Germanium Detector With Sensitivity to MeV Dark Matter

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List Participating Institutions

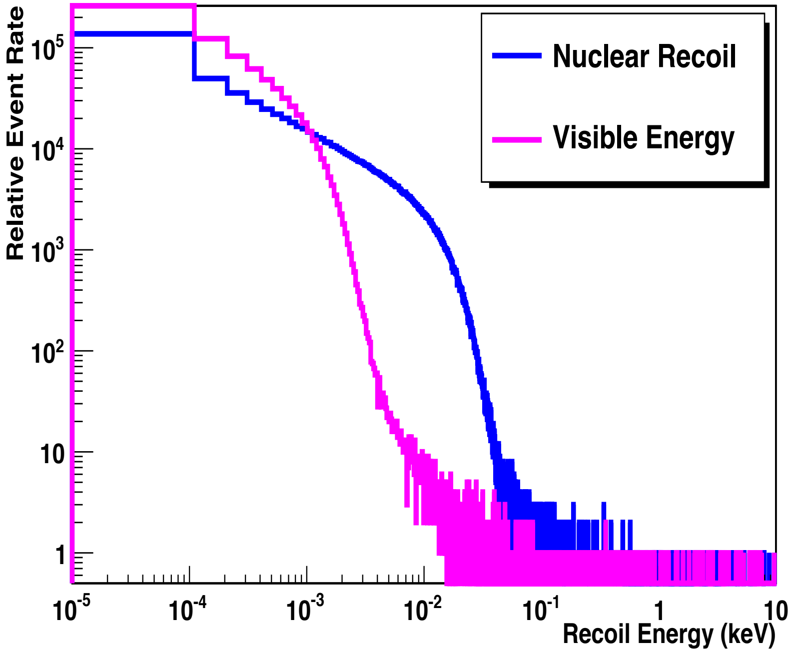
- Domestic Institutions
  - The University of South Dakota
  - The University of Alabama
  - The University of Tennessee
  - Black Hill State
  - Industry Partner - Klytec
- International Institutions
  - Institute of Physics, Academic Sinica, Taiwan
  - Tsinghua University, China
  - Sichuan University, China
  - Yangtze University, China

Primary Physics Goals

- Investigate Low-Mass Dark Matter (LDM)
  - Mass range to be in MeV to sub-GeV
  - Requires very low-energy threshold (~0.1eV)
  - R&D technology on germanium detectors
    - Ge internal amplification
    - Ionization of impurities with appropriate dopant

Experimental Approach - Signal

- Recoil Energy Spectrum by LDM 10 – 1000 MeV

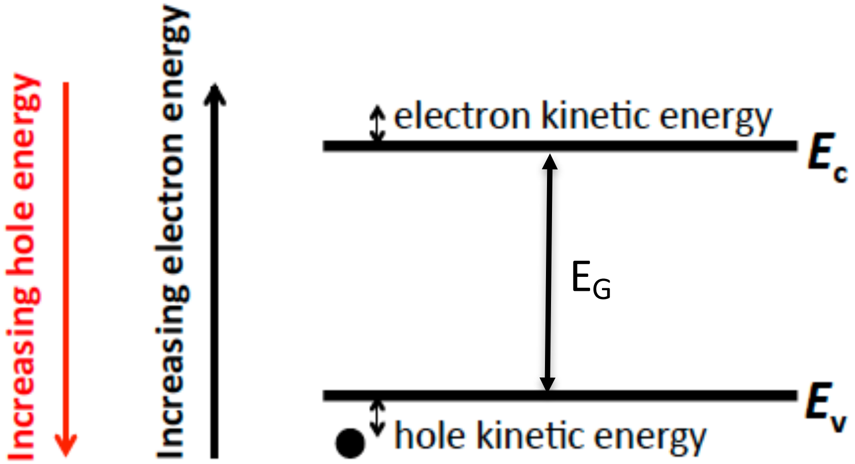


- Characteristics
  - The available energy
    - < 100 eV
  - Possible detection channels
    - Ionization
    - Excitation
    - Dissociation
  - Semiconductor
    - Silicon
    - Germanium

Experimental Approach – Semiconductors

- Conduction electron = occupied state in the conduction band
- Hole = empty state in the valence band
- Electrons & holes tend to seek lowest-energy positions

→ Electrons tend to fall and holes tend to float up (like bubbles in water)

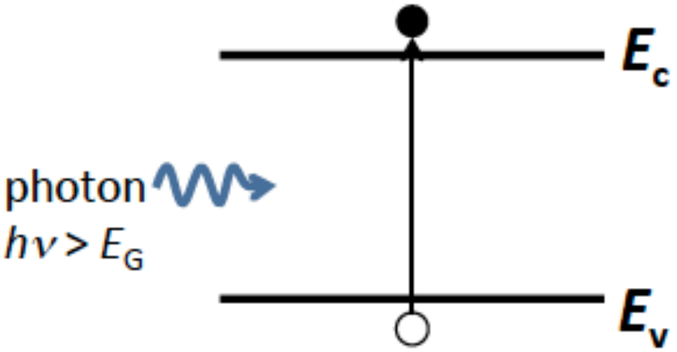


E_c represents the electron potential energy.

$$\text{P.E.} = E_c - E_{\text{reference}}$$

Measuring Band Gap Energy

- E_G can be determined from the minimum energy of photons that are absorbed by the semiconductor

