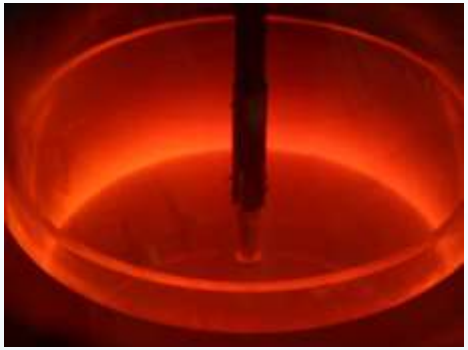
Crystal Growth and Detector Development for Underground Experiments

DE-FG02-10ER46709 and CUBED



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Project Objectives

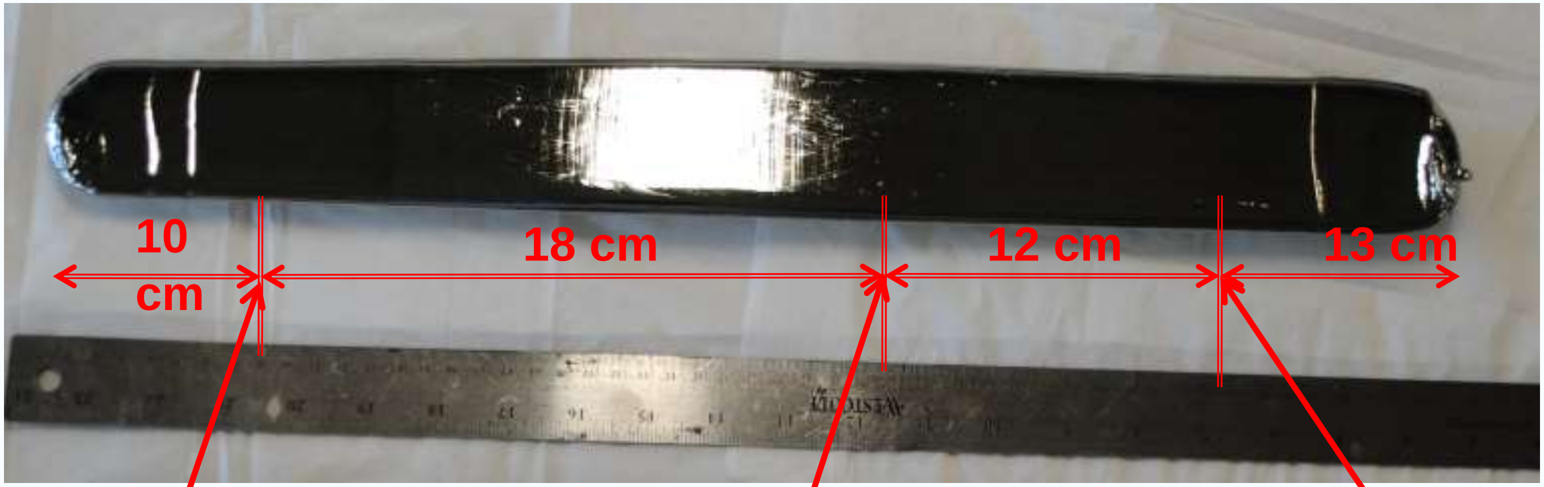
- The objectives:
  - Reduce impurity level from ~10^{14}/cm^3 to ~10^{10}/cm^3
  - Achieve impurity levels of the grown crystals at ~(1-3) x10^{10}/cm^3
  - Grow crystals with diameter of 7 cm and up to 10 cm
  - Fabricate planar detectors with the grown crystals

- Activities:
  - Improving zone-refining methods in order to obtain an impurity level of ~10^{10}/cm^3,
  - Growing large detector-grade crystals for the ton scale Majorana, CDEX, and large scale SuperCDMS experiments,
  - Automating the growth process,
  - Comprehensive characterization of all grown crystals, and
  - Developing new types of detectors with the grown crystals,

Milestones in Zone Refining

- Two Stages
  - Start with graphite boat to remove Al from an impurity level of $\sim 10^{14}/cm^3$ to $\sim 10^{12}/cm^3$
  - Continue with quartz boat to remove Al, B and P from an impurity level of $\sim 10^{12}/cm^3$ to $\sim 10^{10}/cm^3$
- Achievements
  - Consistently produced germanium ingots to an impurity level of $\sim 10^{11}/cm^3$
  - Narrowed a variety of parameters down to one
    - High-purity synthetic quartz boat is needed
    - ~High-purity quartz boat is purchased
    - Achieved $\sim 10^{10}/cm^3$ impurity level as expected
  - Published a paper on the zone refining method

Zone Refining



$|N_A\text{-}N_B|$ = $6.04\text{x}10^{10}/\text{cm}^3$
Resistivity: 2,603 Ohm-cm
Mobility: 39,690 cm^2/Vs

