Highlights in condensed matter (and other) physics

Presented by: Andrea Dotti (adotti@slac.stanford.edu)
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Material from: M. Kelsey and E. Bagli

U.S. DEPARTMENT OF ENERGY Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Acknowledgment

- The material of this presentation is mainly from M. Kelsey (SLAC) presentation at the Stanford Geant4 Tutorial 2014
  - http://geant4.slac.stanford.edu/SLACTutorial14/Agenda.html
- Channeling Effect studies, courtesy of E. Bagli (INFN and University Ferrara, Italy)
- Condensed Matter Physics is developed by CDMS experiment physicists in collaboration with Geant4 developers

Outlook

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- Introduction
- Phonon Physics in cryogenic-temperatures crystals
- Electrons/holes transport
- Channeling effect in crystals

- References
  - Semiconductor phonon and charge transport Monte Carlo simulation using Geant4 ; arXiv:1403.4984
  - A model for the interaction of high-energy particles in straight and bent crystals implemented in Geant4 ; arXiv:1403.5819

Solid-State Physics Developments

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A small group of Geant4 collaborators has been developing tools to support some solid-state physics processes

- Phonon propagation and scattering
- Crystal channelling of charged particles
- Electron/hole production and transportation

Examples available (applies to the first two items)

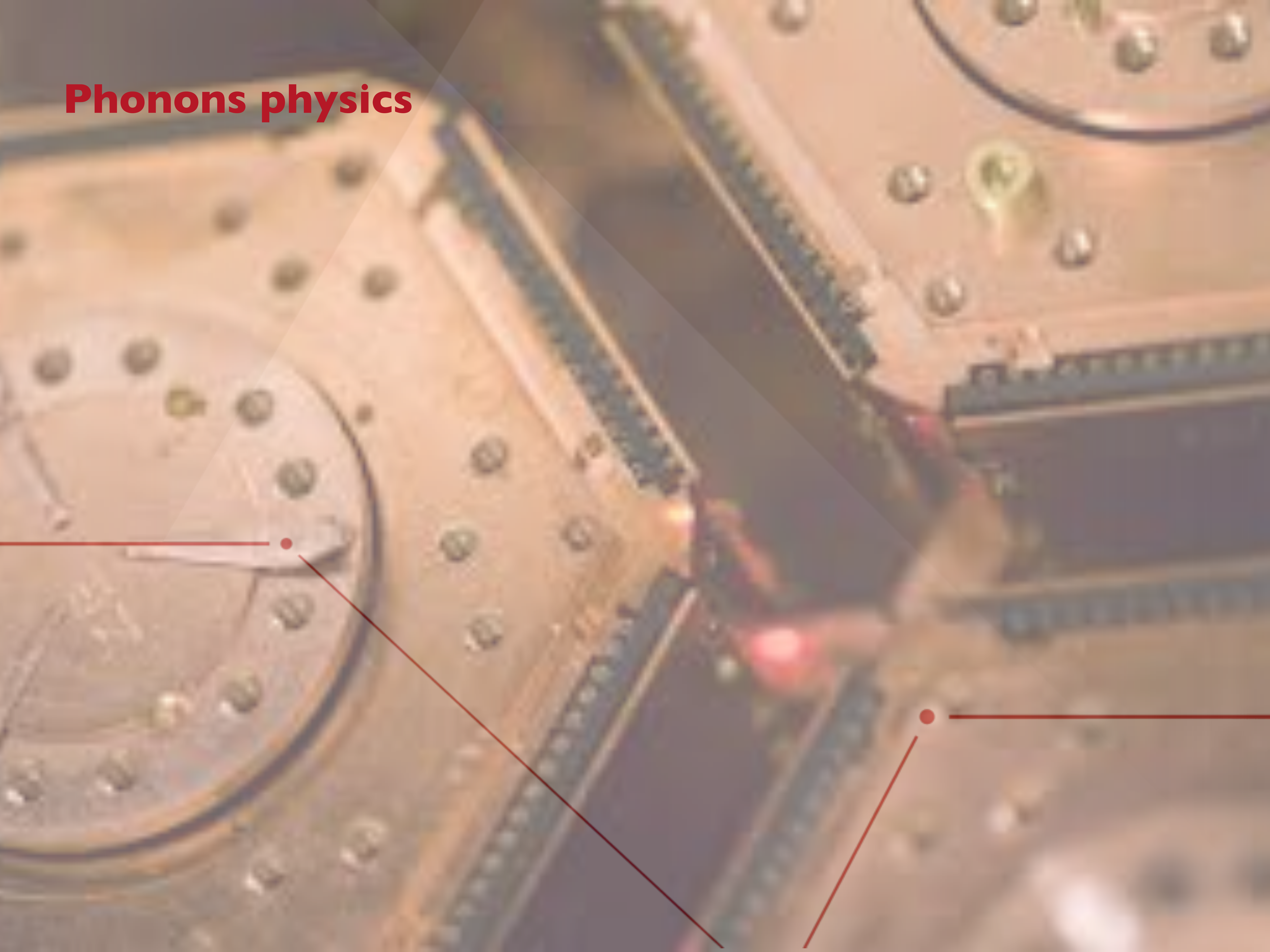
A common feature for these processes is the need to define a "lattice structure" (its numerical parameters) for a volume.

These tools are not yet (fully) ready for release; this presentation is meant to be informational and perhaps inspirational.

Lattices

- Geant4 treats materials as uniform, amorphous collections of atoms. Steps may be of any length, in any direction, and some atom will be at the destination for interaction.
- We have introduced `G4LatticeLogical` as a container to carry around parameters and lookup tables for use with the phonon handling processes.
- There is a singleton `G4LatticeManager` which keeps track of lattices, and how they're associated with materials and volumes.

Phonons physics



Phonons in Geant4

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- See `examples/extended/exoticphysics/phonons`
- The processes developed so far support acoustic phonons, which are relevant for low-temperature (tens of mK) crystals.
- Three polarization states are recognized
  - Longitudinal (**G4PhononLong**)
  - Transverse "slow speed" (**G4PhononTransFast**)
  - Transverse "fast speed" (**G4PhononTransSlow**)
- Currently no production process. Use **G4ParticleGun** to insert a phonon, which then propagates through volume.
  - Production processes being developed

Phonon Propagation

- Phonons are assigned a wave vector $\vec{k}$ for their phase velocity.
  - Group (propagation) velocity $\vec{v}_g$ is different due to the lattice anisotropies.
  - `G4LatticeLogical` has a lookup table to convert between the two.

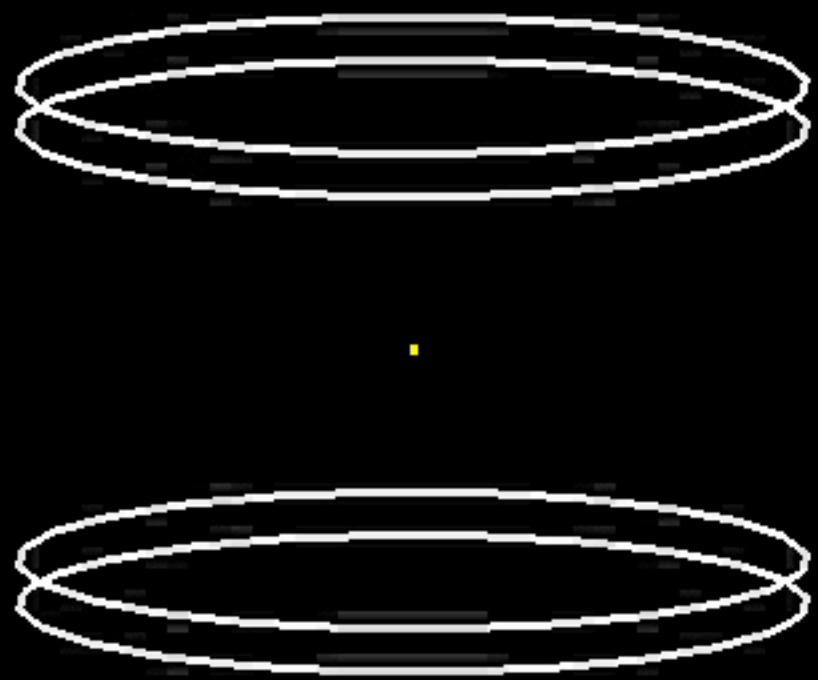
Phonon Interactions

- Three phonon processes are currently available, though may not be fully functional.

