Dissipation-driven quantum phase transition in superconductor-graphene systems

Roman Lutchyn

Collaboration: V. Galitski (UMD), G. Refael (Caltech) and S. Das Sarma (UM

KITP 04/15/09

Outline

- Superconductor-insulator quantum phase transition in Josephson junction arrays
- Dissipation-driven quantum phase transition in superconductor-graphene systems
- Potential applications

R. Lutchyn, V. Galitski, G. Refael and S. Das Sarma, PRL 101, 106402 (2008)

Introduction

Classical phase transitions vs. Quantum phase transitions

- Second order phase transitions
- Spontaneous symmetry breaking
- order parameter

Classical phase transitions	Quantum phase transitions
- thermal fluctuations	- quantum fluctuations
- competition between energy and entropy	- competition between H_1 and $H = H_1 + gH_2$, $[H_1, H_2] \neq 0$
- varying T	- varying g, $T = 0$
paramagnet - ferromagnet	superfluid - insulator

Superconductor-Insulator transition

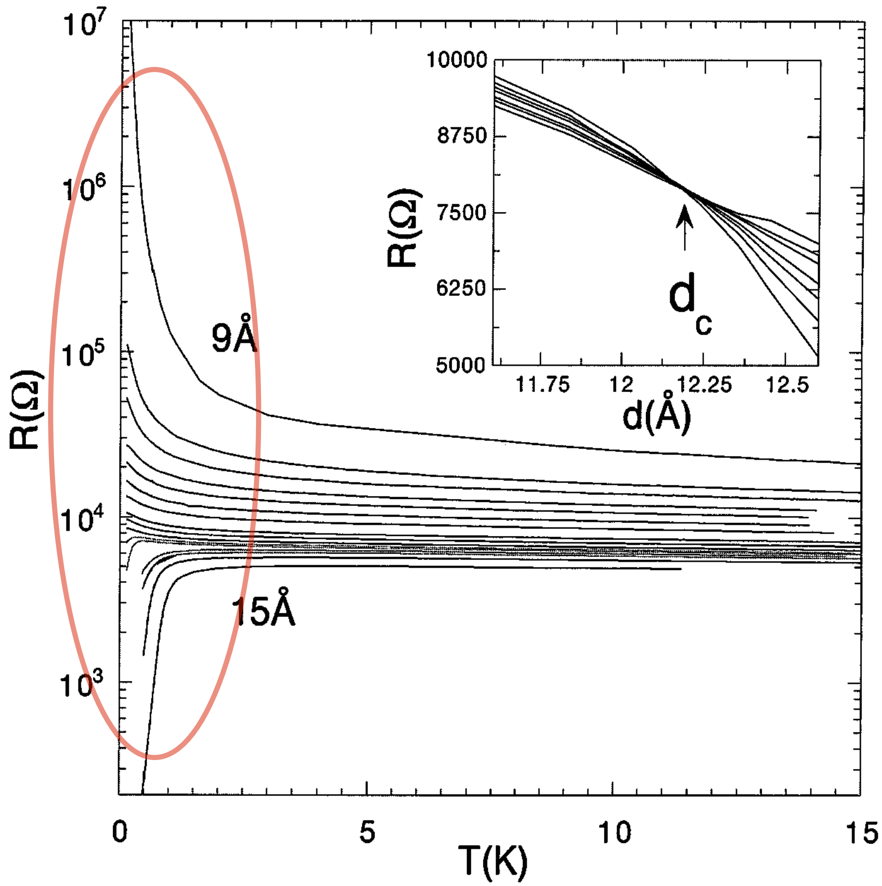


FIG. 1. Resistance per square as a function of temperature for a series of bismuth films with thicknesses ranging from 9 Å (top) to 15 Å (bottom).

Markovic et. al., PRL **81**, 5217(1998)

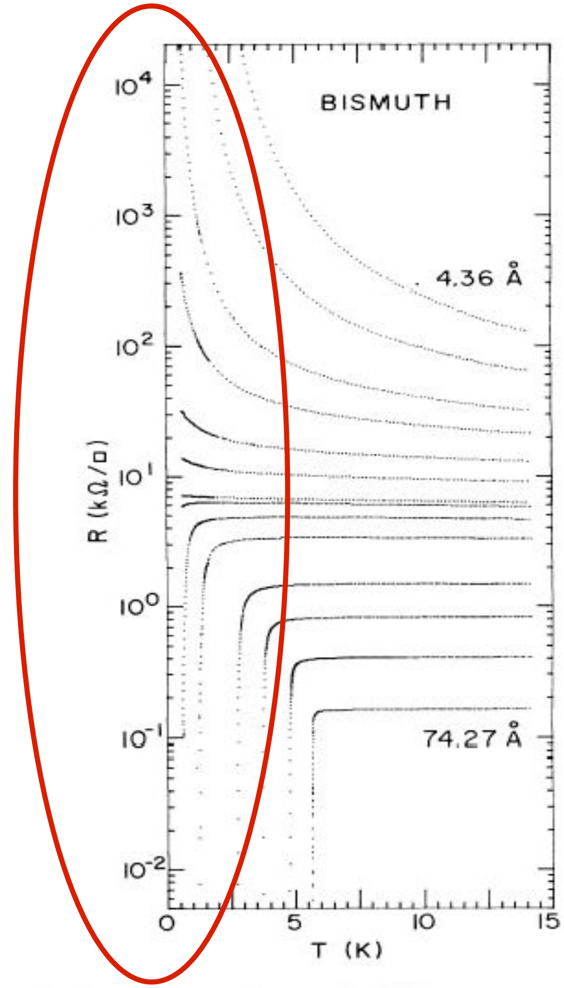
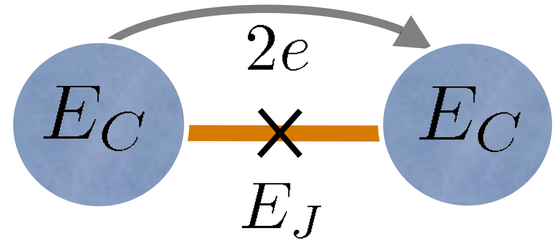