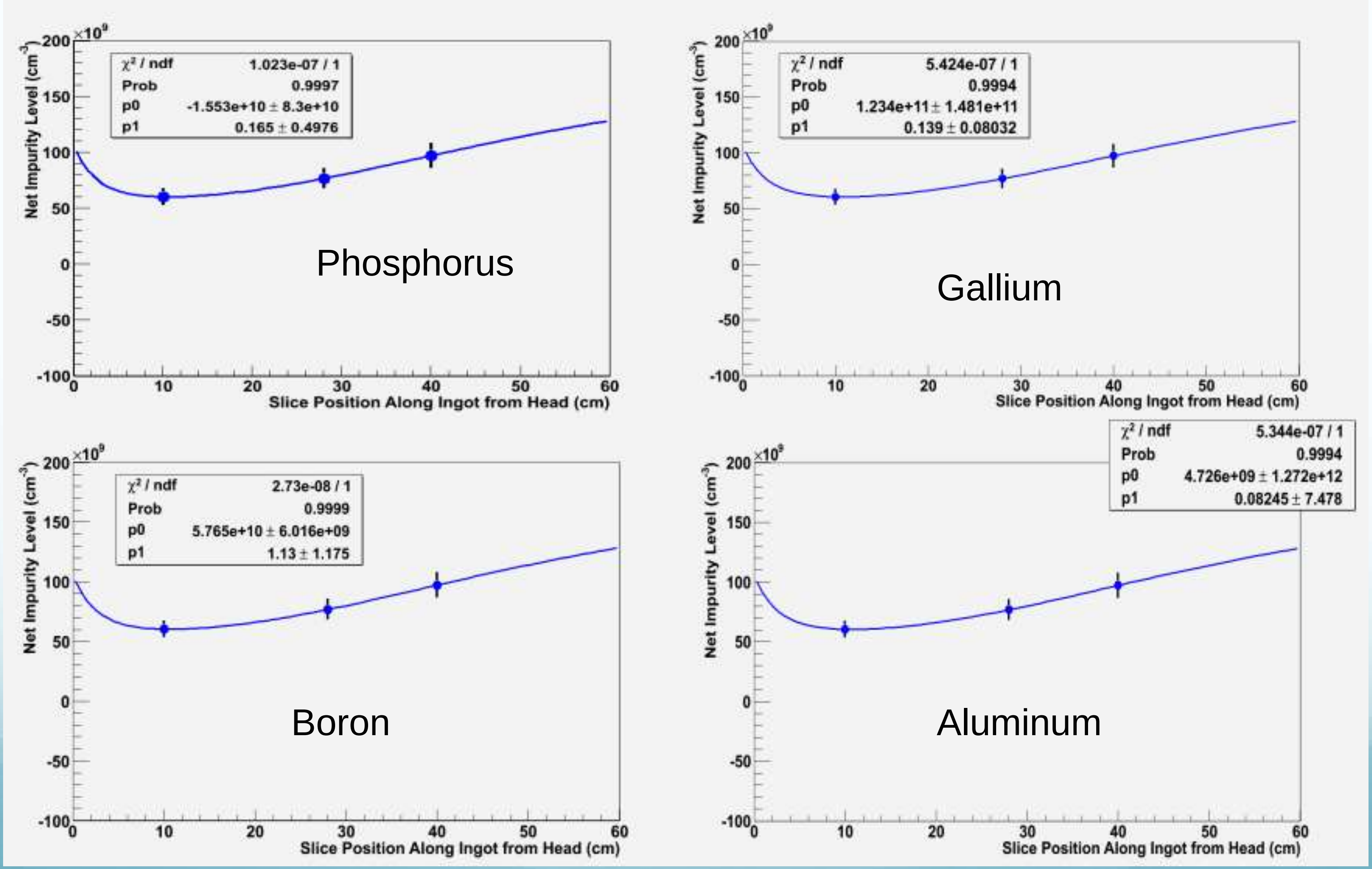
$|N_A\text{-}N_B|$ = $7.68\text{x}10^{10}/\text{cm}^3$
Resistivity: 1,960 Ohm-cm
Mobility: 41,270 cm^2/Vs

$|N_A\text{-}N_B|$ = $9.72\text{x}10^{10}/\text{cm}^3$
Resistivity: 1,583 Ohm-cm
Mobility: 40,580 cm^2/Vs

