



# Magnetic exchange through *s*- and *d*-wave superconductors

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**S/F oxides**



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**Pair conversion**



Dr Guang Yang  
**Non-local spin-valves**



Dr Xavier Montiel  
**S/F Theory**



Lauren McKenzie-Sell  
**Spin-pumping S/F**



Graham Kimbell  
**Oxide interfaces**



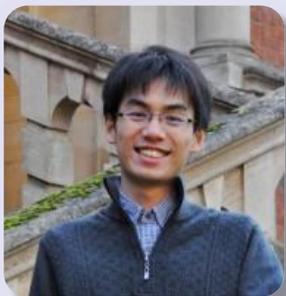
Ben Stoddard-Stones  
**Quasiparticle injection**



Linde Olde Olthof  
**S/F Theory**



Harry Bradshaw  
**Rare-earth interfaces**



Hisakazu Matsuki  
**Spin-pumping S/F**



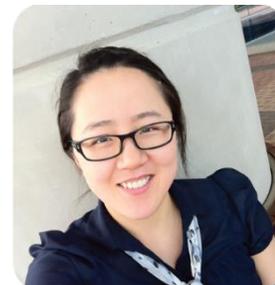
James Devine-Stoneman  
**Triplet spin-mixers**



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**(University of Konstanz)**



Dr. Kun-Rok Jeon  
**(Max Planck)**



Dr. Mi-Jin Jin  
**(Dankook University)**



**Prof. Mark Blamire**  
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University College London



**Prof. Lesley Cohen**  
Imperial College London



**Dr. Kohei Ohnishi**  
Kyushu University



**Dr. Zhanna Devizorova**  
Moscow



**Dr. Sergey Mironov**  
Nizhny Novgorod



**Prof. Alexander Buzdin**  
University of Bordeaux



**Prof. Mario Cuoco**  
University of Salerno



**Prof. Matthias Eschrig**  
University of Greifswald



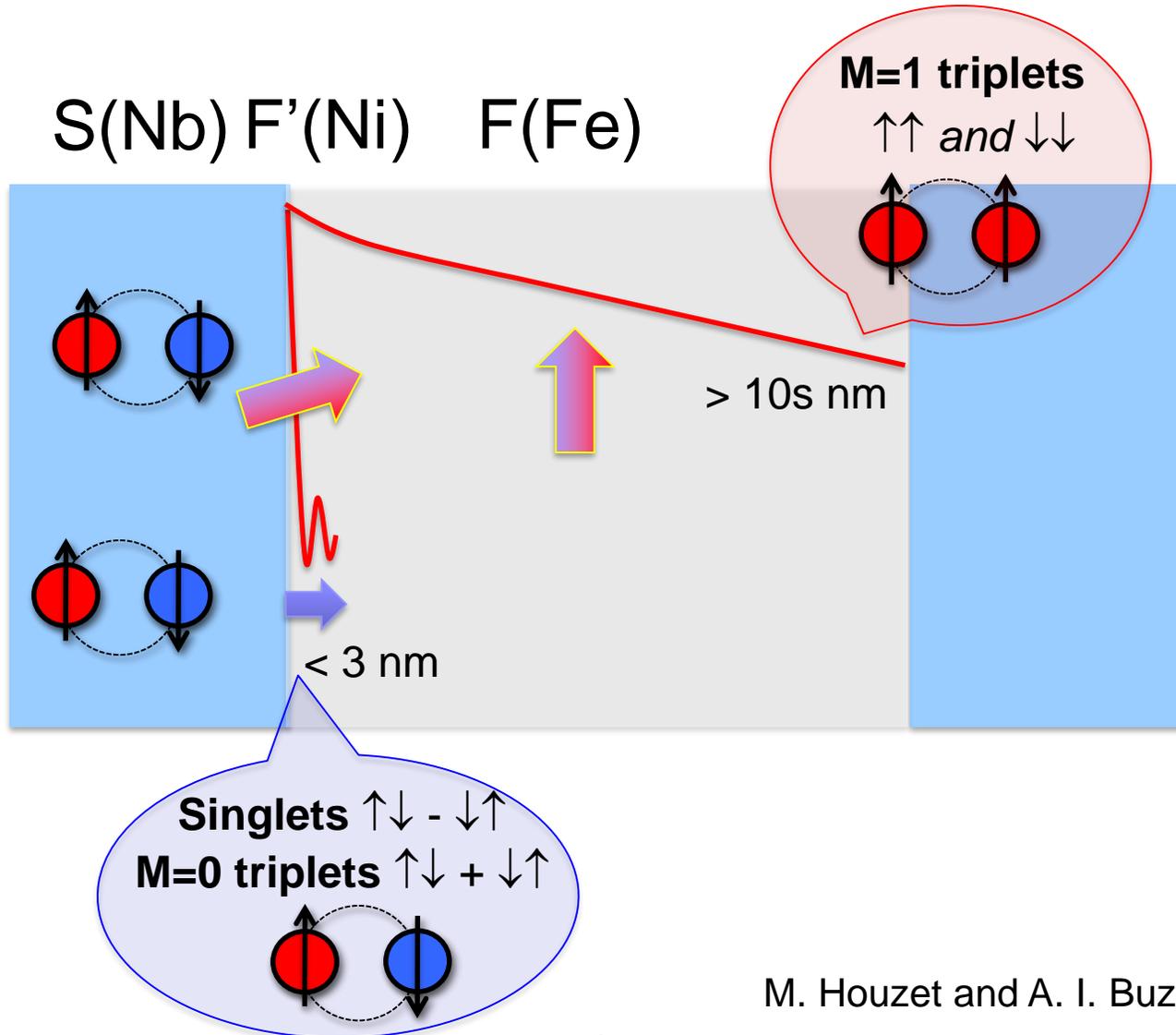
Engineering and Physical Sciences  
Research Council



**SS**

Oxide Superspin  
Core-to-Core Programme

# Creation of spin-polarized (triplet) Cooper pairs



$$|\psi\rangle = \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$

$$k_F^\uparrow - k_F^\downarrow = Q$$

$$|\psi\rangle = \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle e^{iQx} - |\downarrow\uparrow\rangle e^{-iQx})$$

$$= \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle) \cos(Qx) + \frac{i}{\sqrt{2}} (|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle) \sin(Qx)$$

Both are short range

rotation

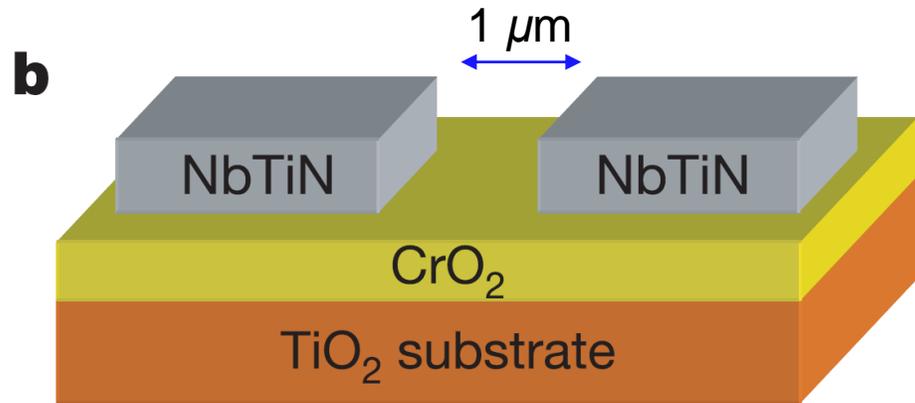
$$|\uparrow\uparrow\rangle ; |\downarrow\downarrow\rangle$$

Long range

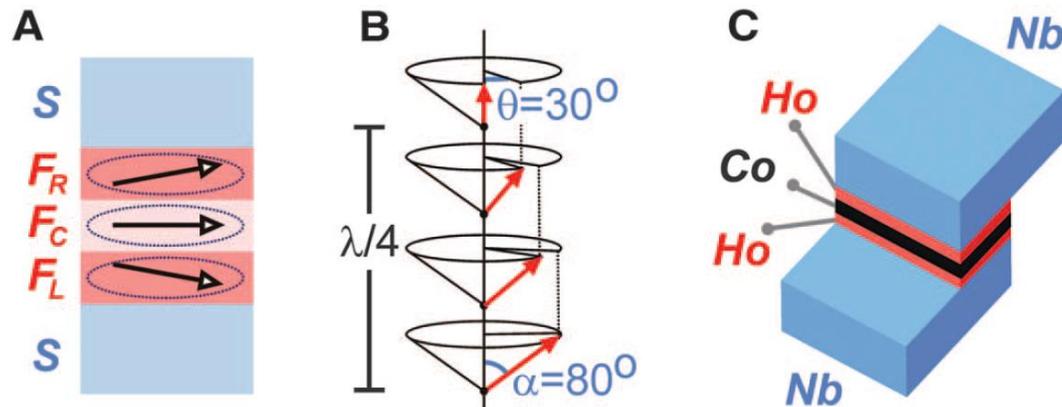
M. Houzet and A. I. Buzdin PRB(R) **74**, 214507 (2007).

