Electron interference effects in cuprate superconductor/graphene junctions

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Acknowledgements

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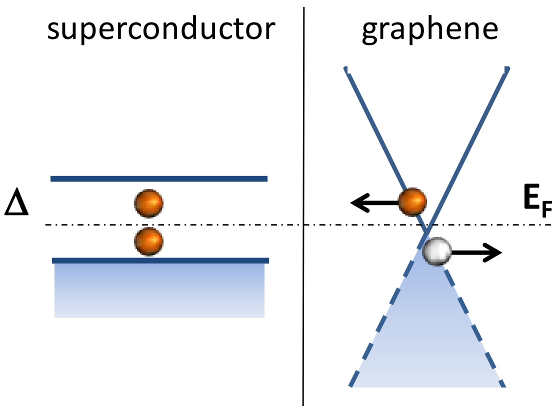
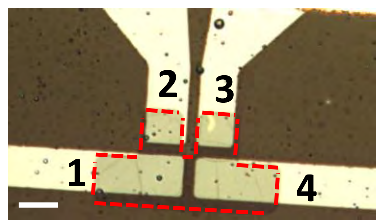
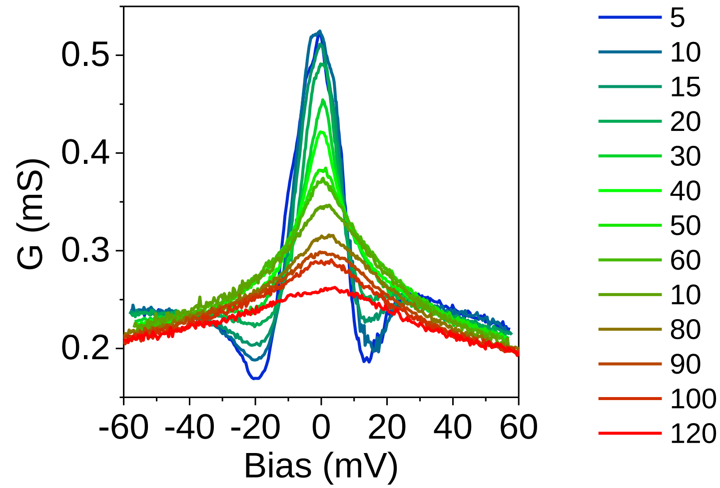
Cambridge, UK

Outline

Electron interferences at high-T_C S/graphene interfaces



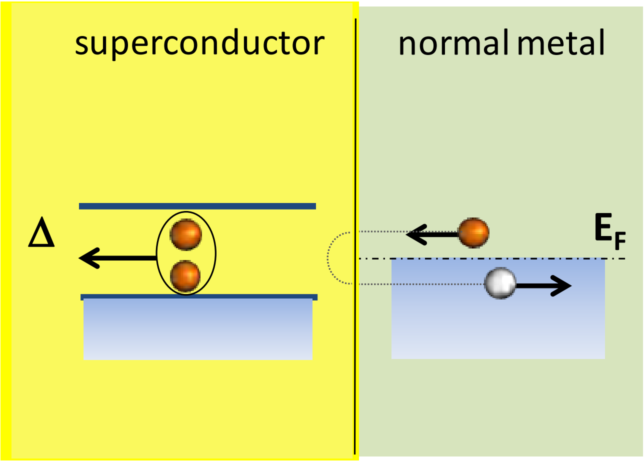




→ KLEIN TUNNELING OF HIGH-T_C PAIRS

→ELECTROSTATIC CONTROL

Proximity effect mechanism: Andreev reflection



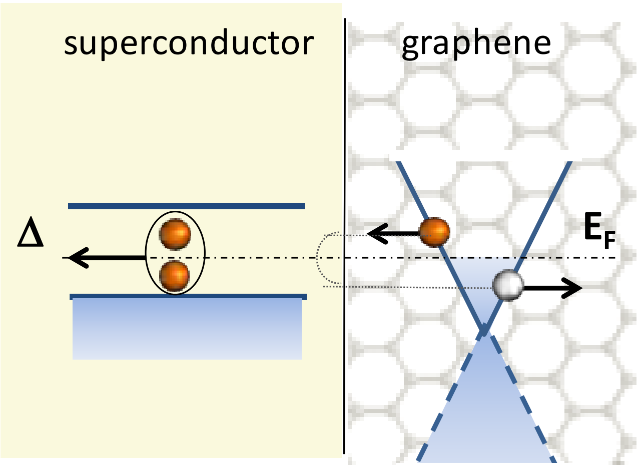
$$\xi_N = \frac{\hbar v_F}{2\pi KT}$$ ballistic

$$\xi_N = \sqrt{\frac{\hbar D}{2\pi KT}}$$ diffusive

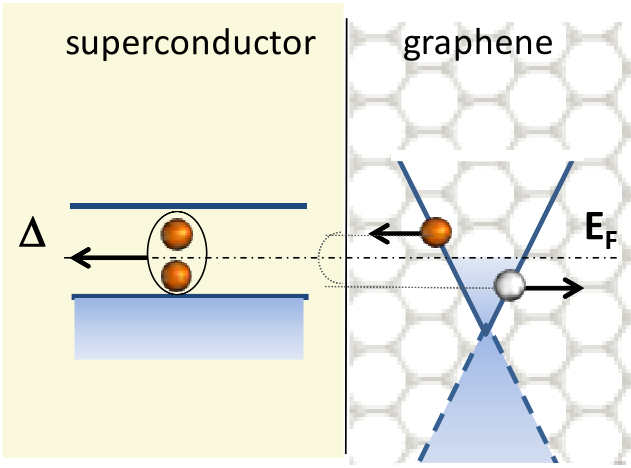
→ ELECTRON/HOLE SUPERCONDUCTING PAIRS

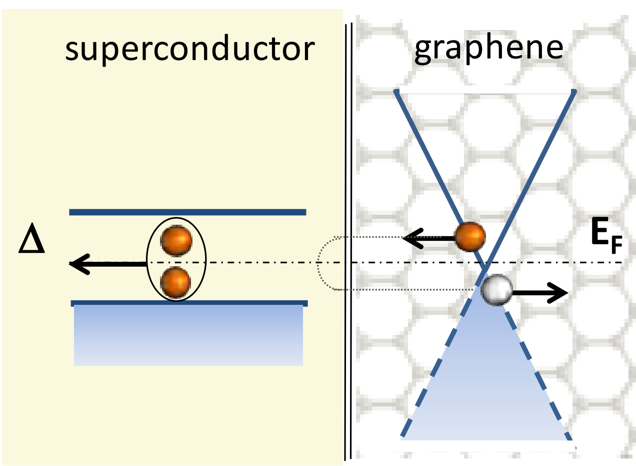
→ METAL BECOMES SUPERCONDUCTING OVER ξ

Band structure affects proximity effect



Band structure affects proximity effect

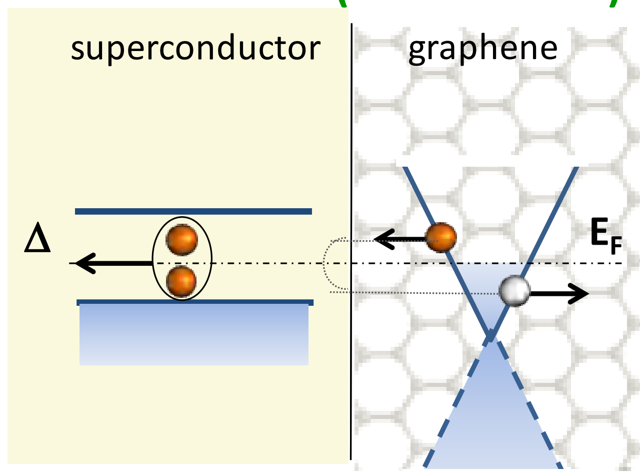




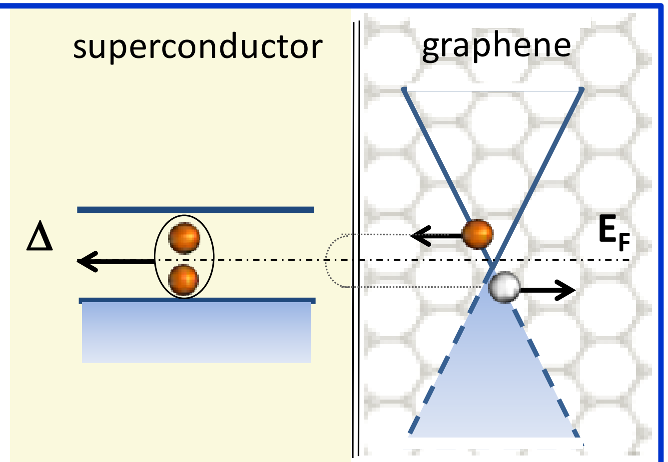
→ **INTRA-BAND OR INTER-BAND PROCESS: TUNABLE BY DOPING**

C.W.J. Beenakker PRL 97 067007, (2006)

Band structure affects proximity effect



Retroreflection (conventional)



Specular (unusual)

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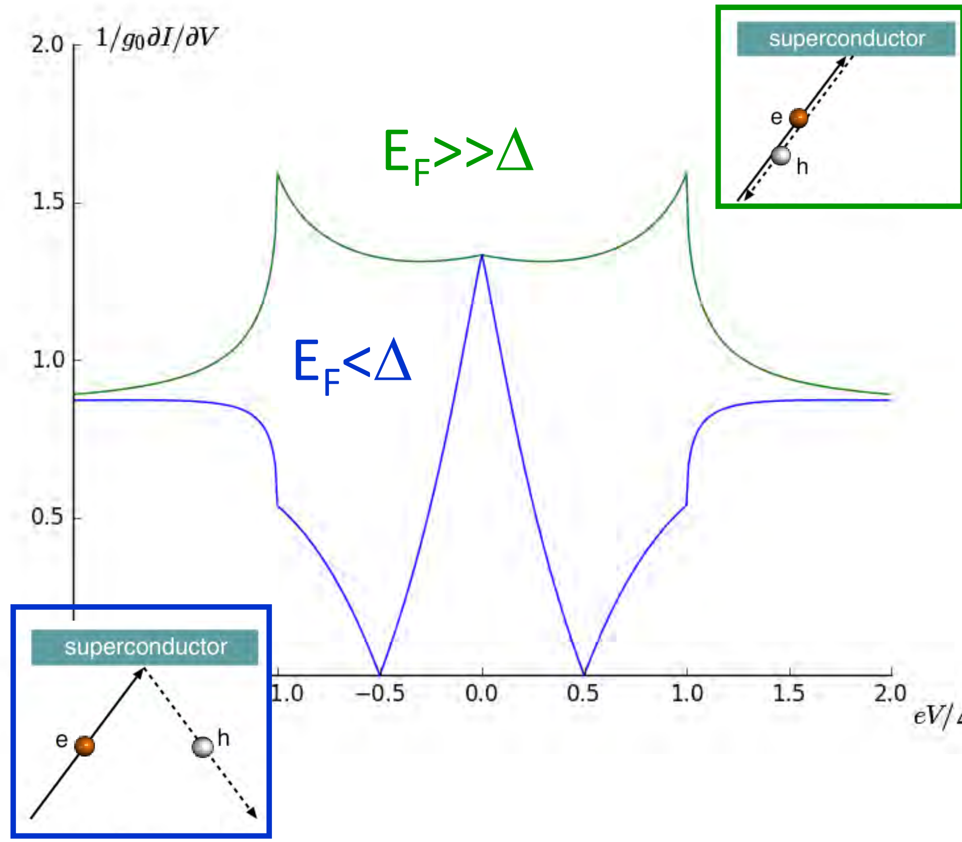
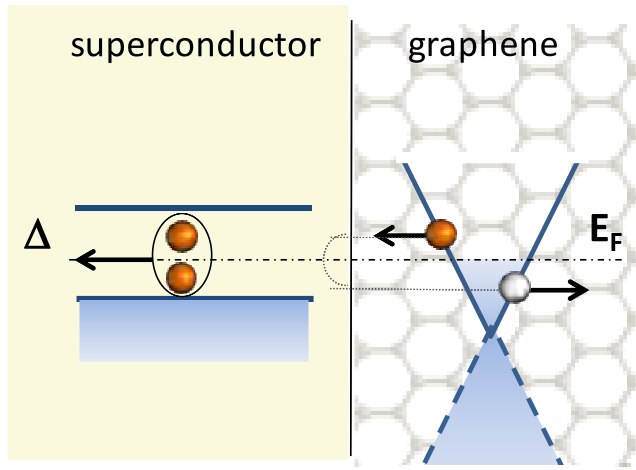
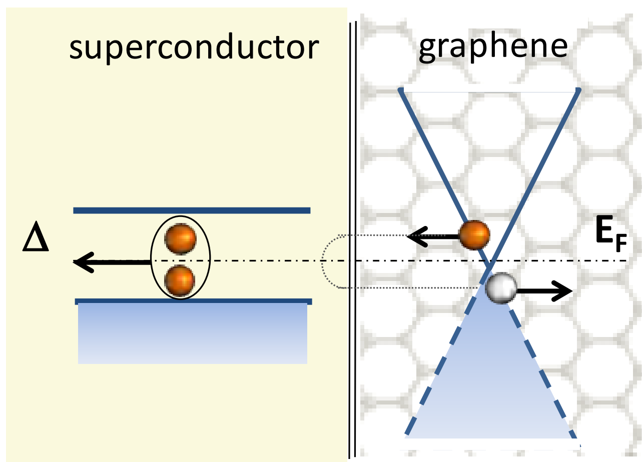
C.W.J. Beenakker PRL 97 067007, (2006)



