Interlayer superconductivity in Graphene Materials

Mir Vahid Hosseini
with
Dr. Malek Zareyan

Outline

- **Superconductivity (Sc)**
  - Introduction
  - BCS Theory
- **Exotic phase of Sc**
  - Breached pairing (Interior gap)
  - Generality of Cooper pairing
- **Graphene**
  - Graphene properties
  - Graphene Sc
- **Interlayer Sc in Graphene materials**
  - Interlayer Sc in Bilayer Graphene
  - Interlayer Sc in Trilayer Graphene
- **Conclusions**

Superconductivity

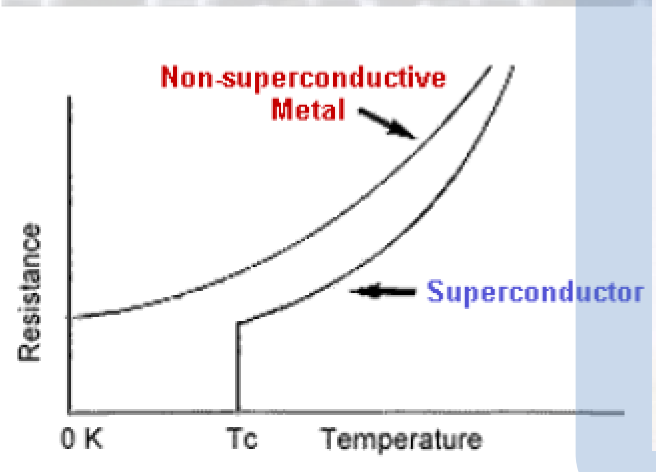
- **Introduction**

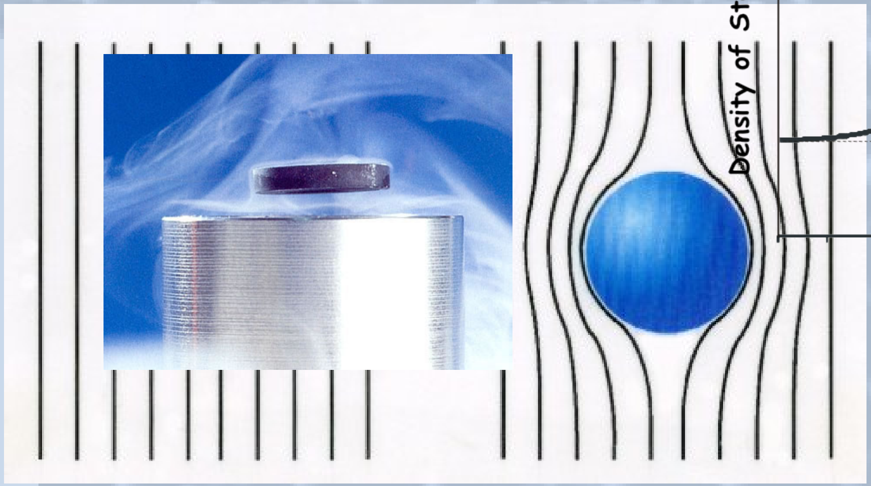
Onnes, 1911
SC Mercury

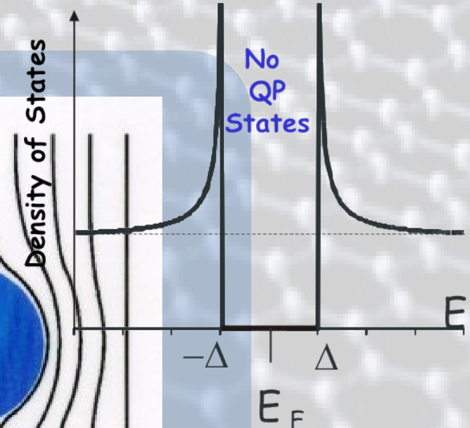
Meissner,
1933

BCS theory, 1957

- Zero resistivity
- Meissner effect



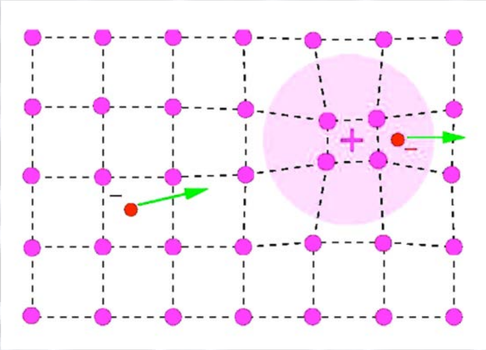


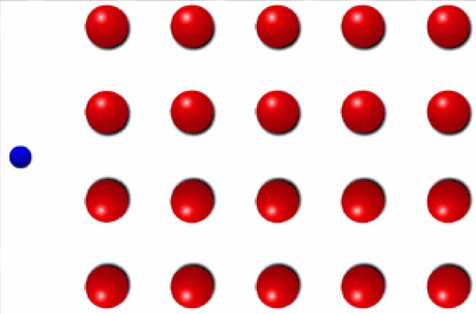


Superconductivity

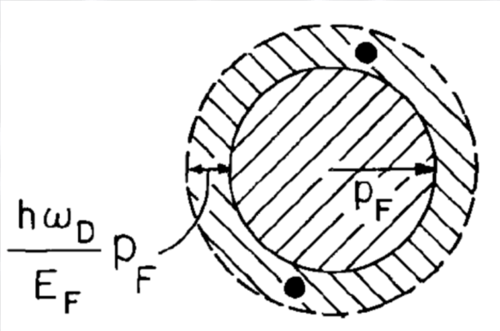
- **BCS Theory**
  - Attractive interaction between electrons

