HYDRODYNAMIC PHENOMENA IN THERMAL TRANSPORT

Universitat Autònoma de Barcelona
F. Xavier Alvarez

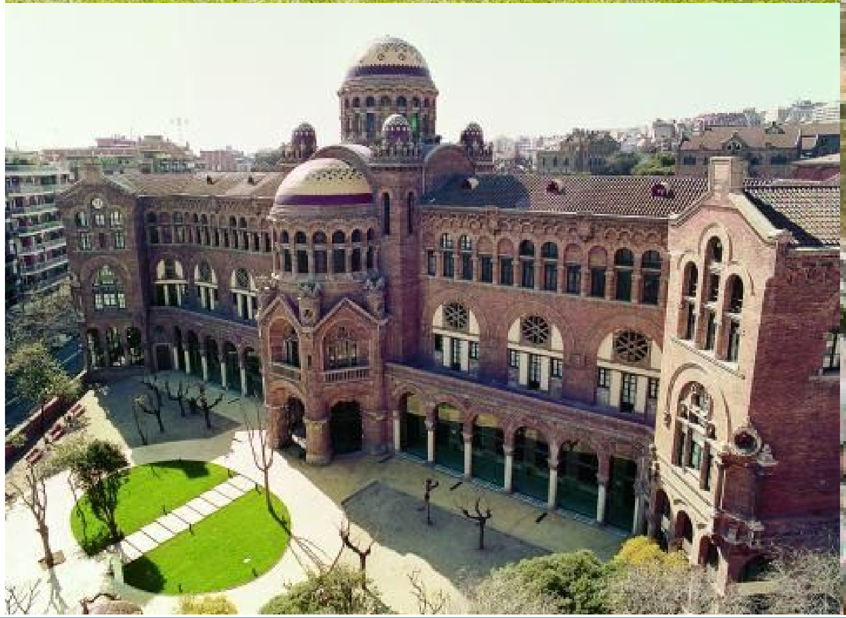
xavier.alvarez@uab.cat

Purdue, July 2022

Universitat Autònoma de Barcelona UAB

UAB

Universitat Autònoma de Barcelona

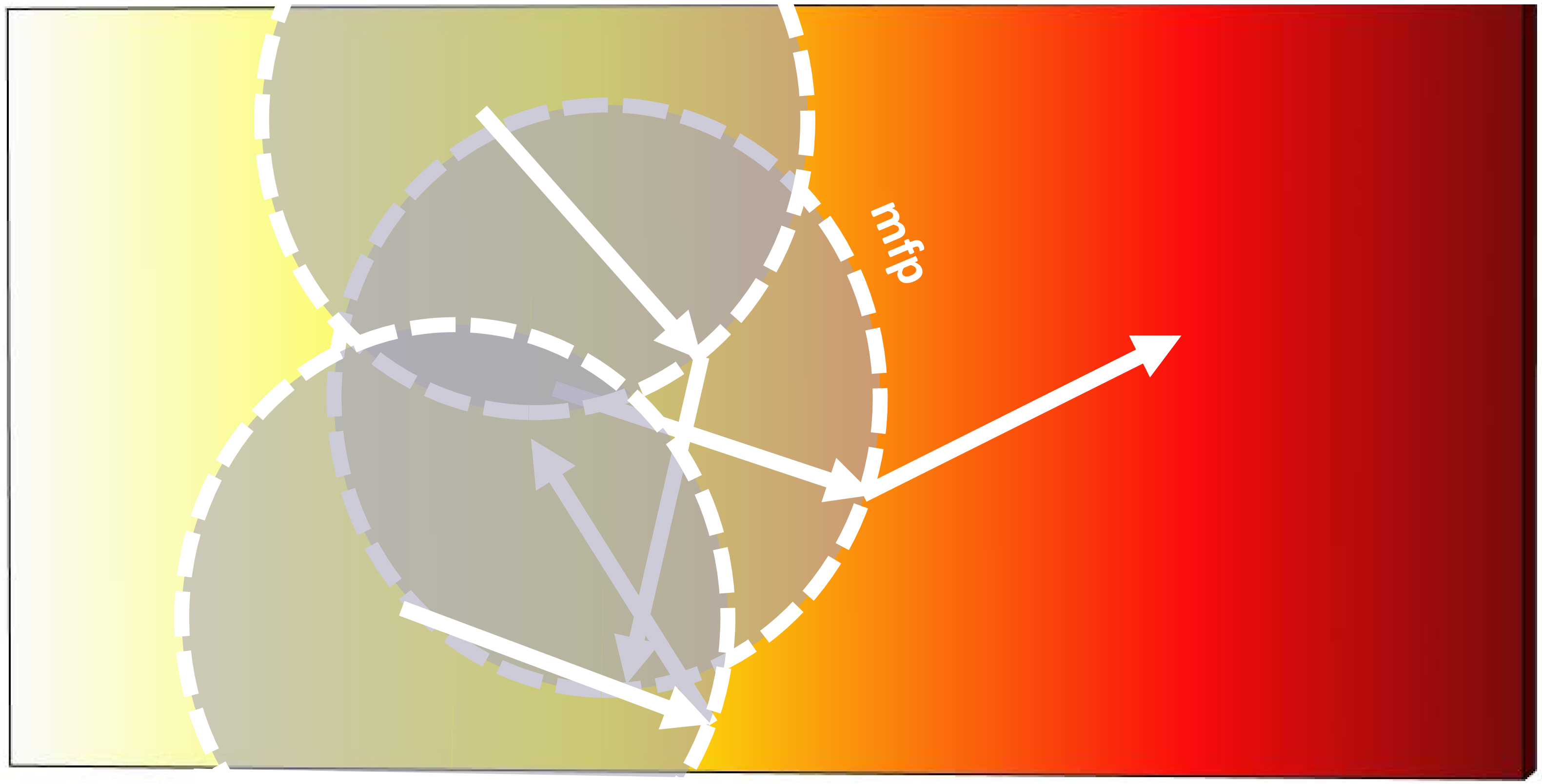


Summary

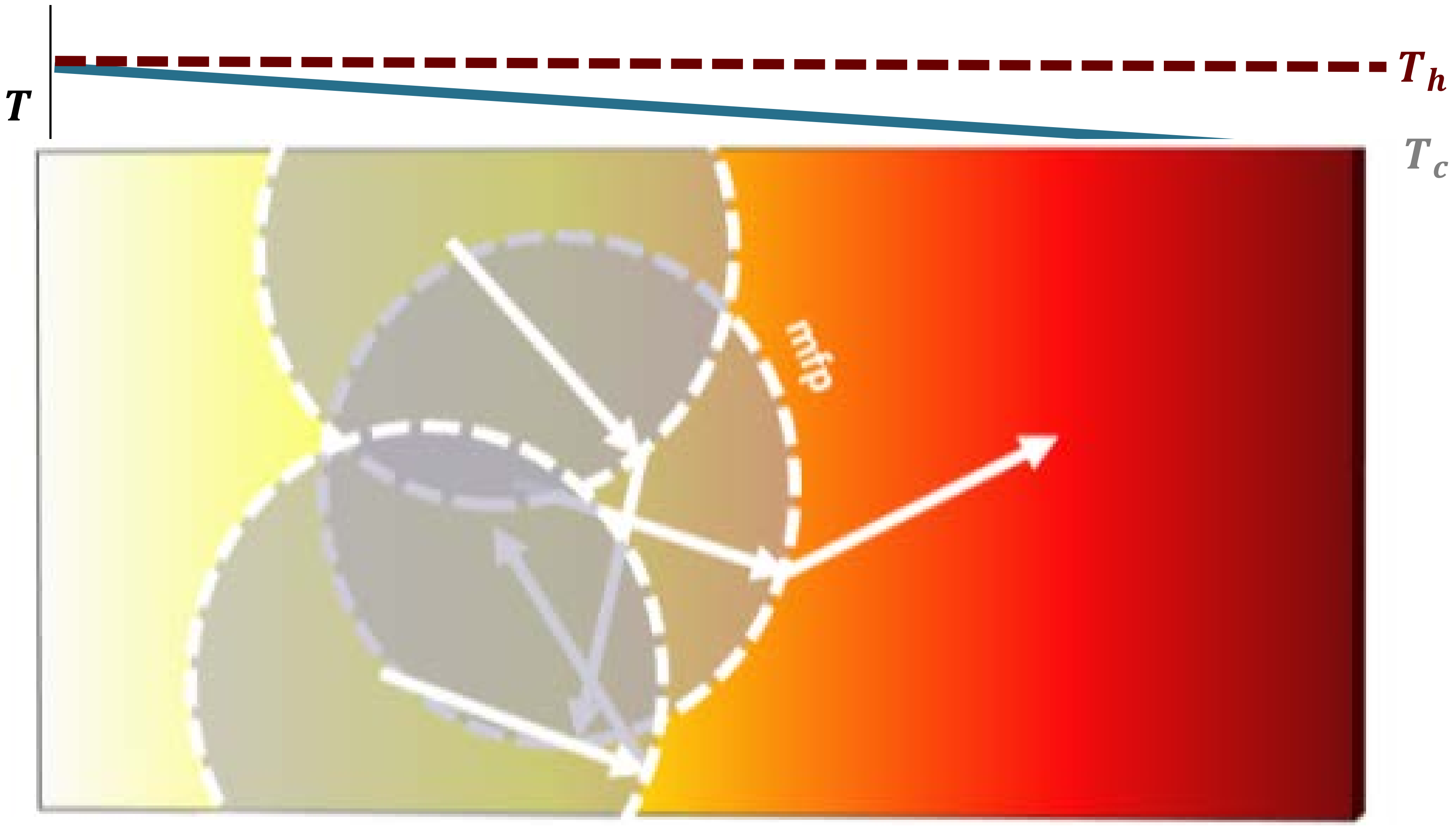
- Introduction.
- From the phonons to the moments basis
- Hydrodynamic behavior of semiconductors
- BTE calculations for hydrodynamic paràmetres
- New phenomena
- Conclusions

INTRODUCTION:
THRERMAL TRANSPORT
AT THE NANOSCALE

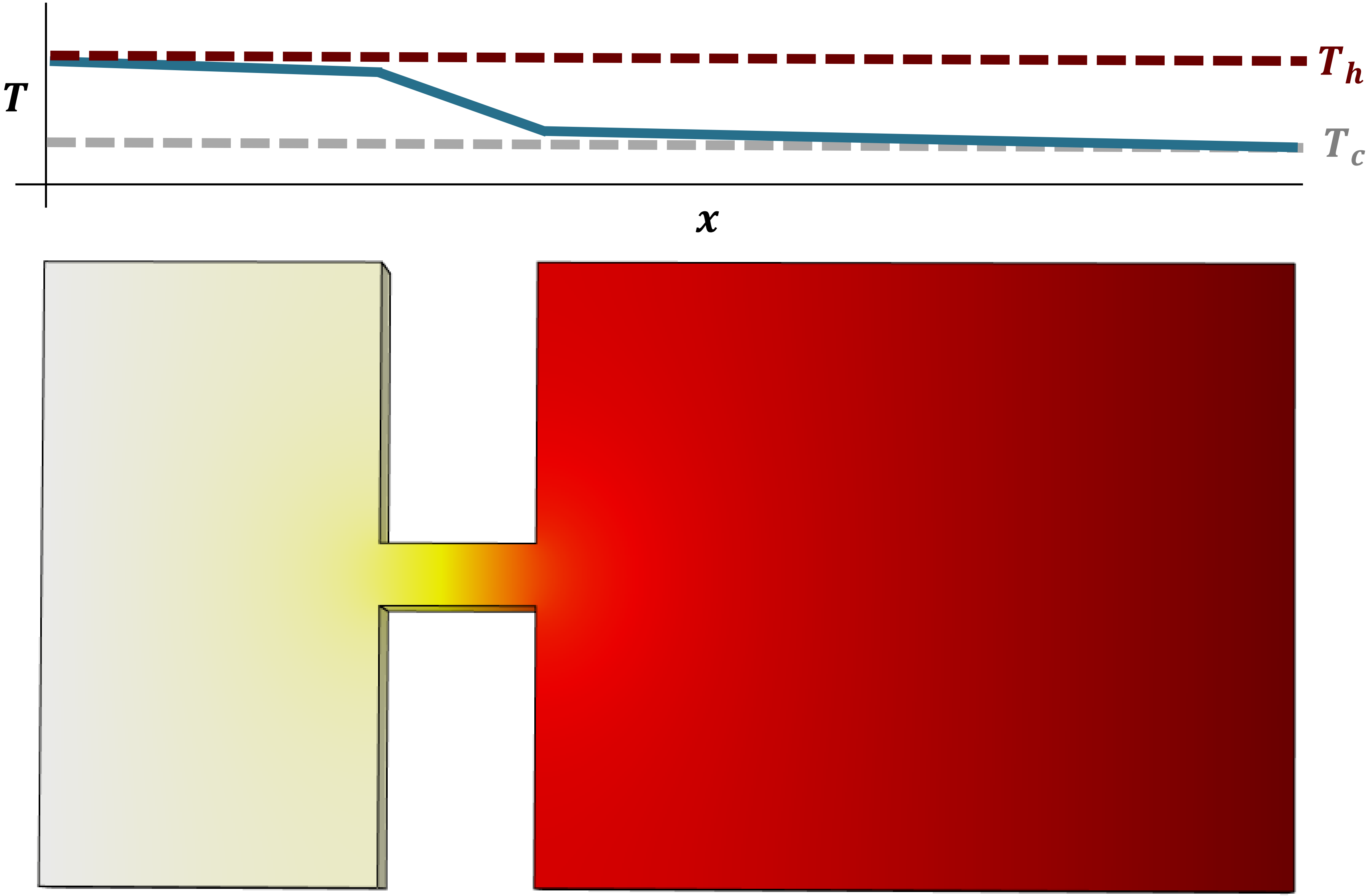
Fourier's law



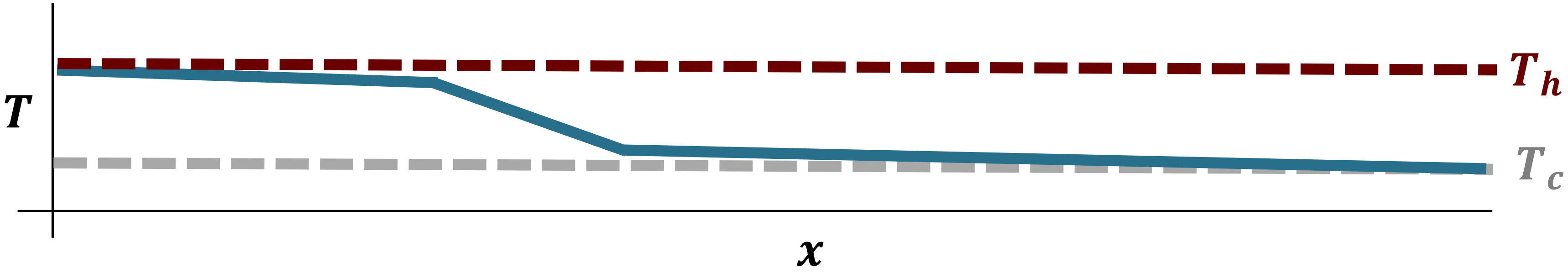
Fourier's law

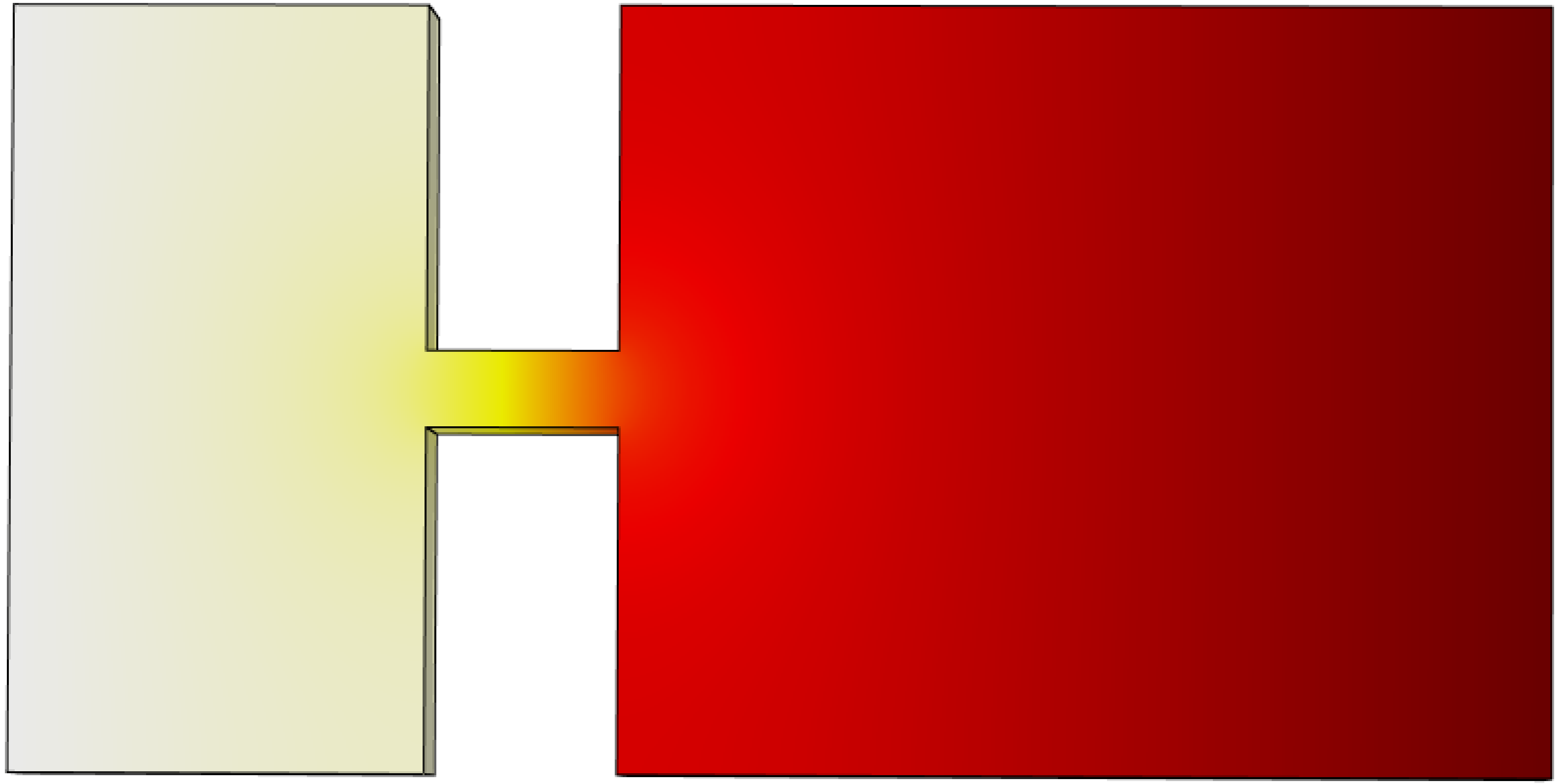


Geometry effects

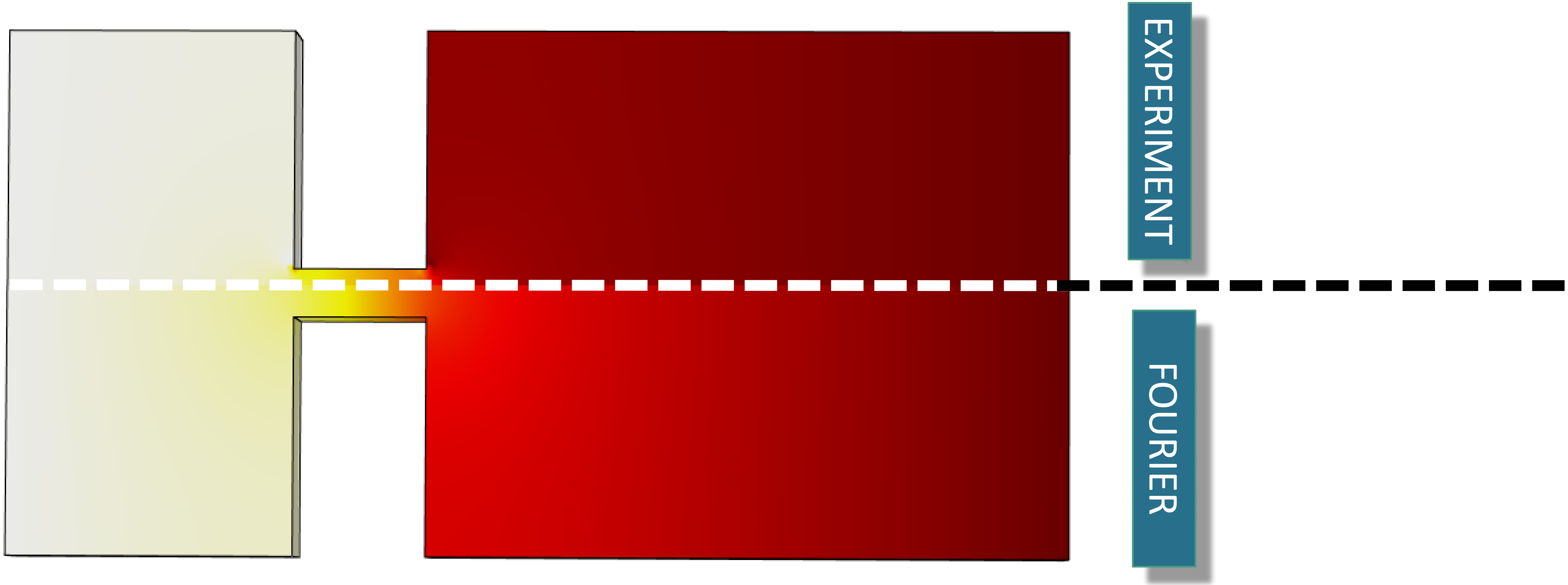


Geometry effects



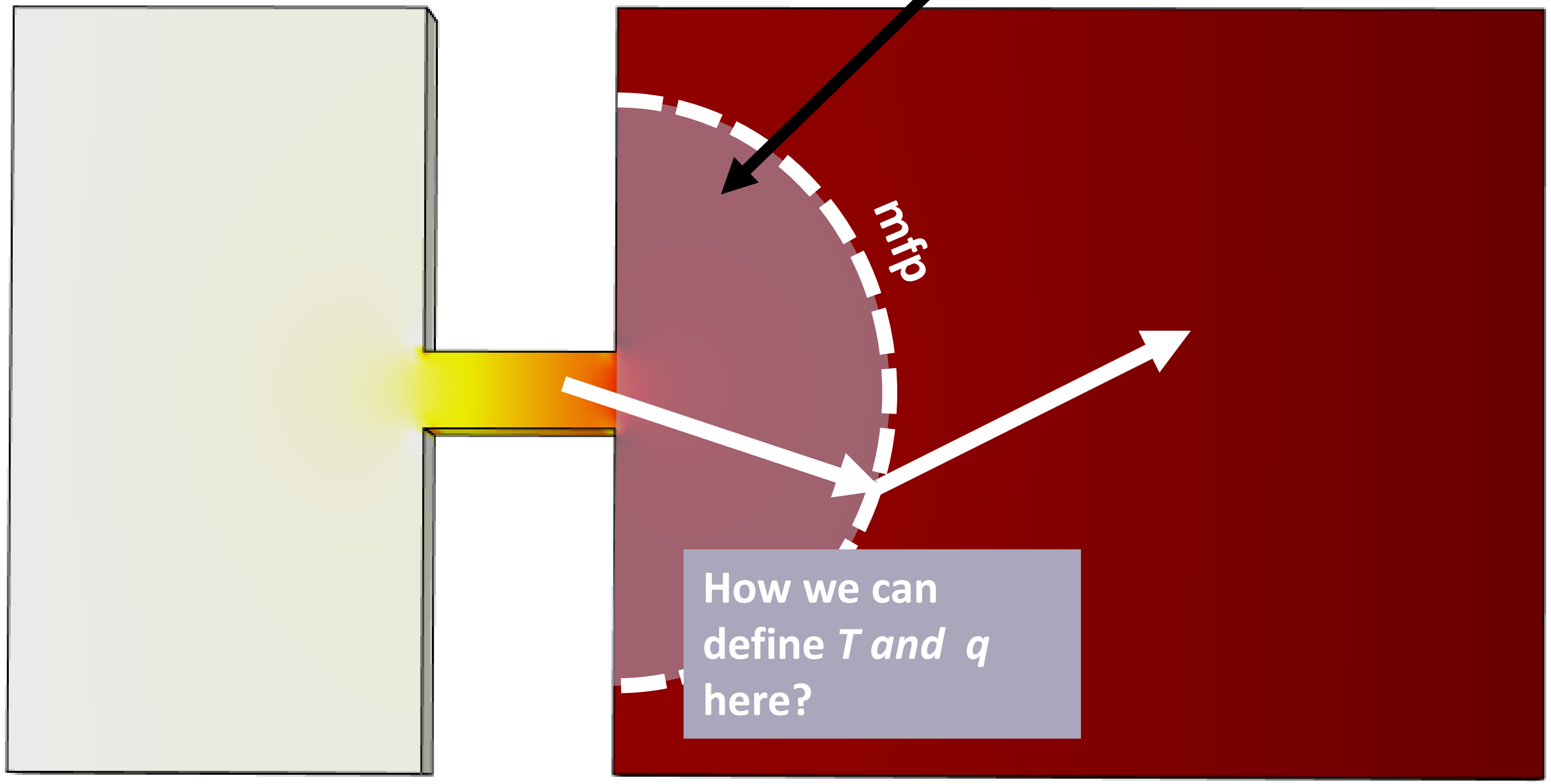


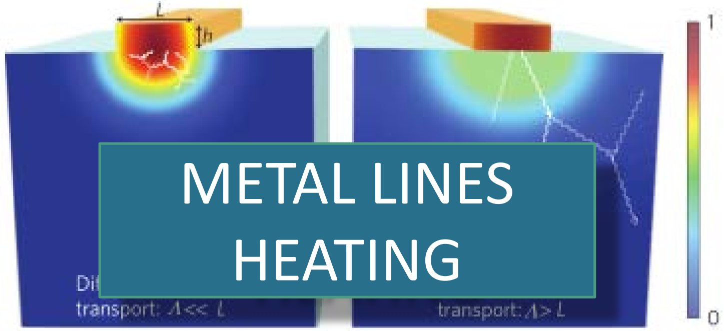
Geometry effects

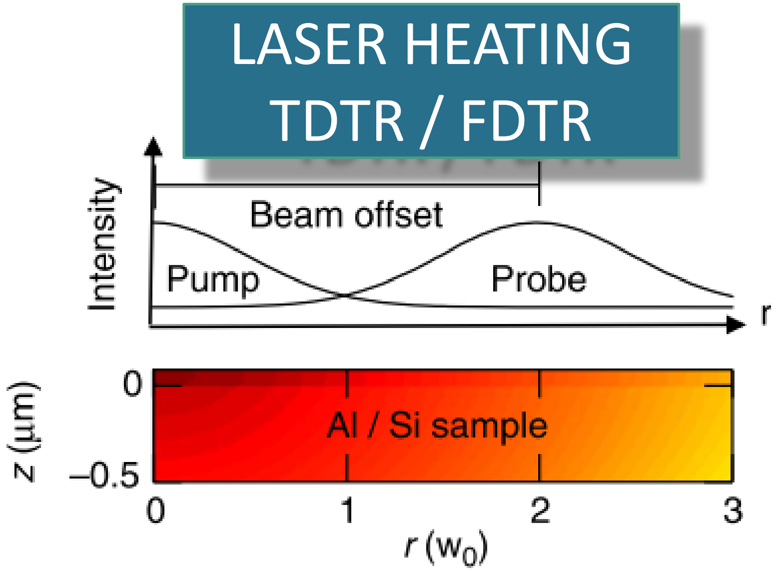


Geometry effects

Fourier does not work
In this region







Mecanical (Hamiltonian) vs Entropic description

The main goal of the talk is to find contact points!

PHONONS VS MOMENTS BASIS

Boltzmann Transport Equation

PHONONS

$$f_k(x,t)$$

↓

BTE

k equations for the *k* modes

$$\frac{\partial f_k}{\partial t} + v \cdot \frac{d f_k}{dT} \nabla T = C(f_k)$$

Boltzmann Transport Equation

PHONONS

$$f_k(x,t)$$

↓

BTE

k equations for the *k* modes

$$\frac{\partial f_k}{\partial t} + v \cdot \frac{d f_k}{dT} \nabla T = \frac{f_k - f_k^0}{\tau_k}$$

From phonons $f(k, x, t)$ to moments $Q^{(n)}(x, t)$

Thermodynamic energy

Phonon energy

0th ORDER: Energy

$$f(\kappa, x, t)$$

1st ORDER: Heat flux

$$q(x,t) = \int \hbar\,\omega_k \vec{v_k} f(\kappa, x, t)\, \frac{d^3k}{(2\pi)^3}$$

2nd ORDER: Flux of the flux

$$Q^{(2)}(x,t) = \int \hbar\,\omega_k (\vec{v_k} \cdot \vec{v_k}) f(\kappa, x, t)\, \frac{d^3k}{(2\pi)^3}$$

nth ORDER

$$Q^{(n)}(x,t) = \int \hbar\,\omega_k (\vec{v_k} \cdots \vec{v_k}) f(\kappa, x, t)\, \frac{d^3k}{(2\pi)^3}$$

From phonons $f(k, x, t)$ to moments $Q^{(n)}(x, t)$

Thermodynamic energy

Phonon energy

0th ORDER: Energy

$$\epsilon(x,t) = \int \hbar\,\omega_k\, f(\kappa, x, t)$$

Thermodynamic Heat flux

Phonon Heat flux

1st ORDER: Heat flux

$$q(x,t) = \int \hbar\,\omega_k \overrightarrow{v_k} f(\kappa, x, t)\,\frac{d^3k}{(2\pi)^3}$$

2nd ORDER: Flux of the flux

$$Q^{(2)}(x,t) = \int \hbar\,\omega_k (\overrightarrow{v_k}\cdot\overrightarrow{v_k}) f(\kappa, x, t)\,\frac{d^3k}{(2\pi)^3}$$

nth ORDER

$$Q^{(n)}(x,t) = \int \hbar\,\omega_k (\overrightarrow{v_k}\cdots\overrightarrow{v_k}) f(\kappa, x, t)\,\frac{d^3k}{(2\pi)^3}$$

From phonons $f(k,x,t)$ to moments $Q^{(n)}(x,t)$

0^{th} ORDER: Energy

$$\varepsilon(x,t) = \int \hbar\,\omega_k\, f(\kappa, x, t)$$

Thermodynamic Heat flux

Phonon Heat flux

1^{st} ORDER: Heat flux

$$q(x,t) = \int \hbar\,\omega_k \overrightarrow{v_k} f(\kappa, x, t)\,\frac{d^3k}{(2\pi)^3}$$

Thermodynamic Flux of the flux

Phonon Stress T

2^{nd} ORDER: Flux of the flux

$$Q^{(2)}(x,t) = \int \hbar\,\omega_k (\overrightarrow{v_k}\cdot\overrightarrow{v_k}) f(\kappa, x, t)\,\frac{d^3k}{(2\pi)^3}$$

n^{th} ORDER

$$Q^{(n)}(x,t) = \int \hbar\,\omega_k (\overrightarrow{v_k}\cdots\overrightarrow{v_k}) f(\kappa, x, t)\,\frac{d^3k}{(2\pi)^3}$$

From phonons $f(k,x,t)$ to moments $Q^{(n)}(x,t)$

0th ORDER: Energy

$$\epsilon(x,t) = \int \hbar\, \omega_k f(\kappa, x, t)$$

1st ORDER: Heat flux

$$q(x,t) = \int \hbar\, \omega_k \vec{v_k} f(\kappa, x, t) \frac{d^3k}{(2\pi)^3}$$

2nd ORDER: Flux of the flux

Thermodynamic Flux of the flux

Phonon Stress T

$$Q^{(2)}(x,t) = \int \hbar\, \omega_k (\vec{v_k} \cdot \vec{v_k}) f(\kappa, x, t) \frac{d^3k}{(2\pi)^3}$$

nth ORDER

$$Q^{(n)}(x,t) = \int \hbar\, \omega_k (\vec{v_k} \cdots \vec{v_k}) f(\kappa, x, t) \frac{d^3k}{(2\pi)^3}$$

Moments are more easily to measure experimentally than phonon abundances:Temperature, fluxes, etc...

