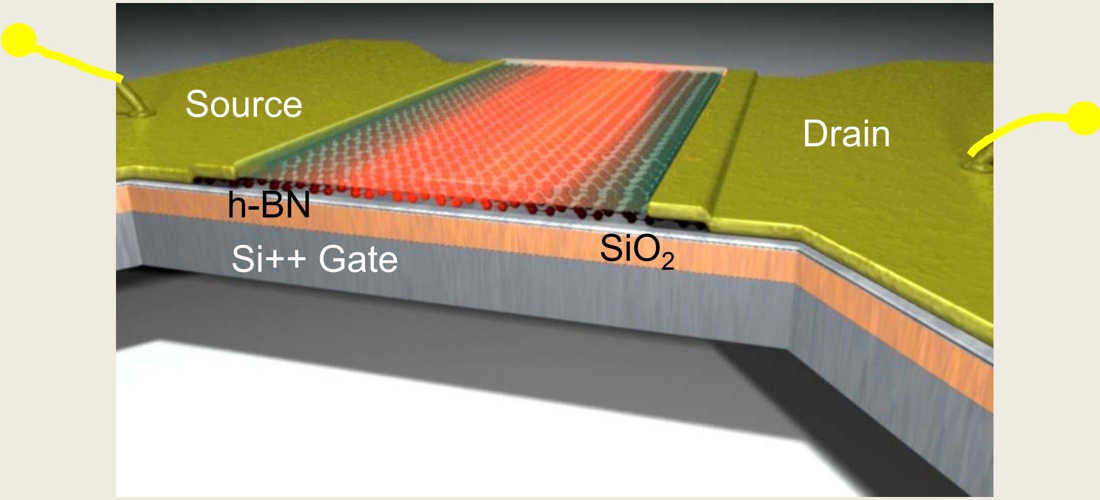
laboratoire pierre aigrain
électronique et photonique quantiques

Supercollision cooling of electrons in graphene



Meso-group : **A.C. Betz, E. Pallecchi, S-H. Jhang**, G. Fève, J-M. Berroir, B. Plaçais
Optic-group : D. Drunel, F. Vialla, C. Voisin, R. Ferreira

Laboratoire Pierre Aigrain – Ecole Normale Supérieure
24 rue Lhomond, 75231 Paris Cedex 05 France
www.lpa.ens.fr

Why studying cooling processes ?

1. Hot carriers affect resolution detectors

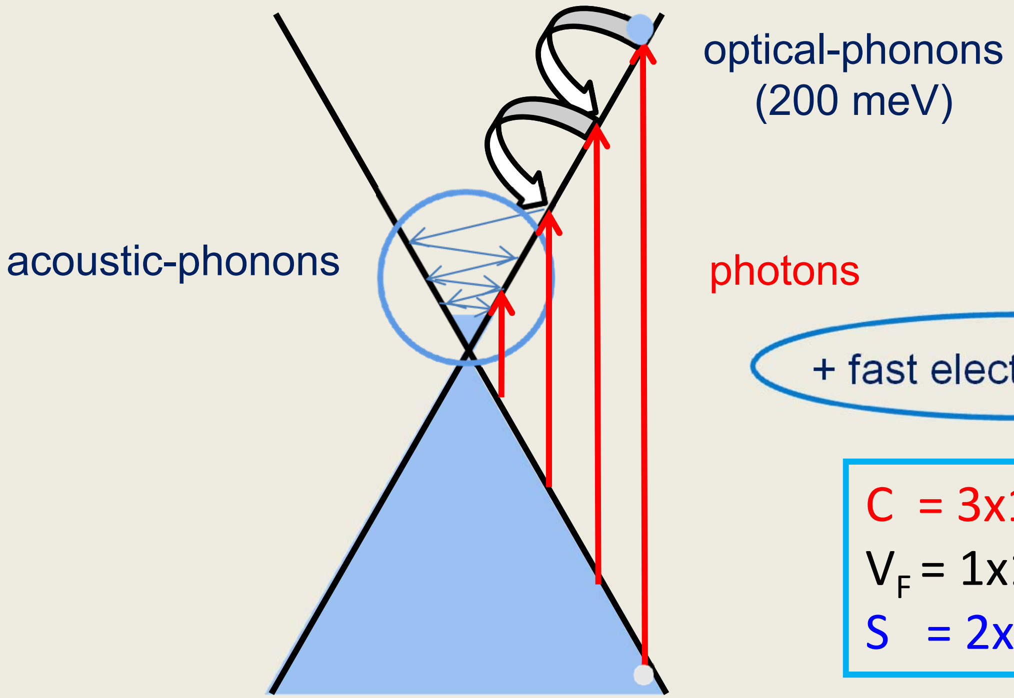
2. Can be useful as bolometers

3. Graphene → lab for electron-phonon physics

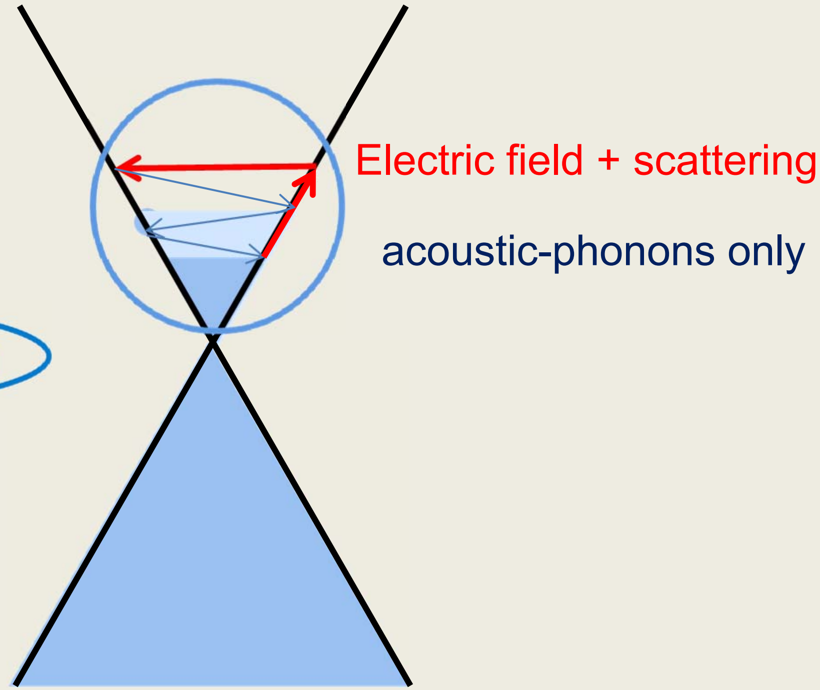
4. Acoustic phonon bottleneck

Acoustic phonon bottleneck

Optical absorption (2.3%)



Joule heating



+ fast electron-electron

$C = 3\text{x}10^8$ m/s
$V_F = 1\text{x}10^6$ m/s
$S = 2\text{x}10^4$ m/s

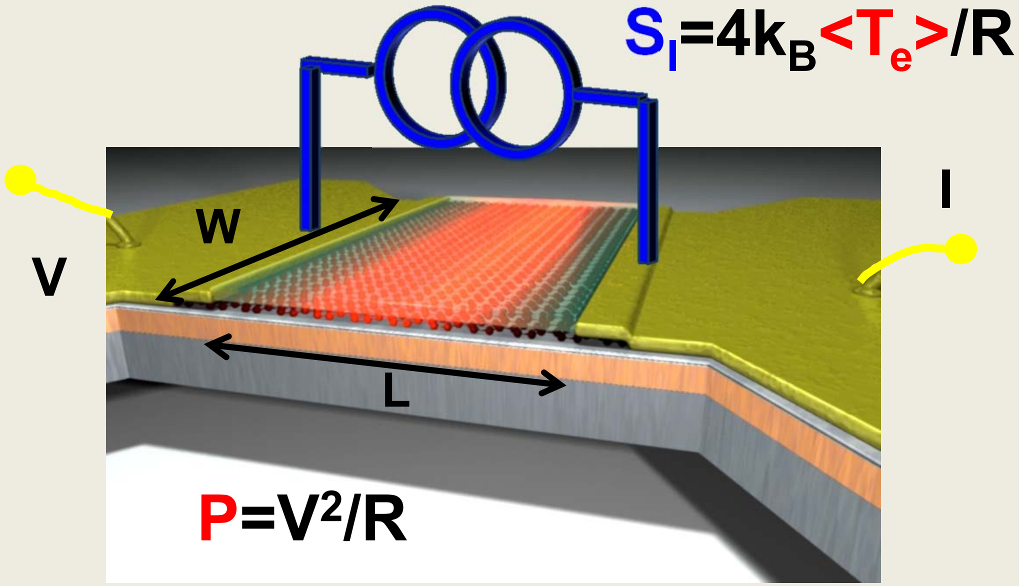
photo-current or pump-probe

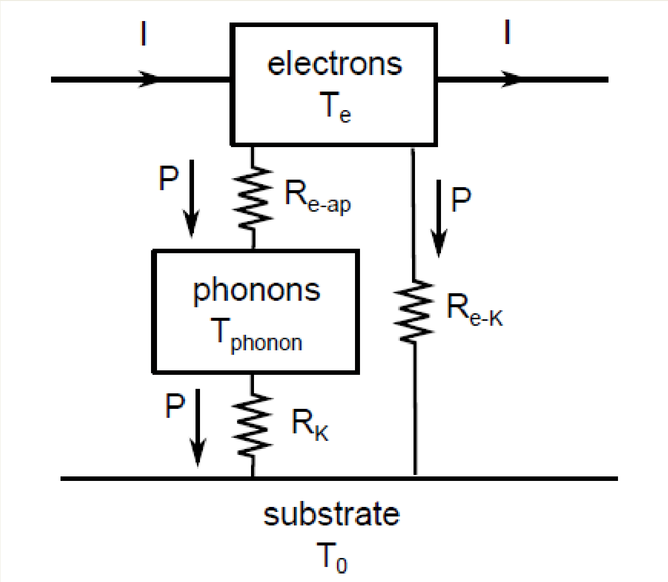
N.M. Gabor et al., Science 334 , 648 (2011)
S. Winnerl et al. PRL 107, 237401 (2011)
J. Yan et al., nnano 7, 472 (2012)
M. Freitag et al., nphoto 453 (2013)
M.W. Graham et al., nphys 19, 103 (2013)

noise thermometry (this work)

F. Wu et al. , APL 97, 262115 (2010) (nanotube)
A. Fay et al., PRB 84, 245427 (2011) (Bilayer)
K.C. Fong, K. C. Schwab, PRX, 031006 (2012)
A.C. Betz et al., PRL 109, 056805 (2012)
A.C. Betz, et al. nphys 19, 109 (2013)

