Thermoelectricity: From Atoms to Systems

Week 3: Thermoelectric Characterization
Lecture 3.5: Thermoreflectance Laser Characterization

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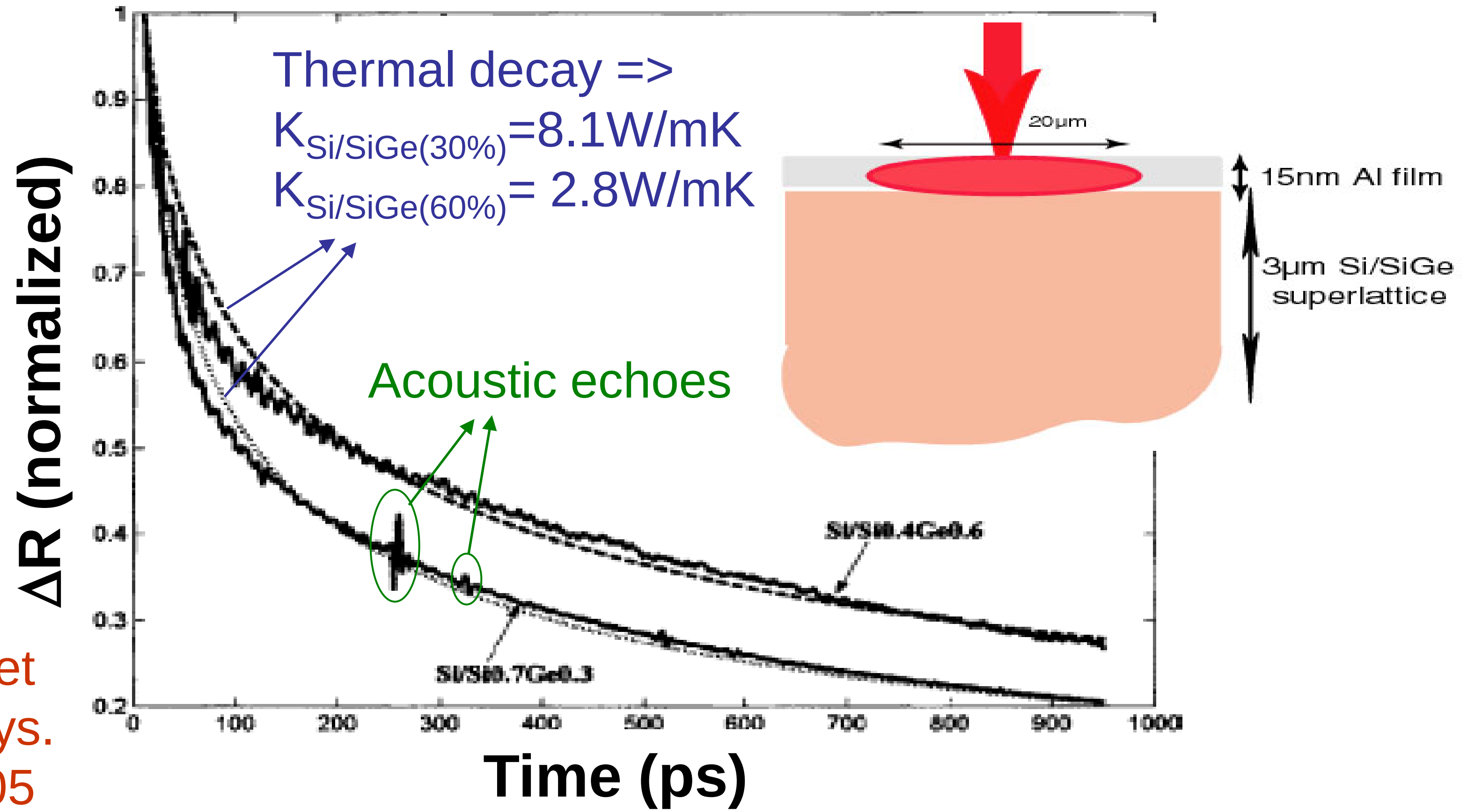
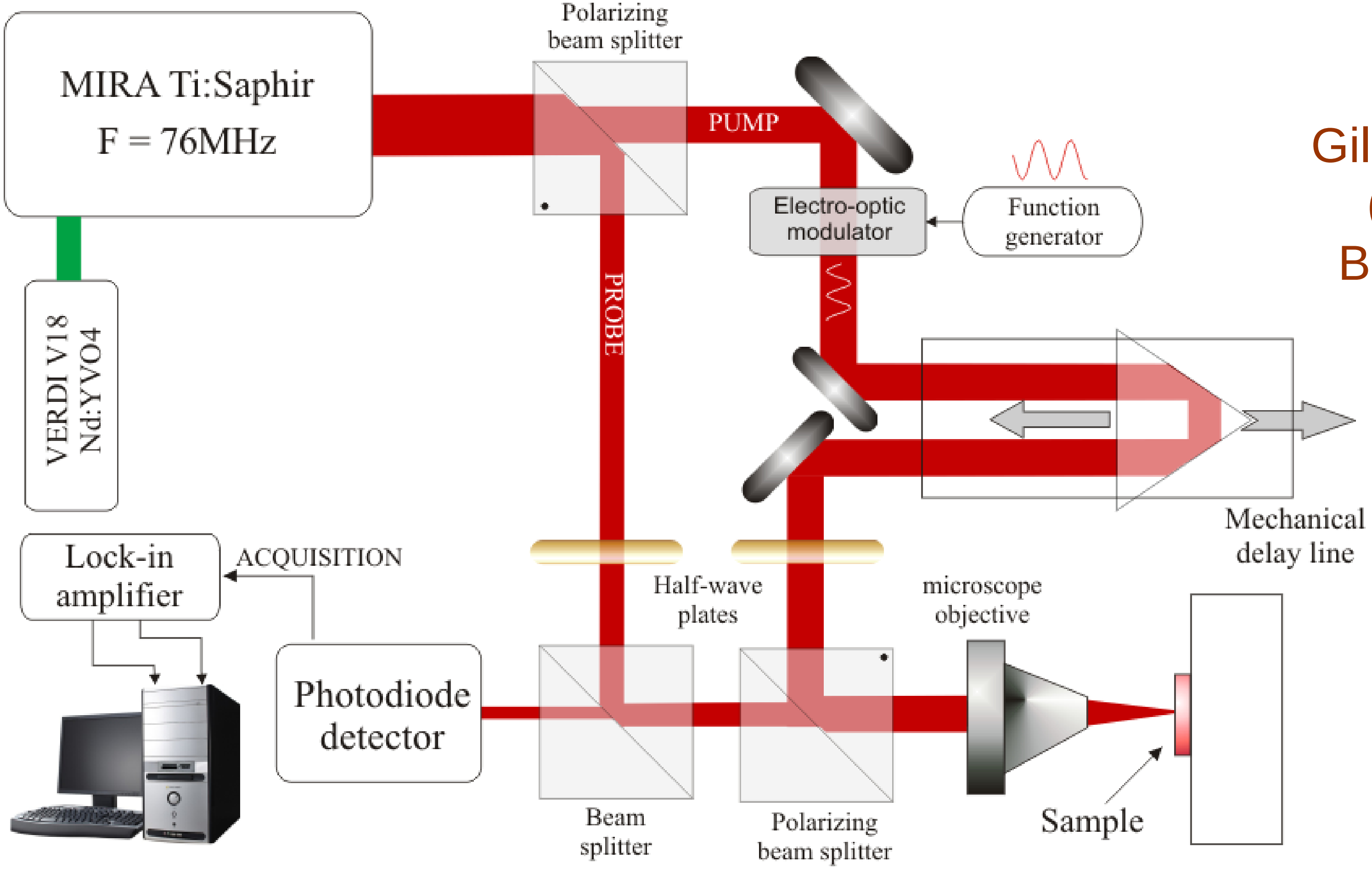
Thin Film Thermal Characterization



