Research Progress Report

Dongming Mei
For GEMADARC collaboration

Outline

- Timeline, Milestones and Deliverables
- Material Advancement
- Detector Developments
- Detector Performance
- Novel and Emerging Ge Research

PIRE-GEMADARC Research Plans

Table 2. PIRE project timeline, milestones, and deliverables. All tasks will accept summer students.

RESEARCH	Year 1			Year 2			Year 3			Year 4			Year 5		
ACTIVITIES	Spring	Summer	Fall	Spring	Summer	Fall	Spring	Summer	Fall	Spring	Summer	Fall	Spring	Summer	Fall
1. Material advancement															
a. Zone-refining	Multiple iterations to achieve **30 kg** ingots with ~10^{10}/cm^{3} impurity level for crystal growth														
b. Crystal growth	Multiple iterations of growth for **20 kg** with an impurity level of (1-3)x10^{10}/cm^{3} and mobility of more than 45,000 cm^{2}/Vs														
c. Characterization	Characterize all grown crystals for electronic and optical properties to enable simulation (**500** samples).														
2. Detector development															
a. Internal amplification	Design, fabricate, and test **1st detector**						Rebuild and test			Build **2nd detector**			Run for certification		
b. SuperCDMS-type detectors	Design, fabricate, and test **1st detector**						Rebuild and test			Build **2nd detector**			Run for certification		
c. Inverted coaxial PPC	Design, fabricate, and test **1st detector**						Rebuild and test			Build **2nd detector**			Run for certification		
3. Detector performance															
a. Test methodology	Understand the correlation between charge generation, transport, trapping, recombination, impurityies, and surface effects														
b. Simulation toolkits	Simulate charge carrier drift and diffusion during the drift process to understand charge trapping and surface effects														
c. Pulse shape discrimination	Measurements of charge pulses						Simulation of pulses			Comparison			Developing models		

Material Advancement

1. Material advancement					
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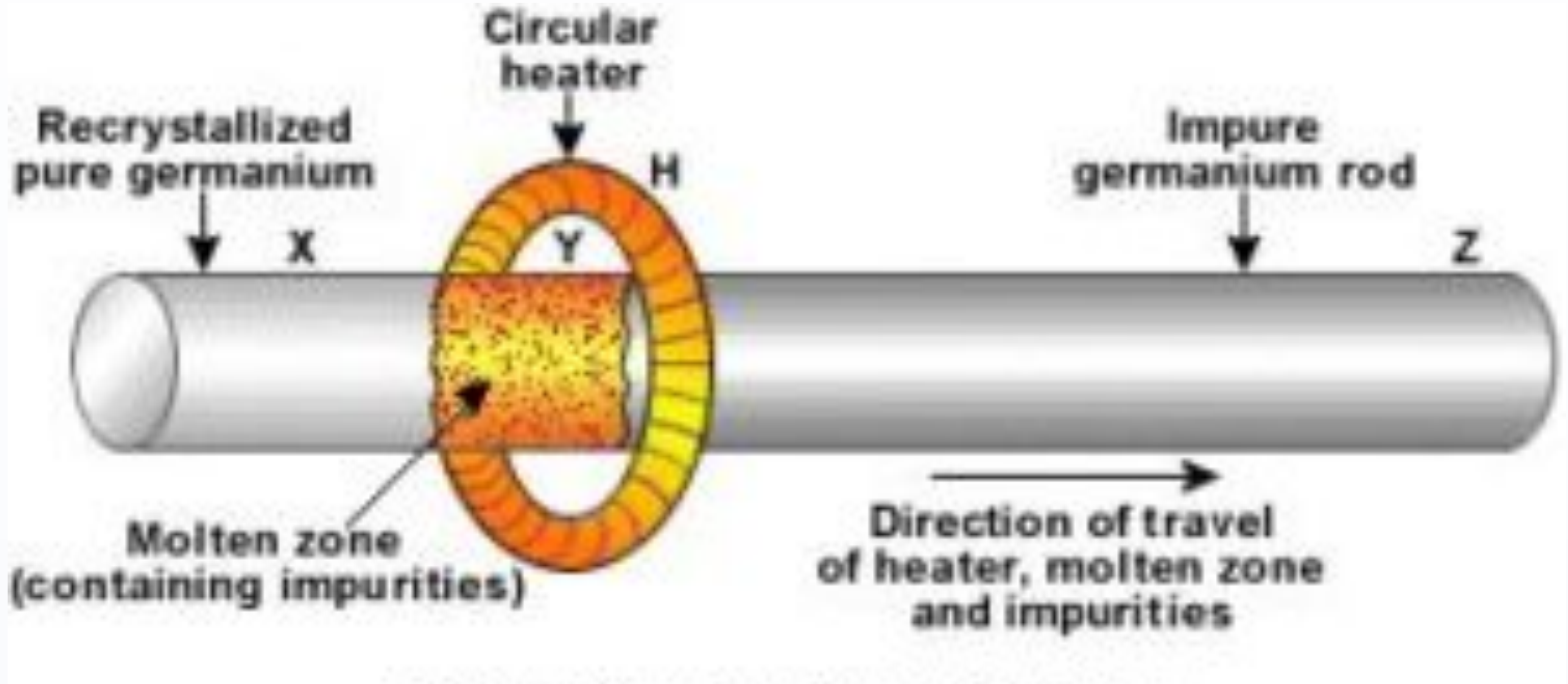
c. Characterization	Characterize all grown crystals for electronic and optical properties to enable simulation (**500** samples).				

Material Advancement – Zone Refining



Zone refining of germanium metal.

Importance:
Increase the yield of zone-refined ingots, since each run takes 160 hours

Advanced Goals
- Continue zone refining research activities by improving its output efficiency from ~70% to 80% through optimizing run parameters
- Study temperature gradient along axial using thermal camera
- Improve understanding of thermal dynamics with respect to impurity segregation

Participants:
USD
Tsinghua
LBNL

Students (8):
Kyler Kooi
Alex Kirkvold
Pramod Acharya
Kunming Dong
Zhangzhi Feng
Qingqing Li
Mathbar Raut
Sanjay Bhattarai

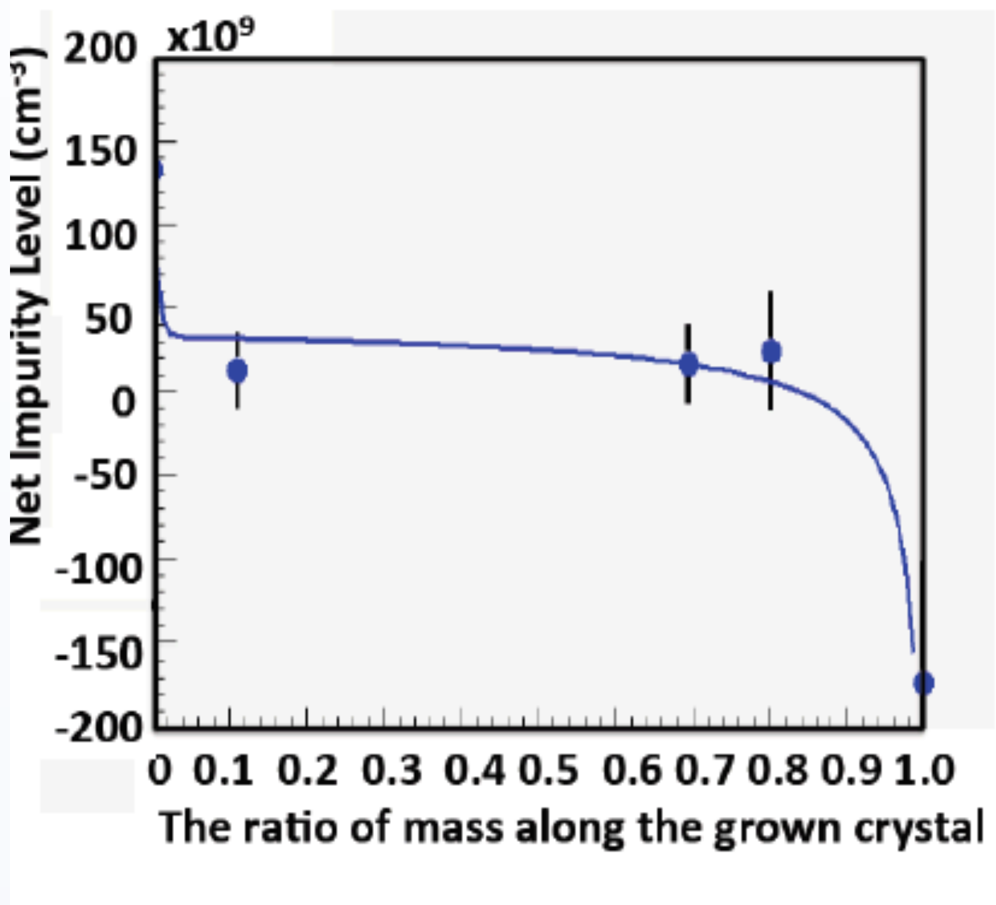
Postdoc (2):
Gang Yang
Hao Mei

Faculty (3):
Jianmin Li
Dongming Mei
Mark Amman

Material Advancement - Crystal Growth and Characterization

Crystal Growth challenges:

- Increase H_2 flow rate
- Exercise diameter and uniformity control
- Increase the production rate/growth



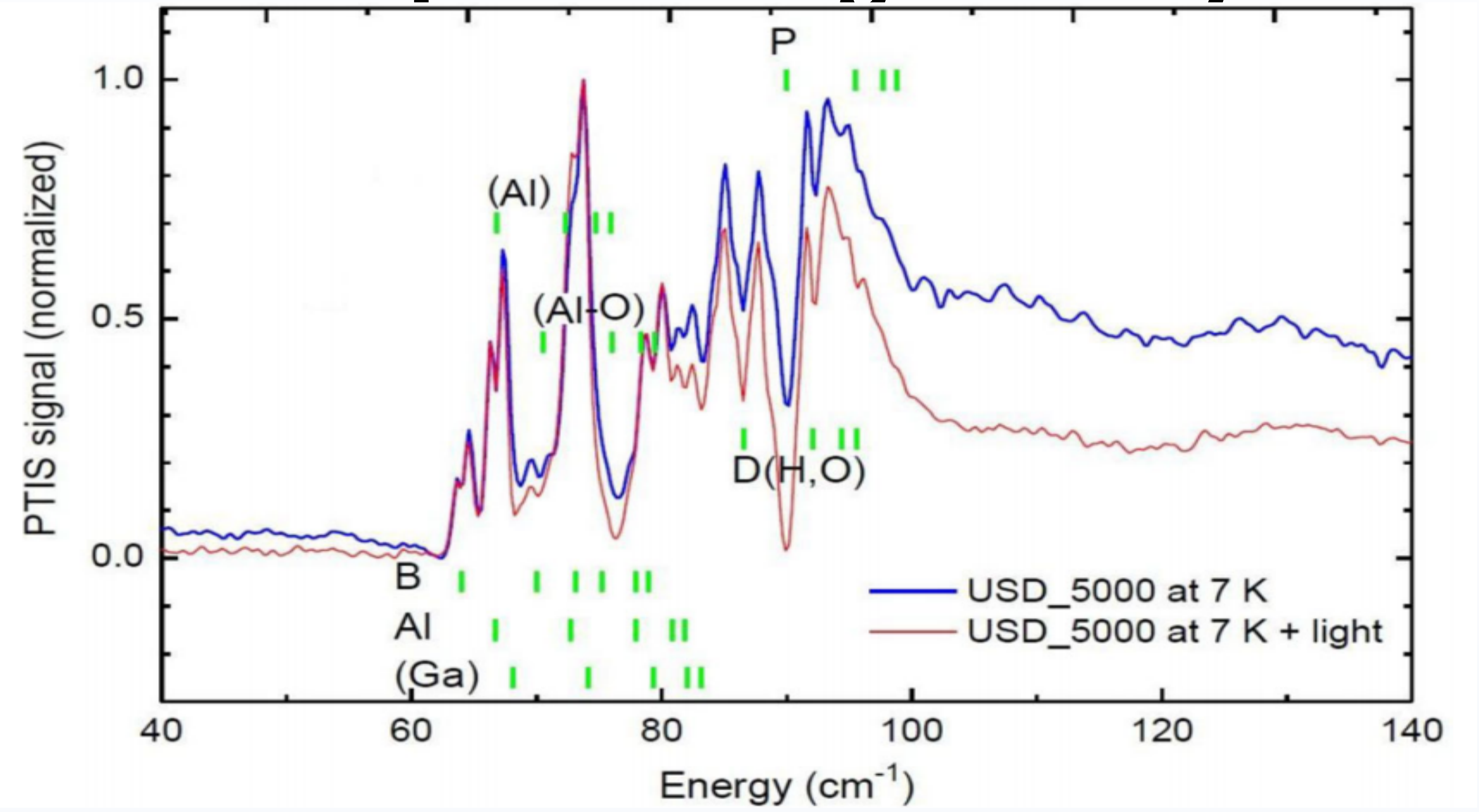
Importance:

Larger detectors can reduce backgrounds, complexity, and cost

Great Progress: 300 – 1500 grams: 3 pulls
1.5 – 2.7 kg: 6 pulls

Crystal Characterization purposes:

- Provide accurate characterization of the net impurity level for developing Ge detectors;
- Improve knowledge about the content of the impurities in grown crystals



Tools

- Hall Effect
- C-V analysis
- PTIS (Photo-Thermal Ionization Spectroscopy)

Participants:
USD
Tsinghua
LBNL

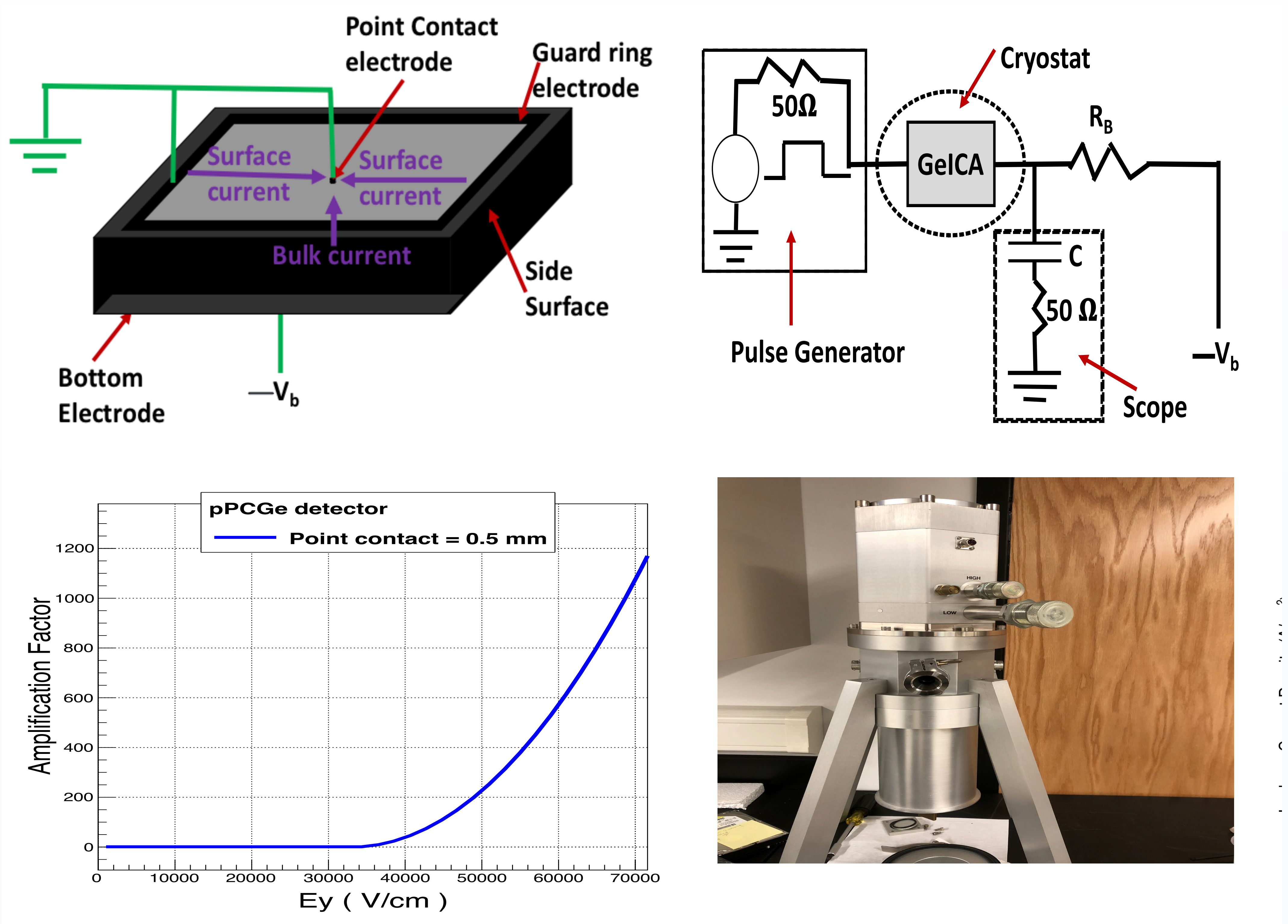
Students:
Pramod Acharya
Mathbar Raut
Sanjay Bhattarai
Kyler Kooi
Kunming Dong

Postdoc:
Hao Mei
Gang Yang

Scientist:
Guojian Wang

Faculty:
Jianmin Li
Dongming Mei
Mark Amman
Brianna Mount

Detector Development – Internal Amplification



Participants:

Students:
Rajendra Panth
Kyler Kooi
Akash Pandey
Chih-Hsiang Yeh
Weiyou Tang

Postdoc:
Wenzhao Wei
Xianghua Meng
Sha-Sha Lv

Faculty:
Henry Wong
Yang Tian
Yulan Li
Xinde Lin
Jing Liu
Dongming Mei
Venktesh Singh

Science Goals:

- Extremely Low leakage current (~fA)
- Amplification of ~1k for sub-eV threshold
- Single e^- – h^+ pair resolution
- Singe e^- – h^+ calibration

Discovery: Evidence of Cluster dipole states at ~4 K

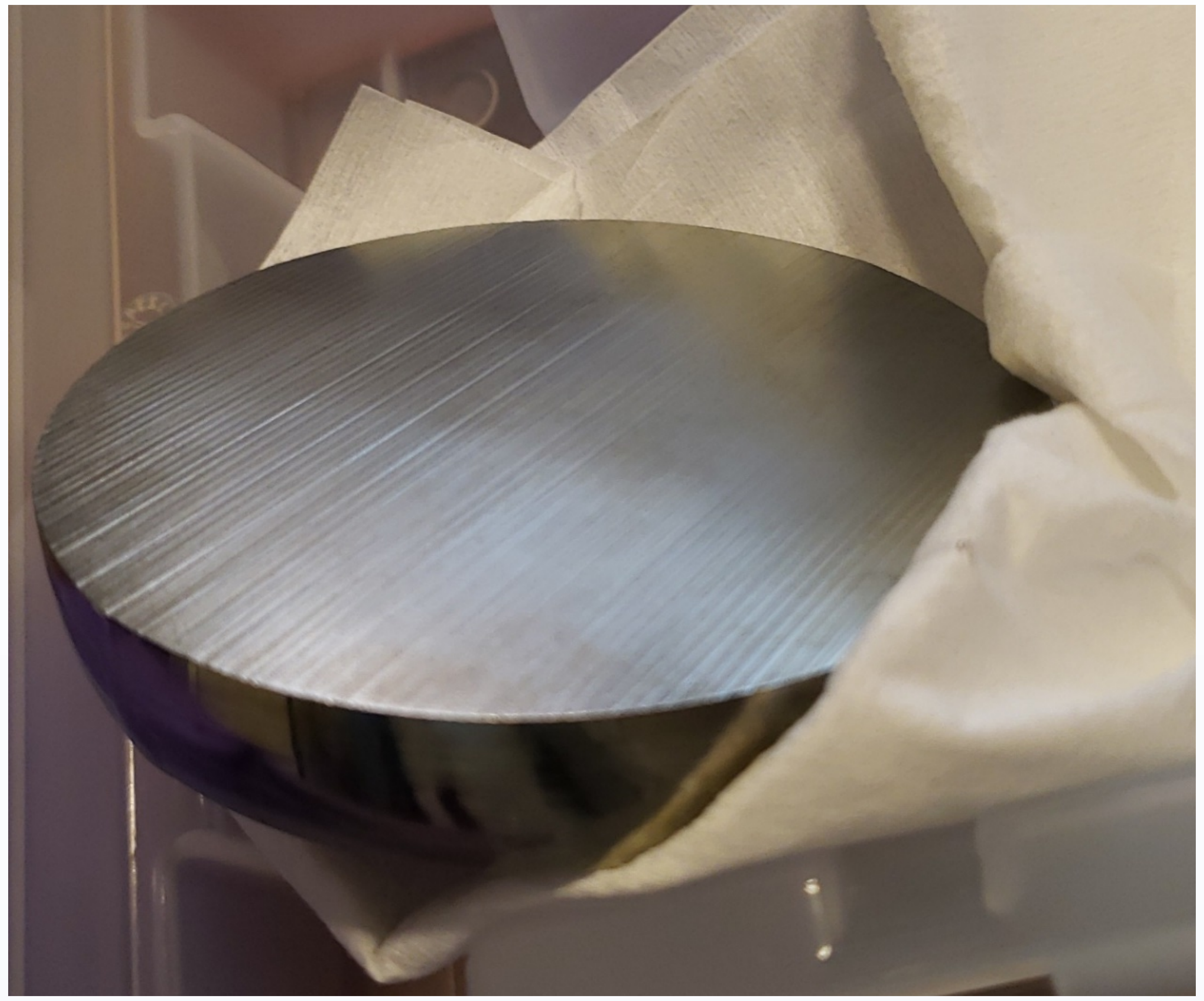
Major activity

- Initial fabrications completed (spring 2020)
- Fabricate a robust breakdown prevention structure
- Fab modest sized detector (>1kg) from USD crystal

