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Andreev-Klein reflection in graphene ferromagnet-superconductor contacts

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Andreev-Klein reflection in graphene ferromagnet-superconductor contacts

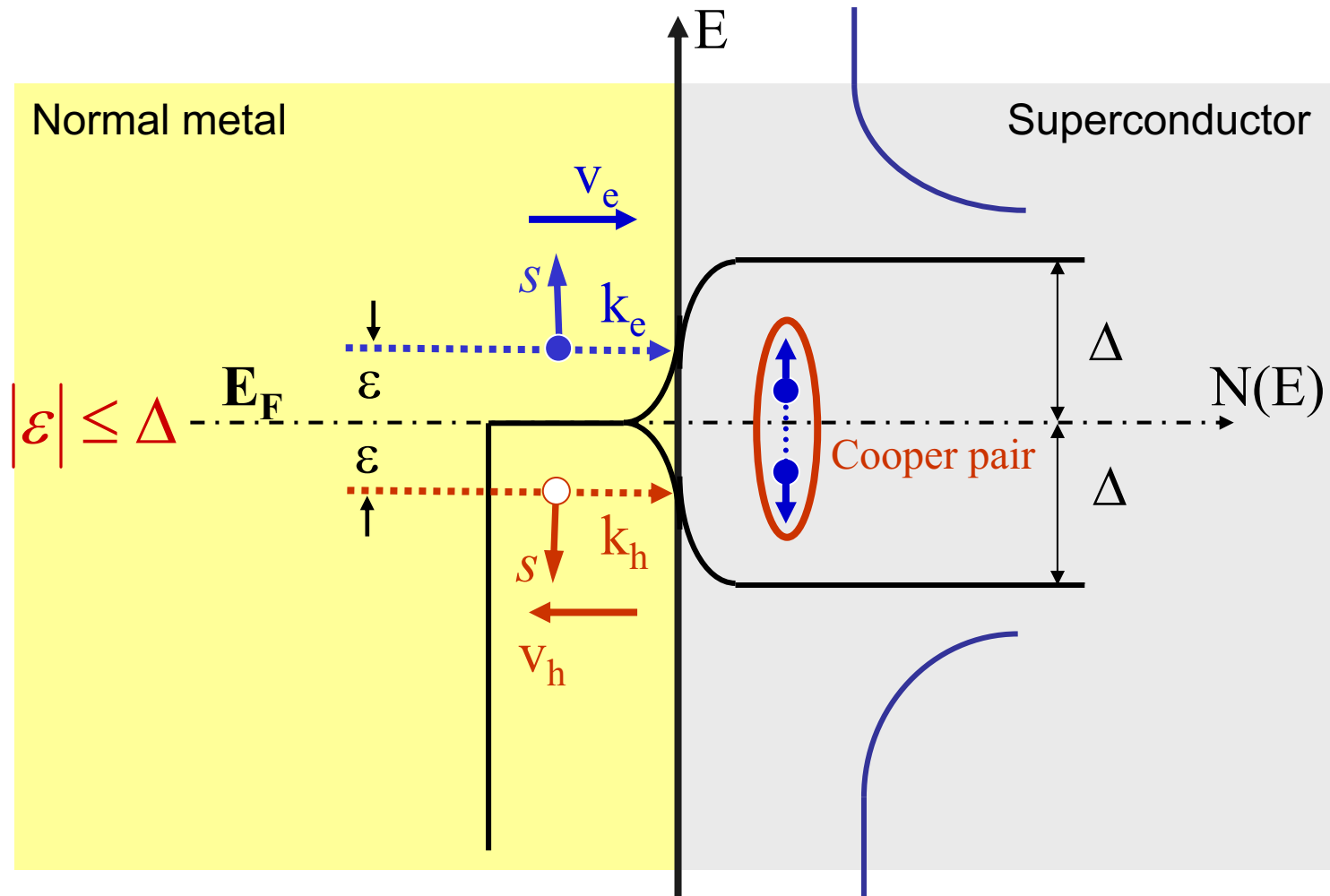
Malek Zareyan

Hakimeh Mohammadpour and Ali G. Moghaddam



ICTP Conference Graphene Week, August 2008

Andreev reflection in metallic NS junctions



[A. F. Andreev, Sov. JETP **19**, 1228(1964)]

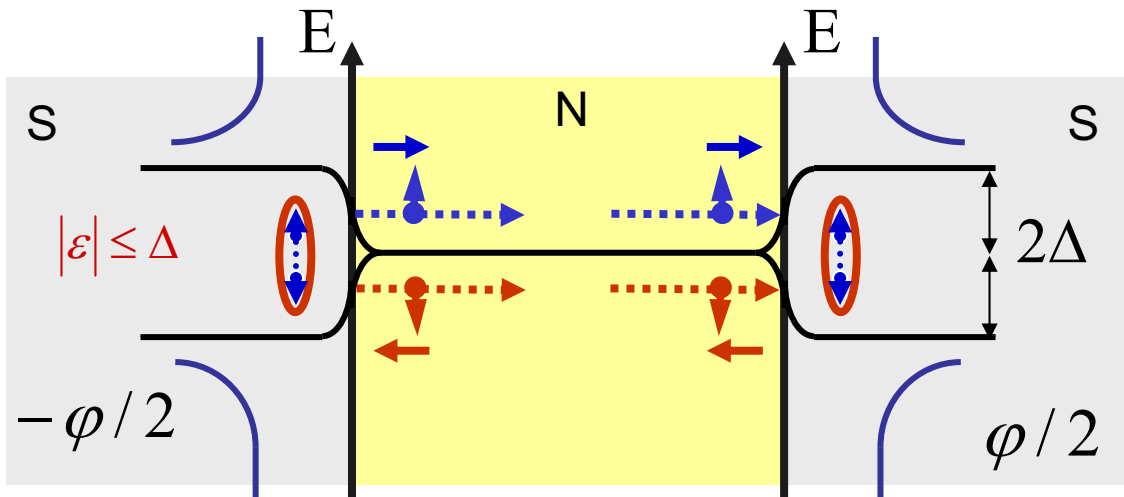
- **Conversion of normal current into supercurrent:**
charge transfer by $2e$

Andreev Conductance:

finite G_{NS} of NS junction at voltages below the superconducting gap Δ/e

for an ideal interface at $T=0$ and $V=0$: $G_{NS} = 2_{AR} G_{NN}$

Josephson current through SNS junctions:



Cooper pair transfer through N:
Supercurrent through Andreev bound states:

**Critical (maximum) current +
current-phase relation**

In a simple case

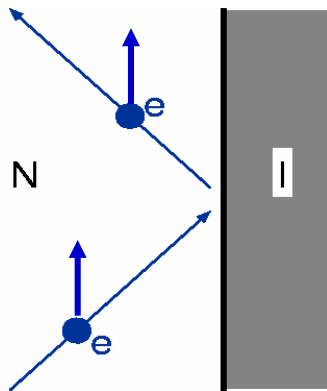
$$I(\varphi) = I_c \sin \varphi$$

[G. E. Blonder, M. Tinkham, and T. M. Klapwijk, Phys. Rev. B **25**, 4515 (1982);
K. K. Likharev Rev. Mod. Phys. 52, 101 (1979);....]