    phonons





  - Cooper pair

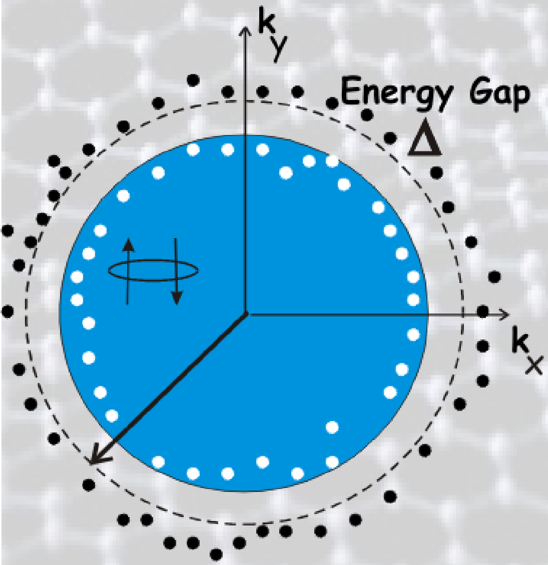


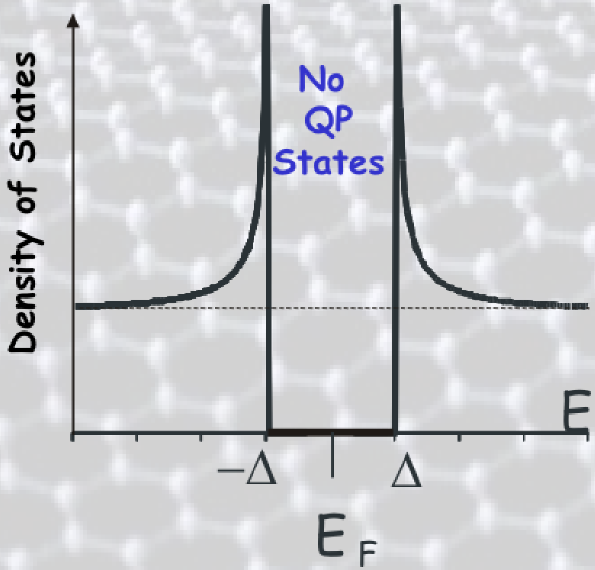
Superconductivity

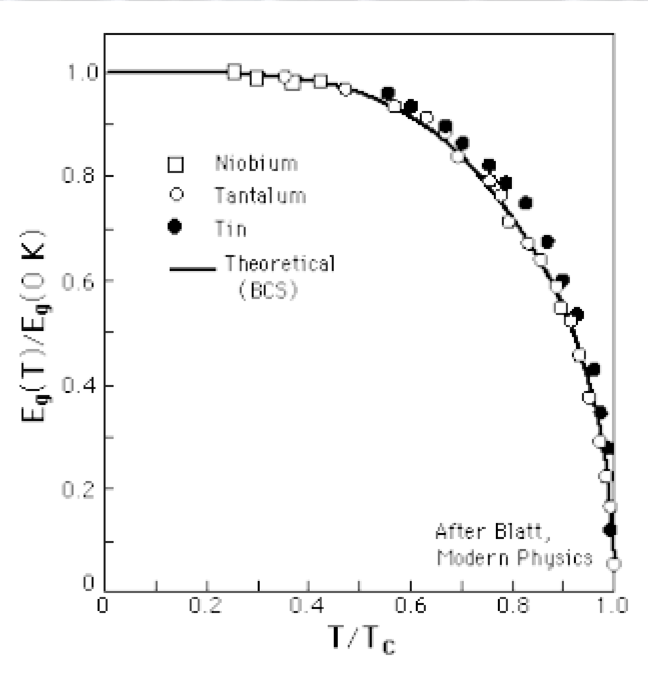
- **BCS Theory**
  - Gap and order parameter

gap equation: $$\Delta_{\mathbf{k}} = -\sum_{\mathbf{k}'} V_{\mathbf{k}\mathbf{k}'} \frac{\Delta_{\mathbf{k}'}}{2E_{\mathbf{k}'}}$$

Excitation spectrum: $$E_{\mathbf{k}'} = \sqrt{\epsilon_{\mathbf{k}'}^2 + |\Delta_{\mathbf{k}'}|^2}$$