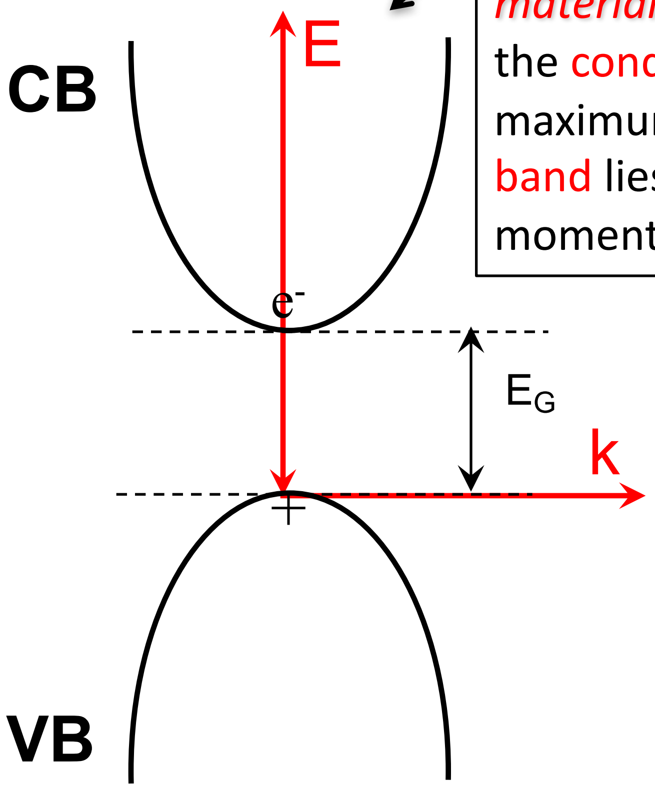


Band gap energies of selected semiconductors

Semiconductor	Ge	Si	GaAs
Band gap energy (eV)	0.67	**1.12**	1.42

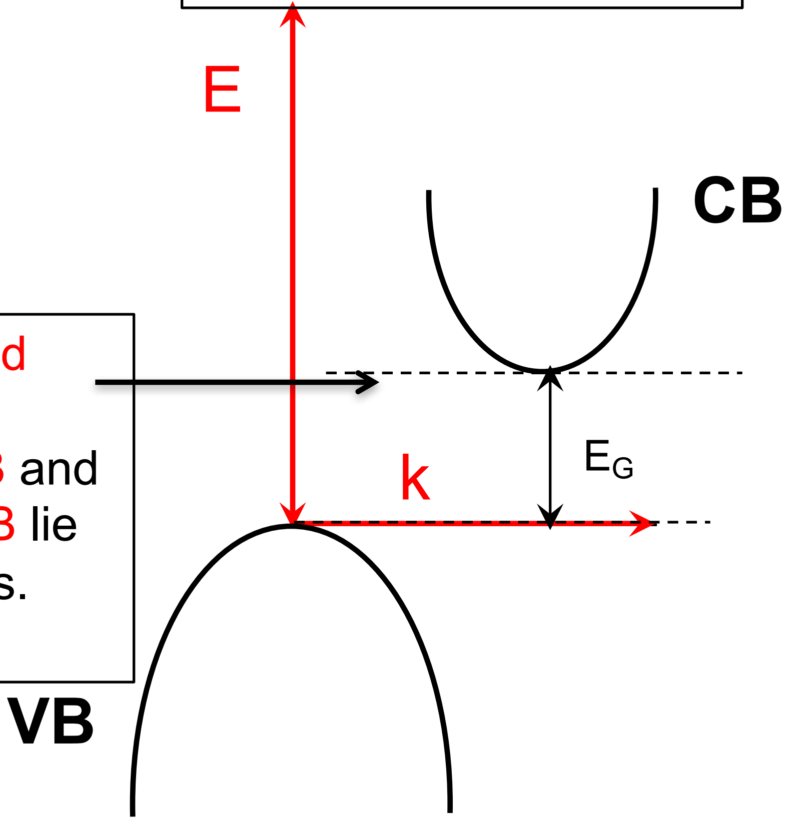
Direct and Indirect Band Gap Materials

Primary Phonon Energy = 0.037 eV



For a *direct-band gap material*, the minimum of the conduction band and maximum of the valance band lies at the same momentum, k, values

For an indirect-band gap material; the minimum of the CB and maximum of the VB lie at different k-values.



Average energy per e-h pair: Si, 3.67 eV, Ge: 2.96 eV >> E_G

Average Energy Required Per Electron-Hole Pair

Target	Band Gap	Average Energy
He	20 eV	43 eV
Ar	13.3 eV	23.6 eV
Xe	9.28 eV	15.6 eV
Ge	0.73 eV	2.96 eV

Ge has much lower average energy and hence can pursue even lower threshold

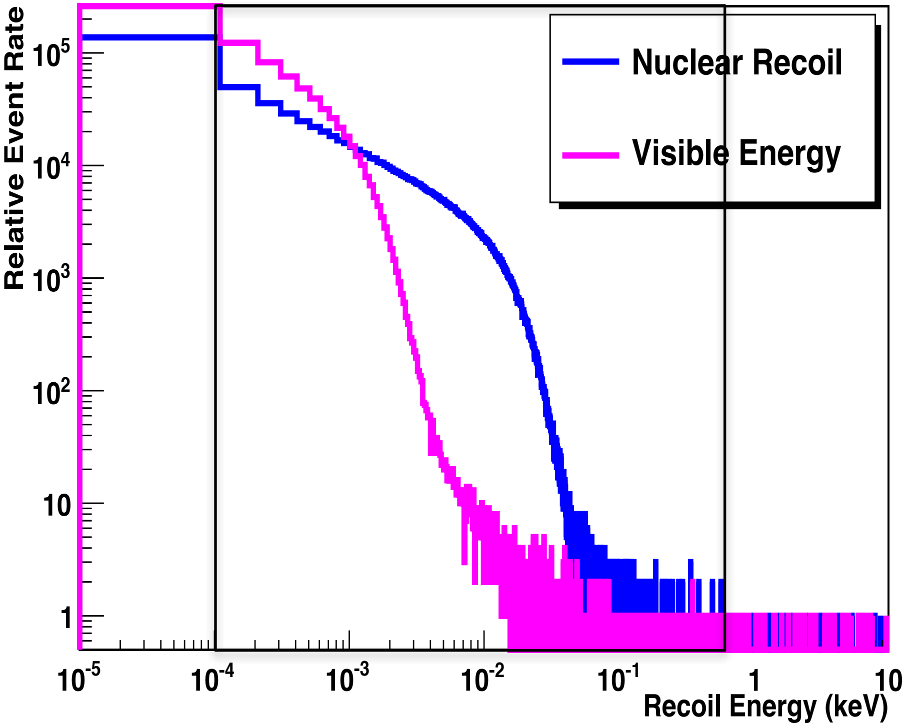
Small Signal Demanding Super Sensitivity

- Recoil energy spectrum

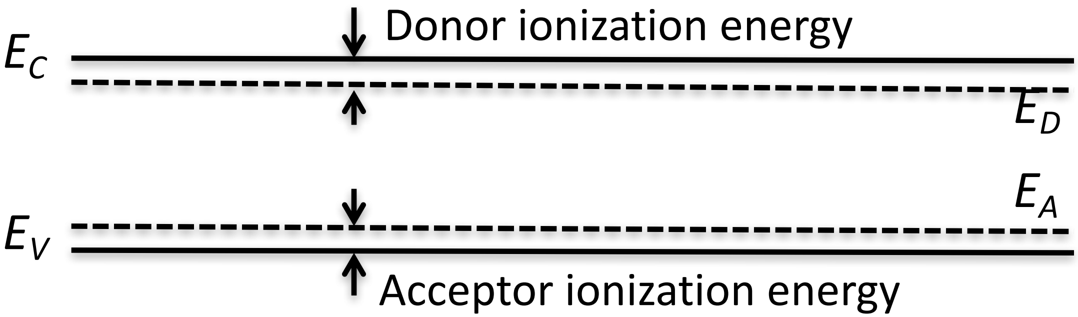
○ **The detector with the best sensitivity should be able to access sub eV region**

○ **Normal Ge detectors can only access ~3 eV region**

○ **New technology is required**



Doping impurity changing band gap energy



Ionization energies of shallow impurities in germanium , meV

	Donors			Acceptors			
Dopant	Sb	P	As	B	Al	Ga	In
Ionization Energy (meV) E_C-E_D or E_A - E_V	9.6	12.0	12.7	10.4	10.2	10.8	11.2

Impurity Impact Ionization

Let: D = any donor, D^X = neutral donor
D^+ = ionized donor, e^- to the conduction band

$$D^X + \triangle E_D \rightarrow e^- + D^+$$

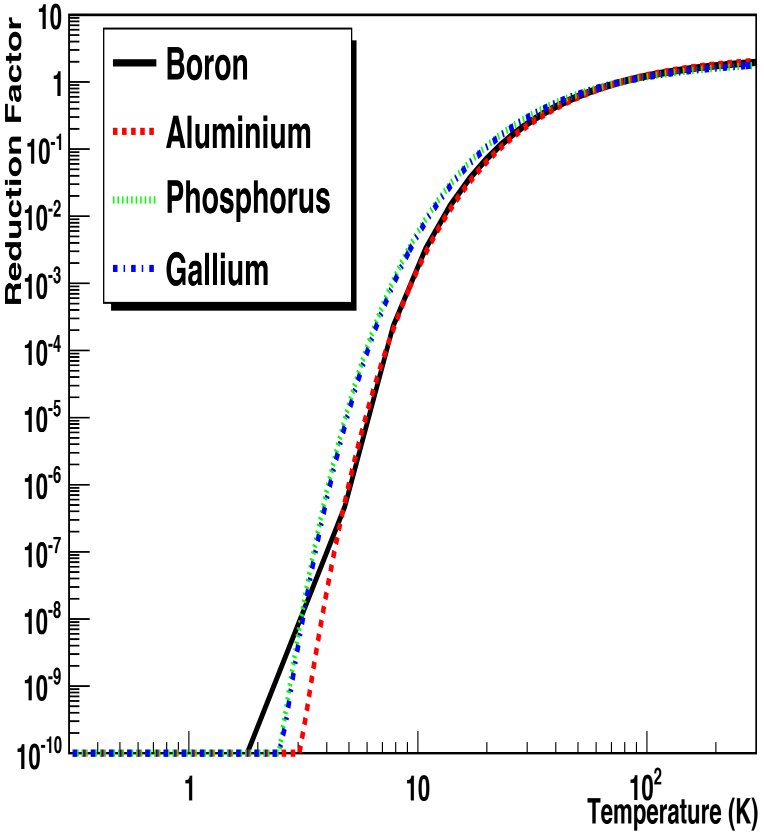
Drift electron to induce charge: signal

Let: A = any acceptor, A^X = neutral acceptor
A^- = ionized acceptor, e^+ in the valence band

