

# Physics II: Decay and Low Energy Processes, Production Thresholds

8<sup>th</sup> International Geant4 Tutorial in Korea

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# Outline

- Particle decays
  - decay channels and tables
  - special decays
- Low Energy Processes
  - Optical photon interactions
  - Phonons and electron/hole propagation/lattices
  - Crystal channeling
- Production Thresholds (Cuts)
  - How they work
  - How to set them
  - Cuts per region

# Particle Decays

- For all unstable, long-lived particles
  - not used for radioisotopes (G4RadioactiveDecay)
- Decay can happen in flight or at rest
  - decay process is discrete + at-rest (G4VRestDiscreteProcess)
- Different from other physical processes
  - mean free path ( $\lambda$ ) for most processes:  $1/\lambda = \Sigma = N\rho\sigma/A$
  - for decay in flight (mean free path):  $\lambda = \gamma\beta c\tau$
  - for decay at rest (mean life time):  $\lambda \rightarrow \tau$
  - at rest processes like decay and capture compete in time
- Same process used for all eligible particles are classified as
  - retrieves branching ratios and decay modes from decay table stored for each particle type

# Particle Decay Modes Available

- Phase space

- two-body:  $\pi^0 \rightarrow \gamma \gamma$  (~98.8%)
- three-body:  $K_L^0 \rightarrow \pi^0 \pi^+ \pi^-$

- Dalitz

- $\pi^0 \rightarrow l^+ l^- \gamma$

- Muon and tau decay

- $\mu^- \rightarrow e^- \text{ anti-}\nu_e \nu_\mu$
- no radiative corrections , mono-energetic neutrinos

- Semi-leptonic K decay

- $K \rightarrow \pi l \nu$

# Defining Decay Channels

- Geant4 provides decay modes for long-lived particles
  - user can re-define decay channels if necessary
- But decay modes for short-lived (e.g. heavy flavor) particles not provided by Geant4
  - user must “pre-assign” to particle
    - proper lifetime
    - decay modes
    - decay products
  - process can invoke decay handler from external generator
    - must use G4ExtDecayer interface
- Take care that the pre-assigned decays from generators do not overlap with those defined by Geant4 (e.g.  $K_S^0$ ,  $\tau$ )

# Specialized Particle Decays

- **G4DecayWithSpin**

- produces Michel electron/positron spectrum with first order radiative corrections
- initial muon spin is required
- propagates spin in magnetic field (precession) over remainder of muon lifetime

- **G4UnknownDecay**

- only for not-yet-discovered particles (SUSY)
- discrete process – only in-flight decays allowed
- pre-assigned decay channels must be supplied by user or generator

# Optical Processes

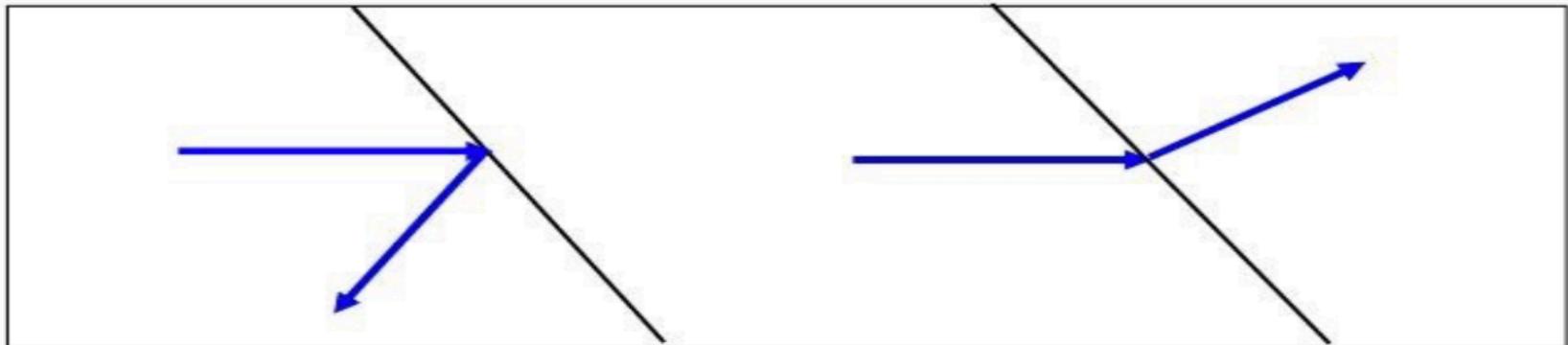
- Propagation of optical photons and their interaction with materials is treated separately from regular electromagnetic processes. Why?
  - wavelengths are much larger than atomic spacing
  - they are treated (partially) as waves; no smooth transition to gammas
  - energy/momentum not generally conserved in G4 optics
- Optical photons produced directly by three processes
  - G4Cerenkov
  - G4Scintillation
  - G4TransitionRadiation

# Optical Photon Transport

- Refraction and reflection at boundaries
- Wavelength shifting
- Bulk absorption
- Rayleigh scattering
  
- Geant4 keeps track of polarization
  - but not overall phase, so no interference
- Optical properties attached to G4Material (by user code)
  - reflectivity, transmission efficiency, dielectric constants, surface properties, including binned wavelength/energy dependences
- Photon spectrum attached to G4Material (by user code)
  - scintillation yield, time structure (fast, slow components)

