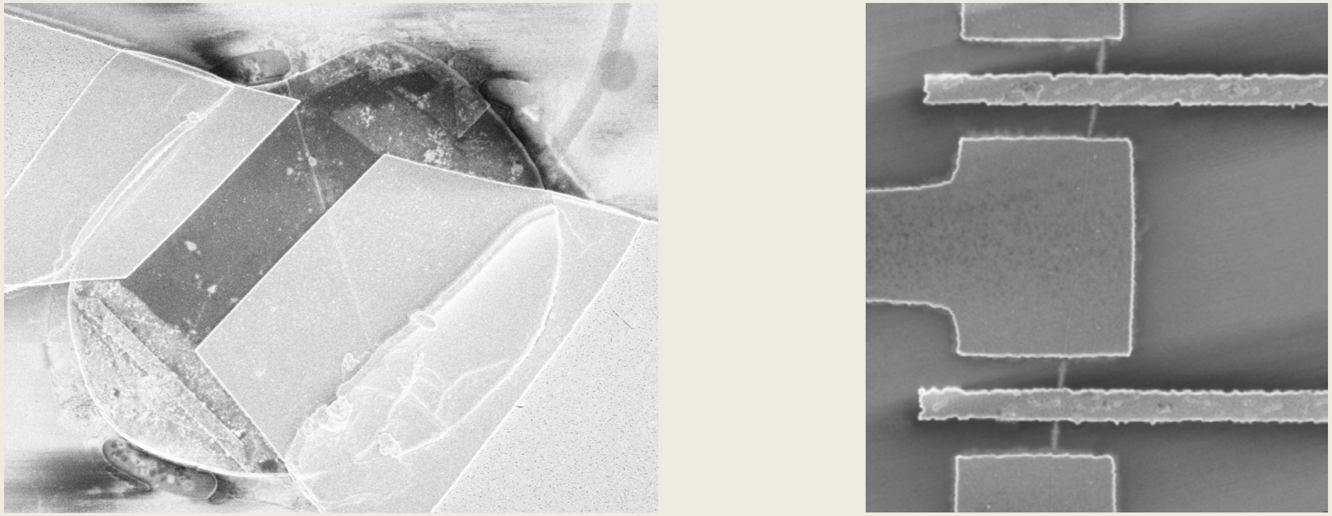
Noise in graphene and carbon nanotube devices



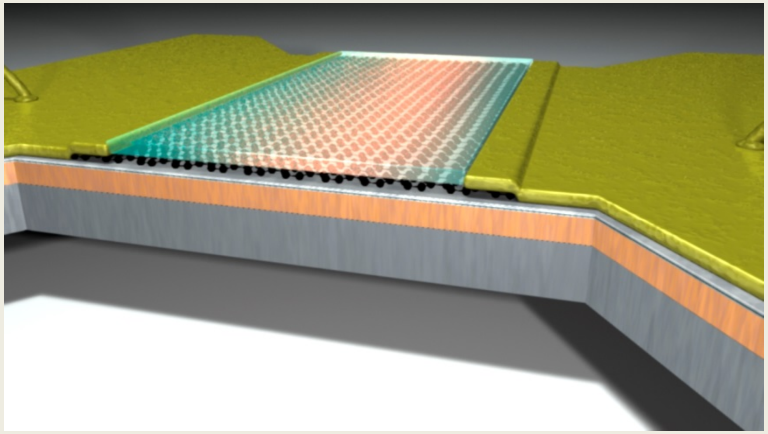
G. Fève, J-M. Berroir, T. Kontos, C. Voisin, B. Plaçais

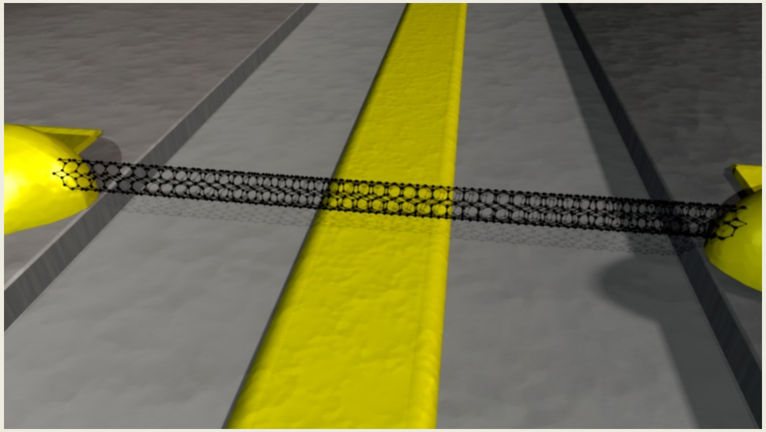
Laboratoire Pierre Aigrain – Ecole Normale Supérieure
24 rue Lhomond, 75231 Paris Cedex 05 France
www.lpa.ens.fr

laboratoire pierre aigrain
électronique et photonique quantiques

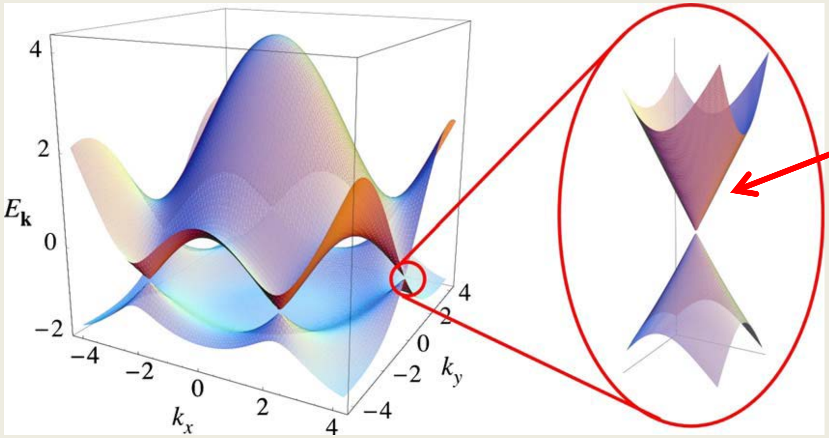
Noise in genuine low-dimensional systems

From 2D graphene to 1D carbon nanotubes





From massless chiral Dirac Fermions to single mode electronic "fibers"

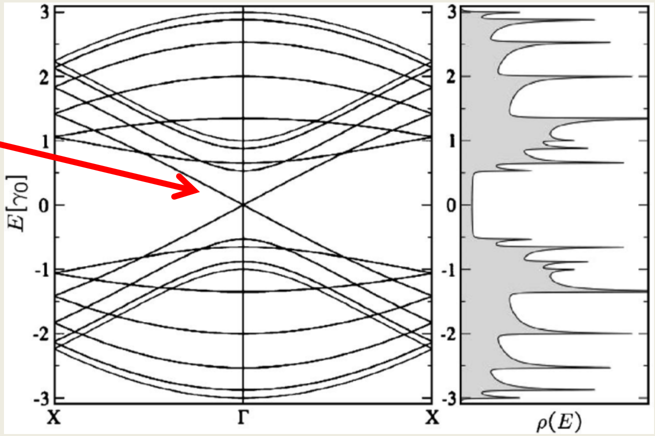


Castro-Neto et al. *RMP-2009*

large Fermi velocity
$v_F = 10^6$ m/s

Long and tunable wave length

Low density of states



Charlier et al., RMP 2007

Outline

❑ Graphene as tunable 2D semi-metal

a) Quantum shot noise in graphene (a brief review)
b) Noise thermometry of hot electrons : electron-phonon in 2D
c) Applications : HEBs, LNAs, Photo-detectors,

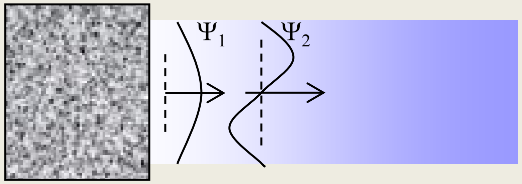
❑ Carbon Nanotubes as single mode nano-conductors (a review)

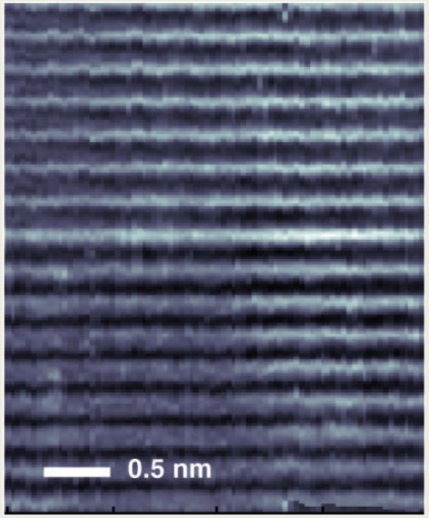
a) Quantum shot noise in cabon nanotube devices
b) Thermal noise in CNT wires and CNT-FETs: the noise conductance

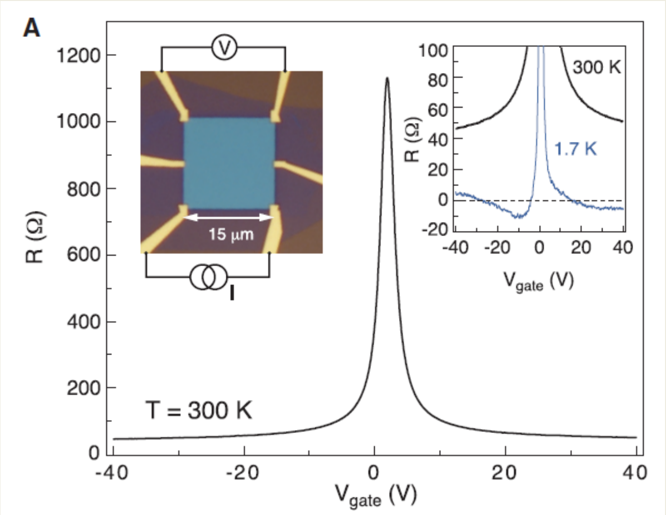
Graphene as a tunable high-mobility metal

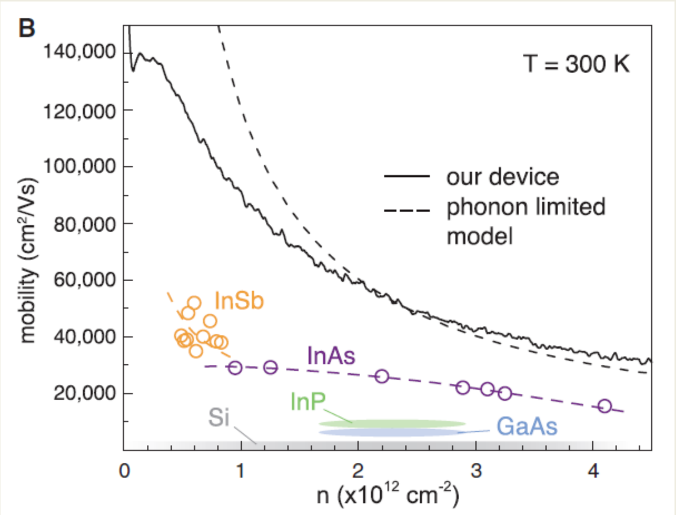
Landauer-Büttiker

h-BN encapsulated graphene









$$G_L = \frac{4e^2}{h} \times \sum_{1}^{N} T_n = \frac{1}{6450\ \Omega} \times \sum_{1}^{N} T_n$$

$$N/W_{\mu m} = \frac{k_F}{\pi} = 56\sqrt{n/10^{12}cm^{-2}} = 5 - 500$$

L. Wang et al., Science 342, 614 (2013)

Quantum Shot Noise in graphene

Conductance is transmission

$$G = \frac{e^2}{h}\sum_{1}^{N} T_n$$

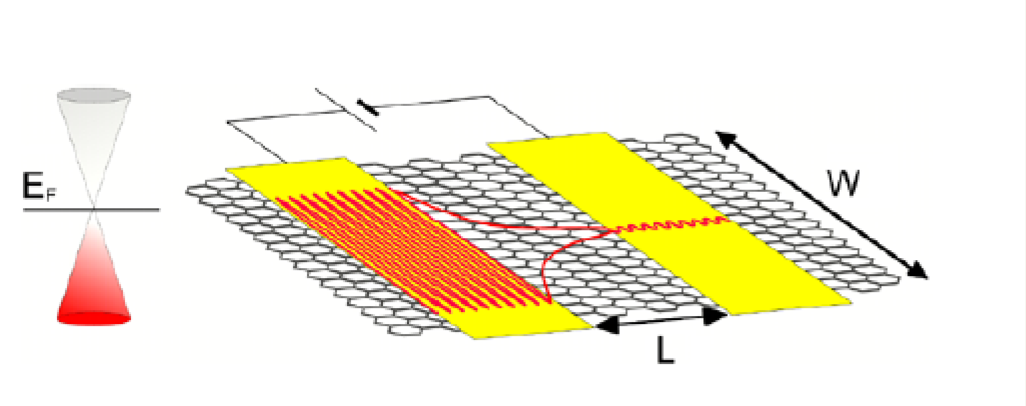
Quantum Shot Noise (QSN)

$$S_I = 2eI\,\frac{\sum T_n(1-T_n)}{\sum T_n} = 2eI \times \text{"}Fano\text{"}$$

Ya.M. Blanter, M. Büttiker / Physics Reports 336 (2000) 1-166

Dirac point : electronic transmission

$$T_n{}^{Dirac} = cosh^{-2}\left[\pi(n+\alpha)\frac{L}{W}\right]$$



Noise

$$Fano^{Dirac} = \frac{1}{3}$$

J. Tworzillo et al. / Phys. Rev. Lett. 96 (2006) 246802

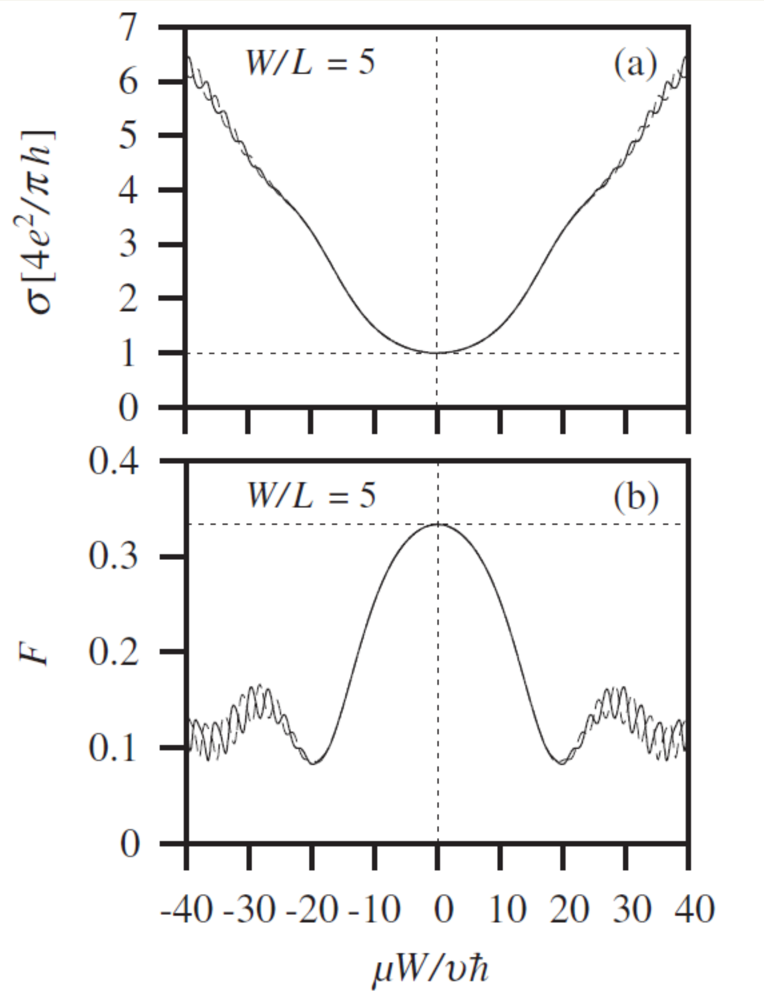
« Conductivity »

$$\sigma^{Dirac} = \sigma^{Dirac}\frac{L}{W} = \frac{4e^2}{h}\frac{L}{W}\int_0^\infty \frac{dk_y}{cosh^2[k_y L]} = \frac{4e^2}{\pi h}$$