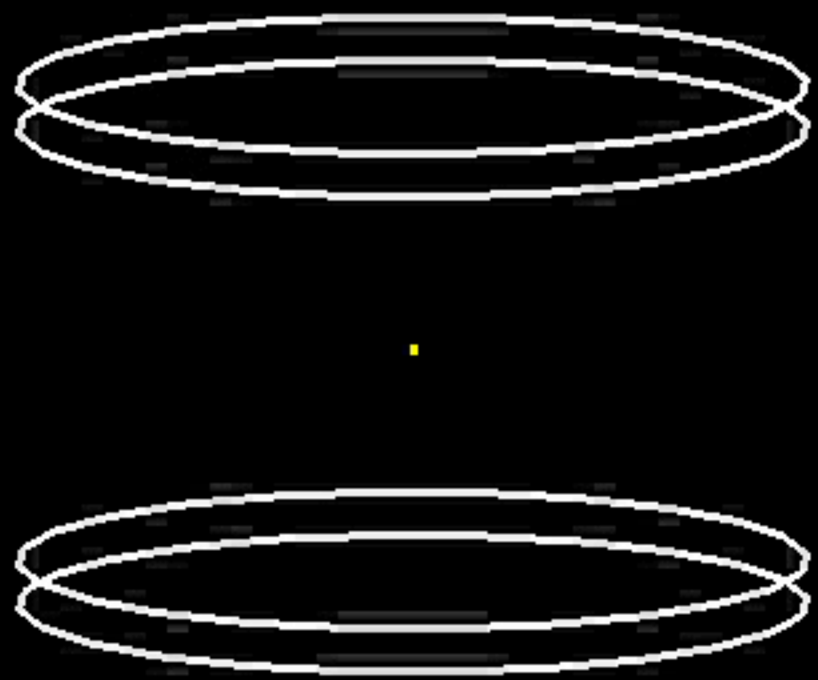
- `G4PhononScattering` Treats scattering of phonons off of isotopic impurities or lattice defects, changing direction and randomizing the polarization state (mode mixing)

- `G4PhononDownconversion` Longitudinal phonons split in two, either L → L'T or L → T T

- `G4PhononReflection` Should handle reflection of phonons of volume boundaries; currently just kills.



120 ns



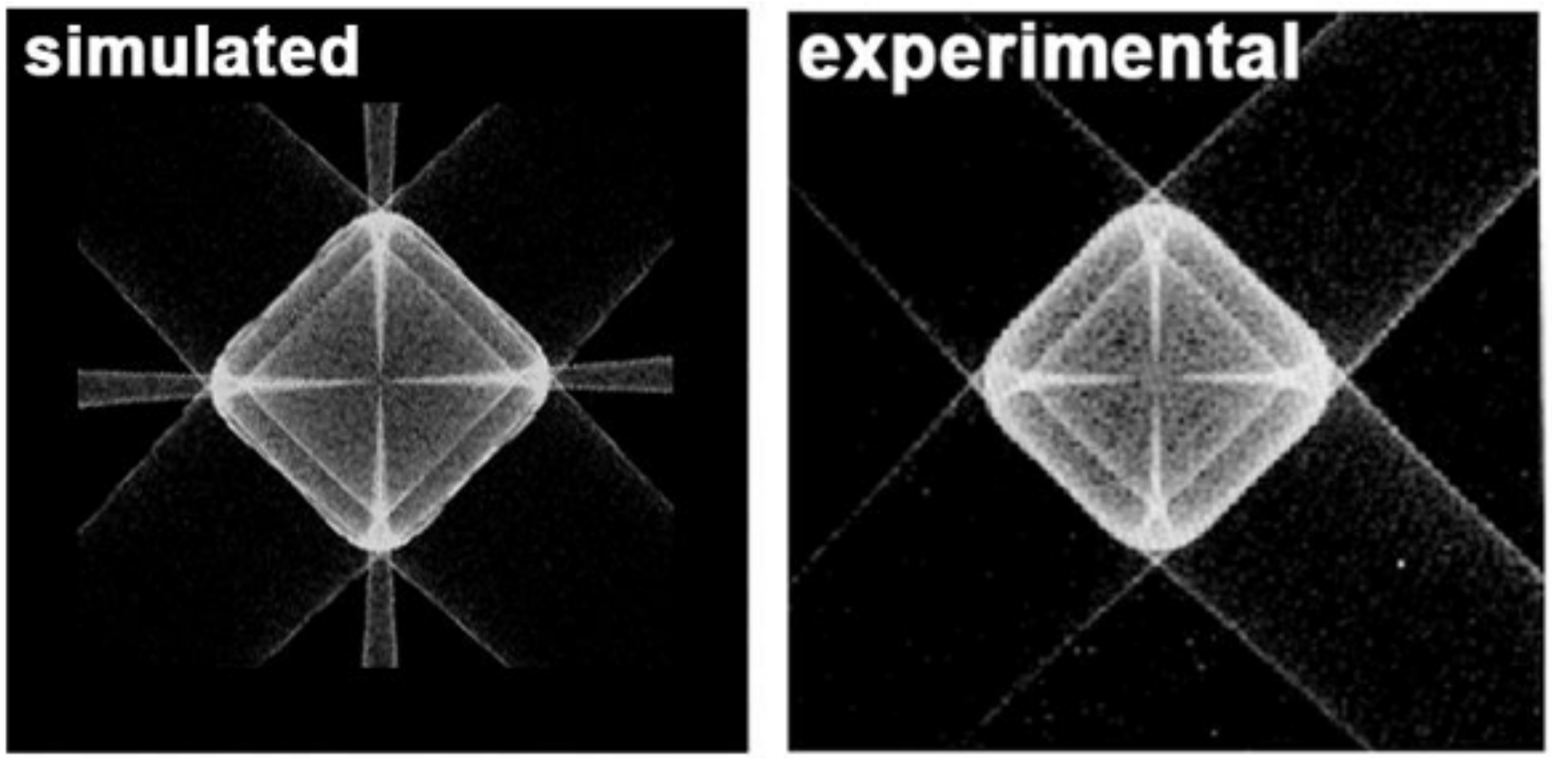
120 ns

Luke Phonon Production

- Charged particles (including holes) drifting through crystal can generate low-energy phonons along their trajectories.
- "Non-ionizing energy loss" can be calculated and stored by a few standard processes.
- Code in development produces phonons which propagate as described previously.

