

G4CMP Modeling of Athermal Phonon Transport in Quantum-Acoustic Detectors

Ziyu Cai

Rakshya Khatiwada, Ryan Edward Linehan, Israel Hernandez

zca117@hawk.illinoistech.edu

Illinois Institute of Technology, Physics Department

CPAD 2026

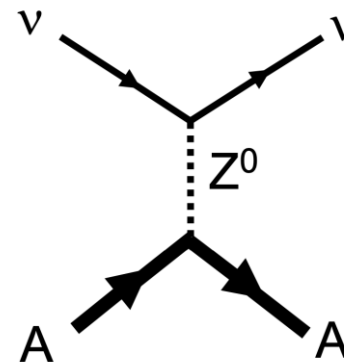
Motivation

■ Goals:

- ❖ Detect neutrinos: **Coherent elastic neutrino–nucleus scattering (CEvNS).**
- ❖ Develop a sensitive quantum acoustic (QA) detector.

■ CEvNS:

$$\nu + A \rightarrow A + \nu$$



- ❖ Targeting MeV-scale neutrinos.
- ❖ Cross section $\sigma \propto N^2$, where N is the number of neutrons.
- ❖ For recoil energy at the sub-eV scale → requires low-energy threshold detectors.

■ We want to understand:

- ❖ Phonon transport physics & quasiparticle (QP) dynamics.
- ❖ Geometry & material properties' effects on phonon collection efficiency (PCE).

CEvNS nuclear recoil

Energy deposited in absorber



Athermal phonons

Energy transport in the detector



Quantum acoustic sensing

Acoustic mode coupling and qubit sensing

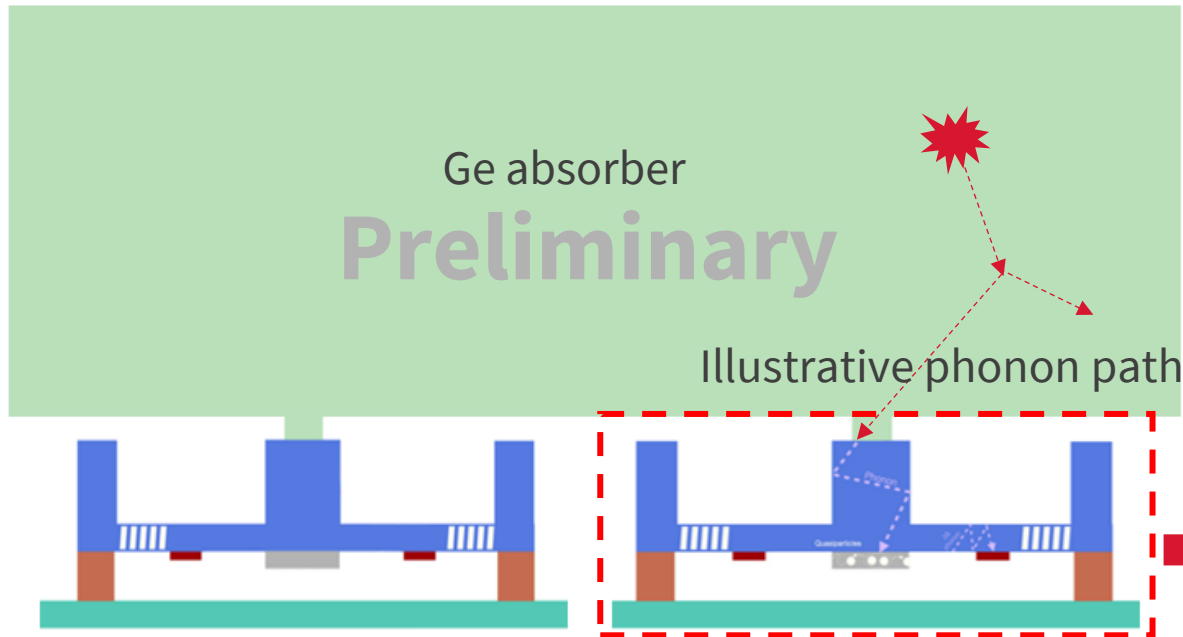
Collaborative work among Institutions: UChicago; Fermilab; IIT; Northwestern; UC San Diego

Quantum Acoustic Detector Design

Detector design geometries and functions:

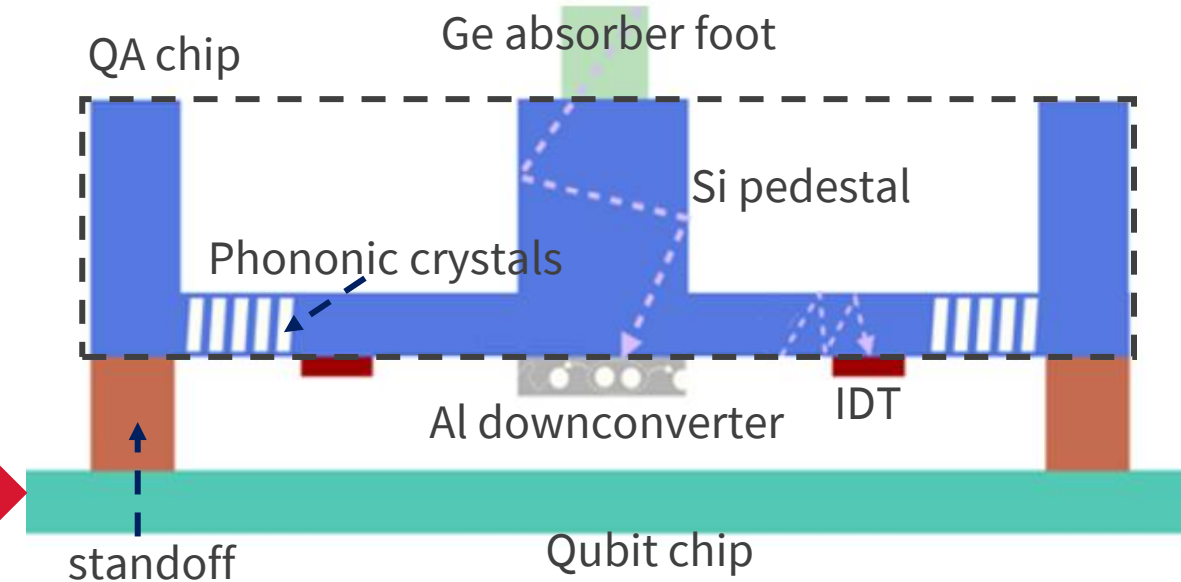
- **Ge absorber:** CEvNS target.
- **Ge absorber foot:** transport phonons to the QA chip.
- **Al Downconverter:** phonon-QP energy conversion.
- **QA chip:** phonon transport.
- **Interdigital transducers (IDTs):** piezoelectric coupling to phonons.

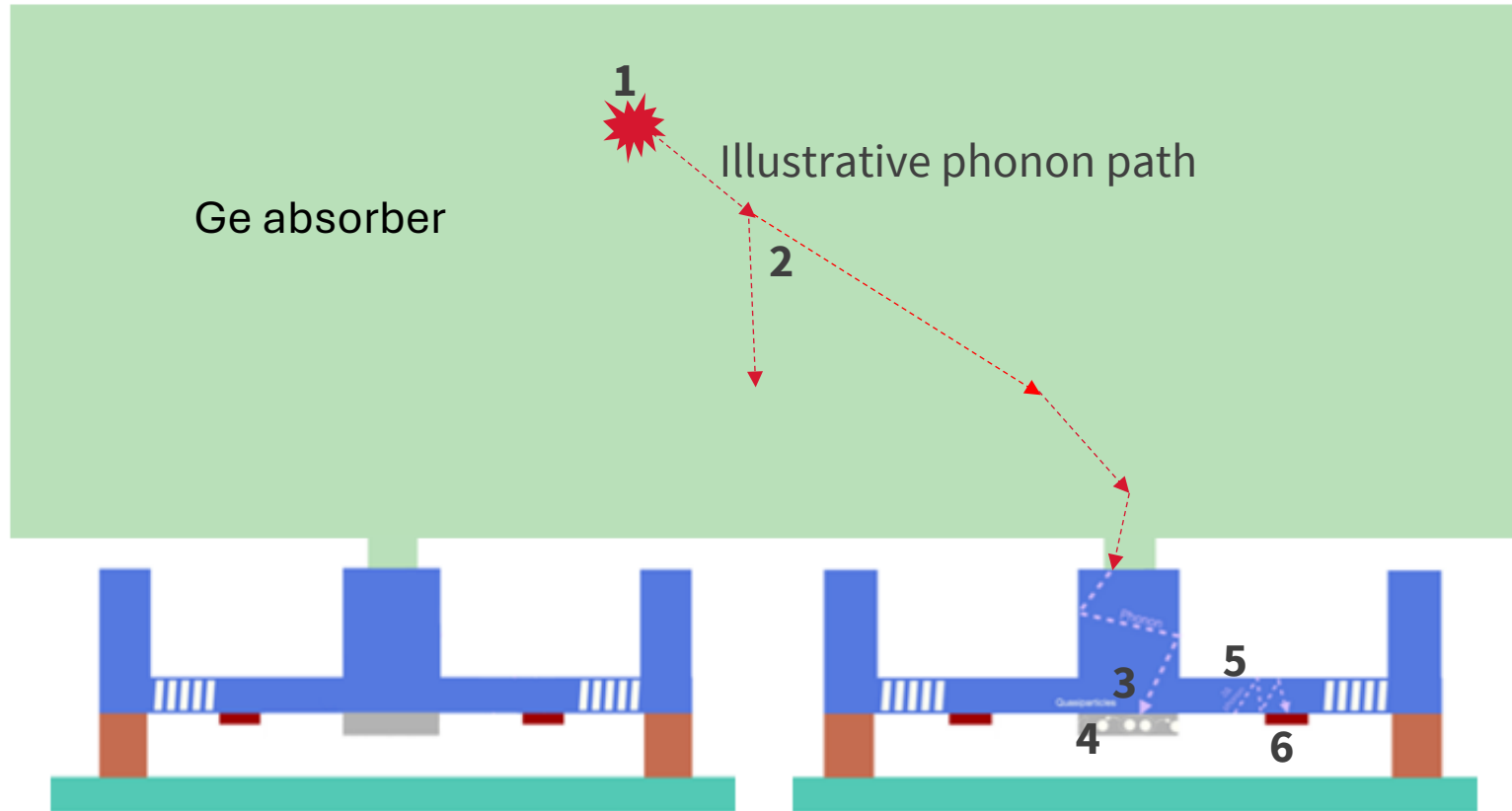
Detector overview(side view)



