# Title

arXiv:0802.3462

# Room-Temperature Superfluidity in Graphene Bilayers?


Hongki Min*, Rafi Bistritzer*, Jung-Jung Su*, A.H. MacDonald

*Department of Physics, The University of Texas at Austin, Austin Texas 78712*

(*These authors contributed equally to this work.)

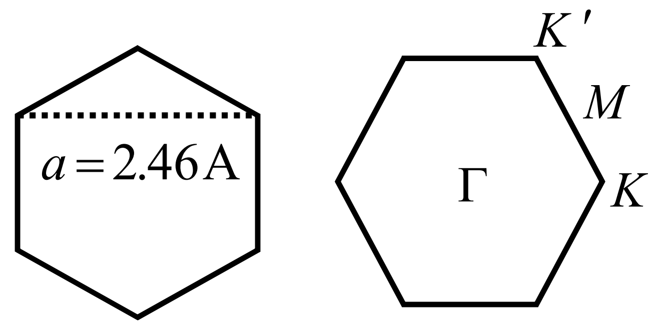


Because graphene is an atomically two-dimensional gapless semiconductor with nearly identical conduction and valence bands, graphene-based bilayers are attractive candidates for high-temperature electron-hole pair condensation. We present estimates which suggest that the Kosterlitz-Thouless temperatures of these two-dimensional counterflow superfluids can approach room temperature.

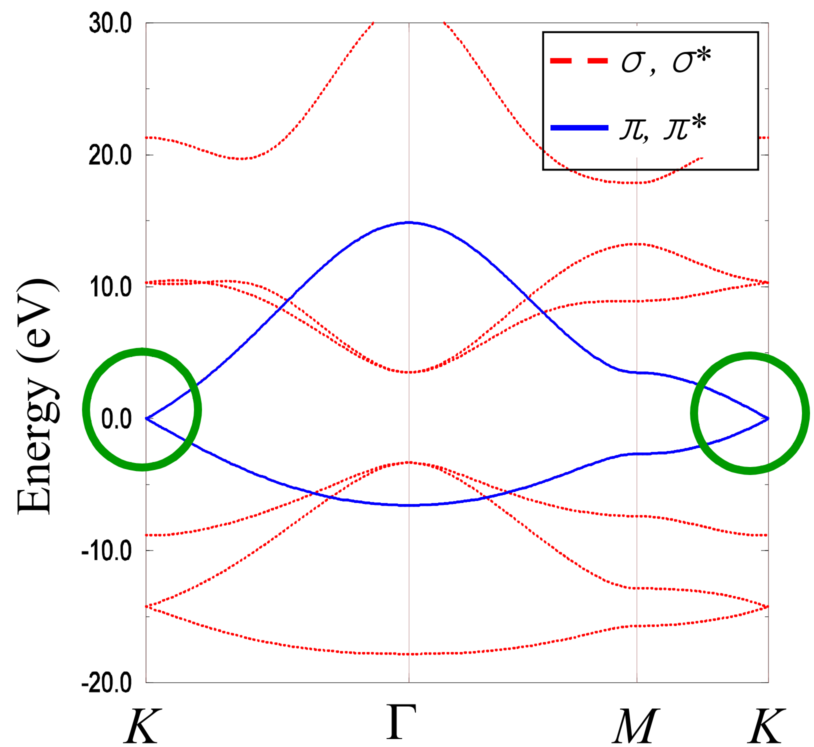
# 1. Introduction (1)

## 1) Graphene

- Two-dimensional honeycomb lattice of carbon atoms.



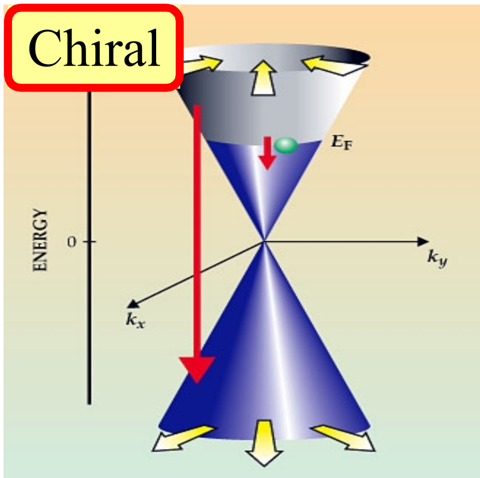

- 2D Dirac-like equation with linear dispersion near $K/K'$.