noise thermometry

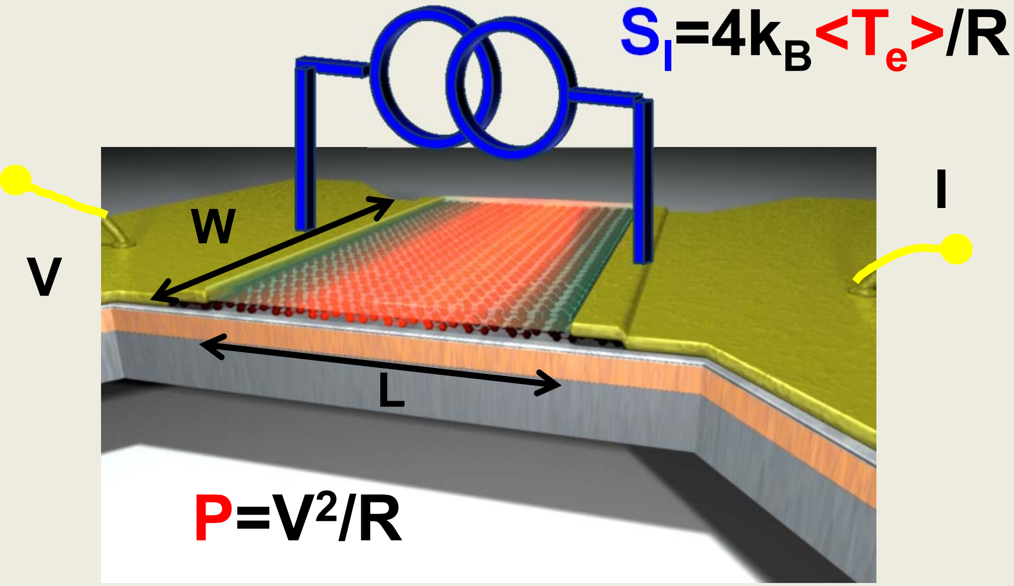




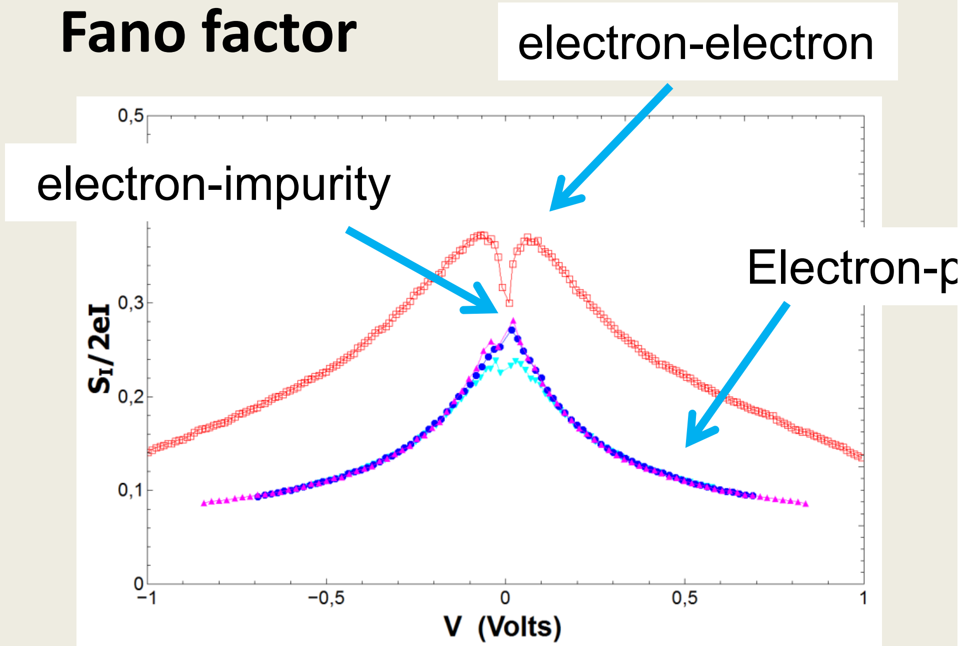
$$\gamma T_e \cancel{\frac{\partial T_e(x)}{\partial t}} - \frac{L}{2RW}\left(\frac{\pi^2 k_B^2}{3e^2}\right)\frac{\partial^2 T_e^2(x)}{\partial x^2} = \frac{V^2}{RLW} - P(T_e, T_{ph})$$

Steady state **Heat conduction** **Joule heating** **phonon $P=T^{\alpha}$**

noise thermometry



Fano factor



$$\cancel{\gamma T_e \frac{\partial T_e(x)}{\partial t}} - \frac{L}{2RW}\left(\frac{\pi^2 k_B^2}{3e^2}\right)\frac{\partial^2 T_e^2(x)}{\partial x^2} = \frac{V^2}{RLW} - P(T_e, T_{ph})$$

Steady state **Heat conduction** **Joule heating** **phonon $P=T^{\alpha}$**

α=5 in 3D metals *(Wellstood, Urbina, Clarke, PRB 1994)*
α=3 in 1D CNTs *(Wu, …, Hakonen, APL 2010)*
α=d+2 => α=4 in 2D graphene ???

Outline

1. Introduction : the Bloch-Grüneisen phonon resistivity

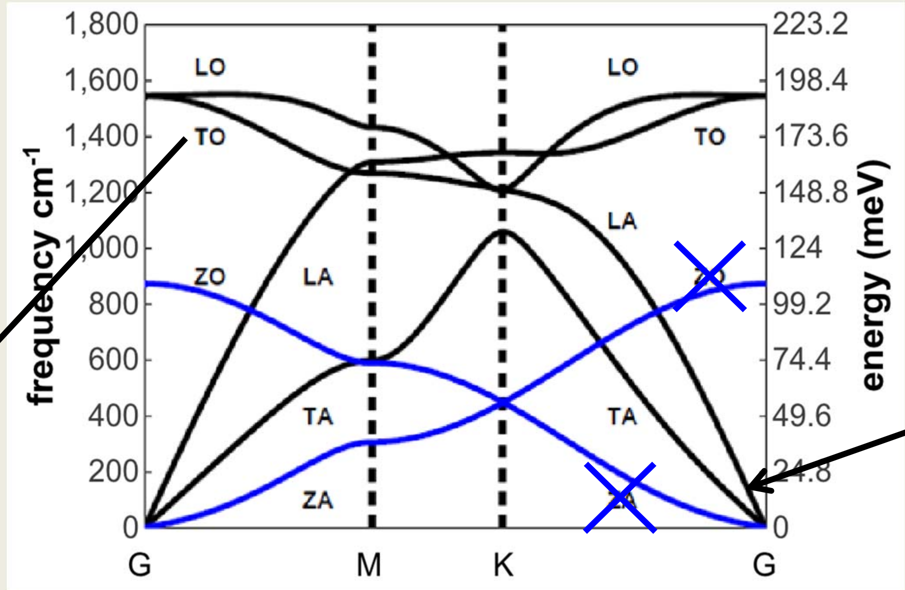
2. Relaxation by acoustic phonons

   Betz et al., PRL 109, 056805 (2012).

3. Disorder assisted relaxation : supercollisions

   Betz et al., Nature Physics 9, 109 (2013)

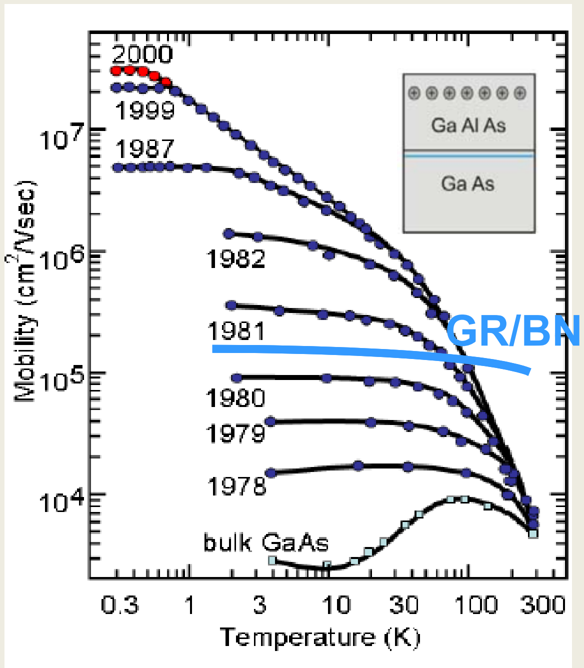
Phonon resistivity



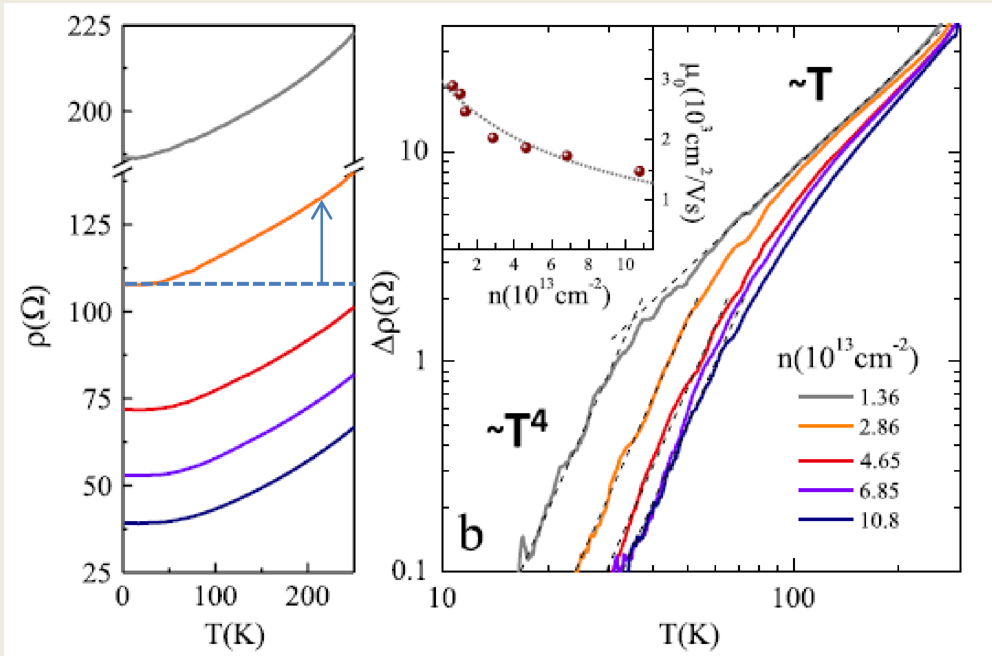
large AC-phonons velocity ($s = 2x10^4$ m/s)

OP-phonons irrelevant

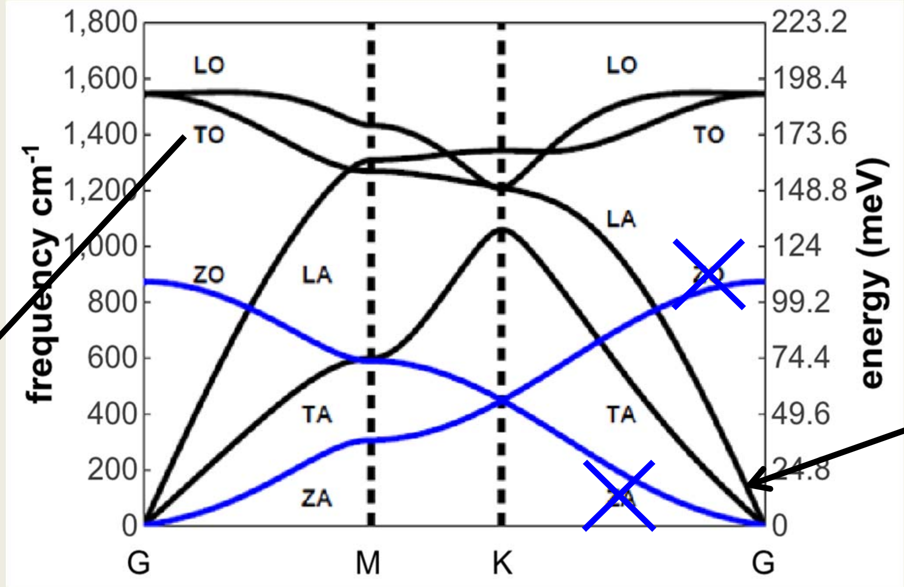
Chen-Fuhrer., Nat. Nano 2008
Efetov-Kim PRL 2010



weak AC-phonons effect



Phonon resistivity in (2D) graphene



OP-phonons irrelevant

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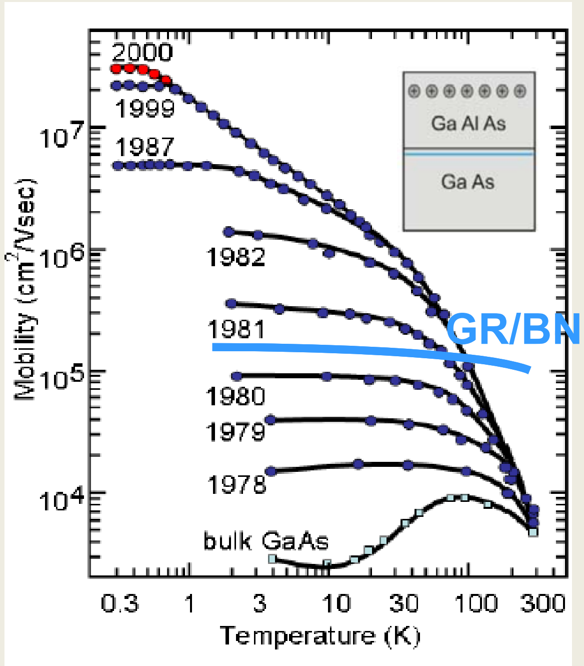
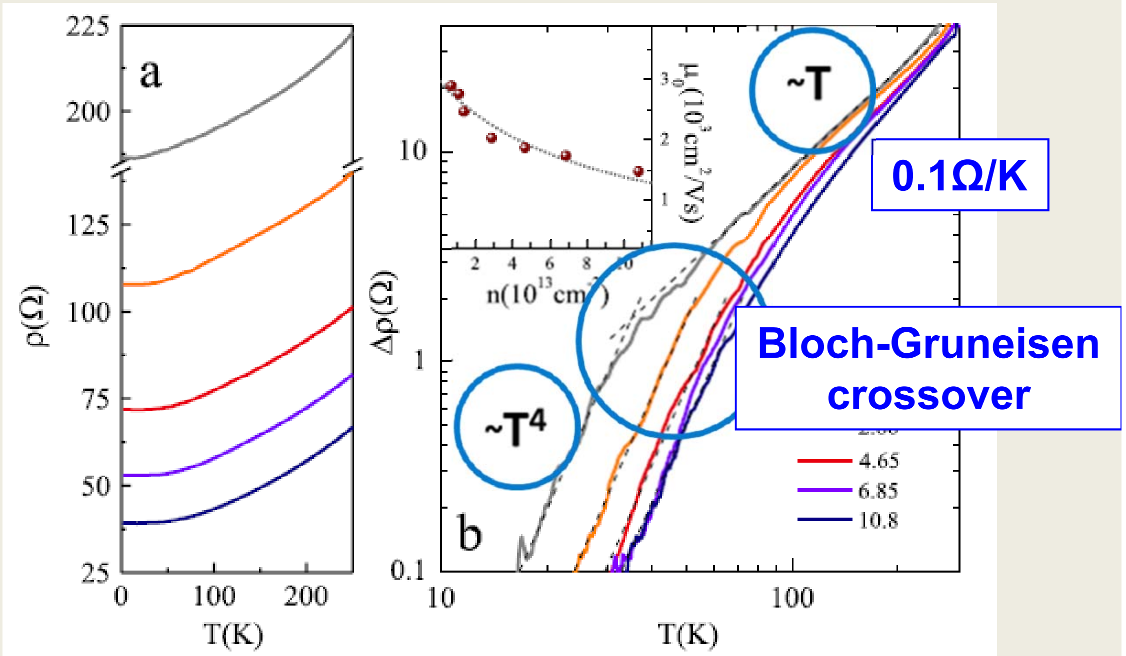
Chen-Fuhrer., Nat. Nano 2008
Efetov-Kim PRL 2010