Detector concept and design: Andrew Cleland and collaborators

Absorber foot (side view)



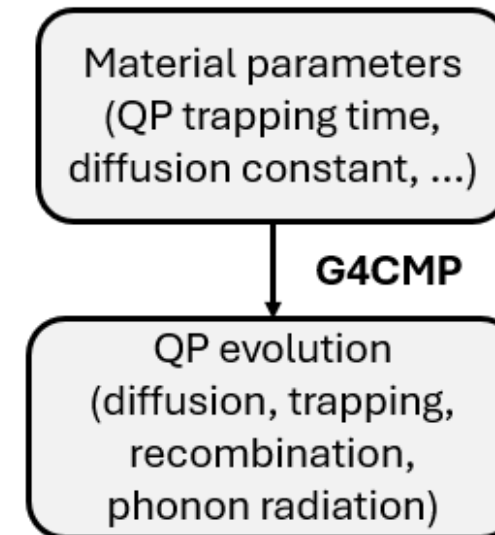
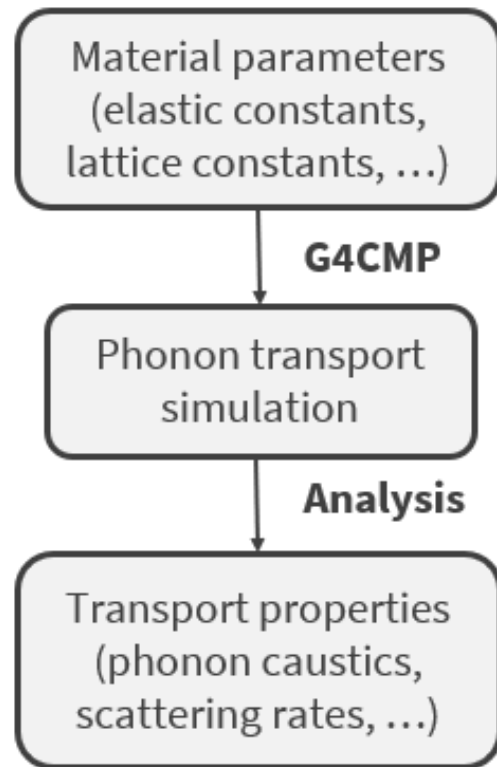


In the geometry:

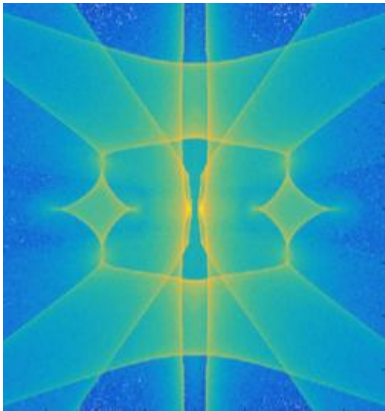
1. CEvNS nuclear recoil
2. Phonon downconversion & transport
3. Pair breaking → QPs
4. QP relaxation & recombination → secondary phonons
5. Phonon propagation
6. Piezoelectric coupling to IDTs

- We use the Geant4 Condensed Matter Physics (G4CMP) simulation framework to model phonon transport and QP processes in the detector.