- New electron-electron interaction physics?
  Ex) magnetism
  superconductivity

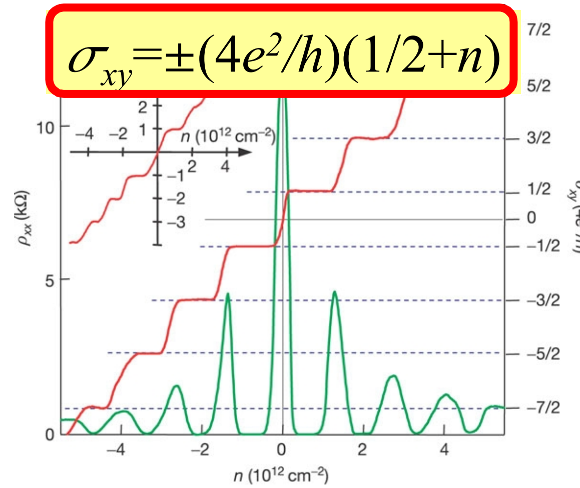
# 1. Introduction (2)

## 2) Extraordinary properties of graphene



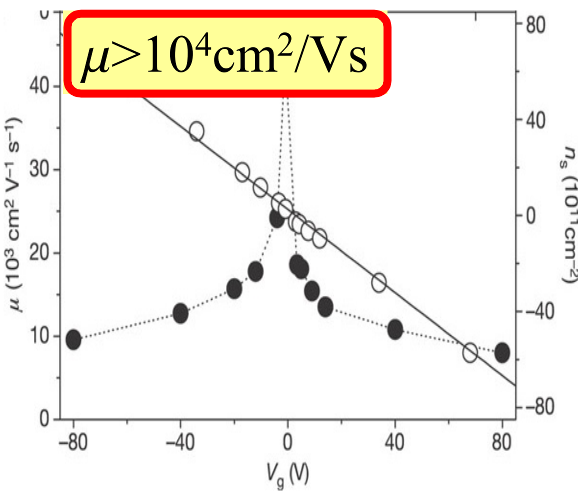

Dirac-like equation

Wallace,
Phys. Rev. (1947)



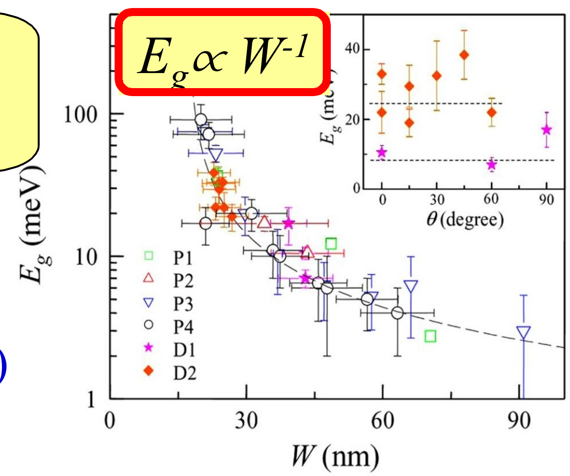

Quantum Hall effect

Novoselov et al.
Nature (2005)




High mobility

Zhang et al.
Nature (2005)




Device application

Han et al.
PRL (2007)