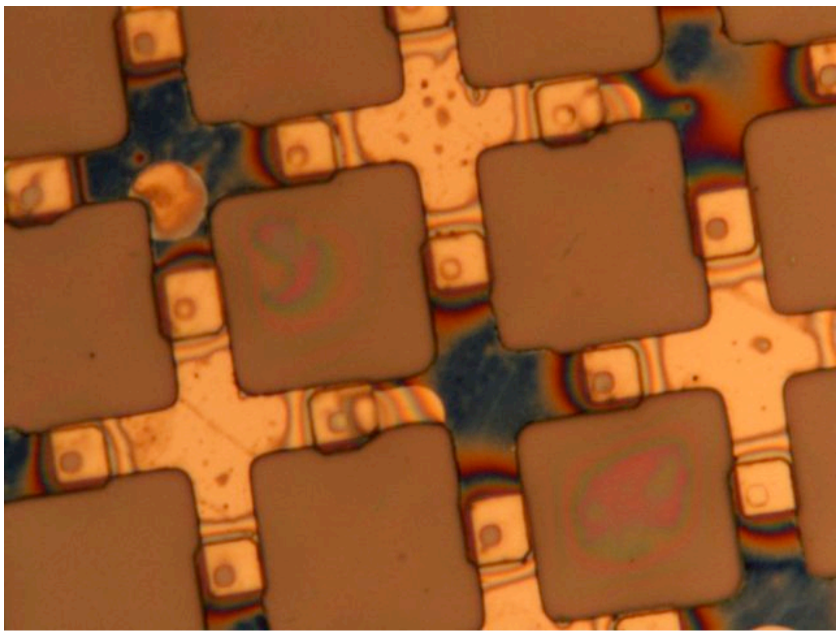
FIG. 1. Evolution of the temperature dependenc sheet resistance $R(T)$ with thickness for a Bi film onto Ge. Fewer than half of the traces actually acq shown. Film thicknesses shown range from 4.36 to 74.

Courtesy of A. Goldman (Minne

Superconductor-Insulator transition

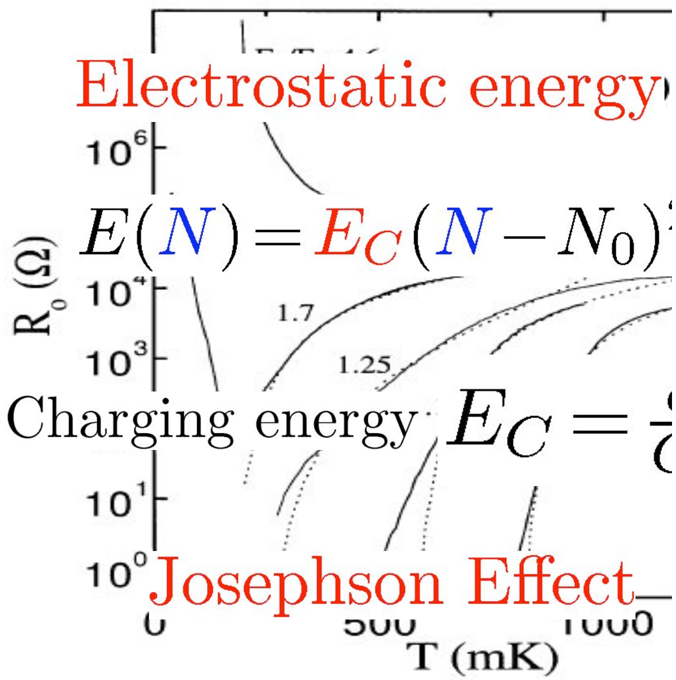
Simplest model for thin films is Josephson junction array mimicking 2D SC islands connected via weak links