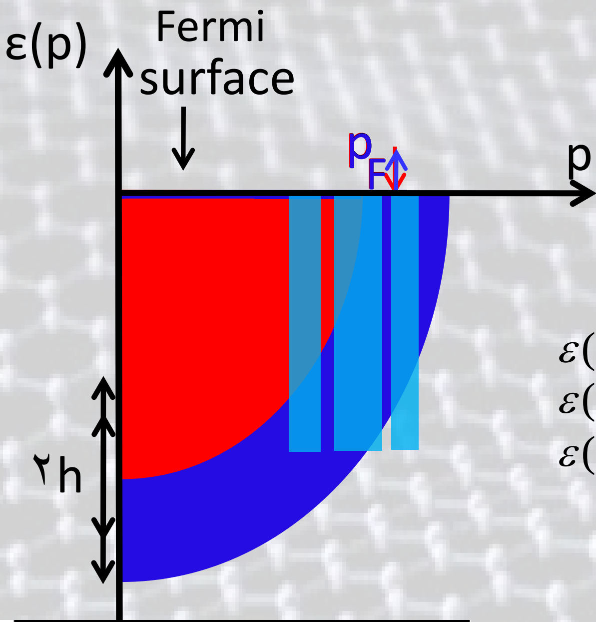






Exotic phase of Sc

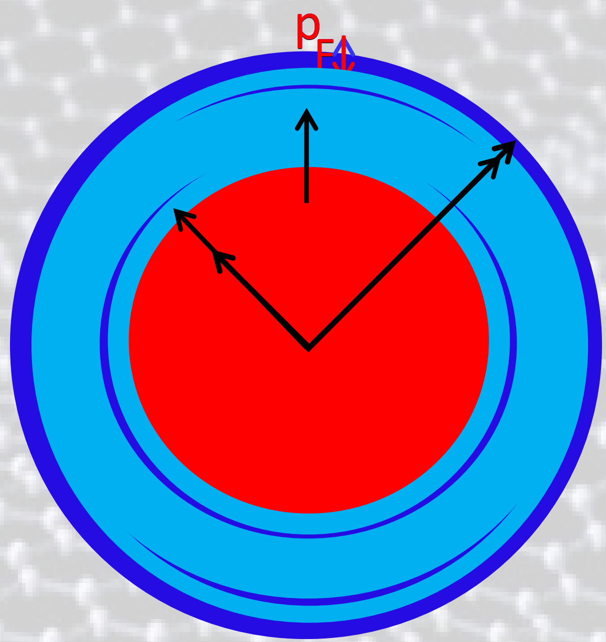
- **Breached pairing**

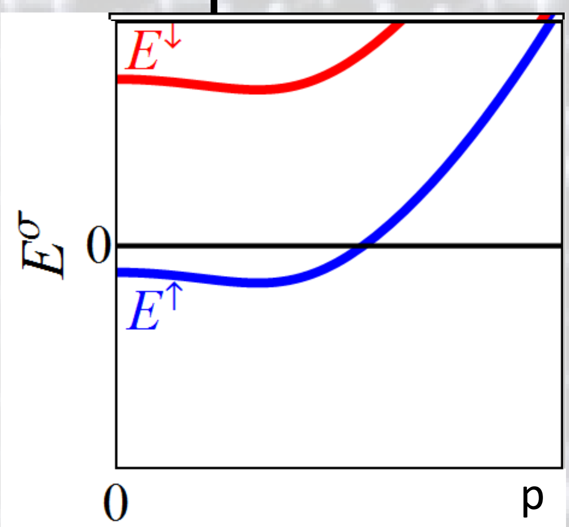


$$\varepsilon(\mathrm{p}) = \left(\frac{p^2}{2m} - \mu\right) + h$$

$$\varepsilon(\mathrm{p}) = \left(\frac{p^2}{2m} - \mu\right)$$

$$\varepsilon(\mathrm{p}) = \left(\frac{p^2}{2m} - \mu\right) - h$$

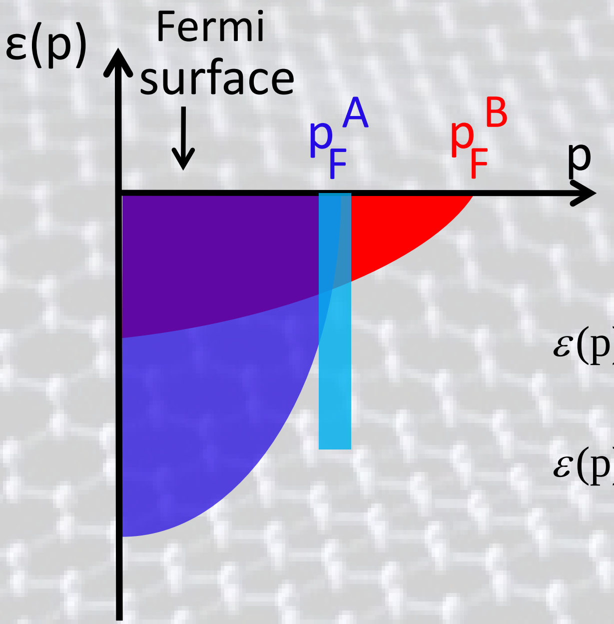




Breached pairing

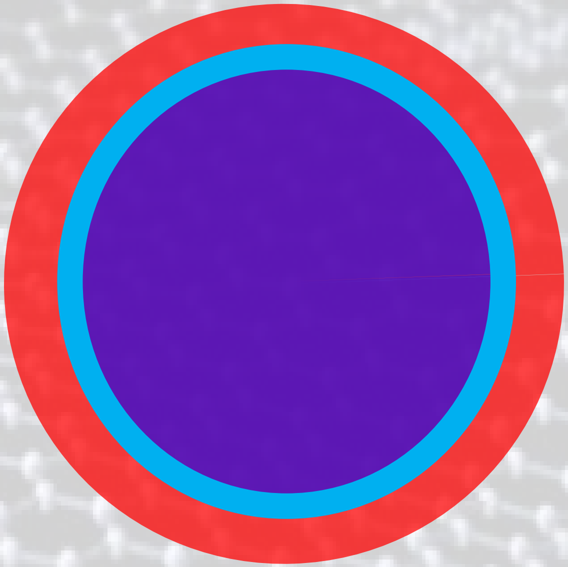
Exotic phase of Sc

- **Breached pairing (Interior gap)**



$$\varepsilon(\mathrm{p}) = \left(\frac{p^2}{2m_B} - \mu\right)$$

$$\varepsilon(\mathrm{p}) = \left(\frac{p^2}{2m_A} - \mu\right)$$



Heavy Fermion: m_B

Light Fermion: m_A

If Fermi $m_B \gg m_A$ then => Interior gap

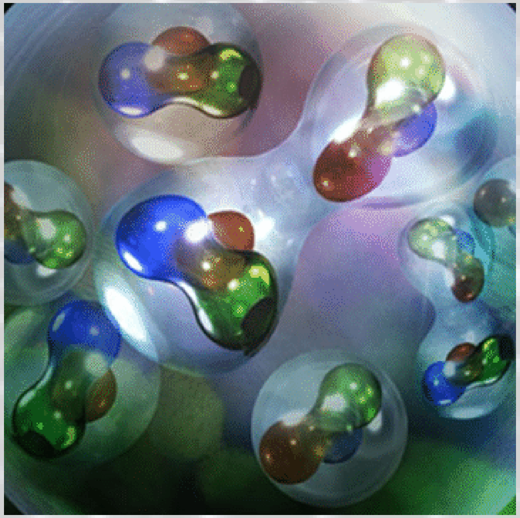
Breached Pairing (Sarma) state = a superfluid + a normal Fermi liquid at T=0; has gapped and gapless quasiparticle excitations.

W. Vincent Liu, F. Wilczek, PRL (2003);

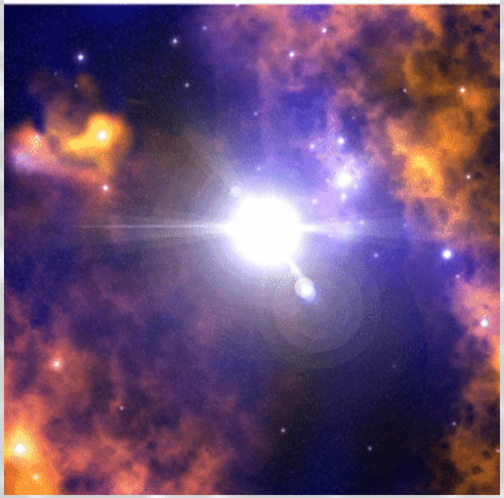
Exotic phase of Sc

- **Generality of Cooper pairing**

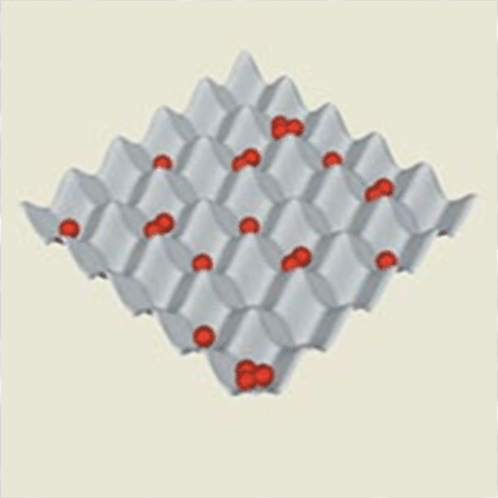
Pairing in Nuclear matter



Pairing in Quark matter



Pairing in Cold atoms



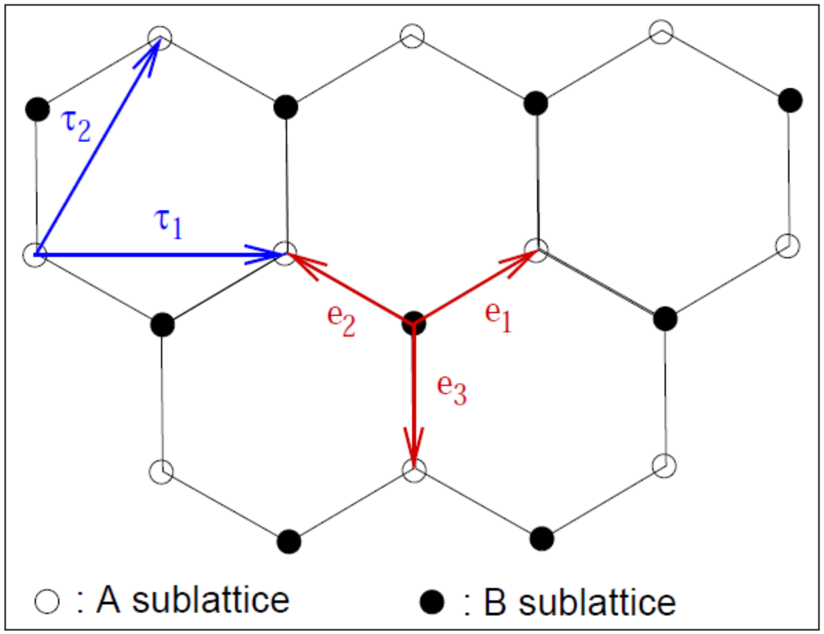
P. Davise, *et al.* Nature 469, 68–71 (06 January 2011)
Fukushima, K. & Warringa, H. *Physical Review Letters* 100, 032008 (2008).

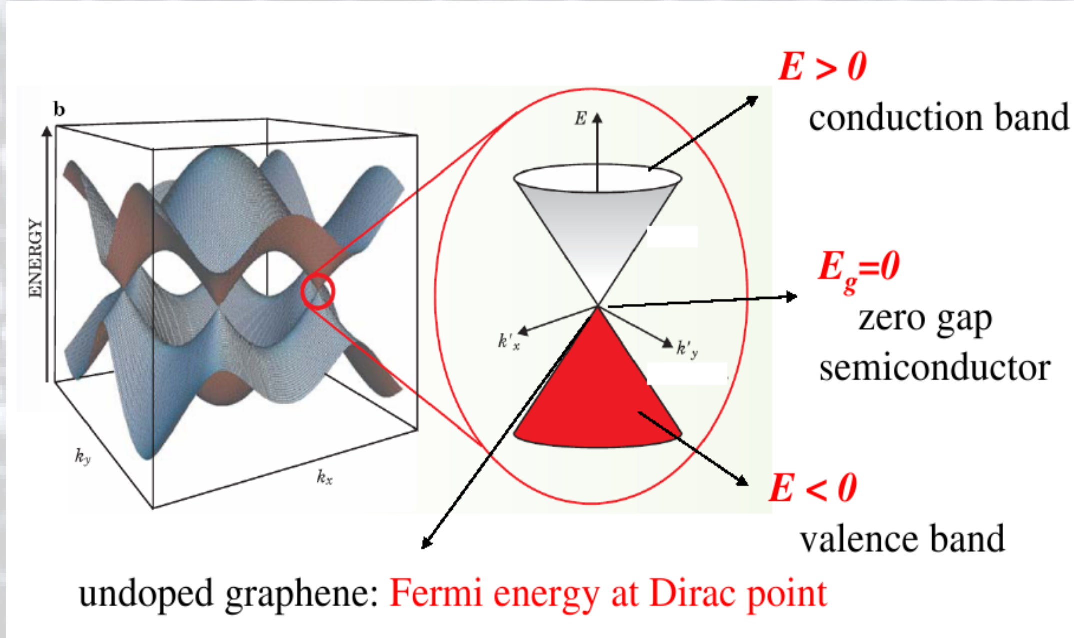
Exotic phase of Sc

Is there new exotic phase of Cooper pairing?

