Scattering approach to disordered graphene

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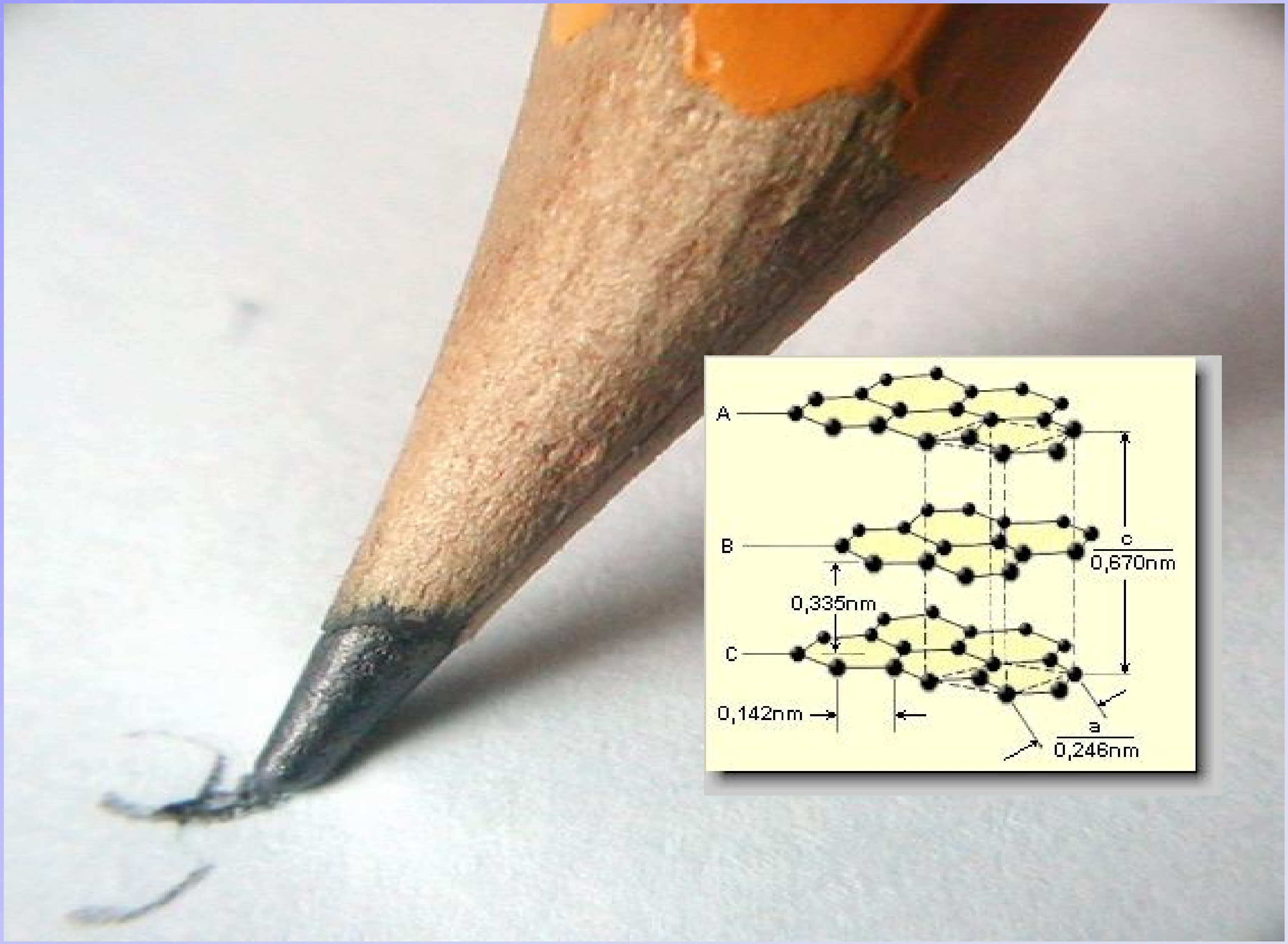
DPG Tagungen, Regensburg, March 2007

Graphene

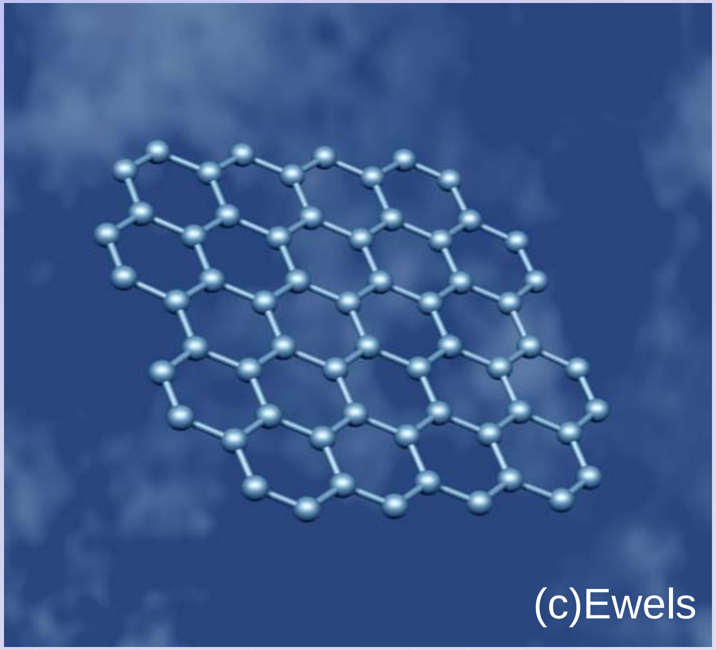
„the form of carbon that is found in pencils"