2D Josephson junction array

Courtesy of A. Goldman



Electrostatic energy

$E(N) = E_C(N - N_0)^2$

Charging energy $E_C = \frac{e^2}{C}$

Josephson Effect

QPT i $I = I_c \cos[\Delta\varphi]$ ion

Mooij group (Delft

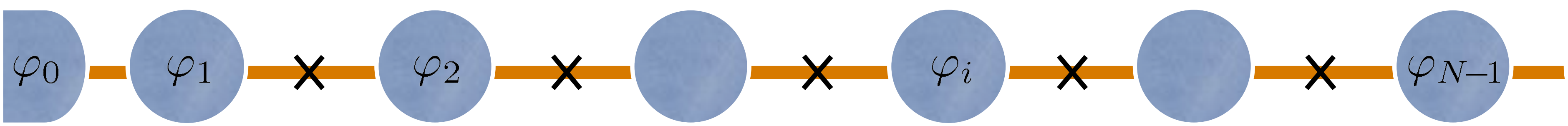
Josephson energy $E_J =$

JJA array: Superconductor-Insulator transition

- Competition between the charging and Josephson energies

$$\hat{H} = \sum_i E_C \hat{n}_i^2 - \sum_{<ij>} E_J \cos(\Delta\hat{\varphi}_{ij})$$

$$[\hat{n}, \hat{\varphi}] = -i$$ Anderson (1964)



At $E_J \gg E_C$ phases φ_i are aligned: global superconductor

At $E_J \ll E_C$ phases φ_i are random: no phase coherence

- Superconductor-Insulator phase transition at $E_C \sim E_J$

Effect of the dissipation on S-I transition

Influence of Dissipation on Quantum Tunneling in Macroscopic Systems

A. O. Caldeira and A. J. Leggett

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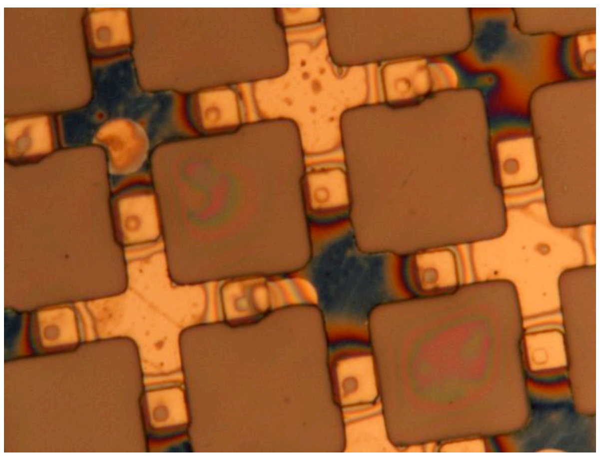
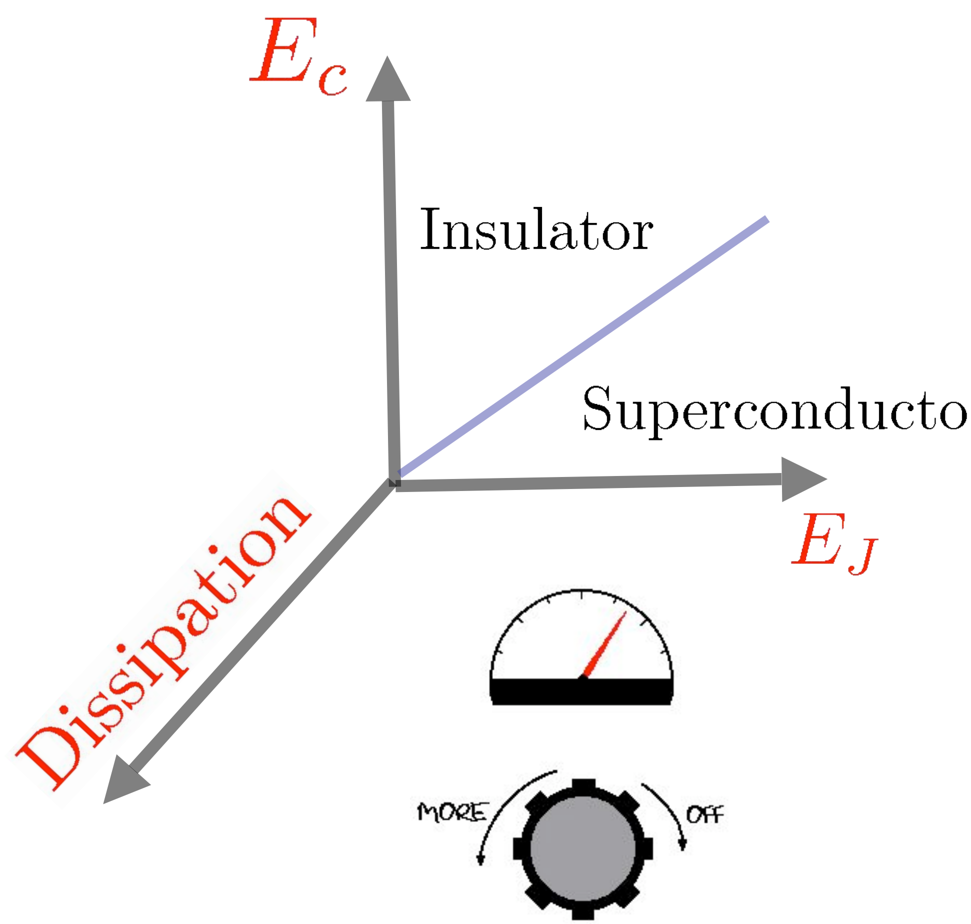
(Received 28 July 1980)

Josephson Junction Array



Problem:

Can not tune E_J and E_c

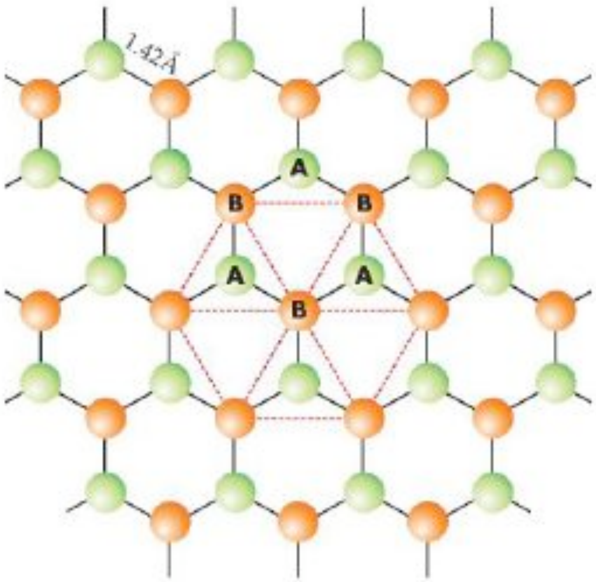


Controlling dissipatio

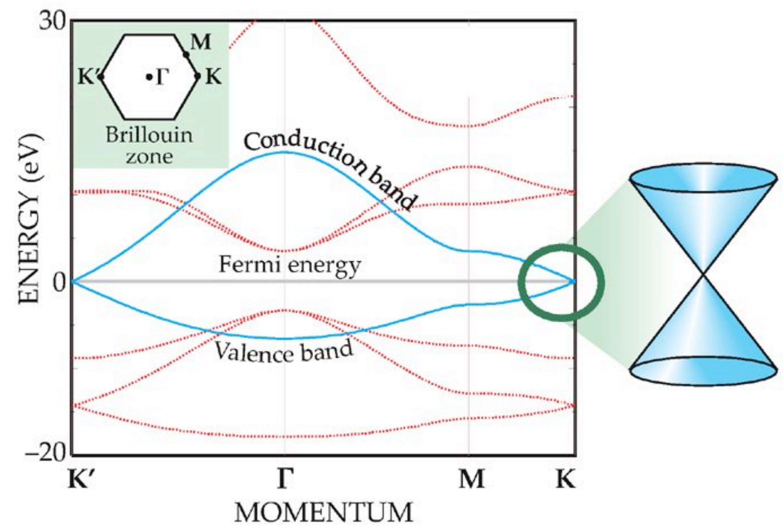
New materials: graphene

Graphene - massless electrons in two dimensions

Graphene is an atomic-scale honeycomb lattice made of carbon atoms



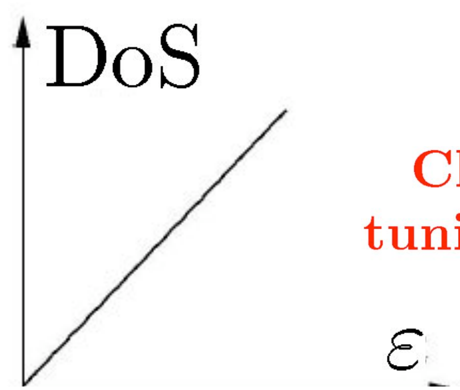
Band structure - linear spectrum



low energy Hamiltonian

$$H = \hbar\gamma\boldsymbol{\sigma}\cdot\boldsymbol{p}$$

chiral massless Dirac fermions



Change the DoS tuning the gate vo

PRL **101,** 106402 (2008) PHYSICAL REVIEW LETTERS week endin
5 SEPTEMBER

Dissipation-Driven Quantum Phase Transition in Superconductor-Graphene Systems

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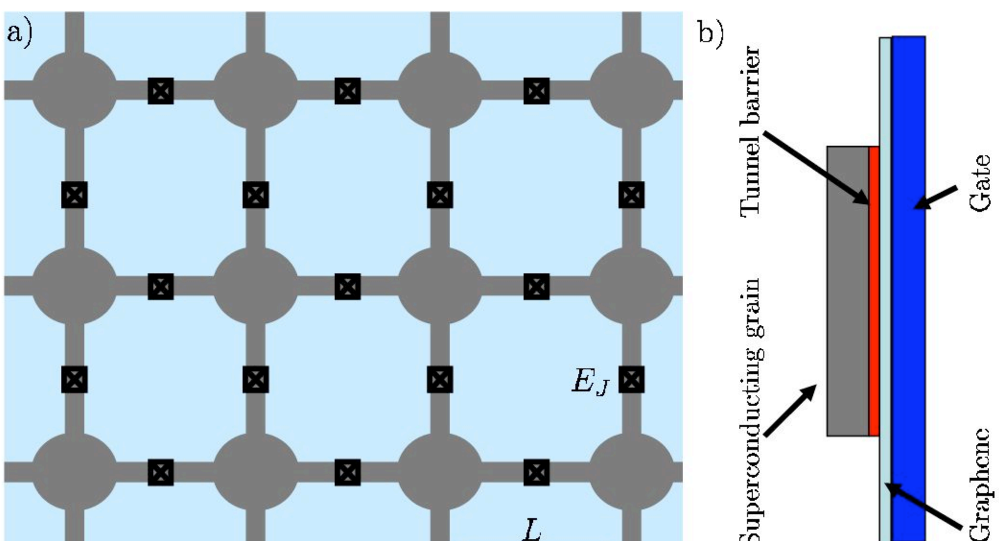
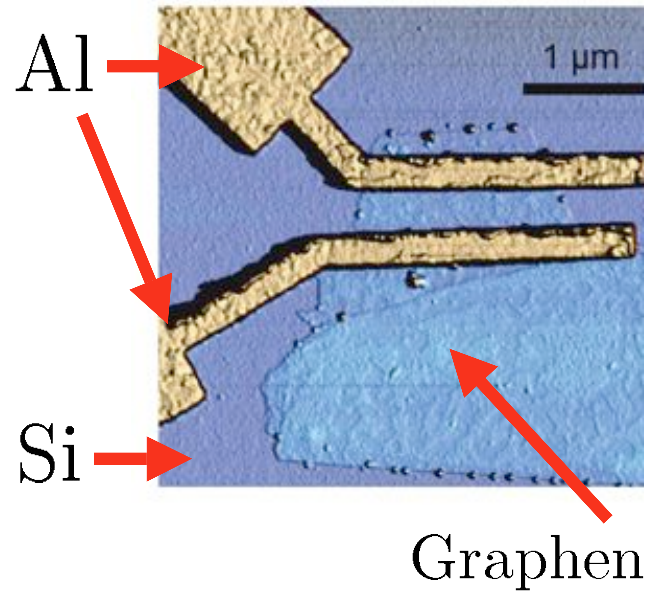
Delft experiment:
Vandersypen et al., Nature(

Proposal: use graphene as a substrate to engineer the dissipation and tune quantum phase transition





First demonstration of t
Josephson effect in S-G-S s

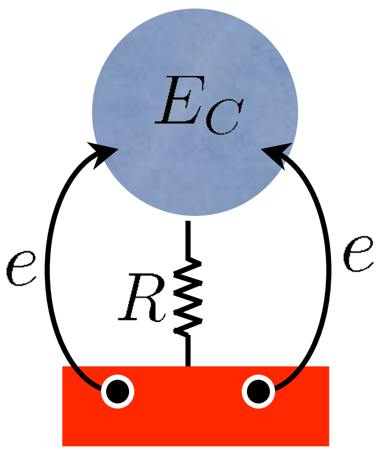
Xu Du, I. Skachko, and Eva Y. Andrei, PRE