Band structure affects proximity effect





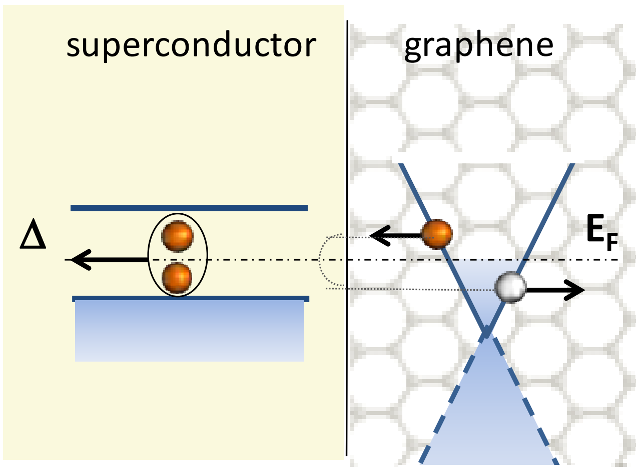
→ **INTRA-BAND OR INTER-BAND PROCESS: TUNABLE BY DOPING**

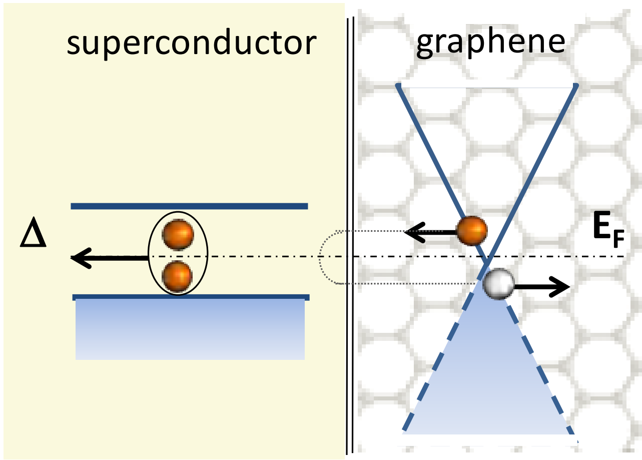
C.W.J. Beenakker PRL 97 067007, (2006)

$$E(K) = \hbar v_F K$$

→ **LINEAR DISPERSION: WAVE-VECTOR INDEPENDENT VELOCITY**

Band structure affects proximity effect





→ INTRA-BAND OR INTER-BAND PROCESS: TUNABLE BY DOPING

C.W.J. Beenakker PRL 97 067007, (2006)

$$E(K) = \hbar v_F K$$

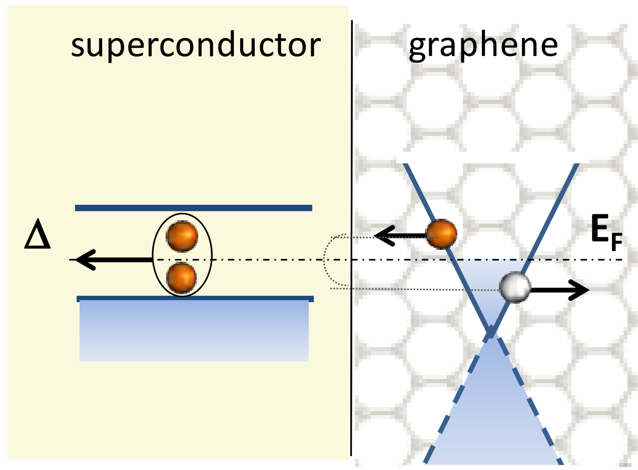
→ LINEAR DISPERSION: WAVE-VECTOR INDEPENDENT VELOCITY

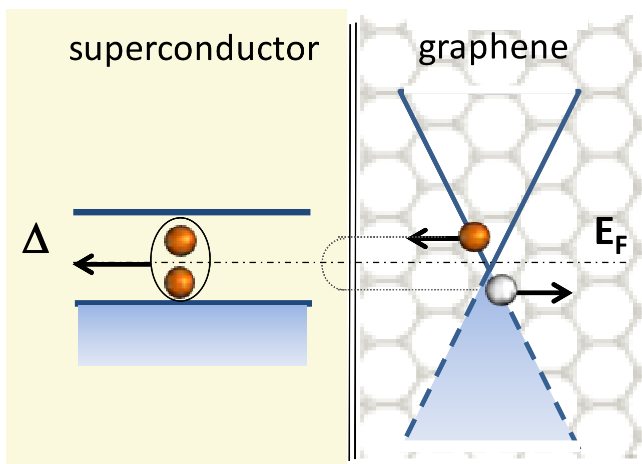
→LOW CARRIER DENSITY

→NEW PHYSICS

→POSSIBILITIES ABSENT IN ORDINARY JOSEPHSON JUNCTIONS

Band structure affects proximity effect





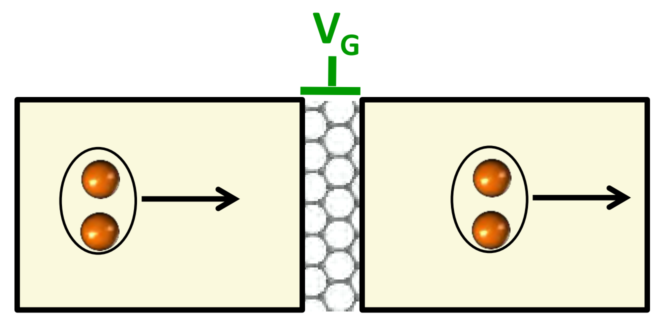
→ **INTRA-BAND OR INTER-BAND PROCESS: TUNABLE BY DOPING**

C.W.J. Beenakker PRL 97 067007, (2006)

$$E(K) = \hbar v_F K$$

→ **LINEAR DISPERSION: WAVE-VECTOR INDEPENDENT VELOCITY**

→ **LOW CARRIER DENSITY**

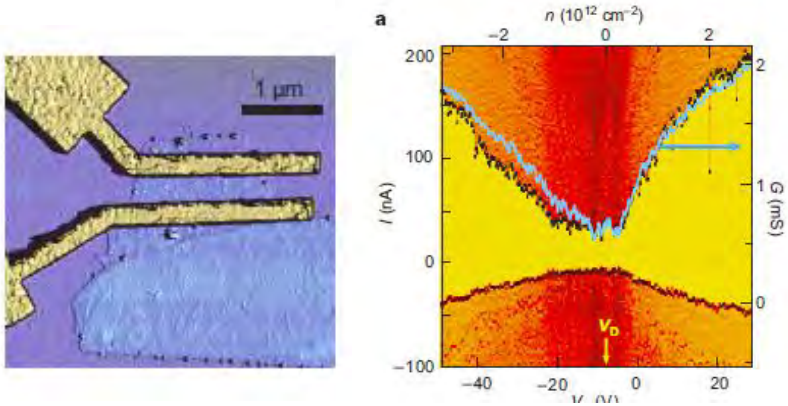


→ **GATE TUNABLE JOSEPHSON JUNCTIONS**

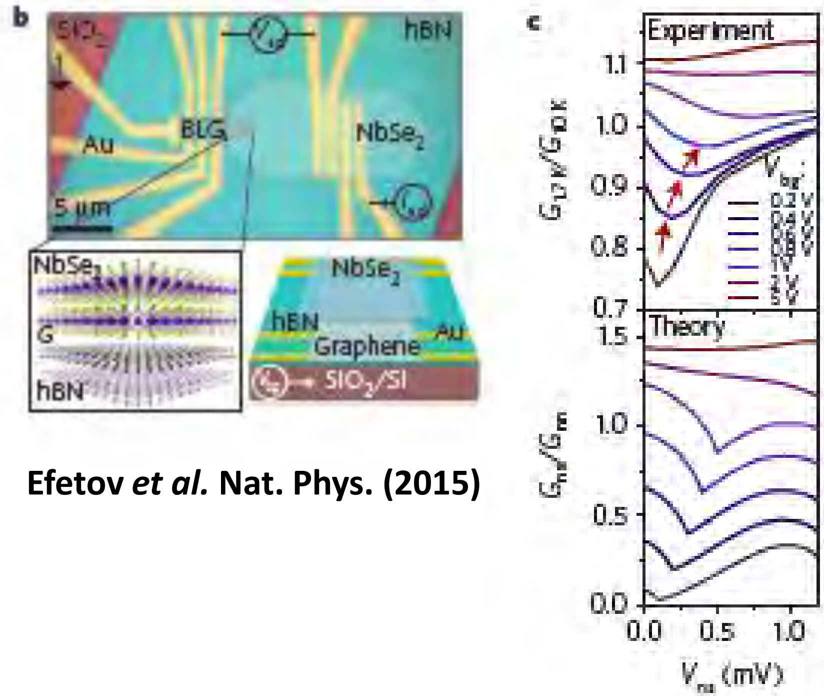
→ **NEW PHYSICS**

→ **POSSIBILITIES ABSENT IN ORDINARY JOSEPHSON JUNCTIONS**

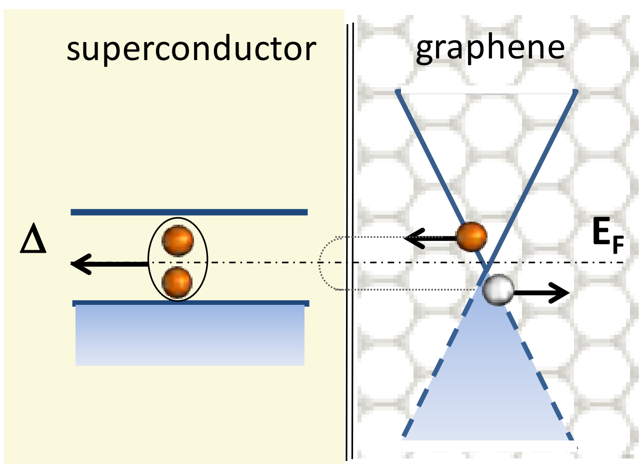
Experiments with low-T_C superconductors



Heersche *et al.* Nature (2007)



Efetov *et al.* Nat. Phys. (2015)

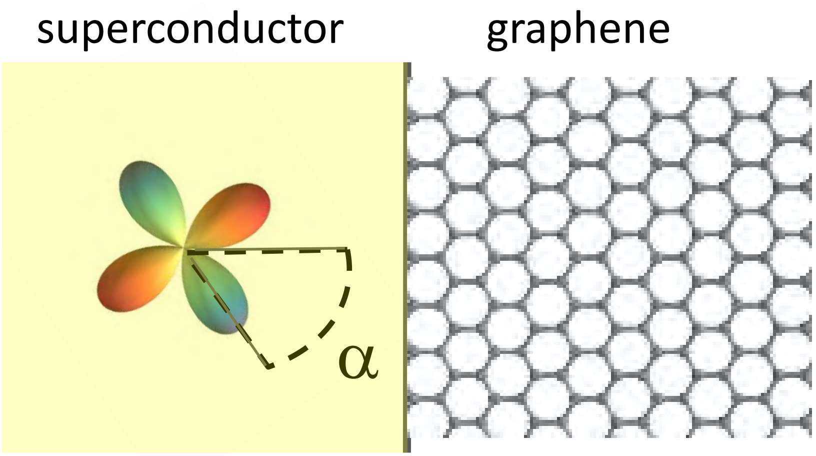


→E_F INHOMOGENEITY MUST BE SMALLER THAN SUPERCONDUCTING GAP Δ !!!!

→LIMITED TO LOW TEMPERATURES (~ 1K)

→PRISTINE EFFECTS ONLY WITH ULTRA-CLEAN GRAPHENE

Motivation for high-T_c superconductor/graphene



→ **DIRECTIONAL EFFECTS DUE TO D-WAVE SYMMETRY**

Linder *et al.* PRB (2008)

SUPERCONDUCTING GAP Δ ~ 10-30 meV
INSTEAD OF Δ ~ 1 meV

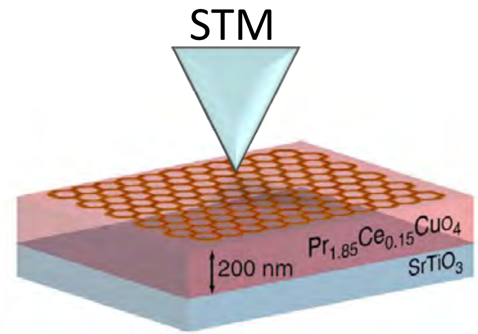
→ **SUPERCONDUCTING EFFECTS ROBUST AGAINST GRAPHENE INHOMOGENEITIES**

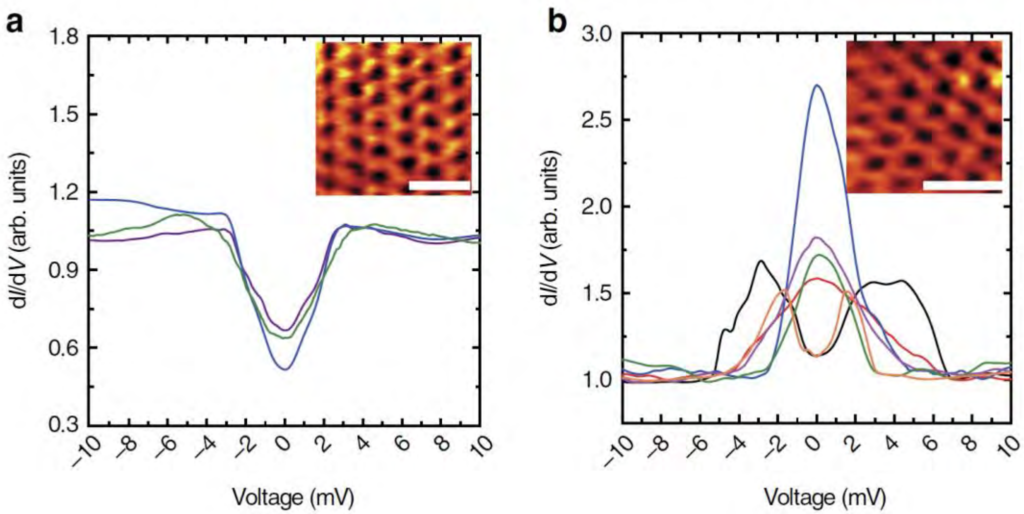
Recent work on high-T_C/graphene

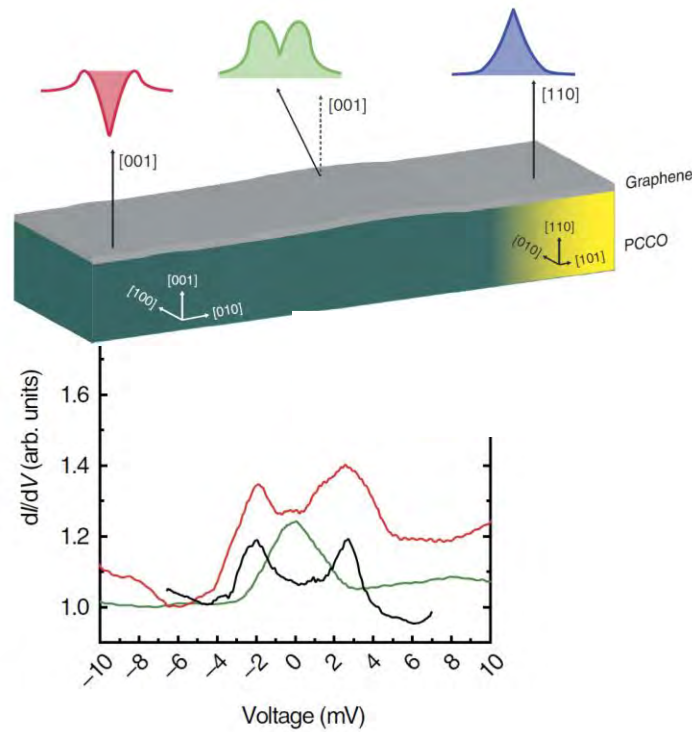
nature COMMUNICATIONS
DOI: 10.1038/ncomms14024 OPEN

p-wave triggered superconductivity in single-layer graphene on an electron-doped oxide superconductor

