All-optical time-resolved nanocalorimetry

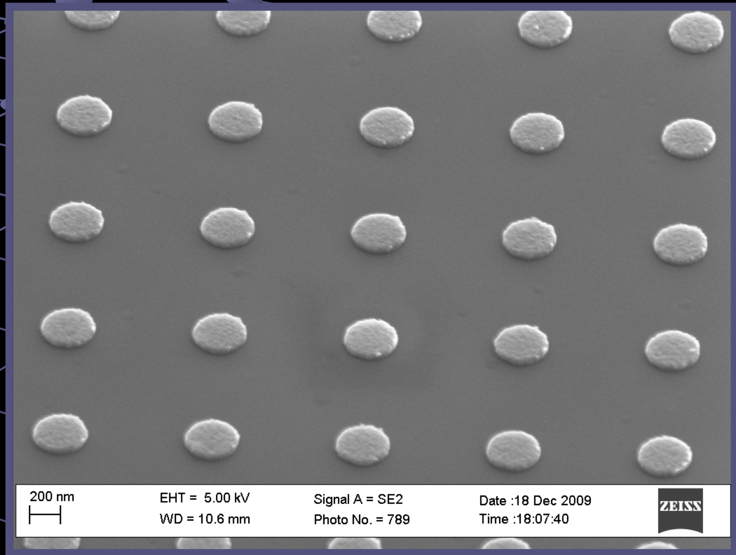
Francesco Banfi

francesco.banfi@dmf.unicatt.it
www.dmf.unicatt.it/elphos

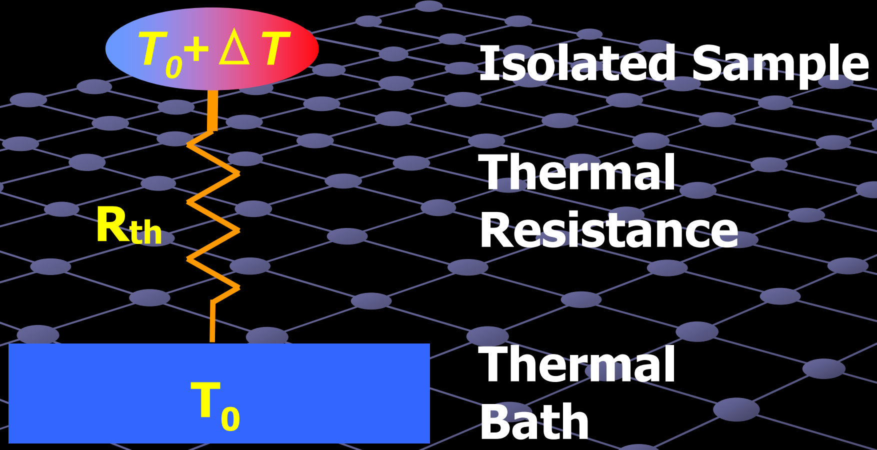
Università Cattolica del Sacro Cuore
Dipartimento di Matematica e Fisica, Via dei Musei 41, Brescia, Italy