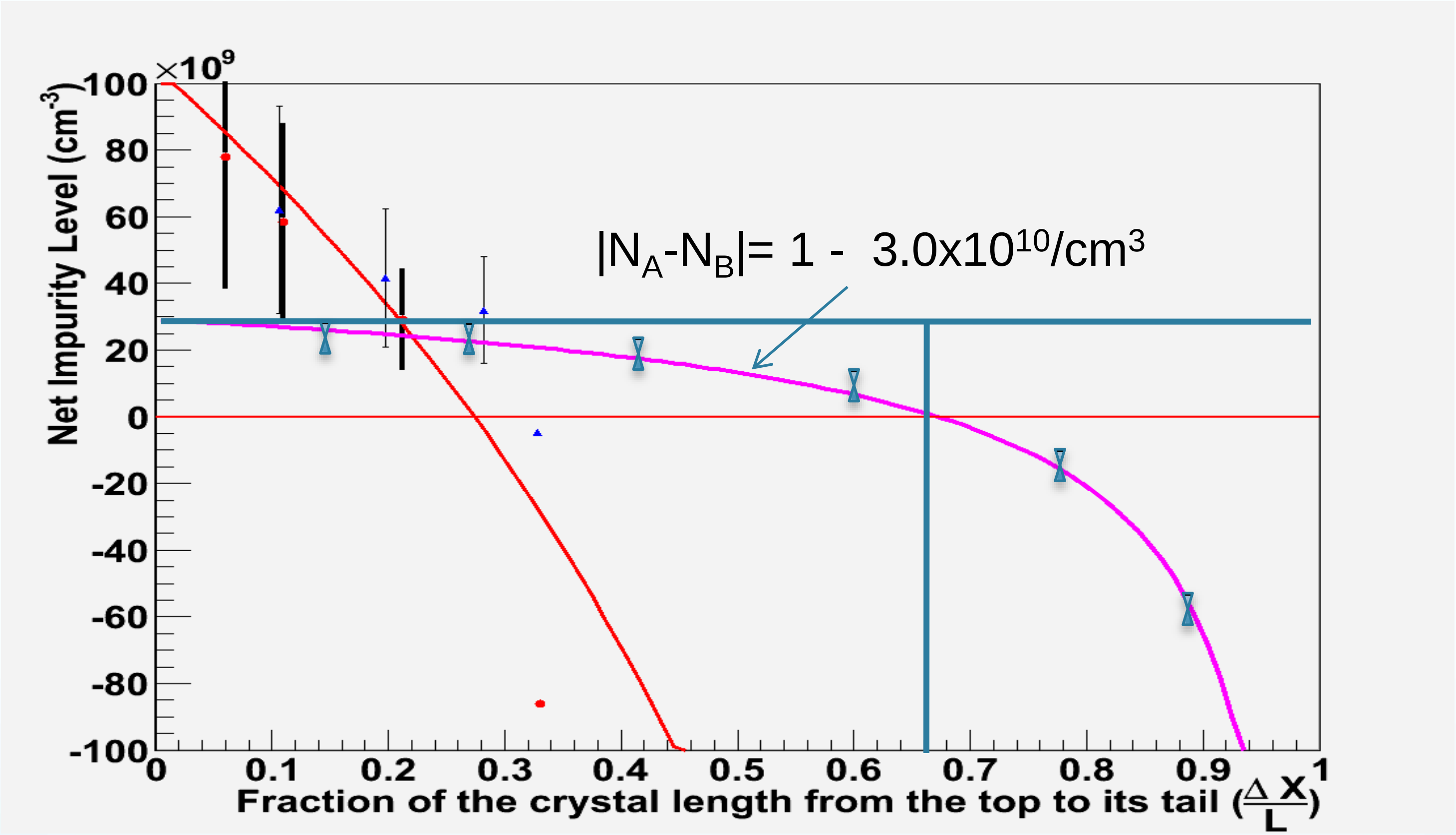
$$|N_A - N_B| = \sum_i C_i \times (1 - (1 - k_{eff}) \times \exp(-k_{eff} \times \frac{L}{\Delta L}))^n$$

$|N_A\text{- }N_B|$: Net impurity level; C_i: the level of Impurity species; k_{eff}: the effective segregation coefficient; L: the length of the ingot; ΔL: the width of the melt: n: the number of passes

Impurity Components



Grow a Crystal with Zone-Refined Ingot



$$|N_A - N_B| = \sum_i C_i \times k_{eff} \times (1 - \frac{\Delta x}{L})^{(k_{eff}-1)}$$

$|N_A - N_B|$: The net impurity; C_i: the level of impurity species;
k_{eff}: the effective coefficient; $\frac{\Delta x}{L}$: the mass ratio of a grown crystals