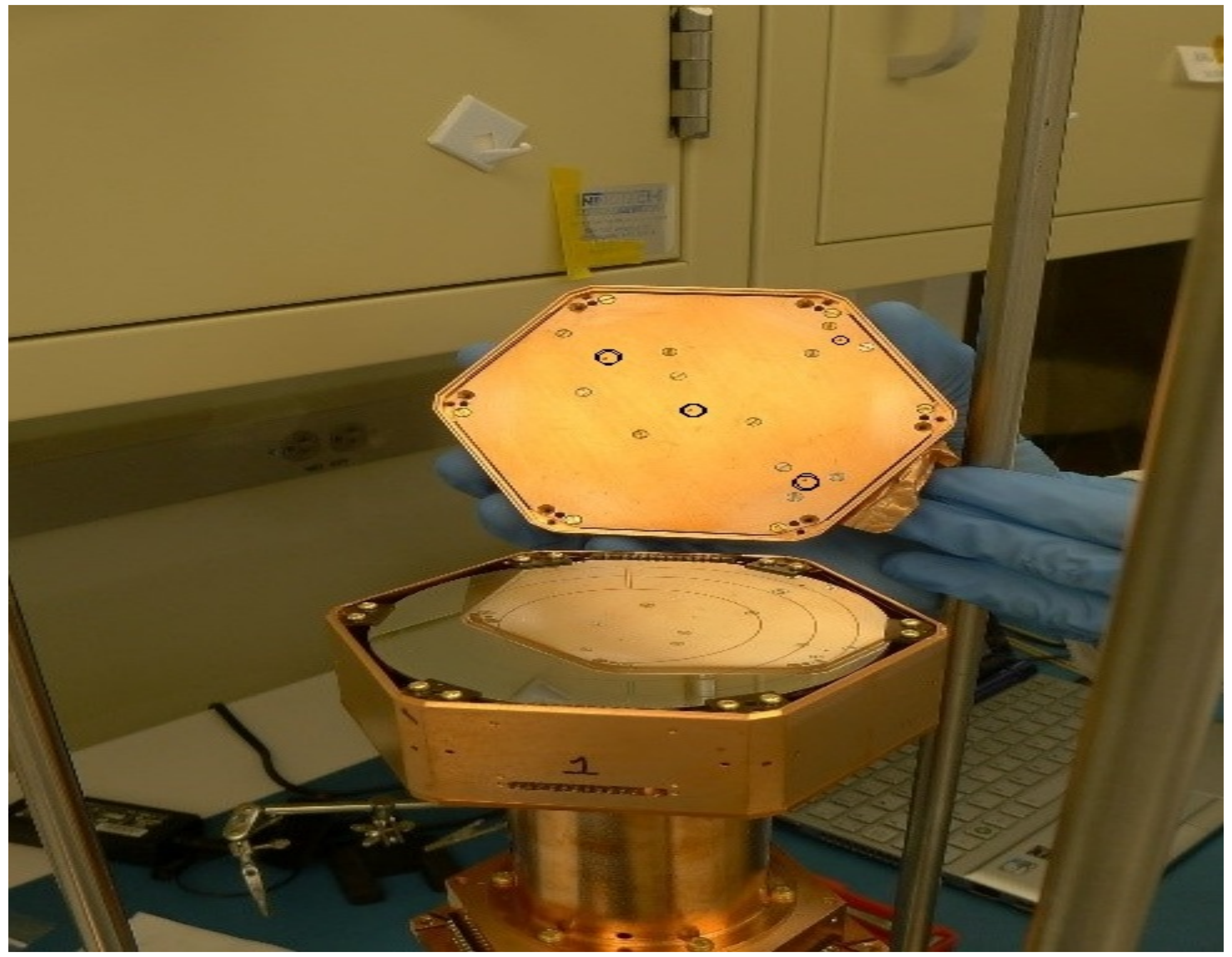
Detector Development

2. Detector development					
a. Internal amplification	Design, fabricate, and test **1st detector**		Rebuild and test	Build **2nd detector**	Run for certification
b. SuperCDMS-type detectors	Design, fabricate, and test **1st detector**		Rebuild and test	Build **2nd detector**	Run for certification
c. Inverted coaxial PPC	Design, fabricate, and test **1st detector**		Rebuild and test	Build **2nd detector**	Run for certification

Detector Development – CDMS-style Detectors



90mm Ge crystal to be shaped/polished to 75mm



N-type SuperCDMS Detector testing

Major Activities:

- Phase II: 75mm Detector (currently in shaping/polishing)
- Pre-test 75mm crystal using contact-free
    - ➢ Validated S/N of same crystal using CDMS and Contact free
- Using a n-type detector to understand electron trapping

Participants:

Students :
Pramod Acharya
Nick Mast
William Baker

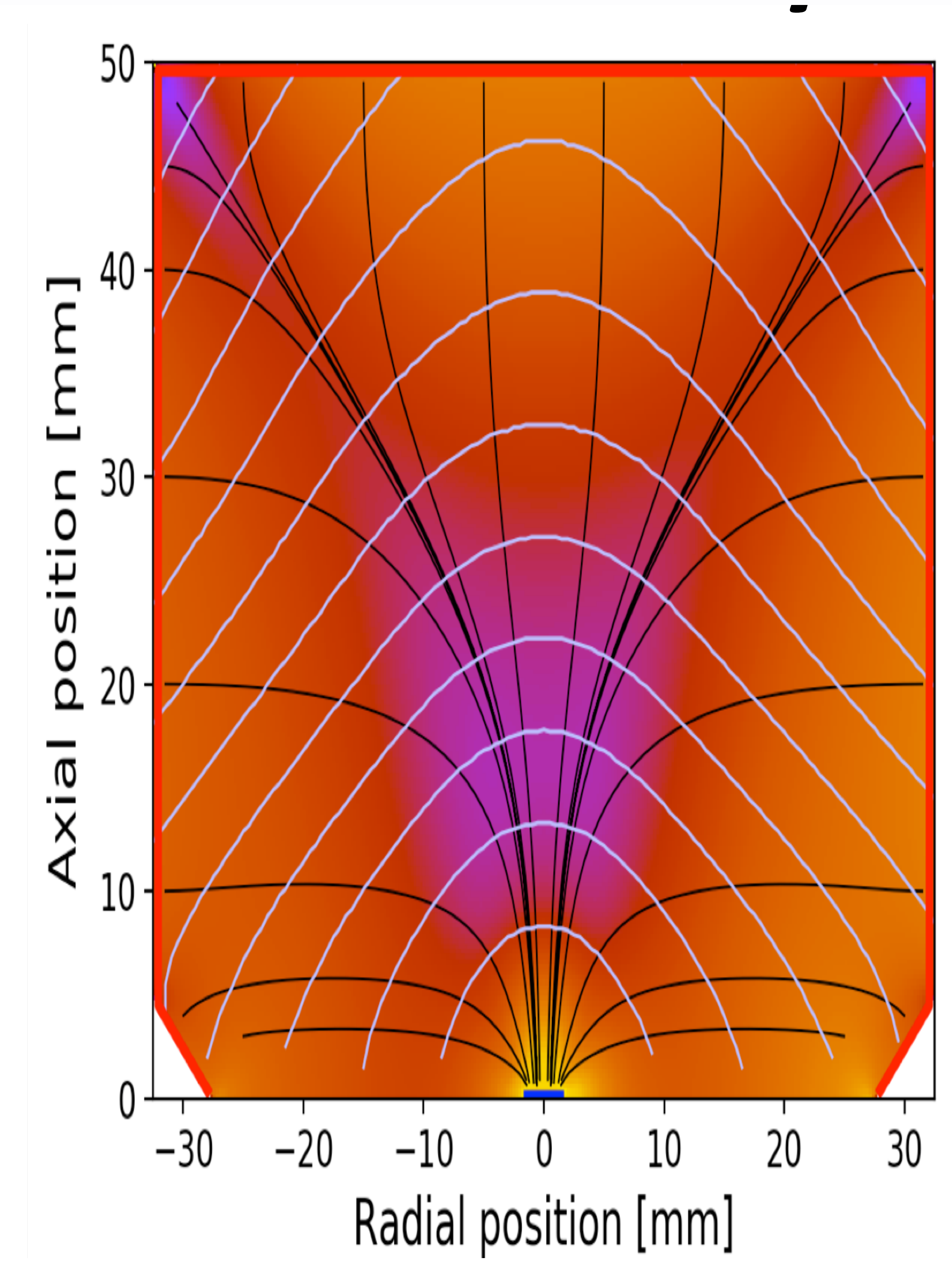
Postdoc :
Wenzhao Wei

Scientist :
Matt Fritts

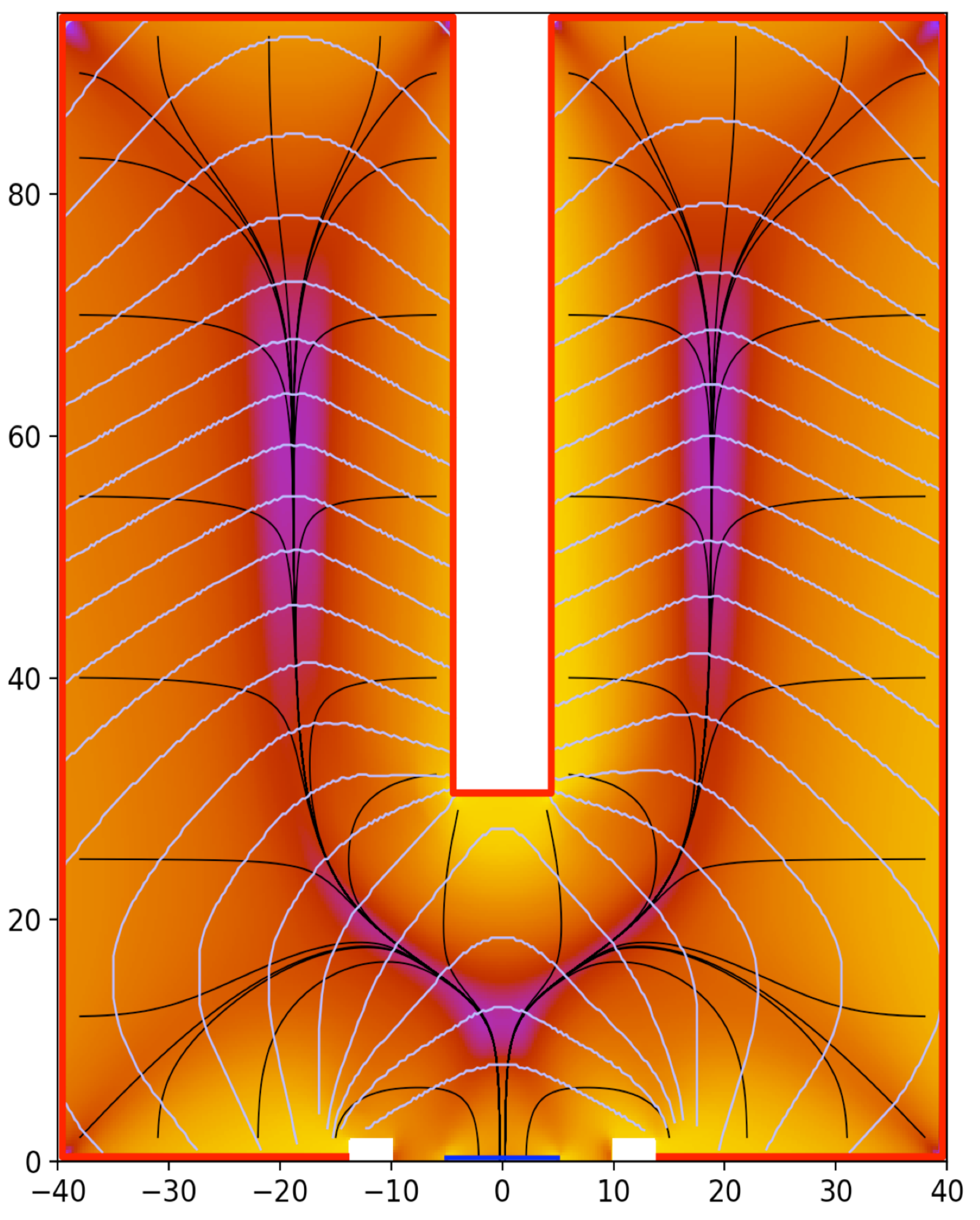
Faculty
Vuk Mandic
Dongming Mei
Rusty Harris

Detector Development – Inverted Coaxial Detectors

LEGEND-Style Detectors



Point Contact (PPC)



Inverted Coaxial PPC

Participants:

UNC
TAMU
USD
MPI
LBNL

Students:
Anna Reine
Chris Haufe
William Baker
Morgan Clark
Carmen Allison

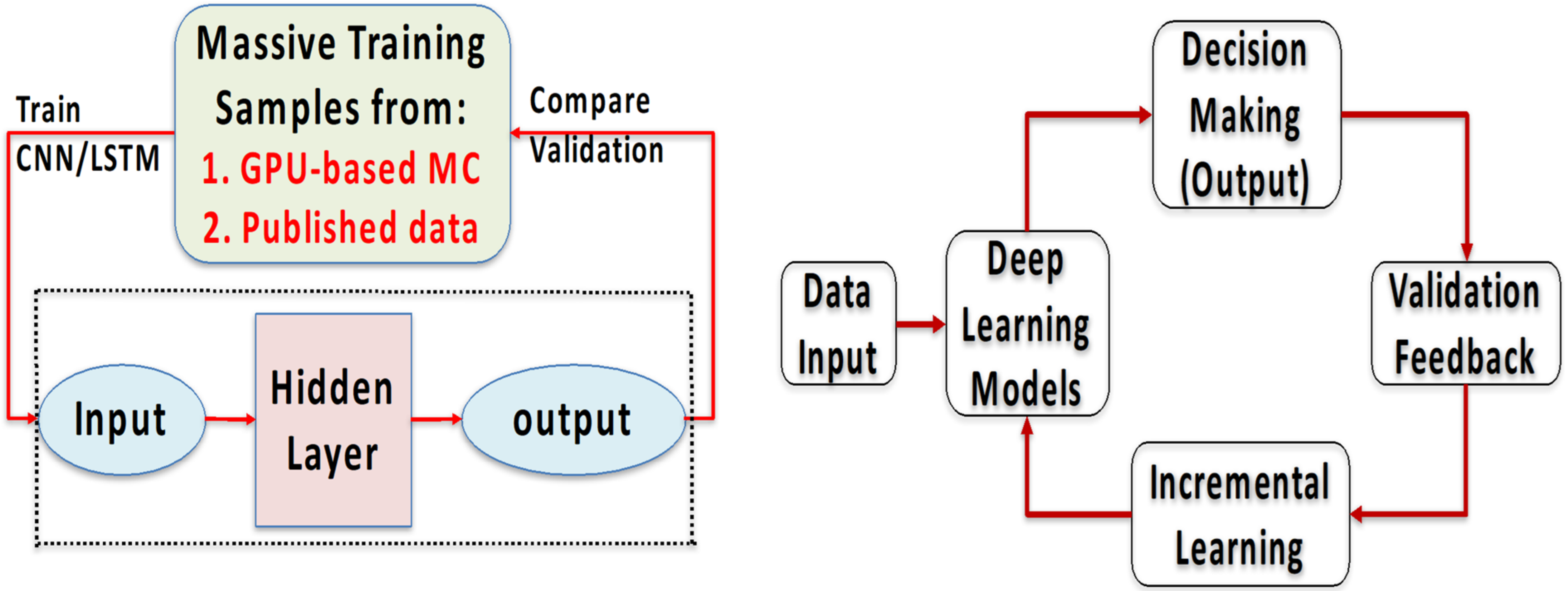
Collaborator:
David Radford

Faculty
John Wilkerson
Rusty Harris
Dongming Mei
Jing Liu
Iris Abt
Mark Amman
Xiang Liu

Major Activities:

- Initial Fabrication
- Fab/test MiniPPC detectors (materials screening)
- Plan and execute Inverted Coaxial PPC with USD xtals.

Detector Development - Simulation Toolkit



1. Active Learning with deep learning models – Convolutional Neural Networks
2. Graphic Processing Units to speedup massive (~billions) Monte Carlo simulation
3. Applying denoising CNNs to further speedup large-scale simulation

Outcomes: Multiple papers and theses. Students will drive the development of new tools

Advanced Goals:

(1) Increase S/N ratio
(2) Produce a large amount of simulation data
(3) Apply machine learning algorithms to increase identification of new particles

Participants: All Institutes

Students:
Anna Reine
Chris Haufe
Morgan Clark
San Meijer
William Baker
Kunming Dong
Zhangzhi Feng

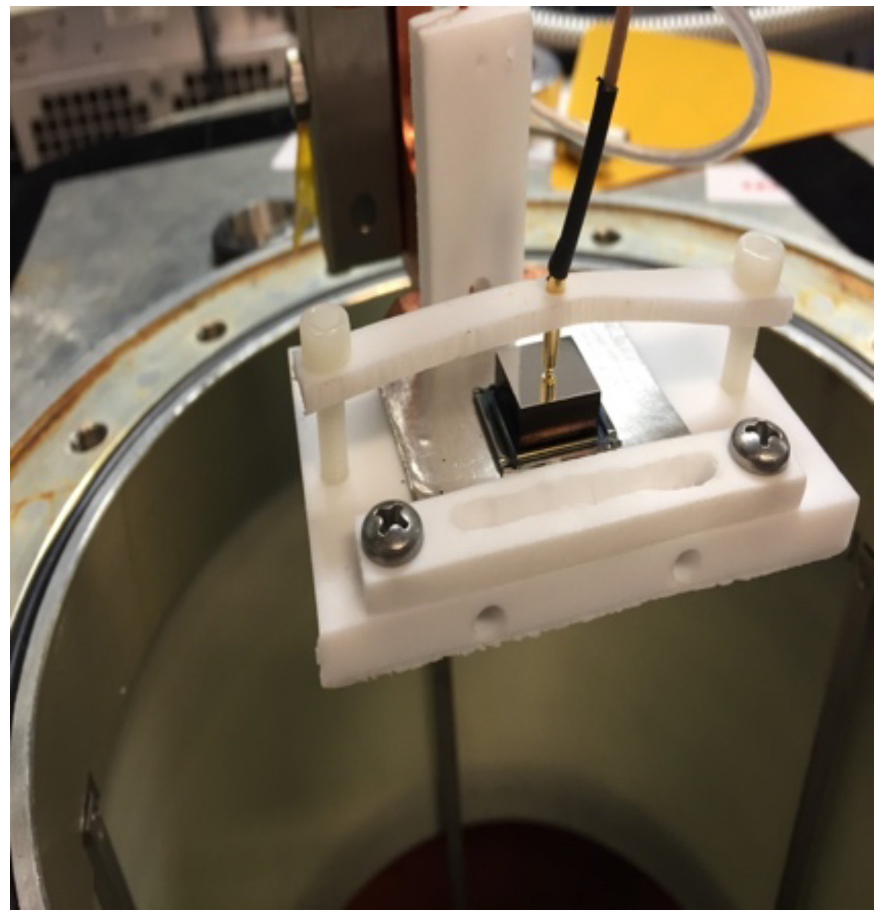
Postdoc:
Wenzhao Wei
Ian Guinn

Faculty
John Wilkerson
Rusty Harris
Jing Liu
Iris Abt
Wenqin Xu

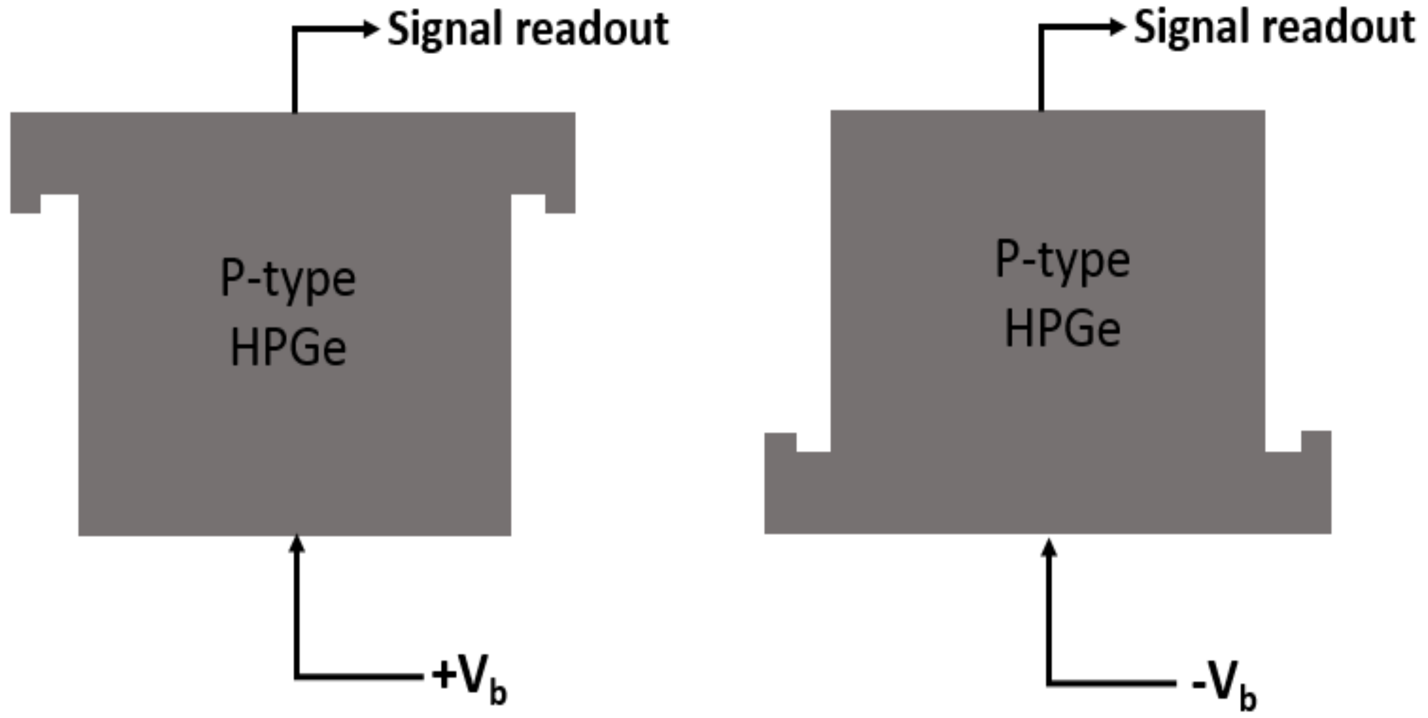
Detector Performance

3. Detector performance				
a. Test methodology	Understand the correlation between charge generation, transport, trapping, recombination, impurityies, and surface effects			
b. Simulation toolkits	Simulate charge carrier drift and diffusion during the drift process to understand charge trapping and surface effects			
c. Pulse shape discrimination	Measurements of charge pulses	Simulation of pulses	Comparison	Developing models

