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Max Planck Institute for Solid State Research

Novel Proximity and Josephson effect with triplet superconductors

Dirk Manske

SPICE (Castle Waldthausen), September 27th, 2017

- Wei Chen (ETH Zürich)
- Gaetano Annunziata (MPI Stuttgart)
- Damien Terrade (MPI Stuttgart)
- Antony Epp (UBC Vancouver)
- Philip Brydon (U Otago, New Zealand)

- Manfred Sigrist + team (ETH Zurich)
- Mario Cuoco + team (CNR-SPIN Salerno)
- Yoshi Maeno + team (Kyoto)
- Tae Won Noh + team (IBS and SNU, Korea)

Motivation

Spin-Triplet Superconductors (TSC)

Spin-Singlet

$$\Delta_0 = V_{\text{eff}} \sum_k \langle c_{-k\downarrow} c_{k\uparrow} \rangle$$

Spin-Triplet

$$\hat{\Delta}(k) = \begin{pmatrix} \Delta_{\uparrow\uparrow}(k) & \Delta_{\uparrow\downarrow}(k) \\ \Delta_{\downarrow\uparrow}(k) & \Delta_{\downarrow\downarrow}(k) \end{pmatrix} = \begin{pmatrix} -d_x(k) + id_y(k) & d_z + \Delta_0 \\ d_z - \Delta_0 & d_x + id_y \end{pmatrix}$$

Spin-Singlet

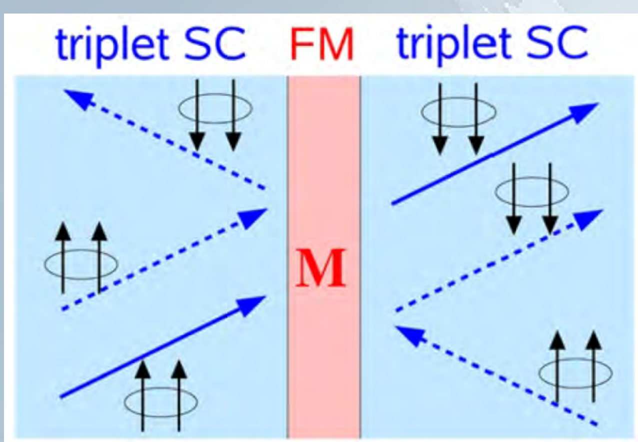
$$\Delta(k) = \Delta_0$$
$$\Delta(k) = \Delta_0 \cdot (\cos k_x + \cos k_y)$$

Spin-Triplet

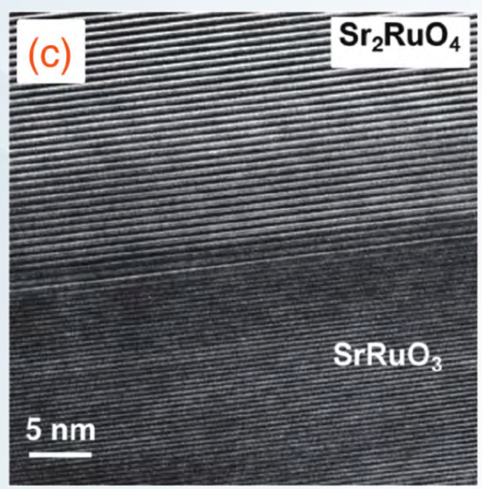
$$\Delta(k) = \Delta_0 \cdot \sin k_x$$
$$\Delta(k) = \Delta_0 \cdot \sin k_y$$
$$\Delta(k) = \Delta_0 \cdot (\sin k_x + i \cdot \sin k_y)$$

TFT Josephson junction

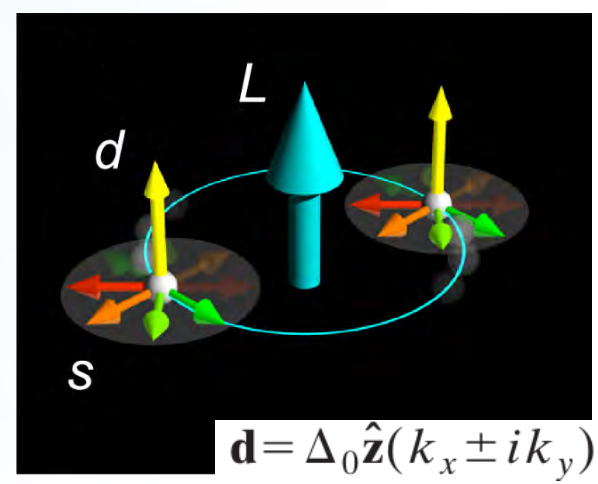
Sr_2RuO_4



D.M. et al., PRL 2006, PRL 2009, PRL 2010, PRL 2013



M.S. Anwar *et al.*, Applied Phys. Express **8,** 015502 (2015)



Y. Maeno *et al.*, J. Phys. Soc. Japan **81,** 011009 (2012)

Outline

- Introduction: what is the d-vector?

  Theorie: the story begins

- 3 case studies of Josephson junctions:
  - Triplet–Ferromagnet–Triplet (T-F-T)
  - Triplet–Ferromagnet–Singlet (T-F-S)
  - NoncentrosymmetricSC–Insulator–Singlet (NCS-I-S)

- Interface effects: good or bad?

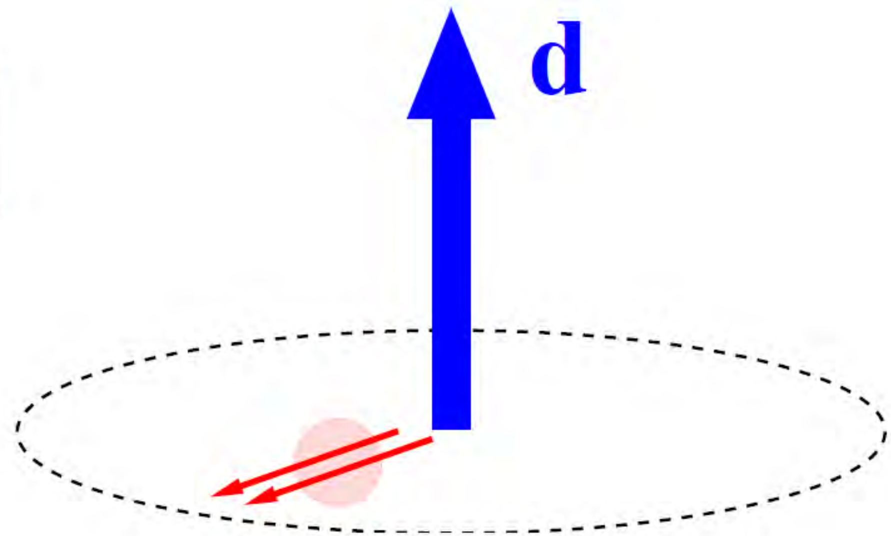
- Experimental situation: the story begins

- Summary

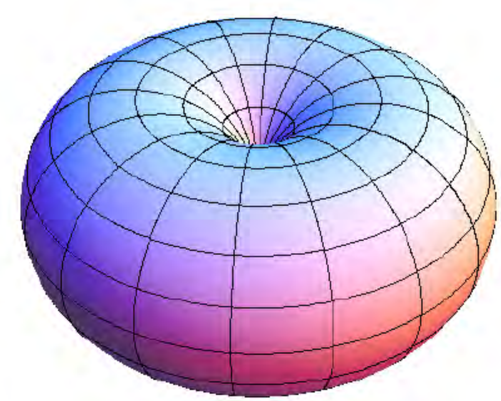
Triplet Superconductivity: Theory reminder

- gap is a spin matrix and written in terms of the ***d***-vector:

$$\Delta(\mathbf{k}) = \begin{bmatrix} -d_x + id_y & d_z \\ d_z & d_x + id_y \end{bmatrix} = -i(\boldsymbol{d} \cdot \hat{\boldsymbol{\sigma}})\hat{\sigma}_y$$



- the spin of the Cooper pair lies in the plane perpendicular to ***d***
- equal spin pairing if ***d*** vector points along same axis for all ***k***



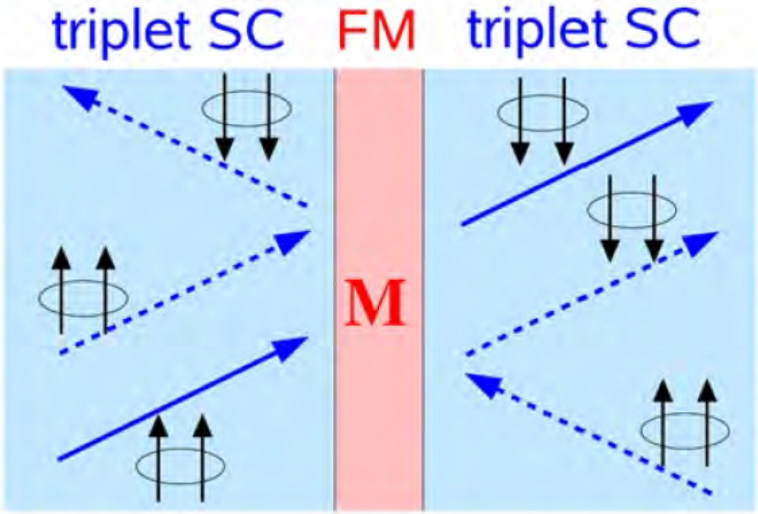
Balian-Werthamer State

$$\boldsymbol{d}_{BW} = \Delta_0(\hat{\boldsymbol{x}}k_x + \hat{\boldsymbol{y}}k_y + \hat{\boldsymbol{z}}k_z)$$

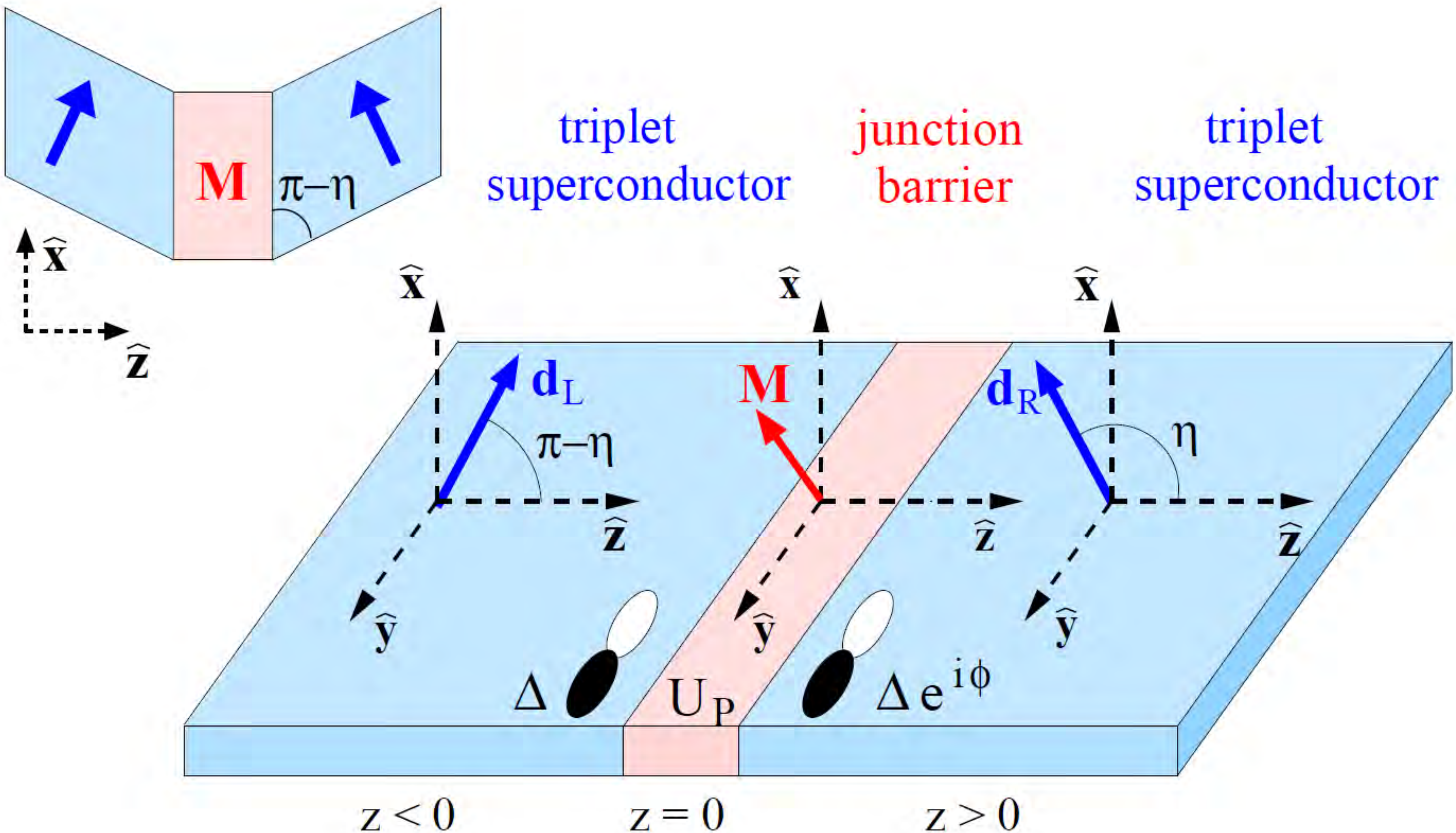
Chiral State $\boldsymbol{d}_{\pm} = \Delta_0\hat{\boldsymbol{z}}(k_x \pm ik_y)$

Triplet-Ferromagnet-Triplet Josephson Junction

- new degree of freedom in Josephson junction physics: the spin of the Cooper pair
- can be accessed using a magnetically-active tunneling barrier to couple to the Cooper pair spin
- Many exciting new discoveries:
  - current sign controlled by orientation of the barrier moment
  - current switches
  - interplay of charge and magnetic scattering
  - non-analyticities in the critical current
  - Josephson spin current
  - fractional flux quanta
  - functional tunneling barriers
- candidate junction material: Sr_2RuO_4



The TFT Junction



$\boldsymbol{d}_L \times \boldsymbol{d}_R \neq 0 \Rightarrow$ intrinsic breaking of time-reversal-symmetry

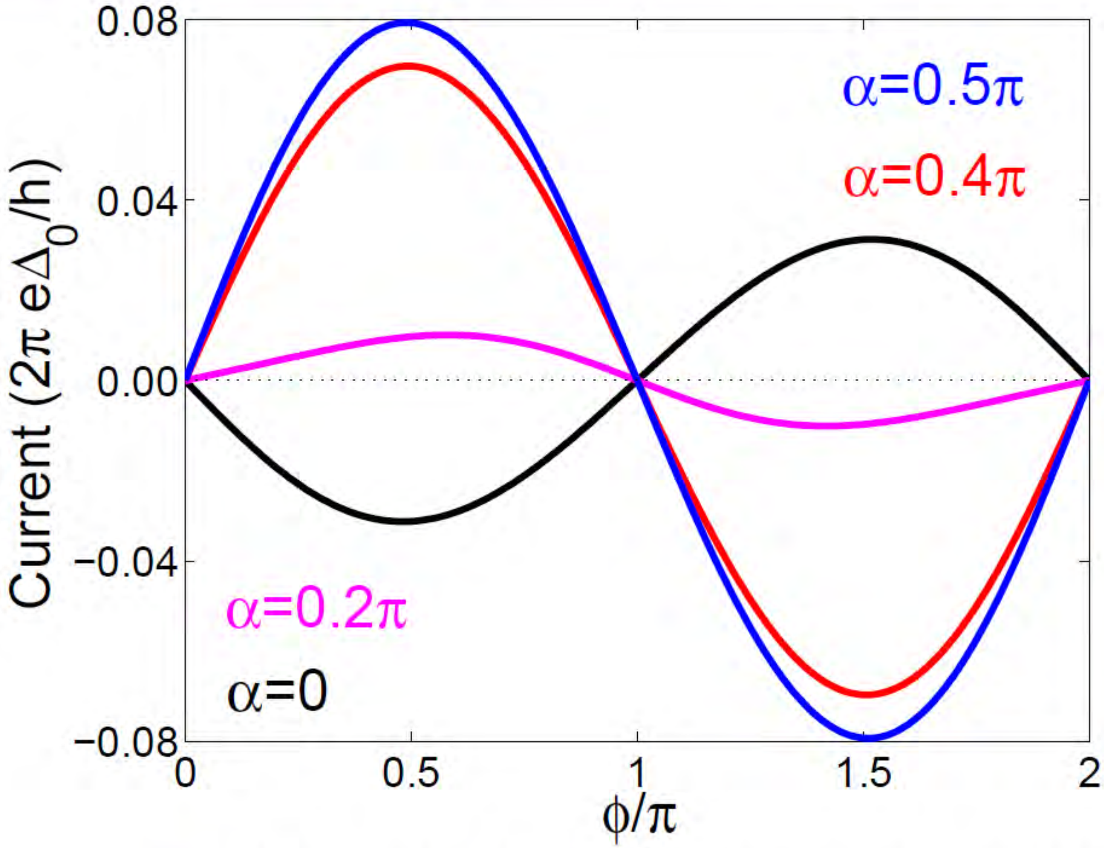
Calculating the current

- superconductors described by weak-coupling theory - use (a) tunneling Hamiltonian, or (b) Bogoliubov-de Gennes equations, or
- (c) calculate the quasiclassical Greens function $\mathbb{G}(\mathbf{r},\tau;\mathbf{r}',\tau')$ for scattering across the junction, which is a 4×4 matrix in Nambu-spin space.
- equilibrium Josephson charge and spin-μ currents are then calculated:

$$I_J^c = -i\frac{e\hbar}{4m}\lim_{z'\to z=0}\left(\frac{\partial}{\partial z'}-\frac{\partial}{\partial z}\right)\frac{1}{\beta}\sum_n\int d\Omega \mathrm{Tr}\left\{\mathbb{G}(\mathbf{r},\mathbf{r}',i\omega_n)\right\}$$

$$I_{J,\mu}^s = i\frac{\hbar^2}{8m}\lim_{z'\to z=0}\left(\frac{\partial}{\partial z'}-\frac{\partial}{\partial z}\right)\frac{1}{\beta}\sum_n\int d\Omega \mathrm{Tr}\left\{\mathbb{G}(\mathbf{r},\mathbf{r}',i\omega_n)\begin{bmatrix}\hat{\sigma}_\mu & \hat{0}\\ \hat{0} & \hat{\sigma}_\mu^*\end{bmatrix}\right\}$$

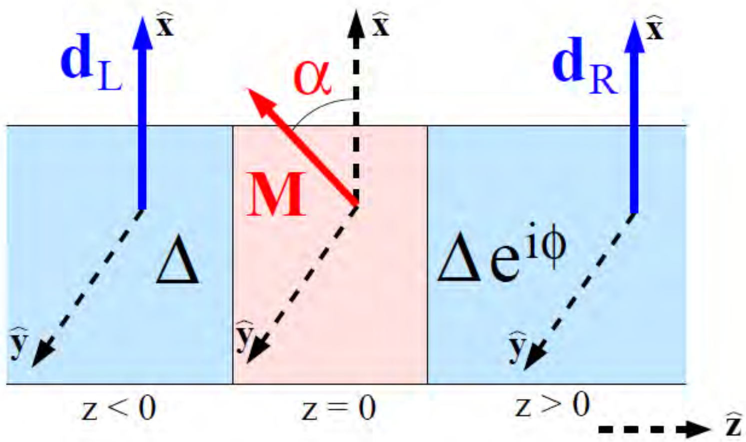
The Orientation of the Moment Matters!



