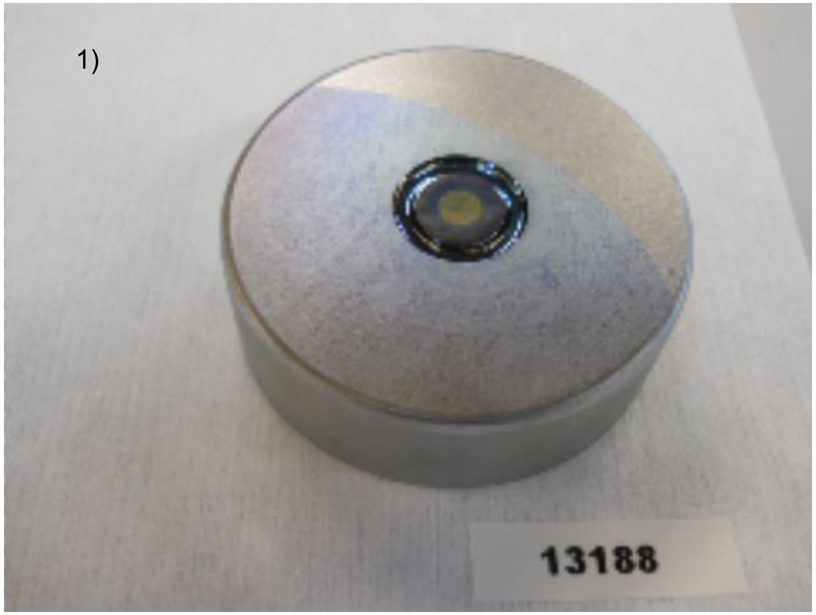
https://nptel.ac.in/courses/115102017/17

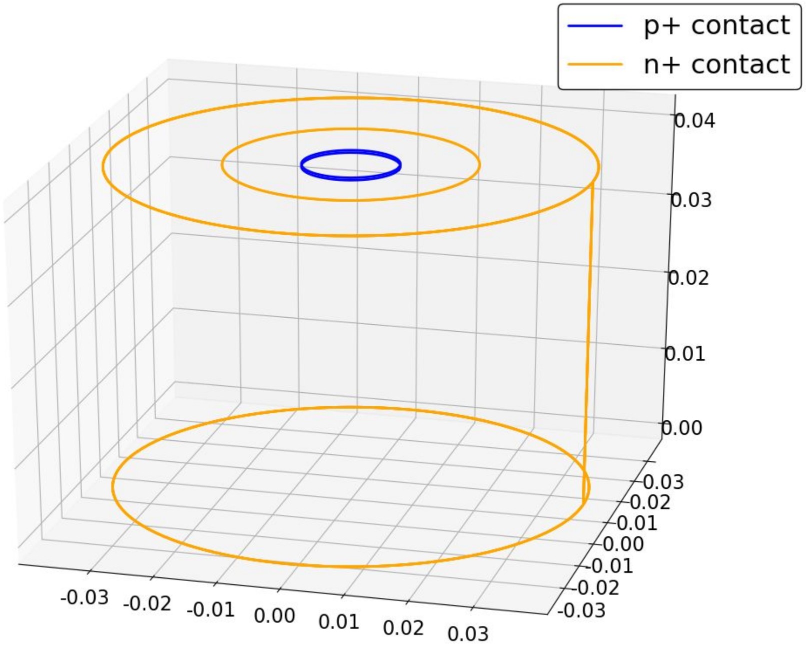
Incident Ionizing radiation creates electron - hole pairs in an amount proportional to the deposited energy

The electrons and holes created in the depletion region move to the respective electrodes
→ Detectable Current!

Charge Drift

Real World Detectors - p-type Point Contact

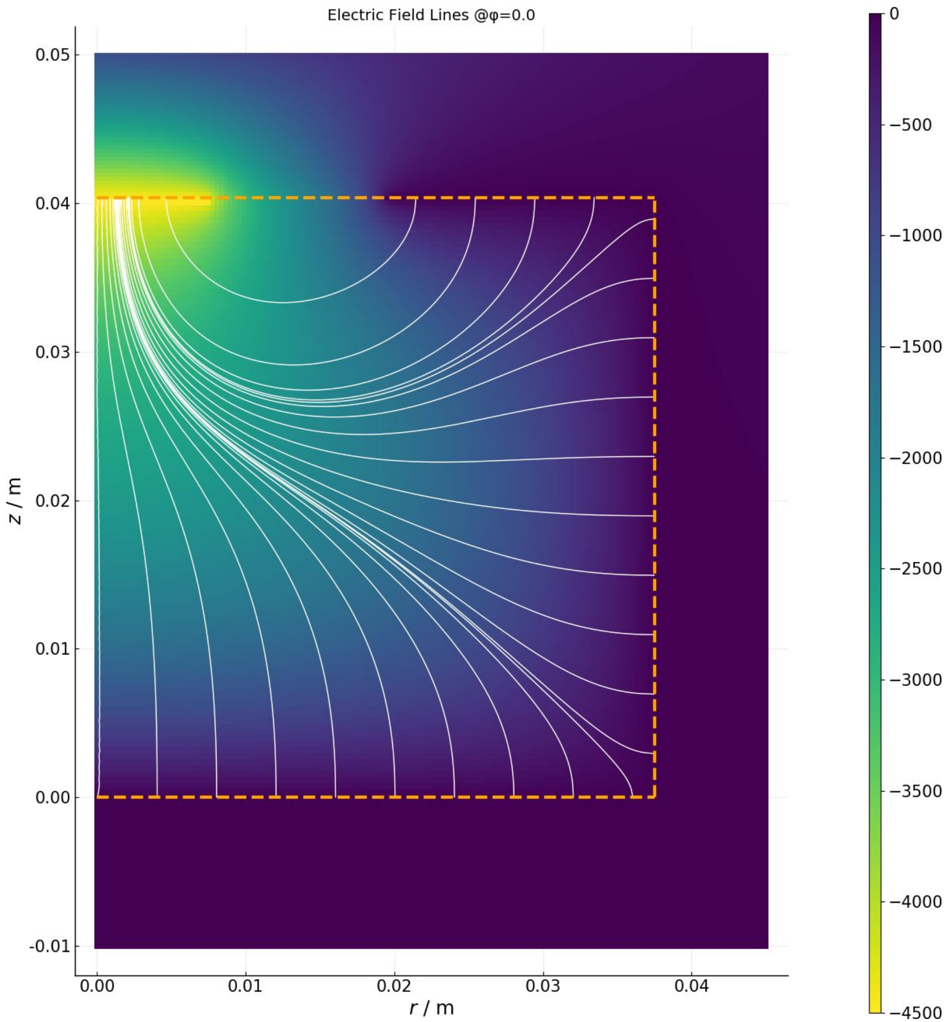




https://github.com/JuliaHEP/SolidStateDetectors.jl

1) **Background-free search for neutrinoless double-β decay of 76Ge with GERDA** Agostini, M.

Electric Potential & Charge Drift



Potential: Solve Gauss' Law

$$\nabla(\epsilon_r(\vec{\mathbf{r}})\nabla\varphi(\vec{\mathbf{r}})) = \frac{\rho(\vec{\mathbf{r}})}{\epsilon_0}\ , \qquad \vec{\mathbf{r}} = (r, \phi, z)$$