Detector Performance - Test Methodology



Detector direct in contact with liquids



Study Charge Trapping Mechanisms

Multiple papers and theses driven by students are expected

Detectors	Top Contact	Bottom Contact
USD-R02	$\varphi_h = (0.31 \pm 0.01)$ eV	$\varphi_e = (0.30 \pm 0.00)$ eV $N_f = (4.68 \pm 3.32) \times 10^{17}$ eV^{-1}cm^{-3}
USD-R03	$\varphi_h = (0.285 \pm 0.005)$ eV $N_f = (4.34 \pm 0.11) \times 10^{18}$ eV^{-1}cm^{-3}	$\varphi_e = (0.28 \pm 0.00)$ eV $N_f = (1.83 \pm 0.33) \times 10^{18}$ eV^{-1}cm^{-3}
USD-W03	$\varphi_h = 0.31$ eV $\varphi_e = (0.31 \pm 0.00)$ eV $N_f = (2.25 \pm 0.02) \times 10^{18}$ eV^{-1}cm^{-3}	$\varphi_e = (0.295 \pm 0.005)$ eV $\varphi_h = (0.29 \pm 0.00)$ eV $N_f = (1.94 \pm 0.04) \times 10^{18}$ eV^{-1}cm^{-3}

Advanced Goals:

(1) Initial fabrications and tests (done)
(2) Fabricate detectors with different contact geometries/materials
(3) Ultimate goal is optimize the parameters for the contact design and reduce the surface backgrounds

Participants:
UNC
MPI
ASIOP
AUD
TAMU
AMN

Students:
Anna Reine
Chris Haufe
Morgan Clark
David Hervas
William Baker
Kyler Kooi
Rajendra Panth
Nick Mast

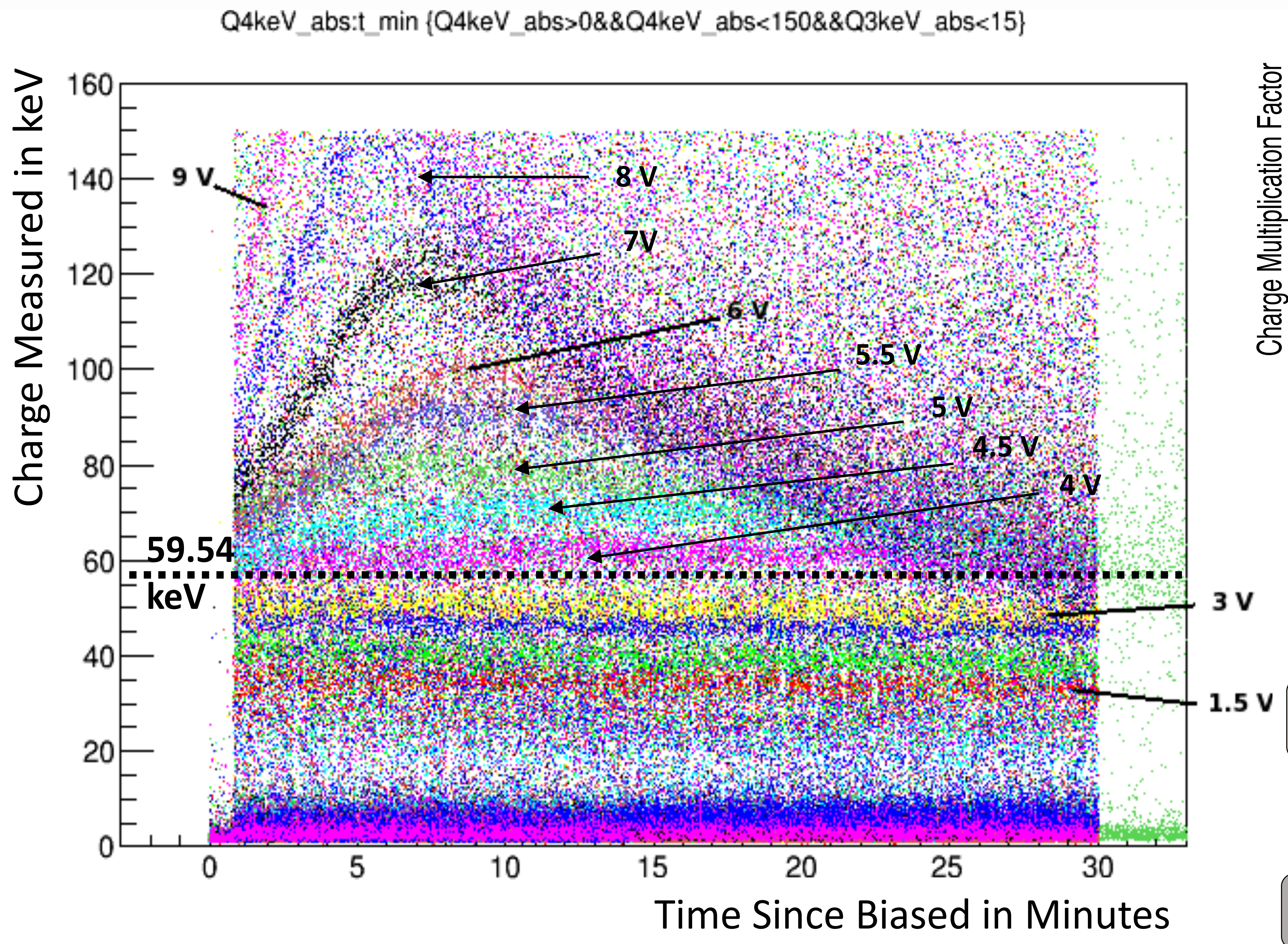
Postdoc:
Ian Guinn
Wenzhao Wei
Eric Martin

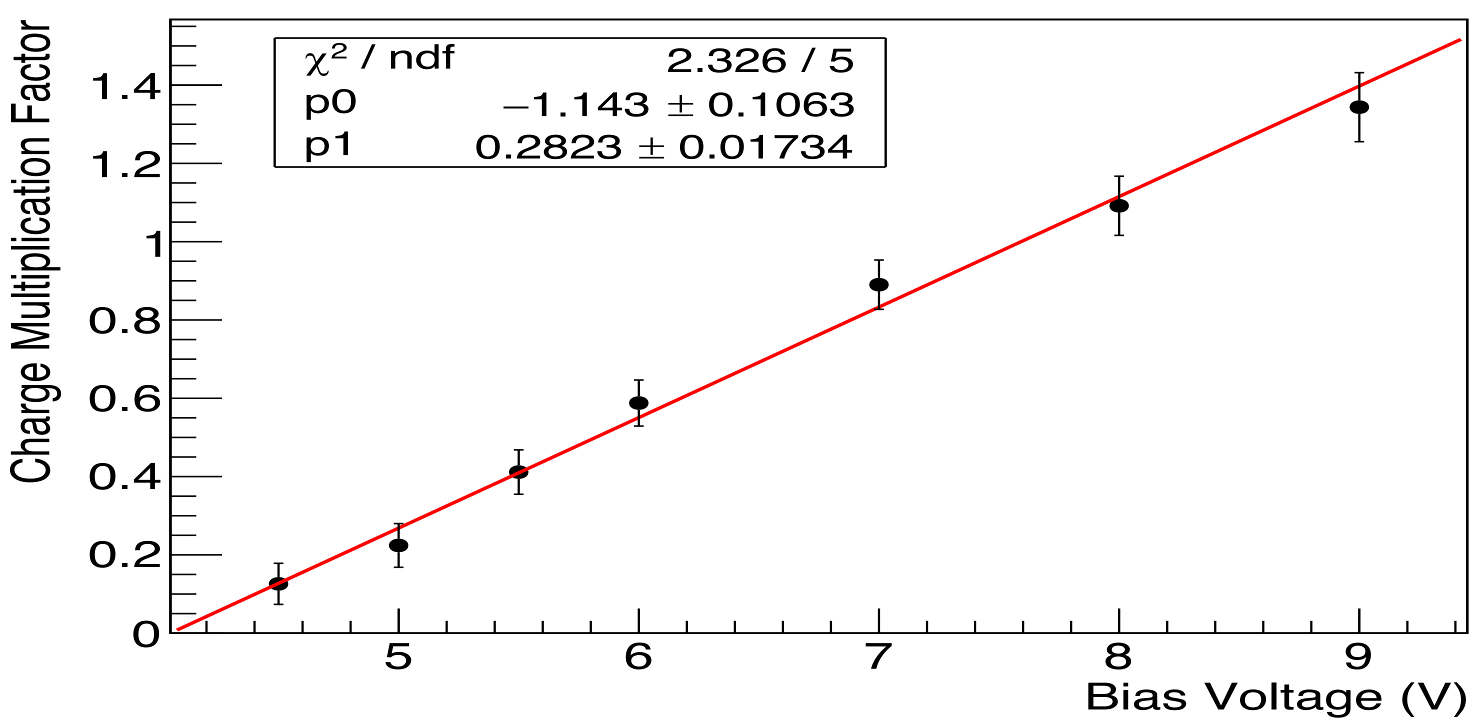
Faculty /Scientist
John Wilkerson
Rusty Harris
Dongming Mei
Jing Liu
Iris Abt
Henry Wong
Matt Fritts
Tom Caldwell
Qian Yue

PIRE GEMADARC

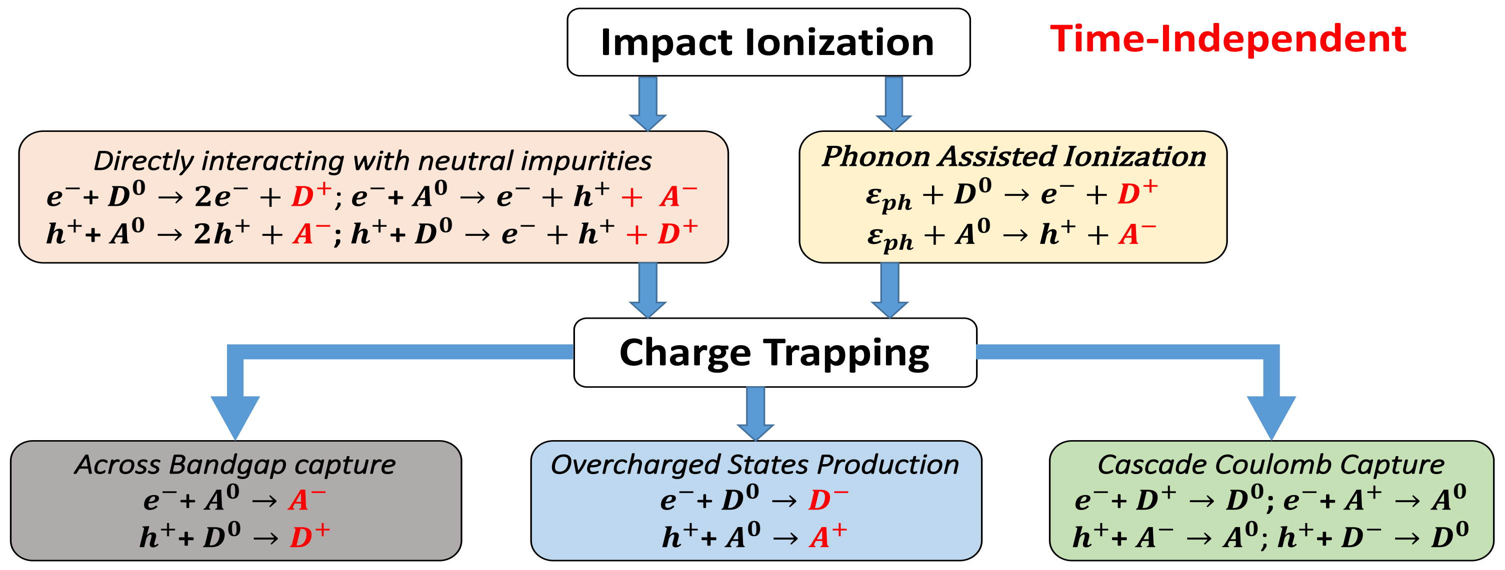
Detector Performance – Simulation Toolkit

Participants:
UNM & USD





Microphysics Processes for a Single Event



Students :
Pramod Acharya
William Baker
Nick Mast

Postdoc :
Wenzhao Wei

Scientist :
Matt Fritts

Faculty
Vuk Mandic
Dongming Mei

Advanced Goals:
(1) Understand the microphysics processes at cryogenic temperature;
(2) Innovate new technology

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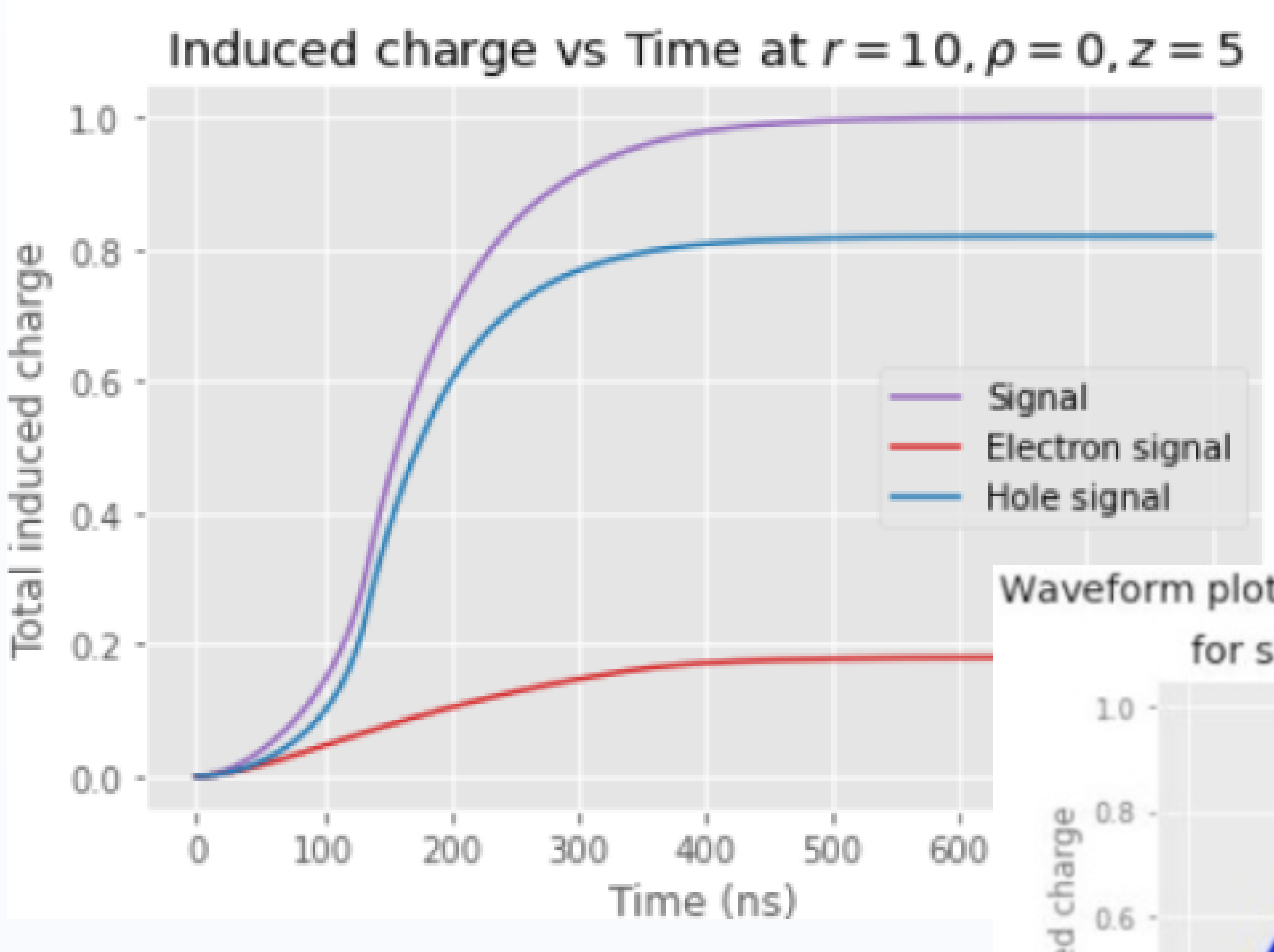
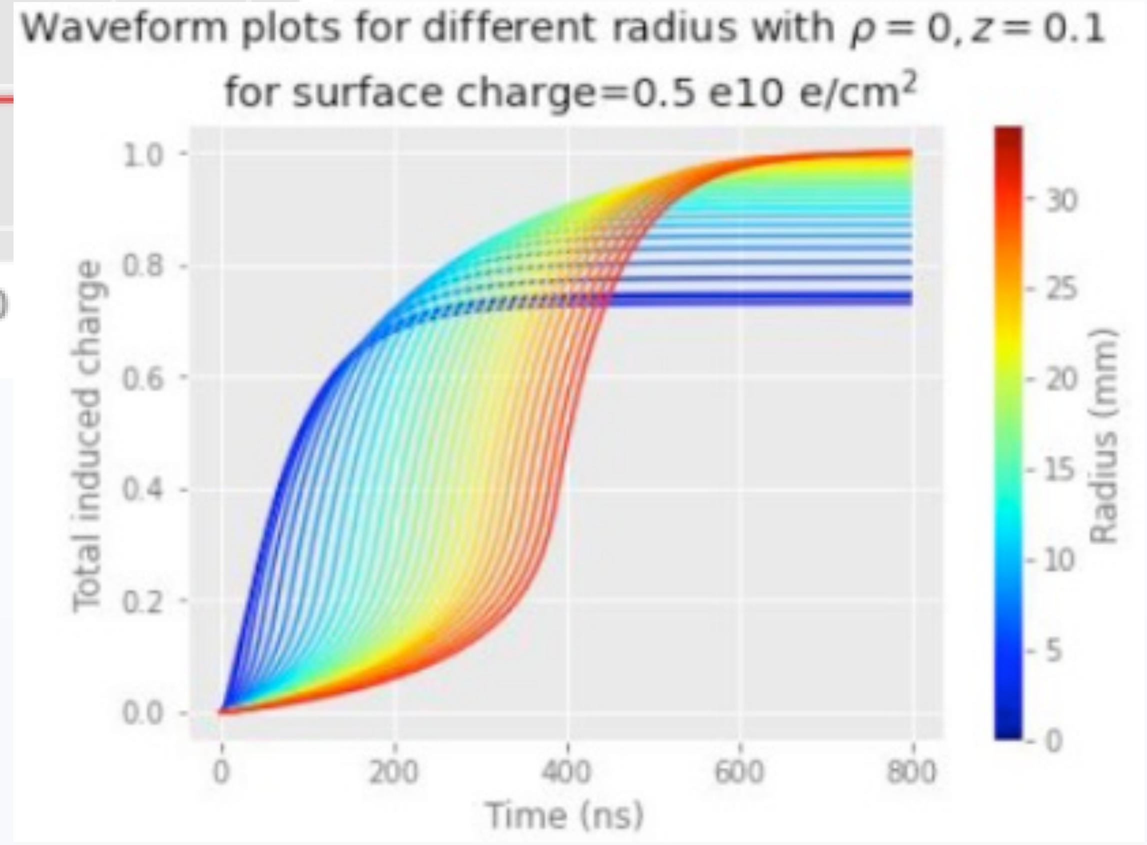
Detector Performance - Pulse Shape Discrimination