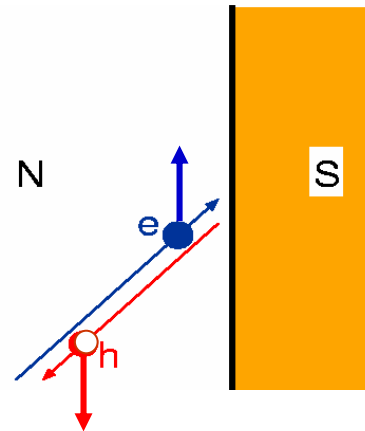
• Momentum is changed by $\sim \varepsilon/v_F \ll p_F$ negligibly small for degenerate N $\Delta \ll E_F$

$$\vec{k}_e \cong \vec{k}_h$$

:AR is Retro Reflection



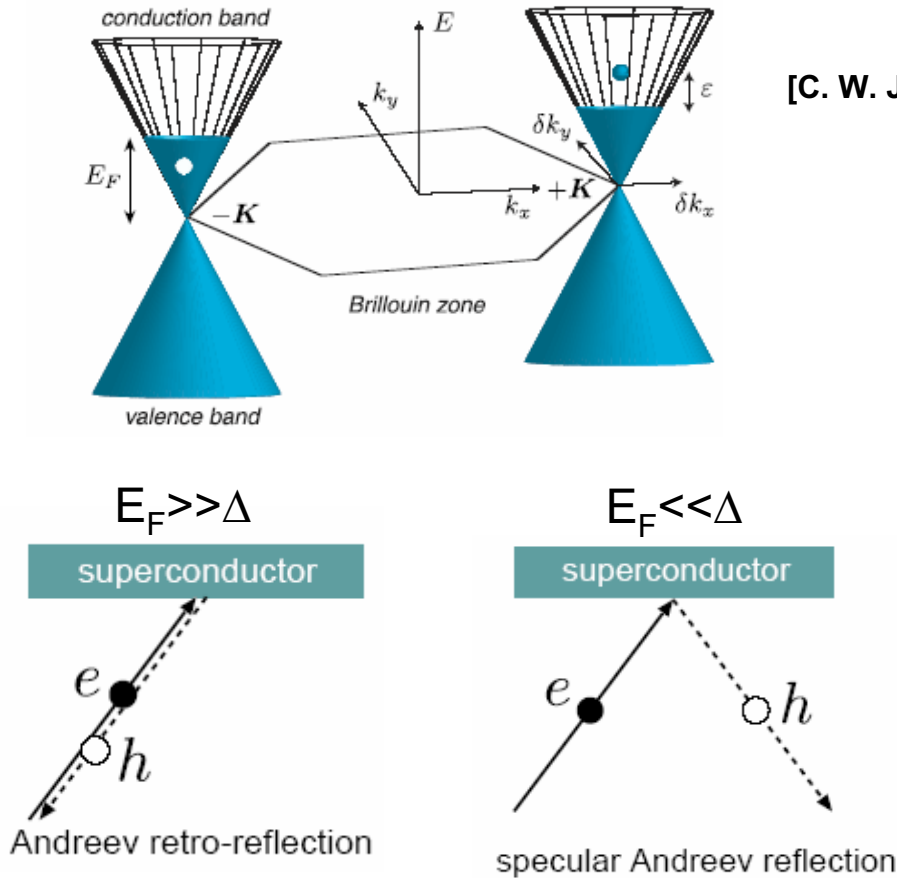
Specular Normal Reflection



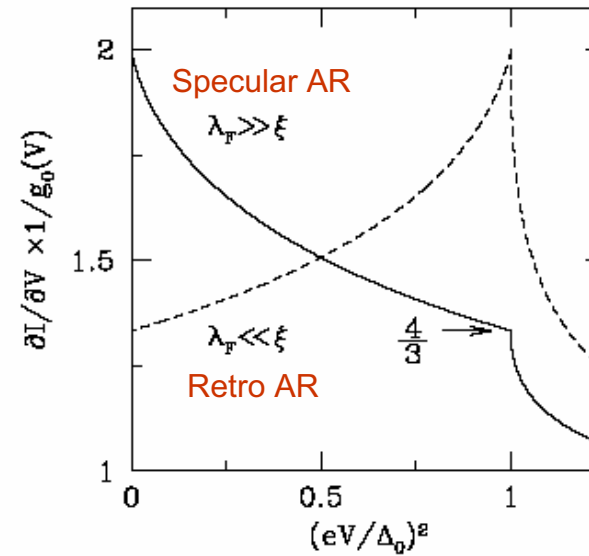
Retro Andreev Reflection

Specular Andreev reflection in graphene NS junctions

Superconducting correlation of Dirac electrons from **different valleys**



[C. W. J. Beenakker Phys. Rev. Lett. 97,067007 (2006)]