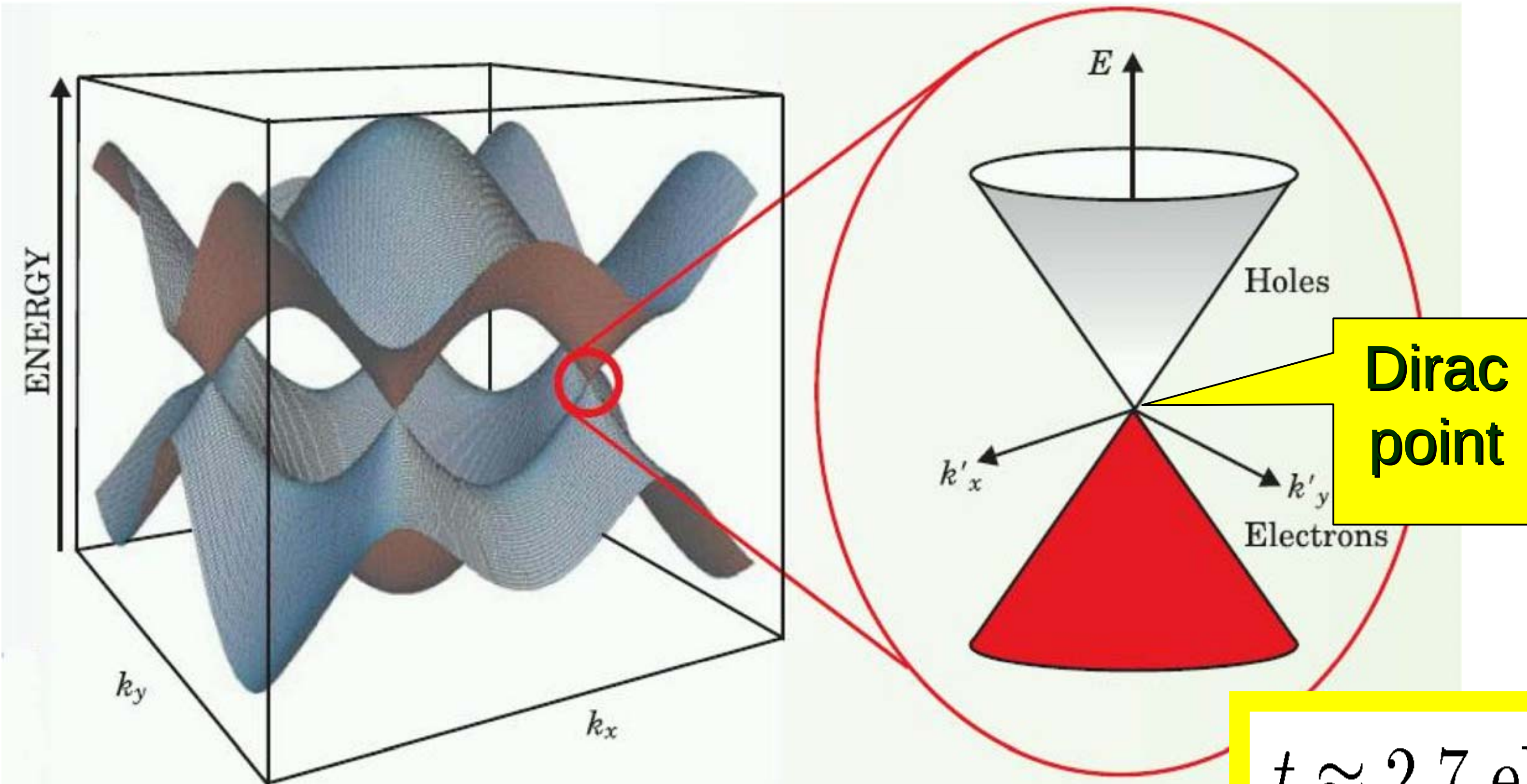
Discovery of graphene

- Fabrication: October 2004, Science
- Conductivity: July 2005, PNAS
- Quantum Hall: November 2005, Nature

Andre Geim
University of Manchester
UK



Band structure

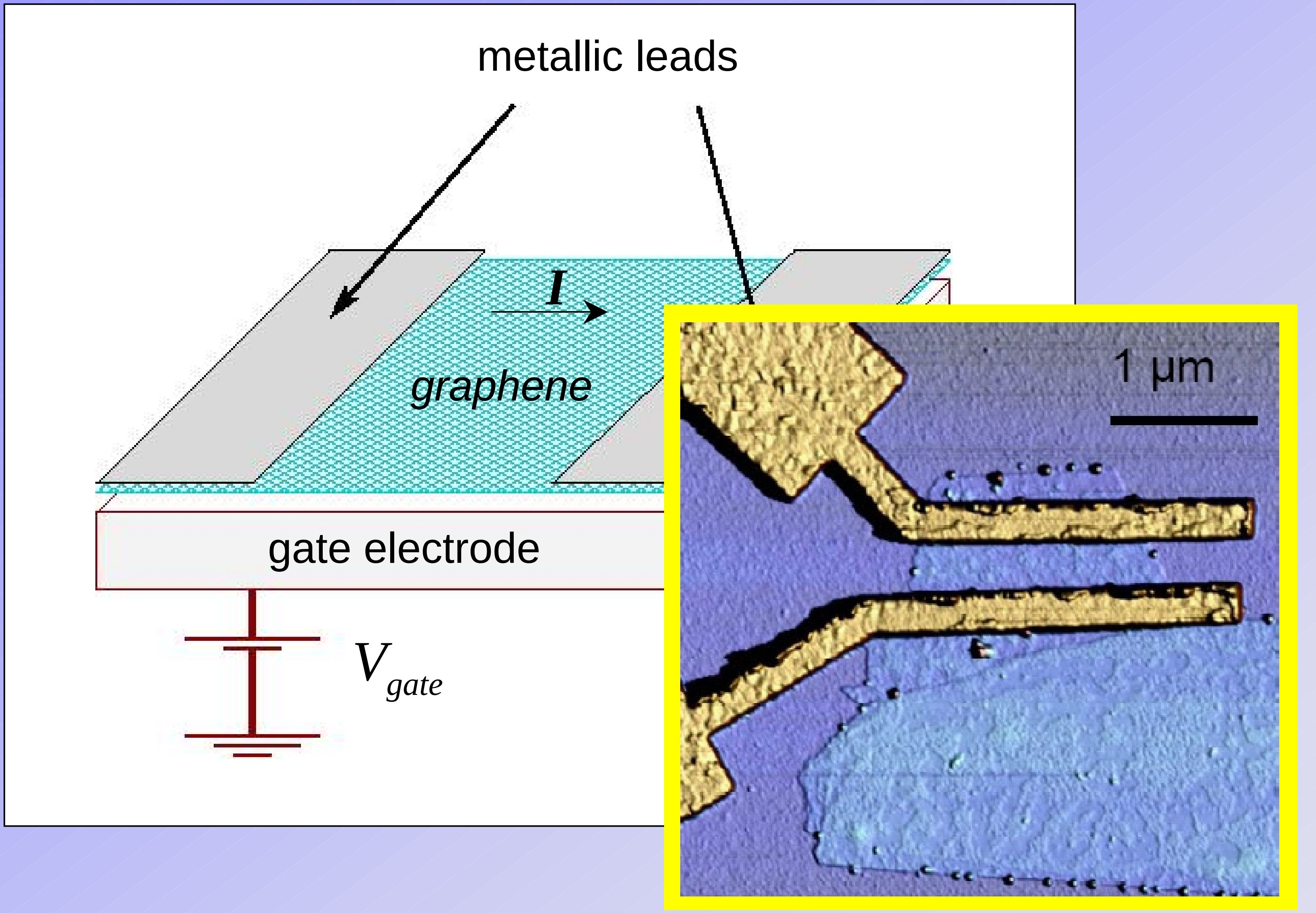


M. Wilson, Physics Today **59**, 21 (2006)

$t \approx 2.7$ eV

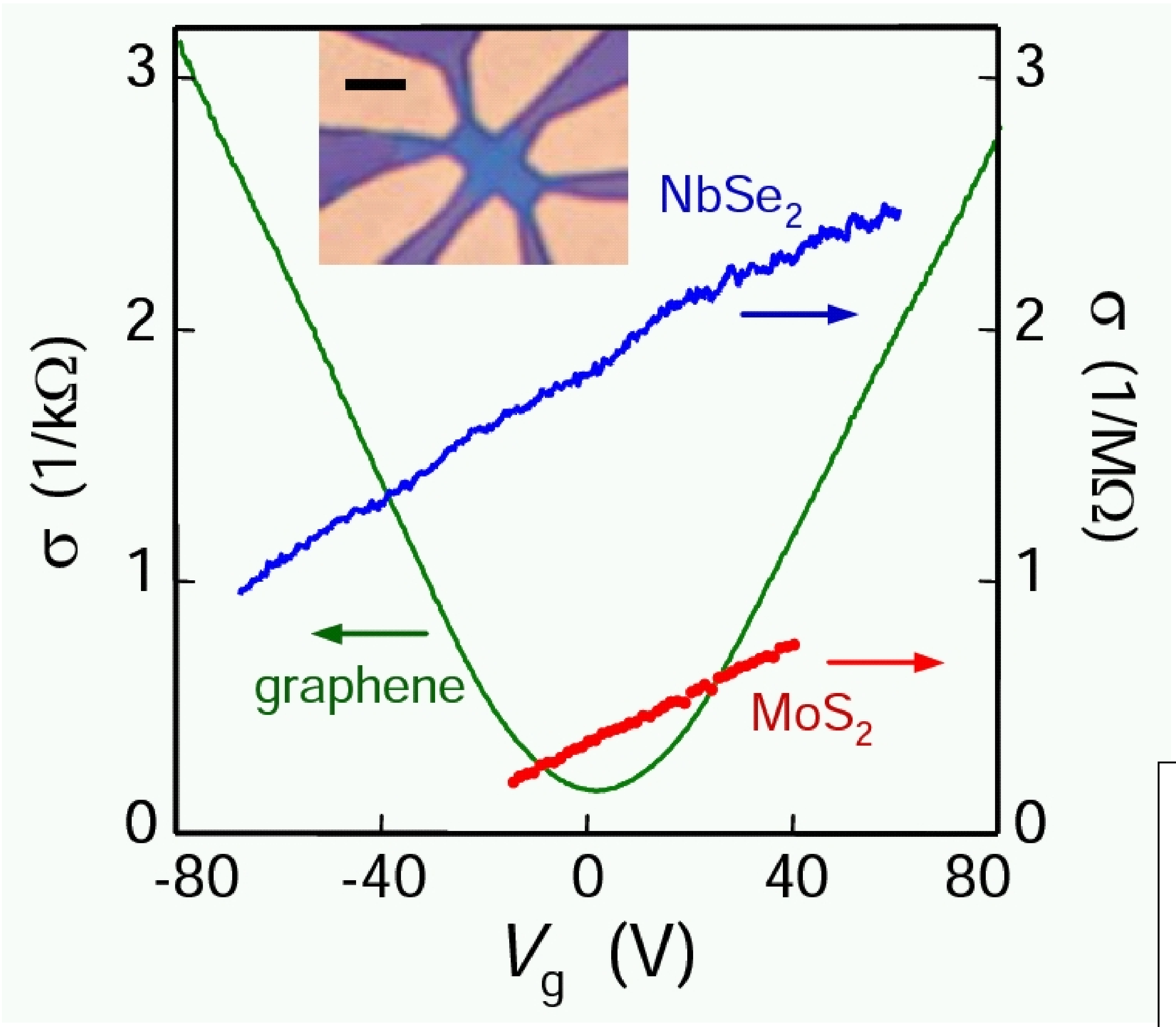
$$\varepsilon_{\mathbf{k}} = t\sqrt{3 + 2\cos(ak_x) + 4\cos(ak_x/2)\,\cos(ak_y\sqrt{3}/2)}$$