Milestones in Crystal Growth

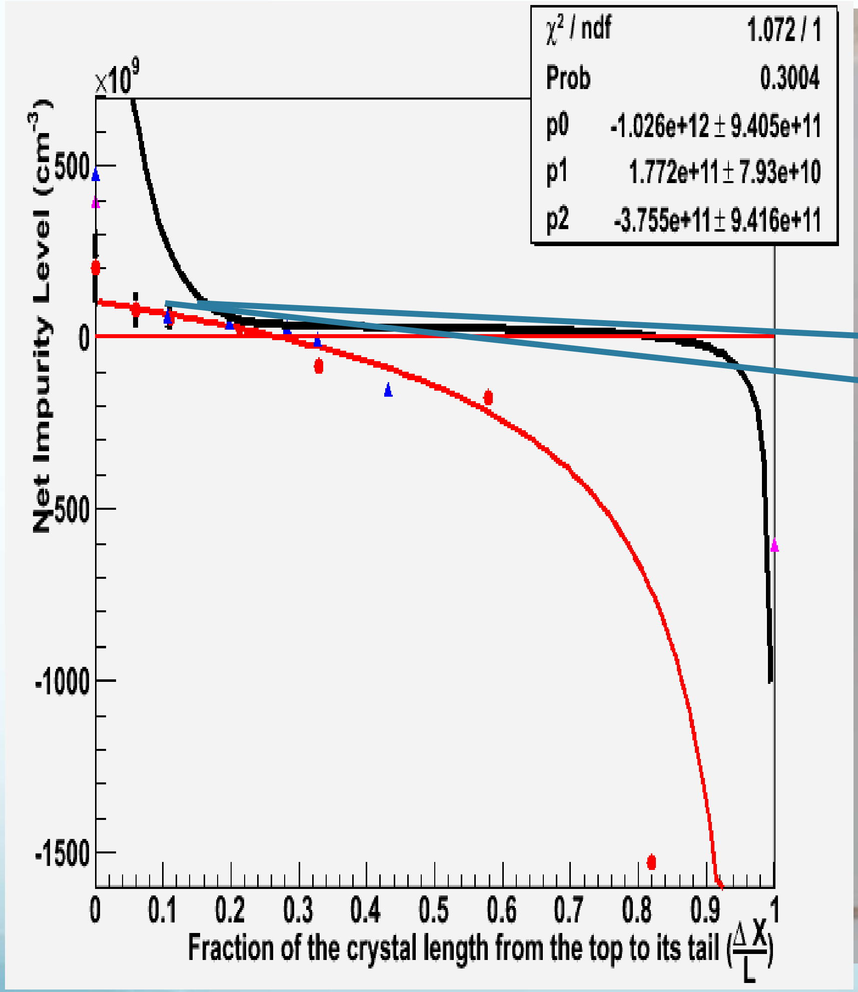
- **Large-size detector grade crystal growth:**
  - **In this year, grew large detector-grade crystal with impurity level of ~10^{10}/cm^3**
  - **Size: 6-10 cm in diameter**
  - **Dislocation density: 300 – 7000 etch pits/cm^2**

- **Achievements:**
  - **Every growth has a portion of detector-grade with a grown crystal**
  - **Increase the portion of detector-grade per grown crystal from 10% to over 30%**
  - **Automation of crystal growth**
  - **Published a paper for large-size crystal growth**