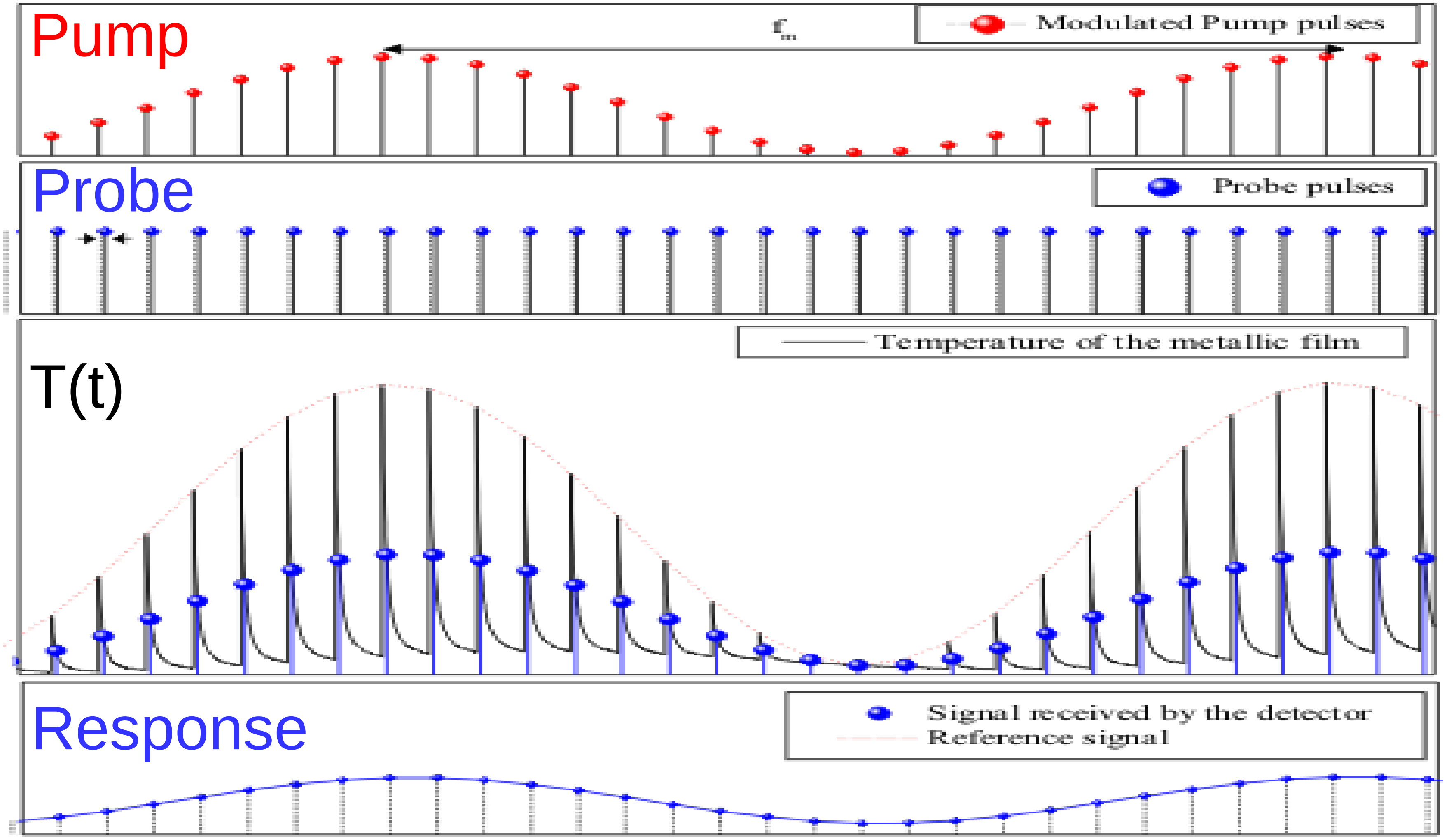
Y. Ezzahri et al. Appl. Phys. Letters 2005

Metal film is heated by laser pulse and it acts both as a heat source and a transducer (creates acoustic waves). It can characterize thermal interface resistances as well as interface quality (acoustic mismatch).

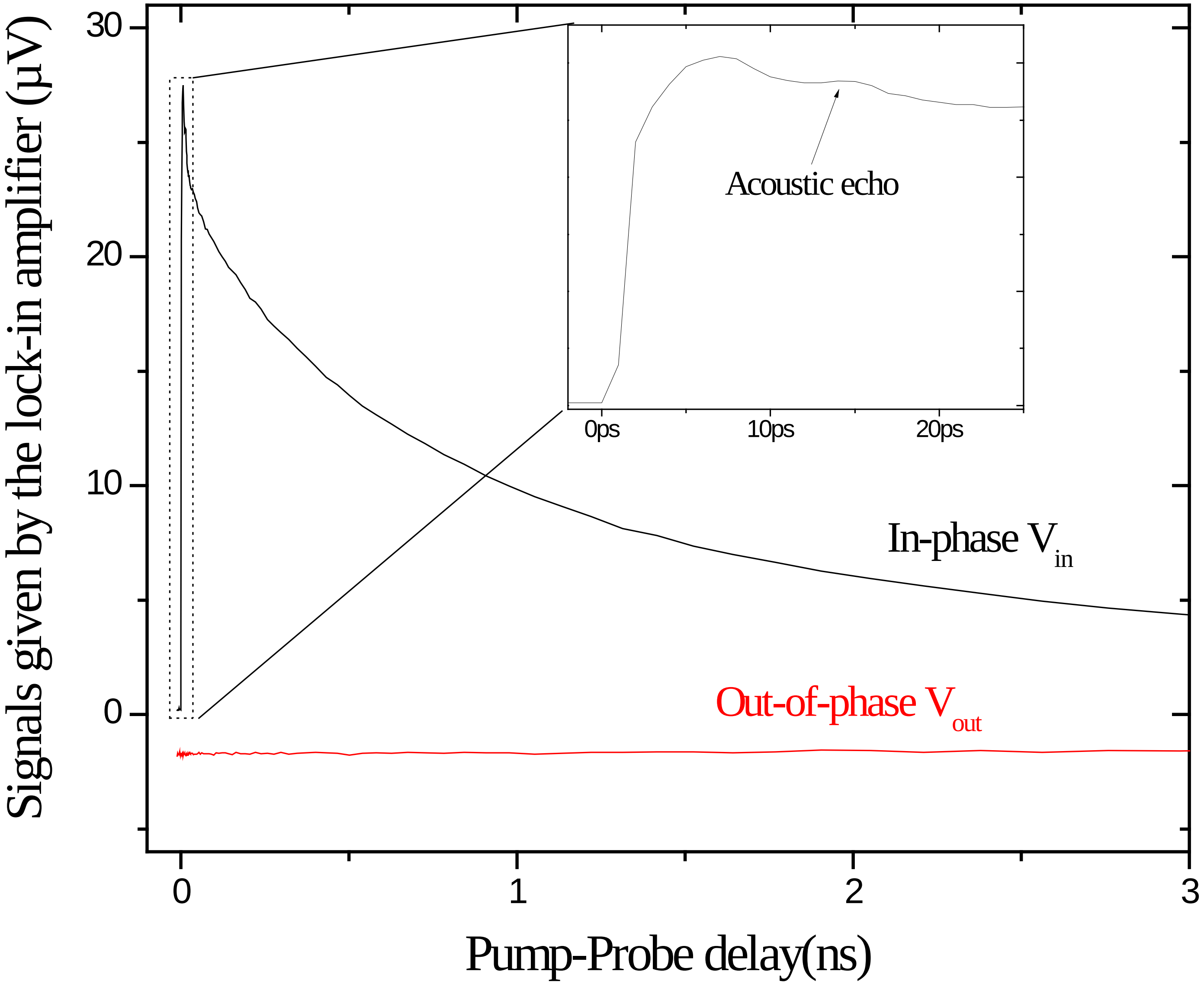
- **Modulated** & **delayed** femtosecond laser pulse used as a **Pump.**
- A **Probe** beam measures **reflectivity variation on the surface**
- The lock-in amplifier gives the **In-phase (V_{in})** and **Out-of-phase (V_{out})** signals.



Gilles Pernot (UCSC, Bordeaux)



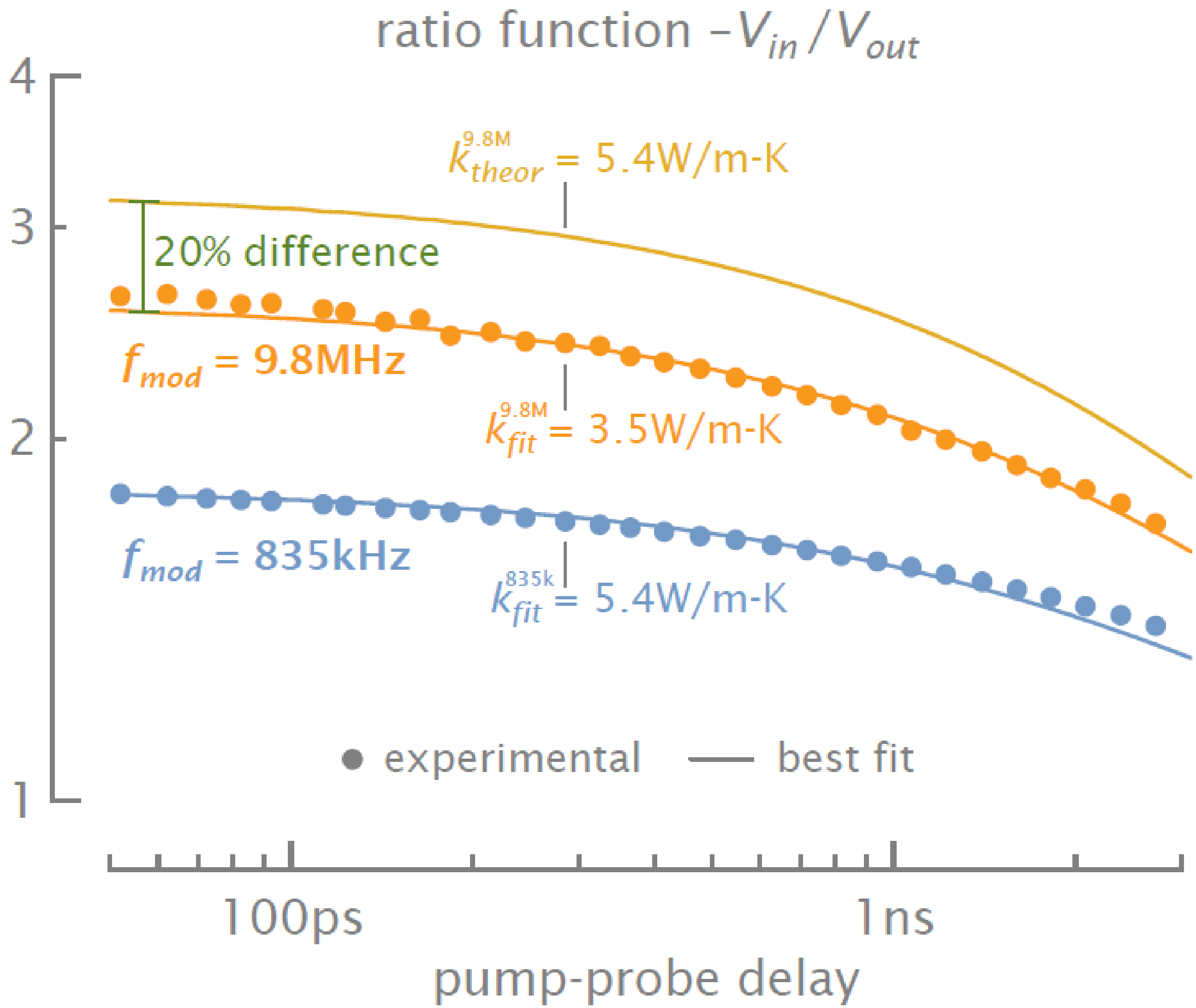
Gilles Pernot (UCSC/Bordeaux), Aaron Schmidt (BU)