# 1. Introduction (3)

## 3) Search for new ordered states in graphene systems

Relativistic Dirac-like wavefunction

+

Non-relativistic electron-electron interaction

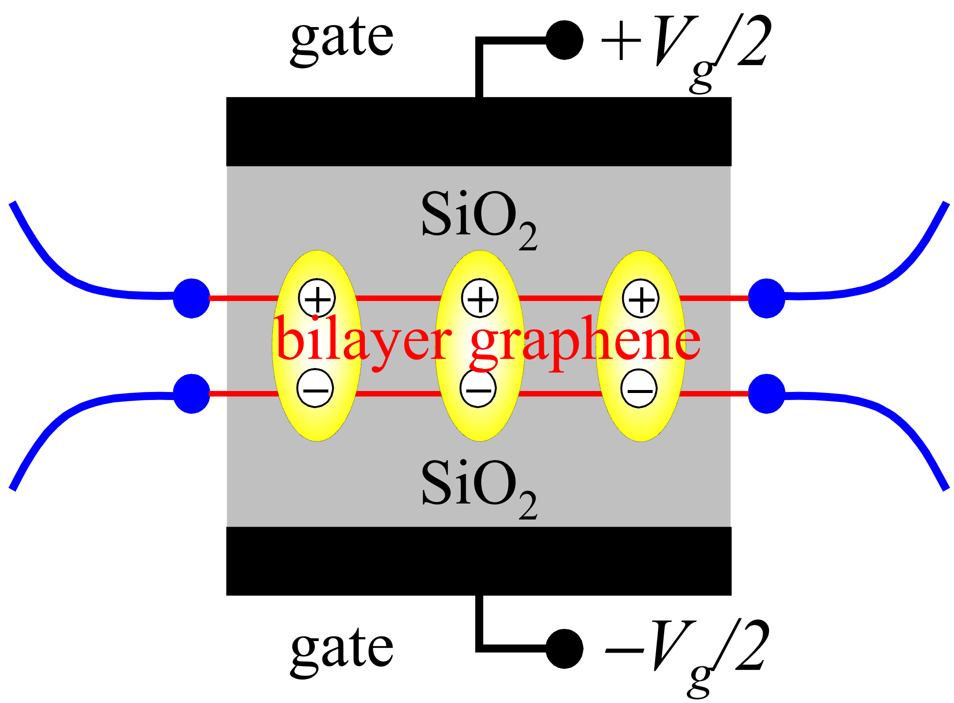
$\Rightarrow$ Possible ordered states in graphene systems

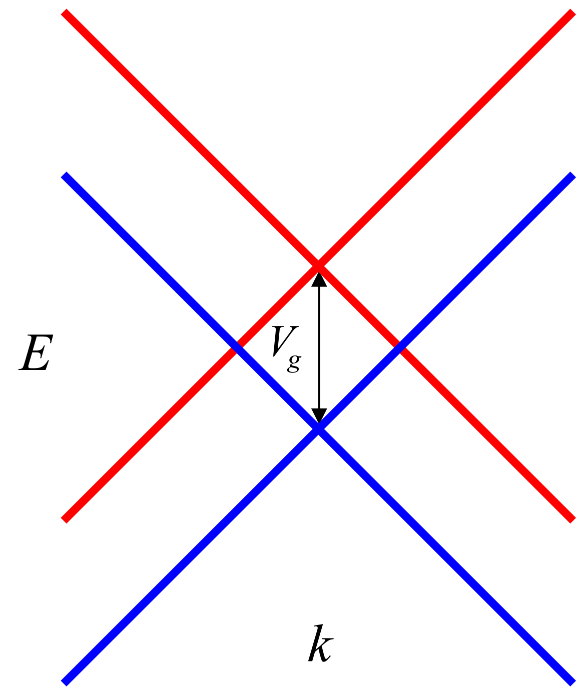
Ex) Exciton condensation in graphene bilayers

# 2. Model (1)

## 1) System

- Two single-layer graphene sheets separated by $SiO_2$ dielectric barrier in the no tunneling limit.




$\Rightarrow$ High-temperature exciton condensation

# 2. Model (2)

## 2) Pair condensation

$$\left\langle \hat{\psi}_{\uparrow}(\mathbf{r})\hat{\psi}_{\downarrow}(\mathbf{r})\right\rangle \neq 0$$

Cooper pairs

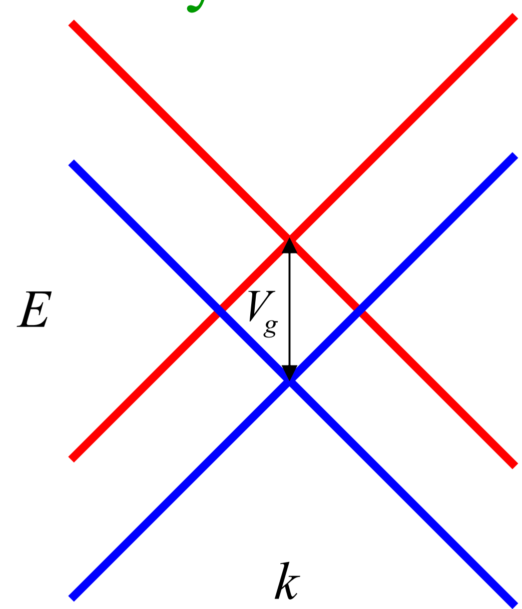
$$\left\langle \hat{\psi}_{t}^{+}(\mathbf{r})\hat{\psi}_{b}(\mathbf{r})\right\rangle \neq 0$$

Bilayer excitons (e-h pairs)

$\Rightarrow$ Exciton condensation is spontaneous interlayer coherence.