From phonons $f(k, x, t)$ to moments $Q^{(n)}(x, t)$

PHONONS BASIS

$$f_k(x, t)$$

MOMENTS BASIS

$$Q^n(x, t) = \sum_k v_k \cdots v_k f_k(x, t)$$

Change of Basis

BTE

k equations for the k phonons

$$\frac{\partial f_k}{\partial t} + v \cdot \frac{d f_k}{dT} \nabla T = \frac{f_k - f_k^0}{\tau_k}$$

MOMENTS EQUATIONS

n equations for the n moments

From phonons $f(k, x, t)$ to moments $Q^{(n)}(x, t)$

$$\frac{\partial f}{\partial t} + v \cdot \nabla f = -\frac{f - f_0}{\tau}$$

$$c_V \frac{\partial T}{\partial t} - \nabla \cdot \boldsymbol{q} = 0$$

0th ORDER: Energy conservation

From phonons $\boldsymbol{f(k,x,t)}$ to moments $\boldsymbol{Q^{(n)}(x,t)}$

$$\int \quad \frac{\partial f}{\partial \mathrm{t}} + \quad v \cdot \nabla f = - \quad \frac{f - f_0}{\tau}$$

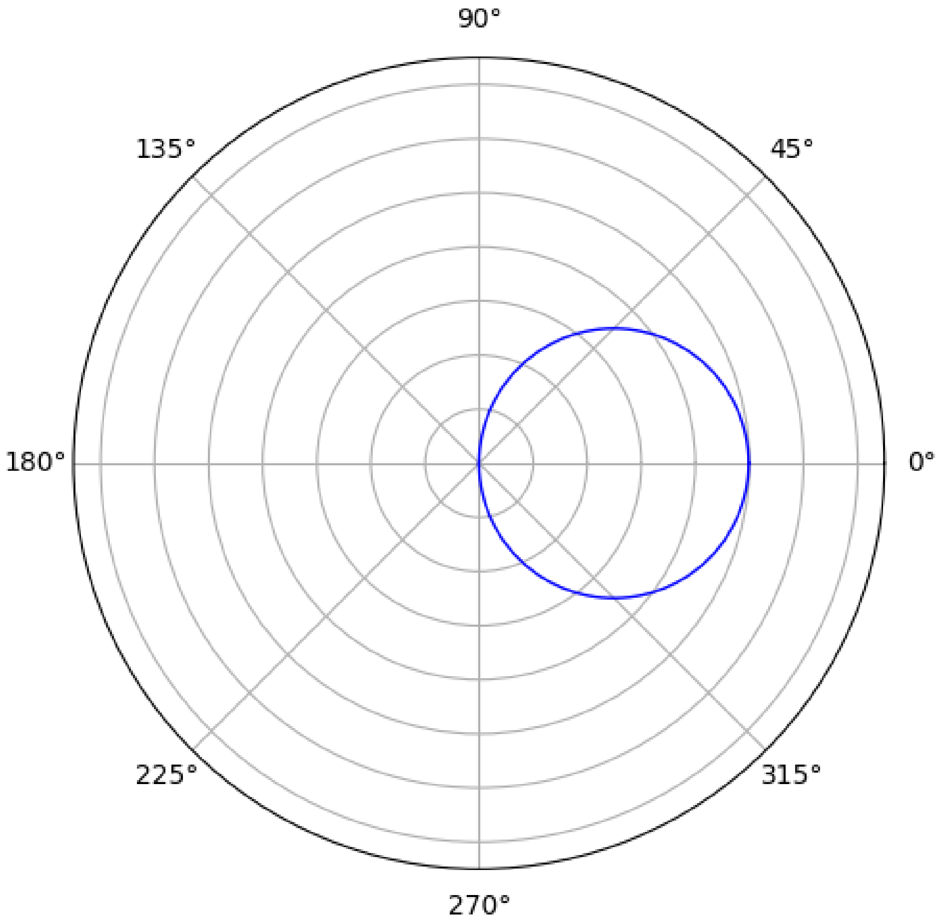
$$\frac{\partial q}{\partial t} \quad -\nabla \cdot \boldsymbol{Q} = \quad \frac{q}{\tau_q}$$

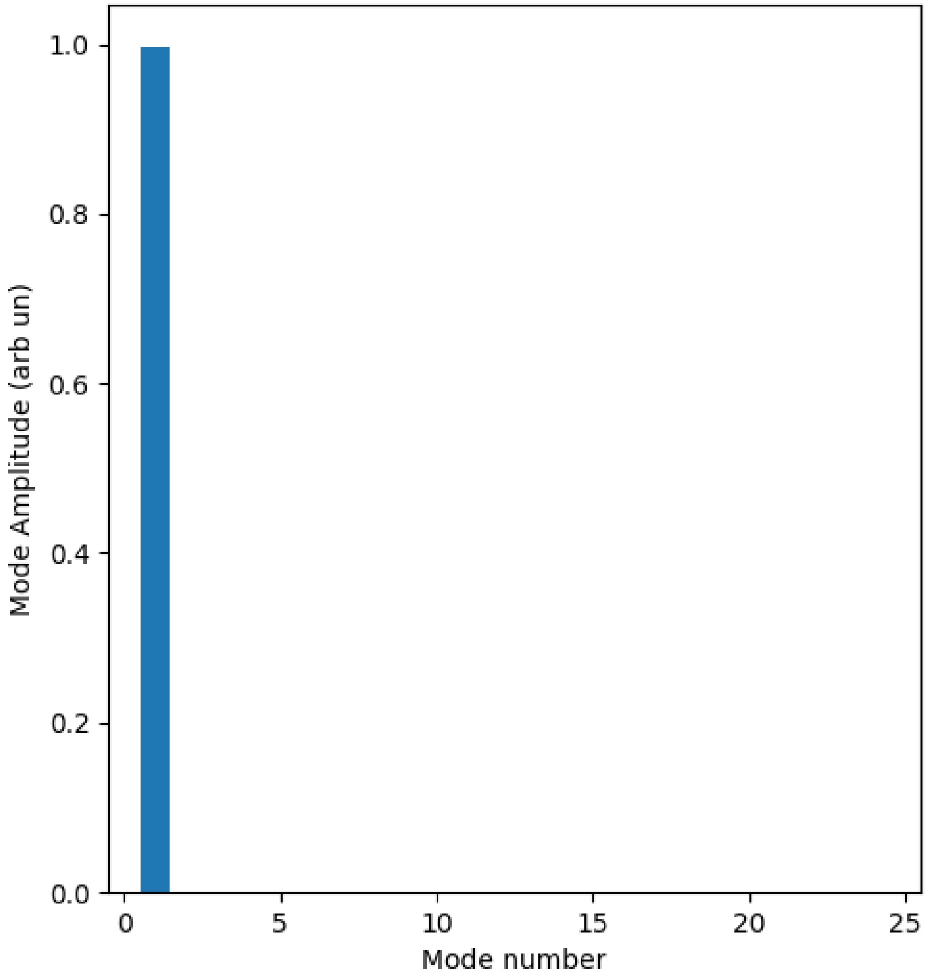
1st ORDER: Energy conservation

From phonons $f(k,x,t)$ to moments $Q^{(n)}(x,t)$

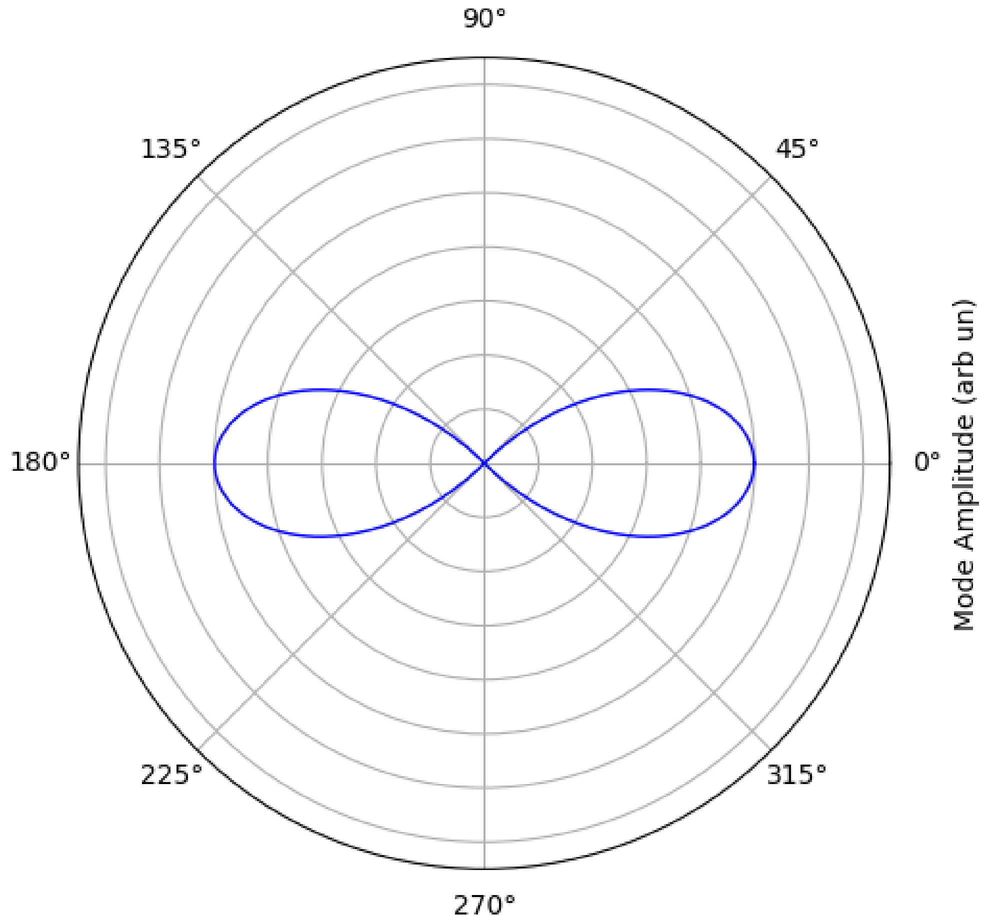
$\partial/\partial t$ (n)	(n)		Div (n+1)	Grad (n-1)	
$\alpha_1 \frac{\partial T}{\partial t}$		$=$	$-\nabla \cdot \boldsymbol{q}$		0^{th} ORDER
$\alpha_2 \frac{\boldsymbol{\partial q}}{\partial t}$	$-\frac{\boldsymbol{q}}{\boldsymbol{\tau_q}}$	$=$	$-\nabla \cdot \boldsymbol{Q}^{(2)}$	$-\beta_1 \nabla T$	1^{st} ORDER
$\alpha_3 \frac{\boldsymbol{\partial Q}^{(2)}}{\partial t}$	$-\frac{\boldsymbol{Q}^{(2)}}{\boldsymbol{\tau_{Q^{(2)}}}}$	$=$	$-\nabla \cdot \boldsymbol{Q}^{(3)}$	$-\beta_2 \nabla \boldsymbol{q}$	2^{nd} ORDER
$\alpha_3 \frac{\boldsymbol{\partial Q}^{(n)}}{\partial t}$	$-\frac{\boldsymbol{Q}^{(n)}}{\boldsymbol{\tau_{Q^{(n)}}}}$	$=$	$-\nabla \cdot \boldsymbol{Q}^{(n+1)}$	$-\beta_n \nabla \boldsymbol{Q}^{(n-1)}$	n^{th} ORDER