Transport in graphene



Heersche *et al.*

Conductivity



One of the first experiments of Manchester group

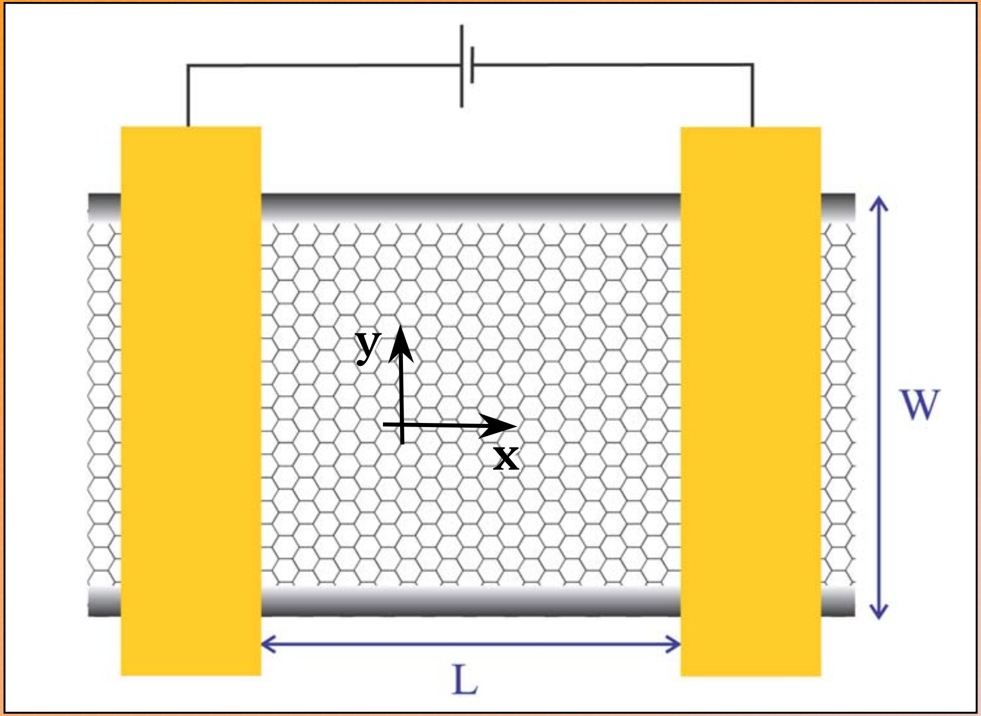
Novoselov *et al.*, PNAS **102**, 10451 (2005)

Universal minimal conductivity

$$\sigma_{\min} \approx \frac{4e^2}{h}$$

Current experiments dispute the universality of the value of $\sigma_{\min}$

Theory
for a ballistic strip of graphene



$$\Psi \propto e^{ik_x x + ik_y y}$$

$$\varepsilon = \hbar v \sqrt{k_x^2 + k_y^2}$$

Near the Dirac point
the states with complex *k*-vector
(evanescent modes)
are important!