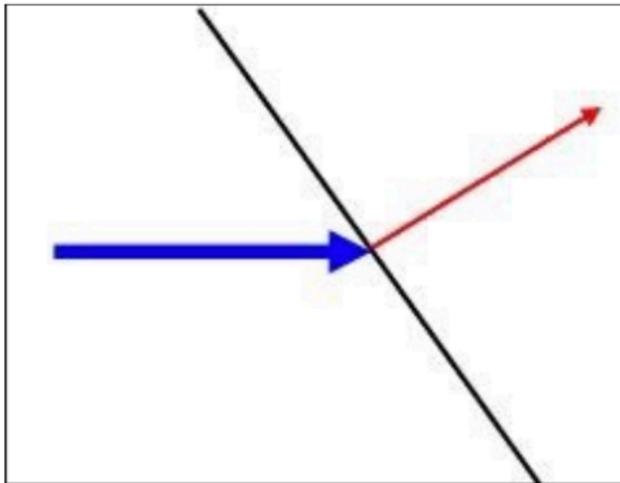
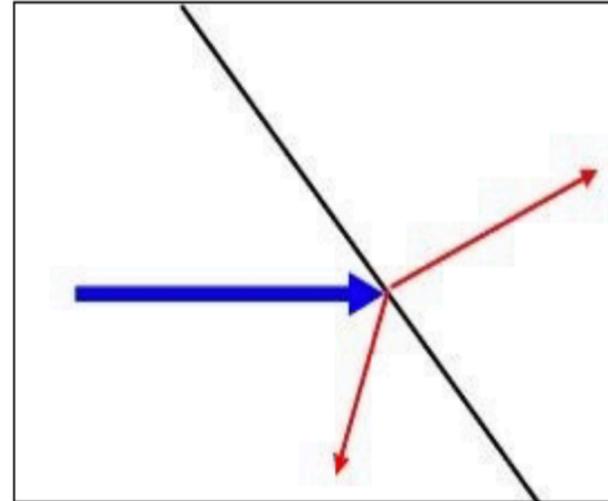
# Optical Boundary Processes

- **G4OpBoundaryProcess**
  - refraction
  - reflection
- **User must supply surface properties using G4OpticalSurfaceModel**
- **Boundary properties**
  - dielectric-dielectric
  - dielectric-metal
  - ...
- **Surface properties**
  - polished
  - ground
  - front- or back-painted
  - ...

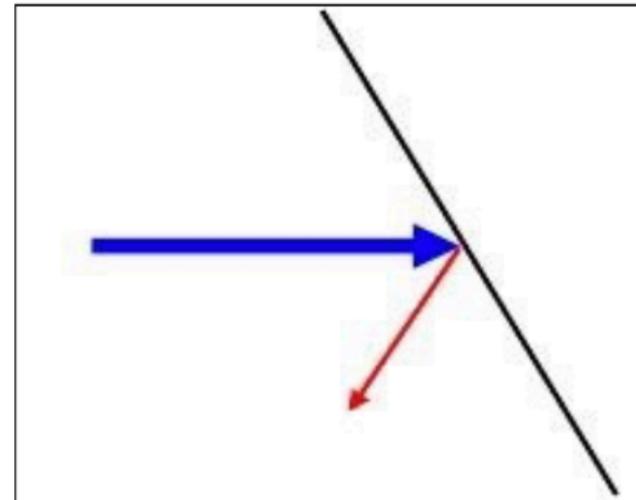


# Reflection or Refraction

- Geant4 events support “particle-like” behavior – no “splitting” of tracks
- Each event has either a reflected or refracted photon, chosen randomly from user-input efficiencies

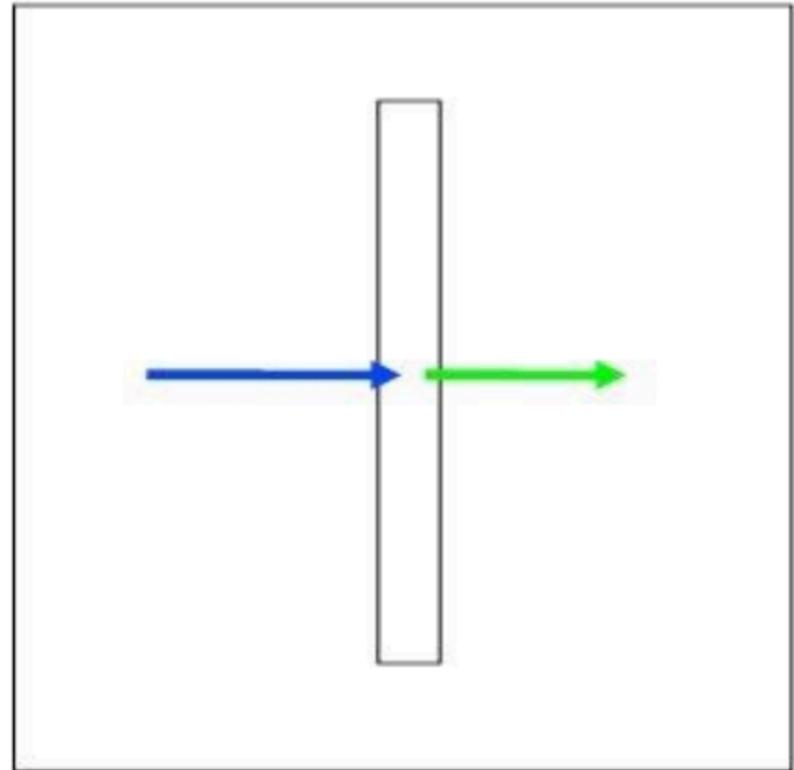


**OR**



# Optical Processes: Wavelength Shifting

- Handled by G4OpWLS
  - initial photon is killed, one with new wavelength is created
  - gets mean free path from physics table
- User must supply:
  - absorption length as function of photon energy
  - emission spectra parameters as function of energy
  - time delay between absorption and re-emission



