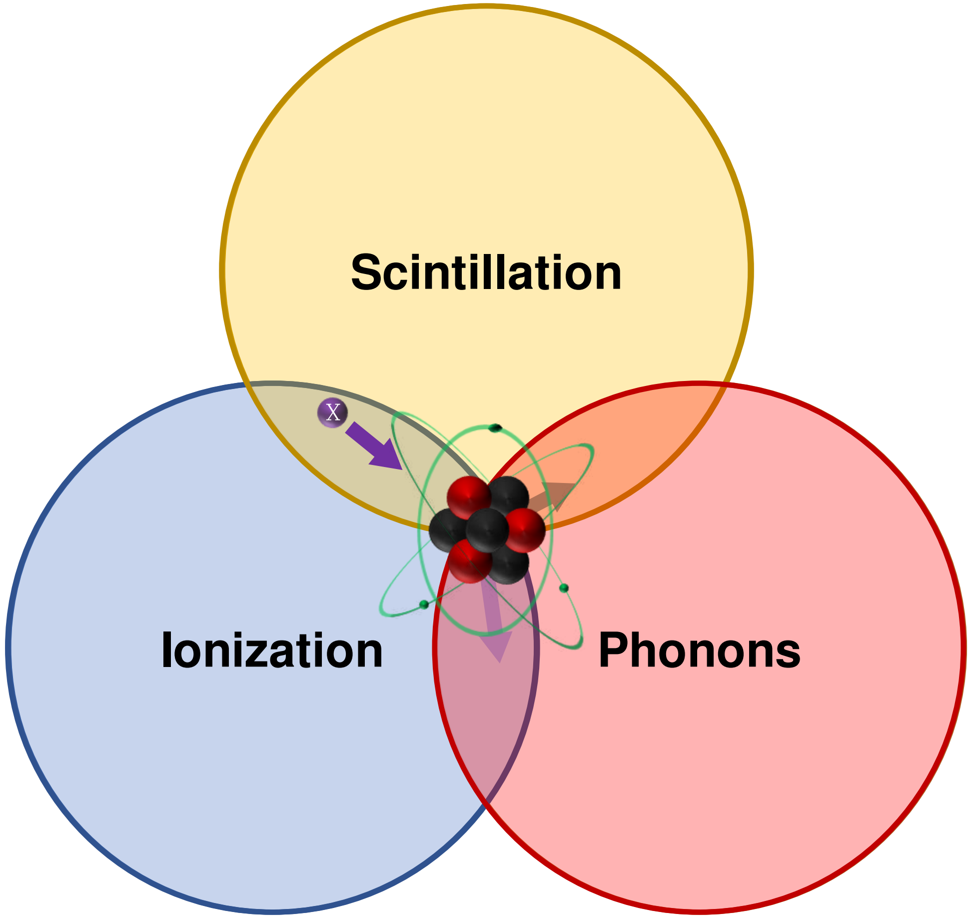
Phonons in Cryogenic Detectors (of COSINUS)

Speaker: Moritz Kellermann

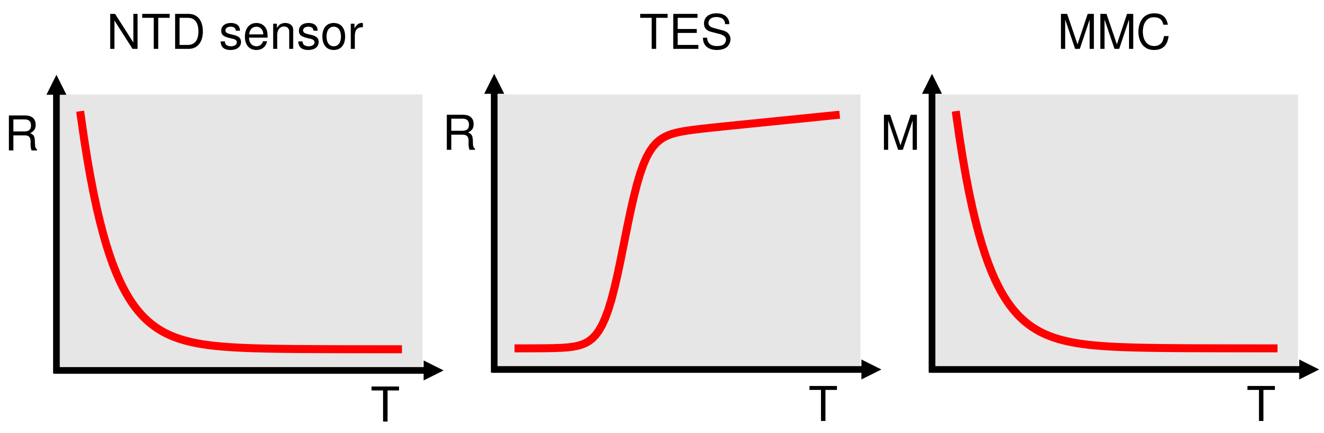
IMPRS Young Scientist Workshop 2023

Direct detection of dark matter



Phonons:
- >90 % of nuclear recoil energy
- Measured at very low temperatures <1 K
- Common use in rare event searches
- Excellent energy resolutions up to ~eV

How to measure phonons:
- Couple cryogenic thermometers to the sample
- Measured temperature $\Delta T = {}^{\Delta E}/_{C}$

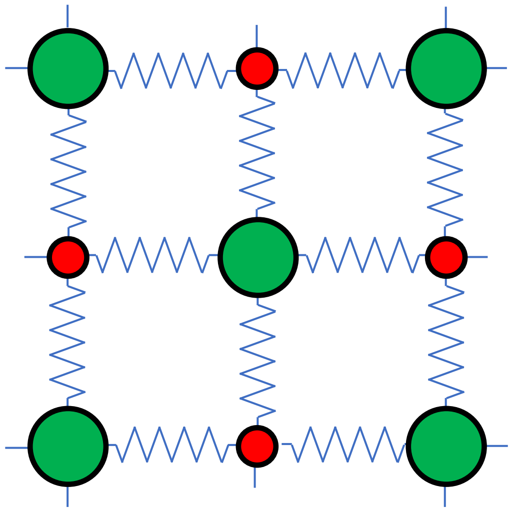


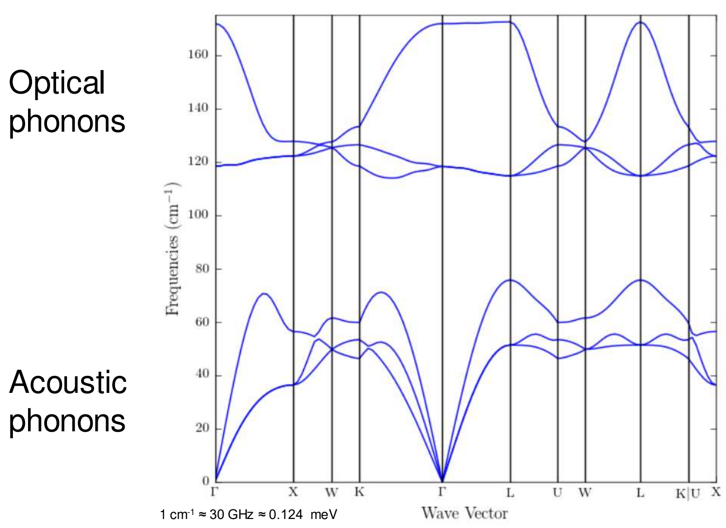
➢ More information in the next talk by Mukund

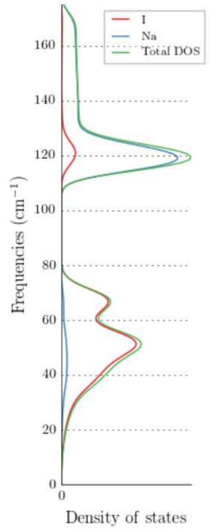
Recap: Phonons

- Crystals at $T > 0$ contain soundwaves of the lattice
- Analogue to photons: waves are described by bosons following Maxwell Boltzmann distribution (phonons)
- Debye model:
  - ➢ Heat capacity of crystals at low temperatures ($T < T_D$) scales with T^3 (phononic heat capacity)
  - ➢ In metals: linear term for free electrons (electronic heat capacity)
- Depending on the lattice and nuclear physics: different acoustic & optical modes