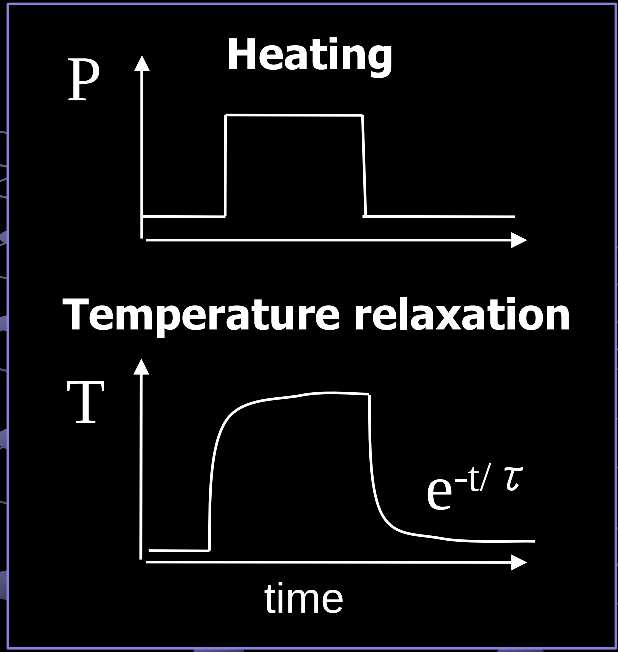
OUTLINE

- **The technique**
- Temperature dynamics
- Conclusions



STANDARD CALORIMETRY: TIME RELAXATION





$$\Delta T(t)=\Delta T_0\, e^{-t/\tau}$$
$$\tau = m\, C_m R_{th}$$

→ provided $Bi=l/k\rho_{th} << 1$

NANOCALORIMETRY: DIMENSIONS MATTER

$$\tau = m\, C_m\, R_{th}$$

Sample downsizing

↓

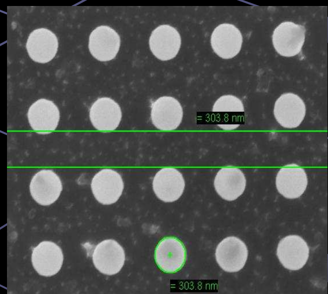
- Fast probe
- Non-perturbing probe

↓

All-optical time-resolved calorimetry

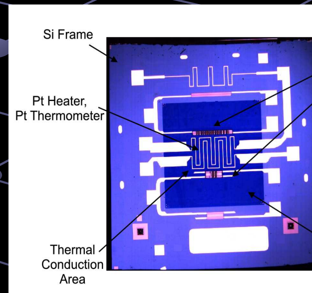
Sample mass ↑

m ~ 10^{-15} g
τ ~ 0.1 ns-10 ns



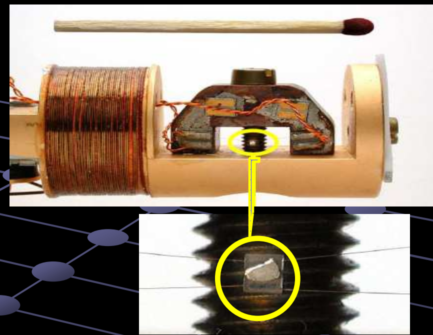
Today

m ~ 1 μg
τ ~ 1 ms-10 s



Hellmann 1993

m > 50 μg
τ ~ 0.1-100 s



Corbino 1910

Relaxation time →

ALL-OPTICAL TIME RESOLVED TECHNIQUES

- Time-resolved thermoreflectance

  R. J. Stoner and and H. J. Maris, *Phys. Rev. B* **48**, 16373 (1993)
  G. Cahill et al., J. Appl. Phys. **93**, 793 (2003)