# Optical Bulk Processes

- **G4OpAbsorption**

- uses photon attenuation length from material properties to get mean free path
- photon is simply killed after a selected path length

- **G4OpRayleigh**

- elastic scattering including polarization of initial and final photons
- builds its own physics table (for mean free path) using G4MaterialTable
- may only be used for optical photons (a different process provided for gammas)

# Solid State Physics Developments

- A group of Geant4 developers has been developing tools to support some solid-state physics processes
  - phonon propagation and scattering
  - electron/hole production and drift
  - crystal channeling of charged particles
- A common feature for these processes is the need to define a “lattice structure” (numerical parameters) for a volume
- Some of these tools (phonon propagation) were released in Geant4 10.1

# Lattices

- Geant4 treats materials as uniform, amorphous collections of atoms. Steps may be of any length, in any direction and it is assumed that some atom will be at the location of the interaction
  - actual lattices are not constructed in Geant4
- **G4LatticeLogical** has been introduced as a container to hold parameters and look-up tables for use with the phonon handling processes
- There is a singleton, **G4LatticeManager**, which keeps track of lattices and how they are associated with materials and volumes

# Phonons in Geant4

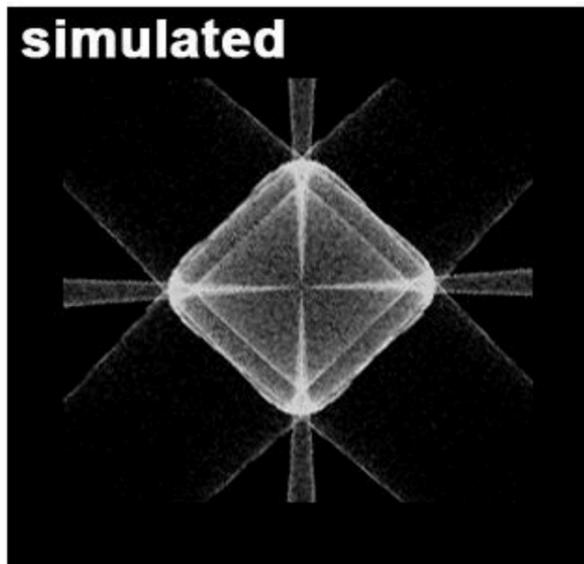
- See [examples/extended/exoticphysics/phonon](#)
- For cryogenic detectors in dark matter searches
  - Ge crystals at 40-60 mK
  - observation of dark matter candidates through recoil with Ge nucleus in lattice and subsequent phonon and electron/hole pair creation
  - transport must be modeled in cryogenic environment
- Processes developed so far support acoustic phonons, which are relevant for low temperature detectors
- Phonon is described by its wave vector  $k$ , frequency  $\omega$  and polarization  $e$ . Three polarization states are recognized:
  - Longitudinal (L) ([G4PhononLong](#))
  - Transverse “slow speed” (ST) ([G4PhononTransSlow](#))
  - Transverse “fast speed” (FT) ([G4PhononTransFast](#))

# Phonon Interactions

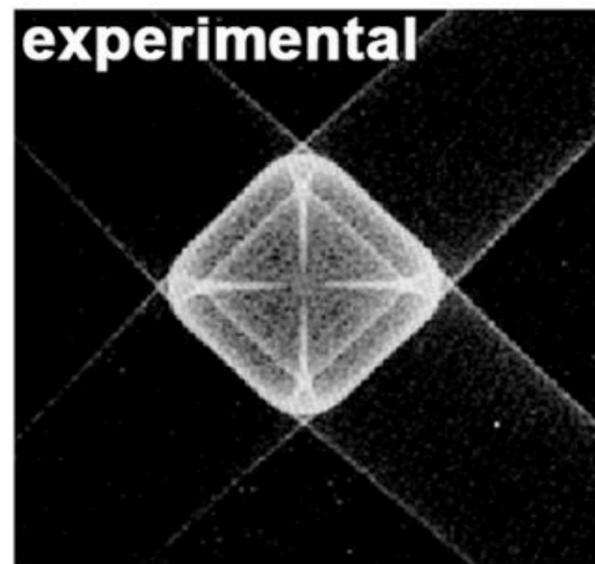
- Currently no production process. Use **G4ParticleGun** to insert a phonon, which then propagates through volume
- Two phonon processes important in cryogenic crystals:
  - isotope scattering
  - anharmonic down-conversion
- **G4PhononScattering**: elastic scattering of phonon from isotopic impurities or lattice defects, during which the phonon momentum vector is randomized and the polarization state can change freely between the L, ST and FT states
- **G4PhononDownConversion**: a single longitudinal phonon can split into two (L + T) or (T + T) phonons with reduced energy. Energy conserved, but not momentum (exchanged with crystal)

# Phonon Caustics in Germanium

- Anisotropic elasticity of crystal leads to phonon transport being focused along preferred directions in the crystal
  - resulting intensity patterns called caustics
- Generate phonons at center of one face of Ge crystal, measure phonon distribution at opposite face