## 3) Why graphene?

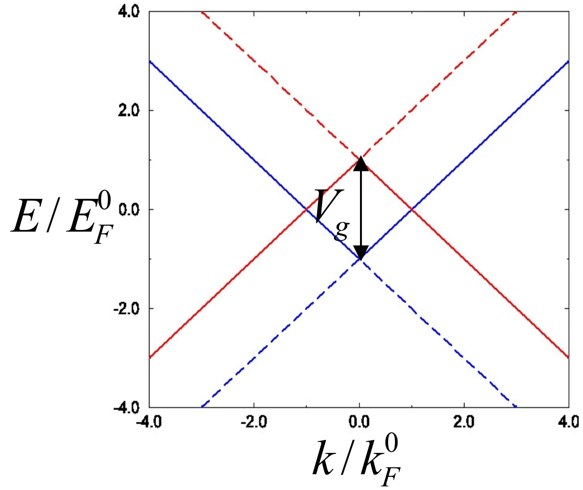
- Gapless semiconductor
- Perfect particle-hole symmetry
- Atomically two-dimensional

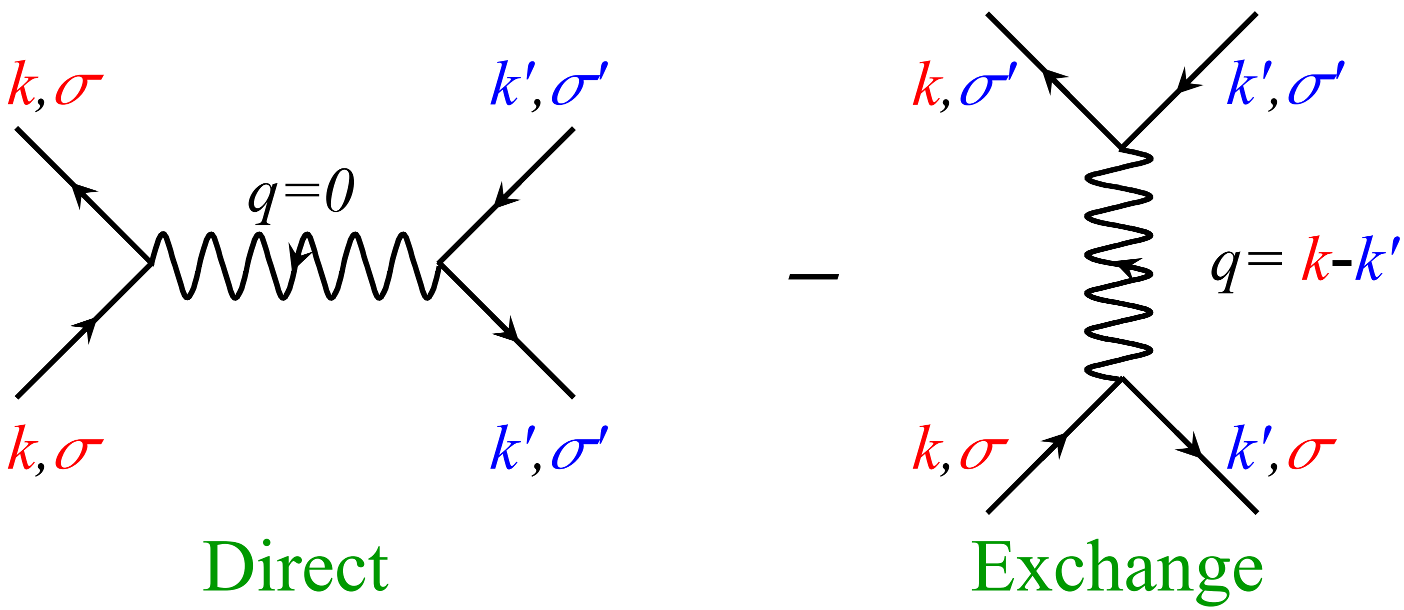


# 3. Mean-field Theory (1)

## 1) Numerical calculation

- A self-consistent mean-field theory neglecting remote bands