Utilizing improved Simulation tools and Machine Learning Methods

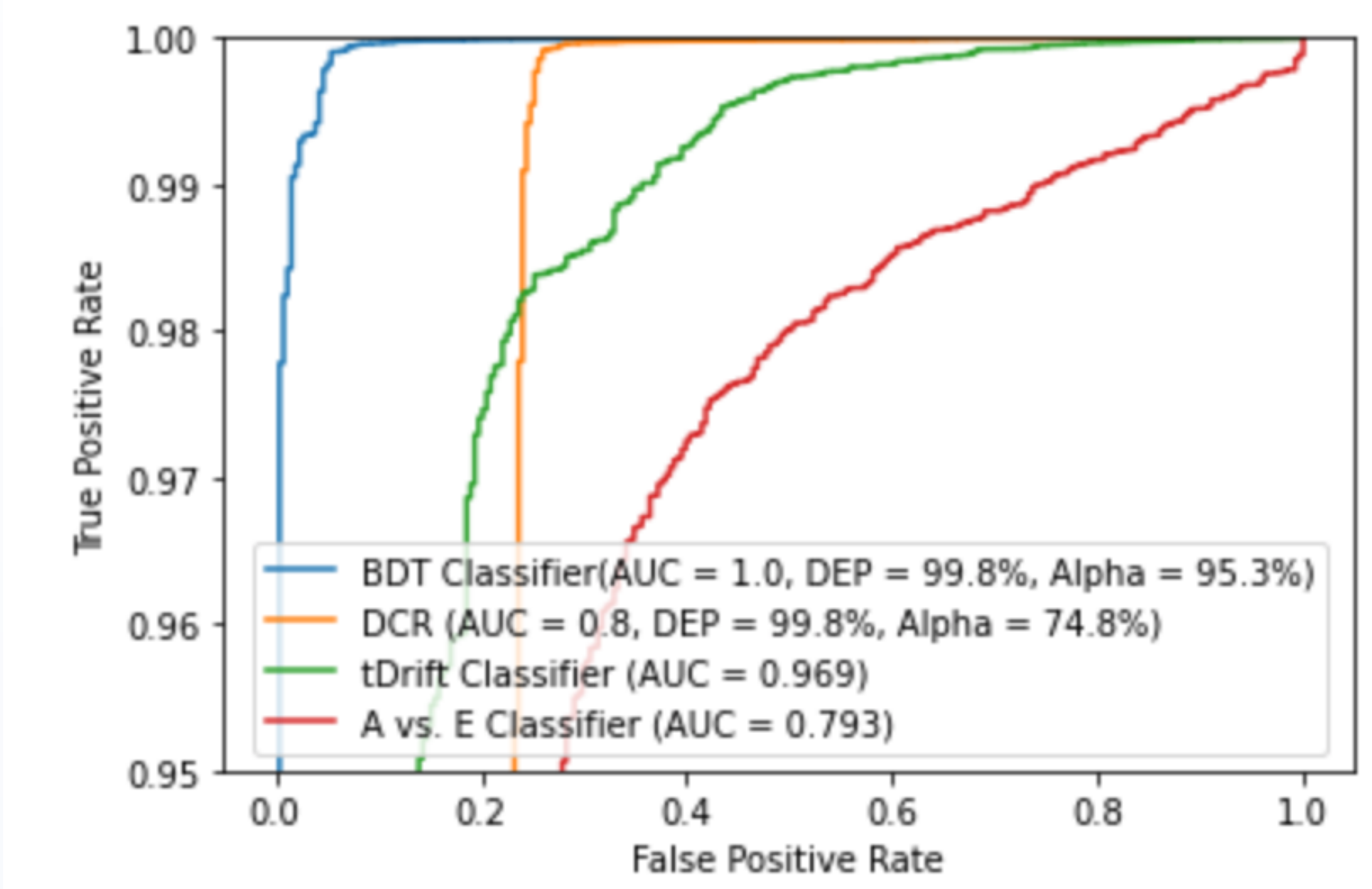
Simulation of surface charges (Bhimani)





- *Fieldgen* calculates the electric field and weighting potentials inside the detector
- *Siggen* generates time evolution of the signals

Boosted Decision Tree Classifier (Li)



- Promising Machine Learning improvements in conjunction with tradition PSD method already seen in some cases

Participants: USD, UNC

Students :
Kevin Bhimani
Jackson Waters

Postdoc :
Ian Guinn
Aobo Li

Scientist :
Tom Caldwell

Faculty
Julieta Gruszko
Reyco Henning
John Wilkerson
Wenqin Xu

Connections to Sim. Toolkit & ML Techniques

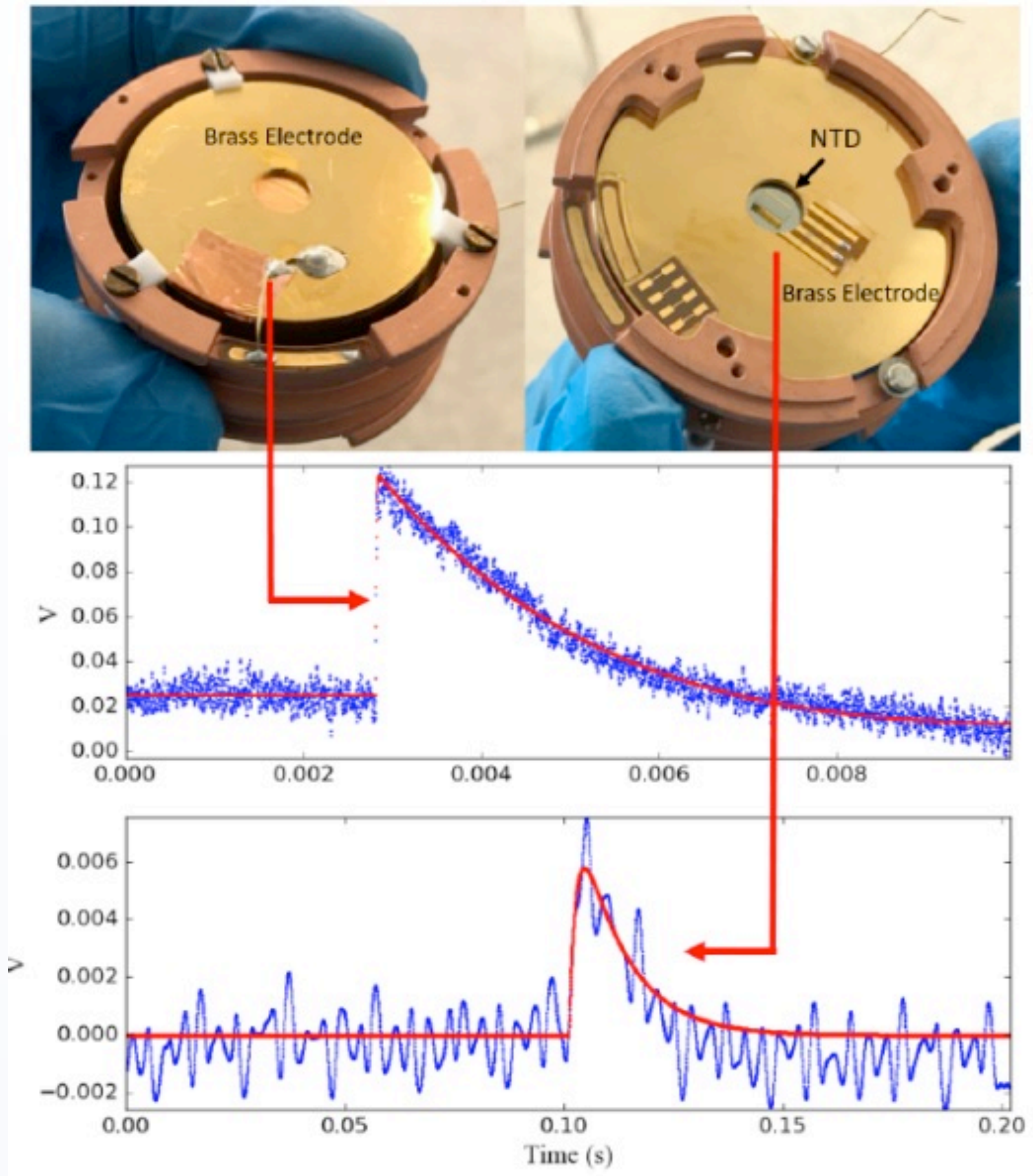
Novel and Emerging Ge research

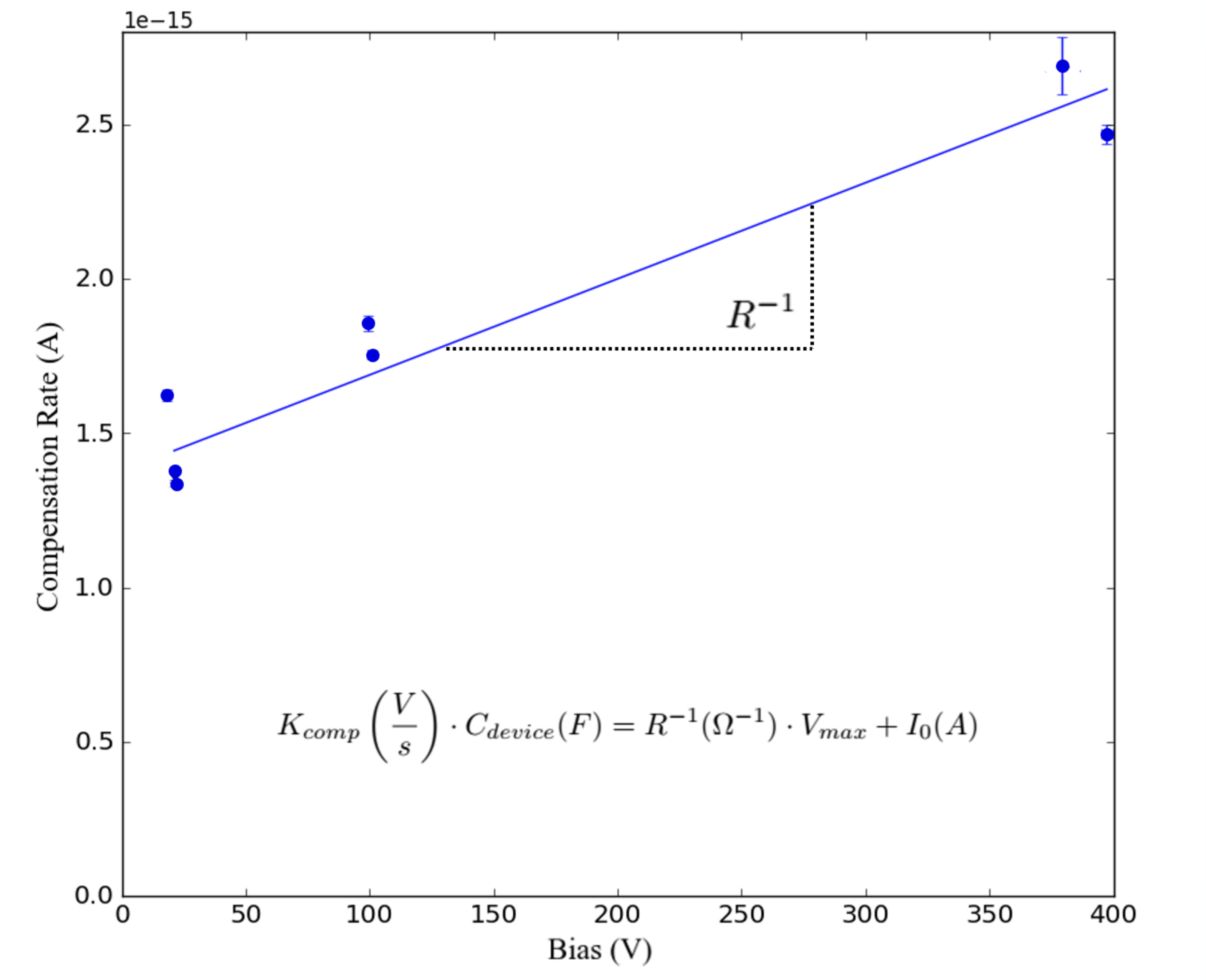
- As GEMADARC Activities continue, we continuously generate
  - New detector/characterization ideas,
  - Important new understanding and
  - Insight into the importance of next-step research opportunities

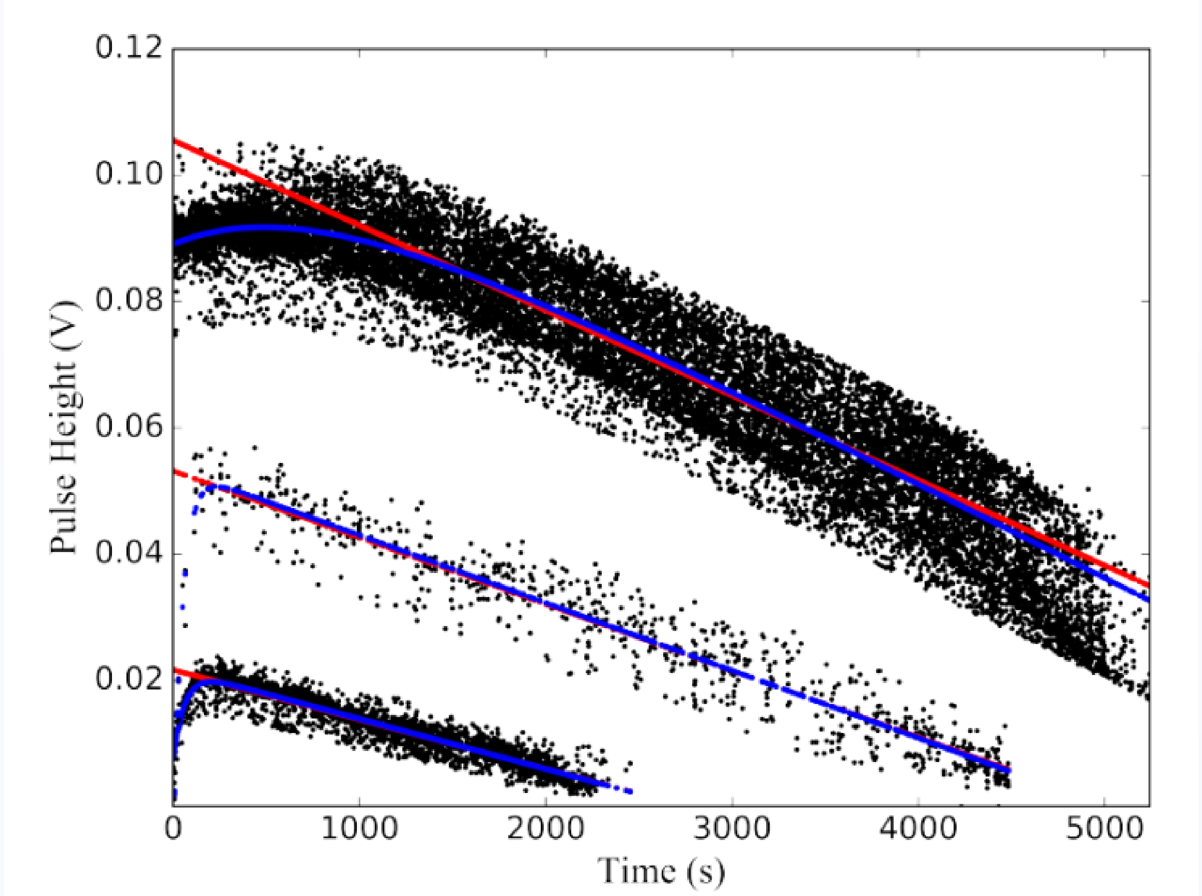
- Leveraging the research and education of GEMADARC has enabled us to embark on additional satellite research ABOVE and BEYOND the original goals
  - **Contact-free, ZERO leakage current detectors**
  - **Ring-contact coaxial detectors**
  - **Machine Learning of Pulse Waveforms**
  - **Hybrid Detector**

Emerging Detector Technology – Contact Free

- Leakage Current is Major Issues with CDMS-Style detectors
  - Results in 2 major problems
    - S/N above certain energies
    - Constant current “bleeding” of ~0.01 pA







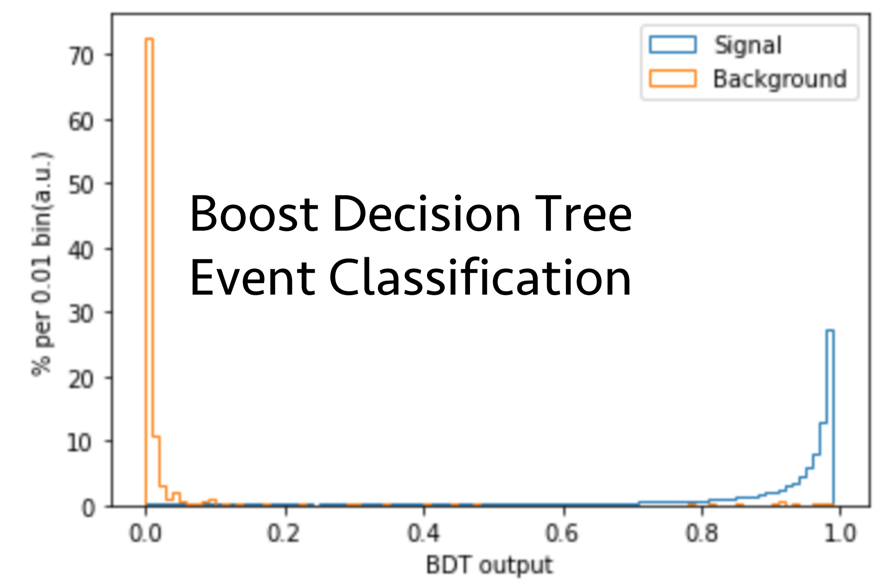
- Contact-Free measurements show decay in pulse height with time
  - slight change in that rate depending on bias
  - Since no contacts are made, leakage is INTRINSIC to Ge itself

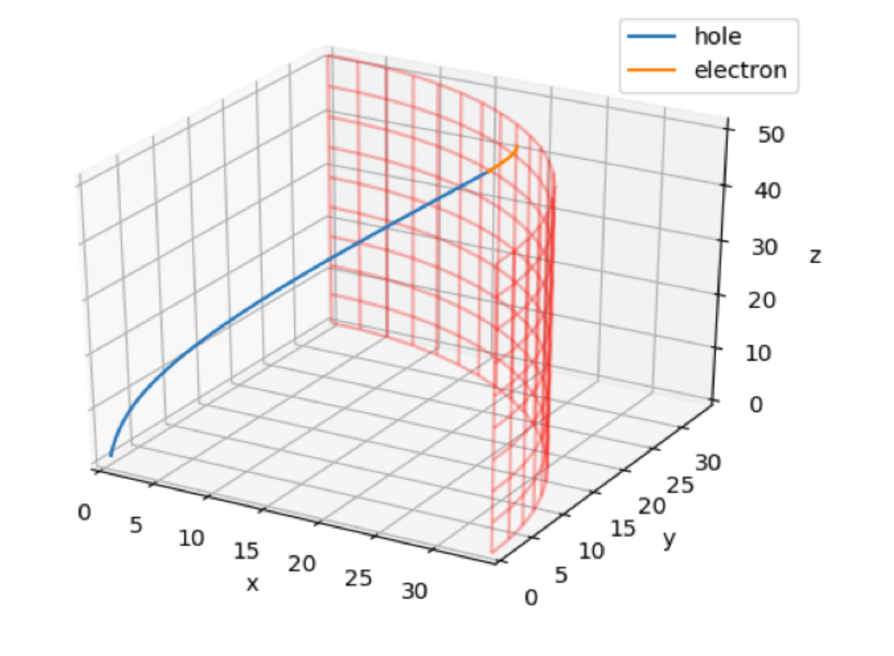
Participants:

TAMU
CSNSM
Students:
William Baker
Abhiram Dinavahi
Fedja Kadribasic
Shahriar Esmaeili

Faculty
Nader Mirabolfathi
Rusty Harris

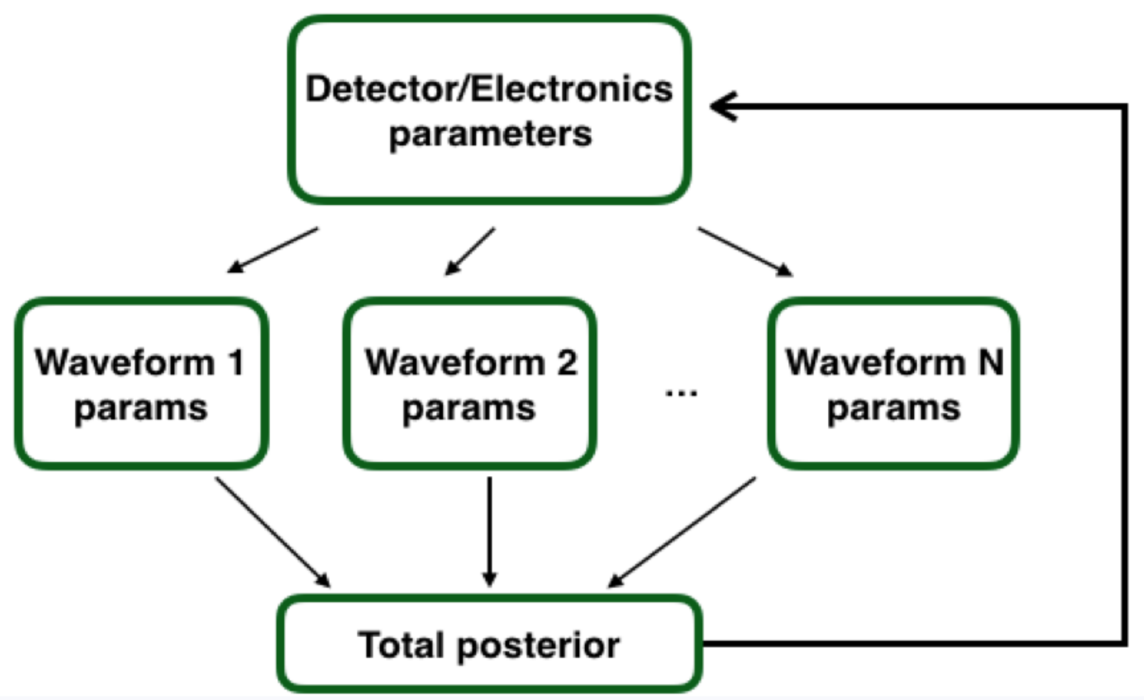
Emerging Detector Technology – Machine Learning Techniques