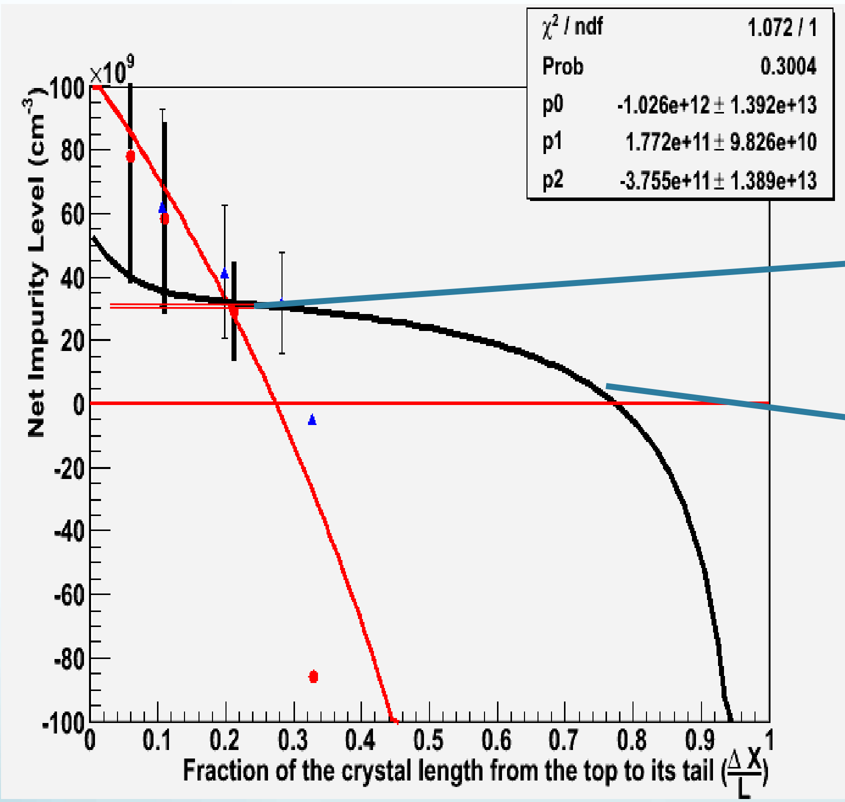
Requirements

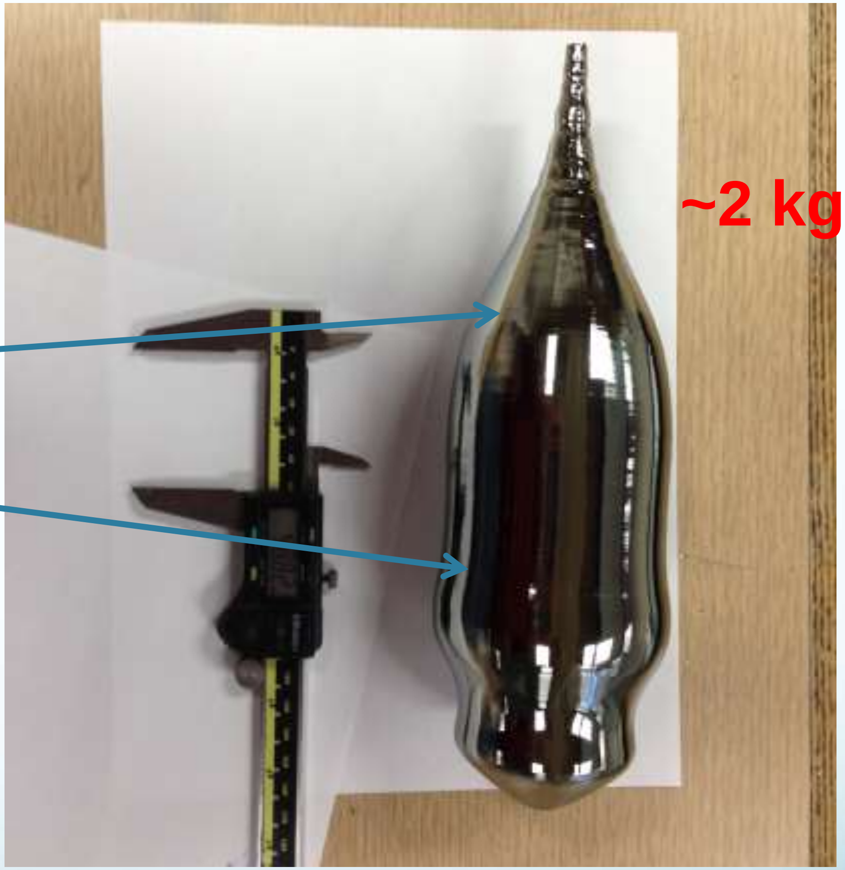
- **Mobility**
  - **Electrons and holes mobility must be greater than 25,000 cm^2/Vs**
  - **Detector-grade requires > 35,000 cm^2/Vs**
- **Impurity**
  - **1 to 3 $x10^{10}/cm^3$**
- **Dislocation density**
  - **300 - 10,000/cm^2**
- **Sizes**
  - **5 to 10 cm in diameter**
  - **3 to 7 cm in length**

Impurity Control – Current Status



Impurity Control – Target (01/2015-03/2016)