Graphene

- **Graphene Band structure**





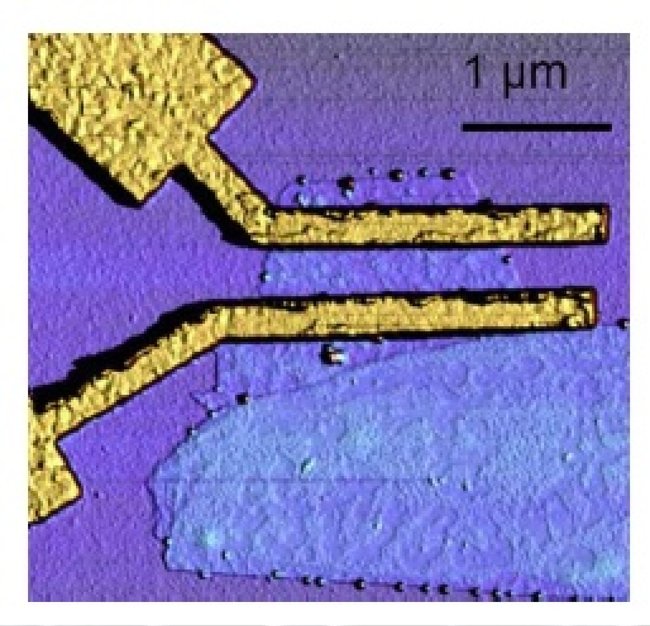
Band-structure calculation in the tight-binding model

$$H_0 = -t \sum_{i \in A} \sum_{j=1}^{3} \left(b^{\dagger}_{\mathbf{R}_i + \mathbf{e}_j} a_{\mathbf{R}_i} + \mathrm{H.c.} \right)$$

$$\gamma_{\mathbf{k}} = \sum_{j=1}^{3} \exp[i\mathbf{k}.\delta_j],$$

Graphene

- **Graphene Superconductivity**

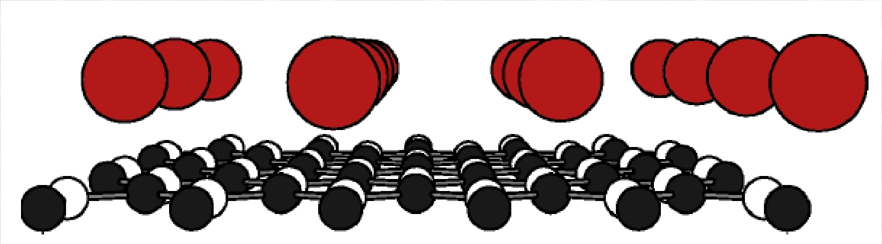


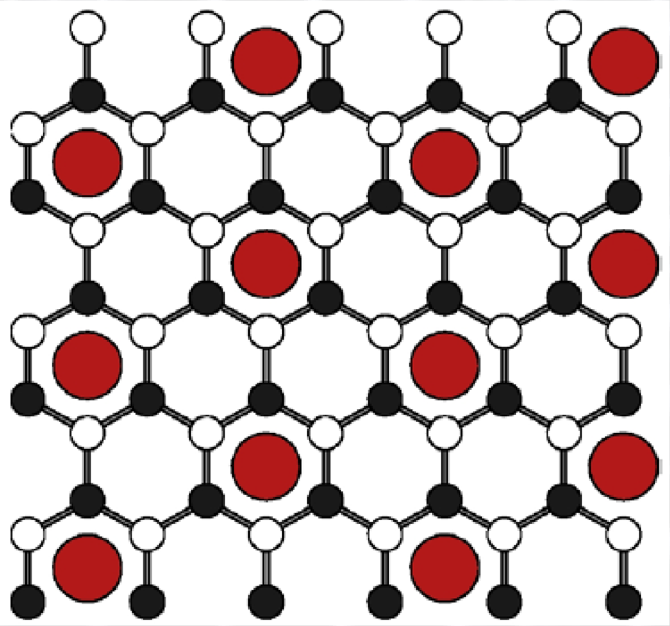
H. B. Heersche, P. JarilloHerrero, J. O. Oostinga,L. M. K. Vandersypen, and A. F. Morpurgo, Nature (London) **446, 56 (2007).**

Graphene

- **Graphene Superconductivity**

phonon and plasmon mechanisms in graphene coated with a layer of a metal





B. Uchoa and A. H. Castro Neto, Phys. Rev. Lett. **98,** 146801 (2007).

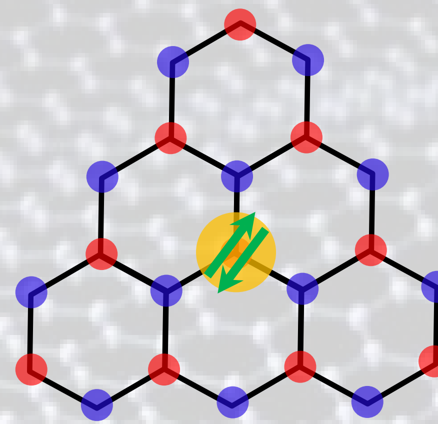
Graphene

- **Graphene Superconductivity**

$$\Delta_0 = -g_0\langle a_{i\downarrow} a_{i\uparrow}\rangle = -g_0\langle b_{i\downarrow} b_{i\uparrow}\rangle$$

$$\Psi = \psi_{S=0} \otimes \psi_{L=0} \otimes \psi_{A-A}$$

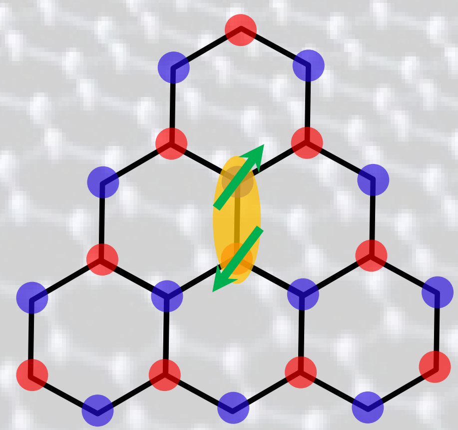
S-wave



$$\Delta_{1,ij} = -g_1\langle a_{i\downarrow} b_{i\uparrow} - a_{i\uparrow} b_{i\downarrow}\rangle$$

$$\Psi = \psi_{S=0} \otimes \psi_{L=1} \otimes \psi_{A-B}$$

P+ip-wave

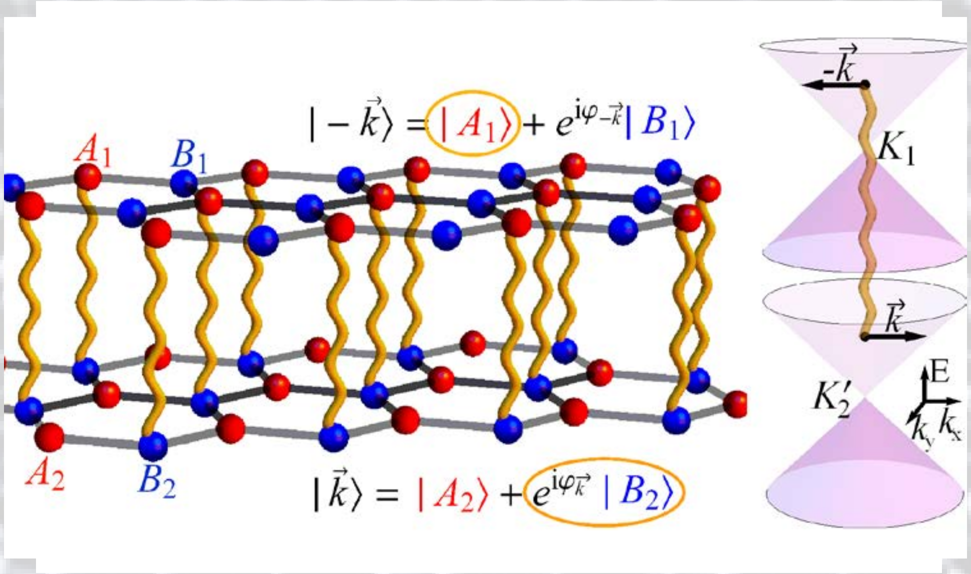


B. Uchoa and A. H. Castro Neto, Phys. Rev. Lett. **98,** 146801 (2007).

M.V.Hosseini and M. Zareyan, Appl. Phys. Lett. 101, 252602 (2012).