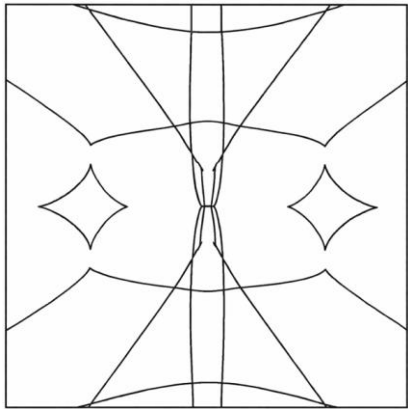
- **G4CMP:** An open-source Monte Carlo toolkit that can simulate phonon and quasiparticle transport in crystals.
- Phonon transport modeling: (for TeO_2 and LiNbO_3)
- QP processes in superconducting film:



TeO₂ caustics (G4CMP)

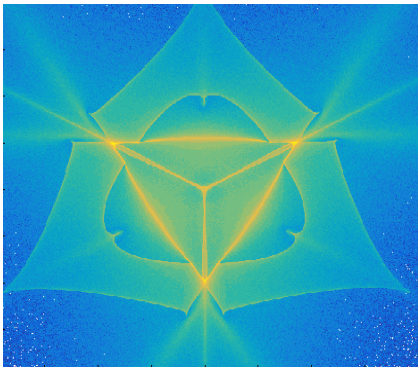


Outline of simulation result
by Hurley & Wolfe (1986)

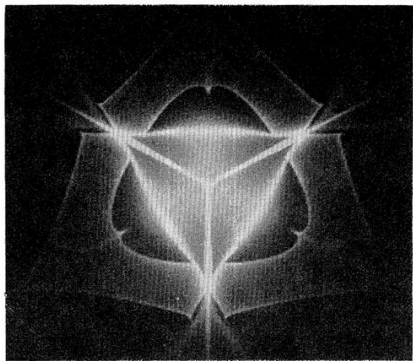


Hurley, D. C., & Wolfe, J. P.
Phys. Rev. B **33**, 4189–4195 (1986).

LiNbO₃ caustics (G4CMP)



Simulation result by Koos
and Wolfe (1984)



G. L. Koos and J. P. Wolfe, *Phys. Rev. B* **30**, 3470–3481 (1984)

Parameters	TeO ₂	LiNbO ₃
Γ_{anh}	1.63e+6 s ⁻¹	1.45e+6 s ⁻¹
Γ_{iso}	7.27e+6 s ⁻¹	1.007e+5 s ⁻¹
FDOS (L)	0.13	0.15
FDOS (TF)	0.32	0.34
FDOS (TS)	0.55	0.51

Γ_{anh} : Anharmonic downconversion rate; Γ_{iso} : Isotopic scattering rate;
FDOS: Fractional Density of States; L: Longitudinal phonon, TS/TF:
Slow/Fast transverse phonon

Conclusions:

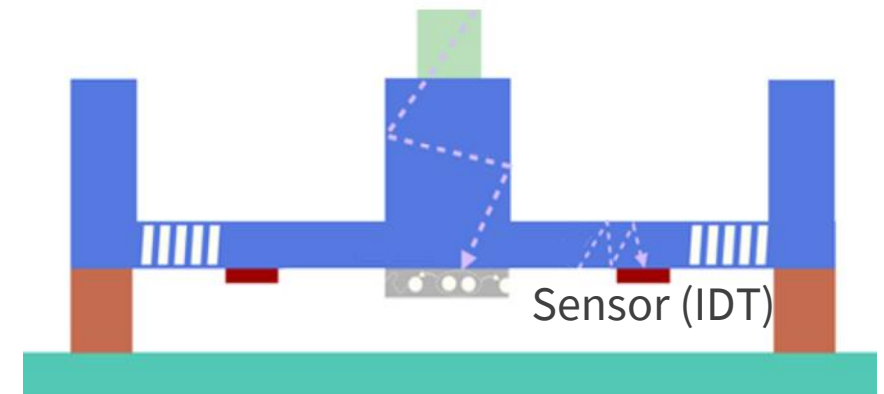
- TeO₂ and LiNbO₃ material properties implemented in G4CMP.
- Simulated phonon caustics show qualitative agreement with published results.