$T = 0.4\,T_c$

$\boldsymbol{M} = \frac{g\mu_B m}{k_F \hbar^2}(\cos\alpha, \sin\alpha, 0)$

$\boldsymbol{d}_L = \boldsymbol{d}_R e^{-i\phi} = \hat{\boldsymbol{x}}\Delta k_y$



- The sign of the Josephson current is controlled by the *orientation* of the magnetic moment
- Universal effect!
- Evidence that the magnetic moment is coupling to the spin of the tunneling Cooper pairs. Spin currents?

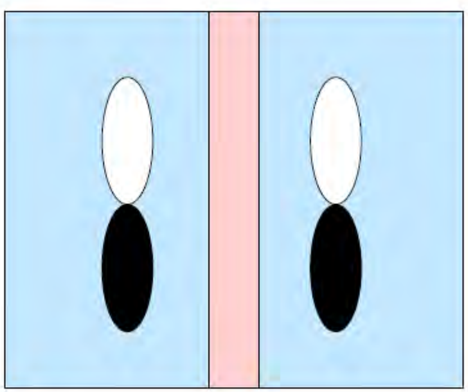
The 0-π Transition

- $T_{sf} \gg T_{sp}$ is true for large barrier moment $M \gg 1$:

$$I_J = -|I_0| \cos(2\alpha) \sin(\phi)$$

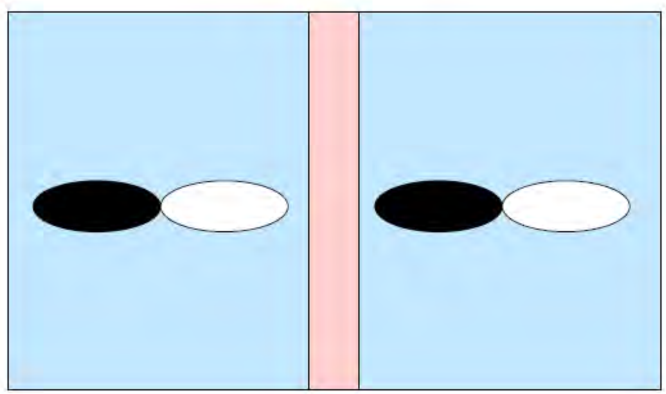
- **Prediction:** π state for $0 \leq \alpha < \frac{\pi}{4}$; 0 state for $\frac{\pi}{4} < \alpha \leq \frac{\pi}{2}$
- **Test:** Use Bogoliubov-de Gennes theory to determine critical angle α_c for different symmetries:

p_y-wave



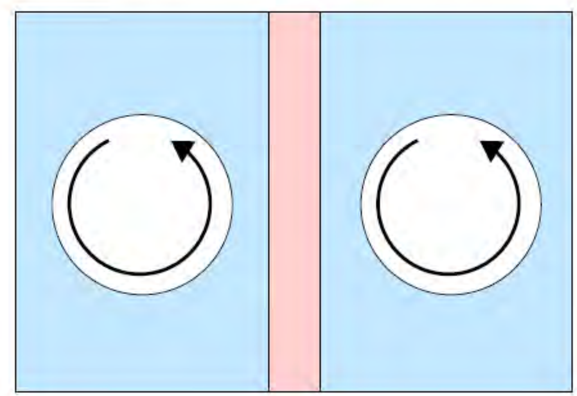
$$\Delta_{\boldsymbol{k}} = \Delta(T) k_y$$

p_z-wave



$$\Delta_{\boldsymbol{k}} = \Delta(T) k_z$$

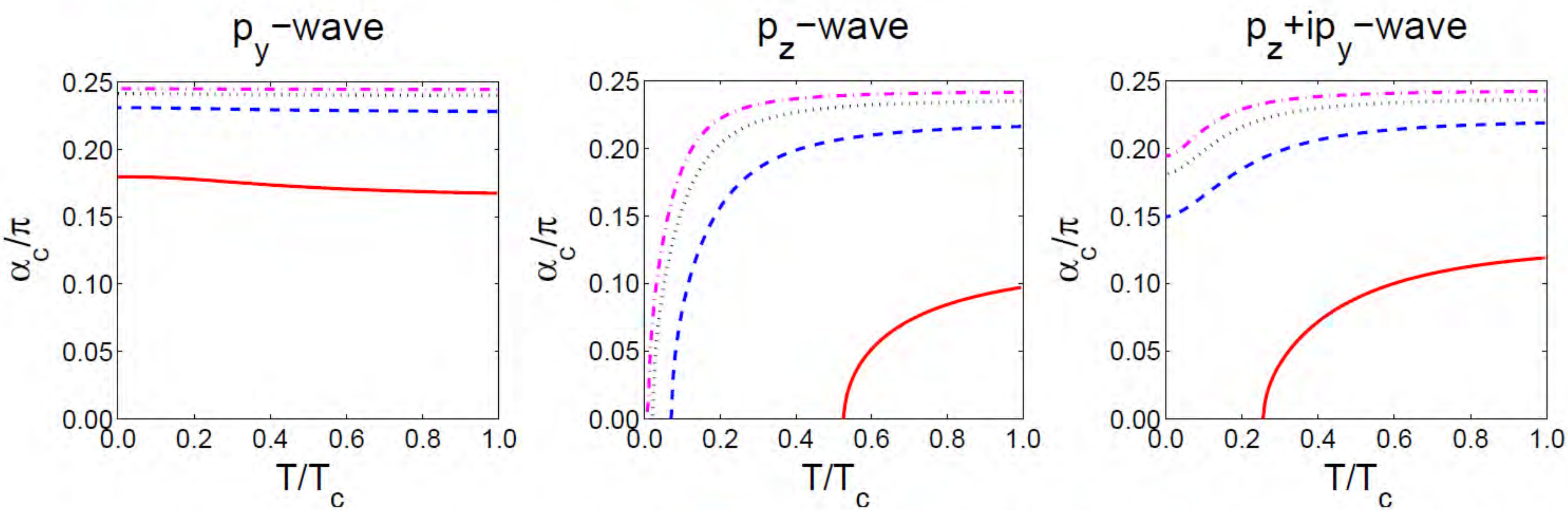
$p_z + ip_y$-wave



$$\Delta_{\boldsymbol{k}} = \Delta(T)(k_z + ik_y)$$

Role of Andreev Bound States

$M = 1$, $M = 2$, $M = 3$, $M = 4$

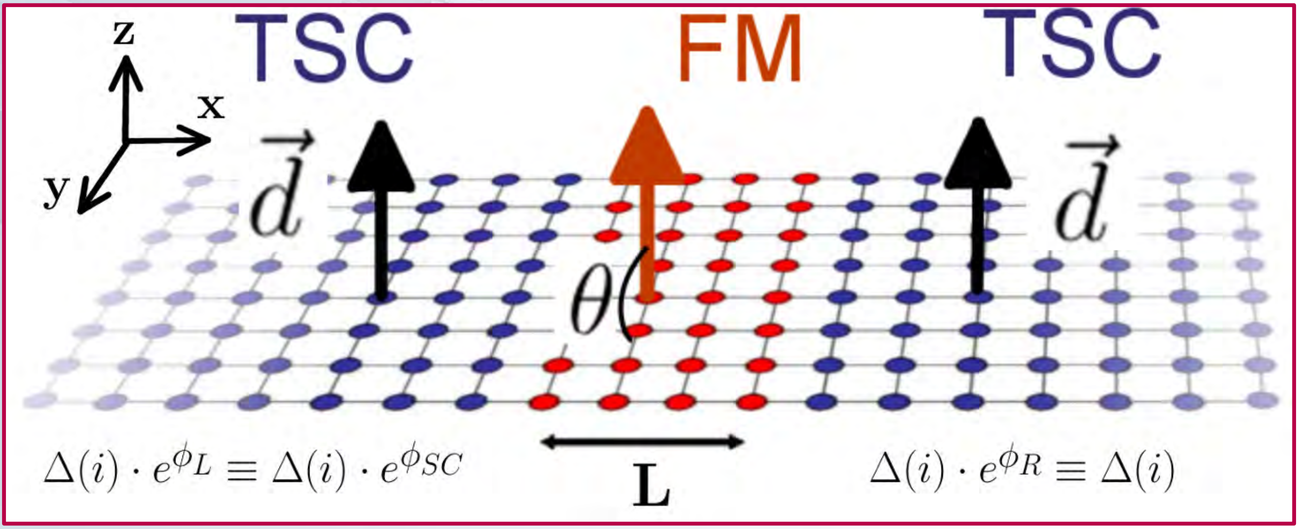


What is happening at small T in the p_z and $p_z + ip_y$ junctions?

Andreev bound states form at the barrier in all junctions: absent in tunneling formalism; present in Bogoliubov-de Gennes

Tunneling through zero-energy Andreev bound states strongly modifies low-T current vs phase relation: these are present in p_z and $p_z + ip_y$ junction

Thickness of FM – More realistic calculations



Results - TFT Josephson Junctions (lattice model)

Current Densities on the Lattice

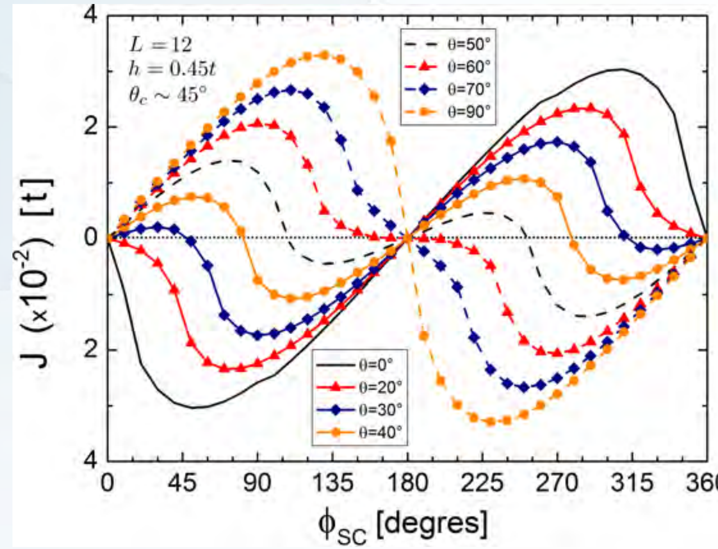
$$J(i) = J_\uparrow(i) + J_\downarrow(i)$$

with $$\mathrm{J}_\sigma(\mathrm{i}) = it \sum_k \left[c^\dagger_{i+1,k\sigma} c_{i,k\sigma} - c^\dagger_{i,k\sigma} c_{i+1,k\sigma} \right]$$

and $$\mathrm{J}^\nu_{\mathrm{s}}(\mathrm{i}) = \frac{it}{2} \sum_k \sum_{\sigma\sigma'} \left[c^\dagger_{i+1,k\sigma} \hat{\sigma}^\nu_{\sigma\sigma'} c_{i,k\sigma'} - c^\dagger_{i,k\sigma} \hat{\sigma}^\nu_{\sigma\sigma'} c_{i+1,k\sigma'} \right]$$

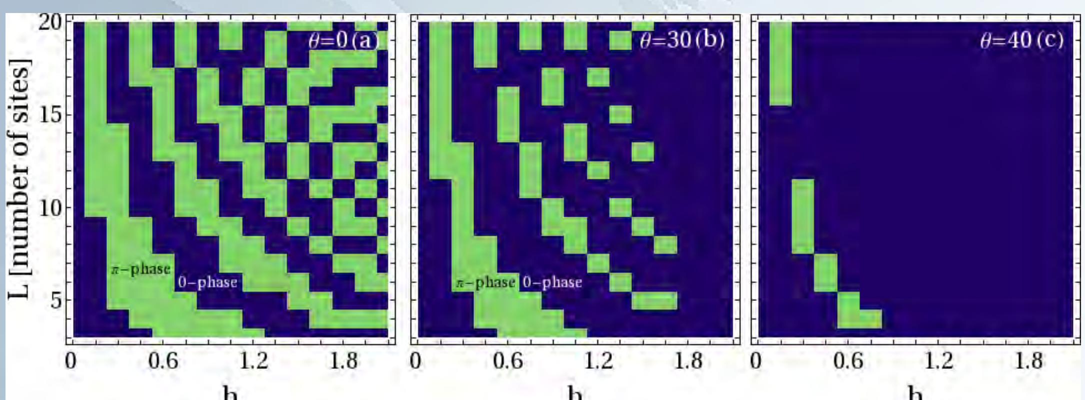
Oscillations lead to 0-π State Transitions

→ Importance of $\vec{M}$ orientation



Phase Diagrams (chiral p_x+ ip_y)

$\vec{M}$ // d-vector



→ θ_c depends on |h| and L

→ θ_c depends on the OPs symmetry

→ θ_c is modified for 3D junctions

→ Results with Self-Consistent Computations

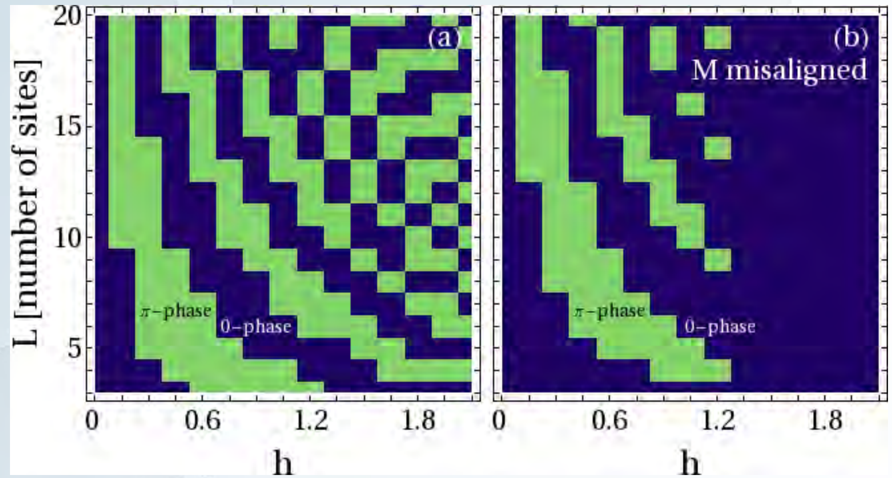
→ Results for 3D-Junctions

→ Results for p_x , p_y and p_x+ ip_y states

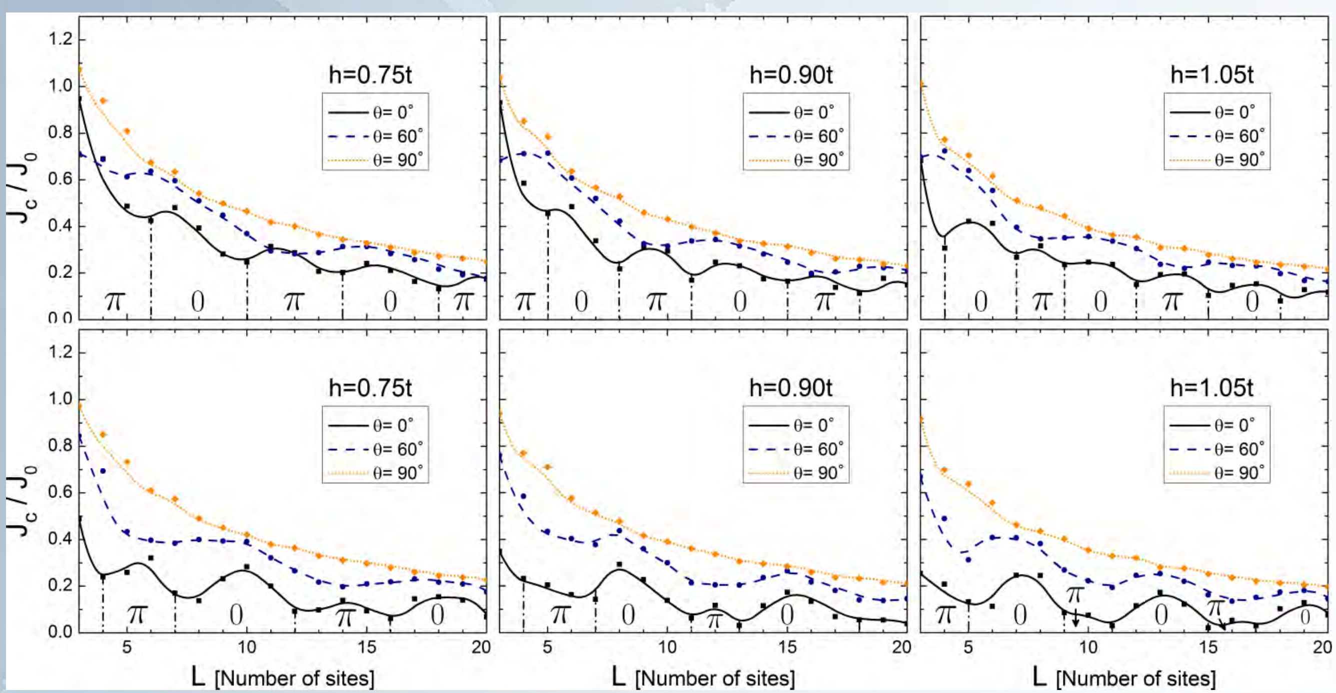
Results - Spin-Active Interface and Critical Current

With a spin-active interface ?
(M_{int} in-plane)