F. S. Bergeret, A. F. Volkov, and K. B. Efentov PRL **86**, 3140 (2001).

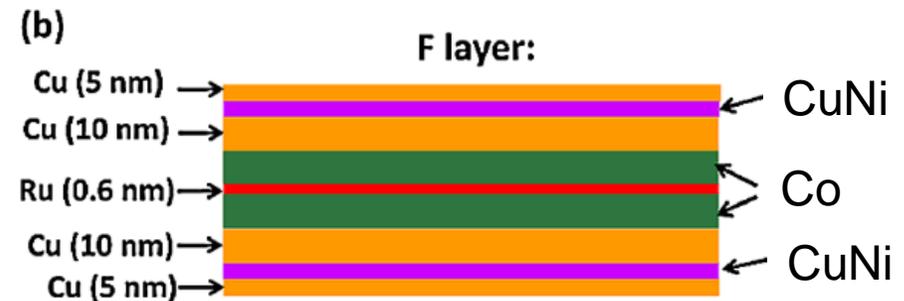
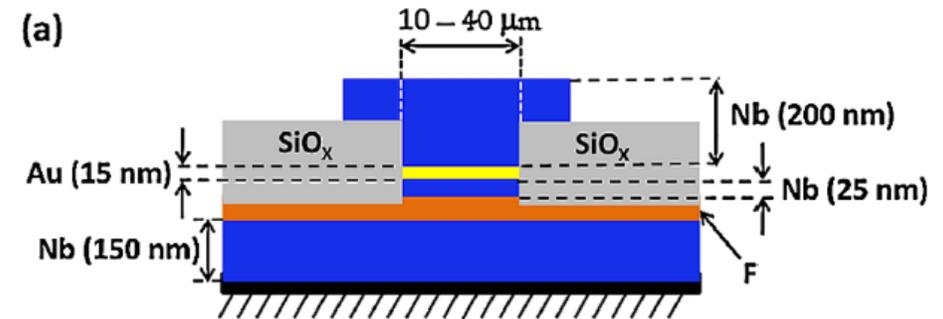
# Earlier observations of triplet Cooper pairs



R. S. Keizer *et al*, Nature **439**, 825 (2006)  
 M. S. Anwar *et al*, PRB **82**, 100501 (2010)

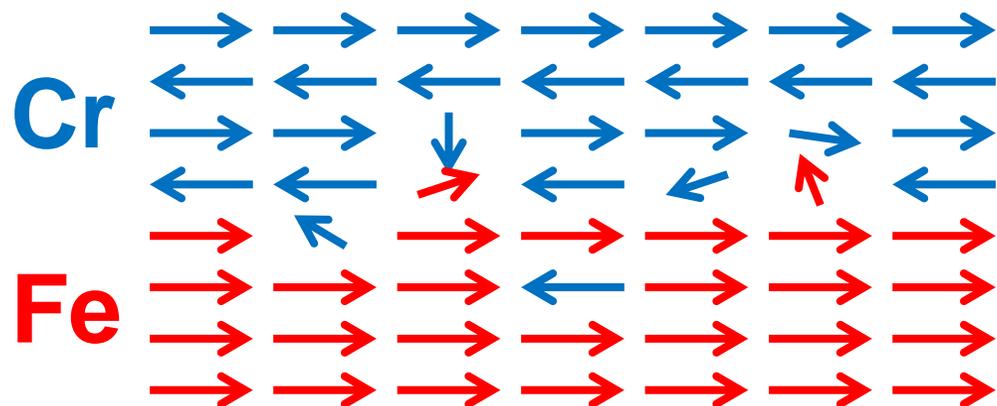


J. Robinson *et al*, Science **329**, 59 (2010)



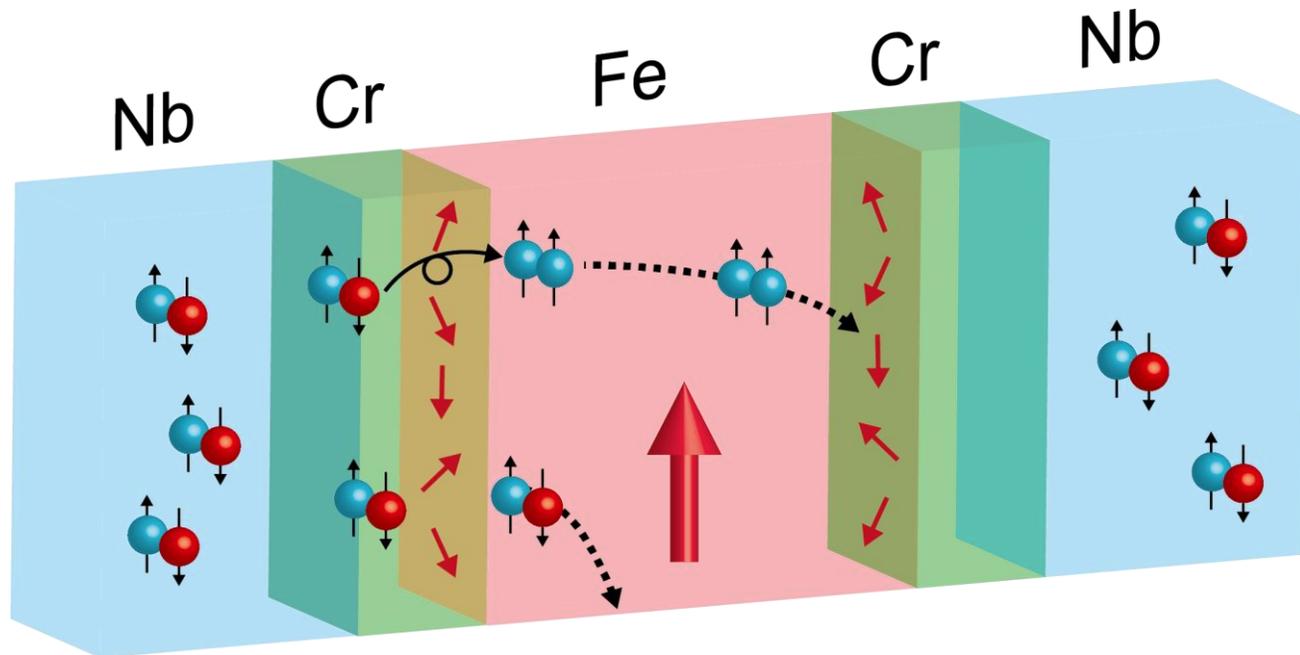
T. S. Khaire *et al*, PRL **104**, 137002 (2010)