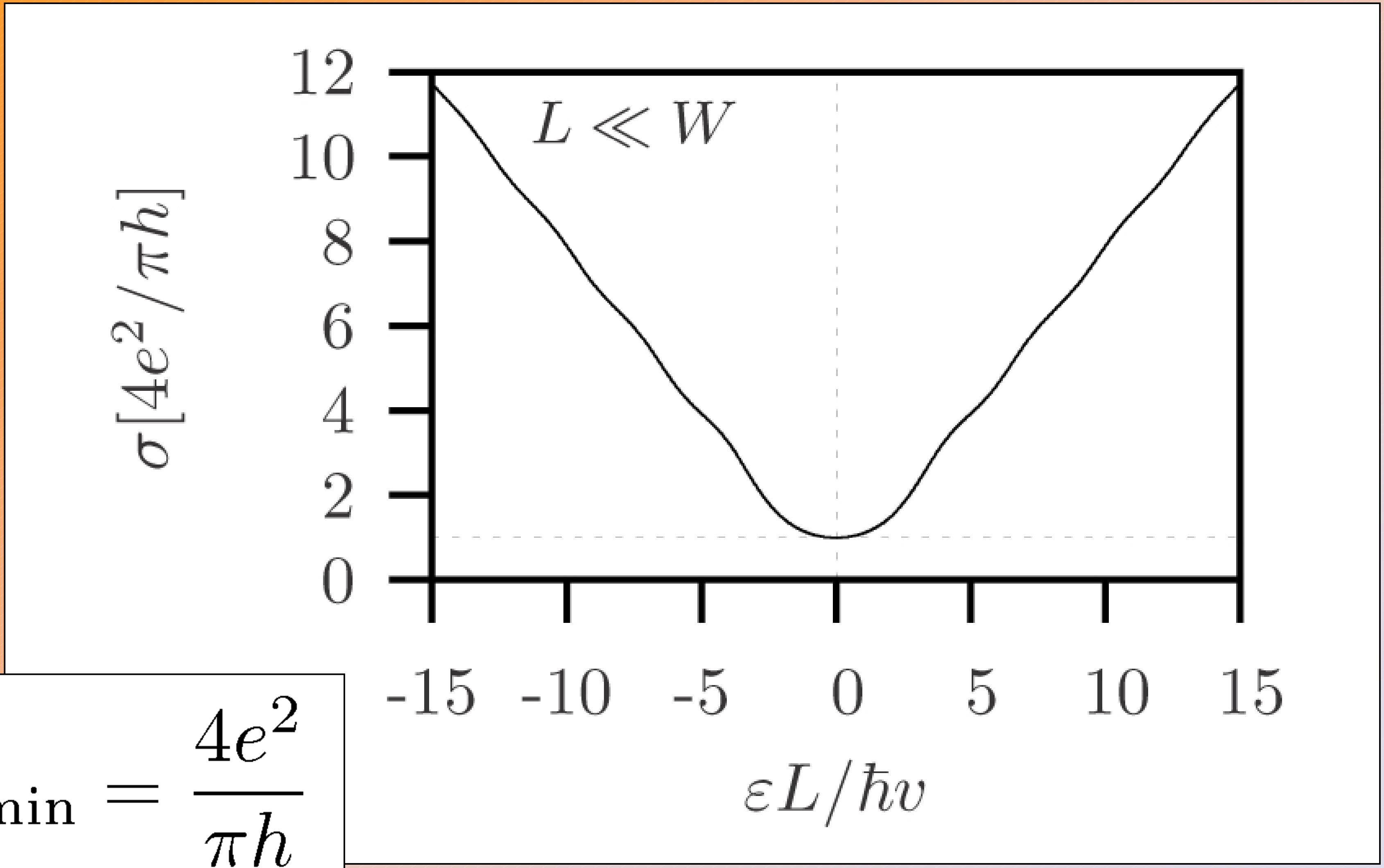
$$k_x \approx \pm i k_y$$

- J. Tworzydlo, B. Trauzettel, M. Titov, A Rycerz, and C. W. J. Beenakker

Sub-Poissonian shot noise in graphene

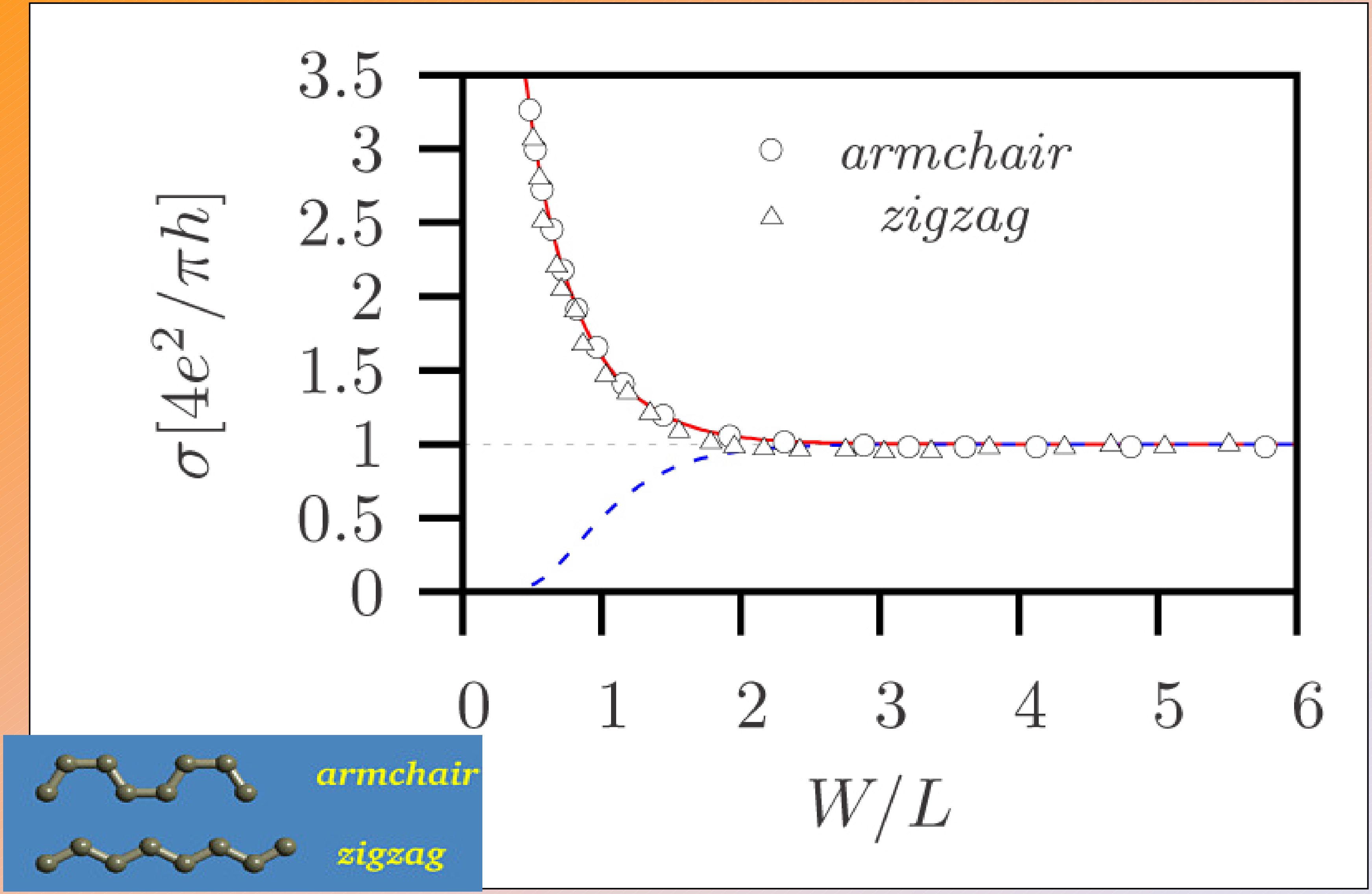
Phys. Rev. Lett. ***96****, 246802 (2006)*

