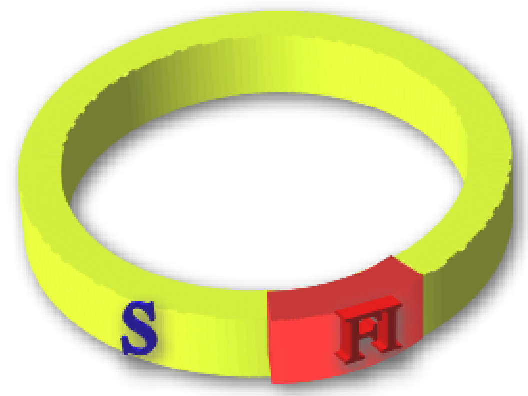
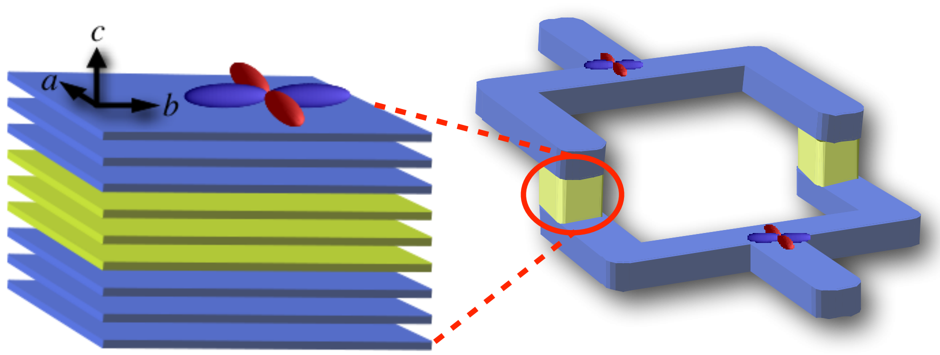
Seminar at HSE Russia, Sep. 23rd 2016

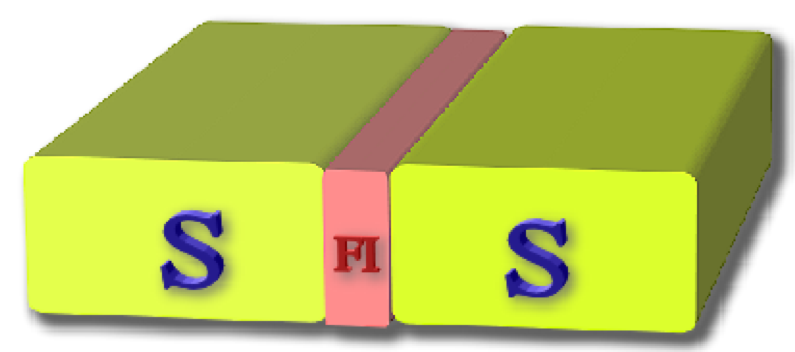
Physics of superconductor/ferromagnet junctions



Shiro Kawabata

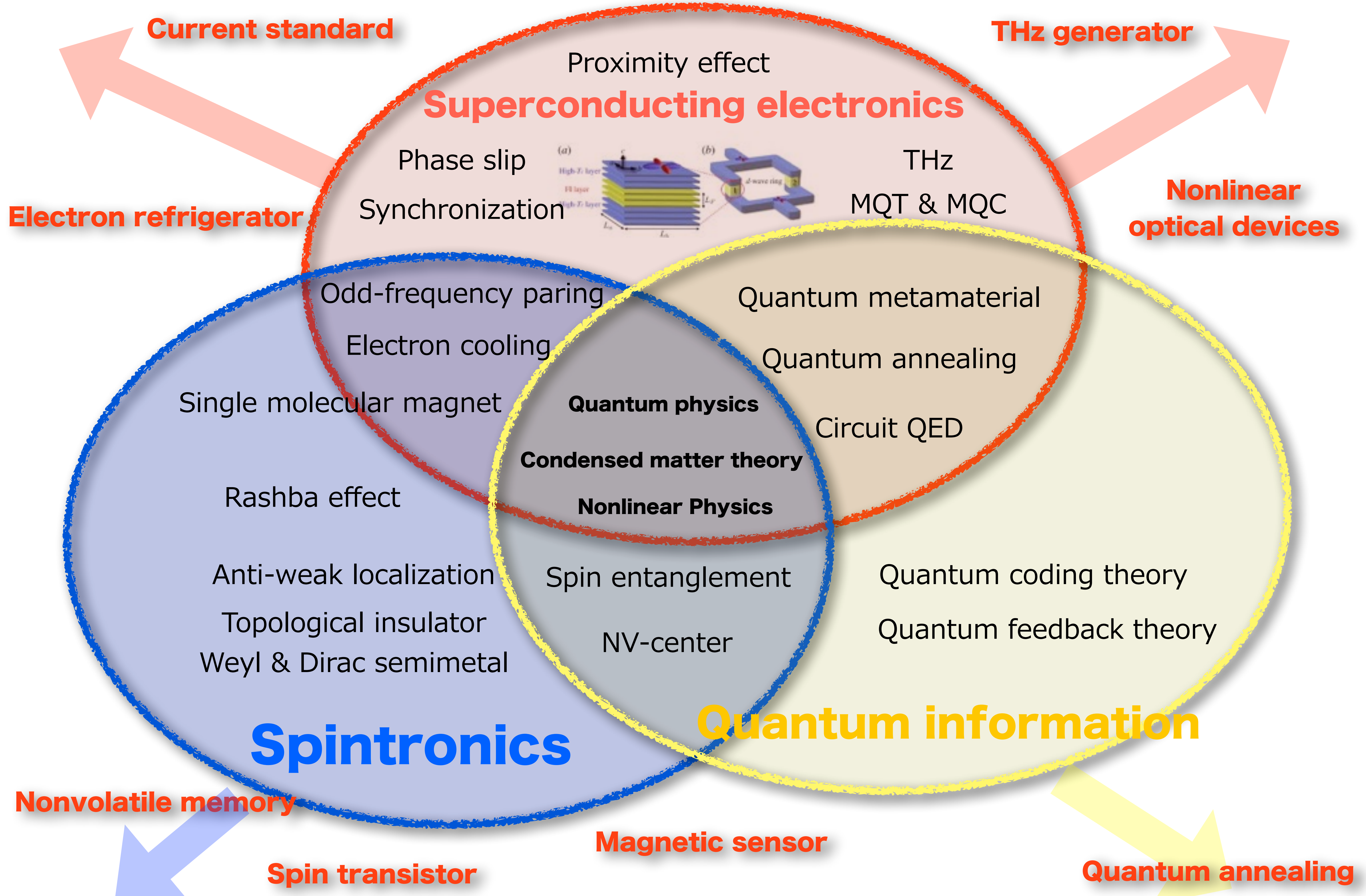
National Institute of Advanced Industrial Science & Technology (AIST), JAPAN





Research field: Overview

From basic to application



Collaboration with Dr. Vasenko (2010~)

S. Kawabata, A. S. Vasenko, A. Ozaeta, F. S. Bergeret & **F. W. J. Hekking**
"*Heat transport and electron cooling in ballistic normal-metal/spin-filter/superconductor junctions*"
Journal of Magnetism and Magnetic Materials 383 (2015) 157

A. S. Vasenko, S. Kawabata, A. Ozaeta, A. Golubov, F. S. Bergeret & **F. W. J. Hekking**
"*Detection of small exchange fields in S/F structures*"
Journal of Magnetism and Magnetic Materials 383 (2015) 175

S. Kawabata, A. Ozaeta, A. S. Vasenko, **F. W. J. Hekking** & F. S. Bergeret
"*Efficient electron refrigeration using superconductor/spin-filter devices*"
Appl. Phys. Lett. 103 (2013) 032602

A. S. Vasenko, A. Ozaeta, S. Kawabata, **F. W. J. Hekking** & F. S. Bergeret
"*Andreev current and subgap conductance of spin-valve SFF structures*"
J Supercond. Nov. Mag. 26 (2013) 1951

S. Kawabata, Y. Tanaka, A. Golubov, A. S. Vasenko & Y. Asano
"*Spectrum of Andreev bound states in Josephson junctions with a ferromagnetic insulator*"
J Supercond. Nov. Mag. 324 (2012) 3467

S. Kawabata, Y. Tanaka, A. A. Golubov, A. S. Vasenko, S. Kashiwaya & Y. Asano
"*Tunneling Hamiltonian description of the atomic-scale 0-π transition in superconductor/ferromagnetic-insulator junctions*", Physica C 471 (2011) 1199

A. S. Vasenko, S. Kawabata, A. Golubov, M. Y. Kupriyanov, **C. Lacroix, F. S.** Bergeret & **F. W. J. Hekking**
"*Current-voltage characteristics of tunnel Josephson junctions with a ferromagnetic interlayer*"
Phys. Rev. B 84 (2011) 024524

A. S. Vasenko, S. Kawabata, A. Golubov & **F. W. J. Hekking,**
"*Dissipative current in SIFS Josephson junctions*"
Physica C 470 (2010) 863

Contents

1. Superconducting spintronics with Ferromagnetic Metals

   - Josephson effect & Proximity effect
   - Josephson π junction
   - Applications
   - Long range triplet Josephson effect

2. Superconducting spintronics with Ferromagnetic Insulators

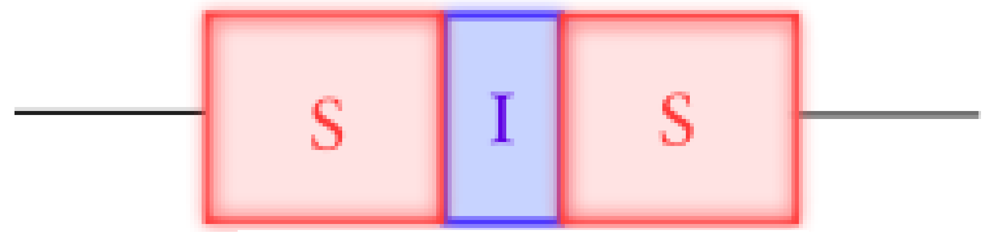
   - Ferromagnetic insulator & Spin-filtering effect
   - Atomic scale 0-π transition
   - Experiments
   - Applications

3. Summary

Josephson junction

Weakly coupled two superconductors

$\Delta e^{i\theta_1}$ $\Delta e^{i\theta_2}$



DC current can flow without bias voltage

Josephson current (= tunneling of cooper pairs)

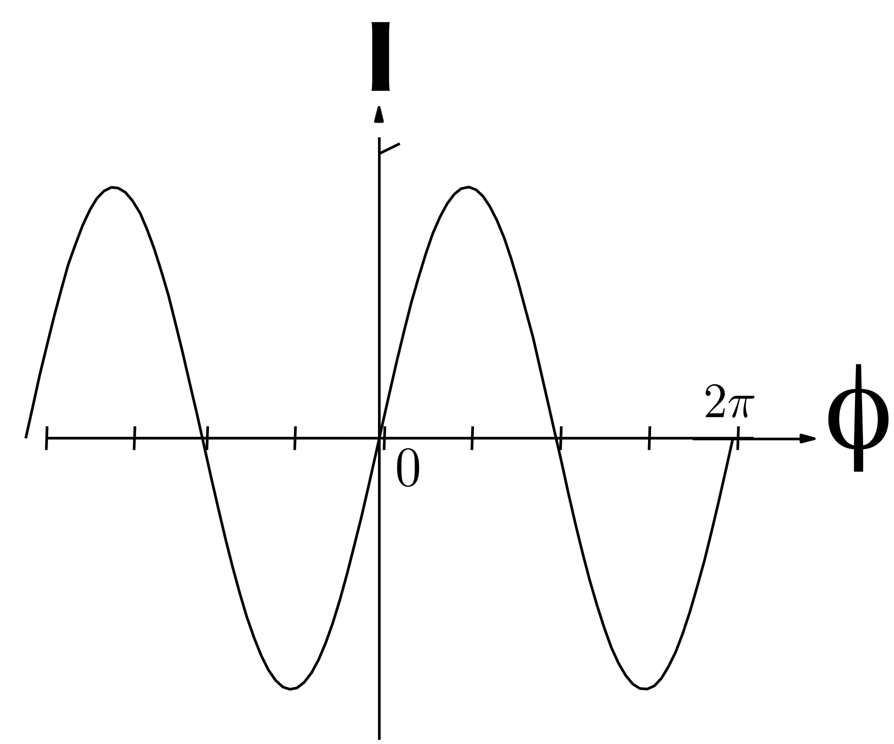
DC Josephson effect

$$I = I_C \sin\phi$$

Ic: Critical current

Driving force = phase difference in the macroscopic wave function

$$\phi = \theta_1 - \theta_2$$



π-junction in S/FM/S systems

Buzdin, Rev. Mod. Phys. 77 (05) 935
Eschrig, Phys. Today 64 (11) 43

FM : Ferromagnetic Metal (Fe, Co, ...)