Electric Field:

$$\vec{\mathcal{E}}(\vec{\mathbf{r}}) = -\nabla\varphi(\vec{\mathbf{r}})$$

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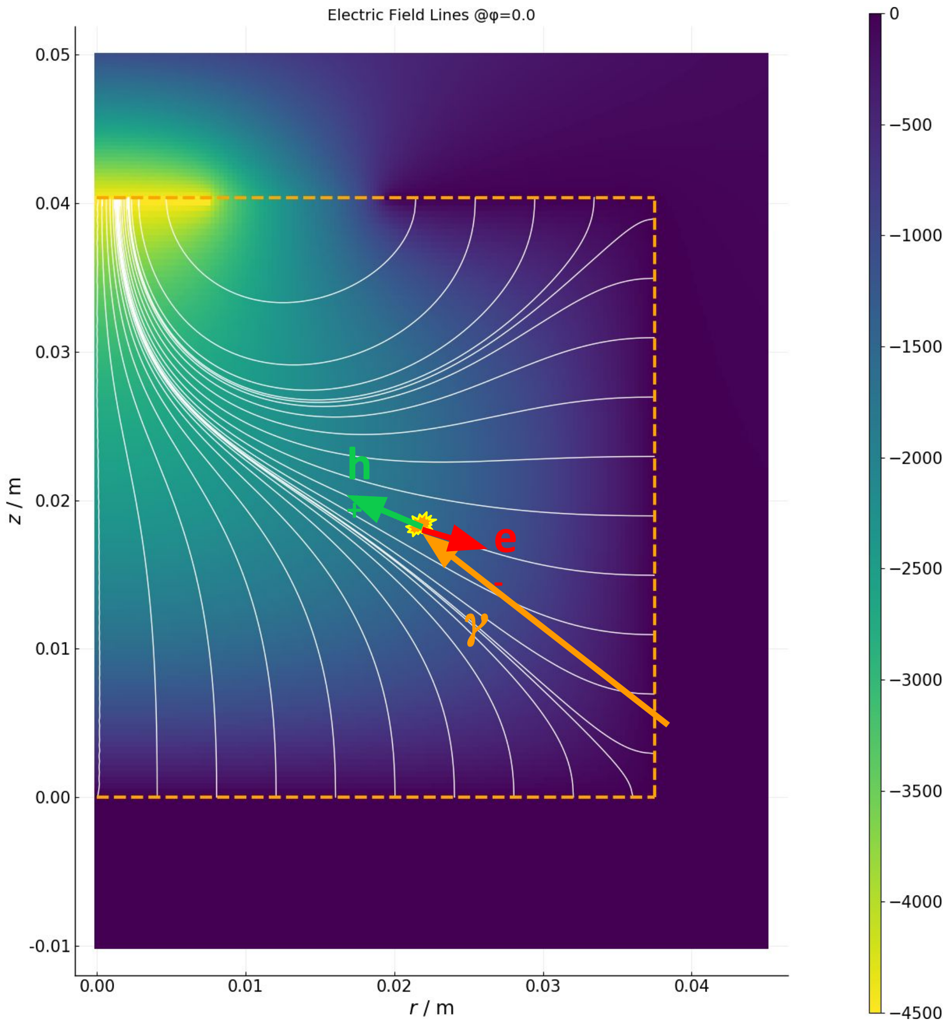
Electric Potential & Charge Drift



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Electric Field:

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Charge Drift Model:

- Effects of Crystal Axes
- Different Mobilities for e^- and h^+
- ...

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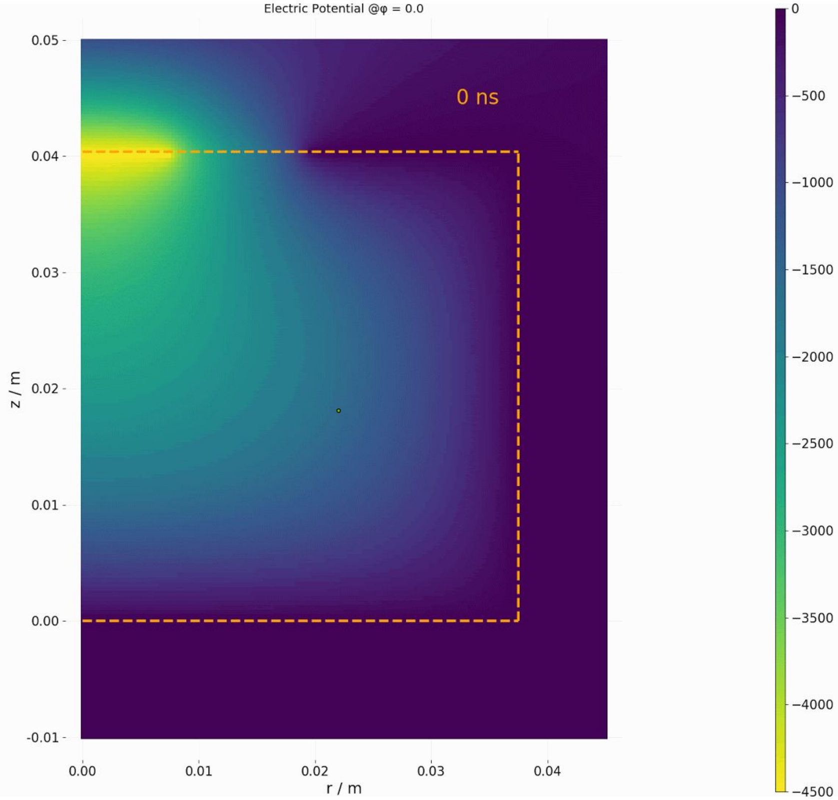
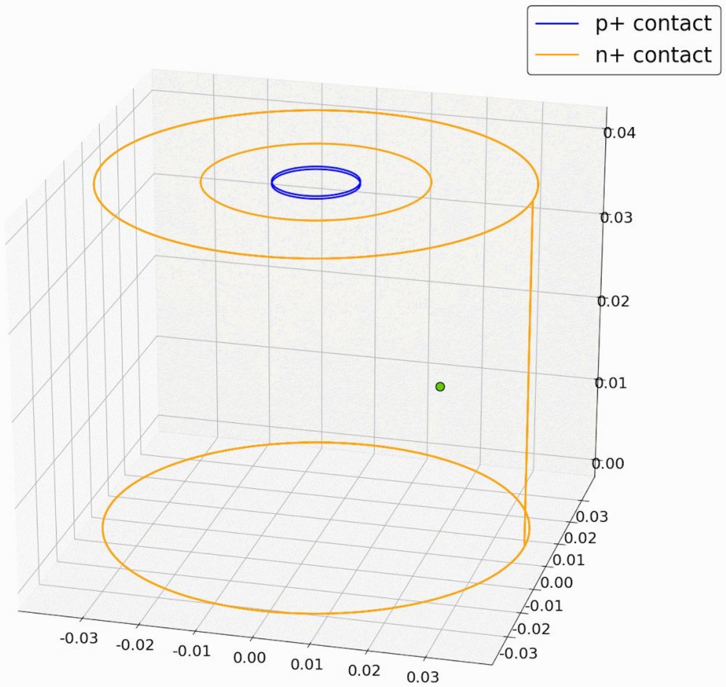
Electric Potential & Charge Drift





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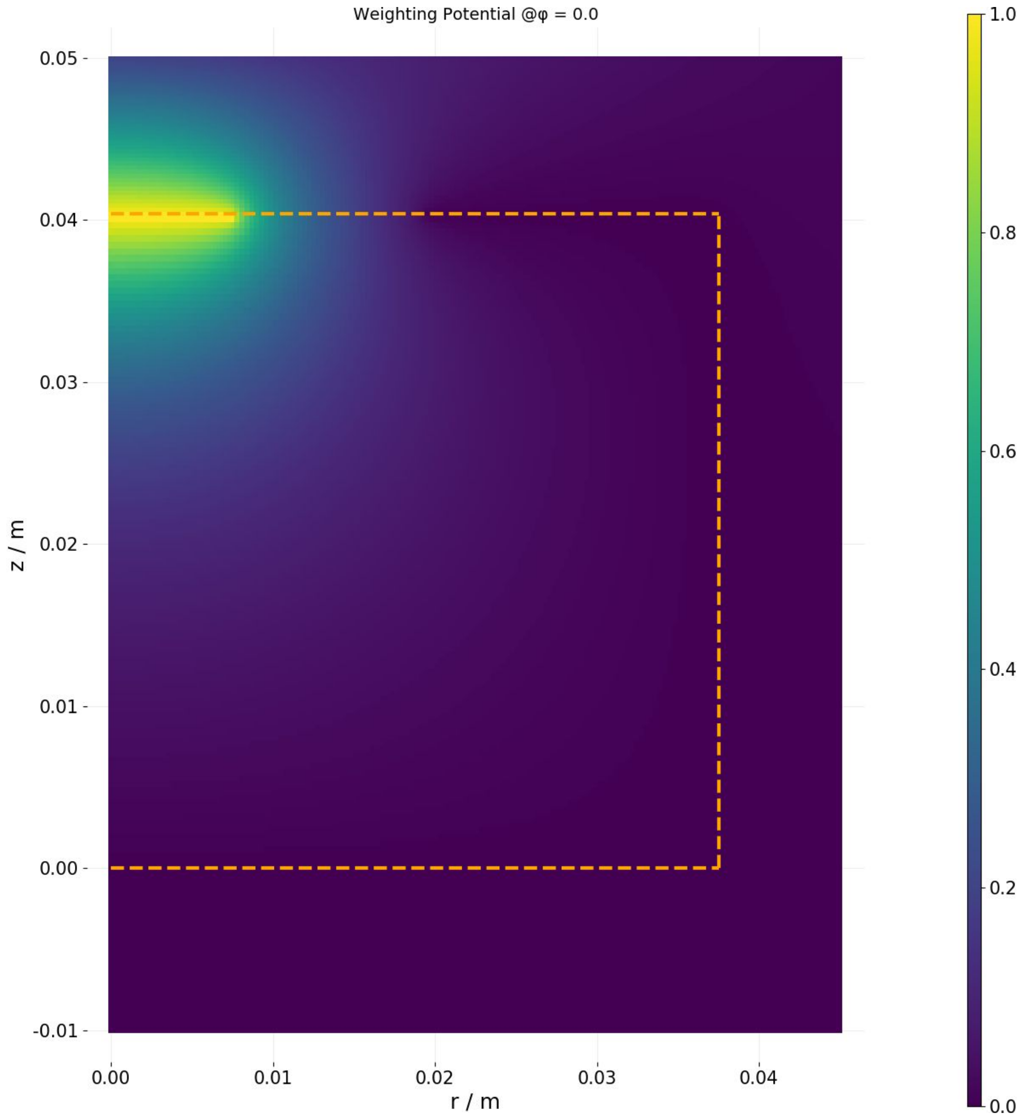
Signal Formation