More experiments:

Effective action for JJA due to graphene dissipation

$$H = H_{\mathrm{JJA}} + H_{\mathrm{Graphene}} + H_{\mathrm{tunneling}}$$

1. Trace out fermionic degrees of freedom



Cost of having unpaired electron is large: $\Delta \gg E_C, E_J$

↓

Only two-electon correlated(Andreev) tunneling processes contr

↓

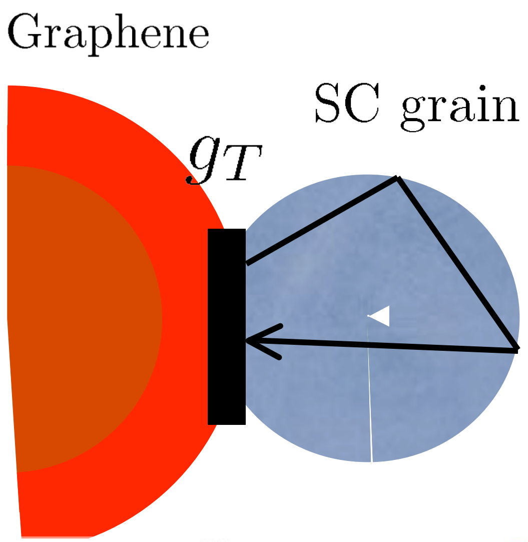
$$S_A \propto t^4 \int_A \prod_{i=1..4} d\boldsymbol{x}_i \mathrm{Re}\Big[F^*(\boldsymbol{x}_1, \boldsymbol{x}_2) G^{(g)}(\boldsymbol{x}_2, \boldsymbol{x}_4) F(\boldsymbol{x}_4, \boldsymbol{x}_3) G^{(g)}(\boldsymbol{x}_3,$$

Mesoscopic grain - coherent backscattering effect

F. Hekking and Yu. Nazarov, PRB(

Coherent backscattering effect

Coherent backscattering effect: spatial correlations are importa



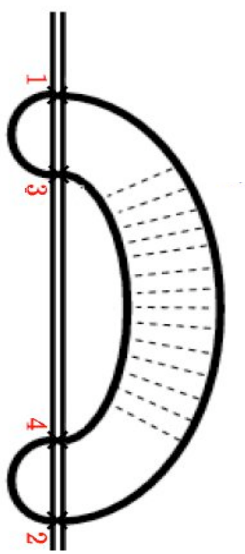
$$\langle F^*(\boldsymbol{x}_1,\boldsymbol{x}_2)F(\boldsymbol{x}_4,\boldsymbol{x}_3)\rangle \propto \left\langle \sum_{n,m} \psi_n(\boldsymbol{r}_1)\psi_n(\boldsymbol{r}_2)\psi_m(\boldsymbol{r}_3)\psi_m(\boldsymbol{r}_4)M(\xi_n\right.$$