Interlayer Sc in Graphene materals

- **Interlayer Sc in Bilayer Graphene**



$$\Delta_{i,\perp} = -g_\perp \langle a_{i\downarrow} b_{i\uparrow} + a_{i\uparrow} b_{i\downarrow} \rangle$$

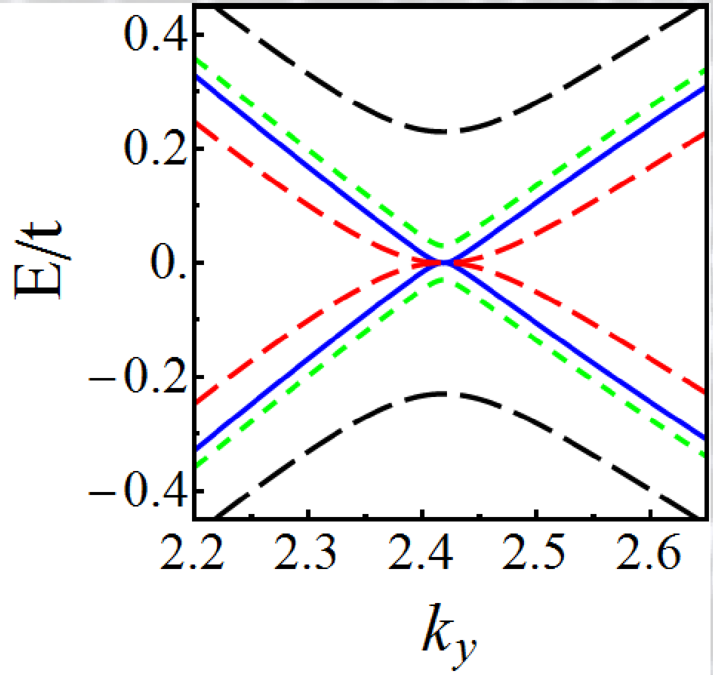
$$\Psi = \psi_{S=1} \otimes \psi_{L=0} \otimes \psi_{A-B}$$

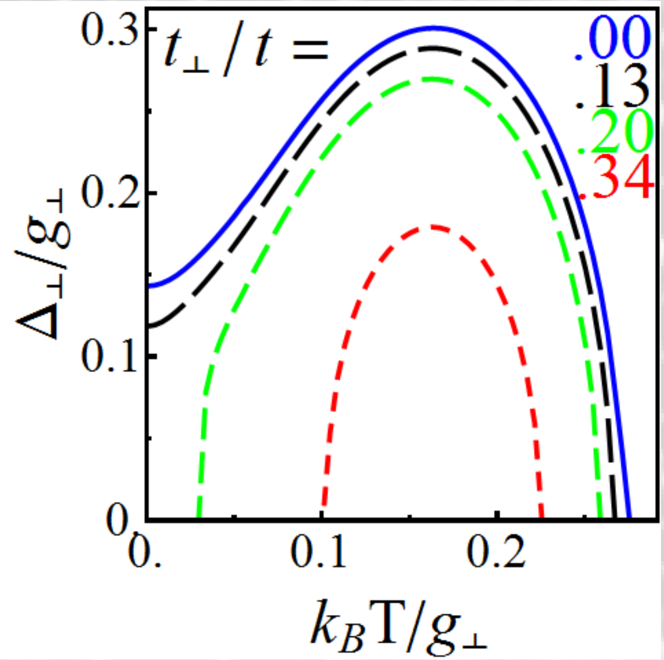
S-wave Spin-Triplet !!!

M.V.Hosseini and M. Zareyan, Phys. Rev. Lett. 108, 147001 (2012).

Interlayer Sc in Graphene materals

- **Interlayer Sc in Bilayer Graphene**

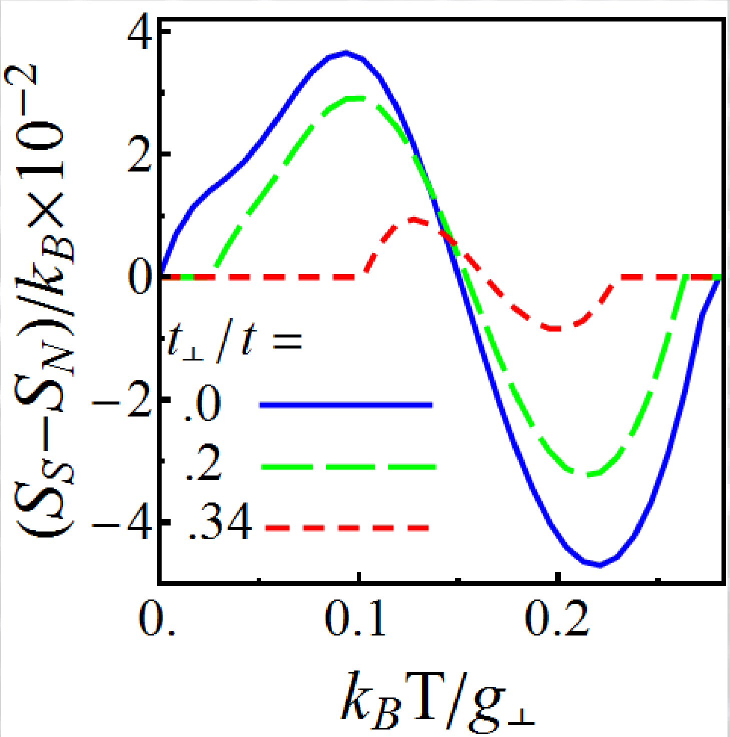


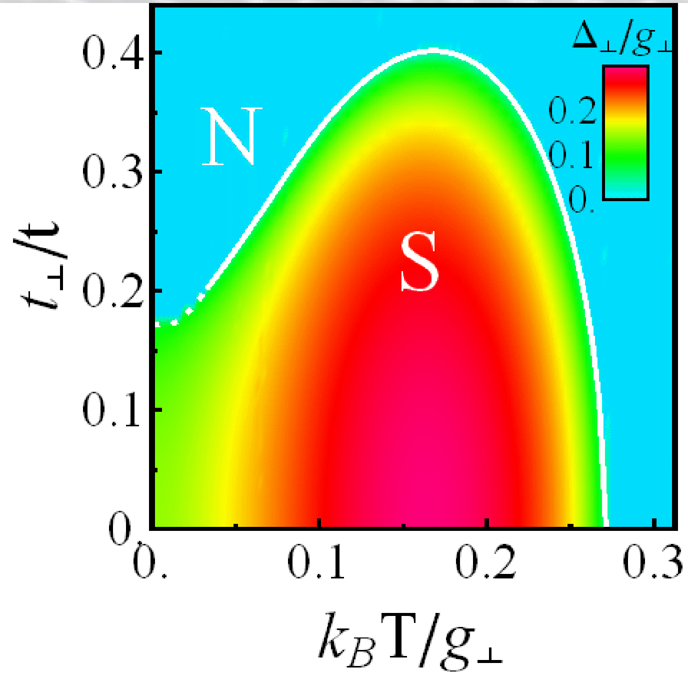


$$\alpha E_{\mathbf{k}}^{sl} = \frac{\alpha}{\text{۲}}\left[\sqrt{(\Delta_\perp + st_\perp)^{\text{۲}} + \text{۴}\epsilon_{\mathbf{k}}^{\text{۲}}} + l(\Delta_\perp + st_\perp)\right],$$