Weighting Potential & Signal Formation



Shockley-Ramo Theorem:
Charge induced on given electrode by motion of charge carriers according to:

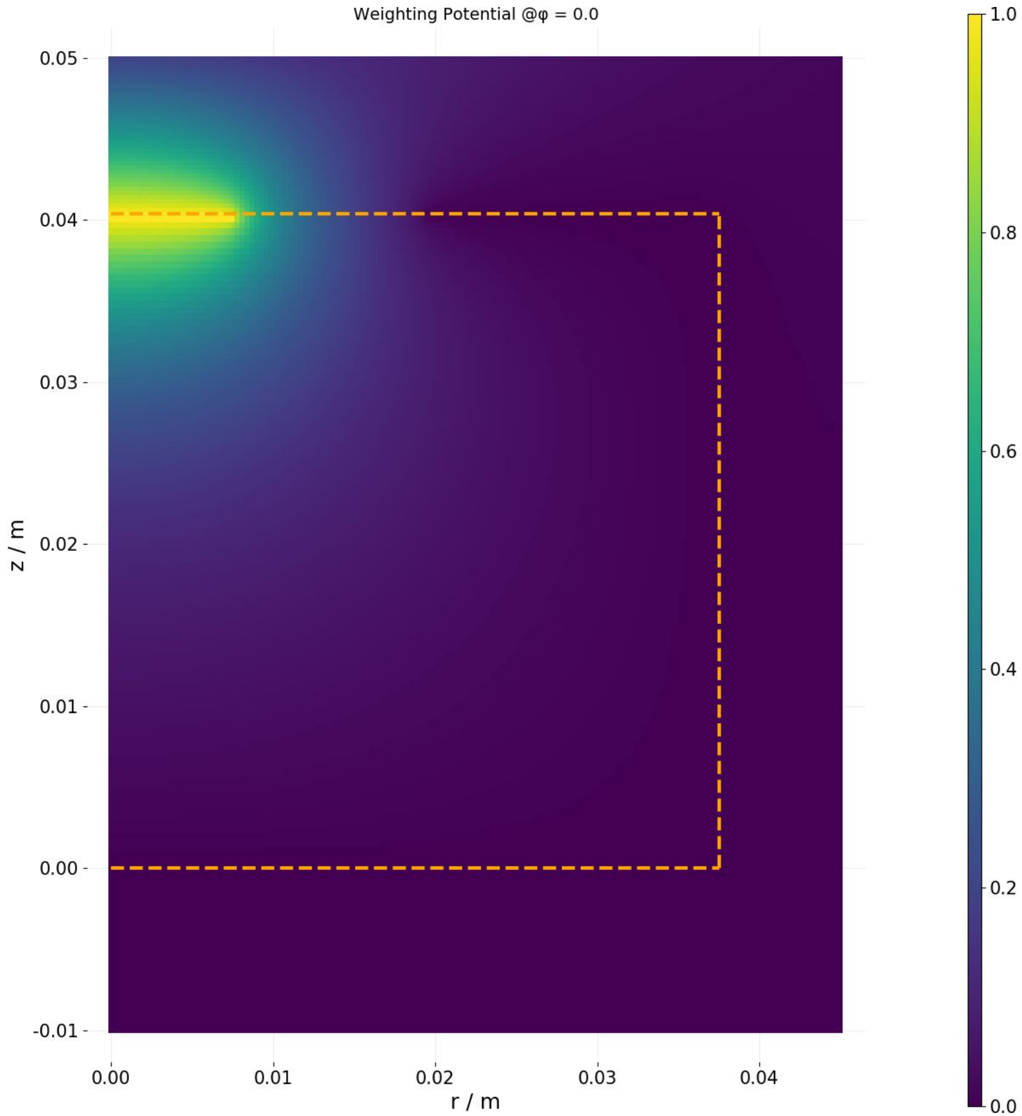
$$Q = q\Delta\varphi_0$$

q = moving charge,
φ_0 = Weighting Potential

Solve:

$$\nabla(\epsilon_r(\vec{\mathbf{r}})\nabla\varphi_0(\vec{\mathbf{r}})) = 0$$

Weighting Potential & Signal Formation



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Solve:

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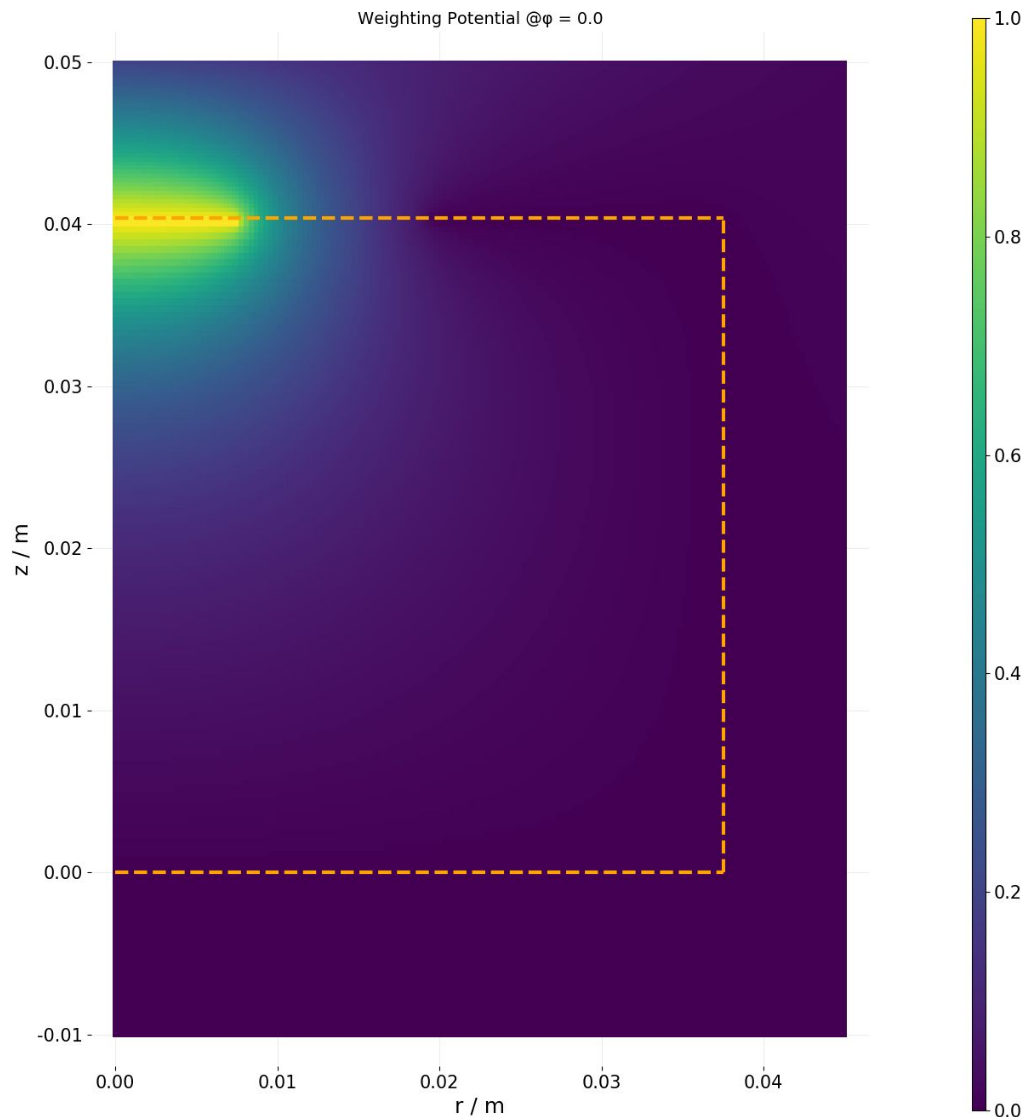
$$Q_e(t) = n_e \cdot (-1 \cdot e) \cdot (\ \varphi_0(\ \vec{\mathbf{r}}_e(t)\ ) - \varphi_0(\ \vec{\mathbf{r}}_e(t_0)\ )\ )$$

$$Q_h(t) = n_h \cdot e \cdot (\ \varphi_0(\ \vec{\mathbf{r}}_h(t)\ ) - \varphi_0(\ \vec{\mathbf{r}}_h(t_0)\ )\ )$$