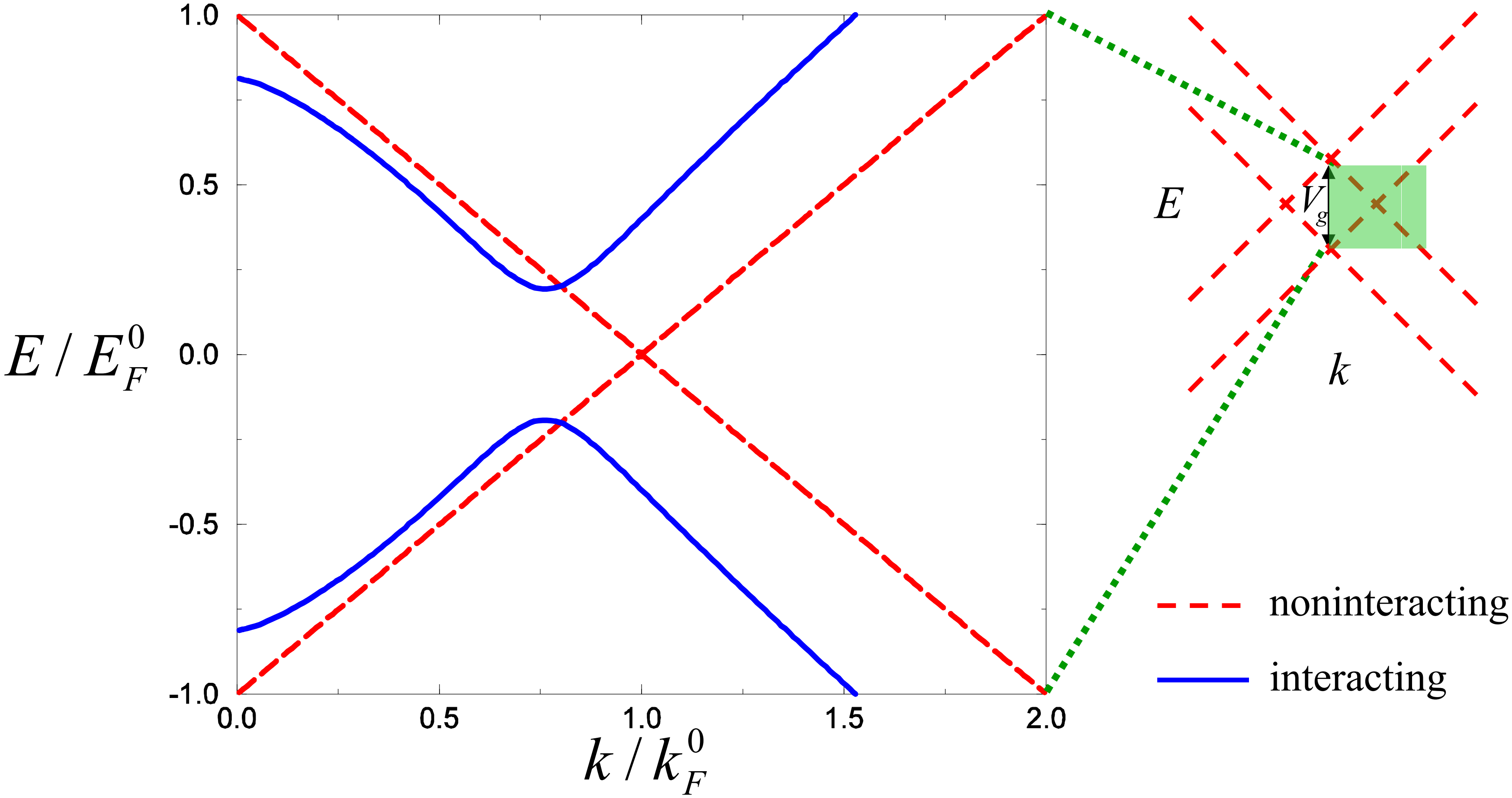


# 3. Mean-field Theory (2)

## 2) Energy band structure

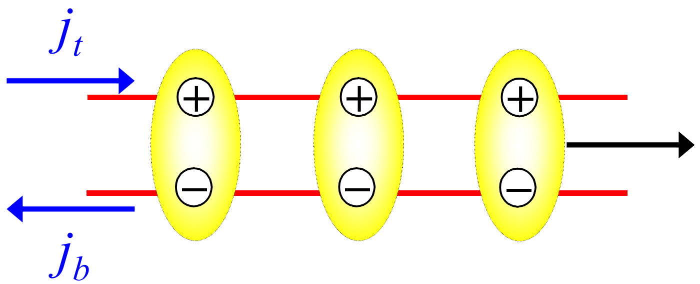
- Cooper instability



# 3. Phase Diagram (1)

## 1) Exciton superfluidity

- Counter-flow current




$$j_Q = \frac{e}{\hbar}\rho_s Q$$

exciton momentum

