ECE 656: Electronic Transport in Semiconductors Fall 2017

# Phonon Scattering

Mark Lundstrom

Electrical and Computer Engineering
Purdue University
West Lafayette, IN USA

9/14/17

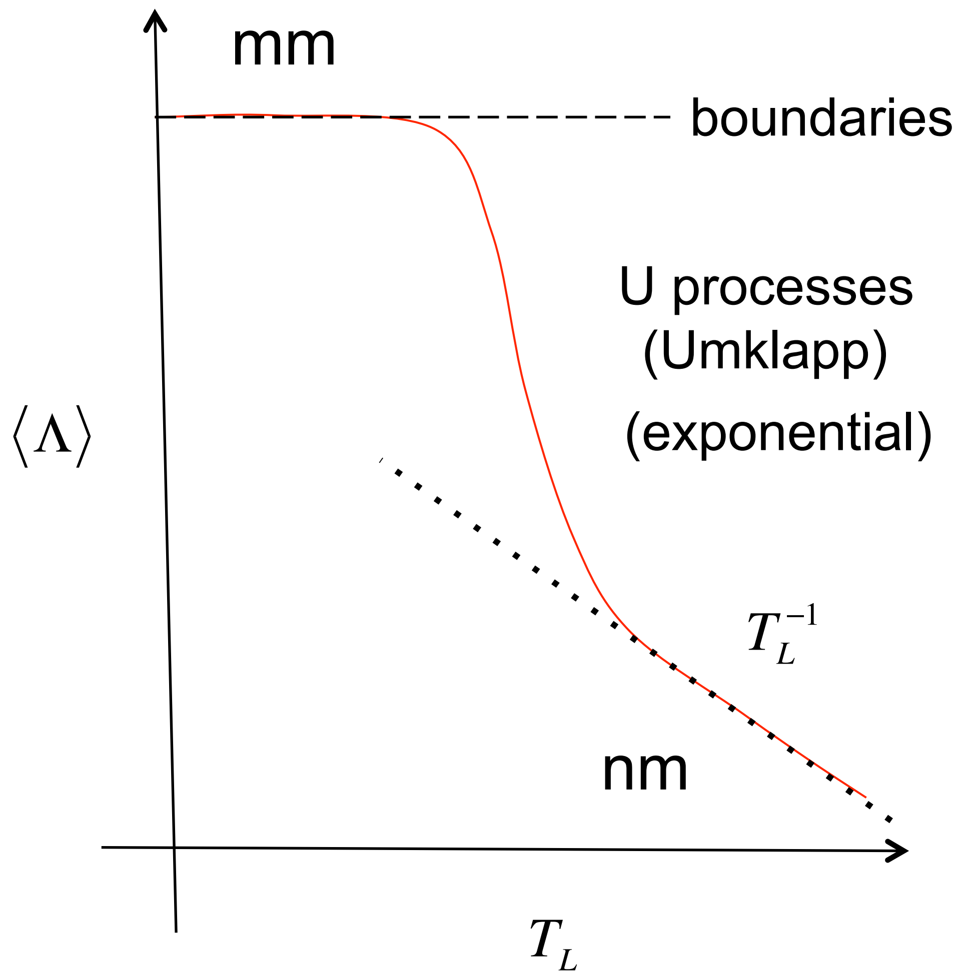
# Phonon scattering

$\tau(E)$

$\tau_m(E)$

Mean free path of acoustic phonons:

$$\Lambda = \upsilon_s \tau_m(E)$$



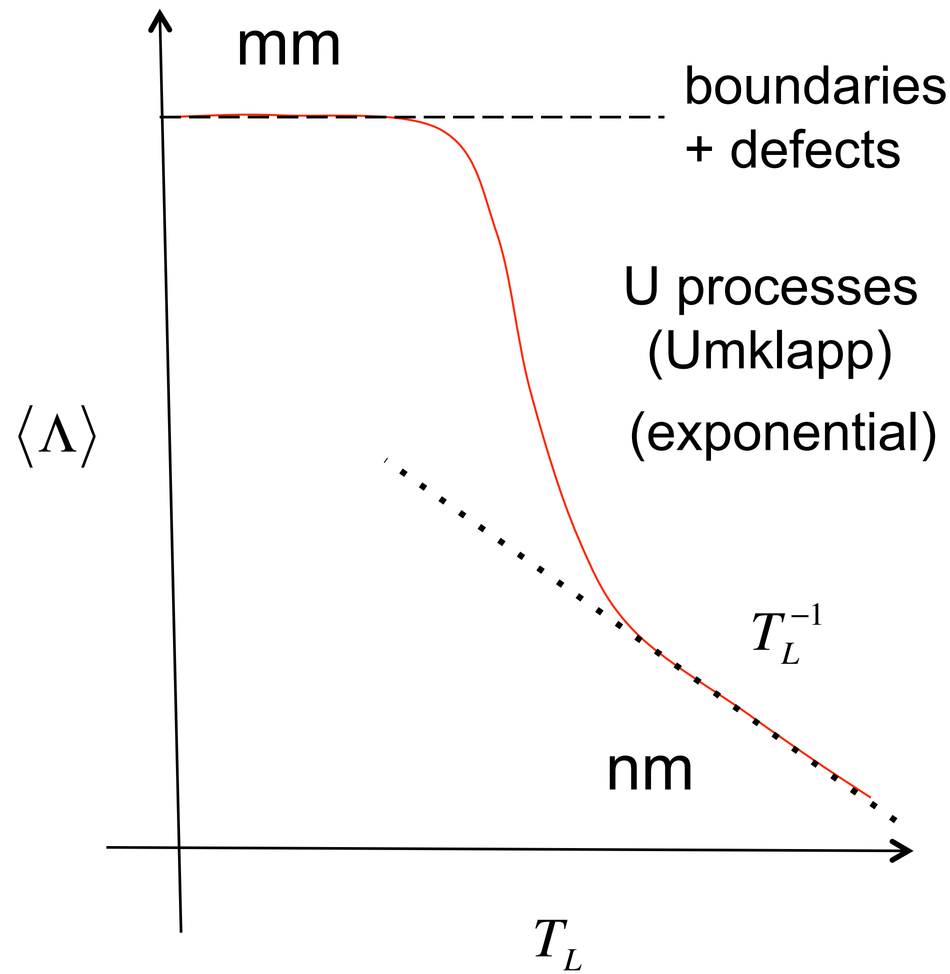
# High temperature limit

$$N_\omega = \frac{1}{e^{\hbar\omega/k_B T_L} - 1}$$

high temperatures"

$$N_\omega \approx \frac{k_B T_L}{\hbar\omega}$$

$$\Lambda \propto \frac{1}{N_\omega}$$



# Phonon scattering

**Electrons** scatter from:

1) defects
 -e.g. charged impurities, neutral impurities, dislocations, etc.

2) phonons

3) surfaces and boundaries

4) other electrons

**Phonons** scatter from:

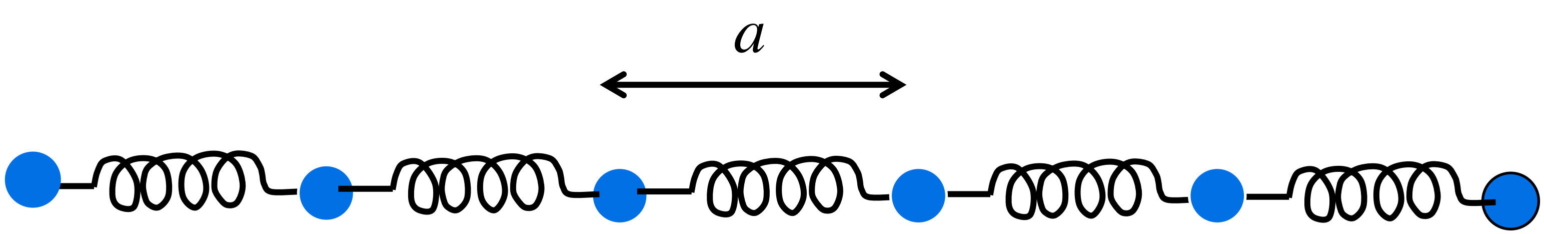
1) defects
 -e.g. impurities, dislocations, isotopes, etc.