Weighting Potential & Signal Formation



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$$Q_h(t) = n_h \cdot e \cdot (\ \varphi_0(\ \vec{\mathbf{r}}_h(t)\ ) - \varphi_0(\ \vec{\mathbf{r}}_h(t_0)\ )\ )$$

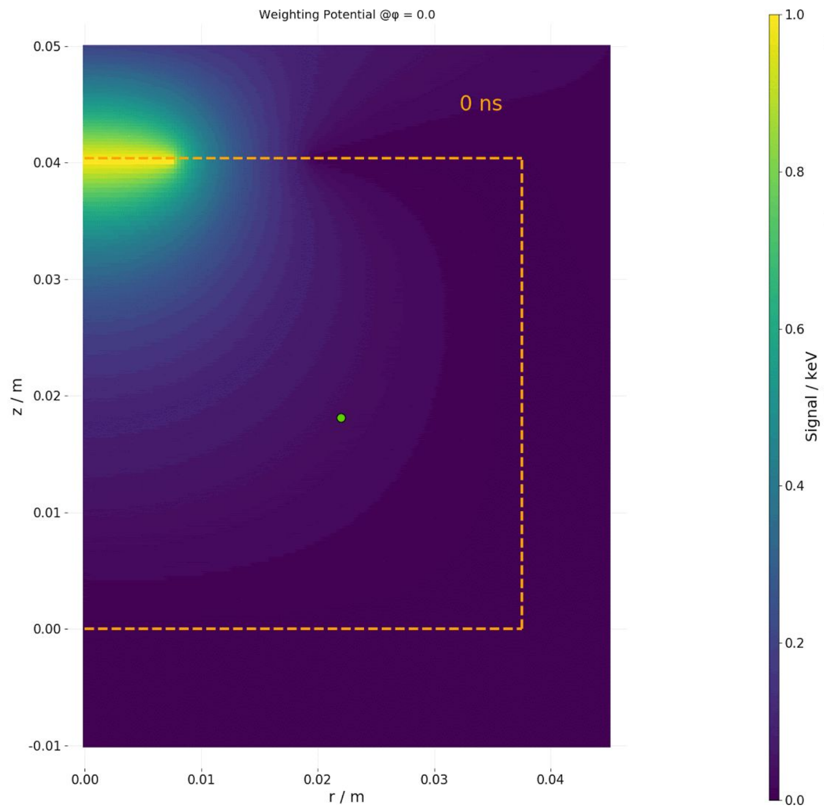
$$n_e = n_h, \qquad \vec{\mathbf{r}}_e(t_0) = \vec{\mathbf{r}}_h(t_0)$$

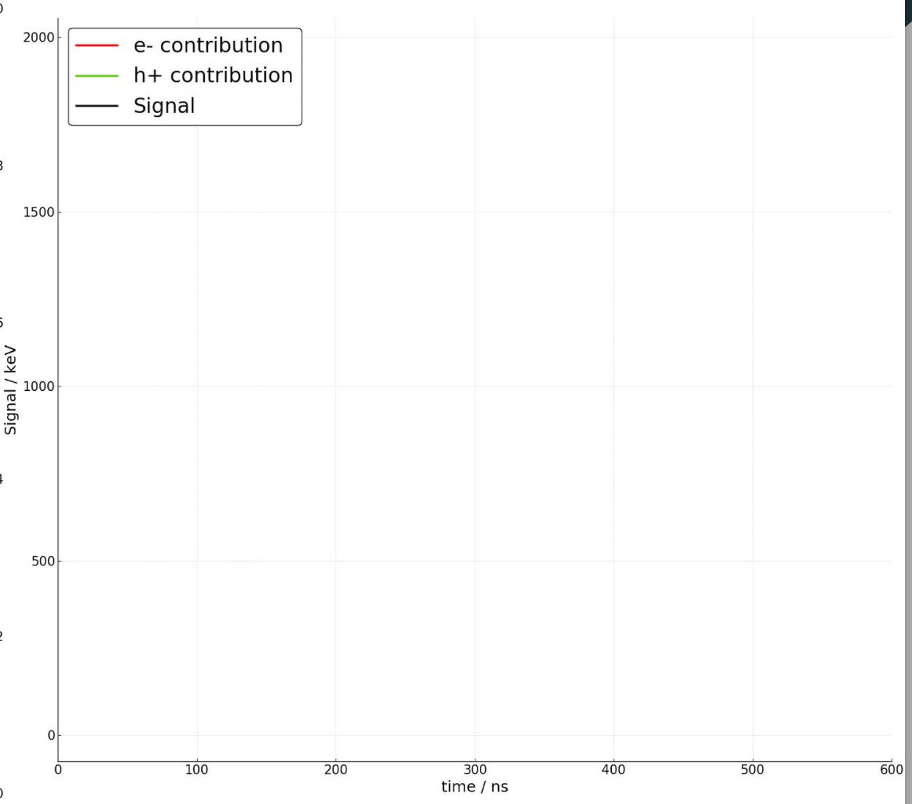
$$Q_{tot} = Q_e + Q_h$$

$$Q_{tot}(t) = n_{e/h} \cdot e \cdot (\ \varphi_0(\vec{\mathbf{r}}_h(t)) - \varphi_0(\vec{\mathbf{r}}_e(t))\ )$$

Weighting Potential & Signal Formation

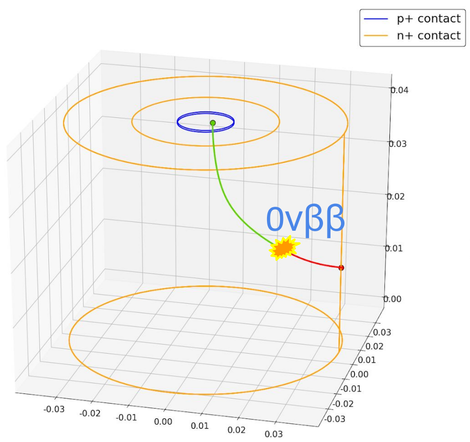
$$Q_{tot}(t) = n_{e/h} \cdot e \cdot (\ \varphi_0(\vec{\mathbf{r}}_h(t)) - \varphi_0(\vec{\mathbf{r}}_e(t))\ )$$

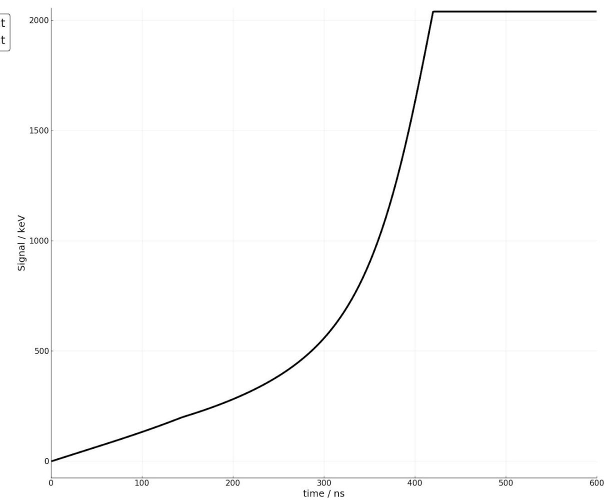




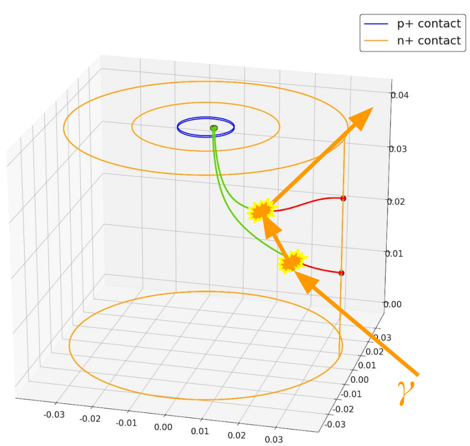
Pulse Shape Analysis(PSA)