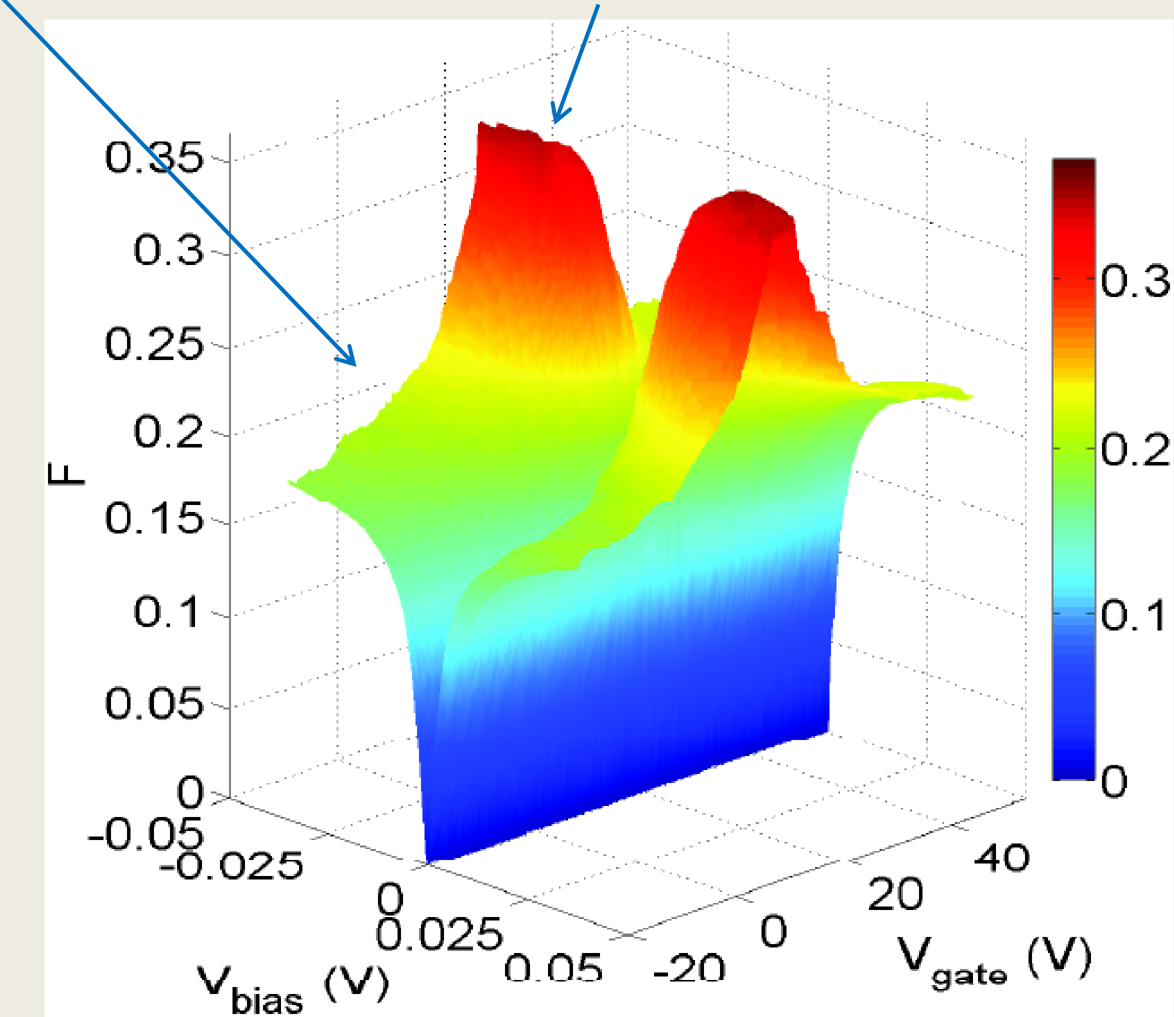
QSN in graphene junctions (Aalto exp.)

Ballistic graphene junctions (W=5L)

F=1/3 at Dirac Point



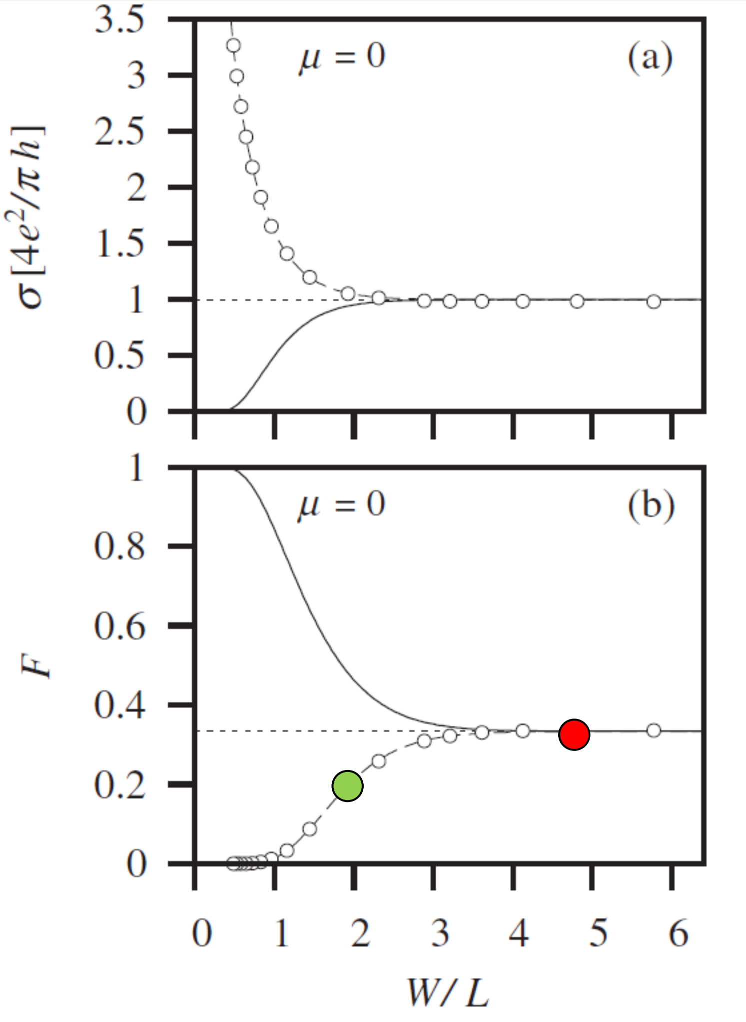
J. Tworzillo et al. / Phys. Rev. Lett. 96 (2006)



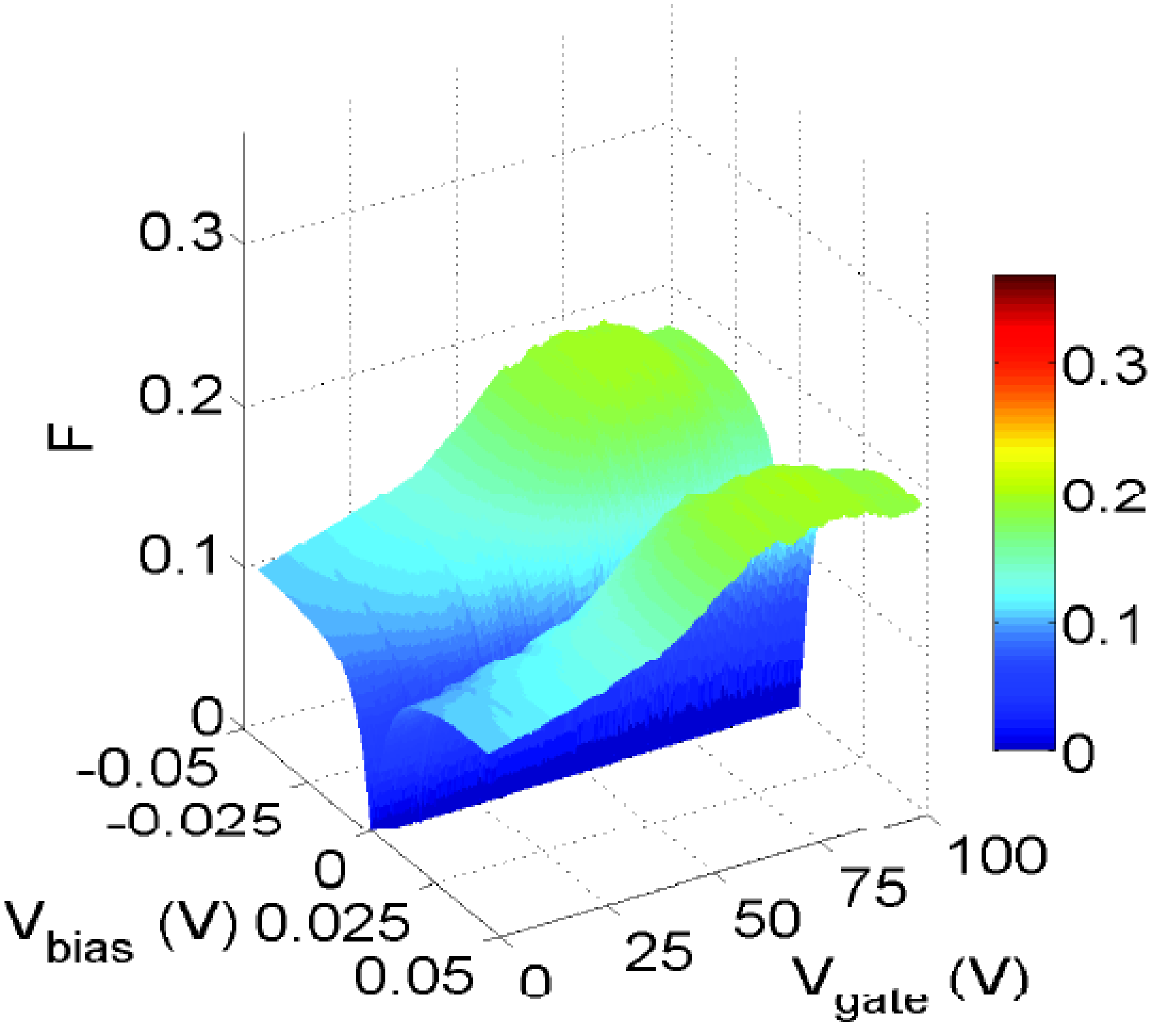
Exp.: R. Danneau et al./ Phys. Rev. Lett. 100 (2008)

QSN in graphene ribbons (Aalto exp.)