Aim: Investigate the effects of geometry designs and material parameters on phonon collection efficiency, further informing future detector design.

Idealized Phonon Collection Efficiency:
$$PCE = \frac{E_{\text{collected at sensors}}}{E_{\text{primary phonons}}} \times 100\%$$

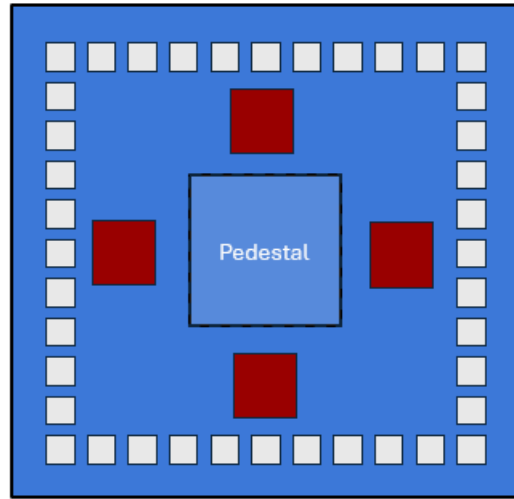
Model assumptions:

- phonon is fully absorbed in sensors;
- Acoustic modes and IDT coupling are not yet explicitly modeled (TBD);
- 1000 primaries $\times$ 4.14 meV | crystal orientation [1,0,0] | bounce limit: 10^9 | QP trapping time τ_{QP} : 1 ms;
- Material-material: 100% phonon transmission;
- Material-vacuum: 100% phonon reflection;
- Material-sensors & material-standoffs: 100% phonon absorption.

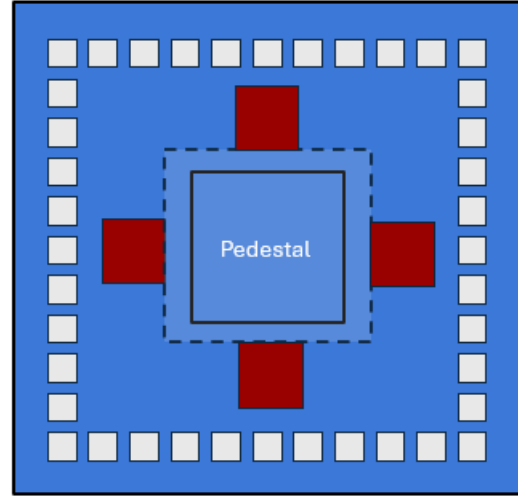


Absorber-foot Simulations: PCE for AI Geometries

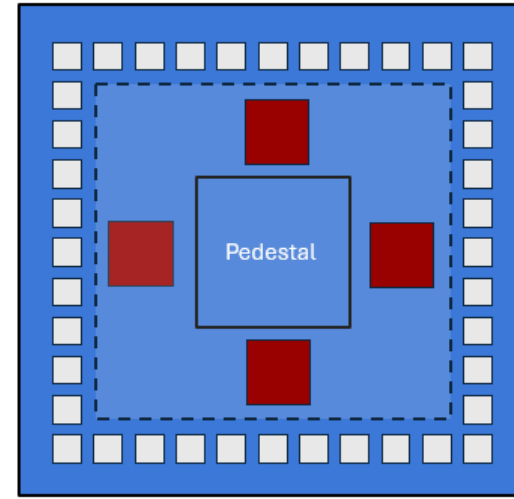
Motivation: Explore PCE changes by extending the AI area towards the sensors.



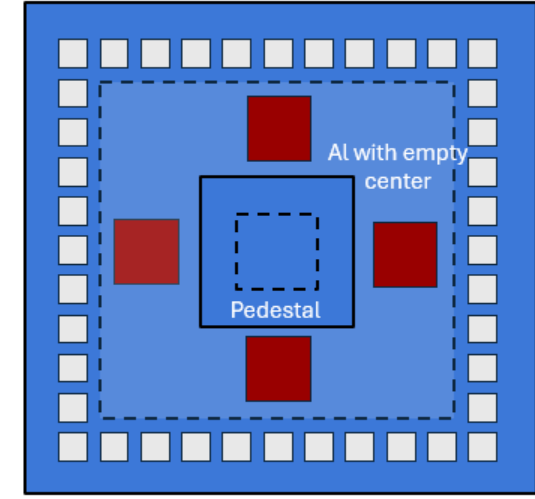
①: Pedestal AI



②: Larger AI



③: Largest AI



④: Largest-empty center AI

Geometry design	AI area (mm ²)	PCE (%)
①	4.00	30.60
②	6.62	30.10
③	17.15	29.98
④	16.15	29.98