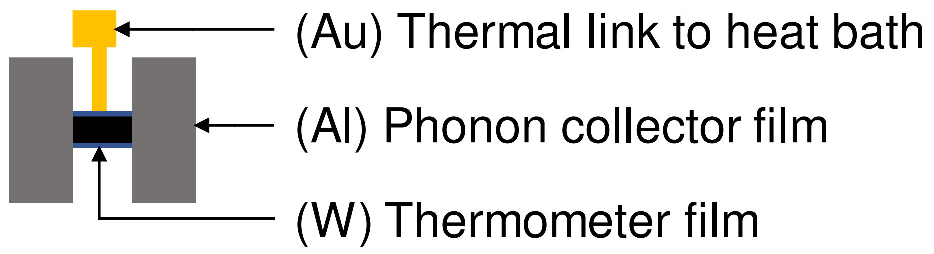
Phonons have a frequency (~1 THz) / energy (~10 meV) → **Energy/heat hides where the phonons are**

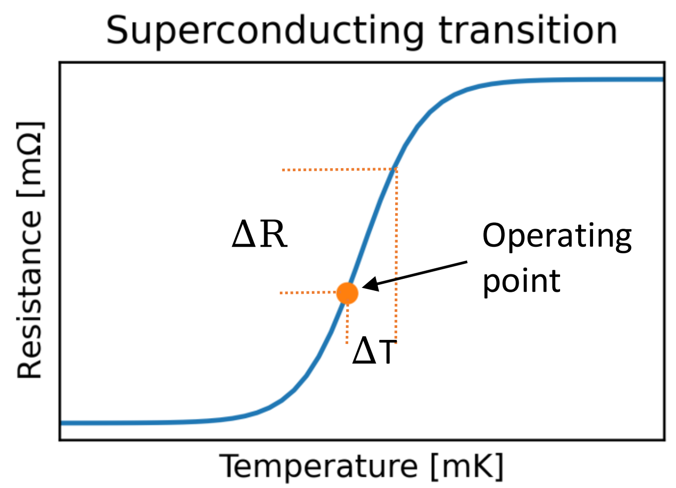


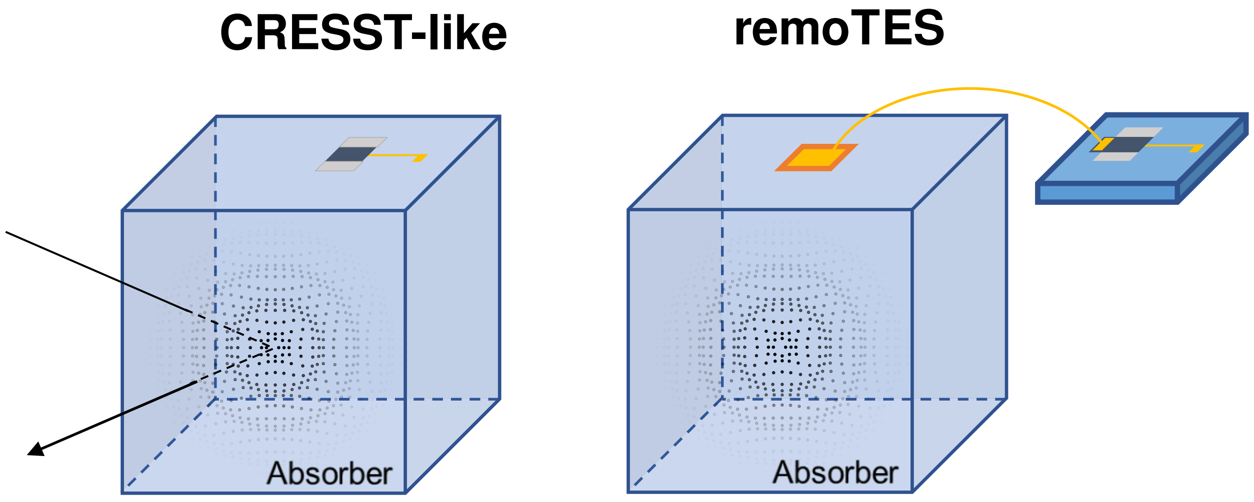


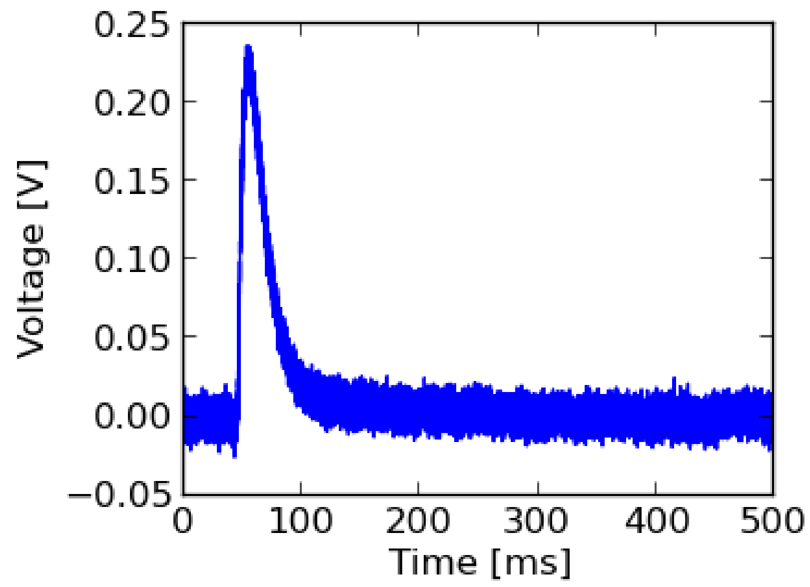


Transition Edge Sensor (TES)









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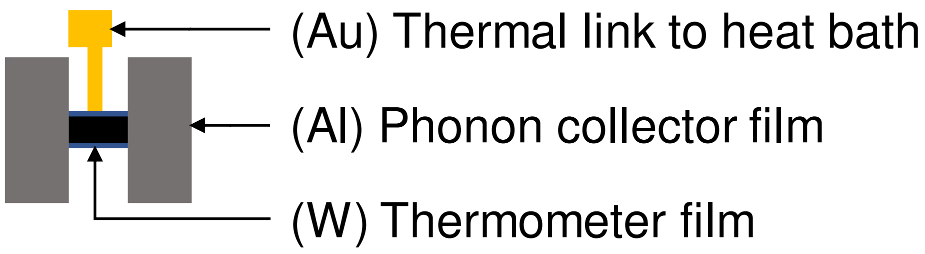