$$\downarrow$$

$$\langle \mathrm{Im}G_{\xi_1}(\boldsymbol{r}_1,\boldsymbol{r}_2)\rangle \langle \mathrm{Im}G_{\xi_2}(\boldsymbol{r}_4,\boldsymbol{r}_3)\rangle + \langle \mathrm{Im}G_{\xi_1}(\boldsymbol{r}_1,\boldsymbol{r}_2)\mathrm{Im}G_{\xi_2}(\boldsymbol{r}_4,\boldsymbol{r}_3)\rangle_{\mathrm{ir}}$$

$$\downarrow$$

Universal Random Matrix limit $\quad E_T \sim \dfrac{\hbar D}{R^2} \gg \Delta \gg E_c, E_J$

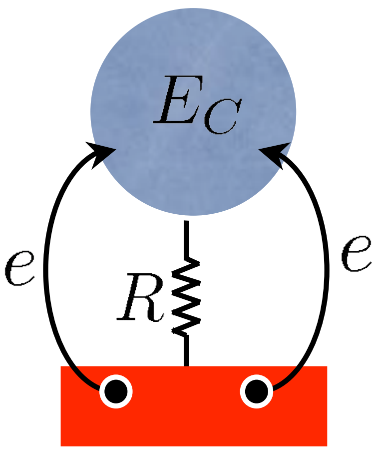


$$\downarrow$$

$$\langle \mathrm{Im}G_{\xi_1}(\boldsymbol{r}_1,\boldsymbol{r}_2)\mathrm{Im}G_{\xi_2}(\boldsymbol{r}_4,\boldsymbol{r}_3)\rangle = N(0)^2 f_{12}f_{43} + N(0)\frac{\delta(\xi_1-\xi_2)}{V}\left[f_{14}f_{23} + f_{13}\right.$$

Dominant contribution to S_A

Effective action for JJA due to graphene dissipation



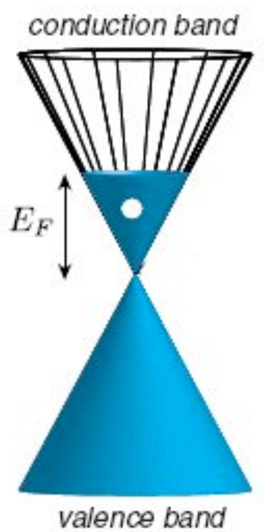
$$S_A = -G \int_0^\beta d\tau \int_0^\beta d\tau' K(\tau-\tau') \cos[\phi(\tau)-\phi(\tau')]$$

$G \propto t^4$

Dissipation kernel

close to Dirac point

away from Dirac poi



$$K(\tau-\tau') \approx \frac{1}{k_F^2 \gamma^2 (\tau-\tau')^4}$$

$$K(\tau-\tau') \approx \frac{(eV_G)^2}{k_F^2 \gamma^2 (\tau-}$$

tunable Ohmic dissipa

Superconductor-insulator transition

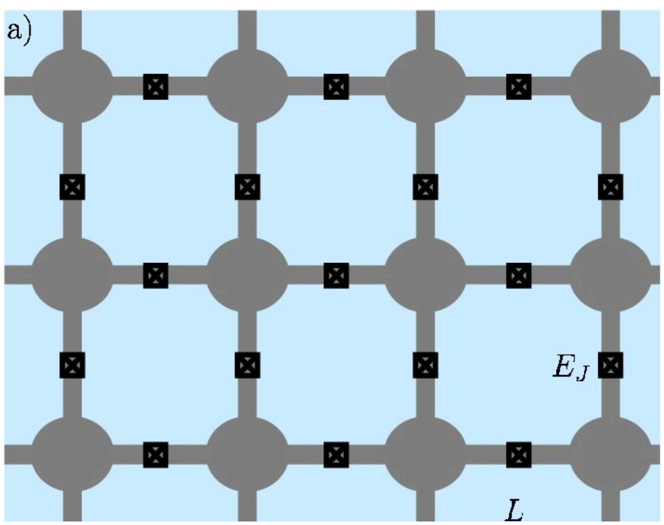
Imaginary time action for JJA: $S = S_0 + S_J$

$$S_0 = \sum_i \left[\int_0^\beta d\tau \frac{\dot{\varphi}_i(\tau)^2}{E_c} - \frac{G(eV_G)^2}{k_F^2\gamma^2} \int_0^\beta d\tau \int_0^\beta d\tau' \frac{\cos\left[\varphi_i(\tau) - \varphi_i(\tau')\right]}{(\tau-\tau')^2} \right]$$

$$S_J = \sum_{<ij>} \int_0^\beta d\tau E_J \cos[\varphi_i(\tau) - \varphi_j(\tau)]$$

M. V. Feigel'man and A. I. Larkin

Superconductor-Insulator transition in 2D



Mean-Field theory:

$$r \propto \frac{1}{zE_J} - \int_0^\beta d\tau \left\langle e^{i\varphi_i(\tau) - i\varphi_i(0)} \right\rangle_0 = 0$$