2) other phonons

3) surfaces and boundaries

4) electrons ("phonon drag")

# Intrinsic phonon scattering

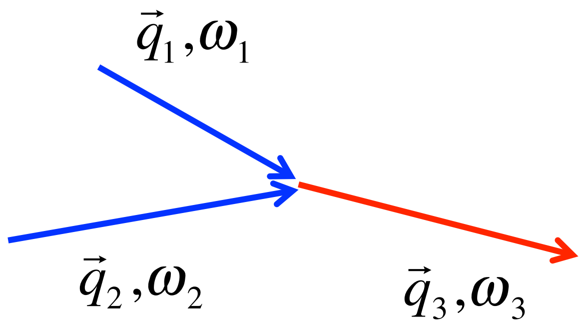



For perfect springs (harmonic oscillator), there is no phonon-phonon scattering.

$$E_r = K_1 (r - r_0)^2 + K_2 (r - r_0)^3 + \ldots$$

Anharmonic terms couple phonons

# Phonon-phonon scattering




i) momentum conservation:

$$\hbar \vec{q}_3 = \hbar \vec{q}_1 + \hbar \vec{q}_2$$

ii) energy conservation:

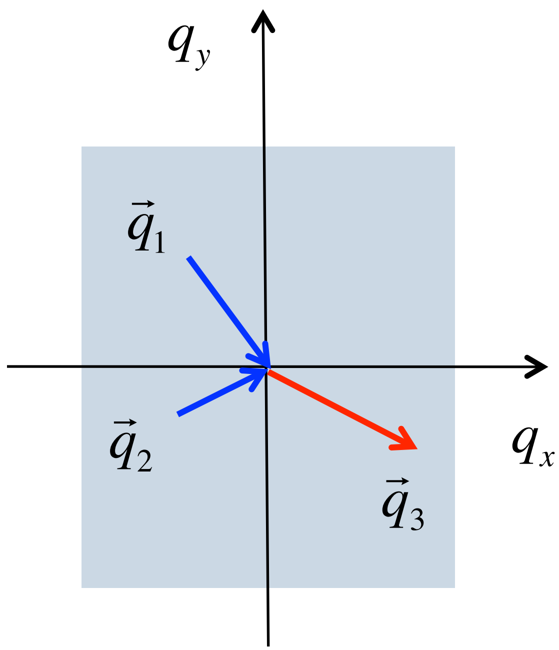
$$\hbar \omega_3 = \hbar \omega_1 + \hbar \omega_2$$

***little effect on thermal conductivity!***

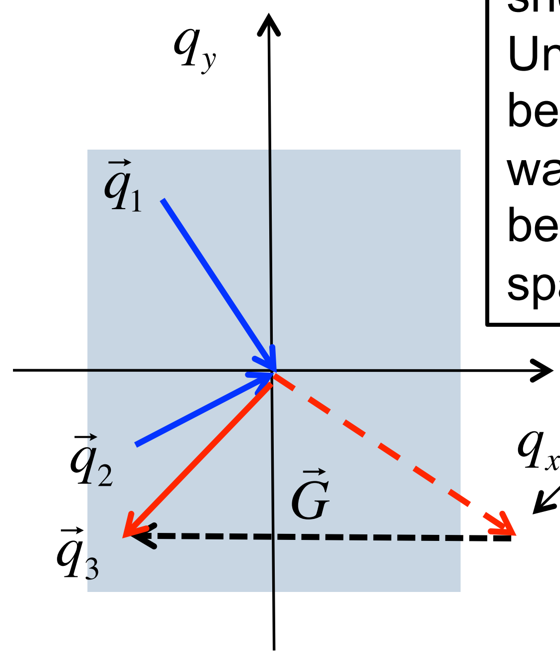
**N-process**

# N and U processes

High *q* implies short wavelength. Unphysical because wavelength would be less than lattice spacing.