theory

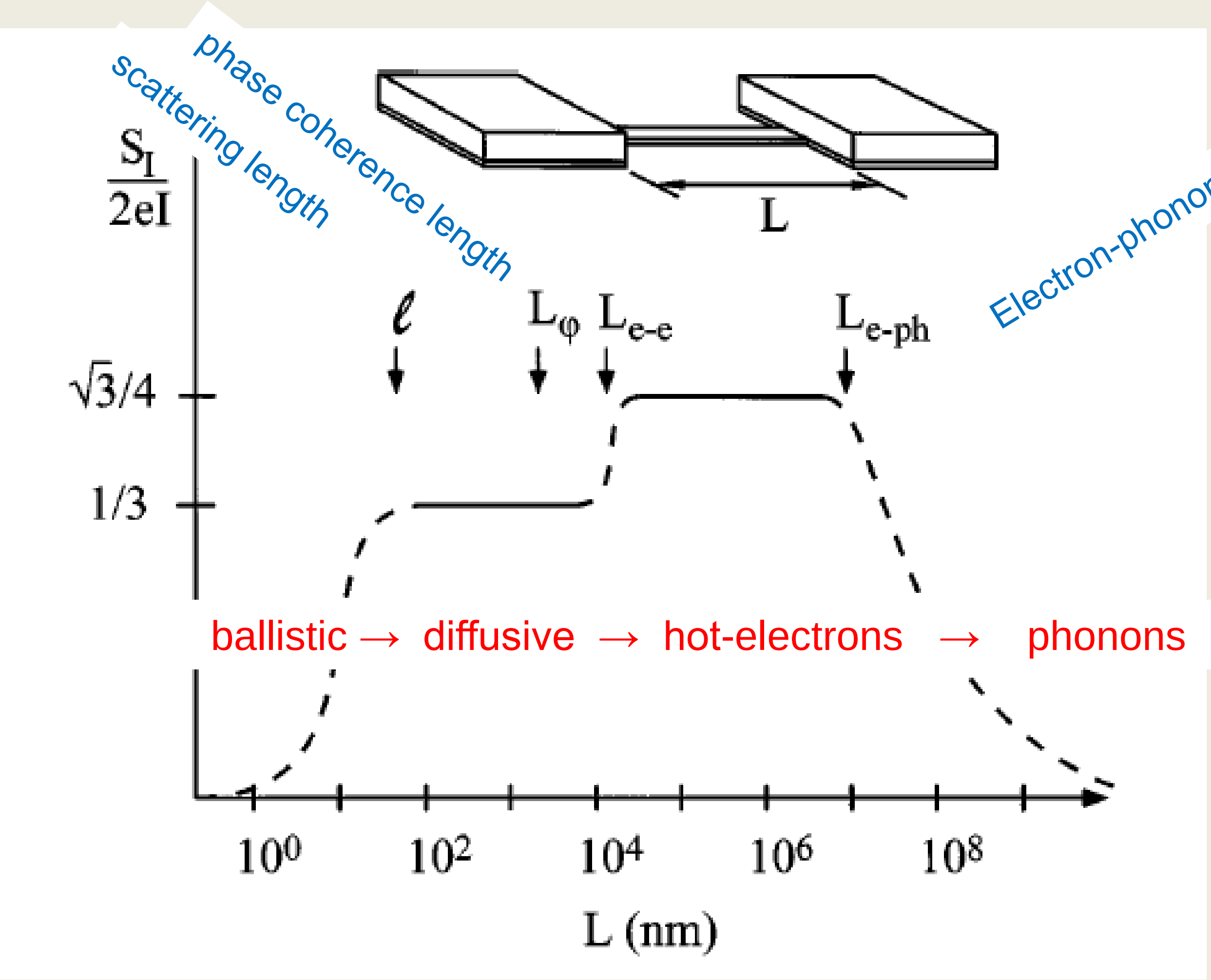


experiment



from quantum to classical

... on increasing sample length



scattering length

phase coherence length

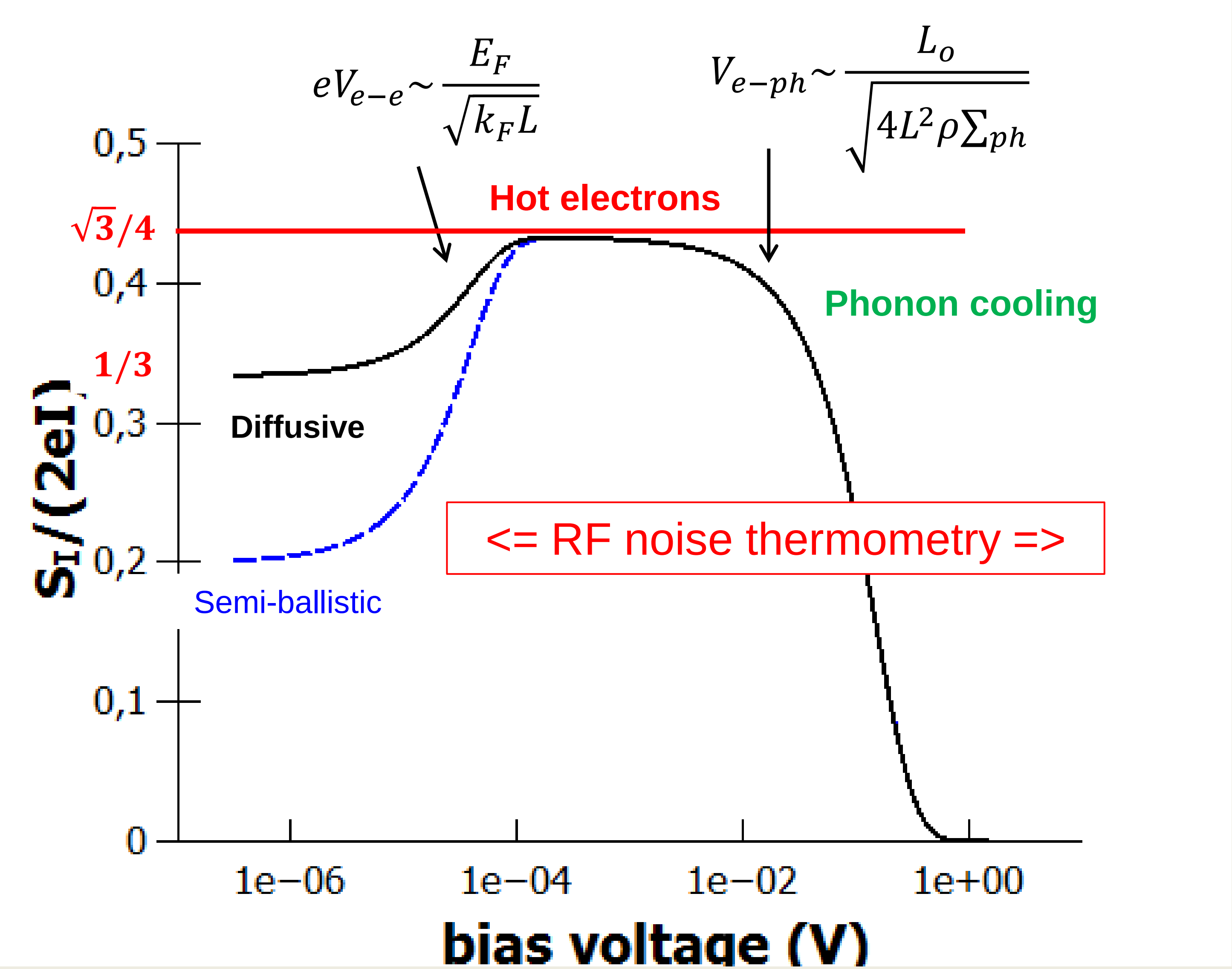
Electron-phonon length

ballistic → diffusive → hot-electrons → phonons → macroscopic world

A.H. Steinbach et al. / Phys. Rev. Lett. 76(1996) 3806

from quantum to thermal

… on increasing bias voltage

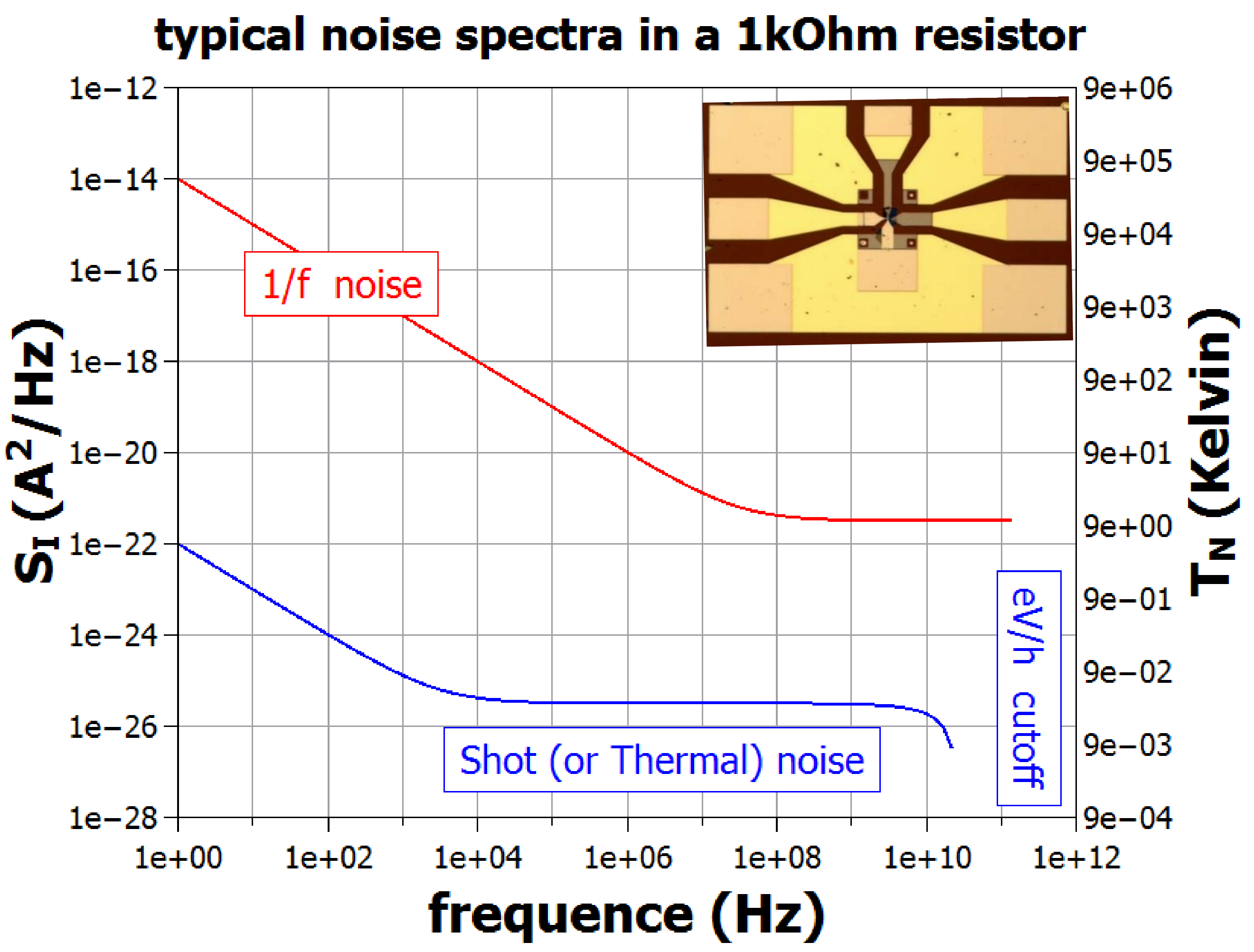


$eV_{e-e} \sim \frac{E_F}{\sqrt{k_F L}}$

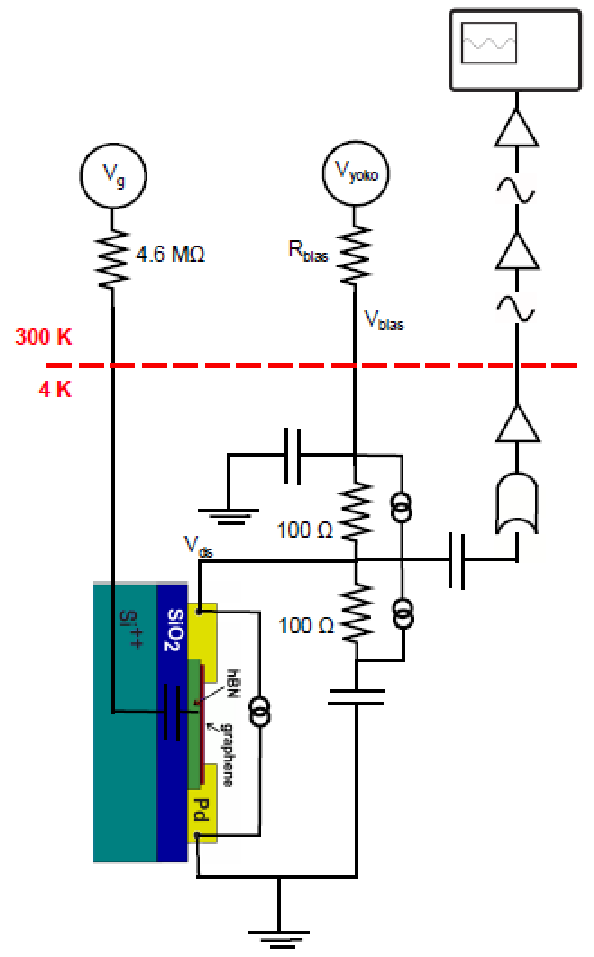
$V_{e-ph} \sim \frac{L_o}{\sqrt{4L^2 \rho \sum_{ph}}}$

RF current-noise measurement

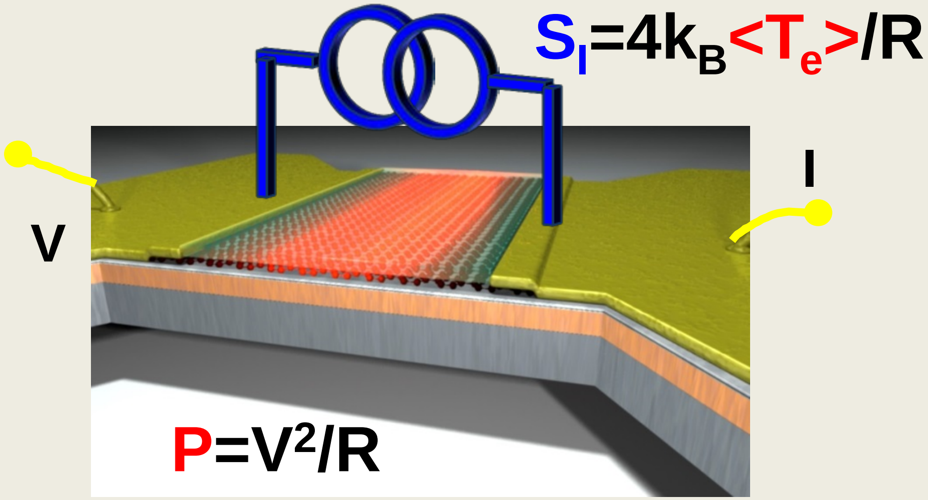
current noise spectrum at high-bias



GHz-setup (LPA)

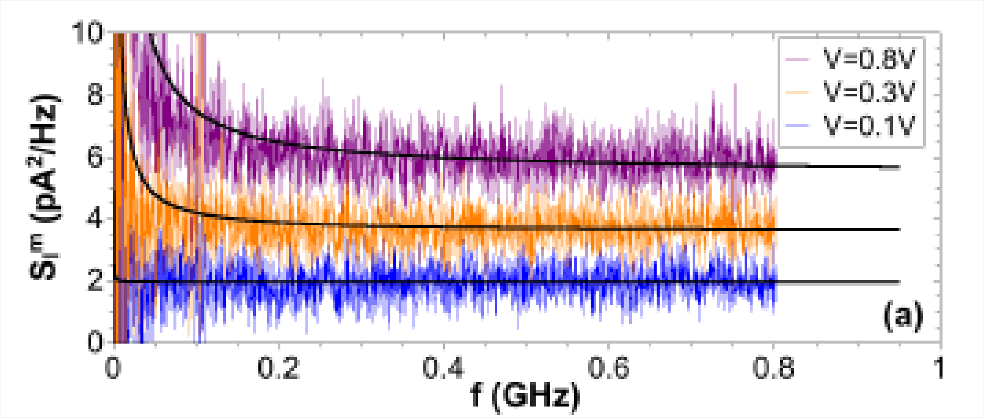


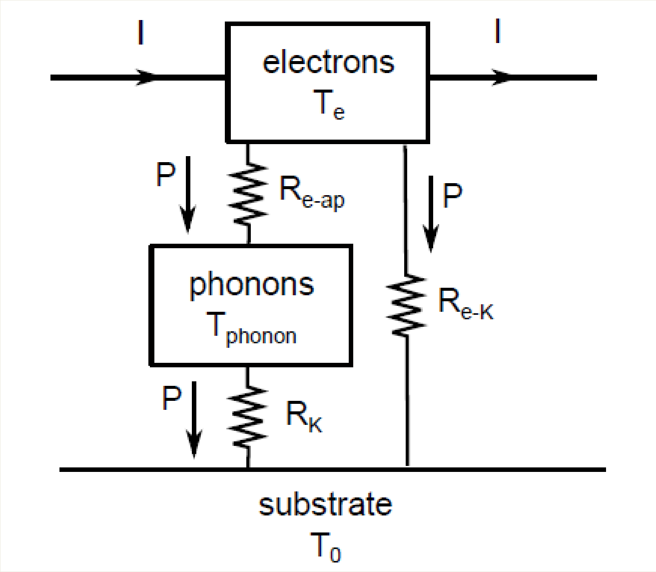
Typical Fano-factor dependence

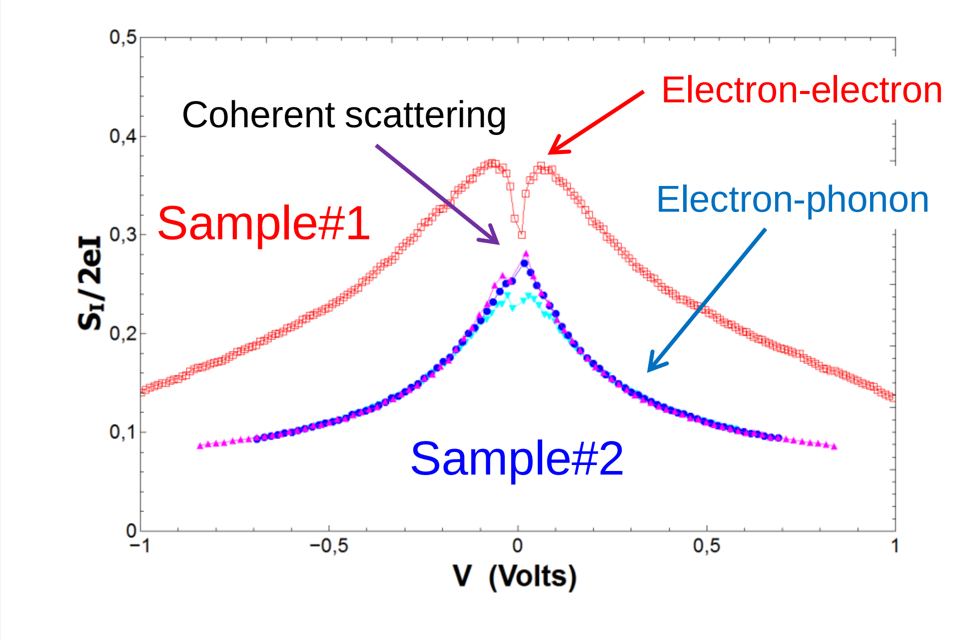


$$S_I=4k_B\langle T_e\rangle/R$$

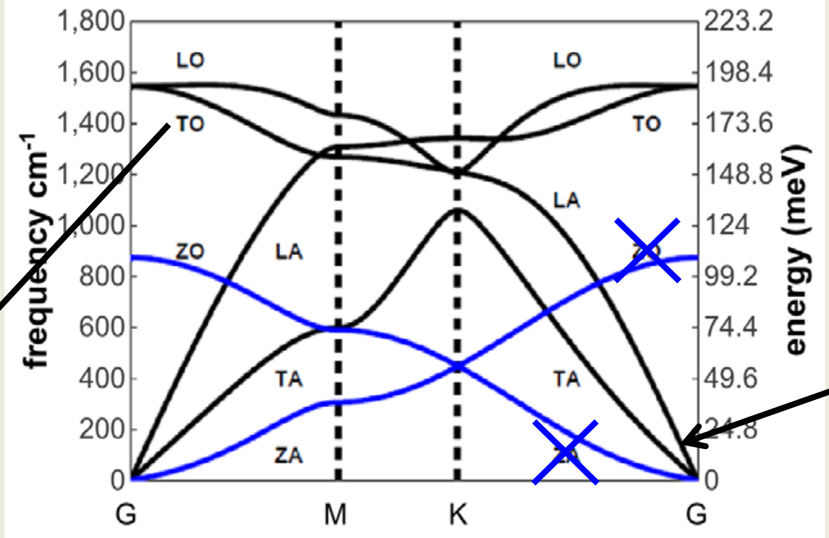
$$P=V^2/R$$





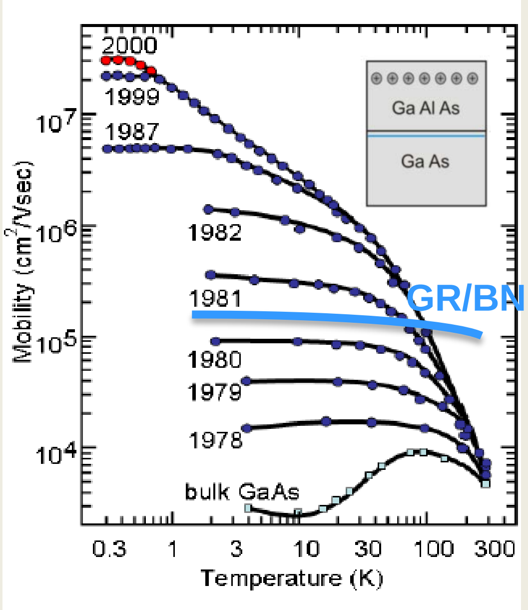


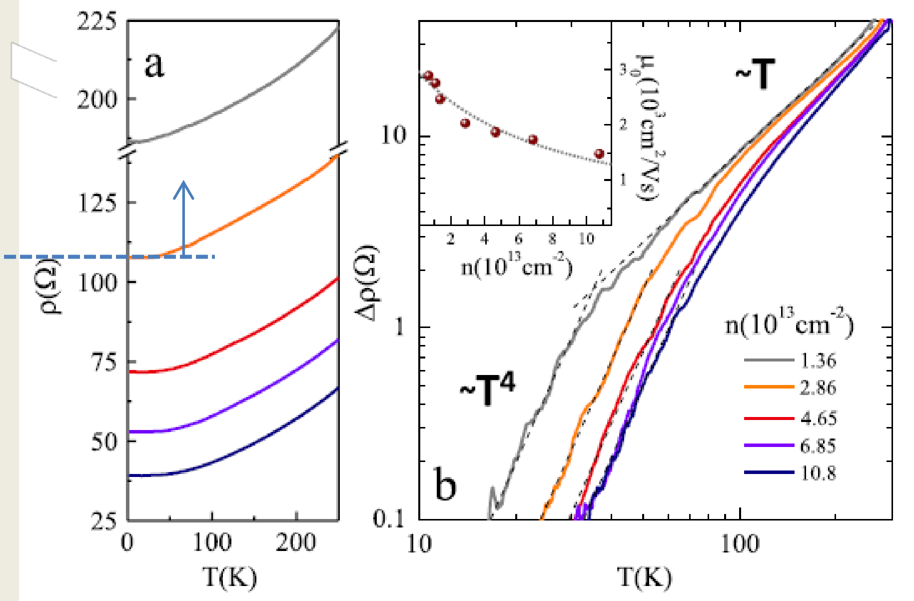
Electron-Phonon in graphene



OP-phonons irrelevant

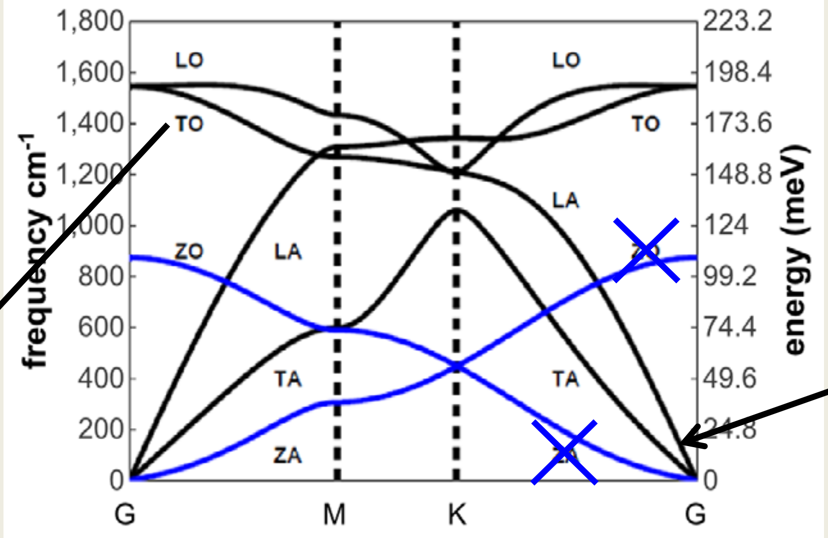
large AC-phonons velocity ($s = 2x10^4$ m/s)