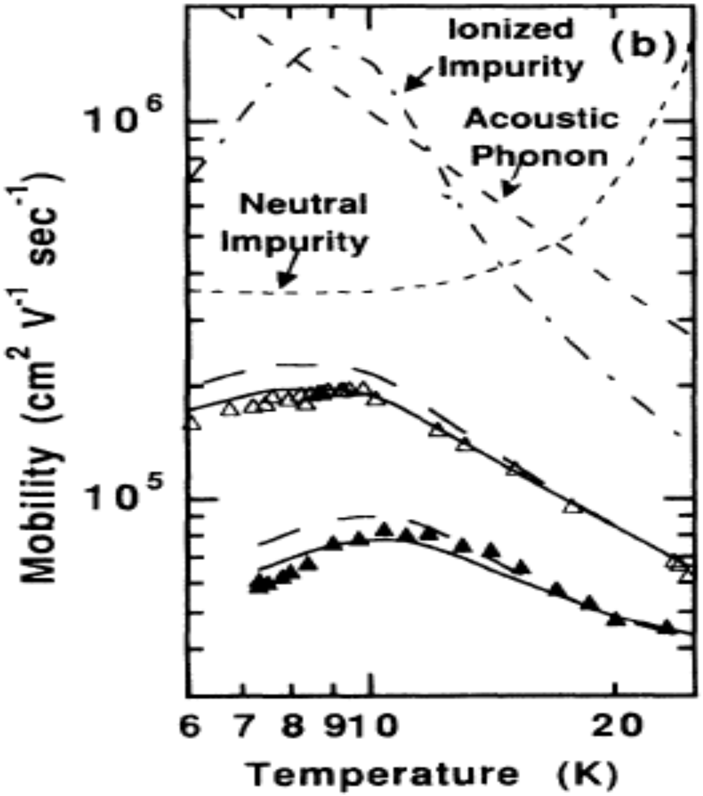
$$A^X + \triangle E_A \rightarrow e^+ + A^-$$

Drift hole to induced charge: signal

How Impact ionization of impurities works



Itoh et al, PRB 50 16995 (1994)



A detector works at helium temperature, ~4K. Nearly all ionized impurities are frozen at this temperature and the charge carriers scattering is dominated by neutral impurity.

How to Observe Sub-eV Signal?

- Electronic noise is at level of ~100 eV
- Amplifying sub-eV charge internally inside germanium crystal

↓

Germanium Internal Amplification

How to make sub-eV threshold?

- **Internal amplification** (A. S. Starostin and A. G. Beda, SarXiv:hep-ex/0002063v1) with multistrip planar germanium detector, similar in design to MWPC. The electric field in MWPC is of the form for one dimension case (the coordinates *x* and *y* relate to an centered on the wire, *x* is parallel to the wire plane, *y* is perpendicular)

$$E(0,y) = \frac{\pi V}{s\left[\frac{\pi L}{s} - \ln\frac{\pi d}{s}\right]} \coth\frac{\pi y}{s}$$

where *V* is applied voltage, *s* is wire spacing, *d* is the diameter of the wire, *L* is the thickness of the planar detector.

Internal Amplification

(A. S. Starostin and A. G. Beda, SarXiv:hep-ex/0002063v1)

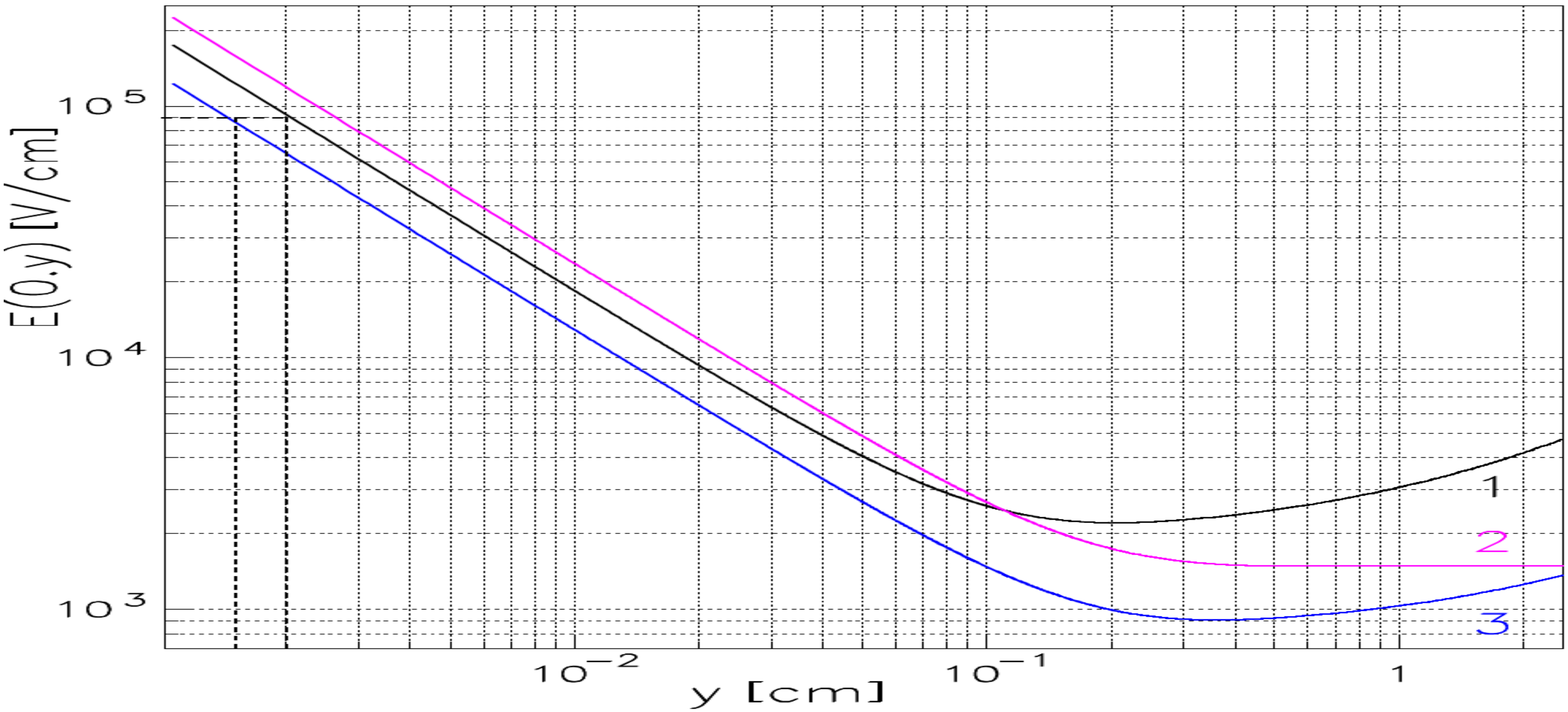


Figure 2: Dependence $E(0, y)$ on y for planar detector from HPGe n-type with d = 20 microns at V = 4000 V and at different values of the others parameters: **1** - $N = 10^{10}\ cm^{-3}$, $L = 1.5\ cm$ and $s = 0.3\ cm$; **2** - $N = 0$ (volume charge is absent), $L = 2.0\ cm$ and $s = 0.5\ cm$: **3** - $N = 2 \times 10^9\ cm^{-3}$, $L = 3.0\ cm$ and $s = 0.5\ cm$. For (**1**) and (**3**) the length of avalanche region is equal 10 and 5 microns, accordingly.