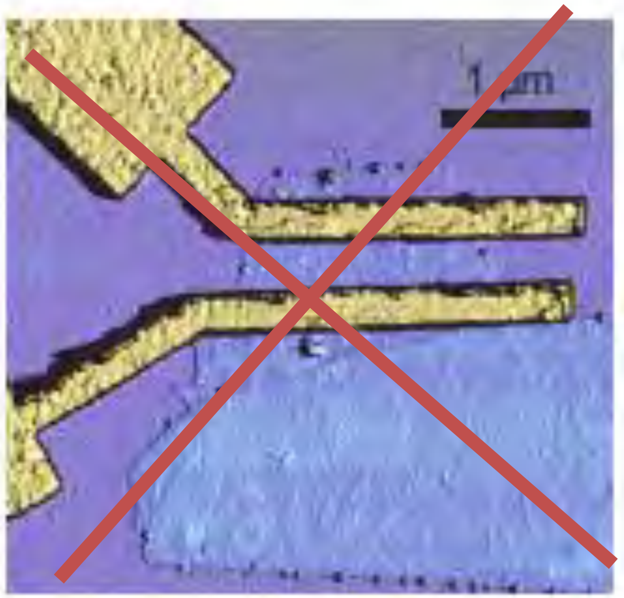
A. Di Bernardo[1], O. Millo[2], M. Barbone[3], H. Alpern[2], Y. Kalcheim[2], U. Sassi[3,†], A.K. Ott[3], D. De Fazio[3], D. Yoon[3], M. Amado[1], A.C. Ferrari[3], J. Linder[4] & J.W.A. Robinson[1]







high-T_c superconductor/graphene "complications"

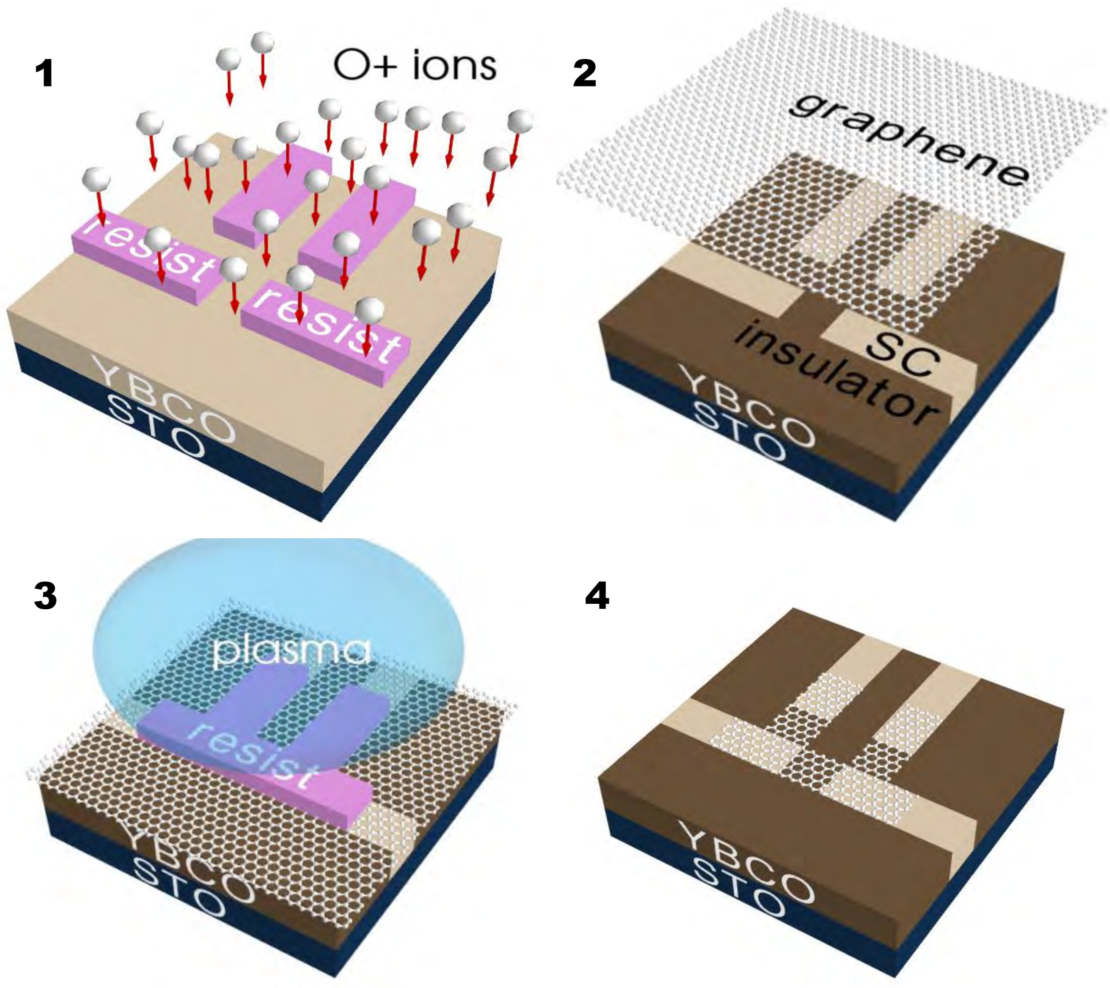


-DEPOSITION OF OXIDE SUPERCONDUCTOR ON GRAPHENE NOT POSSIBLE

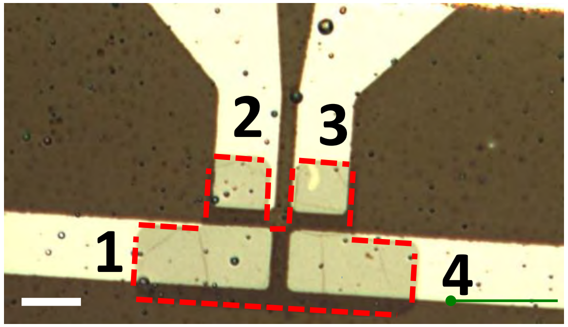
- OXIDE SUPERCONDUCTOR PRONE TO DEGRADATION

→ **NEW FABRICATION APPROACH REQUIRED**

high-T_c superconductor/graphene devices

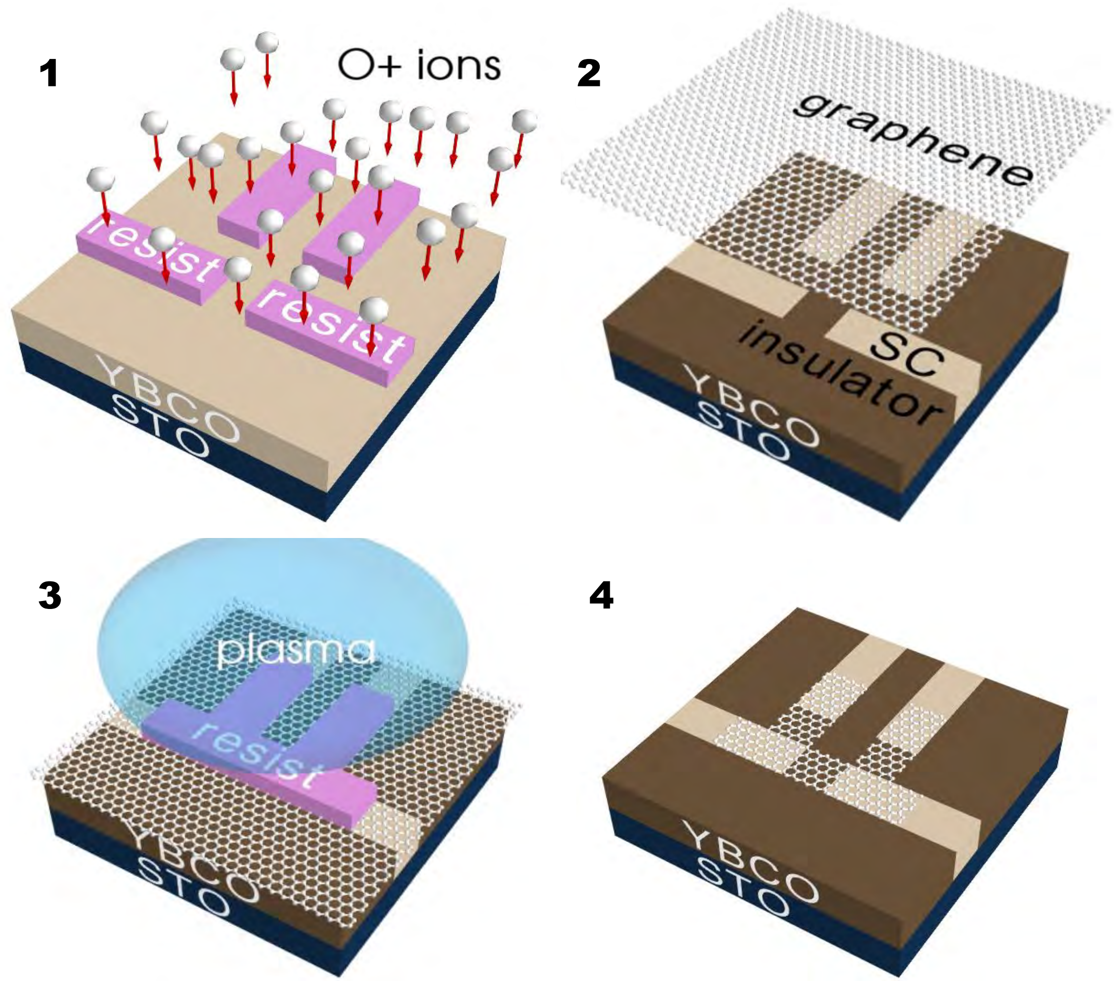


YBCO/Au on STO
+
CVD graphene



→ ION IRRADIATION TO DEFINE PLANAR DEVICE

high-T_c superconductor/graphene devices



YBCO/Au on STO
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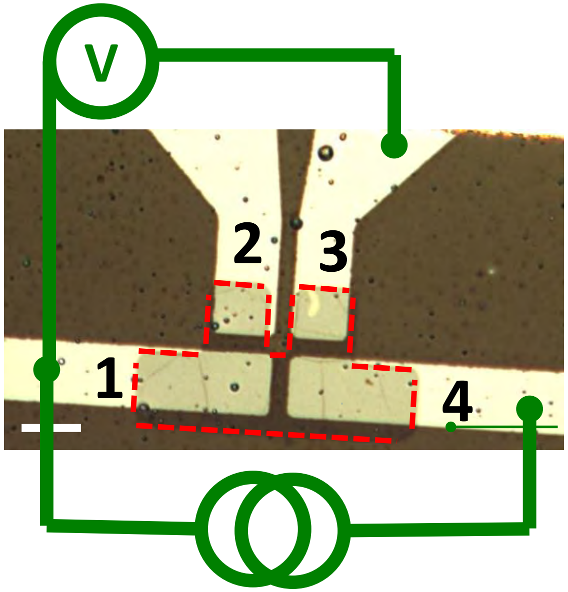
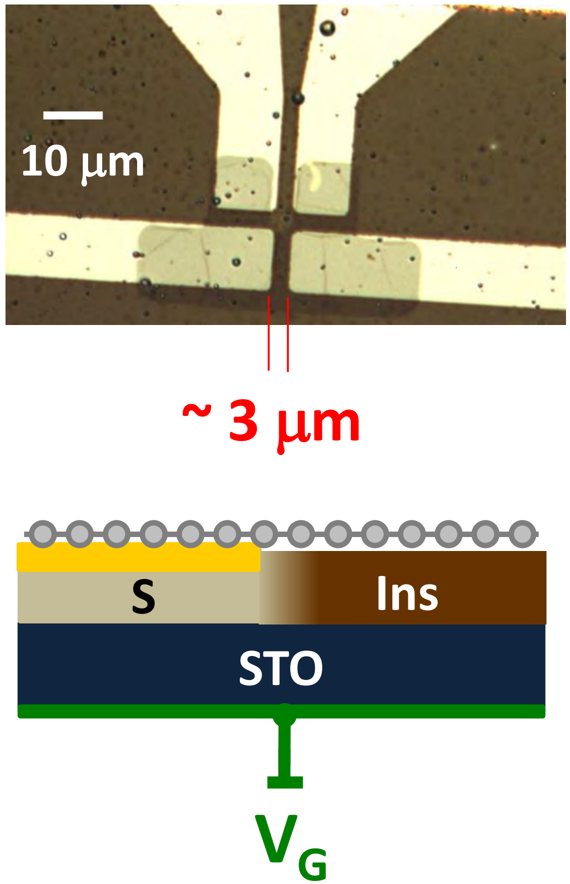
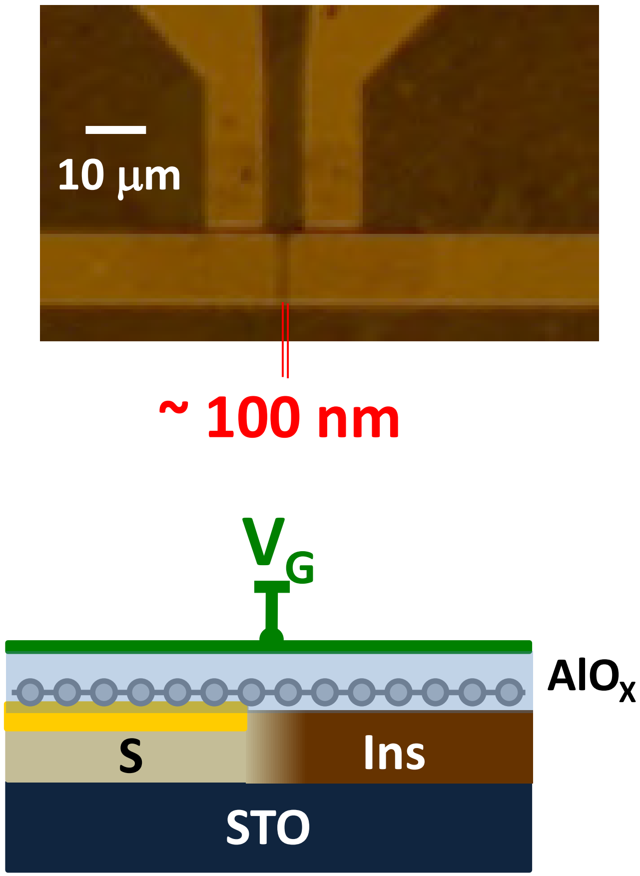