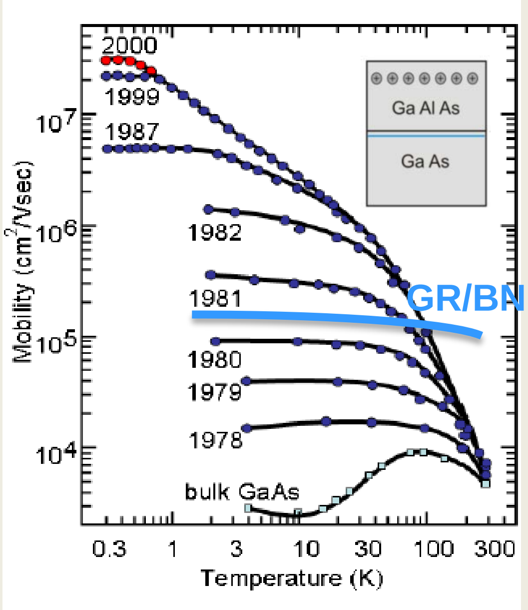
Chen-Fuhrer / Nat. Nano (2008) ; *Efetov-Kim / Phys. Rev. Lett. (2010)*

Electron-Phonon in graphene



OP-phonons irrelevant

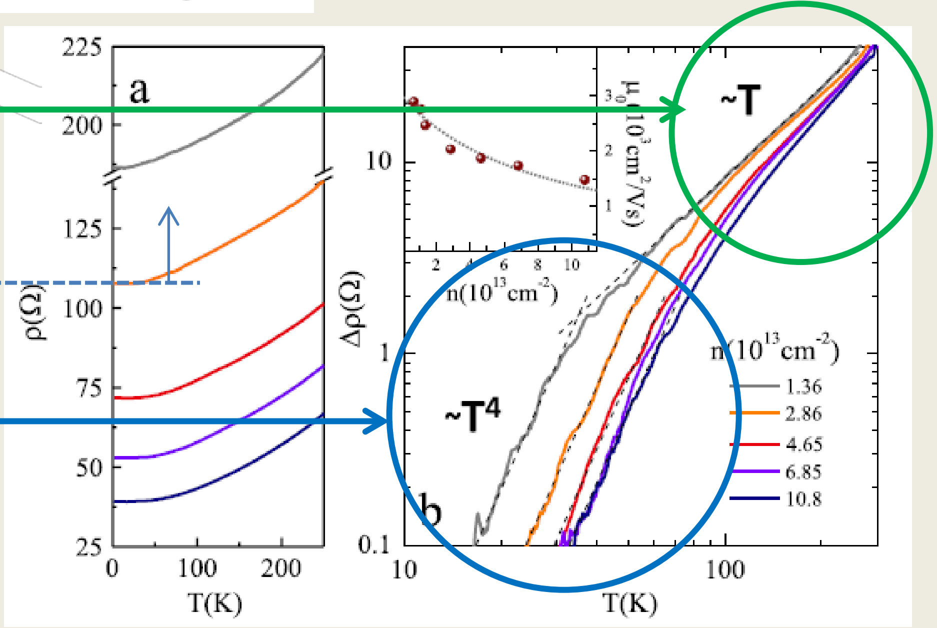
large AC-phonons velocity (s = 2x10^4 m/s)



Very weak Phonon resistivity

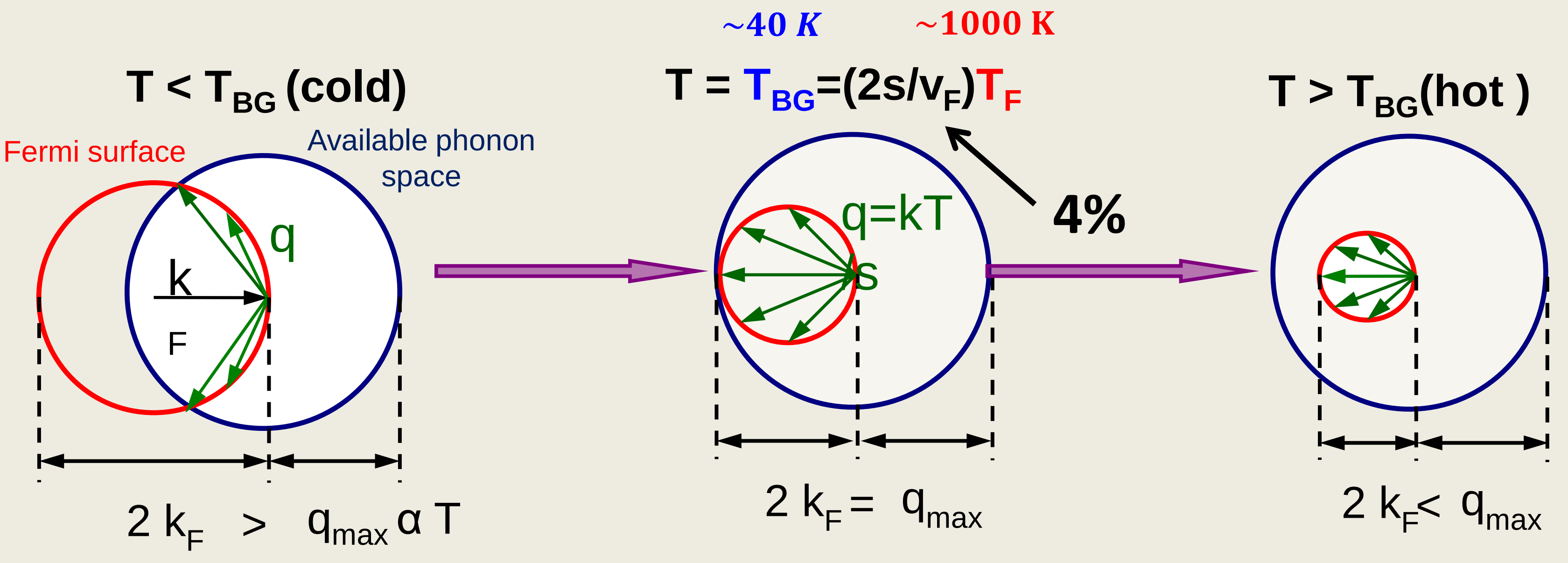
$$\rho \approx 0.1 \times T$$

Bloch-Grüneisen Temp. ~50K



Chen-Fuhrer / Nat. Nano (2008) ; *Efetov-Kim / Phys. Rev. Lett. (2010)*

AC-phonon resistivity



T < T_{BG} (cold)

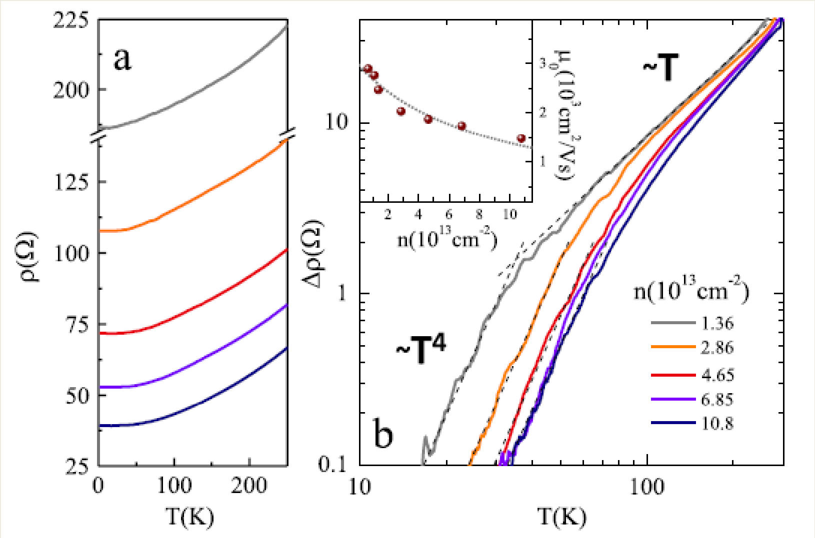
T = T_{BG}=(2s/v_F)T_F

T > T_{BG}(hot)

$2\ k_F\ >\ q_{max}\ \alpha\ T$

$2\ k_F = \ q_{max}$

$2\ k_F < \ q_{max}$



$$\Delta\rho\left(T_{ph} \ll \theta_{BG}\right) = \frac{8D^2 k_F}{\rho_m e^2 s\, v_F{}^2} \times f\left(\frac{T_{BG}}{T_{ph}}\right) \sim T^4$$

$$\Delta\rho\left(T_{ph} \ll \theta_{BG}\right) \sim const. \times\ T\ !!!\ \ ;\ \ const. \approx 0.1\Omega/K\ !!!$$

$$\mu_{ph}(300K) = 1/ne\Delta\rho \approx 2 \times 10^5/n_{12}$$

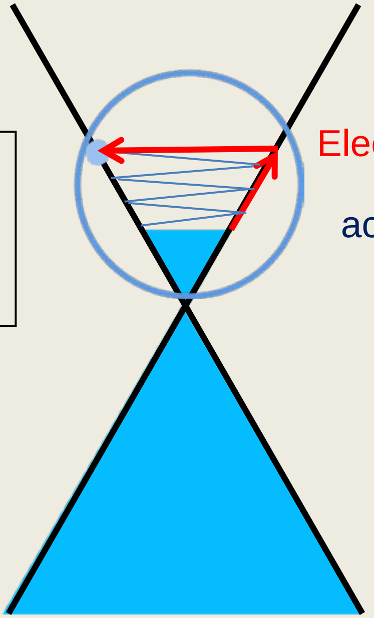
$$l_{ph}(300K) = \mu E_F/ev_F \approx 7\ \mu m\ /\sqrt{n_{12}}$$

Chen-Fuhrer / Nat. Nano (2008) ; *Efetov-Kim / Phys. Rev. Lett. (2010)*

AC-phonon relaxation : T≤T_{BG}

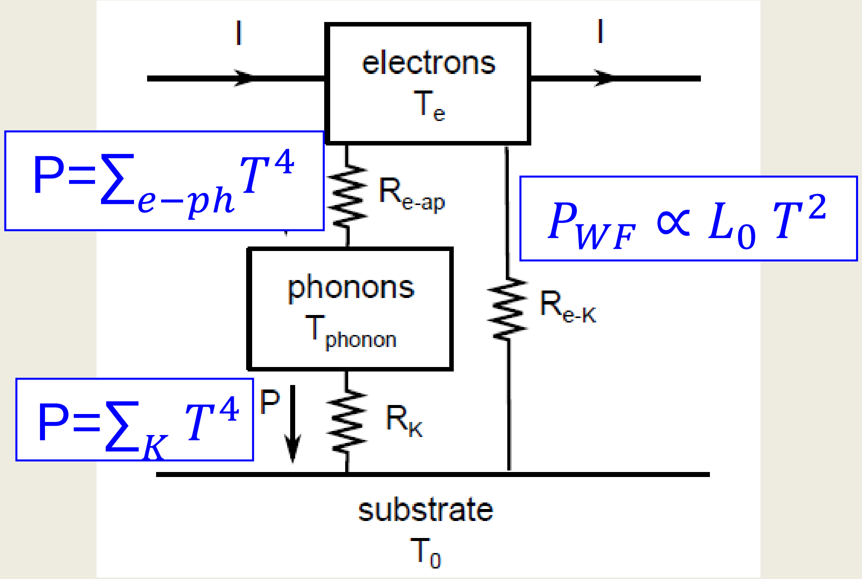
Joule heating + phonon cooling

Graphene :
$V_F=10^6\ m/s$
$s/V_F=0.02$



Electric field + scattering

acoustic-phonons only



$P=\Sigma_{e-ph}T^4$

$P_{WF}\propto L_0\ T^2$

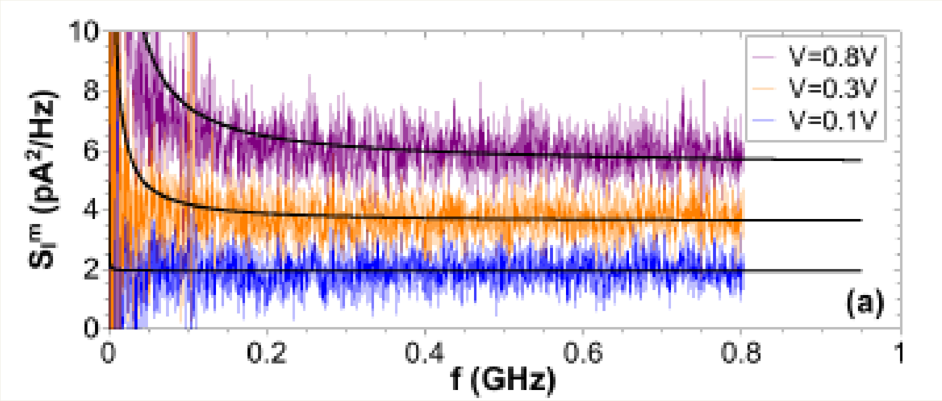
$P=\Sigma_K\ T^4$

$$\boxed{\Sigma_{e-ph}=\frac{\pi^2D^2{k_B}^4\mu_F}{15\rho_m\hbar^5s^2\ {v_F}^5}\le 10mW/m^2K^4\ll P_{Kapitza}\approx 10W/m^2K^4}$$

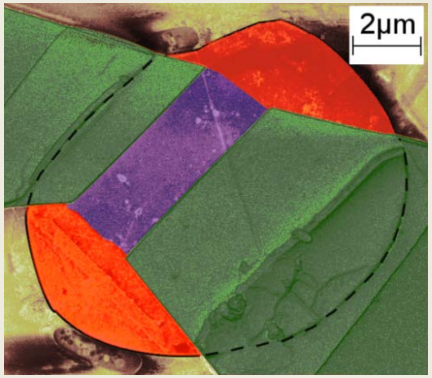
Very weak AC-phonon coupling => very hot electrons

RF-noise thermometry

Thermal + 1/f noise

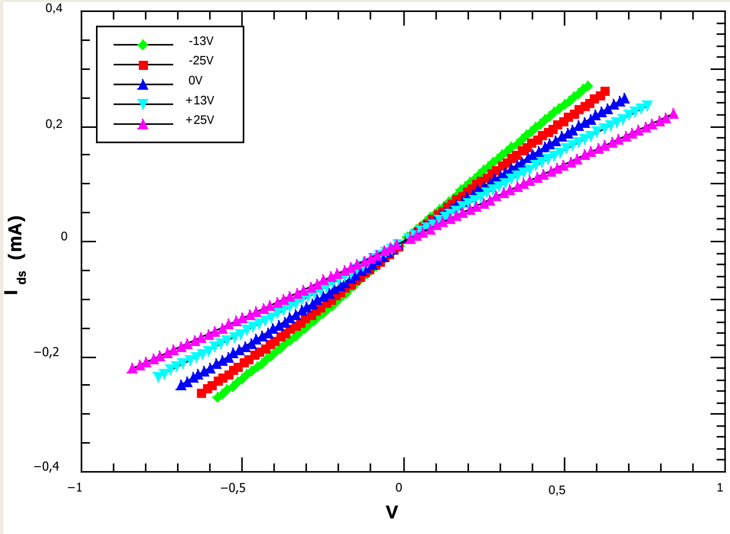


diffusive G/hBN sample



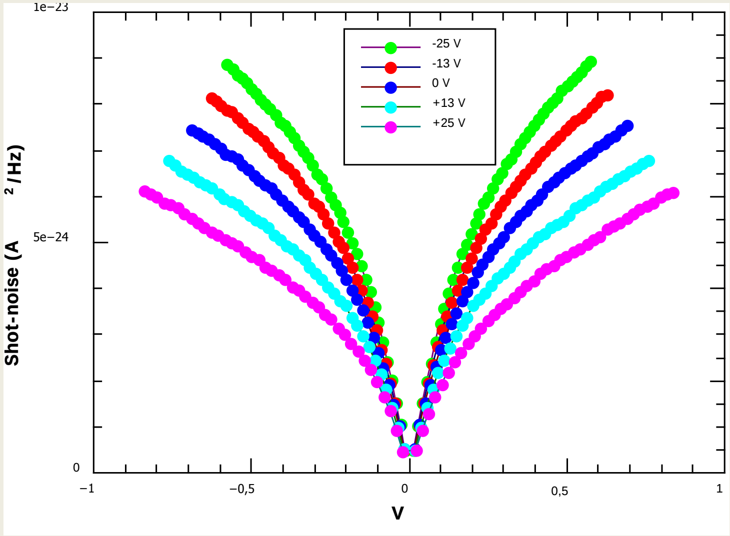
very-BN™
hBN powder
by St Gobain

linear I-V's (diffusive)



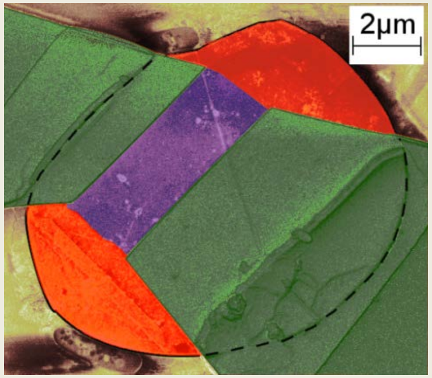
A. Betz et al. / Phys. Rev. Lett. 109 (2012) 056805