David G. Cahill, *Rev. Sci. Instruments* 75, 5119 (2004)

Gilles Pernot (UCSC, Bordeaux)

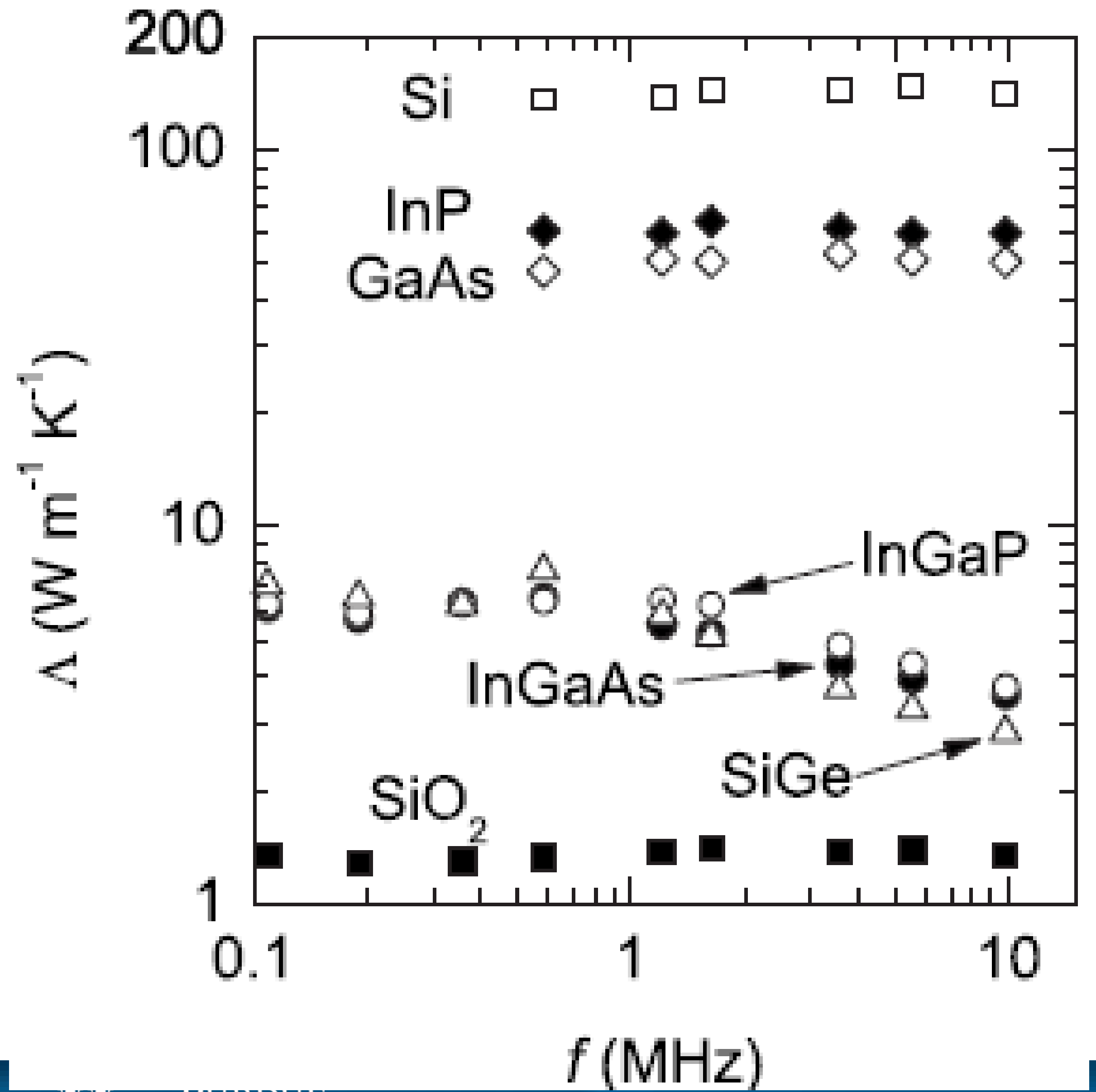
Heat Decay at different modulation frequencies



Alloys such as InGaAs and SiGe

Gilles Pernot (UCSC, Bordeaux)

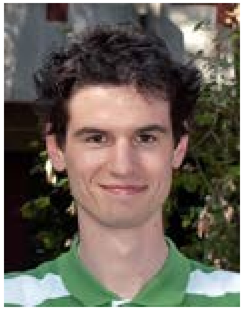
Frequency-Dependent Thermal Conductivity



Koh and Cahill, PHYSICAL REVIEW B 76, 075207 (2007)

See also: Minnich, Nelson, Chen, et al. Physical Review Letters, Vol. 107, 095901 (2011)