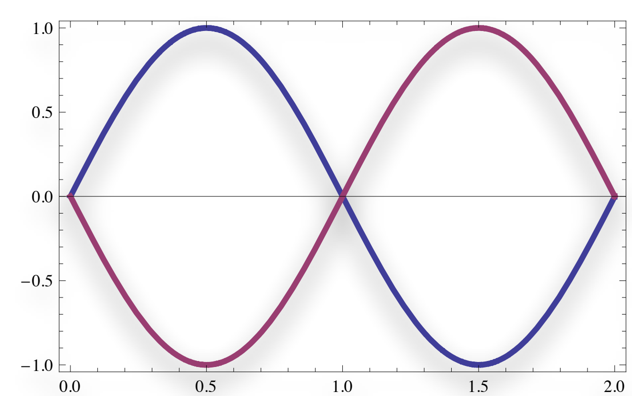
Exchange field

Non-zero momentum due to the spin exchange splitting in FMs

Pair-amplitude oscillation

Josephson Current $I = -I_C \sin\phi = I_C \sin(\phi + \pi)$

I/I_C



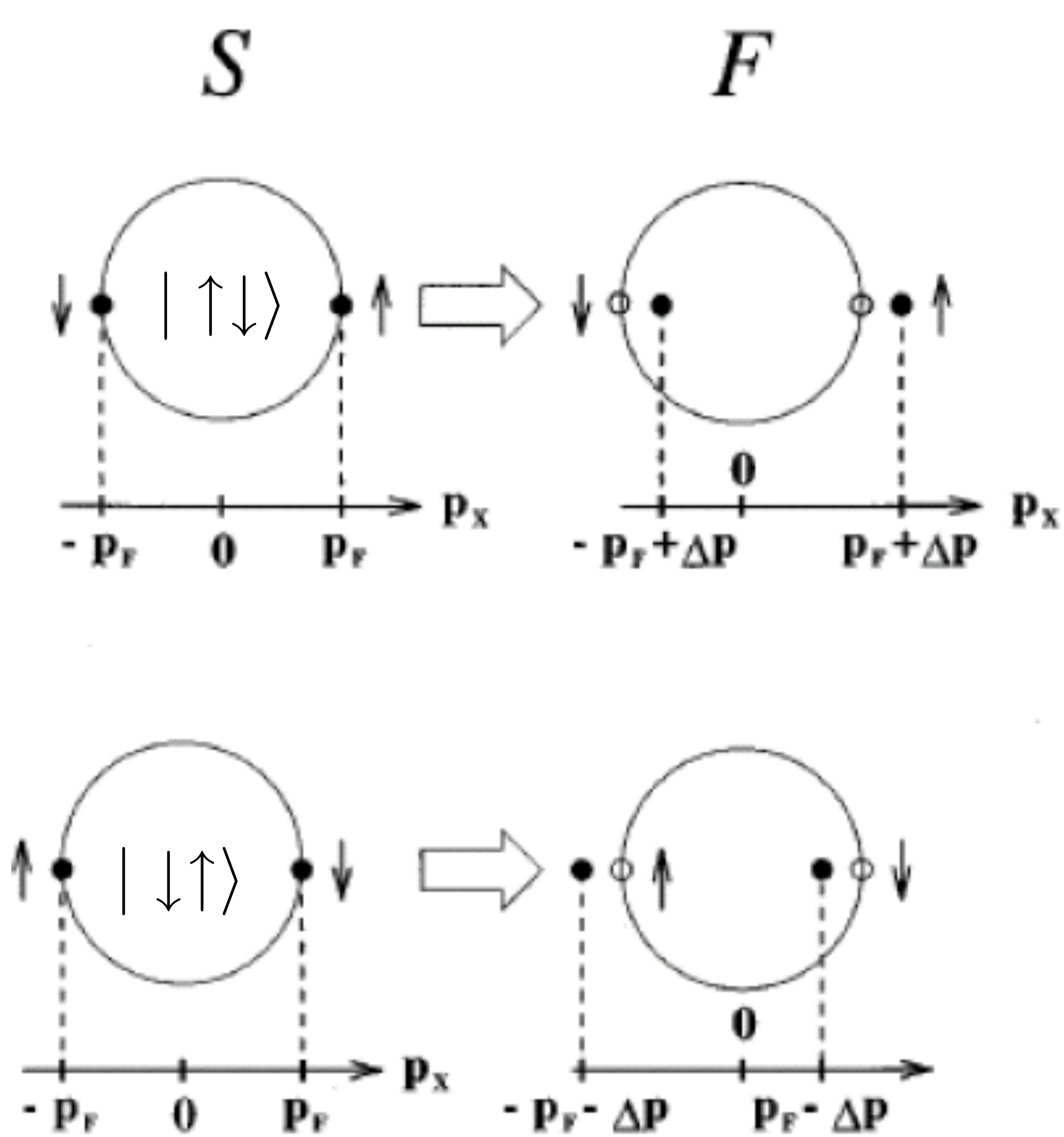
ϕ

π-junction $I = -I_C \sin\phi$

0-junction $I = +I_C \sin\phi$
Conventional

Cooper pair in S/FM hybrids

E. A. Demler et al., Phys. Rev. B, 55, 15174 (1997)



Cooper pair in S $|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

$$|\uparrow\downarrow\rangle \rightarrow e^{ix\Delta p}|\uparrow\downarrow\rangle$$
$$|\downarrow\uparrow\rangle \rightarrow e^{-ix\Delta p}|\downarrow\uparrow\rangle$$

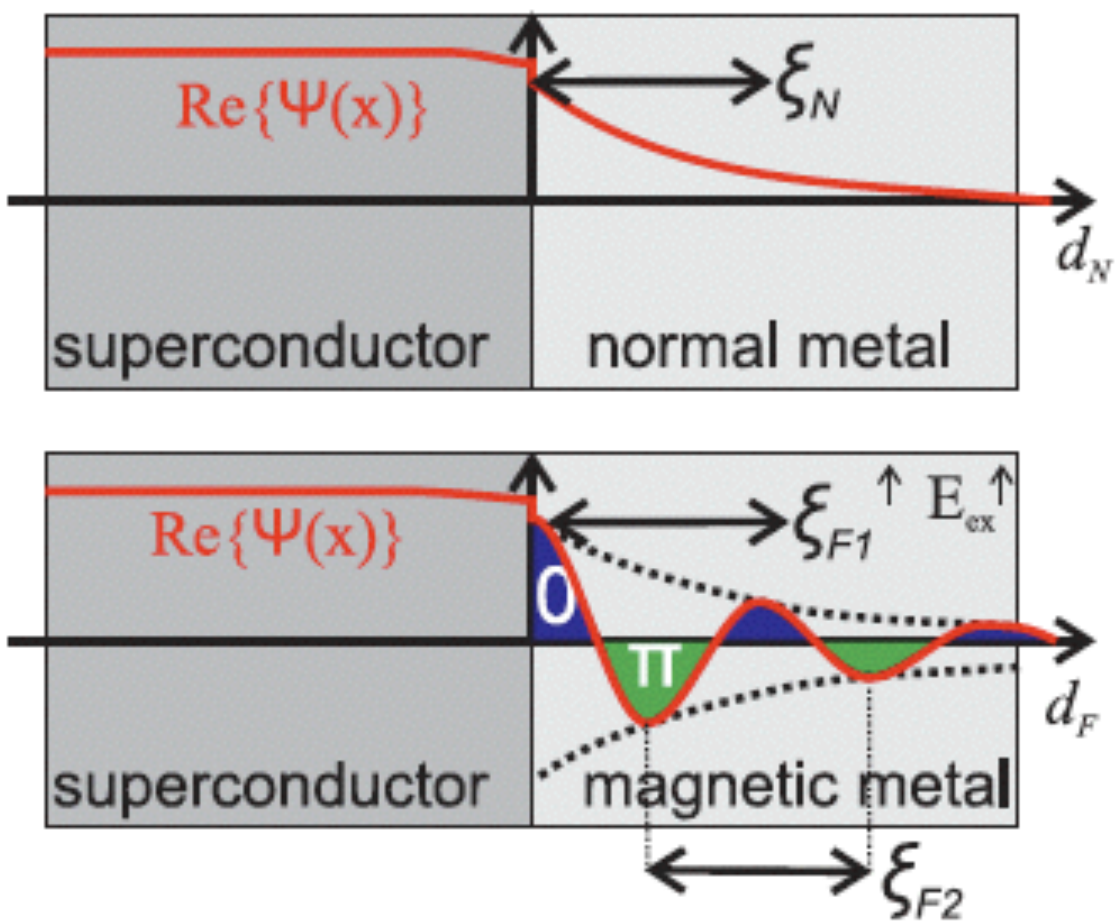
Cooper pair in F $e^{ix\Delta p}|\uparrow\downarrow\rangle - e^{-ix\Delta p}|\downarrow\uparrow\rangle$

$$\Delta p = \frac{2E_{\rm ex}}{\hbar v_F}$$

$$\mathrm{Re}\Psi = \cos(\Delta p x)$$

Spatial oscillation (FFLO Oscillation)

Proximity effect in S/FM hybrids



Weides, Martin P. (2006) Josephson tunnel junctions with ferromagnetic interlayer. PhD thesis, Universität zu Köln.

SN bilayer

$$\Psi = \Psi_0 \cdot e^{-d_N/\xi_N}$$

Proximity decay

SF bilayer

$$\Psi = \Psi_0 \cdot e^{-d_F/\xi_{F1}} \cos\left(\frac{d_F}{\xi_{F2}}\right)$$

E_{ex}: exchange energy

Proximity decay

Order parameter oscillations

Dirty limit

$$\xi_{F1,2} = \sqrt{\frac{\hbar D}{[E_{ex}^2 + (\pi k_B T)^2]^{1/2} \pm k_B T}}$$

D: Diffusion constant

Eex: Exchange energy

T: Temperature

Experiments

Ryazanov et al, PRL 86 (2001) 2427

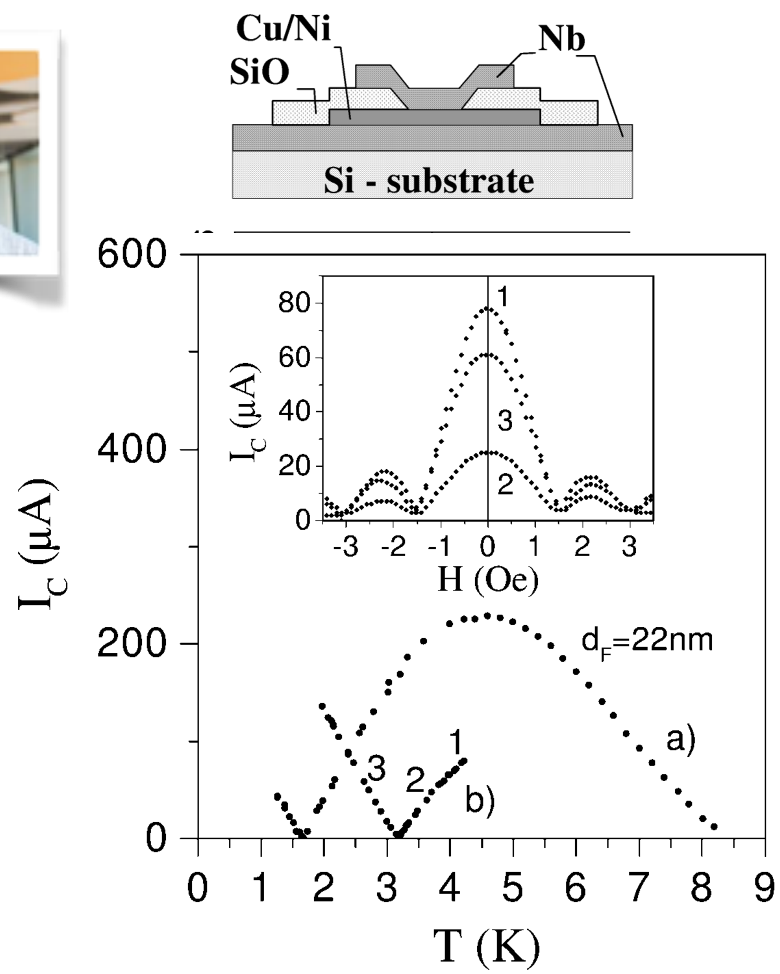
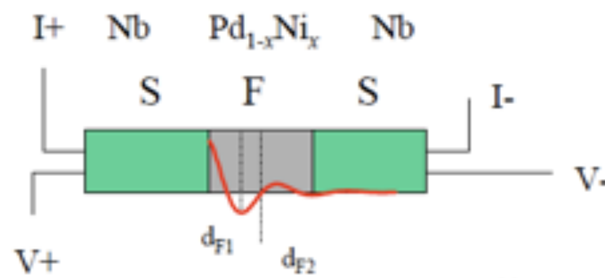
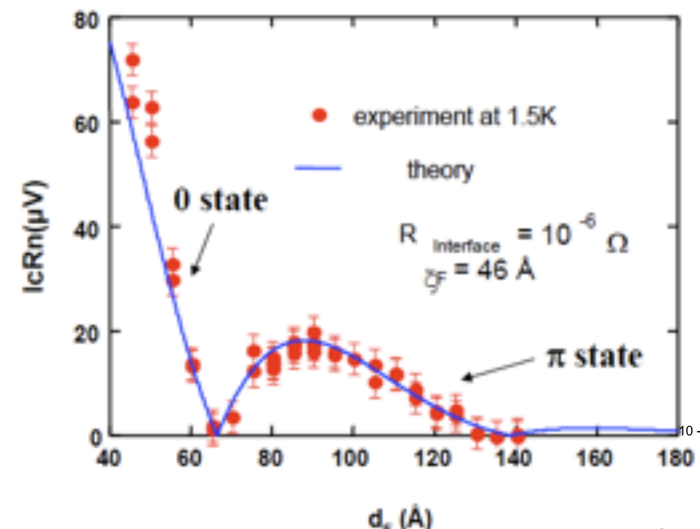
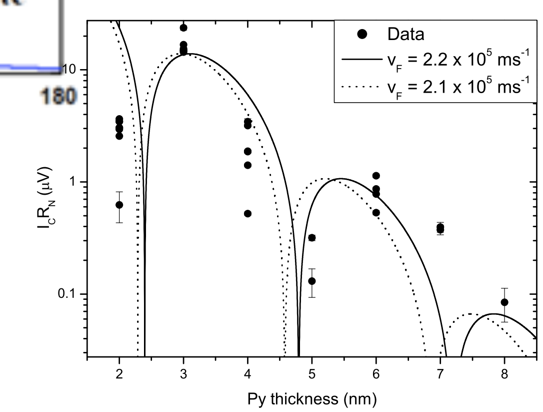


FIG. 3. Critical current I_c as a function of temperature T for two junctions with $Cu_{0.48}Ni_{0.52}$ and $d_F = 22$ nm [17]. Inset: I_c versus magnetic field H for the temperatures around the cross-over to the π state as indicated on curve b: (1) $T = 4.19$ K, (2) $T = 3.45$ K, (3) $T = 2.61$ K.

Kontos et al, PRL 89 (2002) 137007







Nb/CuNi/Nb
Temperature dependence

Nb/PdNi/Nb
FM thickness dependence

Oboznov, Ryazanov, Buzdin (06), Bell, Blamire (06), Weides, Goldobin, Kleiner(06), Birge(09), ...