- Time-resolved spatial modulation spectroscopy

  O. L. Muskens, N. D. Fatti, and F. Vallée, *Nano Lett.* **6**, 552 (2006)

- Time-resolved X-ray diffraction

  A. Plech et al., *IBM J. Res. Dev.* **61,** 762 (2003)
  A. Plech et al., *Chem. Phys.* **299**, 183 (2004)

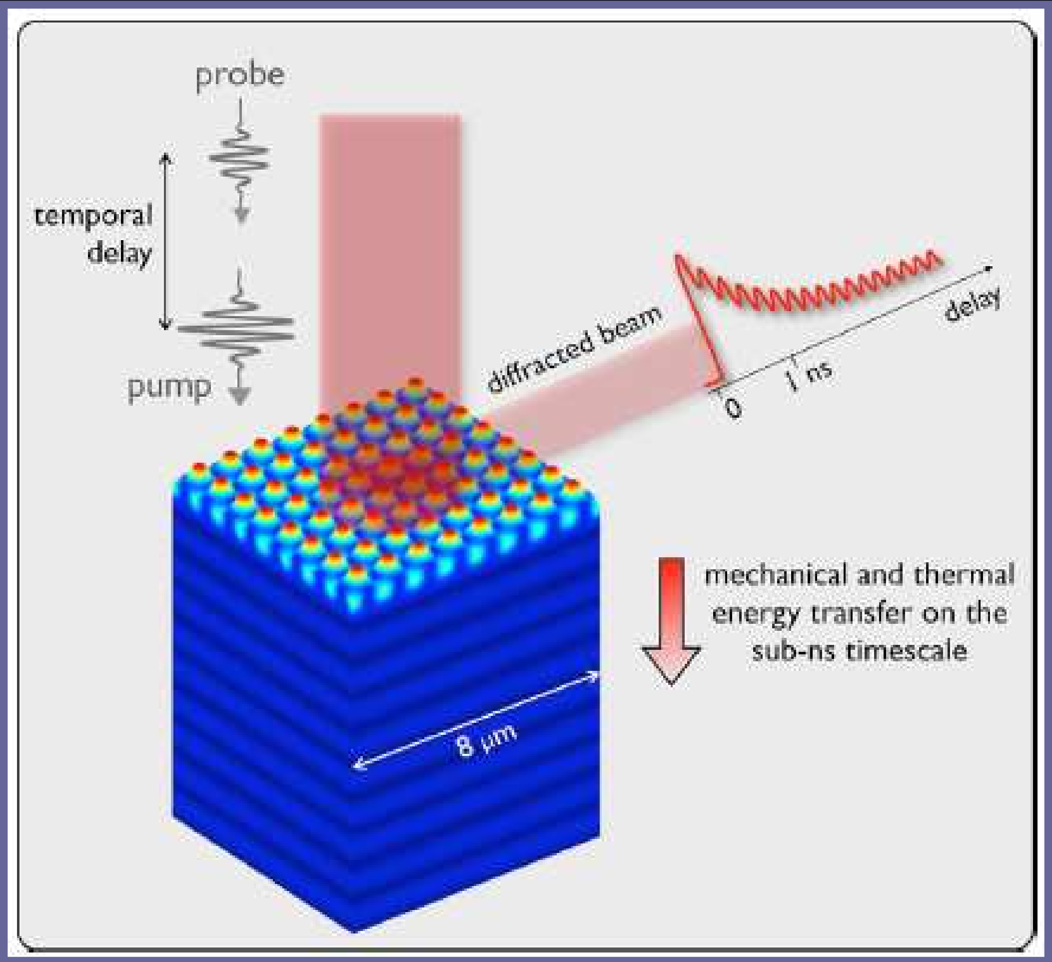
- Time-resolved EUV-diffraction

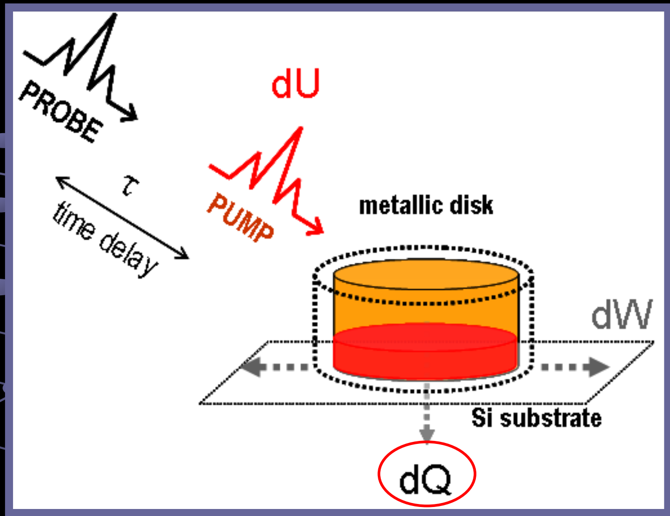
  R. I. Tobey et al., Appl. Phys. Lett. **85**, 584 (2004)

- **Time-resolved near-IR diffraction**

  C. Giannetti *et al., Phys. Rev. B* **76**, 125413 (2007)
  A. Comin *et al., Phys. Rev. Lett.* **97**, 217201 (2006)

ALL-OPTICAL TIME-RESOLVED NANOCALORIMETRY





$dQ/dW \approx 10^6$

Diffracted intensity variation

$$\frac{\delta I_{1D}}{I_{1D}} \approx 2.5 \frac{\delta a(t)}{a}$$

C. Giannetti et al., *IEEE Photonics J.* **1**, 20 (2009)

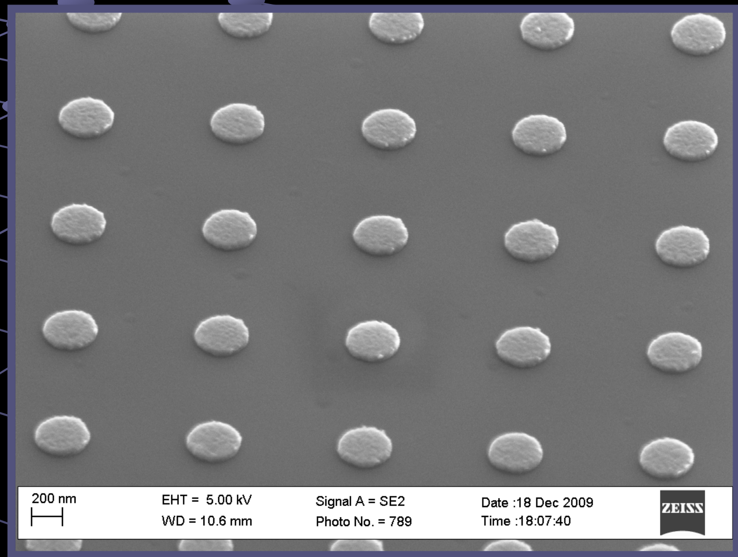
SCOPE

- **Is time-resolved all-optical nanocalorimetry applicable to low temperatures ?**