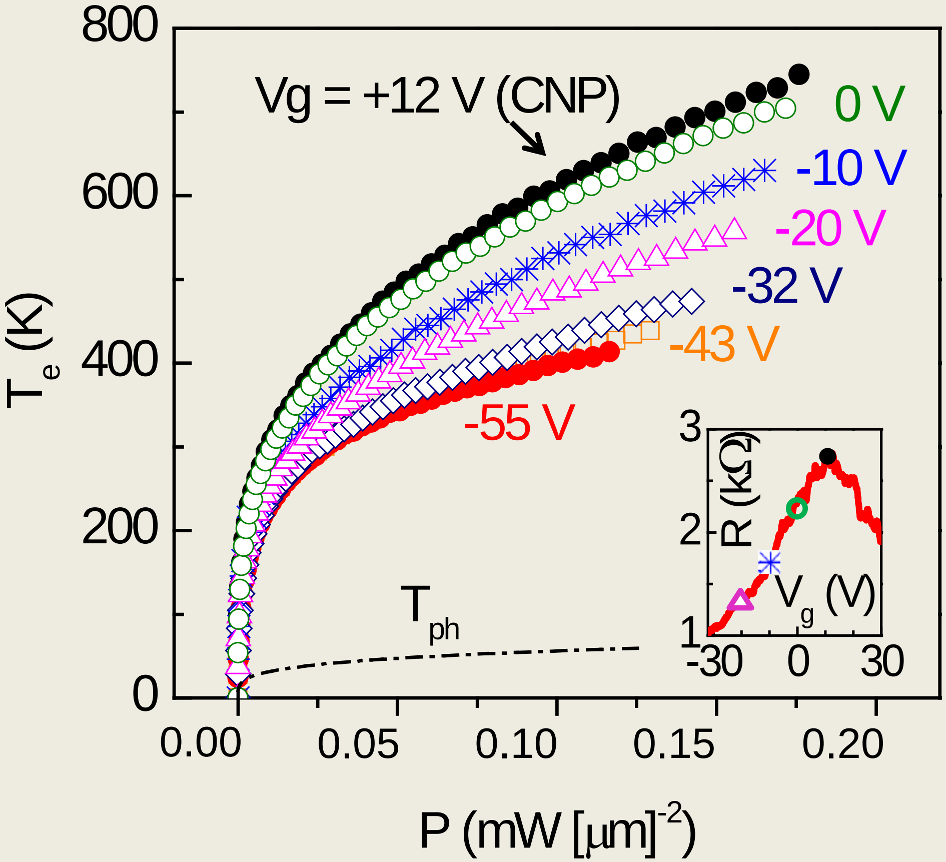
noise: from linear to sublinear



RF noise thermometry

$$\langle T_e \rangle \equiv R\, S_I / 4k_B \quad with \quad P = V \times I$$

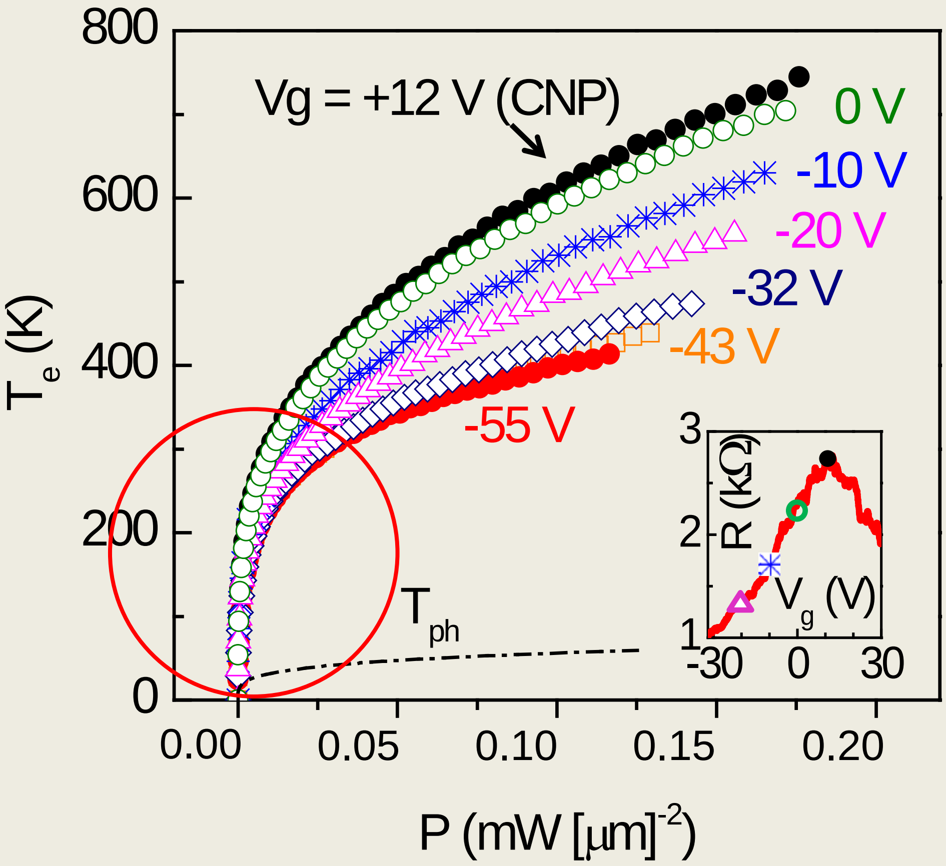


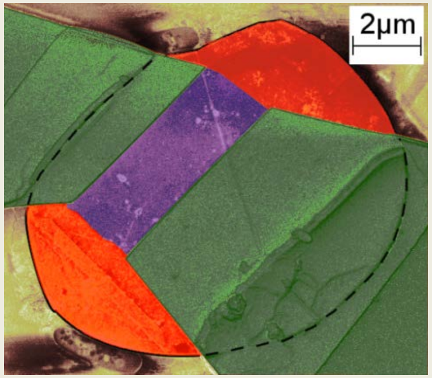


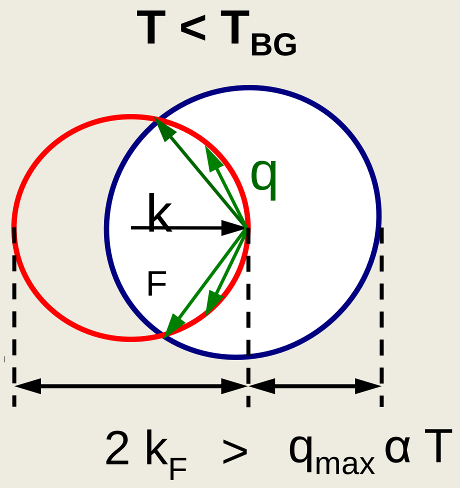
A. Betz et al. / Phys. Rev. Lett. 109 (2012) 056805
A. Betz et al. / Nat. Phys. 9 (2012) 109

RF noise thermometry

$$\langle T_e \rangle \equiv R\, S_I/4k_B \quad with \quad P = \mathrm{V} \times I$$







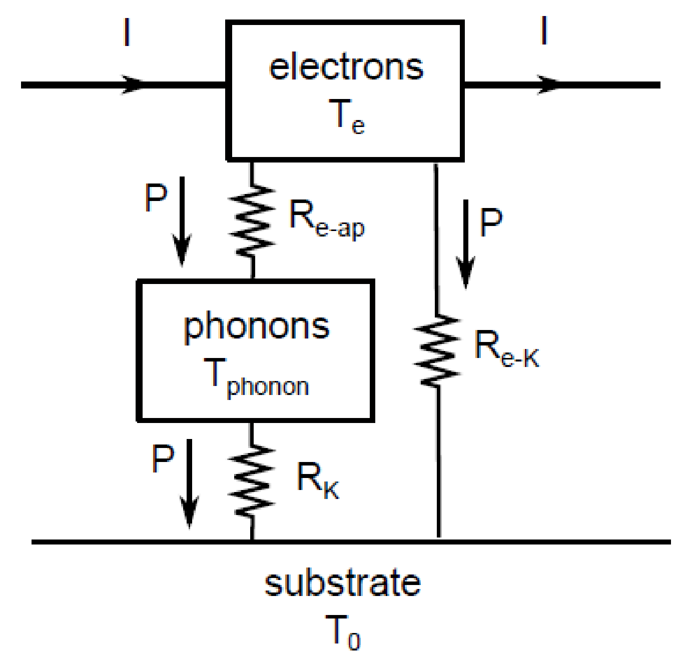
A. Betz et al. / Phys. Rev. Lett. 109 (2012) 056805
A. Betz et al. / Nat. Phys. 9 (2012) 109

Bloch-Gruneisen regime (large doping)

Heat equation (steady state)

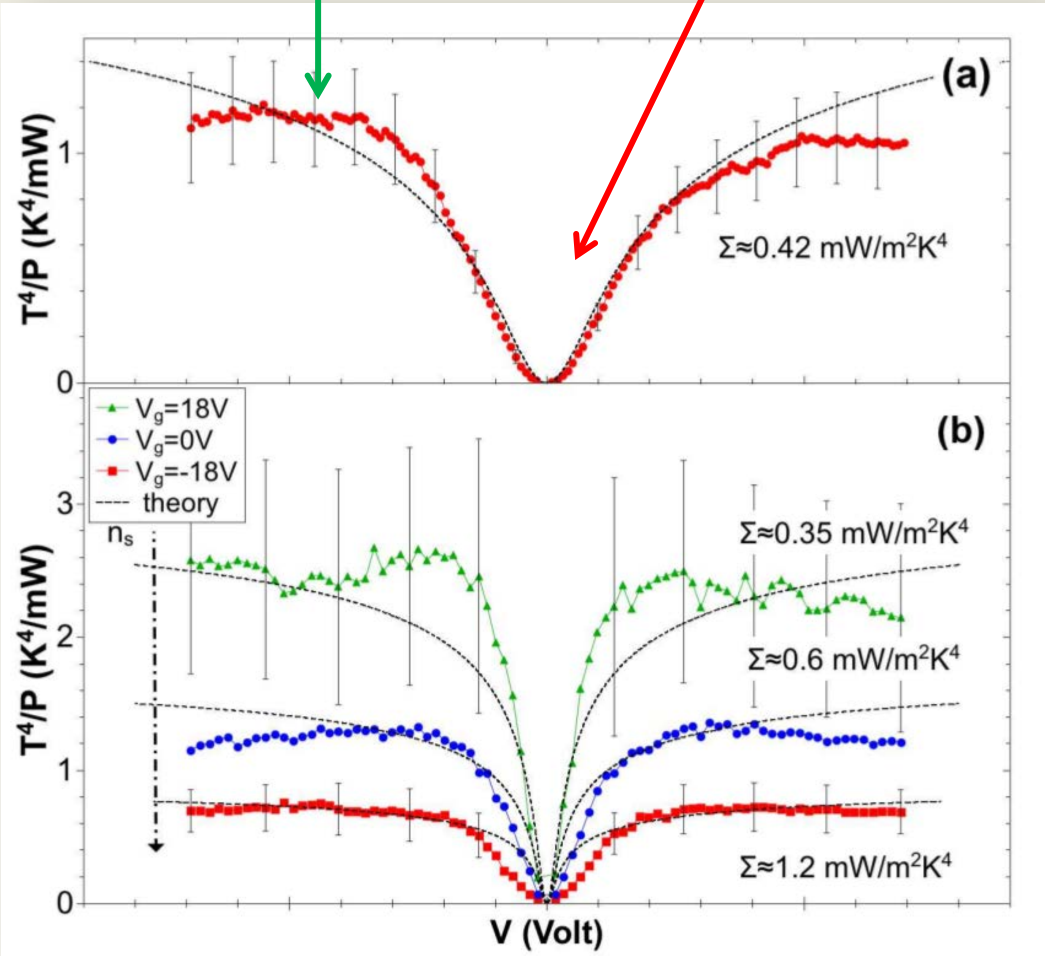
$$\frac{V^2}{R} = LW\Sigma_{e-ph}\ {T_e}^4 - \frac{L_o}{2R}\frac{L^2\partial^2\ {T_e}^2}{\partial x^2}$$

$L_o = \pi^2 {k_B}^2/3e^2$ (Lorenz number)



T^4-BG - hot electrons

T^2-WF - hot electrons



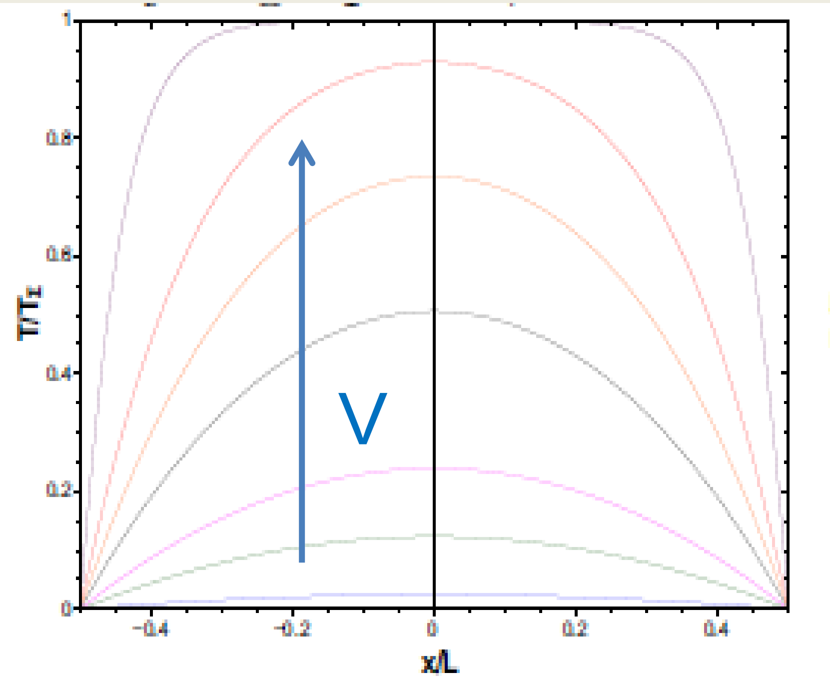
A. Betz et al. / Phys. Rev. Lett. 109 (2012) 056805

Bloch-Gruneisen regime (large doping)

Heat equation (steady state)

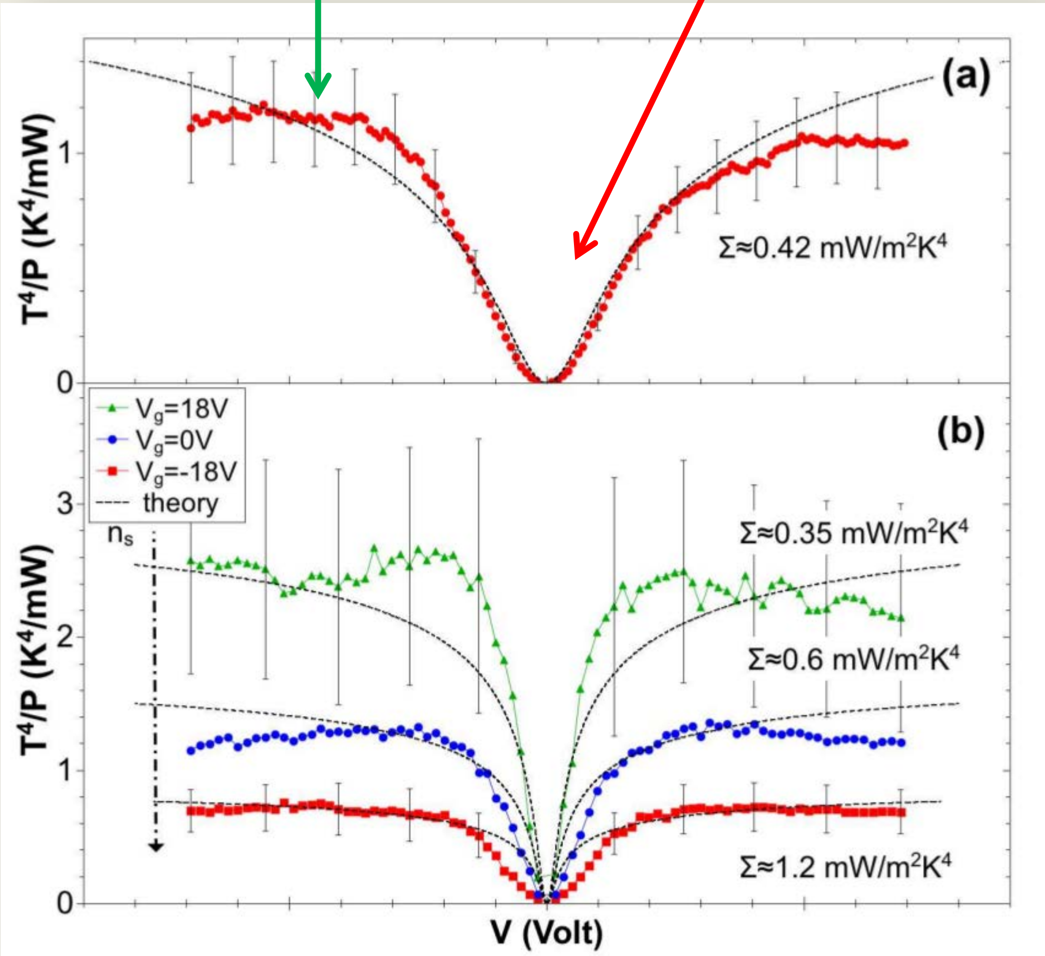
$$\frac{V^2}{R} = LW\Sigma_{e-ph}\ {T_e}^4 - \frac{L_o}{2R}\frac{L^2\partial^2\ {T_e}^2}{\partial x^2}$$

$L_o = \pi^2 {k_B}^2/3e^2$ (Lorenz number)



