Monte Carlo simulations in SuperCDMS

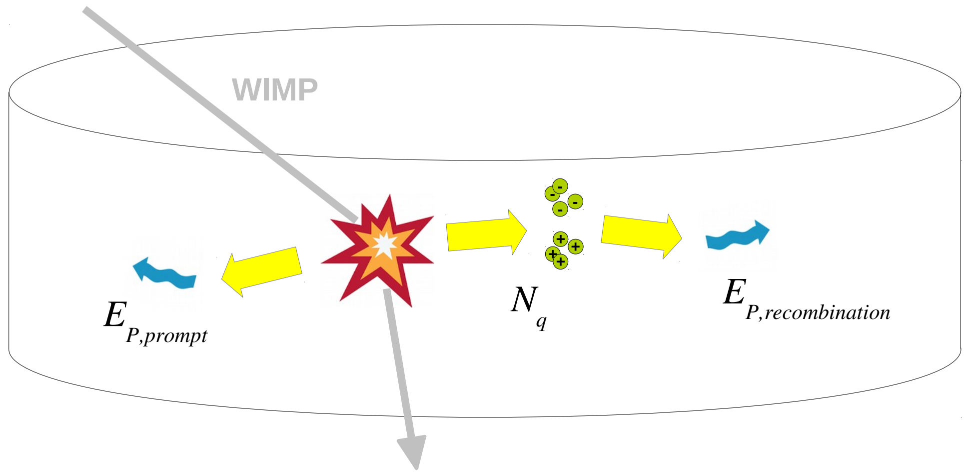
Elías López Asamar

SuperCDMS Durham University IP3

MC4BSM, Durham University, 18th of April 2018

The SuperCDMS approach

Measure <u>phonons</u> (E_P) and <u>charge carriers</u> (N_q) produced by recoiling Ge nucleus



$$\boxed{N_q} = \boxed{Y}\frac{\boxed{E_R}}{\epsilon}, \qquad \epsilon(\mathrm{Ge}) = 3.0\ eV$$

$$\boxed{E_P} = E_{P,prompt} + E_{P,recombination} = \boxed{E_R}$$

E_R: Recoil energy, related to WIMP mass

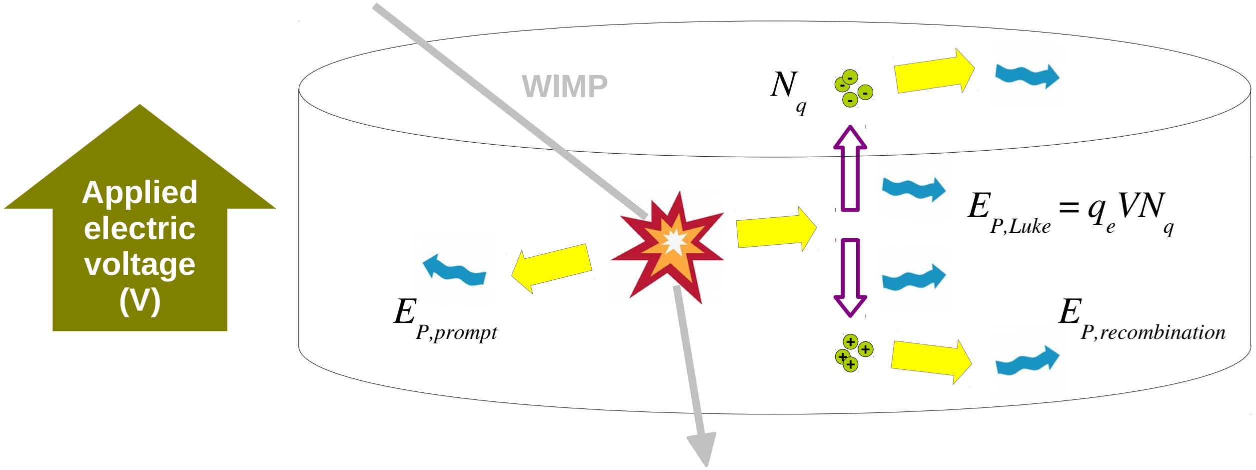
Y: Charge yield, depends on recoiling particle

	Y
Recoiling electron	1
Recoiling Ge nucleus	~0.3

It is possible to know (E_R, Y) from (E_P, N_q)

The SuperCDMS approach

Measure <u>phonons</u> (E_P) and <u>charge carriers</u> (N_q) produced by recoiling Ge nucleus



$$\boxed{N_q} = \boxed{Y}\frac{\boxed{E_R}}{\epsilon}, \quad \epsilon(\mathrm{Ge}) = 3.0\ eV$$

$$\boxed{E_P} = E_R + q_e V N_q = \boxed{E_R}\left(1 + \boxed{Y}\frac{q_e V}{\epsilon}\right)$$

Additional contribution to E_P called “Luke phonons”

E_R: Recoil energy, related to WIMP mass
***Y*: Charge yield, depends on recoiling particle**

	Y
Recoiling electron	1
Recoiling Ge nucleus	~0.3

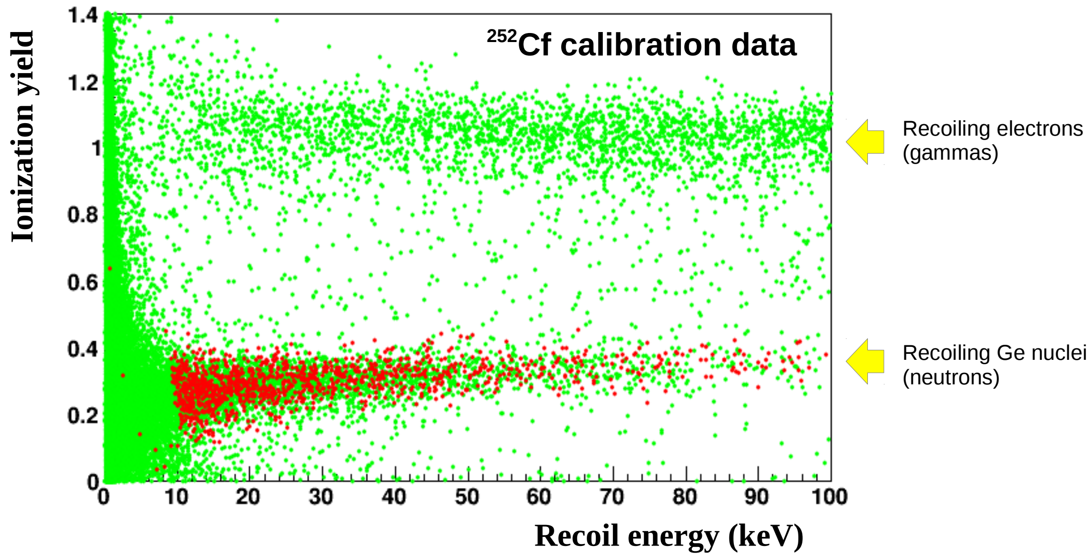
It is possible to know (E_R, Y) from (E_P, N_q)

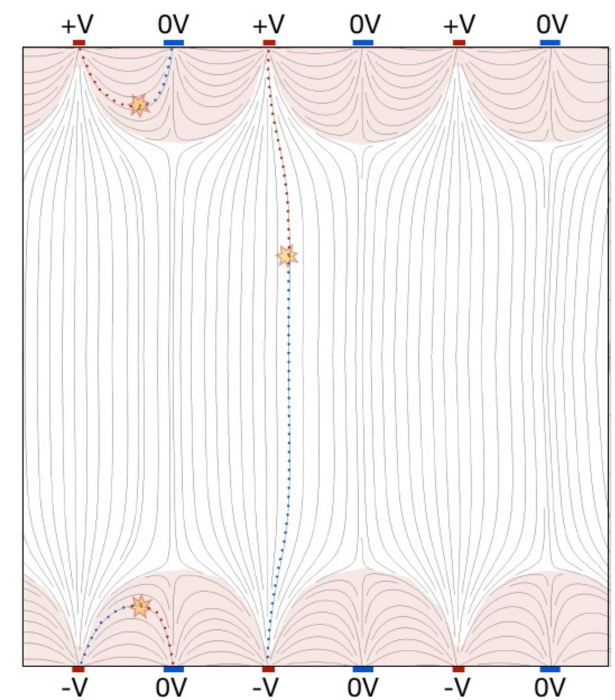
The SuperCDMS approach

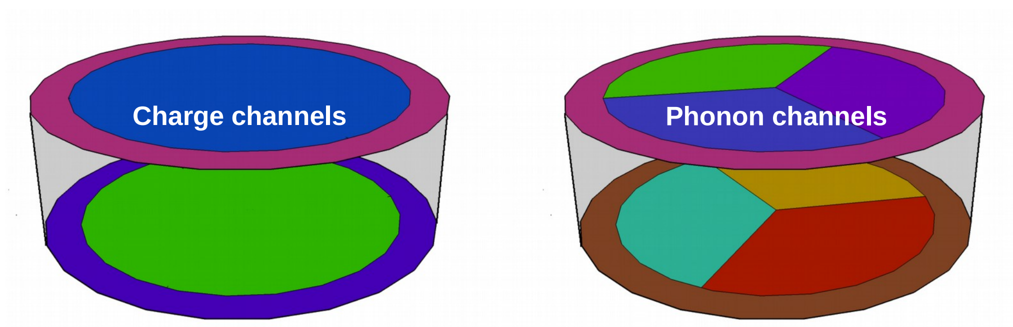
The iZIP (“interleaved z-sensitive ionization and phonon sensors”) approach:

Measuring $Y \Rightarrow$ NR/ER discrimination

Applied electric field (4 V) + segmented readout $\Rightarrow$ full fiducialization







The SuperCDMS approach

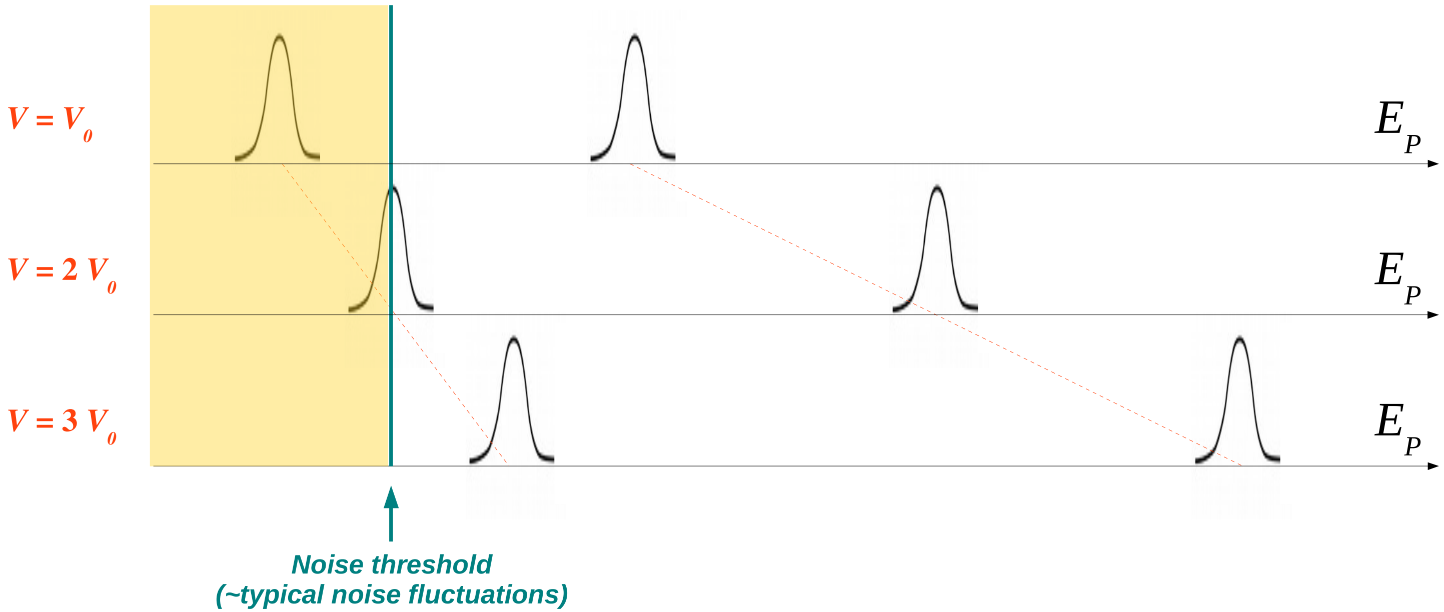
The HV ("high-voltage operation", a.k.a. CDMSlite) approach:

Increased applied voltage (*V*) enables to effectively decrease threshold

$$E_P = E_R + q_e V N_q = E_R(1 + Y\frac{q_e V}{\epsilon}) = \boxed{g(V)} E_R$$

Contribution from applied electric field

$g(V) > 1$



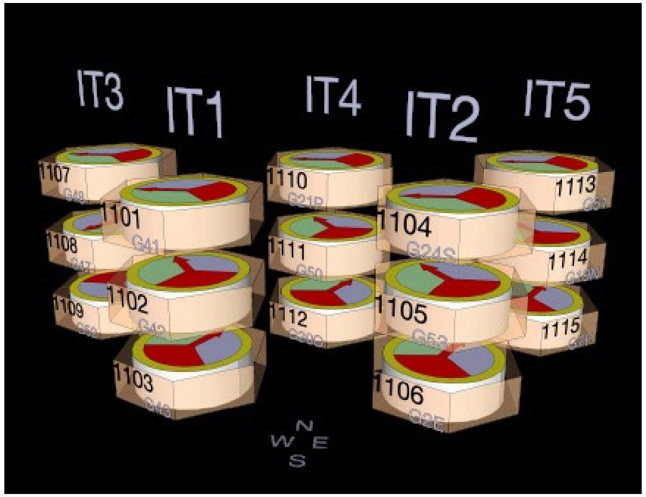
However N_q remains below threshold ⇒ charge signal is useless

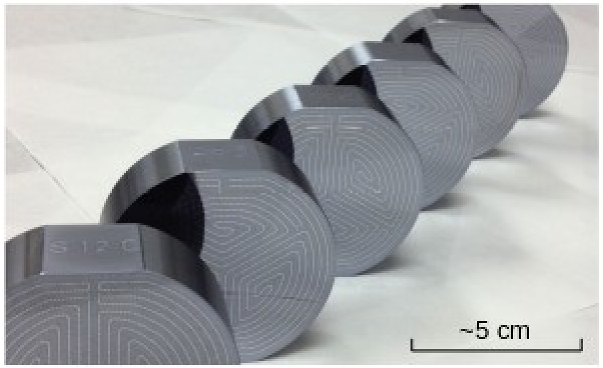
SuperCDMS Soudan

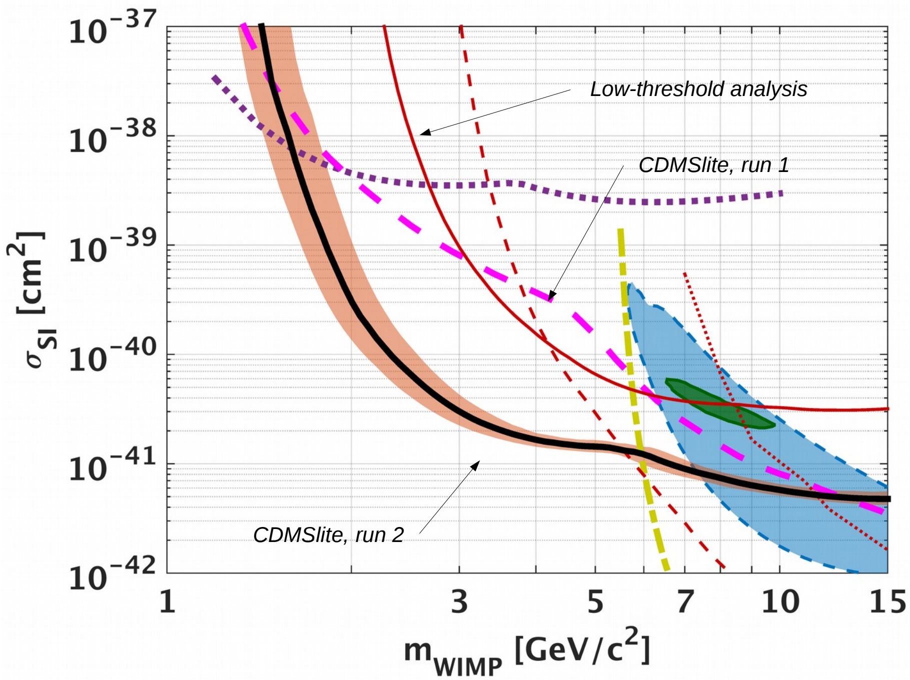
15 cylindrical Ge detectors, 9.2 kg total

Deployed at Soudan Underground Laboratory (US, 714 m depth)