Germanium Detector with Internal Amplification

(A. S. Starostin and A. G. Beda, SarXiv:hep-ex/0002063v1)

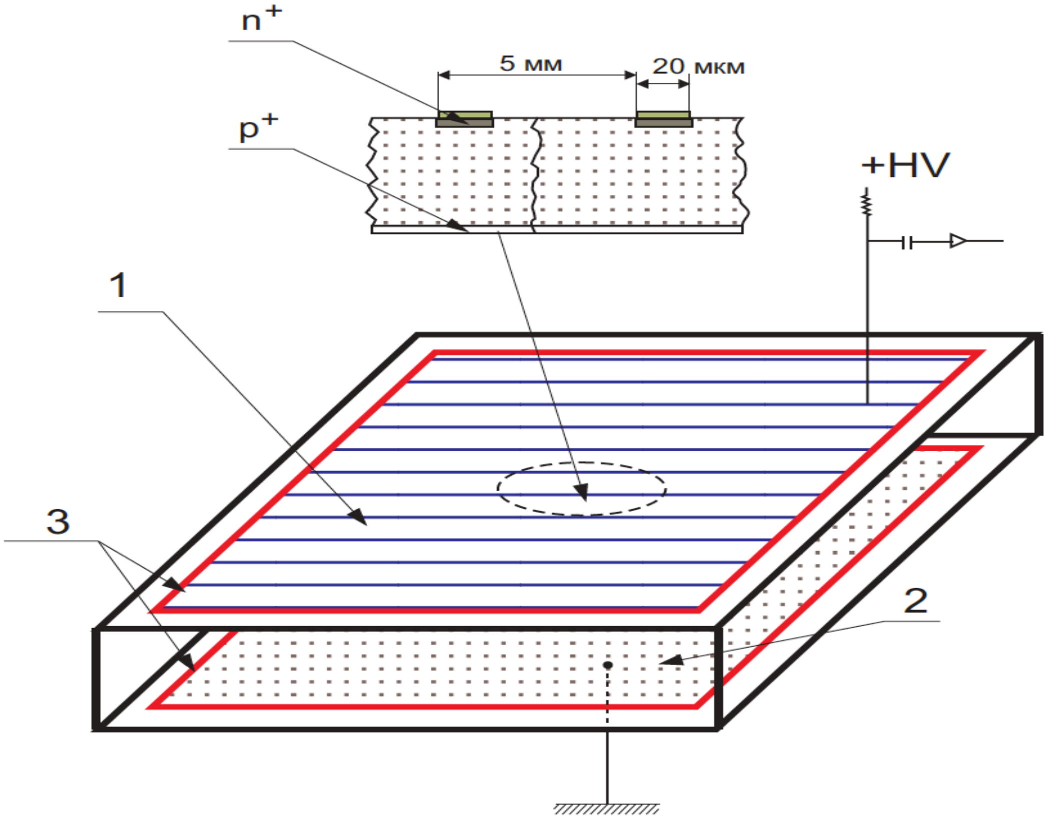
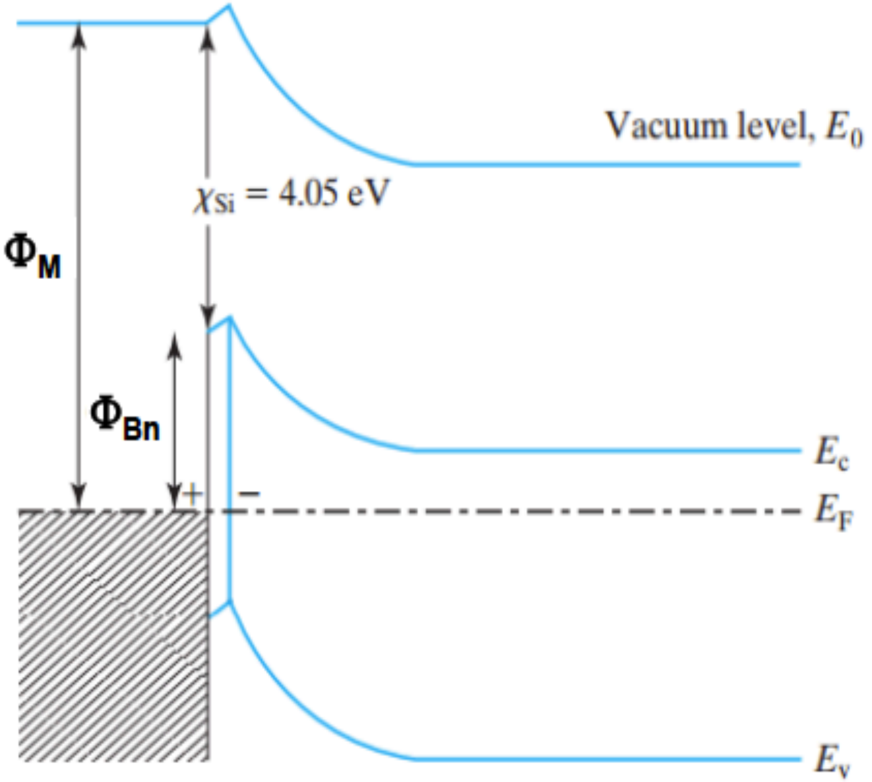


Figure 3: Germanium detector with internal amplification. 1 - anode strips, 2 - cathode, 3 - guard electrodes, the scheme of n^+ and p^+ - layers are shown in the upper part.

Amplification factor: 1000. The energy threshold can be as low as 0.4 eV

Contact Technology



- **Ideal M-S contact:**

  $$\Phi_{Bn} = \Phi_M - \chi$$

- **Real M-S contacts:**

A high density of allowed energy states in the band gap at the M-S interface "pins" E_F to be within the range 0.4 eV to 0.9 eV below E_c

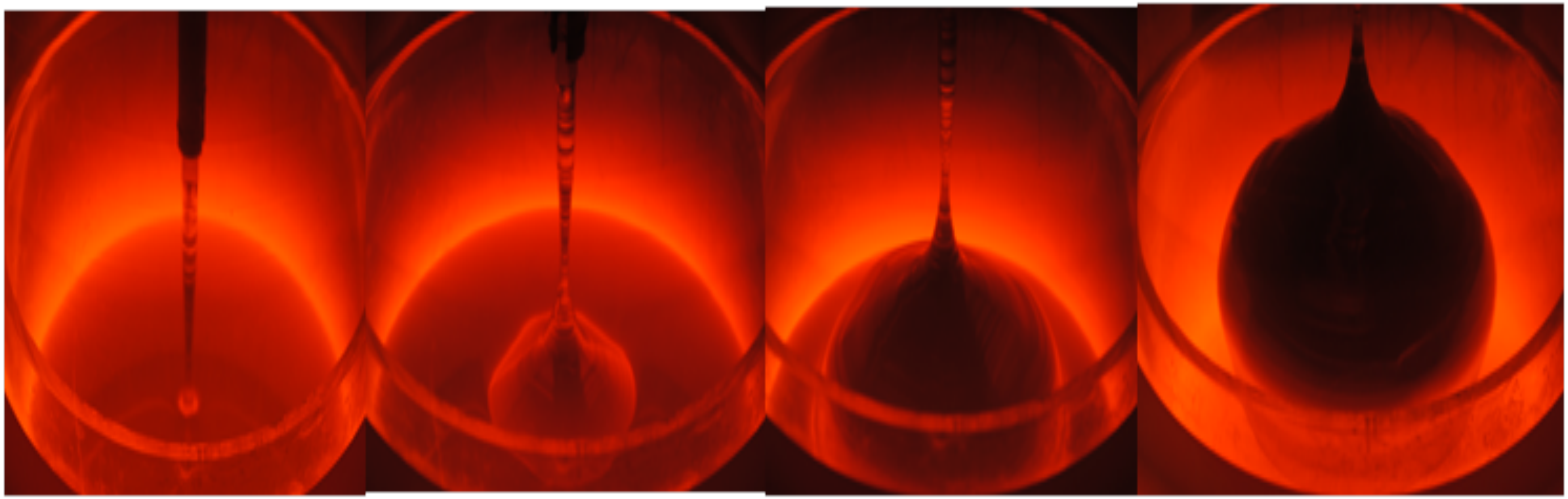
Significant R&D

- Detector technology
  - Appropriate doping level
  - Internal amplification
- Contact technology
  - Appropriate work function
  - Stable contacts
  - Low noise