Phonon Caustics In Germanium

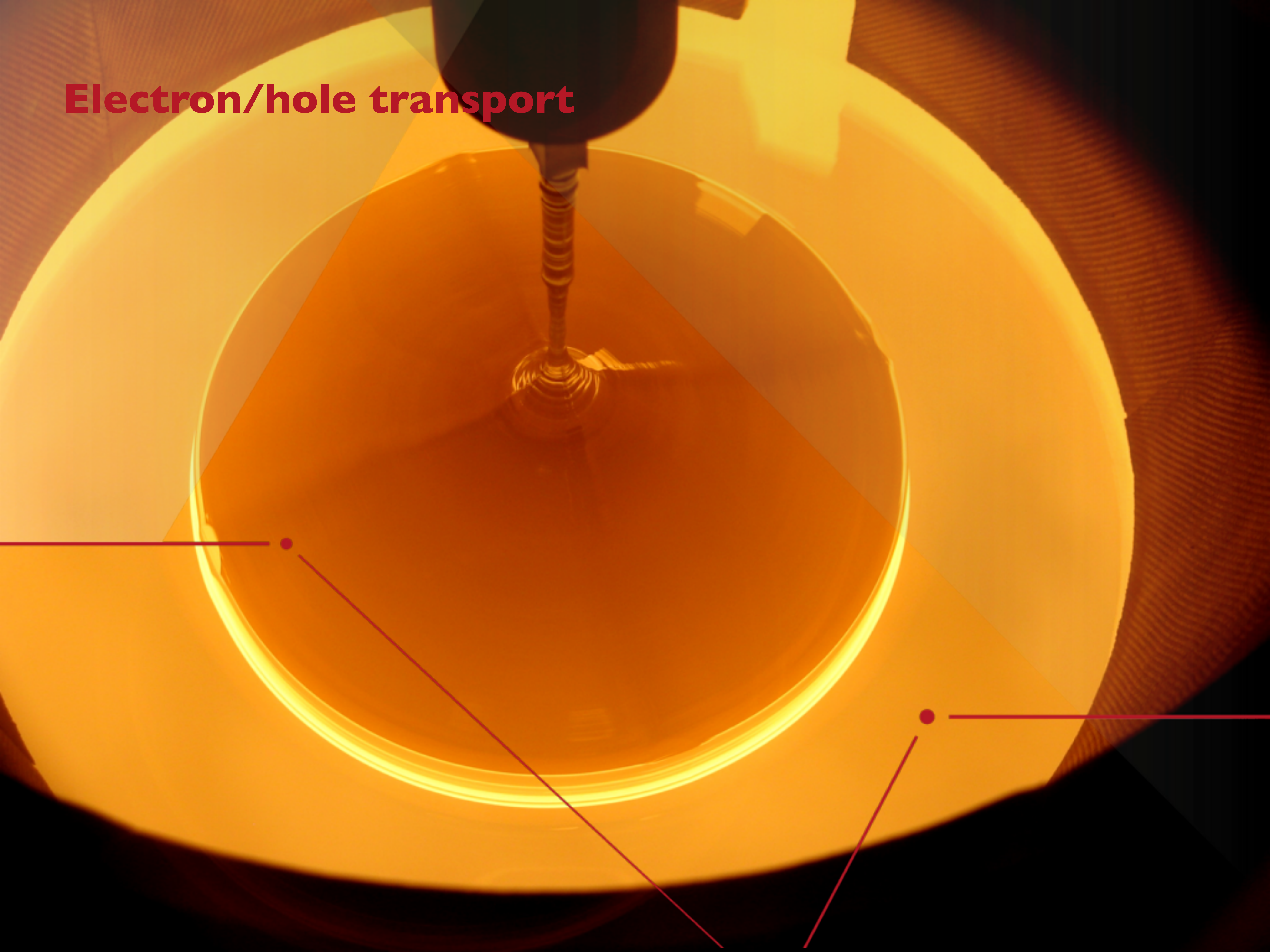
Generate phonons at the center of one face of a germanium crystal, and measuring the distribution of phonons on the opposite face. Focusing produces a pattern of ***caustics***.



Caustics in Ge collected by **phonons** example

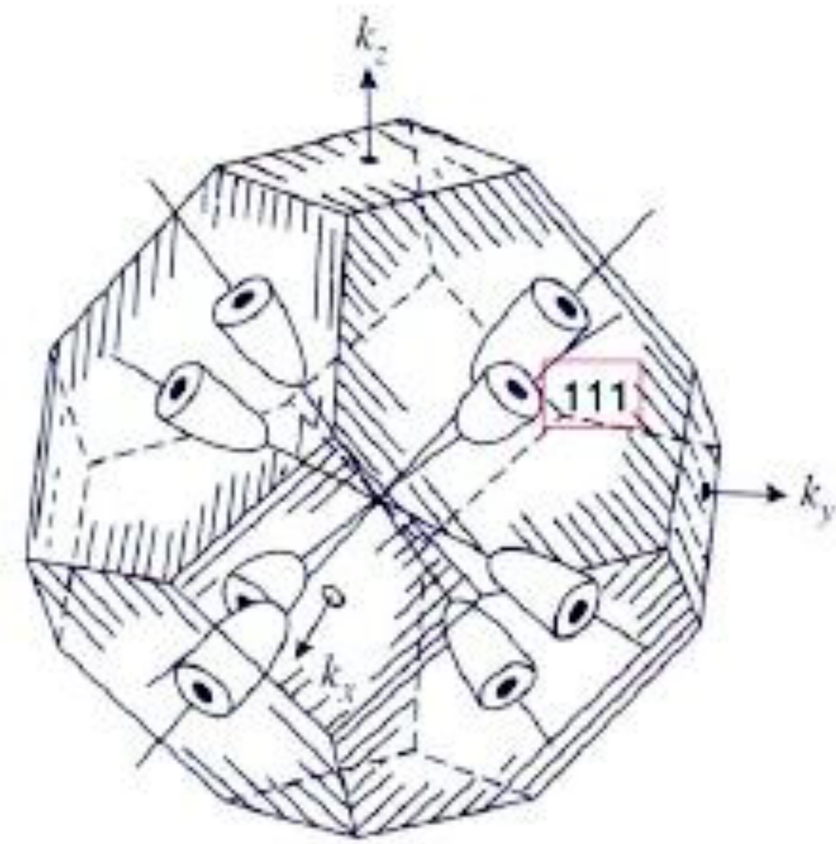
Caustics in Ge observed by Northrop and Wolfe PRL 19, 1424 (1979)

Electron/hole transport



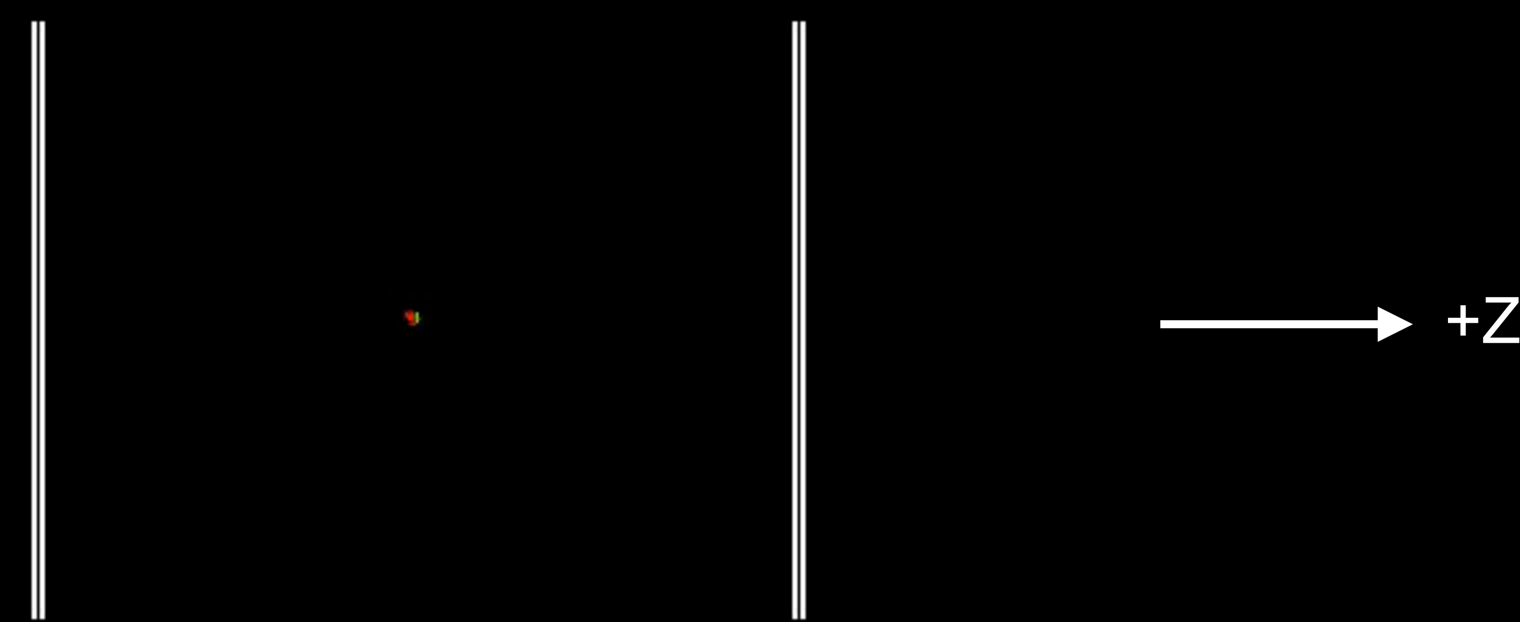
Electron/hole Transport

- Energy-momentum relation (band structure) in Ge is highly anisotropic
  - Eight equivalent minima (right)
  - Electron develops a mass tensor
  - Mass tensor diagonalizes in coordinate system
  - Two components, $m_{||}$ and m_{L} , remain