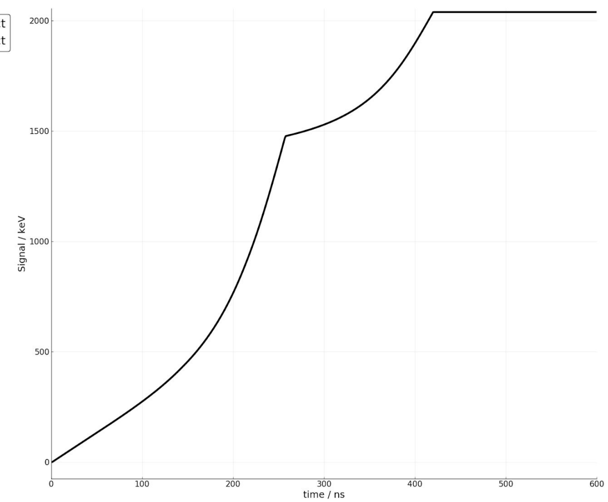
PSA in GERDA / LEGEND (example)





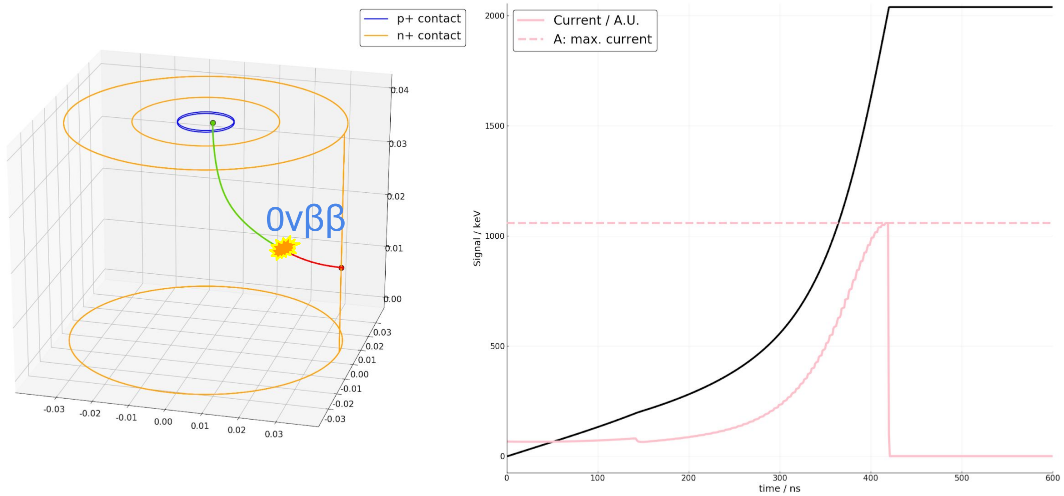
Signature of 0νββ in Ge:
2 e⁻ depositing their energy (2.039 MeV) very locally
→ Single - Site Event



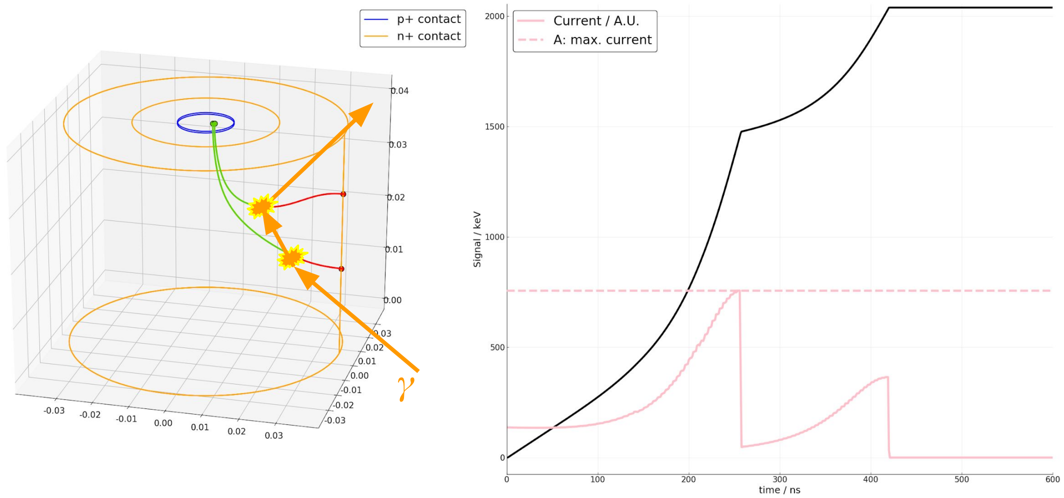


Background in the Region of Interest:
A high energy γ energy Compton scatters within the crystal depositing 2.039 MeV in total
→ Multi - Site Event

PSA in GERDA / LEGEND (example)



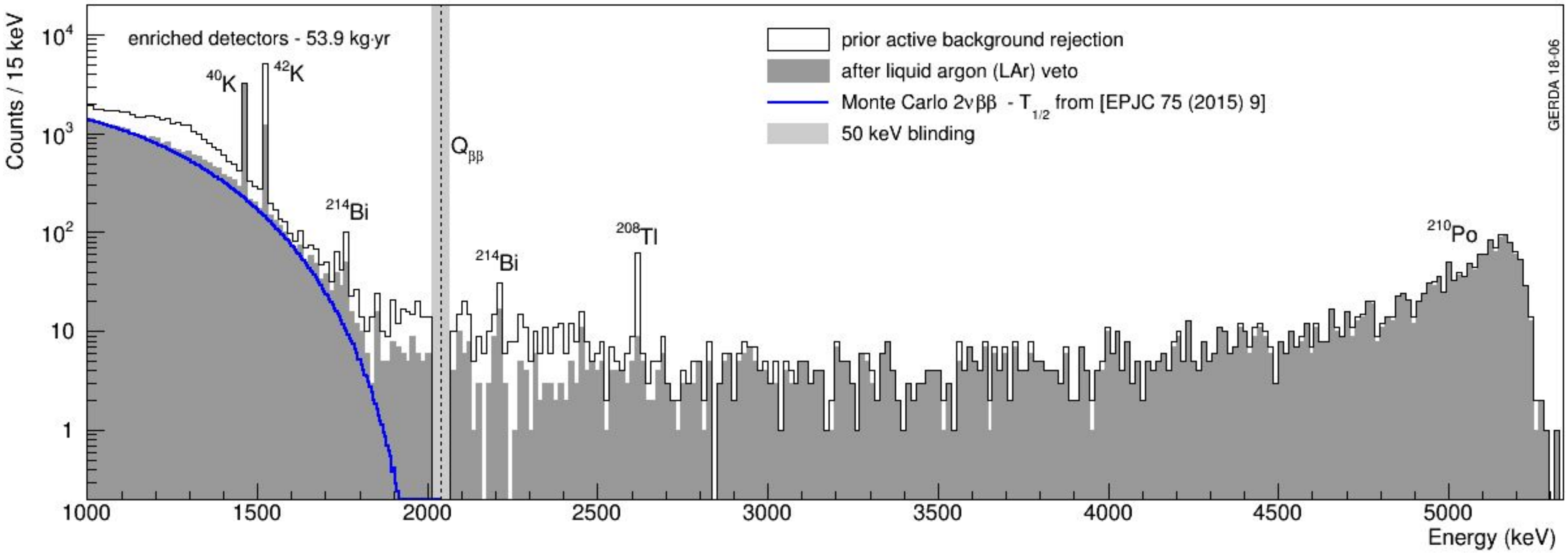
Signal energy: 2039 keV (E)
High max current value (A)