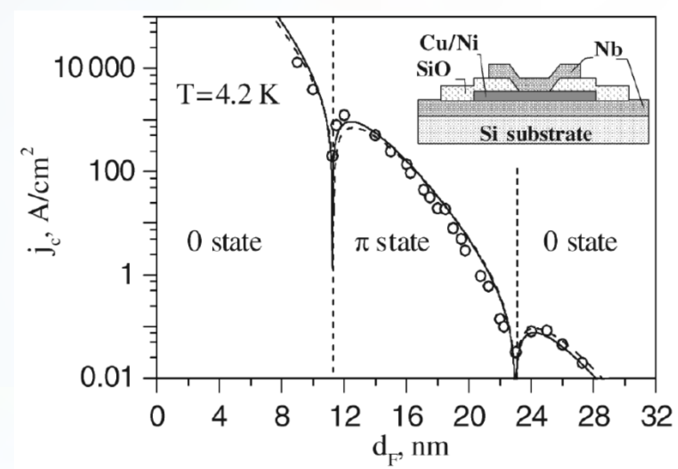
Reduction of the π-state domains ←



Prediction for Experimental Measurements



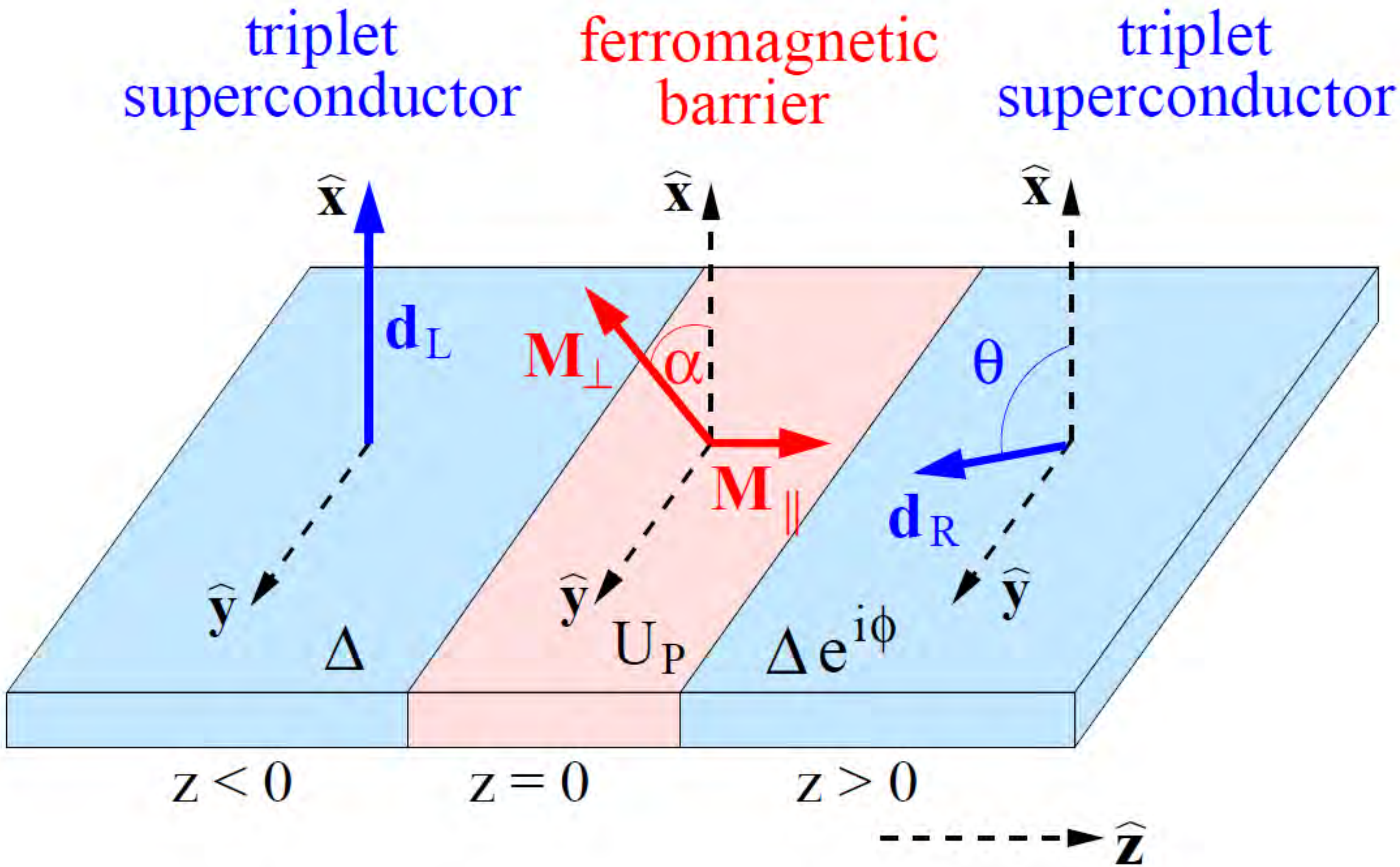
Compare with Spin-Singlet Junction



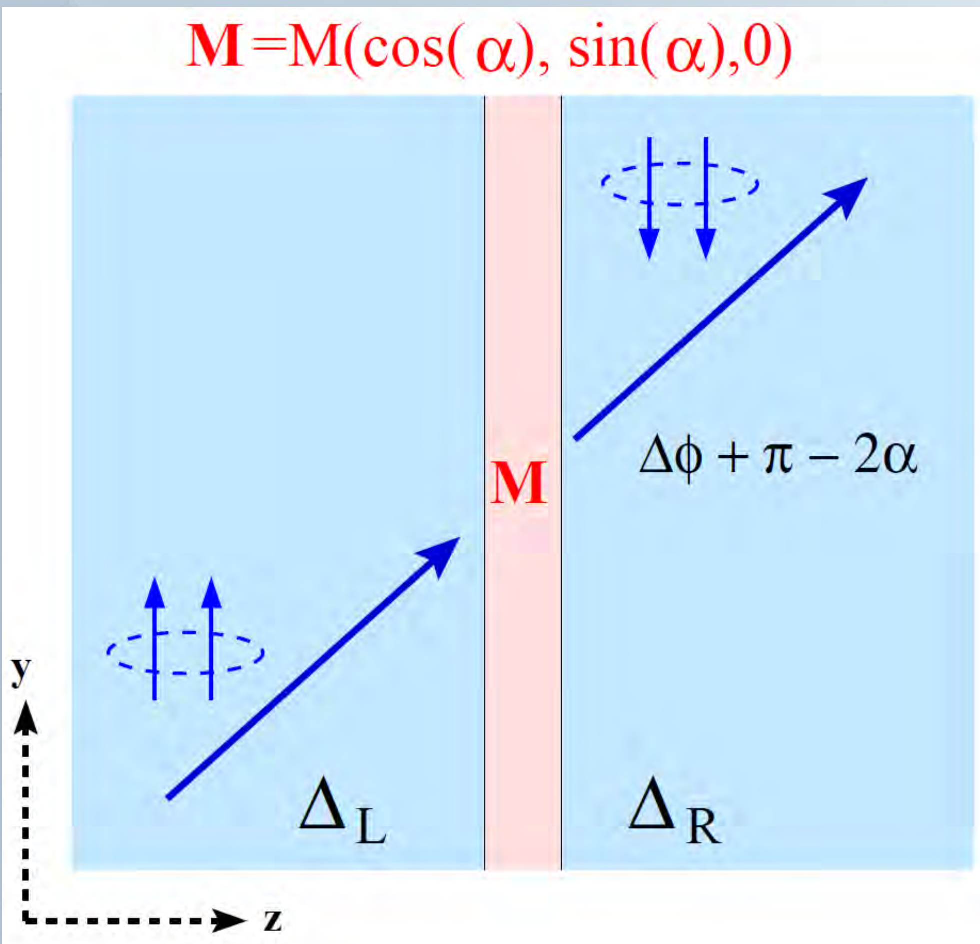
V.A. Oboznov *et al*.
Phys. Rev. Letter **96**, 197003 (2006)

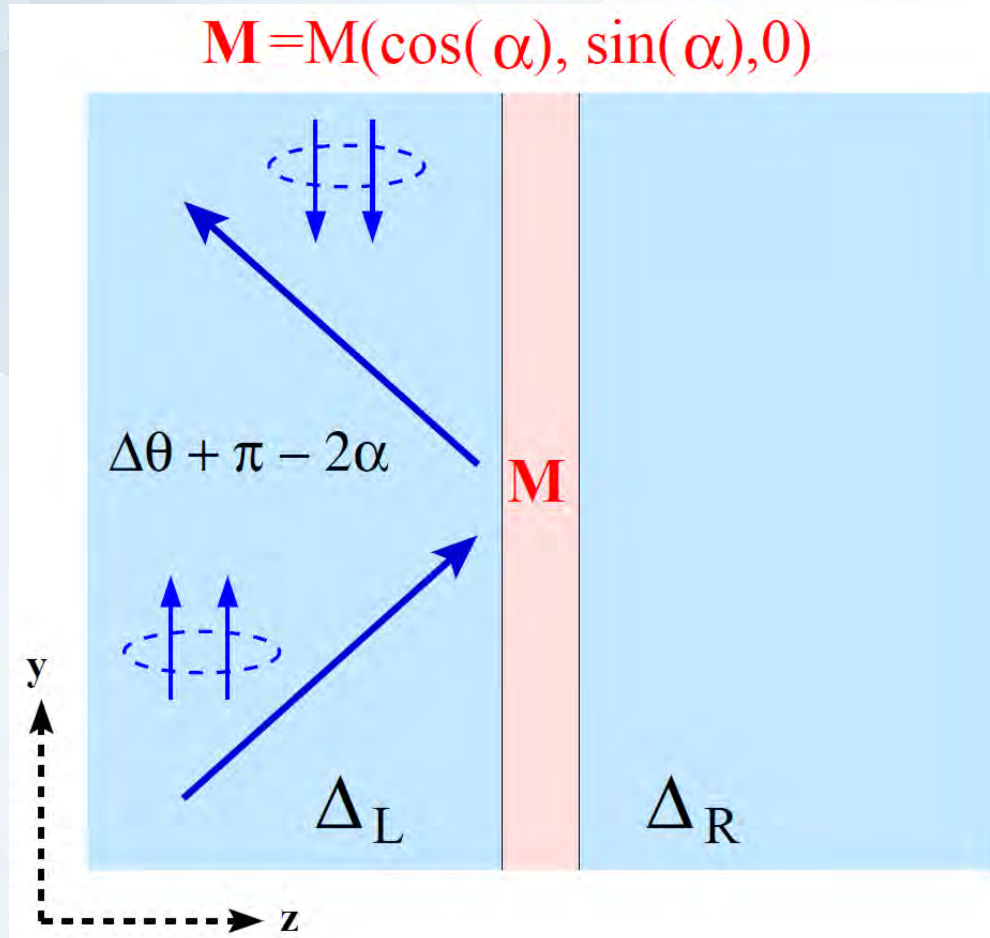
Spin currents: 3 mechanisms

- spin-flipping tunneling barrier
- **d**-vector misalignment
- spin-filtering tunneling barrier

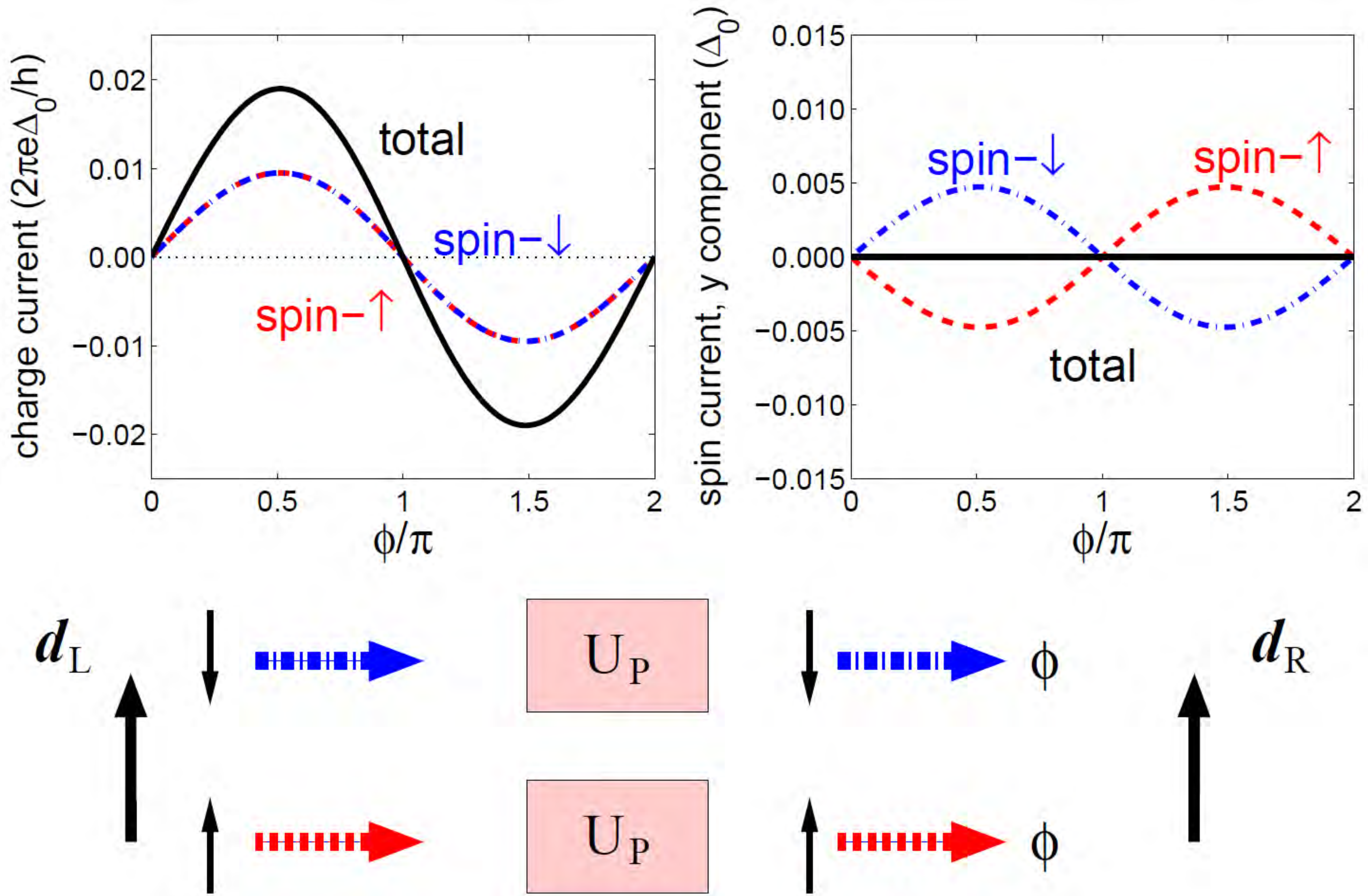


Spin flipping tunneling barrier

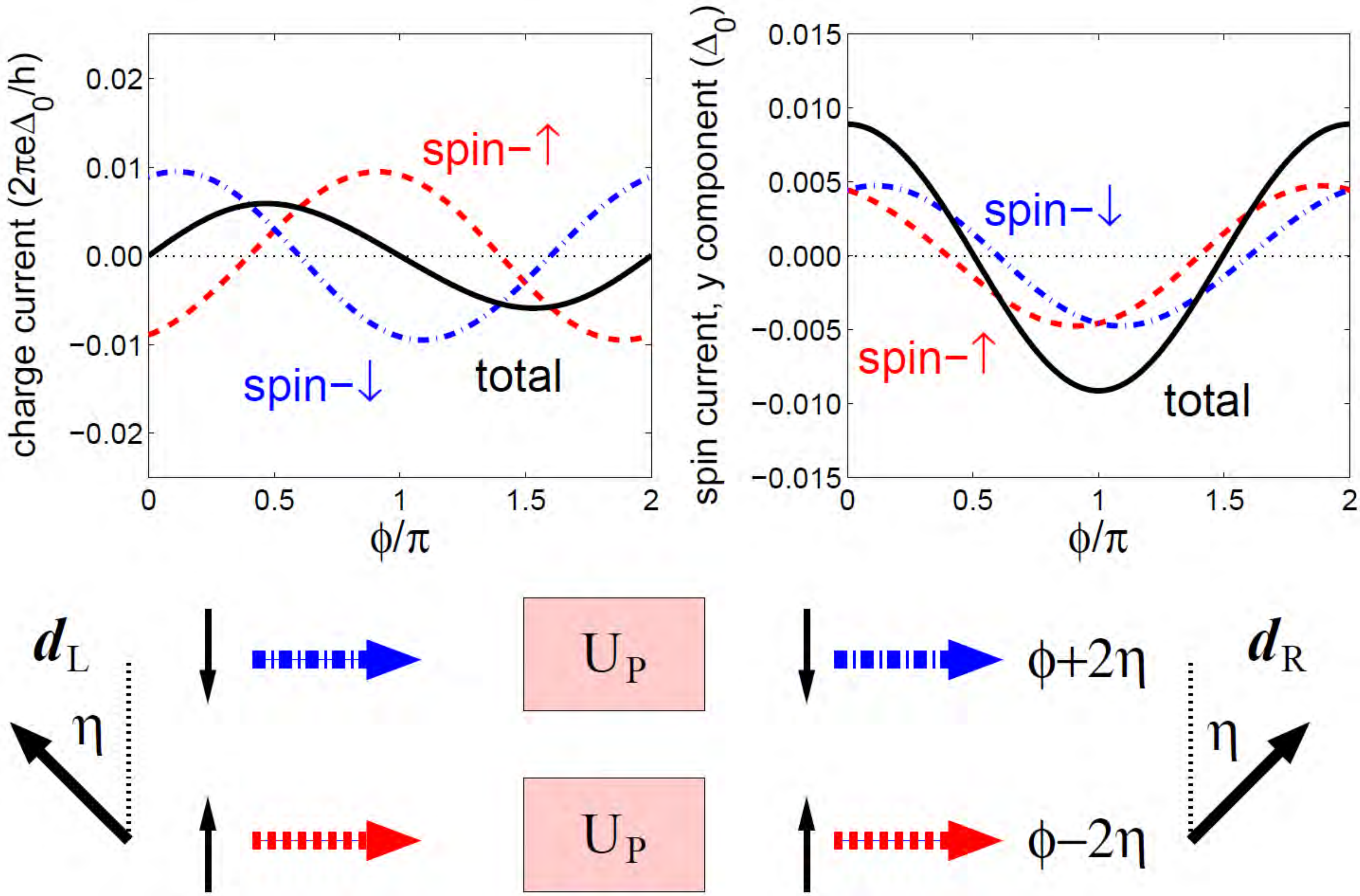




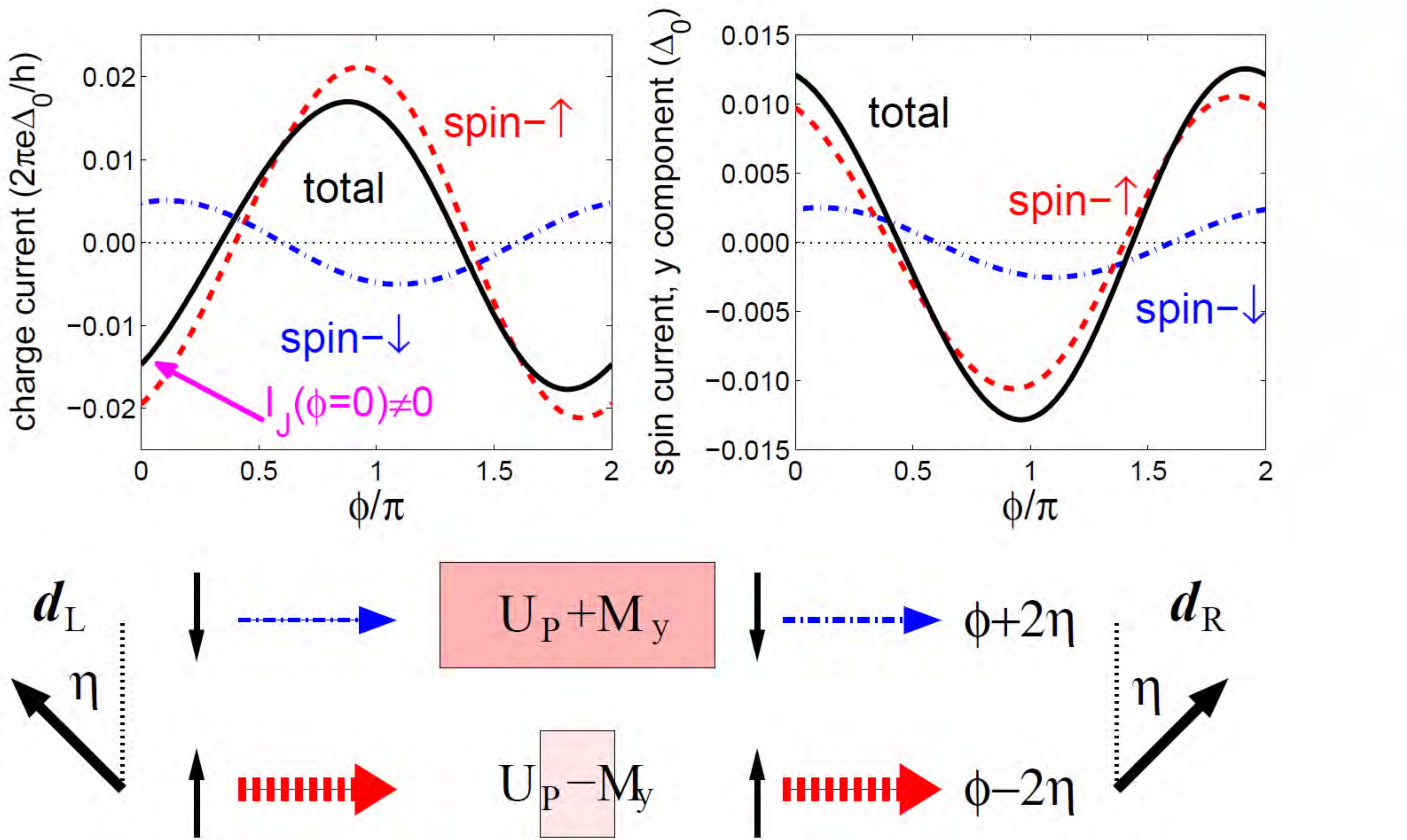
Spin current and time-reversal symmetry breaking