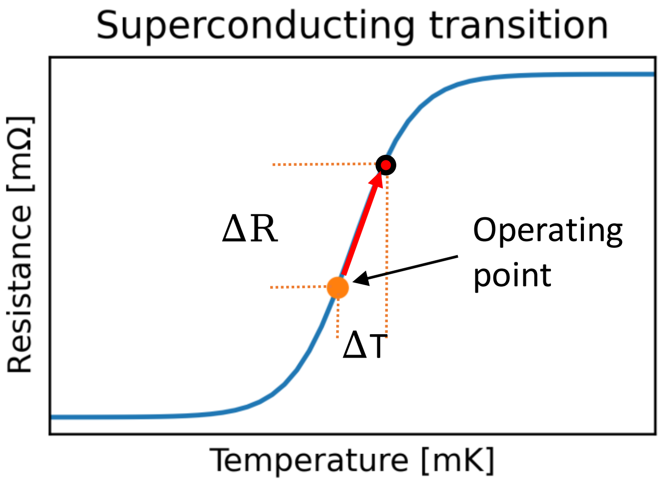

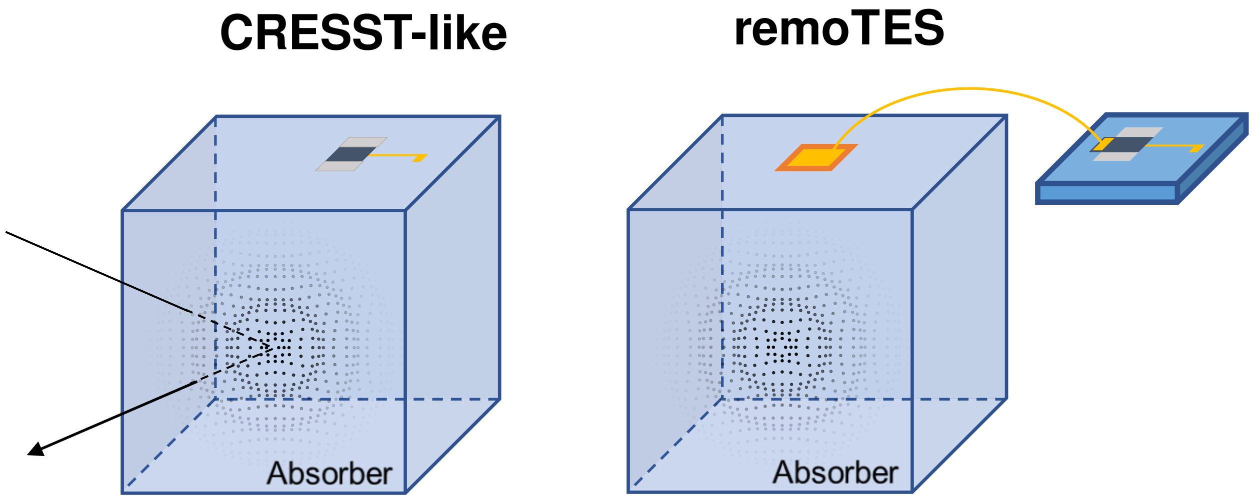

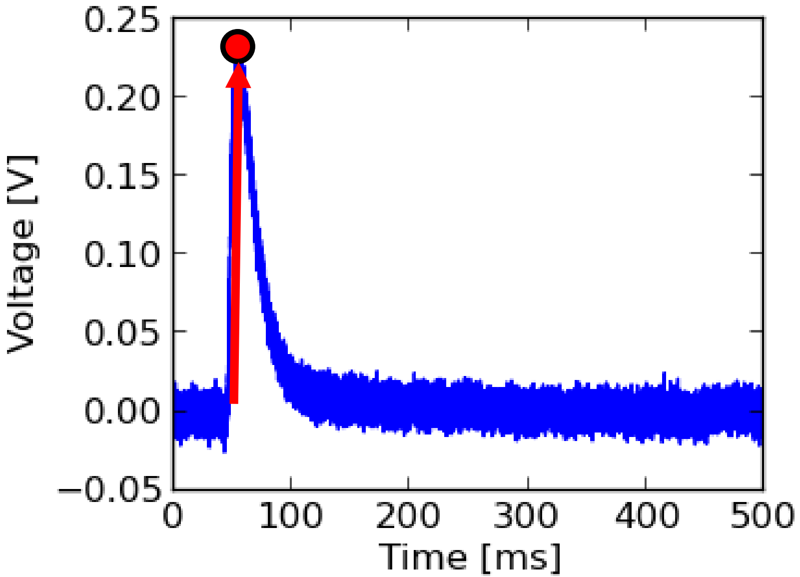

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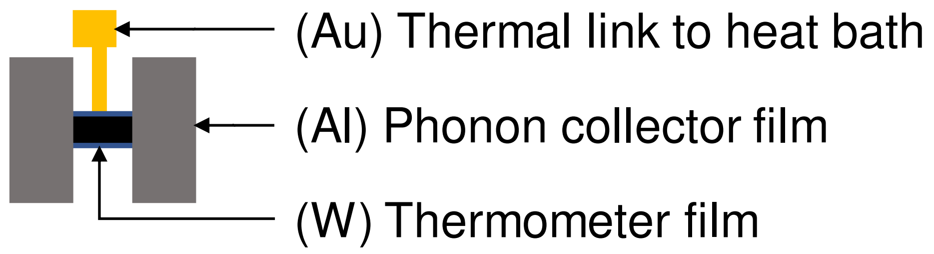
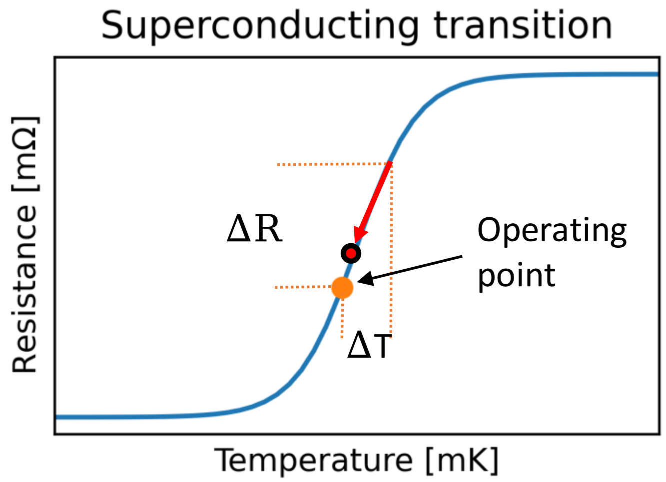
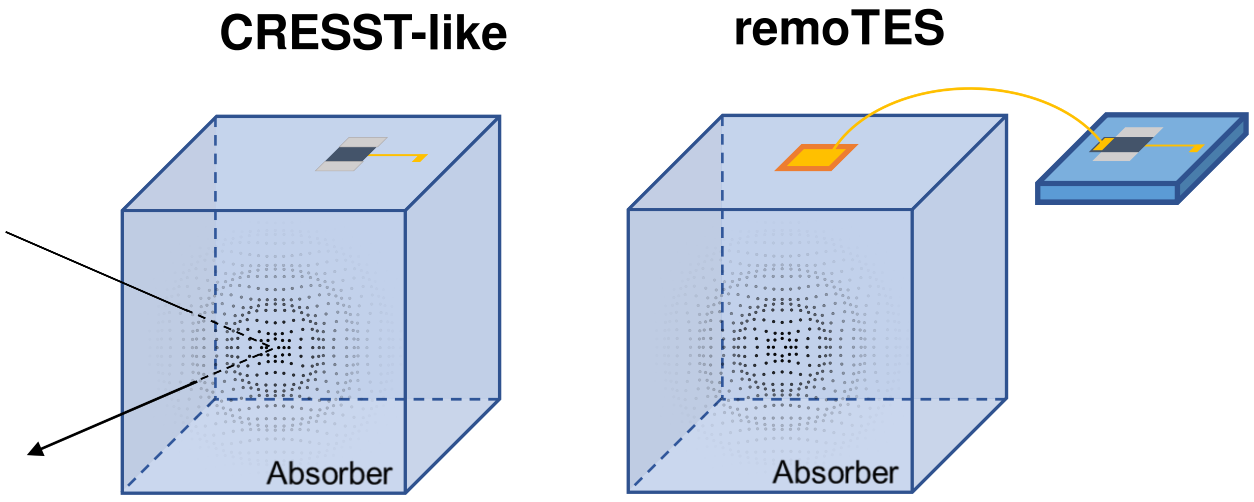
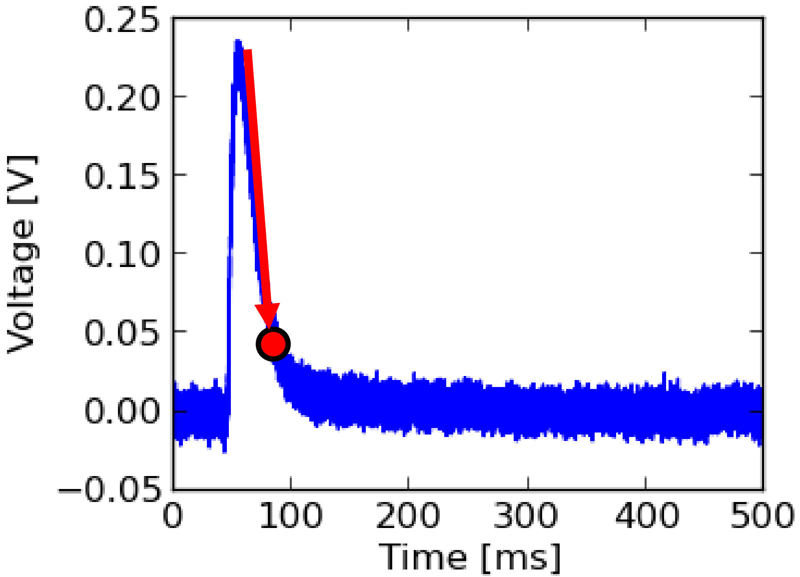
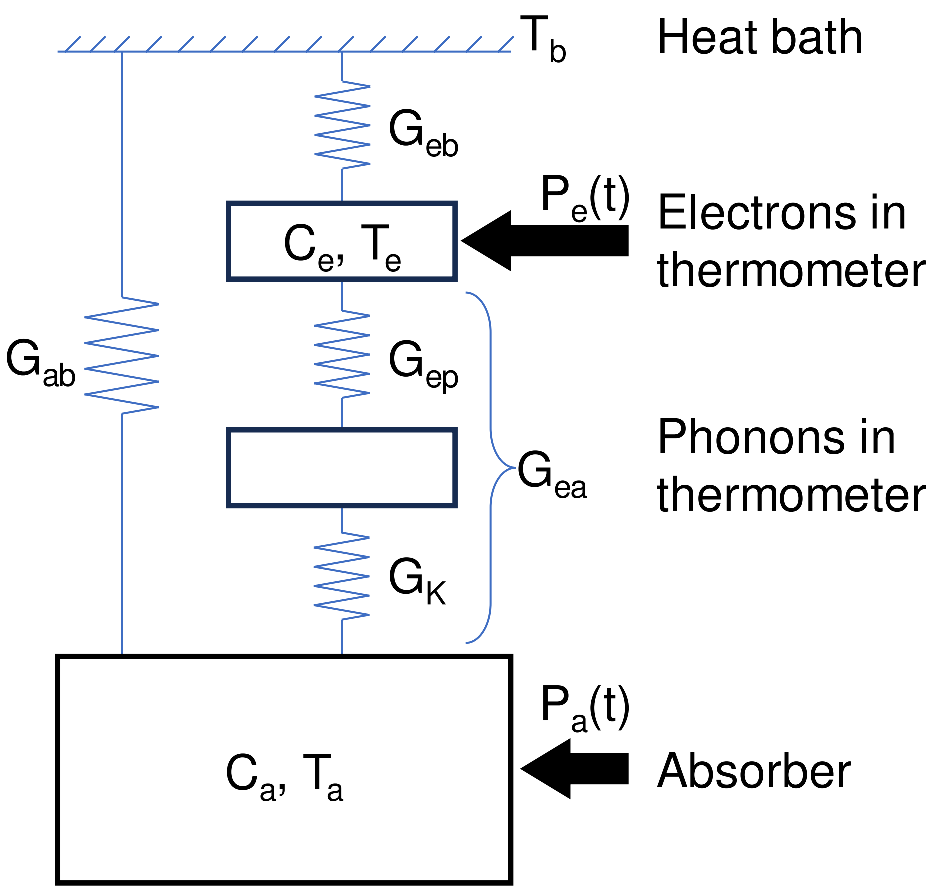