Dependence on the gate voltage



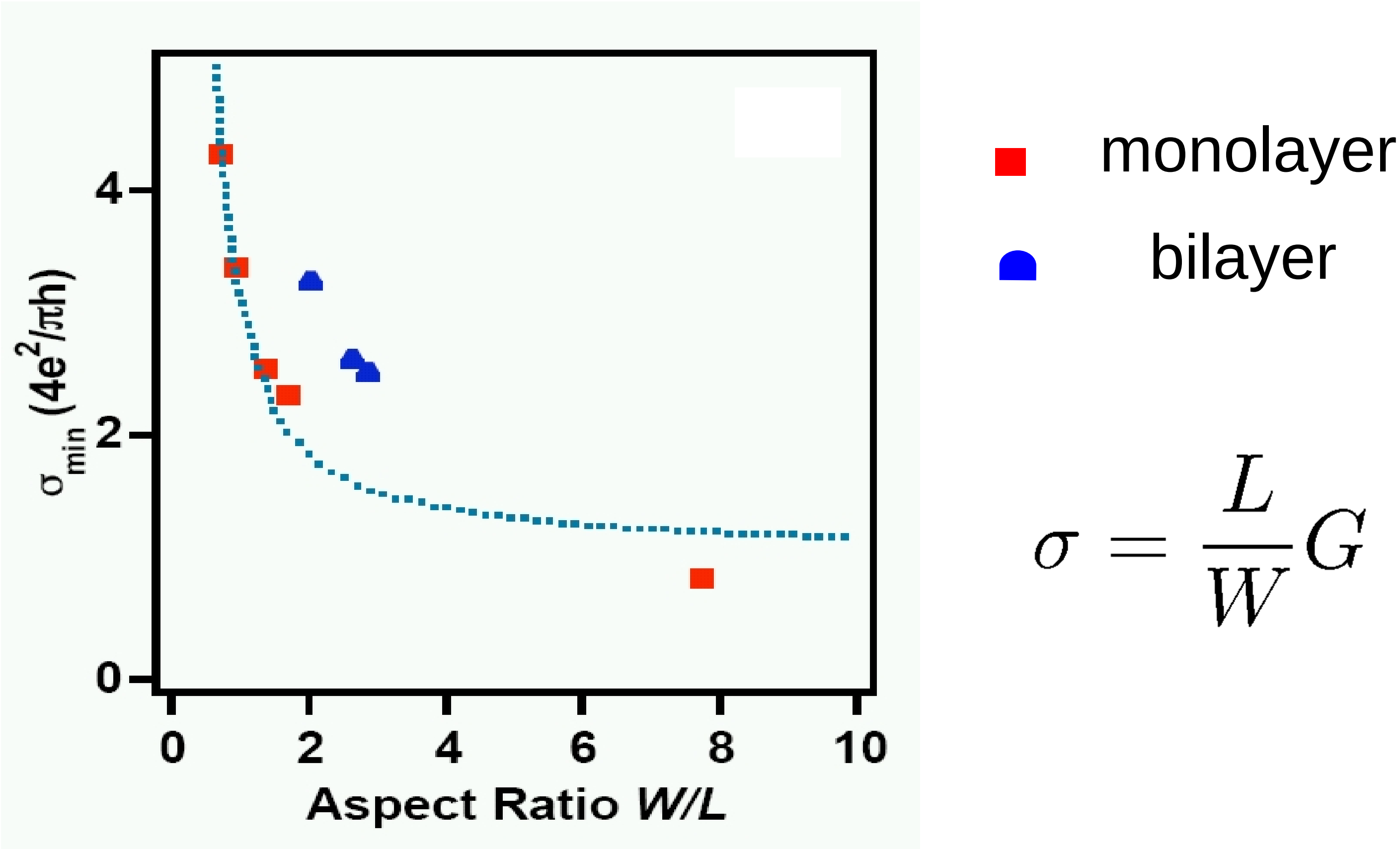
$$\sigma_{\min} = \frac{4e^2}{\pi h}$$

▪ ▪ ▪ Dependence on the aspect ratio



for different boundary conditions in the transversal direction

Comparison with experiments



$$\sigma = \frac{L}{W} G$$

F. Miao, S. Wijeratne, U. Coskun, Y. Zhang, C. N. Lau

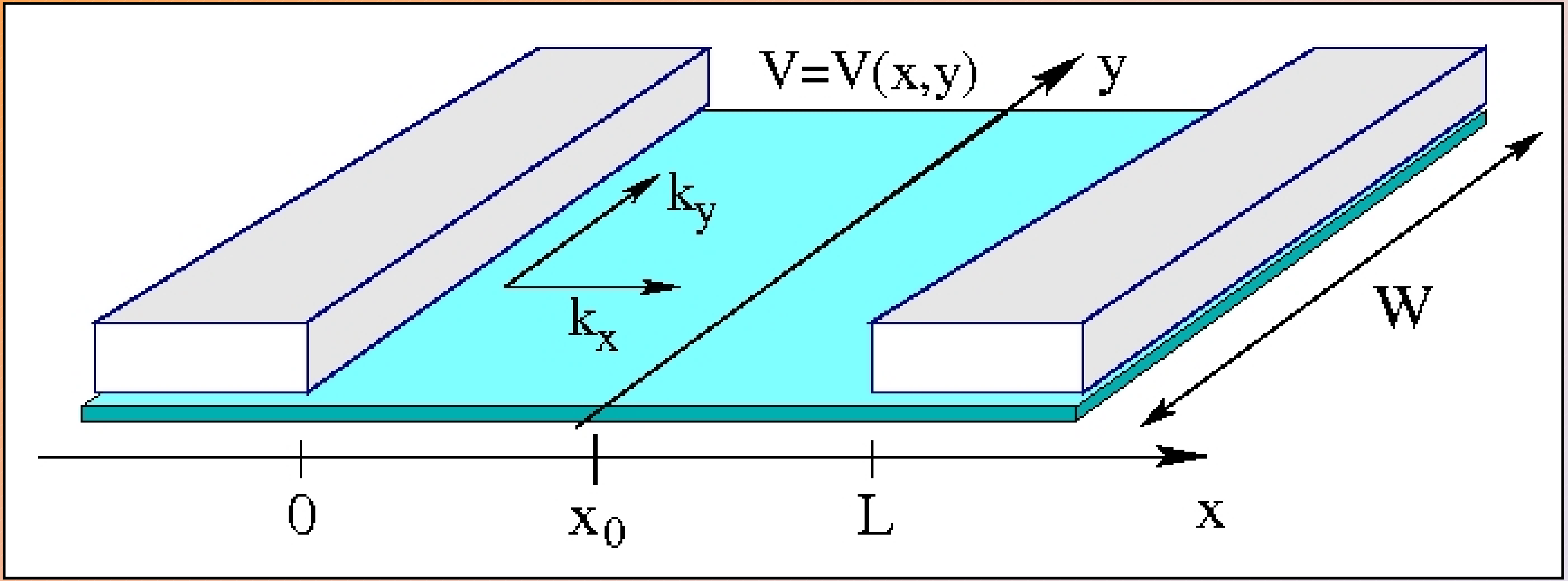
Univerity of California, Riverside

Disorder

- M. Titov, *Impurity-assisted tunneling in graphene*, *cond-mat/0611029*

$$\mathcal{H} = -i\hbar v \left(\sigma_x \partial_x + \sigma_y \partial_y\right) + V(x,y)$$

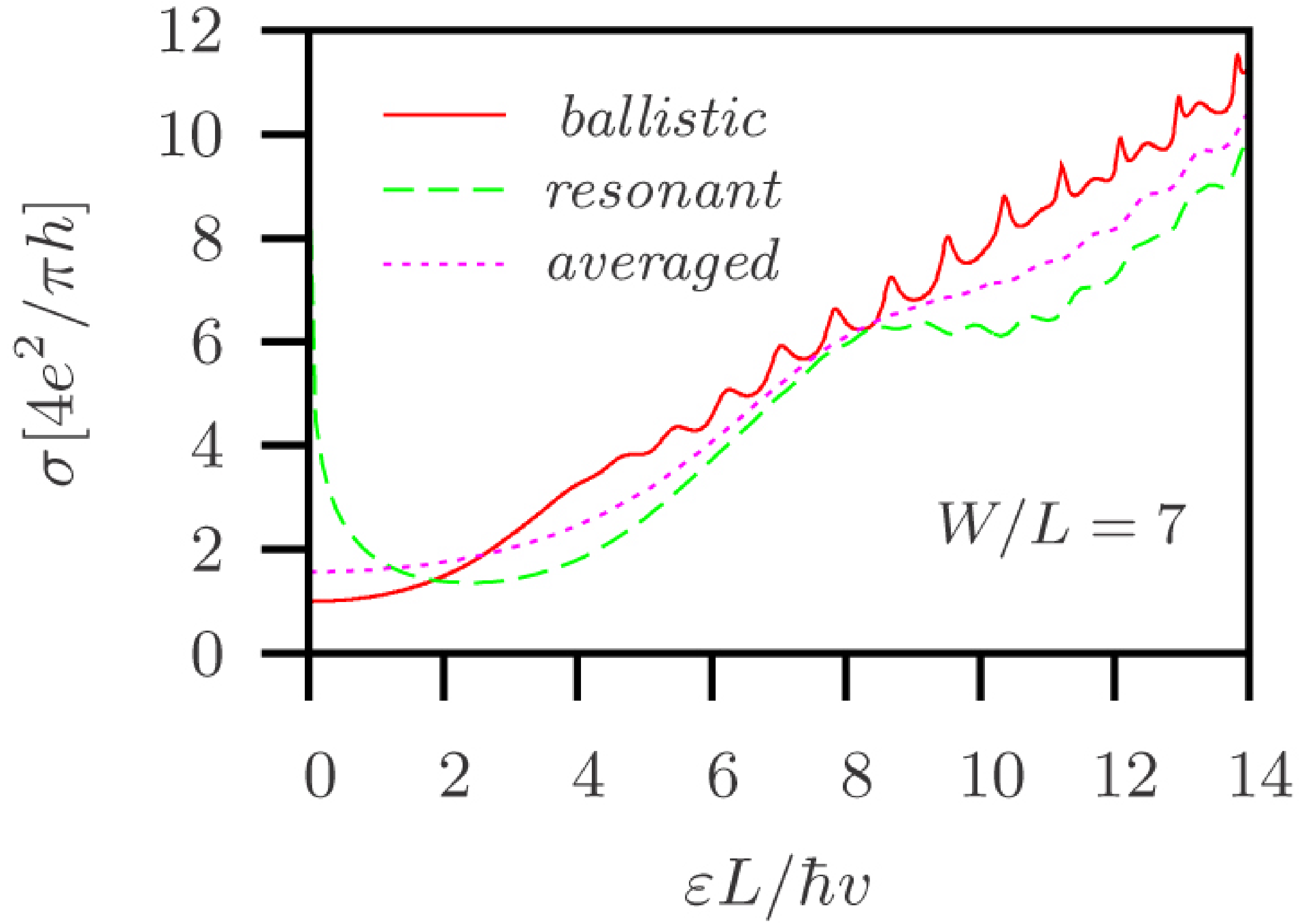
$\propto \mathbb{1}$



$$\frac{\partial \mathcal{T}_x}{\partial x} = \left(\hbar v \sigma_x \otimes \hat{k}_y + i\sigma_z \otimes \left(\varepsilon \mathbb{1} - \hat{V}(x)\right)\right) \mathcal{T}_x$$