L valleys of Ge

- Electrons travel along, scatter between valleys (minima)
- Holes drift along electric field lines



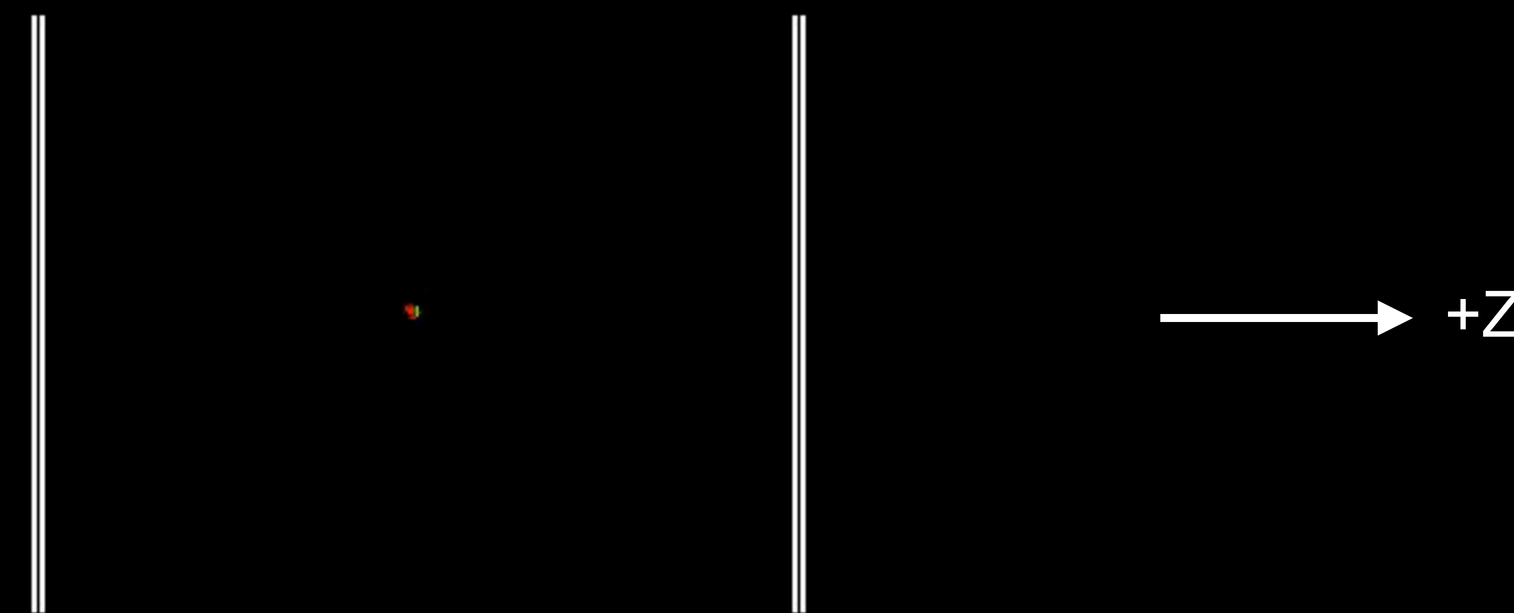
4 ns

Note: crystal is rotating along Z axis

electrons

holes

phonons



4 ns

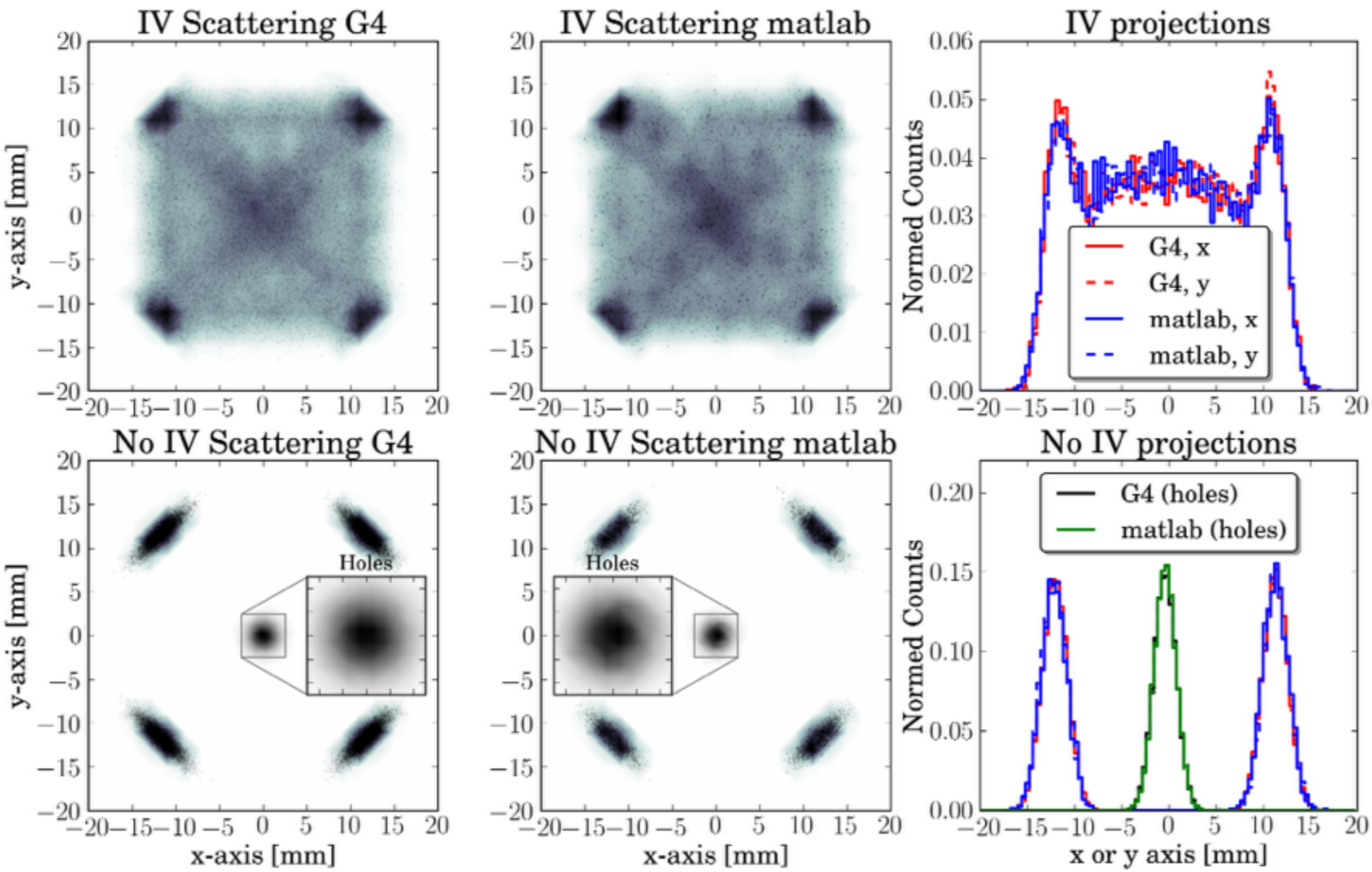
Note: crystal is rotating along Z axis

electrons

holes

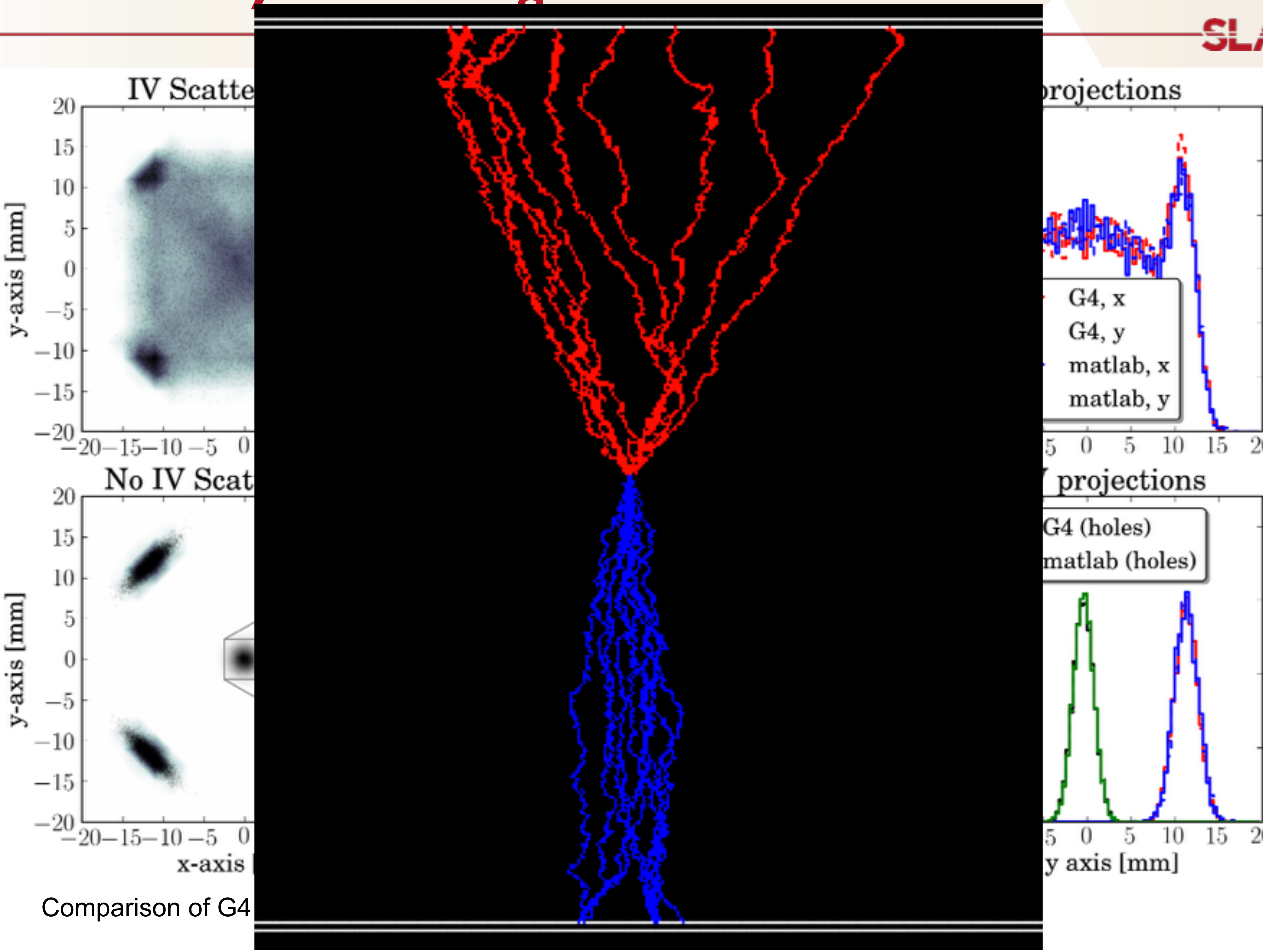