Calculate correlation function for the single grain problem

Superconductor-insulator transition

$$S = \int d\tau \frac{\dot{\varphi}^2(\tau)}{E_c} - \eta \int d\tau d\tau' \frac{\cos\left[\varphi(\tau) - \varphi(\tau')\right]}{(\tau - \tau')^2}$$

$$\eta = \frac{G(eV_G)^2}{k_F^2 \gamma^2}$$

$\eta = 0$ $\quad \langle e^{i\varphi(\tau) - i\varphi(0)} \rangle \propto e^{-E_C \tau}$ phases are uncorrelated at $\tau > E_C^-$

$$\eta \gg 1 \qquad \langle e^{i\varphi(\tau) - i\varphi(0)} \rangle_0 \sim \begin{cases} \left(\frac{\tau_c}{\tau}\right)^{\frac{1}{2\pi^2\eta}}, & \Lambda^{-1} \ll \tau \ll \tau_c \\ \left(\frac{\tau_c}{\tau}\right)^2, & \tau \gg \tau_c, \end{cases}$$

Phase correlations decay much slower, *i.e.* phase fluctuations are suppresse

Partition function for ferromagnetic spin chain $\quad Z = \exp\left(-\frac{1}{T} \int dx dx' \frac{\boldsymbol{S}(x)\boldsymbol{S}(x'}{(x - x')^2}\right.$

$$\boldsymbol{S}(x) = \{\sqrt{1 - \pi(x)^2}, \pi(x)\}$$

Polyakov(1975)
Kosterlitz(1976)
Brezin and Zinn-Justin (1976)
Hofstetter and Zwerger (1998)

Renormalization group analysis

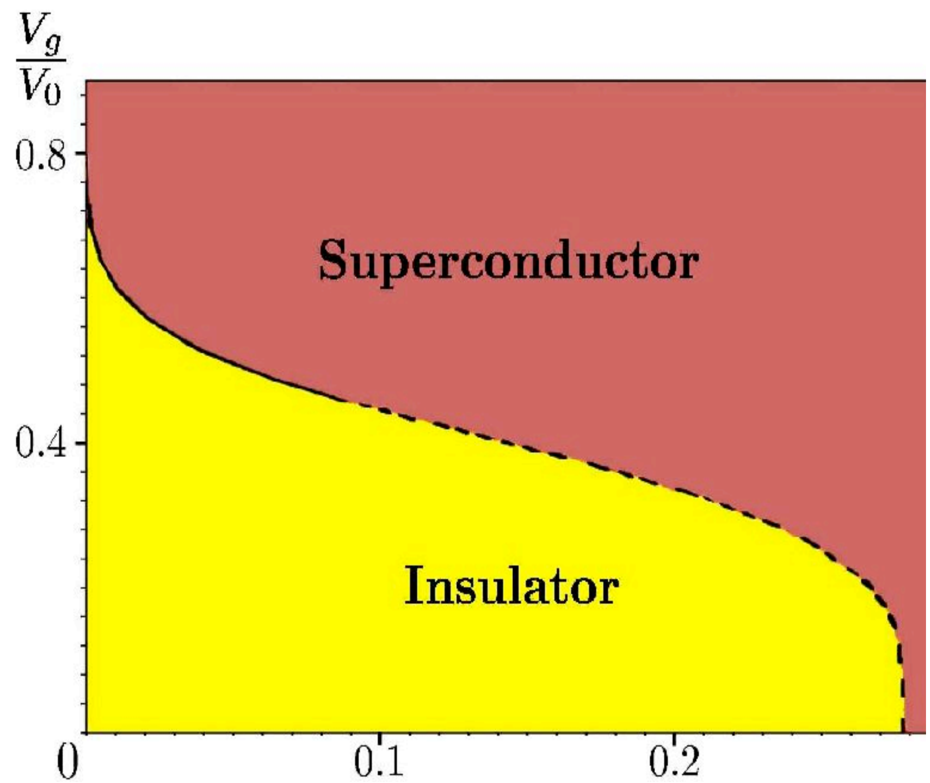
Superconductor-insulator transition

Superconductor-Insulator phase boundary

$$r \propto \frac{1}{zE_J} - \int_0^\beta d\tau \left\langle e^{i\varphi_i(\tau) - i\varphi_i(0)} \right\rangle_0 = 0 \quad \Rightarrow \quad E_J \approx E_C^*$$

Effective charging energy

$$E_C^* \sim E_C \left(\frac{V_G}{V_0}\right)^4 \exp\left[-2\pi^2 \frac{V_G^2}{V_0^2}\right]$$



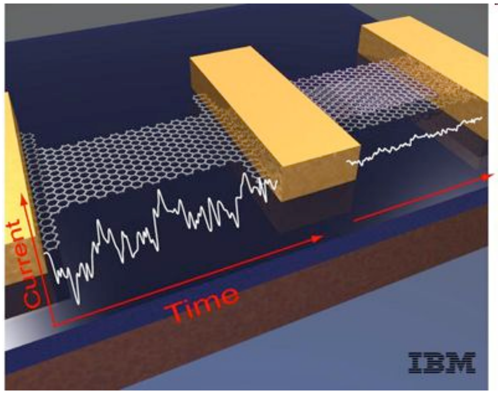
F. Guinea and G. Schon, EPL (1986)