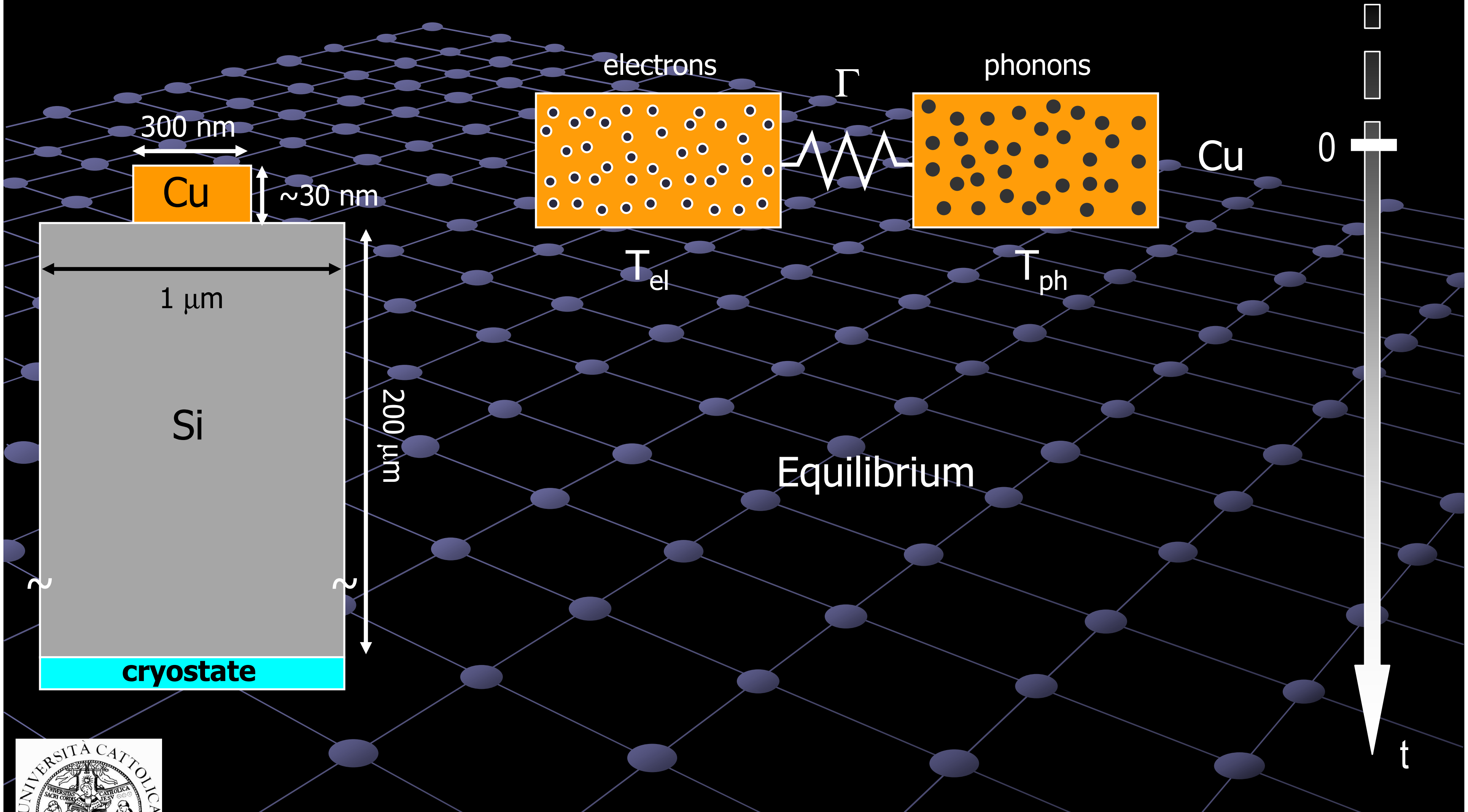
- **What can we learn from the temperature dynamics involved in the technique at low temperatures ?**

OUTLINE

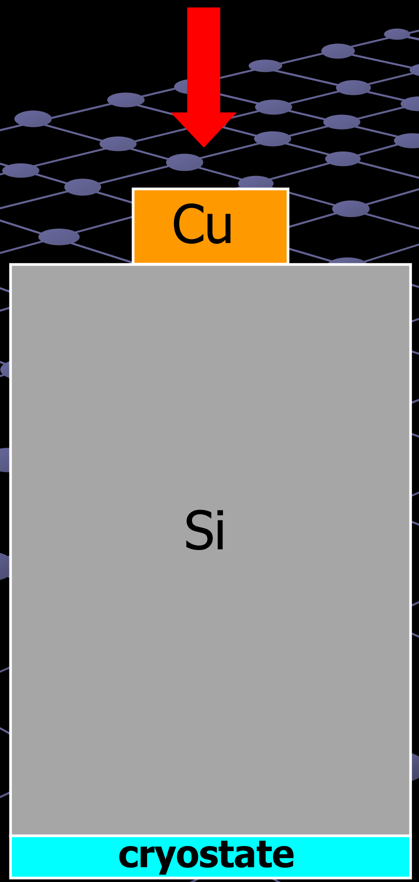
- The technique
- **Temperature dynamics**
- Conclusions