- Multiple detectors or one detector with multiple iterations
- Costly prohibitive and timely impossible to purchase from industry
- Self crystal growth and detector development is required

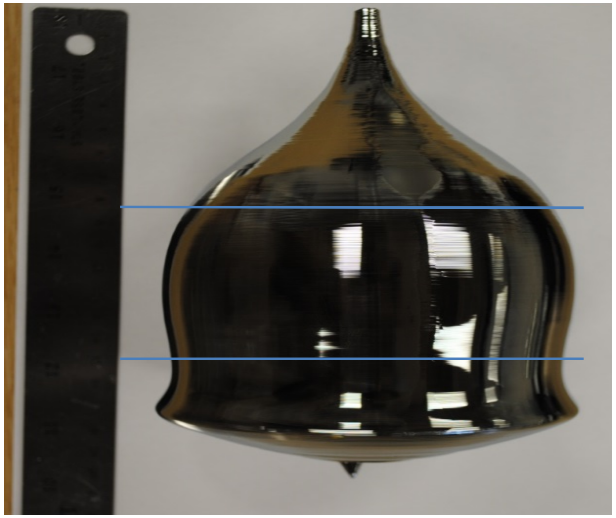
Existing Physics Results

The processes of crystal growth:

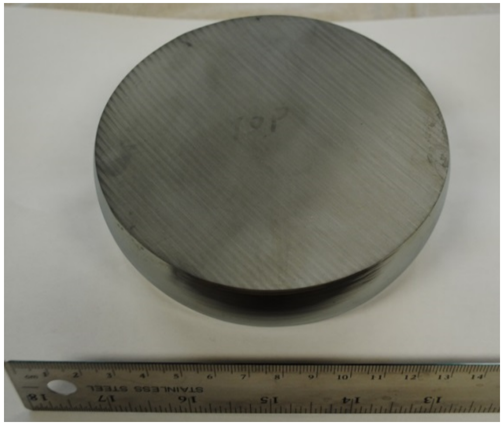


Dash process Shouldering process Equal diameter growth Ending process

A Large grown crystal



5.9Kg



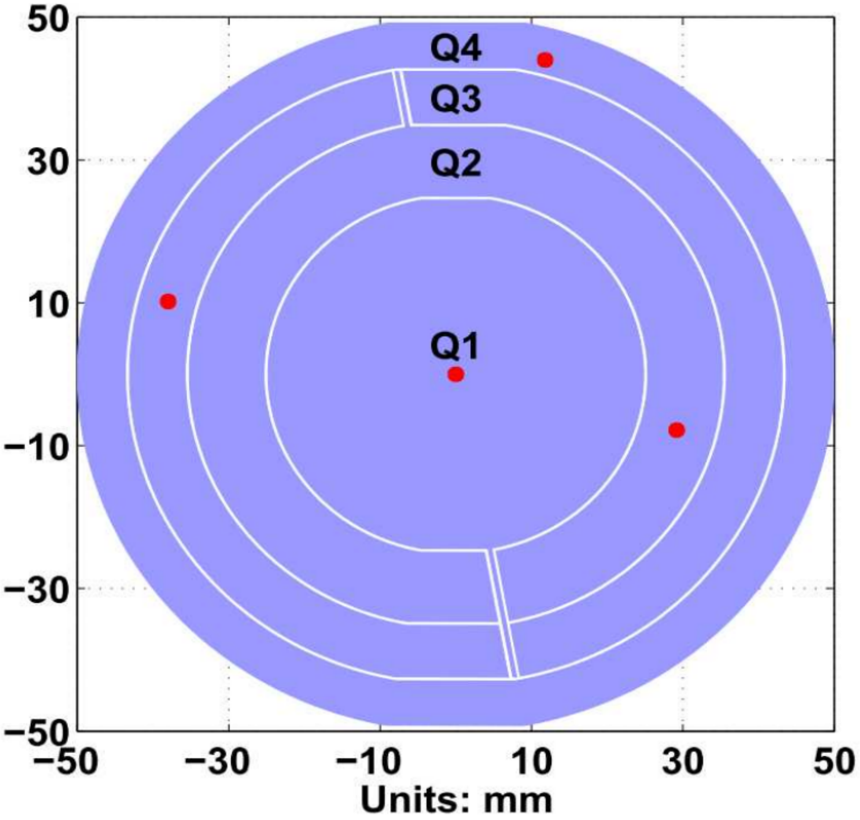
Weight
2.3kg

112mm (top) x 115.7mm (bottom) x 41.1mm thickness.

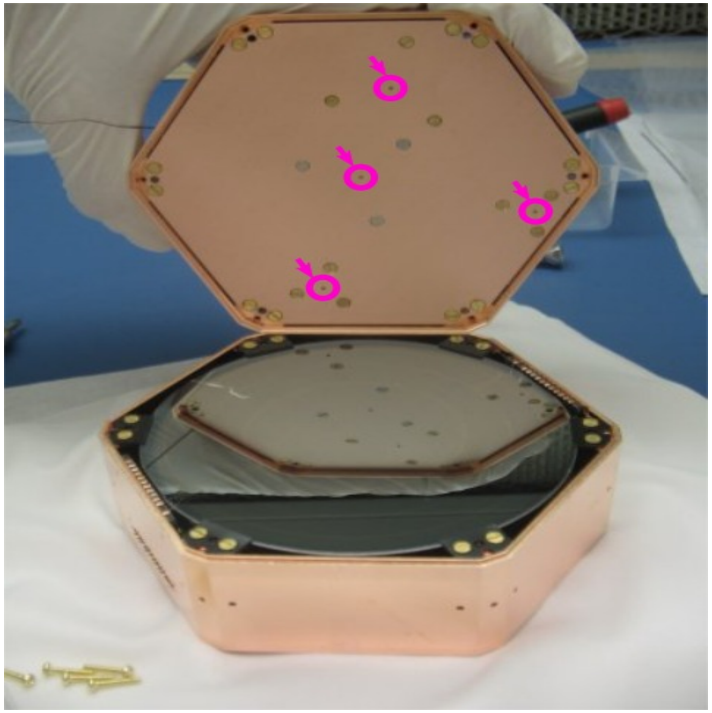
Fabricated into SuperCDMS type detector by Texas A&M University

Detector Performance

Detector fabrication



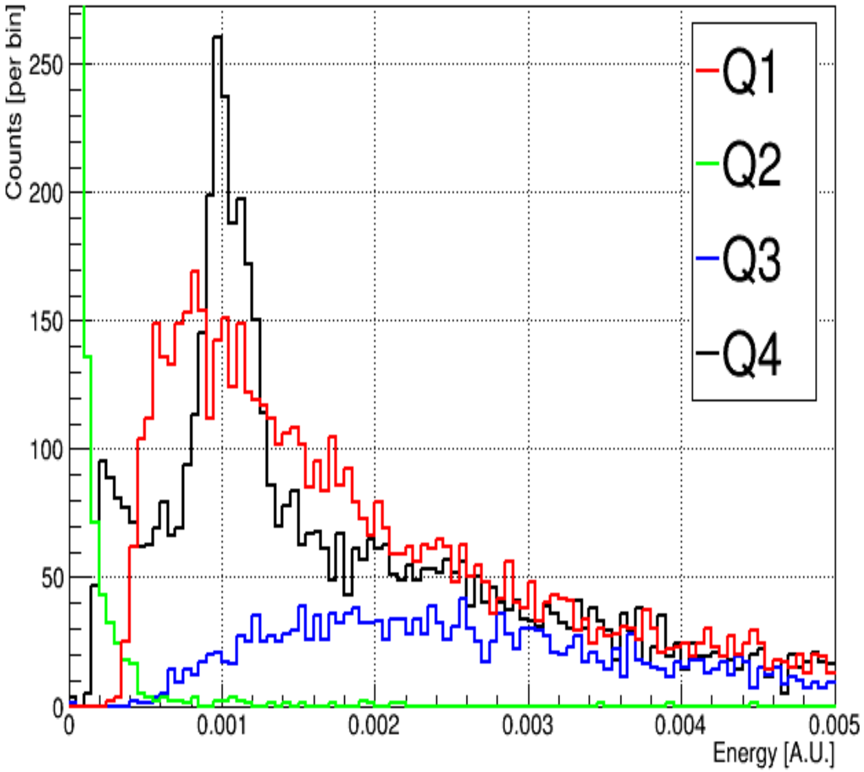
Concentric electrodes were deposited on one side of the crystal