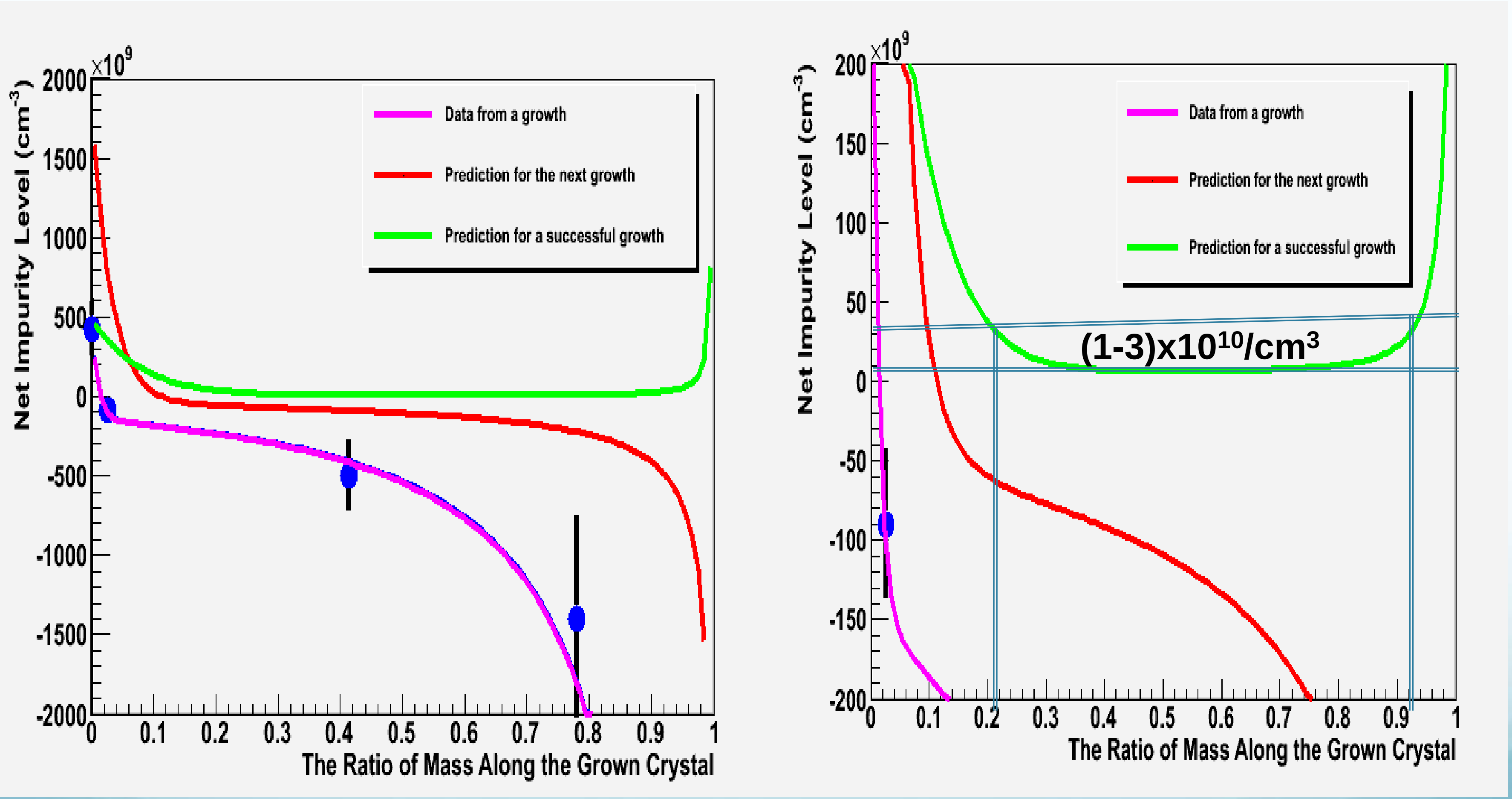


$$k_{eff} = \frac{k}{k + (1 - k)\exp(-R\delta/D)}$$

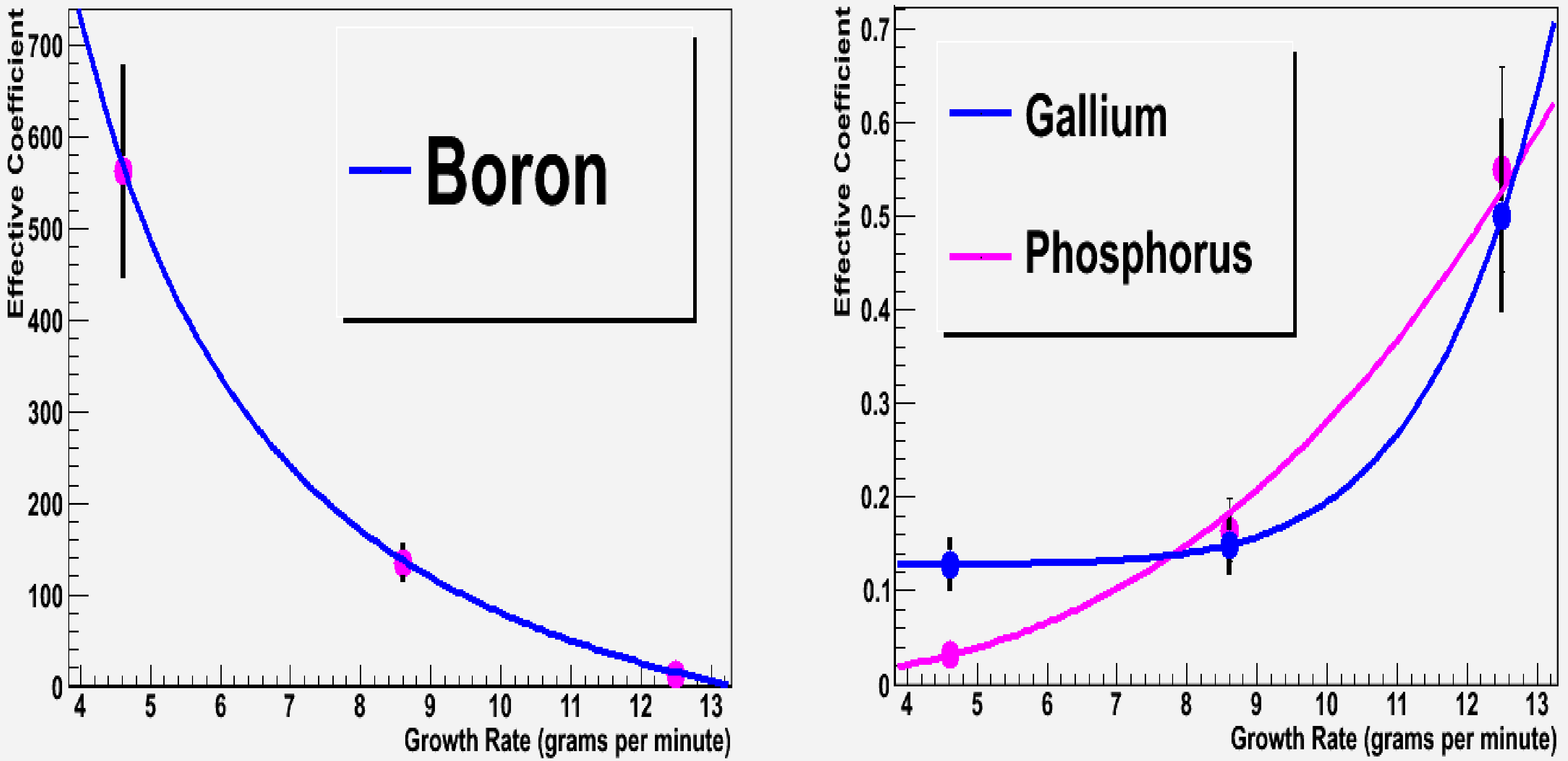
k: segregation coefficient in equilibrium
R: growth rate, δ: the thickness of the growth interface, D: diffusion coefficient