Spin current and time-reversal symmetry breaking

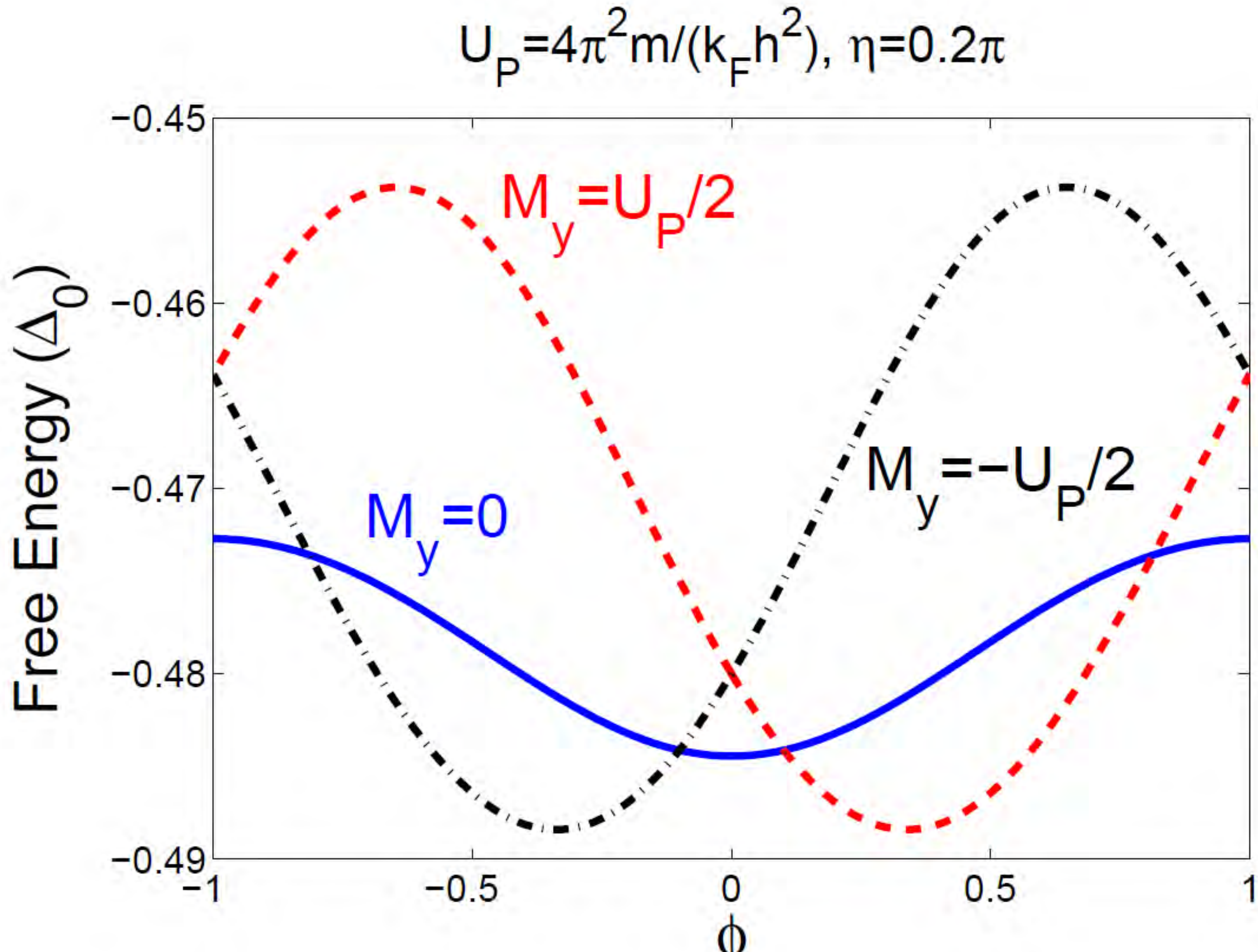


Spin current and time-reversal symmetry breaking



Fractional flux quanta

Free energy of the junction: $F(\phi) = F(0) + \frac{\hbar}{2e}\int_0^{\phi} d\phi' I_J(\phi')$



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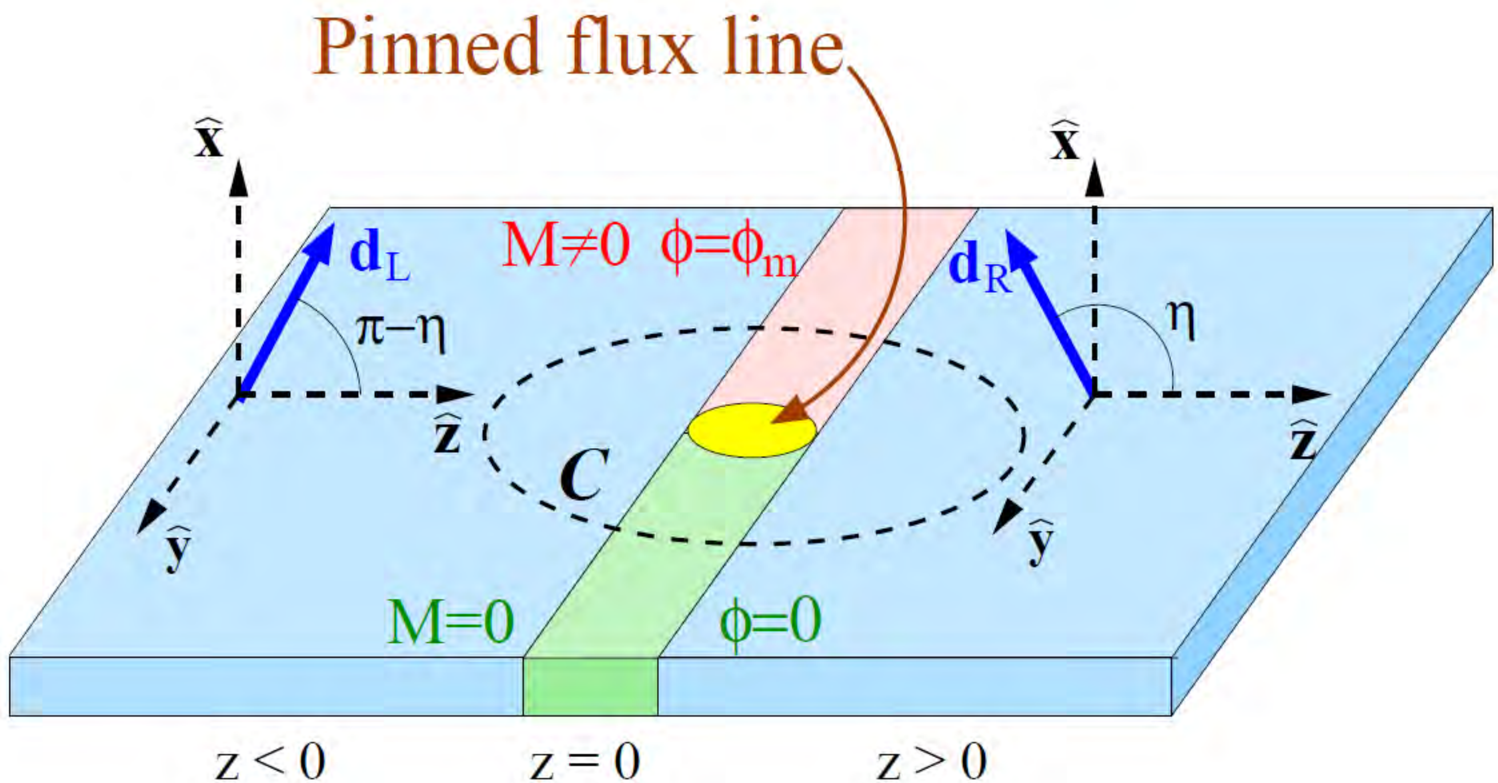
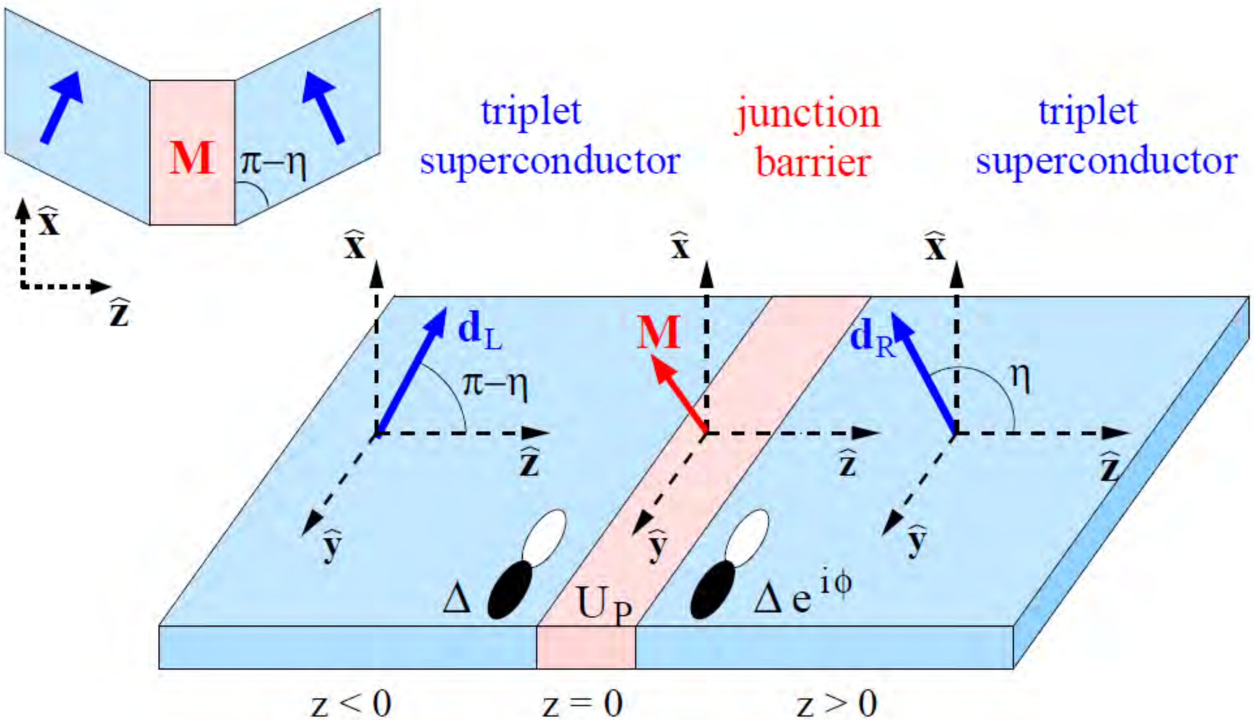


$$\frac{\Phi}{\Phi_0} = n + \oint_C d\boldsymbol{s}\cdot\nabla\phi = n + \frac{\phi_m}{\pi}$$

fractional flux quanta possible! (Φ-junction)

What happens in a non-magnetic junction?

Engineering the fractional state



- might it be possible to induce a magnetic moment in a tunneling barrier sufficiently close to a FM transition, using only the properties of the two superconductors?
- more generally, can the superconductors change the properties of the interface material?

Must go beyond quasiclassical theory...

The Ginzburg-Landau perspective

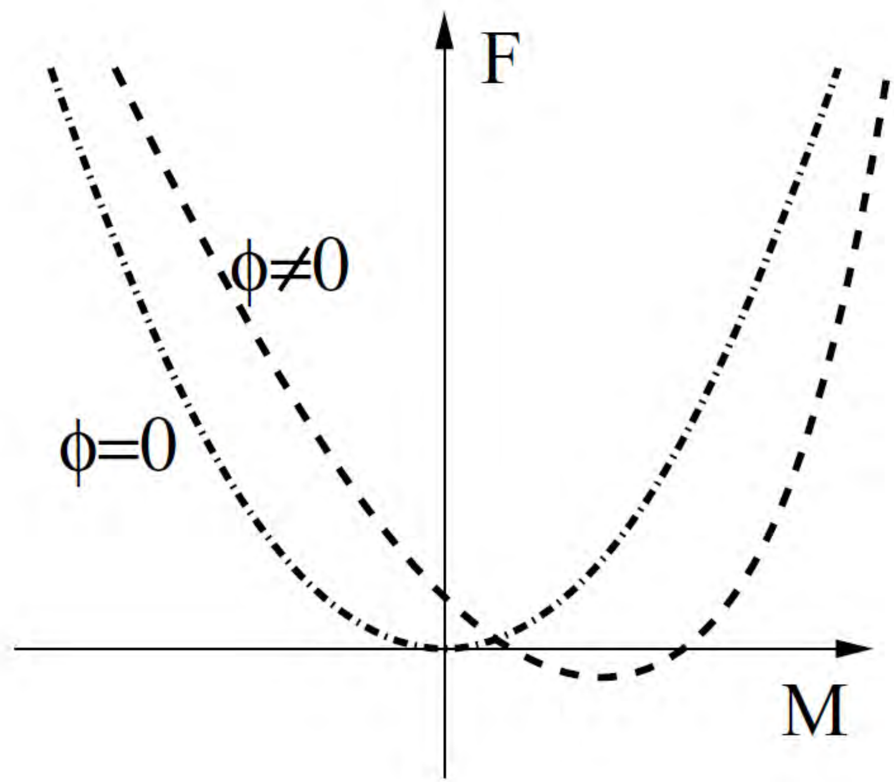
Total free energy: magnetic and electronic contributions

$$F = F_{mag} + F_{el} = \frac{|\boldsymbol{M}|^2}{2\chi} + F_{el}(0) + \frac{\hbar}{2e}\int_0^{\phi} d\phi' I_J(\phi'), \qquad \chi > 0$$

- Expand electronic free energy to lowest order in $\boldsymbol{M}$:

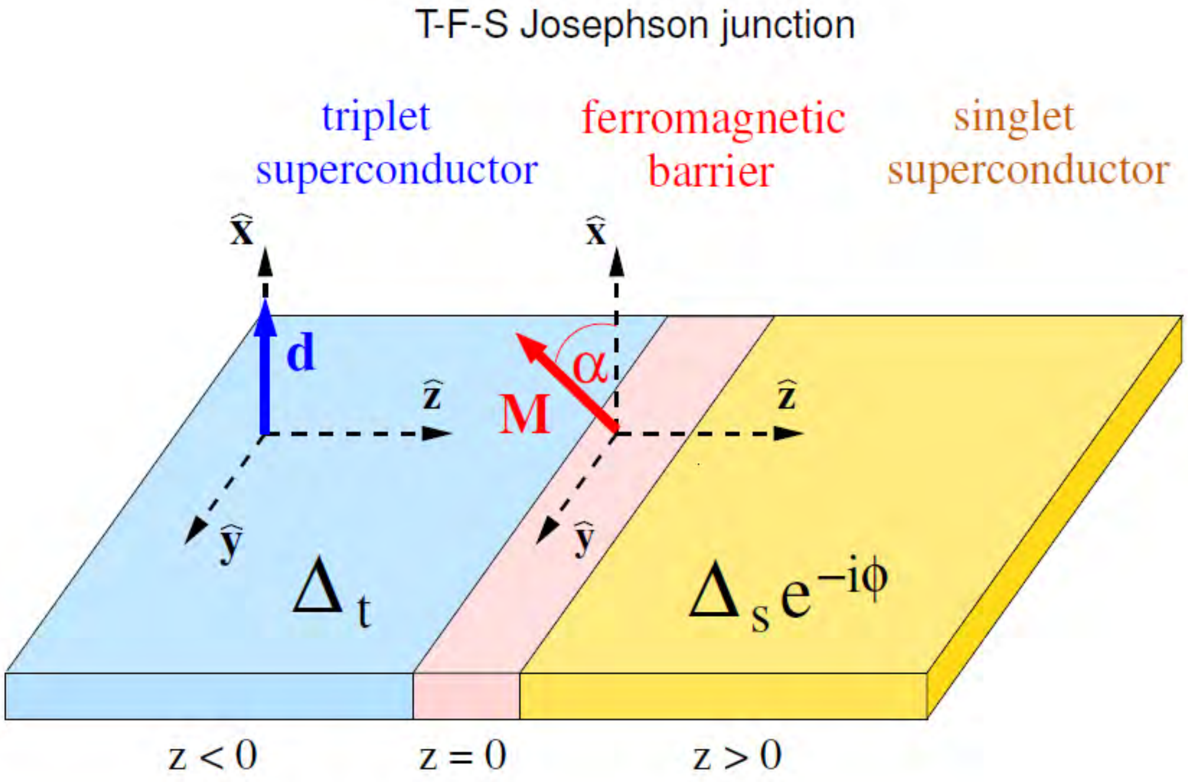
$$\begin{aligned} F &= \frac{|\boldsymbol{M}|^2}{2\chi} - 2t\boldsymbol{d}_L \cdot \boldsymbol{d}_R \cos(\phi) \\ &\quad + 2\gamma \boldsymbol{M} \cdot (\boldsymbol{d}_L \times \boldsymbol{d}_R) \sin(\phi) \end{aligned}$$