Caustics in Ge collected  
by phonons example



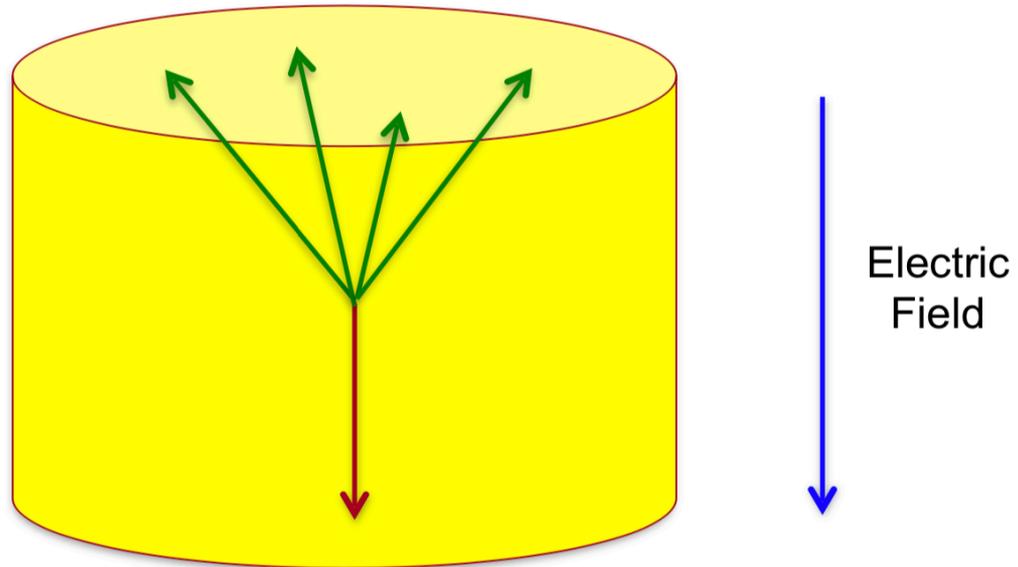
Caustics in Ge observed  
by Northrop and Wolfe  
PRL 19, 1424 (1979)

# Electron Hole Propagation in E Field

- Hole has a scalar effective mass in Ge
  - propagates as a charged particle in vacuum with an applied electric field
- Electron has a tensor effective mass
  - propagates along valleys in momentum space (band structure)
  - inter-valley scattering from lattice or impurity is possible

Electrons travel  
along valleys

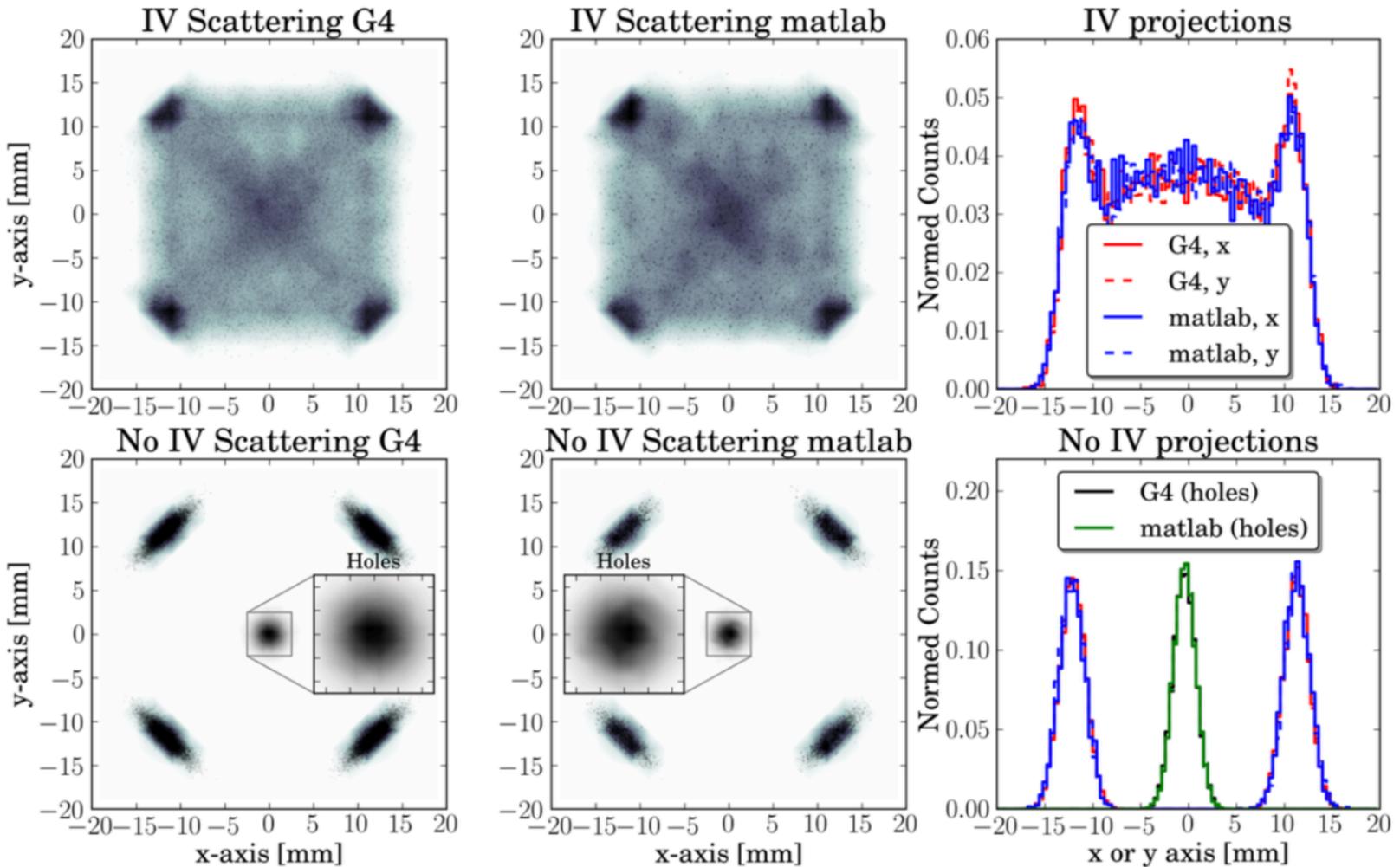
Holes travel along  
field lines



# Luke-Neganov Phonon Production

- Charged particles (including holes) drifting through crystal can generate phonons along their trajectories
  - process analogous to Cerenkov radiation
- “Non-ionizing energy loss” can be calculated and stored by a few standard processes
- Code in development produces phonons which propagate as described previously