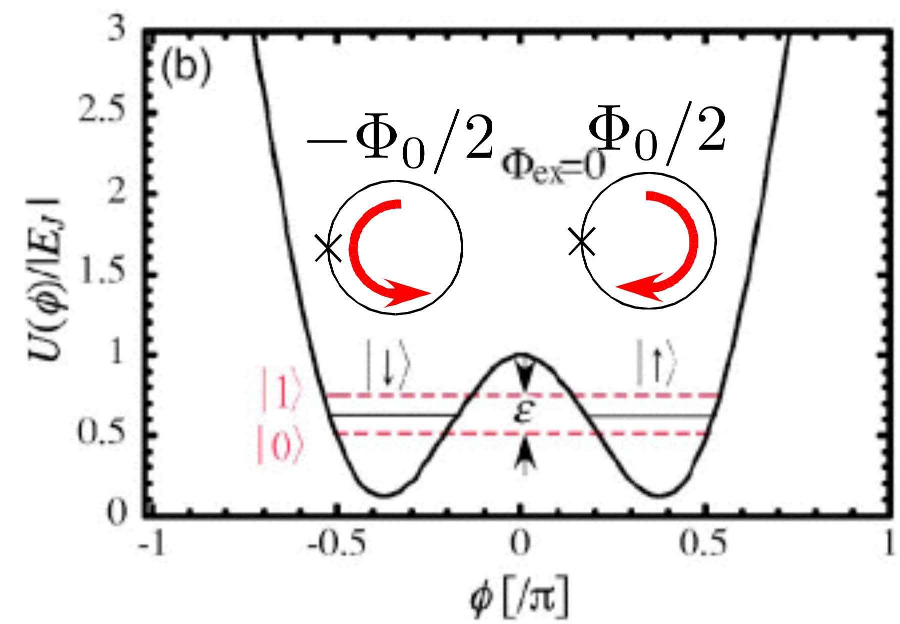
Applications of π junctions

Quiet Qubit

Superconductor ring with single π-junction

Bulaevskii, Kuzii & Sobyanin, JETP Lett. 25 (1977) 291

single-valued nature→ Spontaneous circulating current



Provides natural and precisely-degenerate quantum two-level system

WITHOUT applying external magnetic field

Quiet flux qubit

Ioffe et al, Nature 398 (99) 679
Blatter et al, PRB 63 (01) 174511
Yamashita, Takahashi, Maekawa, PRL 95 (05) 097001

Robust to the fluctuation of external fields

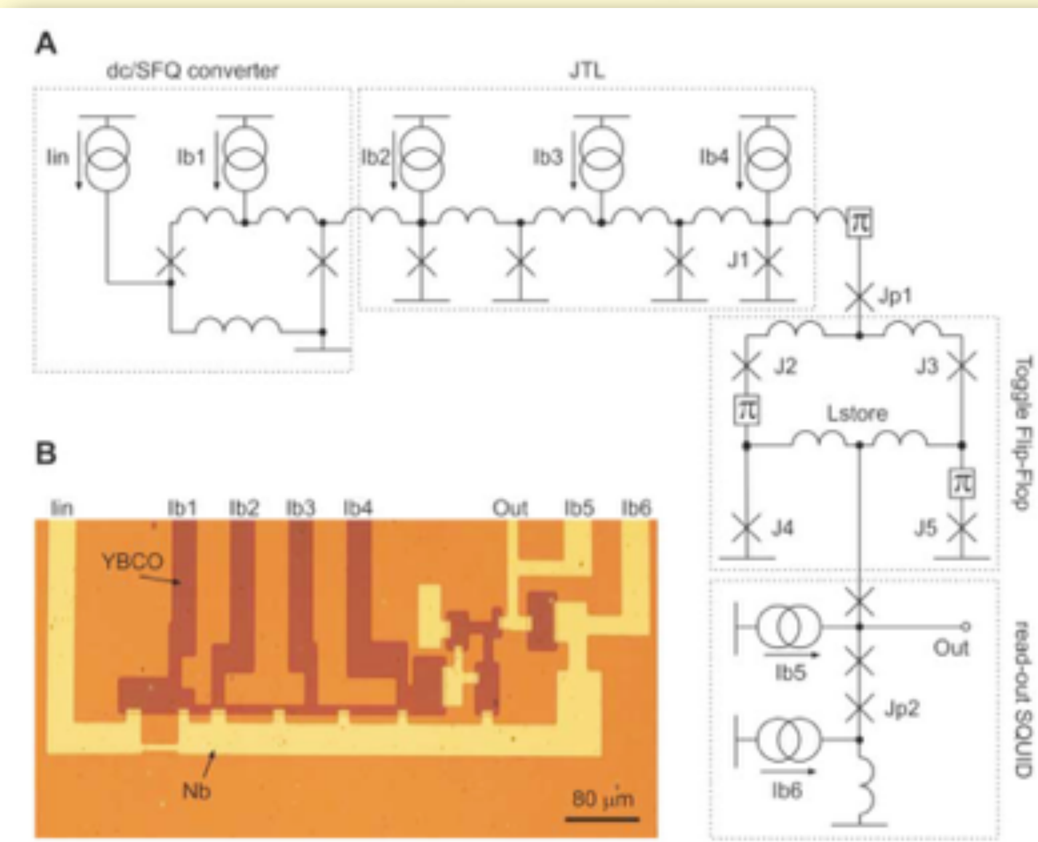
Note: usual flux qubit (0-junction ring): External flux bias is needed

π junction circuits

Classical logic circuit

Ortlepp et al, Science 312 (2006) 1495

Flip flop

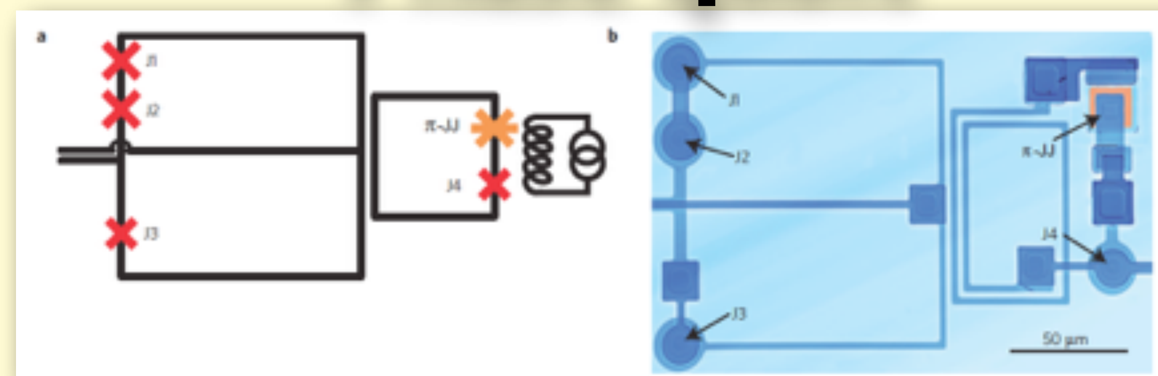


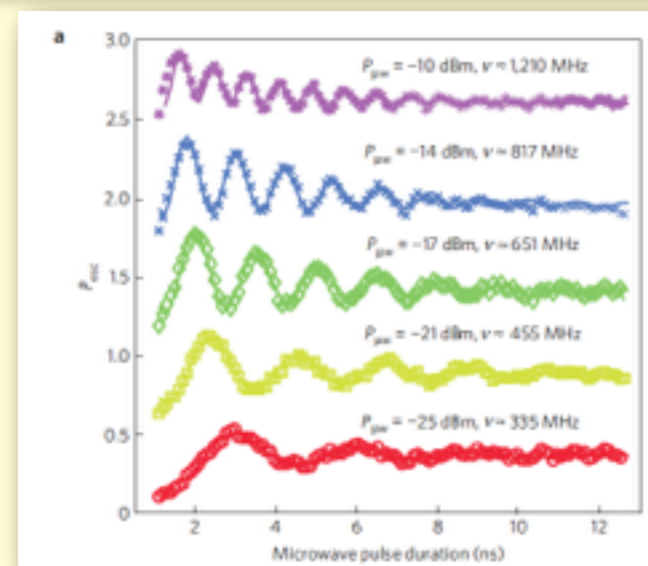
Scalable

Quantum logic circuit

Feofanov Ustinov, et al, Nature Phys. 6 (2010) 593

Phase qubit

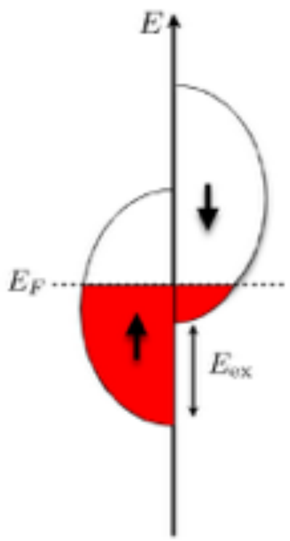




Rabi oscillation

SF hybrid memory: Beak et al., Nature Comm. 5(2014)3888

Drawback of FM for quantum applications



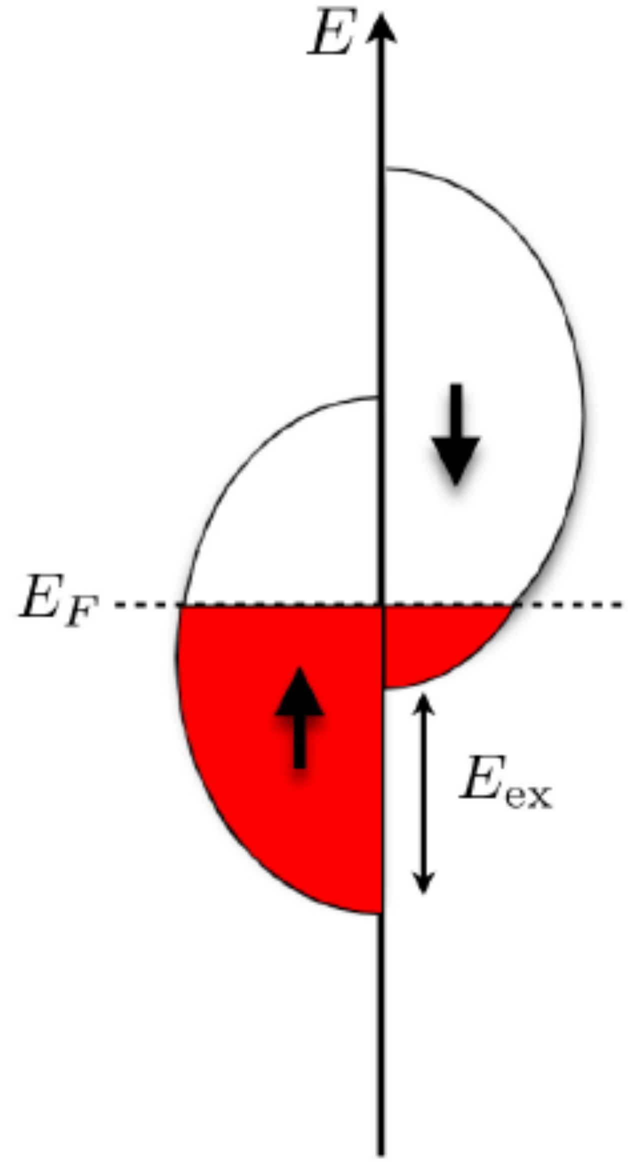
FM is a metal→Low energy quasiparticle excitation
→Strong damping & decoherence

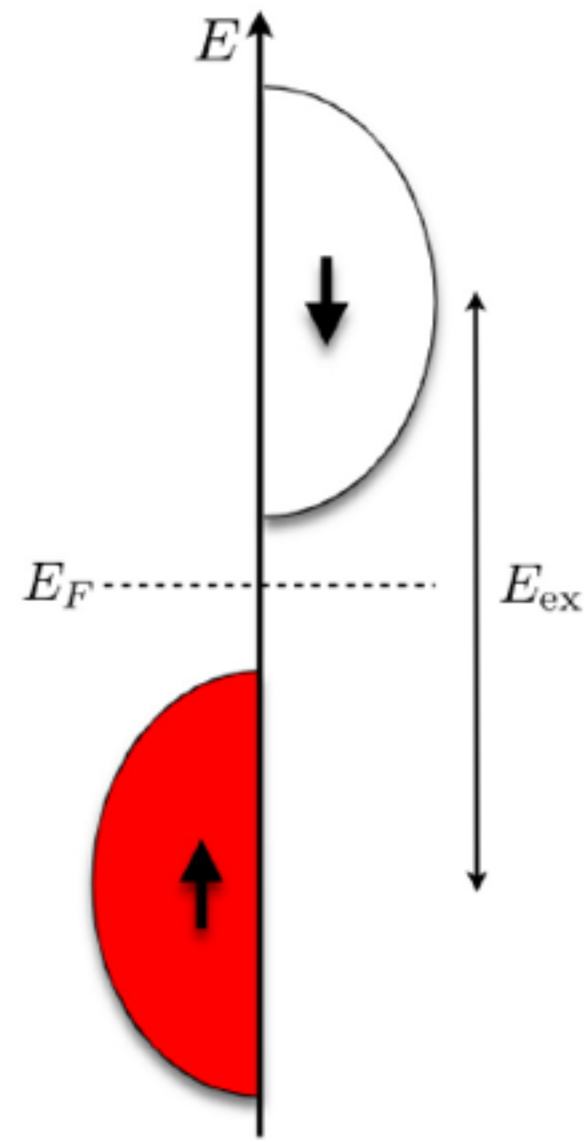
How to avoid?→Ferromagnetic INSULATORS (FIs)!