phonons

Inter-valley Scattering



Comparison of G4 and Matlab simulations of CDMS crystals, R. Agnese, UFL

Inter-valley Scattering



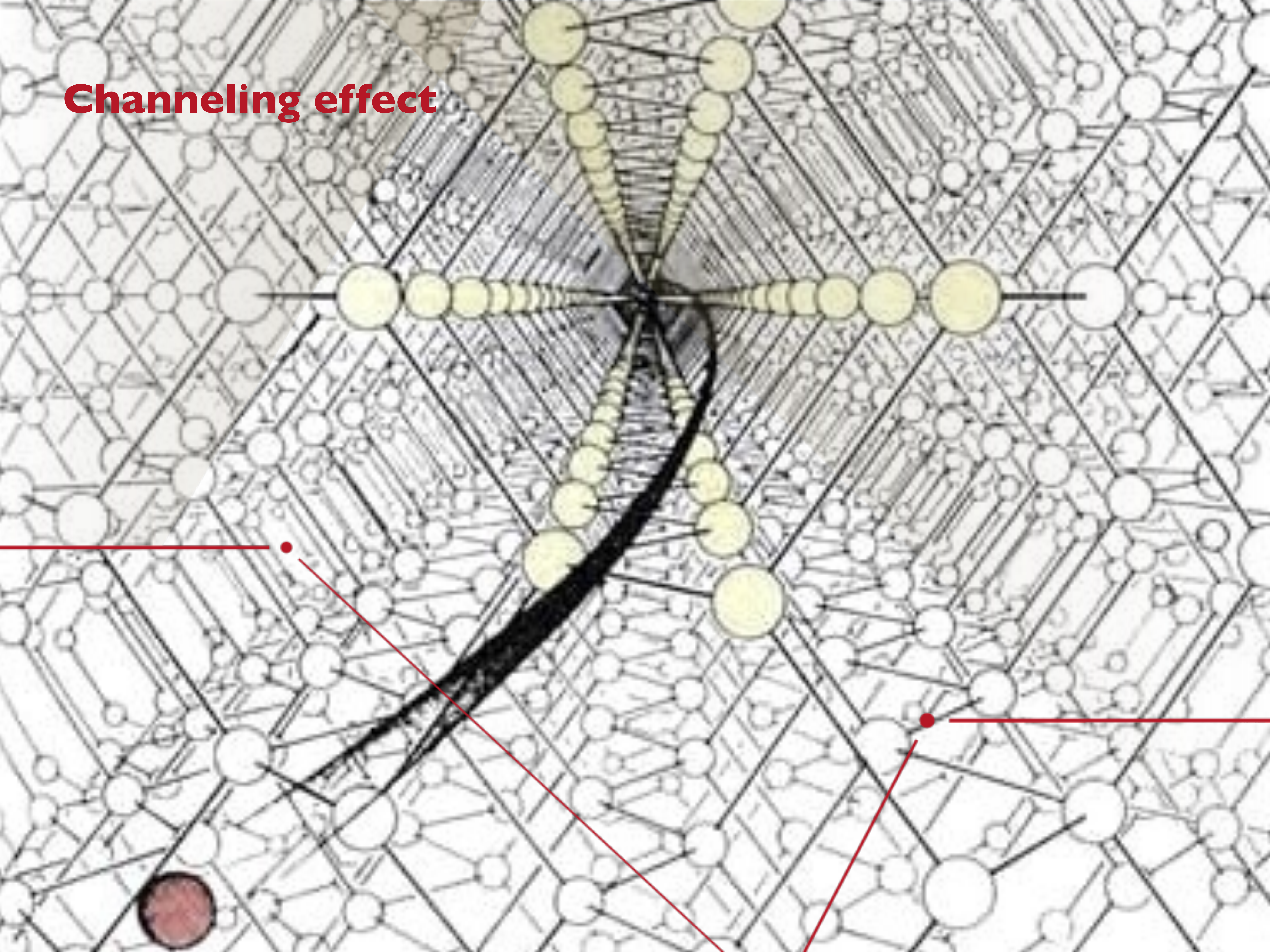
Comparison of G4

Electrons/hole transportation

- e/h transport code is developed mainly by CDMS experiment community with G4 support
  - http://cdms.berkeley.edu
  - Not publicly released (yet)

