Partnership for International Research and Education (PIRE)

PIRE – R&D for Future Experiments

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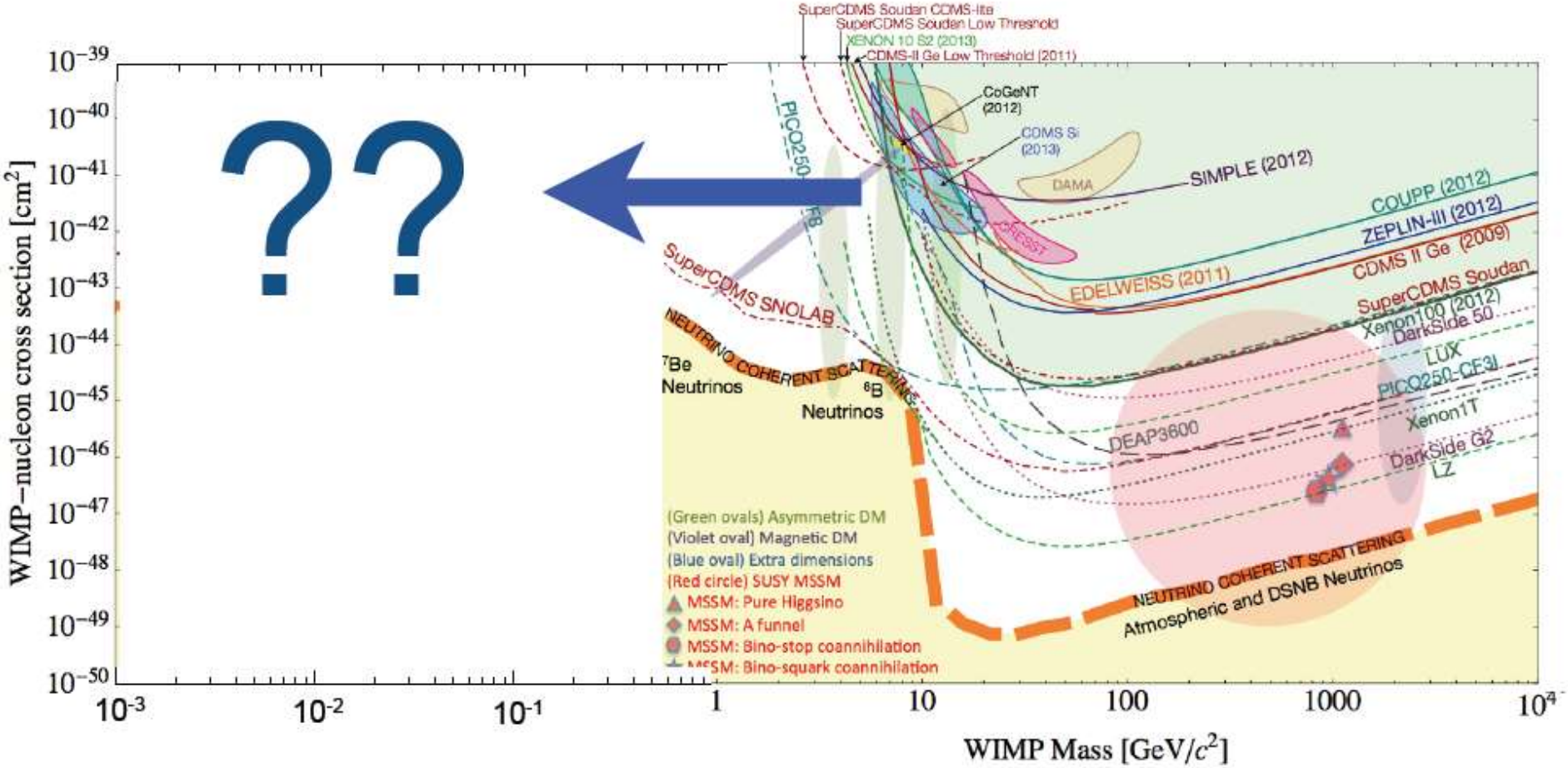
The University of South Dakota

Motivated by Physics

- **Low-Mass Dark Matter**
  - **Mass range to be in MeV**
    - **Require very low-energy threshold (~eV)**
    - **Signal is electronic recoils**
  - **Mass range to be in a few GeV**
    - **Require n/γ discrimination (~keV)**
    - **Signal is nuclear recoils**
  - **R&D technology**
    - **Ge internal amplification Low-Mass Dark Matter**
    - **Pulse shape with plasma time**
- Neutrinoless Double-Beta Decay
  - R&D technology
    - Amorphous Ge contacts
    - Te semiconductor
- Low-Energy Neutrino Physics