Growth Strategy

The key is to understand K_{eff} vs growth rate for gallium and phosphorus



Effective Segregation Coefficients vs Growth Rate



Milestones in Characterization

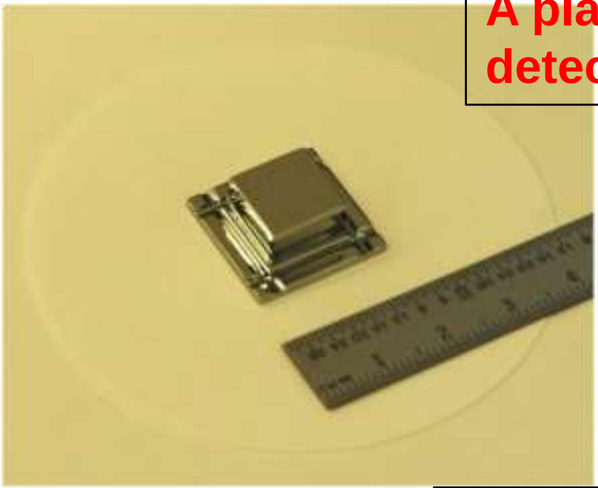
- **Fully understanding of the zone-refined ingots and the grown crystals**
  - **Electronic properties measurements with Hall Effect**
  - **Optical properties for dislocation density**
  - **The origin of impurity with PTIS**
- **Achievements:**
  - **A few hundreds of samples have been measured**
  - **Understood the relation between mobility, resistivity, and impurity at lower temperature than 77 K**
  - **Developed a few papers for publications**

Detector Development

- **Goals**
  - **Learn how to make contacts for planar detectors**
  - **Fabricate planar detectors**
- **Progresses**
  - **Several planar detectors have been made**
  - **Measurements of leakage current to gain feedback**
  - **Improvement of cryostat**