Thermal model for cryogenic detectors



J. Low. Temp. Phys., 100:69–104, 1995

$$C_e \frac{dT_e}{dt} + (T_e - T_a)G_{ea} + (T_e - T_b)G_{eb} = P_e(t)$$

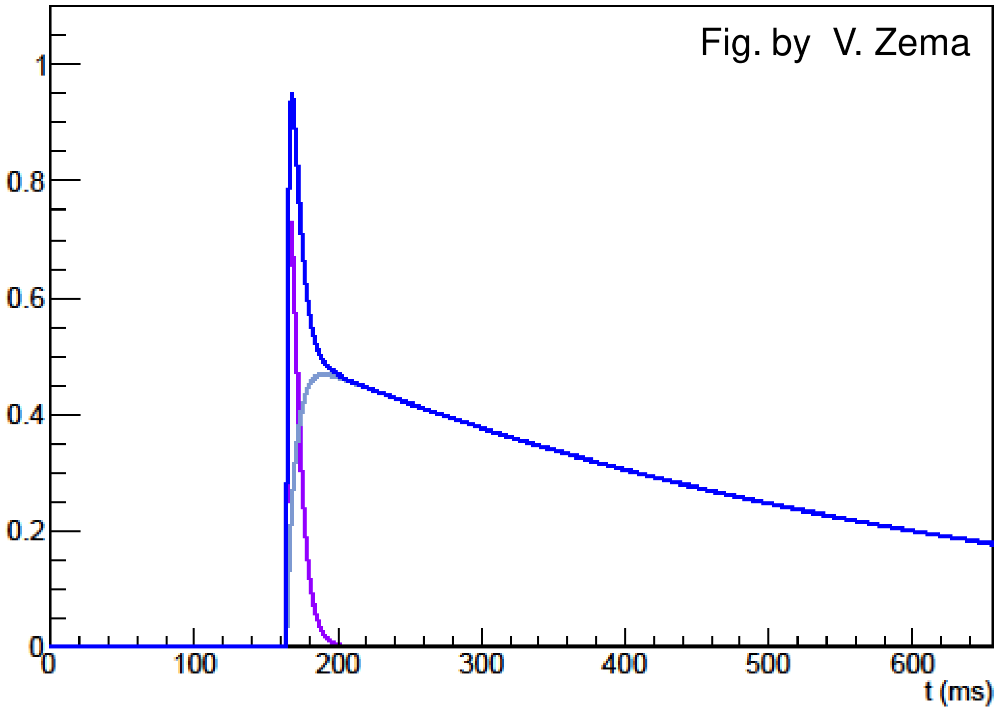
$$C_a \frac{dT_a}{dt} + (T_a - T_e)G_{ea} + (T_a - T_b)G_{ab} = P_a(t)$$

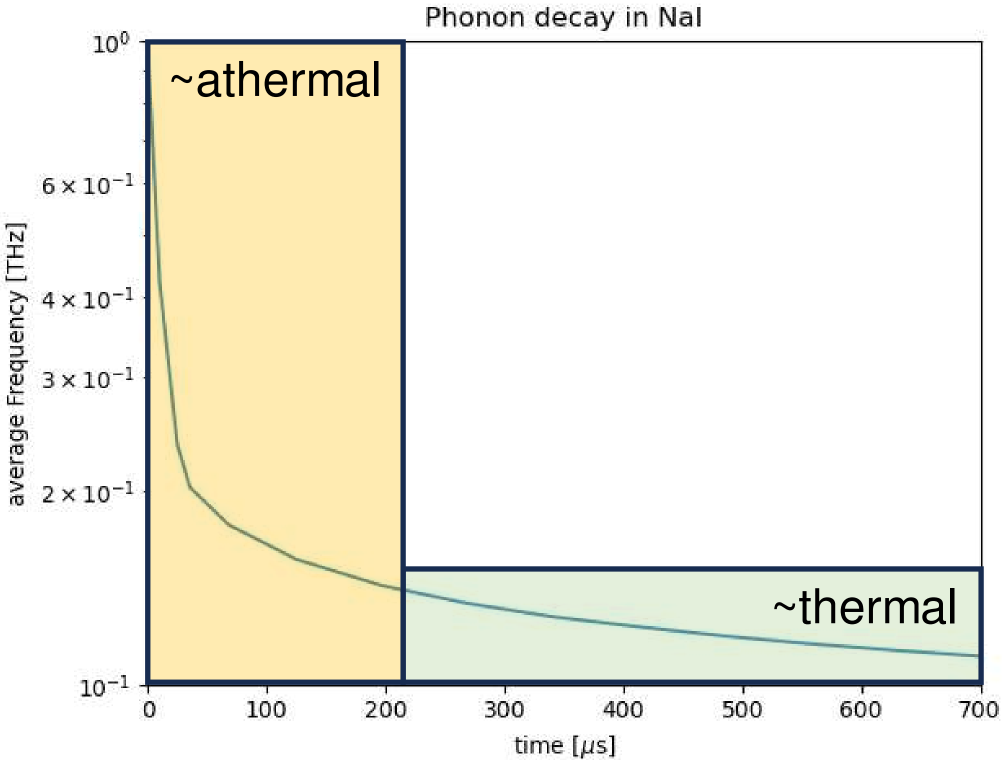
C_a	Absorber heat capacity
C_e	Electronic heat capacity in thermometer
G_{ea}	Thermal coupling between phonons in absorber and electrons in thermometer
G_{ab}	Thermal coupling between phonons in absorber and heat bath
G_{eb}	Thermal coupling between electrons in thermometer and heat bath
$P_e(t)$	Power input in thermometer
$P_a(t)$	Power of phonons thermalizing in absorber

Thermal model for cryogenic detectors

Signals can be described with 2 components

$$\Delta T_e(t) = \theta(t)\left[A_n\left(e^{-t/\tau_n} - e^{-t/\tau_{in}}\right) + A_t\left(e^{-t/\tau_t} - e^{-t/\tau_n}\right)\right]$$