# Pair conversion at Cr/Fe interfaces



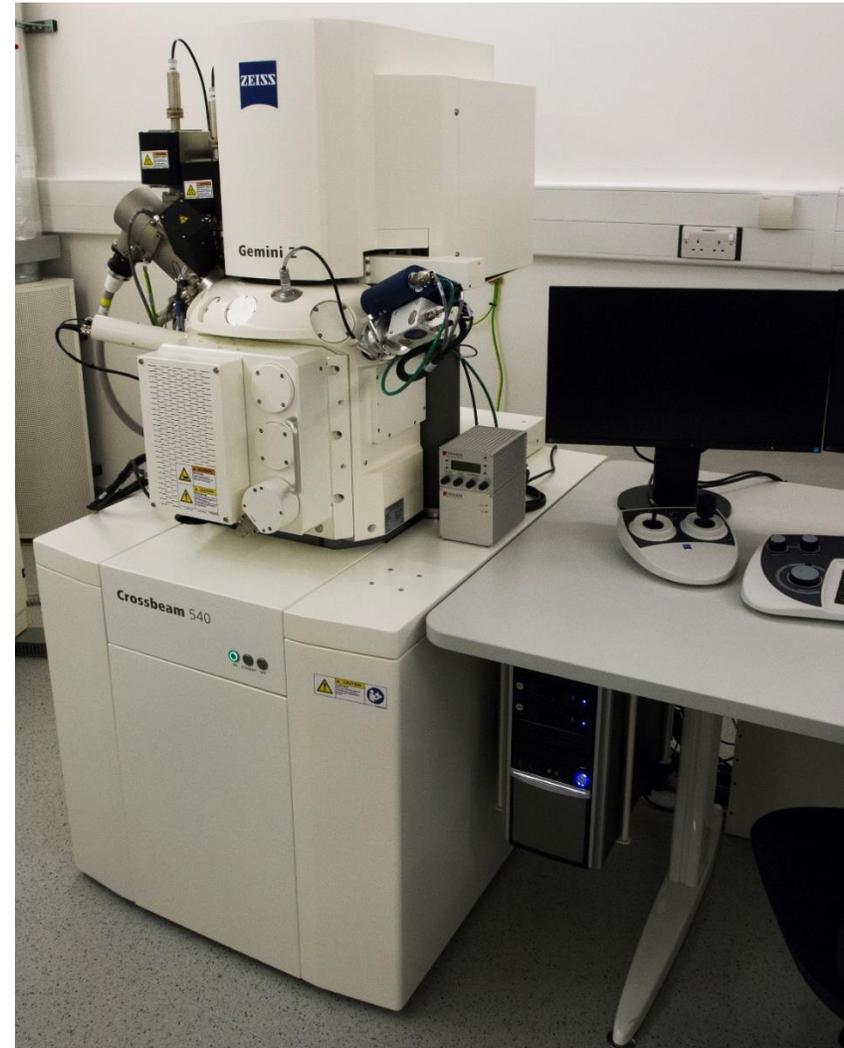
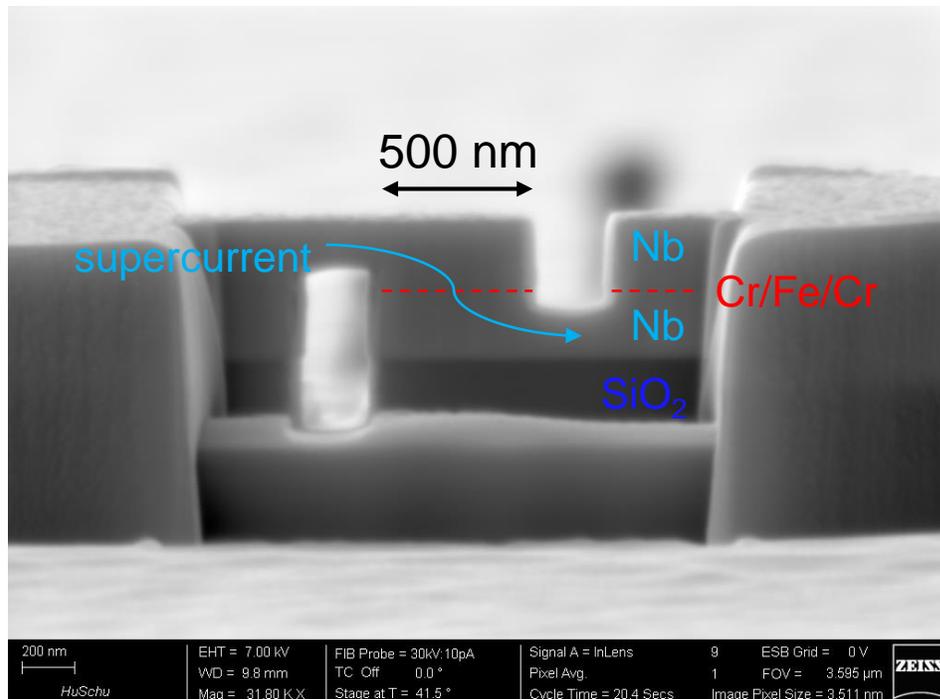
Randomly oriented magnetizations at Cr/Fe interfaces (spin-glass state)

S. K. Burke *et al*, J. Phys. F **13**, 441 (1983).  
 J. Robinson *et al*, PRB **89**, 104505 (2014).



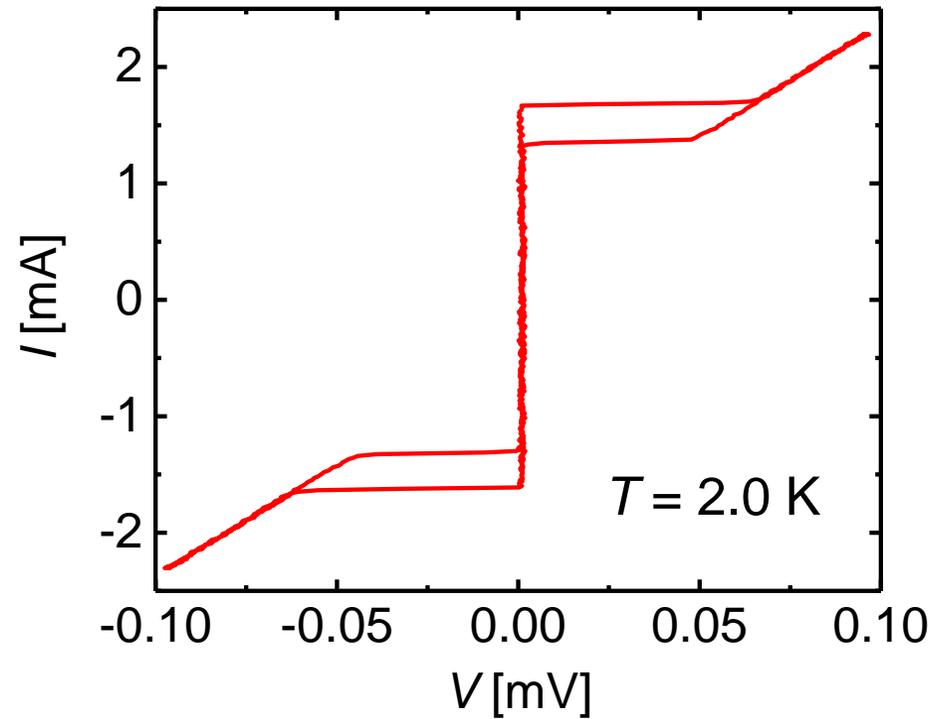
# Fabrication of nano superconducting devices

- DC magnetron sputtering
- Photolithography + Ar ion milling
- Nanopillar fabrication using FIB ( $50 \times 50 \text{ nm}^2 \sim 500 \times 500 \text{ nm}^2$ )