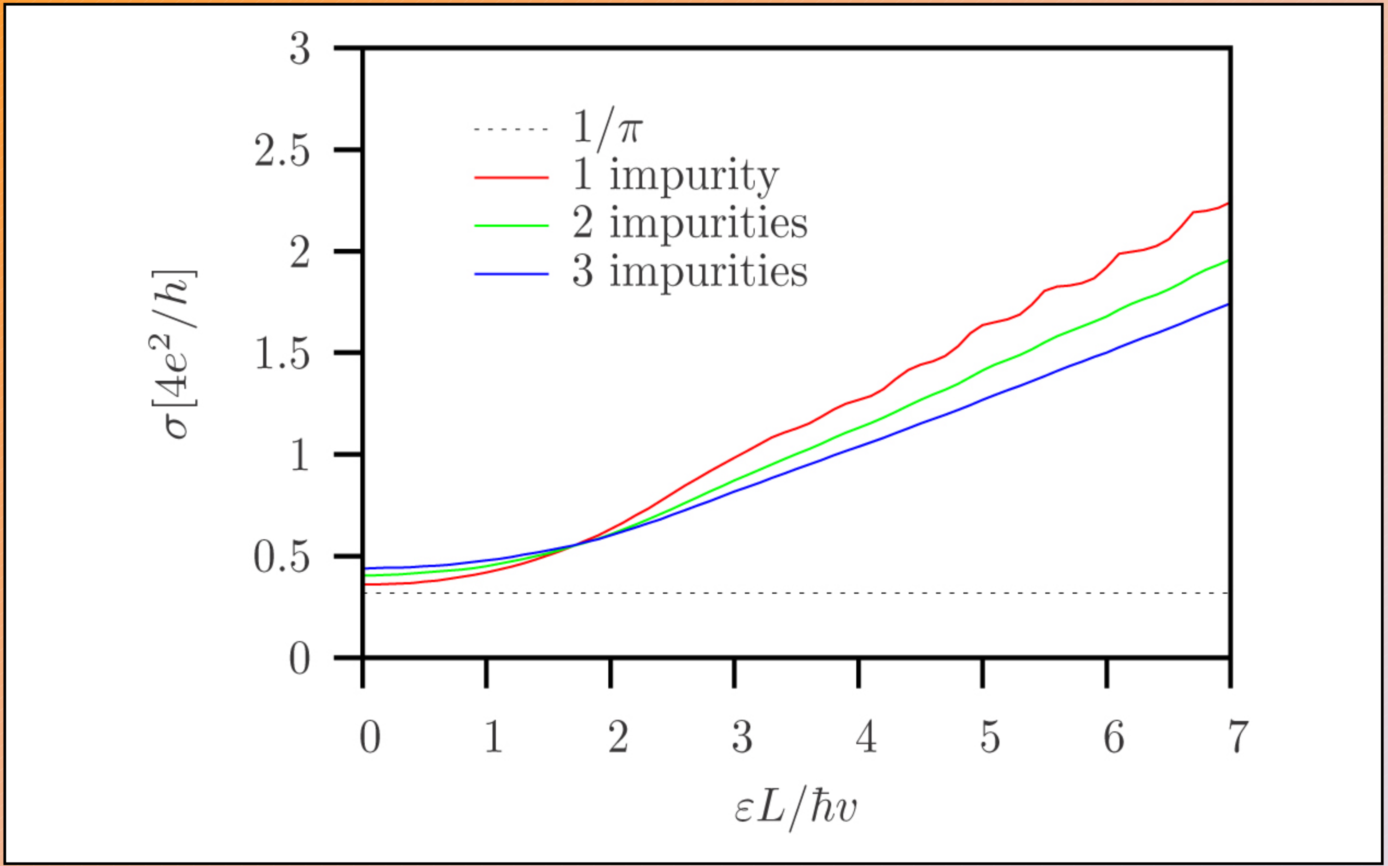
Conductivity enhancement

$$V(x,y) = \hbar v \alpha\, \delta(x - x_0)$$



$\alpha = \alpha_n \equiv \pi/2 + \pi n$ **resonant values**

Does a conductivity fixed point exist?



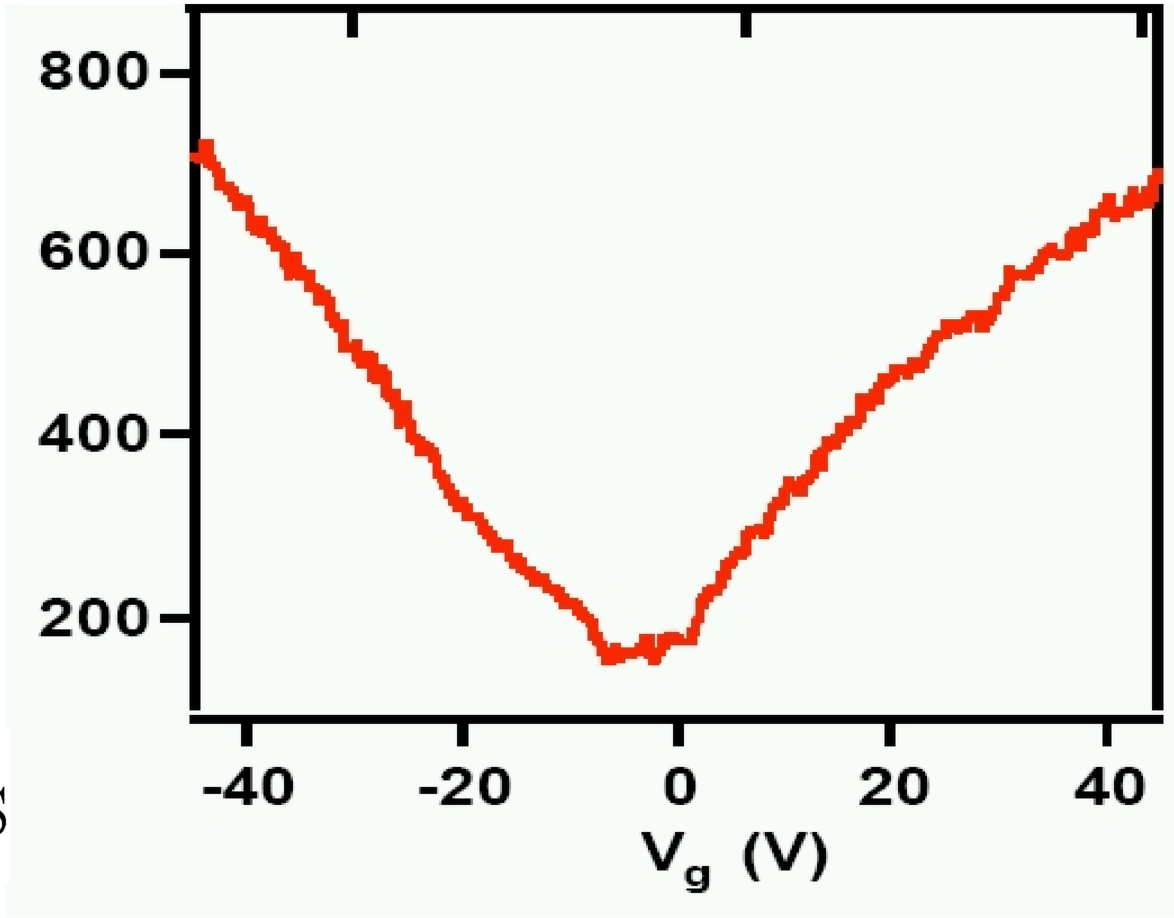
Exact result for 1D disorder:

$$V(x,y) = V(x)$$

$$\sigma \simeq 0.303 \frac{4e^2}{h} \sqrt{\frac{L}{\ell}} \sqrt{1 + \left(\frac{\varepsilon \ell}{\hbar v}\right)^2}$$