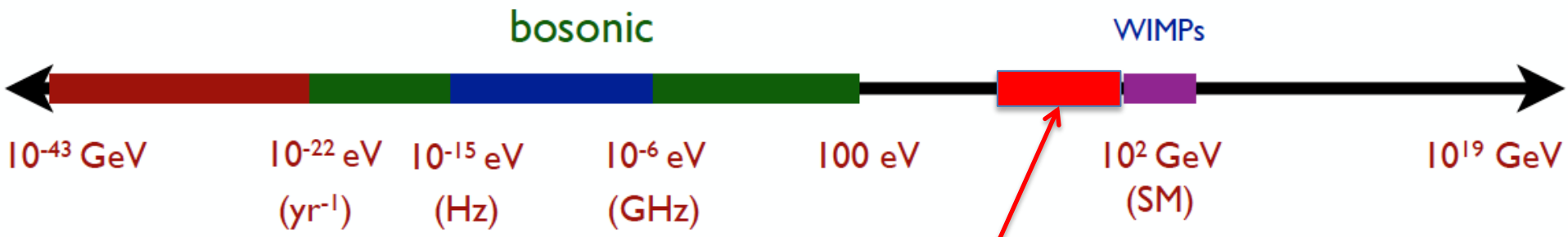
Low-Mass Dark Matter in MeV

Courtesy to Kathryn Zurek from LBNL-Dark Matter Workshop, 6/9/15



Courtesy to Surjeet Rajendran from LBNL Dark Matter Workshop, 6/9/15

Dark Matter Landscape



Fit in galaxy

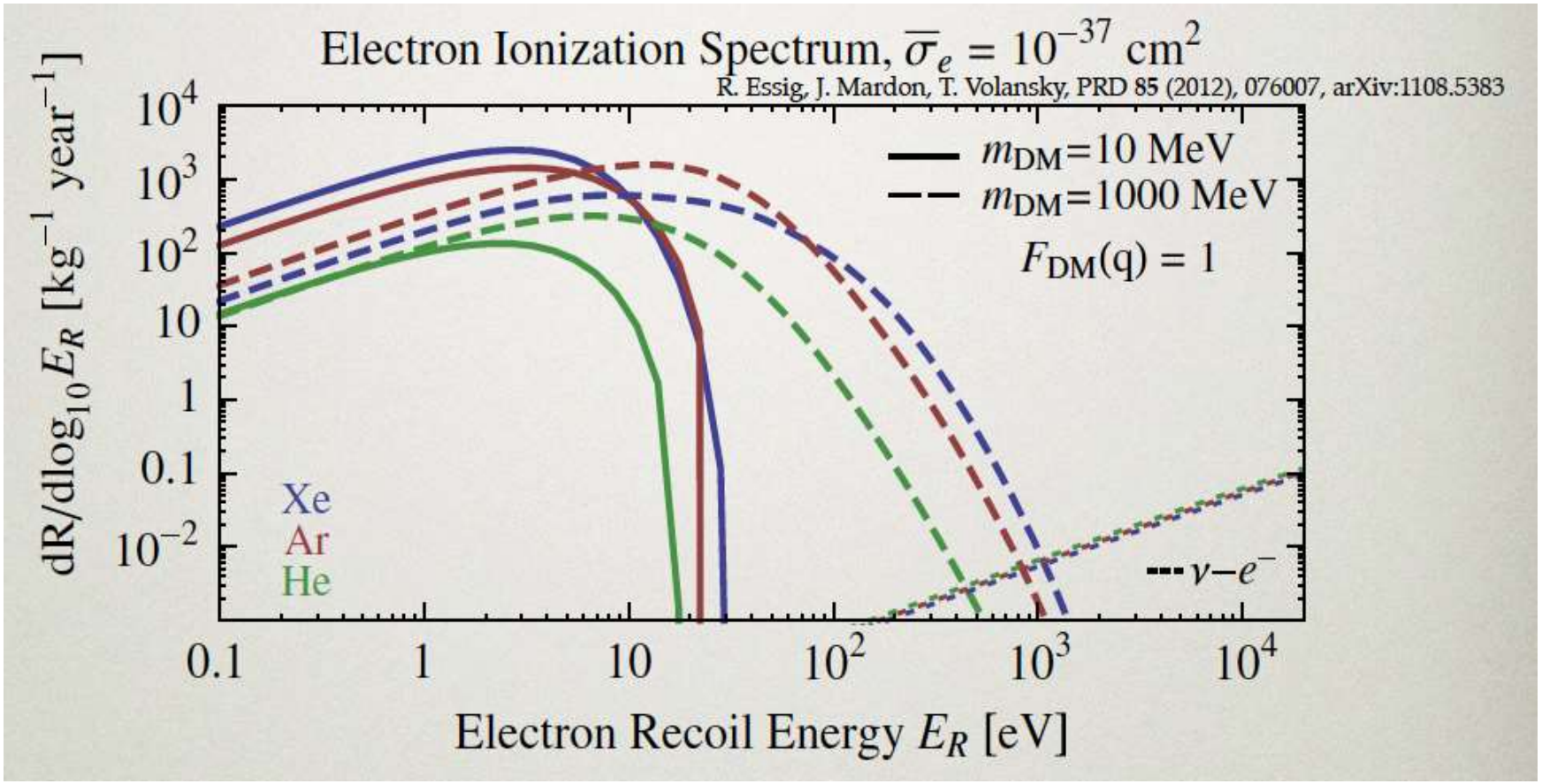
Standard Model scale ~ 100 GeV

One Possibility: Same scale for Dark Matter?
Weakly Interacting Massive Particles (WIMPs)

Other Generic Candidates: Axions, Massive Vector Bosons

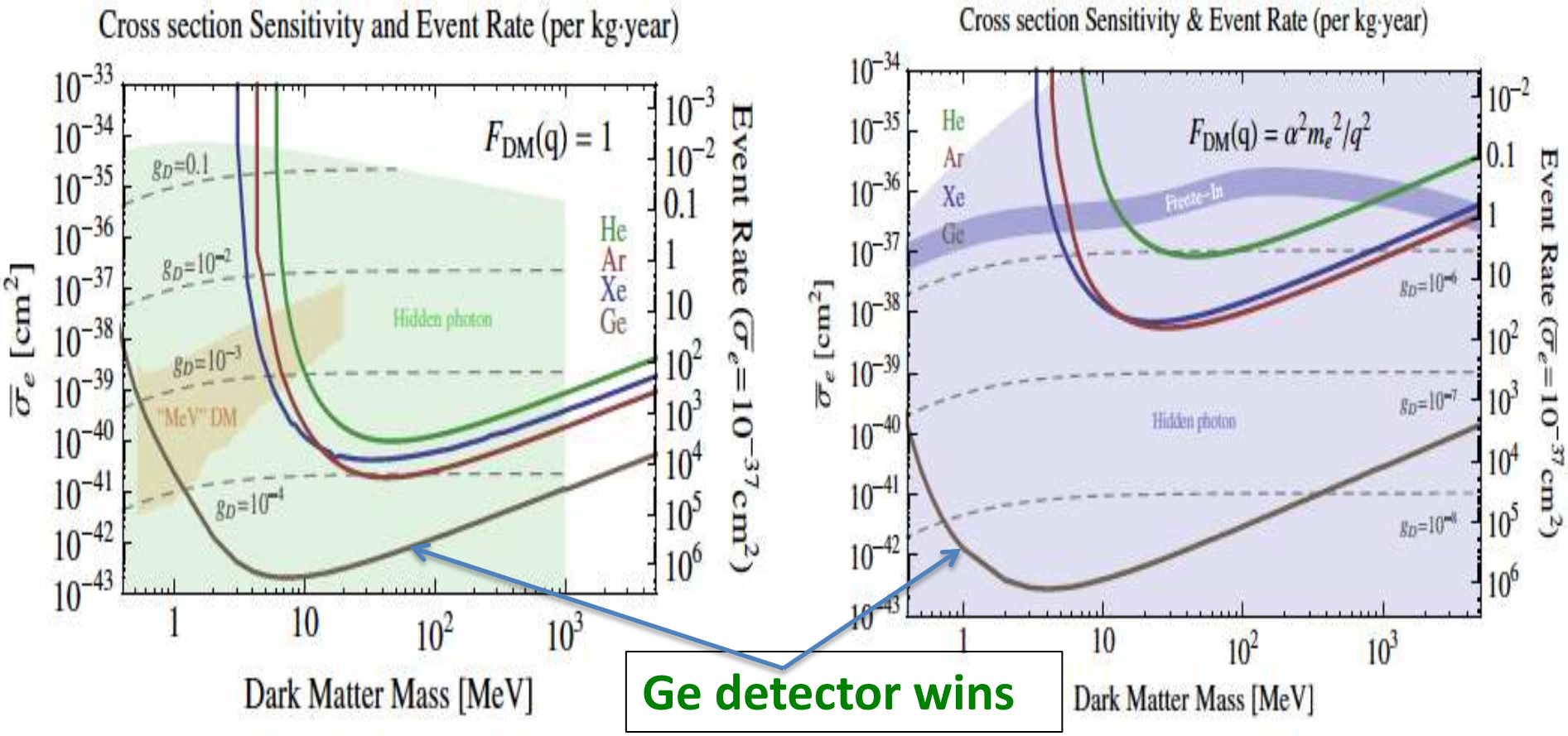
We are interested in: MeV to sub-GeV dark matter candidates

How to Detect Them?



Detectable energy from scattering is in eV range which requires new technology

Expected Sensitivity



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

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

How to make 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)