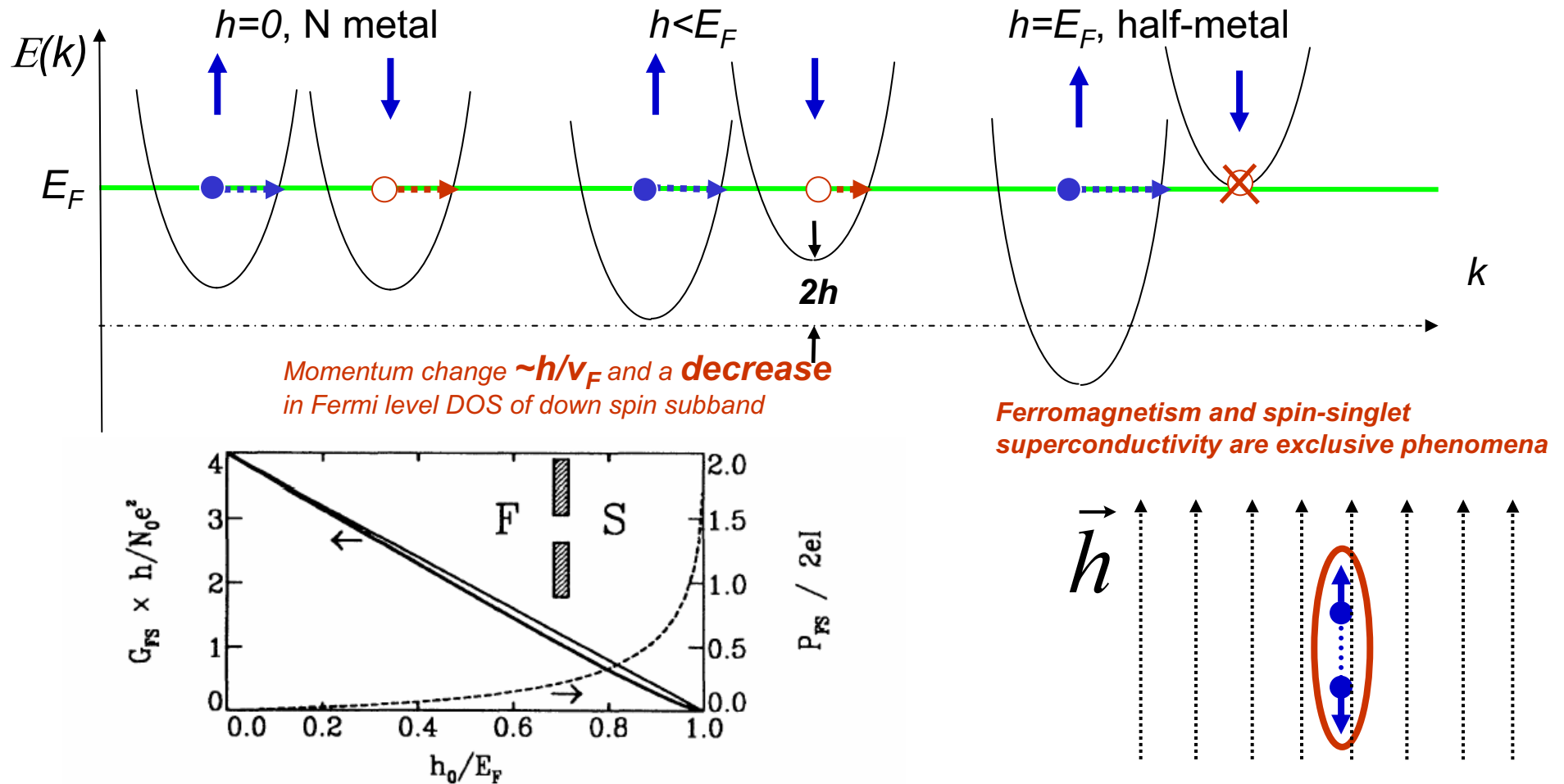


Graphene NS structures

[Titov and Beenakker PRB (2006);
Moghaddam and Zareyan PRB (2006);
Bhattacharjee and Sangupta PRL (2006);
Beenakker (2007); ...]

Andreev reflection in FS junctions

• **Spin is inverted** (has significant consequences if N is a **ferromagnet**)



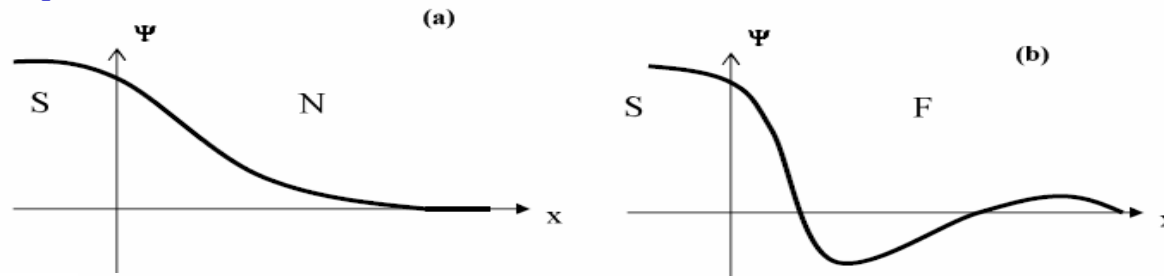
[M. J. M. de Jong and C. W. J. Beenakker Phys. Rev. Lett. **74**,1657 (1995);.....]

FS hybrid structures

Controlled coexistence and Interplay of ferromagnetic ordering and induced superconducting correlations:

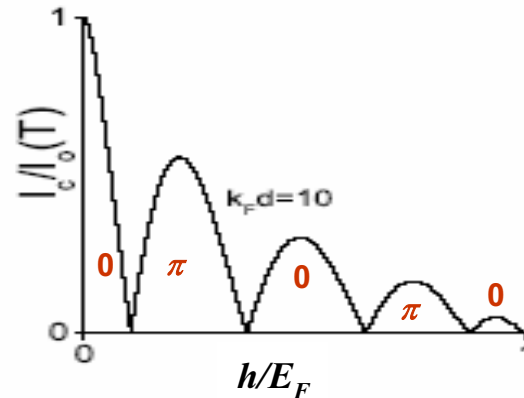
Density of Andreev correlated electron-holes
:induced superconducting order parameter

Spatial oscillations : period $\sim v_F/h$ for ballistic F



π -SFS junction

Short range Josephson coupling
in SFS : $d \sim v_F/h \ll v_F/T$
of SNS junction

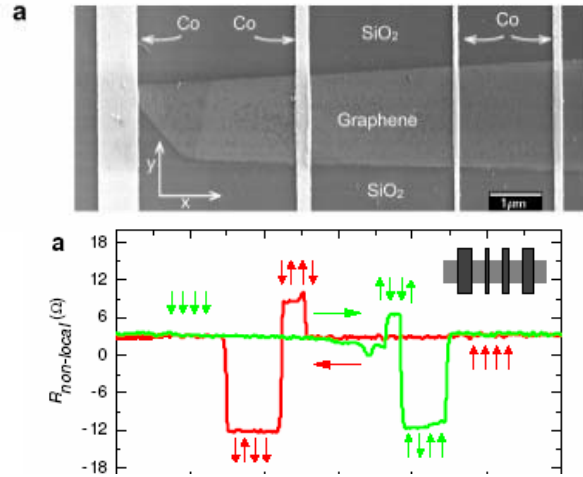


[Buzdin et al, JETP Lett (1984);
Ryazanov et al, PRL (2001);
Zareyan et al, PRL (2001);
Kontos et al, PRL (2001);
Chtchelkatchev et al, JETP Lett (2001);
.....
Cayssol and Montambaux PRB (2005);
...]

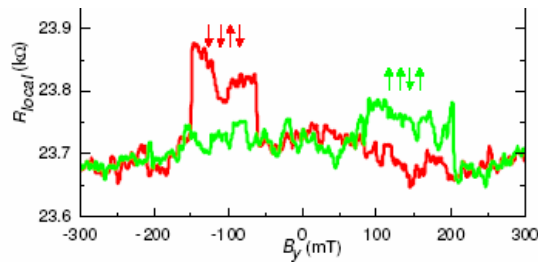
FSF spin valves, long range spin-triplet superconducting proximity effects,

[Golubov et al, Rev. Mod. Phys. **76**,411 (2004); Buzdin Rev. Mod. Phys. **77**, 934 (2005);
Bergeret et al, Rev. Mod. Phys. **77**, 1321 (2005); Keizer et al, Nature **439**, 825 (2006);
Bergeret et al, PRL **86**, 4096(2001); Eschrig and Lofwander, Nature Phys. **4**, 138 (2008);]

Proximity induced superconductivity and spin-polarization in graphene



[N. Tomboros et al, Nature 448, 571(2007):
van Wees talk]