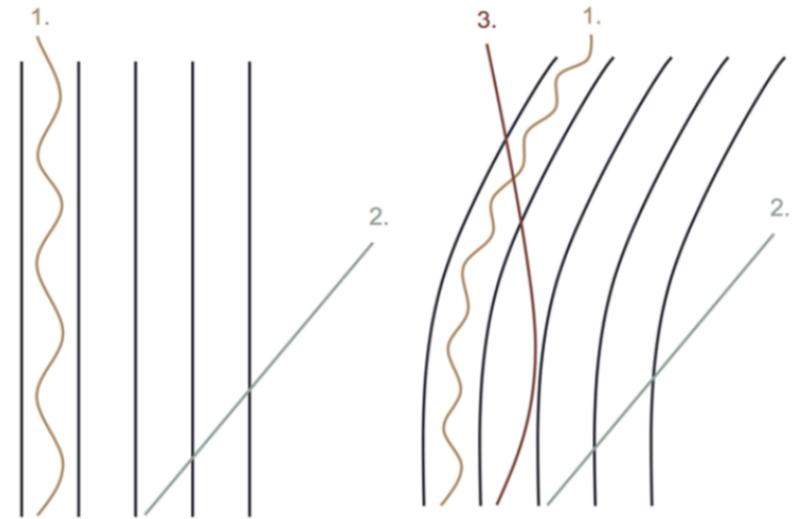
# Intervalley Scattering



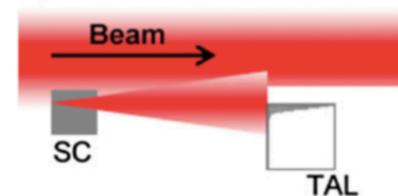
Comparison of G4 and Matlab simulations (w/o inter-valley scattering) of CDMS crystals, R. Agnese, UFL

# Crystal Collimation or Channeling (developed by Enrico Bagli, U. Ferrara)

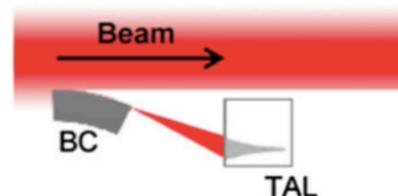
- Particles with directions aligned with crystal planes are channeled (1)
- Crystal can be used as primary collimator to deflect halo particles toward secondary collimator
- Main advantage is the possibility of deflecting halo out and reducing losses



Standard collimation



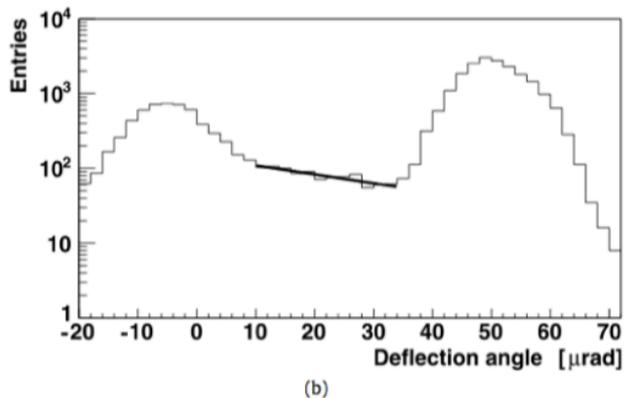
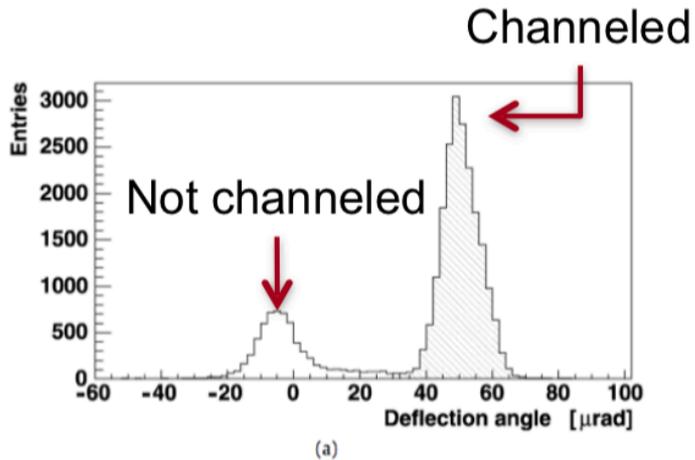
Bent crystal collimation