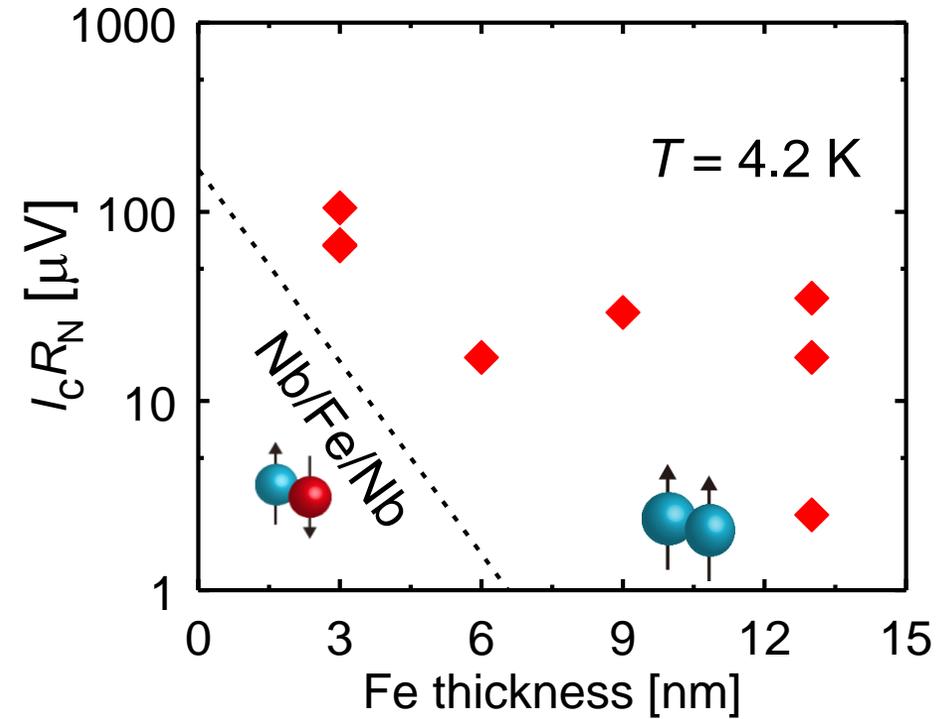


# Long-range triplet supercurrent

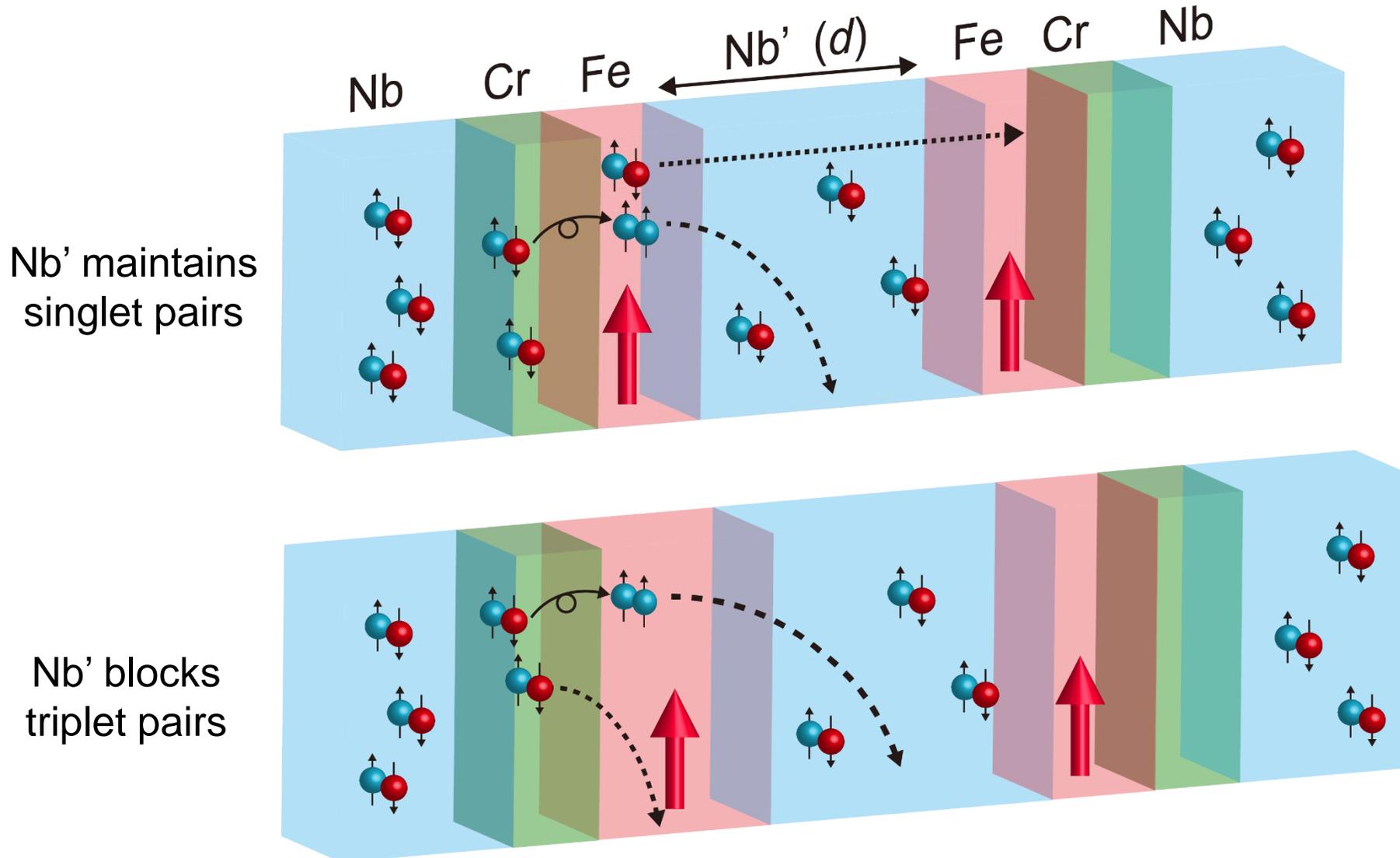
Nb/Cr(1nm)/Fe(9nm)/Cr(1nm)/Nb



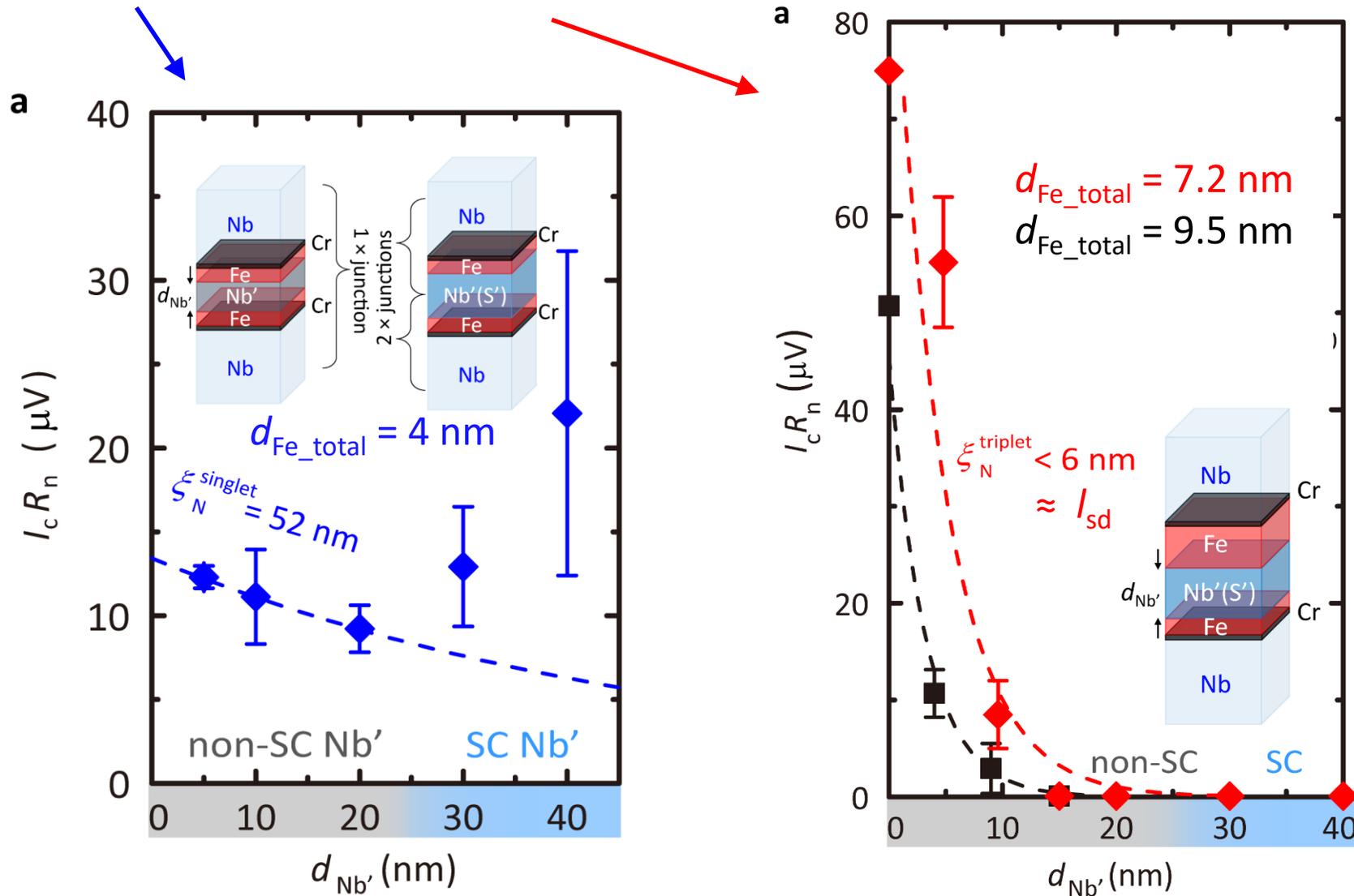
Nb/Cr(1)/Fe(x)/Cr(1)/Nb



# Superconducting blocking of triplet supercurrents

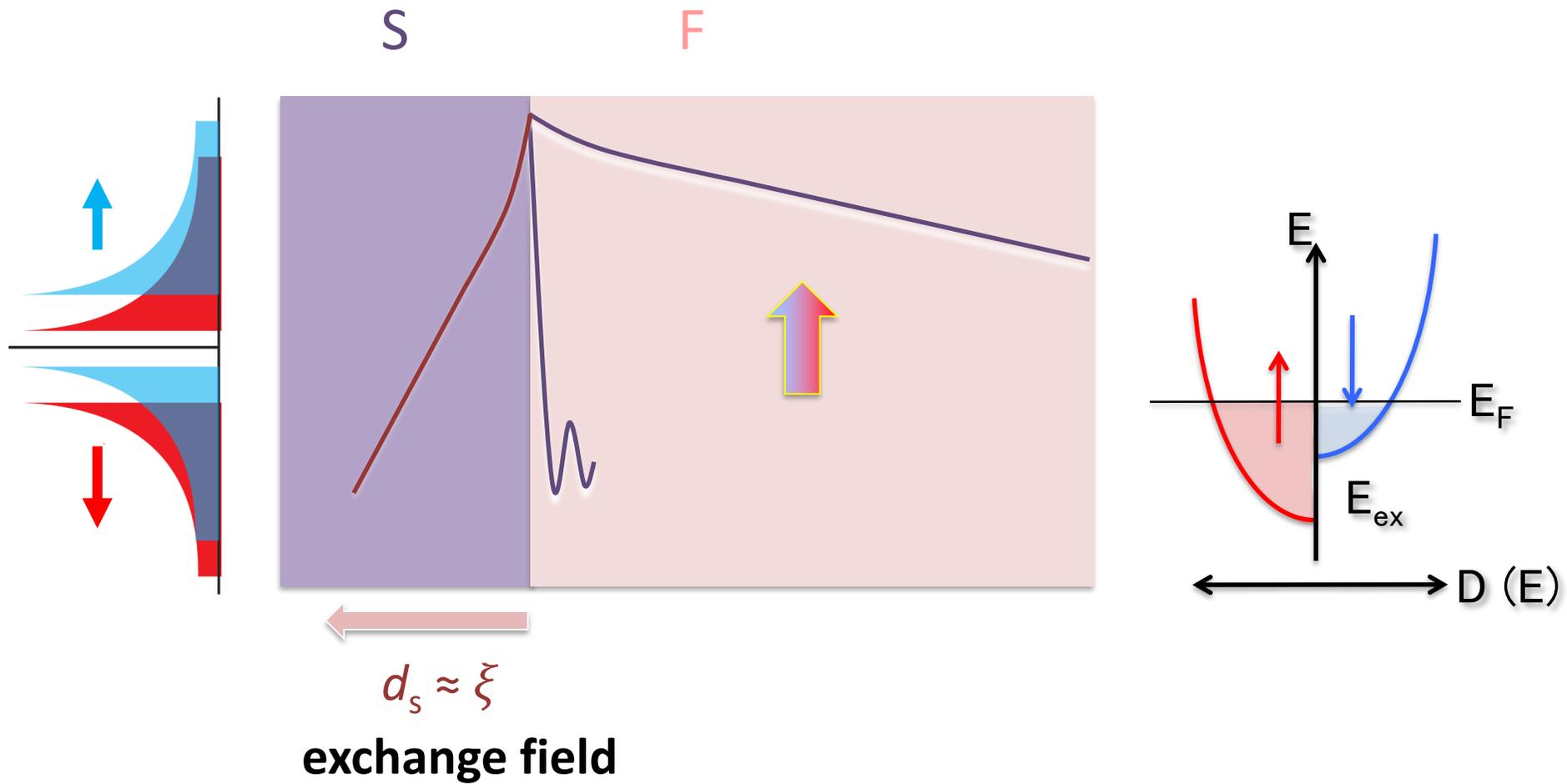