Observations:

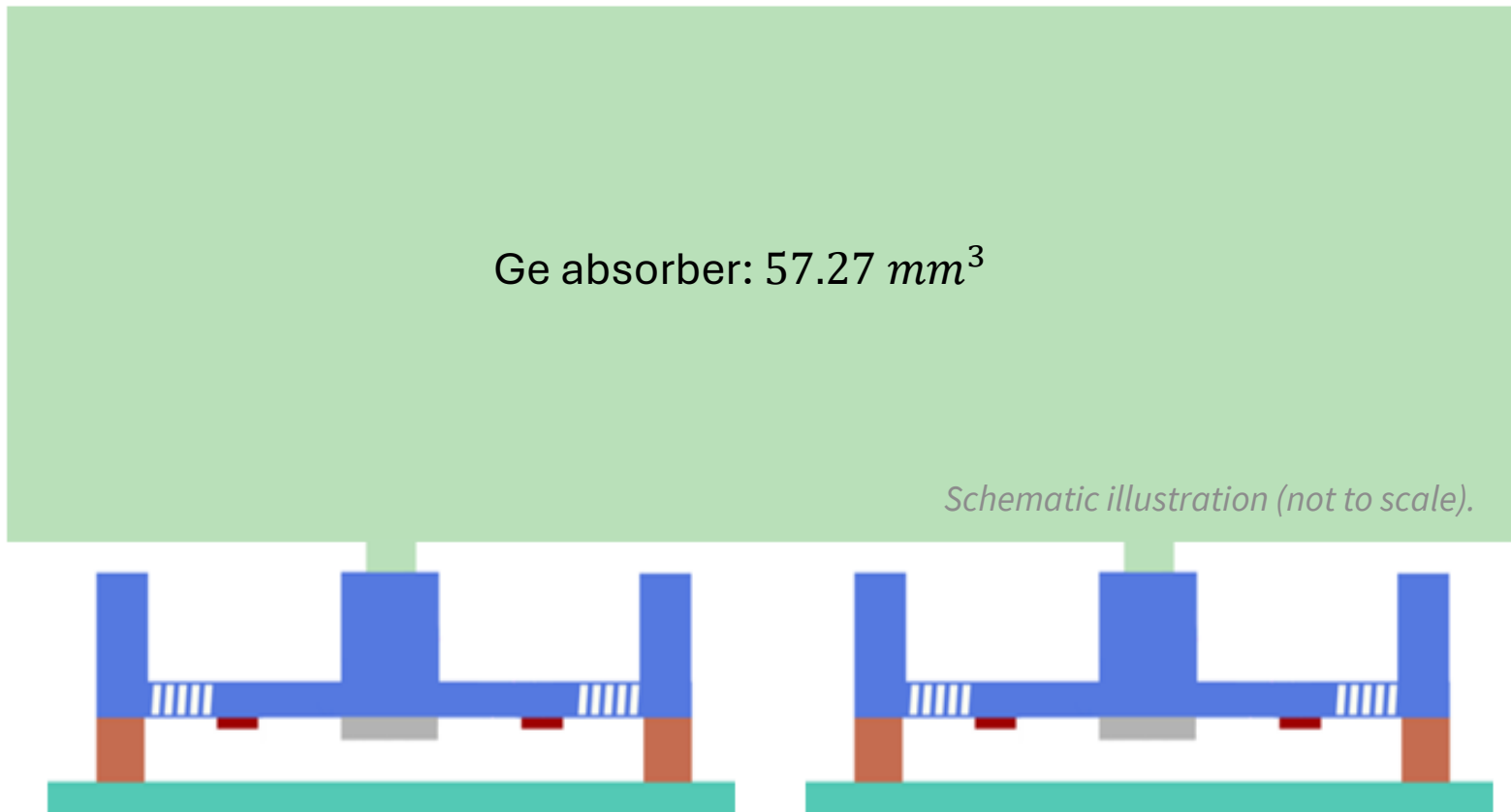
- PCE remains around 30% across the 4 AI designs.
- No clear dependence on AI area is shown by PCE.