Interlayer Sc in Graphene materals

- **Interlayer Sc in Bilayer Graphene**





Interlayer Sc in Graphene materals

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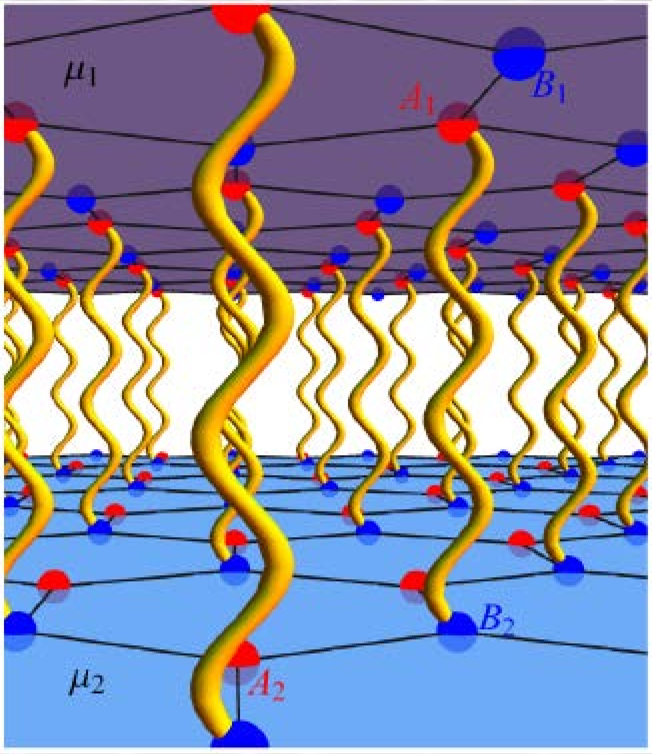


$$h = (\mu_1 - \mu_2)/2$$

M.V.Hosseini and M. Zareyan, Phys. Rev. B 86, 214503 (2012).

Interlayer Sc in Graphene materals

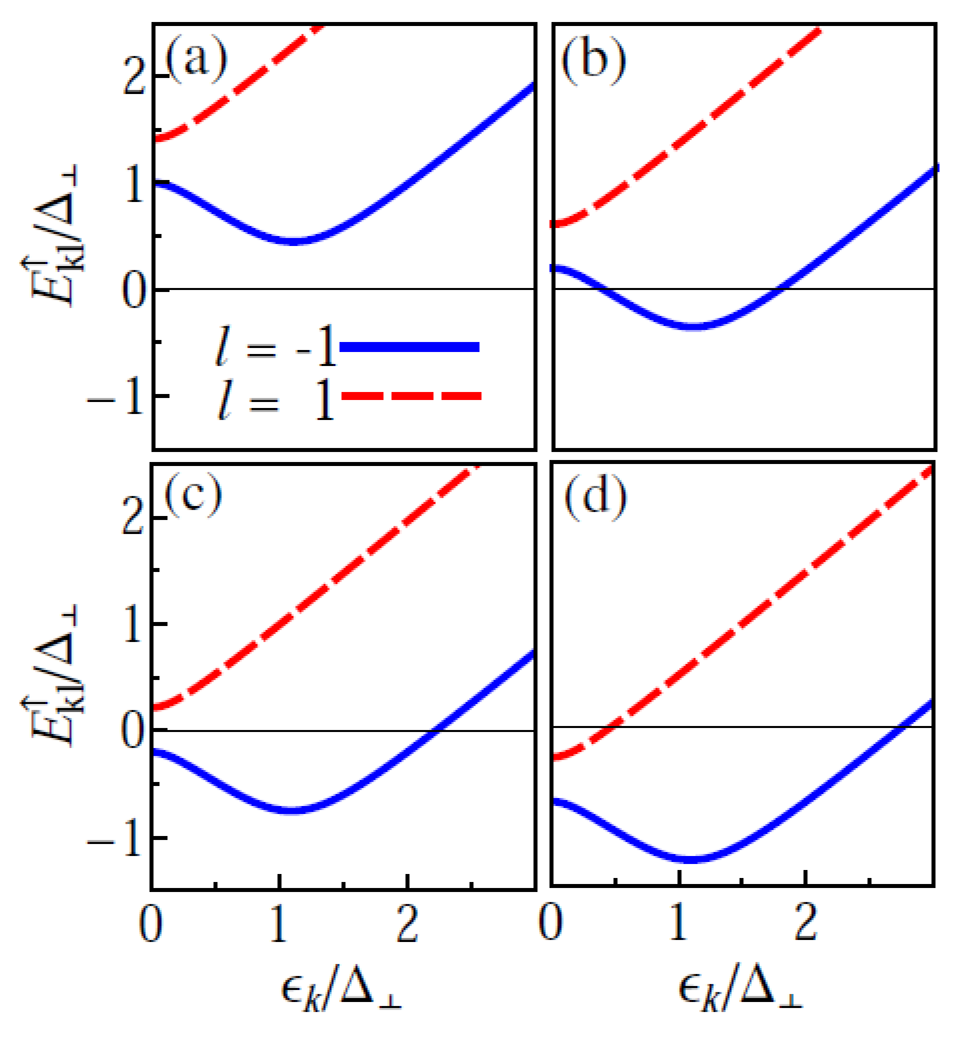
- **Interlayer Sc in Bilayer Graphene**

(a) $$h < \mu\sqrt{\frac{\Delta_\perp^2 - t_\perp^2}{\Delta_\perp^2 - t_\perp^2 + 4\mu^2}},$$

(b) $$\mu\sqrt{\frac{\Delta_\perp^2 - t_\perp^2}{\Delta_\perp^2 - t_\perp^2 + 4\mu^2}} < h < \mu,$$