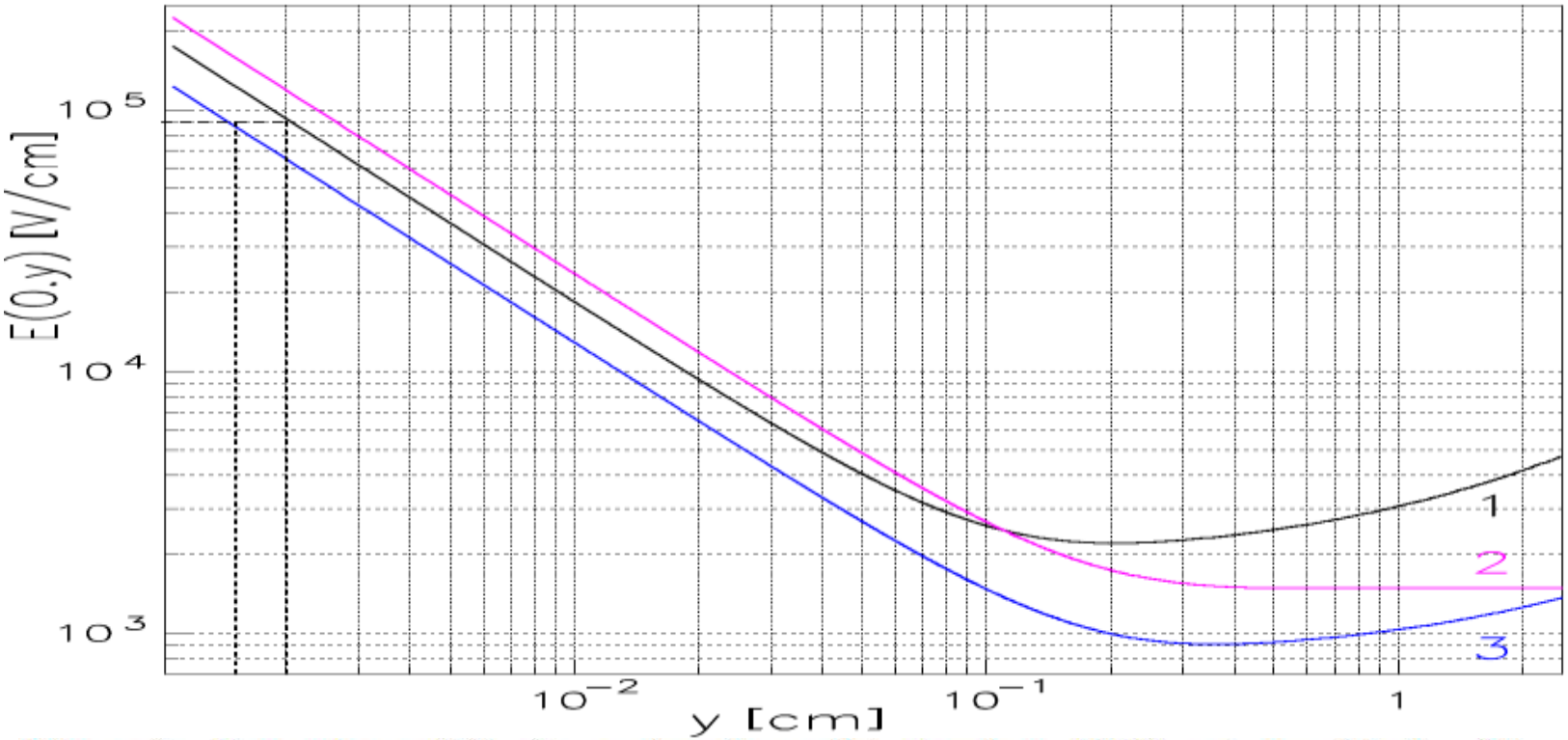
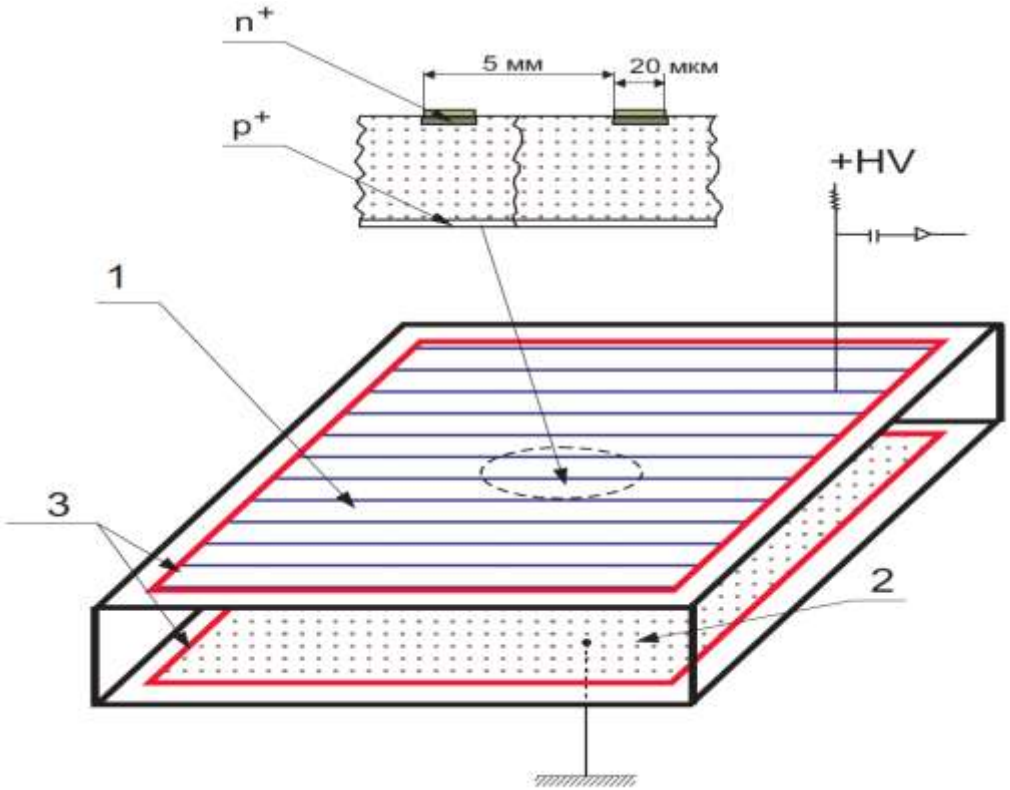


Figure 2: Dependence $E(0, y)$ on y for planar detector from HPGe n-type with d = 20 microns at V = 4000 V and at different values of the others parameters: **1** - $N = 10^{10}\ cm^{-3}$, $L = 1.5\ cm$ and $s = 0.3\ cm$; **2** - $N = 0$ (volume charge is absent), $L = 2.0\ cm$ and $s = 0.5\ cm$: **3**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

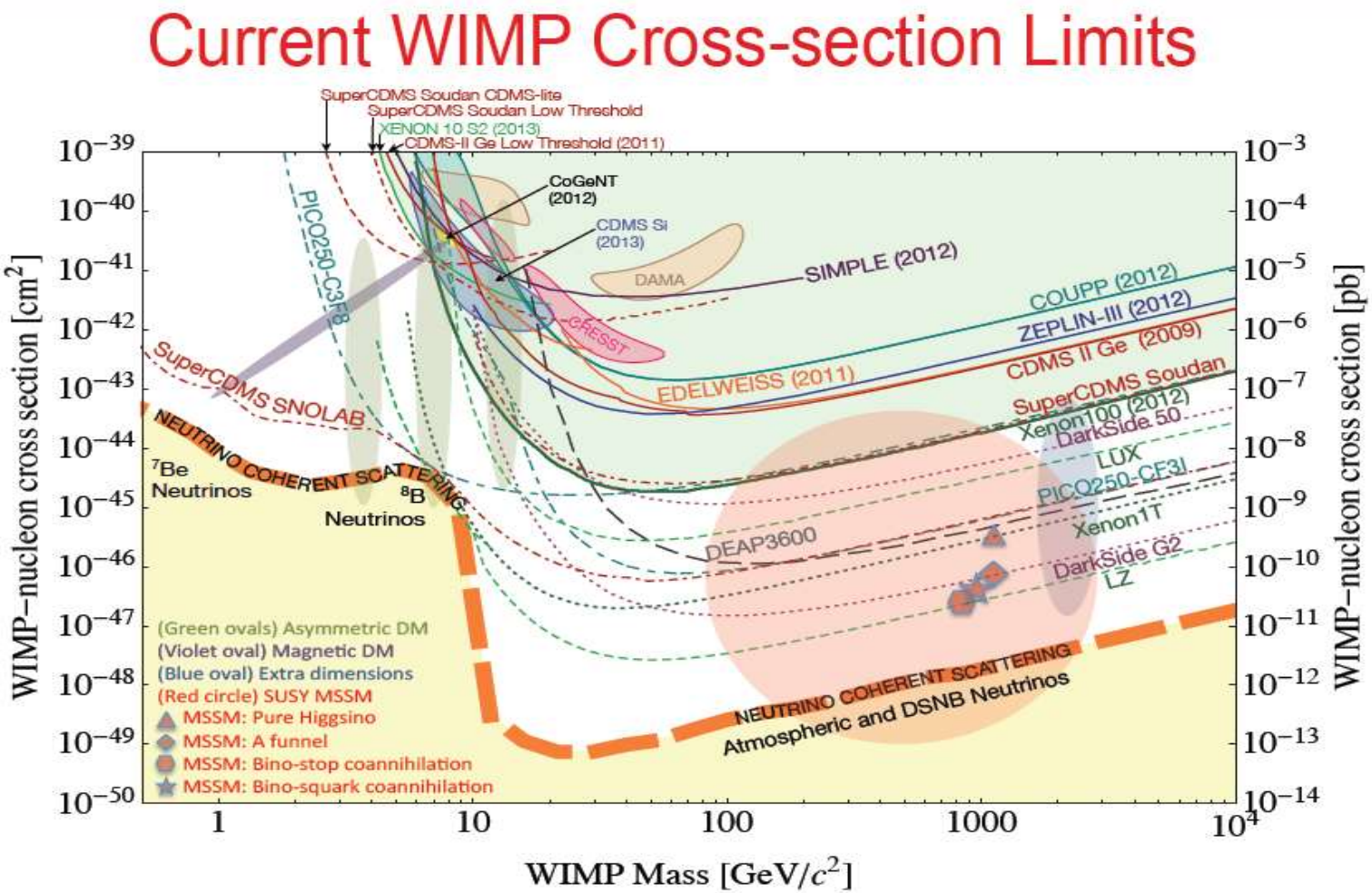
(A. S. Starostin and A. G. Beda, arXiv:hep-ex/0002063v1)