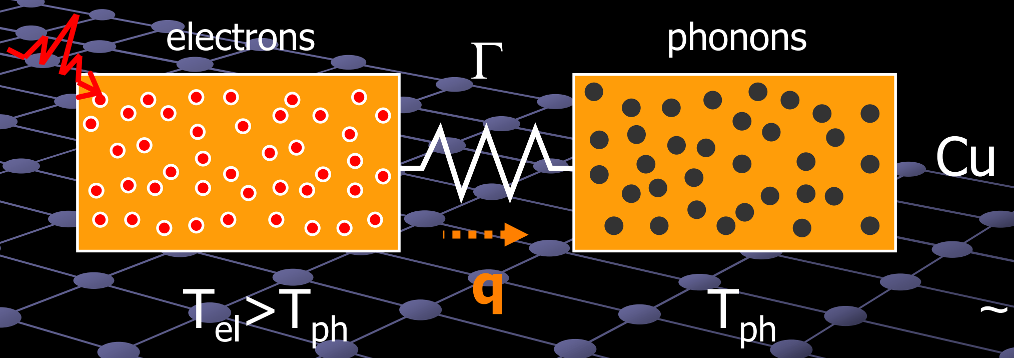


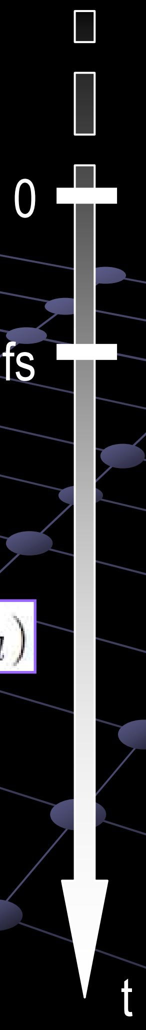
IMPULSIVE THERMAL DYNAMICS: TWO TEMPERATURE MODEL



IMPULSIVE THERMAL DYNAMICS: TWO TEMPERATURE MODEL







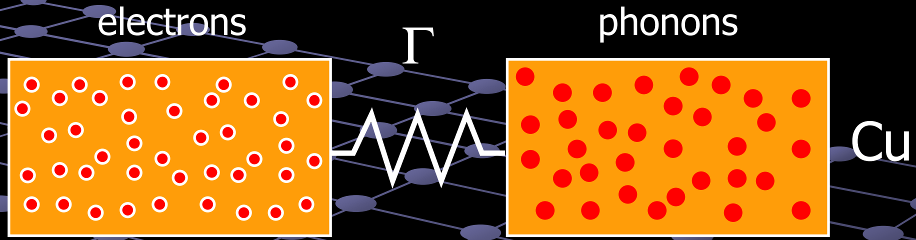
2TM *el-ph* inte… …ure

120 fs pulse @800 nm
1 nJ/pulse
Rep. rate 1MHz
40 μm FWHM

$C_{el}(T_{el})\partial_t T_{el} =$ … $(k_{el}(T_{el})\vec{\nabla}T_{el})$

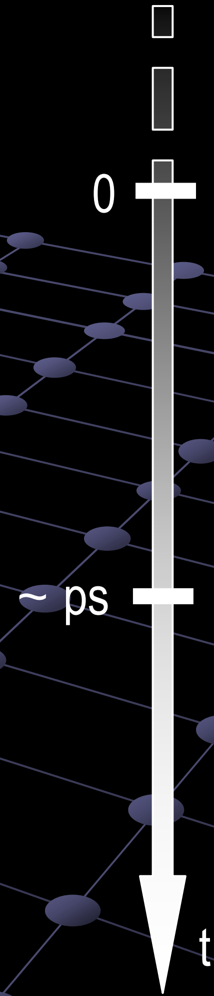
$C_{ph}(T_{ph})\partial_t T_{ph}$ … $_{ph})\vec{\nabla}T_{ph})$

IMPULSIVE THERMAL DYNAMICS: TWO TEMPERATURE MODEL

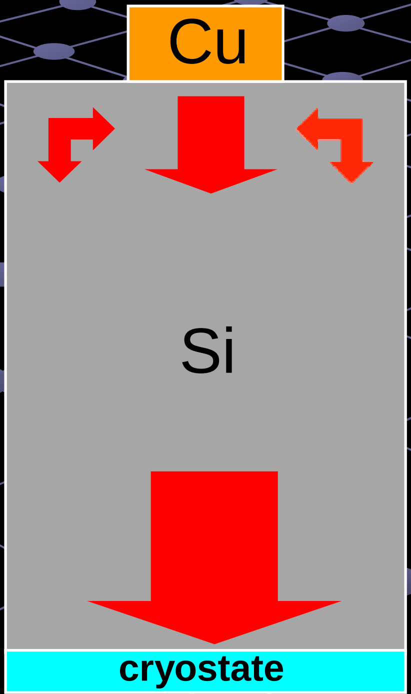


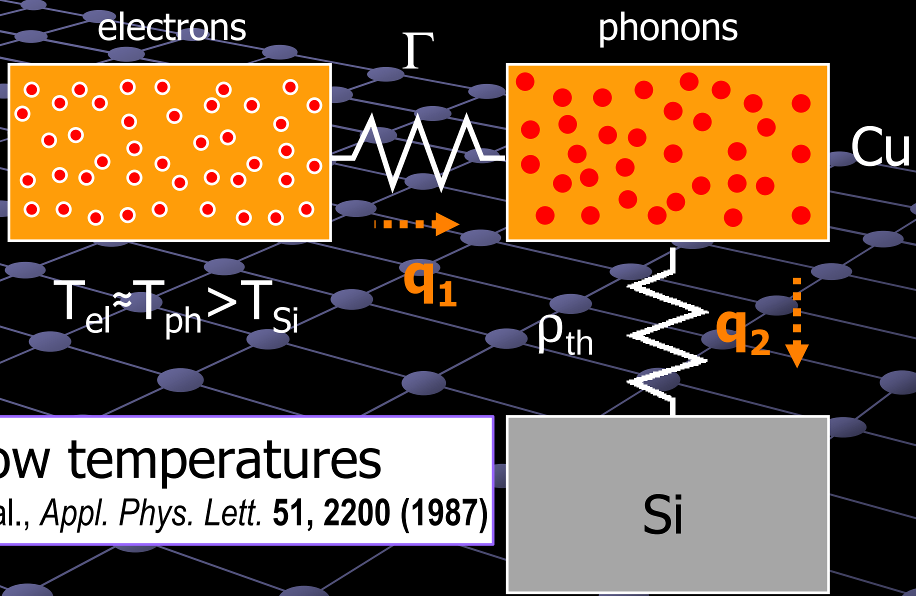
$T_{el}=T_{ph}>T_{Si}$

Isothermal nanostructure



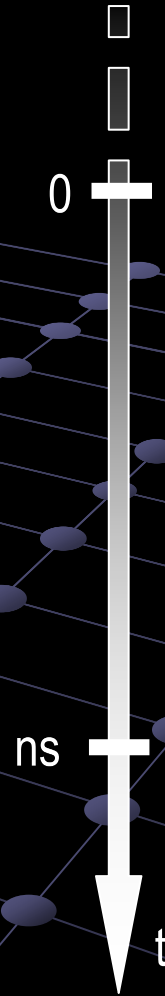
NANOSTRUCTURE-SUBSTRATE THERMALIZATION





AMM at low temperatures

E. D. Swartz et al., *Appl. Phys. Lett.* **51, 2200 (1987)**



Nanostructure-substrate thermalization

$$\widehat{n}_{ph} \cdot k_{ph} \vec{\nabla} T_{ph} + (T_{ph} - T_{Si})/\rho_{th}(T_{ph}) = 0$$