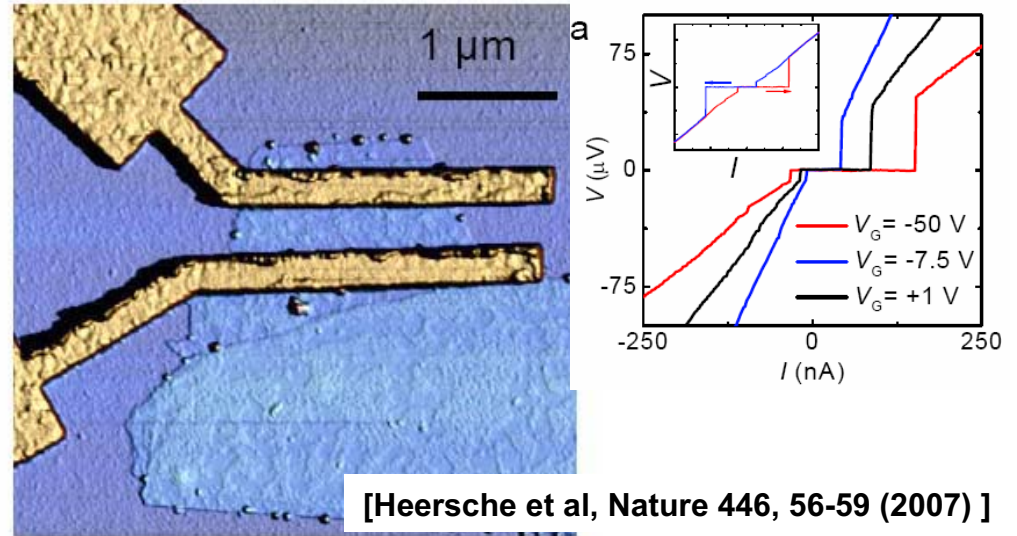


[Also Hill et al, (2006); Jozas et al, PRL (2008)]

Theory: intrinsic as well as extrinsic (magnetic adatoms) spin-polarization

[Peres et al, PRB (2005); Son et al, Nature (2006);
Dugaev et al, PRB (2006); Uchoa et al, PRL (2006); Haugen et al, PRB (2008);.....Castro Neto talk;...]

Ti/AI (10/70nm) superconducting bilayer ($T_c \sim 1.3$ K) on top of graphene sheet



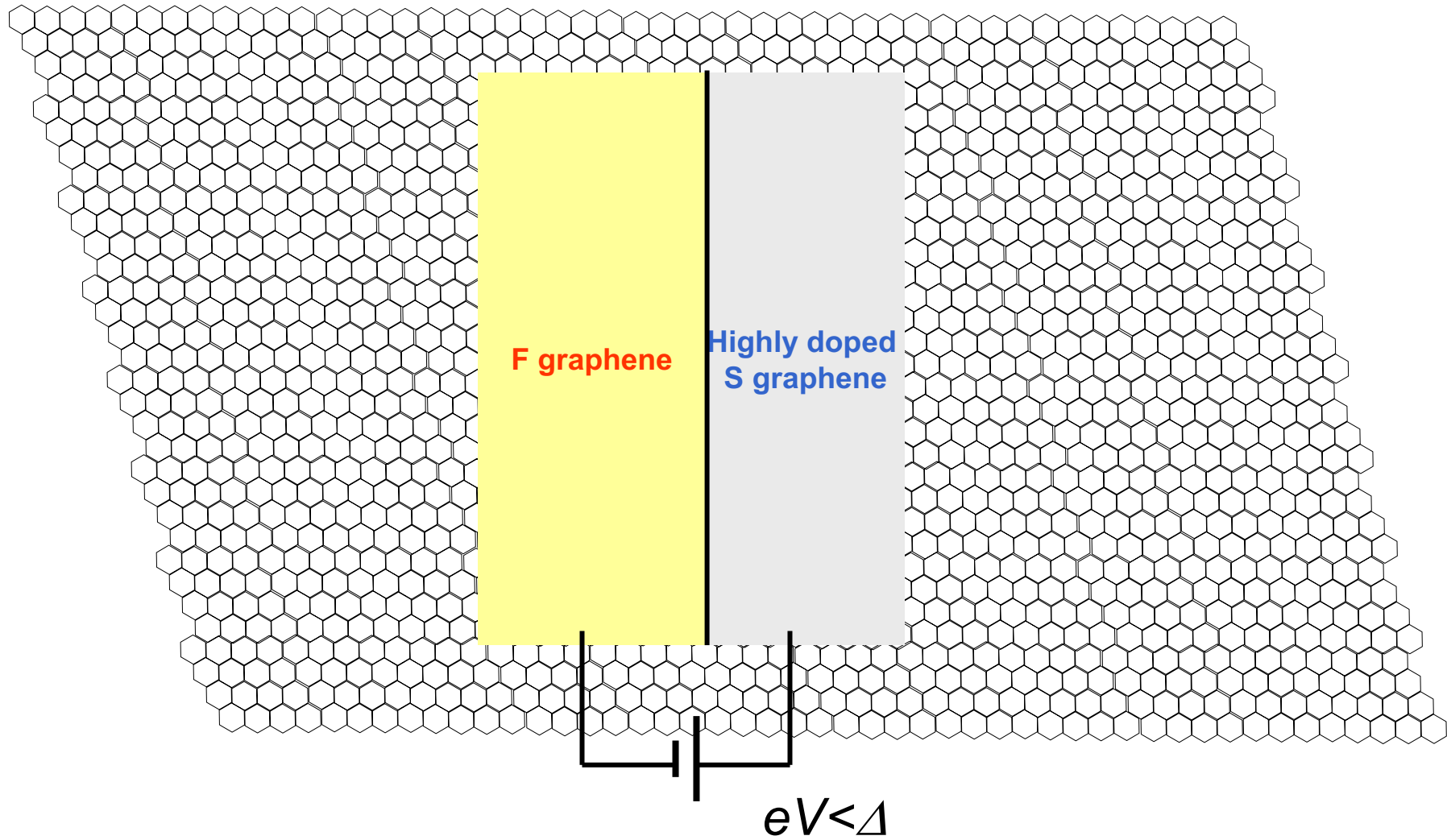
[Heersche et al, Nature 446, 56-59 (2007)]

[Also, Andrei talk ;....]