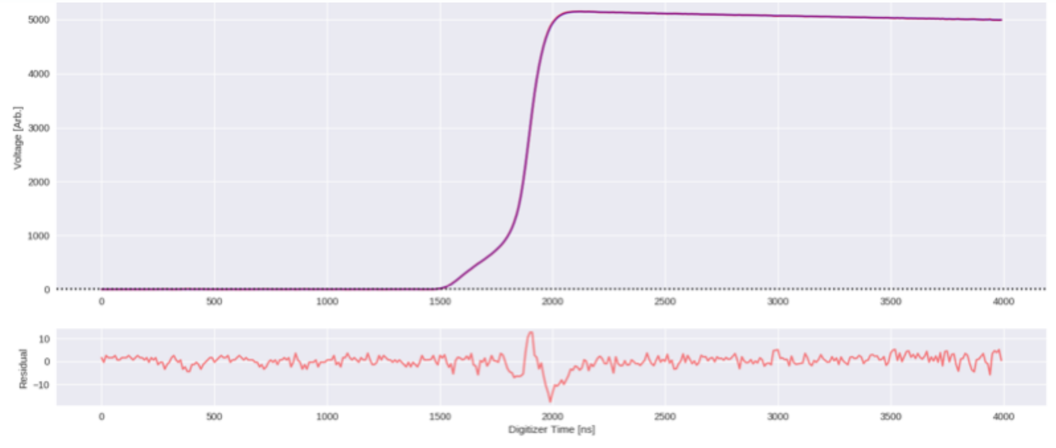




Hierarchical Bayesian Model

Fit done with MCMC
(Diffusive Nested Sampler)





Learn from Waveforms

- Event classifications
- Determination of parameters through ML analytics and Bayesian fitting

Participants:
UNC, MPI, USD, Queens,

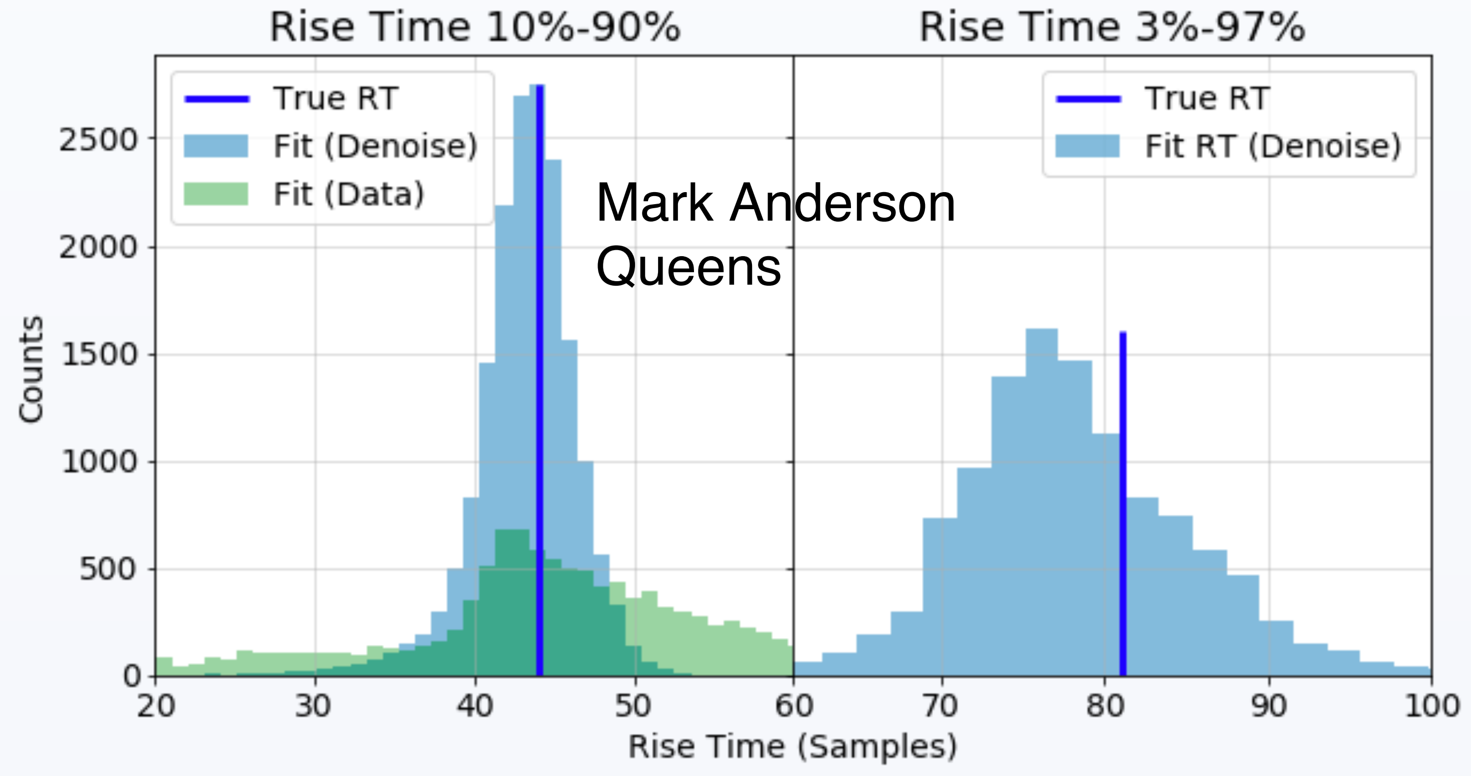
Students:
Mark Anderson
William Baker
Morgan Clark
Esteban Leon
Jianchen Li

Postdoc:
Wenzhao Wei
Ian Guinn
Aobo Li

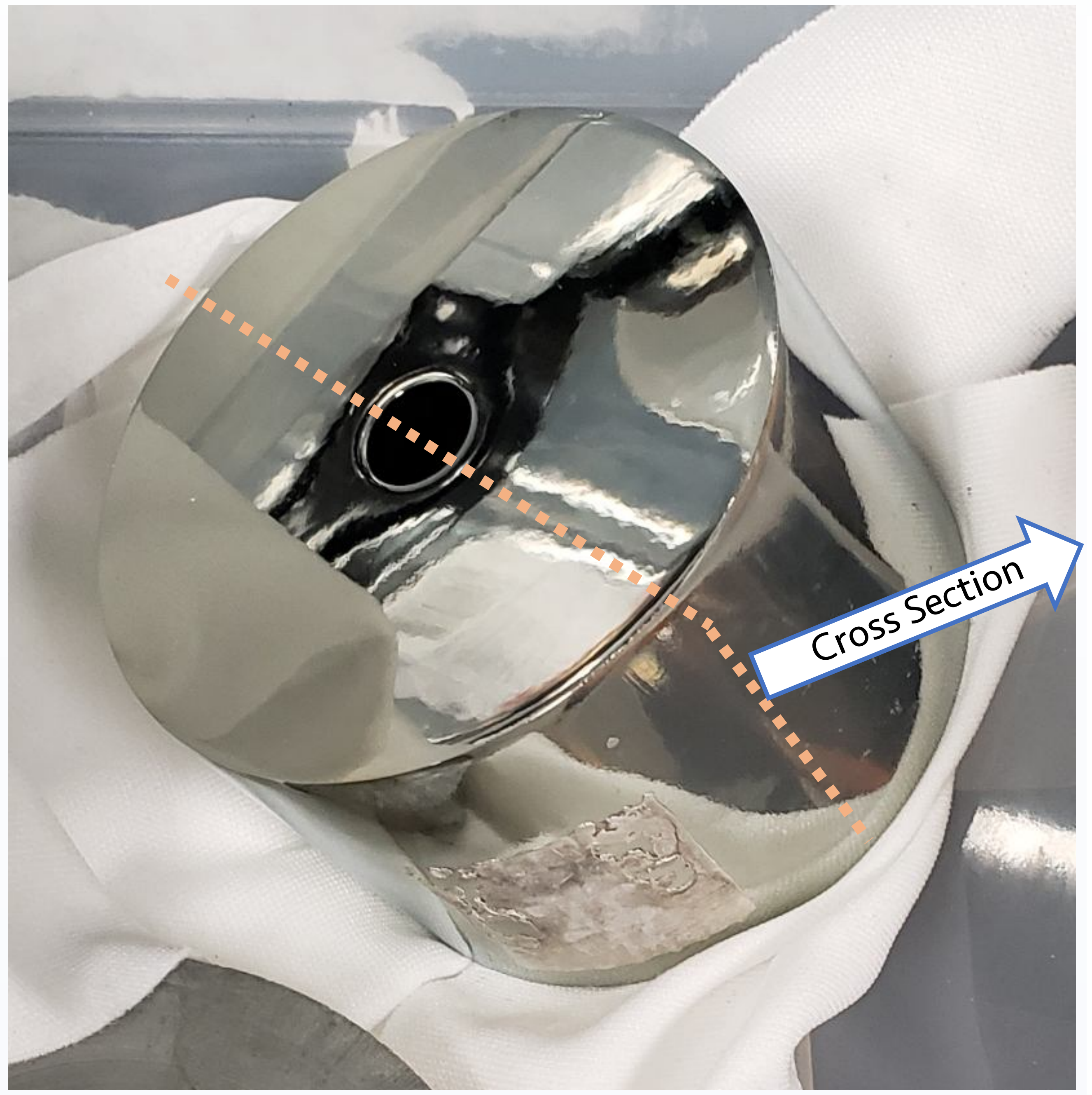
Faculty
Iris Abt
Julieta Gruszko
Rusty Harris
Jing Liu
Ryan Martin
Dongming Mei
John Wilkerson
Wenqin Xu

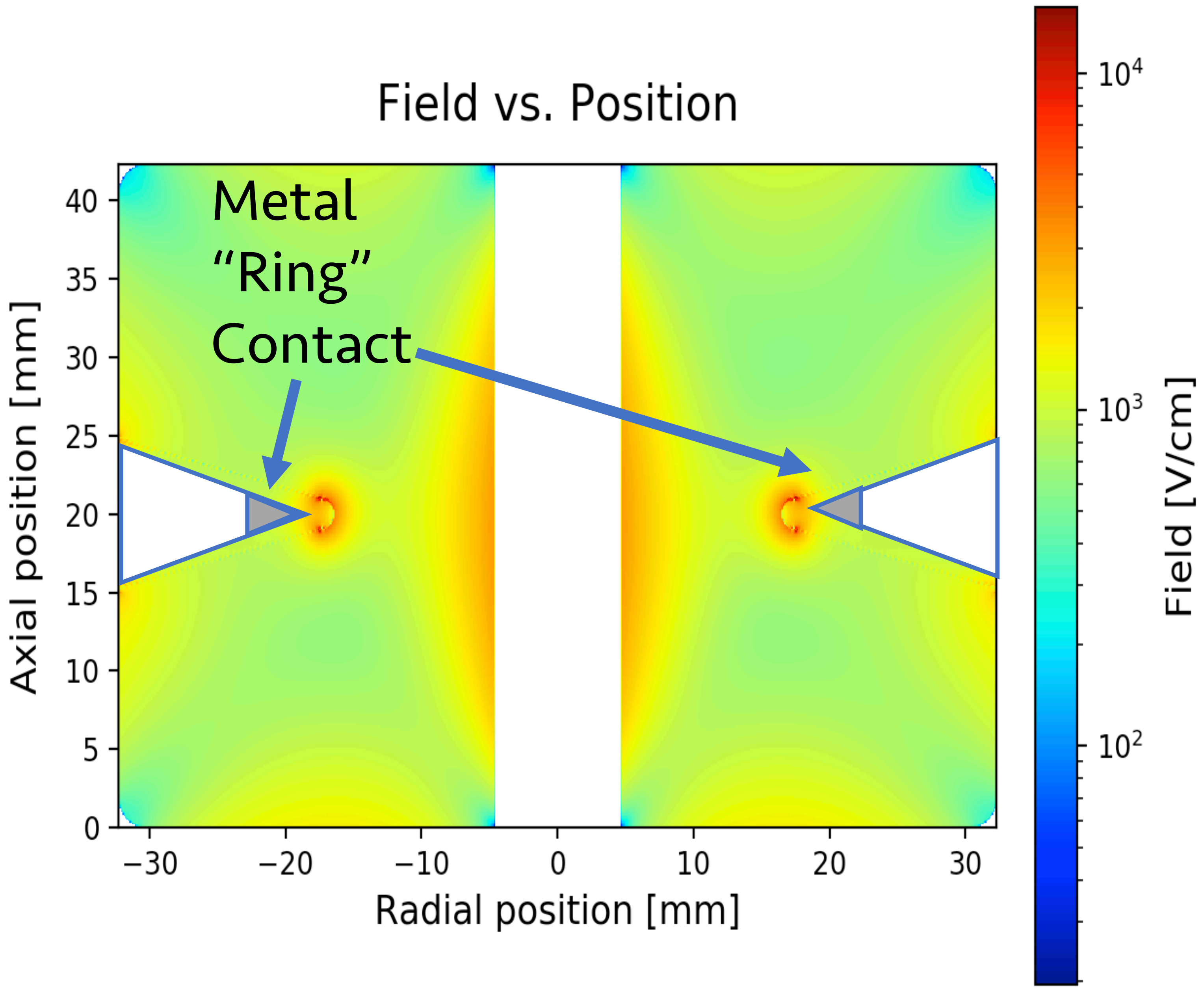
ML-based denoising

- Waveform denoising (Guinn, UNC; Anderson, Queens)
- A denoising CNN technique may achieve good accuracy for microphysics processes faster (Mei, USD)

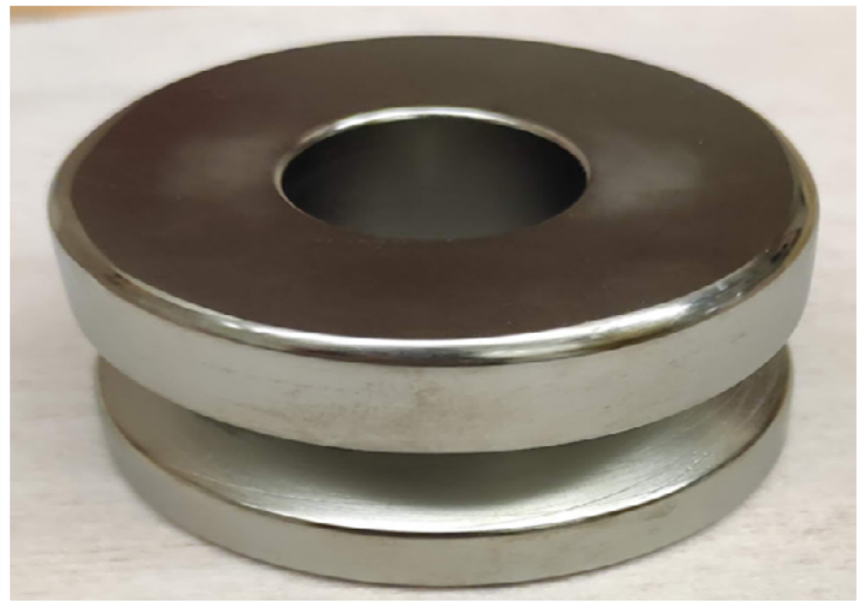


Emerging Detector Technology – Ring Contact Detector





Potential Breakthrough: this detector technology can be made available in a few years to impact $0\nu\beta\beta$ – *LEGEND*



Participants:
UNC
TAMU
LBNL

Students:
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Chris Haufe
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Rajendra Panth
Kunming Dong

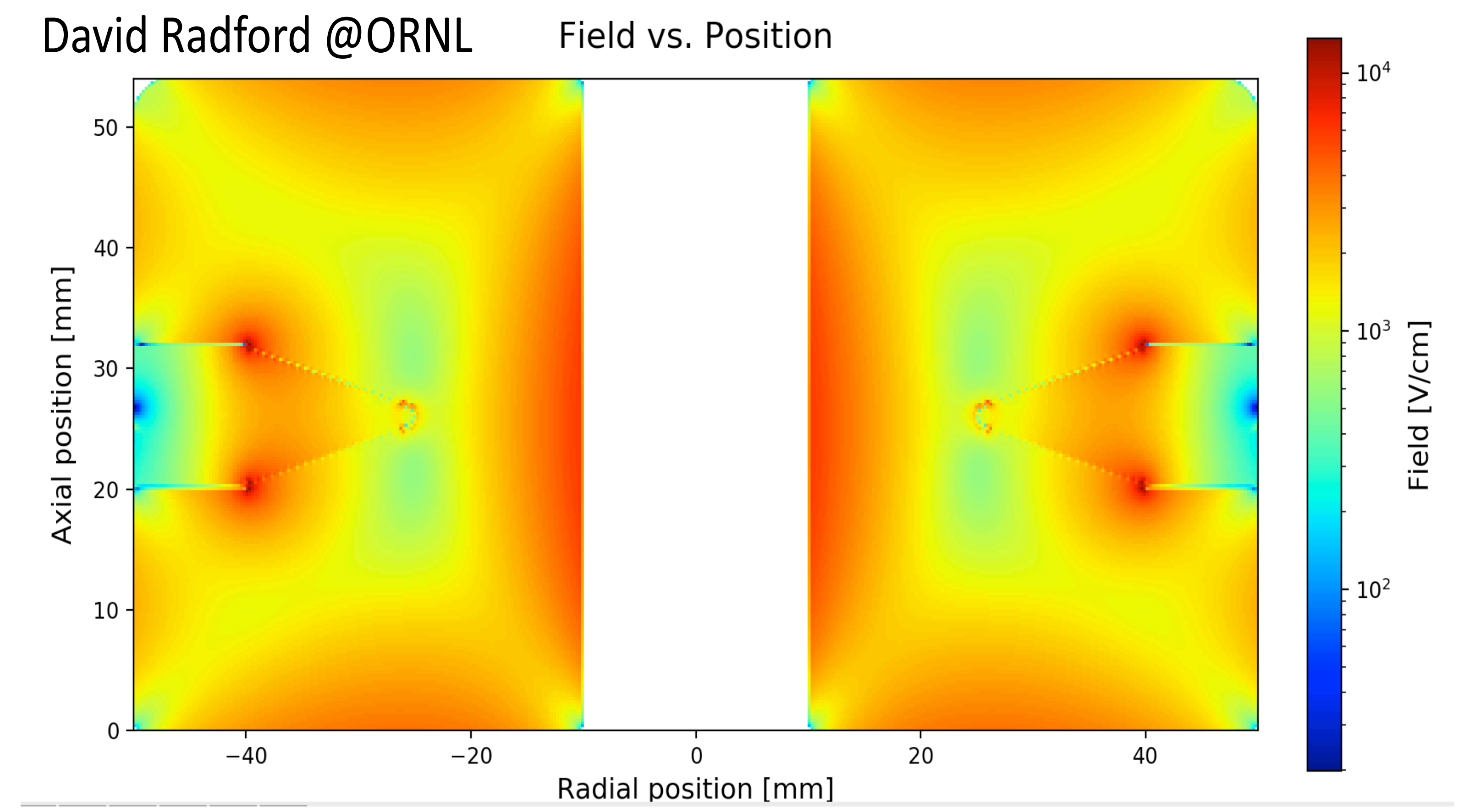
Postdoc:
Wenzhao Wei

Collaborator:
David Redford

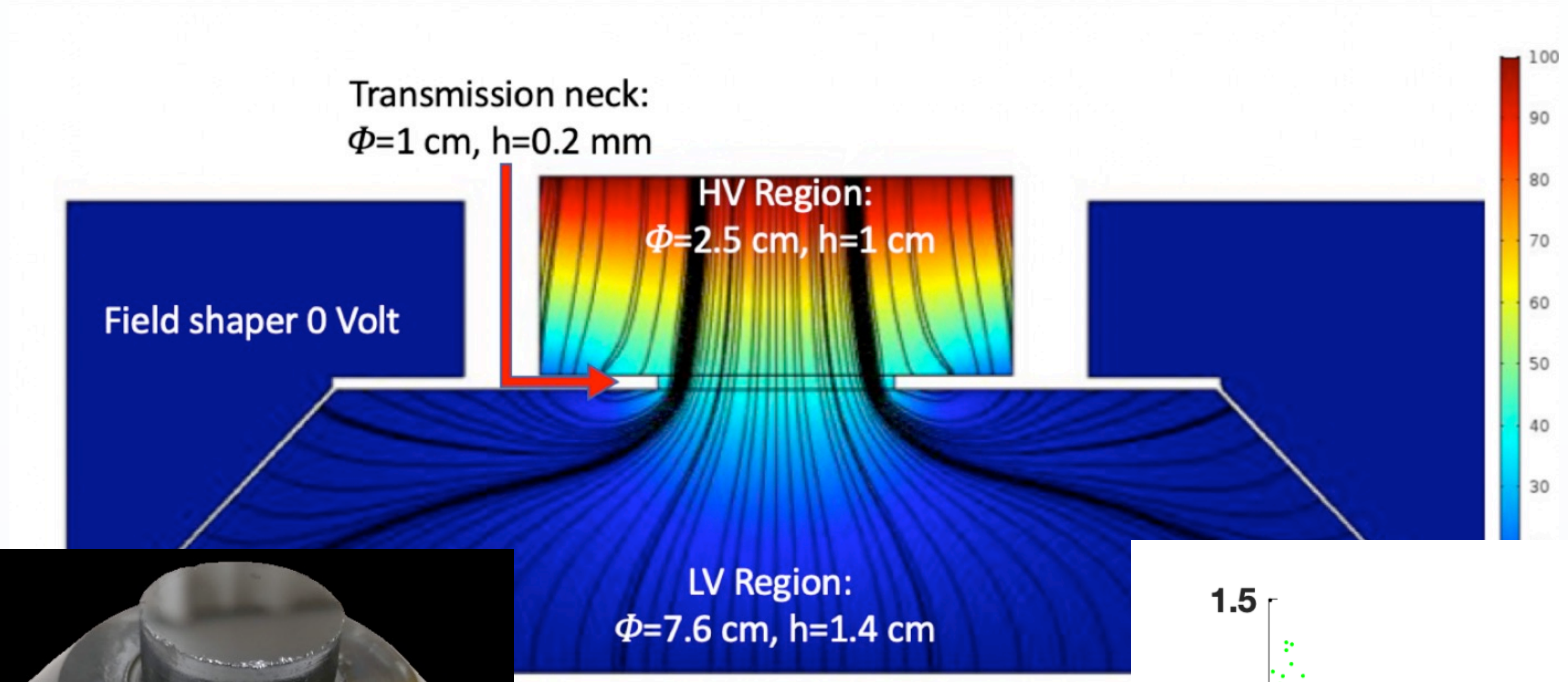
Faculty
John Wilkerson
Rusty Harris
Dongming Mei
Jing Liu