Gilles Pernot

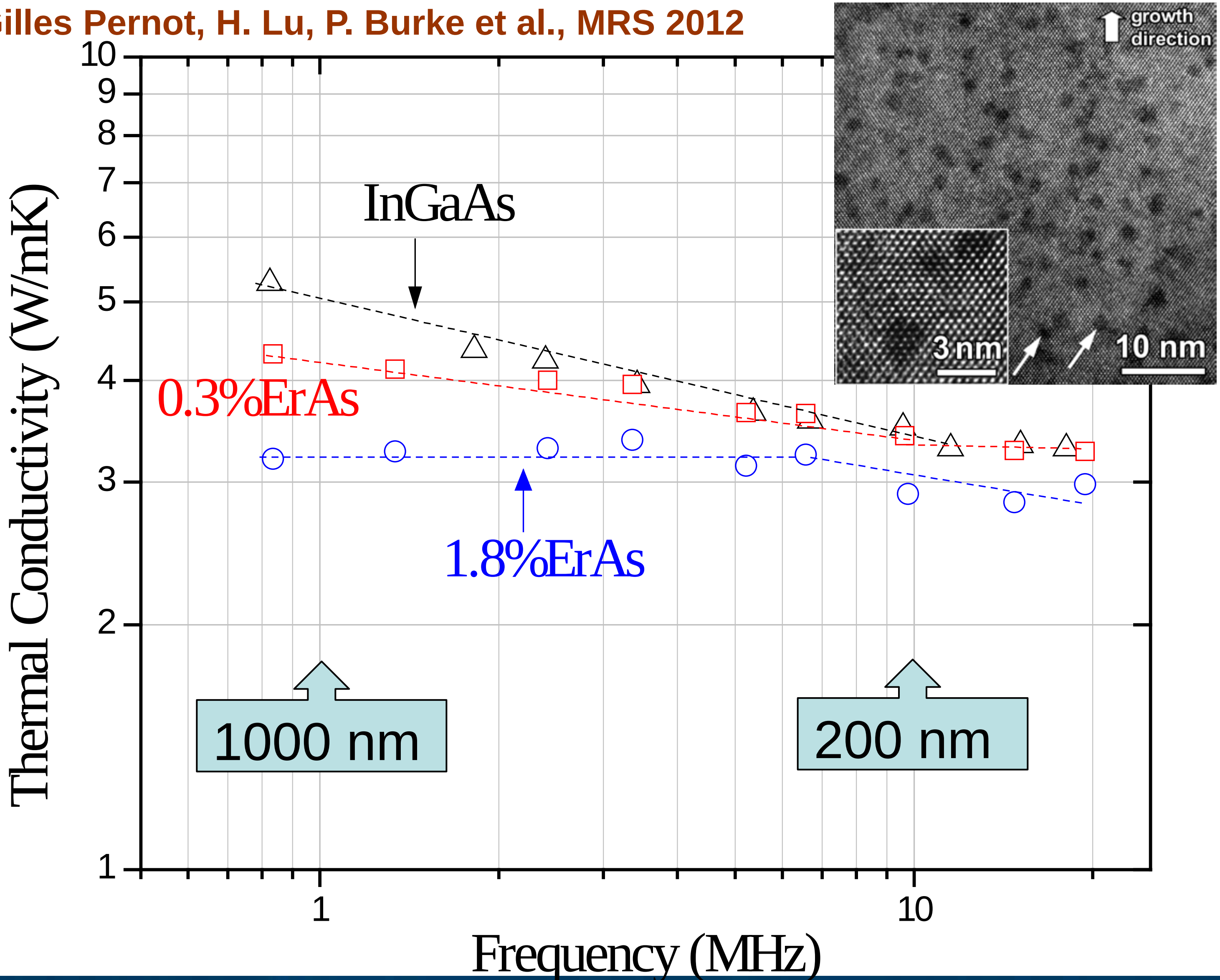


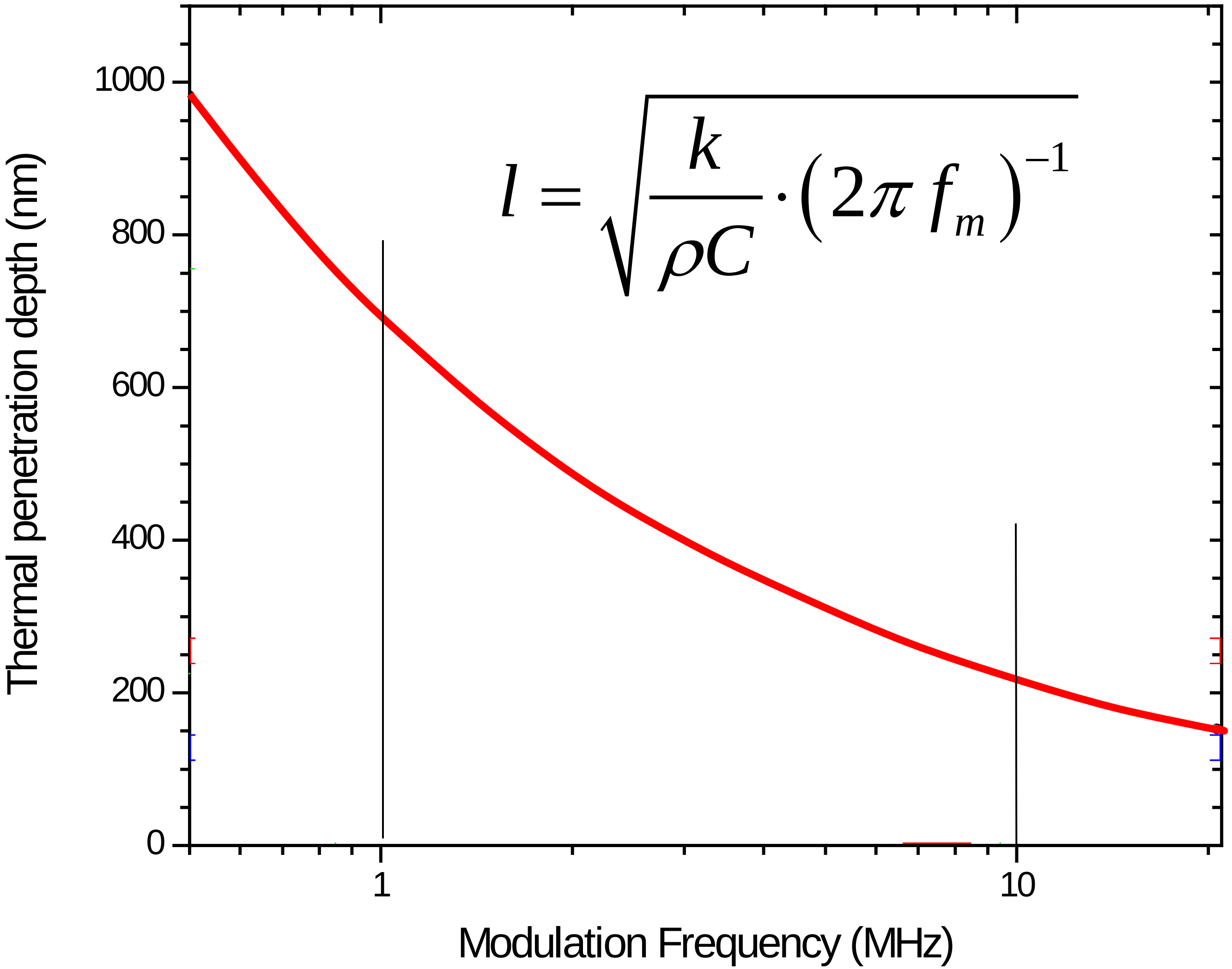
Bjorn Vermeersch

&

Amr Mohamed Shahat

Gilles Pernot, H. Lu, P. Burke et al., MRS 2012





$$l = \sqrt{\frac{k}{\rho C} \cdot (2\pi f_m)^{-1}}$$

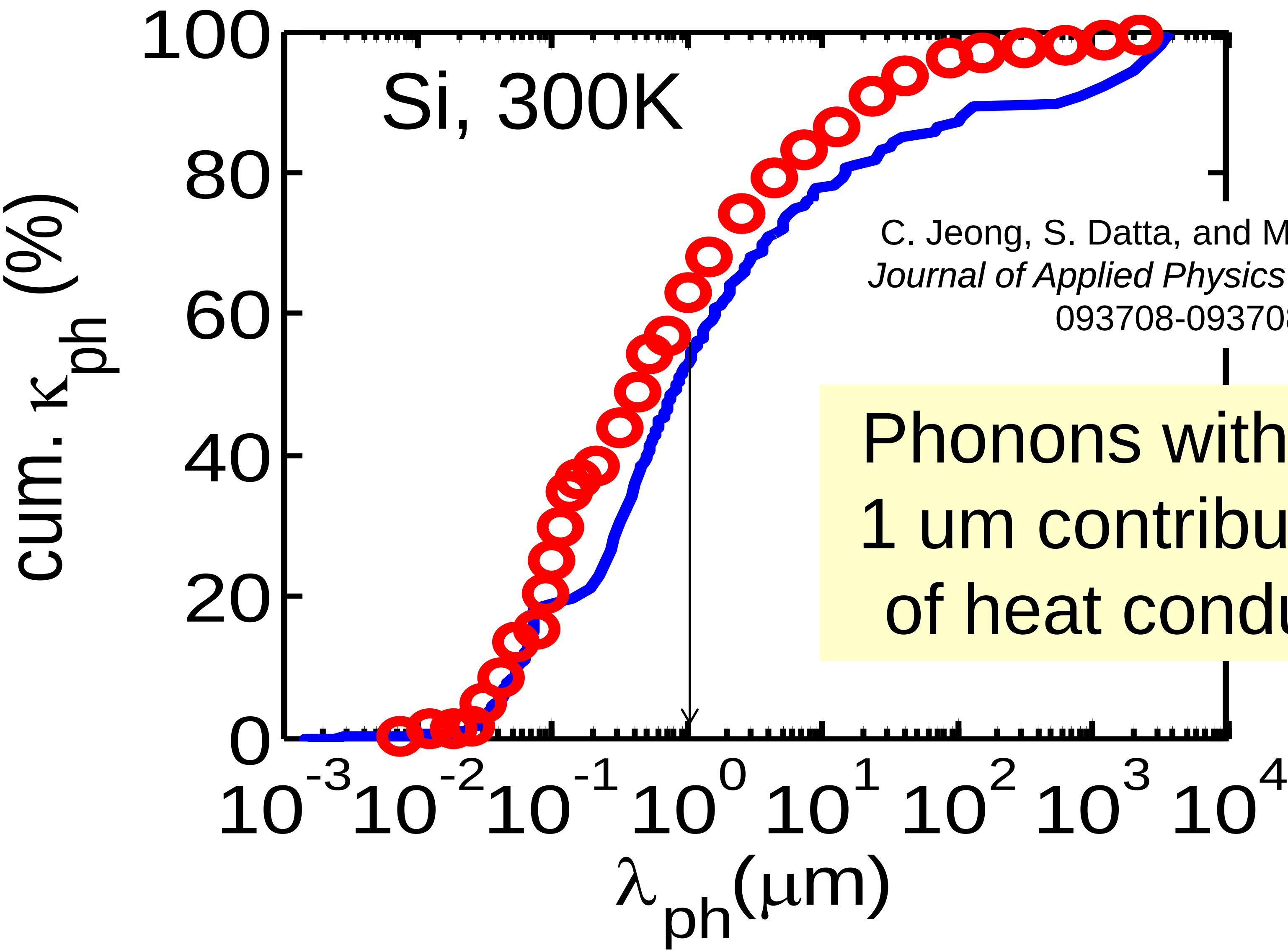
k: thermal conductivity

ρC: volumetric heat capacity

f_m: pump modulation frequency

Gilles Pernot (UCSC, Bordeaux)