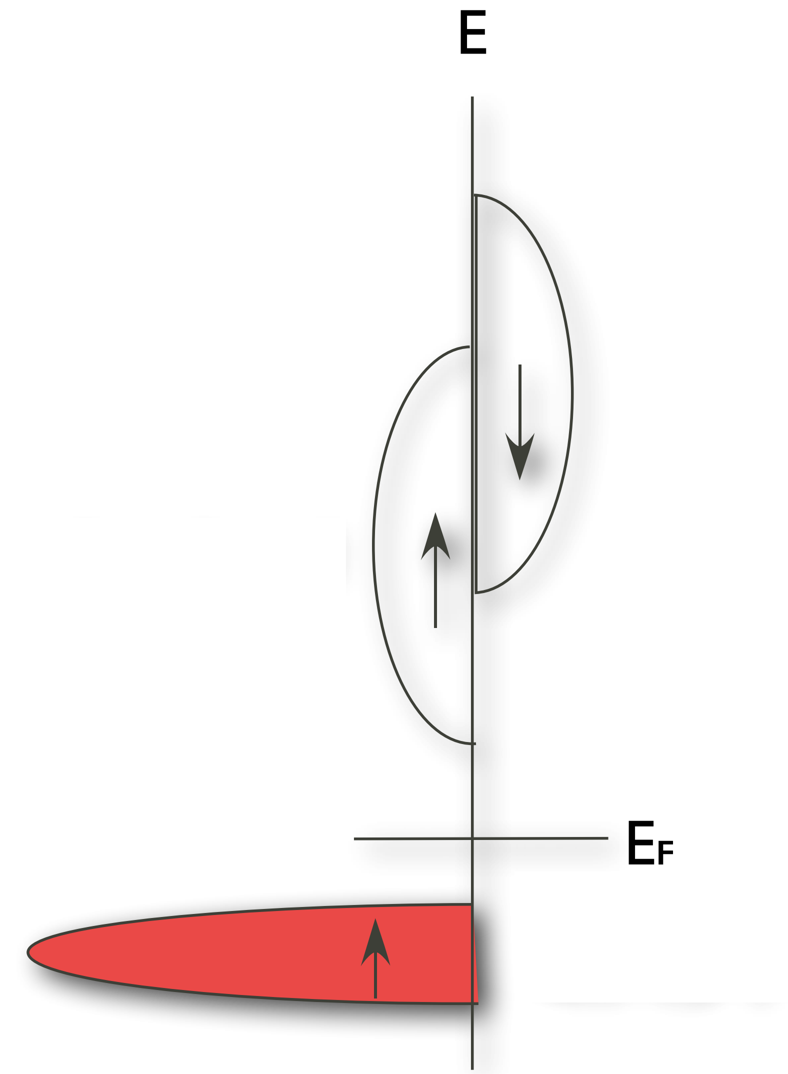
FI based superconducting spintronics

for quantum applications

DOS: FM vs FI







FM: Co, Fe, Ni,…

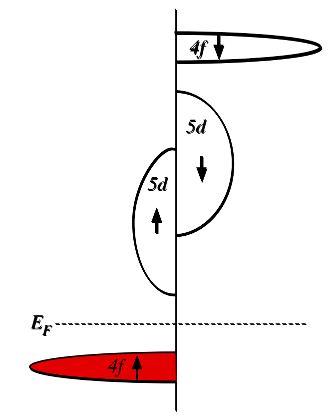
FI: Eu chalcogenides (EuO, EuSe),
Spinel ferrites($NiFe_2O_4$),
Oxides (LMO, LBMO, LCMO)…

Ferromagnetic insulator

Eu chalcogenides

Table 1. Spin-filter materials.

Material	Magnetic behaviour	T_C (K)	Moment (μ_B)	Structure, a (nm)	E_g (eV)	$2\Delta E_{ex}$ (eV)	P (%)
EuO	FM	69.3	7.9	Fcc, 0.514	1.12	0.54	29
EuS	FM	16.6	7.9	Fcc, 0.596	1.65	0.36	86
EuSe	AFM	4.6	7.9	Fcc, 0.619	1.80		100
$BiMnO_3$	FM	105	3.6	Perovskite			22
$NiFe_2O_4$	Ferri-M	850	2	Spinel	1.2		22
$CoFe_2O_4$	Ferri-M	796	3	Spinel	0.57		



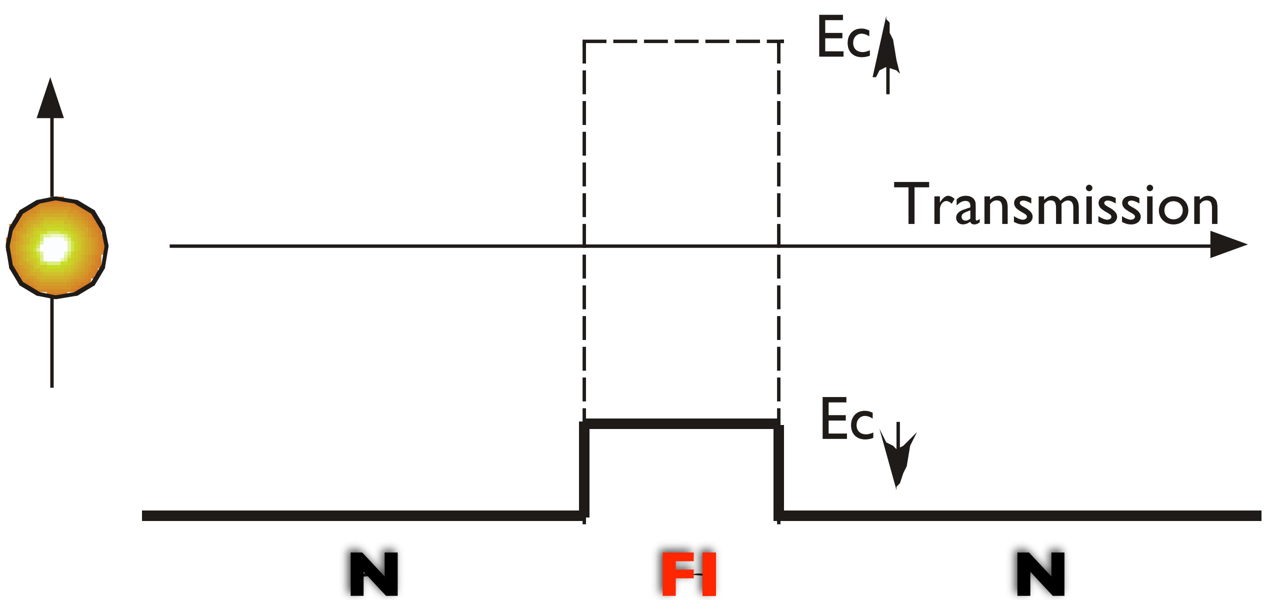
Moodera, Santos & Nagahama J. Phys.: Cond. Mat. 19(2007)165202

→Spin filter

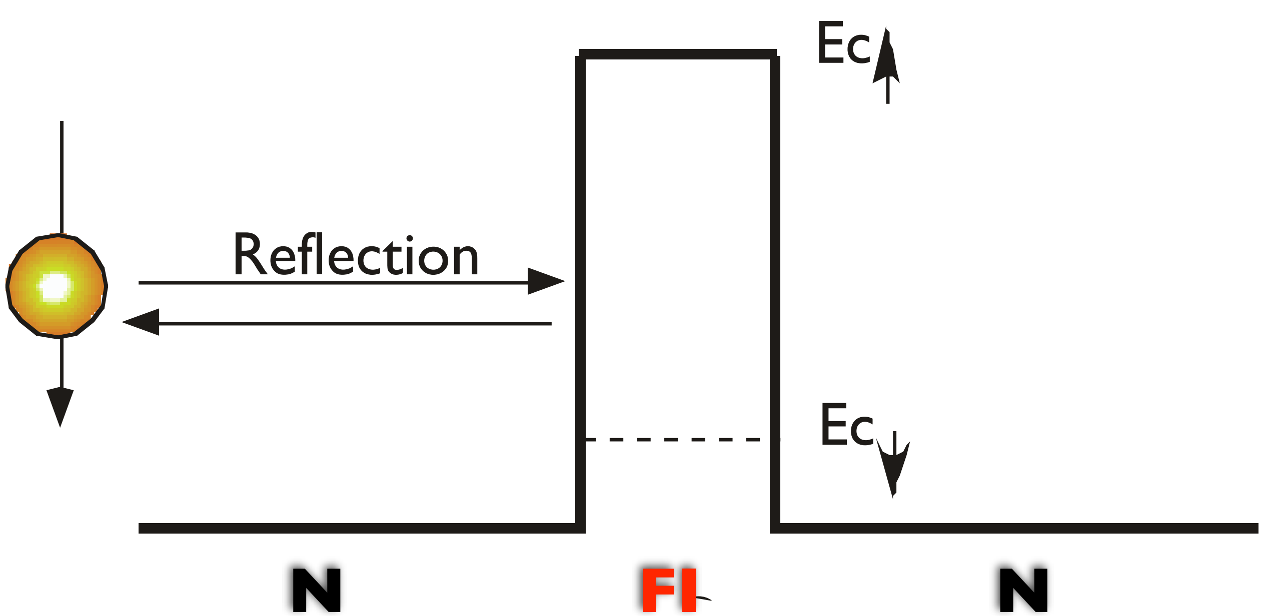
Spin filtering effect

Meservey & Tedrow, Phys. Rep. 238 (1994) 173

G. Printz, Phys. Today No.4 (1995)58.



Experiments:
Eu chalcogenides (EuO, EuSe),
Spinel ferrites($NiFe_2O_4$),
Oxides (LaMnO, LBMO, LCMO)...



Since the transmission probability depends exponentially on the barrier height, a highly-spin polarized current is generated by the barrier.

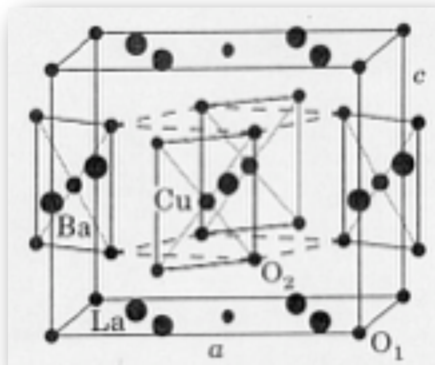
$$t_{\uparrow} \gg t_{\downarrow}$$

Spin-selective tunneling = Spin filter

Ferromagnetic Oxide

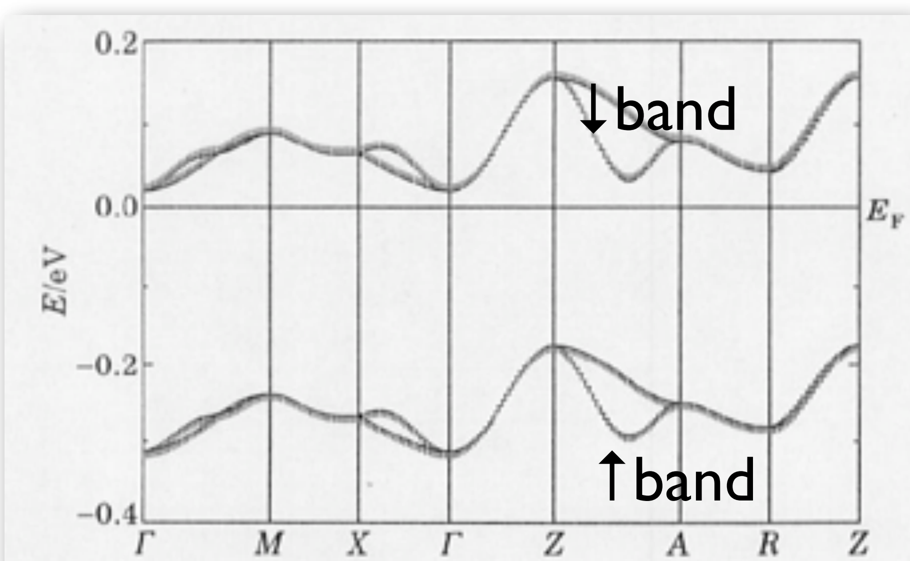
Oxide ferromagnet

La_2BaCuO_5



Mizuno et al, Nature 345 (1990) 788

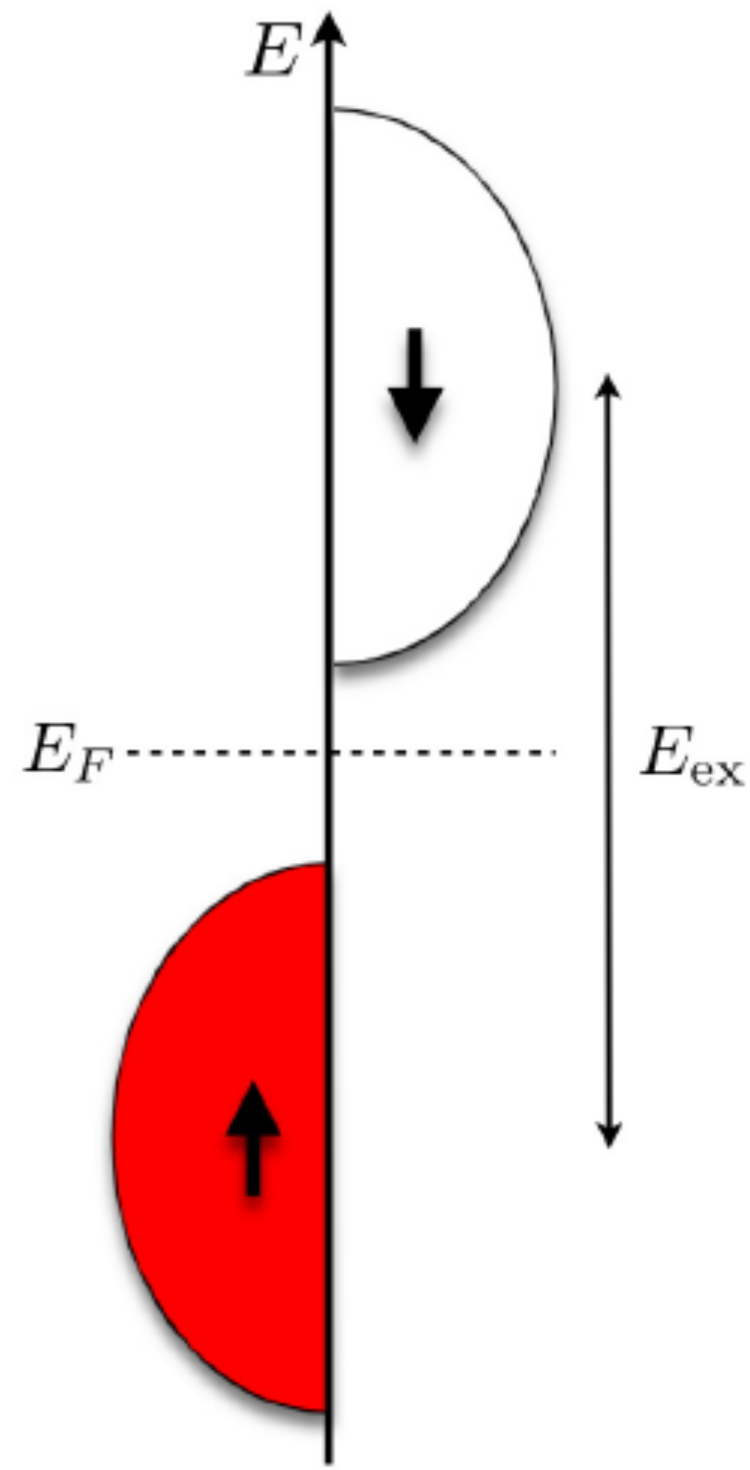
First principle LSDA+U calculation



Both bands (hybridized Cu-d & O-p) are split

$$V_{\rm ex} \sim 0.34{\rm eV}$$

Eyert et al, Europhys. Lett. 31 (1995) 385



FI based superconducting spintronics

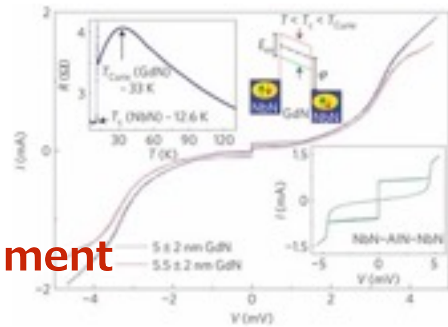
Spin-filter Josephson effect

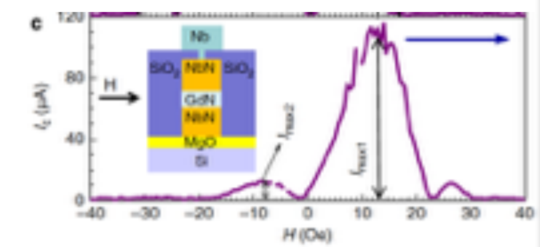
Kashiwaya & Tanaka Physica 274 (1997) 357