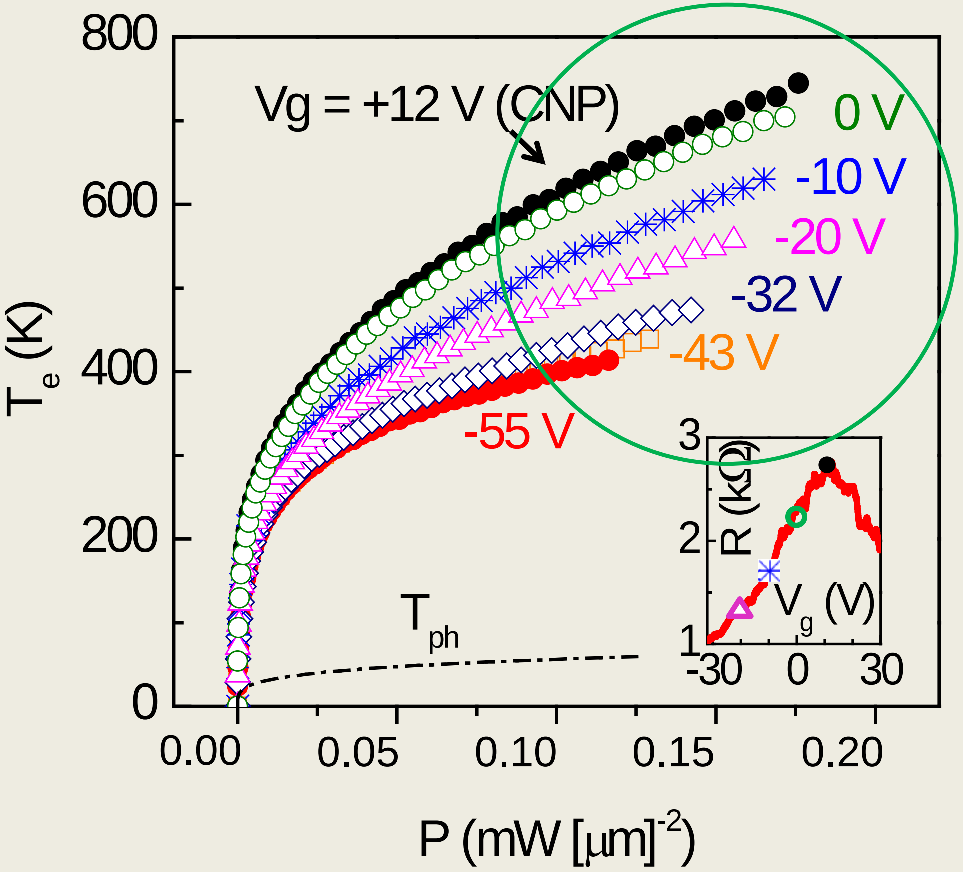
T⁴-BG - hot electrons

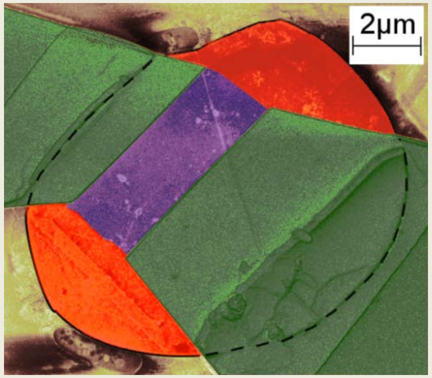
T²-WF - hot electrons

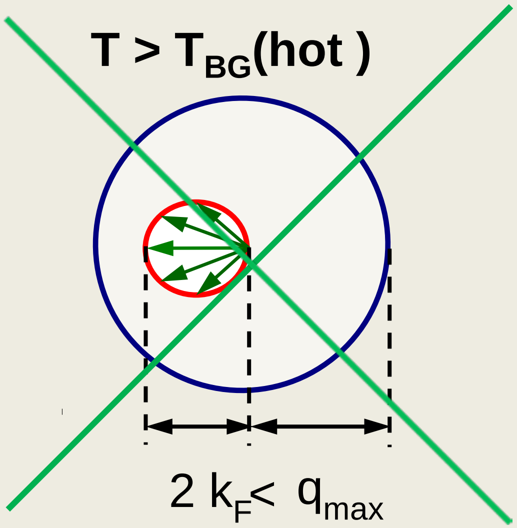


A. Betz et al. / Phys. Rev. Lett. 109 (2012) 056805

Hot-phonon regime (low doping)

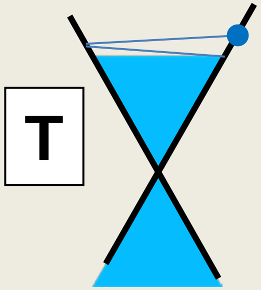




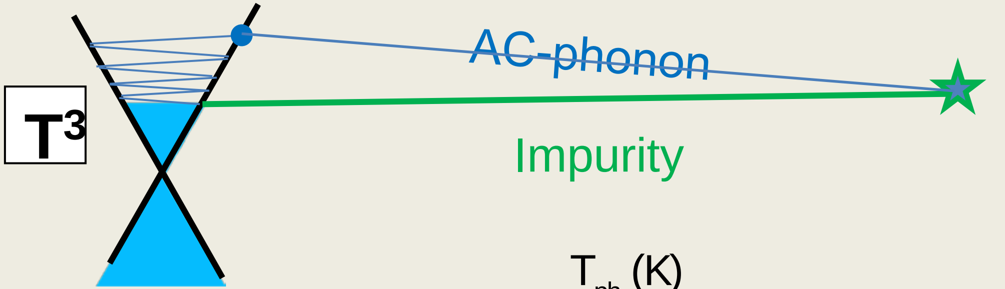


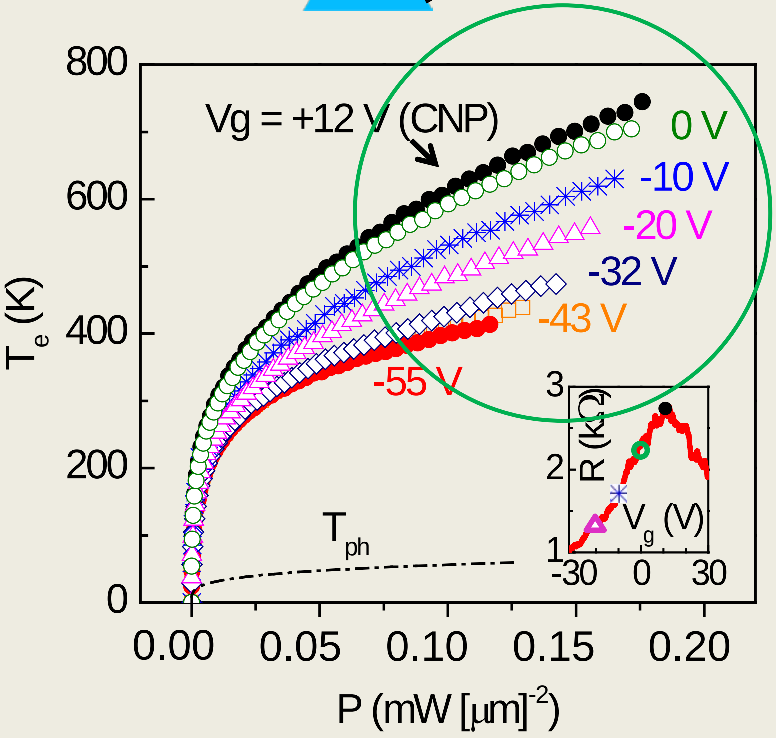
The « supercollision » regime

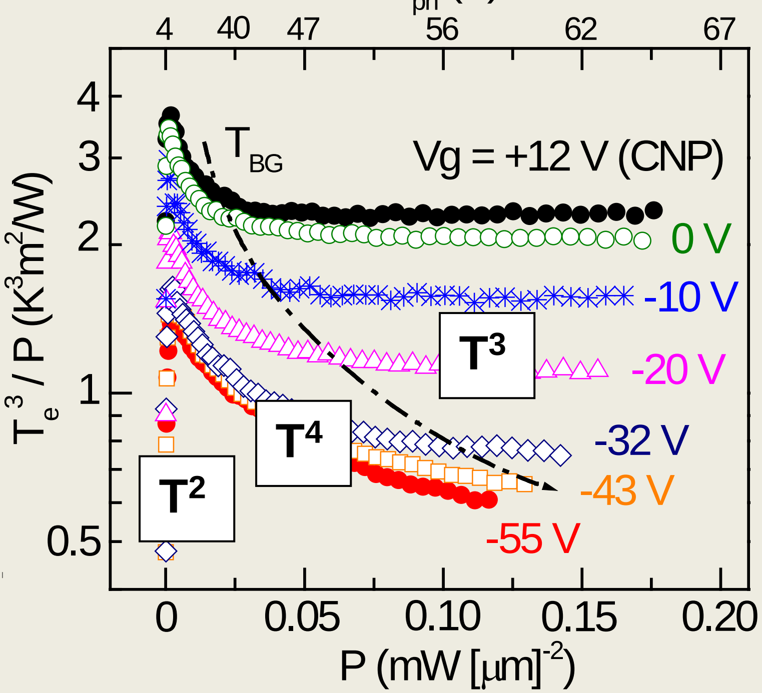
Ordinary electron-phonon collision



3-body electron-phonon impurity

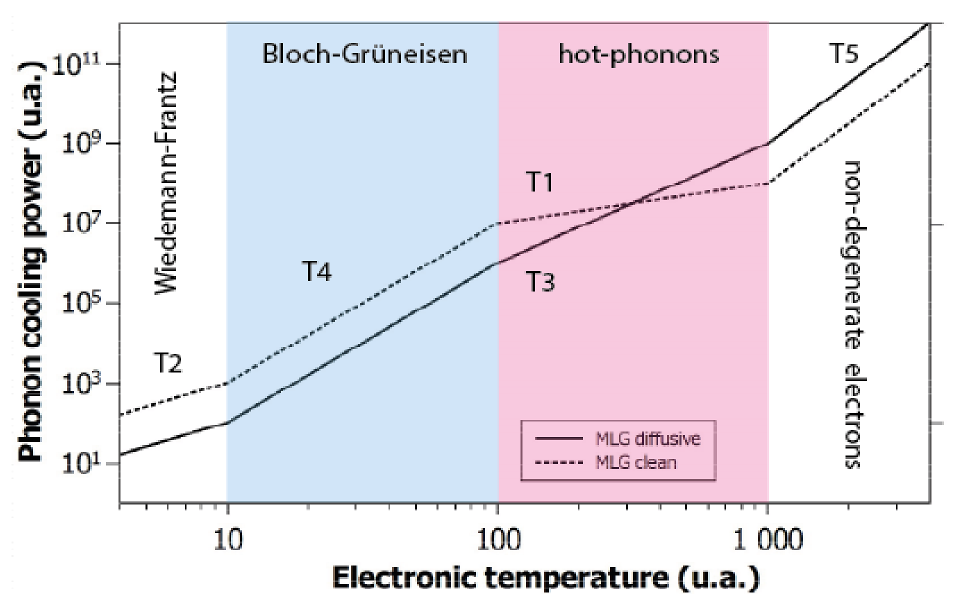


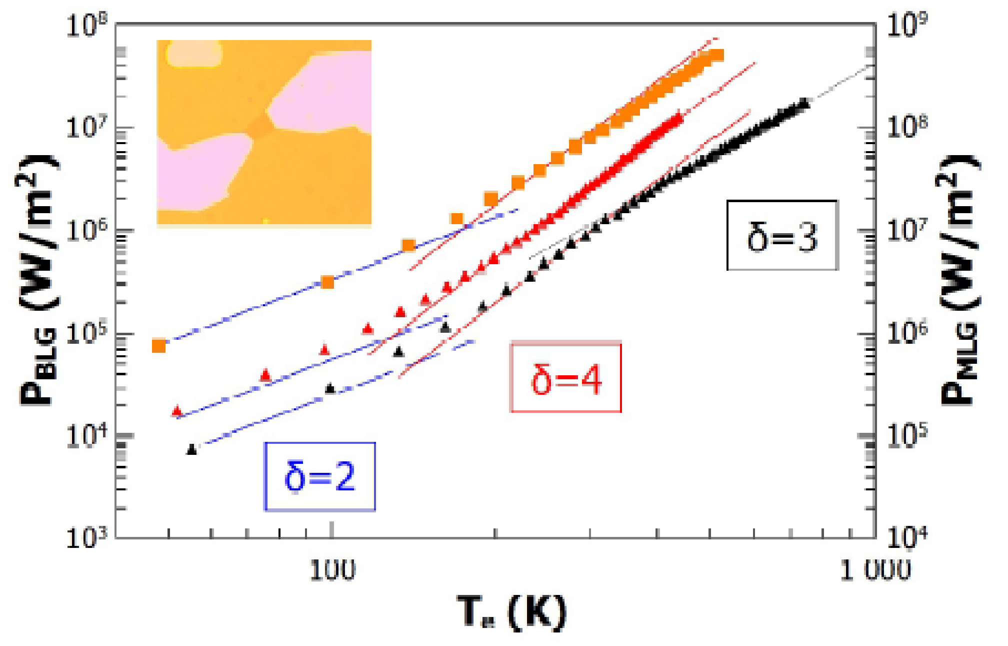




Exp. : Betz et al. / Nat. Phys. 9 (2012)
Th. : Song-Levitov / PRL (2013)

Acoustic-phonon cooling (summary)



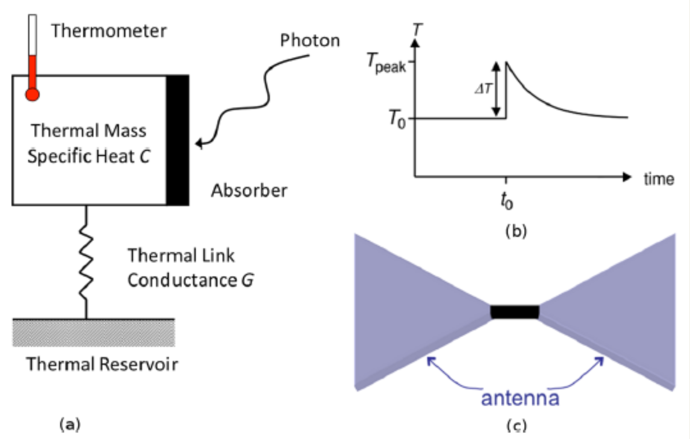


C. Voisin and B. Plaçais / special issue “hot carriers in graphene”, *J. Phys.: Cond. Matter 27 (April 2015)*

T^4	*A. Betz et al. , Phys. Rev. Lett. 109 (2012) 056805*
T^4	*K.C. Fong and K.C. Schwab, PRX 2, (2012)* 031006
T^3	*J.C.W. Song et al., Phys. Rev. Lett. 109 (2012) 10660*
T^3	*A. Betz et al., Nat. Phys. 9 (2012) 109*
T^3	*M.W. Graham et al., Nat. Phys. 9 (2012) 109; Nano Letters 13, (2012) 5497*
T^3	*M.W. Graham et al., Nat. Phys. 9 (2012) 109; Nano Letters 13, (2012) 5497*
T^3	*…/…*
T^3 ,T^5	*A. Laitinen et al. / Nano Lett..14 (2012) 3009.*

Acoustic-phonon cooling (applications)

Hot electron Bolometers for single ptonon detection :
tiny electronic heat capacity + weak electron-phonon relaxation



$$\varepsilon\delta(t) = LW\sum T_e{}^4 - \frac{L_o L^2}{2R}\frac{\partial^2 T_e{}^2}{\partial x^2} + \gamma LW\frac{\partial T_e{}^2}{\partial t}$$

e.g. : Yale group :

McKitterick et al., JAP 113, 044512 (2013)

McKitterick et al., JLTP 176, 291 (2014)

B. Karasik et al., JLTP 176, 249 (2014)

McKitterick et al., JPCM 27 164203 (2015)

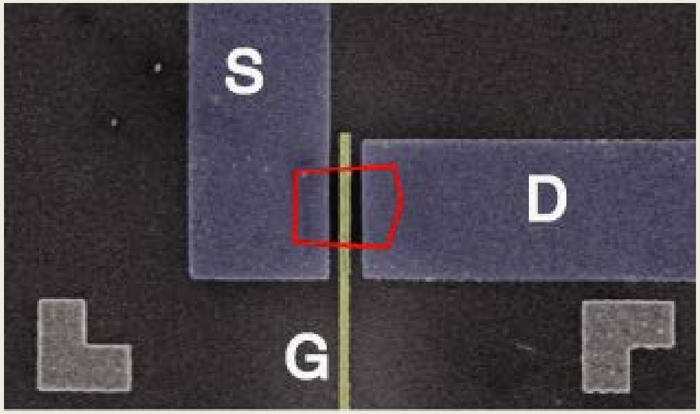
E. Pallecchi et al., JPAP 47, 094004 (2014)