- "normal" $\boldsymbol{M} = \phi = 0$ state unstable when $\chi\gamma^2|\boldsymbol{d}_L \times \boldsymbol{d}_R|^2 > t\boldsymbol{d}_L \cdot \boldsymbol{d}_R$
- microscopic calculation of the electronic free energy desired



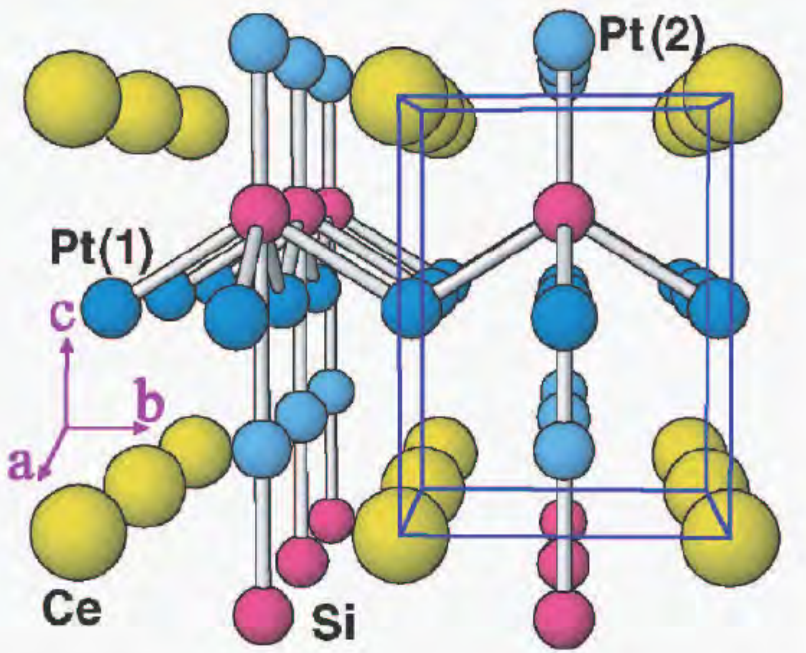
Case II: T-F-S Josephson junction

- Y. Asano (Hokkaido)
- Philip Brydon (now U Maryland)
- Wei Chen (MPI)



Case III: NCS-I-S Josephson junction

$CePt_3Si$ T_c=0.75 K



lack of inversion symmetry:

$$U(\mathbf{r}) \neq U(-\mathbf{r})$$

antisymmetric spin-orbit coupling:

$$\boldsymbol{g}_{\mathbf{k}} \propto \int_{u.c.} d^3r \, \mathbf{j}_{\mathbf{k}}(\mathbf{r}) \times \nabla_{\mathbf{r}} U(\mathbf{r})$$

$$\boldsymbol{g}_{\mathbf{k}} = -\boldsymbol{g}_{-\mathbf{k}}$$

tetragonal point group C_{4v}:

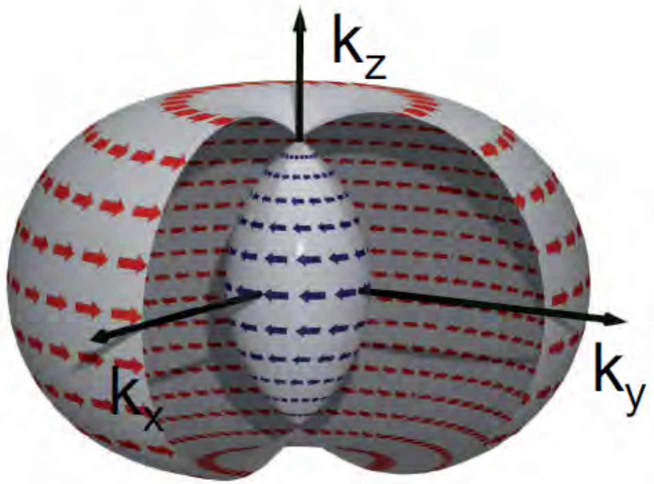
$$\boldsymbol{g}_{\mathbf{k}} = |\boldsymbol{g}_{\mathbf{k}}| \begin{pmatrix} -\sin k_y \\ \sin k_x \\ 0 \end{pmatrix}$$

Rashba coupling

$$\hat{H} = \sum_{\mathbf{k}\sigma\sigma'} \hat{c}^\dagger_{\mathbf{k}\sigma} \left[\xi_{\mathbf{k}} \delta_{\sigma\sigma'} + \boldsymbol{g}_{\mathbf{k}} \cdot \boldsymbol{\tau}_{\sigma\sigma'} \right] \hat{c}_{\mathbf{k}\sigma'}$$

Case III: NCS-I-S Josephson junction

Kramers degeneracy is lifted by the ASOC.



band basis: $\xi_\pm = \xi_{\mathbf{k}} \pm |\boldsymbol{g}_{\mathbf{k}}|$

spin space: $\boldsymbol{\Delta}_{\mathbf{k}} = [\psi_{\mathbf{k}}(T)\mathbf{1} + \mathbf{d}_{\mathbf{k}}(T) \cdot \boldsymbol{\tau}]\, i\tau^y$

$\Downarrow$ unitary transformation; $\mathbf{d}_{\mathbf{k}} || \boldsymbol{g}_{\mathbf{k}}$ [Sigrist *et al.*, 2004]

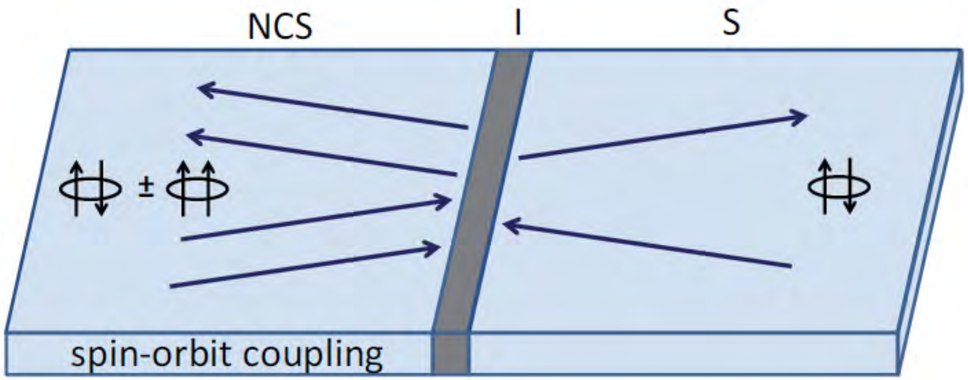
$\Delta_\pm = \psi \pm d|\boldsymbol{g}_{\mathbf{k}}|$

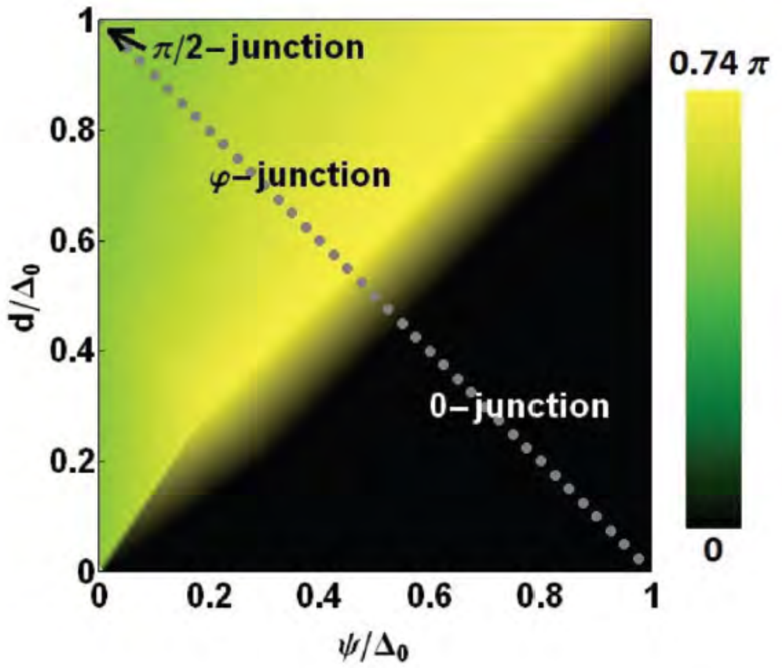
L. Klam, D. Einzel, and D. Manske, Phys. Rev. Lett. **102**, 027004 (2009)
E. Bauer and M. Sigrist (Eds.), *Non-centrosymmetric Superconductors*, Lecture Notes in Physics **847** (Springer, 2012)

Case III: NCS-I-S Josephson junction

- Ludwig Klam (MPI)
- Wei Chen (MPI)
- Toni Epp (now UBC)

NCS-I-S Josephson junction





Closer inspection on the interface

Interplay between and the Spin of the Cooper pairs at the interface

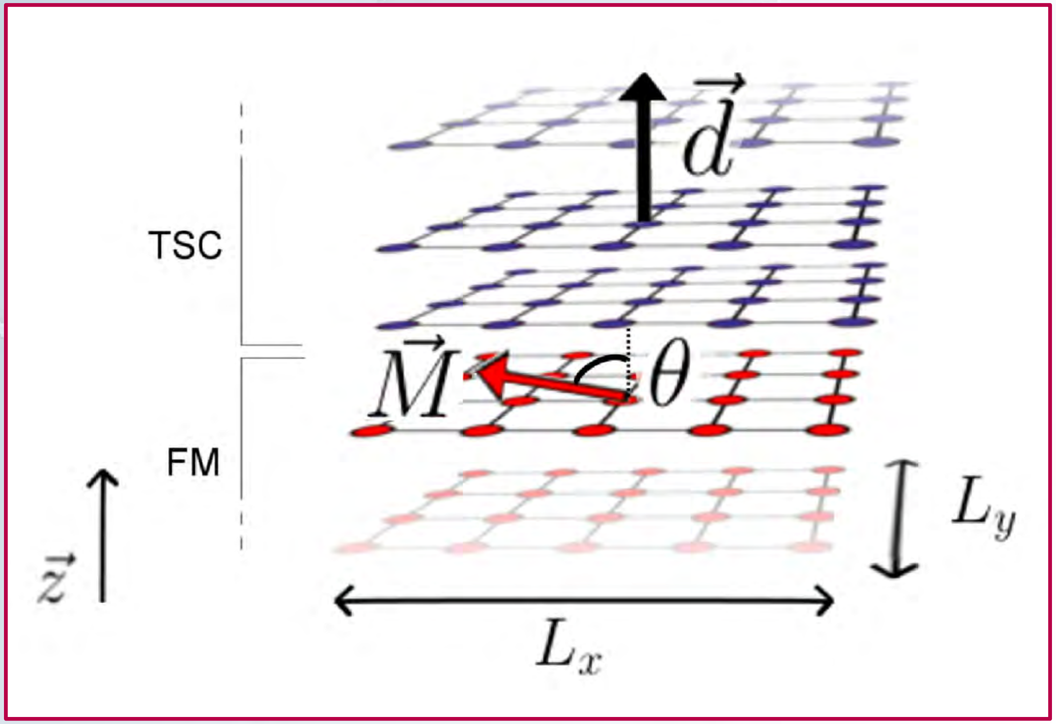
1) FM - Chiral State Interface

OP spatial variations
and magnetic stability

2) FM – Helical State Interface

Control of the helical currents

1) FM – Chiral State Interface



Lattice Model

Extended Tight-Binding Model

$$H_0 = -\sum_{\langle ij\rangle,\sigma} t_{i\sigma}(c^\dagger_{i\sigma}c_{j\sigma} + h.c.) - \mu\sum_{i\sigma} n_{i\sigma} + \sum_{\langle ij\rangle} V_i(n_{i\uparrow}n_{j\downarrow} + n_{i\downarrow}n_{j\uparrow}) + \sum_{\langle ij\rangle} V_i'(n_{i\uparrow}n_{j\uparrow} + n_{i\downarrow}n_{j\downarrow})$$

K. Kuboki,
J. Phys. Soc. Jpn. **70,** 2698 (2001)

K. Kuboki and H. Takahashi,
Phys. Rev. B. **70,** 214524 (2004)

M. Cuoco *et al.*,
Phys. Rev. B. **78,** 054503 (2008)

TSC

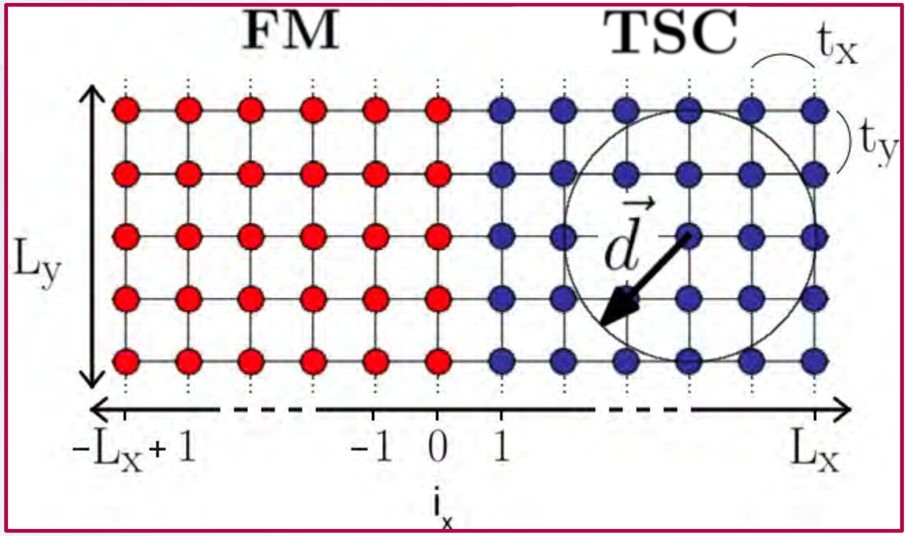
$$V_i n_{i\sigma}n_{j\sigma'} \simeq V[\, F^{\sigma\sigma'}_{ij} c^\dagger_{j\sigma'}c^\dagger_{i\sigma} + F^{\sigma\sigma'*}_{ij} c_{i\sigma}c_{j\sigma'} - |F_{ij}|^2 \,]$$

$$F^{\sigma\sigma'}_{ij} = \langle c_{i\,\sigma}c_{j\,\sigma'}\rangle$$

FM

$$H_M = \sum_i \vec{h}_i \cdot \vec{s}_i$$

$$\vec{s}_i = \sum_{i\sigma\sigma'} c^\dagger_{i\sigma}\vec{\sigma}_{\sigma\sigma'}c_{i\sigma'}$$



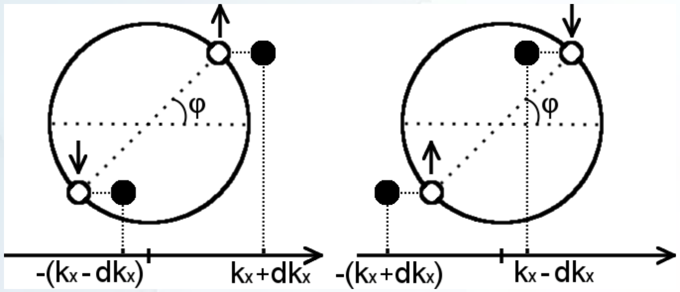
Results - Superconducting Order Parameter

→ Damped oscillatory behavior depending on magnetization angle θ

→ No induced spin-singlet components

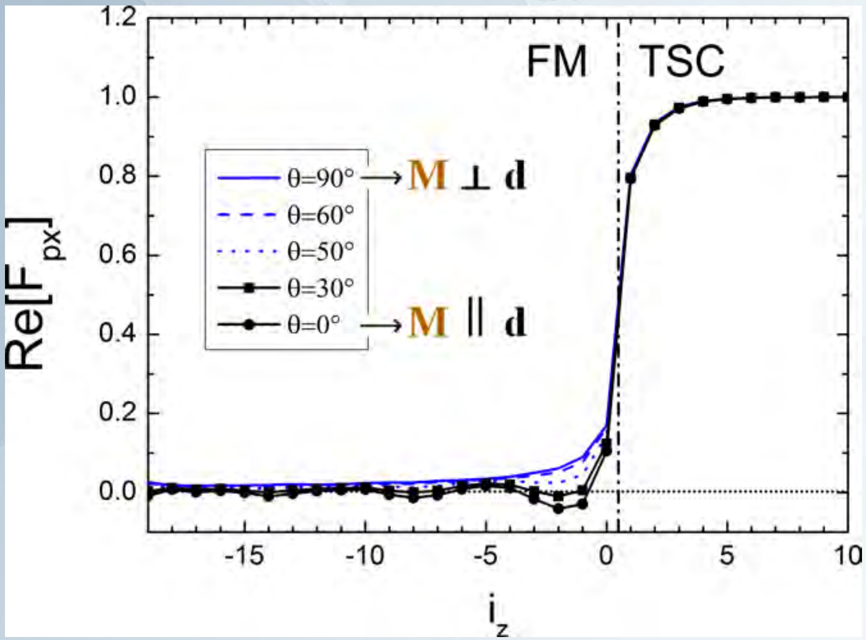
→ Oscillation period depends on |h| and v_F

Cooper pairs entering in the FM region



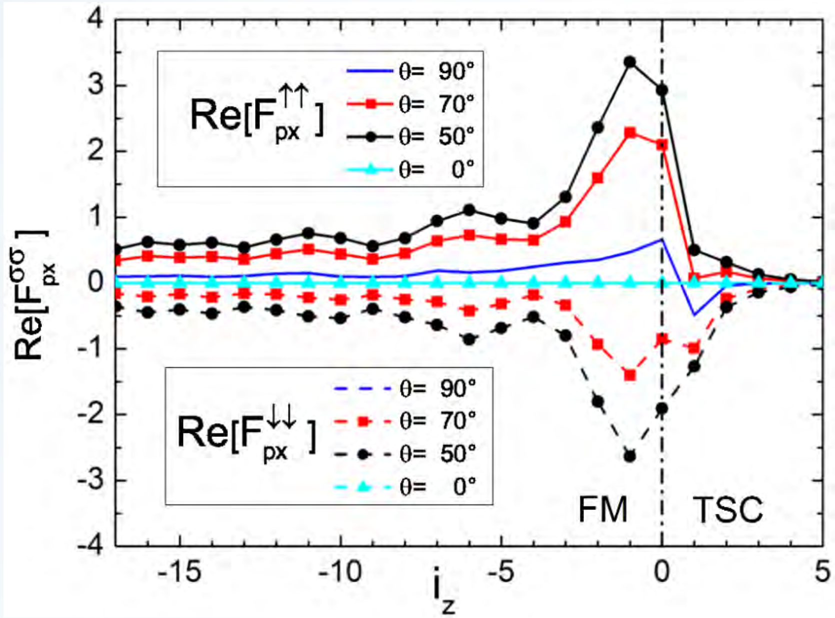
E.A. Demler *et al.*,
Phys. Rev. B **55,** 15174 (1997)