Amplification factor: 1000. The energy threshold can be as low as 12 eV

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.

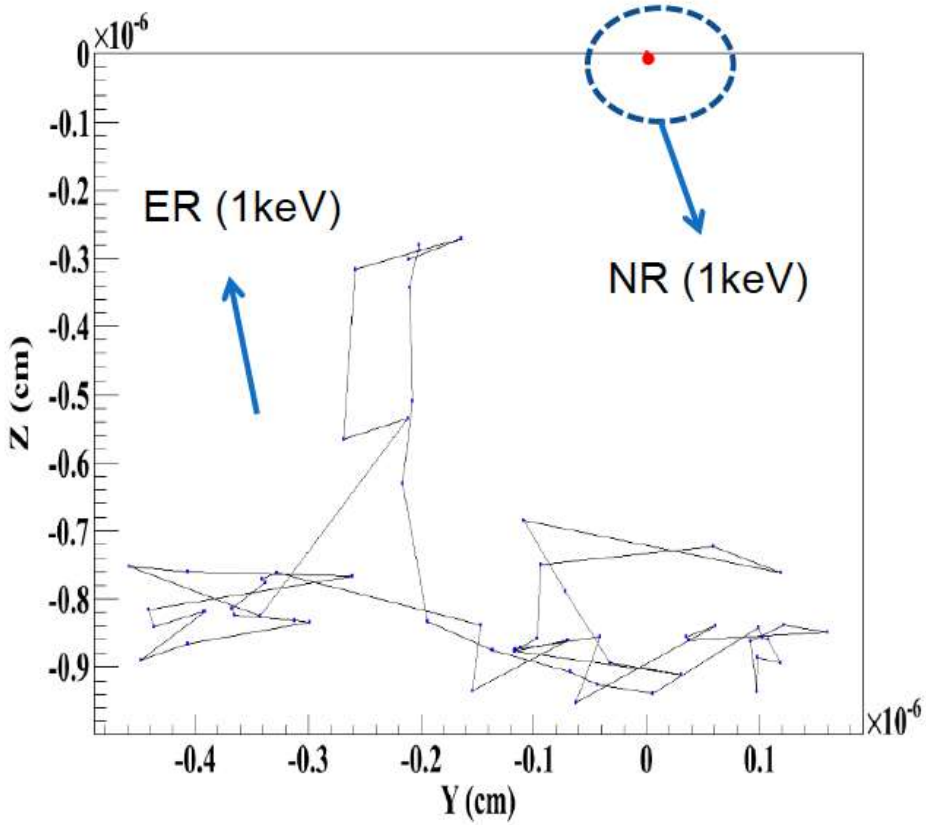
Low-Mass Dark Matter in a few GeV

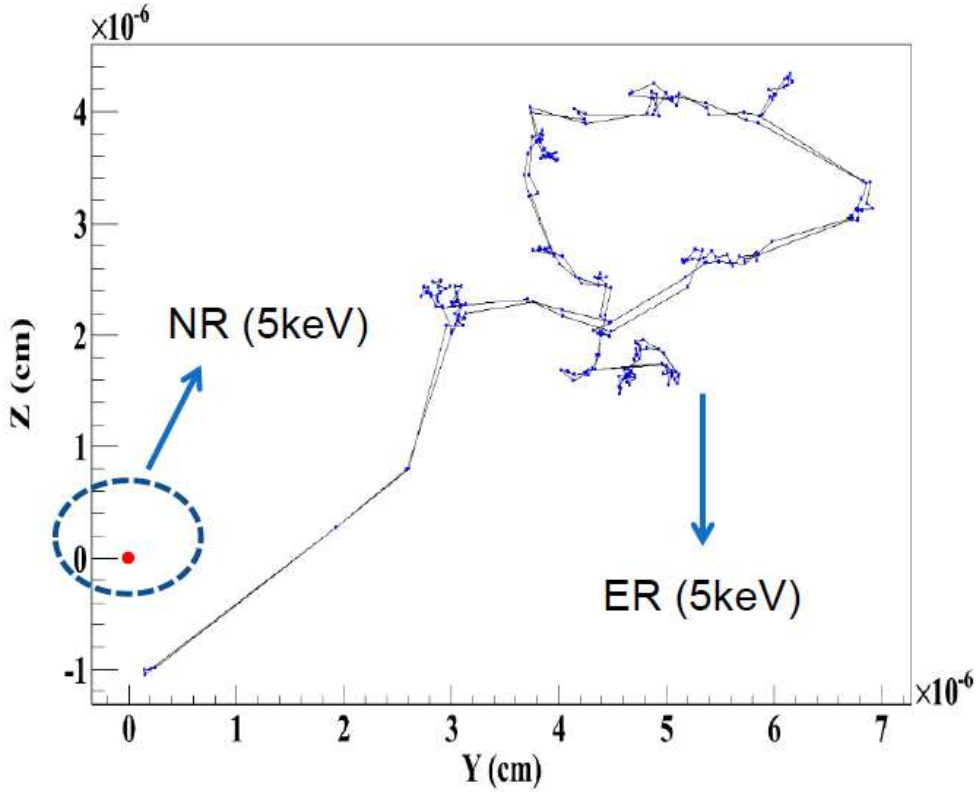


Low-Mass Dark Matter in a few GeV

- **Must be new in technique**
  - **Can we have n/γ discrimination at 77 K?**
    - **Plasma time difference in nuclear recoils and electronic recoils**
  - **How to get there?**
    - **Requirements**
      - **Amorphous-germanium contact without transition layer**
      - **Uniformity of impurity distribution across entire crystal**
      - **Reduction of neutral impurity**