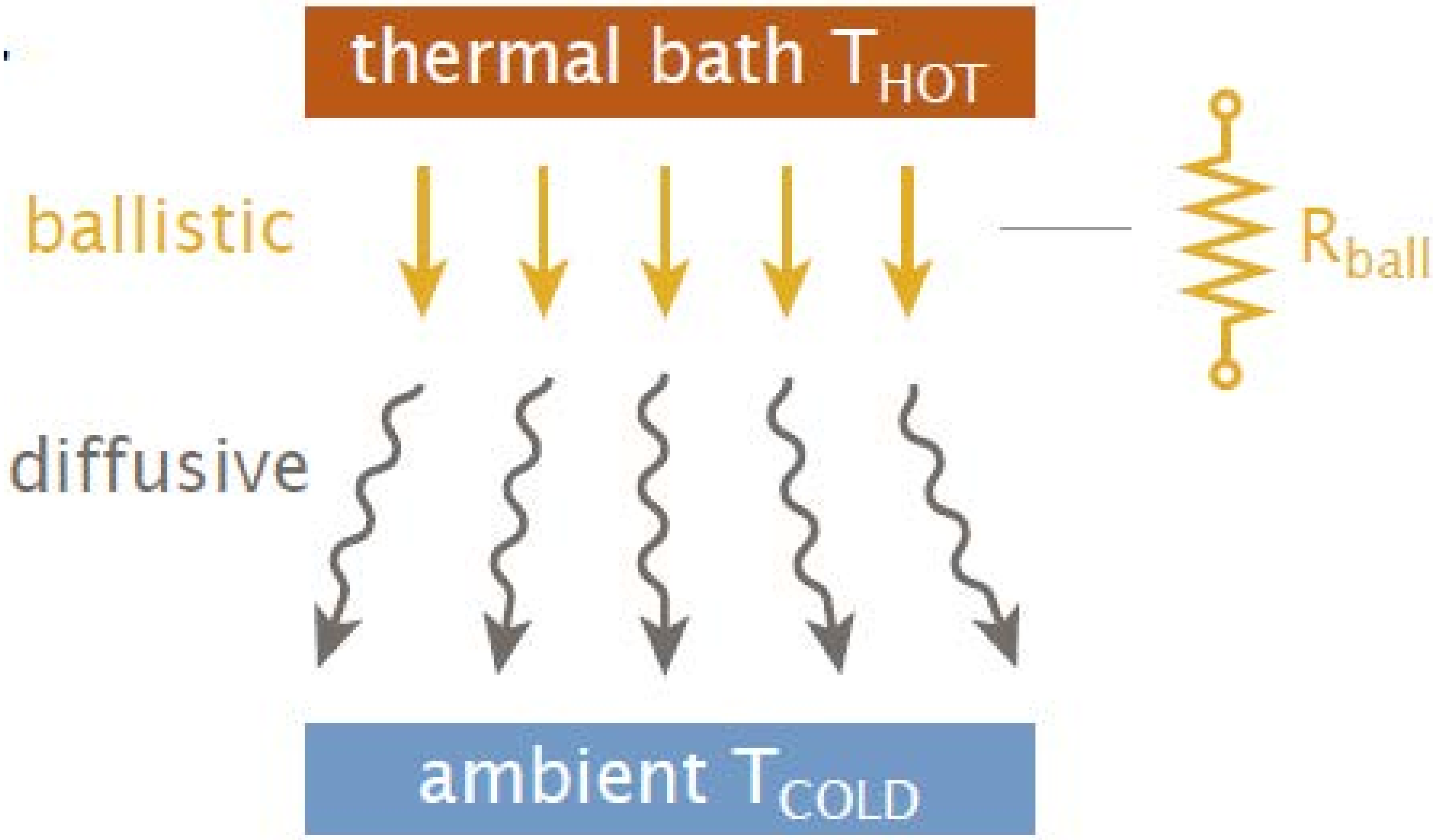
Cummulative κ_{ph} vs. mfp at 300K



C. Jeong, S. Datta, and M. Lundstrom. *Journal of Applied Physics* 111.9 (2012): 093708-093708.

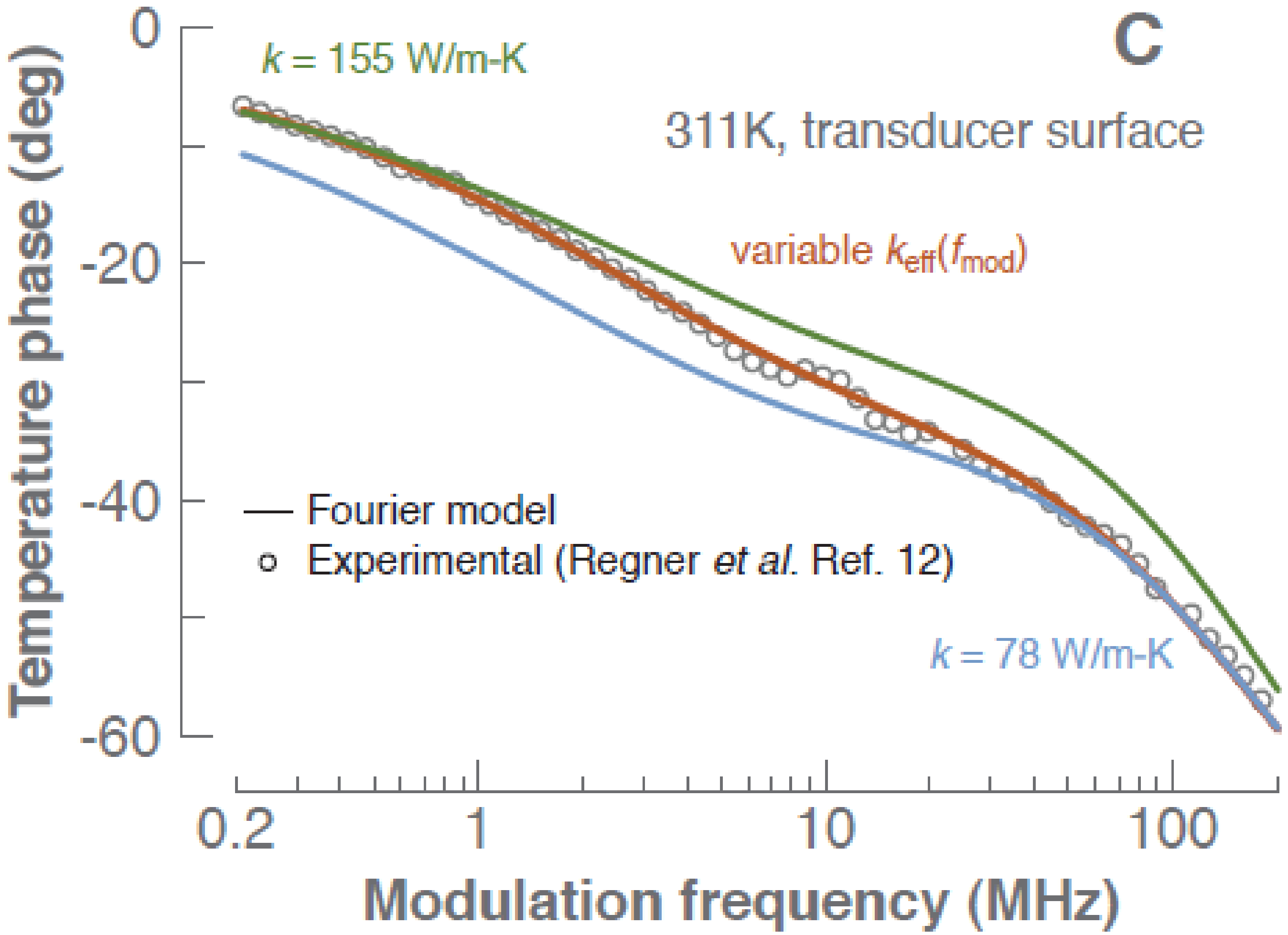
Phonons with mfp > 1 um contribute 50% of heat conduction.