$$-\widehat{n}_{Si} \cdot k_{Si} \vec{\nabla} T_{pSi} - (T_{ph} - T_{Si})/\rho_{th}(T_{ph}) = 0$$

ELECTRON-PHONON INTERACTION TERM

Rate of energy exchange between electrons and phonons in the nanodisk

$$\Gamma = [I(T_{el}) - I(T_{ph})]/V$$

$$I(T) = 2\pi N_c N_{E_F} \int_0^\infty d\omega \alpha^2 F(\omega)(\hbar\omega)^2 n_{BE}(\omega, T)$$

$\alpha^2 F(\omega)$

Eliashberg function:

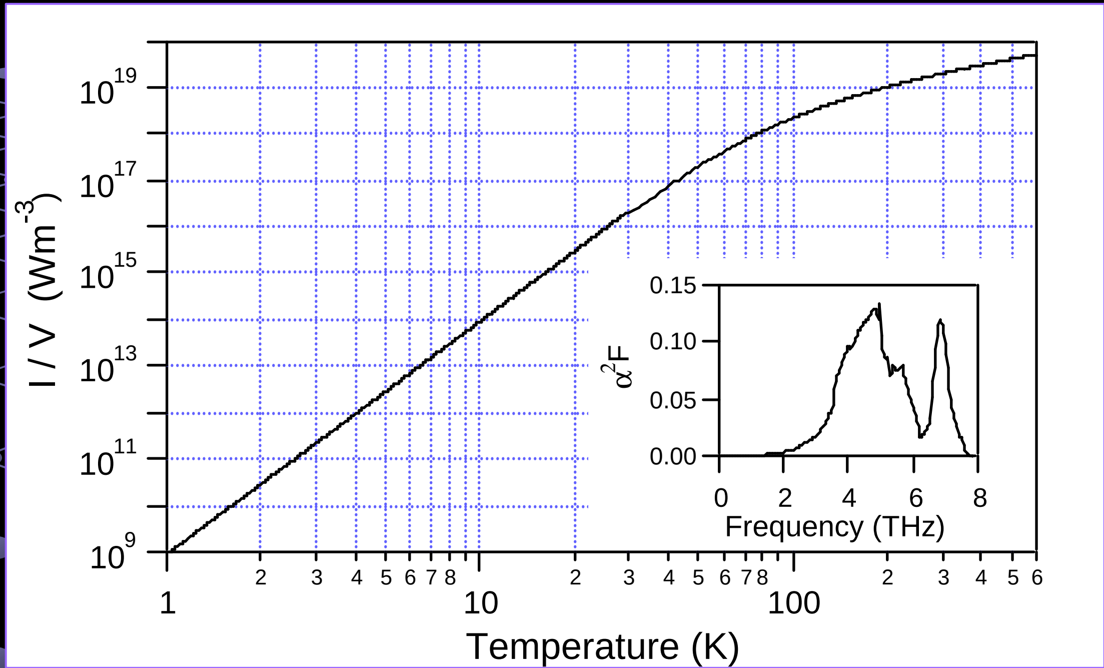
coupling between electrons and phonons

$n(\Omega, T_{e,ph})$

Bose-Einstein distribution

P. B. Allen, *Phys. Rev. Lett.* **59**, 1460 (1987)