## 2) Kosterlitz-Thouless (KT) transition

- In 2D, superfluidity is destroyed by vortex proliferation.

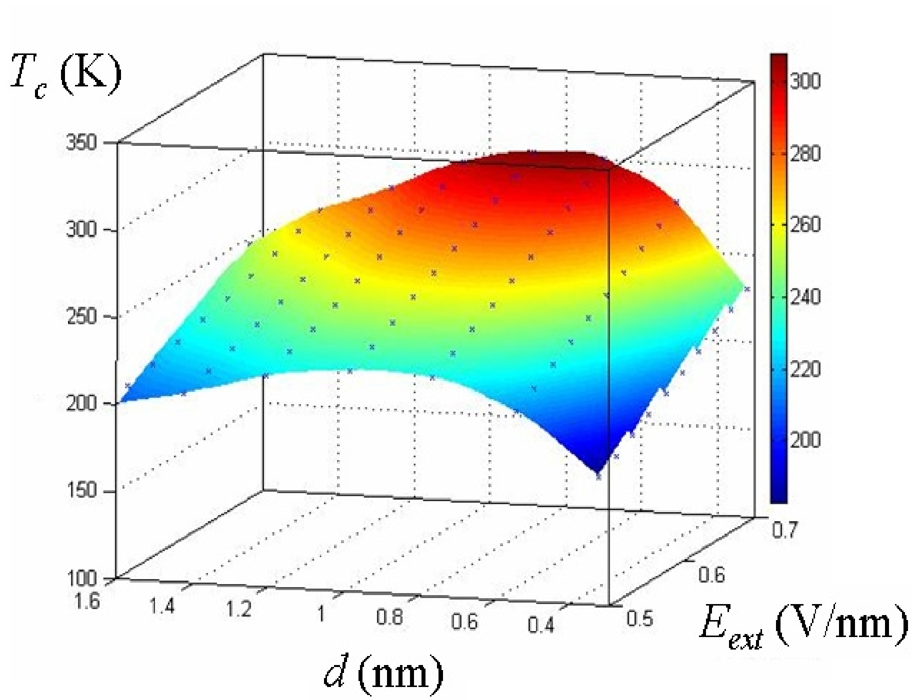
$$k_B T_{KT} = \frac{\pi}{2}\rho_s(k_B T_{KT})$$

# 3. Phase Diagram (2)

## 3) Phase diagram

- $T_c \uparrow$ as $E_{ext} \uparrow$
- Optimal layer separation
- $E_{ext} \sim 0.7$ V/nm, $d \sim 1$ nm