(c) $$\mu < h < \sqrt{\Delta_\perp^2 - t_\perp^2 + \mu^2},$$

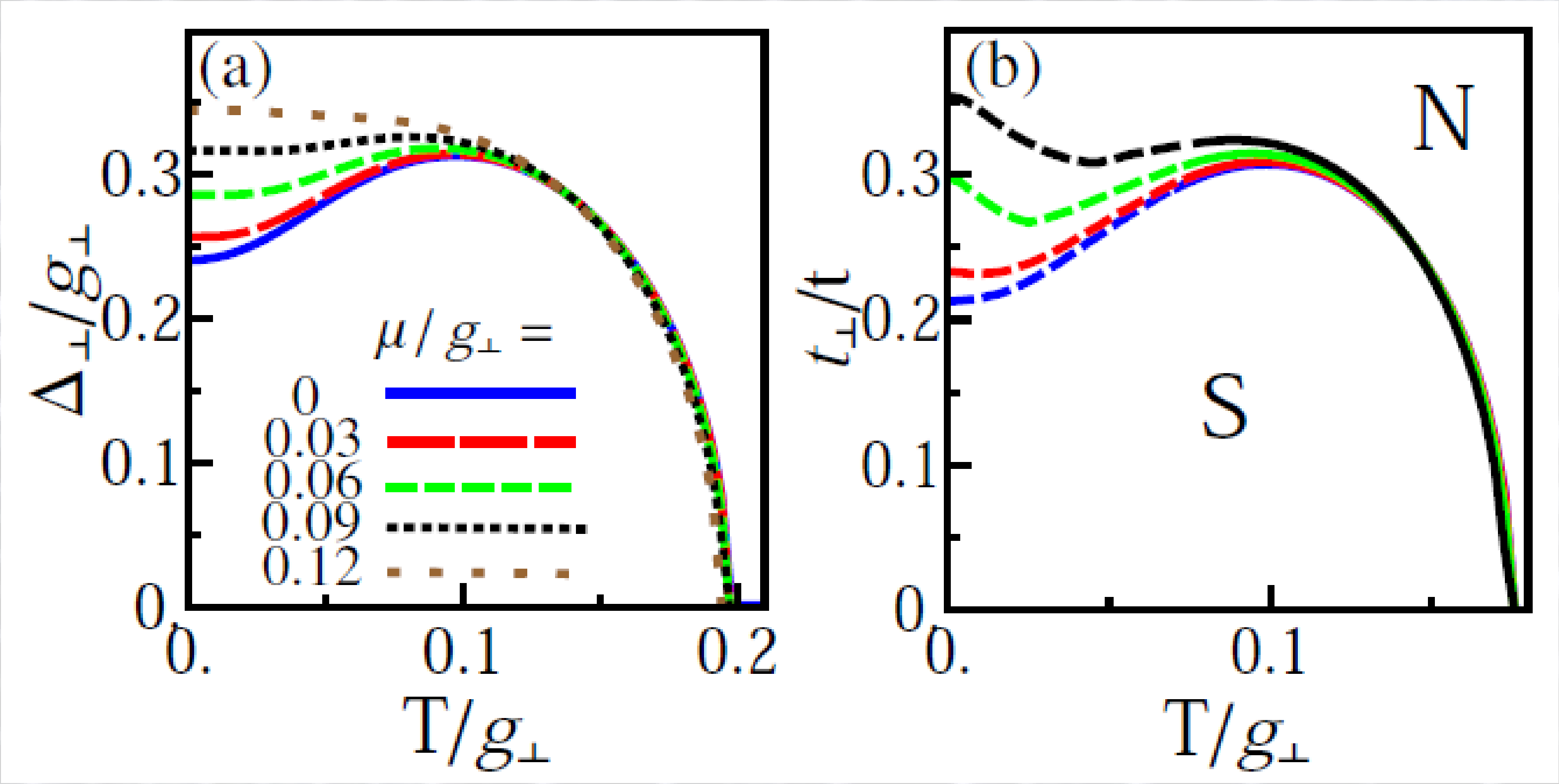
(d) $$h > \sqrt{\Delta_\perp^2 - t_\perp^2 + \mu^2},$$



M.V.Hosseini and M. Zareyan, Phys. Rev. B 86, 214503 (2012).

Interlayer Sc in Graphene materals

- **Interlayer Sc in Bilayer Graphene**

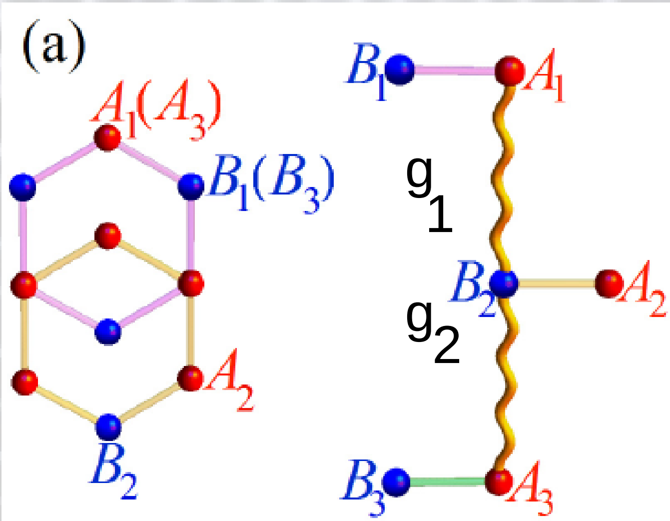


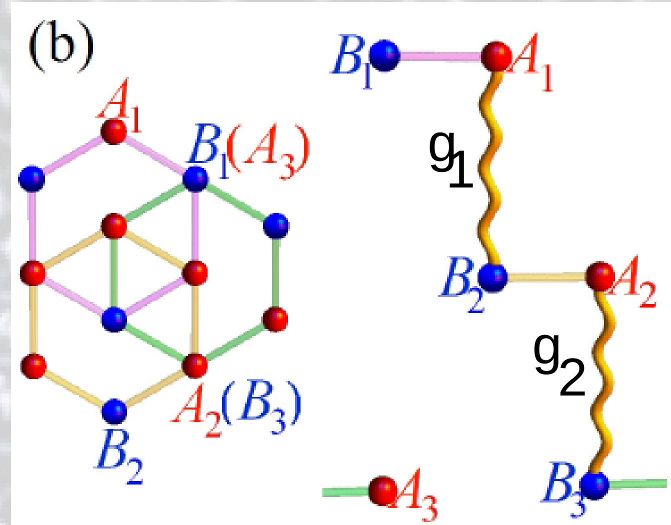
Interlayer Sc in Graphene materals

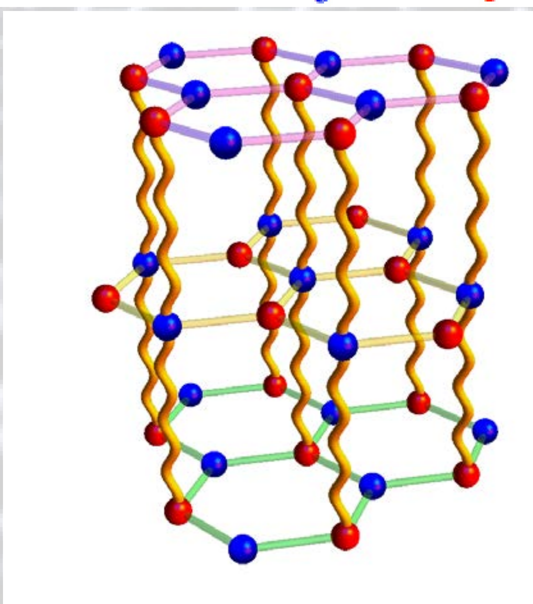
- **Interlayer Sc in Trilayer Graphene**