Induced Pairing Amplitudes

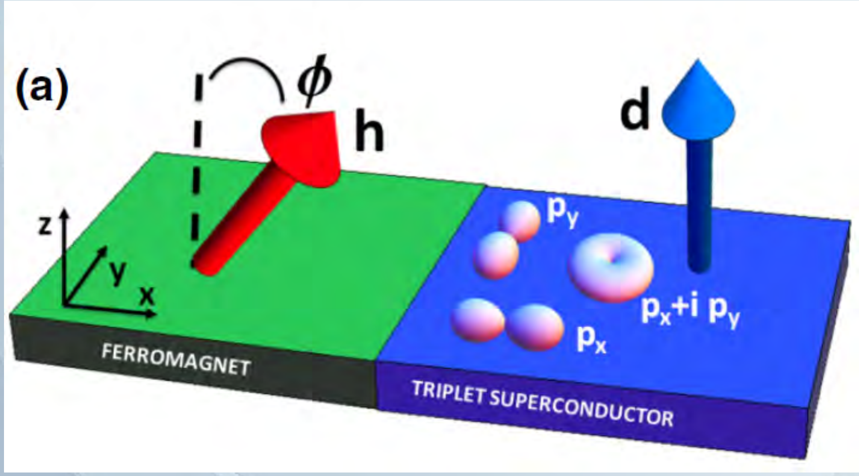


Phys. Rev. B. 88, 054516 (2013)

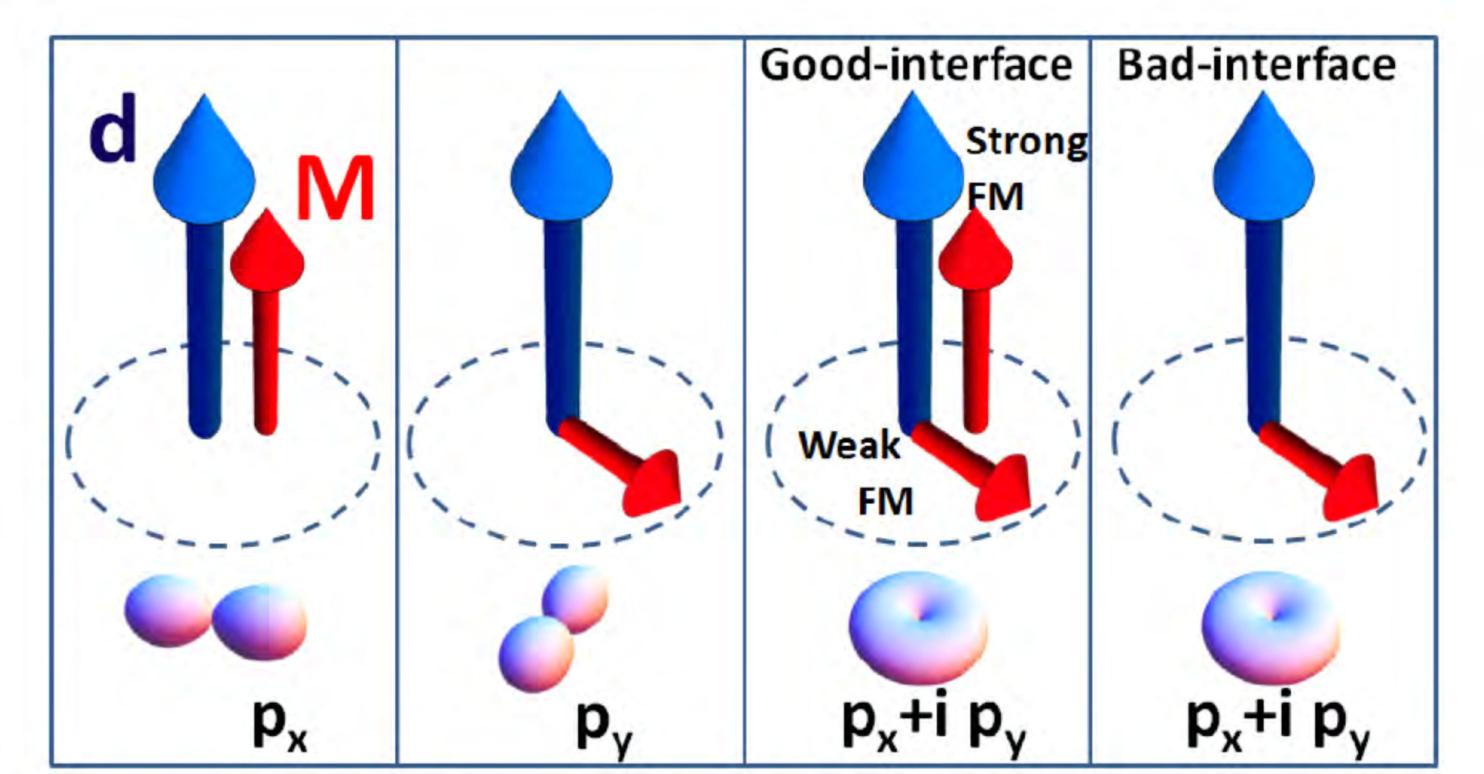
Induced Equal-Spin-Pairing



Results – Influence of spin-orbital coupling



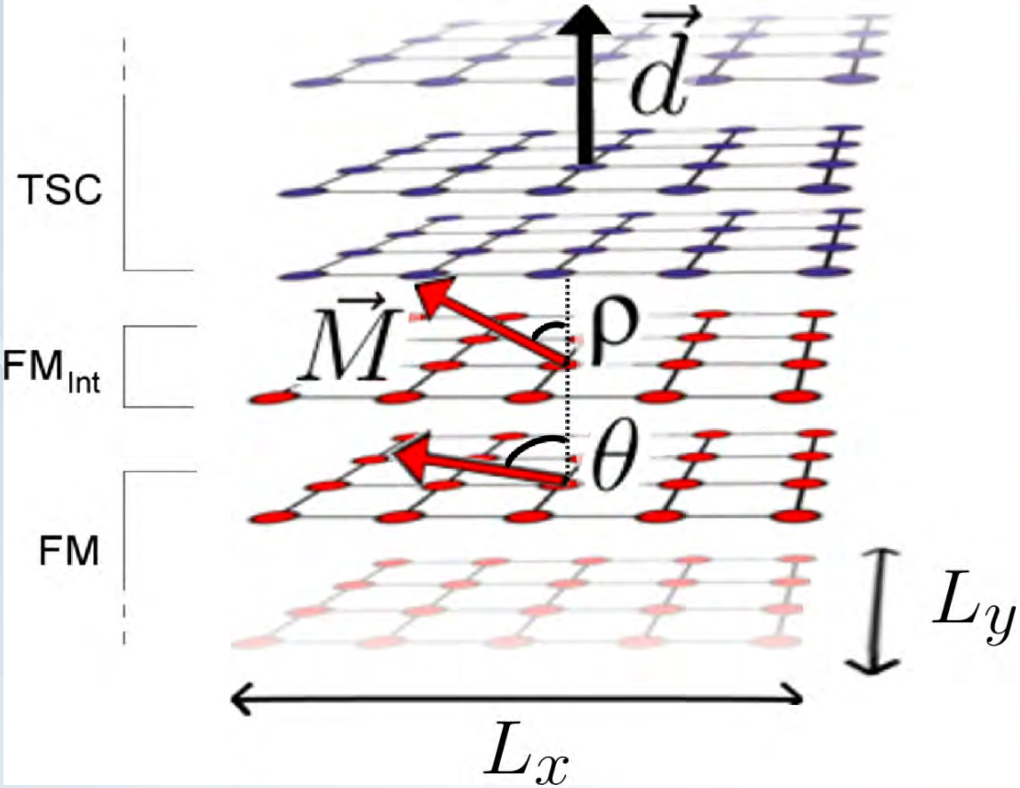
Spin-flip scattering → spin-orbital coupling



h_{ex} ⇔ exchange field couples to chiral symmetry

PRL 111, 097003 (2013)

1) FM – Chiral State Interface plus Spin-Active Interface



Results - Energy Stability & Magnetic Profile

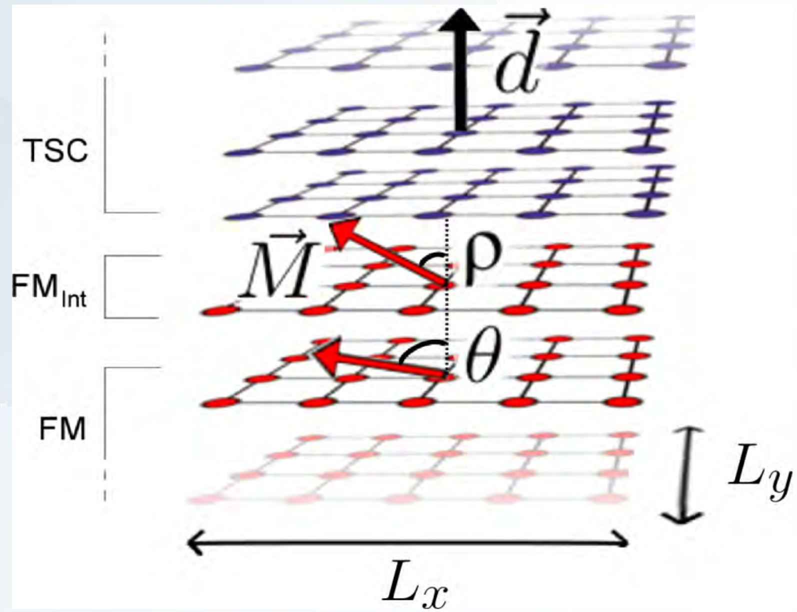
Evaluation of the free energy G

$$G = -\frac{1}{\beta}\ \ln\ \mathrm{Tr}[\mathrm{e}^{-\beta H_{\mathrm{HF}}}]$$

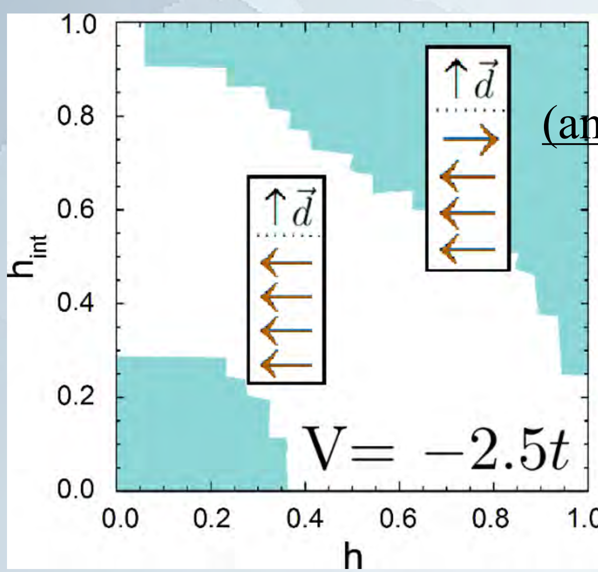
$$E_{\mathrm{op}} = -\left(\frac{2}{L_z}\right)\sum_{i_z>0}\left[|F_{p_x}(i_z)|^2 + |F_{p_y}(i_z)|^2\right]$$

→ $\vec{M}$ tends to be perpendicular to the *d*-vector
→ The TSC favours an antiparallel configuration
→ Induced spin-active interface (weak FM)

Free Interfaced Layer

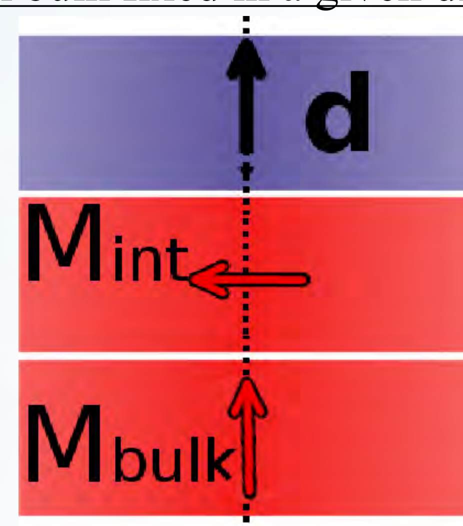


Phase Diagram



(antiparallel)

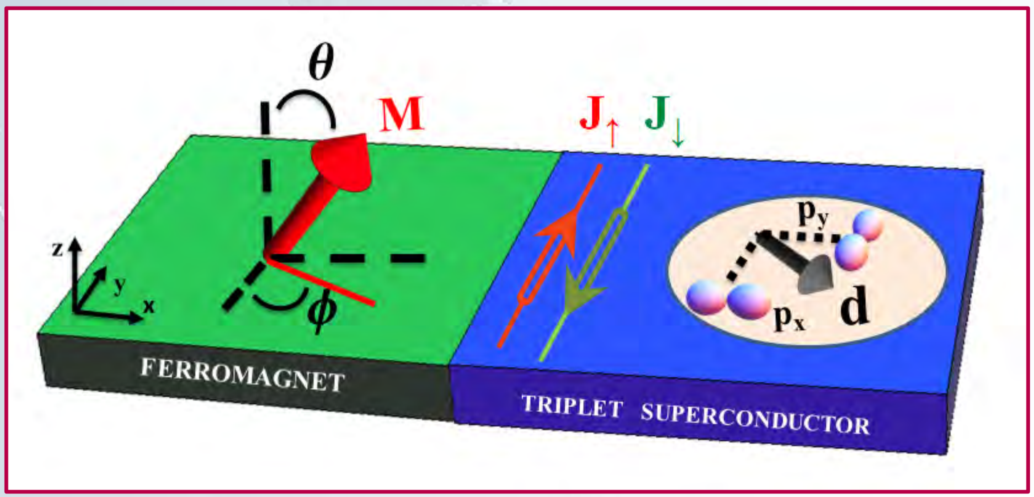
$\vec{M}$ in bulk fixed in a given direction



(misalignment, induced)

(pinned)

2) FM – Helical State Interface



Helical Edge-States and Dissipationless Edge Currents

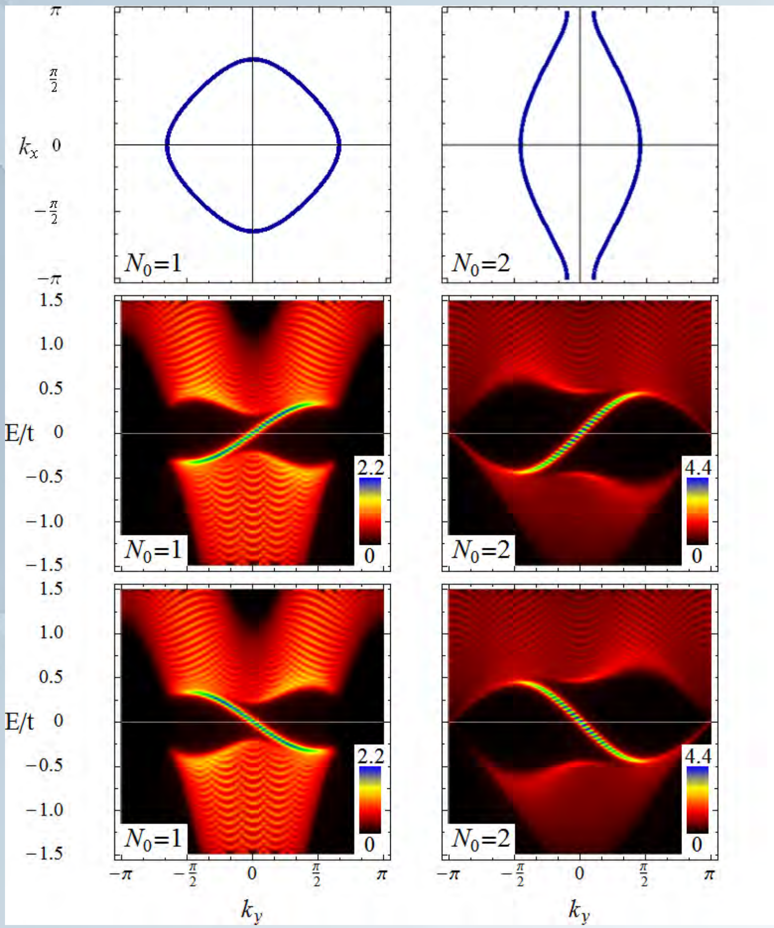
Fermi Surface and Edge States

$$\xi_{\mathbf{k}} = -2t\left[\cos(k_x a) + \cos(k_y a)\right] - \mu$$

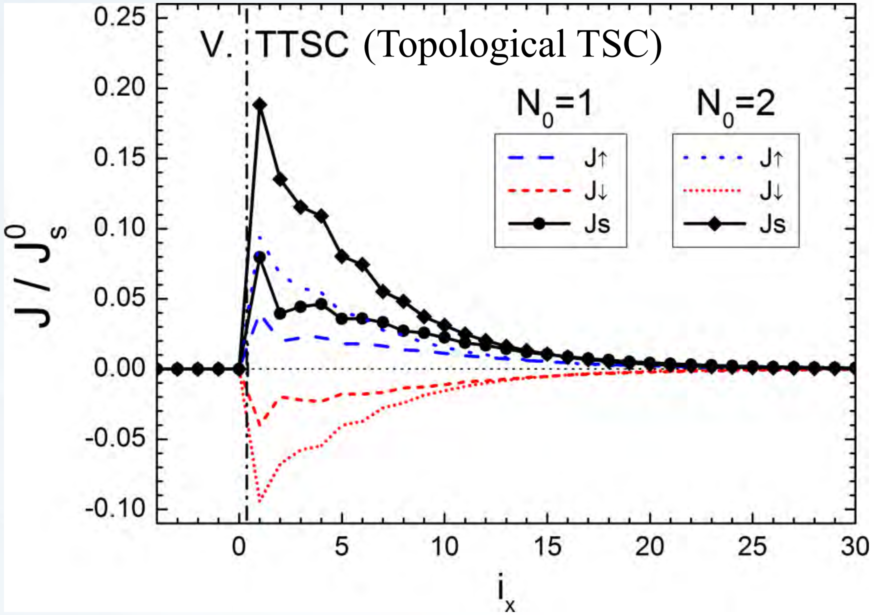
$$\vec{d} = (\sin(k_y), \sin(k_x), 0)$$

→ N_0 gapless helical edge states
→ N_0 depends on the Fermi Surface
→ Carry Edge Currents