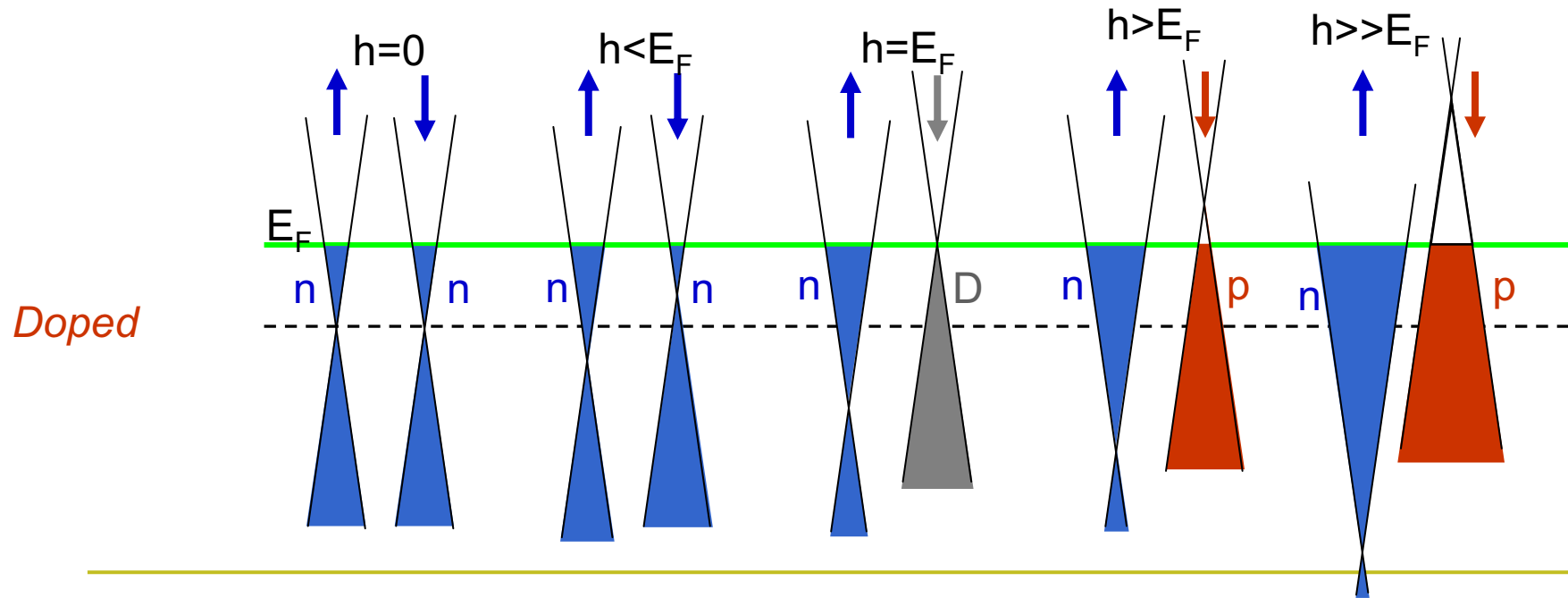
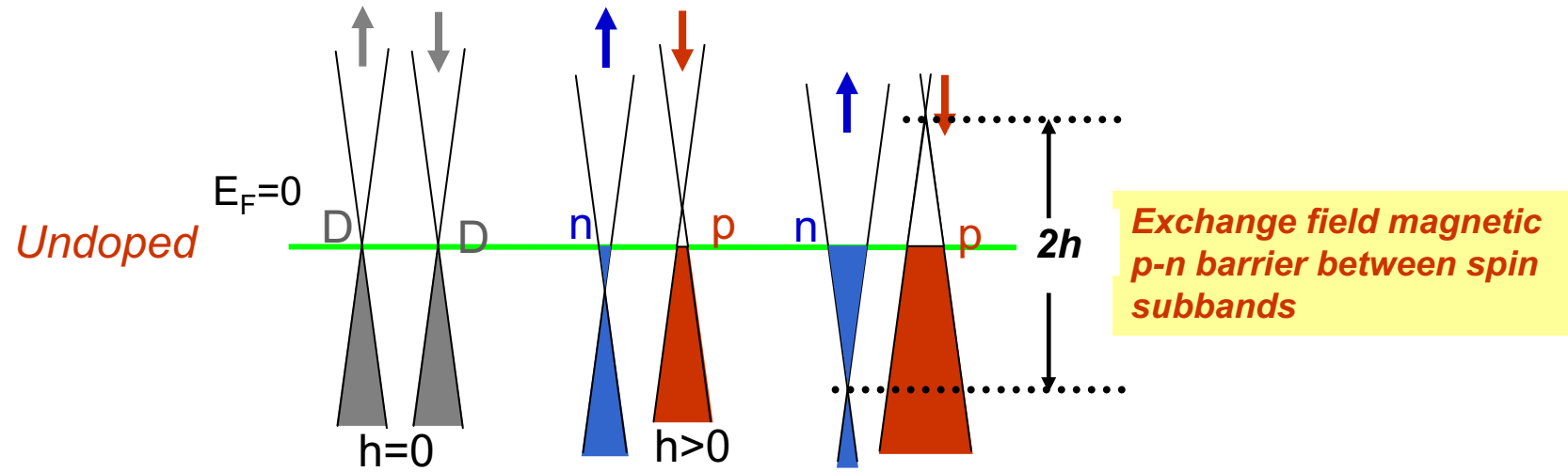
Theory of superconductivity in graphene

[Uchoa and Castro Neto PRL (2007); Sasaki et al, (2007);
Mazin and Balatski (2008); Kopnin and Sonin (2008);
Gonzalez (2008);.....]