Ionization Tracks

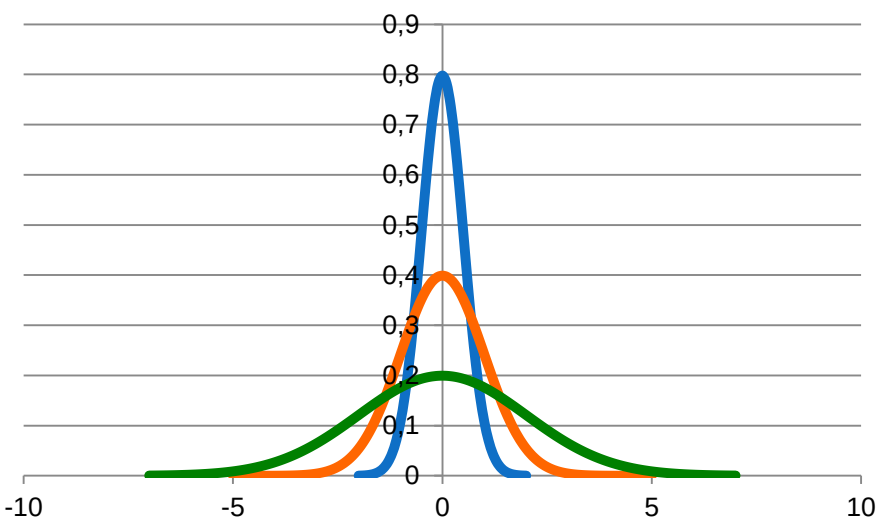




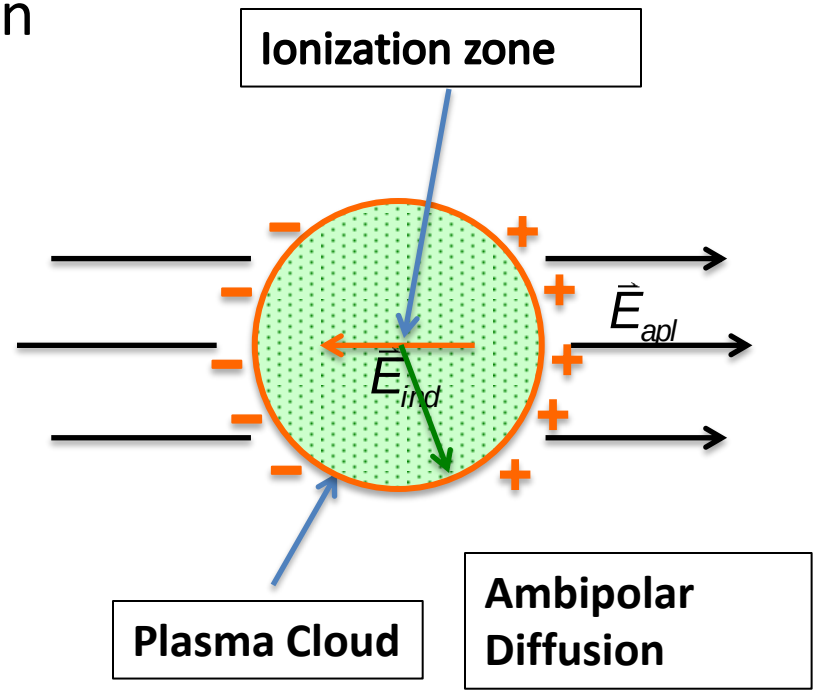
Very different tracks between nuclear recoils and electronic recoils

Principle of Plasma Time

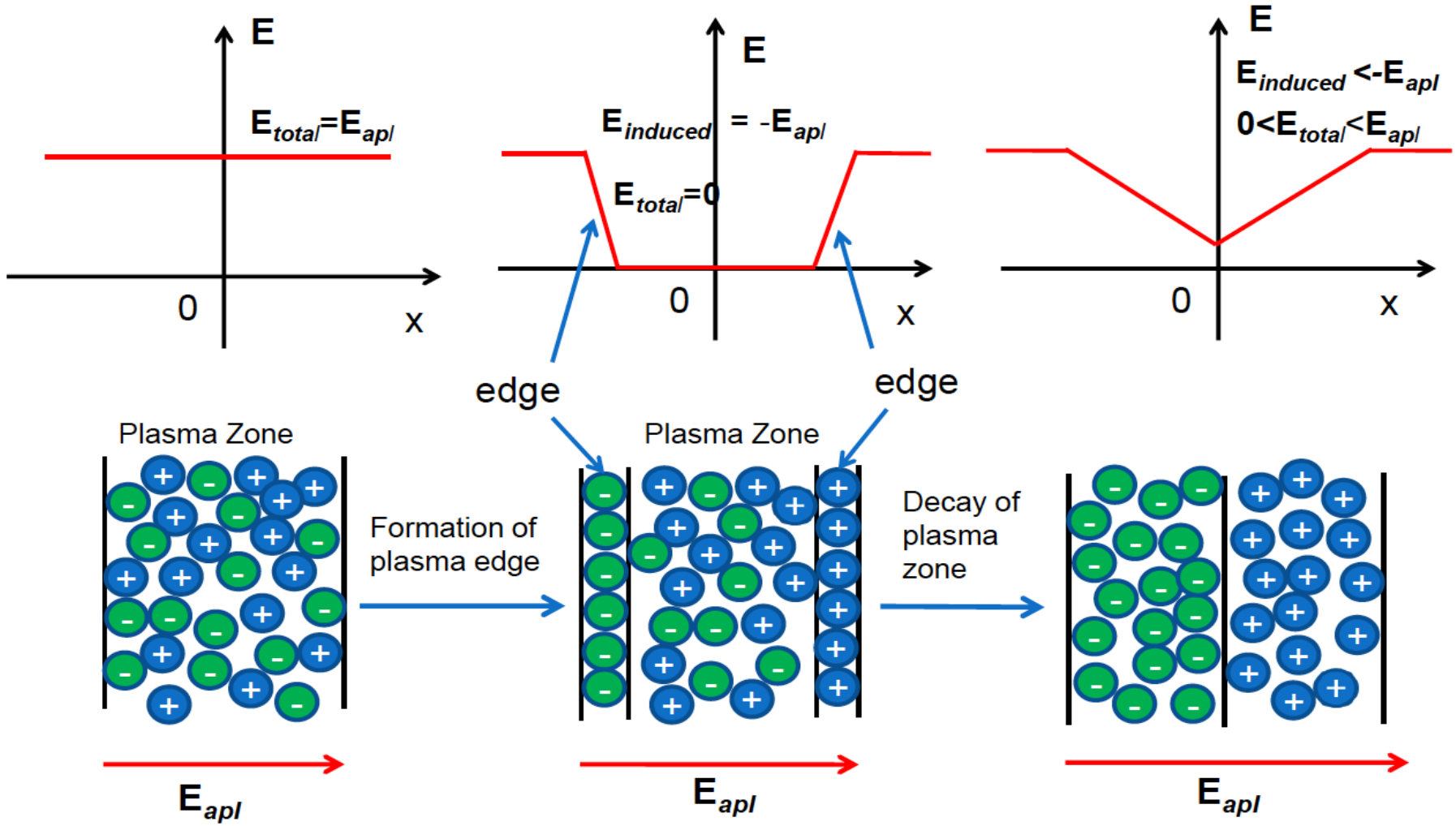
- High density of charge carriers along the ionization track forms a plasma-like cloud
- Outer charges begin to drift due to applied electric field
- Cloud expands radially as the charges diffuse
- Plasma time – time needed for the deterioration of the plasma region