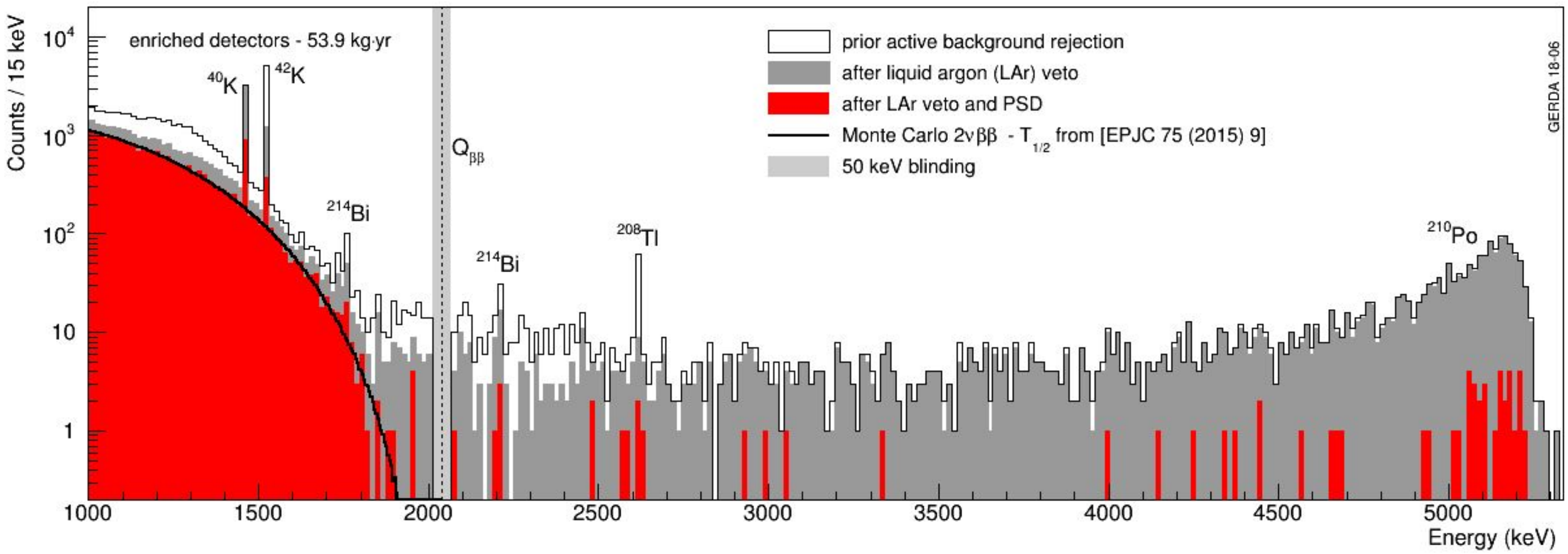
Signal Energy: 2039 keV (E)
Lower max current value (A)