Roll of Ballistic Heat Transport (current theory)



Bjorn Vermeersch, Gilles Pernot, et al. (ITherm 2012)

Frequency-Domain Thermo Reflectance (FDTR)



Silicon

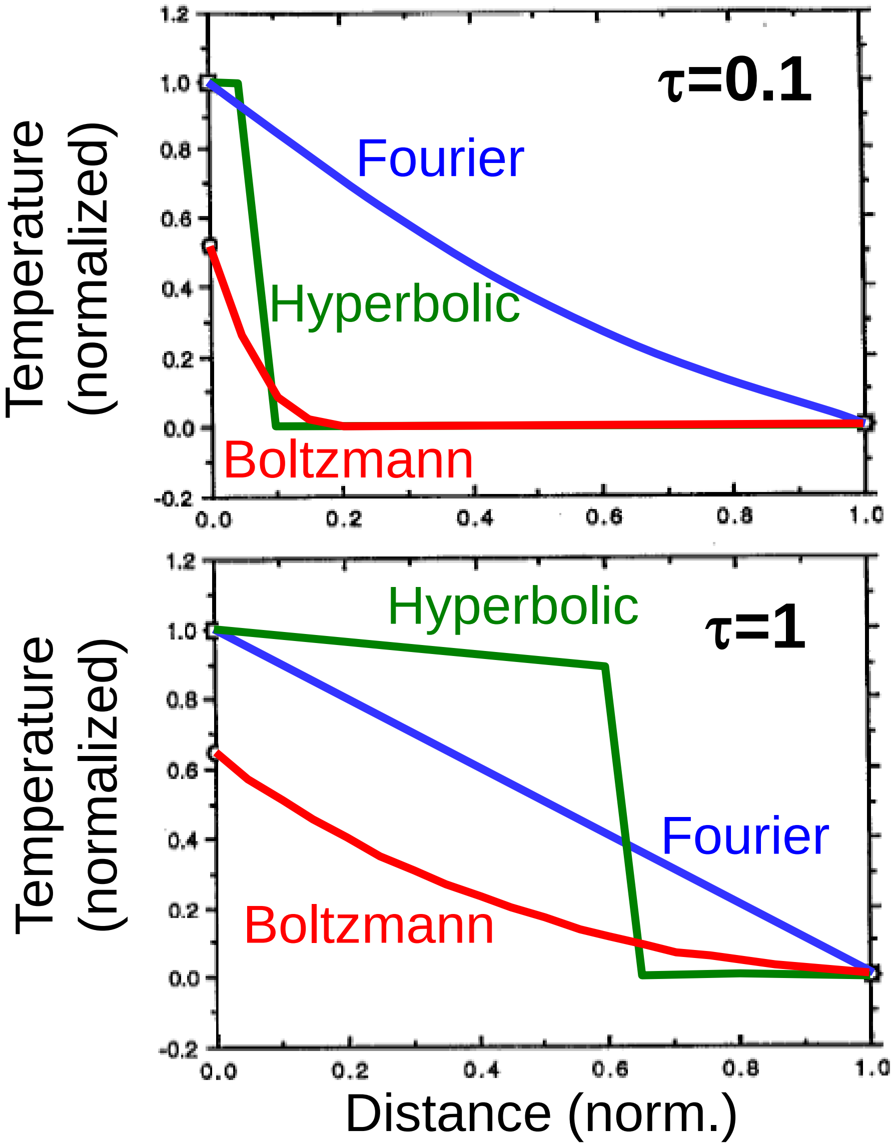
Regner et al. Nature Communications 2013
Bjorn Vermeersch, Amr Shahat et al., Submitted, Sept. 2013

Diffusive or Ballistic Propagation of Heat

D. Joseph et al, Heat Waves, Rev. Mod. Phys. (1989)

A. Joshi and A. Majumdar; J. Appl. Phys. 74, p. 31 (1993)

L=0.1μm Diamond



Fourier

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}$$

α= κ/C

Hyperbolic Heat (Cattaneo)

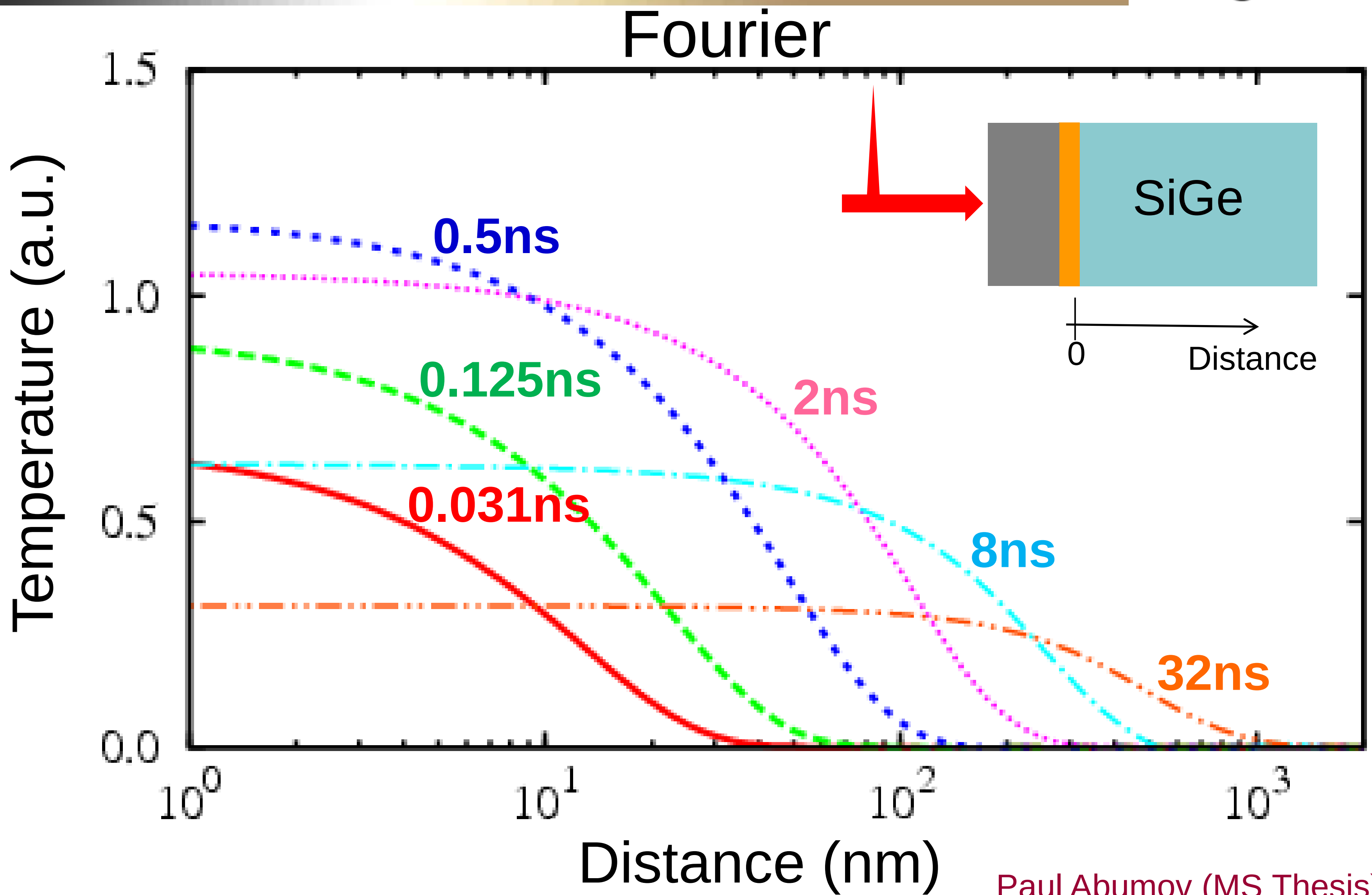
$$\tau_R \frac{\partial^2 T}{\partial t^2} + \frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}$$

Boltzmann (Equation Phonon Radiative Transfer)

$$\frac{\partial N_q}{\partial t} + \mathbf{v} \cdot \nabla N_q = \left(\frac{\partial N_q}{\partial t}\right)_{scat}$$