→ ION IRRADIATION TO DEFINE PLANAR DEVICE

Two different devices studied

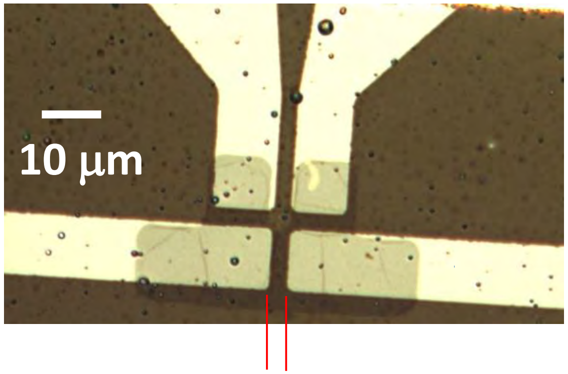


SrTiO$_3$ BACKGATE

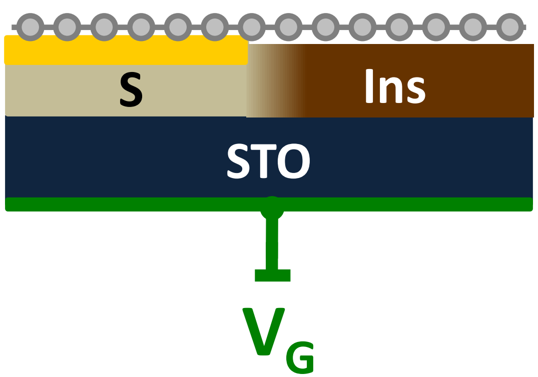


AlOx TOPGATE

Two different devices studied



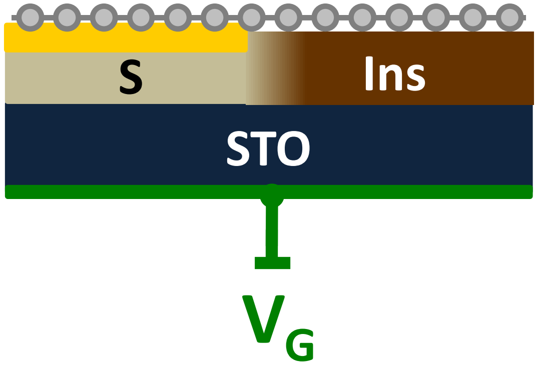
~ 3 μm



$SrTiO_3$ BACKGATE

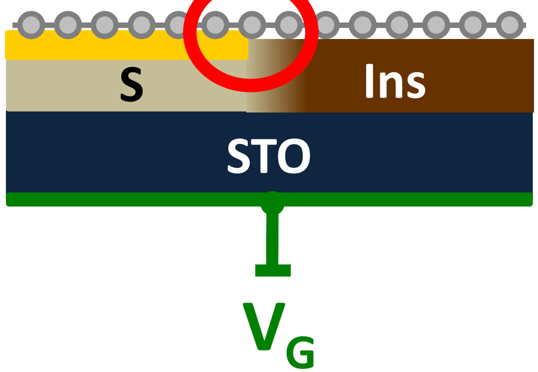
AlOx TOPGATE

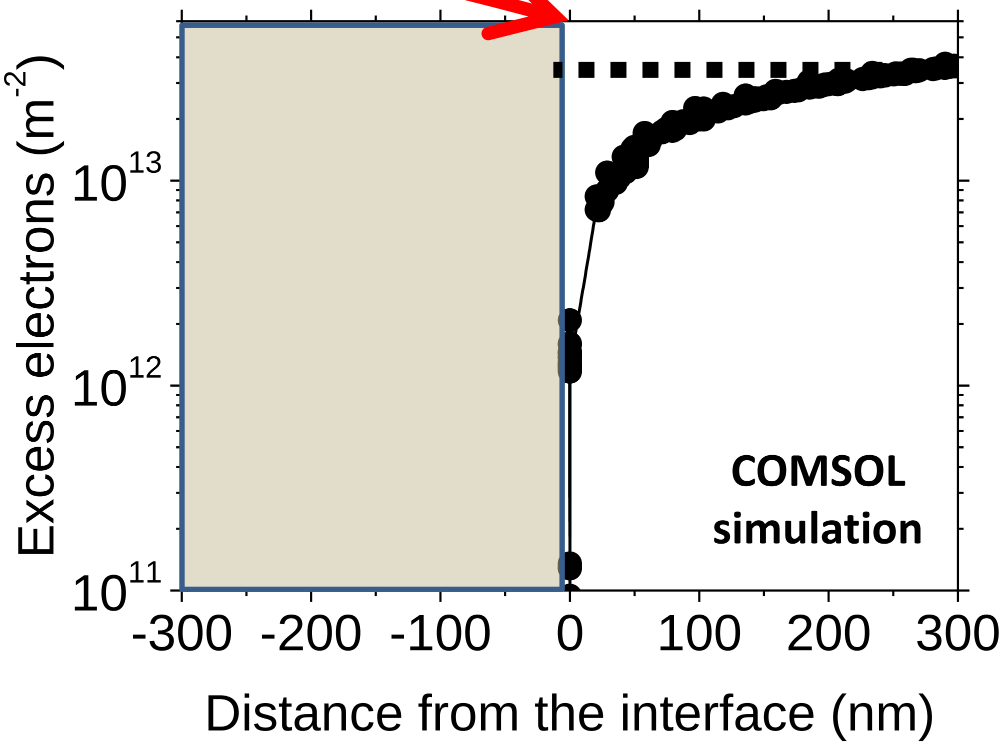
$SrTiO_3$ backgate properties



→ **ONLY GRAPHENE ON INSULATOR IS DOPED**

$SrTiO_3$ backgate properties

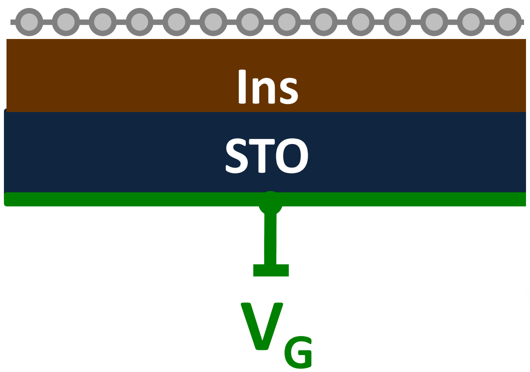




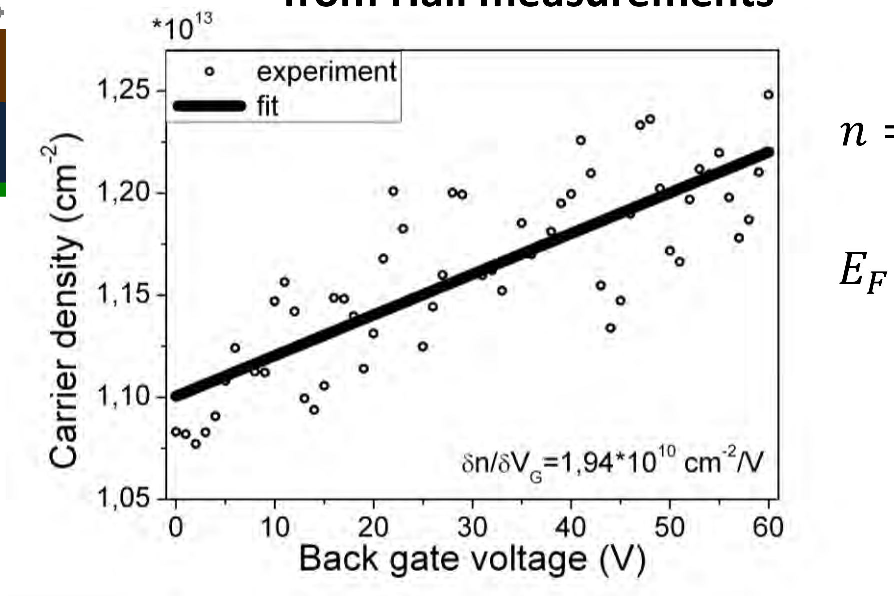
→ **ONLY GRAPHENE ON INSULATOR IS DOPED**

→ **FRINGE FIELDS: INHOMOGENEOUS DOPING**

$SrTiO_3$ backgate properties



from Hall measurements



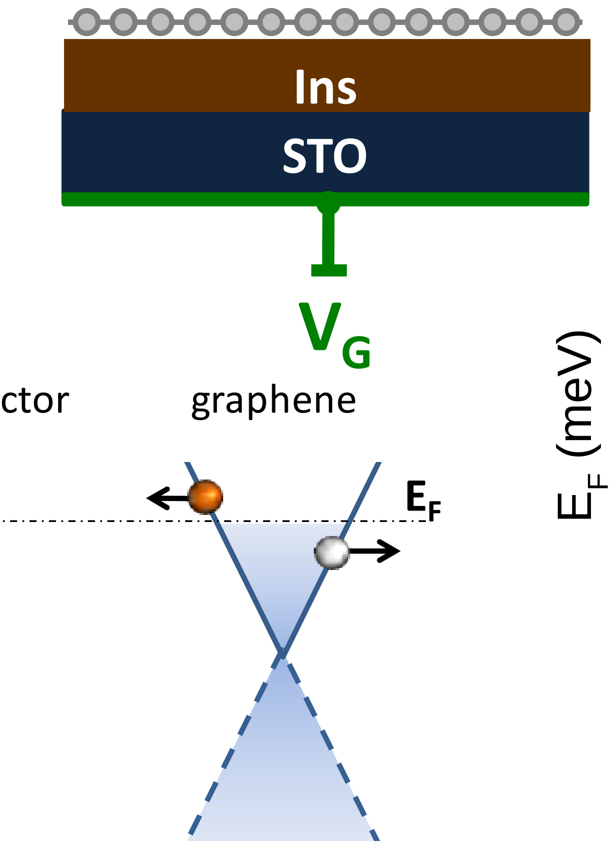
$$n = \frac{1}{e}\frac{\partial B}{\partial R_{xy}} \sim 10^{13} cm^{-2}$$

$$E_F = \hbar v_F k = \hbar v_F \sqrt{\pi n}$$

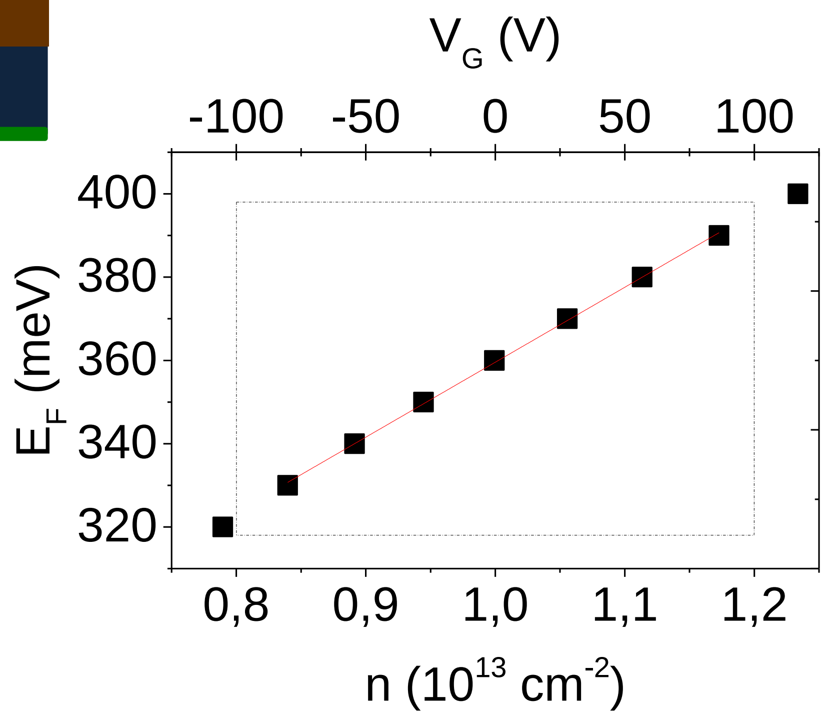
→ DOPING PROPORTIONAL TO V_G

→ HIGH NATIVE DOPING ~10^{13} cm^{-2}

$SrTiO_3$ backgate properties



from Hall measurements



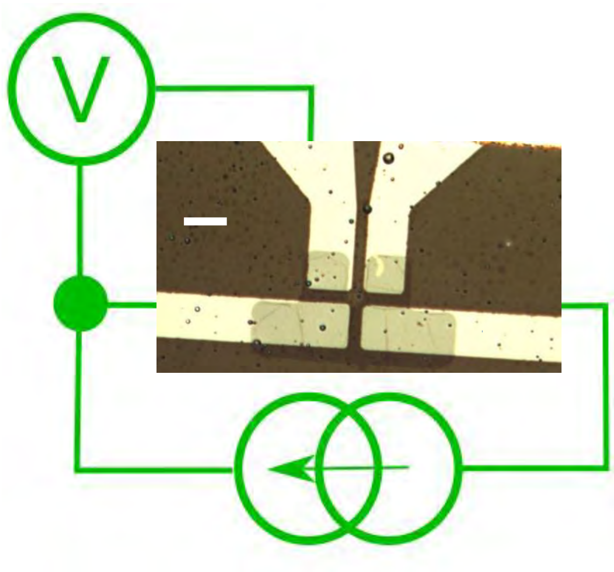
$$n = \frac{1}{e}\frac{\partial B}{\partial R_{xy}} \sim 10^{13} cm^{-2}$$