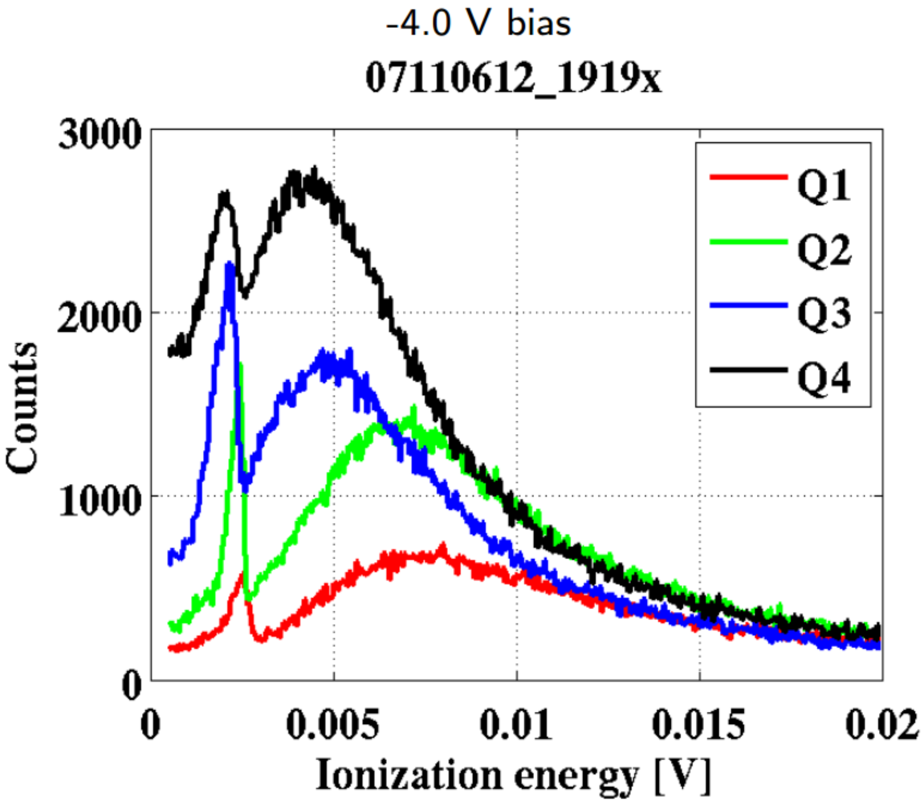
Four Am sources were installed on a plate above the detector. Pinholes sit on the radial midpoint of each electrode and let decay products through to the crystal. Operation temperature is ~50 mK.

Detector fabricated by Mahapatra group at Texas A&M

Test results from UMN



USD1 charge response at +13V



G101 charge response at +4V[1]

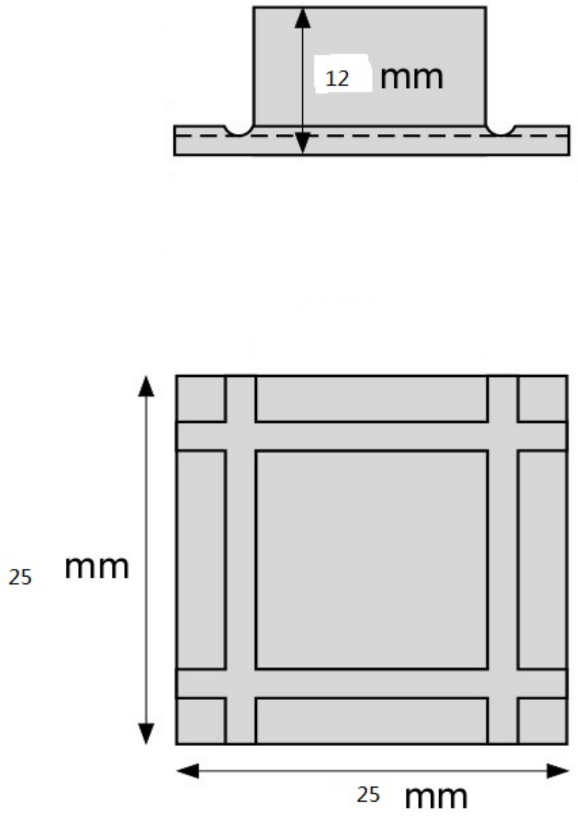
The peaks due to 60 keV gamma-rays from the ^{241}Am sources .

Detector is characterized by Dr. Mandic' group from University of Minnesota

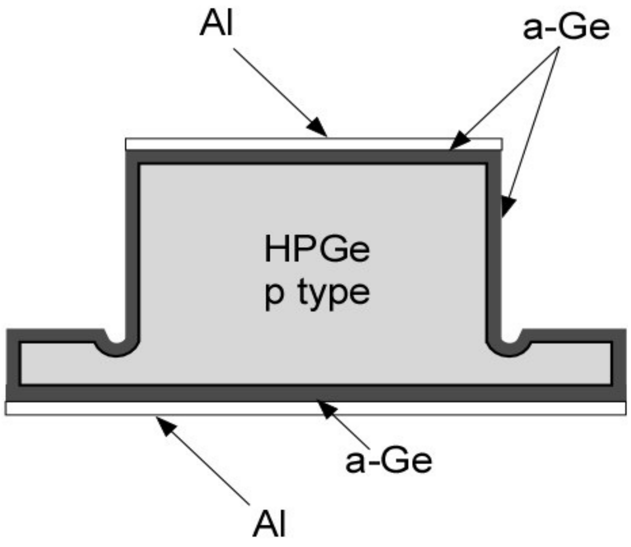
[1] Hassan Chagani, IDM 2012

R&D on Planar Detector with Amorphous Ge Contacts

Detector dimensions
(prior to etching)

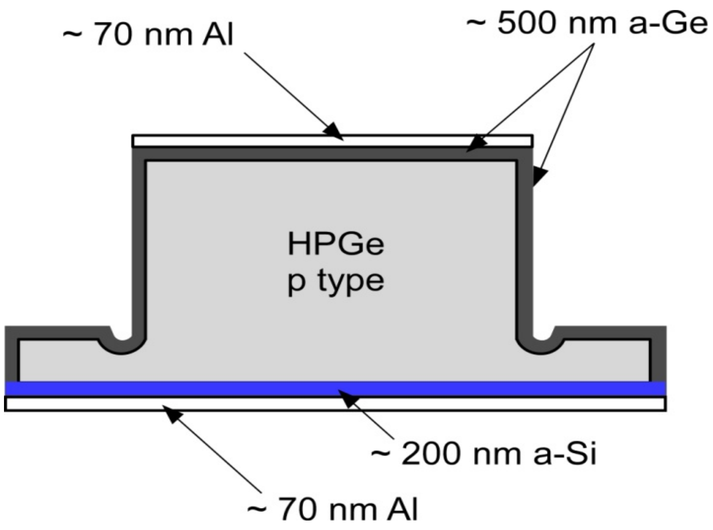


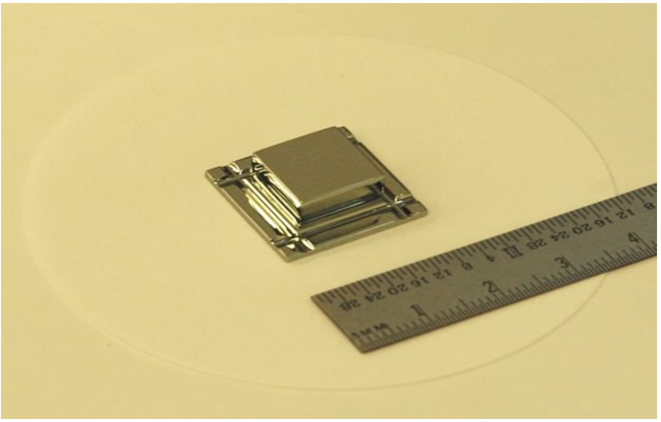
Electrical contact structure
(detector cross-section)