Operated between March 2012 and November 2015





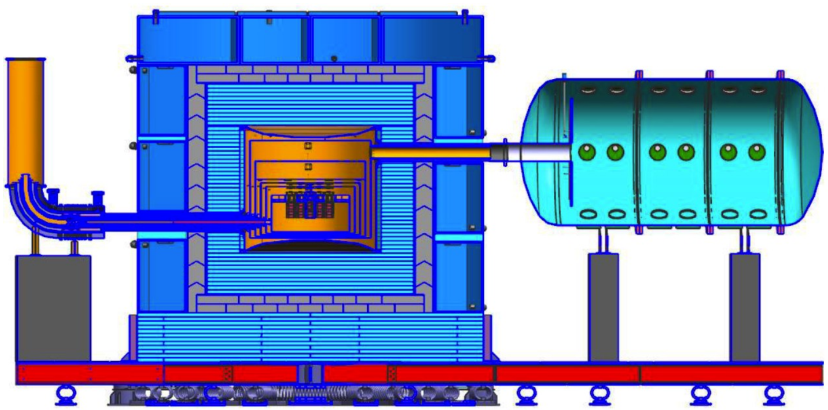


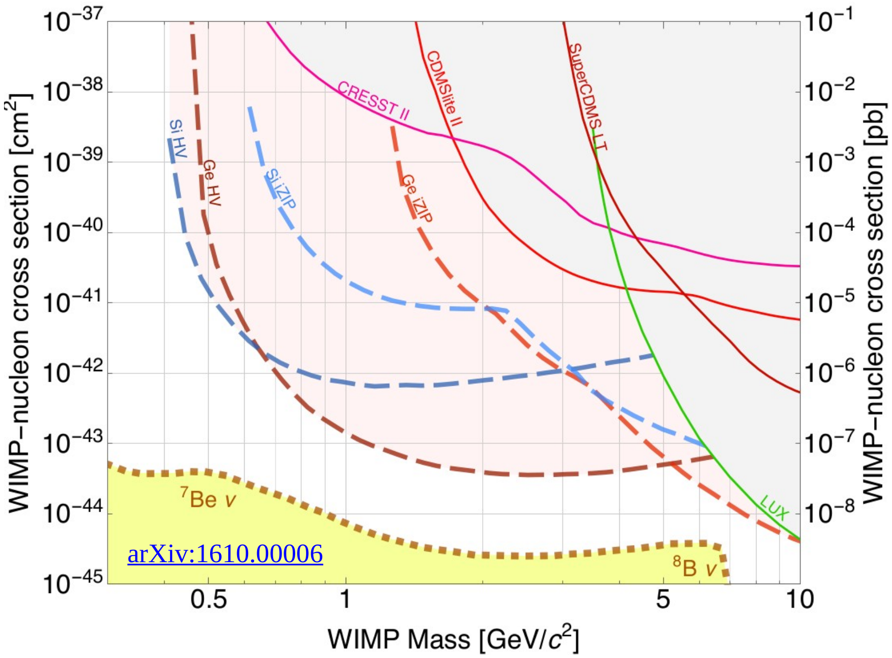
SuperCDMS SNOLAB

Project proposal:

- **iZIP detectors (full background rejection capabilities): 14 kg Ge, 1.2 kg Si**
- **HV detectors (lowered energy threshold): 10 kg Ge, 2.4 kg Si**

In construction phase since project review on January 2018



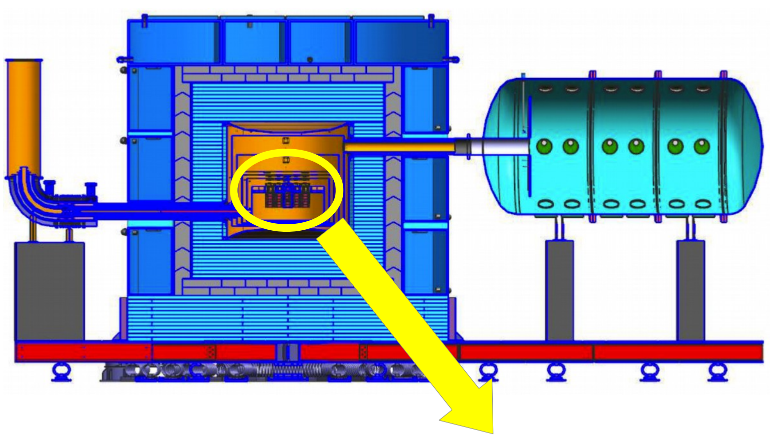


Planned to start operations in 2020, expecting ~5 years of data taking

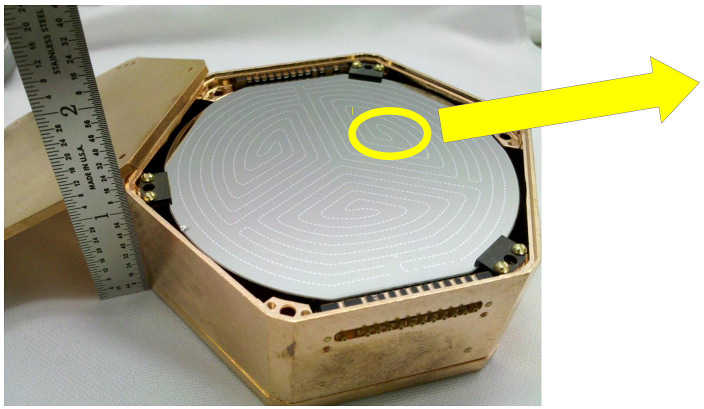
The physics of a SuperCDMS event

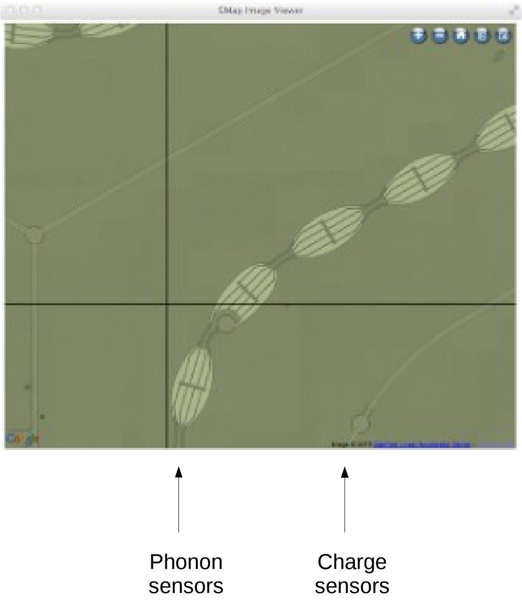
Grouping different simulation levels in a single package: <u>SuperSim</u>

- **Interaction of radiation with experimental setup**
- **Condensed matter physics for phonon and charge in Ge or Si crystal**
- **Response of phonon and charge sensors**



Phonon sensors: Al traps + W transition-edge sensors
Charge sensors: electrodes



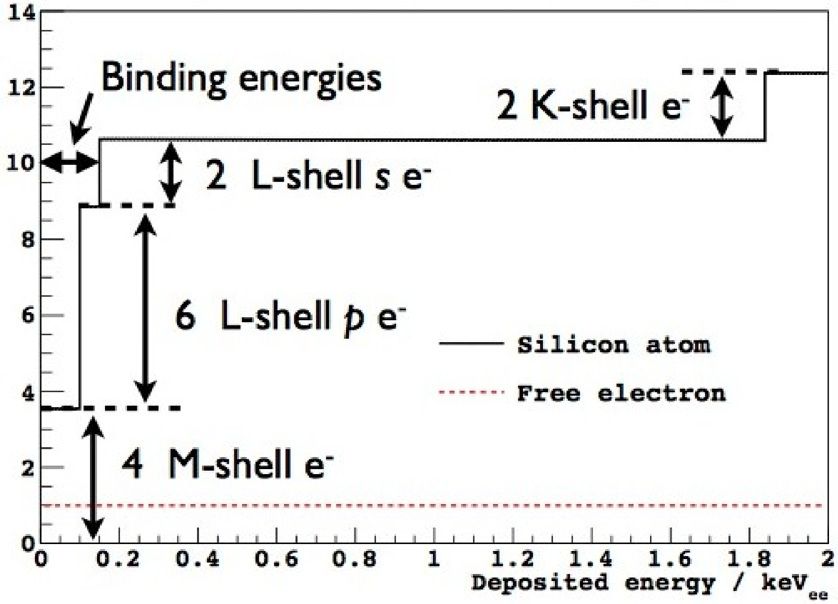


The simulation of the SuperCDMS physics

Grouping different simulation levels in a single package: <u>SuperSim</u>

- **Radiation-matter interaction: standard Geant4**
  - **“Shielding_EMZ” physics list by default**
  - **Able to include Monash University model for Compton scattering**
- **Condensed matter physics: created new Geant4 library (G4CMP)**
- **Sensor response: mainly analytical models**