PCE for Full Geometry

Simulation Setup:

- 10 primaries $\times$ 4.14 meV | crystal orientation [1,0,0] | bounce limit: 10^9 | ideal interfaces | QP trapping time τ_{QP} : 1 ms.

Motivation: Evaluate PCE in the full detector geometry (Ge absorber added).



Preliminary Result:

$$\text{PCE} = 33.86\%$$

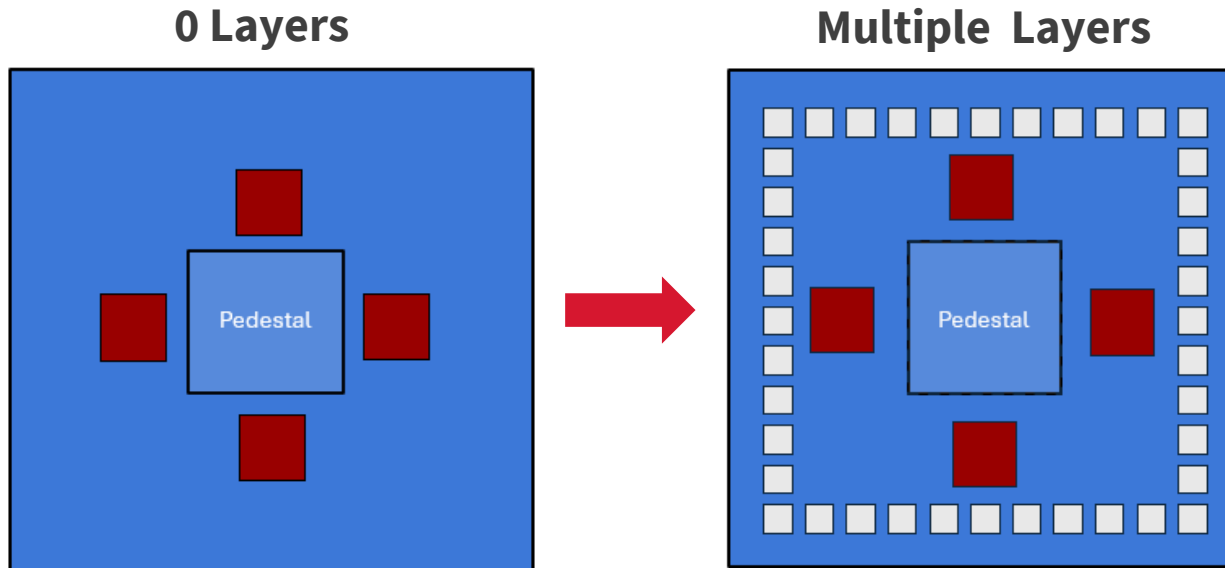
Observations :

- The PCE is at a similar level to the absorber-foot simulations ($\sim 30\%$).
- Higher statistics are needed for quantitative comparison with the absorber-foot geometries.

Effect of Phononic Crystal Layers on PCE

Simulation Setup:

➤ 100 primaries $\times$ 4.14 meV | crystal orientation [1,0,0] | bounce limit: 10^9 | ideal interfaces | QP trapping time τ_{QP} : 1 ms.



Motivation: Explore whether phononic crystal layers improve phonon collection.

Observations:

- The design of phononic crystals improves PCE from 18.14% to $\sim$ 30%.
- No obvious PCE improvement when adding layers from 5 to 9.

Results:

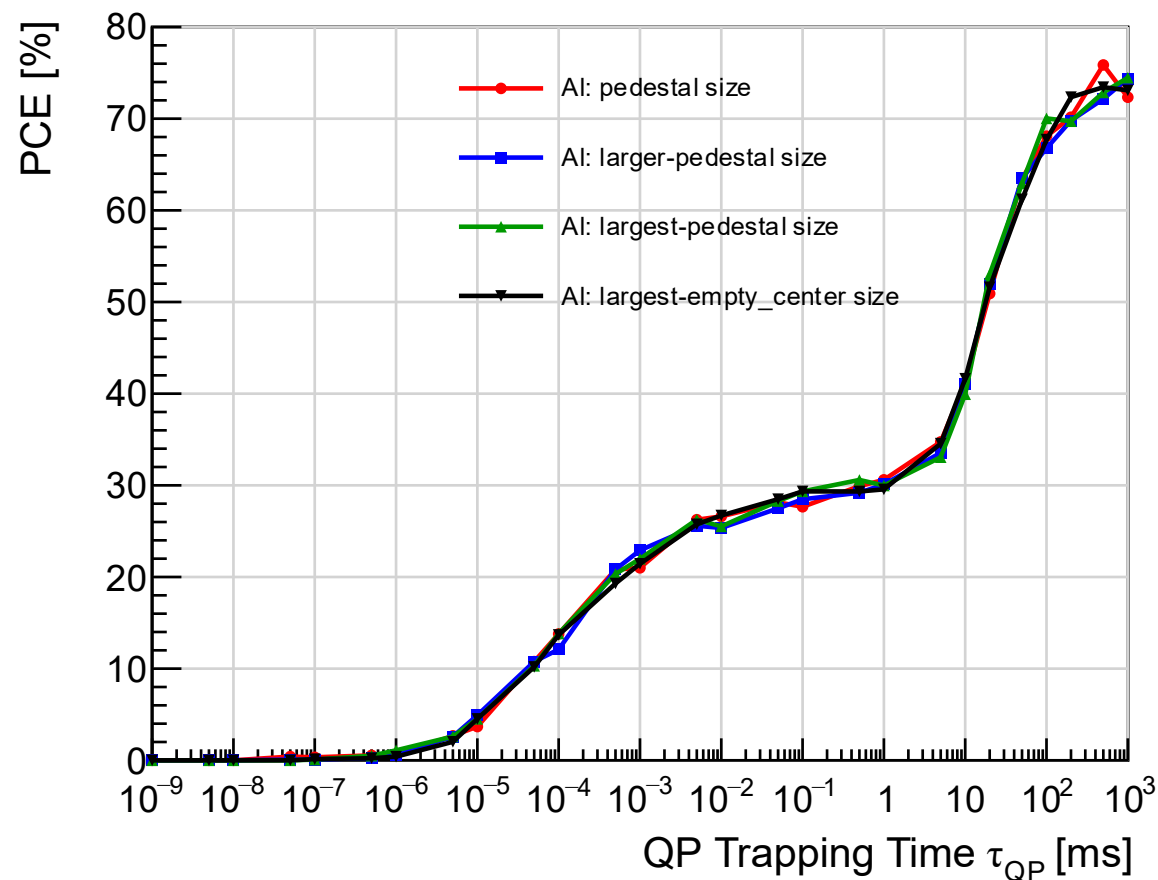
	0 layers	5 layers	6 layers	7 layers	8 layers	9 layers
PCE (%)	18.14	29.63	32.09	29.95	31.11	30.42

Effect of QP Trapping Time on PCE

Simulation Setup:

- 100 primaries $\times$ 4.14 meV | crystal orientation [1,0,0] | bounce limit: 10^9 | ideal interfaces | QP trapping time τ_{QP} range from 1 ps to 1000 ms.

PCE vs QP Trapping Time For Different Al Geometries

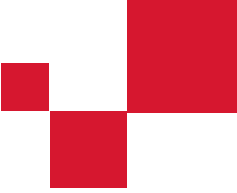


Observations:

- PCE increases when QP trapping time increases.
- The highest PCE is at around the 75% level, as the QP trapping time goes to 1000 ms.

Interpretations:

- Longer QP trapping time reduces trapping losses, allowing more energy to convert to phonons.



Summary:

- Incorporated the part of the quantum acoustic detector geometry into G4CMP with the phonon transport model.
- Implemented new materials (TeO_2 and LiNbO_3) in G4CMP and validated the phonon transport model.
- Investigated how detector geometry and QP trapping time affect phonon collection efficiency under ideal interface conditions:
 - ❖ **4 Al geometries:** PCE remains around 30%, without showing clear dependence on the Al size.
 - ❖ **Full geometry:** PCE level agrees with the 4 absorber-foot cases.
 - ❖ **Phononic crystals:** The increase in the number of layers improves the PCE to around the 30% level.
 - ❖ **QP trapping time:** PCE increases with trapping time, implying the importance of QP dynamics.

Next steps:

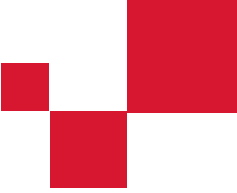
- Optimize PCE by further change geometry and design.

Acknowledgements



- Many thanks to everyone in our IIT group for their support.

- This presentation is based upon work supported by the **Defense Advanced Research Projects Agency (DARPA)**, the Quantum Science Center (QSC), and the Illinois Institute of Technology Physics Department. Work performed at Fermilab.



THANK YOU FOR YOUR ATTENTION

Questions?