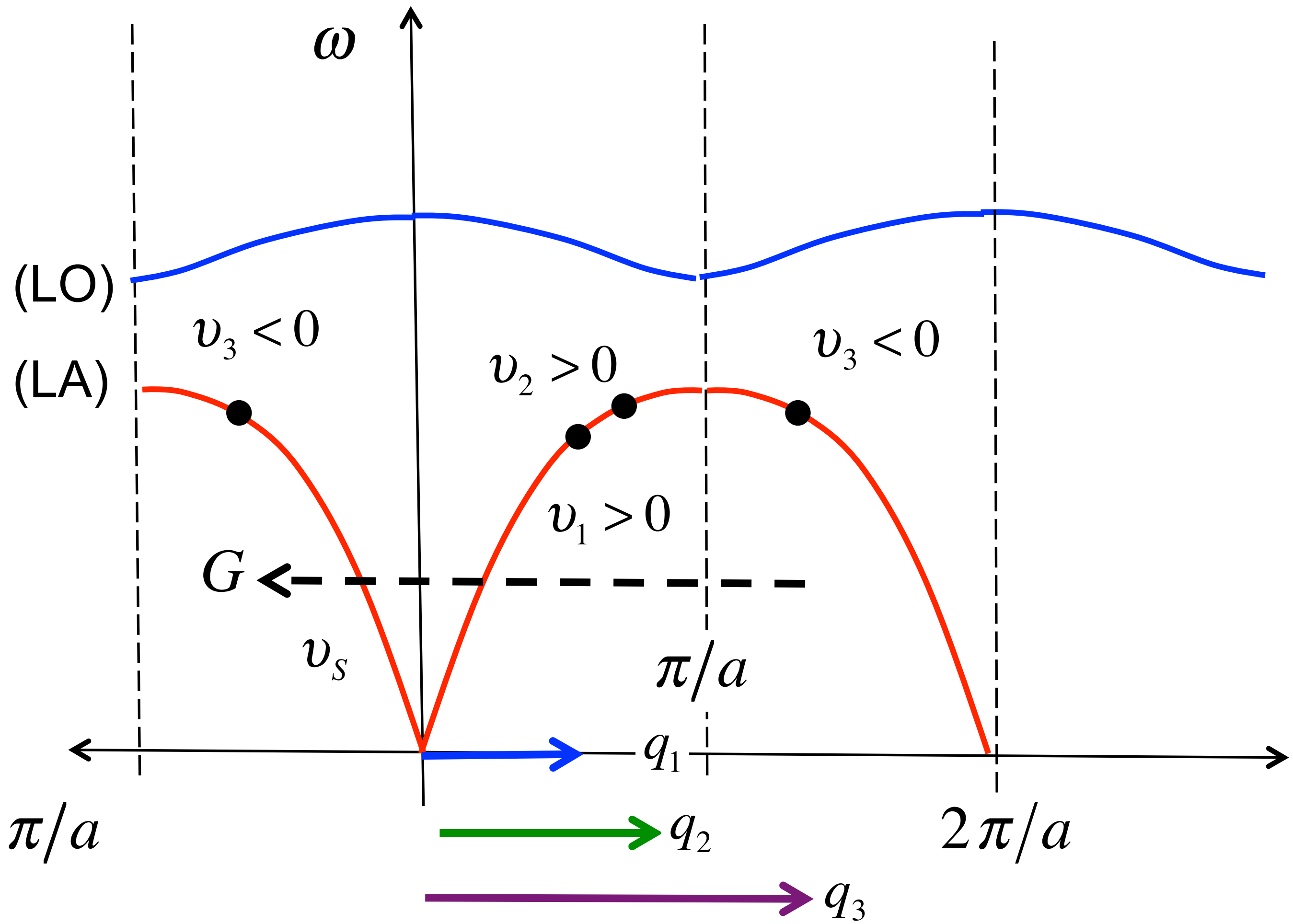



Normal (N) process (momentum conserved) Little effect on $\kappa_L$.




Umklapp (U) process (momentum not conserved). Lowers $\kappa_L$.