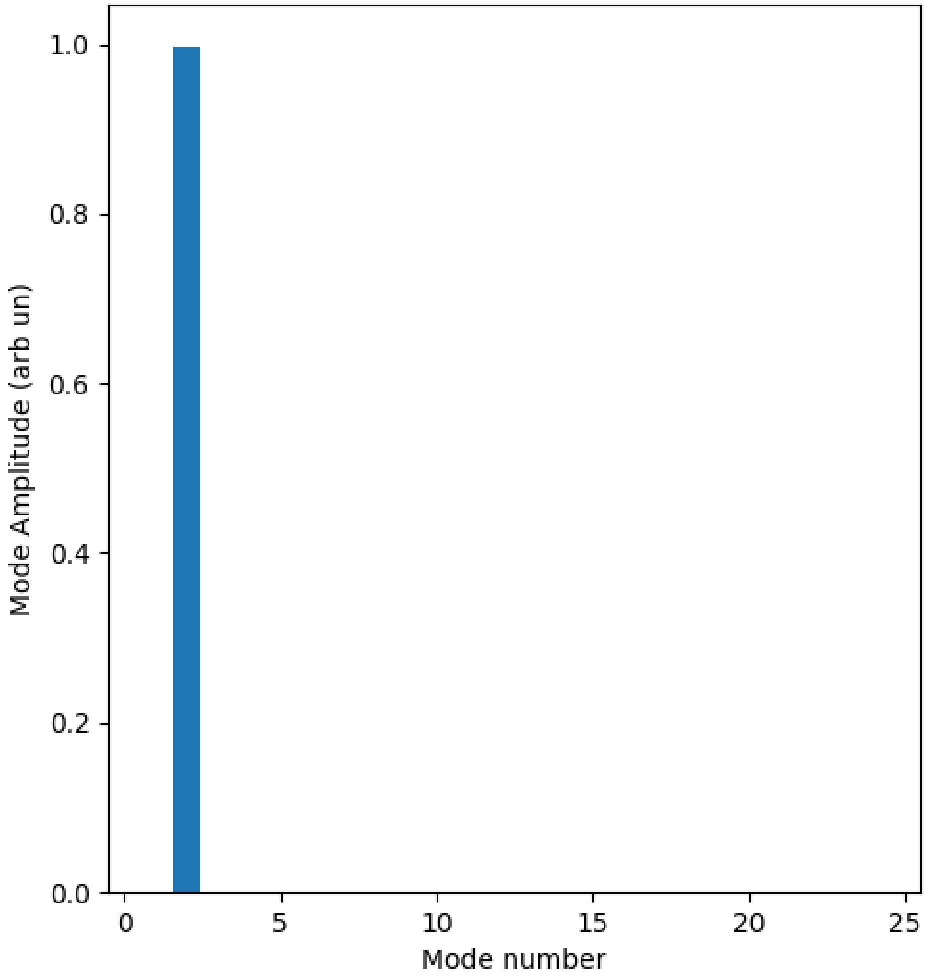
Moments of the distribution





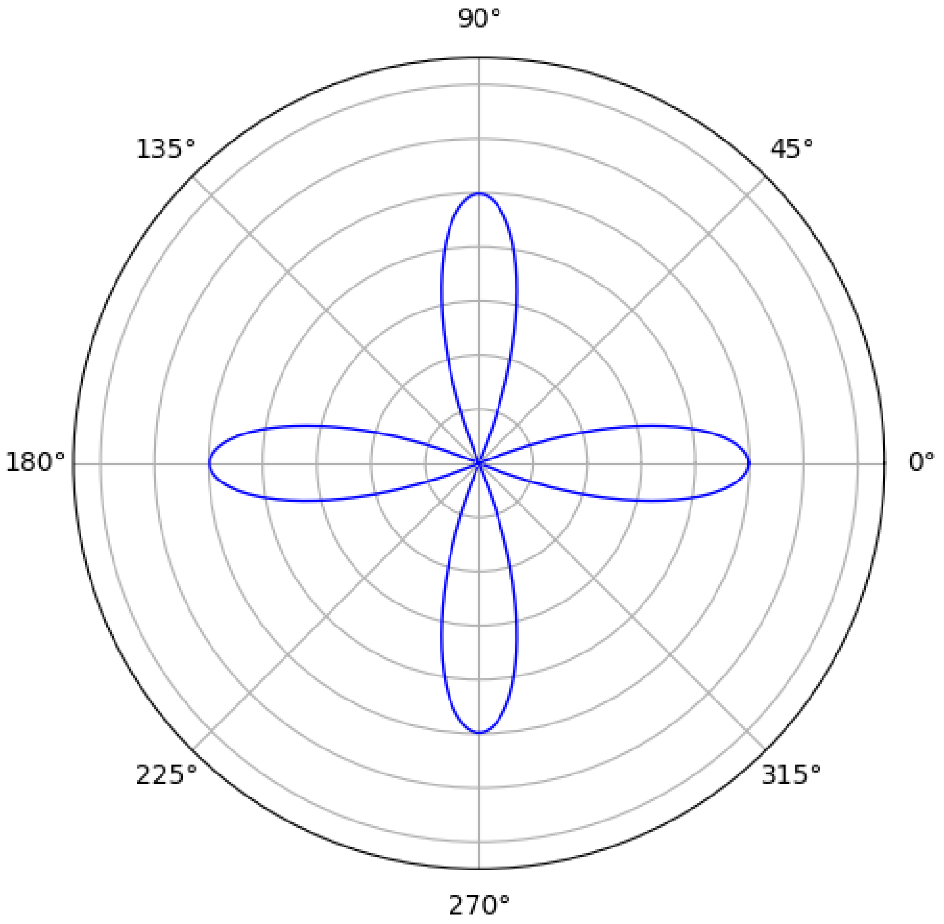
Moments of the distribution

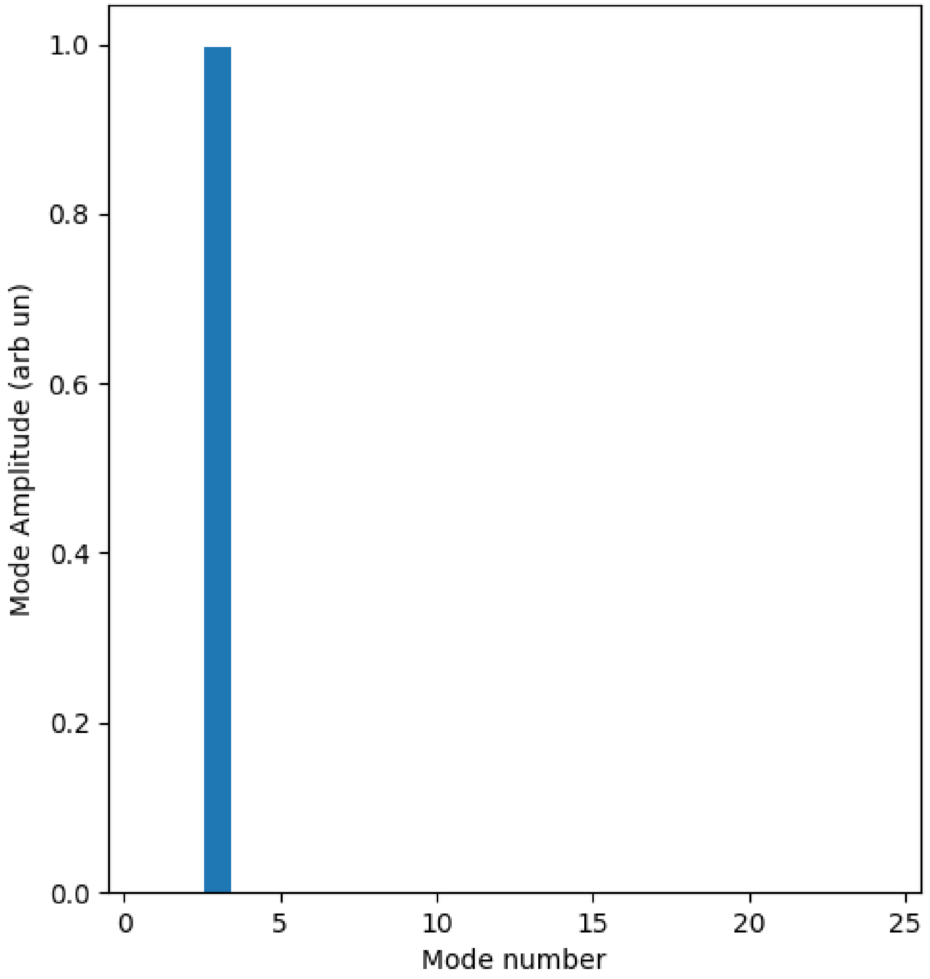




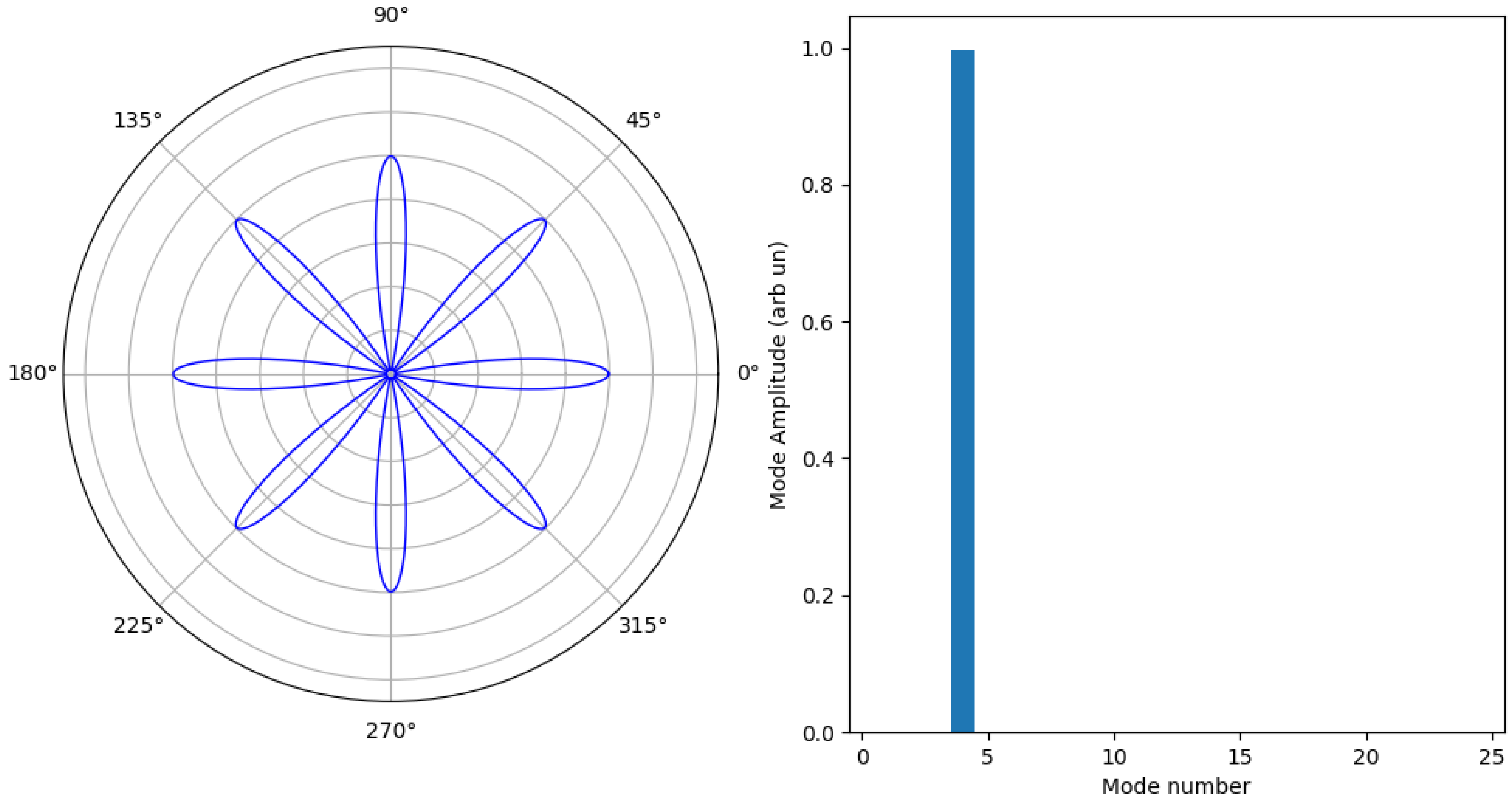
Universitat Autònoma de Barcelona

Moments of the distribution

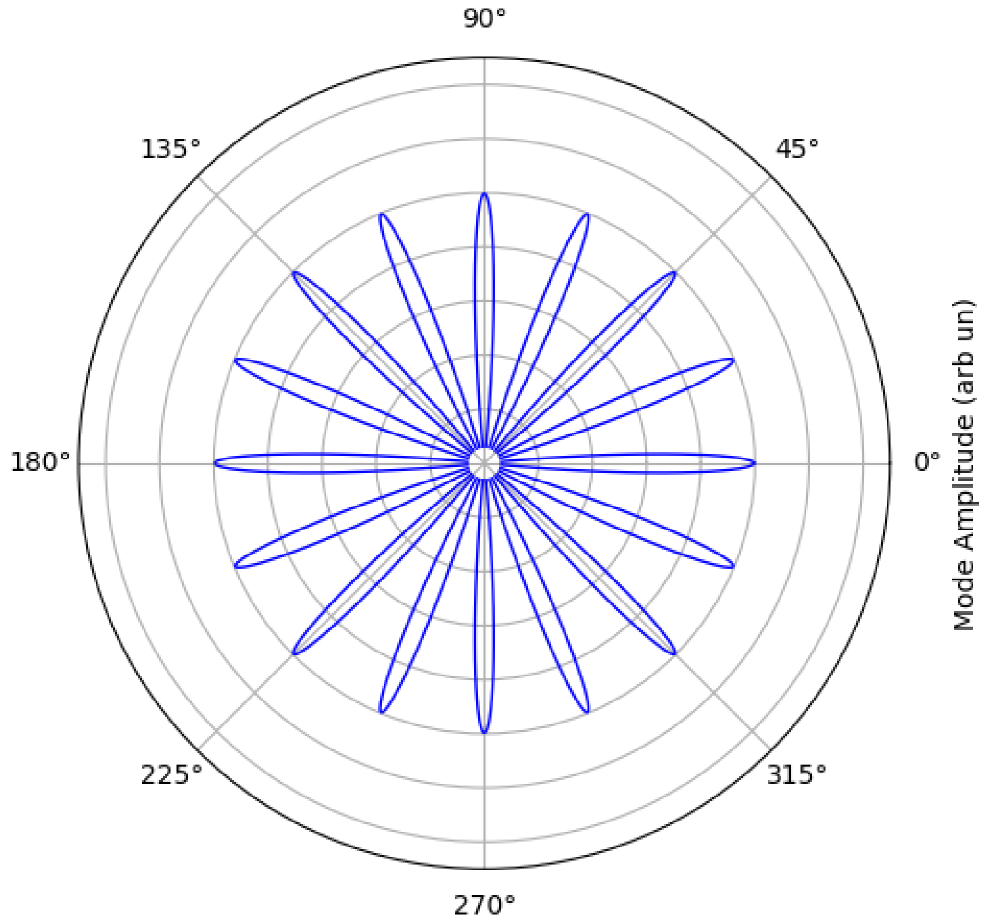


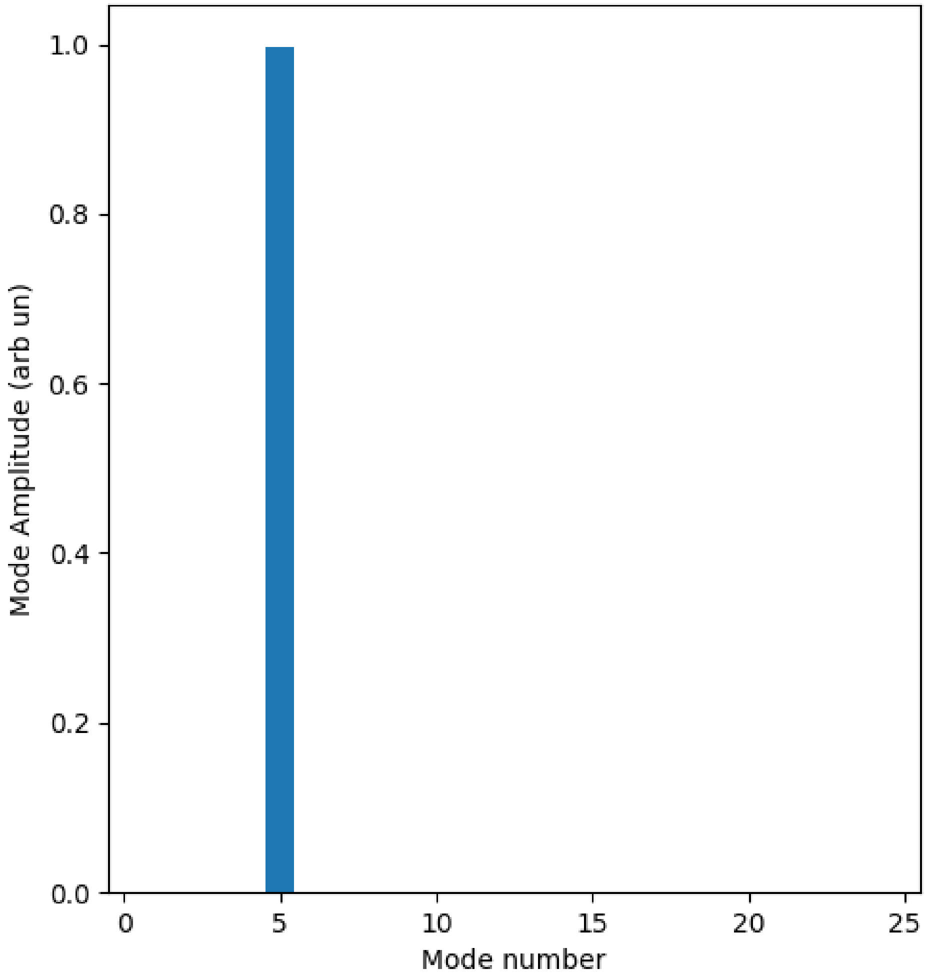


Moments of the distribution

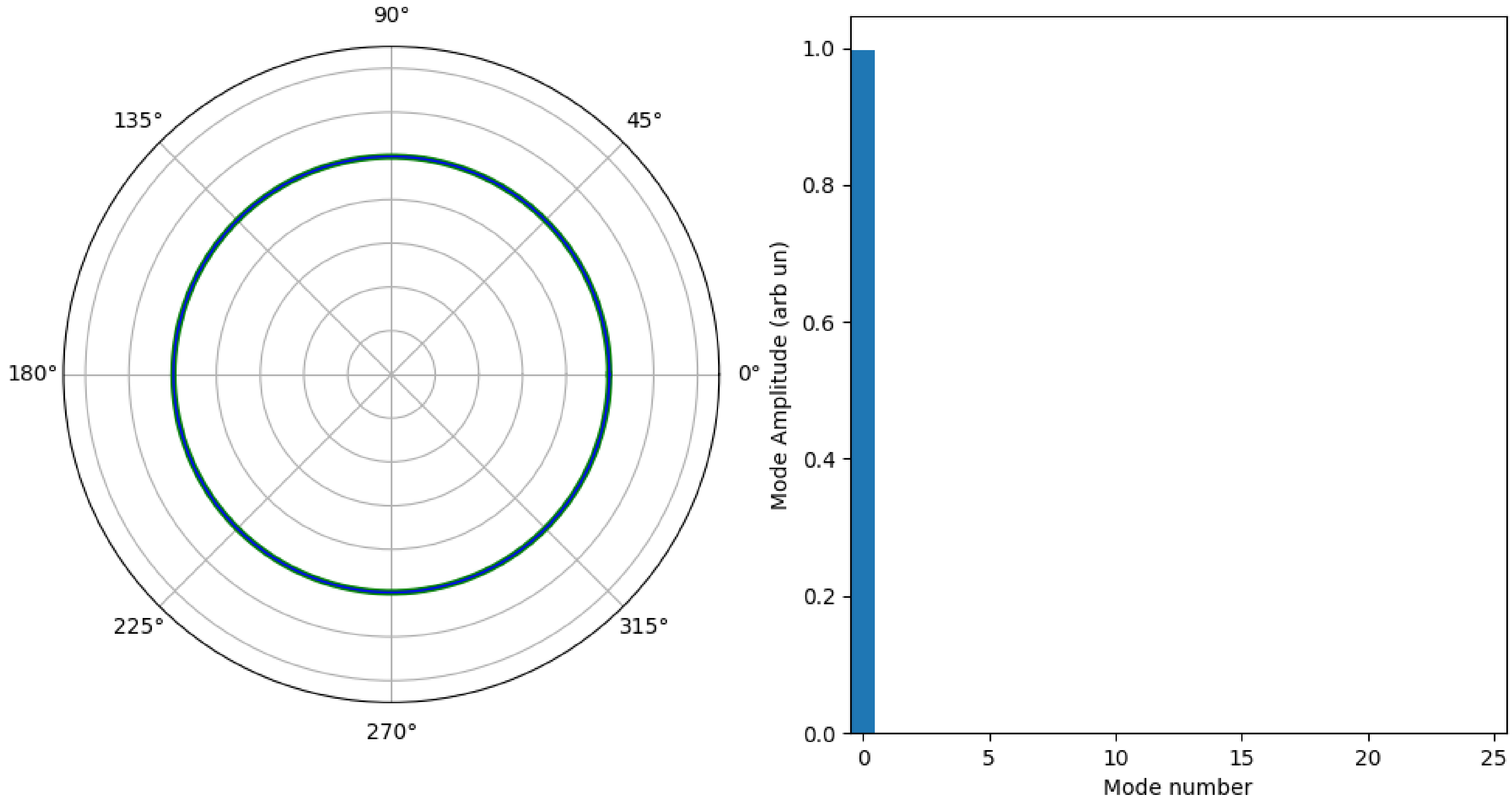


Moments of the distribution

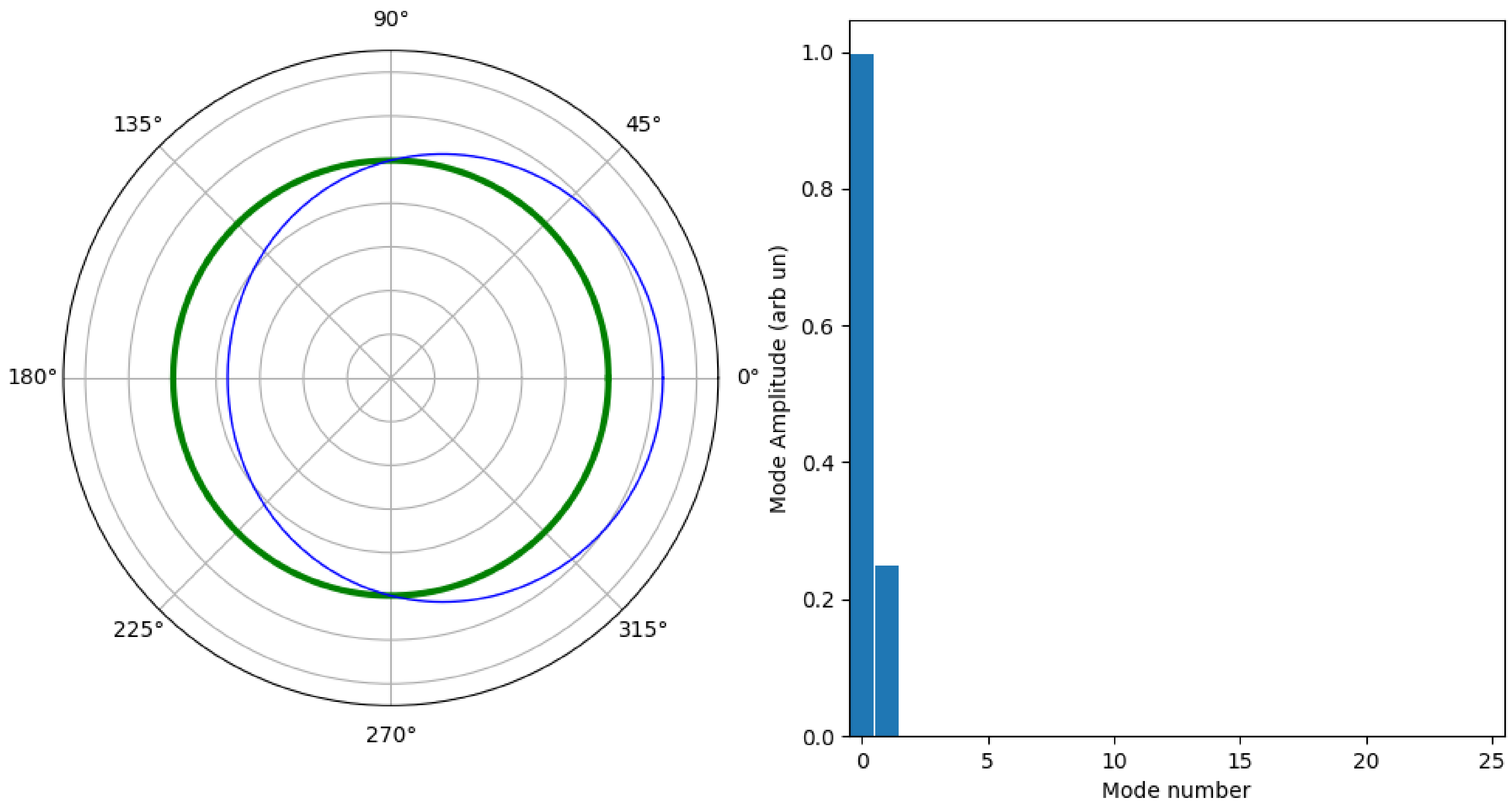




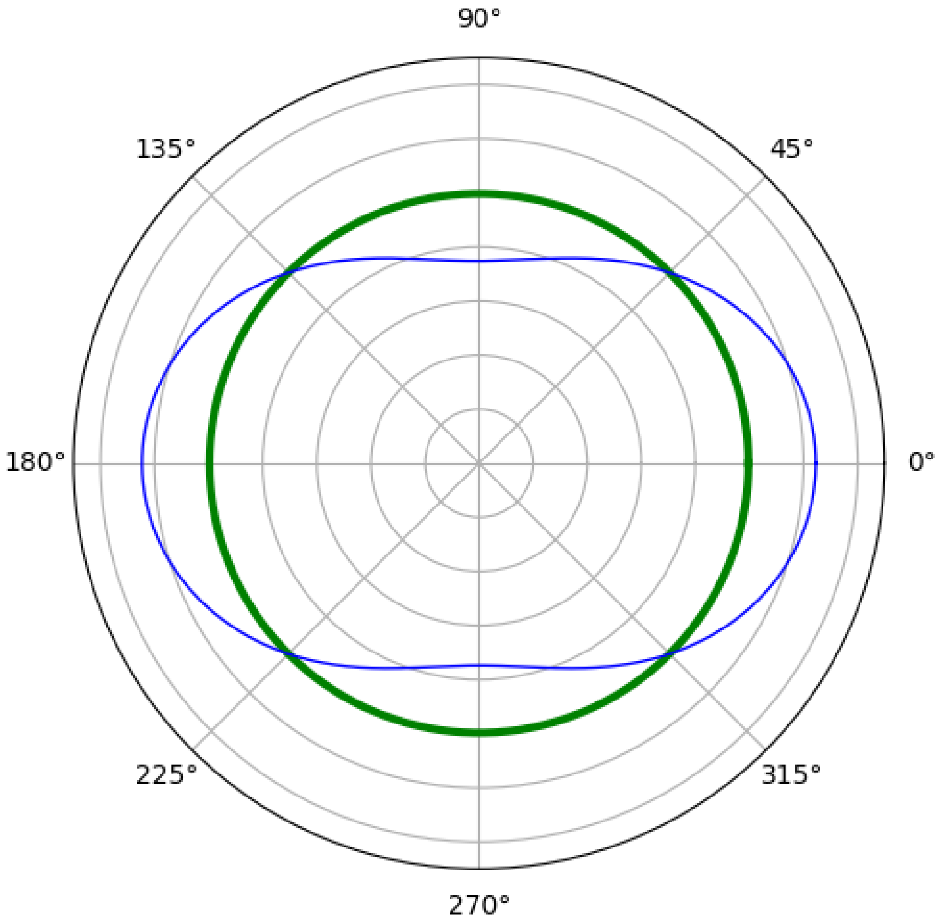
Moments of the distribution

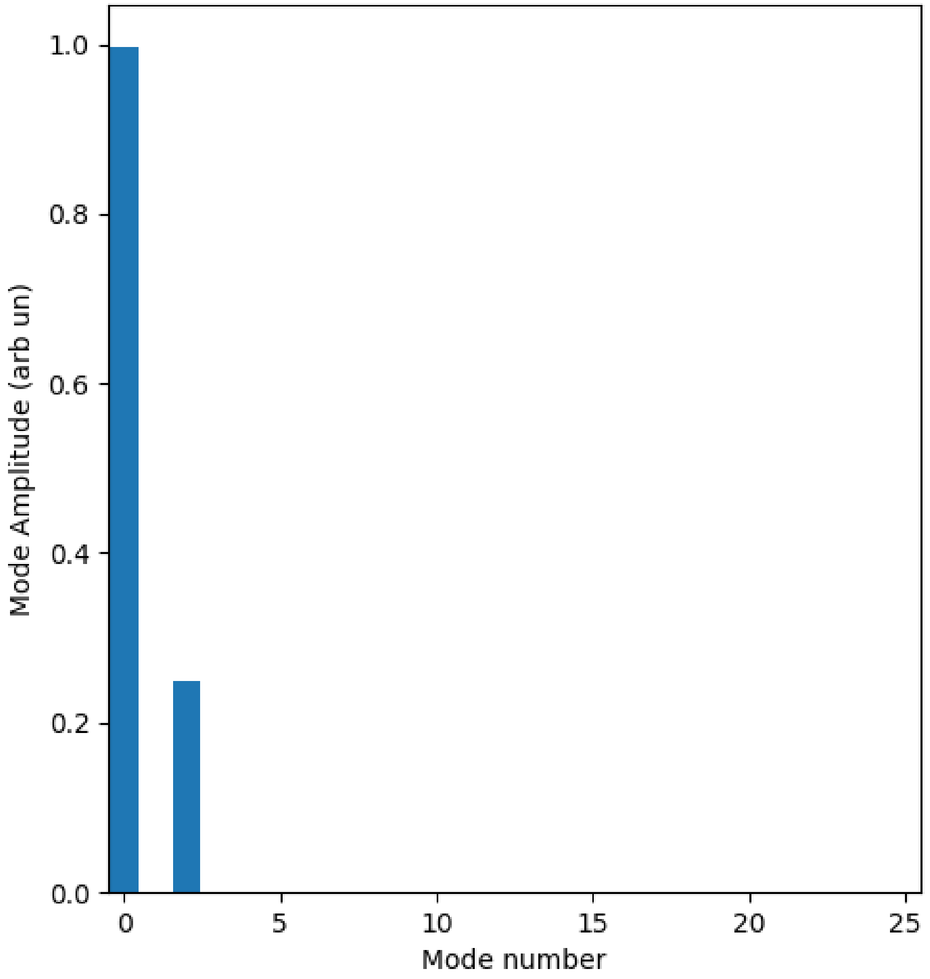


Moments of the distribution

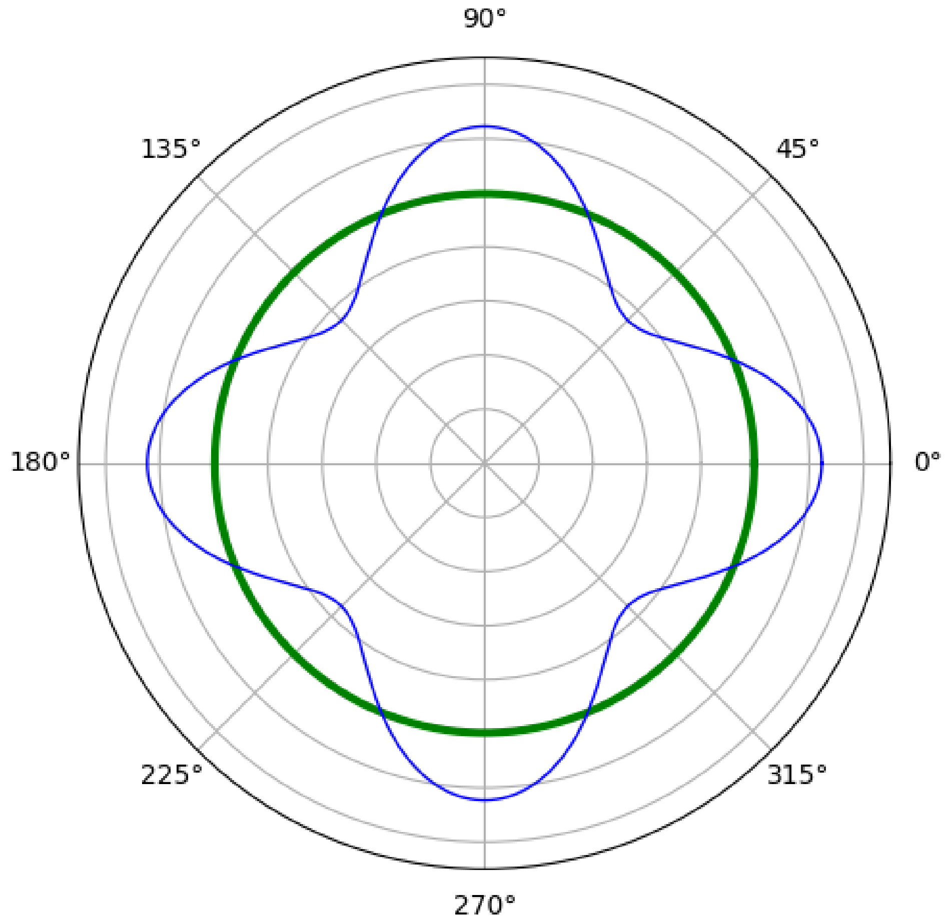


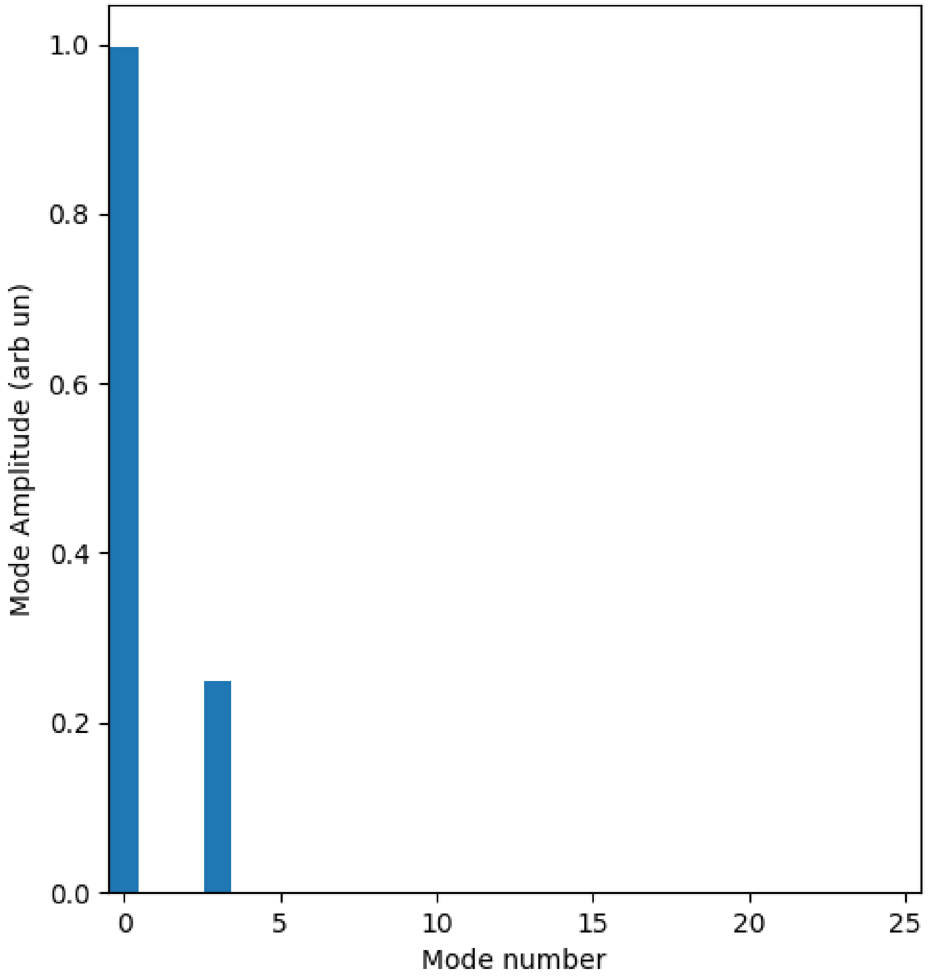
Moments of the distribution



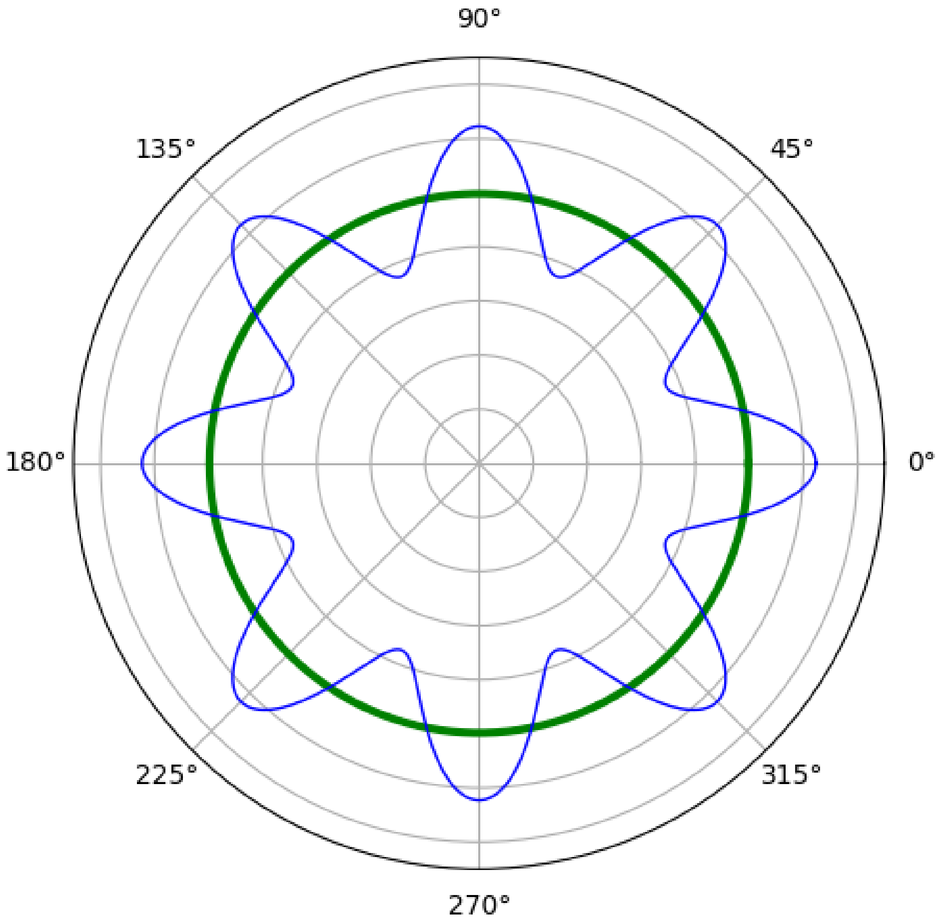


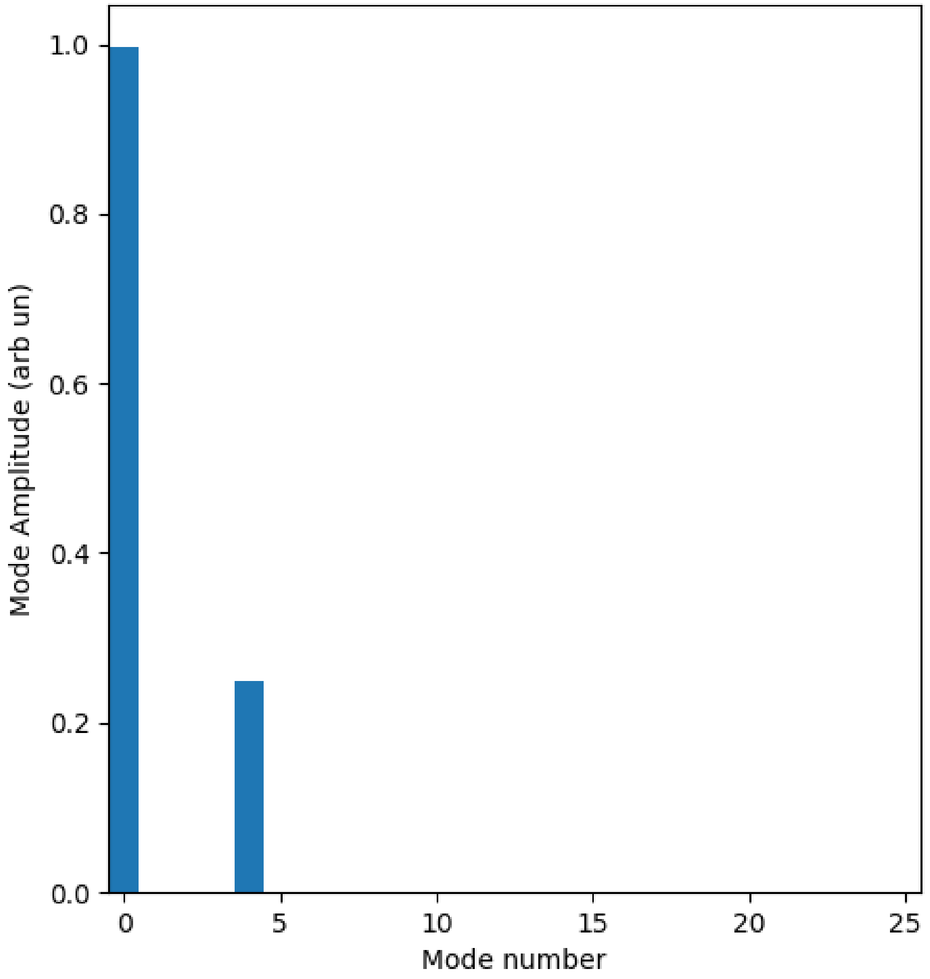
Moments of the distribution



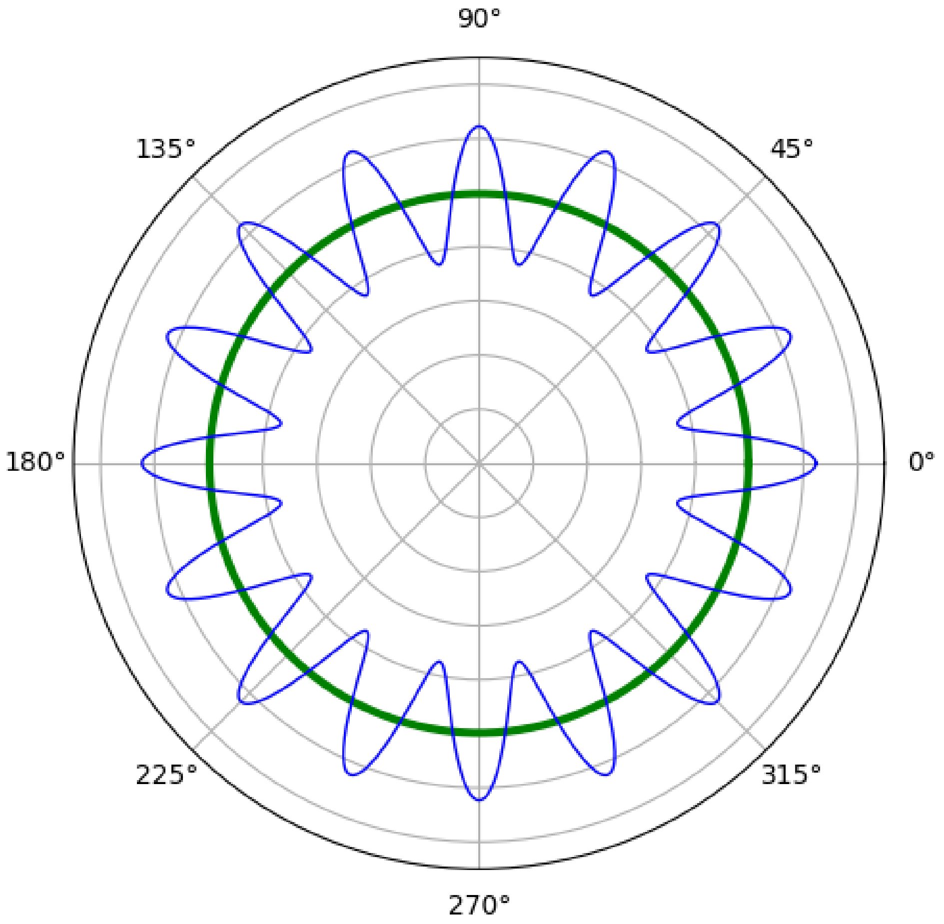


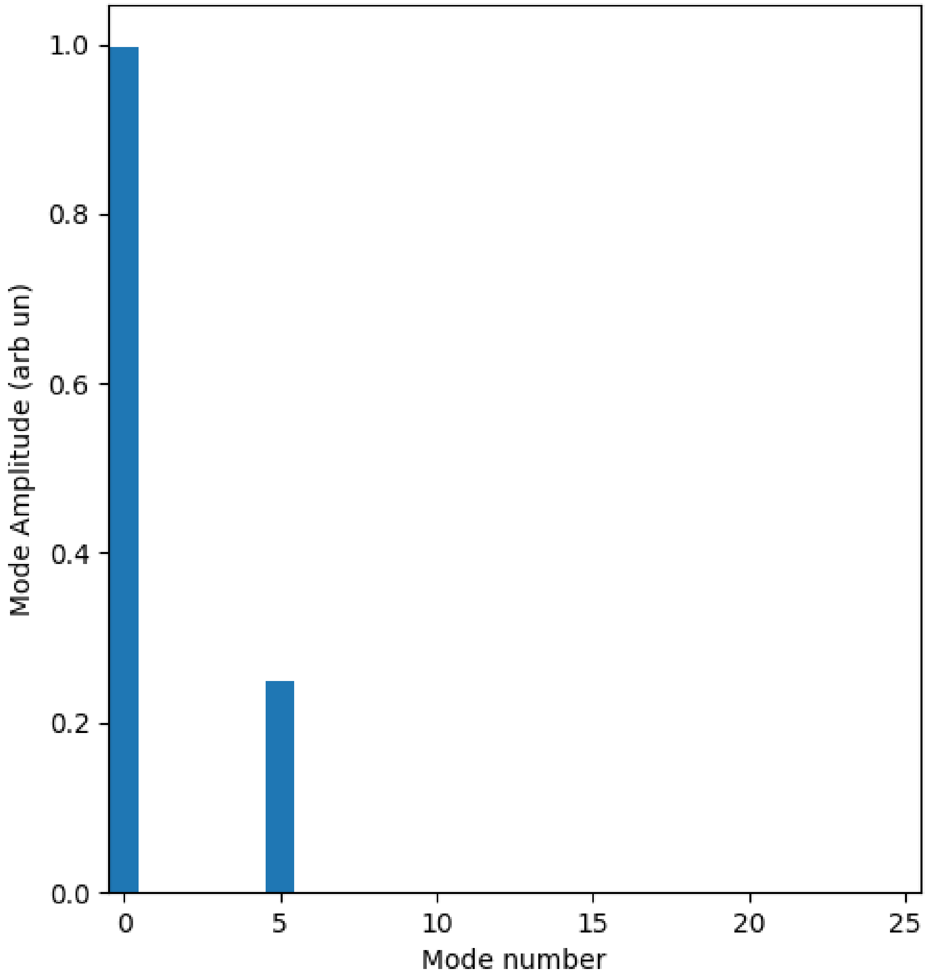
Moments of the distribution



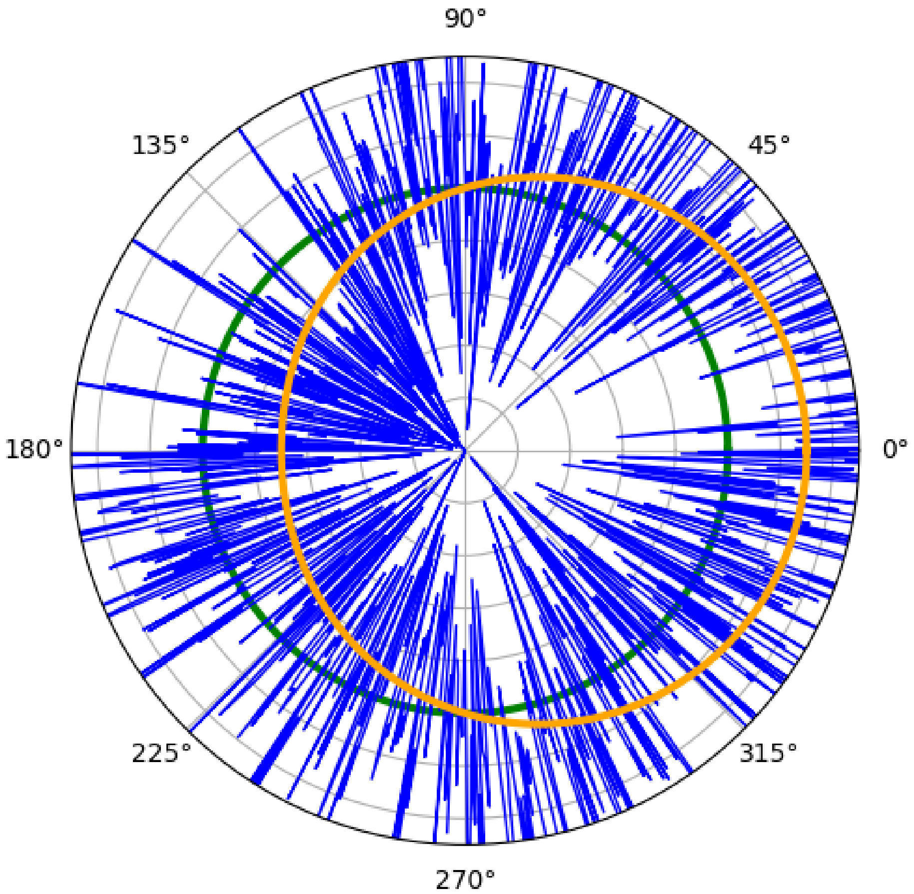


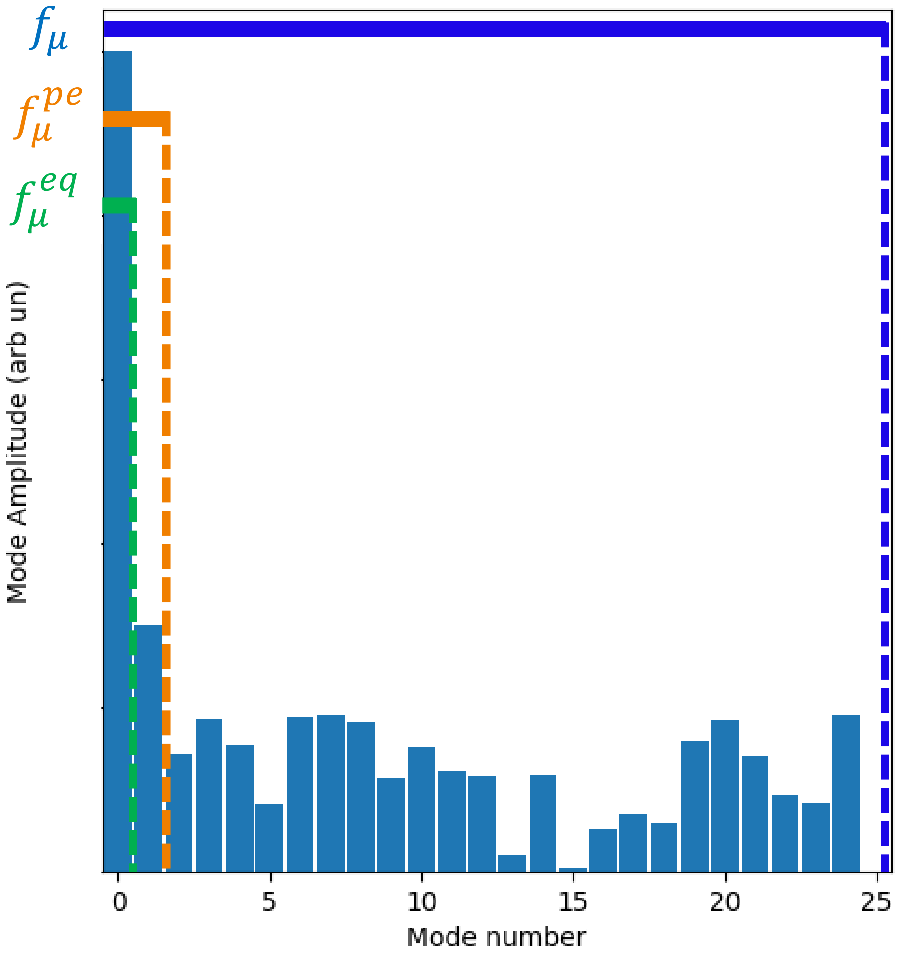
Moments of the distribution



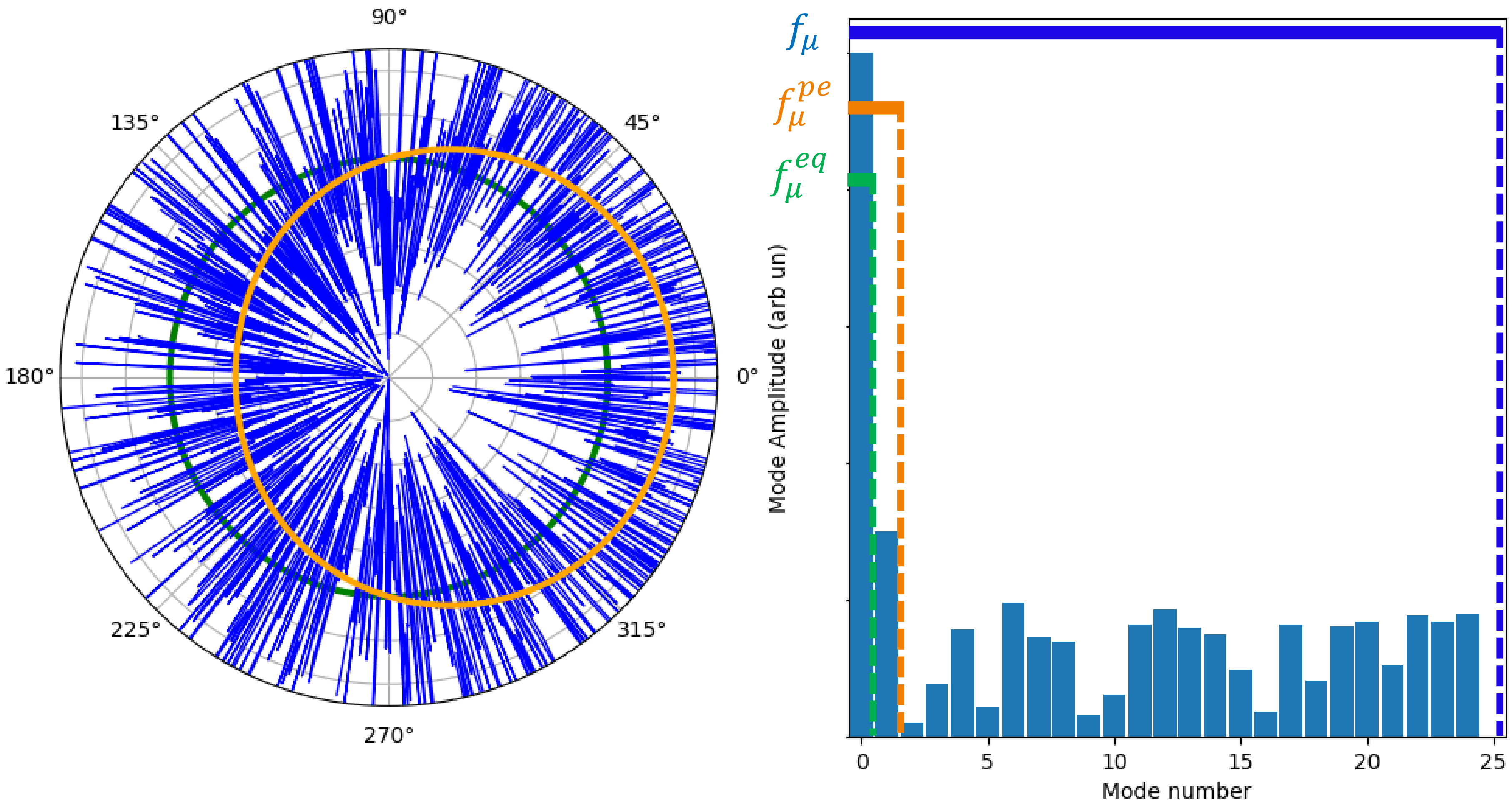


(Pseudo)conserved magnitudes

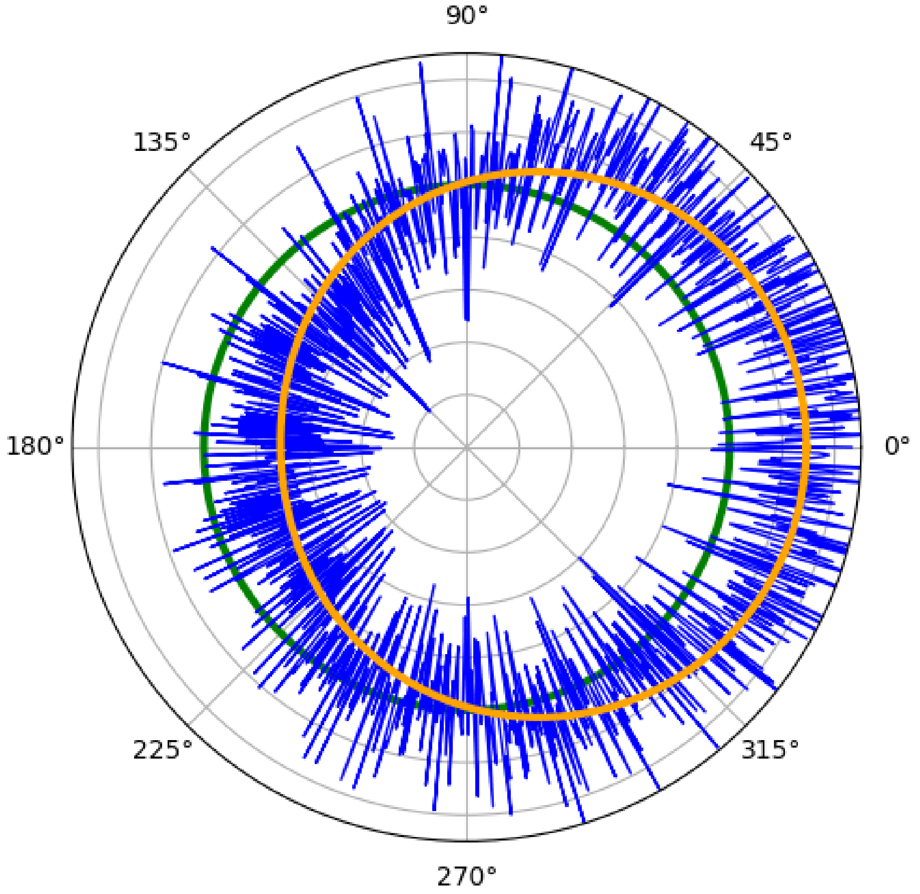


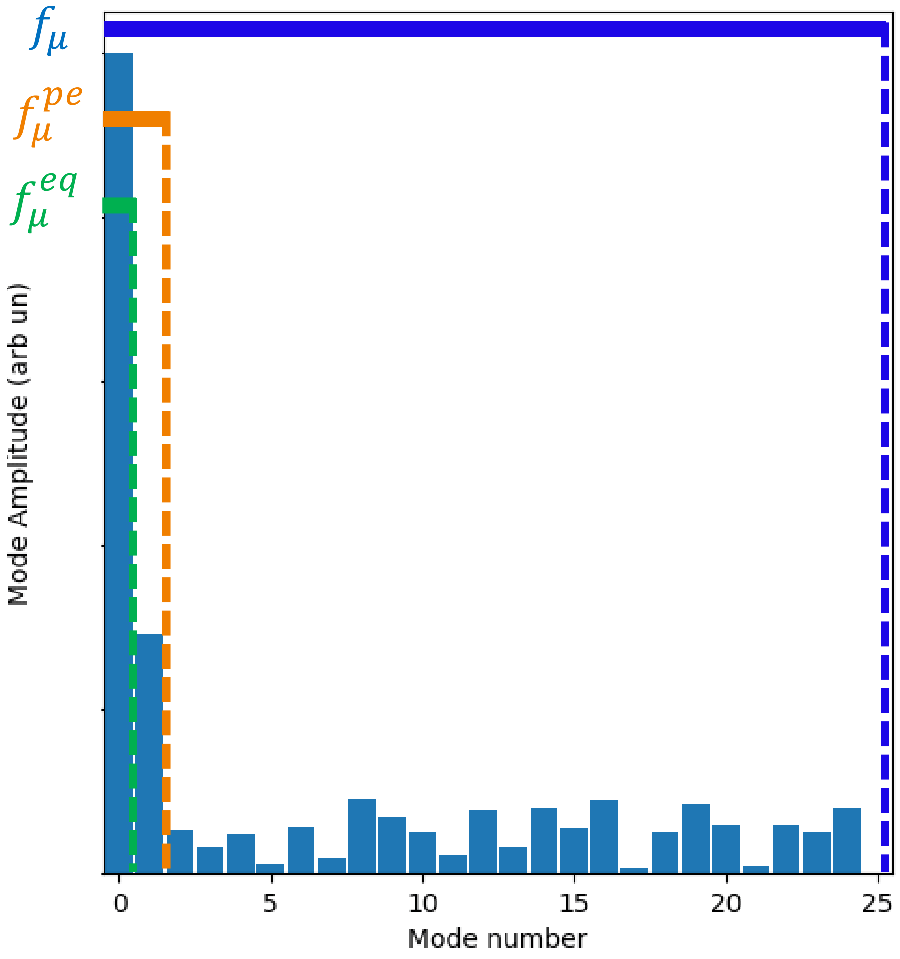


(Pseudo)conserved magnitudes



(Pseudo)conserved magnitudes





Fourier's law

$$\alpha_1 \frac{\partial T}{\partial t} = -\nabla \cdot \boldsymbol{q}$$

$$-\frac{\boldsymbol{q}}{\boldsymbol{\tau_q}} = -\beta_1 \nabla T$$

THERMODYNAMIC EQUATIONS

$$c_v \frac{\partial T}{\partial t} + \nabla \cdot \boldsymbol{q} = 0$$

$$\boldsymbol{q} = -\lambda \nabla \mathrm{T}$$

BTE DISTRIBUTION FUNCT.

$$f = f_{eq} - \frac{3}{c_v v^2} q \cdot v_g \frac{\partial f_{eq}}{\partial T}$$

Guyer and Krumhansl equation

$$\alpha_1 \frac{\partial T}{\partial t} = -\nabla \cdot \boldsymbol{q}$$

$$\alpha_2 \frac{\partial \boldsymbol{q}}{\partial t} - \frac{\boldsymbol{q}}{\boldsymbol{\tau}_{\boldsymbol{q}}} = -\nabla \cdot \boldsymbol{Q}^{(2)} - \beta_1 \nabla T$$

$$\alpha_3 \frac{\partial \boldsymbol{Q}^{(2)}}{\partial t} - \frac{\boldsymbol{Q}^{(2)}}{\boldsymbol{\tau}_{\boldsymbol{Q}^{(2)}}} = -\nabla \cdot \boldsymbol{Q}^{(3)} - \beta_2 \nabla \boldsymbol{q}$$

$$\vdots$$

$$-\nabla \cdot \boldsymbol{Q}^{(n+1)} \quad -\beta\ \nabla \boldsymbol{Q}^{(n-1)}$$

THERMODYNAMIC EQUATIONS

$$c_v \frac{\partial T}{\partial t} + \nabla \cdot \boldsymbol{q} = 0$$

$$\boldsymbol{q} = -\lambda \nabla \mathrm{T} - \mathrm{A}_1 \nabla \cdot Q^{(2)}$$

$$Q^{(2)} = \mathrm{A}_2 \nabla q$$

BTE DISTRIBUTION FUNCT.

$$f \simeq f_{eq} - \frac{3}{c_v v_g^2} \frac{\partial f_{eq}}{\partial T} q_i v_{gi} + \frac{\tau}{c_V} \frac{\partial q_i}{\partial x_i} \frac{\partial f_{eq}}{\partial T}$$

Guyer and Krumhansl equation

$$\alpha_1 \frac{\partial T}{\partial t} = -\nabla \cdot \boldsymbol{q}$$

$$\alpha_2 \frac{\partial \boldsymbol{q}}{\partial t} - \frac{\boldsymbol{q}}{\tau_q} = -\nabla \cdot \boldsymbol{Q}^{(2)} \quad -\beta_1 \nabla T$$