Diffusion over time

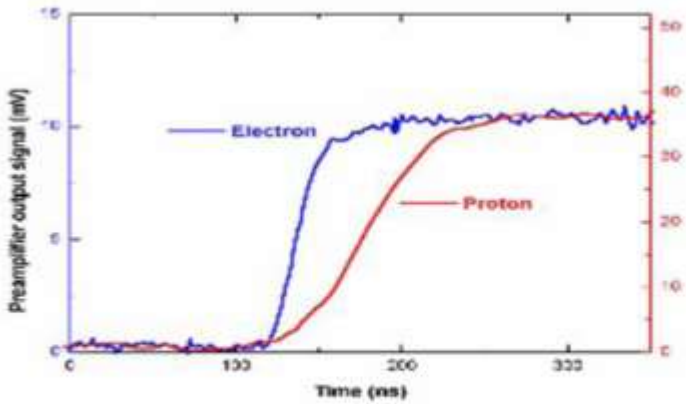


Plasma Effects

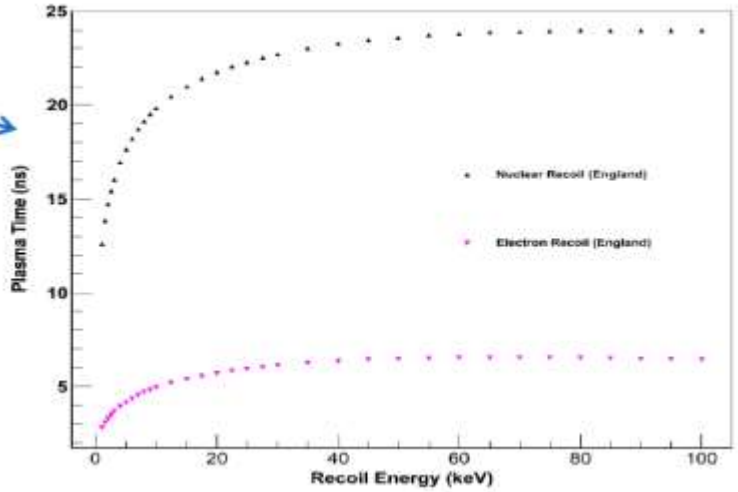


Plasma Effects in Silicon

Year	Authors	Notable Work
1960	G. Miller et al.	Observation of plasma effects
1967	P.A. Tove, W. Seibt	1D & 2D theoretical models
1969	A. Taroni, G. Zanarini	Numeric calculation (agreed with data)
1989	J.B.A England, G. M. Feild	Relate plasma effects to the ionization energy loss of the incident ion
2012	Z. Sosin	Charge distributions are assumed to be Gaussian all the time.



Rise time difference observed in a Silicon Diode detector: Alberto Fazzi et al, 0-7803-8257-9/2004 IEEE



A 3-D Numerical Calculation

$$\begin{cases} \boldsymbol{\nabla j} = -\dfrac{\partial \rho}{\partial t} \rightarrow \begin{cases} \boldsymbol{\nabla j} = -q\dfrac{\partial p}{\partial t} & (for\ holes) \\ \boldsymbol{\nabla j} = q\dfrac{\partial n}{\partial t} & (for\ electrons) \end{cases} \\ \boldsymbol{j} = \dfrac{Q}{At} = \begin{cases} qp\mu\boldsymbol{E} & (for\ holes) \\ qn\mu\boldsymbol{E} & (for\ electrons) \end{cases} \\ \boldsymbol{\nabla E} = \dfrac{\rho}{\varepsilon_r\varepsilon_0} = \dfrac{q(p-n)}{\varepsilon_r\varepsilon_0}\ (for\ both\ holes\ and\ electrons) \\ \dfrac{\partial p}{\partial t} = D\nabla^2 p\ (for\ holes) and\ \ \dfrac{\partial n}{\partial t} = D\nabla^2 n (for\ electrons) \end{cases}$$

Continuity Equation

Current density definition

Differential form of Gauss's law

Diffusion Equation

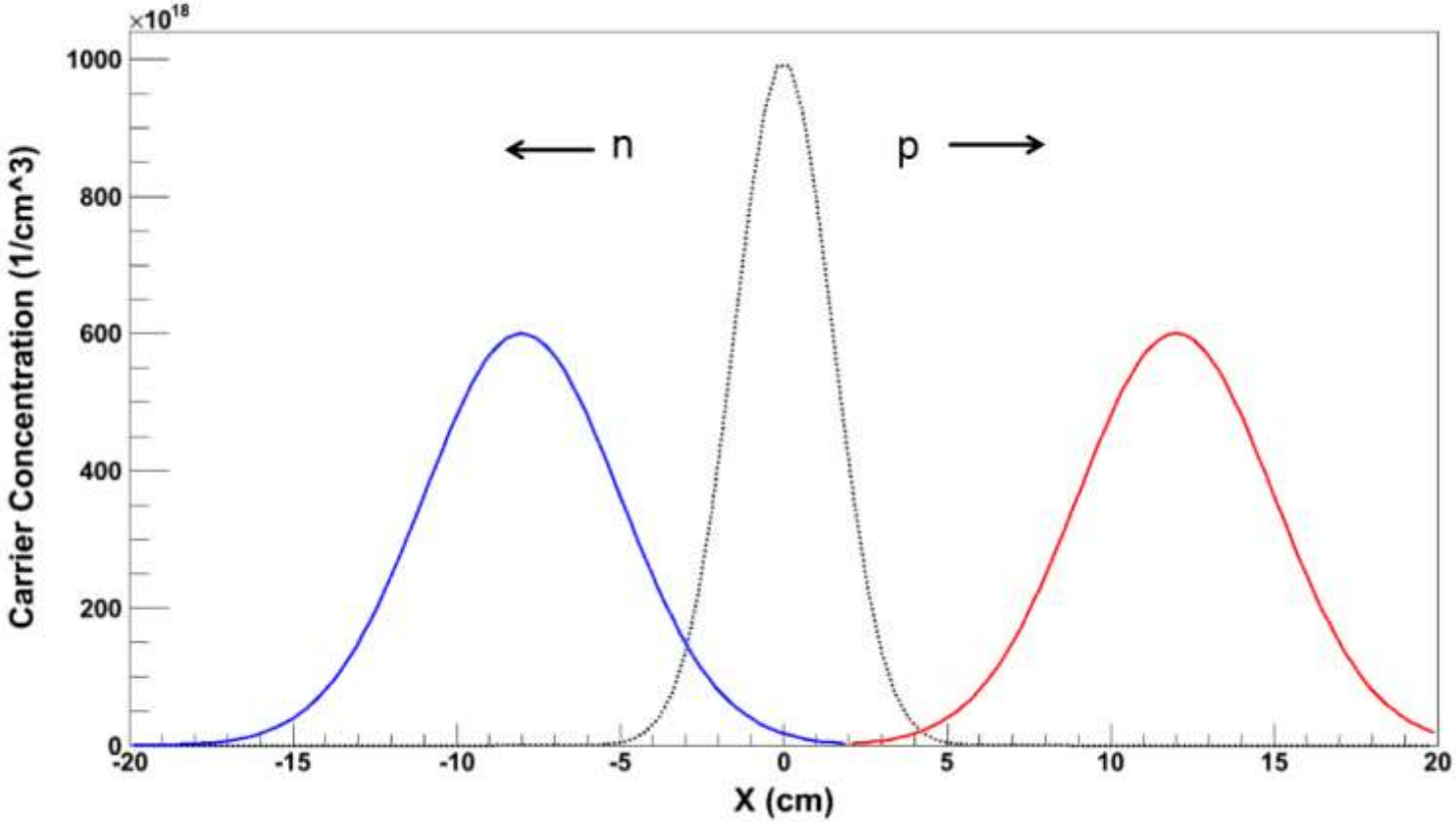
These equations will yield:

$$\begin{cases} \mu\boldsymbol{E}\nabla p + \mu p\boldsymbol{\nabla E} + D\nabla^2 p = -\dfrac{\partial p}{\partial t}, and\ p(t_i) = p(t_{i-1}) + \dfrac{\partial p}{\partial t}dt\ (for\ holes) \\ \mu\boldsymbol{E}\nabla n + \mu n\boldsymbol{\nabla E} + D\nabla^2 n = -\dfrac{\partial n}{\partial t}, and\ n(t_i) = n(t_{i-1}) + \dfrac{\partial n}{\partial t}dt\ (for\ electrons) \end{cases}$$