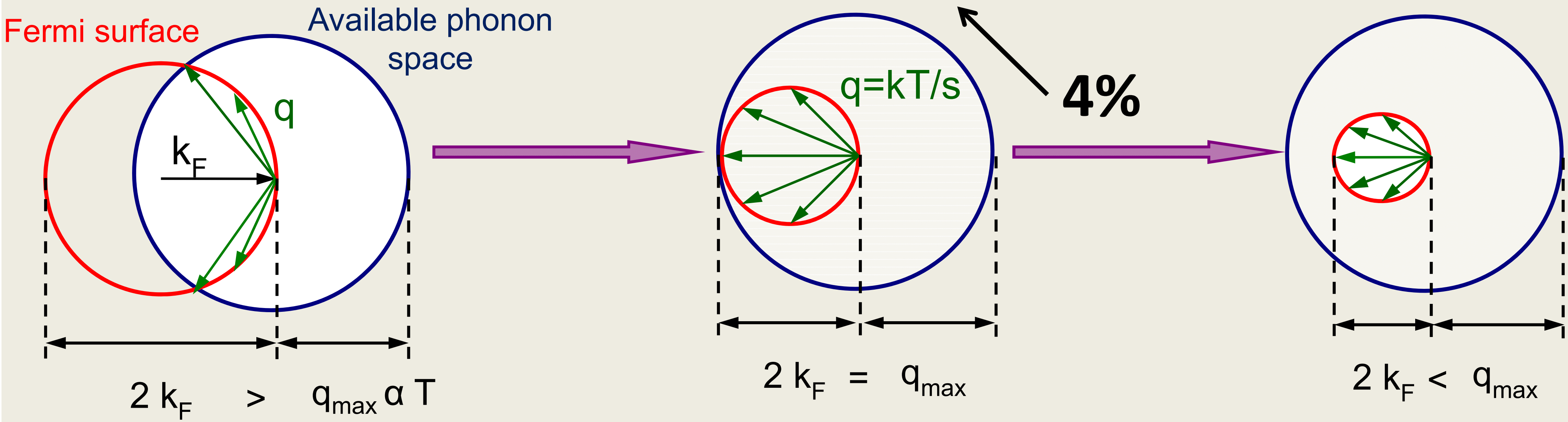


AC-phonons weak effect



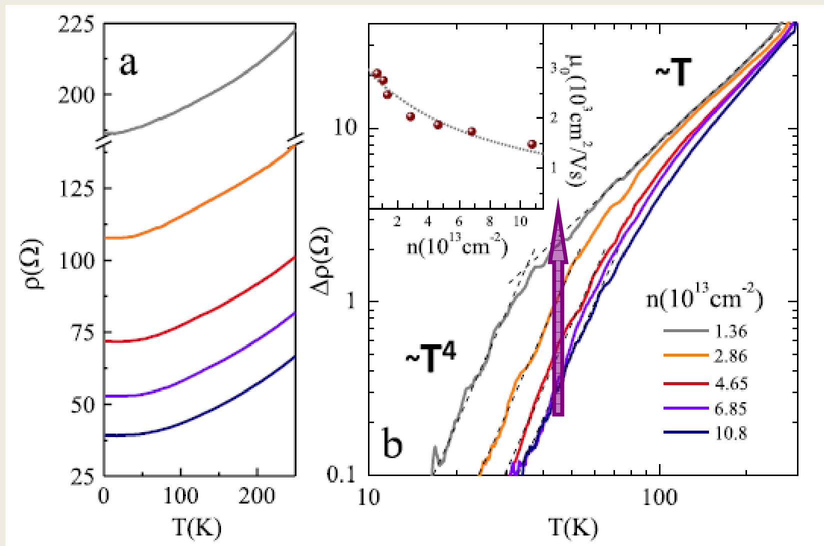
The Bloch-Grüneisen crossover

$T < T_{BG}$ (cold) — **$T = T_{BG} = (2s/V_F)T_F$** — **$T > T_{BG}$ (hot)**



$$\Delta\rho(T) = \frac{8D^2 k_F}{e^2\rho_m s V_F^2} \times f_s\left(\frac{T_{BG}}{T}\right)$$

(Hwang-Das-Sarma PRB2008)



(Efetov-Kim PRL2010)

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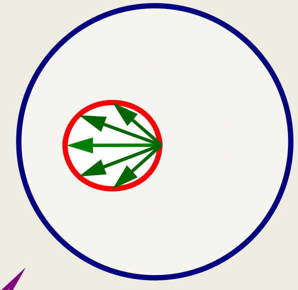
   Betz et al., Nature Physics 9, 109 (2013)

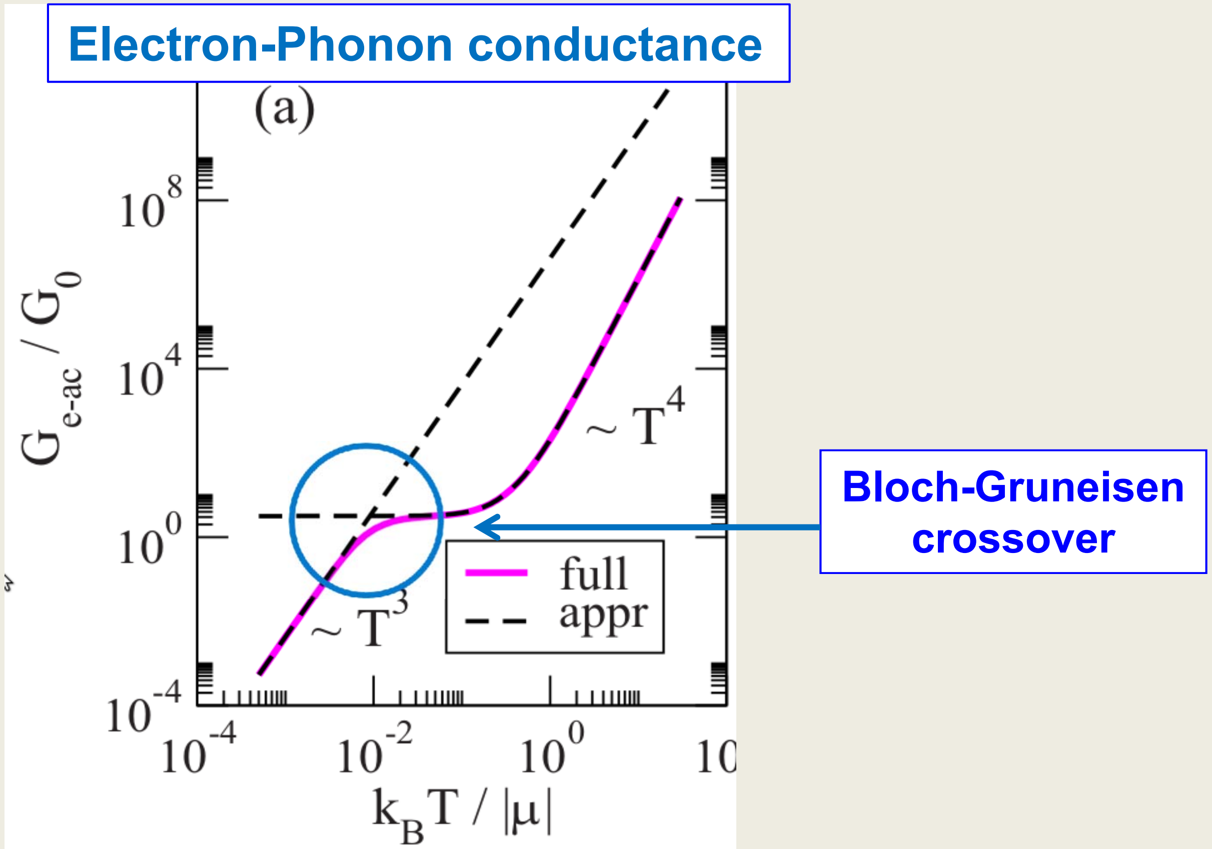
acoustic-phonon cooling (theory)

T > T_{BG} (hot phonons)

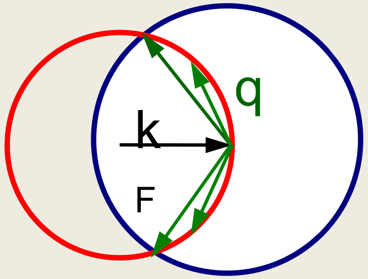
$$P(T \gg \theta_{BG}) = G_o \Delta T$$



(non-degenerate electrons)



T < T_{BG} (cold phonons)



$$P(T \ll \theta_{BG}) = \Sigma \Delta T^4$$

(Viljas-Heikkila PRB 2010)

AC-phonon cooling (principles)

phonon cooling power

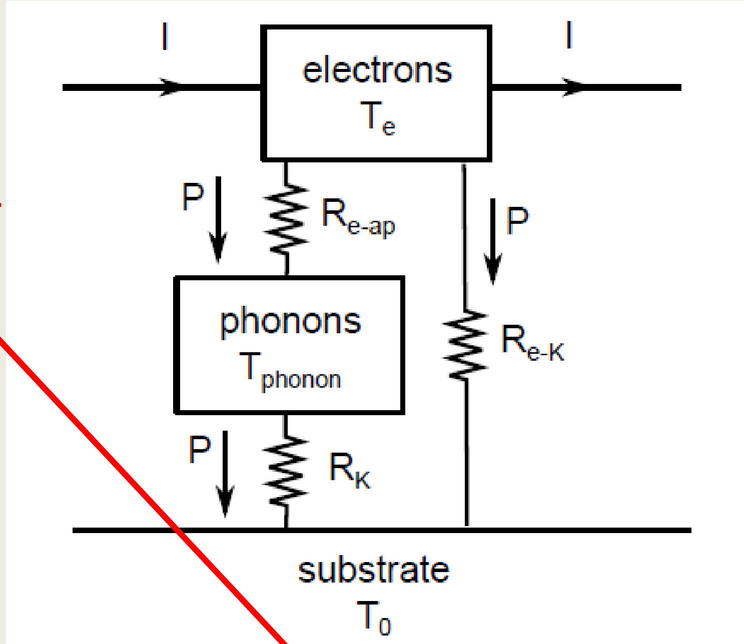
phonon thermal conductance

$$G = 4\Sigma T^3$$

Σ_{ph} ~10 mW/m²/K⁴

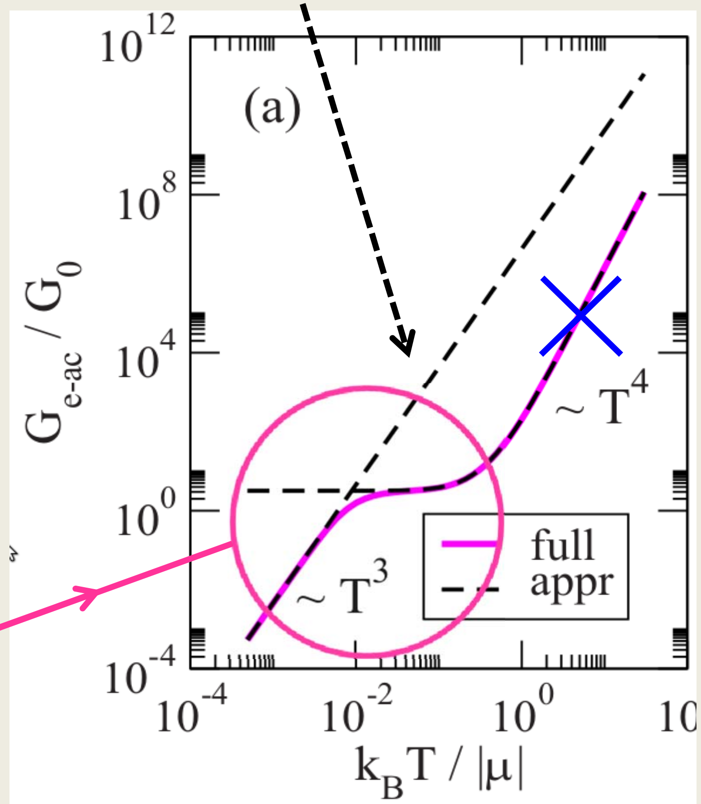
Kapitza

Σ_K ~ 10 W/m²/K⁴



$$P(T \ll \theta_{BG}) = \Sigma \Delta T^4 = \frac{\pi^2 D^2 k_B^4 |\mu|}{15 \rho_m \hbar^5 s^3 v_F^3} \times (T_e^4 - \cancel{T_{ph}^4})$$

$$P(T \gg \theta_{BG}) = G_o \Delta T = \frac{D^2 k_B |\mu|^4}{2\pi \rho_m \hbar^5 v_F^6} \times (T_e - \cancel{T_{ph}})$$