Kaganov et al., *JETP*, **4**, 178 (1957)

ELECTRON-PHONON INTERACTION TERM

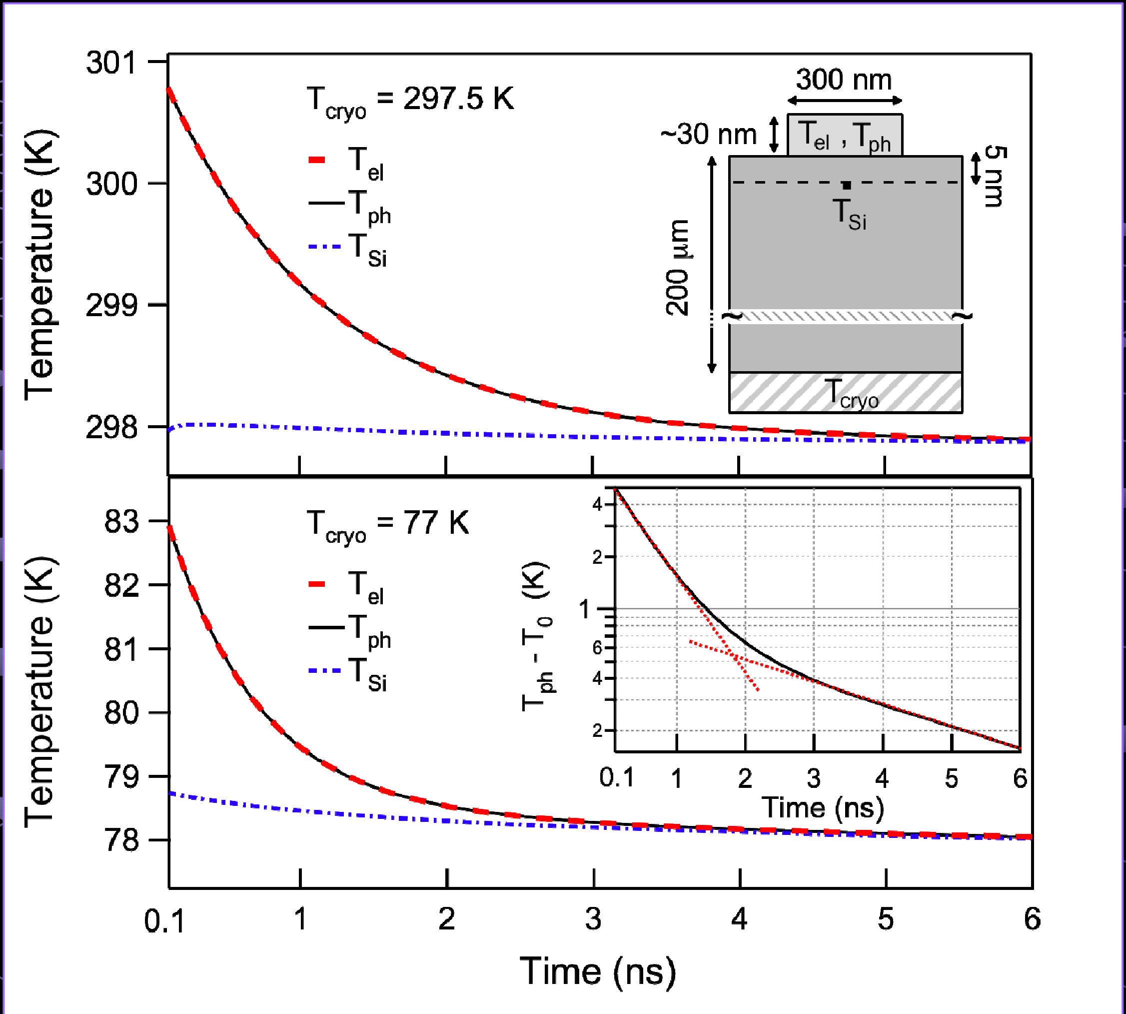


DFT calculations with PWscf code of Quantum ESPRESSO

$I(T)/V =$

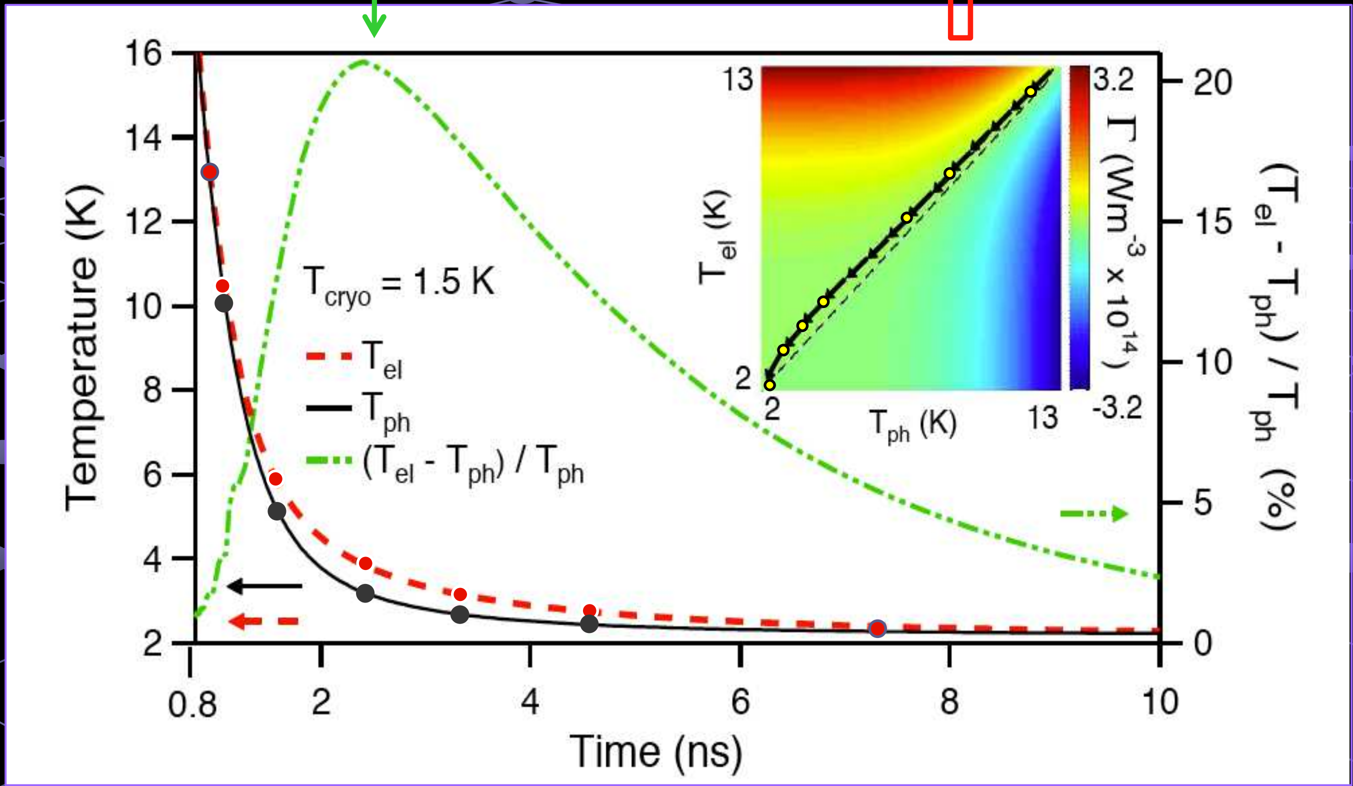
- $(\Sigma_0/V)\, T^5$ for $T \ll \theta_D$; $(\Sigma_0/V) = 2 \times 10^9$ W/Km^3
  in agreement with F. Giazotto et al., *Rev. Mod. Phys.* **78**, 217 (2006)
- $G\, T$ for $T \sim 300$ K ; $G = 8.43 \times 10^{16}$ W/Km^3
  in agreement with H. E. Elsayed Ali et al., *Phys. Rev. Lett.* **58**, 1212 (1987)