Predicted Compton spectrum at low energy



Modelling condensed matter physics

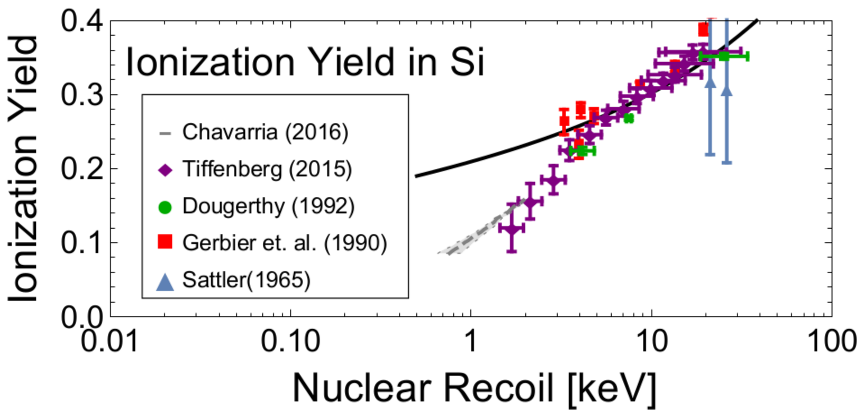
Particle types:

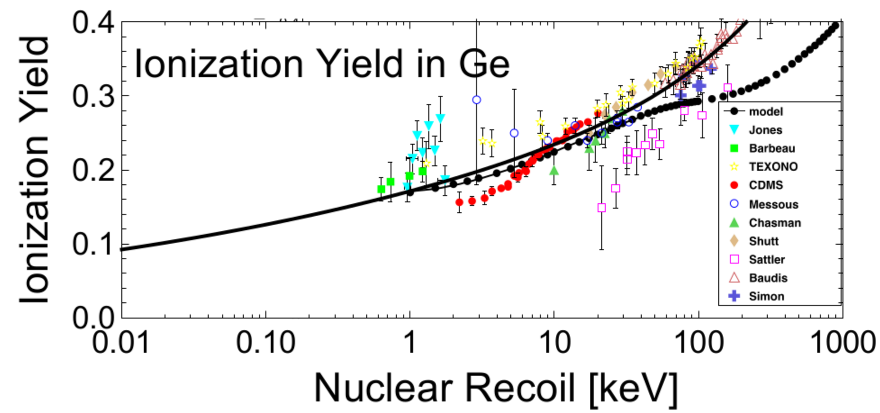
- **Charge carriers: electrons and holes**
- **Phonons: longitudinal (L), transverse slow (TS) and transverse fast (TF)**

Initial particle creation:

- **Energy partition between e-h pairs and prompt phonons: Lindhard model**
- **Prompt phonons: assume $E = \hbar\nu_{Debye}$, isotropic, final polarization distribution**

Simulation results practically insensitive to prompt phonon assumptions





Modelling condensed matter physics

Charge propagation:

- **For electrons velocity (*v*) is not parallel to wave vector (*k*)**

  Effective mass matrix ⇒ oblique propagation along preferred directions

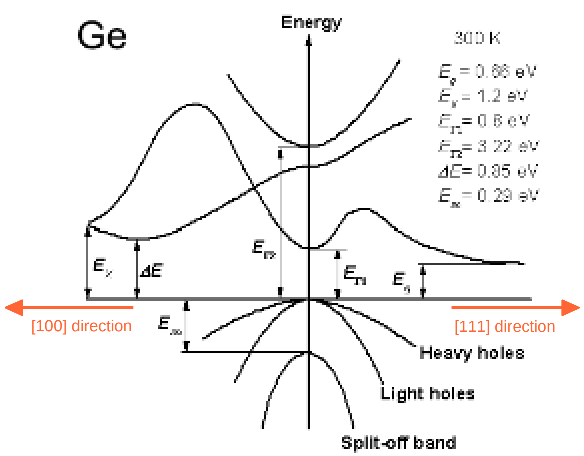
- **Luke scattering: due to carrier-lattice coupling, limits drifting velocity**

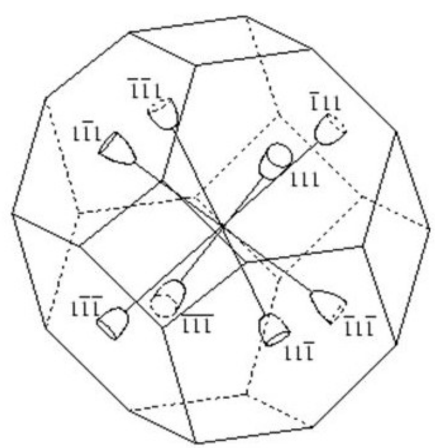
  1) Assume *E* and *k* conservation

  2) Use perturbation theory describing carrier-lattice coupling

- **Inter-valley scattering: jumps between preferred directions of propagation**

Assuming uniform distribution for unconstrained scattering angles

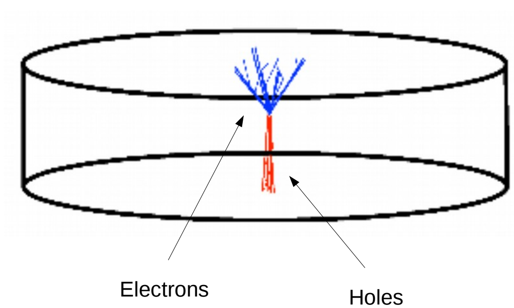




L valleys of Ge

$$\begin{pmatrix} v_{\parallel} \\ v_{\perp} \\ v_{\perp} \end{pmatrix} = \frac{2e[\epsilon\tau(\epsilon)]}{3k_BT} \begin{pmatrix} m_{\parallel}^{-1} & 0 & 0 \\ 0 & m_{\perp}^{-1} & 0 \\ 0 & 0 & m_{\perp}^{-1} \end{pmatrix} \cdot \begin{pmatrix} E_{\parallel} \\ E_{\perp} \\ E_{\perp} \end{pmatrix}$$

Assuming x_1 axis parallel to a preferred direction of propagation



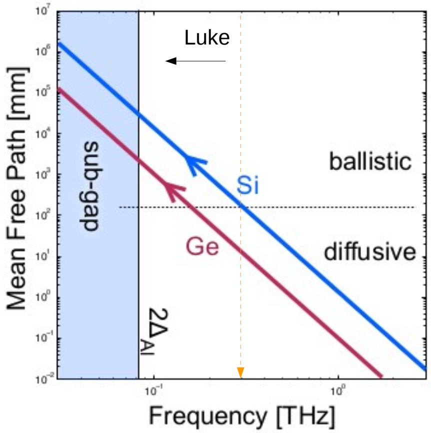
Modelling condensed matter physics

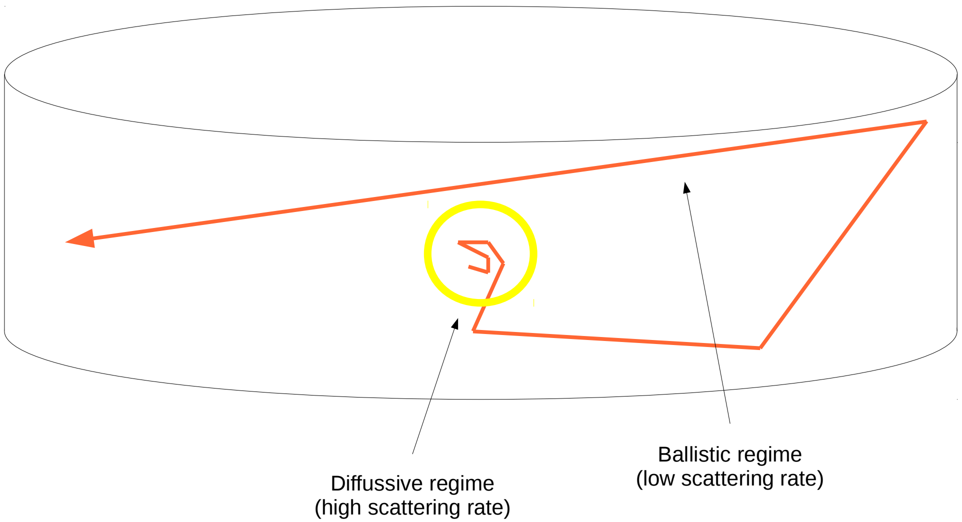
Phonon propagation:

- **Isotope scattering: Ge and Si isotopes break lattice regularity**
  1) **Total cross-section ~ ν^4**
  2) **Assume *E* conservation**
- **Anharmonic decay: due to non-harmonic terms in the phonon hamiltonian**
  1) **Total cross-section ~ ν^5**
  2) **Assume *E* and *k* conservation**

Assuming uniform distribution for unconstrained angles

Initial evolution of prompt phonons is diffusive
Initial evolution of Luke phonons is ballistic





Modelling sensor response

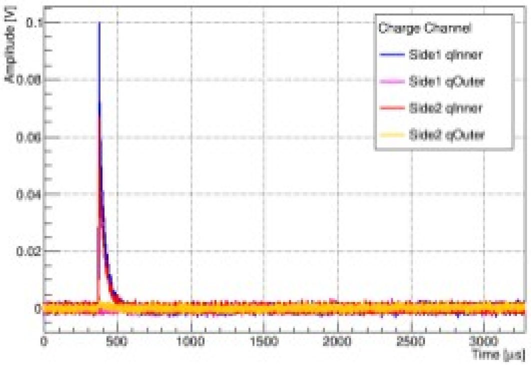
Drifting charge carriers measured by current induced in electrodes

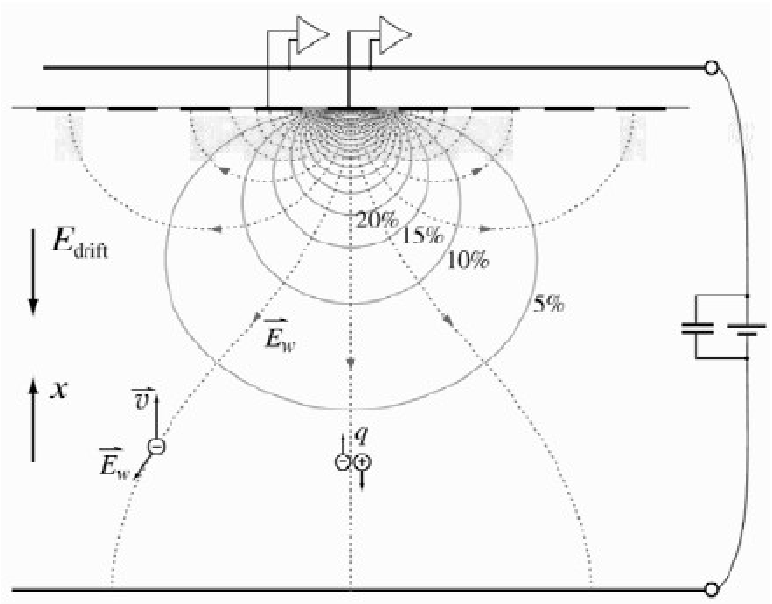
Based on Shockley-Ramo theorem

$$I = e\,\mathbf{E}_w(\mathbf{x}) \cdot \mathbf{v}$$ (instantaneous)

$$Q_{induced} = -e\phi_w(\mathbf{x})$$ (integrated over time)

$E_w(x)$ and $\phi_w(x)$ quantify electrode sensitivity at x (are not related to applied field)





Typical time scale below readout sensitivity ⇒ only $Q_{induced}$ measurable

Analytical model scaling pulse template by $Q_{induced}$, requires to calculate $\phi_w(x)$

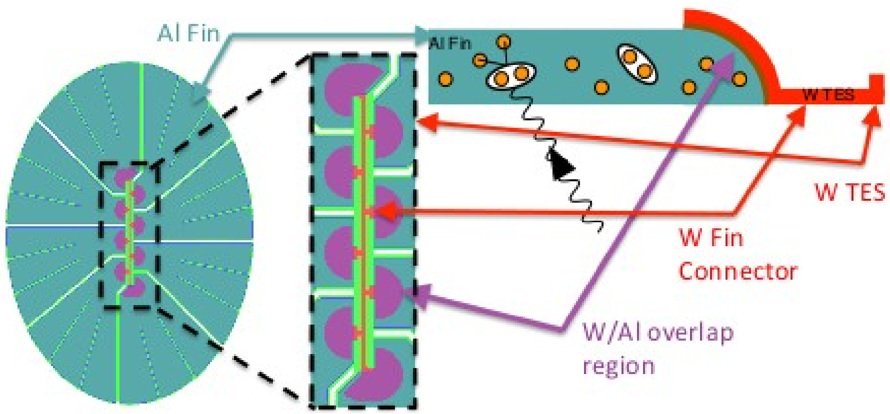
Modelling sensor response

Phonon energy concentrated with superconducting Al quasiparticle (QP) traps

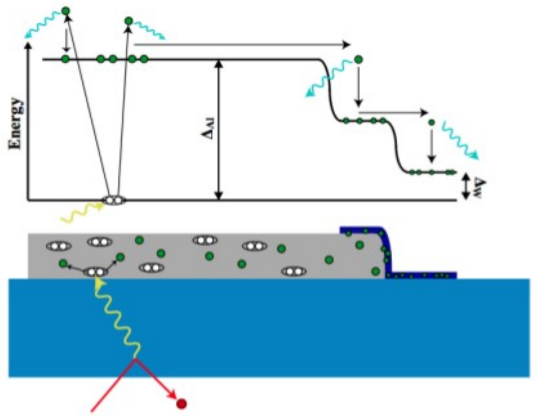
An incident phonon creates a QP if its energy (E_p) is above threshold (Δ)

QP decays to phonons that may create further QPs ⇒ cascade, ends when $E_p < \Delta$

QPs diffuse until finding low Δ regions (Al/W overlap, W), then decay further



QP: excited states in superconducting phase
e-h superposition (⇒ neutral)
Created by breaking Cooper pairs



MC model, using quasiparticle-phonon coupling theory+approximations:

1) Unidimensional phonon propagation, normal to Al-Ge surface

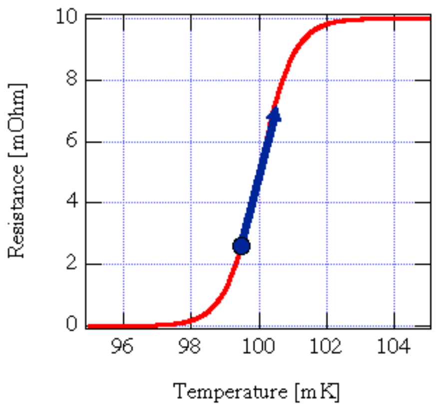
2) Quasiparticle decays only at average position (half Al height)

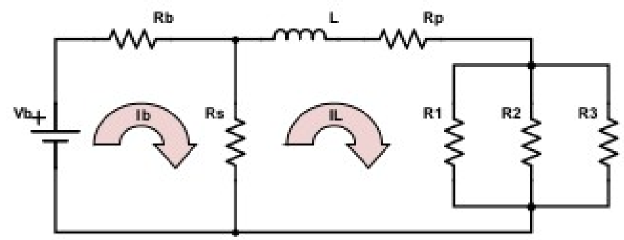
Modelling sensor response

Al traps concentrate phonon energy in W transition-edge sensors (TES)

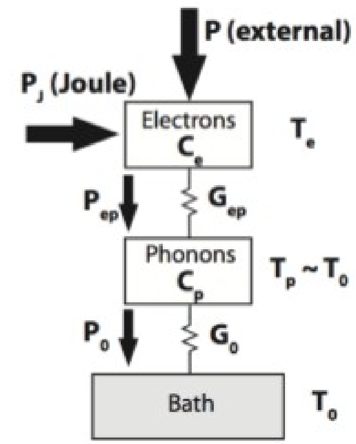
Collected energy heats TES, increasing electric resistance

Stable system: return to equilibrium by electrothermal feedback





Electrical model



Thermal model

$$\dot{I}_L = \frac{V_{b0} - I_L\left(R_0 + \frac{1}{\sum_k G_k}\right)}{L} \quad , \quad R_i(T_i) = \frac{1}{G_i(T_i)} = \frac{R_n}{2}\left(1 + \tanh\frac{T_i - T_c}{T_w}\right)$$

$$\dot{T}_i = \frac{K(T_b^5 - T_i^5) + I_L^2 \frac{G_i(T_i)}{\left(\sum_k G_k(T_k)\right)^2} + P_i^P}{C_n}$$

Analytical model requiring numerical solution of ODE system

Use of simulations in SuperCDMS

Only some examples covered here:

- **Backgrounds assessment for SuperCDMS Soudan**
  - **1) Model of gamma spectrum**
  - **2) Irreducible neutron background (radiogenic+cosmogenic)**
- **Determination of the fiducial volume of SuperCDMS Soudan**
- **Design of event reconstruction for SuperCDMS SNOLAB**