→ Discriminate on A / E ratio

Pulse Shape Analysis Cuts on GERDA

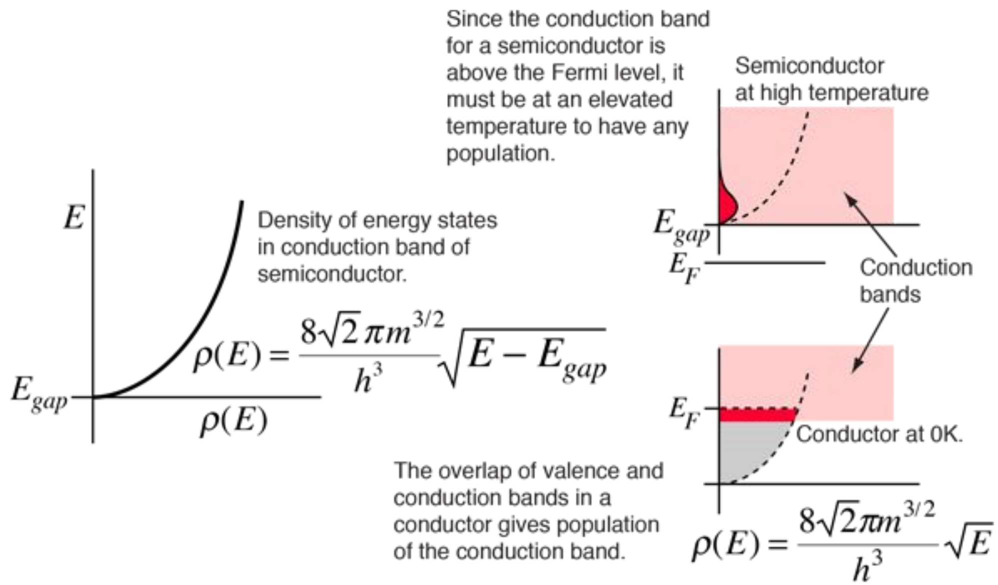


Pulse Shape Analysis Cuts on GERDA

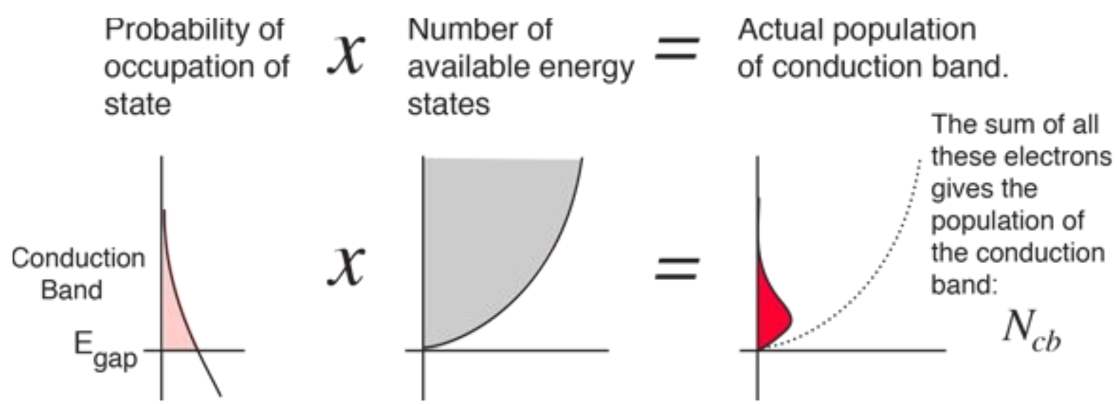


BACKUP

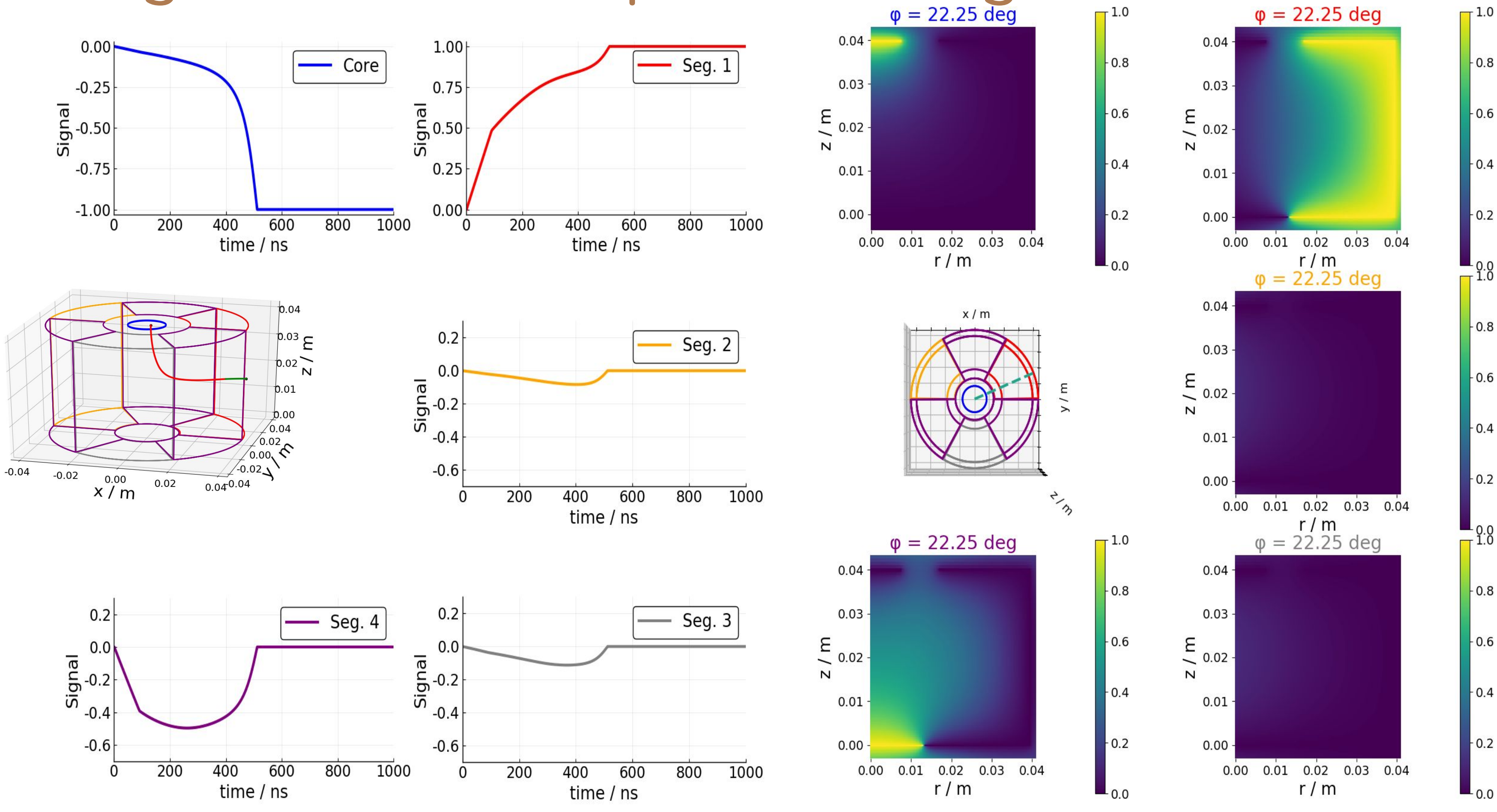
Density of States



Population of Conduction Band



Signal and mirror pulses in segments



M Schuster

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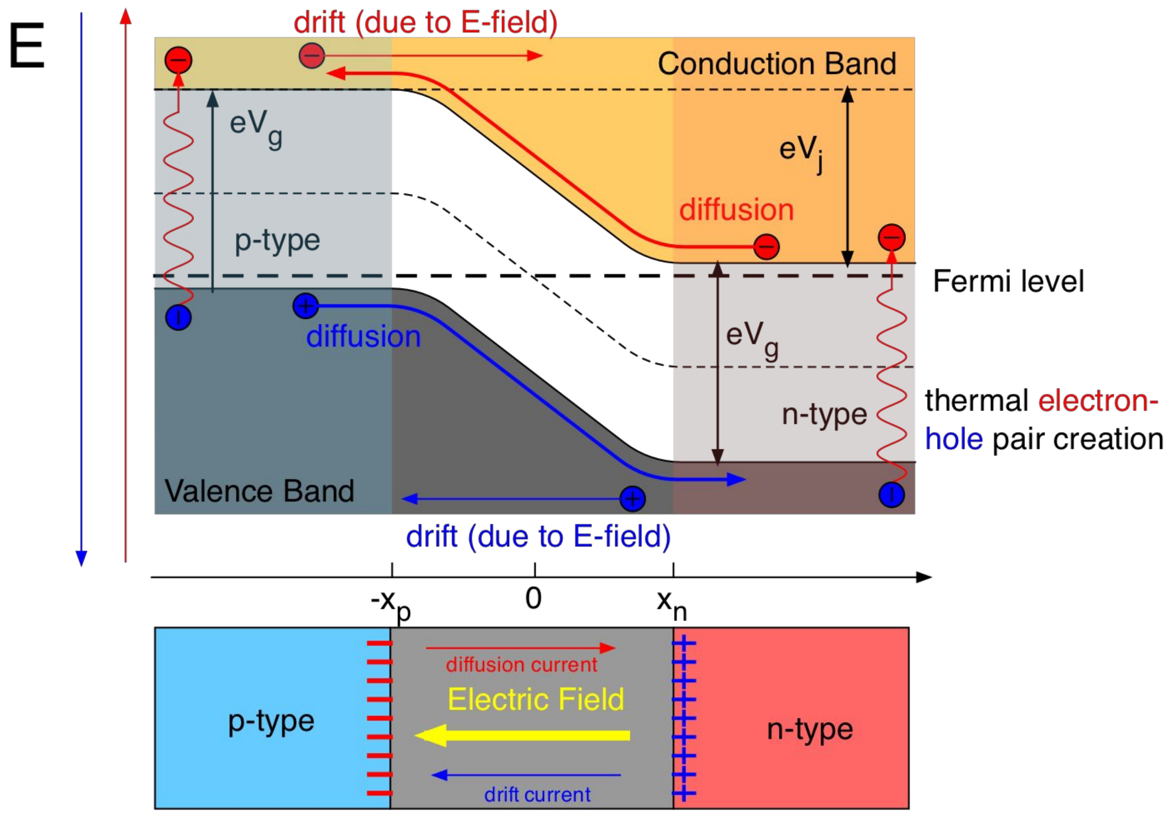
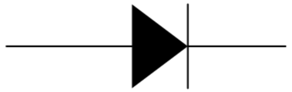
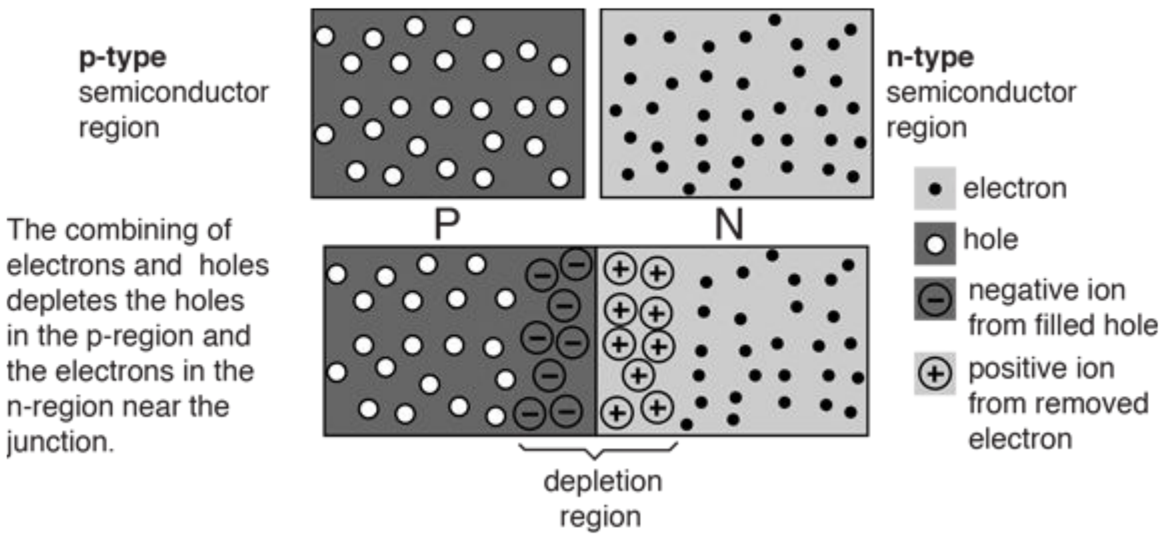
p-n-Junction



Schematic of pn-junction



Depletion Region & Reverse Bias



Field calculation

$$\nabla(\epsilon_r(\vec{\mathbf{r}})\nabla\varphi(\vec{\mathbf{r}})) = \frac{\rho(\vec{\mathbf{r}})}{\epsilon_0} \;, \qquad \vec{\mathbf{r}} = (r, \phi, z)$$