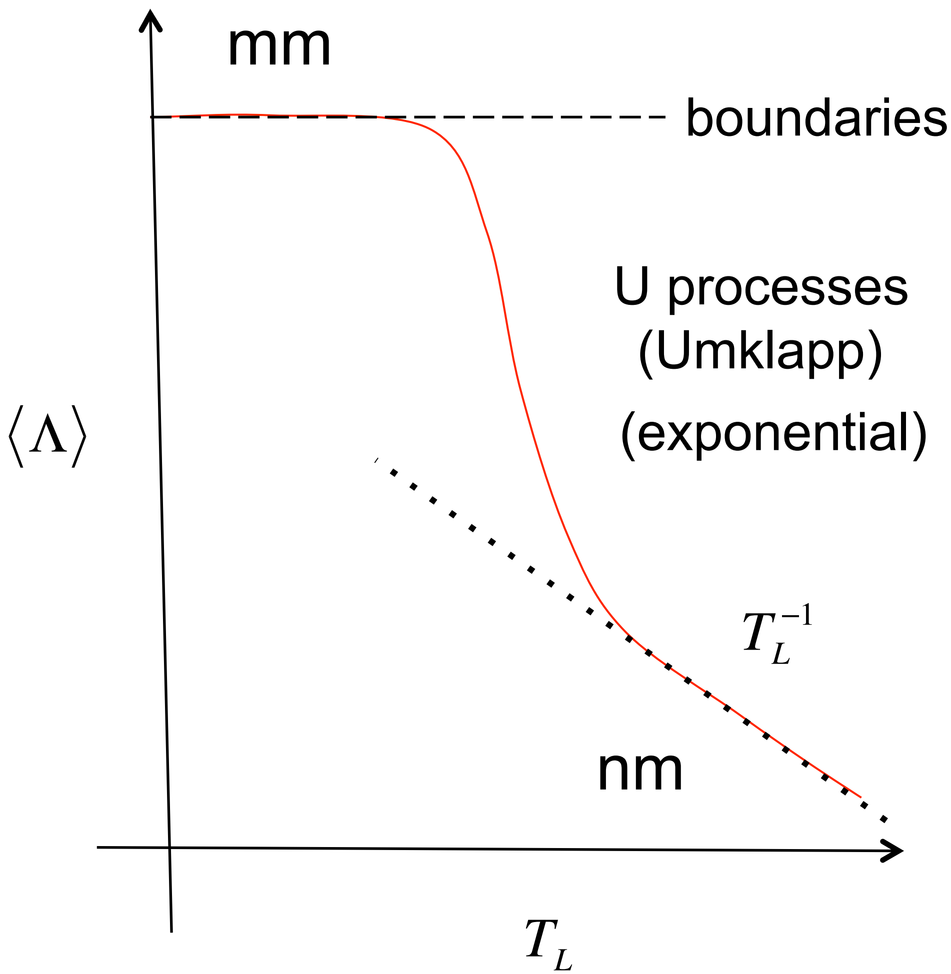
# U processes in extended zone



# High temperature limit

$$N_\omega = \frac{1}{e^{\hbar\omega/k_B T_L} - 1}$$

$$\Lambda \propto e^{\theta_U/k_B T}$$



# Defect scattering

- Point defects (impurities and vacances)
- Line defects (dislocations)
- Grain boundaries
- Surfaces
- Alloy disorder
- Random distribution of isotopes