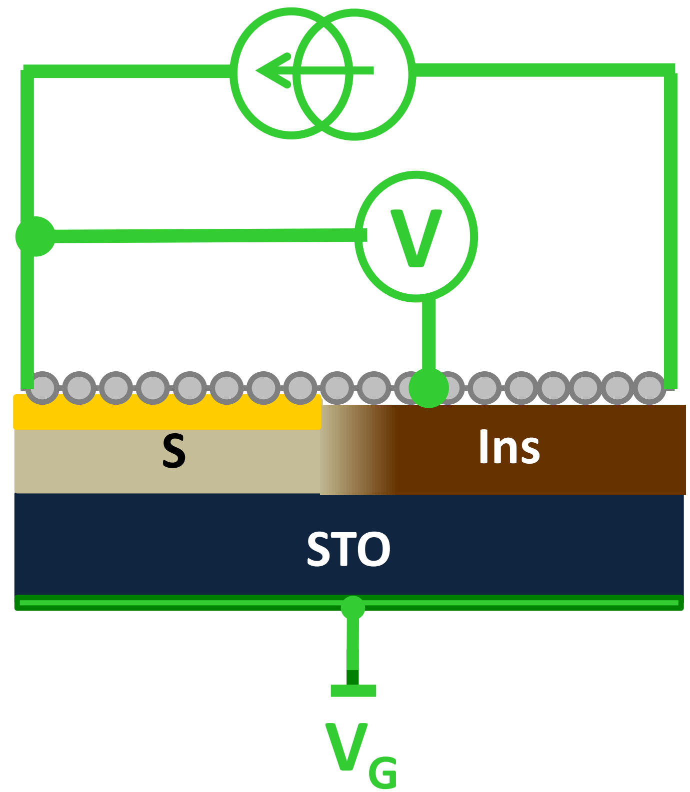
$$E_F = \hbar v_F k = \hbar v_F \sqrt{\pi n}$$

→ VERY FAR FROM DIRAC POINT

→ $E_F >> \Delta$

Measuring geometry

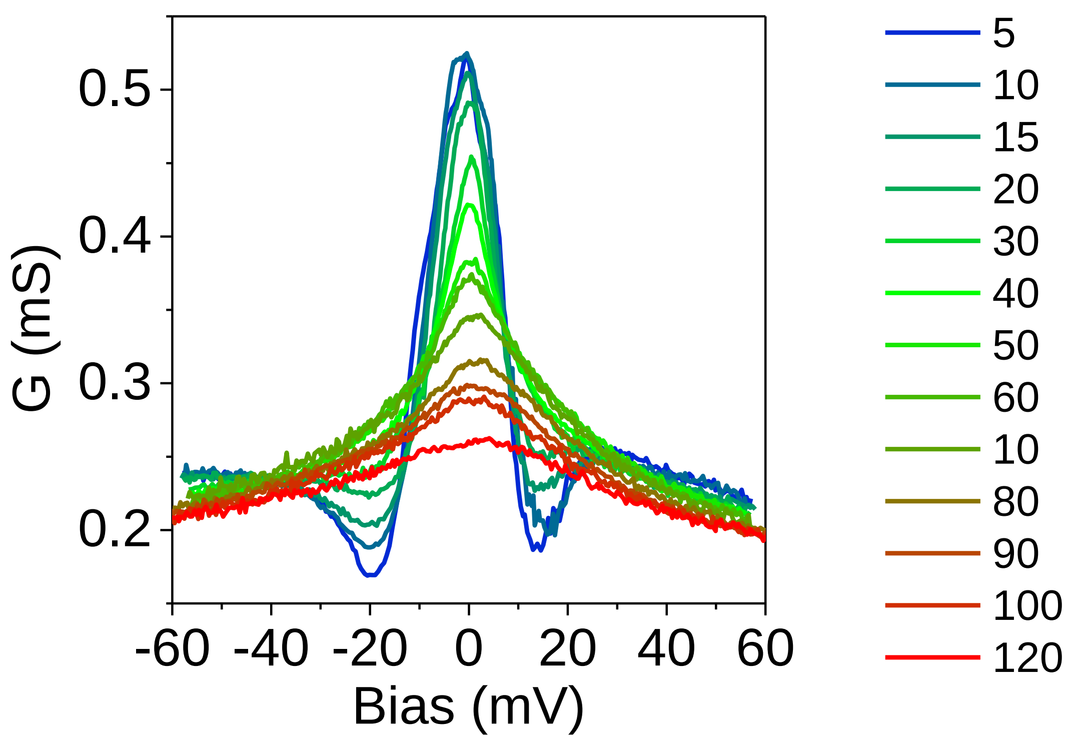




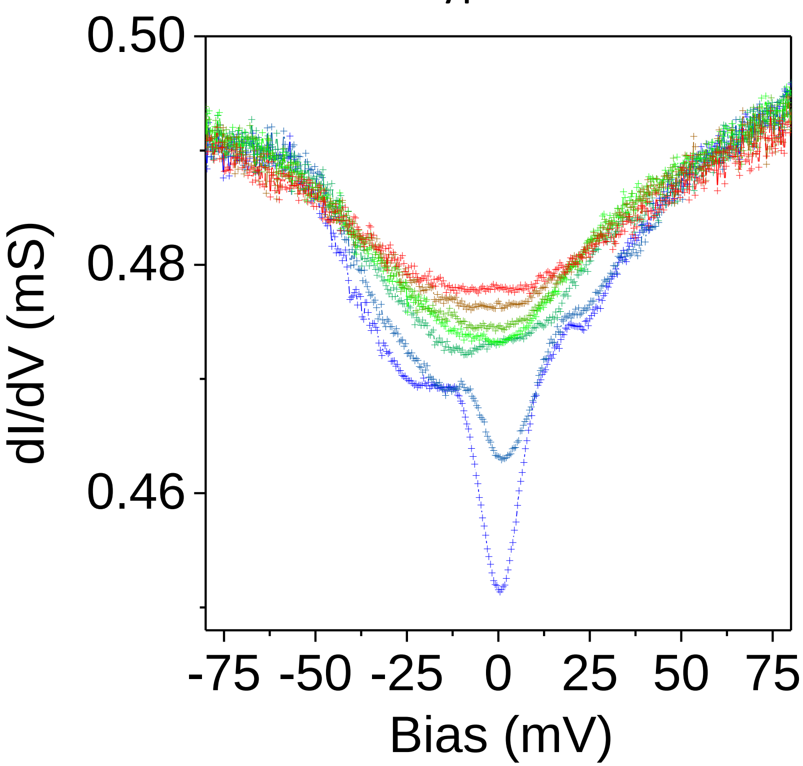
→ **CONDUCTANCE GRAPHENE/S - GRAPHENE/N**

Temperature dependent conductance

Type 1

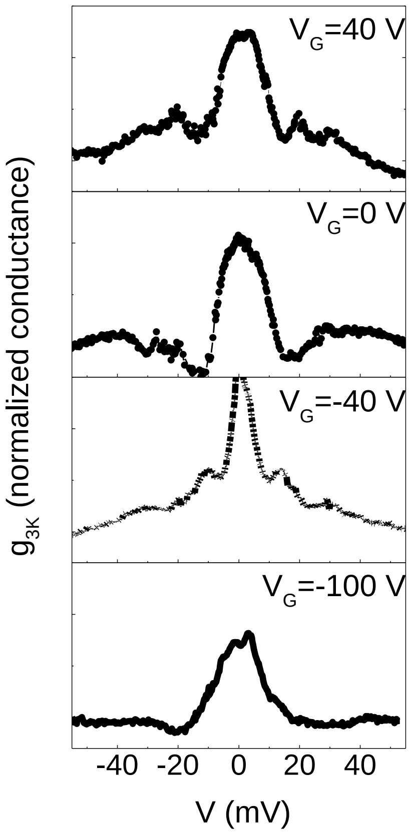


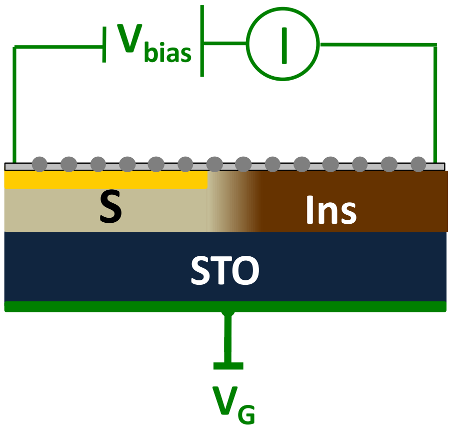
Type 2



→ SAMPLE-DEPENDENT INTERFACE TRANSPARENCY

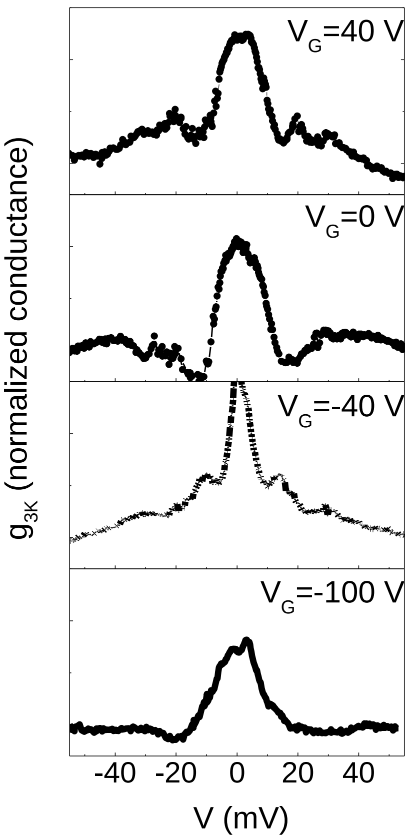
Gate dependent conductance

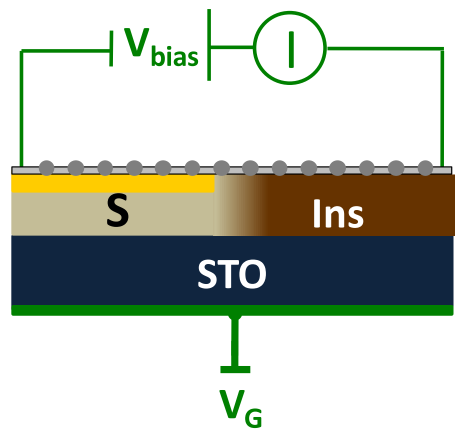


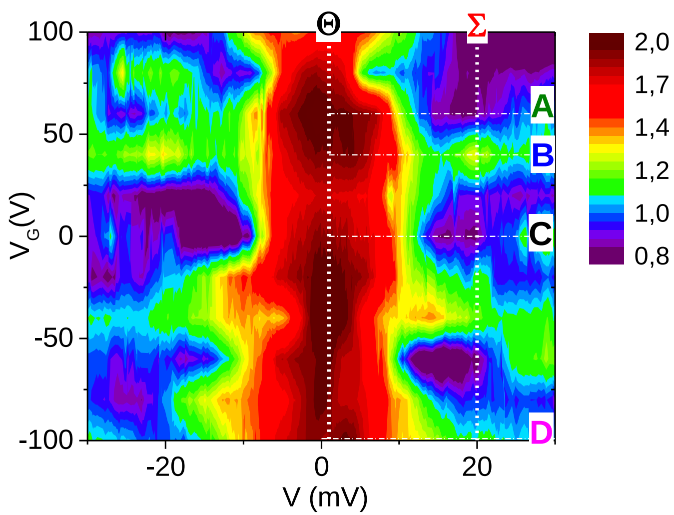


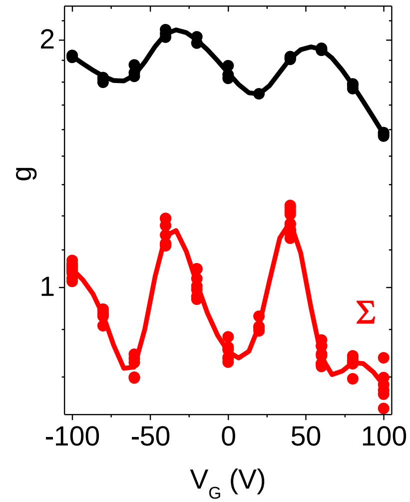
→ PERIODIC MODULATION OF CONDUCTANCE

Gate dependent conductance









→ **PERIODIC MODULATION OF CONDUCTANCE**

Theoretical grounds

PHYSICAL REVIEW B **77**, 064507 (2008)

Tunneling conductance in *s*- and *d*-wave superconductor-graphene junctions: Extended Blonder-Tinkham-Klapwijk formalism

Jacob Linder and Asle Sudbø
Department of Physics, Norwegian University of Science and Technology, N-7491 Trondheim, Norway
(Received 21 August 2007; revised manuscript received 1 November 2007; published 14 February 2008)

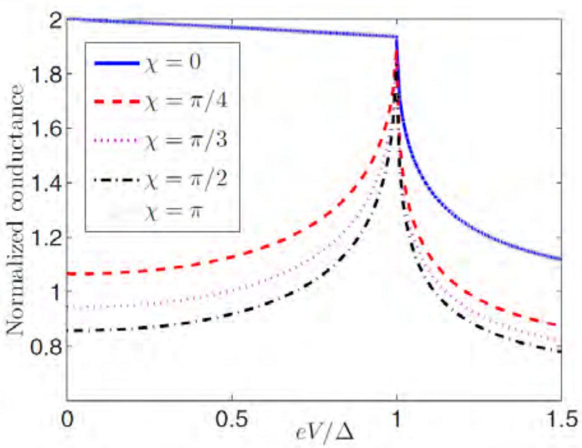


FIG. 11. (Color online) Conductance spectra for a N-I-S graphene junction with $E_F'/\Delta=E_F/\Delta=100$, using *s*-wave pairing. We reproduce the same results as Ref. 12 with a π periodicity in the parameter χ. However, we obtain a phase shift of $\pi/2$ in χ compared to their results. We believe that this difference pertains to a minor sign error in the wave functions used in Ref. 12.