- Electric potential calculated by Gauss’ law

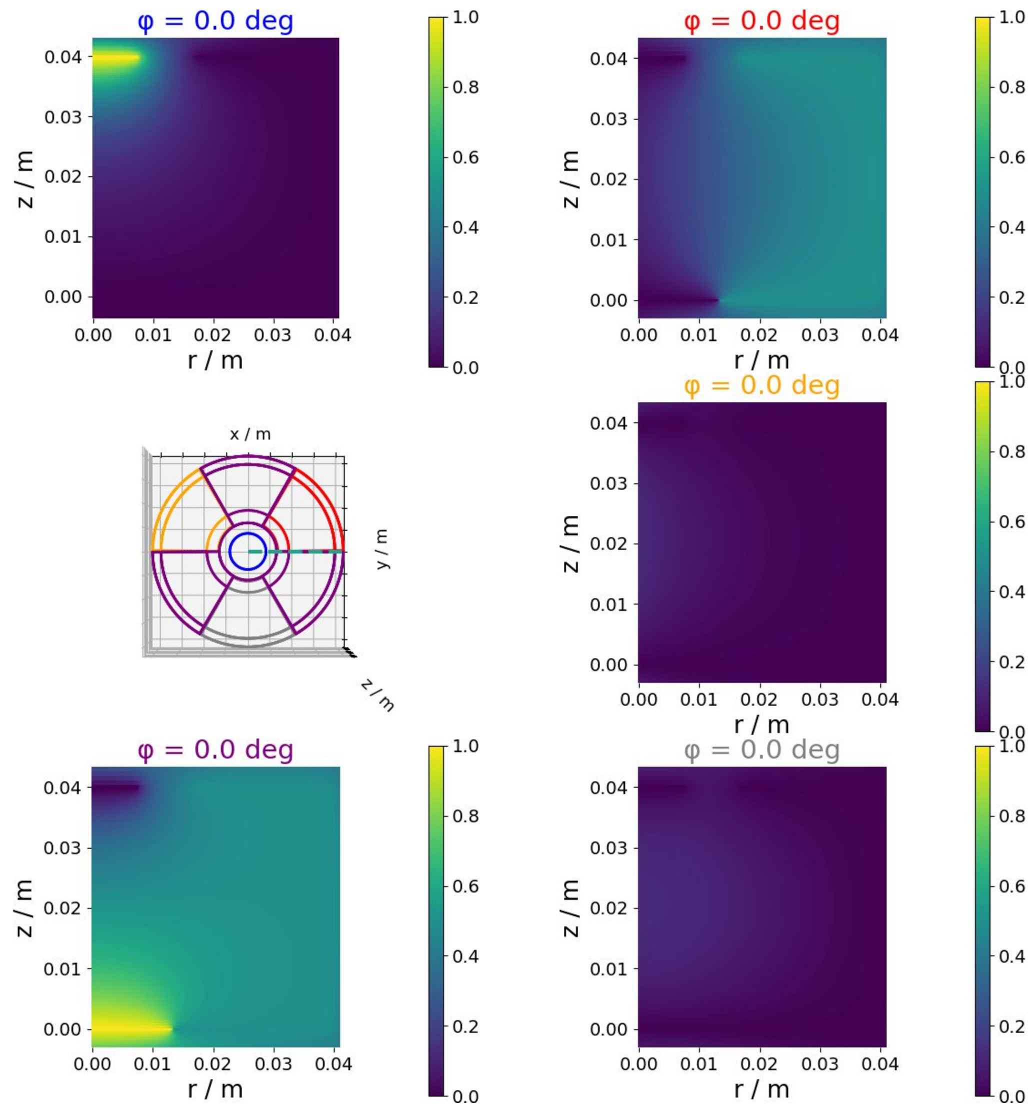
φ(**r**) electric potential, ϵ_0 vacuum permittivity, $_r$= 16 dielectric constant of germanium, ρ(**r**) impurity density

- Weighting potential calculat

$$\nabla(\epsilon_r(\vec{\mathbf{r}})\nabla\varphi_W(\vec{\mathbf{r}})) = 0$$

with the boundary conditions that the weighting potential equals unity on the considered electrode and zero otherwise

Weighting Potentials



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Drift velocity model

$$v_l = \frac{\mu_0 E}{(1 + (E/E_0)^\beta)^{1/\beta}} - \mu_n E$$

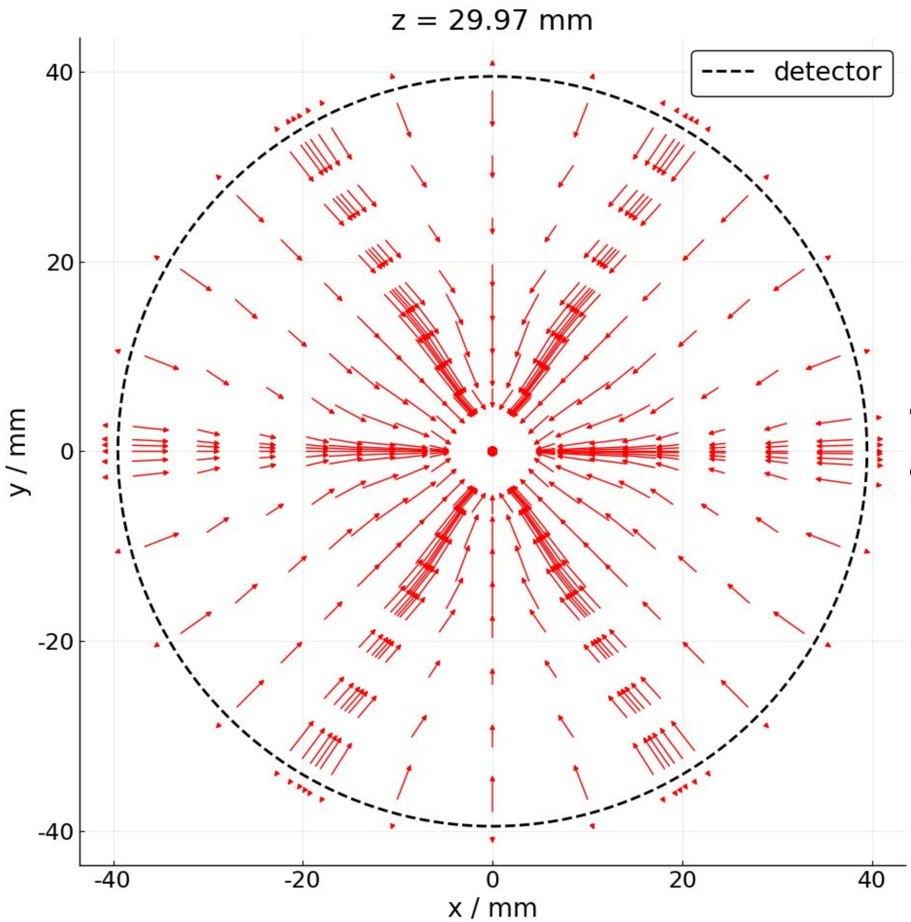
- Parallel to the principal crystal axis the drift velocity is parallel to the electric field

- μ_0, E_0, β and μ_n parameters different for electrons and holes and for <100> and <111> axes
- Different models for electrons and holes implemented from [1] B. Bruyneel et al., NIM A 569 (2006) 764
  also used by e.g. AGATA

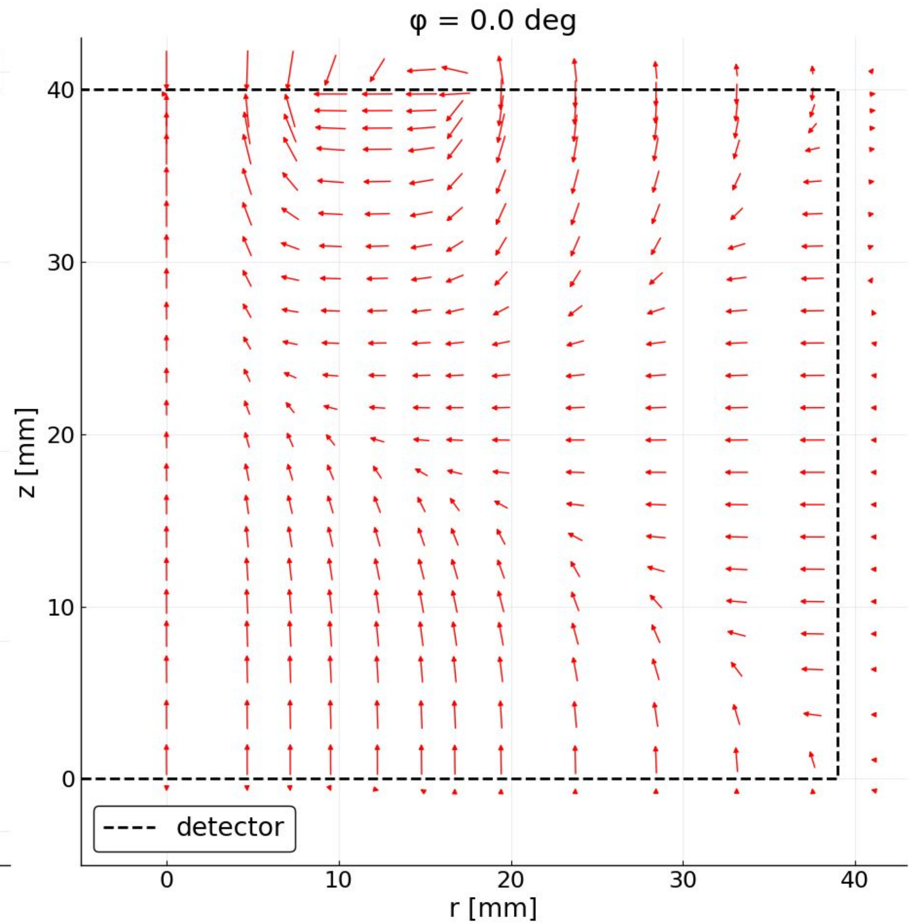
Drift velocity model

Electron Drift Velocity Field

rφ - cut



rz - cut



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