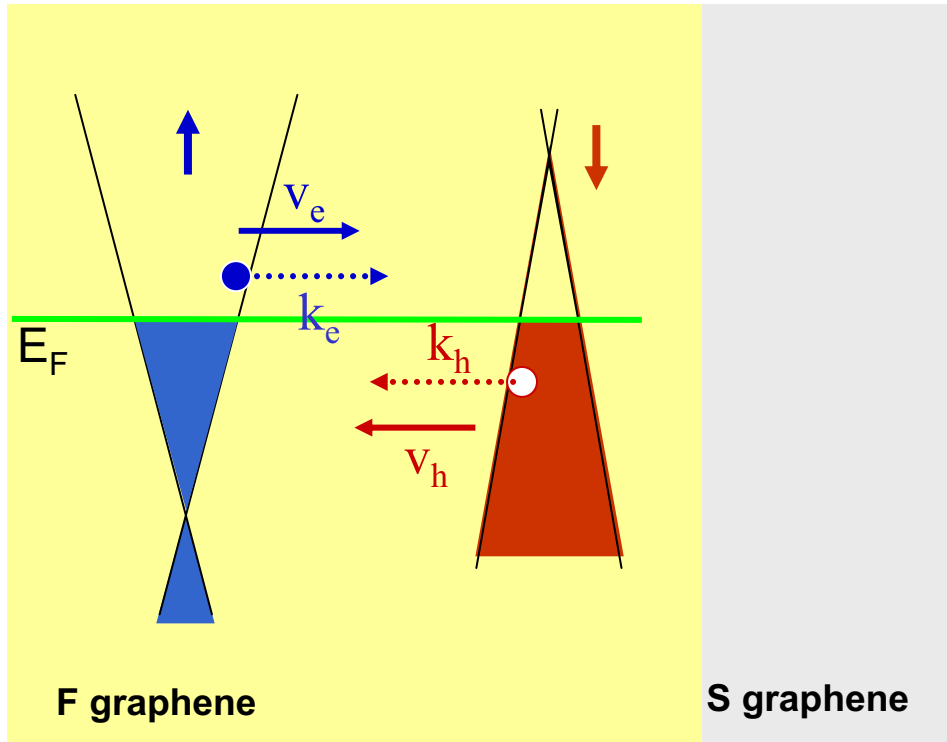
Graphene FS junction



Ferromagnetic graphene

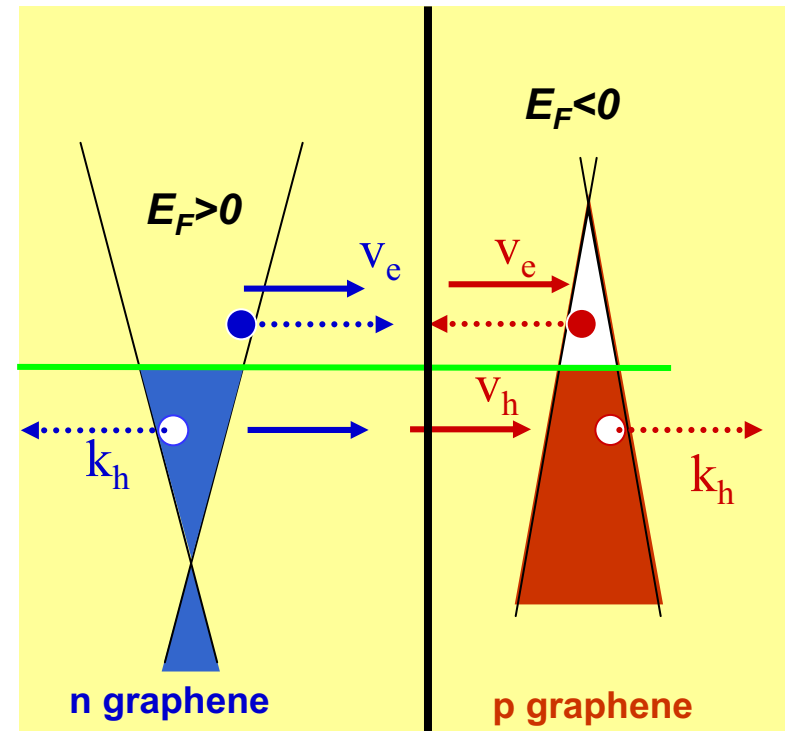


Spin Andreev-Klein tunnelling



[M. Z. , H. Mohammadpour, A. G. Moghaddam, arXiv: 0804.2774v1(2008)]

Reflection-less Klein tunnelling of normally incident chiral electrons through an electrical p-n barrier



[M. I. Katsnelson, et al, Nature Phys. (2006);... Levitov and Goldhaber-Gordon talks.....]

Dirac-Bogoliubov-deGennes equations

$$\begin{pmatrix} v_F \hat{\sigma} \cdot \vec{p} - sh\hat{1} - E_F \hat{1} & \Delta \hat{1} \\ \Delta^* \hat{1} & -(v_F \hat{\sigma} \cdot \vec{p} - \bar{s}h\hat{1} - E_F \hat{1}) \end{pmatrix} \begin{pmatrix} \hat{u}_s \\ \hat{v}_{\bar{s}} \end{pmatrix} = \epsilon_s \begin{pmatrix} \hat{u}_s \\ \hat{v}_{\bar{s}} \end{pmatrix}$$

$s = \bar{s} = \pm 1$

Electron-hole conversion:
superconducting correlations

electron 4-component spinor

Diagonal Dirac Hamiltonian with
exchange field

hole 4-component spinor

Superconducting correlation of massless Dirac electrons
with opposite spin and different valley

[C. W. J. Beenakker Phys. Rev. Lett. 97,067007 (2006)]

Variety of Andreev processes

$$r_{As} = \frac{\sec \beta \sqrt{\cos \phi_s \cos \phi'_s}}{\cos[(\phi_s - \phi'_s)/2] + i \tan \beta \cos[(\phi_s + \phi'_s)/2]}$$

$$\beta = \cos^{-1}(\varepsilon / \Delta)$$

$$r_s = \frac{-\sin[(\phi_s + \phi'_s)/2] + i \tan \beta \cos[(\phi_s - \phi'_s)/2]}{\cos[(\phi_s - \phi'_s)/2] + i \tan \beta \cos[(\phi_s + \phi'_s)/2]}$$

$$\varepsilon_s = \left| E_F \pm \hbar v_F \sqrt{k_x^2 + k_y^2} + sh \right|, \quad \vec{v}_s = \frac{1}{\hbar} \frac{\partial \varepsilon_s}{\partial \vec{k}}$$

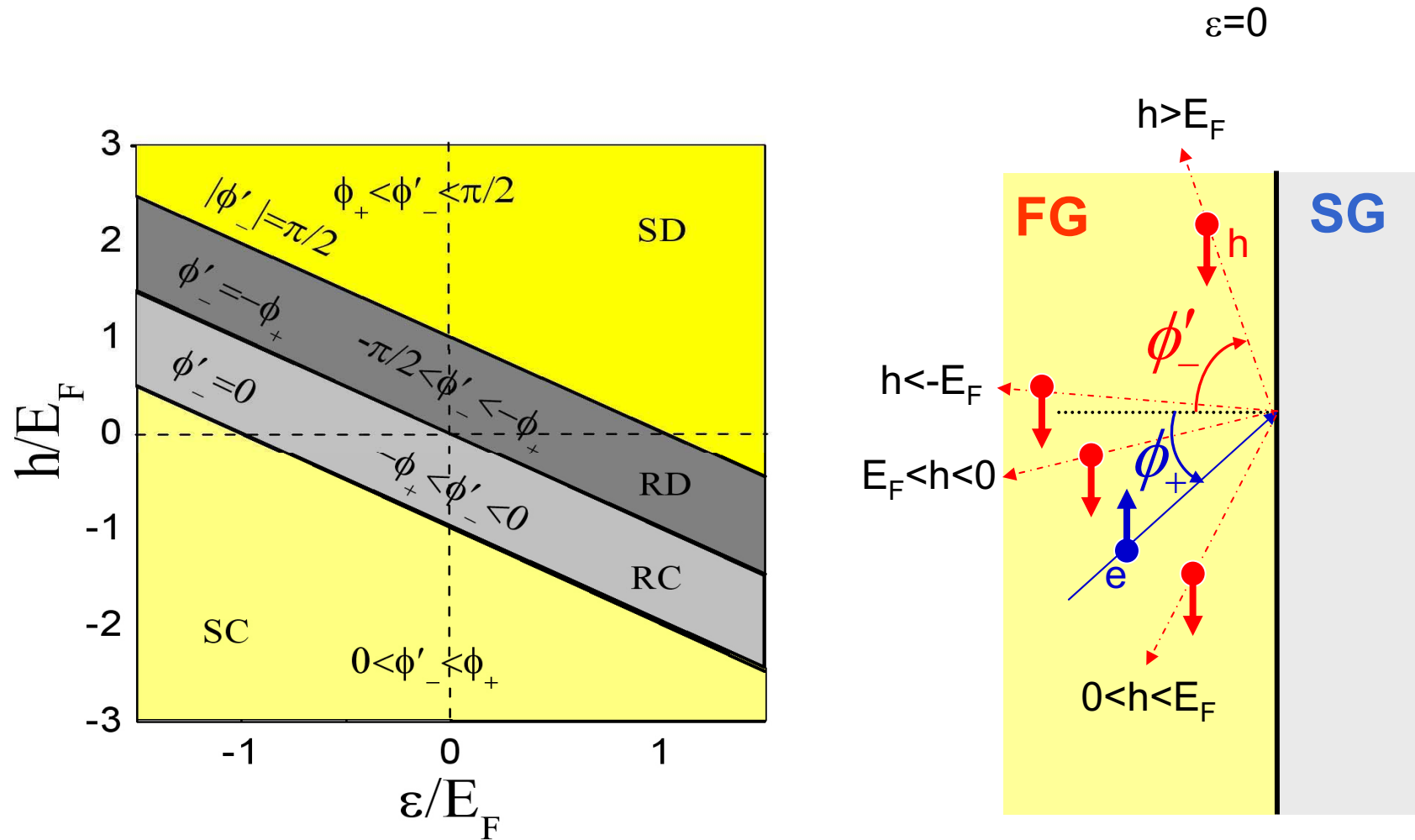
- Conservation of energy
- Conservation of transverse momentum