$\Rightarrow$ $T_c \sim 300$ K




- Comparison with BCS superconductivity

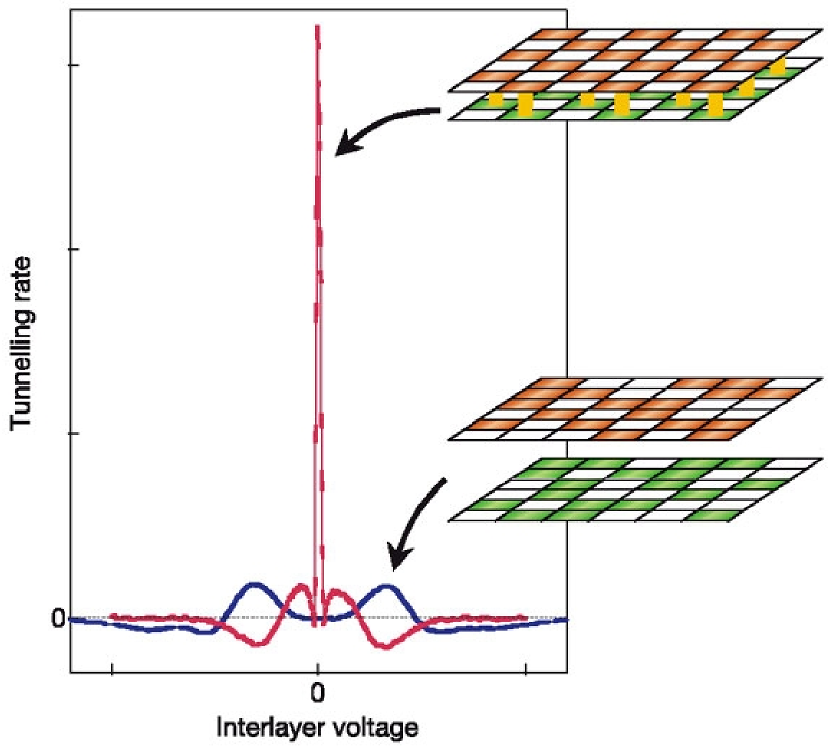
  Cooper pair : limited by $\omega_D$ $\Rightarrow$ $T_c \sim 10$ K

  Bilayer exciton : limited by $v_F/d$ $\Rightarrow$ $T_c \sim 300$ K

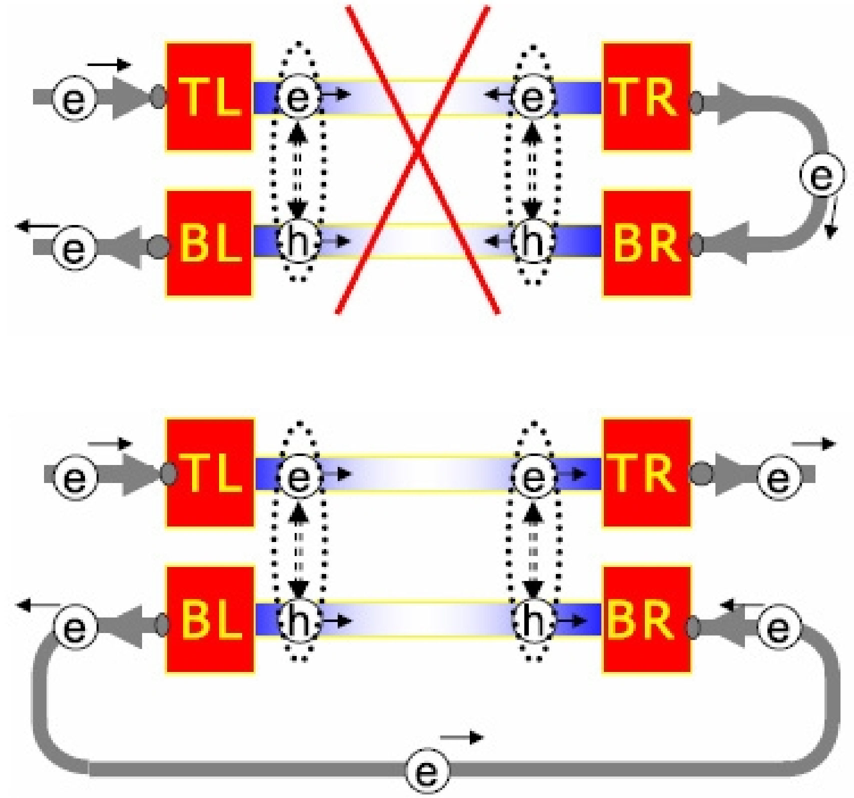
# 4. Discussion (1)

## 1) Experimental search

Tunneling




Transport




Eisenstein and MacDonald, Nature **432**, 691 (2004)

Su and MacDonald, arXiv:0801.3694

# 4. Discussion (2)

## 2) New electronic device scheme

Collective behavior of many electrons

High-temperature superfluidity

$\Rightarrow$ Transistors which could be operated with a gate voltage much smaller than the thermal energy

$\Rightarrow$ Dissipation-free interconnects

$\Rightarrow$ Can extend Moor's law for another decade