Thermal model for cryogenic detectors

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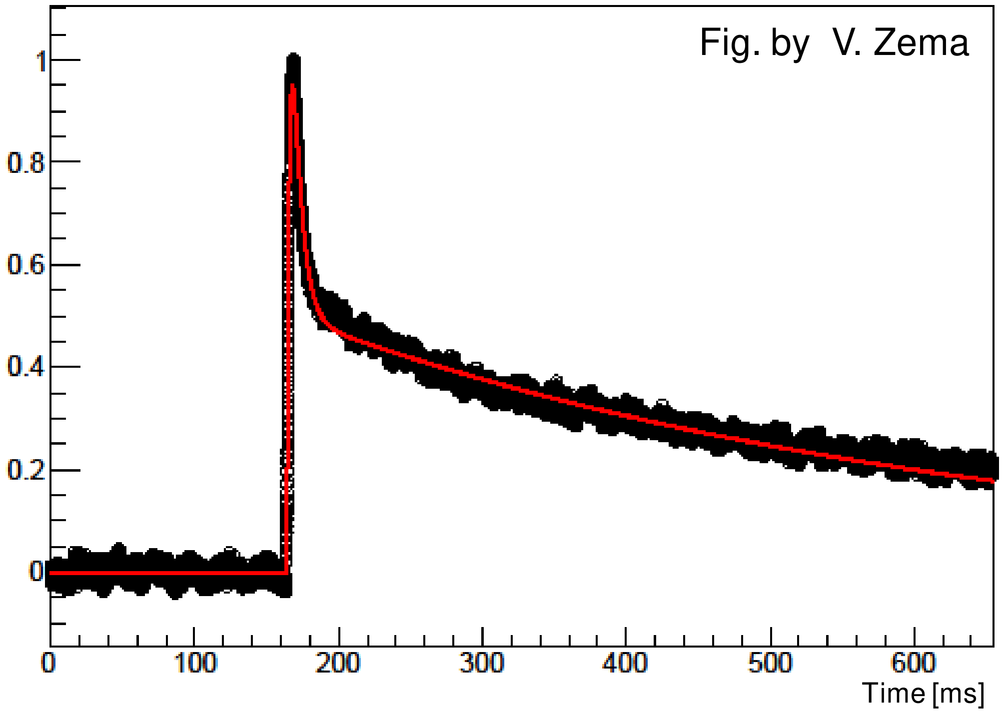
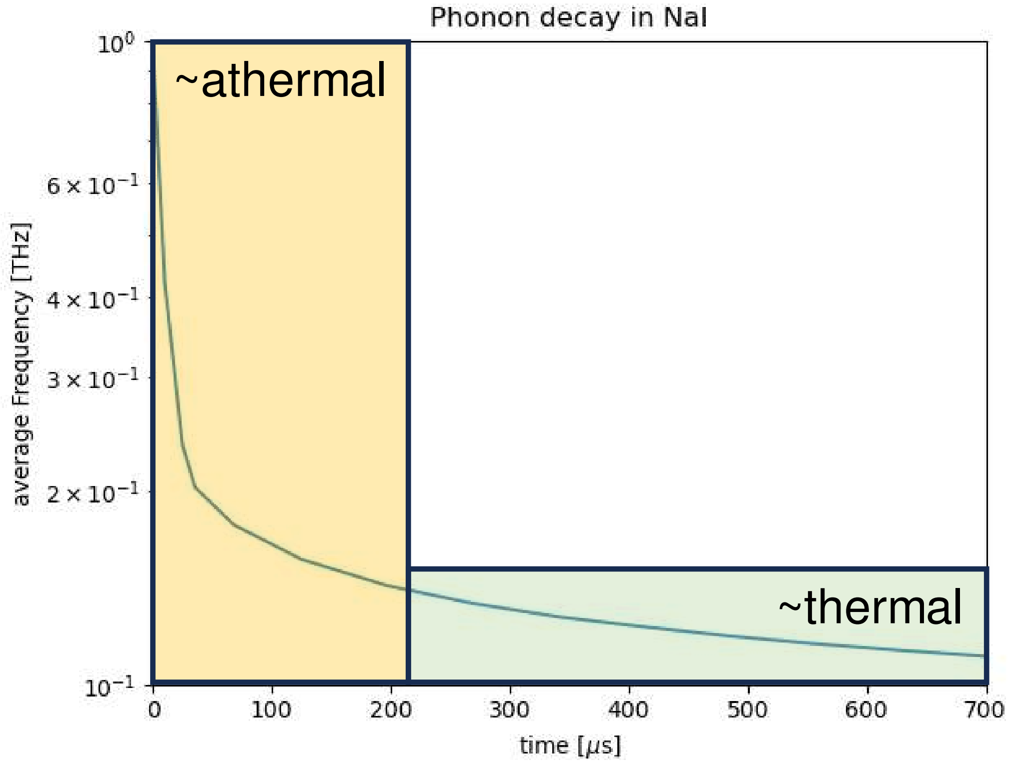
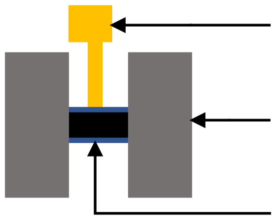
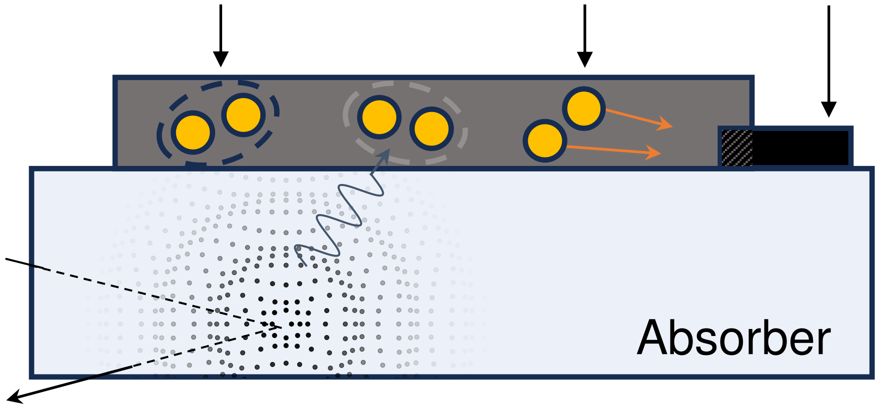




How to improve phonon collection?





<u>Aluminum phonon collectors</u>

Properties of superconductors:

- Superconducting band gap $(Al: 0.34\ meV, T_c = 1.2\ K)$
- Electrons entangle to “Cooper pairs” that behave like bosons
- Negligible heat capacity below critical temperature T_C

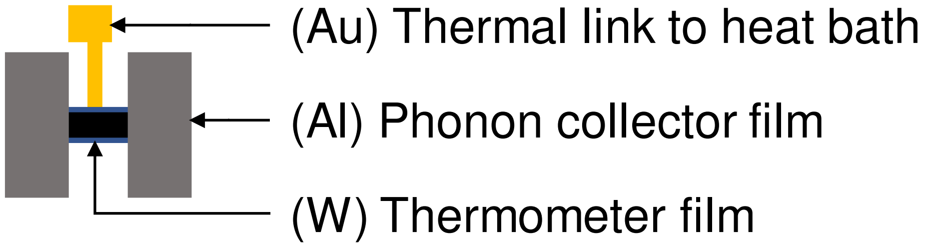
➢ Phonons are collected into phonon collectors and break cooper pairs.

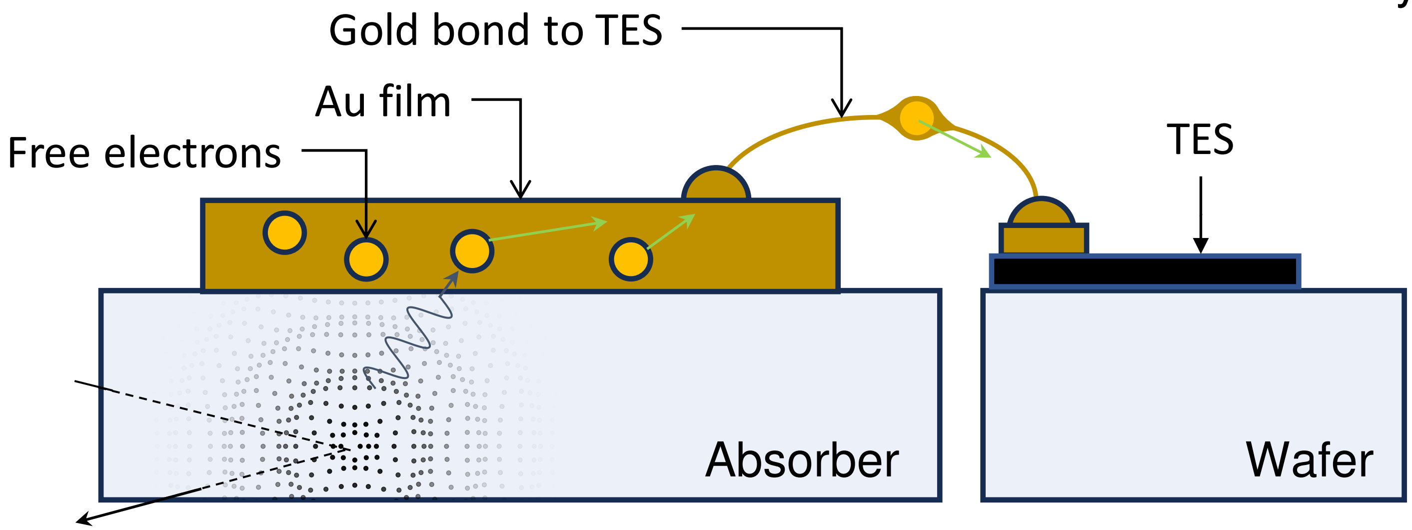
➢ “Quasiparticles” diffuse to thermometer and interact there