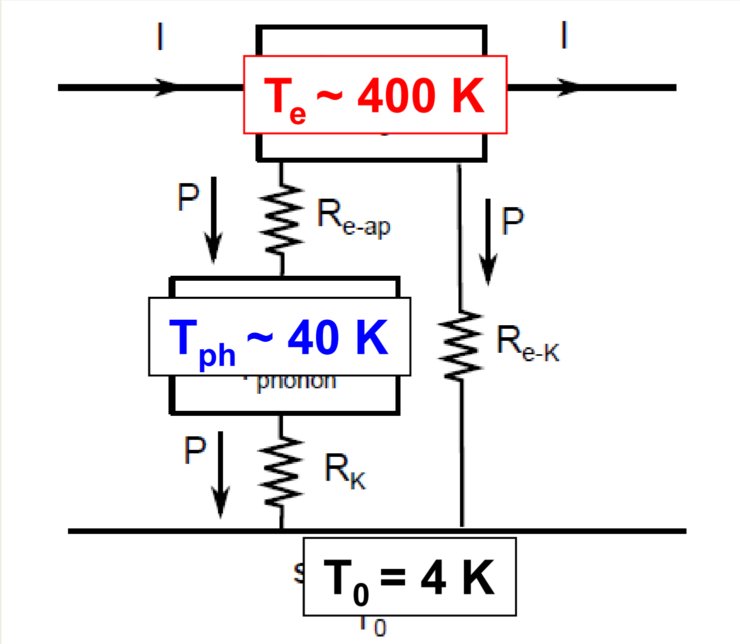
AC-phonon cooling (practicals)

phonon cooling power **phonon thermal conductance**

P ~100 μW/μm²

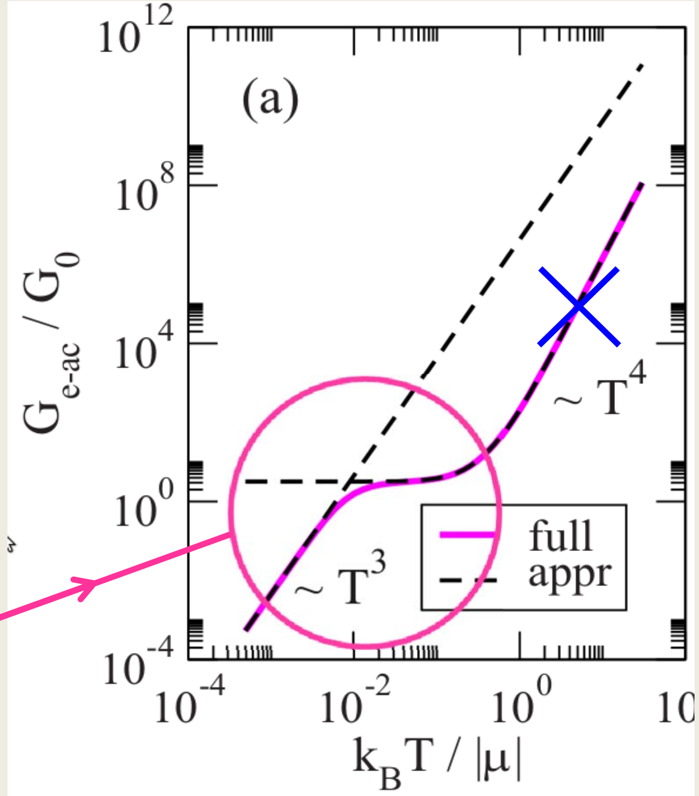
Σ_{ph} ~10 mW/m²/K⁴

Kapitza
Σ_K ~ 10 W/m²/K⁴



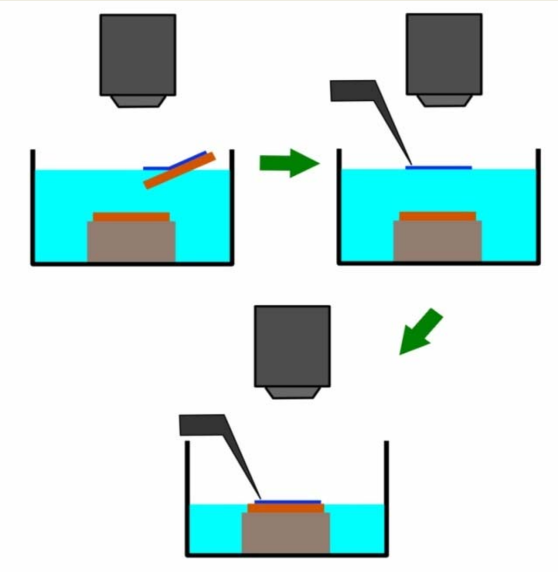
$$P(T \ll \theta_{BG}) = \Sigma \Delta T^4 = \frac{\pi^2 D^2 k_B^4 |\mu|}{15 \rho_m \hbar^5 s^3 v_F^3} \times (T_e^4 - \cancel{T_{ph}^4})$$

$$P(T \gg \theta_{BG}) = G_o \Delta T = \frac{D^2 k_B |\mu|^4}{2\pi \rho_m \hbar^5 v_F^6} \times (T_e - \cancel{T_{ph}})$$

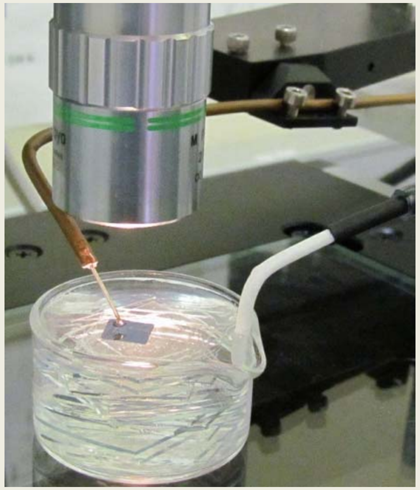


Device fabrication

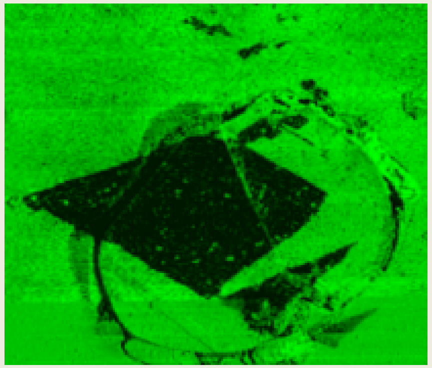
Gr/BN (diffusive)

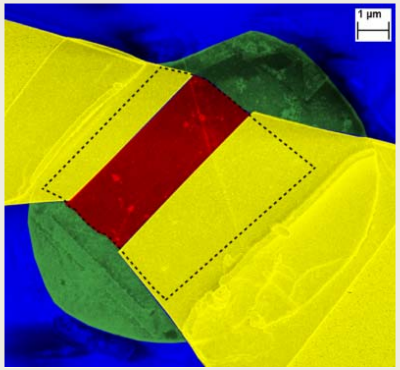


Mitutoyo



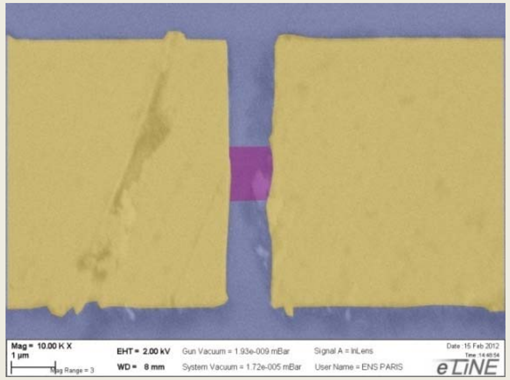
Wedging transfer: polymer CAB & water



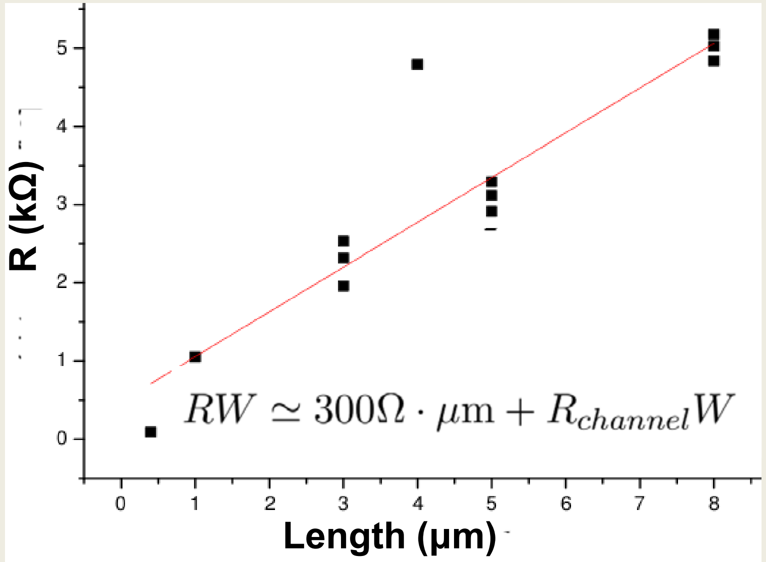


Schneider et al., Nano Letters ***2010*** *10 (5)*

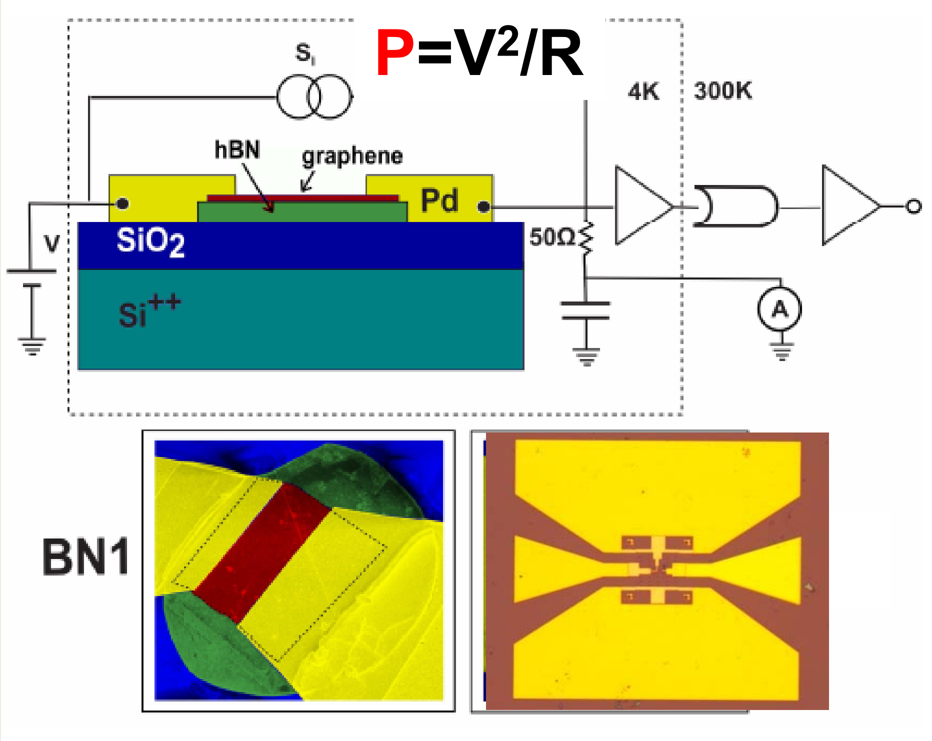
CVD (doped and diffusive)