Kawabata & Asano, Int. J. Mod. Phys. **23** (2009) 4320

Senapati, Blamire & Barber, Nature Mat. 10 (2011) 849 Experiment

Pal, Barber, Robinson & Blamire, Nature Comm. 5(2014)3340 Experiment





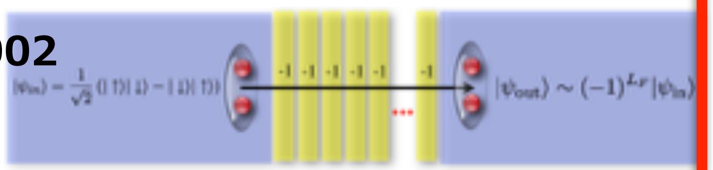
Atomic-scale 0-pi transition

Kawabata, Asano, Tanaka, Golubov & Kashiwaya, Phys. Rev. Lett. 104 (2010) 117002

Kawabata, Asano, Low Temp. Phys. 36 (2010) 915 REVIEW

Kawabata, Asano, Tanaka & Kashiwaya, Physica E 42 (2010) 1010

Kawabata, Tanaka, Golubov, Vasenko, Kashiwaya & Asano, Physica C 471 (2011) 1199

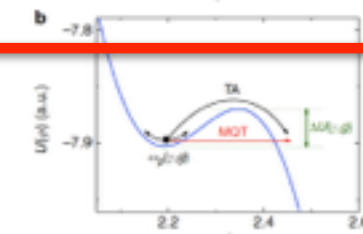


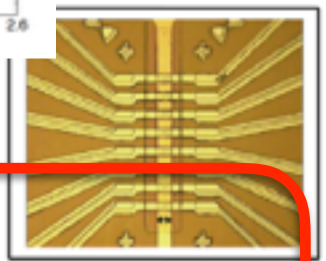
Macroscopic quantum tunneling (MQT)

Kawabata, Kashiwaya, Asano, Tanaka & Golubov, Phys. Rev. B 74 (2006) 180502(R)

Vasenko, Kawabata, Golubov, Kupriyanov, Lacroix, Bergeret & Hekking, Phys. Rev. B 84 (2011) 024524

Massarotti, Pal, Rotoli, Longobardi, Blamire & Tafuri, Nature Comm. 6 (2015) 8376 Experiment





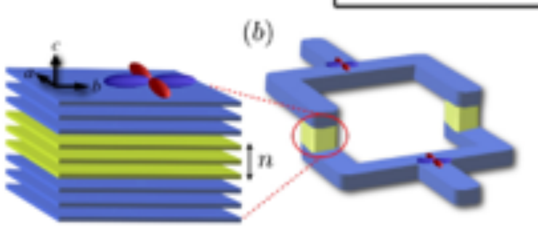
Qubit

Kawabata, Kashiwaya, Asano, Tanaka & Golubov, Phys. Rev. B 74 (2006) 180502(R)

Kawabata, Kashiwaya, Asano & Tanaka, Physica C 427-438 (2006) 136

Kawabata & Golubov, Physica E 40 (2007) 386

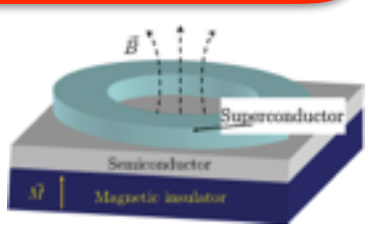
Kawabata, Asano, Tanaka, Kashiwaya & Golubov, Physica C 468 (2008) 701



Majorana fermion & Topological qubit (S/QSHI/FI junction)

Sau, Lutchyn, Tewari & Das Sarma, Phys. Rev. Lett. 104 (2010) 040502

Alicia, Repts. Prog. Phys. 75 (2012) 076501 **REVIEW**



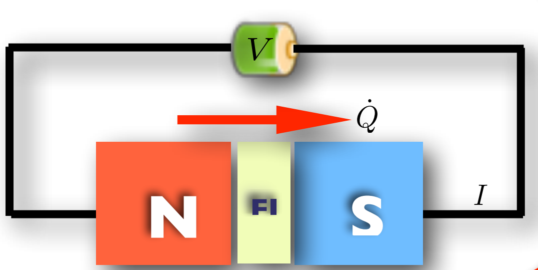
Electron refrigerator & Heat device

Kawabata, Ozaeta, Vasenko, Hekking & Bergeret, Appl. Phys. Lett. 103 (2013) 032602

Kawabata, Vasenko, Ozaeta, Bergeret, & Hekking, JMMM 383 (2015) 157

Linder & Bathen, Phys. Rev. B 93 (2016) 224509

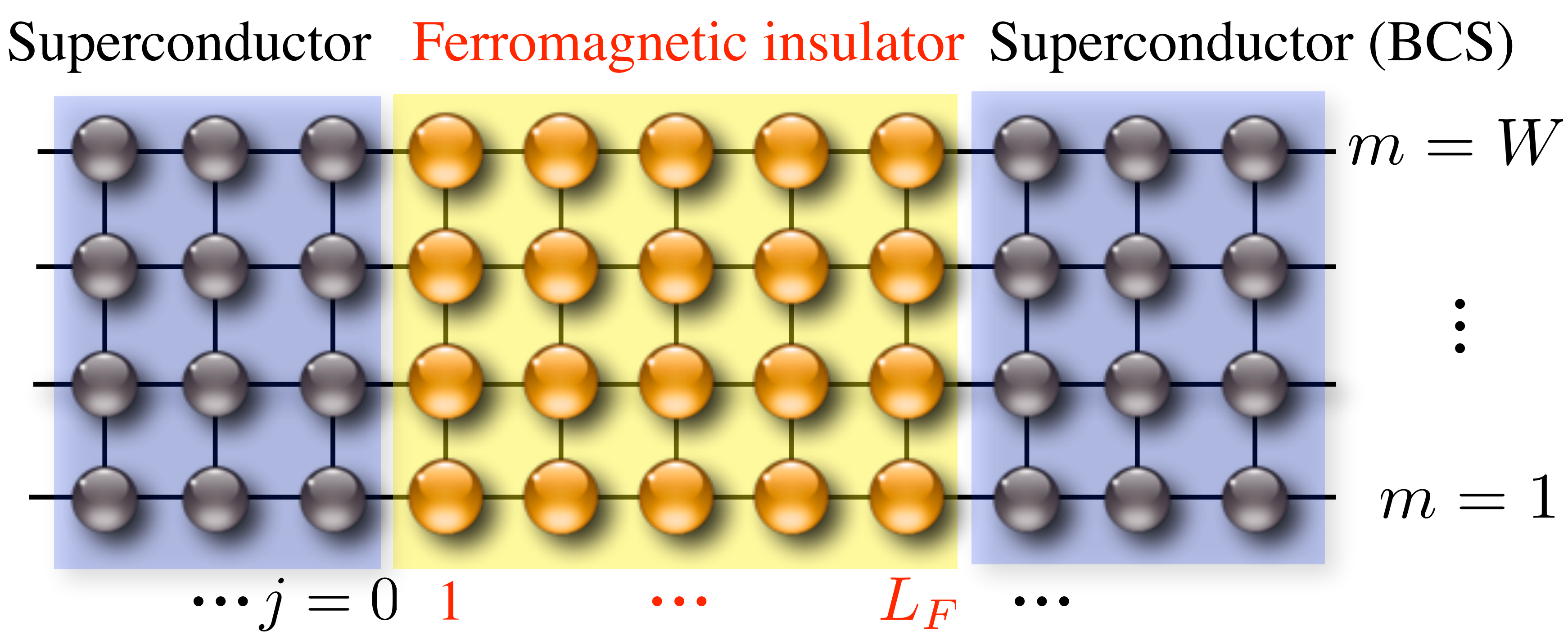
Giazotto et al., Appl. Phys. Lett. 105 (2016) 062602



Josephson effect through FIs

Atomic scale 0-pi transition

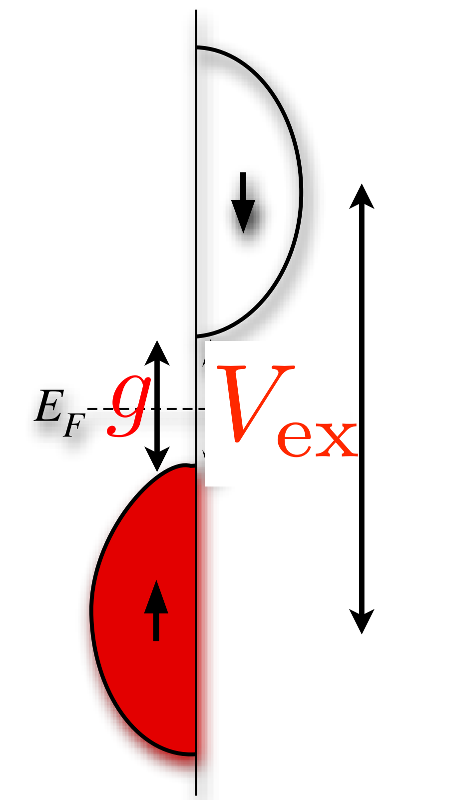
Tight binding BdG calculation



$$\mathcal{H}_{\rm BCS} = \frac{1}{2}\sum_{\boldsymbol{r},\boldsymbol{r}'\in {\rm S}} \left[\tilde{c}_{\boldsymbol{r}}^{\dagger}\, \hat{h}_{\boldsymbol{r},\boldsymbol{r}'}\, \tilde{c}_{\boldsymbol{r}'} - \overline{\tilde{c}_{\boldsymbol{r}}}\, \hat{h}^{*}_{\boldsymbol{r},\boldsymbol{r}'}\, \overline{\tilde{c}_{\boldsymbol{r}'}^{\dagger}}\right] + \frac{1}{2}\sum_{\boldsymbol{r}\in {\rm S}} \left[\tilde{c}_{\boldsymbol{r}}^{\dagger}\, \hat{\Delta}\, \overline{\tilde{c}_{\boldsymbol{r}}^{\dagger}} - \overline{\tilde{c}_{\boldsymbol{r}}}\, \hat{\Delta}^{*}\, \tilde{c}_{\boldsymbol{r}}\right].$$

$$H = -t_n \sum_{r,r',\sigma} c^{\dagger}_{r,\sigma} c_{r',\sigma} + \sum_{r} (4t_n - \mu_n) c^{\dagger}_{r,\uparrow} c_{r,\uparrow} + \sum_{r} (4t_n - \mu_n + V_{ex}) c^{\dagger}_{r,\downarrow} c_{r,\downarrow}$$

Exchange energy



Bogolibov de-Gennes eq.