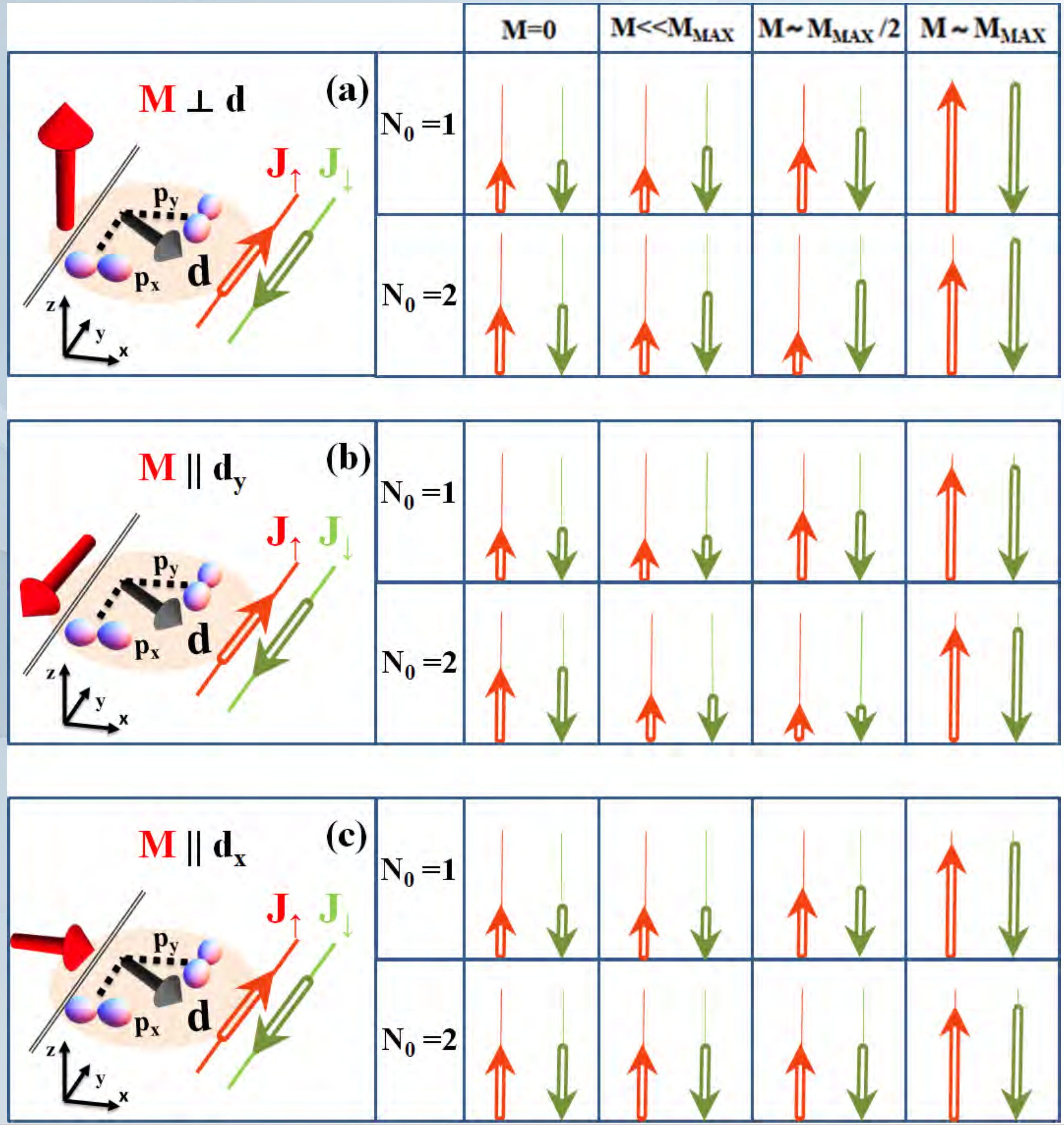
N_0=1 N_0=2



Currents Along the Interface



Results - Charge and Spin Current



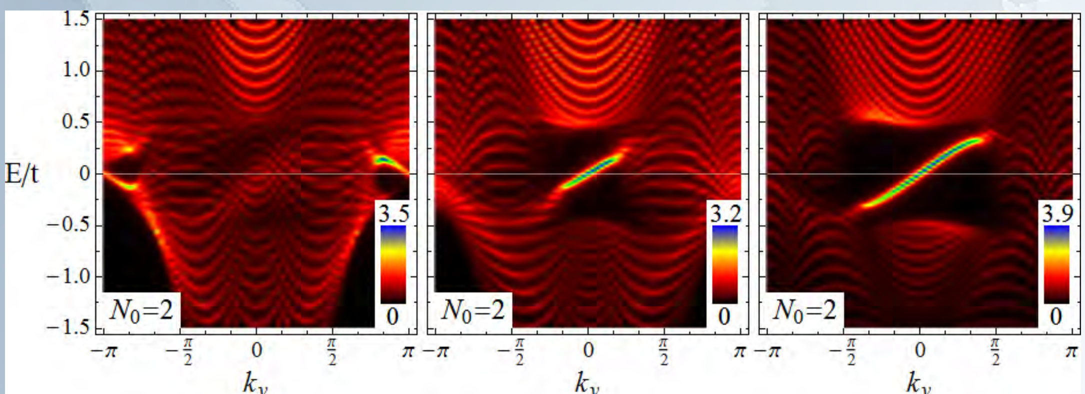
Results - Tuning of the Edge Currents

Total Edge Currents

$$J_\sigma^{tot} = \sum_{i_x \in TTSC} J_\sigma(i_x)$$

$$J_s^{tot} = J_\uparrow^{tot} - J_\downarrow^{tot},$$

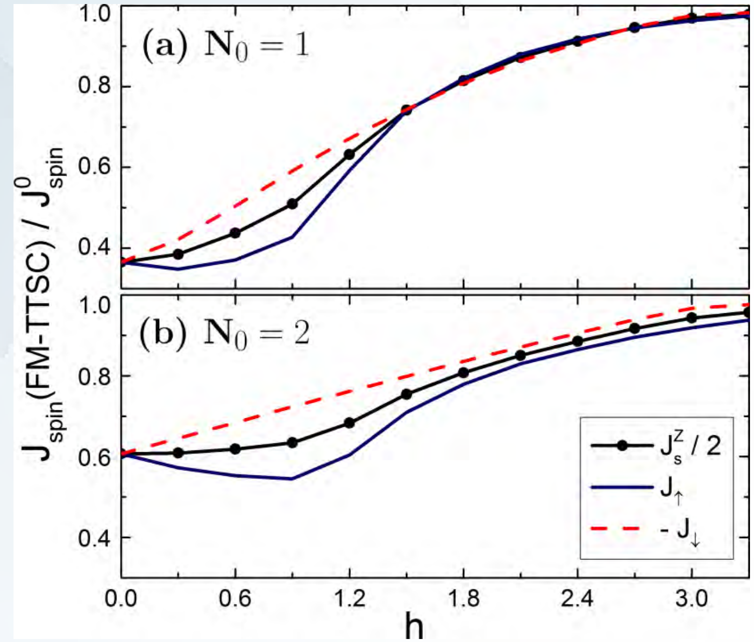
Spectral Functions: $\vec{M}$ // c-axis

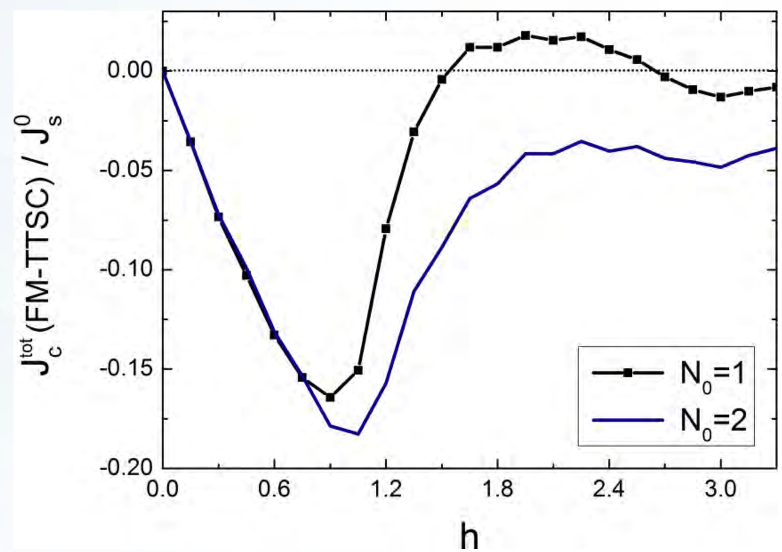


→ Spin and Charge Edge Currents depend on N_0

→ Variations associated to the hybridization of the gapless edge states

Comparison: N_0=1 and N_0=2





Experimental situation: Current development

Experiment: the story begins (1)

PRL **103,** 057201 (2009) PHYSICAL REVIEW LETTERS week ending 31 JULY 2009

Fundamental Thickness Limit of Itinerant Ferromagnetic $SrRuO_3$ Thin Films

Young Jun Chang,[1] Choong H. Kim,[2] S.-H. Phark,[1] Y. S. Kim,[1] J. Yu,[2] and T. W. Noh[1,*]

[1]*ReCOE & FPRD, Department of Physics and Astronomy, Seoul National University, Seoul 151-747, Korea*

[2]*CSCMR & FPRD, Department of Physics and Astronomy, Seoul National University, Seoul 151-747, Korea*

(Received 21 February 2009; published 30 July 2009)

We report on a fundamental thickness limit of the itinerant ferromagnetic oxide $SrRuO_3$ that might arise from the orbital-selective quantum confinement effects. Experimentally, $SrRuO_3$ films remain metallic even for a thickness of 2 unit cells (uc), but the Curie temperature T_C starts to decrease at 4 uc and becomes zero at 2 uc. Using the Stoner model, we attributed the T_C decrease to a decrease in the density of states (N_o). Namely, in the thin film geometry, the hybridized Ru $d_{yz,zx}$ orbitals are terminated by top and bottom interfaces, resulting in quantum confinement and reduction of N_o.

Experiment: the story begins (2)

Applied Physics Express **8**, 015502 (2015)

http://dx.doi.org/**10.7567/APEX.8.015502**

Ferromagnetic $SrRuO_3$ thin-film deposition on a spin-triplet superconductor Sr_2RuO_4 with a highly conducting interface

M. S. Anwar[1*], Yeong Jae Shin[2,3], Seung Ran Lee[2,3], Sung Jin Kang[2,3], Yuske Sugimoto[1], Shingo Yonezawa[1], Tae Won Noh[2,3], and Yoshiteru Maeno[1]

[1]*Department of Physics, Graduate School of Science, Kyoto University, Kyoto 606-8502, Japan*
[2]*Center for Correlated Electron Systems, Institute for Basic Science (IBS), Seoul 151-747, Republic of Korea*
[3]*Department of Physics and Astronomy, Seoul National University, Seoul 151-747, Republic of Korea*
E-mail: anwar@scphys.kyoto-u.ac.jp; m.s.anwar476@gmail.com

Received August 25, 2014; accepted November 19, 2014; published online December 10, 2014

Ferromagnetic $SrRuO_3$ thin films are deposited on the *ab* surface of single crystals of the spin-triplet superconductor (TSC) Sr_2RuO_4 as substrates using pulsed laser deposition. The films are under a severe in-plane compressive strain. Nevertheless, the films exhibit ferromagnetic order with the easy axis along the *c*-direction below the Curie temperature of 158 K. The electrical transport reveals that the $SrRuO_3/Sr_2RuO_4$ interface is highly conducting, in contrast with the interface between other normal metals and the *ab* surface of Sr_2RuO_4. Our results stimulate investigations on proximity effects between a ferromagnet and a TSC.

Experiment: the story begins (3)

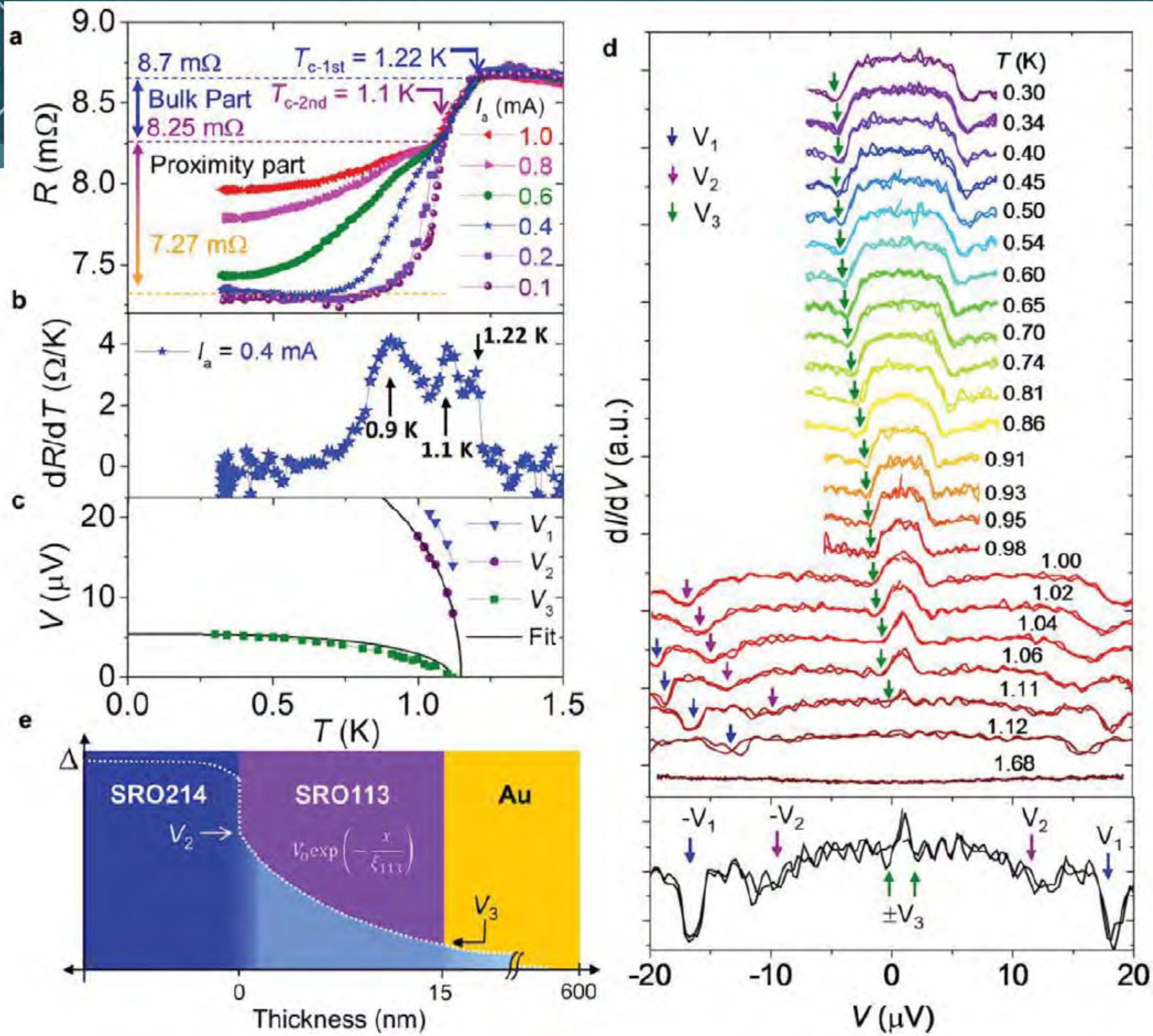
nature COMMUNICATIONS

ARTICLE

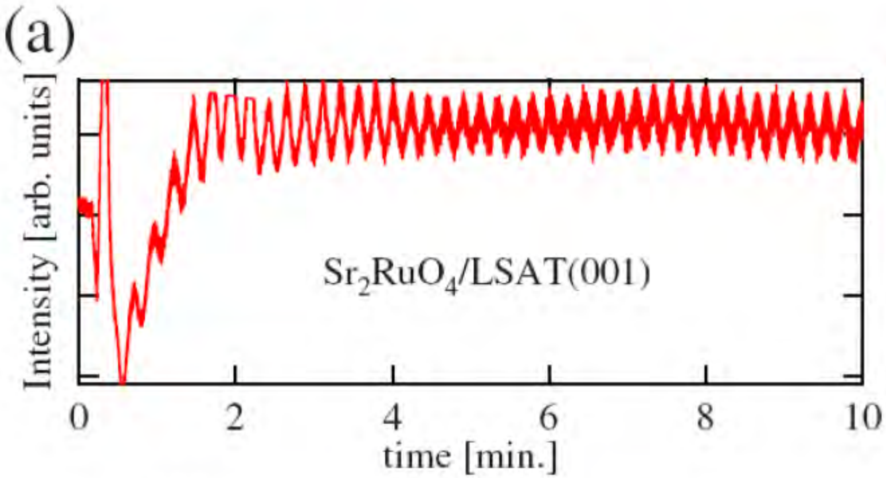
Received 14 Feb 2016 | Accepted 13 Sep 2016 | Published 26 Oct 2016 DOI: 10.1038/ncomms13220 OPEN

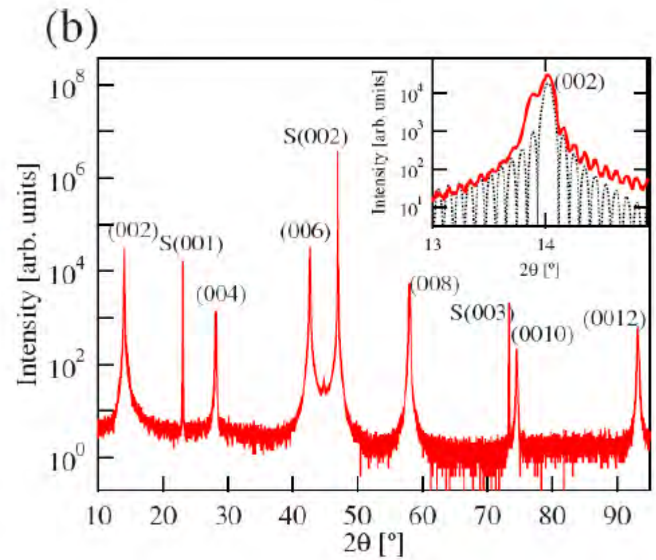
Direct penetration of spin-triplet superconductivity into a ferromagnet in Au/$SrRuO_3$/Sr_2RuO_4 junctions

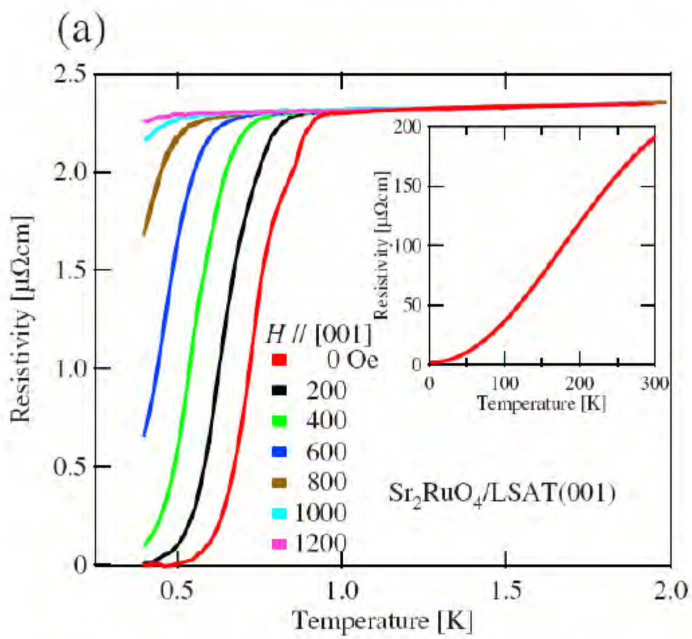
M.S. Anwar[1], S.R. Lee[2,3], R. Ishiguro[4,5,6], Y. Sugimoto[1], Y. Tano[4], S.J. Kang[2,3], Y.J. Shin[2,3], S. Yonezawa[1], D. Manske[7], H. Takayanagi[4], T.W. Noh[2,3] & Y. Maeno[1]