$$\alpha_3 \frac{\partial \boldsymbol{Q}^{(2)}}{\partial t} - \frac{\boldsymbol{Q}^{(2)}}{\tau_{Q^{(2)}}} = -\nabla \cdot \boldsymbol{Q}^{(3)}$$

$$\ldots \quad -\nabla \cdot \boldsymbol{Q}^{(n+1)} \quad -\beta_n \nabla \boldsymbol{Q}^{(n-1)}$$

NEW BOUNDARY CONDITION

GK is a second order PDE, a new boundary condition is needed in order to be solvable

THERMODYNAMIC EQUATIONS

$$c_v \frac{\partial T}{\partial t} + \nabla \cdot \boldsymbol{q} = 0$$

$$\boldsymbol{q} = -\lambda \nabla \mathrm{T} - \ell^2 (\nabla^2 \boldsymbol{q} + 2\nabla\nabla \cdot \mathbf{q})$$

BTE DISTRIBUTION FUNCT.

$$f \simeq f_{eq} - \frac{3}{c_v v_g^2} \frac{\partial f_{eq}}{\partial T} q_i v_{gi} + \frac{\tau}{c_V} \frac{\partial q_i}{\partial x_i} \frac{\partial f_{eq}}{\partial T}$$

GK-ab initio formalism

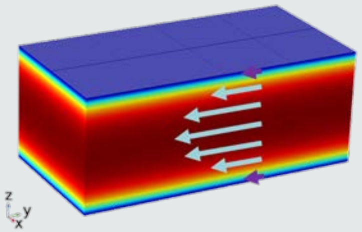
Combination of the **Guyer and Krumhansl** equation with ab initio calculations for the parameters in the framework of **Kinetic Collective Model** offers a **full predictive** model for materials like silicon

GUYER AND KRUMHANSL EQUATION

$$\tau \frac{\partial q}{\partial t} + q = -\kappa \nabla T + \ell^2 \left(\nabla^2 q + \alpha \nabla (\nabla \cdot q) \right)$$

BOUNDARY CONDITIONS

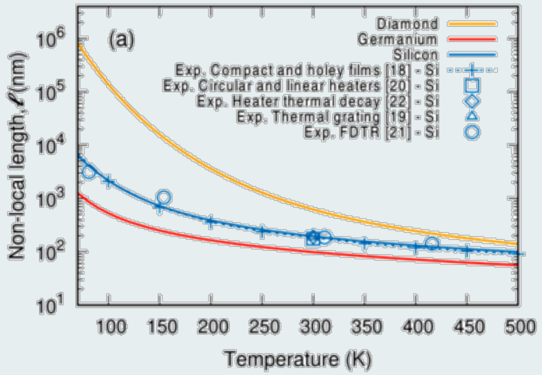
$$\boldsymbol{q_t} = -C\ell \frac{\partial \boldsymbol{q_t}}{\partial n}$$

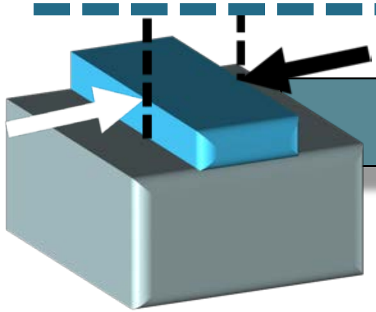


KINETIC COLLECTIVE MODEL

Ab initio

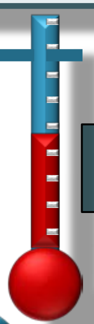
$$\kappa, \ell^2, \tau, \alpha$$





SIZE

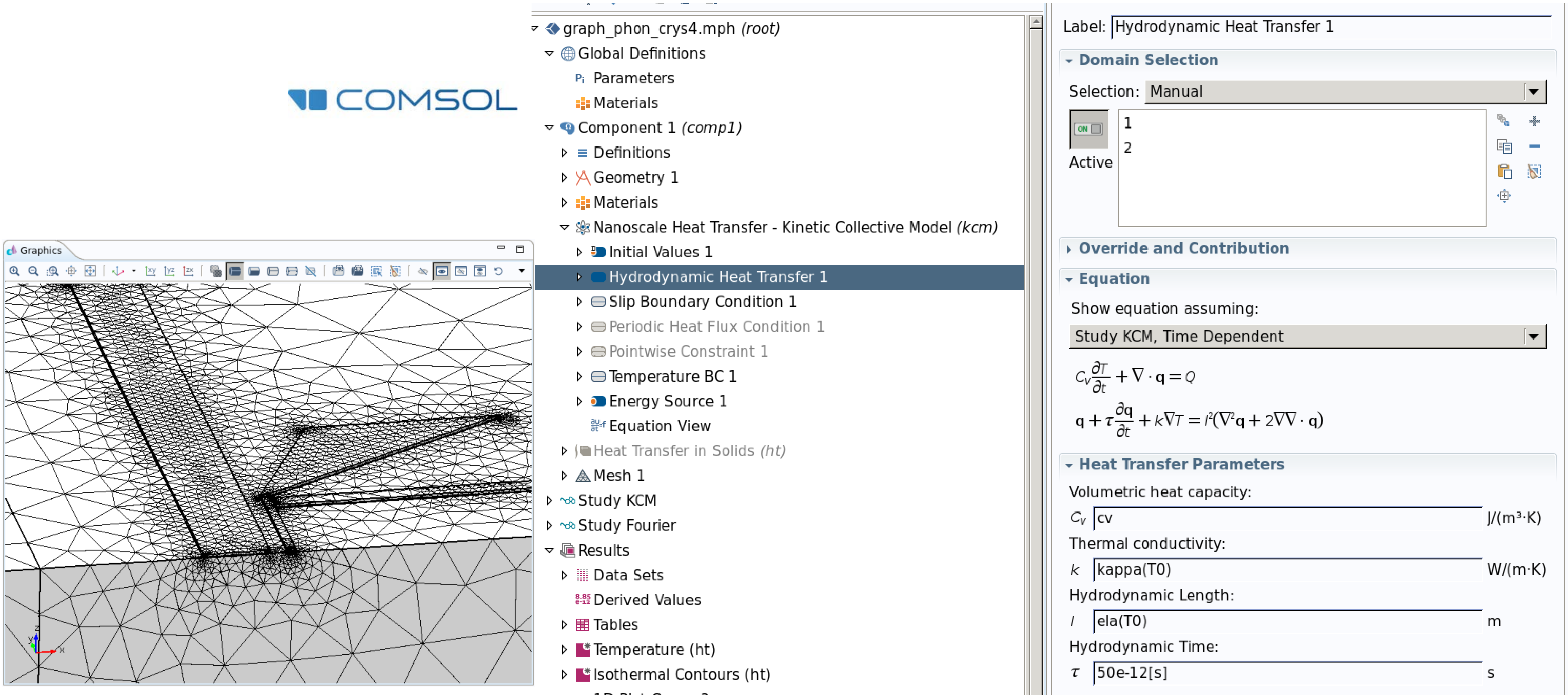
GEOMETRY



TEMPERATURE

FREQUENCY

COMSOL module



EFFECTS OF THE GUYER AND KRUMHANSL TERMS

Fourier's law

TRANSPORT EQUATIONS

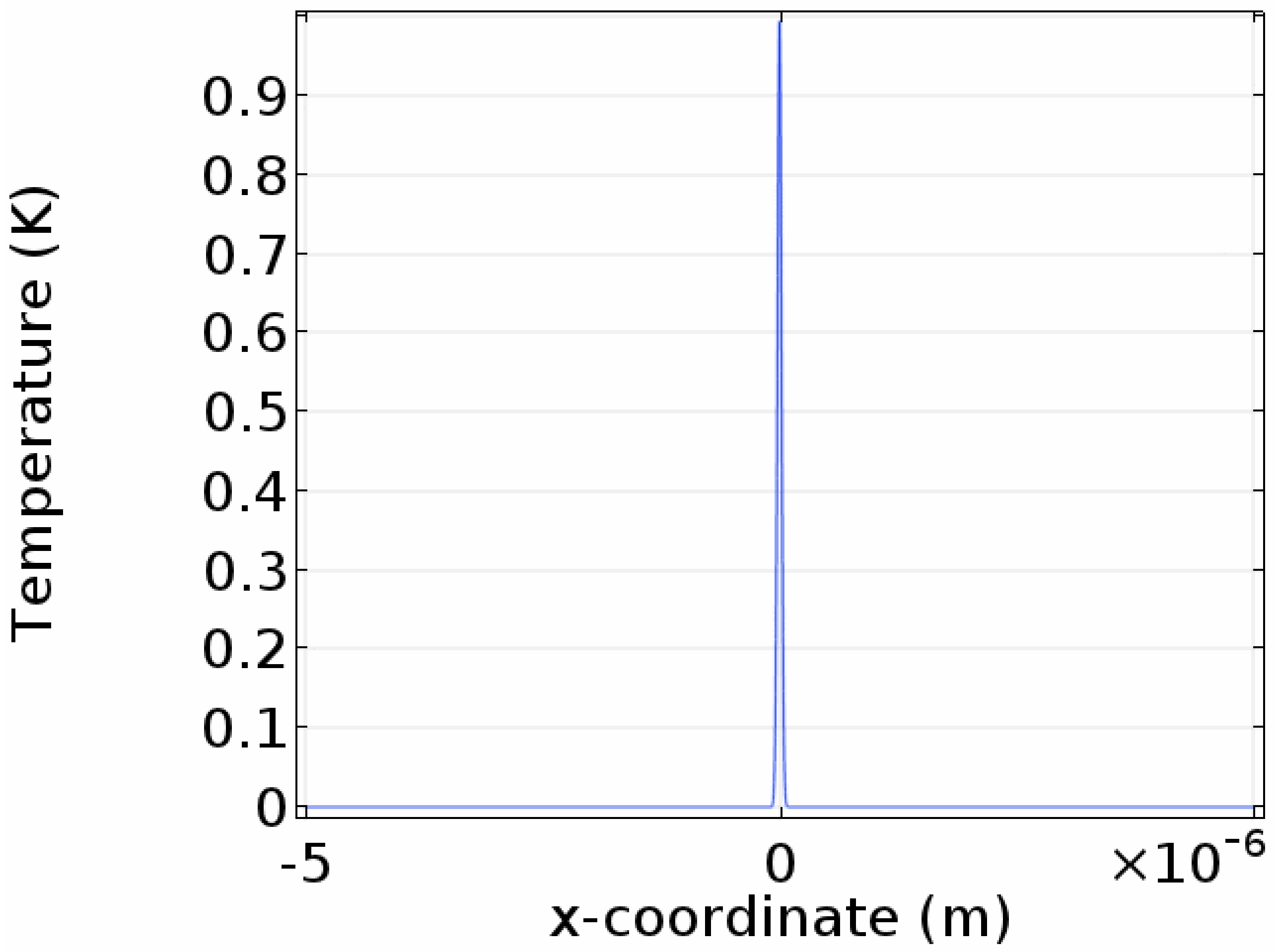
$$c_v \frac{\partial T}{\partial t} + \nabla \cdot \boldsymbol{q} = 0$$

$$\boldsymbol{q} = -\lambda \nabla \mathrm{T}$$

HEAT-DIFFUSION EQUATION

$$\frac{\partial T}{\partial t} = \chi \nabla^2 \mathrm{T}$$

Fourier's law



HEAT-DIFFUSION EQUATION

$$\frac{\partial T}{\partial t} = \chi \nabla^2 \mathrm{T}$$

Memory term

Fast excitation changes $T \ll \tau$

TRANSPORT EQUATIONS

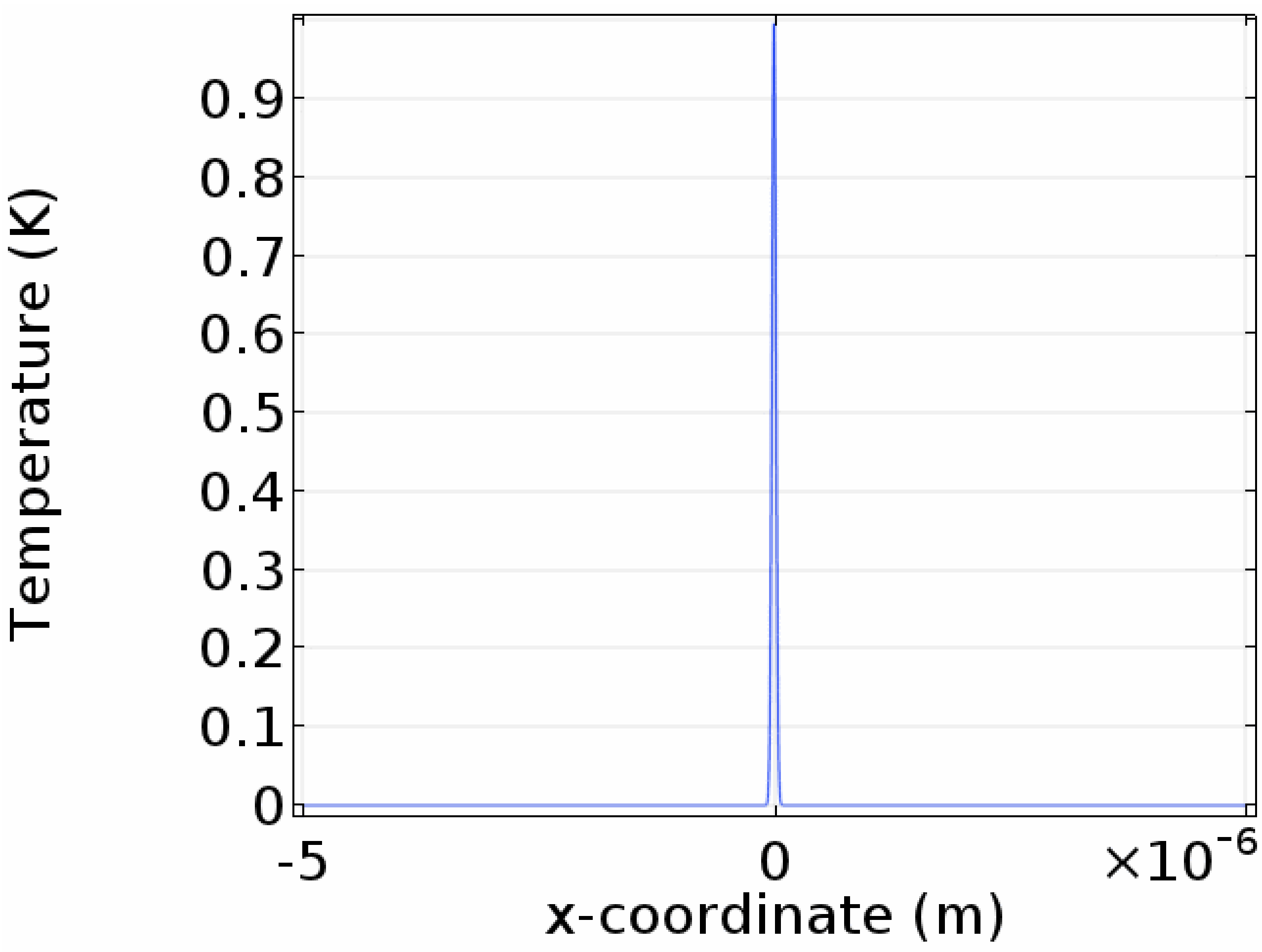
$$c_v \frac{\partial T}{\partial t} + \nabla \cdot \boldsymbol{q} = 0$$

$$\tau \frac{\partial \boldsymbol{q}}{\partial t} + \boldsymbol{q} = -\lambda \nabla \mathrm{T}$$

MAXWELL-CATTANEO EQUATION

$$\tau \frac{\partial^2 T}{\partial t^2} + \frac{\partial T}{\partial t} = \chi \nabla^2 \mathrm{T}$$

Memory term



MAXWELL-CATTANEO EQUATION

$$\tau \frac{\partial^2 T}{\partial t^2} + \frac{\partial T}{\partial t} = \chi \nabla^2 \mathrm{T}$$

Nonlocal term

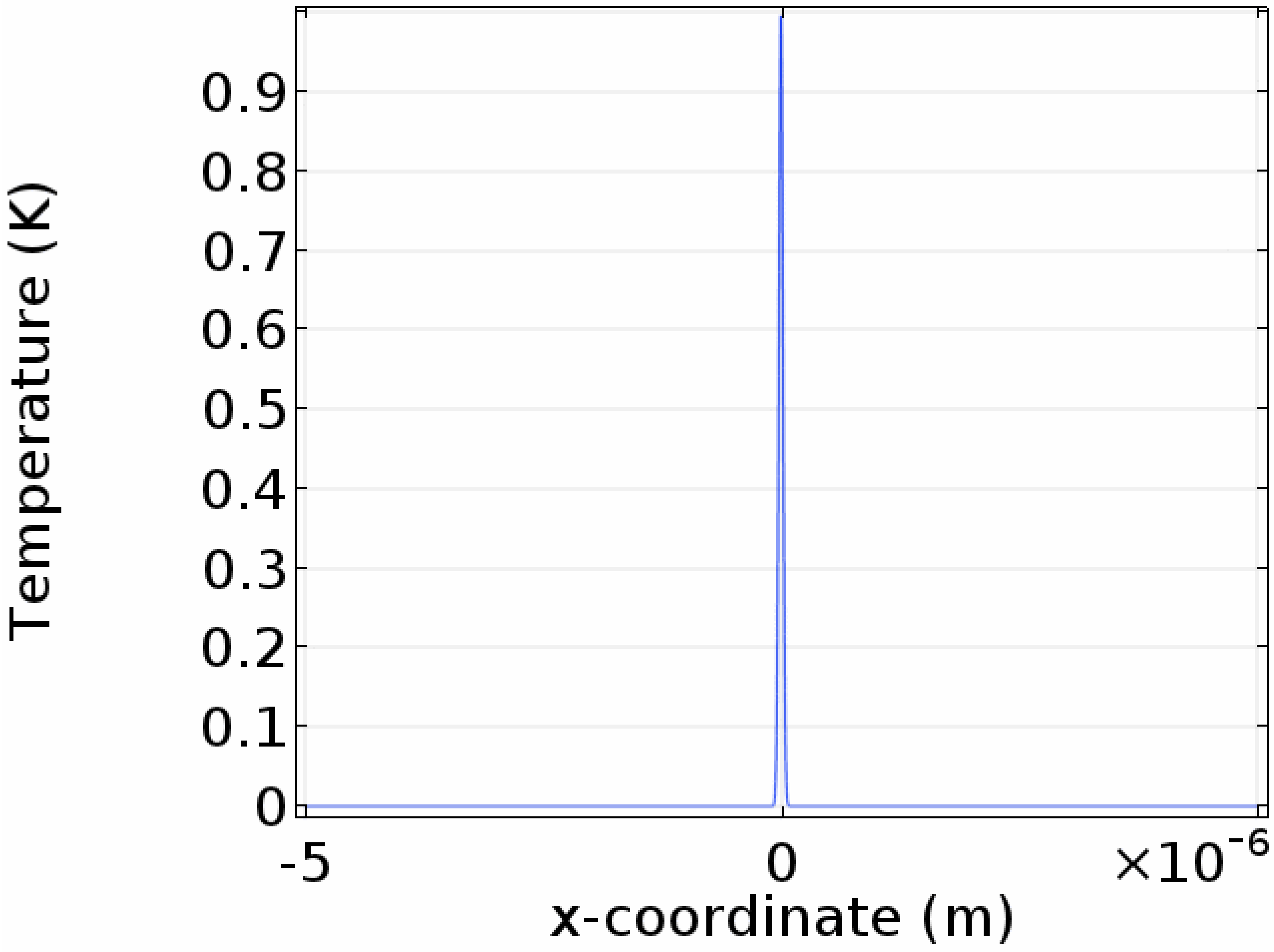
Steep spatial variations $\mathrm{L} \ll \ell$

TRANSPORT EQUATIONS

$$c_v \frac{\partial T}{\partial t} + \nabla \cdot \boldsymbol{q} = 0$$

$$\boldsymbol{q} = -\lambda \nabla \mathrm{T} + \ell \nabla^2 \boldsymbol{q}$$

Nonlocal term



TRANSPORT EQUATIONS

$$c_v \frac{\partial T}{\partial t} + \nabla \cdot \boldsymbol{q} = 0$$

$$\boldsymbol{q} = -\lambda \nabla \mathrm{T} + \ell \nabla^2 \boldsymbol{q}$$

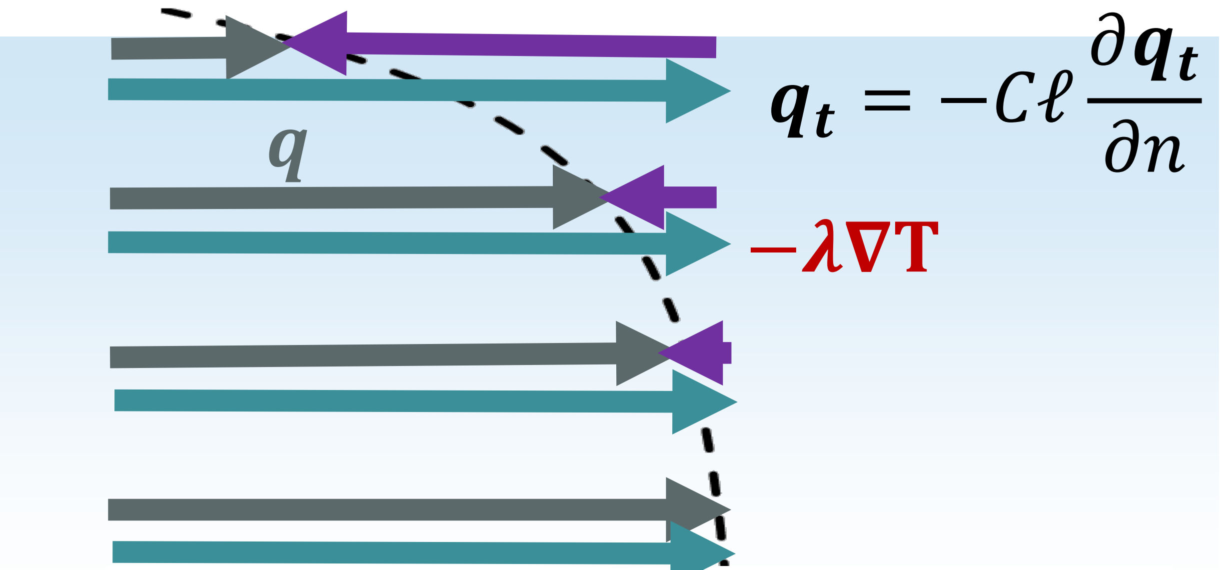
APPLICATIONS

KCM VS KINETIC FORMALISM 1:

SIZE EFFECTS

Hydrodynamic effects I: Boundaries

KCM



$$q = -\lambda \nabla T + \ell^2 (\nabla^2 q + 2\nabla\nabla \cdot q)$$

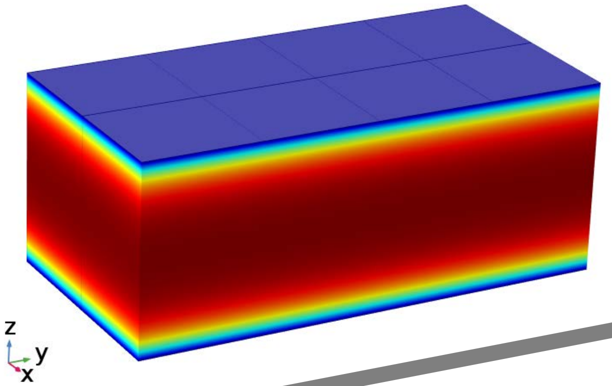
The boundary condition is applied directly to the heat flux in a consistent way with respect to the transport equation

Applicability of hydrodynamic ab initio model

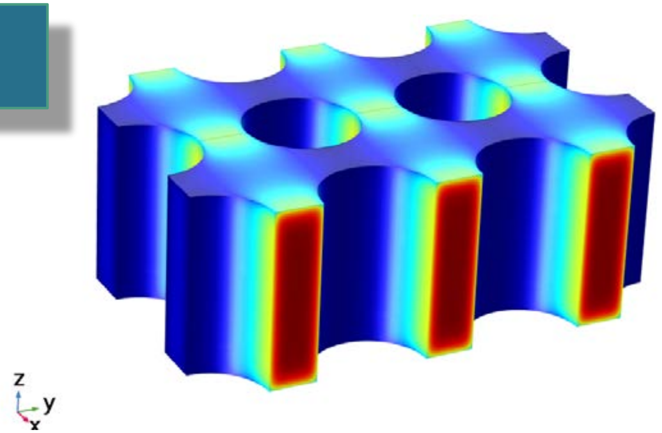
Beardo et al.
Phys. Rev. Appl., **11,** 034003

Thin films

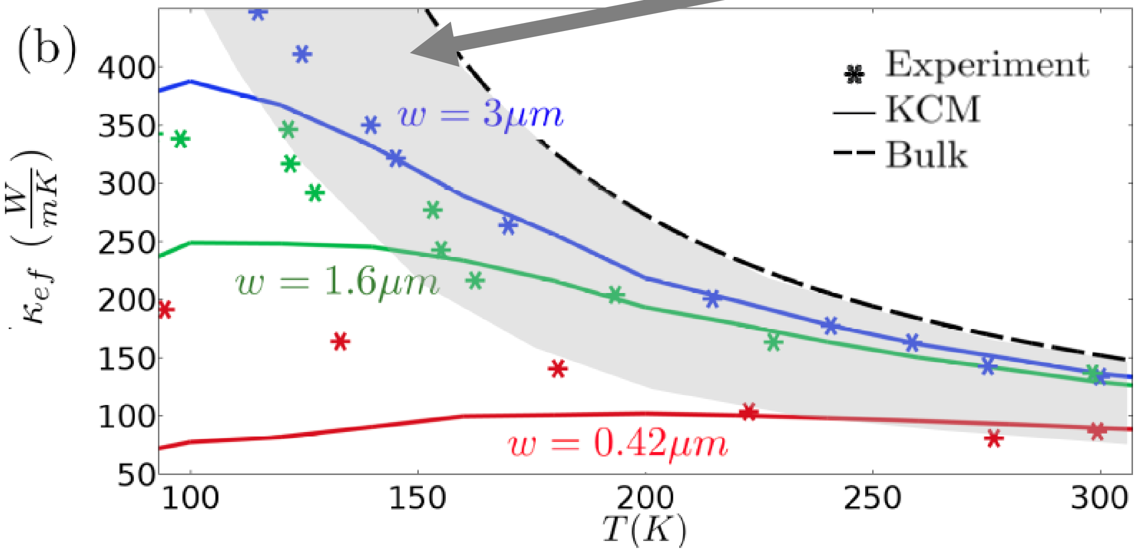
Asheghi et al.
J. Appl. Phys., **91,** 5079 (2002)

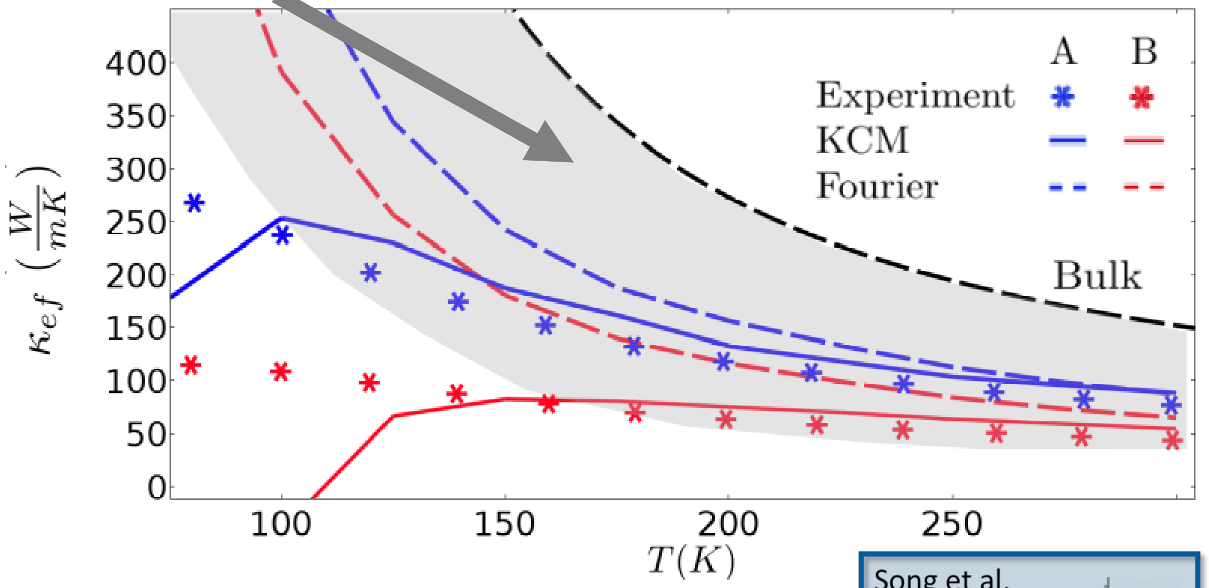


Holey films



Region of predictability
$L < 2\ell$



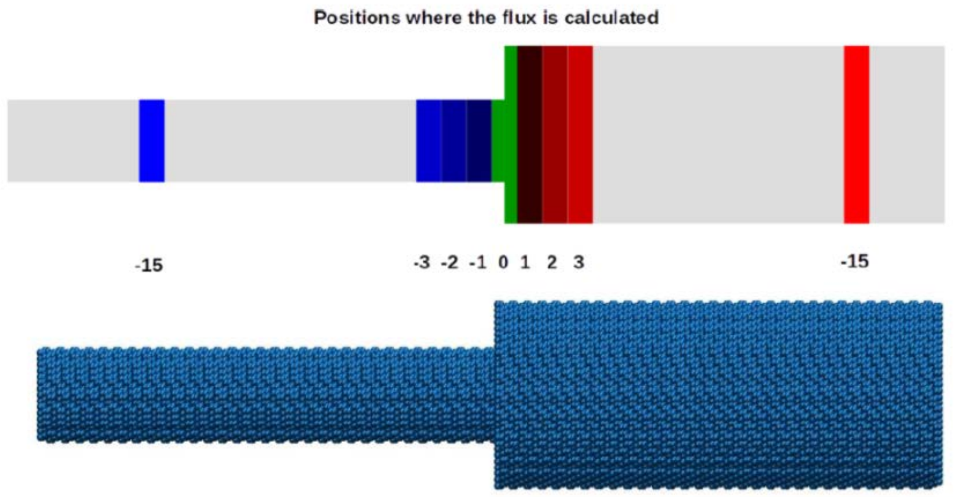


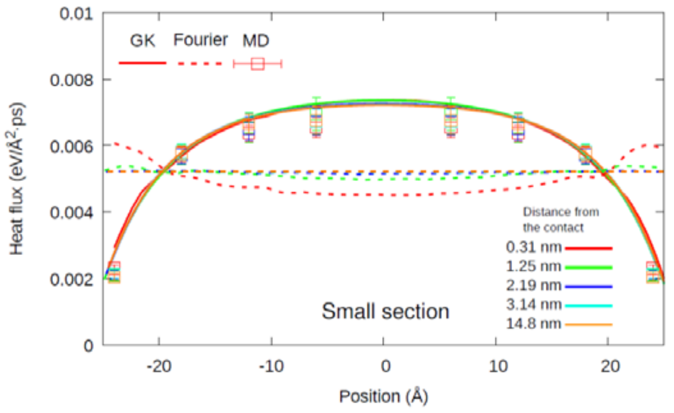
Silicon ℓ =180 nm

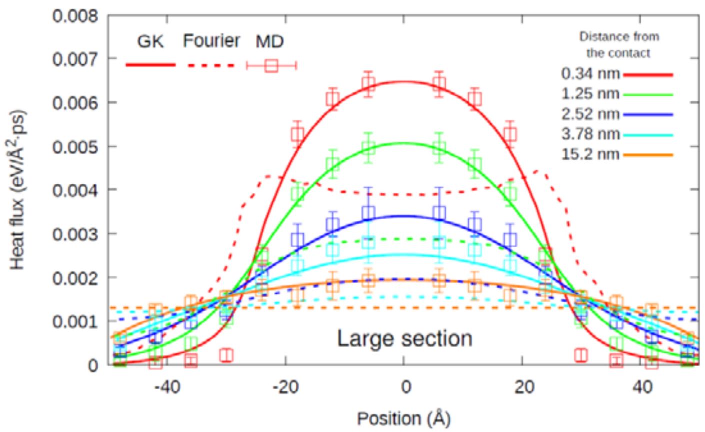
Song et al.
Appl. Phys. Lett., **84,** 687 (2004)

Curved heat flow in MC, MD and FE

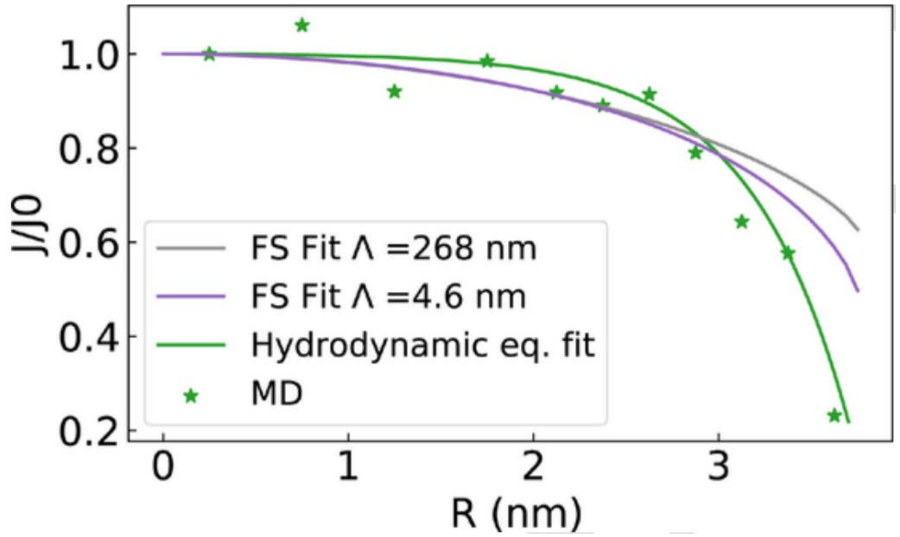
Melis et al.
Phys. Rev. Appl., ***11***, *054059 (2019)*







Desmarchelier et al.
IJHMT, **194** 123003 (2022)

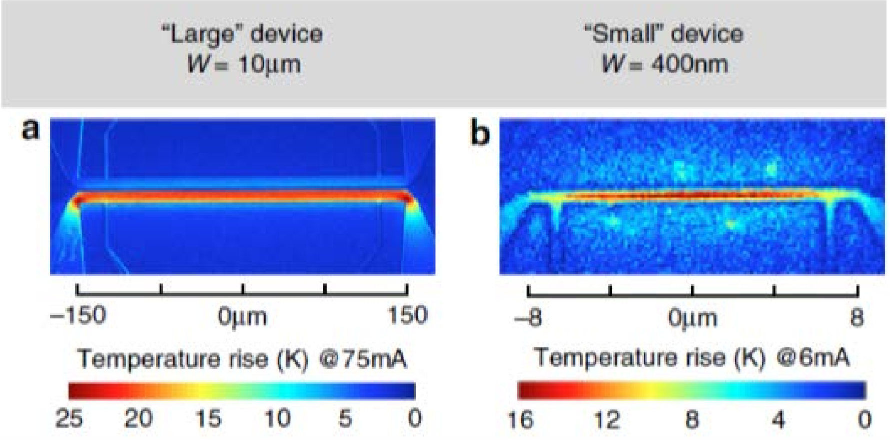


KCM VS KINETIC FORMALISM 2:

THERMAL BOUNDARY RESISTANCE

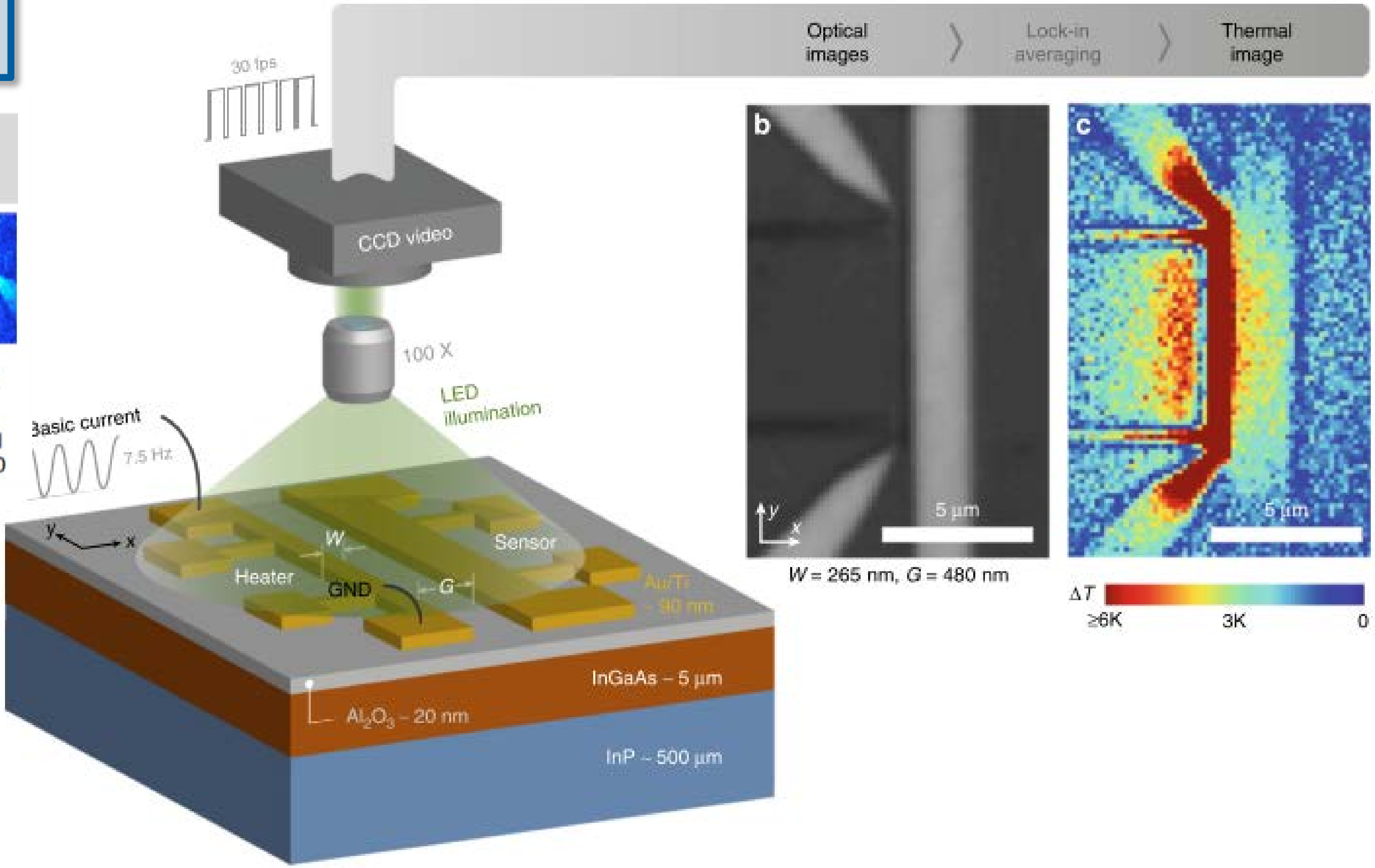
Thermoreflectance Imaging (TRI)

Ziabari et al.
Nat. Commun. **9**, 255 (2018)



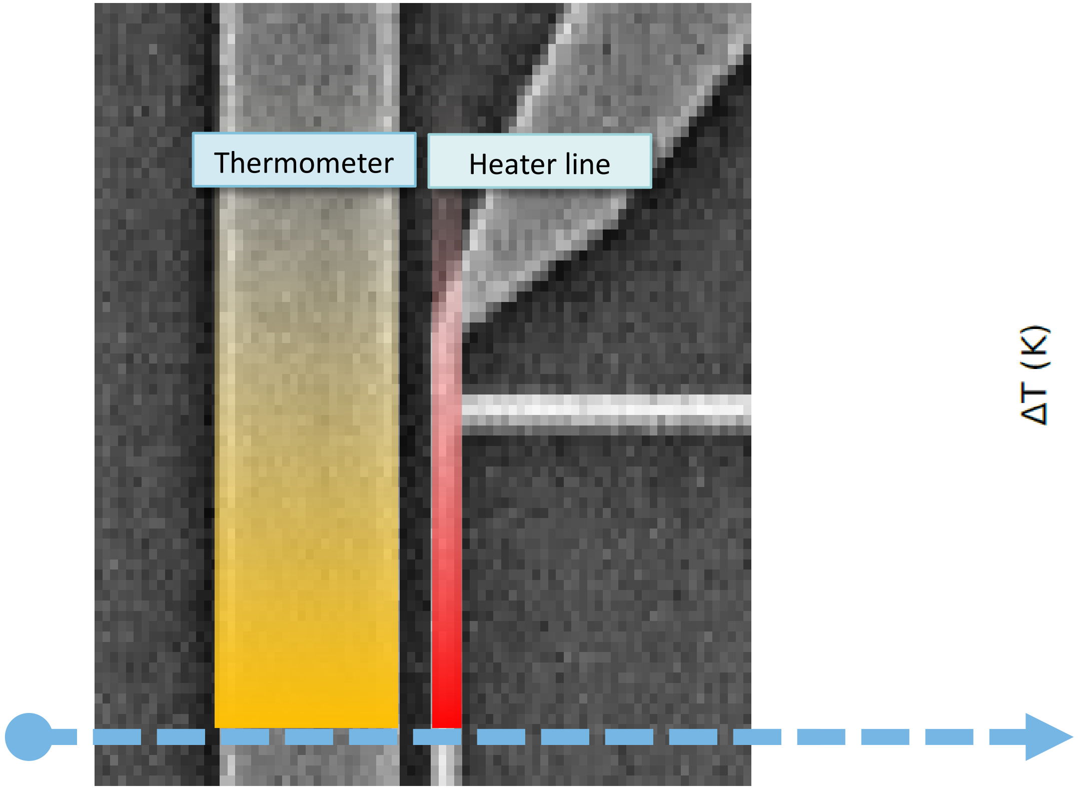
PURDUE UNIVERSITY

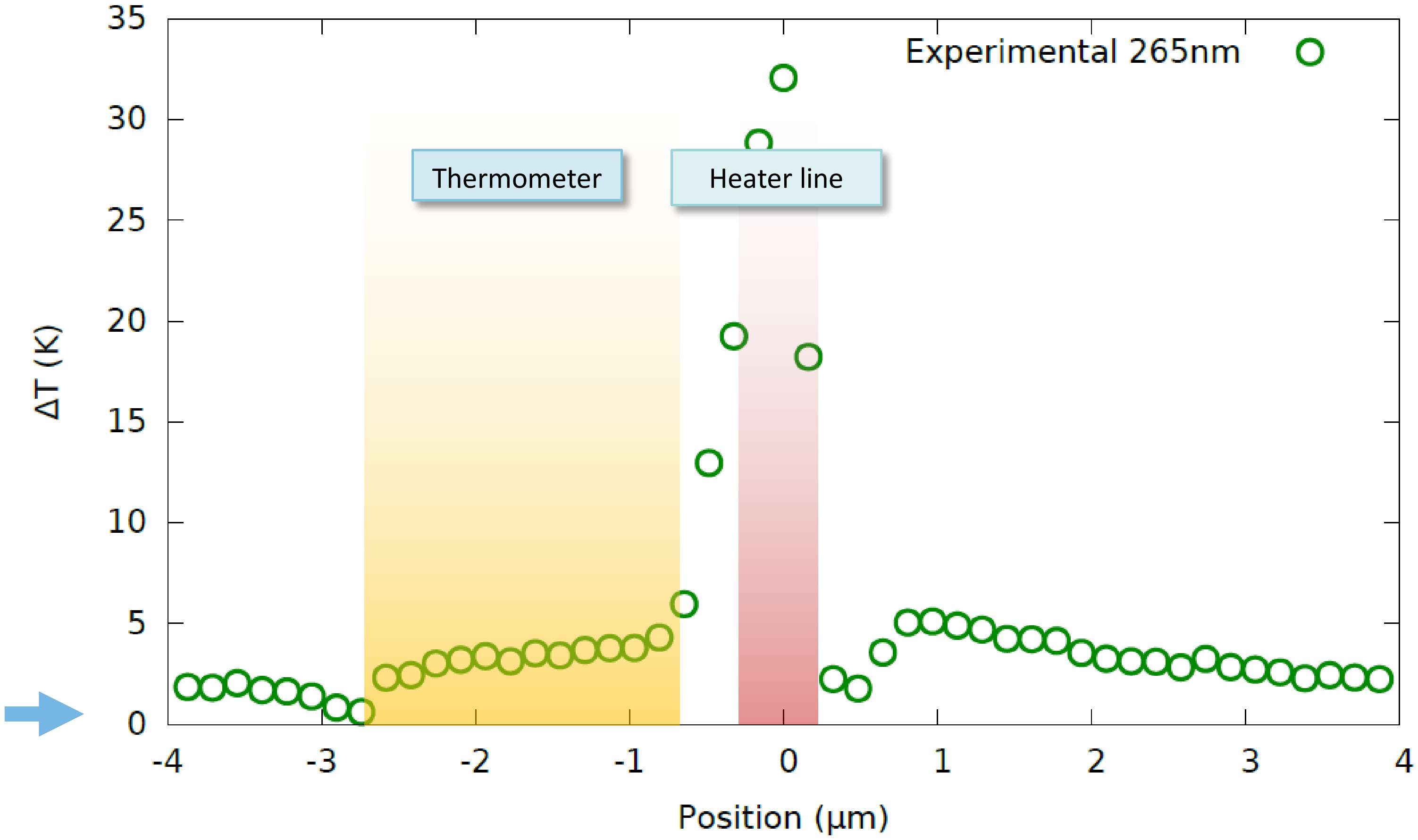
Ali Shakouri



Universitat Autònoma de Barcelona

Experimental Data

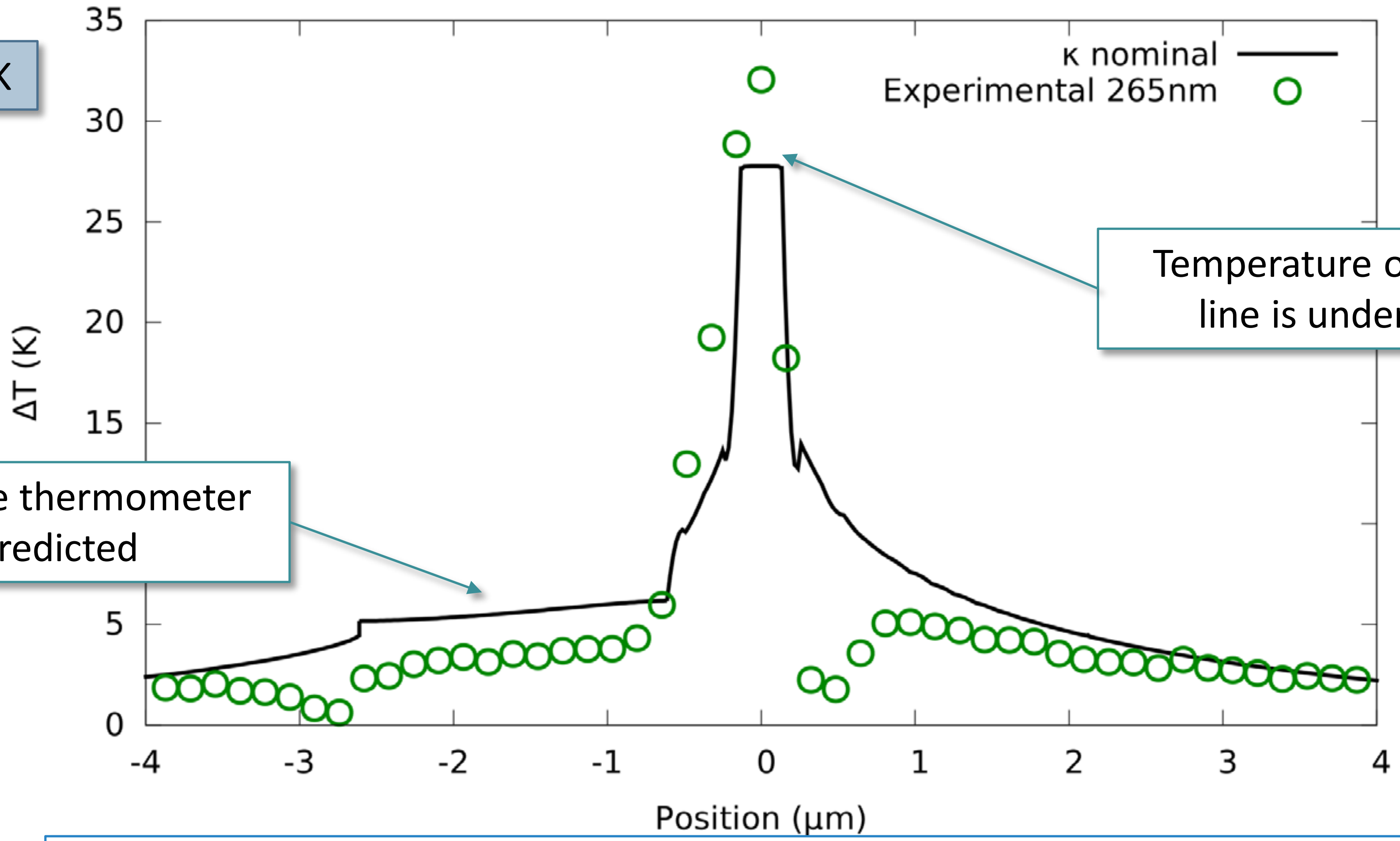




We obtain a thermal map of the surface of the sample using the optical setup.
Heater line and thermometer are also obtained using electrical measurements.