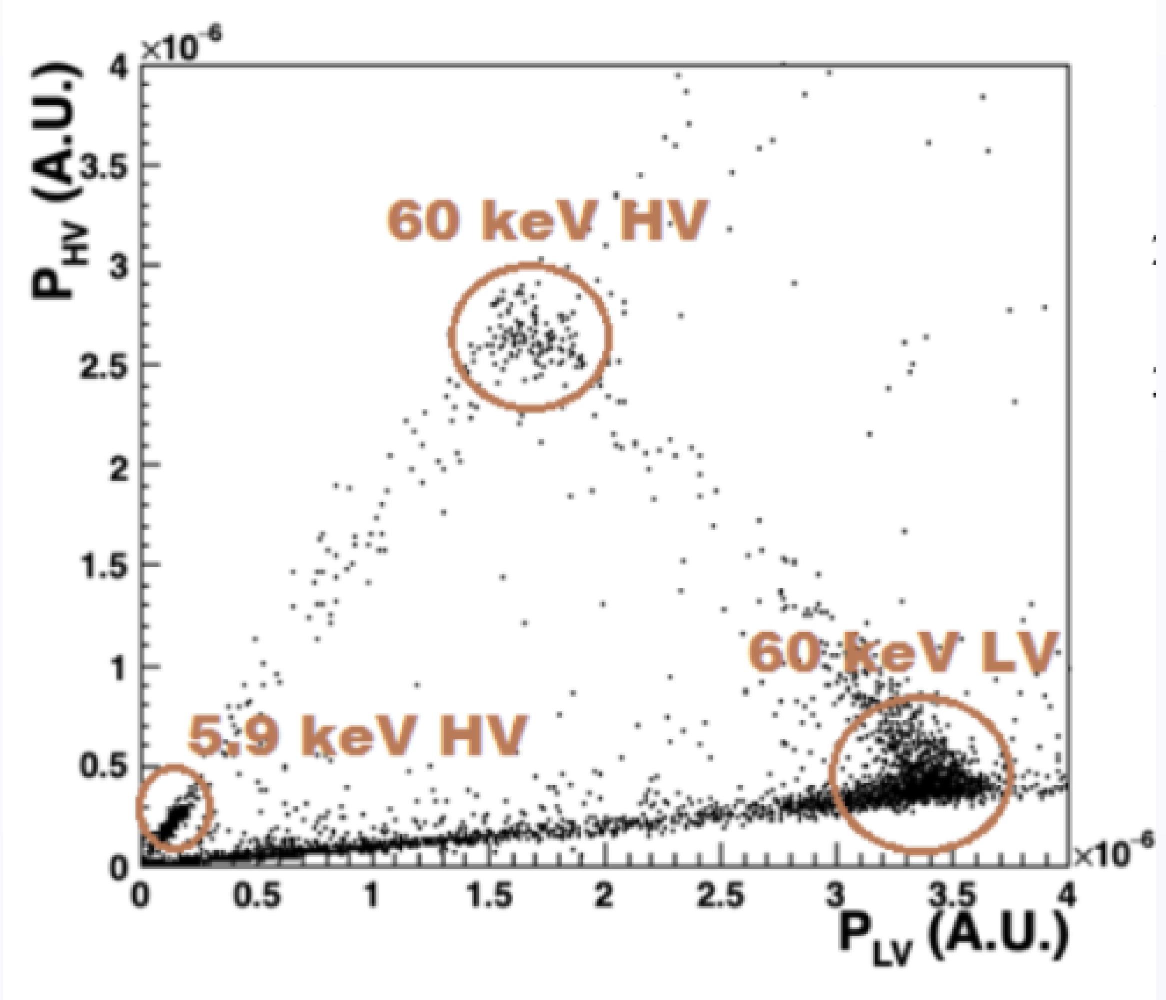
Path Forward

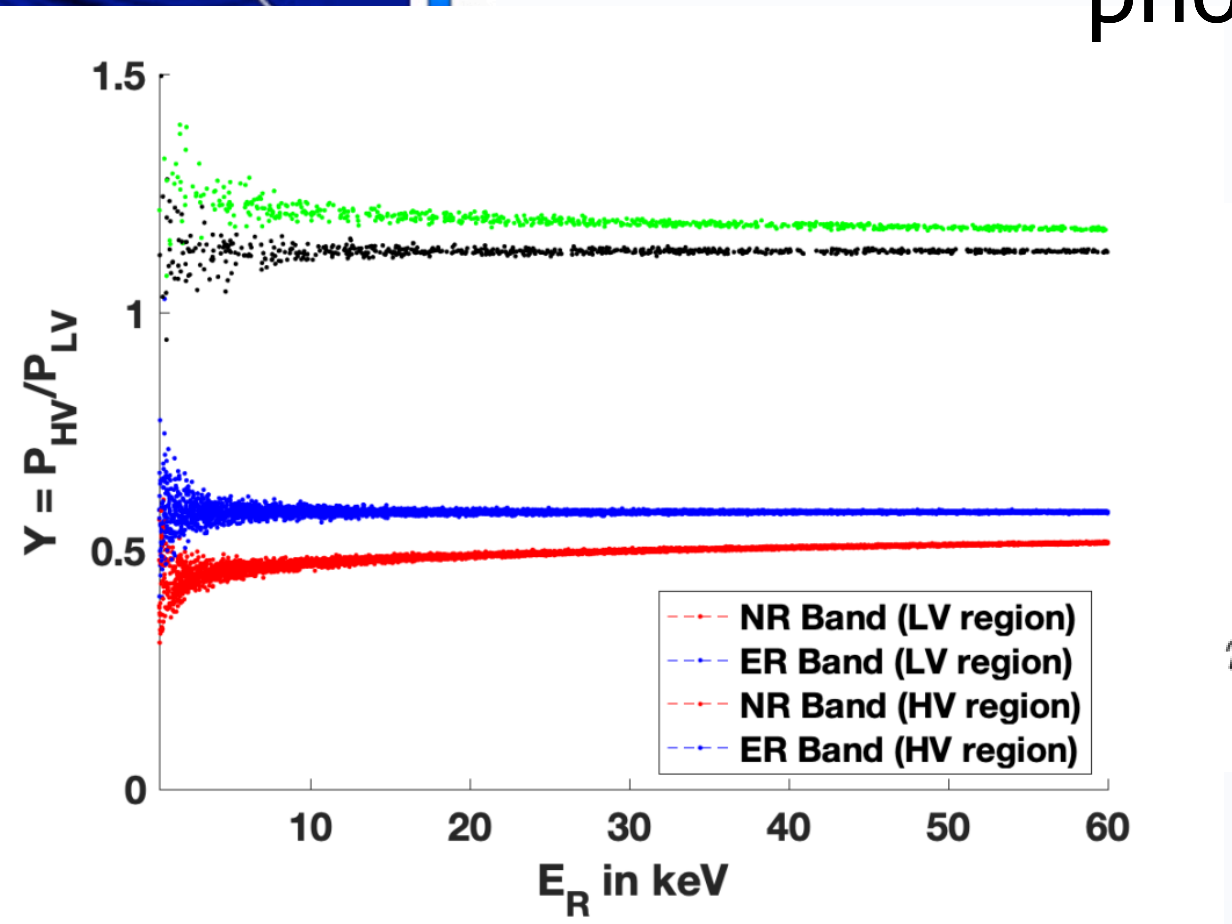
- Initial simulations (done)
- Fabricate and characterize a modest sized test detector (from existing materials)
- Ultimate goal, a large detector from USD crystal

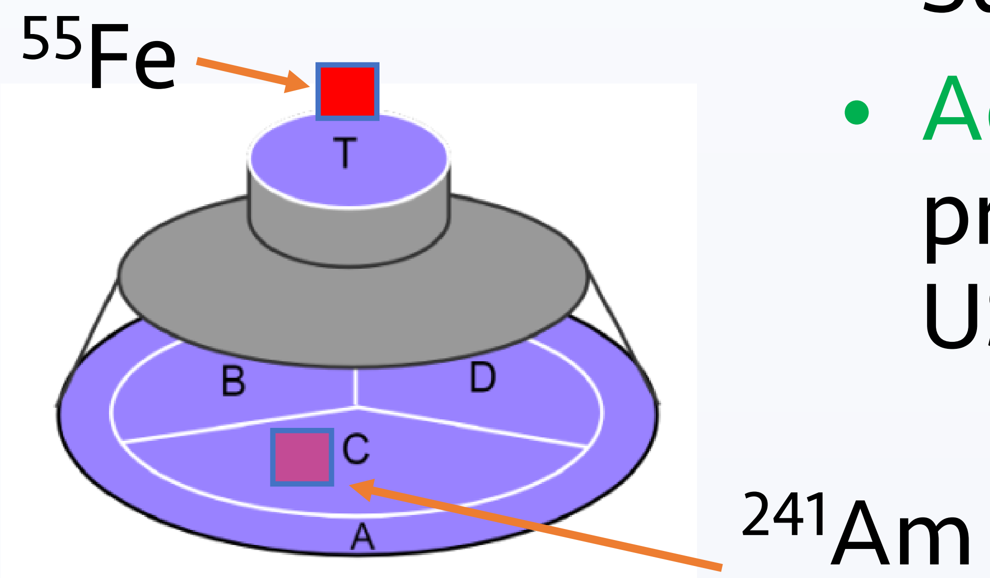


Emerging Detector Technology – Hybrid Detector









Phonon channel layout in the hybrid detector

- Hybrid Detector measures recoiling phonons in LV region and amplifies the charge signal by Luke-Neganov amplification in HV region
  - Avoids polluting the primary phonon signal with Luke phonons

$$\eta_{HL})E_R\frac{V_{HV}L}{\epsilon_{eh}}+\eta_{LH}E_R(1+\frac{V_{LV}L}{\epsilon_{eh}})]$$

$$\eta_{LH})E_R(1+\frac{V_{LV}L}{\epsilon_{eh}})+\eta_{HL}E_R\frac{V_{HV}L}{\epsilon_{eh}}]$$

- Successfully Demonstrated with Si
- Advanced Goals: Demonstrate same principle and benefits with Ge from USD

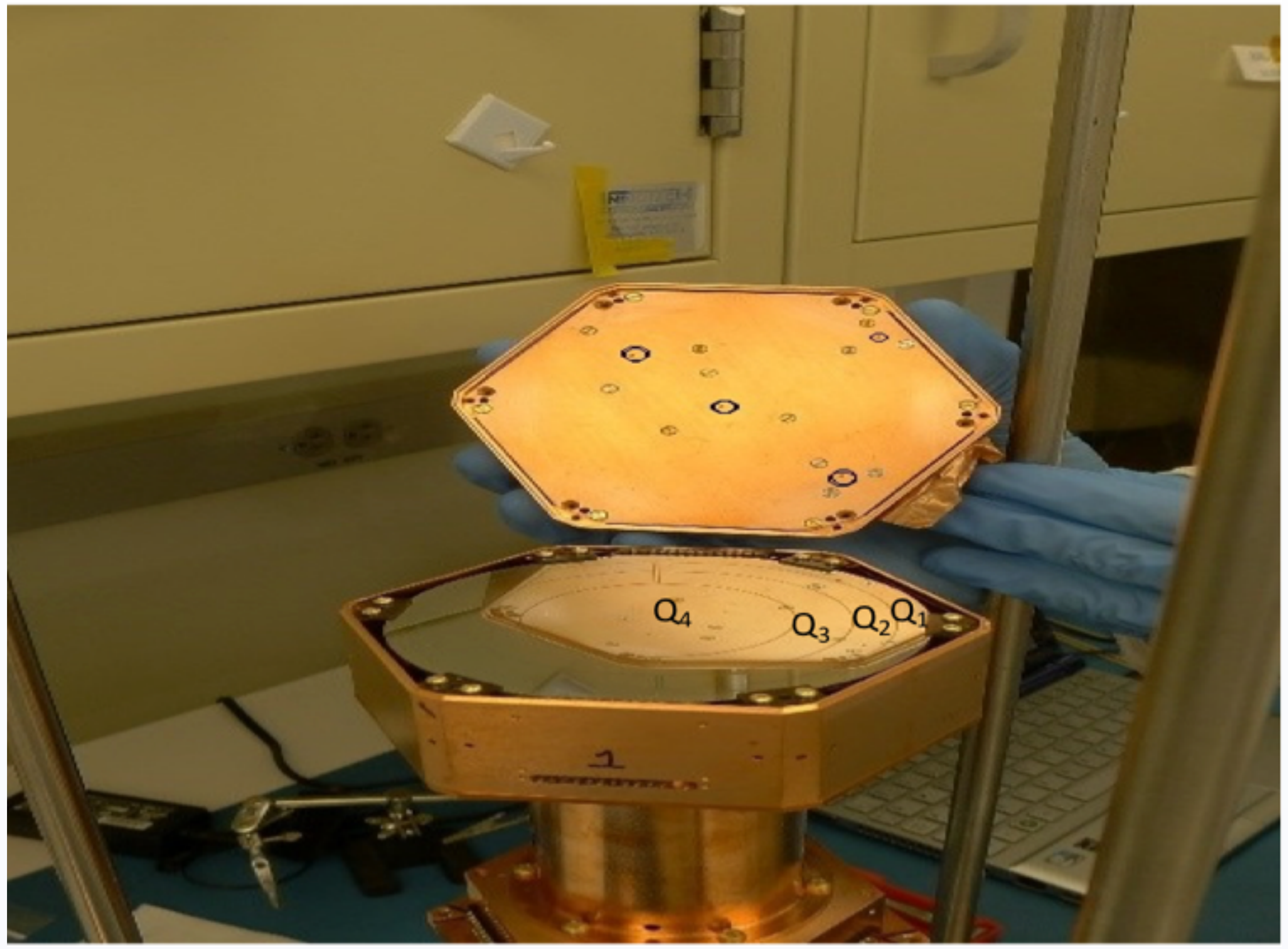
Participants:
TAMU

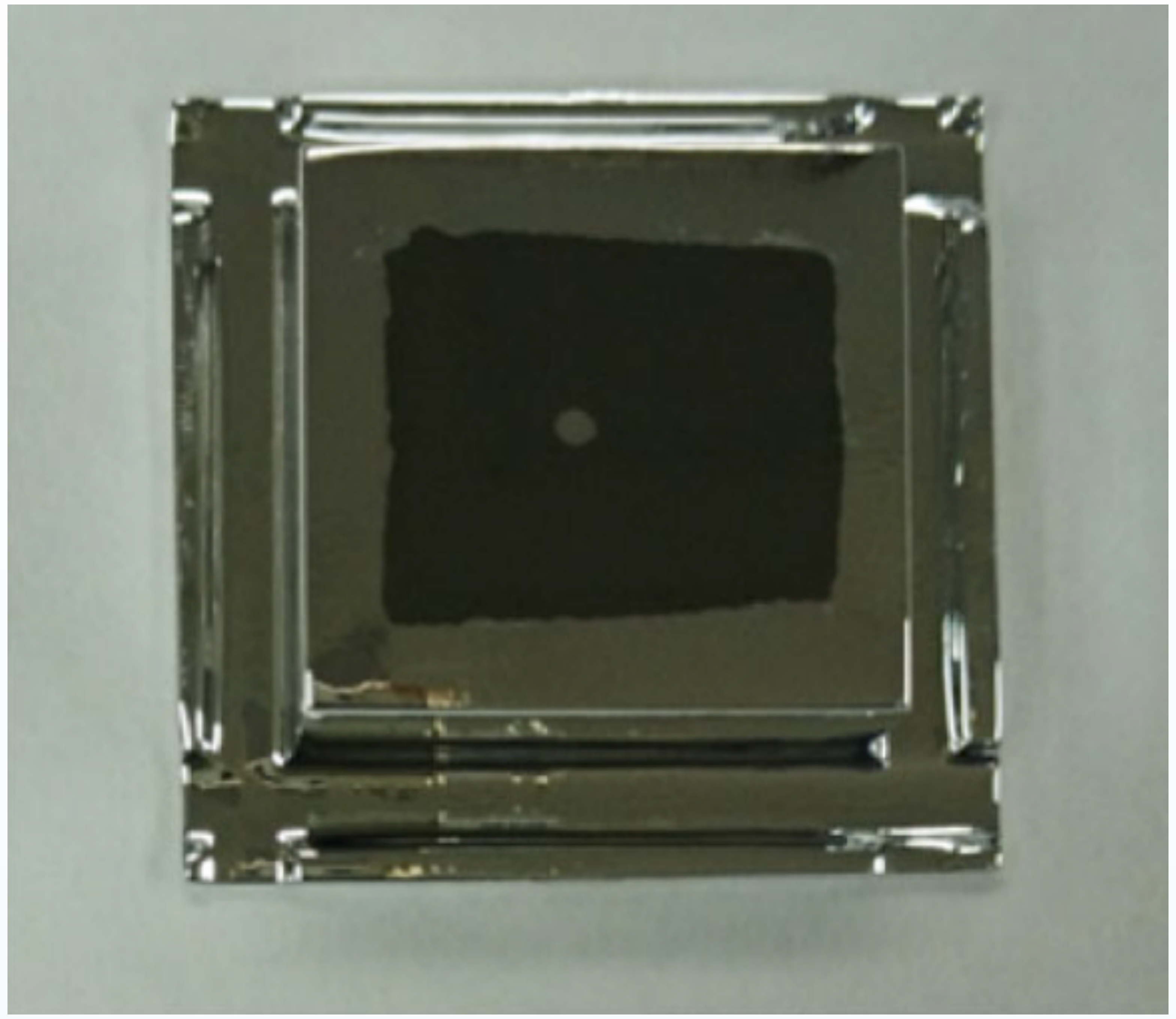
Students:

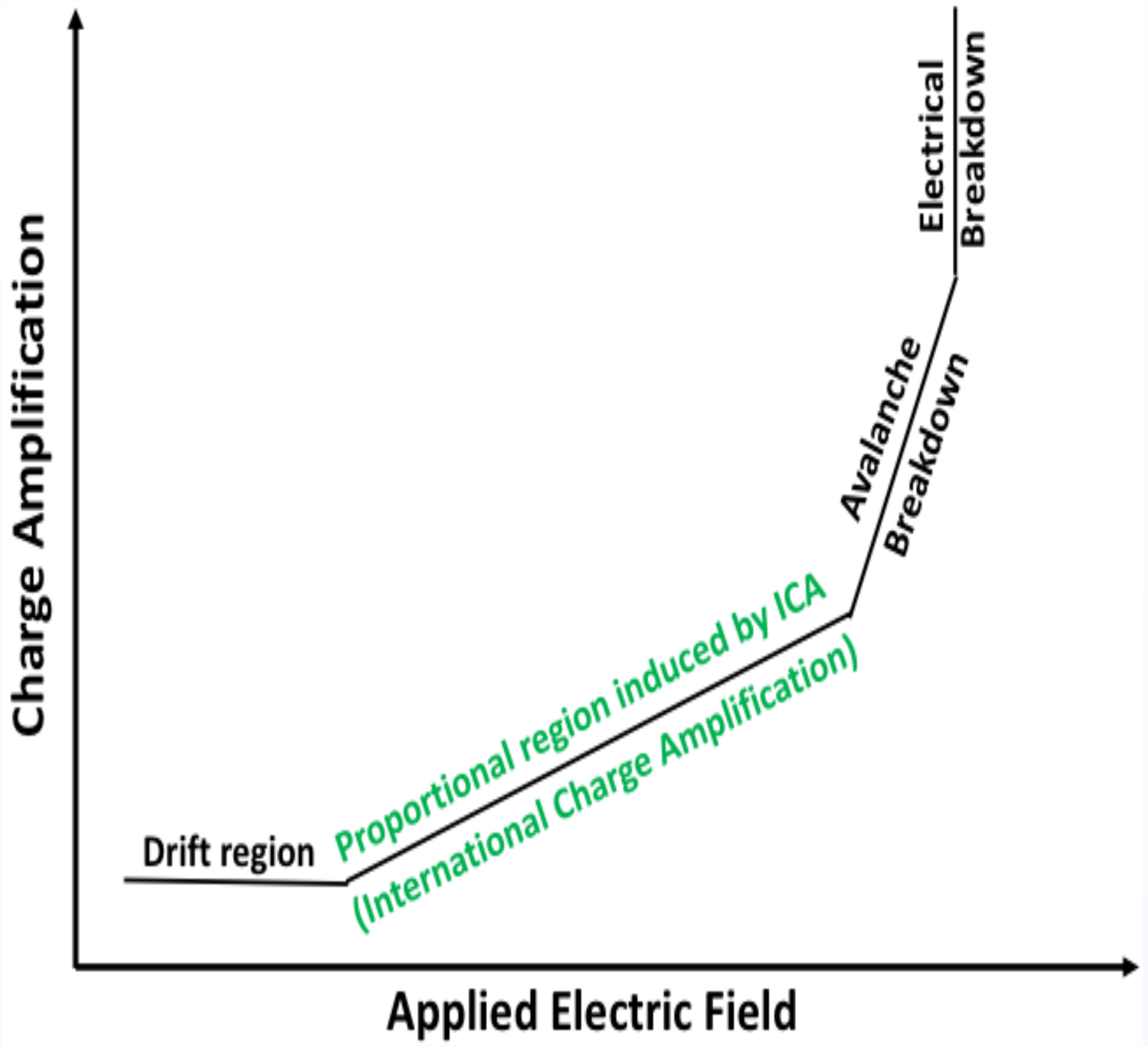
Himangshu Neog
William Baker
Abhiram Dinavahi
Shahriar Esmaeili