$$k'_{y-} = k_{y+}$$

- Angle of Andreev reflection ϕ'_- vs ϕ'_+ angle of incident

$$k'_{x-} = \sqrt{(\varepsilon + h + E_F)^2 - (\varepsilon + h + E_F)^2 \sin^2 \phi_+}$$

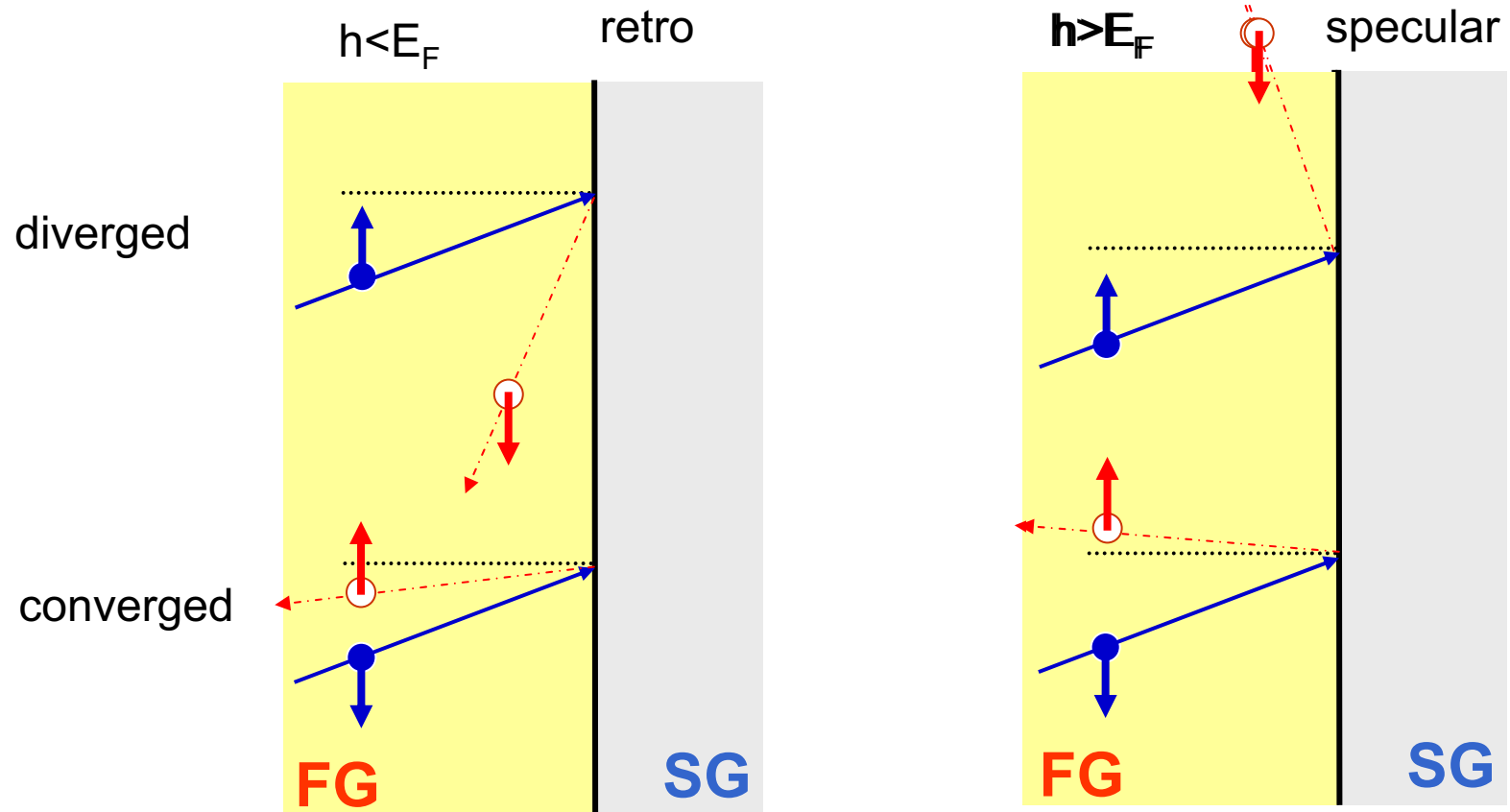
Map of Andreev reflection angle



Every angle possible by tuning h or E_F !

[M. Z. , H. Mohammadpour, A. G. Moghaddam, arXiv: 0804.2774v1(2008)]