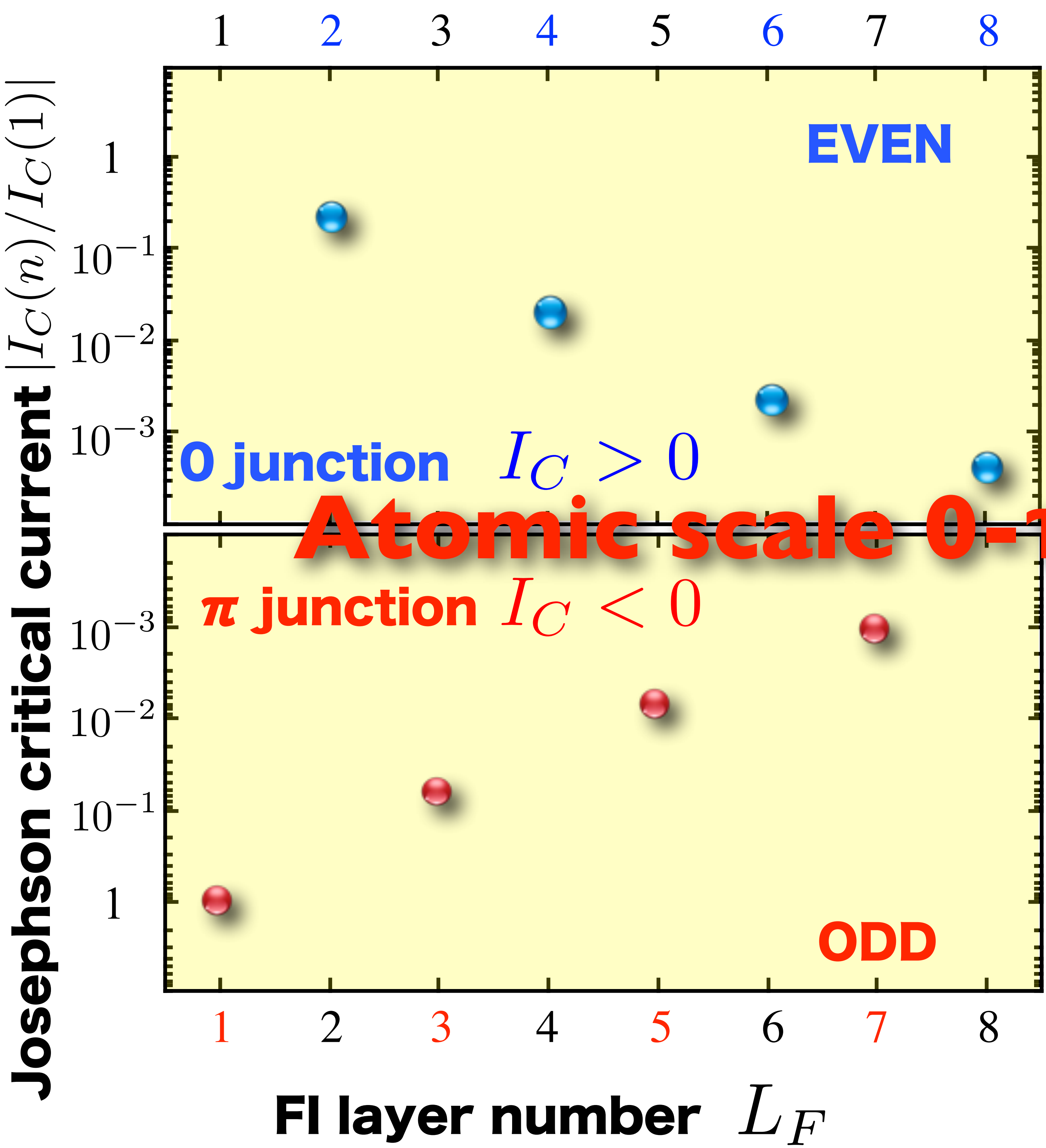
$\varepsilon_n(\phi)$ Andreev levels

$g=V_{ex}-8t$: Band gap

Josephson current $$I_J(\phi) = \frac{2e}{\hbar}\sum_n \frac{\partial \varepsilon_n(\phi)}{\partial \phi} f(\varepsilon_n)$$

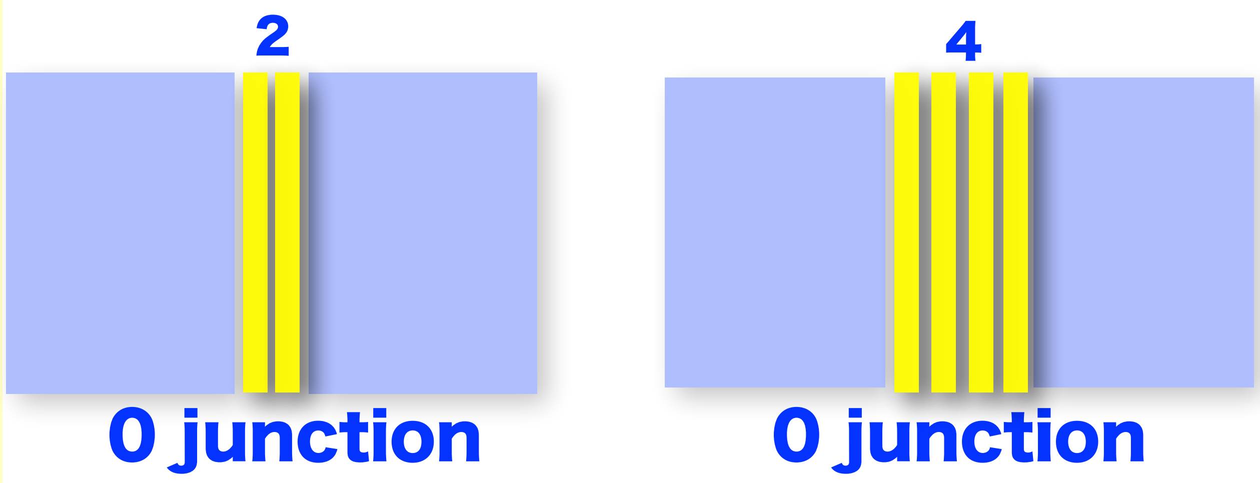
Josephson current

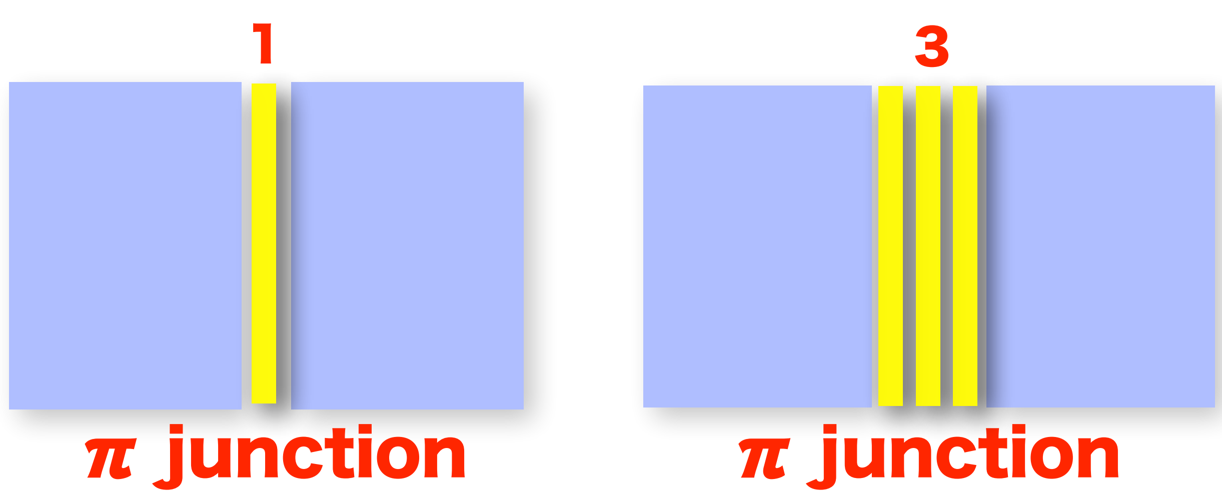
$$I_J = I_C \sin\phi$$



Atomic scale 0-π transition

FI layer number = EVEN



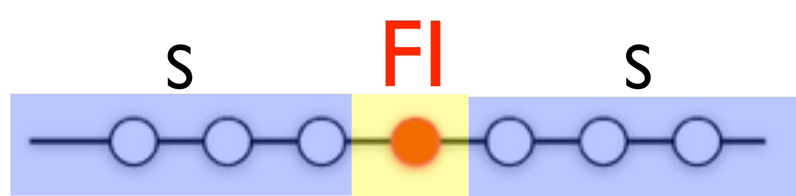


FI layer number = ODD

Kawabata et al., Phys. Rev. Lett. 104(2010)117002

Origin of π

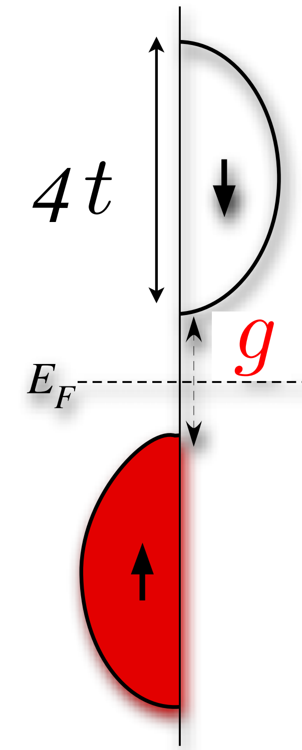
$I_C \propto T_\downarrow^* T_\uparrow$ for the tunneling limit $g \gg t$



Transmission coefficient of an electron through FI barrier

$$T_\uparrow \sim -\frac{t}{g} < 0$$

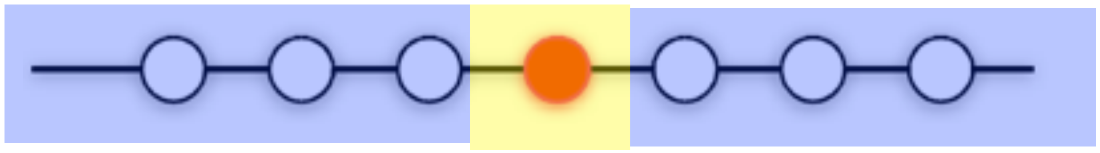
$$T_\downarrow \sim +\frac{t}{g} > 0$$



∴ Ic<0

∴π-junction

Origin of π



$\uparrow$ electron $|\uparrow\rangle \dashrightarrow -|\uparrow\rangle$

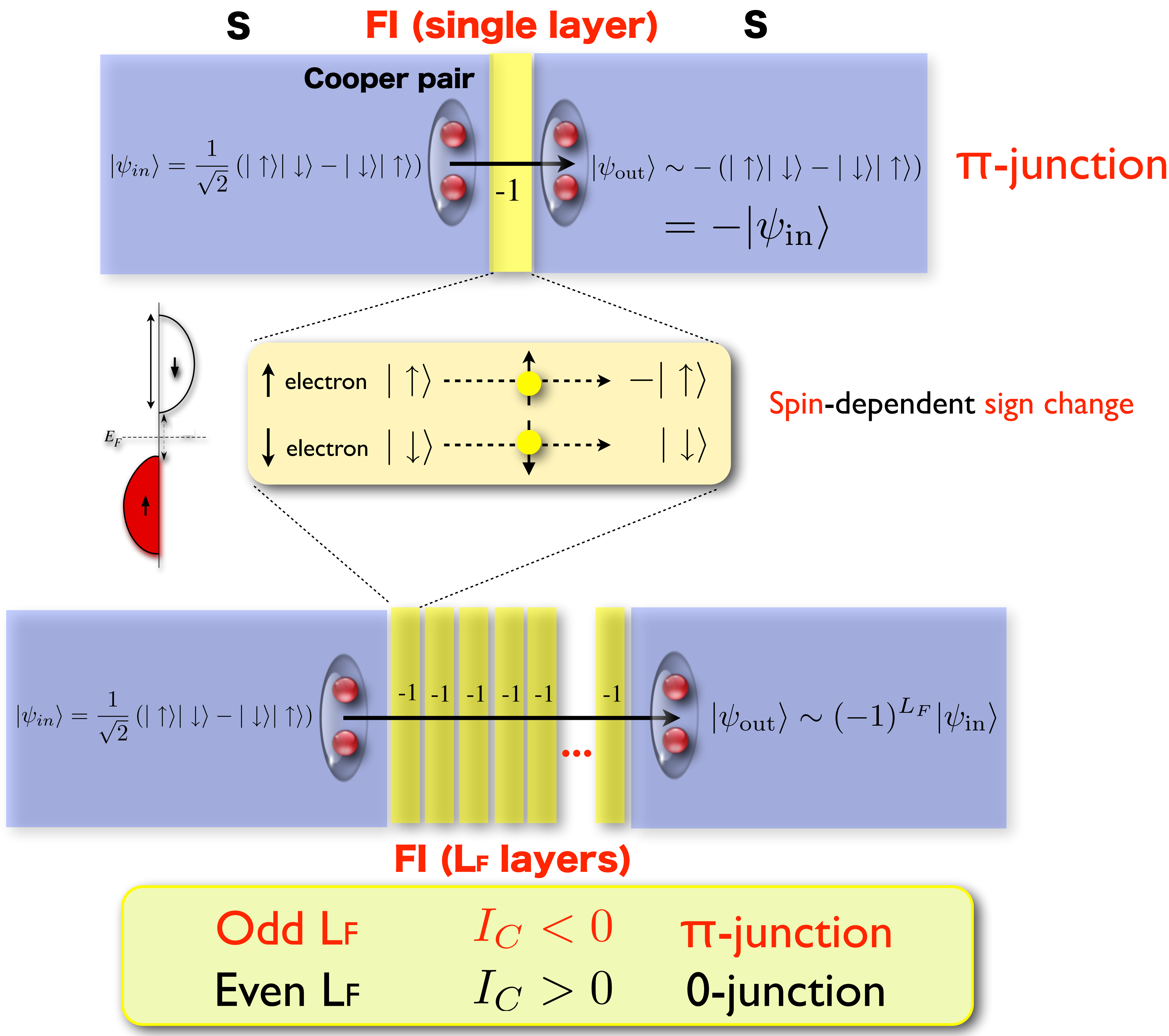
$\downarrow$ electron $|\downarrow\rangle \dashrightarrow |\downarrow\rangle$

Spin-dependent sign change

Cuevas & Fogelstrom PRB 64(01)104502
Zhao, et al., PRB 70(04)124510
Kawabata et al., PRL104(10)117002

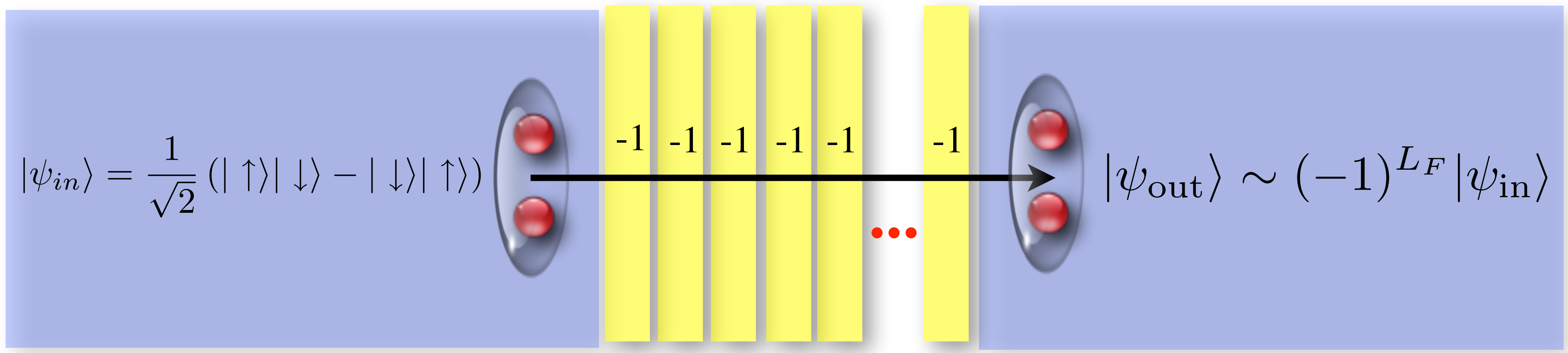
Cooper pair $|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \dashrightarrow -(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$