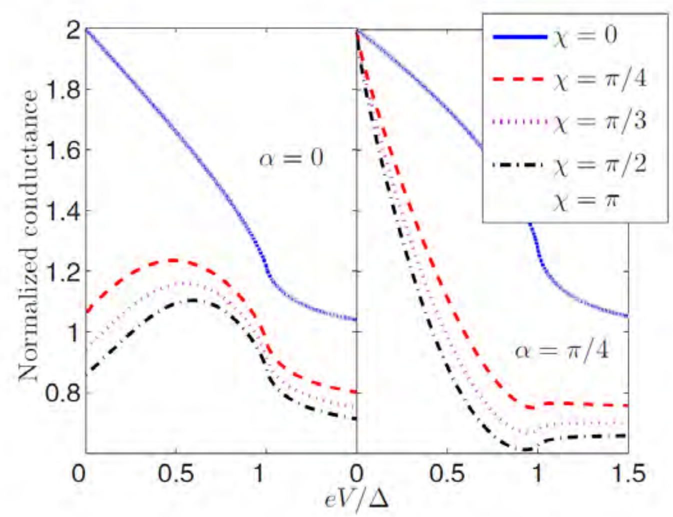
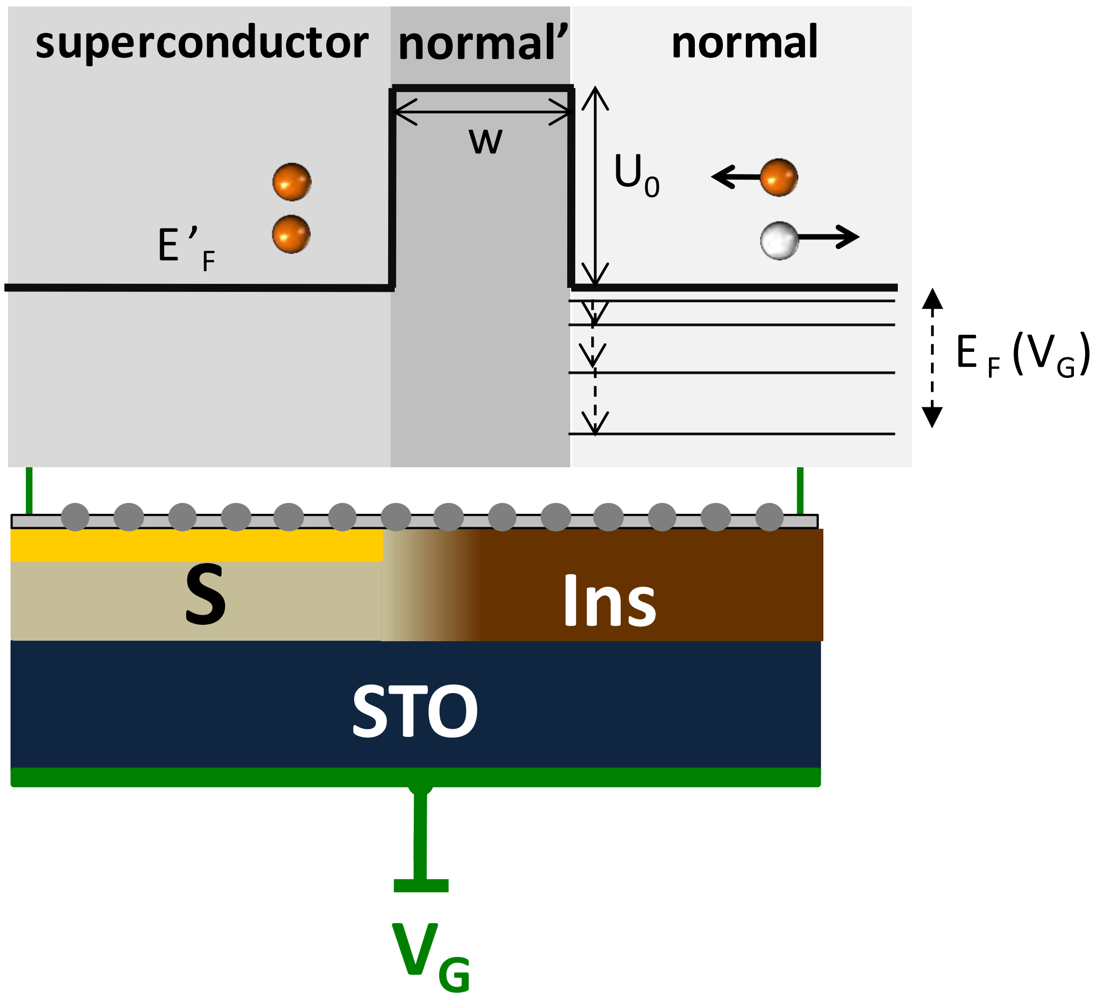


FIG. 13. (Color online) Conductance spectra for a N-I-S graphene junction with $E_F'/\Delta=E_F/\Delta=100$, using *d*-wave pairing.

See also Bhattacharjee et al *Phys. Rev. Lett.* 97, 217001 (2006) for s-wave

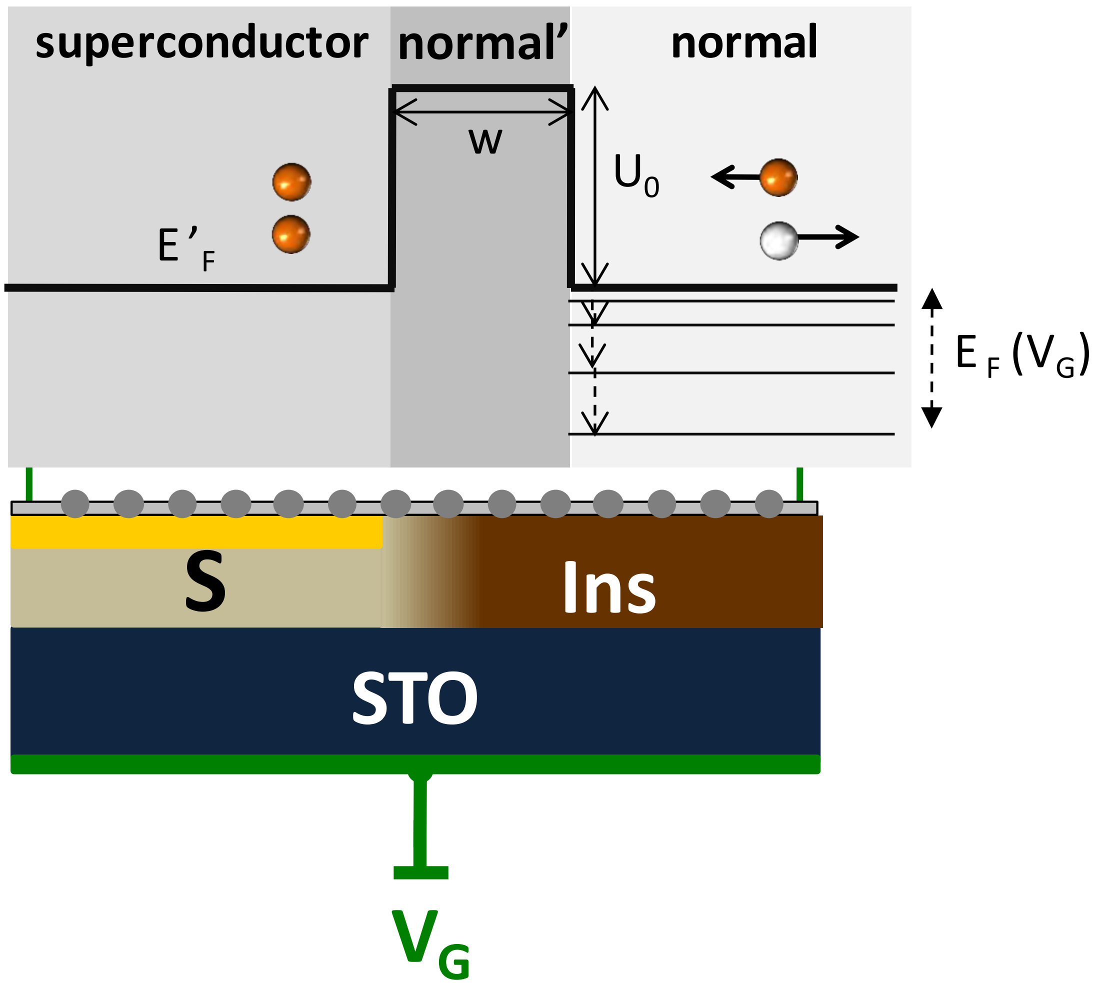
Superconducting / normal graphene interface model

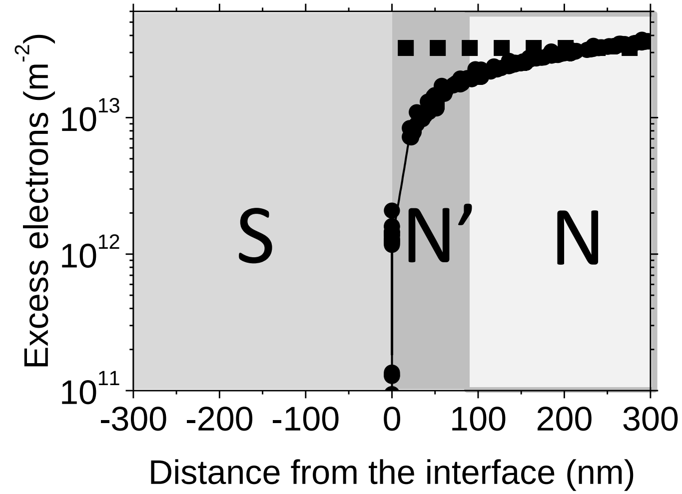


→ **ELECTRON/HOLE INTERFERENCE EFFECTS**

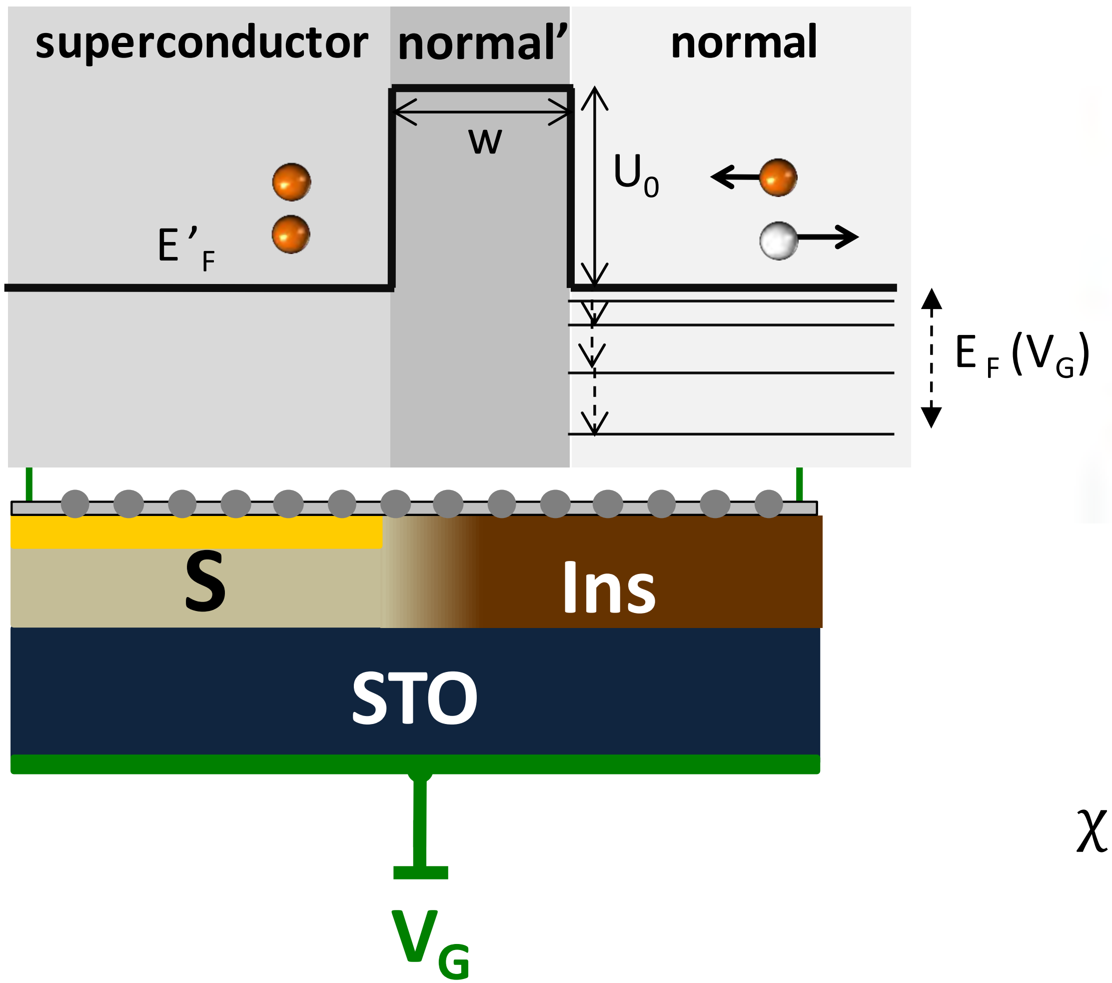
→ **BARRIER U_0 SETS FERMI WAVELENGTH**

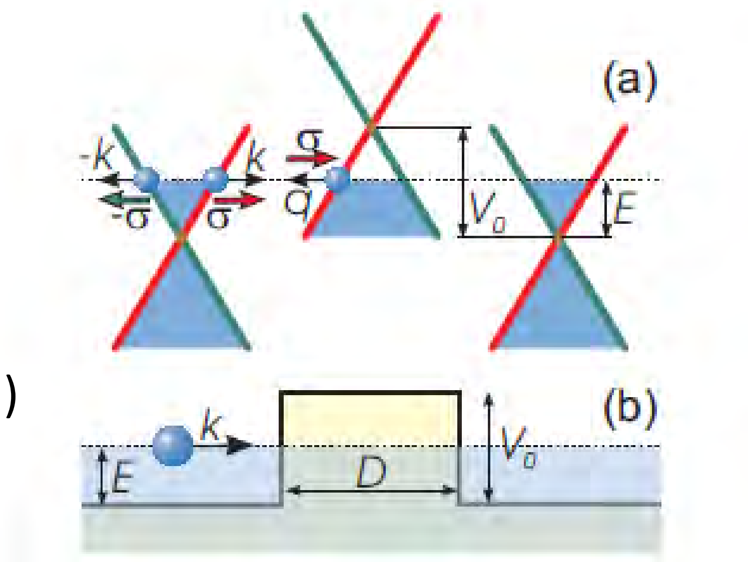
Superconducting / normal graphene interface model