- We do realize the very wide interest such simulation capabilities have
  - We believe extensions could be made to treat e/h in non-cryogenic temperatures
  - Lattice support in G4 could be extended to support other crystals (currently limited to Ge)
- Additional manpower could significantly speed-up development

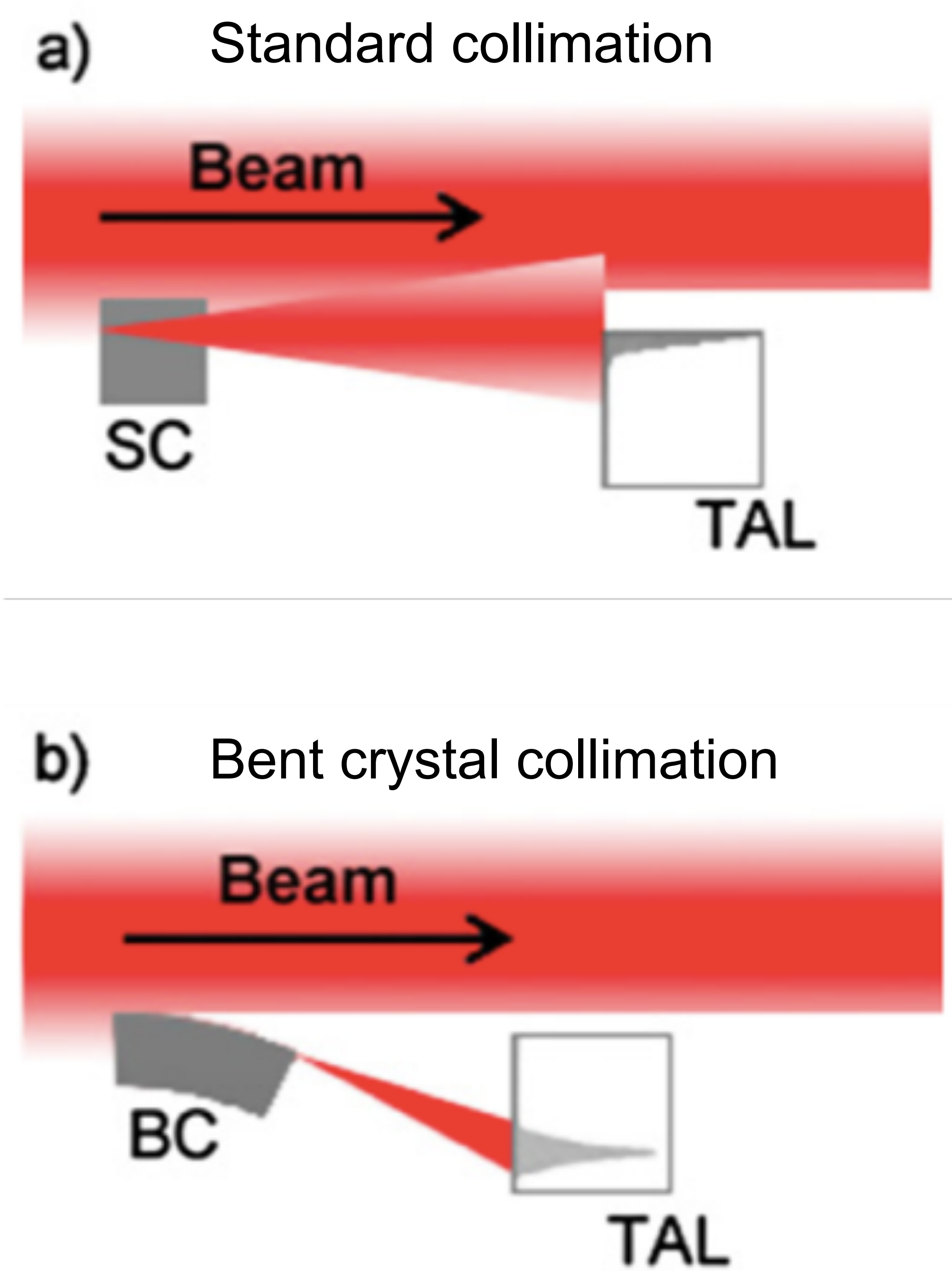
Channeling effect



Crystal Collimation or Channeling

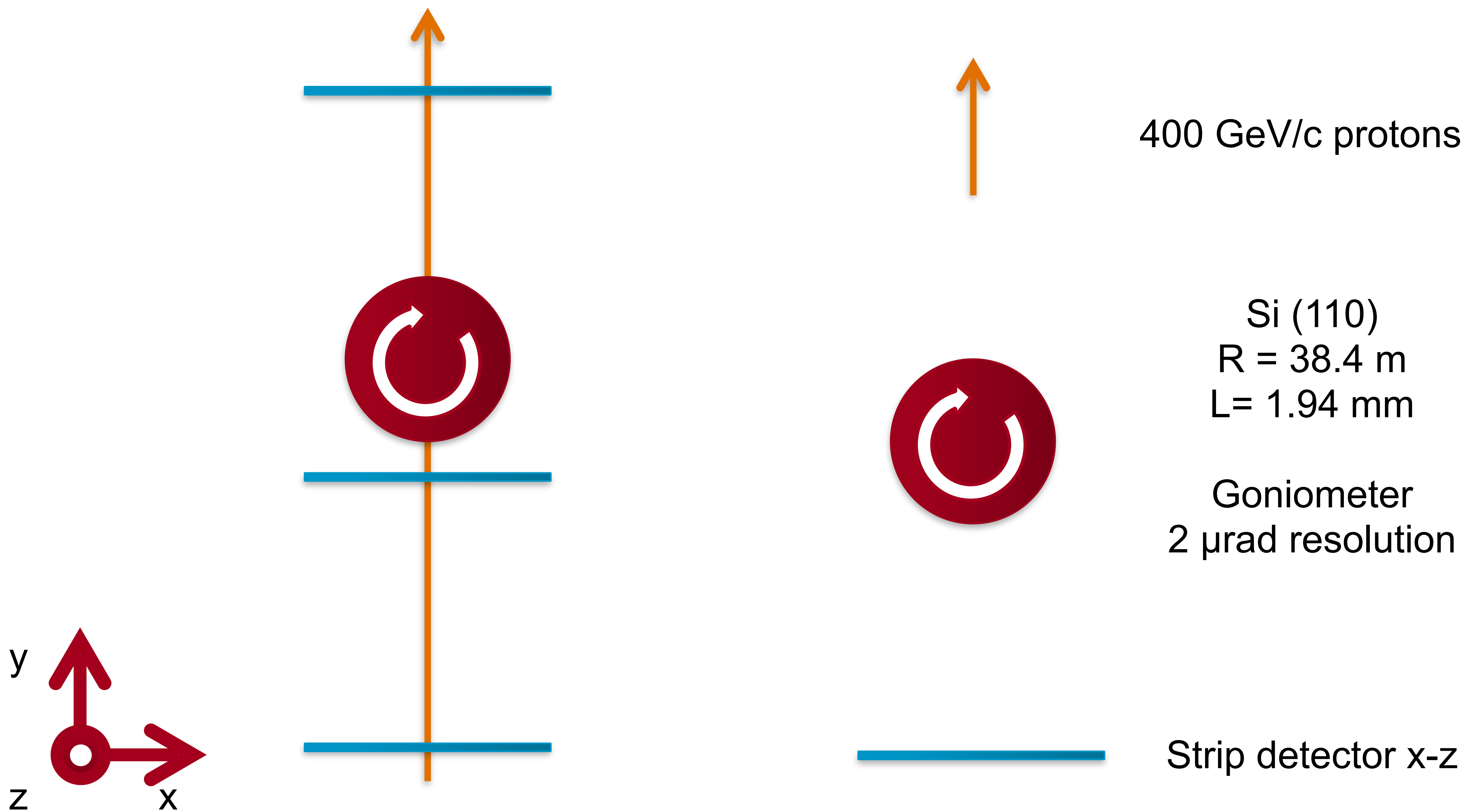
Developed by Enrico Bagli, U. Ferrara

- Crystal can be used as a primary collimator to deflect particles of the halo toward a secondary collimator.
- Main advantage is the possibility to deflect the beam out and reduce the beam losses.