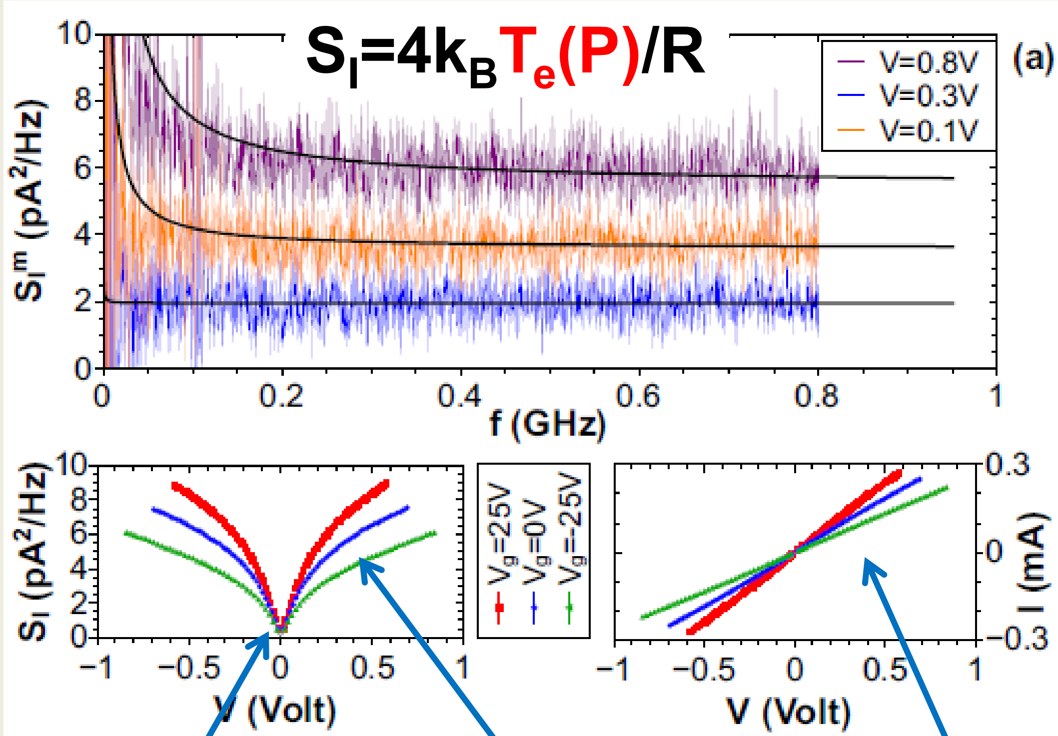


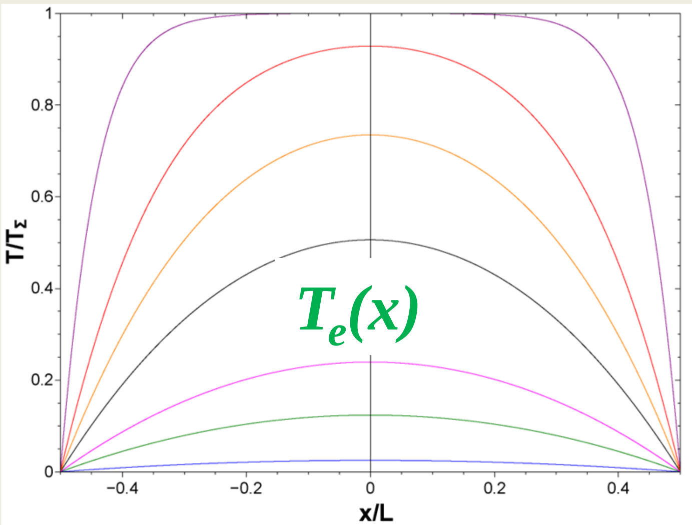
CVD grown on Cu (A. Madouri, LPN)



Noise thermometry







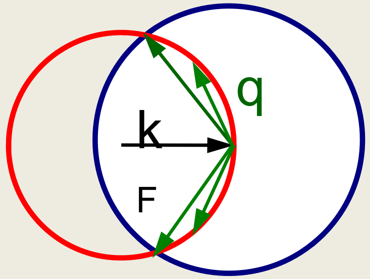
linear **sub-linear** **linear**

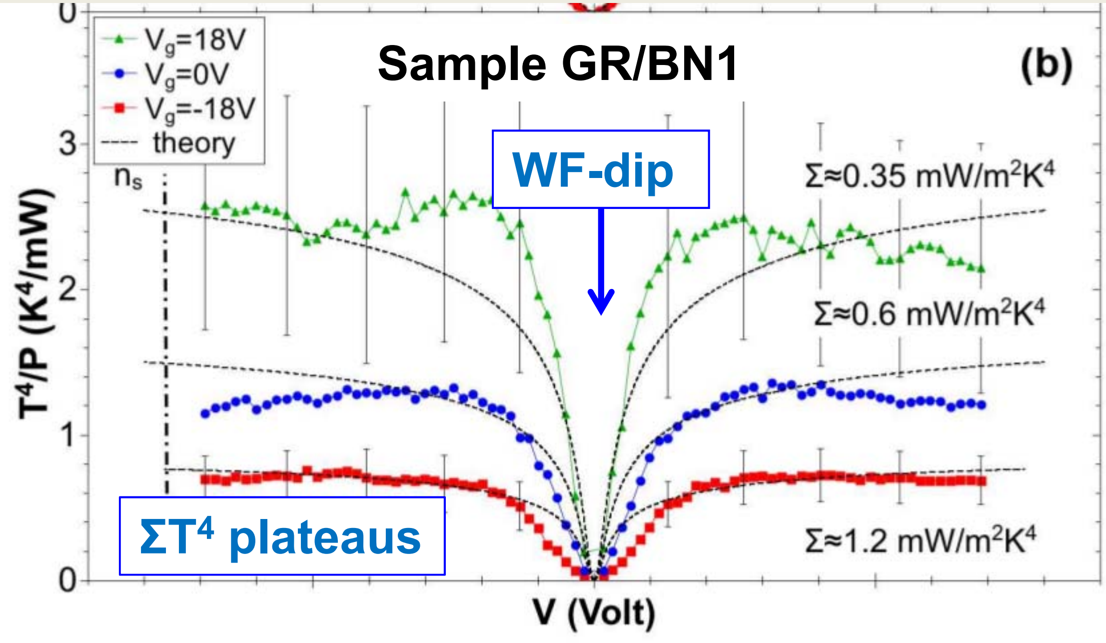
$$\frac{L}{2RW}\left(\frac{\pi^2 k_B^2}{3e^2}\right)\frac{\partial^2 T_e^2(x)}{\partial x^2} = \frac{V^2}{RLW} - \Sigma(T_e^4 - T_{ph}^4)$$

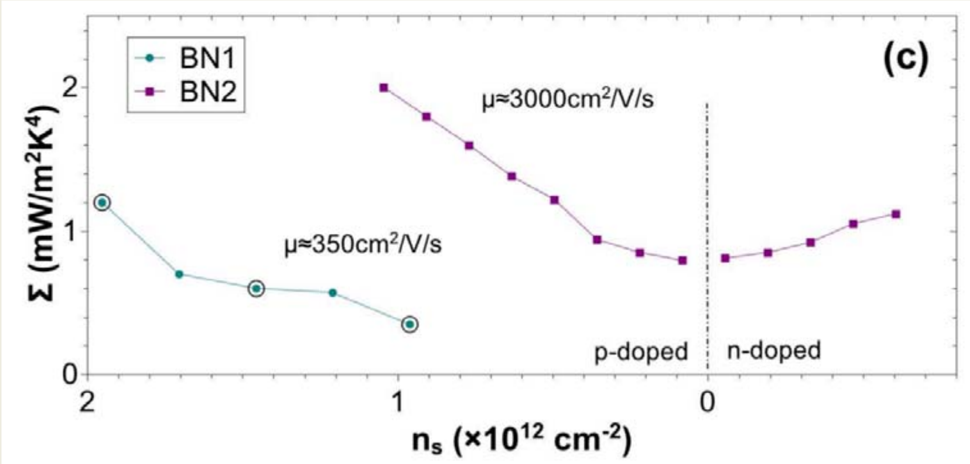
Relaxation by « cold AC phonons »

$$P(T \ll \theta_{BG}) = \Sigma \Delta T^4 = \frac{\pi^2 D^2 k_B^4 |\mu|}{15 \rho_m \hbar^5 s^3 v_F^3} \times (T_e^4 - T_{ph}^4)$$

$T_{ph} < T_{BG}$ (cold phonons)







- **Agreement with T^4 dependence for 2D acoustic phonons**
- **Σ^* =0.5-2 mW/m^2K^4 is disorder dependent and $\Sigma^* < \Sigma$ = 10mW/m^2K^4**

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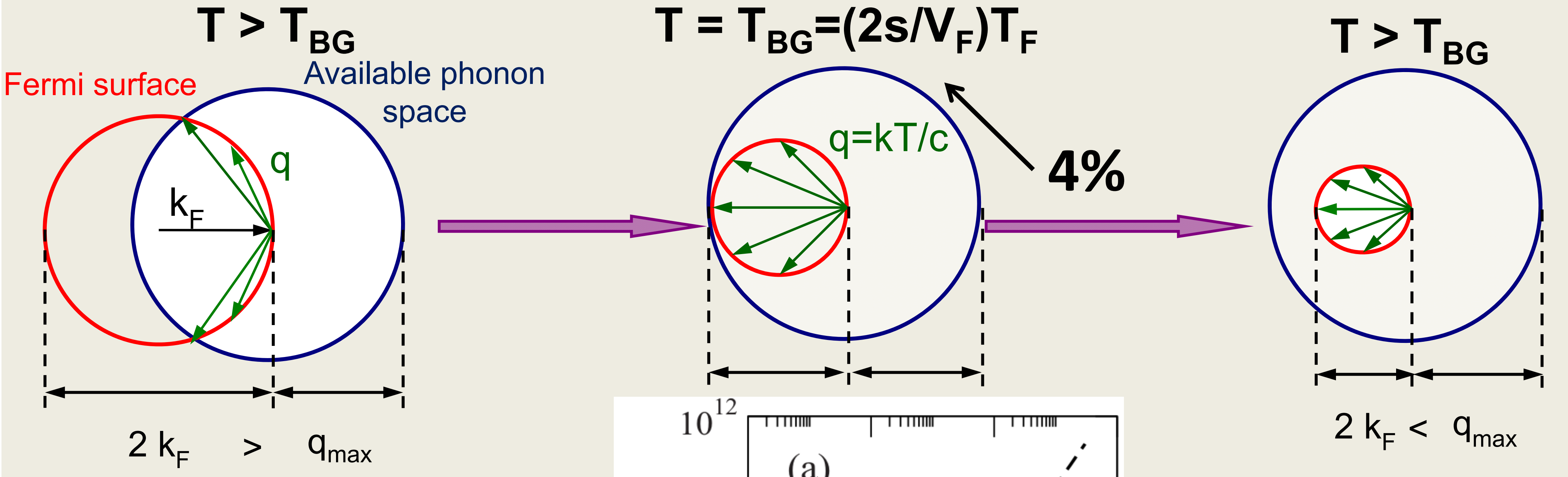
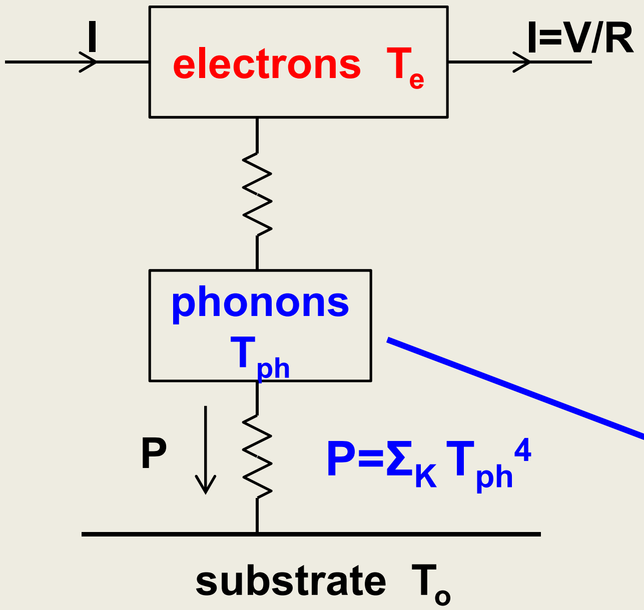
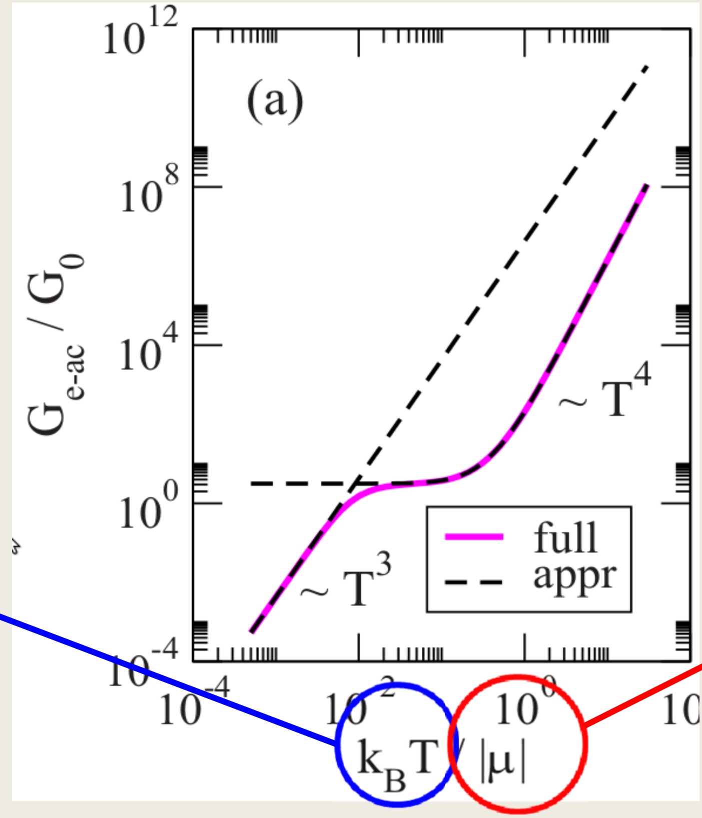
   Betz et al., Nature Physics 9, 109 (2013)