# Singlet ( $\uparrow\downarrow$ ) and triplet ( $\uparrow\uparrow$ ) supercurrents in Nb' interlayer



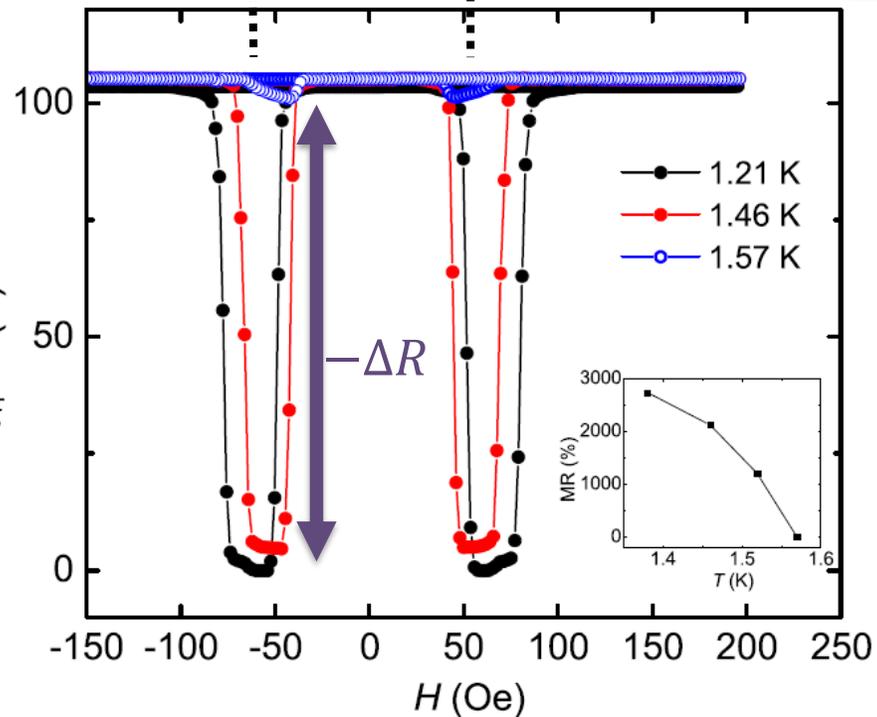
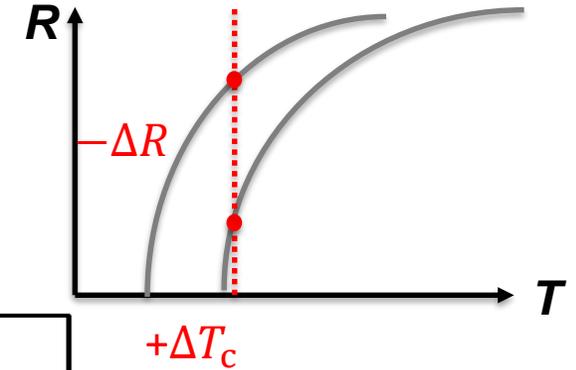
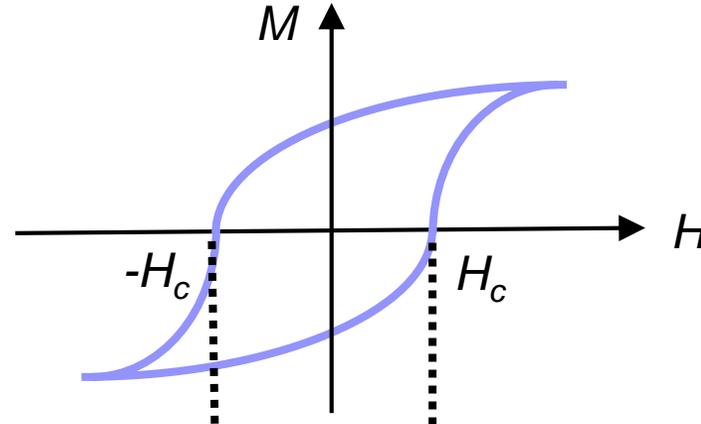
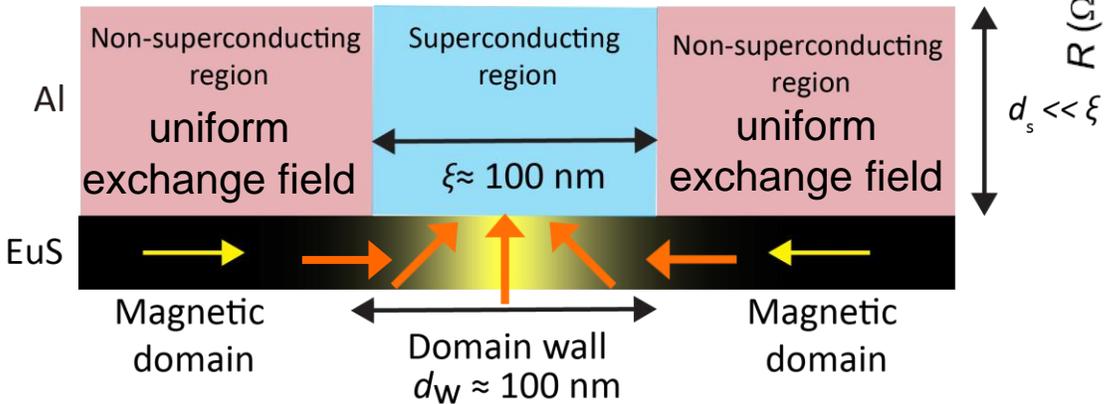
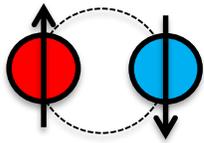
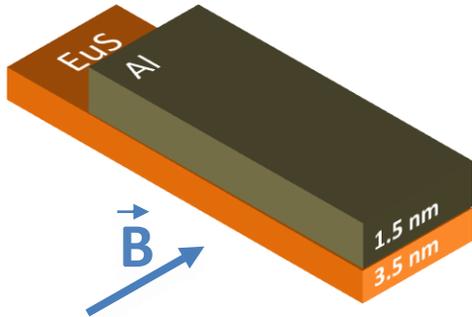