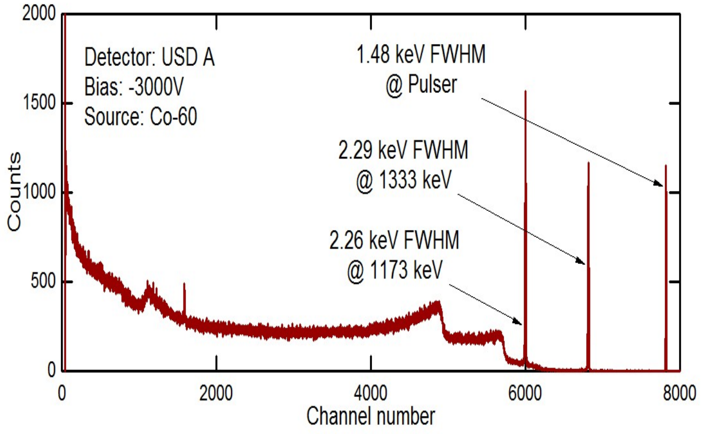


Courtesy to Mark Amman at LBNL

Planar Detector Fabrication and Test



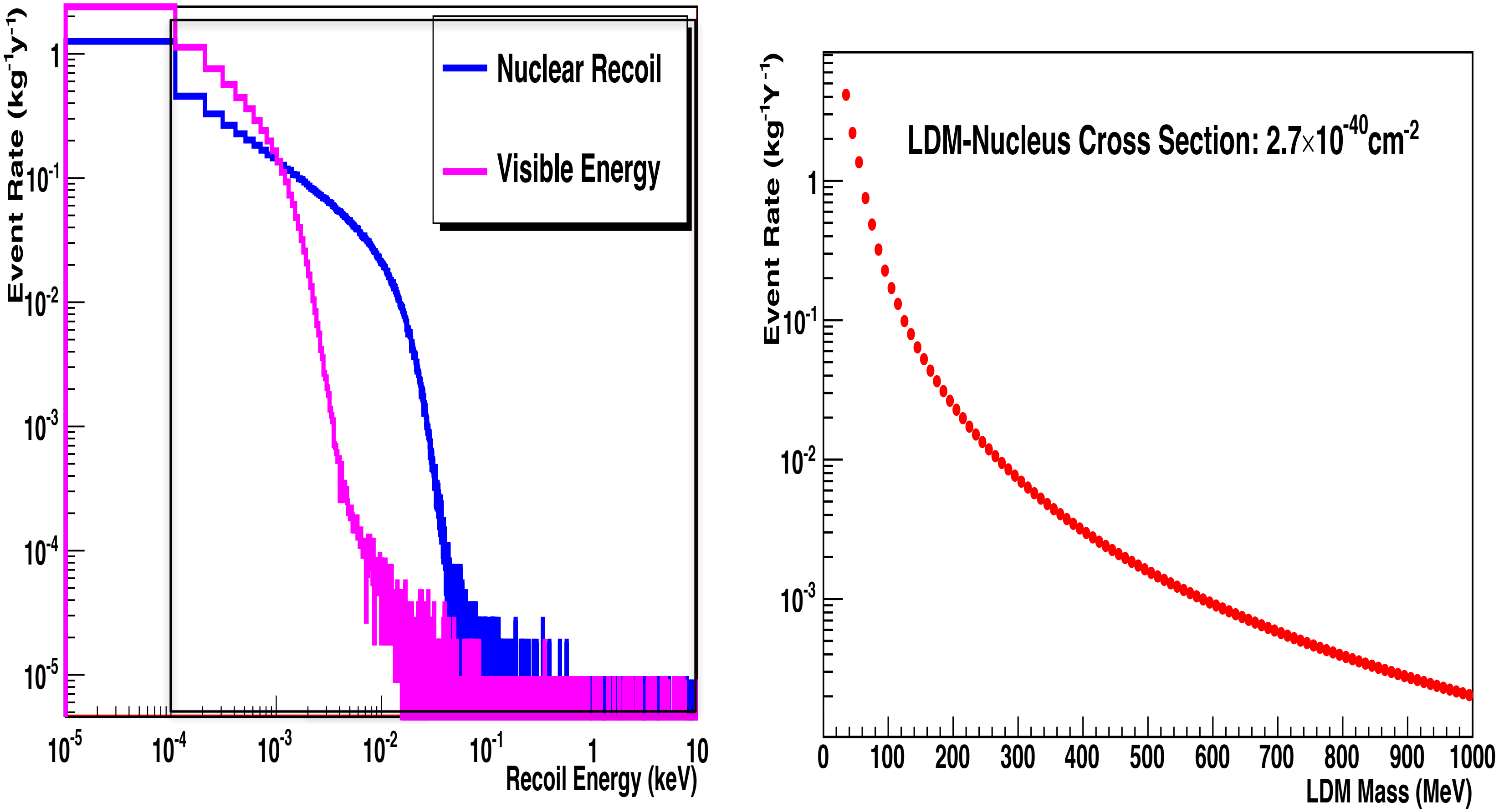




G. Wang et al., Material Science in Semiconductor Processing V39 (2015) 54-60

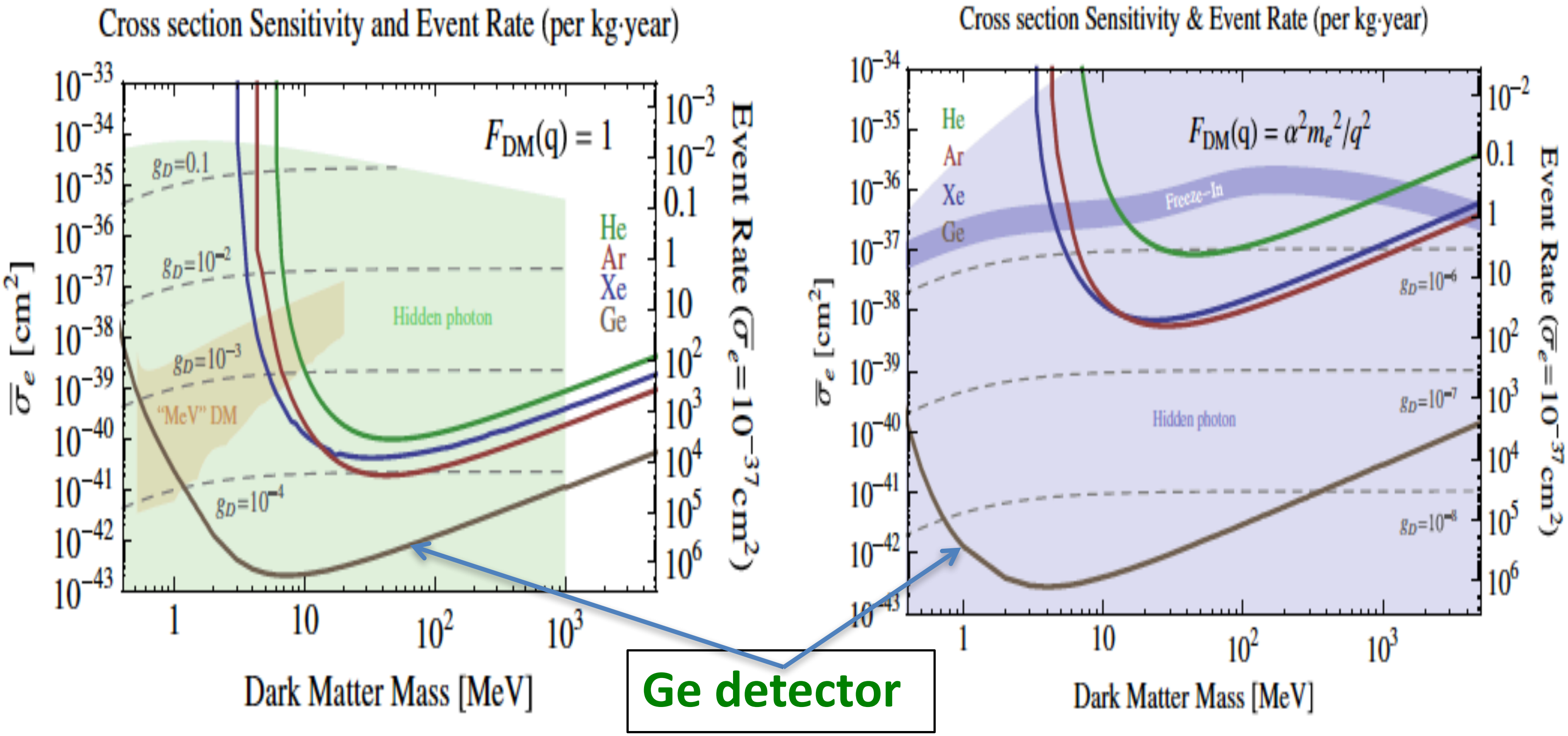
1. **A planar detector with Amorphous Ge contacts was made by Mark Ammen at LBNL**
2. **A variable temperature cryostat is planned for the measurement of impact ionization of impurities**

Sensitivity to Nuclear Recoils



Normalized to LDM-Nucleus cross-section of $2.7\text{x}10^{-40}\text{cm}^2$

Expected Sensitivity for Electronic Recoils



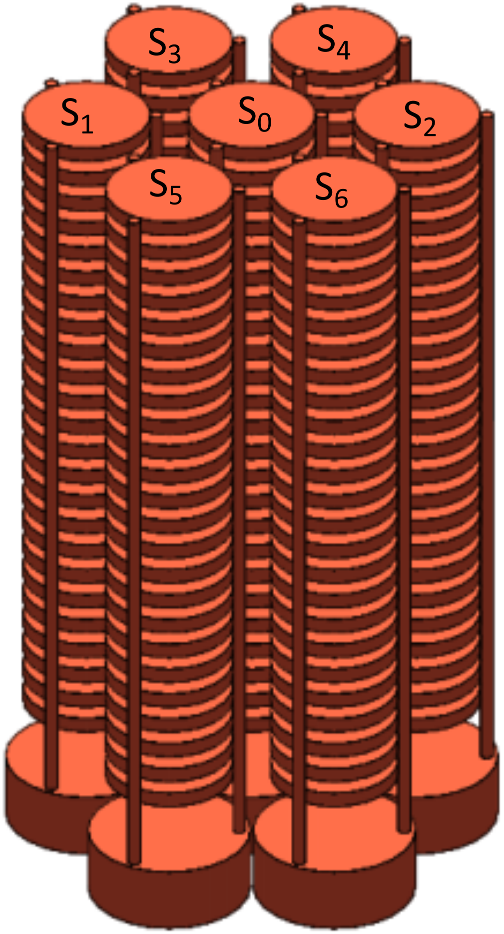
Ge detector

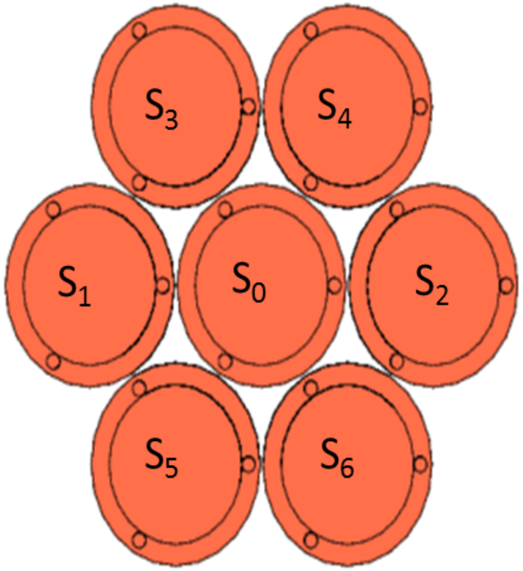
R. Essig, J. Mardon, and T. Volansky, Phys. Rev. D 85 (2012)076007