Conductance measurements

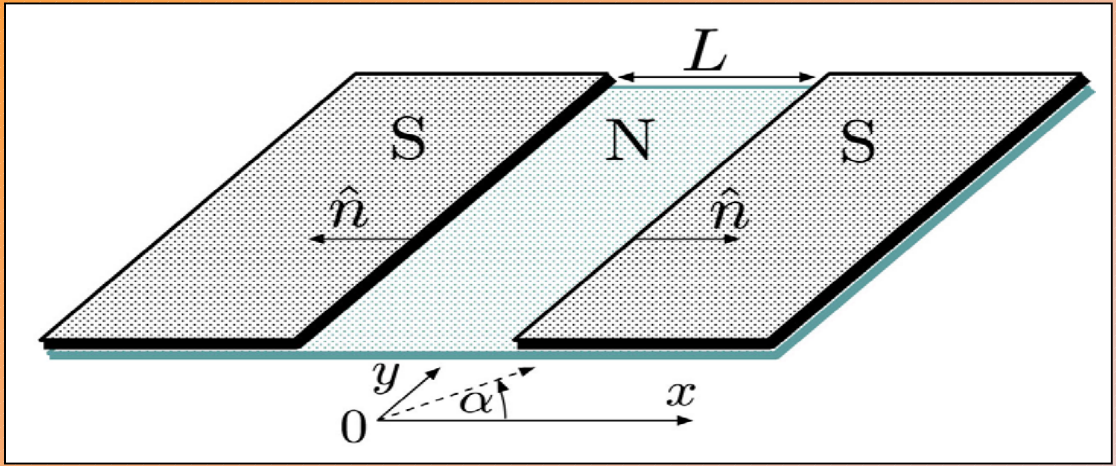
G(μS)



$$\frac{4e^2}{h} \approx 155\mu\text{S}$$

F. Miao, S. Wijeratne, U. Coskun, Y. Zhang, C. N. Lau
Univerity of California, Riverside

Relativistic Josephson effect

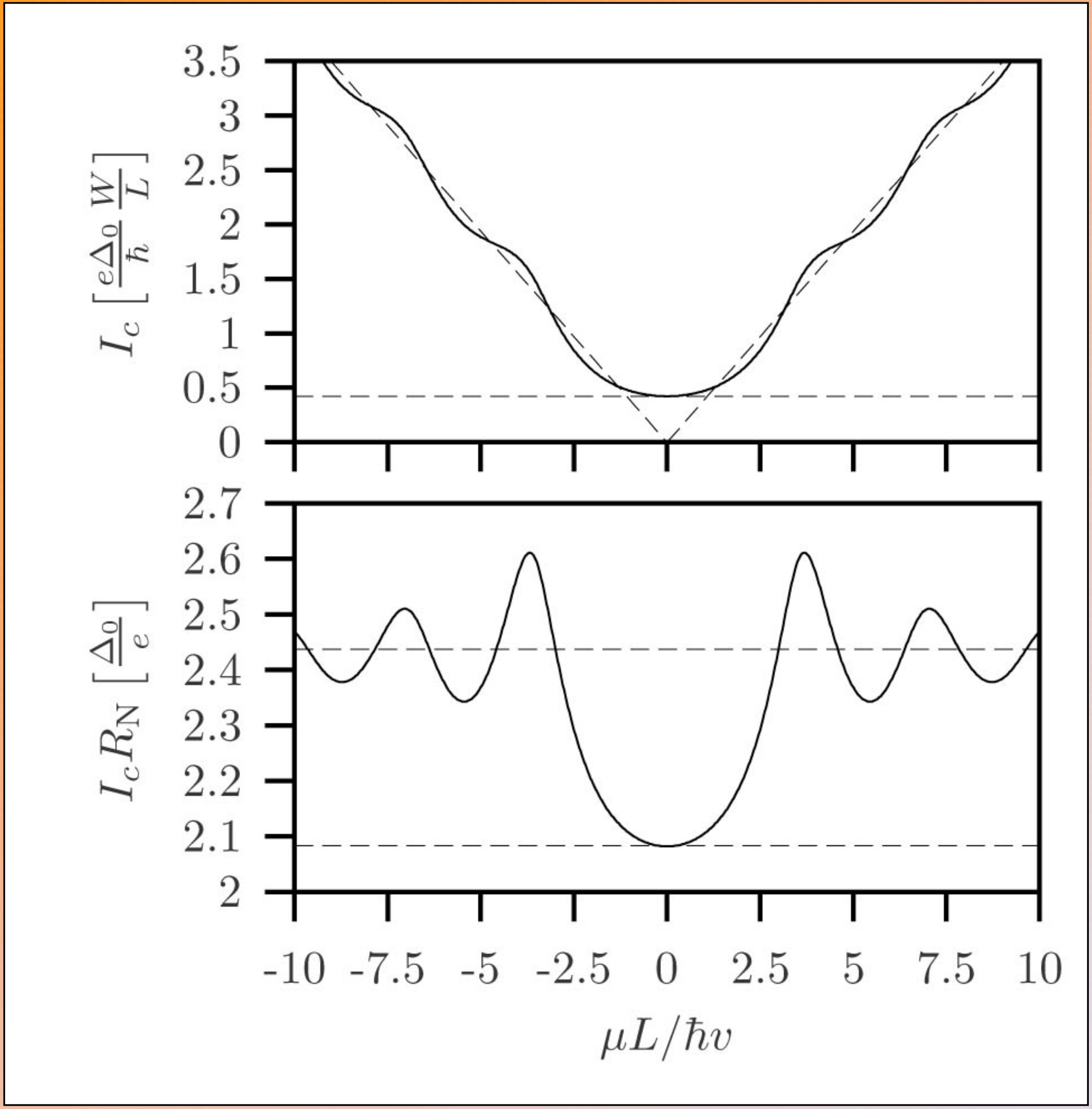


Dirac- Bogoliubov- De Gennes equation

$$\begin{pmatrix} H-\mu & \Delta \\ \Delta^* & \mu - \mathcal{T}H\mathcal{T}^{-1} \end{pmatrix} \begin{pmatrix} \Psi_{K,e} \\ \Psi_{K',h} \end{pmatrix} = \varepsilon \begin{pmatrix} \Psi_{K,e} \\ \Psi_{K',h} \end{pmatrix}$$

- M. Titov and C. W. J. Beenakker, *Josephson effect in ballistic graphene* *Phys. Rev. B* ***74****, 041401(R) (2006)*
- M. Titov, A. Ossipov and C. W. J. Beenakker, *Excitation gap of a graphene channel with superconducting boundaries* *Phys. Rev. B* ***75****, 045417 (2007)*