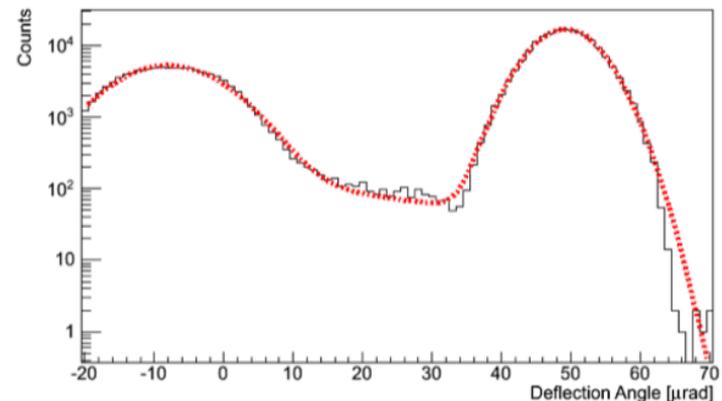
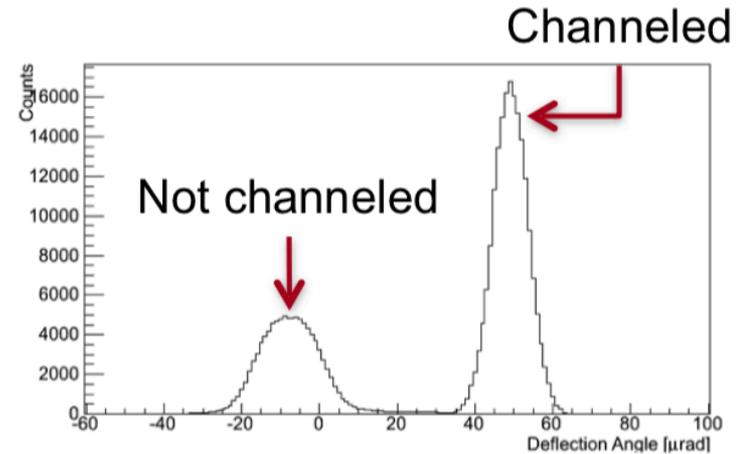
# Nuclear De-channeling Length

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

## Geant4 Channeling



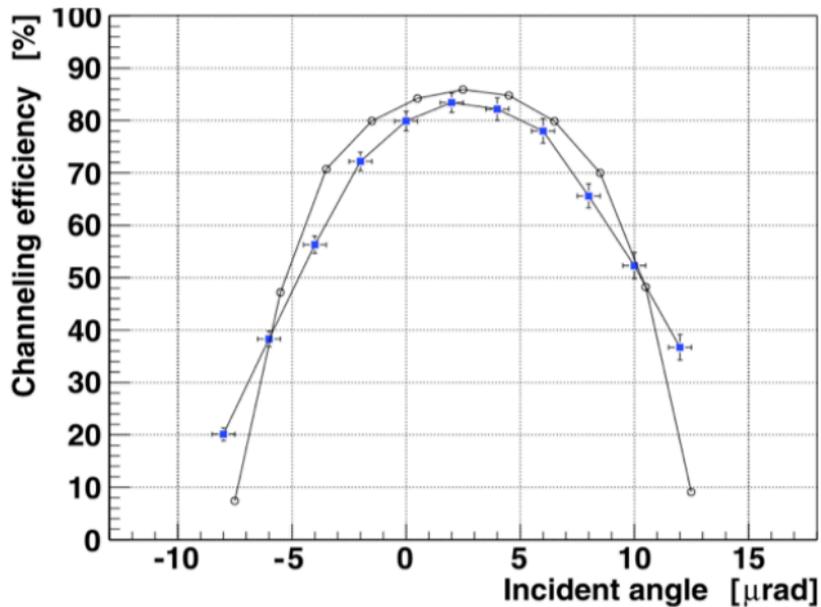
$$L_n = (1.53 \pm 0.35 \pm 0.20) \text{ mm}$$



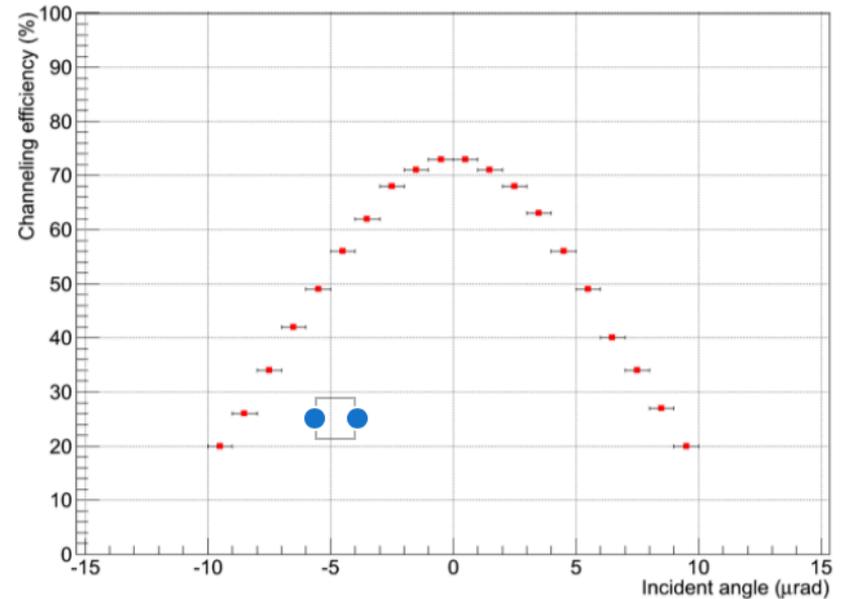
$$L_n = (1.31 \pm 0.05) \text{ mm}$$

# Channeling Efficiency vs. Angle

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



Geant4 Channeling



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

# Cuts and Cuts per Region

# Threshold for Secondary Production

- Every simulation developer must answer the question: **how low can you go?**
  - at what energy do I stop tracking particles?
- This is a balancing act:
  - need to go low enough to get the physics you're interested in
  - can't go too low because some processes have infrared divergence causing CPU to skyrocket
- The traditional Monte Carlo solution is to impose an absolute cutoff in energy
  - particles are stopped when this energy is reached
  - remaining energy is dumped at that point