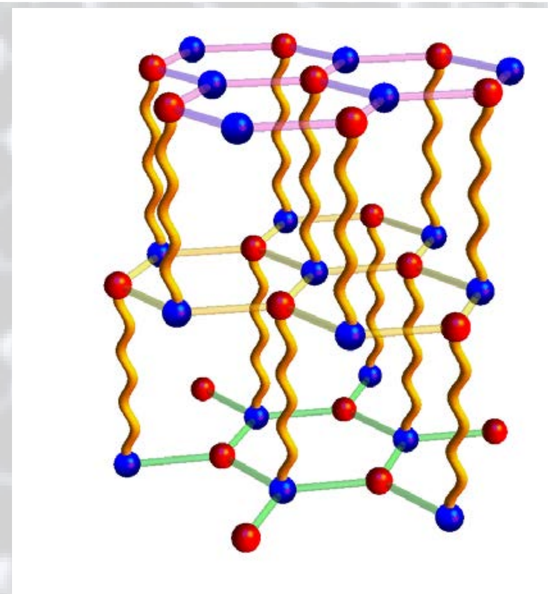
ABA Trilayer

ABC Trilayer



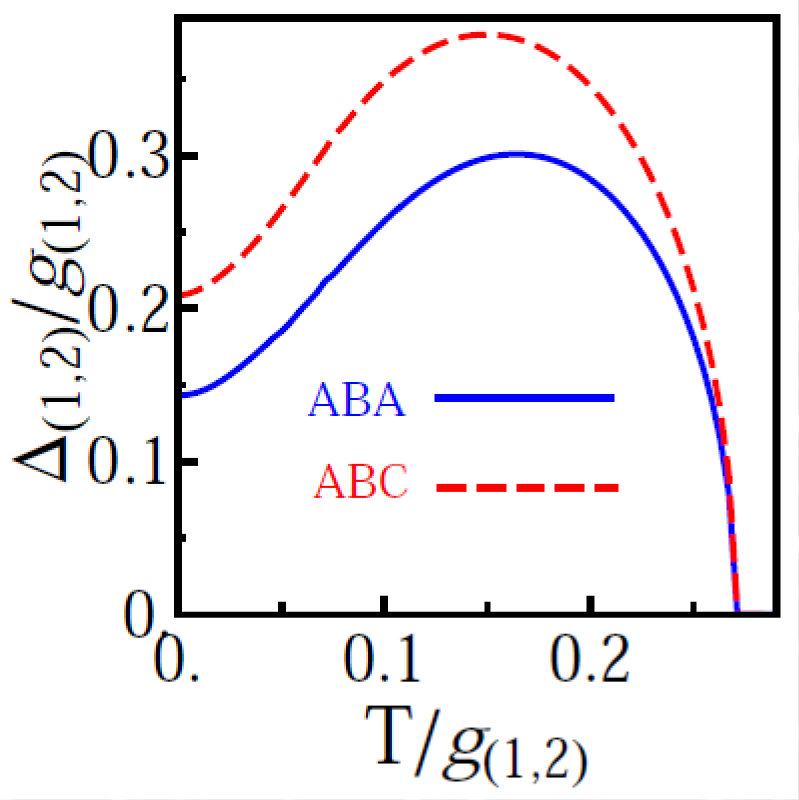






Interlayer Sc in Graphene materals

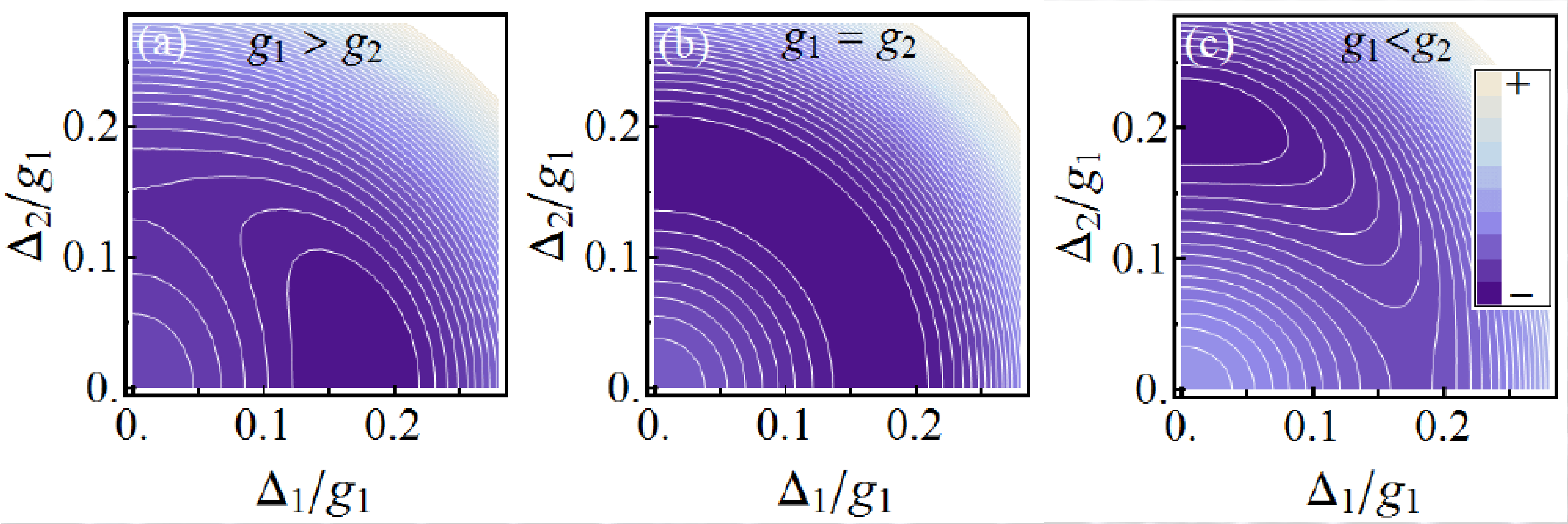
- **Interlayer Sc in Trilayer Graphene**



Interlayer Sc in Graphene materals

- **Interlayer Sc in Trilayer Graphene**

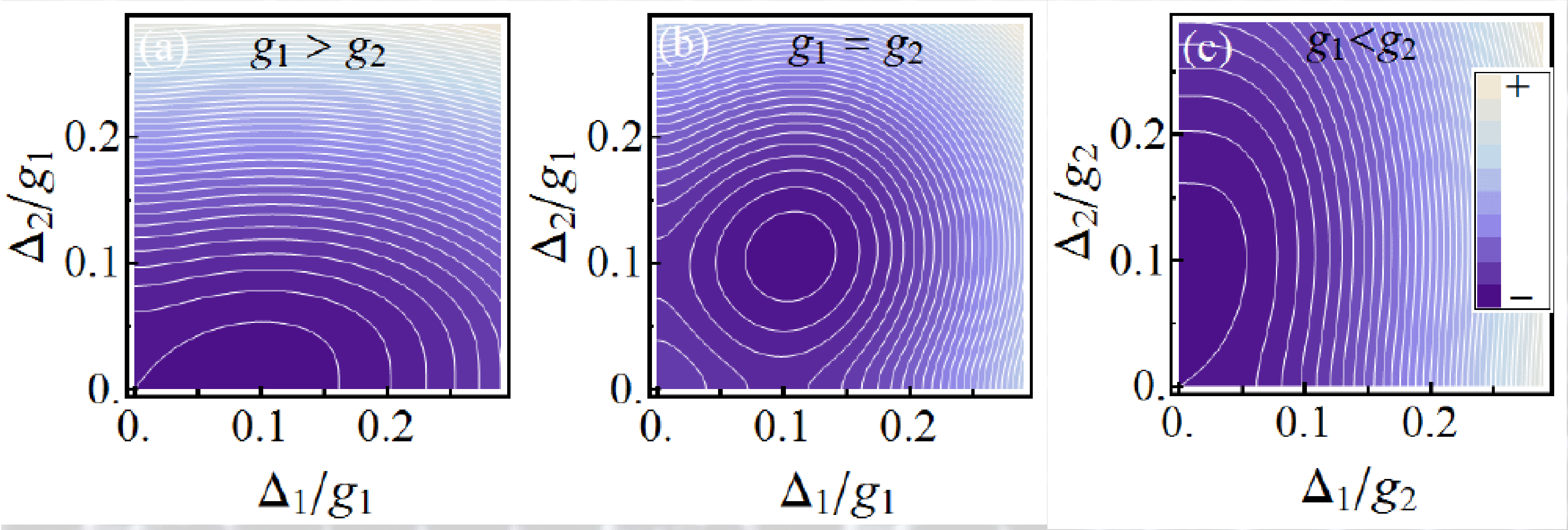
ABA Trilayer



Interlayer Sc in Graphene materals

- **Interlayer Sc in Trilayer Graphene**

ABC Trilayer



Conclusions

(1) We theoretically demonstrate the formation of a new type of unconventional superconductivity in graphene materials.

(2) This superconductivity is based on an interlayer pairing of chiral electrons in bilayer graphene with exotic s-wave spin-triplet condensate order and anomalous thermodynamic properties.

(3) These include the possibility of a temperature-induced condensation causing an increase of the pairing gap with increasing temperature and an entropy of the stable superconducting state which can be higher than its value in the normal state.

(4) At finite mean value chemical potentials of layers removes gapless property of pairing gap and in the high value of mean chemical potential, pairing gap exhibits BCS-like temperature dependence behavior.

(5) While interlayer superconductivity between layers of ABA stacking displays first order phase transition, phase transition of ABC stacking is of second order.

Thank you for your attention