# Inverse proximity effect



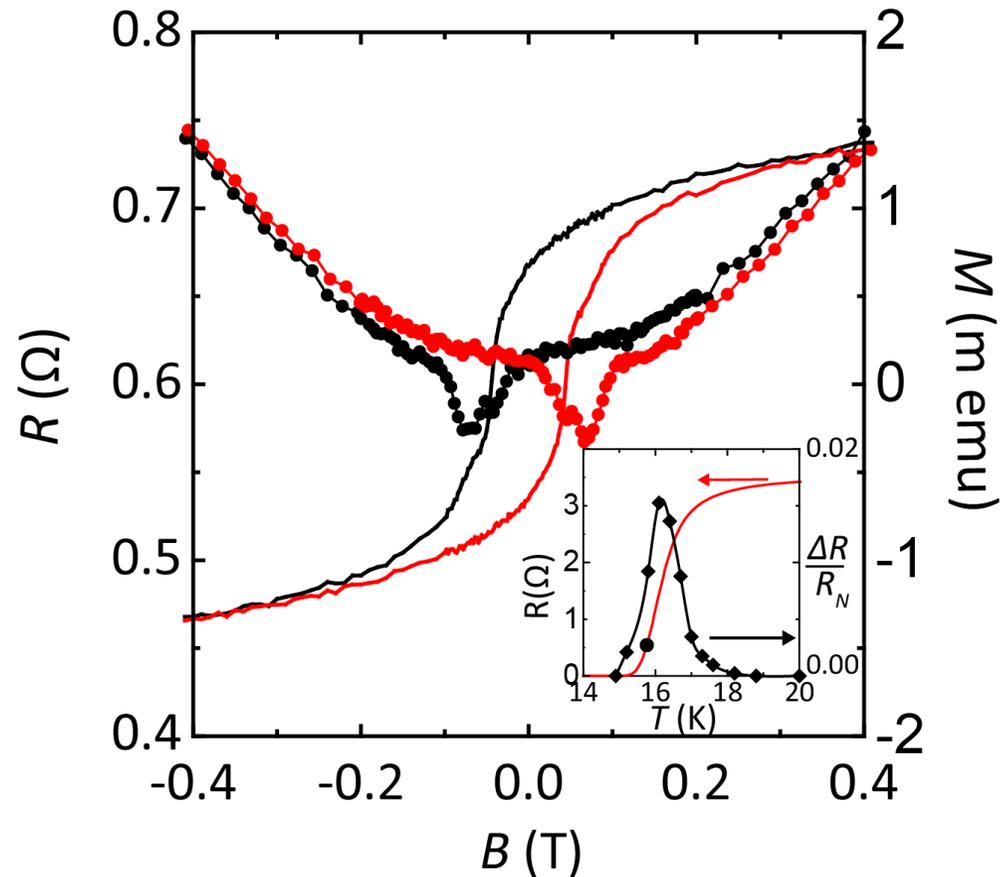
# Inverse proximity effect at a metal S/FI interface

Al(1.5 nm)/EuS(3.5 nm)



B. Li *et al.*, PRL **110**, 097001 (2013).

# Inverse proximity effect at an oxide S/FI interface

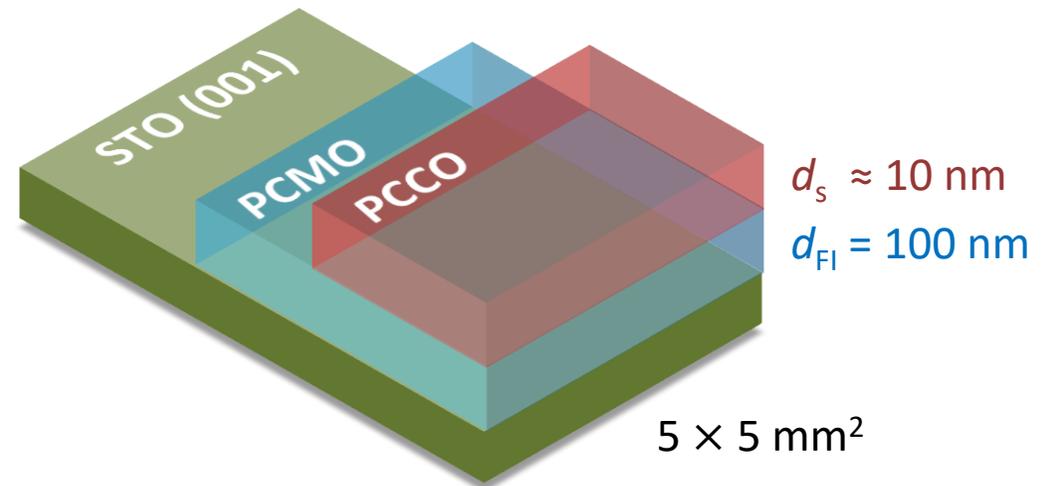


$\text{Pr}_{1.85}\text{Ce}_{0.15}\text{CuO}_{4-\delta}$  (PCCO)