Faculty
Nader Mirabolfathi
Rusty Harris

Low Energy Threshold Detector





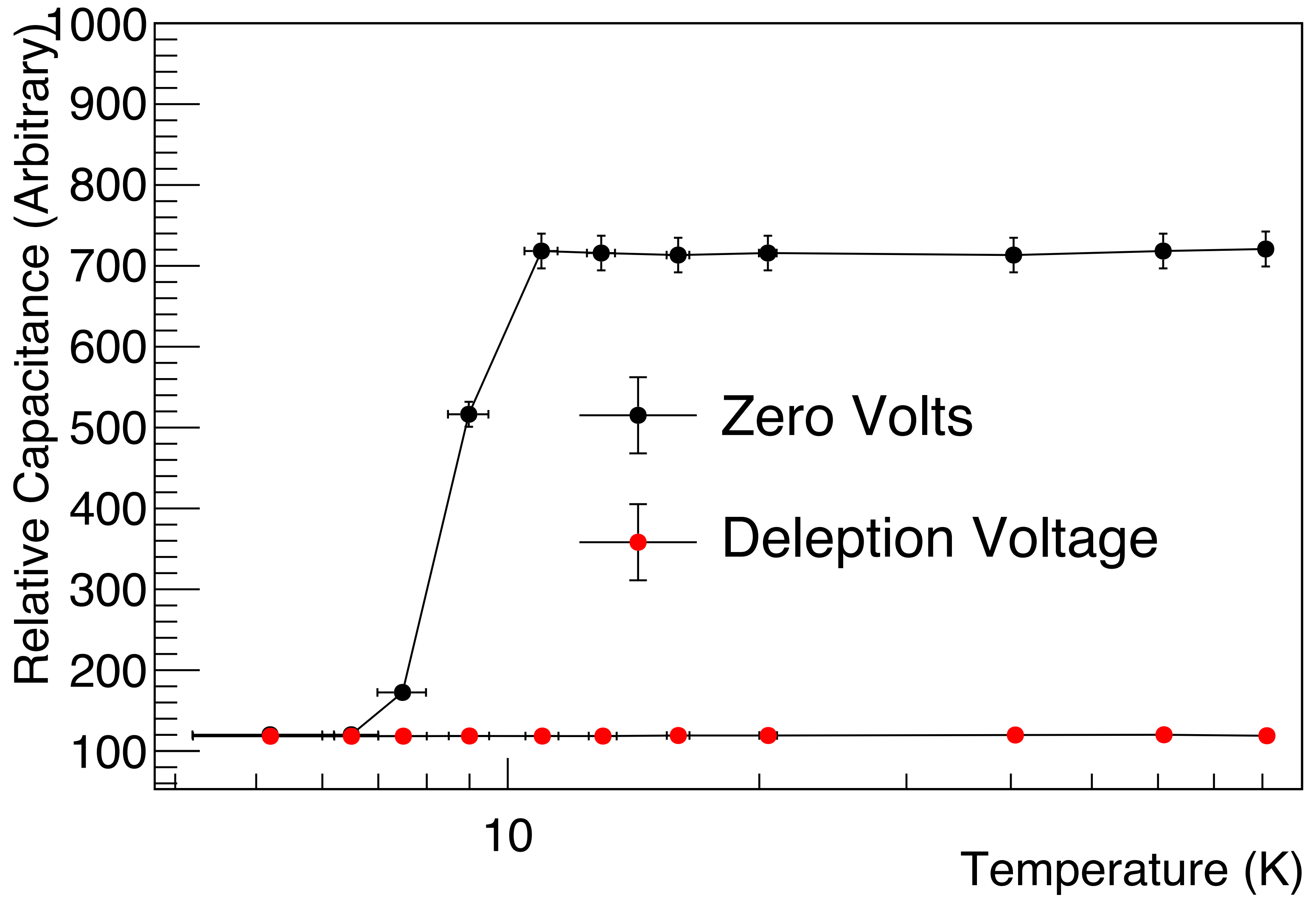


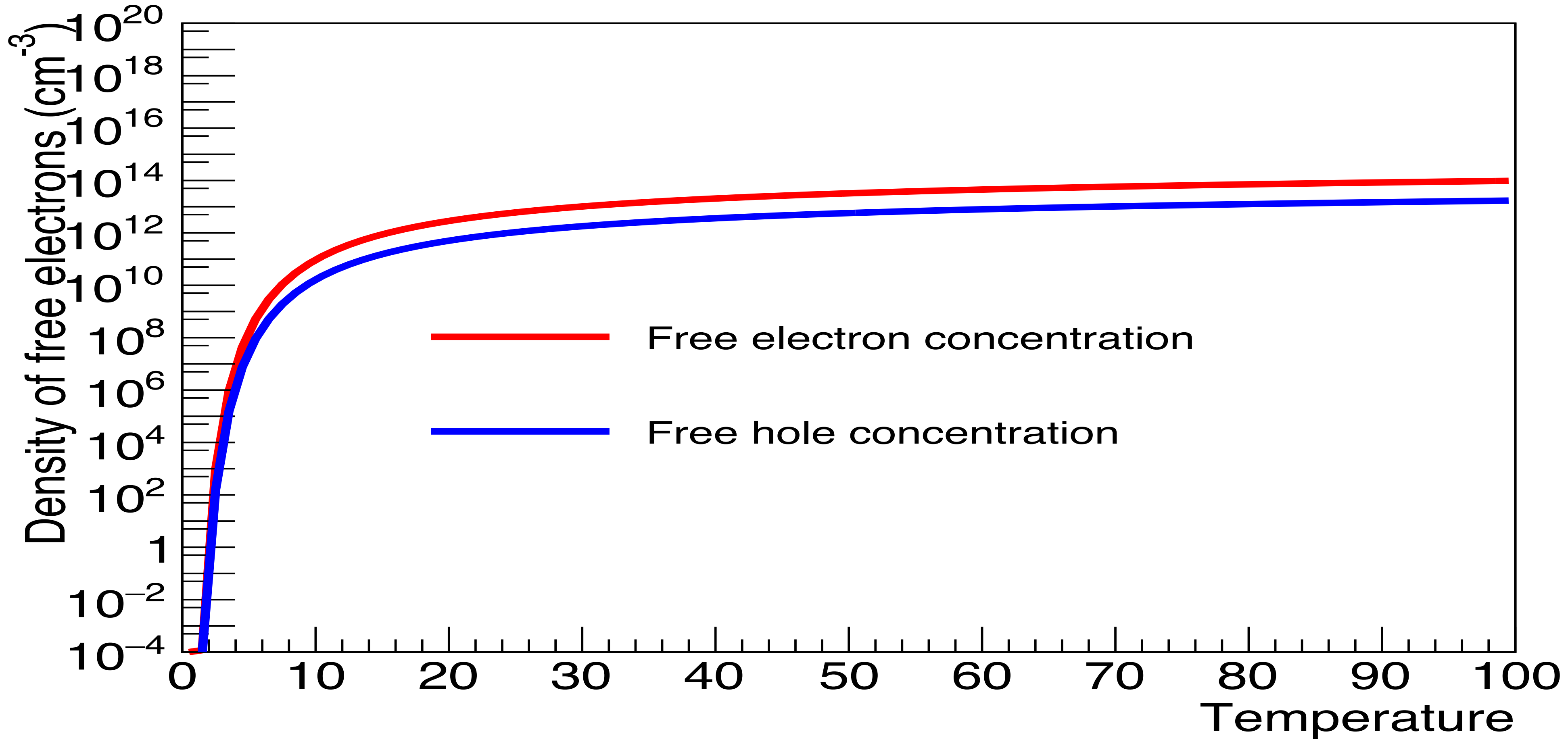
Phonon Amplification: SuperCDMS-style detectors
Threshold: proved down to ~56 eV
Citation: Phys. Rev. D 99, 062001 (2019)

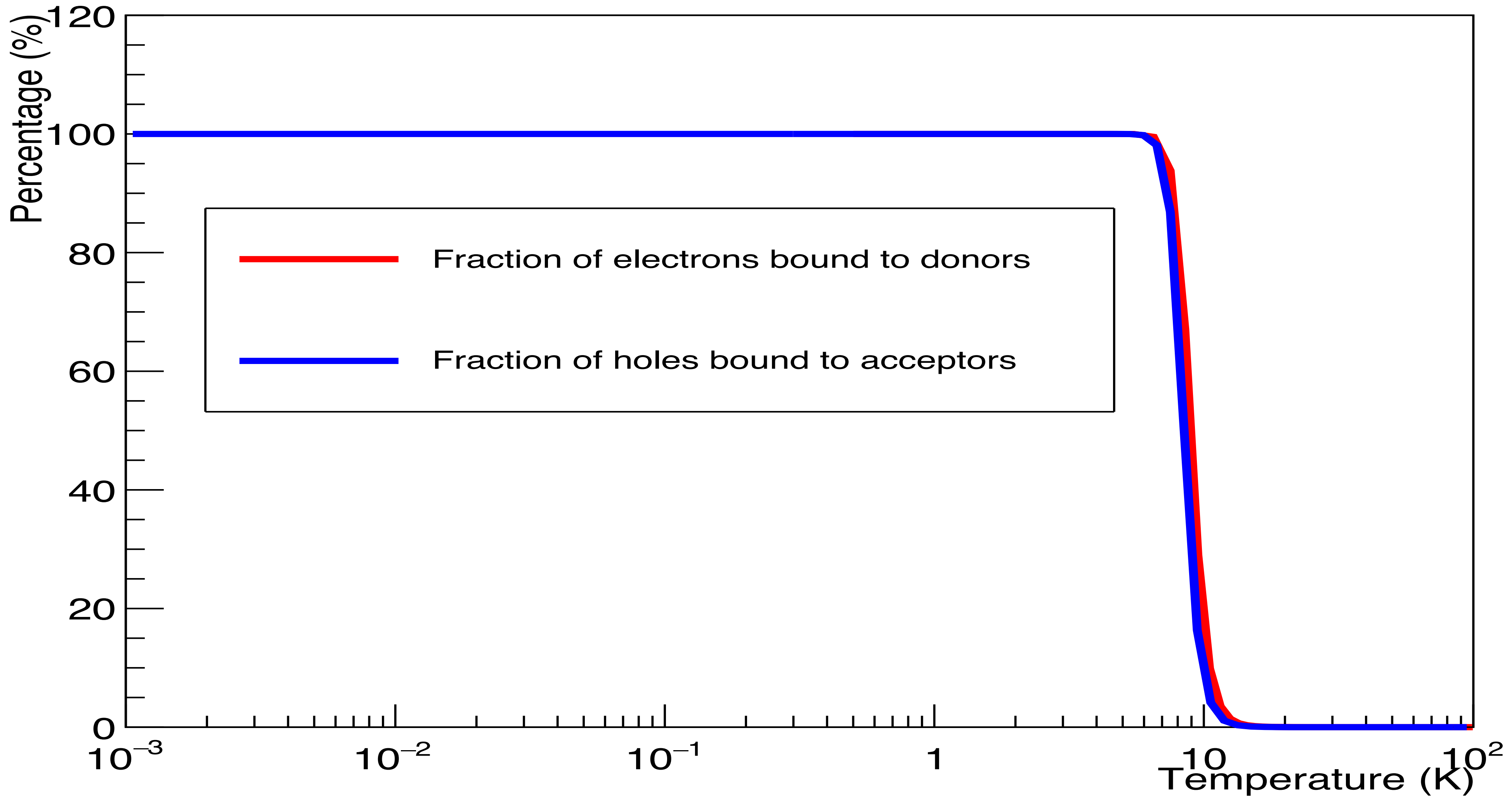
Internal Charge Amplification: GeIA
Threshold: ~0.01 eV
Citation: Eur. Phys. J. C 82 (2022) 3, 203.

Challenge: Electrical prevention structure

Behavior at Low Temperature





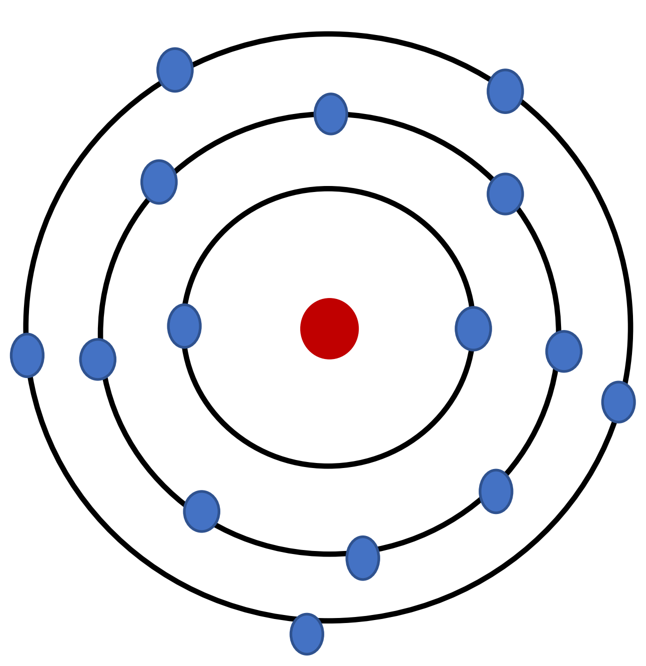


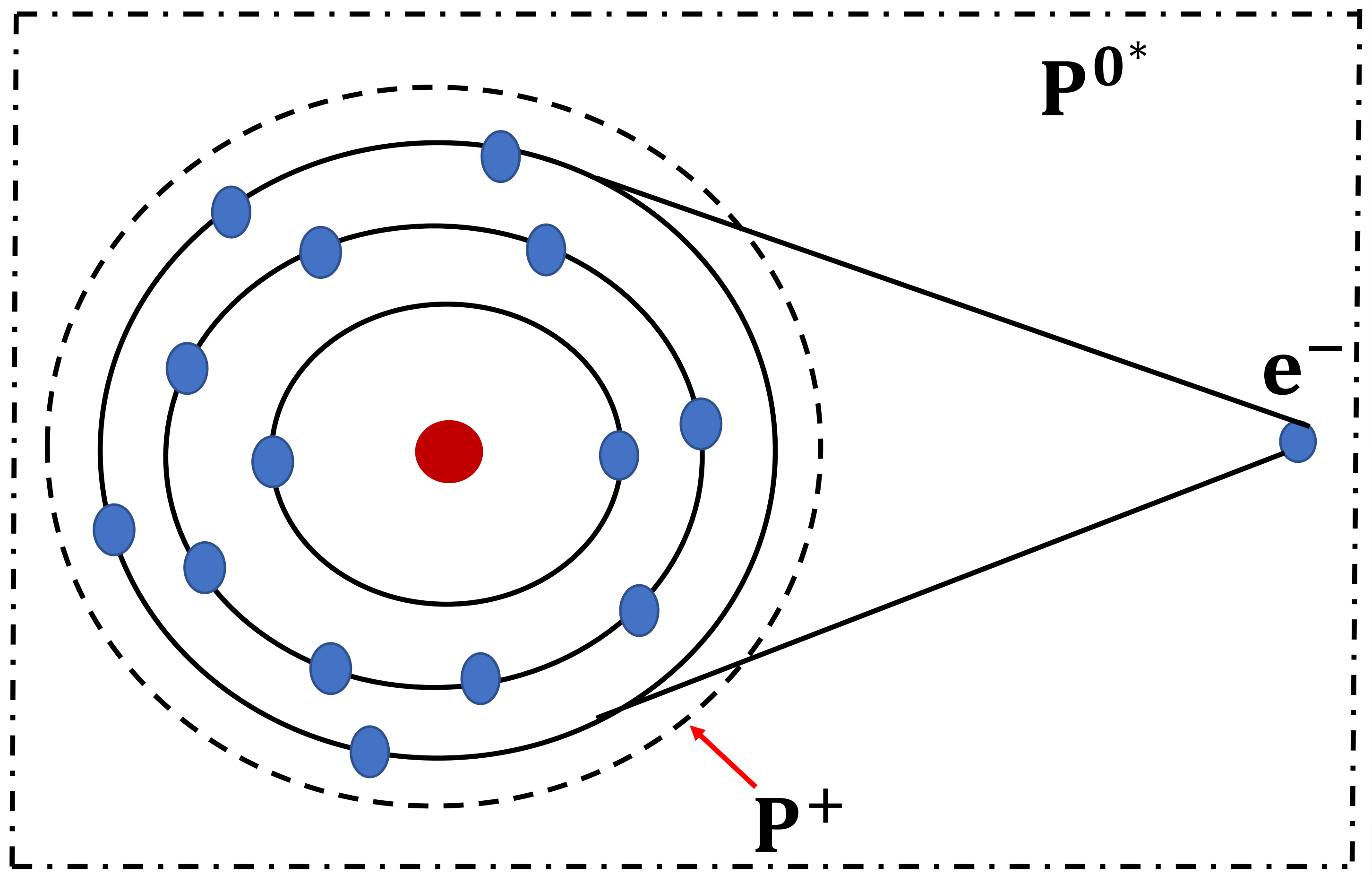
Key Points:

(1) Temperature below 6.5 K, impurity atoms freeze-out from the conduction band Or valance band into localized states – dipole states

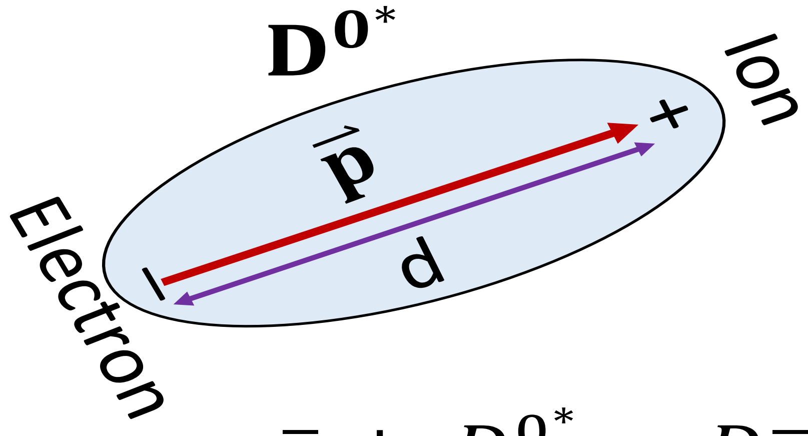
(2) No free charge carriers when temperature is below 4 K.