P=$\Sigma_{e-ph}T^4$

$= 100\frac{aW}{\mu m^2}(T < 1K)$

$= 1\text{photon}/100\text{pS}$

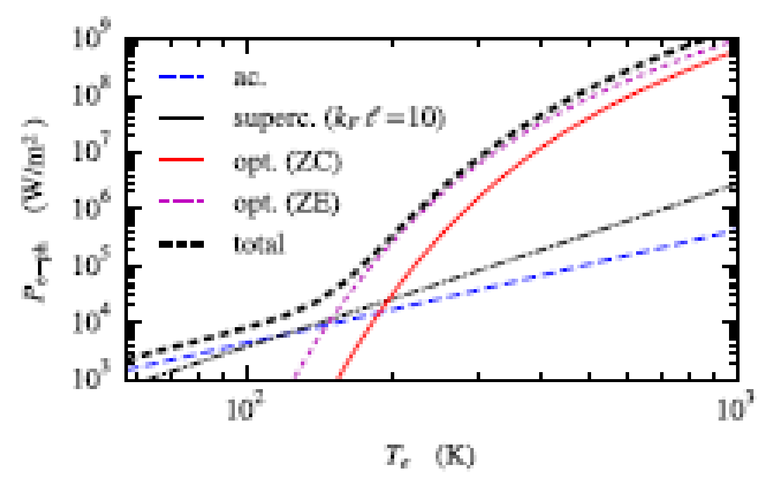
Electronics : Hot-electrons limit the resolution of RF charge detectors



e.g. : LPA graphene group :

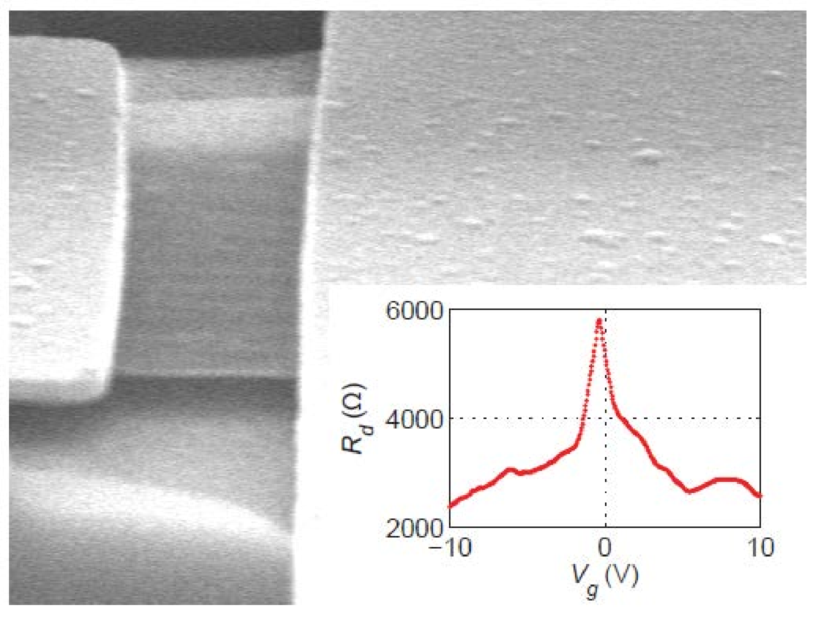
E. Pallecchi et al., JPAP 47, 094004 (2014)

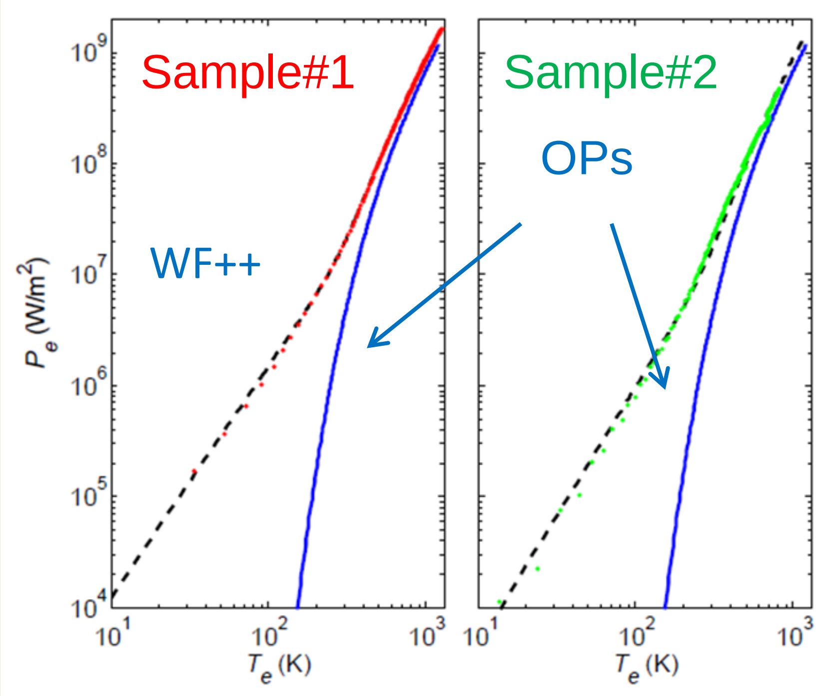
Hot electrons reveal optical-phonons



OP-phonon energy ≈ 2000 K

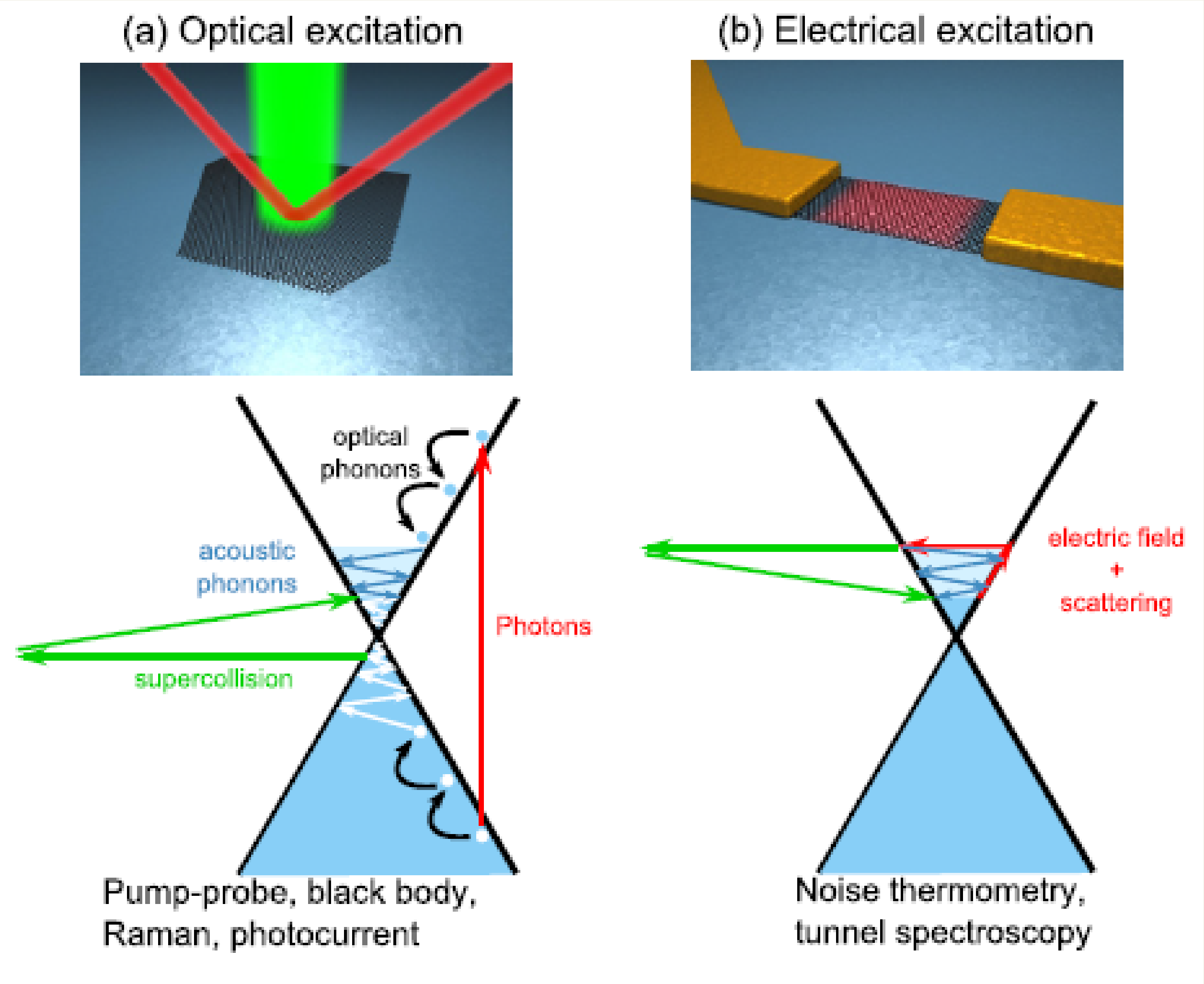
Use suspended BLG :
=> rid of substrate phonons
=> AC-phonon is suppressed
=> But a large WF++





A. Laitinen et al., Phys. Rev. B 91, 121414(R) (2015)

Hot electrons and substrate-phonons

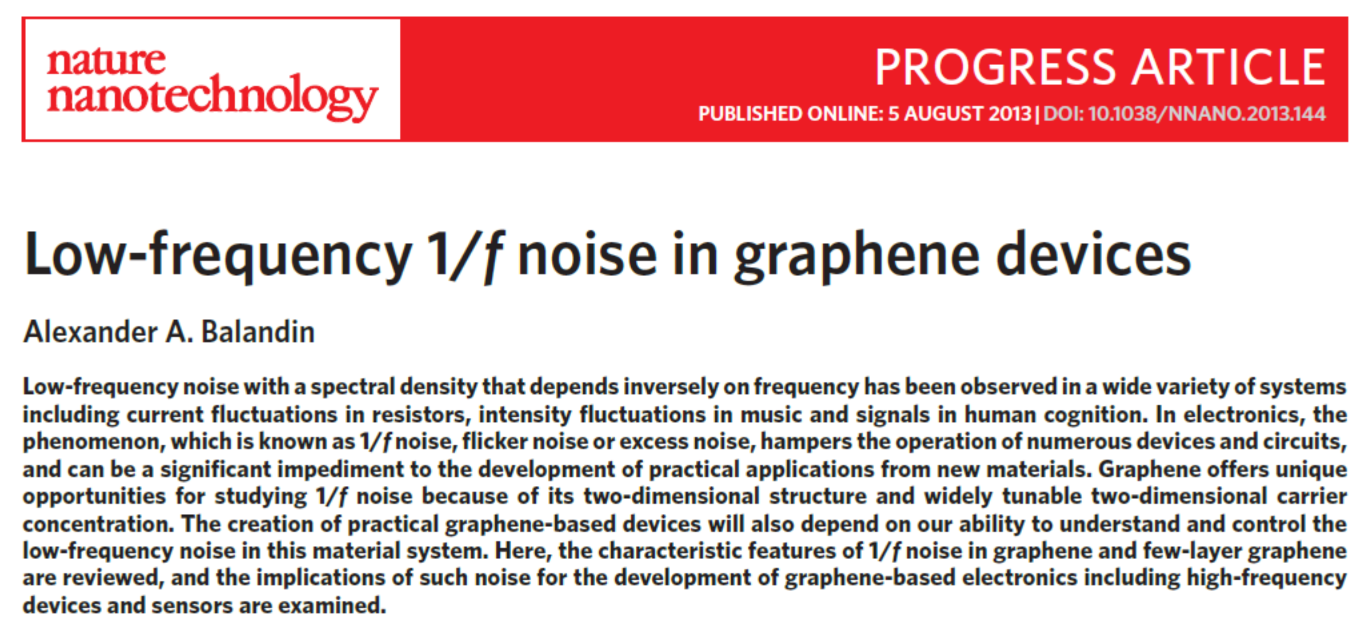


Brunel, Berthou et al., J. Phys. : Condens. Matter 27, 164208 (2015)

UPoN1: Benchmarking optical and Joule heating

UPoN2: Investigate interactions with substrate polar phonons (SPPs)

Low frequency 1/f noise in graphene



nature
nanotechnology

PROGRESS ARTICLE

PUBLISHED ONLINE: 5 AUGUST 2013 | DOI: 10.1038/NNANO.2013.144

Low-frequency 1/*f* noise in graphene devices

Alexander A. Balandin

Low-frequency noise with a spectral density that depends inversely on frequency has been observed in a wide variety of systems including current fluctuations in resistors, intensity fluctuations in music and signals in human cognition. In electronics, the phenomenon, which is known as 1/*f* noise, flicker noise or excess noise, hampers the operation of numerous devices and circuits, and can be a significant impediment to the development of practical applications from new materials. Graphene offers unique opportunities for studying 1/*f* noise because of its two-dimensional structure and widely tunable two-dimensional carrier concentration. The creation of practical graphene-based devices will also depend on our ability to understand and control the low-frequency noise in this material system. Here, the characteristic features of 1/*f* noise in graphene and few-layer graphene are reviewed, and the implications of such noise for the development of graphene-based electronics including high-frequency devices and sensors are examined.

UPoN3 : new clues on 1/f noise and Hooge's law using tunable graphene ?
See next talk by M. Macucci

Hot-plasmon noise in graphene

UPoN4 : investigate interplay between electrons and plasmons in 2D
See pm-talk by L. Varani

Outline

☐ Graphene as tunable 2D semi-metal

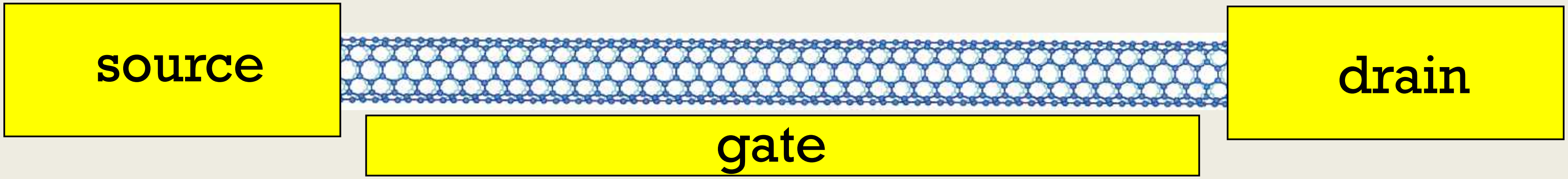
  a) Quantum shot noise in graphene (a brief review)
  b) Noise thermometry of hot electrons : electron-phonon in 2D
  c) Applications : HEBs, LNAs, Photo-detectors,

☐ Carbon Nanotubes as single mode nano-conductors (a review)

  a) Quantum shot noise in cabon nanotube devices
  b) Thermal noise in CNT wires and CNT-FETs: the noise conductance