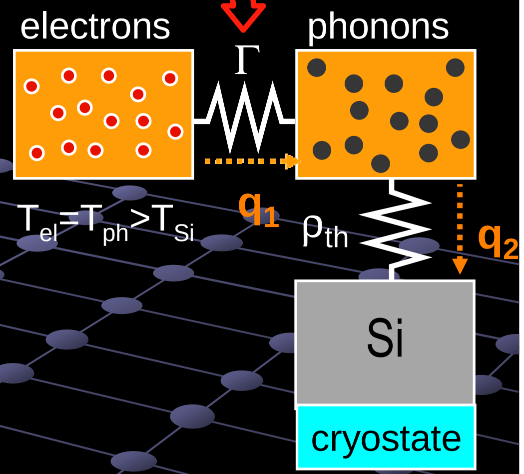
AMBIENT AND LIQUID NITROGEN TEMPERATURE



Max $\Delta T/T$ = 22%

NANOSECOND e-ph DECOUPLING





$q_2 > q_1$

F. Banfi et al., *Phys. Rev. B* **81**, 155426 (2010)

$T_{el} \neq T_{ph}$ ➡

- no calorimetry
- e-ph decoupling @10 K, at variance with transport measurement

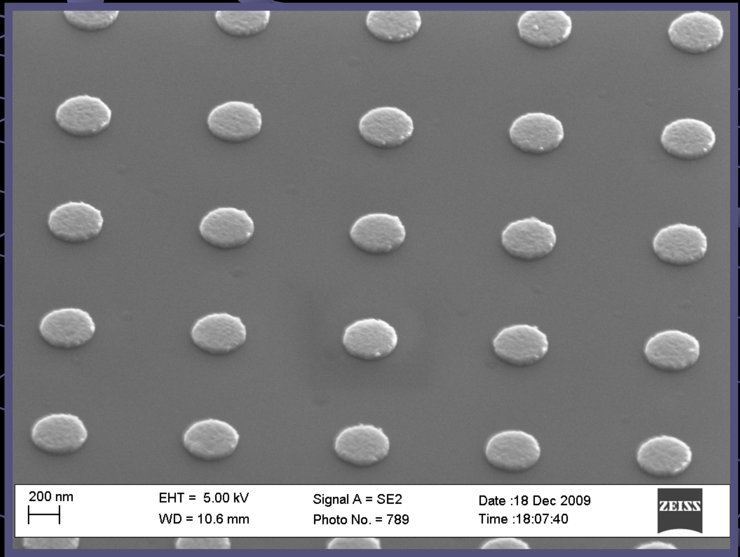
PERSPECTIVES

	Mesoscopic transport measurement	All-optical time-resolved nanocalorimetry
Decoupling temperature	100 mK	10 K
Time scale	> μ s	100 fs-10 ns

A new route for investigating electron phonon decoupling where the **sub-Kelvin temperature** requirement is substituted by the **ns time resolution**

OUTLINE

- The technique
- Temperature dynamics
- **Conclusions**



CONCLUSIONS

- **Is time-resolved all-optical nanocalorimetry applicable to low temperatures ?**
  - **Yes, down to 10 K**

- **What can we learn from the temperature dynamics involved in the technique at low temperatures ?**
  - **e-ph decoupling @10 K on the ns time scale**

- **Ultrafast optics group** (Università Cattolica del Sacro Cuore, Brescia)
  Federico Pressacco, Damiano Nardi, Claudio Giannetti, Gabriele Ferrini

- **Free Electron Laser@ELETTRA**
  Fulvio Parmigiani (Università degli Studi and FEL@Elettra, Trieste)

- **Microsystems group** (*École Polytechnique Fédérale de Lausanne, Lausanne)*
  Bernard Revaz

Thank you