Critical Parameters in the Model

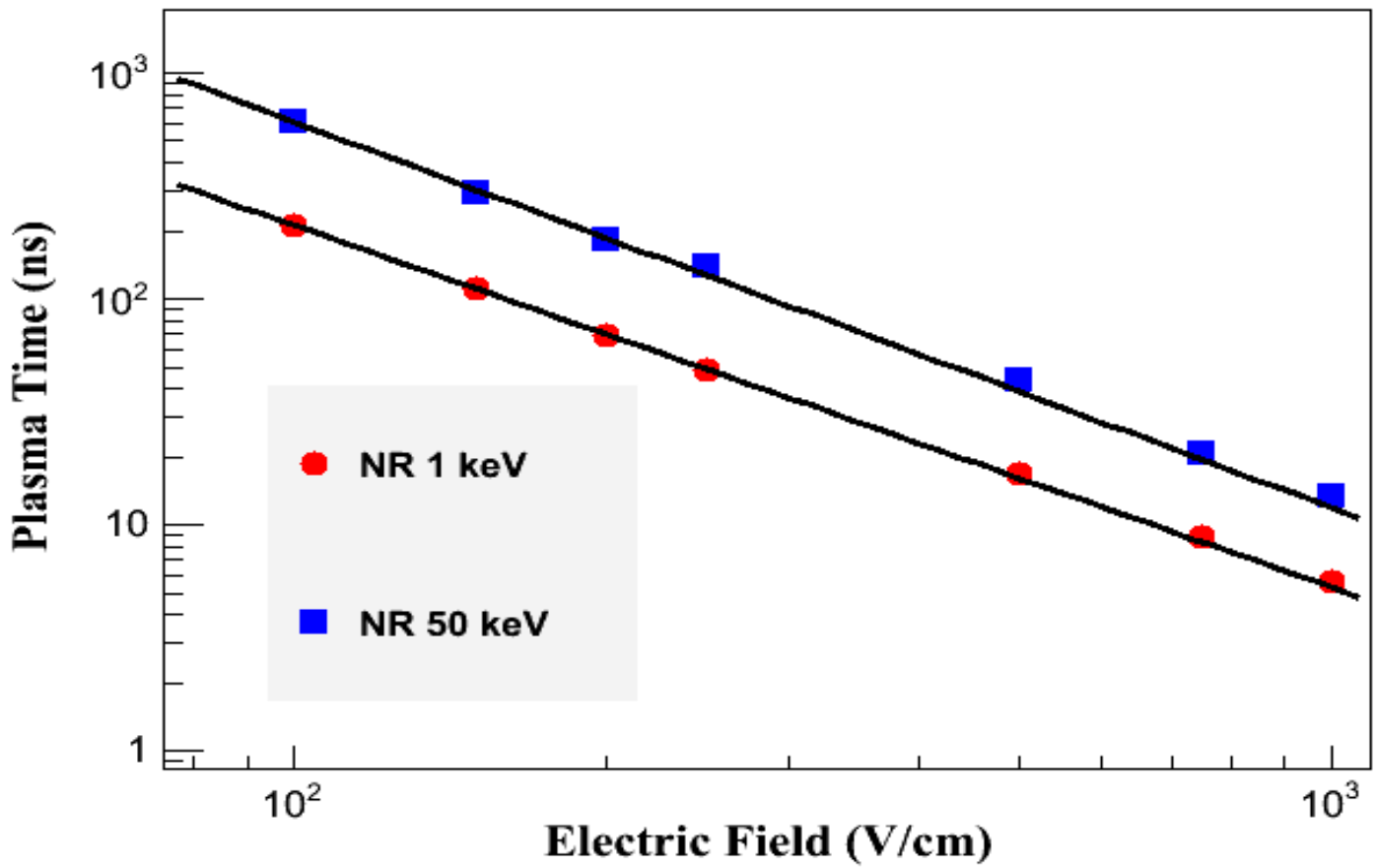
- Ionization density
  - Ionization zone
  - Charge carrier density
- Ambipolar diffusion Coefficient
  - Equation: $D = D_l' \left(1 + \frac{T_e}{T_l}\right)$
- Mobility
  - Einstein relation: $D_l = \frac{kT}{e} m_l$

Evolution of Carrier Concentration Distribution

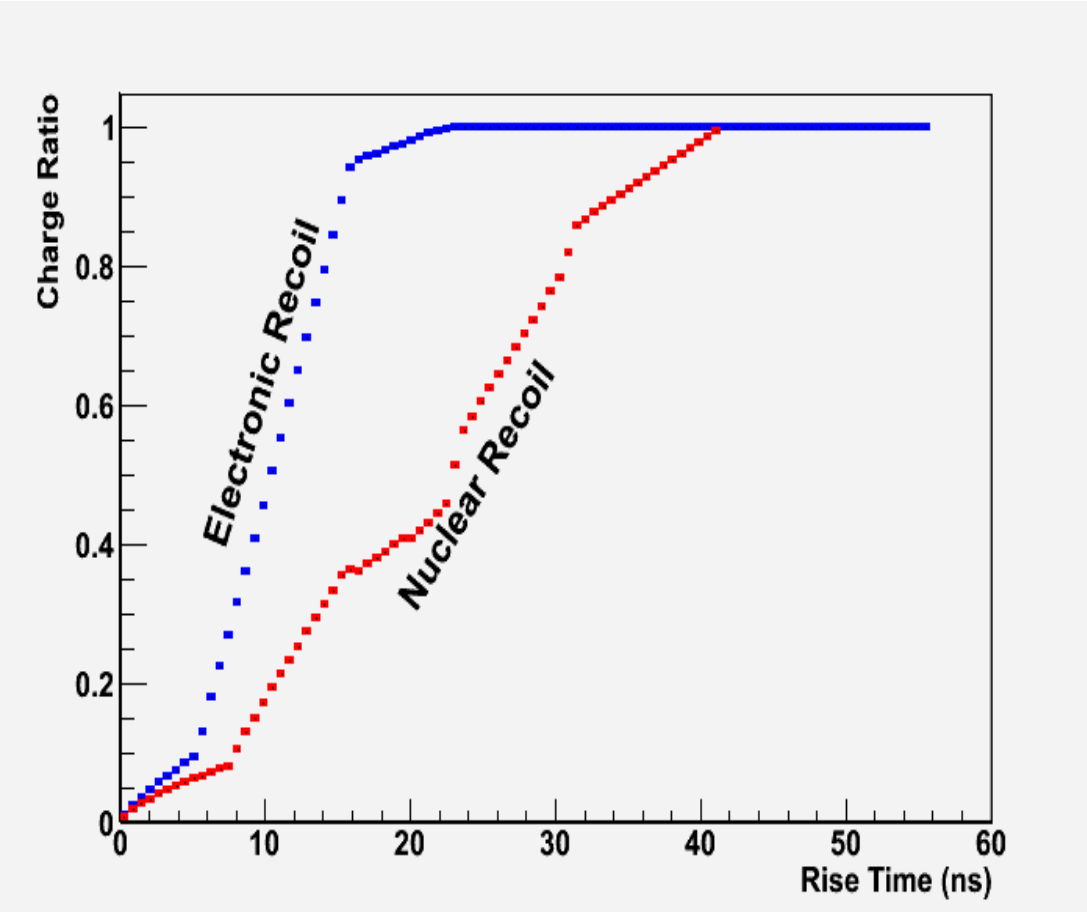


Initial condition: electron and hole concentration have the same Gaussian distribution.