Crossing the Bloch-Gruneisen temperature





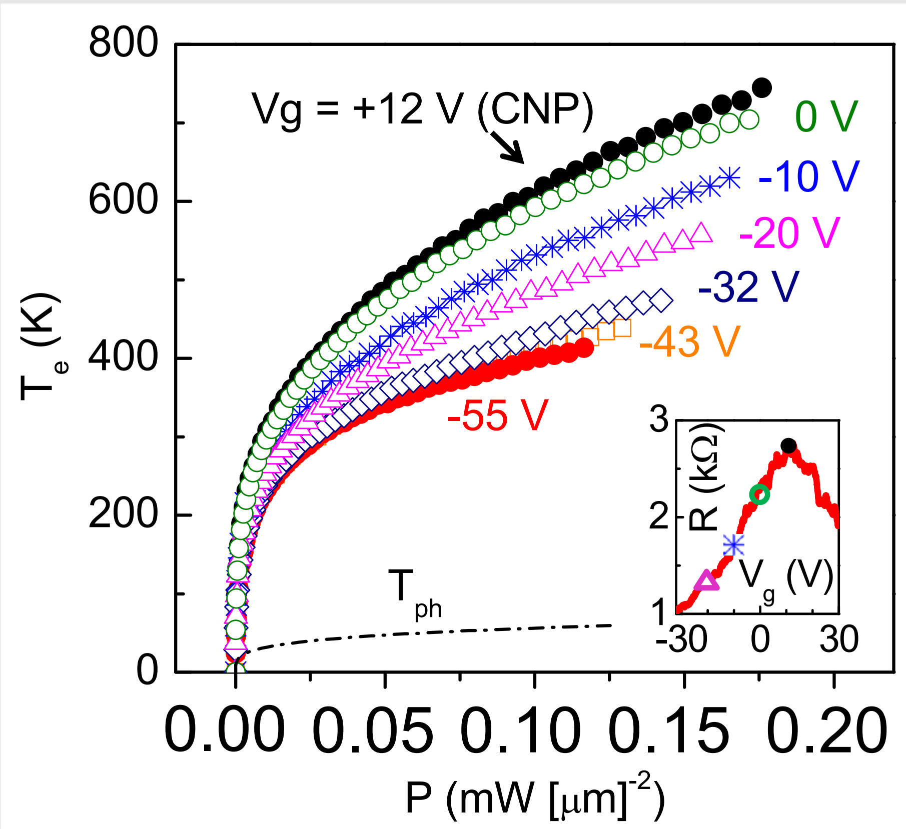


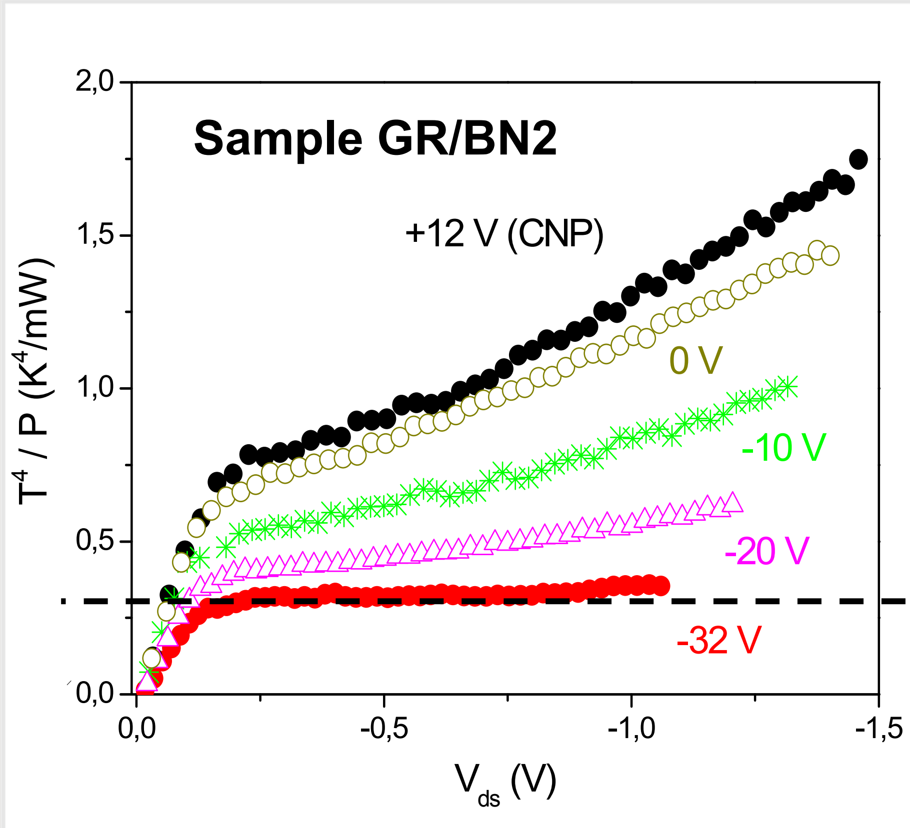
decrease μ

Relaxation at the Charge Neutrality Point

Sample GR/BN2

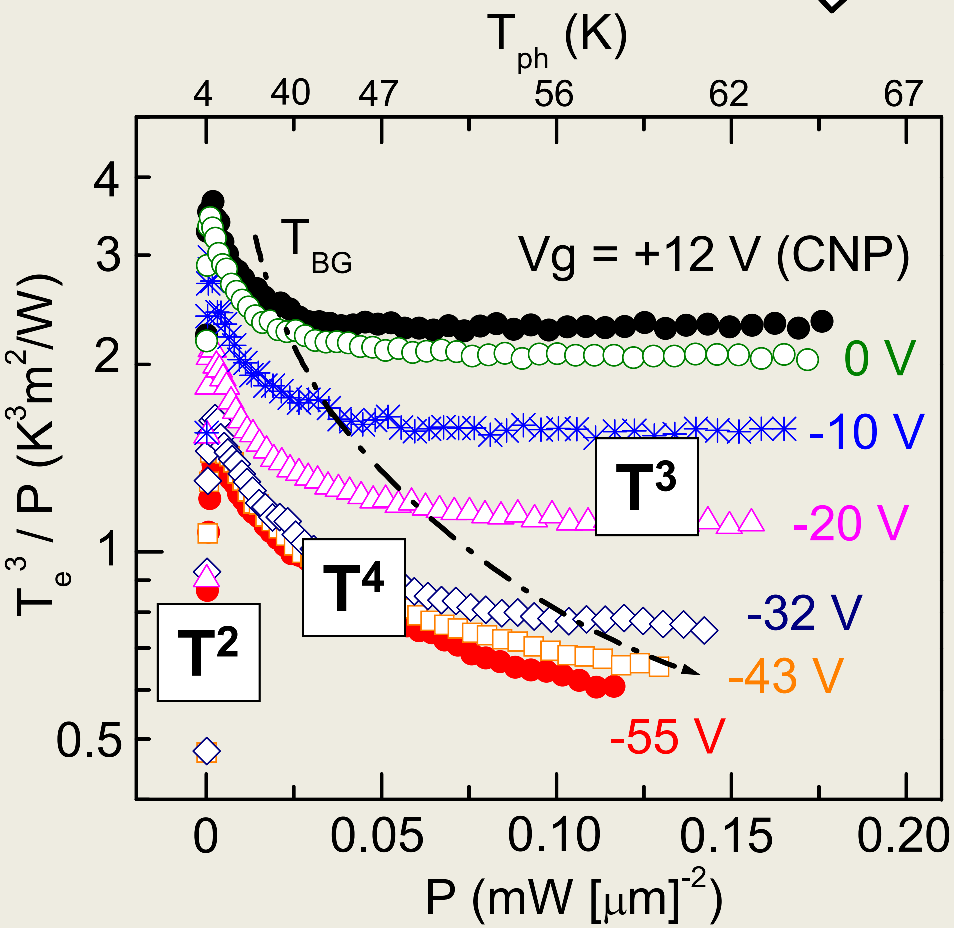
Replot

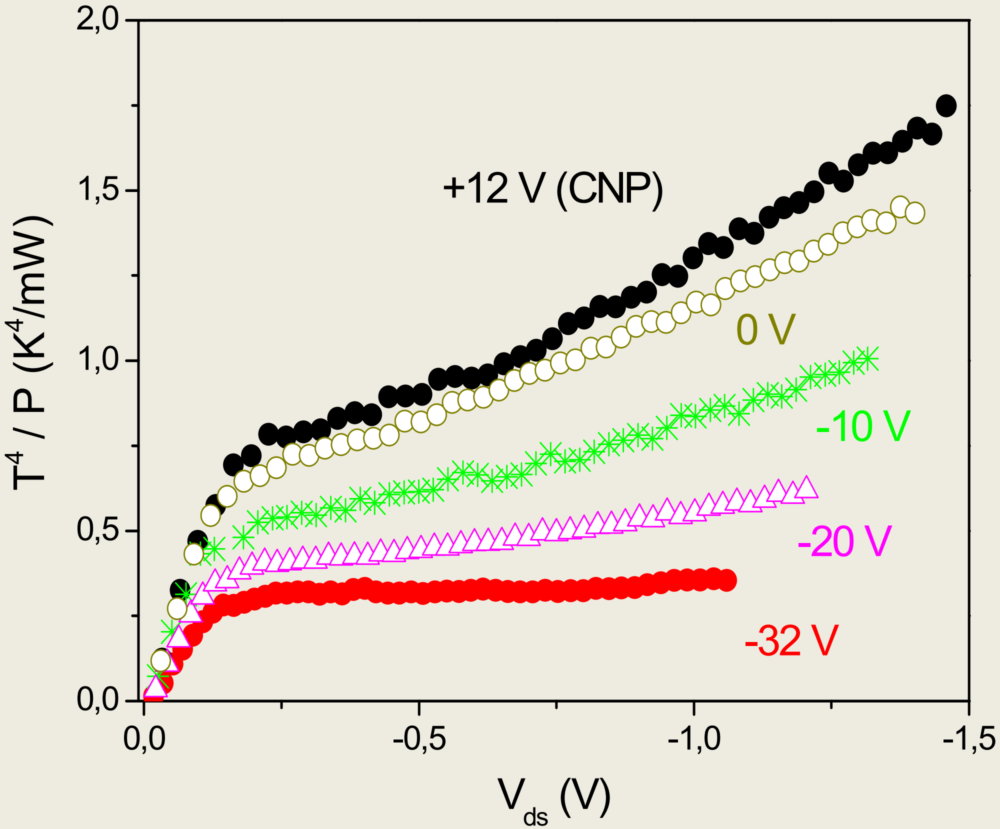




We measure $P \alpha T^3$ instead of $P \alpha T$

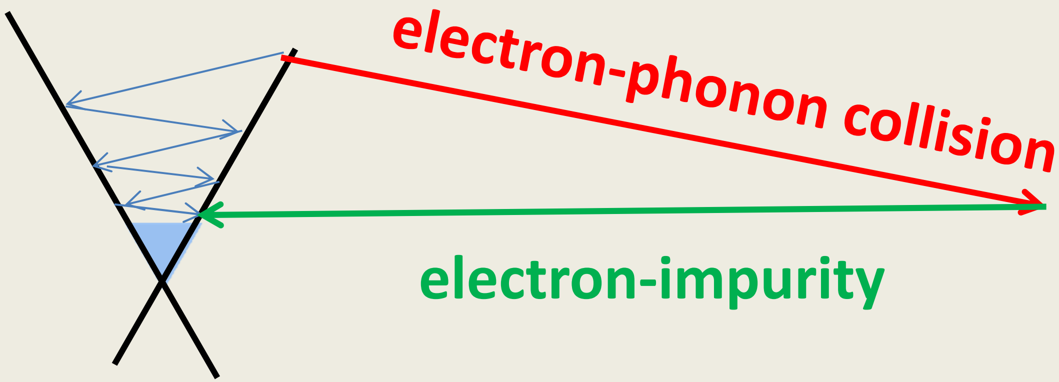
Replot

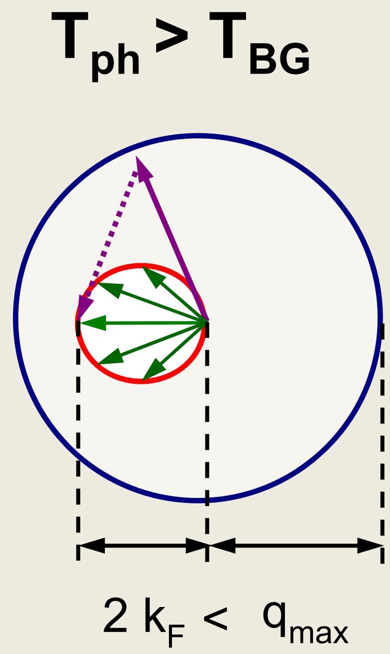




Supercollisions

Ordinary collision