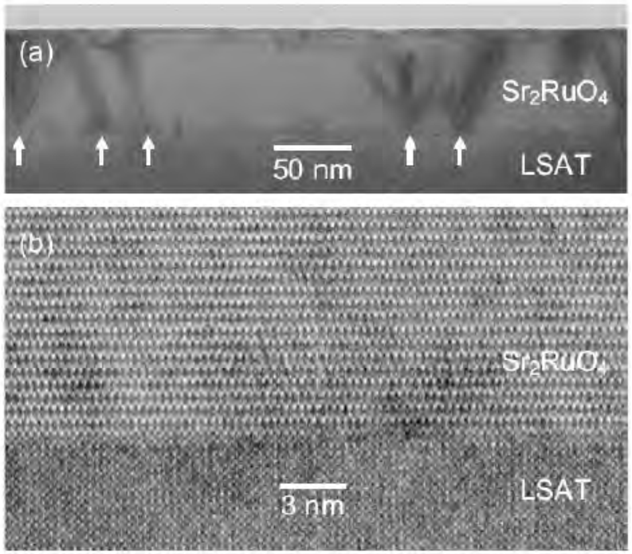

a
b
c
d
e
8.7 mΩ
Bulk Part
8.25 mΩ
Proximity part
7.27 mΩ
$T_{c\text{-}1st}$ = 1.22 K
$T_{c\text{-}2nd}$ = 1.1 K
I_a (mA)
1.0
0.8
0.6
0.4
0.2
0.1
R (mΩ)
I_a = 0.4 mA
0.9 K
1.1 K
1.22 K
dR/dT (Ω/K)
V_1
V_2
V_3
Fit
V (μV)
T (K)
T (K)
0.30
0.34
0.40
0.45
0.50
0.54
0.60
0.65
0.70
0.74
0.81
0.86
0.91
0.93
0.95
0.98
1.00
1.02
1.04
1.06
1.11
1.12
1.68
dI/dV (a.u.)
$-V_1$
$-V_2$
$\pm V_3$
V (μV)
SRO214
SRO113
Au
Δ
$V_0 \exp\left(-\frac{x}{\xi_{113}}\right)$
Thickness (nm)

Experiment: the story begins (4)





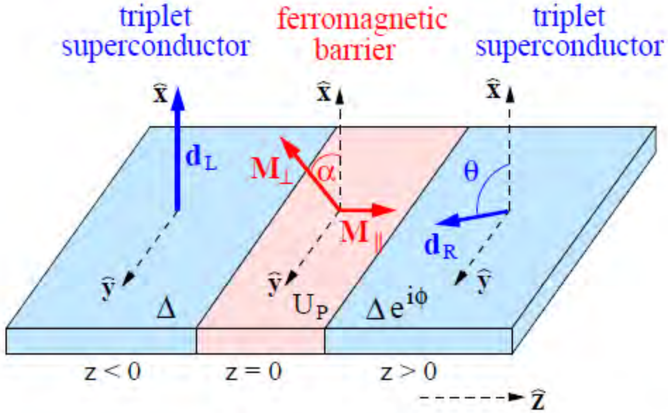


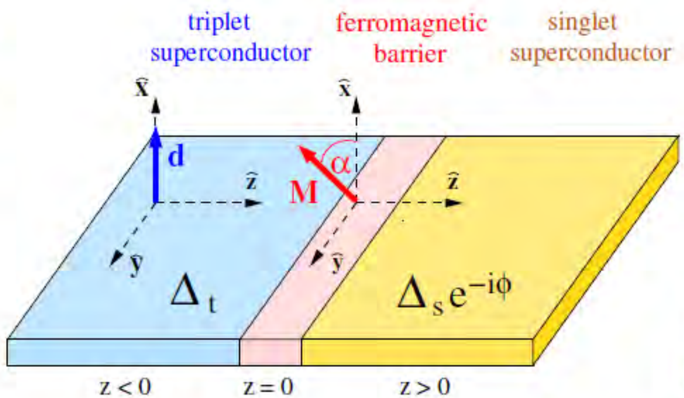


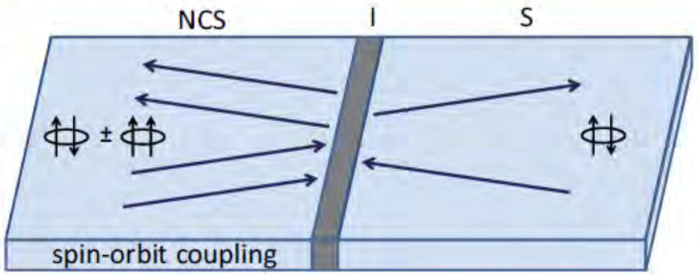
Y. Krockenberger *et al.*, APL **97**, 082502 (2010), Kawasaki lab.

Summary (1): charge current

- spin-preserving tunneling (usual)
- spin-flip tunneling (due to FM moment) NEW!
- reflection at tunneling barrier

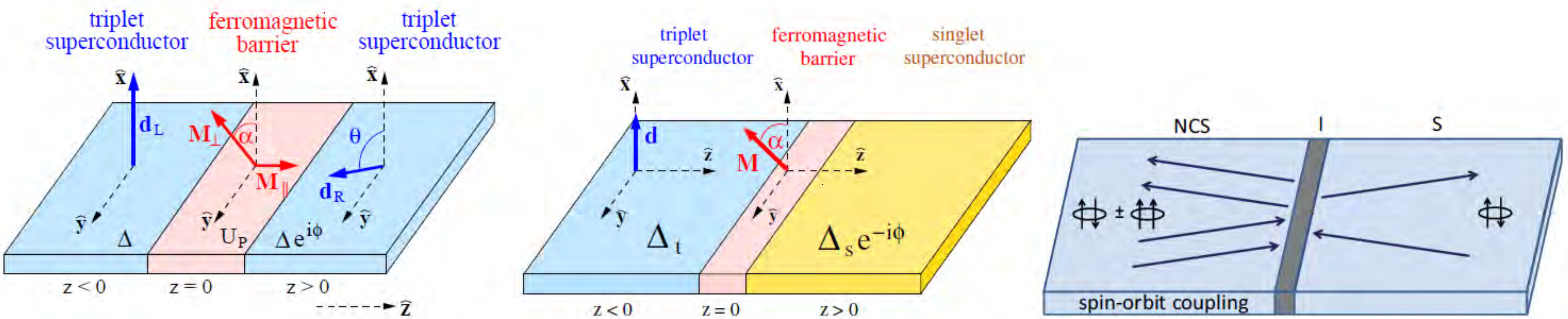






Summary (2): spin current

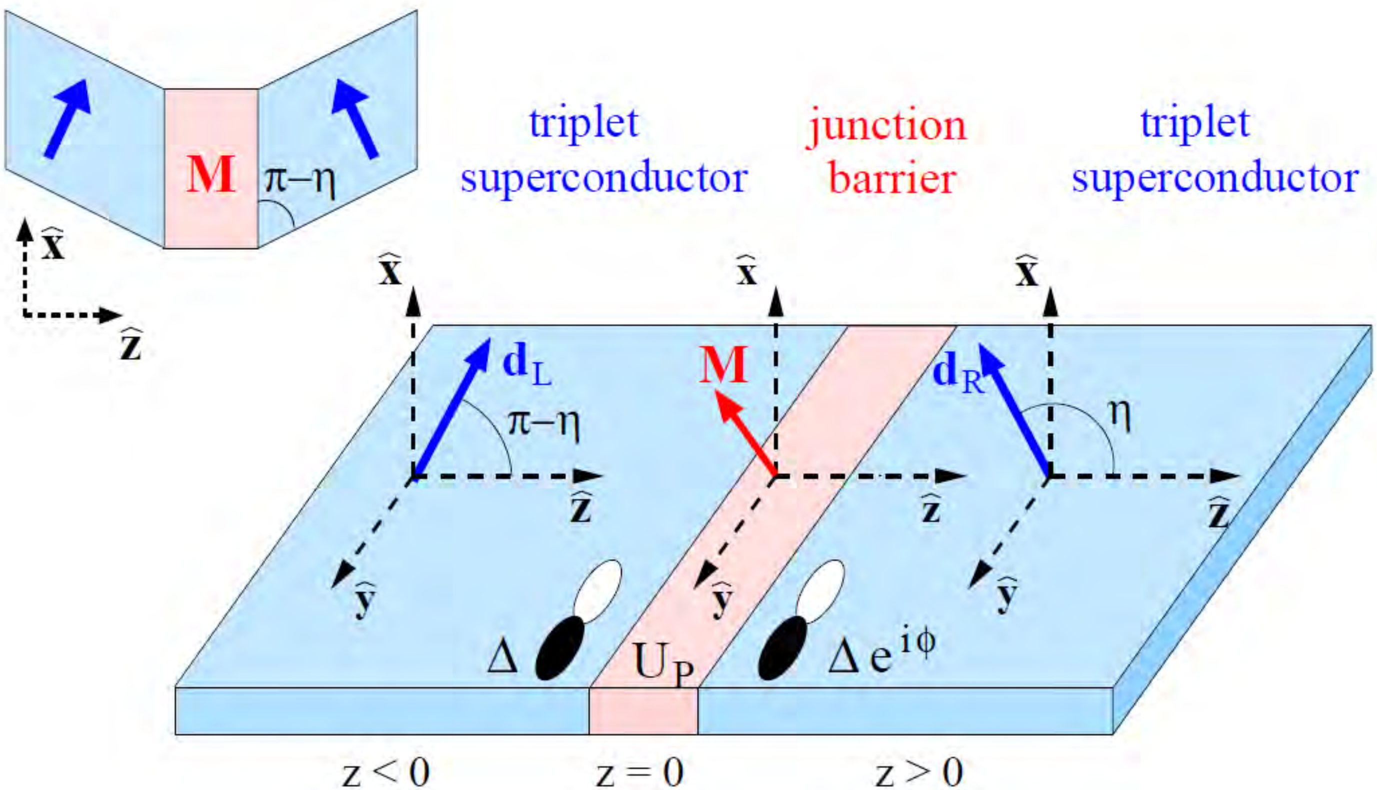
- spin-flipping tunneling barrier
- **d**-vector misalignment (only T-F-T)
- spin-filtering tunneling barrier (only T-F-T)



Summary (3)

What we have discovered from T-F-T junctions (general view):

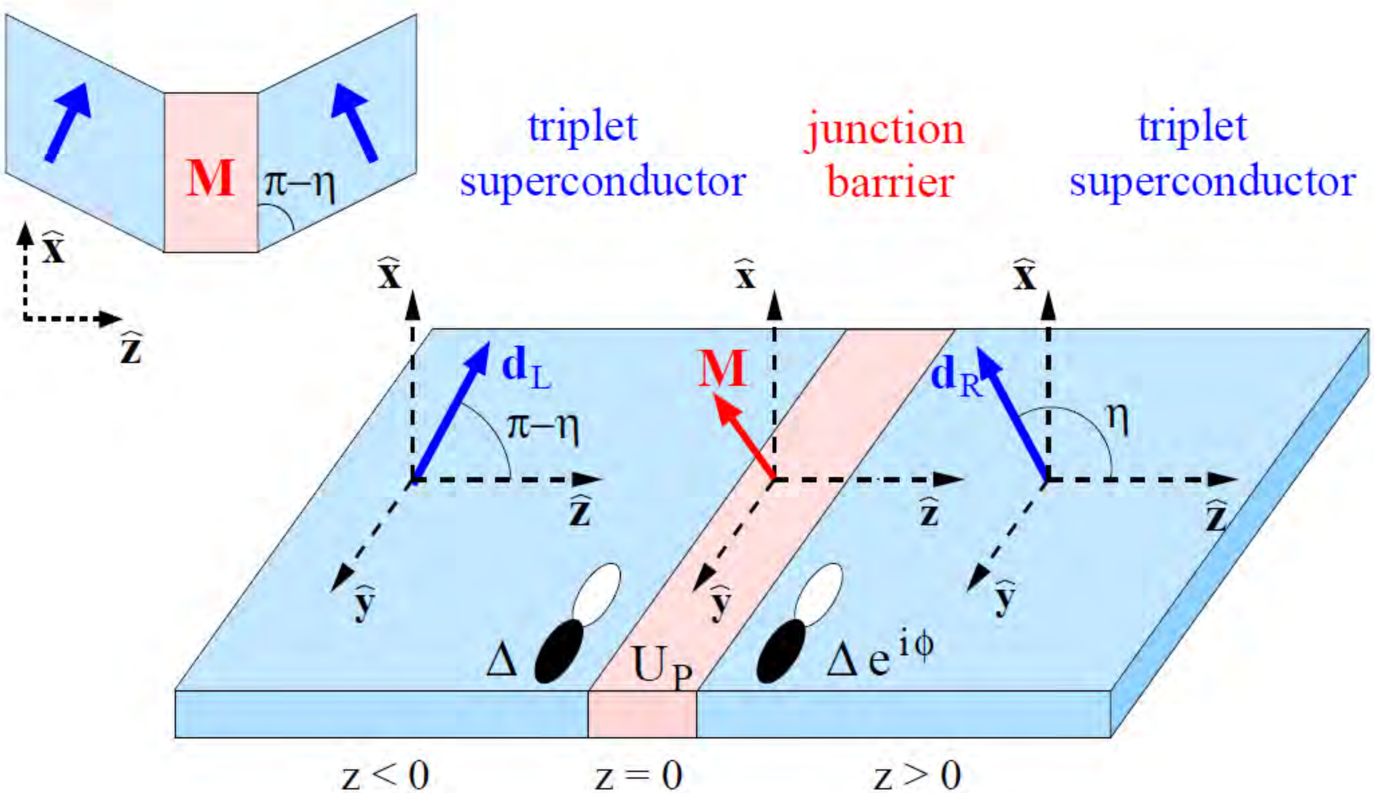
- interdependence of spin and charge degrees of freedom; charge and spin currents; 'universal' 0-π transition
- fractional state with $I_J \neq 0$ at $\phi = 0$



Summary (3)

What we have discovered from T-F-T junctions (general view):

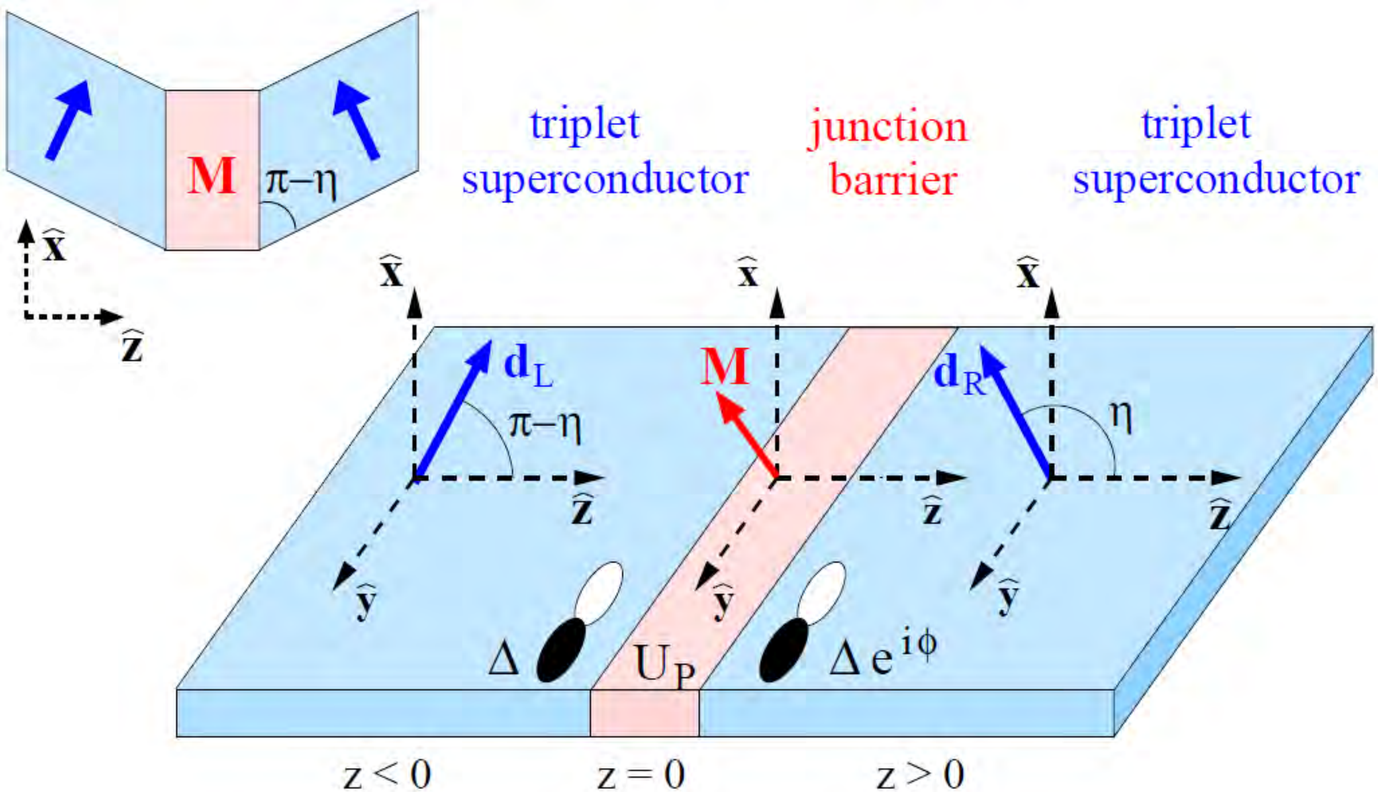
- instability of the tunneling barrier to a magnetic state; fractional flux quanta at the junction
- novel functionality of the barrier material



Summary (3)

What we have discovered from T-F-T junctions (general view):

- Cooper pair spin opens a new degree of freedom in Josephson physics ⇒ superconductor spintronics
- proposed a prototypical magnetic triplet Josephson junction ⇒ playground for new physics



Summary (4): interface effects

Proximity Effects

→ Spatial Variations of the Induced OPs (with or without oscillations)
→ Induced Non-Trivial Magnetic Profile

Inverse Proximity Effects

→ Reorientation of the *d*-vector
→ Induced Spin-Polarization
→ Modification of the Edge States

Experimental Predictions

→ Oscillating or Monotonous decreasing of the Critical Current: Evidence of the 0-π Transitions
→ Existence of an induced Spin-Active Interface
→ Tuning of the Edge Currents at the TTSC interface
→ Modulation of the Total Spin-Polarization

Thank you!