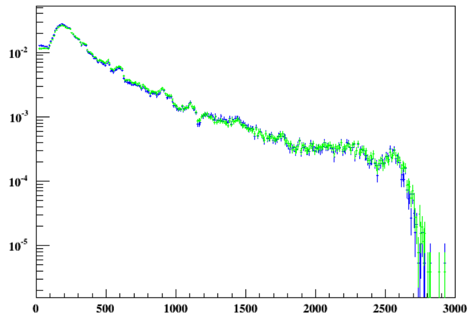
Cases not covered here include shielding design and selection optimisation

Model of gamma spectrum for SuperCDMS Soudan

Procedure:

- **Generate MC spectra for all sources, including detector response**
- **Then find weighted sum that best fits to data**

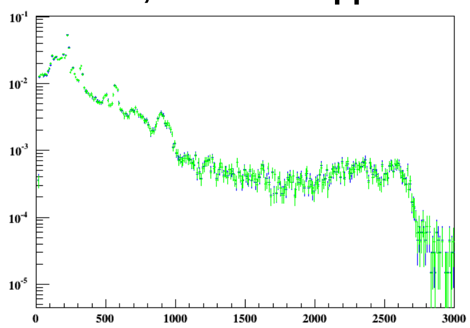
Measured data



$=$

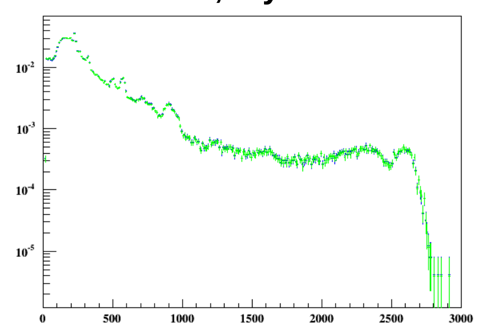
$= w_1 \times$

^{238}Th, detector support



$+ w_2 \times$

^{238}Th, cryostat

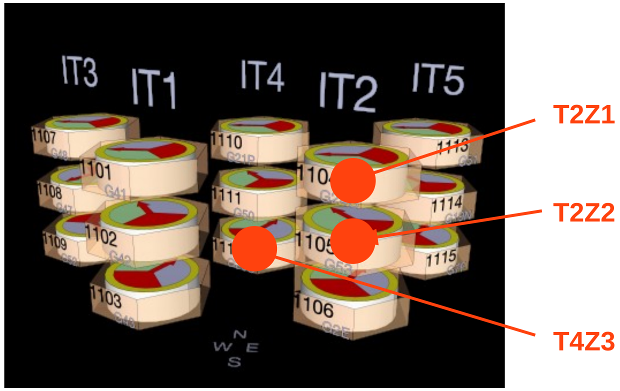


$+ \ldots$

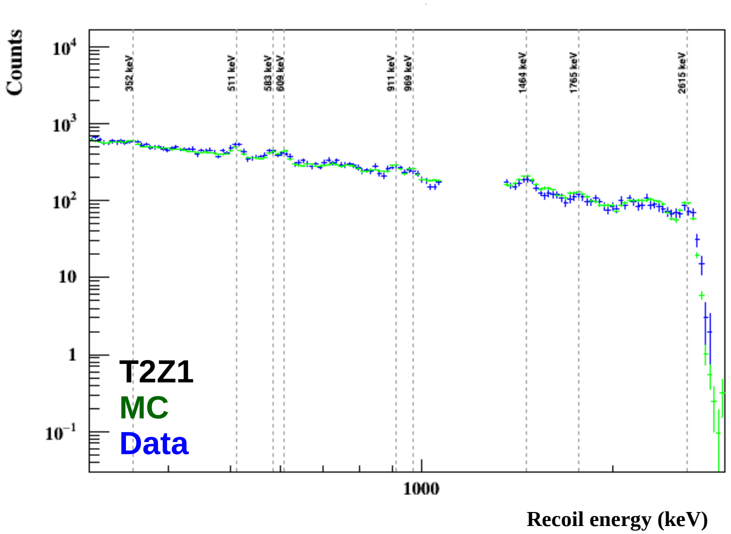
Leads to a measurement of radioactivity levels of the experiment

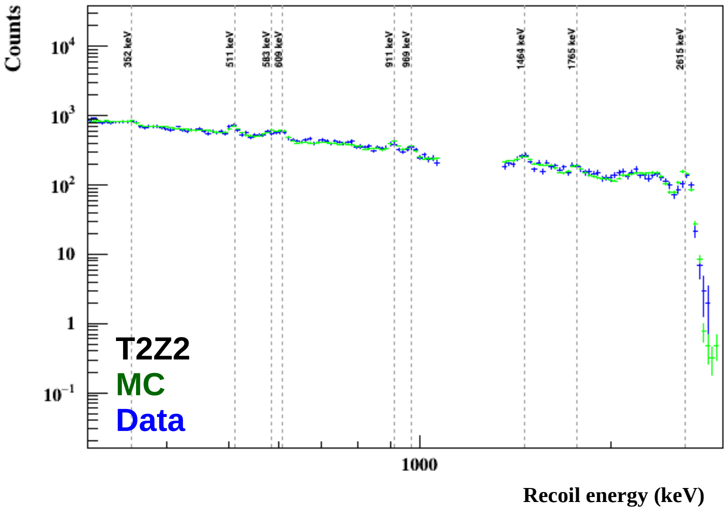
Model of gamma spectrum for SuperCDMS Soudan

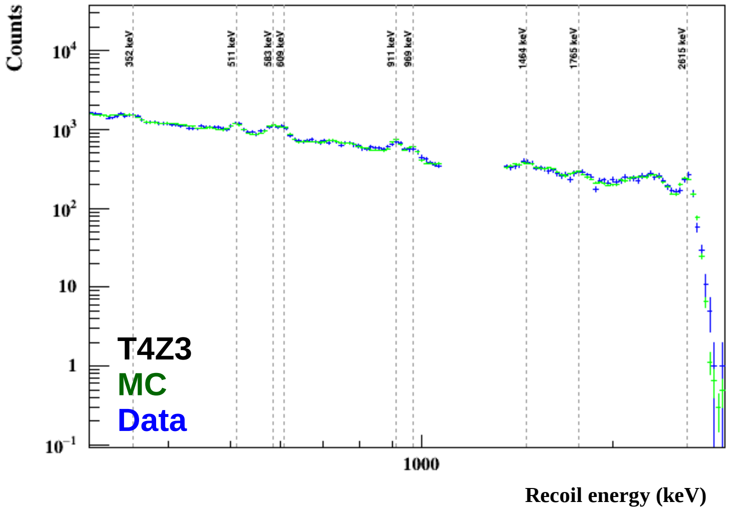
Results from material screenings used as constraints



Orange circles shows detectors used







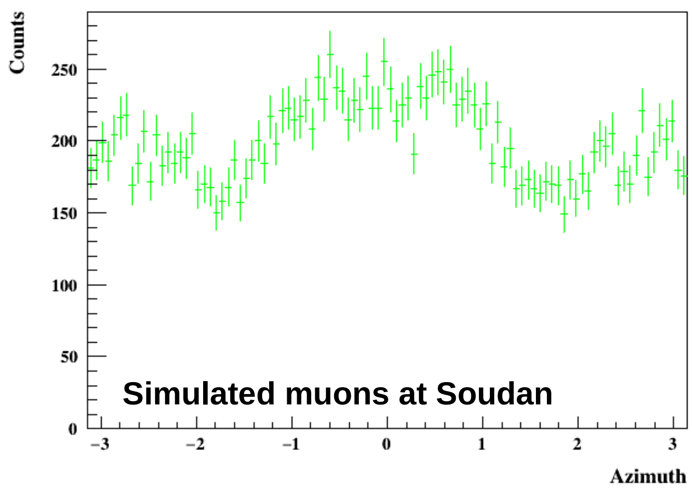
Neutron background in SuperCDMS Soudan

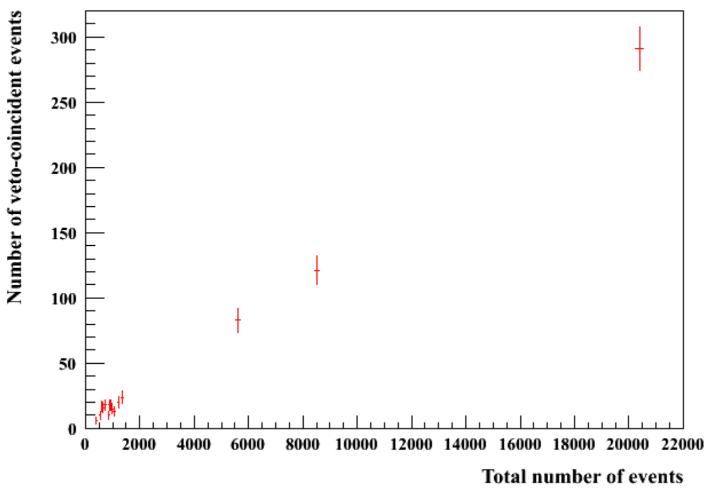
Radiogenic neutron background:

- **Rate of produced neutrons calculated using measured radioactivity levels**
- **Used MC simulation to determine acceptance to produced neutrons**
- **Prediction for WIMP search using full exposure: $0.095^{+0.06}_{-0.05}$ events**

Cosmogenic neutron background:

- **Used MC simulation of muons thrown from 6 m above cavern**
- **Muons generated according to distributions measured in cavern (MUSUN)**
- **Prediction for WIMP search using full exposure: 0.024 ± 0.024 events**





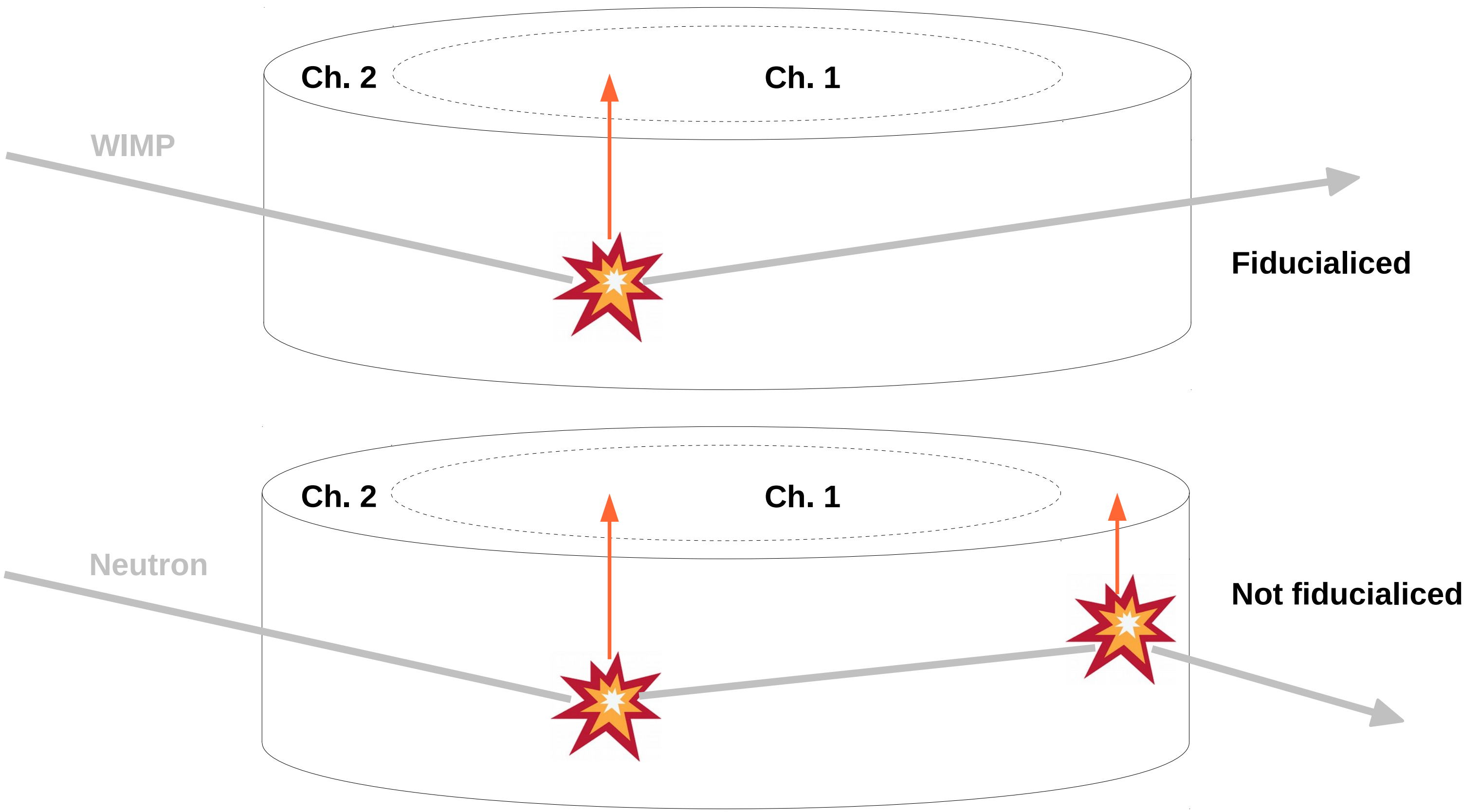
Fiducial volume of SuperCDMS Soudan

Knowing the fiducial volume (FV) is essential to calculate WIMP exclusion limits

For nominal operation data, FV is determined using ^{252}Cf neutrons

Need to correct for multiple neutron scattering in the detector

Otherwise FV is underestimated



Fiducial volume of SuperCDMS Soudan

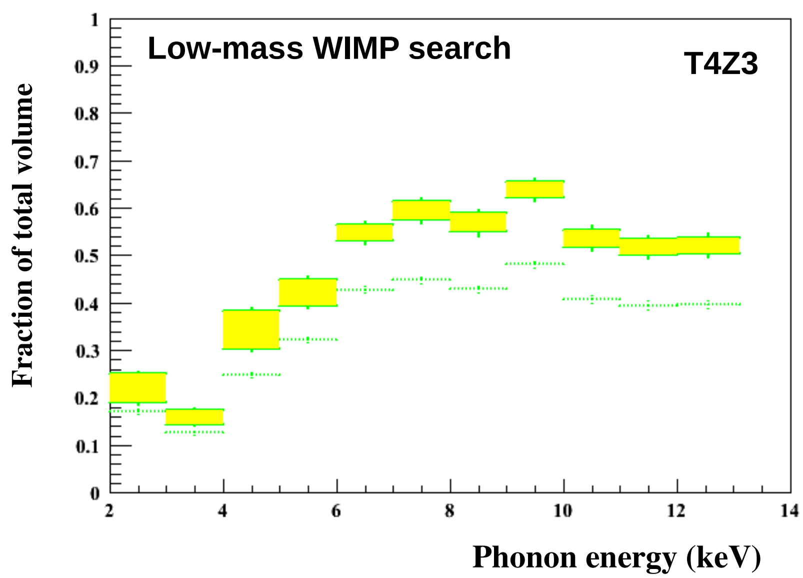
Multiple-scattering correction calculated using MC simulations

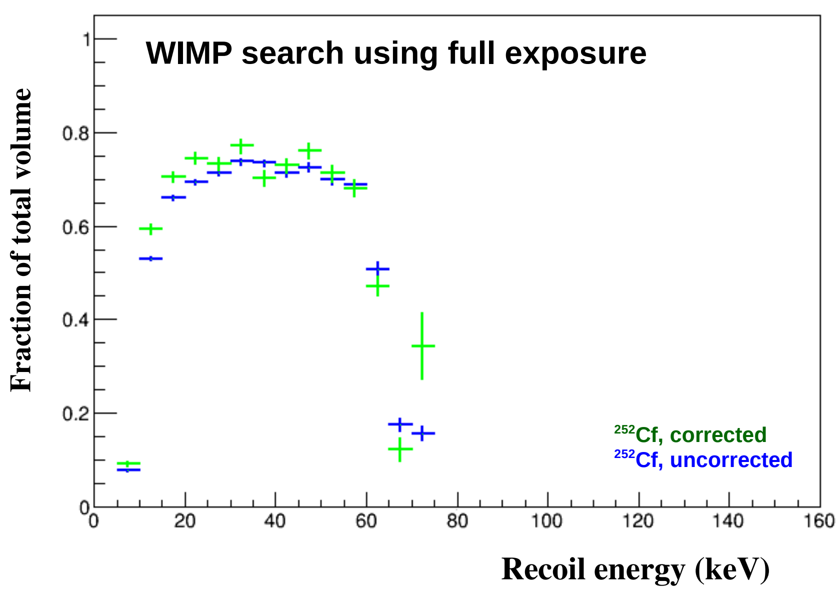
Need to include detector response effects

$$\alpha_\chi = \frac{\tilde{\alpha}_\chi}{\tilde{\alpha}_n}\,\alpha_n \equiv k\,\alpha_n$$