Superconducting / normal graphene interface model





Katsnelson *et al.* Nat. Phys (2006)

$$\chi = -w k_F = n\pi$$

$$\chi = w(E_F - U_0)/\hbar v_F$$

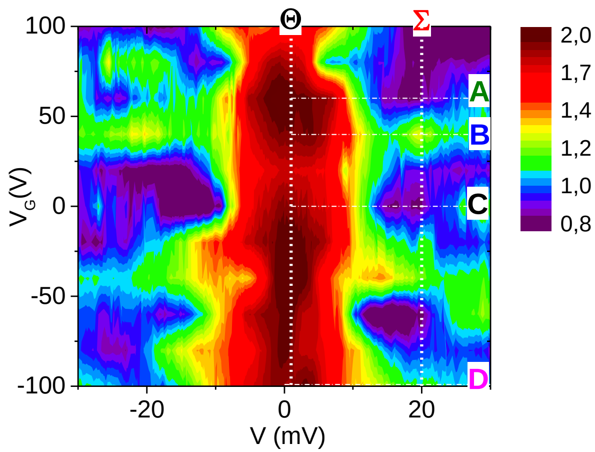
Linder *et al.* PRB (2008)

→ ELECTRON/HOLE INTERFERENCE EFFECTS

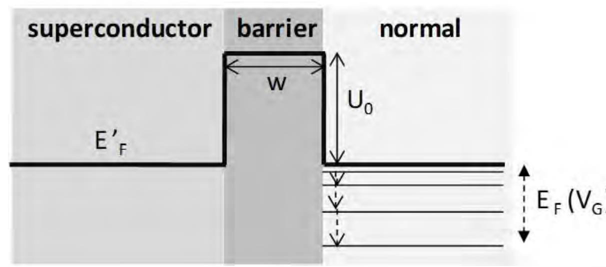
→ BARRIER U_0 SETS FERMI WAVELENGTH

Model simulations

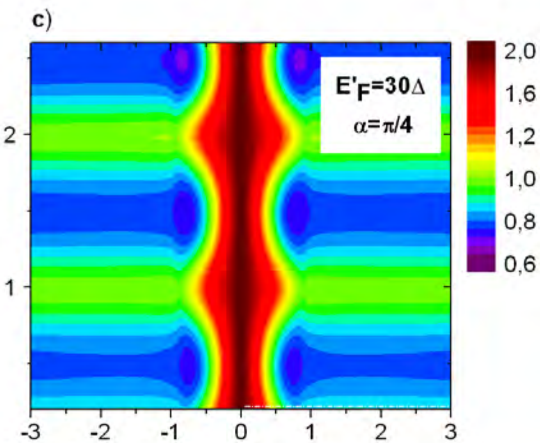
Experiment

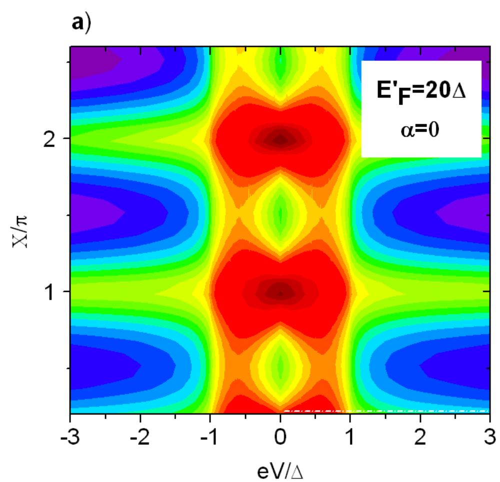


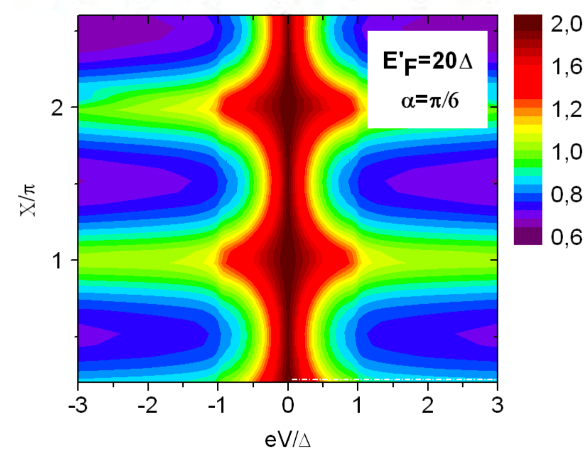
Theory



Linder *et al.* PRB (2008)







KNOWN

$E_F(V_G)$ $\Delta \sim 20$ mV

$\delta\chi/\delta E_F \sim 3\pi/100$

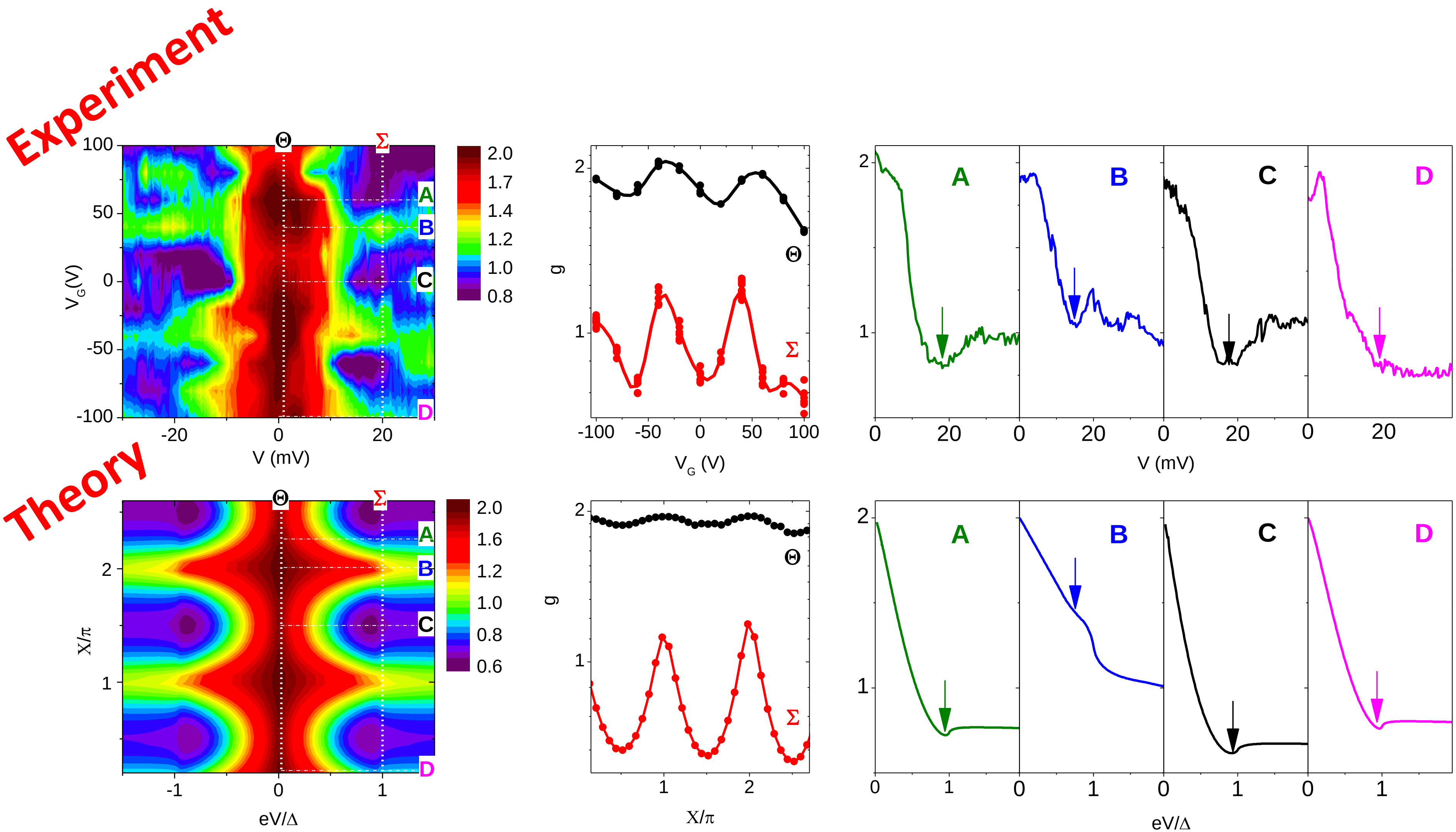
$w = \hbar v_F \, \delta\chi/\delta E_F = 60\ nm$