Timescale of Future Plans

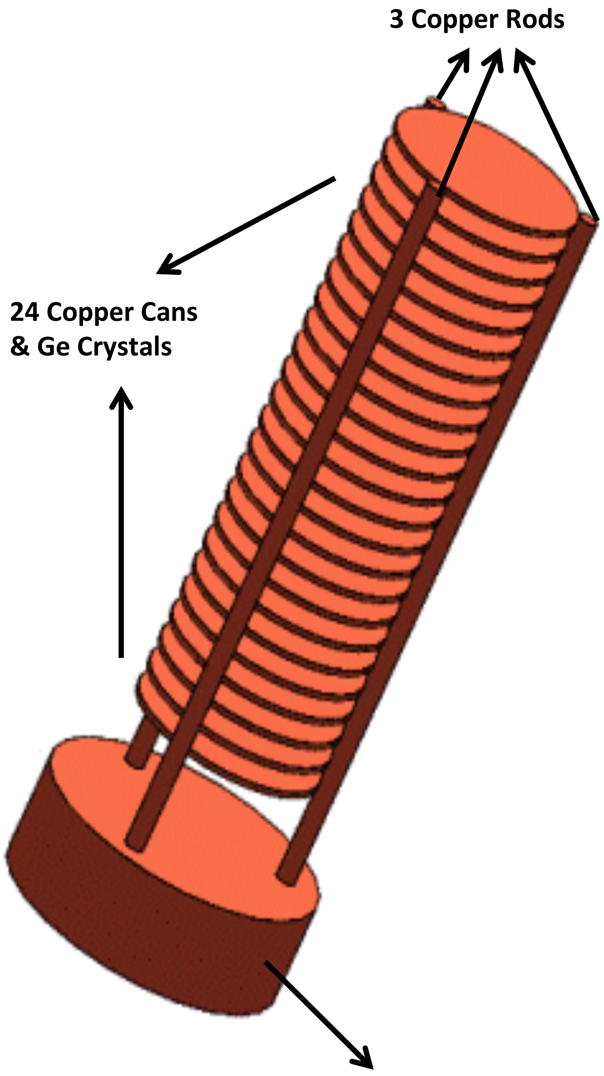
- Detector development : 3 years
  - Internal amplification
  - Doped impurity level for impact ionization of impurity
  - Several iterations of detector fabrication and test
- Experiment at SURF: 10 years
  - Year 4: 1 kg detector
  - Year 5 to Year 6: 10 kg
  - Year 7 to Year 10: 100 kg

Geometry





S_i (i=0, 1, 2, 3, 4, 5, 6) represents the string number.



Simulated geometry for the proposed detector. Left: Side view. Middle: Top view. Right: Structure of each string.

Rough Estimate of Budget

- 3 years R&D: $600k
  - 1 kg scientific experiment at SURF
  - Prove background level and educate students
- 10 kg experiment: $1.5M
  - Discovery potential
- 100 kg experiment: $10M
  - Discovery