Acceptance to ^{252}Cf neutrons

Correction factor calculated from MC



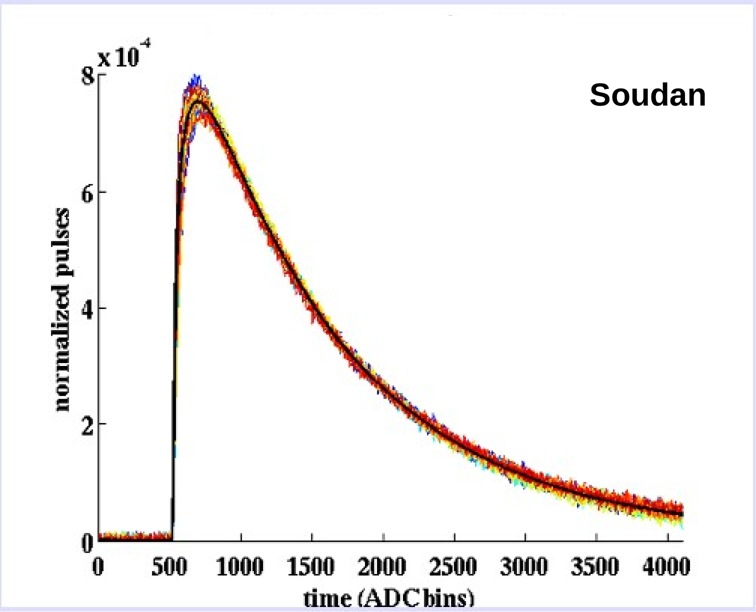


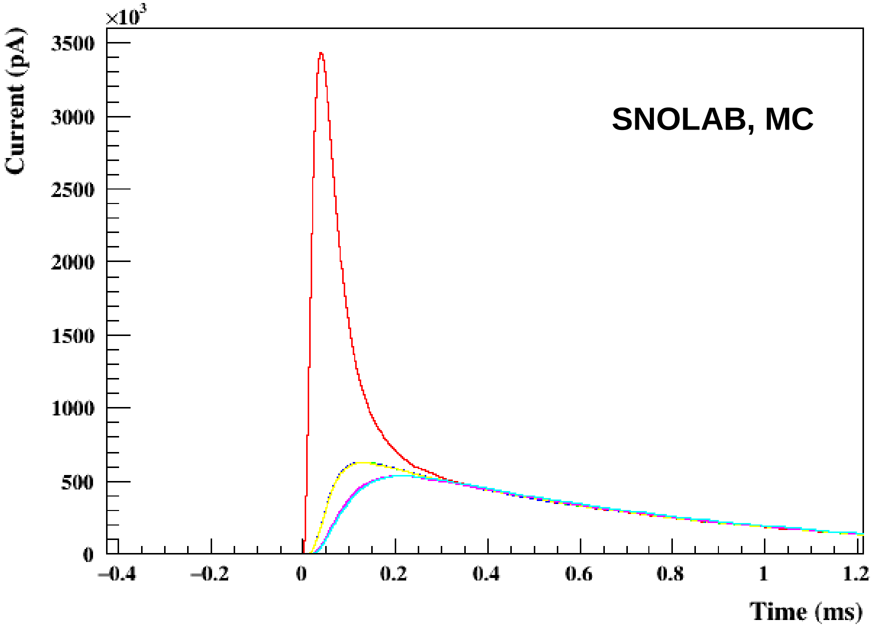
Design of event reconstruction using phonon signal

Pulse shape in SuperCDMS SNOLAB determined by increased sensor coverage

Large fraction of Luke phonons detected before substantial changes in direction
Therefore large pulse variation over channels depending on event position

No longer possible to reconstruct pulses by fitting to fixed templates

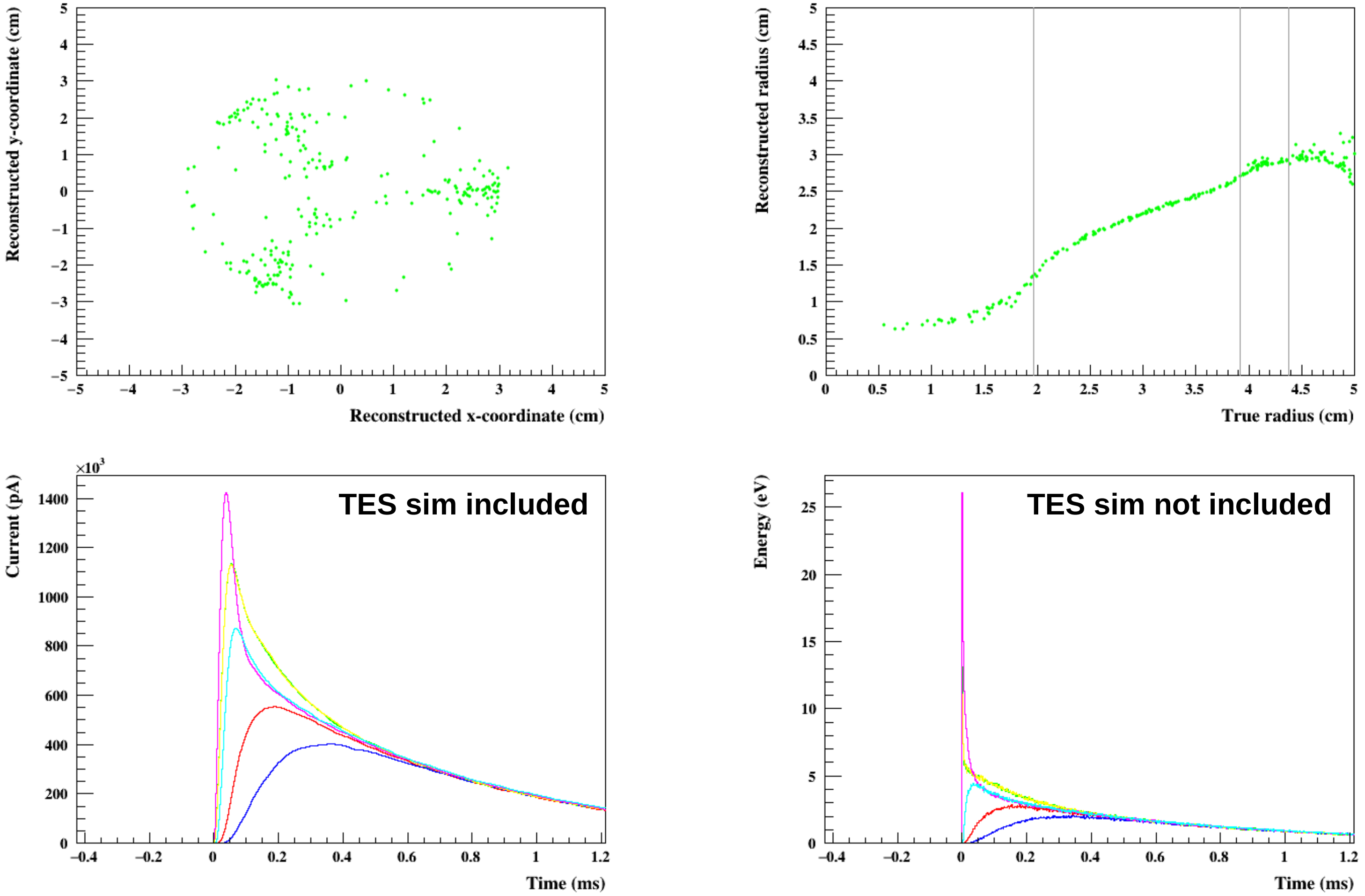




Design of event reconstruction using phonon signal

Simulations are relevant to understand pulse shape variation:

- **Allow to check true event position**
- **Enable to separate phonon physics effects in crystal from TES dynamics effects**



Summary

- **Currently having a mature simulation of the full experiment:**
  - **1) Interaction of radiation with matter**
  - **2) Phonon and charge carrier physics in semiconductor crystals**
  - **3) TES dynamics and current induced in electrodes**

- **Such simulation framework has wide range of uses, among others:**
  - **1) Backgrounds assessment**
  - **2) Determination of fiducial volume**
  - **3) Design of event reconstruction**

Summary

- **Currently having a mature simulation of the full experiment:**
  - **1) Interaction of radiation with matter**
  - **2) Phonon and charge carrier physics in semiconductor crystals**
  - **3) TES dynamics and current induced in electrodes**

- **Such simulation framework has wide range of uses, among others:**
  - **1) Backgrounds assessment**
  - **2) Determination of fiducial volume**
  - **3) Design of event reconstruction**

Thank you for your attention...