Formation of Dipole States in n-Type Ge



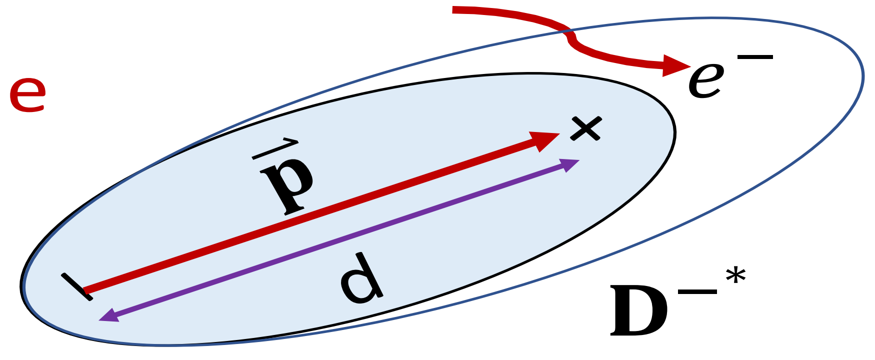


Formation of a dipole



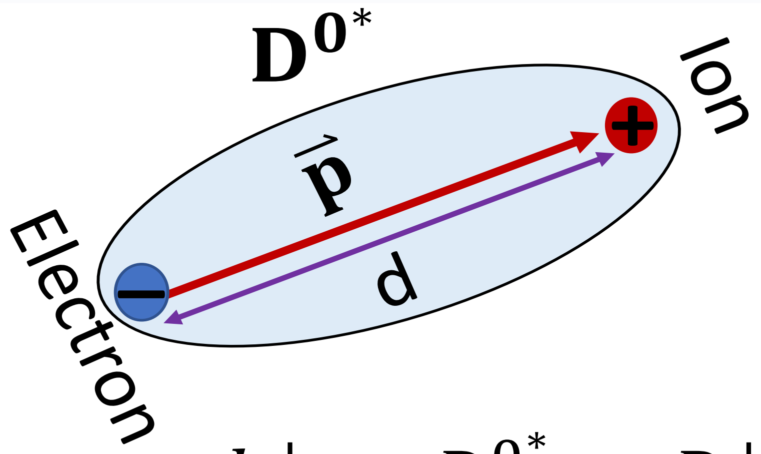
$$e^- + D^{0^*} \rightarrow D^{-^*}$$

Trapped by electric dipole



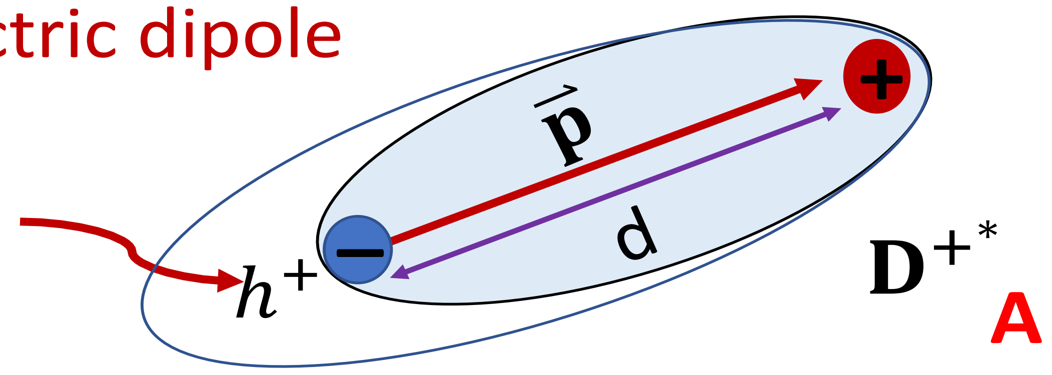
Phonon Ionization of D^{-^*} $\Delta E_{phonon} + D^{-^*} \rightarrow D^{0^*} + e^-$

Formation of a dipole



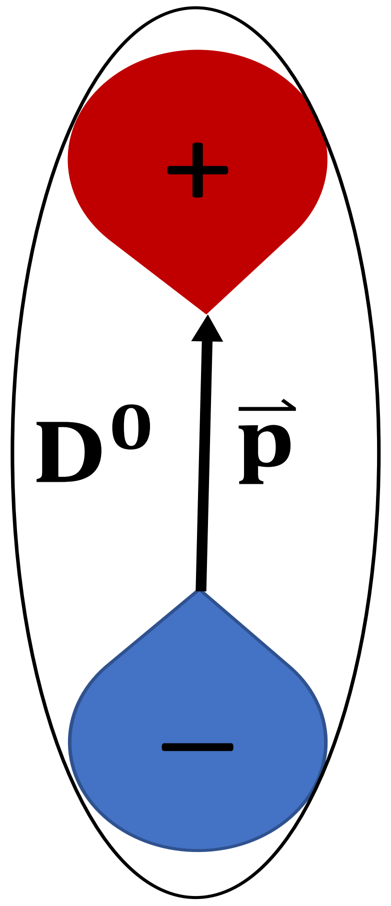
$$h^+ + D^{0^*} \rightarrow D^{+^*}$$

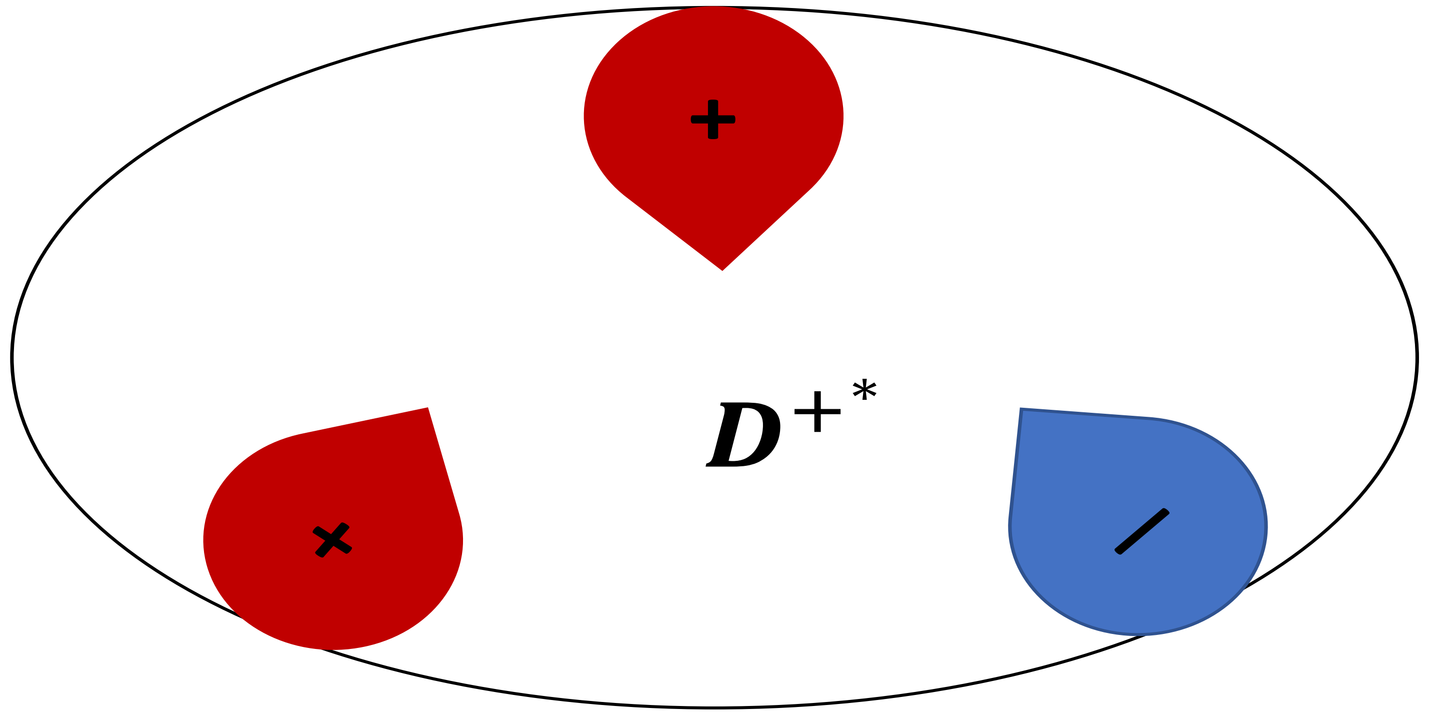
Trapped by electric dipole



A cluster charge state

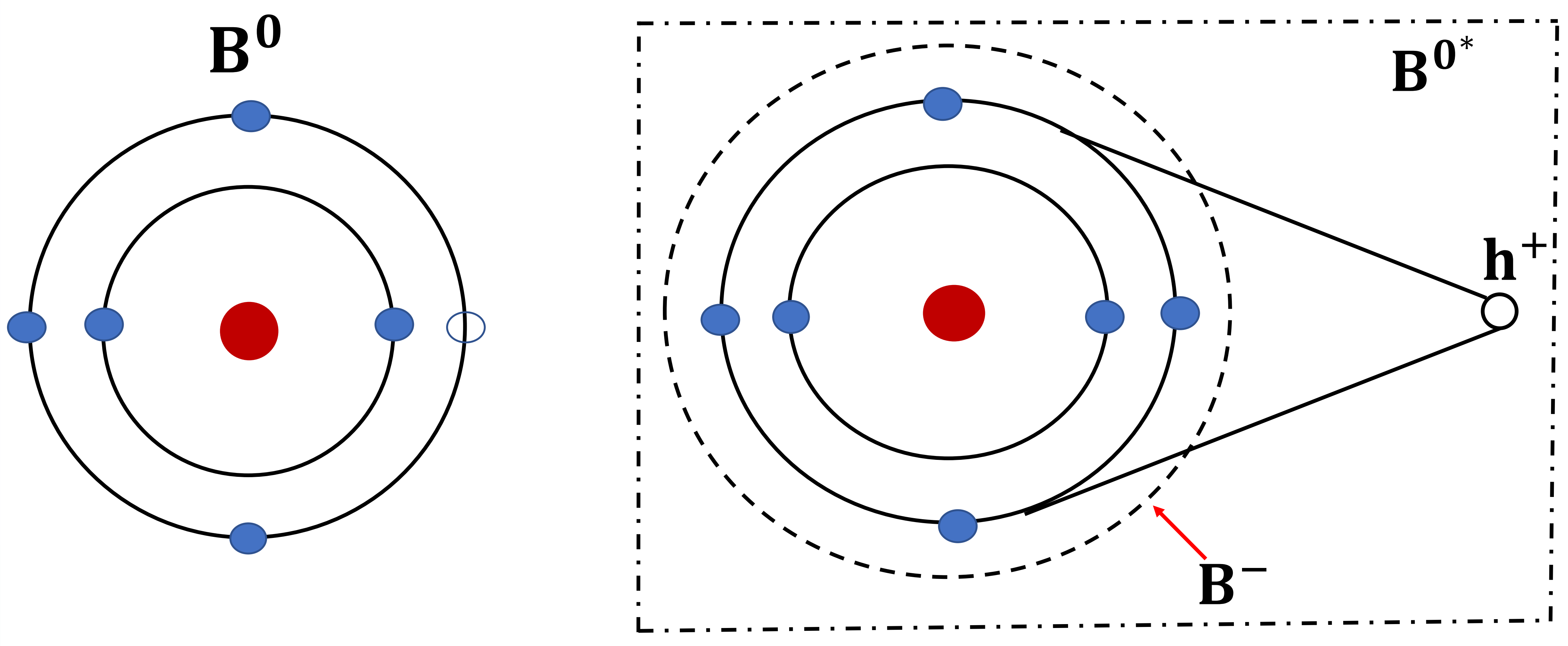
Phonon Ionization of D^{+^*} $\Delta E_{phonon} + D^{+^*} \rightarrow D^0 + h^+$

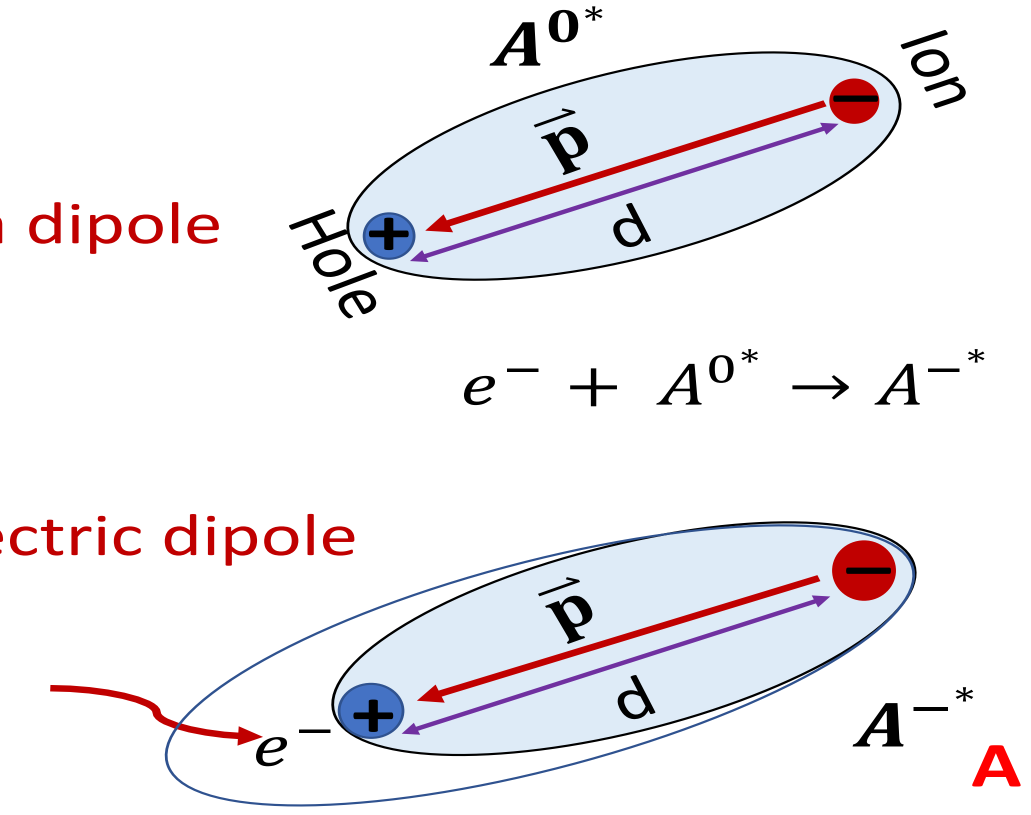




A cluster charge state

Formation of Dipole States in p-Type Ge





Formation of a dipole

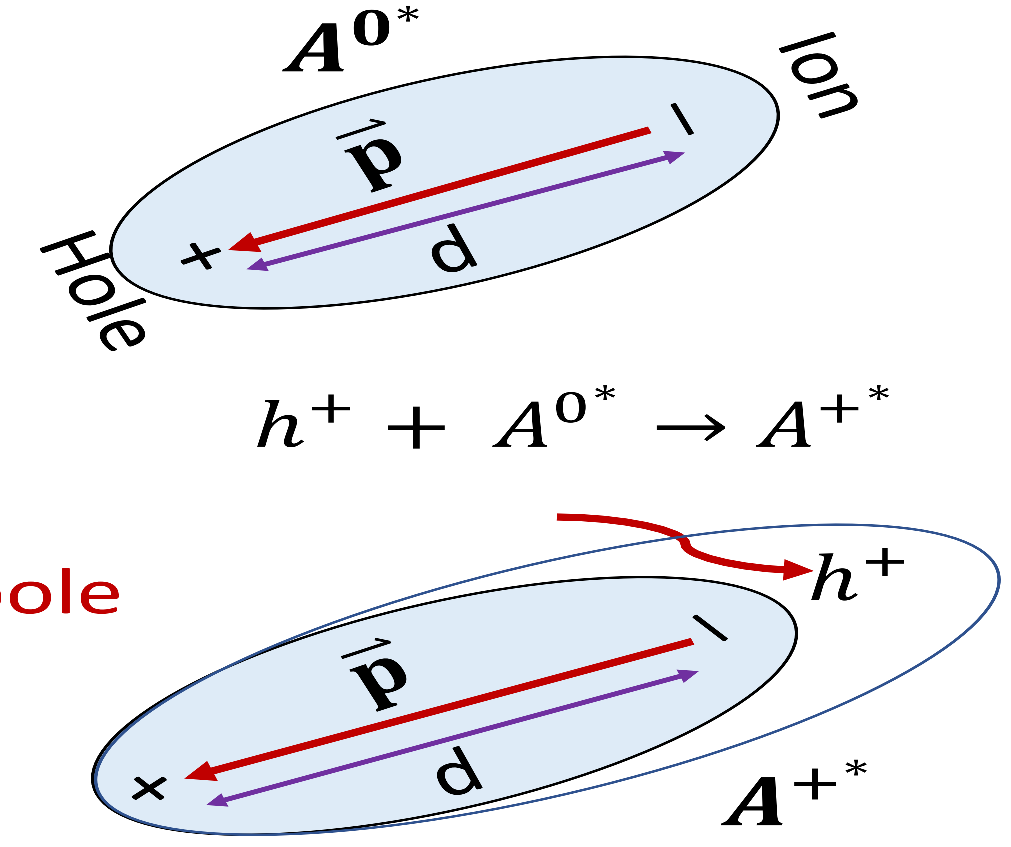
$e^- + A^{0^*} \to A^{-^*}$

Trapped by electric dipole

A cluster charge state

Phonon Ionization of A^{-^*} $\Delta E_{phonon} + A^{-^*} \to A^{0^*} + e^-$

Impact Ionization of A^{-^*} $h^+ + A^{-^*} \to A^- + e^- + 2h^+$

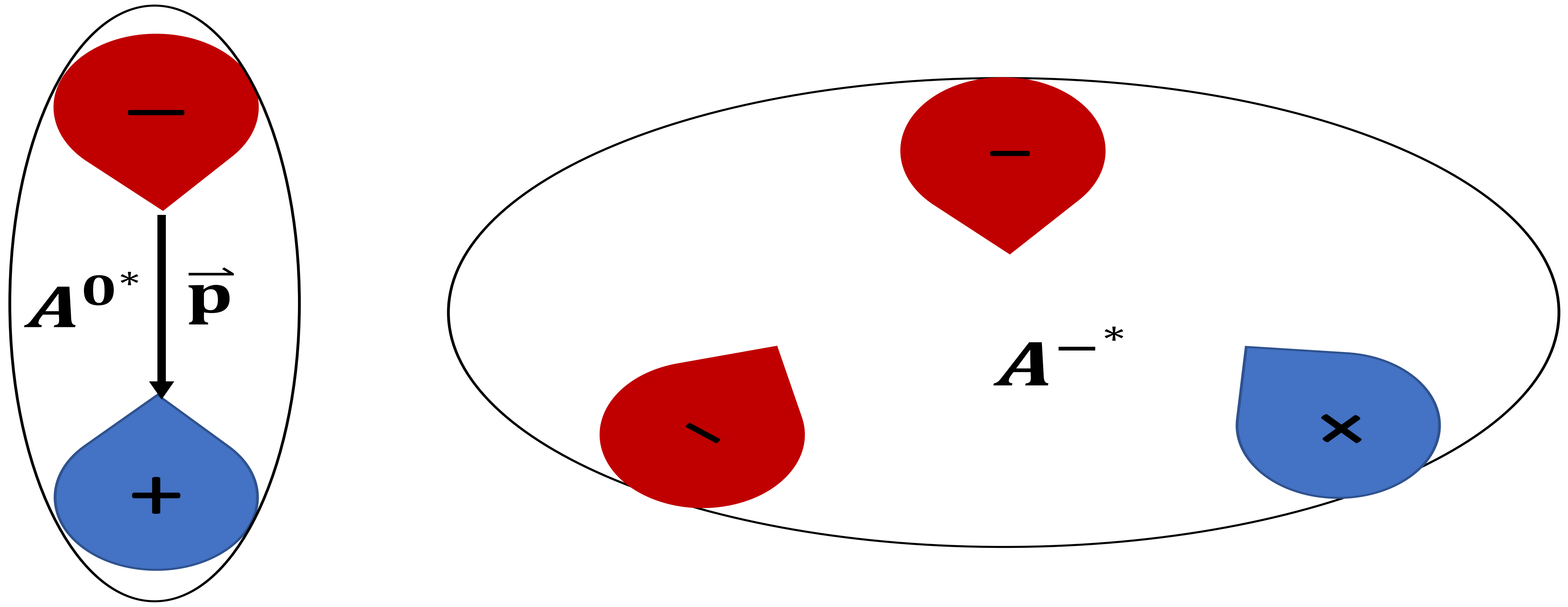


Formation of a dipole

$h^+ + A^{0^*} \to A^{+^*}$

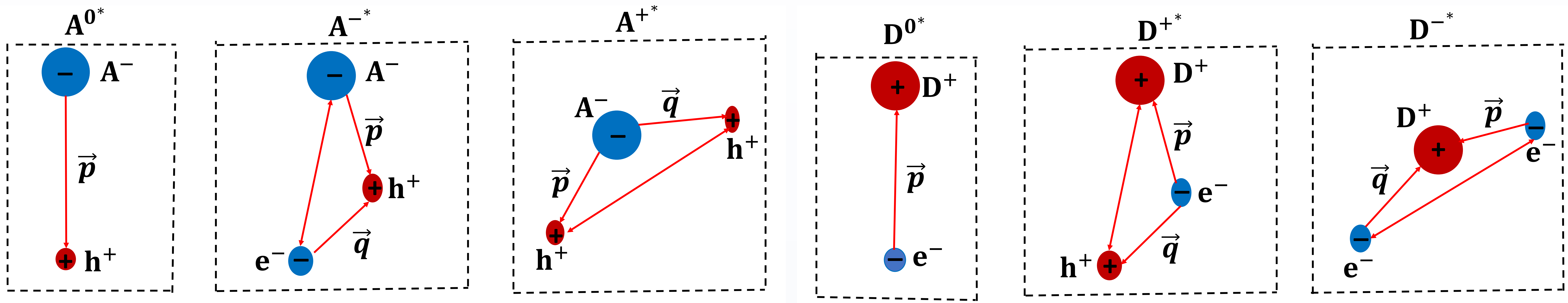
Trapped by electric dipole

Phonon Ionization of A^{+^*} $\Delta E_{phonon} + A^{+^*} \to A^{0^*} + h^+$



A cluster charge state

Binding Energy of Dipole States



A dipole state | A cluster dipole state | A cluster dipole state | A dipole state | A cluster dipole state | A cluster dipole state

Binding energy: ~ 8 meV
arXiv: 2303.16807

Binding energy: ~ 8 meV
arXiv: 2302.08414V1

PIRE GEMADARC

Summary and Conclusion

What we aim to achieve:

- **Materials Advancement**
  - Increase the production of zone-refined ingots per run from 70% to 80%
  - Increase the production of large-size HPGe crystals (2– 3 kg) per growth
  - Improve the accuracy of characterizing HPGe crystals with the Hall Effect system
- **Novel Detector Development**
  - Develop GeIA technology
  - Develop SuperCDMS-style detectors
  - Develop LEGEND R&D detectors for LEGEND
- **Improvement of Detector Performance**
  - Development of new testing technology
  - Applying machine learning for pulse shape analysis

Thank you and questions?

New and exciting:

- **GeIA technology**
  - Charge amplification factor of ~1000
  - Single electron-hole pair sensitivity
  - Impact low-mass dark matter searches
- **Contact Free technology**
  - S/N ratio increase without breakdown
  - Without breeding leakage current
  - Impact Super-CDMS experiment
- **Ring Contact technology**
  - Decrease background per detector
  - Impact LEGEND ton-scale experiment for $0\nu\beta\beta$ experiment
- **Hybrid Detectors**
  - discrimination between electron and nuclear recoils with phonon-only sensors
  - potential for low threshold dark matter search