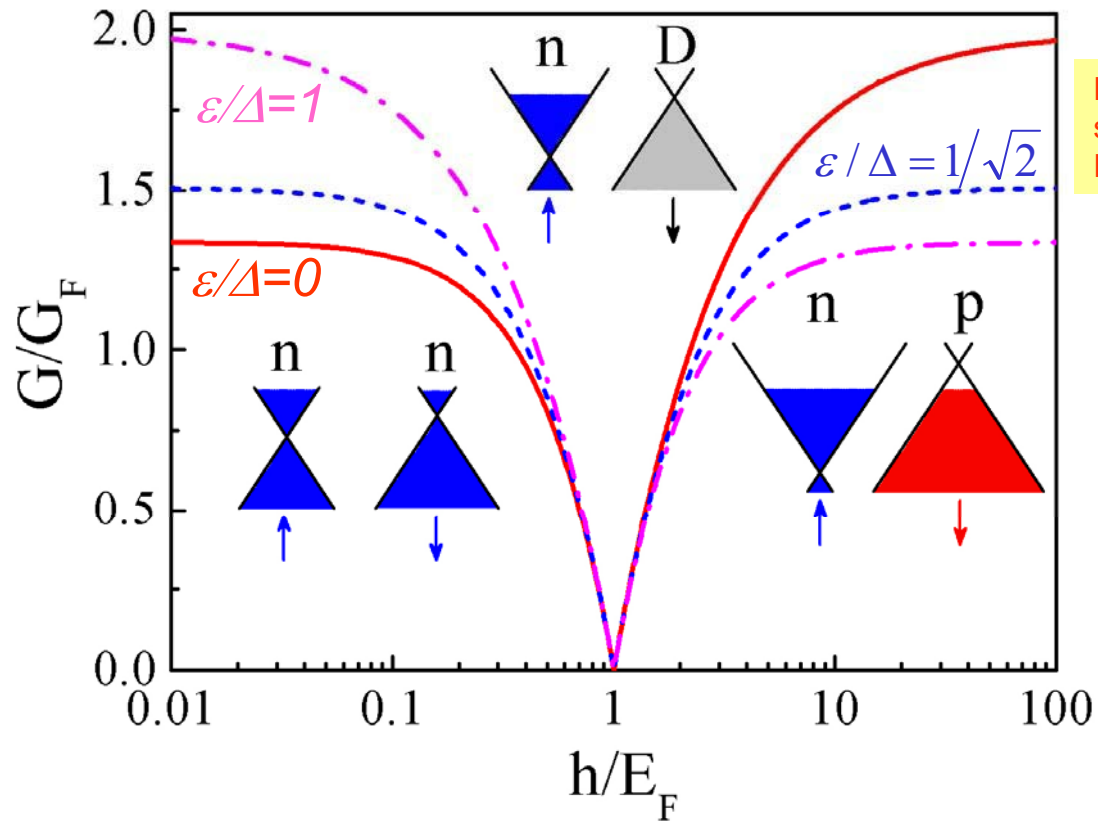
$\varepsilon=0$



Useful in spintronics?

Andreev-Klein conductance of FS contacts

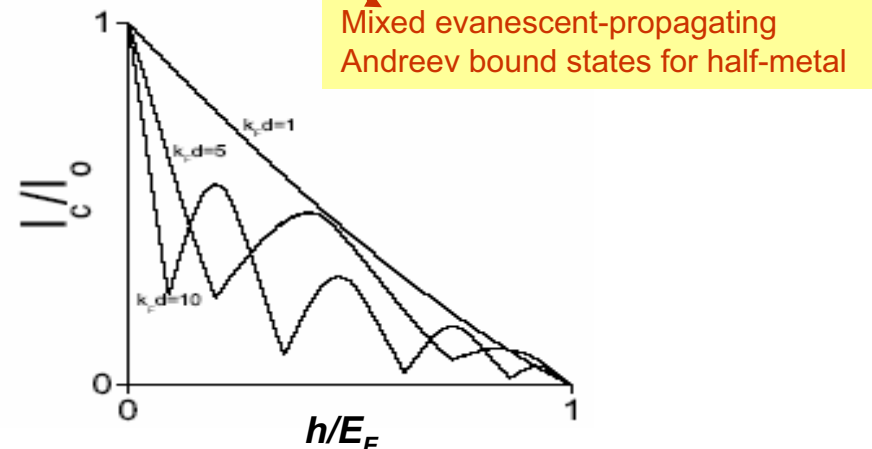
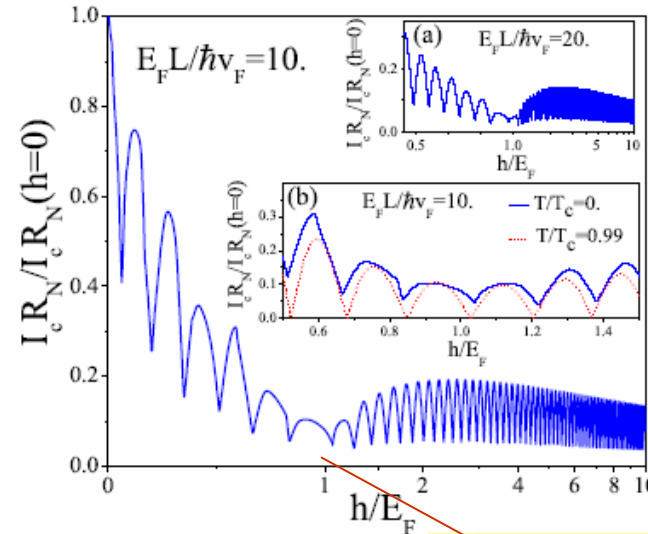
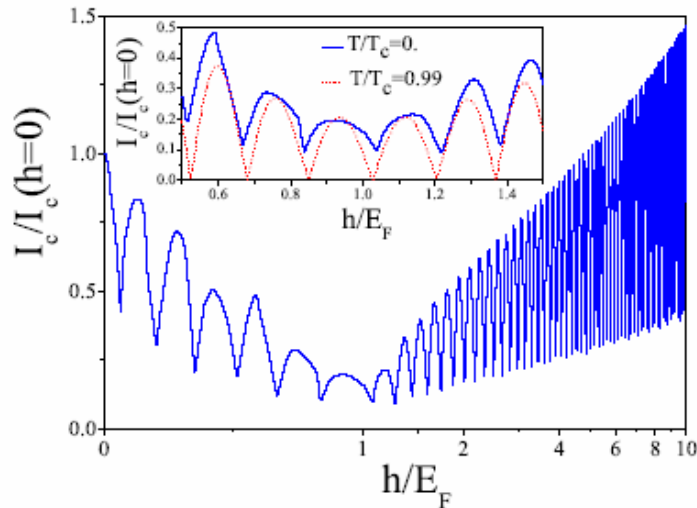
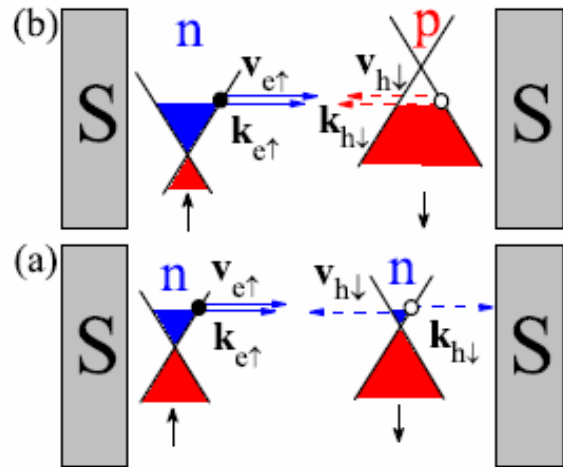
$$G = \sum_{s=\pm} G_s \int d\phi_s \cos \phi_s (1 - r_s + r_{As}), \quad G_F = \sum_{s=\pm} G_s$$



Exchange field amplifies spin-singlet superconducting correlations at FS-interface !!!

[M. Z. , H. Mohammadpour, A. G. Moghaddam, arXiv: 0804.2774v1(2008)]

Long-range Josephson coupling



[Asano et al, PRB (2008); Linder et al, PRL (2008);

[A. G. Moghaddam, M.Z., to appear in PRB (2008) arXiv: 0806.3611v1] Cayssol and Montambaux PRB (2005);....]

Conclusion

- AR from FS interface is fundamentally different for $\hbar > E_F$: associated with **spin Klein tunnelling** of chiral electrons through exchange field p-n barrier: **Andreev-Klein reflection**
- **Depending on spin**: It can be **retro** or **specular** in both **convergent** way and **divergent** way
- Exchange field induced enhancement of Andreev conductance: **ferromagnetic ordering amplifies spin-singlet superconducting correlations !!!**
- Long-range Josephson coupling in graphene SFS junctions