FREE

E'_F

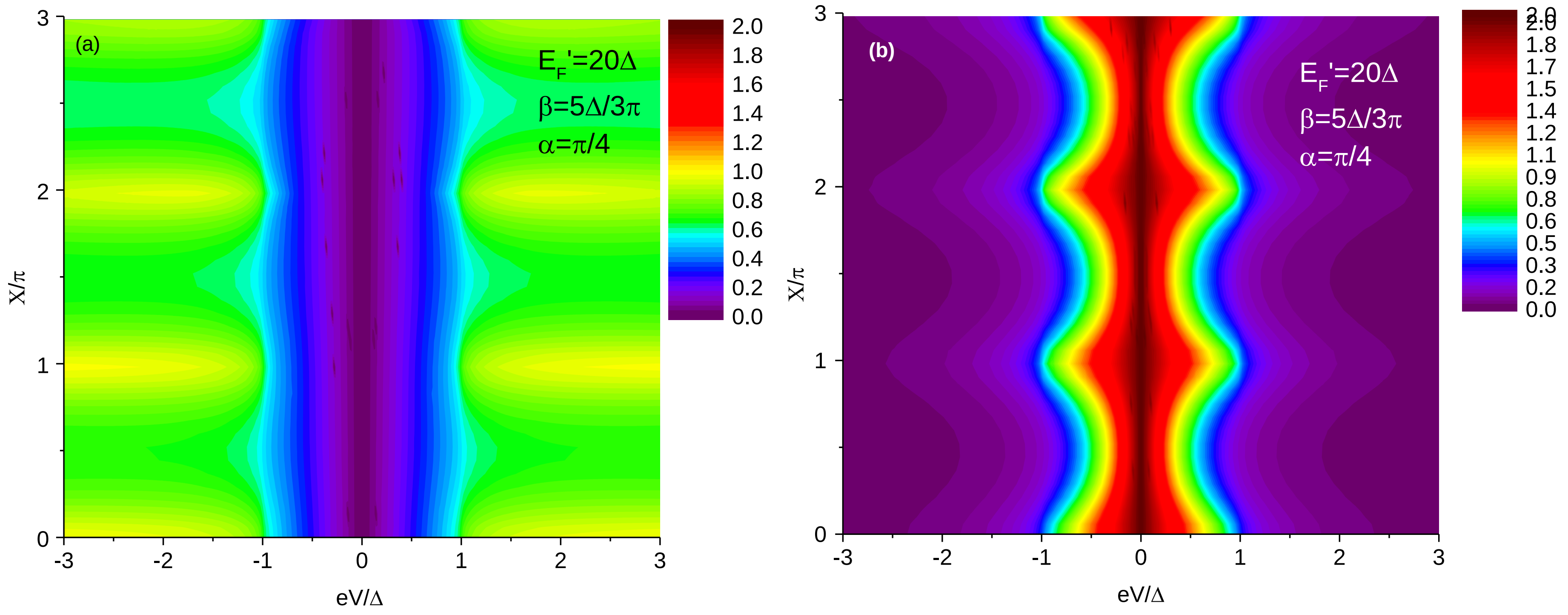
α

Theory vs. experiment



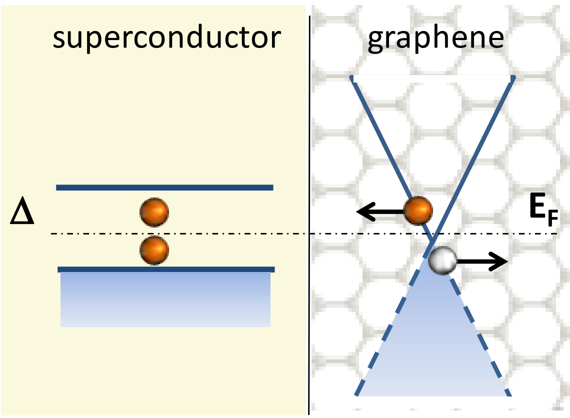
E'_F=0.4 eV α=α/4

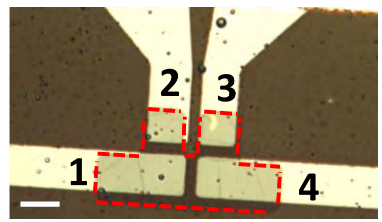
Gate tuning of superconducting carriers

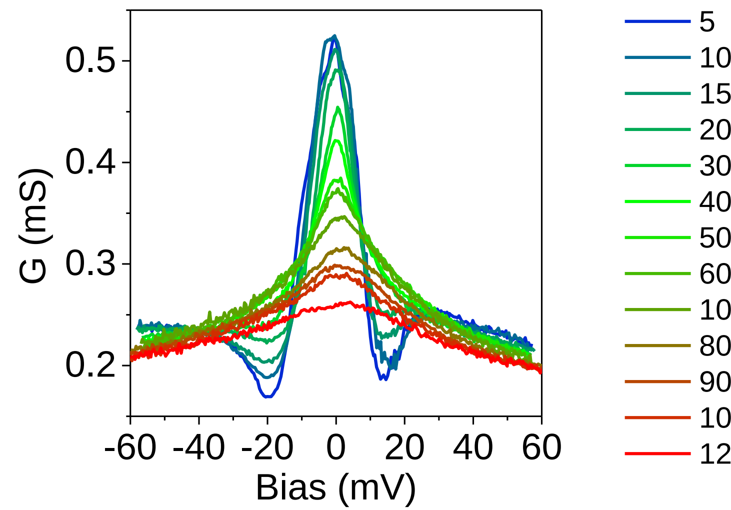


→ FRACTION OF SUPERCARRIERS TUNABLE BY GATING

Conclusions





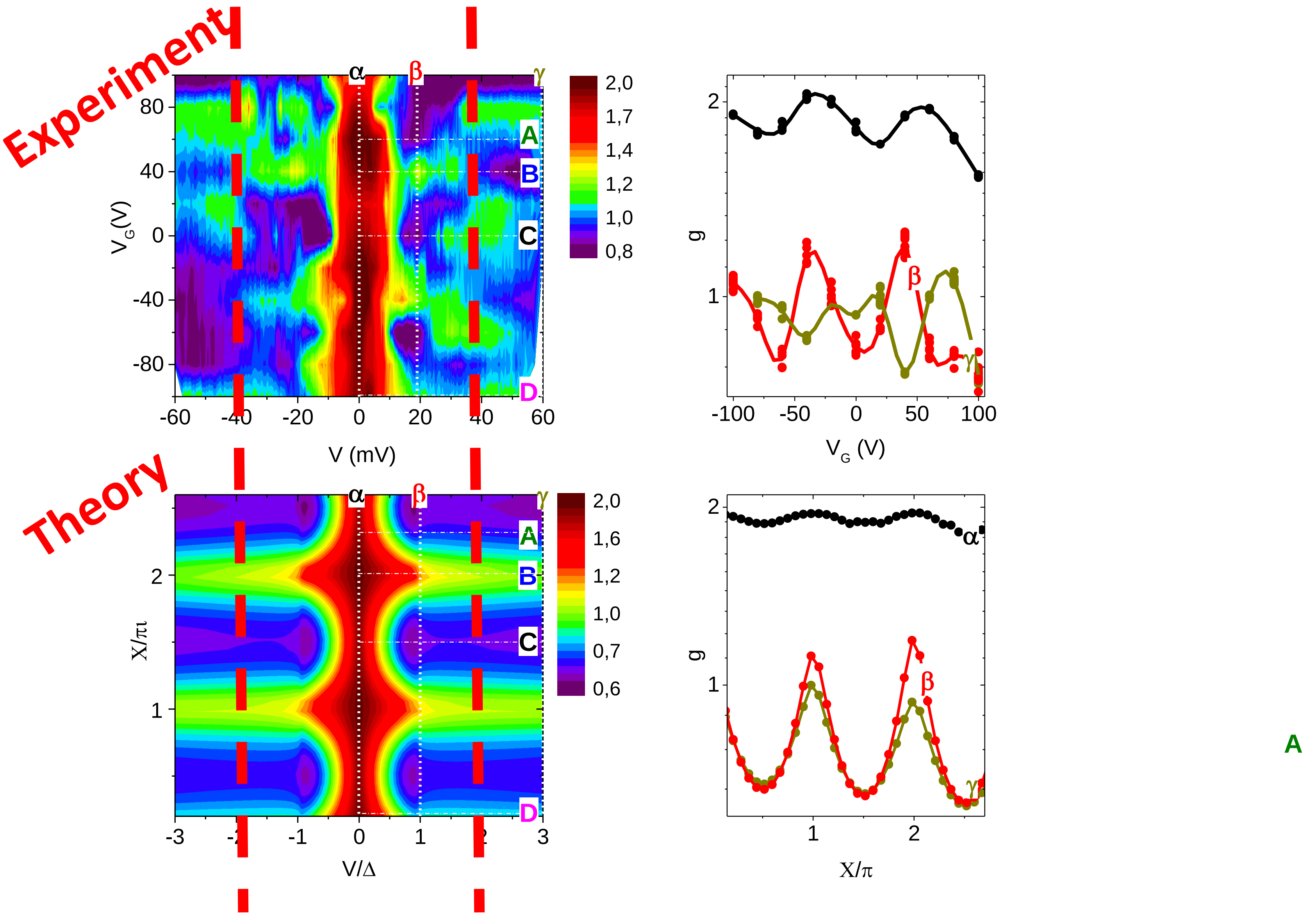


→ **HIGH-T_C SUPERCONDUCTOR / GRAPHENE DEVICES**

→ **GATE TUNABLE PROXIMITY IN CVD GRAPHENE**

→ **ROBUST QUANTUM INTERFERENCE EFFECTS**

Theory vs. Experiment disagreement



COST
EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

NANOSCALE COHERENT HYBRID DEVICES FOR SUPERCONDUCTING QUANTUM TECHNOLOGIES

Funded by the Horizon 2020 Framework Programme of the European Union

http://www.cost.eu/COST_Actions/ca/CA16218

→ €€ for short term visits

→ €€ for conferences and workshops

GET IN TOUNCH WITH THE NATIONAL PROPOSERS

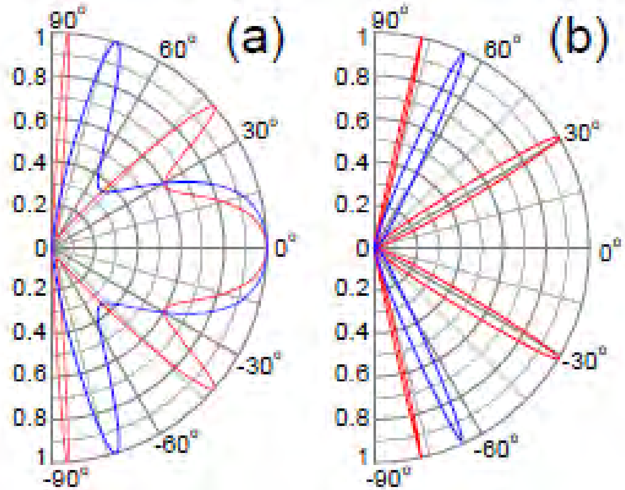


FIG. 2: Klein-like quantum tunneling in graphene systems. Transmission probability T through a 100-nm-wide barrier as a function of the incident angle for (a) single- and (b) bi-layer graphene. The electron concentration n outside the barrier is chosen 0.5×10^{12} cm^{-2} for all cases. Inside the barrier, hole concentrations p are 1×10^{12} and 3×10^{12} cm^{-2} for red and blue curves, respectively (such concentrations are most typical in experiments with graphene). This corresponds to the Fermi energy E of incident electrons ≈ 80 and 17 meV for single- and bi-layer graphene, respectively, and $\lambda \approx 50$ nm. The barrier heights V_0 are (a) 200 and (b) 50 meV (red curves) and (a) 285 and (b) 100 meV (blue curves).

Katsnelson *et al.* Nat. Phys (2006)

PHYSICAL REVIEW B VOLUME 49, NUMBER 17 1 MAY 1994-I

Dielectric properties of sputtered $SrTiO_3$ films

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(Received 8 November 1993)

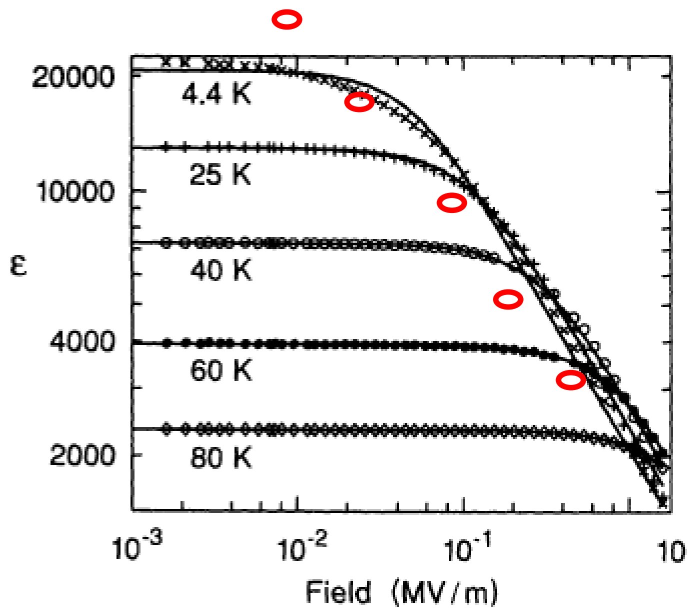

FIG. 2. Field dependence of the dielectric constant ε of single-crystal $SrTiO_3$ at various temperatures. Solid lines are fits to Eqs. (3) and (4).

$\varepsilon_{STO} \sim 10^4$ $d_{STO} = 500\ \mu m$
$\varepsilon_{STO} \sim 10^4$ $d_{YBCO} = 50$ nm

$$\frac{\delta n}{\delta V_G} = \varepsilon_0 \left[\left(\frac{d_{STO}}{\varepsilon_{STO}} + \frac{d_{YBCO}}{\varepsilon_{YBCO}} \right) 2e \right]^{-1}$$

$$\frac{\delta n}{\delta V_G} \sim 5\ 10^{10}\ (\mathrm{cm}^{-2} V^{-1}).$$

ELEMENTARY EXCITATIONS IN THE VICINITY OF A NORMAL METAL-SUPERCONDUCTING METAL CONT

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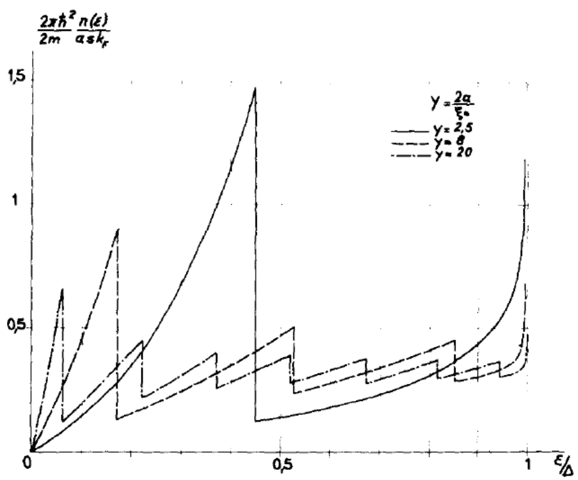

Fig. 1. Density of states.

PHYSICAL REVIEW B **77**, 184507 (2008)

Josephson current and multiple Andreev reflections in graphene SNS junction

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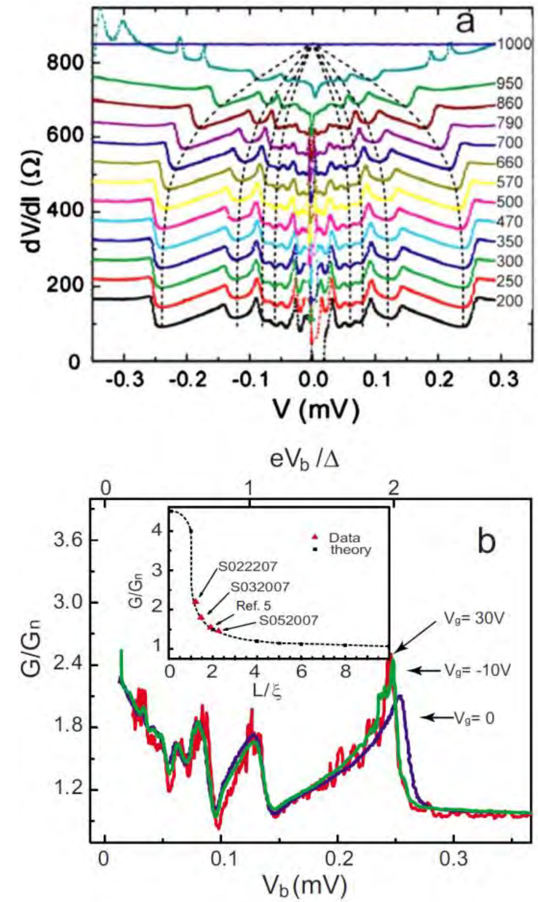
(Received 26 March 2008; published 9 May 2008)



VOLUME 92, NUMBER 1 PHYSICAL REVIEW LETTERS week ending 9 JANUARY 2004

Proximity Effect in Gold-Coated $YBa_2Cu_3O_{7-\delta}$ Films Studied by Scanning Tunneling Spectroscopy

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(Received 6 July 2003; published 8 January 2004)

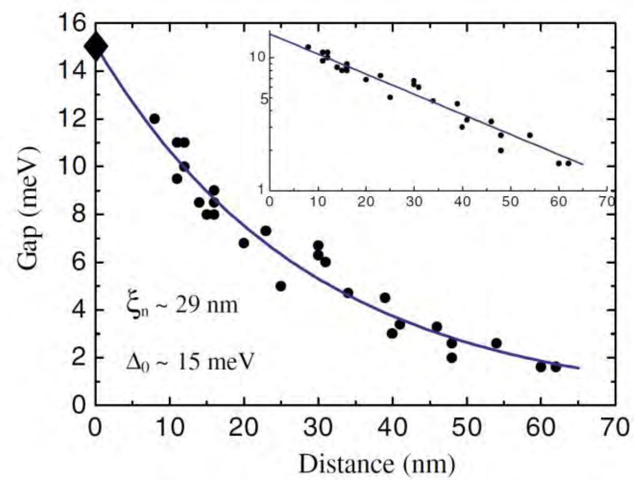

FIG. 3 (color online). Measured gap size as a function of distance from the *N-S* interface (solid circles). The distance is estimated from the distance to the crystallite edge, measured form the STM topographic images, taking into account the nominal Au film thickness. The solid line is a fit to a decaying exponential form, with normal coherence length (penetration depth) $\xi_N \approx 29$ nm, and interface gap value $\Delta_0 \approx 15$ meV (the diamond symbol). The inset shows the data in a semilog scale.