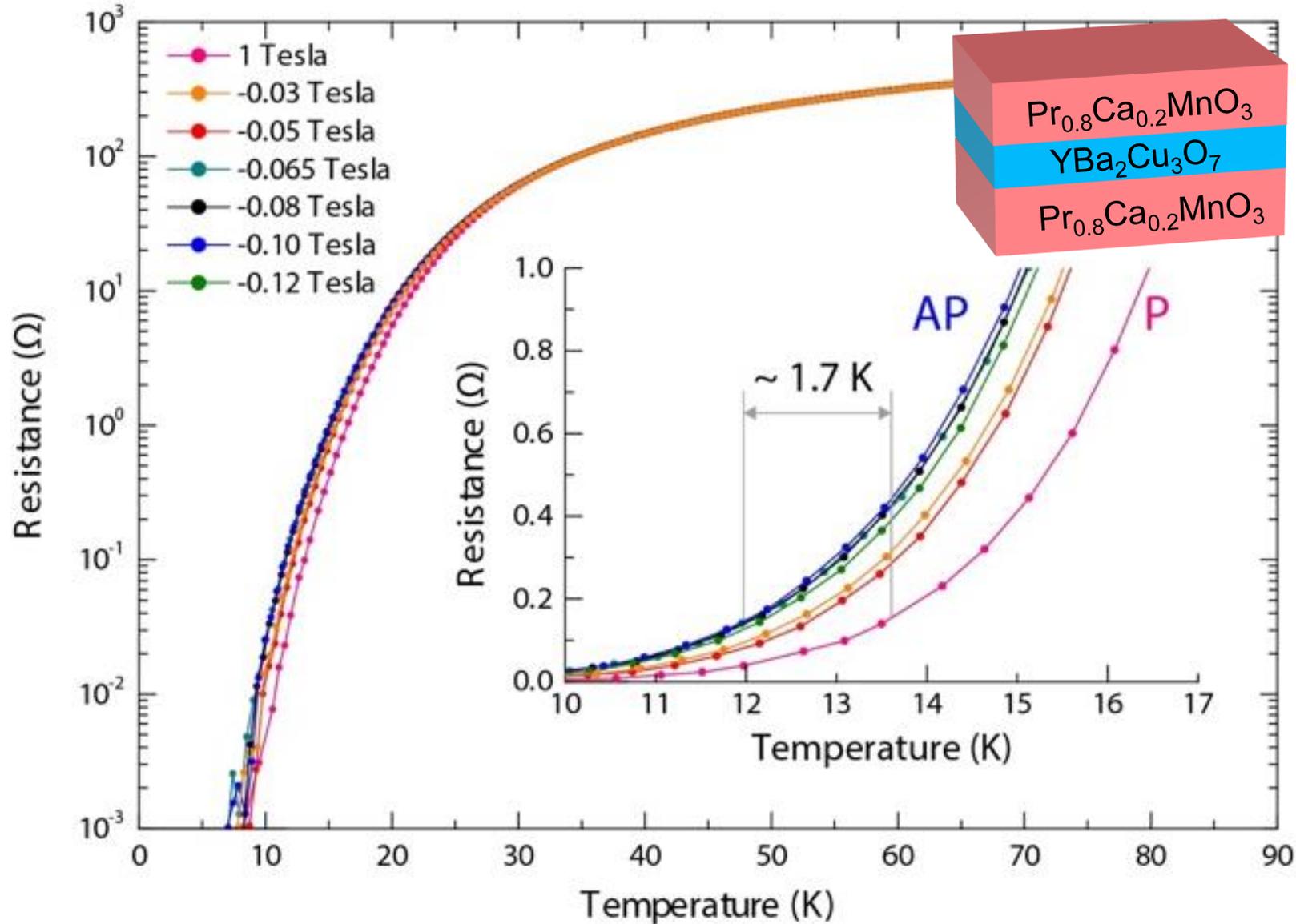
$\xi_{ab} \sim 10$  nm

$\text{Pr}_{0.8}\text{Ca}_{0.2}\text{MnO}_3$  (PCMO)

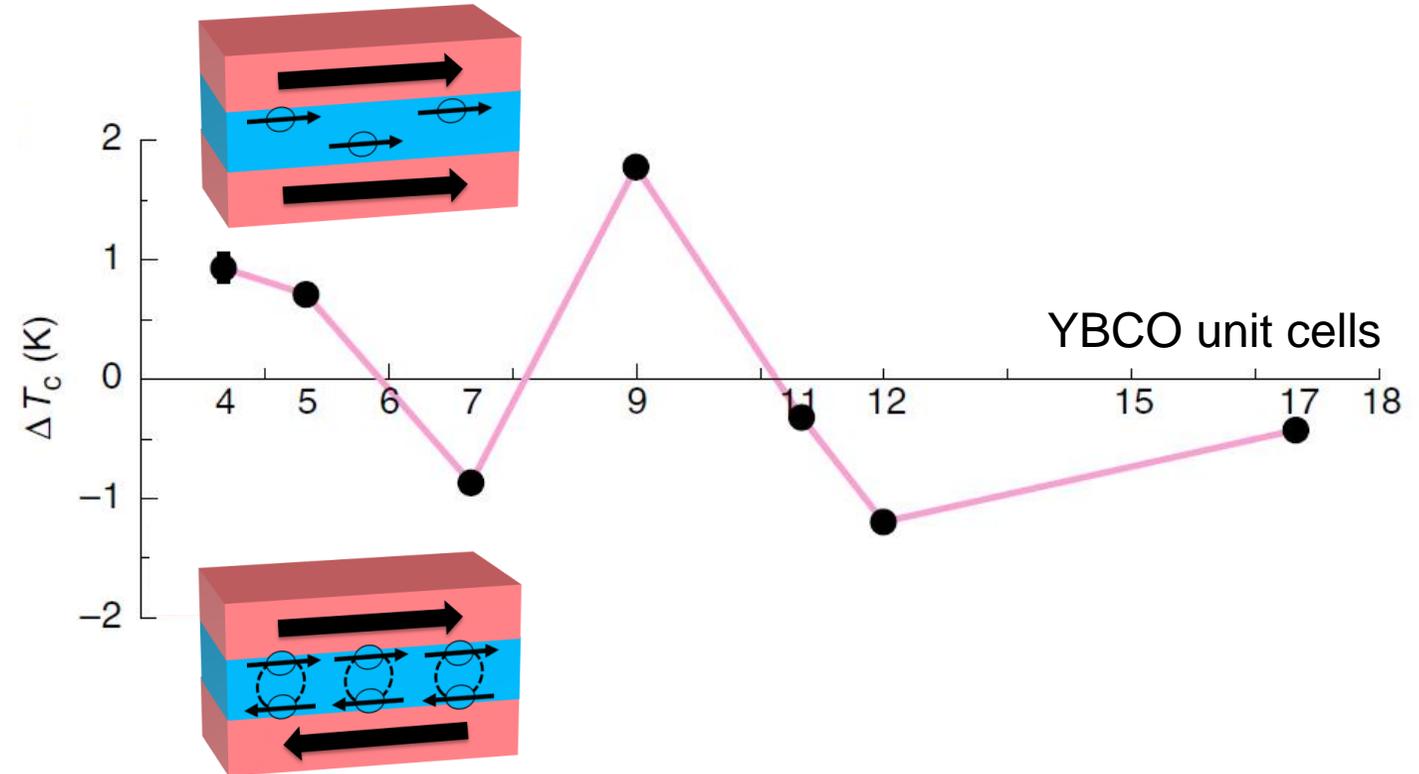
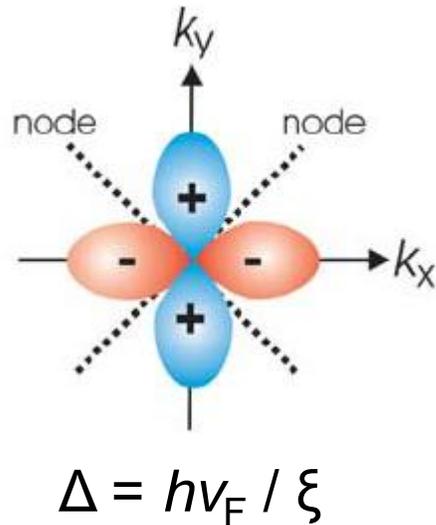
Domain wall width  $d_w \sim 20$  nm ( $T = 10$  K)