# Threshold for Secondary Production

- But such a cut may cause imprecise stopping location and deposition of energy
- There is also a particle dependence
  - range of a 10 keV  $\gamma$  in Si is a few cm
  - range of a 10 keV  $e^-$  in Si is a few microns
- And a material dependence
  - suppose you have a detector made of alternating sheets of Pb and plastic scintillator
  - if the cutoff is OK for Pb, it will likely be wrong for the scintillator which does the actual energy measurement

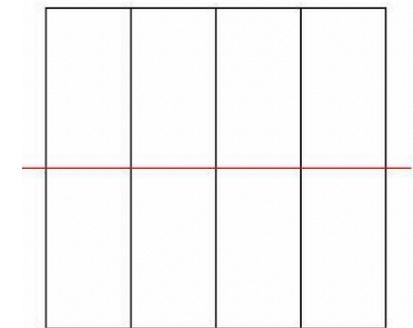
# Threshold for Secondary Production

- Geant4 solution: impose a production threshold
  - this threshold is a distance, not an energy
  - default = 1 mm
  - the primary particle loses energy by producing secondary electrons and gammas
  - if primary no longer has enough energy to produce secondaries which can travel at least 1 mm, two things happen:
    - discrete energy loss ceases (no more secondaries produced)
    - the primary is tracked down to zero energy using continuous energy loss
  - stopping location is therefore correct
- Only one threshold distance is needed for all materials because it corresponds to different energies depending on the material