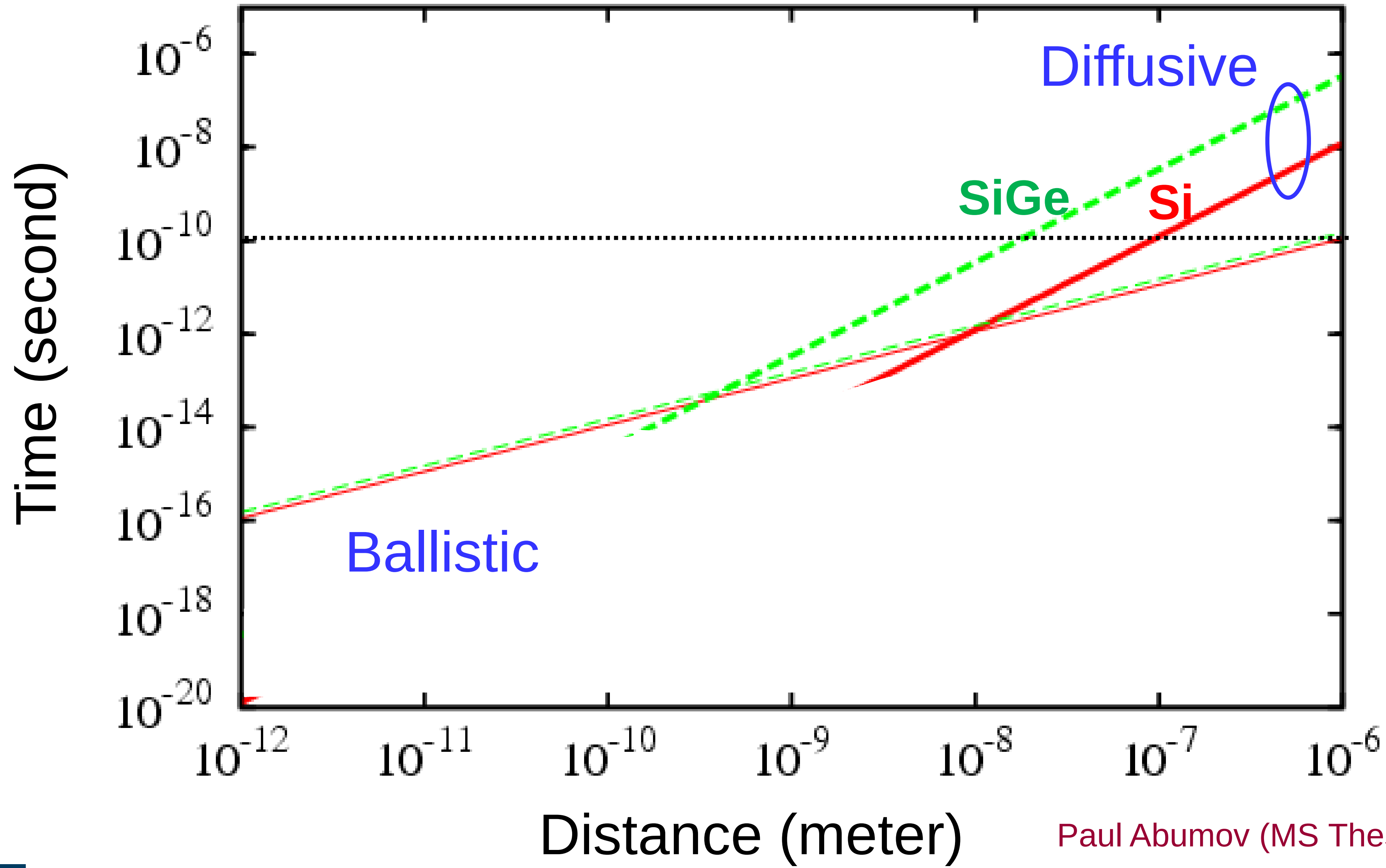
Phonon Number: $N_q(x,t)$

Temperature profile inside SiGe at different times



Paul Abumov (MS Thesis)

At what range ballistic heat transport matters?



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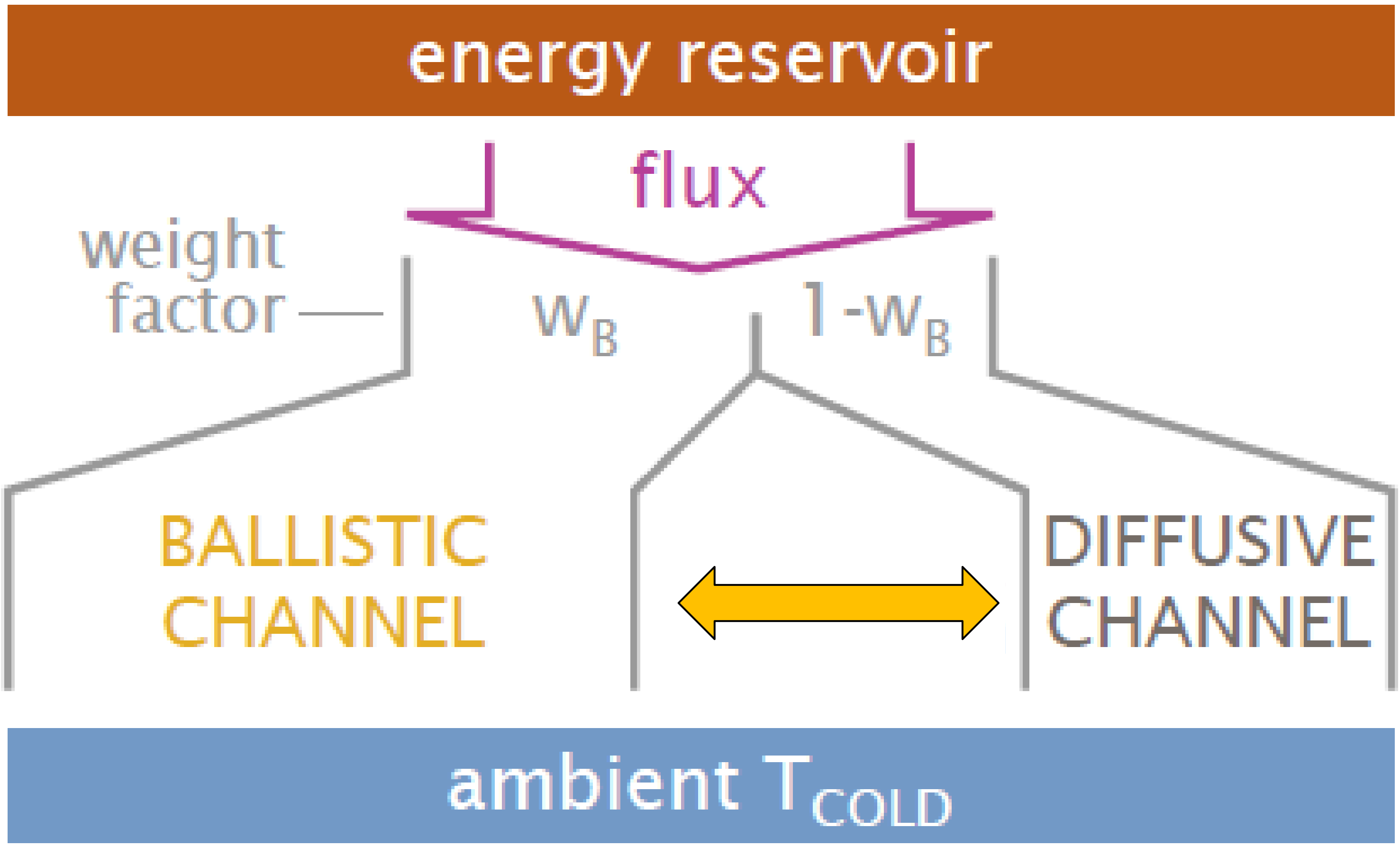
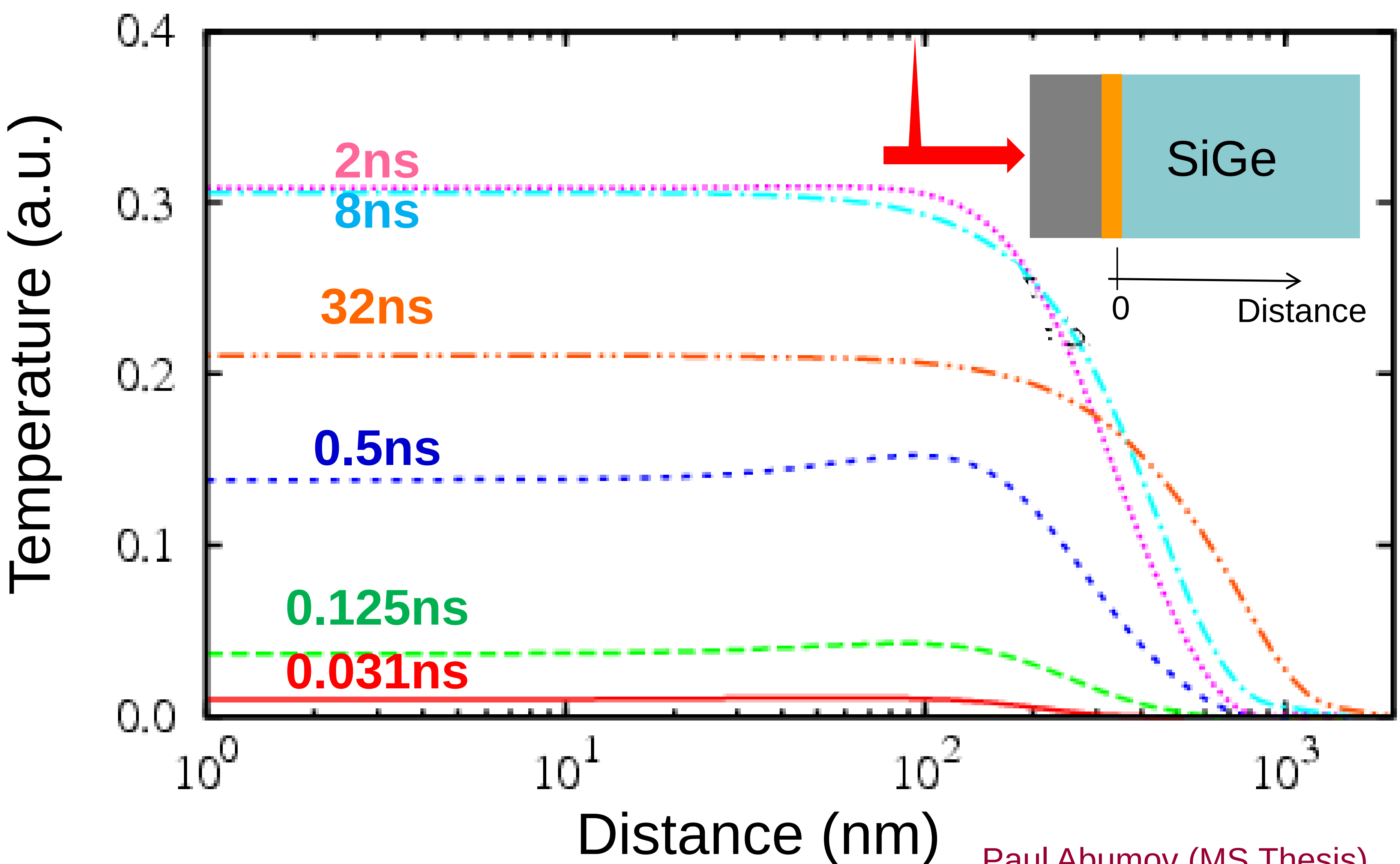
Ballistic/Diffusive Heat Transport