# scattering summary

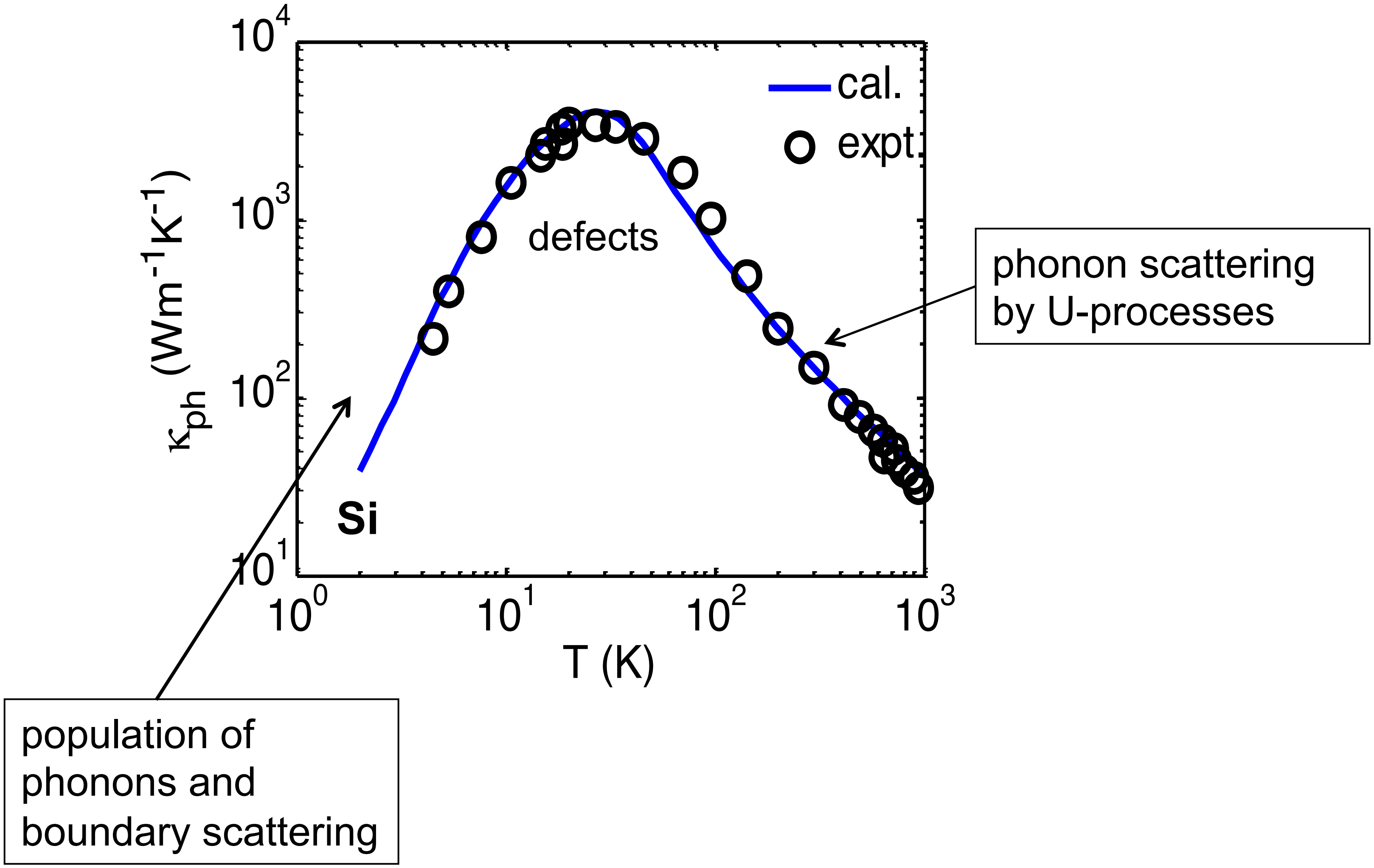
$$\frac{1}{\tau_{ph}(\hbar\omega)} = \frac{1}{\tau_D(\hbar\omega)} + \frac{1}{\tau_B(\hbar\omega)} + \frac{1}{\tau_U(\hbar\omega)}$$

1) point defects and impurities: $1/\tau_D(\hbar\omega) \propto \omega^4$ "Raleigh scattering"

2) boundaries and surfaces: $1/\tau_B(\hbar\omega) \propto \upsilon_{ph}(\hbar\omega)/t$

3) Umklapp scattering: $1/\tau_U(\hbar\omega) \propto T_L$ $\left\{1/\tau_U(\hbar\omega) \propto e^{-T_D/bT_L} T_L^3 \omega^2\right\}$

# Temperature-dependent thermal conductivity



# Summary

1) N-processes
2) U-processes
3) Other processes

**Key points:**

Phonon MFPs varies substantially with temperature − from mm to nm

At room temperature, there is typically a **very wide** distribution of MFPs (Key difference with electrons).