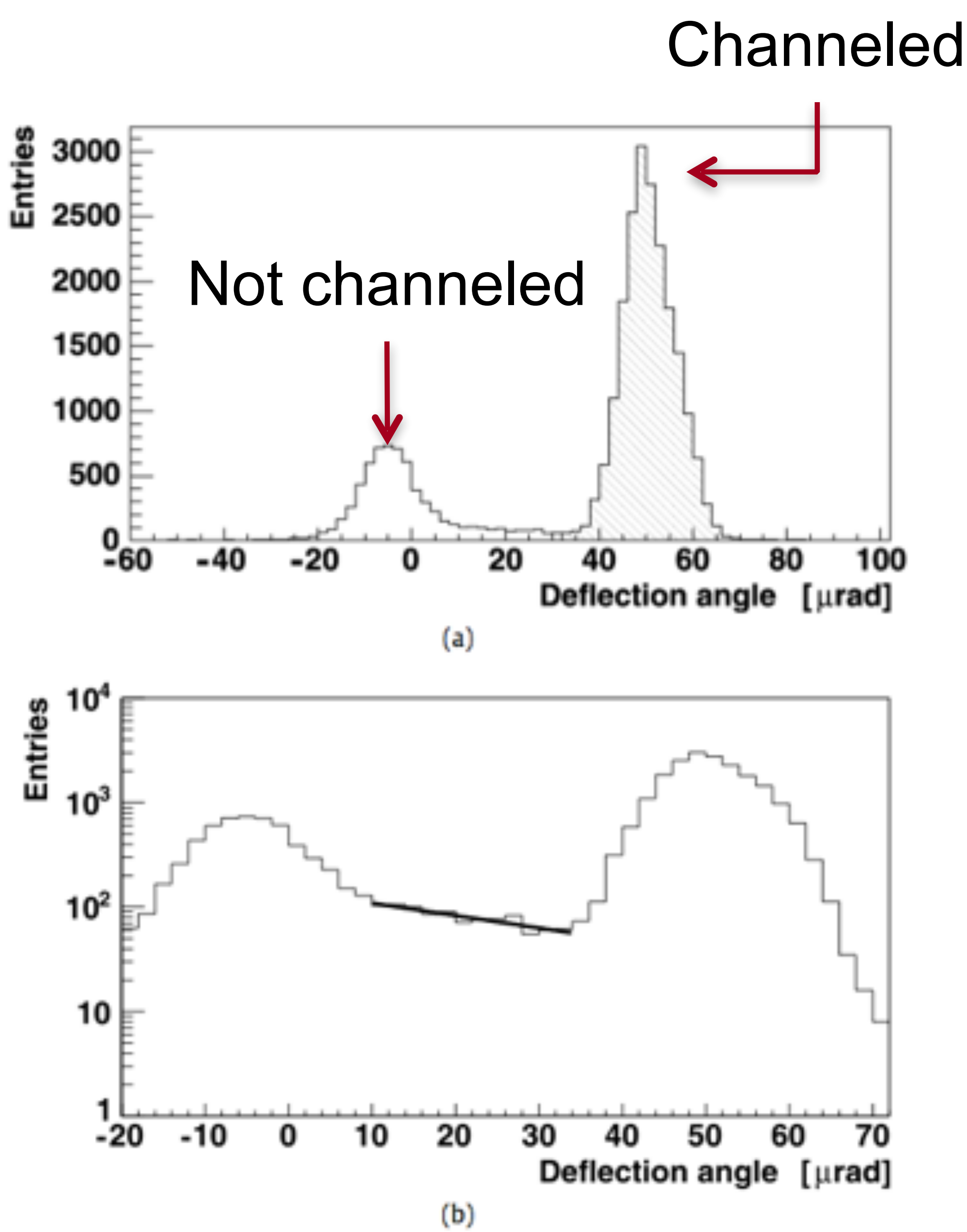
400 GeV/c proton beam on Si

W. Scandale et al., Phys. Lett. B 680 (2009) 129



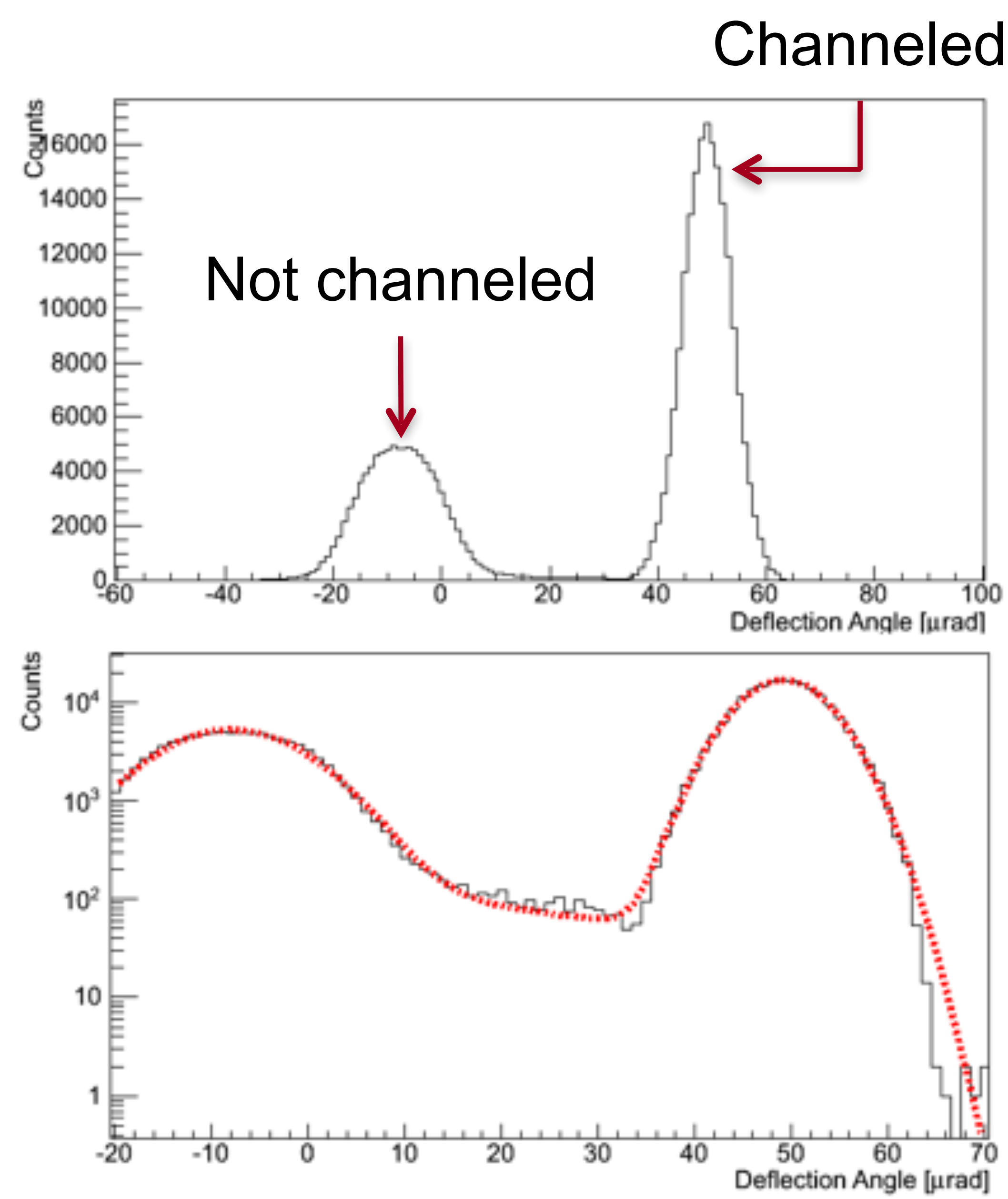
Nuclear Dechannelling Length

W. Scandale et al., Phys. Lett. B 680 (2009) 129



L_n = (1.53 ± 0.35 ± 0.20) mm

Geant4 Channeling



L_n = (1.31 ± 0.05) mm

Channeling Efficiency vs. Angle

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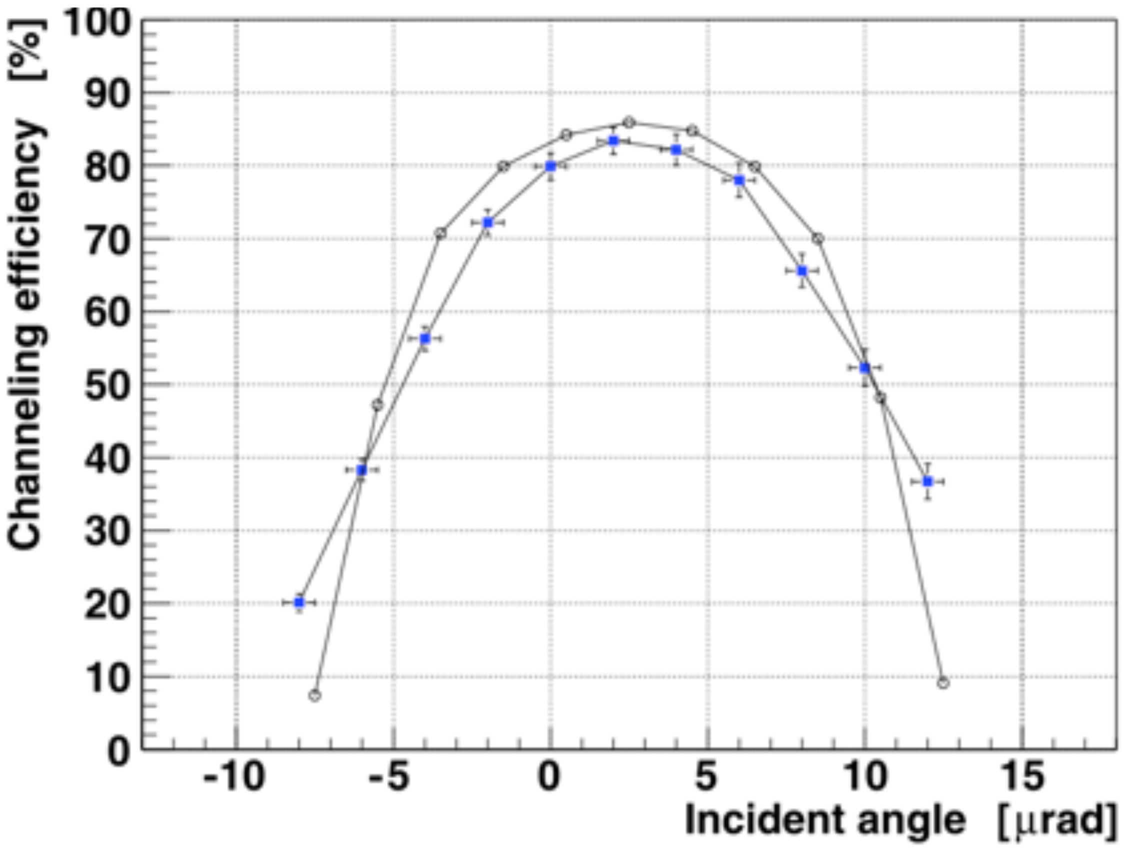
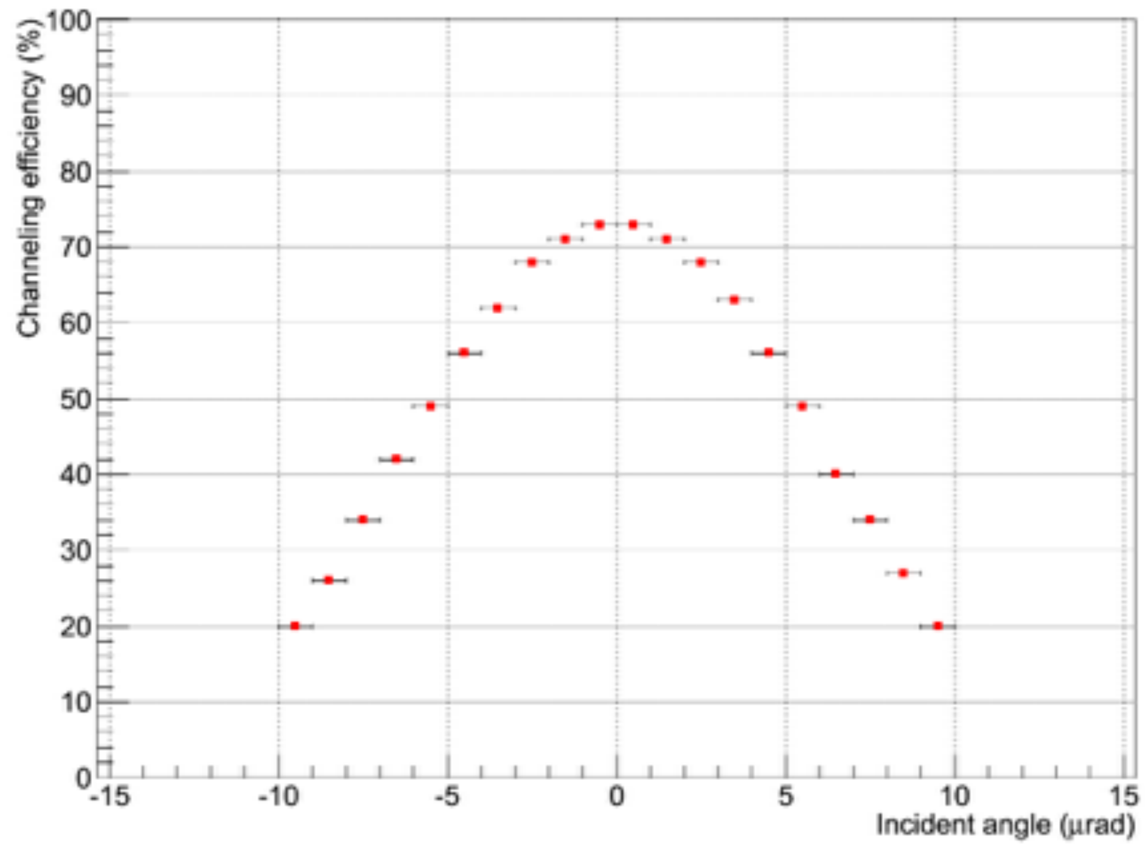
W. Scandale et al., Phys. Lett. B 680 (2009) 129



Geant4 Channeling



- Experimental measurements (a)
- UA9 collaboration simulations (a)
- Geant4 Simulations (b)

Conclusions

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- Geant4 provides two examples that show a modified transportation in crystal lattice
  - Phonon transportation in cryogenic temperatures crystals
  - Channeling effect of high energy particles
- Electron-hole code being developed by CDMS collaborators
- Motivated by "HEP style" requirements
  - However e/h code could be extended to lower energies and higher temperatures
- In all cases the introduction of the concept of a lattice structure allowed these developments