π junction



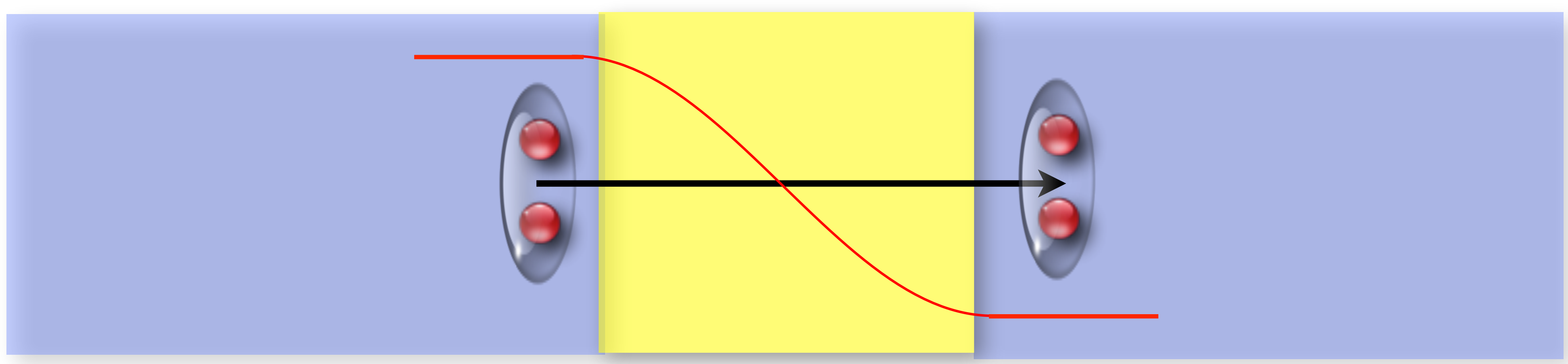
S
FI (single layer)
S
Cooper pair
$|\psi_{in}\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle|\downarrow\rangle - |\downarrow\rangle|\uparrow\rangle)$
-1
$|\psi_{\text{out}}\rangle \sim -(|\uparrow\rangle|\downarrow\rangle - |\downarrow\rangle|\uparrow\rangle)$
$= -|\psi_{\text{in}}\rangle$
π-junction
E_F
↑ electron $|\uparrow\rangle$ → $-|\uparrow\rangle$
↓ electron $|\downarrow\rangle$ → $|\downarrow\rangle$
Spin-dependent sign change
$|\psi_{in}\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle|\downarrow\rangle - |\downarrow\rangle|\uparrow\rangle)$
-1 -1 -1 -1 -1 -1
...
$|\psi_{\text{out}}\rangle \sim (-1)^{L_F}|\psi_{\text{in}}\rangle$
FI (L_F layers)
Odd L_F $I_C < 0$ π-junction
Even L_F $I_C > 0$ 0-junction

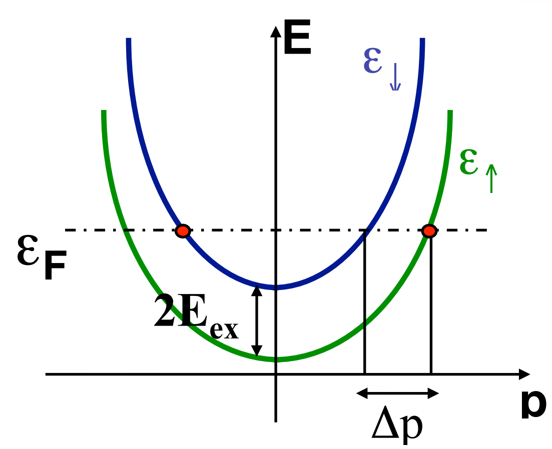
FI



Spin-dependent phase shift

FM

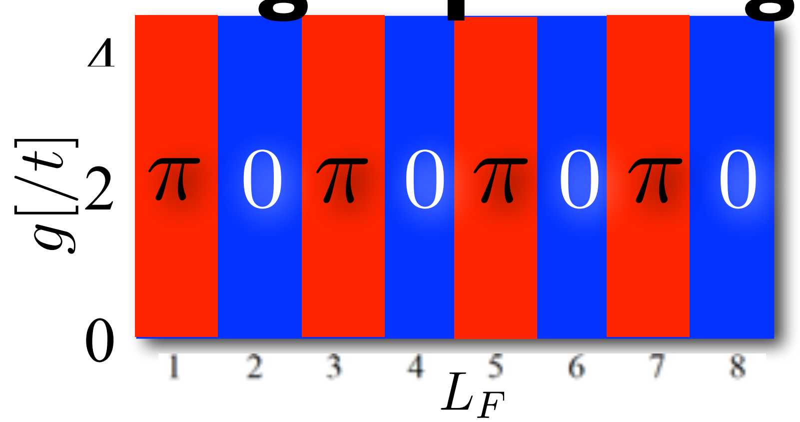




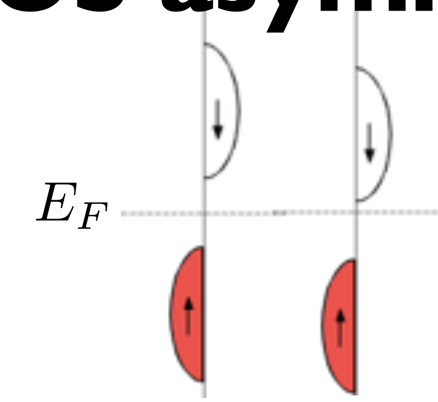
Finite center of mass momentum due to the exchange splitting

Robustness of the atomic scale 0-π transition

Exchange splitting: g

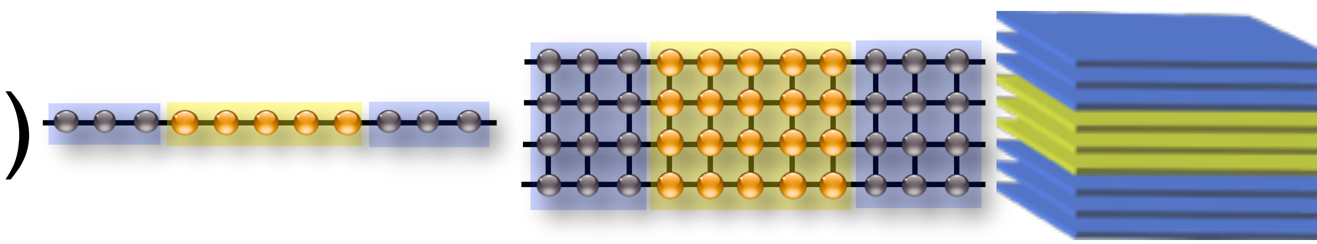


DOS asymmetry

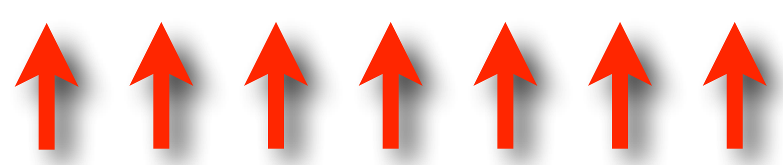


Temperature: T

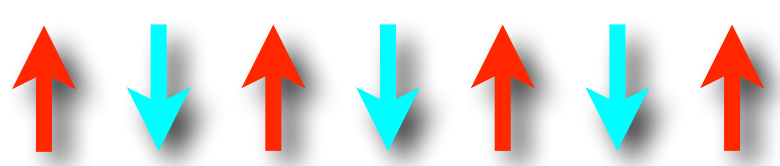
Dimensionality (1D, 2D, & 3D)



Magnetization configuration (Colinear)



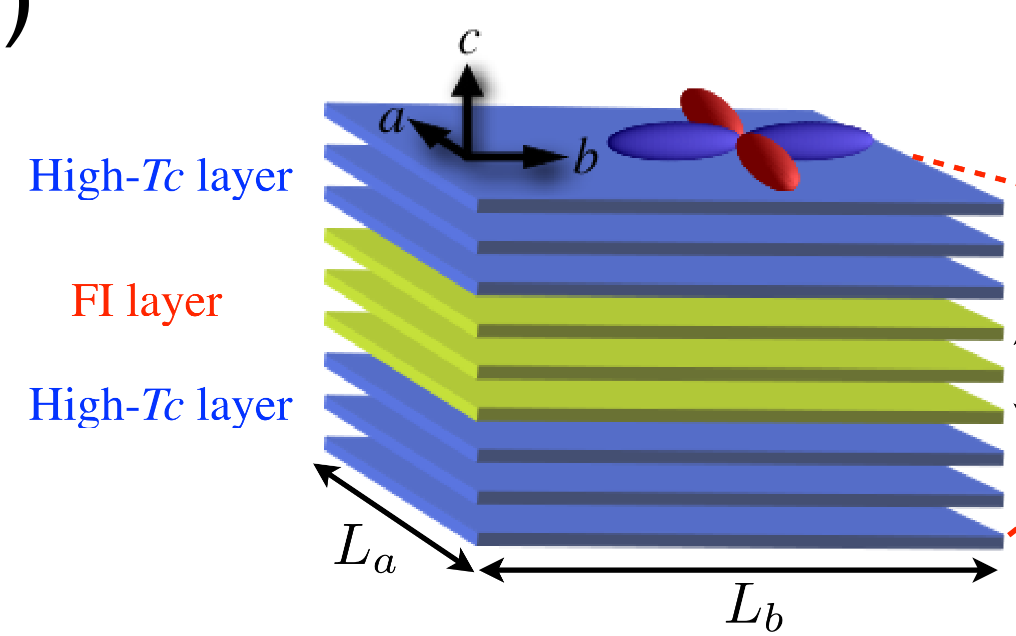
Ferro (uniform)