Fourier's law test (I)

κ_{InGaAs} = 5.4 W/m·K



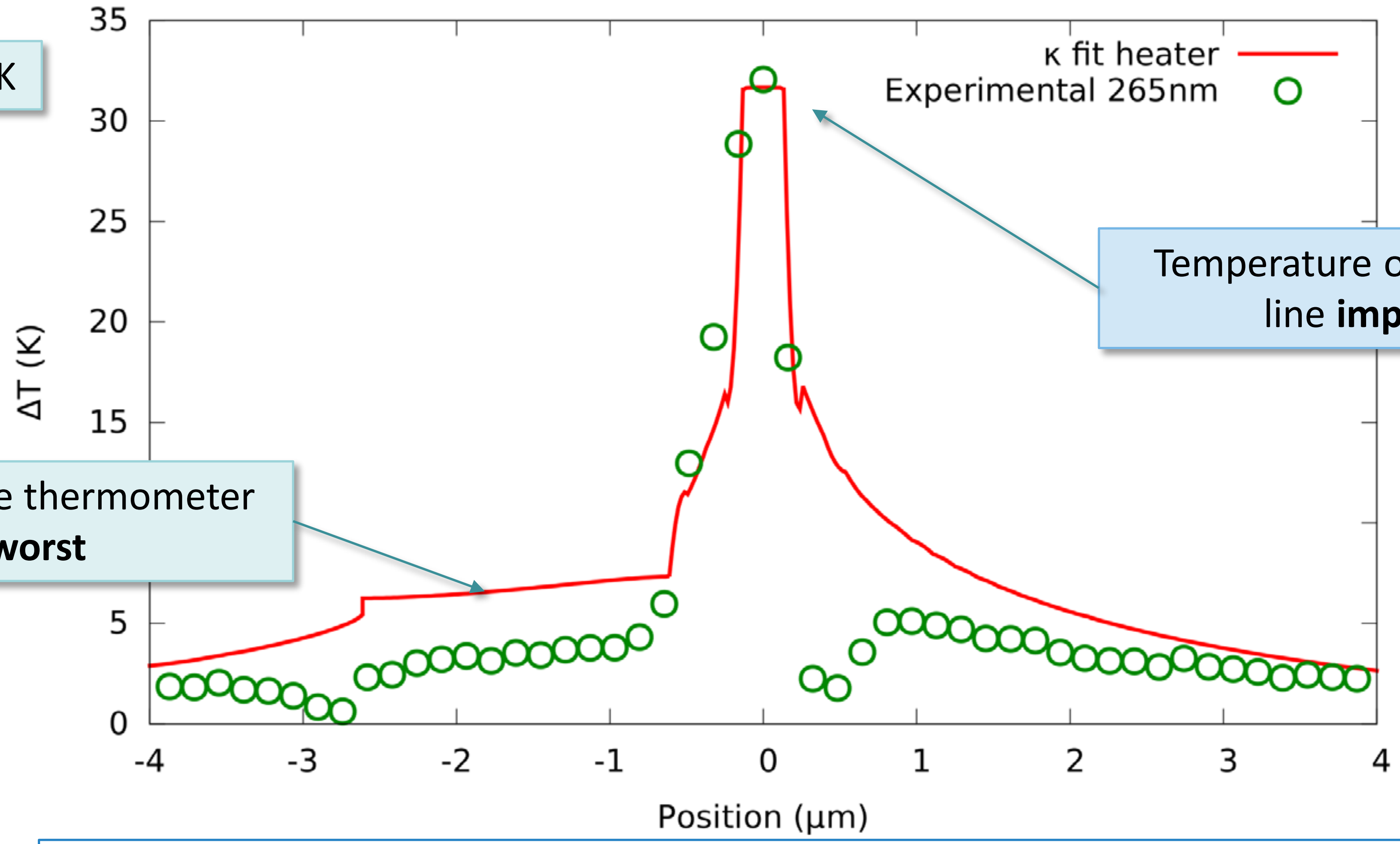
Temperature of the heater line is underpredicted

Temperature of the thermometer line is overpredicted

Using a finite element software (COMSOL) we test the validity of the Fourier's law using the nominal value of the thermal conductivity of InGaAs

Fourier's law test (II)

κ_{InGaAs} = 4.4 W/m·K



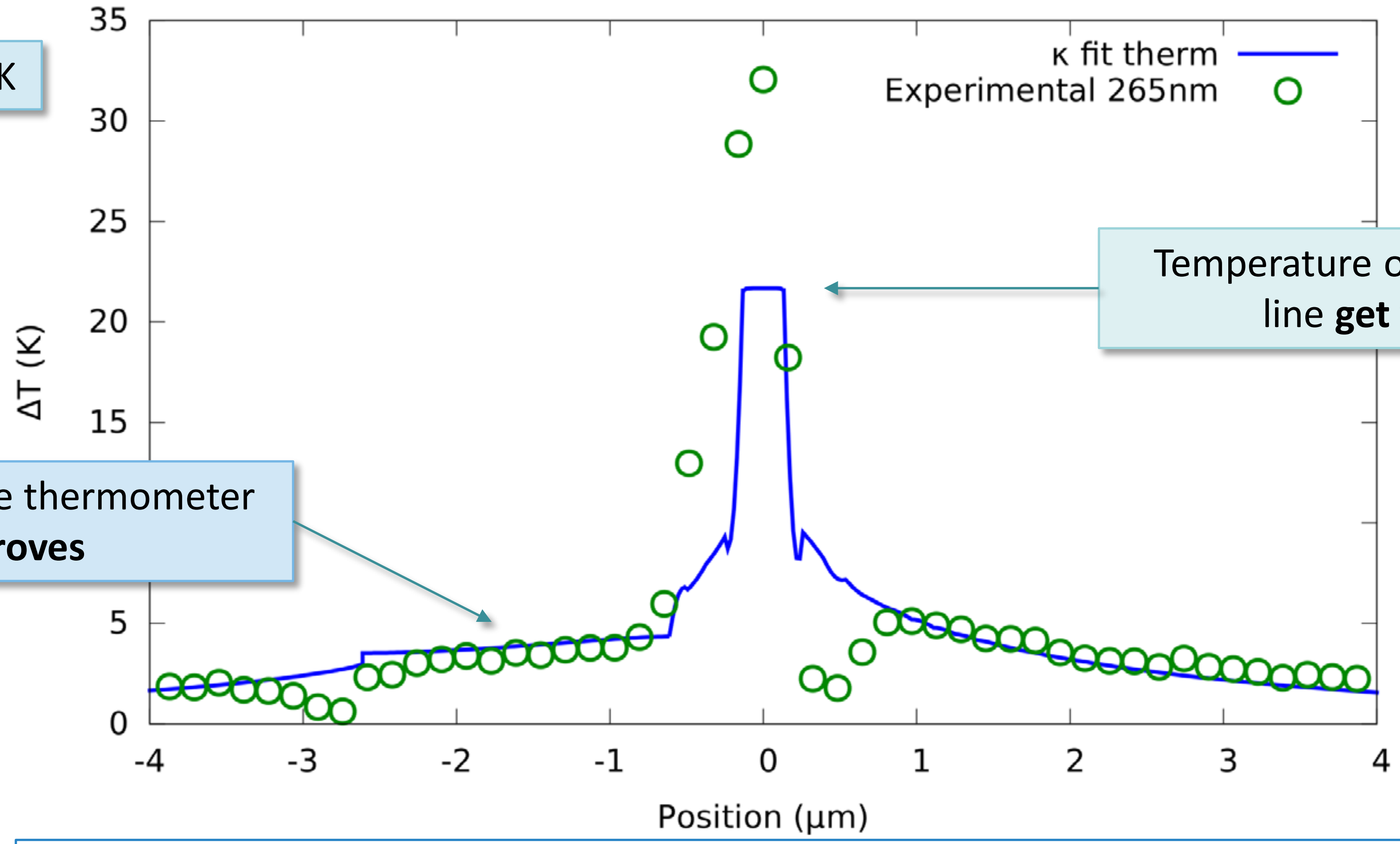
Temperature of the heater line **improves**

Temperature of the thermometer line **get worst**

Using a finite element software (COMSOL) we test the validity of the Fourier's law using a fitted value of the thermal conductivity of InGaAs to fit the heating line

Fourier's law test (III)

κ_{InGaAs} = 6.4 W/m·K

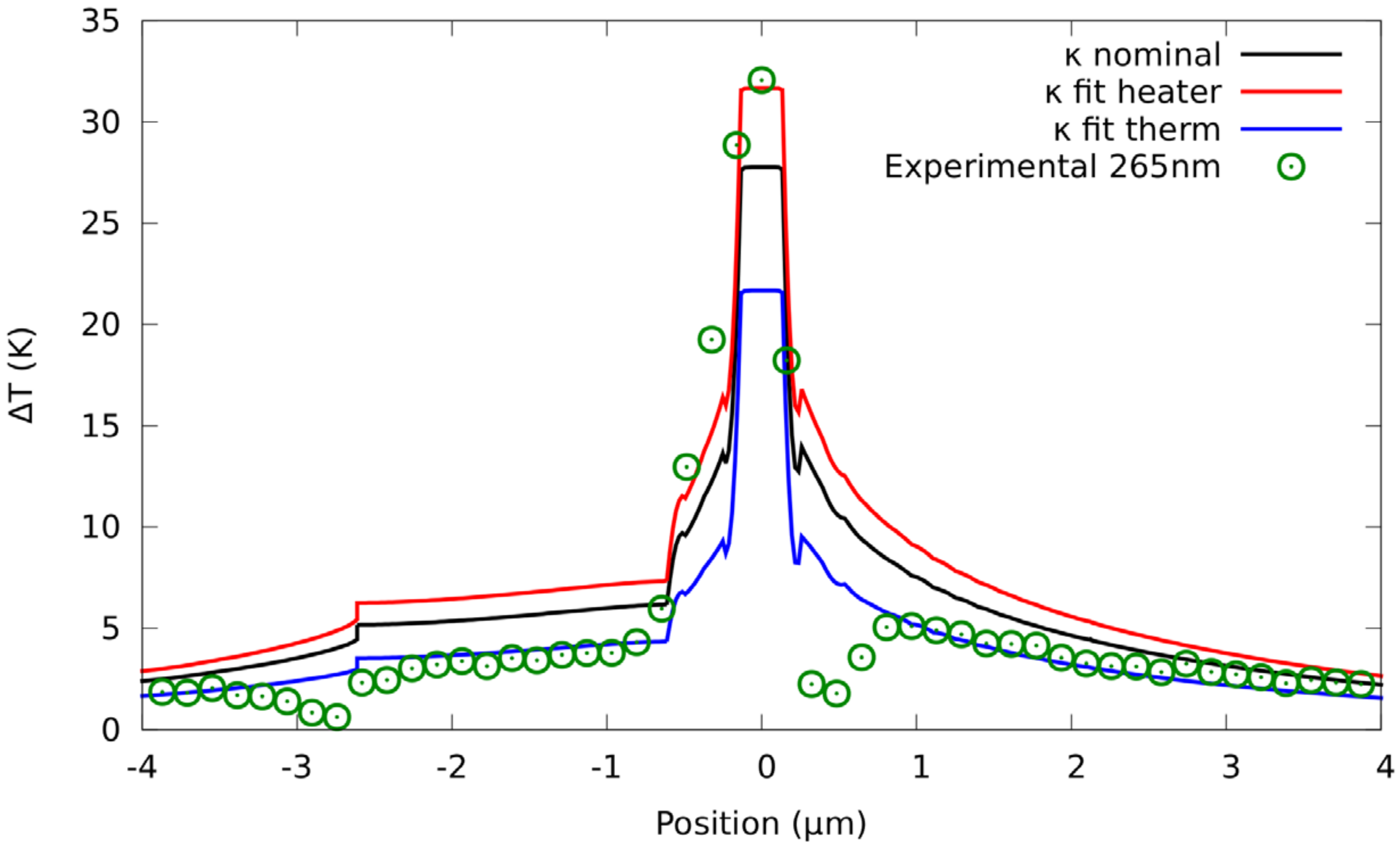


Temperature of the heater line **get worst**

Temperature of the thermometer line **improves**

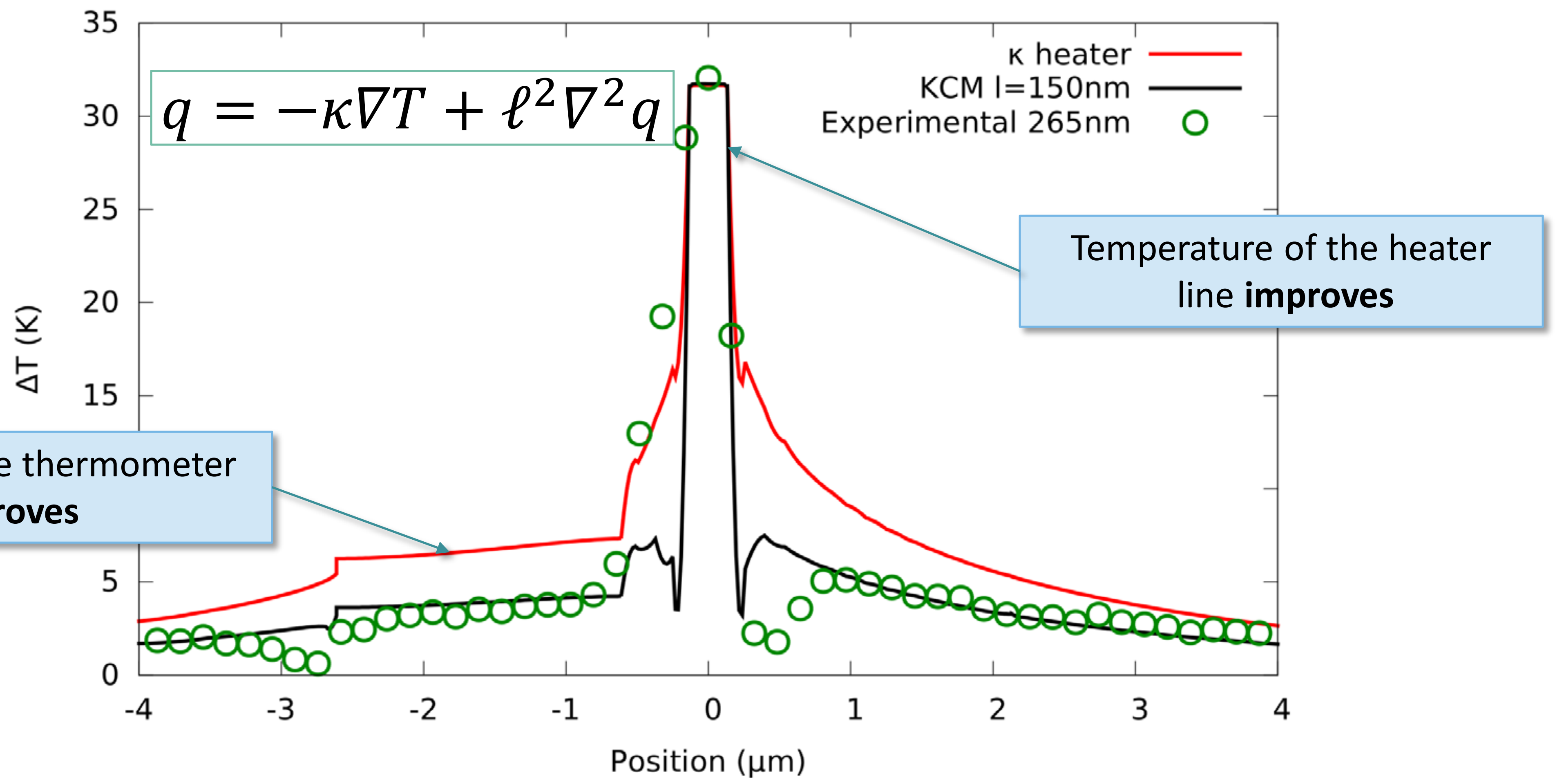
Using a finite element software (COMSOL) we test the validity of the Fourier's law using a fitted value of the thermal conductivity of InGaAs to fit the thermometer line

Fourier’s law summary



Conclusion: Fourier’s law cannot describe thermal transport in this setup.
New equation is needed.

GK equation

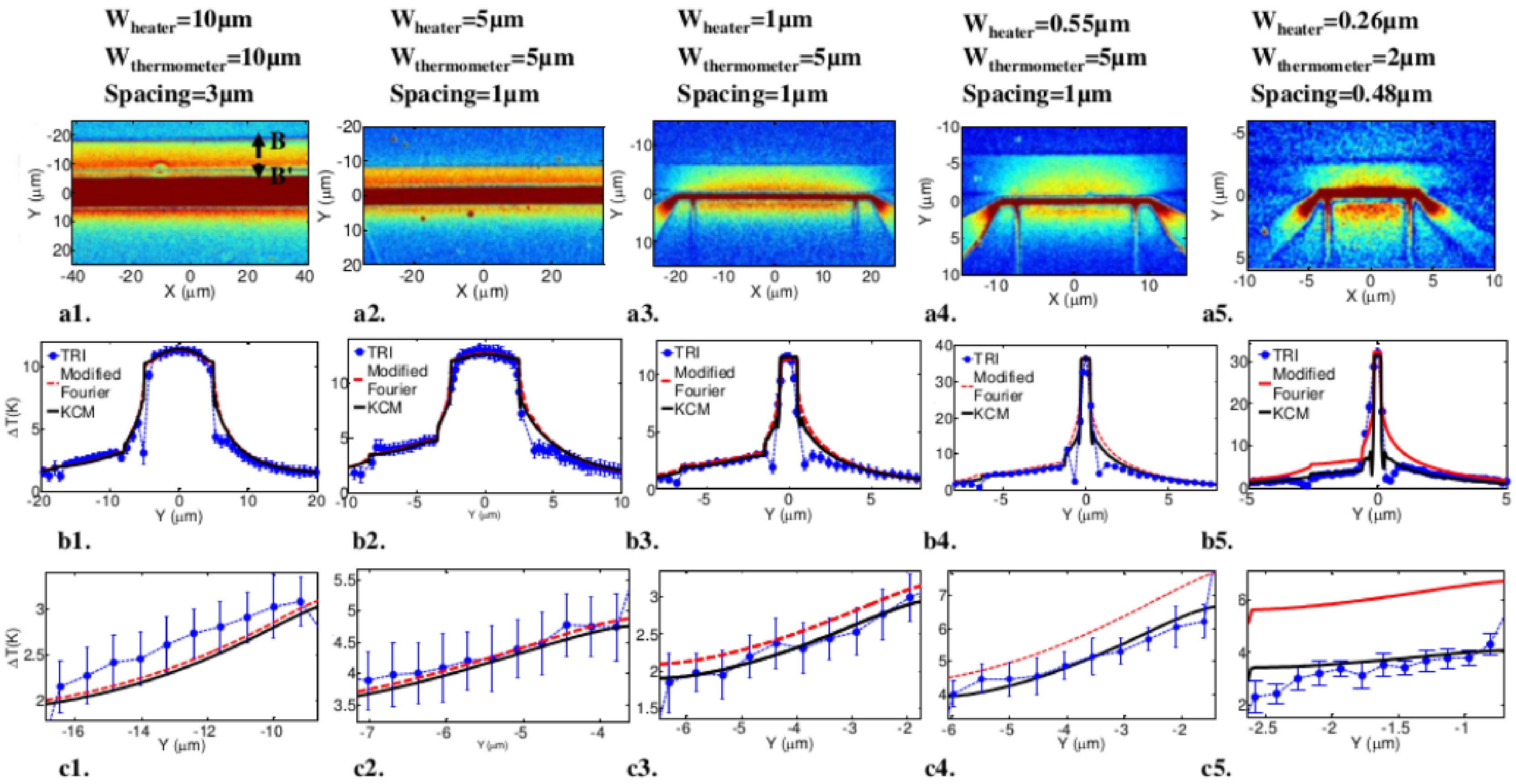


Kinetic Collective Model fits better to experimental data

Kinetic Collective Model + Guyer and Krumhansl

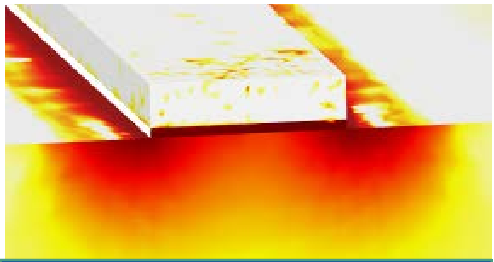
At large sizes we recover Fourier model

The smaller the size, the larger the effect

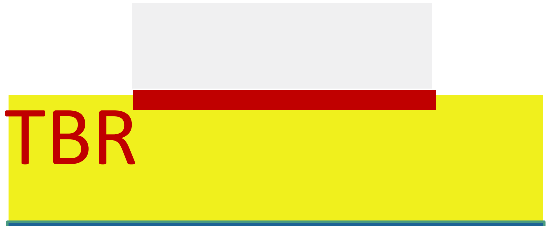


Universitat Autònoma de Barcelona

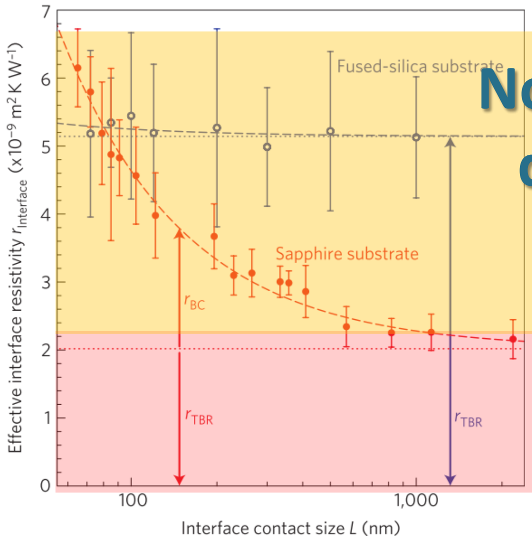
TBR vs hydrodynamics



KCM

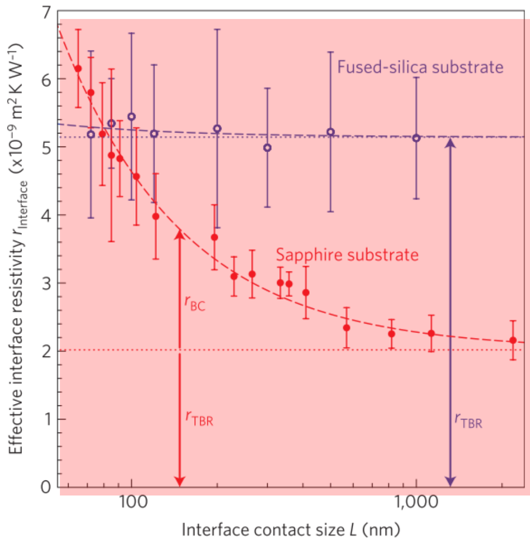


FOURIER



Non-local effects depending on $\ell^2\nabla^2 q$

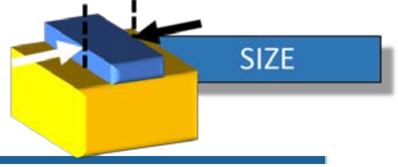
Constant TBR

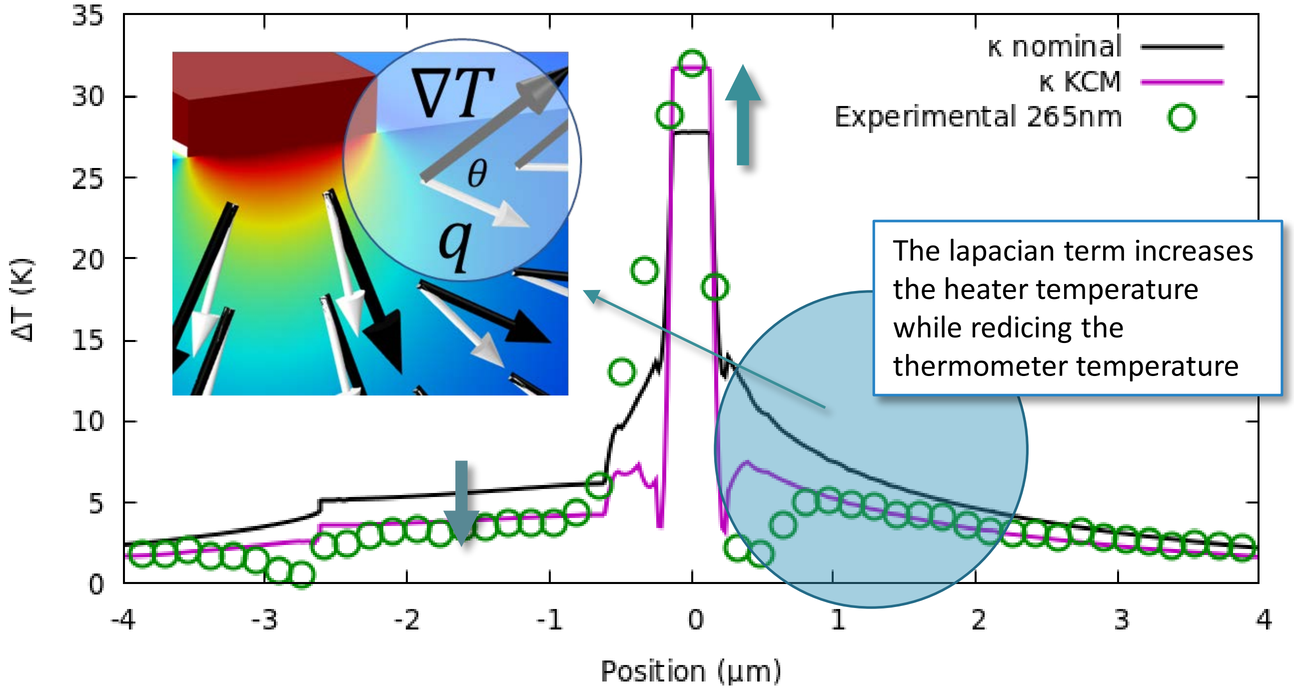


TBR depending on size

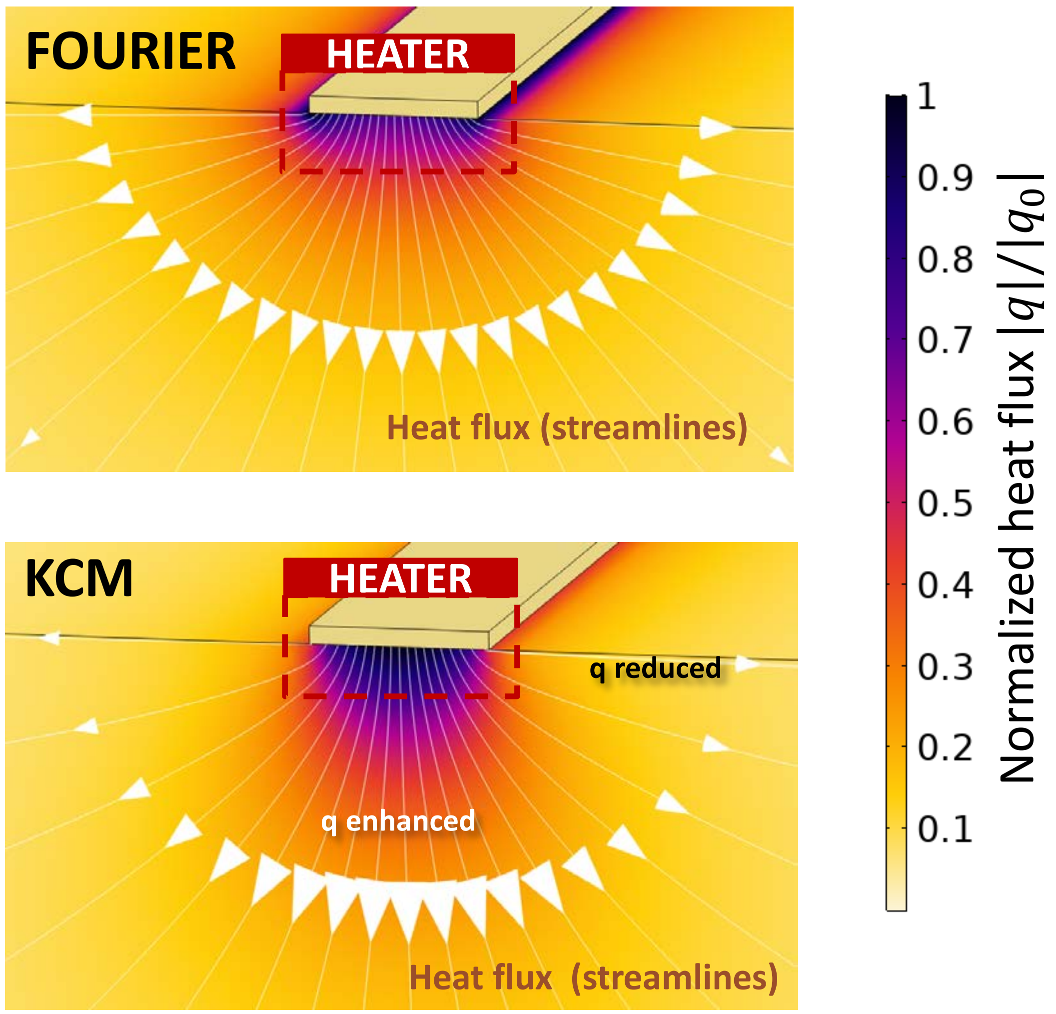
KCM-GK solution

Ziabari et al.
Nat. Commun. **9**, 255 (2018)





$$q = -\kappa \nabla T + \ell^2 \nabla^2 q$$



Universitat Autònoma de Barcelona

OTHER HYDRODYNAMIC SIGNATURES IN SILICON

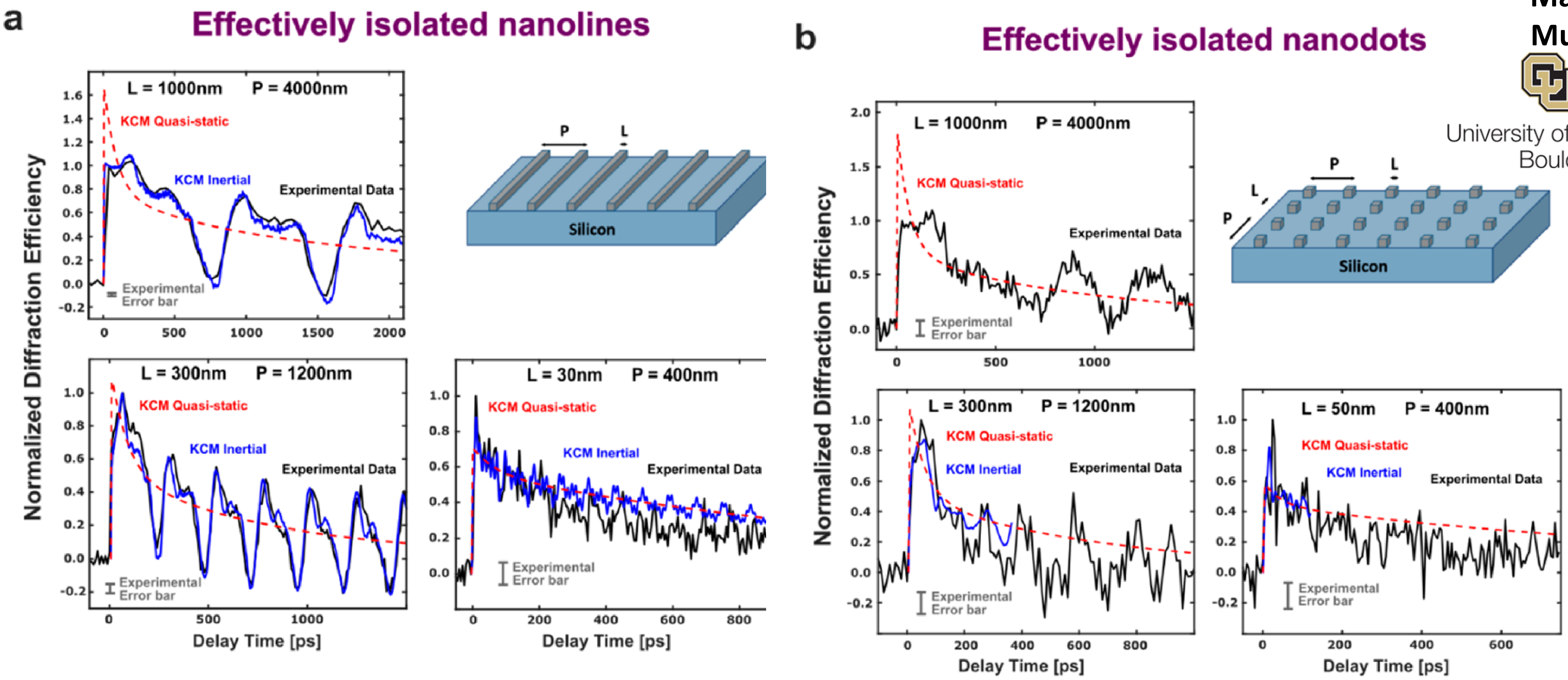
OBSERVATION OF HYDRODYNAMIC TIME SCALES

Temperature decay of metalic lines

Beardo, Knobloch et al.
ACS Nano 15, 13019 (2021)

Margaret Murnane

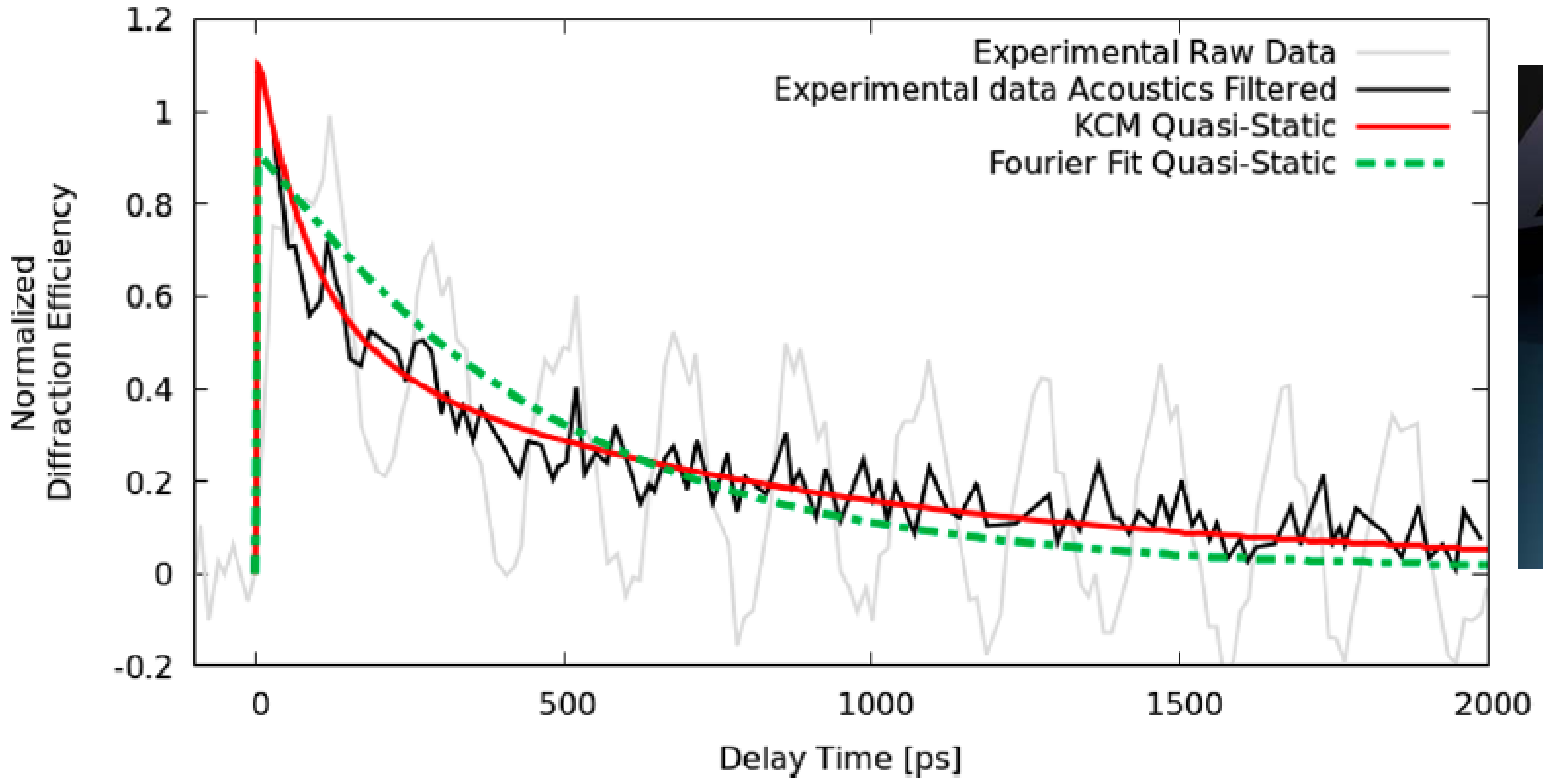
University of Colorado Boulder

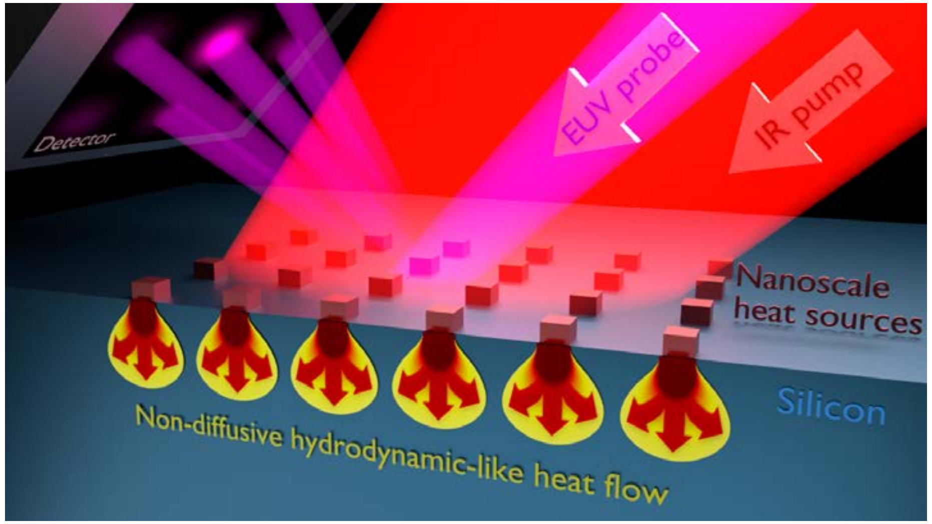


UAB Universitat Autònoma de Barcelona

Non-Fourier decay / Double exponential

Beardo, Knobloch et al.
ACS Nano 15, 13019 (2021)