# FI/S/FI oxide spin-valve

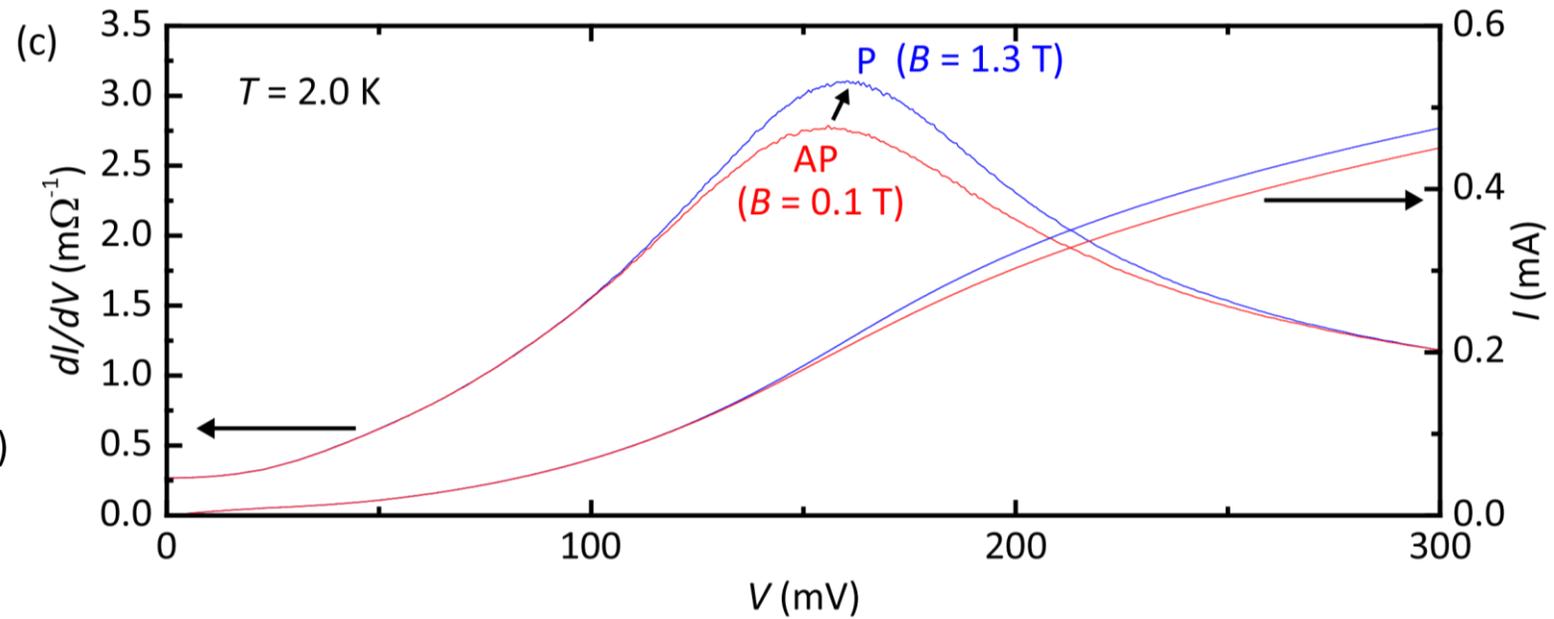
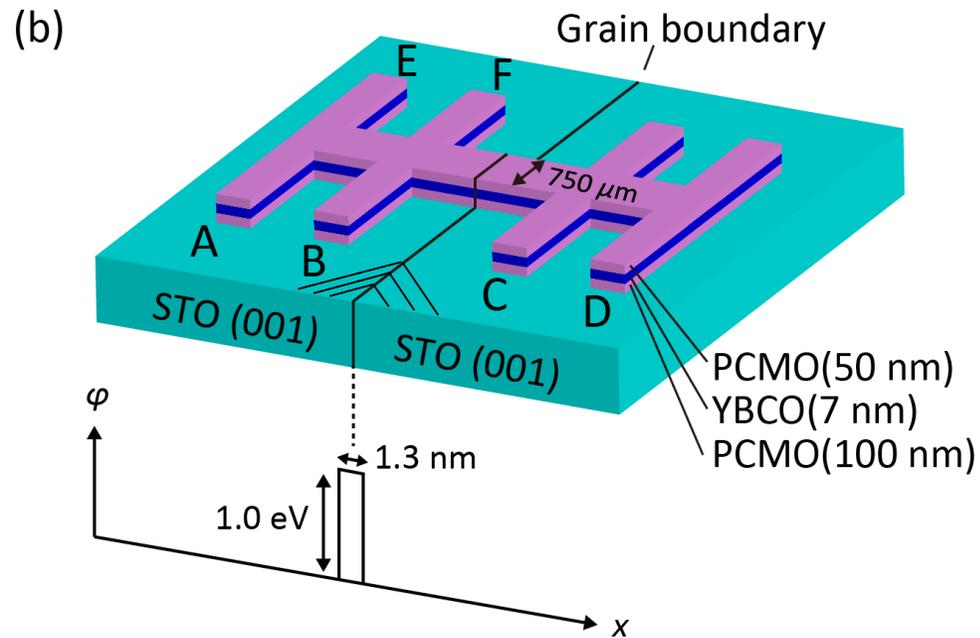


# Long-range exchange interaction

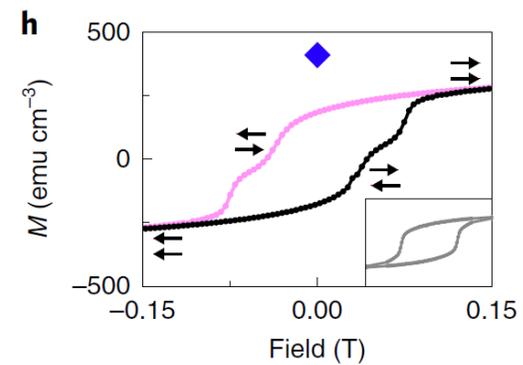
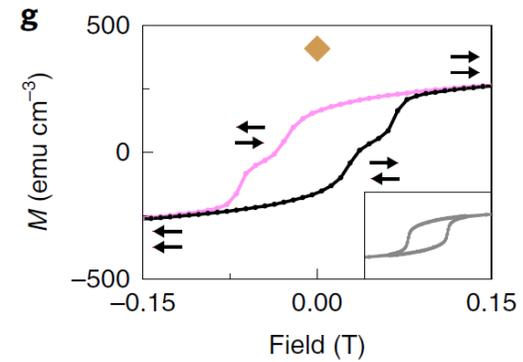
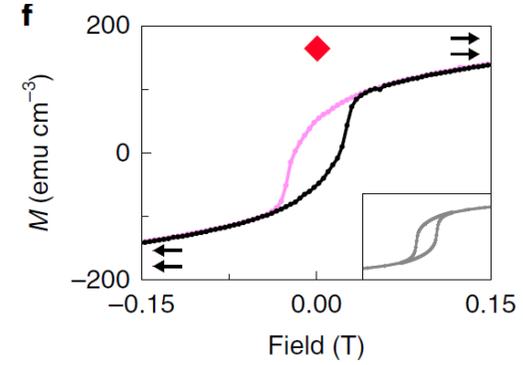
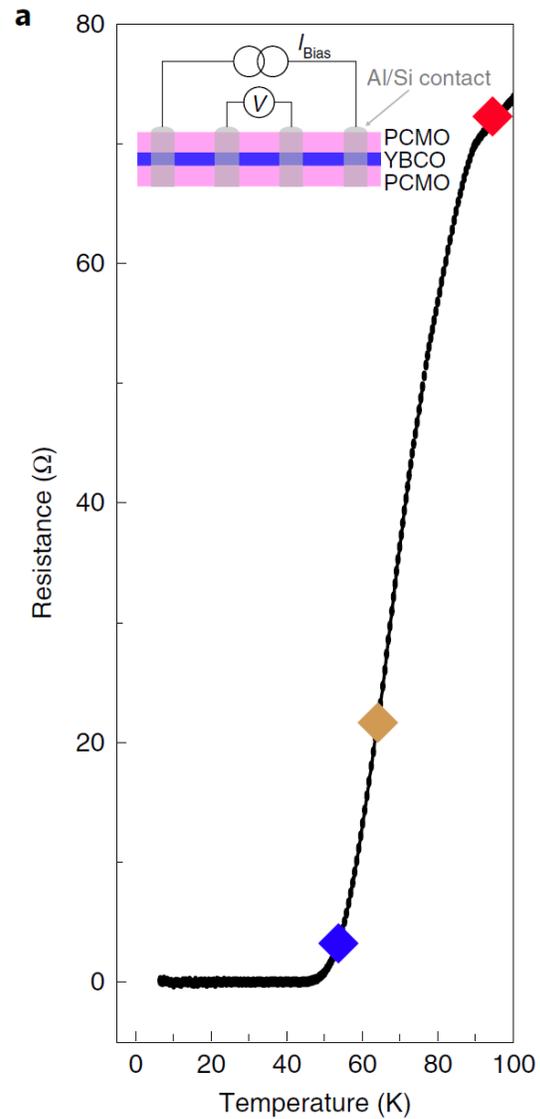


A. Di Bernardo, S. Komori, G. Livanas, G. Divitini, P. Gentile, M. Cuoco, J. W. A. Robinson, **Nat. Mater.**, **18**, 1194 (2019).

# Tunneling spectroscopy for a superconducting spin-valve



# Superconducting control of magnetizations



# Summary

- Spin-polarized triplet pairs created at Cr/Fe interfaces

  - Long range penetration into a ferromagnet

  - Strong suppression in a singlet superconductor

S. Komori, J. M. Devine-Stoneman, K. Ohnishi, G. Yang, Zh. Devizorova, S. Mironov, X. Montiel, L. A. B. Olde Olthof, L. F. Cohen, H. Kurebayashi, M. G. Blamire, A. I. Buzdin, J. W. A. Robinson, **arXiv:2006.16654**

- Unconventional exchange coupling at oxide S/F interfaces

  - Long-range penetration of magnetic exchange fields into a *d*-wave S

  - Superconducting control of magnetization

A. Di Bernardo, S. Komori, G. Livanas, G. Divitini, P. Gentile, M. Cuoco, J. W. A. Robinson, **Nat. Mater.**, **18**, 1194 (2019).

S. Komori, A. Di Bernardo, A. I. Buzdin, M. G. Blamire, J. W. A. Robinson, **Phys. Rev. Lett.**, **121**, 077003 (2018).