Anti-ferro

Order parameter symmetry

s-wave JJ & d-wave c-axis JJ



Kawabata, Asano, Tanaka, Golubov & Kashiwaya, Phys. Rev. Lett. 104 (2010) 117002

Kawabata & Asano, Low Temp. Phys. 36 (2010) 915

Kawabata, Asano, Tanaka & Kashiwaya, Physica E 42 (2010) 1010

Kawabata, Tanaka, Golubov, Vasenko, Kashiwaya & Asano, Physica C 471 (2011) 1199

Nakamura, Souma, Ogawa & Kawabata, Physics Procedia 27 (2012) 308

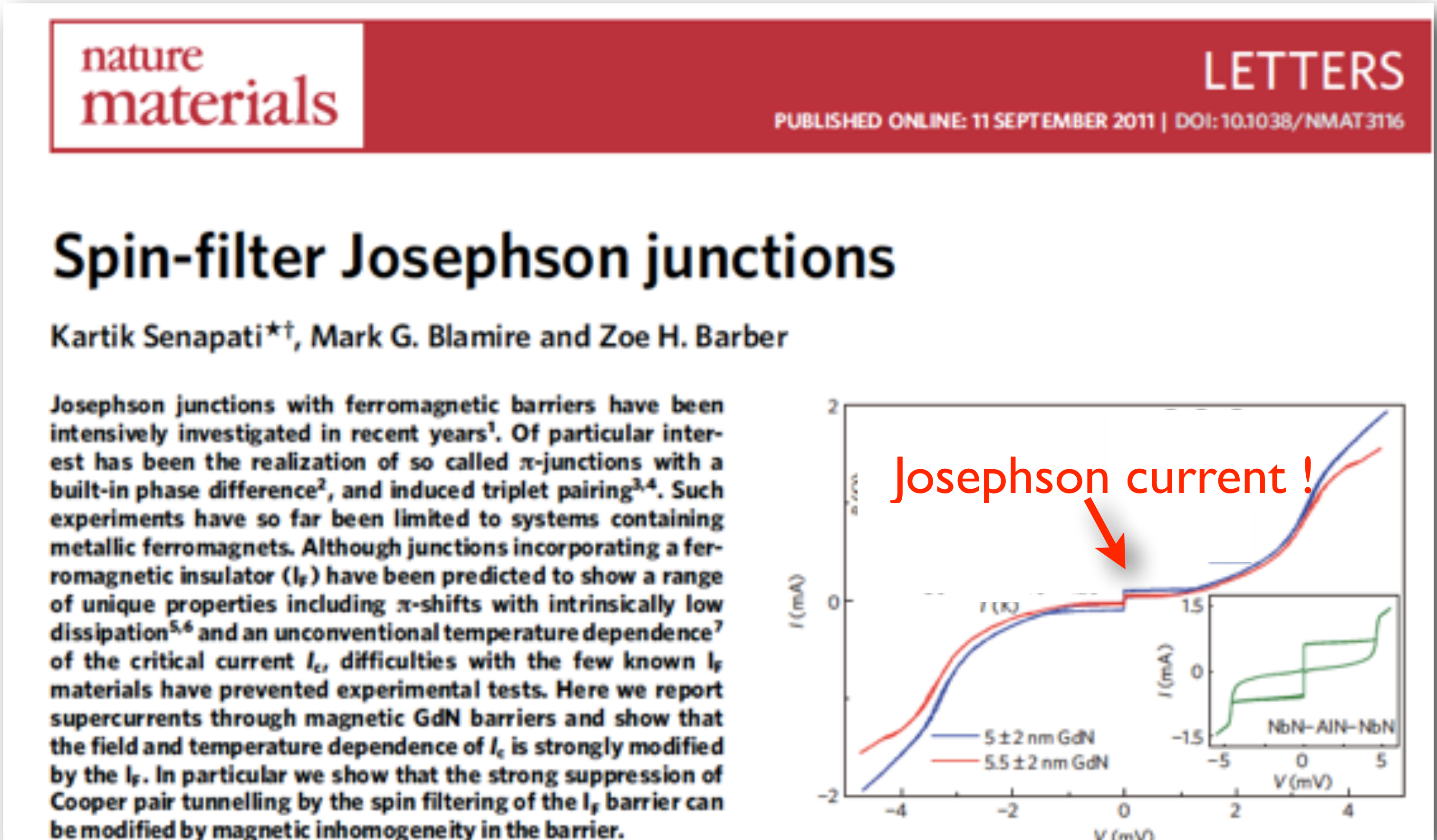
Experiments

Experiments

NbN/Spin-filter(GdN)/NbN

Spin-filter Josephson effect

Senapati, Blamire & Barber, Nature Mat. 10 (2011) 849



nature materials

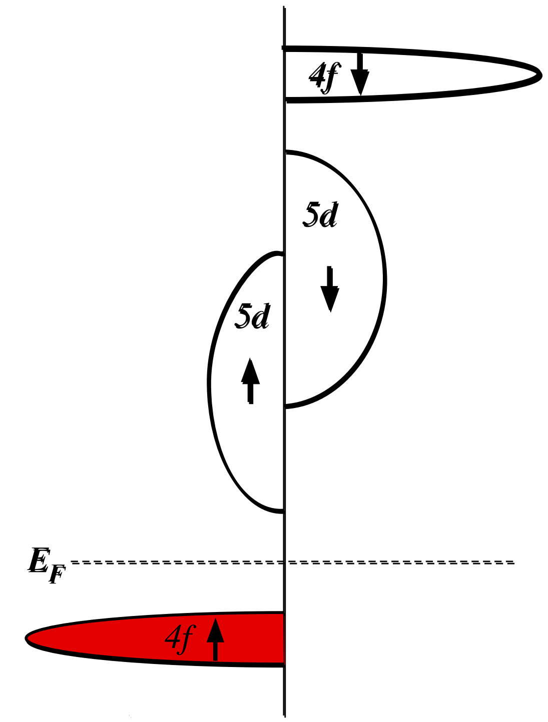
LETTERS

PUBLISHED ONLINE: 11 SEPTEMBER 2011 | DOI: 10.1038/NMAT3116

Spin-filter Josephson junctions

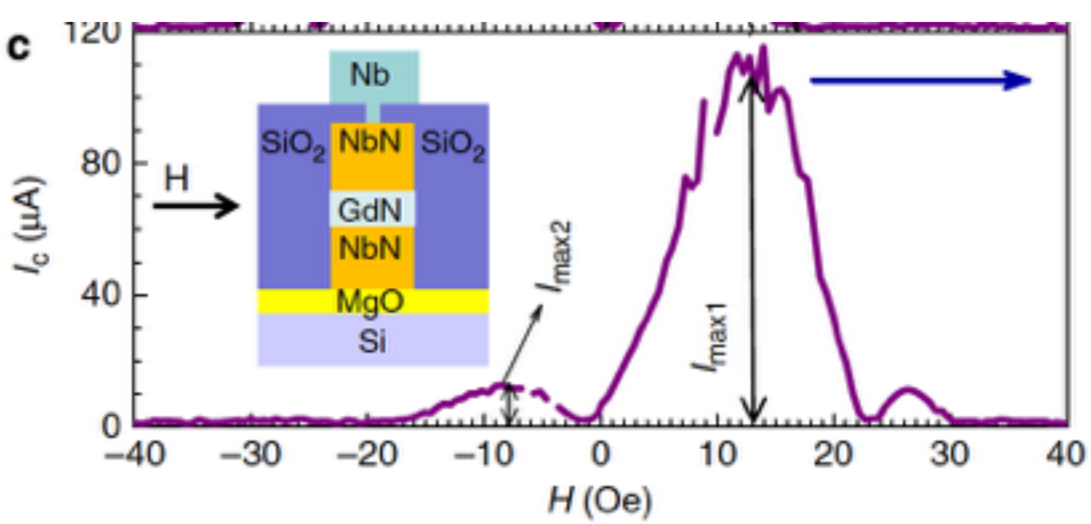
Kartik Senapati*†, Mark G. Blamire and Zoe H. Barber

Josephson junctions with ferromagnetic barriers have been intensively investigated in recent years[1]. Of particular interest has been the realization of so called π-junctions with a built-in phase difference[2], and induced triplet pairing[3,4]. Such experiments have so far been limited to systems containing metallic ferromagnets. Although junctions incorporating a ferromagnetic insulator (I_F) have been predicted to show a range of unique properties including π-shifts with intrinsically low dissipation[5,6] and an unconventional temperature dependence[7] of the critical current I_c, difficulties with the few known I_F materials have prevented experimental tests. Here we report supercurrents through magnetic GdN barriers and show that the field and temperature dependence of I_c is strongly modified by the I_F. In particular we show that the strong suppression of Cooper pair tunnelling by the spin filtering of the I_F barrier can be modified by magnetic inhomogeneity in the barrier.



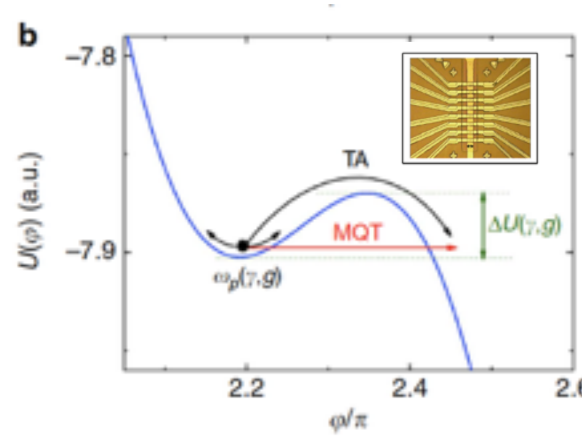
Fraunhofer pattern & Pure 2nd harmonics

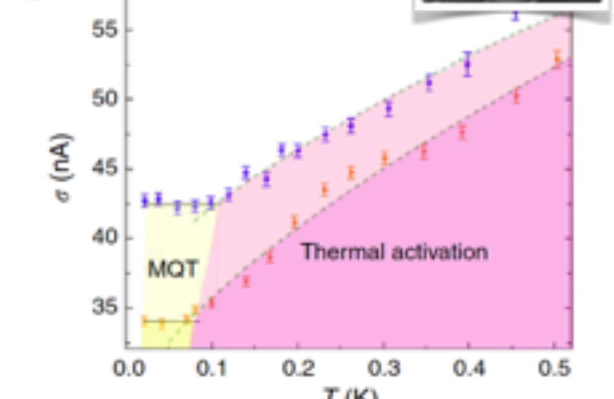
Pal, Barber, Robinson & Blamire, Nature Comm. 5(2014)3340



Macroscopic quantum tunneling (MQT)

Massarotti, Pal, Rotoli, Longobardi, Blamire & Tafuri, Nature Comm. 6 (2015) 8376





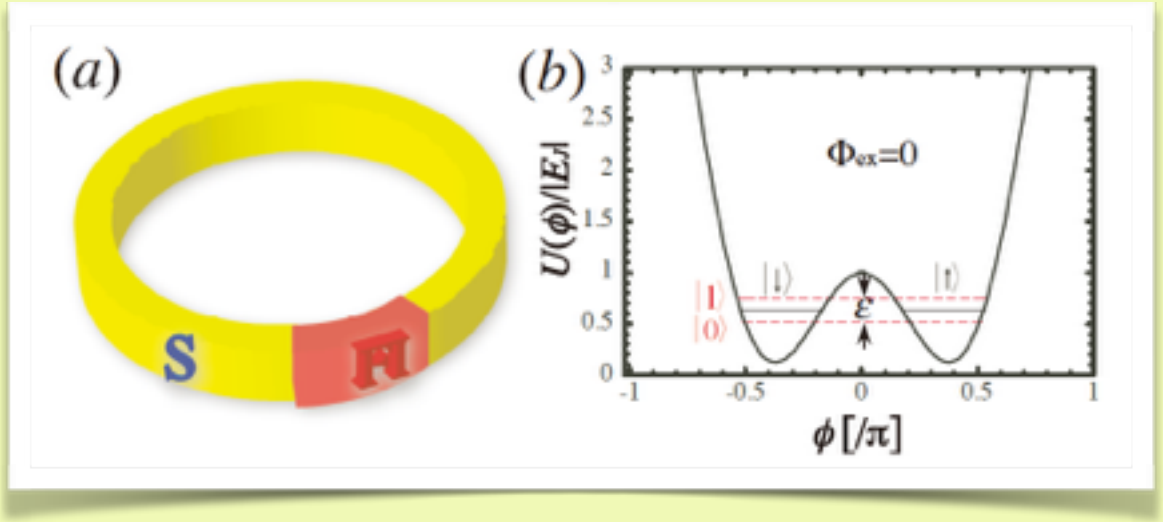
Theory: Kawabata, et al., Phys. Rev. B 74 (2006) 180502(R)

Applications

Quantum application

Coherent π-qubit

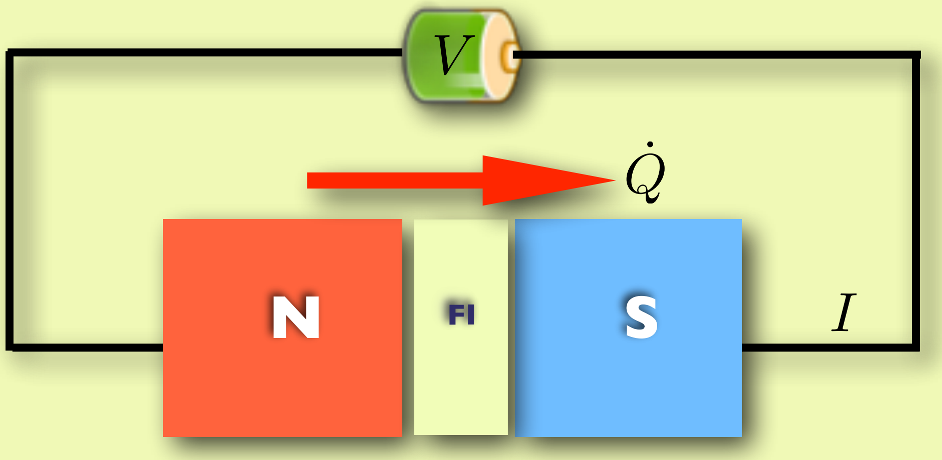
Kawabata, Kashiwaya, Asano, Tanaka & Golubov, Phys. Rev. B 74 (2006) 180502(R)



Highly coherent flux qubit

Electron refrigerator

Kawabata, Ozaeta, Vasenko, Hekking & Bergeret, Appl. Phys. Lett. 103 (2013) 032602



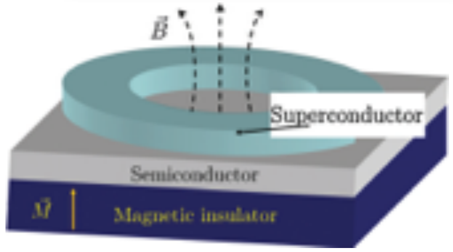
Highly efficient cooler
for quantum devices

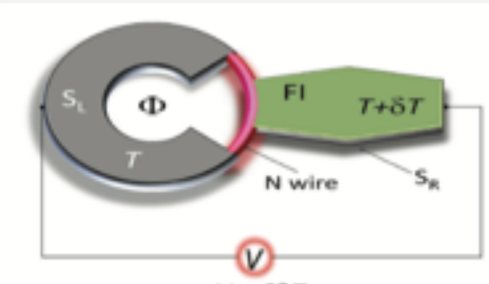
Other applications:

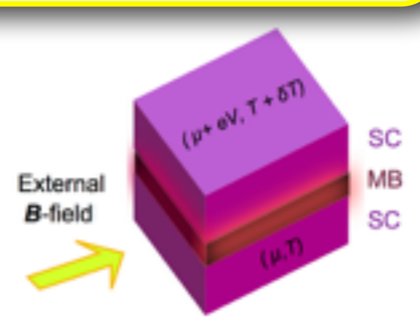
Topological qubit: Sau, Lutchyn, Tewari & Das Sarma, Phys. Rev. Lett. 104 (2010) 040502

Heat transistor: Giazotto et al., Appl. Phys. Lett. 105 (2016) 062602

Spin caloritronics: Linder & Bathen, Phys. Rev. B 93 (2016) 224509



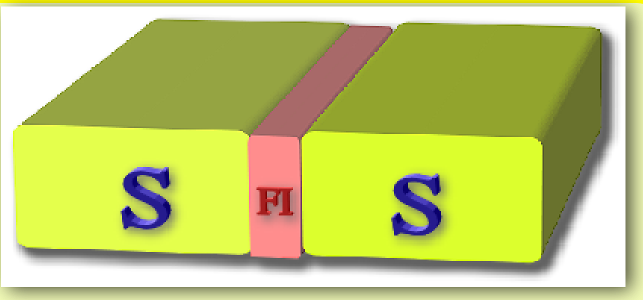




Summary

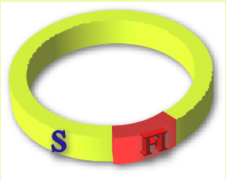
Superconductor spintronics based on ferromagnetic insulators

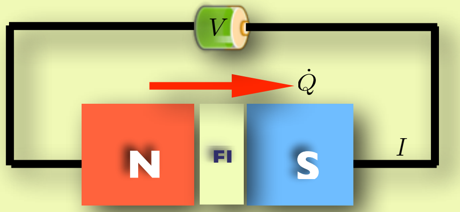
Josephson effect : Atomic scale 0-π transition
Macroscopic Quantum Tunneling



Kawabata, Asano, Tanaka, Golubov & Kashiwaya, Phys. Rev. Lett. 104 (2010) 117002
REVIEW: Kawabata & Asano, Low Temp. Phys. 36 (2010) 915

Applications : Coherent qubit & Efficient electron refrigerator





Kawabata, Kashiwaya, Asano, Tanaka & Golubov, Phys. Rev. B 74 (2006) 180502(R)
Kawabata, Ozaeta, Vasenko, Hekking & Bergeret, Appl. Phys. Lett. 103 (2013) 032602
Kawabata, Vasenko, Ozaeta, Bergeret, & Hekking, JMMM 383 (2015) 157

Ferromagnetic-insulator based superconducting-spintronics would be useful for future QUANTUM & COOLING businesses.