Fabry-Pérot CNT devices

good contacts + ballistic carbon nanotube => Fabry-Pérot electronic cavity

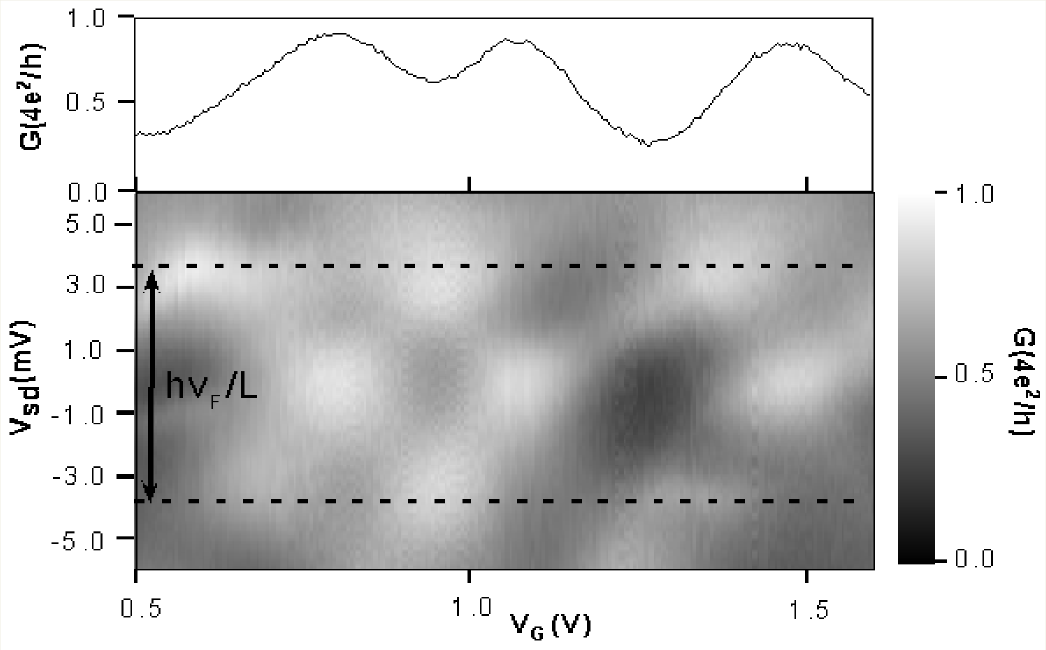


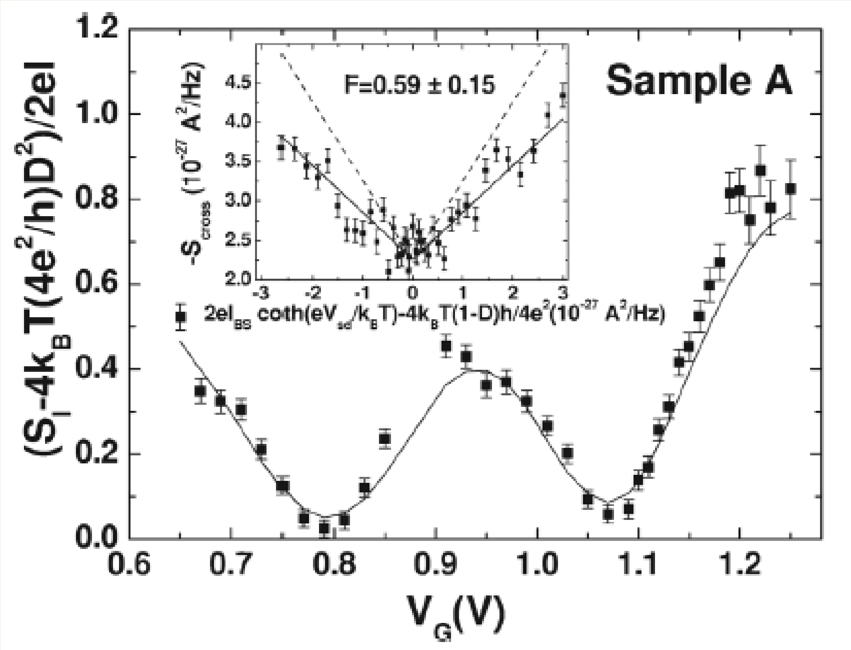
source

drain

gate

Checkerboard conductance pattern => QSN suppression : $S_I = 2eI(1-T)$

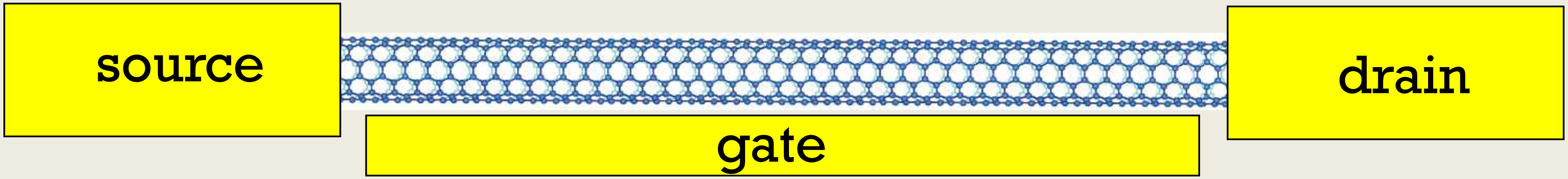




L. Hermann et al., Phys. Rev. Lett. 99 (2007) 156804

Kondo CNT-devices

Medium contacts + interactions + odd e-number => Kondo effect

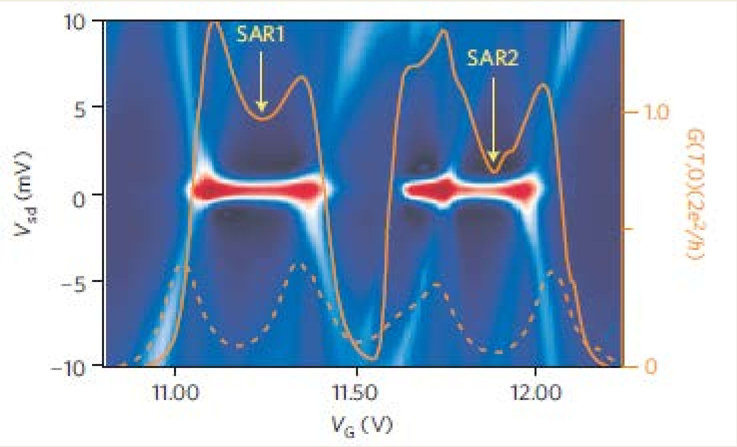


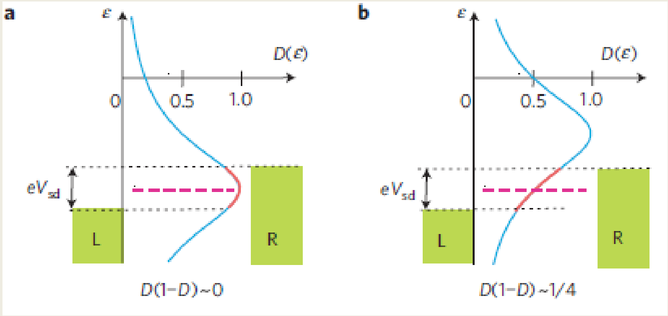
source

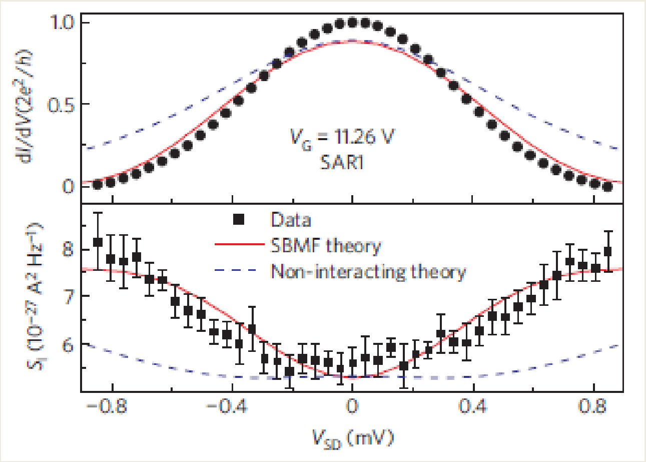
drain

gate

Kondo ridge => QSN suppression



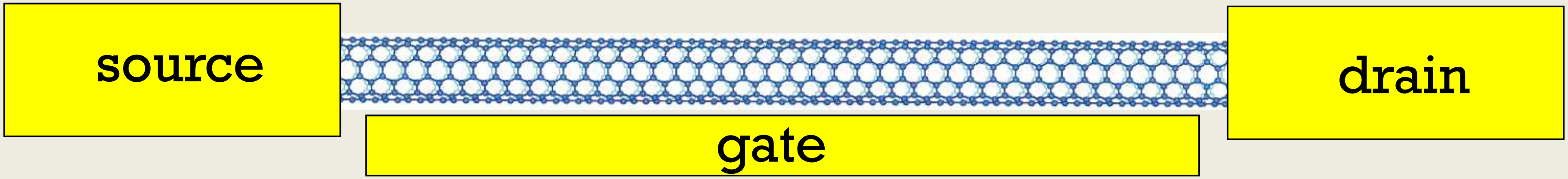




T. Delattre et al., Nat. Phys. 99 (2007) 156804

Coulomb-blockade devices

Poor contacts + interactions = quantum dot => Coulomb blockade

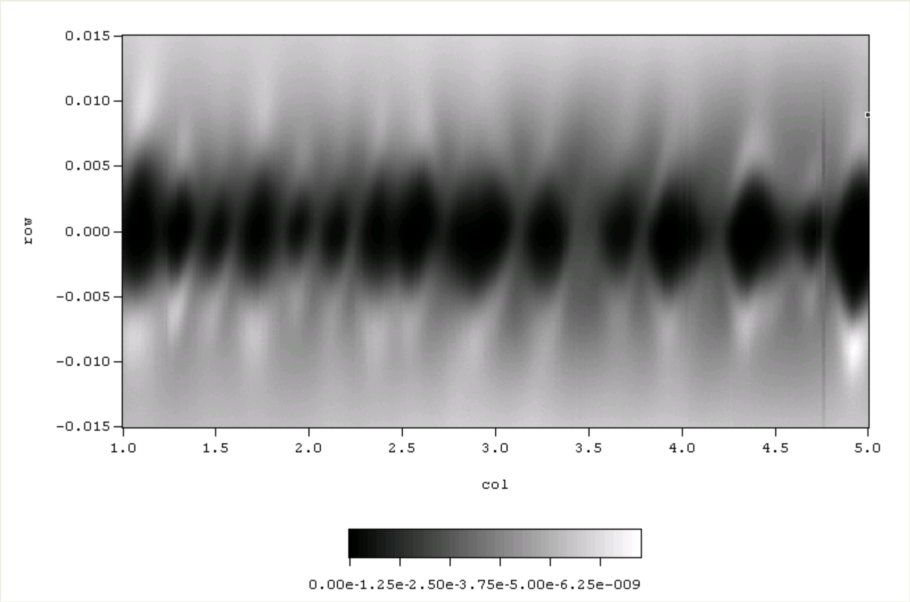


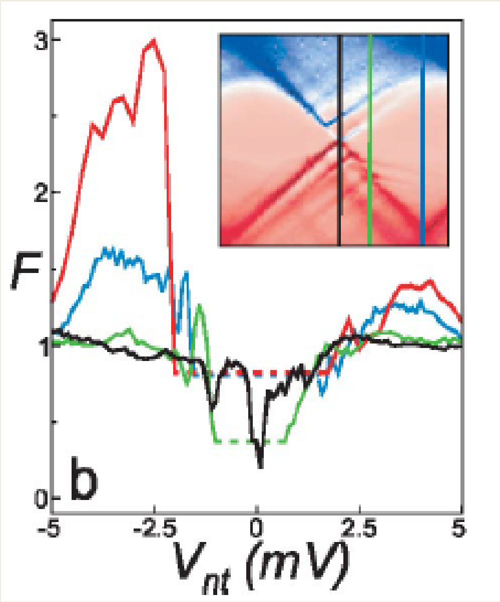
source

drain

gate

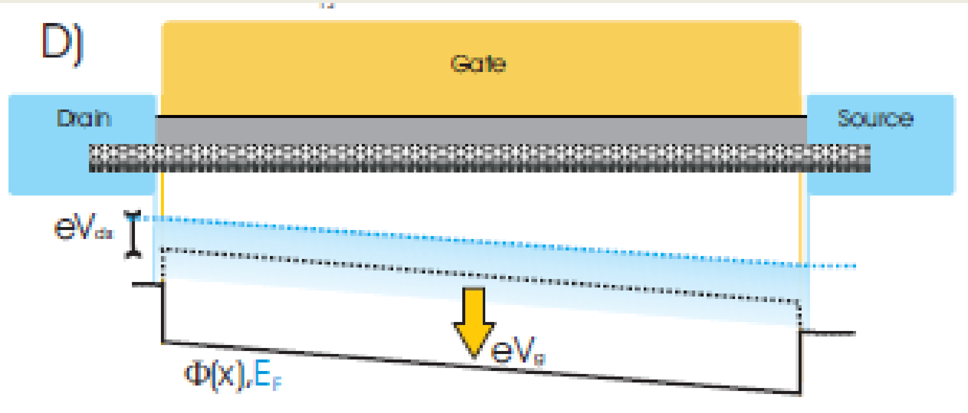
Coulomb Blockade + inelastic cotunneling => superpoissonian noise





E. Onac et al., Phys. Rev. Lett. 96, 026803 (2006)

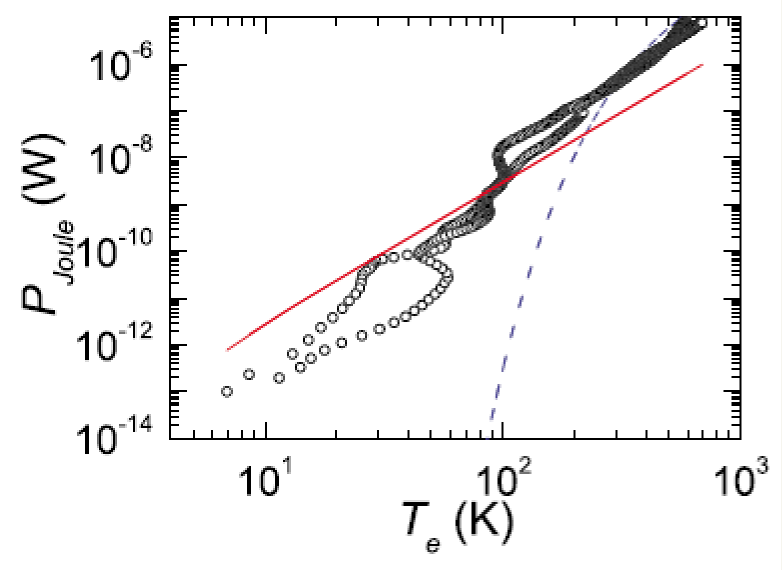
Hot electrons in 1D carbon nanotubes



$$P_{ph} = \sum \left({T_e}^{d+2} - {T_{ph}}^{d+2} \right)$$

Graphene : $P_{ph} = \sum \left({T_e}^4 - {T_{ph}}^4 \right)$

Carbon nanotube : $P_{ph} = \sum \left({T_e}^3 - {T_{ph}}^3 \right)$



F. Wu et al., Appl. Phys. Lett. 97, 262115 (2010)

The thermal noise conductance in FETs

Thermal noise in eld effect transistors *:* JA. van der Ziel, Proc. IRE 50, 1808 (1962)

Two-terminal conductors

$$S_I(\omega) = 4k_B T_e \times G_{diff}(\omega)$$

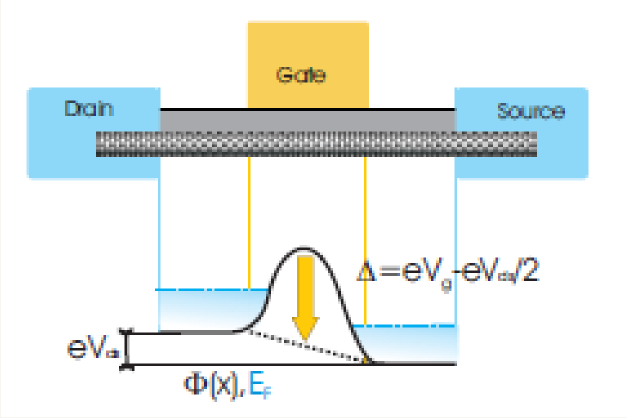
Three-terminal conductors

$$S_I(\omega) = 4k_B T_e \times G_{noise}$$

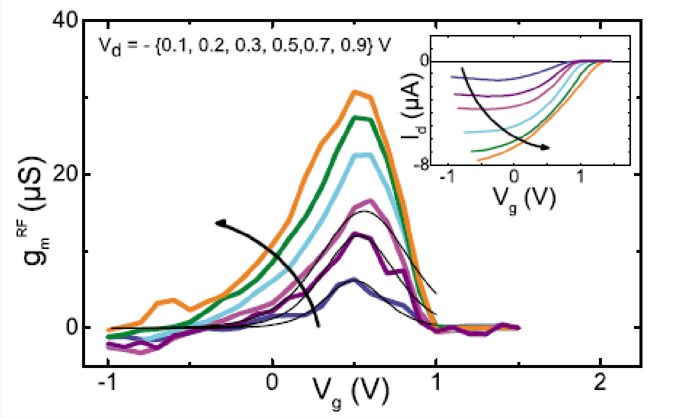
See also : talk on noise temperature fluctuations and the Noise Thermal Impedance by E. Pinsolle and B. Reulet

The noise conductance of nano-FETs

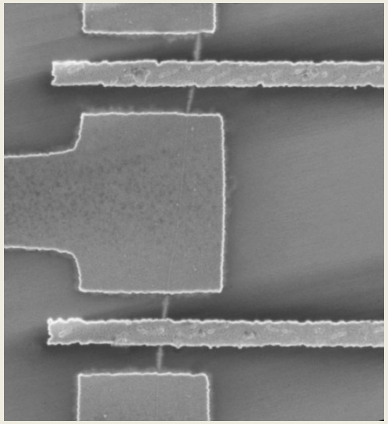
CNT-nano-FET



transconductance



GHz-CNT-FET



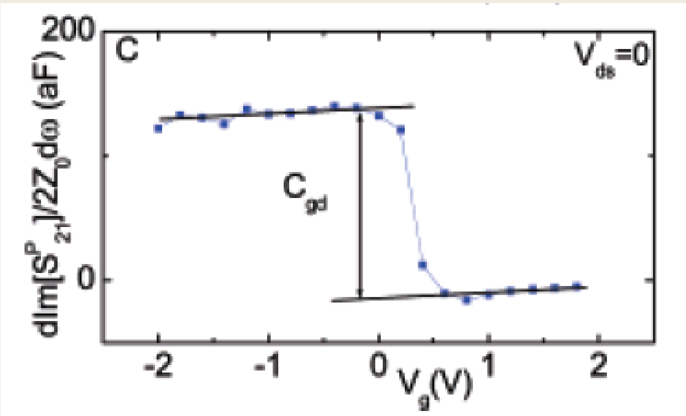
$$G_{noise} = G_{ds} + G_m \frac{C_Q}{2C_{gs}}$$

$$G_{ds} = \frac{4e^2}{h} \times f_d(\Delta)$$

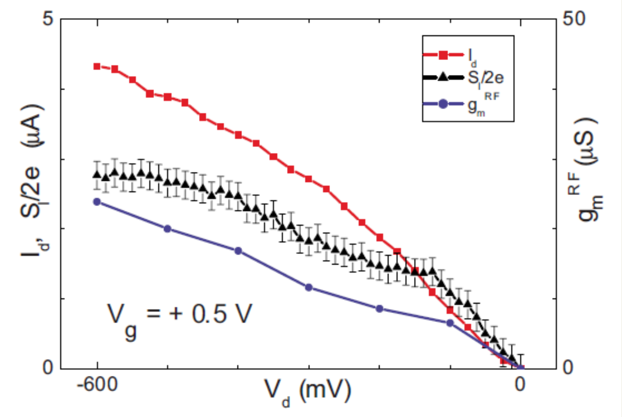
$$G_m = \frac{4e^2}{h} \times [f_s(\Delta) - f_d(\Delta)] \times \frac{C_{gs}}{C_Q}$$

$$G_{noise} = \frac{4e^2}{h} \times [f_s(\Delta) + f_d(\Delta)]$$

Quantum capacitance



current noise



J. Chaste et al., Nano Lett. 8, 525 (2008); J. Chaste et al., Appl. Phys. Lett. 96, 192103 (2010)

The end

Thank you for your attention