Plasma Time vs Recoil Energy



Expected Charge Pulses



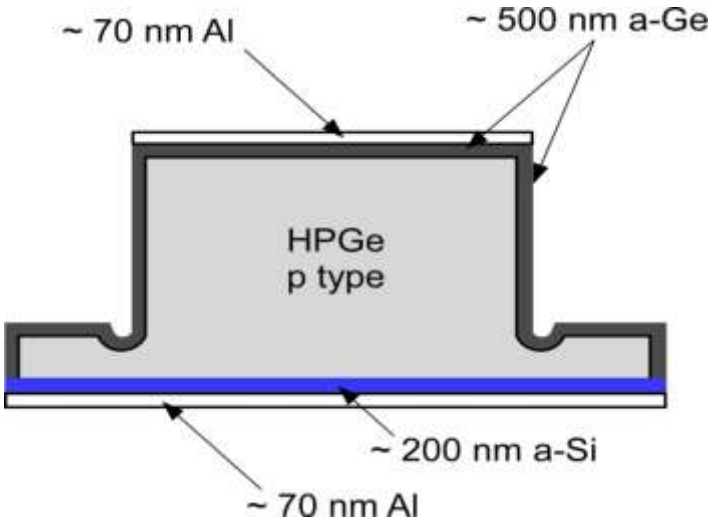
Three noticeable effects:

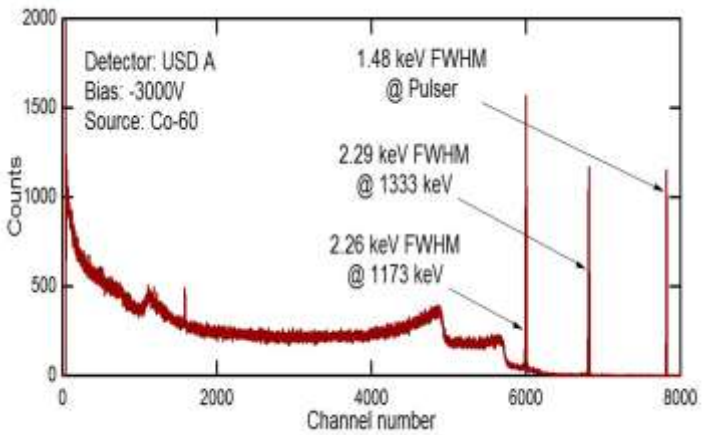
(1) The rise time of the pulse is much slower which results in a delayed charge collection time

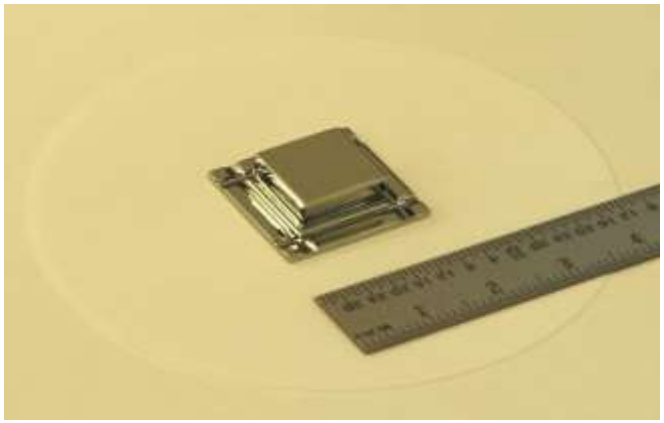
(2) During the delay within the plasma zone, electrons and holes have time to recombine so that total collected charge is less than what is created, which leads to pulse height defect

(3) Plasma time is inversely proportional to the external field and is about 5-30 ns at an external field of ~1000 V/cm.

Planning for a Measurement







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

1. **Four planar detectors with Amorphous Ge contacts were made by Mark Amman at LBNL**
2. **A portable cryostat is planned for measurement**

Detector Requirement

- Depletion length
  - Assume applied field is 100 V and d = 2 cm

N = ~1.0 x 10^9/cm^3

$$d = \sqrt{\frac{2\varepsilon V}{eN}}$$

Achievable by zone-refining

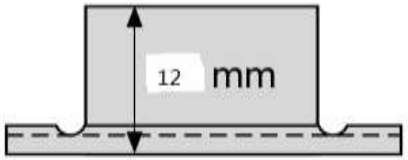
- Good time resolution
  - Uniform Electric filed
  - Uniform Impurity distribution
  - Uniform mobility (>45,000 cm^2/s) distribution

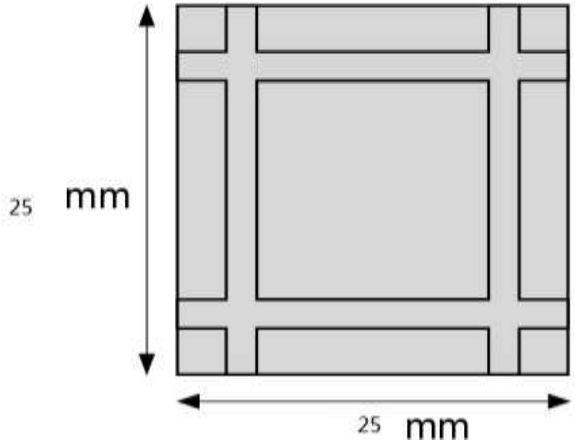
Improving time resolution

- Work with experts (Mark Ammen) at LBNL to use amorphous germanium to make contacts without transition layer
- Grow crystal with uniform impurity distribution across the entire crystal
  - Use zone refined ingots
  - Control the growth process

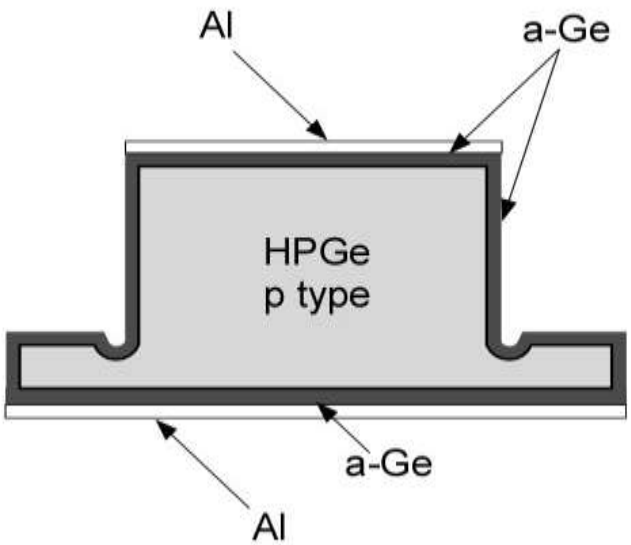
R&D on PPC Detector with Amorphous Ge Contacts

Detector dimensions
(prior to etching)





Electrical contact structure
(detector cross-section)



Courtesy to Mark Amman

Summary

- Grow desirable crystals for developing novel detectors
- R&D: Developing new detectors in next five years
  - Dark matter, neutrinoless double-beta decay, neutrino-nucleus coherent scattering, neutrino magnetic moment
- Build an experiment in combination with some of R&D detectors
  - If R&D is successful, build 10 kg R&D dark matter detector

Acknowledgement

- Funding support for crystal growth and detector development
  - DOE Award Number: DE-FG02-10ER46709
  - South Dakota Governor's Research Center
- Funding for a Workshop on Germanium Detectors and Technology
  - NSF Award Number: Award No. IIA-1434142