Improve by:

- Increase collection efficiency (by increasing area)
- Limited by diffusion length of quasiparticles

How to improve phonon collection?





remoTES Gold pad

- Phonons interact with electrons of Gold.
- Electrons interact with electrons of TES

Improve by:

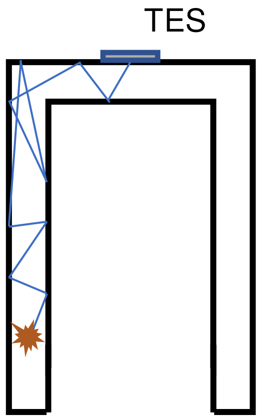
- Increase collection efficiency (by increasing area)
- Limited by added heat capacity of gold

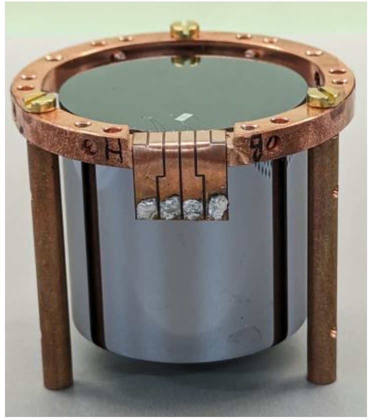
Shortcomings of this model

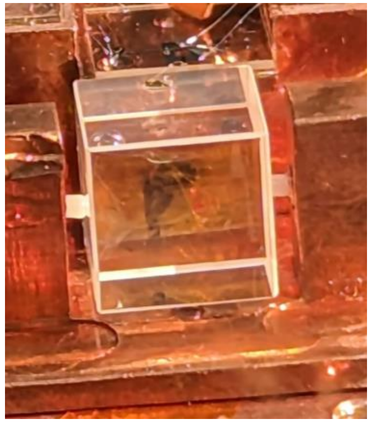
- Only the signal is considered
  - Readout circuit & noise is neglected
  - No direct translation into energy resolution
  - ➢ more complete electro-thermal model in development by collaborators in Vienna

- Model based on many parameters
  - All parameters are temperature and structure dependent (e.g. foil vs bulk)
  - Most parameters are unknown at mK and have to be studied
  - ➢ Many measurements are taken to understand all parameters

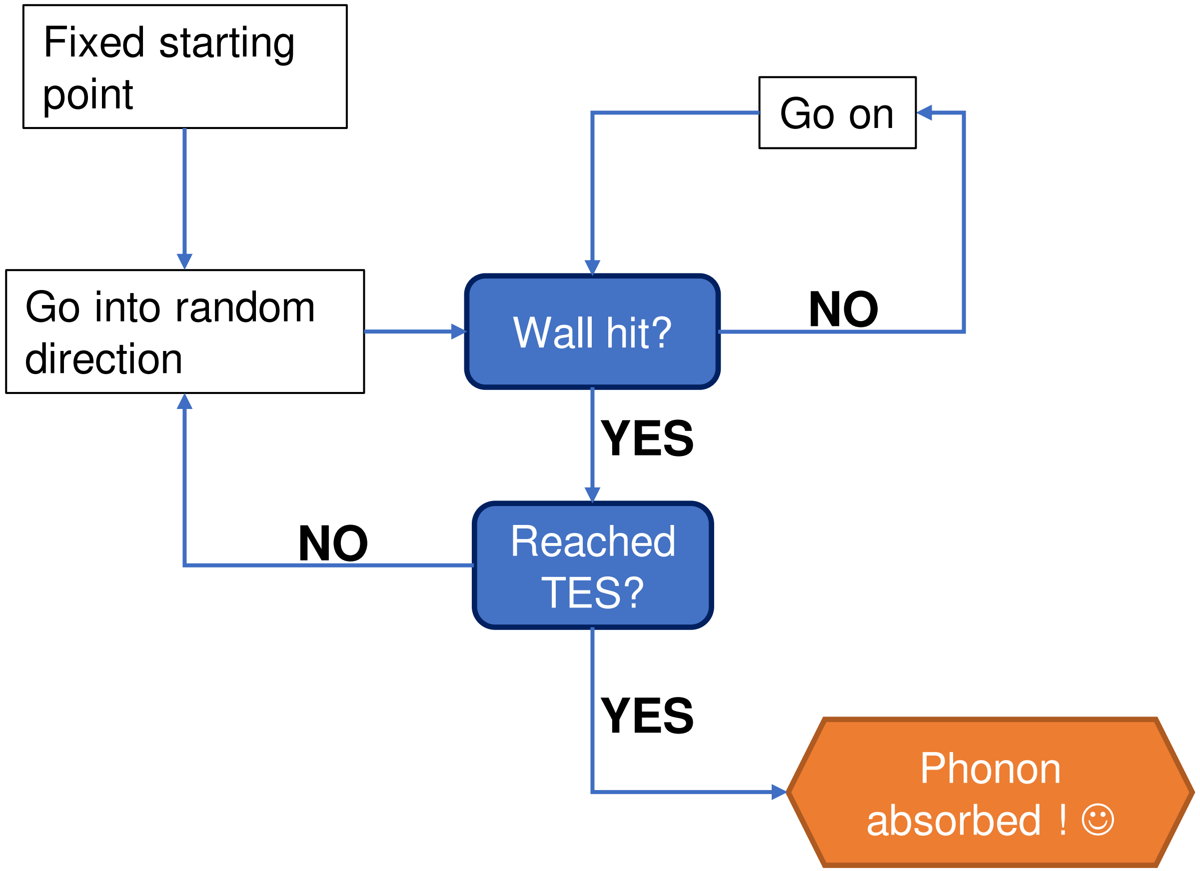
- Real detectors are not ideal: impurities, cracks, damages & exotic geometries exist
- Position dependence on the initial nuclear recoil?

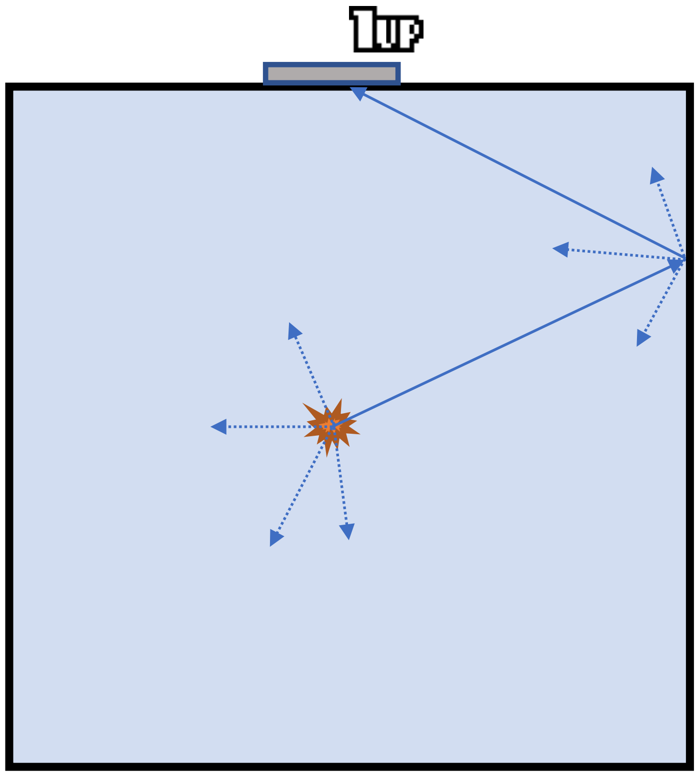






How to simulate ballistic random scattering?