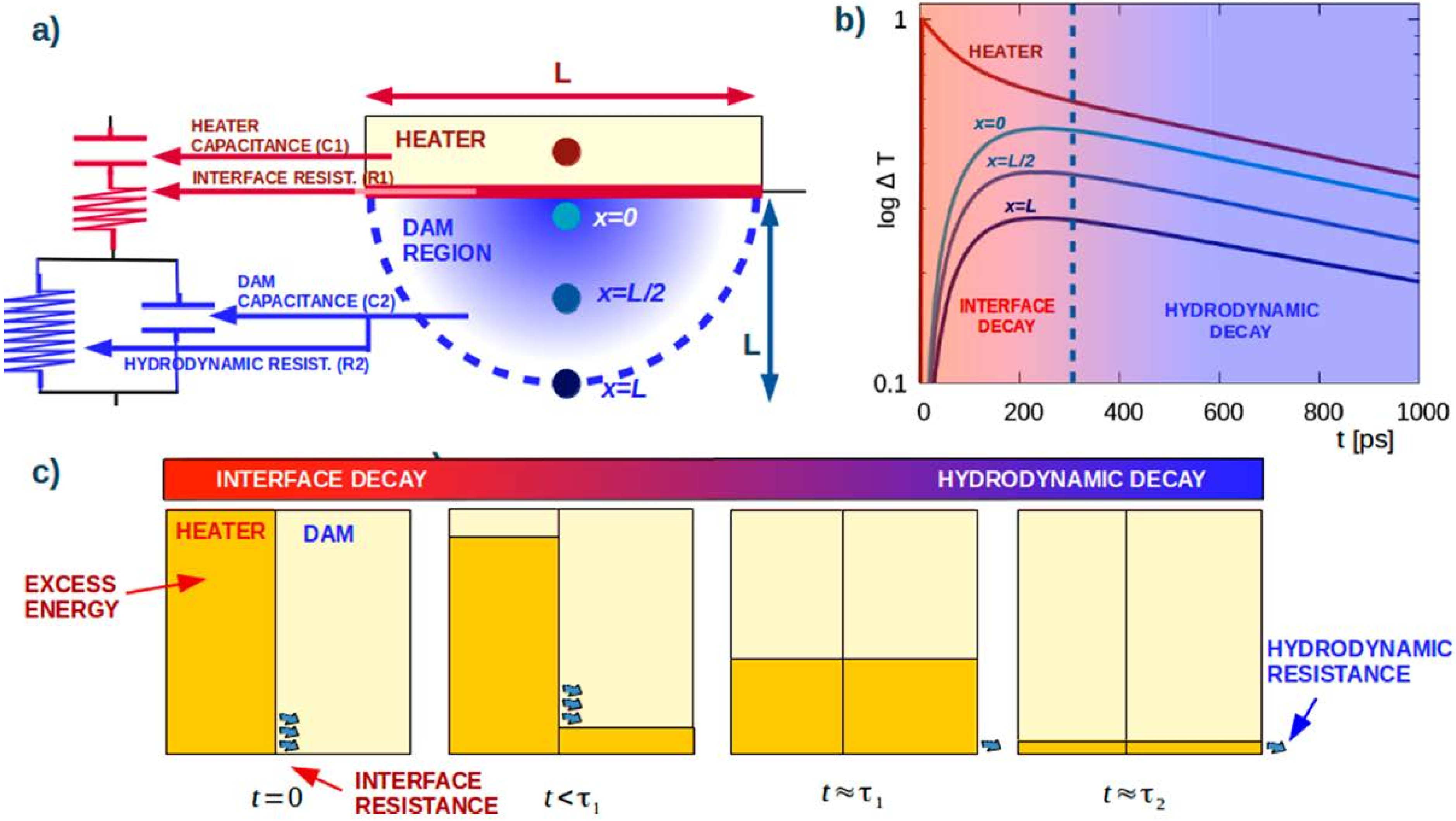


EUV SCATTEROMETRY SETUP

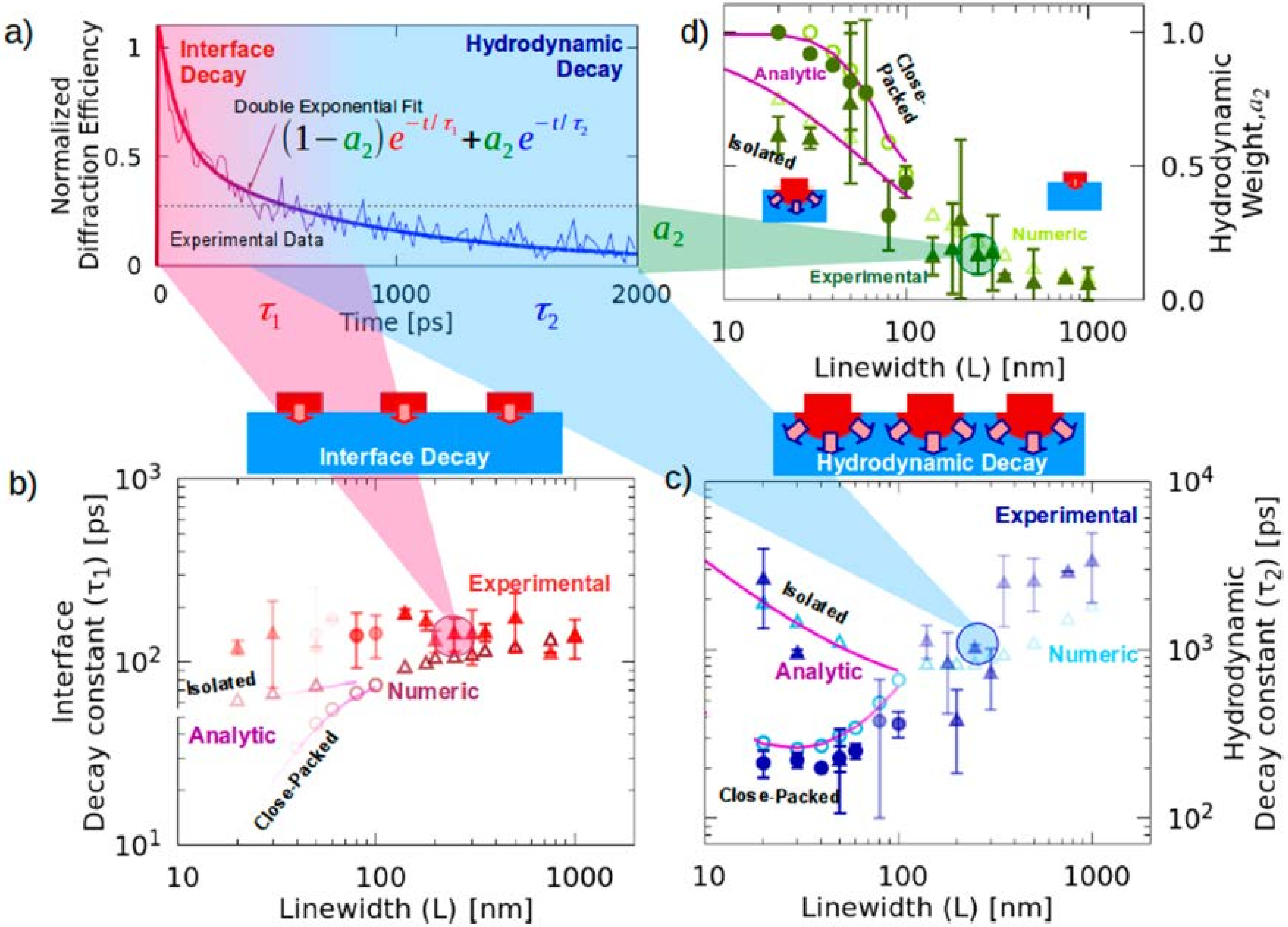
University of Colorado Boulder

Two Box model – The Dam region

Beardo, Knobloch et al.
ACS Nano 15, 13019 (2021)

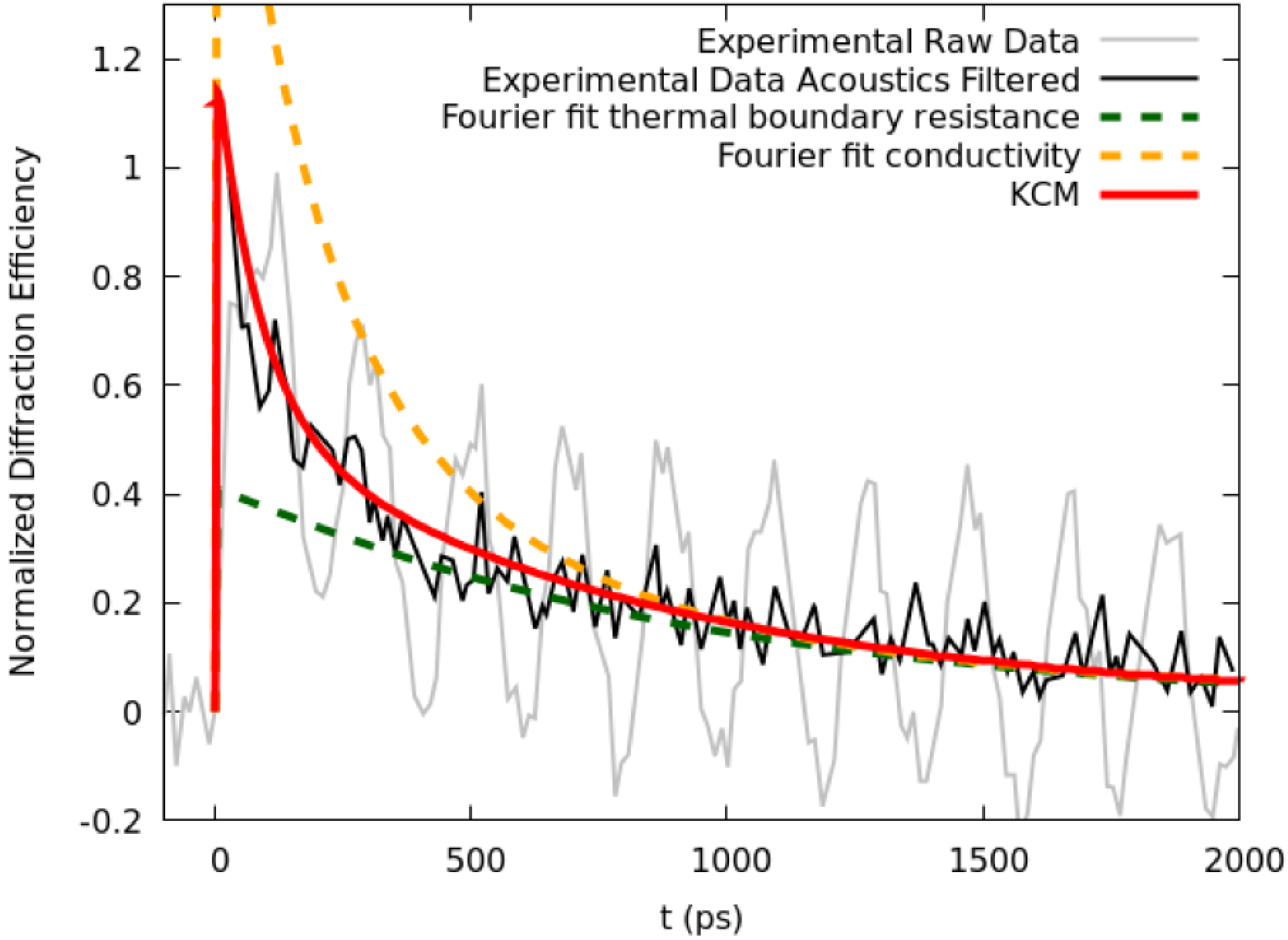


Two Box model / TBR and hydrodynamic relaxation times



Universitat Autònoma de Barcelona

Two Box model / TBR and hydrodynamic relaxation times

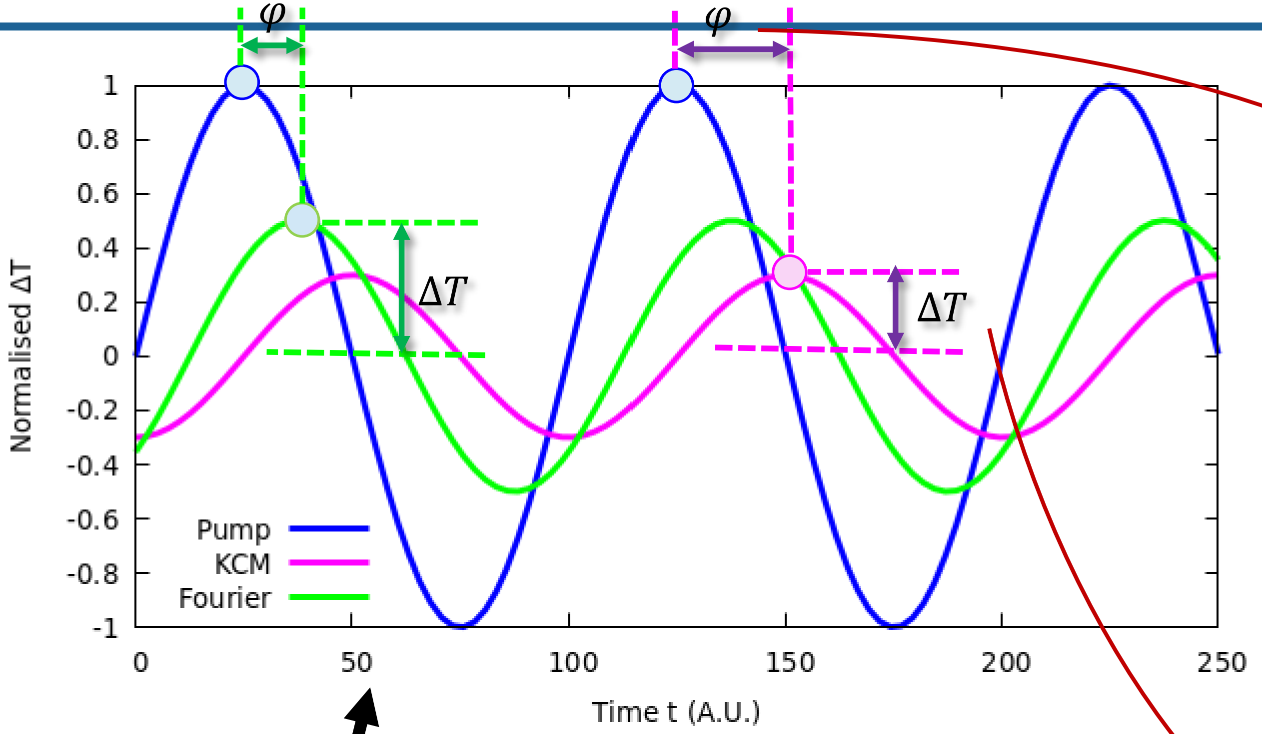


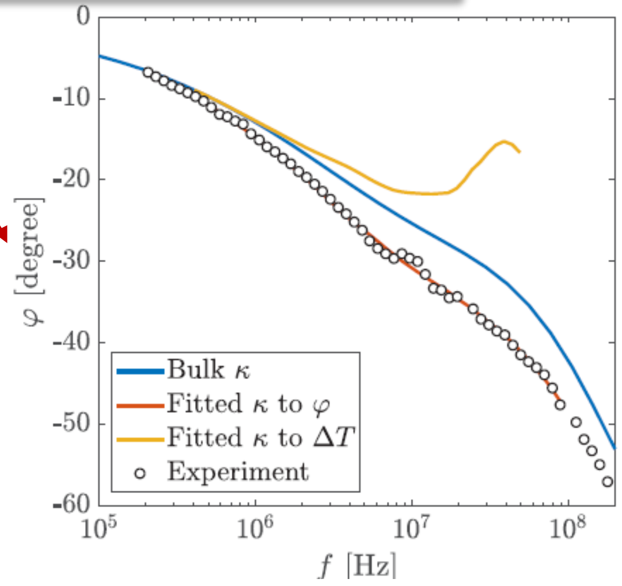
SECOND SOUND

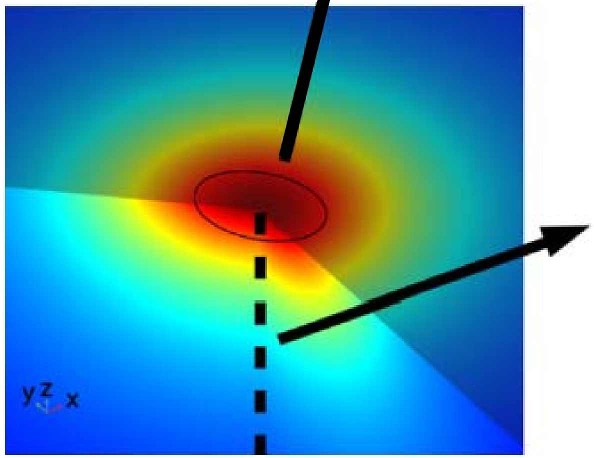
Frequency Domain Thermoreflectance (FDTR)

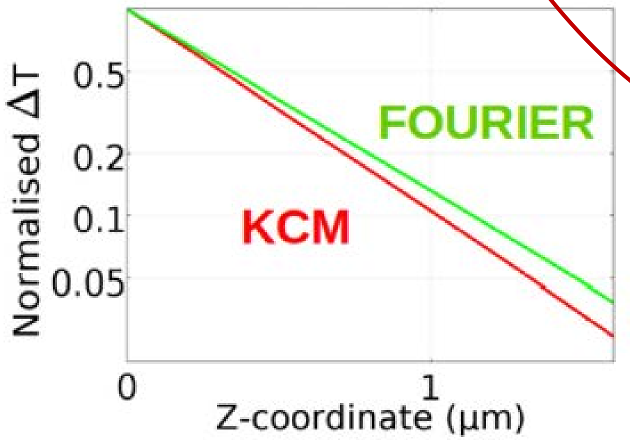
Regner et al.
Nat. Communic. ***4****, 1640* (2013)

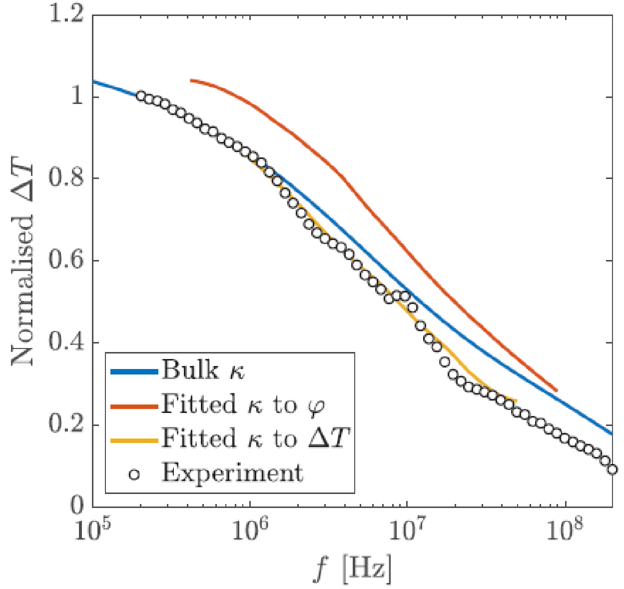
FREQUENCY







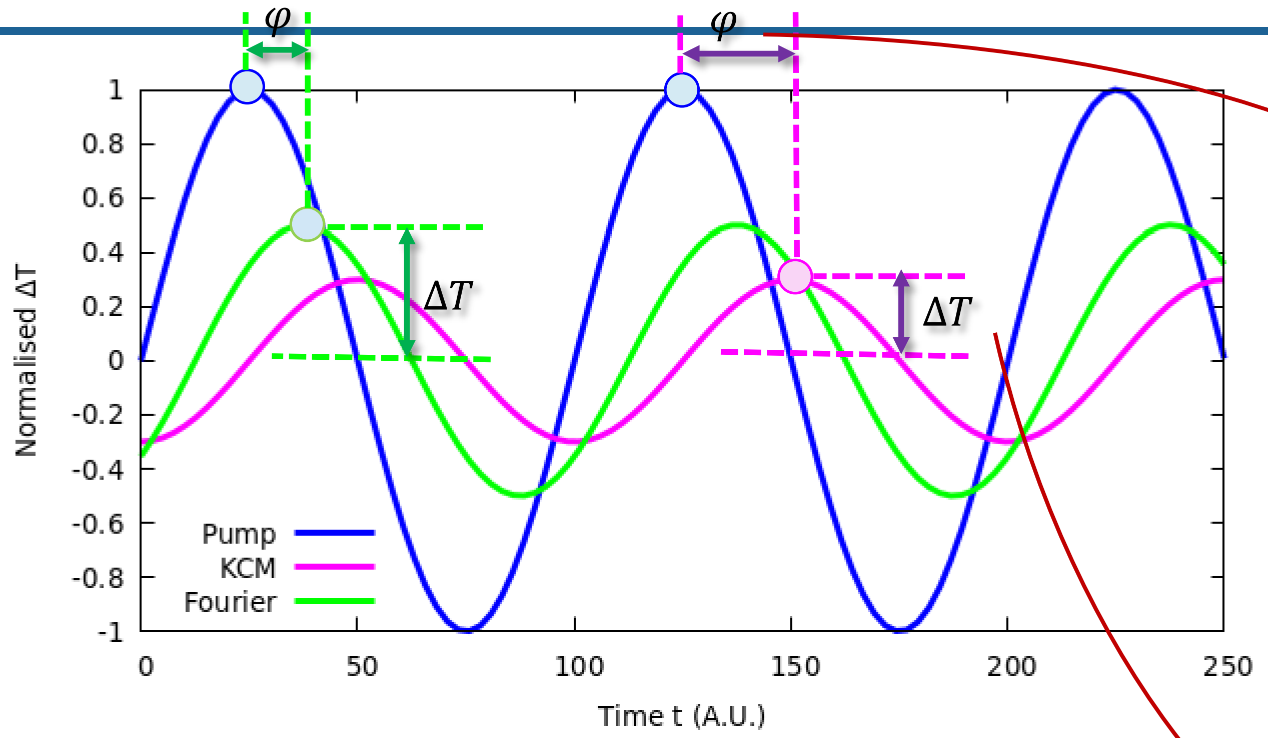


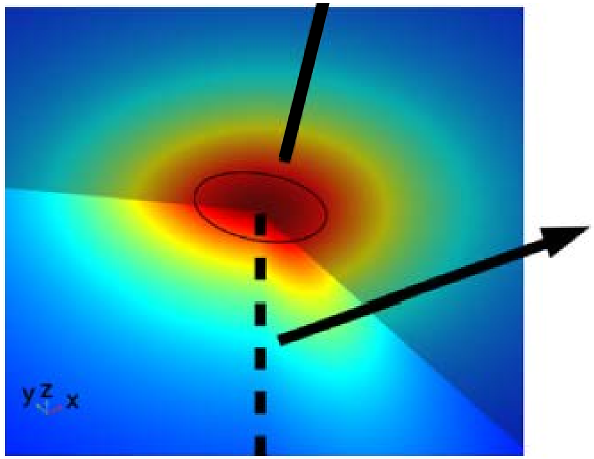


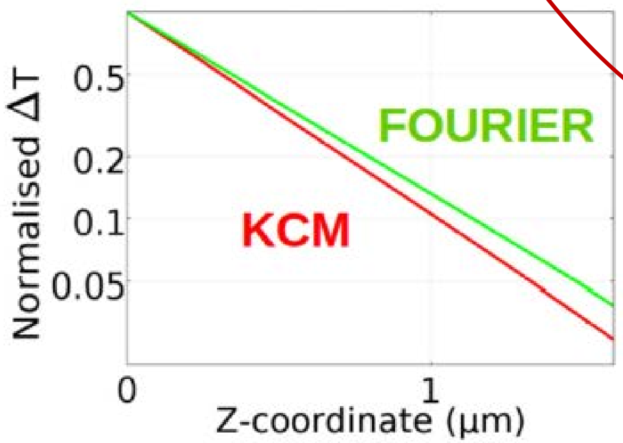
Frequency Domain Thermoreflectance (FDTR)

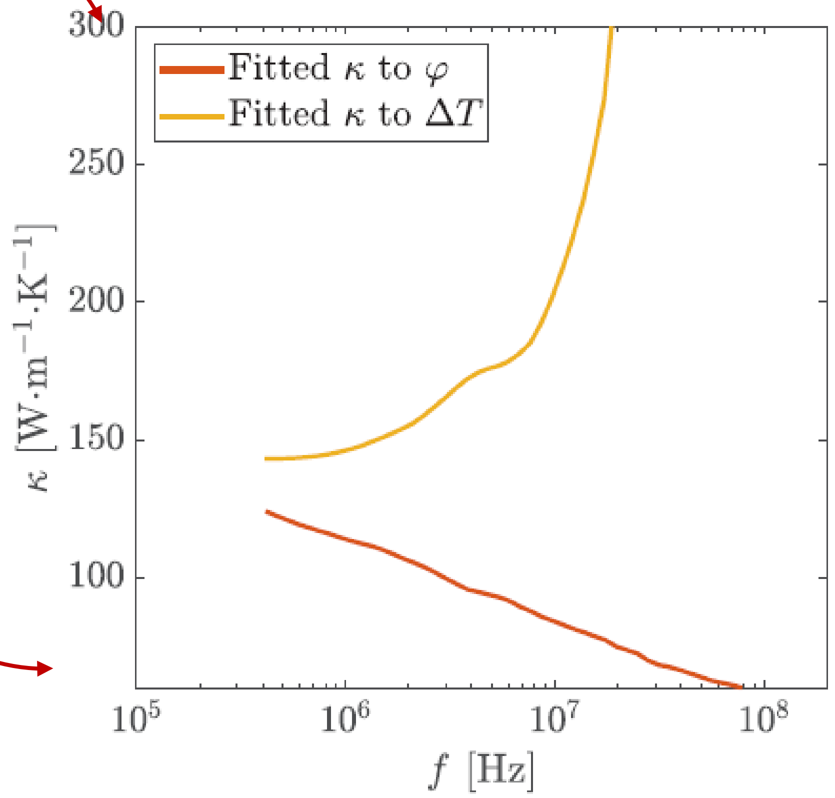
Regner et al.
Nat. Communic. ***4****, 1640* (2013)

FREQUENCY









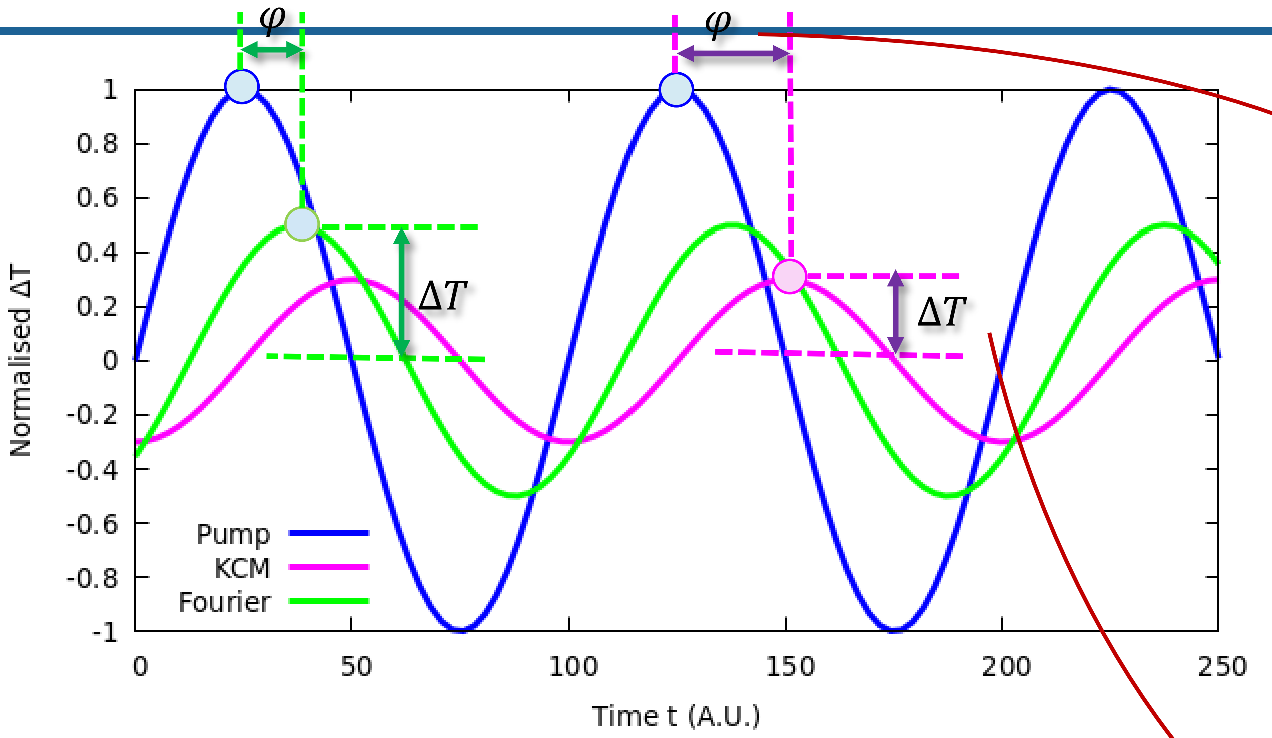
Beardo et al.
PRB ***101****, 075303* (2020)

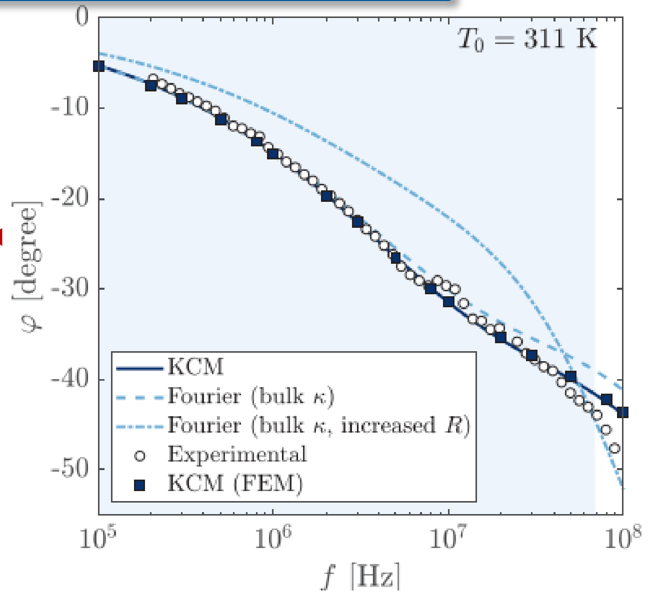
Universitat Autònoma de Barcelona

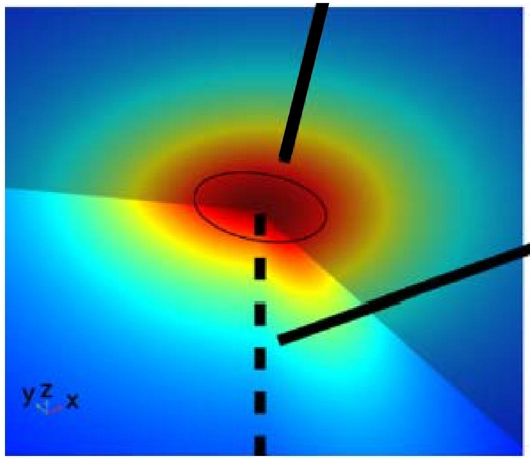
Frequency Domain Thermoreflectance (FDTR)