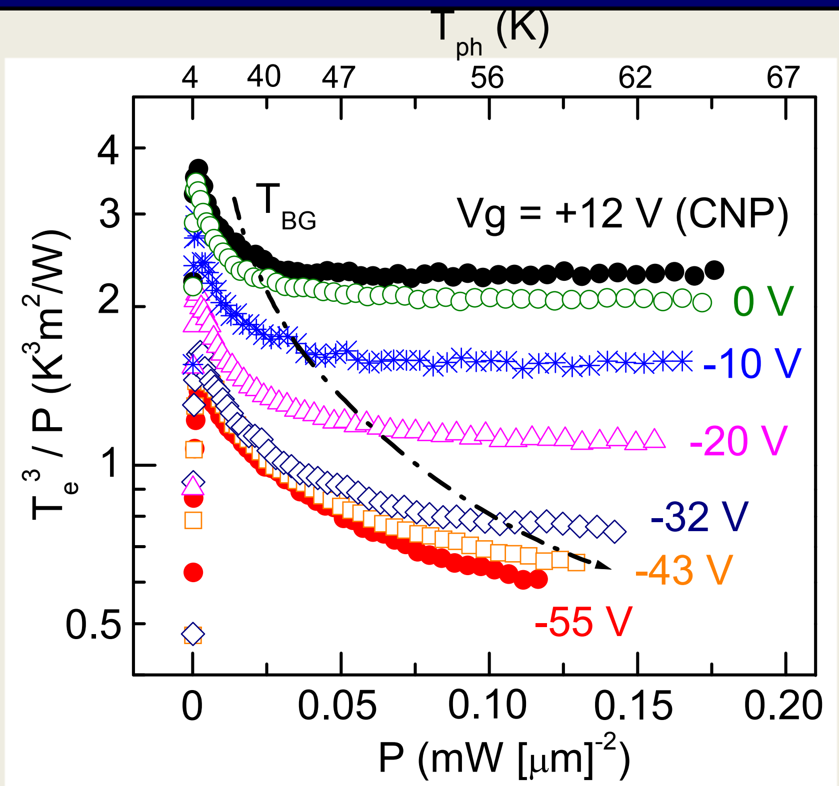


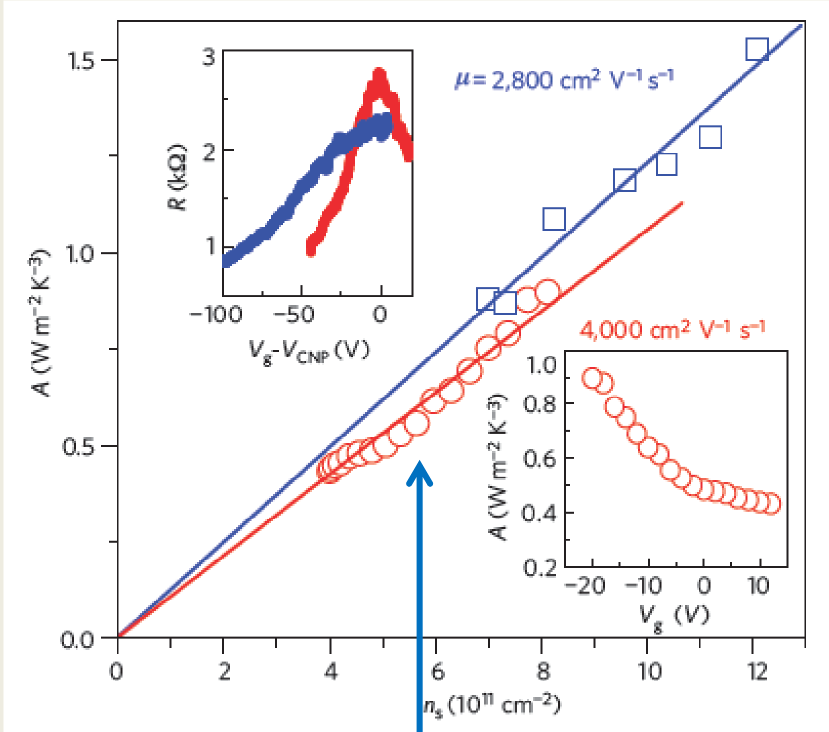


$$P(T \geq \theta_{BG}) = A\Delta T^3 = \frac{1}{kl} \times \frac{9.62 D^2 k_B^3 |\mu|^2}{8\pi^2 \rho_m \hbar^5 s^2 v_F^4}(T_e^3 - T_{ph}^3)$$

Theory : Song-Reizer-Levitov, PRL 109, 106602 (2012)

supercollisions





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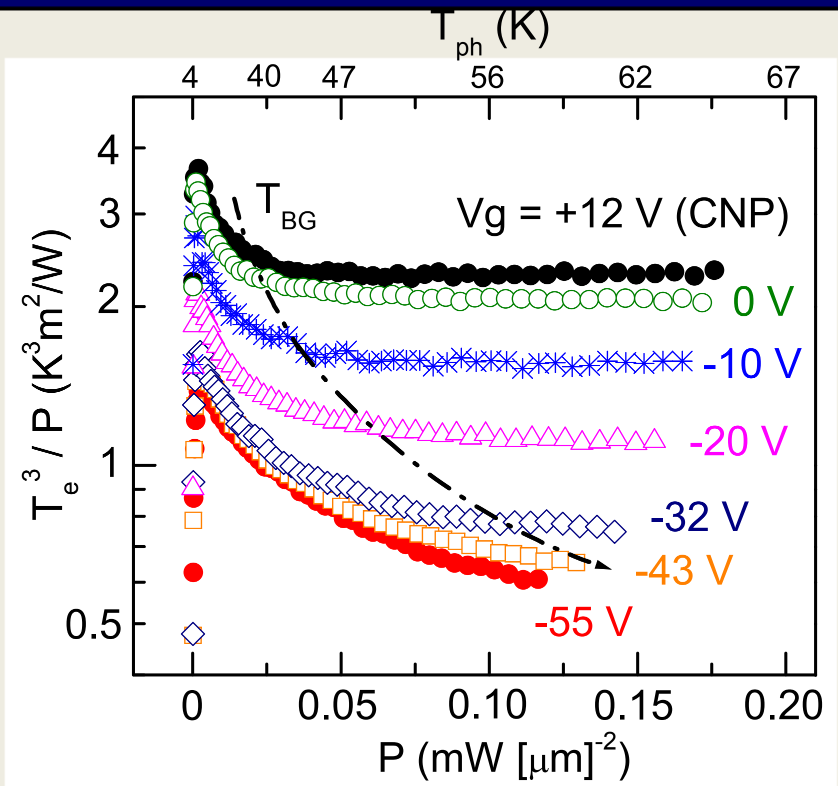
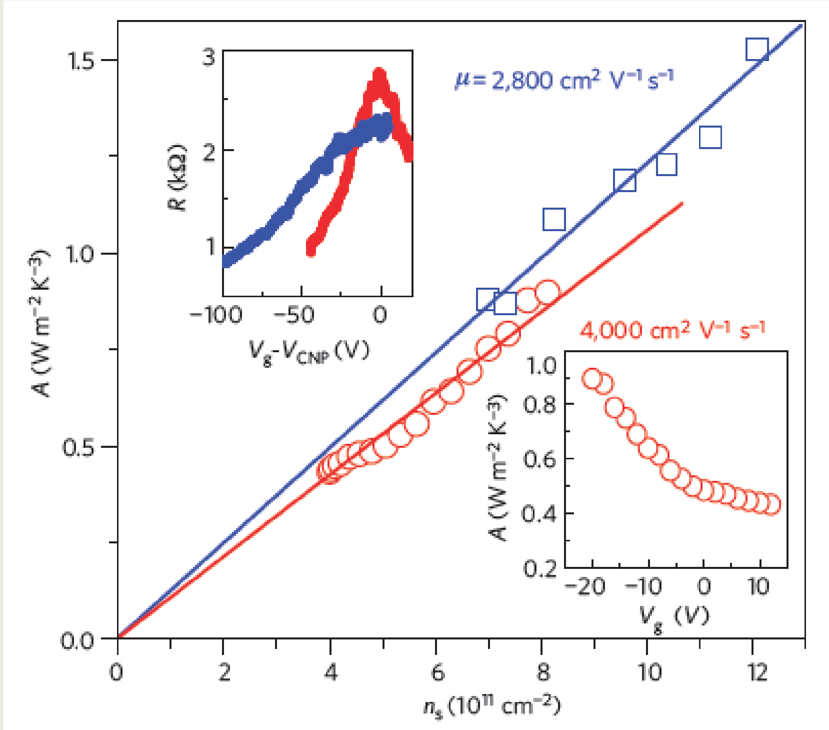
supercollisions