Panyukov and Zaikin, PRL (1991)

Falci, Schon and Zimanyi, PRL (1995)

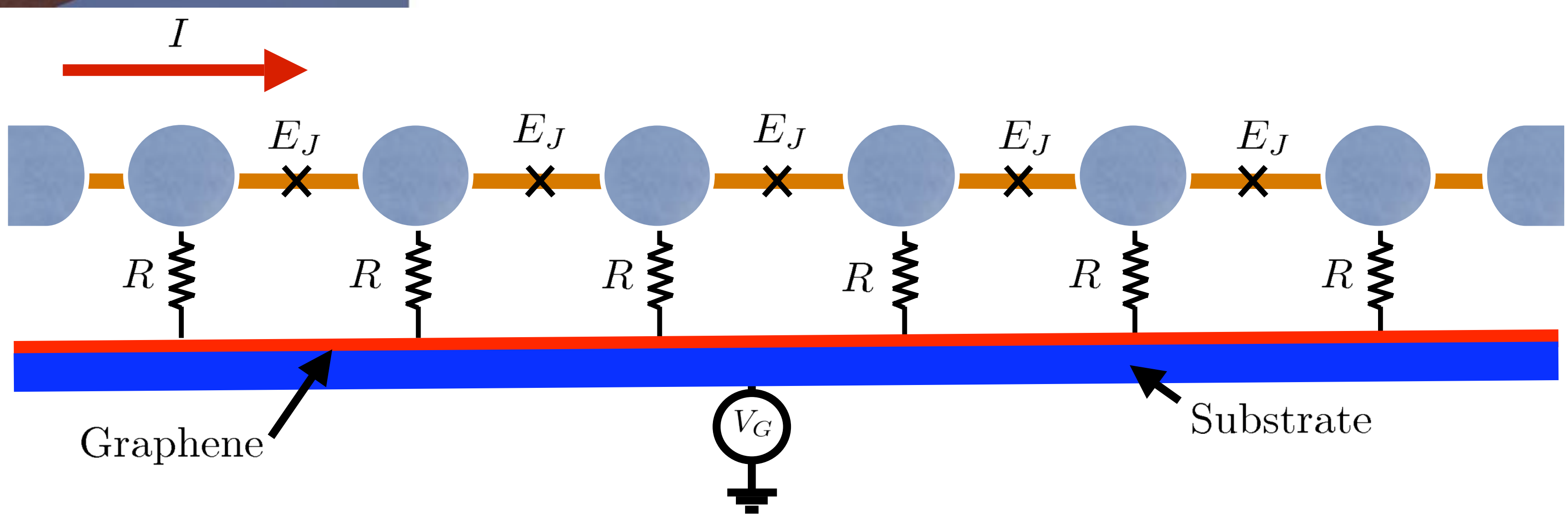
Lukyanov and Werner, J of Stat Mech (2006)

Low temperature current switching devices



New SC circuit applications ?

Current switching devices based on JJA proximity coupled to the graphene



V_c - critical gate voltage

$V < V_c$

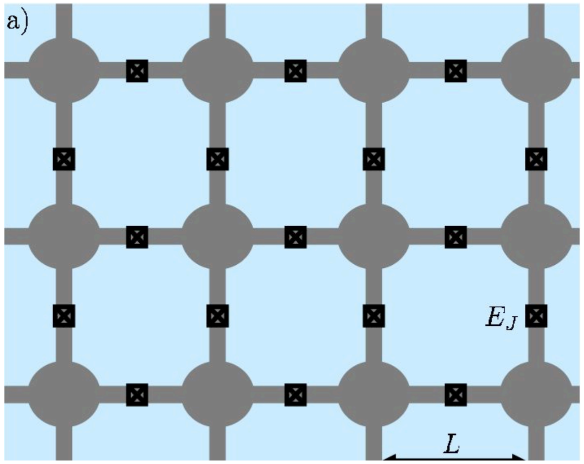
Insulator: $I_c \to 0$

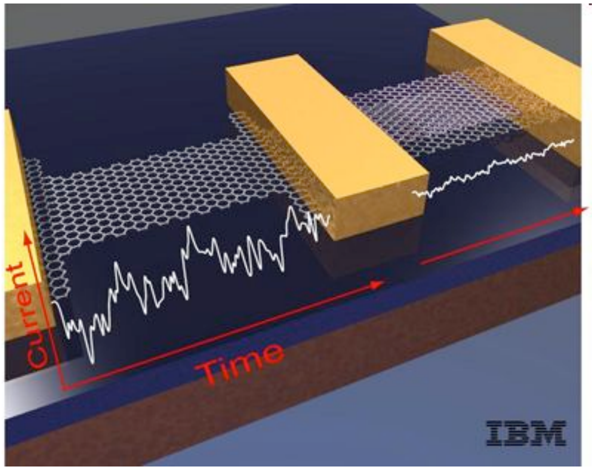
$V > V_c$

Global superconductor: I_c

Conclusions

- Dissipation driven QPT
- Engineering dissipation using graphene
- Low temperature current switching devices





Thank you