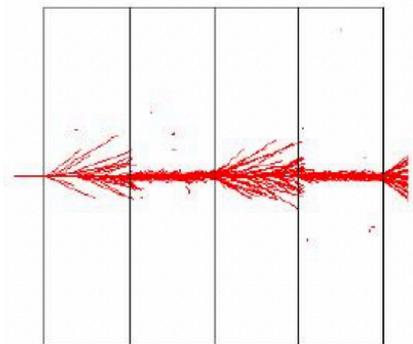
# Production Threshold vs. Energy Cut

- Example: 500 MeV p in LAr-Pb Sampling Calorimeter

## Geant3 (and others)

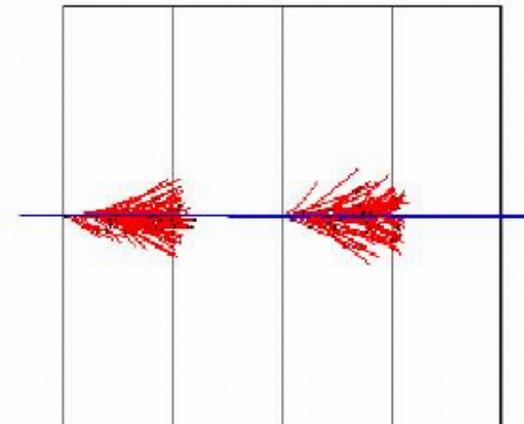


Cut = 2 MeV



Cut = 450 keV

## Geant4

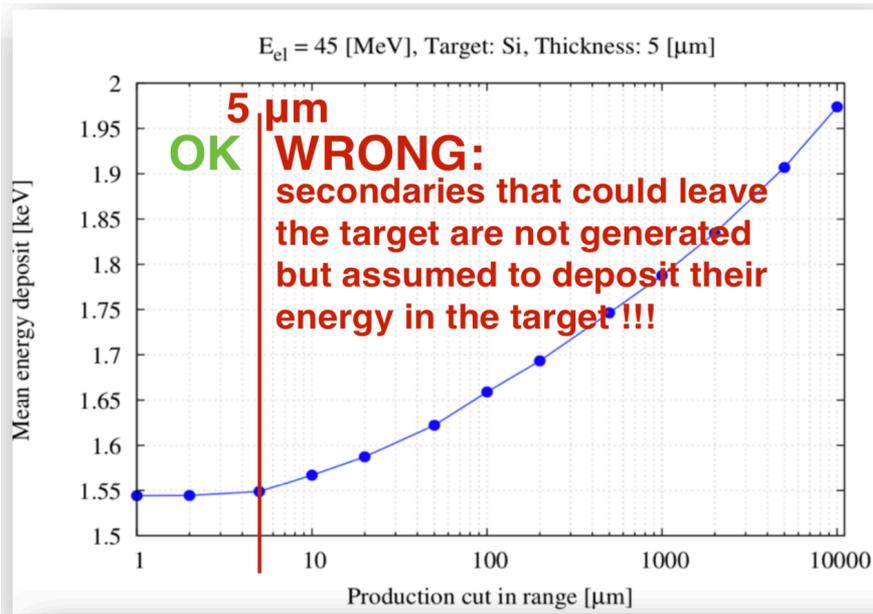


Production range = 1.5 mm

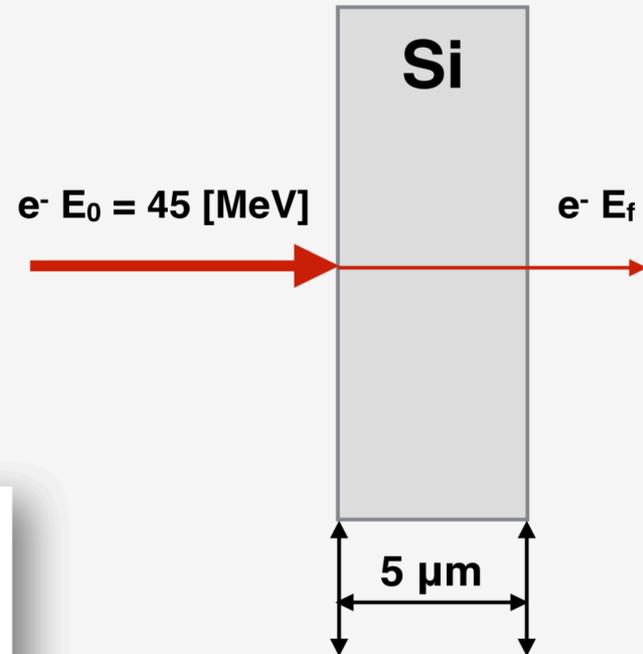
# Threshold for Secondary Production

- Geant4 recommends the default value of 1 mm
  - user needs to decide the best value
  - will depend on size and sensitive elements within the simulated detector, and on available CPU
- This value is set in the SetCuts() method of your physics list
  - defined for  $\gamma$ ,  $e^-$ ,  $e^+$ , proton secondaries
  - UI commands
    - `/run/setCut 0.1 mm`
    - `/run/setCutForAGivenParticle e- 0.1 mm`
- Instead of “secondary production threshold distance” it is more convenient to simply say “cuts”
  - but please remember that this does not mean that any particle is stopped before it runs out of energy

# Choosing the Correct Production Threshold



Compute the mean of the energy deposit ( $E_f - E_0$ ) in the target



cut [ $\mu\text{m}$ ]	mean $E_{\text{dep}}$	rms $E_{\text{dep}}$	prod. thres. [keV]		mean num. sec.	
			$\gamma$	$e^-$	$\gamma$	$e^-$
1	1.54423	0.000573911	0.99	0.99	0.0006811	0.1018230
2	1.54443	0.000583879	0.99	2.9547	0.0006843	0.0316897
5	1.54882	0.000605834	0.99	13.1884	0.0006857	0.0068261
10	1.56717	0.000665733	0.99	31.9516	0.0006730	0.0028232
20	1.58734	0.000743473	1.08038	47.8191	0.0006651	0.0018811
50	1.62223	0.000912408	1.67216	80.7687	0.0006557	0.0011304
100	1.65893	0.001108240	2.32425	121.694	0.0006518	0.0007536
200	1.69338	0.001342180	3.2198	187.091	0.0006465	0.000477
500	1.74642	0.001774670	5.00023	337.972	0.0006184	0.0002617
1000	1.78751	0.002219870	6.95018	548.291	0.0006054	0.0001622
2000	1.83440	0.002861020	9.66055	926.09	0.0005786	9.3e-05
5000	1.90700	0.004243030	14.9521	2074.3	0.0005427	4.07e-05
10000	1.97378	0.006036600	20.6438	4007.59	0.000521	2.22e-05

# Cuts per Region

- In a complex detector there may be many different types of sub-detector involving
  - finely segmented volumes
  - very sensitive materials
  - large, undivided volumes
  - inert materials
- The same value of the secondary production threshold may not be appropriate for all of these
  - user must define regions of similar sensitivity and granularity and assign a different set of production thresholds (cuts) for each
- **Warning: this feature is for users who are**
  - **simulating the most complex detectors**
  - **experienced at simulating EM showers in matter**

# Cuts per Region

- A default region is created automatically for the world volume
  - it uses the cut values which you set in SetCuts() in your physics list
  - these will be used everywhere except for user-defined regions
- In the geometry an instance of G4Region must be created which corresponds to the volume where the cuts are to be changed
- To define different cuts for this special region, user must
  - create a G4ProductionCuts object
  - initialize it with the new cuts
  - assign it to a new region which has already been created

# Cuts per Region

- `void MyPhysicsList::SetCuts() {`  
    `SetCutValue(defaultCutValue, "gamma"); // same for e-, e+, p`  
  
    `// Get the region`  
    `G4Region* aRegion =`  
        `G4RegionStore::GetInstance()->GetRegion("RegionA");`  
  
    `// Define cuts object for the new region and set values`  
    `G4ProductionCuts* cuts = new G4ProductionCuts();`  
    `cuts->SetProductionCut(0.01*mm); // here, same for all`  
  
    `// Assign cuts to region`  
    `aRegion->SetProductionCuts(cuts);`  
  
    `}`

# Summary

- Geant4 provides decay processes for all long-lived elementary particles
  - short-lived and yet-to-be-discovered particles can also be treated with decay files and special classes
- A versatile optical photon package provides all basic low energy photon interactions with volumes and surfaces
  - particle-like approximation to wave-like physics
  - further details: [http://geant4-userdoc.web.cern.ch/geant4-userdoc/UsersGuides/PhysicsReferenceManual/html/electromagnetic/optical\\_photons/optical.html](http://geant4-userdoc.web.cern.ch/geant4-userdoc/UsersGuides/PhysicsReferenceManual/html/electromagnetic/optical_photons/optical.html)
- Phonon propagation in crystals is now available
  - developing area
  - watch for future developments: [http://geant4-userdoc.web.cern.ch/geant4-userdoc/UsersGuides/PhysicsReferenceManual/html/solidstate/phonon\\_lattice\\_interactions/index.html](http://geant4-userdoc.web.cern.ch/geant4-userdoc/UsersGuides/PhysicsReferenceManual/html/solidstate/phonon_lattice_interactions/index.html)

# Summary

- The precision of particle stopping and the production of secondary particles are determined by a **secondary production threshold**
  - which is a length
- For complex detectors with varying types of sensitive volumes, different production thresholds may be defined for different regions within the detector