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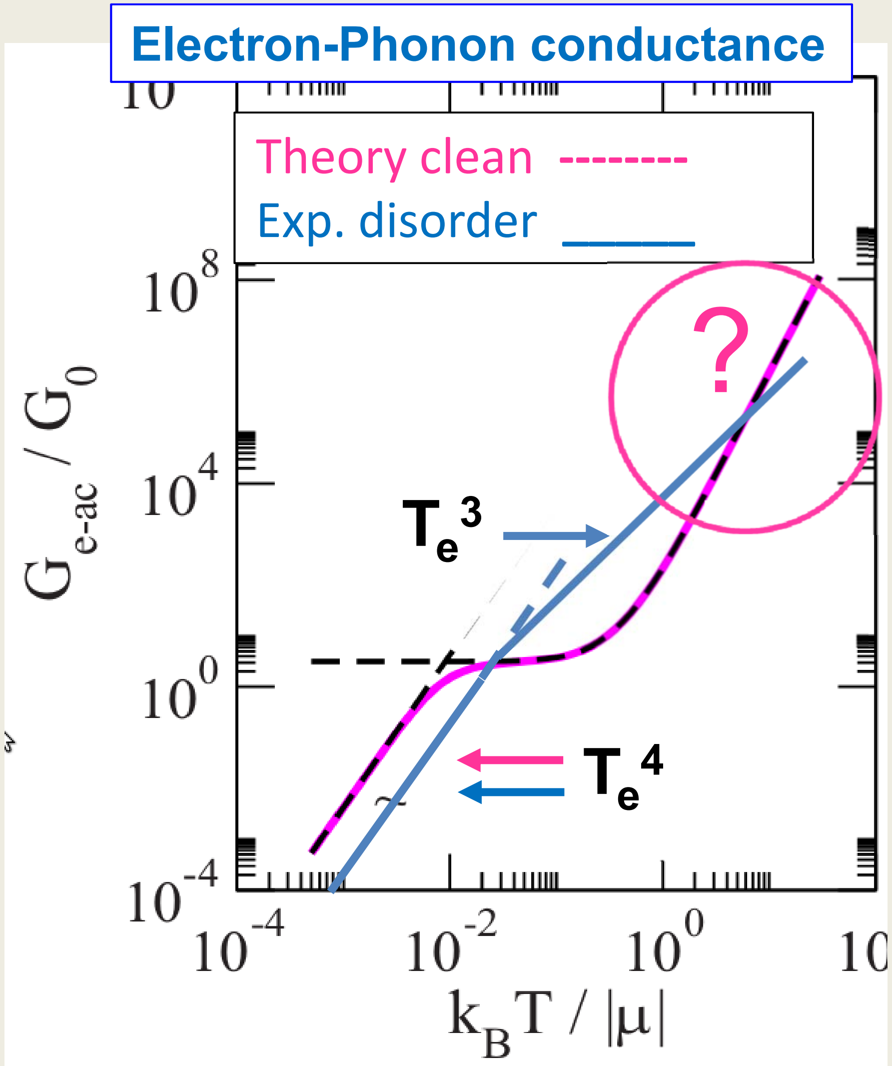
Experiment

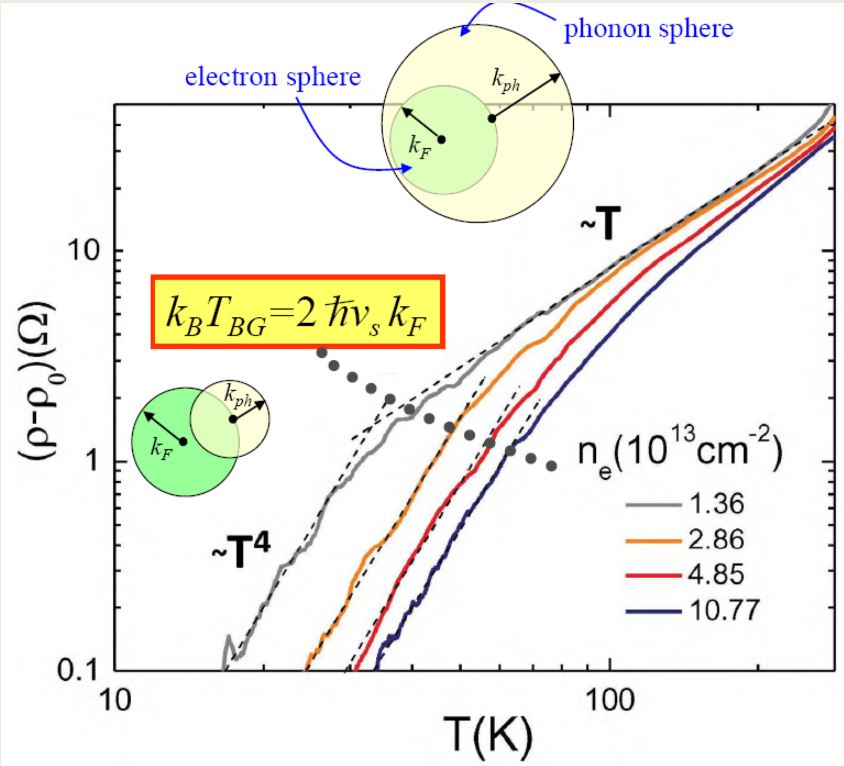
$$k_F l \simeq 3.5 \;\Rightarrow\; D \simeq 70 \text{ eV}$$

Effect of disorder on relaxation

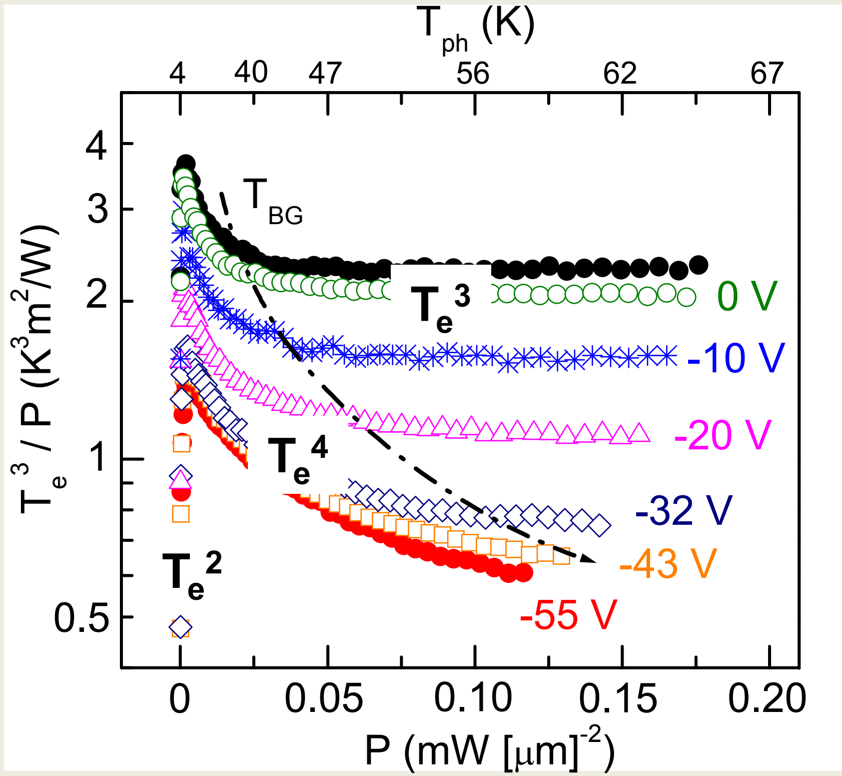


Conclusion

“ordinary collisions” rule momentum

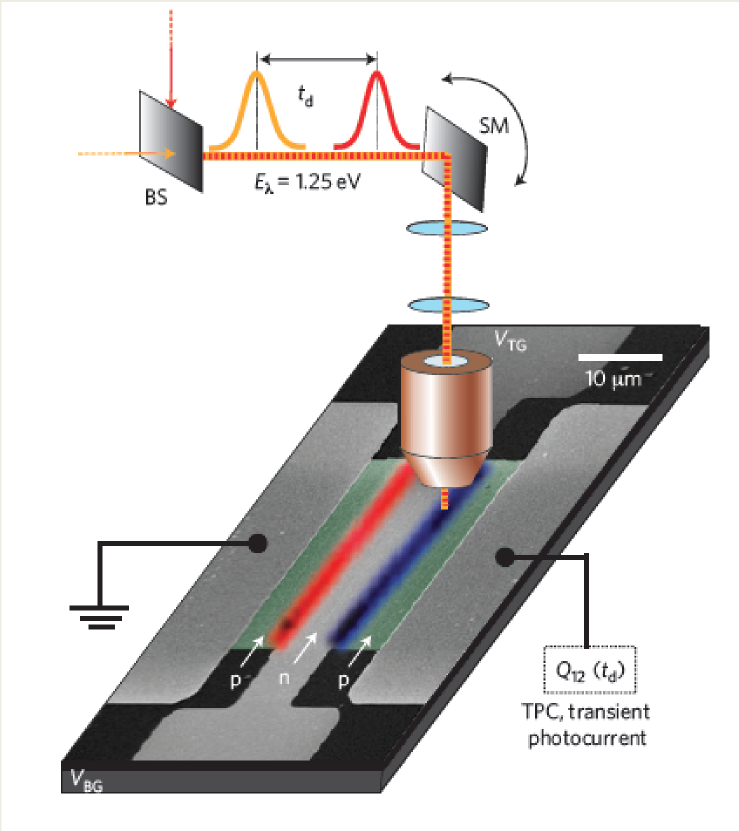


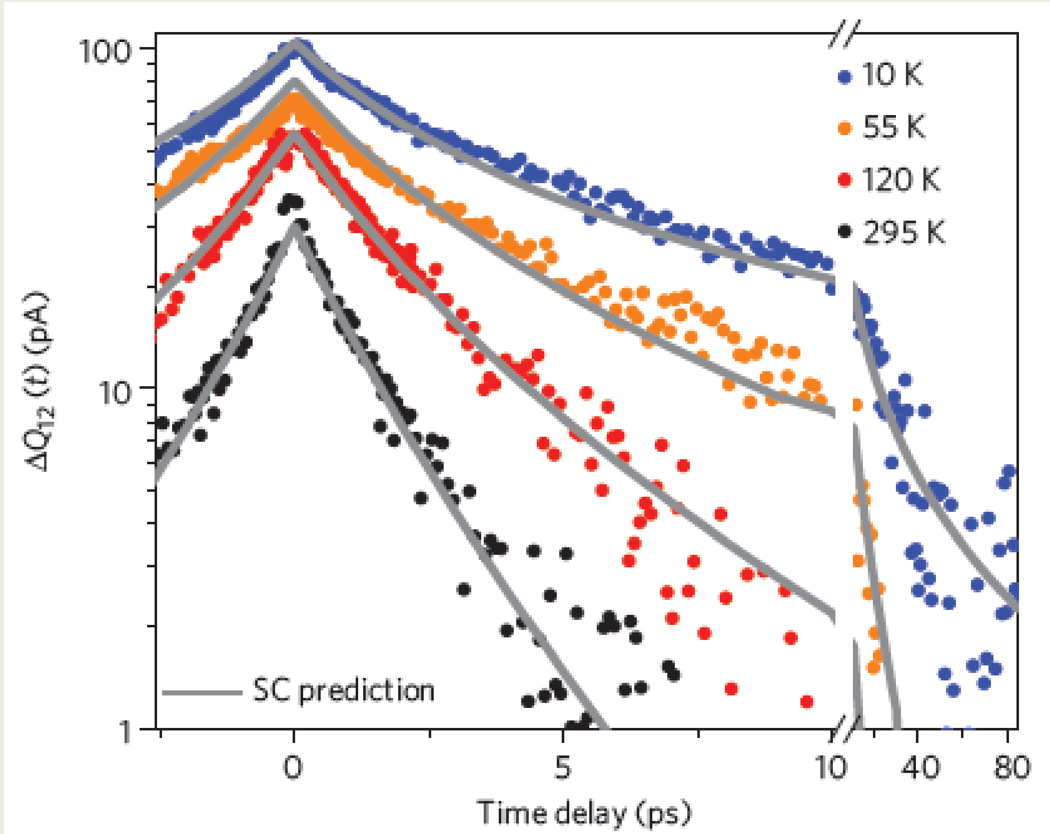
“Supercollisions” rule energy



Supercollision in the photocurrent

(Graham et al. Nat Phys. 2013)





$$2\rho(\mu)\left(\frac{\pi^2 k_B^2}{3e^2}\right)\frac{\partial T_e^2(x)}{\partial t} - \cancel{\frac{L}{2RW}\left(\frac{\pi^2 k_B^2}{3e^2}\right)\frac{\partial^2 T_e^2(x)}{\partial x^2}} = \cancel{\frac{V^2}{RLW}} - A(T_e^3 - T_{ph}^3)$$

~μ

τ ~100 ps

~μ²

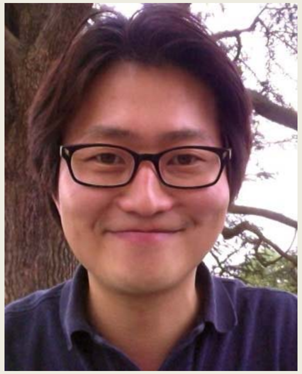
Conclusions and perspectives

- Ordinary phonon collisions observed at low temp (T^4 law)
- Phonon bottelneck (T law) is overcomed by supercollisions (T^3 law)
- Need for a theoretical approach for disorder
- Hot electrons useful for photodetection (from UV to THz)

  C. McKitterick et al., JAP 2013 and arXiv:1307.5012v1

Graphene teams at LPA-ENS

Mesoscopic physics team



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GRAPHENE FLAGSHIP

post-doc positions at ENS-LPA !!!!



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