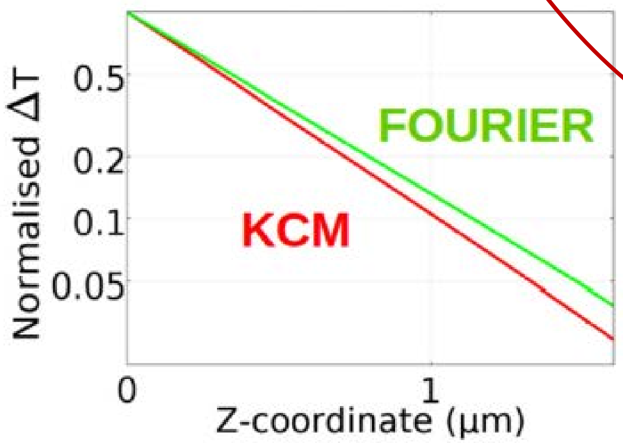
Regner et al.
Nat. Communic. ***4****, 1640* (2013)

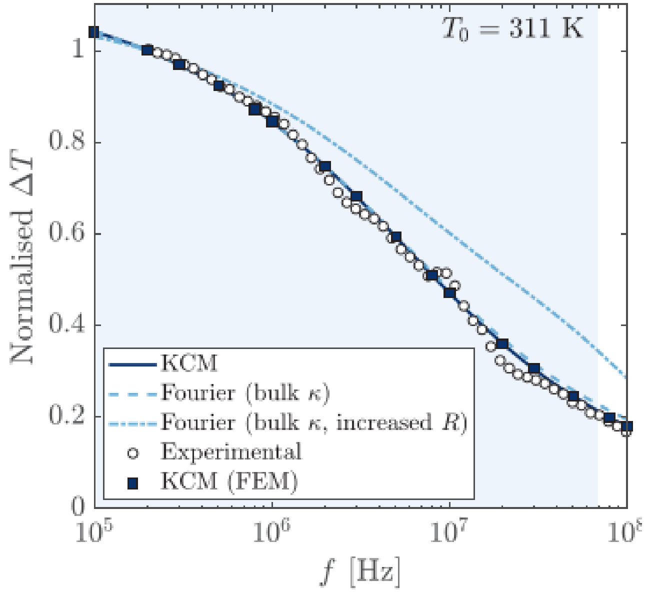
FREQUENCY











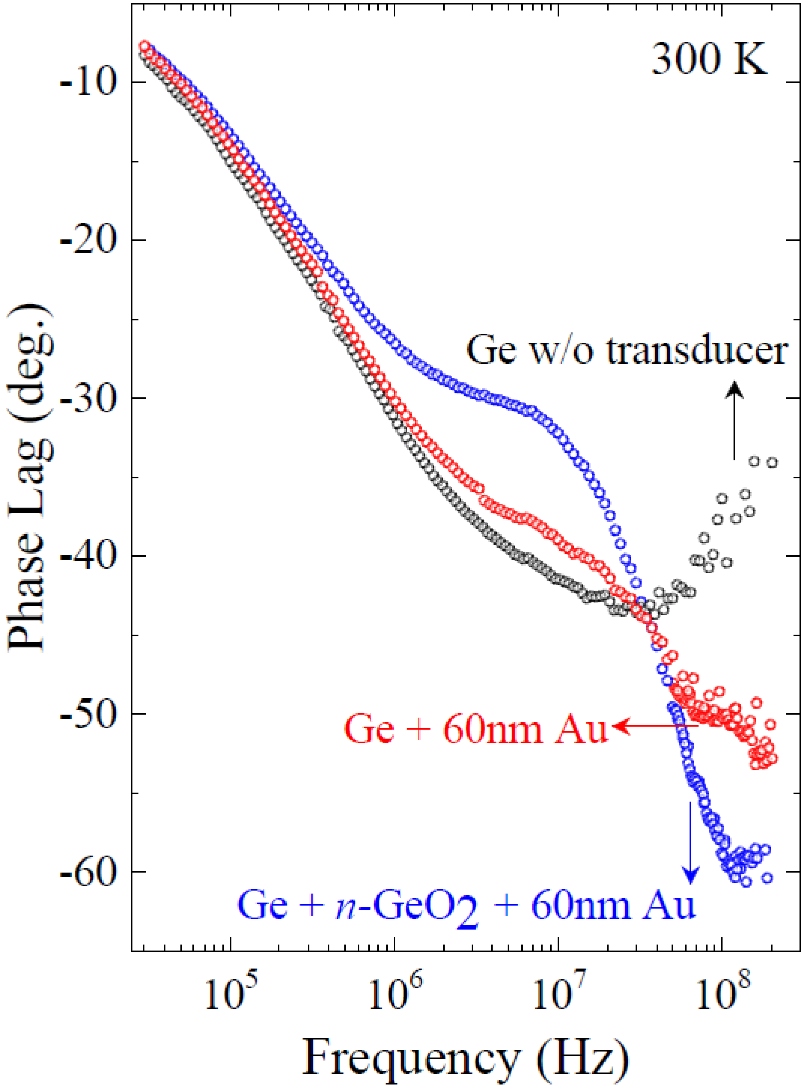
Universitat Autònoma de Barcelona

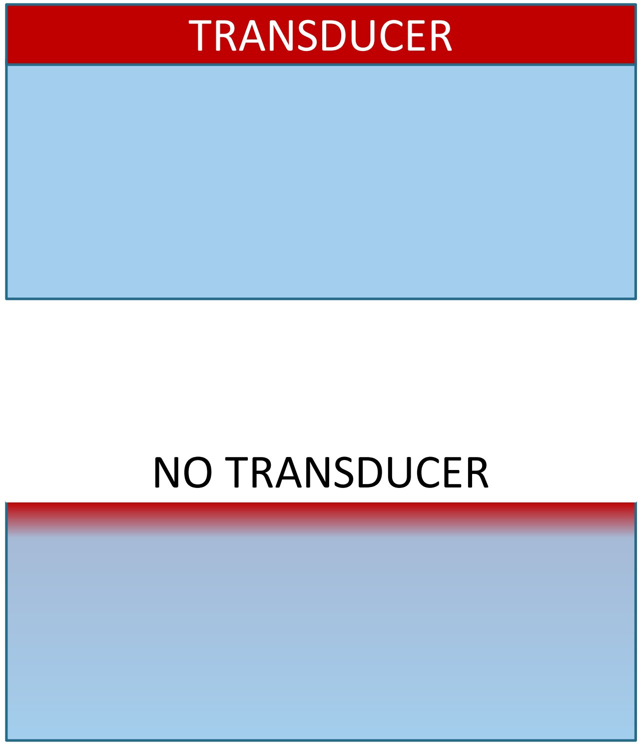
Memory effects / Second sound

Beardo et al.
Sci. Adv. 7, eabg4677 (2021)

ICMAB

Sebastian Reparaz

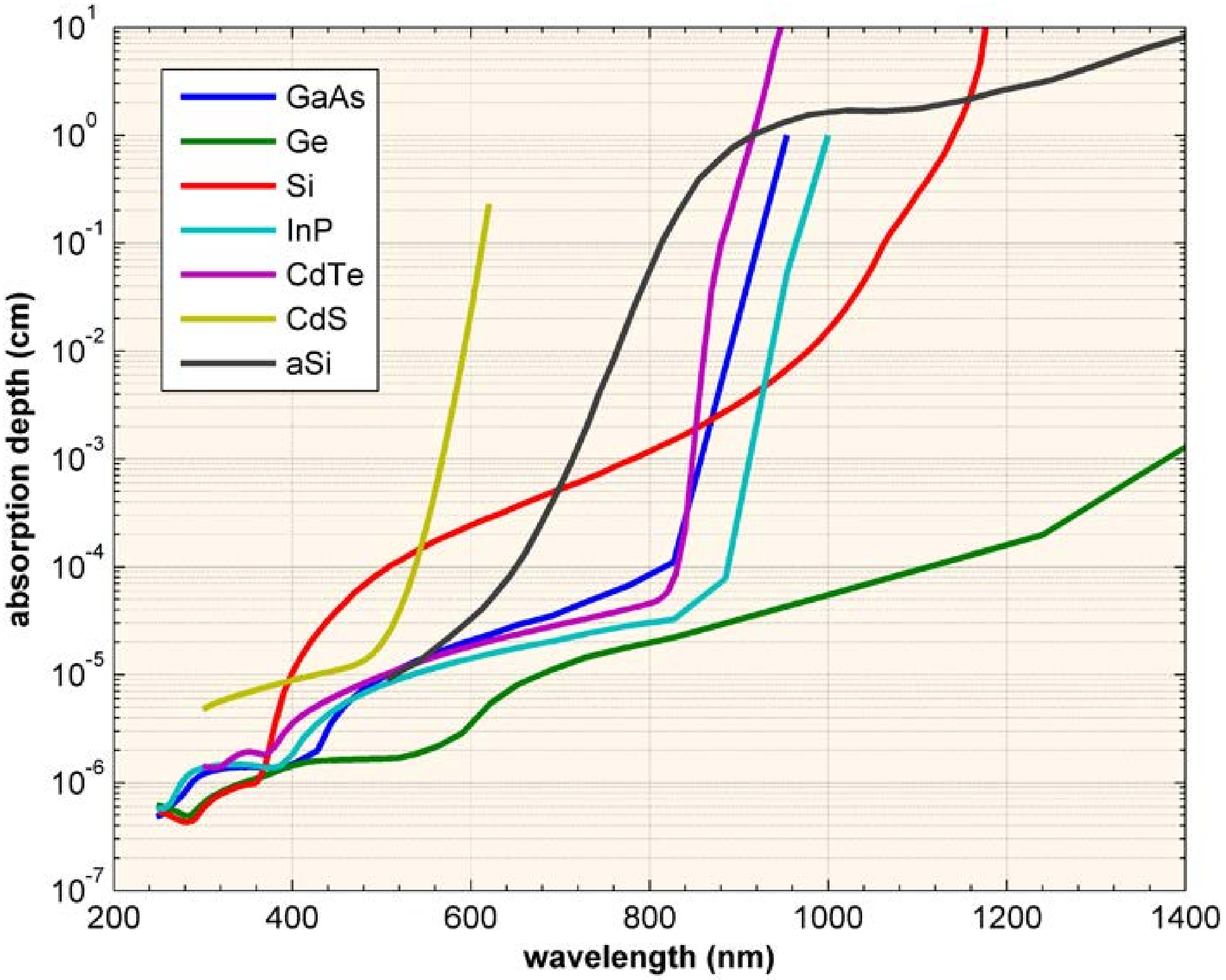


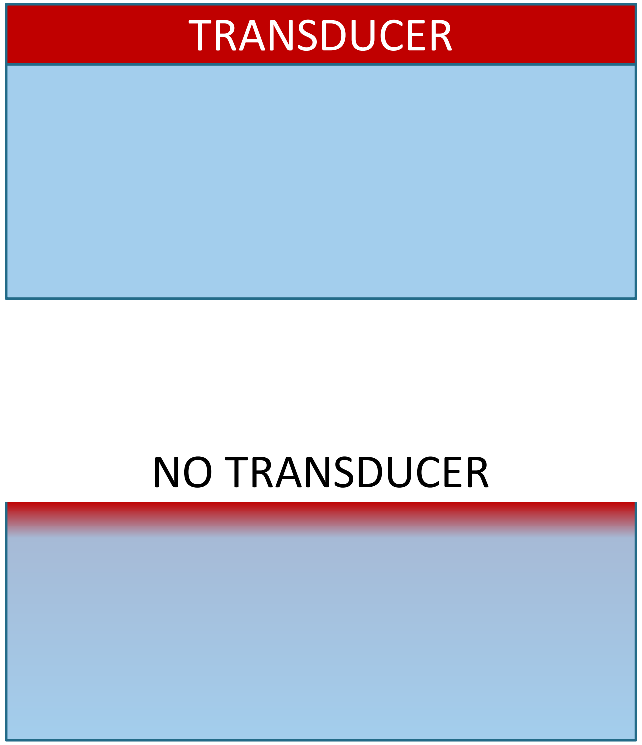


Universitat Autònoma de Barcelona

Memory effects / Second sound

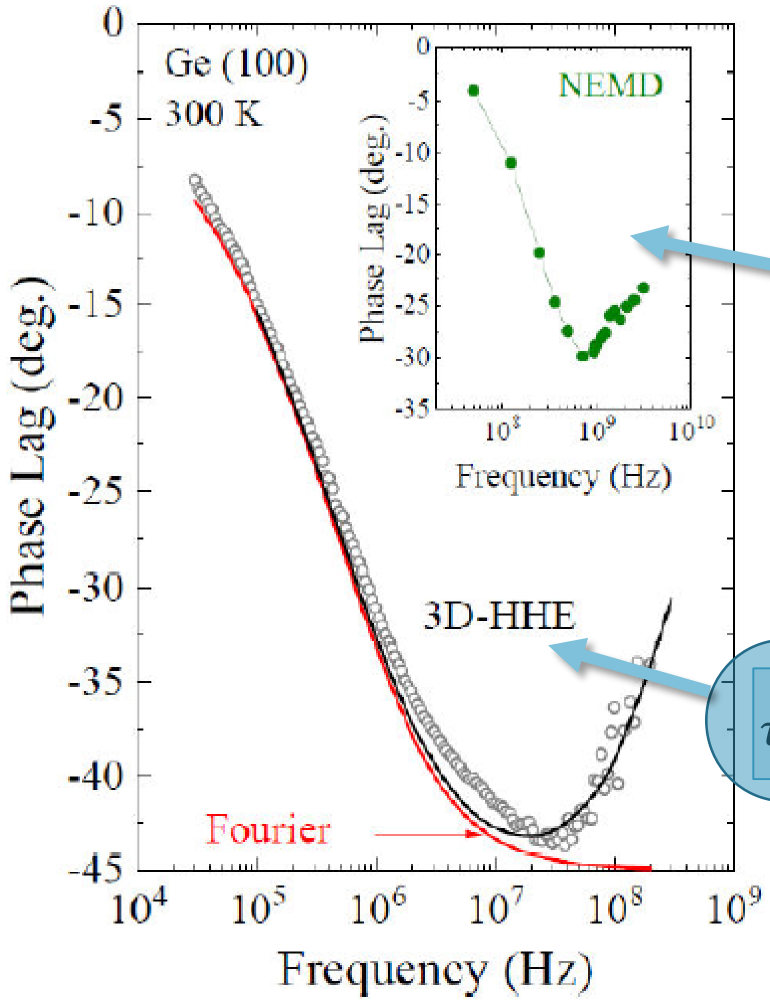
Beardo et al.
Sci. Adv. 7, eabg4677 (2021)

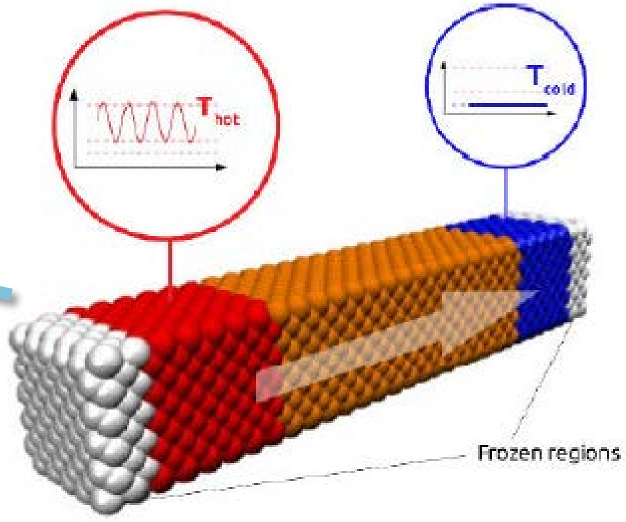




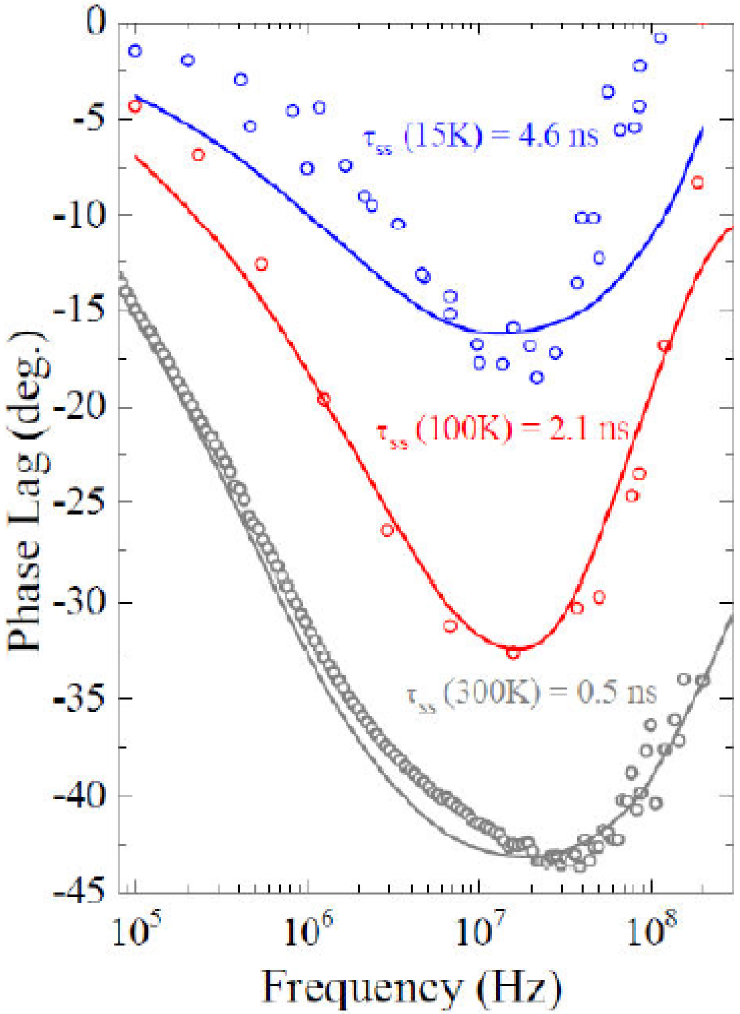
Memory effects / Second sound

Beardo et al.
Sci. Adv. 7, eabg4677 (2021)



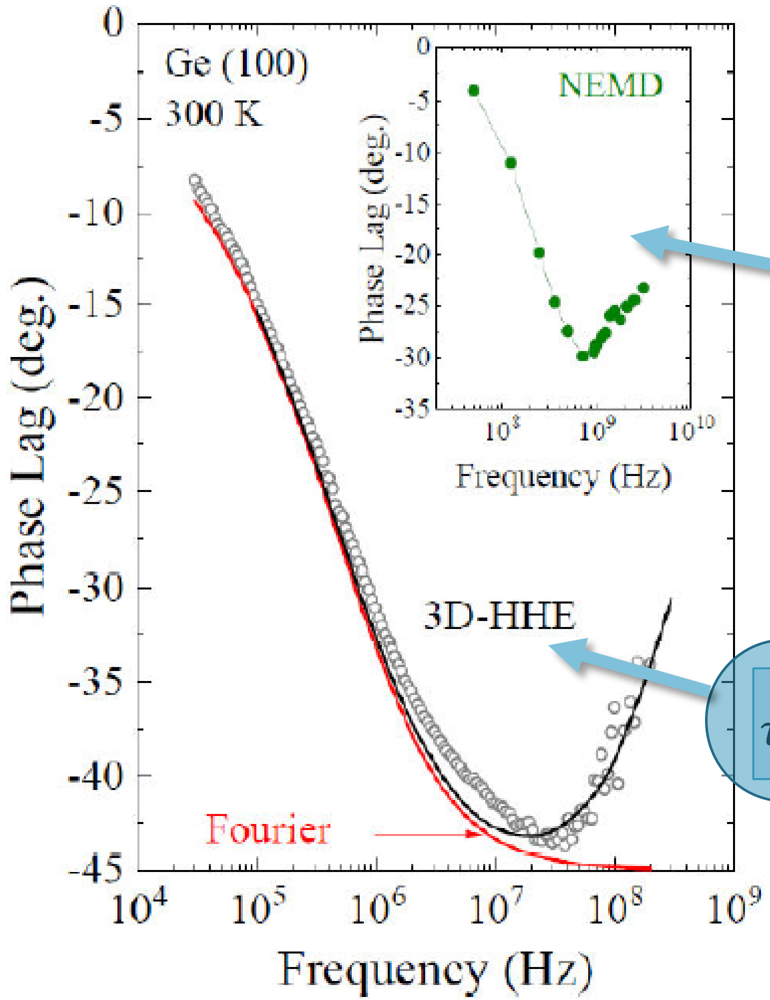


$$\tau \frac{\partial q}{\partial t} + q = -\kappa \nabla T + \ell^2 (\nabla^2 q + \alpha \nabla (\nabla \cdot q))$$

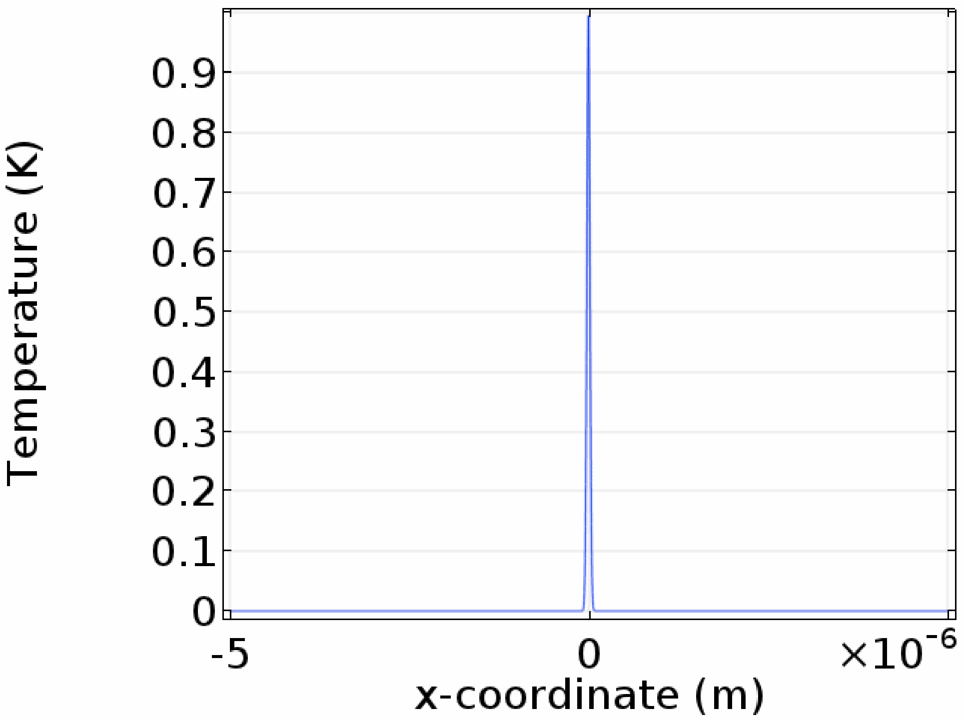


Memory effects / Second sound

Beardo et al.
Sci. Adv. 7, eabg4677 (2021)

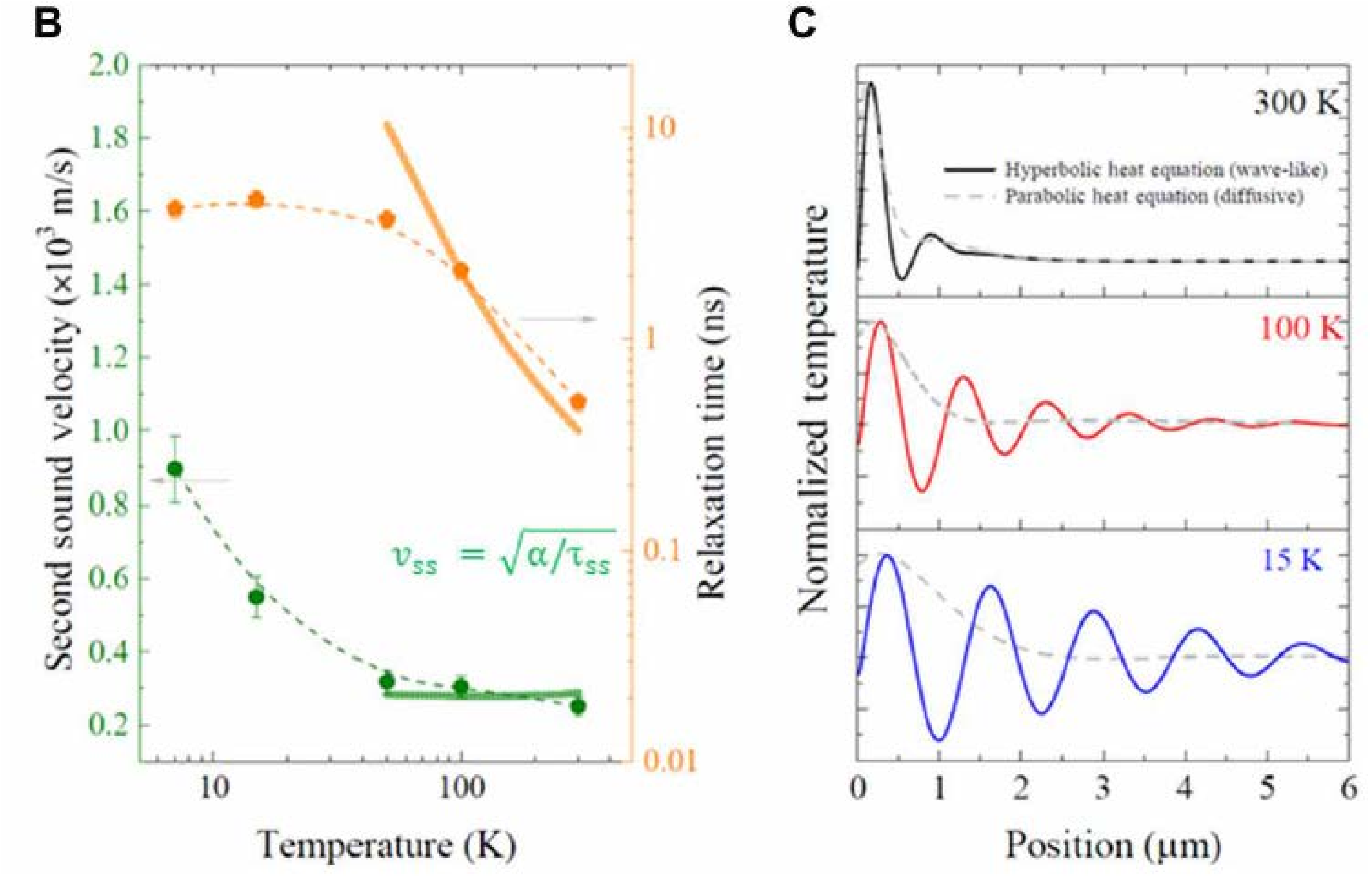


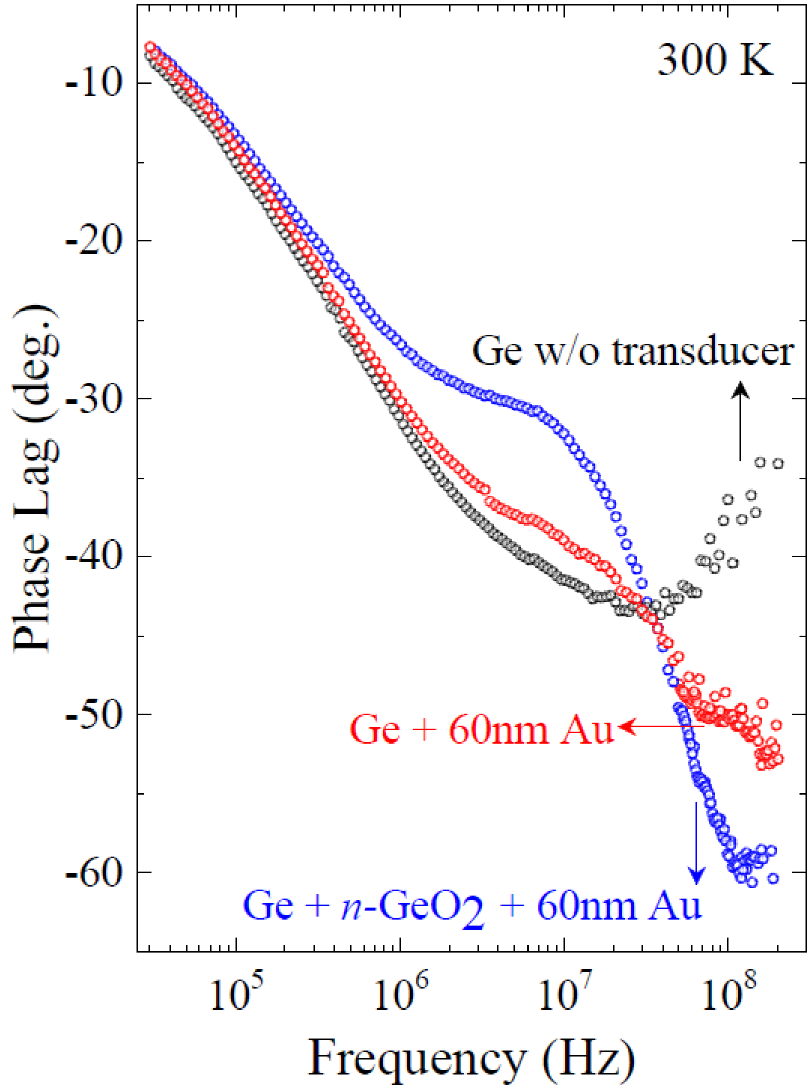
$$\tau \frac{\partial q}{\partial t} + q = -\kappa \nabla T + \ell^2 (\nabla^2 q + \alpha \nabla (\nabla \cdot q))$$



Memory effects / Second sound

Beardo et al.
Sci. Adv. 7, eabg4677 (2021)





Universitat Autònoma de Barcelona

Conclusions

My approach is fundamental

I'm pure

He's a phenomenological approach

He's a wrong approximation to the field

Conclusions

H and S approaches are connected!

Universitat Autònoma de Barcelona

Conclusions

- Combination of **Guyer and Krumhansl** equation with **ab-initio Kinetic Collective Model** for the transport properties allows the prediction of a large set of experiments

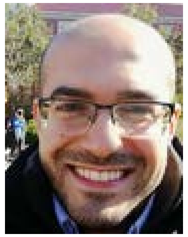
- The possibility to solve this model in a **Finite Element (COMSOL)** allows the direct comparison with any experimental setup despite its geometrical complexity

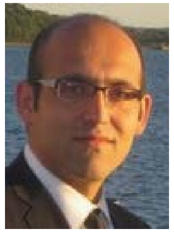
- The large set of experimental data on silicon explained by GK with a single abinitio set of parameters is an evidence in favor of a **hydrodynamic regime** in silicon

Thank you

THERMOREFLECTANCE IMAGING

PURDUE UNIVERSITY


Sami Alajlouni

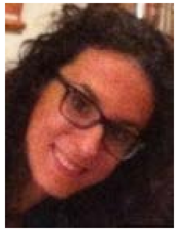

Amirkoushyar Ziabari


Ali Shakouri

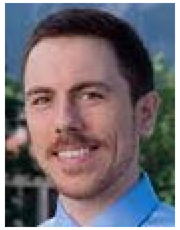
EUV SCATTEROMETRY SETUP

University of Colorado Boulder


Margaret Murnane


Begoña Abad


Joshua L. Knobloch


Travis Frazer


Brendan McBennett

FDTR SETUP

ICMAB


Sebastian Reparaz

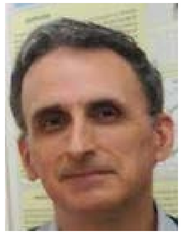

Riccardo Rurali

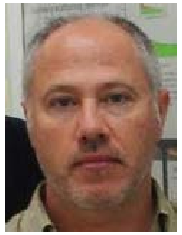
GK-KCM MODEL

UAB
Universitat Autònoma de Barcelona


Lluc Sendra


Albert Beardo


Javier Bafaluy


Juan Camacho

ELEPHONT
GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMIA Y COMPETITIVIDAD
UNIÓN EUROPEA
Fondo Europeo de Desarrollo Regional
"Una manera de hacer Europa"