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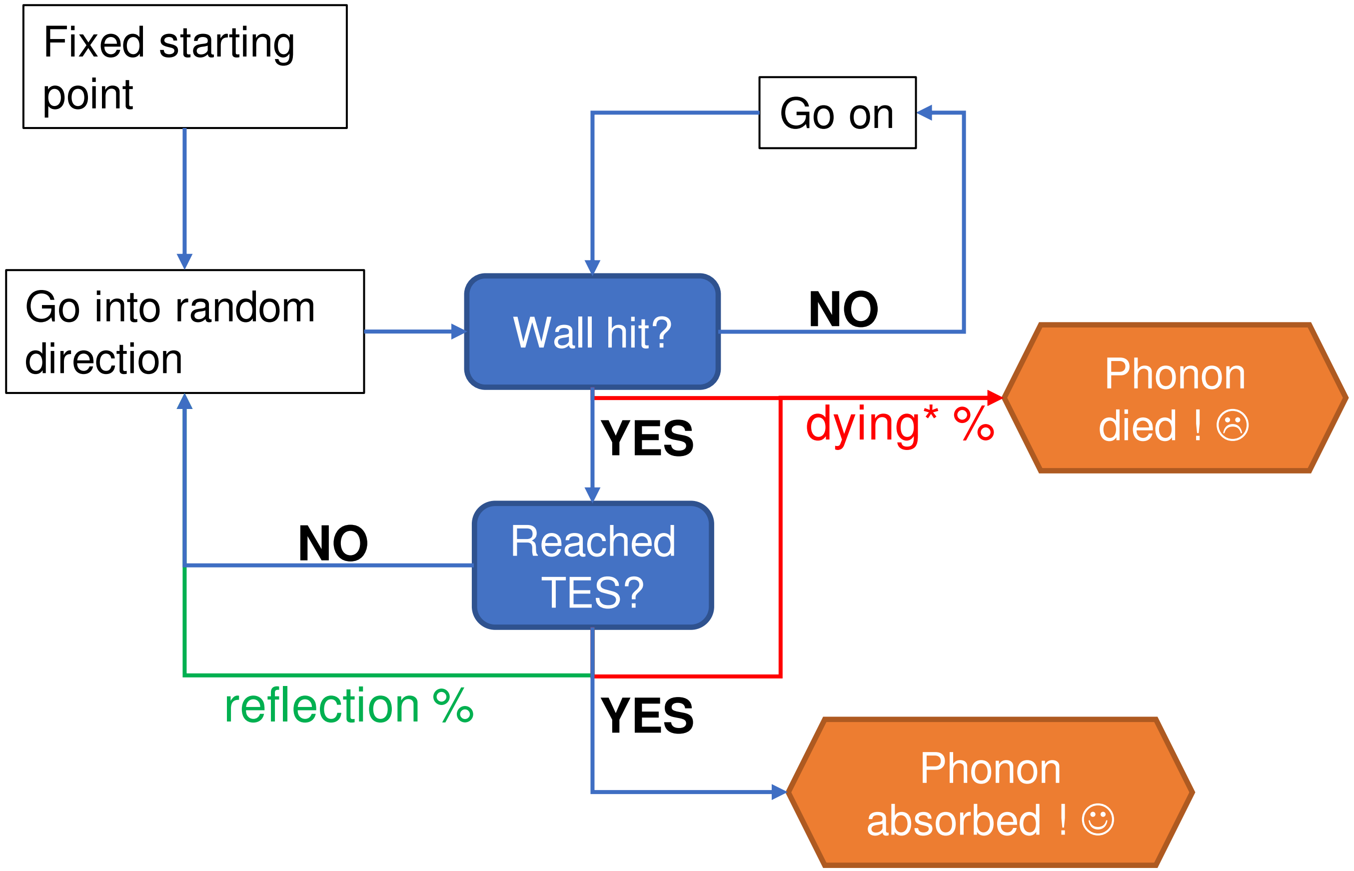
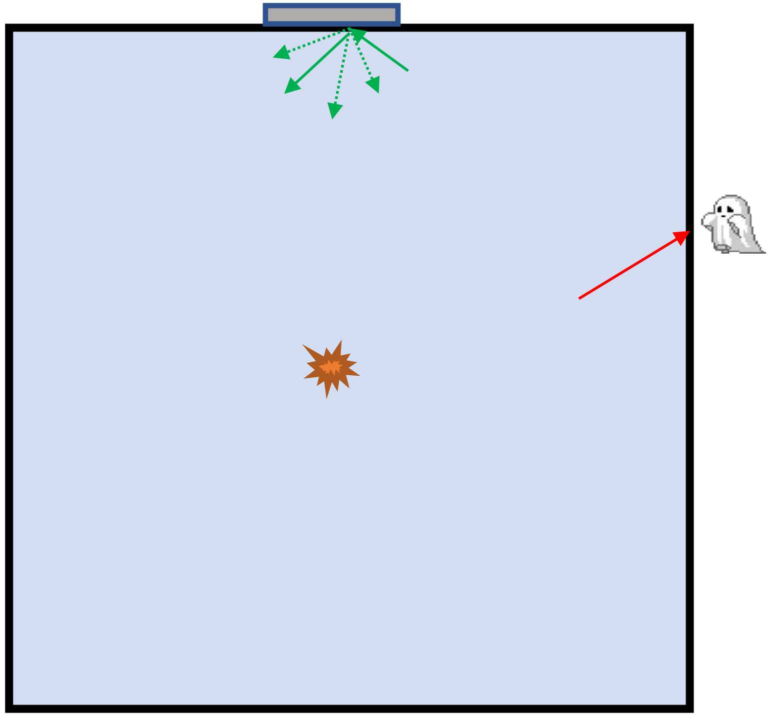




*Multiple zones with different survival probabilities are possible

Cuboid simulation

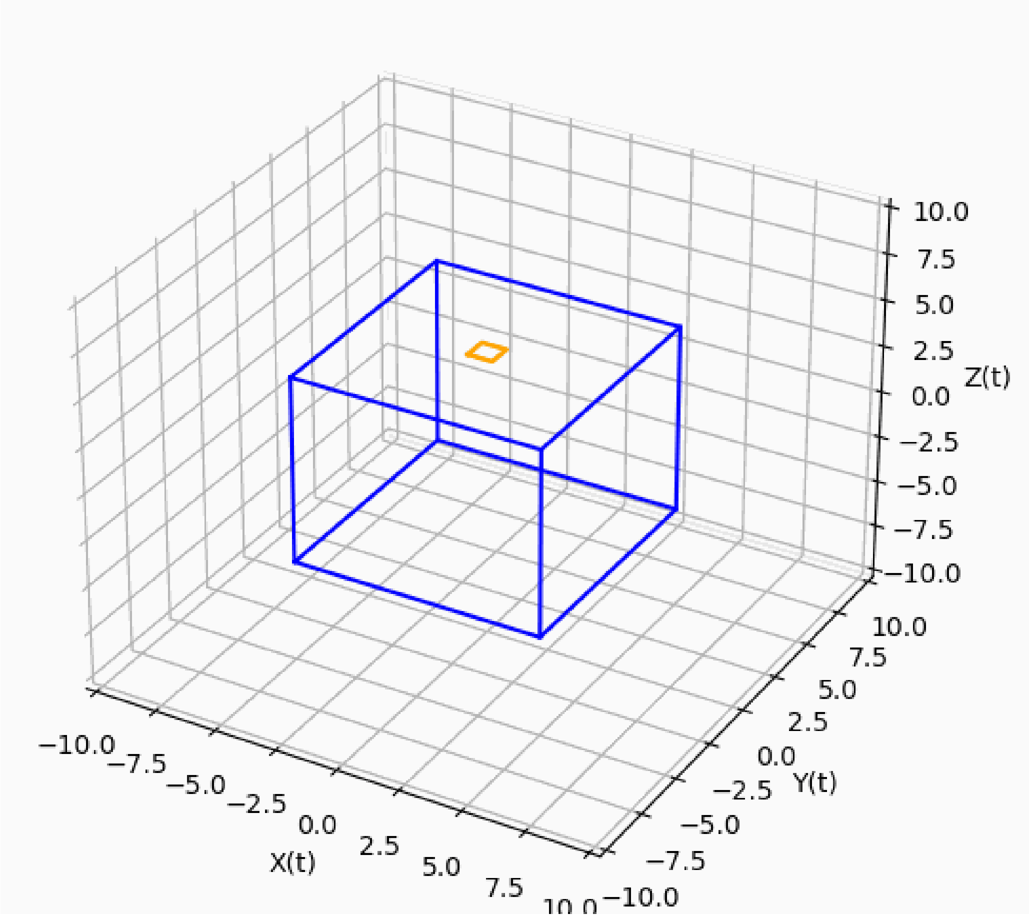
Input parameters:

- Absorber sizes
- TES/Au-pad size + position
- Initial position
- Survival probability (on surface)
- Survival probability (at TES/Au)
- Reflection probability (at TES/Au)
- Mean free path of phonons (for dirty crystals)

Output parameters:

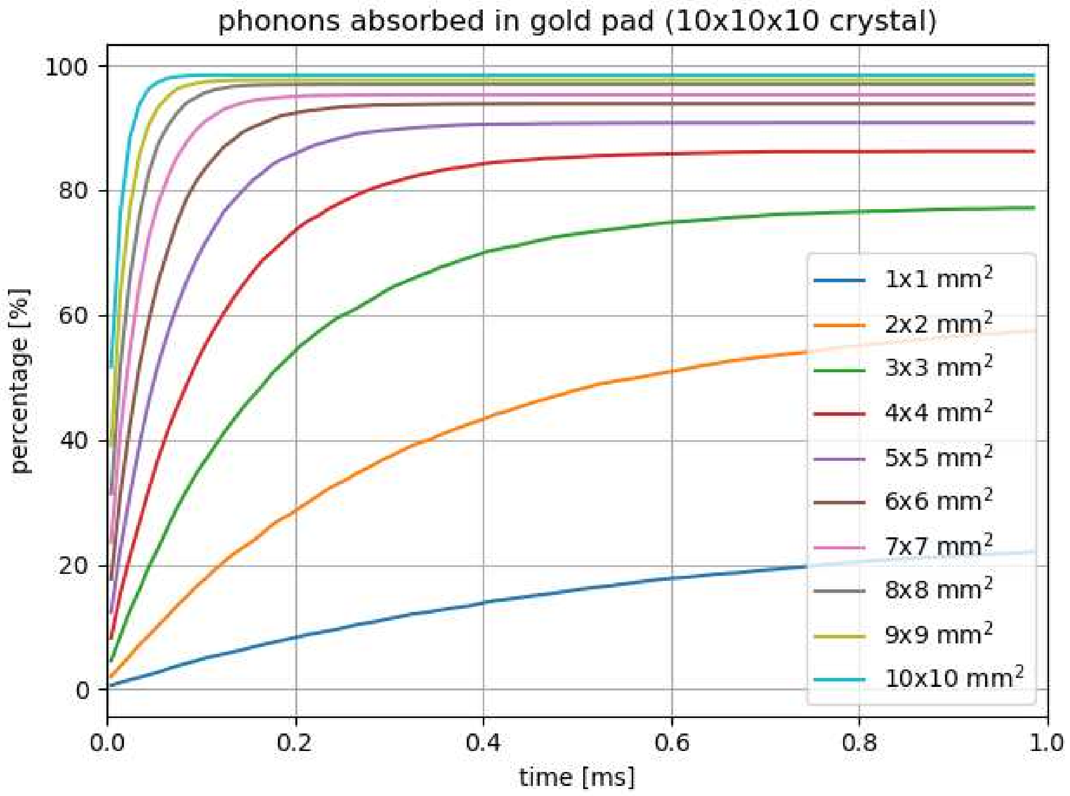
- # of scatters
- Total distance travelled (per phonon)
- Optional: complete path travelled

Performance: ~5 min for 10^5 simulated phonons (100 % numpy)



What can we do with the results?

- Simulate collection efficiency of athermal phonons
- Exclude non feasible absorber geometries (e.g. very thin 2D absorbers)
- Caclulate time constant for absorption
  - Phonon path length / speed of sound = time needed to reach sensor



- 2 component fit for real measurement on silicon:

τ_n = 56.1 ms

τ_{in} = 0.872 ms

τ_t = 7.71 ms

- Simulation of same geometry: **τ_{in} ~0.5 ms**

➢ **The simulation is already quite close to the measurement**

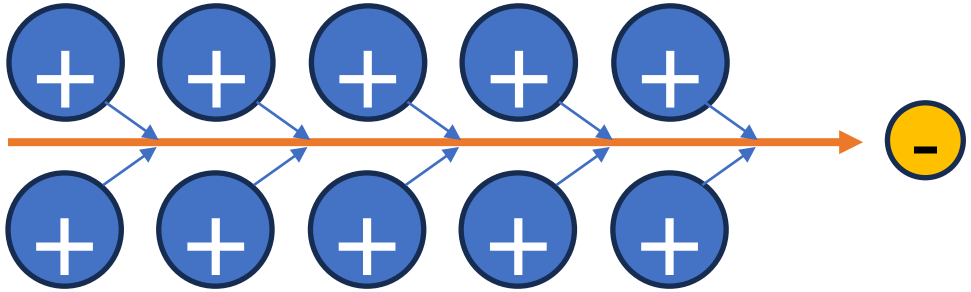
Summary & Outlook

- Recoil events create phonons that can be measured with cryogenic detectors
- TES signals consist of a thermal and non-thermal part
- Increasing the collection efficiency of athermal phonons can increase energy resolution
  - Increasing the collecting area is the common method to reach this
- There are currently 3 complementary ways for detector optimization in development
  1. (electro-)thermal modelling
  2. R&D measurements with real detectors
  3. Simulations of phonon behaviour

Thank You

Backup: Superconductivity / BCS theory

- Attractive force between electrons due to electron phonon interaction
- Intuitive picture:
  1. Electron moves through lattice
  2. Positive charge density increases following the electron
  3. Second electron is attracted by charge density



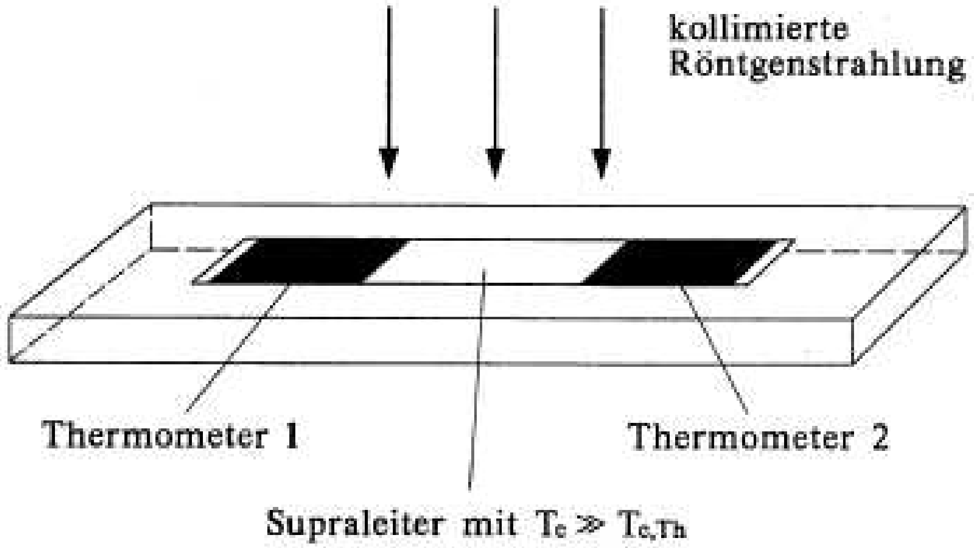
BCS theory in weak coupling limit $(\nu_0 D(E_F) \ll 1)$

$$\left.\begin{aligned} \Delta_0 &= 2\hbar\omega_D e^{-\frac{2}{\nu_0 D(E_F)}} \\ k_B T_c &= 1.14\ \hbar w_D e^{-\frac{2}{\nu_0 D(E_F)}} \end{aligned}\right\} \Delta_0 = 1.76\ k_B T_c$$

Δ_0	Band gap at T = 0
ω_D	Debye frequency
ν_0	Constant for electron phonon interaction
$D(E)$	Density of states
E_F	Fermi energy
T_c	Critical temperature

Backup: How Quasiparticles diffuse

- Credits to M. Loidl



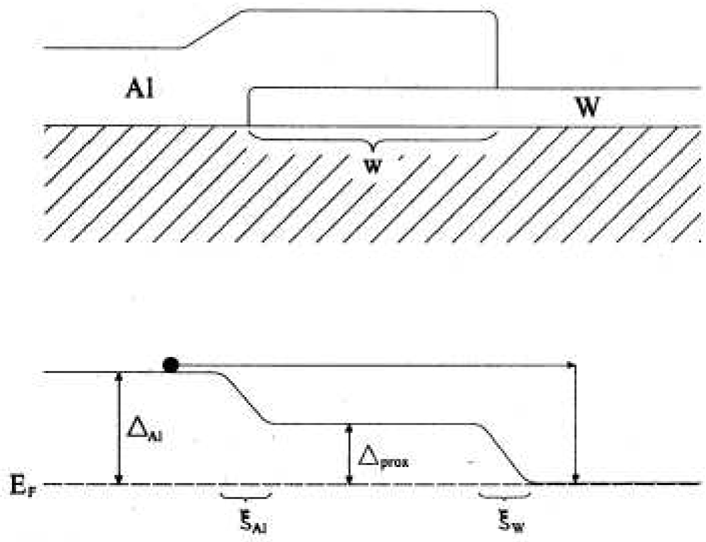


Abbildung 2.4: Oben: Schnitt durch die Übergangszone von Kollektor- (links) und Thermometer-Film; das Substrat ist schraffiert dargestellt. Darunter: qualitativer Verlauf der Energielücke.