Highlighted Products

Large-size detector-grade crystal



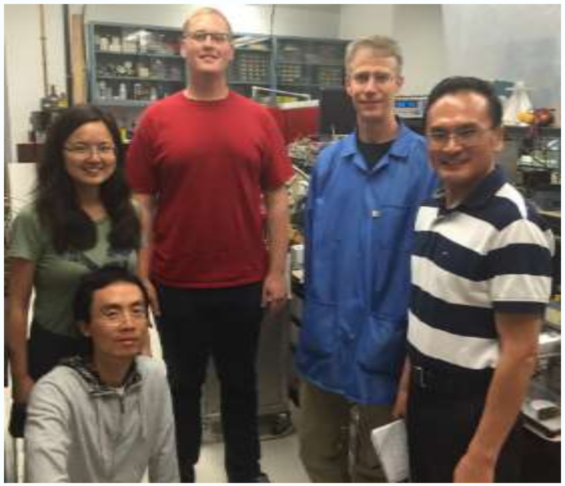
A planar detector

A large crystal for SuperCDMS

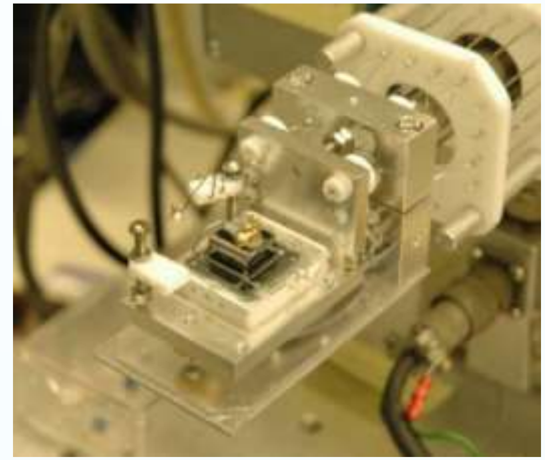
A SuperCDMS detector

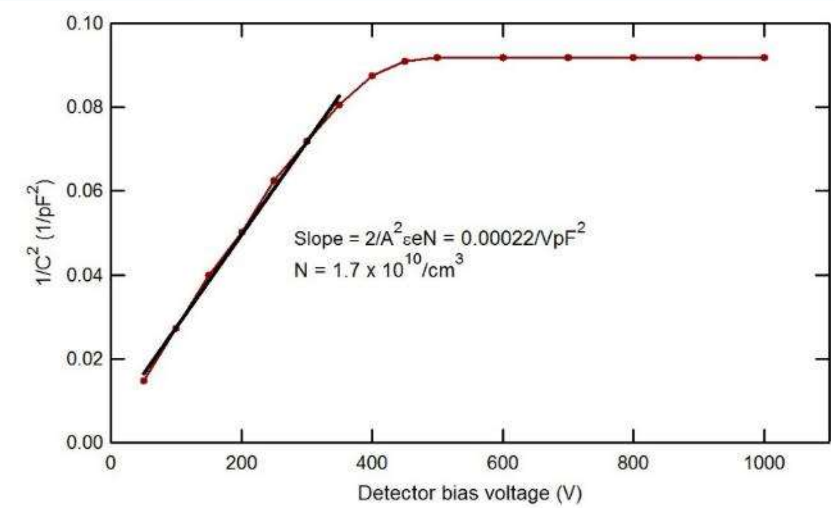
Collaborate with LBNL

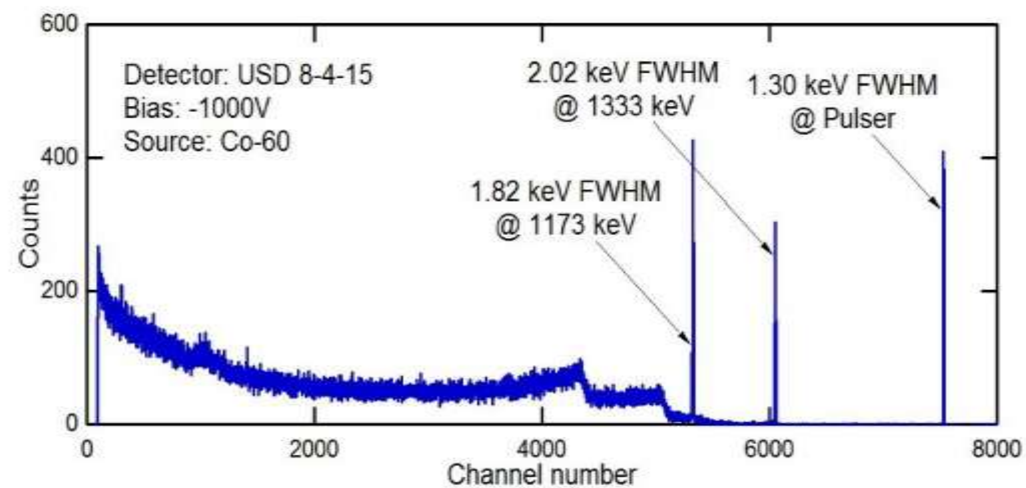
A week-long visit at LBNL, August, 2015



- Ge crystals, USD
- A-Ge surface, LBNL







Plan for Next

- **Zone refining to continue achieving ~10^{10}/cm^3**
  - **Use ultra-pure synthetic quartz boat**
- **Crystal growth to achieve 60% detector-grade per grown crystal**
  - **Use ultra-pure synthetic quartz tube for enclosure**
- **Continue fully understanding of the grown crystals**
  - **Publish a few papers**
- **Fabricate planar detectors**
  - **Spatter machine for making contacts**
- **R&D on new type of detectors**
  - **Beyond G2 experiments**

Summary

- **Verification from TAMU, LBNL, and Tsinghua**
- **Grow crystals for increasing production per growth**
- **Develop new detectors with LBNL, MPI, and Tsinghua University an the PIRE collaboration**
- **Push a ton-scale germanium-based neutrinoless double-beta decay experiment**
- **Held a workshop on germanium detectors and technologies in September 2014**