Critical current



For $\mu \ll \frac{\hbar v}{L}$

$$I_c = 1.33 \frac{e\Delta}{\hbar} \frac{W}{\pi L}$$

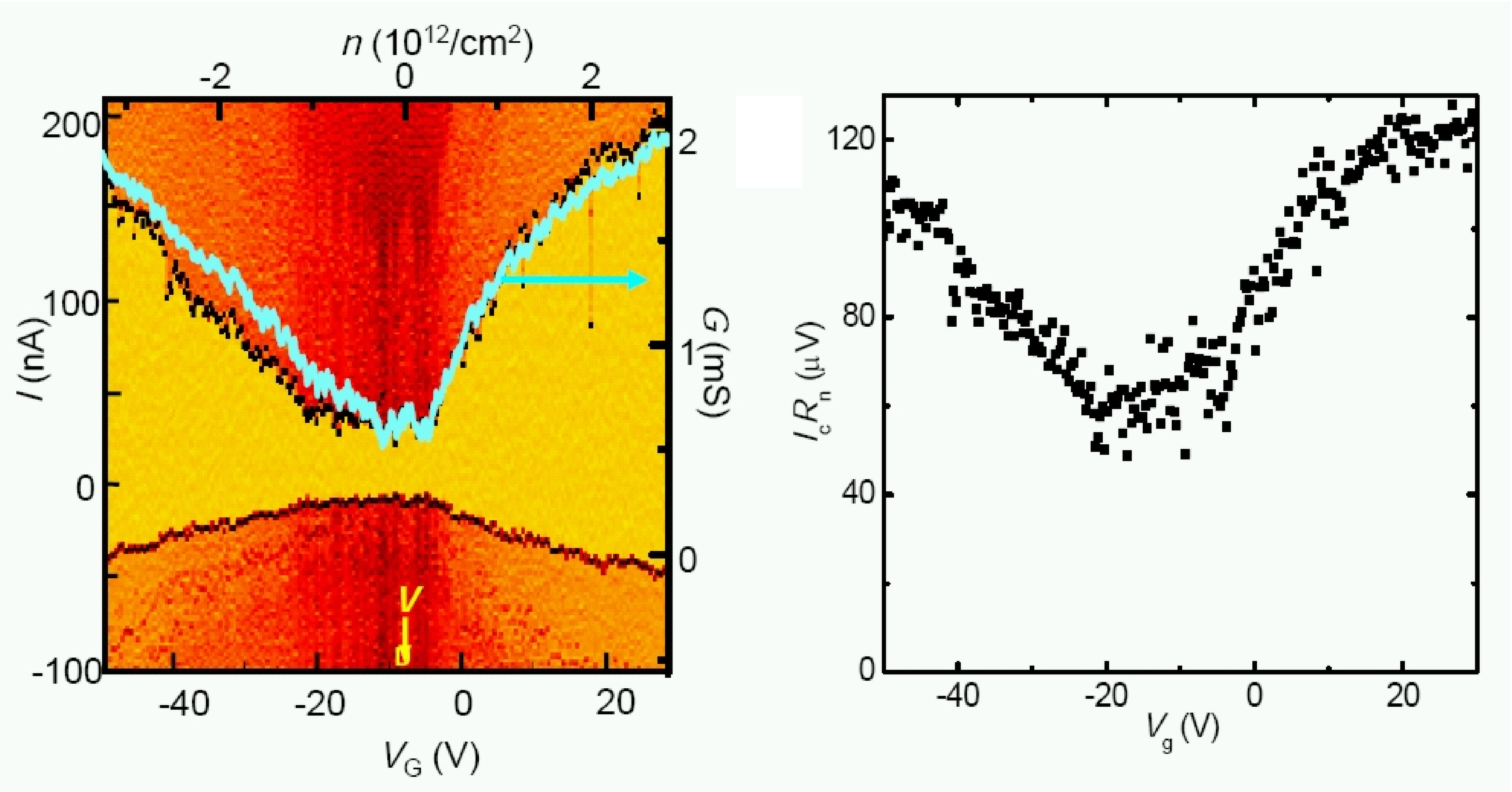
$$I_c R_N = 2.08 \frac{\Delta}{e}$$

For $\mu \gg \frac{\hbar v}{L}$

$$I_c = 1.22 \frac{e\Delta}{\hbar} \frac{\mu W}{\pi \hbar v}$$

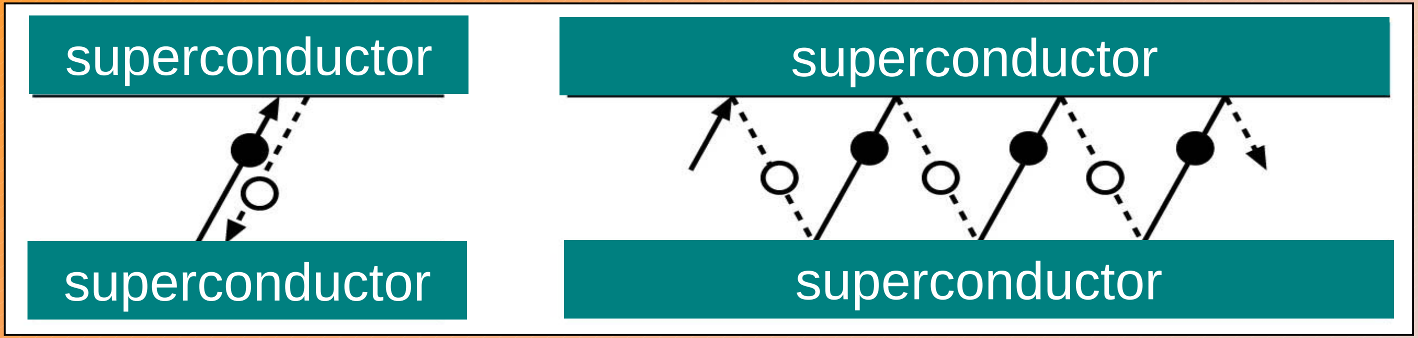
$$I_c R_N = 2.44 \frac{\Delta}{e}$$

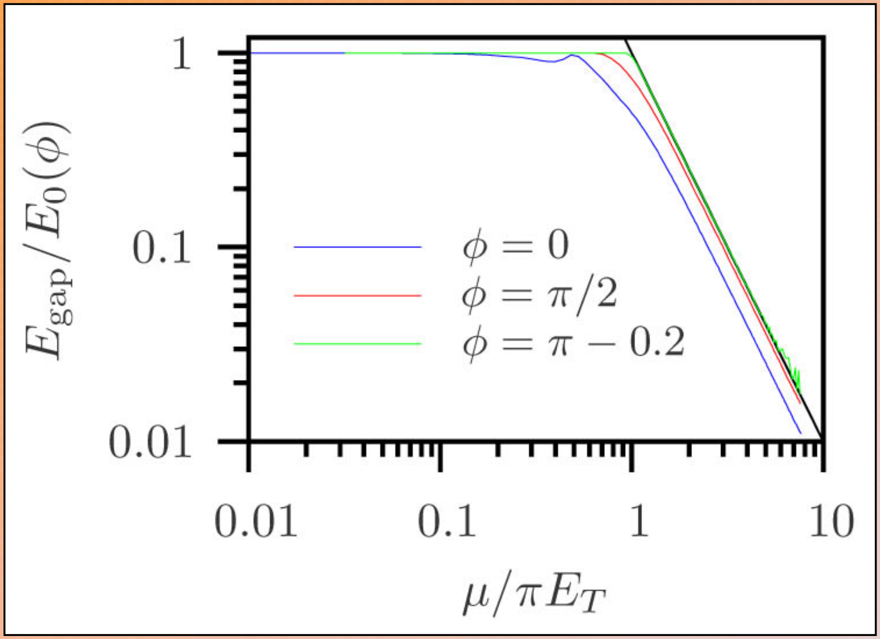
First experiments

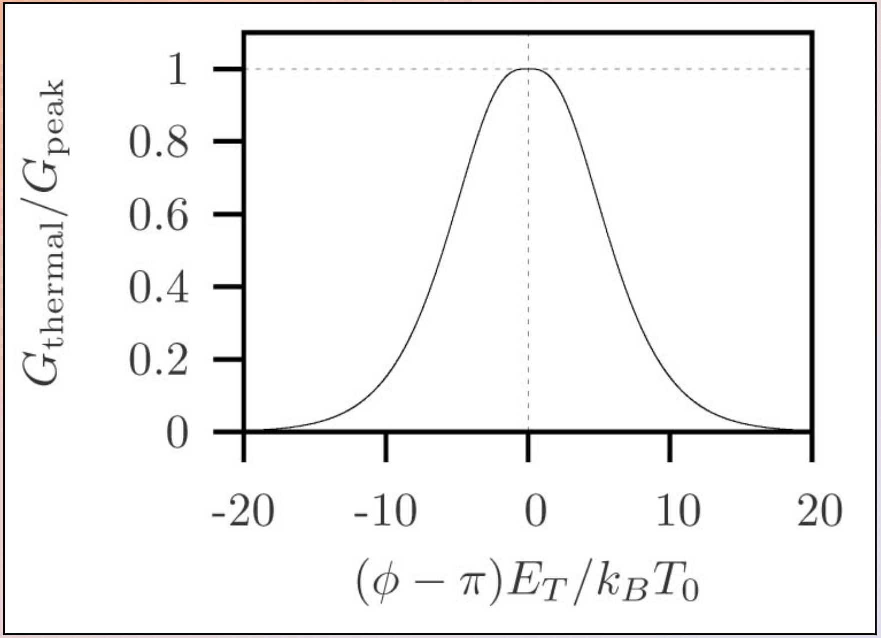


H. B. Heersche, P. Jarillo-Hererro, J. B. Oostinga, L. M. K. Vandersypen, A. F. Morpurgo, cond-mat/0612121

Propagating Andreev modes







ϕ-dependent excitation gap of Andreev levels

ϕ-dependent thermal conductance along the channel

Thank you
for your attention!