Bjorn Vermeersch, Gilles Pernot, et al. (ITherm 2012)

Ballistic phonons as internal heat source in Fourier diffusion equation (Hypothesis)



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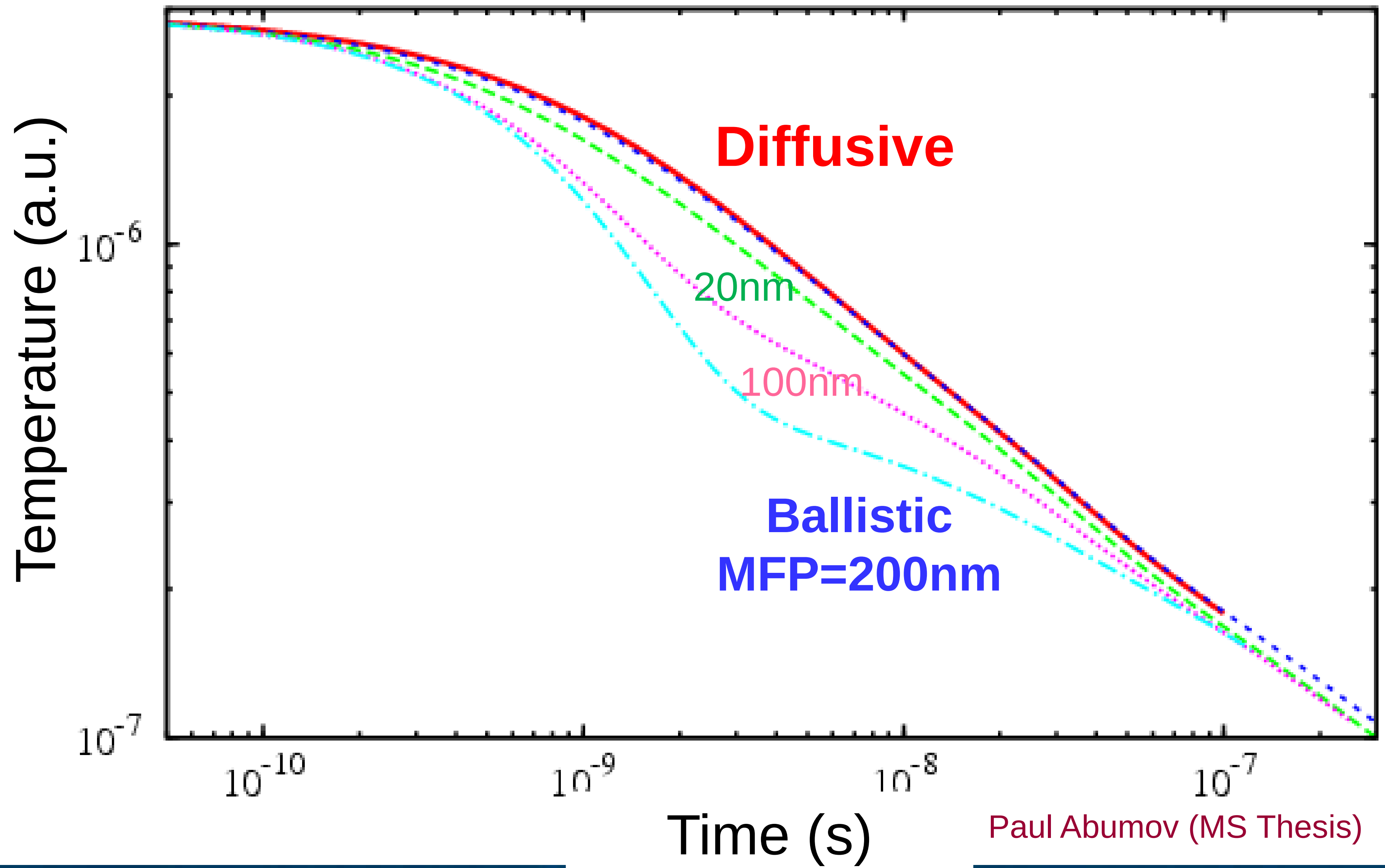
Temperature of metal surface on SiGe



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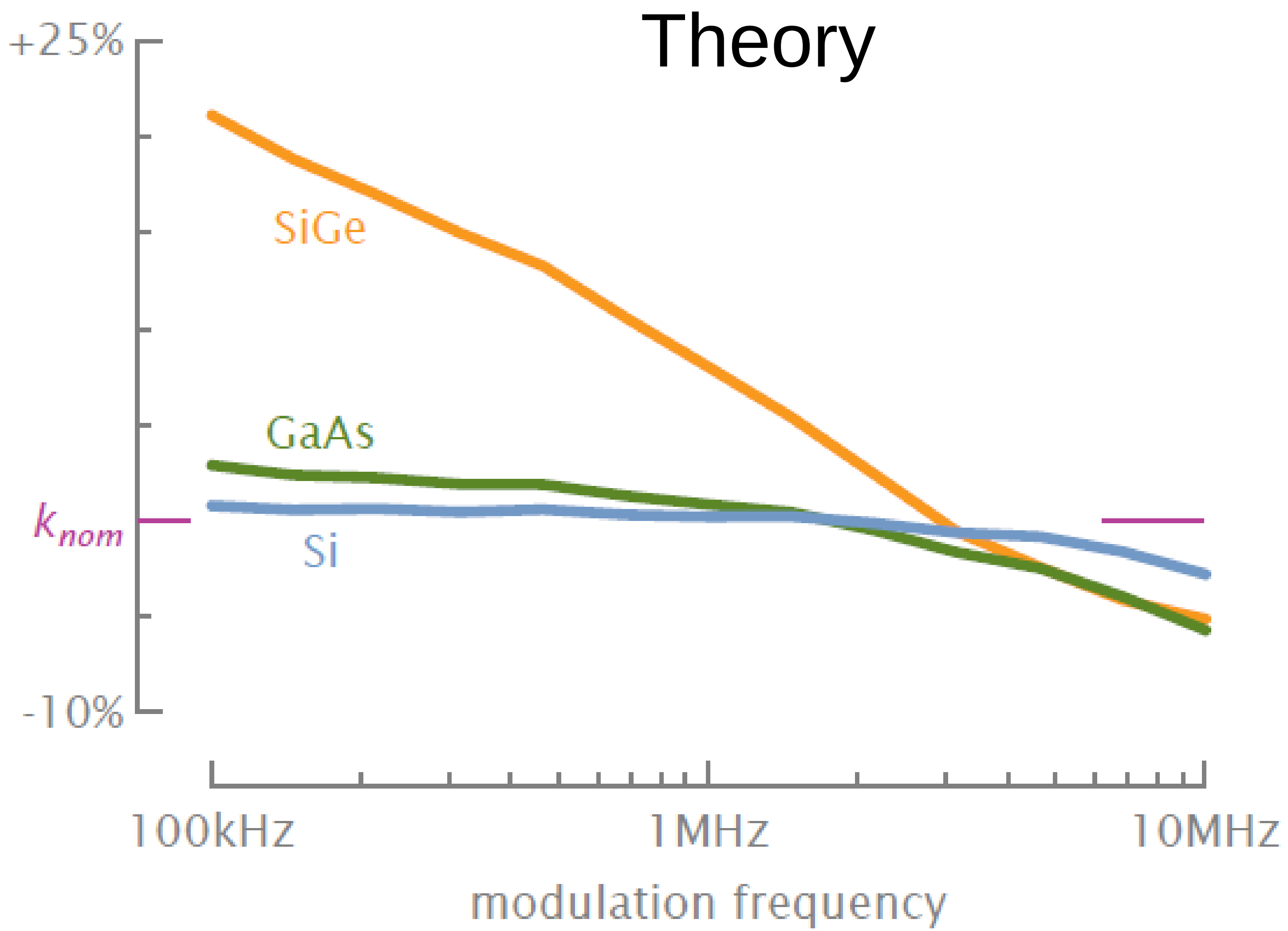
Apparent Thermal Conductivity: κ(ω)



Bjorn Vermeersch, Gilles Pernot, Paul Abumov et al. (ITherm 2012)

Lecture 3.5: Summary

- Time-Domain Thermo Reflectance
  - Experimental setup
  - Fitting of experimental data (ratio curve)
  - Apparent frequency-dependent thermal conductivity
- Frequency-Domain Thermo Reflectance
- Ballistic vs. Diffusive heat conduction
  - Hyperbolic (Cattaneo) equation
  - Beyond "ballistic phonons don't contribute to thermal conduction": should NOT use Fourier equation (see: B. Vermeersch et al. 2013-14)